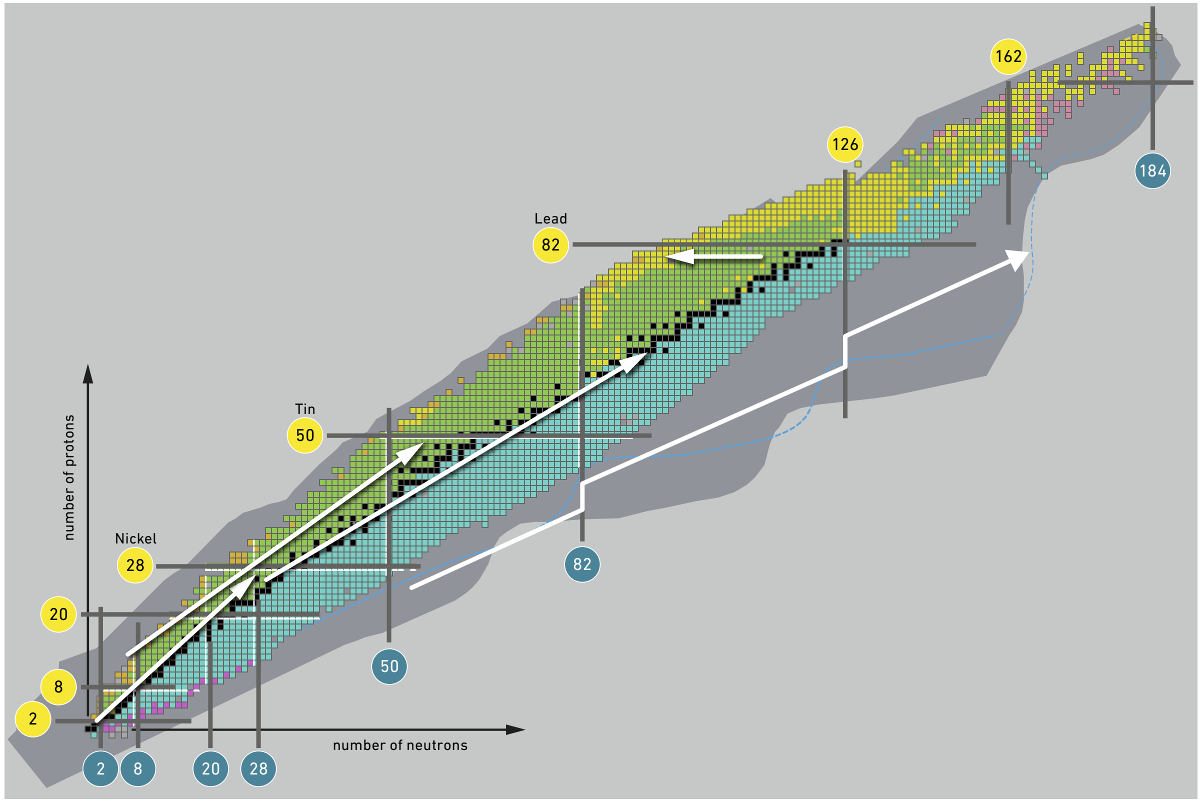
Isotopes in Cosmic Sites: Observations and Lessons

Roland Diehl

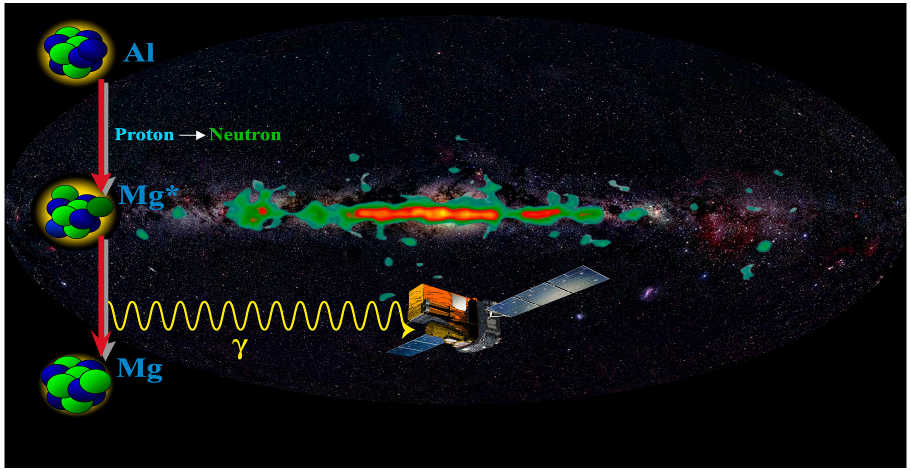
Max Planck Institut
für extraterrestrische Physik
Garching, Germany

How cosmic isotopes are being made, and how measurements enable us to study this



Contents:

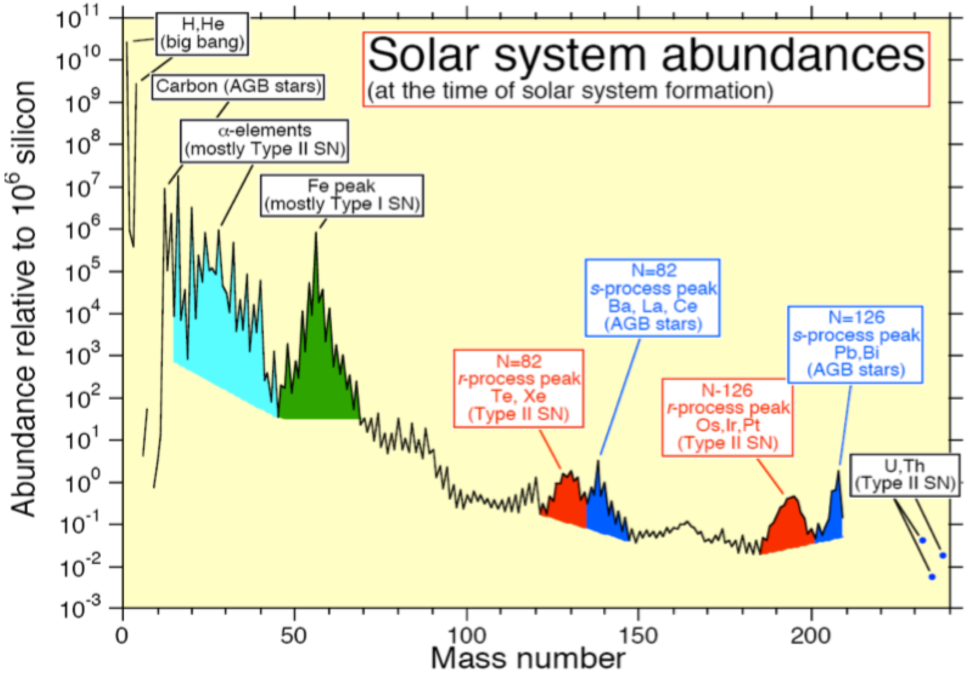
1. Isotopes in the cosmos
2. Nuclear reactions and cosmic sites
3. Astronomy of cosmic isotopes
4. Lessons learned and open questions



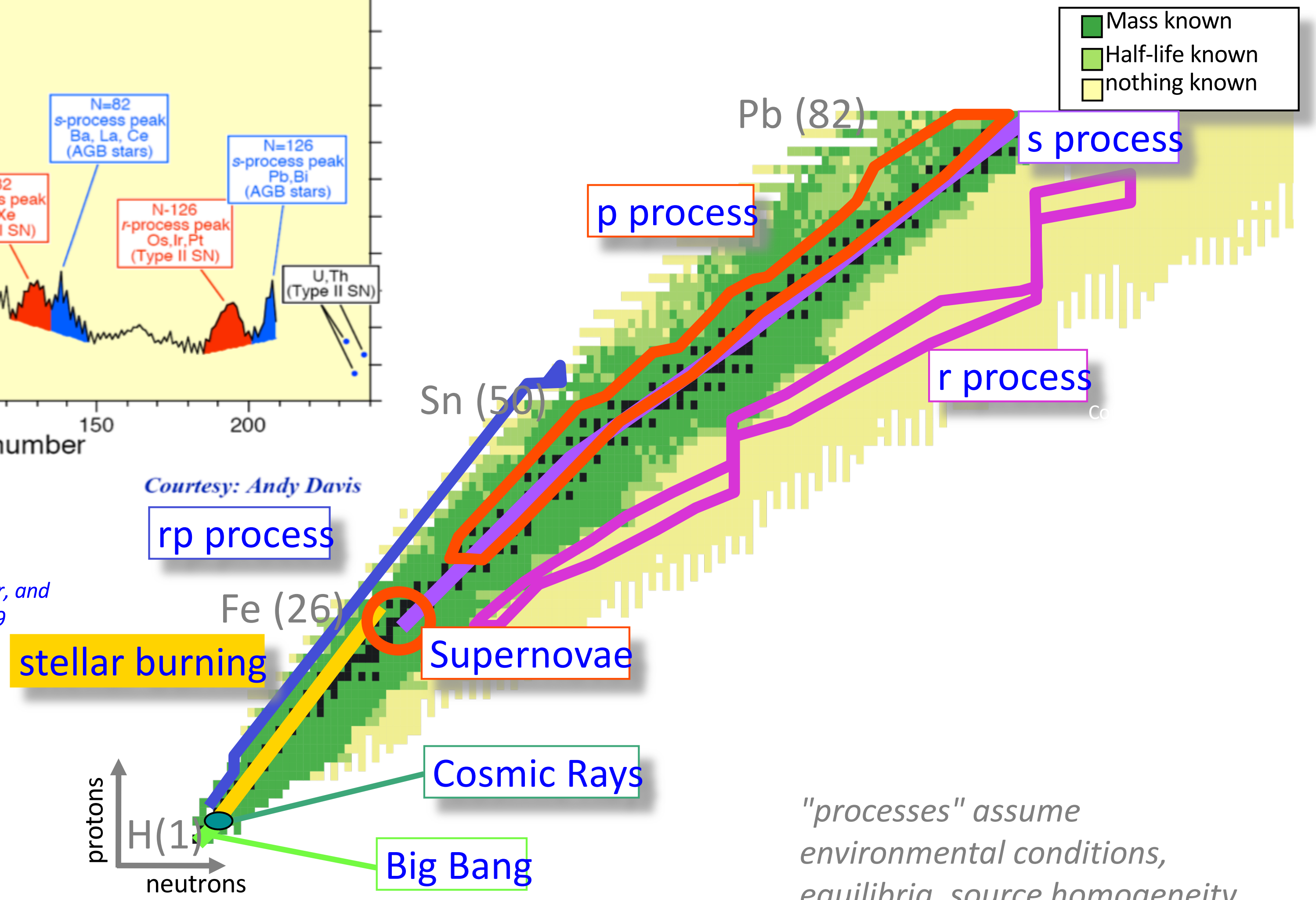
Cosmic origins of the variety of nuclides

- Associating different "processes" with nuclide groups – that's what we teach…

  … and know is superficial (or even wrong)



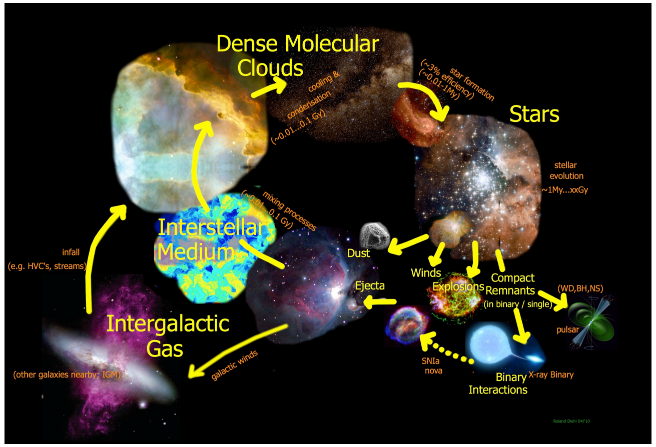
Courtesy: Andy Davis

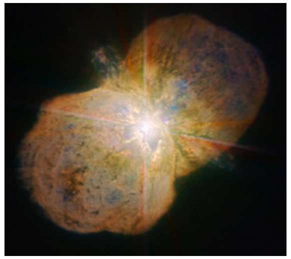


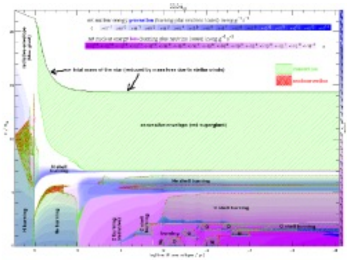
cmp. Burbidge, Burbidge, Fowler, and Hoyle, RMP 1959

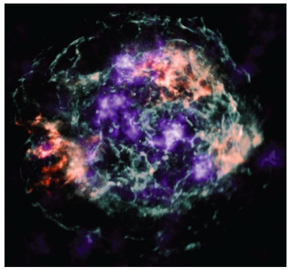
"processes" assume environmental conditions, equilibria, source homogeneity, …

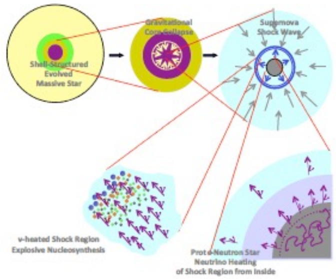
Science with Cosmic Isotopes

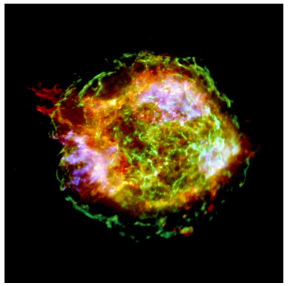


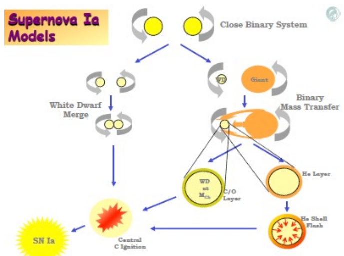












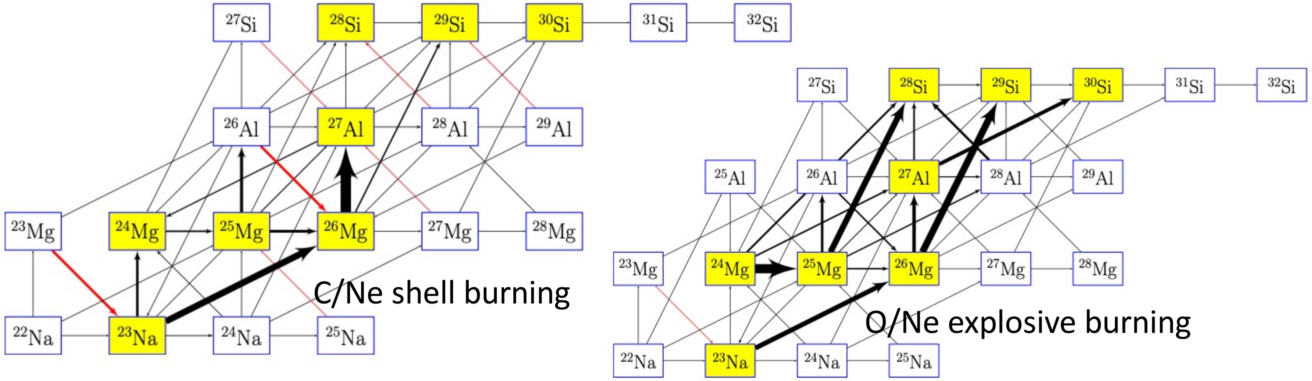
☆Trace the forms of cosmic matter

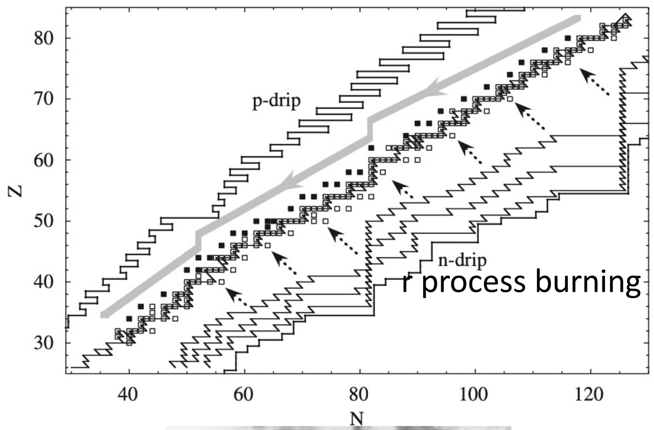
☆Understand the sources of new nuclei

rare sources are a challenge (& speculation)....

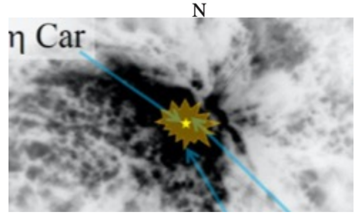
Messengers for Cosmic Nucleosynthesis: Issues

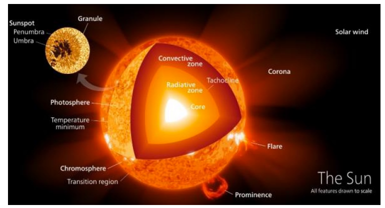
- Complex and variate nuclear-reaction flows

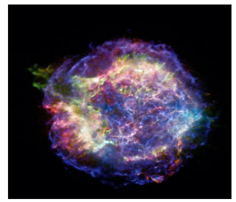


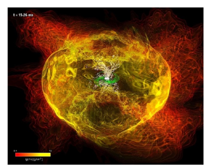


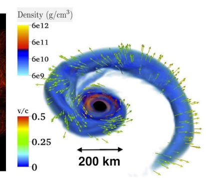
- Cosmic nuclear-reaction sites are embedded
  - ☆ Stars:
    - inactive envelope is ~90% of stellar mass
  - ☆ Supernovae:
    - envelopes large (SN II) or small (SN Ia)
  - ☆ Kilonovae:
    - envelopes are highly dynamic, assymmetric
  - ☆ ...





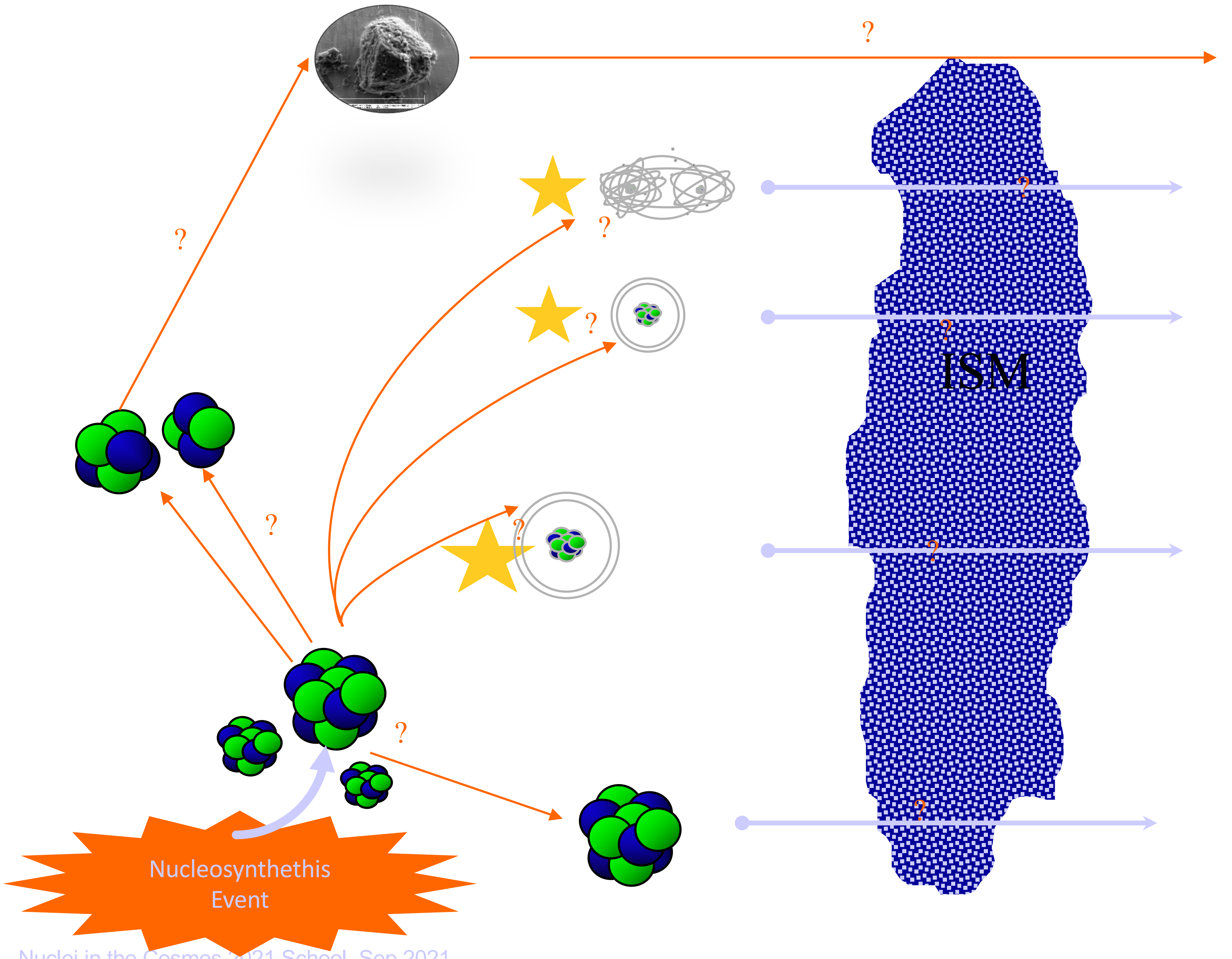






How do we measure nuclei in cosmic sites?

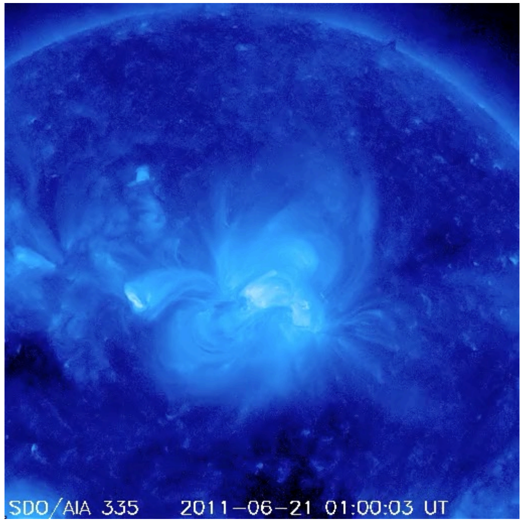
Diversity of Complementing Observing Methods



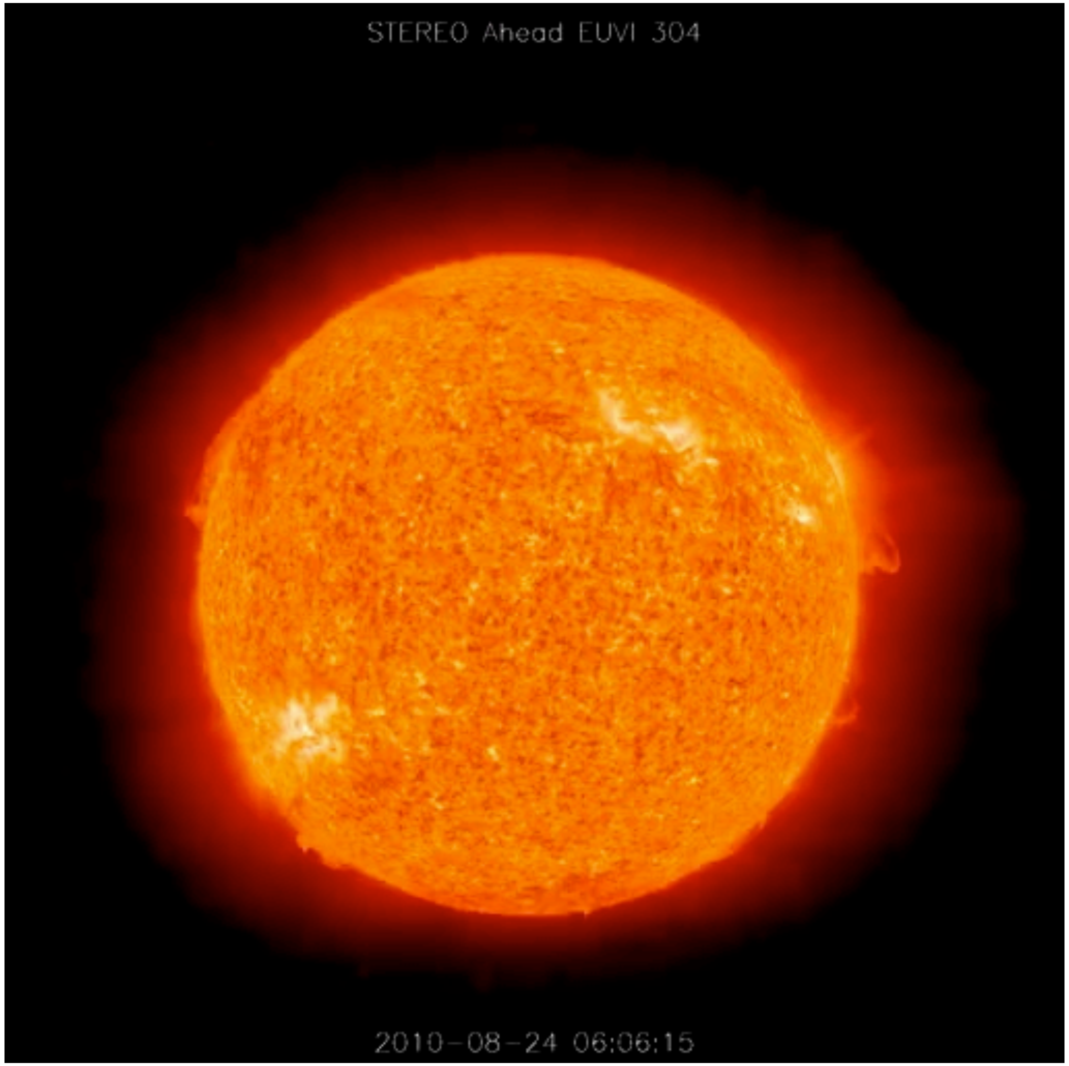
- Meteoritic stardust Studies, Cosmic Rays
- Molecular Absorption-lines (Radio,IR)
- Atomic Absorption-lines (opt,UV)
- Atomic Emissionlines (opt,UV,X)
- Gamma-Ray Lines from Radioactive Isotopes

A closer look: The Sun

Telescopes can see many exciting surface phenomena...

