Nucleosynthesis: Connecting Nuclear Properties and Observations - II

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TRIUMF

FRIB Theory Alliance

NSERC CRSNG

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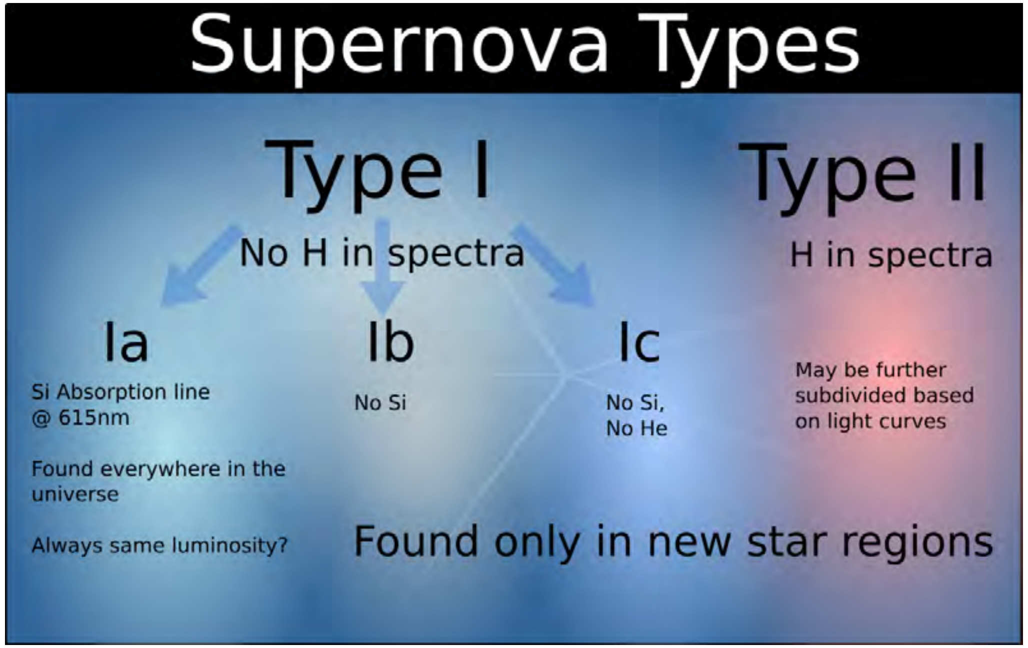
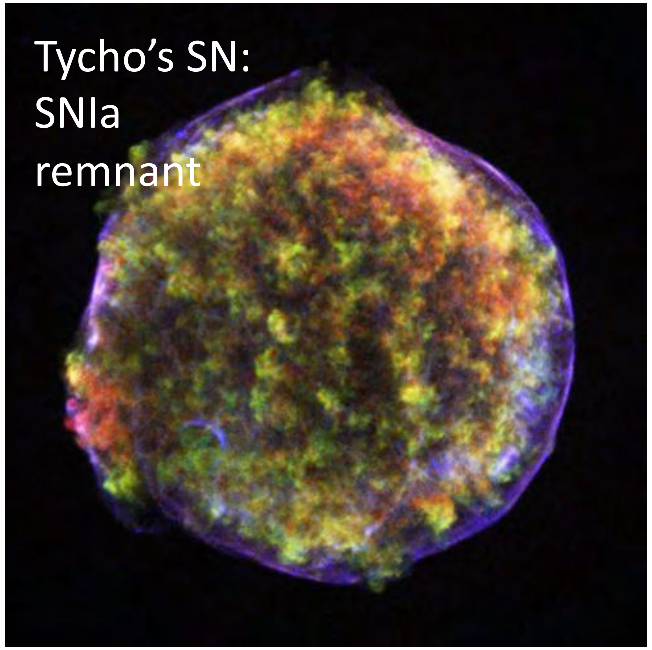
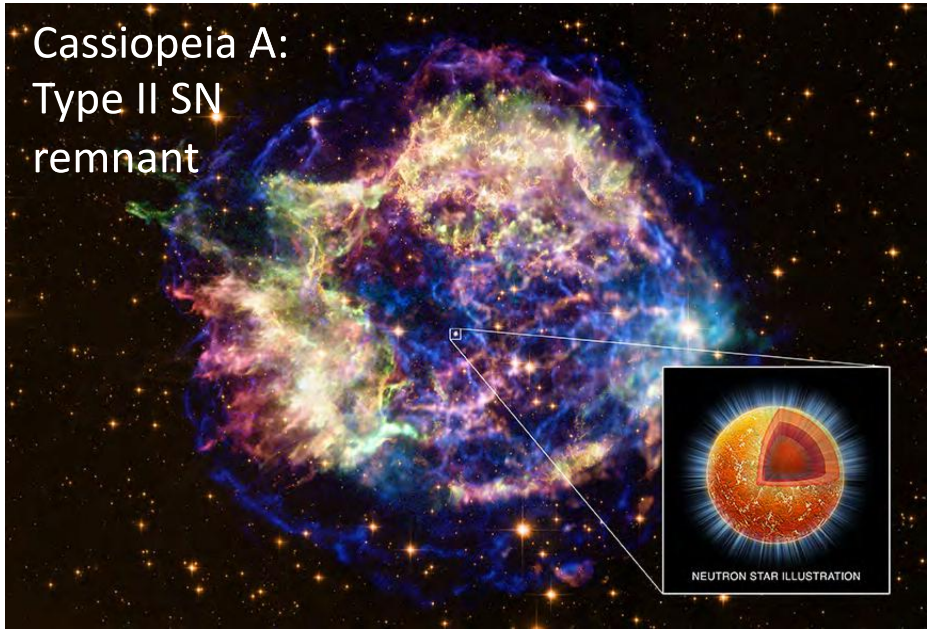
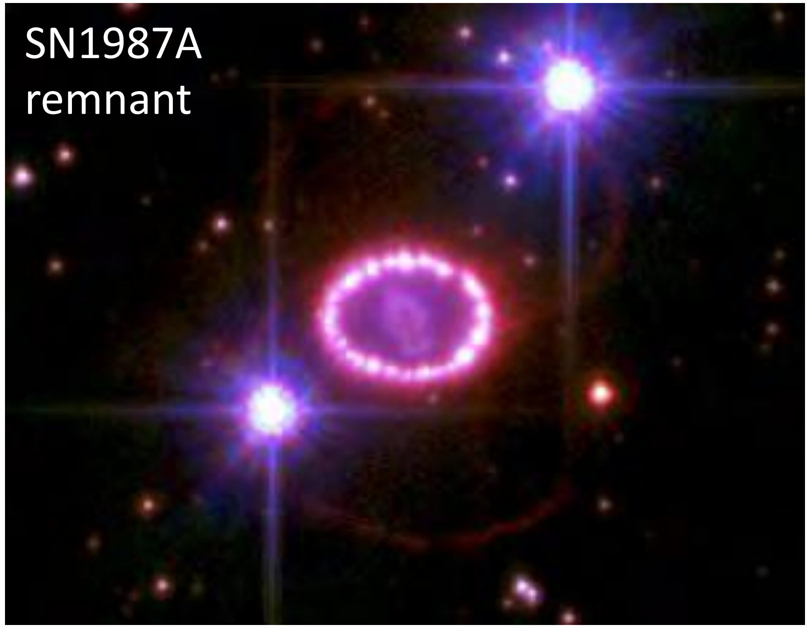
Outline for lecture II

- Supernovae: types and nucleosynthesis [3-7]
- Making the heaviest elements: neutron capture nucleosynthesis [9-19]
- Neutron star mergers: gravitational waves, kilonovae, and nucleosynthesis [21-30]
- Impact of nuclear physics uncertainties on *r*-process predictions [32-55]
- Galactic chemical evolution [57-60]


Supernova Types
Type I
No H in spectra
Ia
Si Absorption line @ 615nm
Found everywhere in the universe
Always same luminosity?
Ib
No Si
Ic
No Si, No He
Type II
H in spectra
May be further subdivided based on light curves
Found only in new star regions

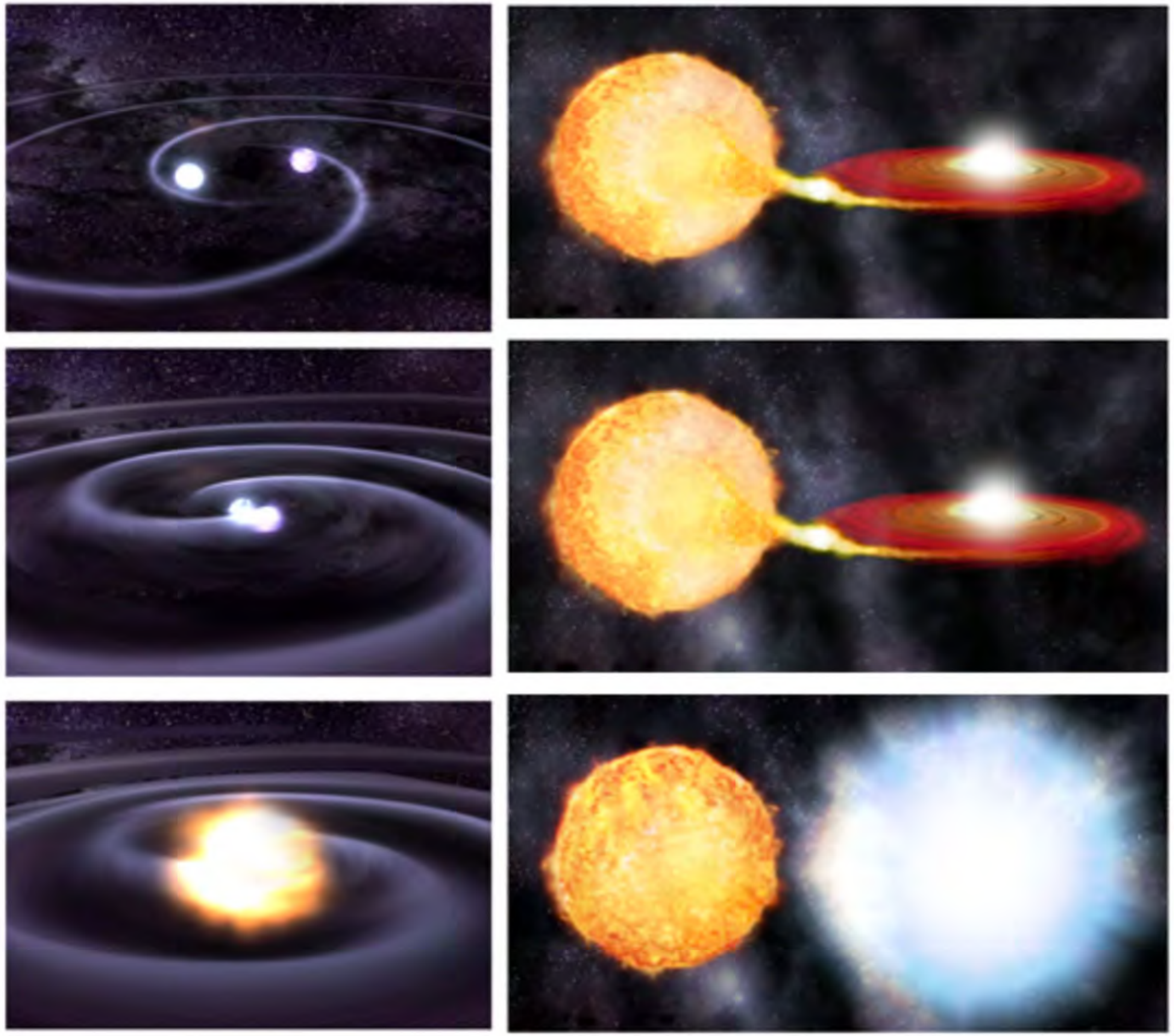

Tycho's SN: SNIa remnant


Cassiopeia A: Type II SN remnant
NEUTRON STAR ILLUSTRATION


SN1987A remnant

Thermonuclear Supernovae (Type Ia)

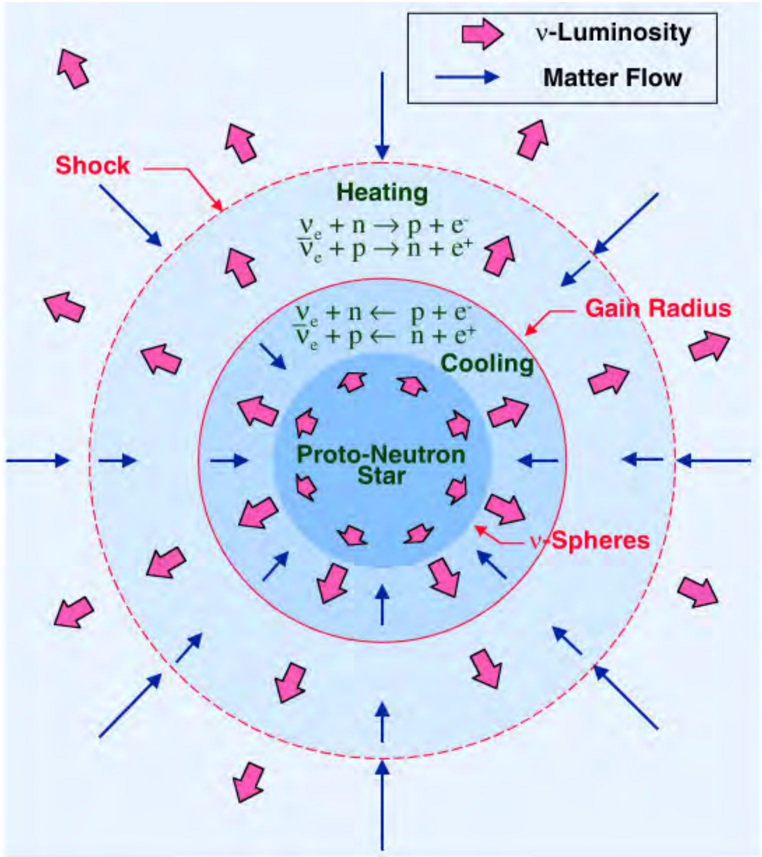
Double degenerate model   Single-degenerate model



- Single-degenerate model:
  - C-O white dwarf accretes H- or He-rich matter from a companion (main sequence star, red giant, or helium star); mass of white dwarf increases until approaches Chandrasekhar limit (1.4 $M_{\odot}$), triggering explosion
  - Explains similar peak luminosity and early spectra for SN-Ia since 1.4 $M_{\odot}$ implies natural limit on ^{56}Ni
  - main problem is must accrete 0.3 $M_{\odot}$ to explode since max white dwarf mass is 1.1 $M_{\odot}$

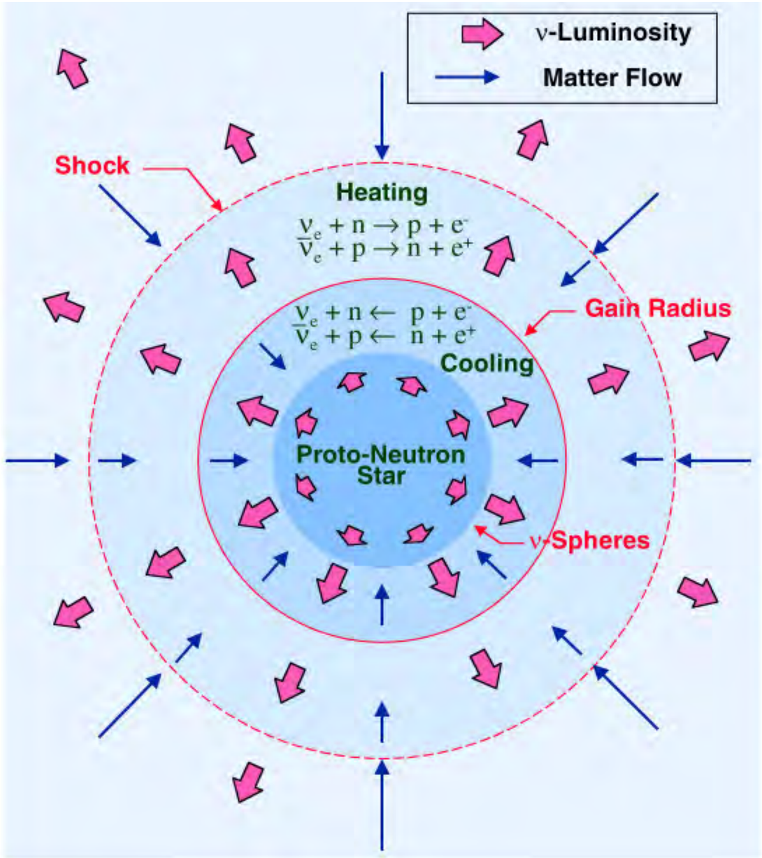
- Double-degenerate model:
  - Two C-O white dwarfs merge due to gravitational wave radiation, triggering explosion
  - Does not easily explain similar peak luminosity of SN-Ia due to wide range of ^{56}Ni production

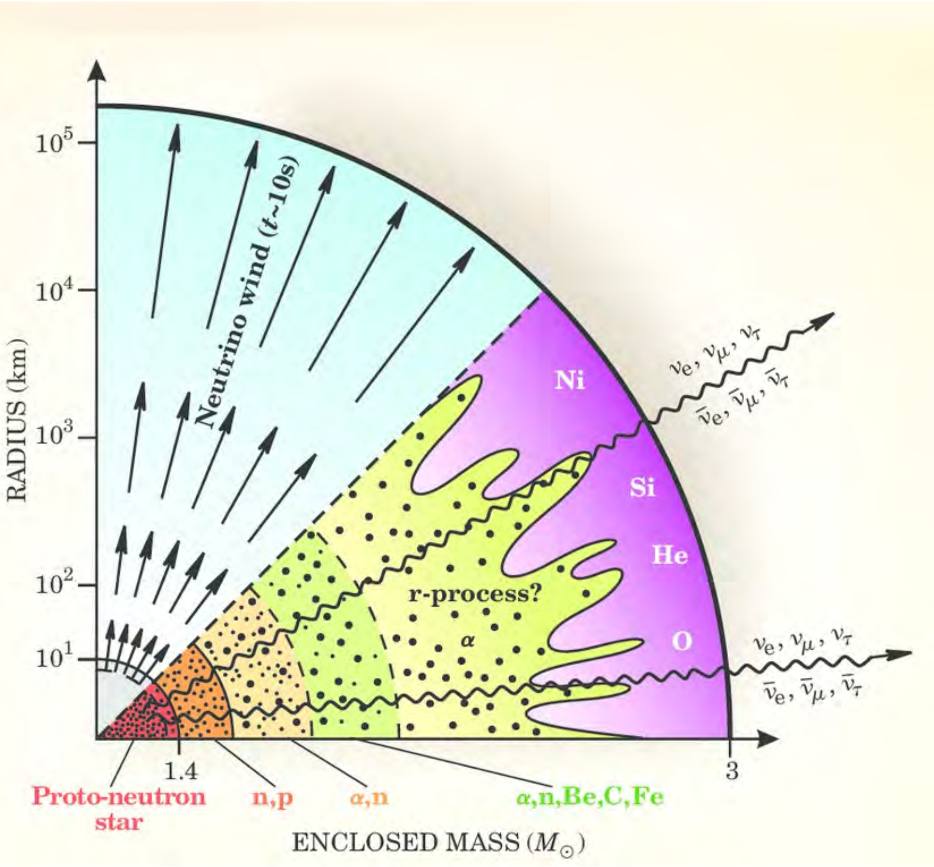
Core-collapse SN and neutrino-driven winds



- The proto-neutron star cools through neutrino emission (99% star's binding energy released as ν)
- Cooling via *Urca processes* (lepton + baryon → baryon + ν) as well as $e^+e^- \rightarrow \nu_l \bar{\nu}_l$ where $l = e, \mu, \tau$

Core-collapse SN and neutrino-driven winds





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

- The proto-neutron star cools through neutrino emission (99% star's binding energy released as ν)
- Cooling via *Urca processes* (lepton + baryon → baryon + ν) as well as $e^+e^- \rightarrow \nu_l \bar{\nu}_l$ where $l = e, \mu, \tau$

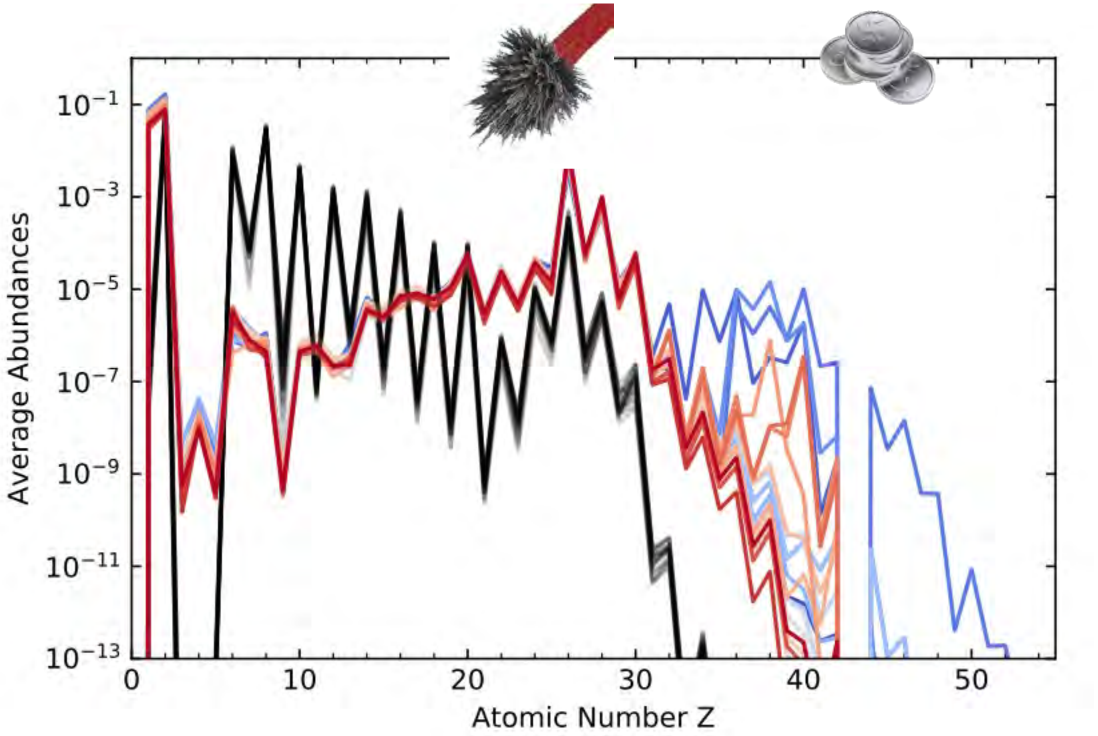
Supernovae and heavy elements?
Light heavy elements and (α,n) in core-collapse SN

All exploding 15 $M_\odot$ models

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 (right) find some cases develop neutrino driven winds but not a standard feature for successful explosions



Witt+21; see also Bliss+18

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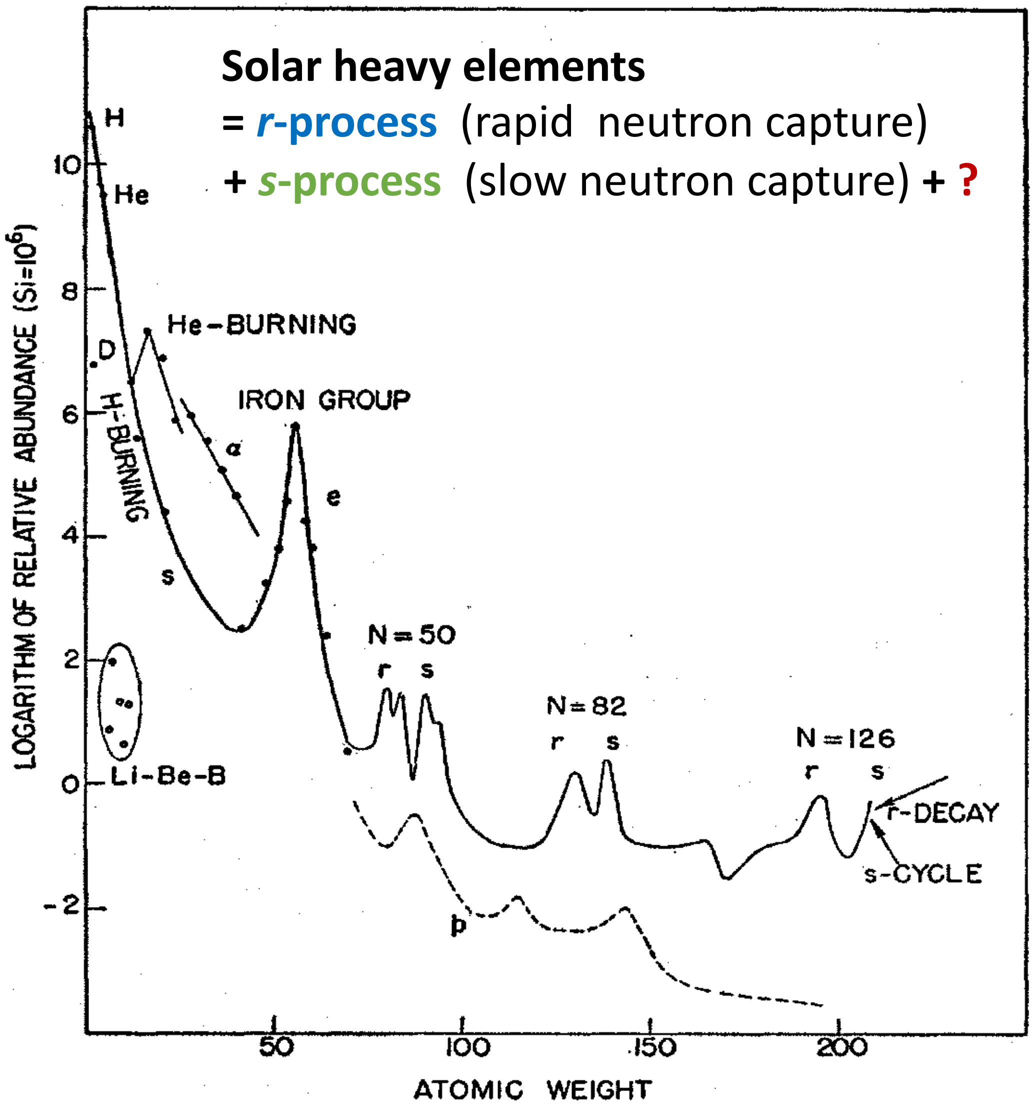
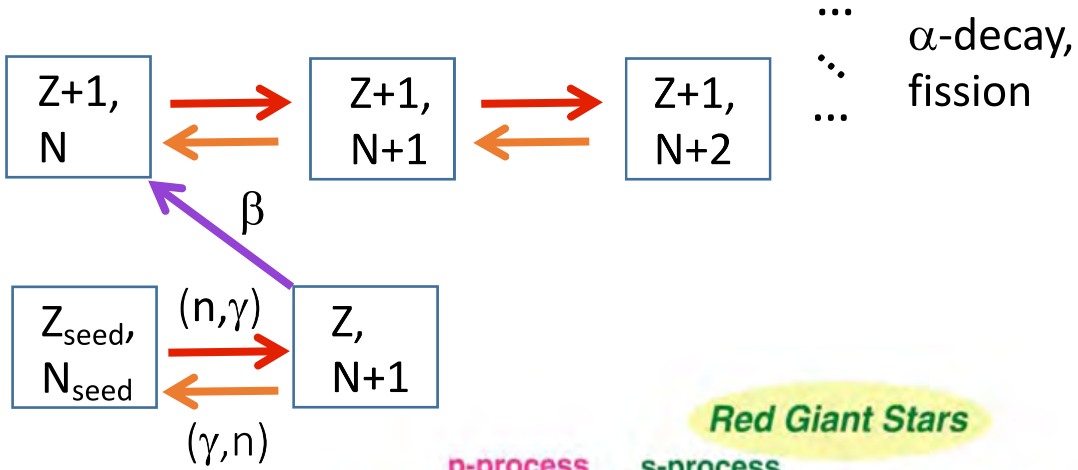
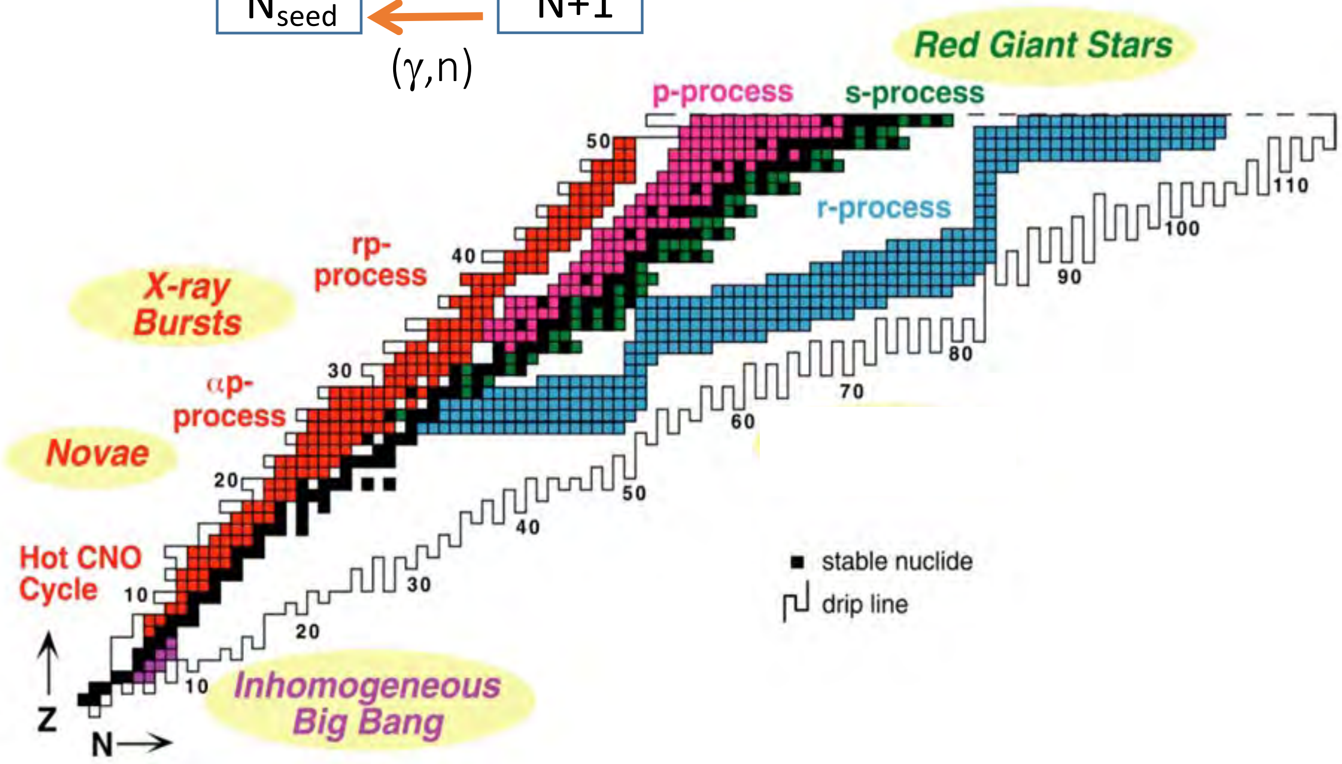
Neutron capture processes to make the heaviest elements



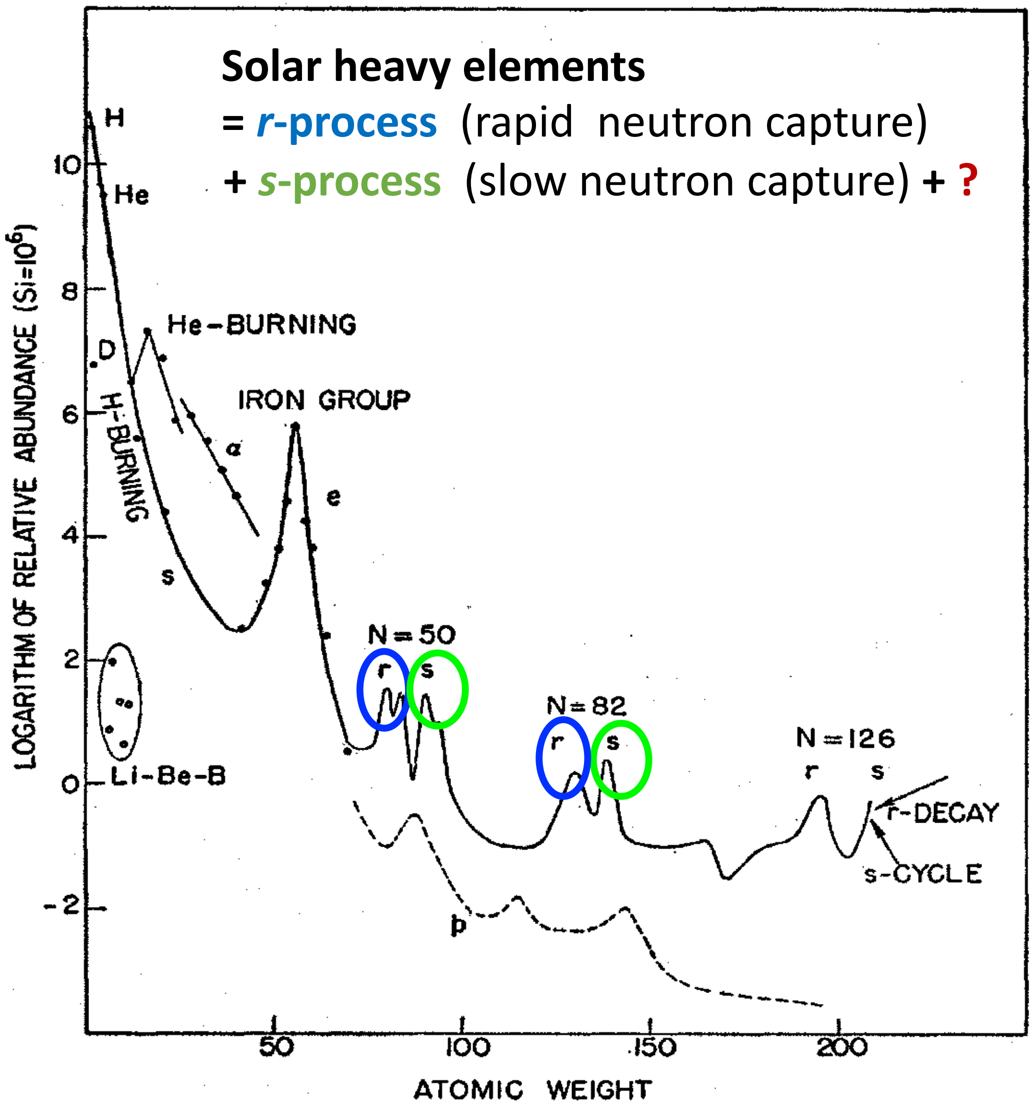
Burbidge, Burbidge, Fowler, and Hoyle (B²FH) (1957)





Smith&Rehm 01

Neutron capture processes to make the heaviest elements



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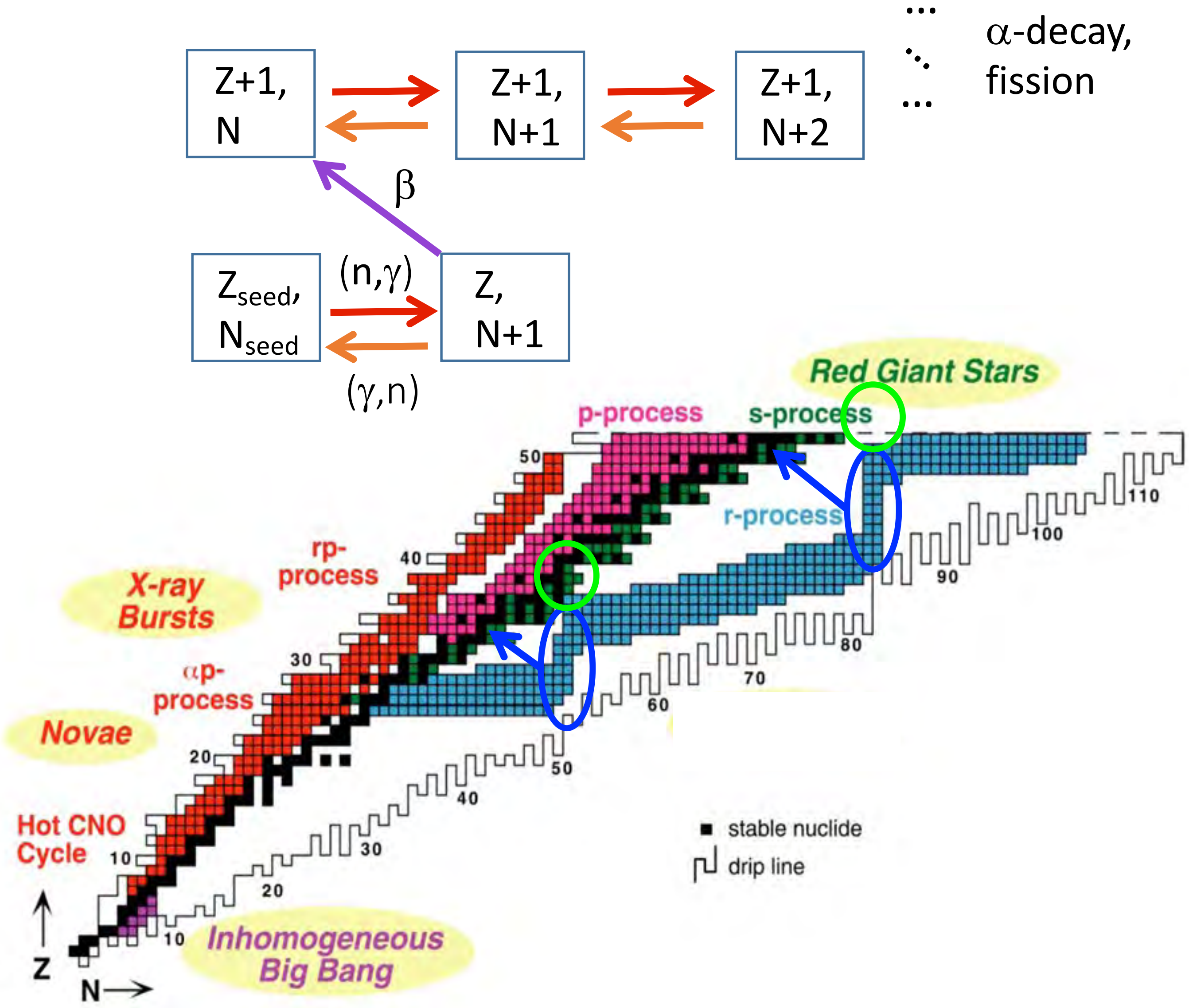

