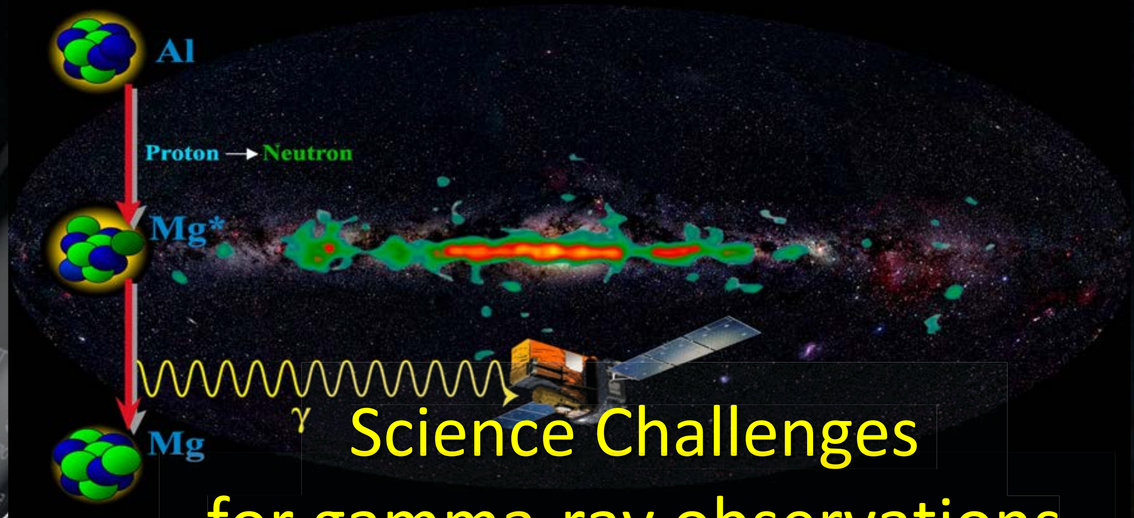


Science Challenges for gamma-ray observations at MeV energies

Roland Diehl

Technical University München and
MPE and Origins Cluster emeritus

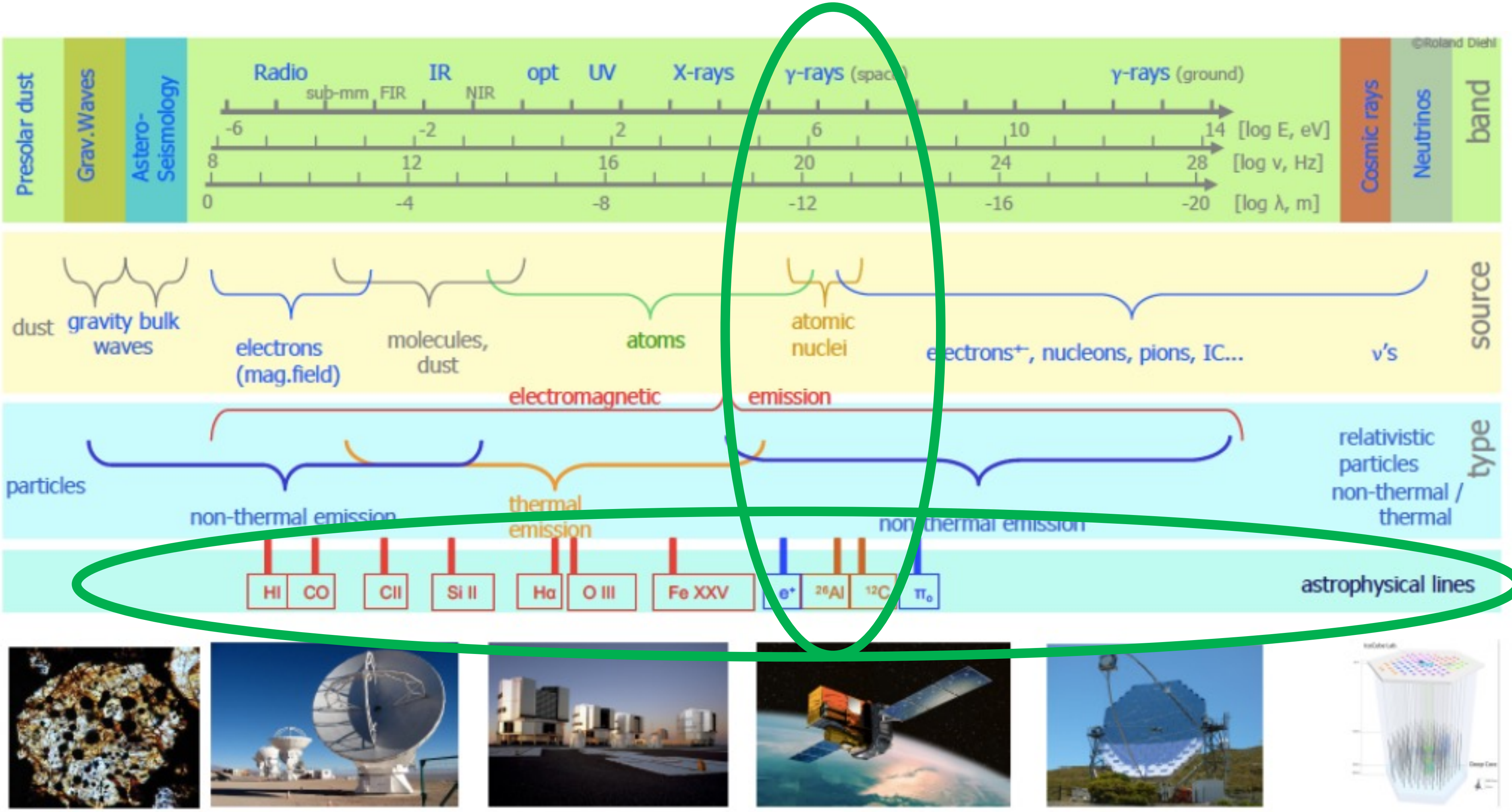
Contents:

1. Science across astrophysical messengers
2. Positrons: particles with a 0.5 MeV signal
3. Relativistic particles: sources and propagation
4. Explosions: a diversity, need for a diversity of tools
5. Stellar evolution: a remaining challenge
6. Ejecta flows and cosmic chemical evolution
7. Science goals of a next MeV γ-ray line mission

with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

Figure: ChETEC 2021

Astronomy with ~MeV lines : a new case with broad implications

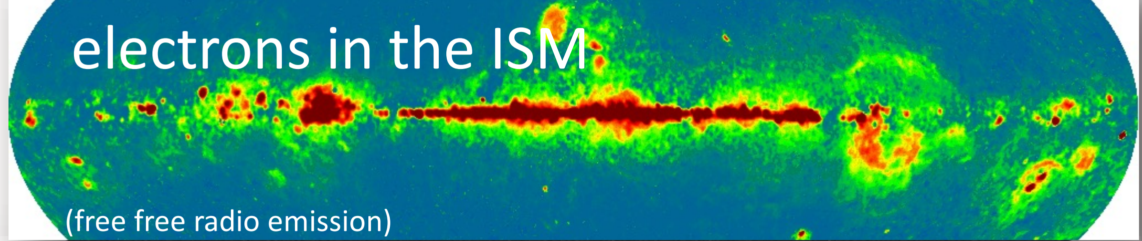


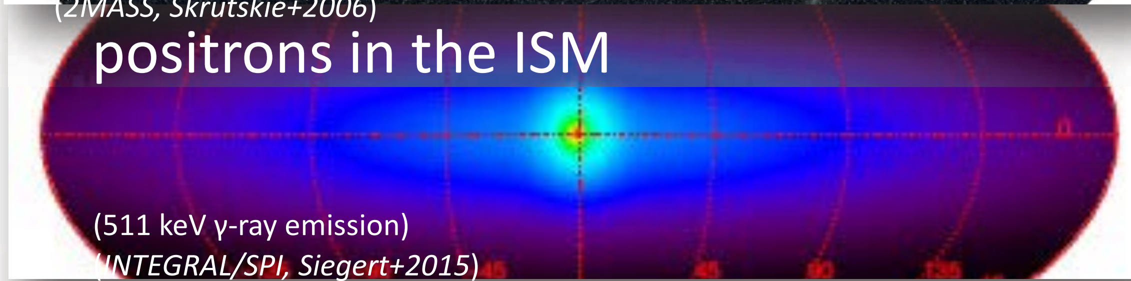
Ways to argue science goals...

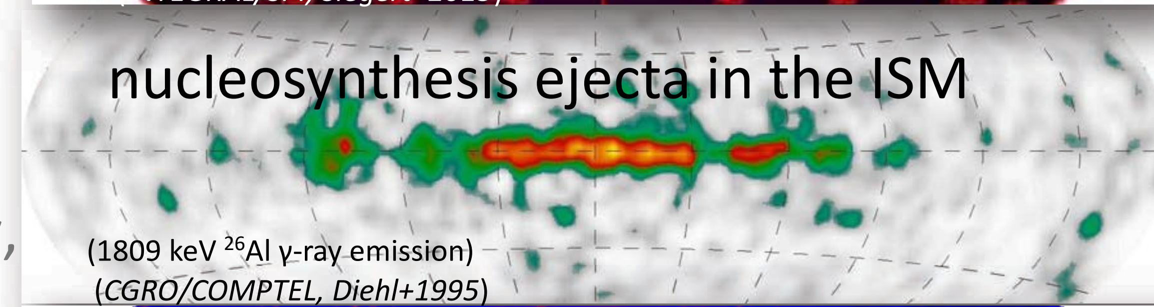
- "Target Science"
    - ☞ A convincing case where a mission will "solve" an open science issue
  - ☆ Nice way to convey concisely what science the mission will achieve
  - ☆ Could often be argued about: No method is unique and exclusive
  - ☆ Many 'killer science' targets were not achieved in past missions
    - ☞ Examples:
      - cosmic microwave background (COBE, WMAP, Planck, ... ACT)
      - first stars (JWST)
      - missing metals (XMM, Hitomi,...)
- "Exploration"
    - ☞ A detailed exposure of the science potential of a particular astronomical window
  - ☆ Open-minded way to demonstrate the complementarity of astronomy
  - ☆ Could be misinterpreted as having no convincing science goals
  - ☆ Many 'explorations' did not achieve broader science highlights
    - ☞ Examples:
      - Hubble Space Telescope, ...JWST
      - ALMA, VLA, FAST
      - CGRO

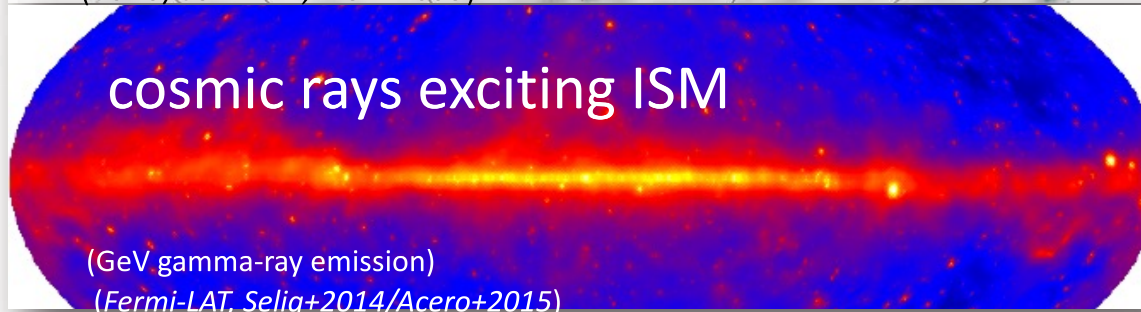
Galactic Messengers

- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …
- Positron annihilation ~traces CR propagation



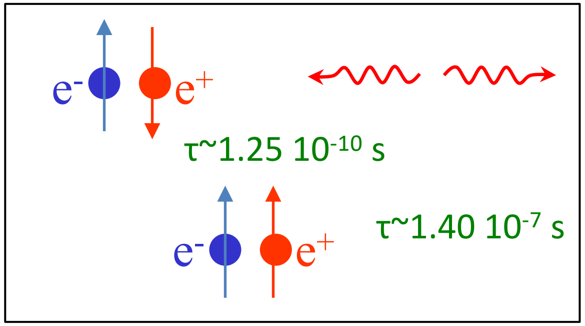




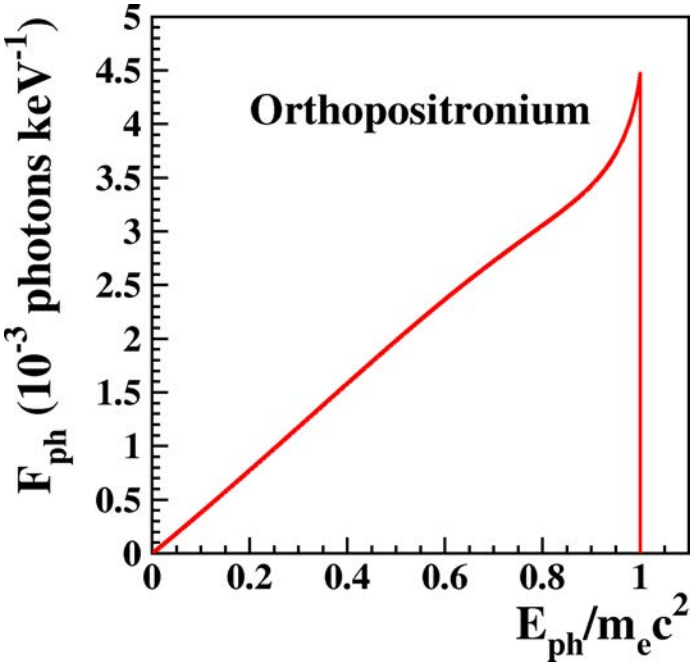


Positronium – the intermediate step of e^+ annihilation

- "Atom" with e^- and e^+
- Relative Spin Orientations →
  - ☆ Singlet State $^1S_0$/ Para-Positronium
  - ☆ Triplet State $^3S_1$/ Ortho-Positronium



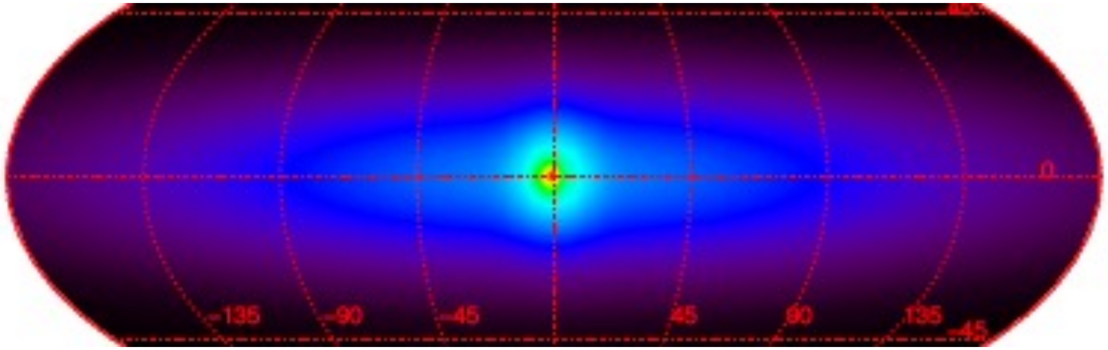
- Annihilation Spectrum
  - ☆ 2-Photon Annihilation Only for Para-Ps:
  - ☆ 3-Photon Annihilation from Ortho-Ps



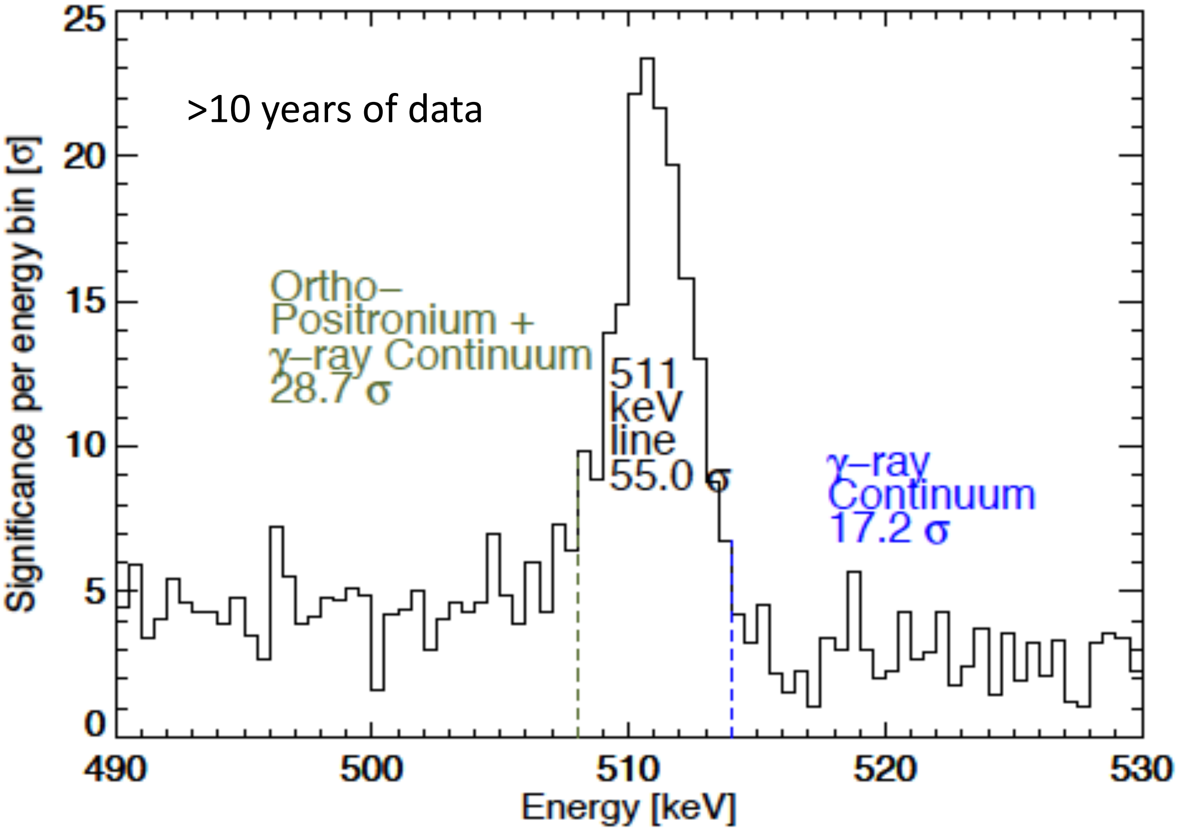
e^+: INTEGRAL/SPI measurement over >10 years

Siegert et al., A&A (2016)

→ Image of
Annihilation emission



Line spectroscopy
and continuum emission



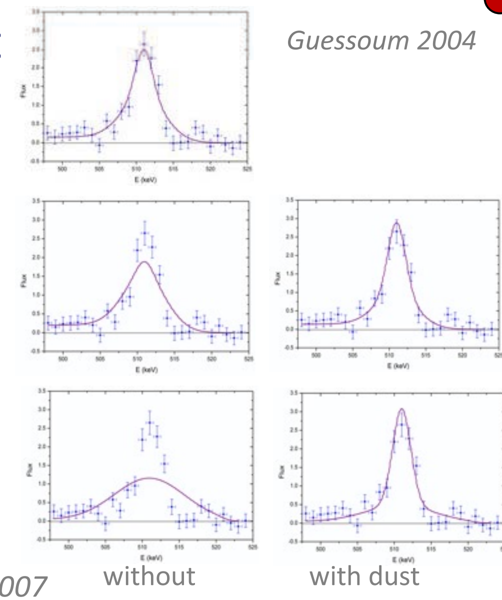
Annihilation Conditions: Which ISM Phase?

Warm Ionized ISM is the dominating annihilation environment

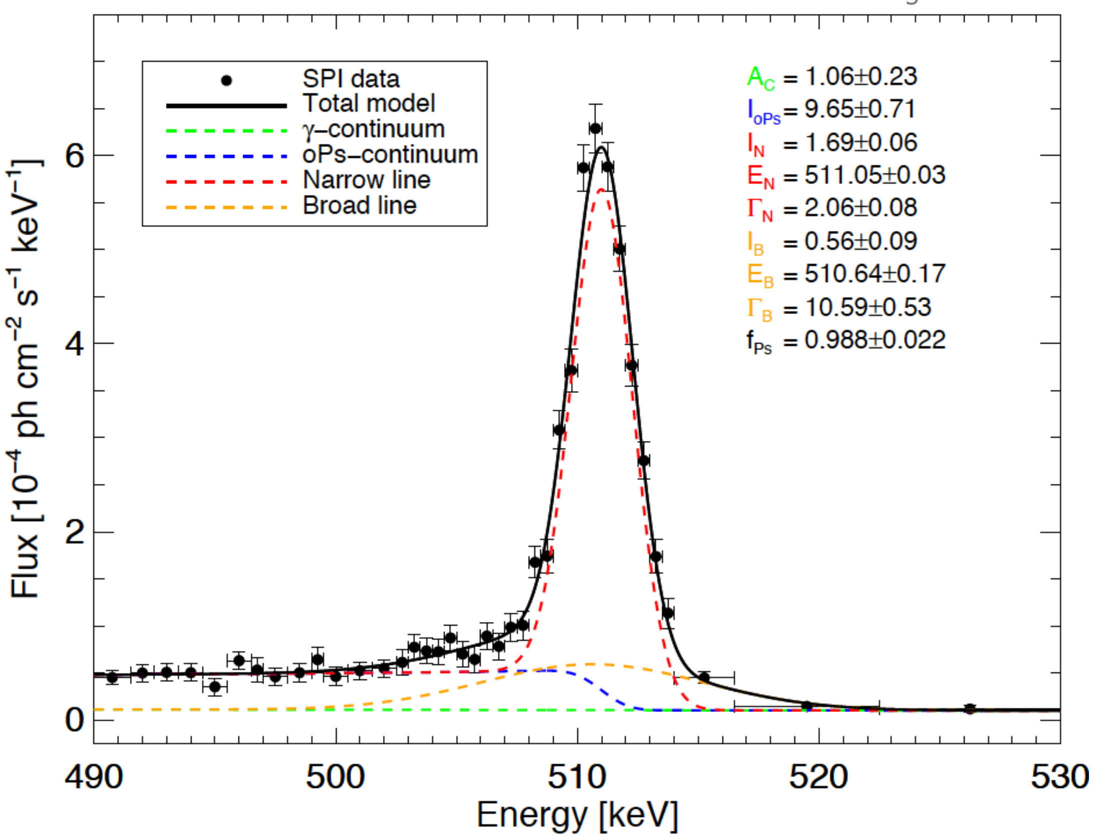
→ Ps formation

- Fitting different phases with their characteristic spectral shapes *(Jean+2003, 2006)*
- Determining the best-matching conditions for Ps: temperature, ionization fraction

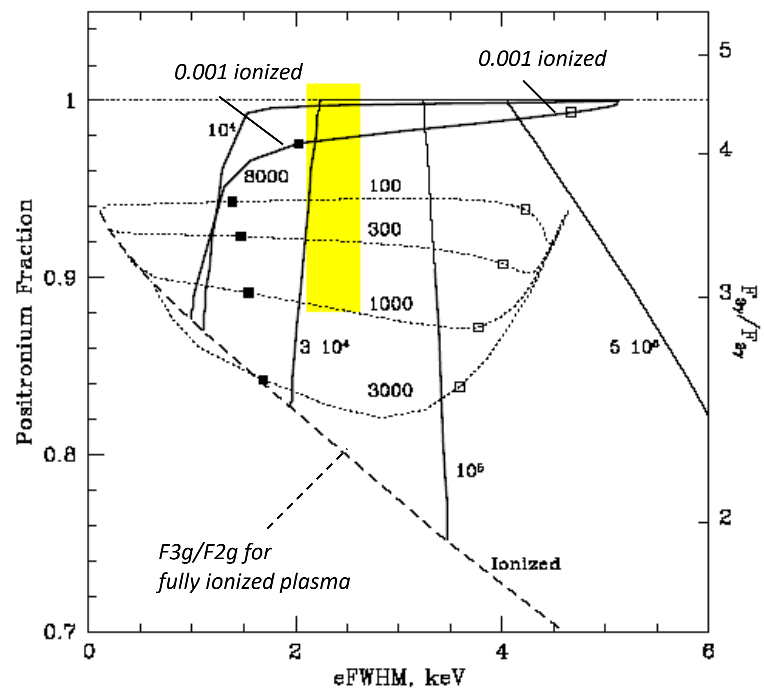
Guessoum 2004



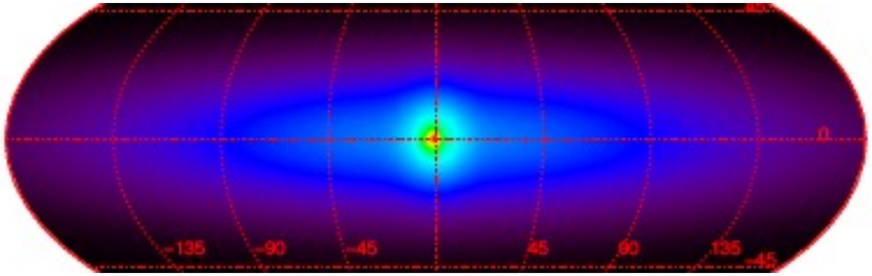
Siegert+2016



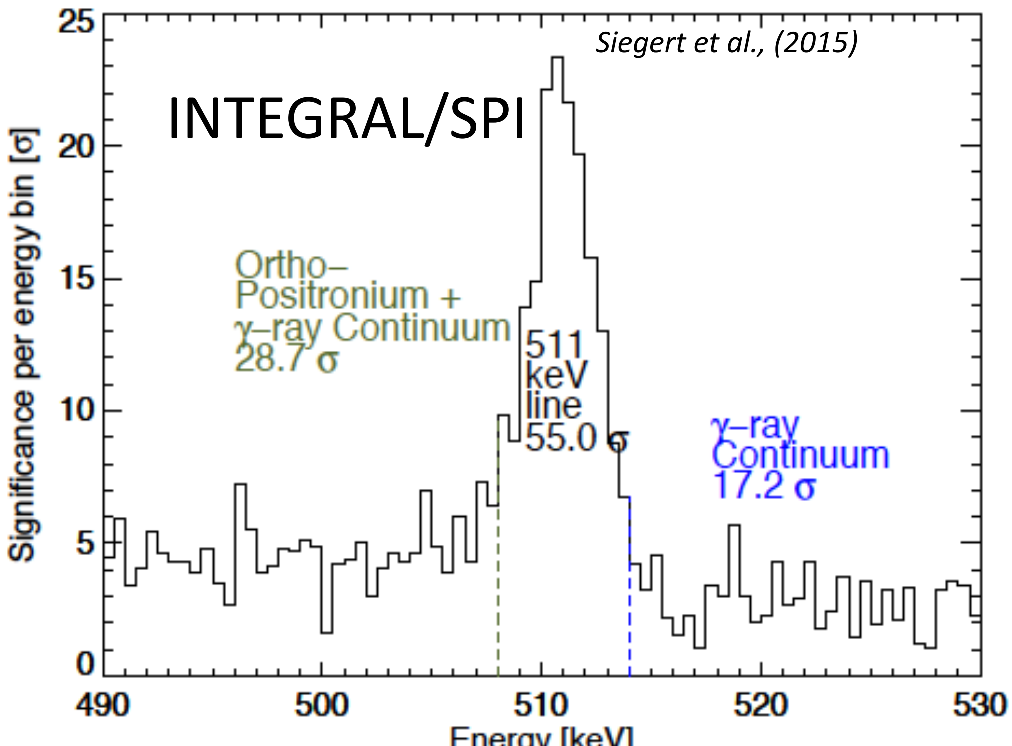
Churazov+2007

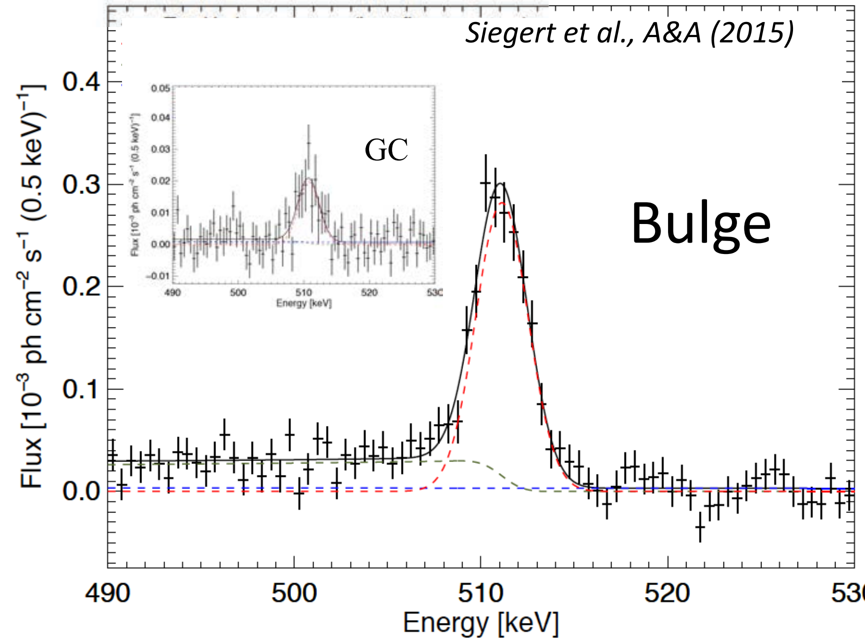


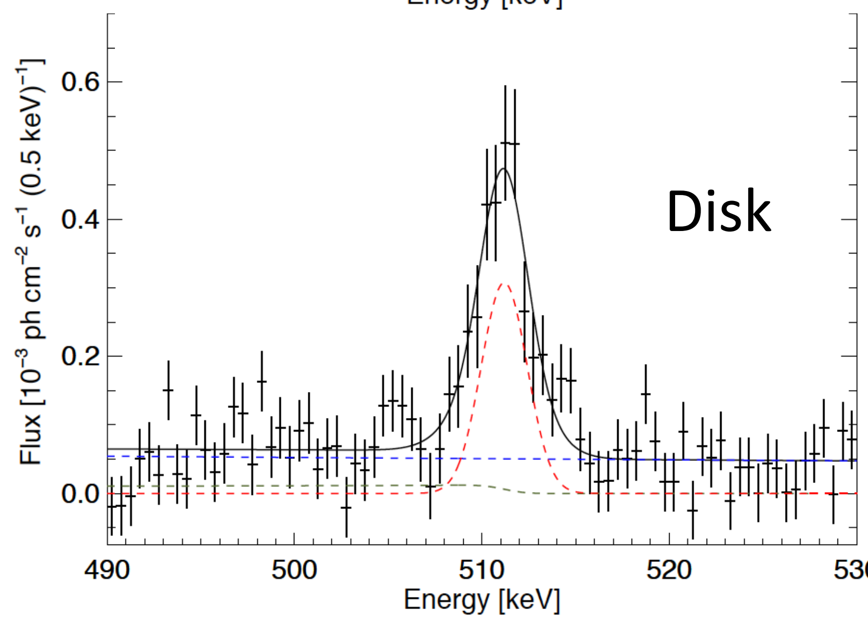
Positron annihilation within our Galaxy



☆ Derive/discriminate spectra from different regions

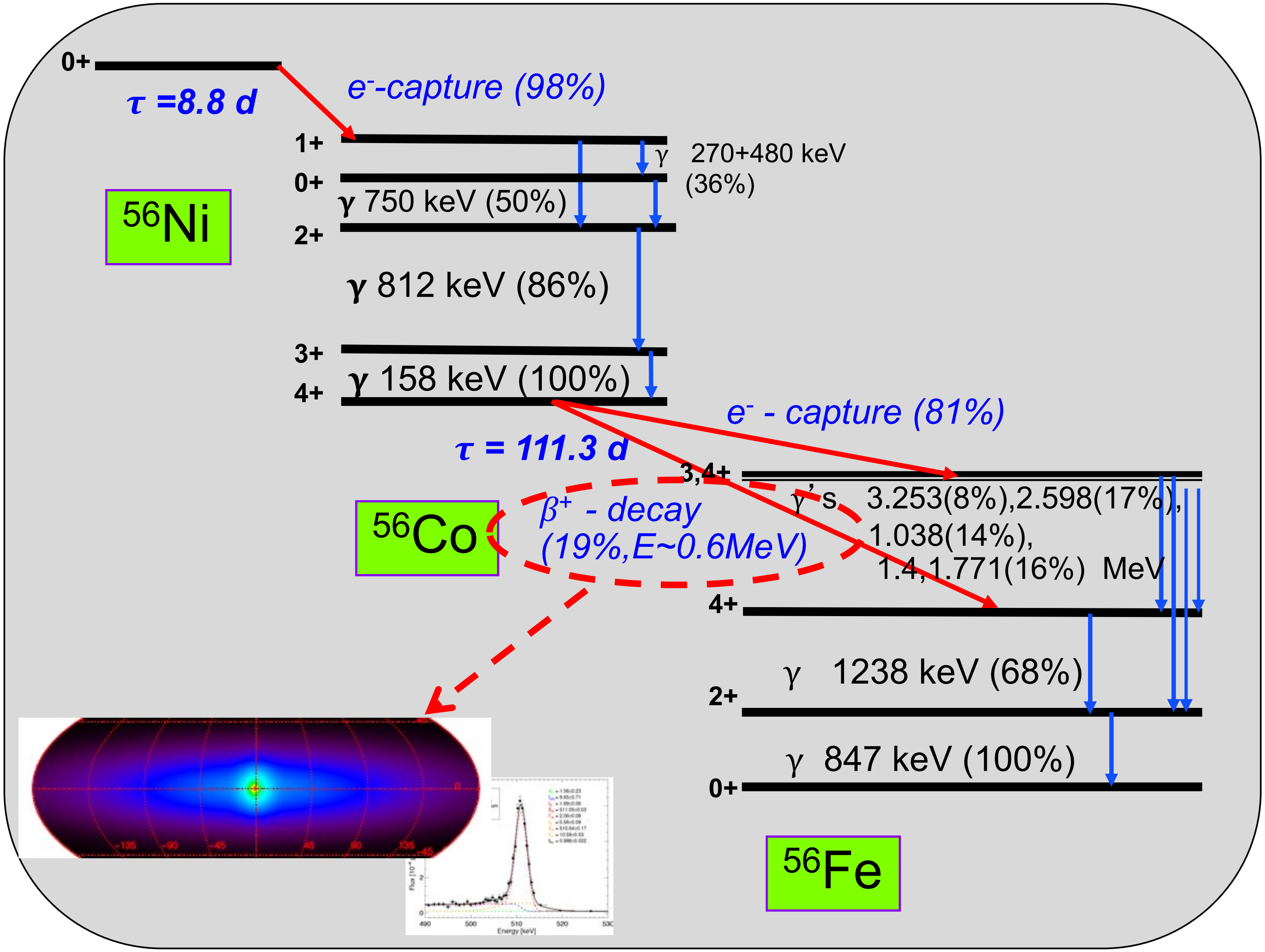






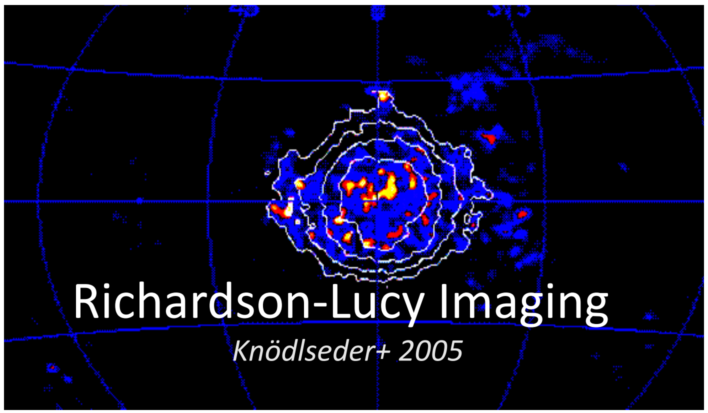
^{56}Ni Radioactivity from SNIa: the main source of positrons?

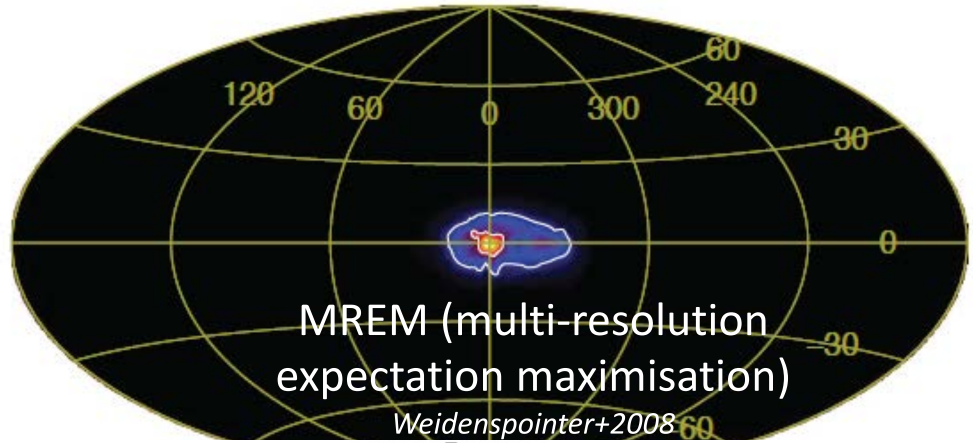
☞



Imaging Approaches with SPI

- ☆ No direct imaging (i.e. locating the original directions of detected photons)
  - Imaging deconvolutions of different types
    - – Maximum Likelihood, RL, ME, MREM, ...
  - Model fitting





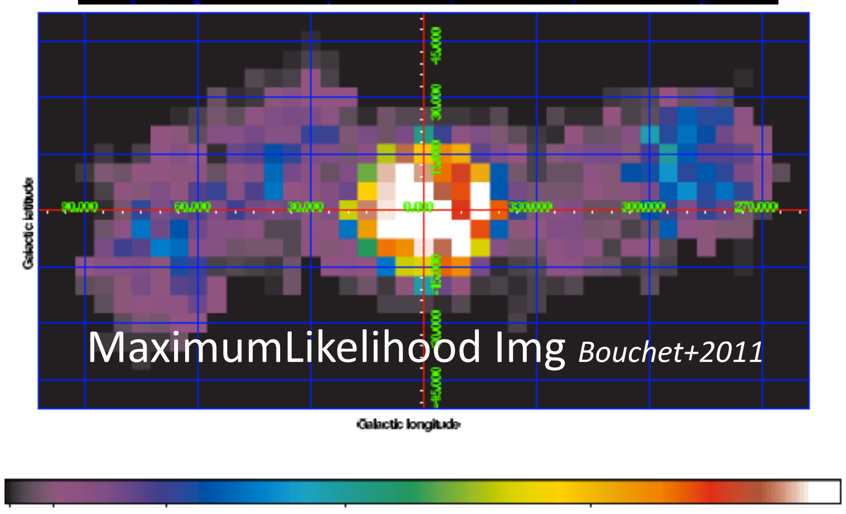
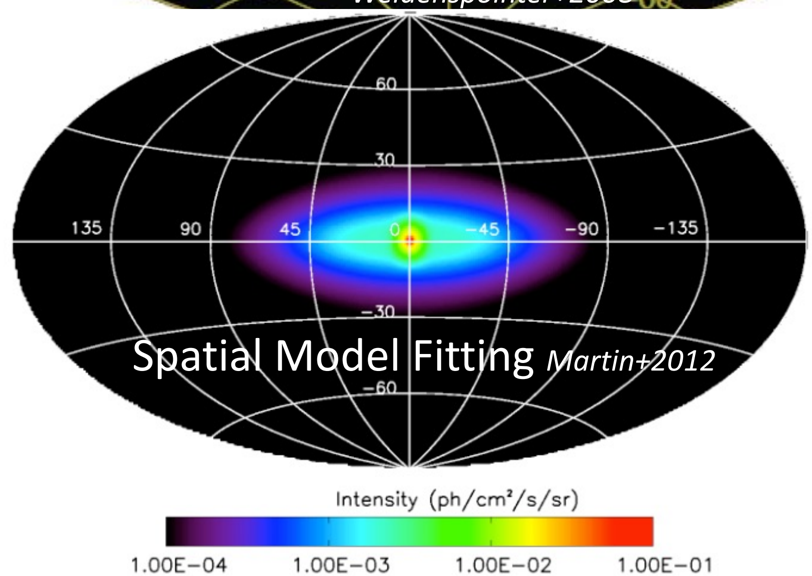


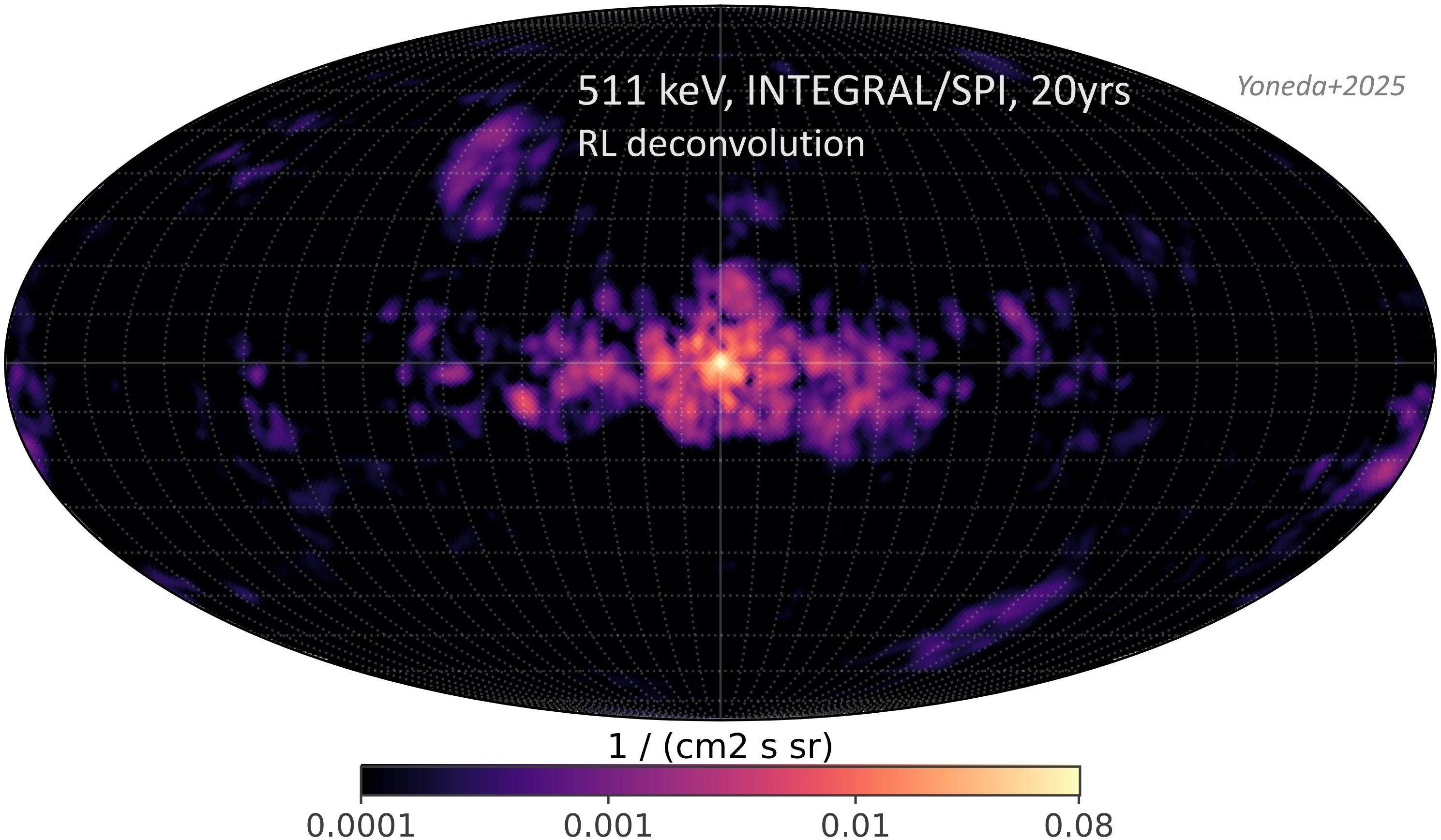
Figure 7. 508.25–513.75 keV *INTEGRAL* SPI smoothed (top hat of 2 pixels) intensity map in photons $cm^{-2} s^{-1}$. Pixel size is 5° × 5°.



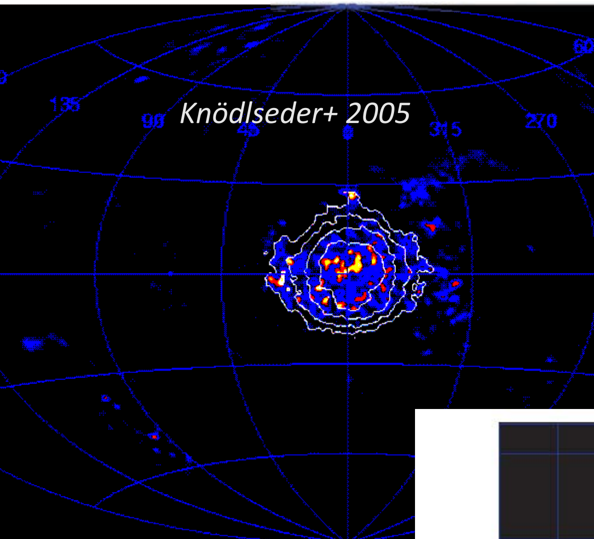
Imaging positron annihilation emission with SPI

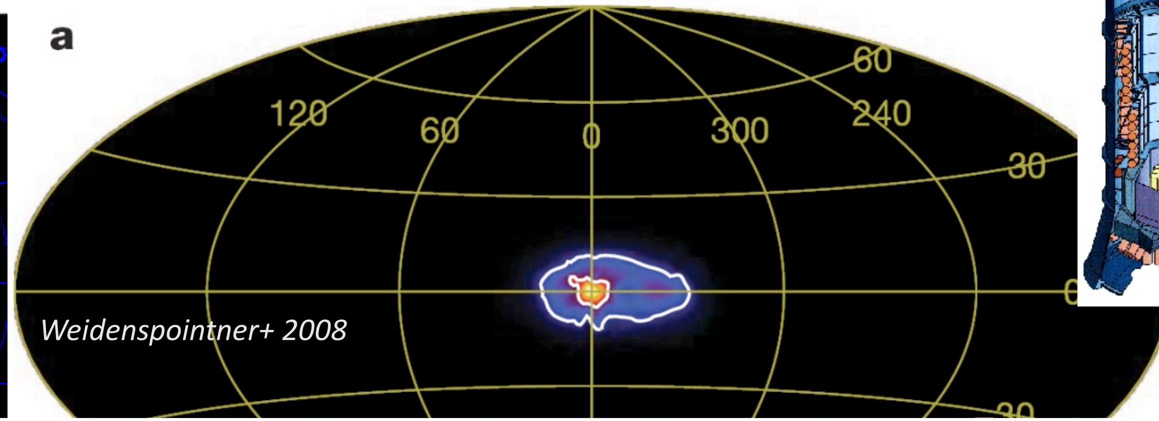
Searching for finest image structures:

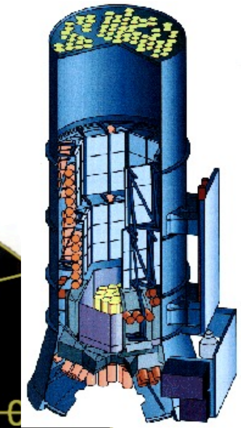
- ☆ using the RL method, no smoothing is inherent to the imaging algorithm (but, this may enhance noise effects into imaged structures)
- ☆ MREM only accepts 'significant' structure, proceeding from large to small

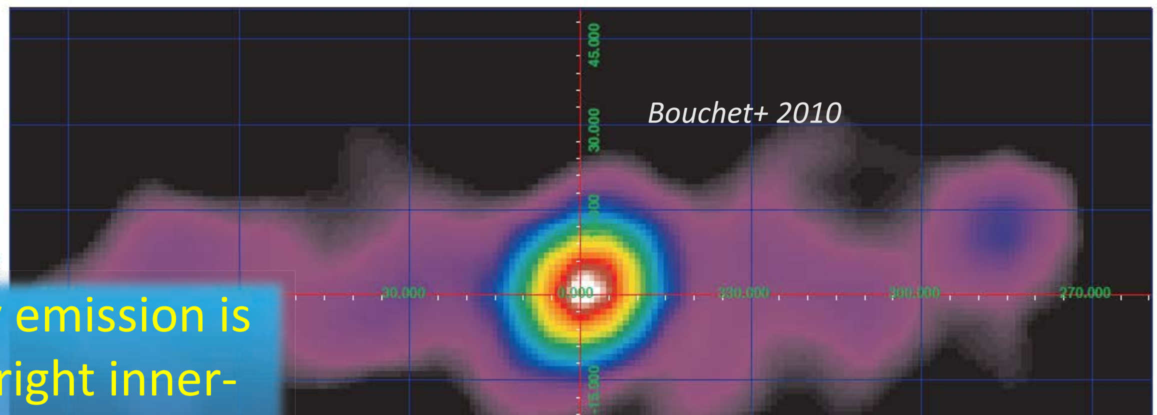


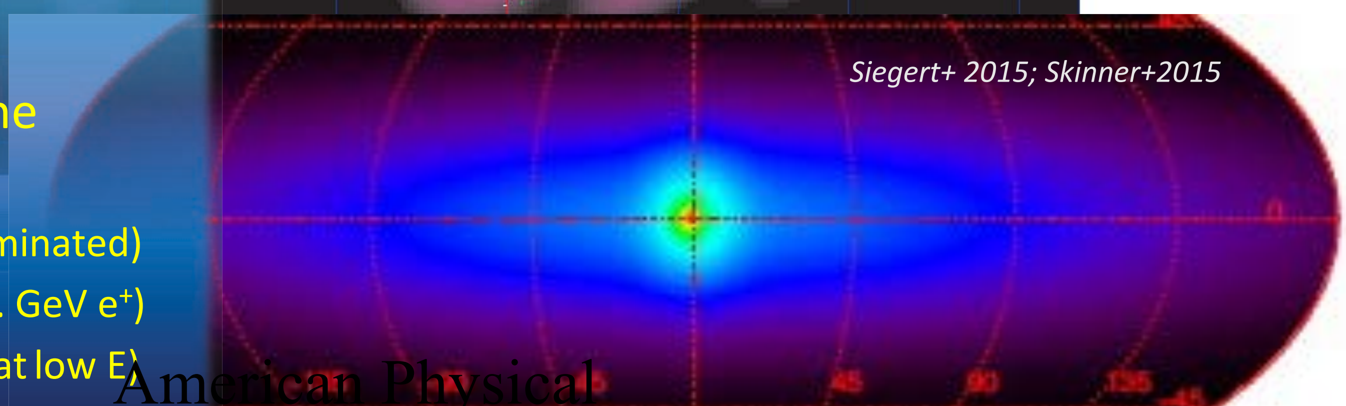
Imaging Galactic Positron Annihilation with SPI











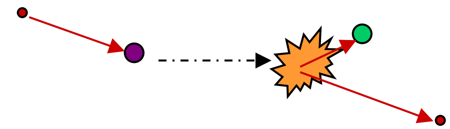
- ☆ Annihilation γ-ray emission is dominated by a bright inner-Galaxy component
- ☆ The morphology of the emission is a Puzzle:
  - ☞ e^+ Sources ? (disk dominated)
  - ☞ Propagation !! (MeV.. GeV e^+)
  - ☞ Annihilation sites (e^+ at low E)

American Physical Society Meeting

Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions

- ☆ e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$



- ☆ Pion Production in HE Collisions

$$p + p \rightarrow \pi^+ + X$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad (\tau = 2{,}6\cdot 10^{-8}\ s)$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad (\tau = 2{,}2\cdot 10^{-6}\ s)$$

✓ Hot-Plasma Pair Production

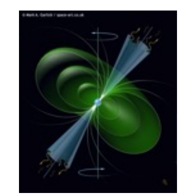
- ☆ 'kT>MeV'-Plasma
  - ☞ Accretion Columns & Disks
  - ☞ Jet Bases

$$\gamma+\gamma \rightarrow e^+ + e^-$$

✓ E.M.-Cascade Pair Production

- ☆ Strong Magnetic Fields
  - ☞ Pulsars
  - ☞ Jets

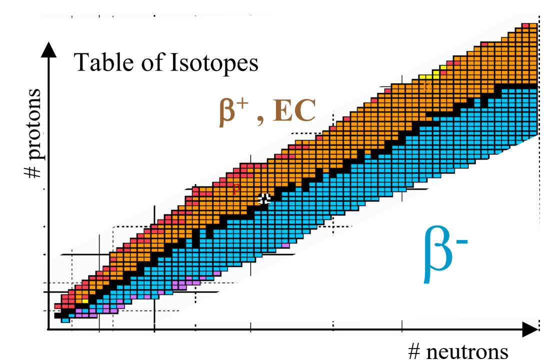
$$\gamma+B \rightarrow e^+ + e^-$$



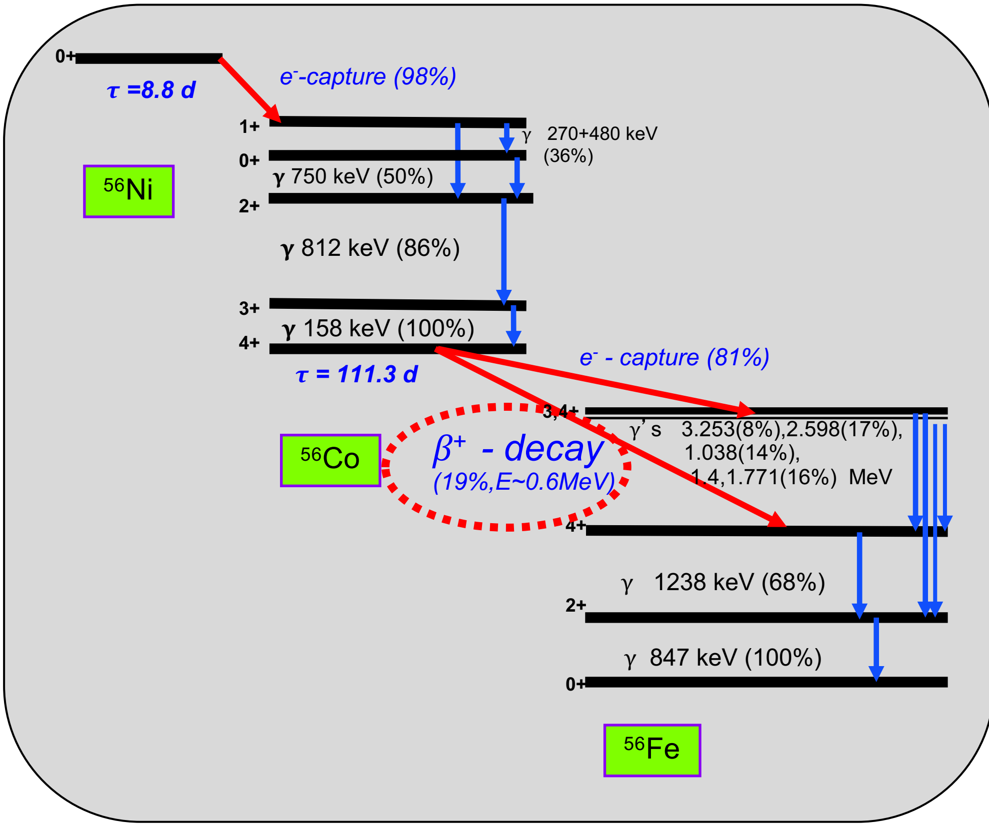
✓ Nucleosynthesis

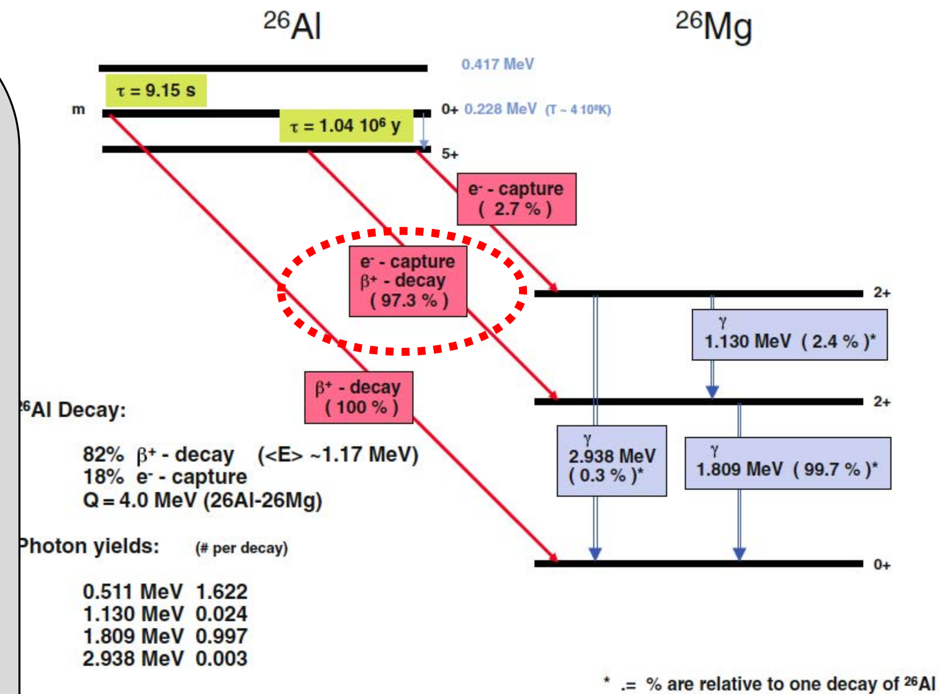
- ☆ e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$, $^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{18}F(\beta^+)$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$



radioactive decay → energy sources = γ rays and positrons





photons *and positrons* may escape into interstellar medium

Candidate sources of cosmic β⁺ decay positrons

Table 1 List of astrophysically important positron emitting nuclei, sorted by lifetime τ. The columns are the nucleus, its lifetime, the probability to emit a positron while decaying, possibly associated γ-ray emission from the daughter nucleus in units of MeV, and potential sources

Nucleus	τ	p_β	E_γ	Sources
^{26}Al	1.05 Myr	0.82	1.809	Massive stars, AGB stars, Supernovae
^{44}Sc	81 yr[a]	0.94	1.157	Supernovae
^{22}Na	3.75 yr	0.90	1.275	Novae
^{56}Co	111.4 d[b]	0.20	0.847, 1.238	Supernovae
^{48}V[d]	23.1 d	0.50	0.983, 1.312	Supernovae
^{57}Ni[d]	2.14 d	0.43	0.127, 1.378, 1.920, 0.122[c], 0.136[c]	Supernovae
^{18}F	2.64 h	0.97	–	Novae, Solar flares
^{52}Mn[d]	30.4 min	0.29	0.744, 0.936	Supernovae
^{11}C[d]	29.3 min	> 0.99	–	Cosmogenic (cosmic-ray interactions, spallation), Solar flares
^{13}N	14.4 min	> 0.99	–	Novae, Earth atmosphere / lightning, Solar flares
^{15}O	2.94 min	> 0.99	–	Novae, Earth atmosphere / lightning, Solar flares

[a]The nucleus ^{44}Sc only has a half-life time of 3.9 h and exists only as an intermediate step from the decay of ^{44}Ti. The relevant astrophysical timescale, for example for heating of supernova remnants, is that of the longer-living ^{44}Ti.

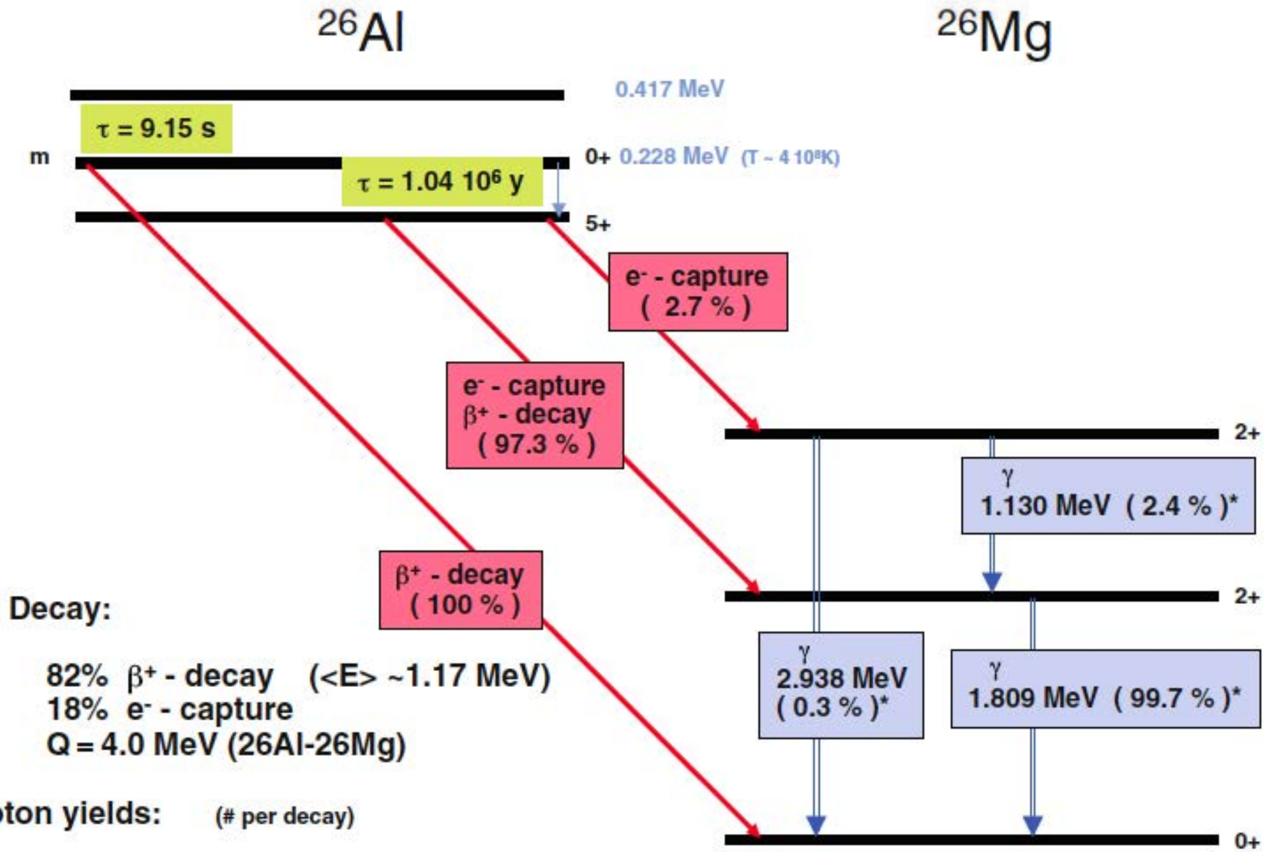
[b]The nucleus ^{56}Co is the daughter product of the shorter-lived ^{56}Ni that is dominantly produced in supernovae. The relevant timescale here is again that of the longer-living ^{56}Co.

[c]The γ-rays at 122 and 136 keV come from the daughter nucleus' decay, $^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}$ (τ 271 8 d) which is no β -decay, but the γ-rays might indicate that positrons have been emitted throughout the ^{57}Ni decay chain.

[d]These isotopes have not been considered for the Positron Puzzle so far but may play a role.

from Siegert 2017; 2023

^{26}Al decay: γ rays, positrons, and heating



^{26}Al Decay:

82% β⁺ - decay (<E> ~1.17 MeV)
18% e⁻ - capture
Q = 4.0 MeV (26Al-26Mg)

Photon yields: (# per decay)

0.511 MeV 1.622
1.130 MeV 0.024
1.809 MeV 0.997
2.938 MeV 0.003

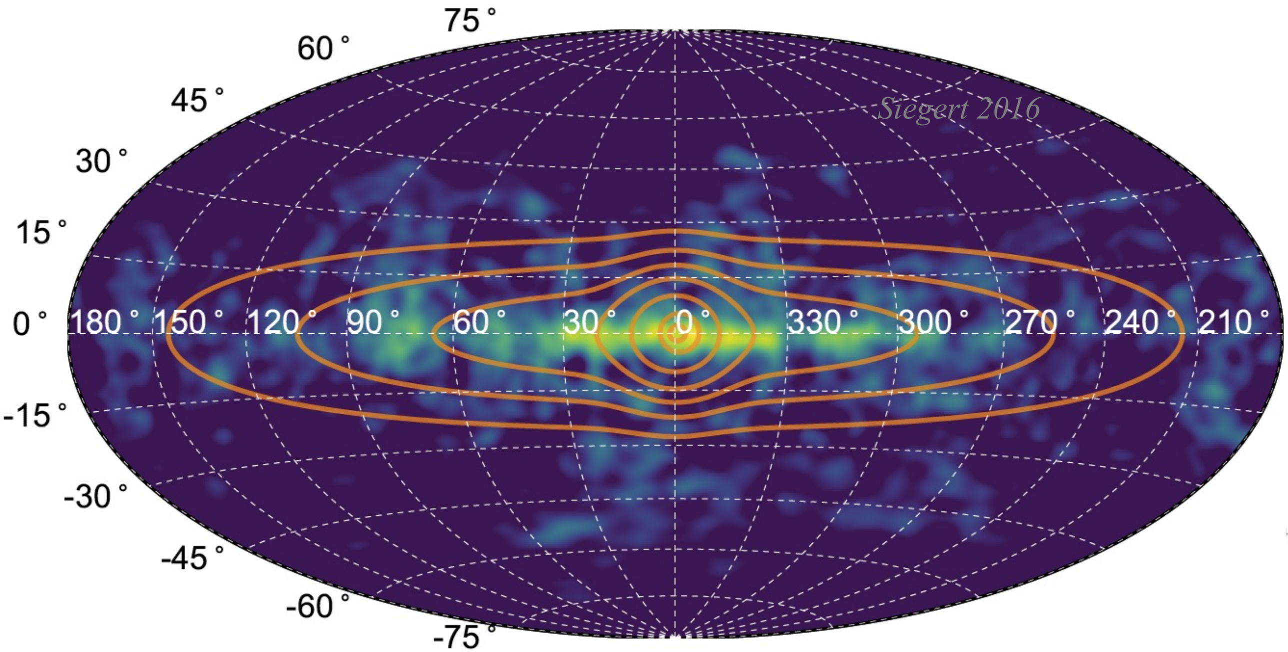
* .= % are relative to one decay of ^{26}Al

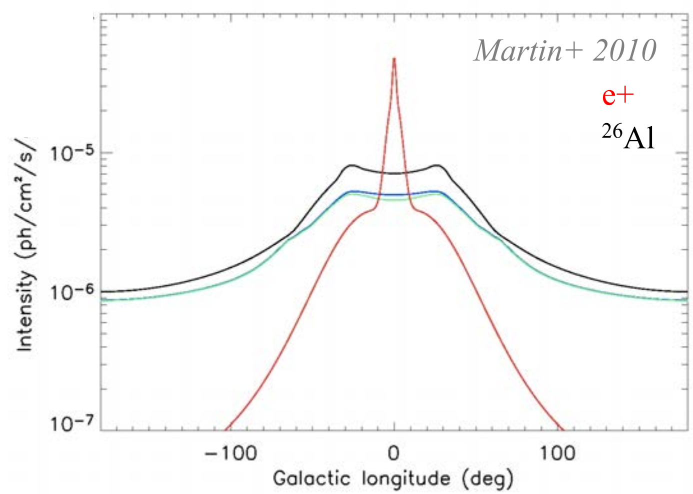
Q-value 4.004 MeV → gamma-ray photons, positrons (neutrinos)

→heating rate: $$H = \frac{\Delta Q}{M}\bigg|_{26\text{Al-decays}} \cdot \frac{1}{\tau_{26Al}} \approx 0.5\left[\frac{W}{kg}\right]$$ → evaporization of water??

The Galactic Positron Annihilation

Is it all from ^{26}Al?



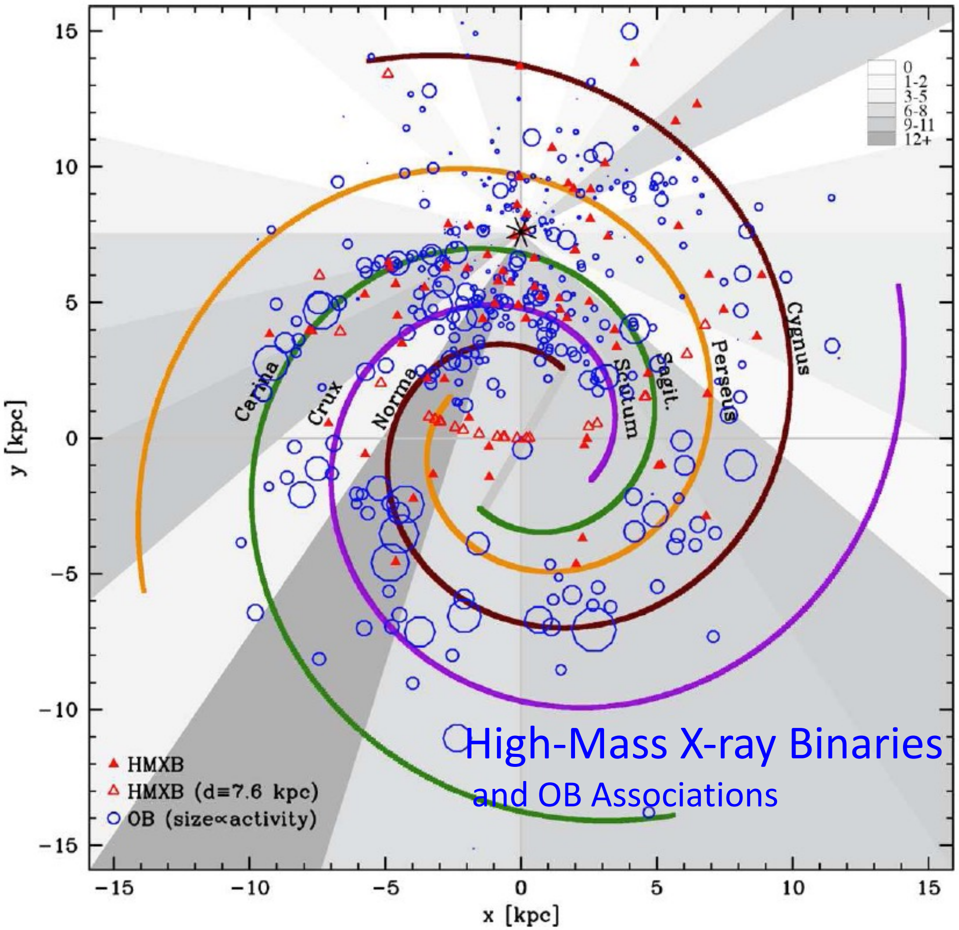


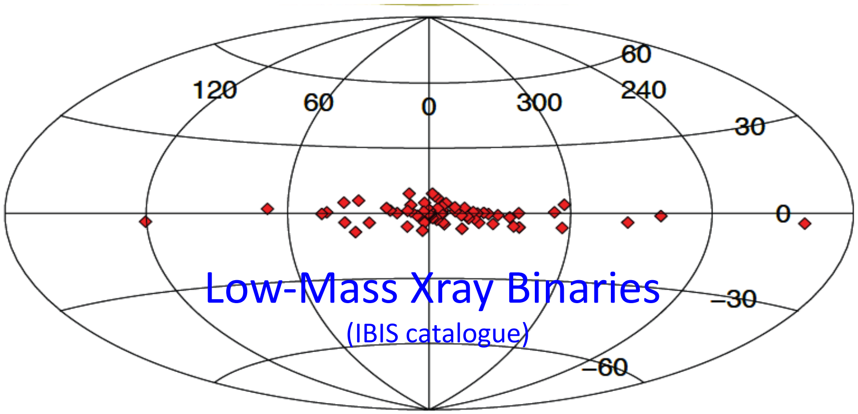
Morphology of emissions is different

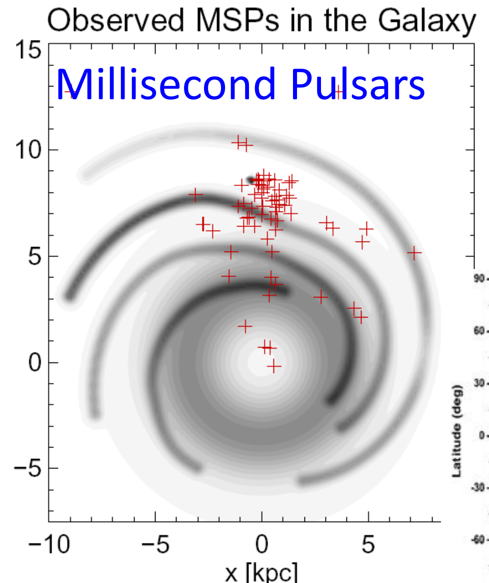
→ annihilation astrophysics + other sources

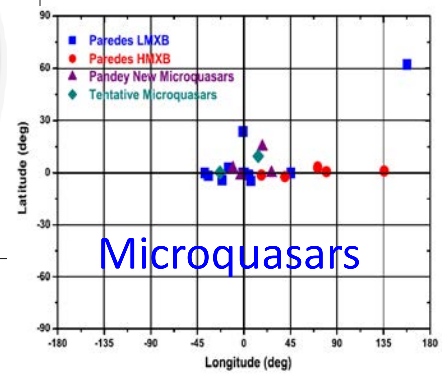
Locations of Candidate Sources

- e.g. LMXBs: Matter from Companion Star Accretes onto Compact Star → X-Rays
  - LMXBs, HMXBs, Micro-Quasars, Millisecond-Pulsars, X-ray Bursters
  - candidate locations for SNIa: binaries from old stellar population (→ bulge)







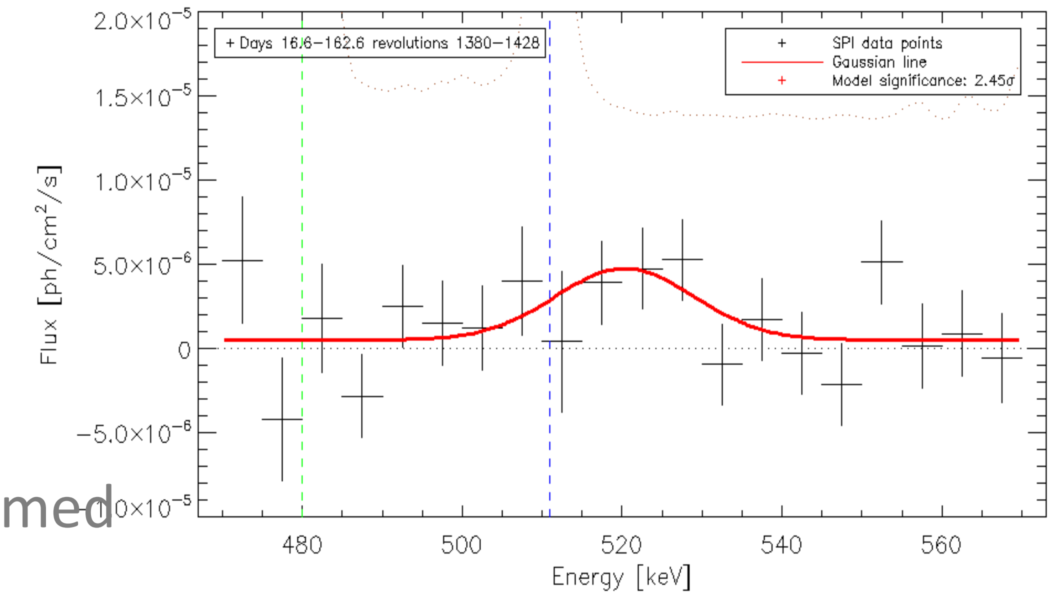


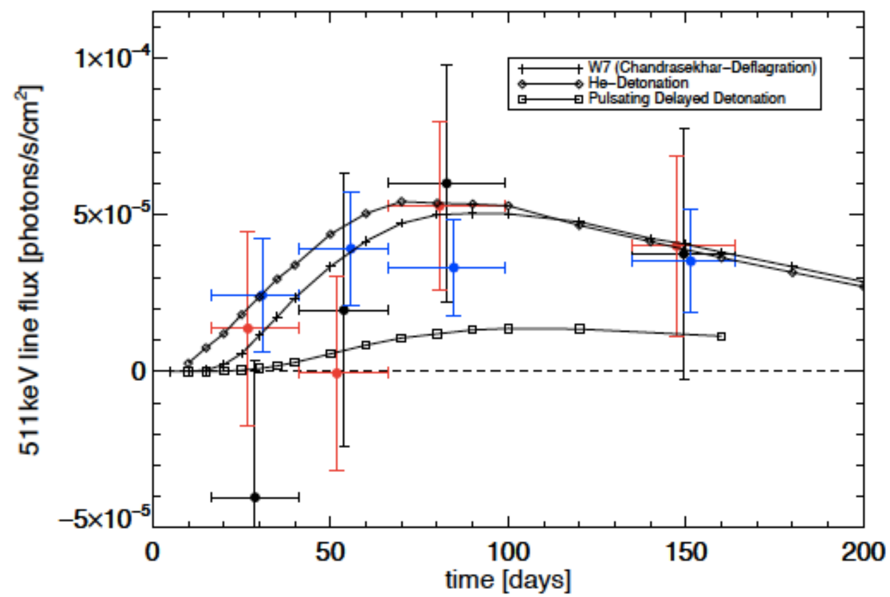
- Observational / Selection Biases!