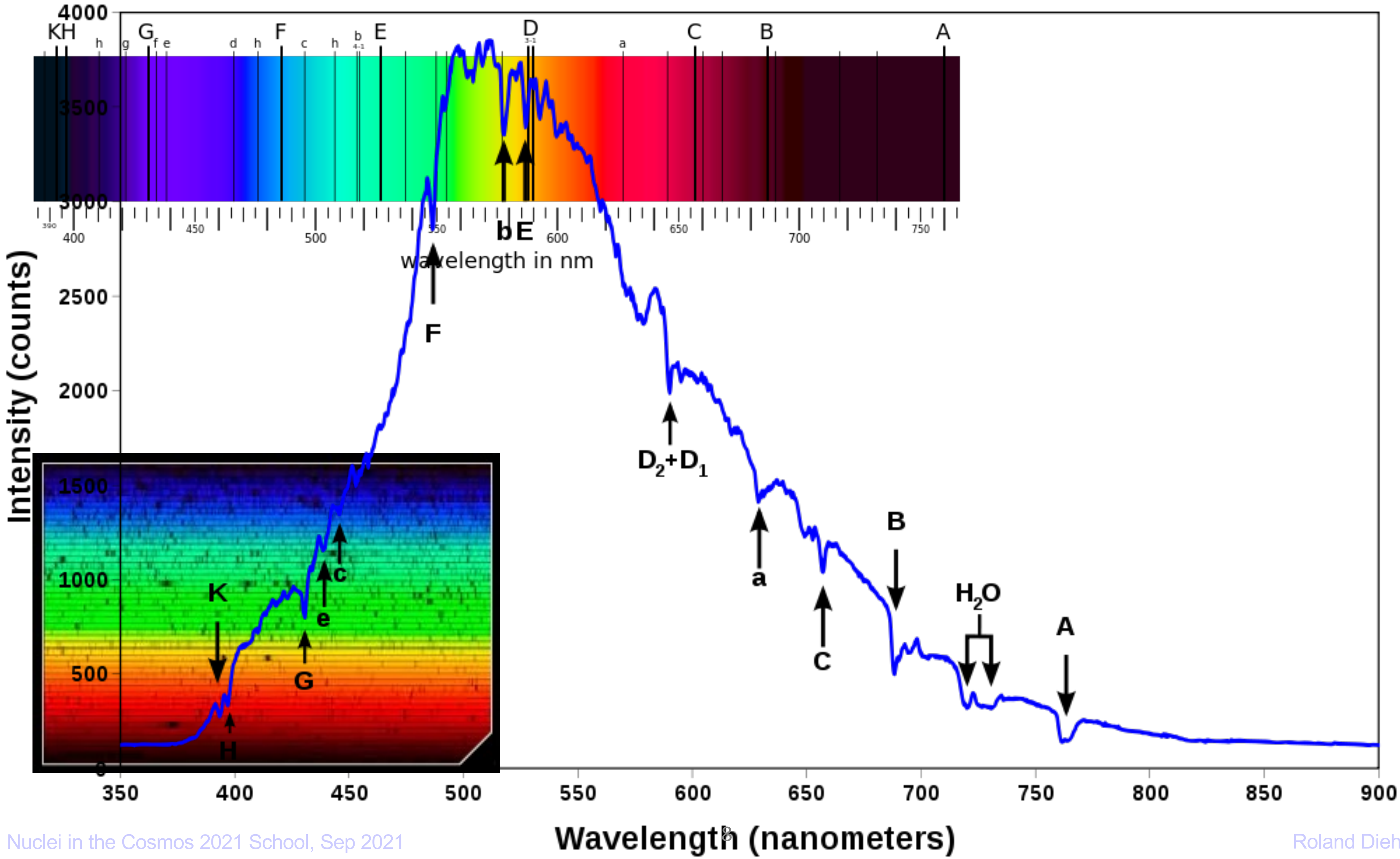


Solar Dynamic Observatory



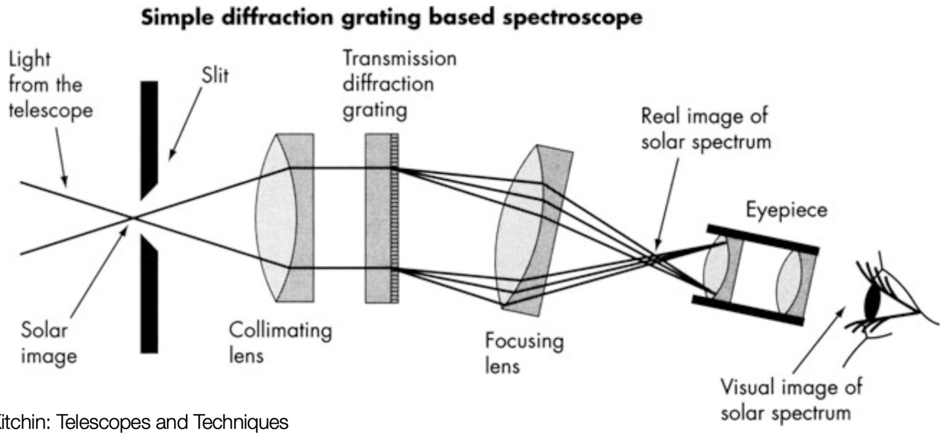
Signatures of Elements

Spectral lines in the spectrum of Sunlight



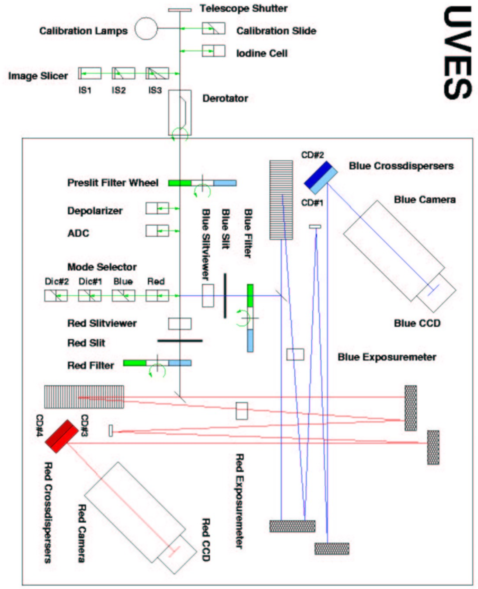
Spectrographs in optical telescopes today

- Make use of wavelength-dependent propagation in materials



Kitchin: Telescopes and Techniques

Modern Spectrograph layout



Dispersion elements

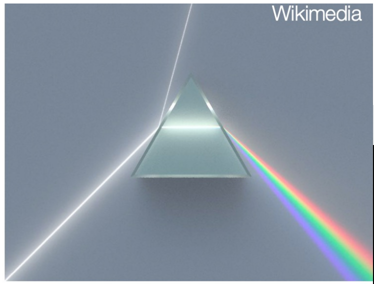
- prism
  - low dispersions
  - can be used as objective prism
    - slitless spectroscopy
- diffraction grating
  - mostly reflective
  - equally spaced grooves

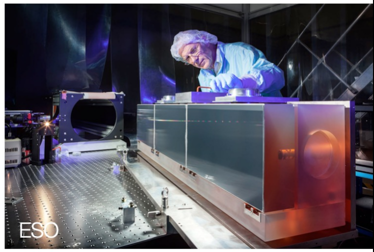
$m\lambda = \sigma(\sin\beta + \sin\alpha)$

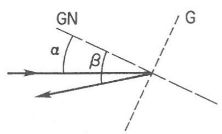
with m order number

σ distance between grooves

- called the *grating constant*



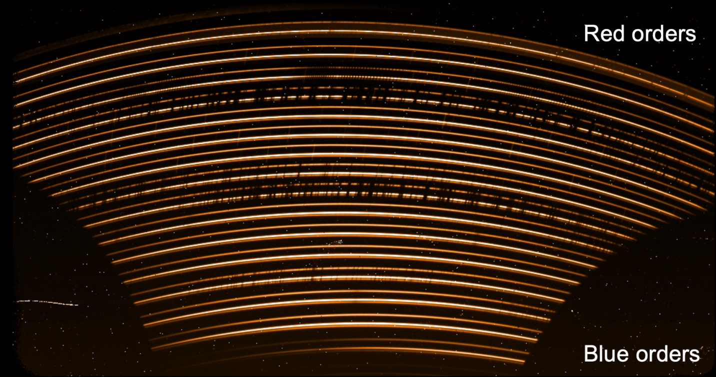




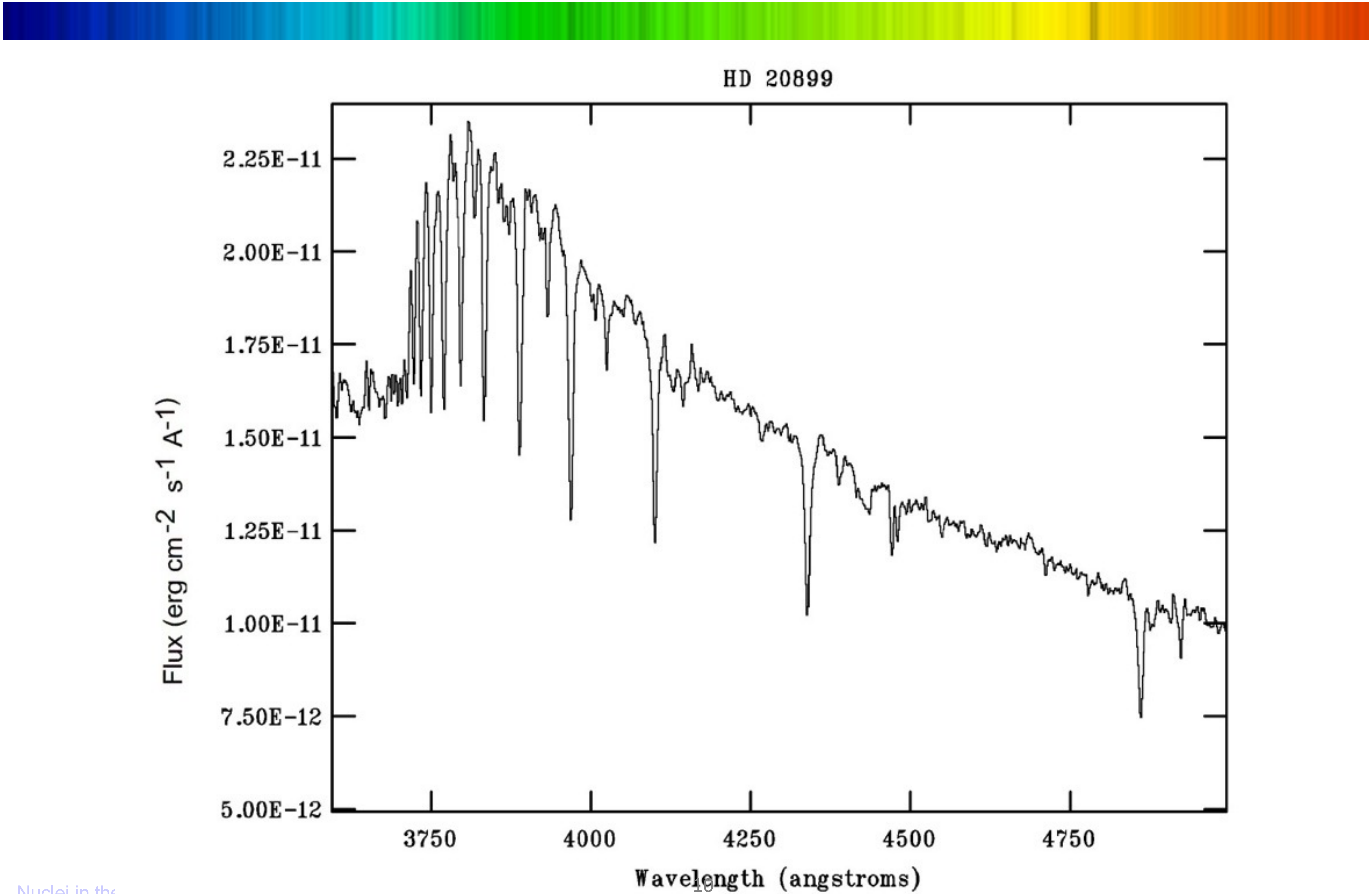
Schroeder: Astronomical Optics

Cross-dispersed echelle

- X-shooter



Optical Spectra: Observables of Stars

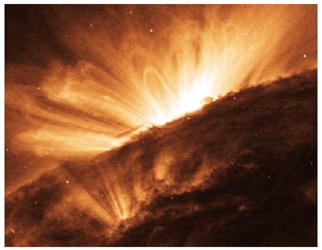


Jacoby, G. H., Hunter, D. A., and Christian, C. A. 1984, Astrophys. J. Supp. Ser., 56, 257

Solar Photospheric Abundances

improvements of

- ☆ measurement technique,
- ☆ interpretation (line shape modeling)
  - ☞ 3D atmopshere models for convective motion
  - ☞ atomic-line calibrations
  - ☞ non-LTE population of ionisation states



→ C,N,O abundances reduced 2009 by ~30% wrt 1998 reference

☞ *Asplund+2009, 2015...*

Lodders 2010

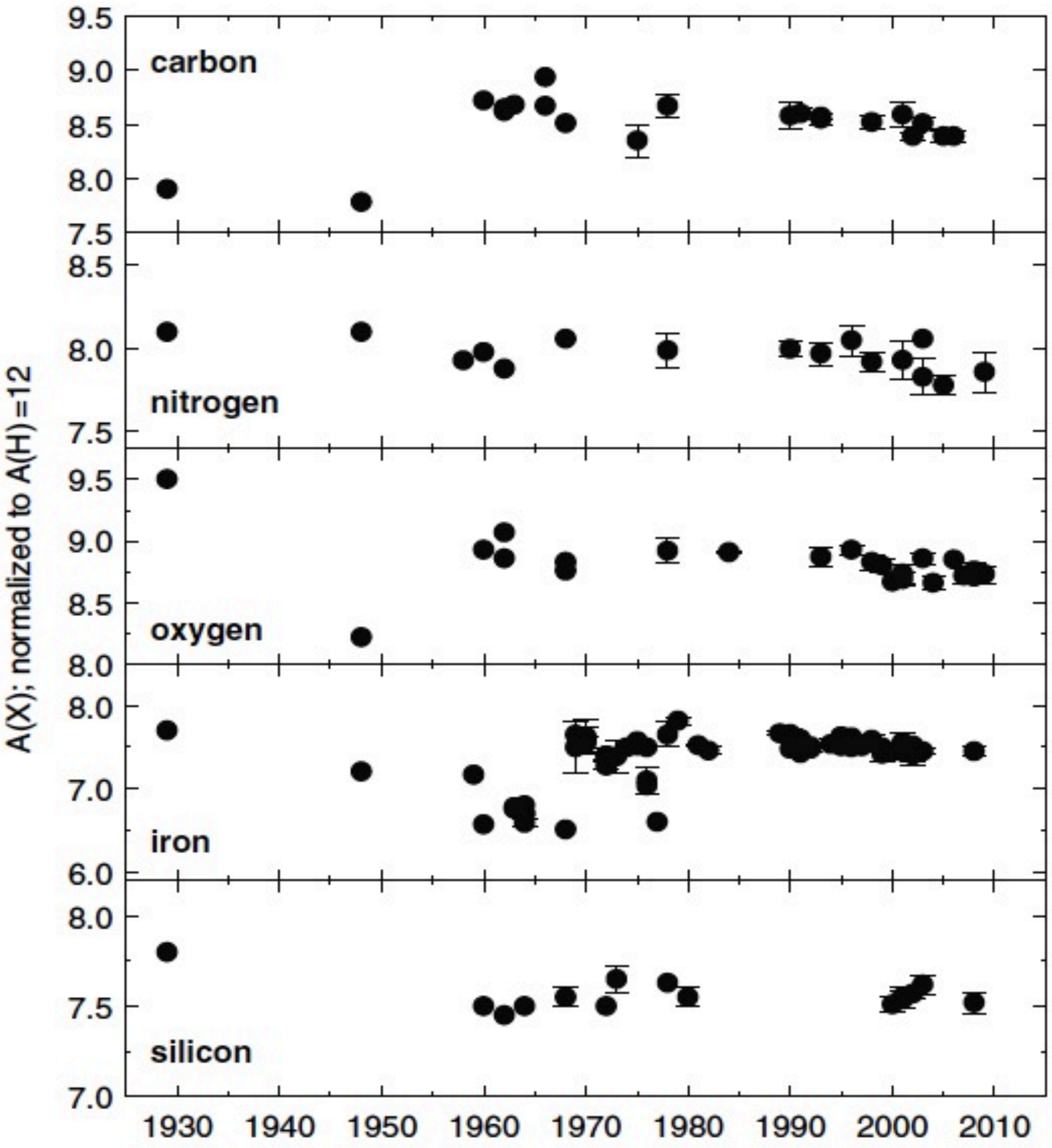
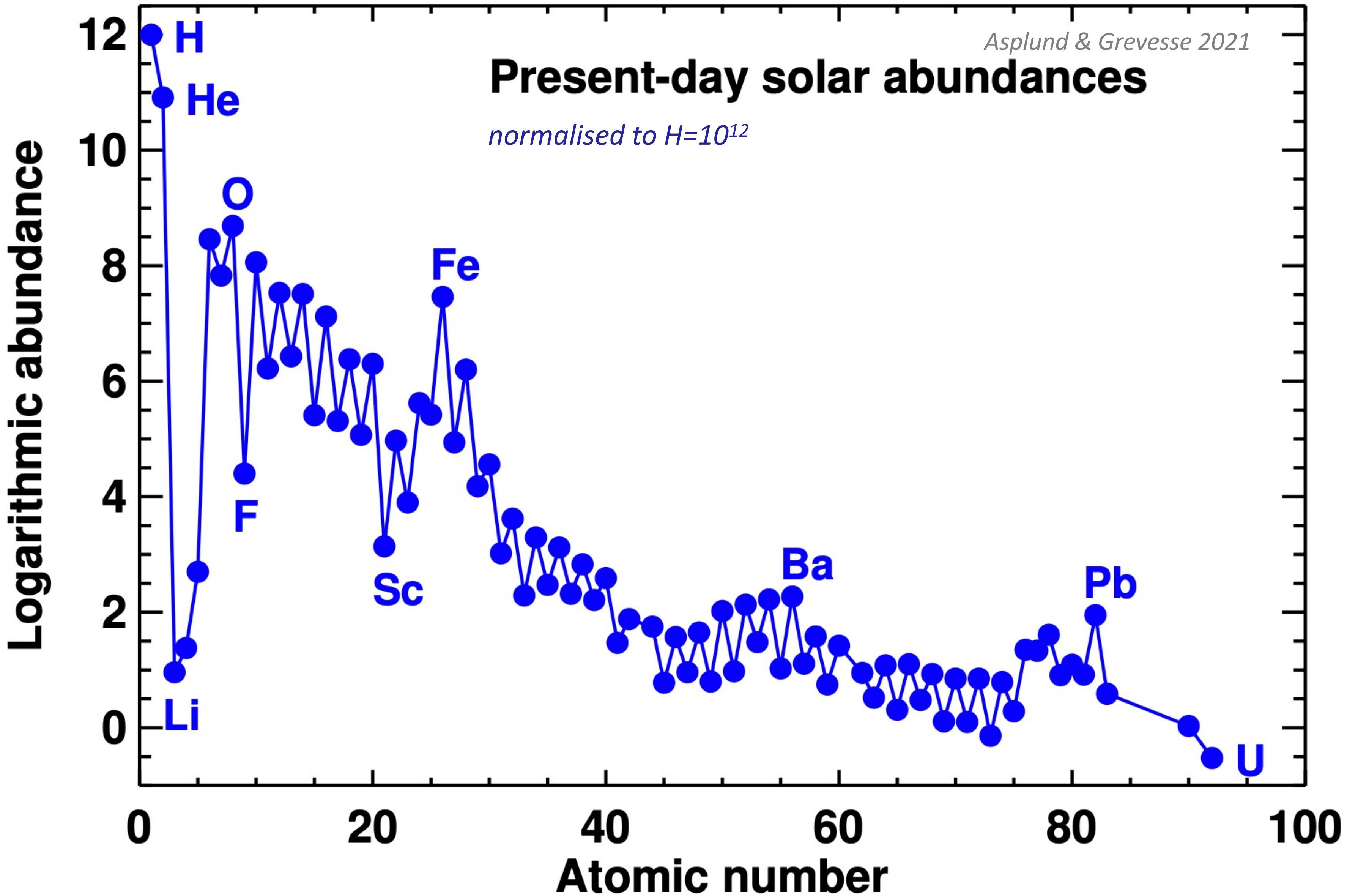


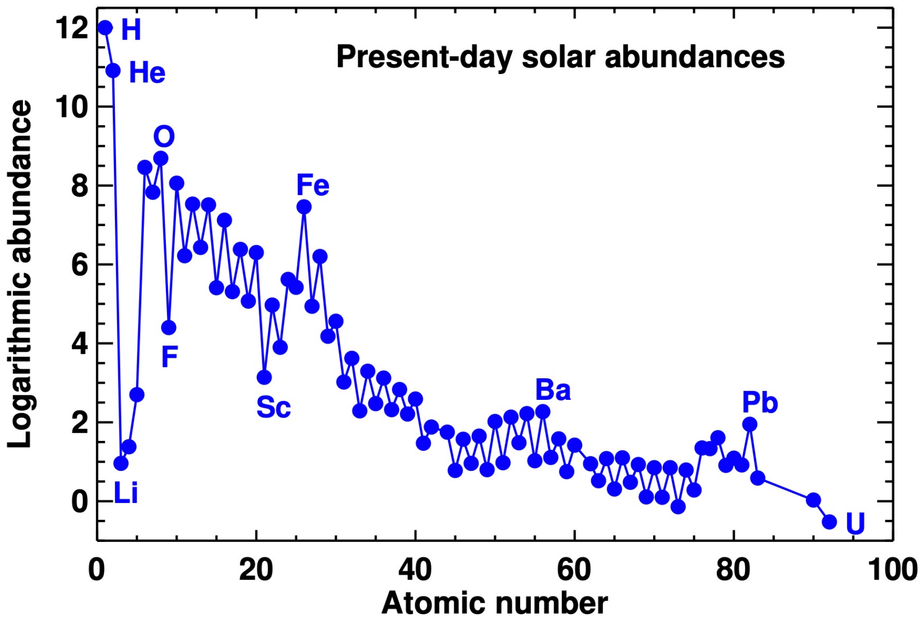
Fig. 2. Photospheric abundance determinations over time

Solar Elemental Abundances

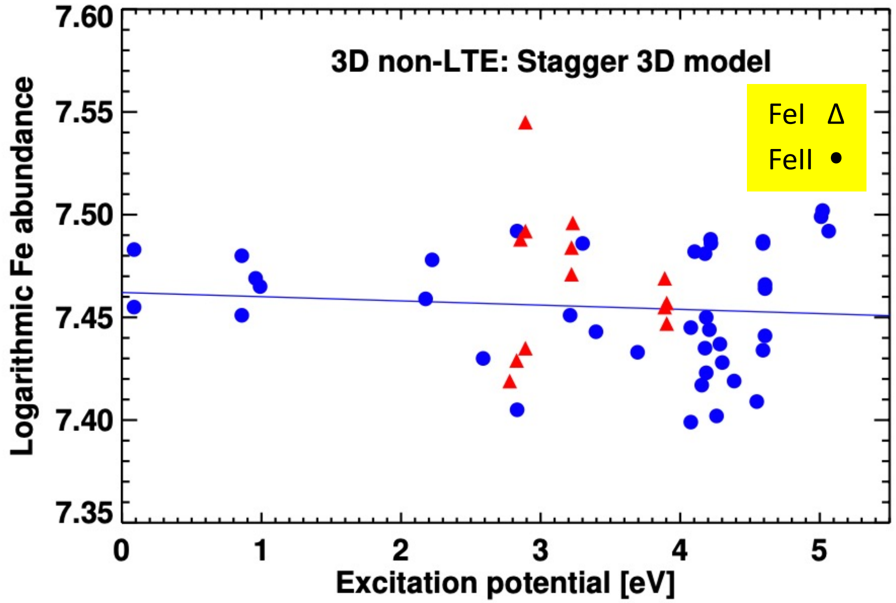


determined from 3D-NLTE analyses of solar spectra

Solar Elemental Abundances

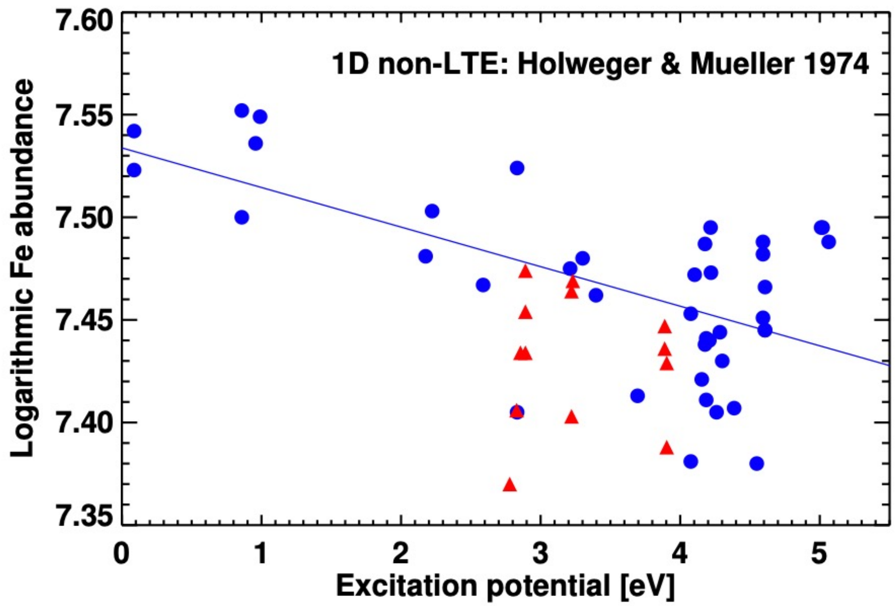


Asplund & Grevesse 2021



3D-NLTE analyses of solar spectra reveal differences to previous spectral analyses:

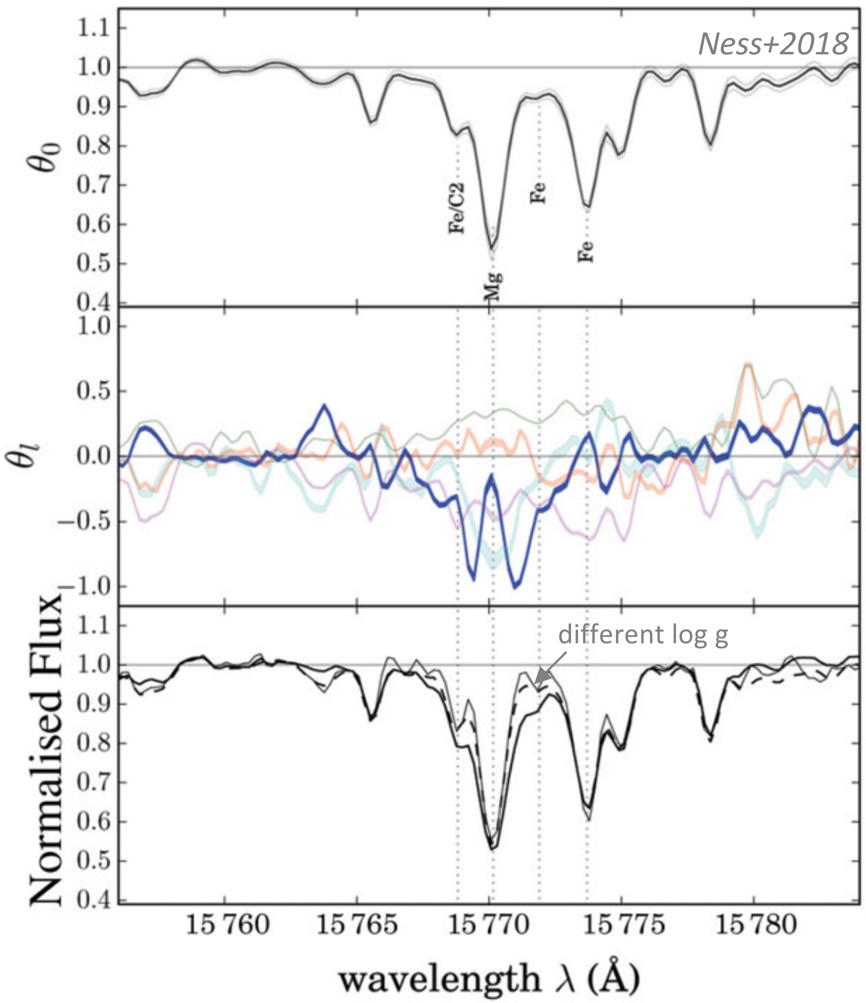
Fe abundance independent of the particular line excitation energies



Stellar Surface Spectroscopy

- This messenger of cosmic abundances is applied widely
- Multiple lines per species, with different ionization states; wavelength-dependent depth / location of photosphere: gas kinematics (microturbulence) determines line shapes
- Spectral modeling, using atomic data & atmosphere model, is key to precision results

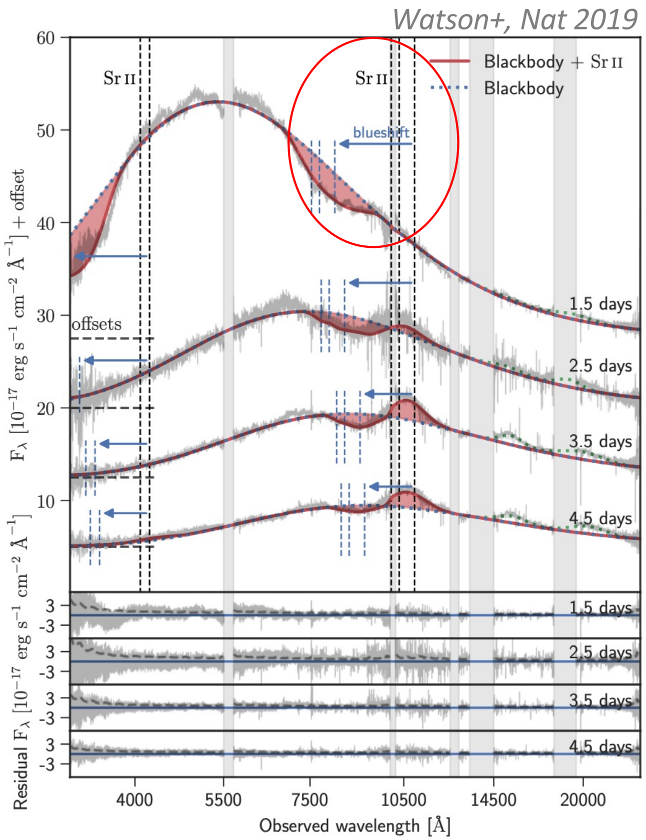
Spectral Modeling (CANNON), varying log g



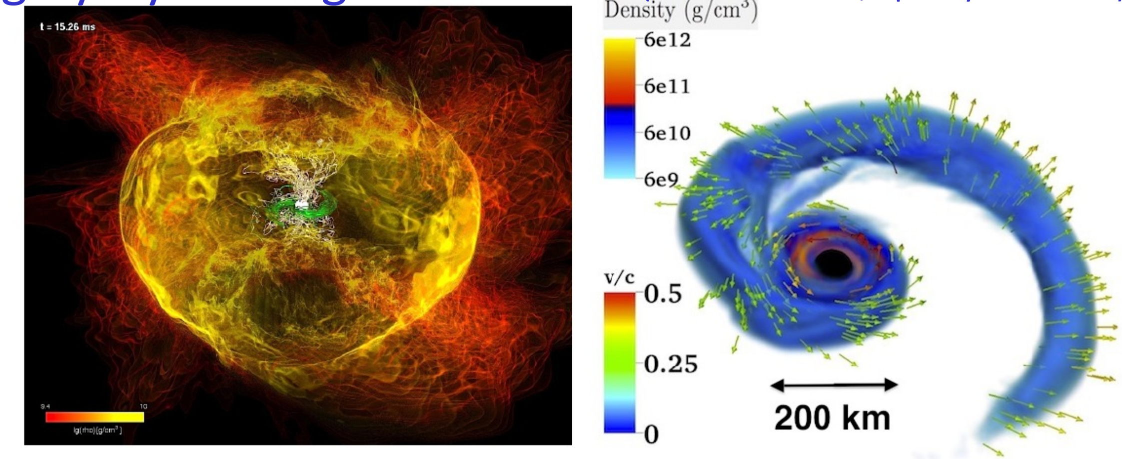
- Astrophysical history of photospheric gas requires modeling (gravitational settling; nuclear burning; chemical processing, ...)

Challenge: r-process ejecta from neutron star collisions?