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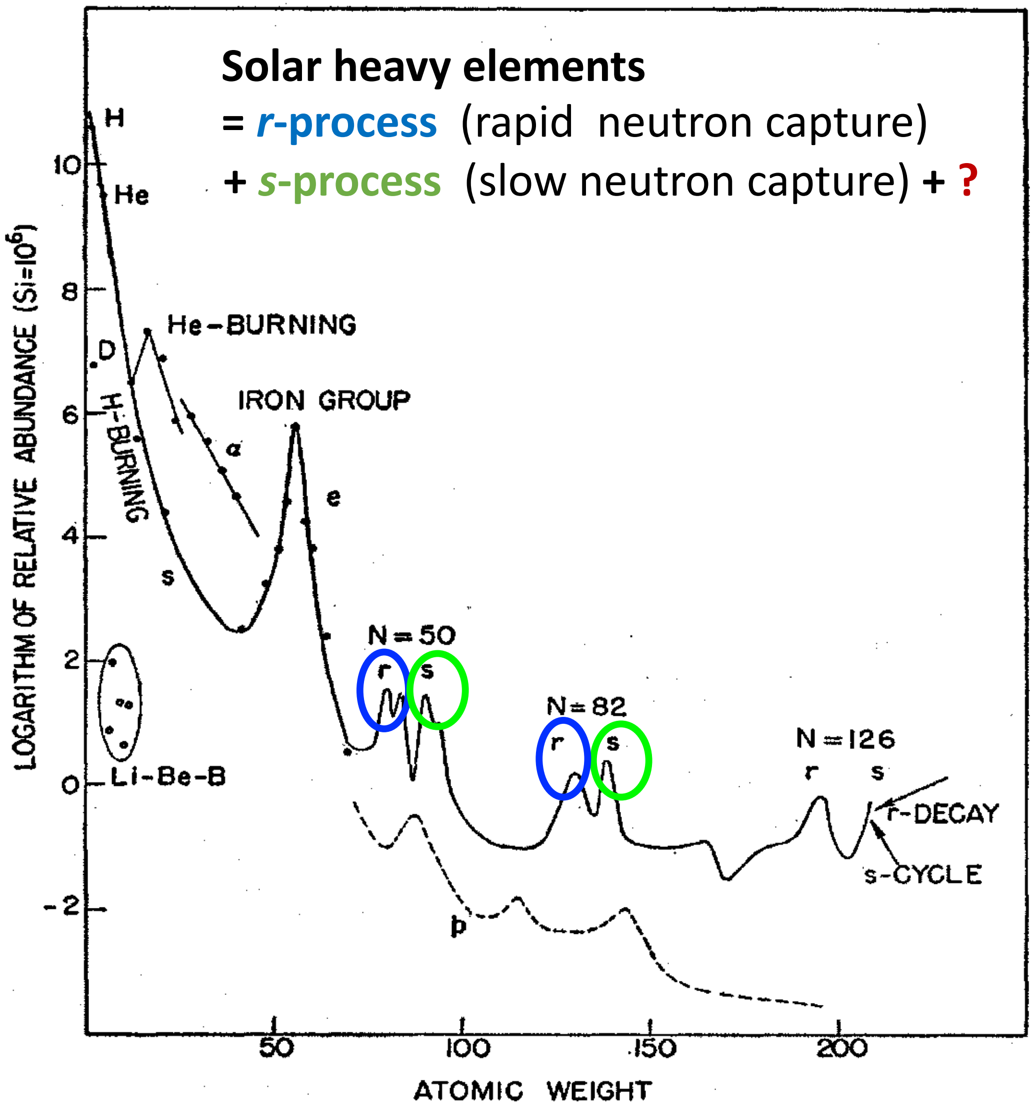

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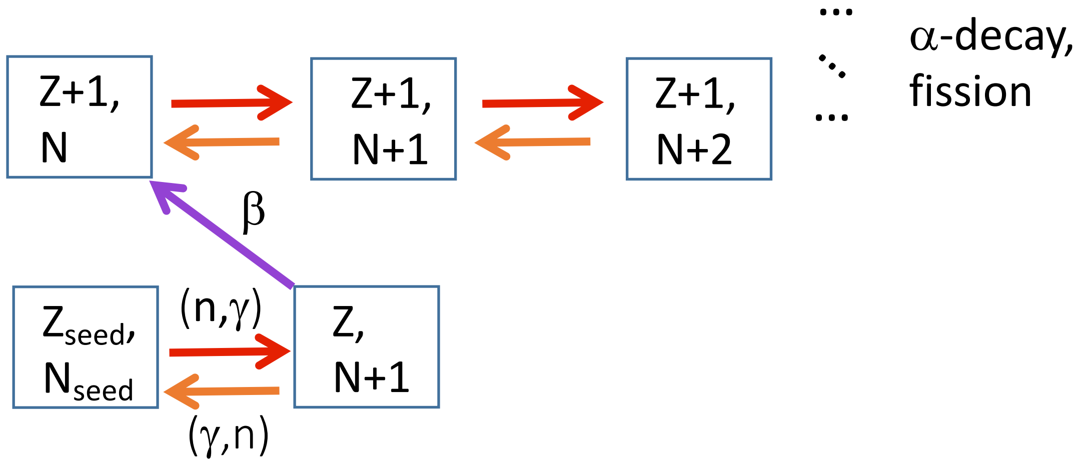
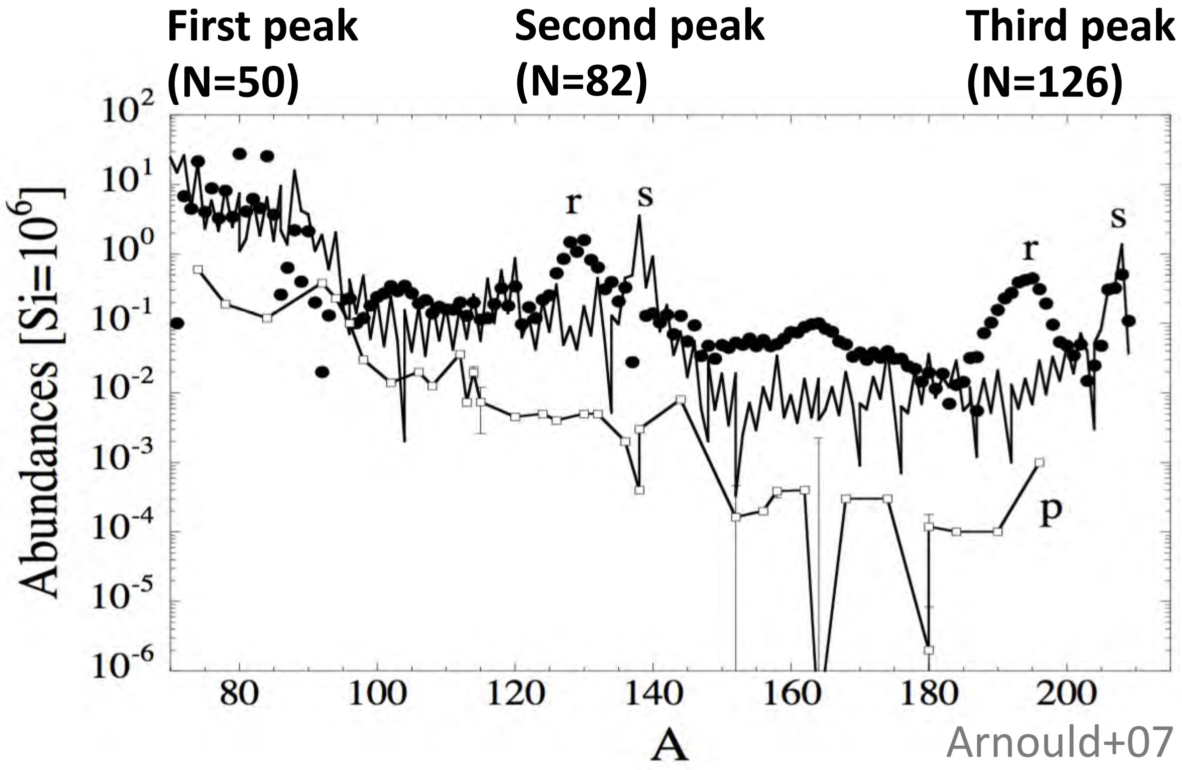




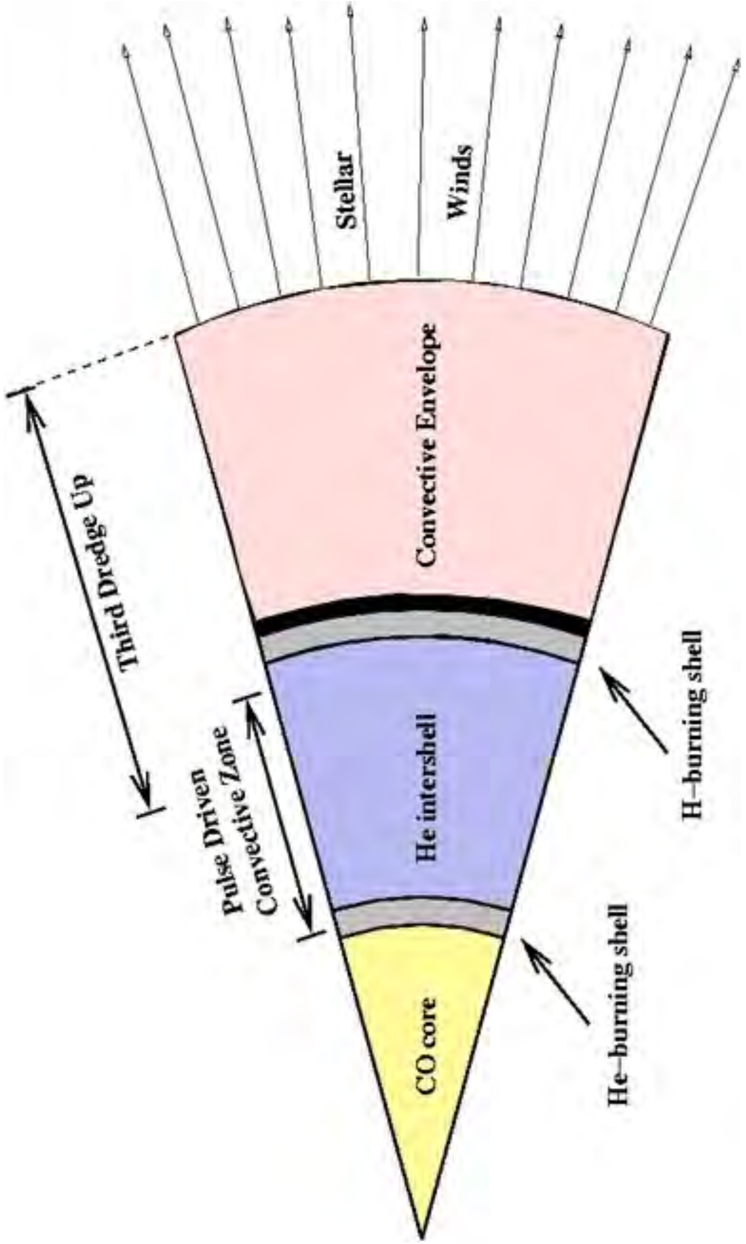
Arnould+07

Slow neutron capture (*s*-process) pathway

Courtesy of Maria Lugaro

- *s*-process number density of neutrons ~10^8 cm^{-3} (compare to ~10^{24} cm^{-3} for the *r* process)
- Capture is "slow" relative to β-decay; implies a path close to stable species
- Note how the different paths imply some isotopes to be s-only or r-only
- *s*-process "seeds" are heavy nuclei such as ^{56}Fe (star enriched by past events)

Slow neutron capture (*s*-process) in AGB stars

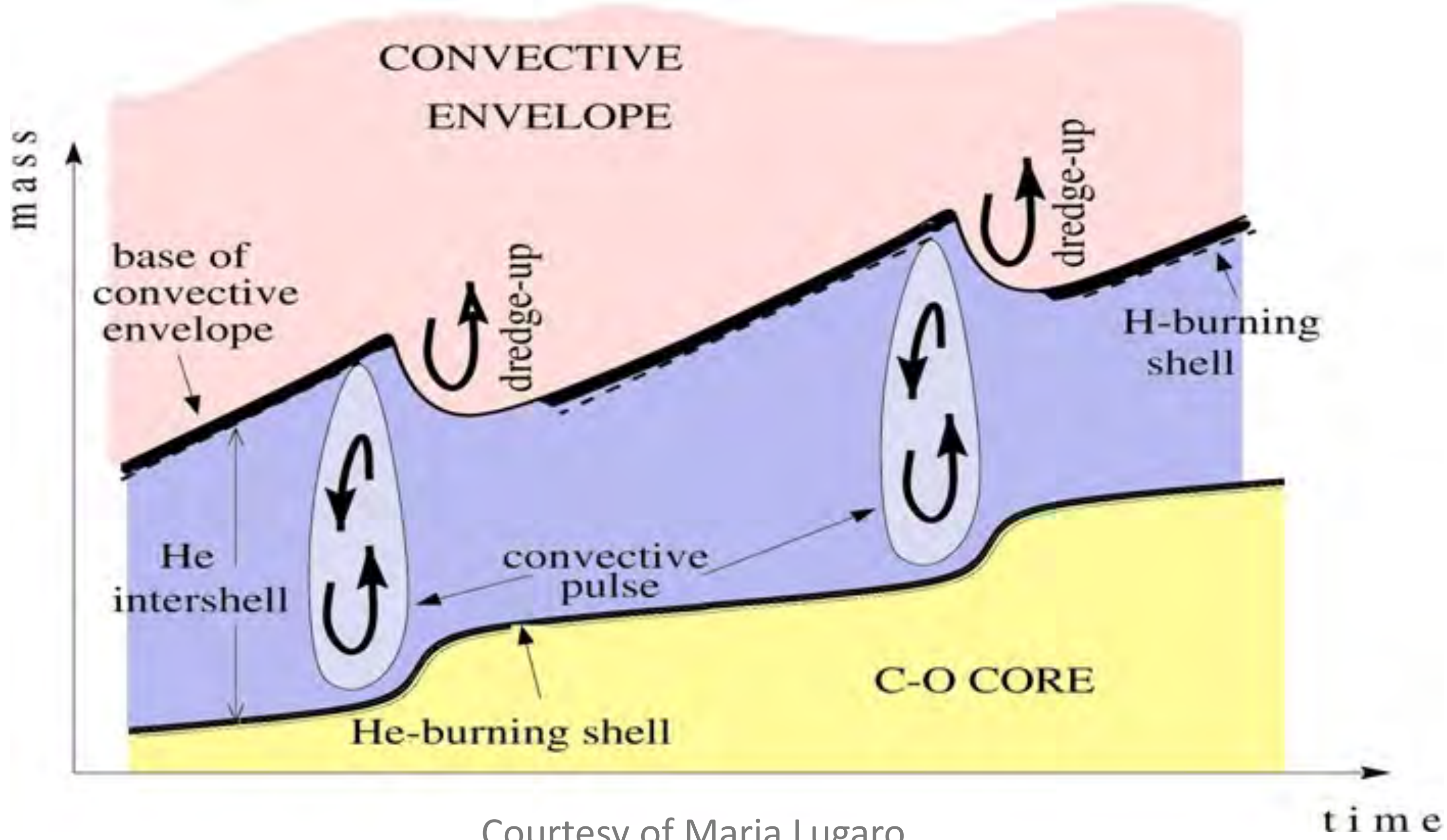


Where do the neutrons come from?

$$^{12}C(p,\gamma)^{13}N$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_{e}$$

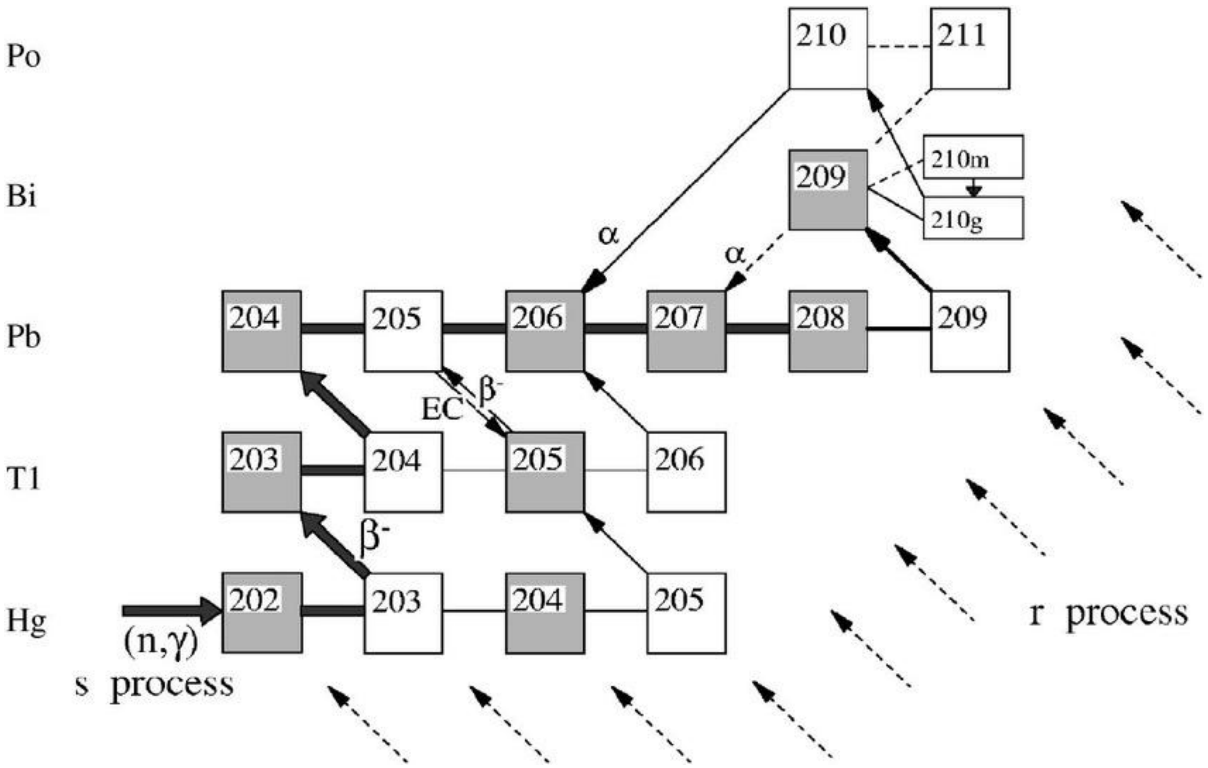
$$^{13}C(\alpha,n)^{16}O$$



Courtesy of Maria Lugaro

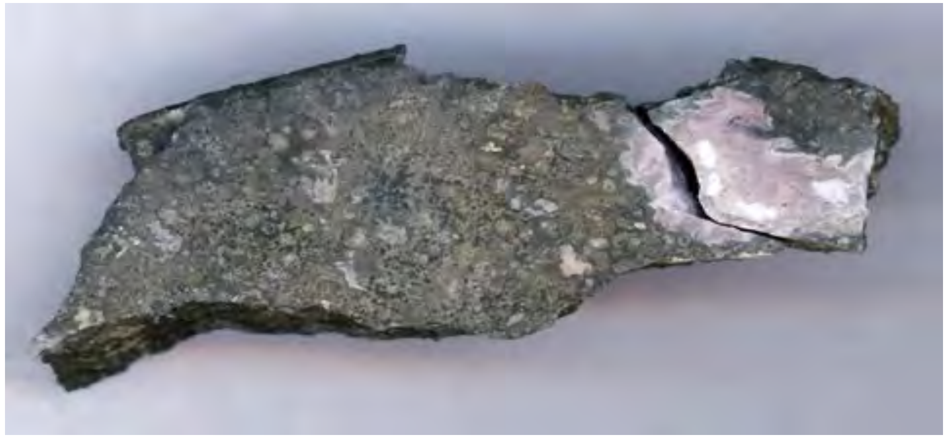
How do we know there is something more than an *s*-process?
Actinides (Z=89-103)

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

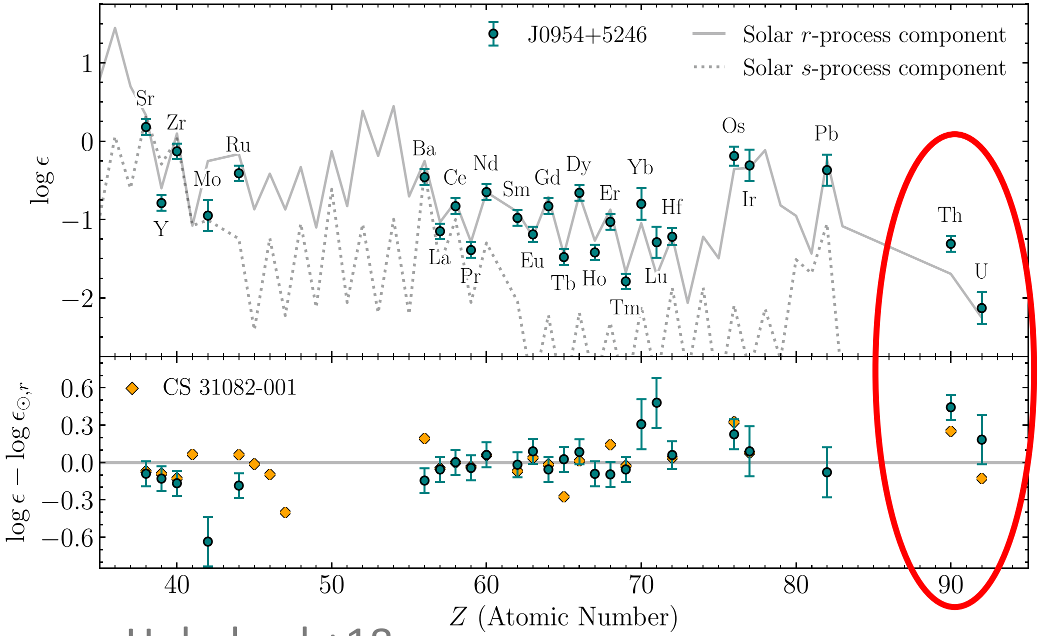


Ratzel+04

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



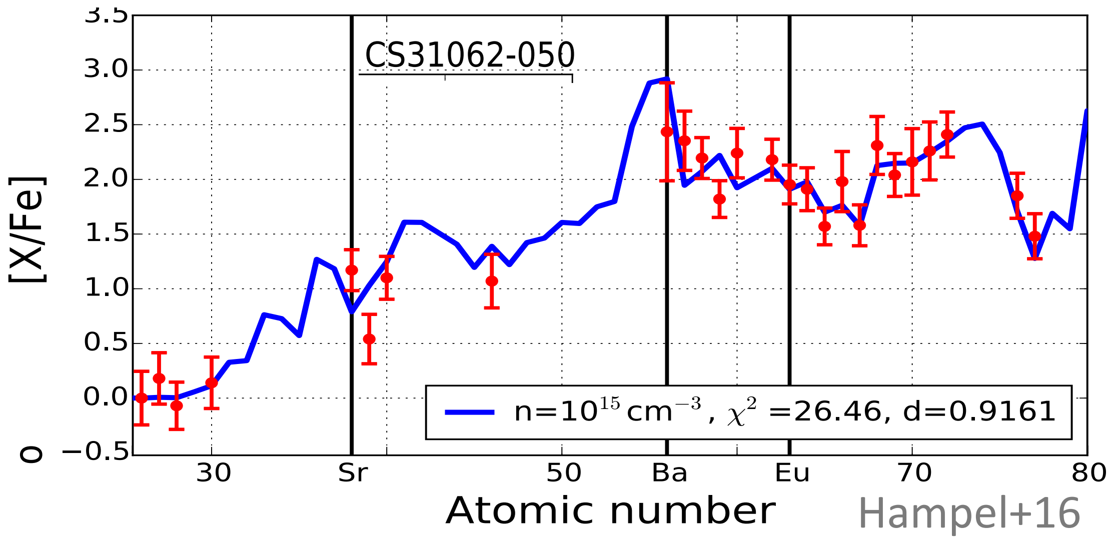
Actinide boost stars compared to solar



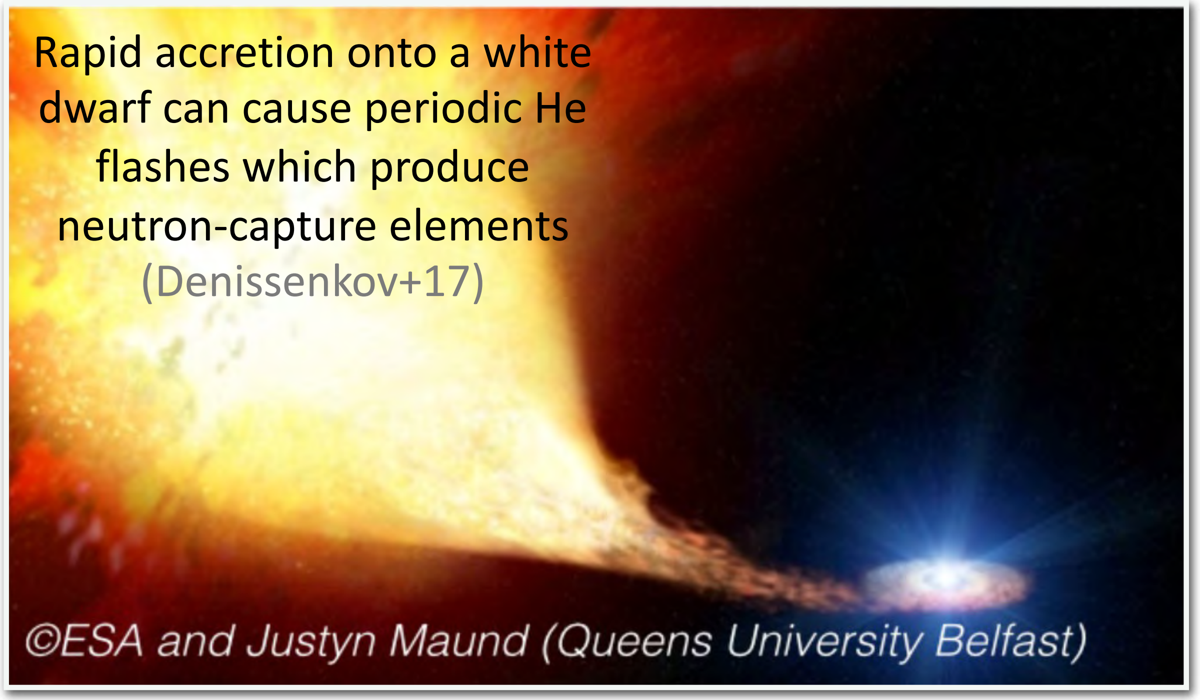
Holmbeck+18

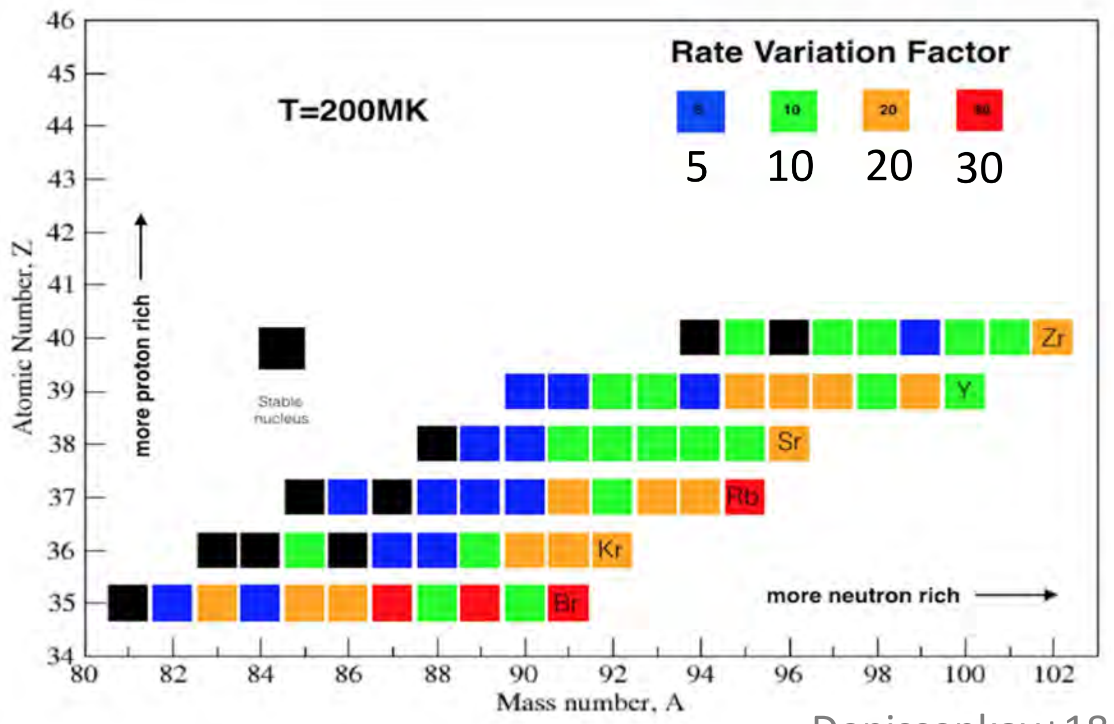
The intermediate neutron capture process (*i*-process): CEMP-i stars and (n,γ) uncertainties

Best fit when use neutron densities << *r*-process



Hampel+16





Denissenkov+18

(n,γ) rate variations informed by variations on theoretical **γ-strength functions** and **nuclear level densities**

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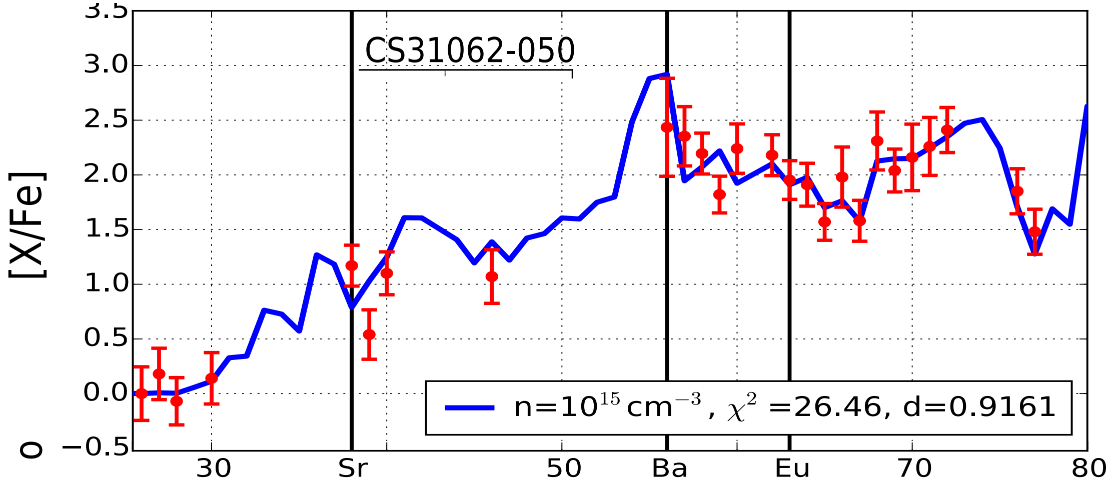

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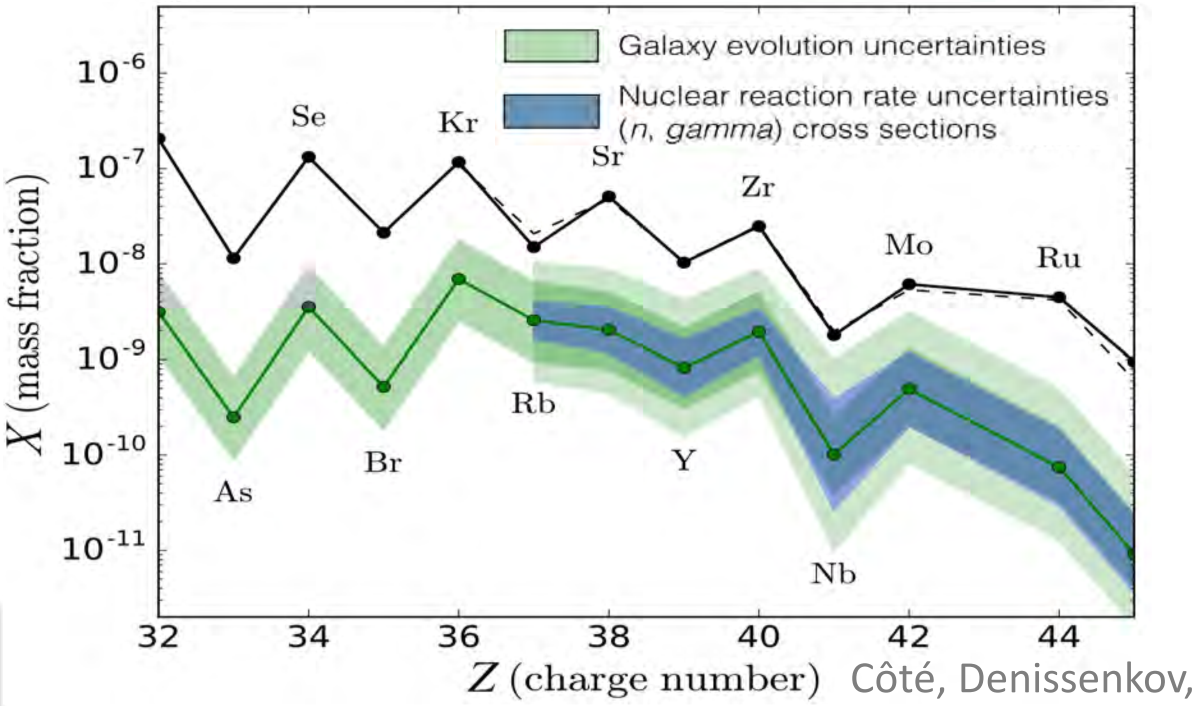
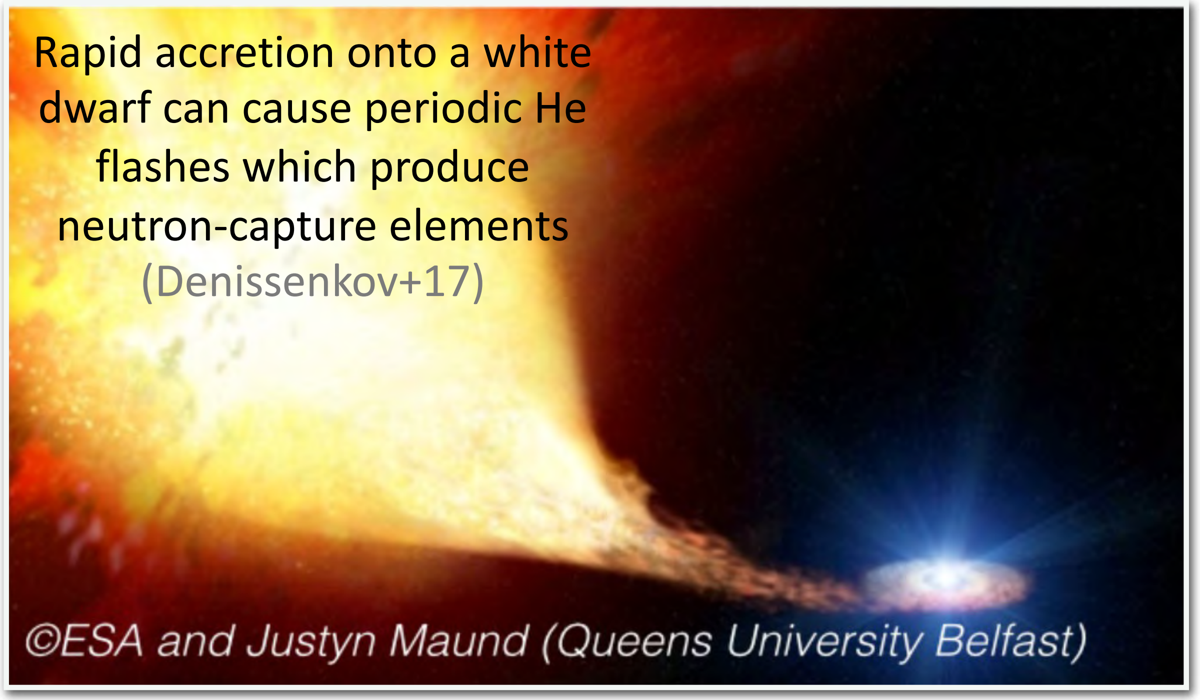


Côté, Denissenkov, Herwig+18

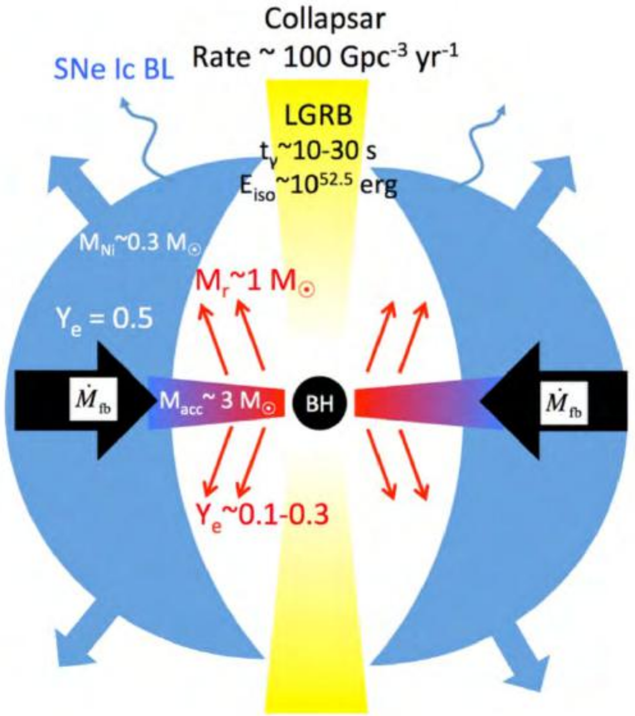


(n,γ) rate variations informed by variations on theoretical **γ-strength functions** and **nuclear level densities**

(n,γ) uncertainties introduce up to ~an order of magnitude uncertainty in the RAWD contribution to solar system heavy elements

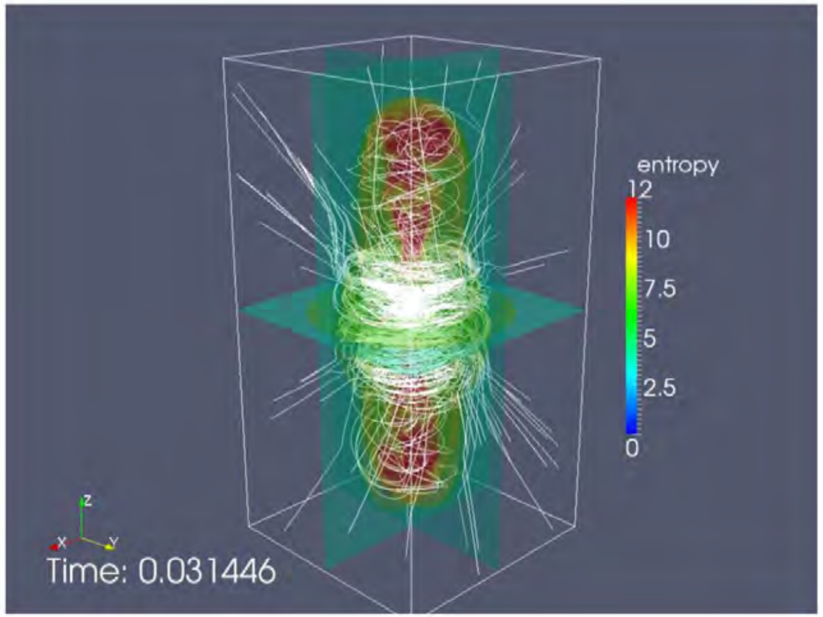
Some candidate sites for *r*-process element production