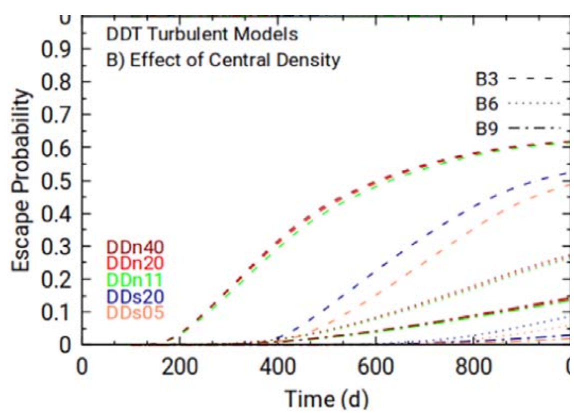
Positrons from SNIa and SN2014J

- Indicated 511 keV line emission (1.7σ)
  - ☆ ?? Blue-shifted by 10-15 keV
  - ☆ Flux consistent with ~^{56}Co line fluxes
    → ~all e^+ annihilating locally
- Typically, ~3-5% escape assumed
- Model study
  - ☞ positron escape is ~10^{52}/SNIa (<2% of all Galactic e^+)

Sonnberger 2019



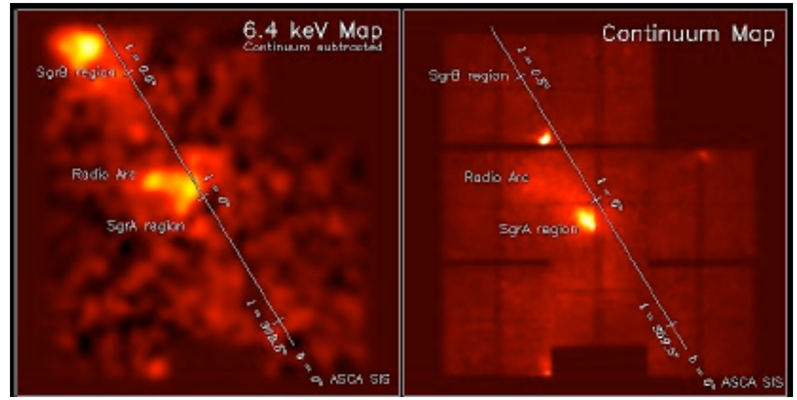




Mera Evans+ 2022

The Galaxy's Supermassive Black Hole

- Accretion onto SMBH
  - ☞ Hadronic Outflow/Jet
  - ☞ Leptonic Jet

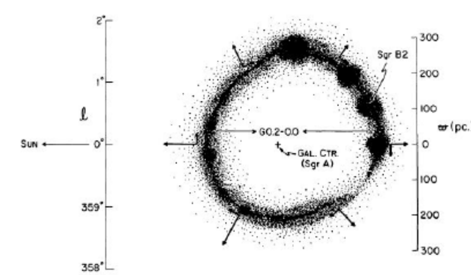


☆ Hadronic-Jet Model:

- ☞ $10^{52\ldots54}$ erg in HE Protons
  - – Massive-Star (30-50 M_0) Accretion ~10^7 yrs ago → 10^{54} erg
  - – Normal Star (1 M_0) Accretion Every ~10^5 yrs → 6 10^{52} erg
- ☞ Pion Production in Target Cloud
  - – ~ few 10^{42} e^+ s^{-1}
- ☞ *Cheng et al., 2006, 2007*

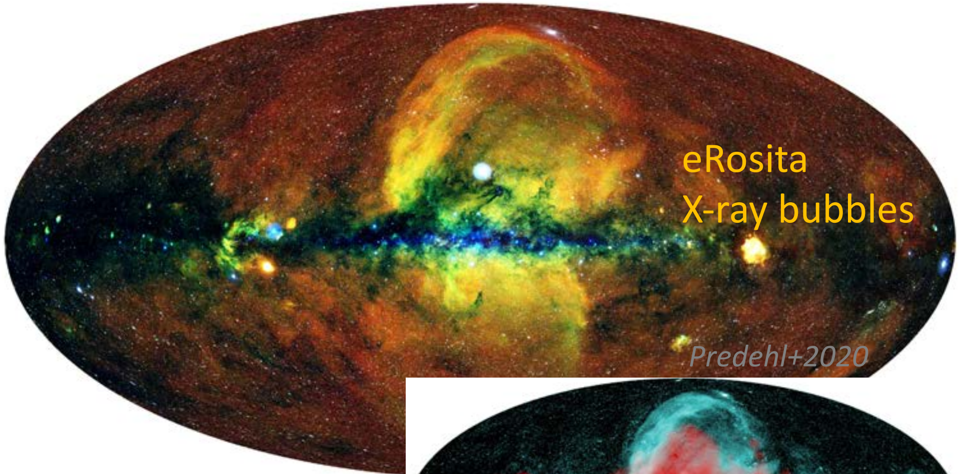
☆ Leptonic-Jet Model

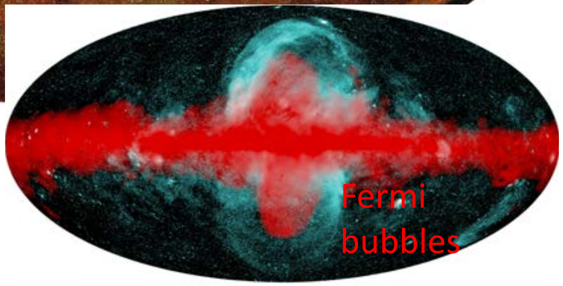
- ☞ Accretion Rate of SgrA was $10^{3\text{-}4}$ Higher in Past 10^7 y
  - – Reflection Nebulae, Expanding Molecular Ring,...
- ☞ Radiatively-Inefficient Accretion Flow (RIAF)
- ☞ Outflows
  - – ~ 10^{43} e^+ s^{-1}
- ☞ *Totani 2007, 2008*

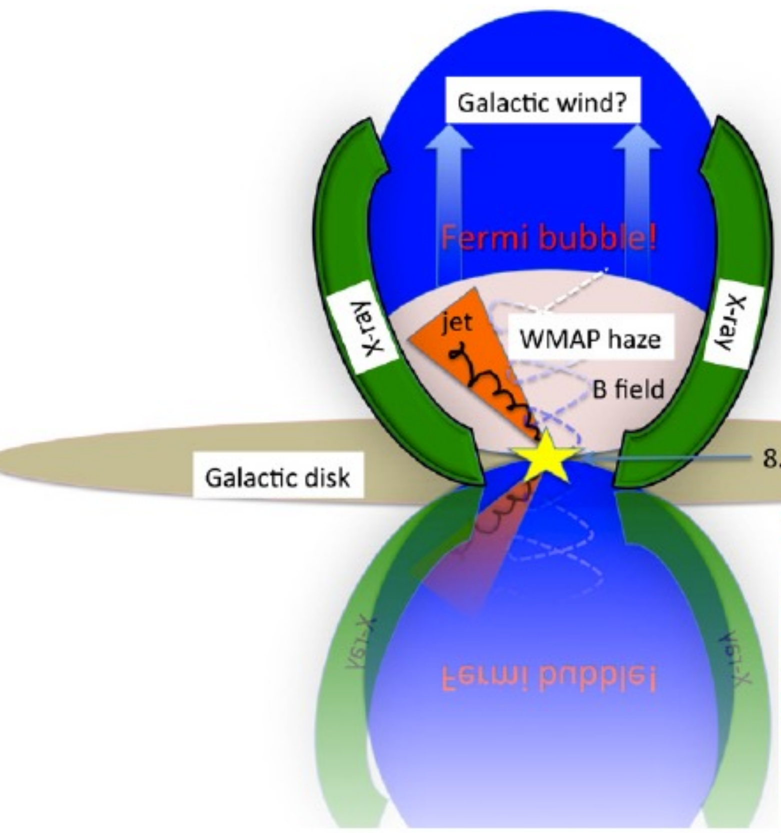


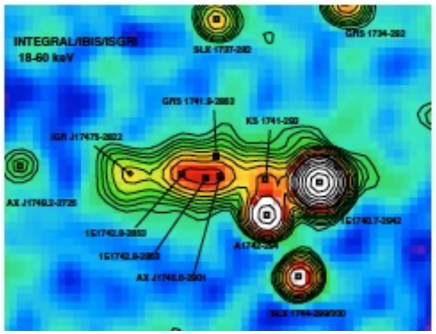
The Galaxy's Central Region

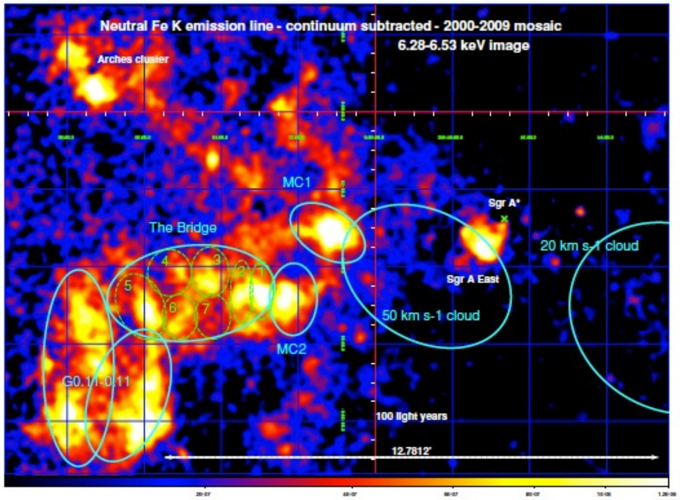
- A recent starburst, a chimney region, superbubbles
  - ☆ Evidences:
    - ☞ Echoes from near-GC Molecular Clou
    - ☞ Fermi Bubbles
    - ☞ X rays, radio structures





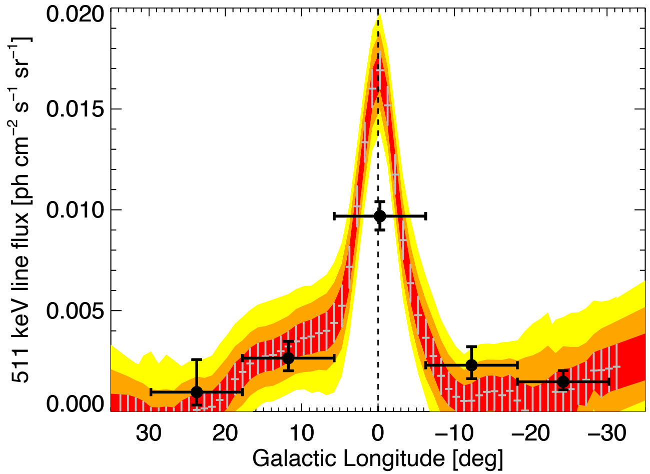




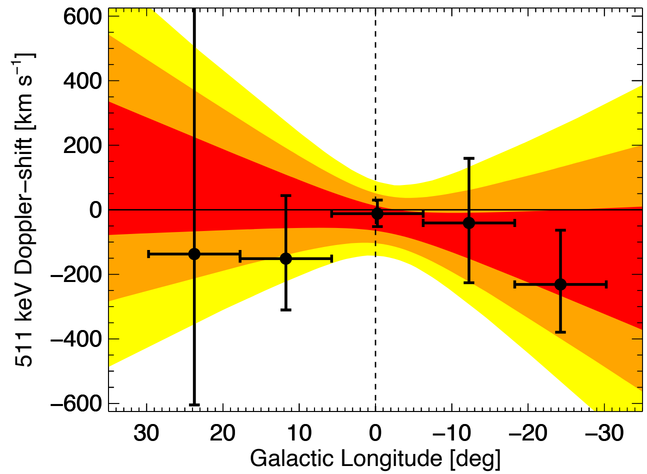


Homogeneity of e⁺ annihilation signal across inner Galaxy

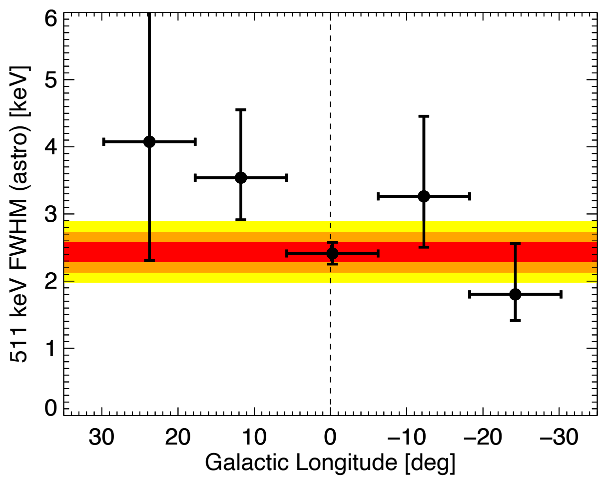
☆ Simultaneous spectral fitting of separate longitude regions along Galactic plane



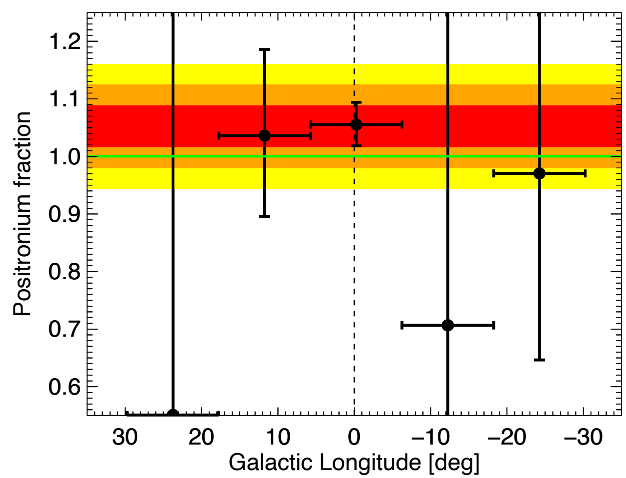
(a) Integrated 511 keV line flux I_L.



(b) Line of sight Doppler-velocity v_{los}.



(c) Astrophysical FWHM Γ_L.



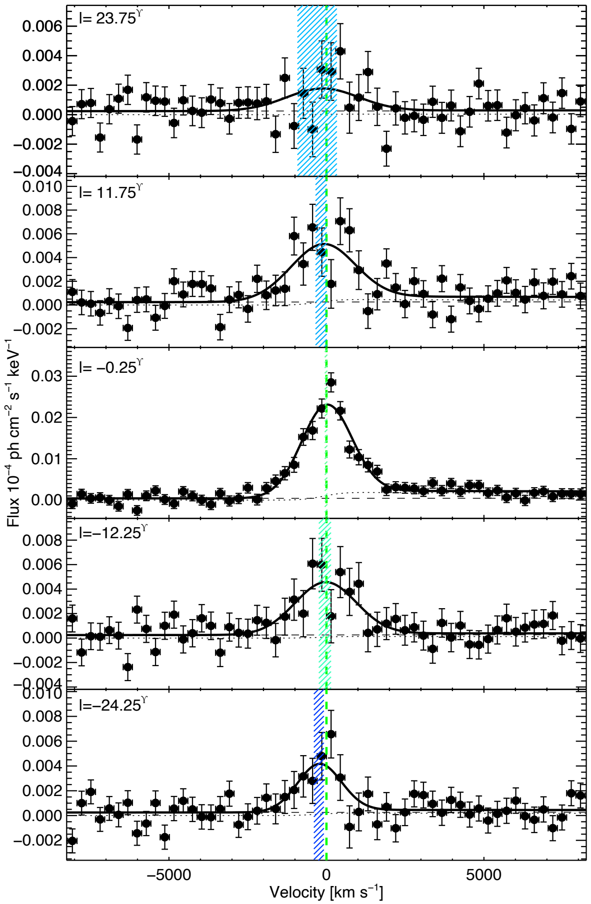
(d) Positronium fraction f_{Ps}.

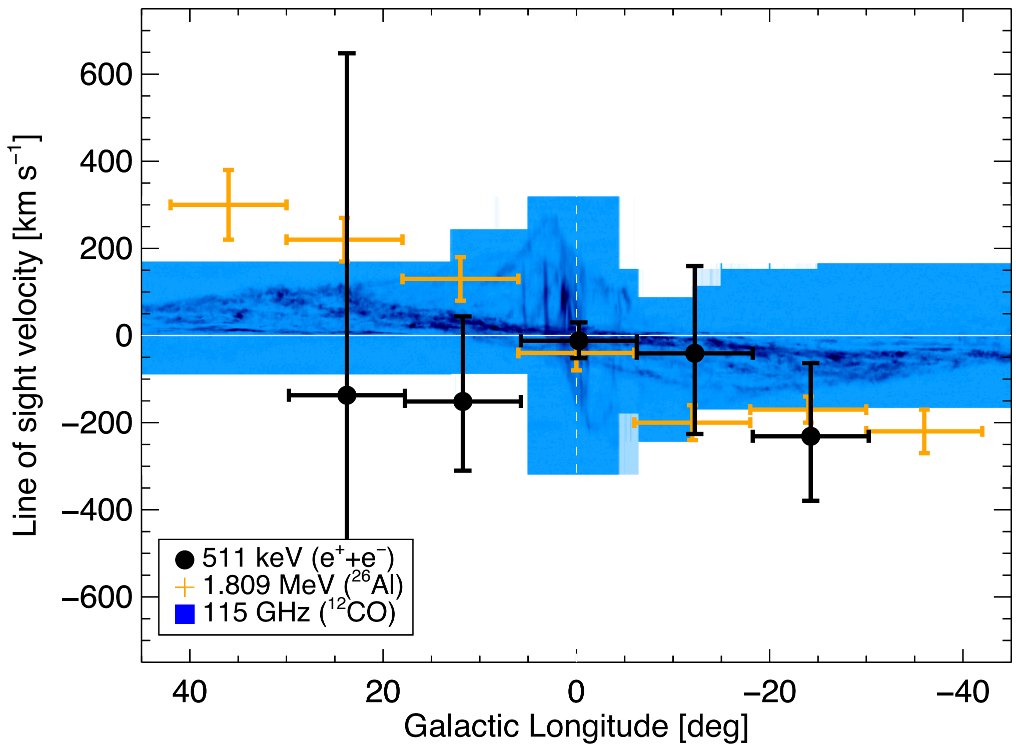
Siegert+ 2019

☆ no significantly different kinematics nor annihilation conditions. Hints?

Kinematics constraints on annihilating positrons

☆ Spectra for different regions in Galactic longitude → galactic rotation?





Siegert+ 2019

☆ No indication for deviations from Galactic rotation of ISM (~CO)

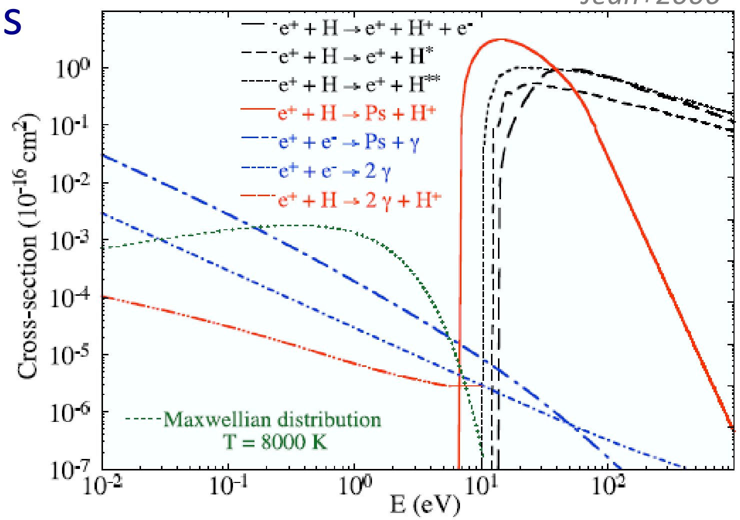
☆ Some kinematics contribution to line width → annihilation conditions uncertain

☆ No connection to ^{26}Al enhanced-velocity signature

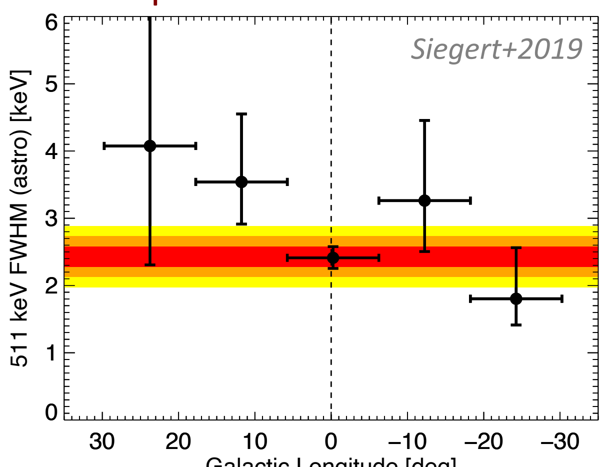
511 keV line width: kinematic broadening?

- ☆ All positron sources inject e^+ at relativistic energies > 0.5 MeV
- ☆ Annihilation occurs prediminantly in the 6.8 eV...100 eV window
- ☆ What about e+ propagation between sources and annihilation sites?
  - ☞ Constraints from Bremstrahlung emission: $E_{injection}$ < 50 MeV *(Das+2025)*
  - ☞ Modeling of ISM: significant propagation distances >100 pc *(Jean+2009, Alexis+2014)*

e^+ annihilation *Jean+2006*



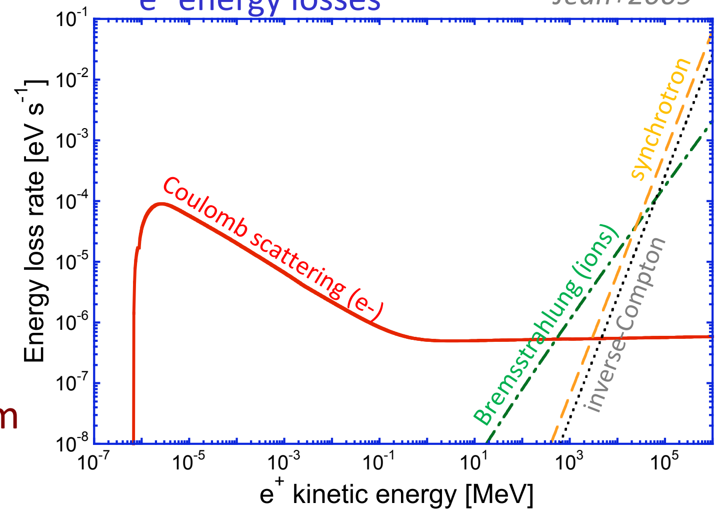
- ☆ Expect modest kinematic broadening
  - ☞ Comparison to measurements:



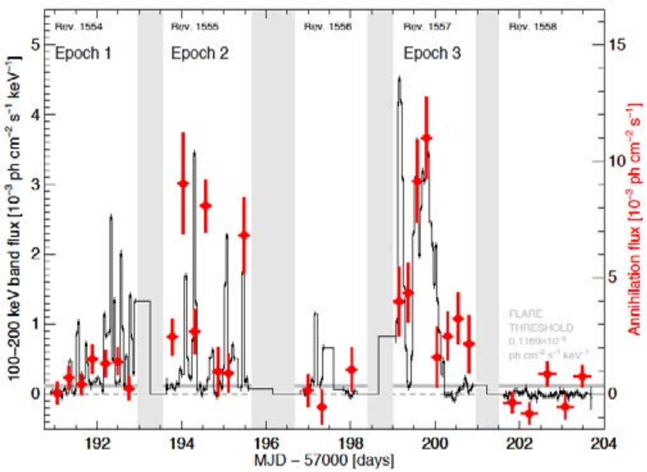
2.43 +/-0.14 keV FWHM
0.26 keV expected GalRot

significant broadening from kinematics in annihilation region

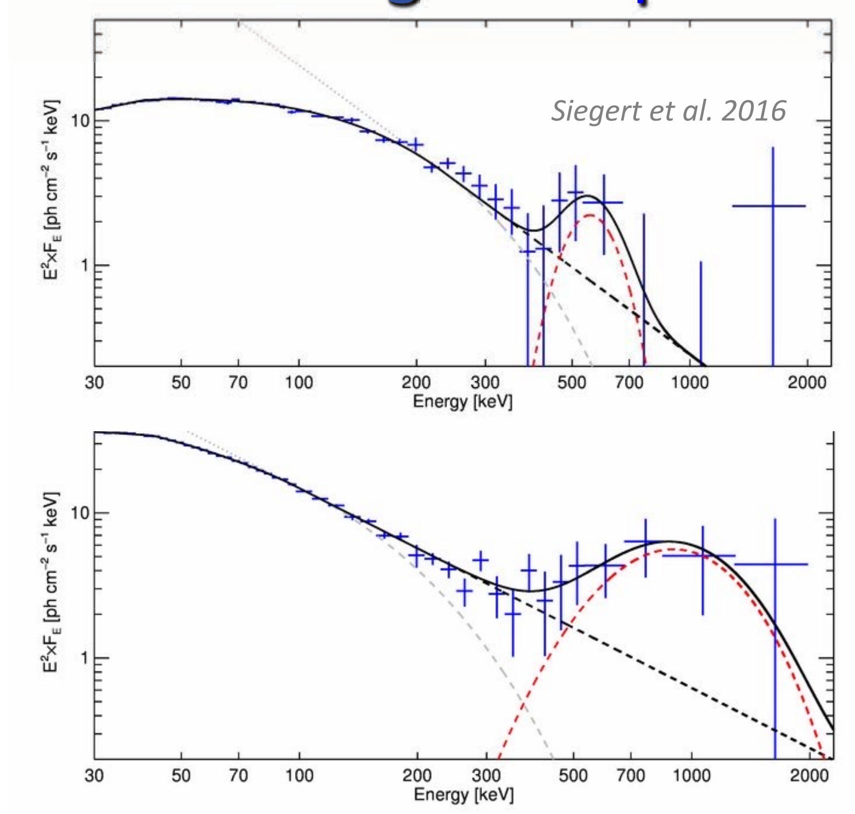
e^+ energy losses *Jean+2009*



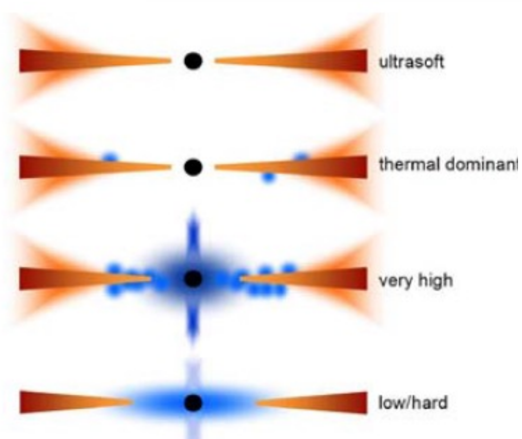
Pair plasma from a black hole in a flaring microquasar

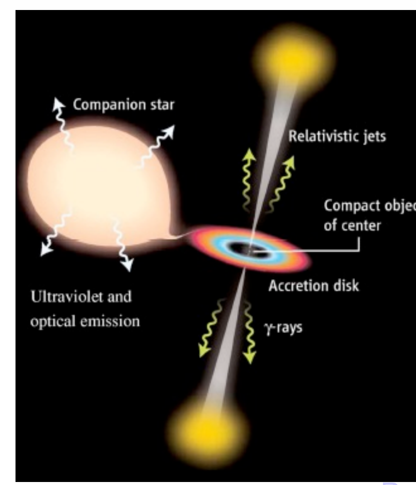


V404Cyg
Jun 2016



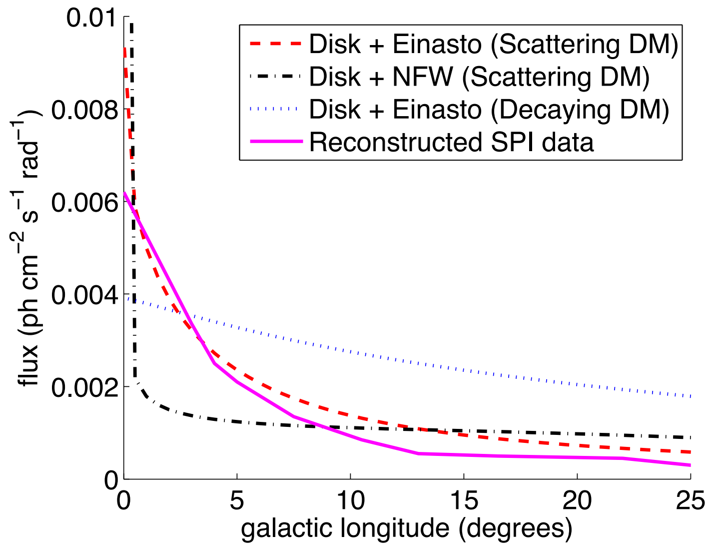
- V404 Cyg flare spectra show e^+ annihilation
- annihilation conditions vary across flaring period
- jet base is the plausible pair production region
- accreting BH binaries may be significant e^+contributors in the Galaxy





Dark Matter and e^+ production

- DM particle interactions:
  - within a DM halo, (rare) interactions of DM particles of any mass might produce intermediate and excited particle X with a small ΔE~MeV
  - de-excitation often would involve a pair-producing step in the cascade
  - spatial profile $\sim n^2_{DM}$, i.e. sharp peak in central region (NFW; Einasto w/o cusp)
  - spatial profile $\sim n_{DM}$, if X produced in DM scatterings
- DM decay:
  - If DM particle is light (MeV energies): direct decay into e+e- likely
  - spatial profile $\sim n_{DM}$, i.e. peak in central region
- Comparison to INTEGRAL/SPI data:
  - fitting a DM profile component, in addition to known e+ components
    Vincent+2012; 8 yrs of data, initial such study
  - No significant DM detected; sharply-peaked profile excluded



Dark Matter and e+ gamma rays

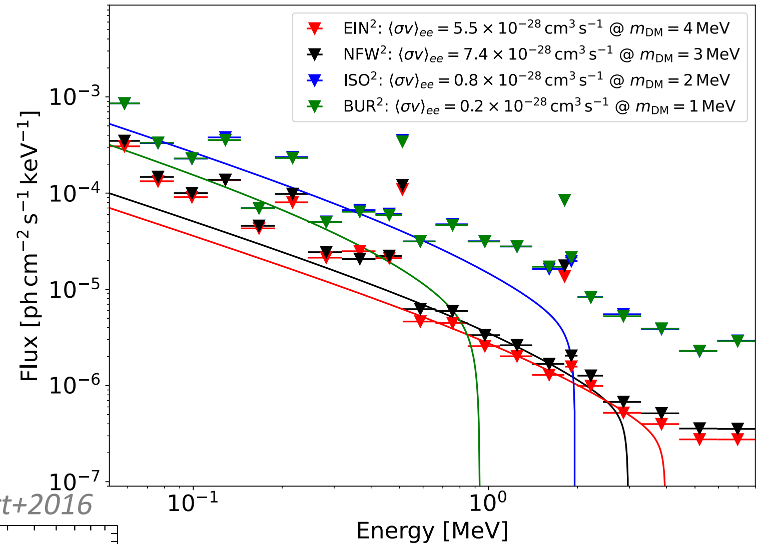
- Decay and/or annihilation of DM is a candidate source of 511 keV
- The annihilation gamma-rays of the Galaxy:

  ☞ ...if galaxies have a DM halo, and decay and/or annihilation occurs through e+ secondaries

  ☆ Candidate spatial emission profiles and SPI constraints: (2σ upper limits)

  ☞ potential correlations with point sources in particular in GC region

Siegert+2024



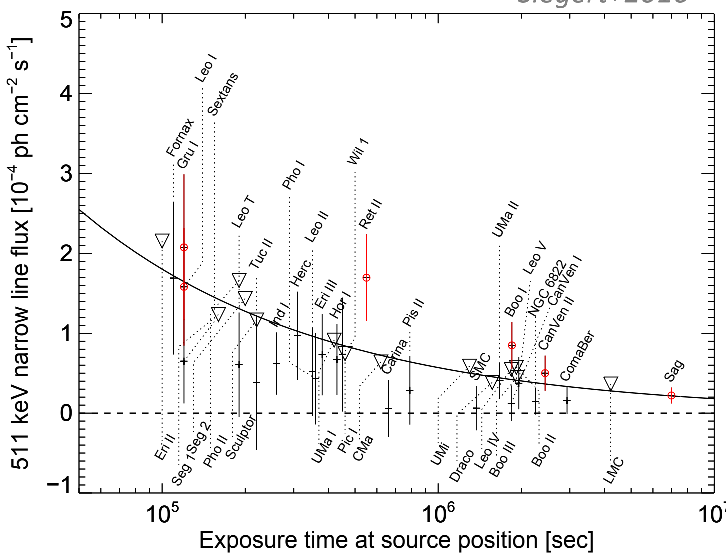
- dSph galaxies:

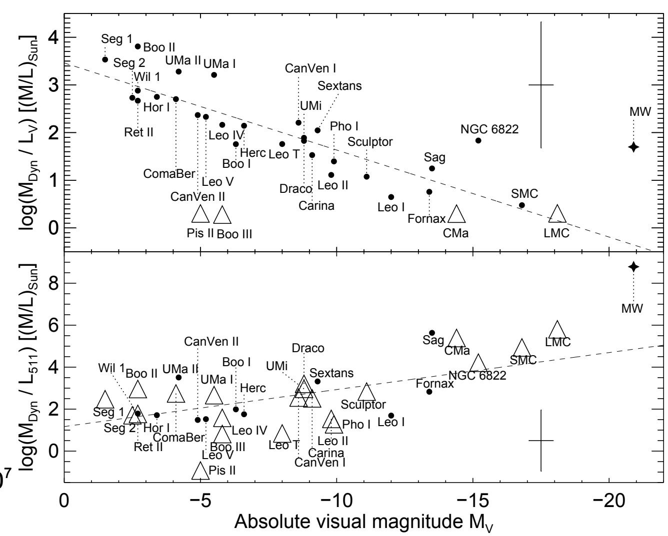
  ☞ no signal

  ☞ Ret II?

  ☞ not the expected correlation

Siegert+2016





Candidate e^+ sources and their properties

TABLE IX. Properties of candidate positron sources in the Milky Way.

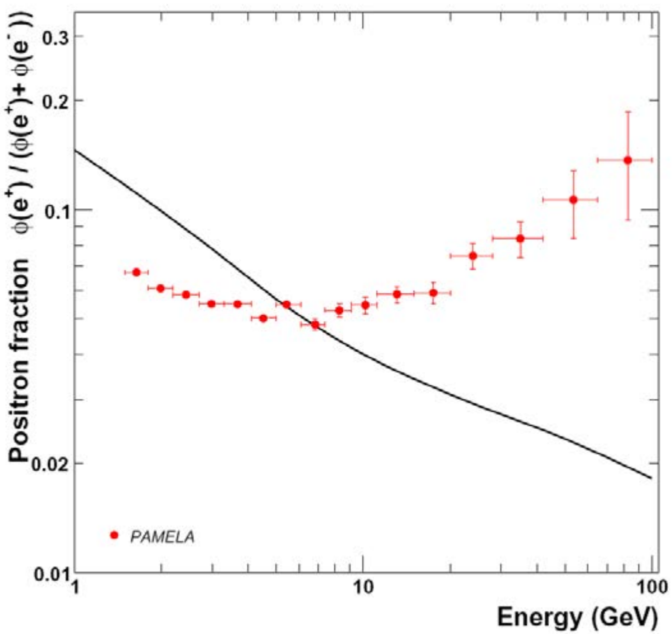
Source	Process	$E(e^+)$[a] (MeV)	e^+ rate[b] $\dot{N}_{e^+}$ (10^{43} s^{-1})	Bulge/disk[c] B/D	Comments
Massive stars: ^{26}Al	β^+ decay	~1	0.4	<0.2	$\dot{N}$, B/D: Observationally inferred
Supernovae: ^{24}Ti	β^+ decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+ decay	~1	*2*	<0.5	Assuming $f_{e^+,\mathrm{esc}} = 0.04$
Novae	β^+ decay	~1	*0.02*	<0.5	Insufficient e^+ production
Hypernovae/GRB: ^{56}Ni	β^+ decay	~1	?	<0.2	Improbable in inner MW
Cosmic rays	p-p	~30	0.1	<0.2	Too high e^+ energy
LMXRBs	γ-γ	~1	*2*	<0.5	Assuming $L_{e^+} \sim 0.01\, L_{\mathrm{obs},X}$
Microquasars (μQs)	γ-γ	~1	*1*	<0.5	e^+ load of jets uncertain
Pulsars	γ-γ/γ-γ_B	>30	*0.5*	<0.2	Too high e^+ energy
ms pulsars	γ-γ/γ-γ_B	>30	*0.15*	<0.5	Too high e^+ energy
Magnetars	γ-γ/γ-γ_B	>30	*0.16*	<0.2	Too high e^+ energy
Central black hole	p-p	High	?		Too high e^+ energy, unless $B > 0.4$ mG
	γ-γ	1	?		Requires e^+ diffusion to ~1 kpc
Dark matter	Annihilation	1 (?)	?		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	?		Only cuspy DM profiles allowed
	Decay	1	?		Ruled out for all DM profiles
Observational constraints		<7	2	>1.4	

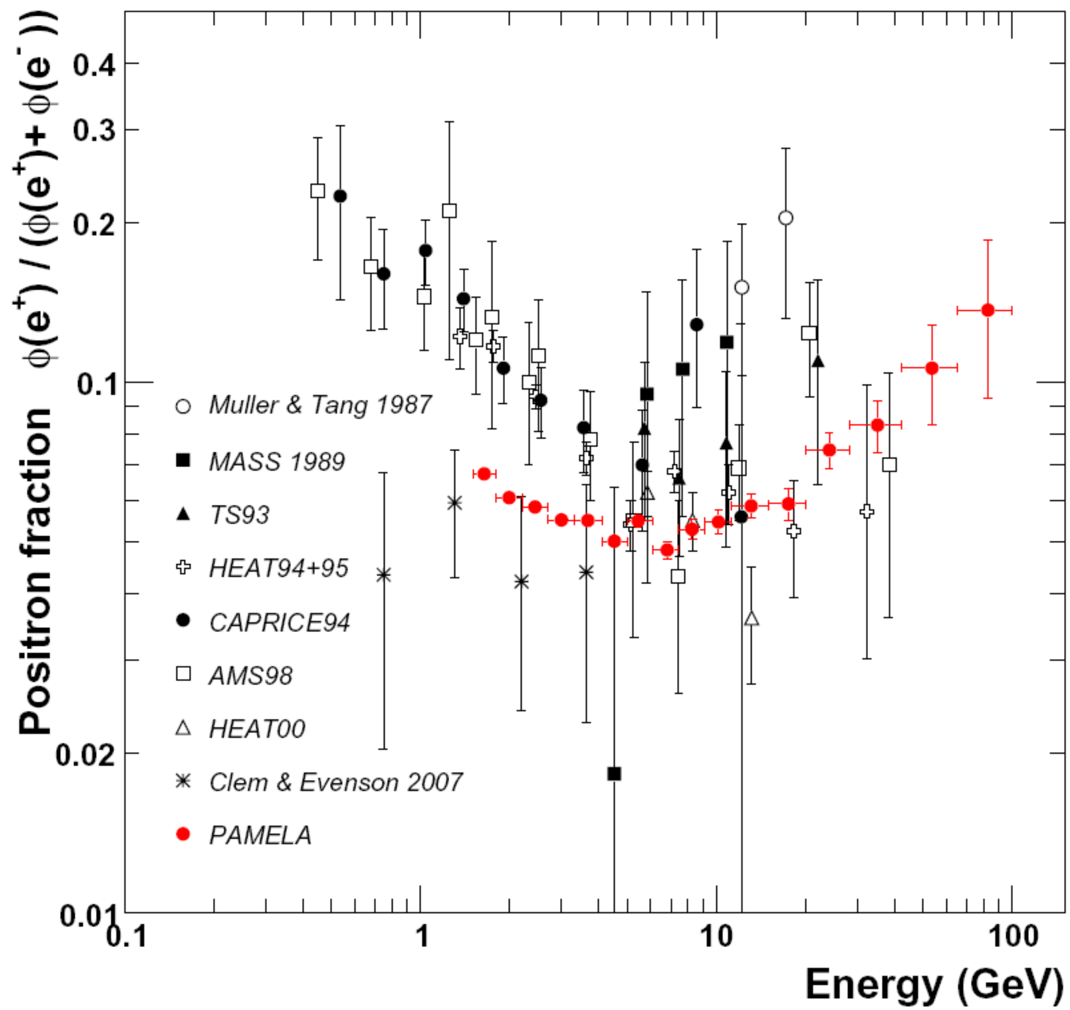
[a]Typical values are given.
[b]e^+ rates: in roman: observationally deduced or reasonable estimates; in italic: speculative (and rather close to upper limits).
[c]Sources are simply classified as belonging to either young ($B/D < 0.2$) or old (< 0.5) stellar populations.

from Prantzos+ 2011

Positrons in Cosmic Rays

- ☆ Pair-Production in Hadronic Cascades -> Generate e-,e+
- ☆ Results:
  - ☞ recent: Pamela
  - ☞ Inconsistent with Expectations from Propagation Model:





  - ☞ Dark Matter Annihilations??

The puzzle of the 511 keV Line Emission

After 13 y of measurements and various different analyses:

Surprisingly-bright extended “bulge-like” emission

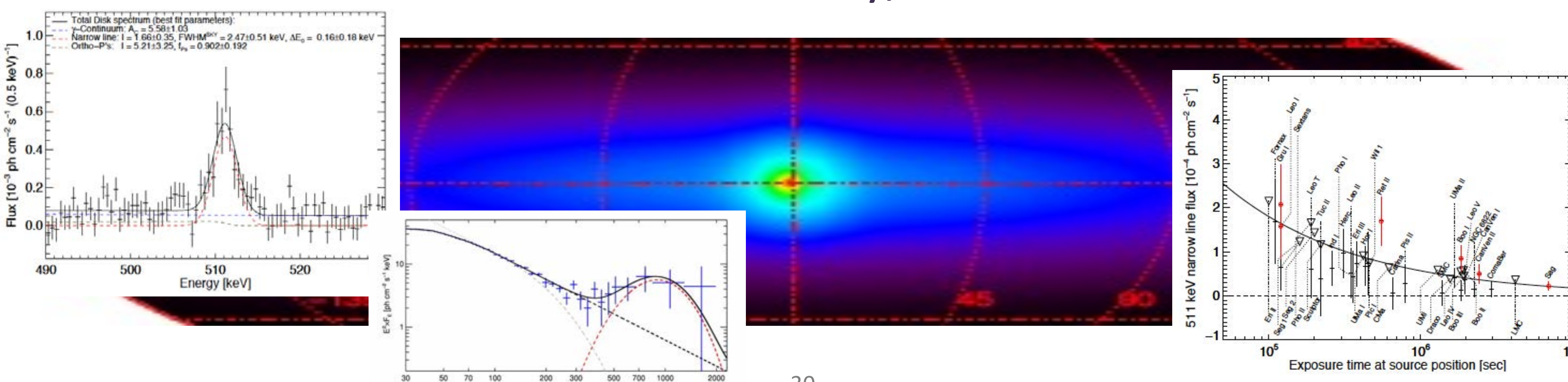
- None of the plausible candidate sources would produce this
- The centroid appears offset by ~1 deg towards 4th quadrant
- Sgr A*(?) appears to contribute ‘point-like’ emission, but cannot explain the extended bulge

The disk appears quite extended → e^+ outflows?

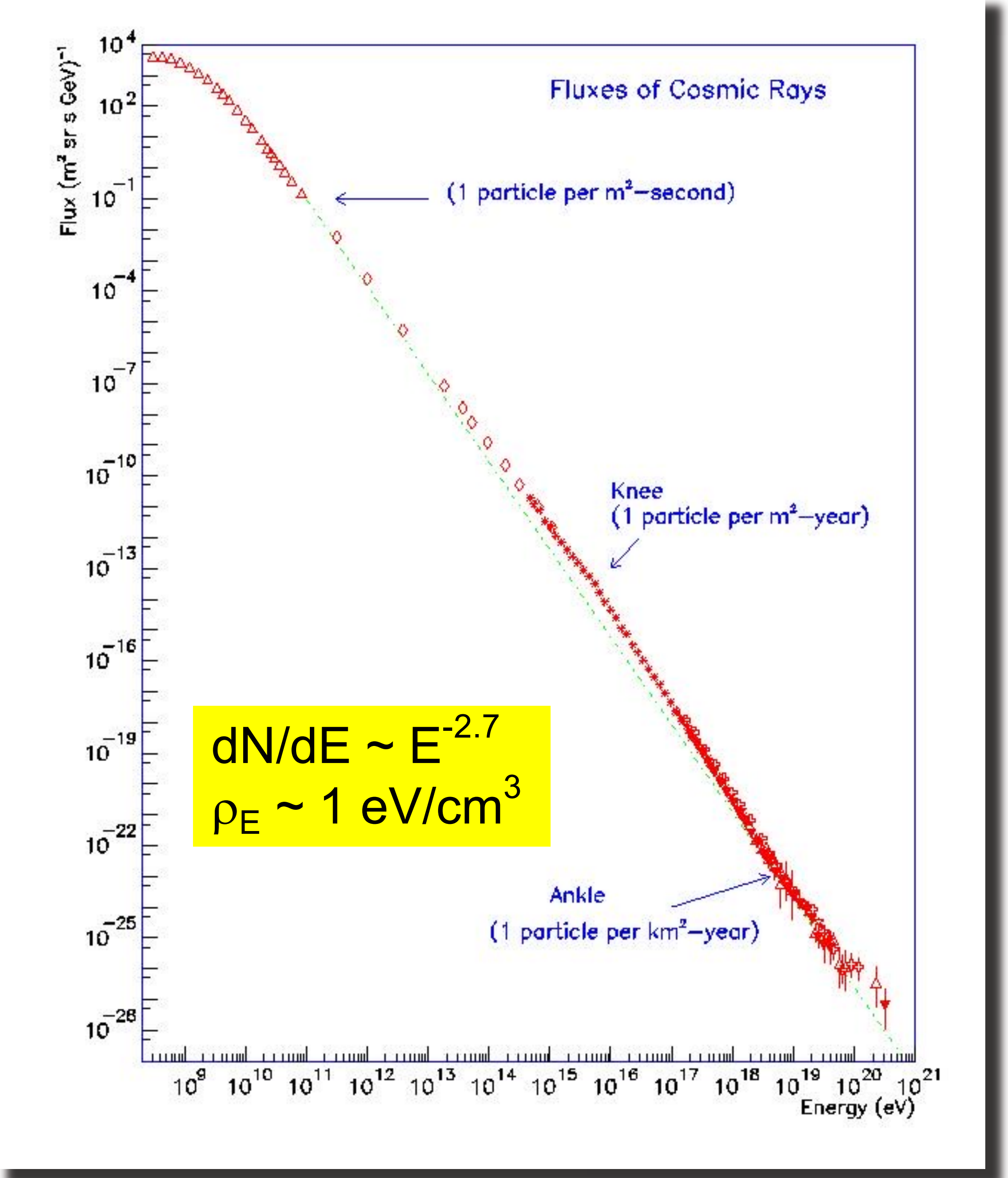
Pulsars, microquasars (!), SNe, …: Do they fill a ‘reservoir’?

- Annihilation appears not directly related to the sources

Dark matter contributions are unlikely/small

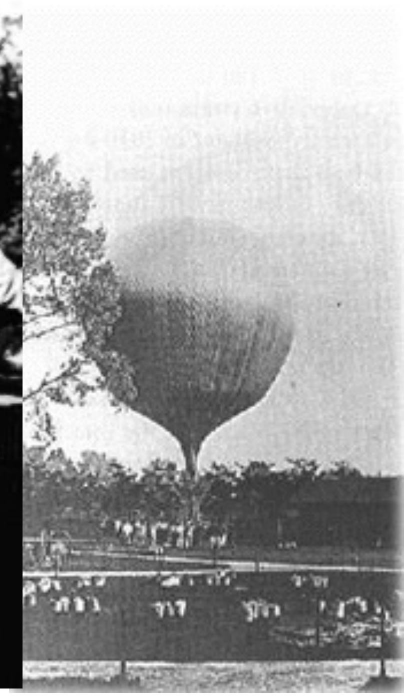


Cosmic rays: relativistic particles throughout the universe



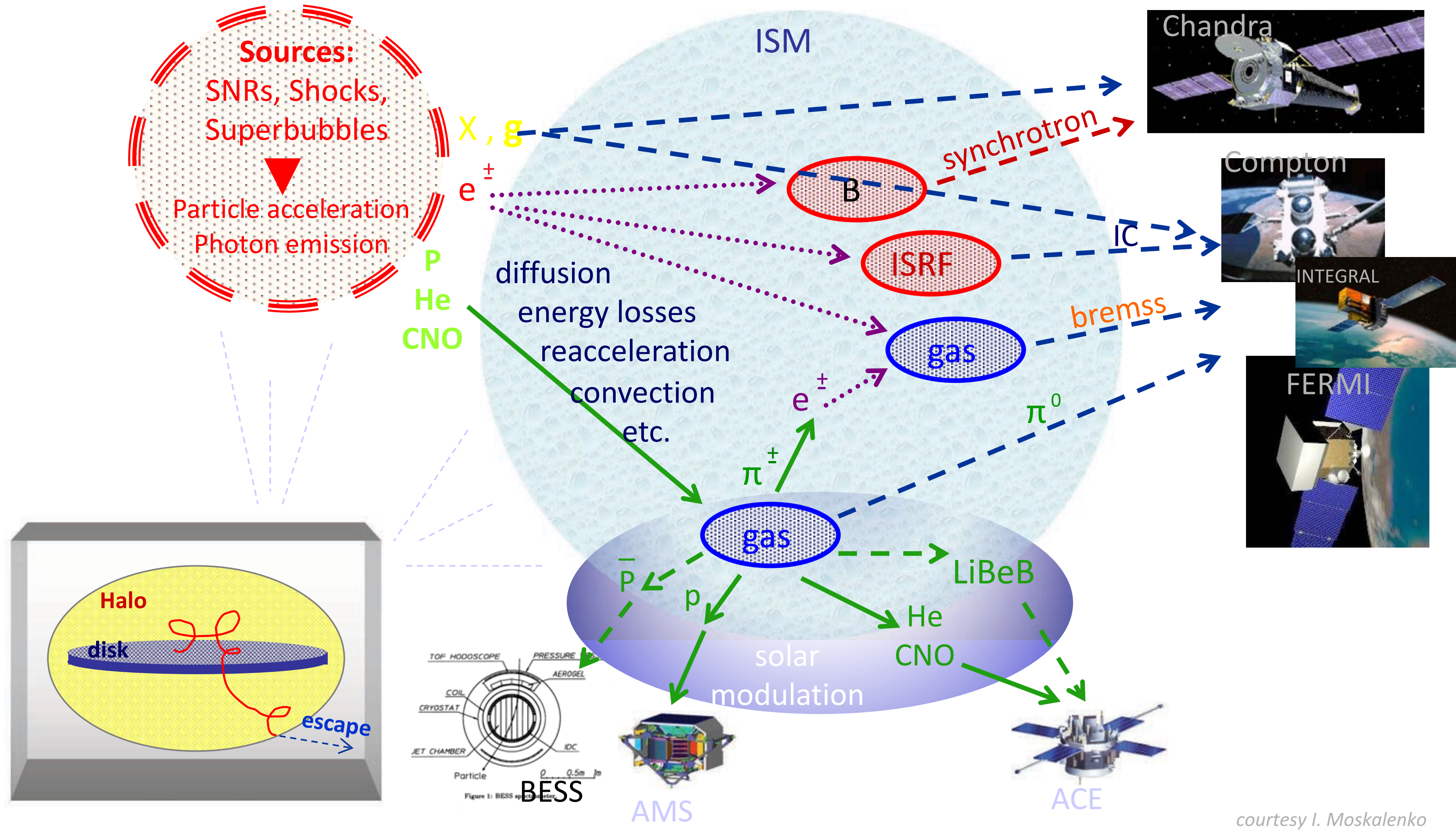
$dN/dE \sim E^{-2.7}$

$\rho_E \sim 1\ eV/cm^3$



- Cosmic rays were discovered in 1912
- They can be traced over 21 orders of magnitude in energy
- Uncovering their origin is a major astrophysics challenge

Cosmic Rays in the Galaxy, and their Messengers



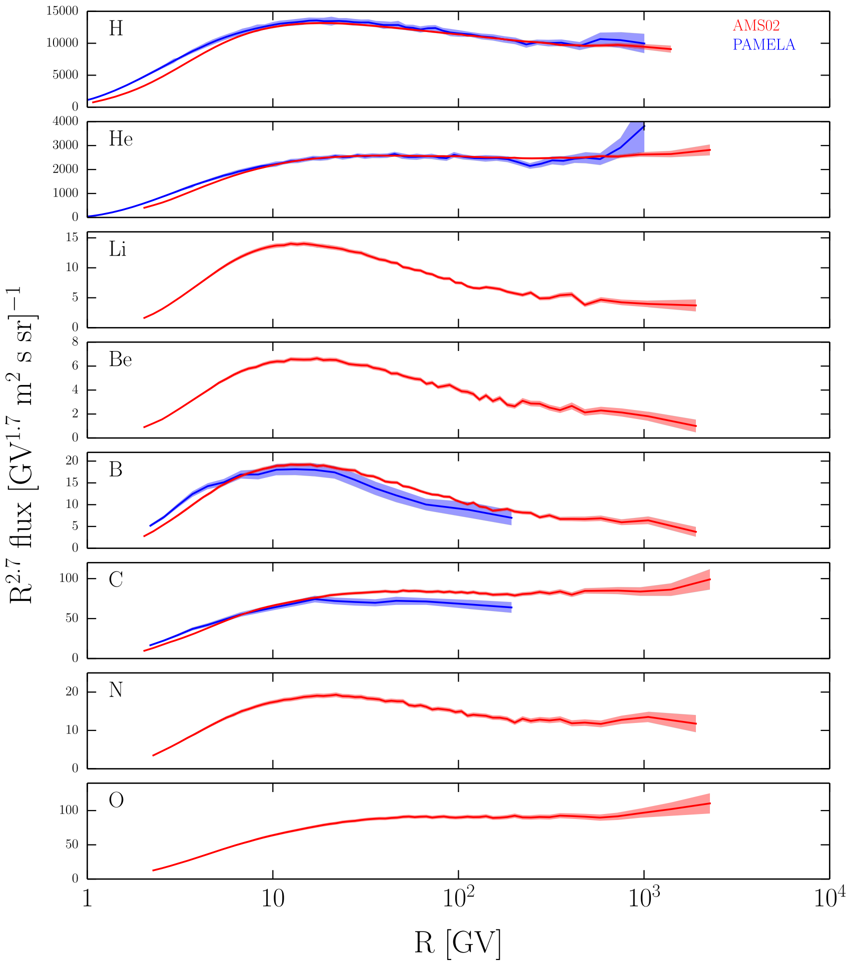
courtesy I. Moskalenko

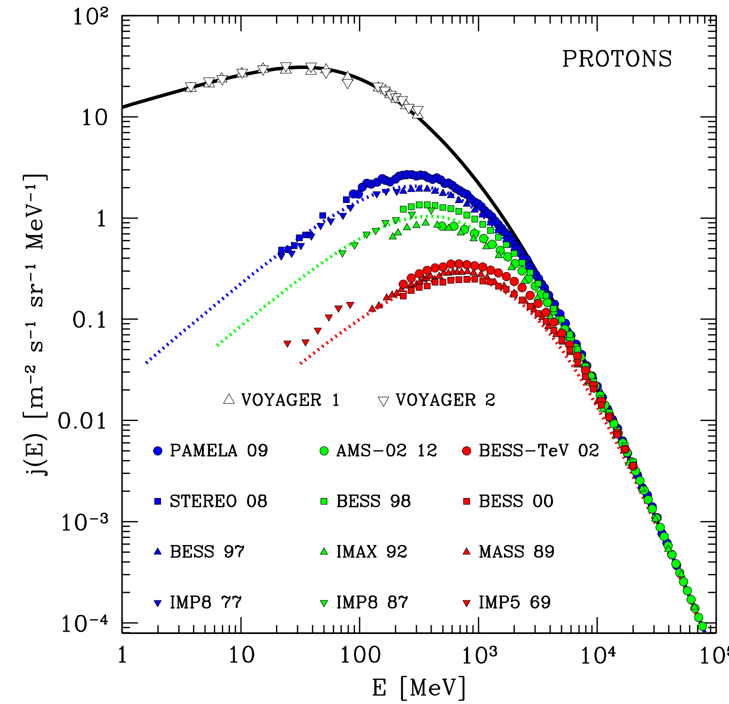
Cosmic ray measurements near Earth

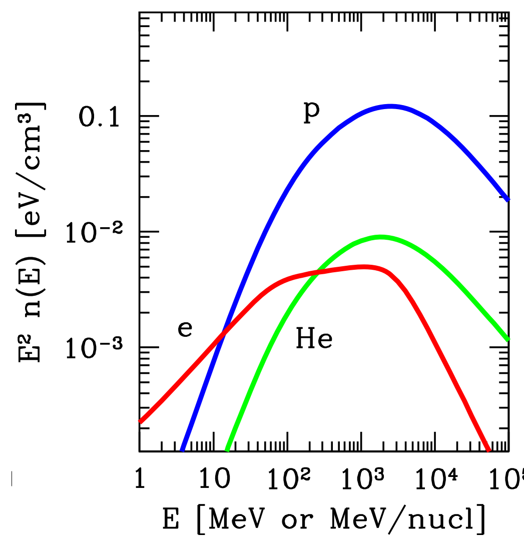
Gabici 2022

Solar modulation prevents reliable data on LECRs

Spectra different per nuclear species



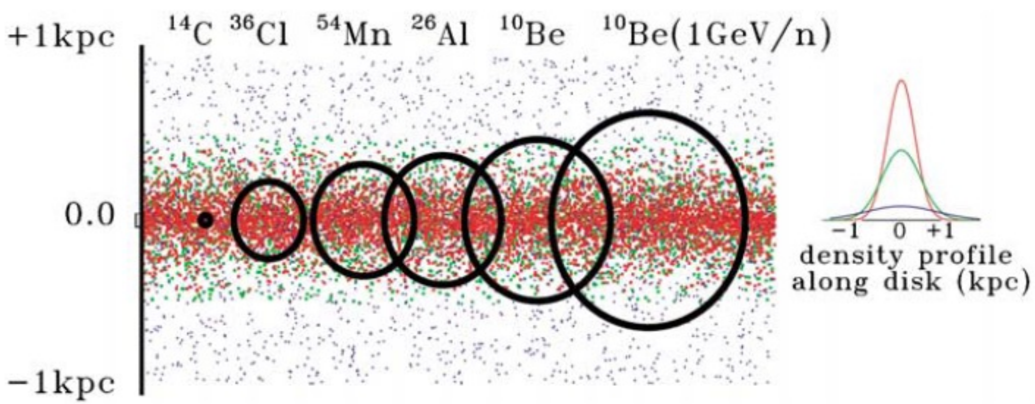


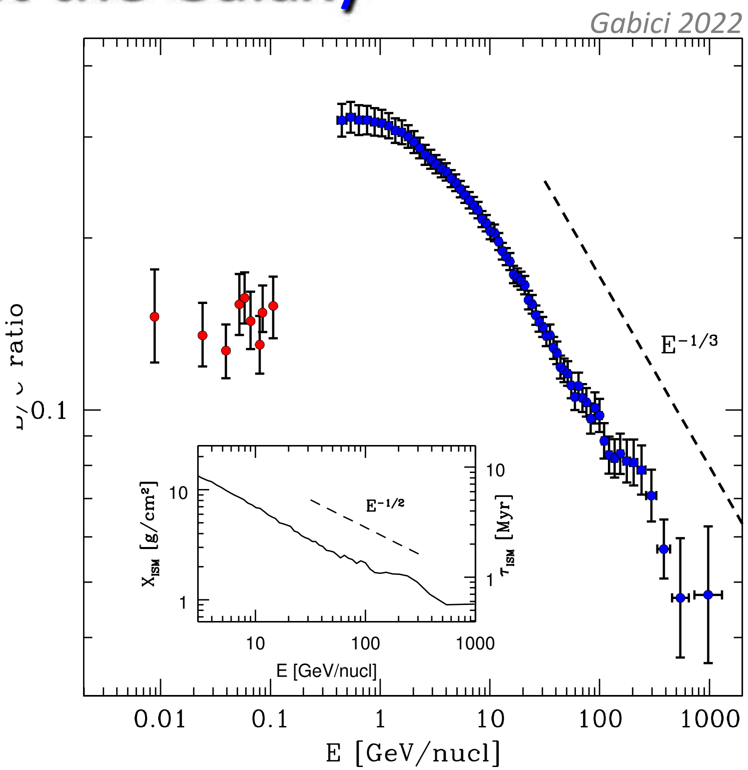


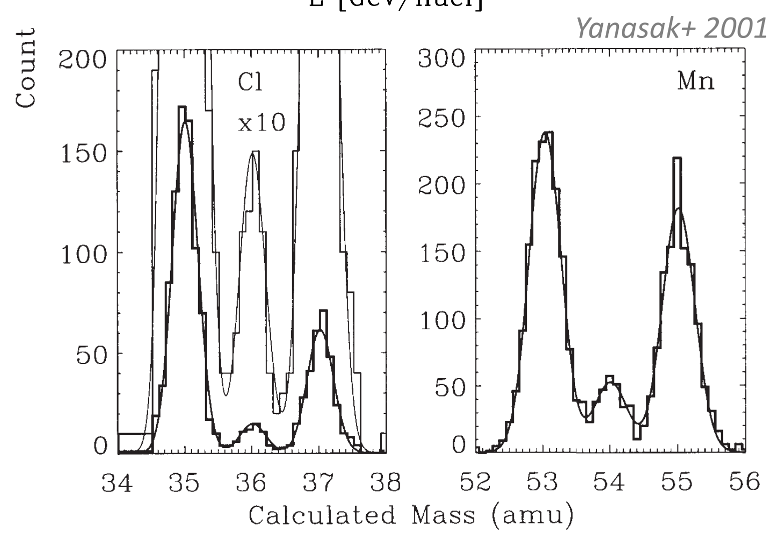
energy density of CRs in local ISM

Cosmic Rays throughout the Galaxy

- Radioactive isotopes, and spallation results (B/C ratio) ➔ CR's are ~isotropic and reside in the Galaxy for ~4...8 My's before escaping







- CRs diffuse through the Galaxy, scattering is efficient and eliminates source-related signatures

Processes for CR's and their spectral signatures in gamma rays

- continuum science in the MeV region -

- ☆ for e- (p) at 1 (100) TeV →
  - ☞ e- and p distinguishable
  - ☞ primary particle spectra
    → broadening of signatures

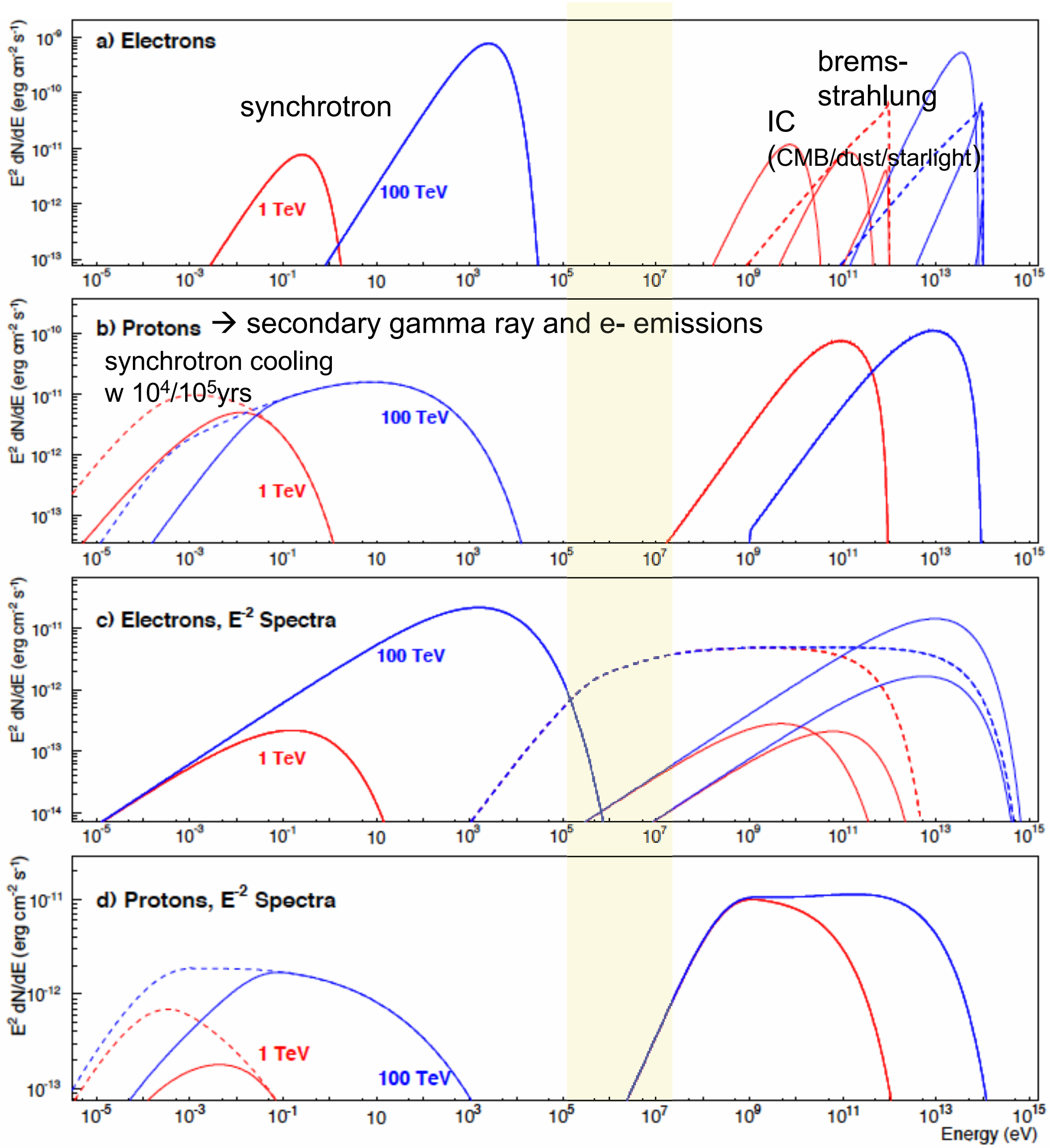
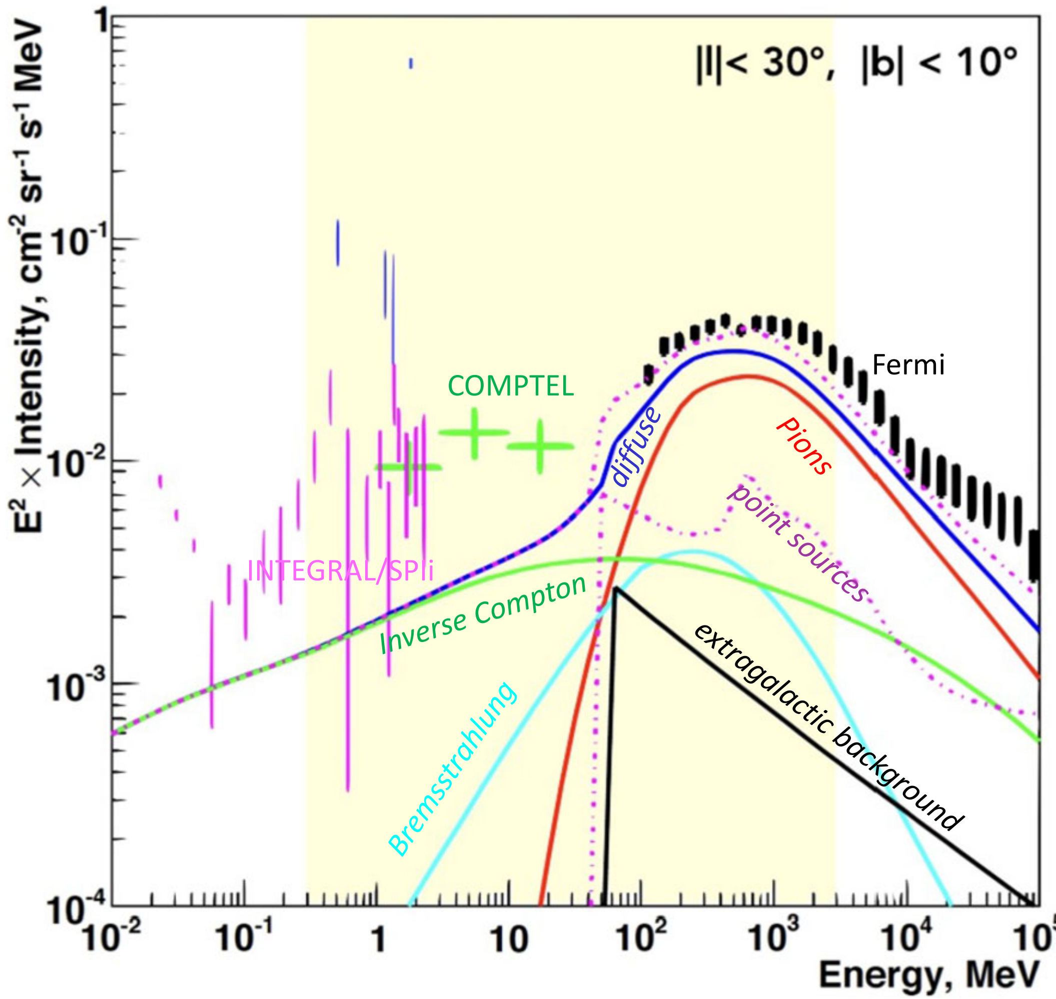


Figure 2: **a)** SEDs for radiation of mono-energetic 1/100 TeV electrons (red/blue curves): Synchrotron and IC (solid curves) and Bremsstrahlung (dashed curves). Three IC curves are shown for each primary energy: (from low to high) on the CMB ($kT = 2.35 \times 10^{-4}$ eV, $b \approx 4 \times 10^{-3}/0.4$), on dust-emitted FIR ($kT = 0.02$ eV, $b \approx 0.3/30$), and on visible (star) light ($kT = 1.5$ eV, $b \approx 20/2000$). Note that for 100 TeV electrons scattering on optical photons the IC energy distribution is effectively a delta-function at 100 TeV. The curve normalizations are appropriate for a total particle energy of 10^{47} erg at 1 kpc distance in a magnetic field of 3 μG, a matter density of 100 hydrogen atoms cm^{-3} and radiation fields of density 0.26 eV cm^{-3} (CMB and FIR) and 1 eV cm^{-3} (starlight). **b)** SEDs for γ-rays and synchrotron radiation of secondary electrons from strong interactions of mono-energetic protons. The magnetic field is increased to 30 μG to illustrate the effects of cooling and steady injection over 10^4 yr (dashed curves 10^5 yr) is assumed. The input energy is 10^{48} erg. **c)** and **d)** – as for a) and b) but for cut-off power-law distributions of particles: $dN/dE \propto E^{-2} \exp -E/E_c$ with $E_c = 1$ TeV (red) and 100 TeV (blue).

Diffuse gamma-ray emission from the Galaxy

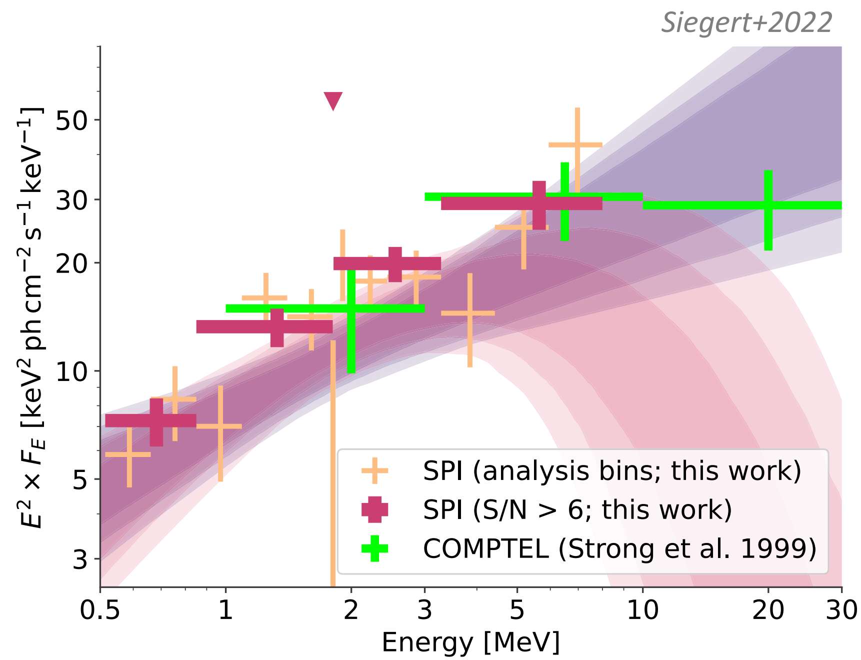
Strong+2004, 2005, 2011

- Cosmic rays are main sources of diffuse gamma-ray emission from the Galaxy
- In the MeV region, the CR propagation models appear insufficient to explain data
  - ☆ diffuse emission in specific gamma-ray lines:
    - ☞ ^{26}Al radioactivity
    - ☞ ^{60}Fe radioactivity
    - ☞ e^{+} annihilation
    - ☞ LECR nuclear lines?
    - ☞ pulsars? binaries?
    - ☞ + ???

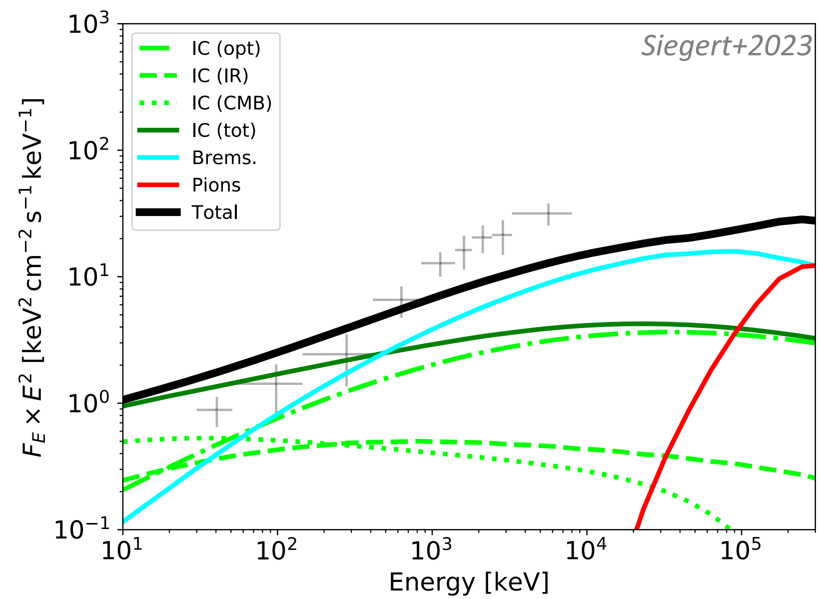


Diffuse MeV emission from the Galaxy: INTEGRAL data

- Consistency with previous results (COMPTEL) for diffuse-continuum only (i.e., ^{26}Al line emission and e^+ annihilation emission excluded)



- CR propagation (GALPROP model) can be fitted to INTEGRAL/SPI.
  → different normalisation for summed e- interactions: scattering on interstellar radiation field and with ISM
  → IC emission & Bremsstrahlung
- *Is this a mis-interpretation?*



Nuclear Lines from Cosmic-Ray Collisions

Cosmic-ray collisions with ambient matter lead to characteristic nuclear de-excitation lines, with interesting diagnostic line features

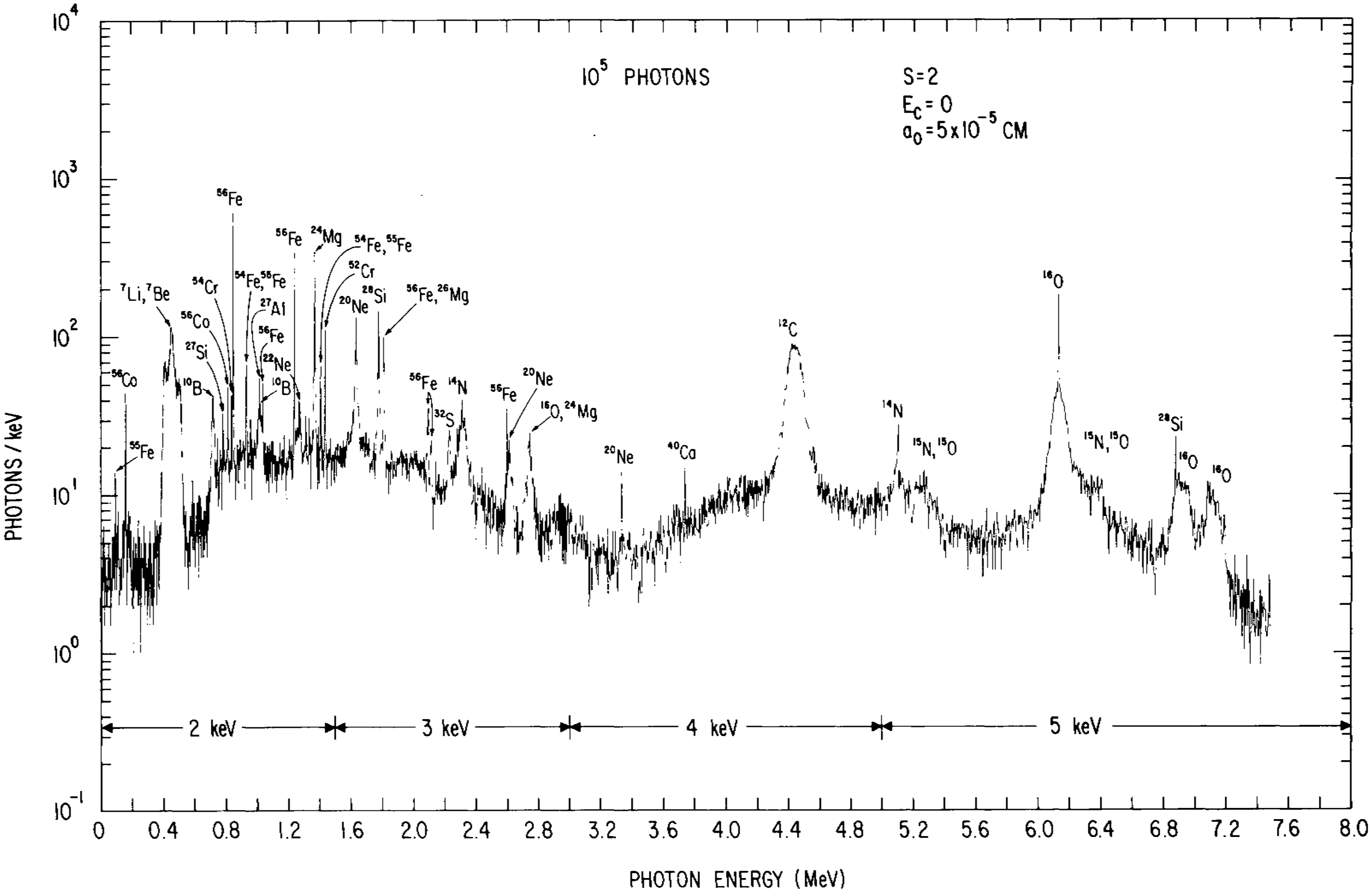
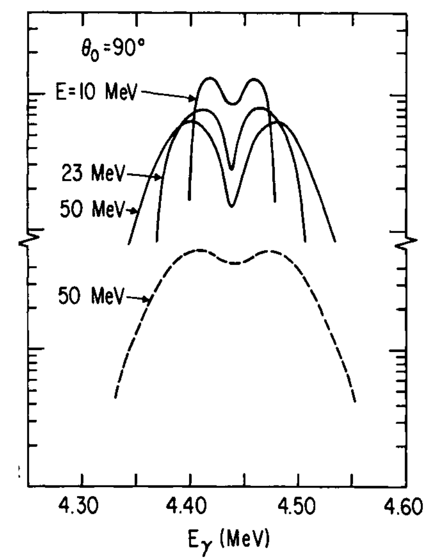


FIG. 18.—Monte Carlo simulated γ-ray spectrum for energetic particles and ambient medium having solar compositions; s and E_c are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

Ramaty & Lingenfelter 1979



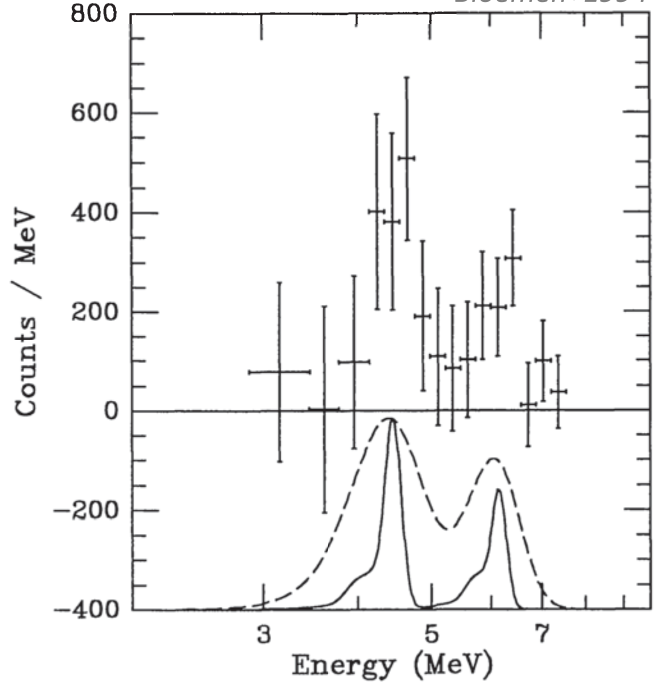
-Profile of the 4.44 MeV γ-ray line from the reac- p′)$^{12}C^*$. The bombarding protons are mono- l confined to a beam, and the γ-rays are observed ie beam. The top curves are calculated for an ilation of the spin states of the $^{12}C^{*4.439\,MeV}$ level. urve is calculated for isotropic γ-ray emission.

Observing nuclear lines from CR collisions

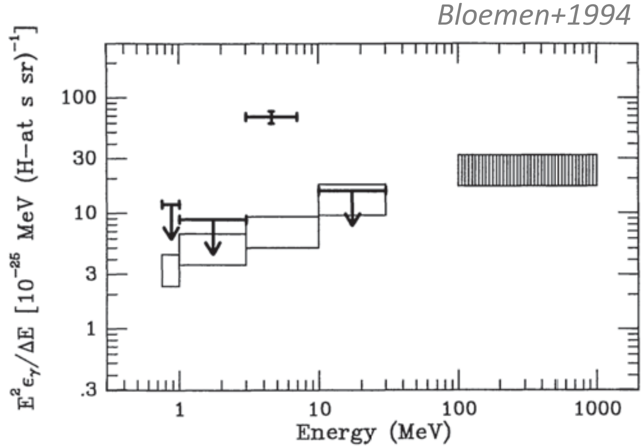
The Orion region hosts massive stars, and is a promising most-nearby region for creation of cosmic rays and thus characteristic gamma-rays from their collisions

COMPTEL interpreted a signal excess at 3-7 MeV in terms of nuclear de-excitation, but withdrew this result later due to doubts about systematics

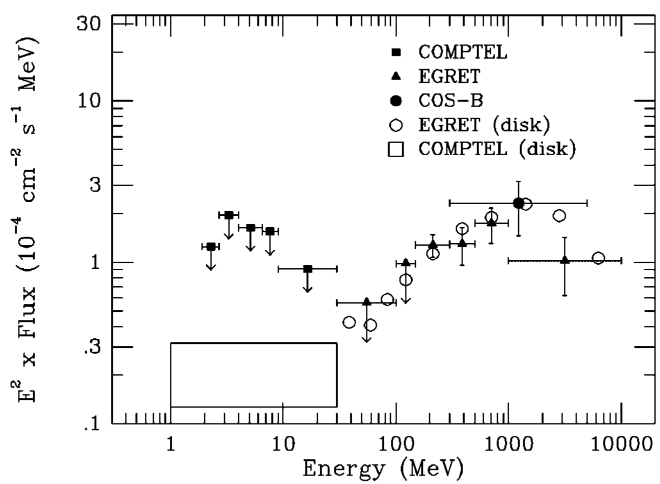
Bloemen+1994



Bloemen+1994

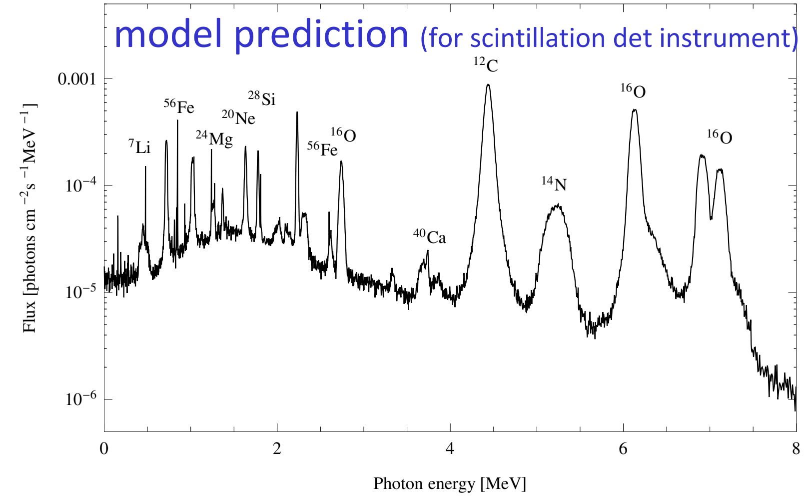


Bloemen+1999

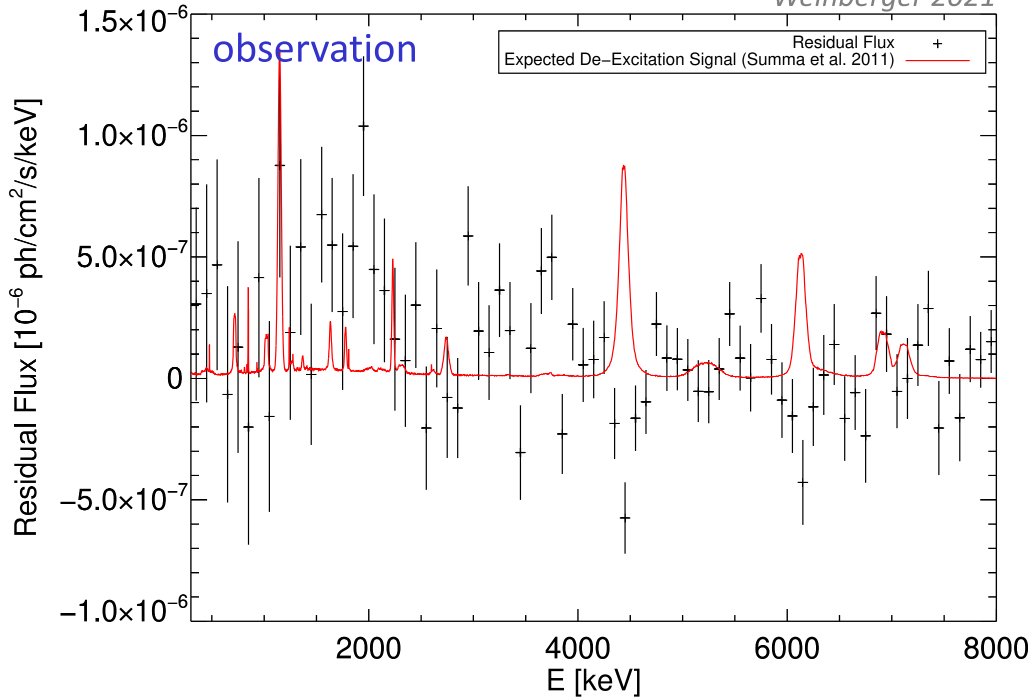


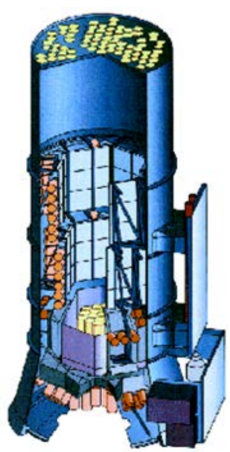
Observing nuclear lines from CR collisions in Cas A

The Cas A supernova remnant is a promising most-nearby accelerator for cosmic rays, due to its young age. Characteristic gamma-rays from their collisions with the outer SNR boundary are expected.