Watson+, Nat 2019



Highly-dynamic gas evolution (→ bulk motion, opacity evolution)



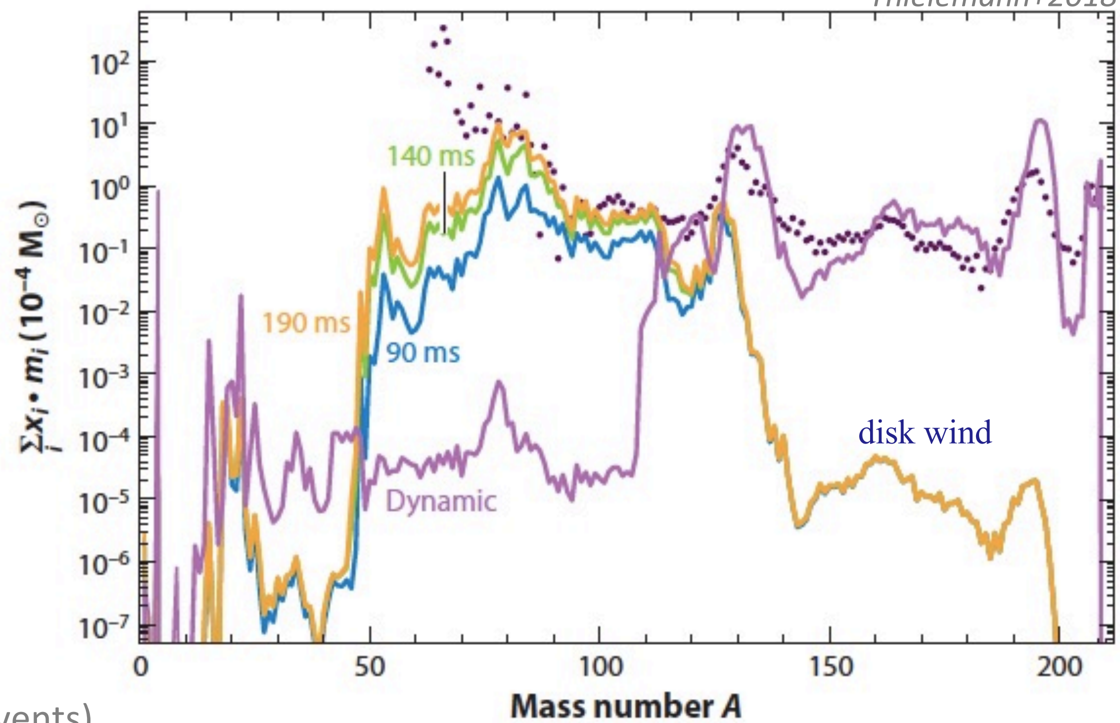
→ elemental-lines are broad / fuzzy
due to Doppler shifts & broadenings
of dynamic ejecta
Large number of lines (~10^5), need for
laboratory references & libraries

➔ unclear abundance signatures,
unclear chemical-evolution impact

(ejecta masses, fresh vs prior synthesis, rare events)

Elemental yields are expected in variety

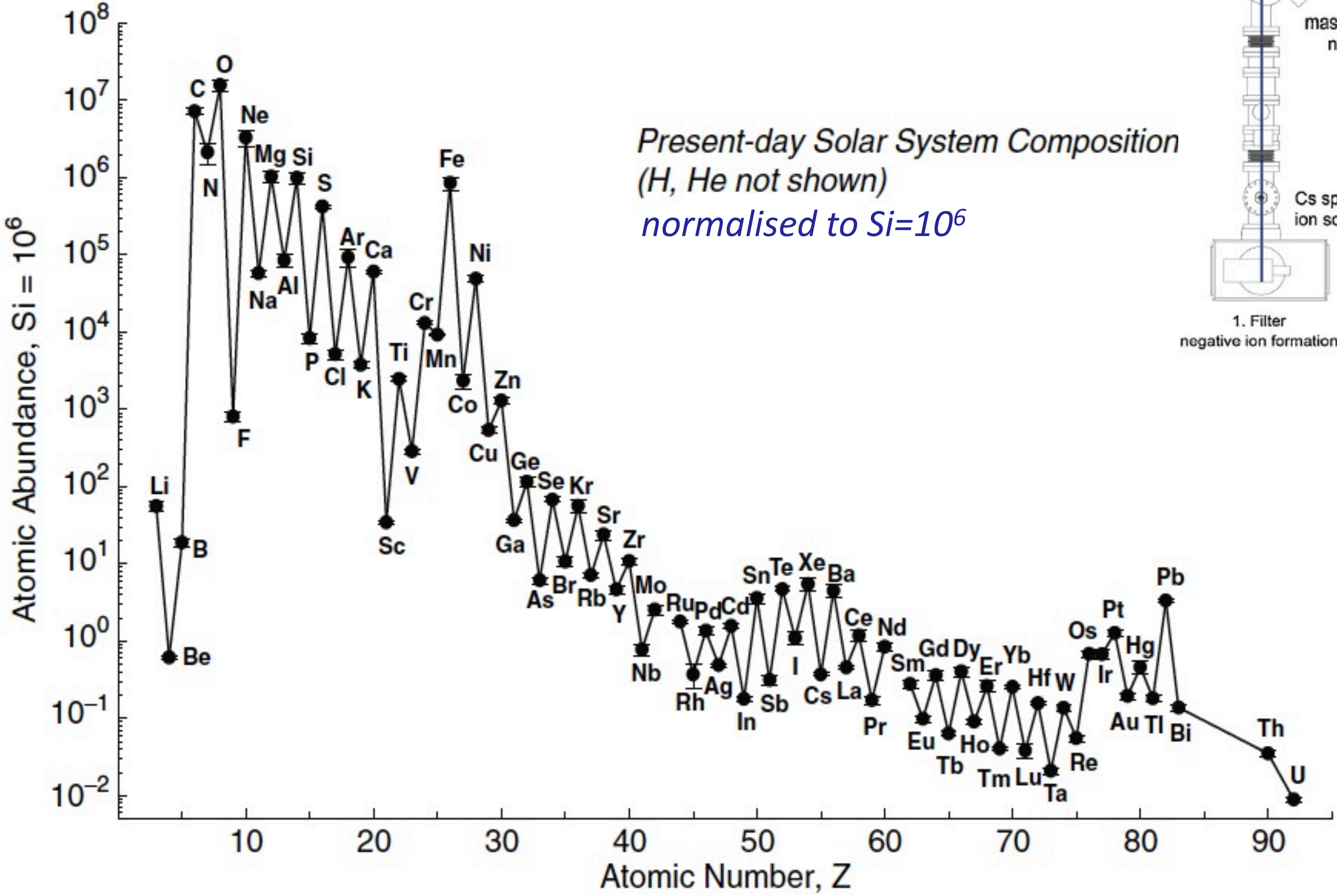
Thielemann+2018

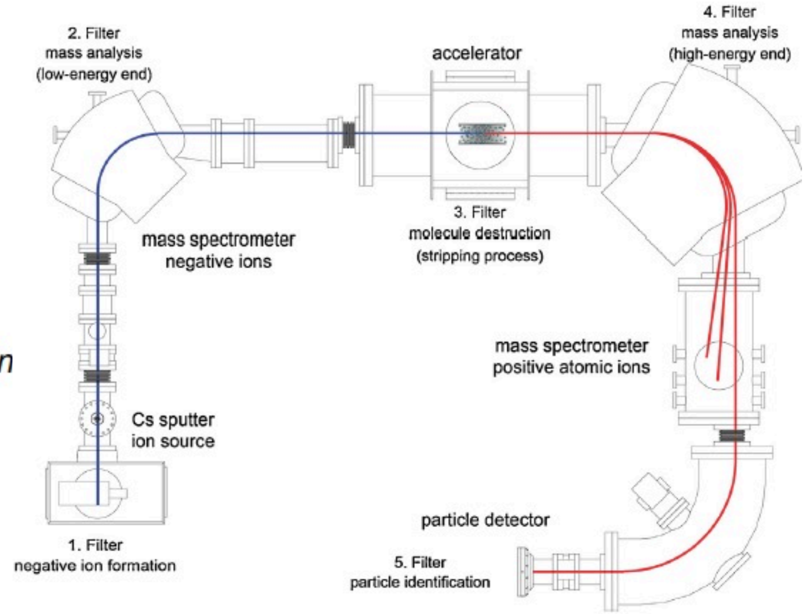


Solar Elemental Abundances

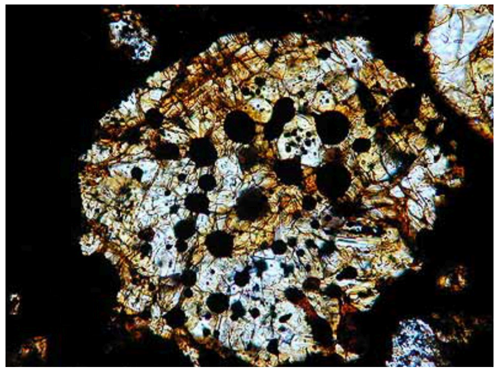
Lodders 2009

Present-day Solar System Composition
(H, He not shown)
normalised to Si=10^6





AMS; Synal 2013



determined from laboratory analyses of meteoritic material (CI chondrites=oldest)

pre-solar grains: a new astronomical messenger

☆ isotopic anomalies wrt solar-system materials by many orders of magnitude

➔ *Liu lecture*

Stardust in the Laboratory 9

Zinner 2008

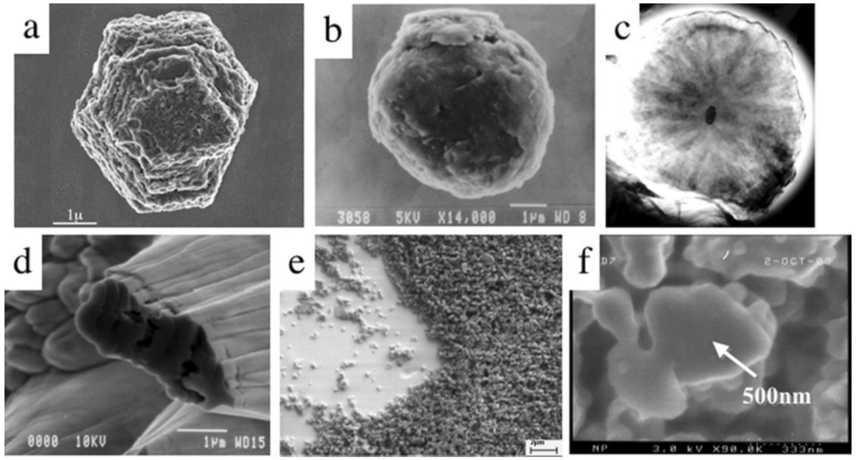
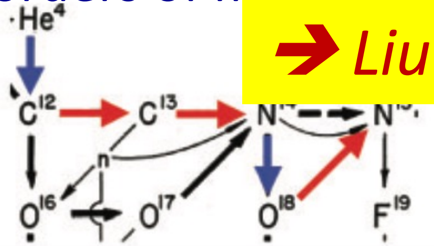
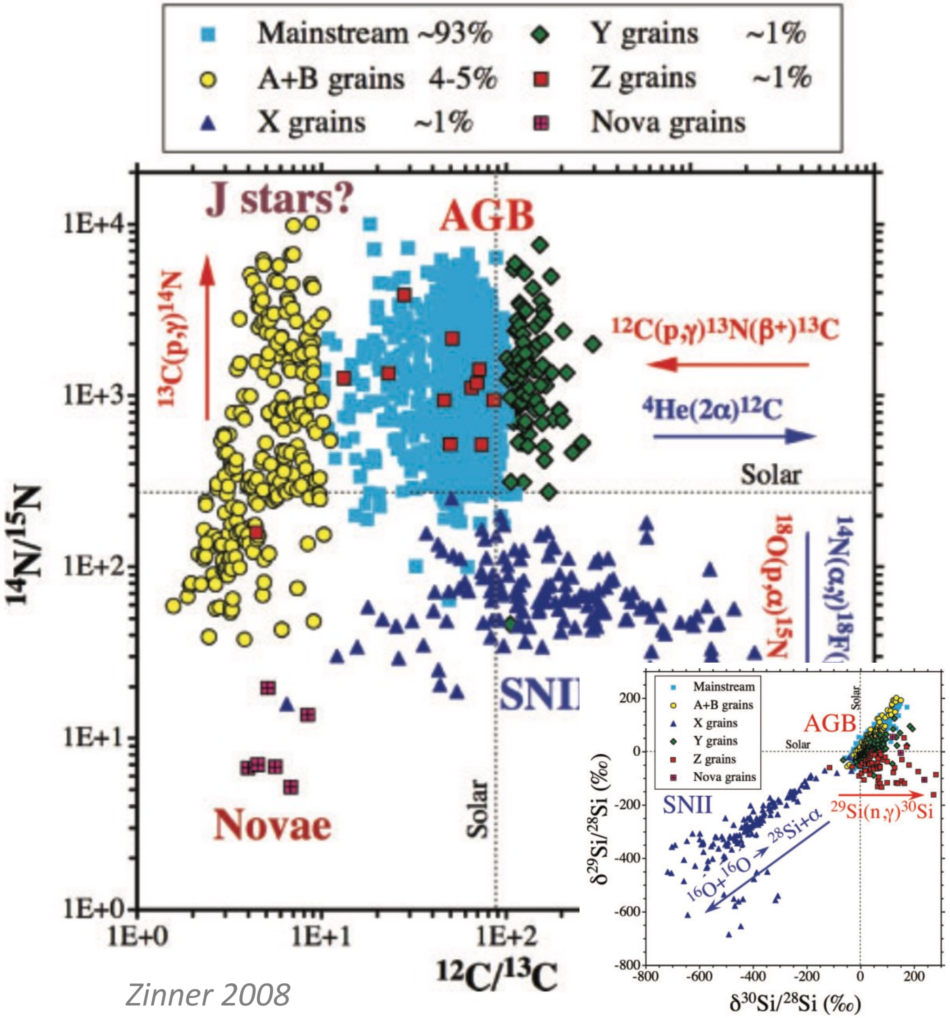


Figure 1 Scanning electron micrographs of presolar dust grains. (a) Silicon carbide, (b) Graphite, (c) TEM image of graphite slice with interior TiC grain, (d) Aluminum oxide, (e) Spinel (only ~2% of the grains in this image are presolar), (f) Silicate.

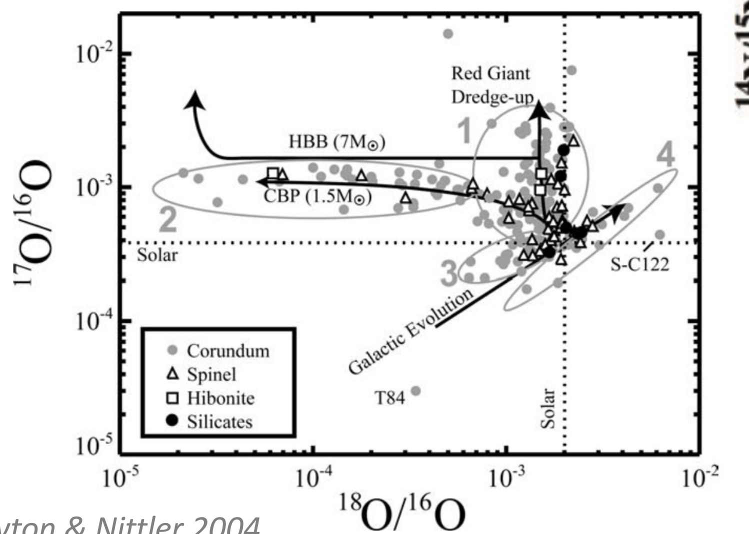




Zinner 2008

☆ study AGB stars (=dust producers)

- nuclear burning in shells of AGB star (HBB)
- s process



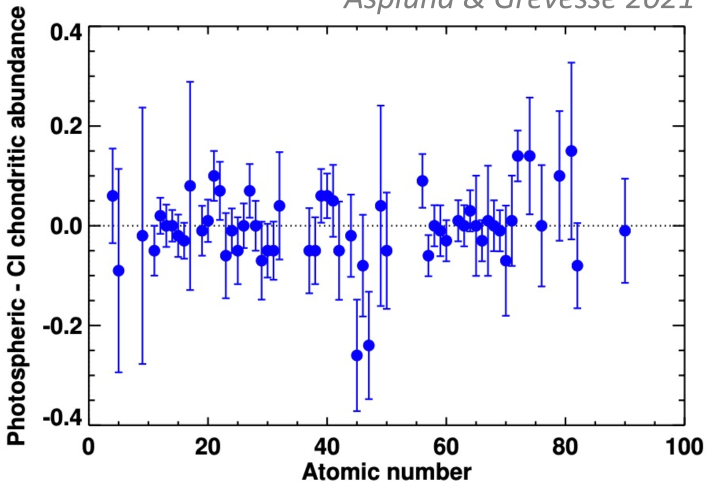
Clayton & Nittler 2004

Solar Abundances: Photospheric vs Meteoritic

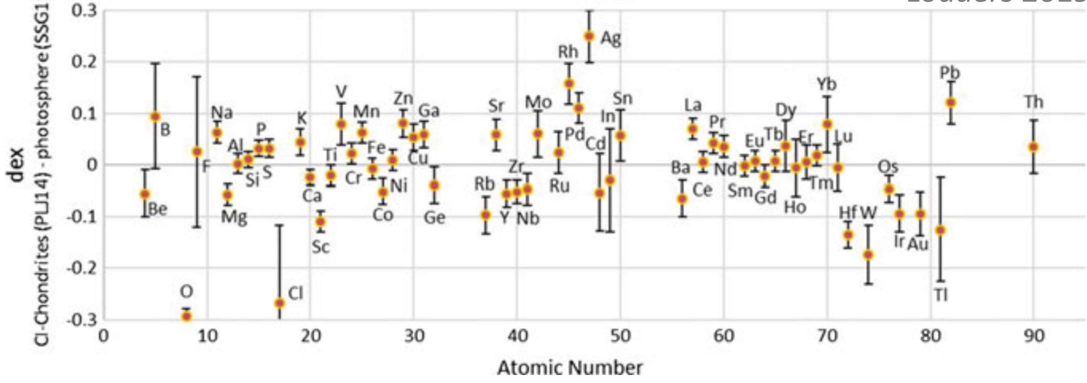
General agreement,

but upon closer inspection also discrepancies:

Asplund & Grevesse 2021



Lodders 2019



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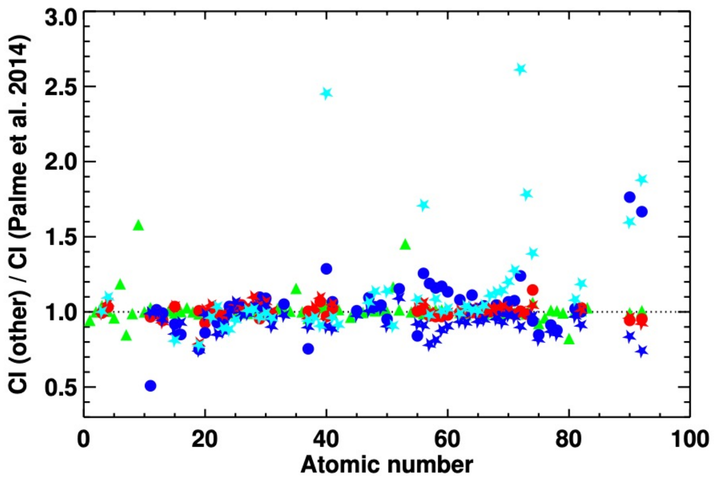
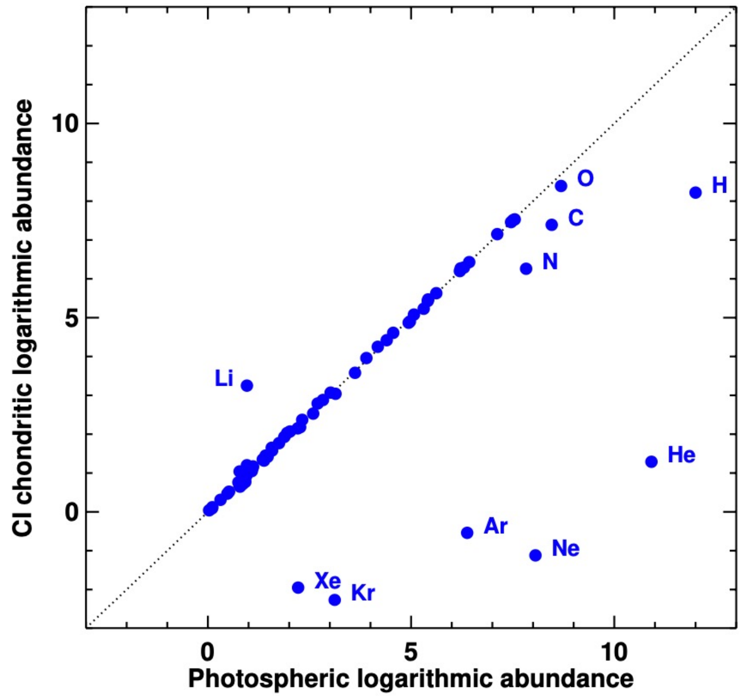
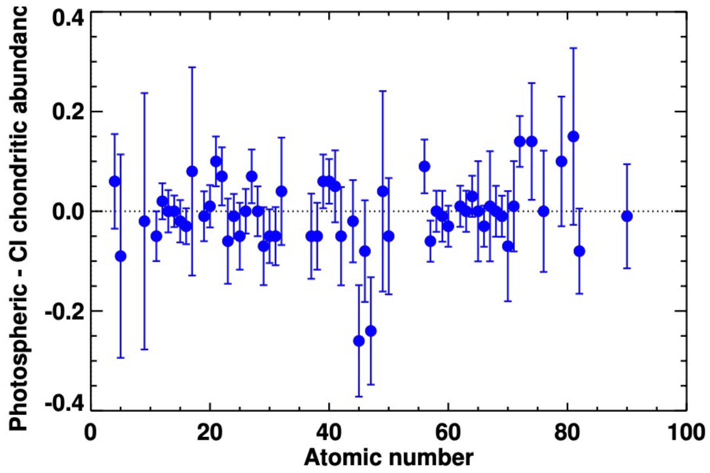
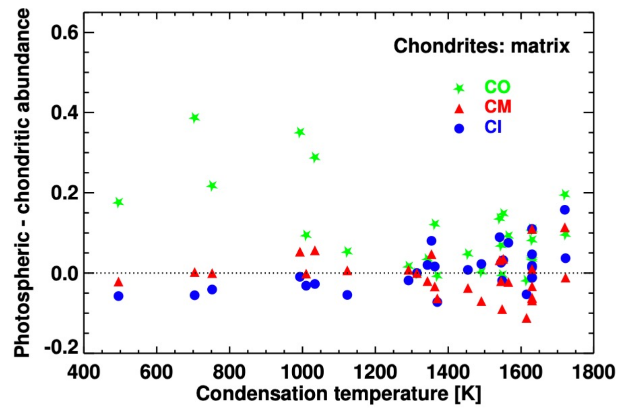




- gases & volatile elements underabundant in CI meteorites
- moderately-volatile elements enriched in CI meteorites
- other primitive meteorites (CM matrix) agree better to photospheric abundances → CI formation bias?

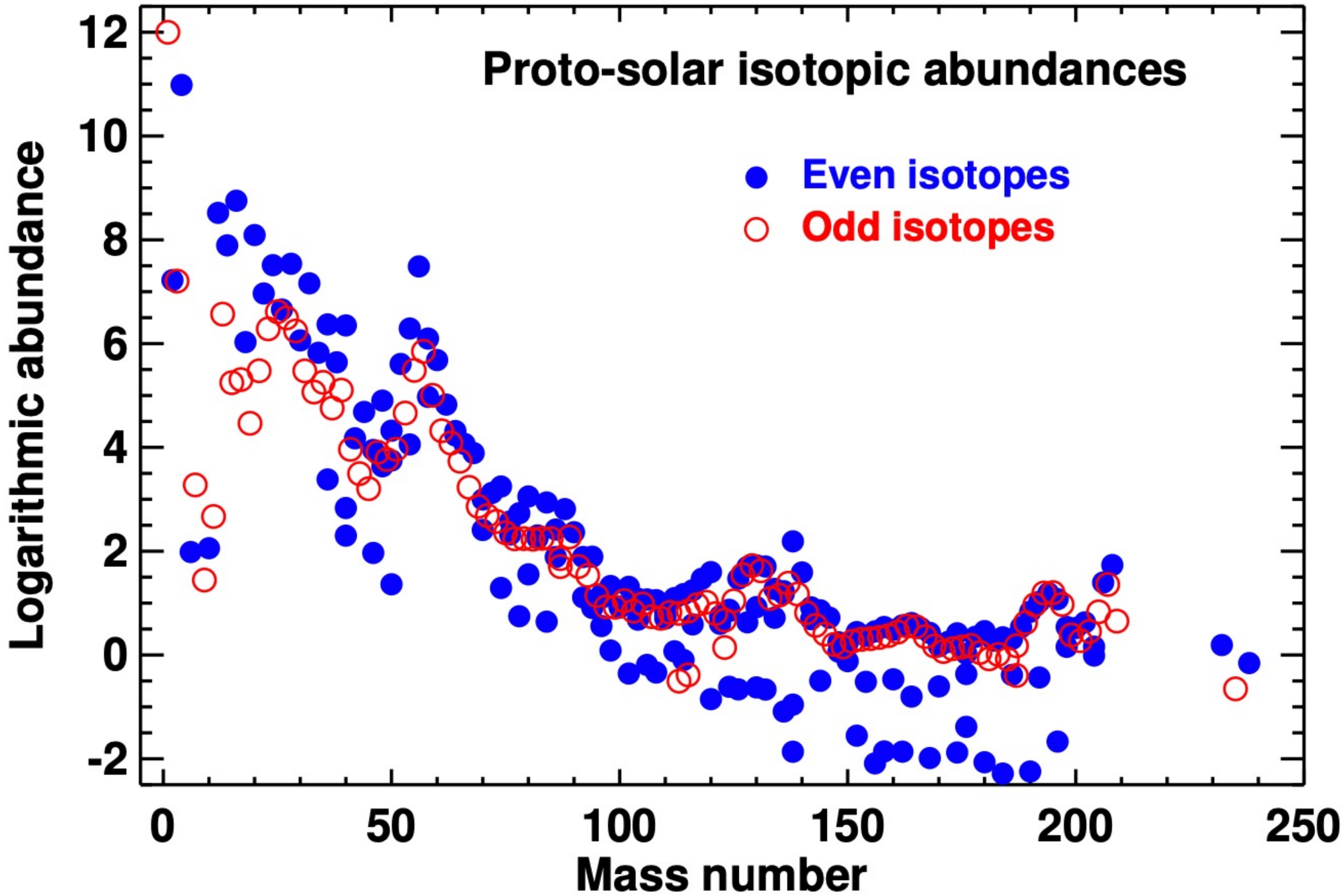




Solar abundances: isotopes

- Careful before interpretation:
  Biases of material samples are significant
  - ☆ using meteoritic & solar-wind data and theory for estimations of their evolutionary biases

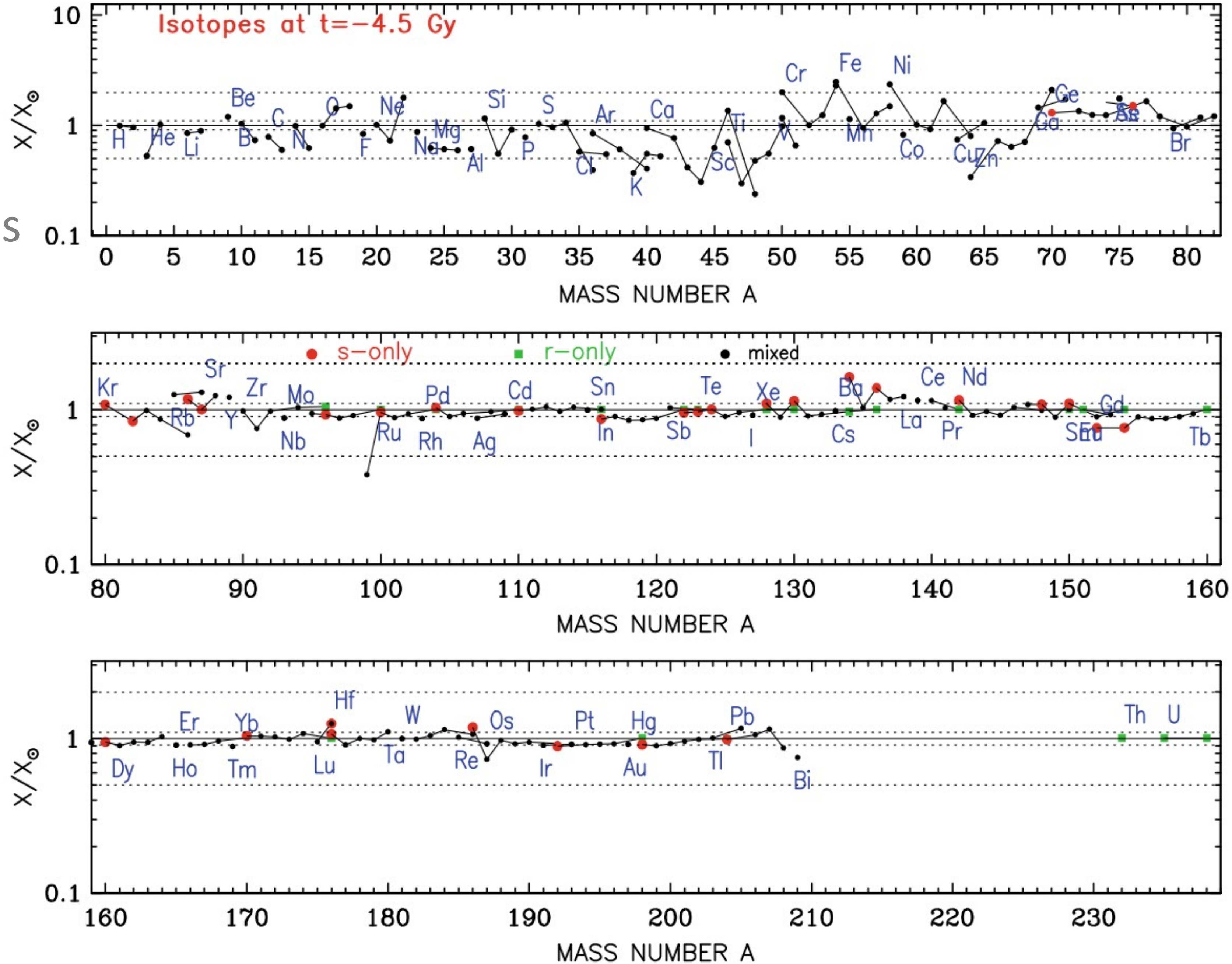
Asplund & Grevesse 2021



Solar Isotopic Abundances: Data vs ChemEv Model

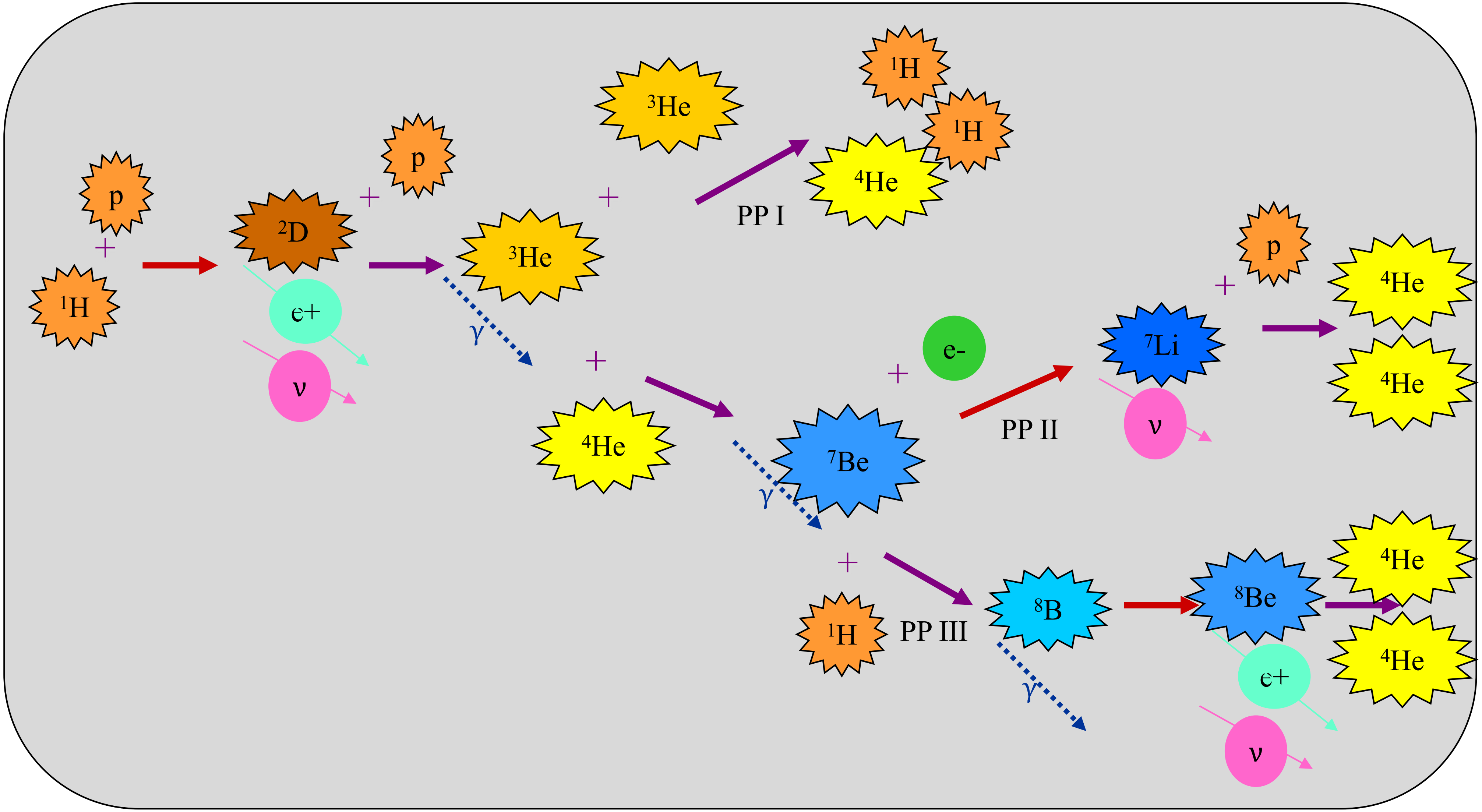
Prantzos 2019

Chemical evolution model using yields from SNIa, rotating massive stars, ccSNe, ..