Collapsar disk winds



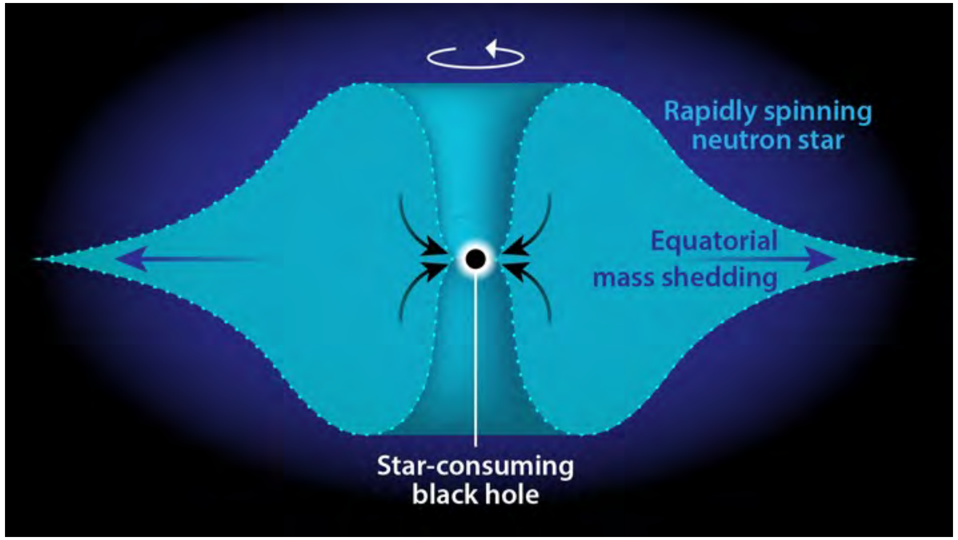
Siegel+18; see also McLaughlin&Surman 05, Miller+19

Magneto-rotationally driven (MHD) supernovae



Winteler+12; see also Mosta+17

Primordial black hole + neutron star

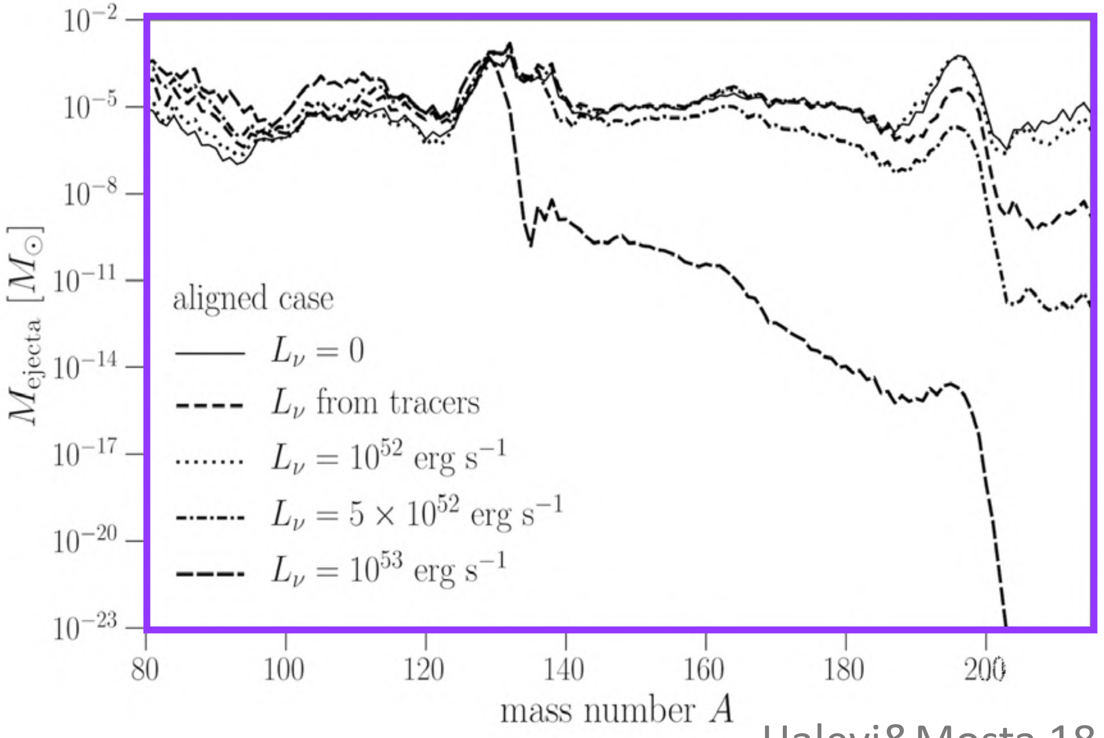


Credit: APS/Alan Stonebraker, via *Physics*

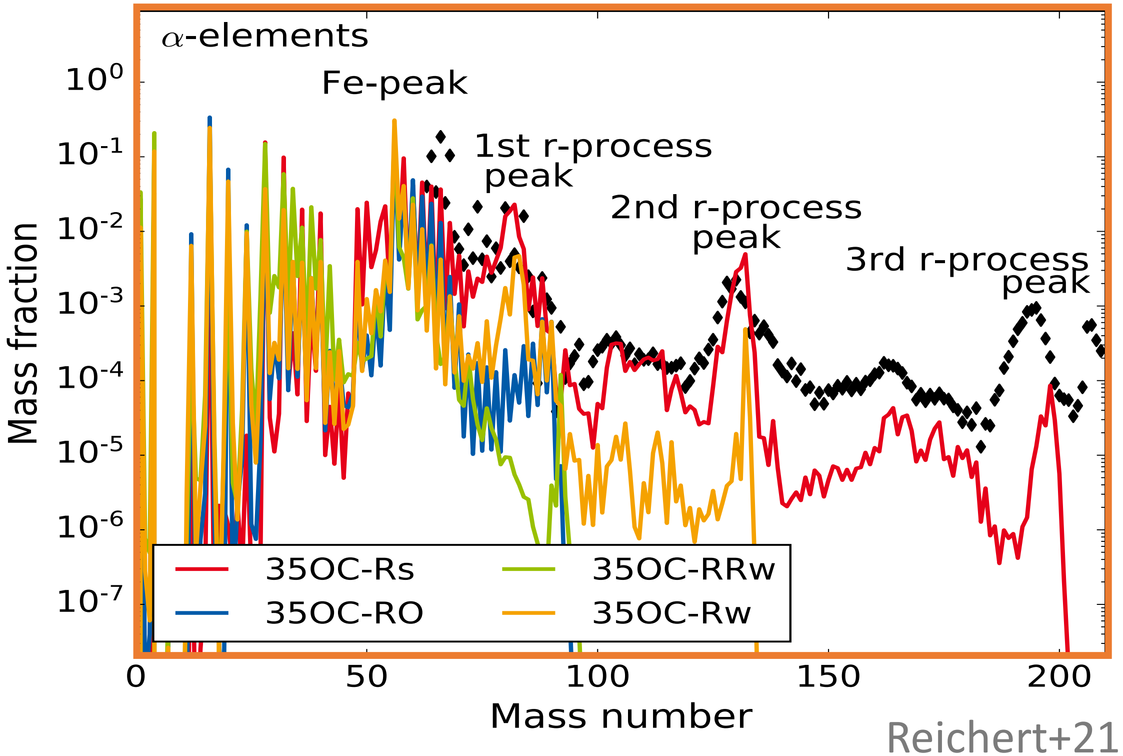
Fuller+17

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

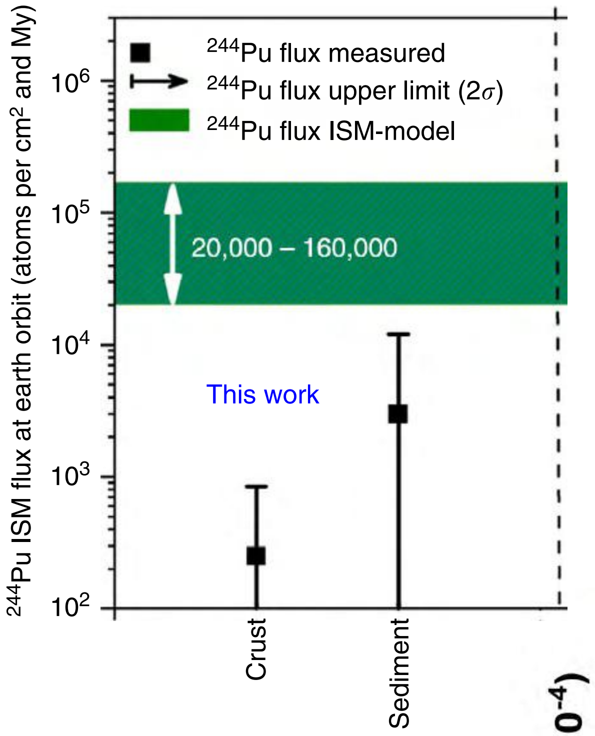


Reichert+21

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)

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

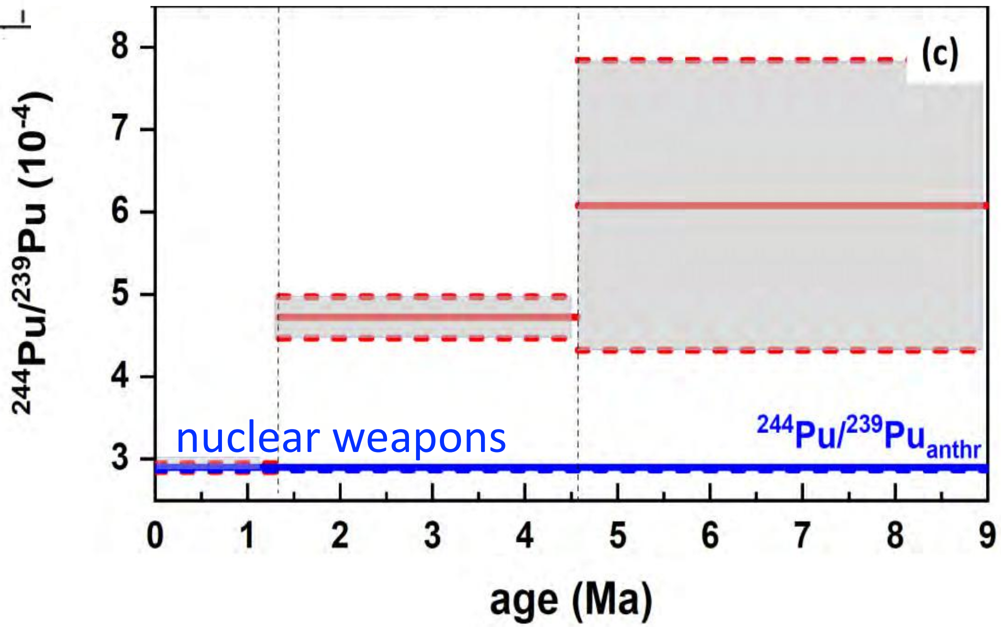


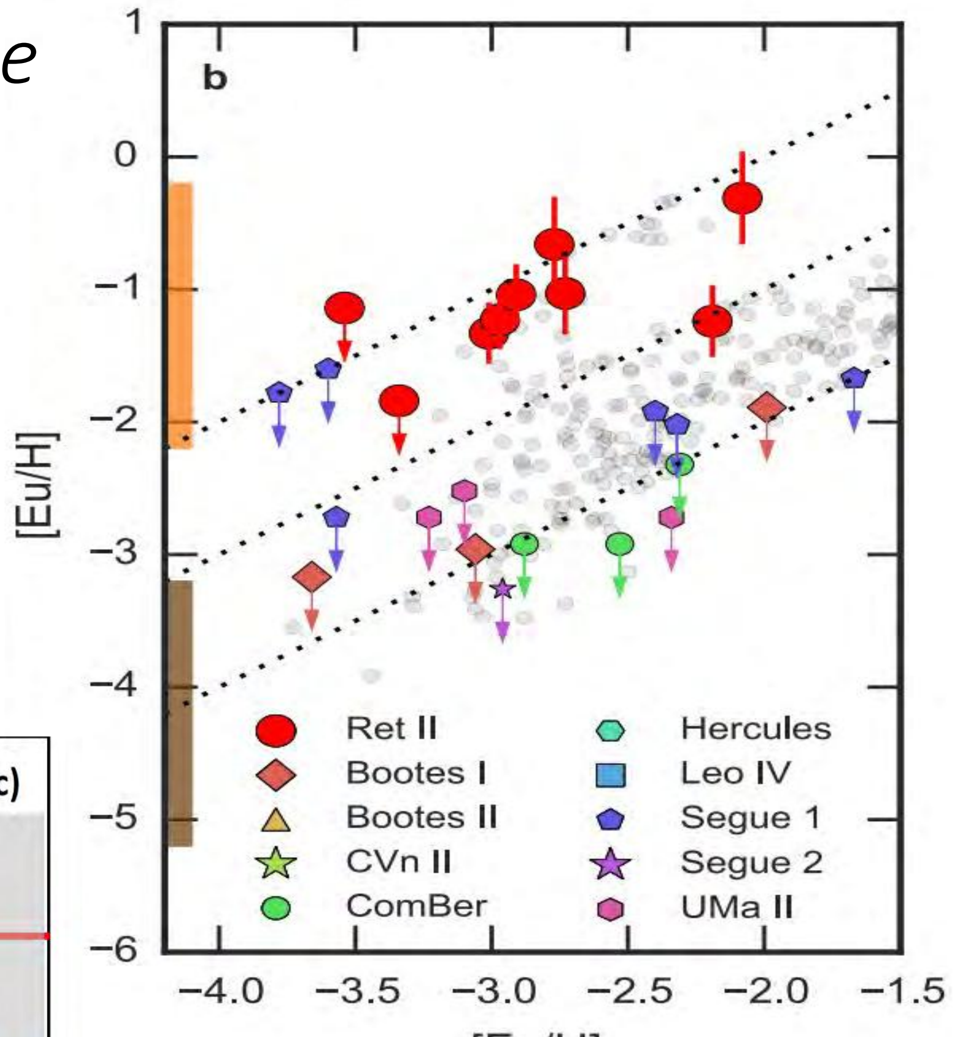
Pu-244 in deep-sea ocean crusts compared to a model which assumes a source as frequent as supernova

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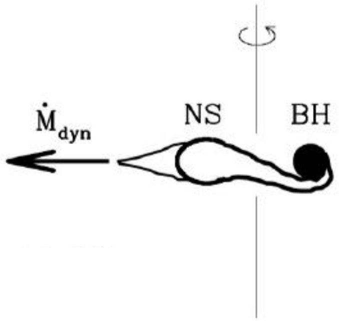
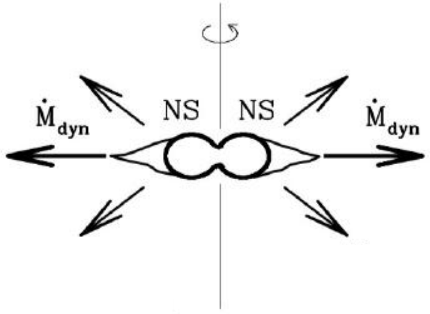
Neutron star mergers and the *r* process: a bit of history

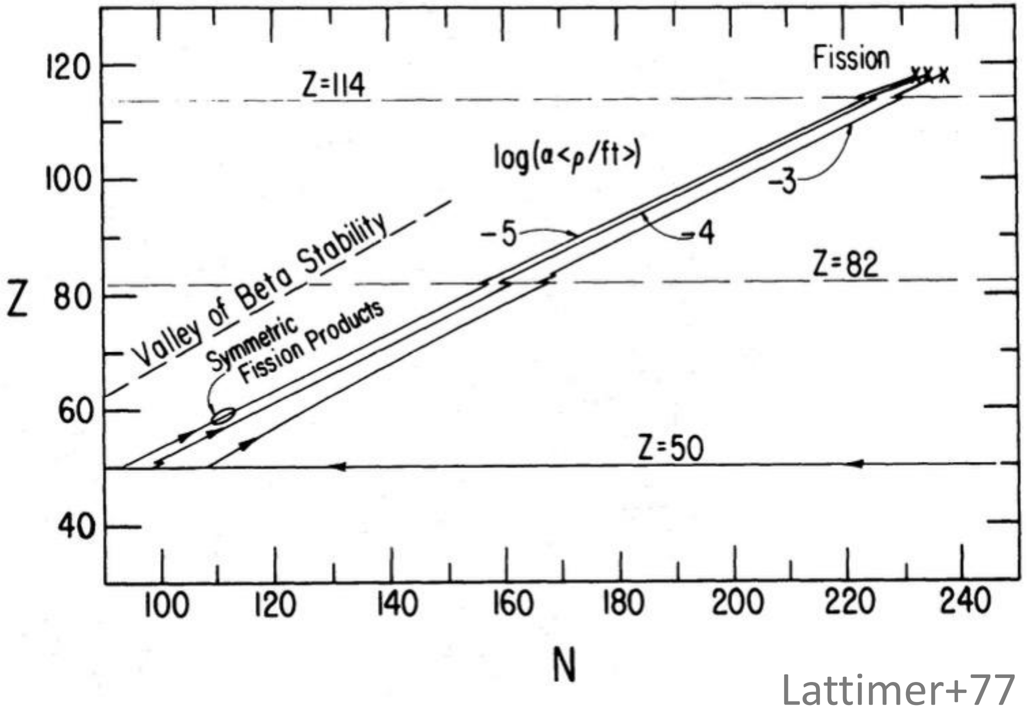
Neutron-rich ejecta from neutron stars > 40 years ago



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

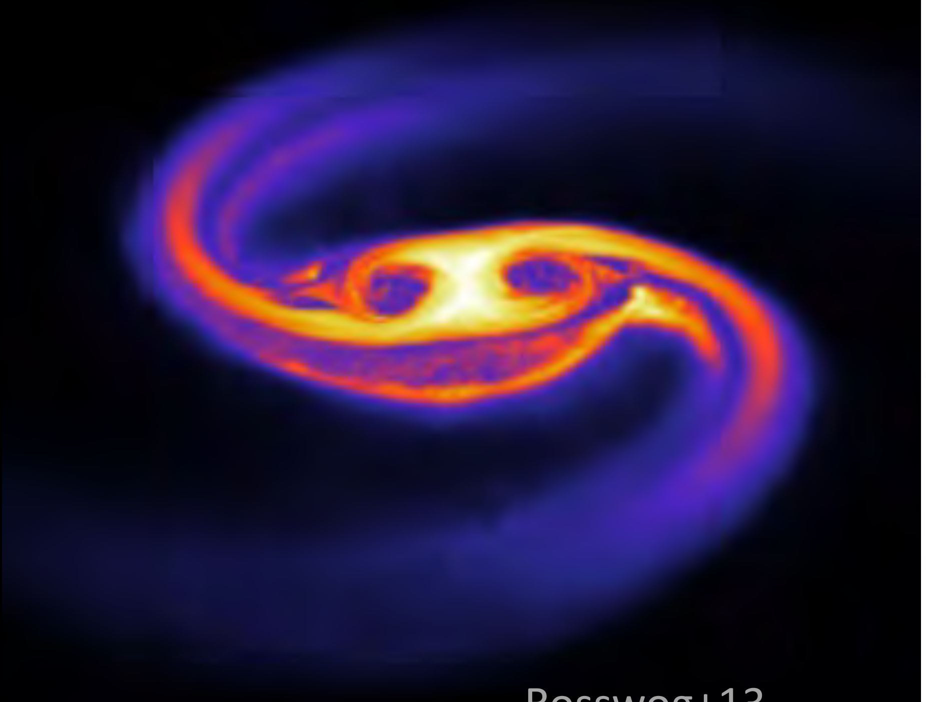


Lattimer+ (1977): initially cold, expanding neutron star matter → fission cycling *r* process capable of super heavy element formation



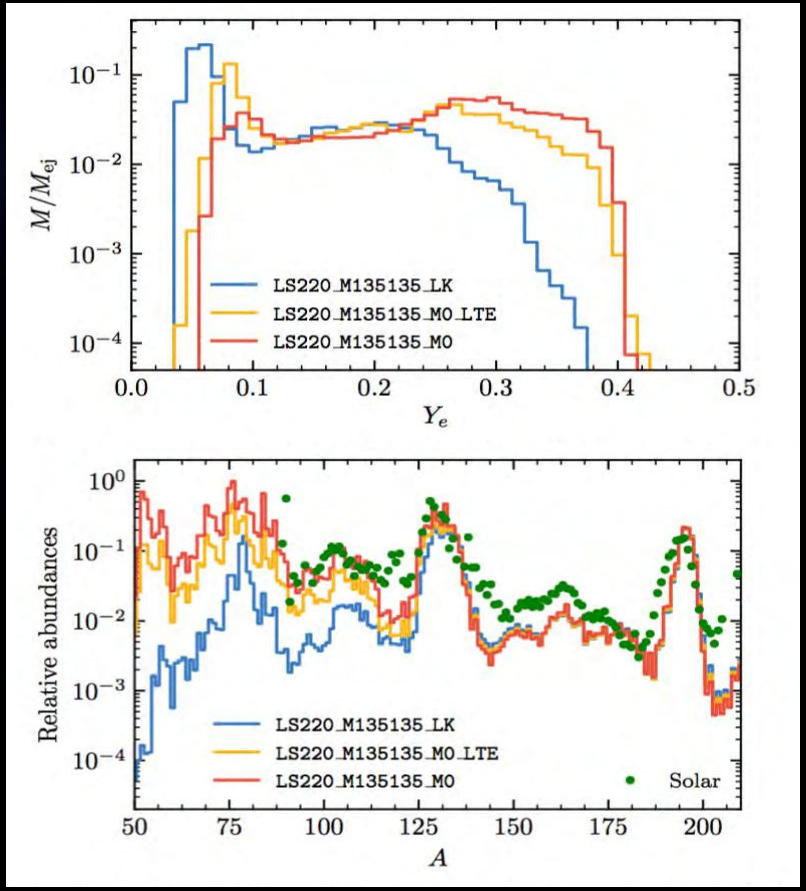
Lattimer+77

NSM dynamical ejecta



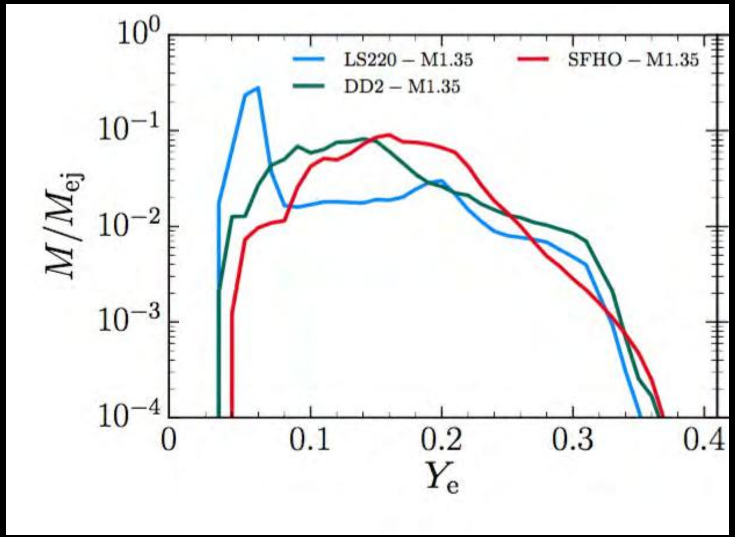
Rosswog+13

Effect of neutrinos



Radice+19; see also Perego+19

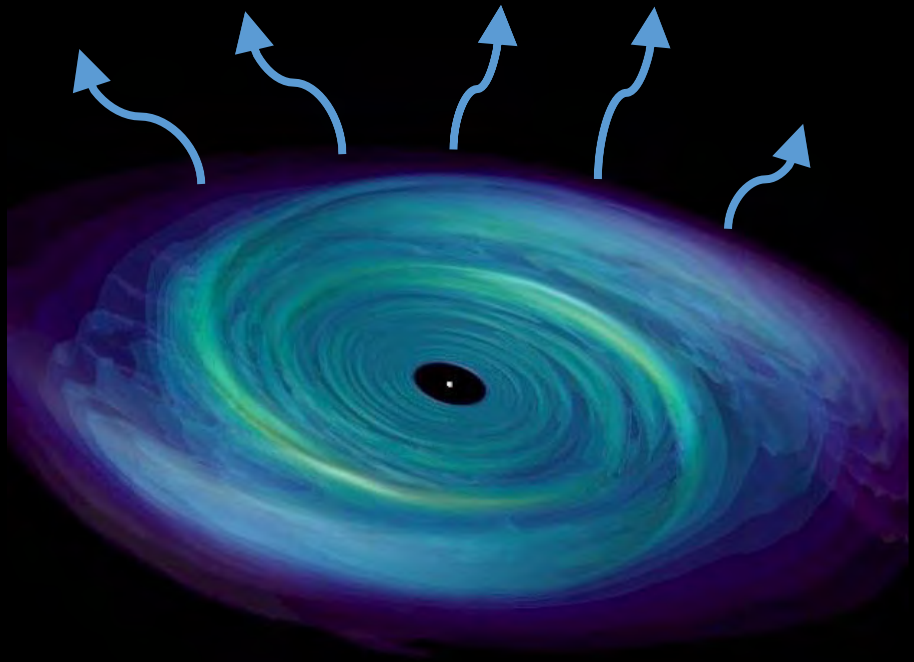
Equation of state



Bovard+17

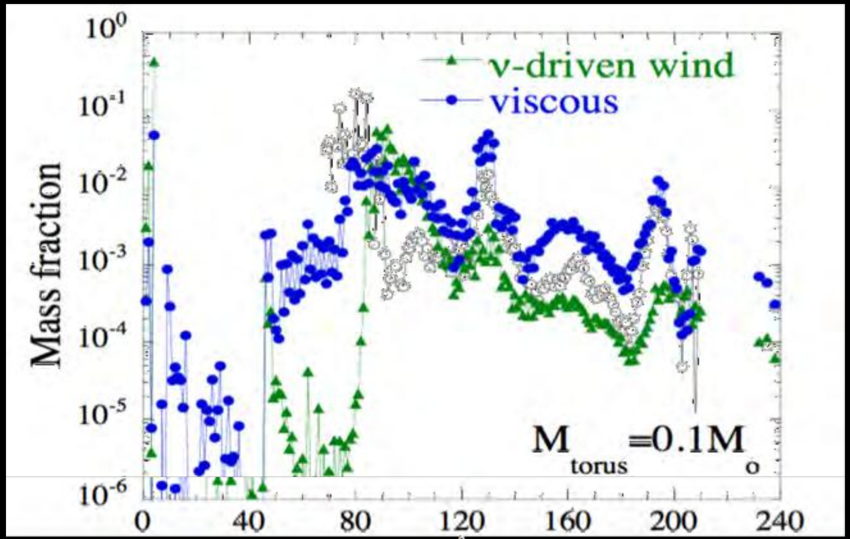
See also Wanajo+14, Vincent+19, Foucart+20….

Post-merger disk ejecta

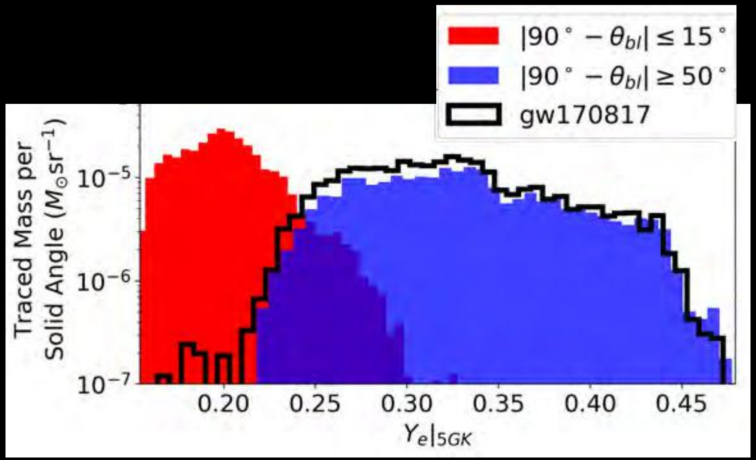


Owen&Blondin 05

Neutrino driven vs viscous



Just+16



Miller+19

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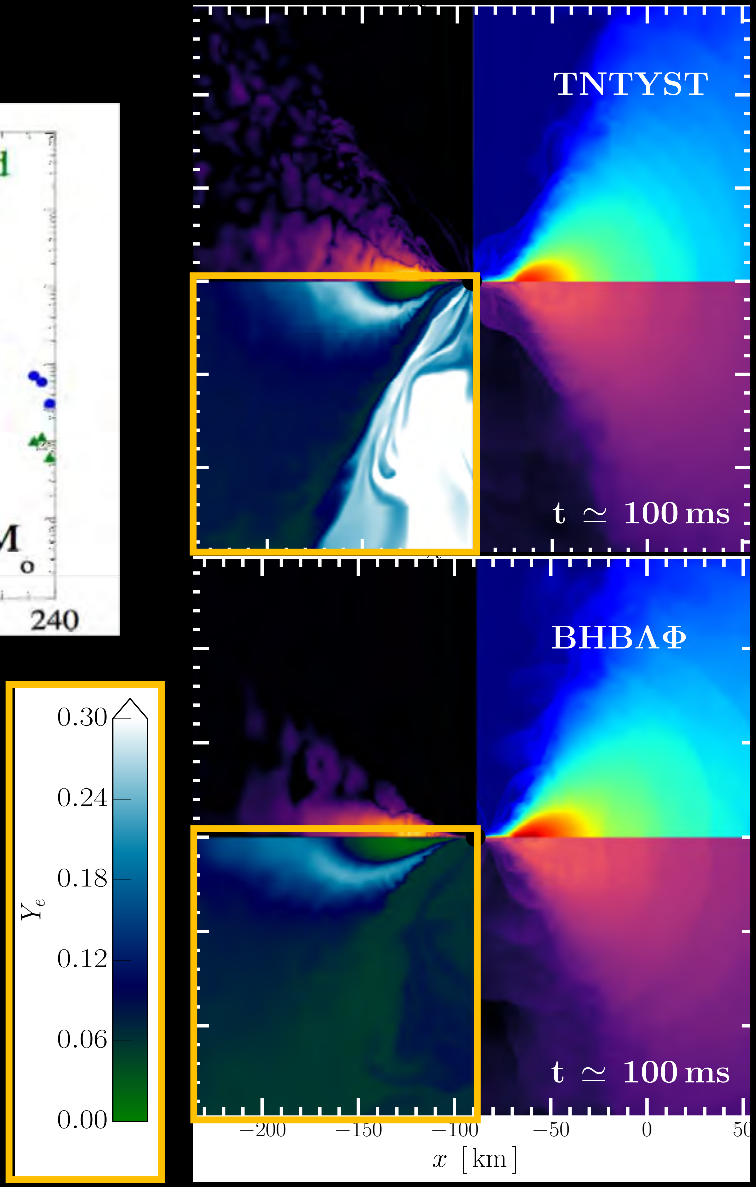
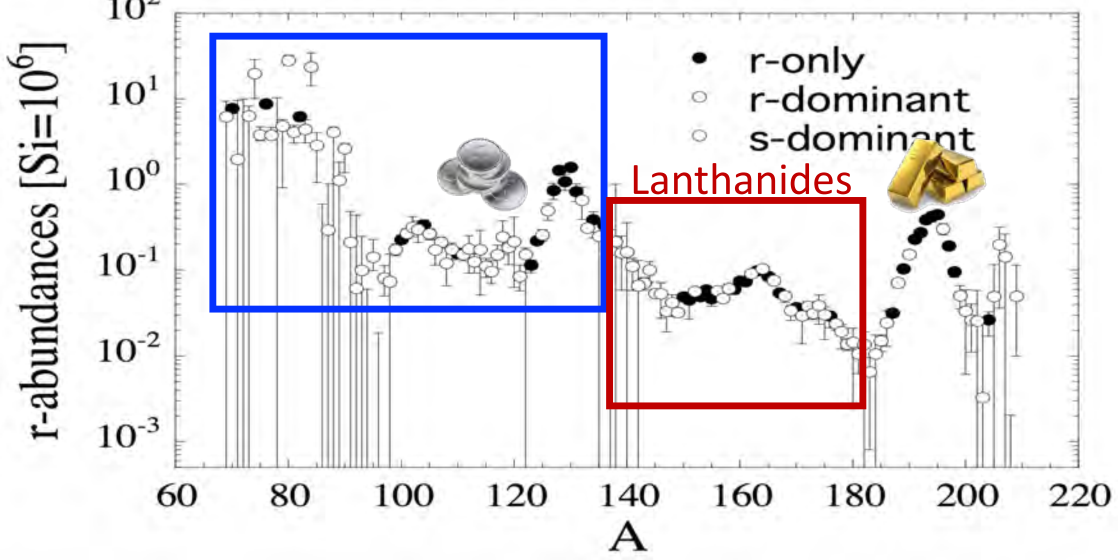


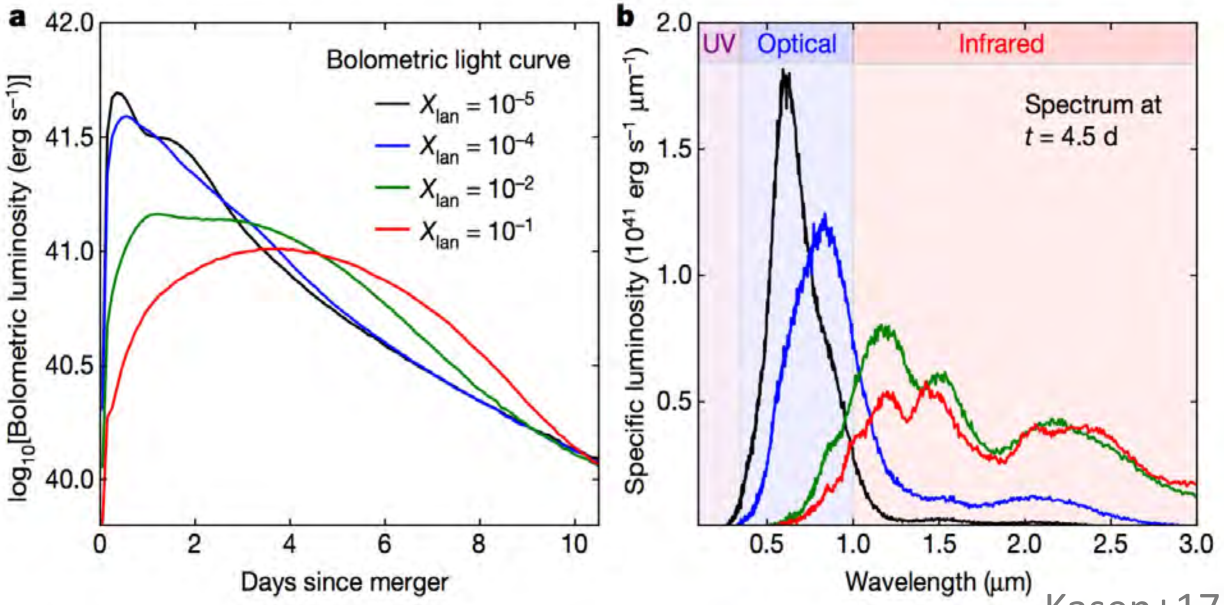
Most+21

GW170817 & AT2017gfo: “red” and “blue” kilonovae

Arnould+07



Model



Kasen+17

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)

GW170817 & AT2017gfo: “red” and “blue” kilonovae

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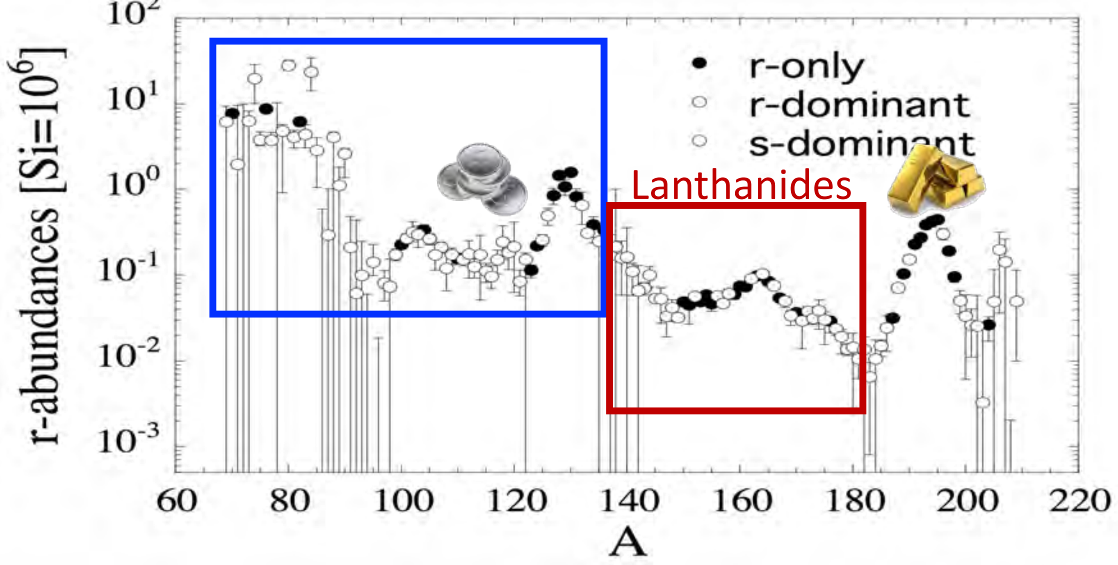
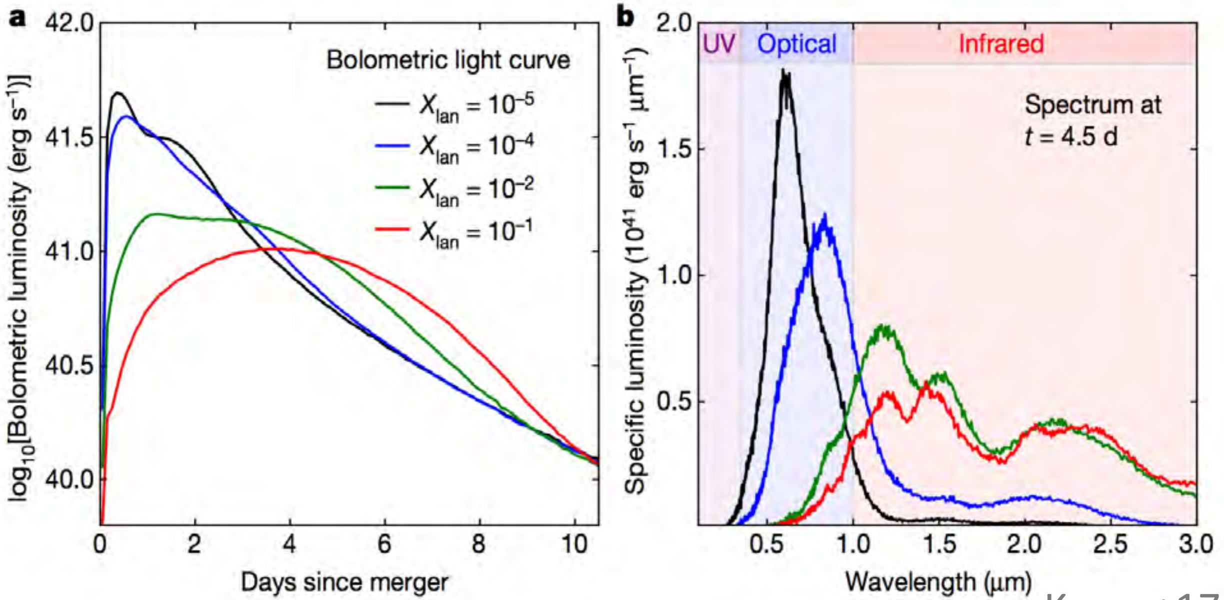
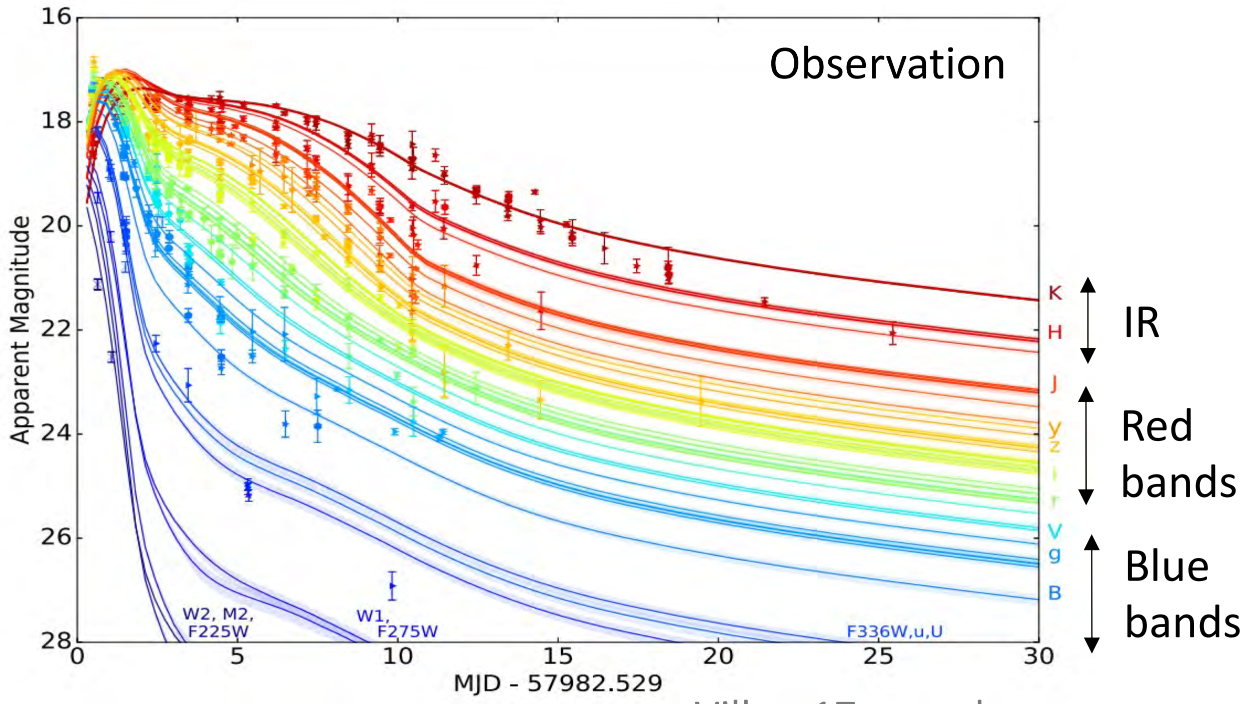
Arnould+07