INTEGRAL/SPI could not detect any excess emission of e.g. the ^{12}C and ^{16}O lines

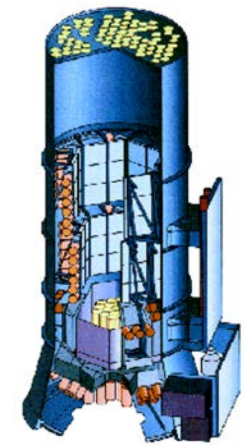




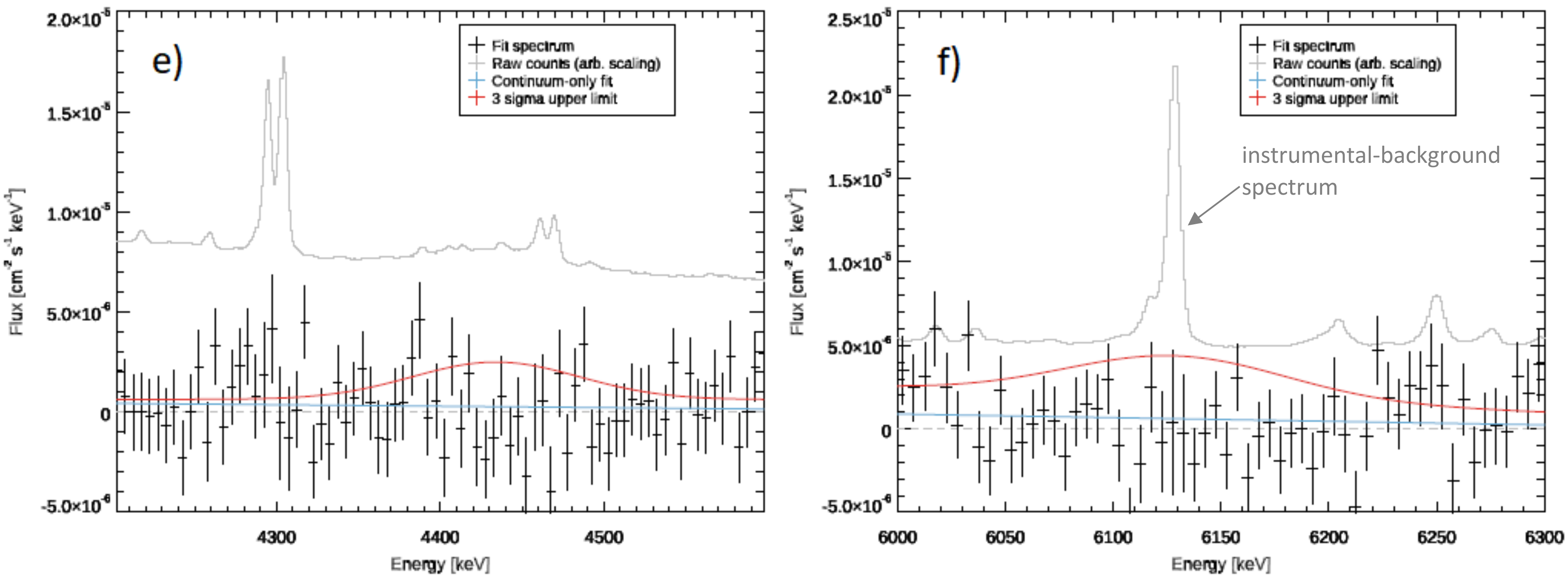
Observing nuclear lines from CR collisions

The inner Galaxy has been seen in continuum gamma rays originating from cosmic rays. Characteristic gamma-rays from nuclear excitations are also expected.

INTEGRAL/SPI could not detect any excess emission of the ^{12}C and ^{16}O lines



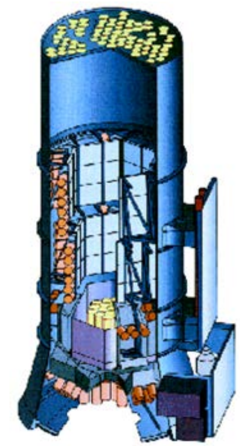
Kuhn 2021



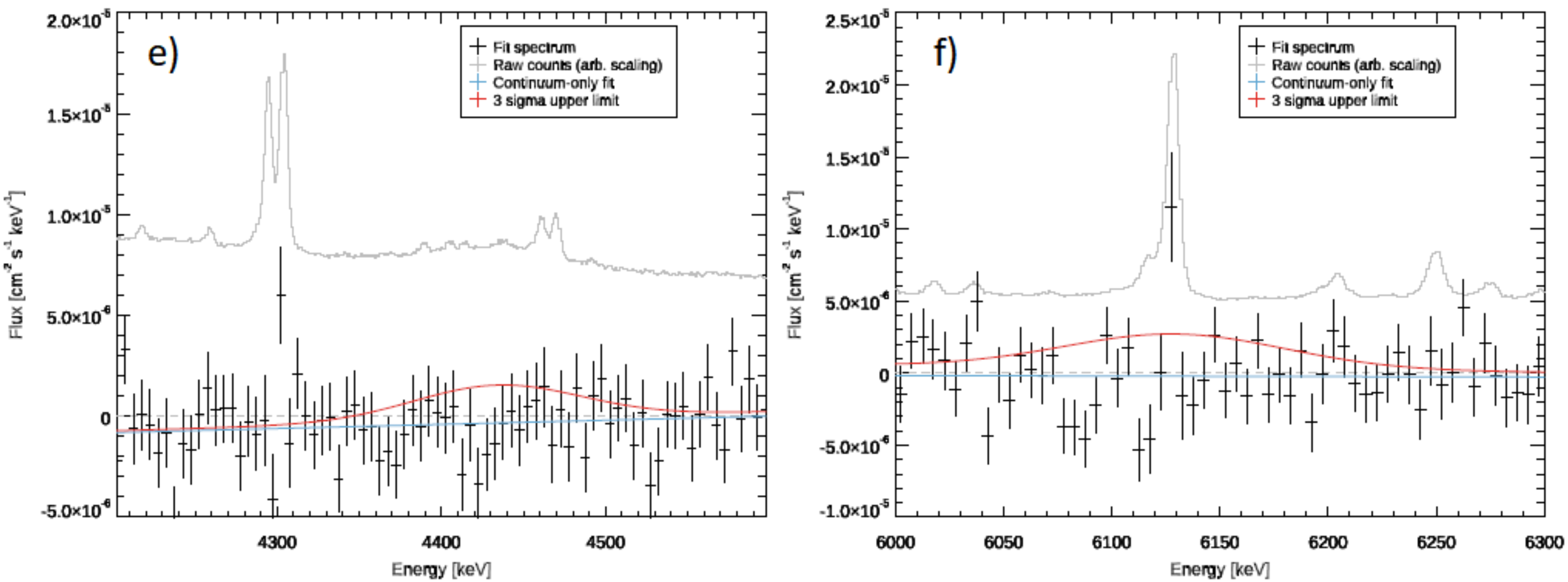
Observing nuclear lines from CR collisions

The Orion region has been a candidate for haracteristic gamma-rays from nuclear excitations, from COMPTEL data.

INTEGRAL/SPI could not detect any excess emission of the ^{12}C and ^{16}O lines



Kuhn 2021



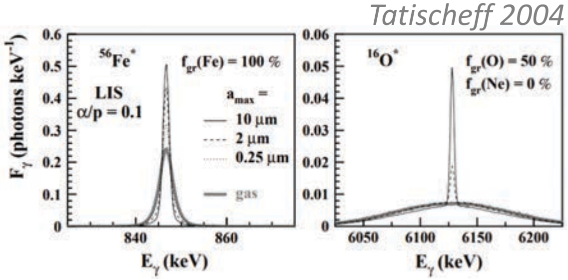
Constraints on nuclear lines from CR collisions

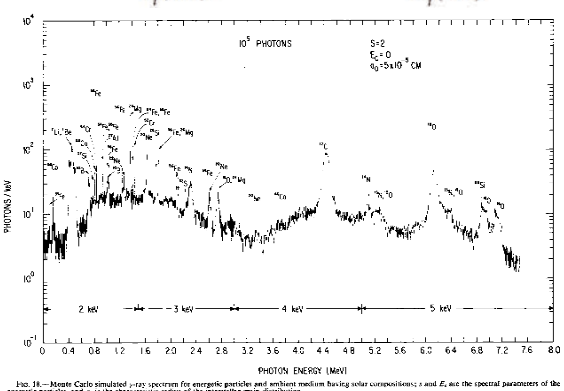
Kuhn 2021

Various predictions for characteristic gamma-rays from nuclear excitations could not be tested yet with INTEGRAL/SPI.

Possibly the grain compnent is dominant?

Tatischeff 2004





Publication	Line	Predicted Flux $[10^{-5}cm^{-2}\ s^{-1}]$	SPI upper limit $[10^{-5}cm^{-2}\ s^{-1}]$
Ramaty et al. 1979 [26]	4.4 MeV, FWHM 110 keV	1.2 - 7.2	24
	6.1 MeV, FWHM 110 keV (+ narrow)	0.6 - 3.0	32 (8.6)
Tatischeff et al. 2004 [27]	4.4 MeV, FWHM 150 keV	0.07	24
	6.1 MeV, FWHM 120 keV (+ narrow)	0.03	32 (8.6)
Dogiel et al. 2009 [9]	4.4 MeV, FWHM 160 keV[1]	1.2	24
Indriolo et al. 2009 [29]	4.4 MeV, FWHM 100 keV[2]	0.9 - 8.3	24
	6.1 MeV, FWHM 100 keV[2]	0.4 - 5.9	32
Benhabiles-Mezhoud et al. 2013 [28]	4.4 MeV, FWHM 100 keV	0.1 - 2.0	24
	6.1 MeV, FWHM 100 keV (+ narrow)	0.1 - 1.0	32 (8.6)

Table 6.1: Predictions for the flux in the strongest expected nuclear de-excitation lines at 4.4 MeV and 6.1 MeV from the past decades, compared to the upper limits for these lines, as obtained in this thesis with SPI. For each paper, the lines and their predicted widths (FWHM) are listed, followed by the predicted fluxes for each line and the closest comparable upper limits from table 5.1. Some authors predict an appreciable percentage of the 6.1 MeV line flux to be in a very narrow line component due to a portion of the emitting oxygen nuclei being locked up in dust grains; for these, the corresponding narrow-line upper limit from table 5.1 is also given (in parentheses).

[1] Very different predicted spatial distribution and line width; comparability to other predictions and SPI results limited.

[2] Indriolo et al. do not explicitly state the width of their predicted gamma ray lines, but from context a FWHM of 100 keV is likely. See text for a more detailed explanation.

Gamma-ray line spectroscopy: the science potential

Radioactive trace isotopes are by-products of nucleosynthesis reactions

Released into circum-source ISM, we can observe gamma-ray afterglows:

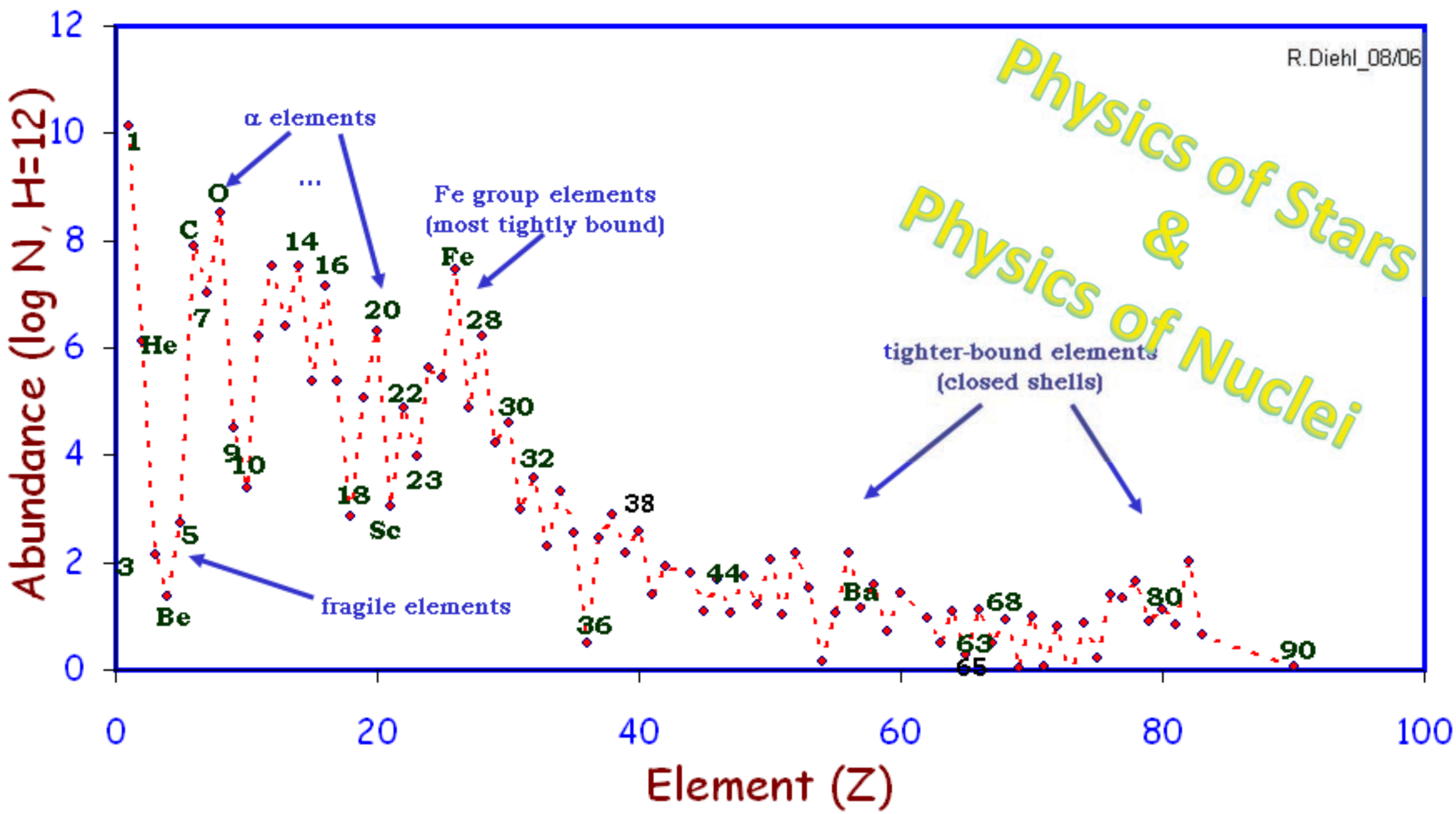
Isotope	Mean Decay Time	Decay Chain	γ -Ray Energy [keV]	Detected Source	Source Type
^{7}Be	77 d	^{7}Be → ^{7}Li*	478	(none)	Novae
^{56}Ni	8.8 d; 111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812; 847, 1238	SN2014J; SN1987A, SN1991T(?)	Supernovae
^{57}Ni	390 d	^{57}Co→ ^{57}Fe*	122	SN1987A	Supernovae
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e^{+}	1275	(none)	Novae
^{44}Ti	85 y	^{44}Ti→^{44}Sc*→^{44}Ca*+e^{+}	78, 68; 1157	SNR Cas A	Supernovae
$^{229/230}$Th	~1.0 10^5 y	$^{229/230}$Th →·····→^{206}Pb	352... 609...2615	(none)	Neutron Star Mergers, SNe
^{126}Sn	3.3 10^5 y	^{126}Sn →^{126}Sb*→^{126}Te	666; 695; 87; 64	(none)	Neutron Star Mergers, SNe
^{26}Al	1.04 10^6 y	^{26}Al → ^{26}Mg* + e^{+}	1809	Massive-Star Groups Cyg, Ori…	Stars, Novae Supernovae
^{60}Fe	3.5 10^6 y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332	Galaxy (?)	Supernovae, Stars
e^{+}	10^5… 10^7 y	e^{+}+e^{-} → Ps → γγ..	511, <511	Galactic Bulge, Disk	Supernovae, Novae, Pulsars, Microquasars…

- Only the most-plausible candidates per source type are listed

(abundance; decay time (weeks<τ<10^8y) long enough to survive ejection/not too long to be bright)

plus: nuclear excitation lines (^{12}C, ^{16}O, ...) (from CRs)

Hints from Cosmic Elemental Abundances



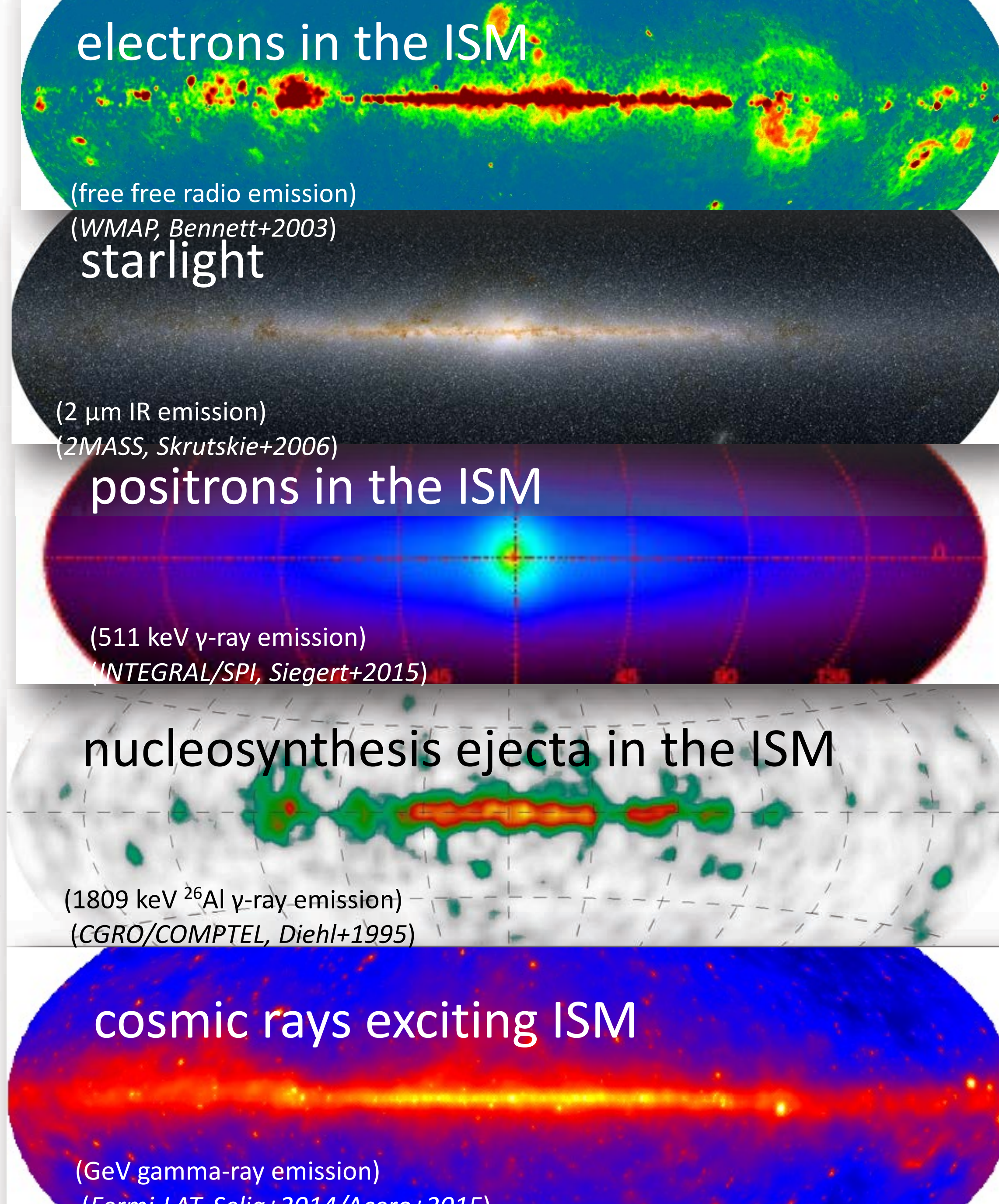
These signatures are a result from the characteristic physical processes within…

… atomic nuclei (which of these can be produced more-easily/more abundantly?)

… cosmic sources (which nuclear-fusion environments occur more often/abundantly?)

Galactic Messengers

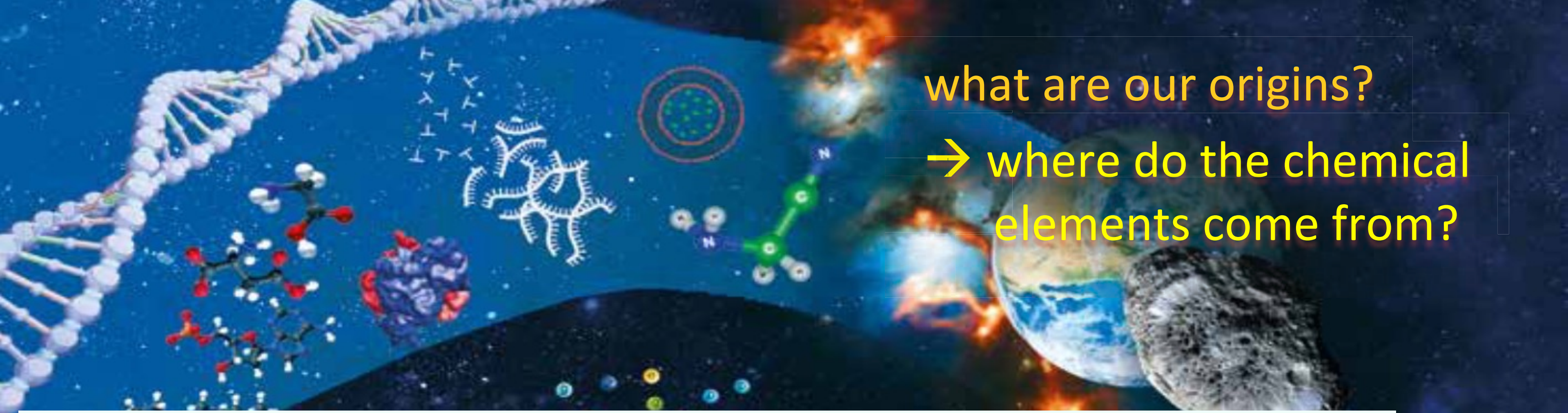
- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …
- Positron annihilation ~traces CR propagation




what are our origins?

what are our origins?

→ where do the chemical elements come from?



IUPAC Periodic Table of the Elements

Key: atomic number / **Symbol** / name / conventional atomic weight / standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.008 [1.0078, 1.0082]																	2 **He** helium 4.0026
3 **Li** lithium 6.94 [6.938, 6.997]	4 **Be** beryllium 9.0122											5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]	8 **O** oxygen 15.999 [15.999, 16.000]	9 **F** fluorine 18.998	10 **Ne** neon 20.180
11 **Na** sodium 22.990	12 **Mg** magnesium 24.305 [24.304, 24.307]											13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974	16 **S** sulfur 32.06 [32.059, 32.076]	17 **Cl** chlorine 35.45 [35.446, 35.457]	18 **Ar** argon 39.948
19 **K** potassium 39.098	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.956	22 **Ti** titanium 47.867	23 **V** vanadium 50.942	24 **Cr** chromium 51.996	25 **Mn** manganese 54.938	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933	28 **Ni** nickel 58.693	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922	34 **Se** selenium 78.971(8)	35 **Br** bromine 79.904 [79.901, 79.907]	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.468	38 **Sr** strontium 87.62	39 **Y** yttrium 88.906	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906	42 **Mo** molybdenum 95.95	43 **Tc** technetium	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.91	46 **Pd** palladium 106.42	47 **Ag** silver 107.87	48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.90	54 **Xe** xenon 131.29
55 **Cs** caesium 132.91	56 **Ba** barium 137.33	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.95	74 **W** tungsten 183.84	75 **Re** rhenium 186.21	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.22	78 **Pt** platinum 195.08	79 **Au** gold 196.97	80 **Hg** mercury 200.59	81 **Tl** thallium 204.38 [204.38, 204.39]	82 **Pb** lead 207.2	83 **Bi** bismuth 208.98	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Nh** nihonium	114 **Fl** flerovium	115 **Mc** moscovium	116 **Lv** livermorium	117 **Ts** tennessine	118 **Og** oganesson

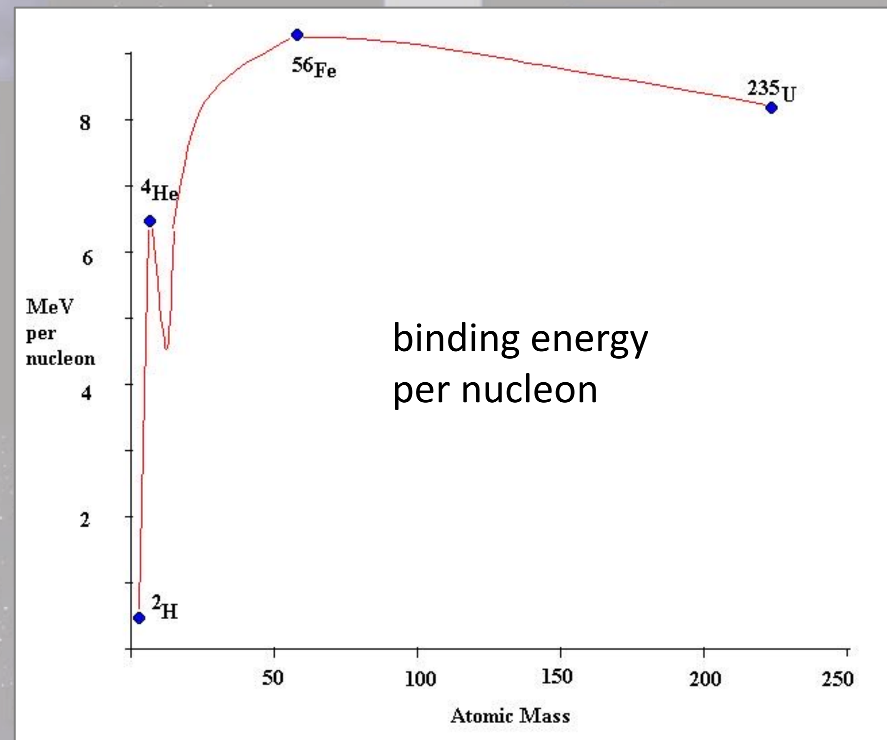
57 **La** lanthanum 138.91	58 **Ce** cerium 140.12	59 **Pr** praseodymium 140.91	60 **Nd** neodymium 144.24	61 **Pm** promethium	62 **Sm** samarium 150.36(2)	63 **Eu** europium 151.96	64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.93	66 **Dy** dysprosium 162.50	67 **Ho** holmium 164.93	68 **Er** erbium 167.26	69 **Tm** thulium 168.93	70 **Yb** ytterbium 173.05	71 **Lu** lutetium 174.97
89 **Ac** actinium	90 **Th** thorium 232.04	91 **Pa** protactinium 231.04	92 **U** uranium 238.03	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 28 November 2016.

Cosmic nucleosynthesis

- Big-bang nucleosynthesis
- Stellar-interior nucleosynthesis (hydrostatic)
- Stellar-explosion nucleosynthesis (explosive)
- High-energy collisions (spallation)

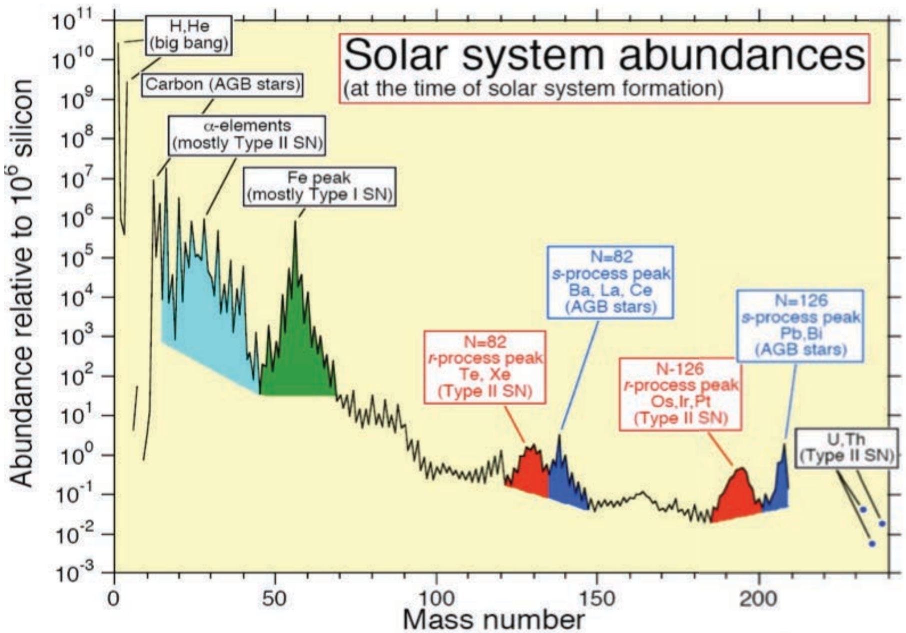


in all cases:
rearrangement of bound nucleons (p,n) in nuclei by nuclear reactions towards tighter binding

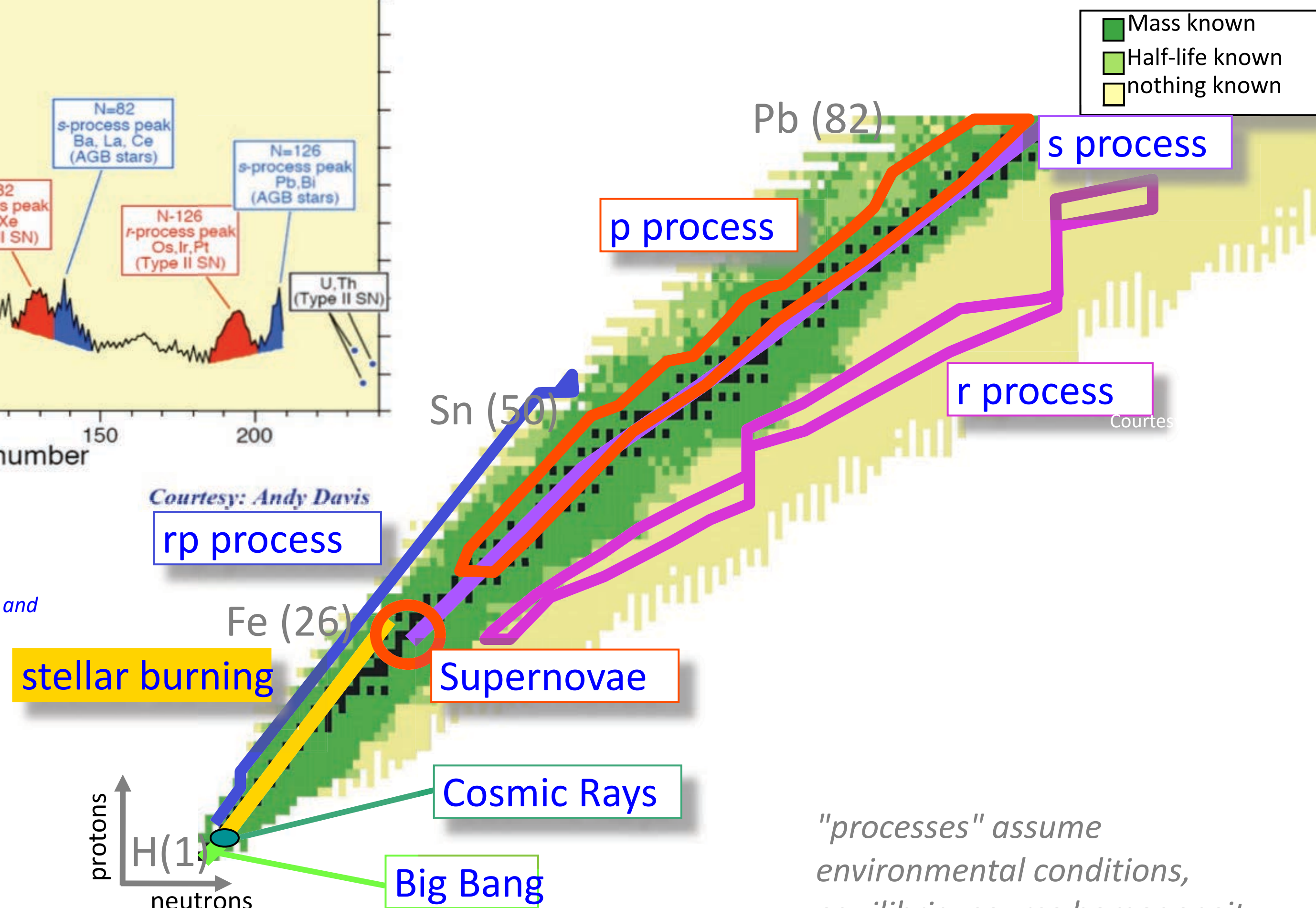
Cosmic origins of the variety of nuclides

Associating different "processes" with nuclide groups – *what we teach…*

… and know it to be superficial (or even wrong)



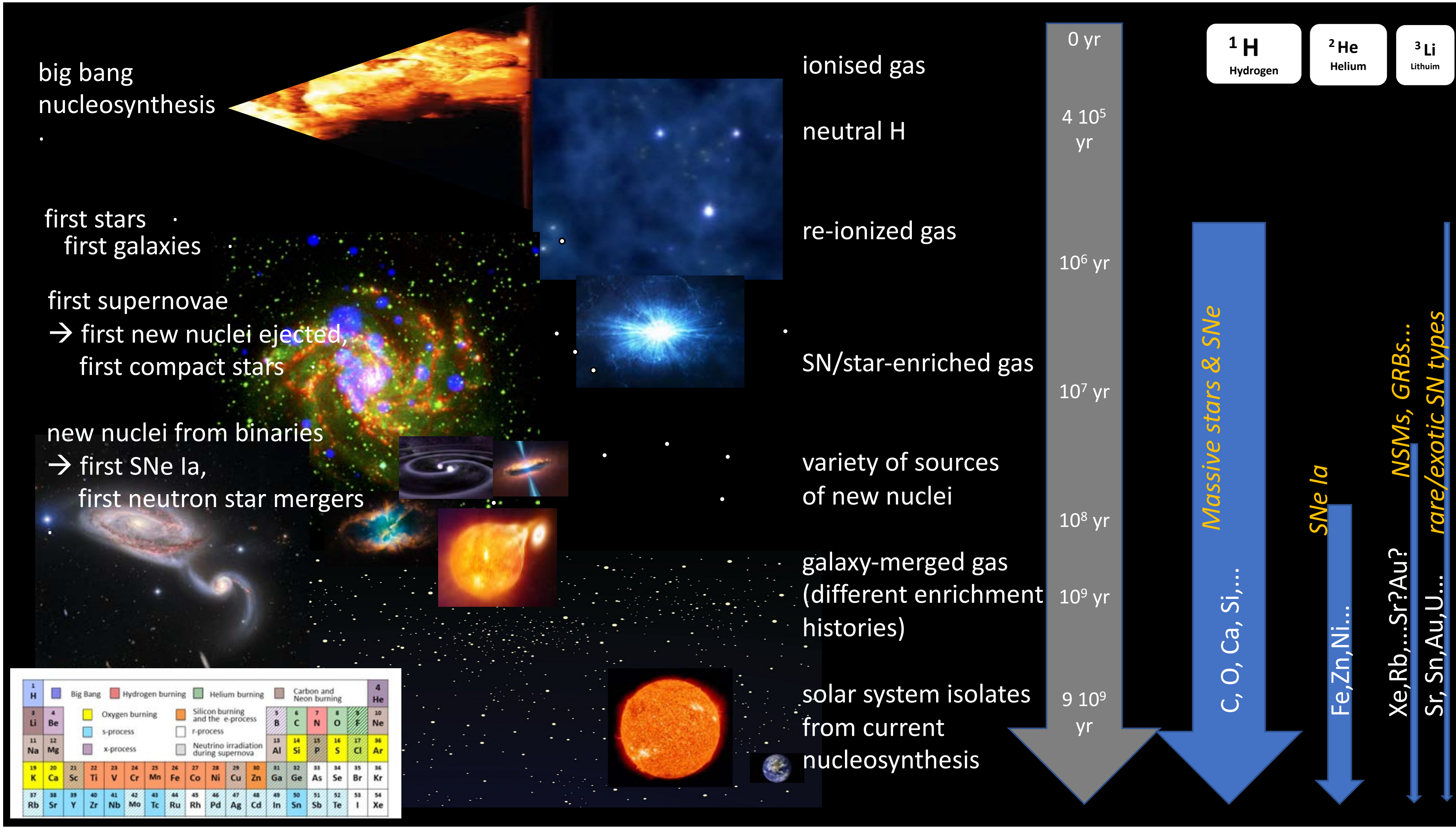
Courtesy: Andy Davis



cmp. Burbidge, Burbidge, Fowler, and Hoyle, RMP 1959

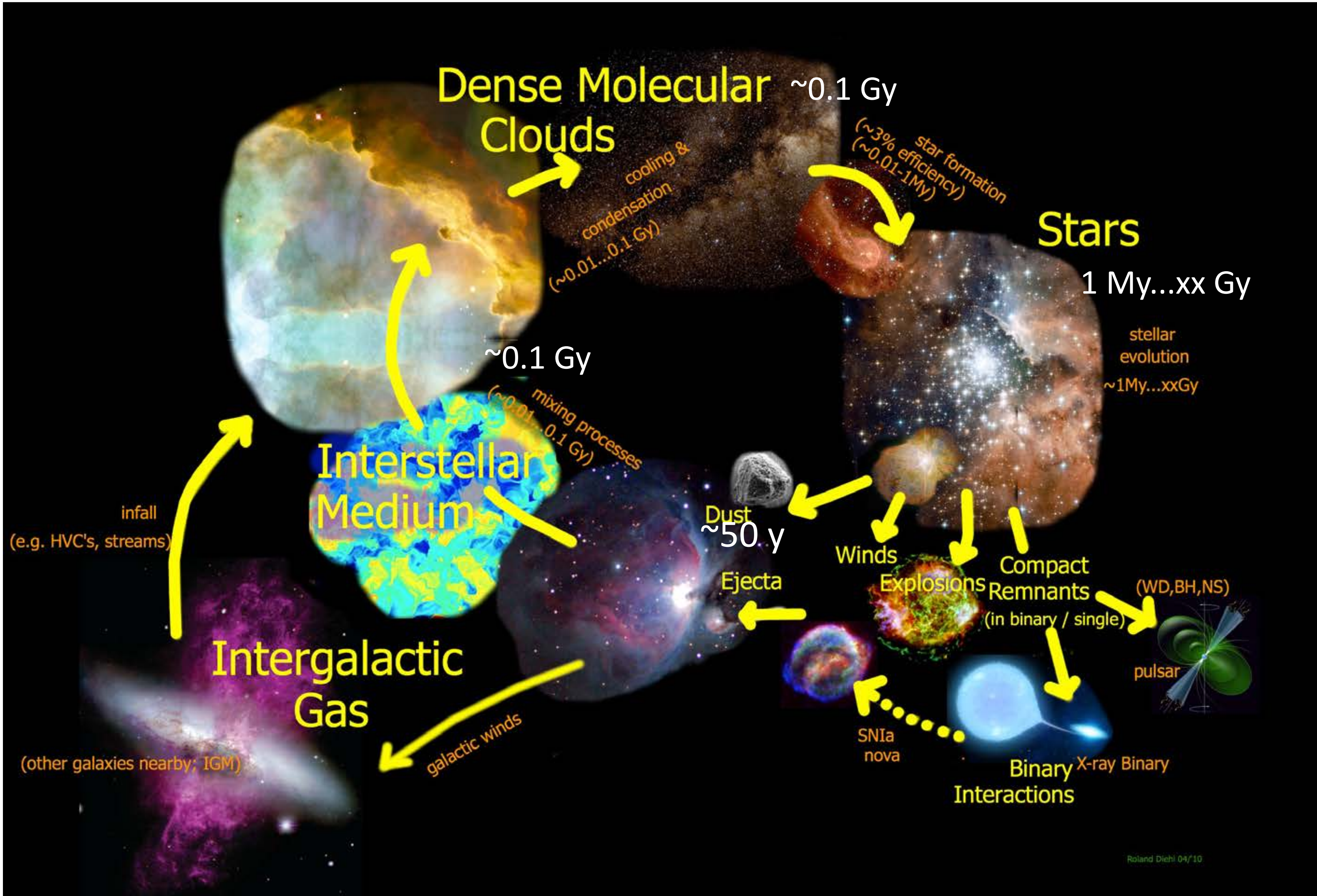
"processes" assume environmental conditions, equilibria, source homogeneity, ...

The broad context: evolving isotopic composition

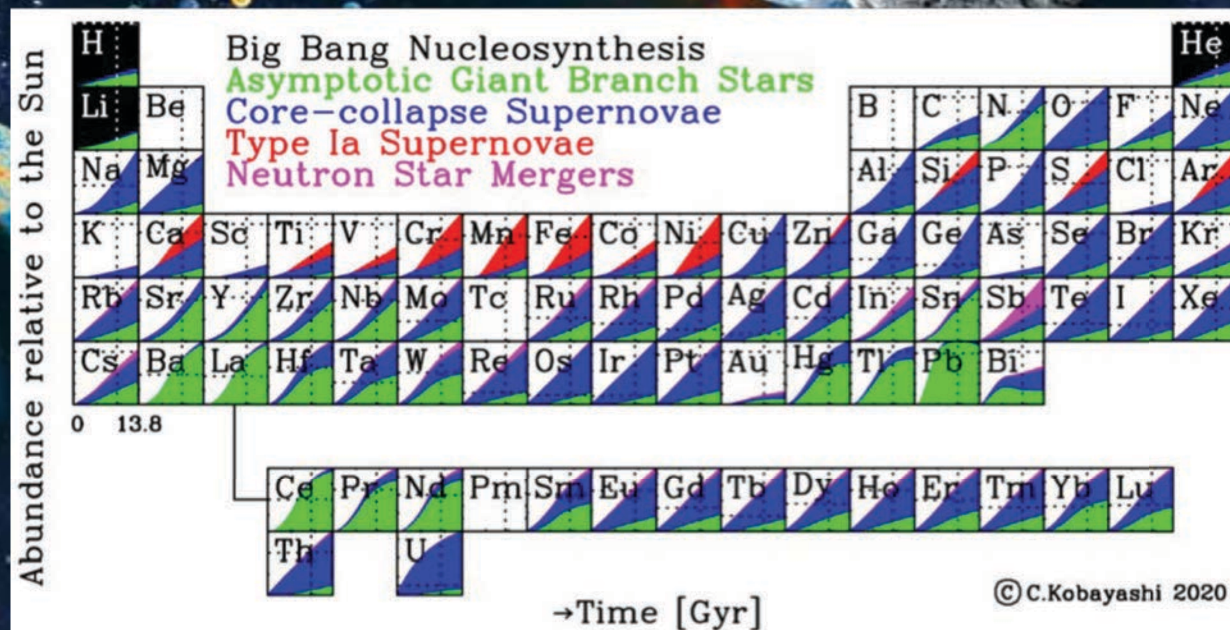


... the coarse picture of cosmic nucleosynthesis.

On-going Enrichments from Nucleosynthesis Sources

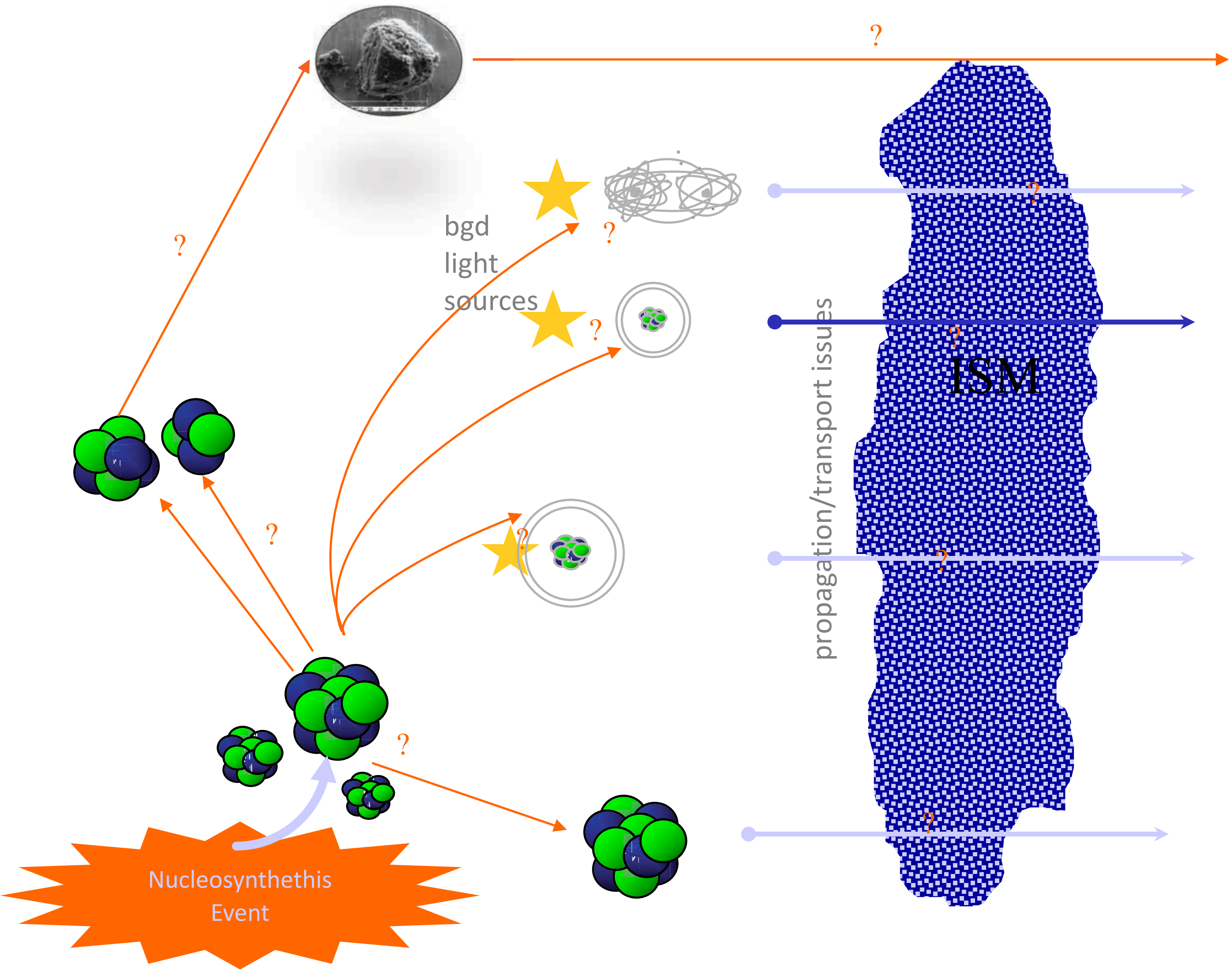


what are our origins?



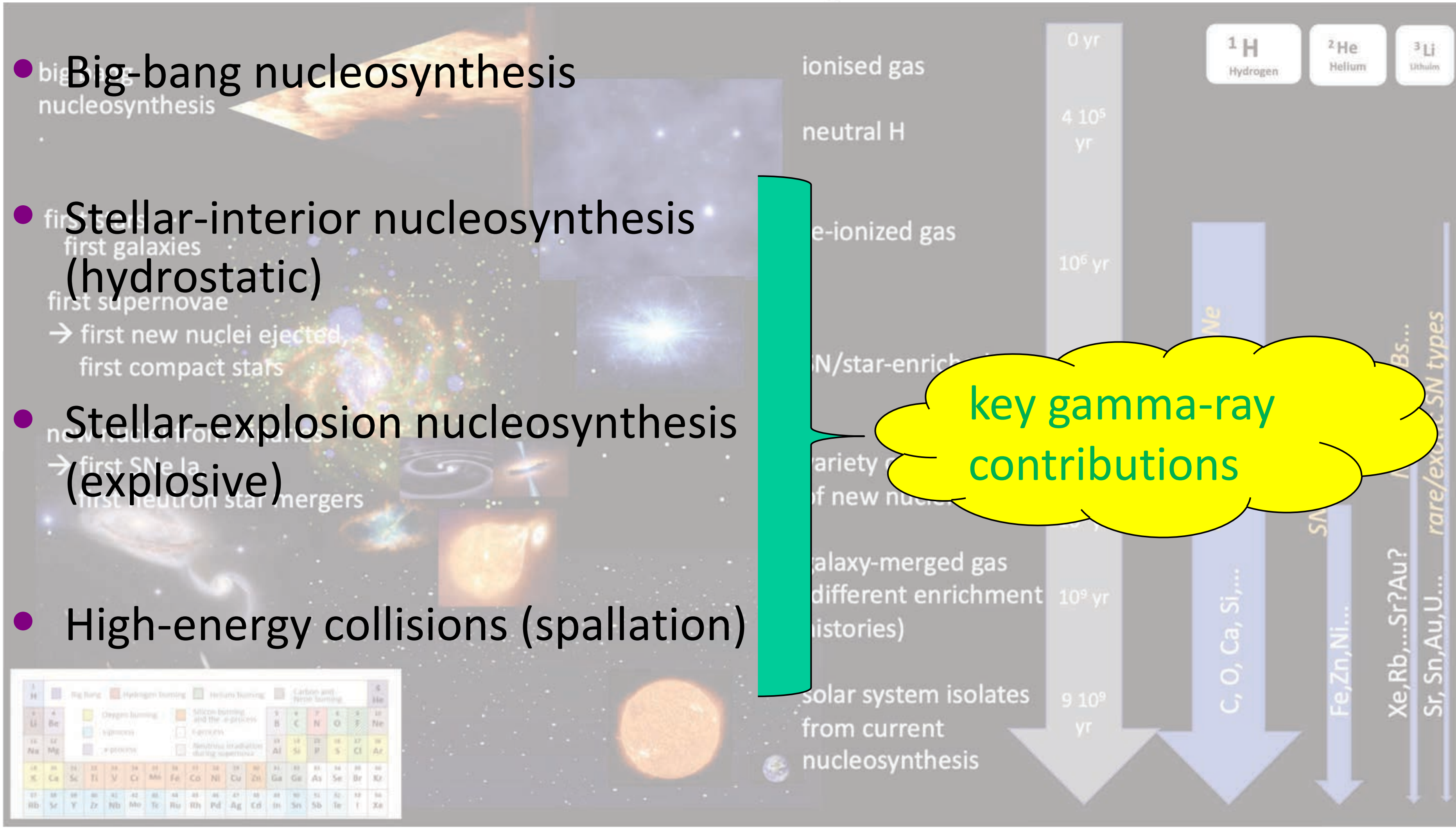
The answers include: models of the sources and the nuclear rates within, and of cosmic evolution including transport and recycling

Different Complementing Observing Methods



- Stardust in meteorites, Cosmic rays
- Molecular absorption lines (Radio,IR)
- Atomic absorption lines (opt,UV)
- Atomic emission lines (opt,UV,X)
- Gamma-ray lines from radioactive isotopes

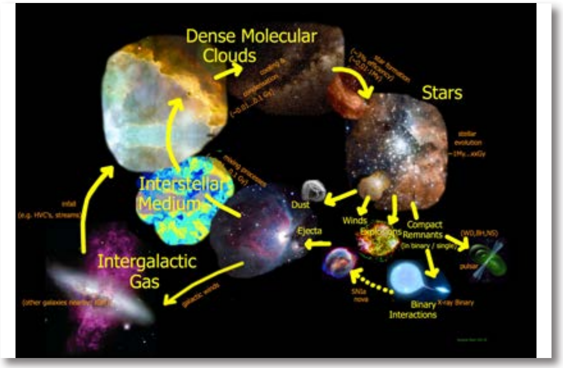
Cosmic nucleosynthesis

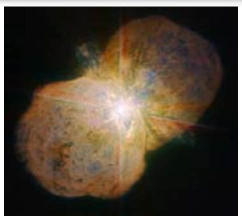


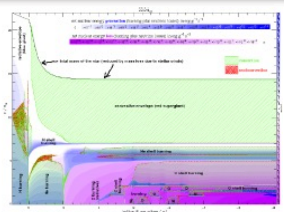
- Big-bang nucleosynthesis
- Stellar-interior nucleosynthesis (hydrostatic)
- Stellar-explosion nucleosynthesis (explosive)
- High-energy collisions (spallation)

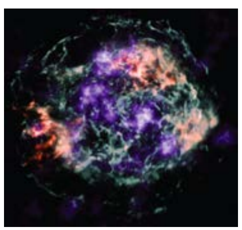
key gamma-ray contributions

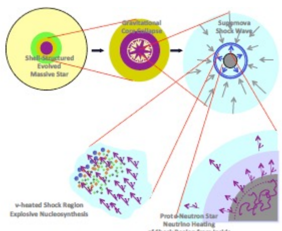
Drescribing Compositional Evolution: the Challenges

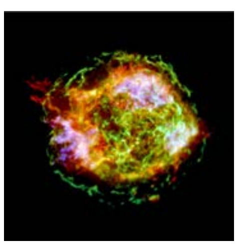


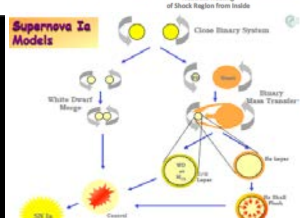


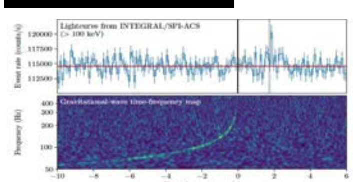


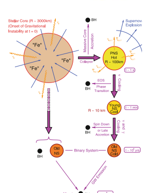












☆ Changes in the forms of cosmic matter:

- ☞ stars and gas **flows**:

$$m = m_{\rm gas} + m_{\rm stars} + m_{\rm infall} + m_{\rm outflow}$$

$$\frac{dm_G}{dt} = -\Psi + E + [\, f - o \,]$$

$\Psi(t)$ is the Star Formation Rate (SFR) and $E(t)$ the *Rate of mass ejection*

- ☞ gas which is ejected from stars: **when?**

$$E(t) = \int_{M_t}^{M_U} (M - C_M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

- ☞ newly-contributed ashes from nucleosynthesis: **what?**

The *mass of element/isotope i* in the gas is $m_i = m_G X_i$

$$\frac{d(m_G\, X_i)}{dt} = -\Psi X_i + E_i + [\, f X_{i,f} - o X_{i,o} \,]$$

$$E_i(t) = \int_{M_t}^{M_U} Y_i(M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

☆ Ingredients:

- ☞ Sources: How fast do they evolve to return (new) gas?

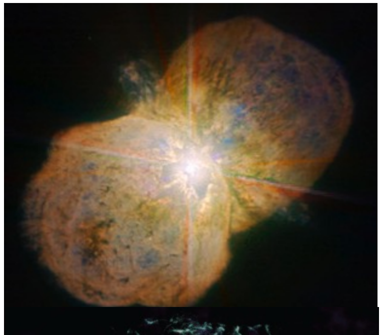
the star of mass M, created at the time $t - \tau_M$, dies at time t

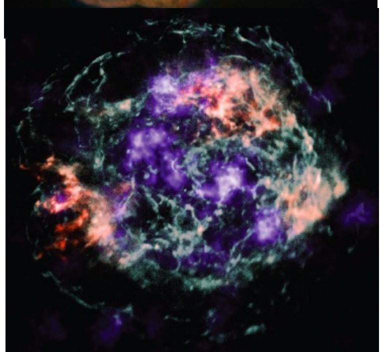
- ☞ Sources: How much of species i do they eject (and/or bury)?

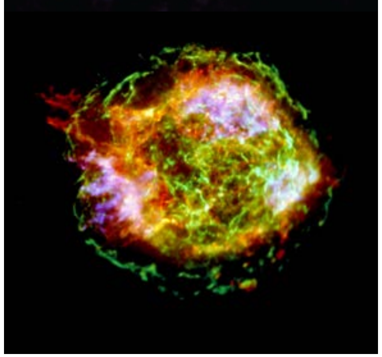
$Y_i(M)$ the mass ejected in the form of that element by the star of mass M

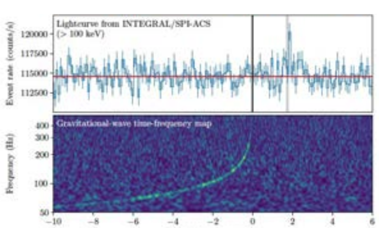
- ☞ ... (locations and environments of star formation, gas flows, ...)

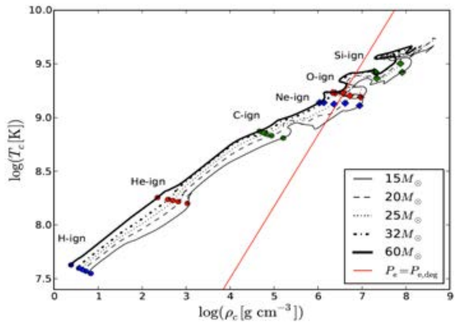
Cosmic nucleosynthesis sources

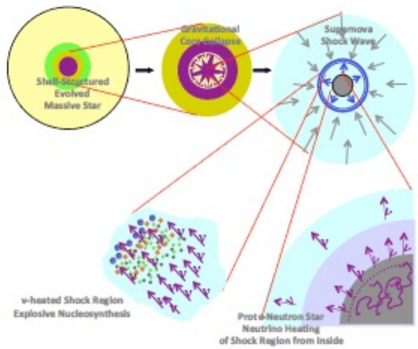


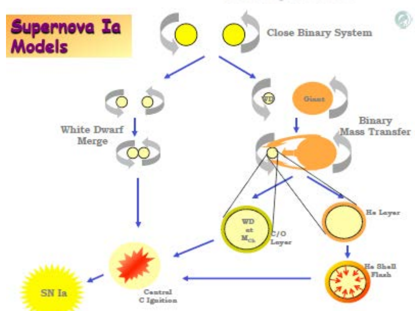


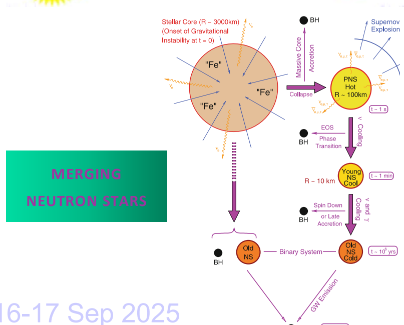












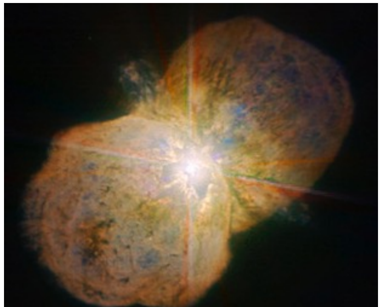
- Nuclear fusion reactions power all stars
- Many stars explode as a supernova at the end of their evolution
- Some binary systems including white dwarf stellar remnants explode as a supernova
- Some binary systems including neutron stars eventually merge to form a black hole

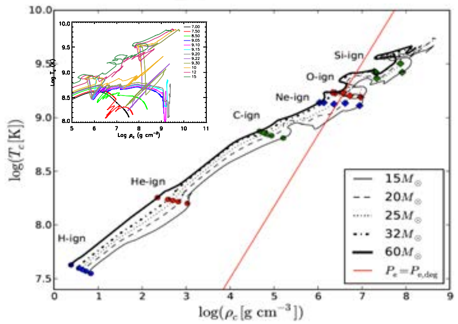
➢ When do they eject ashes?

➢ How many new nuclei in ejecta??

Understanding cosmic nucleosynthesis sources

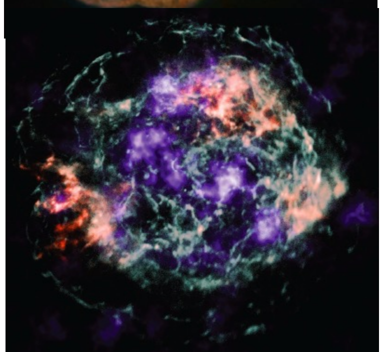
Stars

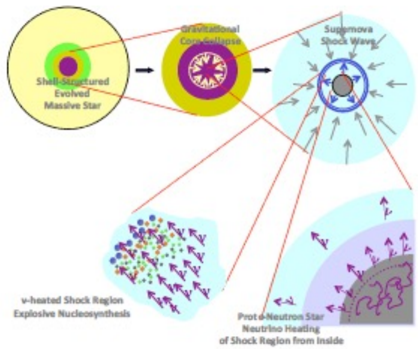




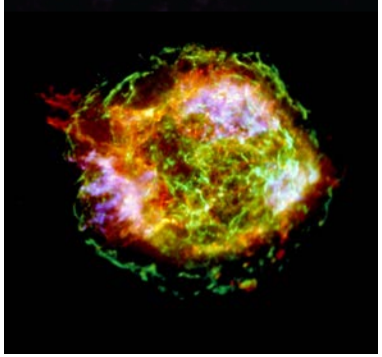
- How much matter is ejected in winds?
- How far out are fusion products mixed?
- What is the composition of remnant star?

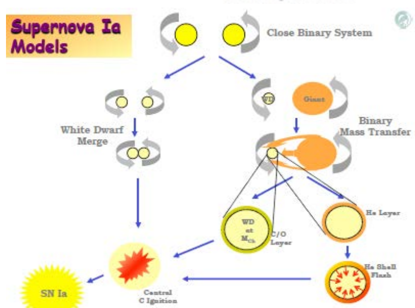
Stellar Explosions: Supernovae (ccSN, SN Ia, NSM)



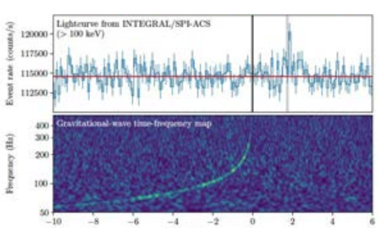


- Which stars explode as a supernova?
- Which parts of collapsing star are ejected?
- How far did the pre-SN evolution proceed?

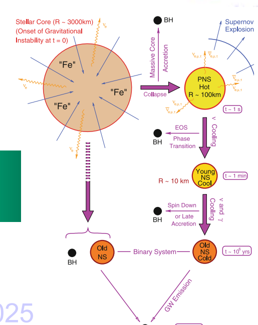




- Which white dwarfs explode?
- How is the explosion triggered?
- Which nuclear burnings will occur?

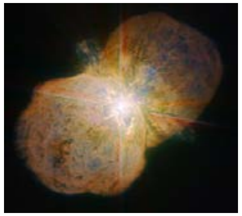


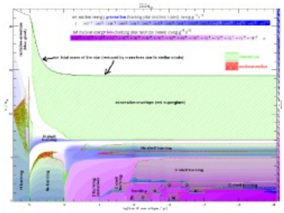
MERGING NEUTRON STARS

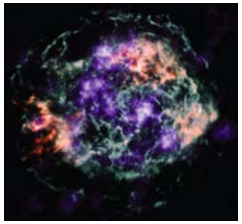


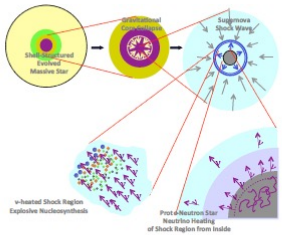
- Which compact stars may merge, when?
- How is the black hole formed?
- Which materials may escape?

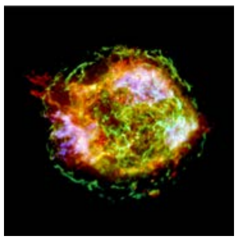
The Challenges

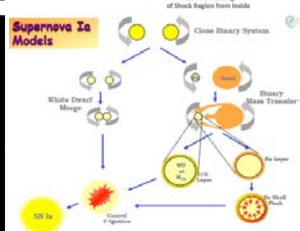


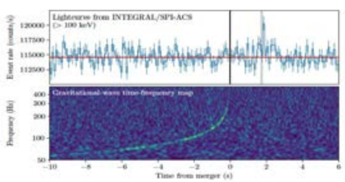


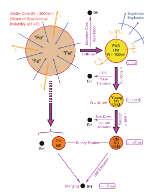




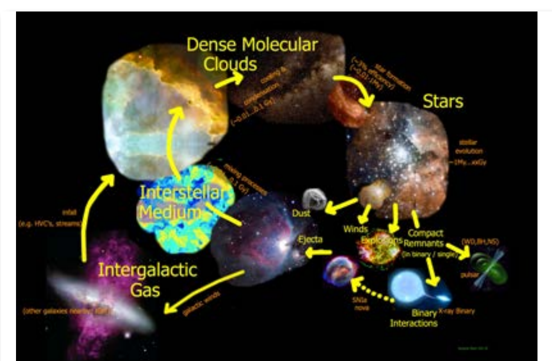






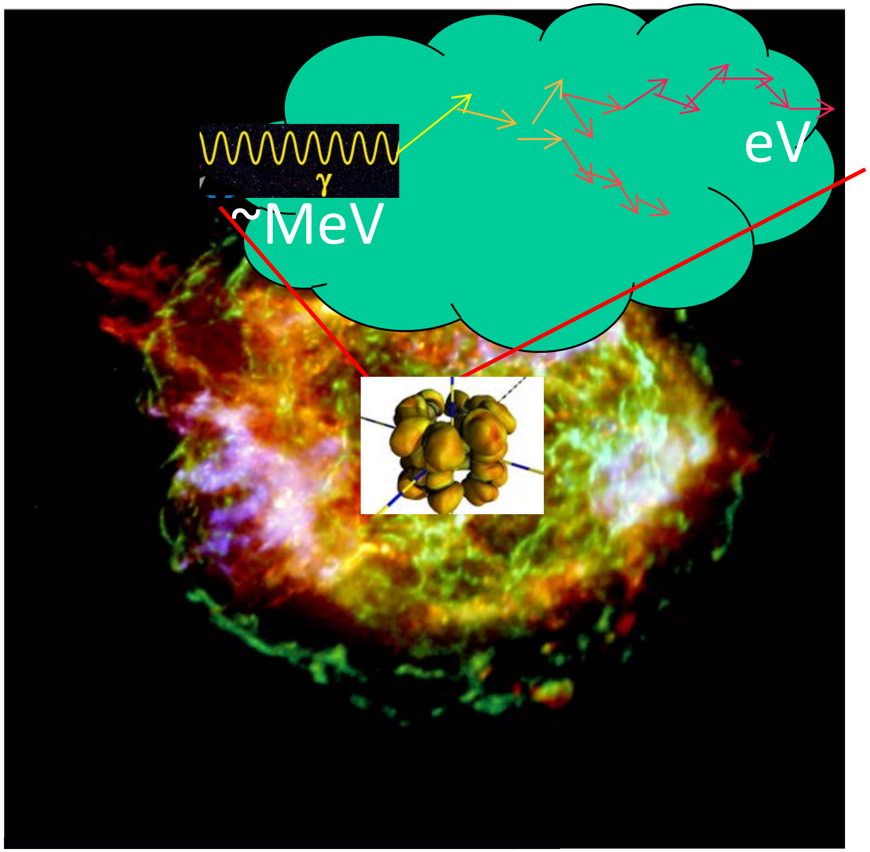


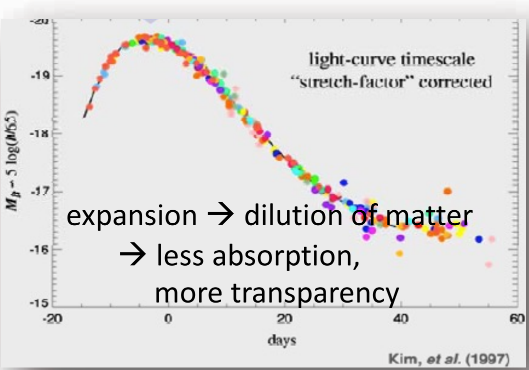
☆Understand the sources of new nuclei



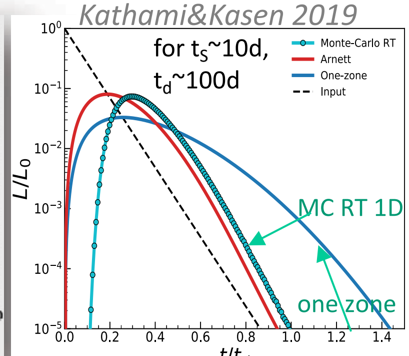
☆Trace the flows of cosmic matter

Radiation Measurements from an Exploding Star





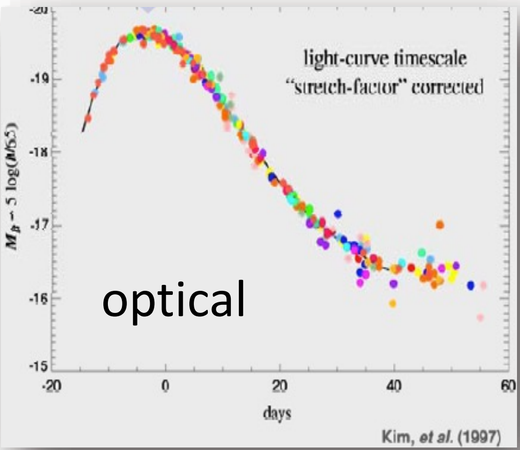
Kathami&Kasen 2019

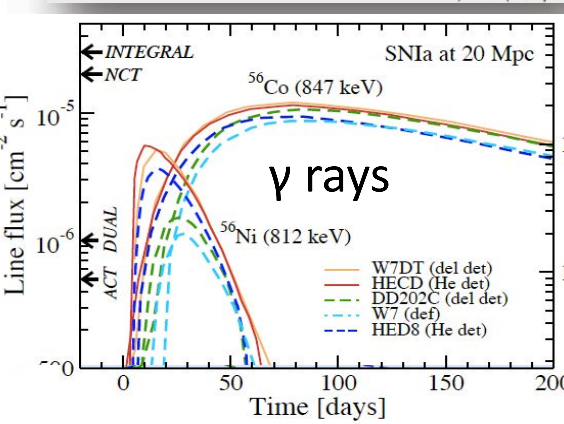


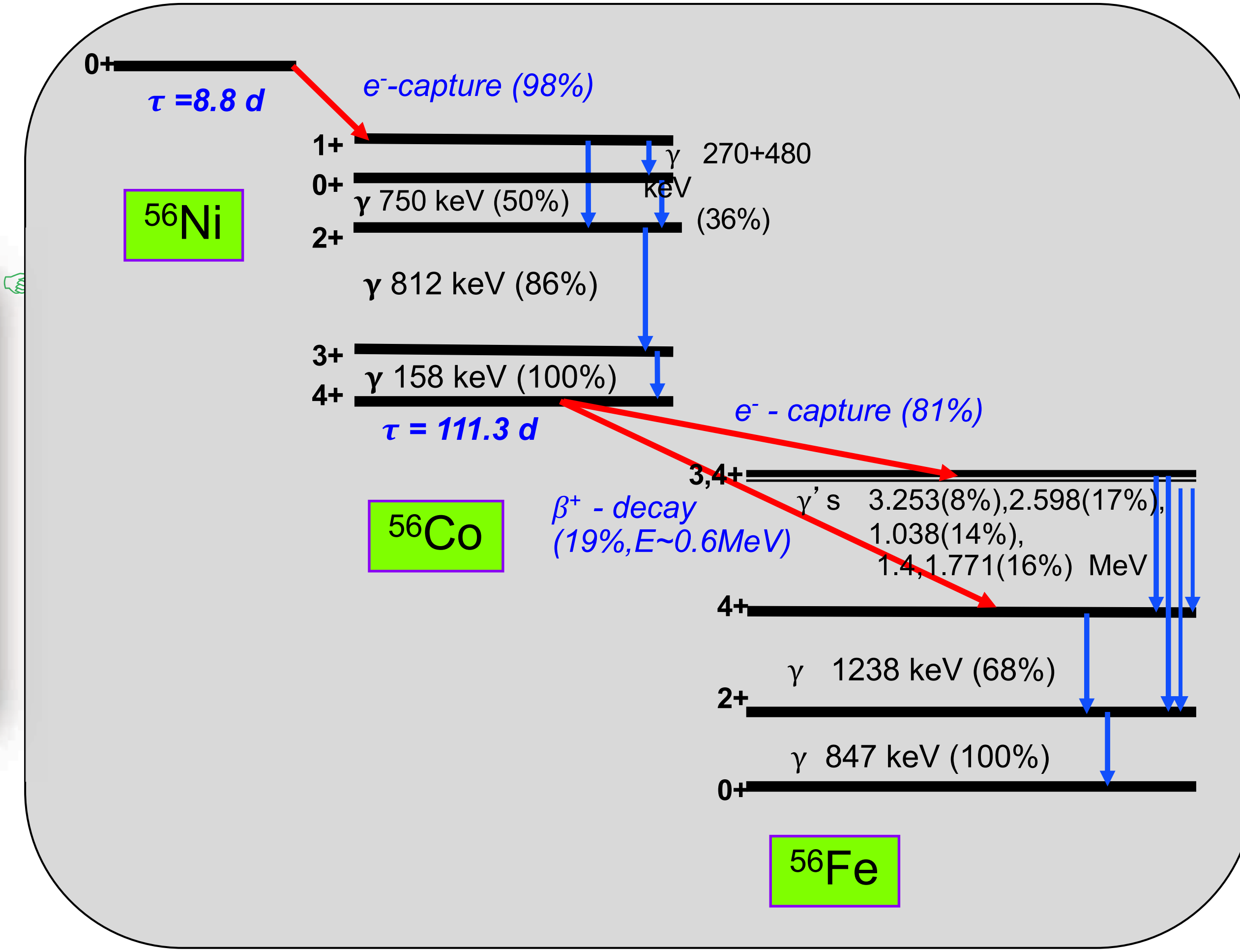
- γ rays: radioactive decay ^{56}Ni, ^{56}Co
- X rays: recombination of highly-ionized atoms; thermal (10^6K)
- UV: recombination of atoms thermal (10^4K)
- opt: thermal (10^3K); atomic and molecular transitions
- IR: thermal gas and dust emission (10^{1-2}K); molecular transitions

^{56}Ni radioactivity → γ-Rays, e$^+$ → leakage/deposit evolution

SN Ia

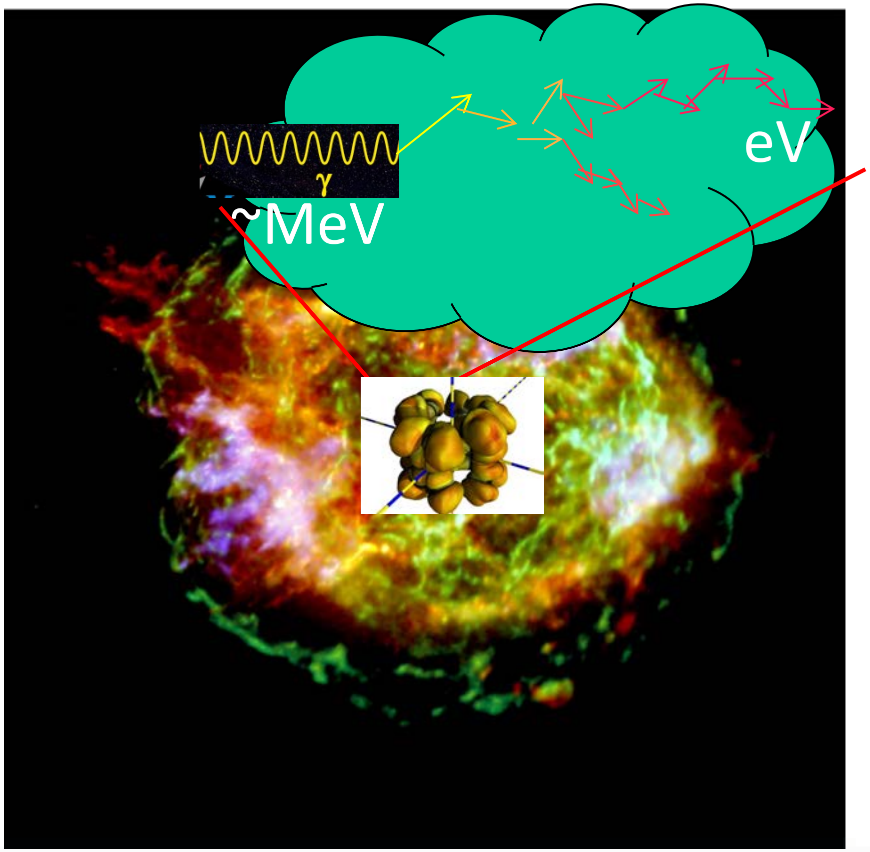


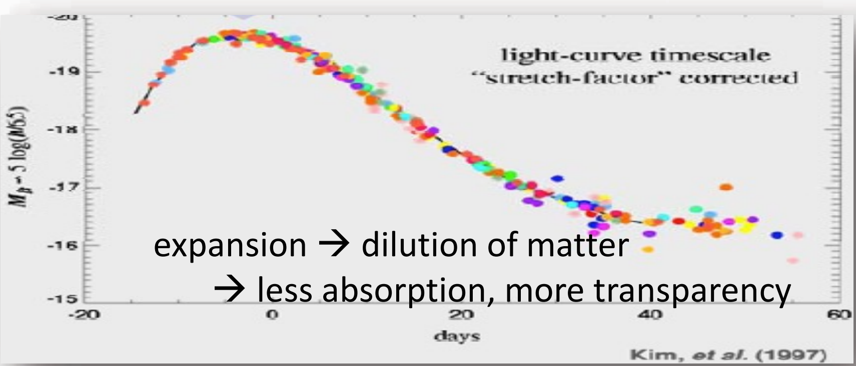




- Nuclear BE release from 0.6M$_\odot$ [C,O → ^{56}Ni] = ~1.1 10^{51} erg (>2*BE$_{WD}$)
- Deposit of γ rays and e+ in expanding/diluting envelope
- Re-radiation of deposited energy in low-energy (thermal) radiation

Radiation Measurements from an Exploding Star





- γ rays: radioactive decay ^{56}Ni, ^{56}Co

  where in the envelope is the ^{56}Ni?
- X rays: recombination of highly-ionized atoms; thermal (10^6K)

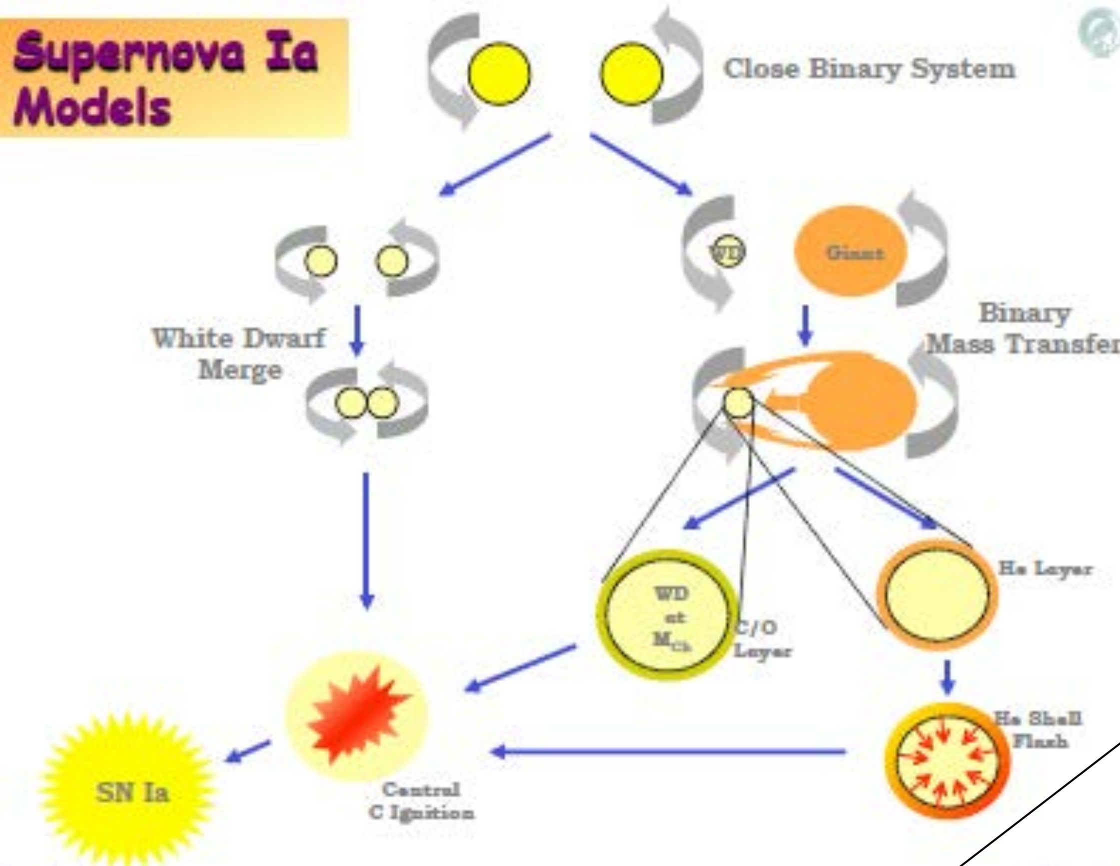
  what are the states of ionizations?
- UV: recombination of atoms; thermal emission (10^4K)

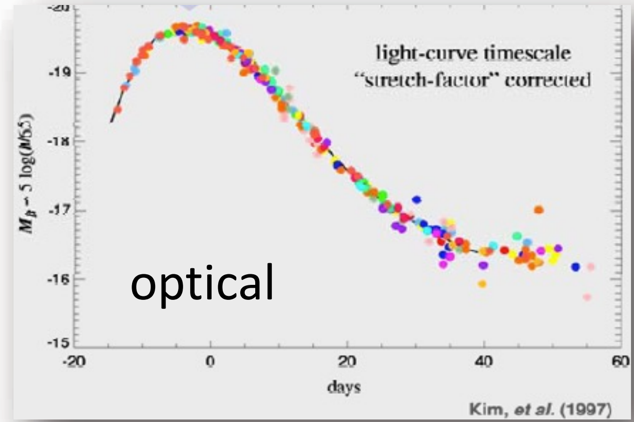
  what are gas temp & ionization?
- opt: thermal (10^3K); atomic and molecular transitions

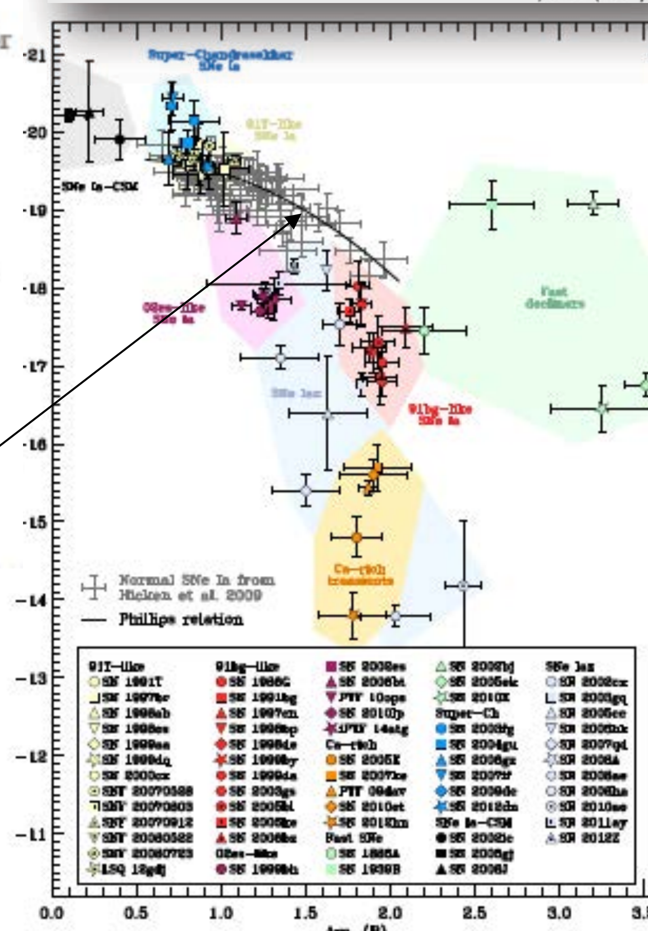
  which transitions are important?
- IR: thermal gas and dust emission (10^{1-2}K); molecular transitions

  which transitions? τ gas vs. dust?