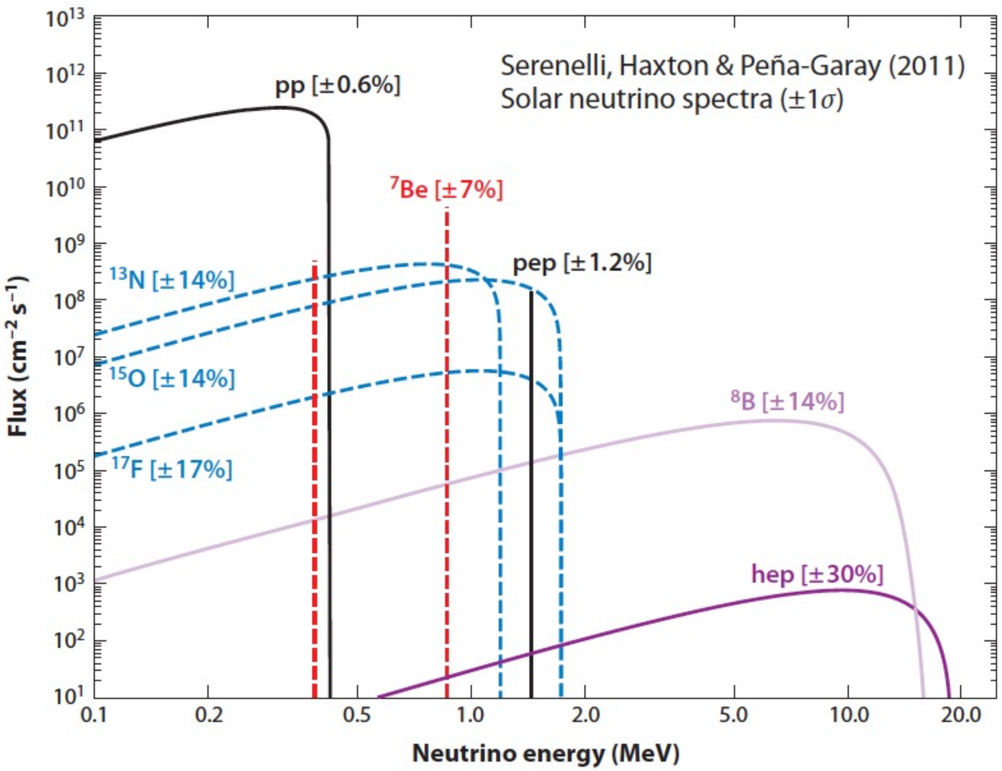
Nuclear Burning: H to He

- H Burning: the p-p Chains

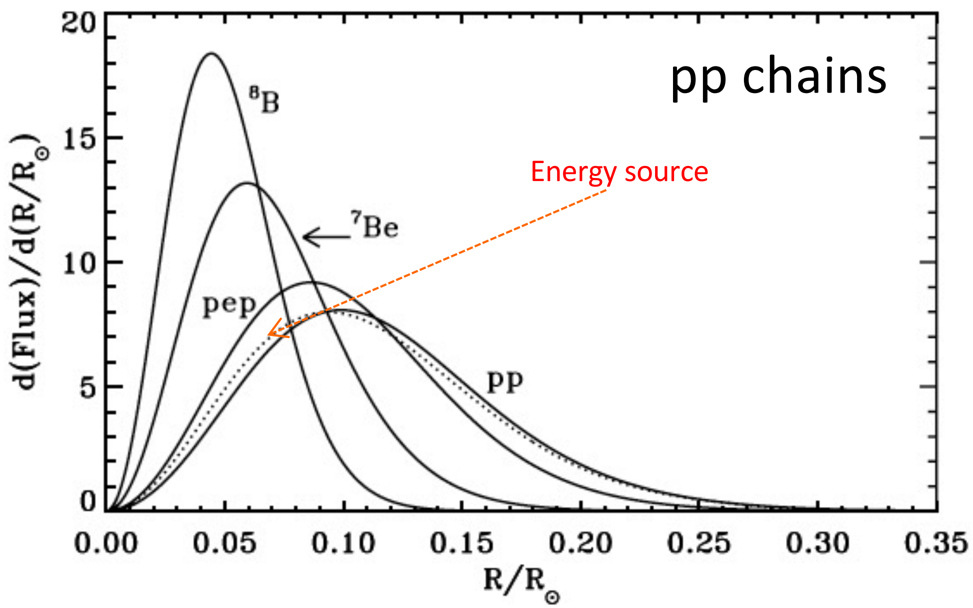


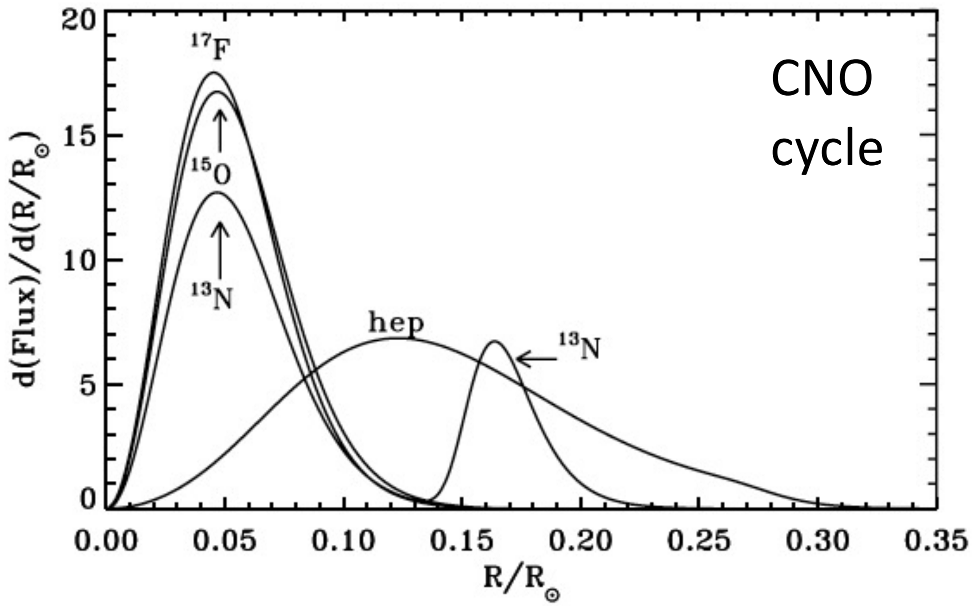
Modeling our Sun: Neutrinos from H fusion reactions

- Core hydrogen burning, hydrostatic equilibrium
- Parameters:
  - Y (He abundance), Z (metallicity)
  - Mixing length α
- Outputs:
  - Luminosity (energy), neutrinos



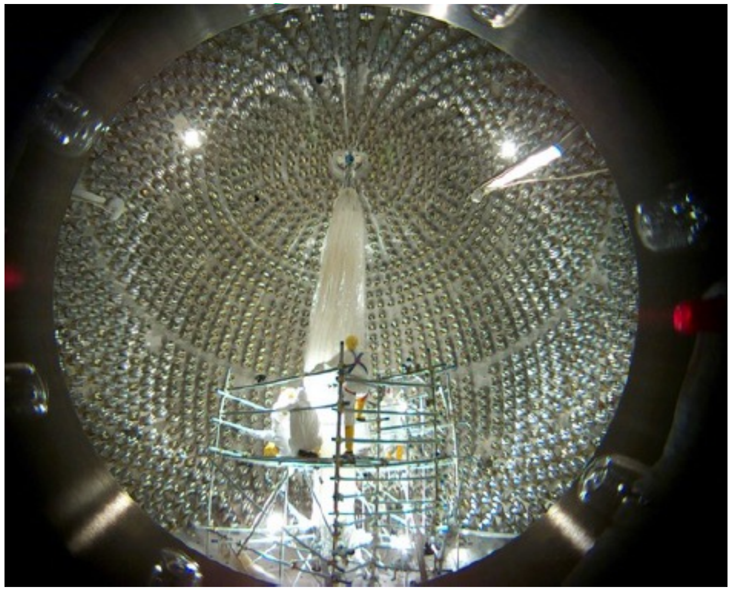
Bahcall+2006



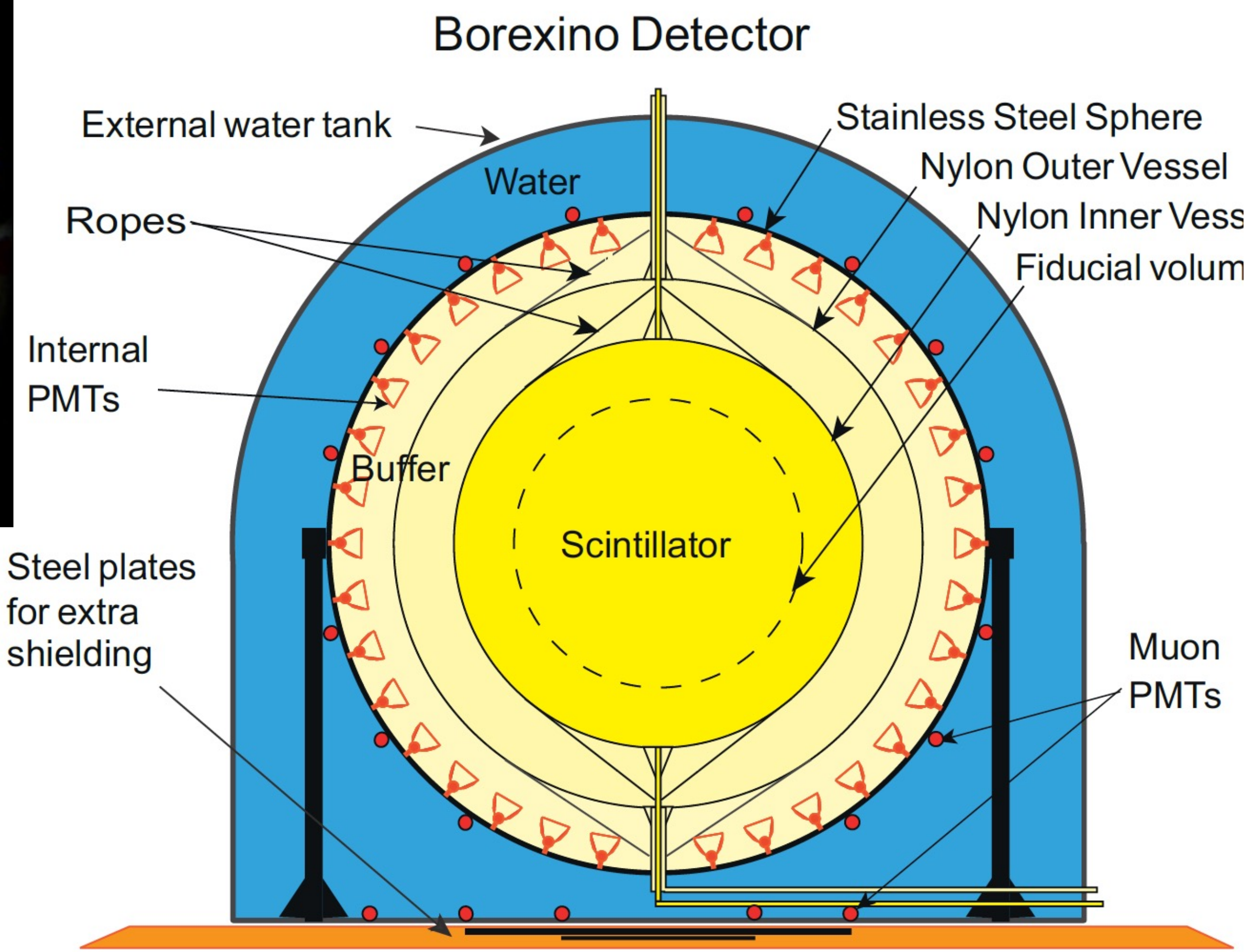


Borexino: lower energy neutrinos (<^{8}B)

- Scintillation Detector in Gran Sasso Lab. (Italy)



operated since May 2007



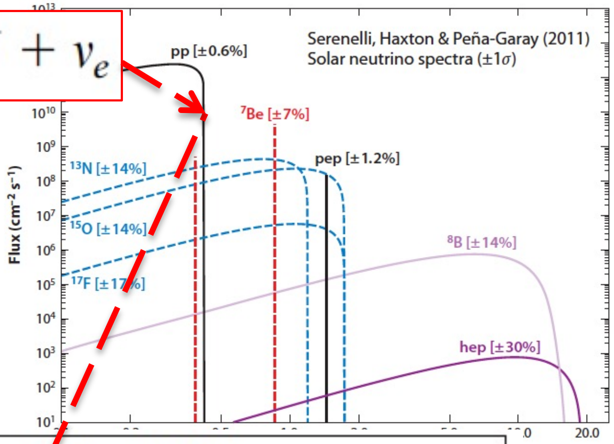
☆ Principle:

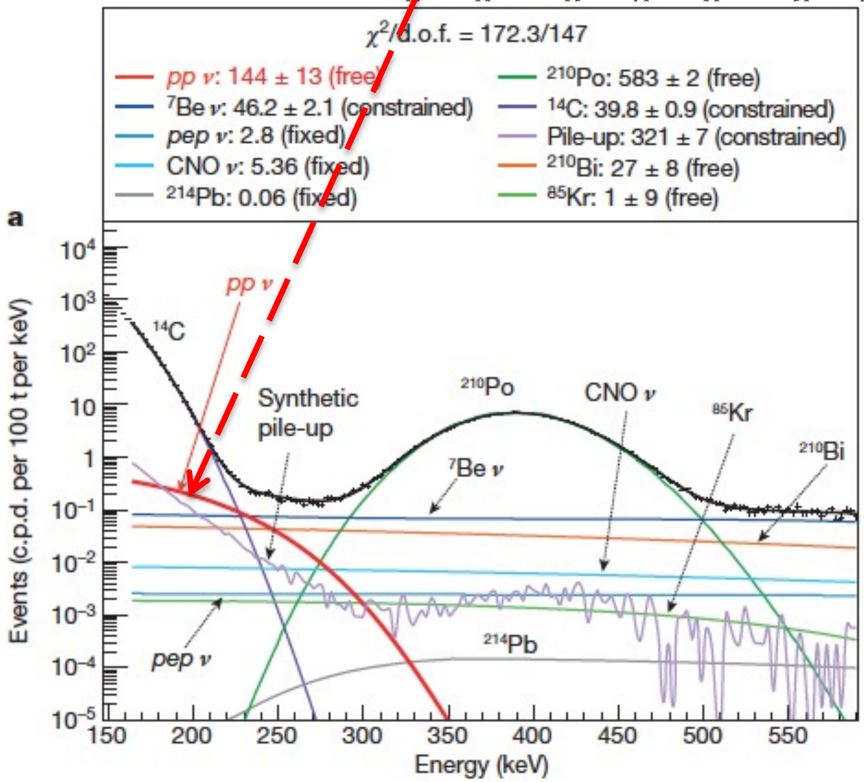
- ☞ search for events without external trigger, creating recoil e-, protons, or C nuclei (detect scintillation)
- ☞ suppress very efficiently other background

Neutrinos from H burning confirm solar model basics

- from pp chain

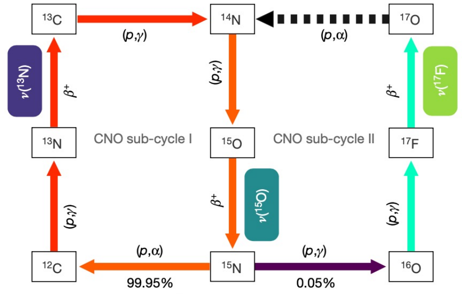
$$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$$

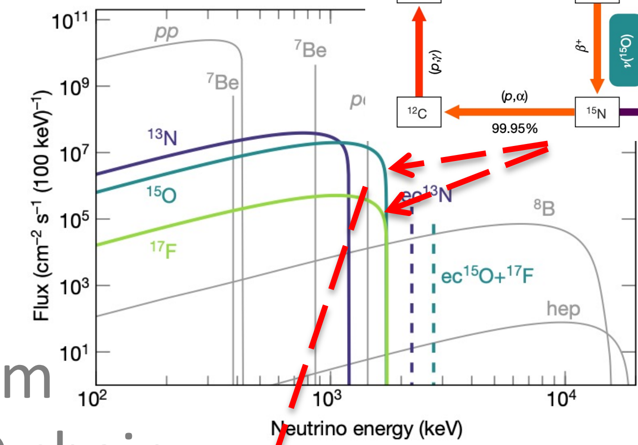


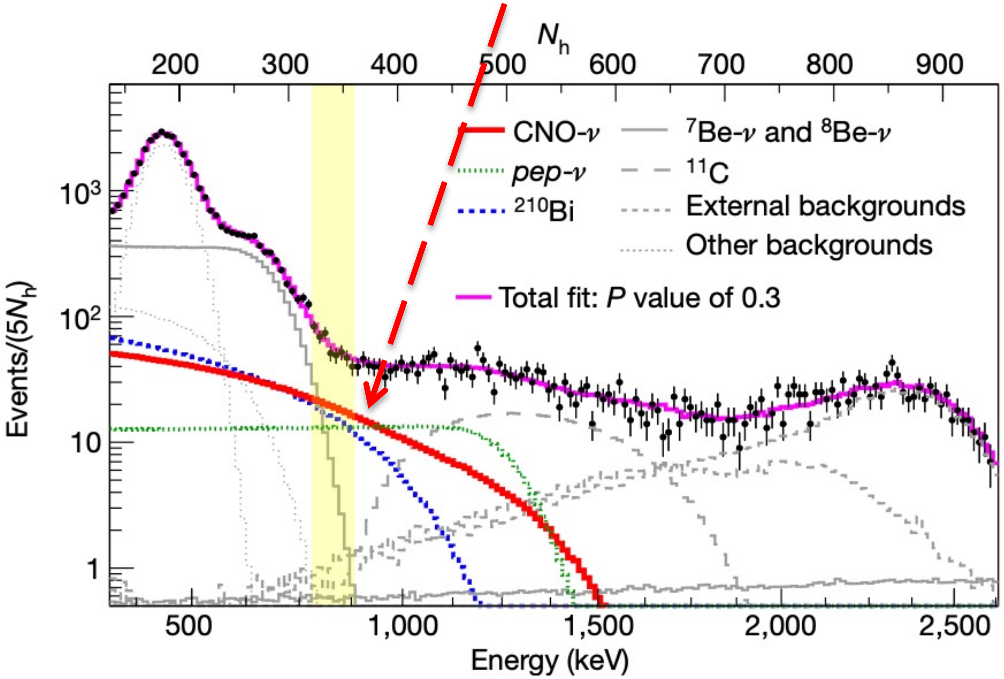


Borexino Collab. (2013)

- from CNO chain



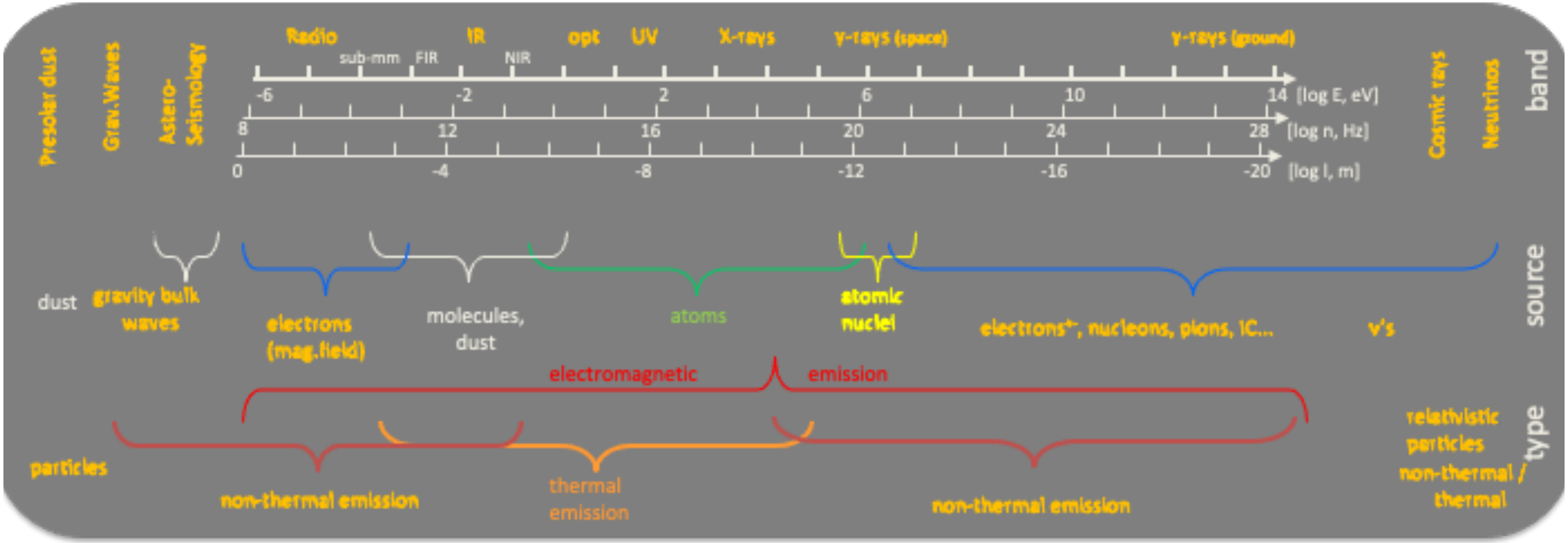




Borexino Collab. (2020)

The variety of "astronomies"

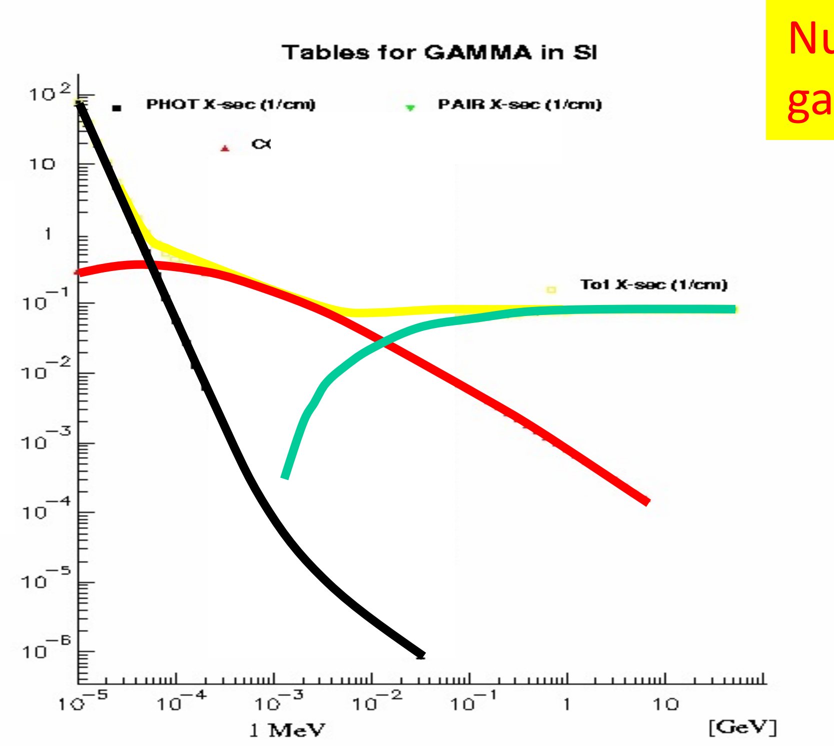
... beyond astronomical telescopes of optical light:



Detection of Radiation from Isotopes

Nuclear radiation
gas gamma-ray energies (MeV)

Interaction Cross Section of Photons in Matter



Energy

Pair Creation (> 10 MeV)
Photons completely converted to e^+e^-

Telescope:
Tracking chambers
to visualize the pairs

Photoeffect(< 100 keV)

Photons effectively blocked and stopped

Telescopes:

Collimators
Coded Mask Systems

Compton Scattering (0.2-10 MeV)
Photon Crossection Minimum
Scattered photons with long range
Telescope:
Compton Camera Coincidence System

courtesy G. Kanbach

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

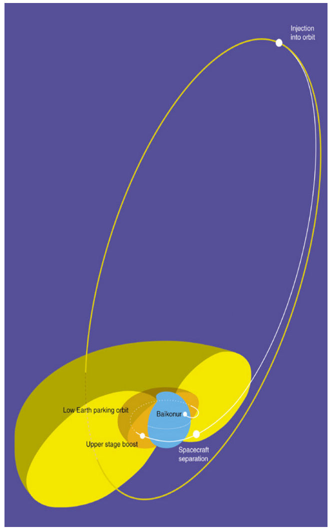
2002-(2021+..2029)

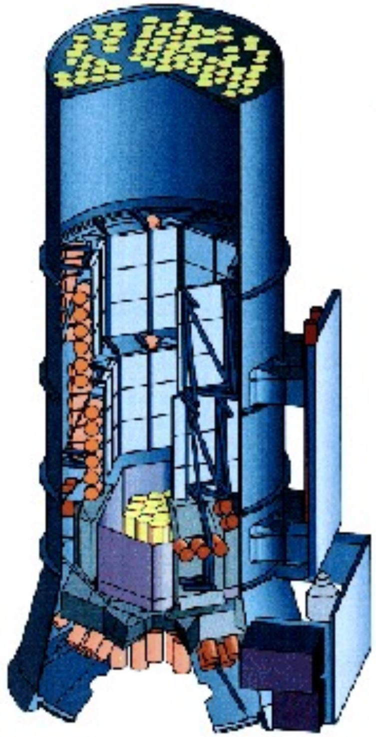
ESA

high E resolution

Ge detectors

15-8000 keV





NuSTAR (only <80 keV!)