Model



Kasen+17



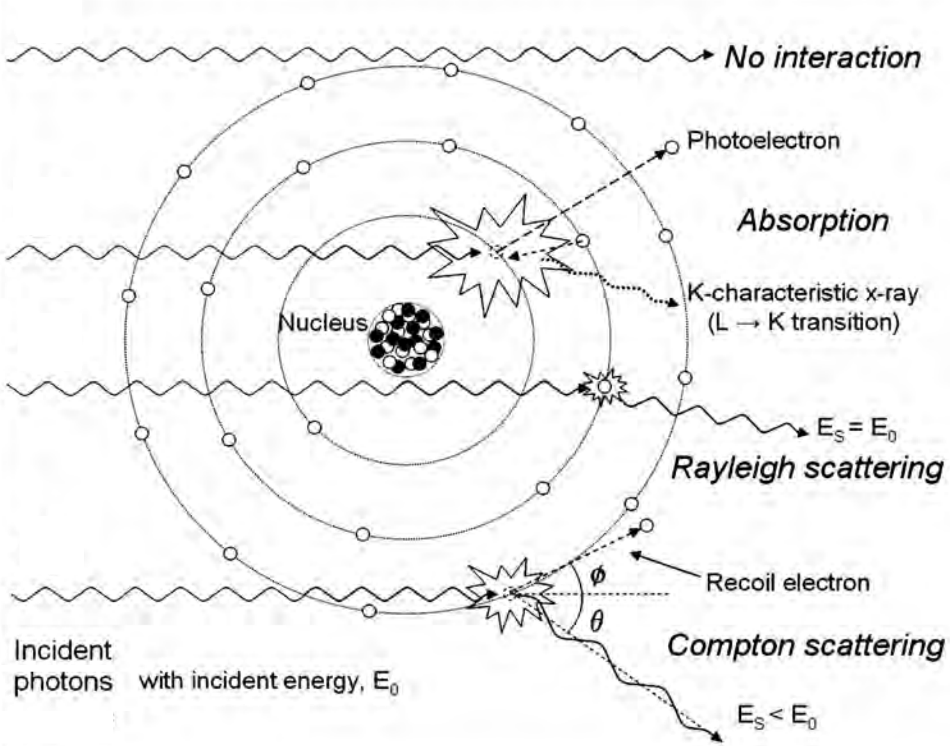
Days

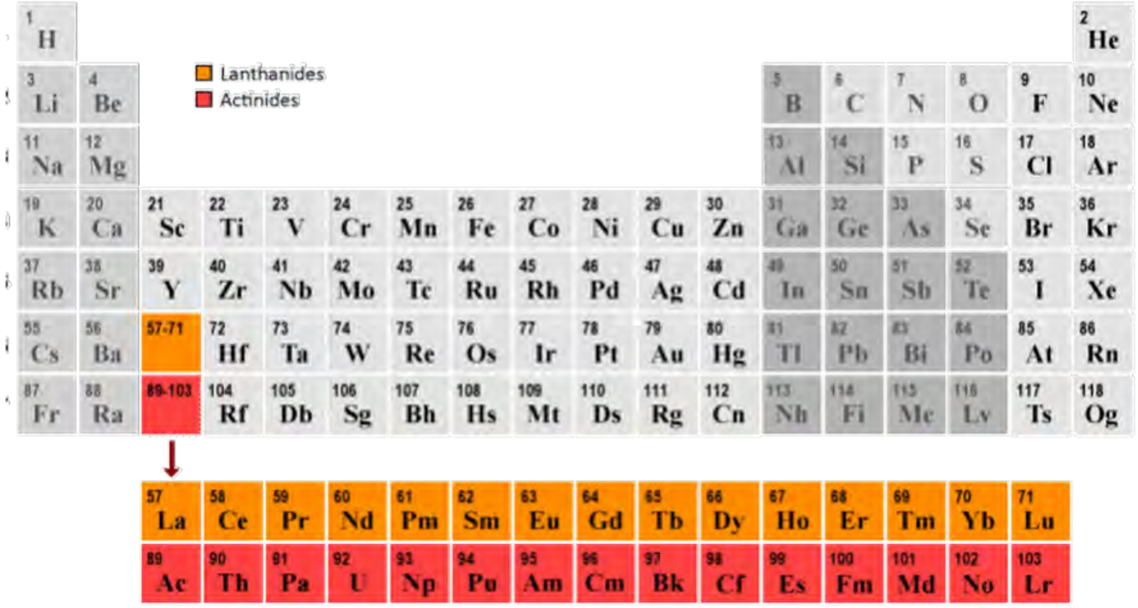
Villar+17; see also Cowperthwaite+17

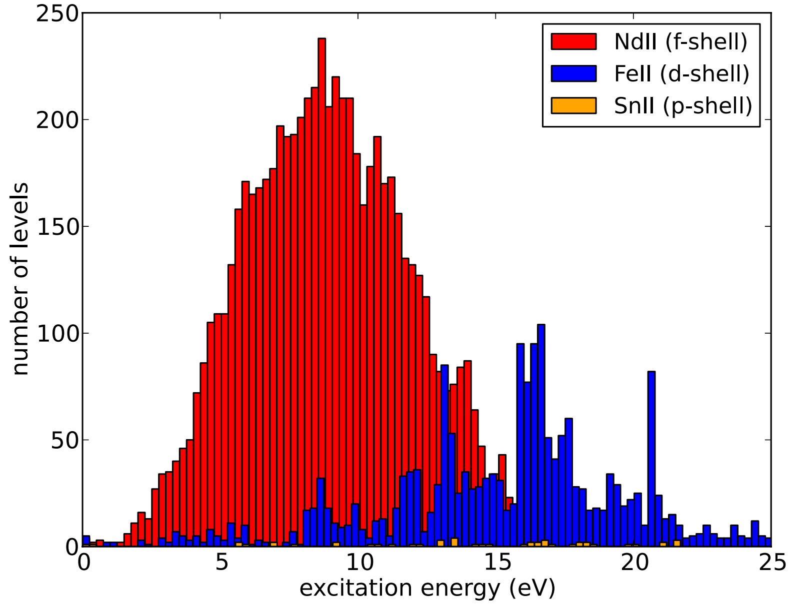
GW170817 & AT2017gfo: photon opacity

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



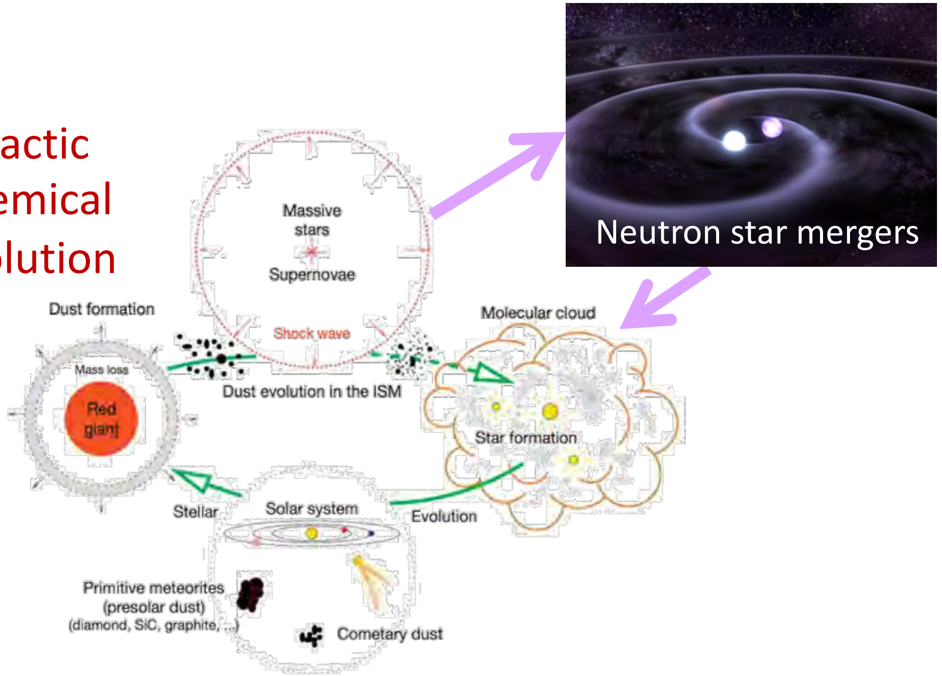




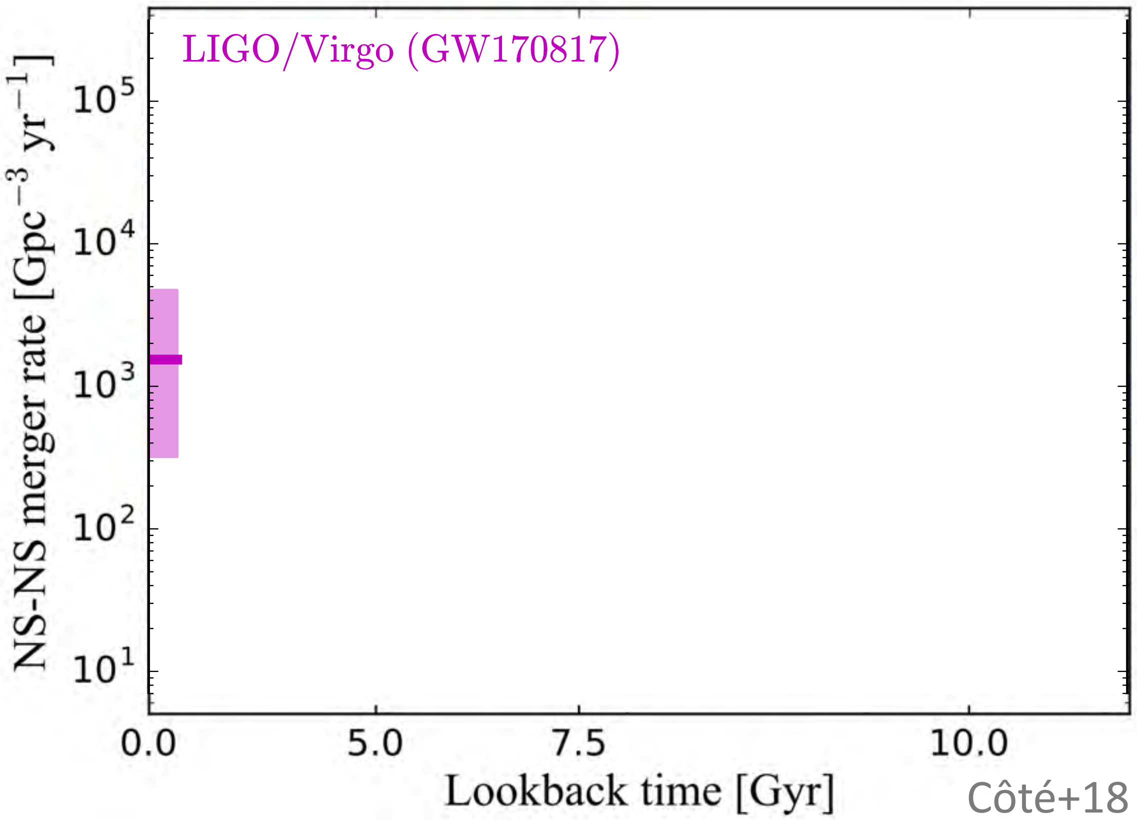
Kasen+13; see also Fontes+20, Tanaka+20

Do binary NSMs make enough heavy elements?

Galactic Chemical Evolution



Palm+14



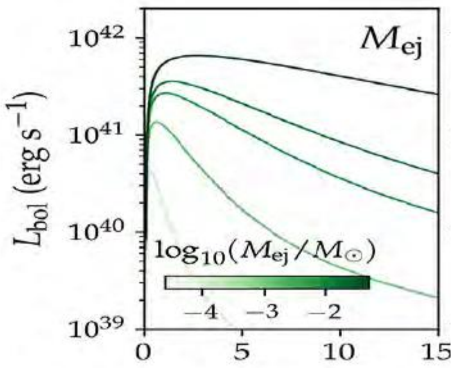
Côté+18

Do binary NSMs make enough heavy elements?

Light Curves

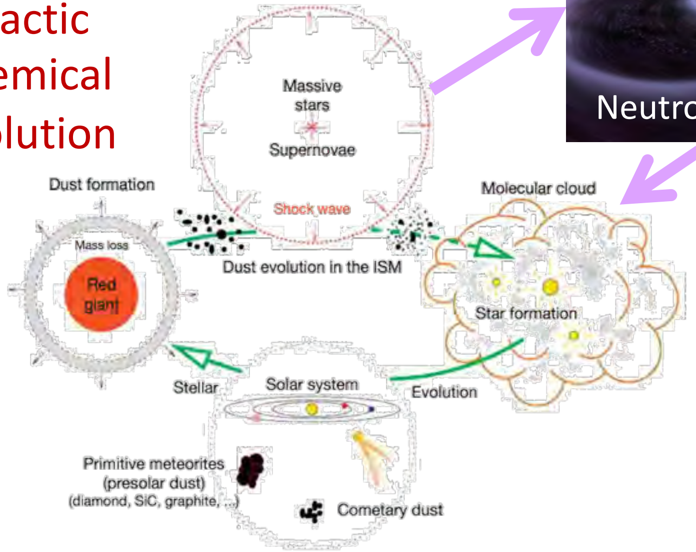
Take estimates for GW170817 mass ejection range from literature

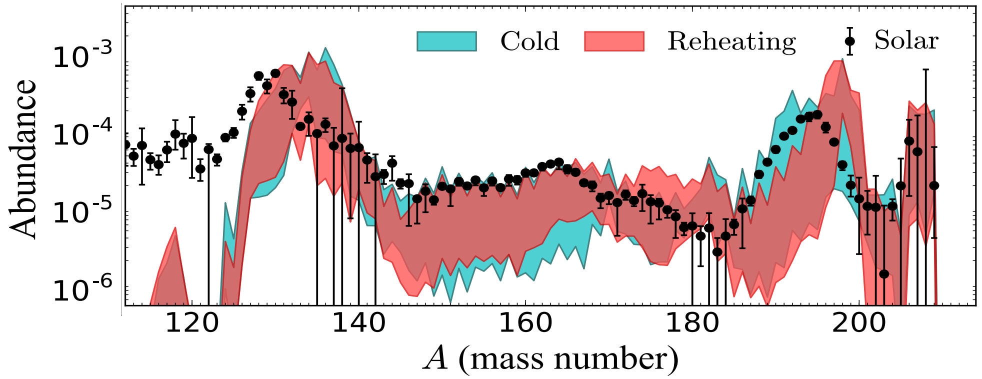
Barnes 20

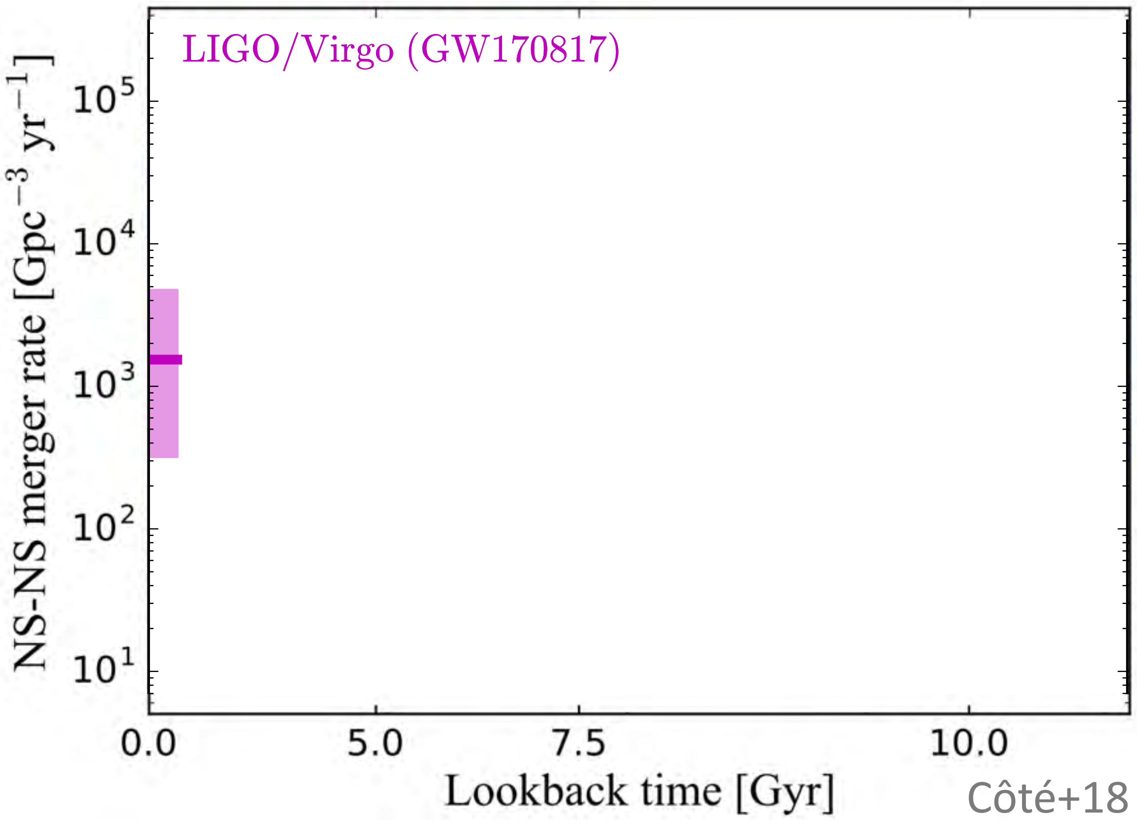


Galactic Chemical Evolution

Palm+14







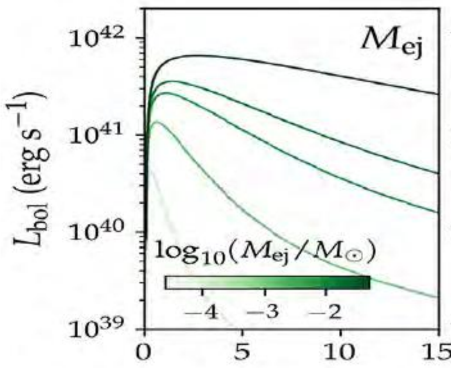
Côté+18

Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models

Do binary NSMs make enough heavy elements?

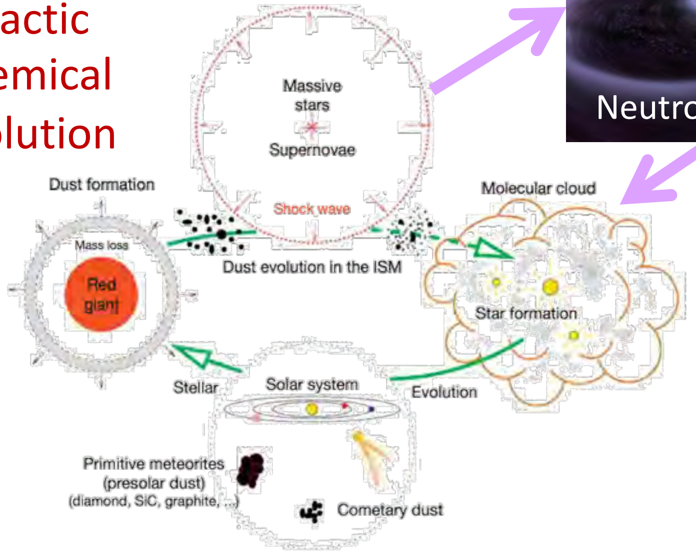
Barnes 20



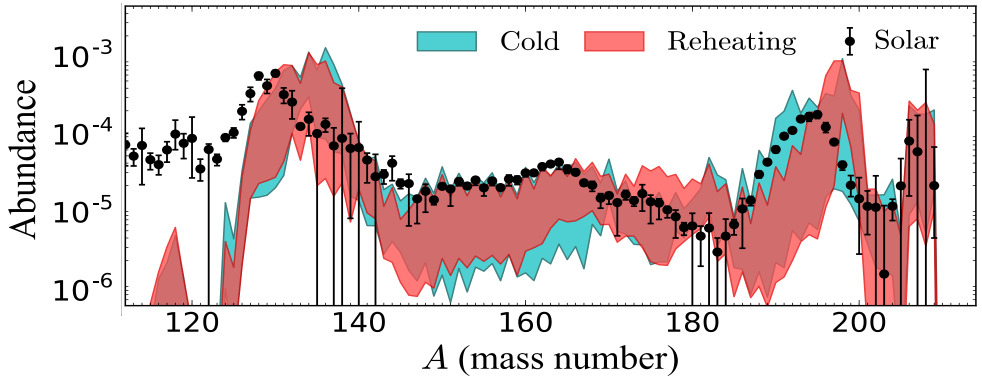
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

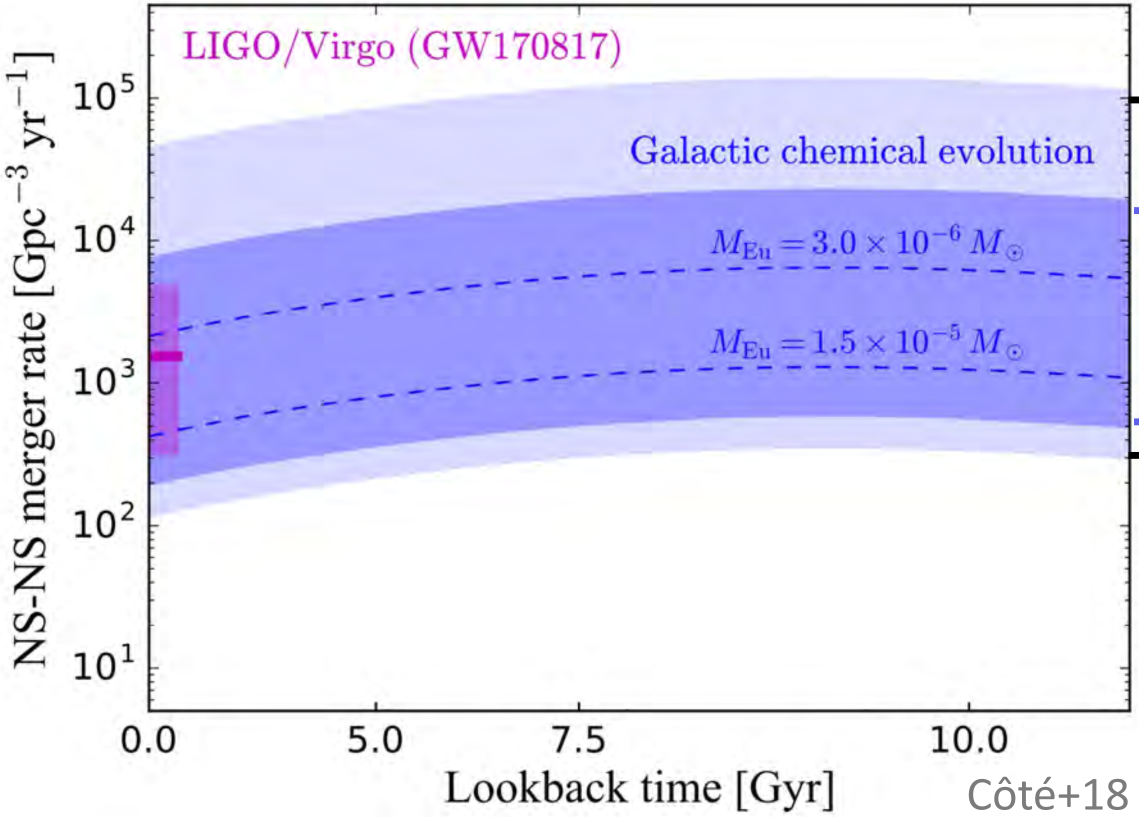


Palm+14



Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models



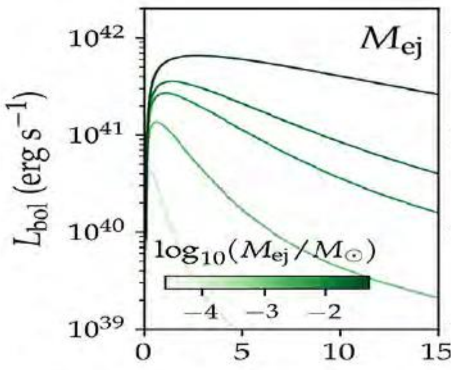
Côté+18

GCE with Solar Abund.

nuclear physics uncertainties

Do binary NSMs make enough heavy elements?

Barnes 20

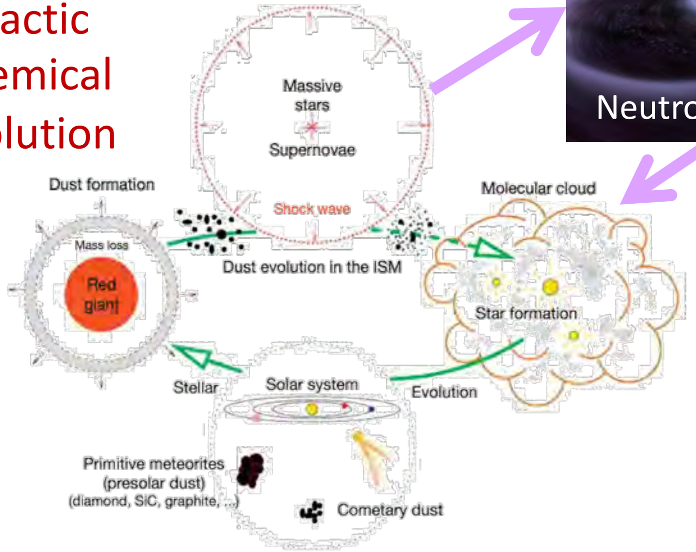


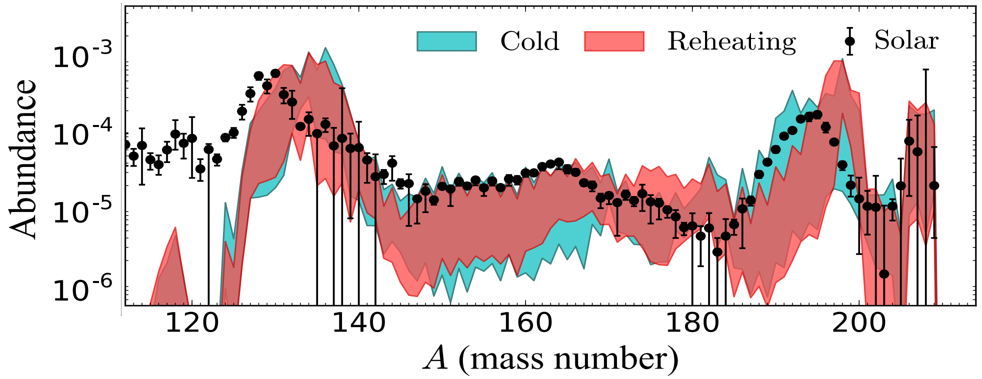
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

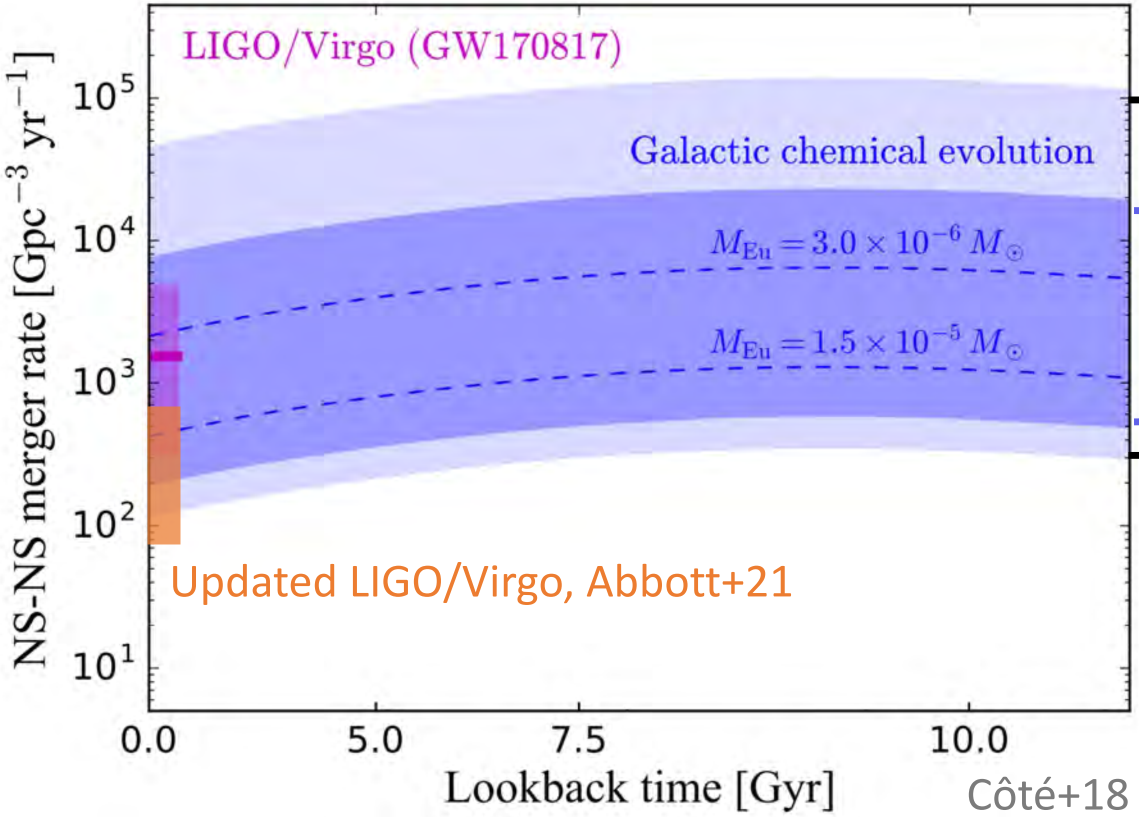
Palm+14





Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models



Côté+18

GCE with Solar Abund.

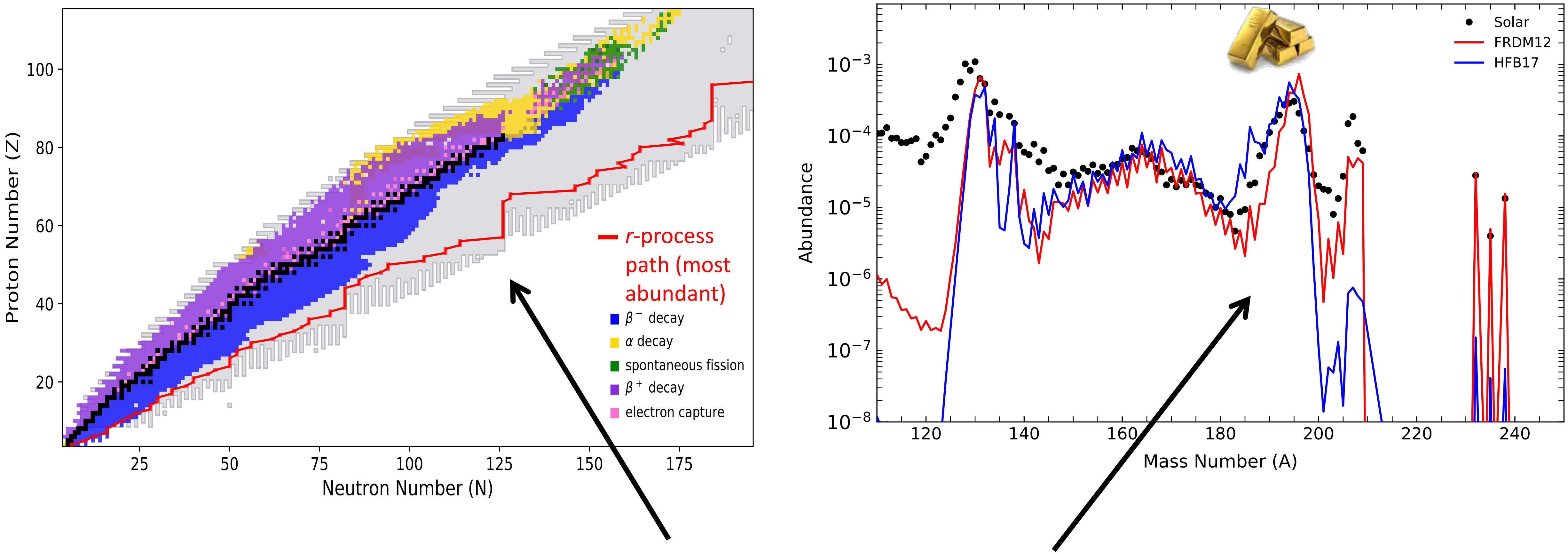
nuclear physics uncertainties

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

Outline for lecture II

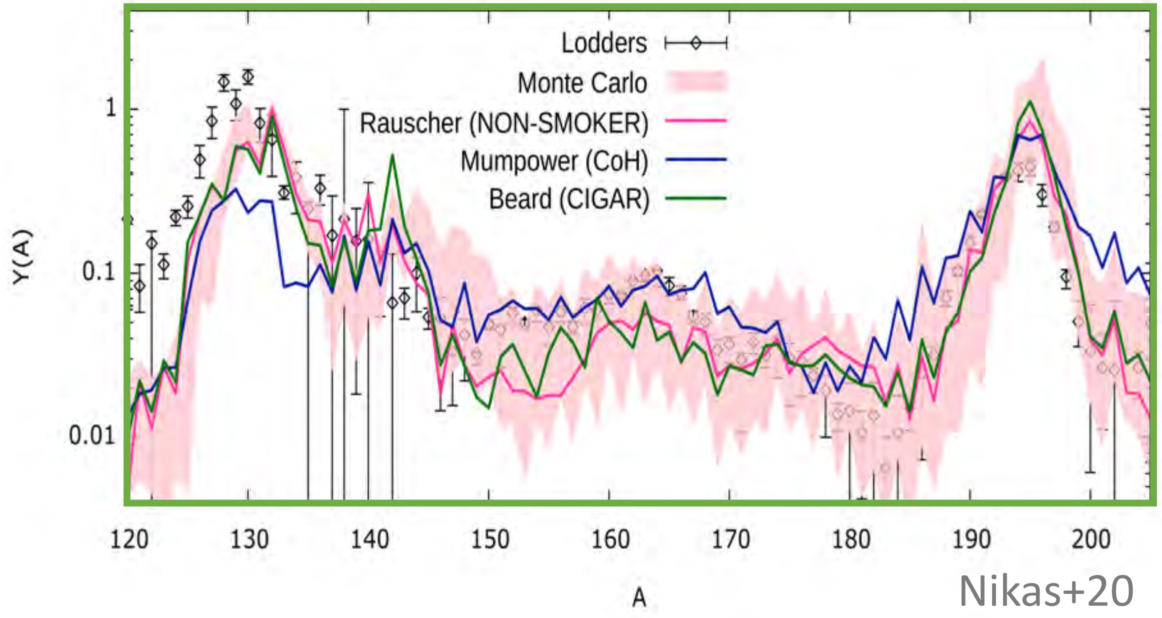
- Supernovae: types and nucleosynthesis [3-7]
- Making the heaviest elements: neutron capture nucleosynthesis [9-19]
- Neutron star mergers: gravitational waves, kilonovae, and nucleosynthesis [21-30]
- Impact of nuclear physics uncertainties on *r*-process predictions [32-55]
- Galactic chemical evolution [57-60]

Impact of nuclear physics uncertainties: *r*-process N=126 peak example

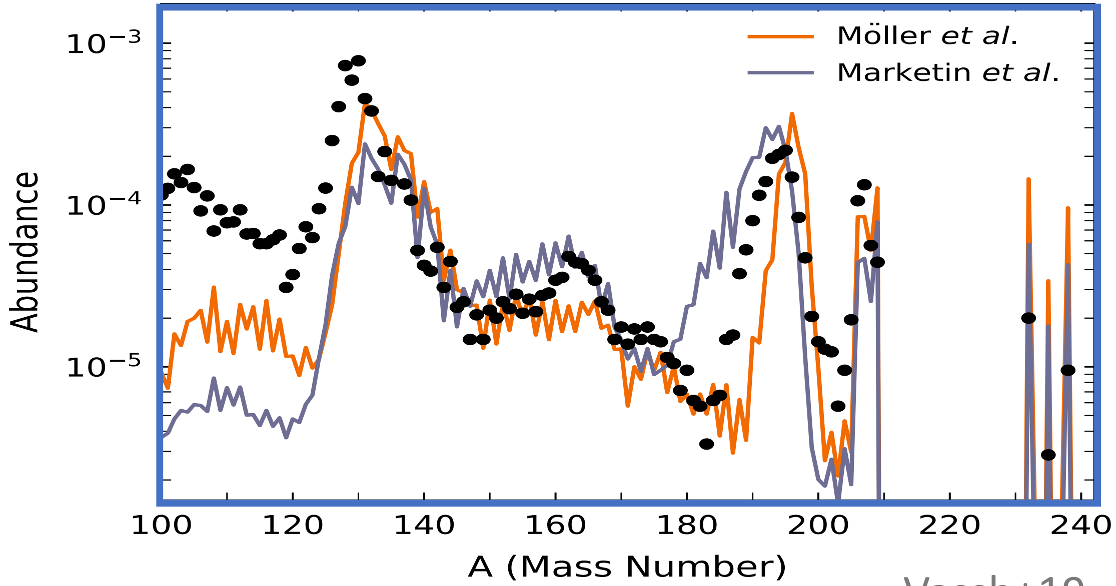


- Little to no experimental data on the neutron-rich side at N=126; nuclear mass models predict different shell closure strengths and thus different amounts of elements like gold and platinum
- The N=126 shell closure is the "gateway" to the actinides and thus affects how strongly elements like uranium-238 are produced