Supernovae of type Ia





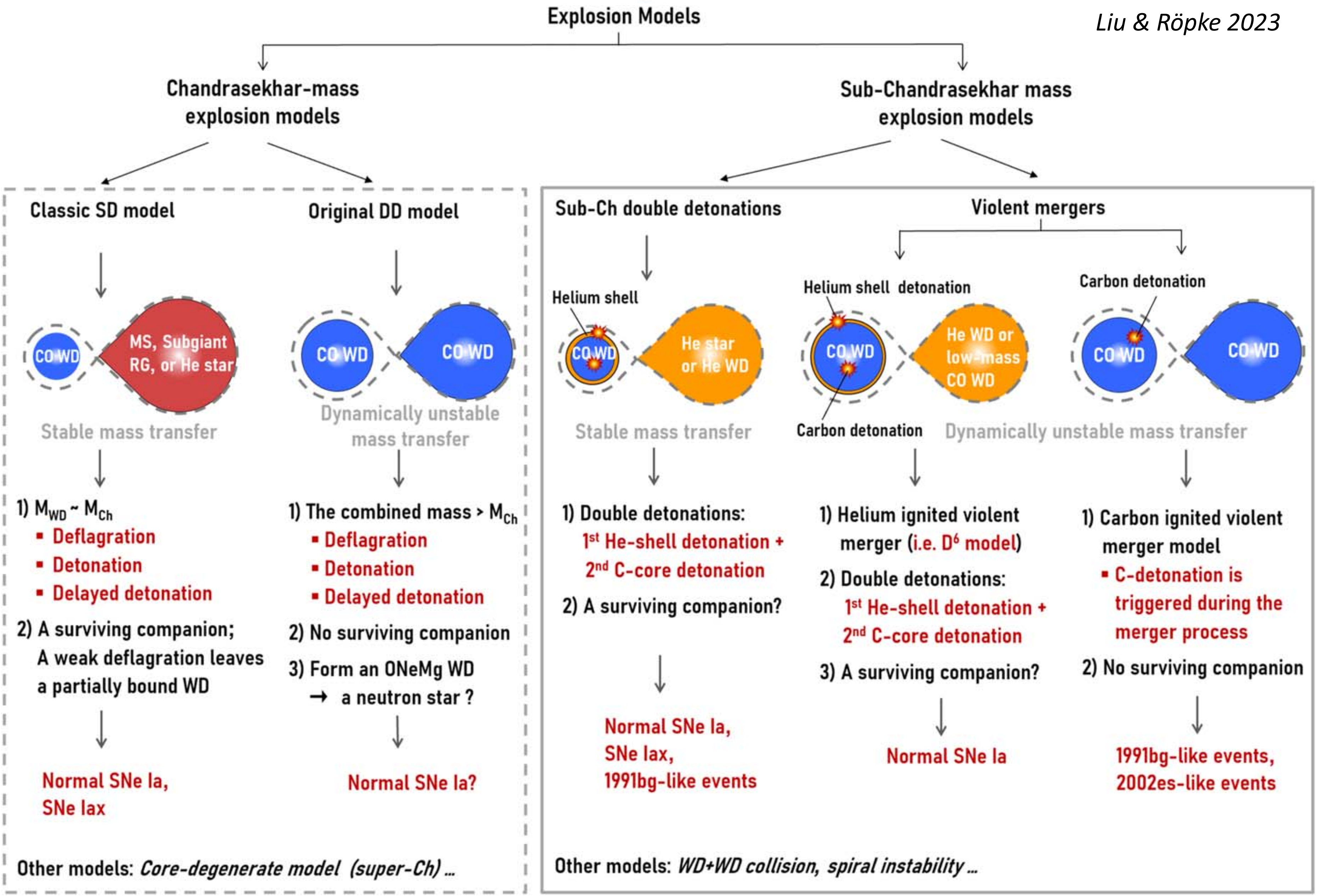


Taubenberger 2017

...also from γ-ray observations:
→ SN Ia are a variety

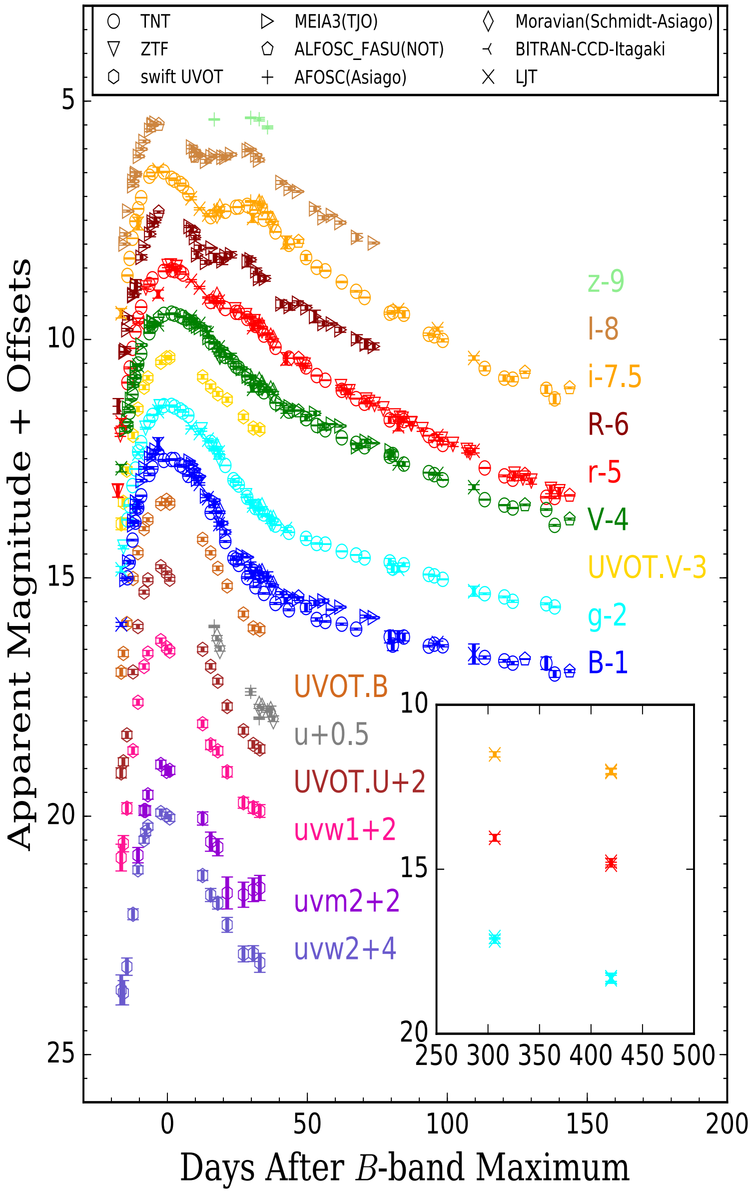
(the "standardizable candles"??)

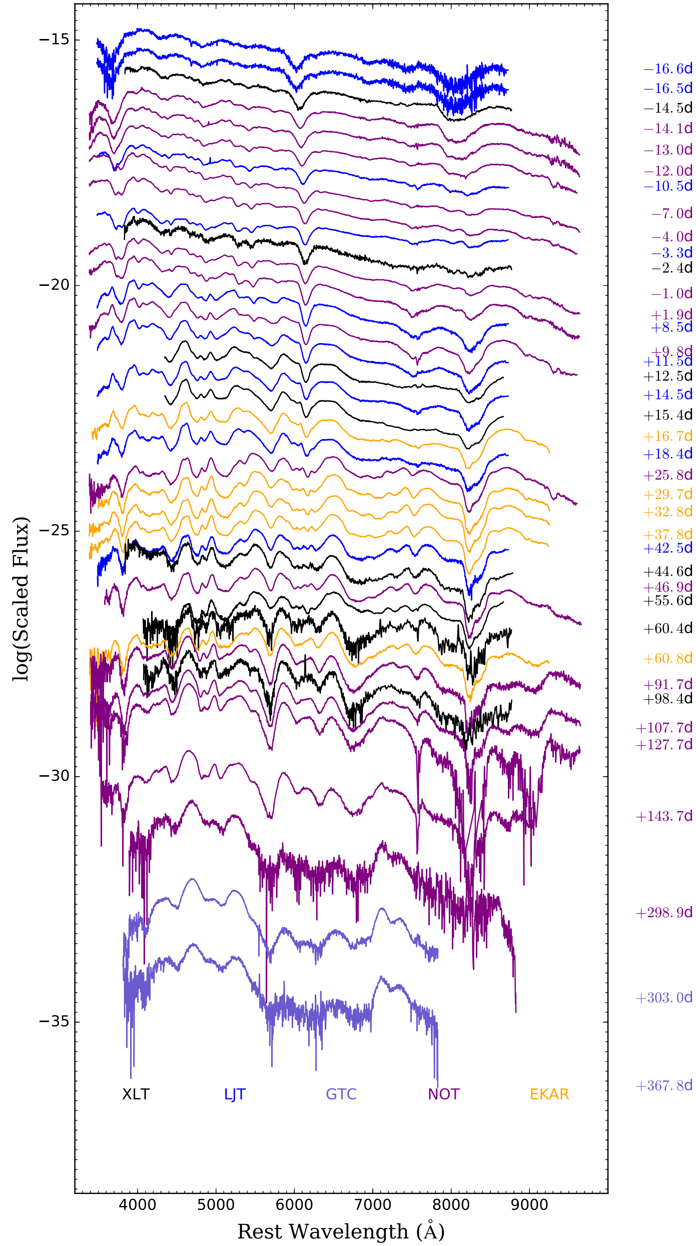
Modeling a SN Ia



Radiation from SNe Ia: Example UVOIR

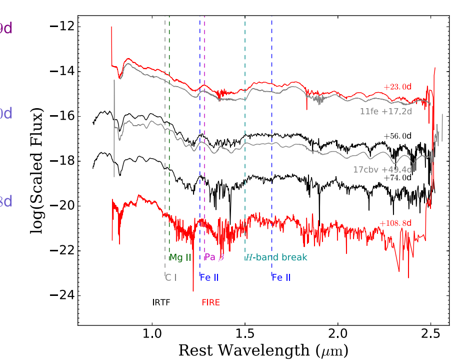
Sai+2022





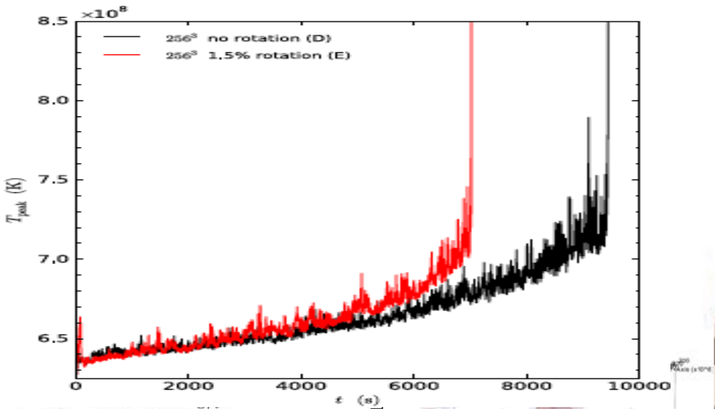
SN2019np: Light Curves, Spectra evolve with different characteristics in each wavelength regime

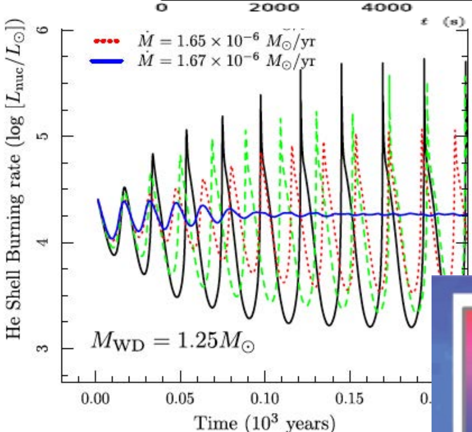
~ as expected

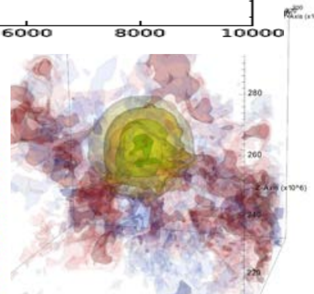


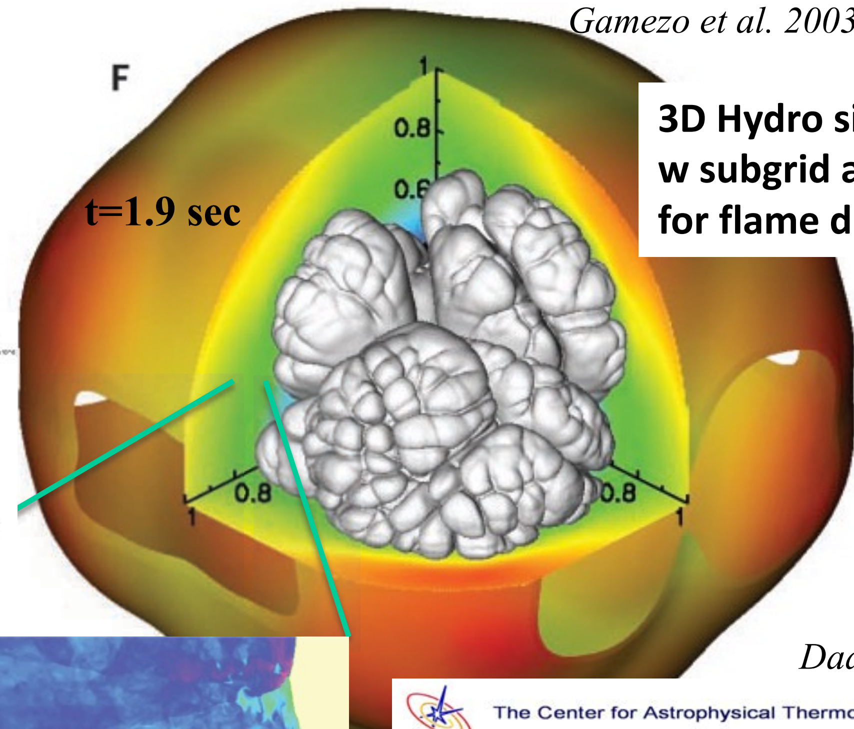
SNIa Ignition and Burning Simulations

→ plume-like & far-reaching flame surface, thickness µm…cm





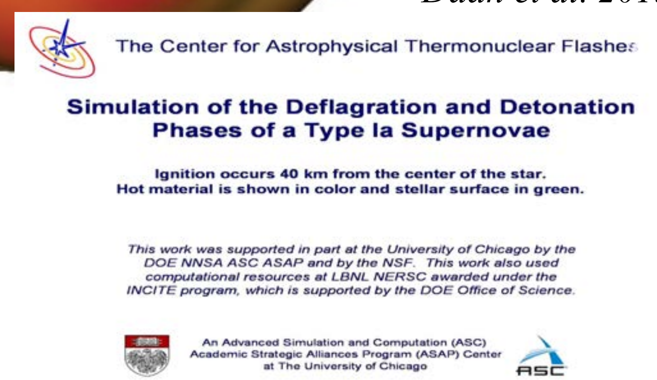




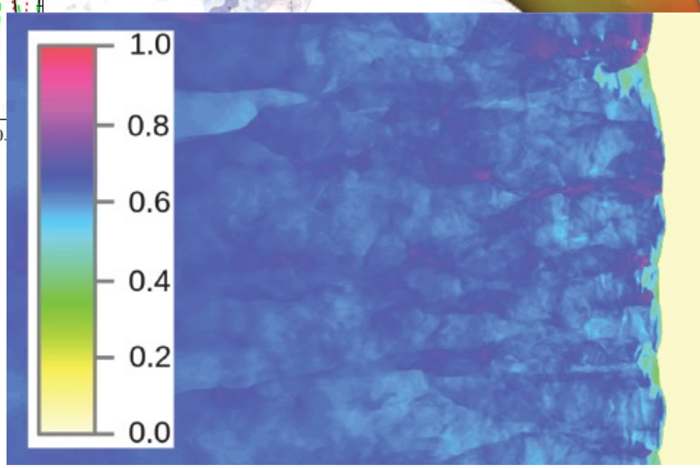
Gamezo et al. 2003

3D Hydro sim
w subgrid approx
for flame dimensions

Daan et al. 2015



3D High-resolution of flame, "reactive flow" sim



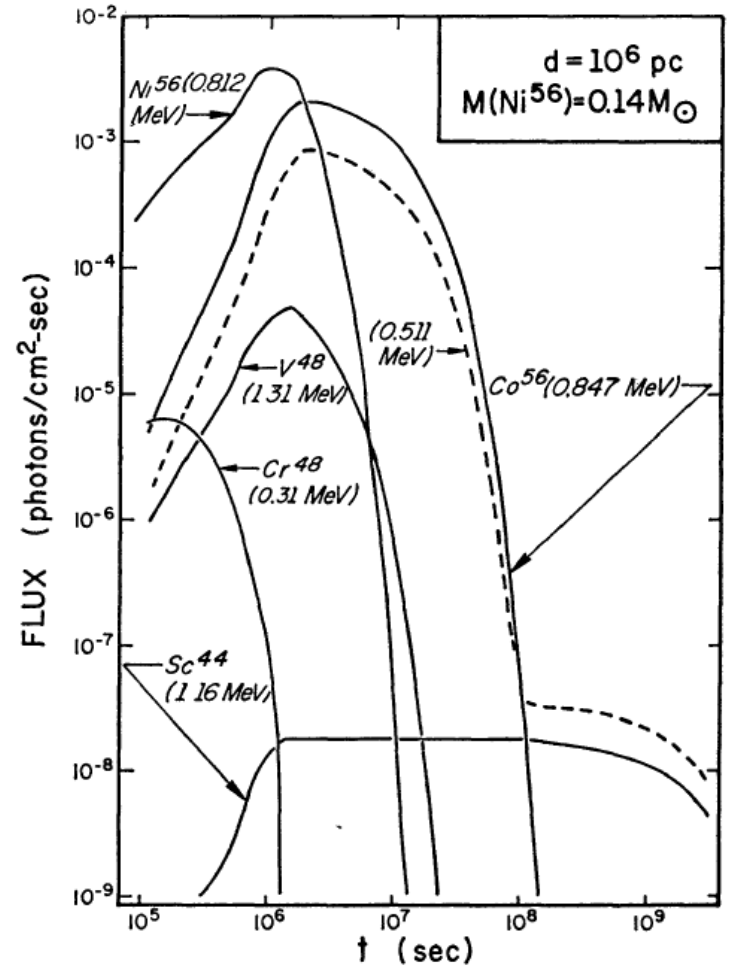
Khokhlov et al. 2012

Gamma-Ray Lines from SN Ia

The gamma-ray luminosity of a typical type I supernova remnant has been calculated by assuming that the origin of the optical luminosity is due to the energy of the radioactive decay of Ni^{56}. It is expected that Ni^{56} is the most abundant nucleus resulting from silicon burning in the supernova shock conditions. The requisite mass of Ni^{56} ($0.14\ M_\odot$) gives rise to gamma-ray lines with energies near 1 MeV that should be detectable in young supernova remnants at distances up to a few Mpc. Future detectors aboard satellites should be able to detect events at the rate of about two observable events per year. A few supernova remnants in the Galaxy should be observable at all times in lines following the decay of Ti^{44}.



The Astrophysical Journal, Vol. 155, January 1969



GAMMA-RAY LINES FROM YOUNG SUPERNOVA REMNANTS

Donald D. Clayton*
Rice University, Houston, Texas

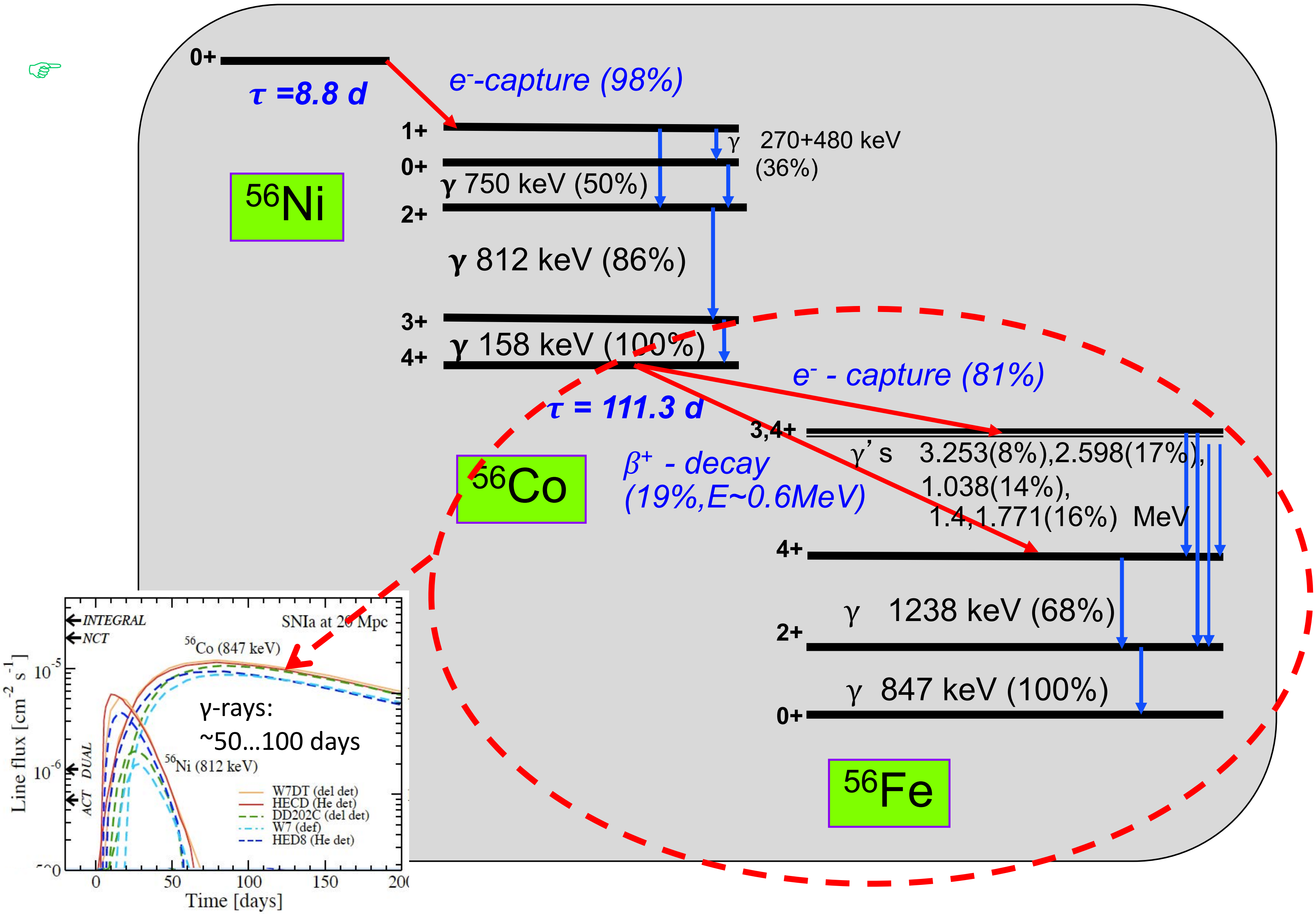
Stirling A. Colgate
New Mexico Institute of Mining and Technology, Socorro

and

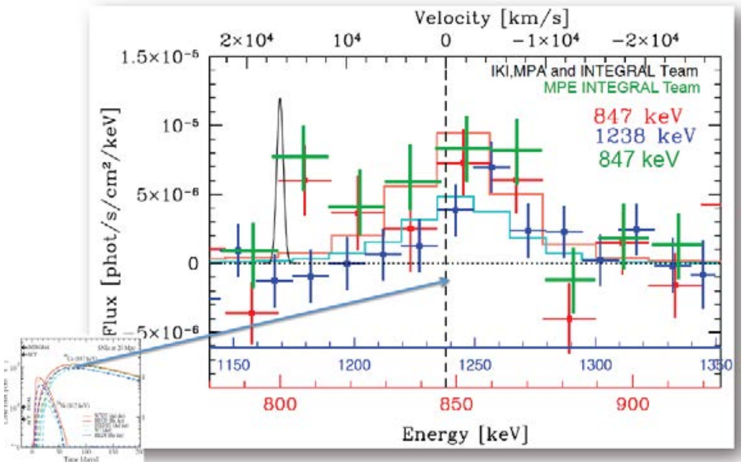
Gerald J. Fishman
Rice University, Houston, Texas

Received May 20, 1968; revised June 24, 1968

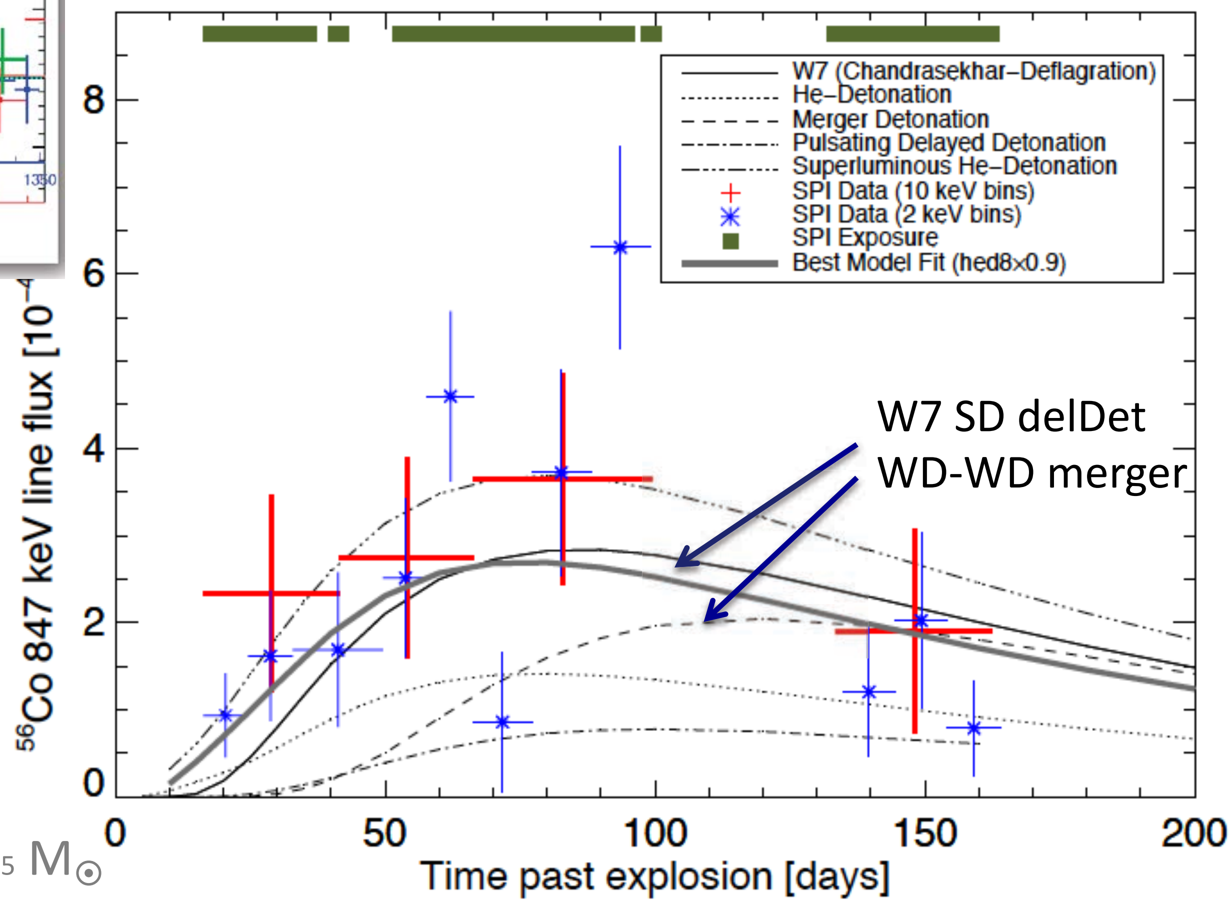
^{56}Ni Radioactivity: Decay Chain and Gamma-Rays



SN2014J light evolution in the 847 keV ^{56}Co line



INTEGRAL/SPI γ ray measurements



☆ ^{56}Ni mass: 0.49 +/-0.09 $M_\odot$

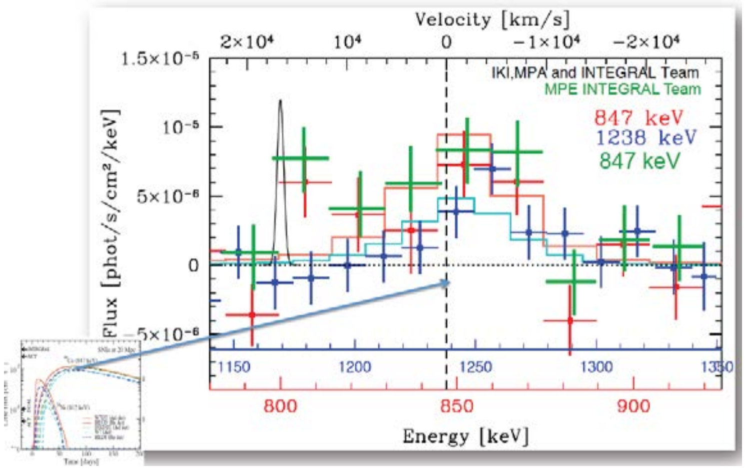
(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

☞ *Diehl et al., A&A 2015*

SN2014J data Jan – Jun 2014: ^{56}Co lines

- ☆ Doppler broadened ✓

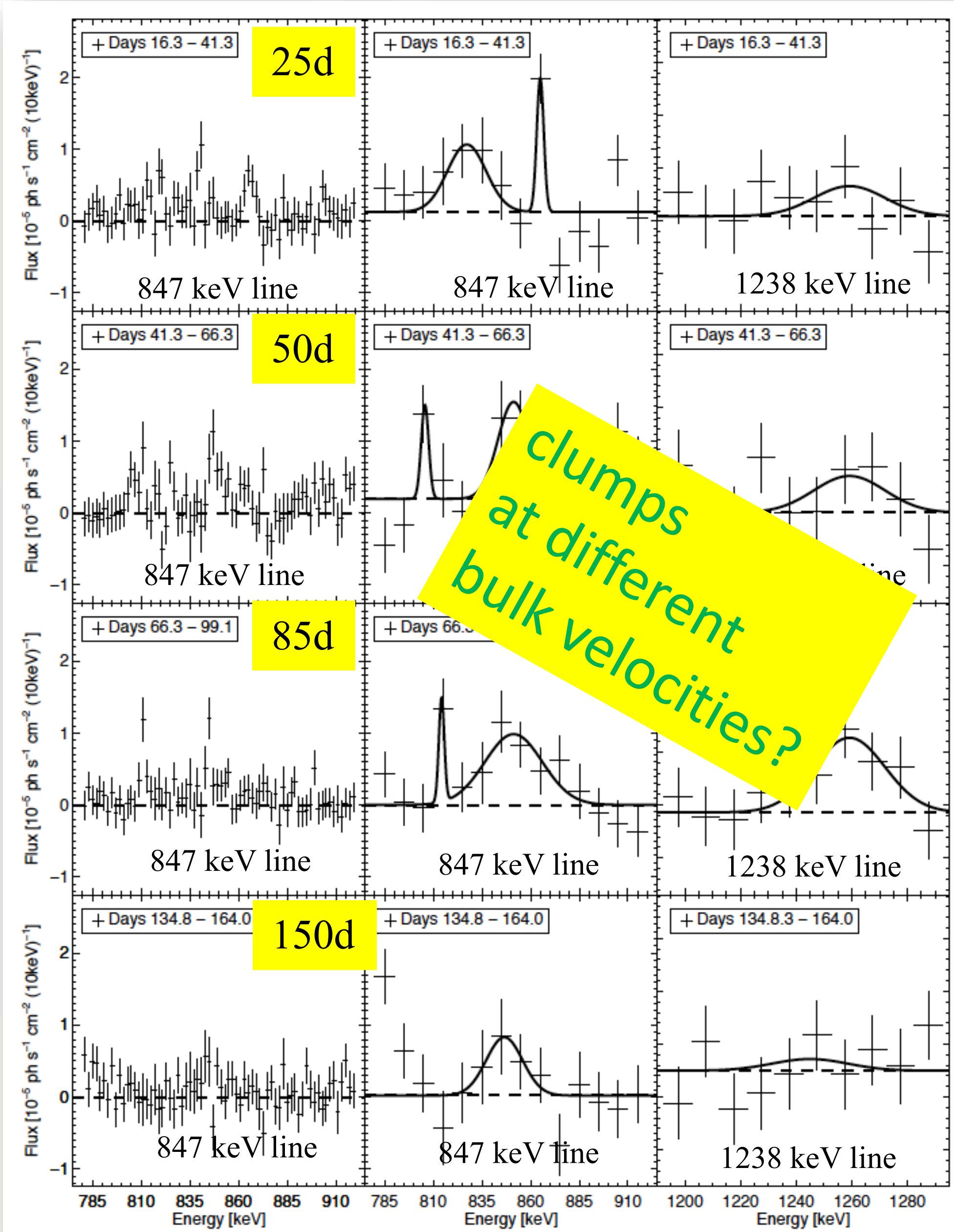


- ☆ Split into 4 time bins
- ☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

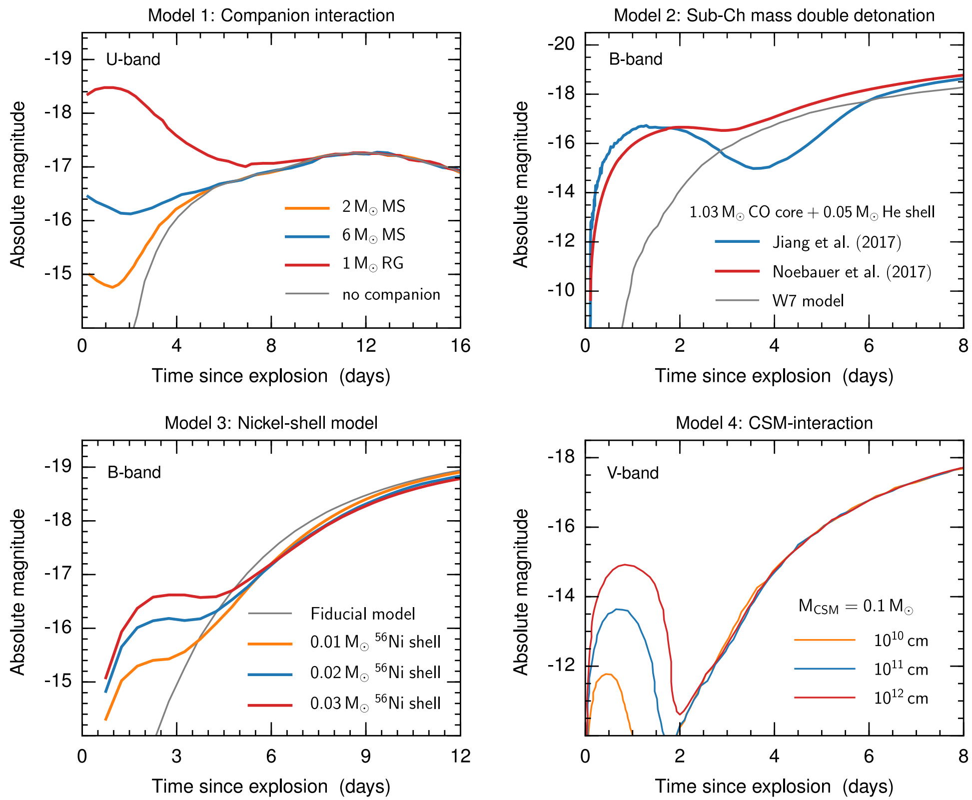
– expected: gradual appearance of broadened ^{56}Co lines

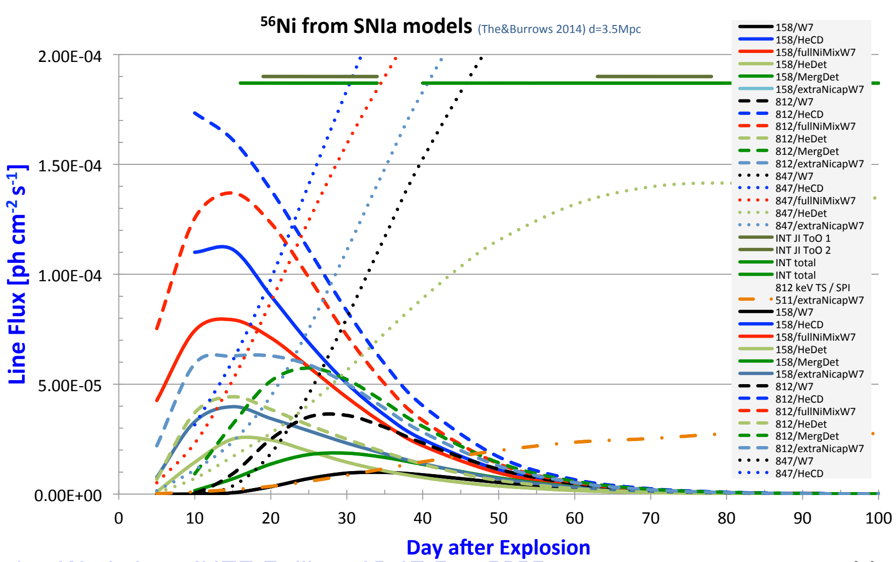
☞ *Diehl et al., A&A (2015)*



- ☆ *note: normally, we do not see such fluctuations in 'empty-source' spectra!*

Different effects may shape the early evolution





- Distribution of ^{56}Ni within the exploding object
- early (triggering) explosion before SN
- Interaction with circumstellar matter
- Interaction with the companion star
- …

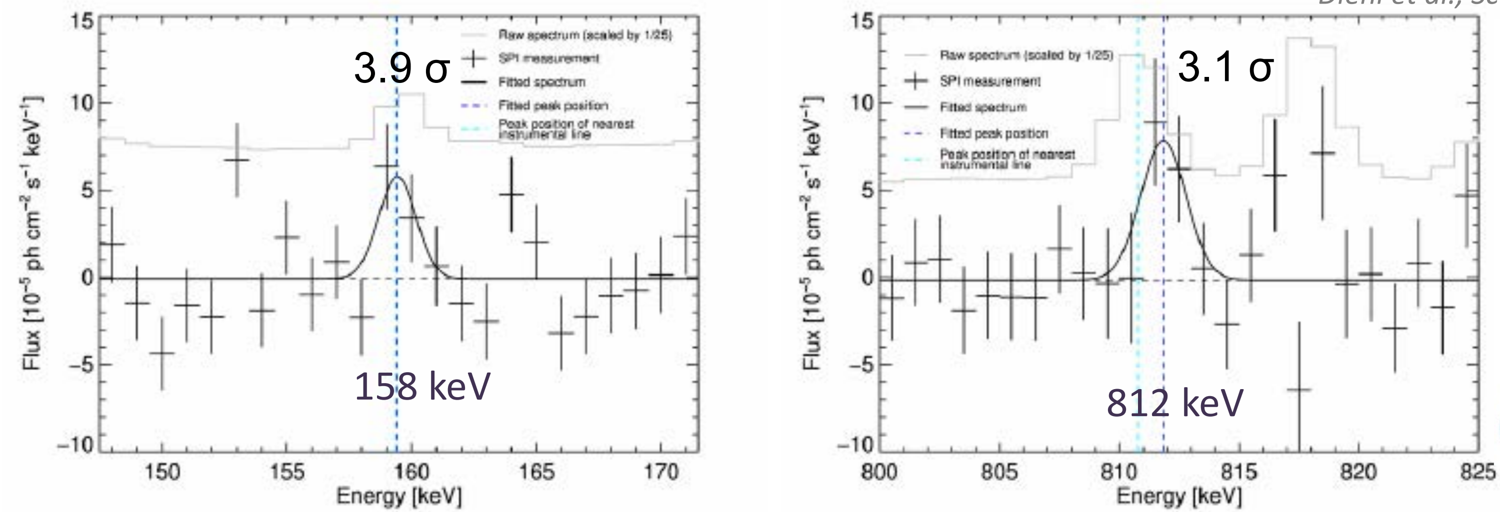
much observational effort regarding early light curve in recent years

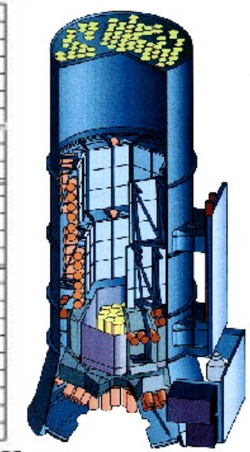
SNIa and SN2014J: Early ^{56}Ni (τ~8.8d)

Spectra from the SN at ~20 days after explosion

Clear detections of the two strongest lines expected from ^{56}Ni (should be embedded!)

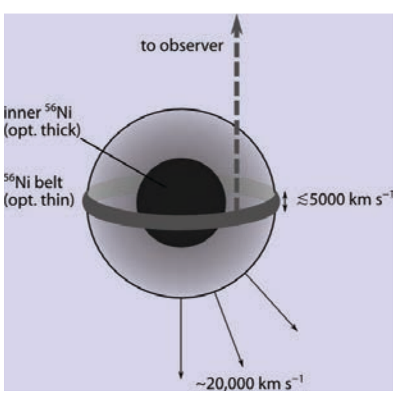
Diehl et al., Science (2014)





^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_{\odot}$ (~10%)

i.e.: not the single-degenerate $M_{chandrasekhar}$ model,



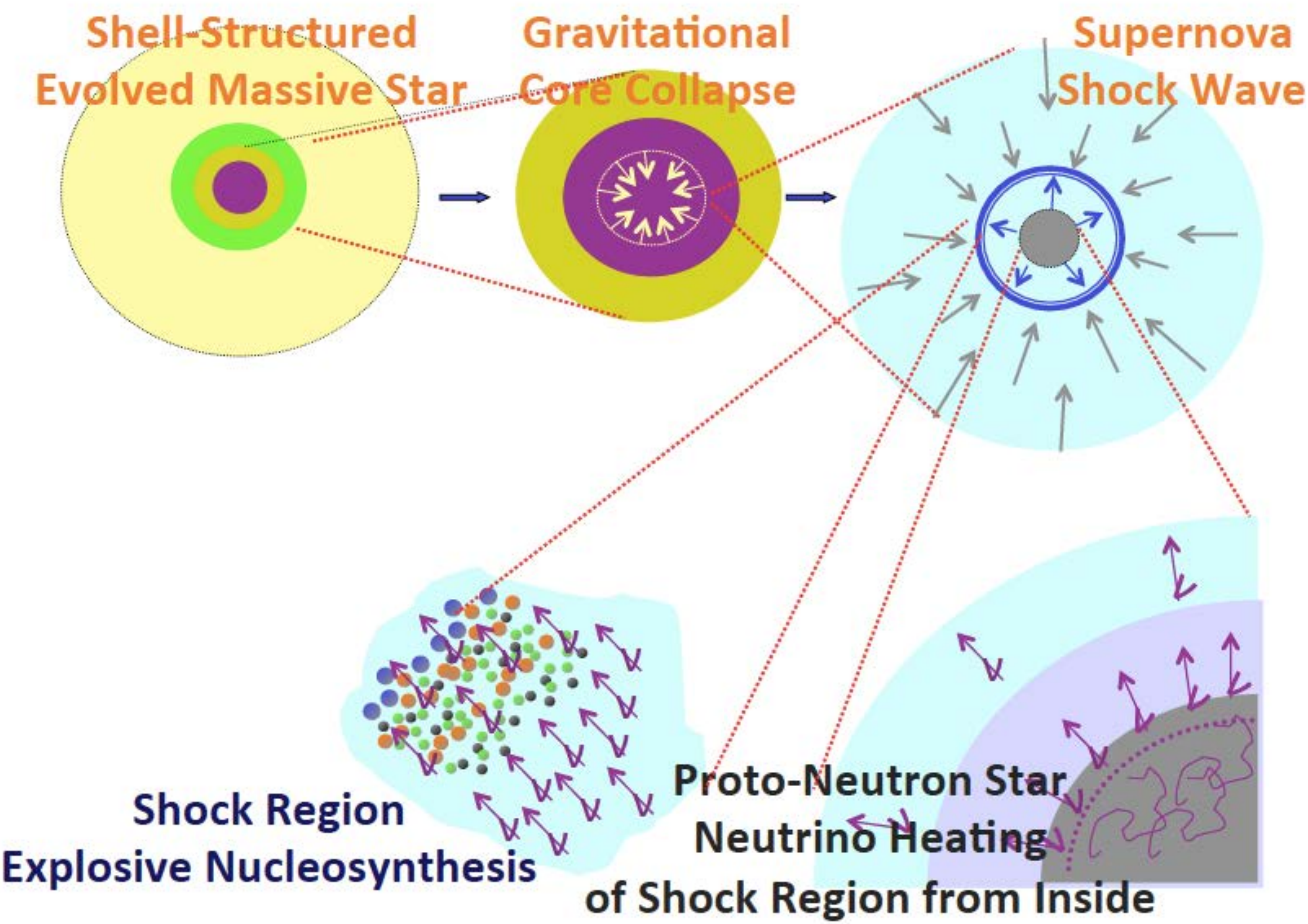
but rather a 'double detonation, i.e.

either 2 WDs (double-degenerate)

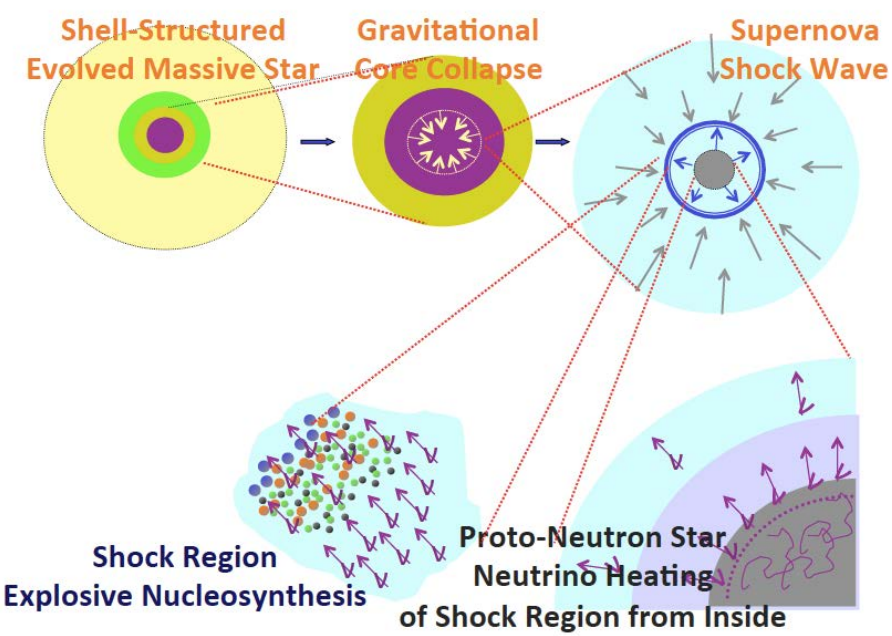
or a He accretor (He star companion)

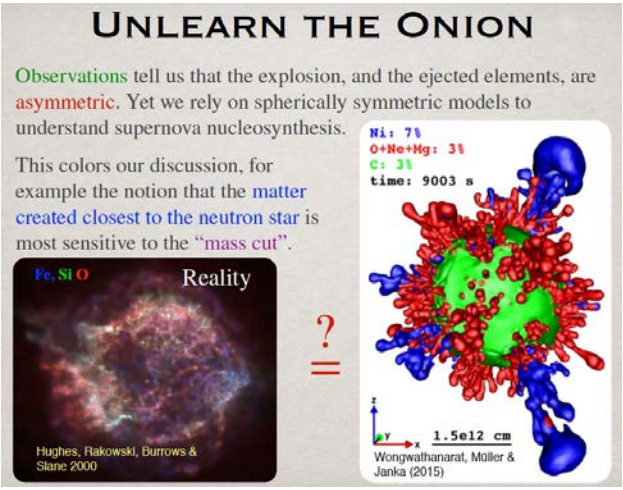
→ SN 2014J looks "normal", but is not

Gravitational Collapse and SN

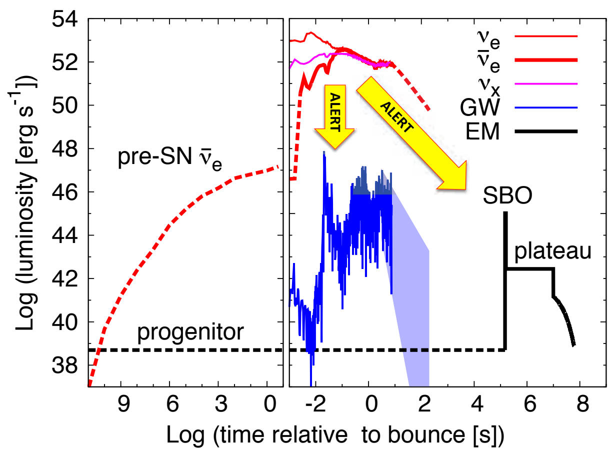


Complexities of Gravitational Collapse and SN



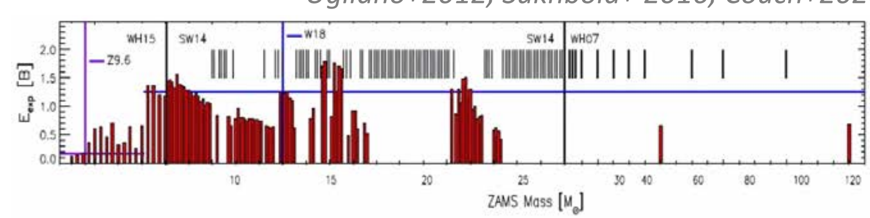


Raph Hix 2016



Kharoussi+ 2020

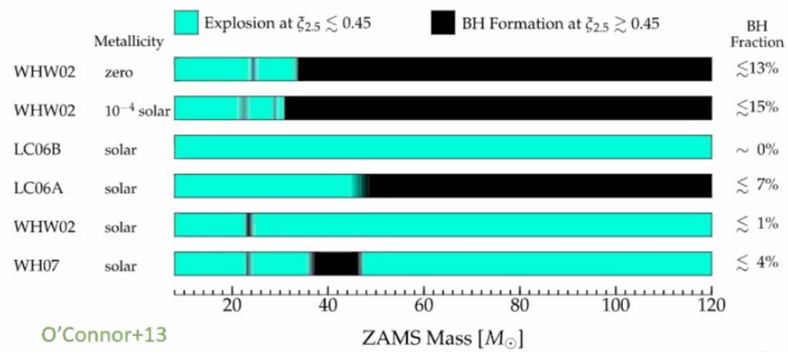
Ugliano+2012, Sukhbold+ 2016, Couch+2020



- ☆ Basic processes are more complex than the 'standard model' says:
  - pre-SN structure is complex
  - collapse, ignition, and outflows all occur simultaneously
  - collapse and accretion continue long after ignition of nuclear burning
  - late accretion and fallback make explosion fail for more massive stars

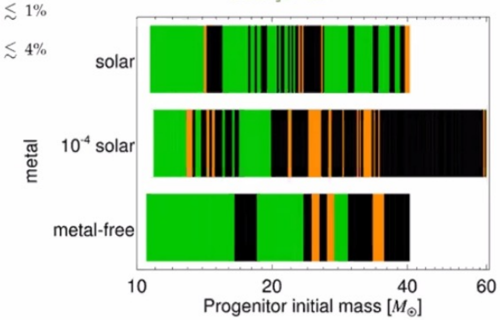
"Explodability" of core collapses

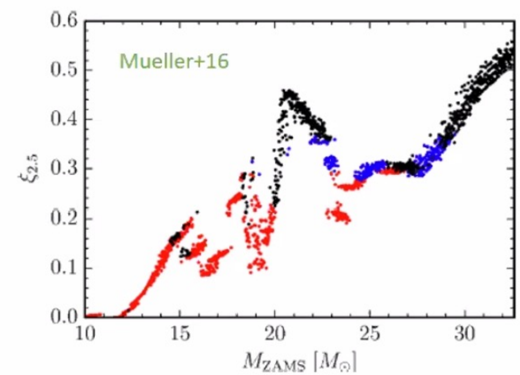
- successful explosion (and mass ejection) depends on subtle balances of internal processes and their kinematic implications
  - ☆ turbulence from gravitational accretion and neutrino energy deposits enhanced by instabilities in flows (Rayleigh-Taylor etc)



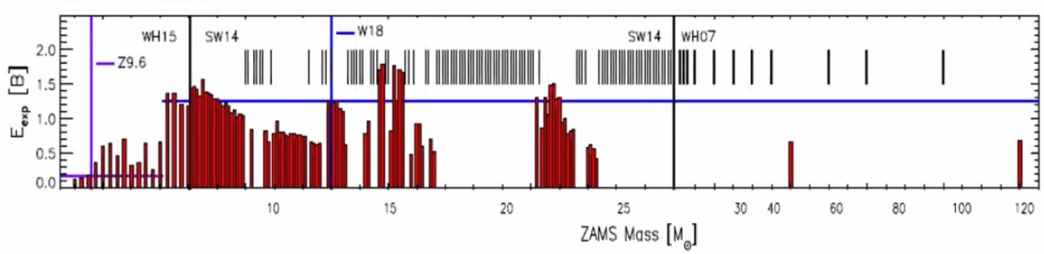
O'Connor+13

Pechja+15

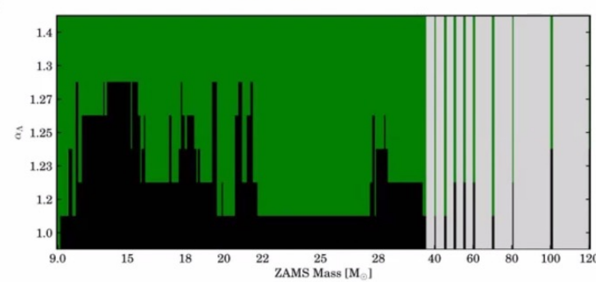




Ugliano+2012
Ertl+16
Sukhbold+2016



Couch+20



NIC-XVI (21-25 Sept 2021)

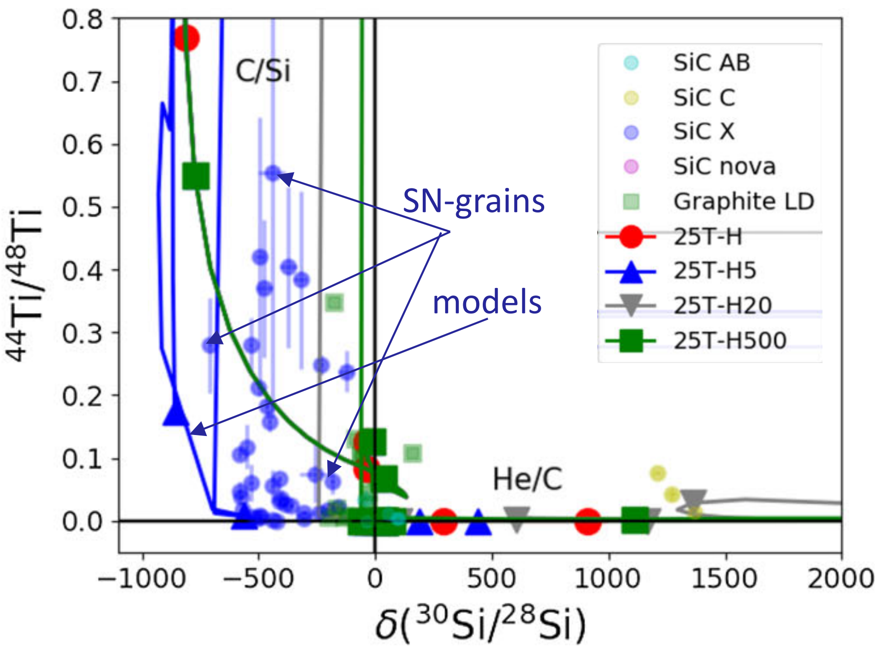
Carla Frohlich (NCSU)

Diagnostics from presolar grains attributed to ccSNe

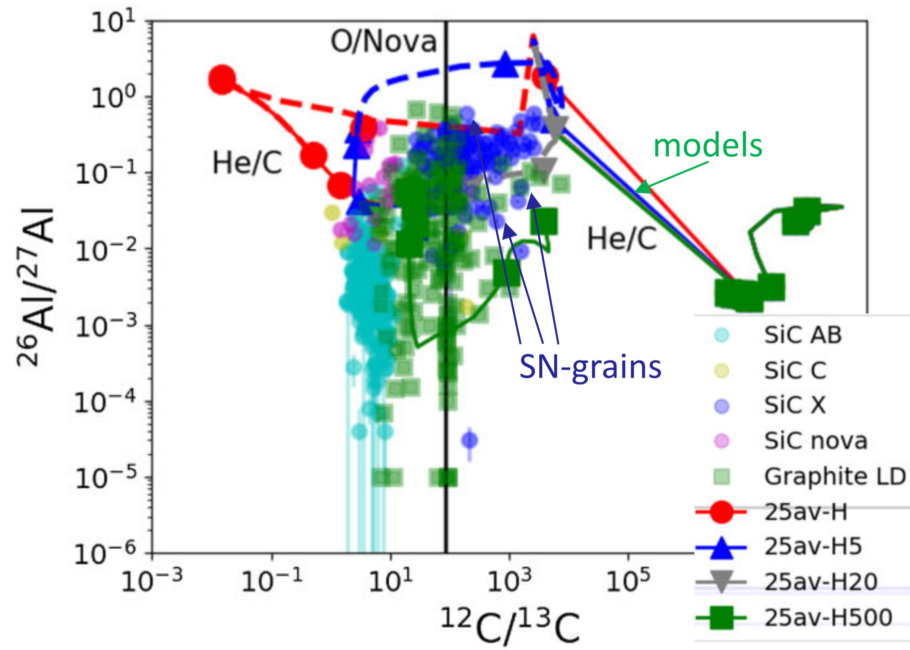
"X grains" are rare presolar grains attributed to a ccSN origin.

Isotopic ratio diagnostics for different elements (measured/modelled):

Schofield+2022



^{44}Ti can be produced when He is burning after the inner Si-rich regions have been photodisintegrated in the collapse



^{26}Al can be produced when H is ingested into the He zone before the SN shockwave of not-so energetic explosions ignites explosive burning

→ Models of core-collapse nucleosynthesis can be tuned (mixing and H ingestion; explosion energy) to reproduce observed signatures

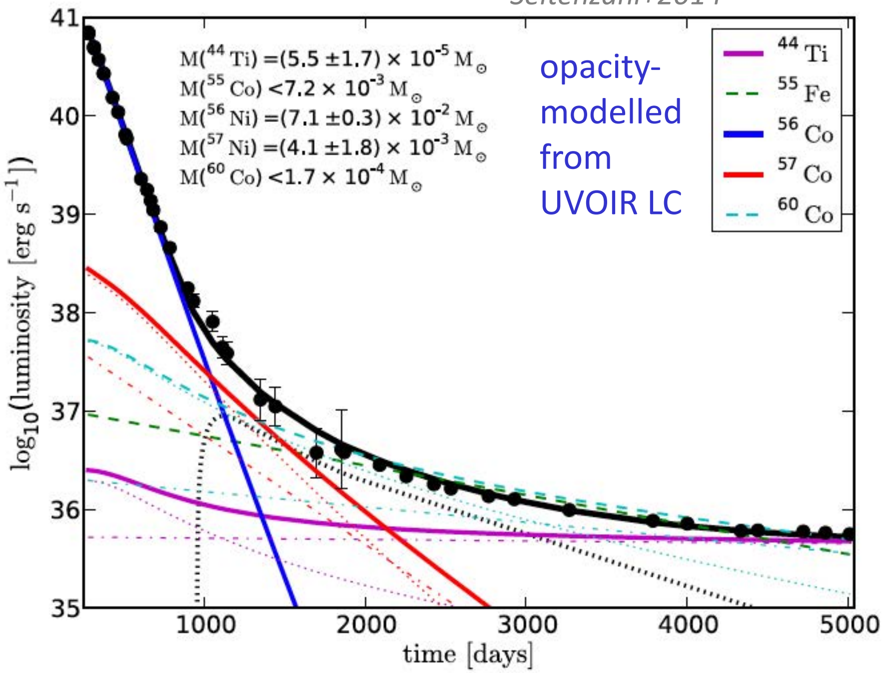
Issues: Systematics/ranges of models? X-grain bias?

^{44}Ti from SN1987A

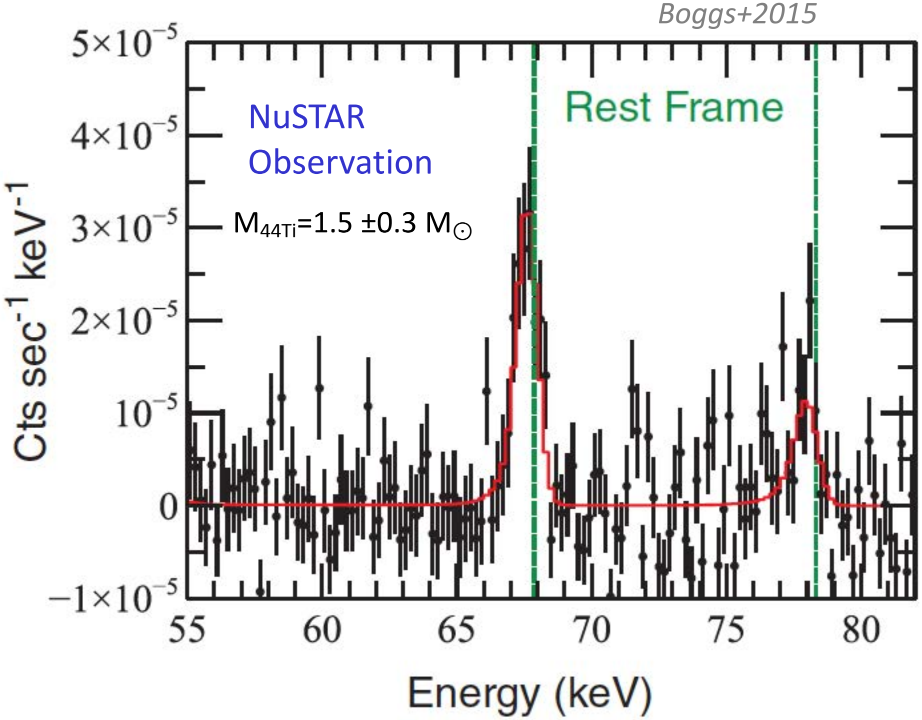
☆ ab-initio models
→ $M_{44Ti} \approx 0.x\ 10^{-5}\ M_\odot$ (spherical)
to $0.x\ 10^{-4}\ M_\odot$ (aspherical)

☆ UVOIR LC + energy deposition models
→ $M_{44Ti} \approx 0.5...5\ 10^{-4}\ M_\odot$

Seitenzahl+2014



Boggs+2015



☆ ^{44}Ti X-ray result NuSTAR
→ $M_{44Ti} \approx 1.5\ _{\pm 0.3}\ 10^{-4}\ M_\odot$

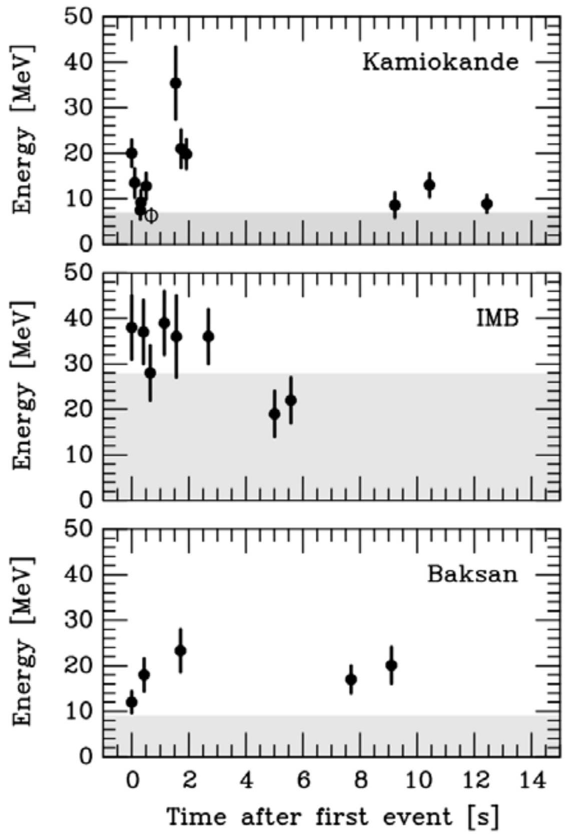
☆ ^{44}Ti line measurements INTEGRAL
→ $M_{44Ti} < 3.1\ _{\pm 0.8}\ 10^{-4}\ M_\odot$ (2σ) (IBIS)

☆ → $M_{44Ti} < 7.5\ 10^{-4}\ M_\odot$ (2σ) (SPI)

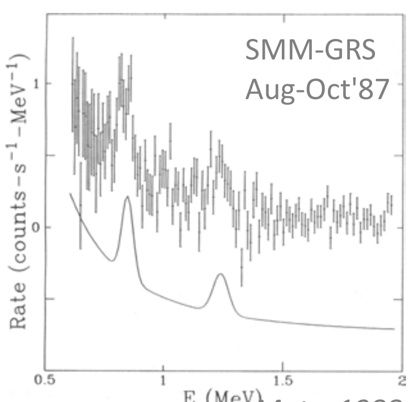
SN1987A

- Witnessing the final core collapse of a massive star of mass 22 $M_\odot$ in Feb 1987

- Witness neutrino burst from core collapse

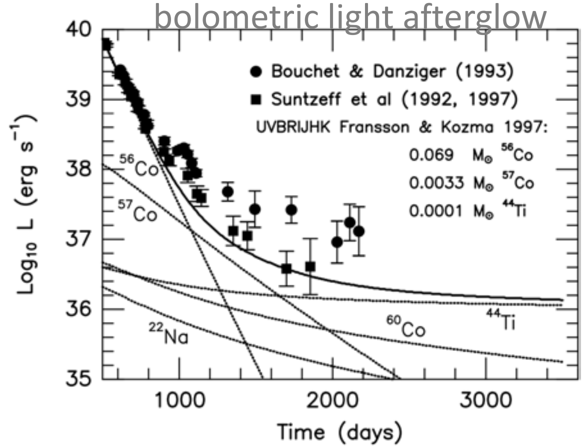


- Witness radioactively-powered SN afterglow and γ rays



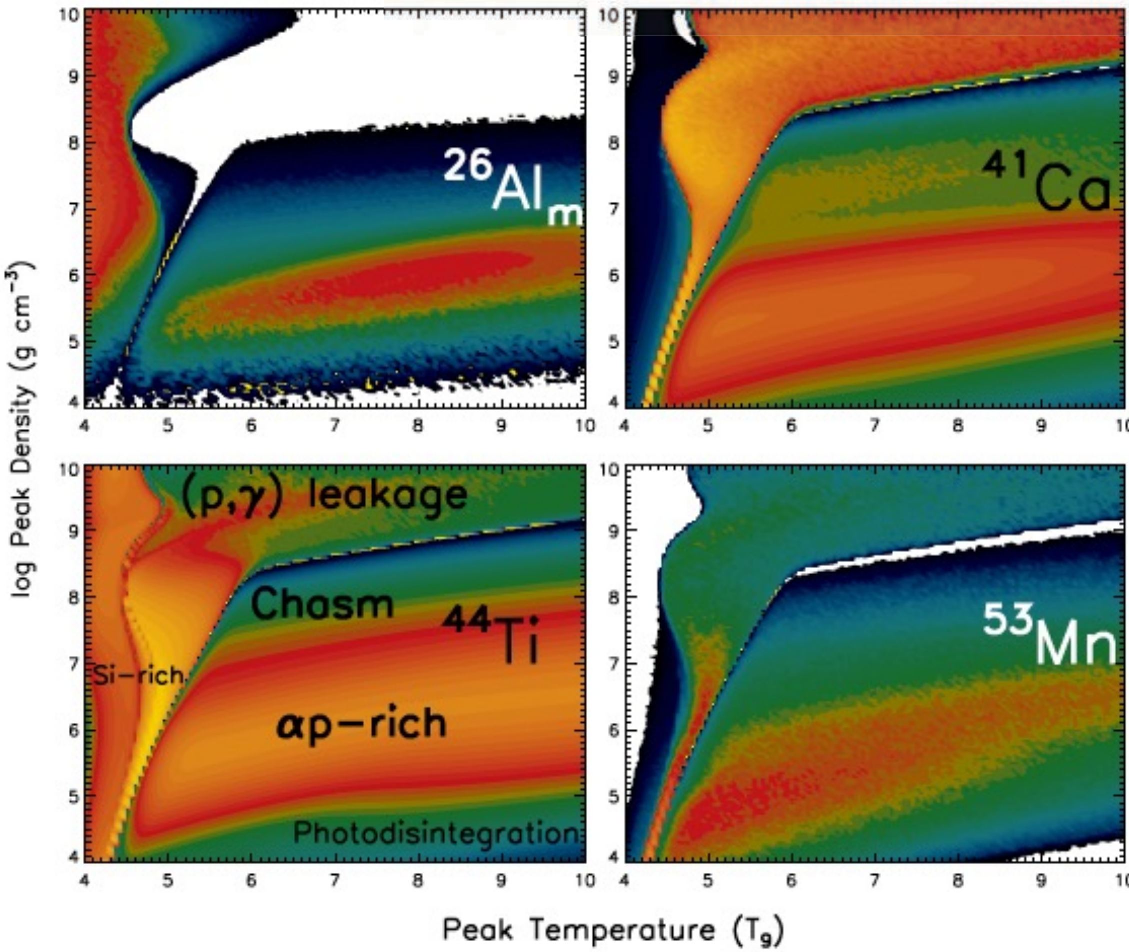
Matz+1988

bolometric light afterglow



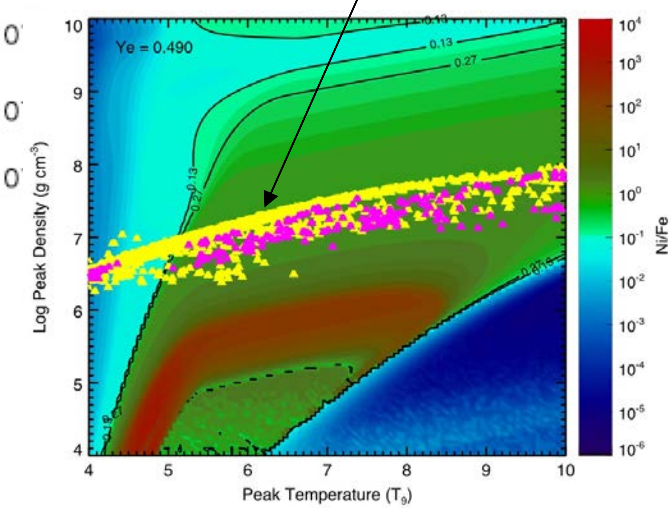
Nucleosynthesis in cc-SN : Density/Temperature Regimes

NuGrid collaboration (Magkotsios et al., ApJ 2011)



typical ccSN parameter regions

(Jerkstrand et al., ApJ 2015)



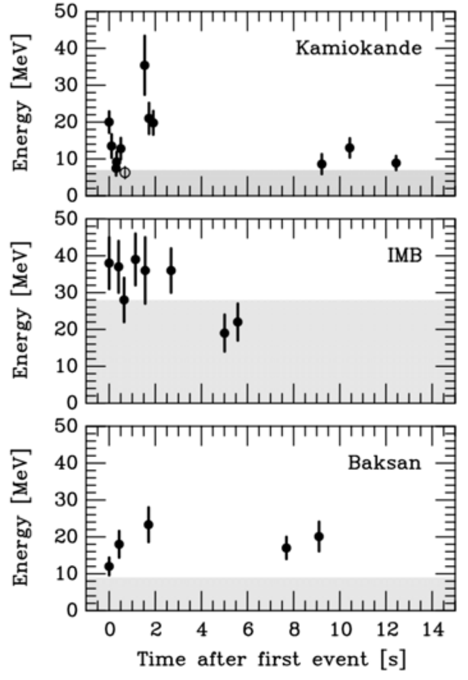
"For each region only certain reactions affect the yields of ^{44}Ti"

SN1987A

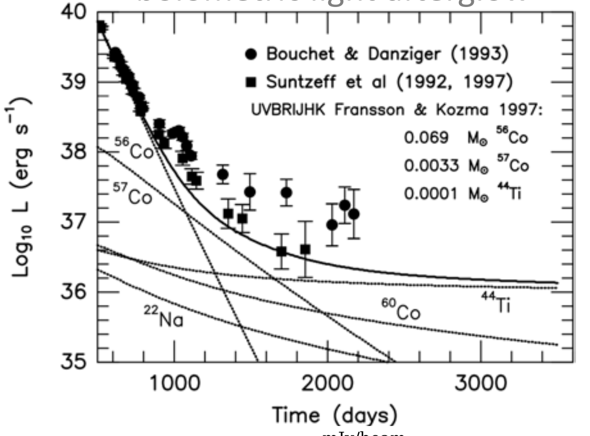
- Witnessing the final core collapse of a massive star of mass 22 $M_\odot$ in Feb 1987

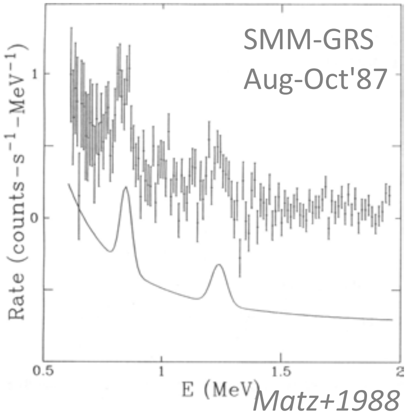
- Witness neutrino burst from core collapse

- Witness radioactively-powered SN afterglow and γ rays as its source

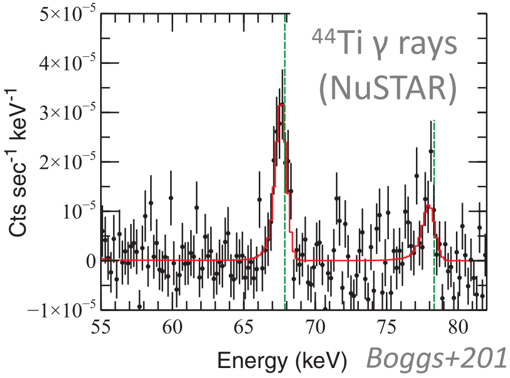


bolometric light afterglow



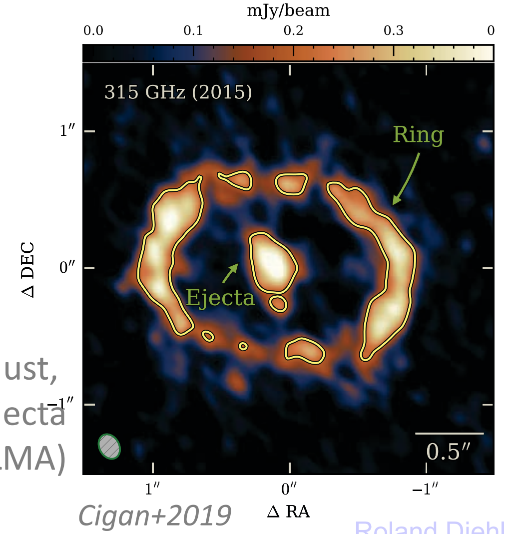


Matz+1988



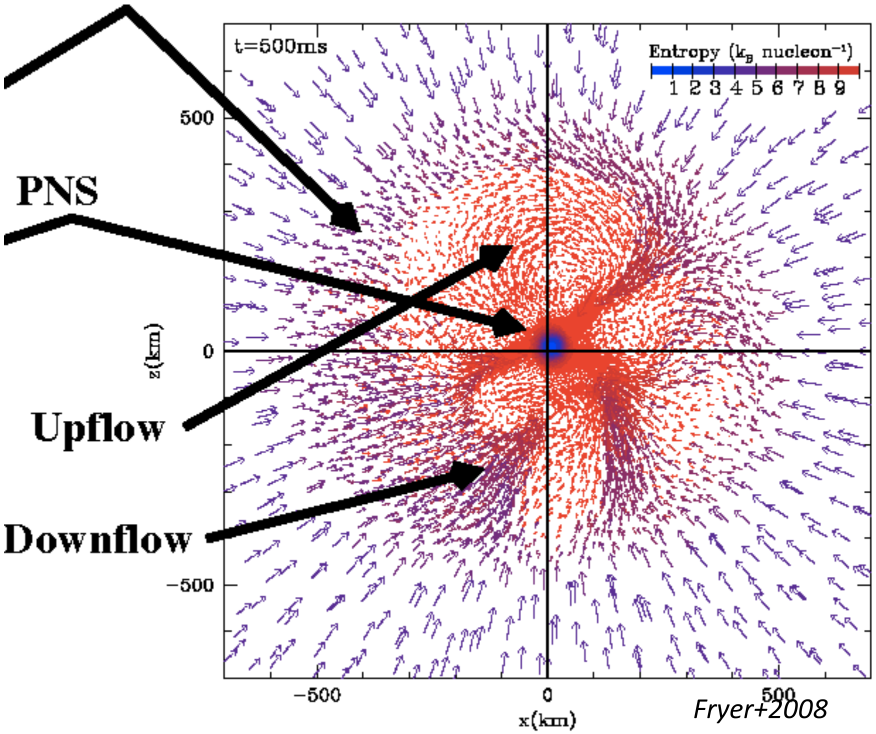
Boggs+2015

CSM, dust, ejecta (ALMA)



Cigan+2019

Nucleosynthesis in (3D!) cc-SN : Density/Temperature Regimes in INNER Regions

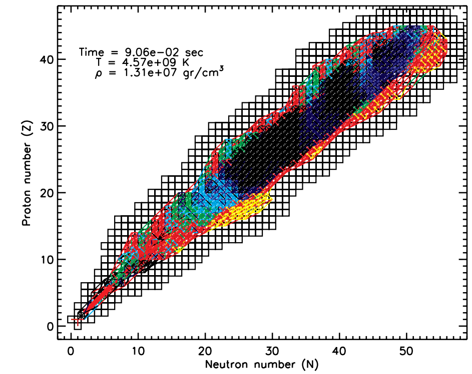


Fryer+2008

Final Mass fraction

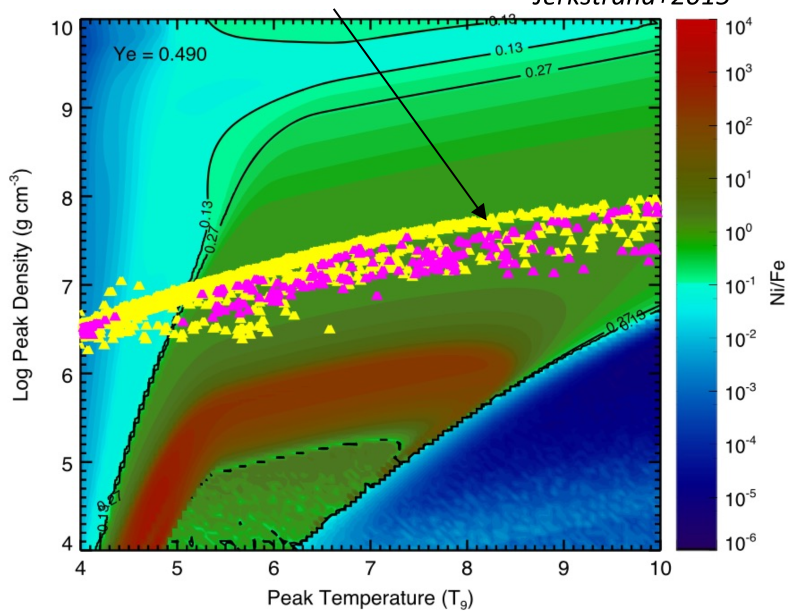
NuGrid collaboration (Magkotsios et al., ApJ 2011)

nuclear reaction network



typical ccSNparameter regions

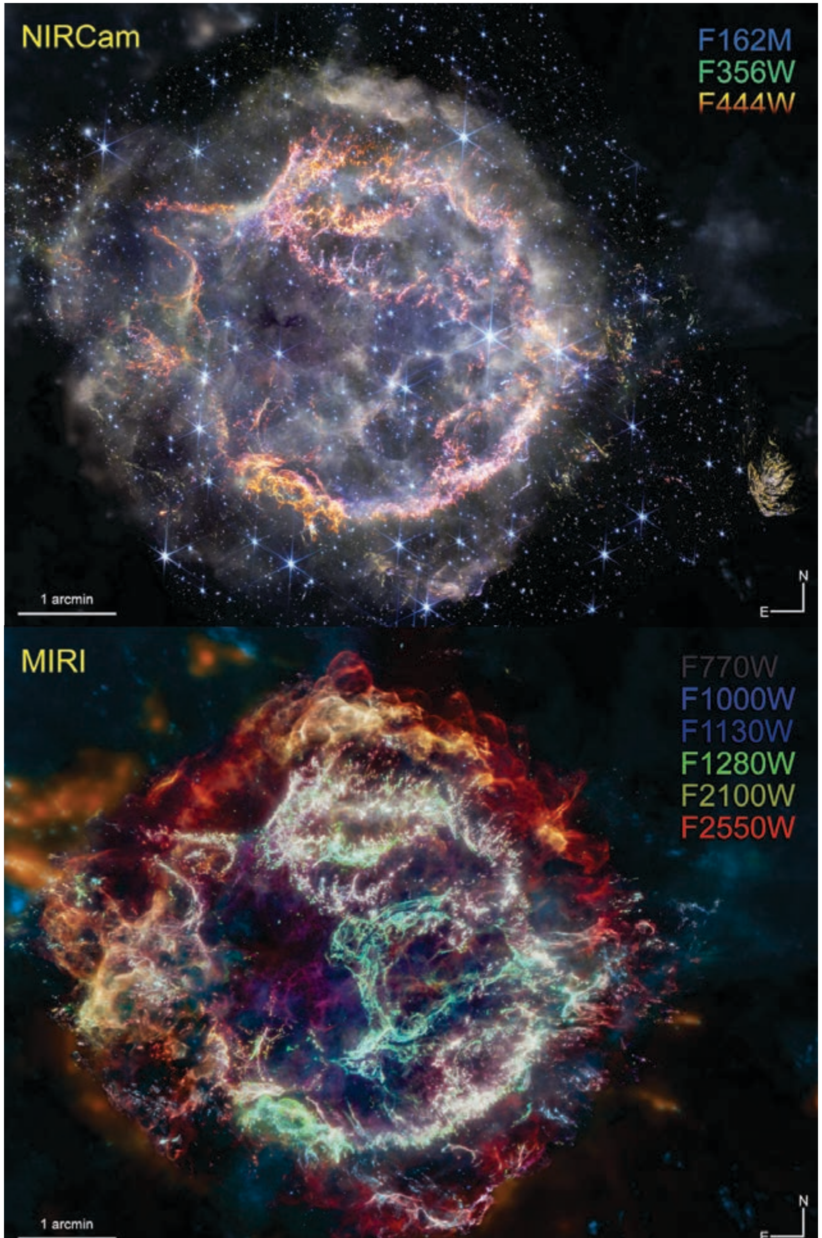
Jerkstrand+2015



"For each specific region, only certain reactions affect the yields of ^{44}Ti"