2012-(2022+) …

NASA

hard X ray

imaging <80 keV

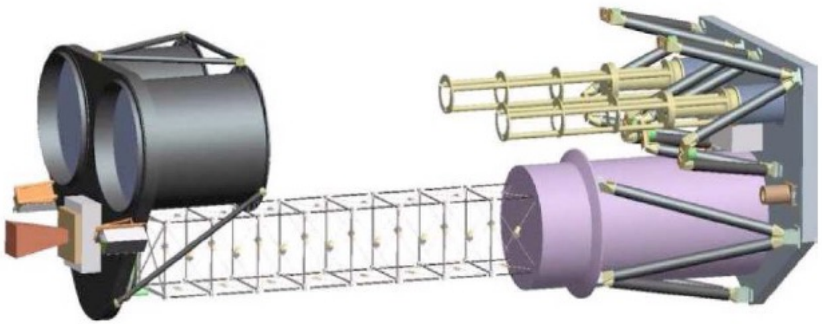
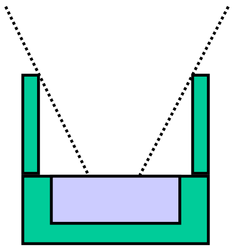
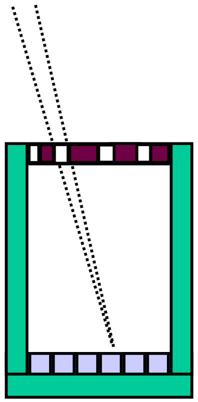


Fig. 1. NuSTAR telescopes in deployed configuration

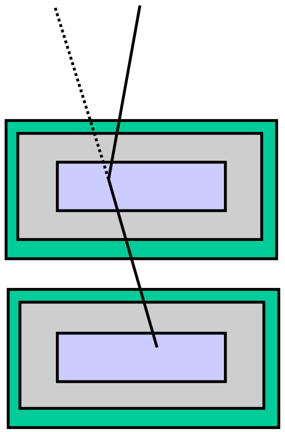
MeV Range Gamma-Ray Telescope Principles



- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield



- **Coded Mask & Detector Array**
  (e.g. SIGMA, INTEGRAL, SWIFT)
  Spatial Resolution Defined by Mask & Detector Elements Sizes

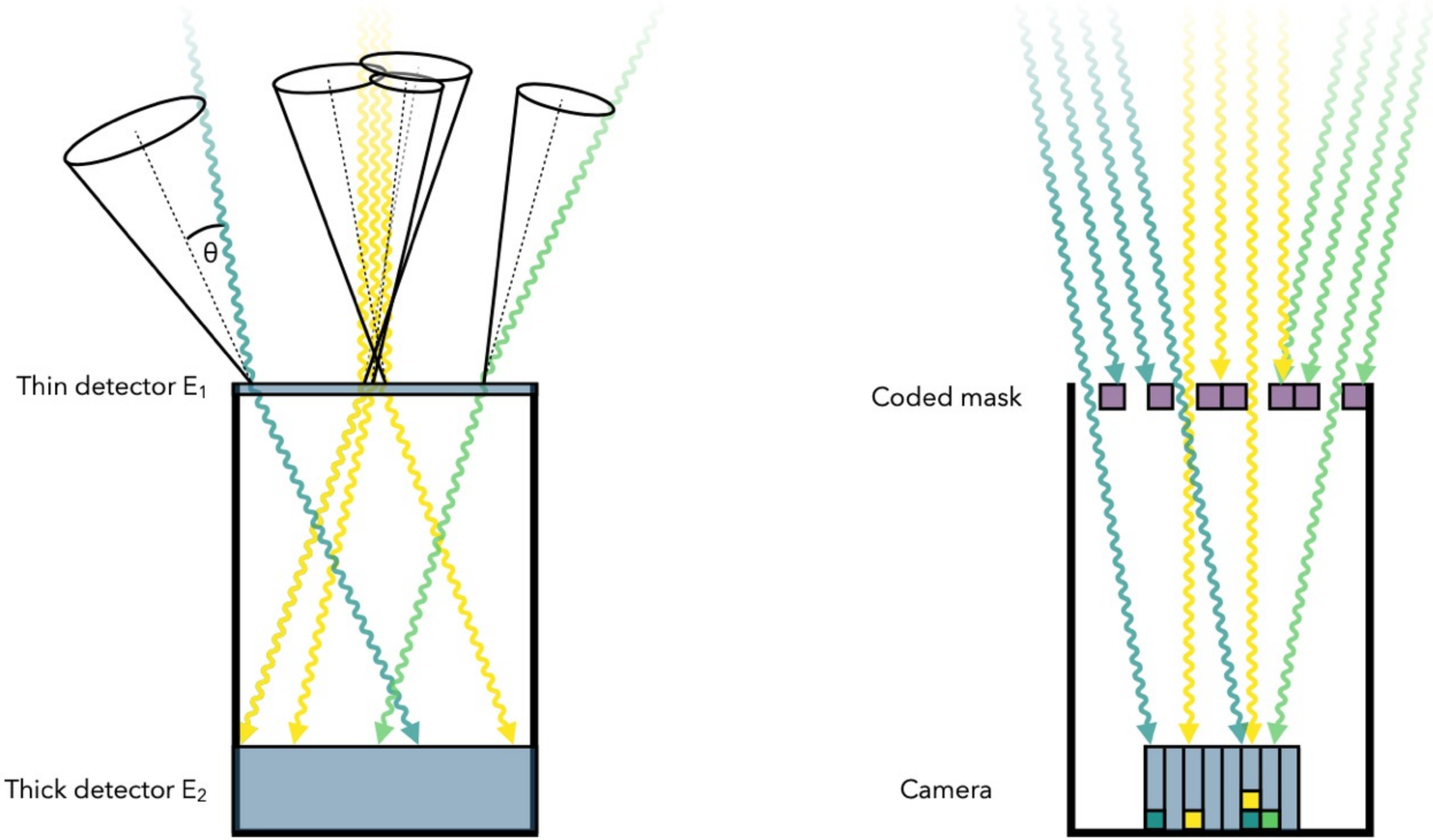


- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGO-COMPTEL, MEGA, ACT, GRIPS, eASTROGAM)
  Spatial Resolution Defined by Detectors' Spatial Resolution

Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution $\geq$ deg

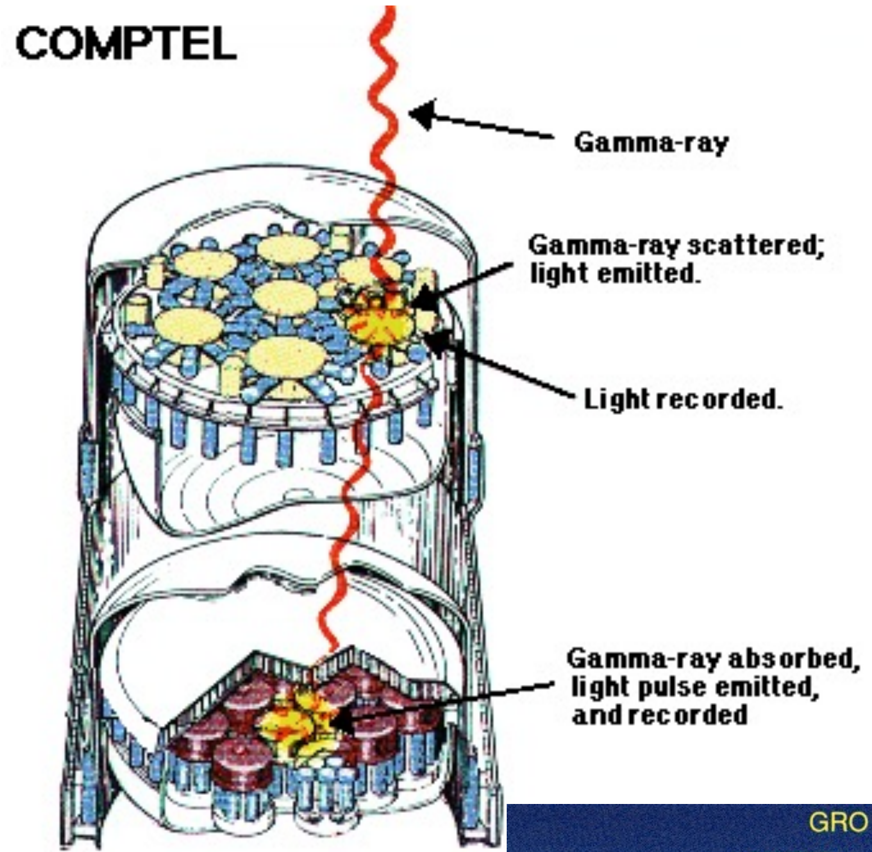
MeV Range Gamma-Ray Telescope Imaging Principles

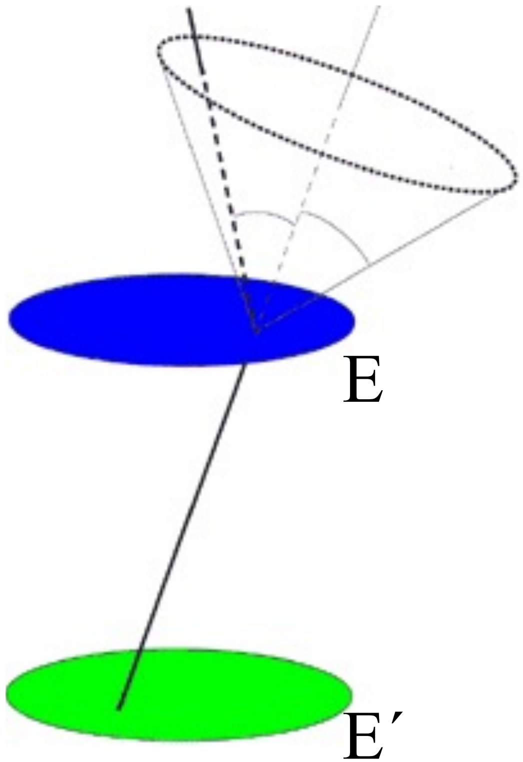
Compton Telescopes and Coded-Mask Telescopes

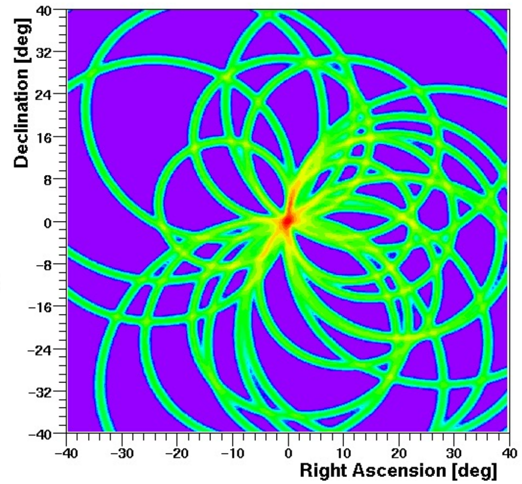


Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

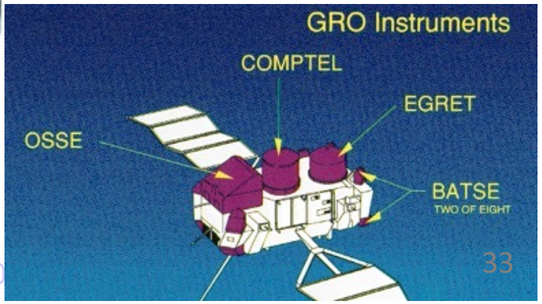
Compton Scattering: Coincidence Experiments







$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

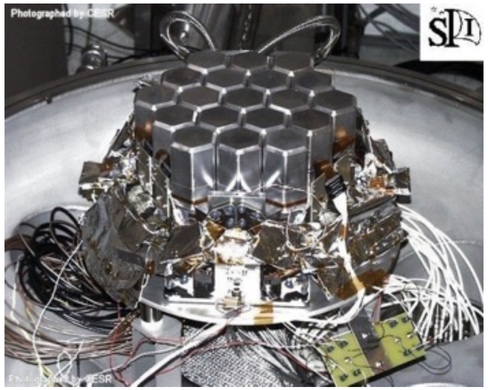


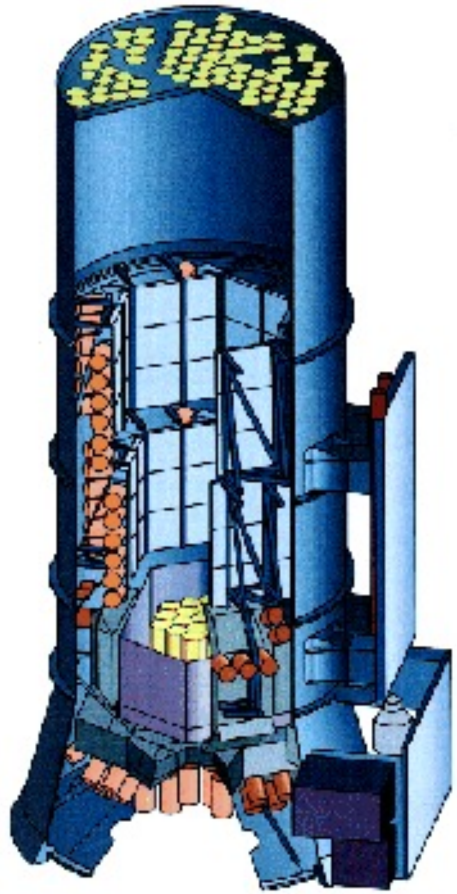
$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E}\right)\right\}$$

Casting a Source Shadow: Coded Mask Telescopes

ref. e.g.: Skinner

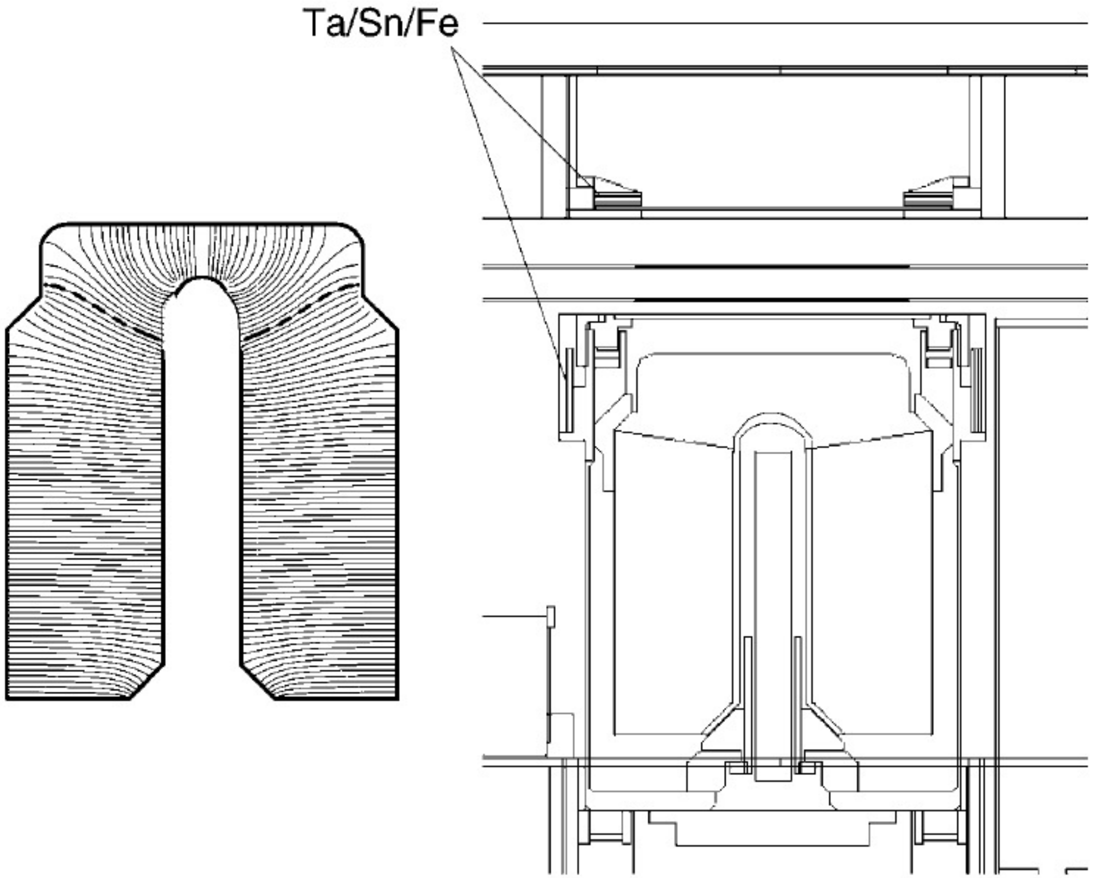
- A Semi-Transparent Mask Occults Part of the Position-Sensitive Gamma-Ray Detector Plane
- Recognition of the Mask Shadow in the Detectors' Signal -> "Imaging a Source"
  - Telescope = Mask & Detector Hardware + Imaging Software
- Masks
  - Uniformly Redundant Arrays
  - Adapted to Detector Spatial Resolution
  - Optimized for Larger Field of View
    - Partially/Fully Coded FoV
- Imaging
  - Correlation
  - Fourier-Domain Filtering





SPI on INTEGRAL

Ge Detectors in Space Telescopes



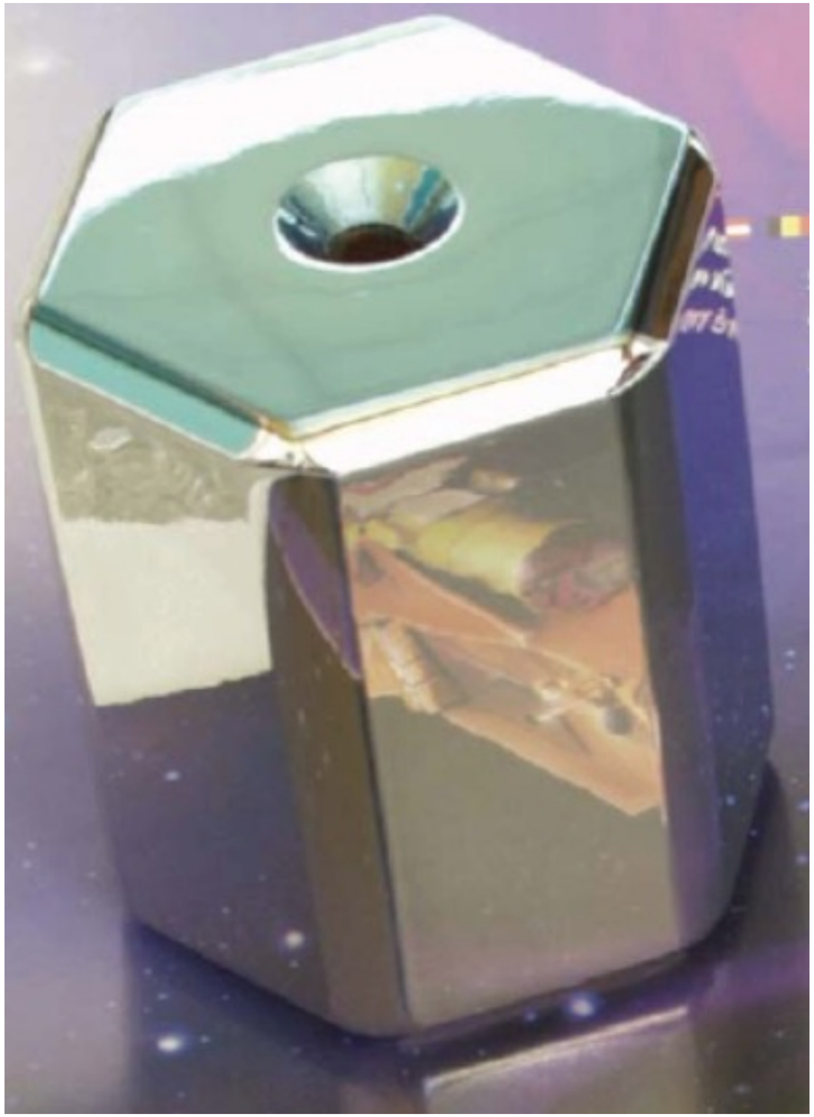
Detector Cross Section

Electric potential

Mechanics

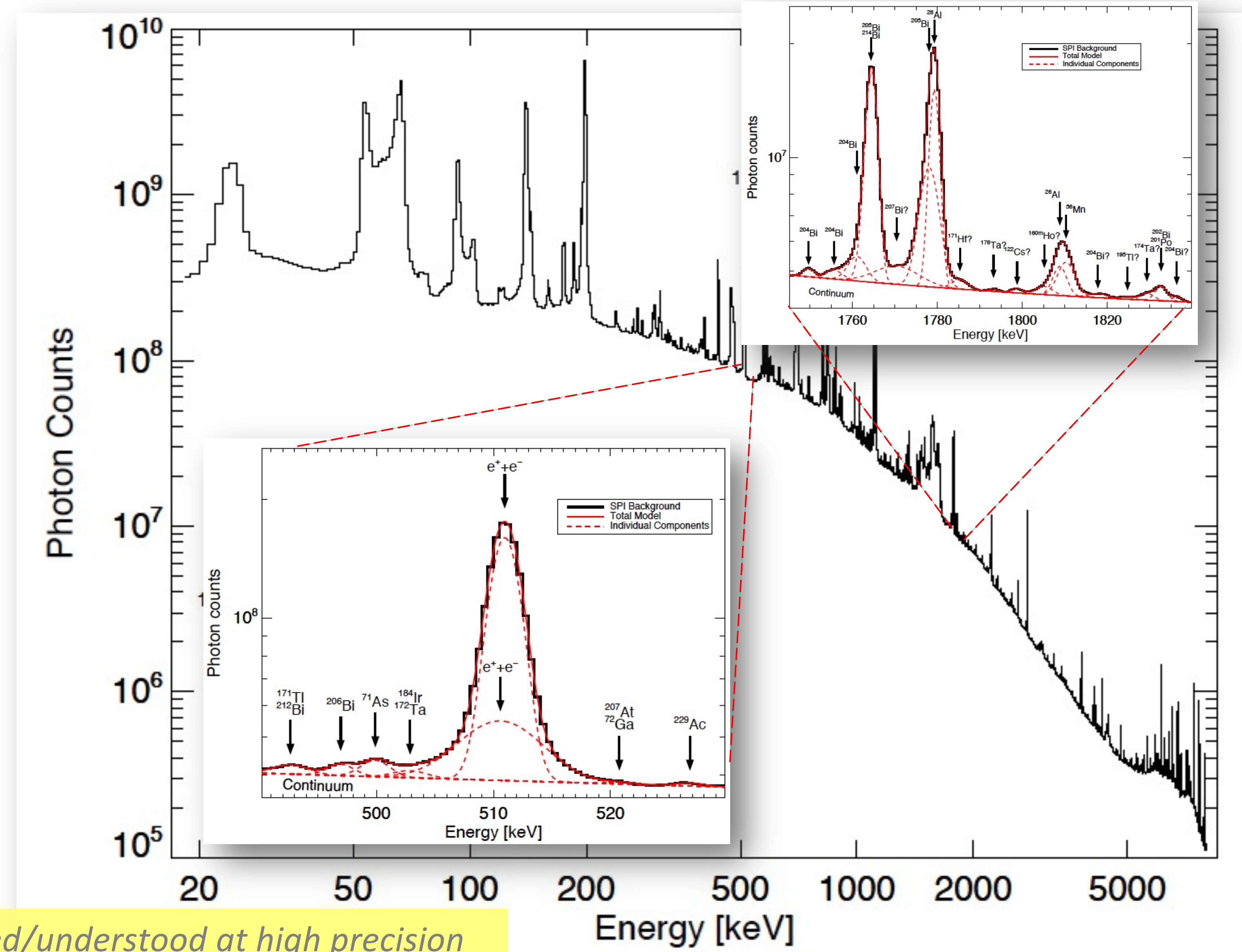
(RHESSI)

Detector of SPI/INTEGRAL



Dominance of instrumental background

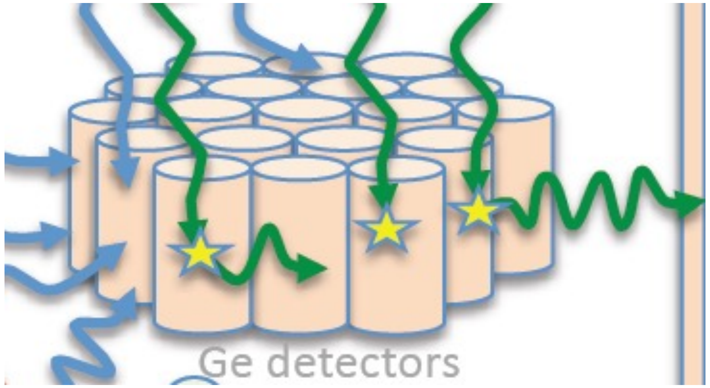
SPI Ge detector spectra

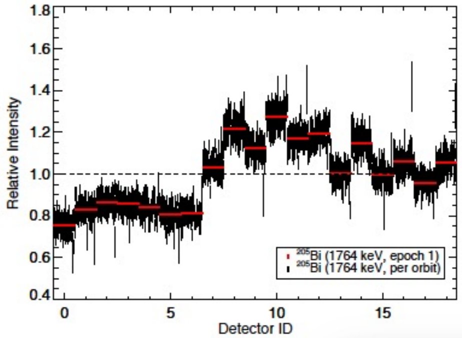


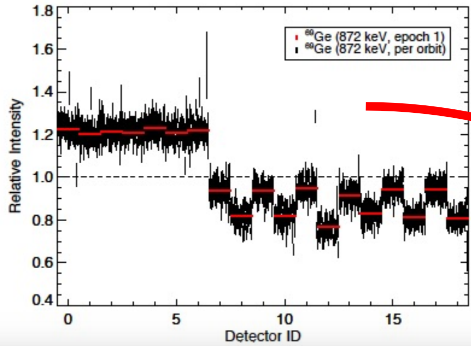
Modelled/understood at high precision

Discriminating Background and Sky Signals

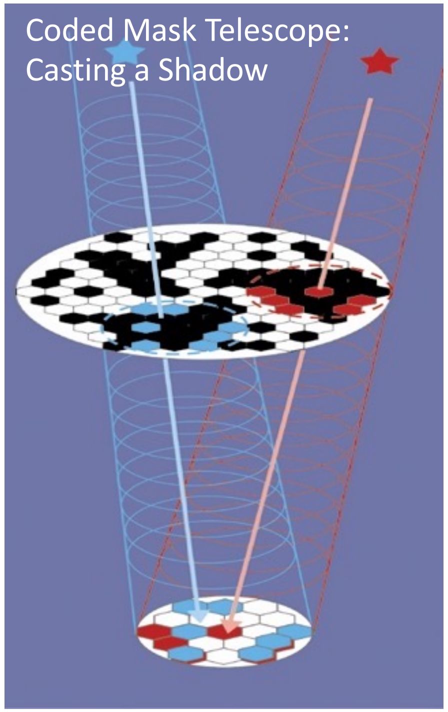
- Tracking the relative count rate ratios among detectors

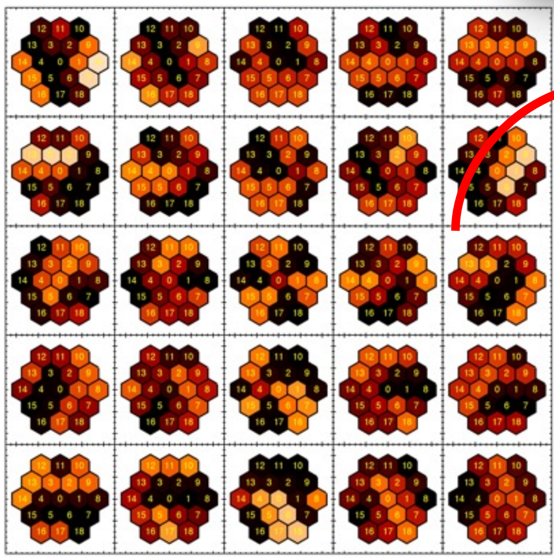


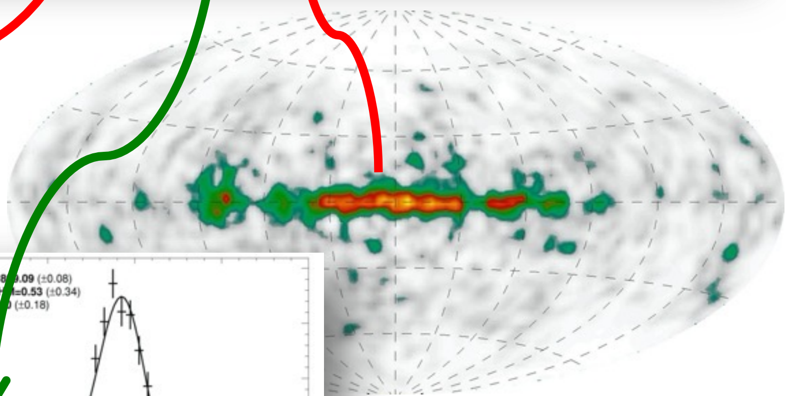


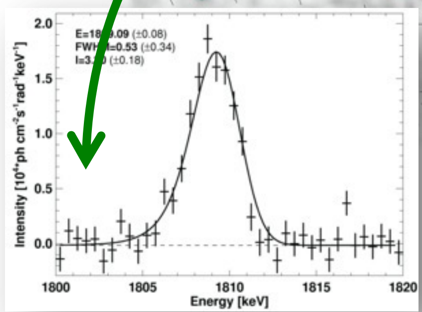


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$





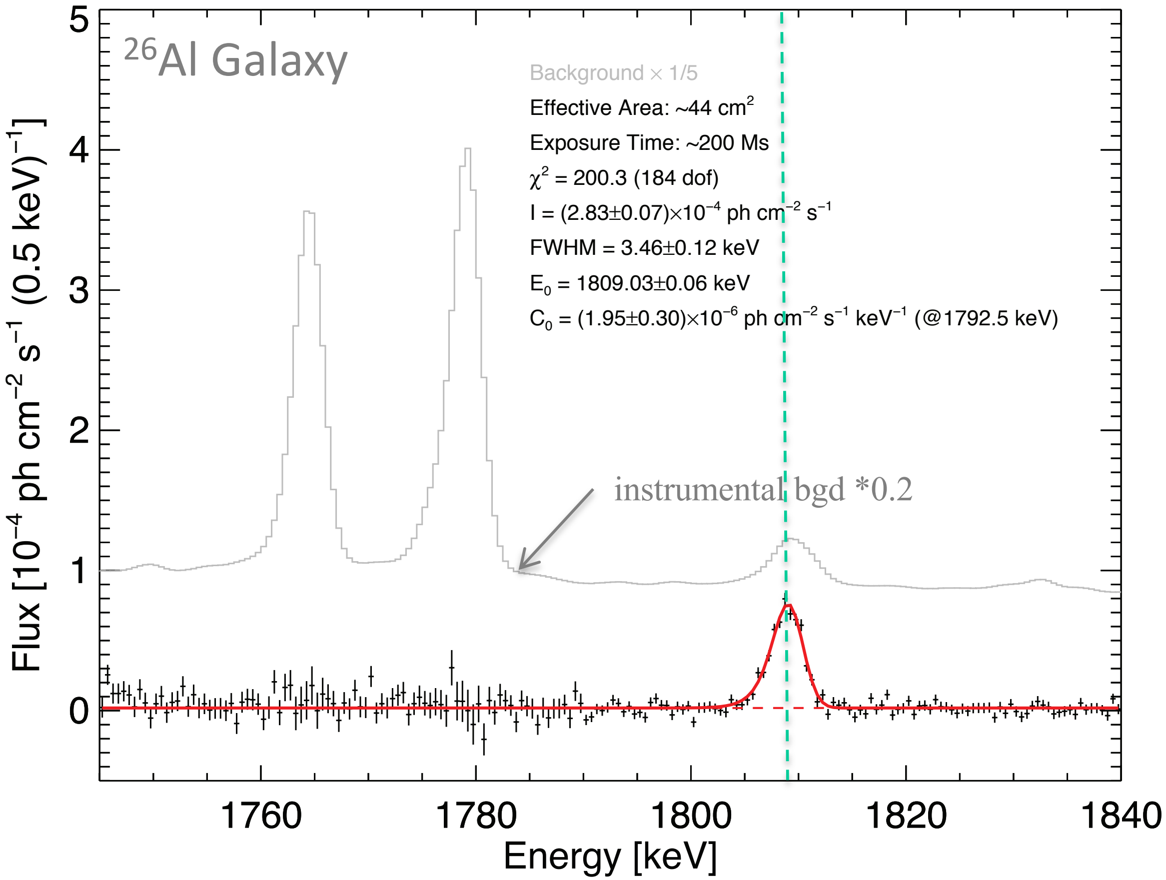


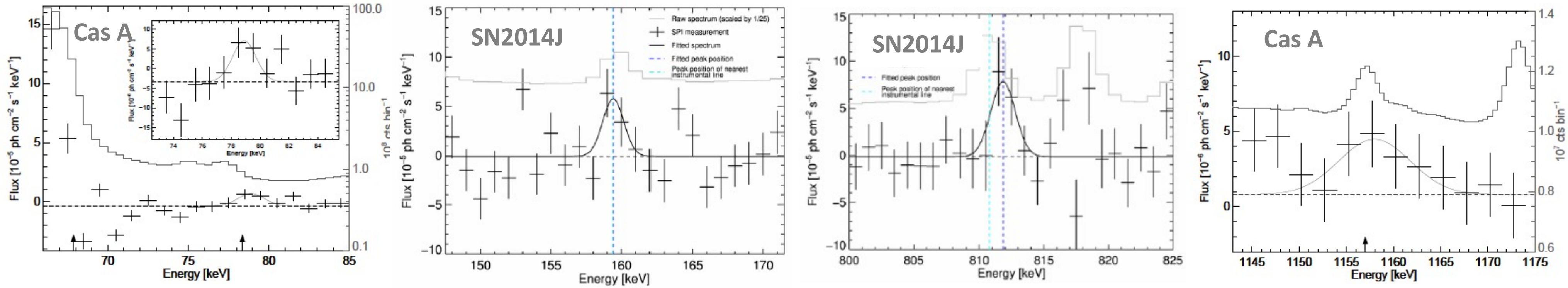


Gamma ray spectroscopy with SPI

...it works!

