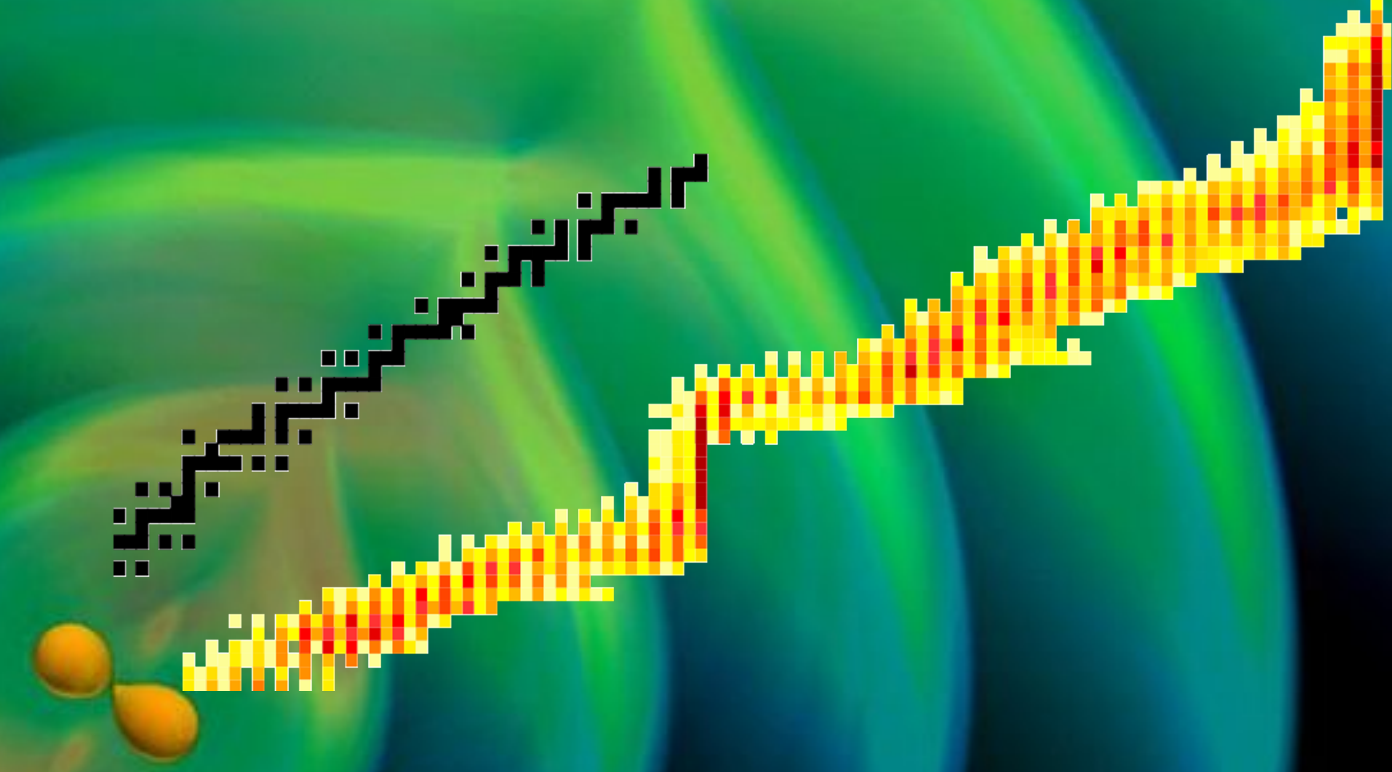
r-process nucleosynthesis



TRIUMF

JINA-CEE

FIRE

Fission In R-process Elements

Nicole Vassh

TRIUMF Theory Group

NIC School Lecture,

Live from home wishing I could see pandas :/

September 13, 2021

Outline

- Observational evidence that the *r* process occurs [4-9]

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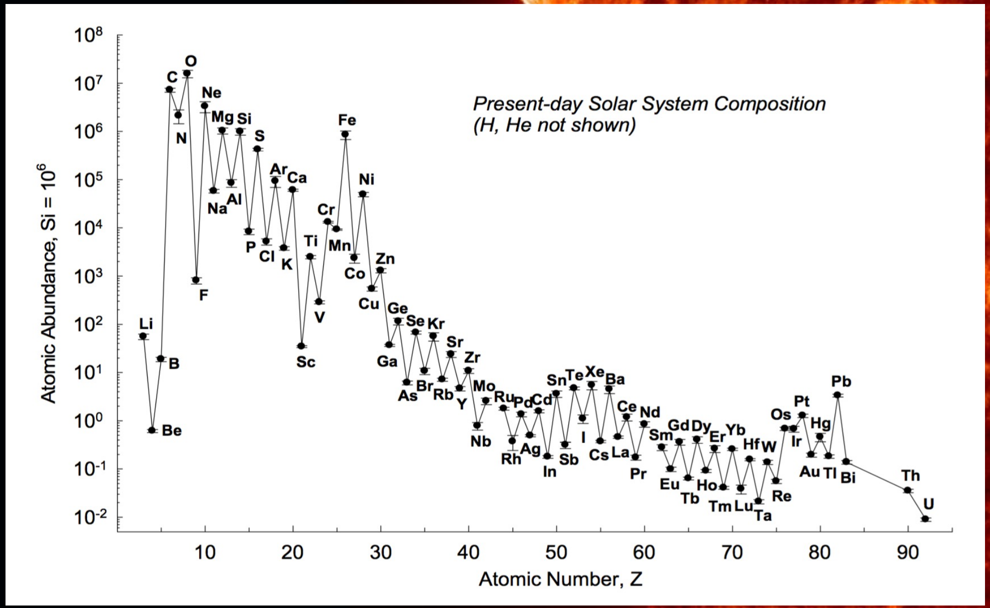
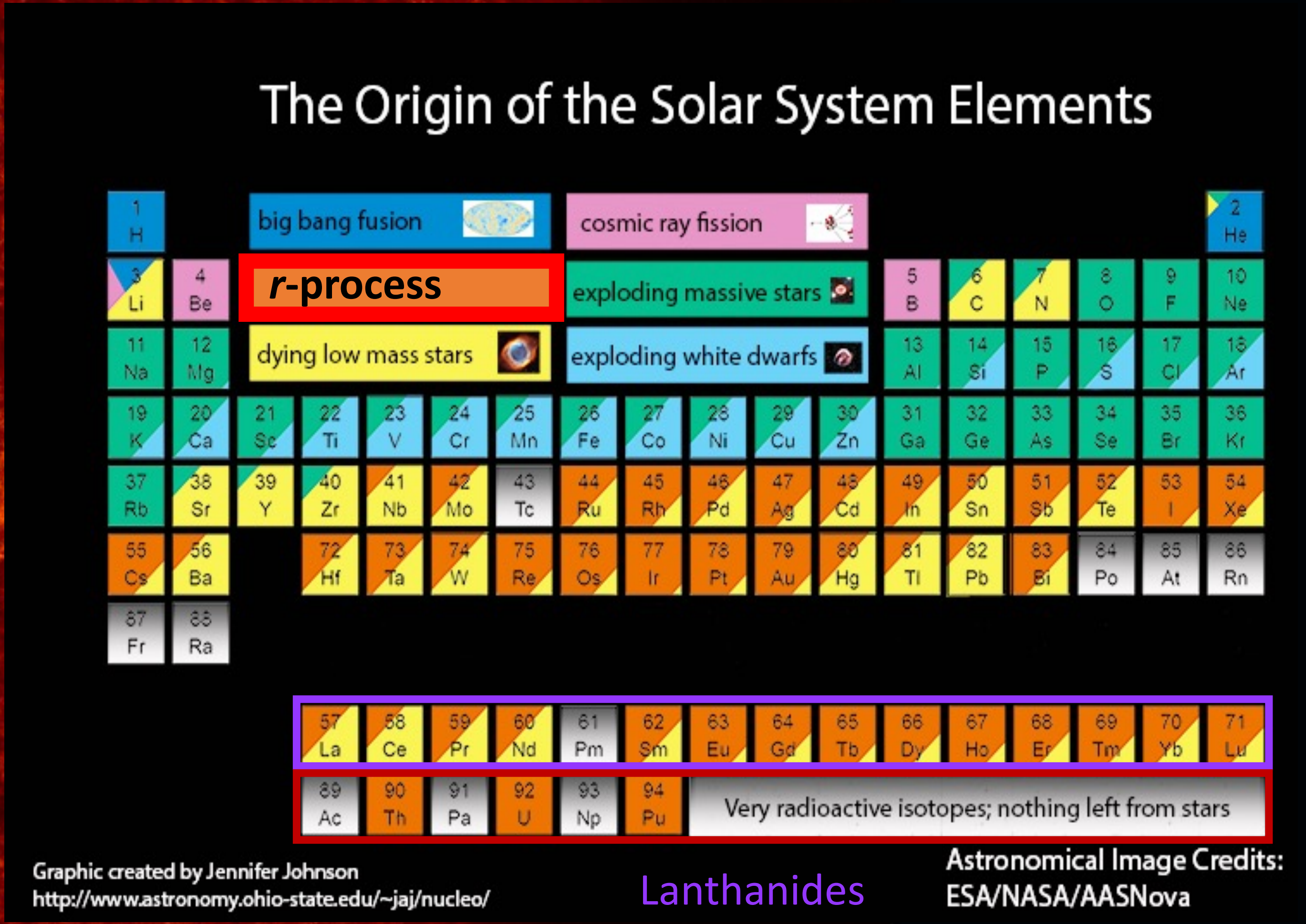
The solar composition can be decomposed into many processes → multiple nucleosynthesis sites enriched the solar system



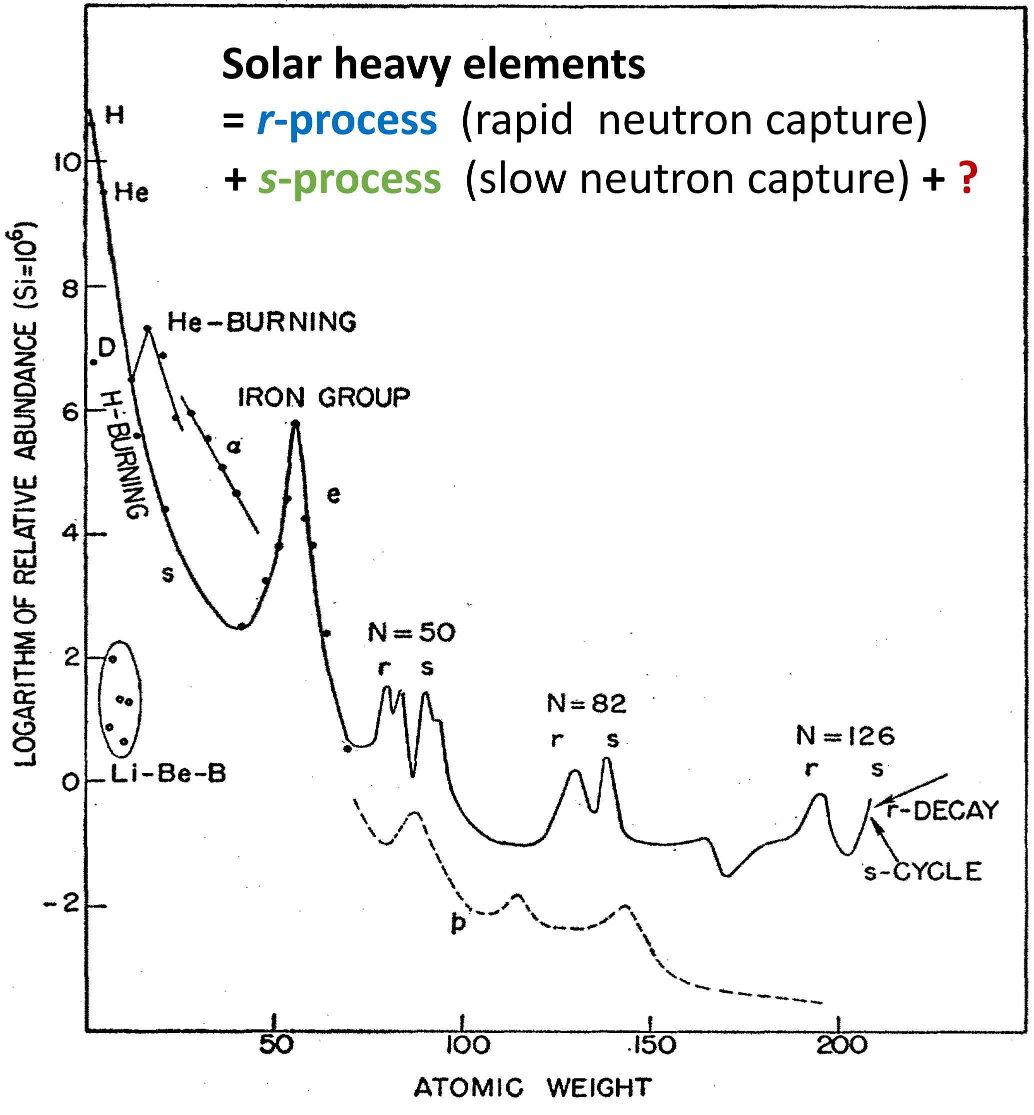
Lodders 10



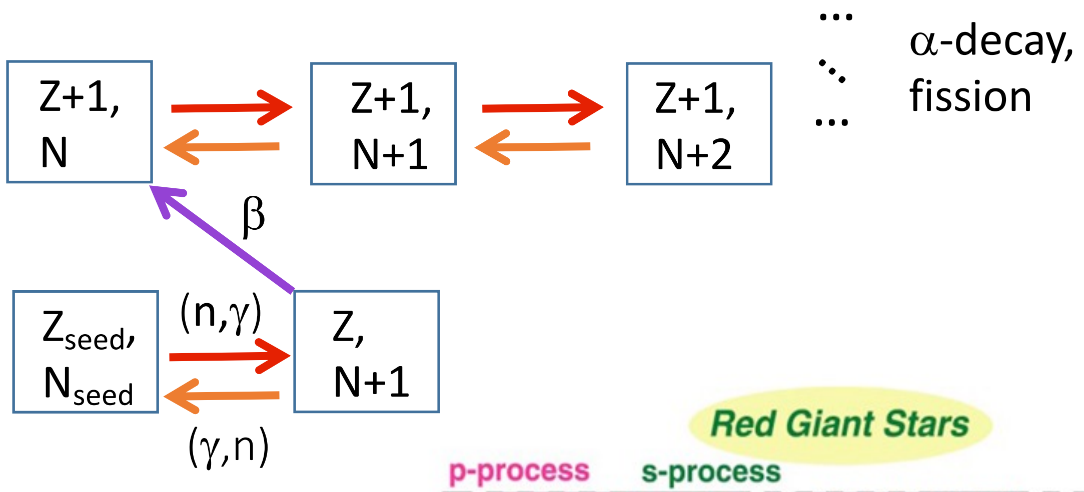
Lanthanides

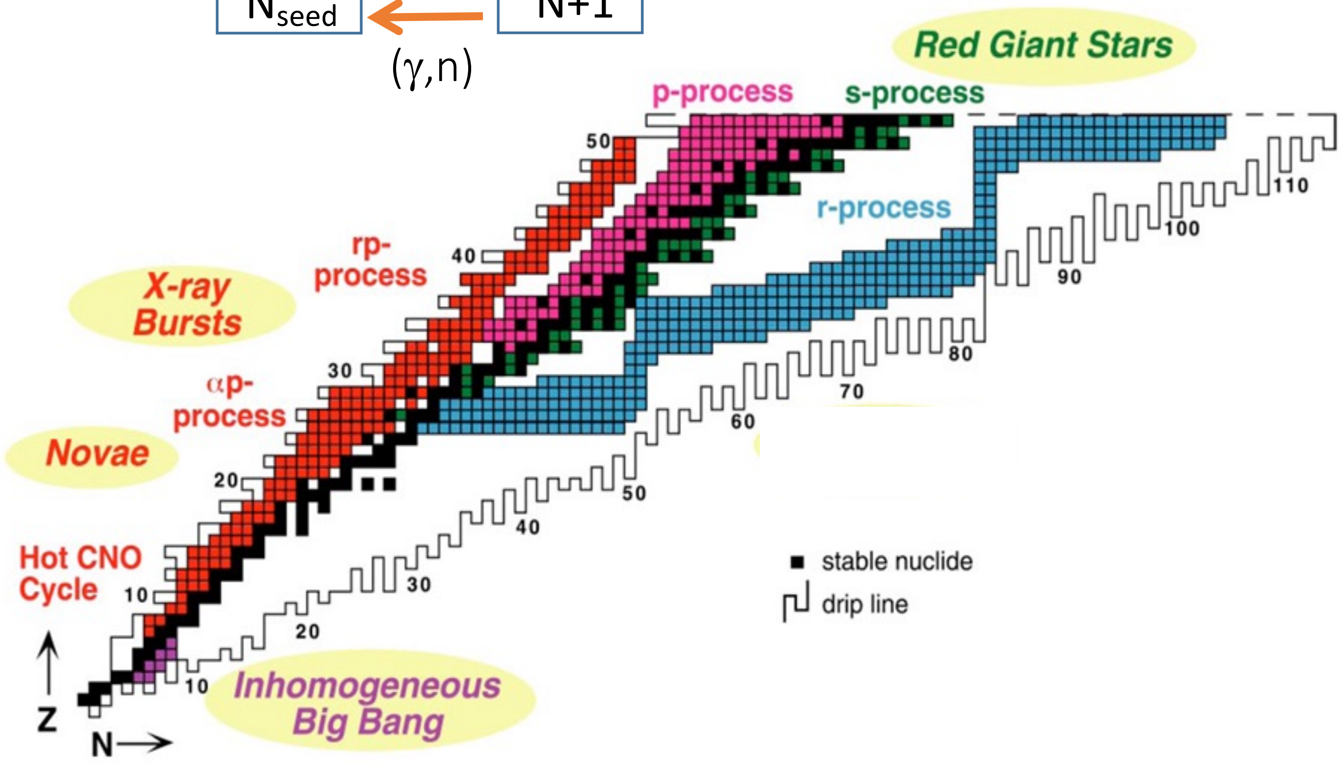
Actinides

How do we know there is an *r*-process? Solar abundance peaks



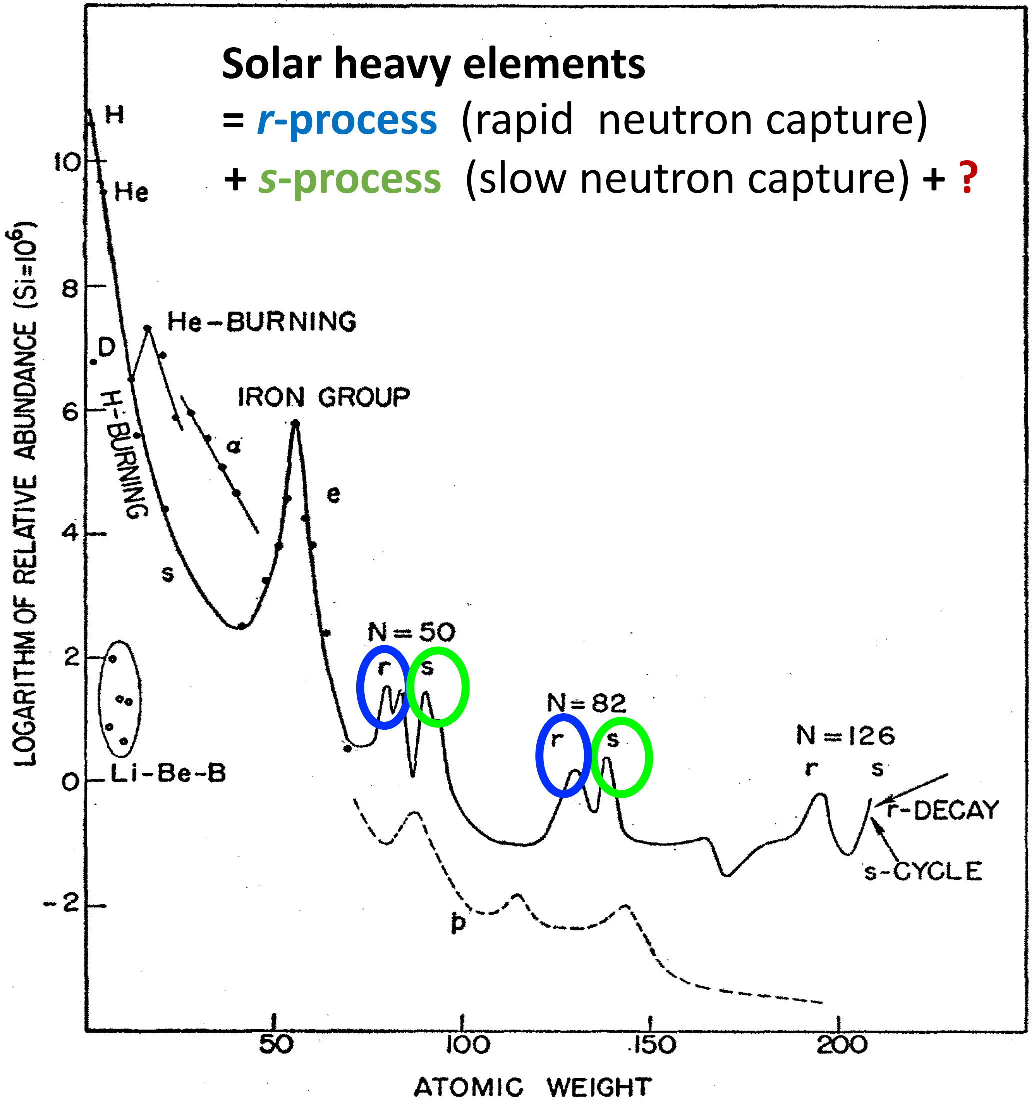
Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)





Smith&Rehm 01

How do we know there is an *r*-process? Solar abundance peaks



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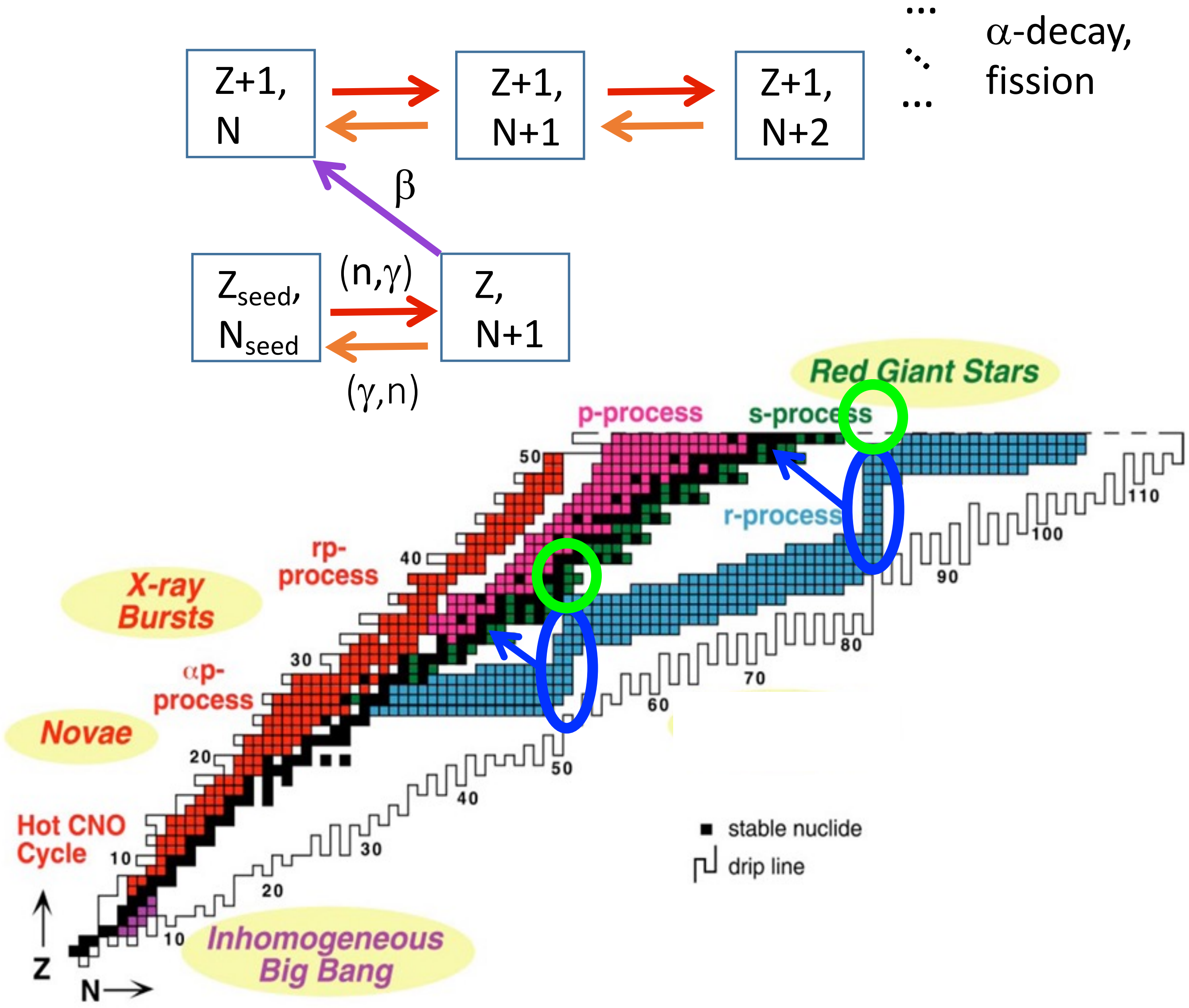

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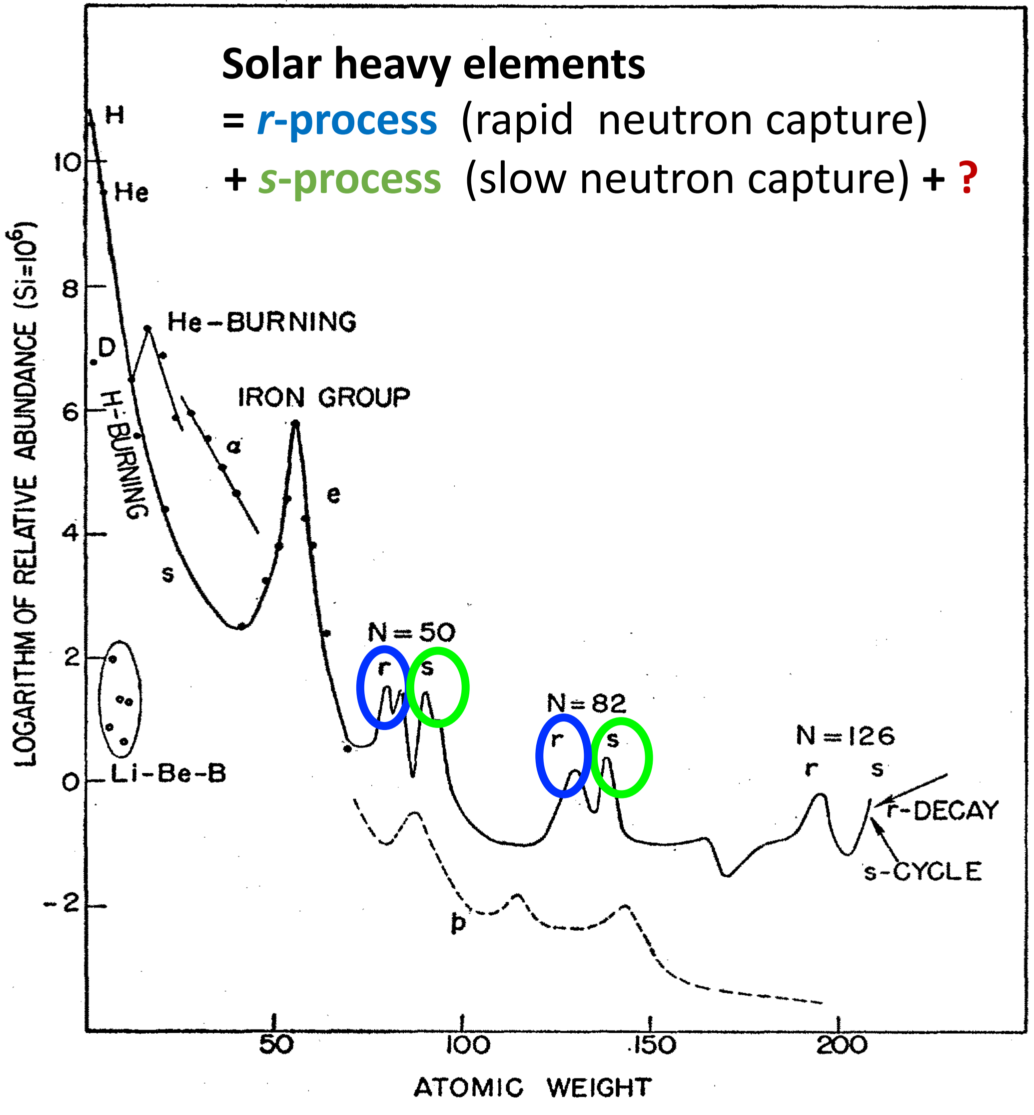

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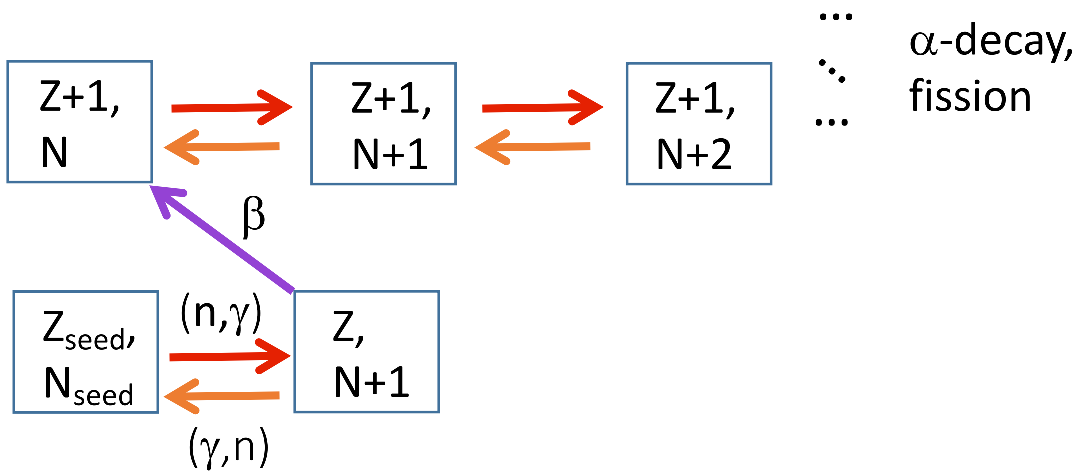
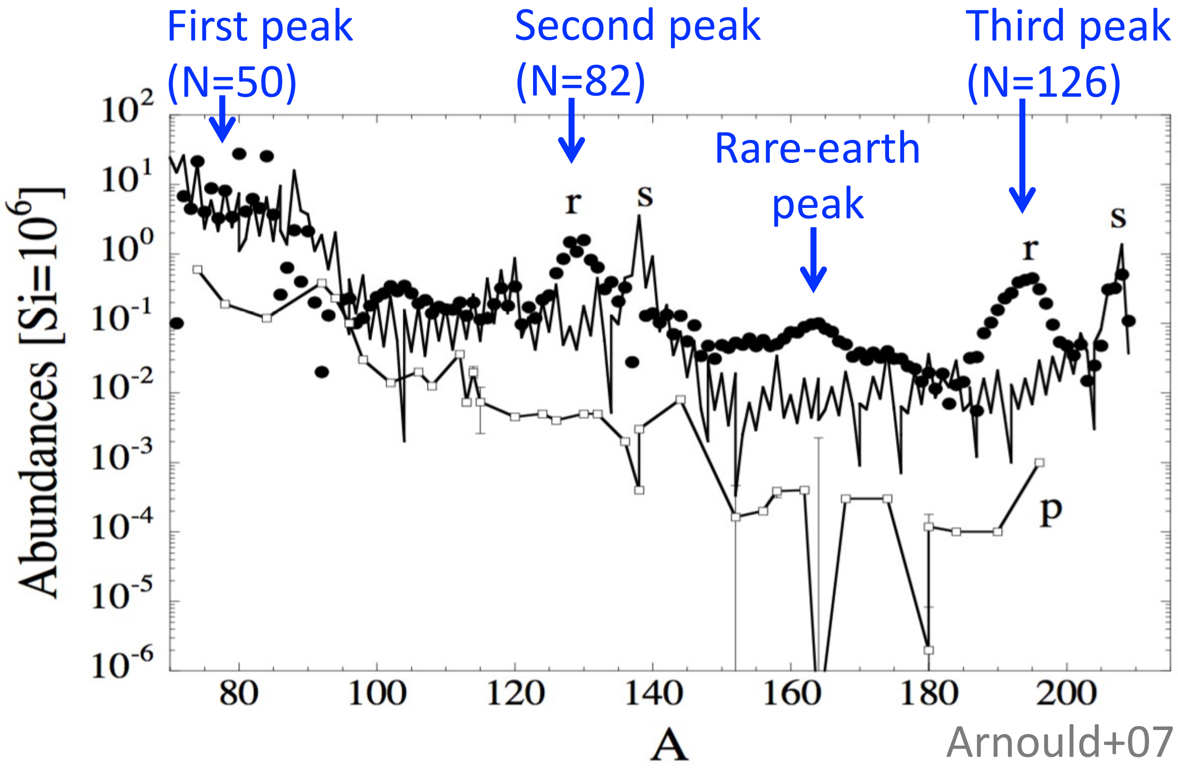
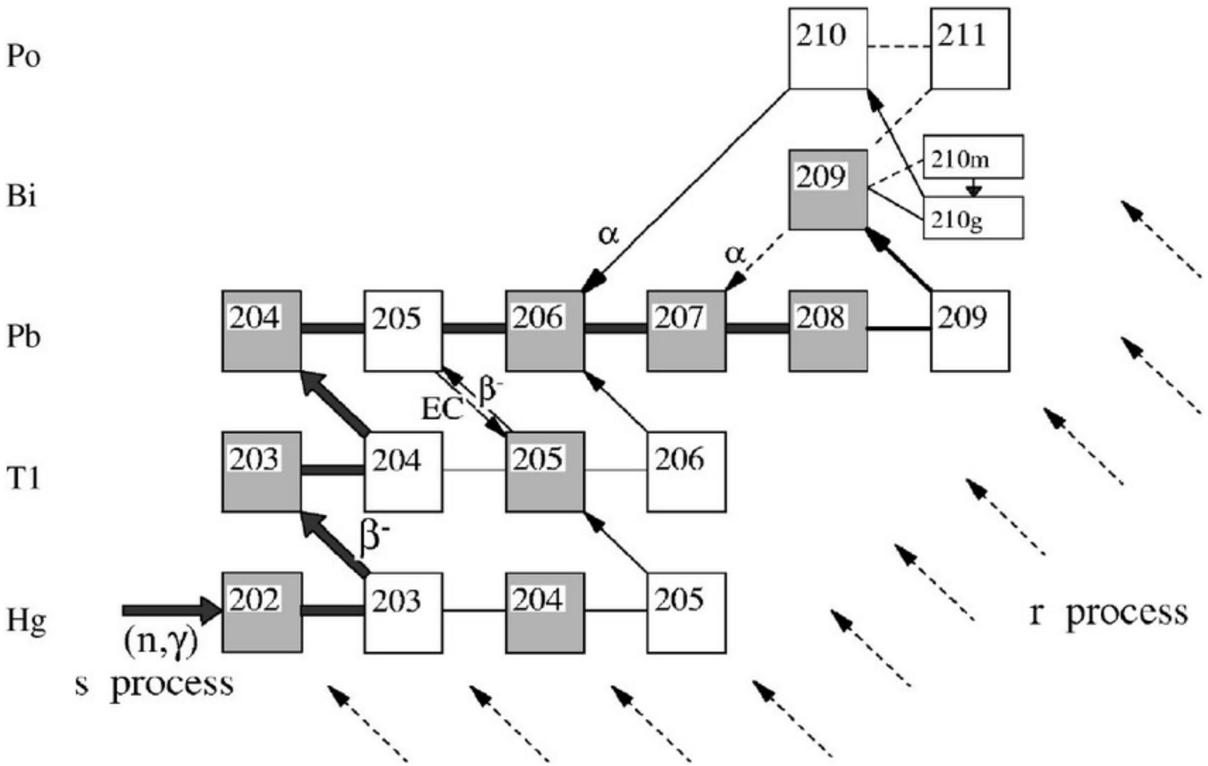




Arnould+07

How do we know there is an *r*-process? Actinides (Z=89-103)

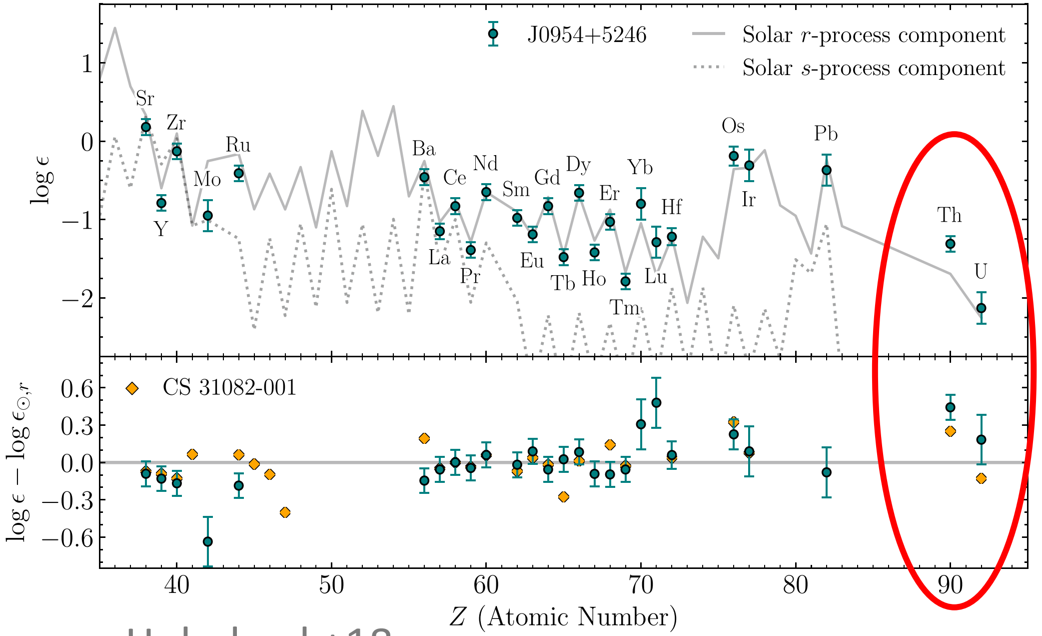
The *s*-process terminates at Pb-208 (Z=82) but *we observe actinides* in meteorites, Earth ocean crusts, our Sun, and other stars



Ratzel+04

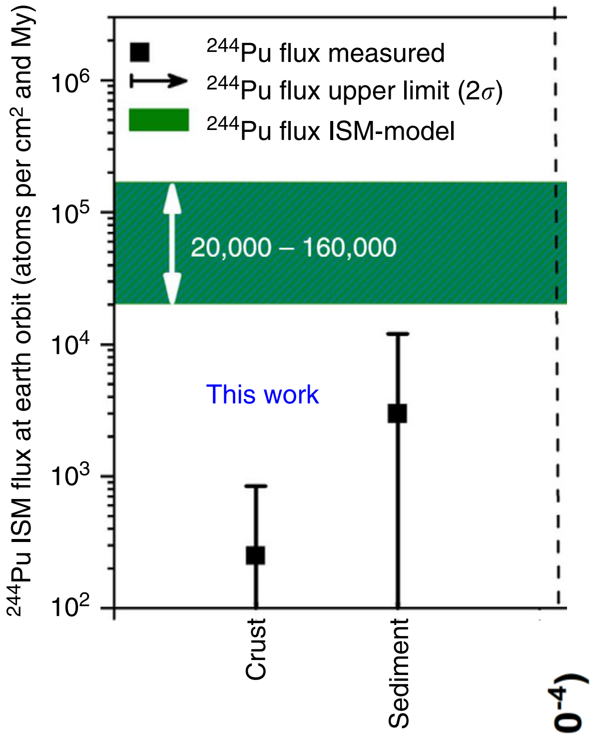
"Curious Marie" sample of Allende meteorite shows excess U-235 which is a trace of Cm-247

Actinide boost stars compared to solar



Holmbeck+18

r-process species must be from a *rare source*

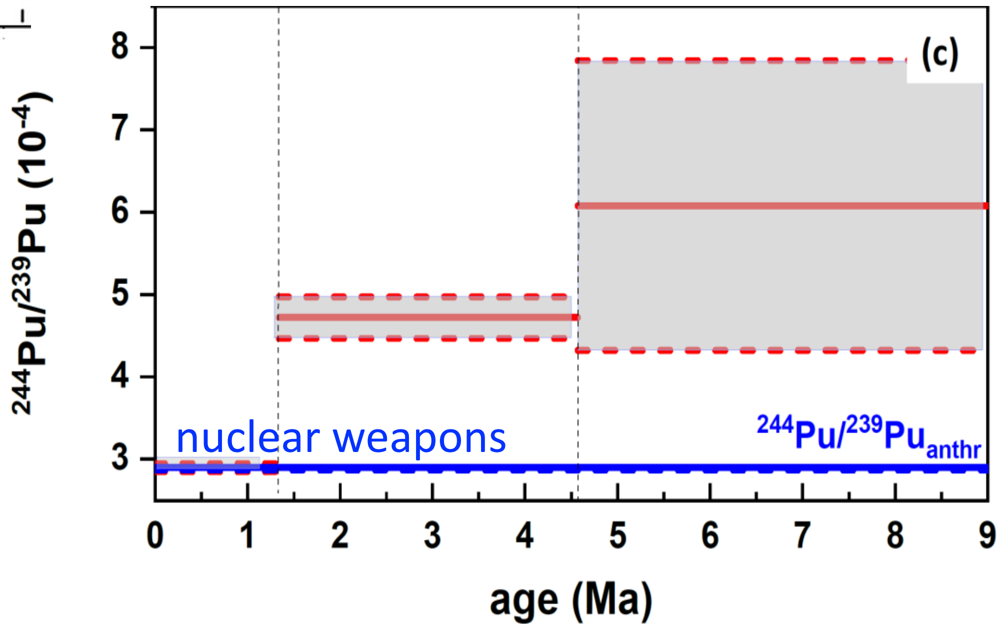


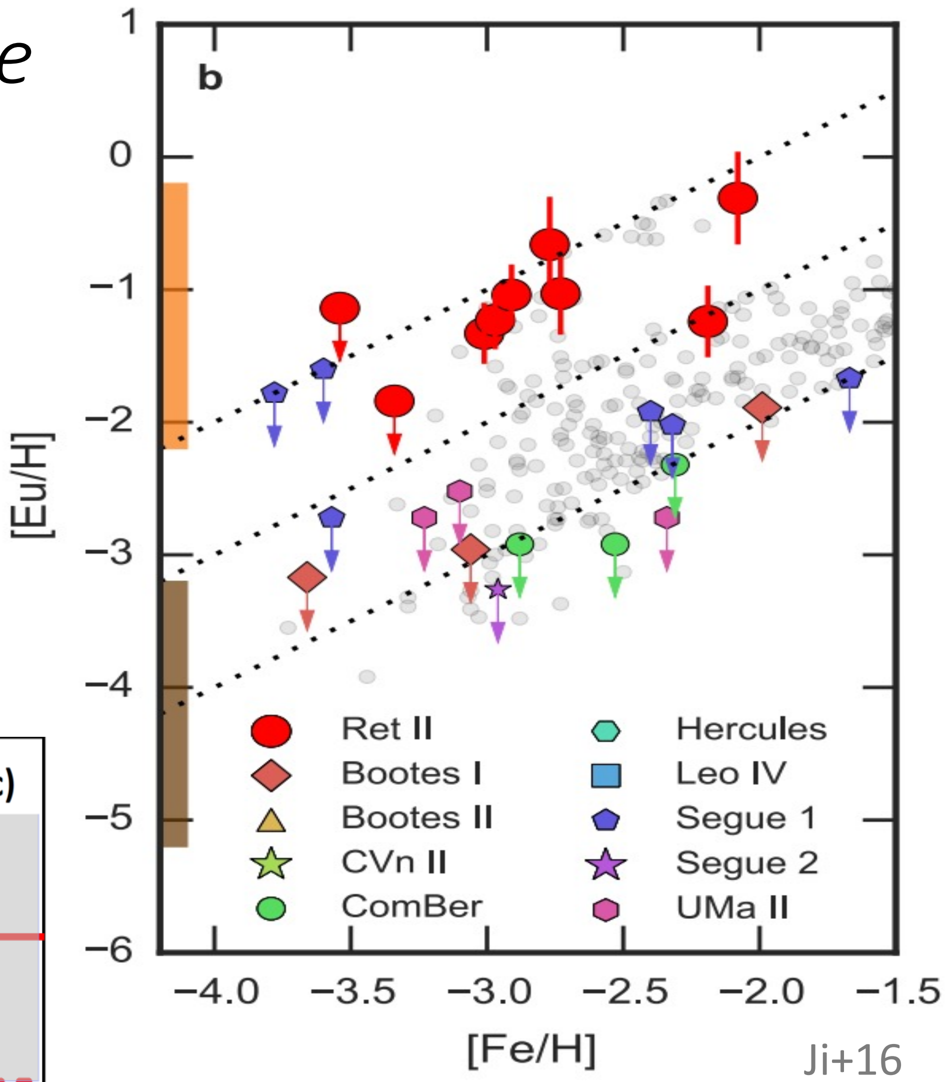
Pu-244 in deep-sea ocean crusts compared to a model which assumes a source as frequent as supernova

Wallner+15

Most recent measurements are still consistent with a rare extraterrestrial source for Pu-244 (long lived compared to Pu-239)

Wallner+21





Ji+16

Ultra faint dwarf galaxies (formed shortly after first stars) rarely show an enhancement in *r*-process elements like in Reticulum II (MW in grey)

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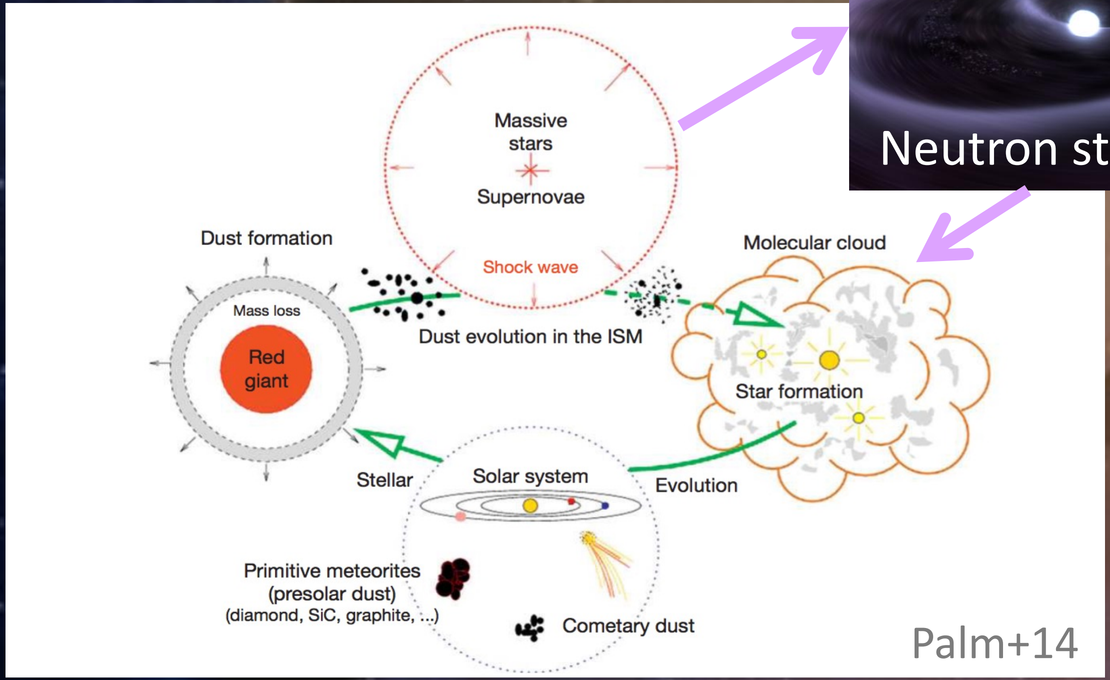
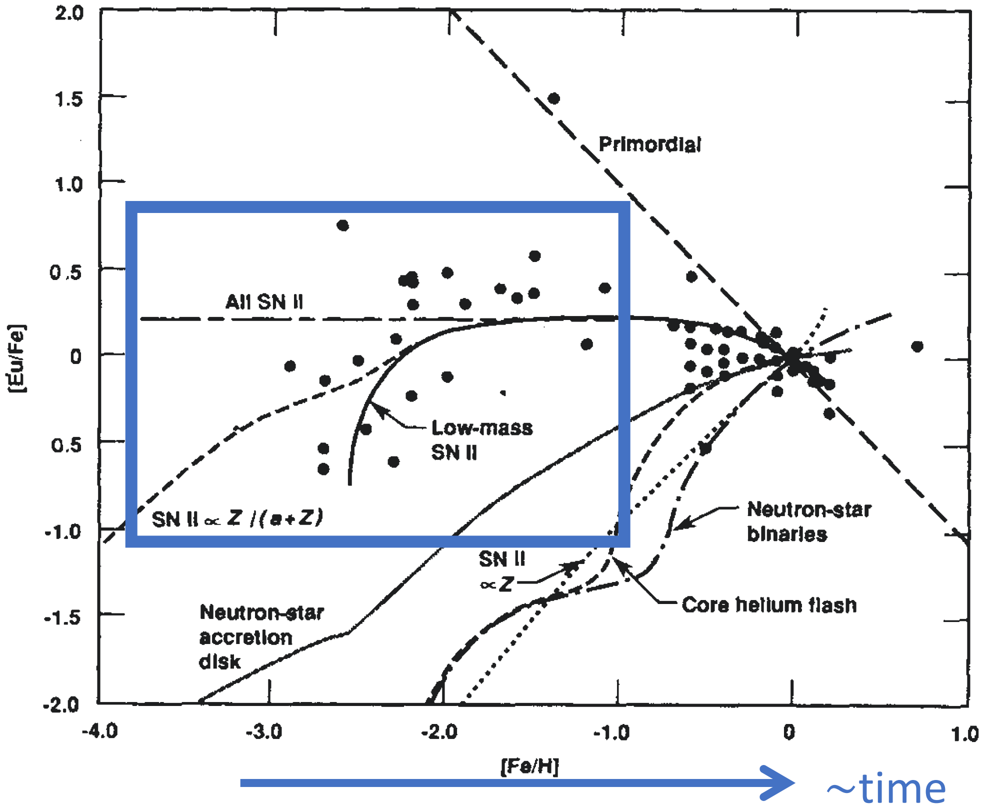
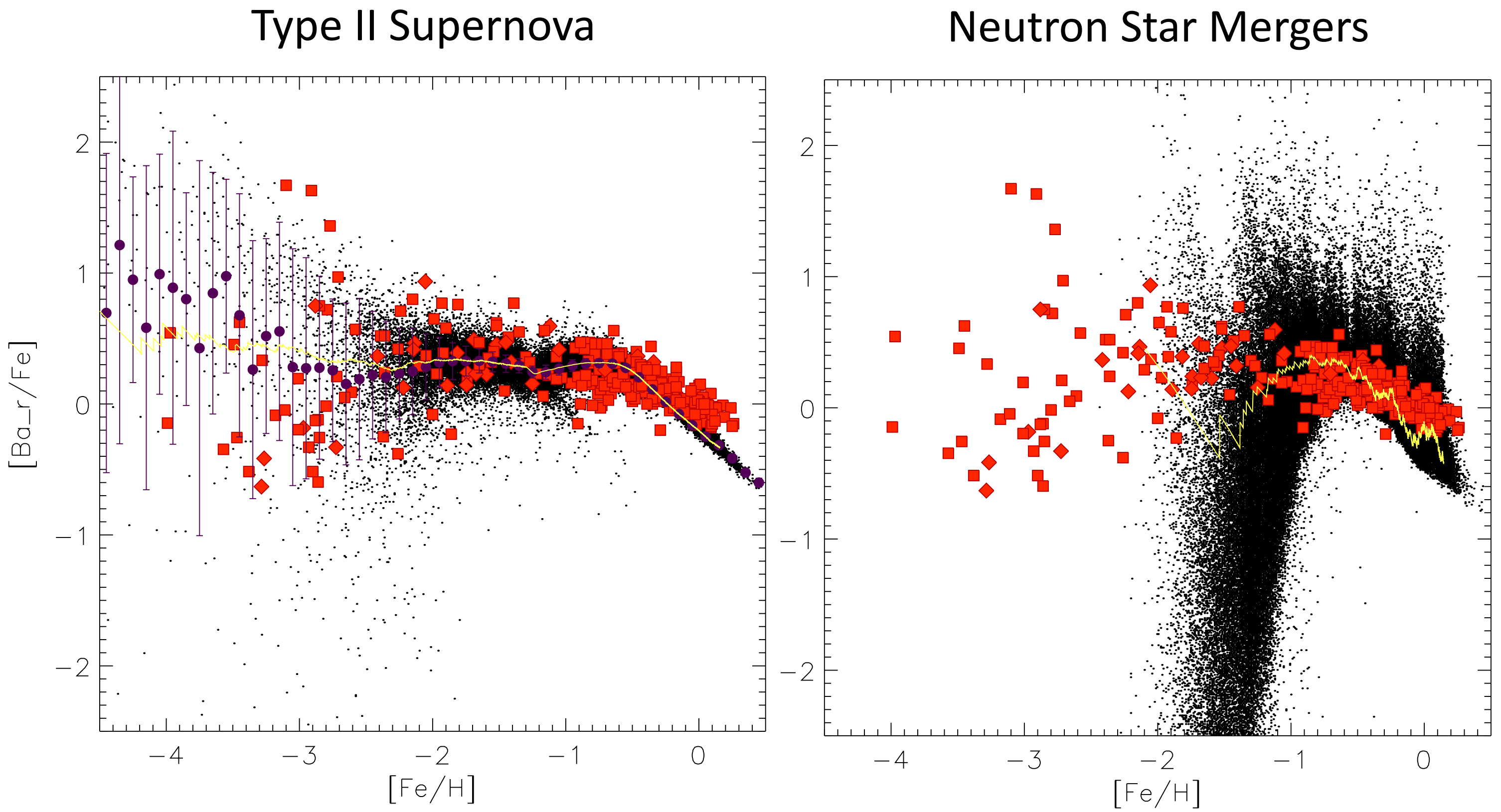
Which astrophysical sites enriched our solar system?