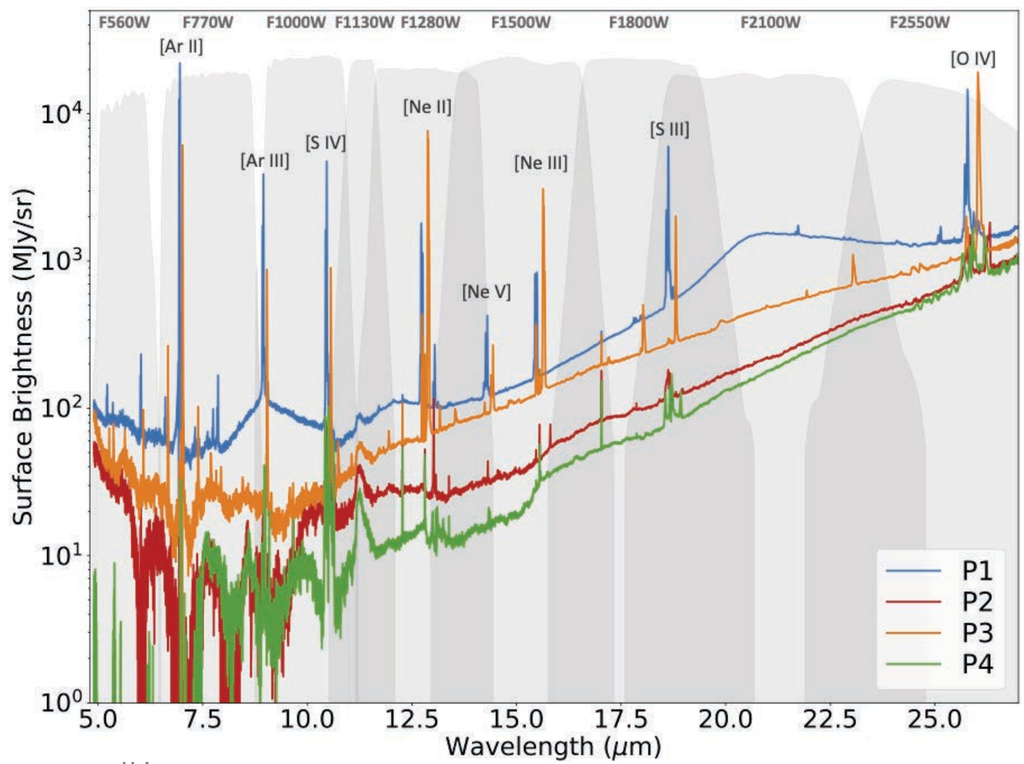
The Cas A SNR from a ccSN

Milisavljevic+2023



- Cas A SNR observations with JWST:

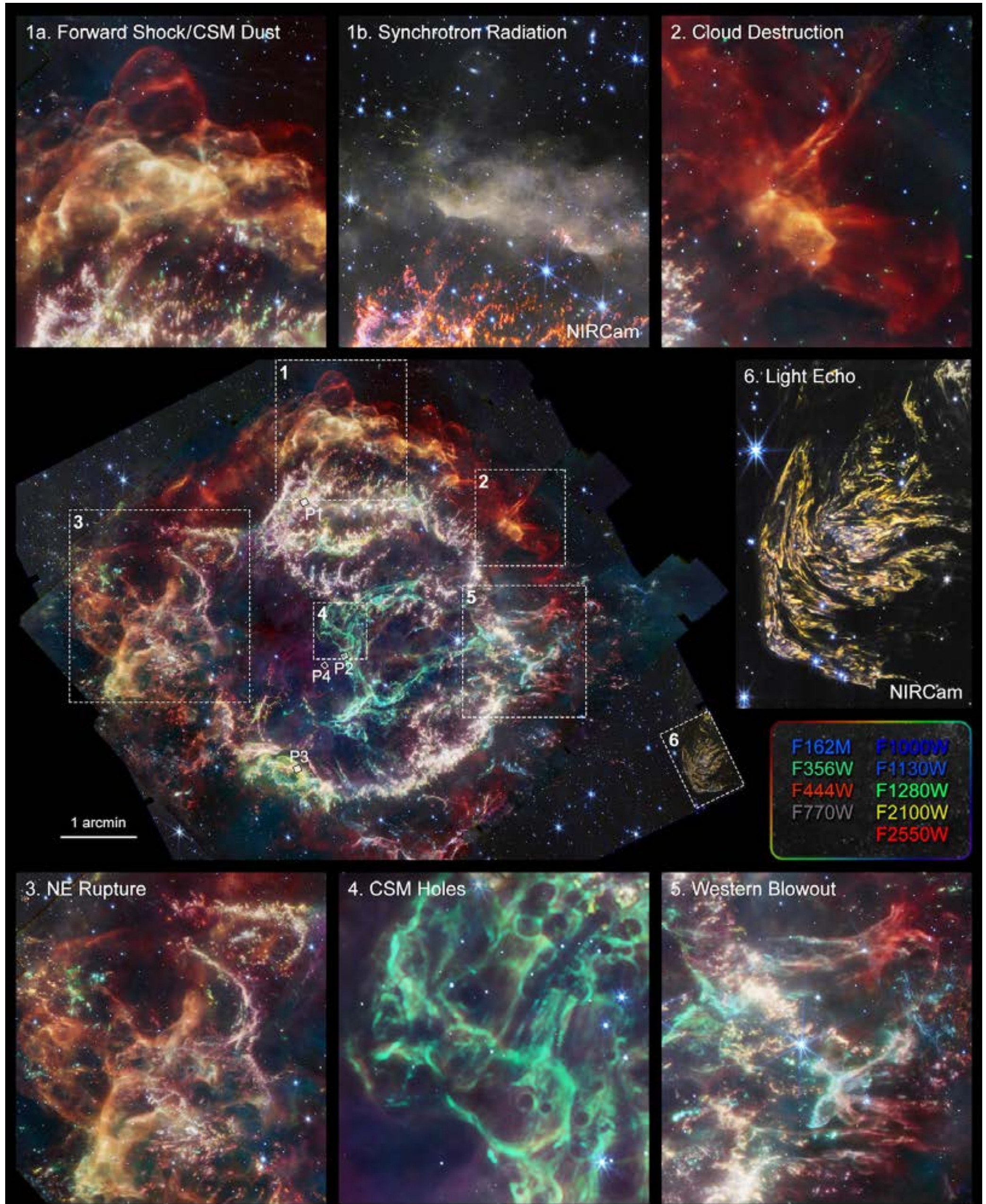
Instrument	Filter	λ_p (μm)	BW (μm)	PSF ($''$)	t_{exp} (sec)	Sources of strong emission
NIRCam	F162M	1.626	0.168	0.055	3350	[Fe II] 1.644; [Si I] 1.645; synchrotron
	F356W	3.563	0.787	0.116	1675	[Ca IV] 3.207, [Si IX] 3.936; PAHs; synchrotron; dust
	F444W	4.421	1.024	0.145	1675	[Si IX] 3.936; [Ca V] 4.159; [Mg IV] 4.487, [Ar VI] 4.530; [K III] 4.618; CO; synchrotron; dust
MIRI	F560W	5.6	1.2	0.207	1598	[Mg V] 5.61; dust; synchrotron
	F770W	7.7	2.2	0.269	1598	[Ar II] 6.99; PAHs, dust
	F1000W	10.0	2.0	0.328	1598	[Ar III] 8.991; [S IV] 10.511; dust
	F1130W	11.3	0.7	0.375	1598	PAHs; dust
	F1280W	12.8	2.4	0.420	1598	[Ne II] 12.814; [Ne V] 14.32; dust
	F1800W	18.0	3.0	0.591	1598	[Fe II] 17.94; [S III] 18.713; dust; H_2
	F2100W	21.0	5.0	0.674	1598	[S III] 18.713; dust
	F2550W	25.5	4.0	0.803	1598	[O IV] 25.89; dust



Cas A with JWST

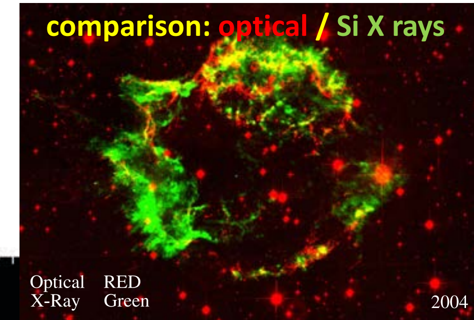
Milisavljevic+2023

- The Cas A SNR displays a great variety of features that reflect the ccSN explosion history and dynamics
  - ☆ interaction of the SN shock with surrounding CSM
    - ☞ shock and dust
    - ☞ synchrotron emission
    - ☞ destruction of ISM clouds
  - ☆ internal dynamics of the expanding remnant
    - ☞ CSM structure remains
    - ☞ explosion asymmetry remains
    - ☞ RT lobes
    - ☞ jets
    - ☞ reverse-shocked ejecta
  - ☆ light echoes



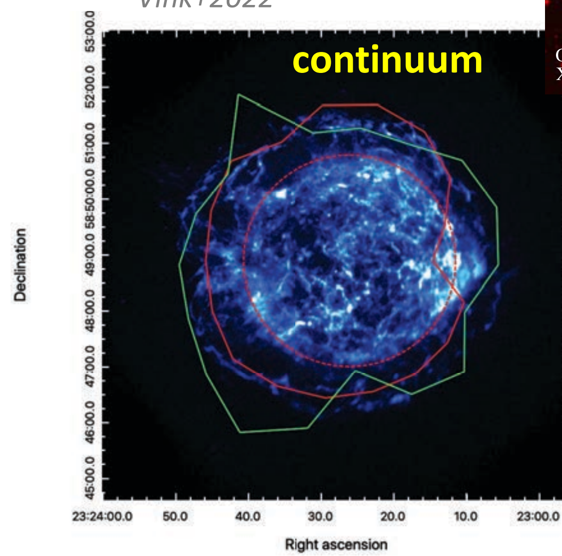
Cas A in X rays

- Cas A SNR composition and dynamics is reflected in X rays
  - ☆ interaction of the SN shock with surrounding CSM
    - ☞ shock acceleration (e^-)
    - ☞ synchrotron emission, non-thermal Bremsstrahlung
  - ☆ composition of remnant
    - ☞ reverse-shocked ejecta
    - ☞ characteristic lines from highly-ionised species



Patnaude&Fesen2014

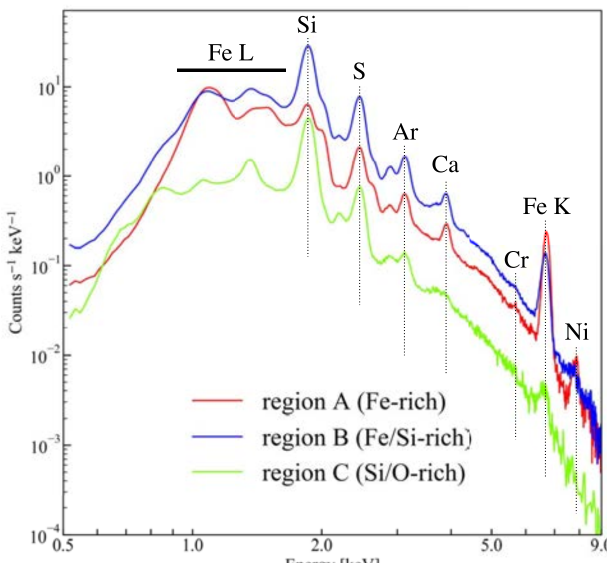
Vink+2022



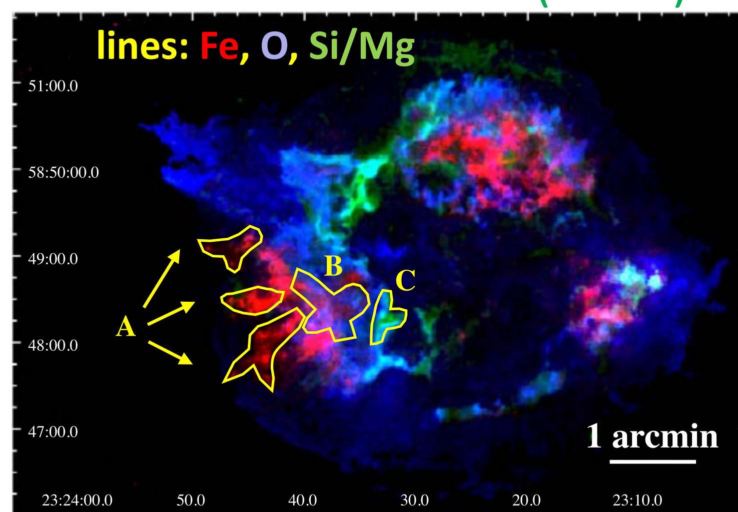
➔ complex shock dynamics

➔ overturn of ejecta material (shells)?

0.9- 9 keV, Chandra



Tsuchioka+2022



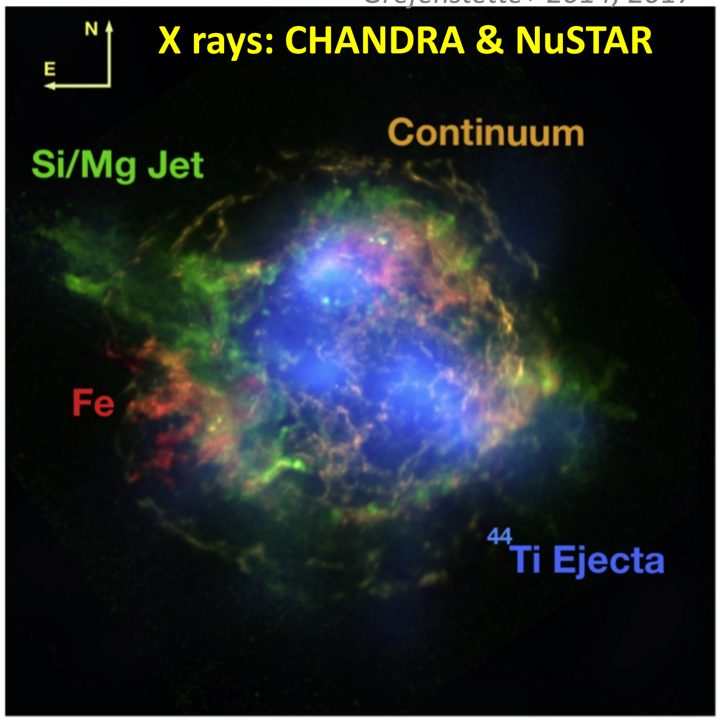
Beyond X rays: Locating the inner Ejecta in Cas A

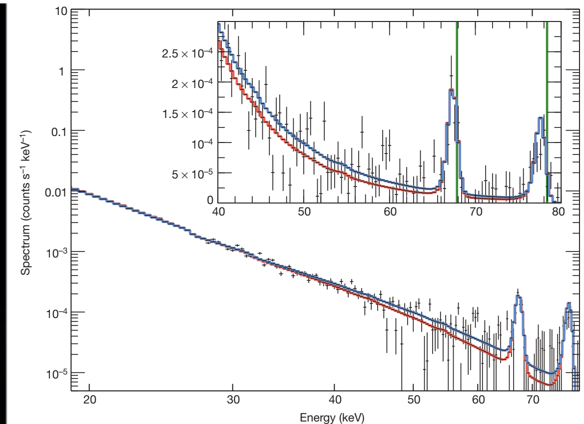
NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

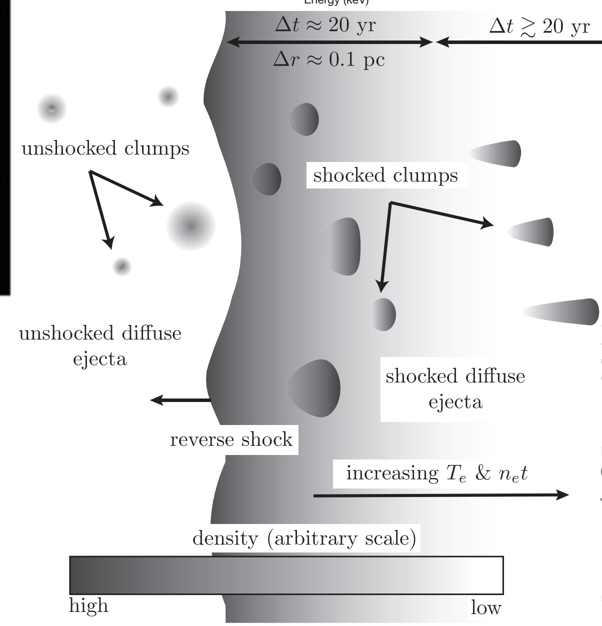
☞ first mapping of radioactivity in a SNR

- Both ^{44}Ti lines detected clearly
- redshift ~0.5 keV
  → 2000 km/s asymmetry
- ^{44}Ti flux consistent with earlier measurements
- Doppler broadening: (5350 ± 1610) km s^{-1}
- Image differs from Fe!!

Grefenstette+ 2014; 2017







Patnaude&Fesen2014

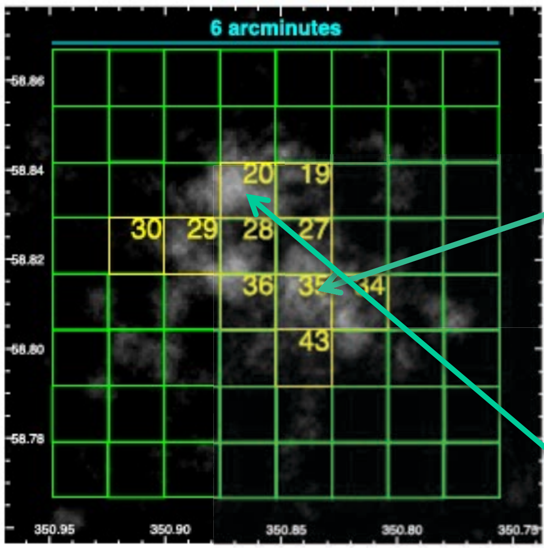
☞ ^{44}Ti→ TRUE locations of inner-SN ejecta

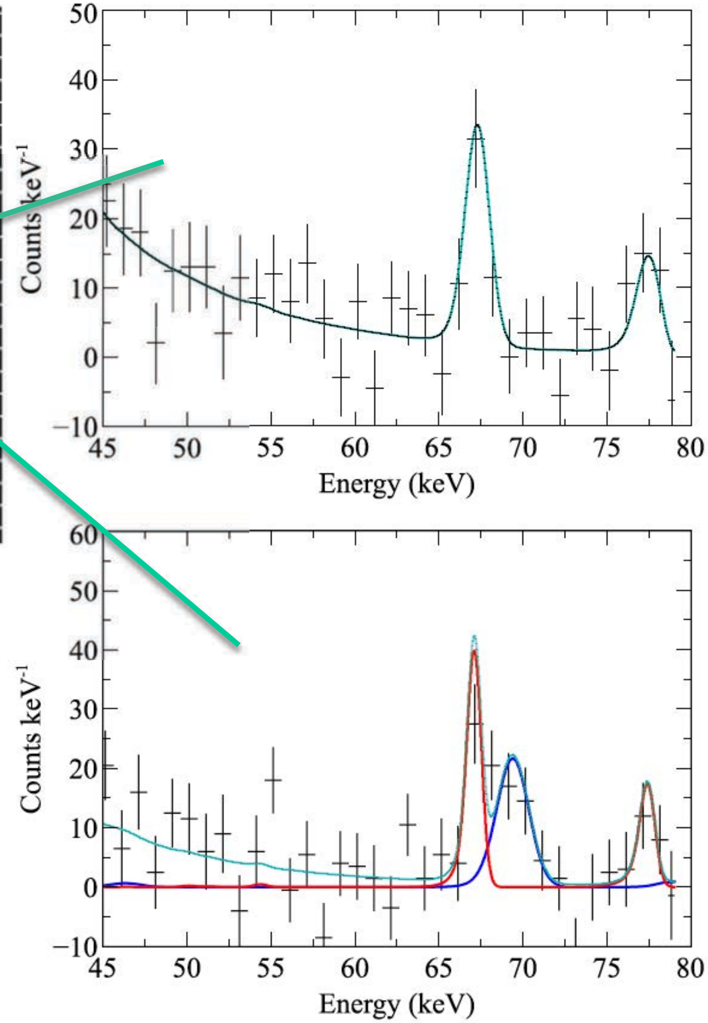
☞ Fe-line X-rays are biased from ionization of plasma by reverse shock

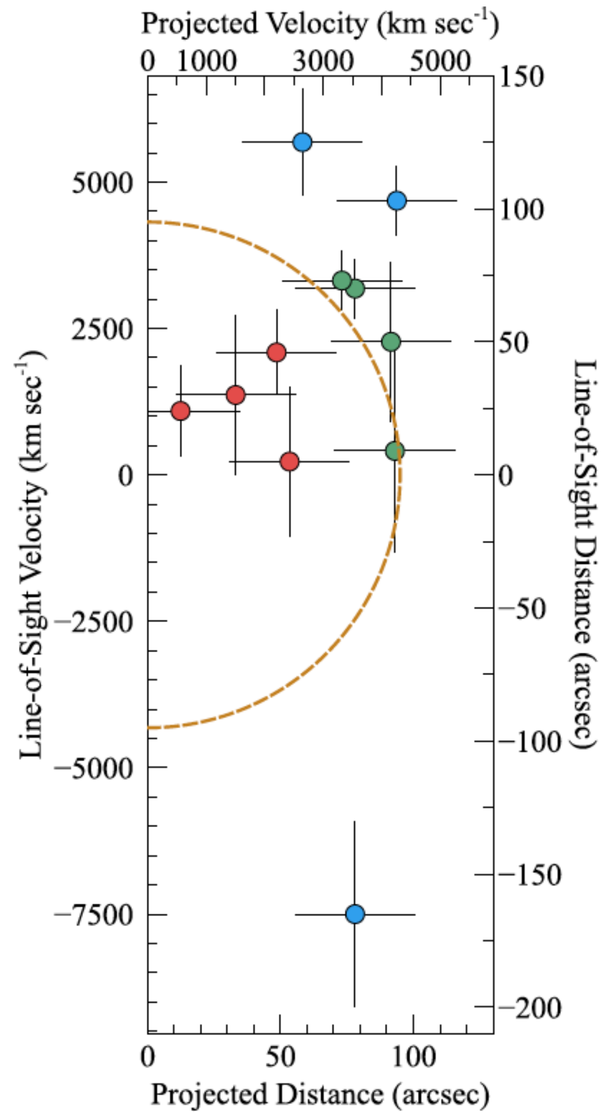
NuSTAR update: ^{44}Ti in Cas A

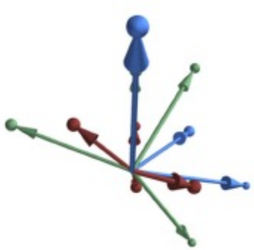
☆ Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

2.4 Msec NuSTAR campaign
Grefenstette et al. 2017



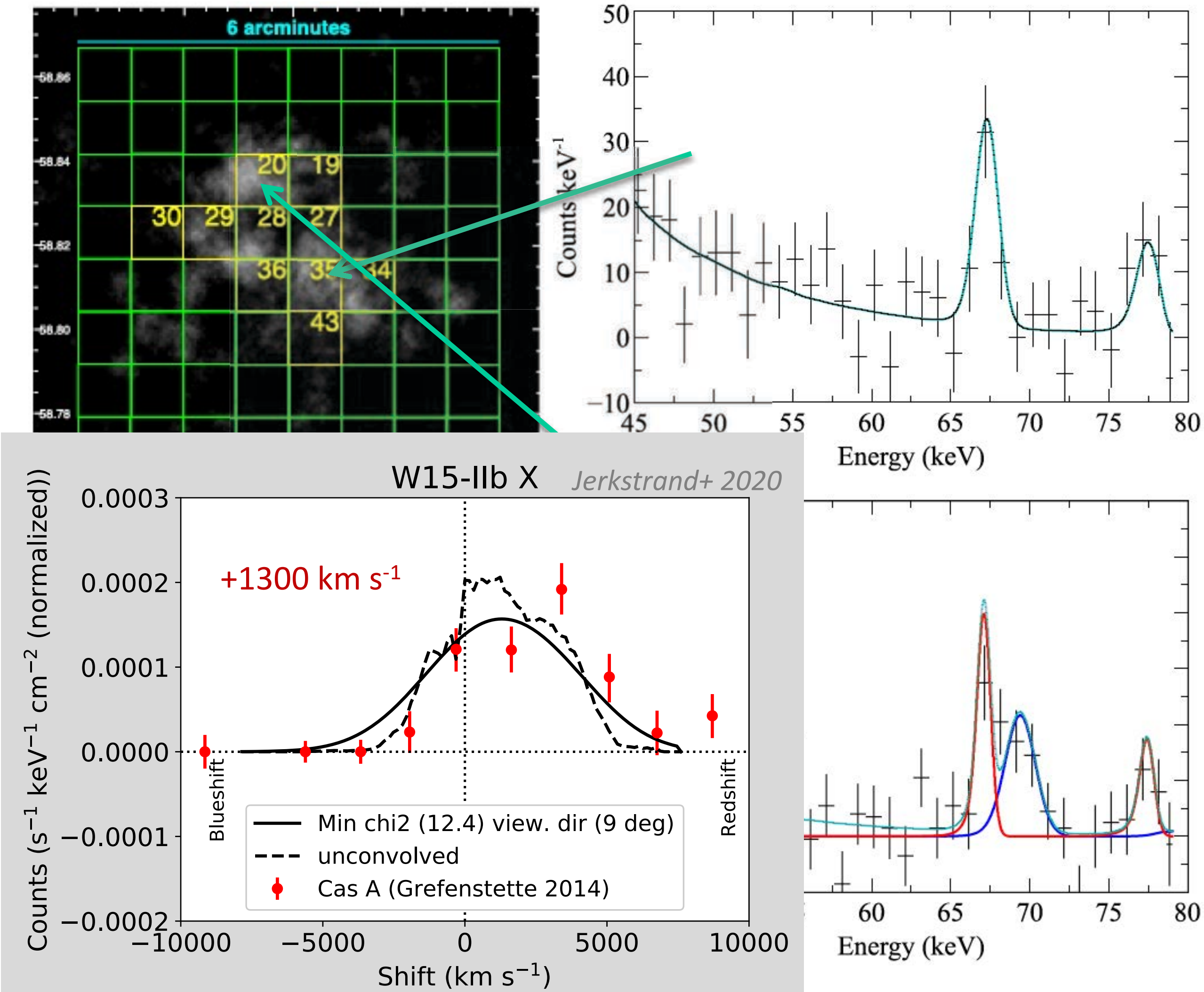






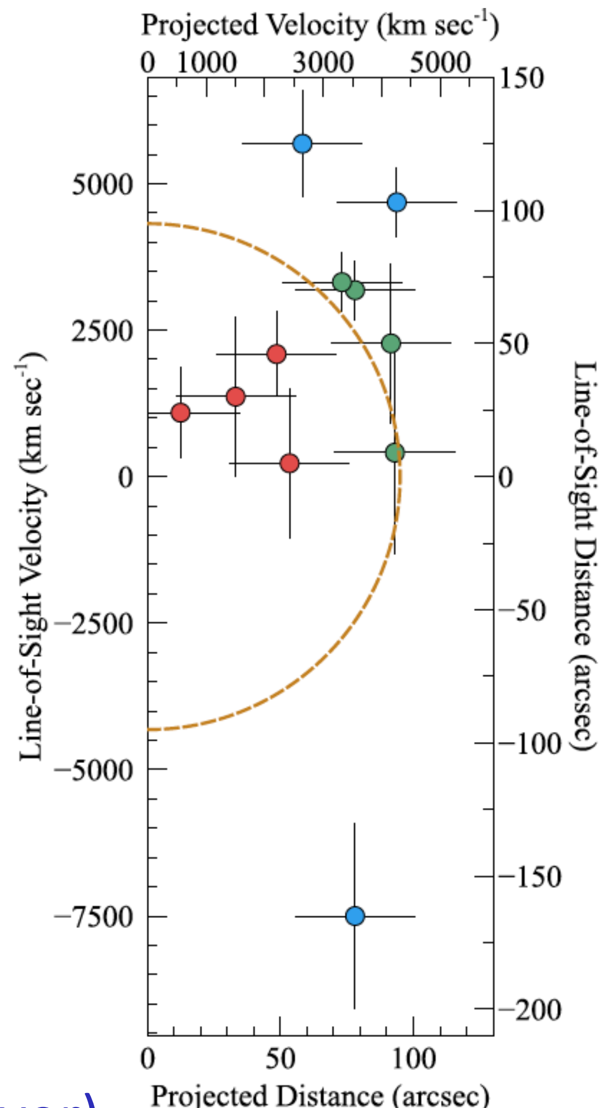
NuSTAR details of ^{44}Ti in Cas A

☆ Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:



2.4 Msec NuSTAR campaign

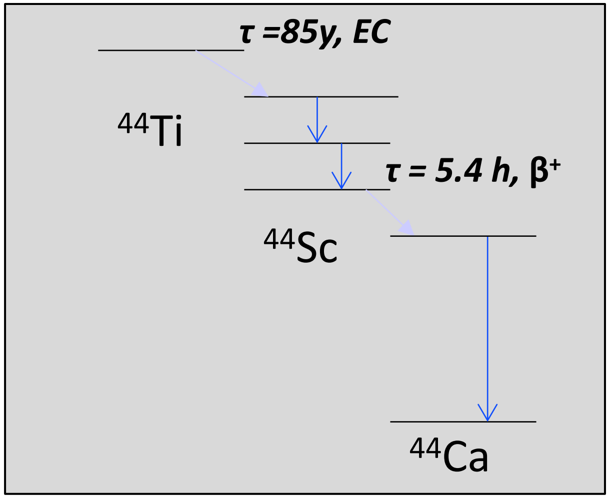
Grefenstette et al. 2017



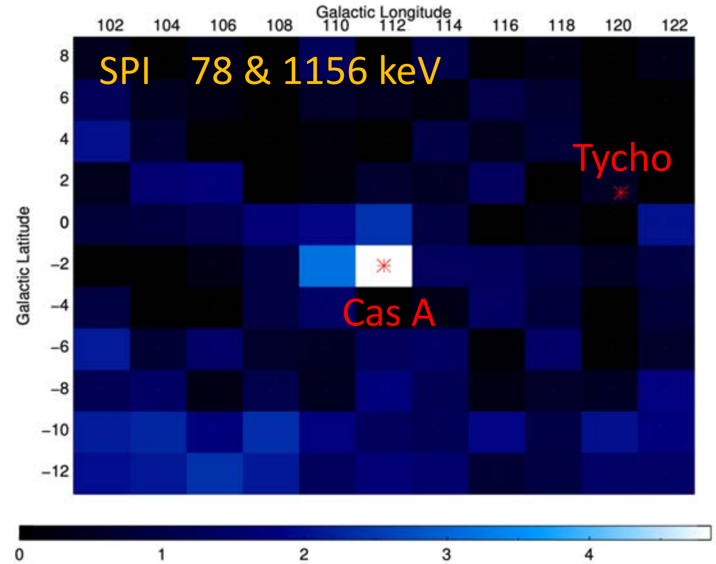
→ bulk red-shifted ^{44}Ti (away from observer)

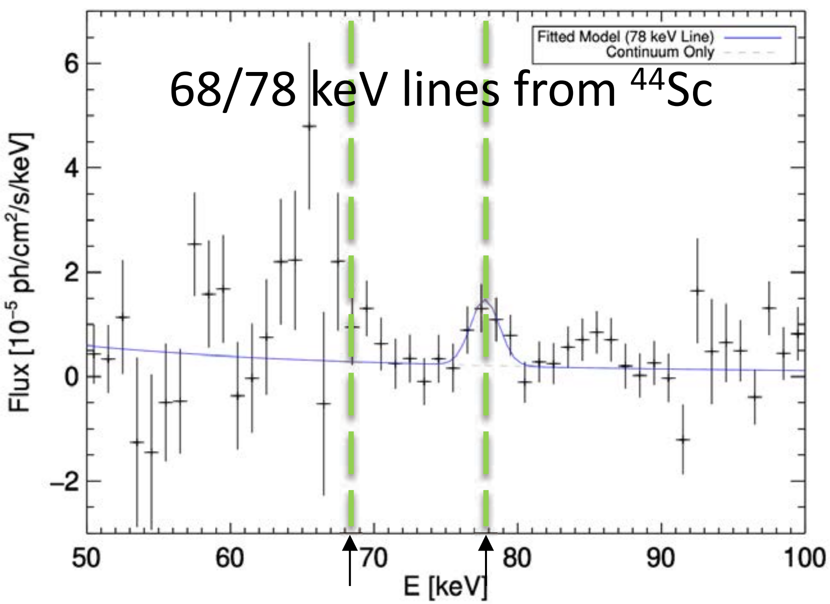
^{44}Ti Cas A: INTEGRAL/SPI confirmations of bulk redshift

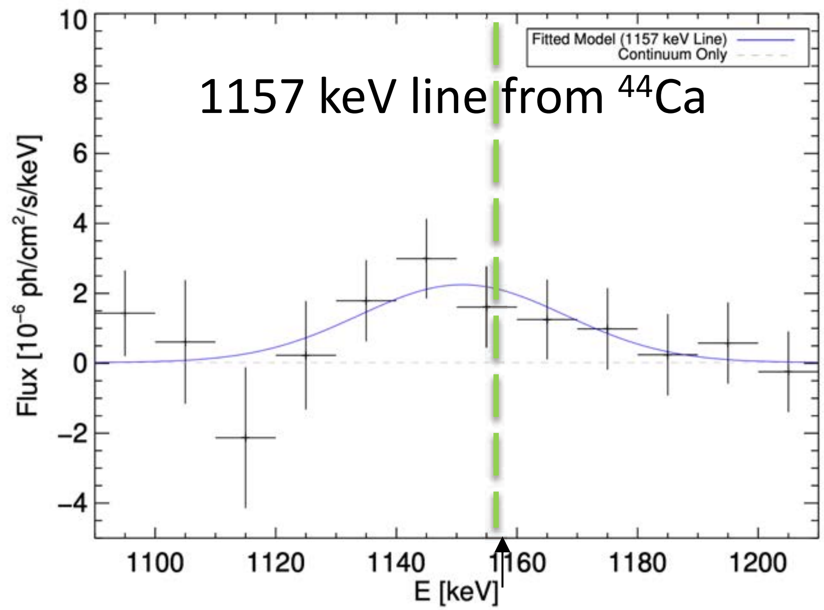
The ^{44}Ti decay chain with INTEGRAL/SPI:



Weinberger+ 2021

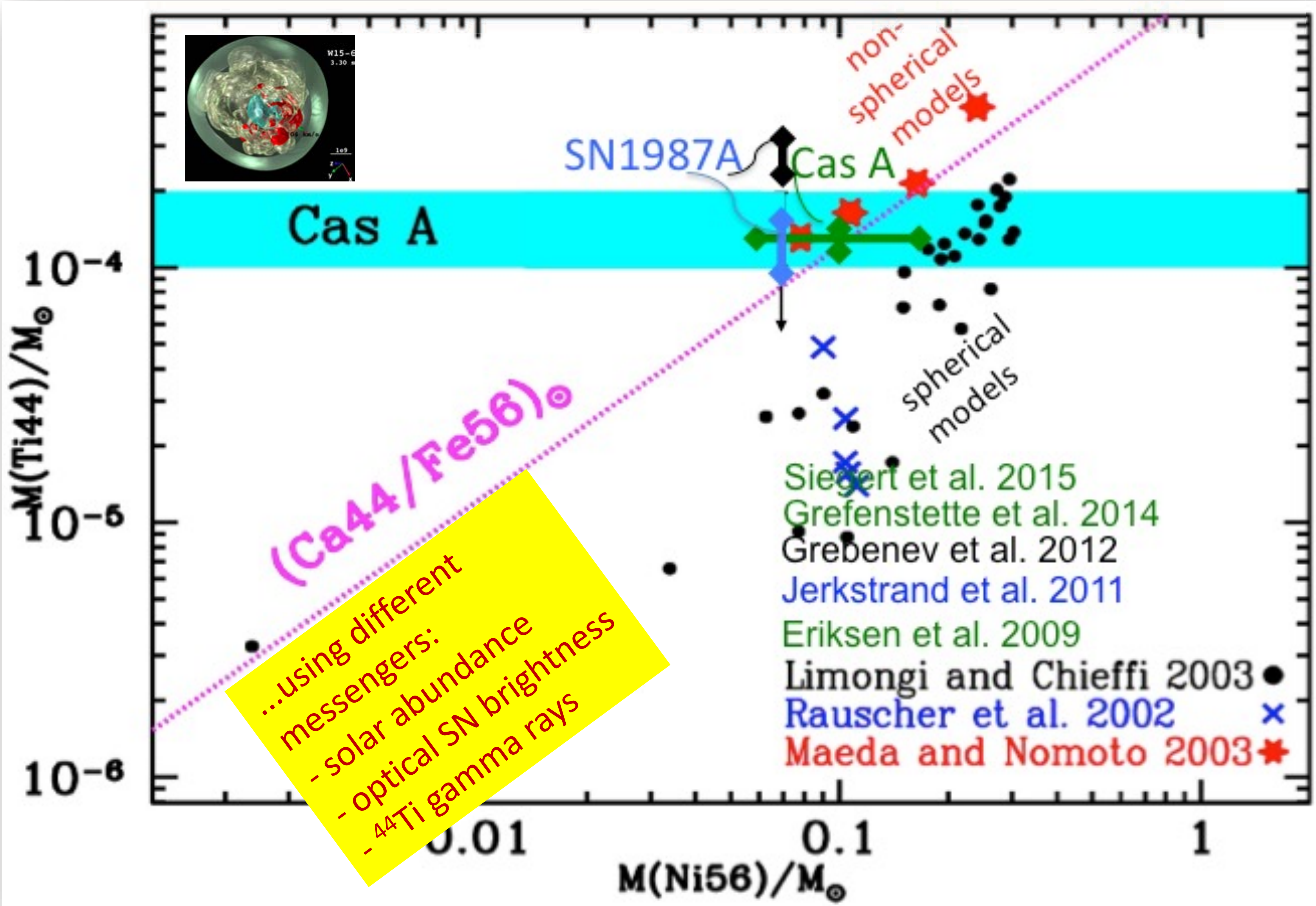






→ clear Doppler shift of ^{44}Ti (1800 ±800 km s^{-1} away from observer)

The case for asymmetries in ccSNe that eject ^{44}Ti

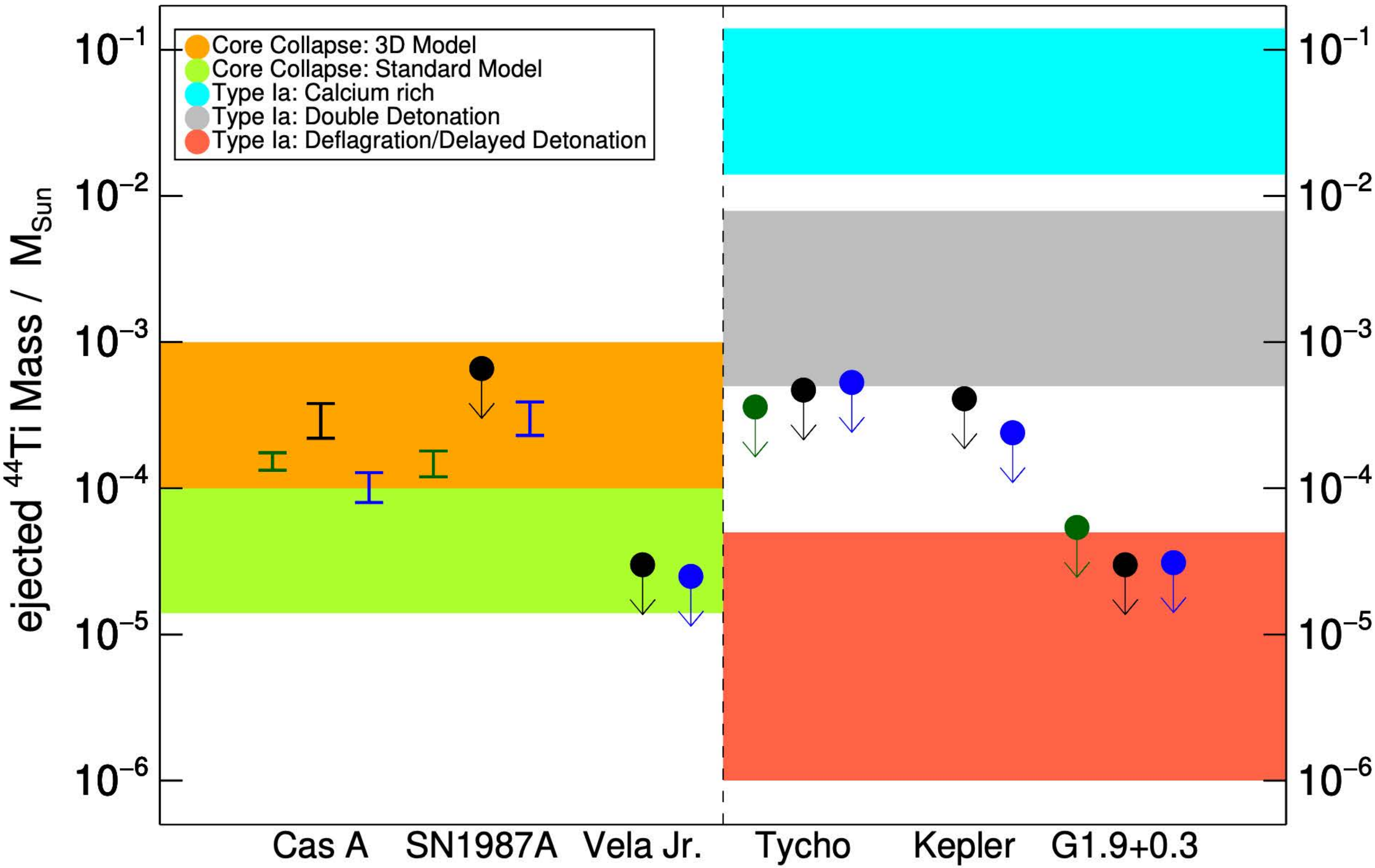


⇨ Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios

⇨ *The et al. 2006; Dufour&Kaspi 2013*

Is ^{44}Ti ejection part of a supernova?

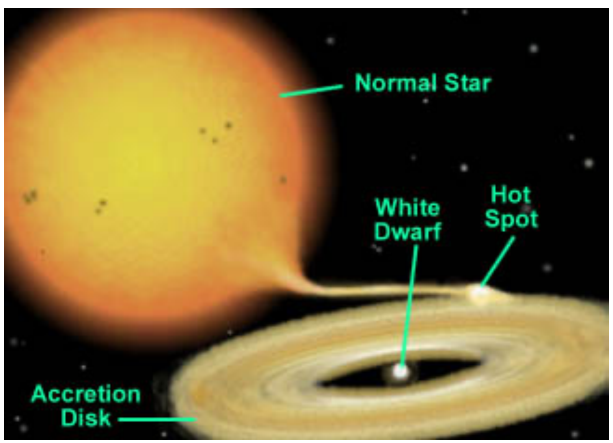
Weinberger 2021

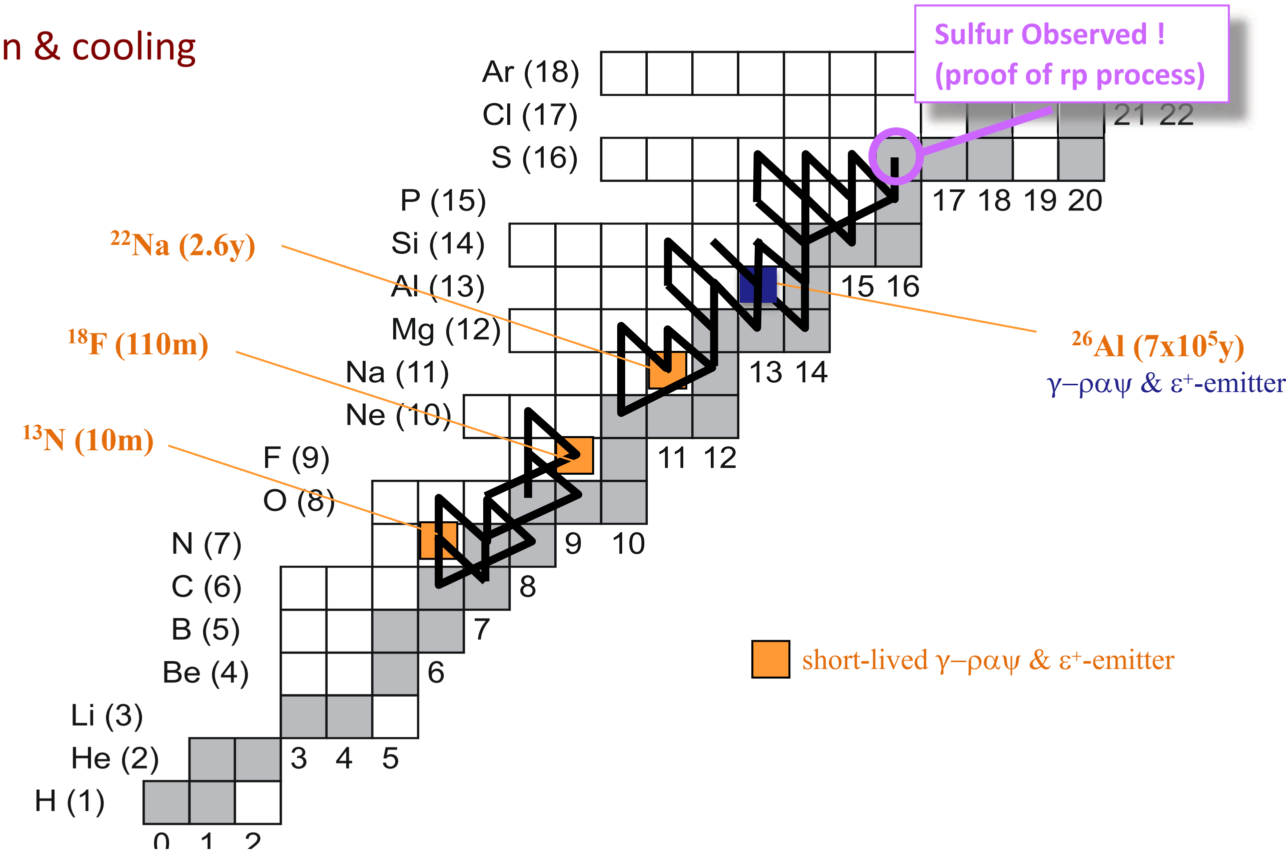


Nova Nucleosynthesis

- H-burning in a runaway on WD surface
  - ☞ Accretion of H from companion star
  - ☞ H ignition → T~few 10^8K
  - ☞ envelope expansion & cooling

$$\dot{M} \sim 10^{-8} M_{\odot} y^{-1}$$





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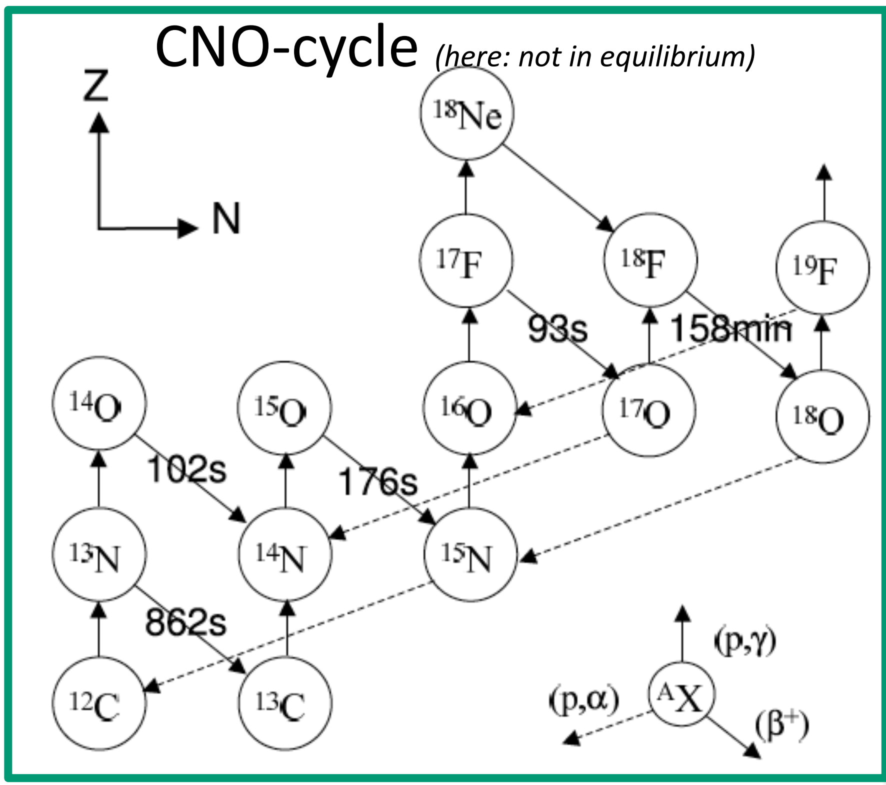
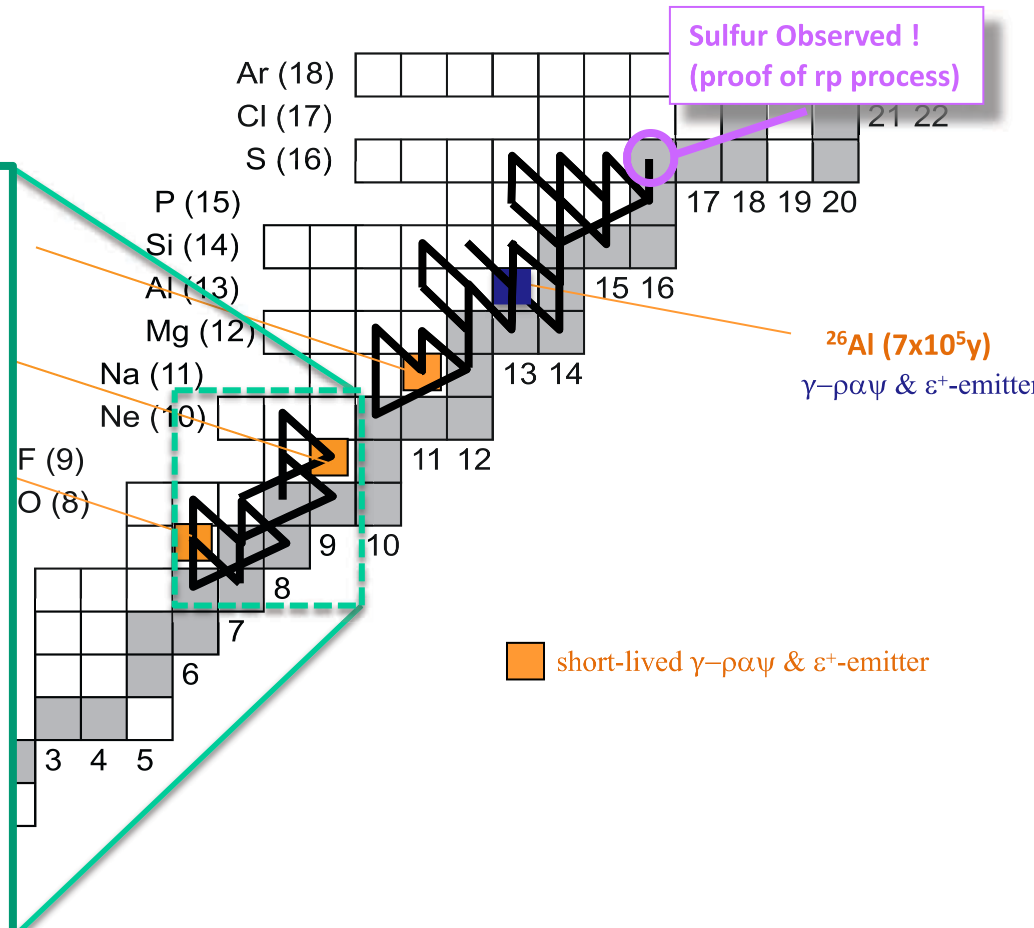
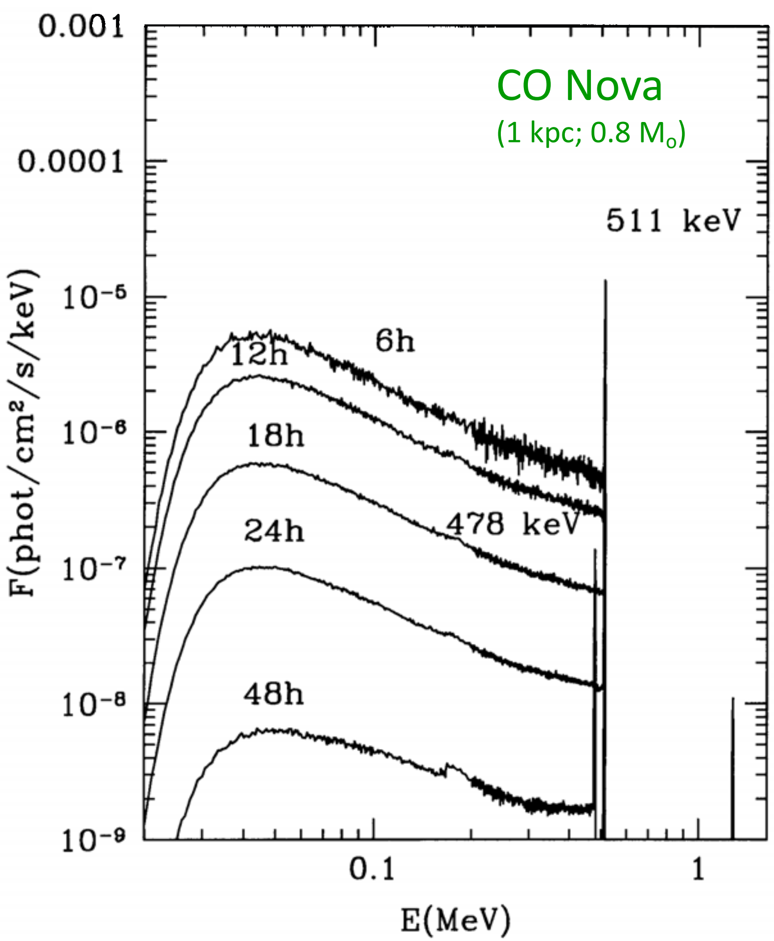
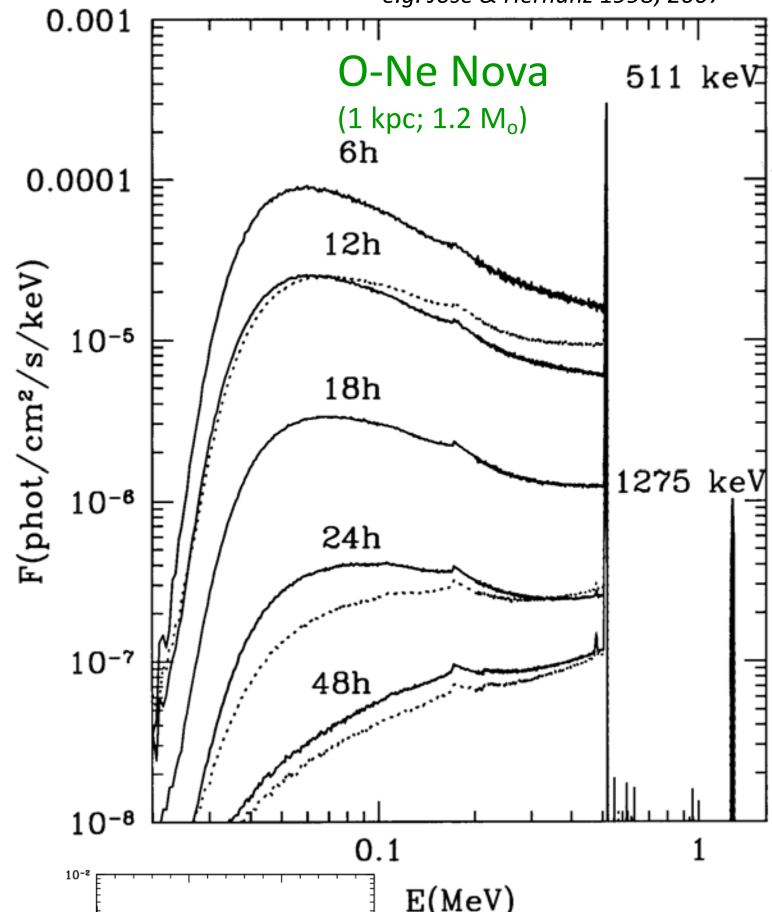


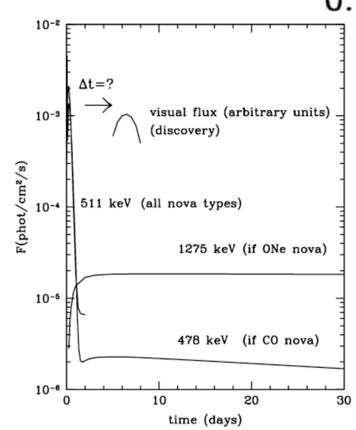


Nova Diagnostics Prospect with Nuclear Lines

e.g. Jose & Hernanz 1998; 2007





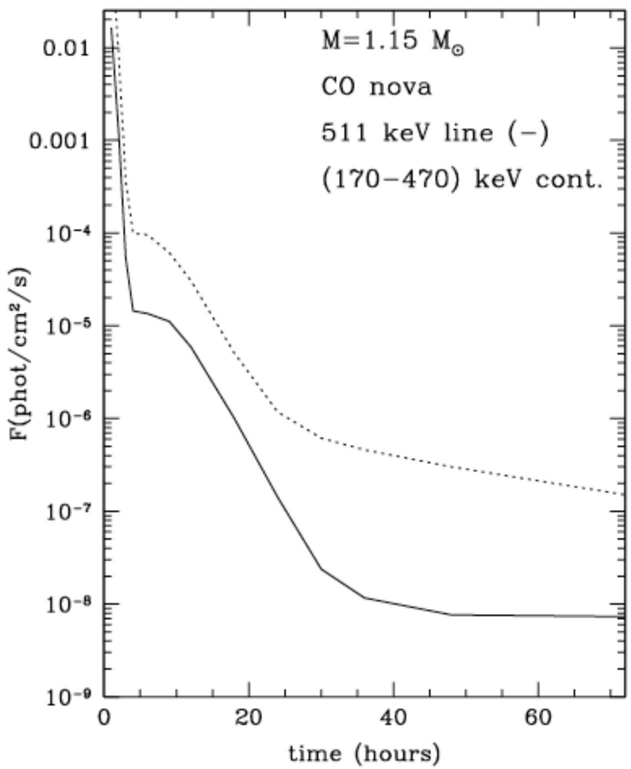


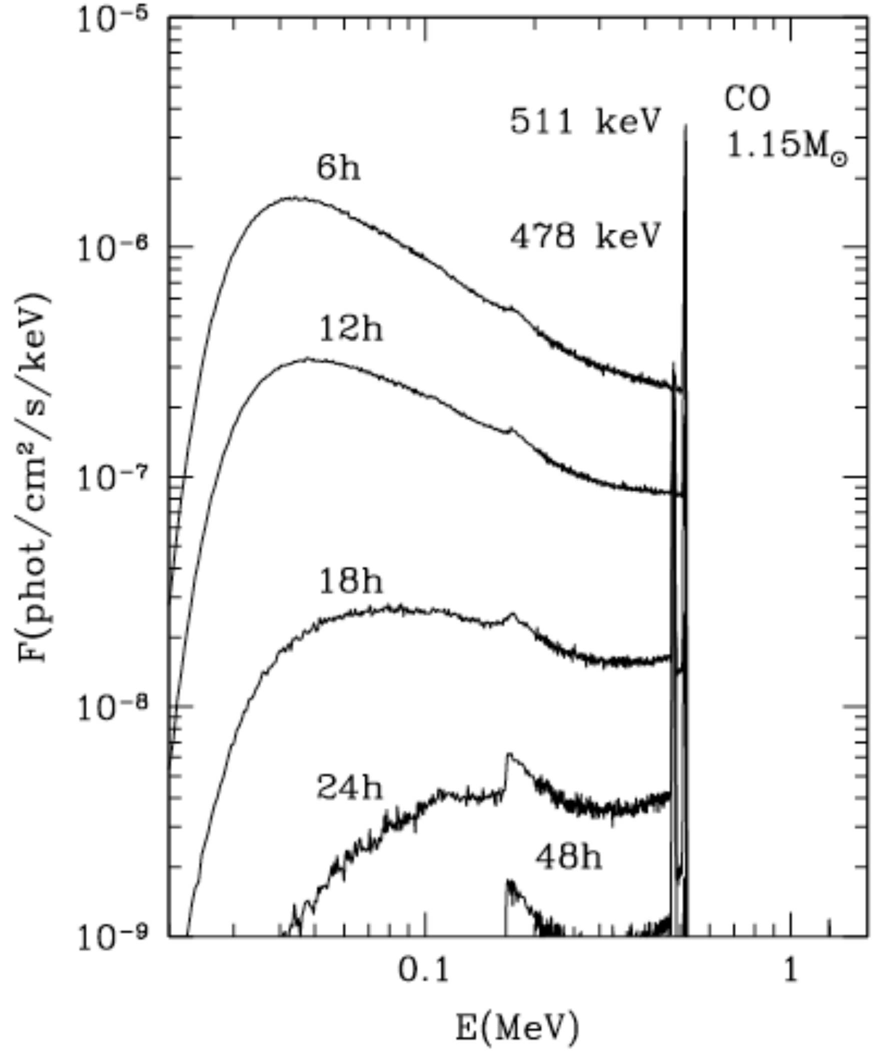
- ☆ Brief flash due to e^+ annihilations, with 511 keV line and β^+ decay continuum *(before optical nova!)*
- ☆ ^{7}Be radioactivity (CO novae)
- ☆ ^{22}Na radioactivity (O-Ne novae)

CO Nova Gamma-ray Line Emission

☞ updates in ^{18}F yields (downward revision) since 1998…2007

Hernanz+ 2013; 2017



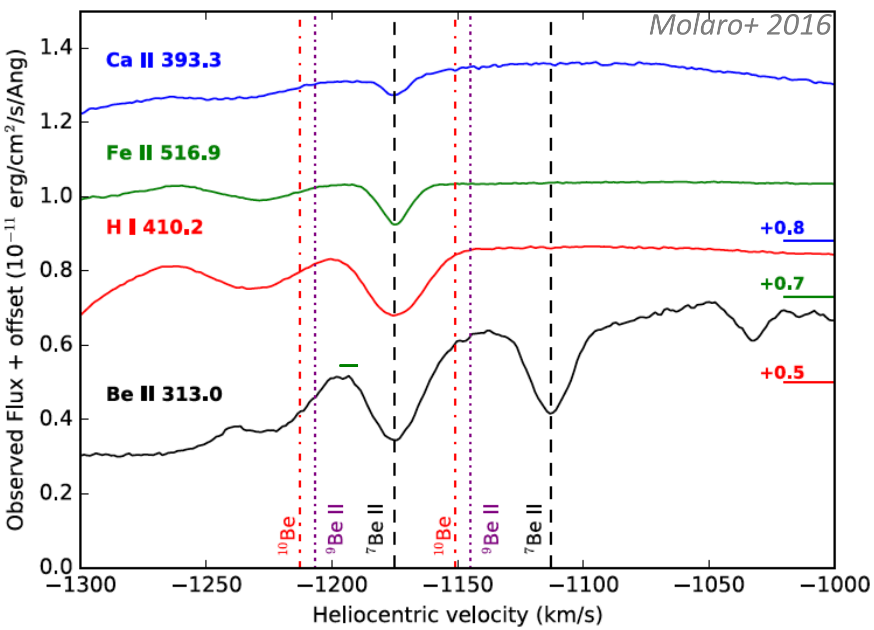


Li nucleosynthesis in a nova?

$$^{7}Li \xrightarrow{EC;\tau\approx 77\,d} {}^{7}Be + 478\,keV$$

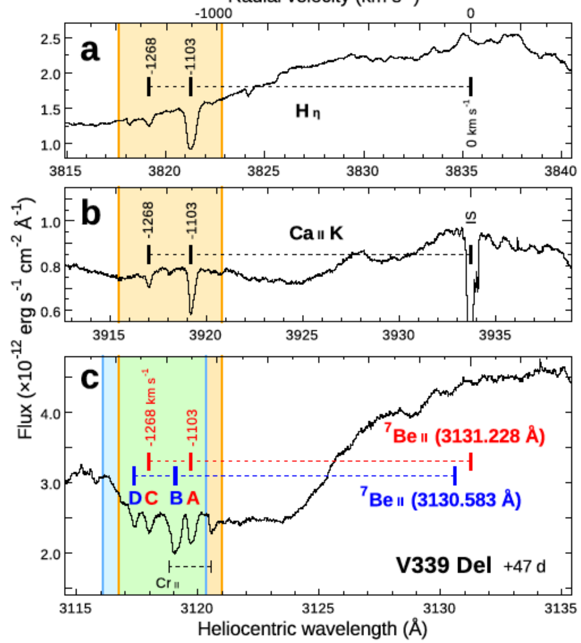
- Li, Be spectral features seen in three nova outbursts
  - ☞ kinematic calibration
  - ☞ characteristic doublets

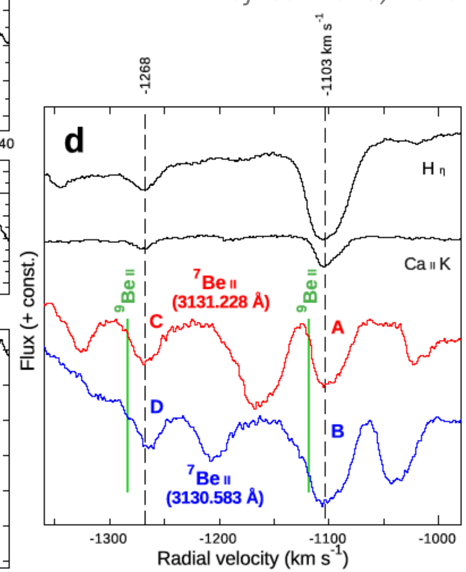
Nova Sgr 2015 (V5668 Sgr)



Nova Del 2013 (V339 Del)

Tajitsu+2015, 2016





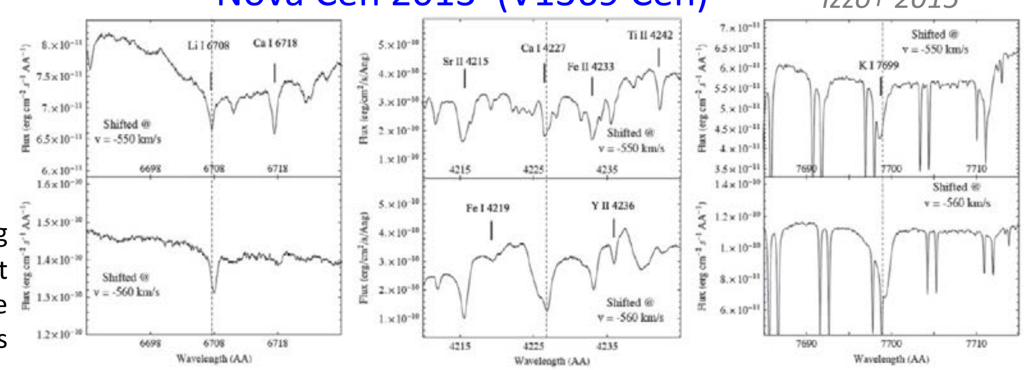
$$M_{\rm Li} \approx 7 \times 10^{-9} M_\odot$$

"new Li problem"? (A. Coc)

Nova Cen 2013 (V1369 Cen)

Izzo+ 2015

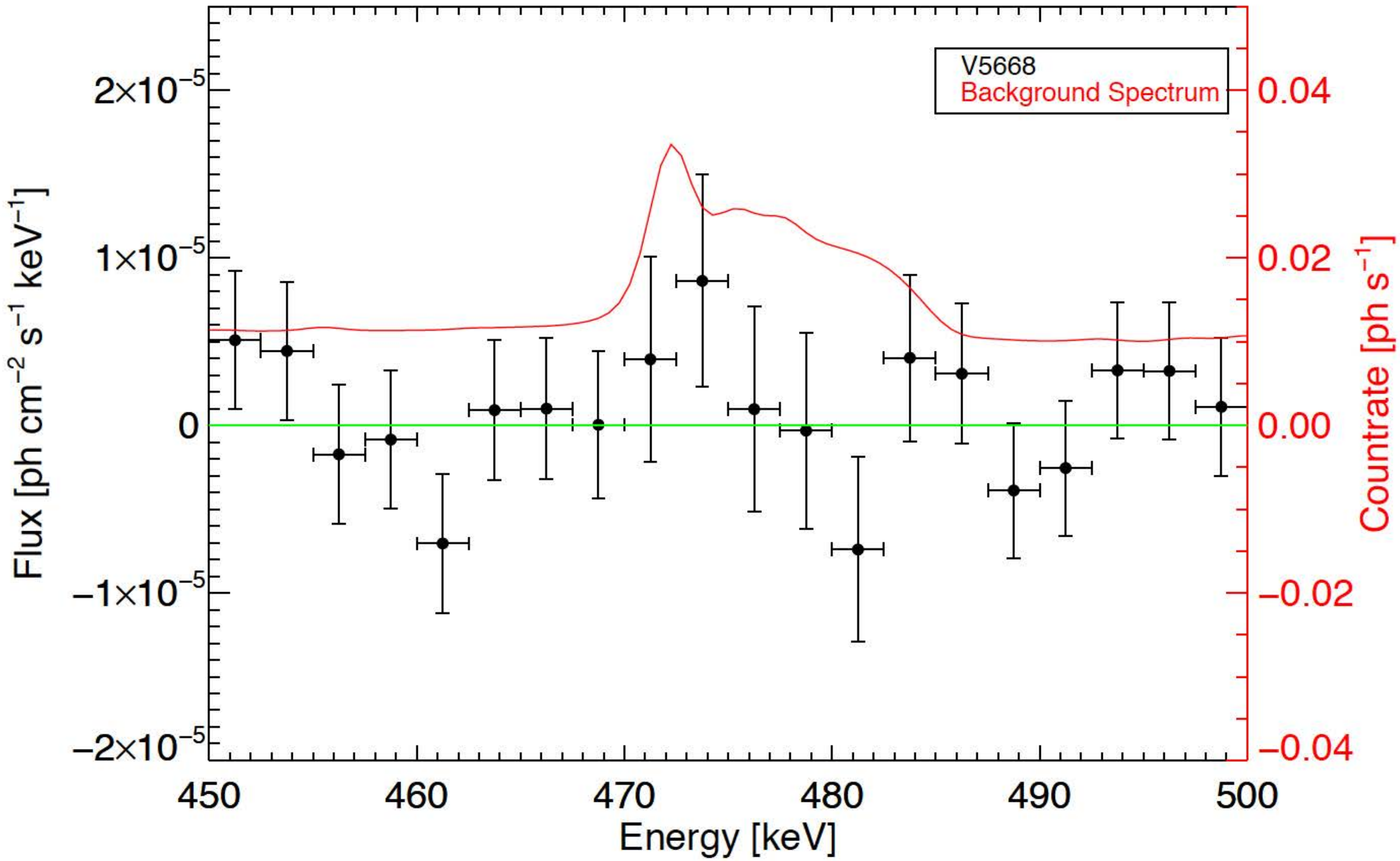
using Na doublet to calibrate kinematics



Line limits on nova from SPI/INTEGRAL

☞Nova Sgr 2015 (V5668), opt max 21 Mar 2015

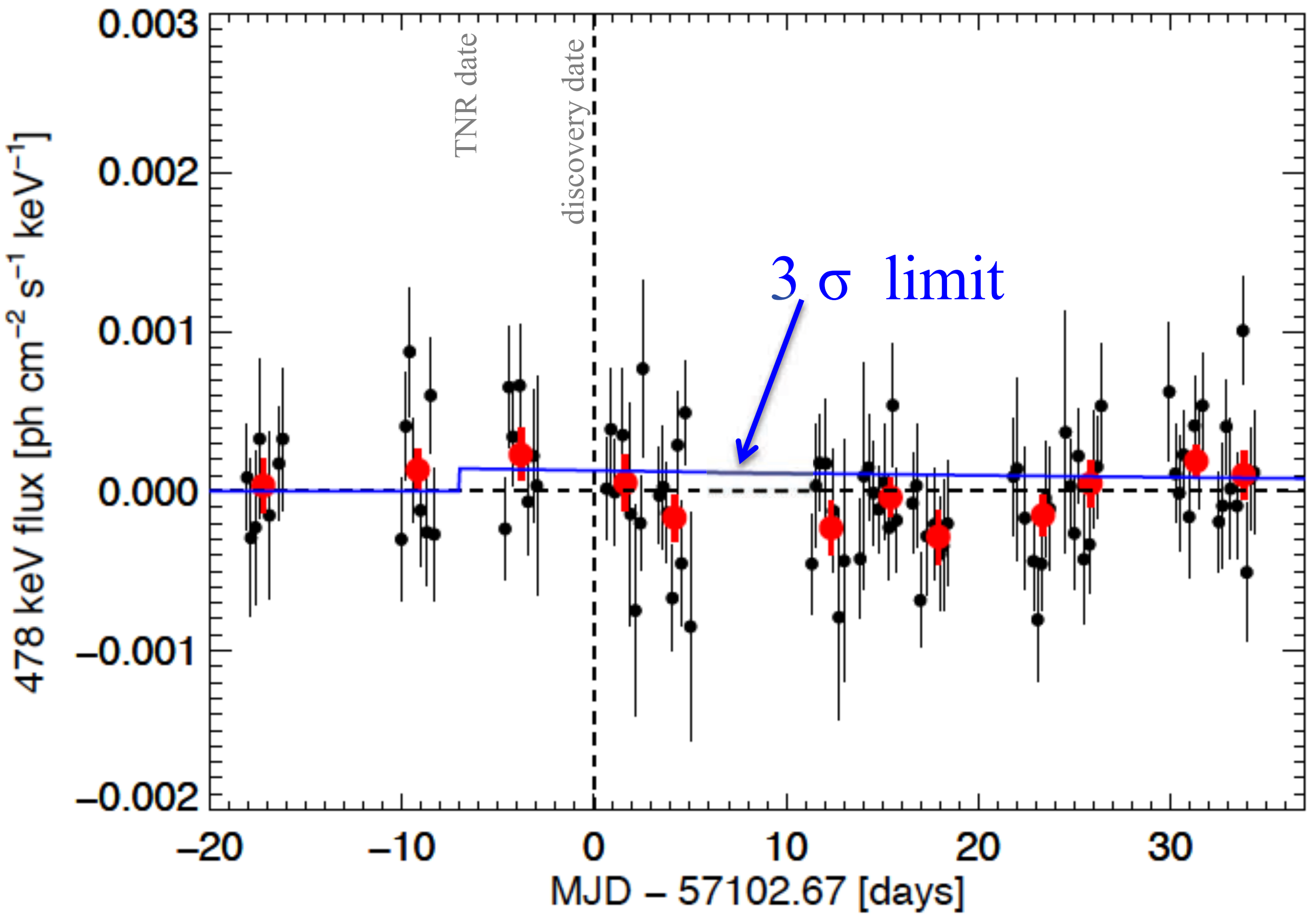
Siegert+2018



Be line limits on a nova from SPI/INTEGRAL

☞ Nova Sgr 2015 (V5668), opt max 21 Mar 2015

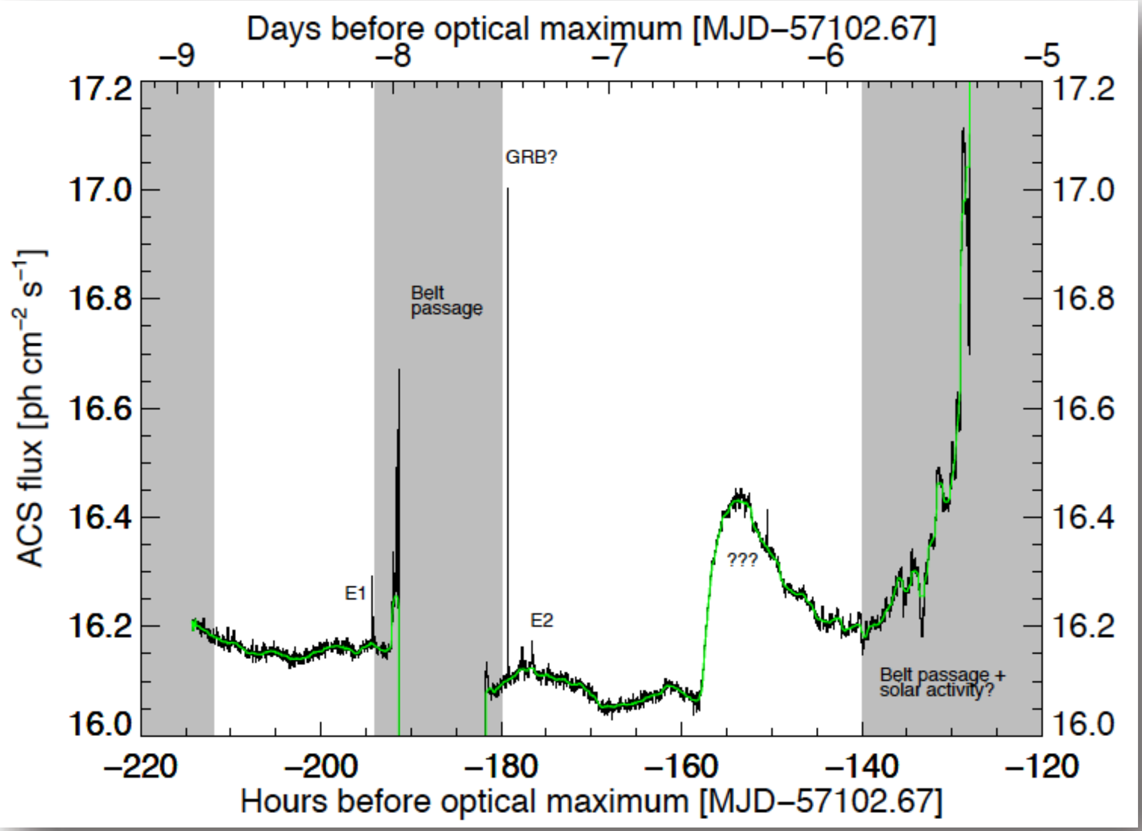
Siegert+2018

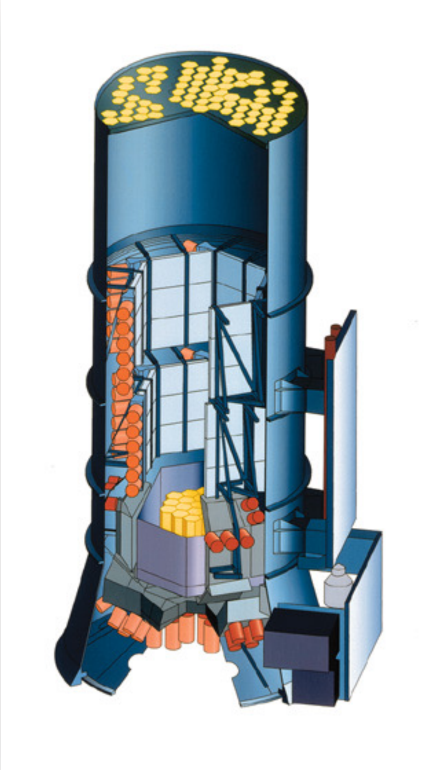


Pre-nova flash from β^+ decays?