- ☆ ^{26}Al line 1808.6 keV
- ☆ instrumental lines
  - ☞ 1810 keV
  - ☞ 1779 keV
  - ☞ 1764 keV
- ☆ ...also: SN ^{56}Ni, ^{44}Ti





Gamma-Ray Lines from Cosmic Radioactivity

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

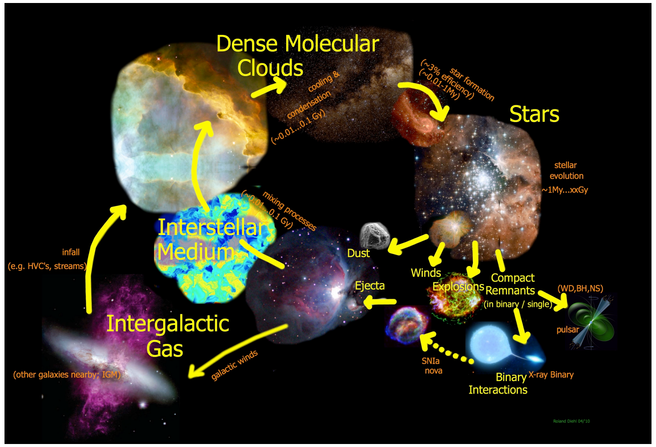
- Only the most-plausible candidates per source type are listed

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

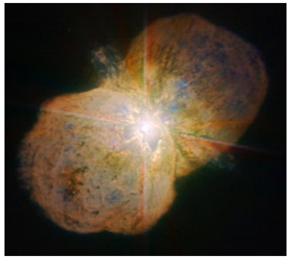
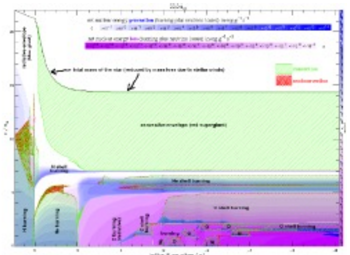
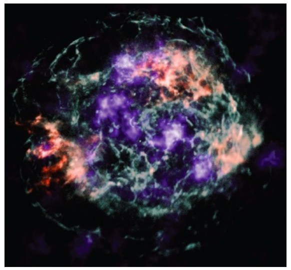
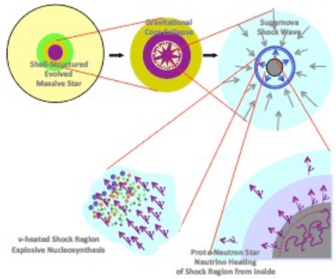
How do we learn about isotopes in the cosmos?

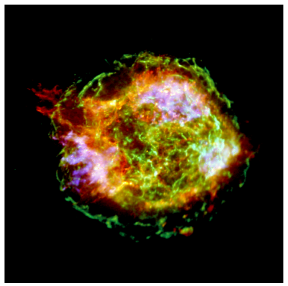
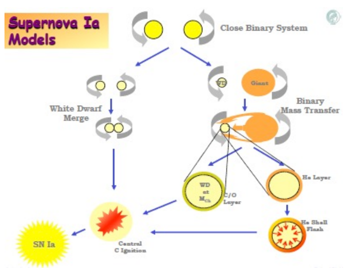
a few examples...

Science with Cosmic Isotopes



☆Trace the forms of cosmic matter

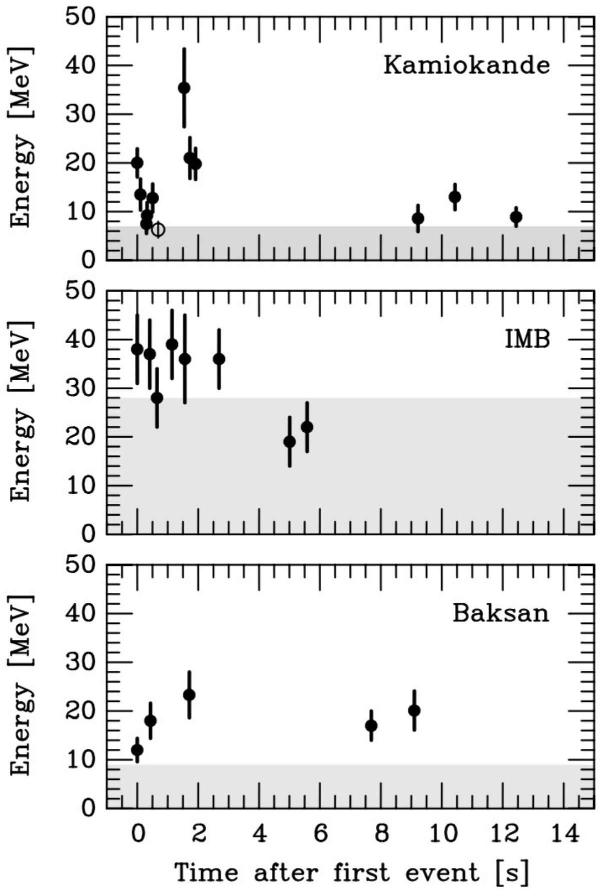



☆Understand the sources of new nuclei

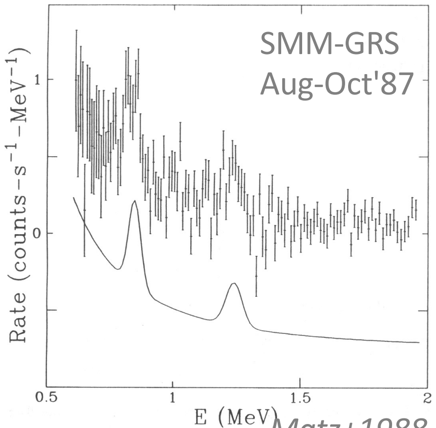
SN1987A: multiple messengers exploited

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

- Witness neutrino burst from core collapse

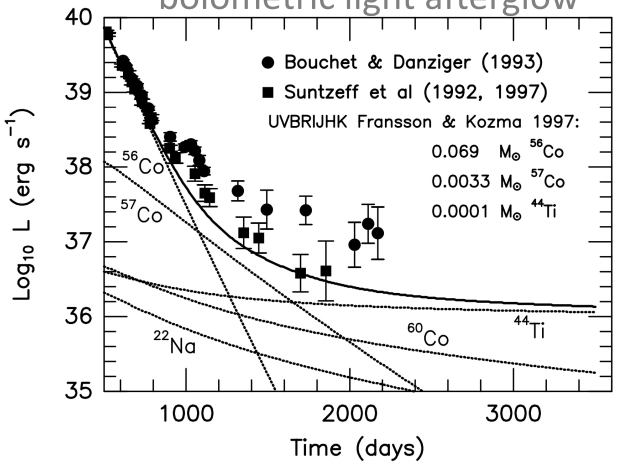


- Witness radioactively-powered SN afterglow and γ rays



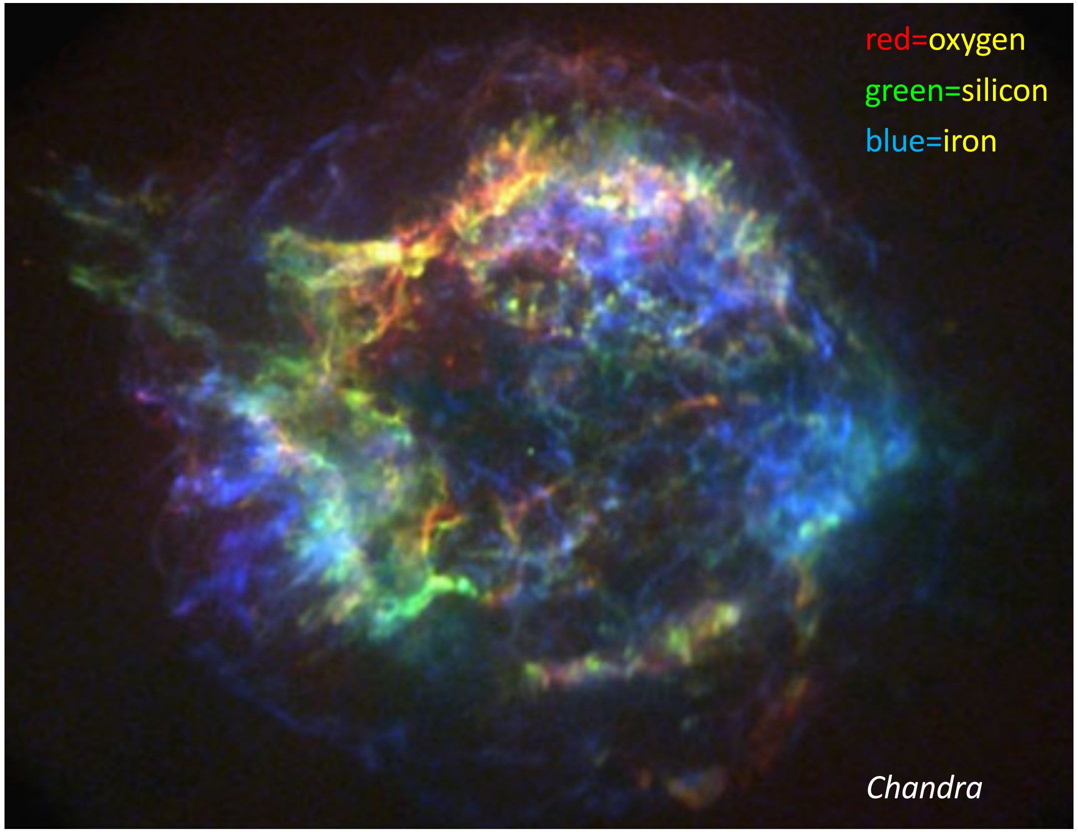
Matz+1988

bolometric light afterglow

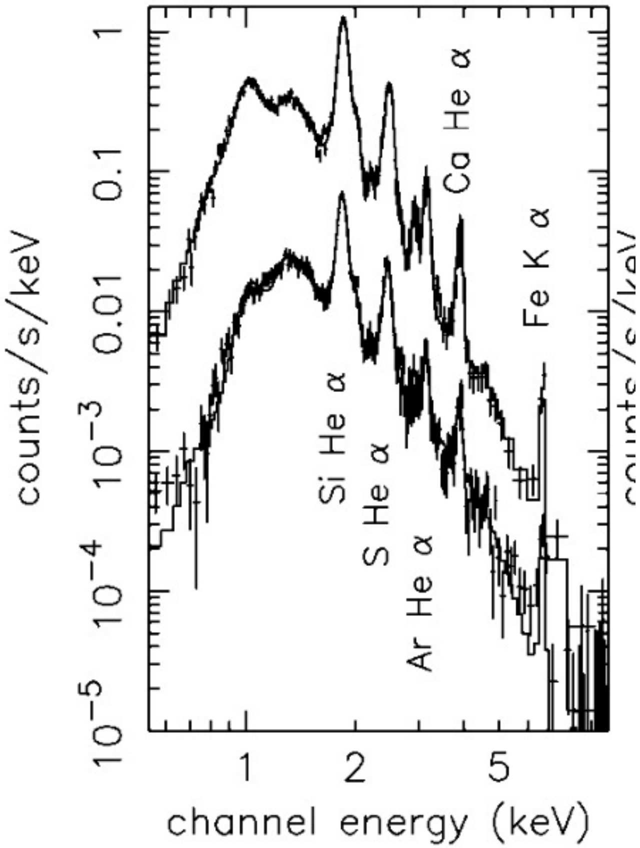


Cas A, a 360-year old SNR – X rays:

X-ray image surprise:
Fe rich knots outside of Si, S → overturn of material??



Hwang+ 2004



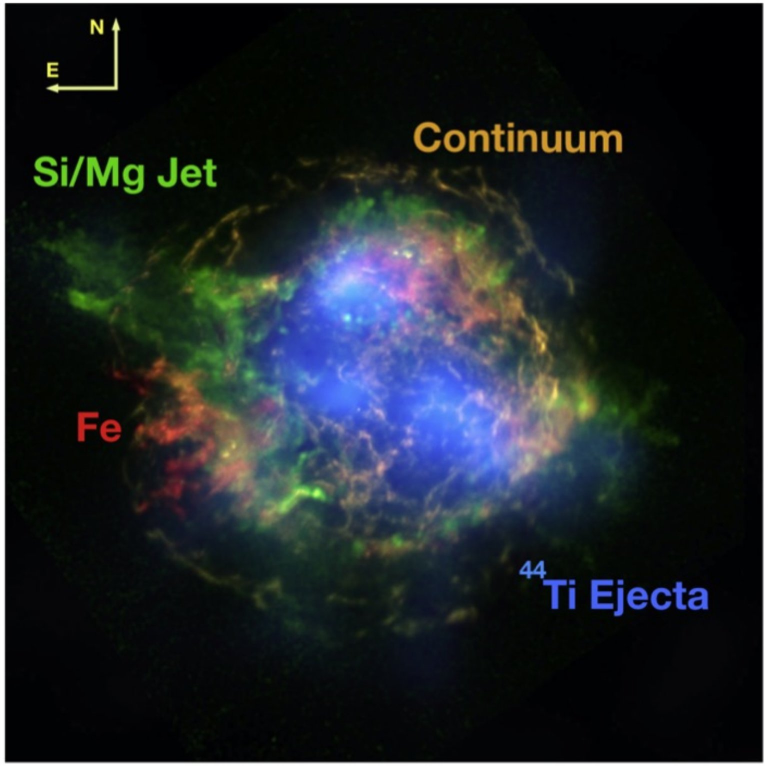
^{44}Ti radioactivity in Cas A: Locating the inner Ejecta

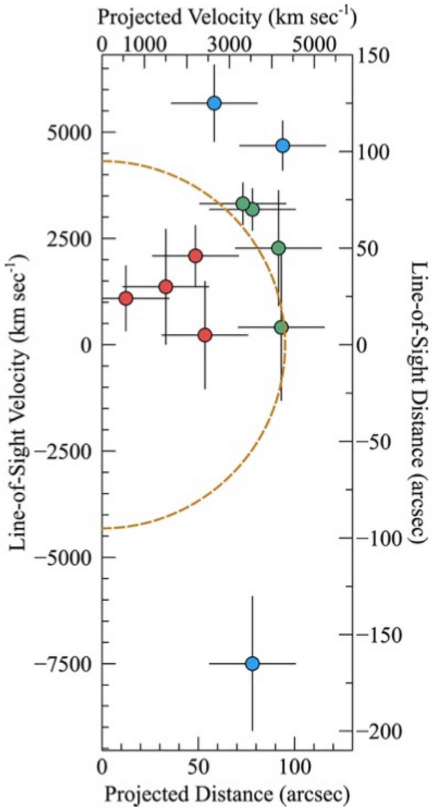
NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

☞ first mapping of radioactivity in a SNR

Grefenstette+ 2014; 2017

- Both ^{44}Ti lines detected clearly
- line 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!!

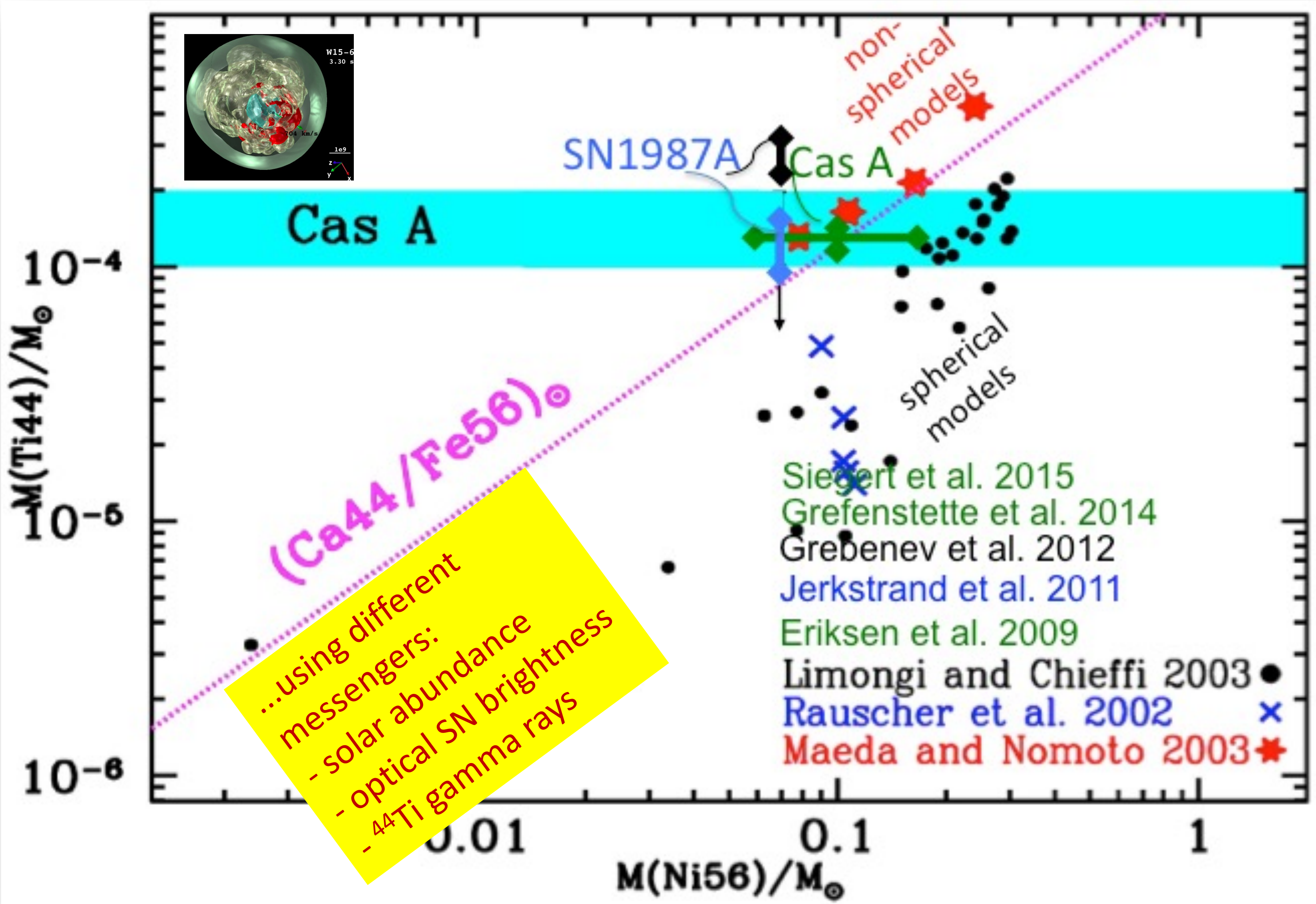




☞ ^{44}Ti→ TRUE locations of ejecta from the inner supernova

☞ Fe-line X-rays are biased from ionization of shocked plasma

"Rare" Core Collapse Supernovae as ^{44}Ca (=^{44}Ti) Sources?

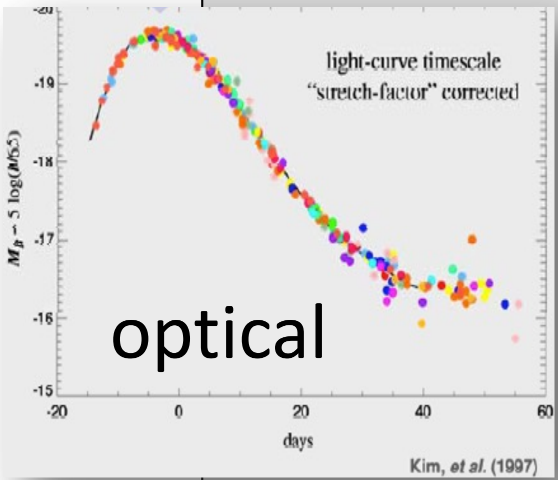


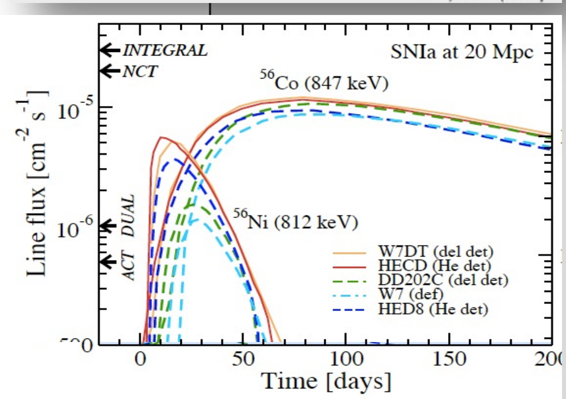
⇨ Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios

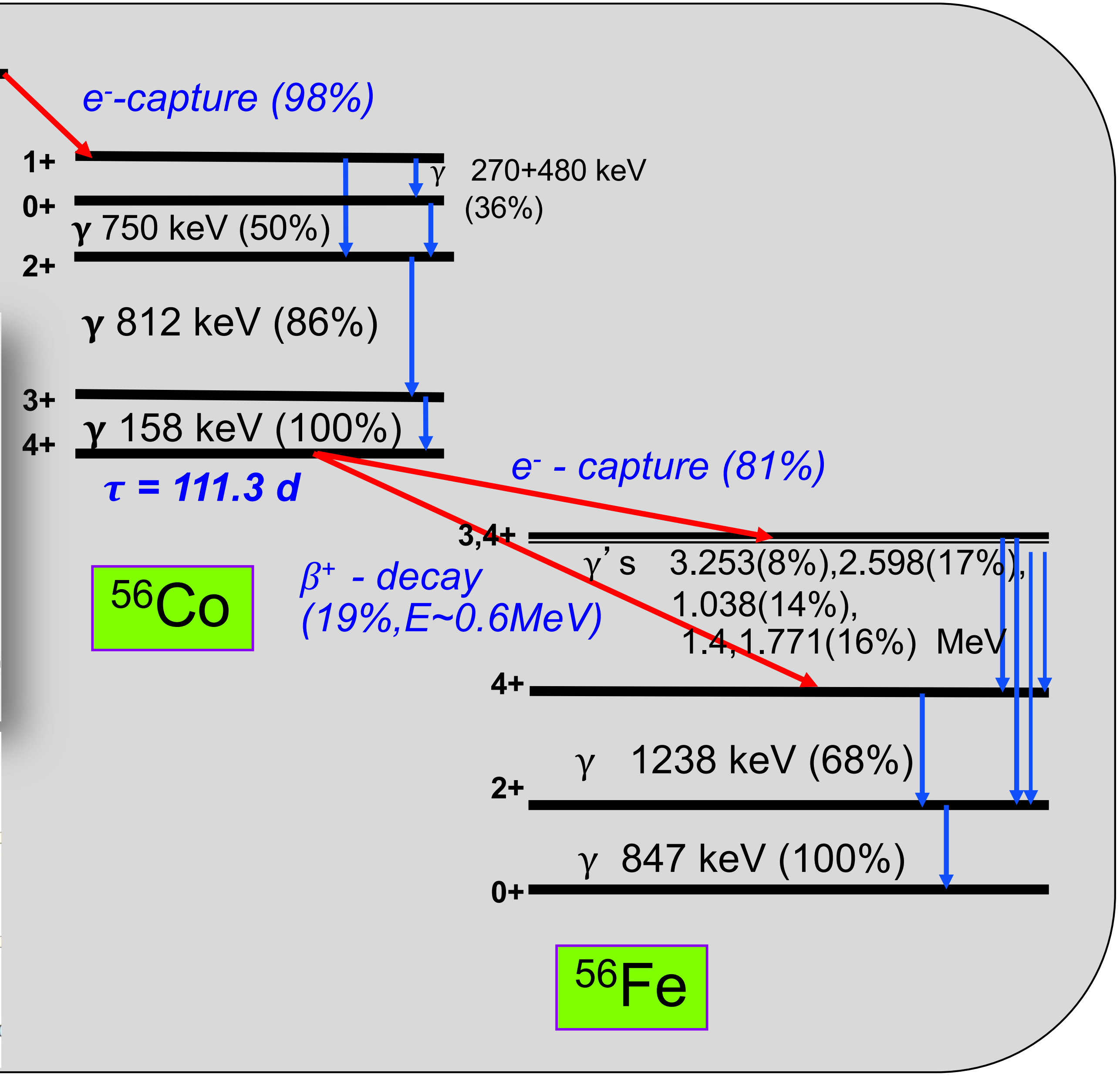
⇨ *The et al. 2006; Dufour&Kaspi 2013*

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

SN Ia



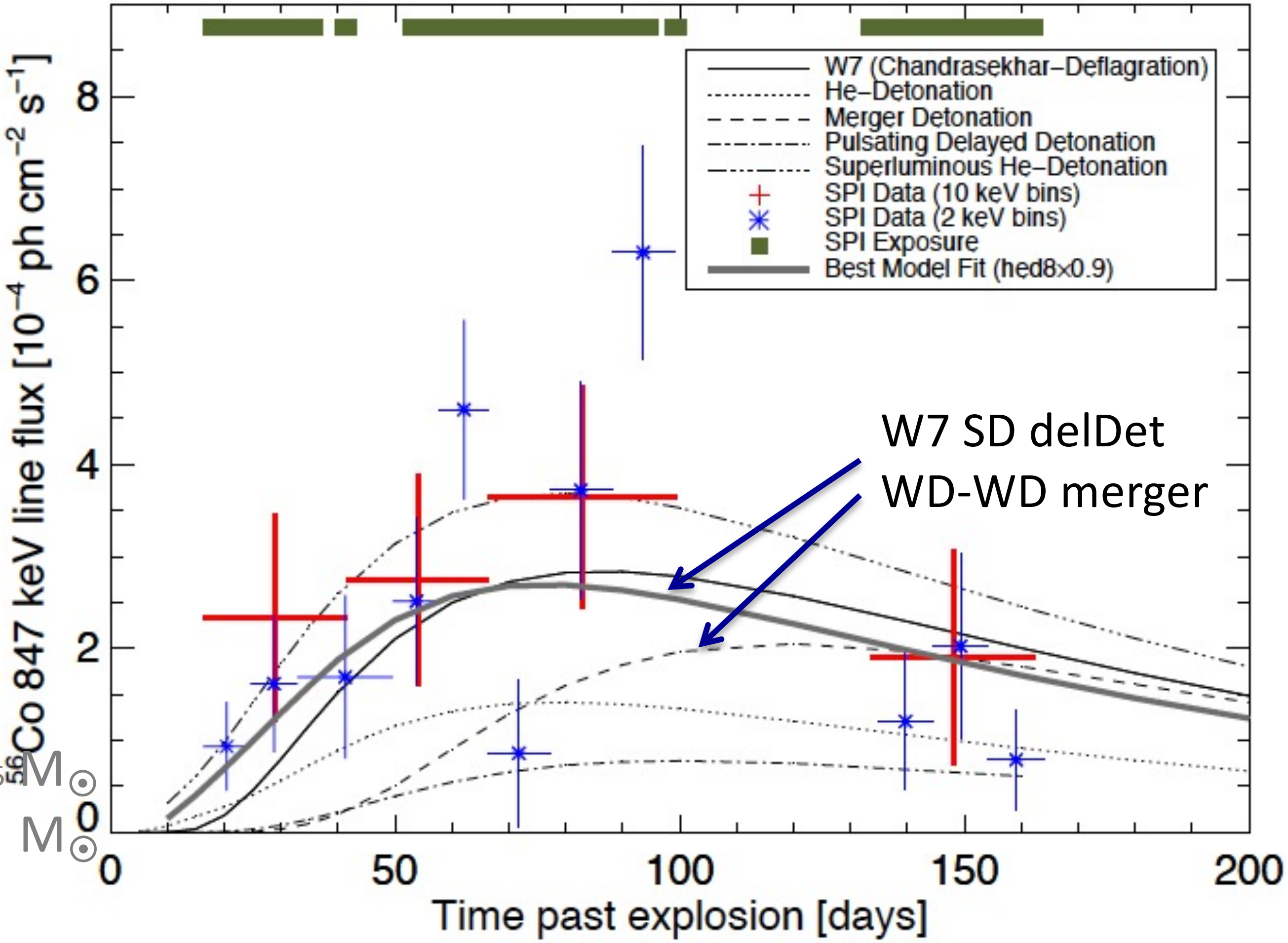




SN2014J light evolution in the 847 keV ^{56}Co line

- ☆ smooth(??) brightness evolution?