Supernovae as the *r*-process source?
Galactic chemical evolution (GCE) and low metallicity stars



Mathews & Cowan 90



Argast+04

*The stars in the box seem to be more consistent with supernovae since neutron stars take time to merge

◆ ■ observations
● • model stars
average ISM abundances

Supernovae as the *r*-process source?
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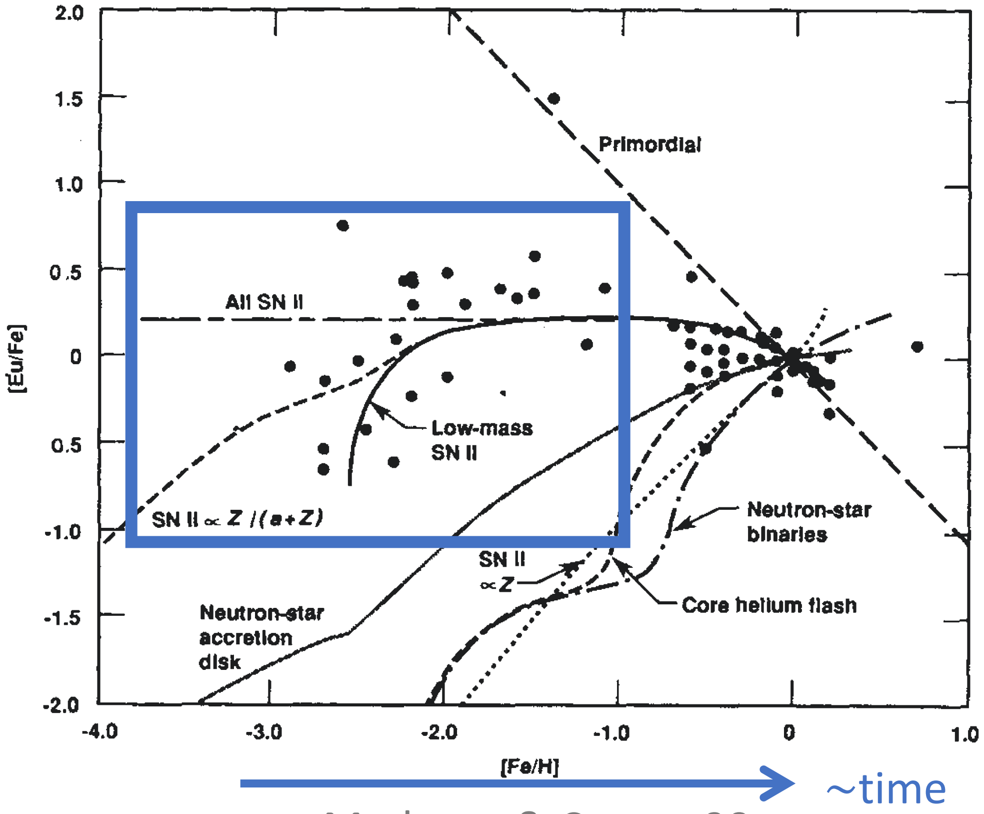
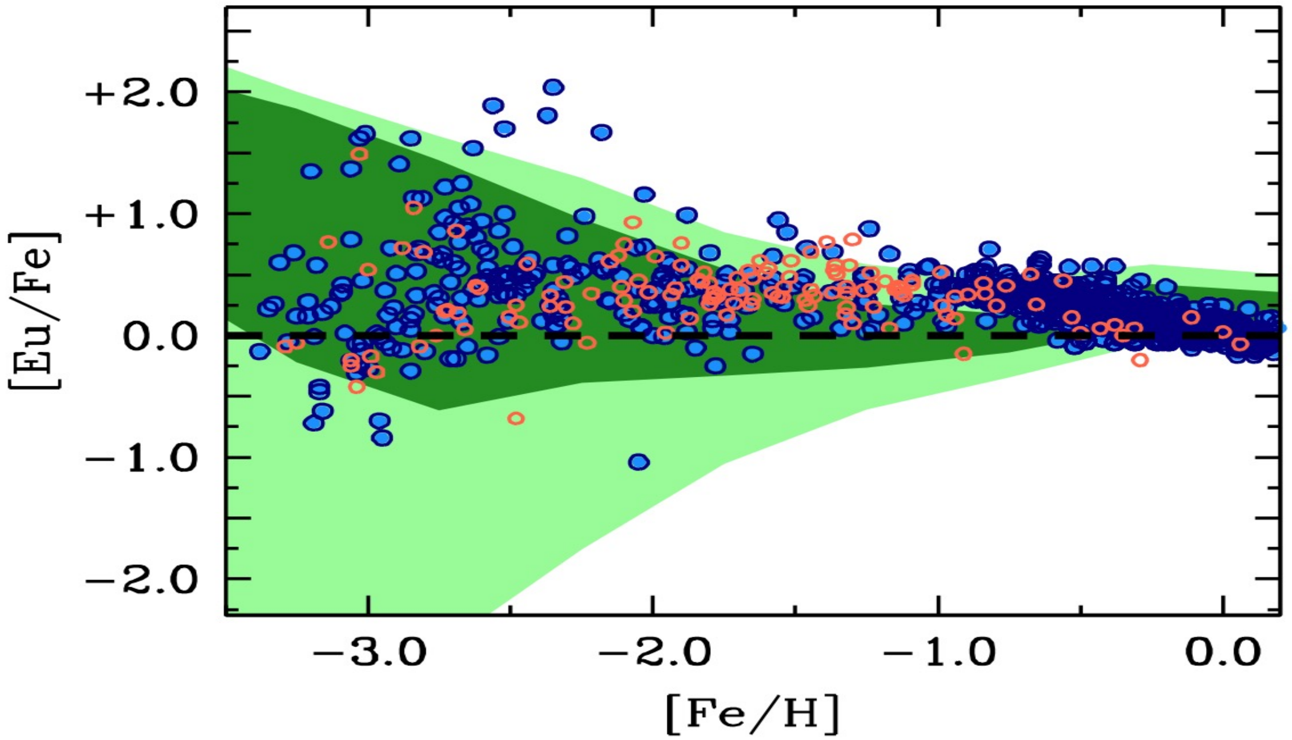


Mathews & Cowan 90

Neutron Star Mergers only

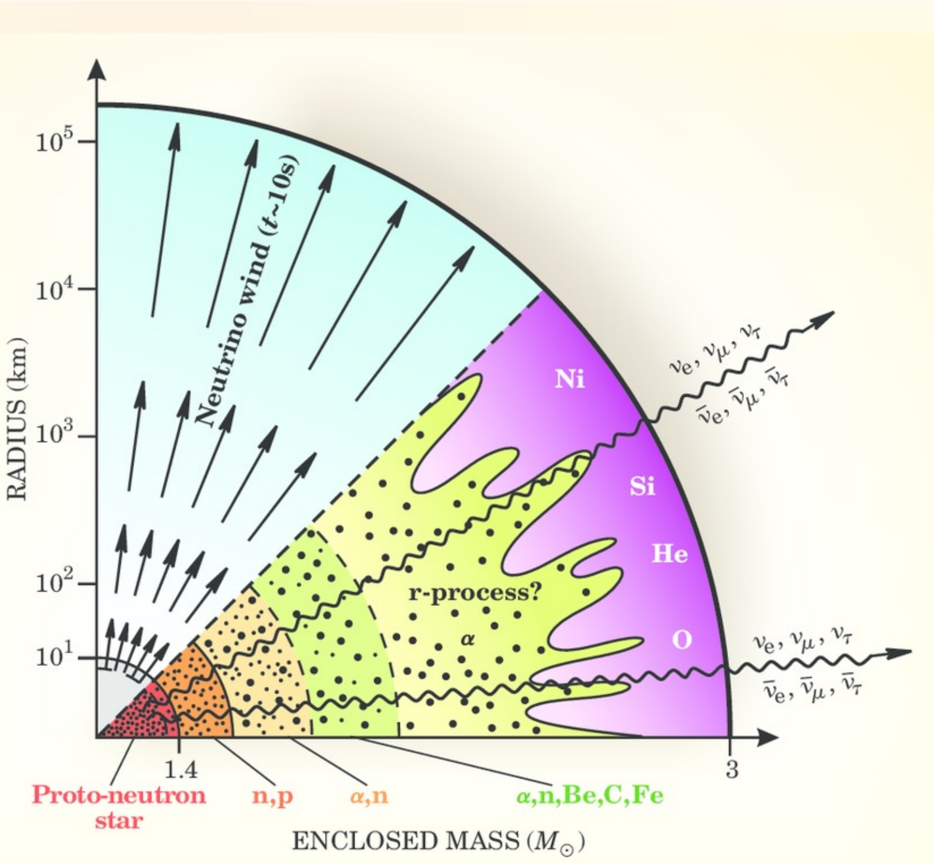


Shen+15

*The stars in the box seem to be more consistent with supernovae since neutron stars take time to merge

Hydrodynamic mixing accounting for inhomogeneities in the interstellar medium could explain how *r*-process elements find their way to low metallicity regions

Supernovae as the *r*-process source? Simulations and neutrino-driven winds (NDWs)



Woosley&Janka 06; see also Panov&Janka 08

Neutrinos set the neutron to proton ratio

$$Y_e = \frac{n_p}{n_p + n_n}$$

via weak interactions

$$\nu_e + \mathrm{n} \rightarrow \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + e^+$$

and the influence of these reactions depends on the neutrino luminosities and average energies

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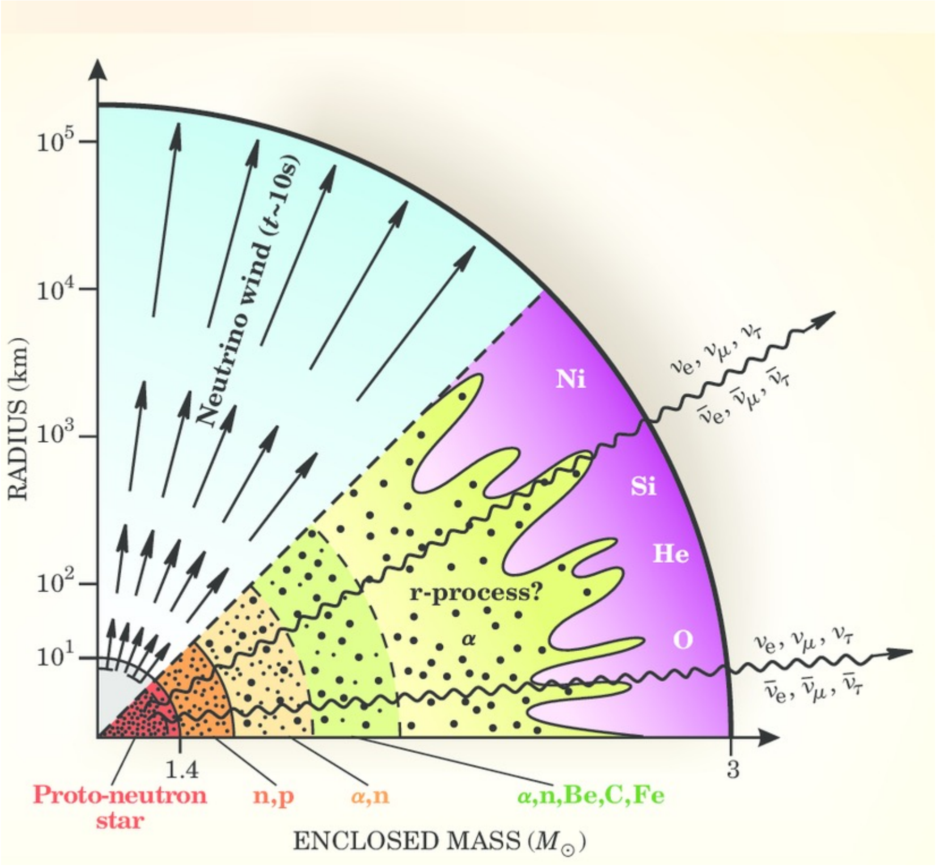

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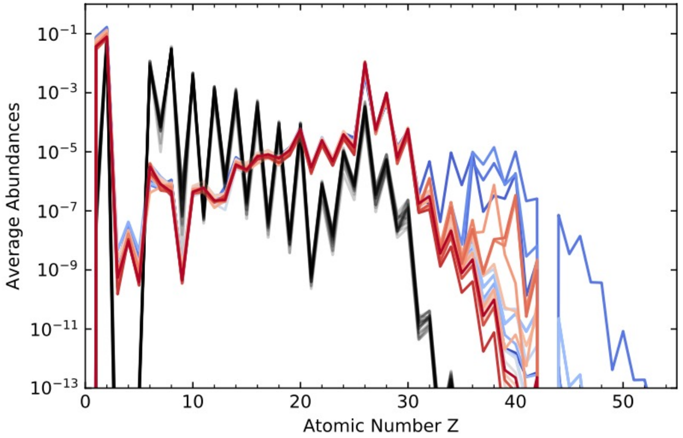
and the influence of these reactions depends on the neutrino luminosities and average energies

Conditions which synthesize A>130 are not found by most modern core-collapse SNe simulations (e.g. Arcones+07, Wanajo+09, Fischer+10, Hüdepohl+10)

In such events other processes such as (α,n) and νp process could reach up to A~100 (e.g. Pruet+06, Fröhlich+06, Bliss+18)

Recent simulations find some cases develop NDWs but not standard feature for successful explosions

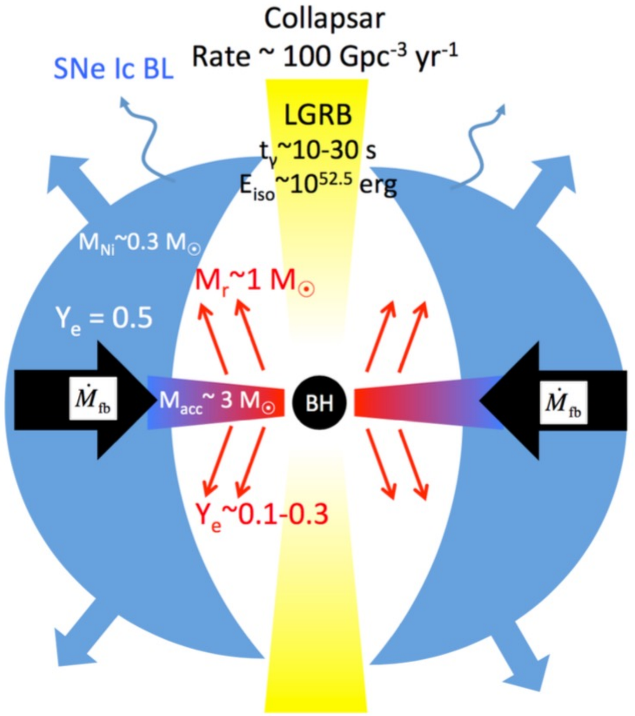


All exploding 15 $M_\odot$ models

Witt+21

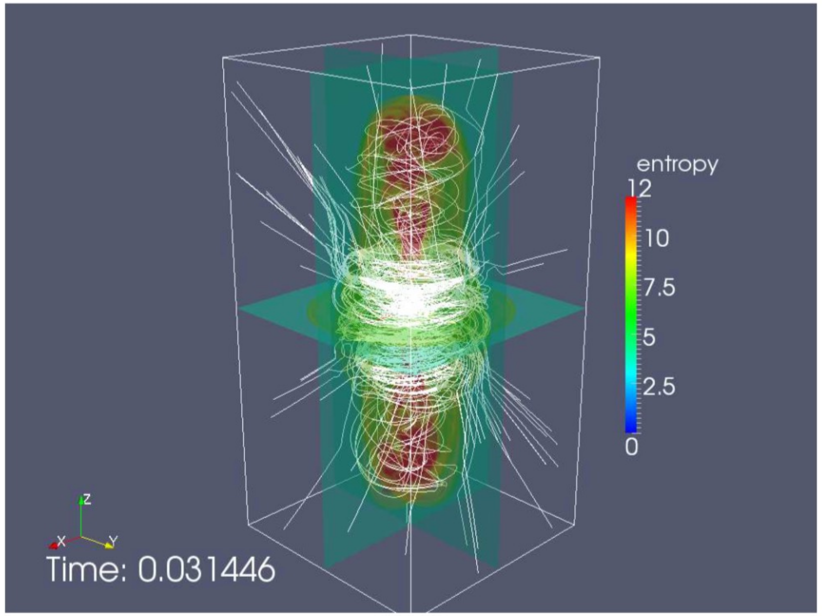
Some candidate sites for *r*-process element production

Collapsar disk winds



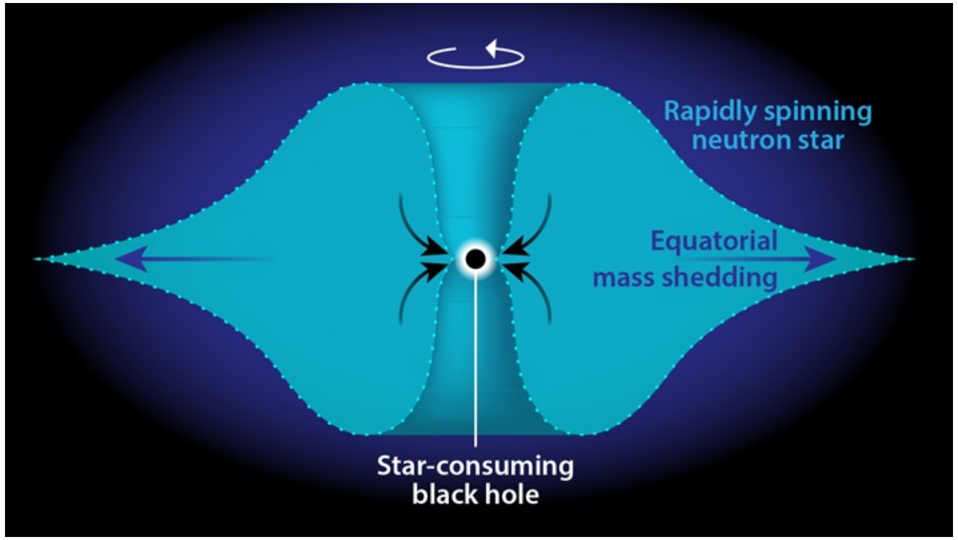
Siegel+18; see also McLaughlin&Surman 05, Miller+19

Magneto-rotationally driven (MHD) supernovae



Winteler+12; see also Mosta+17

Primordial black hole + neutron star

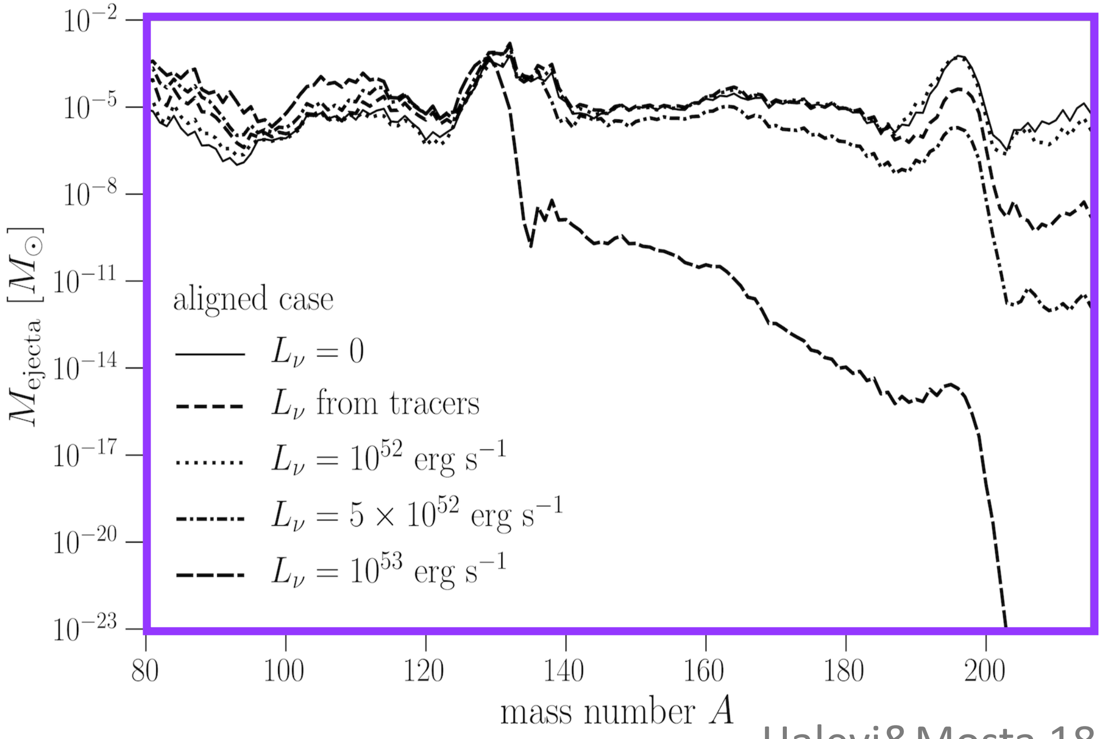


Credit: APS/Alan Stonebraker, via *Physics*

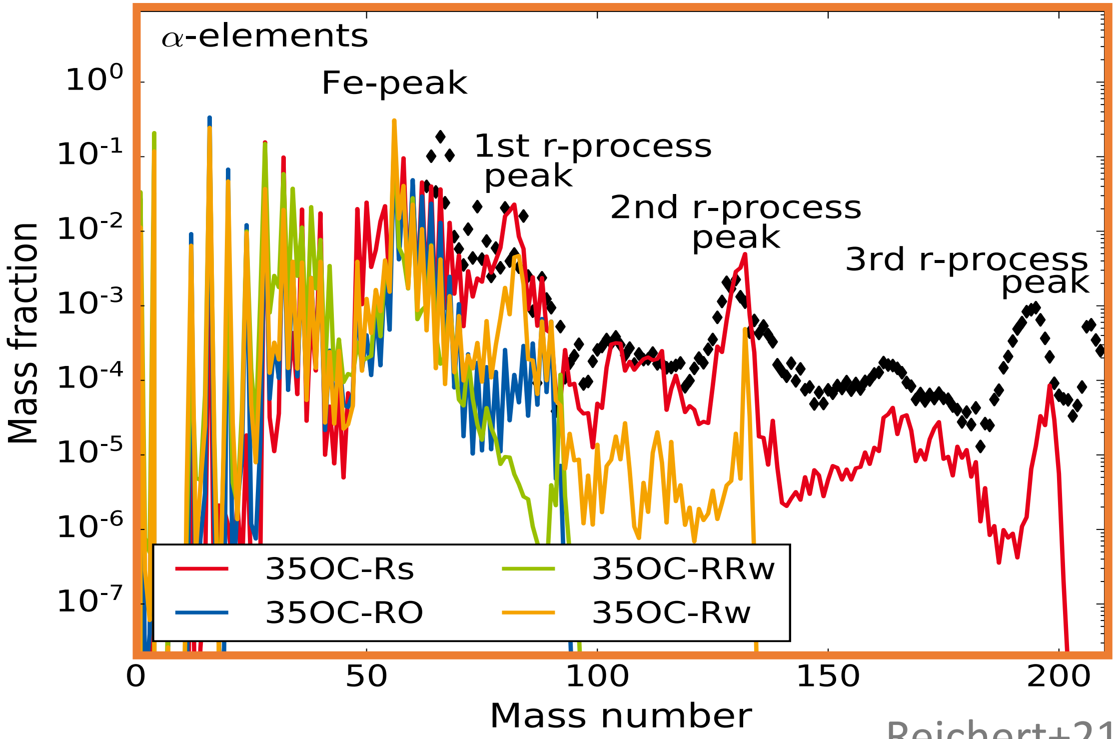
Fuller+17

Spotlight on MHD supernovae

Whether MHDs undergo only a "weak" *r* process reaching the second peak rather than a "main" or "strong" *r* process reaching the third peak or beyond depends on the influence of neutrinos and the magnetic field strength



Halevi&Mosta 18



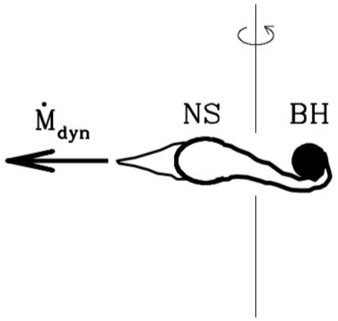
Reichert+21

Just like in CCSNe, neutrino energies and luminosities are crucial to determine the *r*-process reach

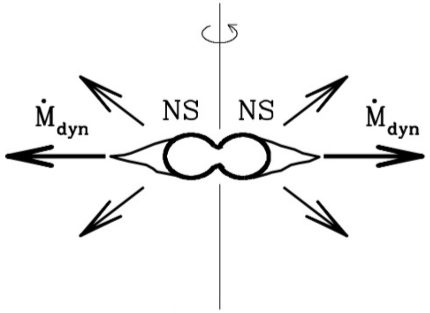
Simulations with higher magnetic field strength (ex 350C-Rs → 10^{12} G) undergo a stronger *r* process than those with lower magnetic field strength (ex 350C-Rw → 10^{10} G)

Neutron star mergers and the *r* process: a bit of history

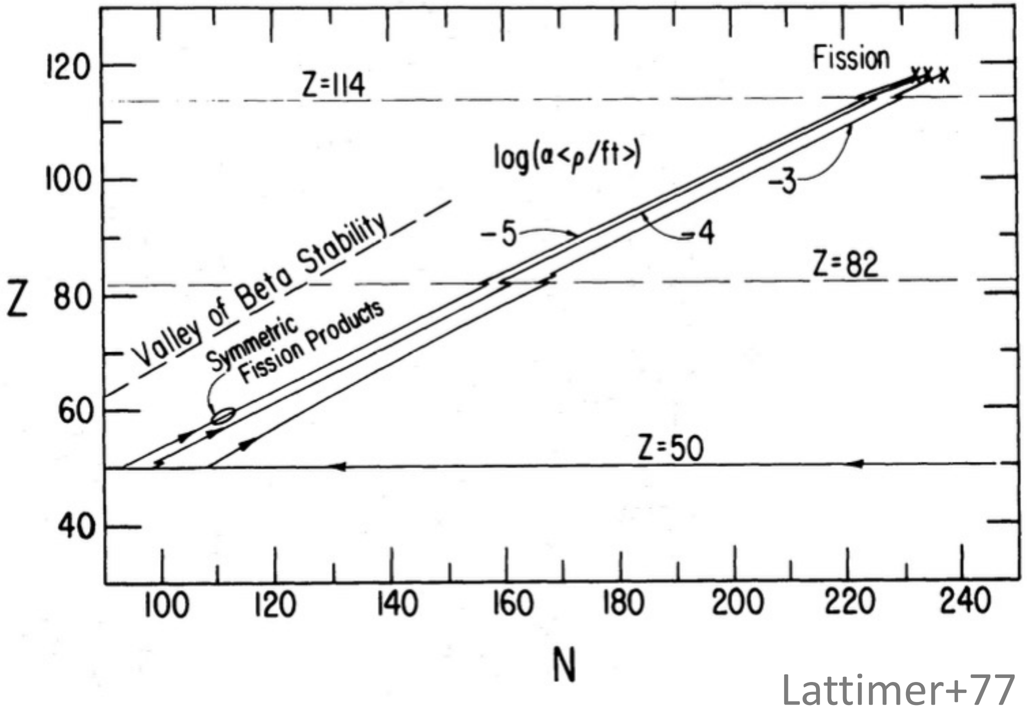
Neutron-rich ejecta from neutron stars > 40 years ago



Lattimer&Schramm (1974): ~5% of the neutron star ejected as n-rich matter

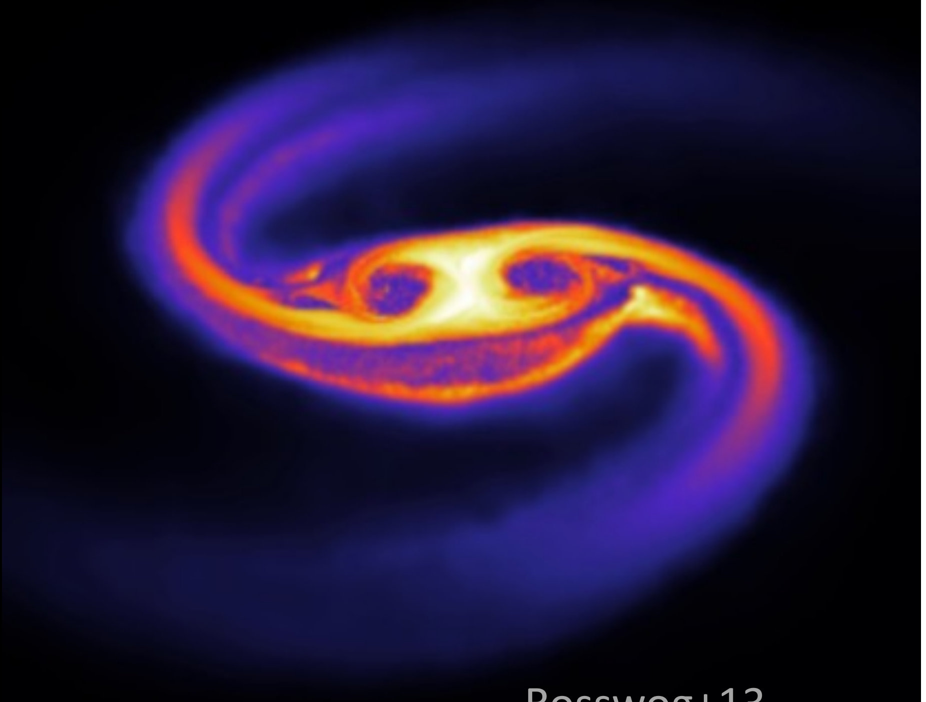


Lattimer+ (1977): initially cold, expanding neutron star matter → fission cycling *r* process capable of super heavy element formation



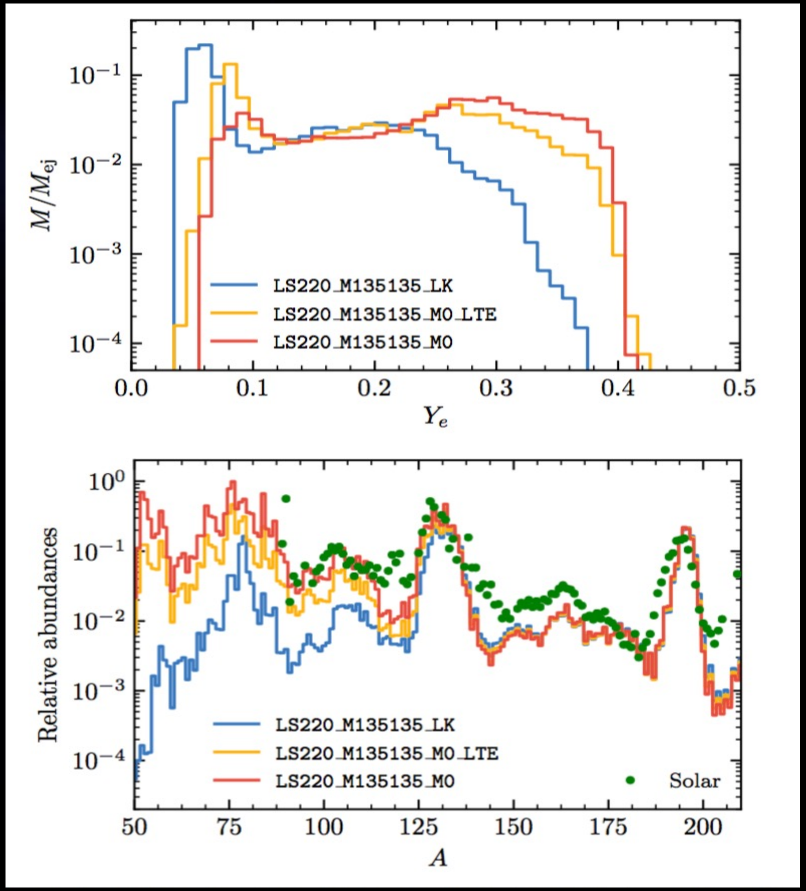
Lattimer+77

NSM dynamical ejecta



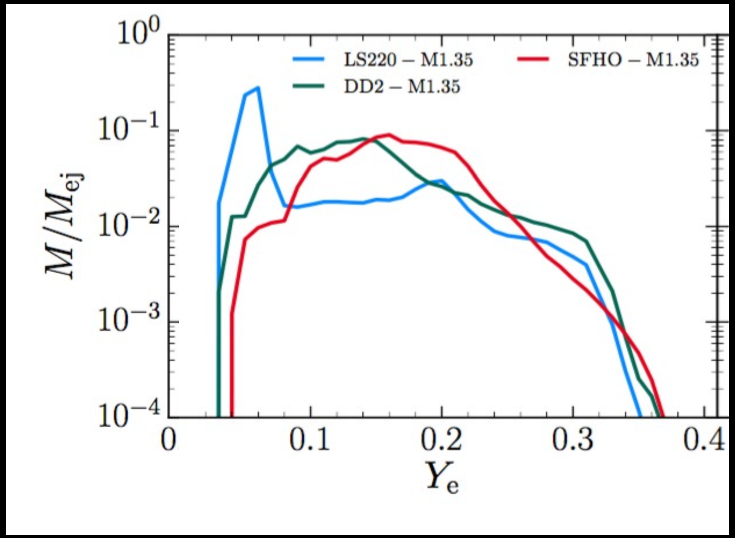
Rosswog+13

Effect of neutrinos



Radice+19; see also Perego+19

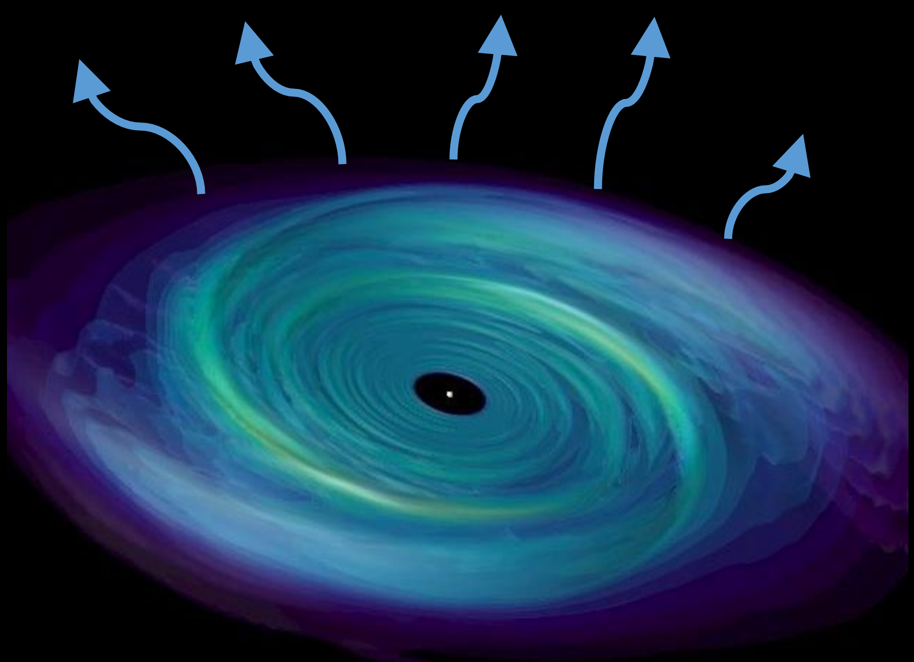
Equation of state



Bovard+17

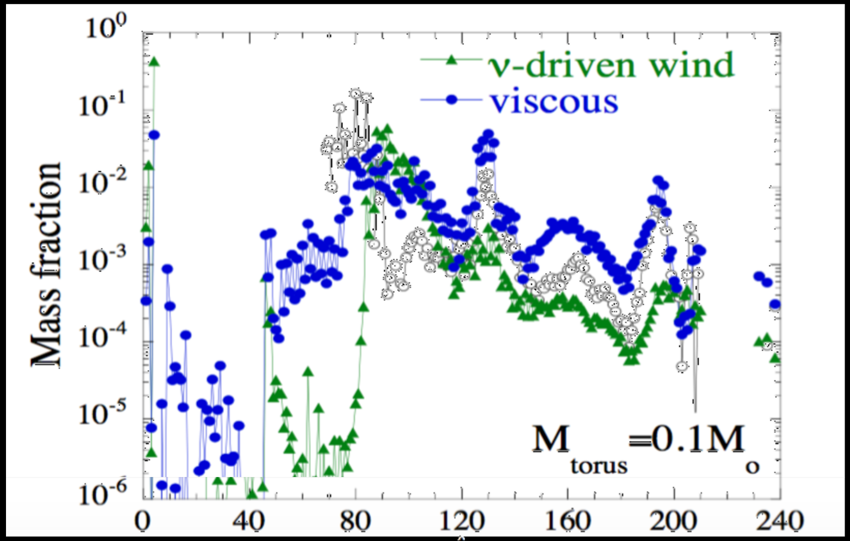
See also Wanajo+14, Vincent+19, Foucart+20….

Post-merger disk ejecta

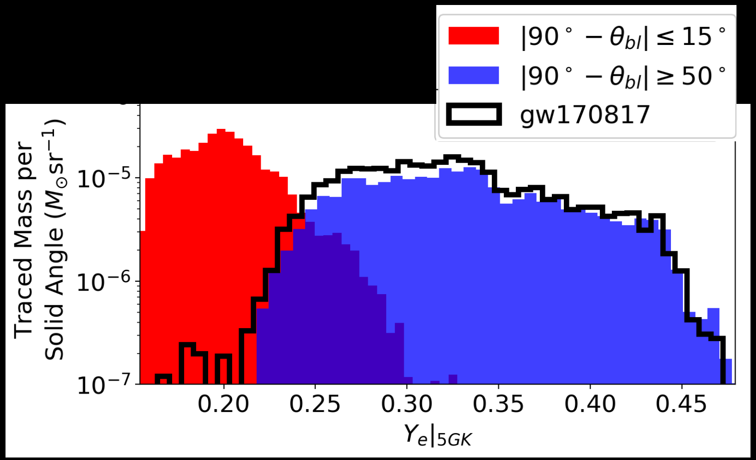


Owen&Blondin 05

Neutrino driven vs viscous

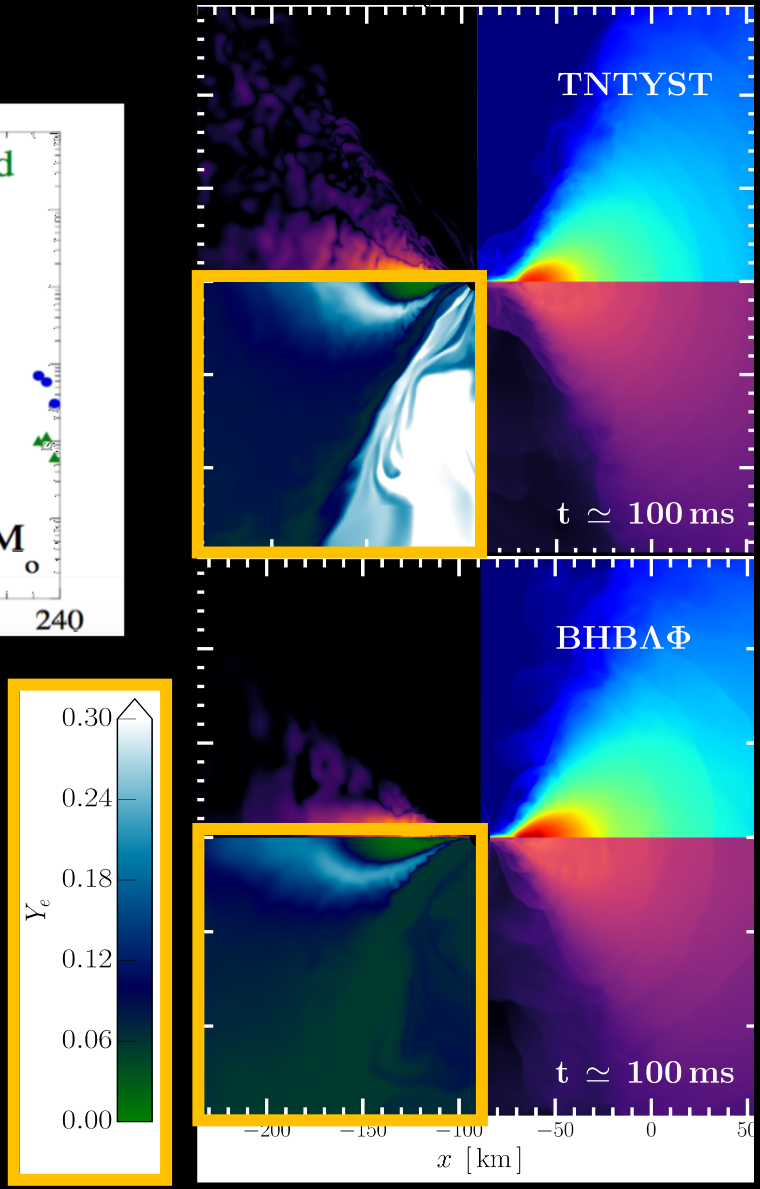


Just+16



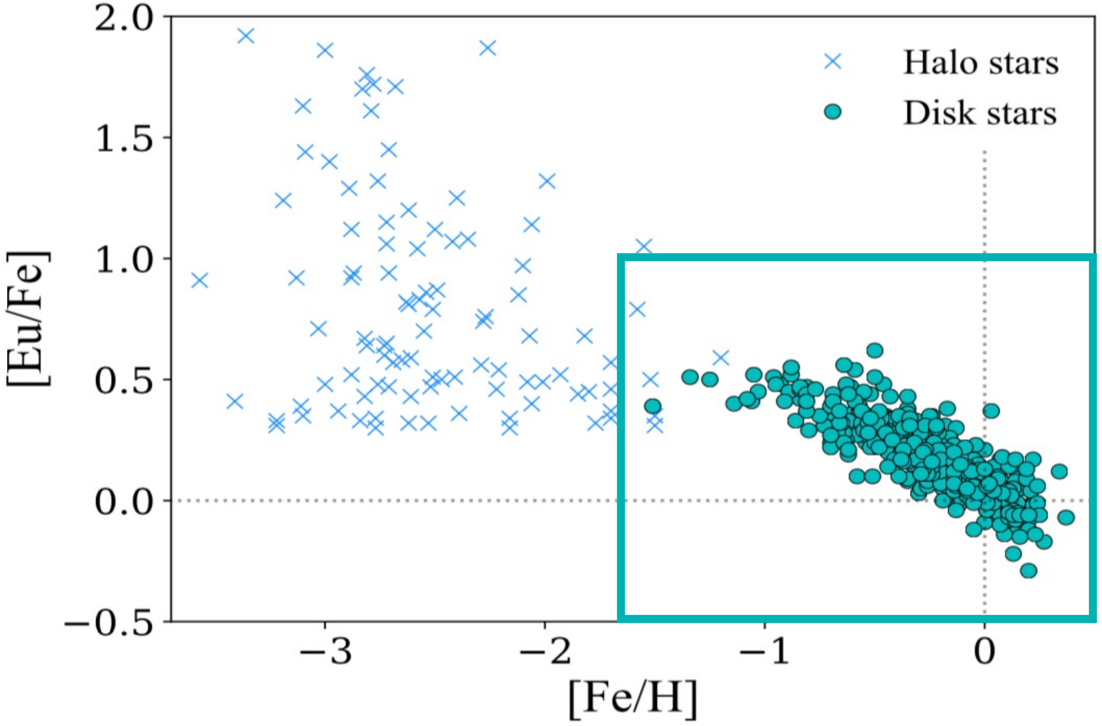
Miller+19

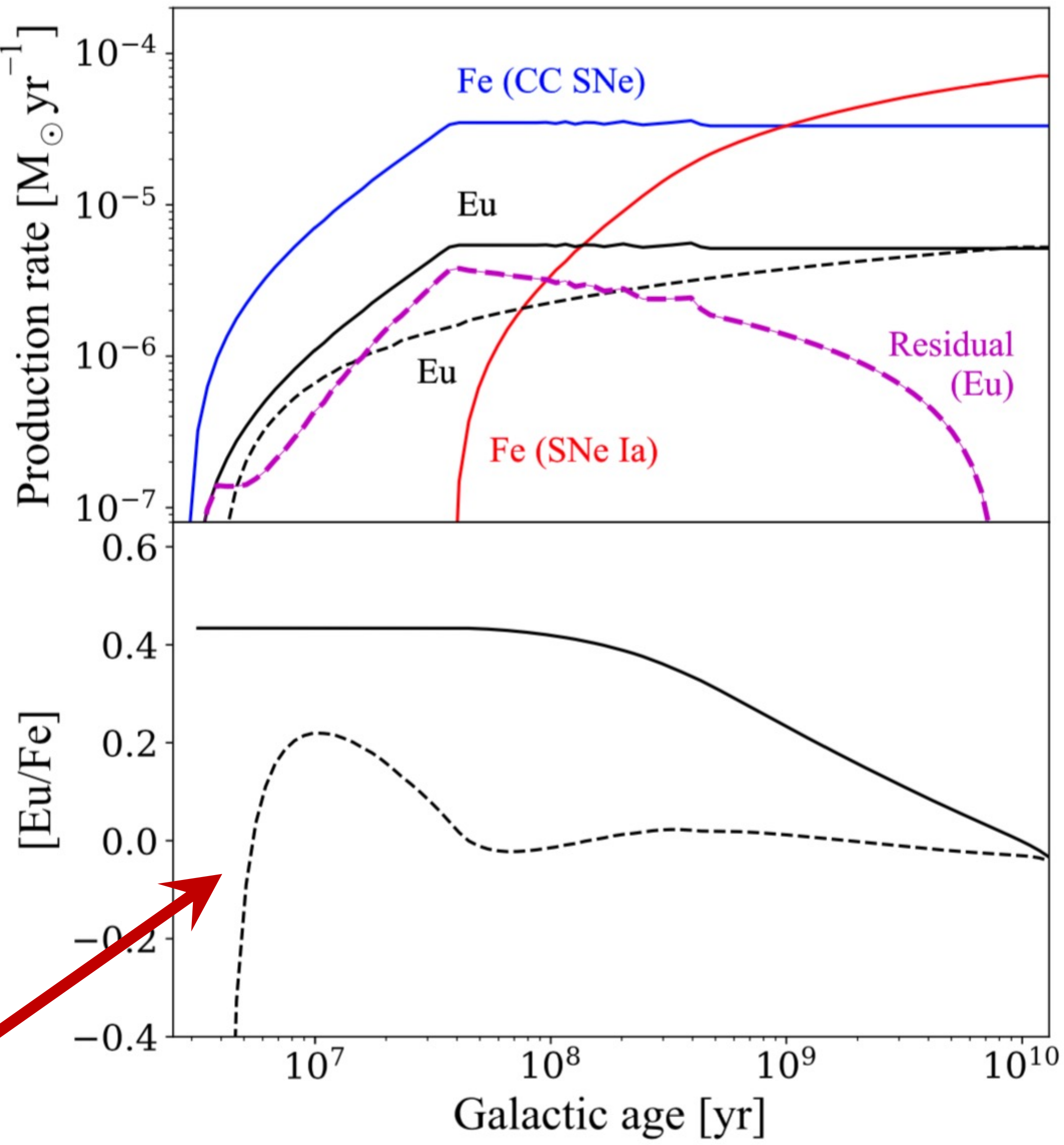
Equation of state



Most+21

Could NSMs be the only *r*-process source? Back to GCE but now consider stars in the Galactic disk





Eu production rate must reach equilibrium before onset of SNeIa in order to reproduce [Eu/Fe] of disk stars

NSM with delay times ~t^{-1} don't reproduce this behavior: earlier sources?