- Searching the INTEGRAL/SPI database in SPI ACS
  - ☞ Nova V5668 Sgr:

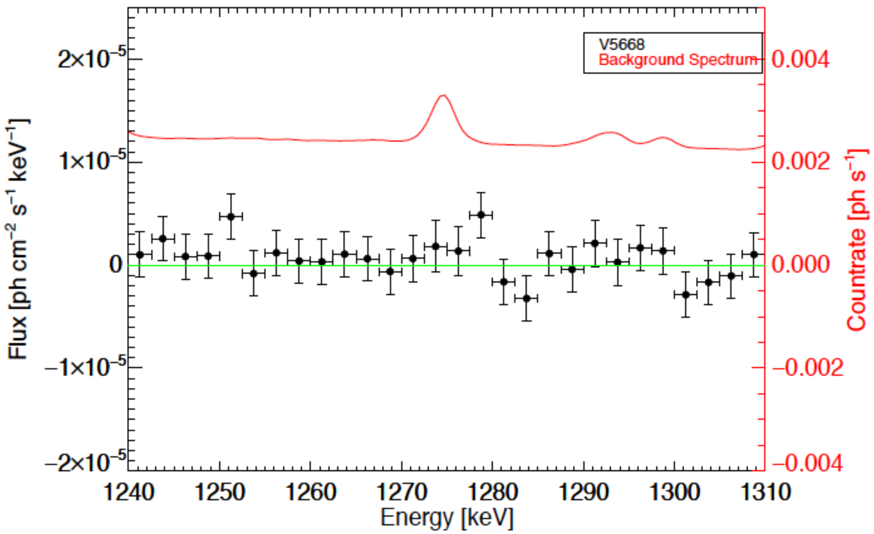
Siegert+2018

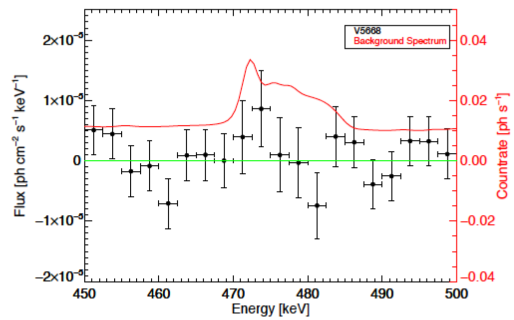


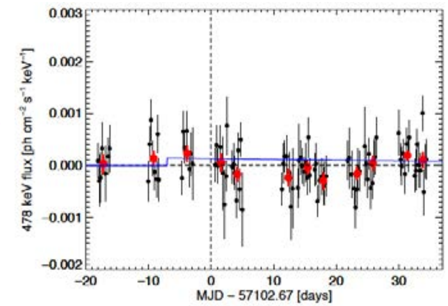


Summary: Nucleosynthesis gamma-ray lines from a nova?

- Search in INTEGRAL/SPI Ge detector data:

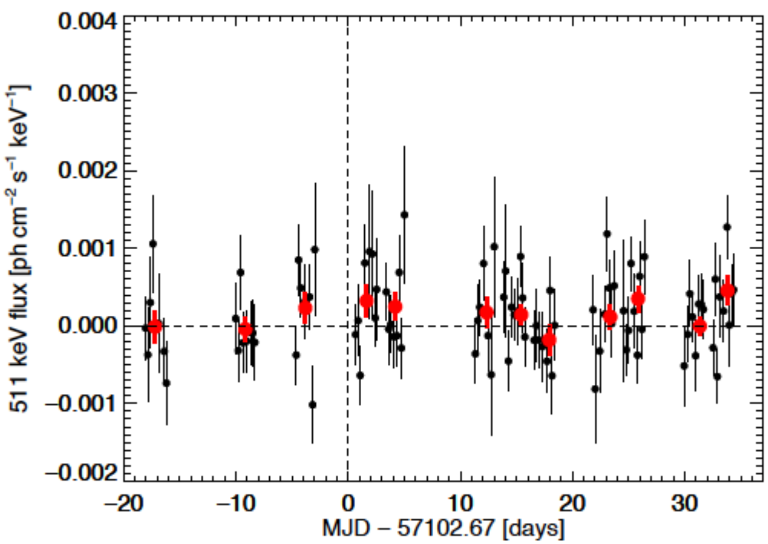






$$M_{3\sigma}^{7\mathrm{Be}} < 4.8 \times 10^{-9} \left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$

$$M_{3\sigma}^{22\mathrm{Na}} < 2.4 \times 10^{-8} \left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$



	Flux (spectrum)	Mass (spectrum)	Mass (light curve)
^{7}Be	$< 8.2 \times 10^{-5}$	$< 4.8 \times 10^{-9}(d/\mathrm{kpc})^2$	$< 6.4 \times 10^{-9}(d/\mathrm{kpc})^2$
^{22}Na	$< 7.6 \times 10^{-5}$	$< 2.4 \times 10^{-8}(d/\mathrm{kpc})^2$	-
	Flux (spectrum)	Annihilation rate	
$e^+ + e^- \to 2\gamma$	$< 17 \times 10^{-5}$	$< 4 \times 10^{40}$	
	From spectrum	From light curve	
Distance	> 1.1	> 1.2	

Siegert+2018

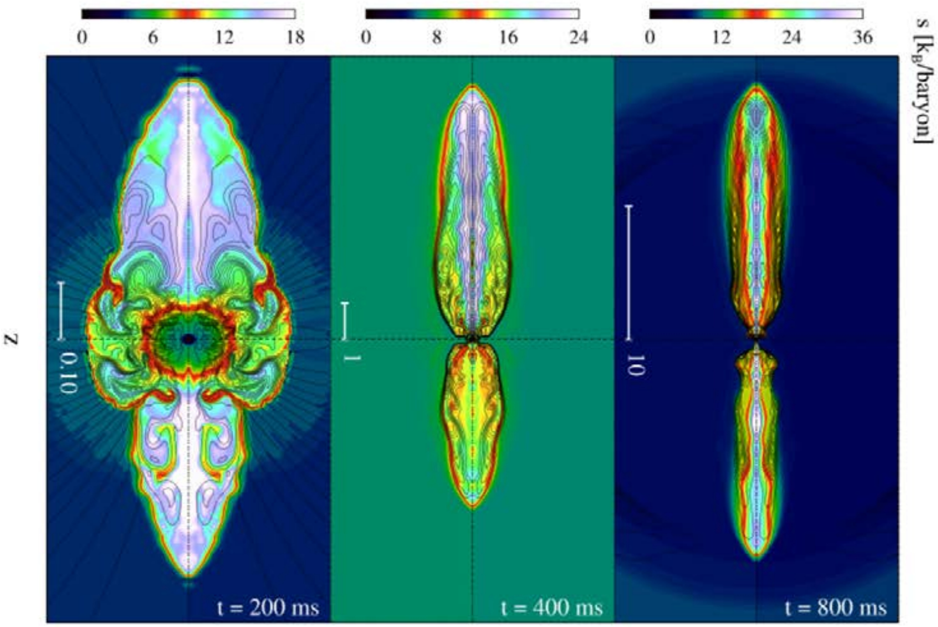
Sources which may realise the 'r process'

neutron star matter includes high-A nuclei and neutrons

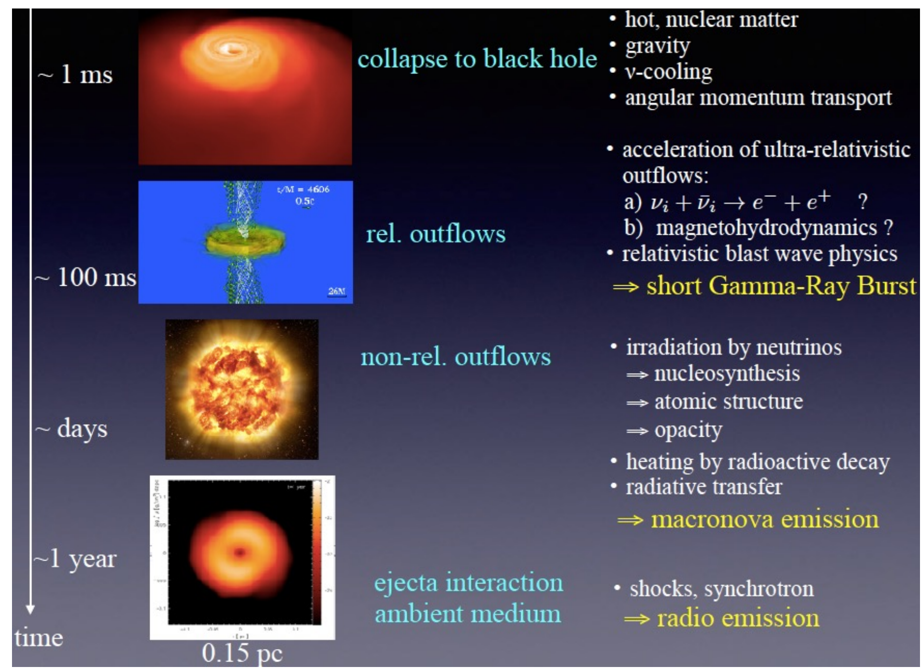
an explosive trigger will likely include nuclear reactions

→

core-collapse supernova (high-entropy jets) | binary neutron star collision (merger)



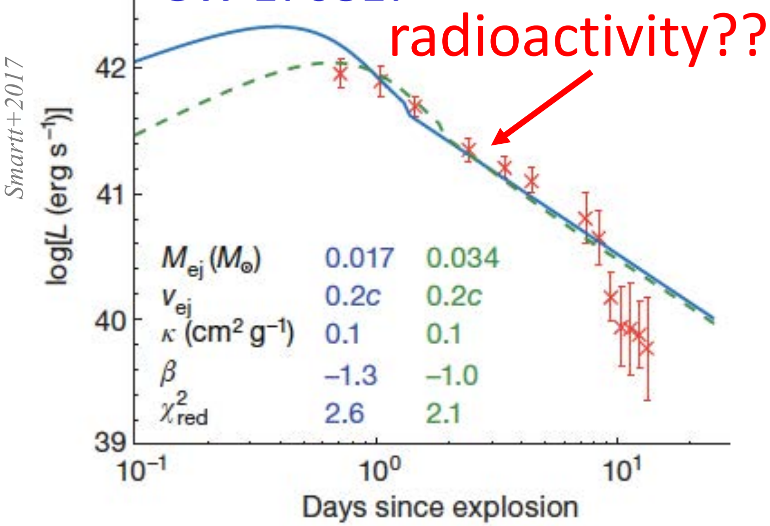
Obergaulinger & Alloy 2020

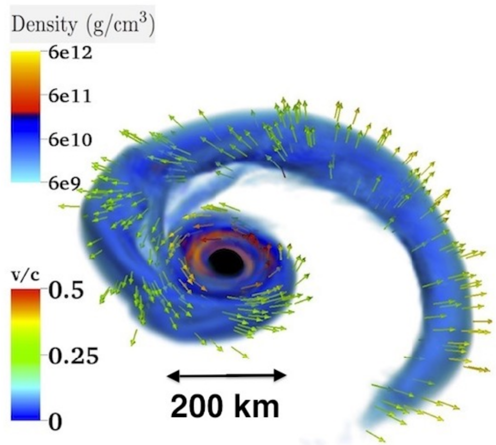


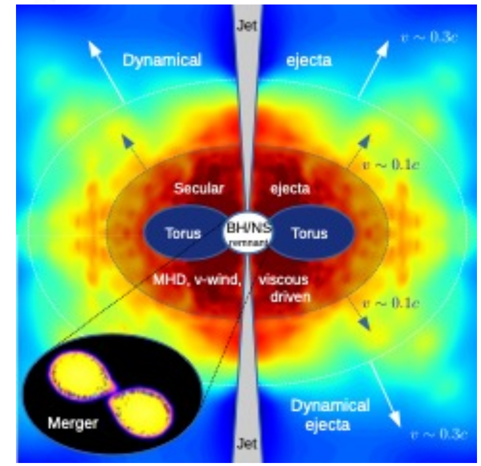
courtesy Stephan Roswog

Neutron star collisions: explosive nucleosynthesis

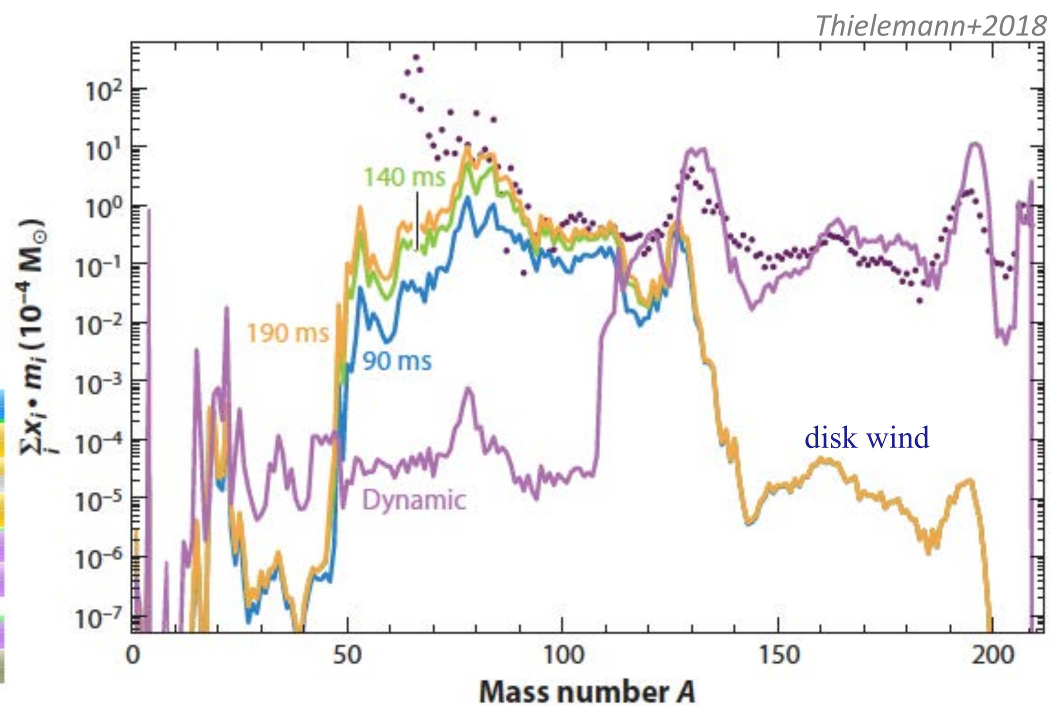
The expected "kilonova" was seen after a unique gravitational-wave signal GW 170817





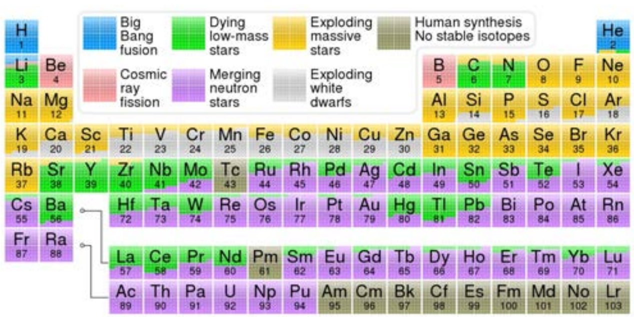


Elemental yields reminiscent of r-process pattern



great enthusiasm...

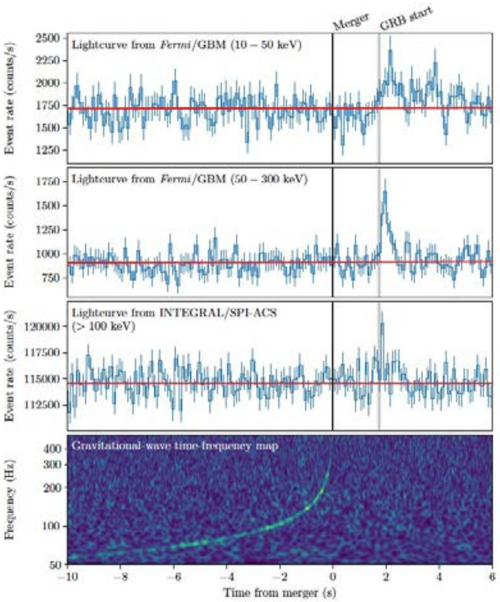
very rare events!

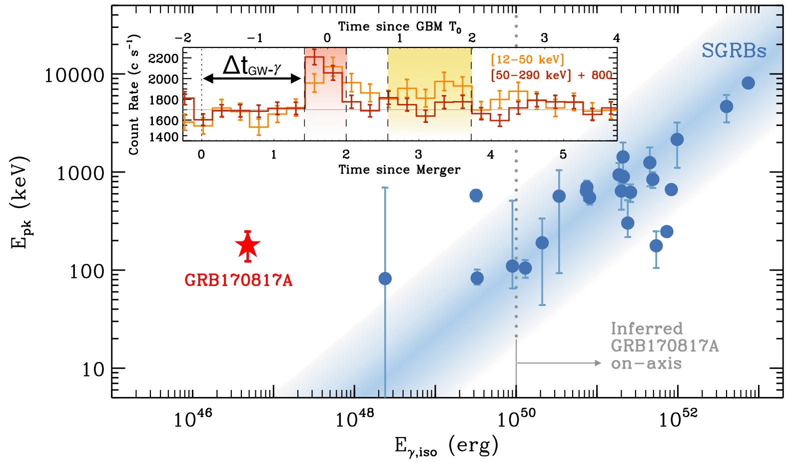


GW170817 / AT2017gfo

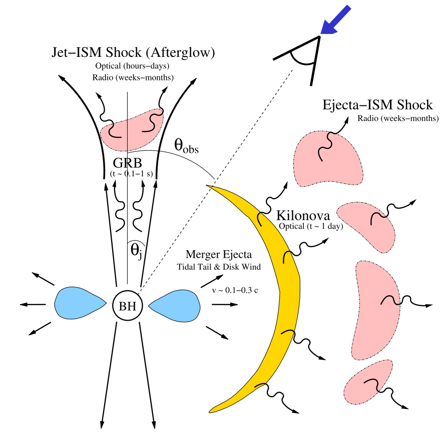
gravitational-wave & γ-ray burst triggered multi-band follow-up of NSM

Abbott+2017; Goldstein+2017; Savchenko+2017

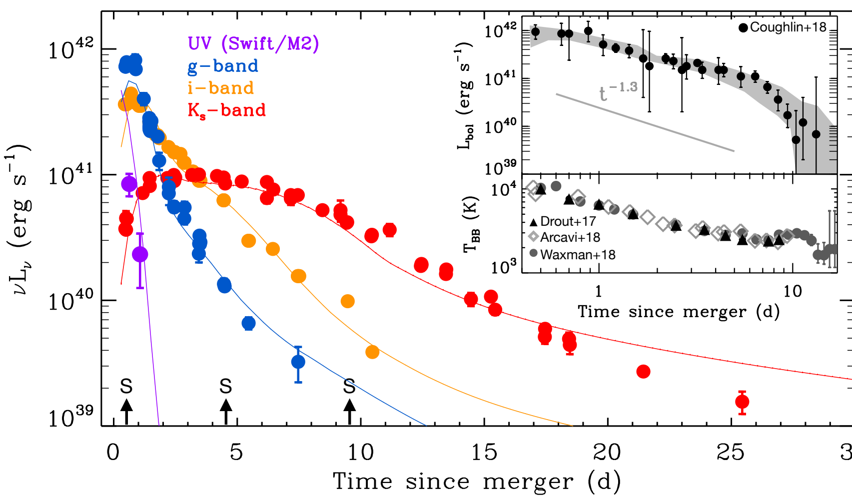




lucky coincidence: seeing a weak sGRB from a large aspect angle

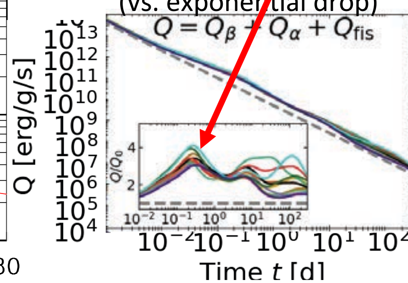


Margutti+2021



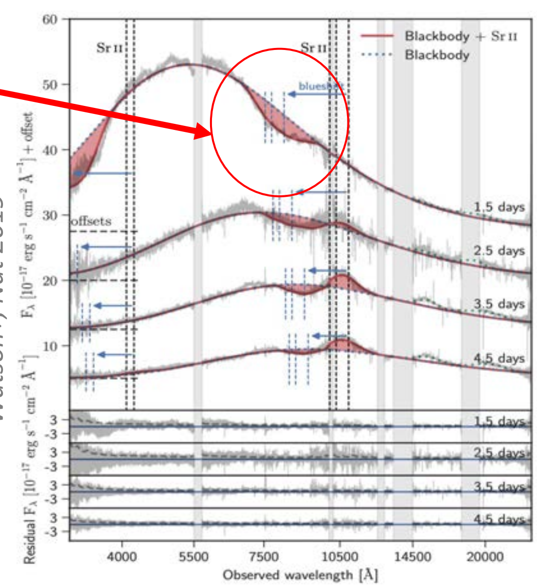
r process synthesis (Sr)?

radioactive heating (vs. exponential drop)



Kullmann+2022

Watson+, Nat 2019

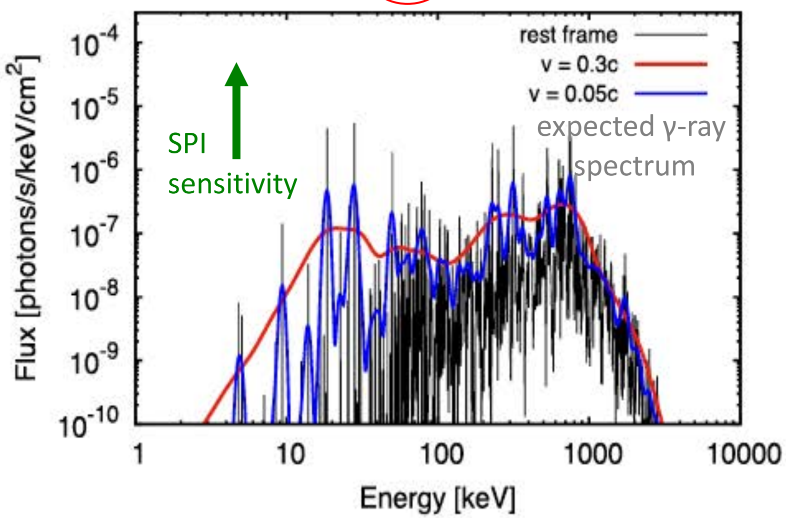


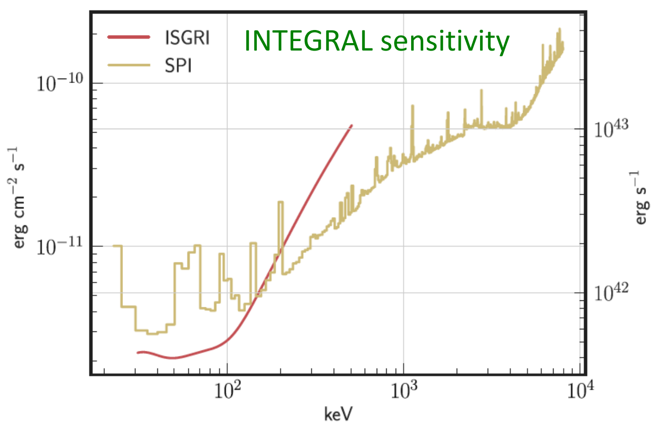
γ-ray line diagnostics of characteristic nuclear lines

GW170817 was too distant! (other NSMs will be even more...)

Hotokezaka+ 2016

INTEGRAL 1day, 3Mpc, 0.01Msun

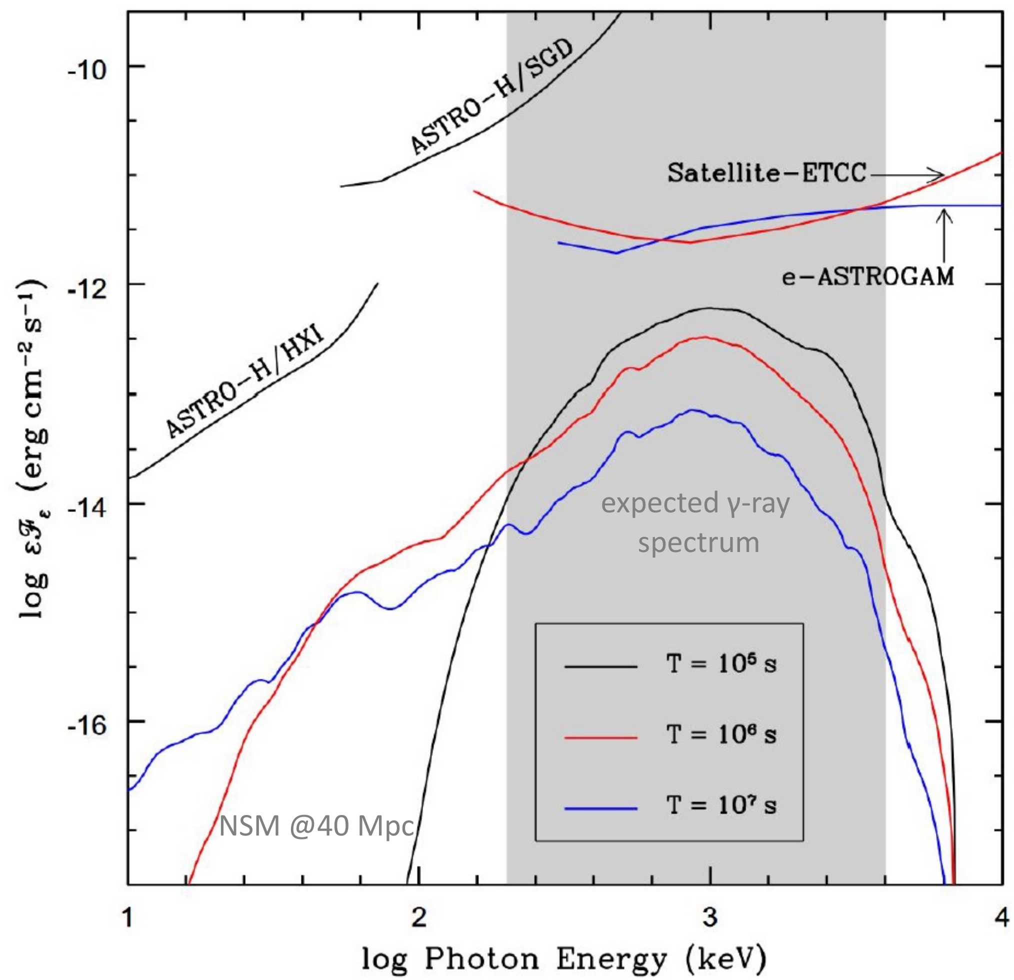




Savchenko et al. 2017

other instruments

Li+ 2018



Exotic supernovae: Opportunities for MeV diagnostics

Hypernovae:

- ☆ from very massive stars
- ☆ additional energy source: circumstellar-medium interactions
- ☆ constraints on radioactive ('normal-SN-) energy from ^{56}Ni

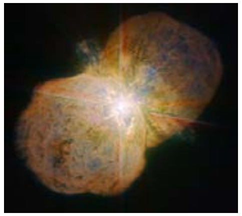
Pair instability supernovae:

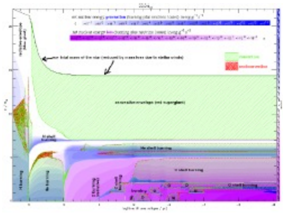
- ☆ pair creation from γ-γ interactions in hot stellar core for $M > 70 M_{\odot}$
- ☆ pulsations → large envelope releases, high amounts of ^{56}Ni (several $M_{\odot}$)
- ☆ disruption of entire star for $M > 140 M_{\odot}$

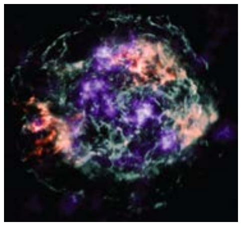
Magnetic-jet Supernovae:

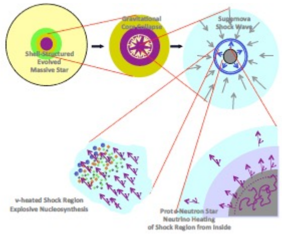
GRB-supernovae:

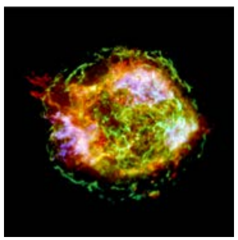
The Challenges

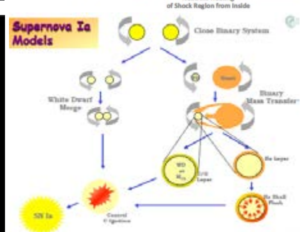


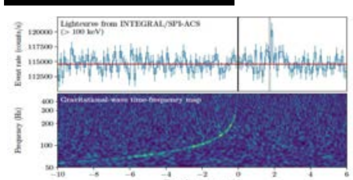


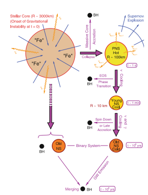




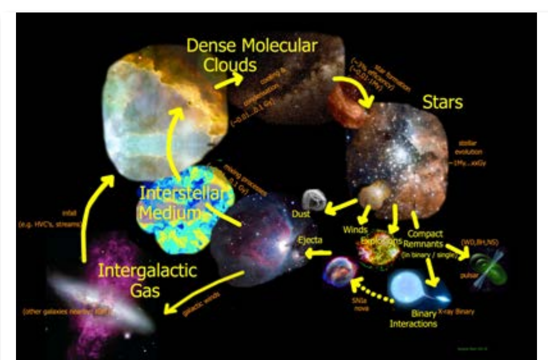






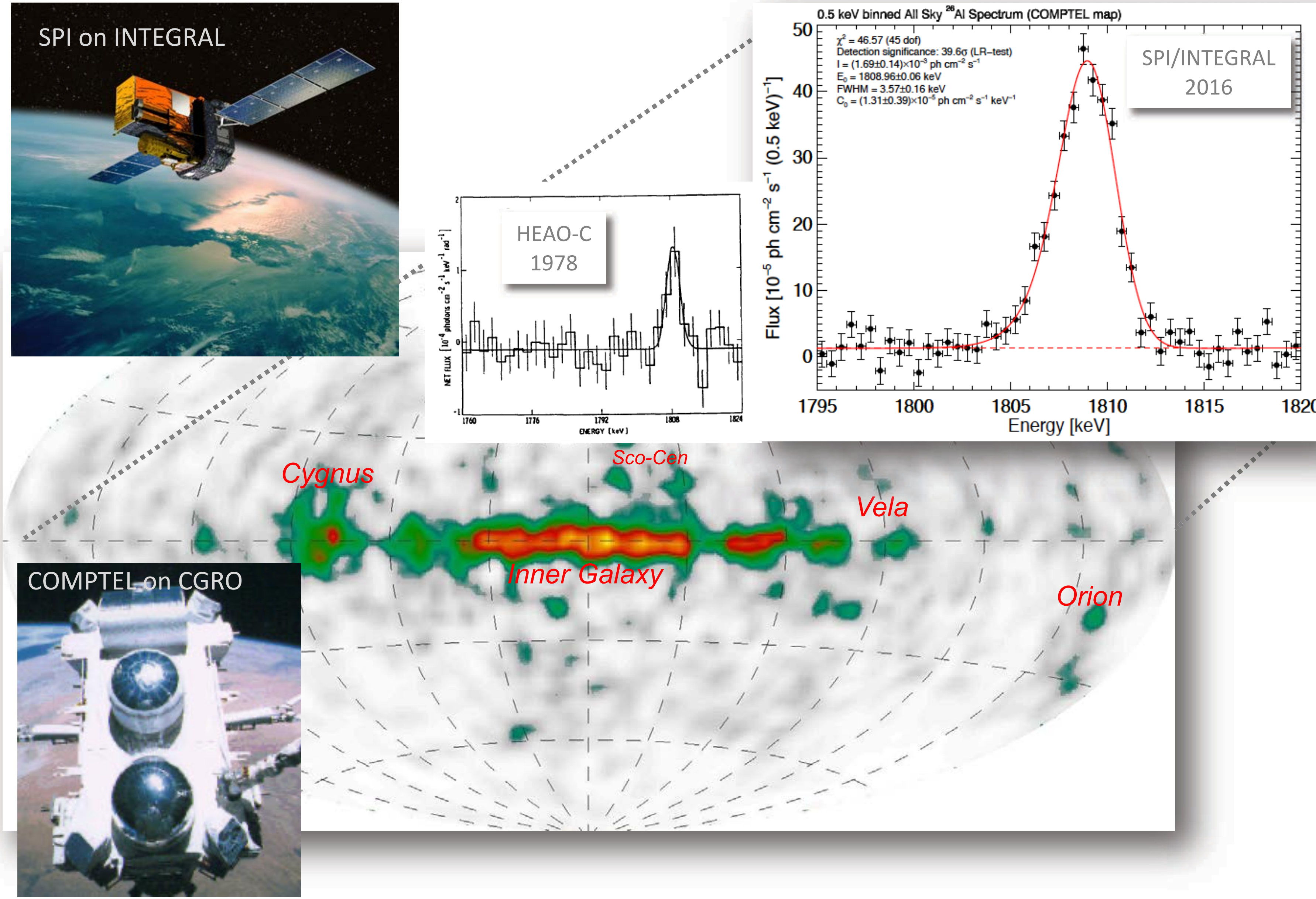


☆Understand the sources of new nuclei



☆Trace the flows of cosmic matter

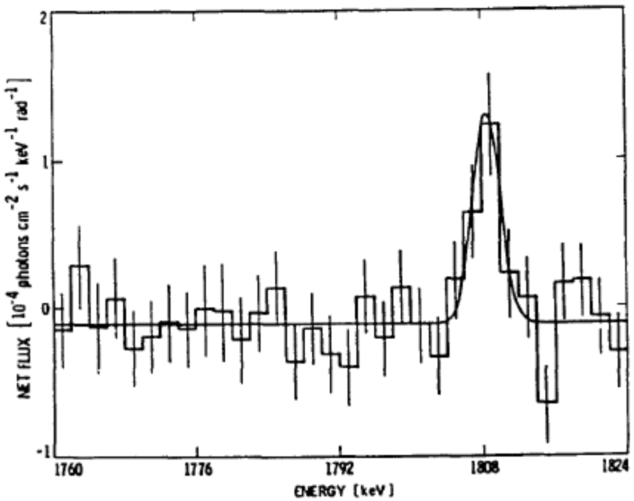
^{26}Al γ-rays from the Galaxy

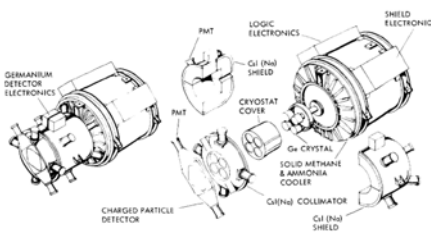


Radio-Isotopes with ~My lifetimes: ^{26}Al , ^{60}Fe

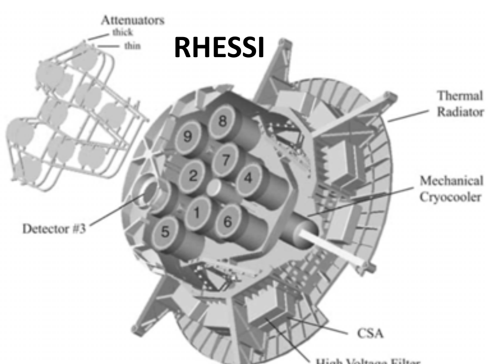
Discoveries

Mahoney+1982

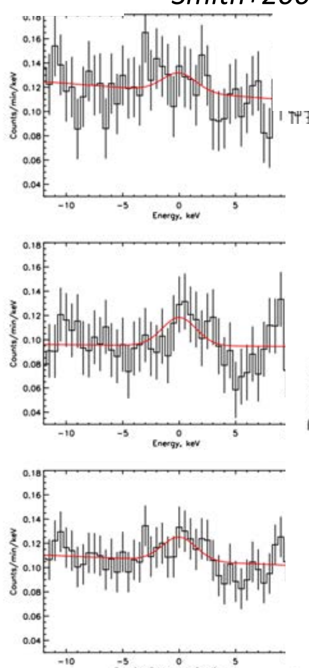




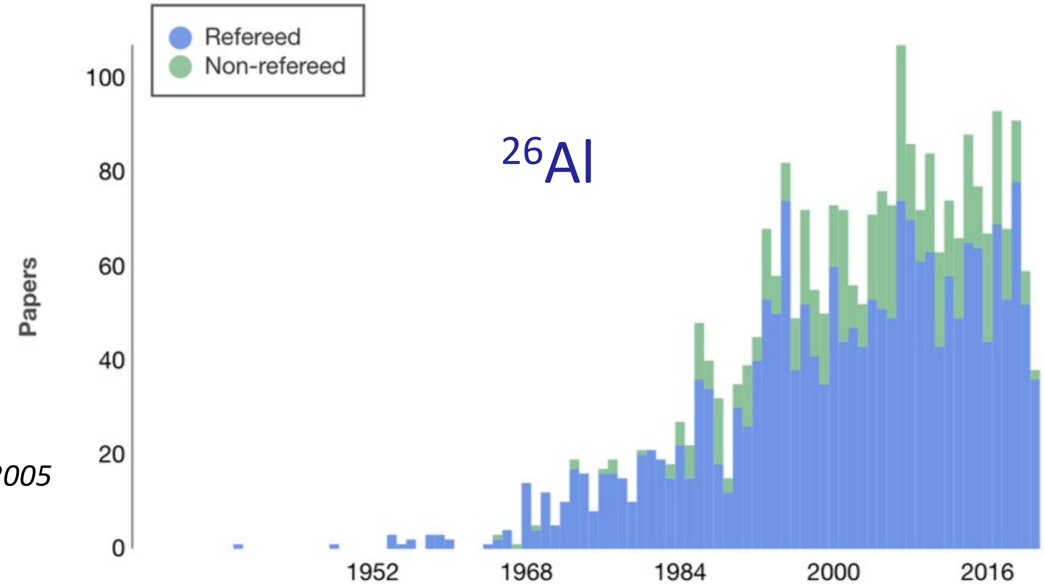
HEAO-C

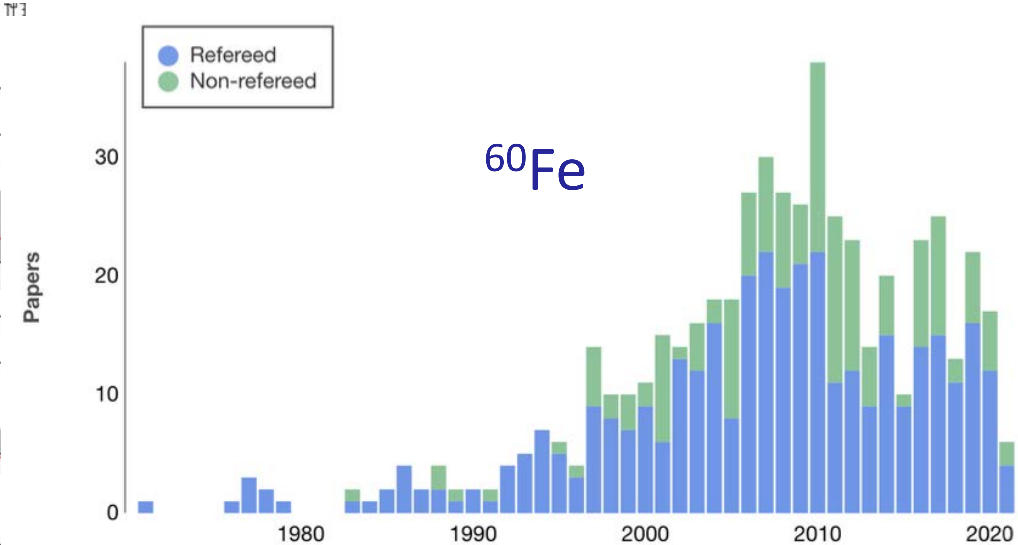


Smith+2005

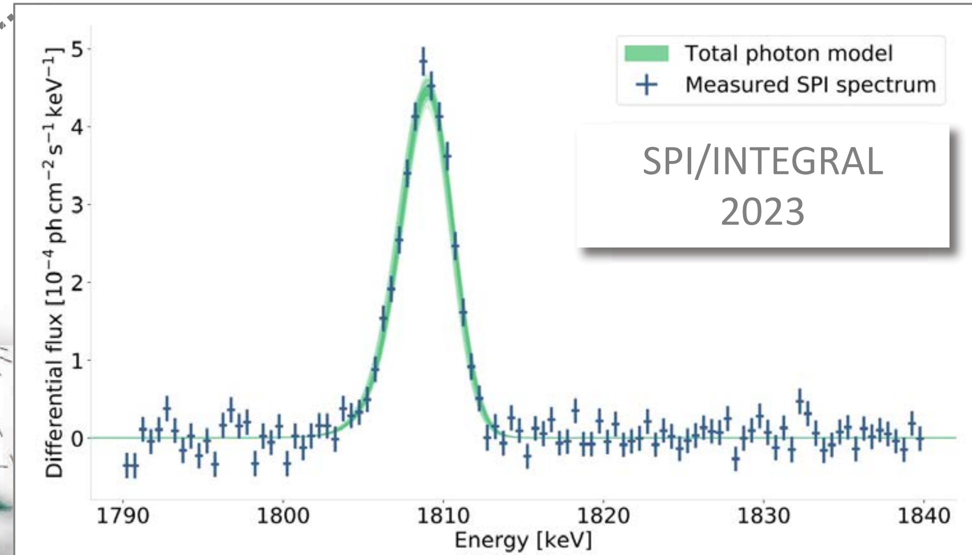


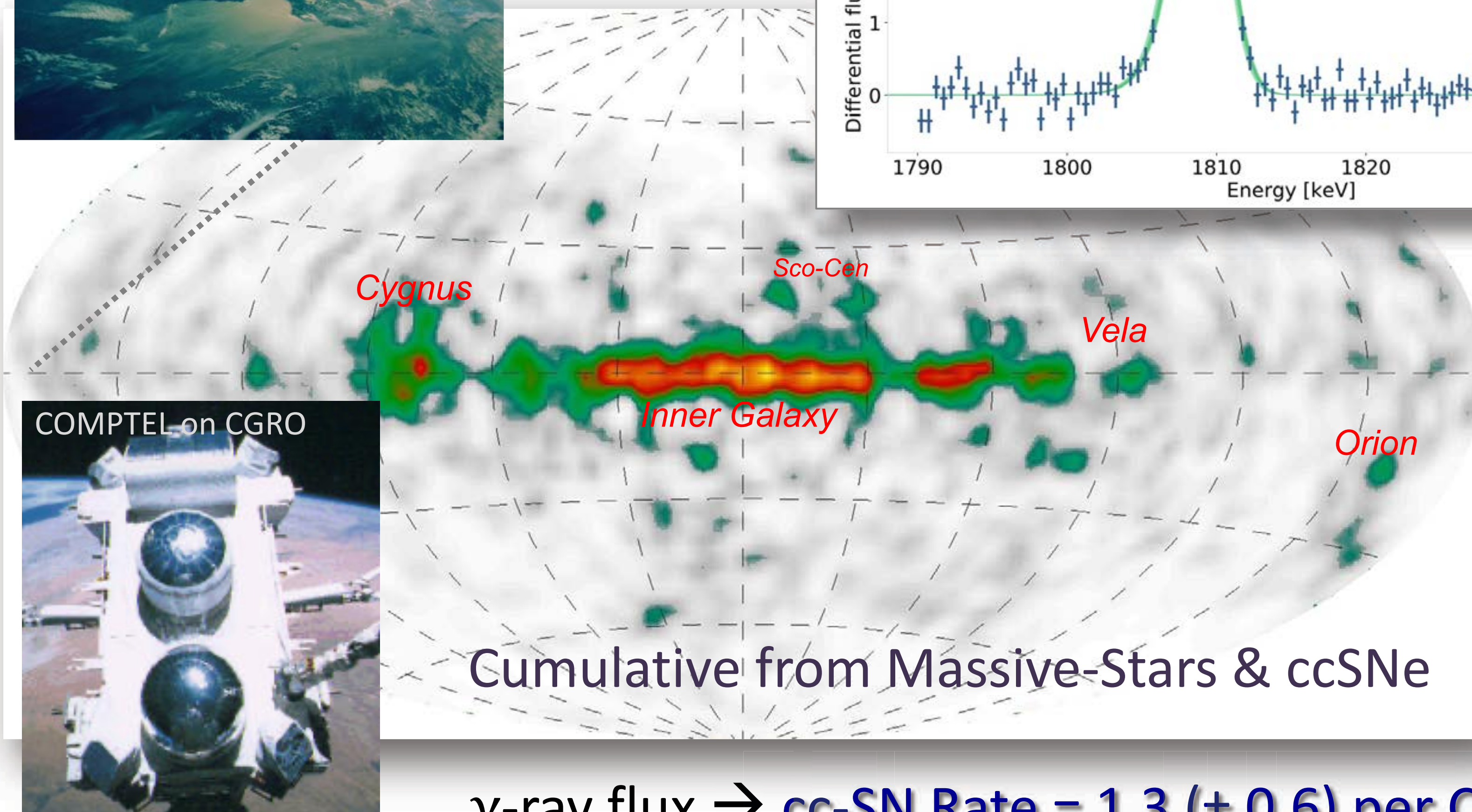
Temporal evolution of studies





^{26}Al γ-rays and the galaxy-wide massive star census

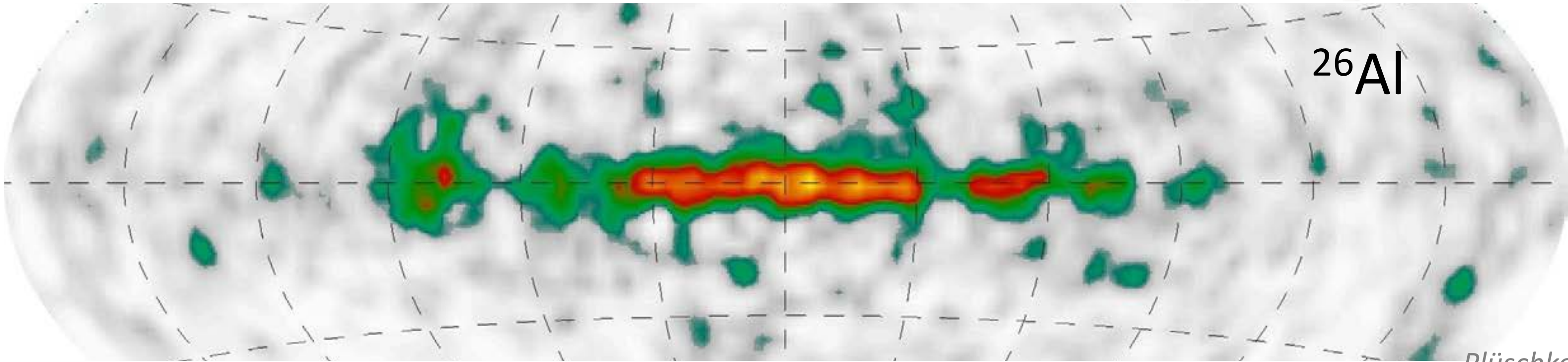




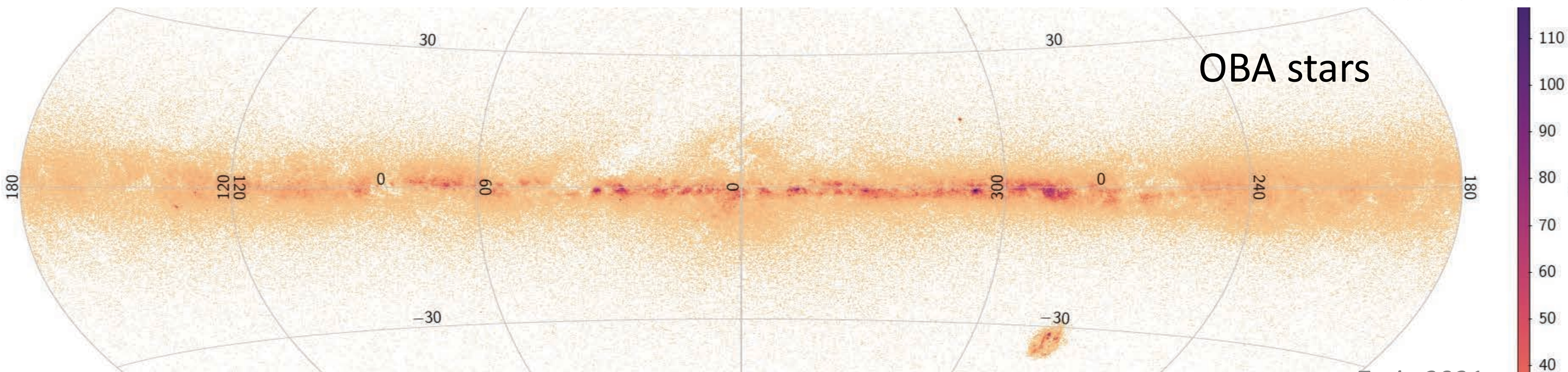
γ-ray flux → **cc-SN Rate = 1.3 (± 0.6) per Century**

Diehl+2006;2018

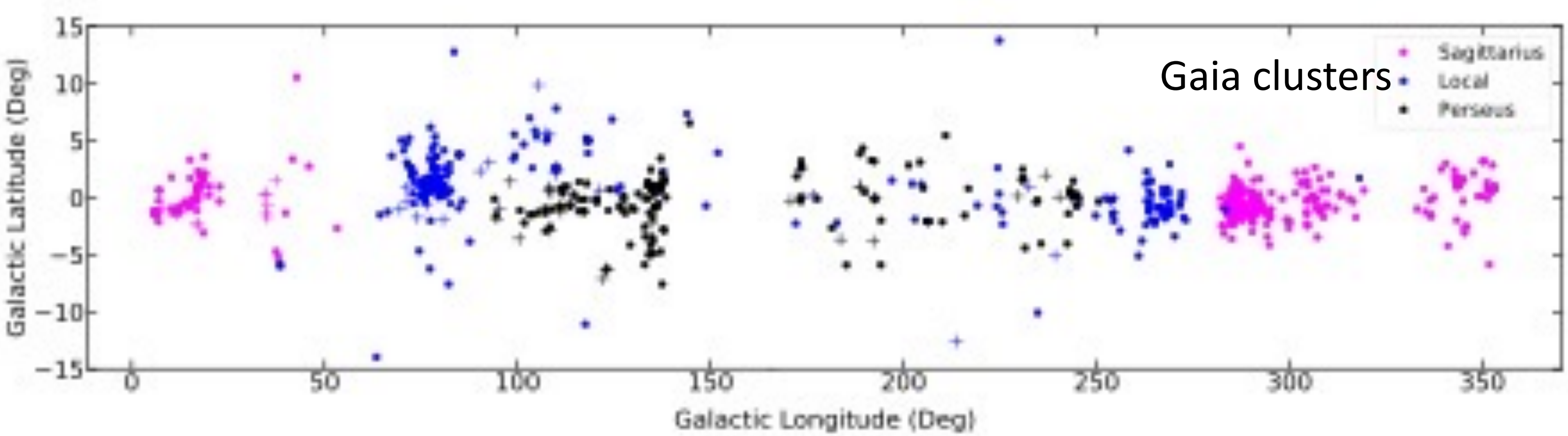
Massive stars and ^{26}Al radioactivity (τ≃1 My)



Plüschke+ 2001



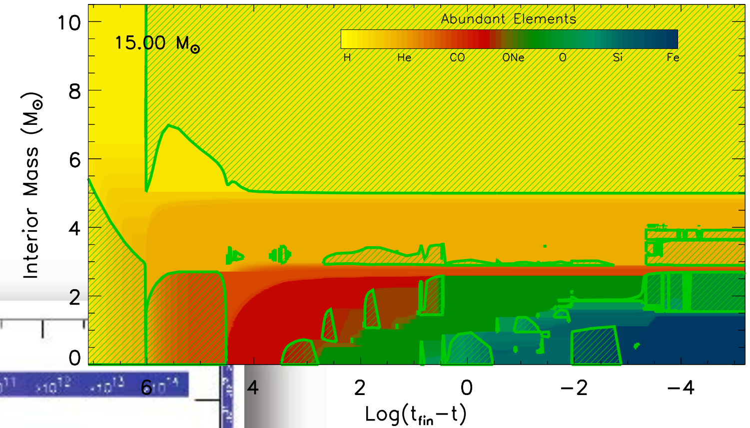
Zari+ 2021



Xu+ 2021

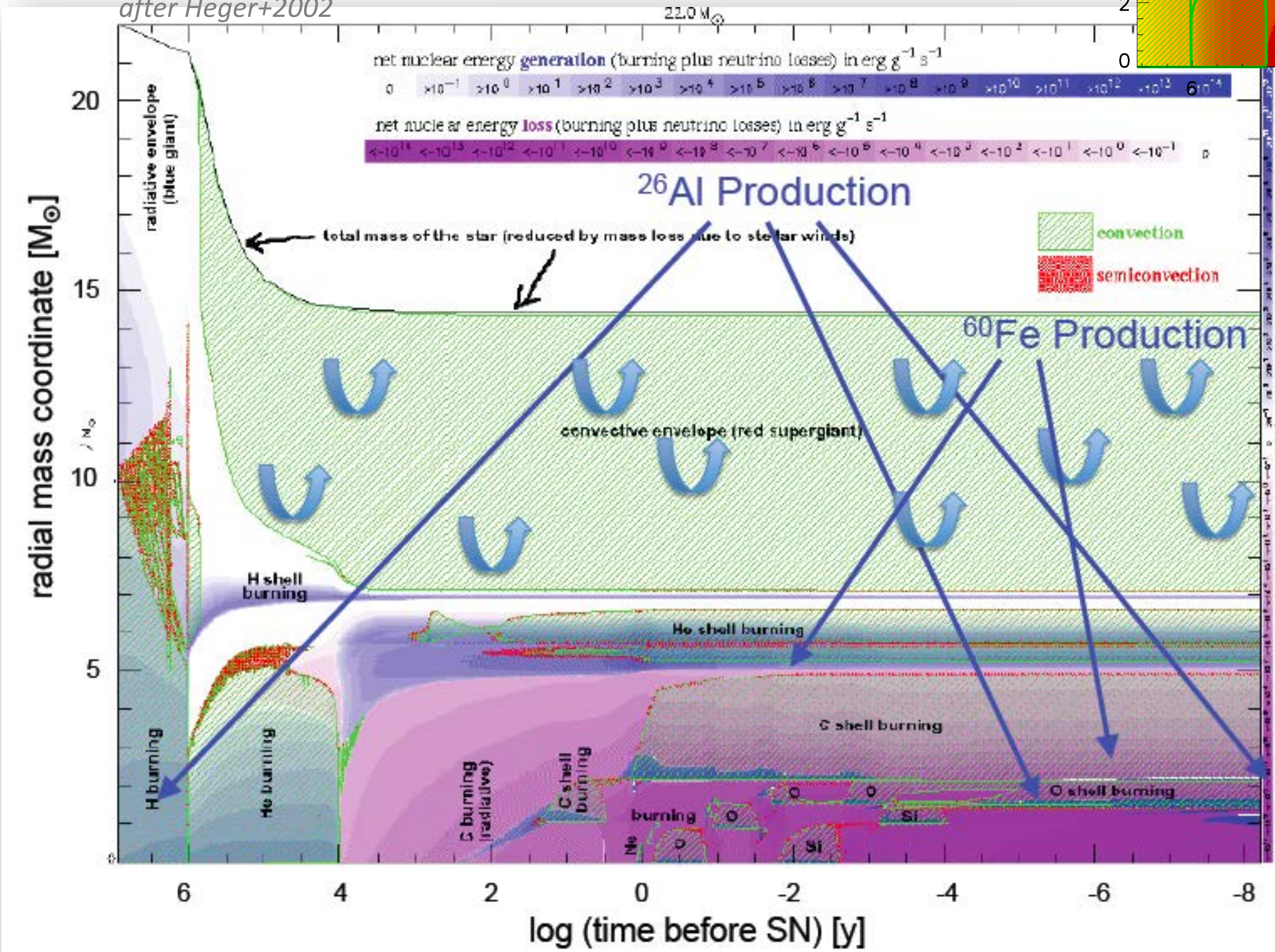
Limongi+2024

^{26}Al Radioactivity from massive stars



Stellar evolution modeling ('Kippenhahn diagrams")

after Heger+2002



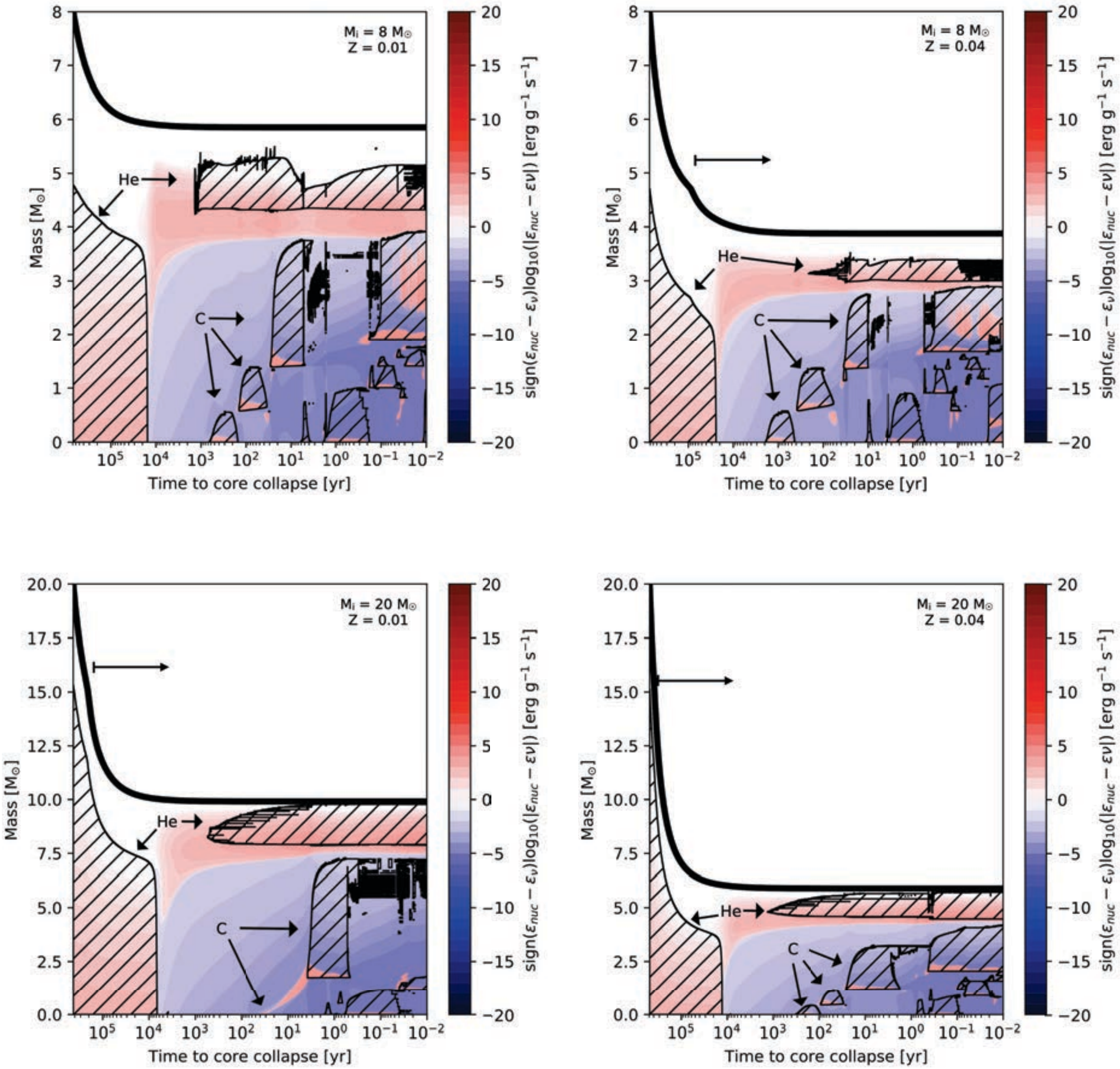
Processes:

- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*

Complexities of late stellar evolution

example: giant and pre-SN evolution in stripped-envelope stars

Aguilera-Dena+2022



stripping the envelope from binary interaction affects late stages

→ explosive yields affected!

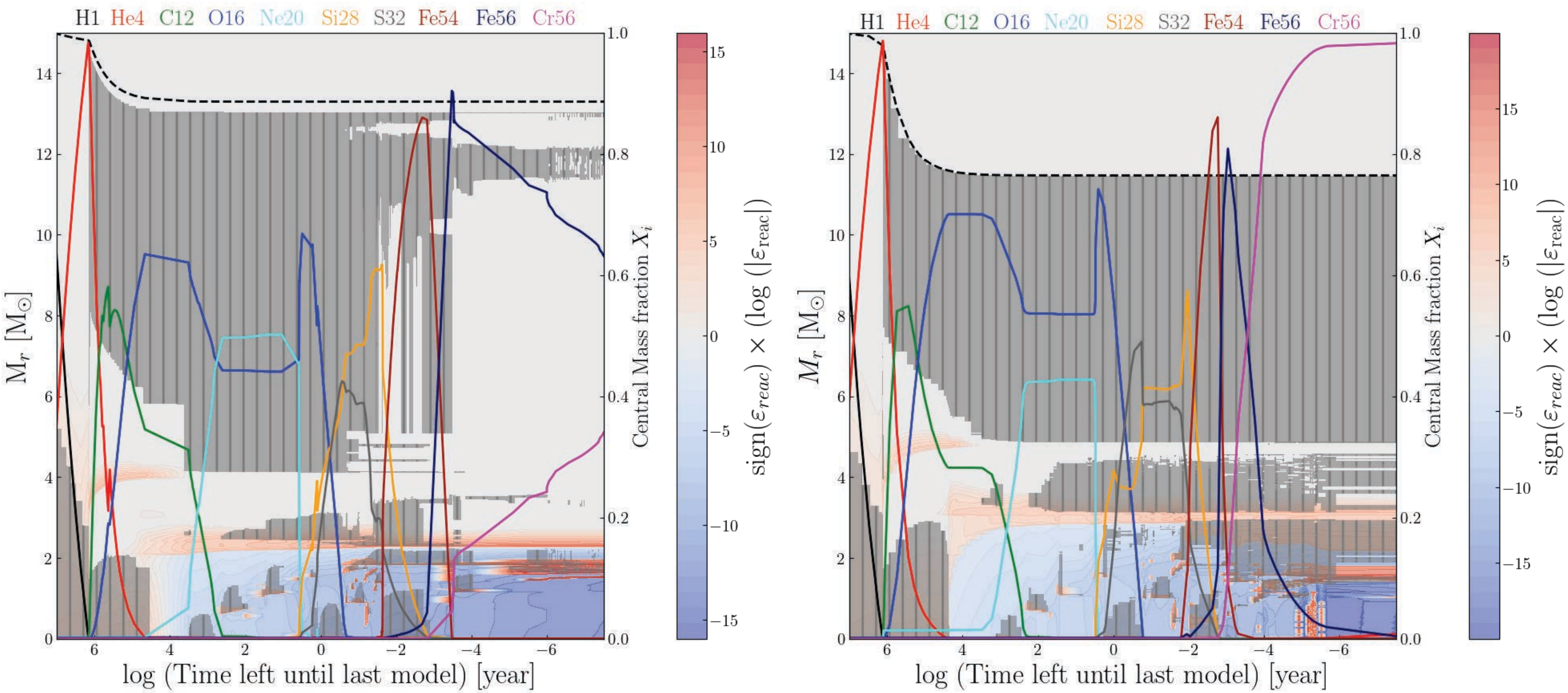
(not yet addressed, e.g., in Brinkman+2019)

Uncertainties in evolution of massive-star structure

('Kippenhahn' diagrams)

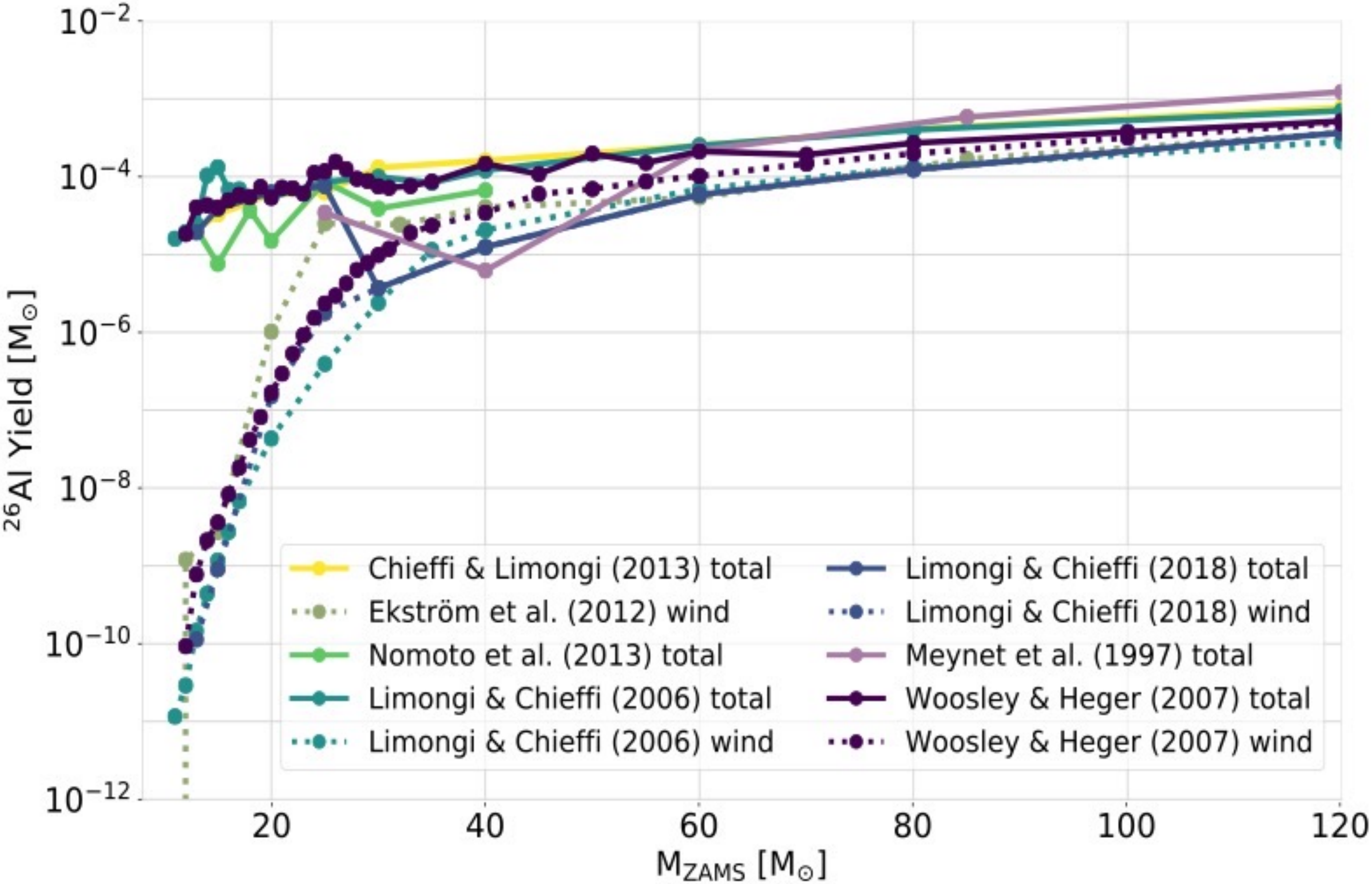
15 $M_\odot$ 2 codes/models (1D)

GENEC MESA *Griffiths+2025*



- the challenge of properly treating the 3D nature of mixing, specifically near shell boundaries

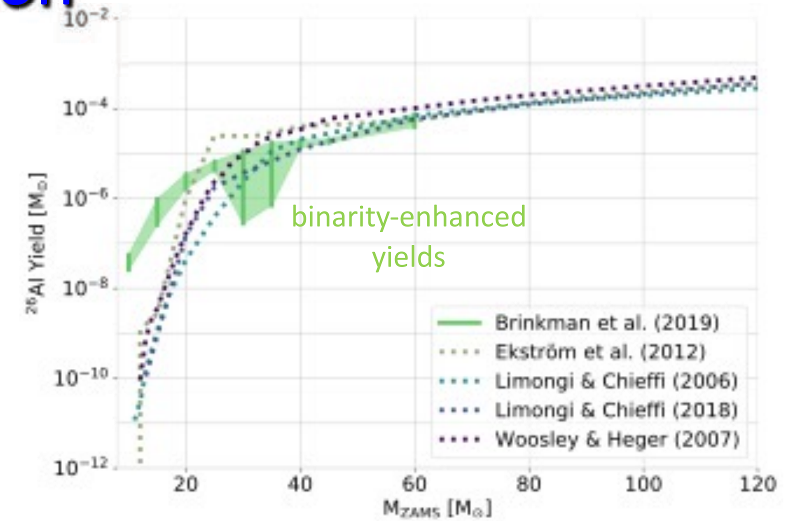
^{26}Al Yields versus mass, for massive stars and their SNe

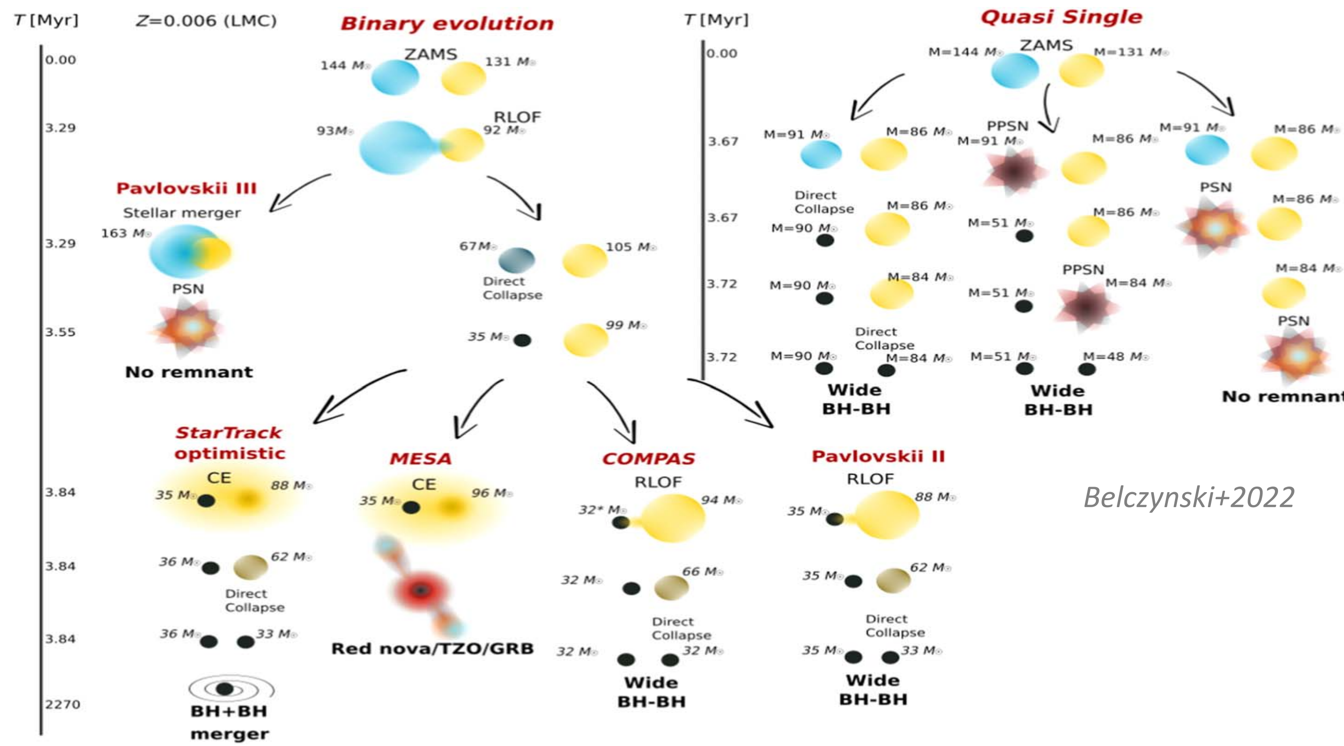


☞ ccSNe dominate for lower-mass range,
winds dominate over explosive ejecta for more-massive stars

Binary Evolution

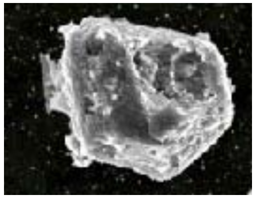
- For ^{26}Al, binary contributions are ~small/negligable
- Binary evolution is a highly complex topic, important for much of what we currently believe to know on stellar evolution...





Belczynski+2022

Sources of ^{26}Al: Results from Presolar Grains



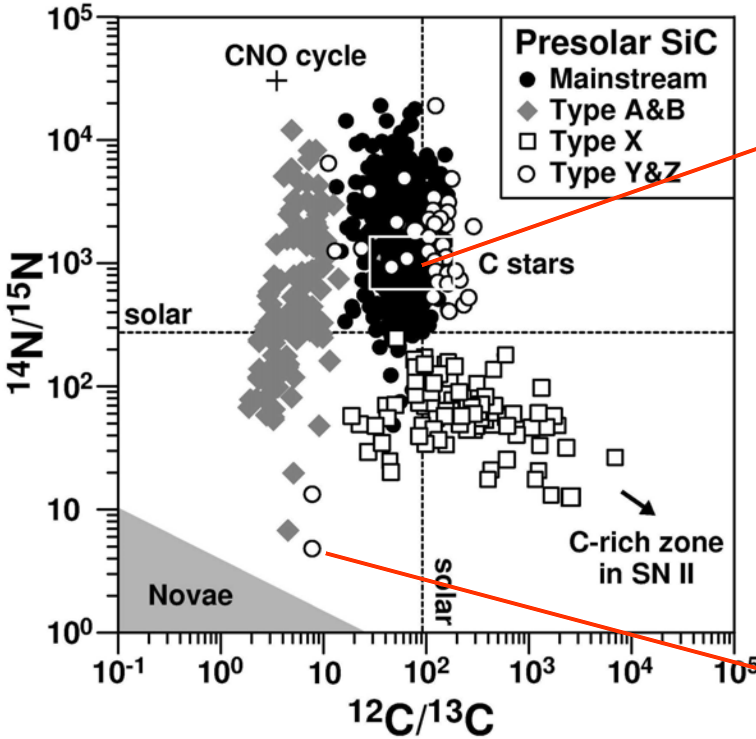
← 1 µm →

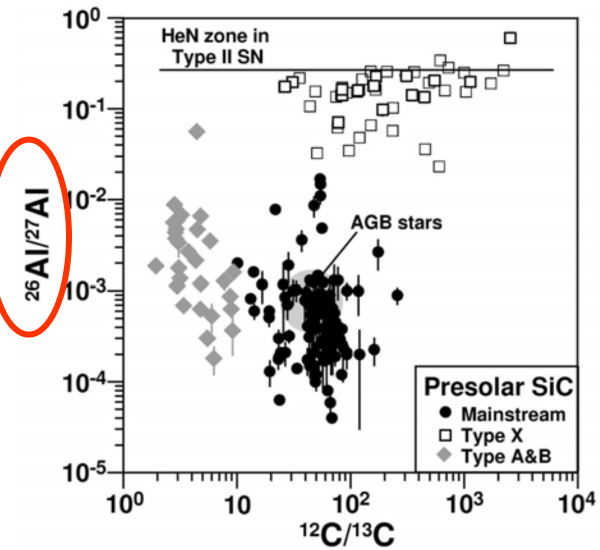
Isotopic Ratios in C,N,Si,…→ Source Type of Presolar Grain

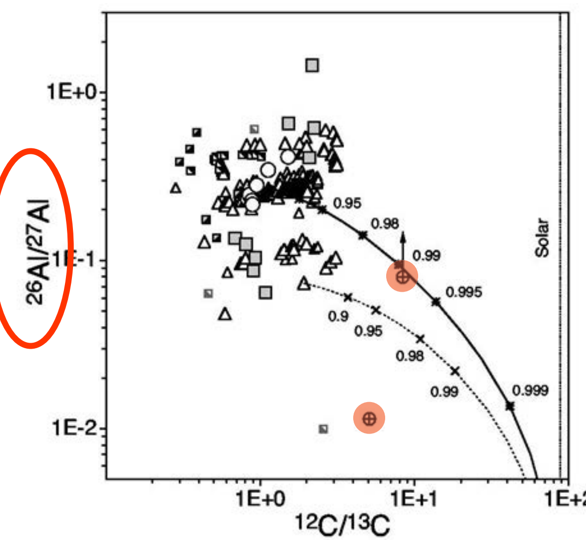
AGB Stars

Supernovae

Novae







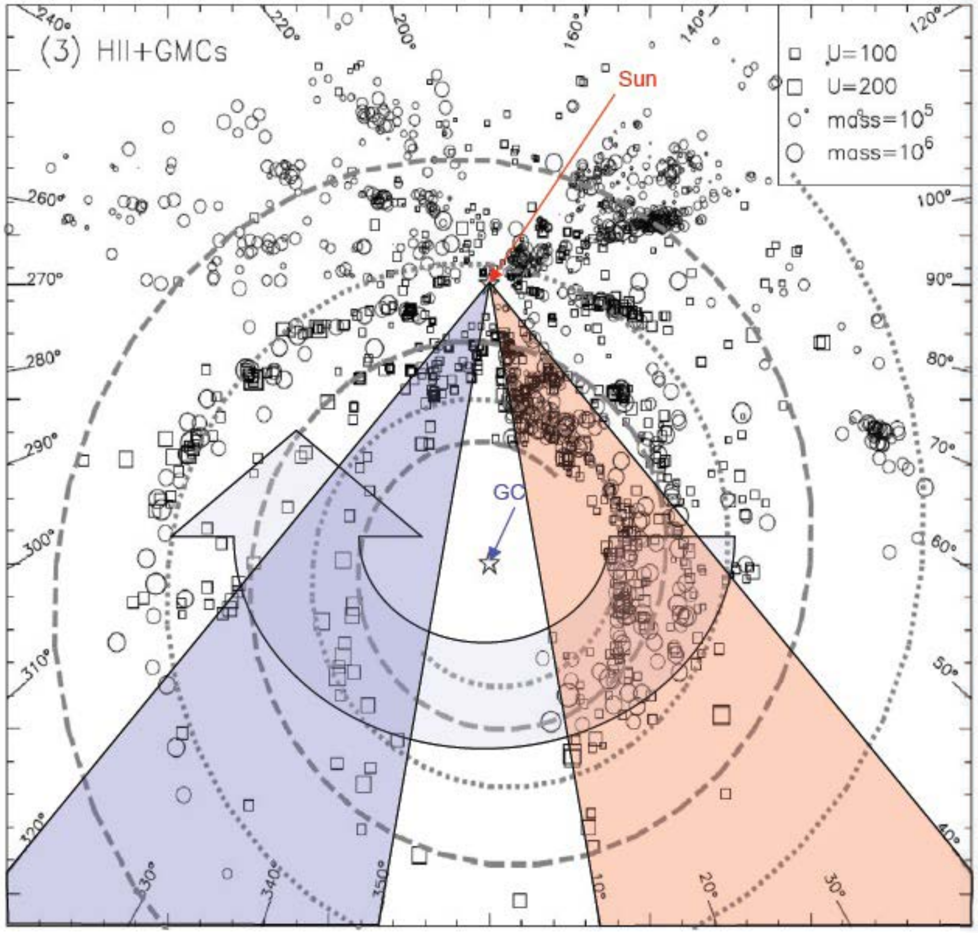
Amari, Nittler, Hoppe, Zinner, … et al.

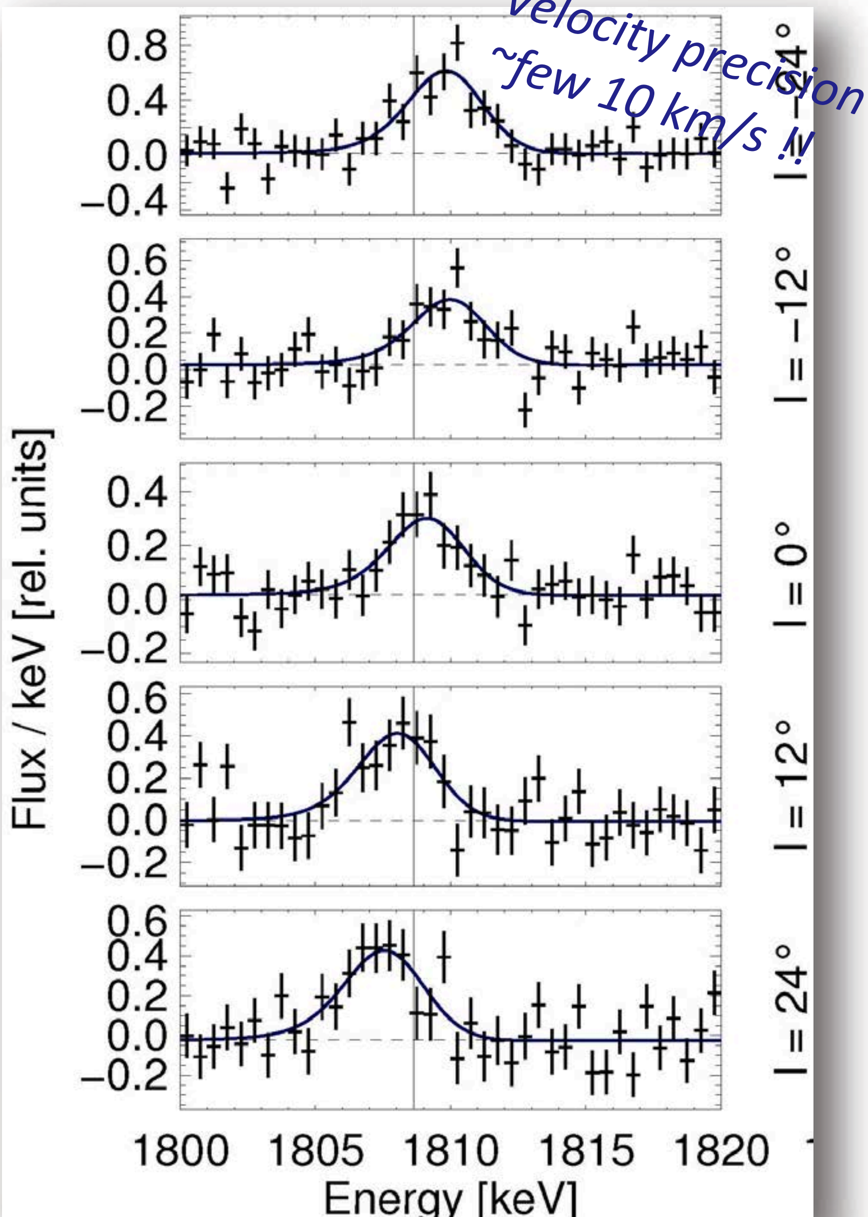
^{26}Al Found

in ~ALL Candidate Sources → what are yields per source type??