→ Compare high/low res data to models



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

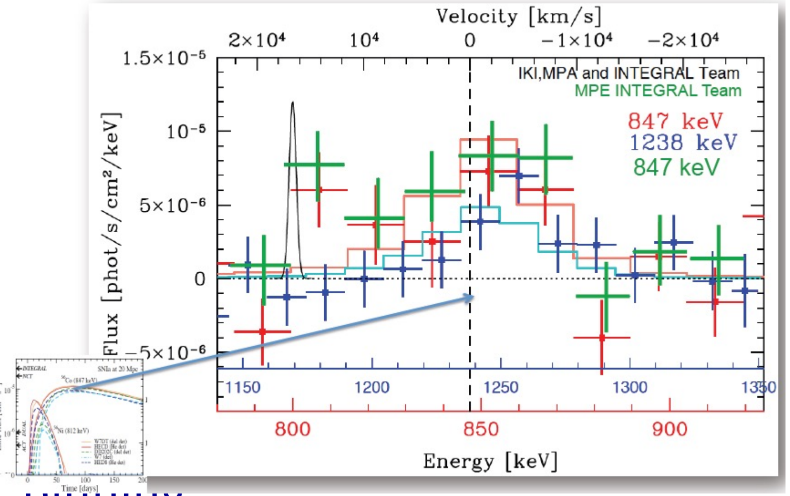
(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

☞ *Diehl et al., A&A 2015*

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

☆ Doppler broadened ✓

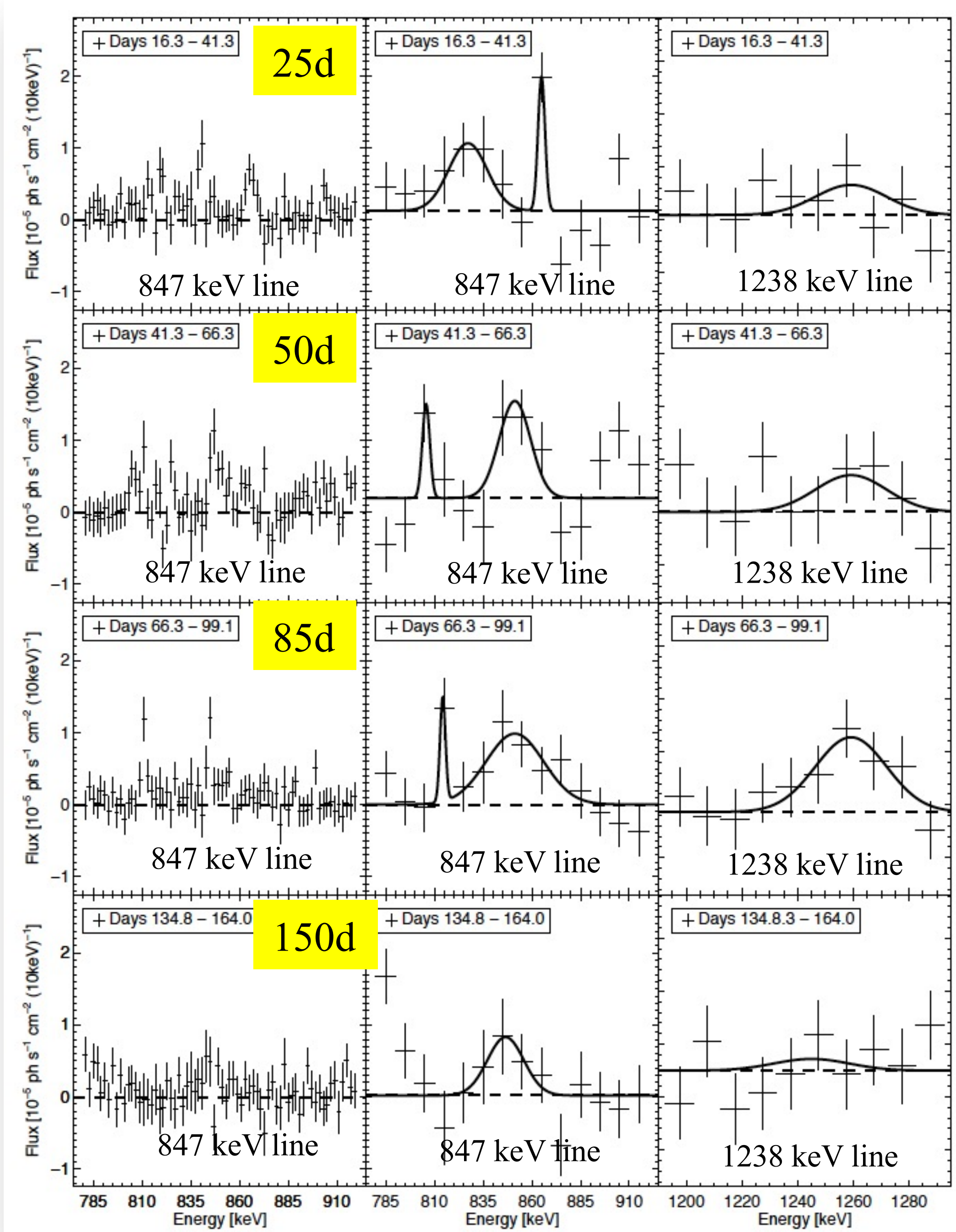


binning

→ Observe a structured and evolving spectrum

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

☞ *Diehl et al., A&A (2015)*

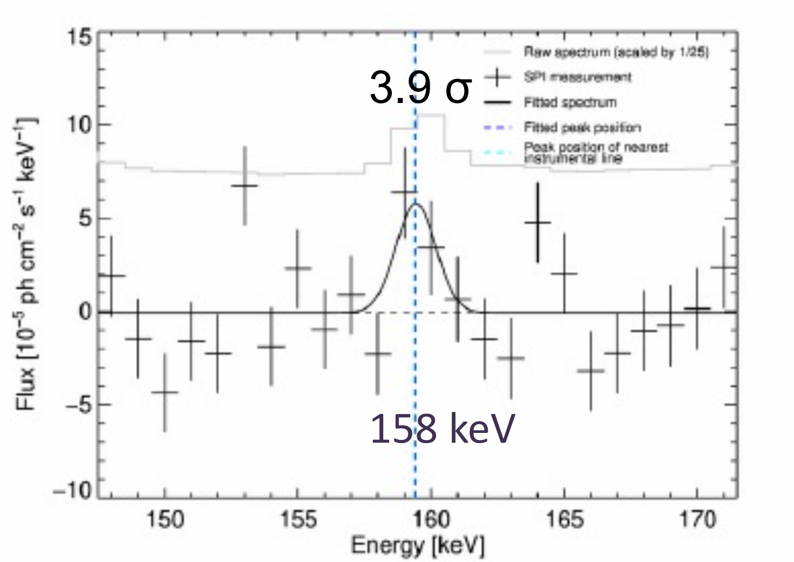


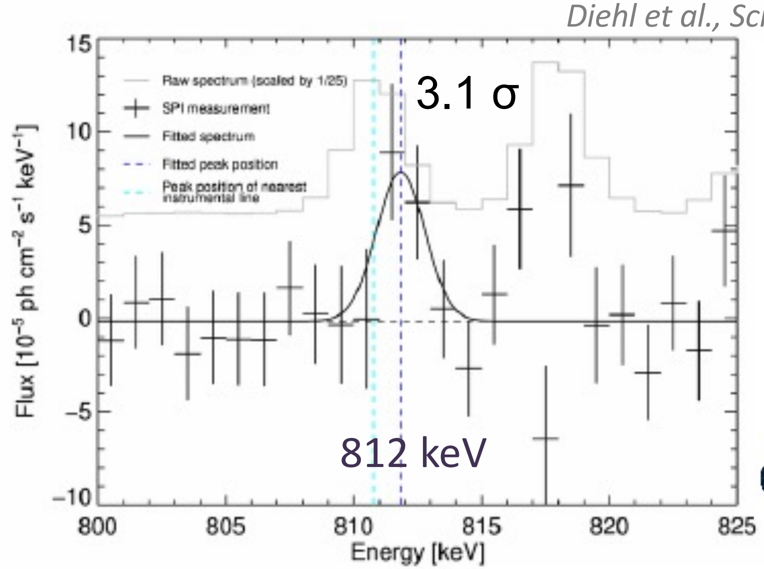
SNIa and SN2014J: Early ^{56}Ni (τ~8.8d)

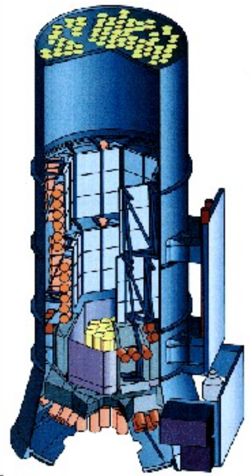
Spectra from the SN at ~20 days after explosion

Clear detections of the two strongest lines expected from ^{56}Ni

Diehl et al., Science (2014)

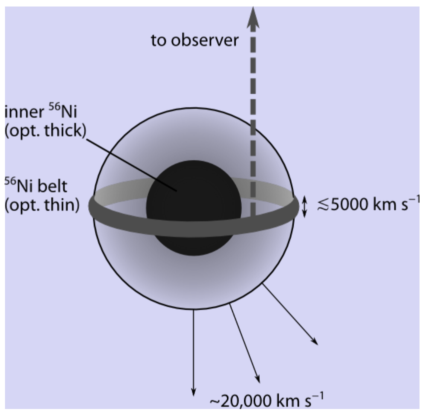


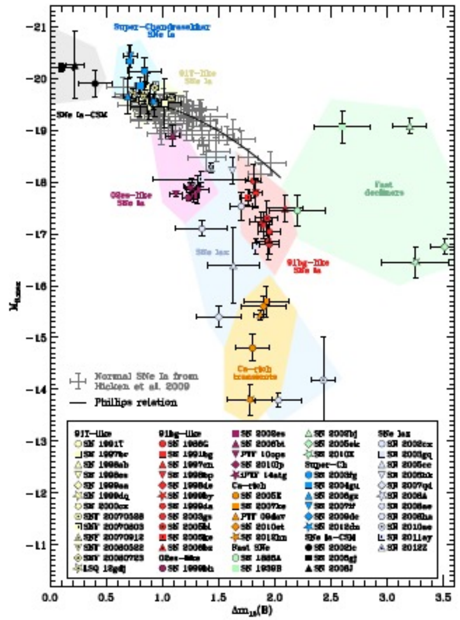




^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_\odot$ (~10%)

i.e.: not the single-degenerate $M_{chandrasekhar}$ model, but 2 WDs (double-degenerate)





Taubenberger 2017

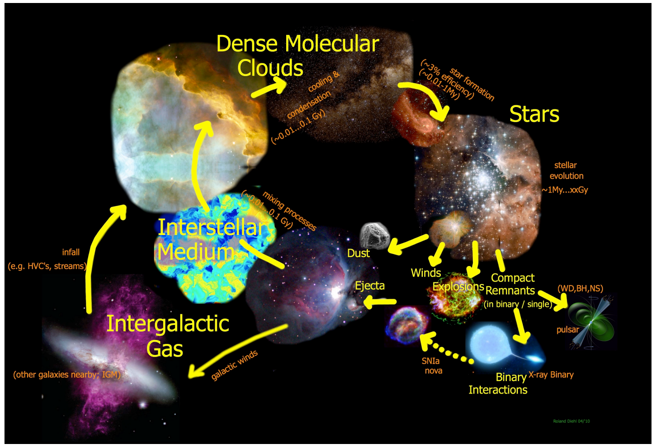
→ SN Ia are a variety

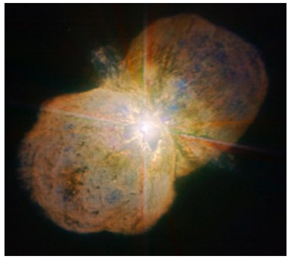
Sources of Nucleosynthesis

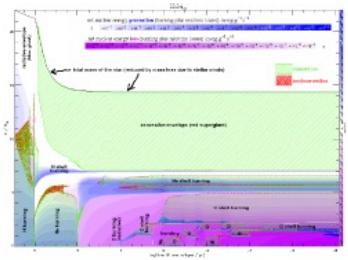
- Our current inventory:

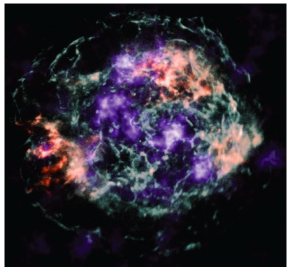
source	main products	frequency
core-collapse supernovae	Ni Fe Si Ca Ti U Th	10^{-3} y^{-1} $galaxy^{-1}$
thermonuclear supernovae	Fe Mn Ca	10^{-4} y^{-1} $galaxy^{-1}$
novae	F Na	30 y^{-1} $galaxy^{-1}$
jet-driven/magnetic supernovae	Eu	10^{-6} y^{-1} $galaxy^{-1}$
hypernovae	Zn	10^{-6} y^{-1} $galaxy^{-1}$
neutron star collisions	La	10^{-9} y^{-1} $galaxy^{-1}$
massive stars	O Ca Si Mg Al Fe	lifetime ~My...100My, birth rate 1 y^{-1} $galaxy^{-1}$
intermediate-mass stars	C Ba Pb	lifetime ~0.1-1 Gy, birth rate 1 y^{-1} $galaxy^{-1}$
low-mass stars	He	lifetime ~>10 Gy, birth rate 1 y^{-1} $galaxy^{-1}$

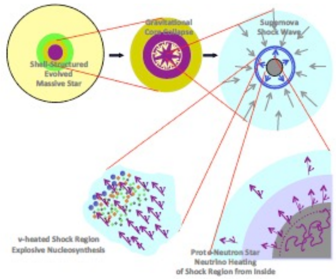
Science with Cosmic Isotopes

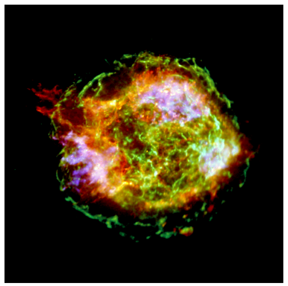


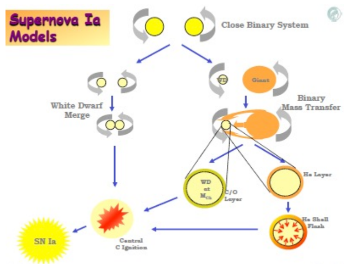






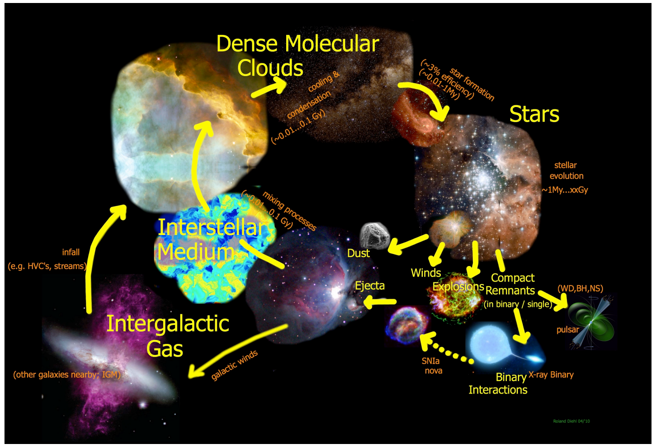






☆Trace the forms of cosmic matter

☆Understand the sources of new nuclei

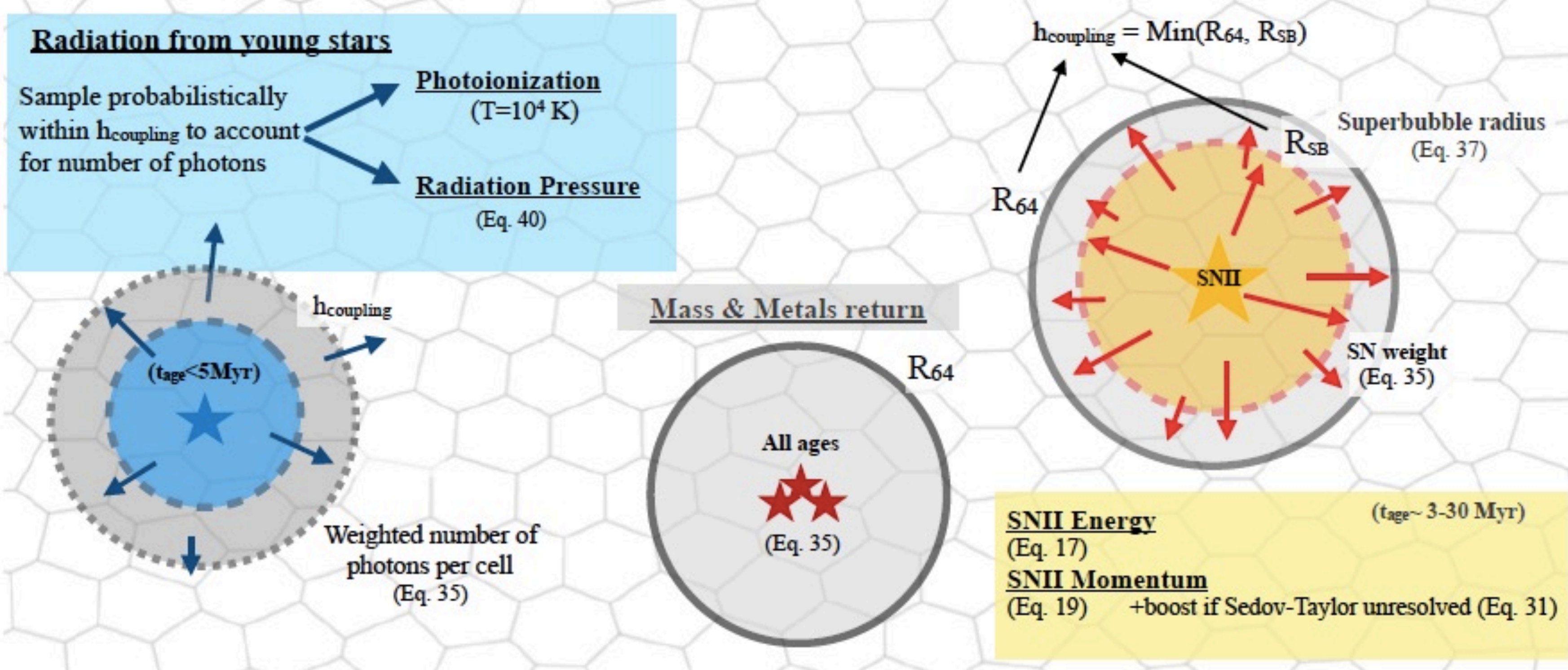


spreading of new nuclei across time & space...

Stellar Feedback

- Astrophysical processes:

Marinacci+2019

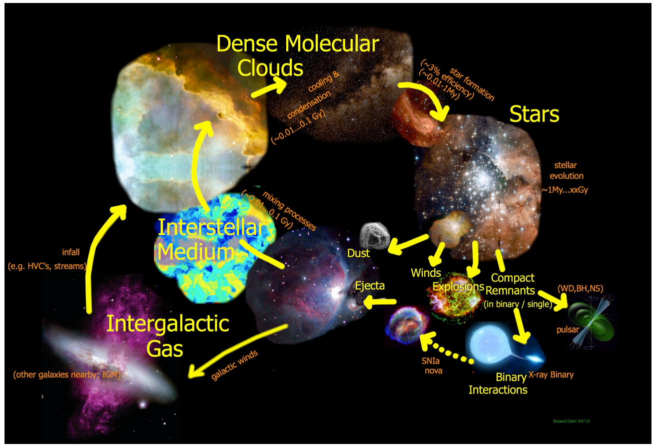


☞ Approximate treatments in current simulations:

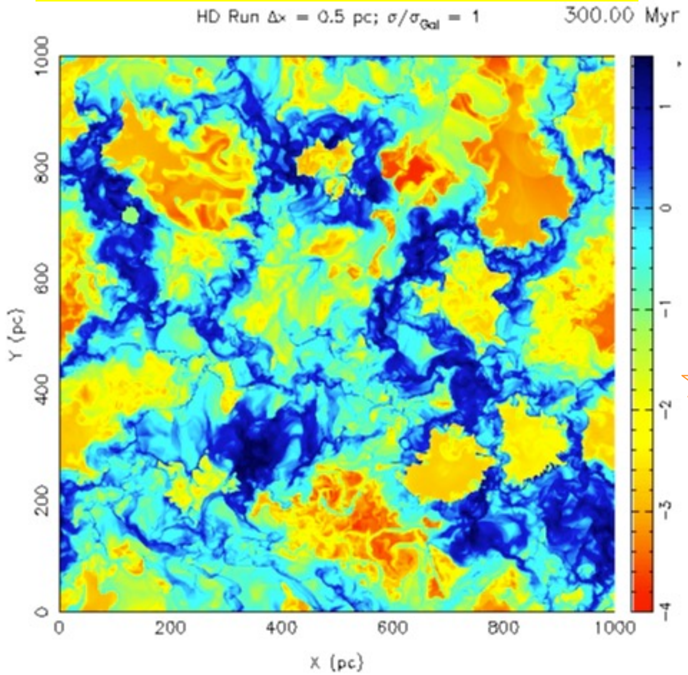
Springel 2020

Star formation and winds
- Variant of Springel & Hernquist (2003)
- Cold dense gas stabilized by an ISM equation of state
- Winds are phenomenologically introduced, with an energy given as a fixed fraction of the supernova energy
- The wind velocity is variable, the mass flux follows for energy-driven winds
- Fiducial model scales wind with local dark matter velocity dispersion
- Winds are launched outside of star-forming gas, and metal-loading can be reduced if desired

Modeling Compositional Evolution



100 Myrs in a kpc³ of a galaxy:



courtesy Miguel de Avillez

☆ Changes in the forms of cosmic matter:

- stars and gas flows:

$$m = m_{\text{gas}} + m_{\text{stars}} + m_{\text{infall}} + m_{\text{outflow}} \qquad m_{\text{stars}} = m_1 + m_c$$

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

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

- gas ejected from stars:

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

- newly-contributed ashes from nucleosynthesis:

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

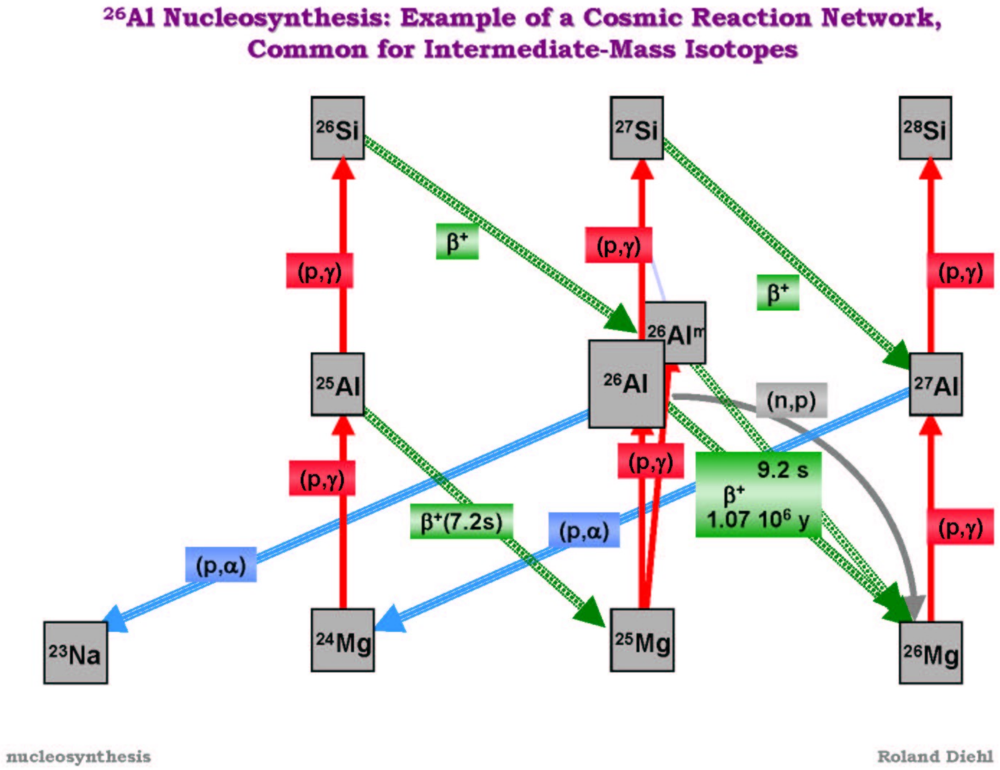
- Sources: How much of species i do they eject (and/or bury)?

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

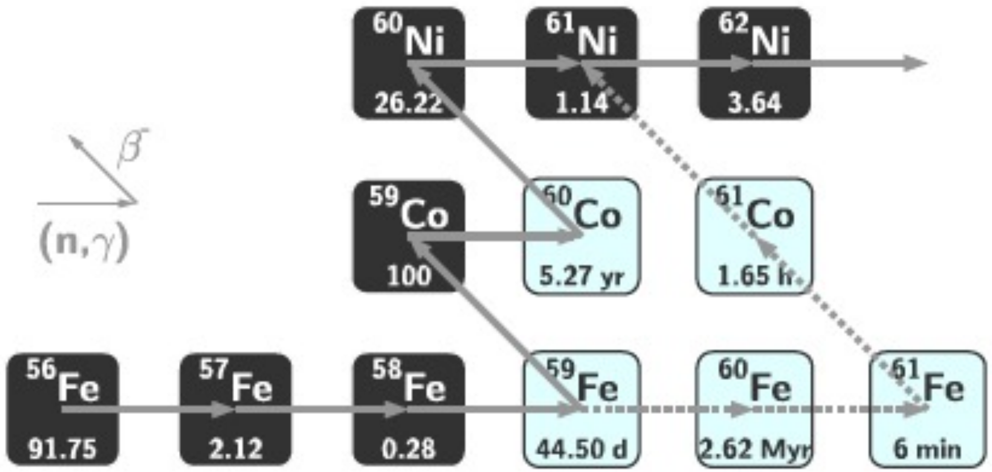
- ... (locations and environments of star formation, gas flows, ...)

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

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



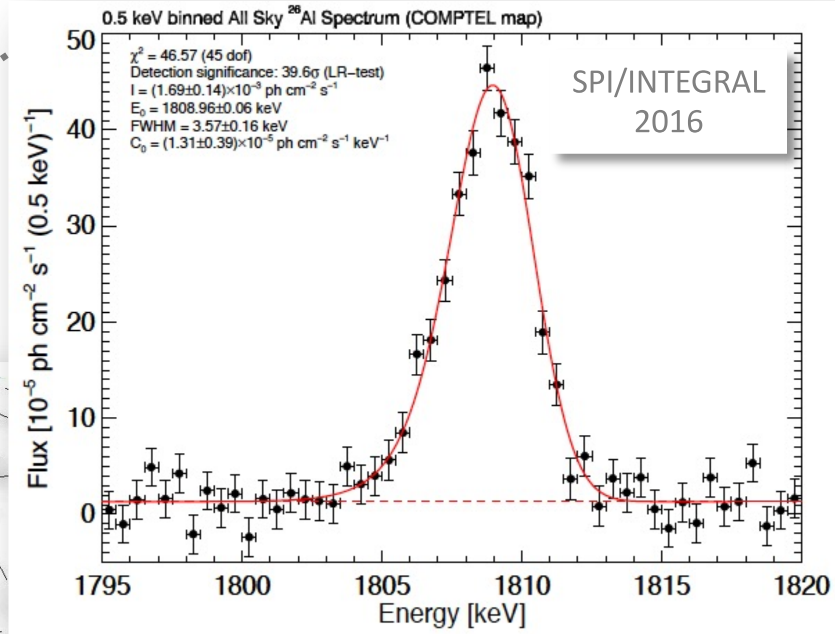
- Neutron capture on Fe in massive-star shells

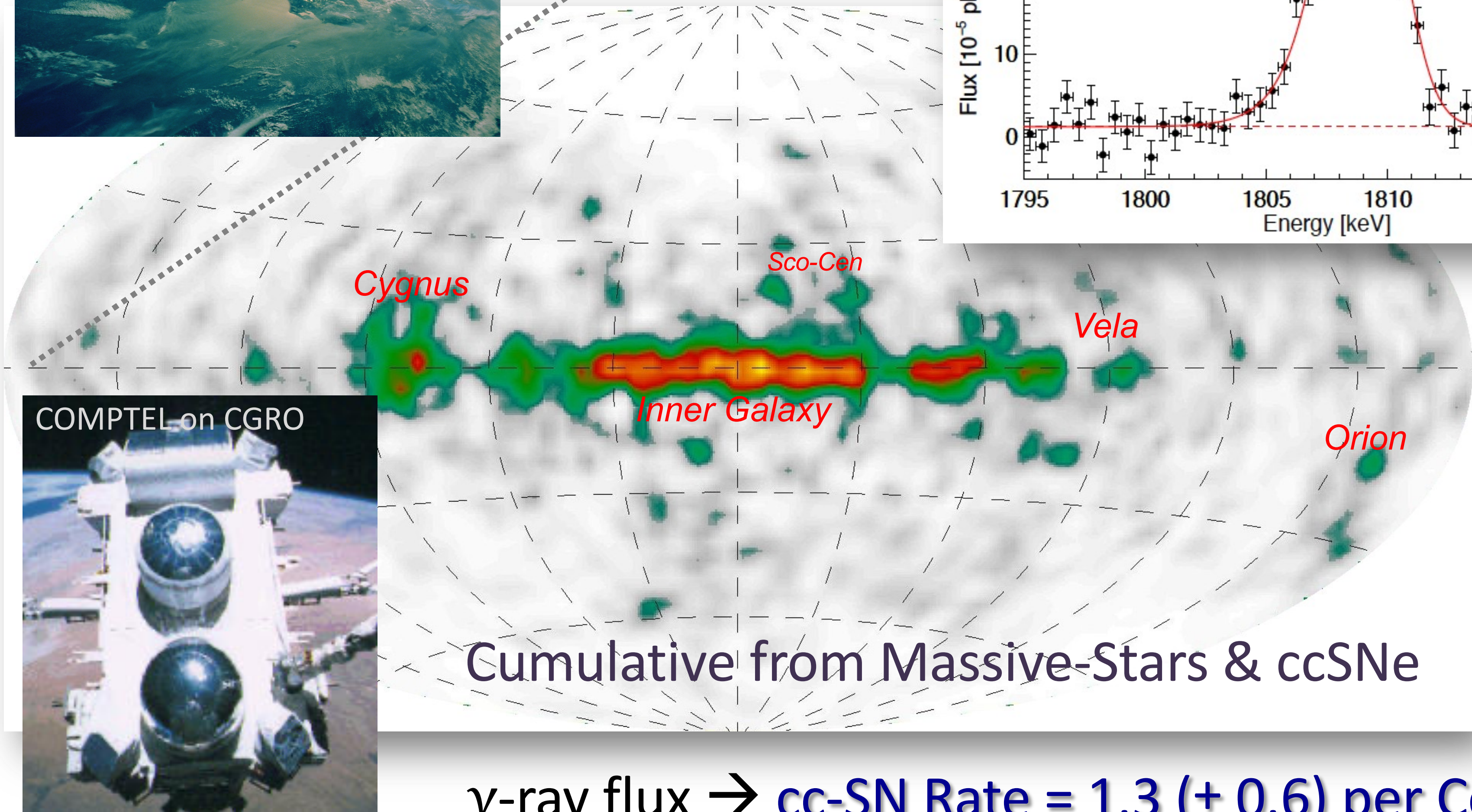


☆ What are the n capture rates?

☆ What are the β decay lifetimes?