Côté,Eichler+18

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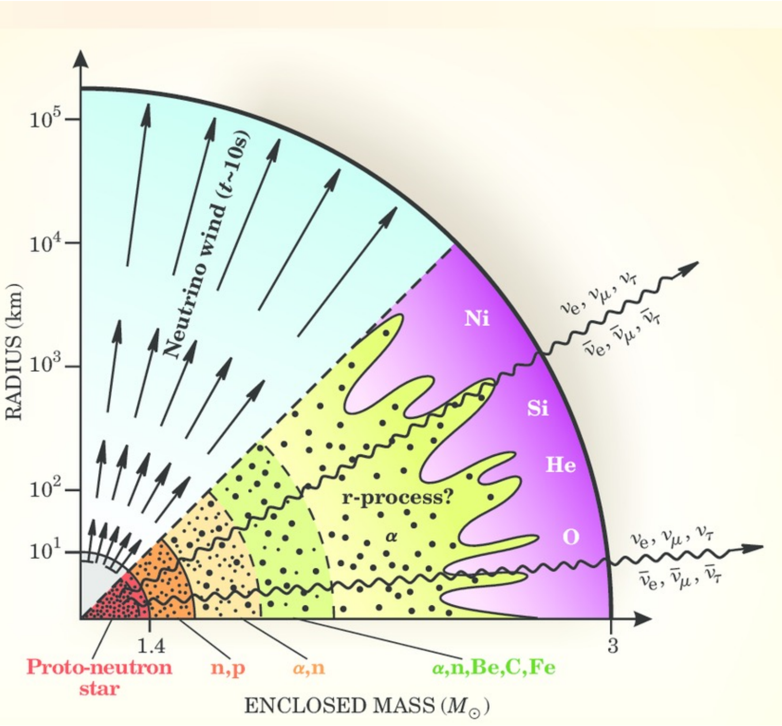
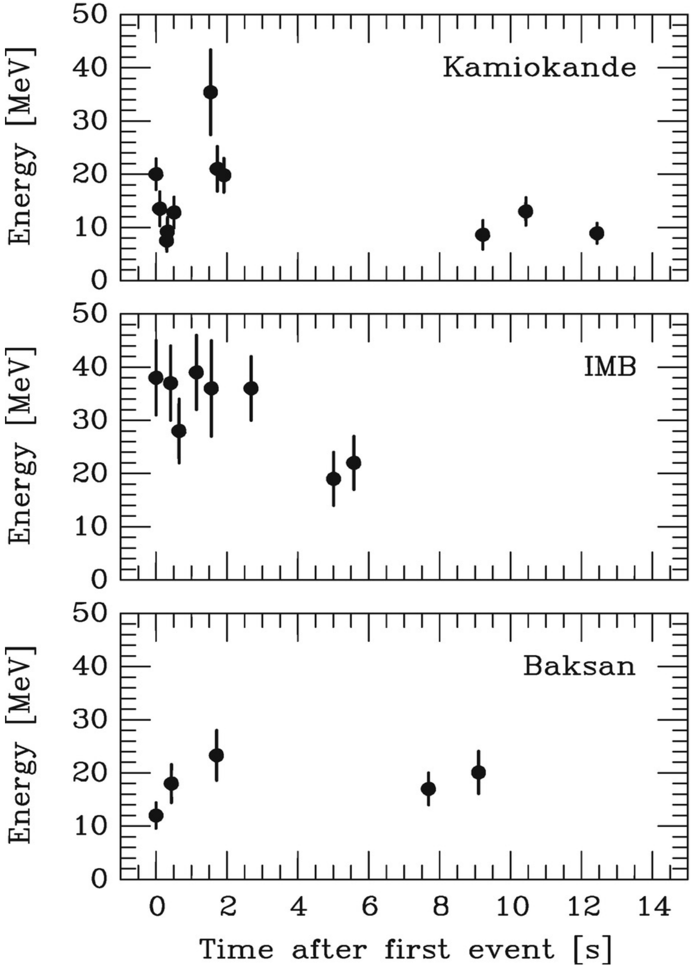
What is a multi-messenger event?

SN1987A:
A famous core-collapse supernova

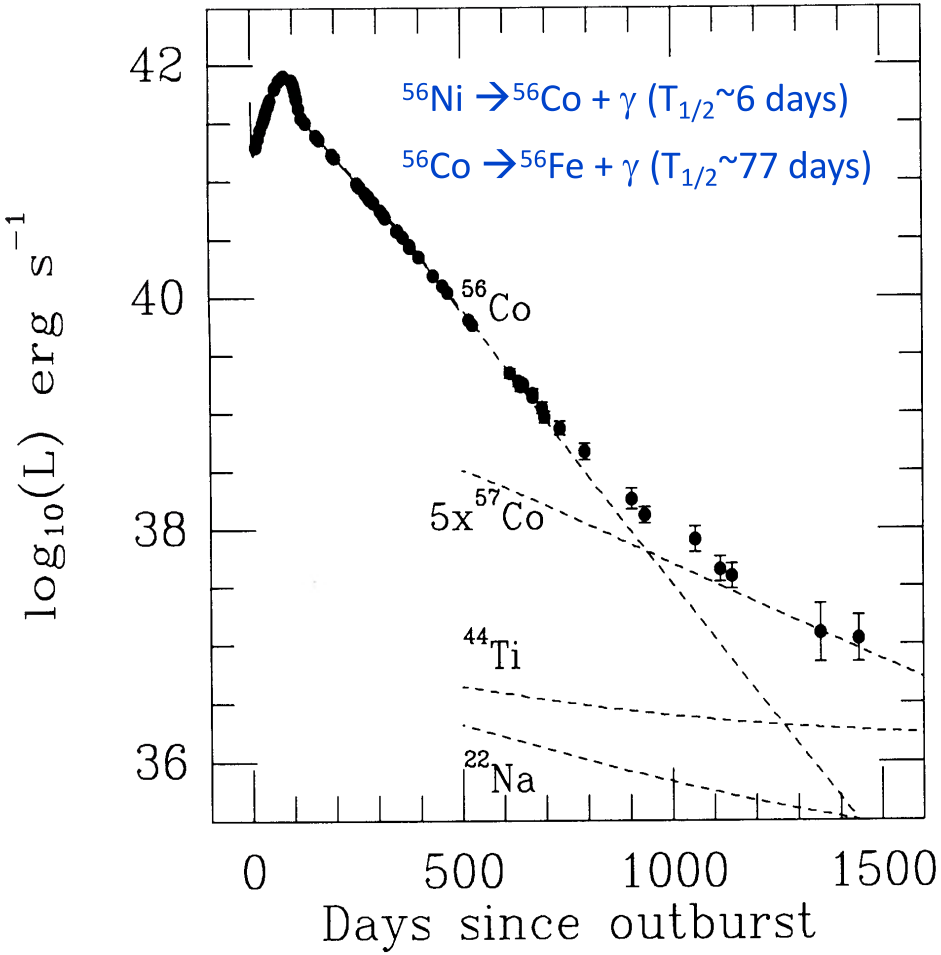


Woosley&Janka 06

Neutrinos



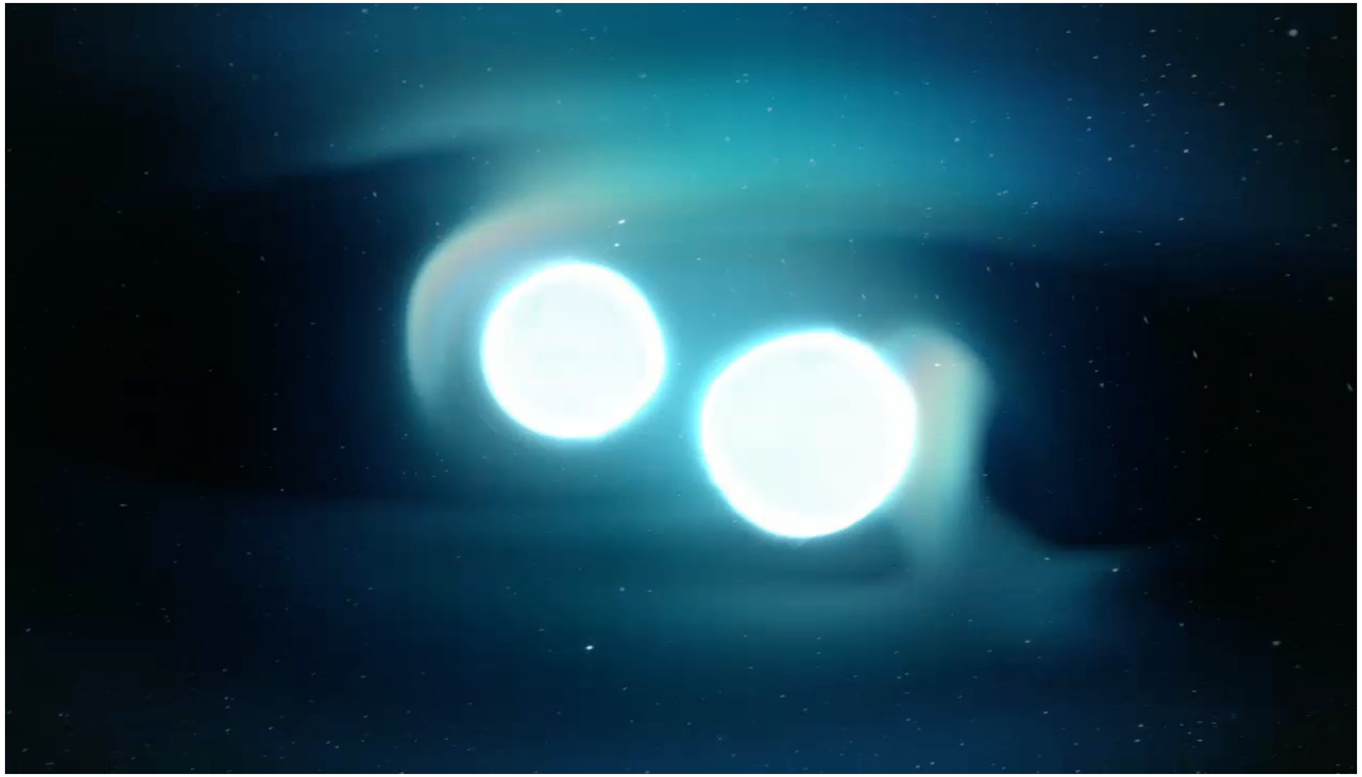
Light curve



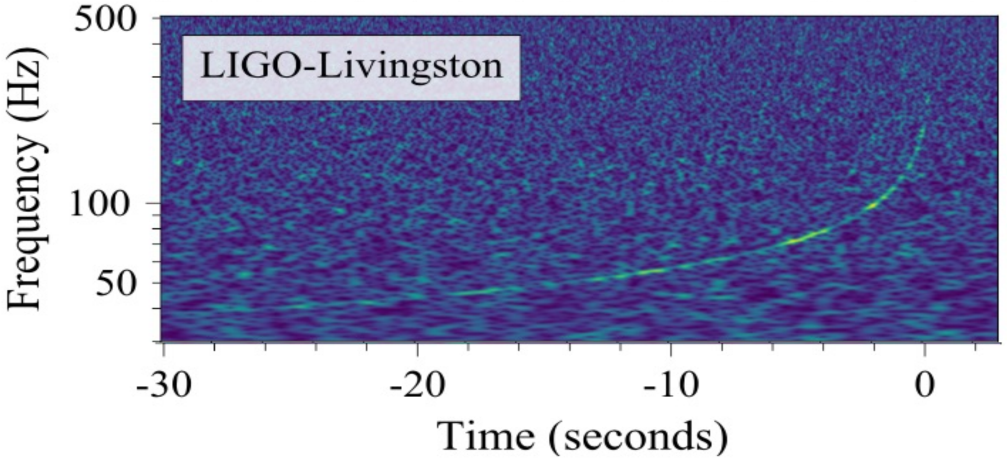
Suntzeff+92

A new kind of messenger: gravitational waves

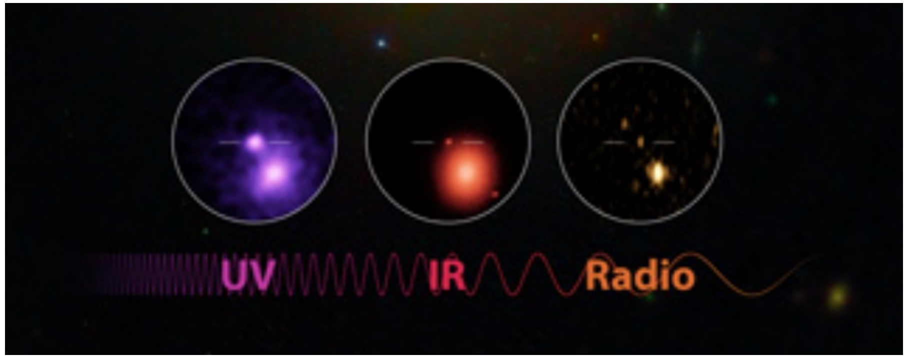
GW170817 & AT2017gfo:
Binary neutron star merger



NASA Goddard



Abbott+17



Hurt/Kasliwal/Hallinan, Evans, and the GROWTH collab.

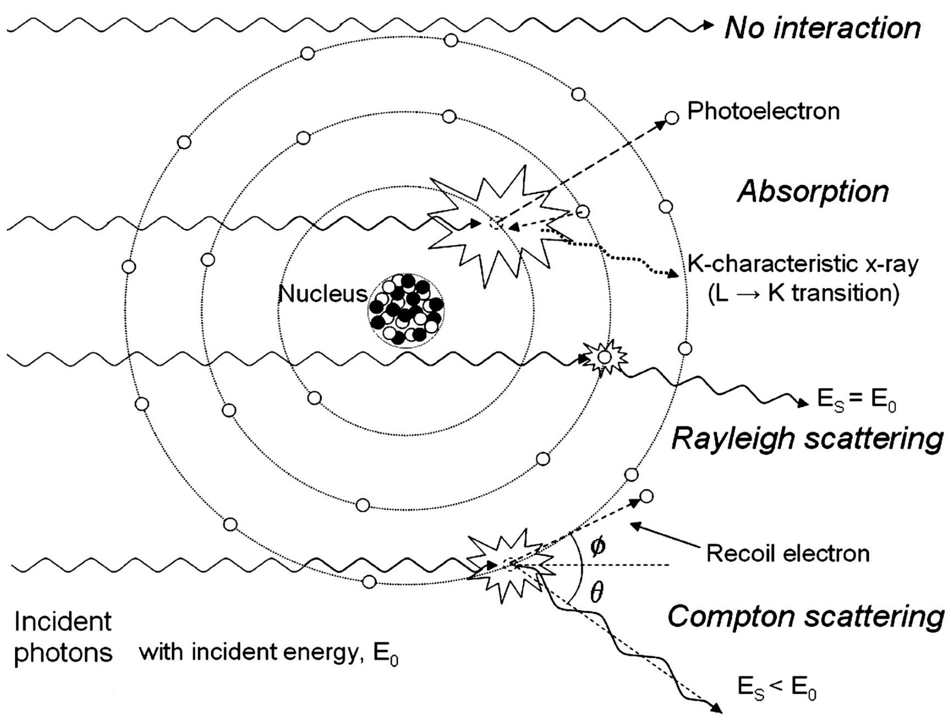
Over ~70 observing teams (~1/3 of the worldwide astronomical community) followed up on the merger event!

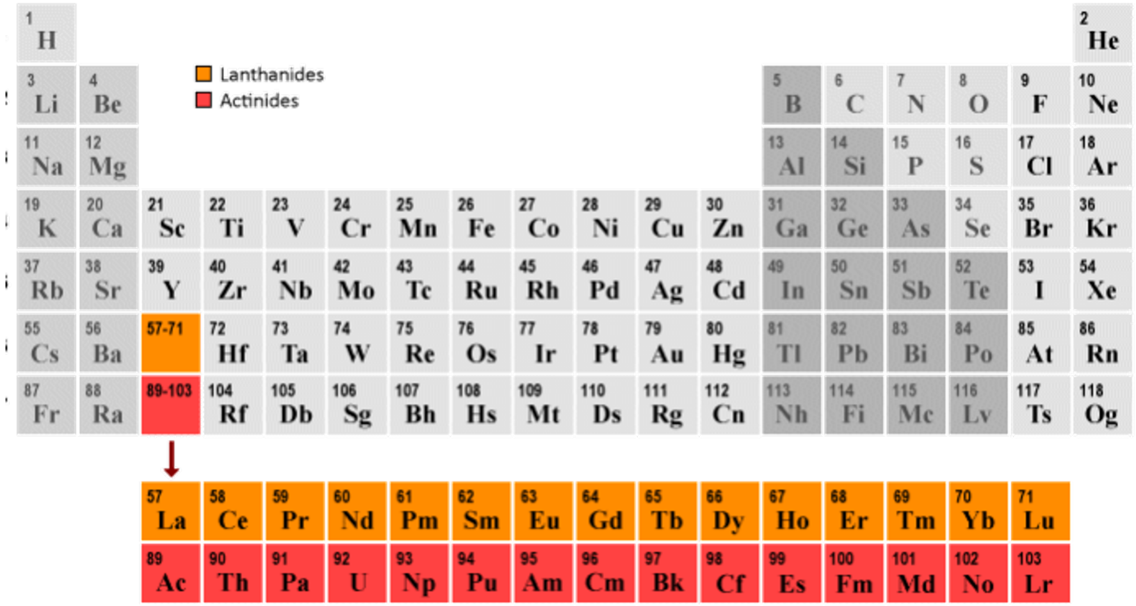
Ultraviolet (left, NASA Swift satellite)
Infrared (middle, Gemini South telescope)
Radio (right, Very Large Array)
γ-ray, X-ray, and optical also observed

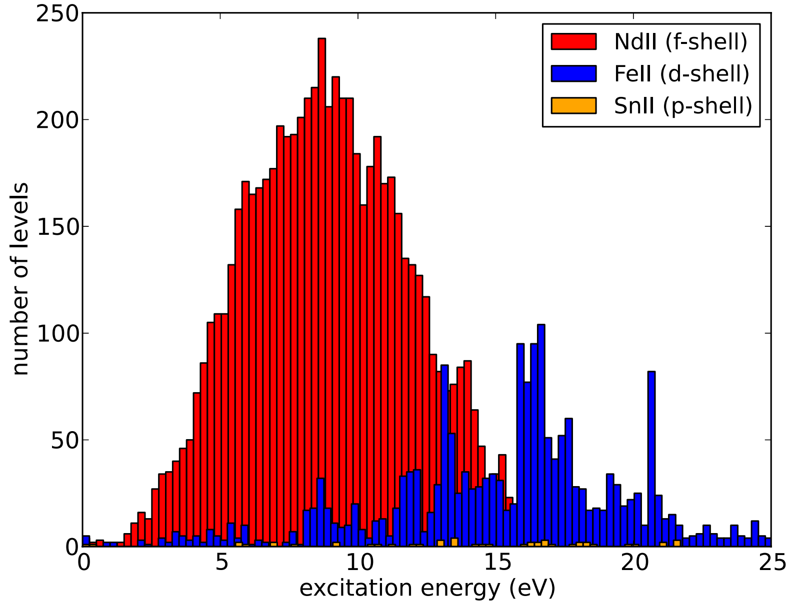
GW170817 & AT2017gfo: photon opacity

Opacity sources include (*most important in NSM ejecta):

- ***bound-bound transitions** –** photoelectric absorption: photon absorbed or emitted as an electron moves between levels
- ***bound-free* –** photoionization: electron absorbs photon and escapes
- ***free-free scattering* –** bremsstrahlung: free electron passing close to ion or nucleus can emit or absorb a photon
- ***electron scattering* –** inelastic (Compton) scattering and elastic (Rayleigh) scattering: photons scatter off electrons

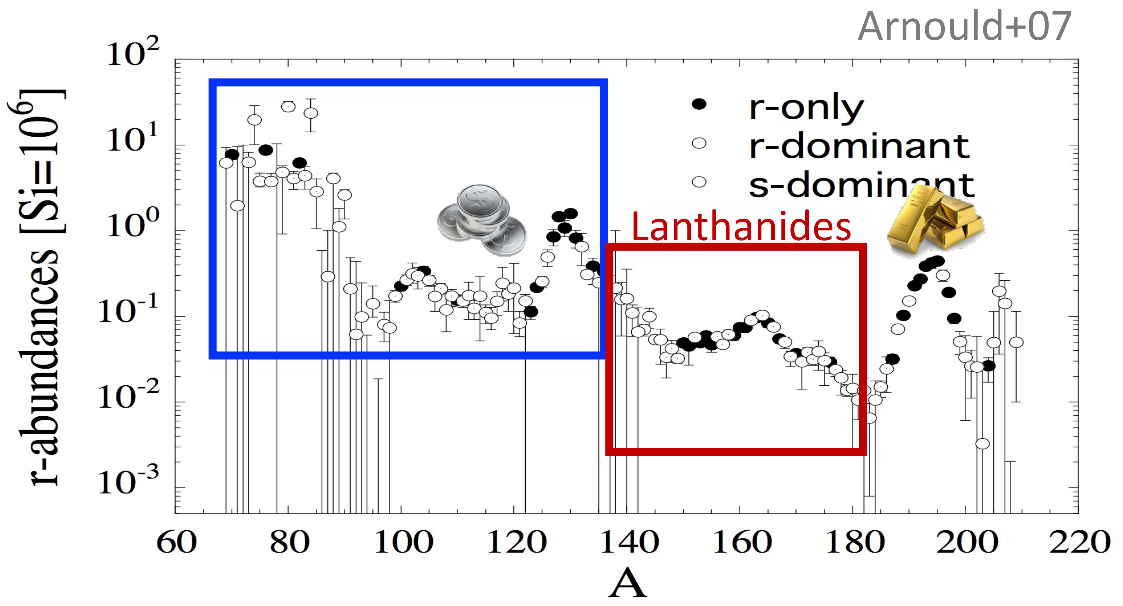






Kasen+13; see also Fontes+20, Tanaka+20

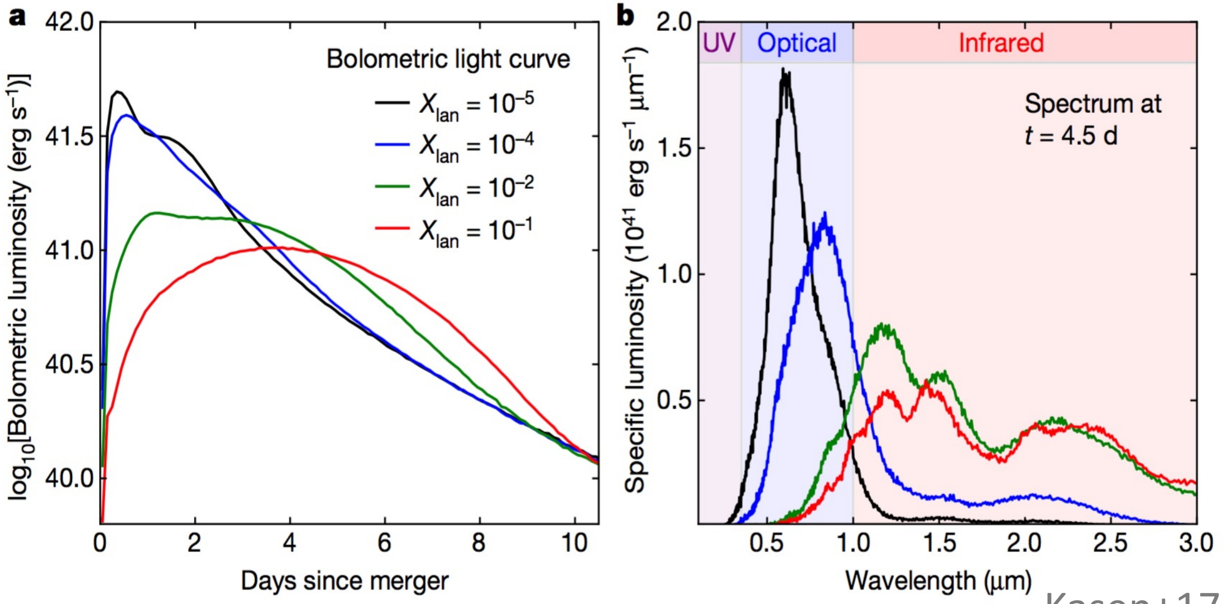
GW170817 & AT2017gfo: "red" and "blue" kilonovae



Spectra and light curves depend on the species present; Lanthanide and/or actinide mass fraction ↑, opacity ↑, longer duration light curve shifted toward infrared

(e.g. Metzger+10, Lippuner+15, Barnes+16,21, Wanajo+18, Watson+19, Hotokezaka+20, Korobkin+20, Zhu+18,21, Wang+20)

Model



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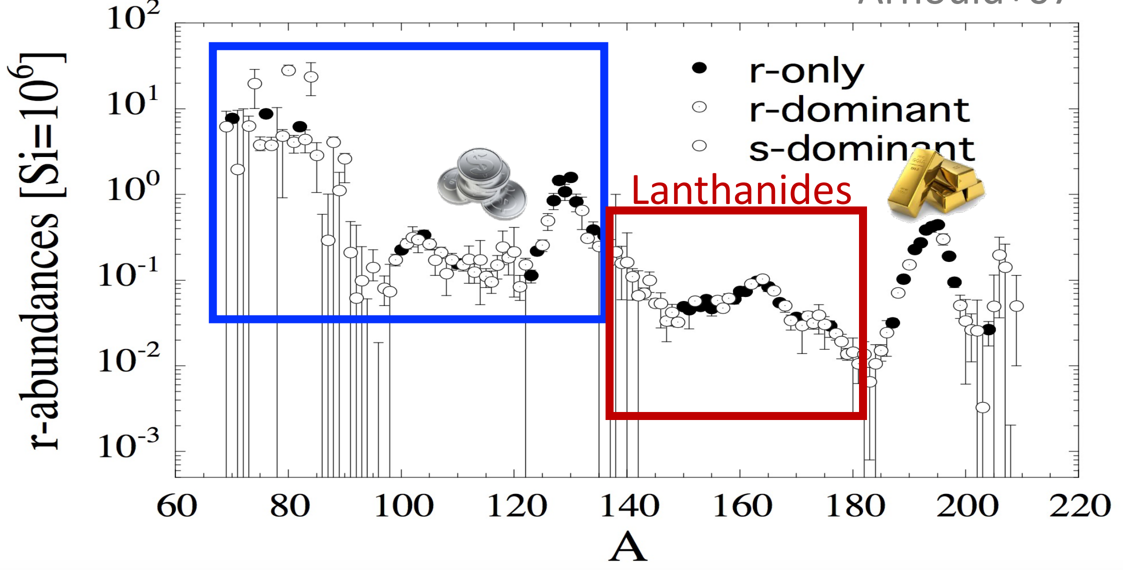
GW170817 & AT2017gfo: "red" and "blue" kilonovae

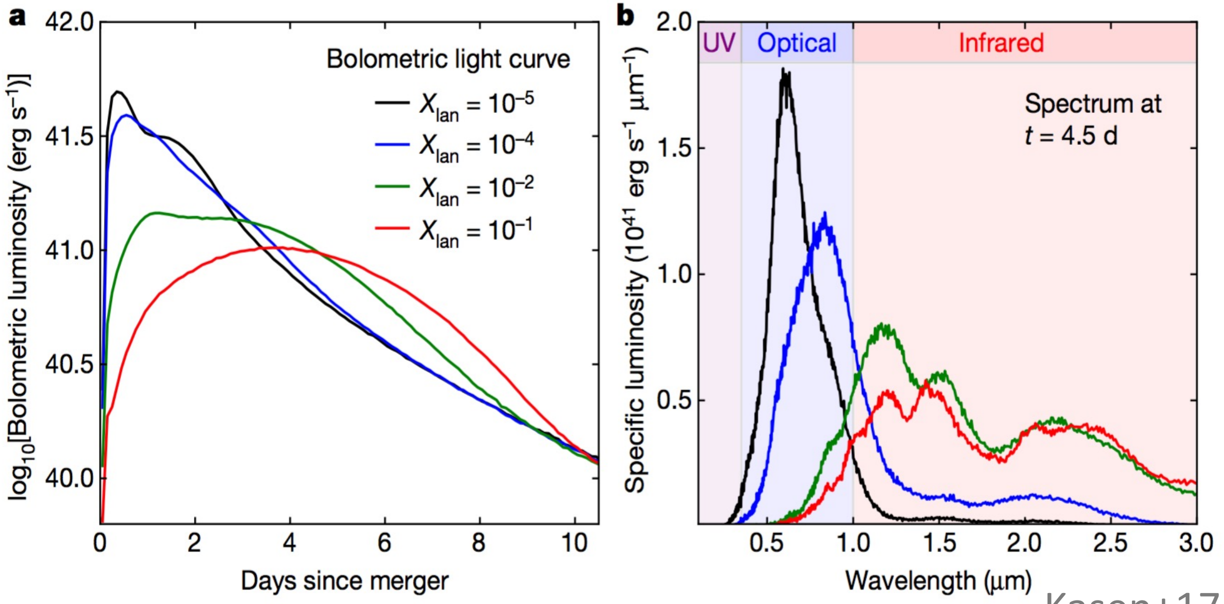
Arnould+07



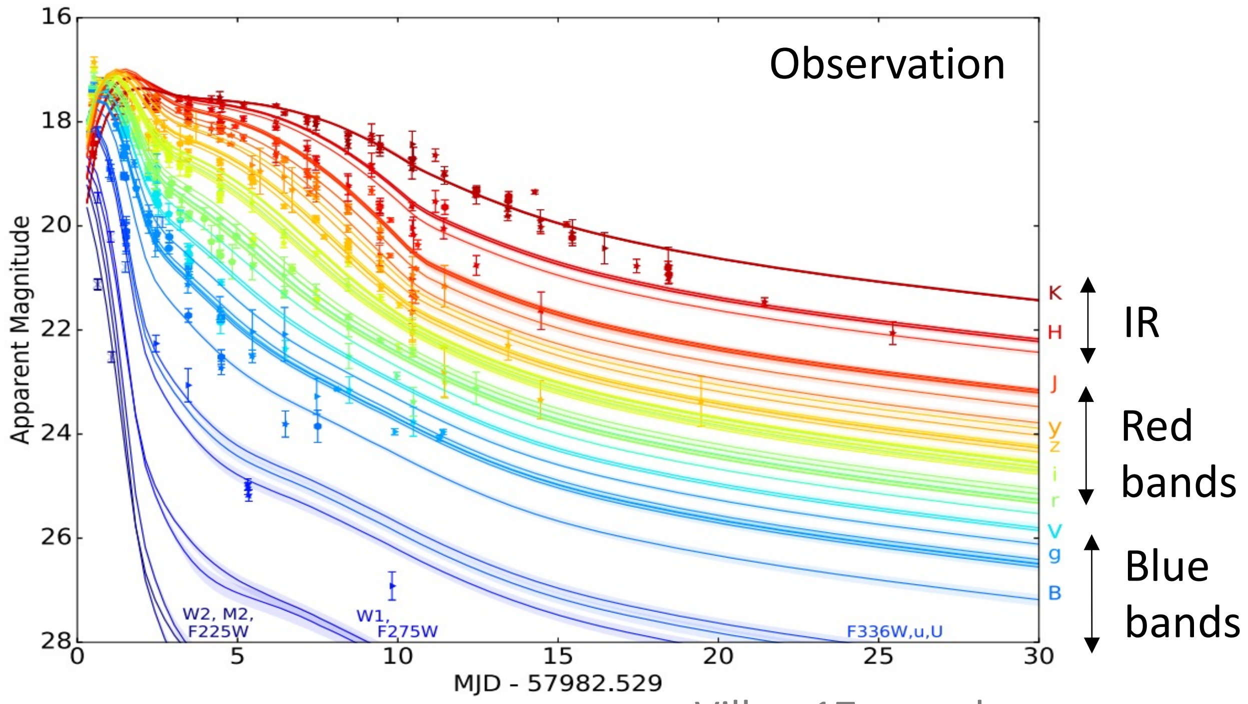
Spectra and light curves depend on the species present; Lanthanide and/or actinide mass fraction ↑, opacity ↑, longer duration light curve shifted toward infrared

(e.g. Metzger+10, Lippuner+15, Barnes+16,21, Wanajo+18, Watson+19, Hotokezaka+20, Korobkin+20, Zhu+18,21, Wang+20)

Model



Kasen+17

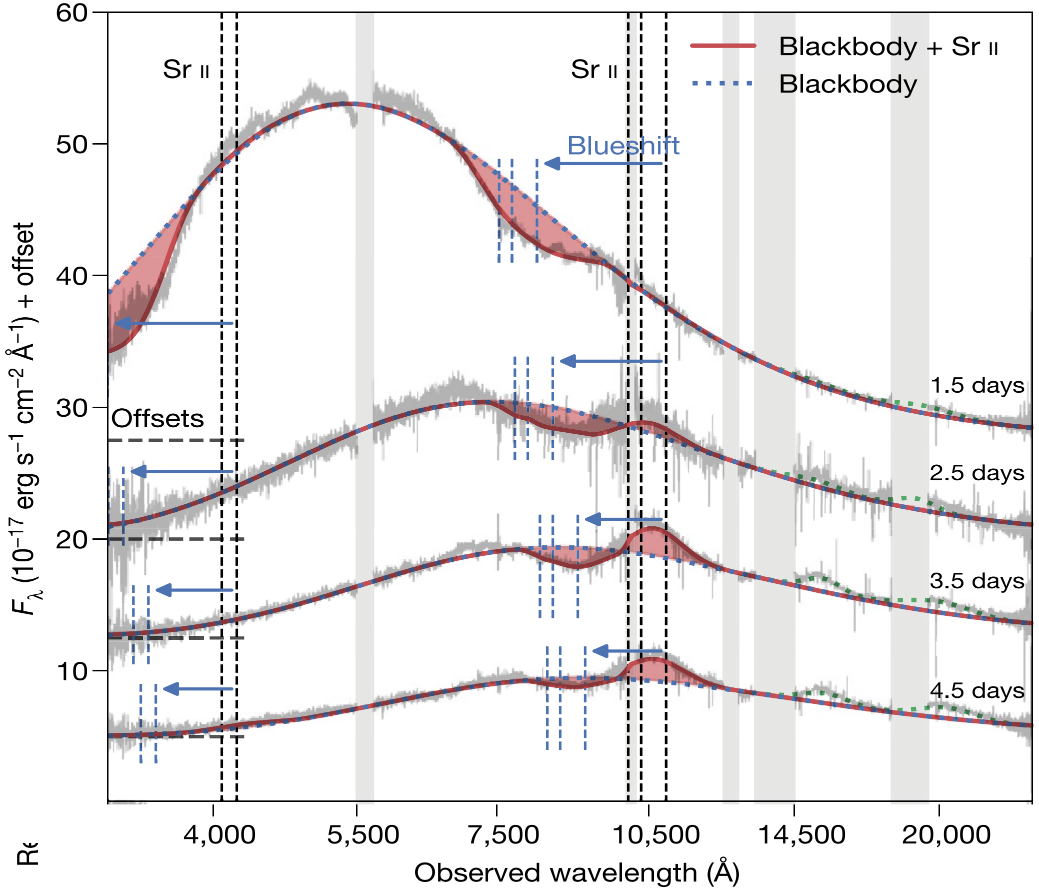


Days

Villar+17; see also Cowperthwaite+17

Observing individual elements from NSMS?

AT2017gfo and individual element identification:
Observation of strontium in reanalysis of spectra



Watson+19

Sr (1st *r*-process peak) gives the observed strong, broad absorption feature around 800 nm

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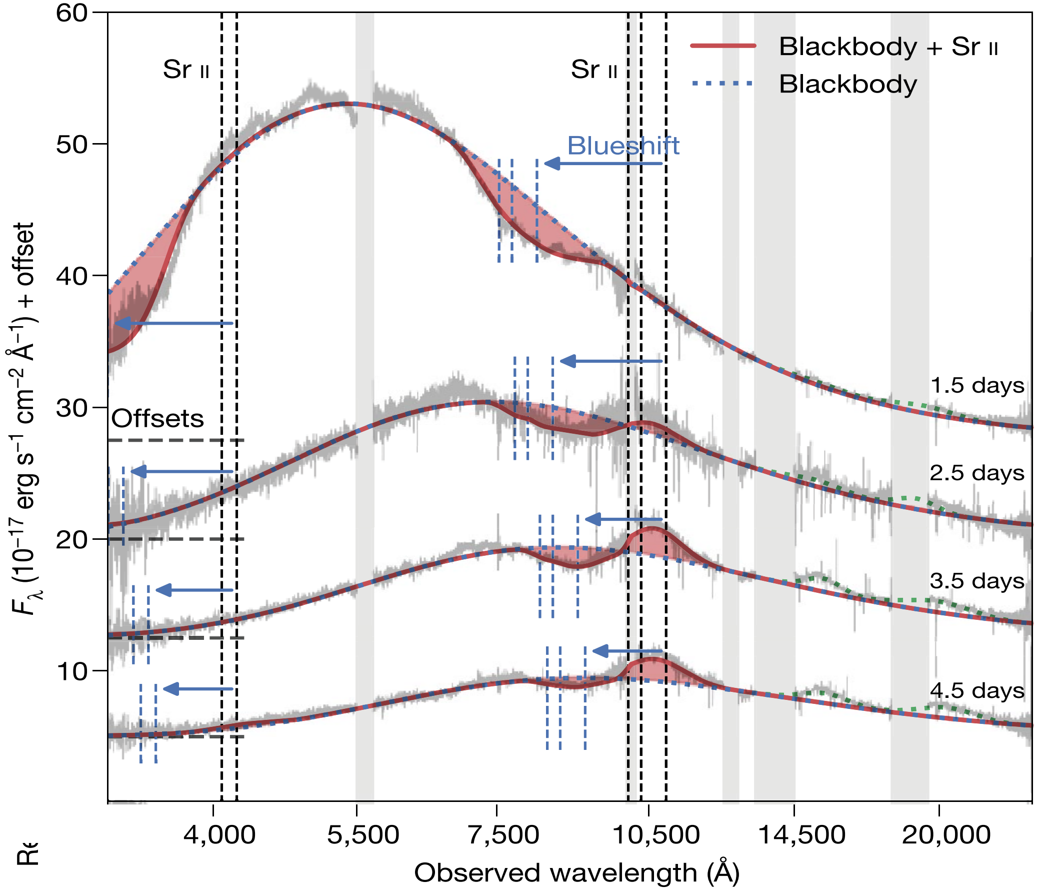

Watson+19

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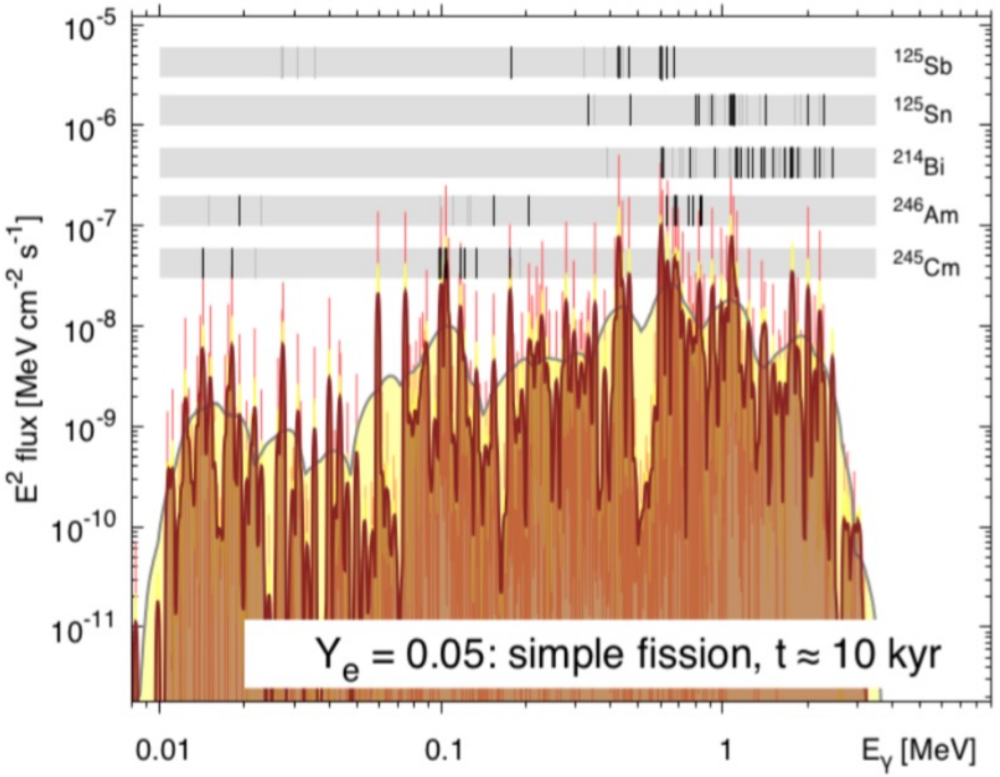
Searching for neutron star merger *remnants*:
modeling spectral lines from β-decay and α-decay

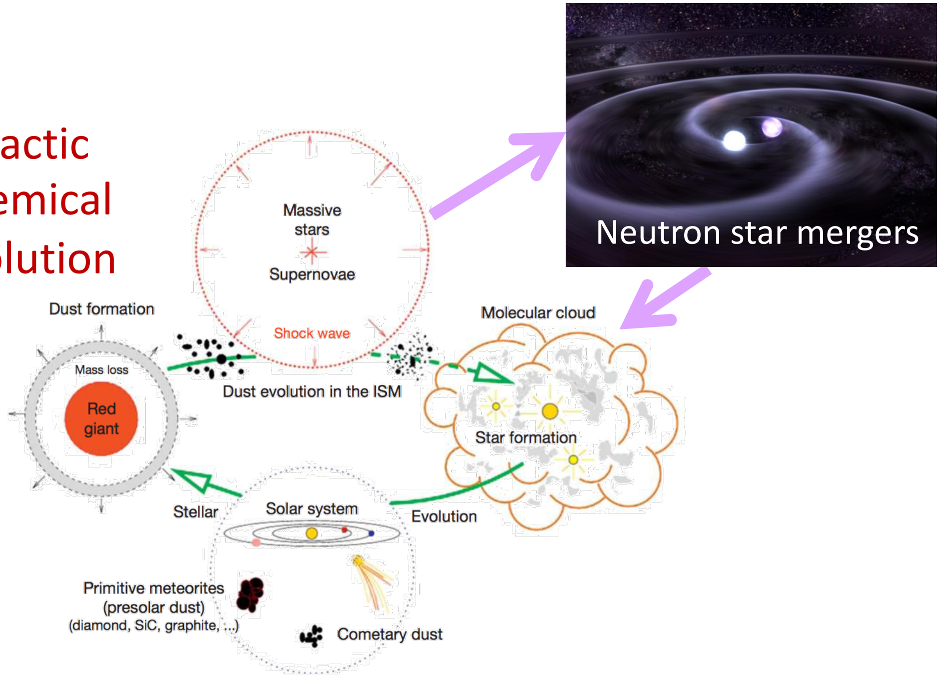


Korobkin+20; see also Wu+19

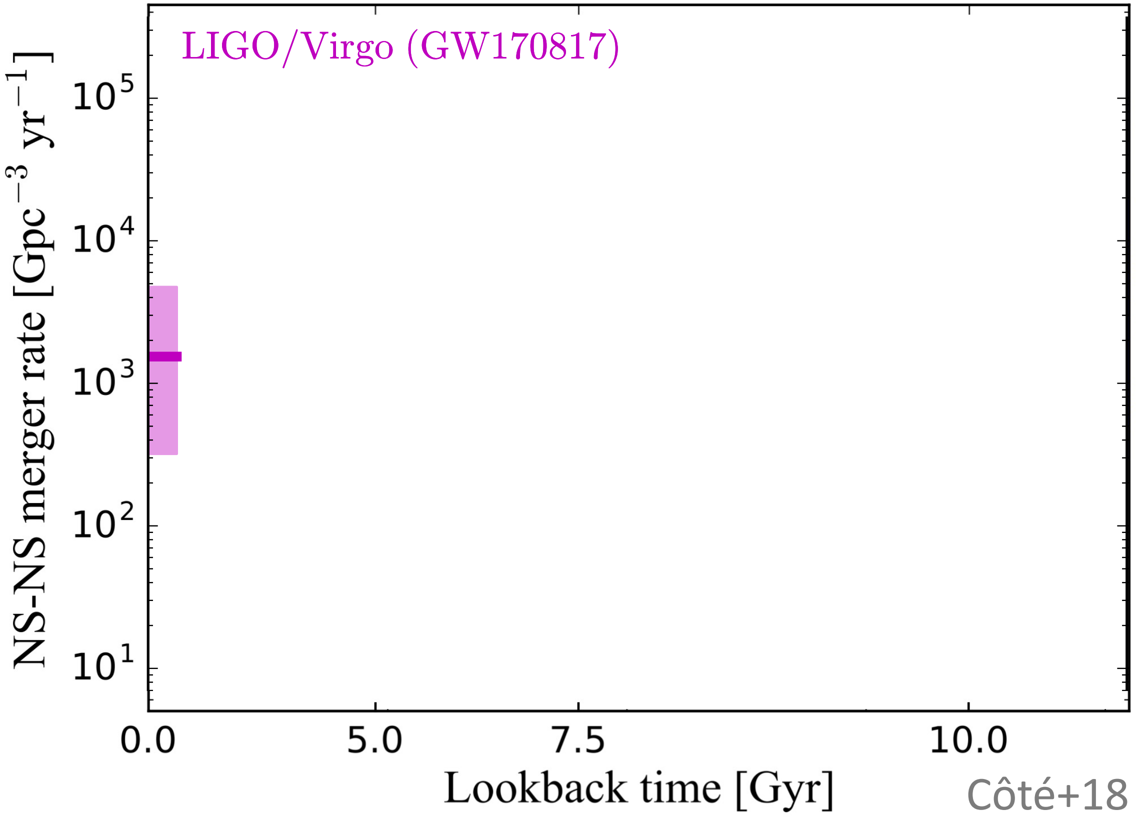
Above at 10 kpc (within Milky Way) and shows how Doppler broadening can wash away features; for reference AT2017gfo was at 40 Mpc

Do binary NS mergers make enough heavy elements?

Galactic Chemical Evolution



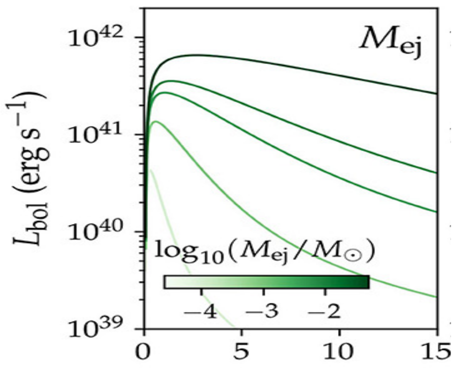
Palm+14



Côté+18

Do binary NS mergers make enough heavy elements?

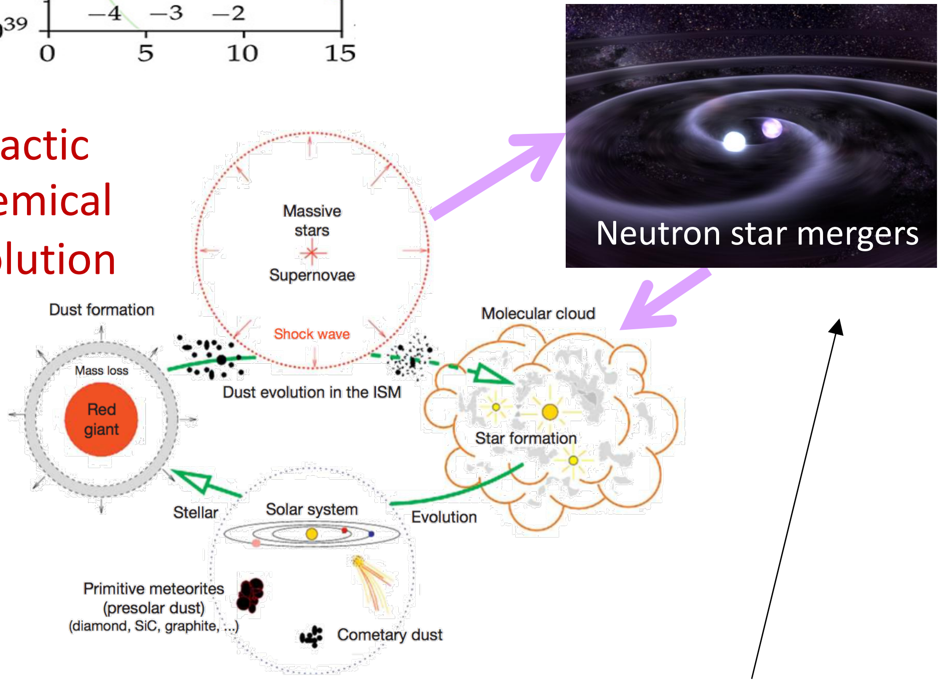
Barnes 20



Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution



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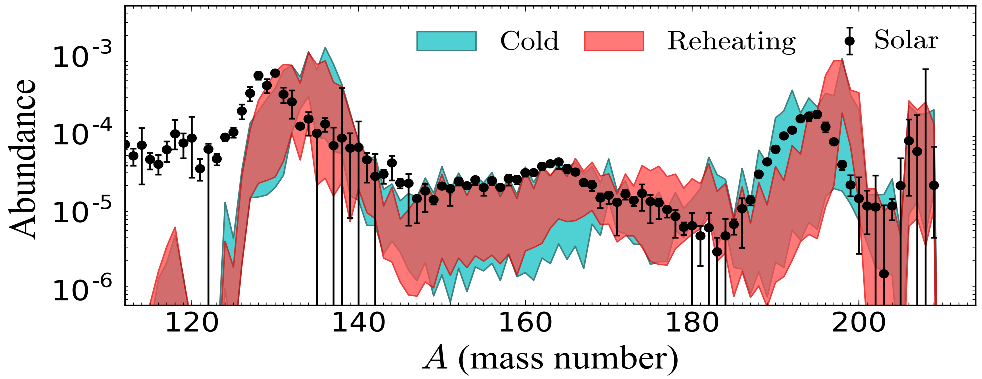
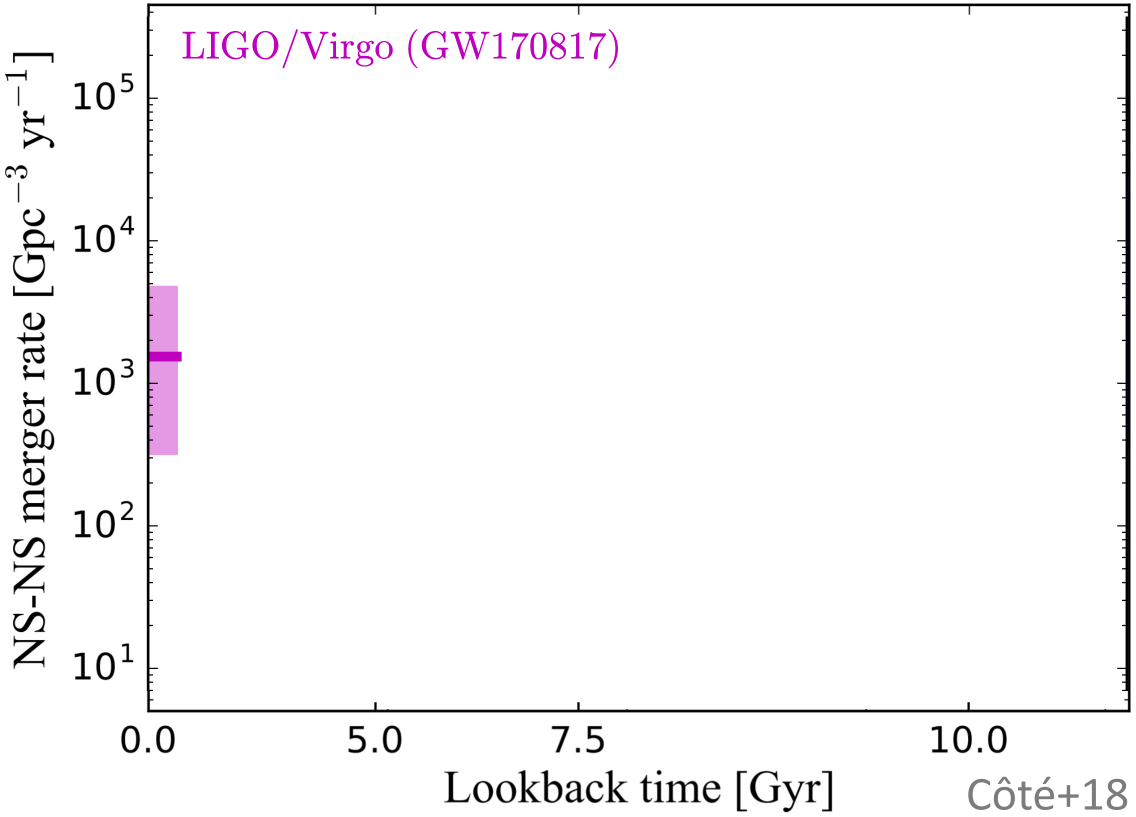


Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models



Côté+18

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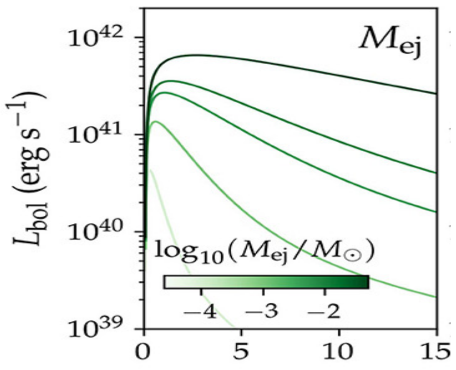

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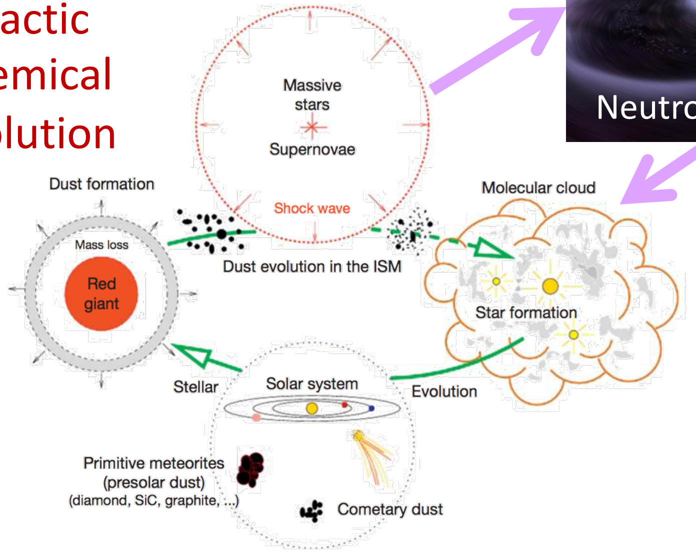
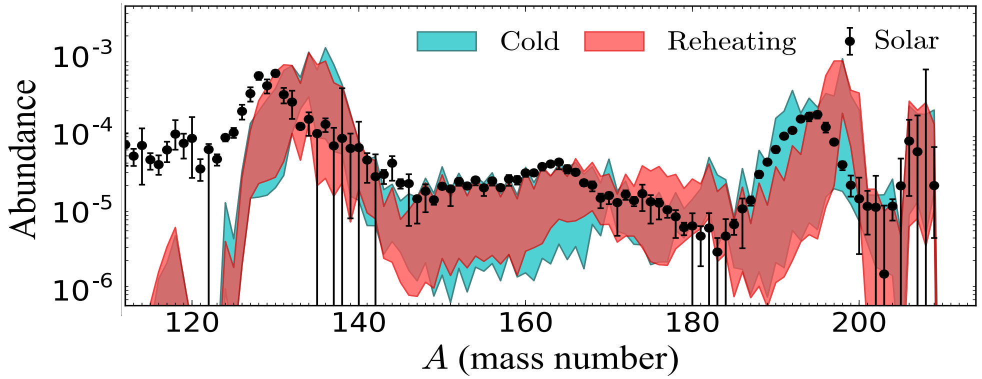


Palm+14



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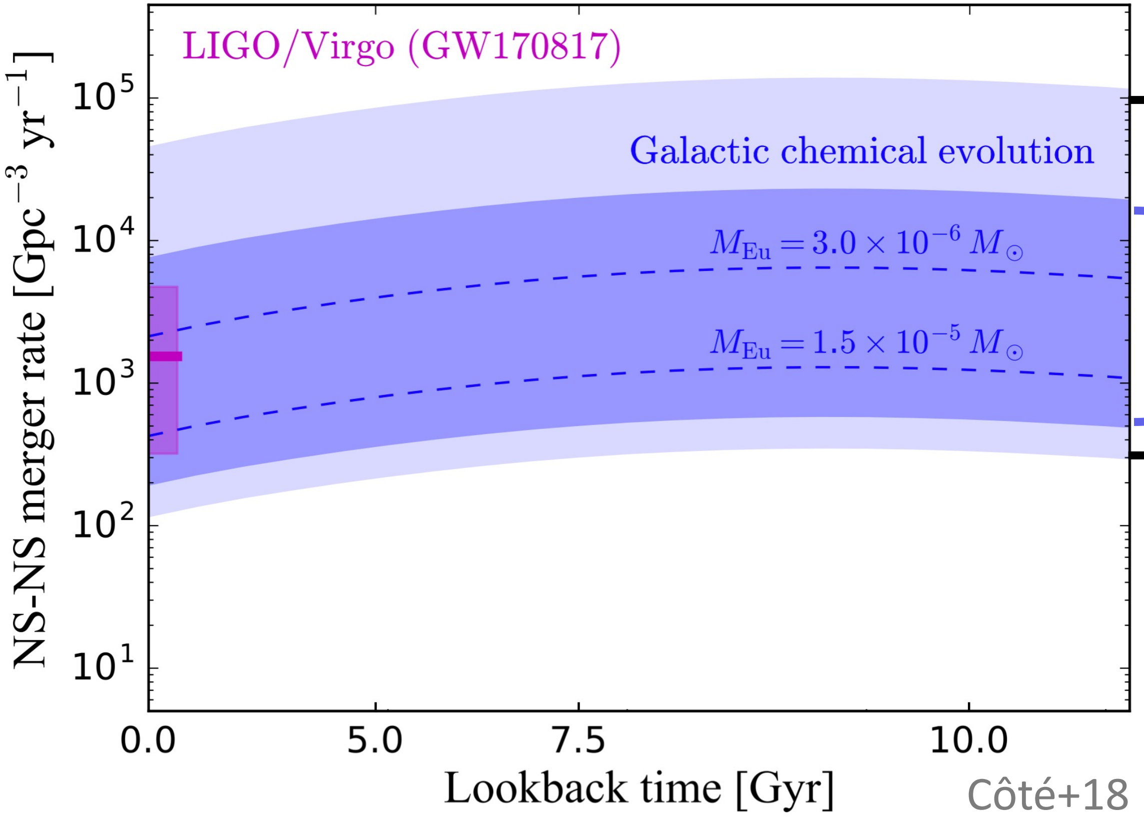


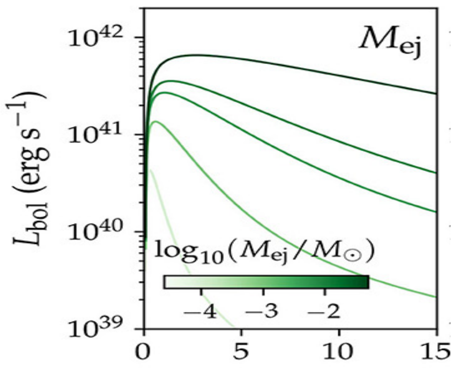
Côté+18

GCE with Solar Abund.

nuclear physics uncertainties

Do binary NS mergers make enough heavy elements?