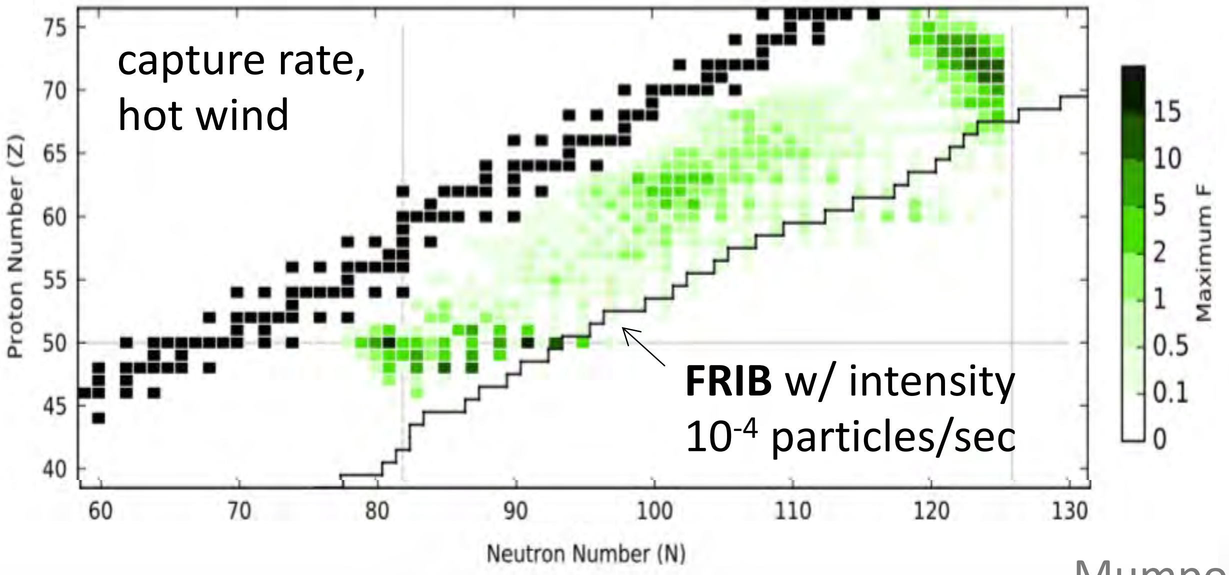
Sensitivity of *r*-process abundances to neutron capture and β-decay

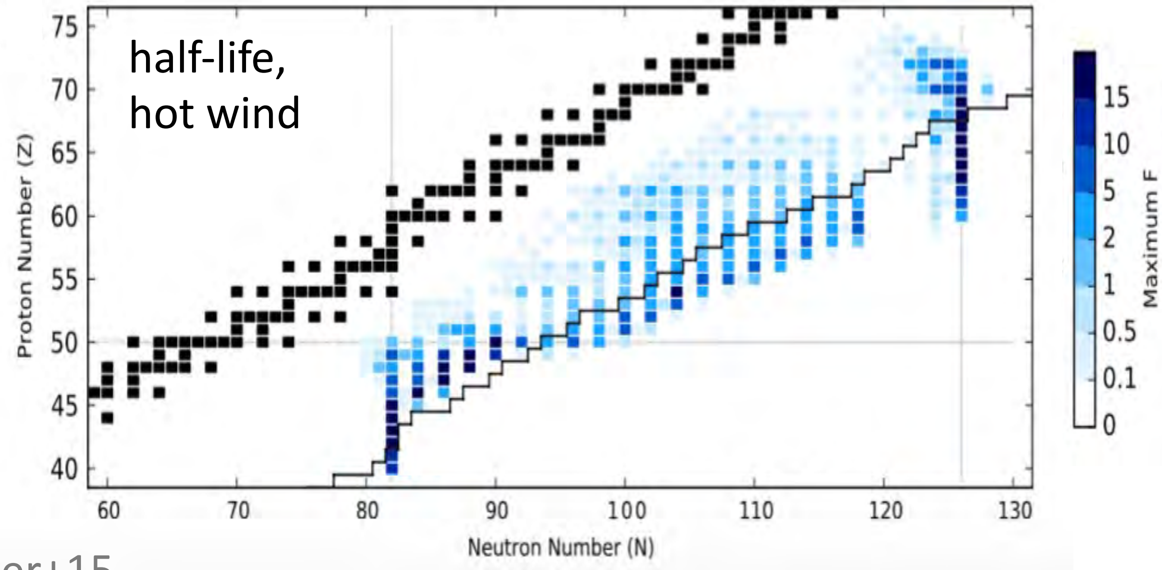


Nikas+20



Vassh+19

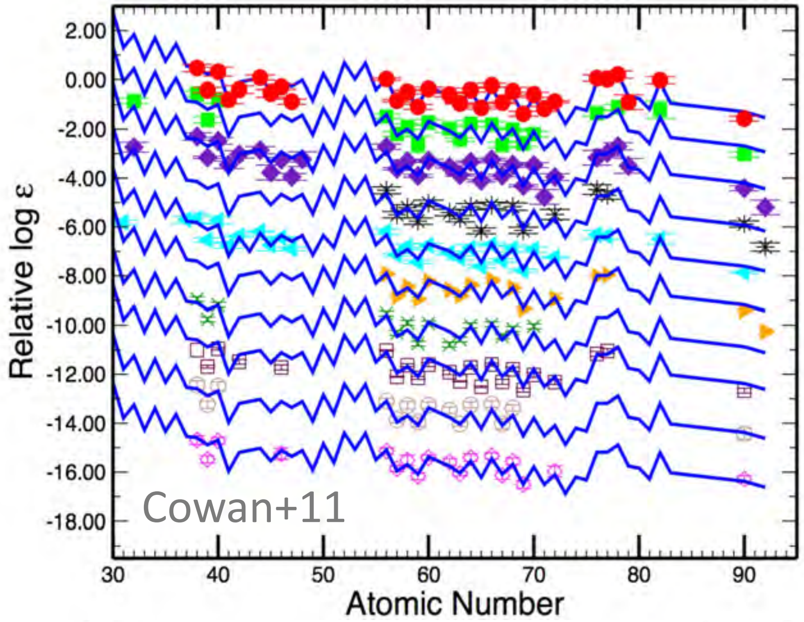


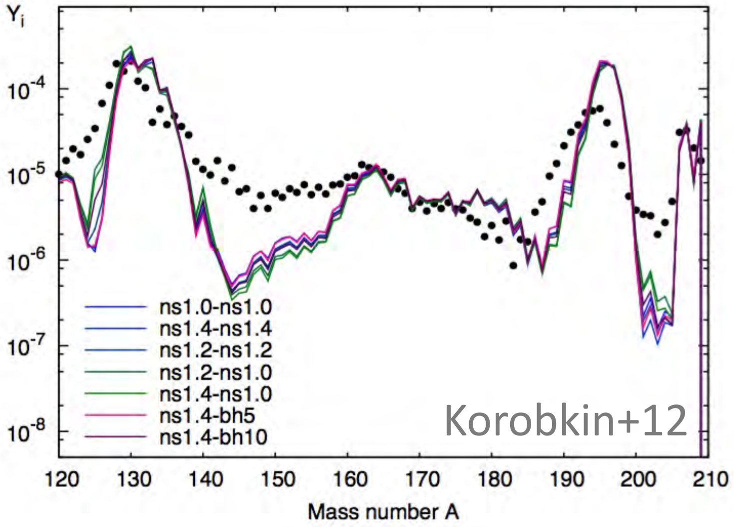


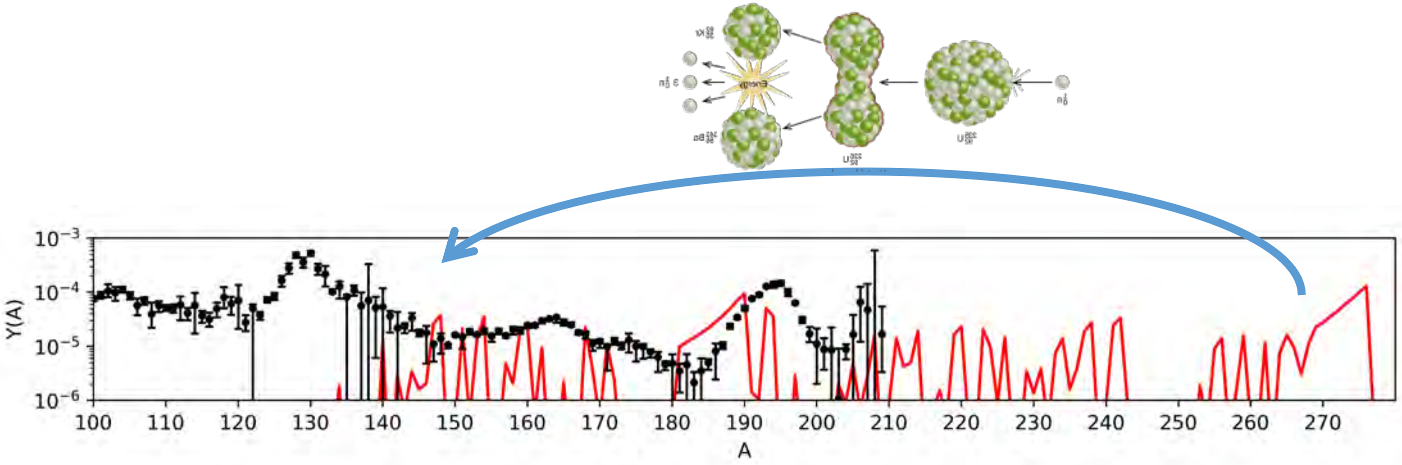
Mumpower+15

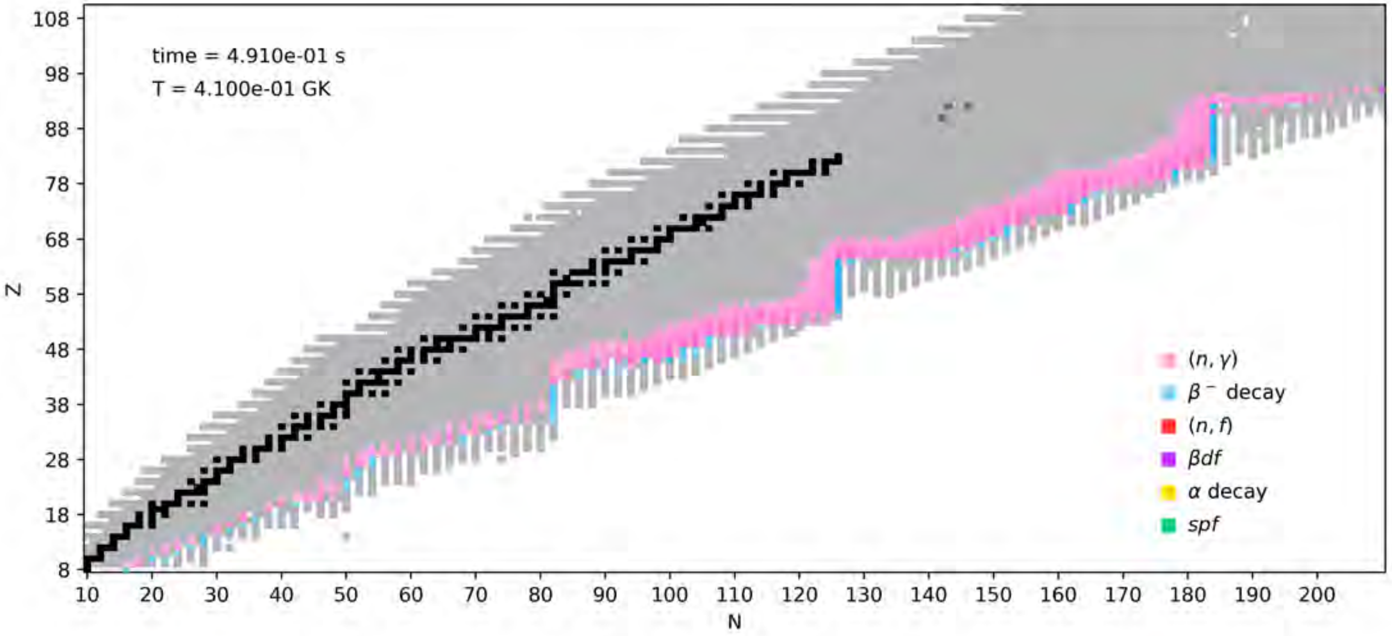
Fission cycling to explain observed robustness of lanthanide abundances?

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

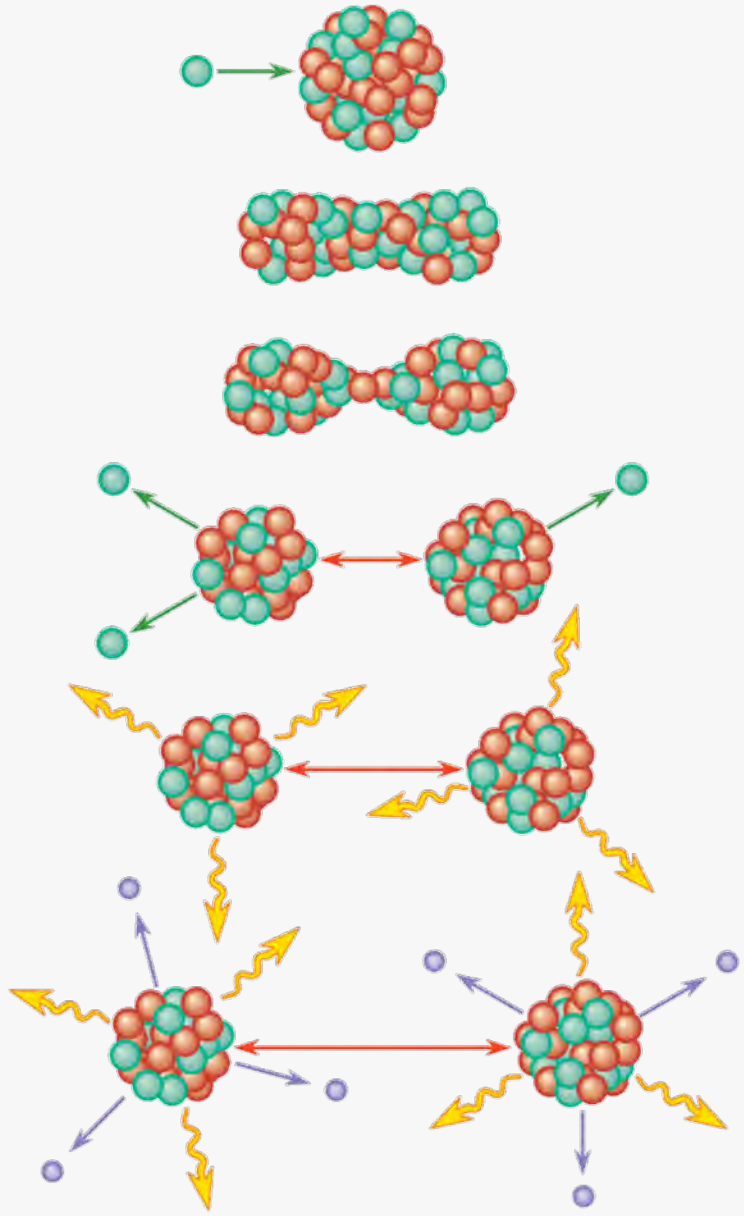
Deformation

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



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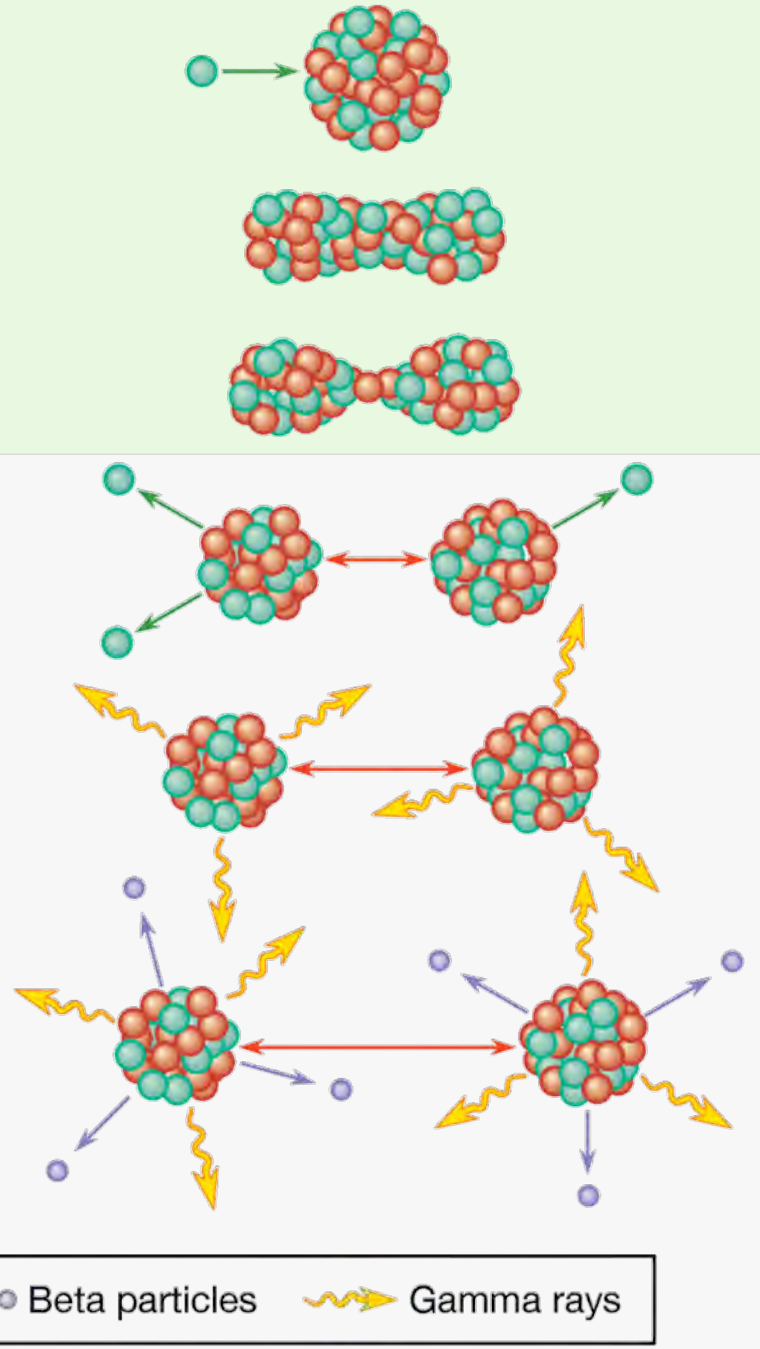

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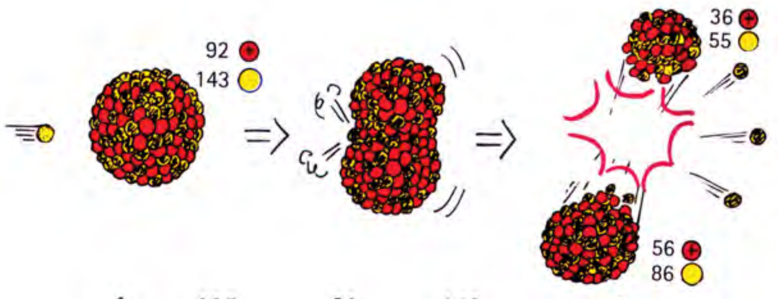
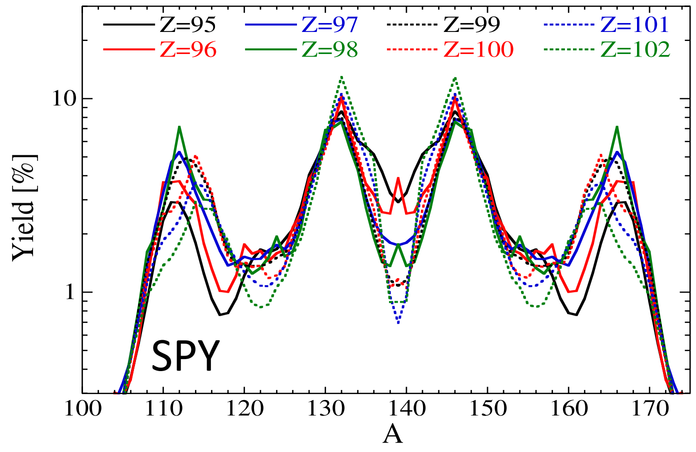
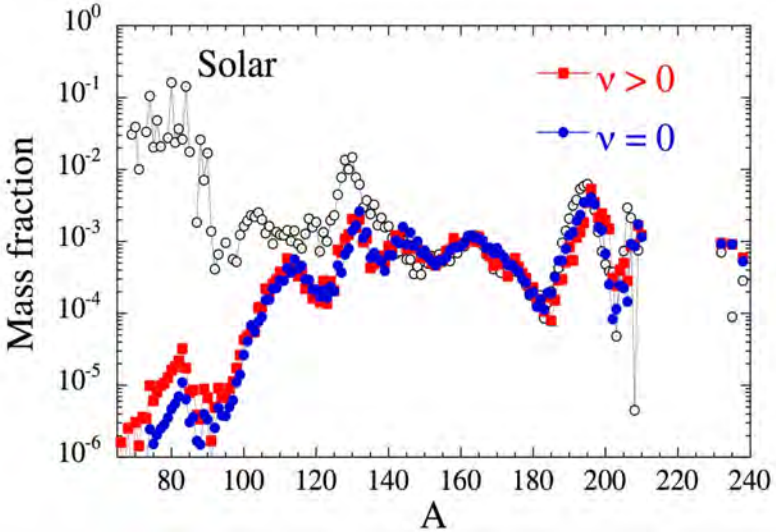
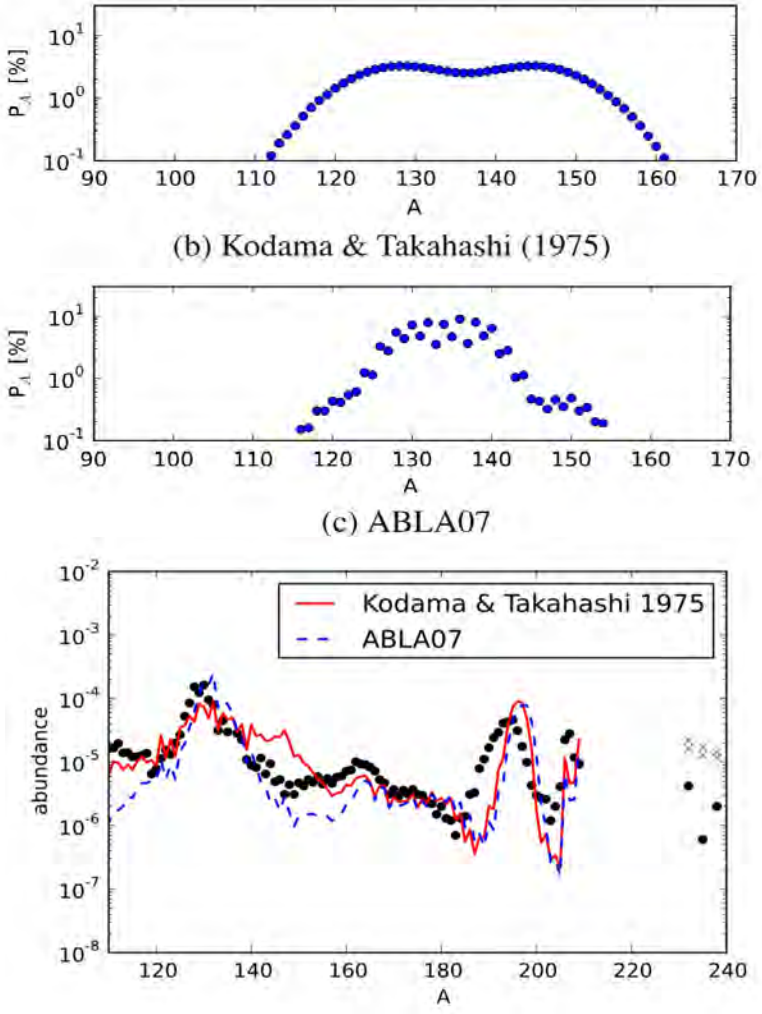
Dependence of *r*-process abundances on fission yields



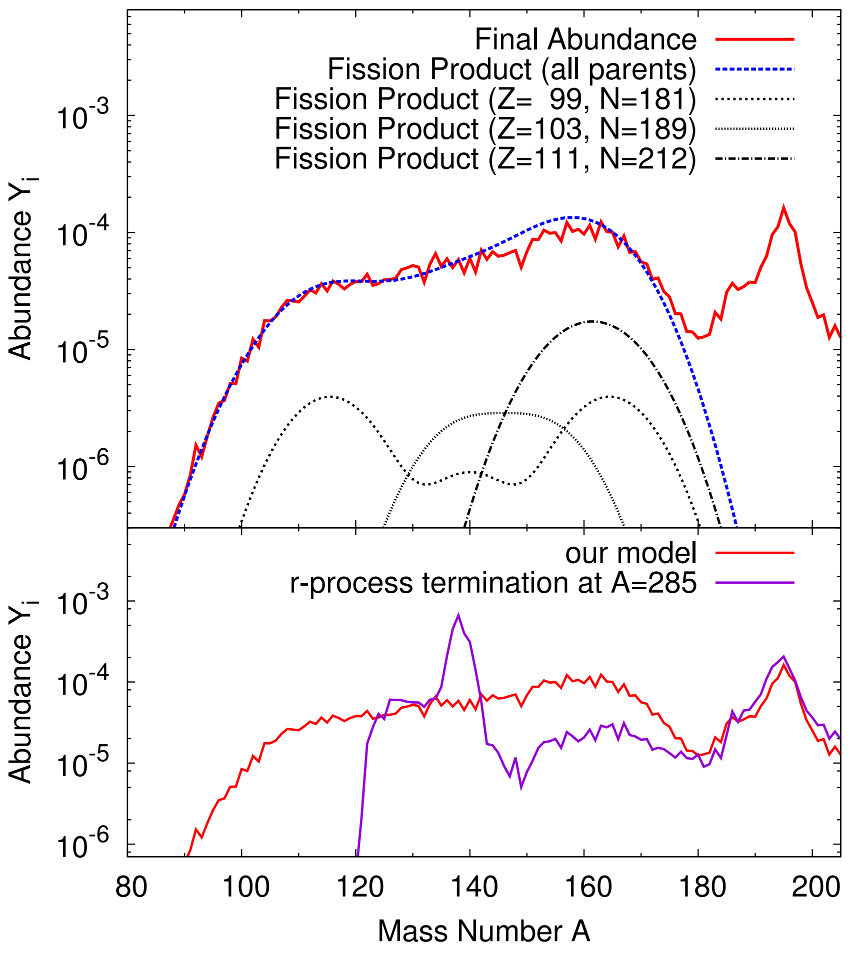




Goriely+13,15; see also Lemaître+21

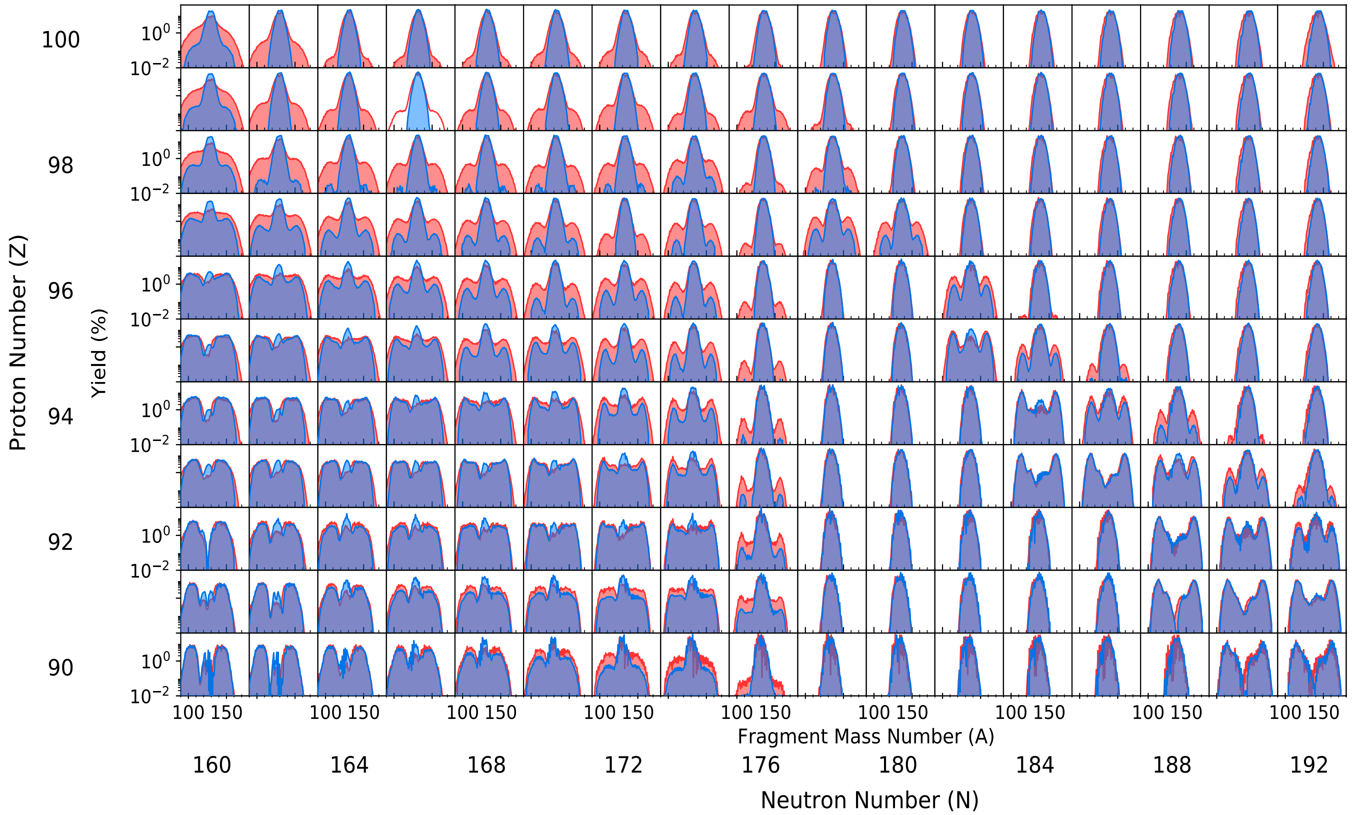


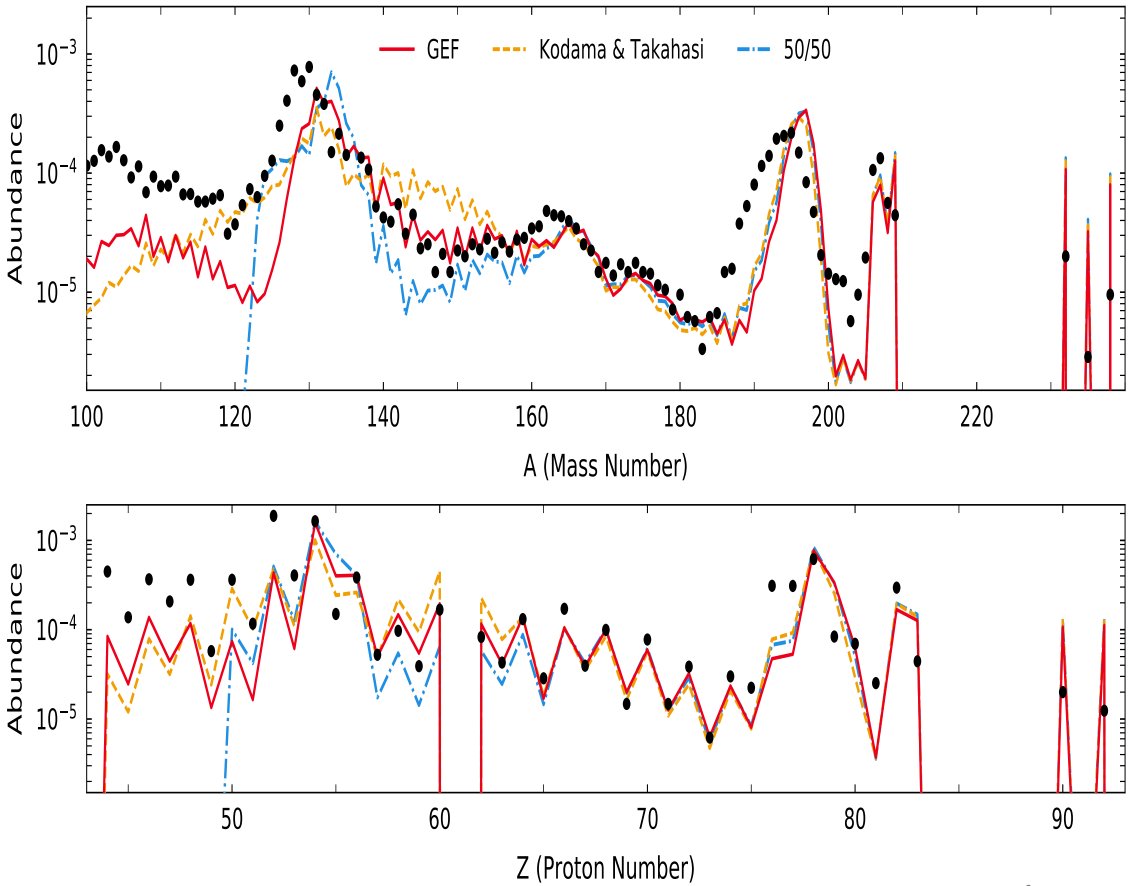
Eichler+15



Shibagaki+16

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



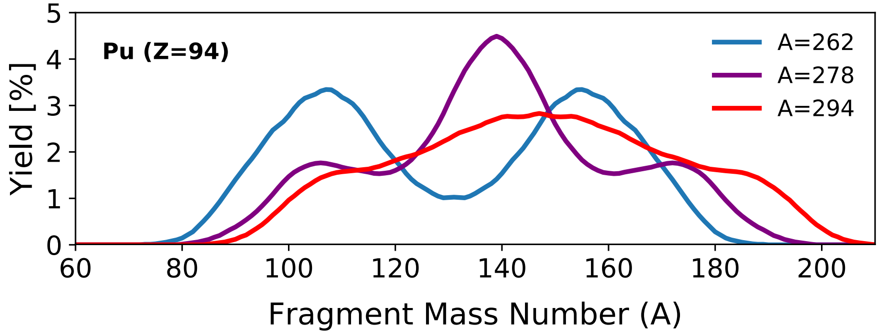


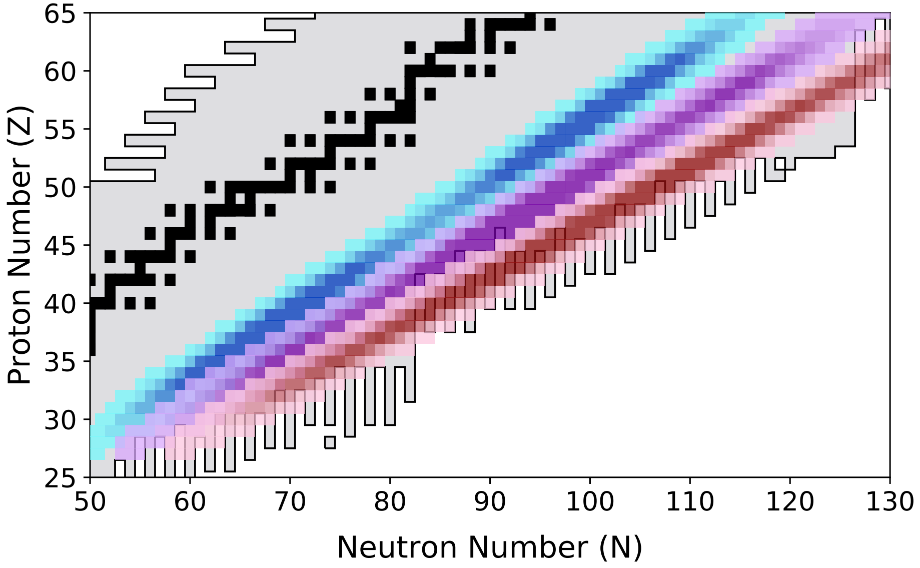
Vassh+19

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

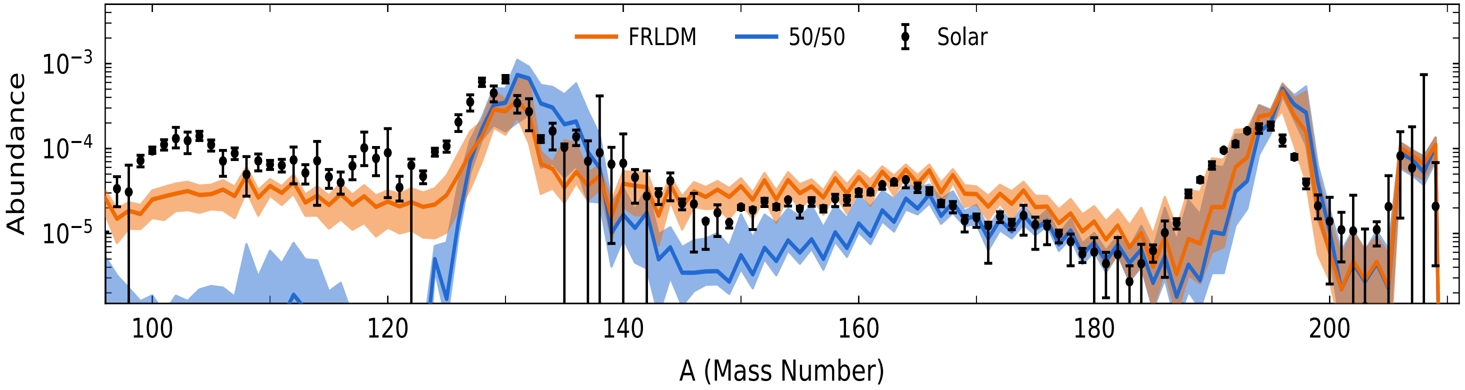
Using fission yields and fission rates calculated with self-consistent fission barriers