Massive Star Groups in our Galaxy: ^{26}Al γ-rays

☞ Large-scale Galactic rotation



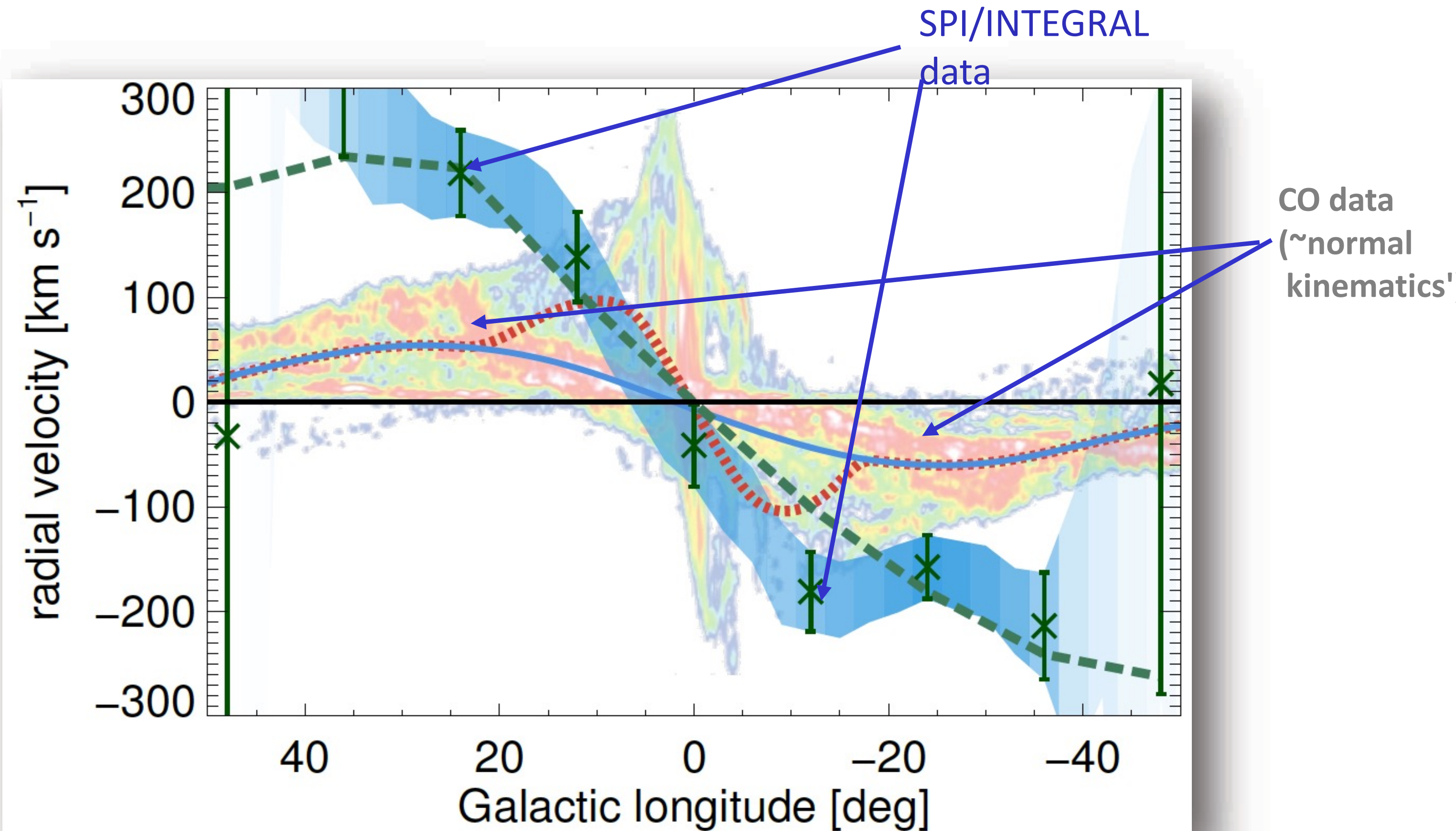


Kretschmer et al., A&A (2013)

How massive-star ejecta are spreading…

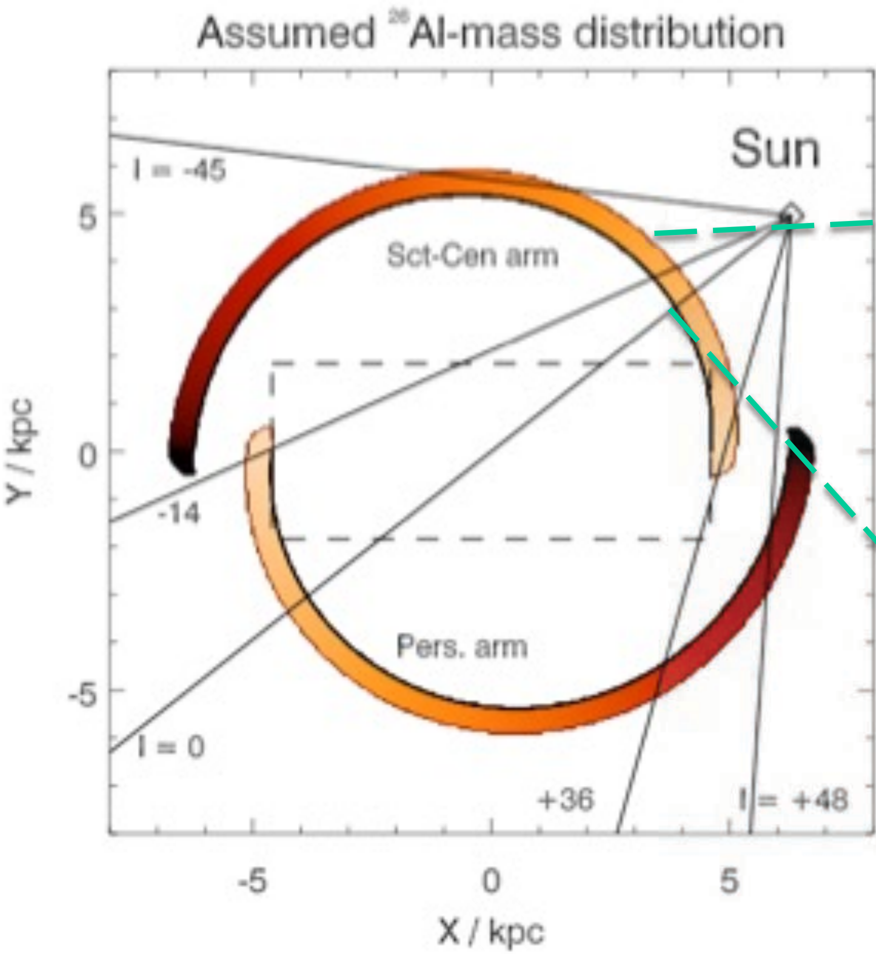
- ^{26}Al shows apparently higher galactocentric rotation (?)

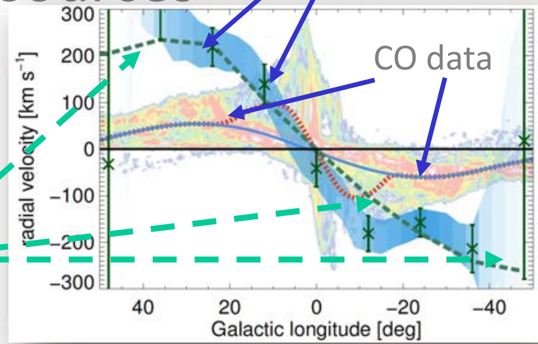
Kretschmer+(2013)



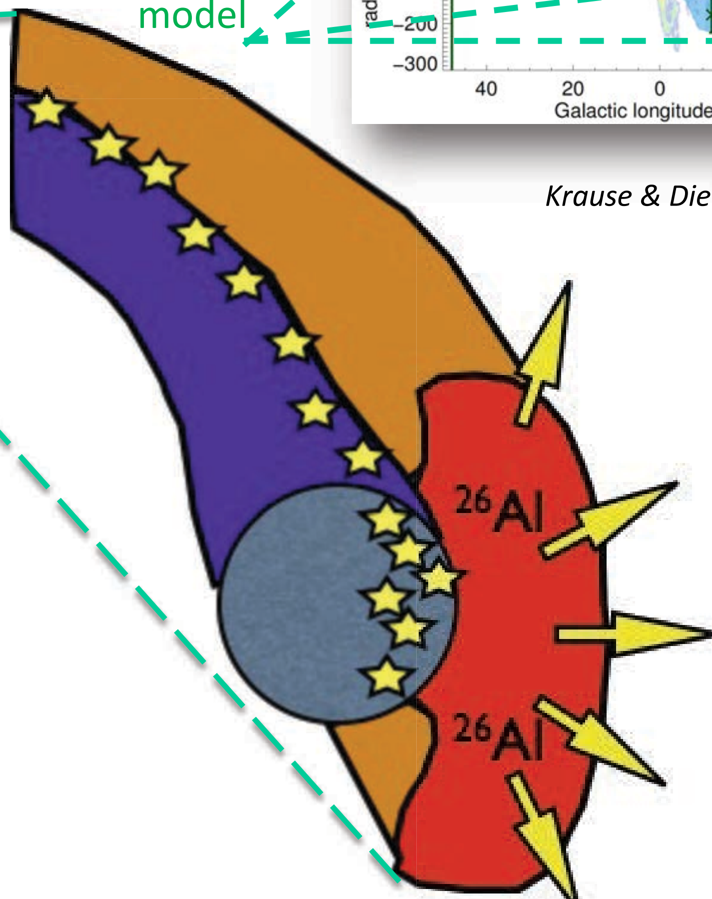
How massive-star ejecta are spreading…

- ^{26}Al shows apparently higher galactocentric rotation (?)
- ..blown into cavities that are asymmetric wrt sources

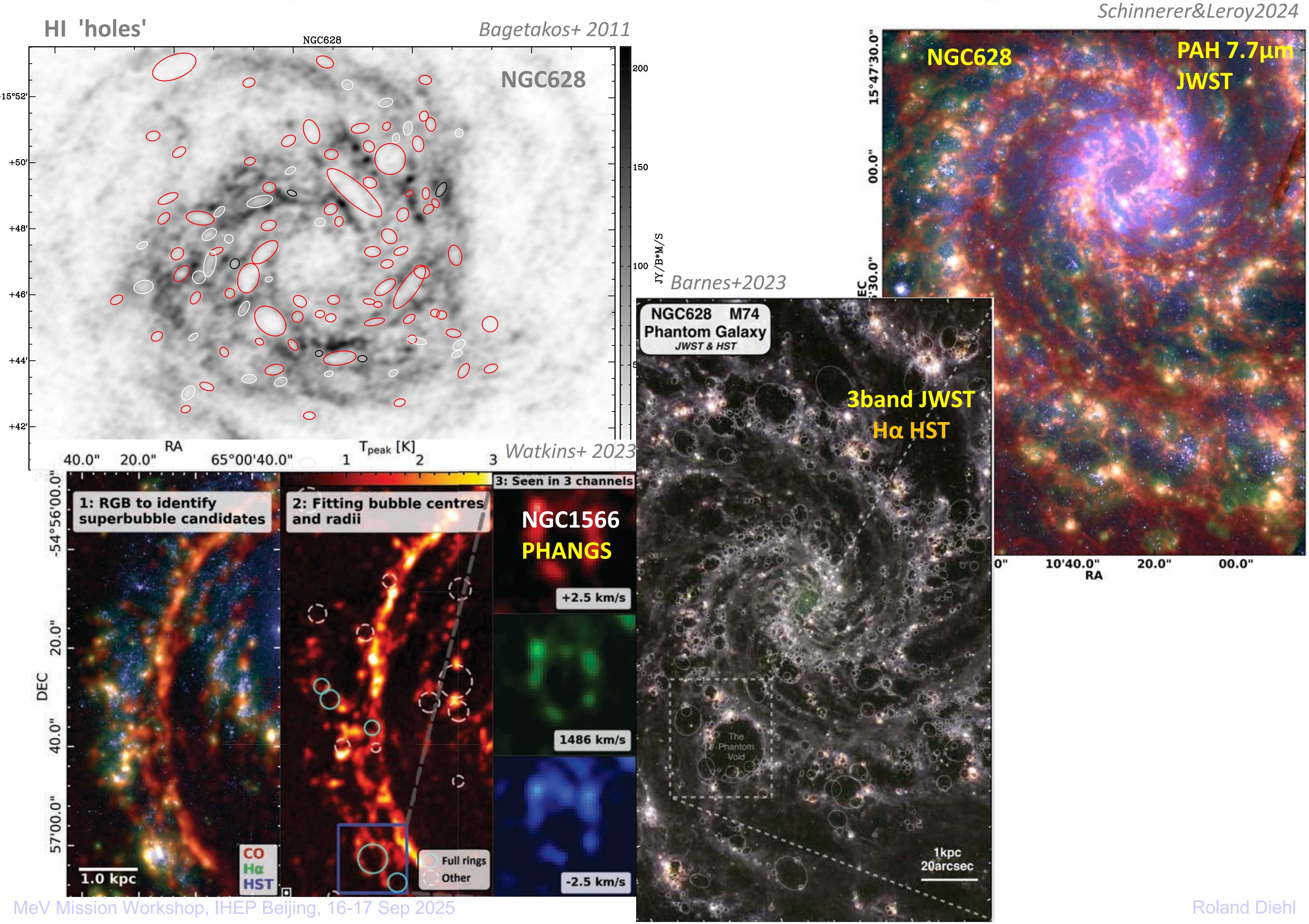




Krause & Diehl, ApJ (2014)

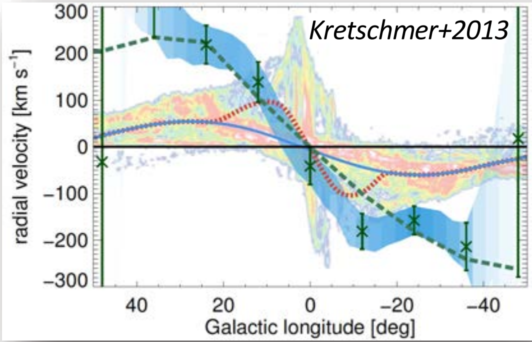


Superbubbles observations in other galaxies



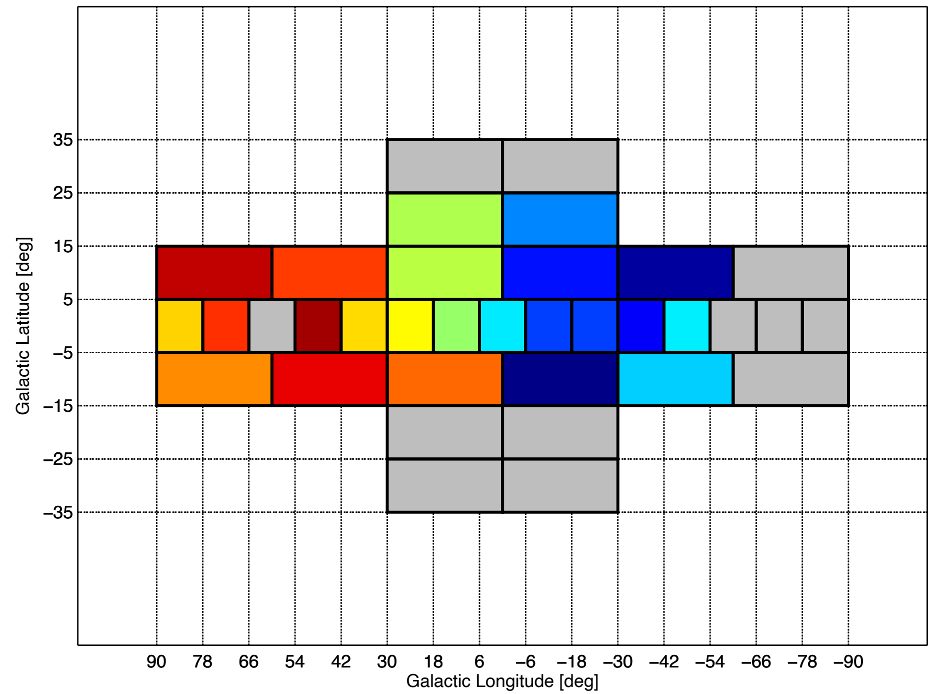
^{26}Al γ-rays: More detail on kinematics at large

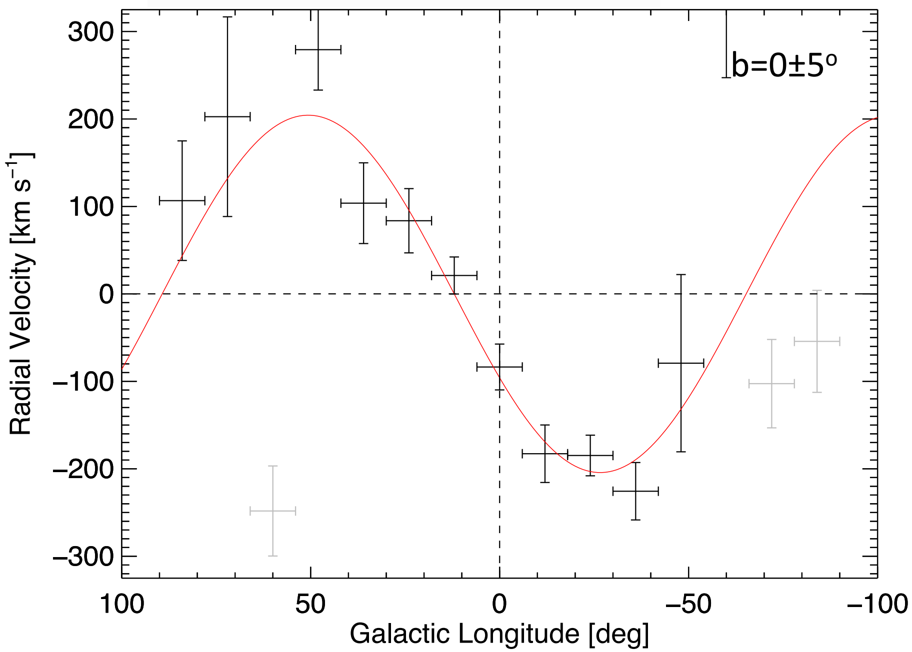
☞ Large-scale Galactic rotation in 3D

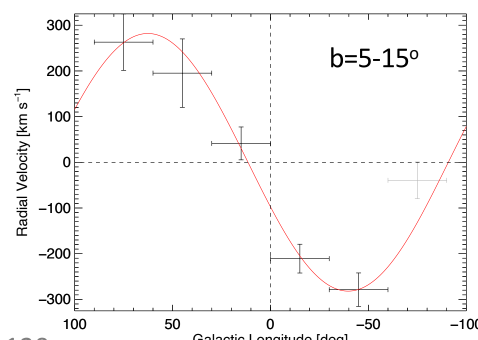


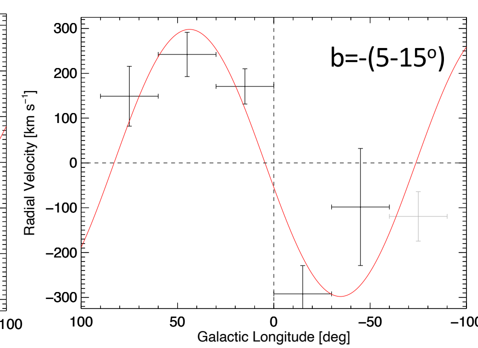
→ velocities appear even larger above the plane

Siegert (2016)







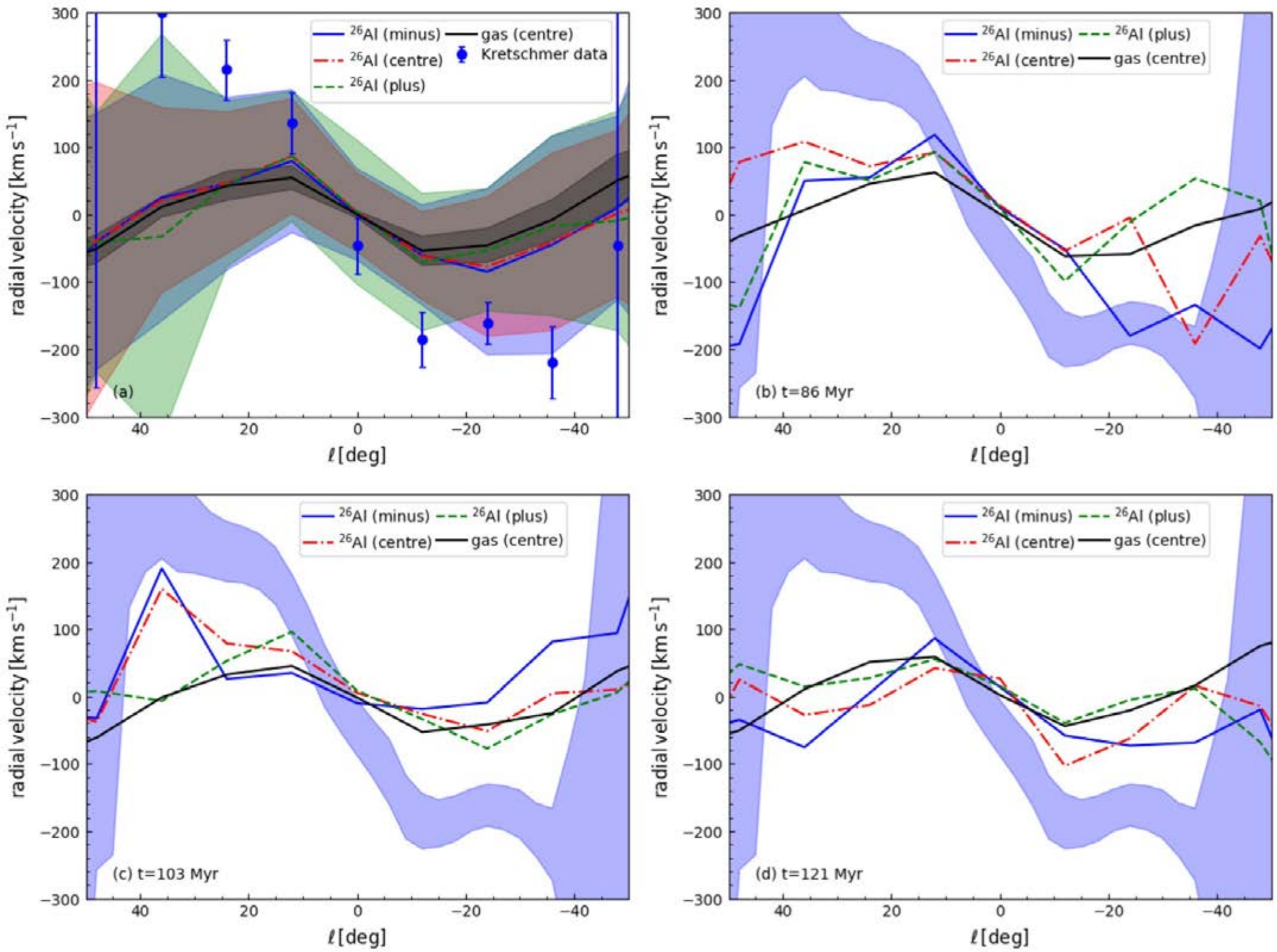


^{26}Al trajectories in simulations

'3D map' projections of a simulated galaxy's evolution in radioactive ^{26}Al

→ rarely obtain views on asymmetric cavities nearby

Rodgers-Lee+ 2019



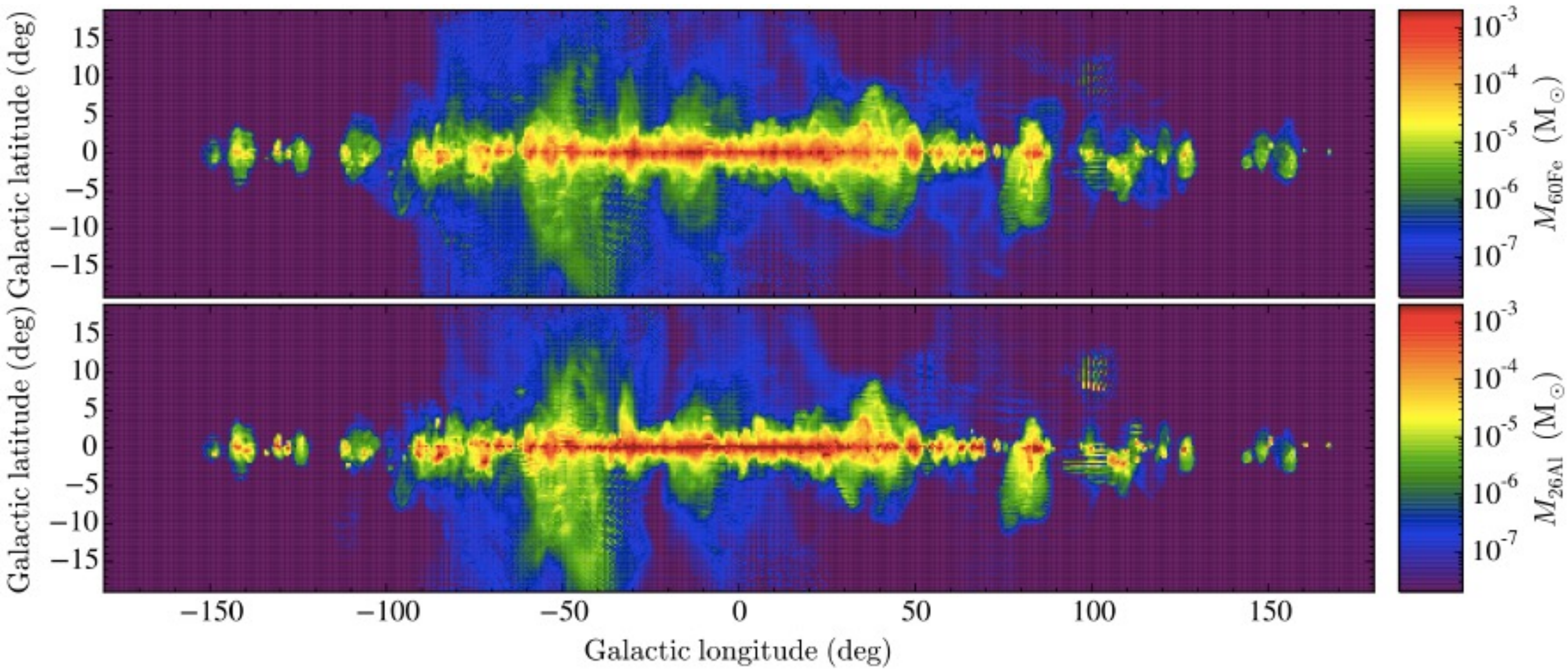
^{26}Al trajectories in simulations

3D hydrodynamical simulations on kpc scales have become feasible
(with sufficient resolution to trace nucleosynthesis events):

- ☆ 128^3 cells, cell size 7.8 pc (more-precise than cosmological simulations, but still crude)
- ☆ starting fom 'current galaxy' model (Tasker&Tan 2009), no bulge nor spiral arms initially
- ☆ star formation by Toomre criterion on single cells, efficiency set tp 1%

→ 'map' of a simulated galaxy in radioactive ^{26}Al (and ^{60}Fe)

Fujimoto+ 2018

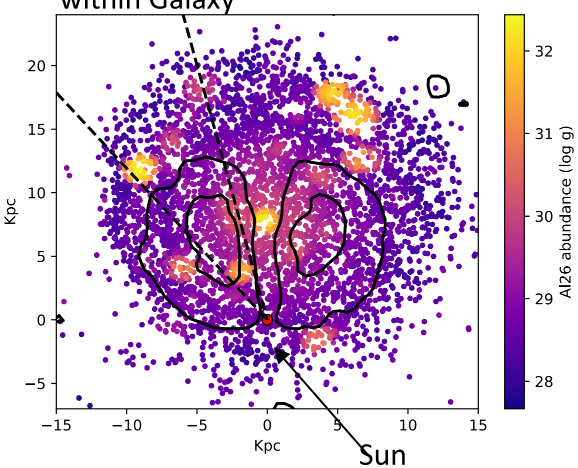


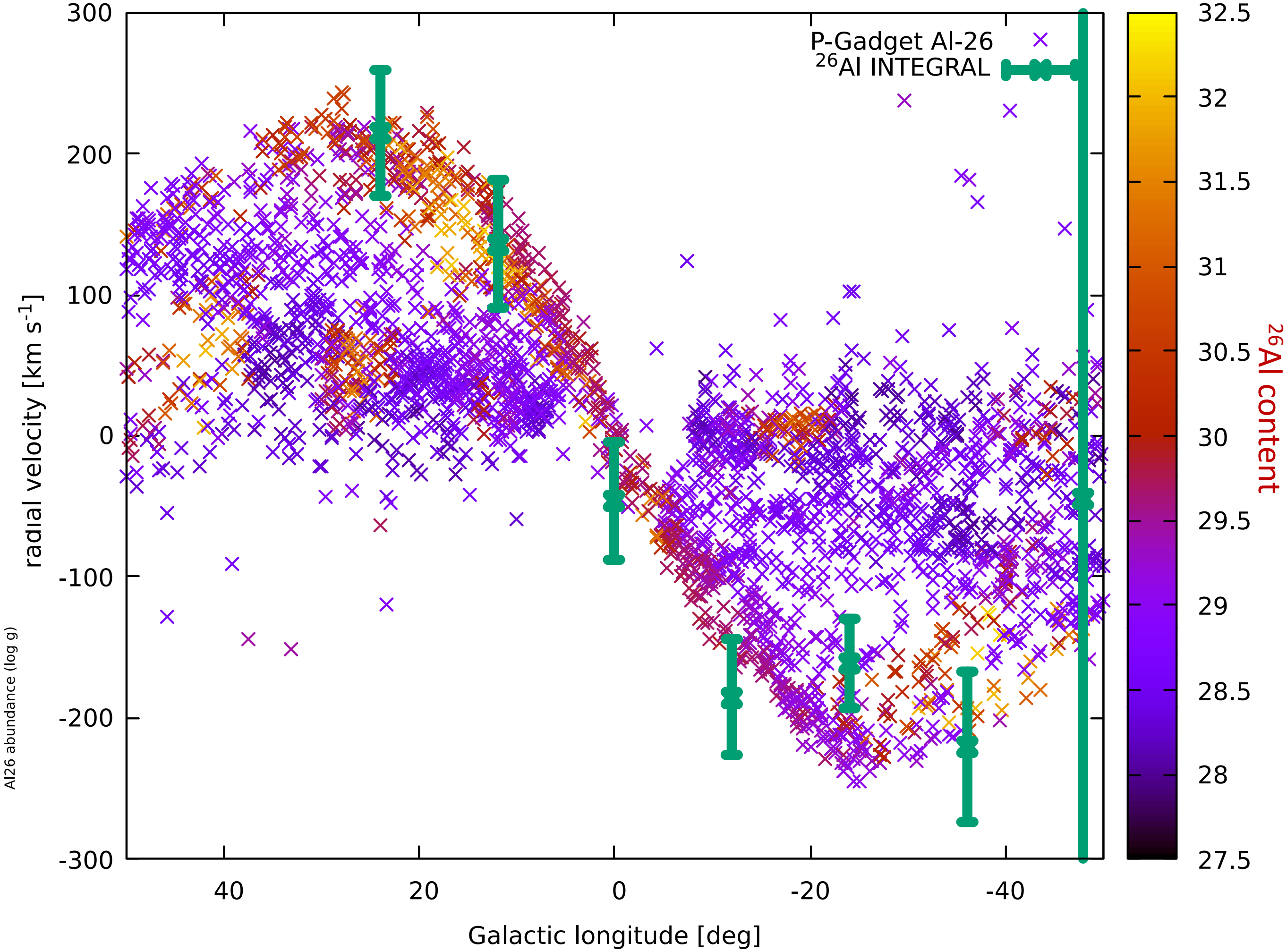
Simulations of (inhomogeneous) galactic evolution

→ ejecta with excess velocities appear naturally within a spiral galaxy

3D SPH simulation: analyze velocities of ^{26}Al-enriched matter from star formation activity

Wehmeyer + 2025



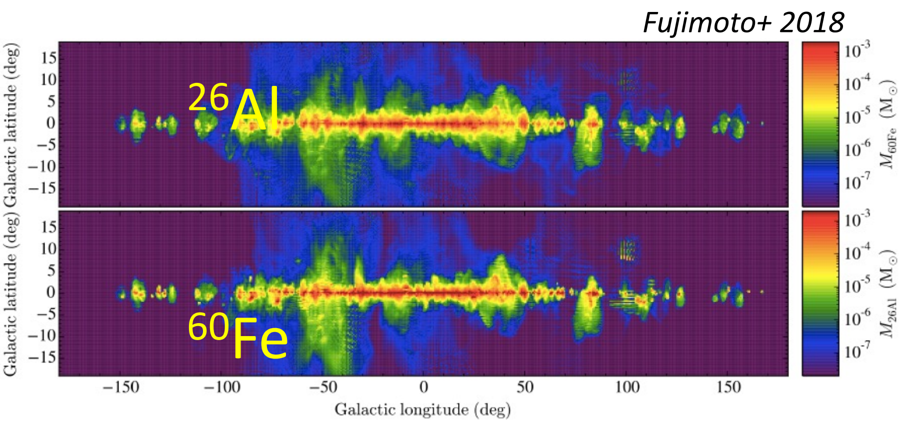


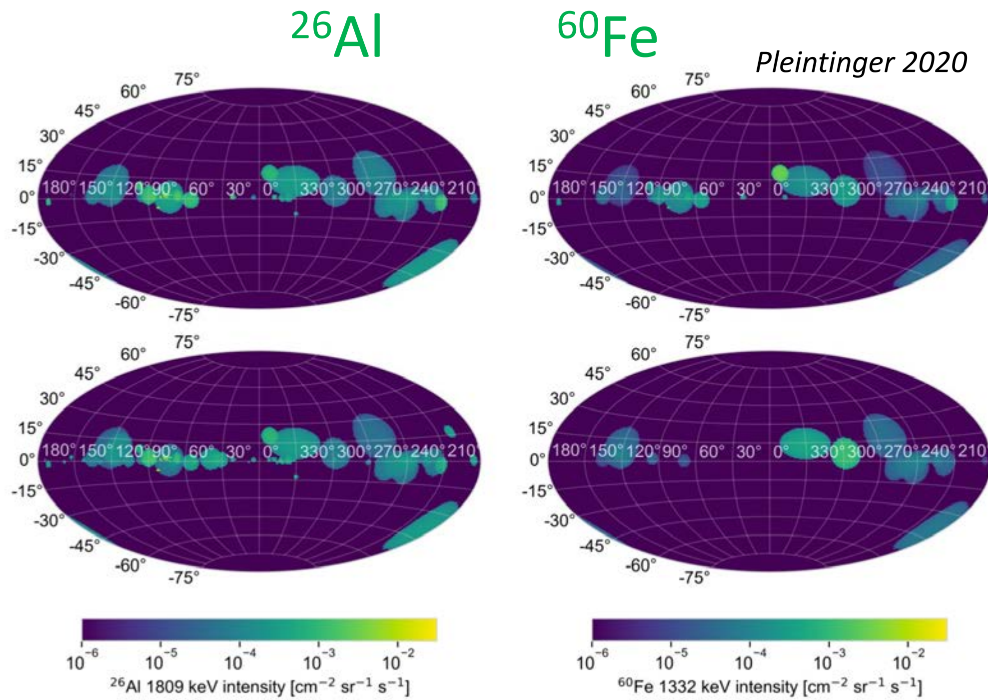
Estimating an image of ^{60}Fe

- Assuming the fundamental sources to be massive stars & their SNe

3D hydro simulations
a generic galactic disk

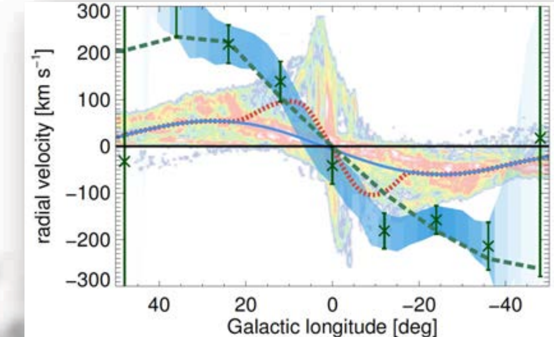
Population synthesis
Nearby massive-star groups



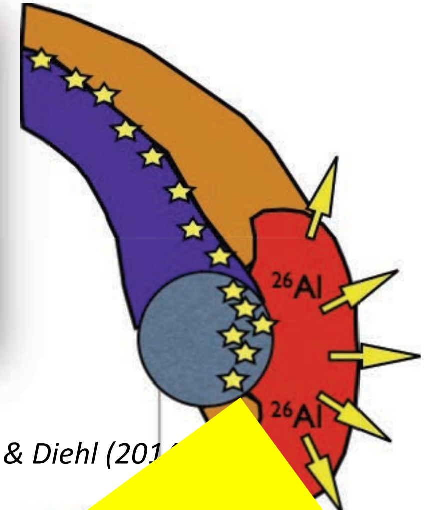


How massive-star ejecta are spread out…

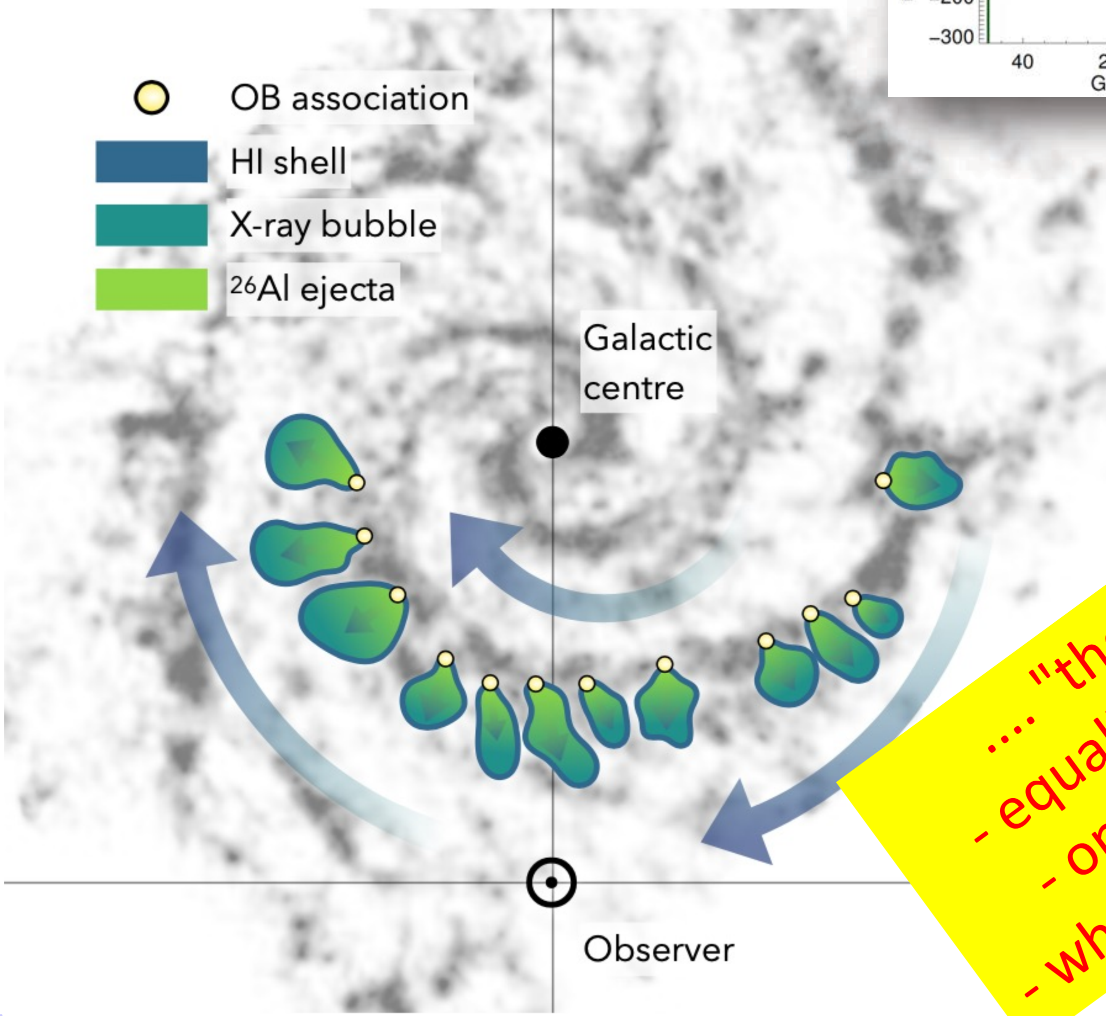
Superbubbles extended away from massive-star groups

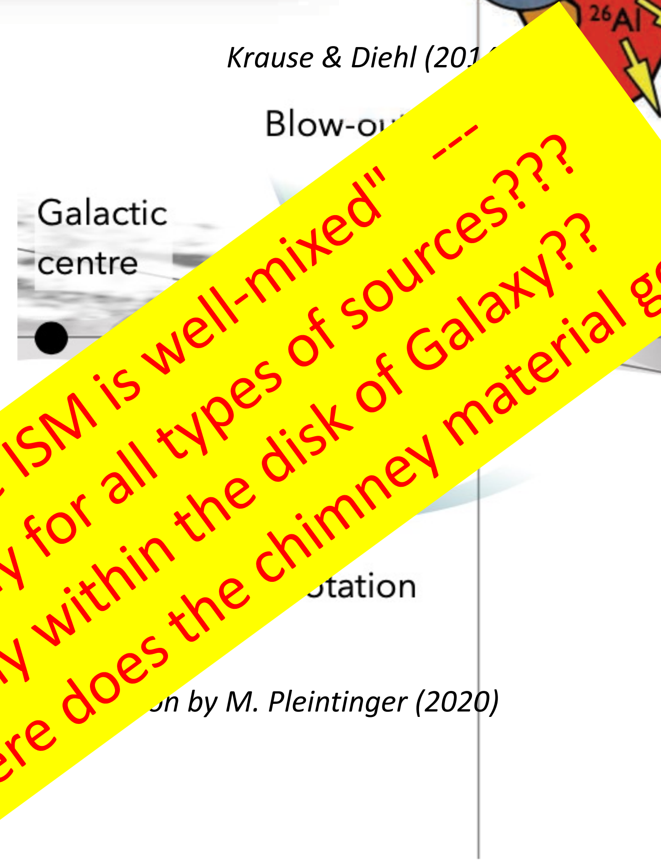


Kretschmer+(2013)



Krause & Diehl (201



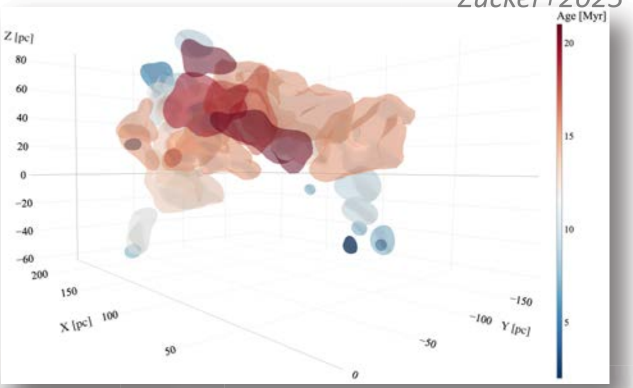


on by M. Pleintinger (2020)

…. "the ISM is well-mixed" ---
- equally for all types of sources???
- only within the disk of Galaxy??
- where does the chimney material go?

Stellar feedback in the nearerst massive-star region (Sco-Cen)

Zucker+2023



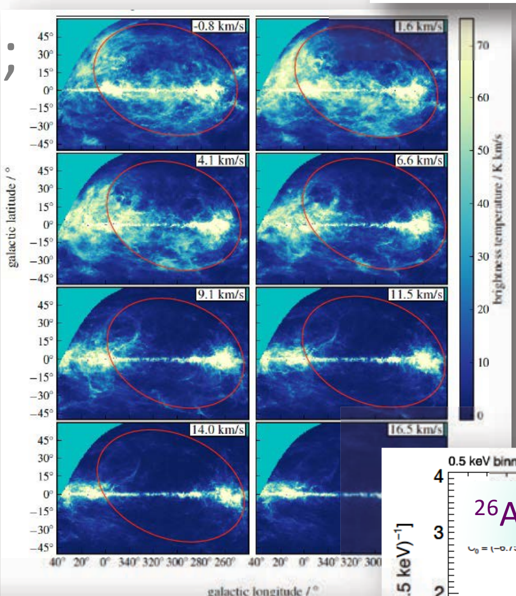
The stellar population covers a wide age range

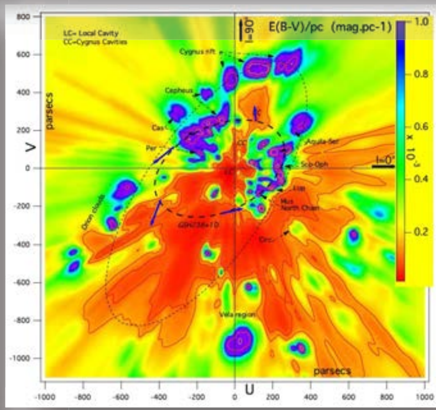
no clear coeval subgroups, SF ongoing for ~15+ My; distance~140pc)

The interstellar medium holds
a network of cavities

ISM dynamics is not easy to unravel

^{26}Al (t~1My) covers a large solid angle;
can we measure the flow?

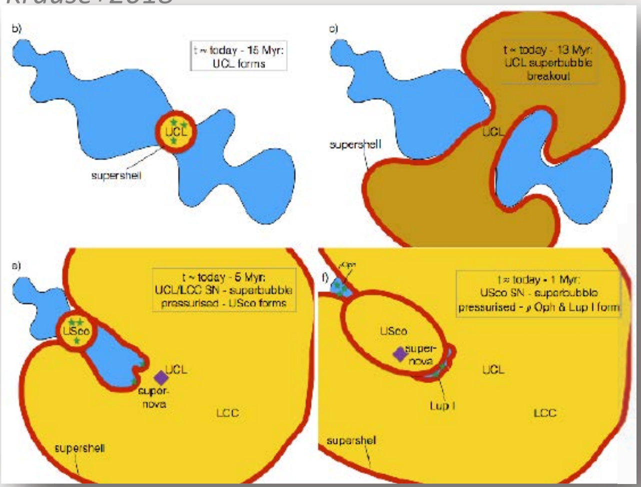




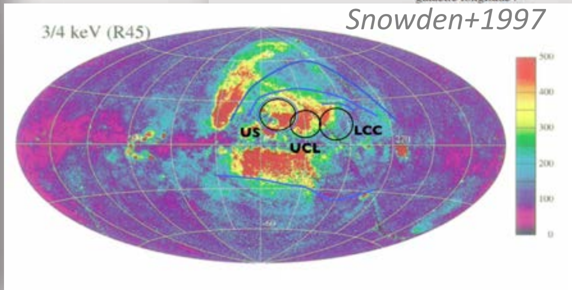
→ *"surround & squish"*

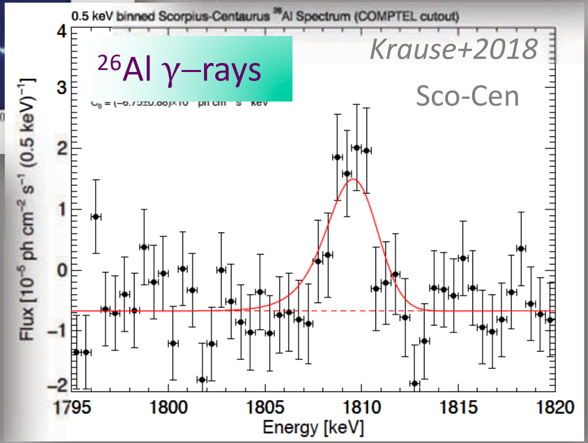
rather than "triggered" star formation

Krause+2018



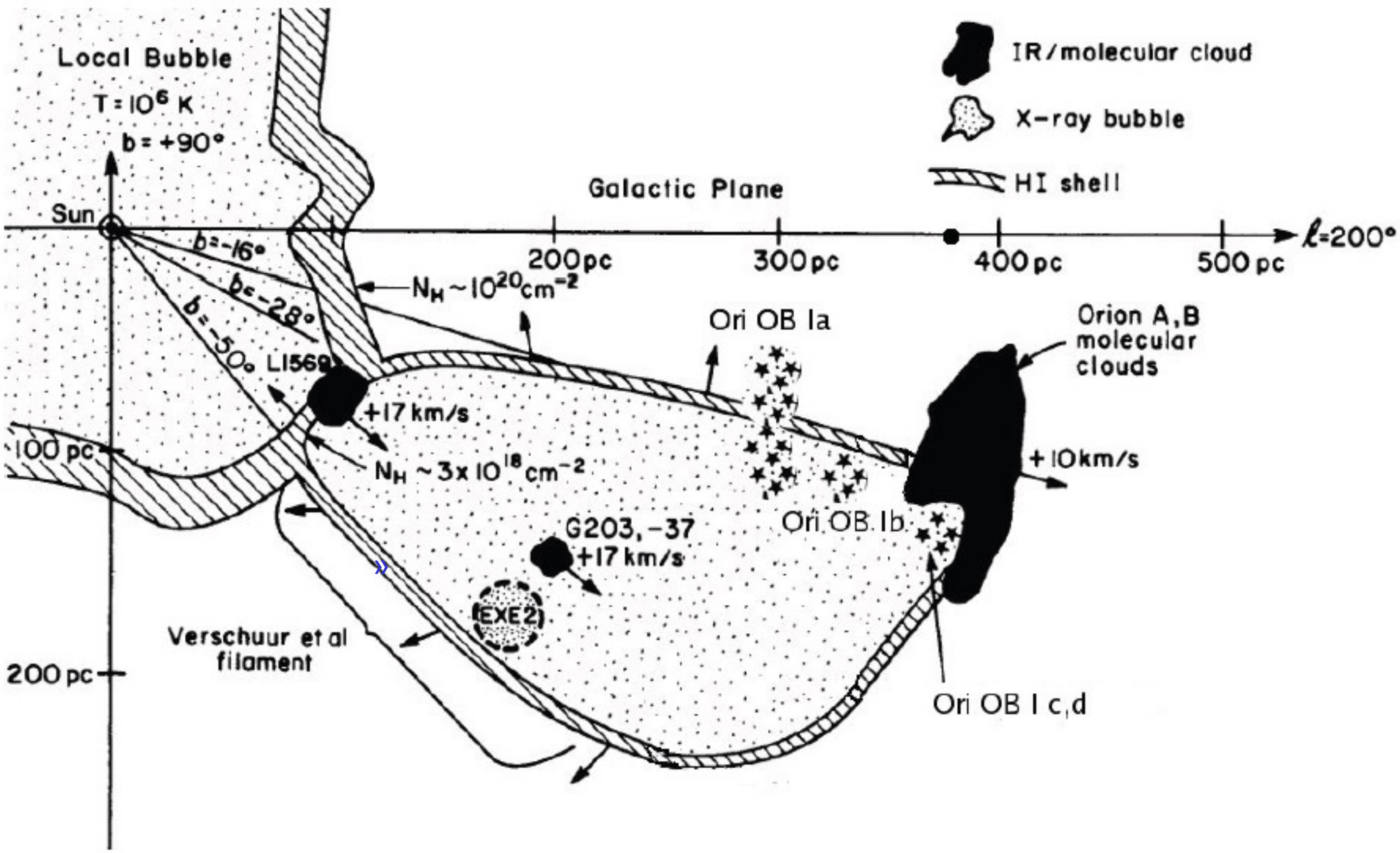
Snowden+1997



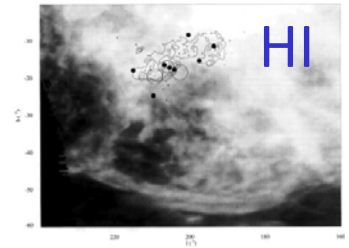


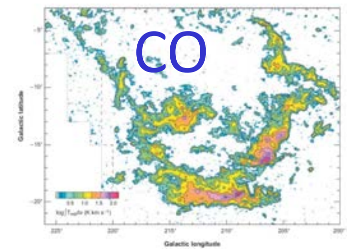
Orion-Eridanus: A superbubble blown by stars & supernovae

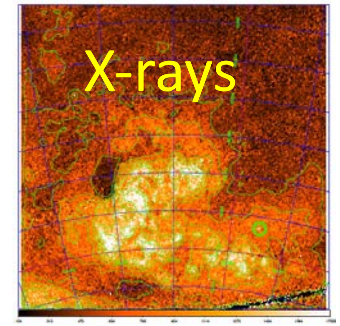
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

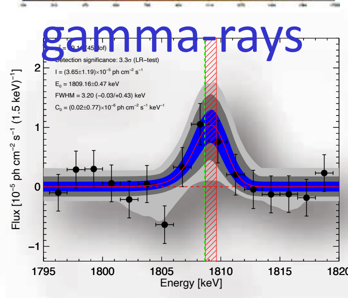


Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003, Siegert 2016









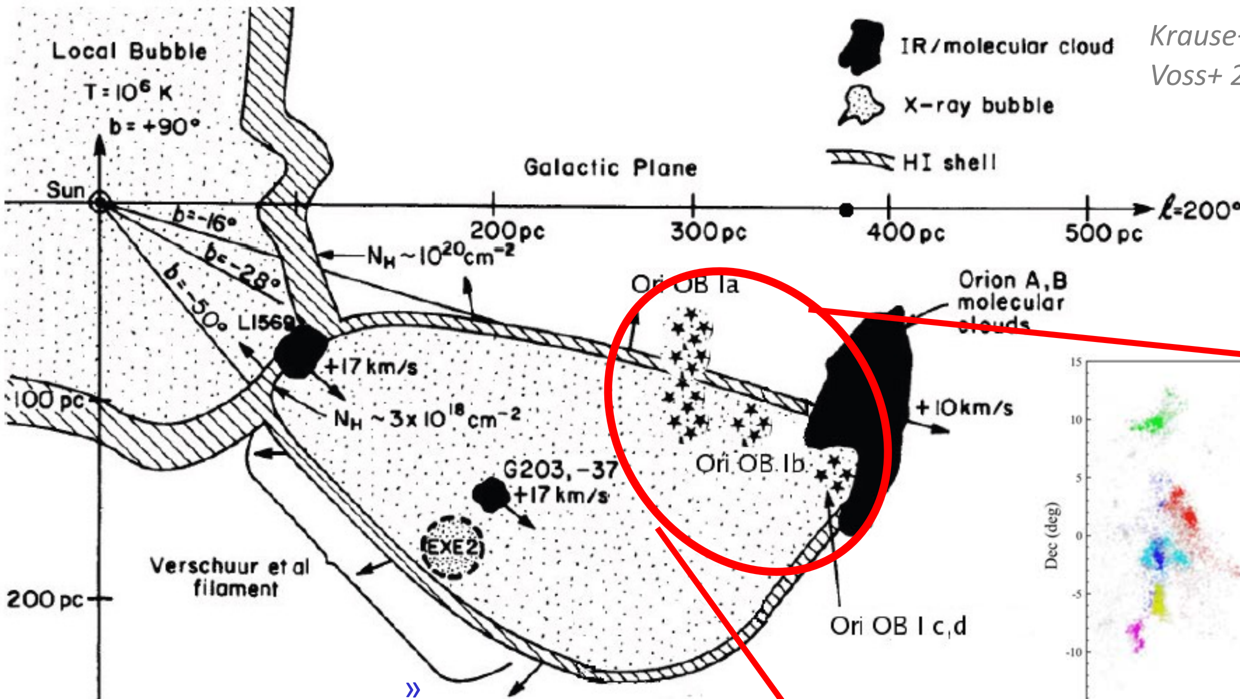
3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff

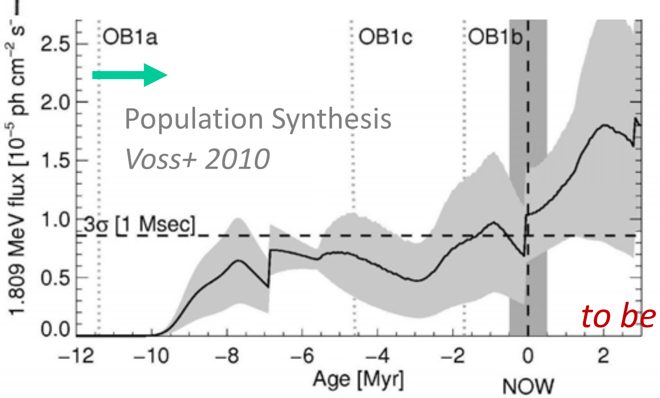
Stars, structures, & shells

ISM is driven by stars and supernovae

→ Use stellar census for estimation of driving energy & nucleosynthesis (^{26}Al)

Krause+ 2014, Fierlinger+ 2016, Voss+ 2010, Diehl+2003





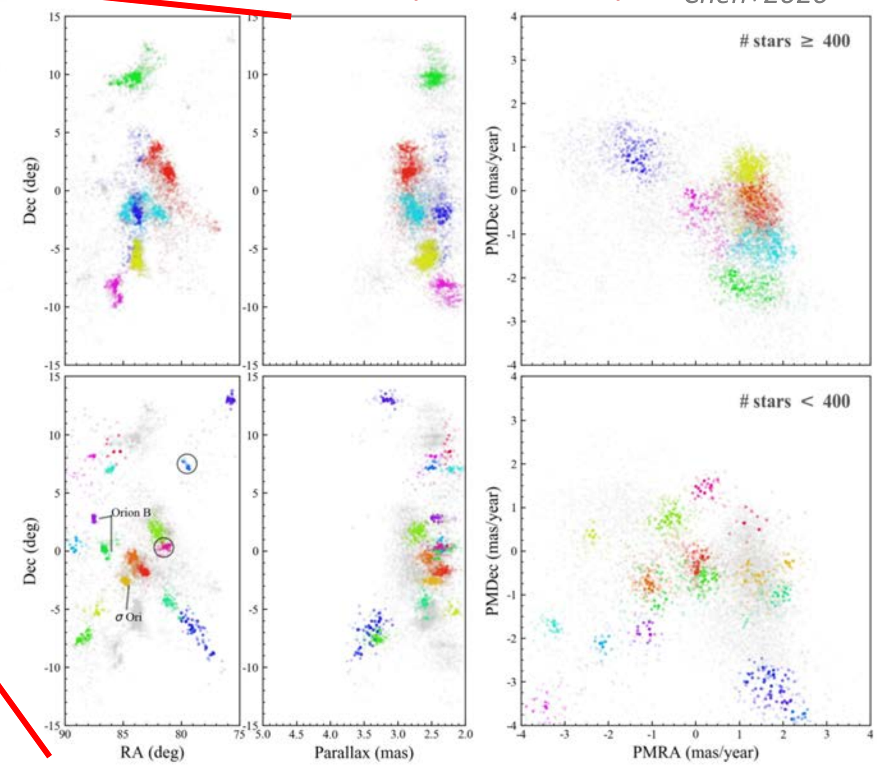
to be renewed...

Gaia parallax analyses

→ 22 stellar groups

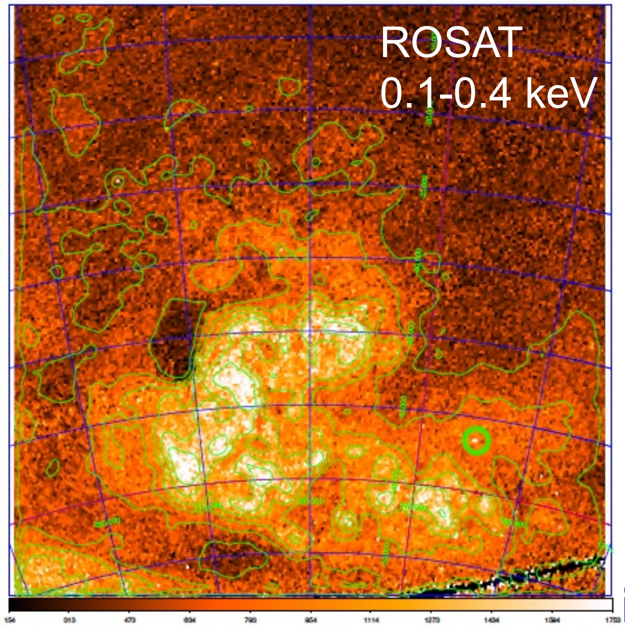
-150pc<MCs<50pc

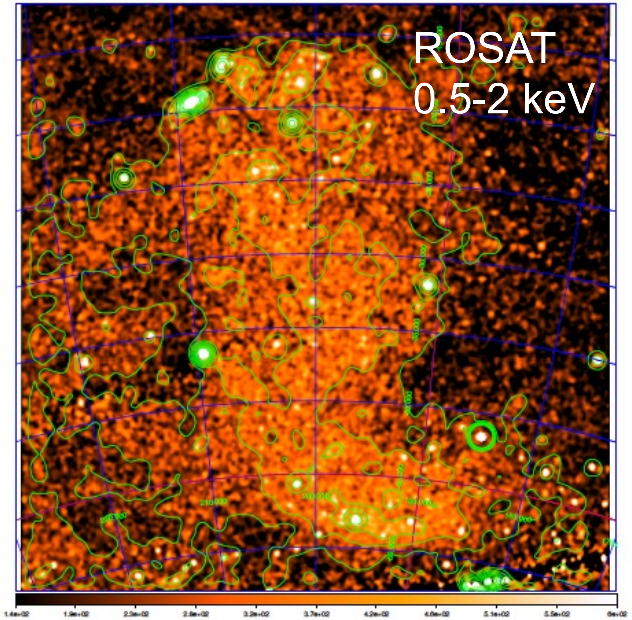
Chen+2020



Understanding the Eridanus Superbubble

- X-ray Emission, size, ^{26}Al





e
ic

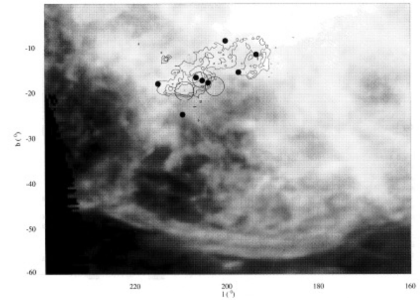
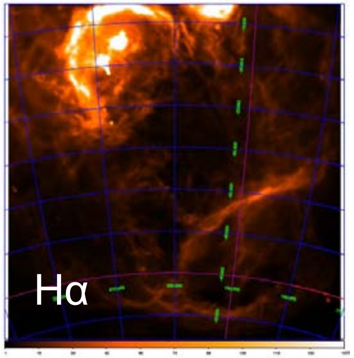
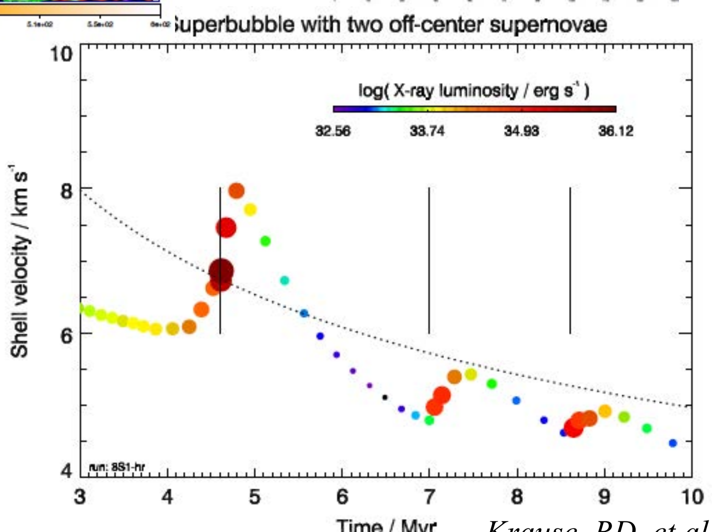


Fig. 7. The position of the Orion OB1 association with respect to the H I shell. The grey scale image is a logarithmically scaled representation of integrated H I emission in the velocity interval $-1\ \mathrm{km\,s^{-1}} \le v_{LSR} \le +8\ \mathrm{km\,s^{-1}}$. The contours outline the 100 μm (IRAS) emmission from the Orion A and B molecular clouds (the ring around $(\ell, b) = (195°, -12°)$ is the λ-Orionis ring). The dots show the brightest stars in the Orion constellation. The circles show the positions of the three main subgroups of Orion OB1. From right to left are shown 1a, 1b and 1c



☆ spatial oscillations



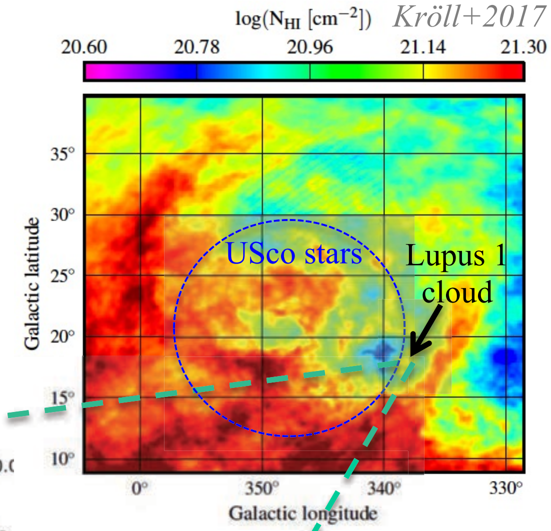
Krause, RD, et al. 2015

sweeping up gas: star formation?

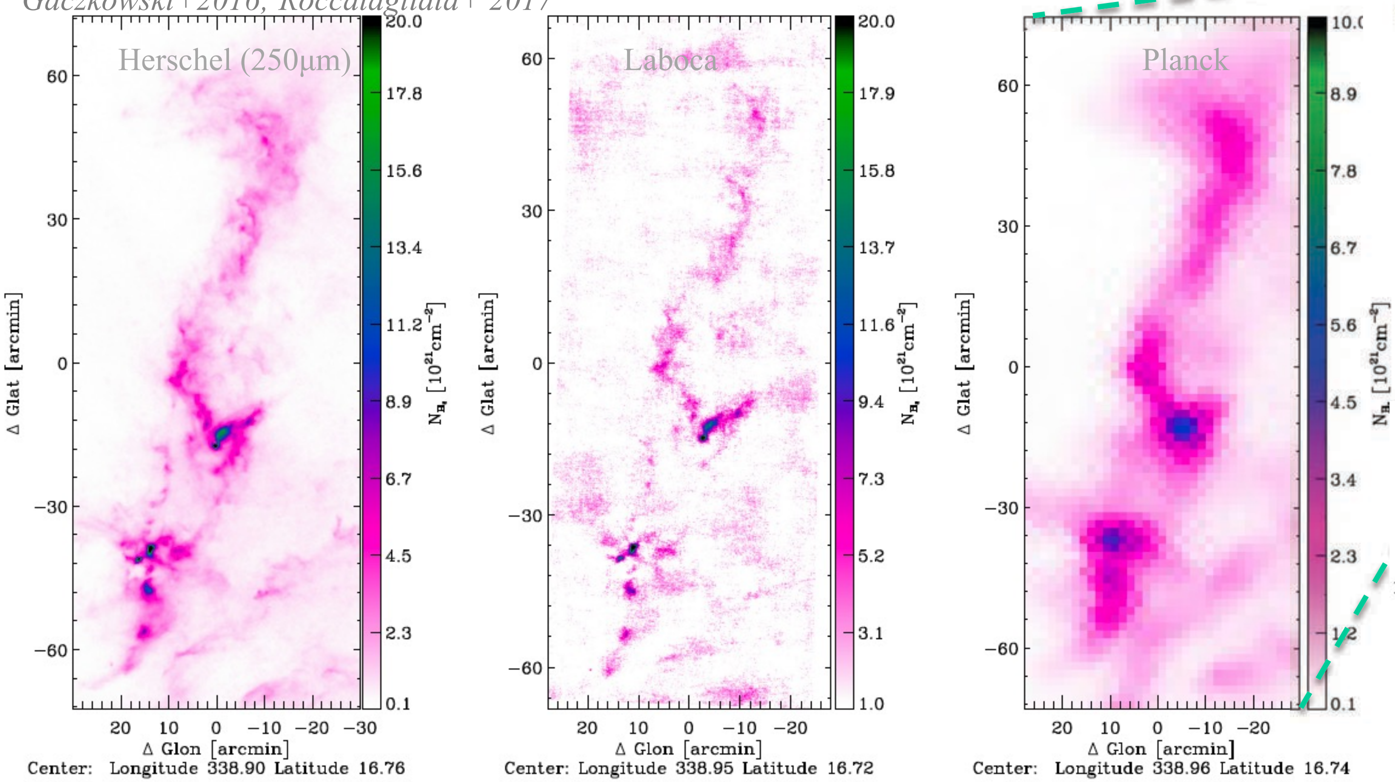
the Lupus I cloud:
We see current star formation

» USco expanding supershell sweeping up ISM, compression of turbulent ISM → SF?

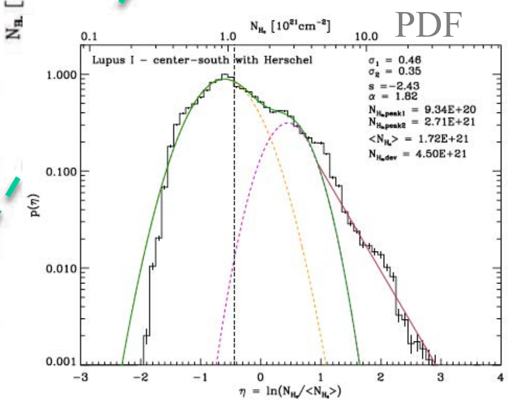
Kröll+2017



Gaczkowski+2016; Roccatagliata+ 2017

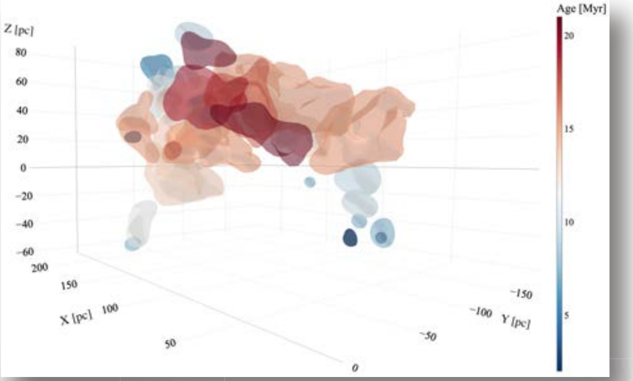


→ double-peaked density PDF



Stellar feedback in the nearerst massive-star region (Sco-Cen)

Zucker+2023



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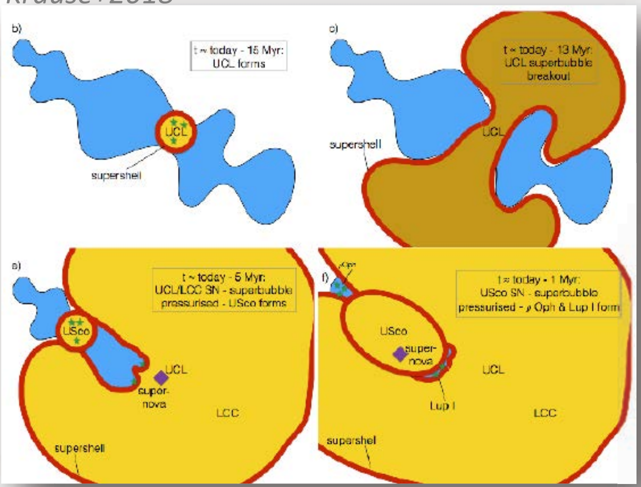
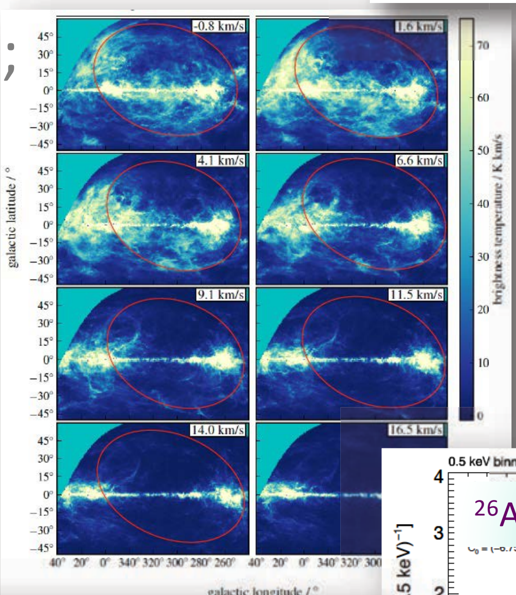
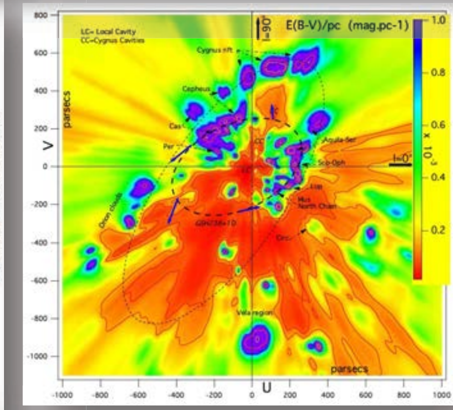
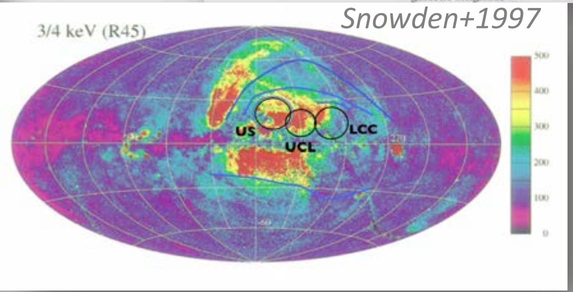
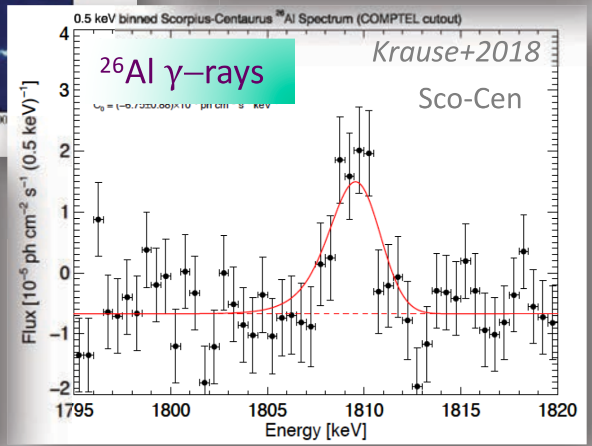






Snowden+1997

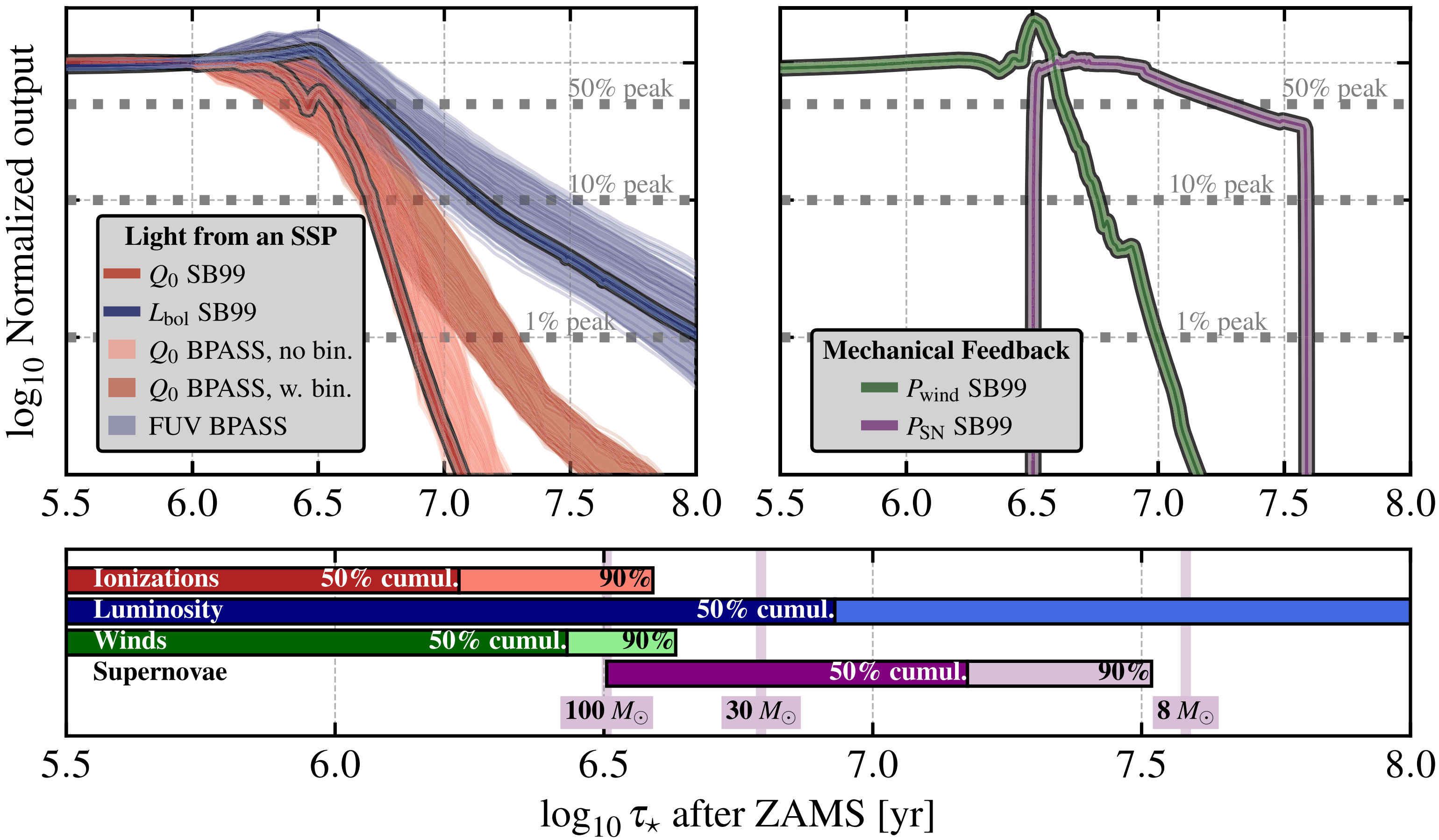


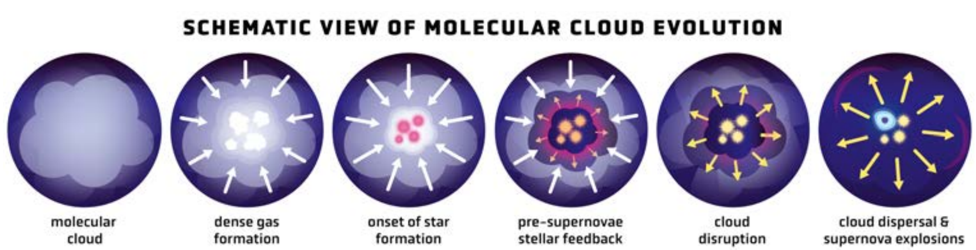


Evolution of a Stellar Cluster, Feedback

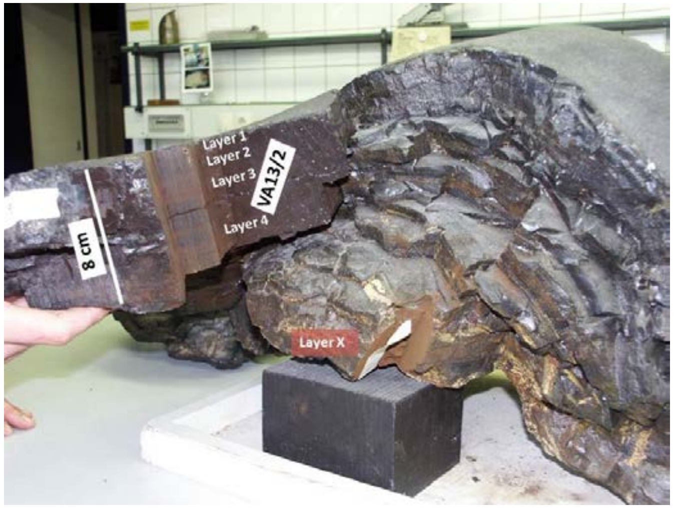
Feedback now also recognised by cold-gas community...

Schinnerer & Leroy ARAA2024

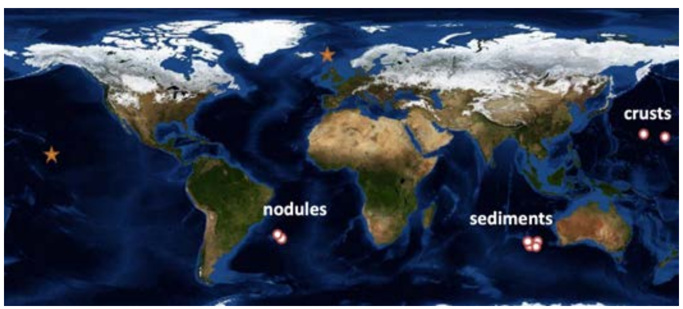




^{60}Fe and ^{244}Pu from nearby nucleosynthesis found on Earth

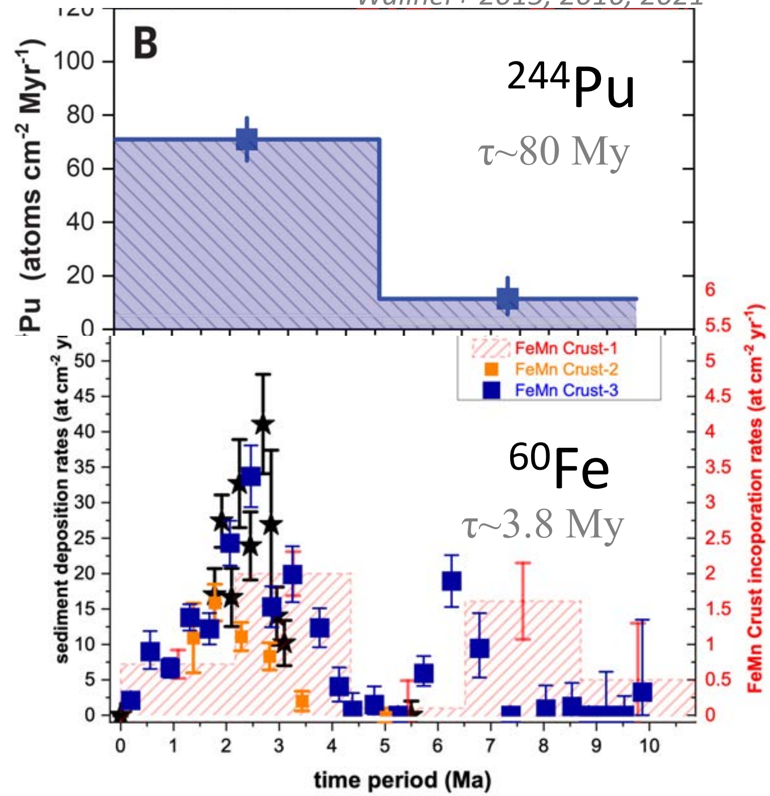


Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ...



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021



peak of radioactivity influx
≈3 & 6-8 My ago!

What are its sources?