Barnes 20



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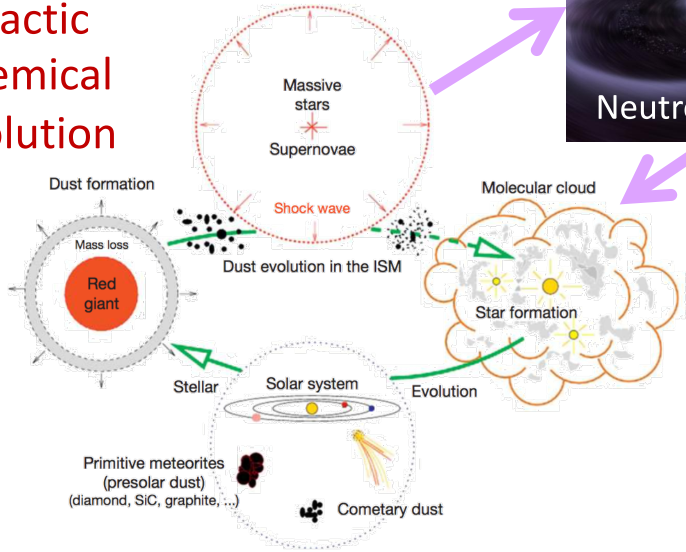

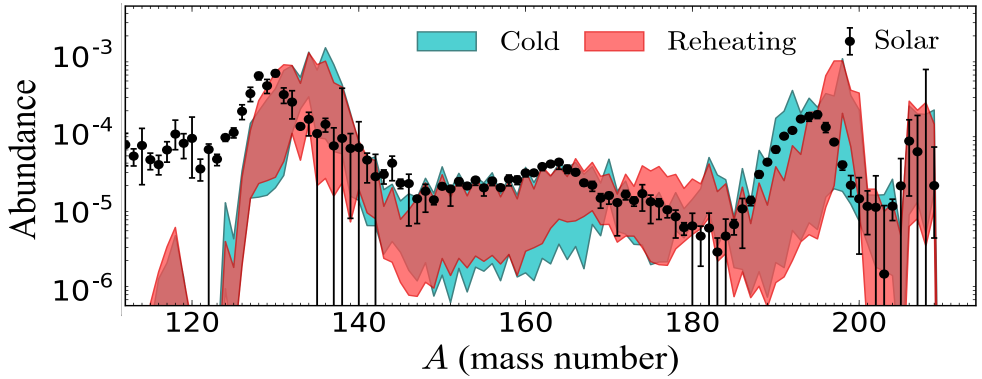

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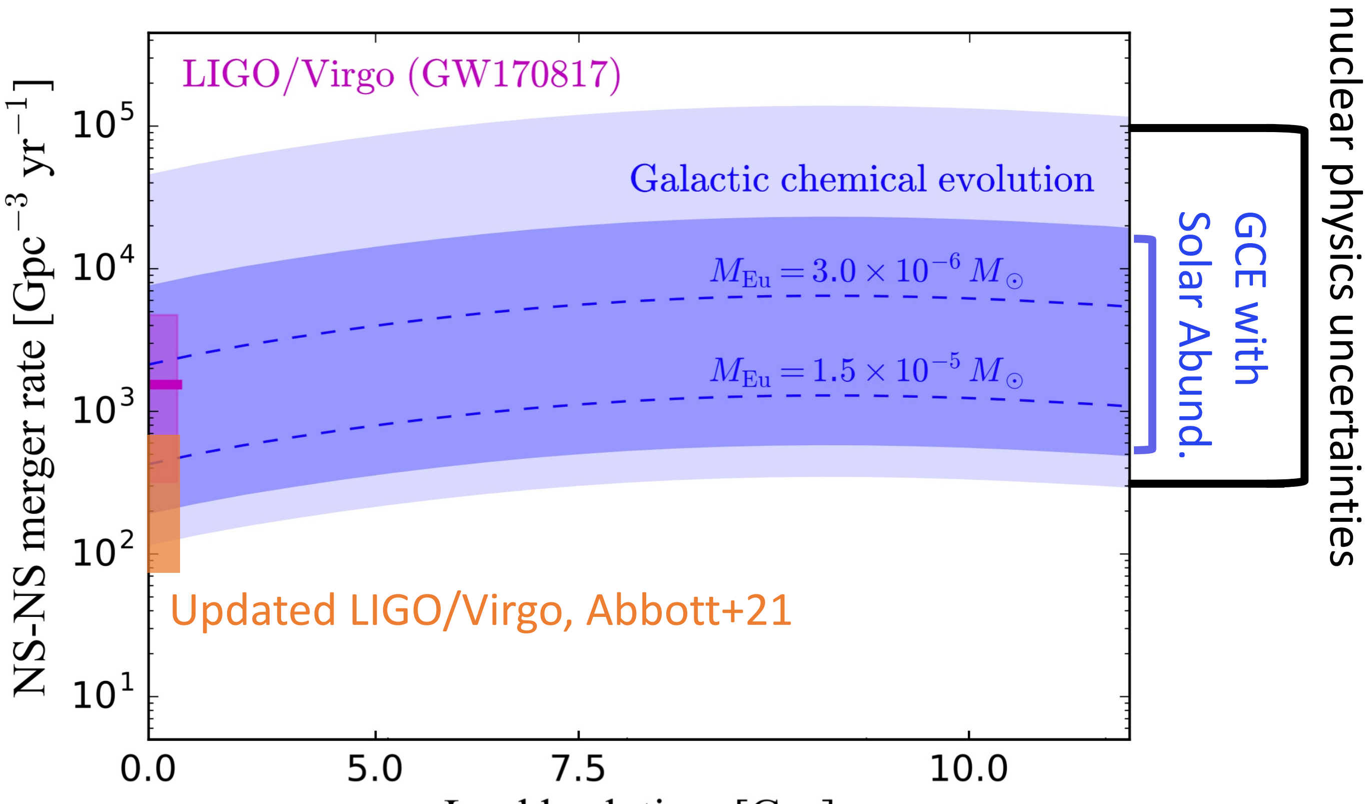


Côté+18

*Now another confirmed NSNS merger GW190425 as well as a June 2021 confirmation of two NSBH mergers GW200105 and 200115!

Outline

- Observational evidence that the *r* process occurs [4-9]
- Discussion of astrophysical sites (history (CCSNe), candidate sites, MHD SNe, NSNS/NSBH) [11-21]
- Spotlight on GW170817 and AT2017gfo: the first multi-messenger NSNS event [23-33]
- *r*-process calculations (intro to reaction rates and equilibrium, history (classical *r* process), intro to using networks and trajectories, *r*-process dynamics) [35-52]
- The fundamental role of nuclear physics [54-82]

Some definitions and intro to astrophysical rates: consider $\mathrm{B} + x \rightarrow C + D$

$Q = (M_B + M_x - M_c - M_D)c^2$

$Q =$ energy released (+) or absorbed (-), aka Q-value [MeV]

$S_n(Z, A+1) = M_{Z,A} + M_n - M_{Z,A+1}$

S_n = one neutron separation energy [MeV]

$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B$

n_B = number density [cm^{-3}], ρ = density [g · cm^{-3}], N_A= Avogadro's number (6.022×10^{23}) [g^{-1}]

$\frac{X_B}{A_B} = \frac{\text{mass fraction } (\sum_i X_i = 1)}{\text{mass number (\# protons + \# neutrons)}}$, Y_B = abundance

$Y_e = \sum_i Z_i Y_i = \frac{n_p}{n_p + n_n}$

Y_e = electron fraction (formula assumes charge neutrality); lower Y_e is more neutron rich

$r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}} \langle \sigma v \rangle$

$\langle \sigma v \rangle$ = thermally averaged cross section = $\int \sigma \; v \, f(v) \, dv$ where $f(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2kT}}$ is the Maxwell-Boltzmann distribution ($\sim e^{-E/kT}$) and $m = \frac{m_B m_x}{m_B + m_x}$ (the reduced mass)

$\lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_x \rho N_A \langle \sigma v \rangle$

r = interaction rate or reaction rate [cm^{-3} s^{-1}],
λ = "stellar reaction rate"(per target nucleus) [s^{-1}] (Note units of $N_A \langle \sigma v \rangle$=cm^3/s/g)

Nuclear Statistical Equilibrium (NSE)

If the environment is hot enough to overcome Coulomb barriers and has high energy photons, neutron and proton captures on (Z,N) are in chemical equilibrium with reverse photodissociations:

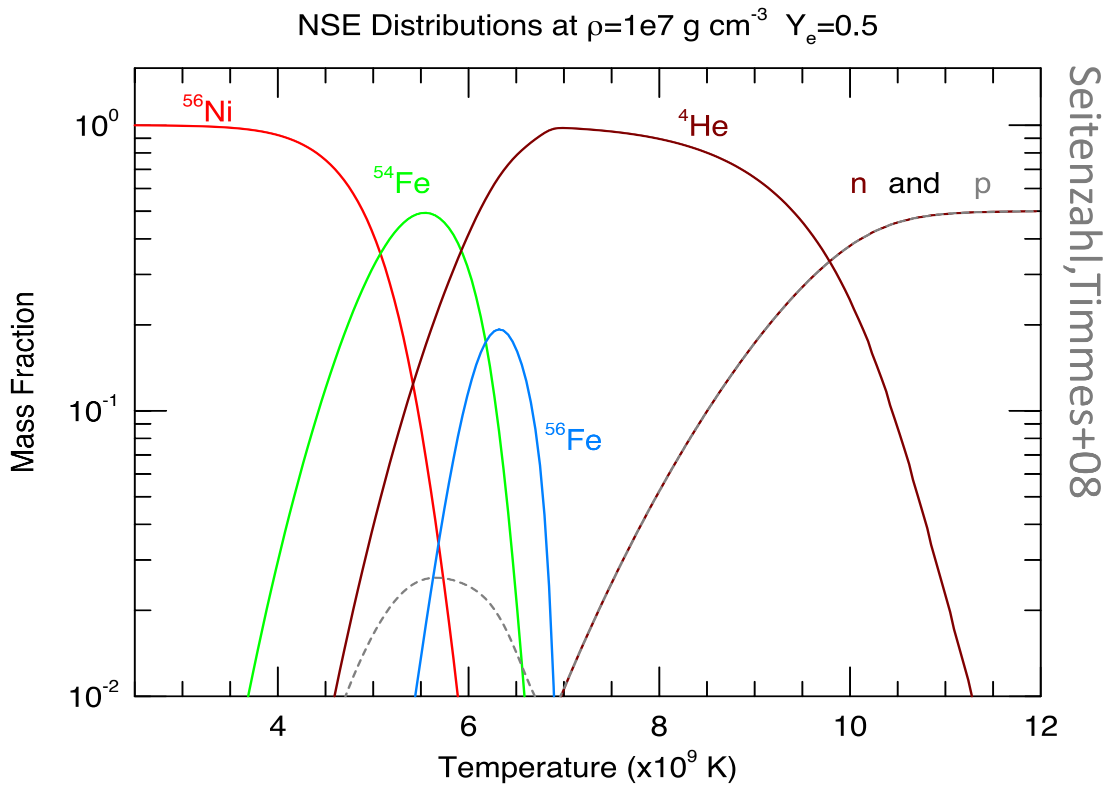
$$N \text{ neutrons} + Z \text{ protons} \rightleftarrows (Z,N)$$

$$N\mu_n + Z\mu_Z = \mu_{Z,N}$$

where μ is the chemical potential; nucleons and nuclei are described by Maxwell-Boltzmann distributions (note G_i is the partition function):

$$\mu_i = m_i c^2 + kTln\left[\rho N_A \frac{Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right]$$

*The above equations are used along with $\sum_i A_i Y_i = 1$ and $\sum_i Z_i Y_i = Y_e$ to solve for abundances at a given ρ, T, Y_e



For high temperatures, favors a composition of n, p, and α due to photodissociation, for lower temperatures nuclei with the highest binding energy are favored (^{56}Fe for $Y_e < 0.5$ and ^{56}Ni for $Y_e = 0.5$)

Recall definitions for $\mathrm{B} + x \rightarrow C + D$

$$Q = (M_B + M_x - M_c - M_D)c^2 \qquad r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}} \langle \sigma v \rangle$$

$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1 + \delta_{Bx}} Y_x \rho N_A \langle \sigma v \rangle$$

Reverse rate for $C + D \rightarrow \mathrm{B} + x$ from detailed balance (equilibrium): Saha Equation

If $B \neq x$ and $\mathrm{C} \neq D$ with all being nuclei:

$$r_{Bx} = r_{CD} \Rightarrow \frac{n_C n_D}{n_B n_x} = \frac{\langle \sigma v \rangle_{Bx}}{\langle \sigma v \rangle_{CD}}$$ along with $$\frac{\sigma_{Bx}}{\sigma_{CD}} = \frac{g_C g_D}{g_B g_X} \frac{A_C A_D E_{CD}}{A_B A_x E_{Bx}}$$

where g=2J+1; can then obtain:

$$\frac{n_C n_D}{n_B n_x} = \frac{\langle \sigma v \rangle_{Bx}}{\langle \sigma v \rangle_{CD}} = \frac{g_C g_D}{g_B g_X} \left(\frac{A_C A_D}{A_B A_x} \right)^{3/2} e^{+Q/kT}$$

*See Fowler, Caughlan, and Zimmerman (1967) for more details

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If instead C is a photon:

$$r_{Bx} = r_{D\gamma} \Rightarrow \frac{n_D}{n_B n_x} = \frac{\langle\sigma v\rangle_{Bx}}{\lambda_\gamma}$$

Gives:

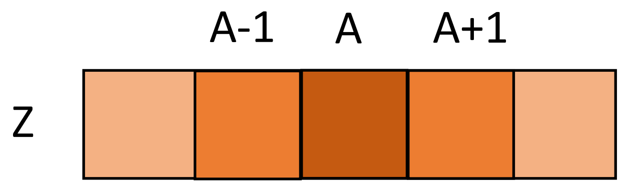
$$\frac{n_D}{n_B n_x} = \frac{\langle\sigma v\rangle_{Bx}}{\lambda_\gamma} = \frac{g_D}{g_B g_X}\left(\frac{A_D}{A_B A_x}\right)^{3/2}\left(\frac{2\pi\hbar^2}{mkT}\right)^{3/2} e^{+Q/kT}$$

*See Fowler, Caughlan, and Zimmerman (1967) for more details

Classical approach to *r*-process calculations: $(n,\gamma) \rightleftarrows (\gamma,n)$ + steady β flow

Assume $(\mathrm{n},\gamma) \rightleftarrows (\gamma,\mathrm{n})$ equilibrium to obtain relative abundances of neighboring isotopes:

$$\frac{Y_{A+1}}{Y_A} = \frac{n_{A+1}}{n_A} \approx n_n \frac{g_{A+1}}{g_A g_n}\left(\frac{A+1}{A}\right)^{3/2}\left(\frac{2\pi\hbar^2}{A m_n m_n kT}(A+1)m_n\right)^{3/2} e^{+S_n/kT}$$



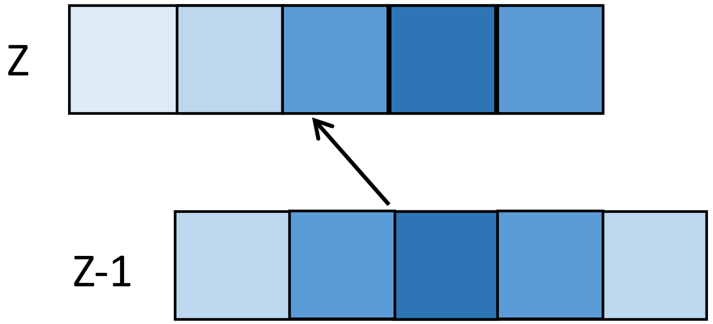
*Sets the relative abundances along an isotopic chain

The evolution of abundances is determined from flow of β-decay:

$$\frac{dn(Z)}{dt} = \lambda_{Z-1} n(Z-1) - \lambda_z n(Z) \quad \text{where} \quad \lambda_z = \textstyle\sum_A n(Z,A)\lambda_\beta(Z,A)$$

Steady flow equilibrium (or β-flow equilibrium) assumes $\lambda_z n(Z)$~constant

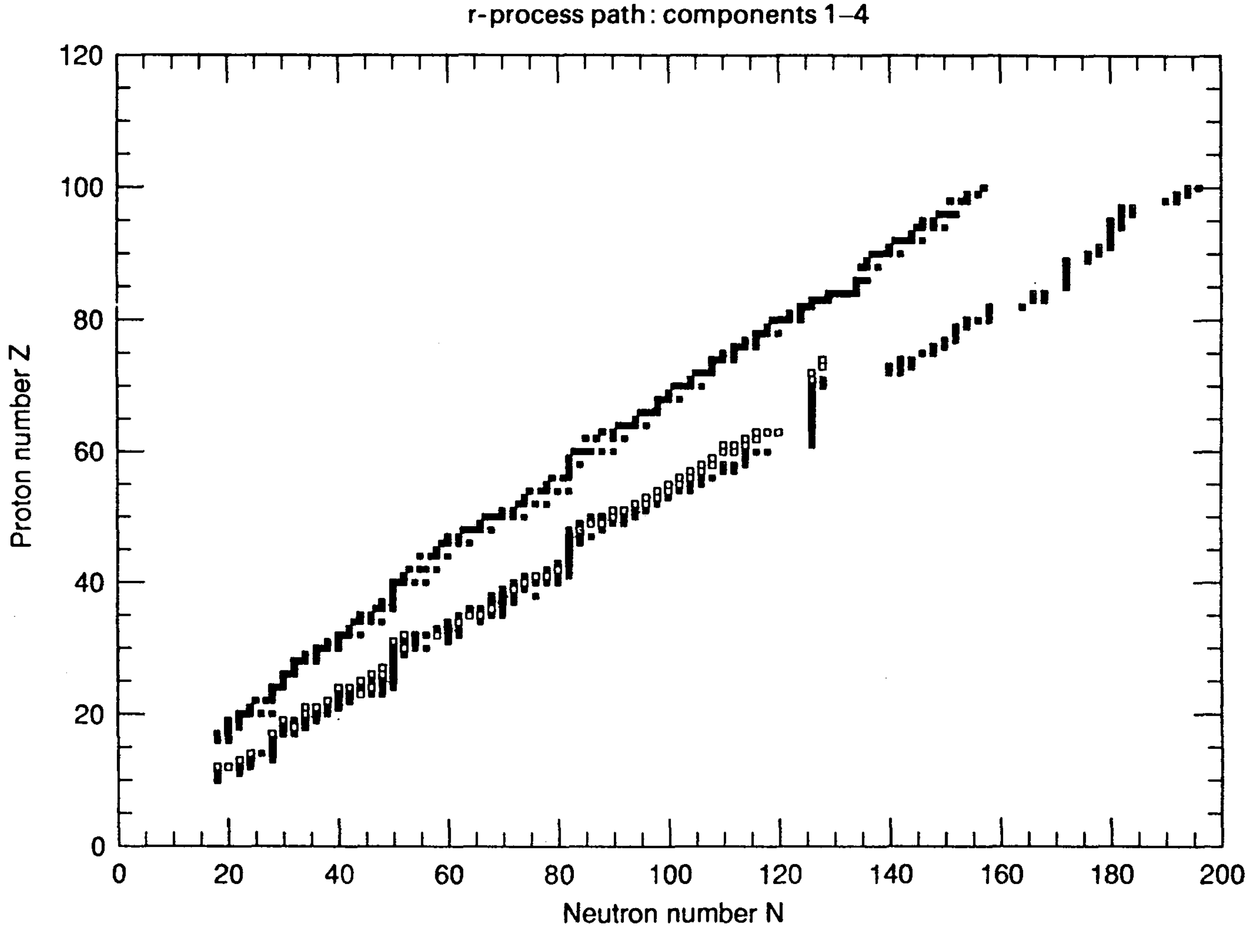
*Note: also called "waiting point approximation" since the nucleus with the maximum abundance in each isotopic chain must wait for the longest β-decay



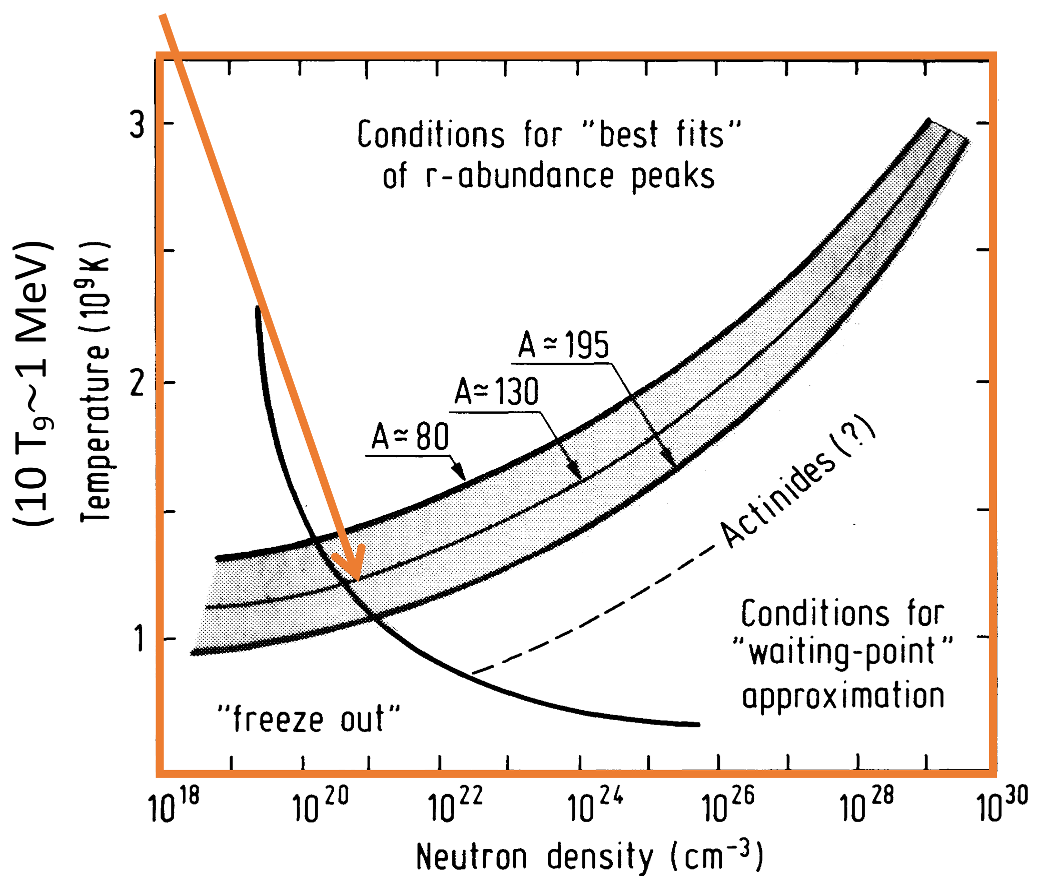
*Allows for the chain to move to elements with higher proton numbers or in the case of steady flow sets relative Z abundances

The *r*-process "path"

= Location of the maximum abundance for all isotopic chains
(what N is most populated for a given Z)



n_n = 9.5x10^{20} cm^{-3}, T=1.2 GK



Classical calculation (with steady flow equilibrium) of the different paths for four n_n-T values which reproduce solar features

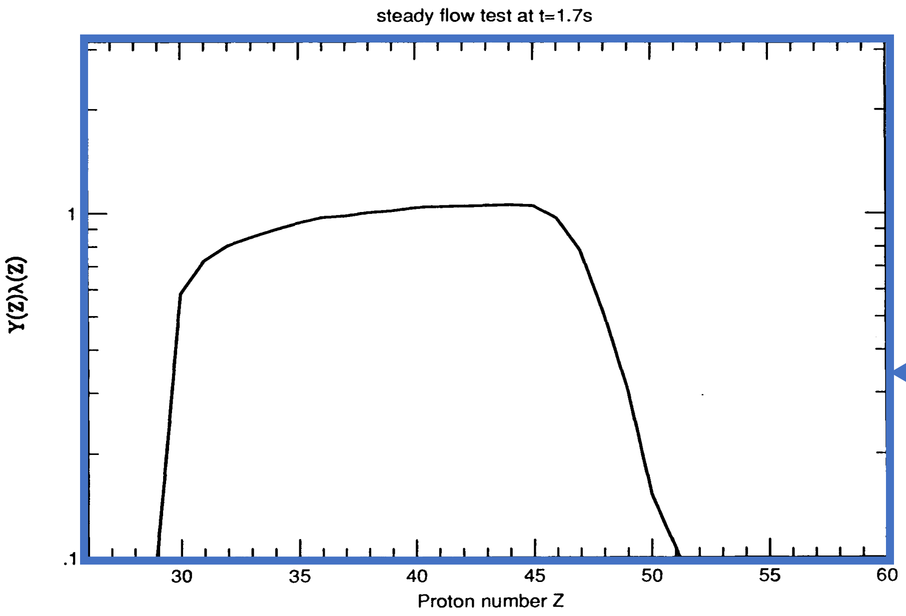
Kratz, Bitouzet, Thielemann, Möller, and Pfeiffer (1993)

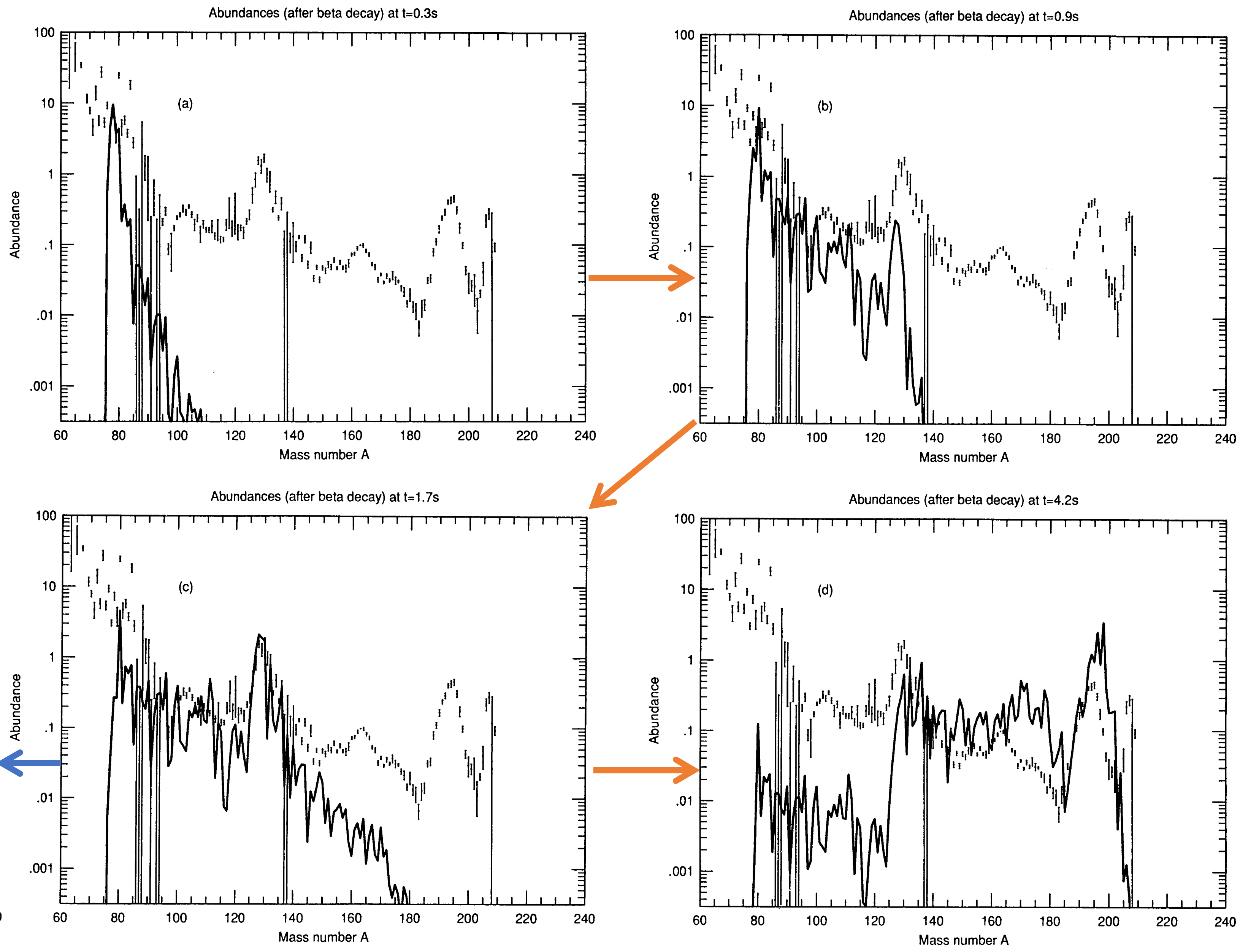
*Note "freeze-out" is when equilibrium fails, can be prompted by neutron-to-seed ratio → 1

An example of a classical *r*-process calculation

Here abundances from detailed balance are evolved in time by applying $\frac{dn(Z)}{dt} \neq 0$

The steady flow condition $\lambda_Z n(Z) \sim$constant can then be tested for this case





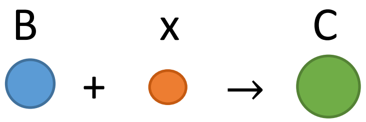
Kratz, Bitouzet, Thielemann, Möller, and Pfeiffer (1993); see also Hillebrandt 77

A short intro to reaction networks

$$Q = (M_B + M_x - M_c - M_D)c^2 \qquad r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}}\langle\sigma v\rangle$$

$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_x \rho N_A \langle\sigma v\rangle$$

For the two-body reaction



$$\frac{dn_B}{dt} = -n_B\lambda_{Bx} = -n_B Y_x \rho N_A \langle\sigma v\rangle$$

$$\frac{dn_C}{dt} = +n_B\lambda_{Bx}$$

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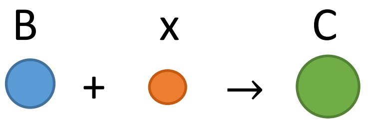
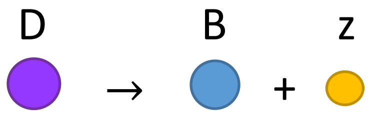


$$\frac{dn_B}{dt} = -n_B \lambda_{Bx} = -n_B Y_x \rho N_A \langle \sigma v \rangle$$

$$\frac{dn_C}{dt} = +n_B \lambda_{Bx}$$

Now if a one-body decay produces B



$$\frac{dn_B}{dt} = -n_B Y_x \rho N_A \langle \sigma v \rangle + n_D \lambda_D$$

$$\frac{dn_D}{dt} = -n_D \lambda_D$$

A short intro to reaction networks

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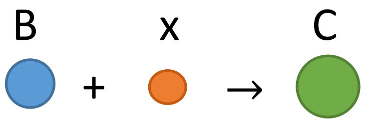

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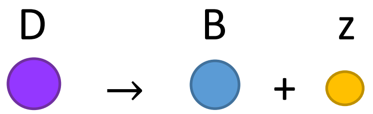


$$\frac{dn_B}{dt} = -n_B Y_x \rho N_A \langle\sigma v\rangle + n_D\lambda_D$$

$$\frac{dn_D}{dt} = -n_D\lambda_D$$

Thus network equations can be written as:

$$\dot{Y}_i = \sum_j \xi^i_j \lambda_j Y_j + \sum_{j,k} \xi^i_{j,k}\rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} \xi^i_{j,k,l}\rho^2 {N_A}^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l$$

Where ξ is + when i created, - when i consumed, and corrects for overcounting in a reaction involving identical particles

*Coupled differential equations can be put into matrix form so networks use matrix solvers

A short intro to reaction networks

$$Q = (M_B + M_x - M_c - M_D)c^2 \qquad r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}}\langle\sigma v\rangle$$

$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_x \rho N_A \langle\sigma v\rangle$$

Written out in a more schematic way, for the r process this means:

$\dot{Y}_i = \sum(\text{2body reactions into } i) - \sum(\text{2body reactions out of } i)$ (ex: n capture, photodissociation)

$+\sum(\text{3body reactions into } i) - \sum(\text{3body reactions out of } i)$ (ex: $\alpha\alpha$n, (n,2n))

$+\sum(\text{decays into } i) - \sum(\text{decays out of } i)$ (ex: β-decay, β-delayed n emission, α-decay)

$+\sum(\text{fission into } i)$ OR $-\sum(\text{fission out of } i)$ (ex: neutron-induced, β-delayed, spontaneous fission)

Thus network equations can be written as:

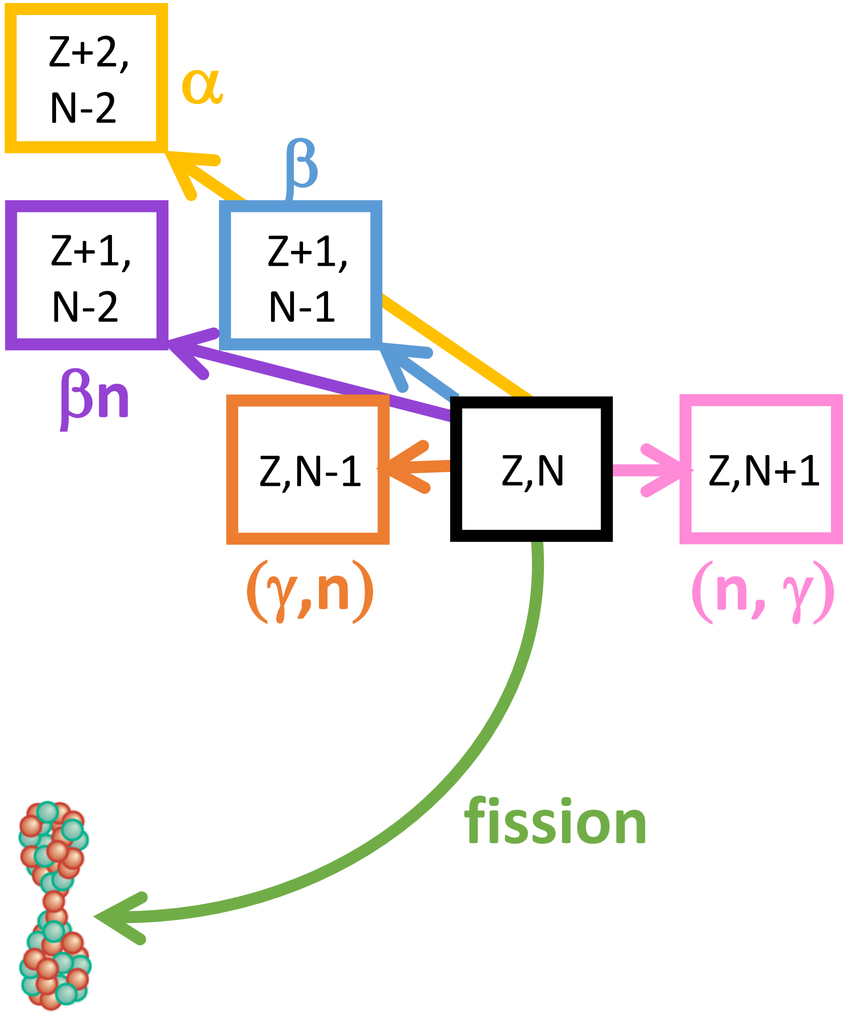
$$\dot{Y}_i = \sum_j \xi^i_j \lambda_j Y_j + \sum_{j,k} \xi^i_{j,k} \rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} \xi^i_{j,k,l} \rho^2 {N_A}^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l$$

Where ξ is + when i created, - when i consumed, and corrects for overcounting in a reaction involving identical particles

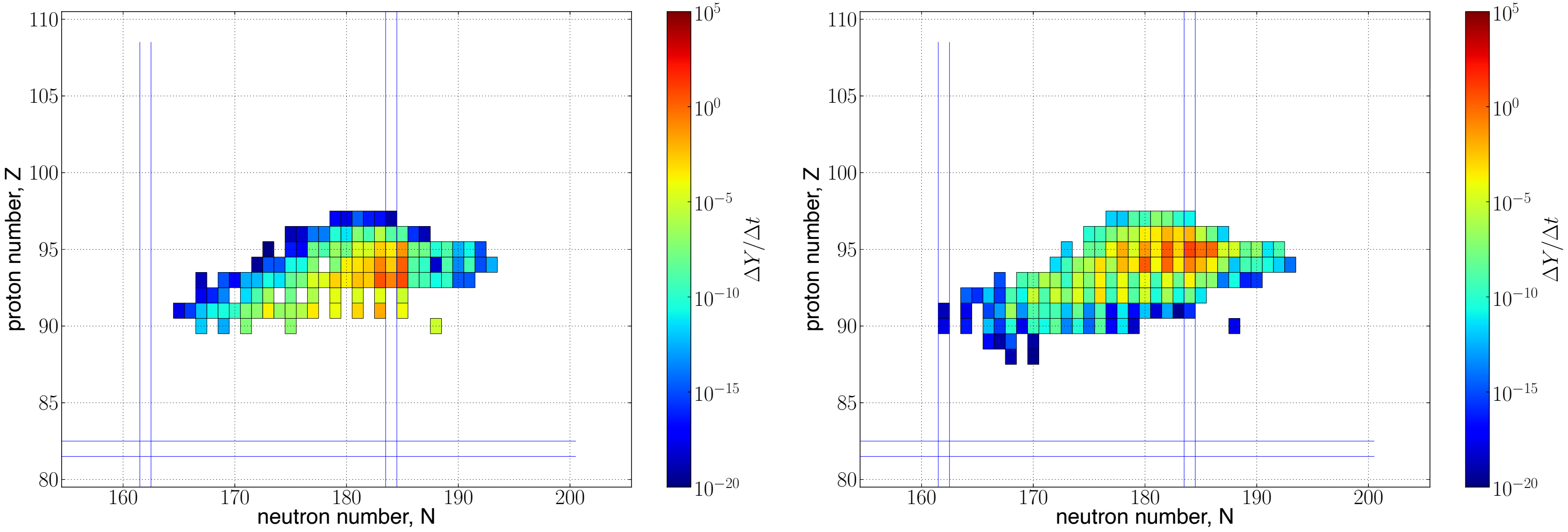
*Coupled differential equations can be put into matrix form so networks use matrix solvers

Some reaction network codes used for the *r*-process include PRISM, SkyNet, NucNetTools, Xnet, and WINNET; See e.g. Hix&Meyer 06, Lippuner&Roberts 18 for discussions of solving network equations

Analyzing the reactions in your network calculation: *Flows= rate x abundance*

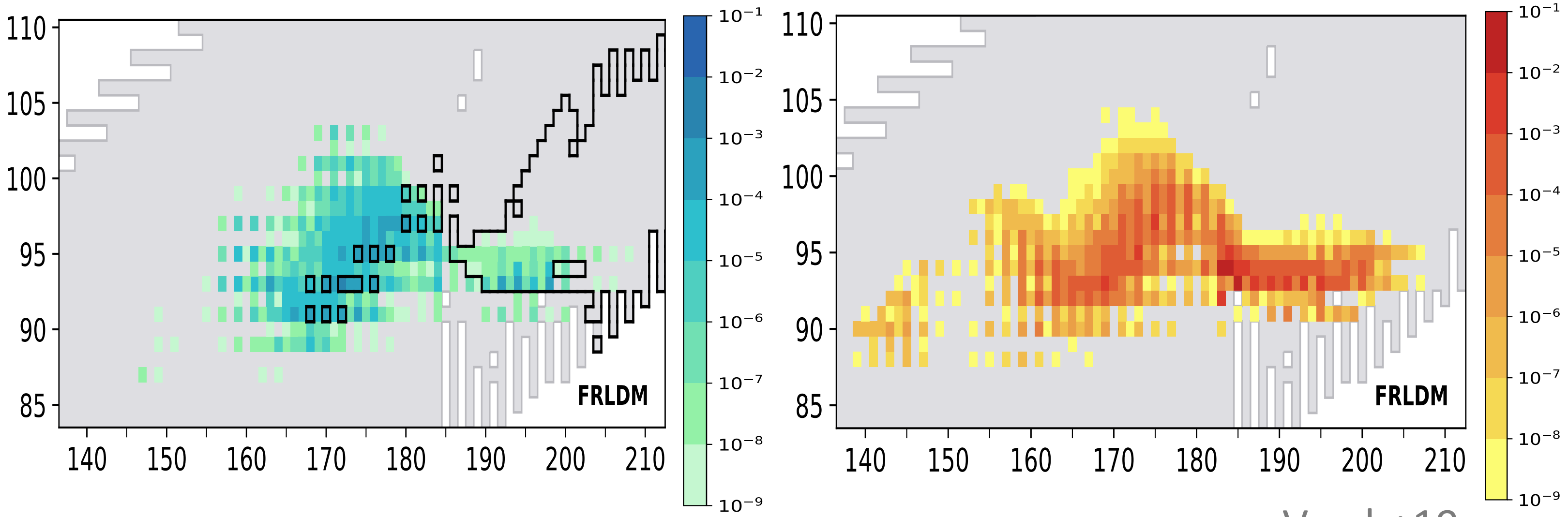


β-delayed (left) and neutron-induced (right) fission flows *at an instance in time* (here t=1 s)



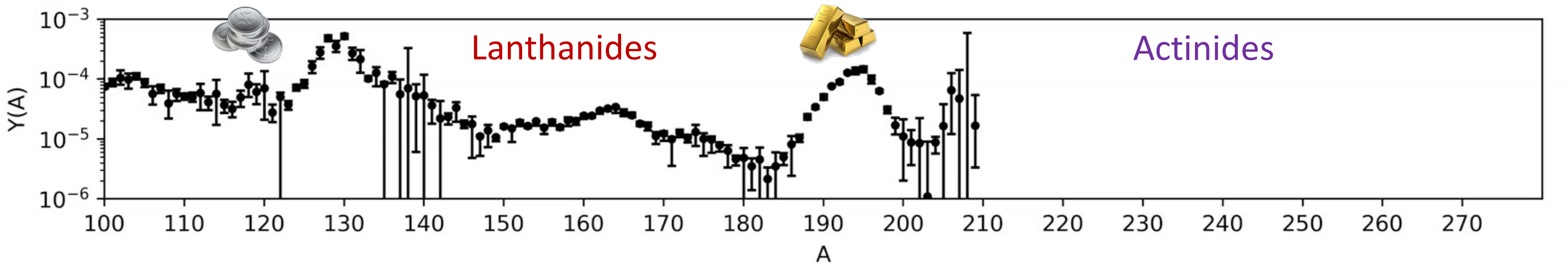
Eichler+15

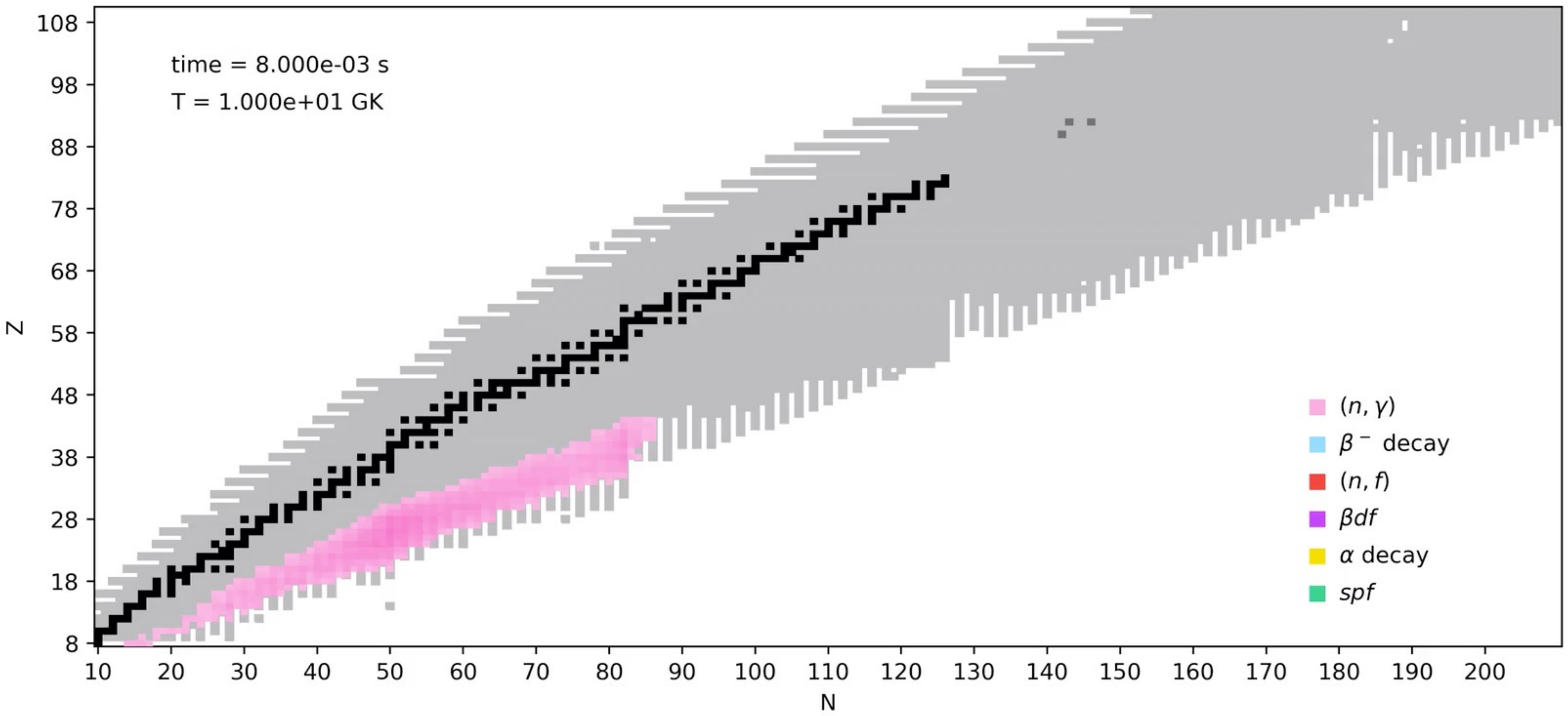
β-delayed (left) and neutron-induced (right) fission flows *integrated over time*