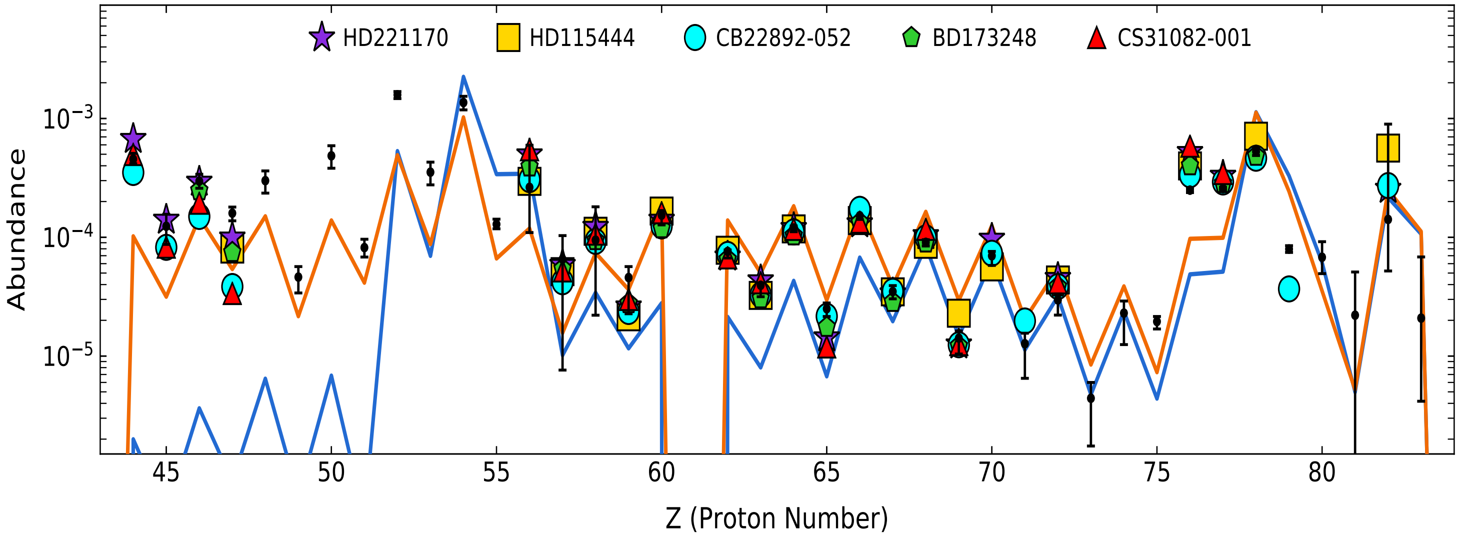
FRLDM Yields from Mumpower+20





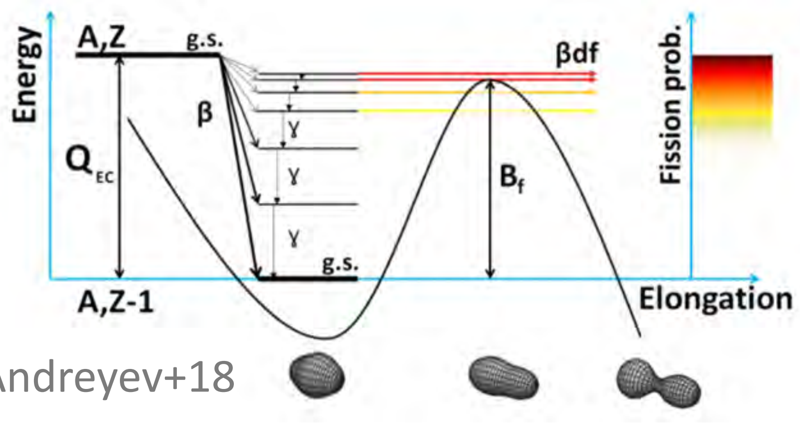
Range from Rosswog+13 NSM dynamical ejecta (Ye~0.01-0.05)





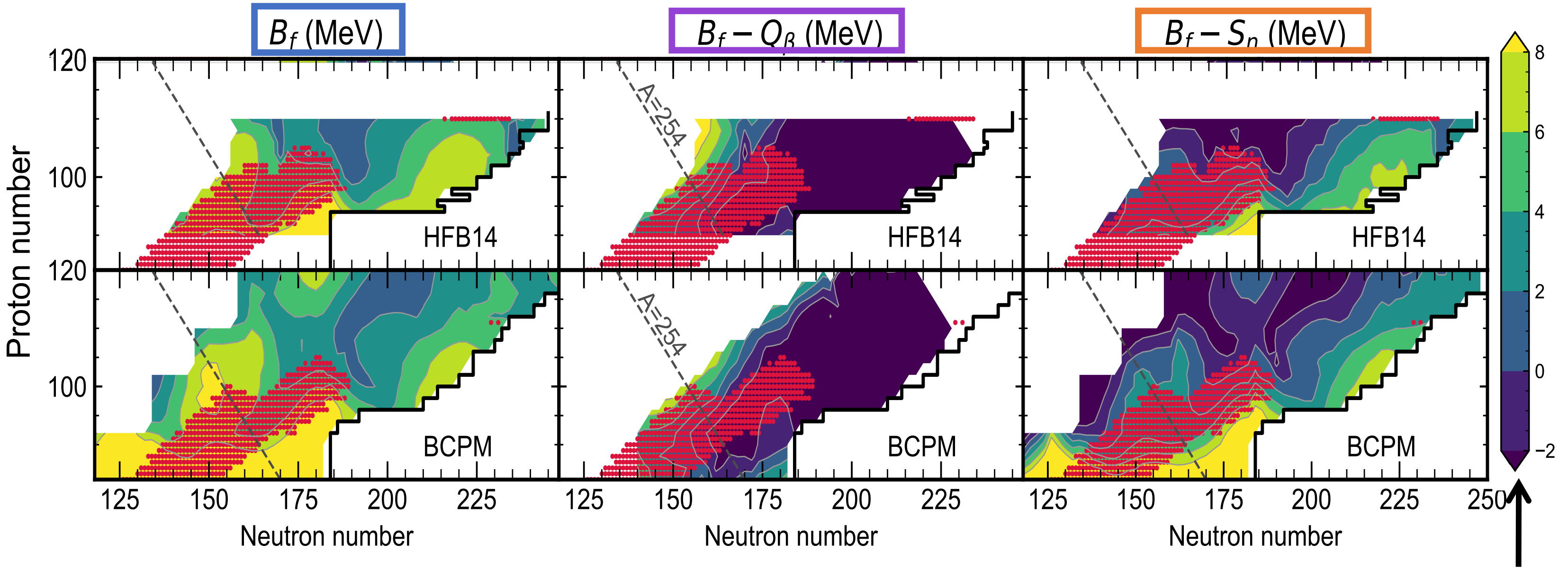
Vassh+20

Fission and the ultimate reach of the *r* process



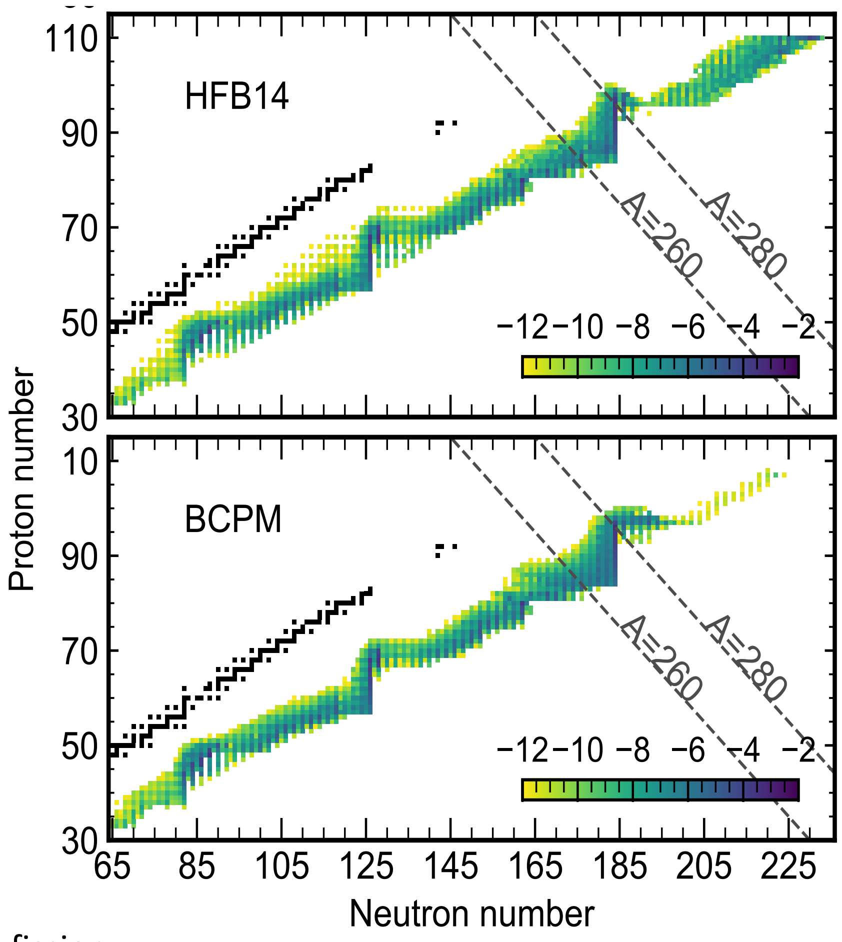
Andreyev+18

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



Smaller ⇒ larger fission probability

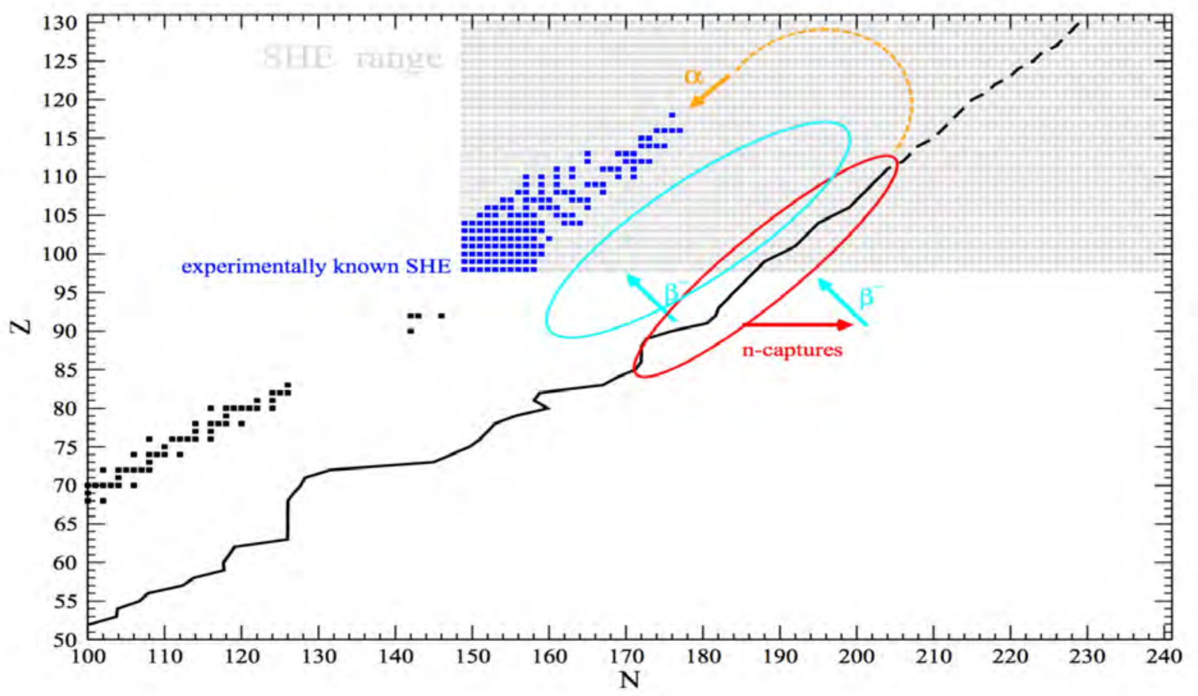
Giuliani+20



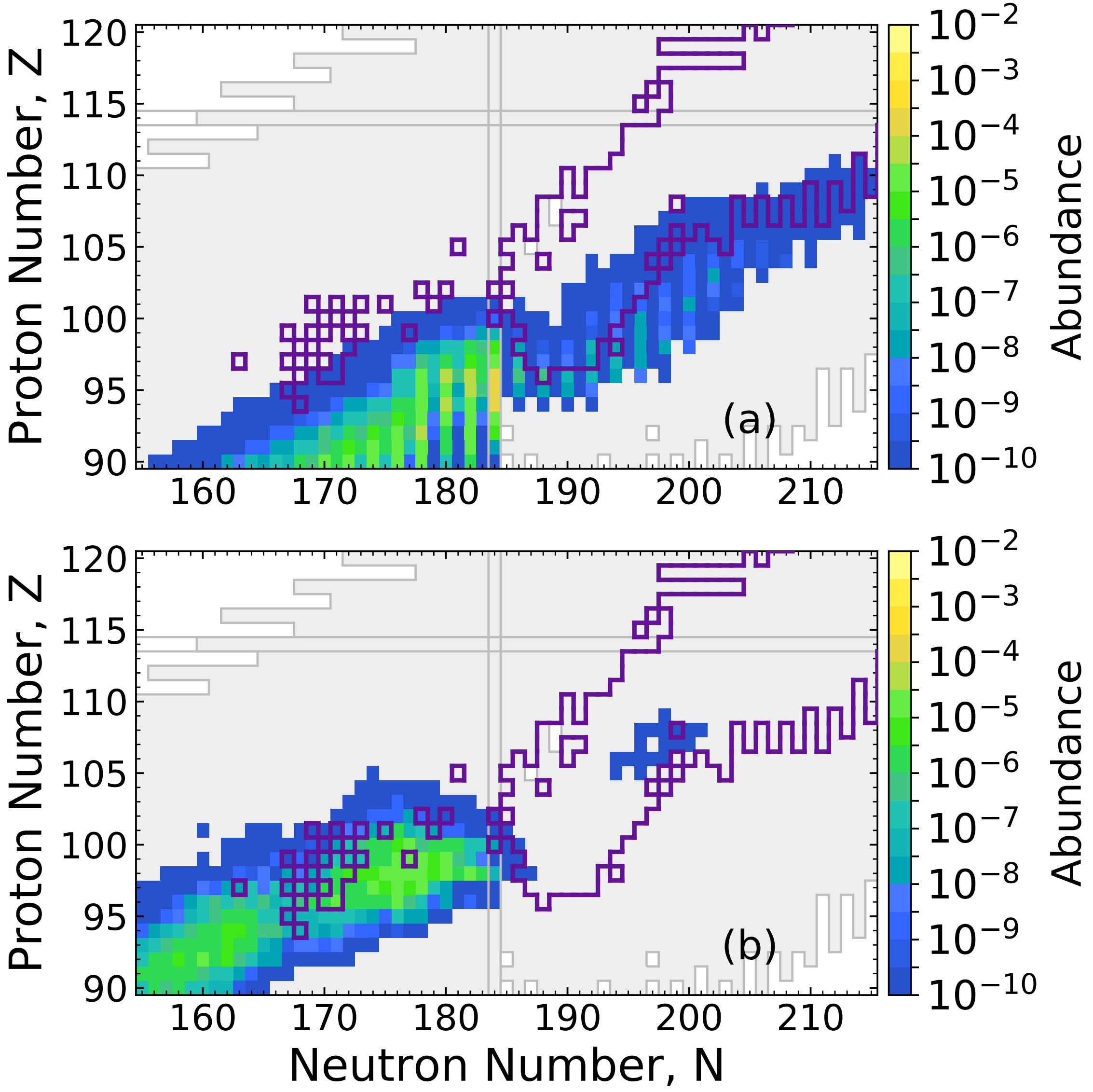
r-process production of superheavy elements?

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 (including Vassh)

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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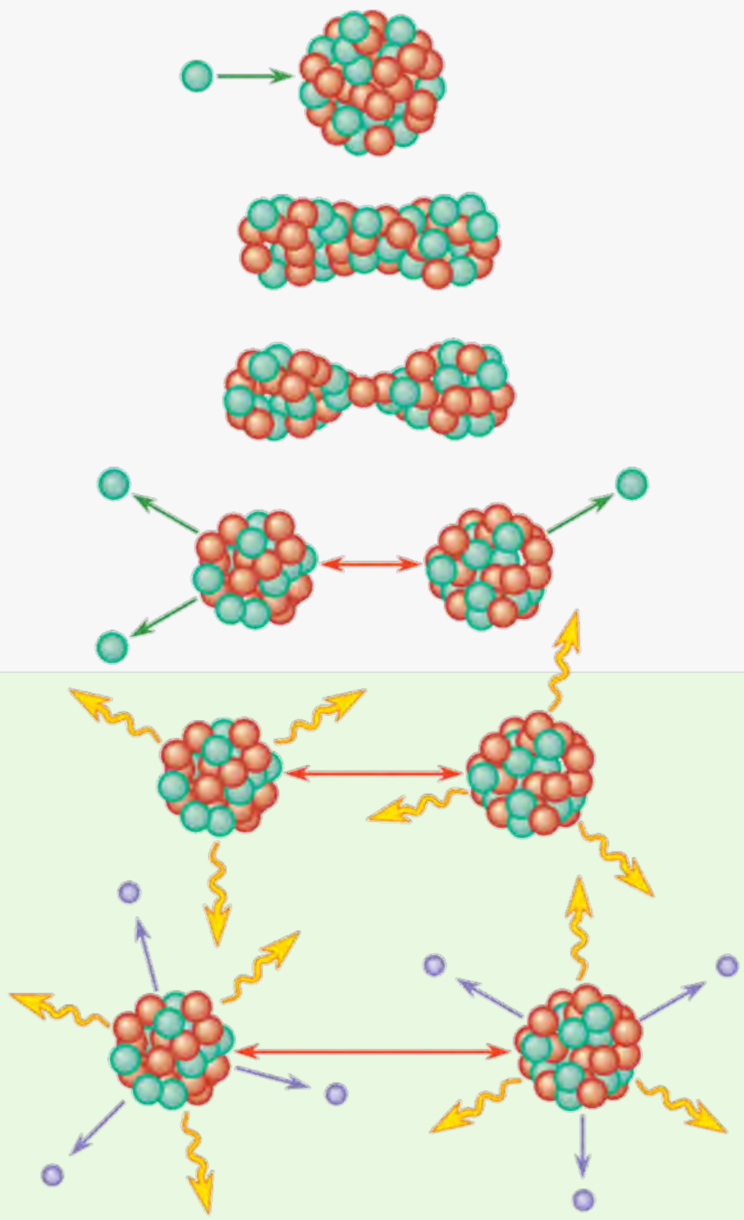

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Are actinides produced in neutron star mergers?

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

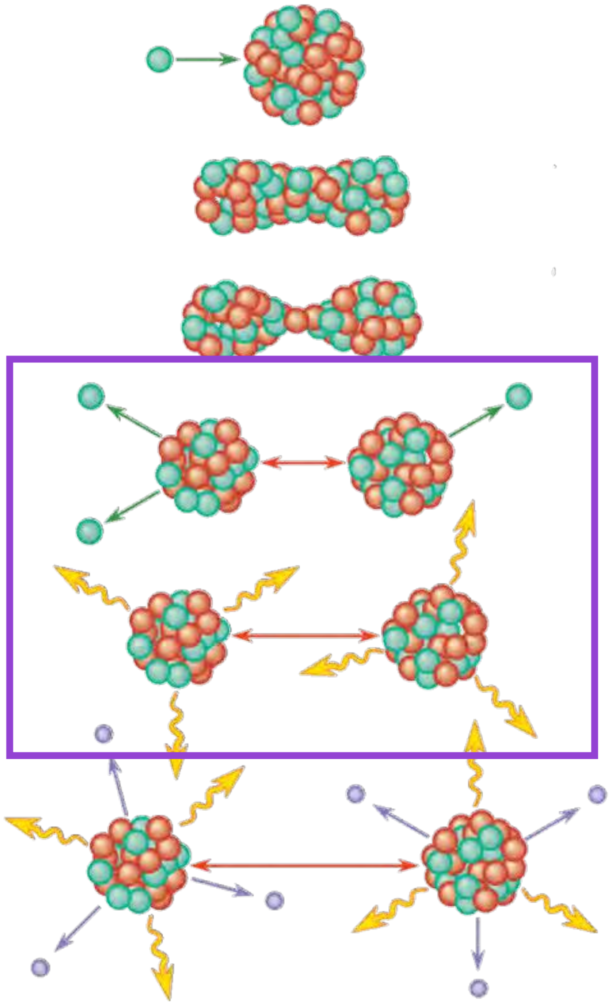
G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

and

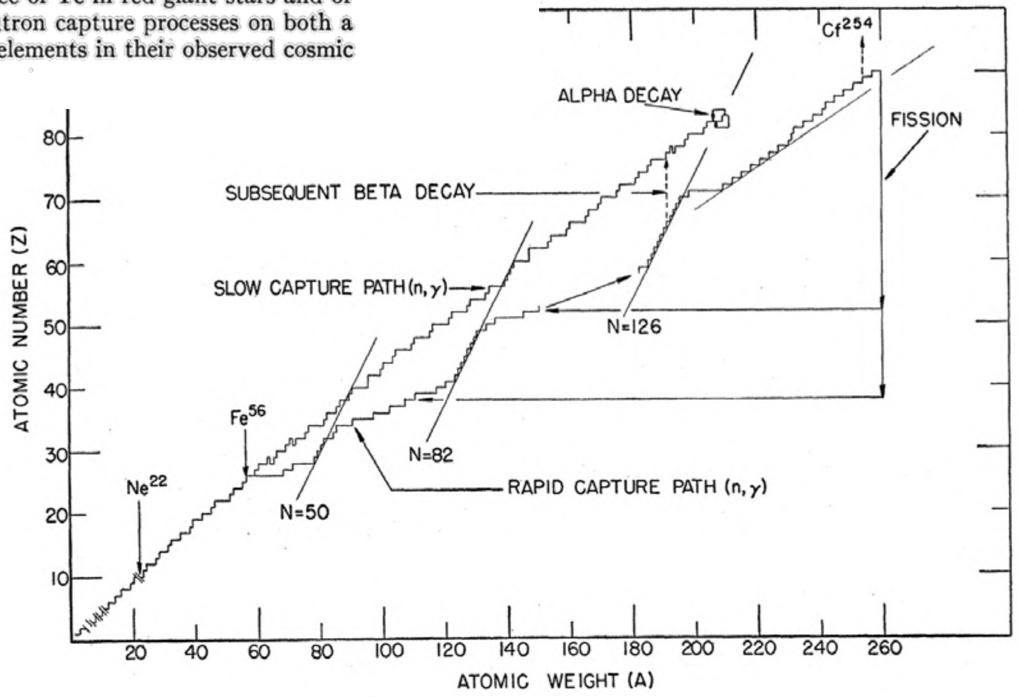
E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

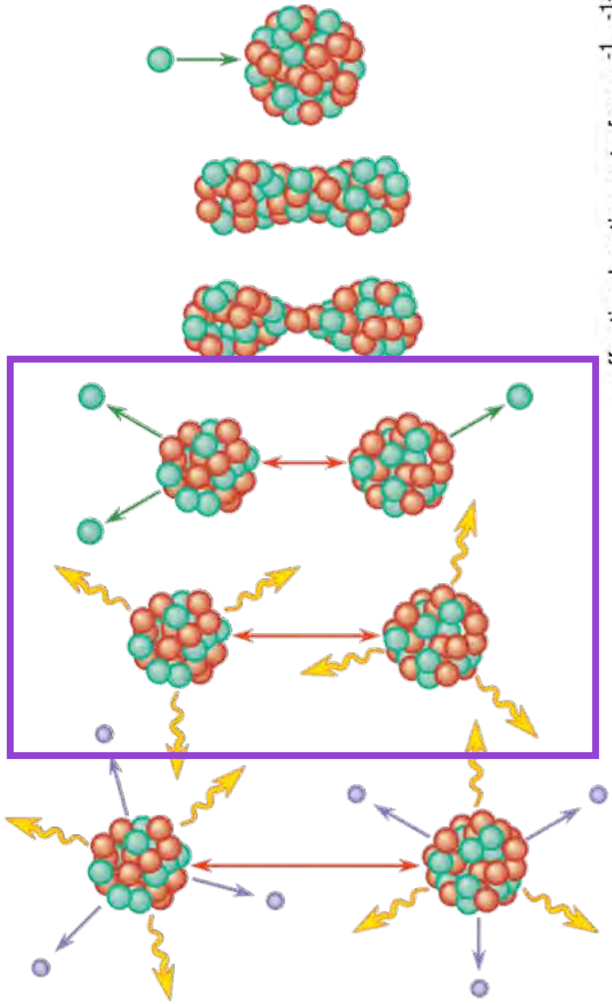


Fission heating can greatly impact light curves



Burbidge, Burbidge, Fowler and Hoyle (1957)

Are actinides produced in neutron star mergers?



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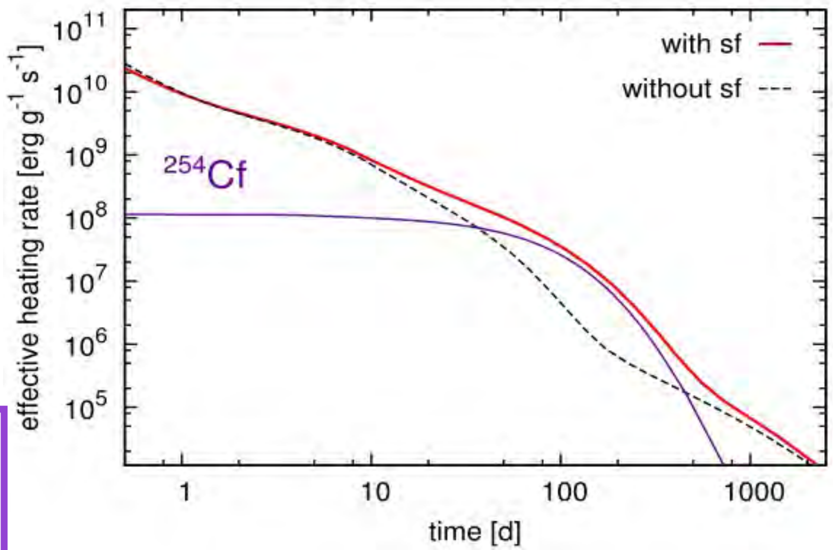
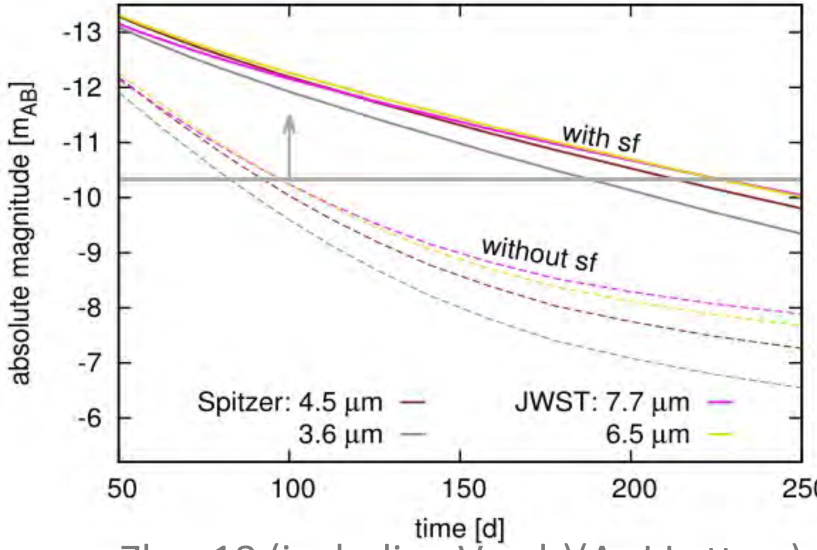
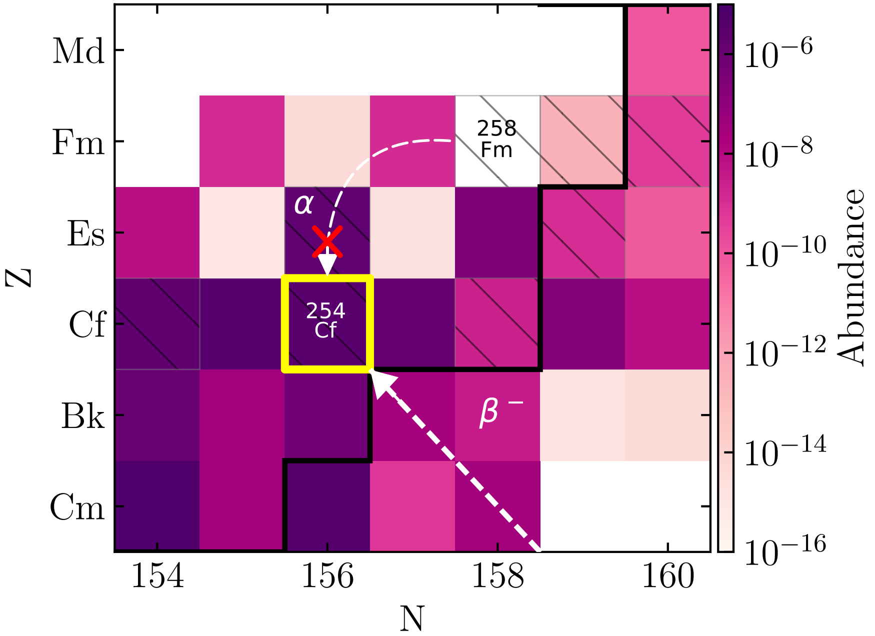




Zhu+18 (including Vassh)(ApJ Letters)



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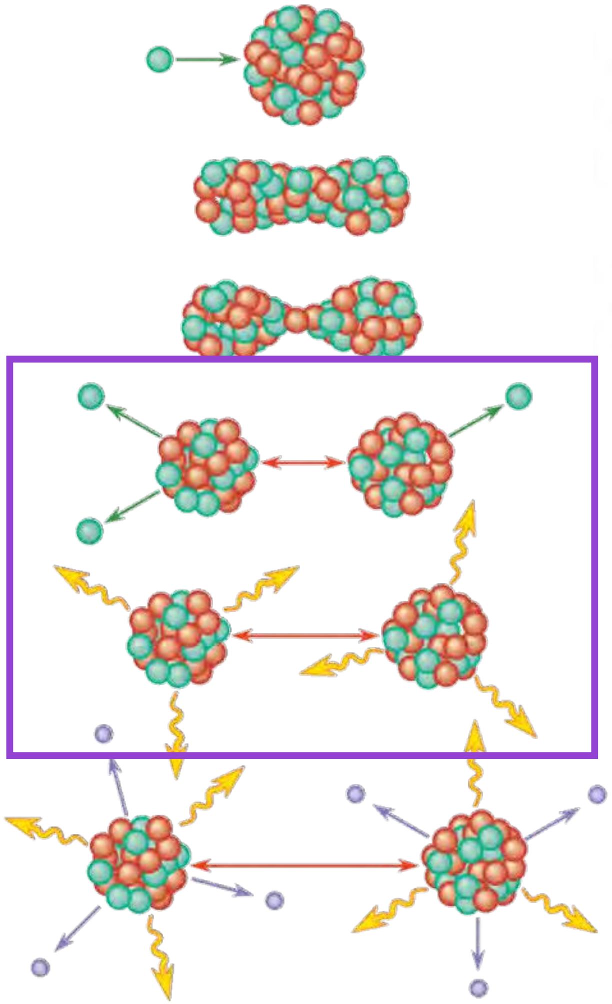

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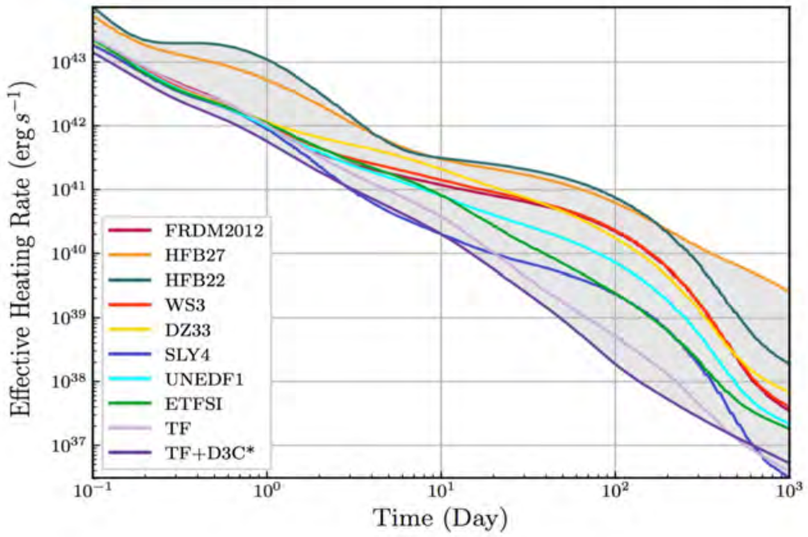
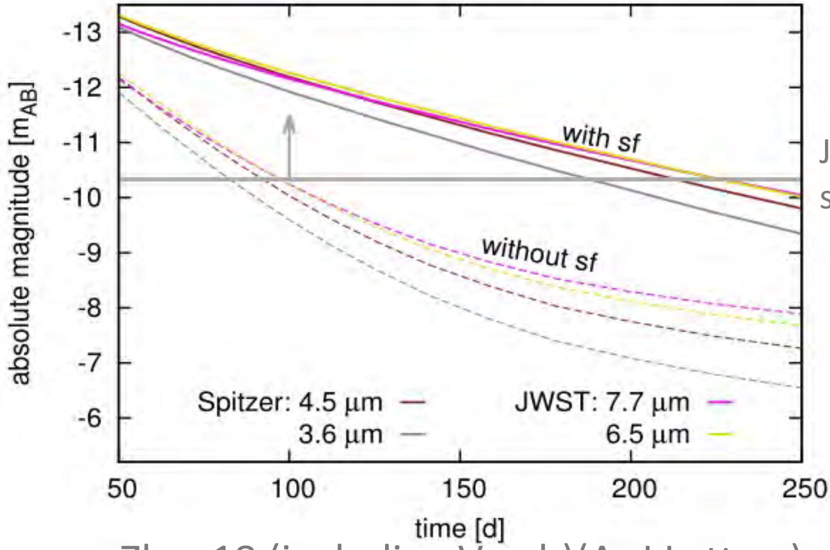
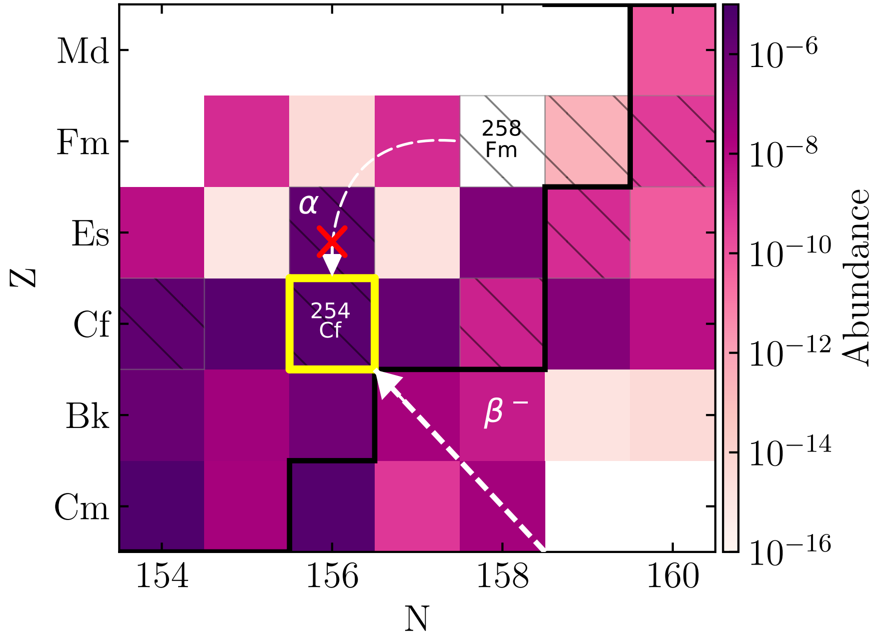


Zhu+21 (including Vassh)(ApJ)



JWST sensitivity

Zhu+18 (including Vassh)(ApJ Letters)



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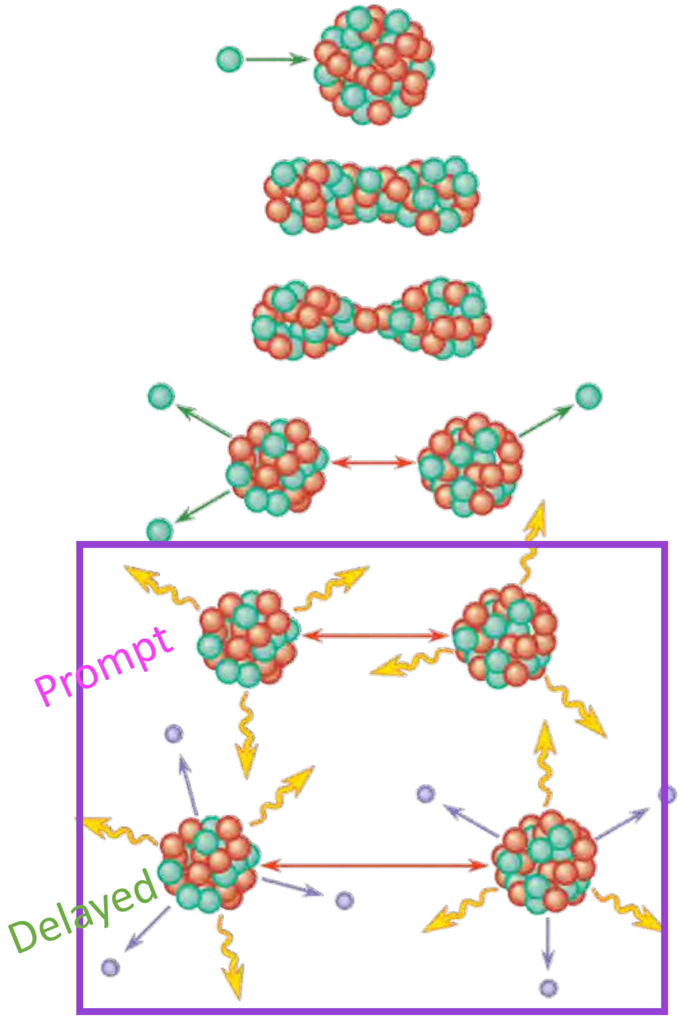
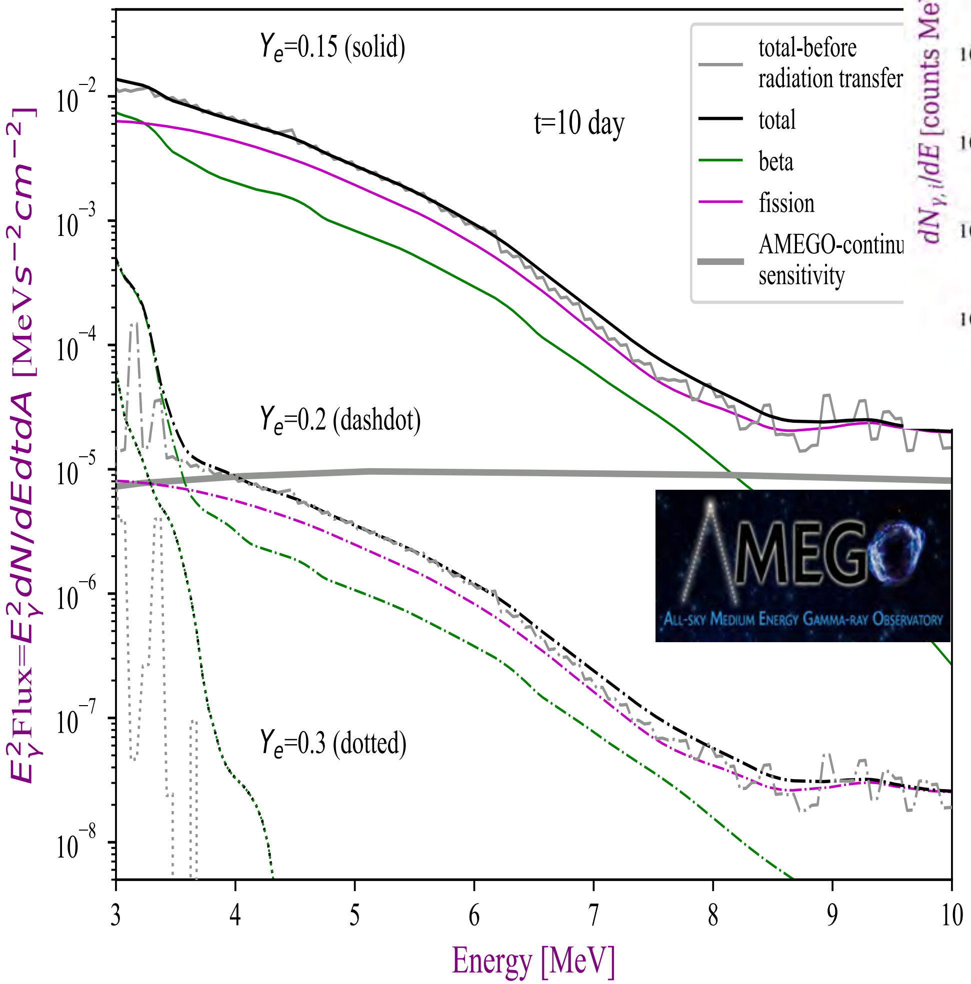
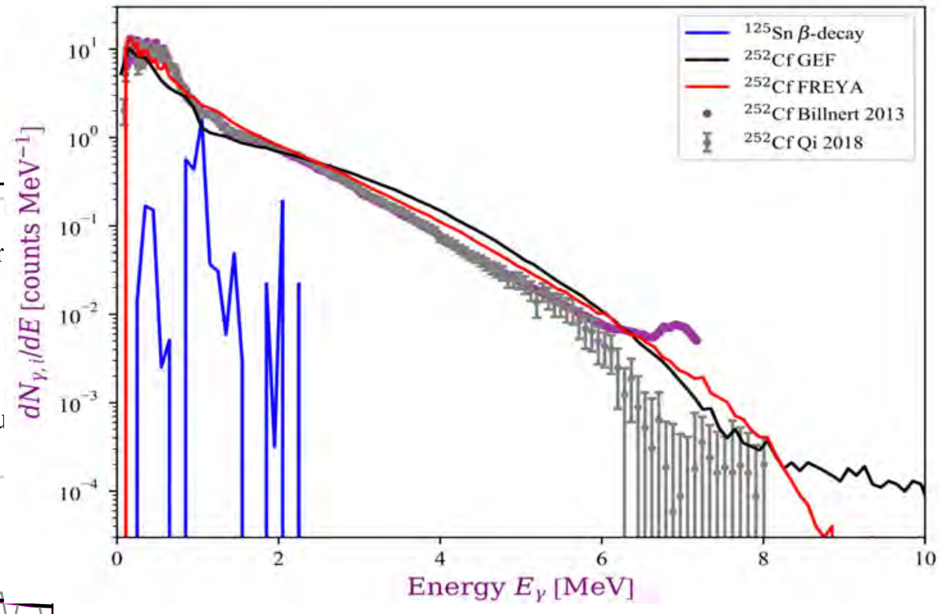