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





Cumulative from Massive-Stars & ccSNe

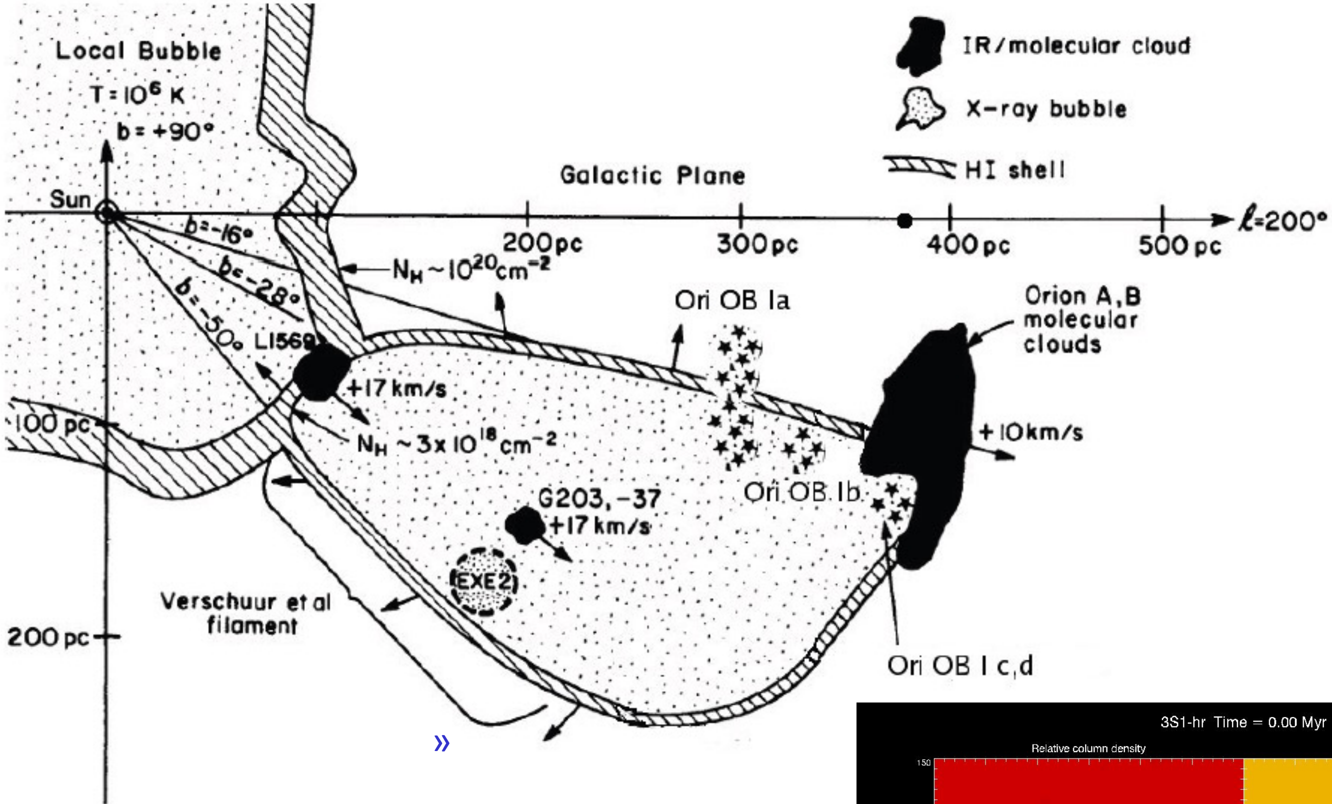
γ-ray flux → cc-SN Rate = 1.3 (± 0.6) per Century

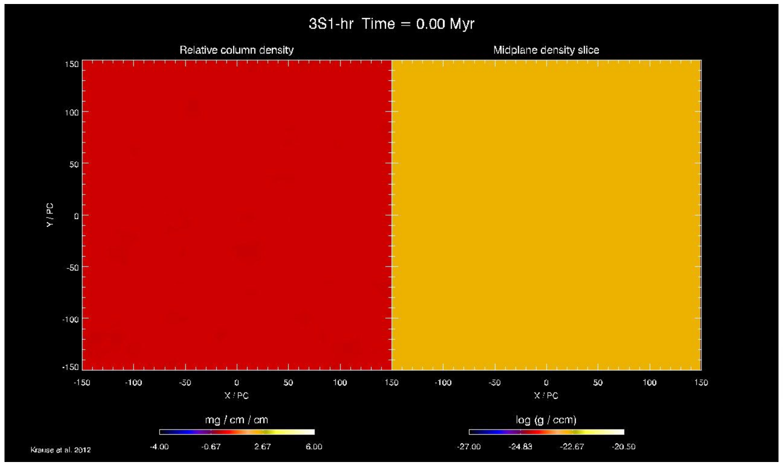
Diehl+2006;2018

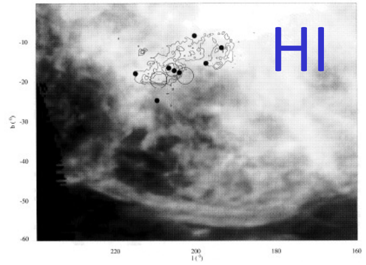
Ejecta and cavities blown by stars & supernovae

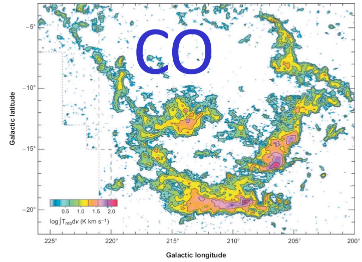
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

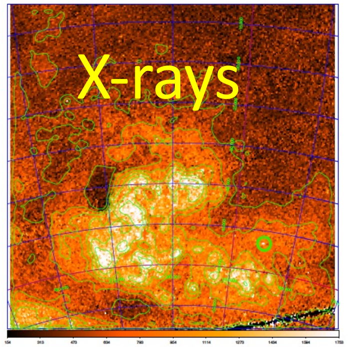
here: the Orion region with the Eridanus cavity

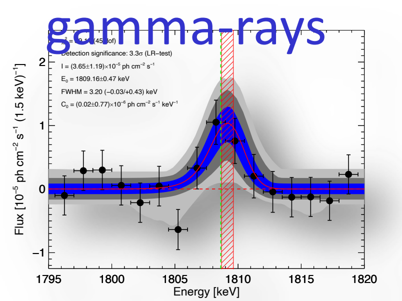






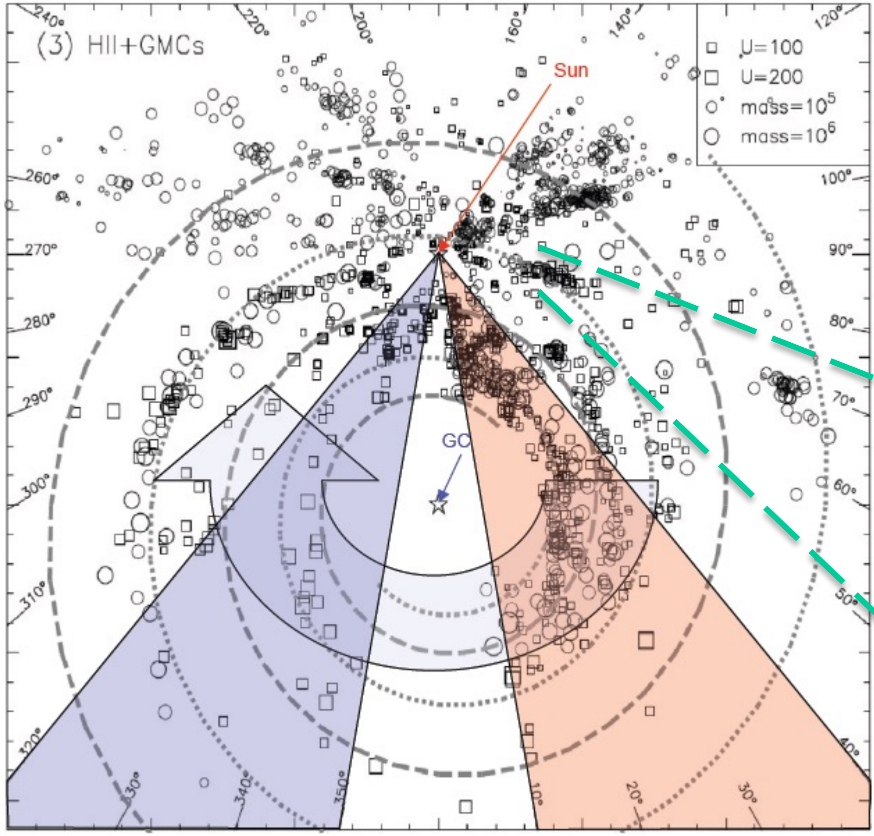


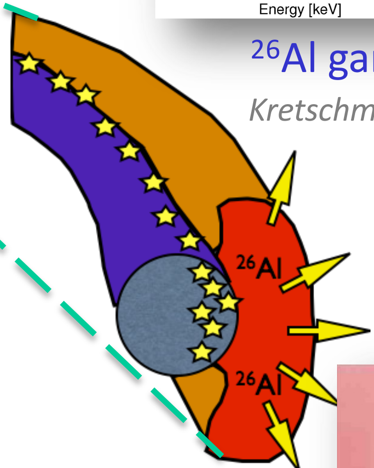


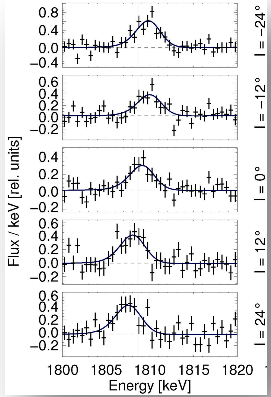


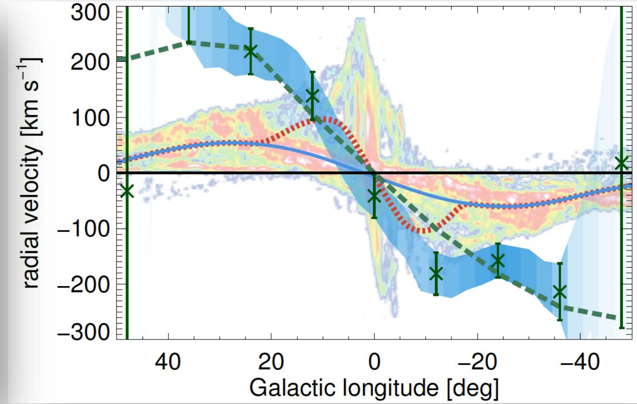
How massive-star ejecta are spread out...

Superbubbles are blown into lower-density regions







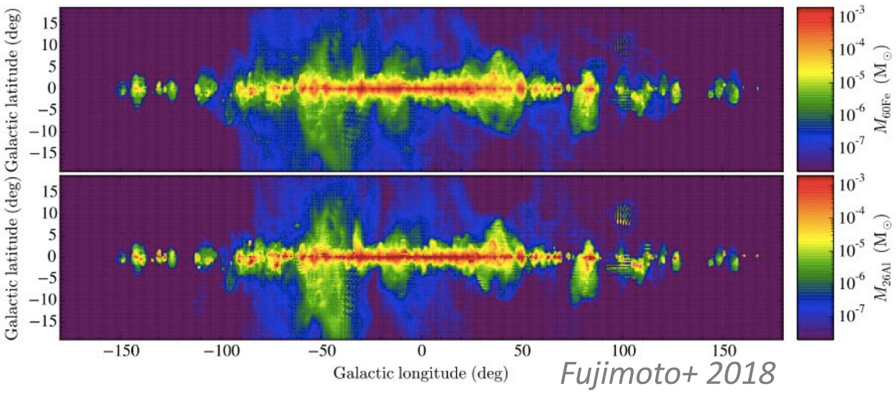


^{26}Al gamma-ray observations

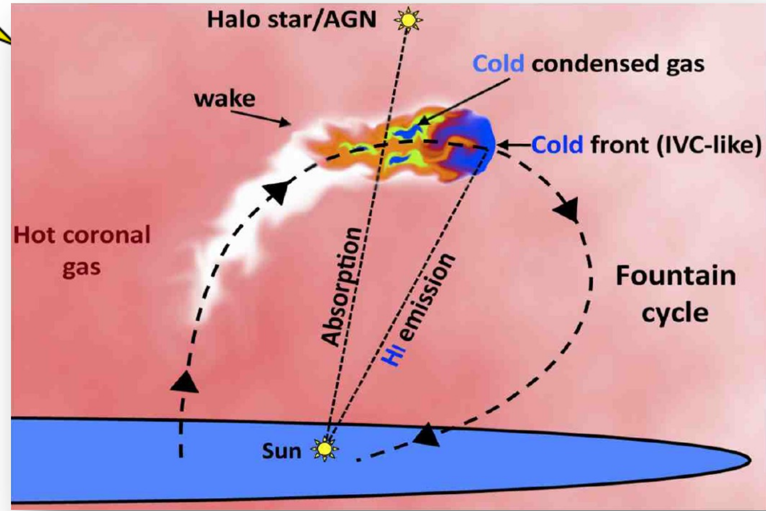
Kretschmer+2013; Krause & Diehl 2015

→ kpc-sized cavities are commonplace

3D MHD simulations



Fujimoto+ 2018



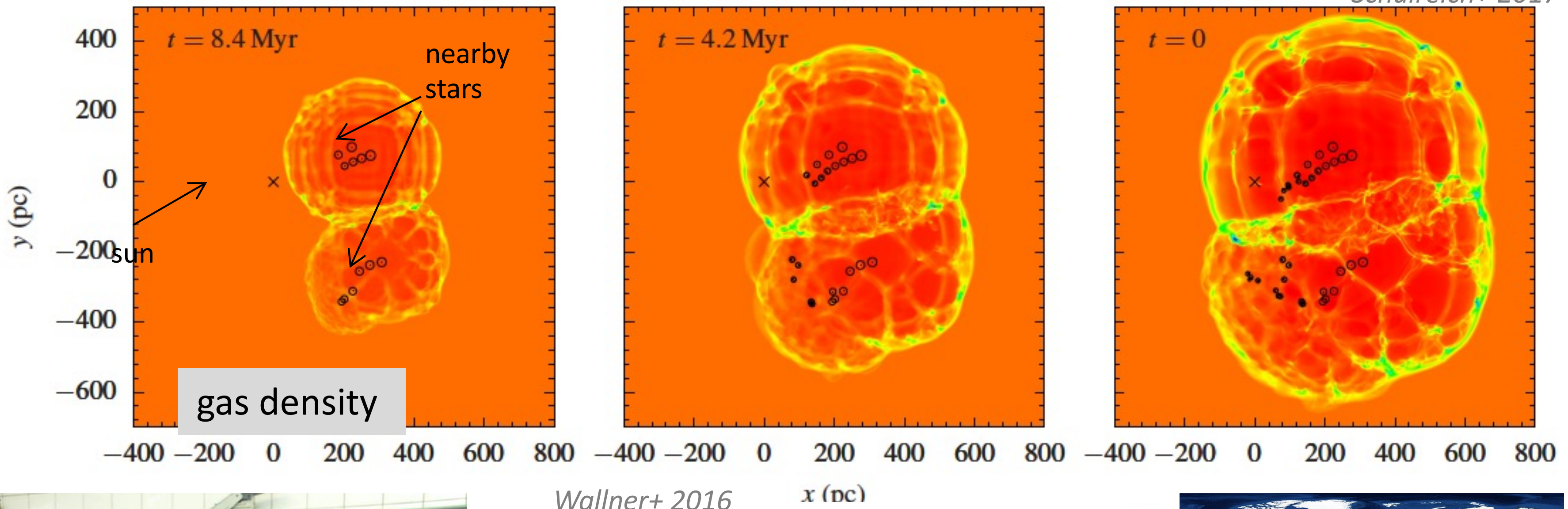
Fraternali+ 2015

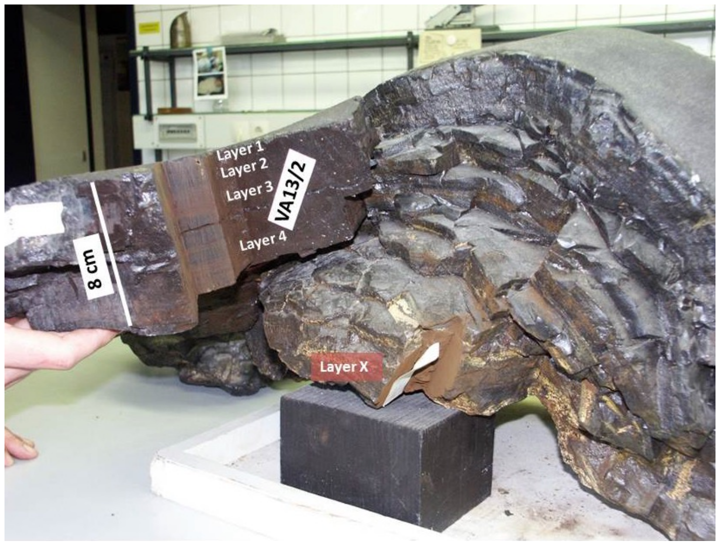
^{60}Fe from a nearby supernova on Earth

The Sun is located inside a hot cavity (Local Bubble & Loop-1)

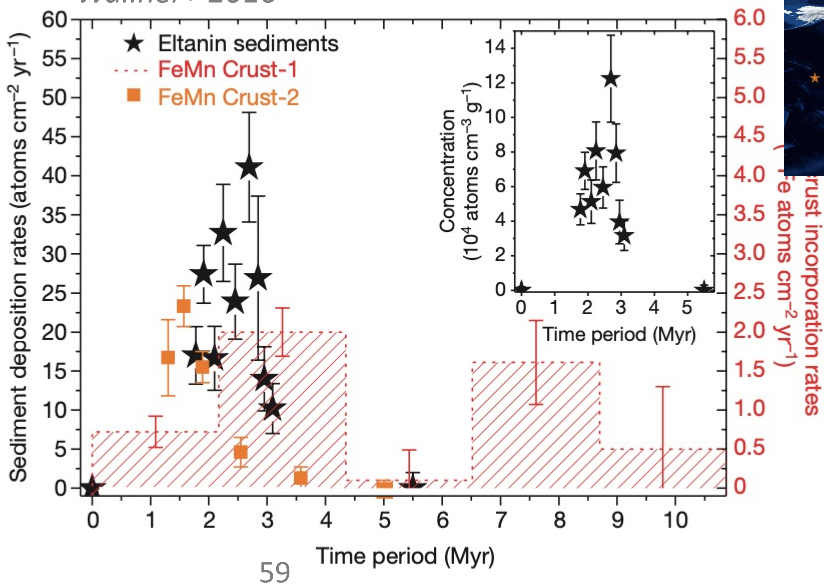
SN explosions within → ejecta flows reach the Solar System

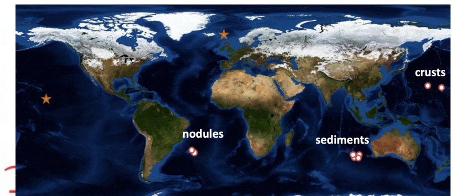
Schulreich+ 2017





Wallner+ 2016

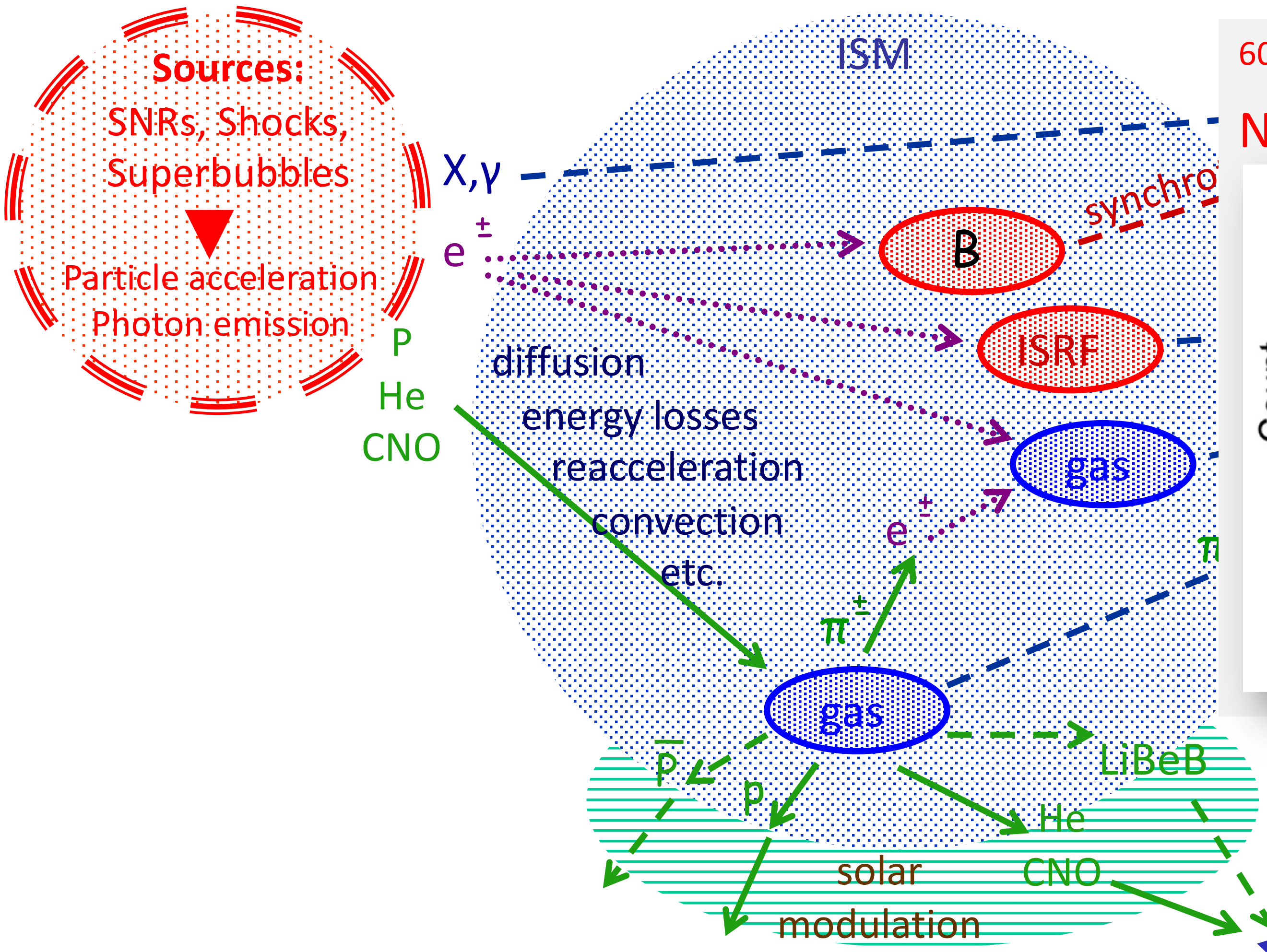




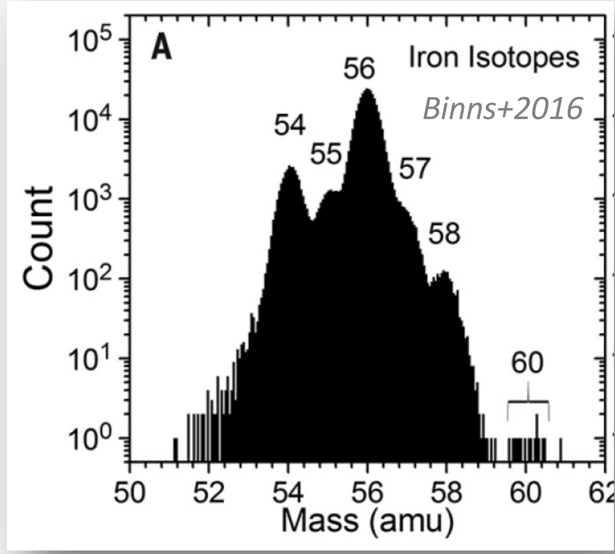
influx peak

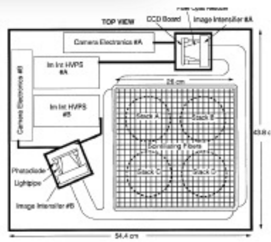
≈3 My ago!

Cosmic Rays: From sources to direct observation

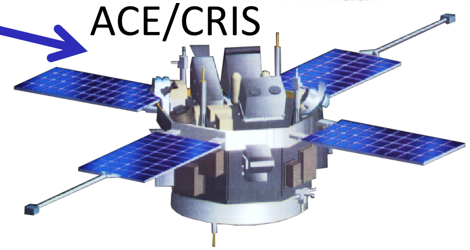


^{60}Fe in CRs: from Sources,
Not from spallation!



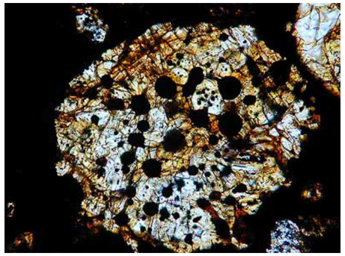


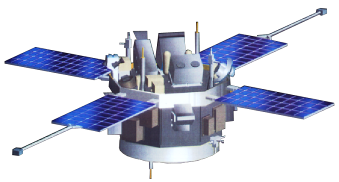
ACE/CRIS



- ☞ Propagation from nearby sources (~few 100 pc)?
- ☞ Acceleration in ISM/Superbubbles?

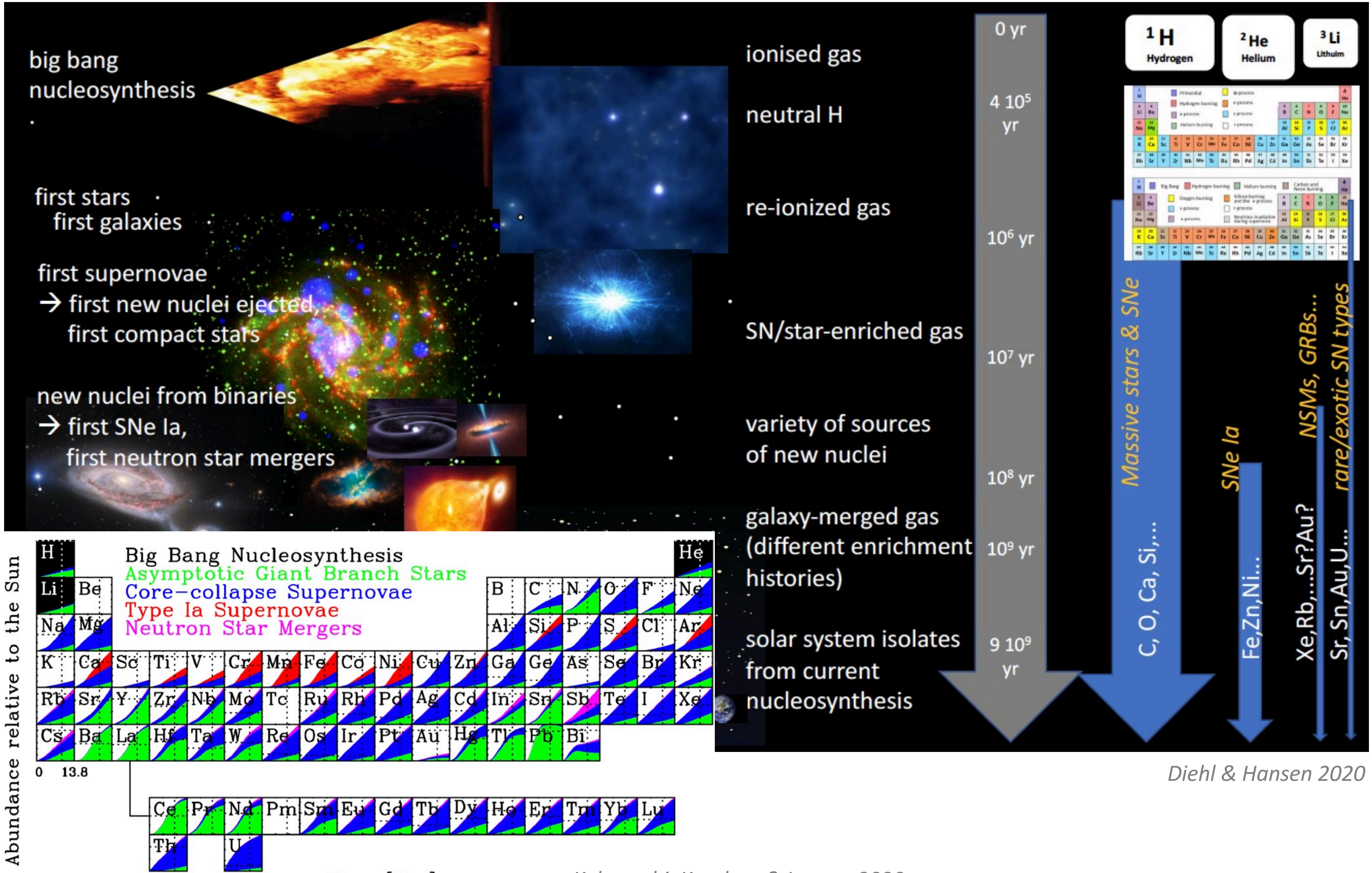
Messengers from cosmic nucleosynthesis

messenger	*message*
photons (optical/UV)	identify atomic species
meteorites	discover variety of elements & isotopes
neutrinos	proof of gravitational collapse proof of H burning reactions
photons (optical; time domain)	oscillation modes of stars
photons (gamma rays)	identify freshly-produced isotopes
photons (X rays)	identify highly-ionised atoms (hot plasma)
sediments on Earth & Moon	identify ejecta cloud from recent nearby SNe
presolar grains	identify isotopic signatures of nucleosynthesis processes in AGB, SNe, ...
cosmic rays	verify fresh SN ejecta within nearby CR-propagation distances

Cosmic Nucleosynthesis Overview

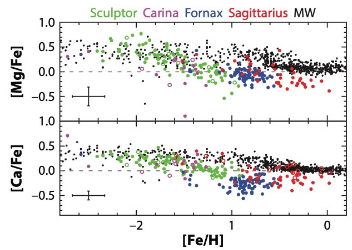


Diehl & Hansen 2020

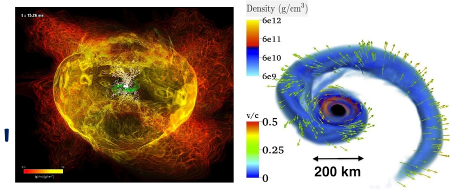
Kobayashi, Karakas, & Lugaro 2020

Observing Cosmic Nuclei - Status Summary

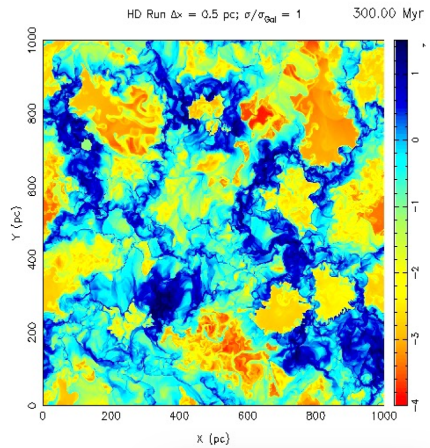
- ☆ Stellar spectroscopy / galactic archeology is in an era of precision
  - ☞ large surveys >10^6 sources with spectra; metallicity fully covered
  - ☞ better stellar ages allows evolutionary-model test



- ☆ Specific sources and their understanding are a challenge
  - ☞ Models for stars and supernovae are not (yet?) fundamental 'physics'
    - – SNIa diversity (^{56}Ni and how it reveals its radiation) → sub-Chandra models?
    - – ccSupernovae are fundamentally 3D/asymmetric (^{44}Ti ; jetSNe, HNe)
    - – rare events (e.g. kilonovae/NSMs) are multi-variate; astronomy?



- ☆ Cycling of cosmic gas through sources and galaxies is a challenge
  - ☞ source environments are a variety (dense clouds.... cavities)
  - ☞ evolutionary time delays and locations are poorly known



- ☆ Varied messengers complement each other with essential diagnostics
  - ☞ Radioactivity provides a unique / different view on cosmic isotopes (γ rays!)
  - ☞ particle measurements (sediments/meteorites/stardust/CRs) are essential
  - ☞ new astronomies contribute unique aspects (seismology, gravity waves)