Vassh+19

Putting it all together: evolution of abundances and dominant flows

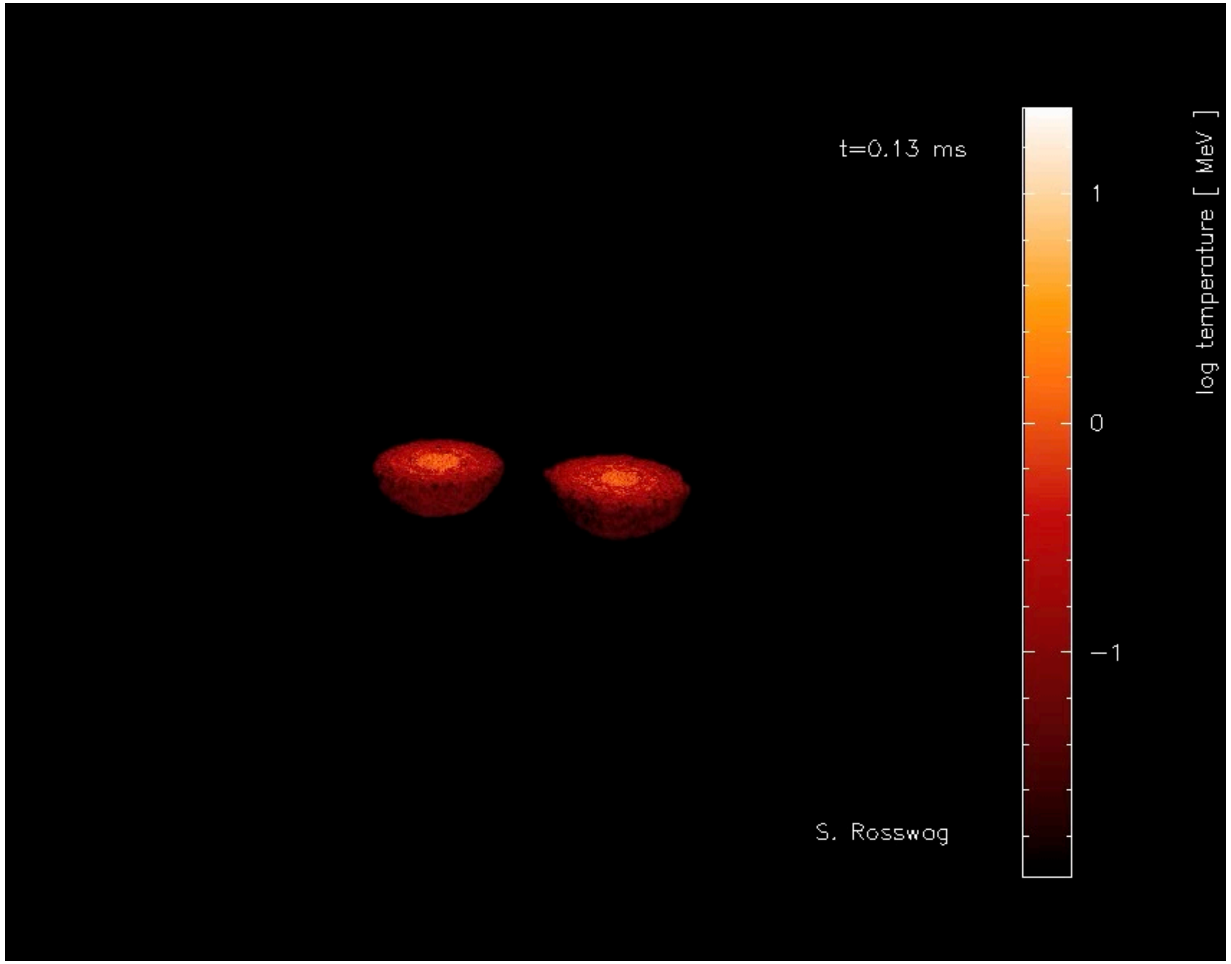


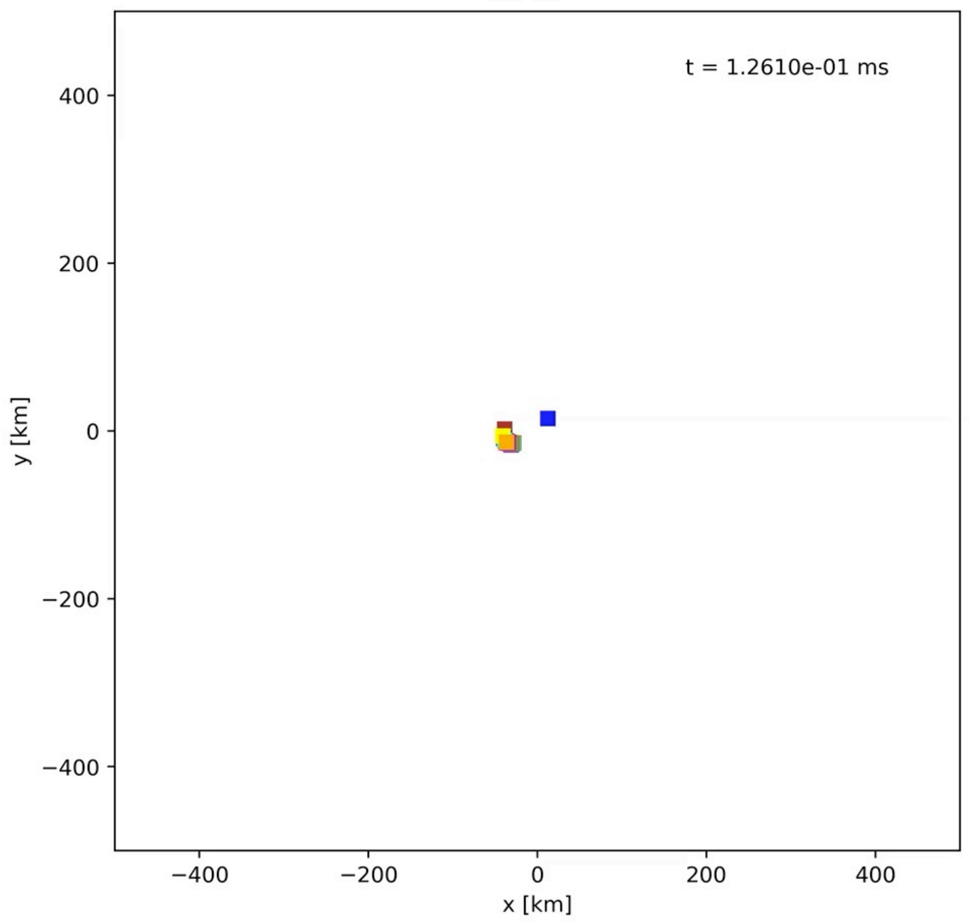


Movie by Vassh

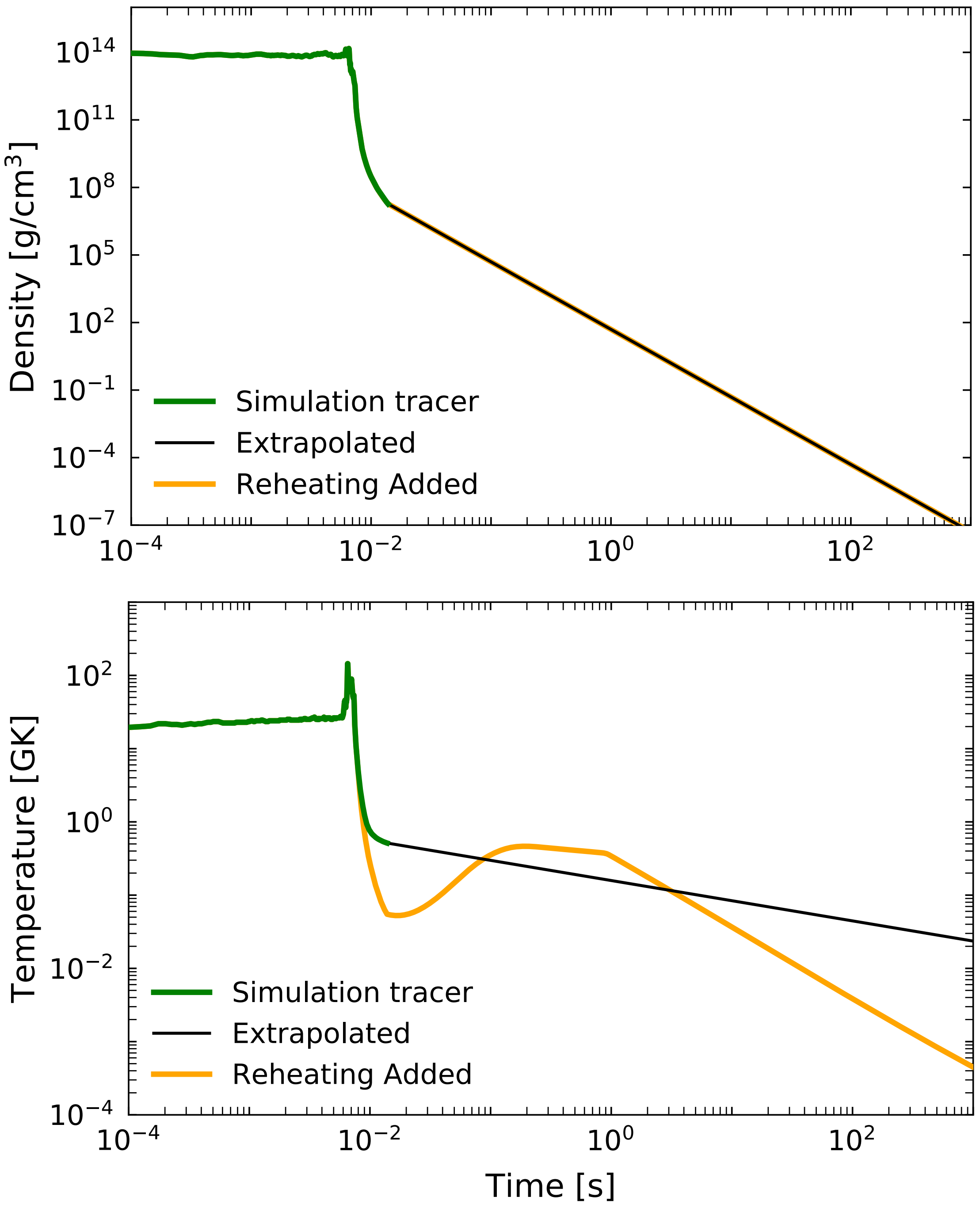
Using simulation tracers

Networks permit *r*-process calculations to account for the *time evolution of the temperature and density of a particular mass element in an astrophysical environment (aka trajectory)*





Using simulation tracers: Extrapolating trajectories and reheating



The density beyond the ~ms timescale considered in hydrodynamic simulations is typically extrapolated assuming "free expansion" (homologous expansion such that $r = vt$):

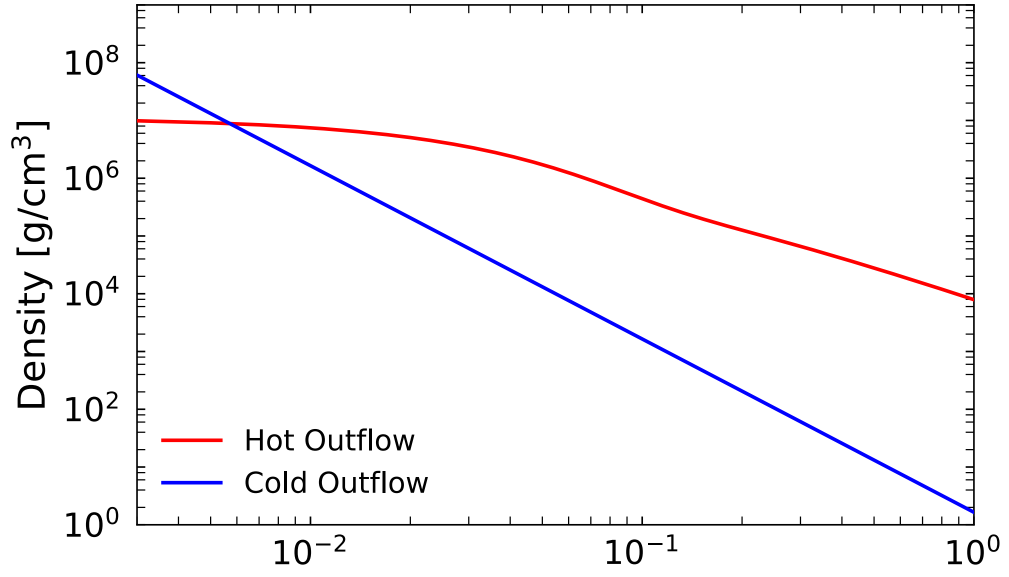
$$\rho(t) = \rho_0 \left(\frac{t}{t_0}\right)^{-3}$$

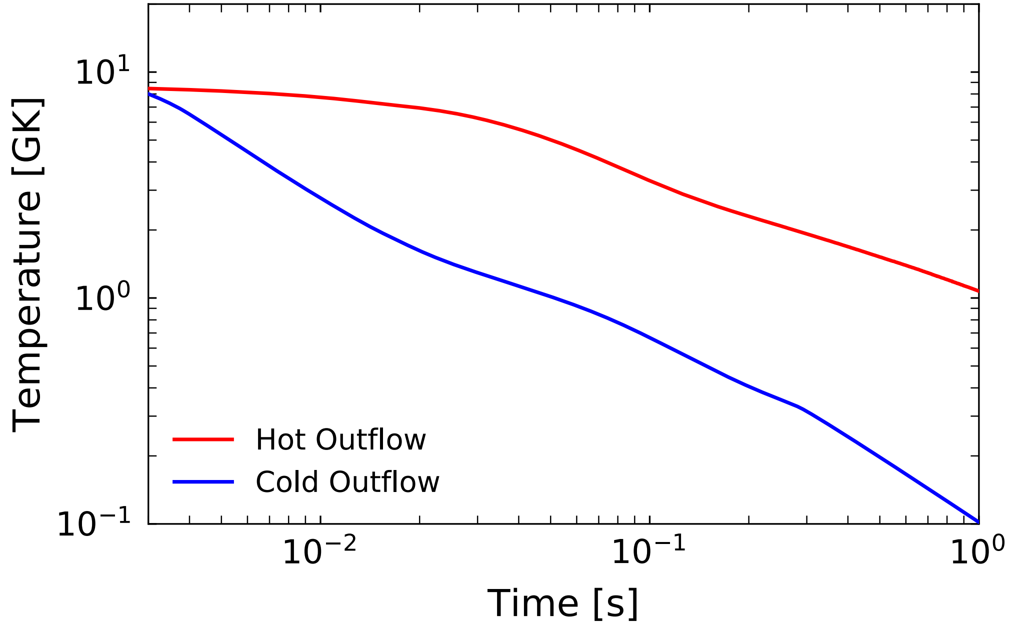
Given $\rho(t)$, the composition, and the entropy s_0, the change in entropy can be calculated via the nuclear equation of state (EOS) which is then linked to temperature $\left(\Delta s = \frac{\Delta Q}{T}\right)$ thus

$$T(t) = \mathrm{EOS}[s_0, \rho(t), \mathrm{Y}(t)]$$

This is called "reheating" or "self-heating" since the changes in the composition from nuclear reactions heat the system

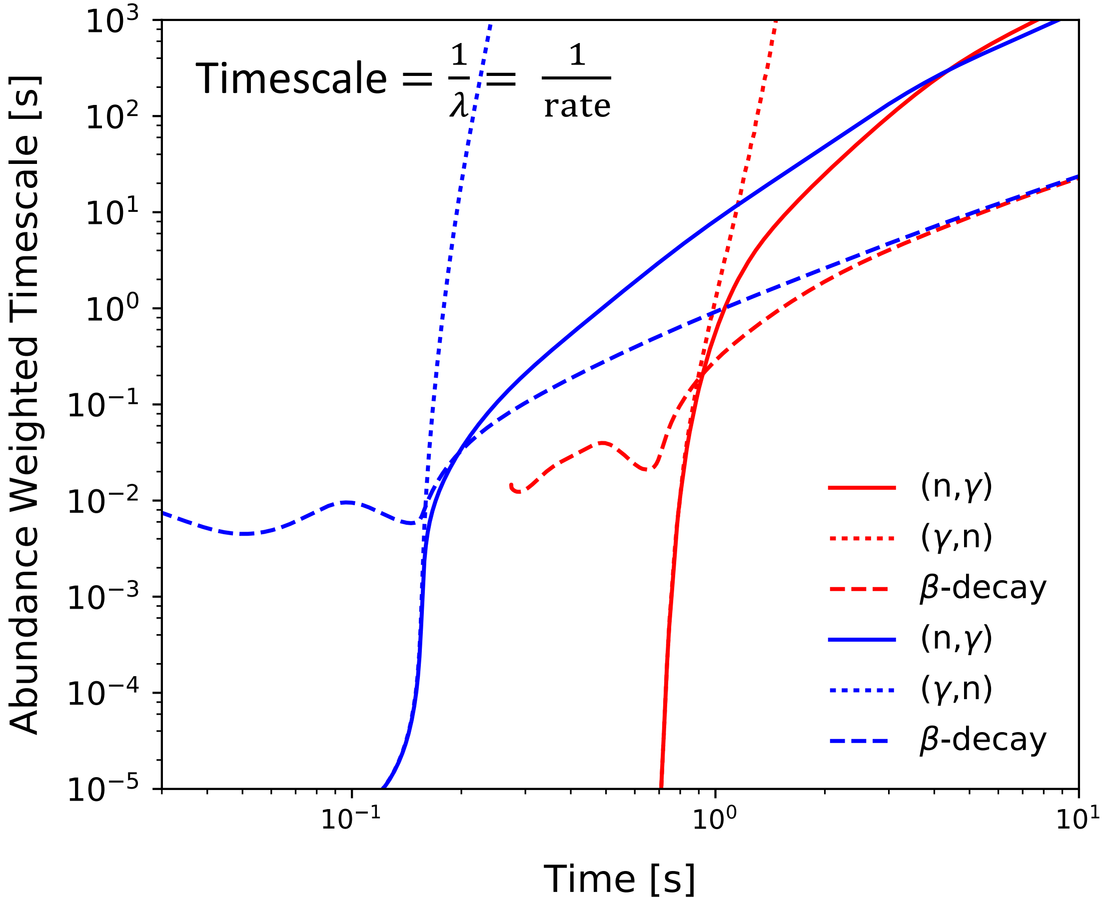
Introduction to timescales and *r*-process dynamics



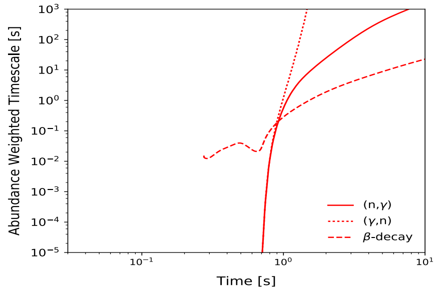


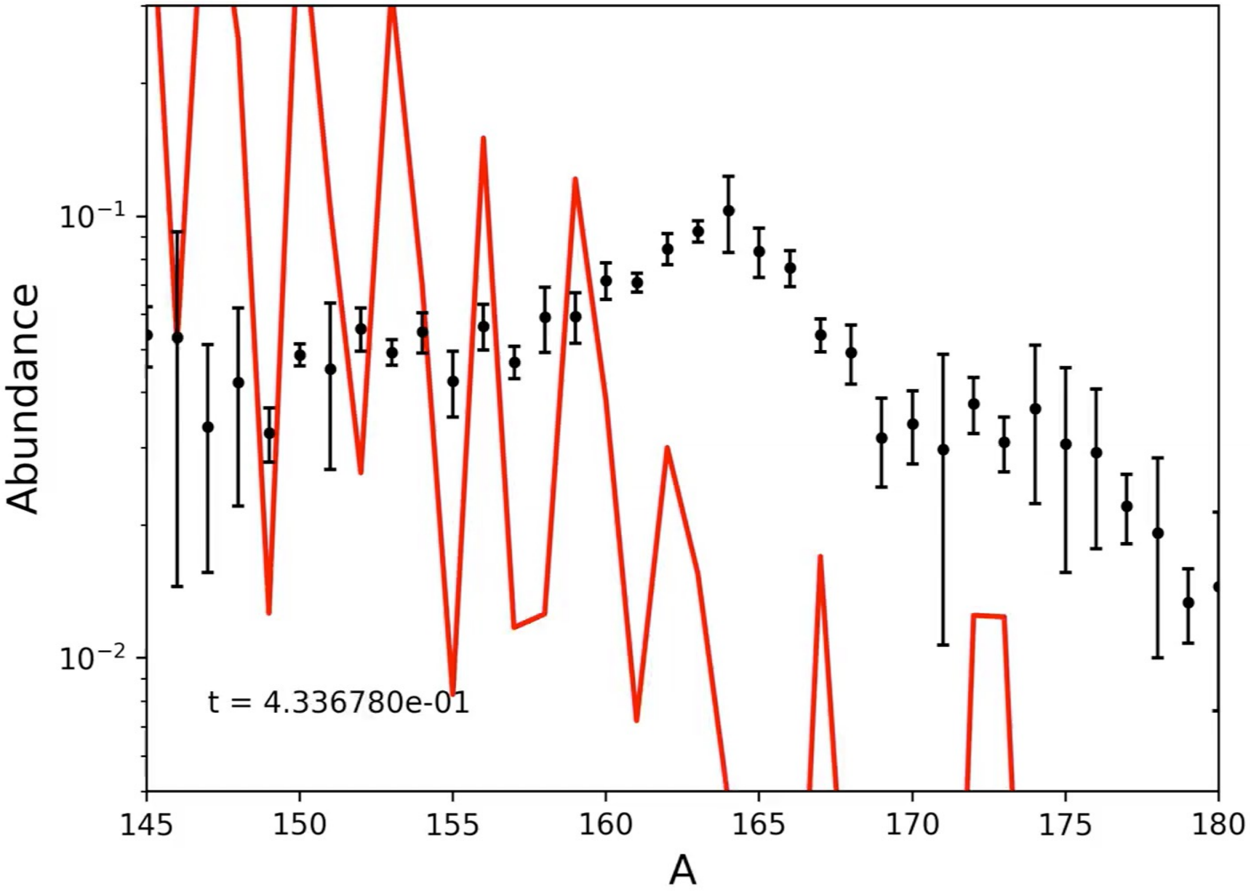
Consider two cases which both start n-rich (Y_e=0.2) but differ in their initial entropy (s/k=10 vs s/k=30) as well as their density evolution (τ=3 ms vs τ=70 ms with $\rho(t) \sim e^{-3t/\tau}$)

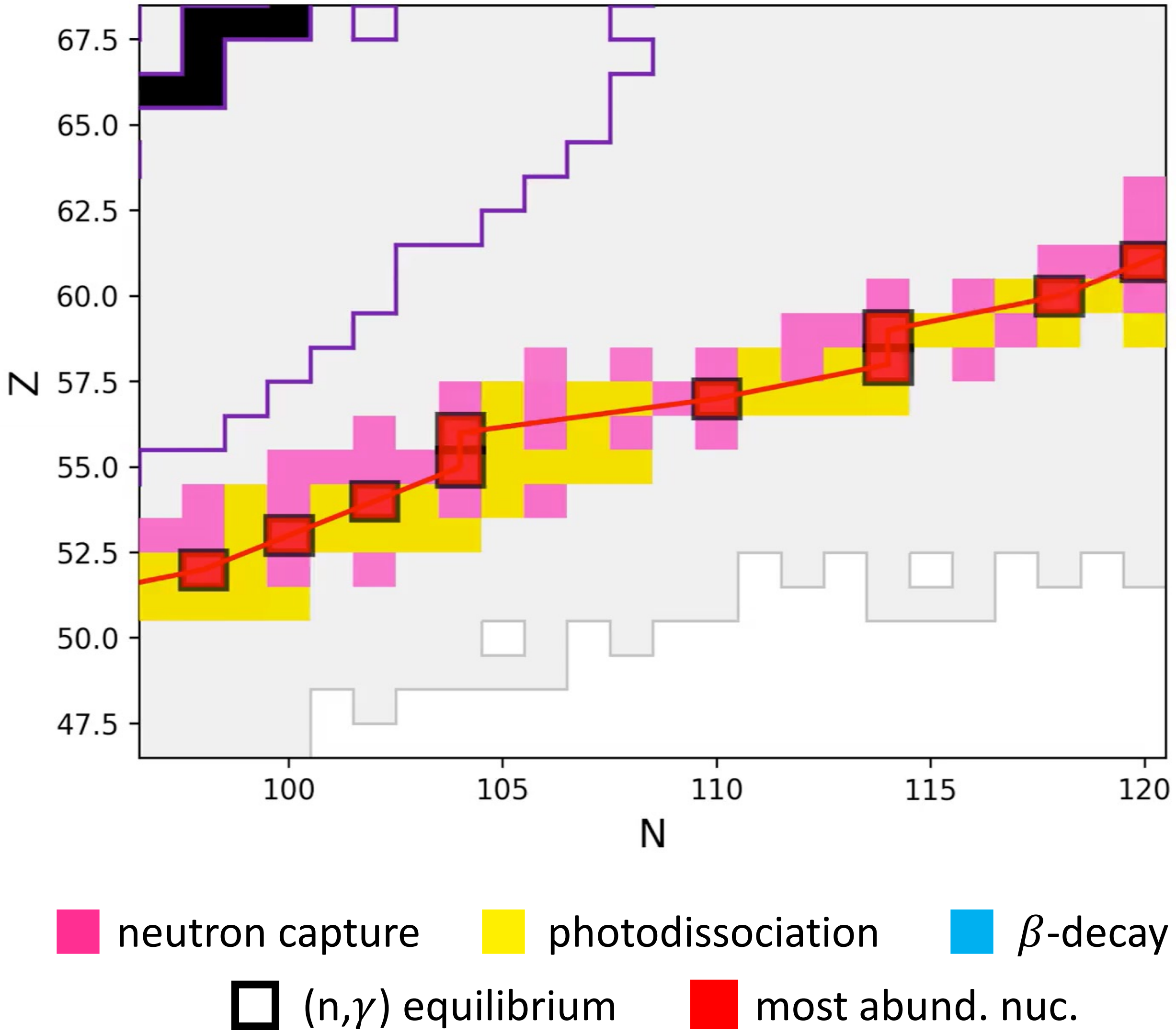
"Hot" dynamics: extended $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium
"Cold" dynamics: photodissociation falls out early



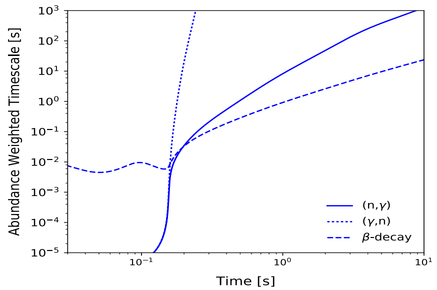
Dynamics of a “hot” r process with an extended $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium

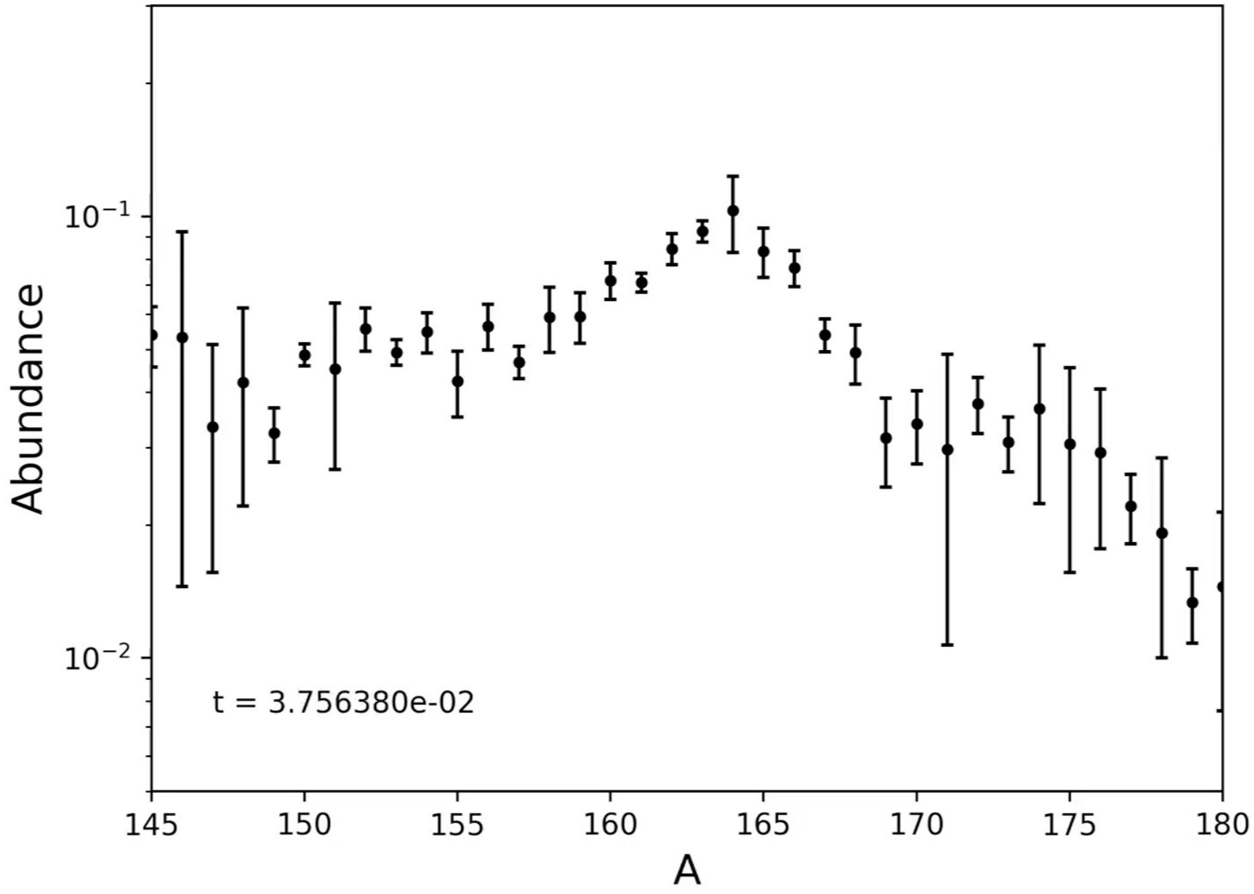


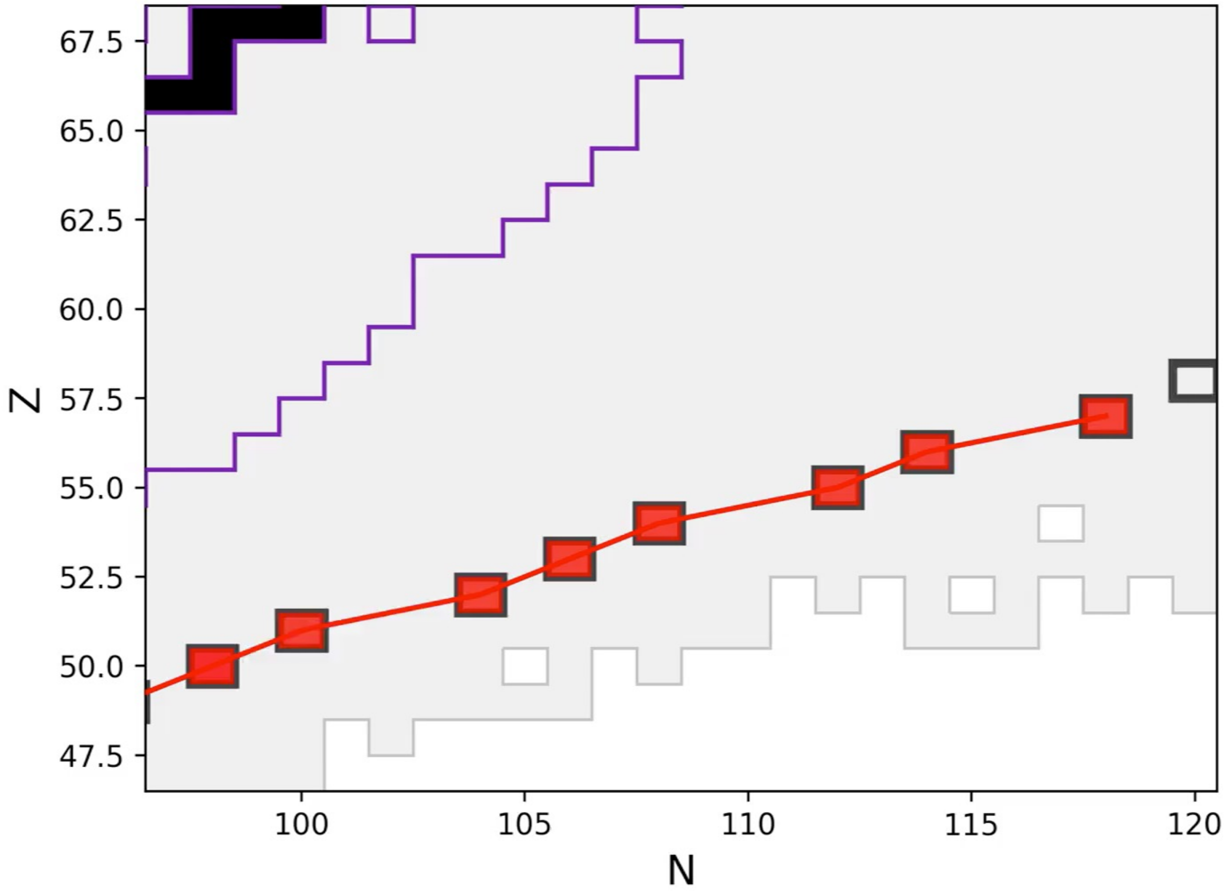




Dynamics of a "cold" *r* process where photodissociation falls out early







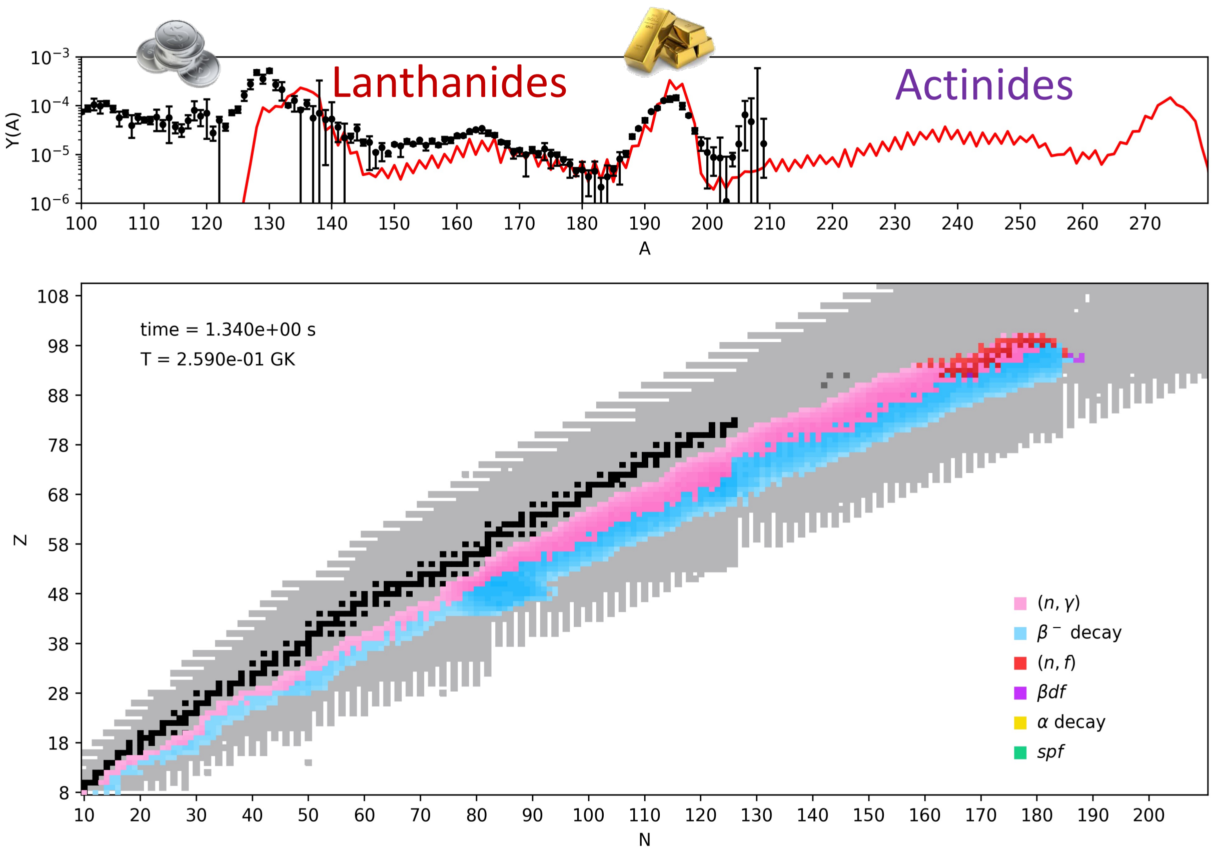
neutron capture photodissociation β-decay

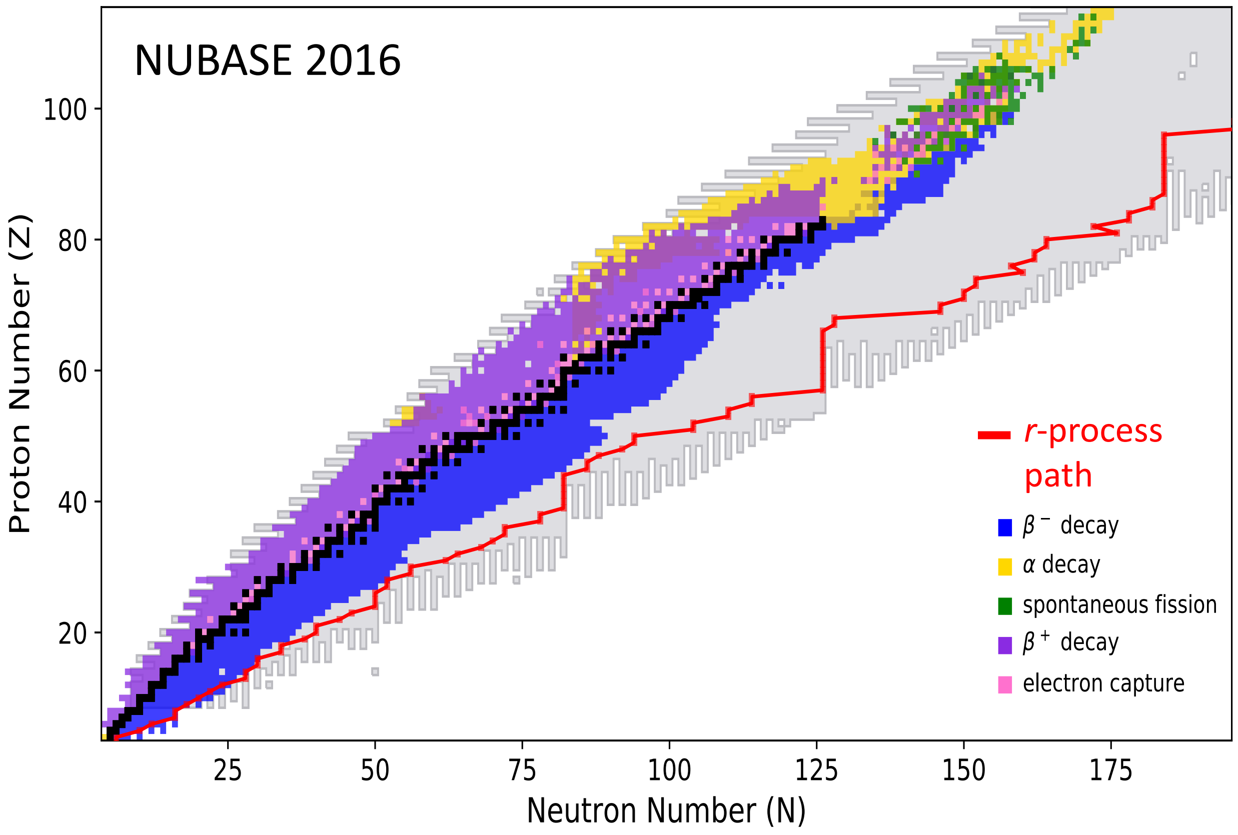
(n,γ) equilibrium most abund. nuc.

Outline

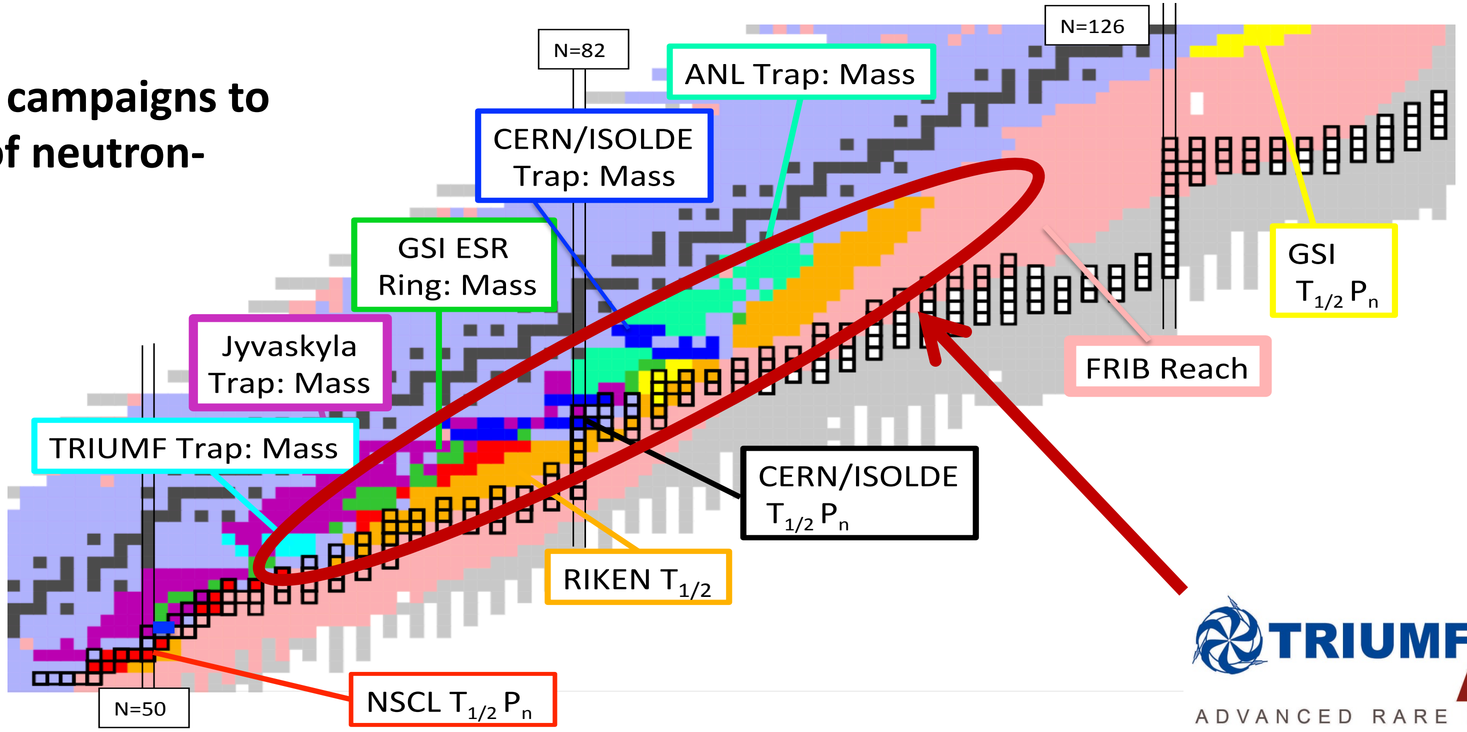
- Observational evidence that the *r* process occurs [4-9]
- Discussion of astrophysical sites (history (CCSNe), candidate sites, MHD SNe, NSNS/NSBH) [11-21]
- Spotlight on GW170817 and AT2017gfo: the first multi-messenger NSNS event [23-33]
- *r*-process calculations (intro to reaction rates and equilibrium, history (classical *r* process), intro to using networks and trajectories, *r*-process dynamics) [35-52]
- The fundamental role of nuclear physics [54-82]

Nuclei synthesized by the *r* process compared to experimentally studied species



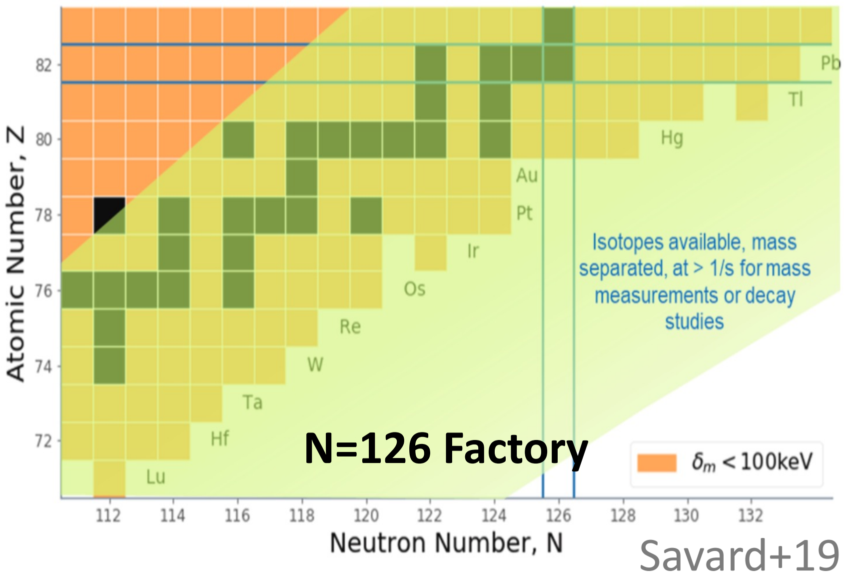


Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives,
reaction rates…

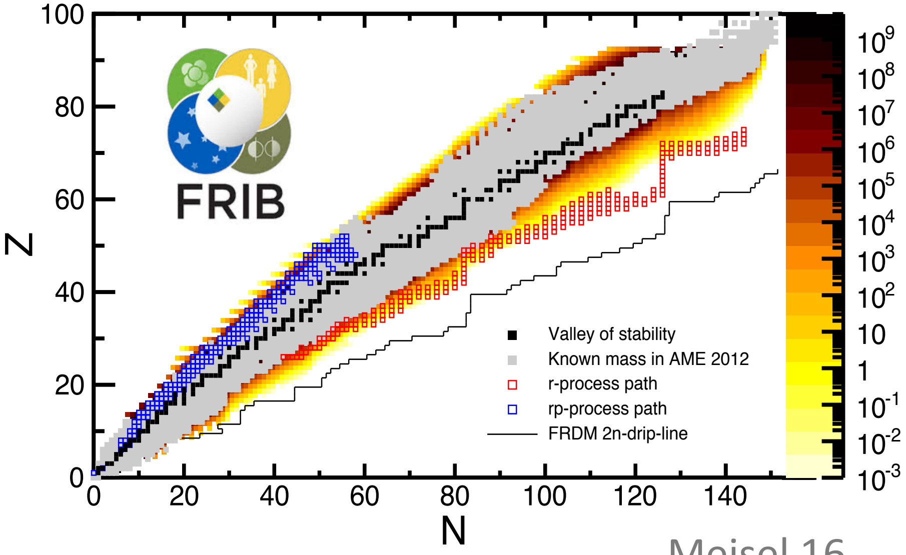


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

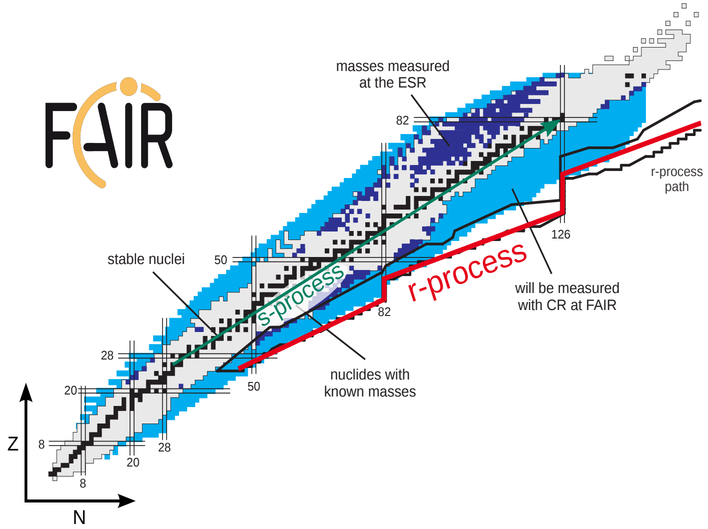
Horowitz+18



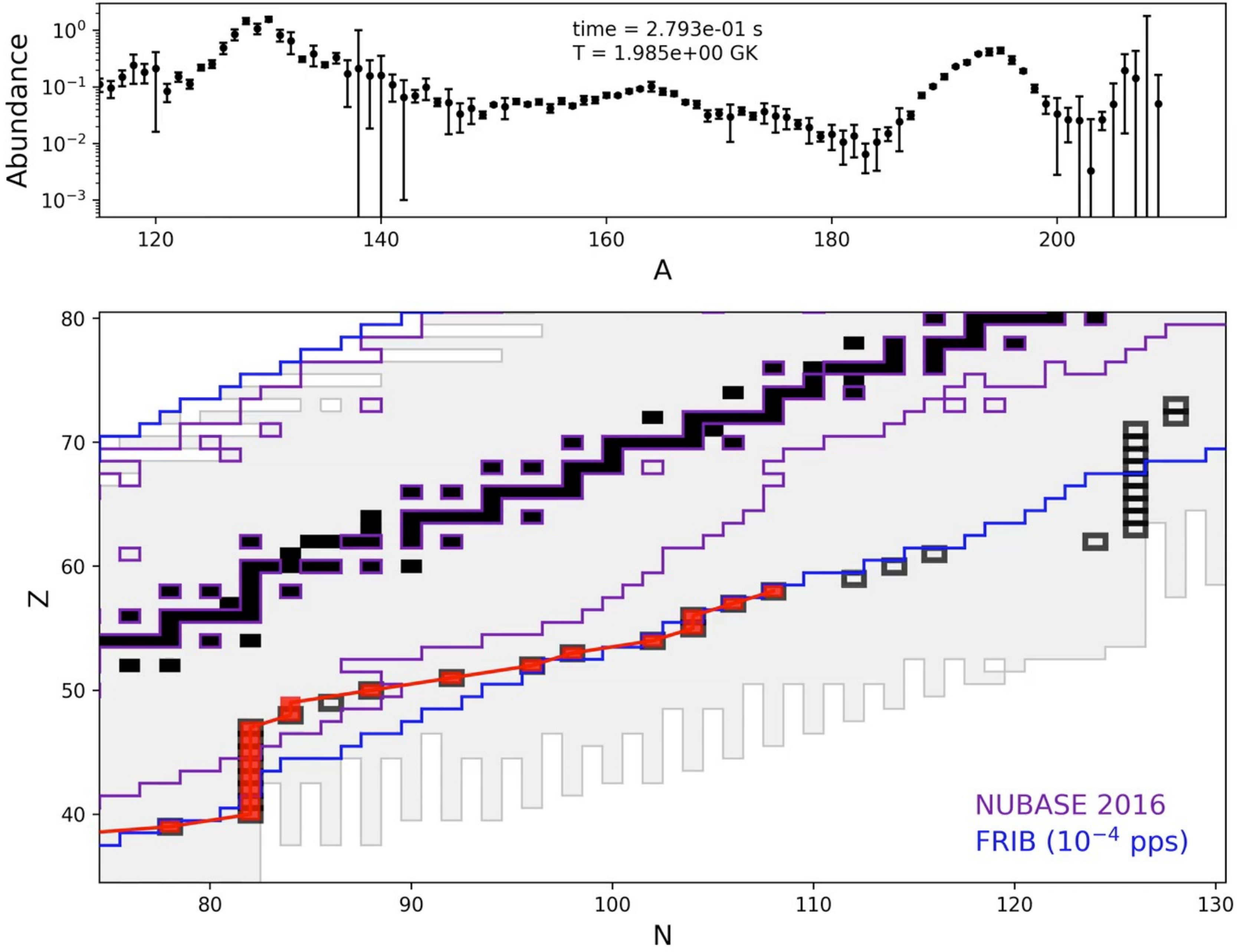
Savard+19



Meisel 16



Future experiment meets the *r*-process path

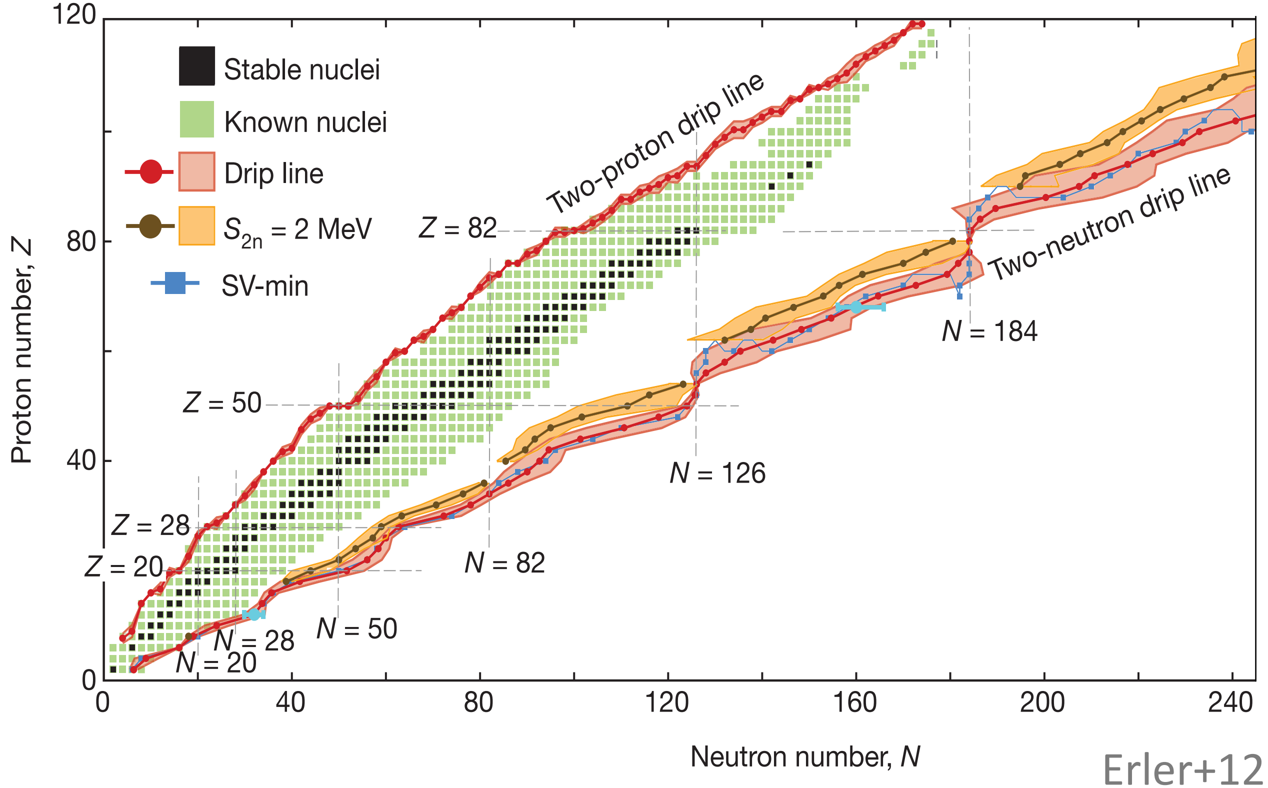


*reach of future experiment in key regions impacting the evolution of abundances (note moderately n-rich conditions used here)

Movie by N. Vassh

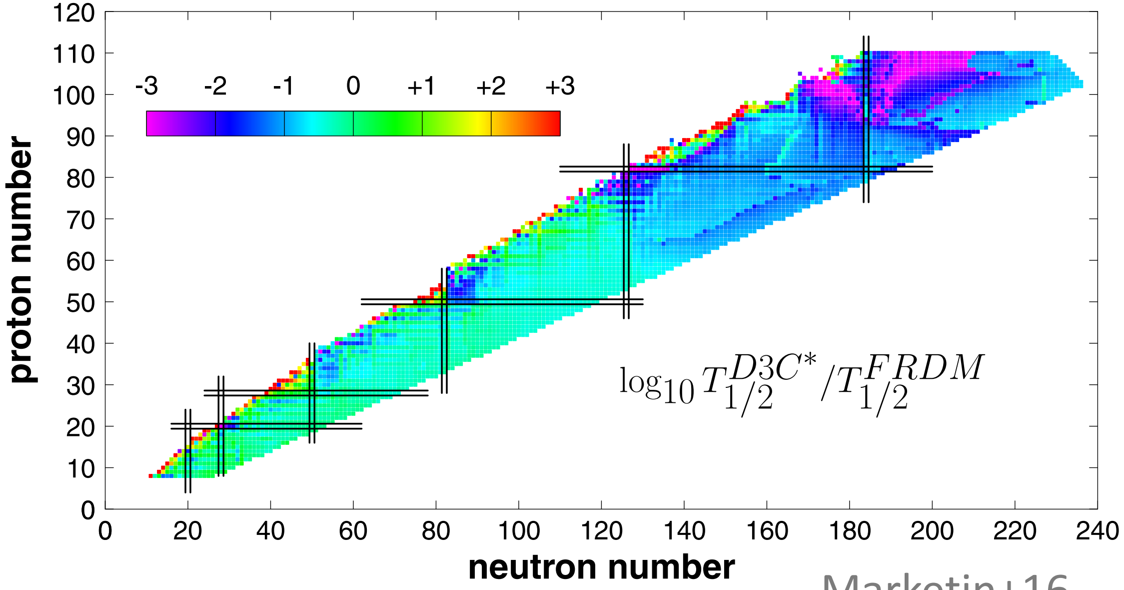
Theory developments:
Structure theory (masses, deformation, level densities…), reaction theory (capture cross sections…), fission yields and rates, and β-decay rates….