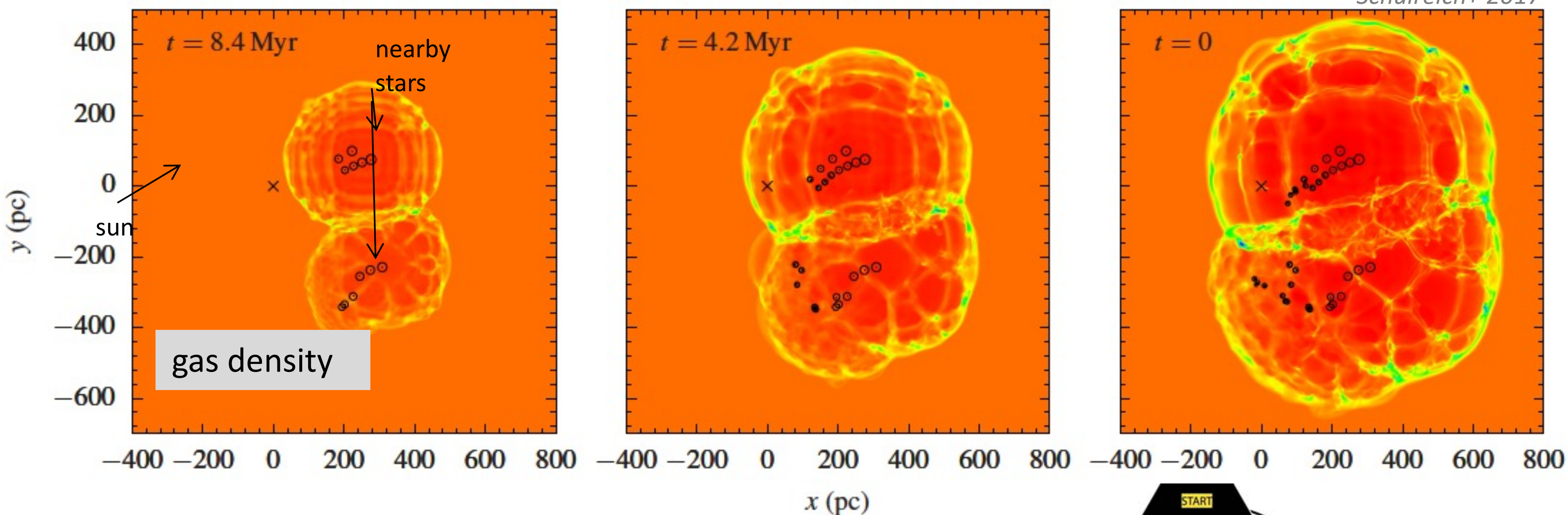
How did these traces of nucleosynthesis get here?

^{60}Fe on Earth from recent nearby supernovae?

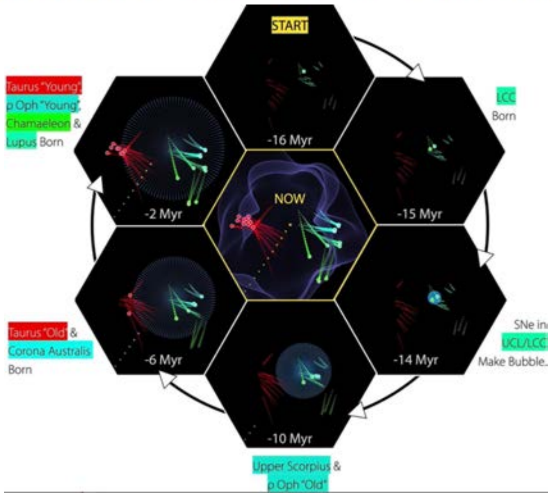
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions within LB → ejecta flows reach the Solar System

Schulreich+ 2017



see also Zucker+ 2022
for a recent update on the Local Bubble and the Sco-Cen SN activity, confirming this local superbubble interpretation with dust cloud maps and Gaia data

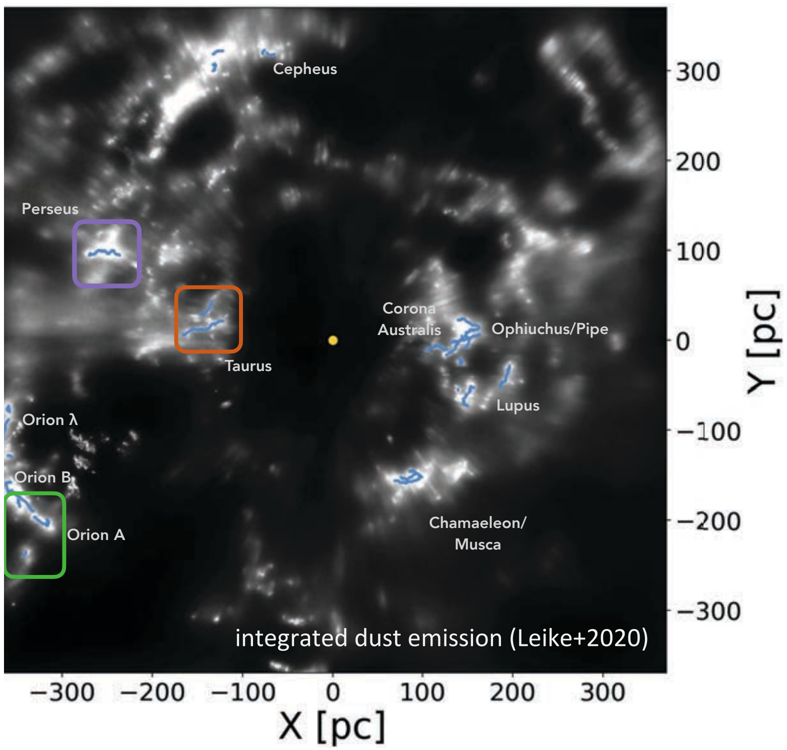


Recent nearby supernovae and the Local Bubble

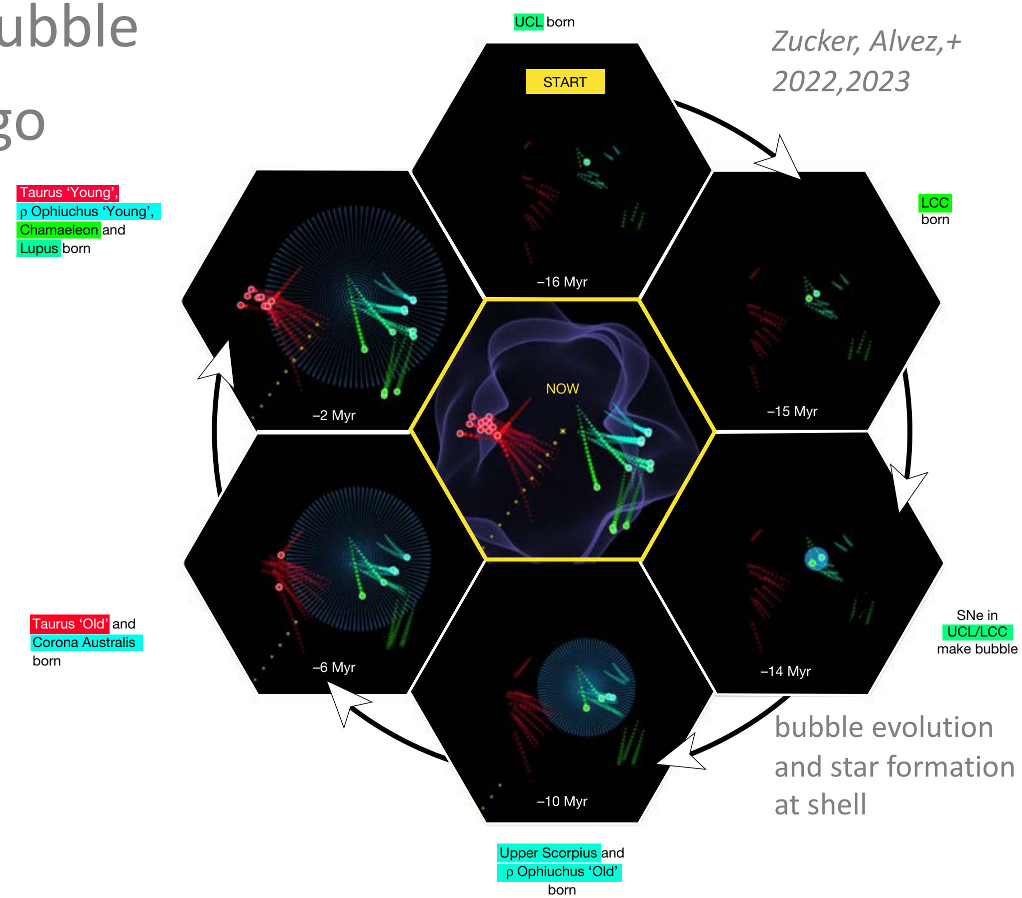
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions created the Local Bubble

The Sun entered the LB ~10 My ago



Zucker, Alvez,+ 2022,2023



bubble evolution and star formation at shell

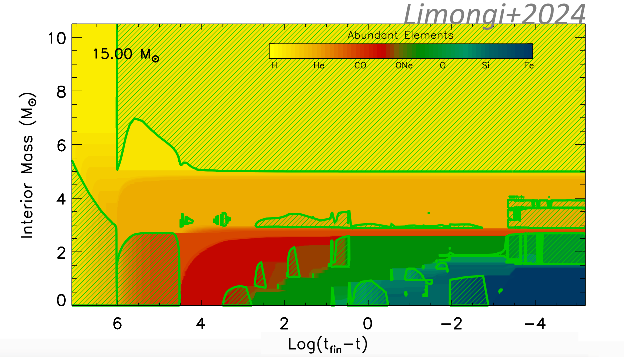
ISM dynamics and trajectory of the Sun lead to encounters with SB wall and quenching of the heliosphere from cloud encounters

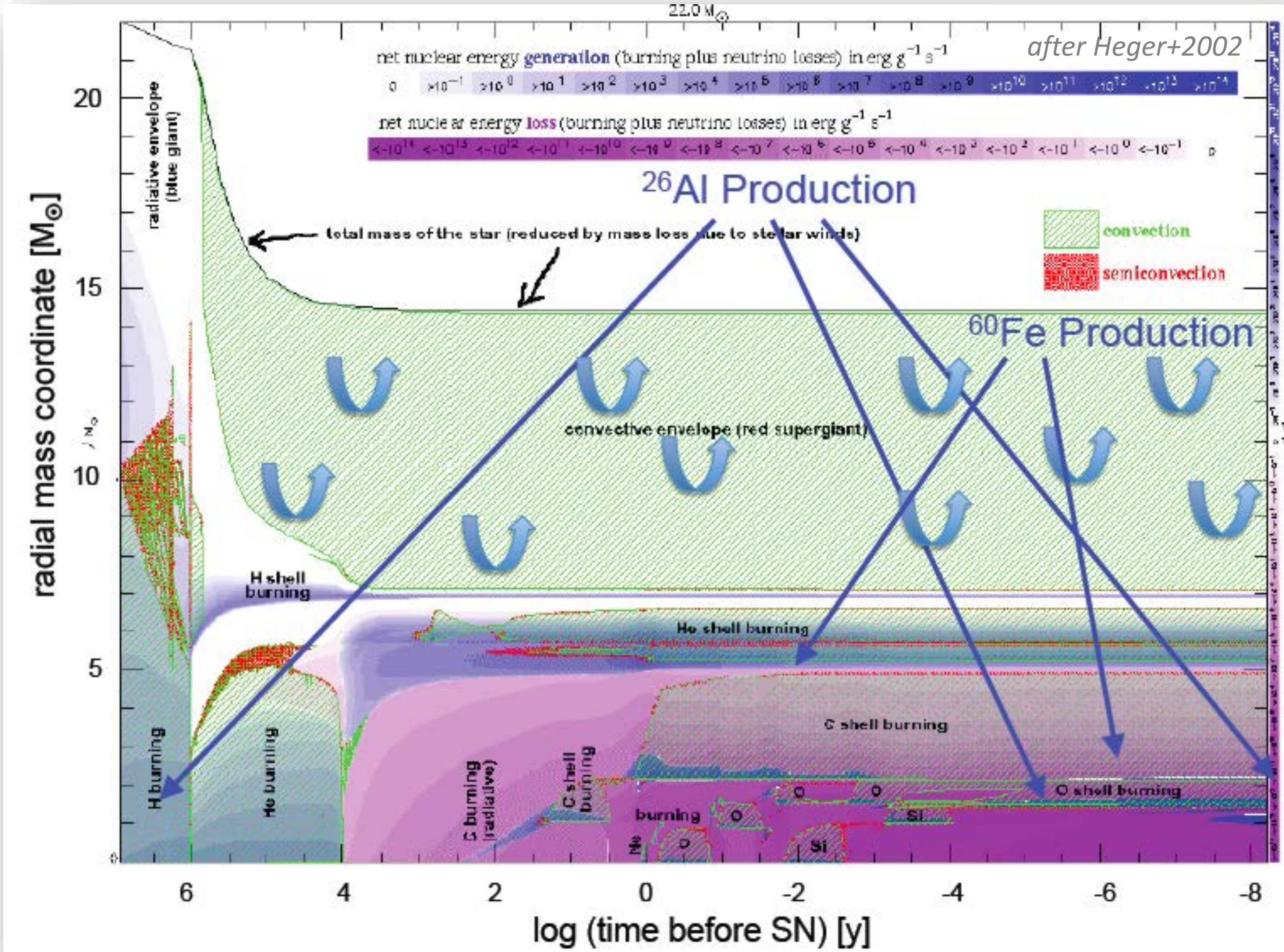
→ nucleosynthesis ejecta flows can reach the Solar System

Radioactivities from massive stars: ^{60}Fe, ^{26}Al

→ Messengers from Massive-Star Interiors!

…complementing neutrinos and asteroseismology!





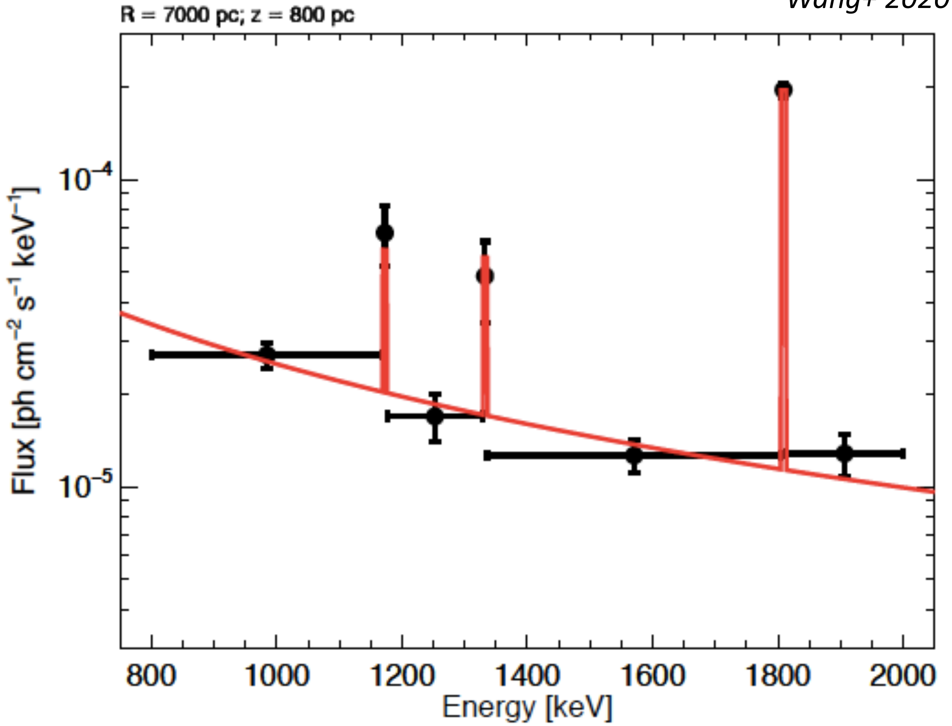
Processes:

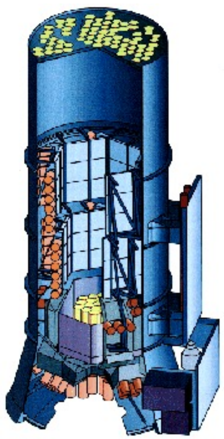
- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*

^{60}Fe Diffuse Gamma-Ray Emission

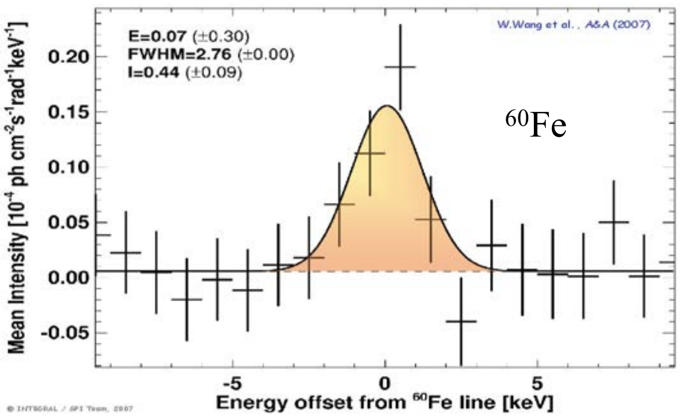
Update with 15+ years of data:

Wang+ 2020



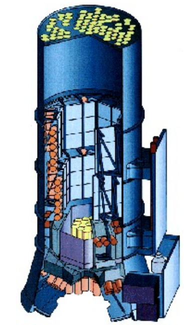


Wang+ 2007

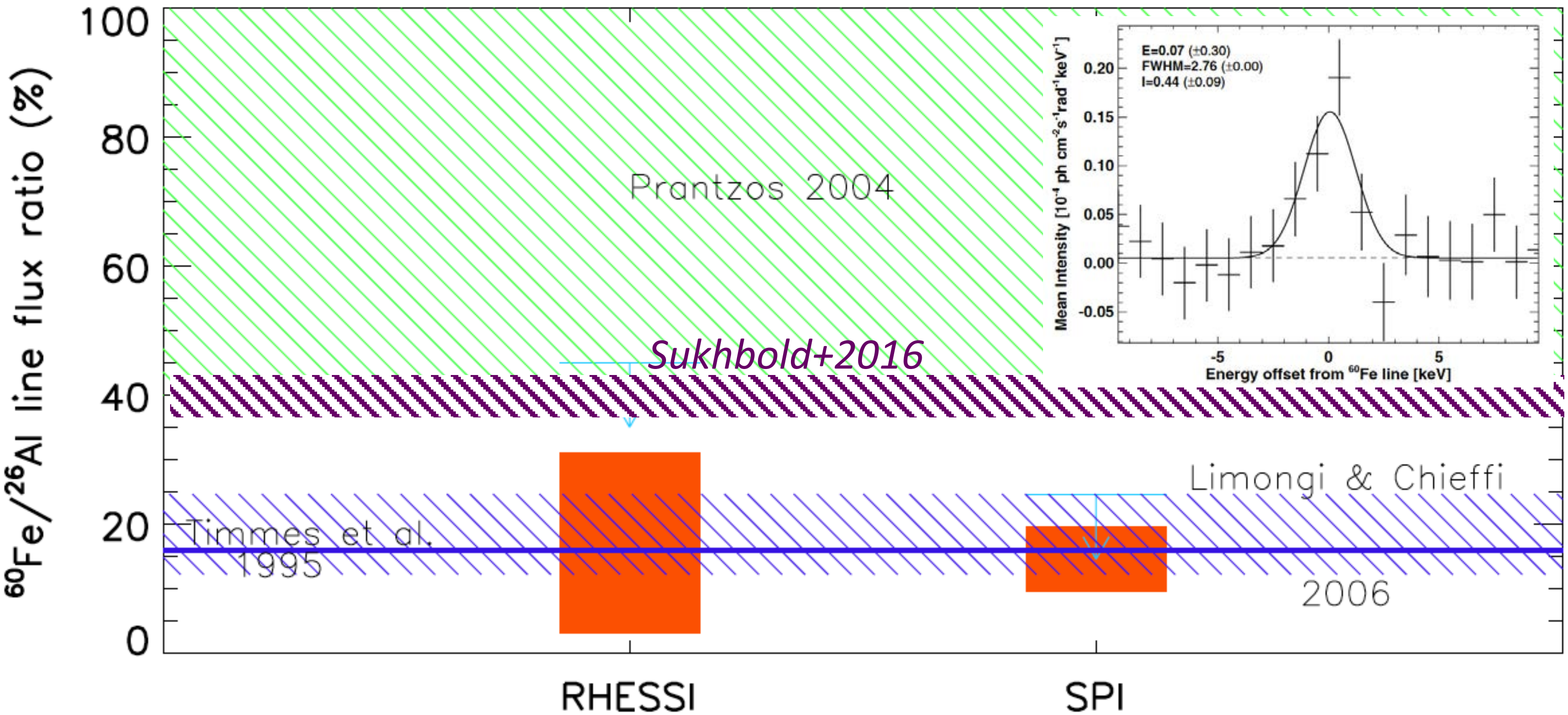


Significant emission ~5 σ

^{60}Fe in the Current Galaxy's ISM



- Observed ^{60}Fe/^{26}Al Intensity Ratio ~15% (±4%)

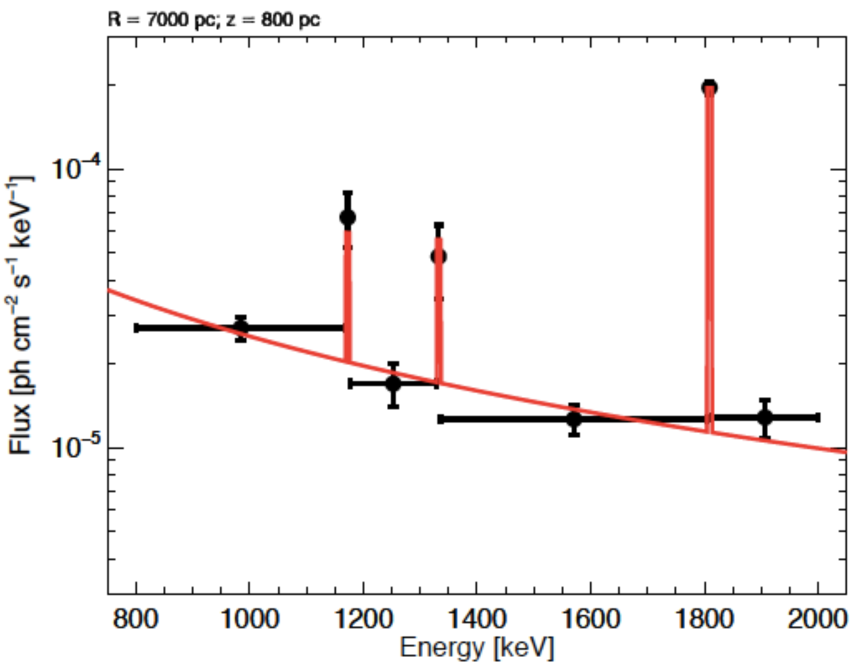


☞ ^{60}Fe/^{56}Fe isotope ratio in current ISM = 1.5 10^{-7} (model: 7 10^{-4} *Sukhbold+2016*)

- using M_{ISM}=4.95 10^{9} $M_{\odot}$ and SAD 7.5 and M_{26Al}=2.25 $M_{\odot}$ → M_{60Fe}~1.2 $M_{\odot}$

Diffuse gamma-ray emission from ^{60}Fe in the Galaxy

^{26}Al and ^{60}Fe analysis with same INTEGRAL dataset (15+ years) and models



^{60}Fe emission too faint for imaging etc

Variability study on ^{60}Fe/^{26}Al ratio

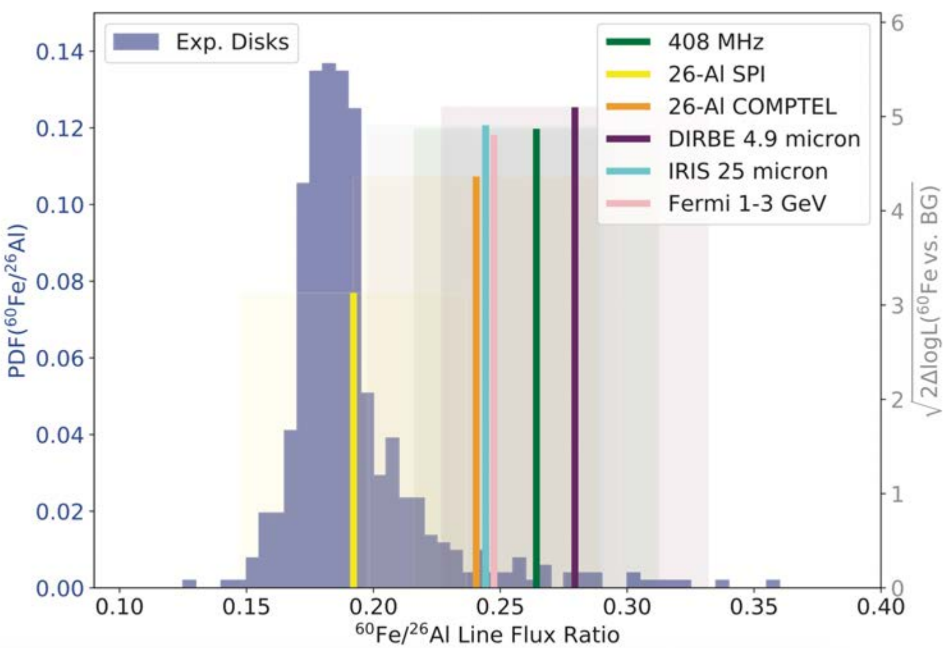
(systematics!)

➔ ^{60}Fe/^{26}Al < 0.4 in Galaxy

cmp theory: 0.2...1,

and oceancrusts: >0.2

Wang+ 2020



The Al Isotope Ratio $^{26}Al/^{27}Al$

^{27}Al is enriched with Galactic Evolution, i.e. ~time

^{26}Al decays, so from current/recent nucleosynthesis only

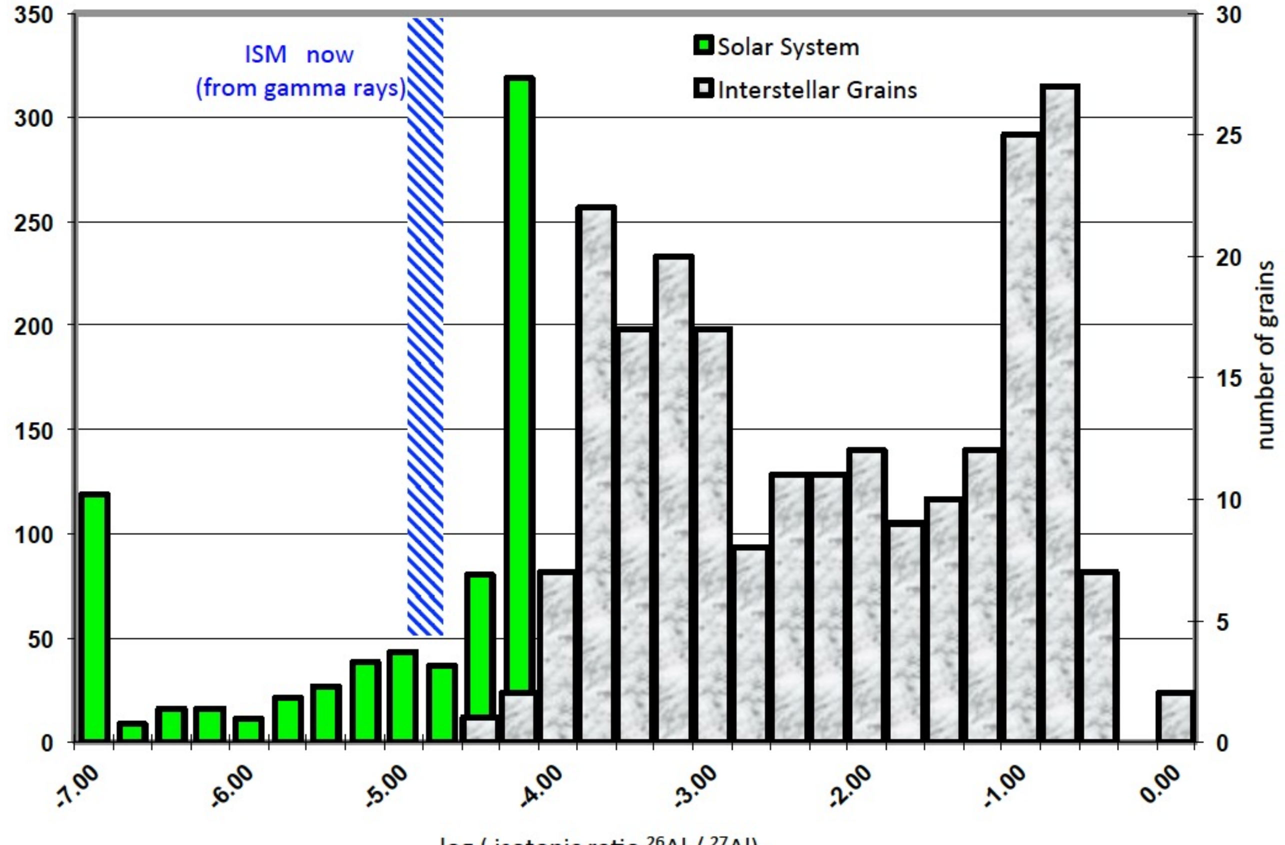
Early solar system meteorites measure ESS environment 4.6Gy ago (→ ^{26}Al enriched?)

Pre-solar grains measure nucleosynthesis in dust-producing sources (→ much larger)

'canonical' value for ESS of ~5 10^{-5}
(McPhersson+1995)

'supra-canonical' up to 6.5 10^{-5} ??
(Krot+2012, Makide+ 2013 ...)

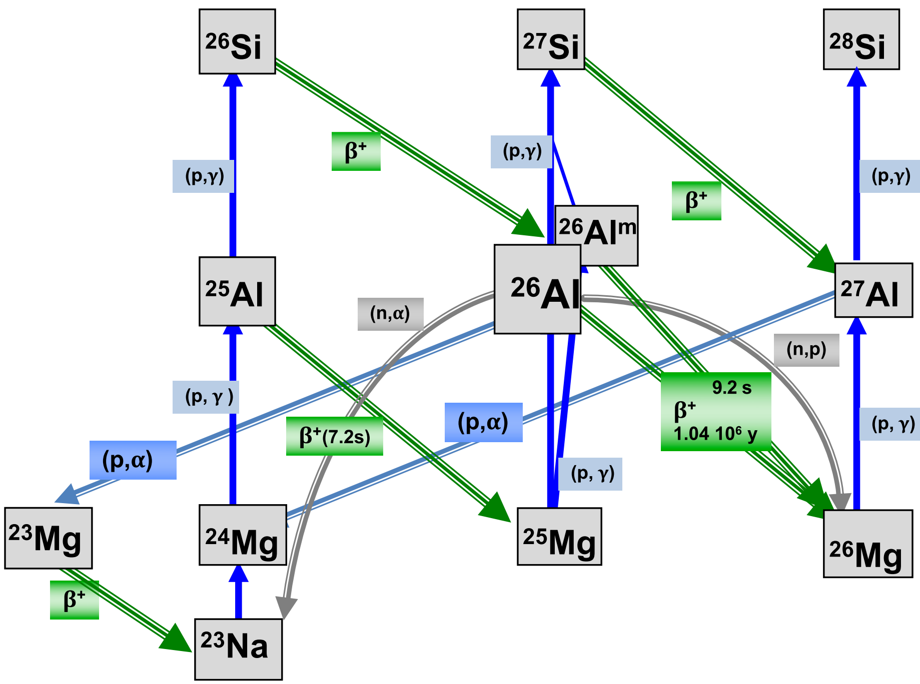
Consolidated ESS
(5.23±0.13) 10^{-5}
(Jacobsen+2013)



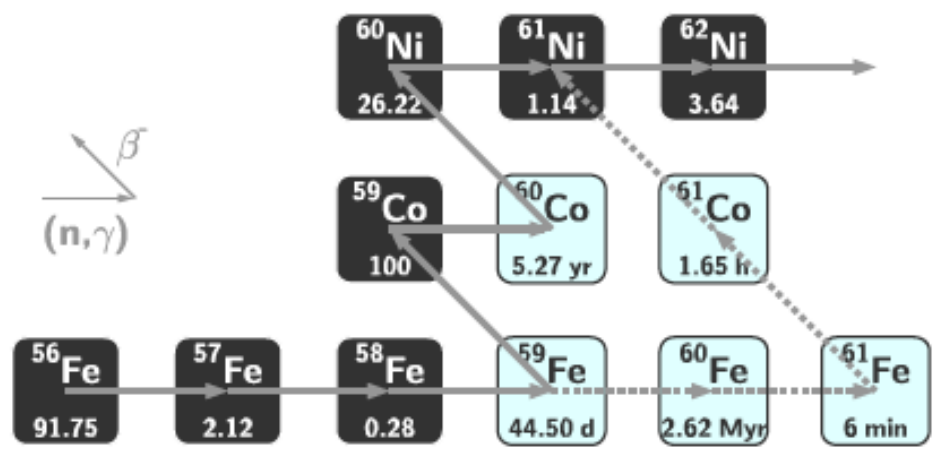
Nuclear reactions to produce ^{26}Al , ^{60}Fe

The Na-Al-Mg cycle: p captures (H burning in stars, +...)

☆ production versus destruction reactions...



Neutron capture on Fe
in massive-star shells



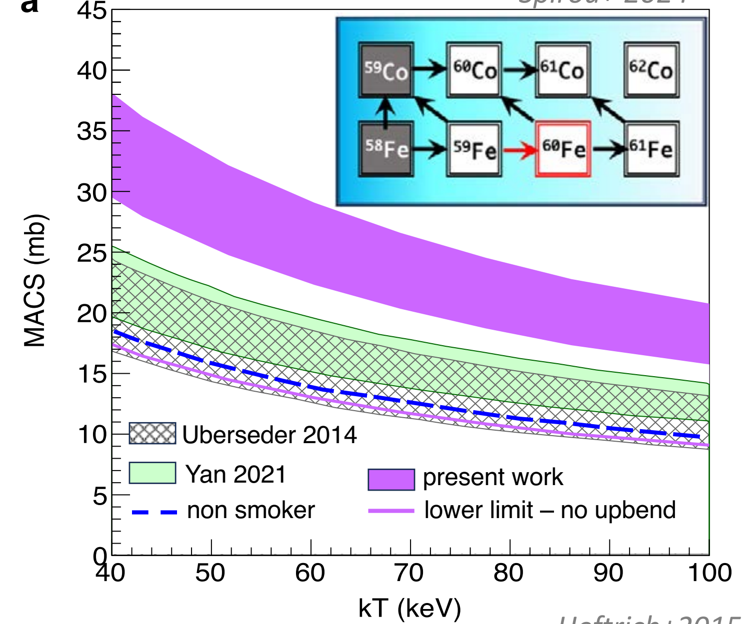
☆ What are the n capture rates?

☆ What are the β decay lifetimes?

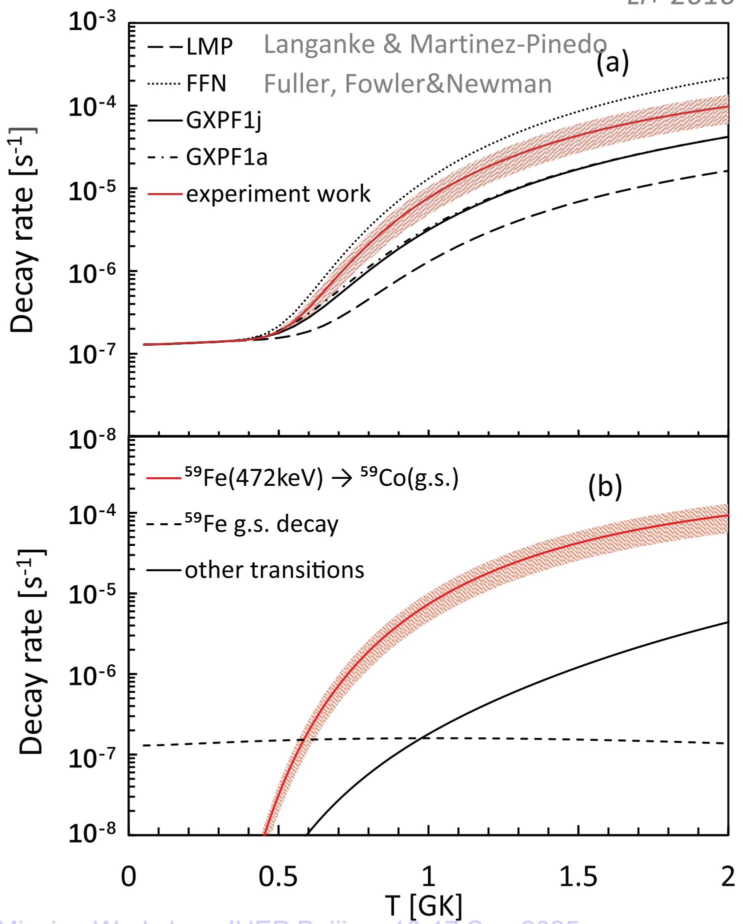
Experimental constraints on relevant nuclear reactions

Spirou+ 2024

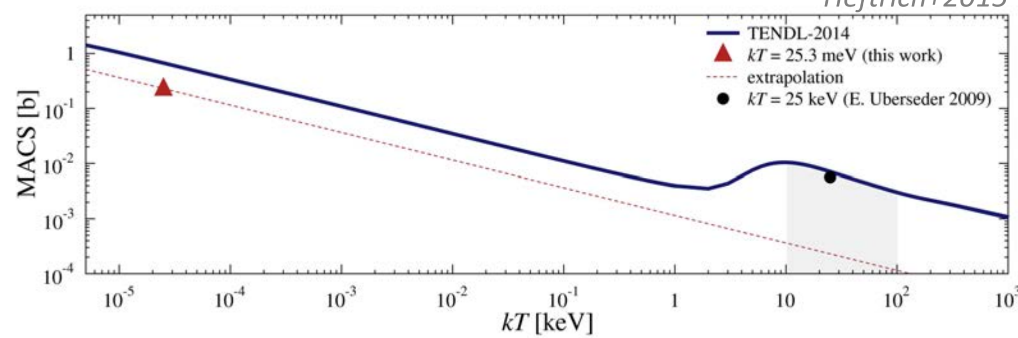
n capture on ^{59}Fe appears
more intense in a recent study
→ increase of yields by ~factor 2



Li+ 2016



Heftrich+2015



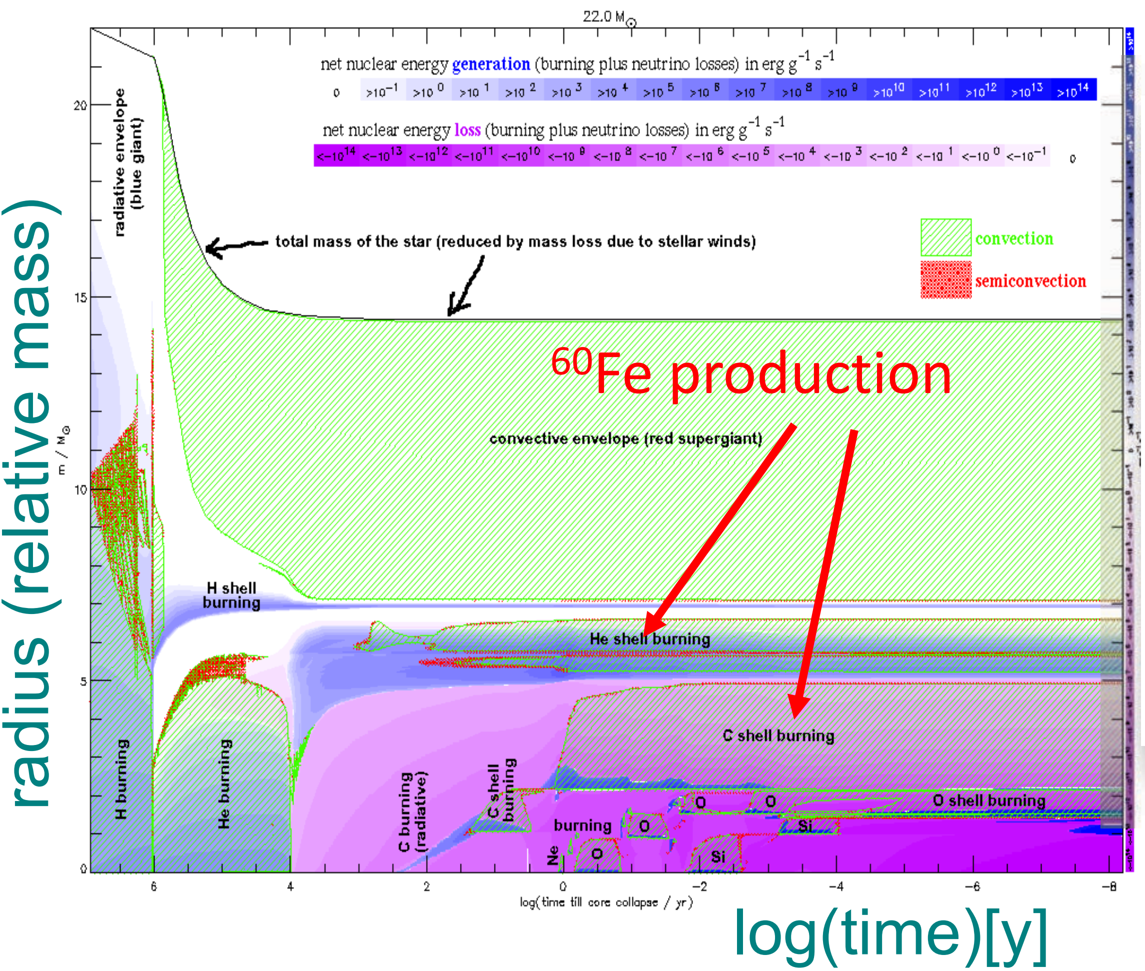
β decay of ^{59}Fe appears
more intense than thought (LMP)
→ decrease of yields by ~factor 3

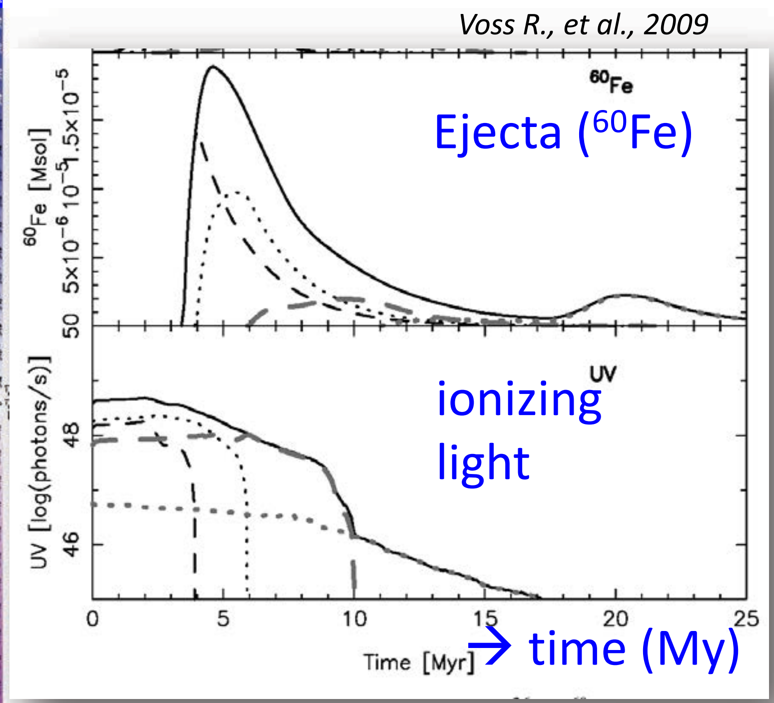
How massive stars stars evolve towards the ccSN

- ☆ neutron-releasing reactions only in He and C burning
- ☆ ^{60}Fe production only in late evolution → released only with ccSN

Kippenhahn diagramn of stellar evolution

evolution of a group of stars (popSyn)



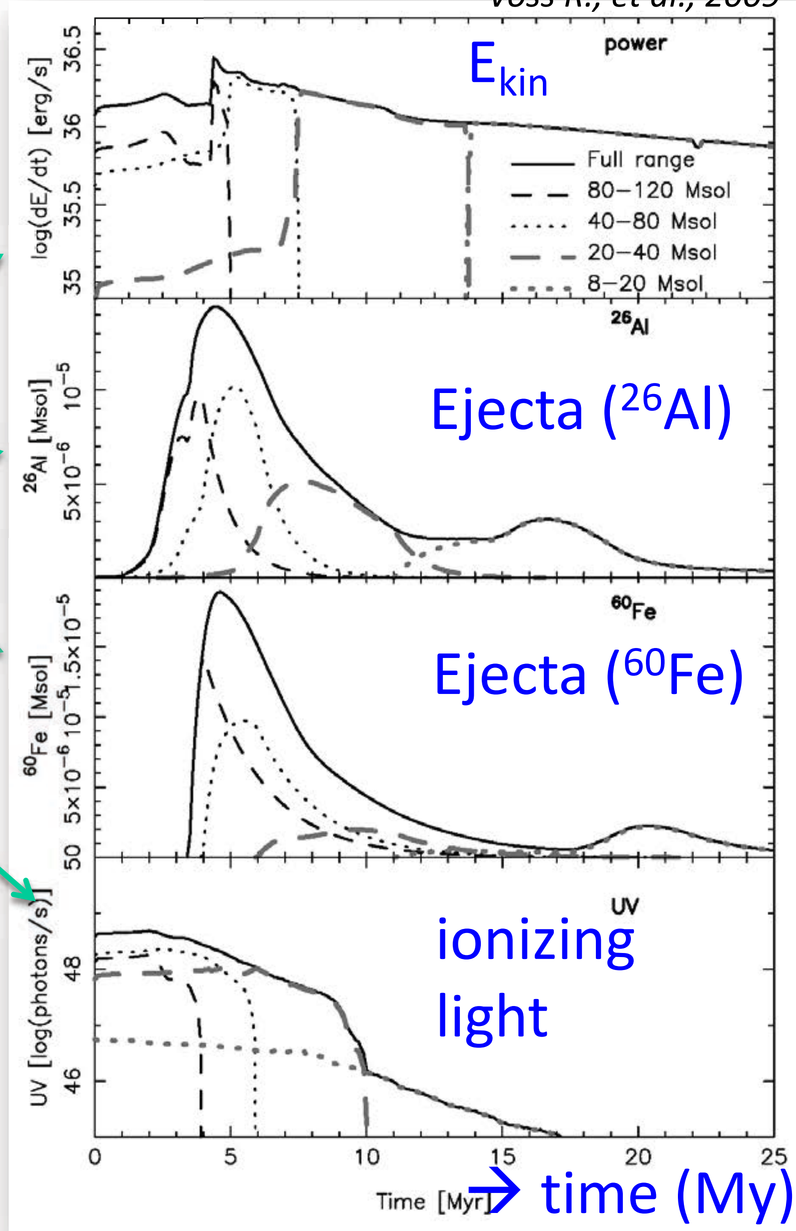


Massive-Star Groups

- We study the "outputs" of massive stars and their supernovae
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation

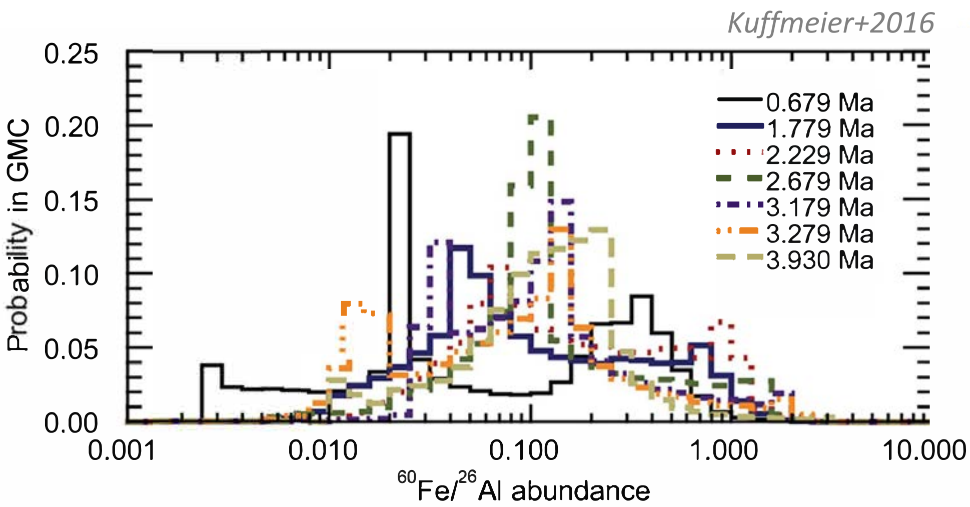
- We get observational constraints from
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

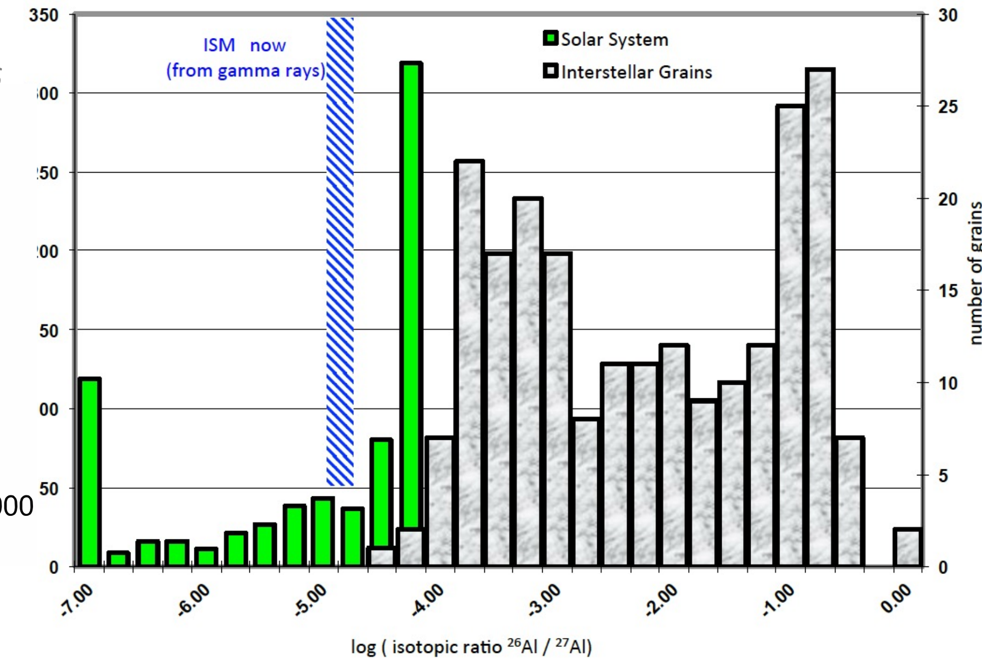
Voss R., et al., 2009



Star formation in active star-cluster regions

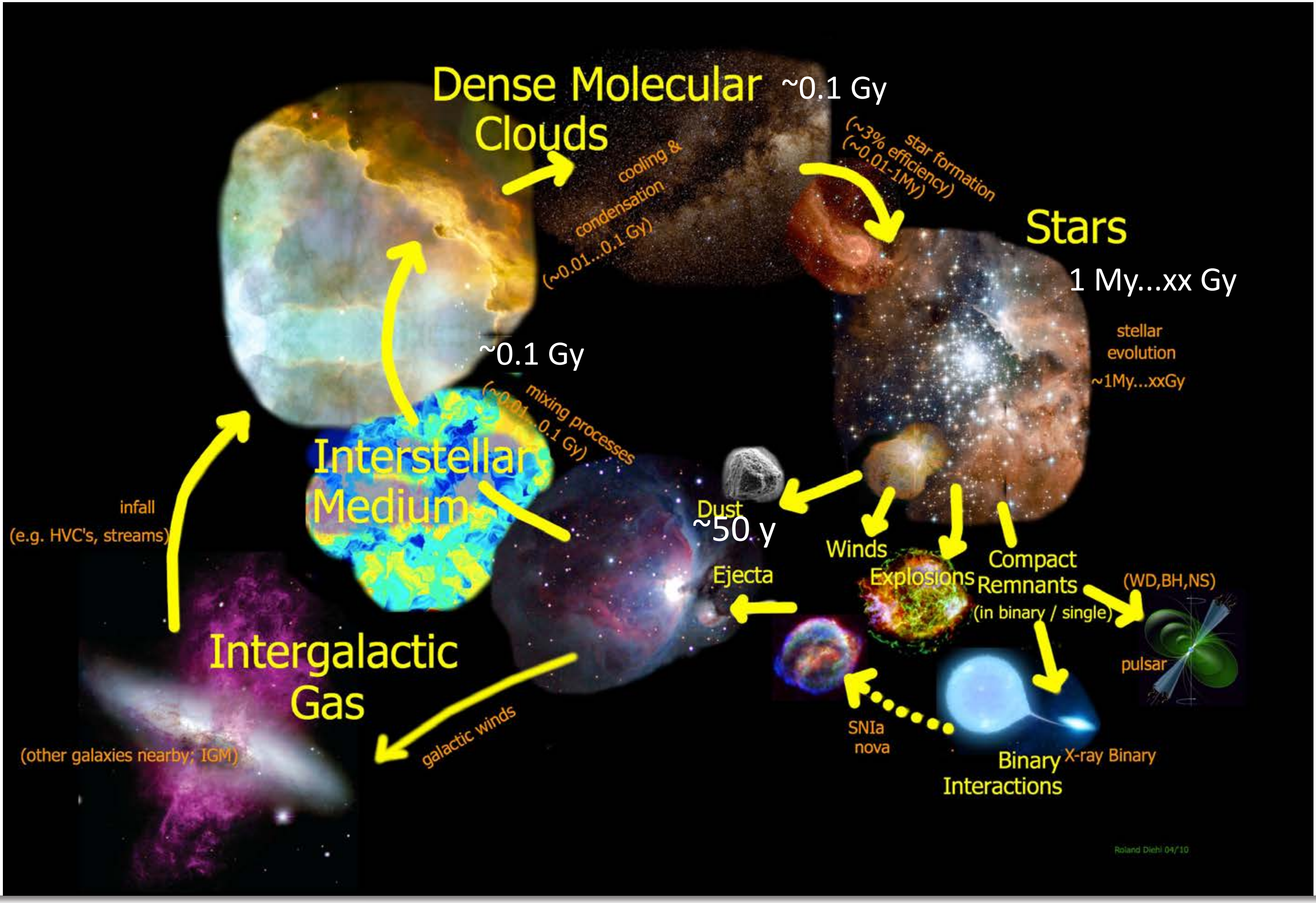
- The composition will vary locally, near newly-ejected ashes
  - ☆ example: massive stars and ccSupernovae: ^{26}Al and ^{60}Fe
  - ☆ ^{60}Fe/^{26}Al ratio differences: →



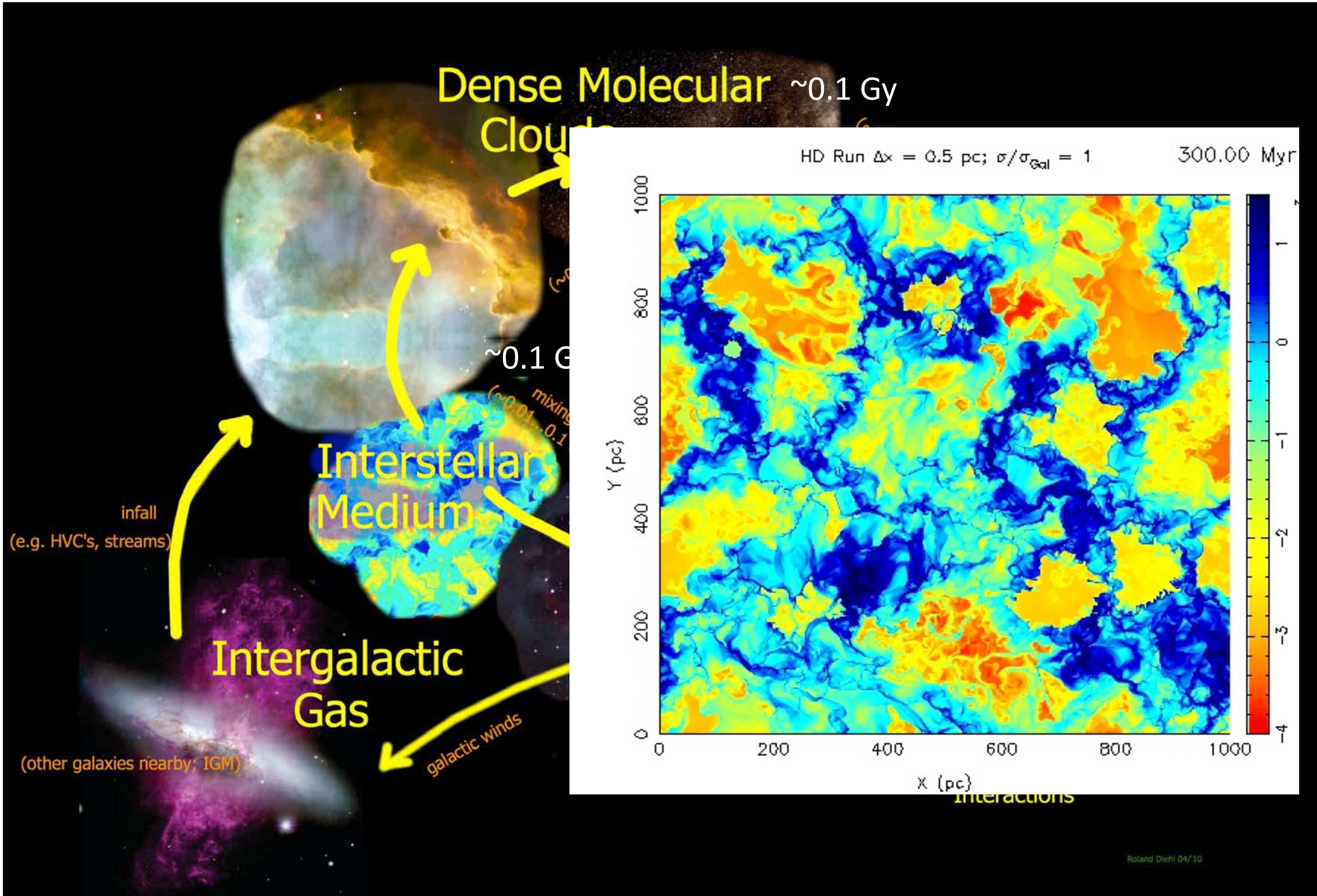


  - ☆ theory: major dependencies on GMC morphology (→ 'feedback'?!!)
- Newly ejected ashes could be incorporated into 2nd gen stars (Sun?)
- The Galaxy at large has ^{60}Fe/^{26}Al ~ 0.5, the ESS ~0.002 – why?

Iterative enrichments of stellar gas from nucleosynthesis



chemical-evolution models: how to capture ejecta in a star…



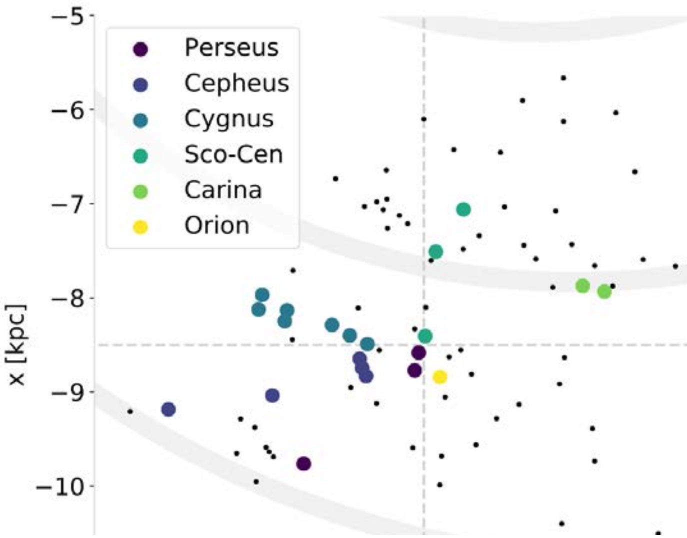
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling

- Use stellar / SN yields and evolution times
- Include knowledge about sources (stellar groups)
- Include known groups; sample unknown groups

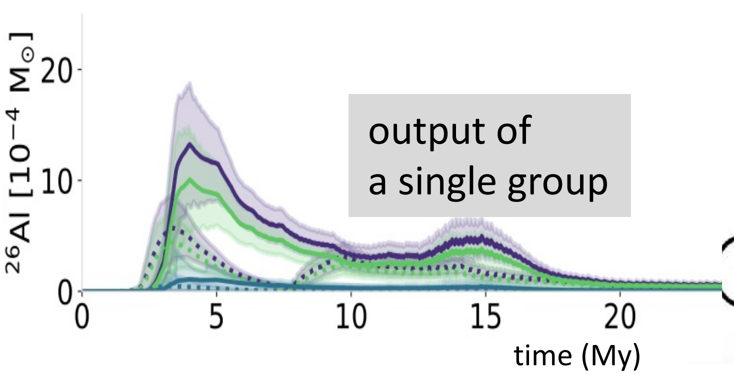
→ bottom-up model for the ^{26}Al observations

Pleintinger PhD thesis 2020 (see also Siegert+ 2023)

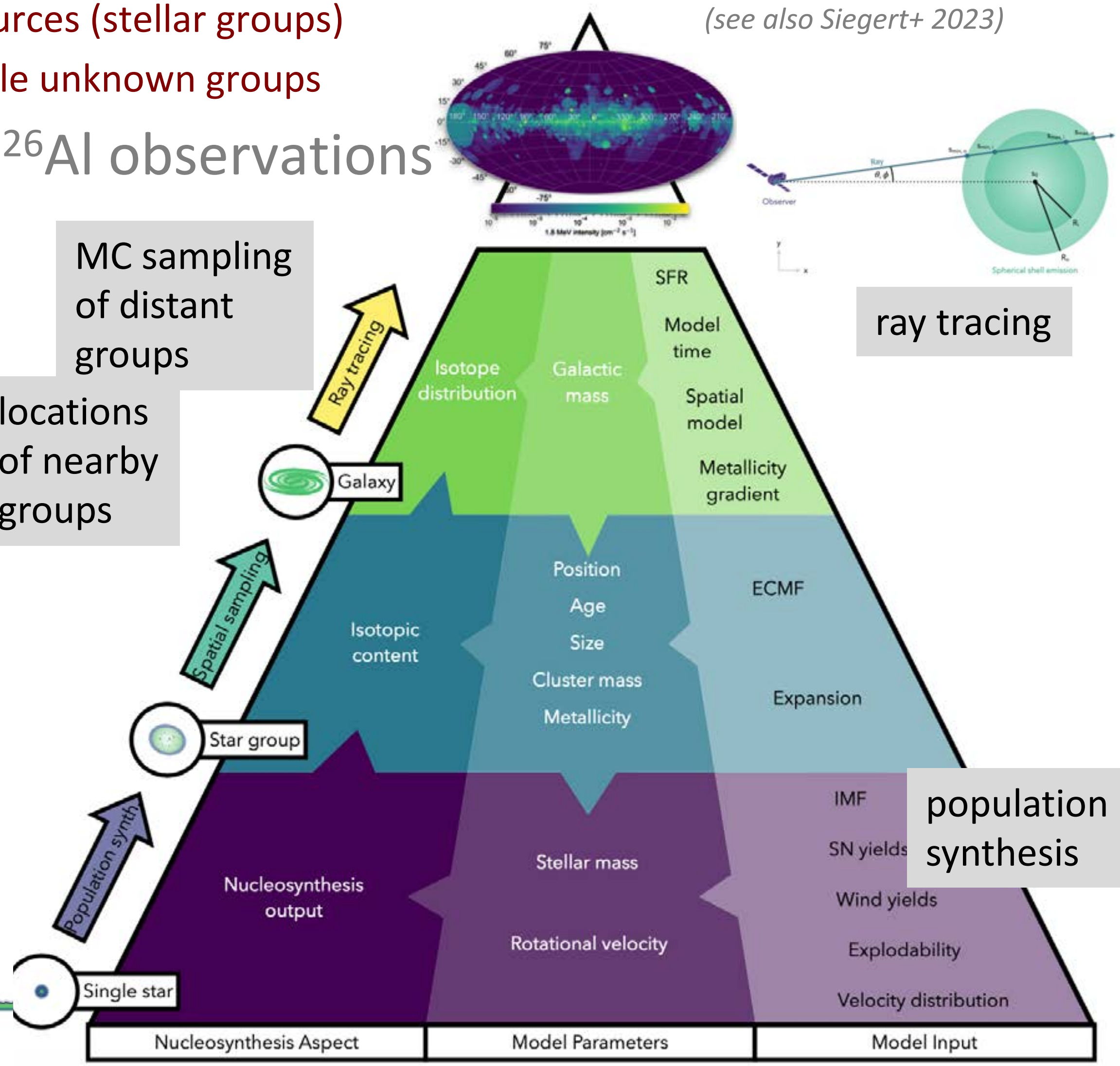


MC sampling of distant groups

locations of nearby groups



output of a single group



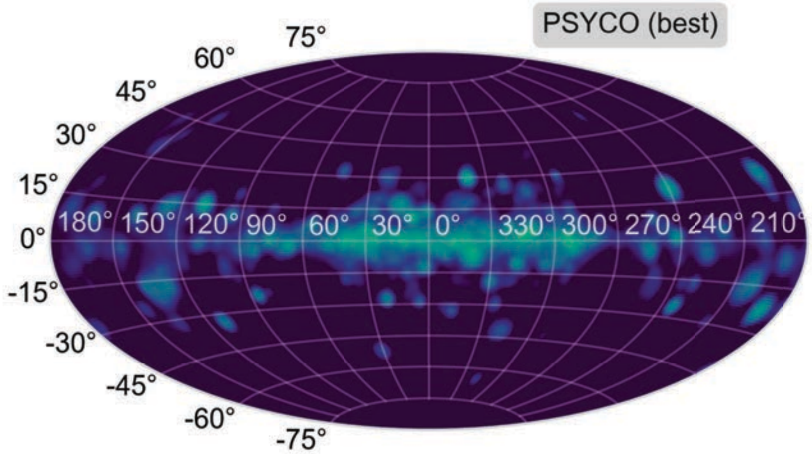
ray tracing

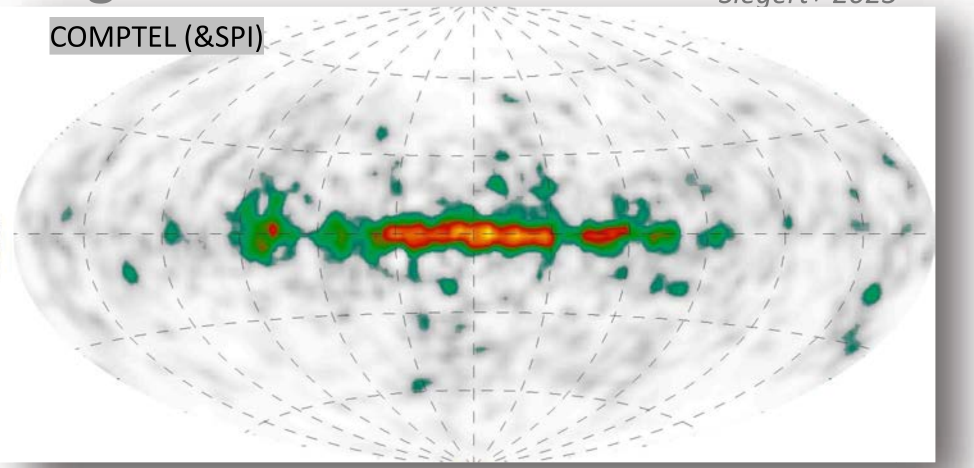
population synthesis

Diffuse radioactivity throughout the Galaxy

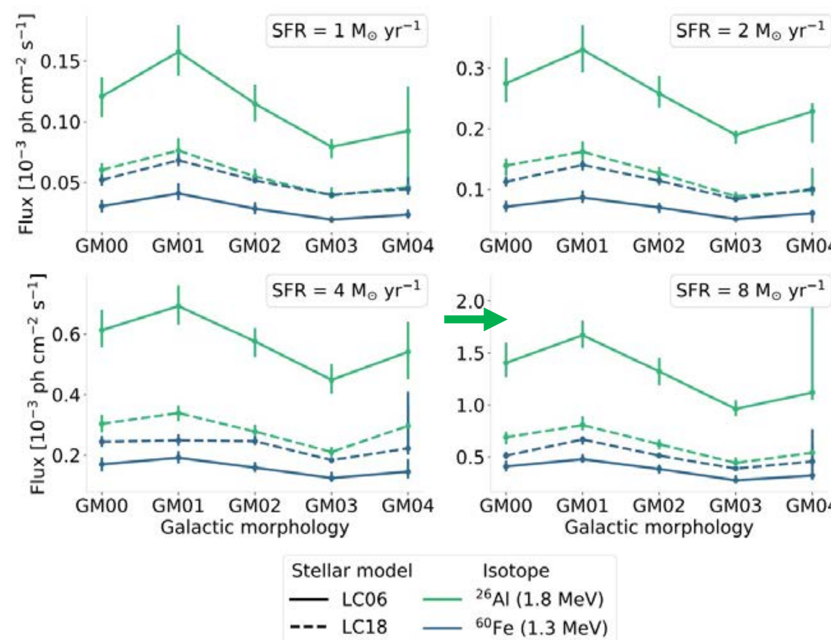
Galactic Population Synthesis Modelling versus observations

Pleintinger 2020
Siegert+ 2023





- PSYCO modeling: (30000 sample optimisation)
  → best: 4-arm spiral 700 pc, LC06 yields, SN explosions up to 25 $M_\odot$
- SPI observation: → full sky flux
  $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1}
- flux from model-predicted ^{26}Al:
  → $(0.5..13)\ 10^{-4}$ ph cm^{-2} s^{-1} → too low
- Best-fit details (yield, explodability) depend on superbubble modelling
  (here: sphere only)



cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{-1} *(Zari+2022)*

Estimating an image of ^{60}Fe

- Assuming the fundamental sources to be massive stars & their SNe

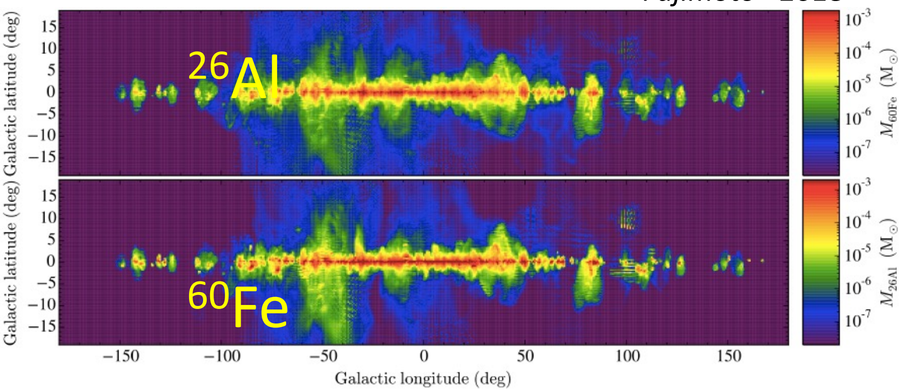
3D hydro simulations
a generic galactic disk

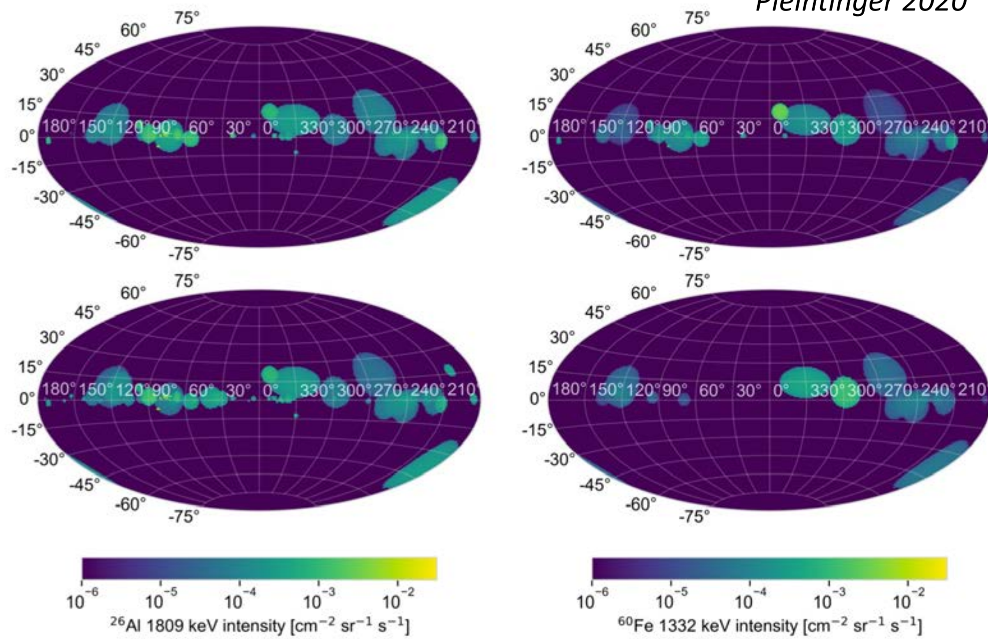
Population synthesis
Nearby massive-star groups

^{26}Al ^{60}Fe

Pleintinger 2020

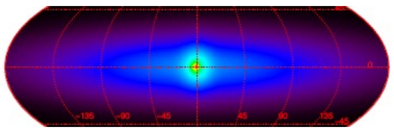
Fujimoto+ 2018





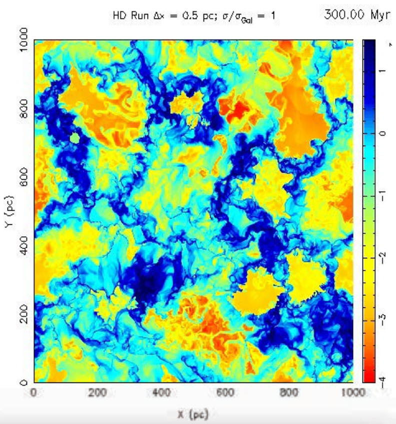
Science Challenges for Gamma-Ray Spectroscopy - Summary

- Positron science is a unique astrophysical puzzle and study theme
  - origins are unknown, and include exotic sources (plasma jets, dark matter,...)
  - annihilation signatures are a diagnostic of ISM and CR propagation

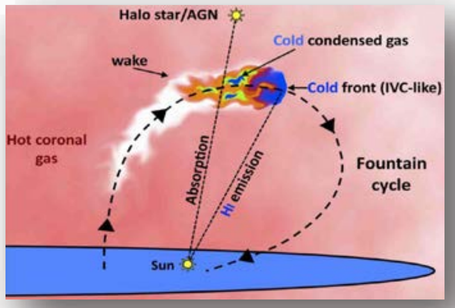


- Nuclear lines are a unique window for cosmic ray studies at <GeV
  - key targets are cosmic-ray acceleration regions, and fully-ionised plasma

- Supernova explosion astrophysics receives key insights at MeV
  - SN Ia explosions are not spherically symmetric; explosion triggering
  - morphology of radioactive versus other envelope ejecta measured at MeV
  - ccSN interior nucleosynthesis conditions reflected in 44Ti, 56Ni
  - exotic/rare explosion types may have key diagnostics at MeV γ's (PISN...)



- Other/exotic/rare explosion types provide unique opportunities
  - NSMs/kilonovae are fundamentally asymmetric, & rare
  - Hypernovae, PISNe, jet SNe should have unusual MeV signatures
  - Nova explosions of different types have unique MeV signatures
- Stellar interior structure is probed through ^{26}Al/^{60}Fe ratio
- Cycling of cosmic gas through sources and ISM is reflected in diffuse radioactivity signals
  - ^{26}Al shows flows from massive star groups in superbubbles
  - ^{60}Fe is a SN/wind ejecta diagnostic, and traces nearby SNe

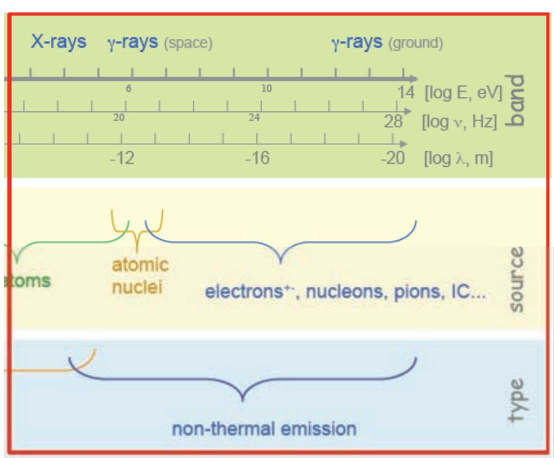


Science goals for a new MeV mission: Suggestions for discussion

- "target science"
  - ☞ A convincing case where a mission will "solve" an open science issue
  - ☆ The positron puzzle
  - ☆ short-lived radioactivities from nucleosynthesis events (SNe, Novae, KNe)
  - ☆ Supernova explosion models and radiation transfer
  - ☆ Interior structure of massive stars
  - ☆ The role of massive star clusters for galactic structure and evolution
  - ☆ Acceleration of relativistic particles

- "Exploration"
  - ☞ A detailed exposure of the science potential of this particular astronomical window
  - ☆ 511 keV (e^+) astronomy
  - ☆ ^{26}Al astronomy
  - ☆ Non-thermal emission from high-energy sources
  - ☆ Nuclear-line emission from otherwise non-visible cosmic plasma (LECRs, IGM,..)
  - ☆ Dark-matter signatures
  - ☆ ...

the 'MeV gap' challenge: significant astrophysics with new instruments

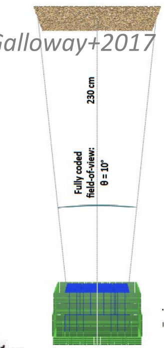


We can build on achievements for brightest sources

(and prospects from theoretical considerations: 'new'!)

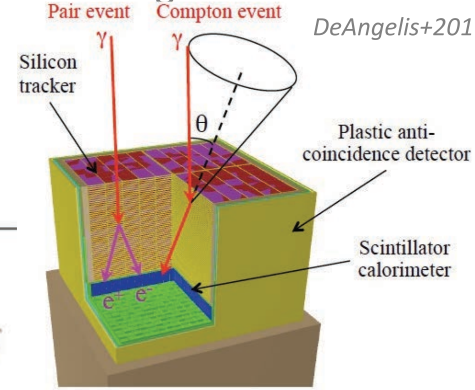
We can do now >one o.o.m. better now

Compton Telescopes+.. are being developed in labs



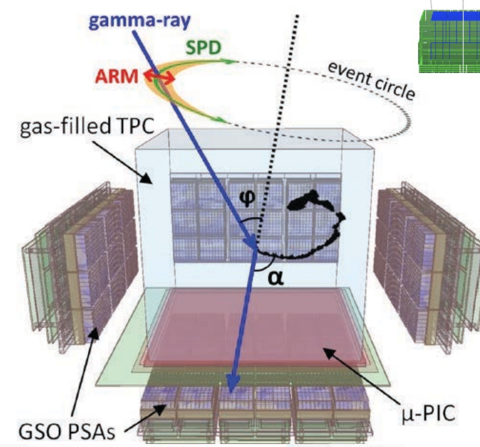
eAstrogam

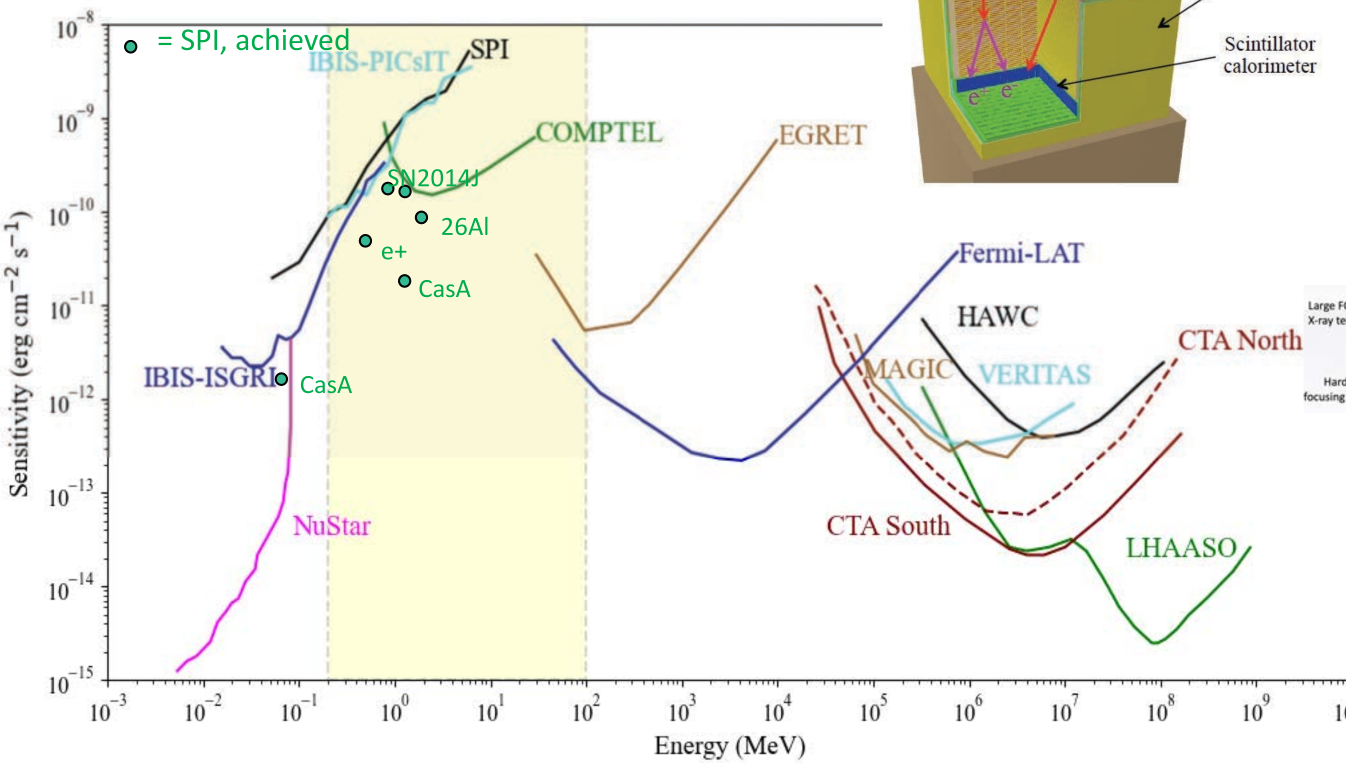
DeAngelis+2017, 2018



ETCC

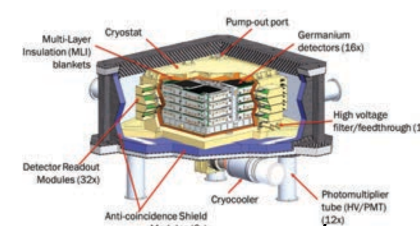
Tanimori+2015





CAST/CNSA

Peng+2020



COSI/NASA

Tomsick+2021