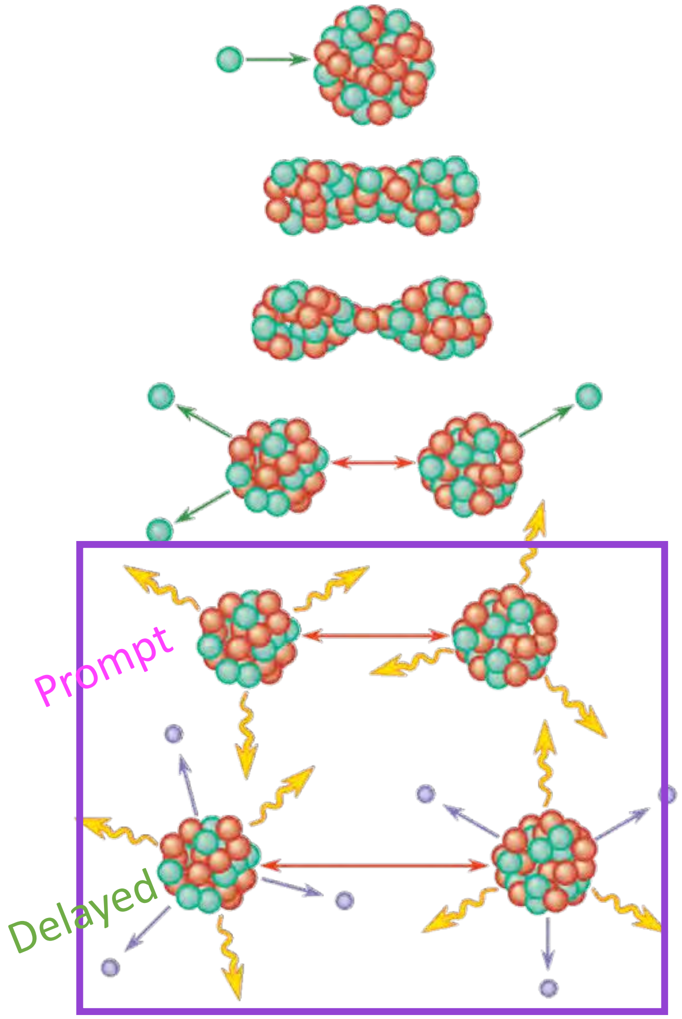


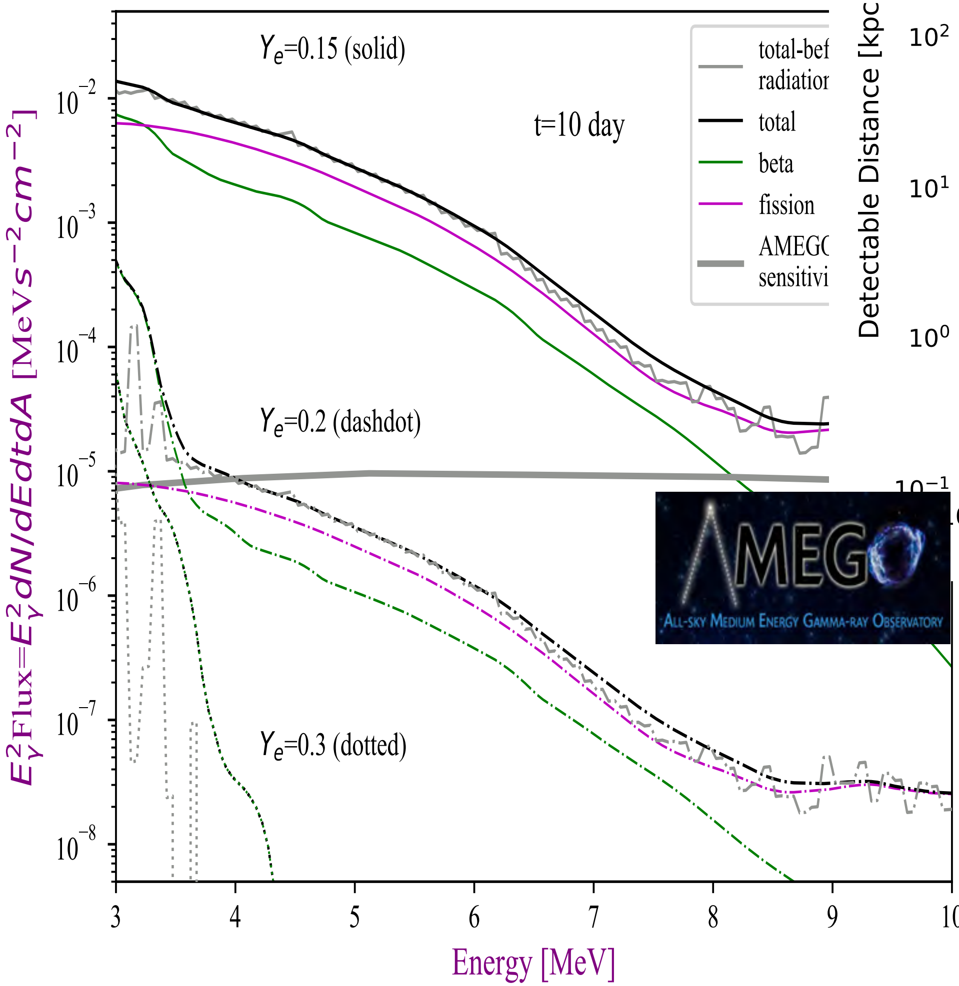


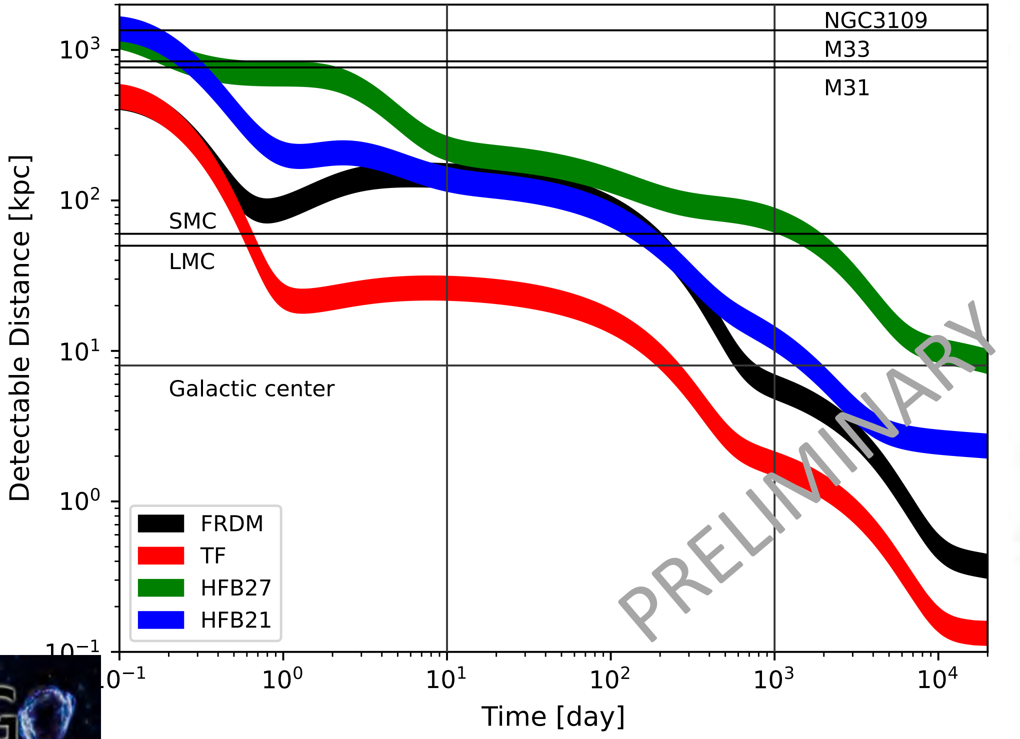
Wang,Vassh+20 (ApJ Letters)

Gammas > 3.5 MeV: signature of prompt and delayed fission gammas in a merger event!

Are actinides produced in neutron star mergers?



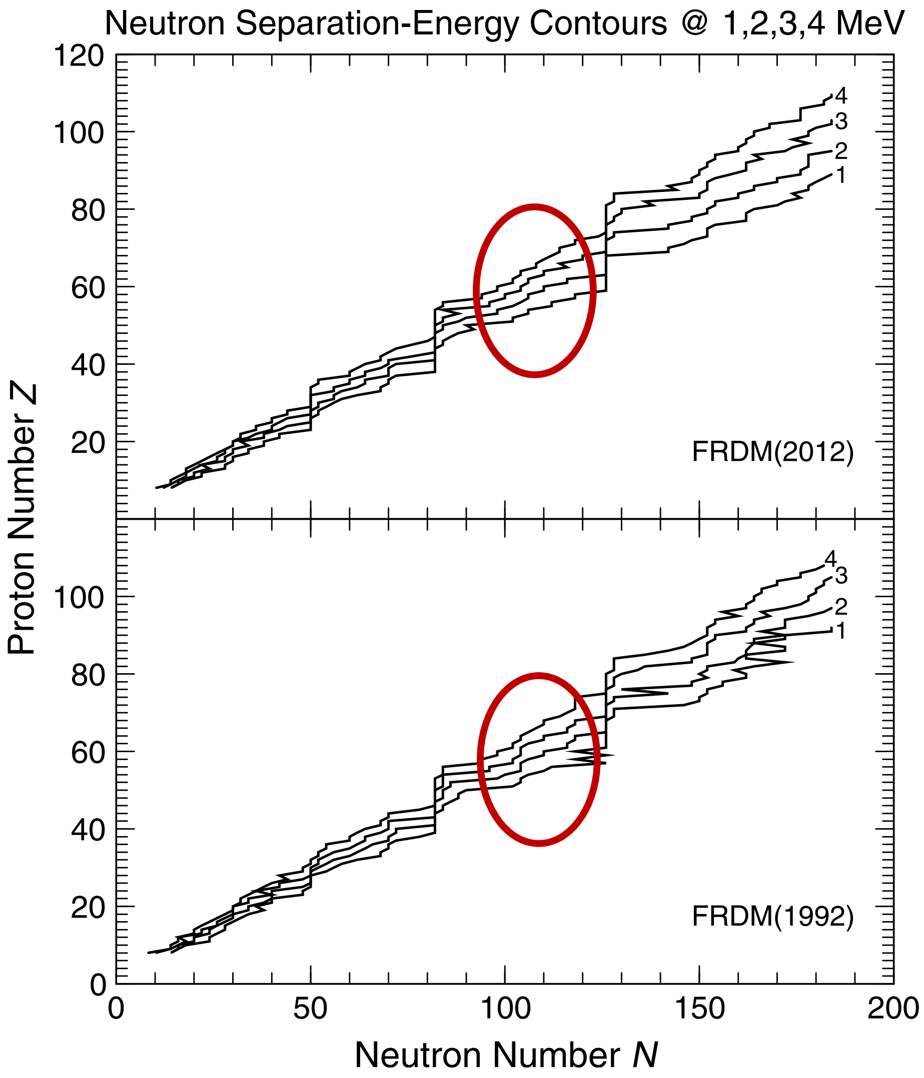




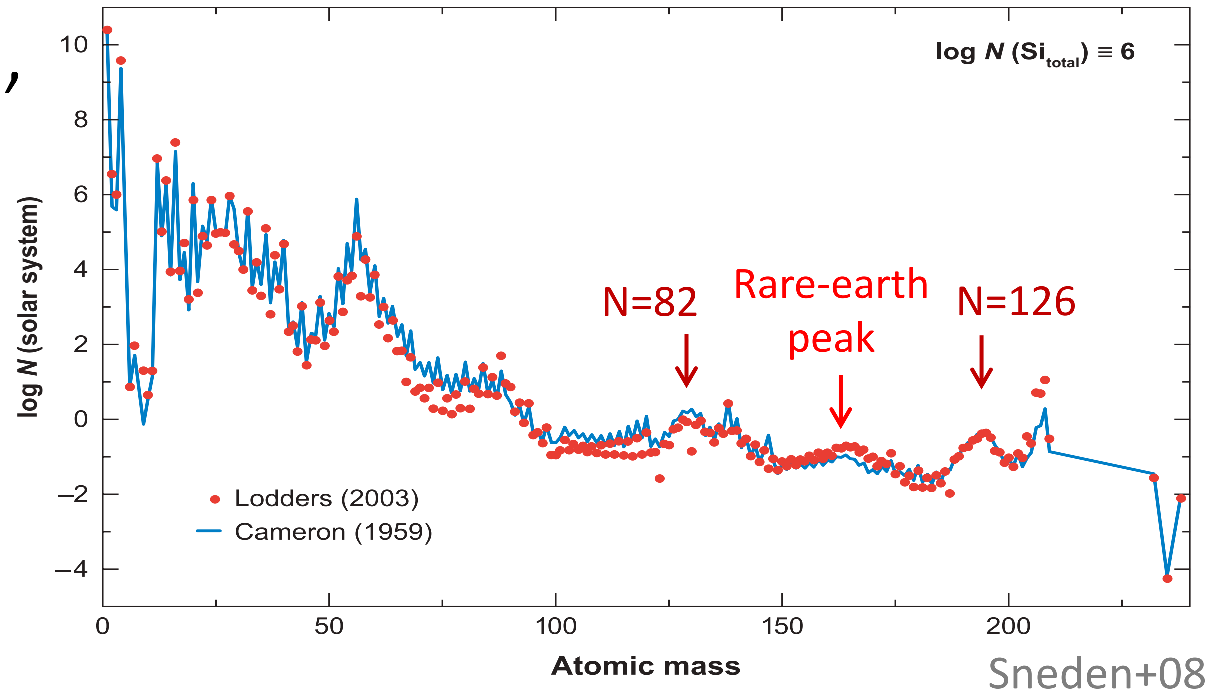
Wang,Vassh+23 (in prep)

Gammas > 3.5 MeV: signature of prompt and delayed fission gammas in a merger event!

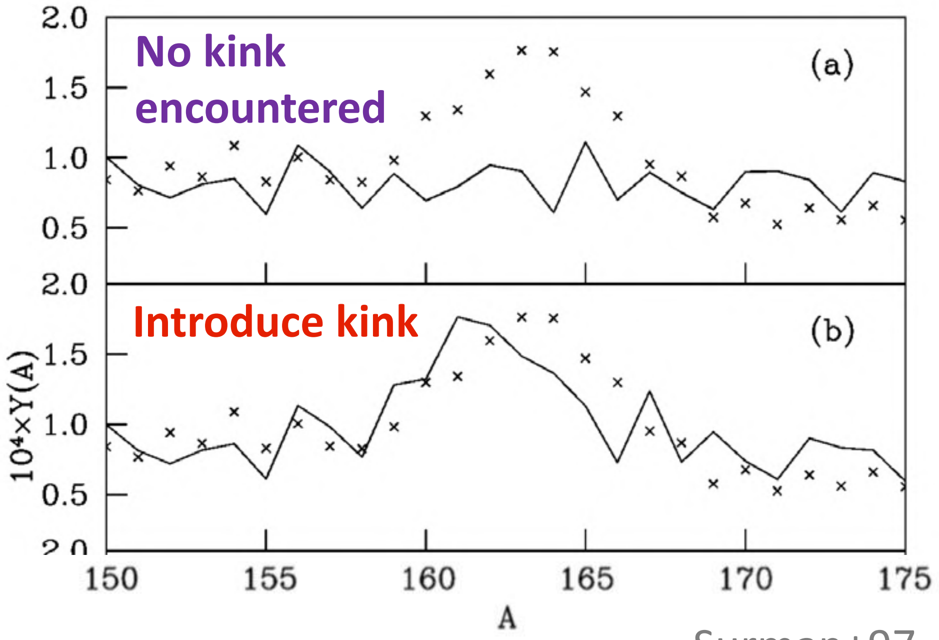
Nuclear masses, nuclear structure, and the rare-earth peak



Möller+12

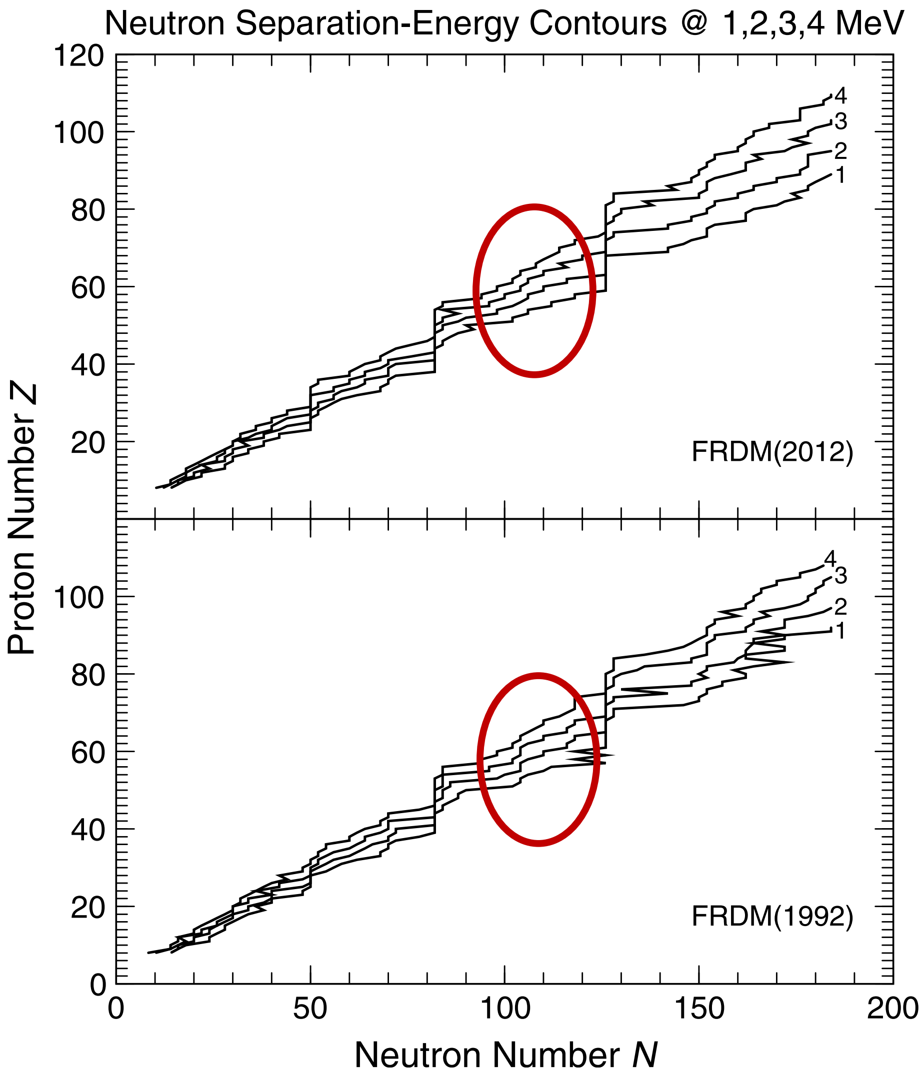


Sneden+08

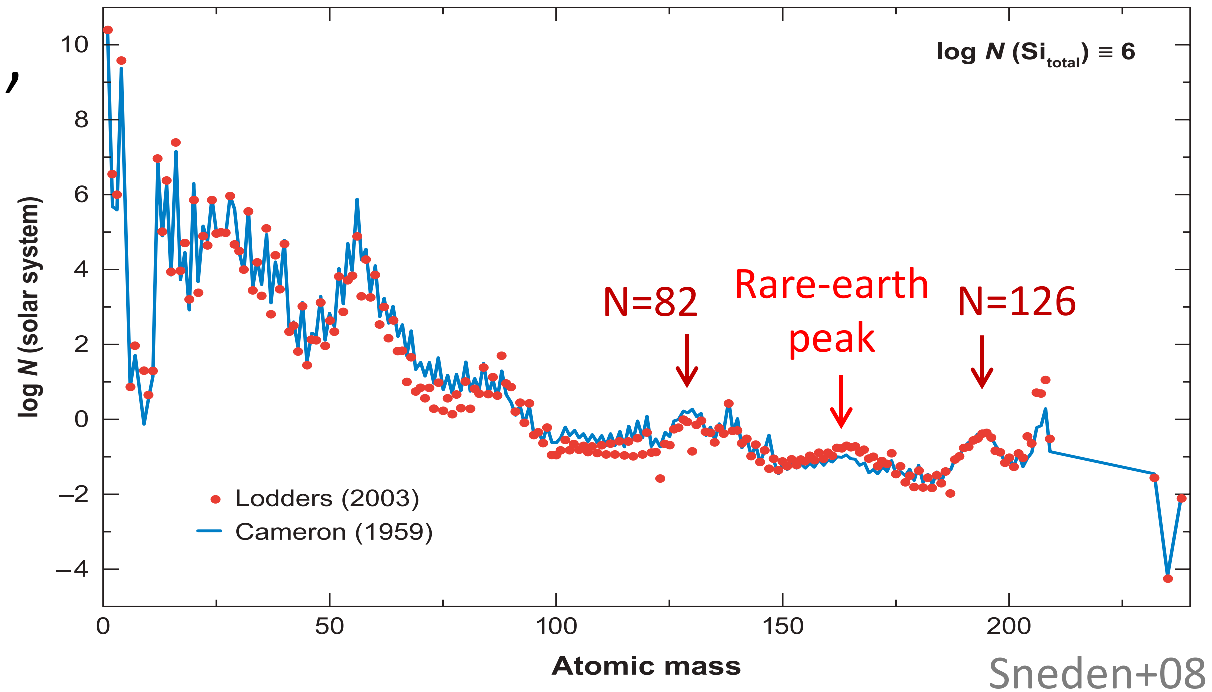


Surman+97

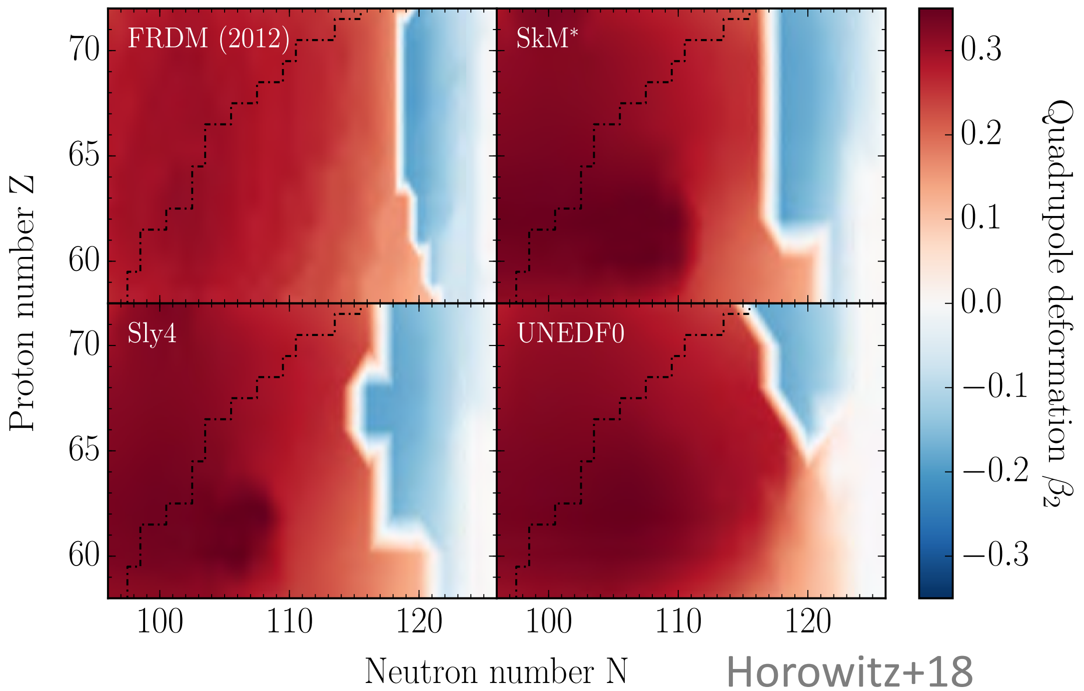
Nuclear masses, nuclear structure, and the rare-earth peak



Möller+12



Sneden+08



Horowitz+18

Markov Chain Monte Carlo (MCMC):

Uses observational data to discern nuclear properties such as masses as well as constrain the conditions present at nucleosynthesis sites

- Monte Carlo mass corrections

$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

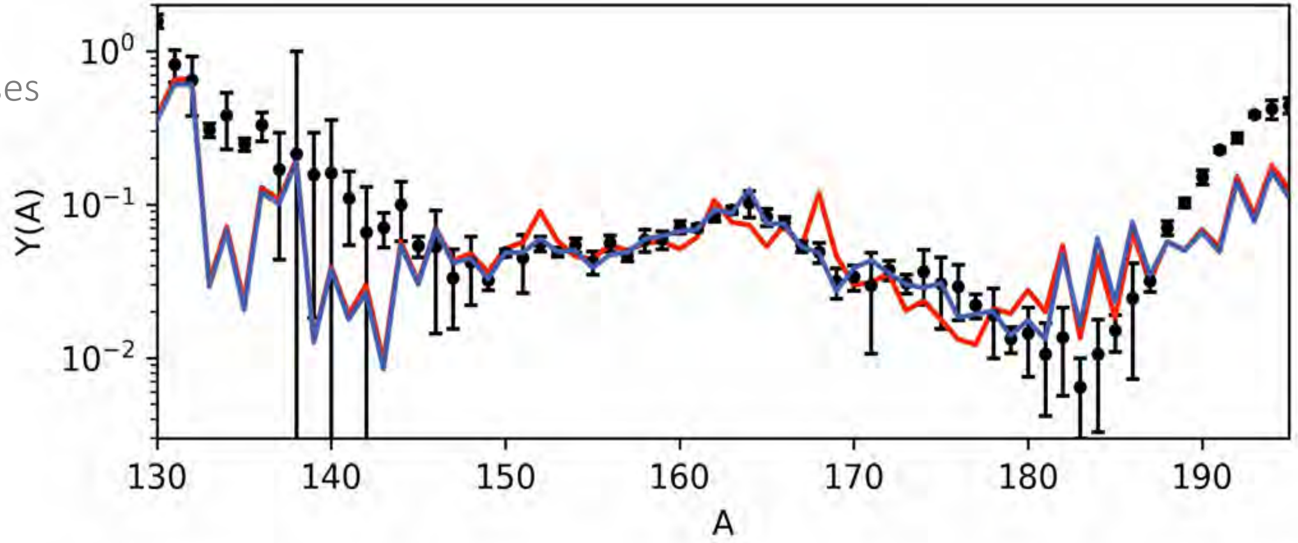
- Calculate: $\sigma^2_{\text{rms}}(M_{\text{AME12}}, M) \leq \sigma^2_{\text{rms}}(M_{\text{AME12}}, M_{DZ})$
- Calculate:

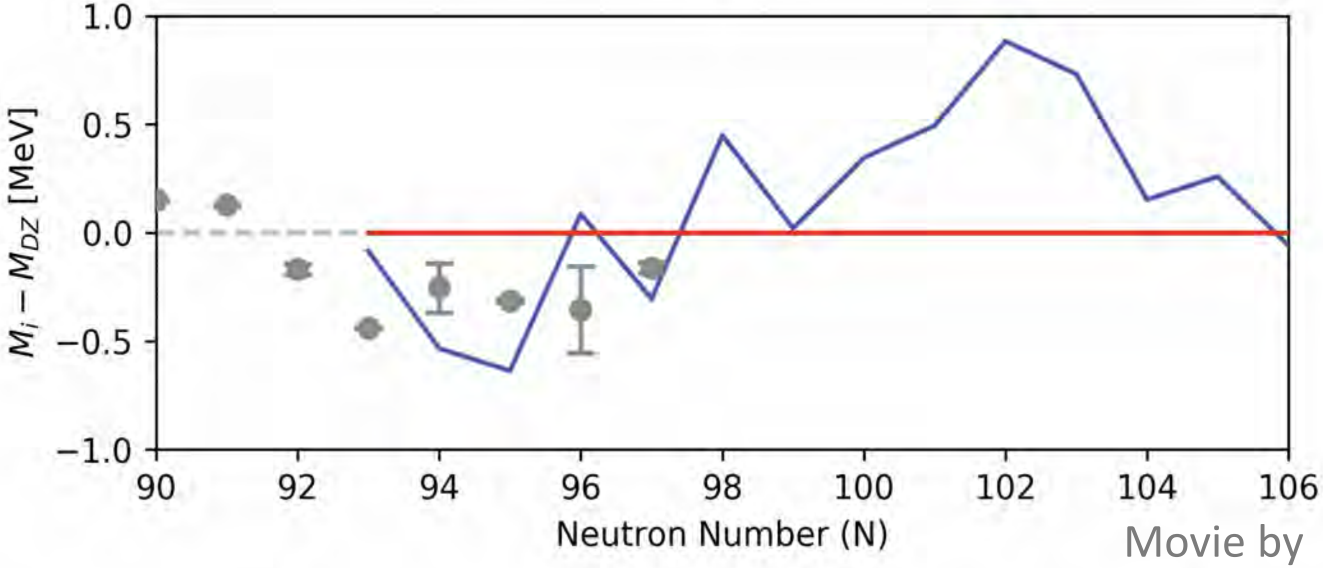
$$D_n(Z,A) = (-1)^{A-Z+1}\big(S_n(Z,A+1) - S_n(Z,A)\big) > 0$$

- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{(Y_{\odot,r}(A) - Y(A))^2}{\Delta Y(A)^2}$
- Update parameters OR revert to last success

$$\mathcal{L}(\text{m}) = \exp\left(-\frac{\chi^2(\text{m})}{2}\right) \rightarrow \alpha(\text{m}) = \frac{\mathcal{L}(\text{m})}{\mathcal{L}(\text{m}-1)}$$

See Orford,Vassh+18 (PRL), Vassh+21 (ApJ), Orford,Vassh+22 (PRC Letters), Vassh+22 (Frontiers in Phys.)





Movie by N. Vassh

Black – solar abundance data
Grey – AME 2012 data
Red – values at current step
Blue – best step of entire run

Markov Chain Monte Carlo (MCMC):

Uses observational data to discern nuclear properties such as masses as well as constrain the conditions present at nucleosynthesis sites

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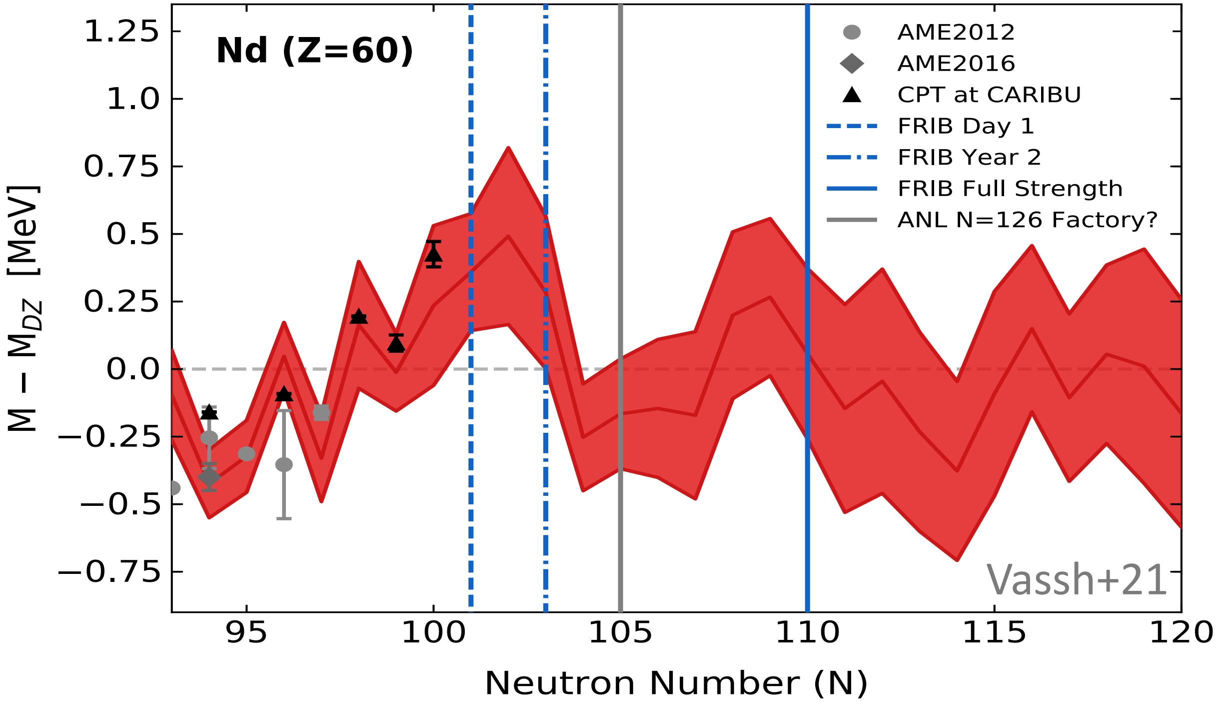
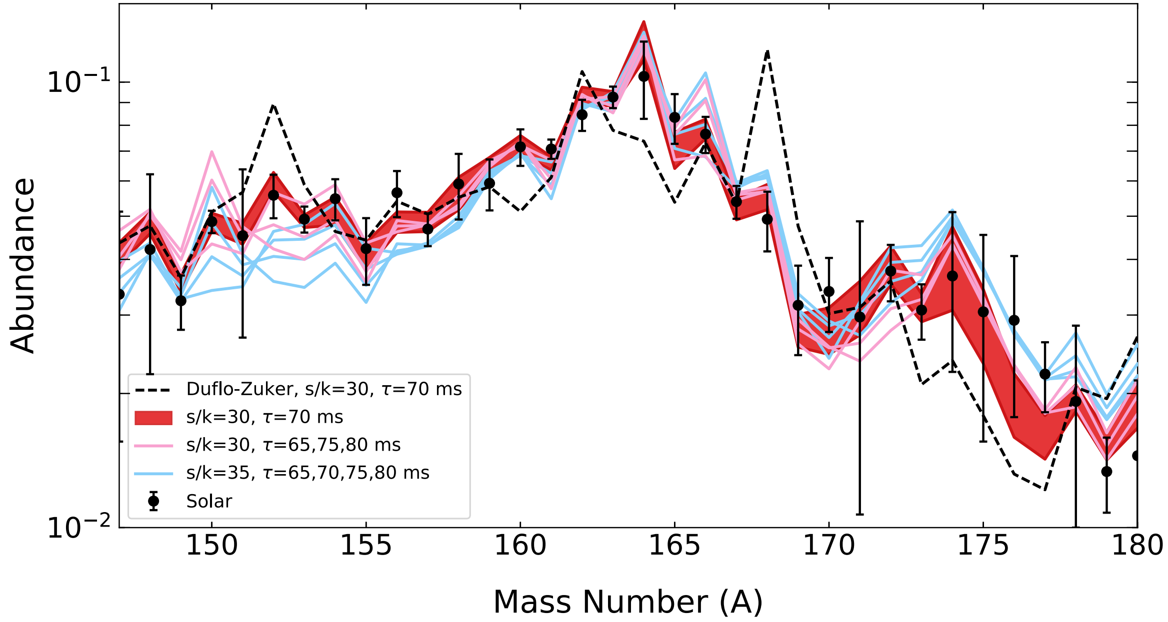
See Orford,Vassh+18 (PRL), Vassh+21 (ApJ), Orford,Vassh+22 (PRC Letters), Vassh+22 (Frontiers in Phys.)