Modeling masses all the way to the dripline



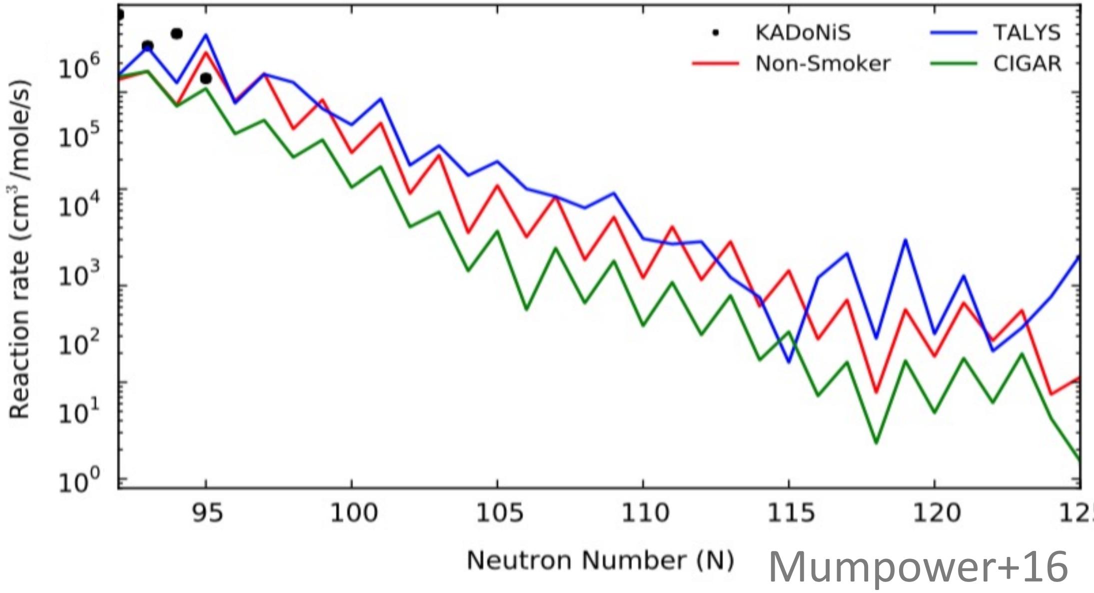
Erler+12

β-decay calculations



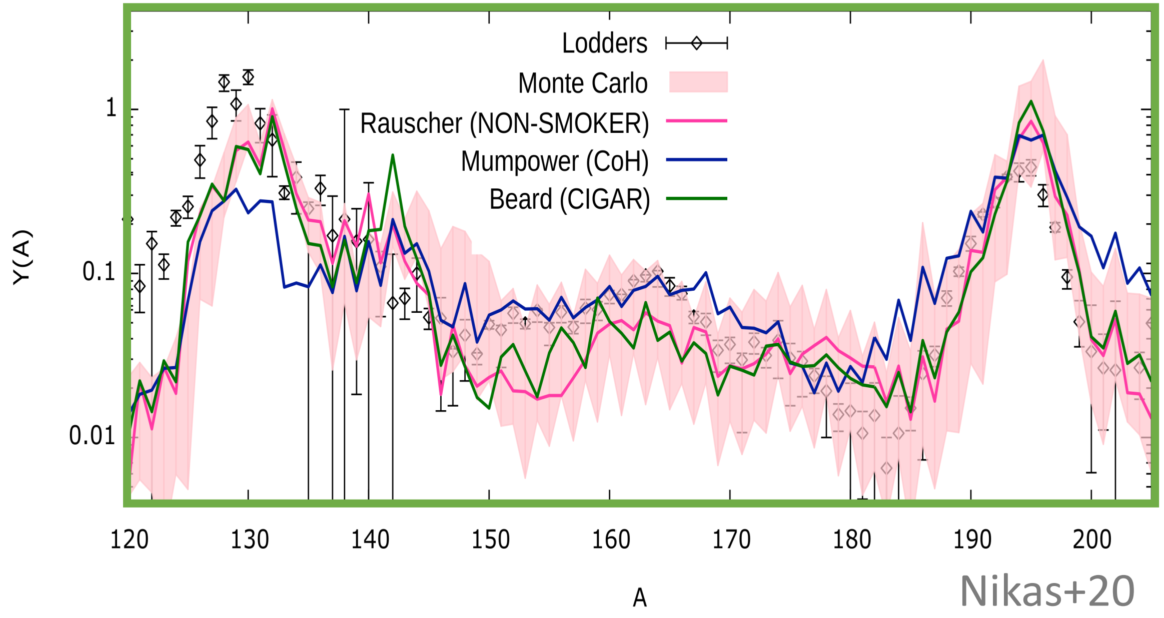
Marketin+16

Neutron capture models

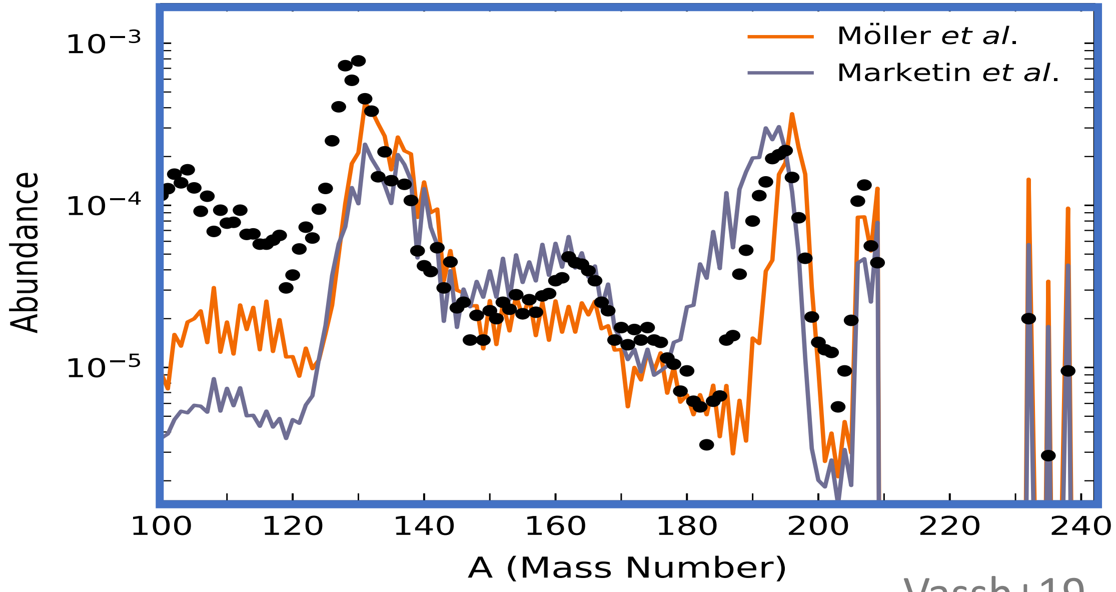


Mumpower+16

Sensitivity of *r*-process abundances to neutron capture and β-decay

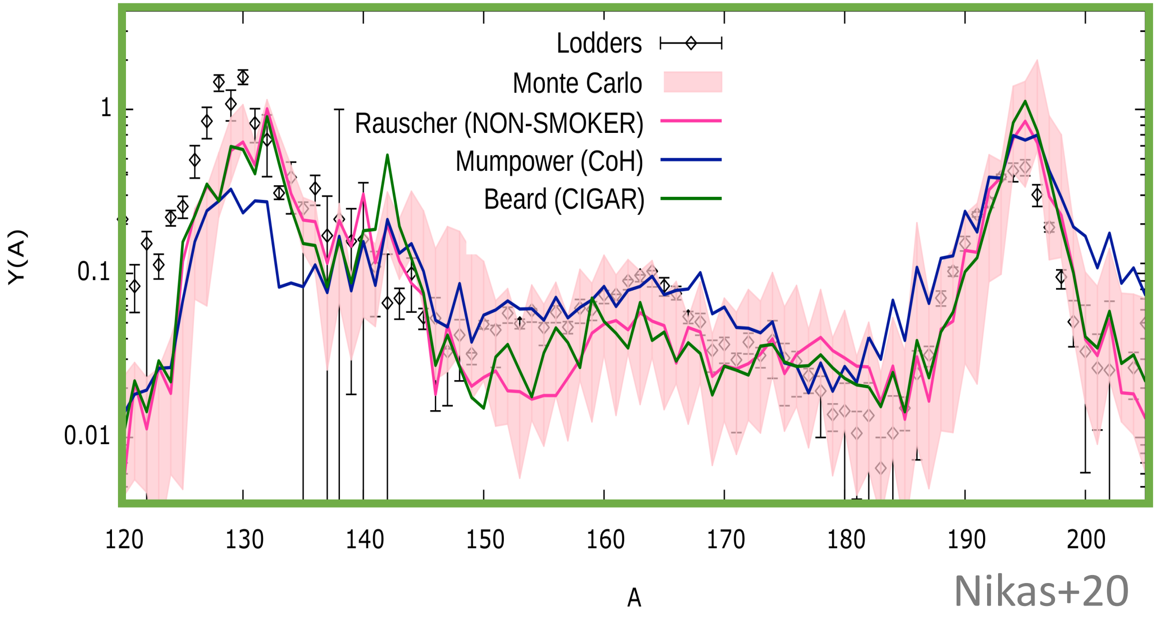


Nikas+20

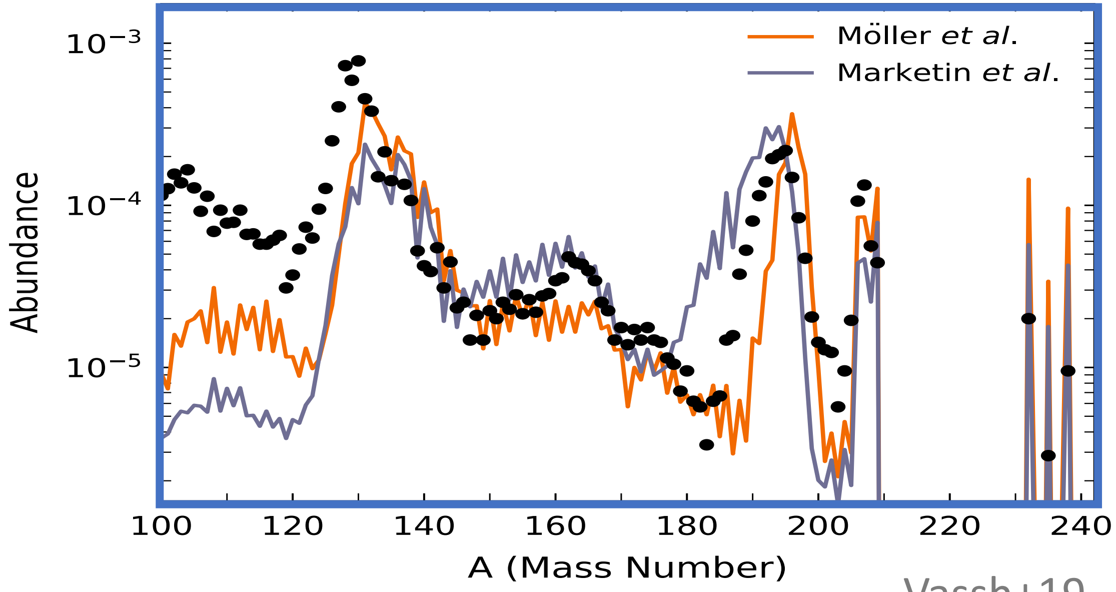


Vassh+19

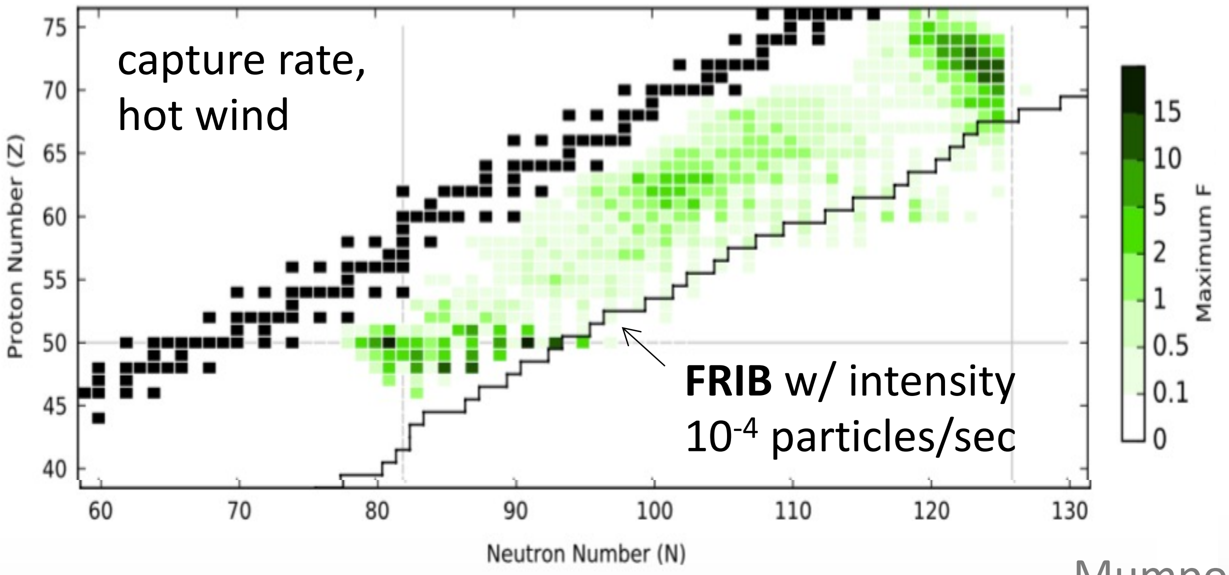
Sensitivity of *r*-process abundances to neutron capture and β-decay

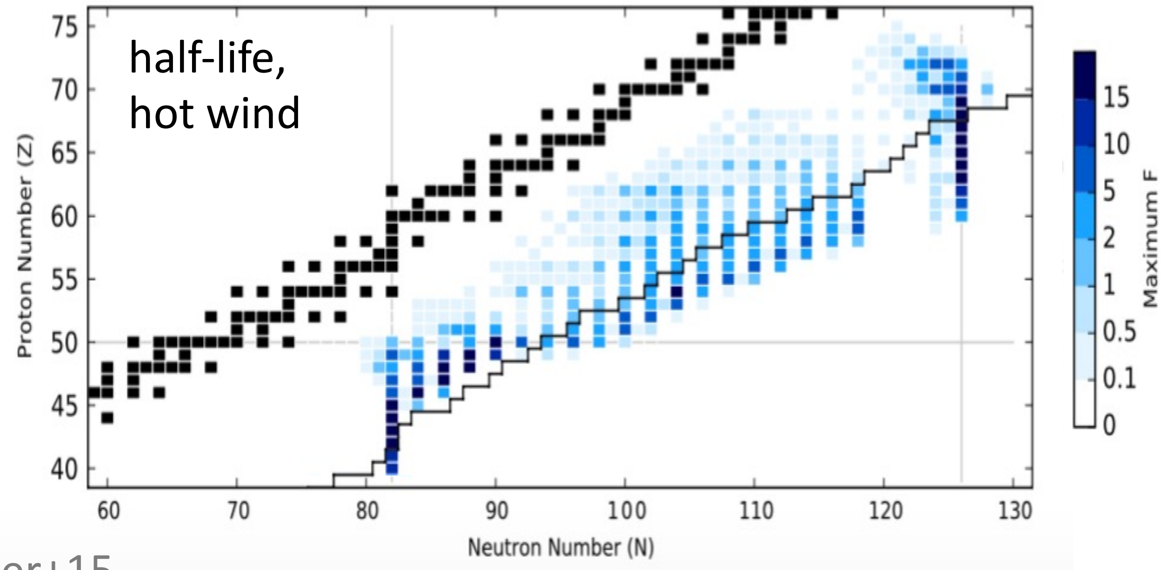


Nikas+20



Vassh+19





Mumpower+15

Spotlight on the impact of nuclear masses

Masses determine key quantities that go into calculating capture and decay rates; for instance:

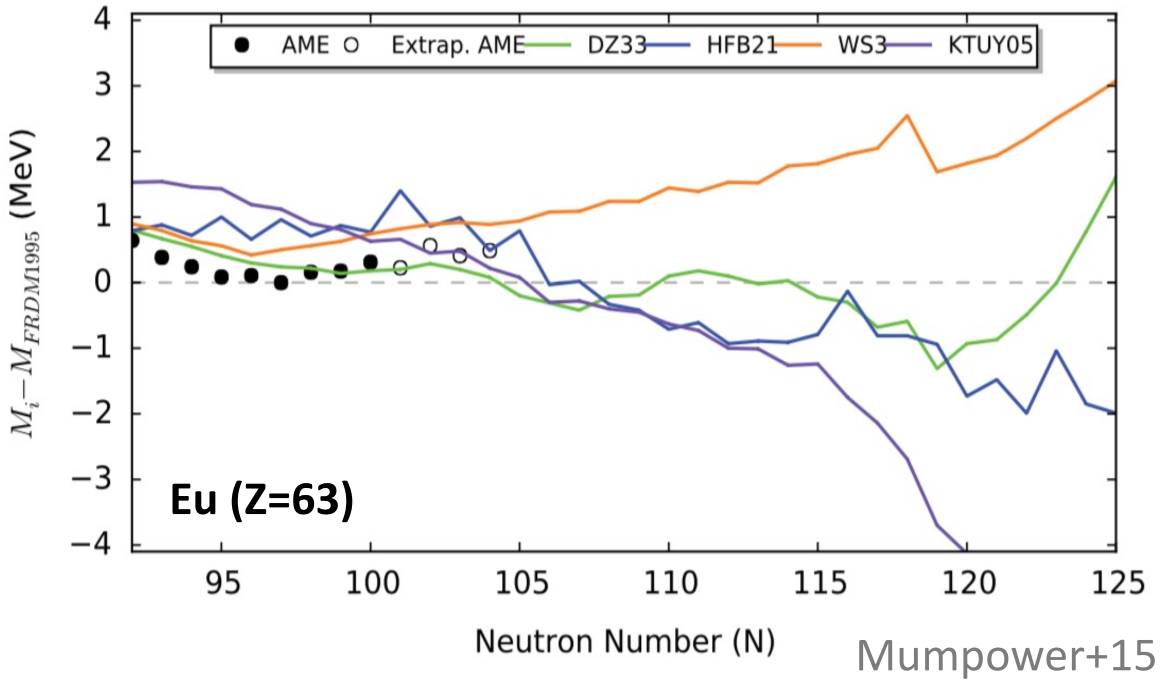
r-process calculations should use datasets which *self-consistently* assume the same nuclear masses, but this isn't always done since availability of theory data in the n-rich regions is limited

Neutron capture rates depend on

$$S_n(Z, A+1) = M_{Z,A} + M_n - M_{Z,A+1}$$

β⁻-decay rates depend on

$$Q_{\beta^-} = \left(M_{\text{parent}} - M_{\text{daughter}}\right)c^2$$



Mumpower+15

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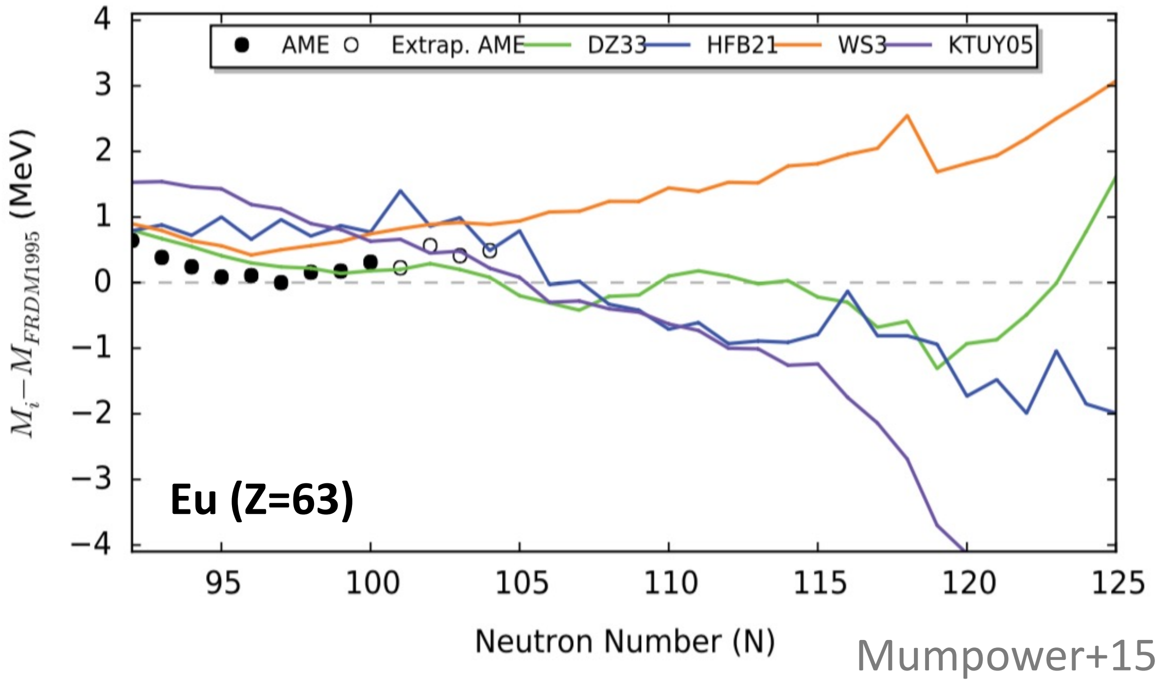
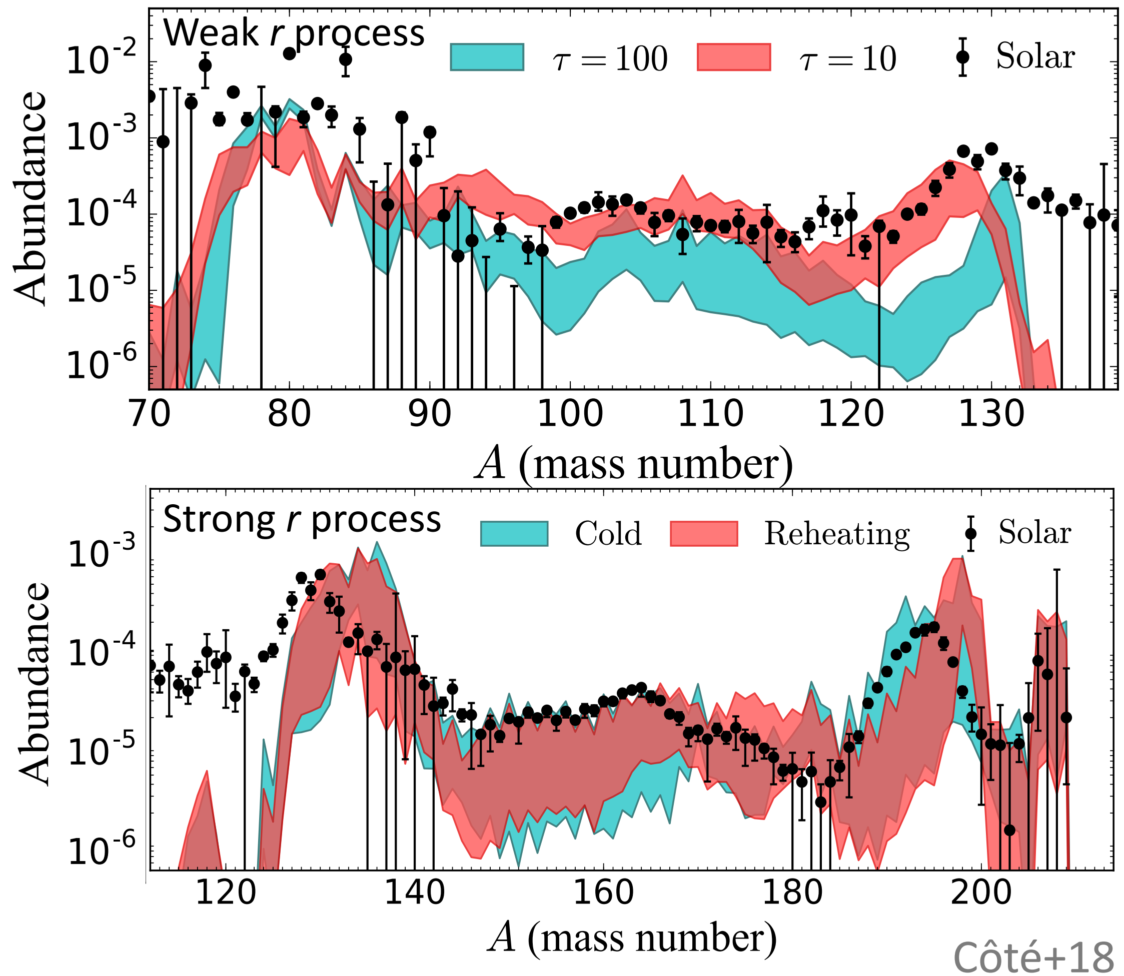


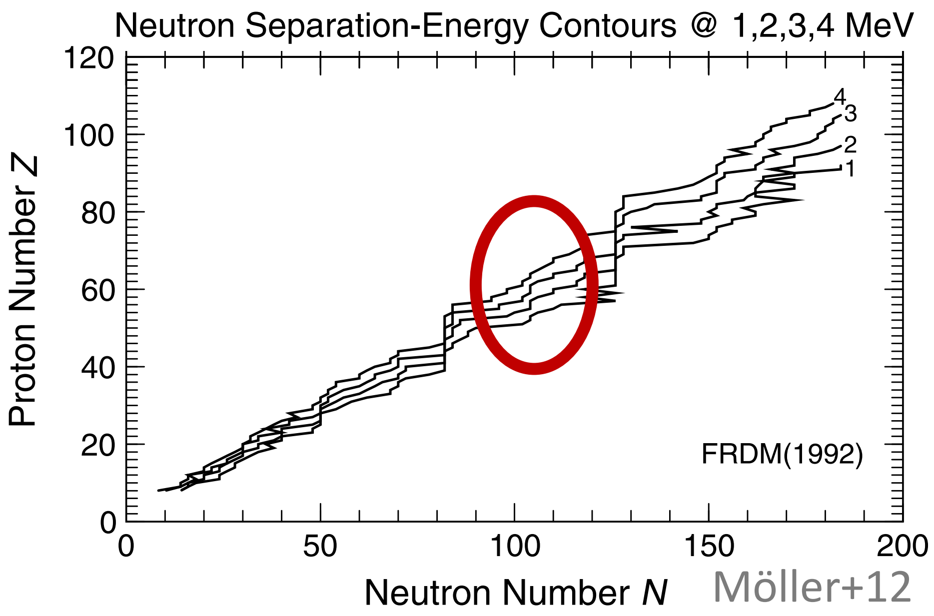
Mumpower+15

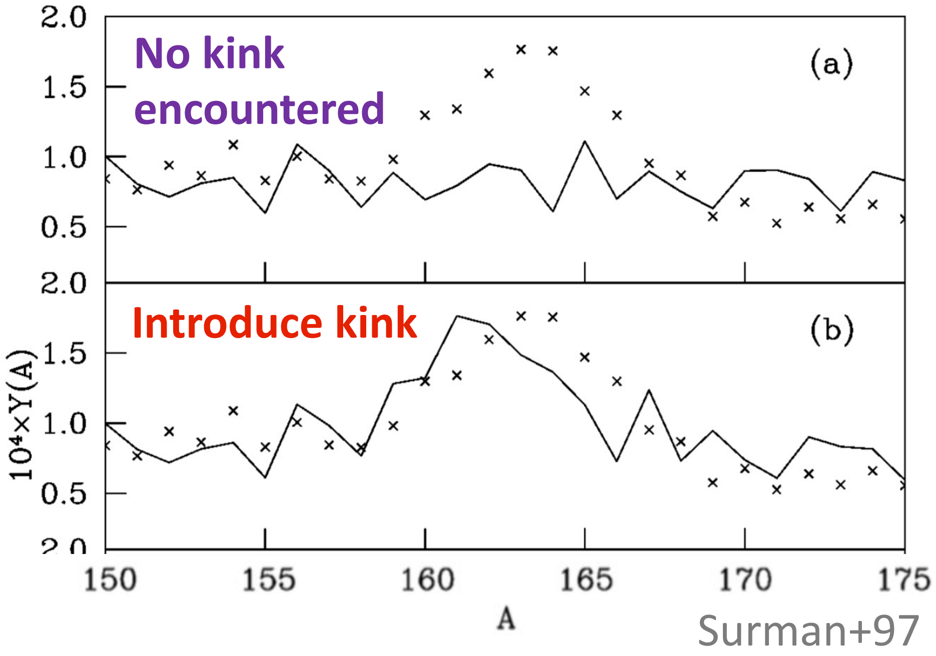
Abundance range from 10 mass models



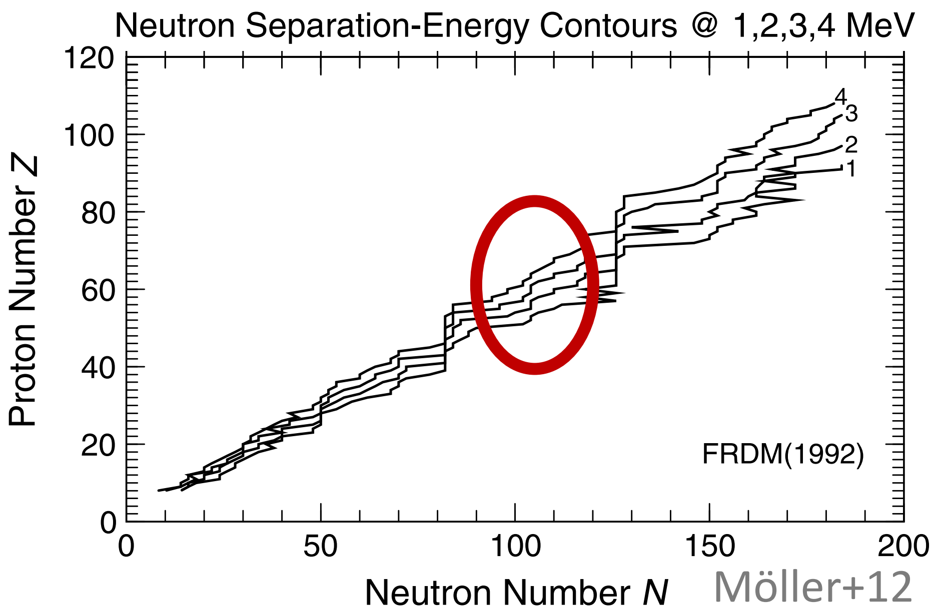
Côté+18

The rare-earth peak and nuclear structure

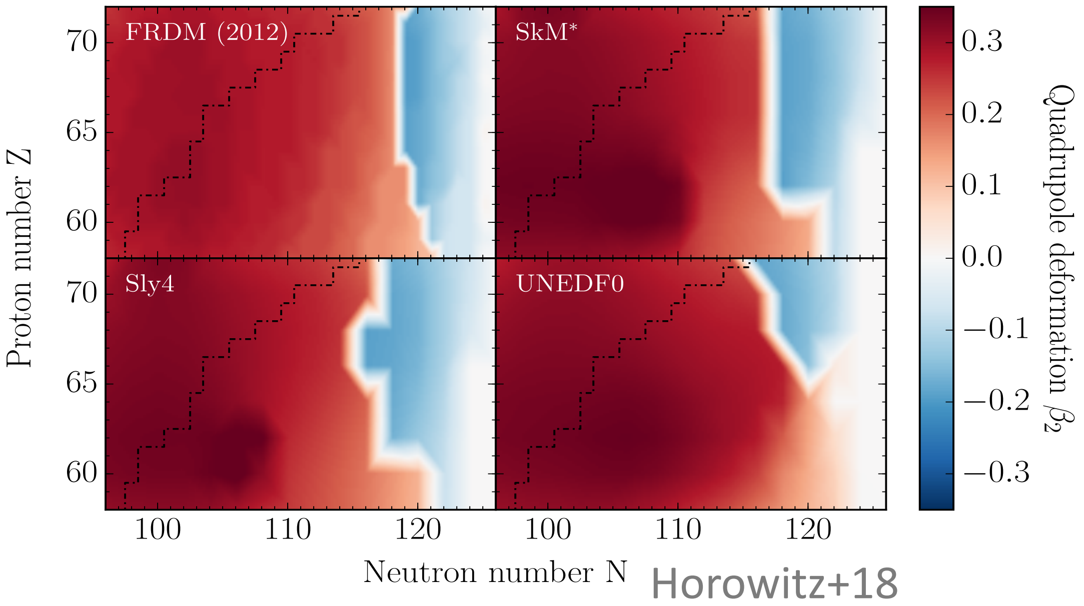


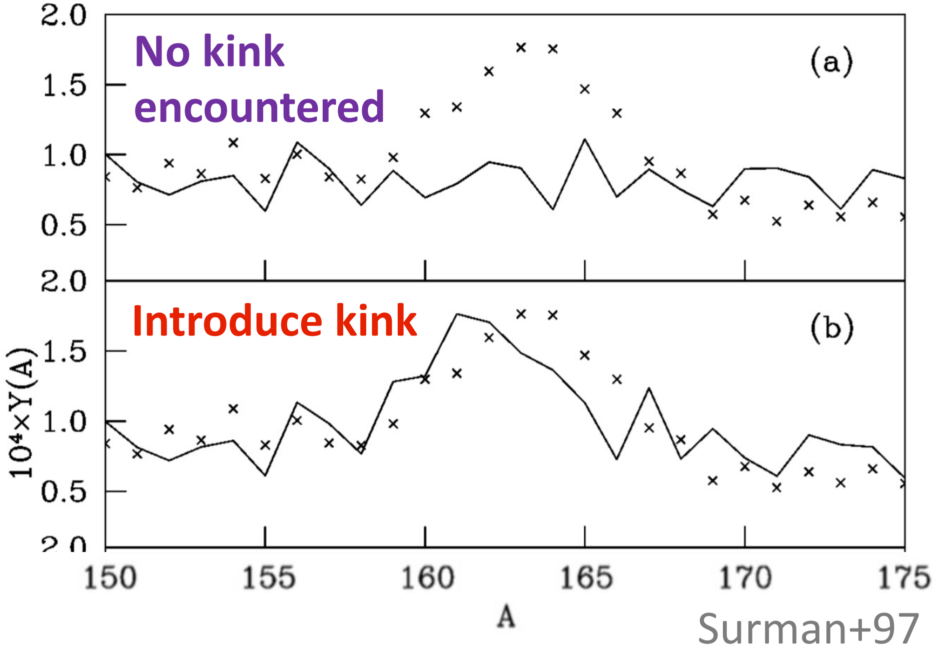


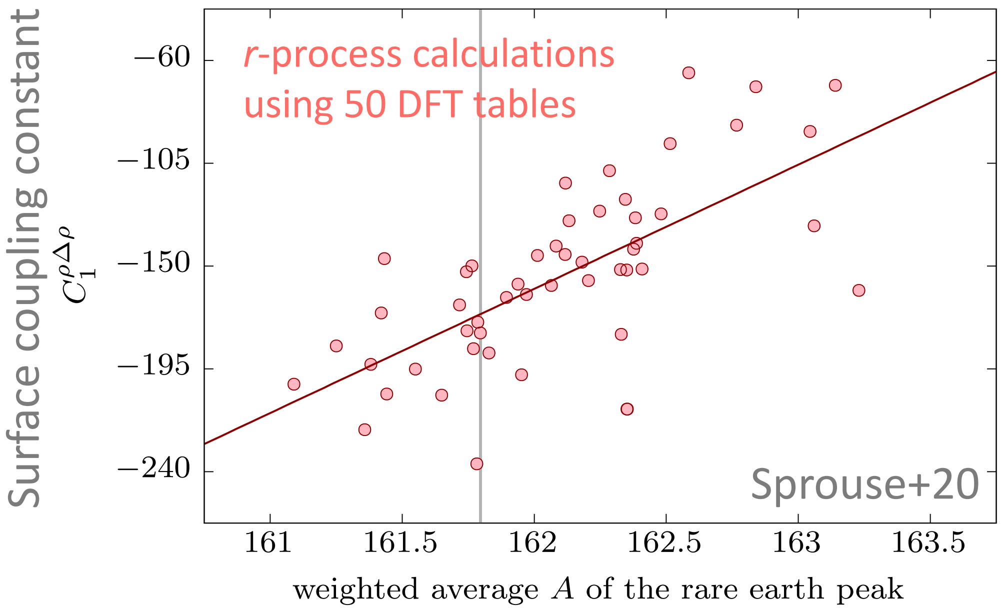
The rare-earth peak and nuclear structure



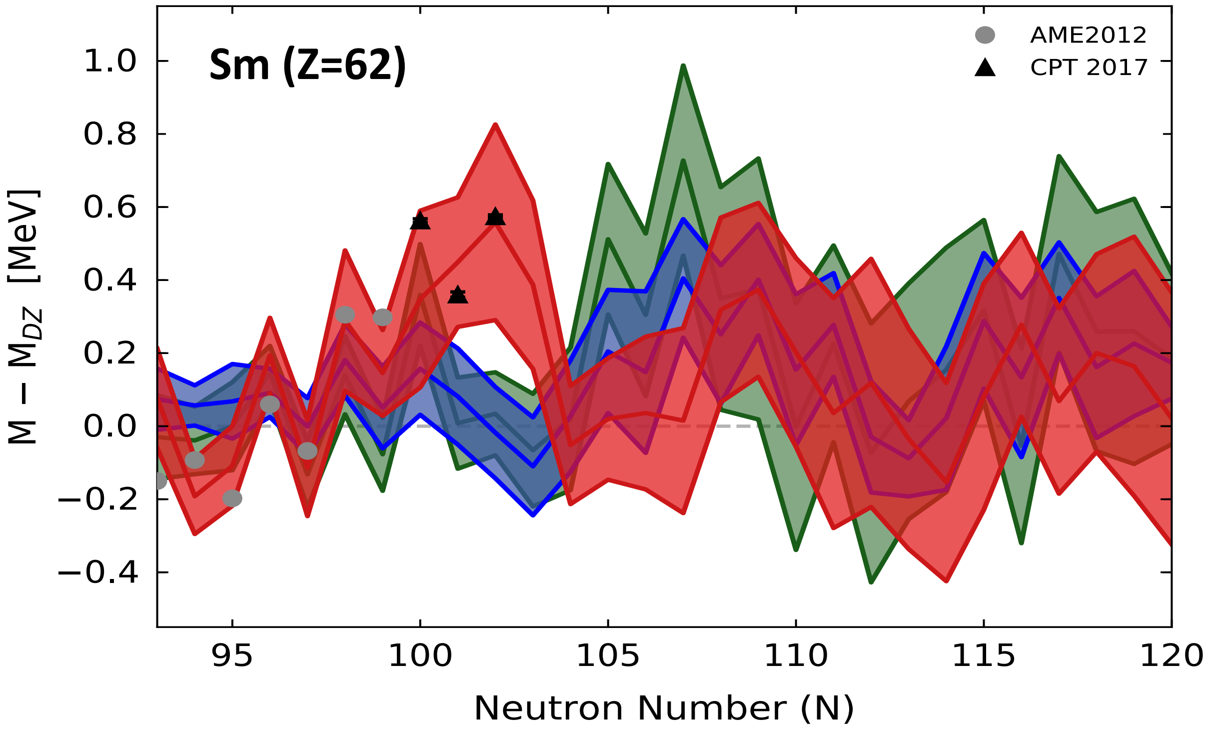
Droplet model compared to density functional theory







Markov Chain Monte Carlo calculations: finding the masses capable of forming the peak in *distinct* outflows

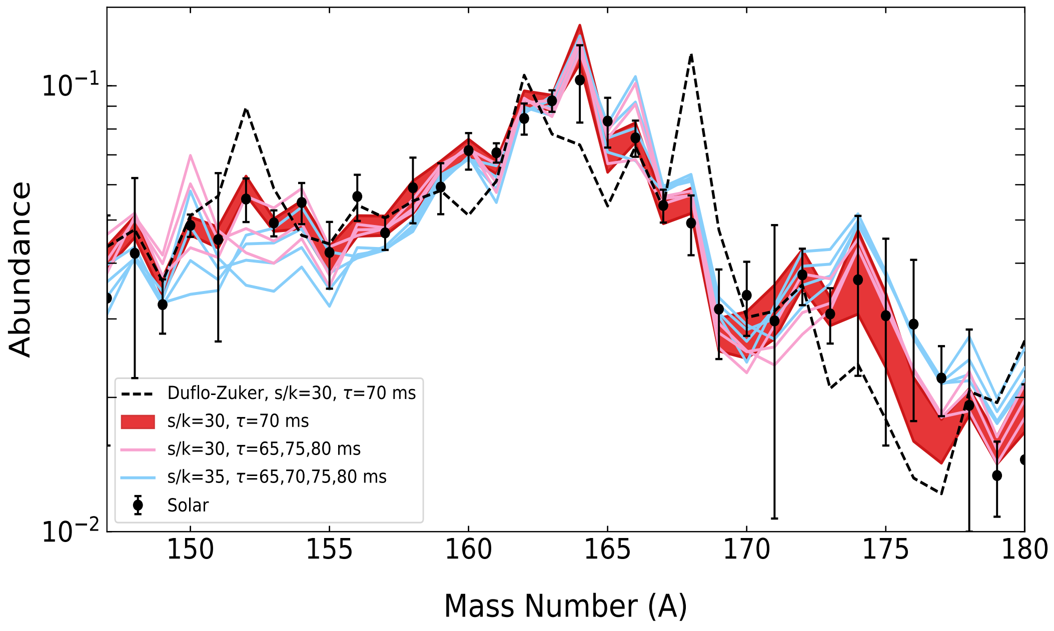


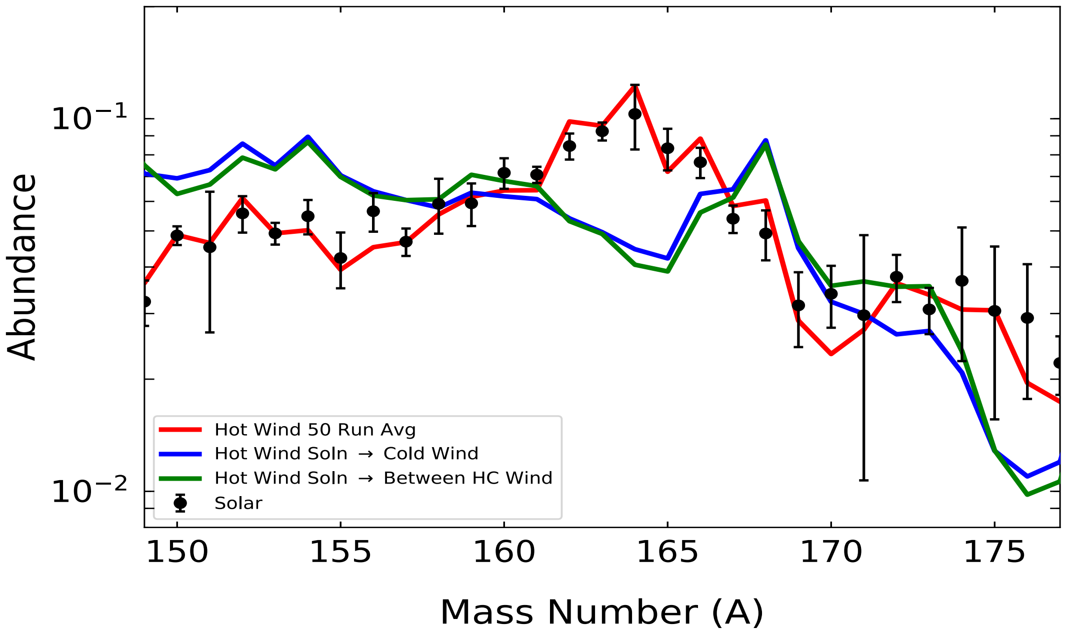
Neutron star merger accretion disk winds with:

Hot = extended (n,γ)⇆(γ,n) equilibrium

Cold = photodissociation falls out early

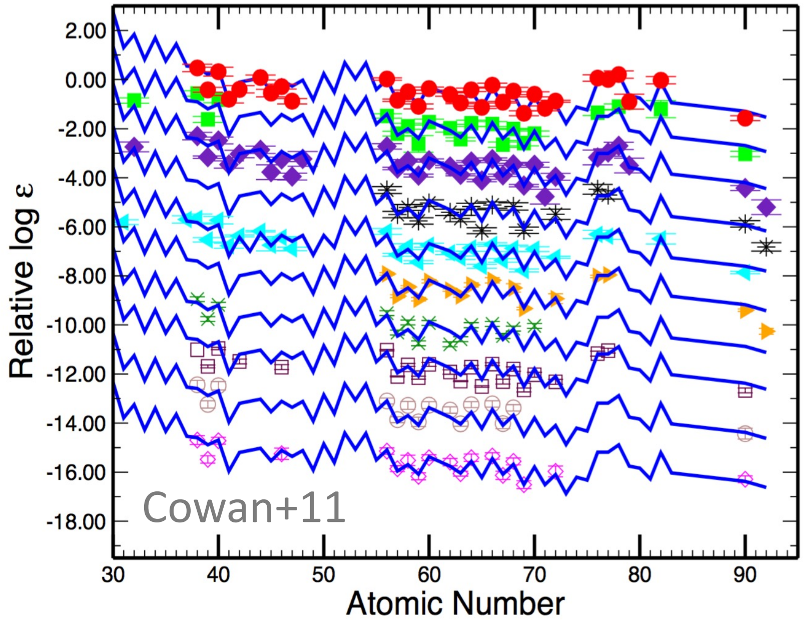
Vassh+21, Orford,Vassh+18

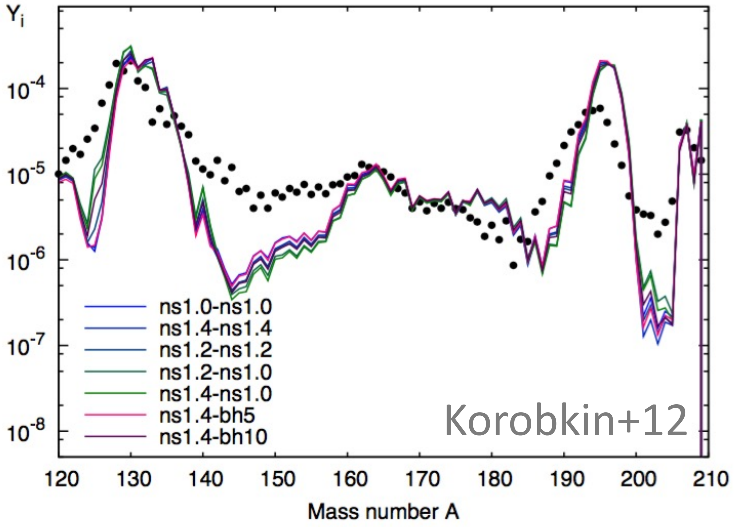


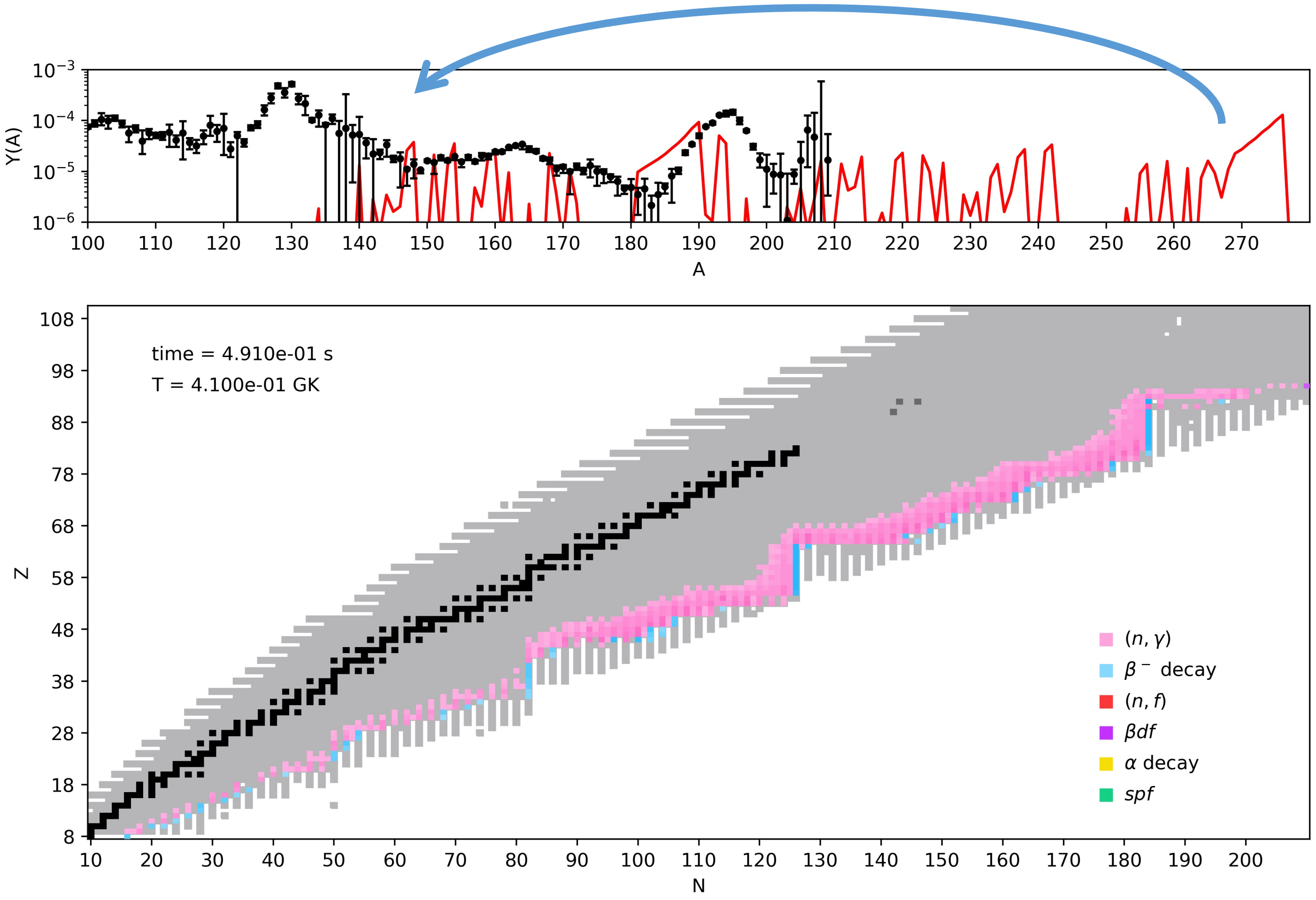


Fission cycling to explain observed robustness of lanthanide abundances?

10 *r*-process rich halo stars compared to Solar







NSM dynamical ejecta using Rosswog+13 simulation conditions
(very neutron-rich with robust fission)

Nuclear Fission (in Astrophysics)

Incident neutron strikes

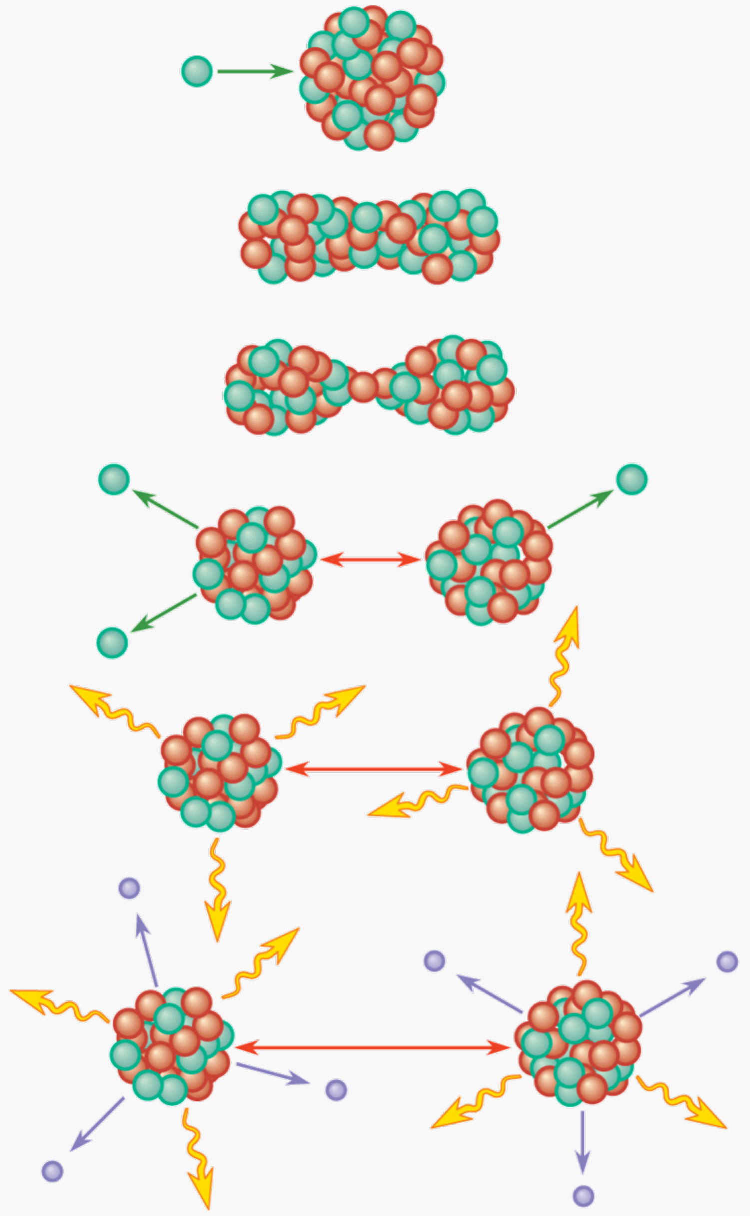
Deformation

Scission

Prompt Neutron Emission from excited fission fragments (~2-3)

Energy release ~200 MeV with kinetic energy of fragments ~170 MeV

Delayed emission from β-decay of neutron-rich fission products



Neutrons Protons Beta particles Gamma rays

Nuclear Fission (in Astrophysics)

Incident neutron strikes

Deformation

Scission

Prompt Neutron Emission from excited fission fragments (~2-3)

Energy release ~200 MeV with kinetic energy of fragments ~170 MeV

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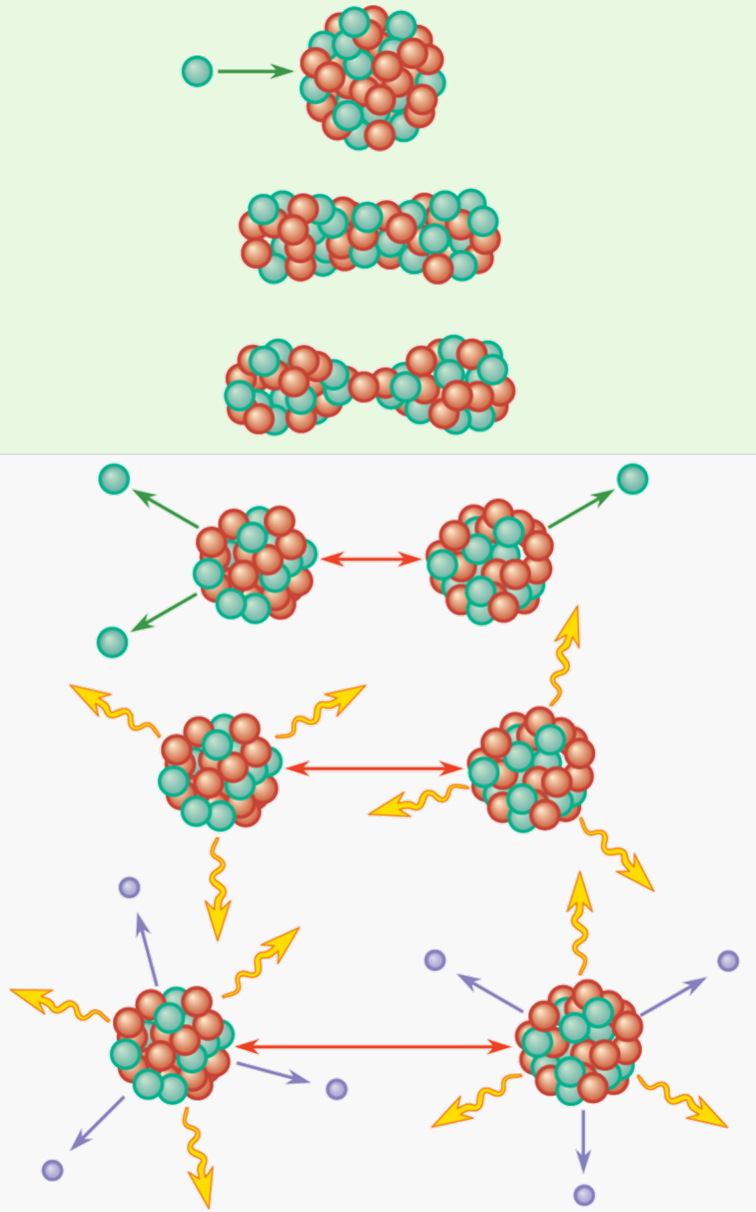
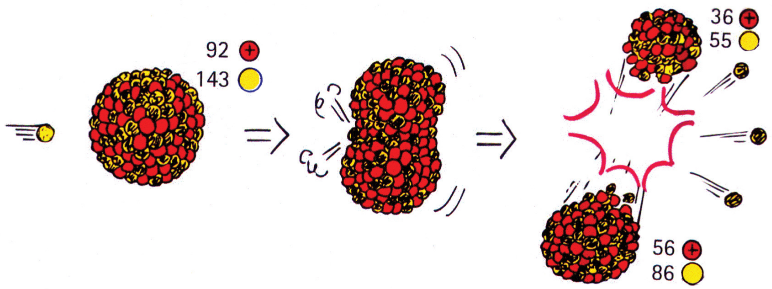
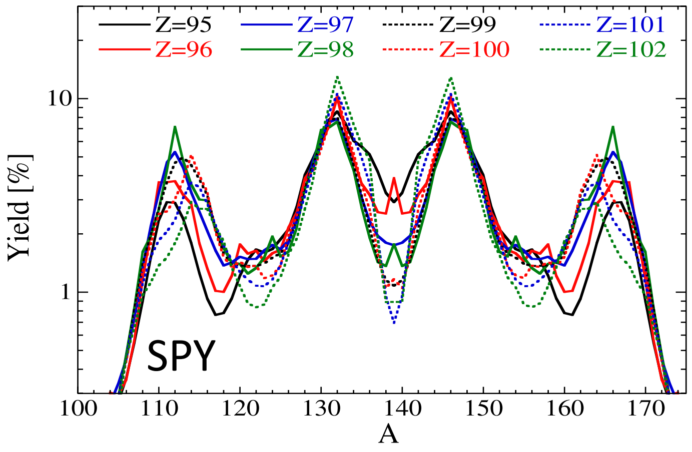
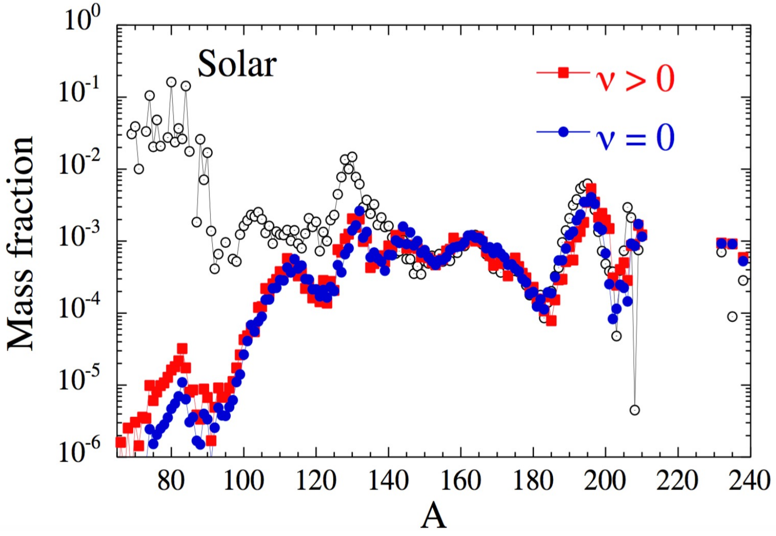


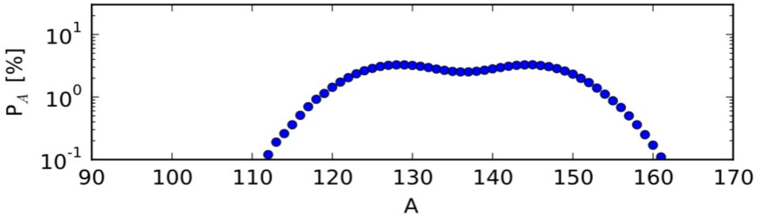
Dependence of *r*-process abundances on fission yields



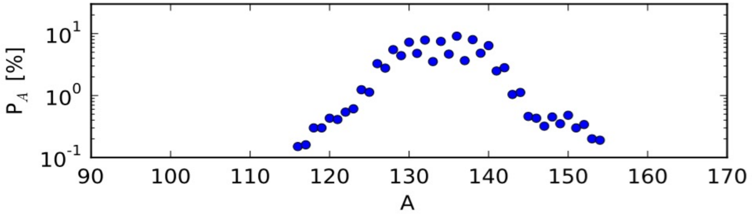




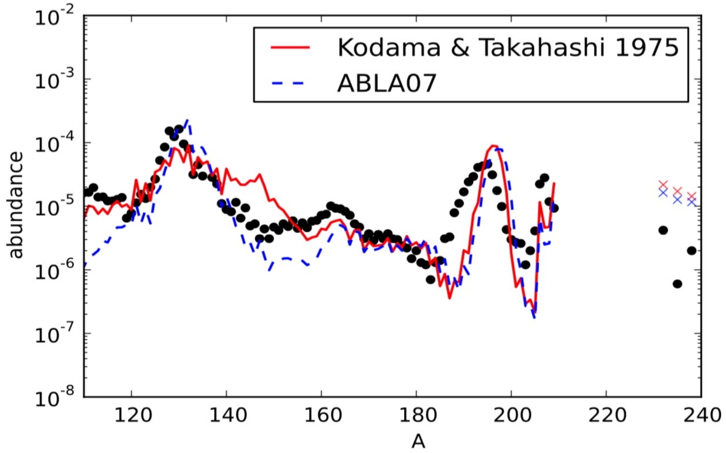
Goriely+13,15; see also Lemaître+21



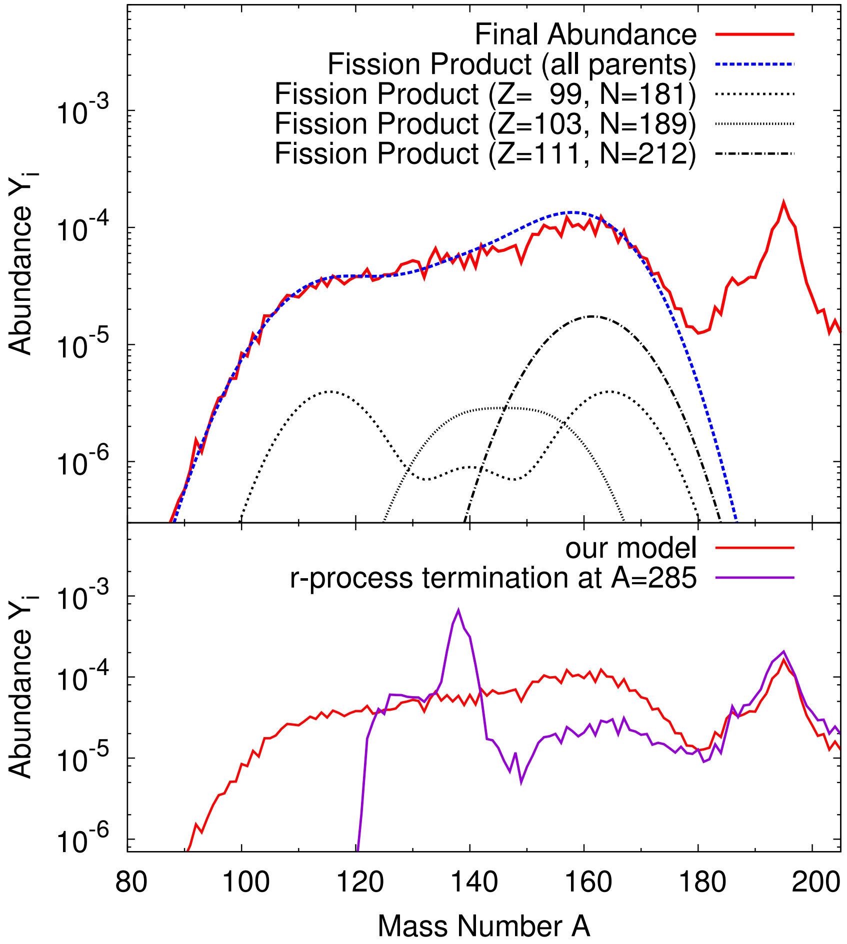
(b) Kodama & Takahashi (1975)



(c) ABLA07

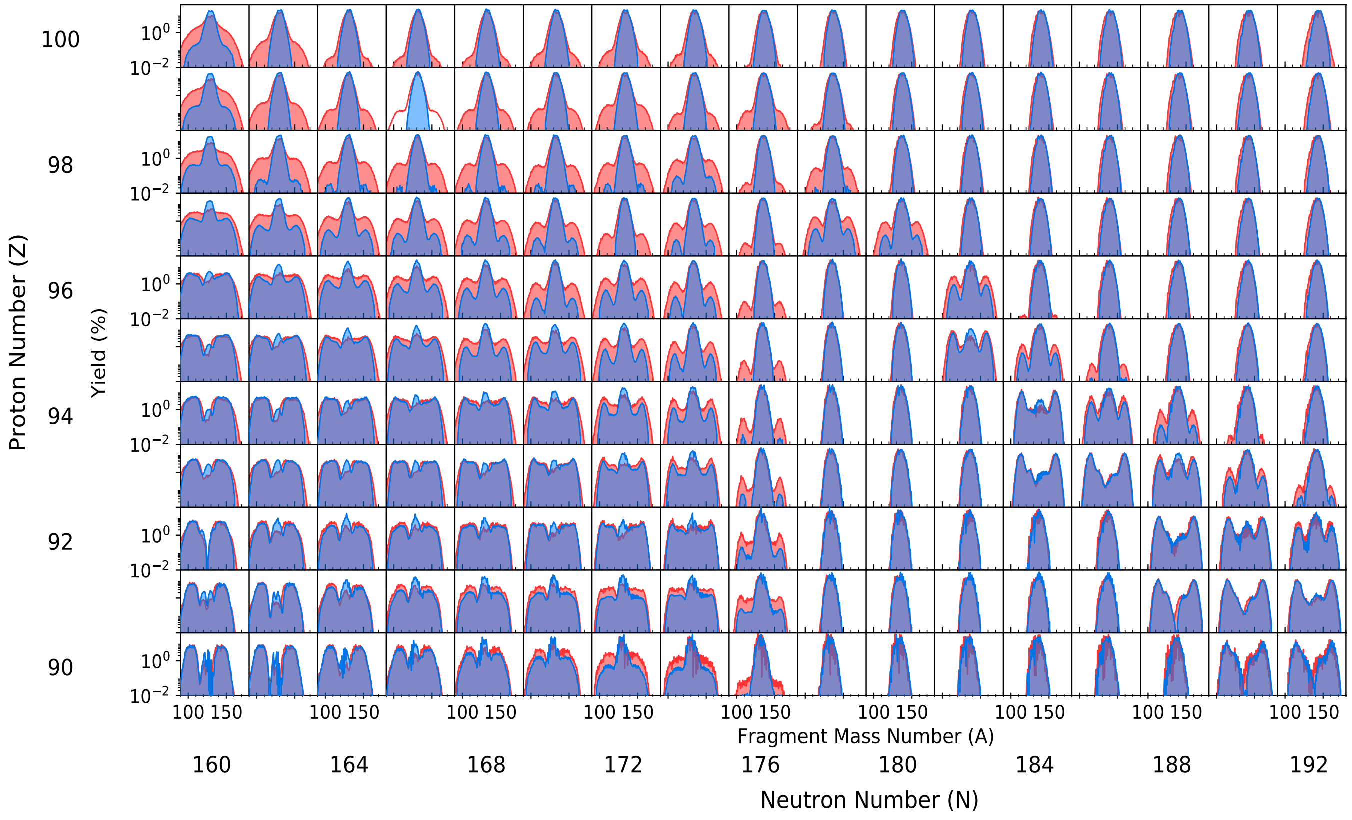


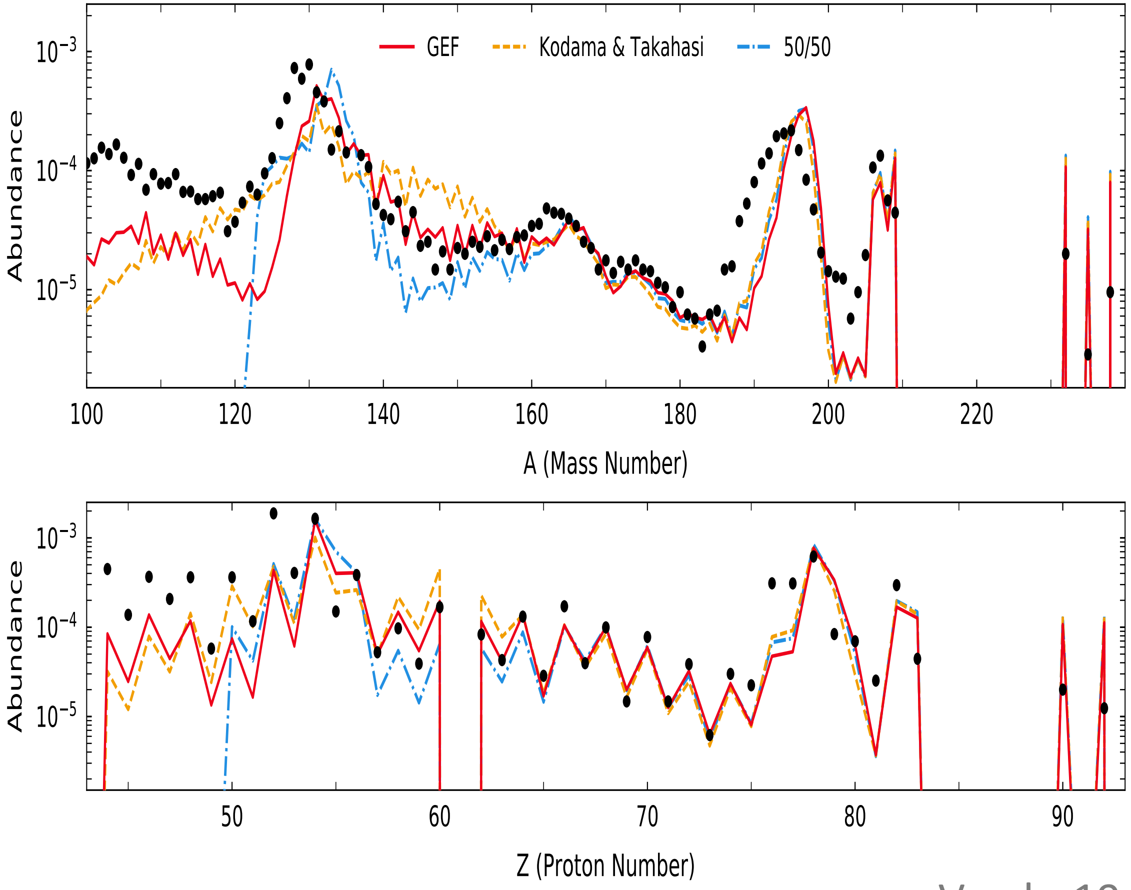
Eichler+15



Shibagaki+16

Excitation energy dependence: distinct fission yields for neutron-induced, β-delayed, and spontaneous fission

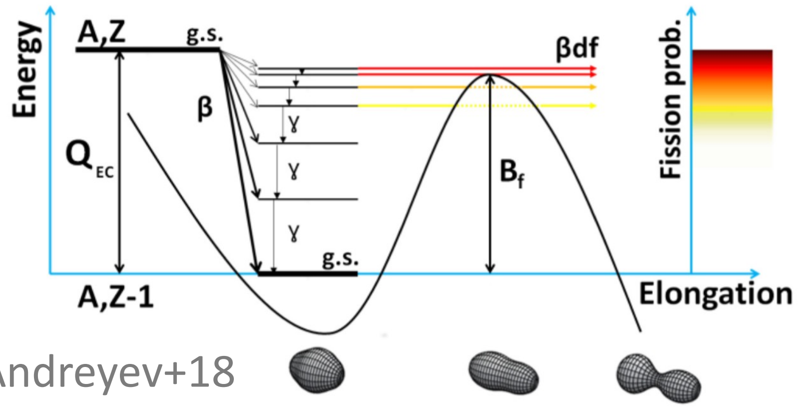




Vassh+19

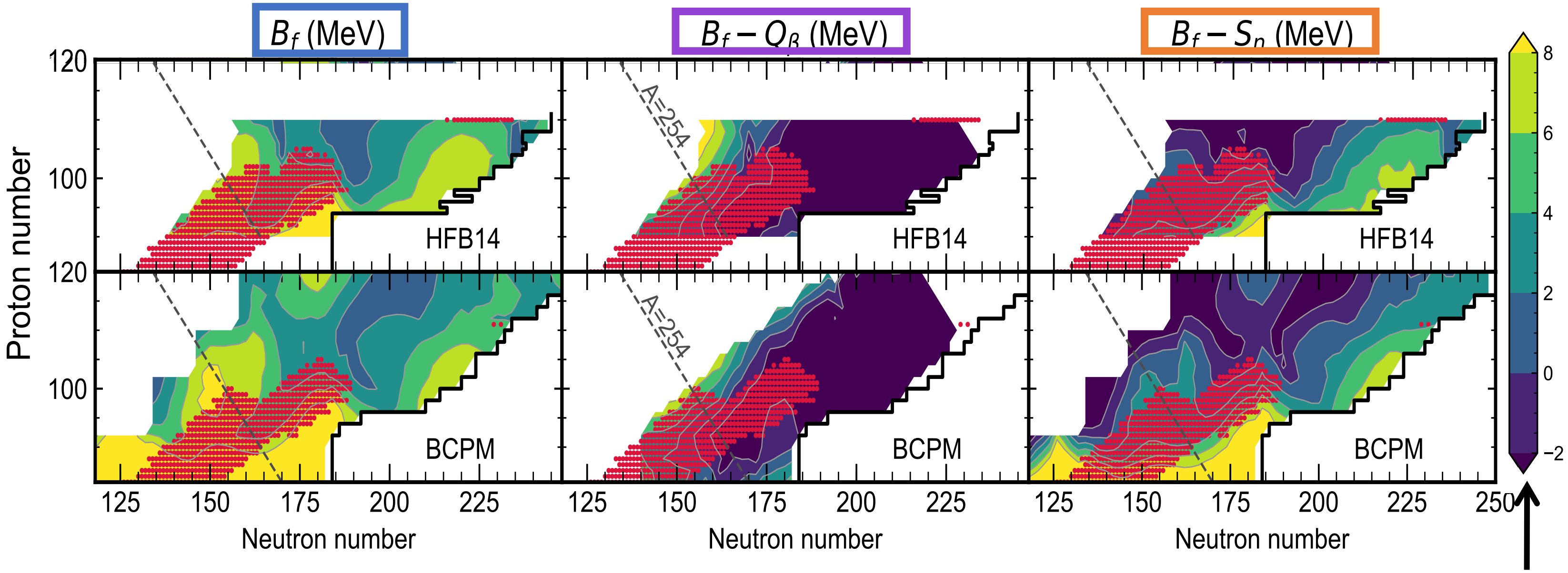
(n,f) yields with excitation energy $E_i + S_n$ differ from sf yields which have zero excitation energy (above from GEF 2016)

Fission and the ultimate reach of the *r* process

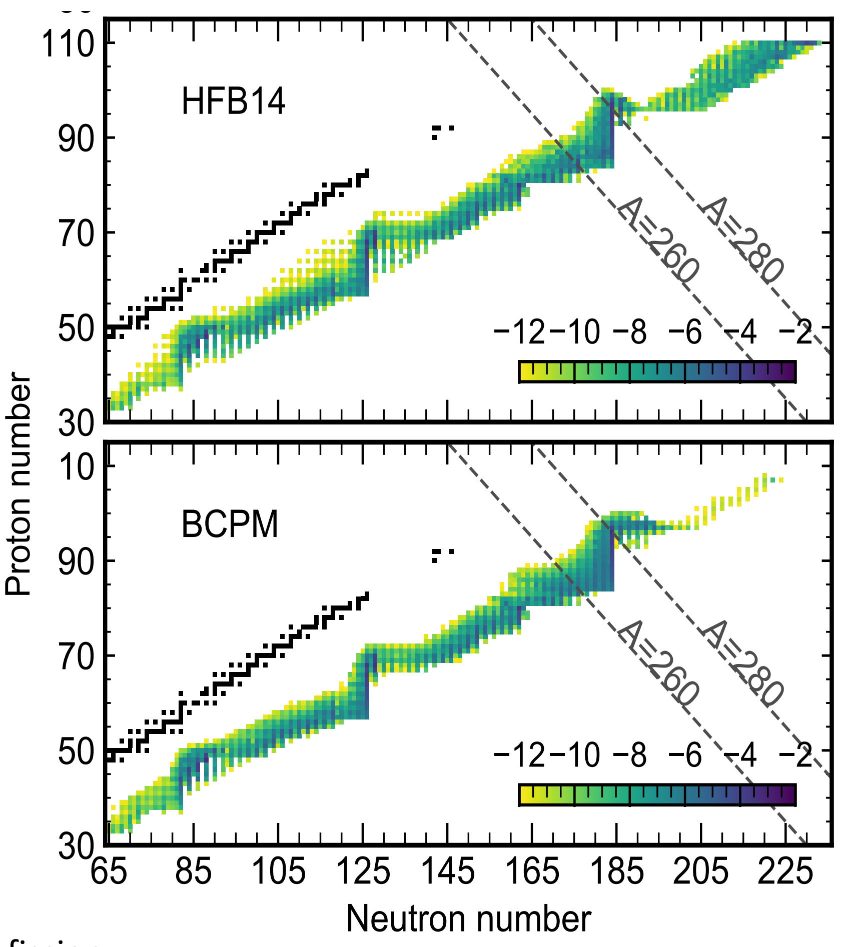


Andreyev+18

Fission barriers and masses are used to determine spontaneous, β-delayed, and neutron-induced fission rates



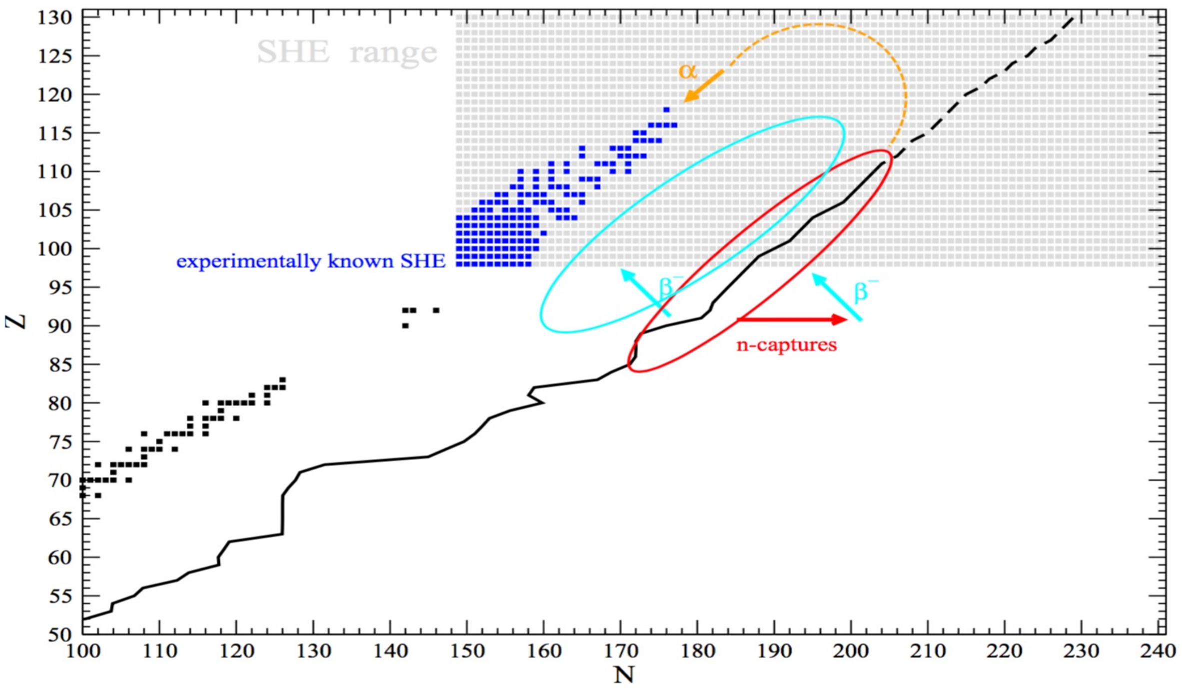
Giuliani+20



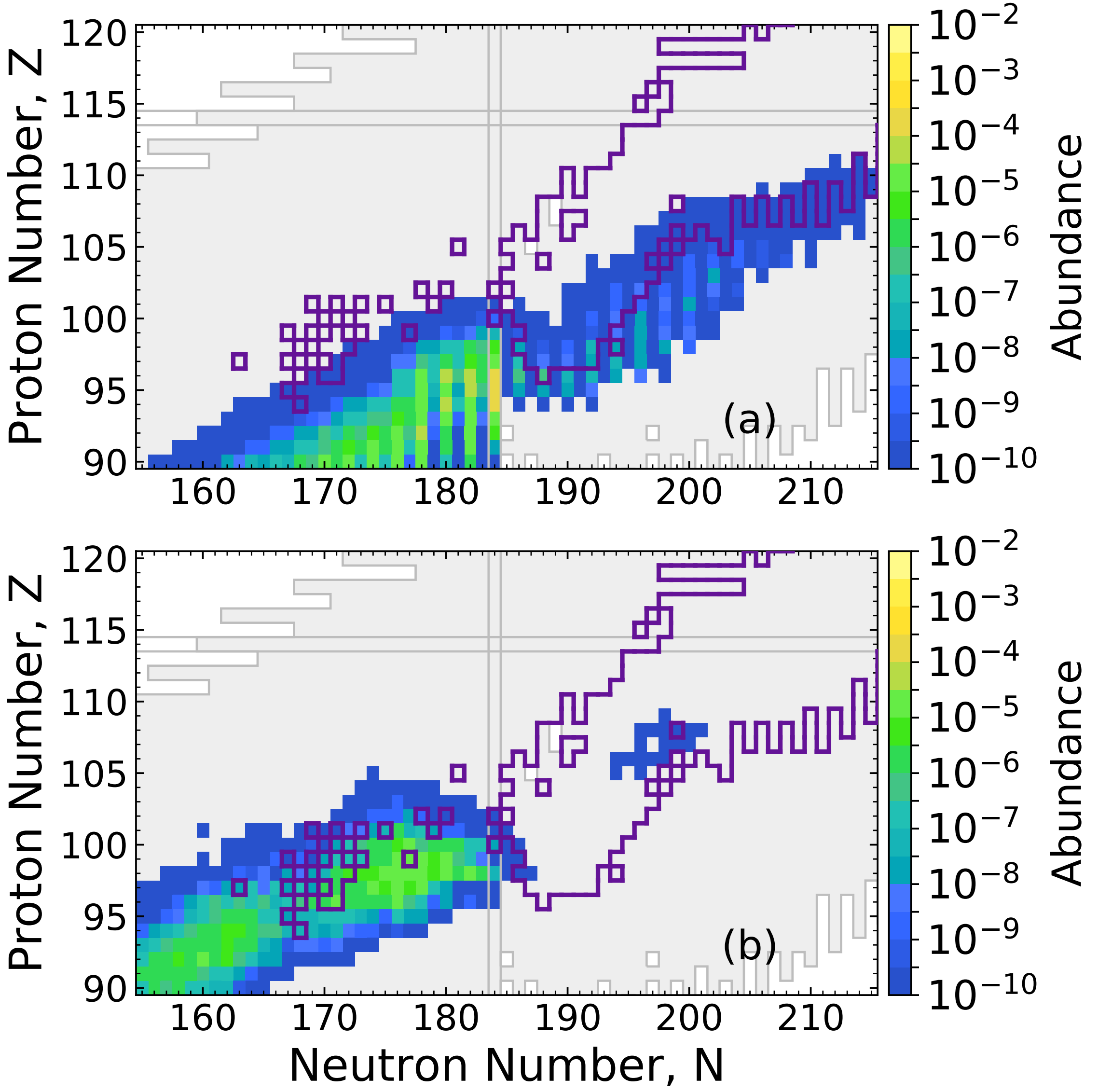
r-process production of superheavy elements?

Super heavy elements (Z ≳ 103) have been produced in laboratories and models predict an "island of stability" at Z=114, N=184, but current *r*-process calculations see fission prevent the population of such species

→ if observed in nature, fission barriers would have to differ from theory predictions



Petermann+12

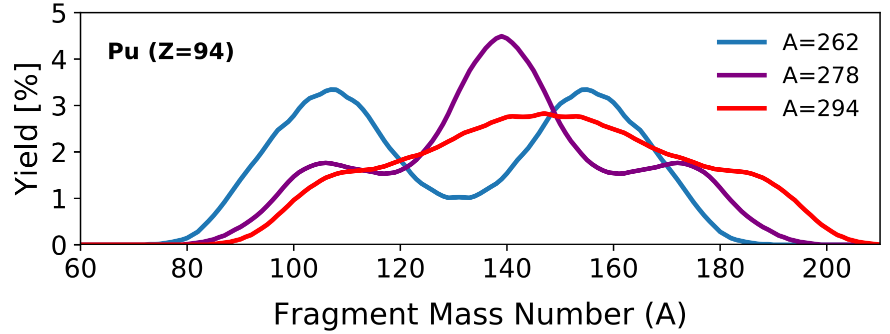


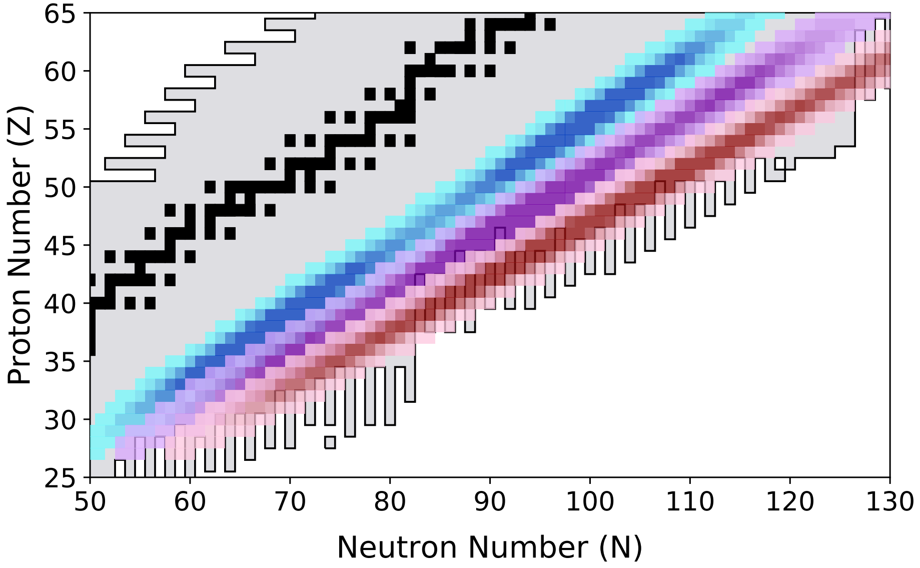
(purple outline – probability of βdf ≥ 90%)

Mumpower+18

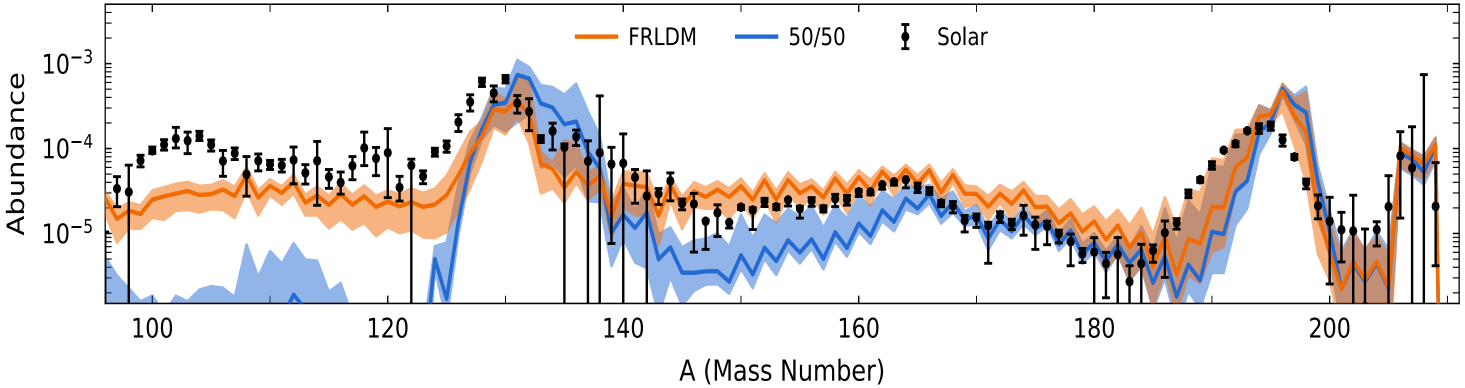
Using fission yields and fission rates calculated with self-consistent fission barriers

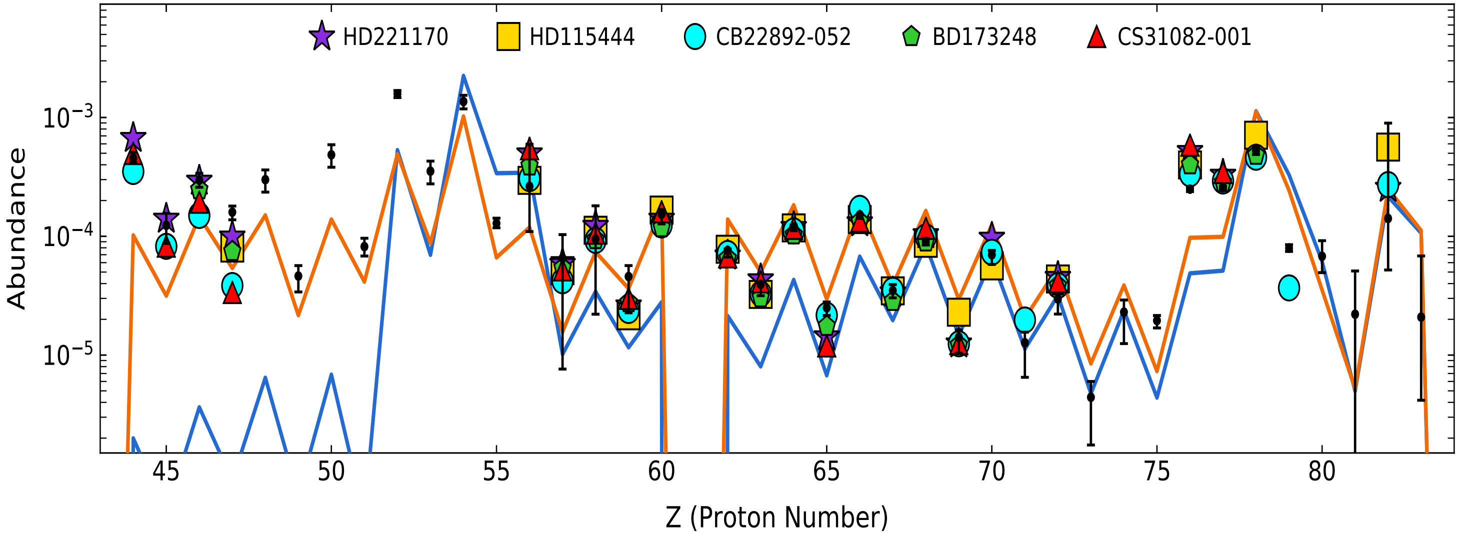
FRLDM Yields from Mumpower+20





Range from Rosswog+13 NSM dynamical ejecta (Ye~0.01-0.05)





Vassh+20

Nuclear Fission (in Astrophysics)

Incident neutron strikes

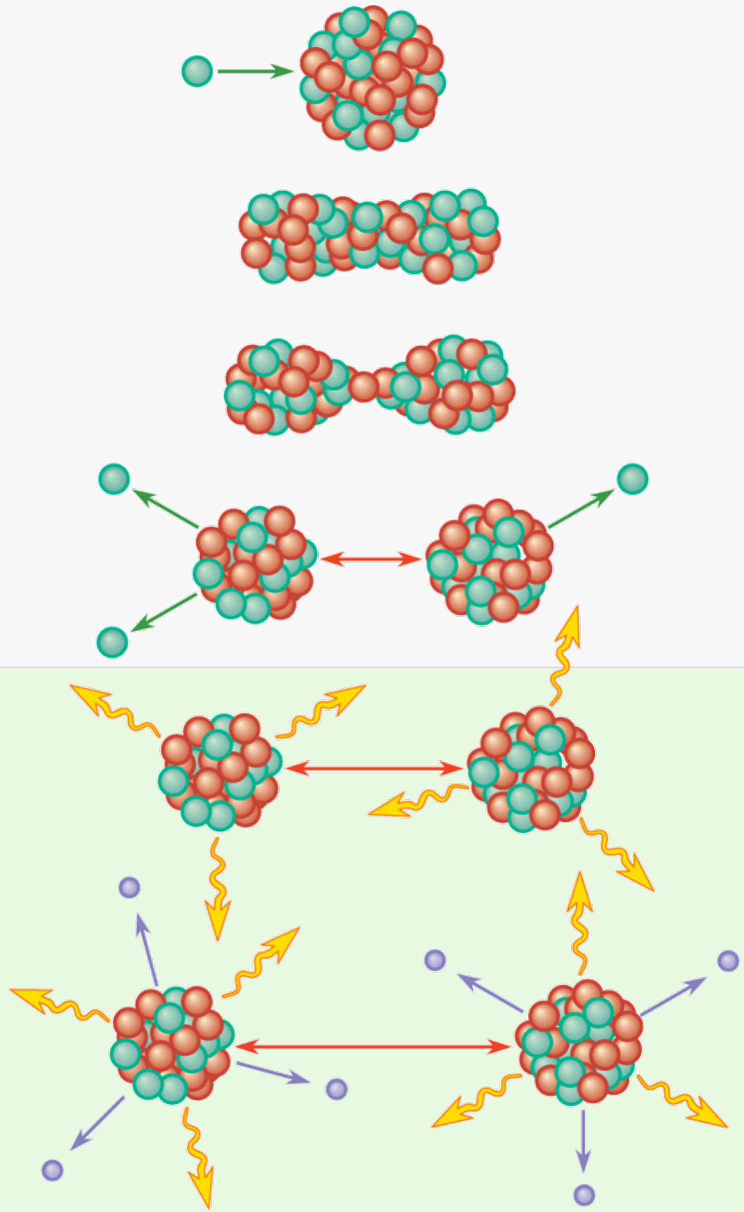
Deformation

Scission

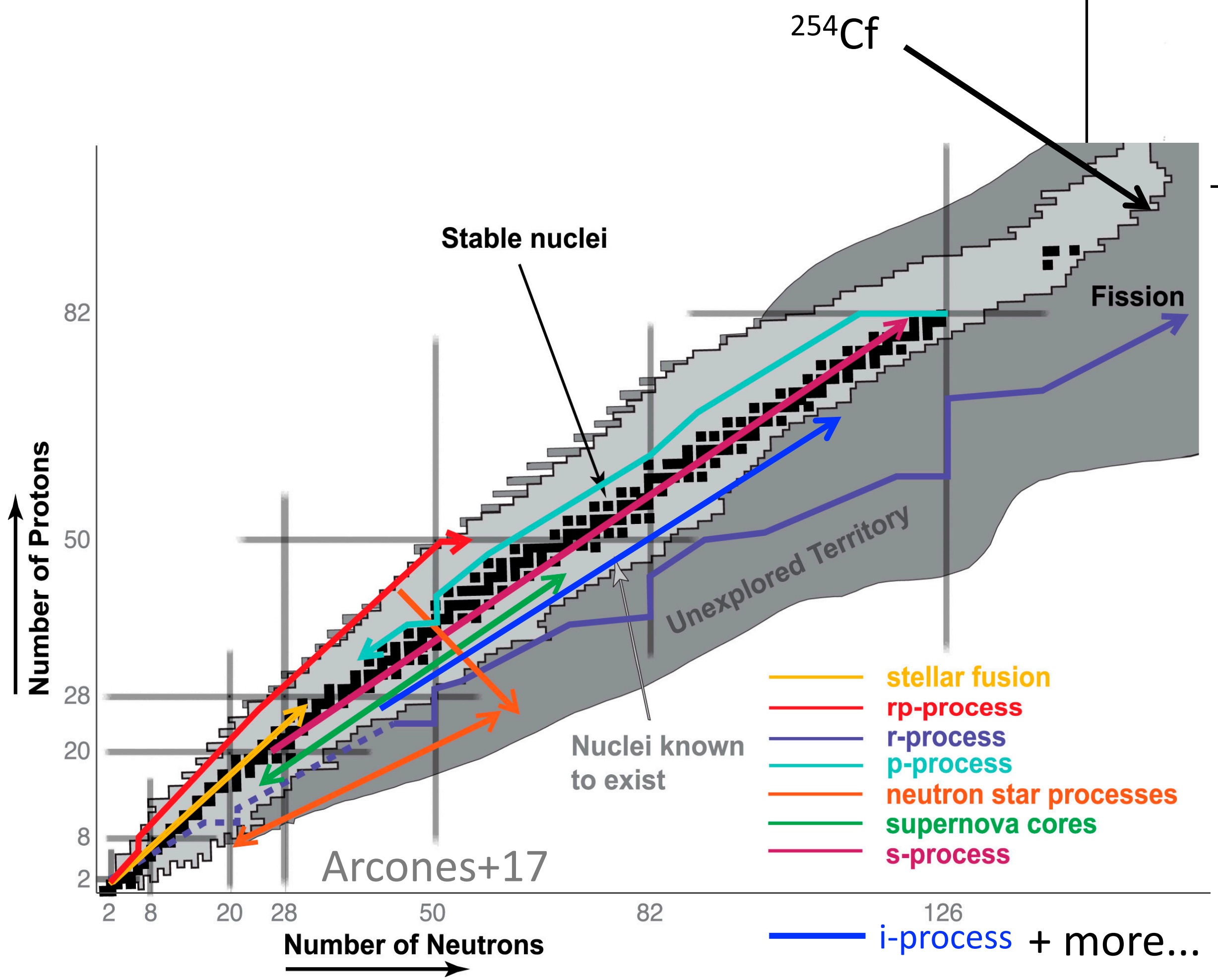
Prompt Neutron Emission from excited fission fragments (~2-3)

Energy release ~200 MeV with kinetic energy of fragments ~170 MeV

Delayed emission from β-decay of neutron-rich fission products



Late time kilonova light curves can shed light on actinide production



PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

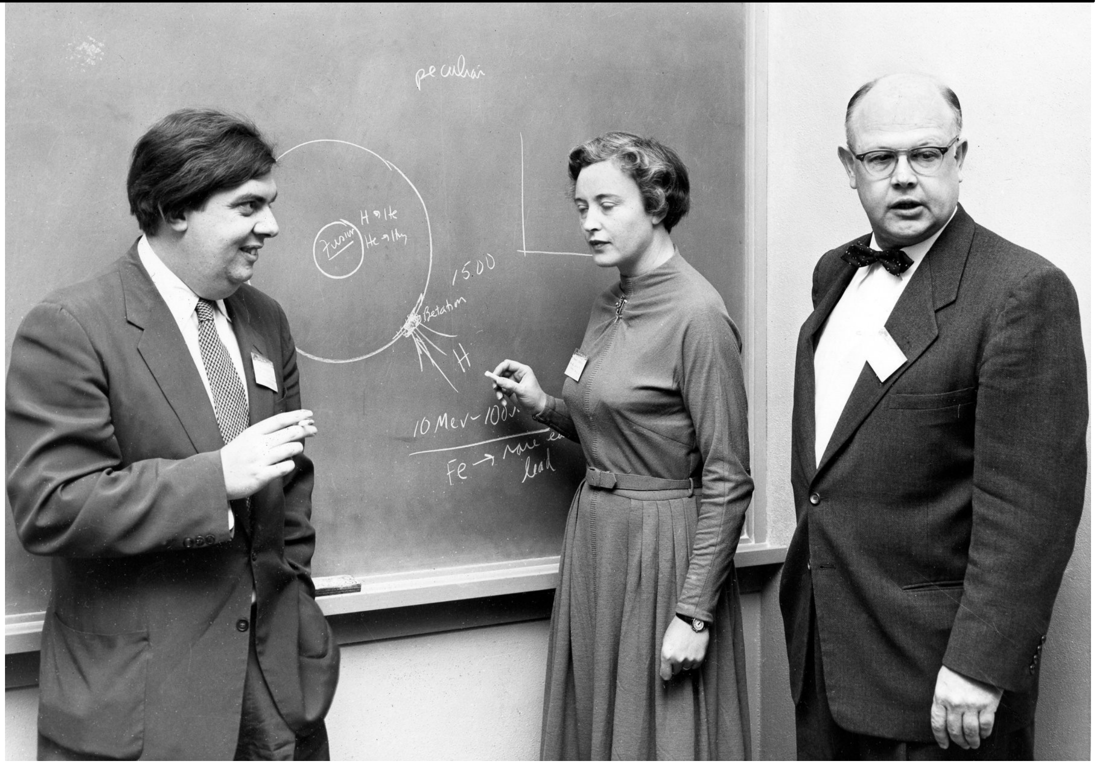
Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

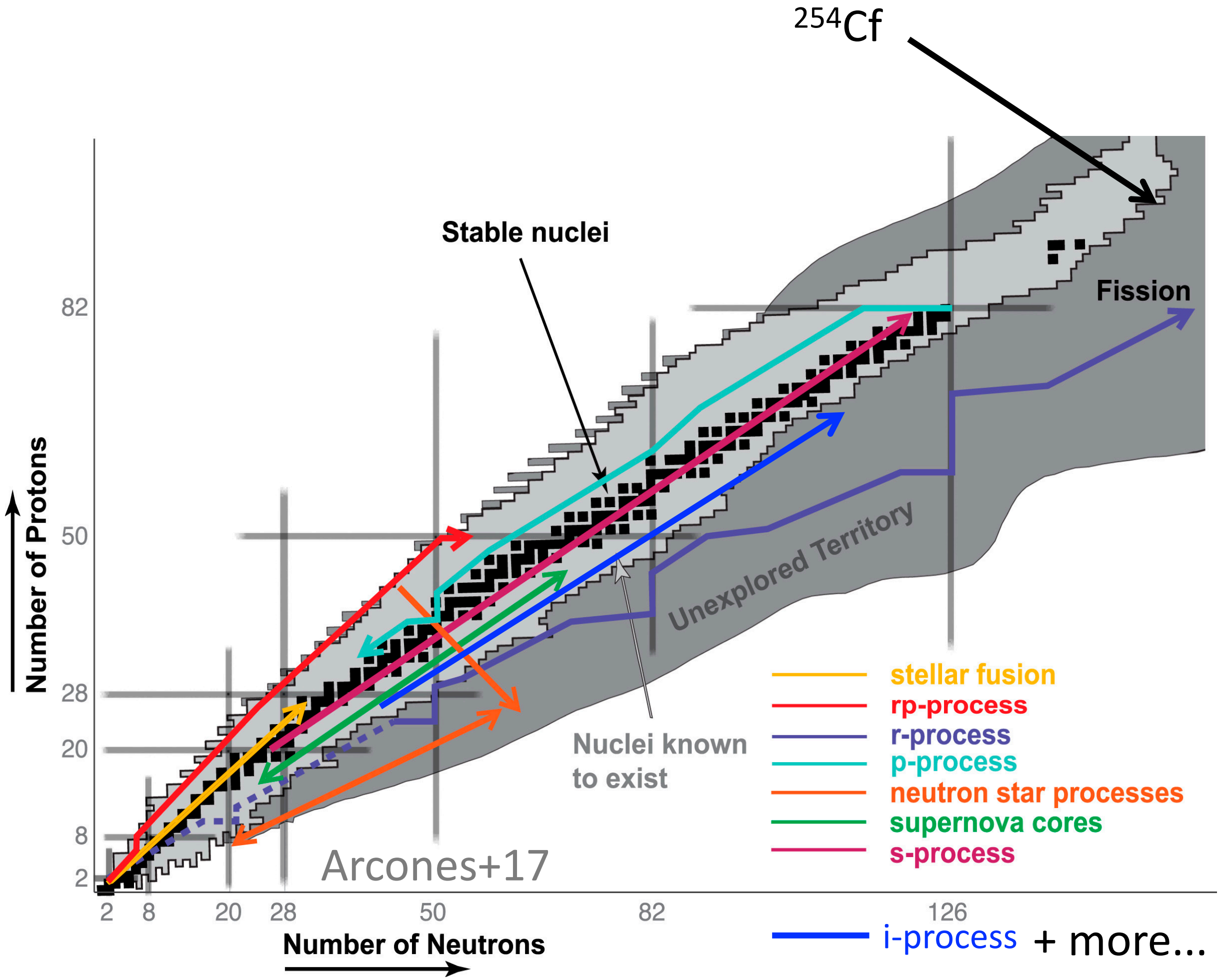
E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

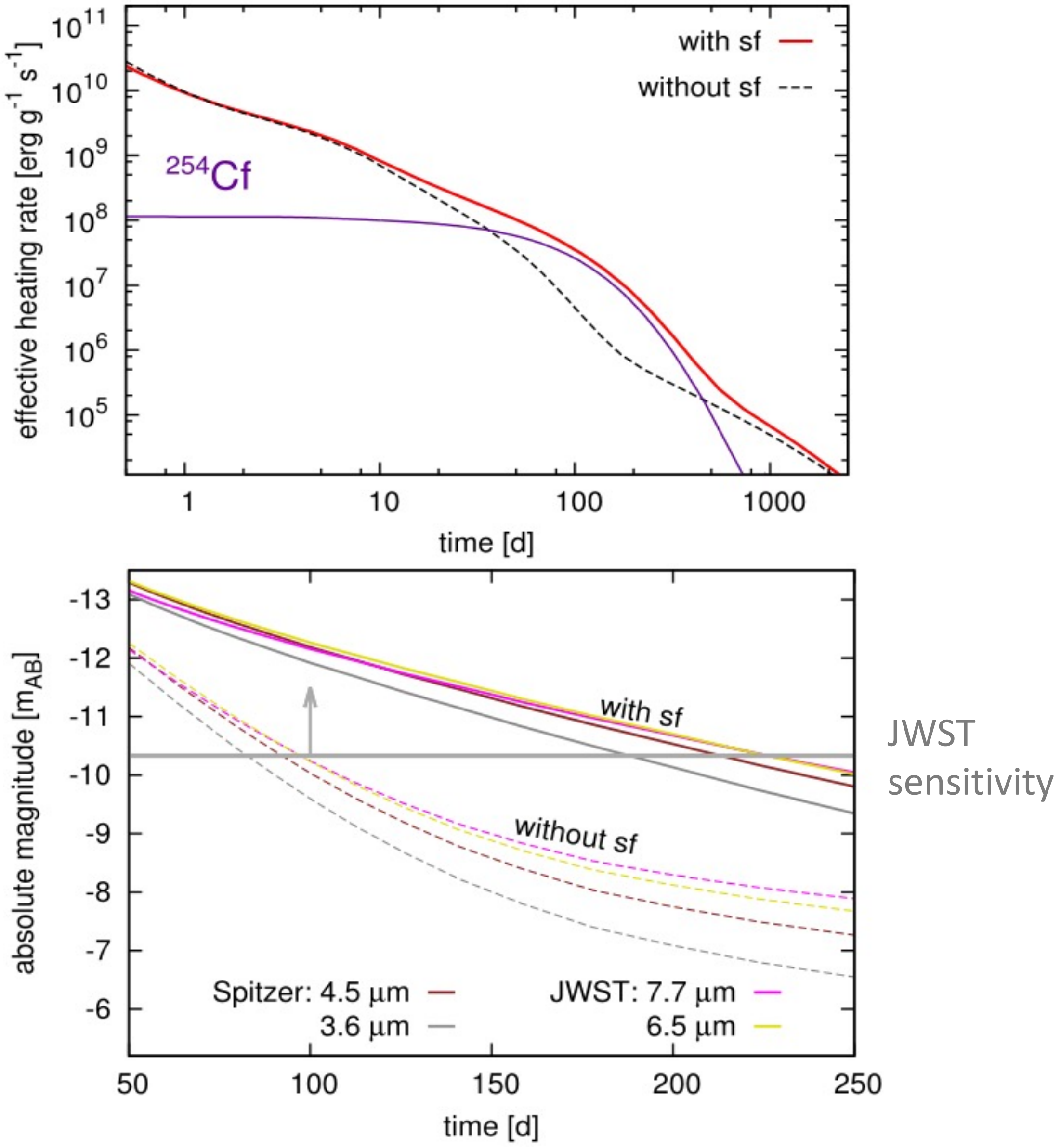
(Received May 17, 1956)



W. W. Girdner/Caltech Archives

Late time kilonova light curves can shed light on actinide production

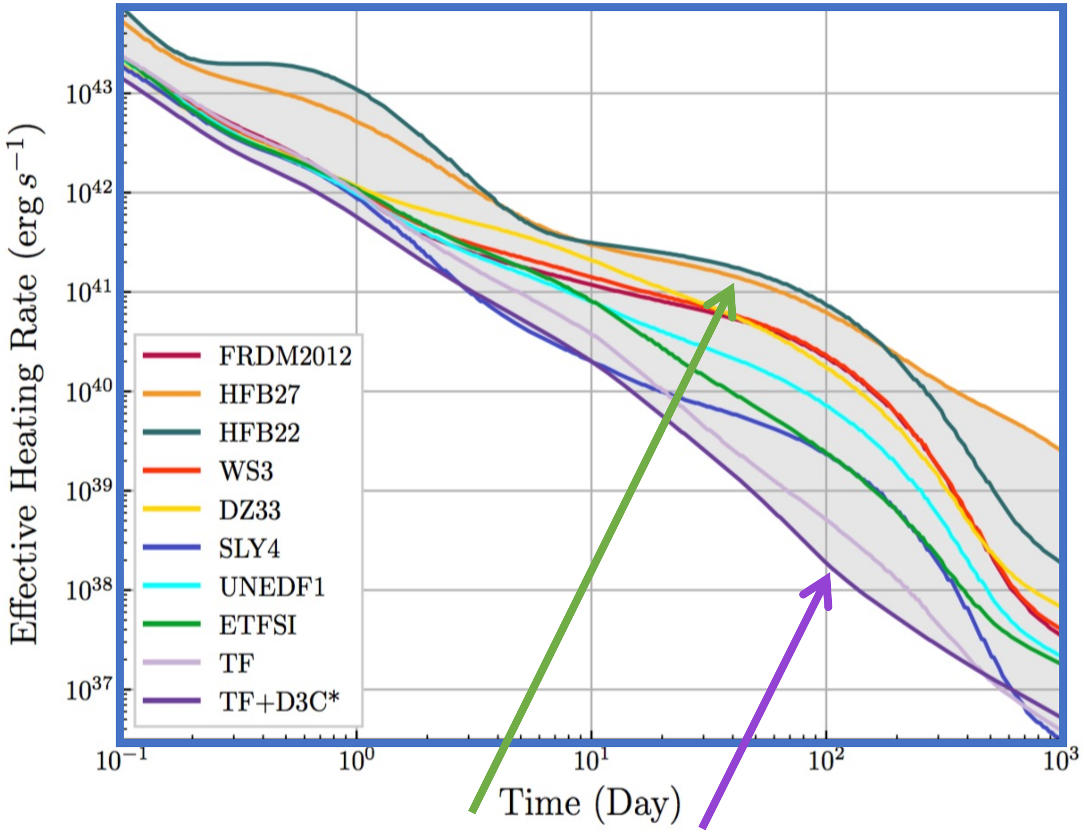




Zhu+18; see also Wu+19

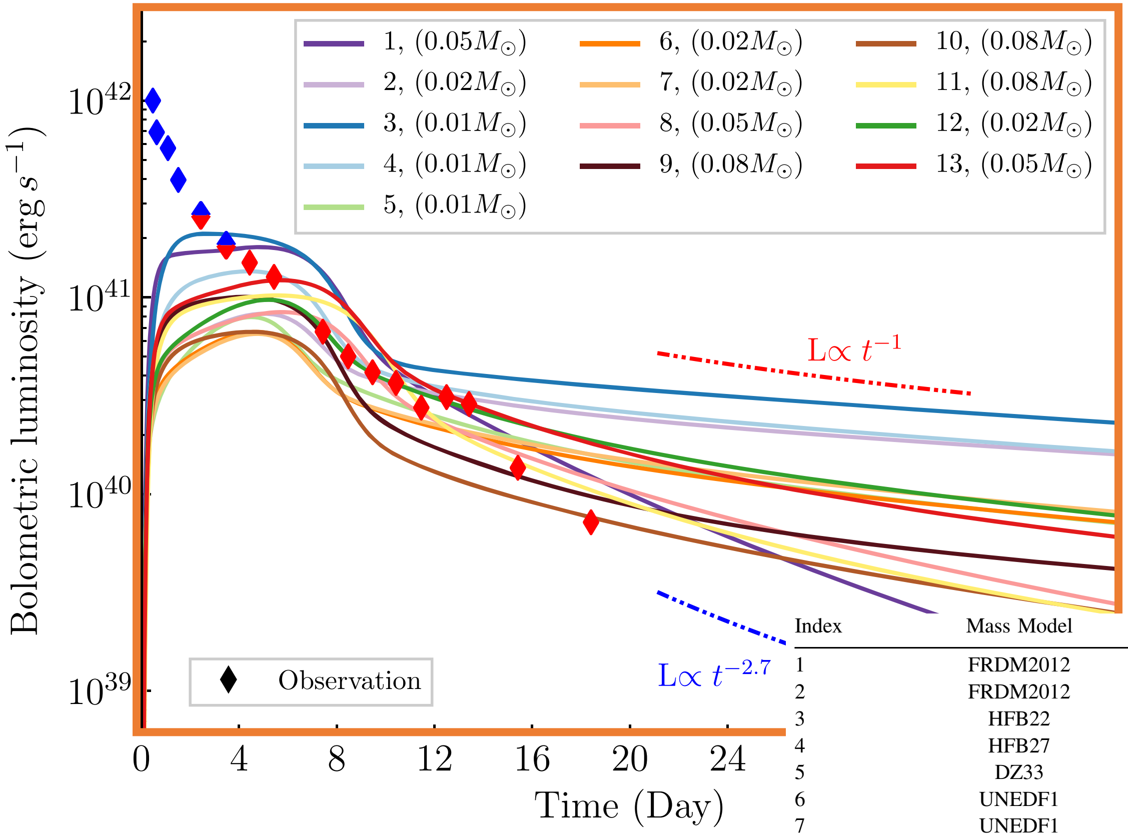
Nuclear model influence on interpreting kilonova

Different abundance predictions affect nuclear heating, bolometric luminosity, and inferred ejecta mass by roughly an order of magnitude or more



Nuclear models that strongly populate long-lived actinides

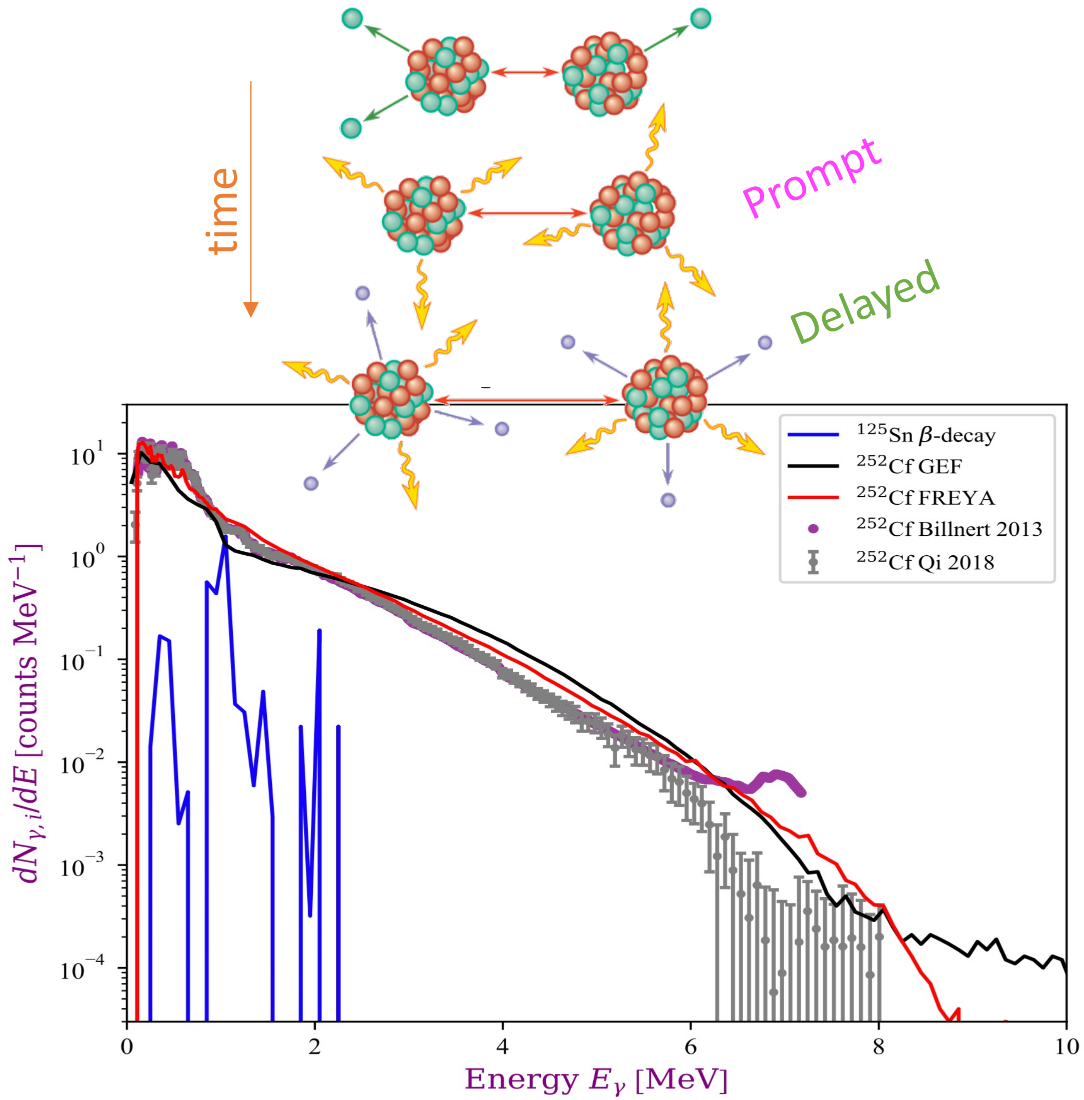
Nuclear models that don't

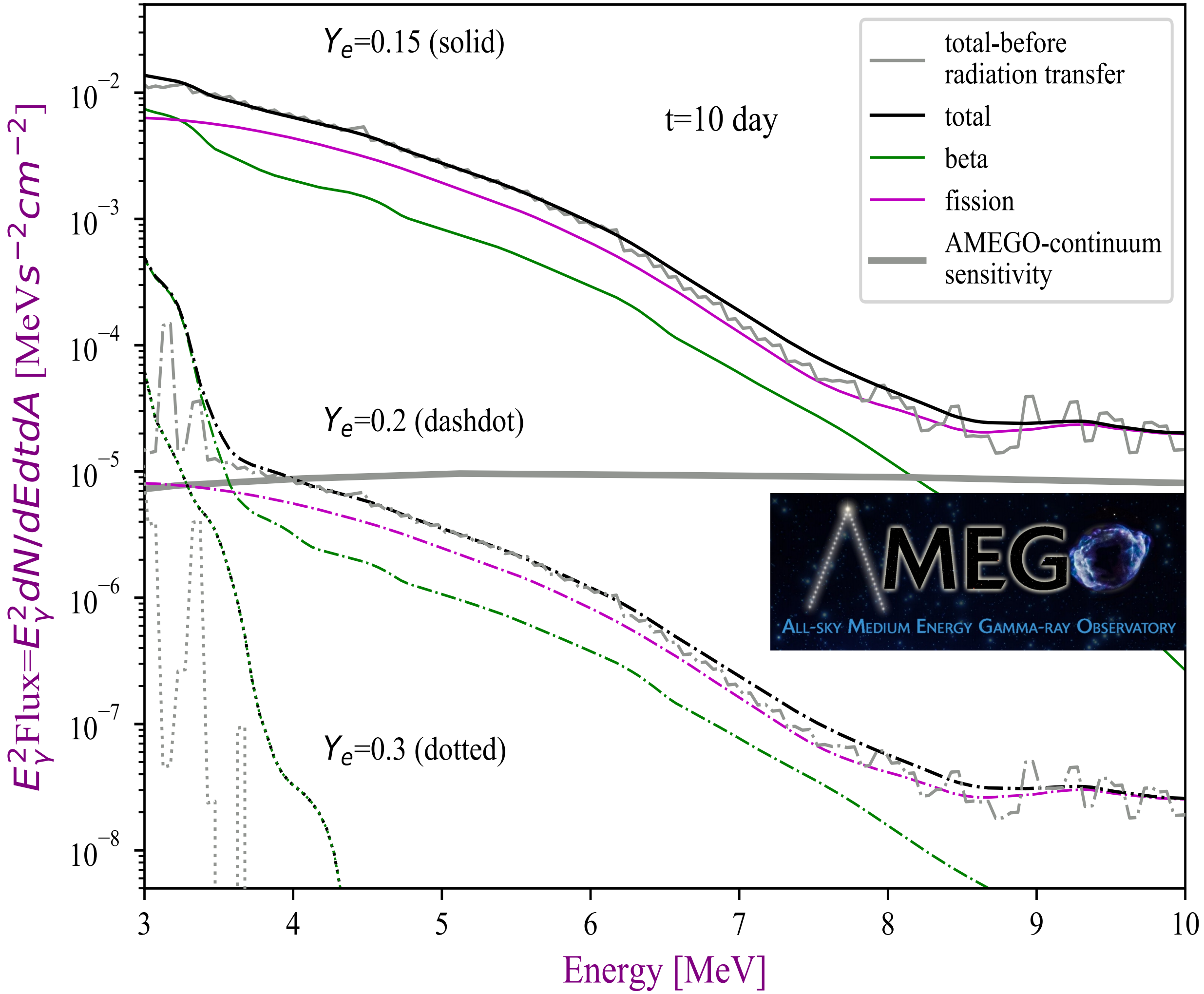


Index	Mass Model	Y_e
1	FRDM2012	0.28
2	FRDM2012	0.16
3	HFB22	0.16
4	HFB27	0.16
5	DZ33	0.16
6	UNEDF1	0.16
7	UNEDF1	0.16
8	UNEDF1	0.24
9	SLY4	0.18
10	SLY4	0.21
11	TF+D3C*	0.16
12	DZ33	Mixture[a]
13	UNEDF1	Mixture[b]

Zhu,Lund+21; See also Barnes+21

Another possible signature of fission: MeV gamma rays



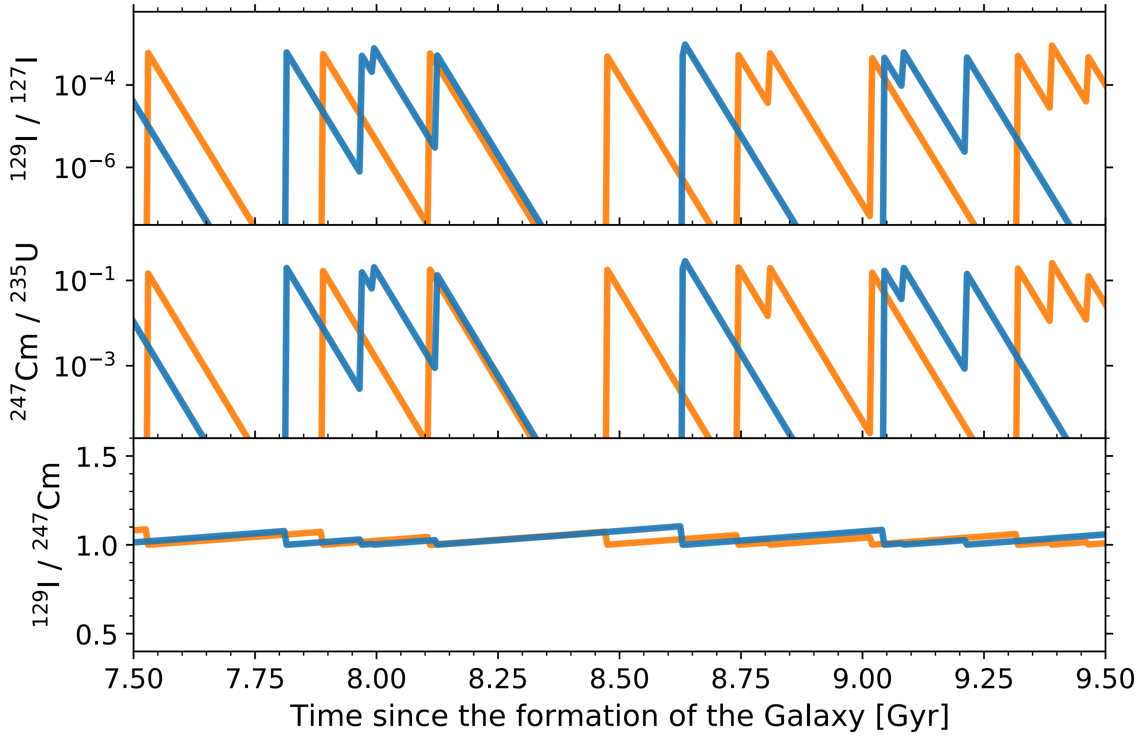


Wang,Vassh+20 using GEF inputs from Vassh+19

A closer look at Curious Marie: the nature of the last *r*-process event in our solar system

Only 4 radioactive isotopes in meteorites linked to *r* process with $T_{1/2} < 1$ Gyr:

^{129}I	$T_{1/2}$ = 15.7 Myr	^{244}Pu	$T_{1/2}$ = 80 Myr
^{247}Cm	$T_{1/2}$ = 15.6 Myr	^{235}U	$T_{1/2}$ = 700 Myr



Côté+21

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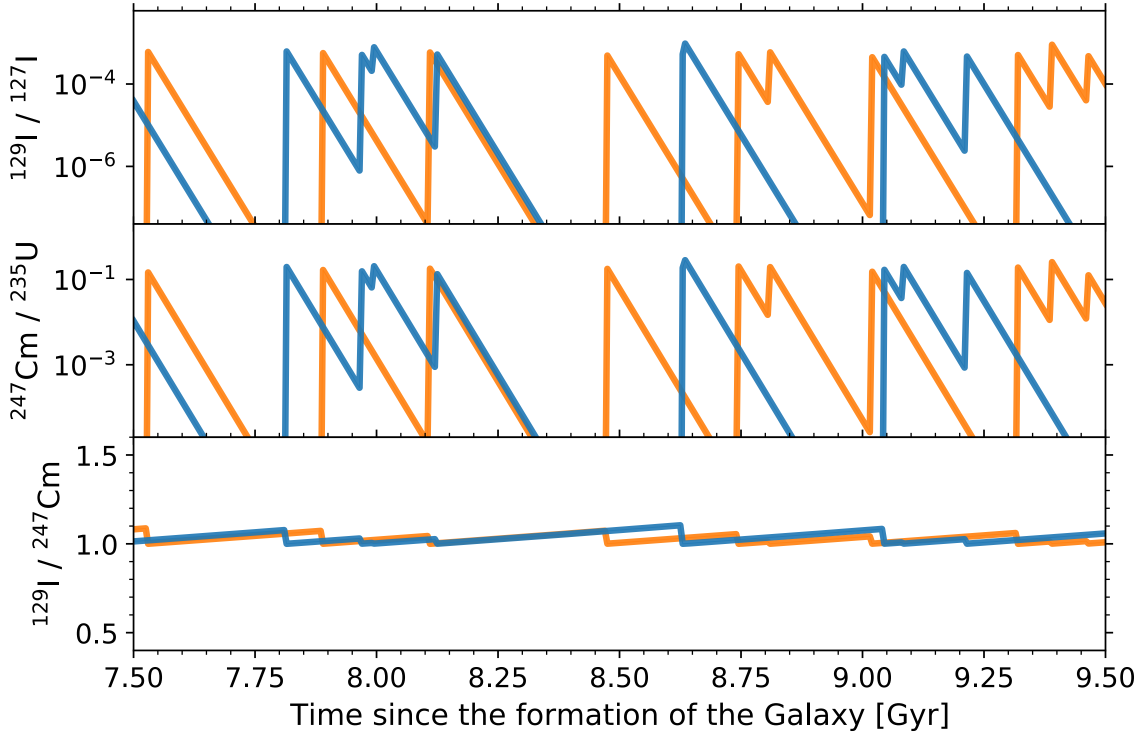
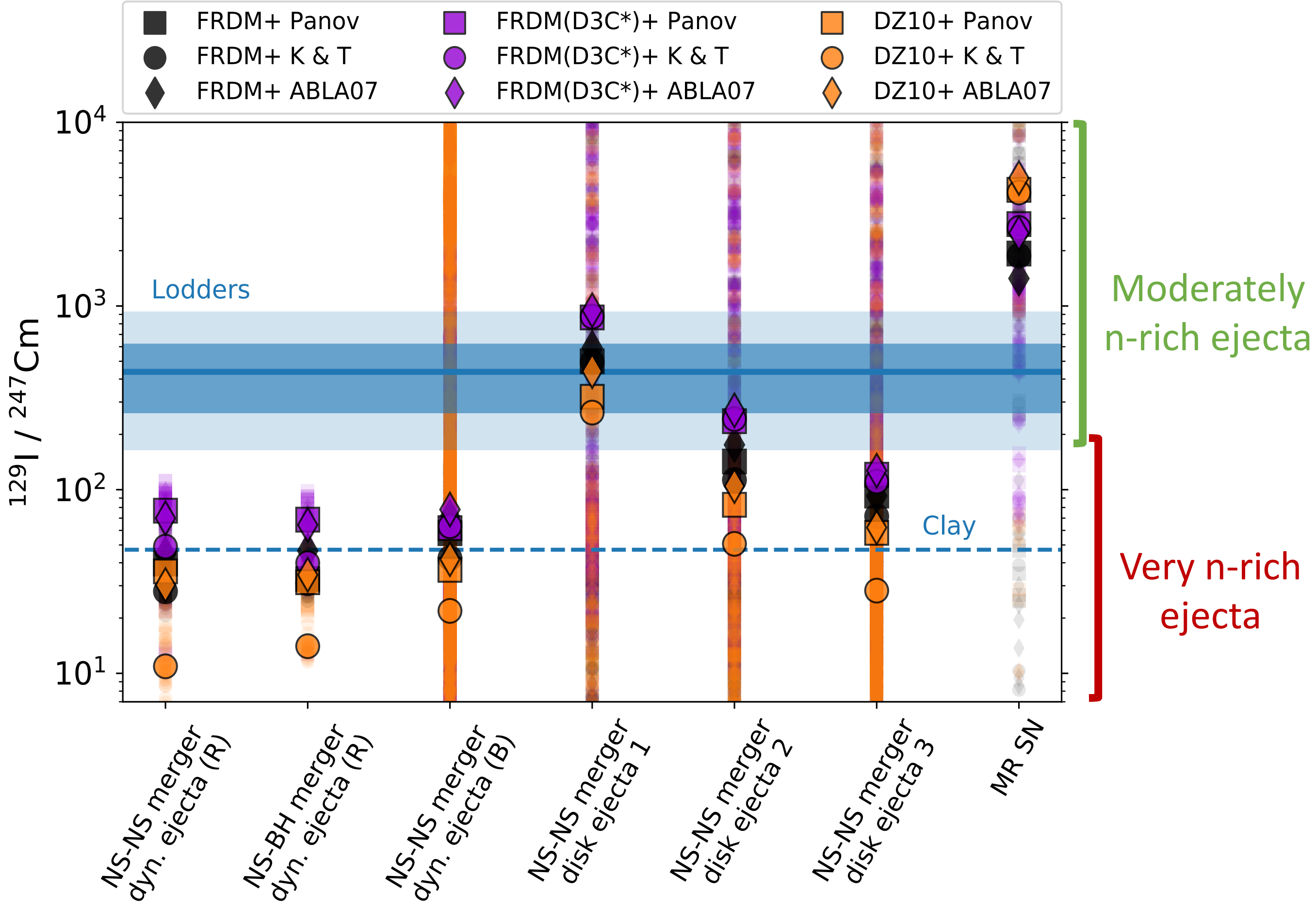
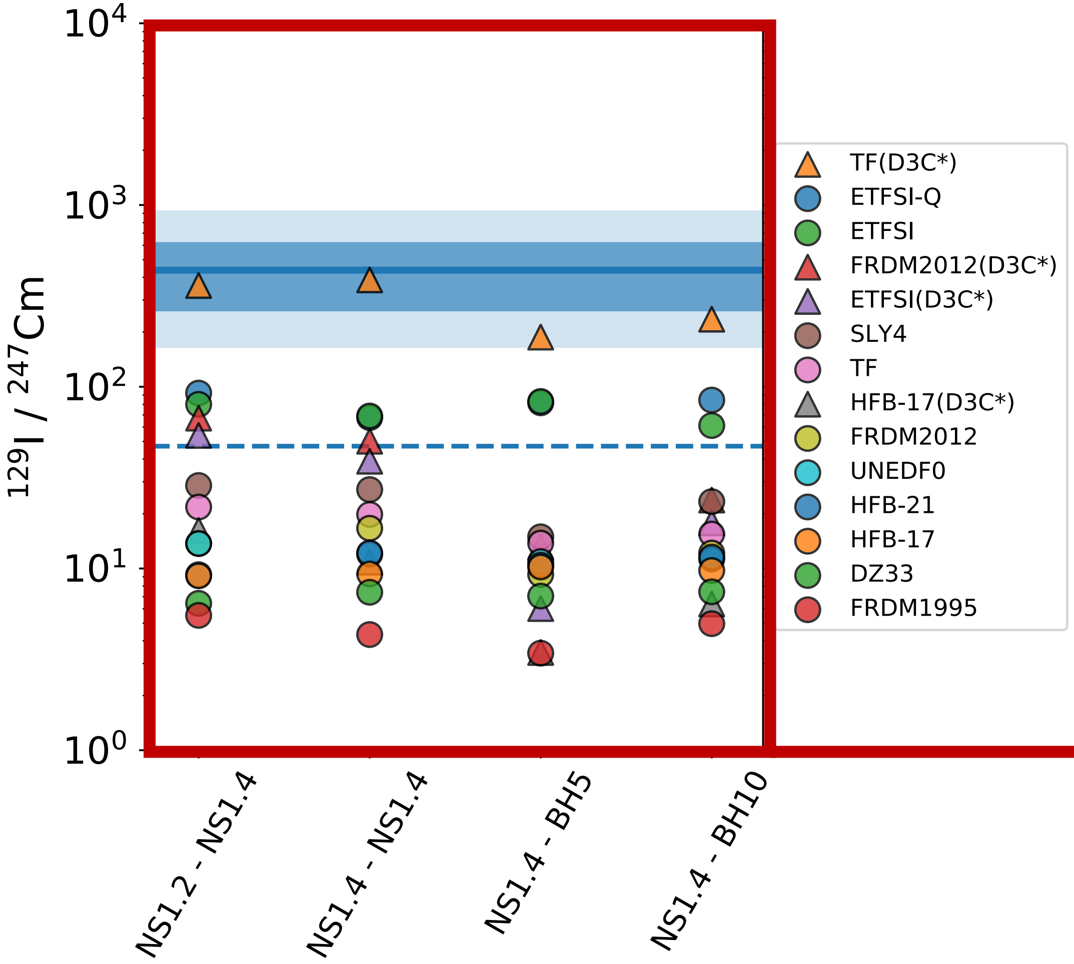


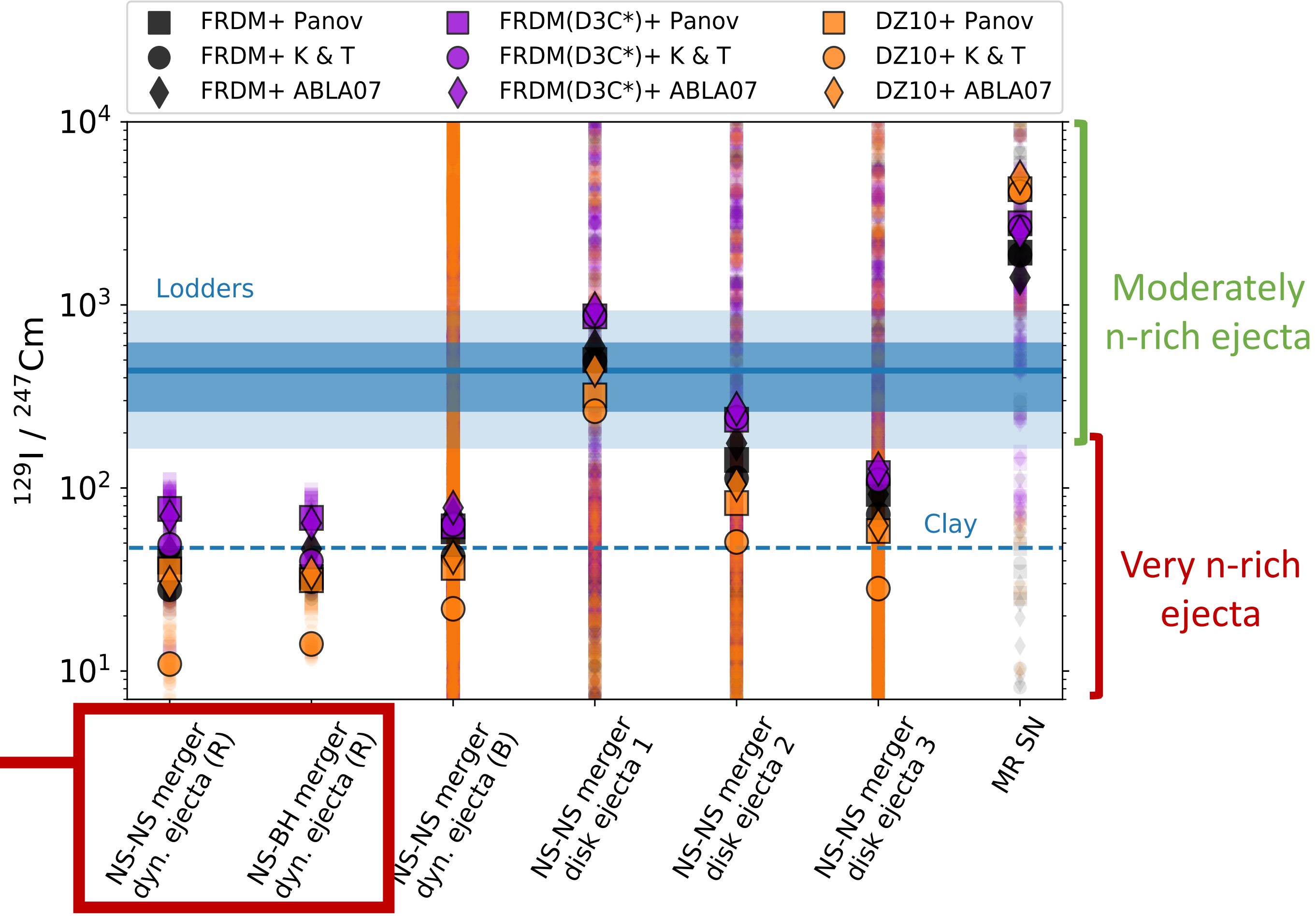


Côté+21

A closer look at Curious Marie: the nature of the last *r*-process event in our solar system

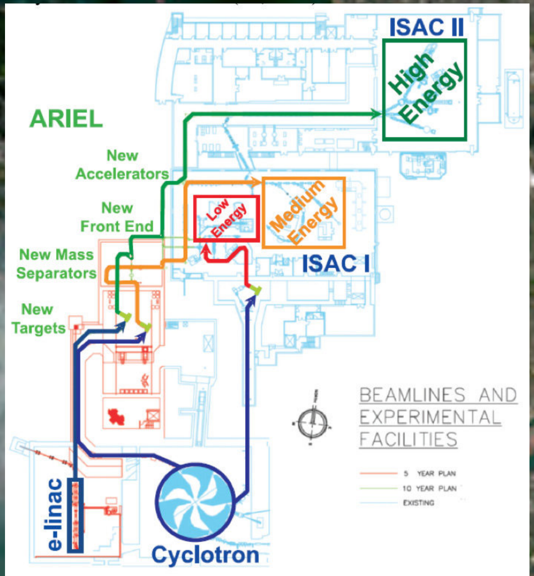
PRISM calculations with 12 sets of nuclear data

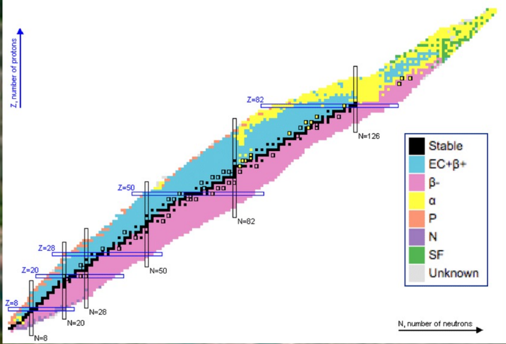




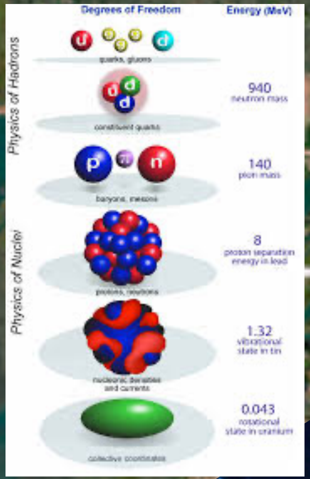
Côté+21

Multi-messenger nuclear astrophysics

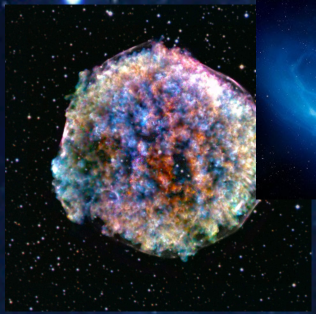




Experiment + Fundamental Theory ⟷ Nuclear Properties

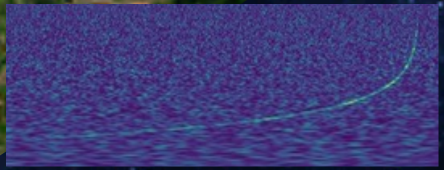


Astrophysical Sites

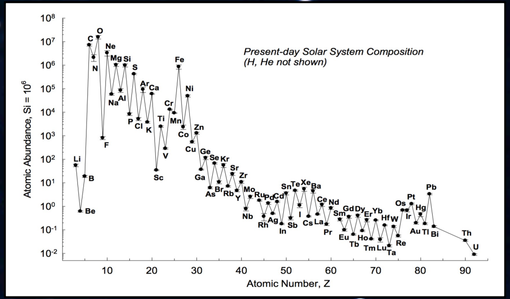


Astrophysical Observables

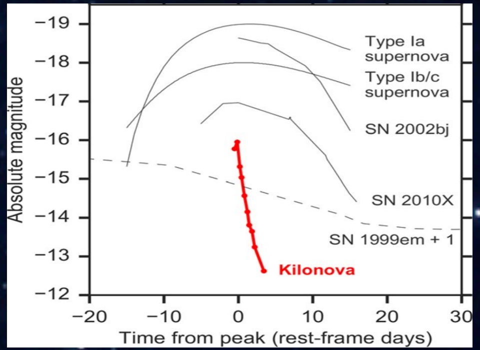
Gravitational Waves



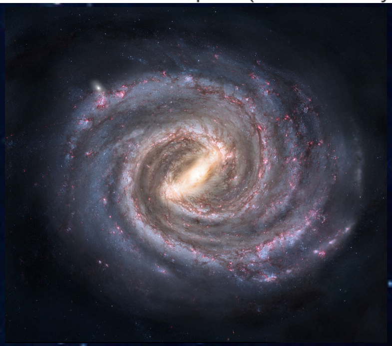
Solar and Stellar Abundances



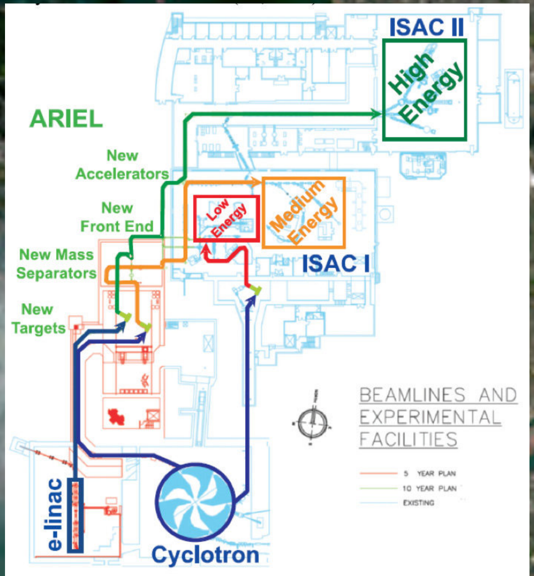
Electromagnetic Emission

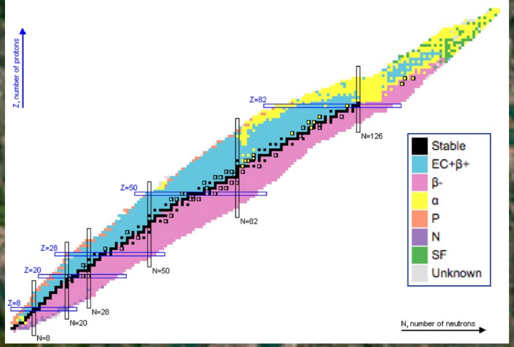


Galactic Origins



Multi-messenger nuclear astrophysics





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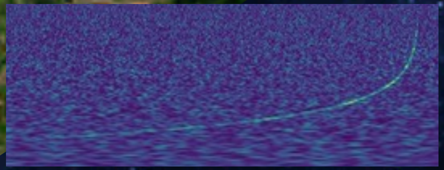

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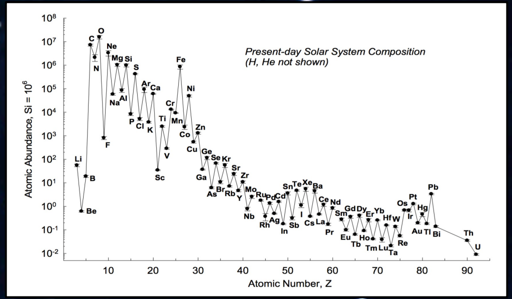

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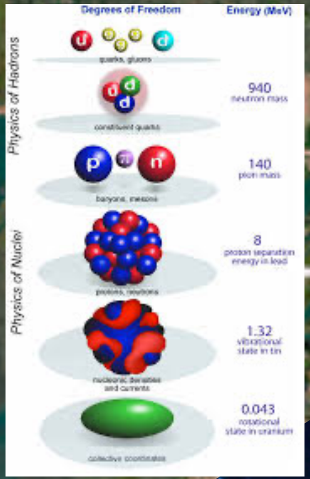
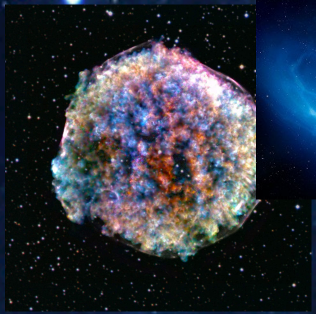


Nuclear Properties

+

Astrophysical Sites



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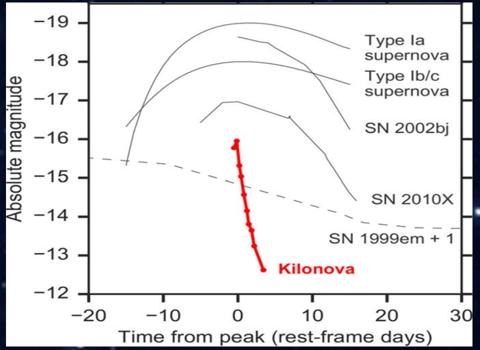

Galactic Origins