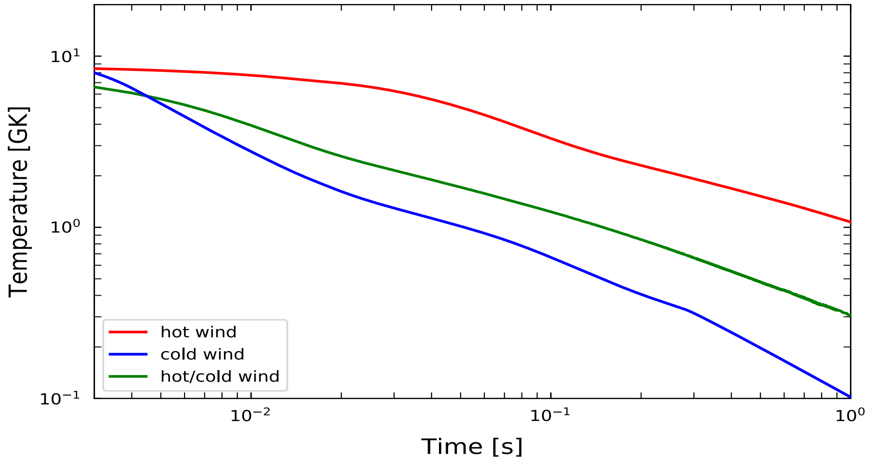
hot low entropy accretion disk wind (moderately n-rich)

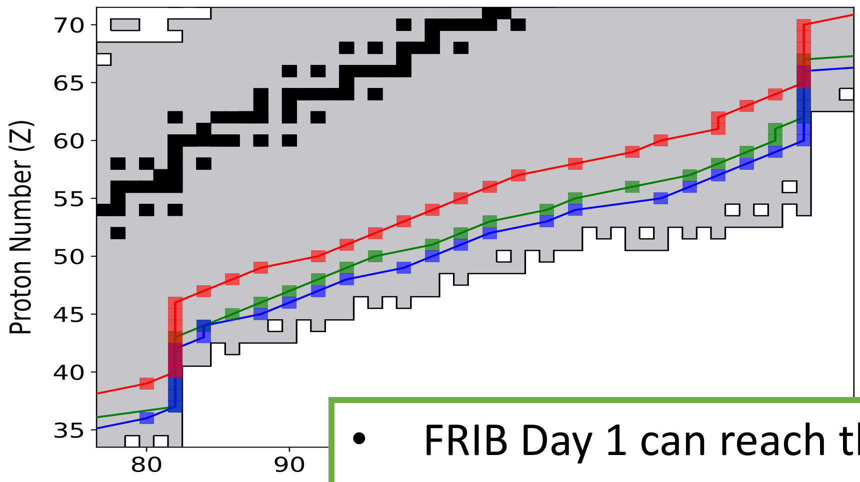




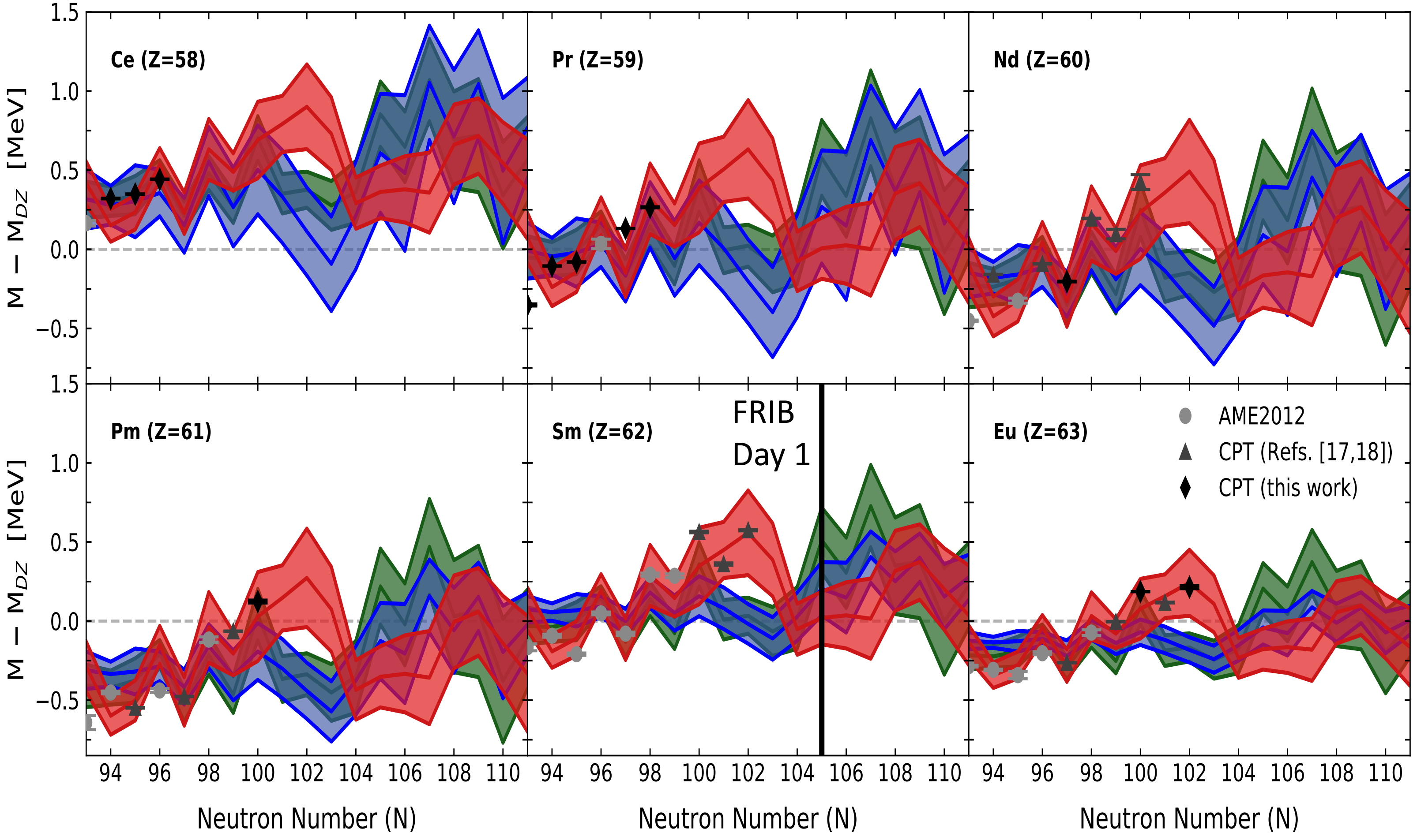
Ejecta Outflow Parameters

Outflow Type	Entropy (s/k_B)	Timescale (ms)	Y_e
Hot	30	70	0.2
Hot/cold	20	10	0.2
Cold	10	3	0.2





hot vs cold low entropy accretion disk winds (moderately n-rich)

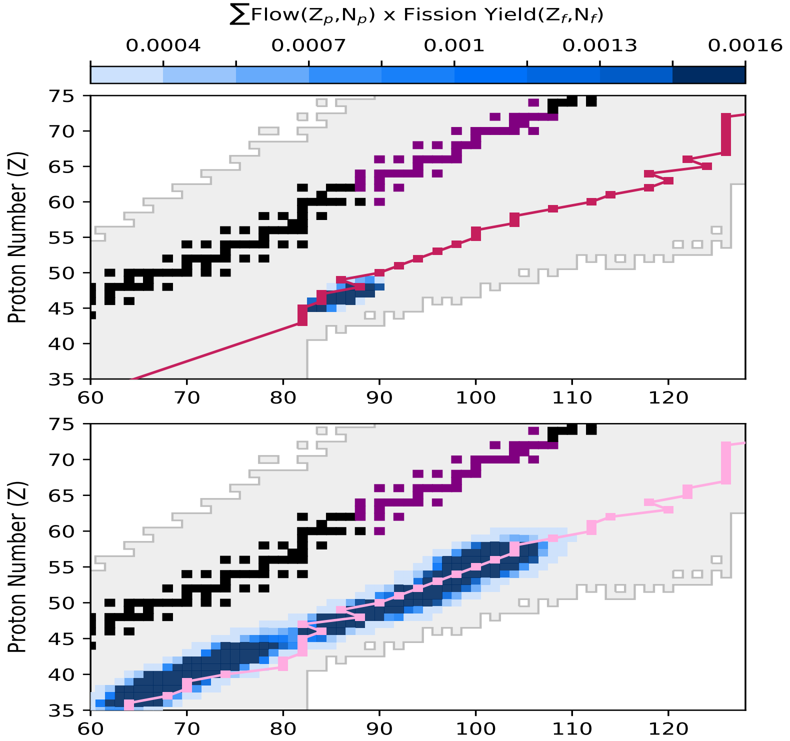


Orford,Vassh+22 (PRC Letters)

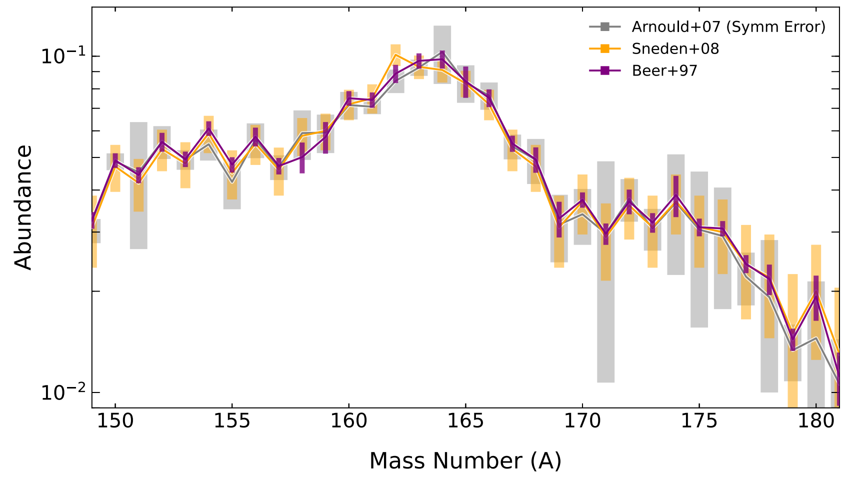
- FRIB Day 1 can reach the N=104 feature forming the peak in hot conditions
- Future FRIB reach will cover the N=108 and N=106 features utilized with cold and in between dynamics

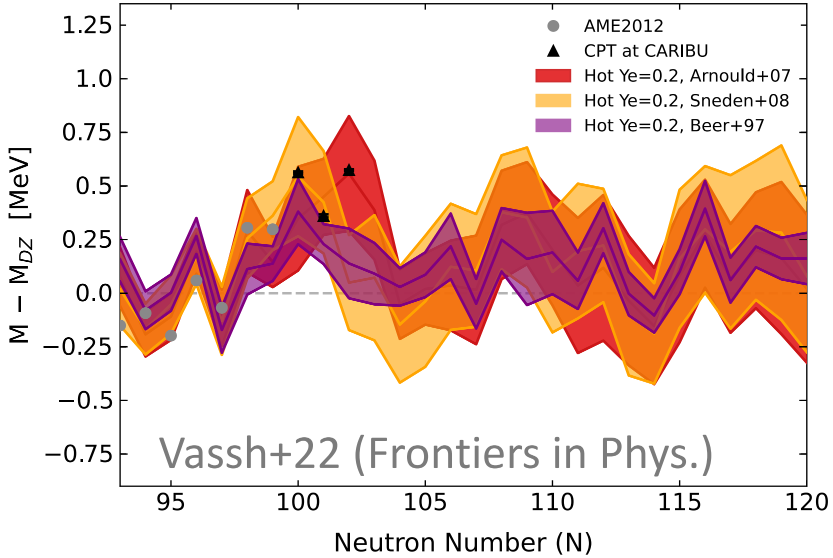
Recent work:

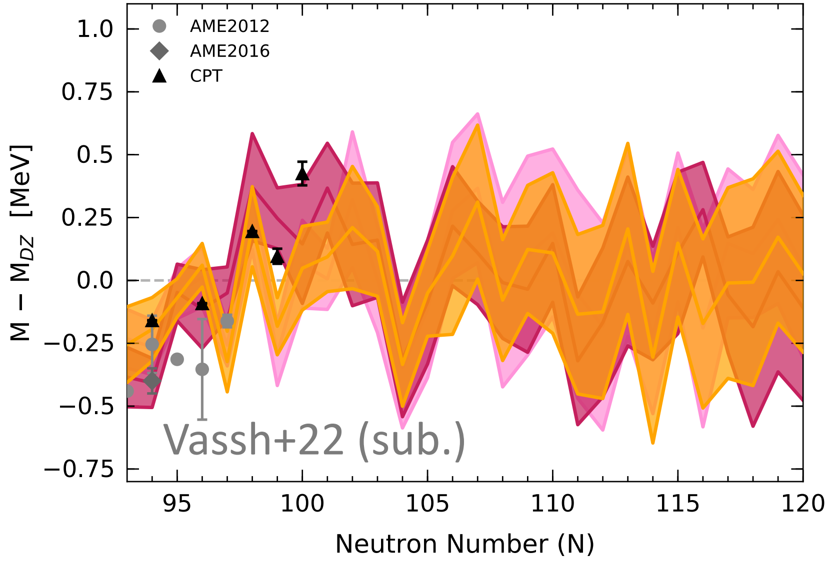
Very n-rich conditions with fission deposition



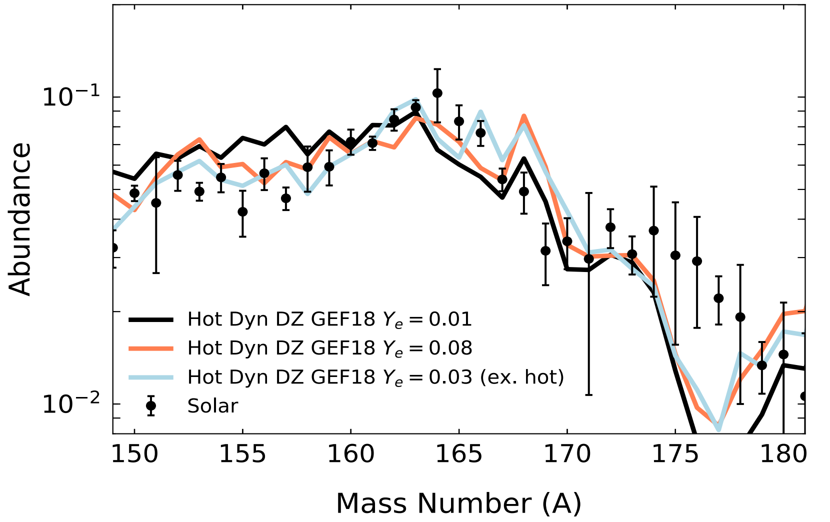
Solar abundance variations

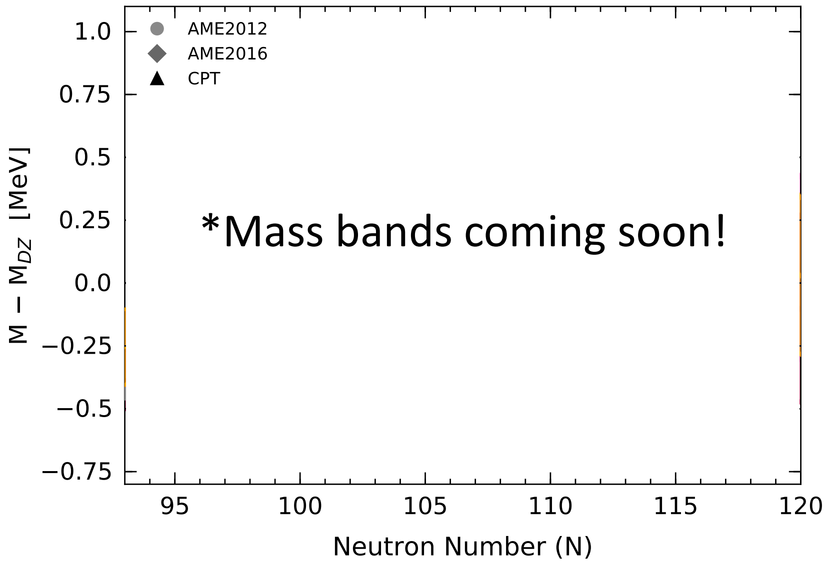




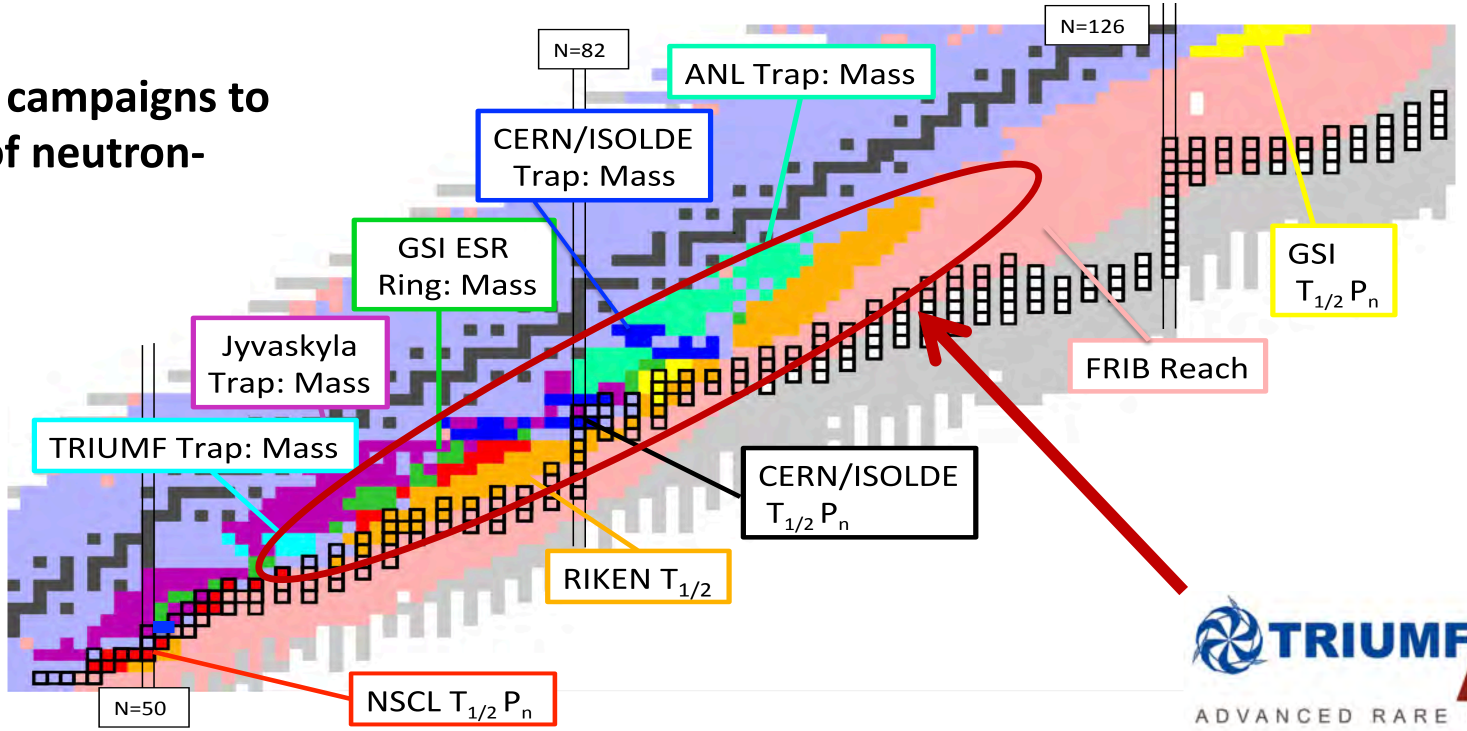


A wider variety of n-richness



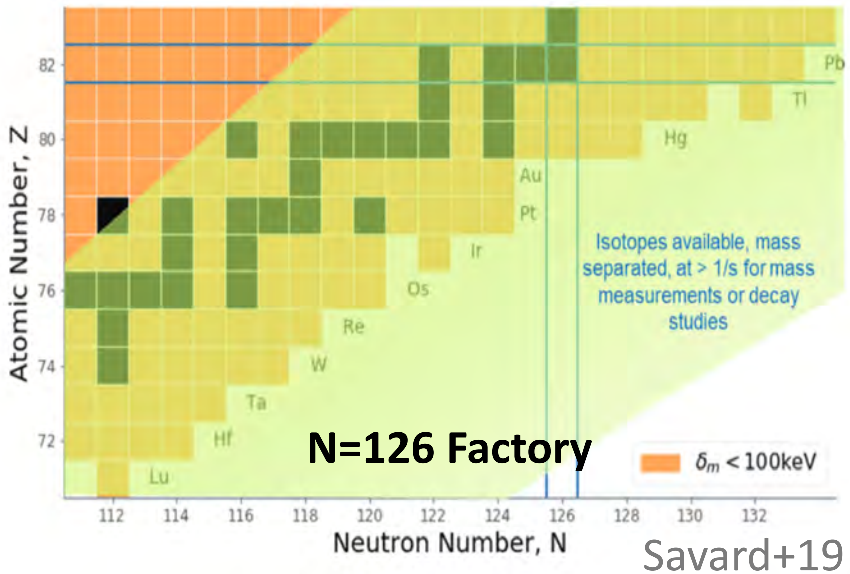


Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives,
reaction rates…

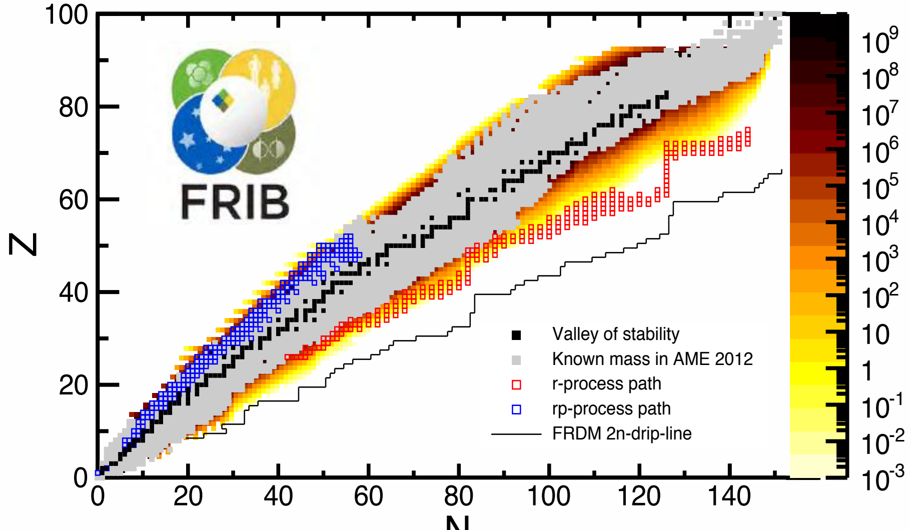


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

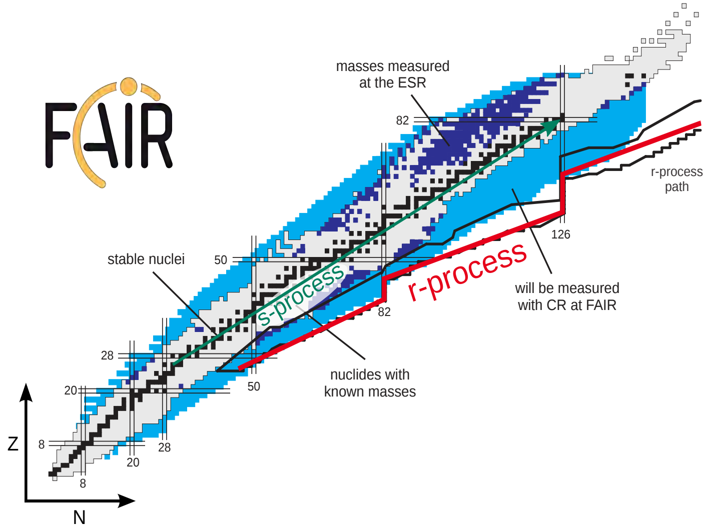
Horowitz+18



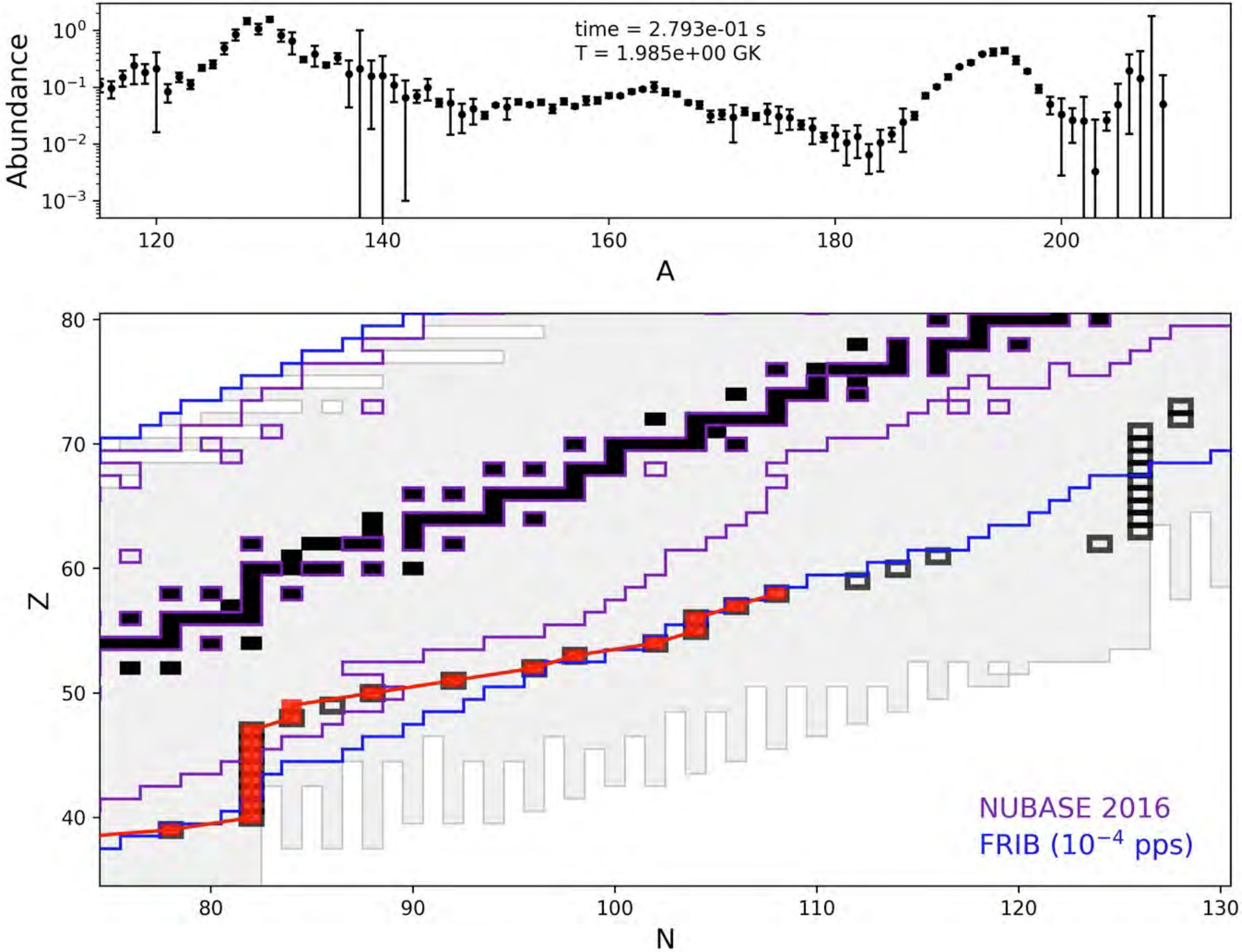
Savard+19



Meisel 16



Future experiment meets the *r*-process path



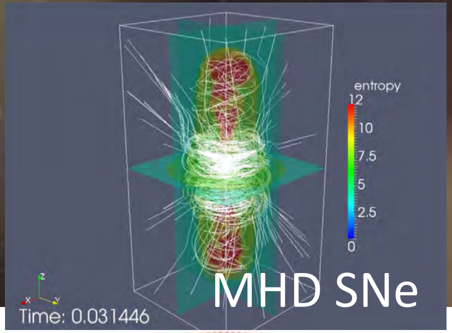
*reach of future experiment in key regions impacting the evolution of abundances (note moderately n-rich conditions used here)

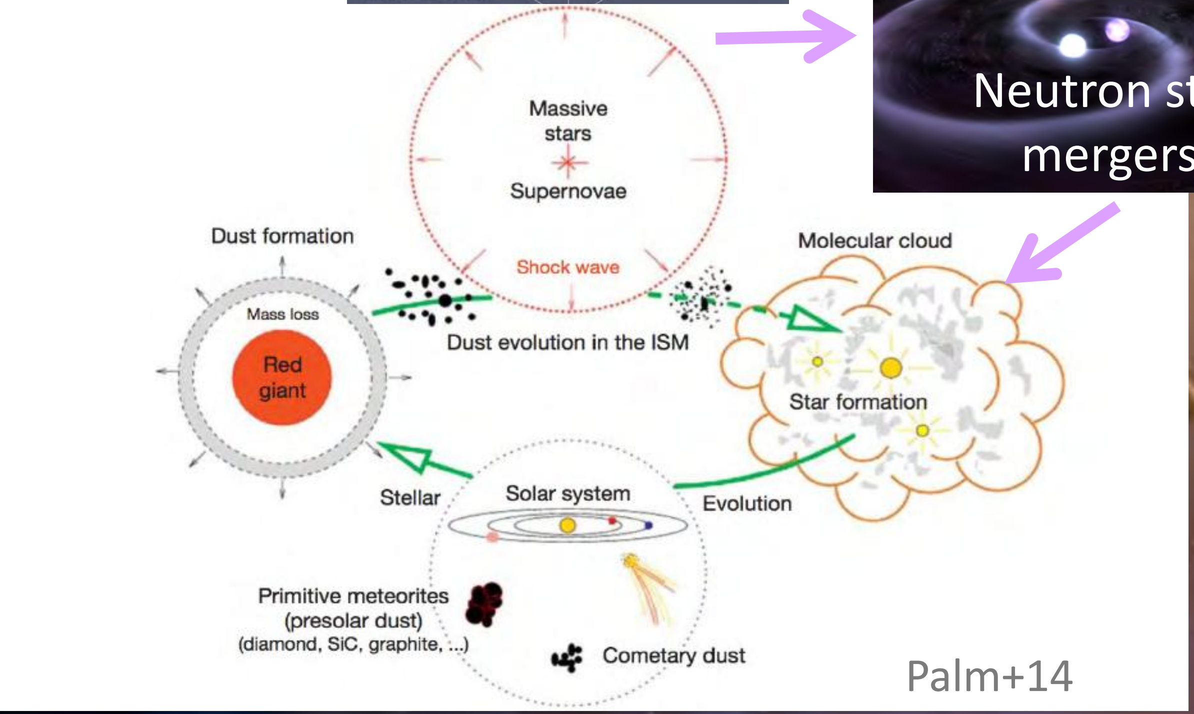
Movie by N. Vassh

Outline for lecture II

- Supernovae: types and nucleosynthesis [3-7]
- Making the heaviest elements: neutron capture nucleosynthesis [9-19]
- Neutron star mergers: gravitational waves, kilonovae, and nucleosynthesis [21-30]
- Impact of nuclear physics uncertainties on *r*-process predictions [32-55]
- Galactic chemical evolution [57-60]

Where *and when* were the heavy elements we see in stars produced?

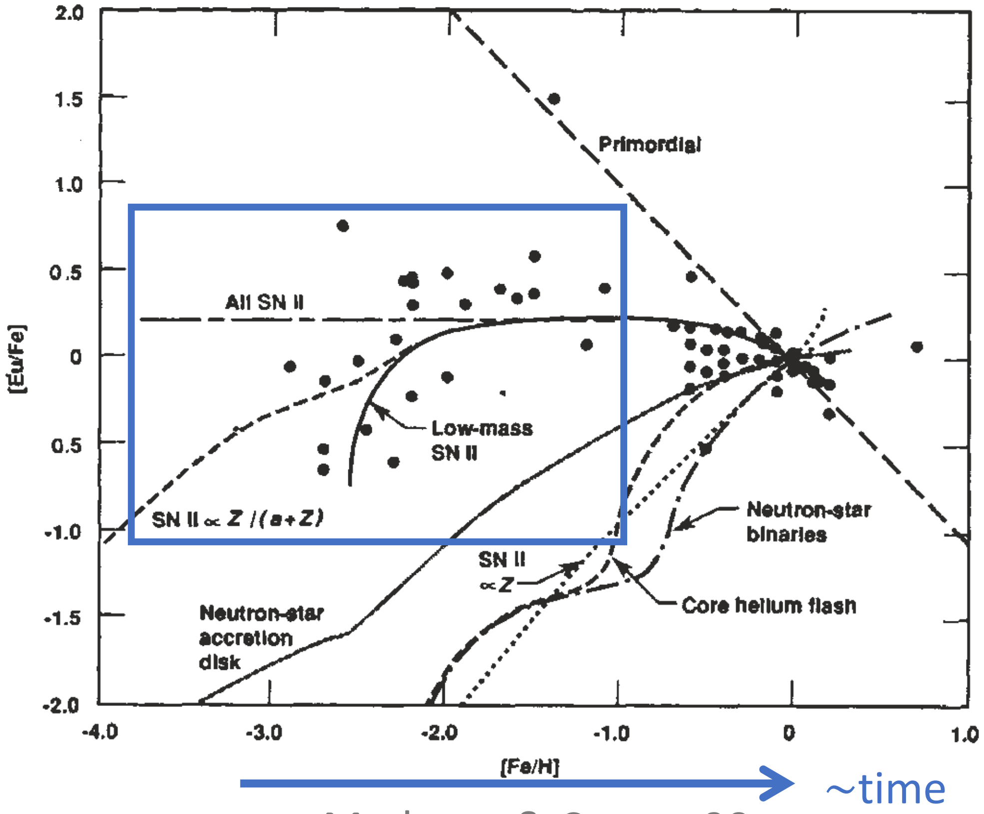




Palm+14

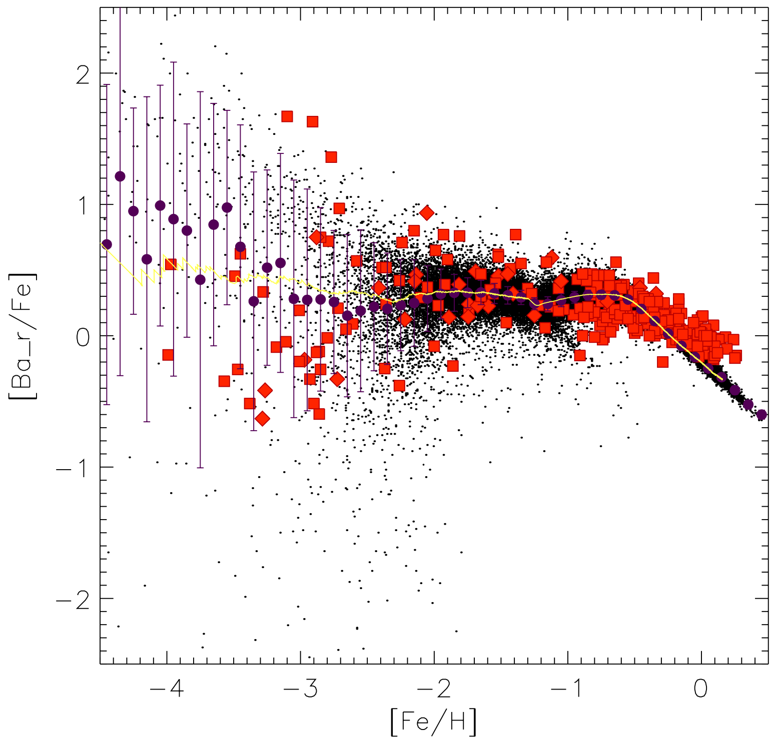
For our Milky Way (present day):
CCSNe ~ 2 per century
SNe Ia ~ 0.4 per century
RAWDs ~ 0.05 per century
NSMs ~ 0.004 per century

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

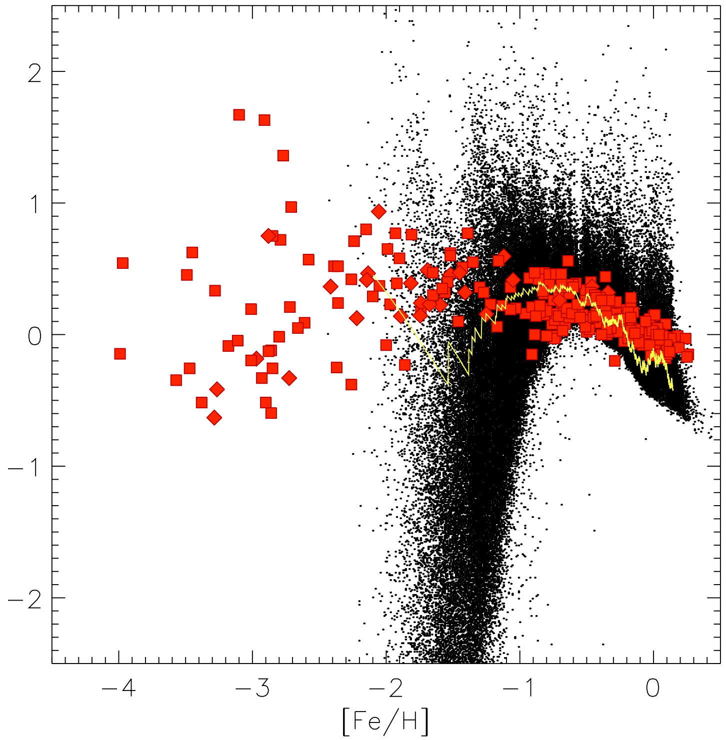


Mathews & Cowan 90

Type II Supernova



Neutron Star Mergers



Argast+04

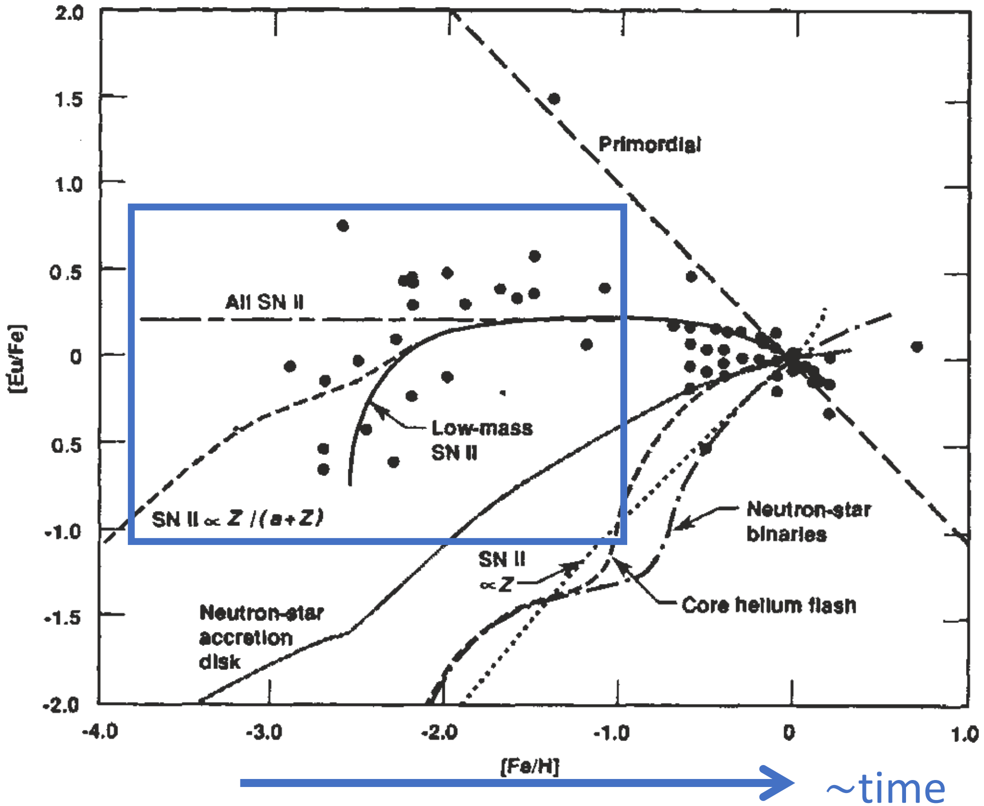
*The stars in the box seem to be more consistent with supernovae since neutron stars take time to merge

◆ ■ observations

● • model stars

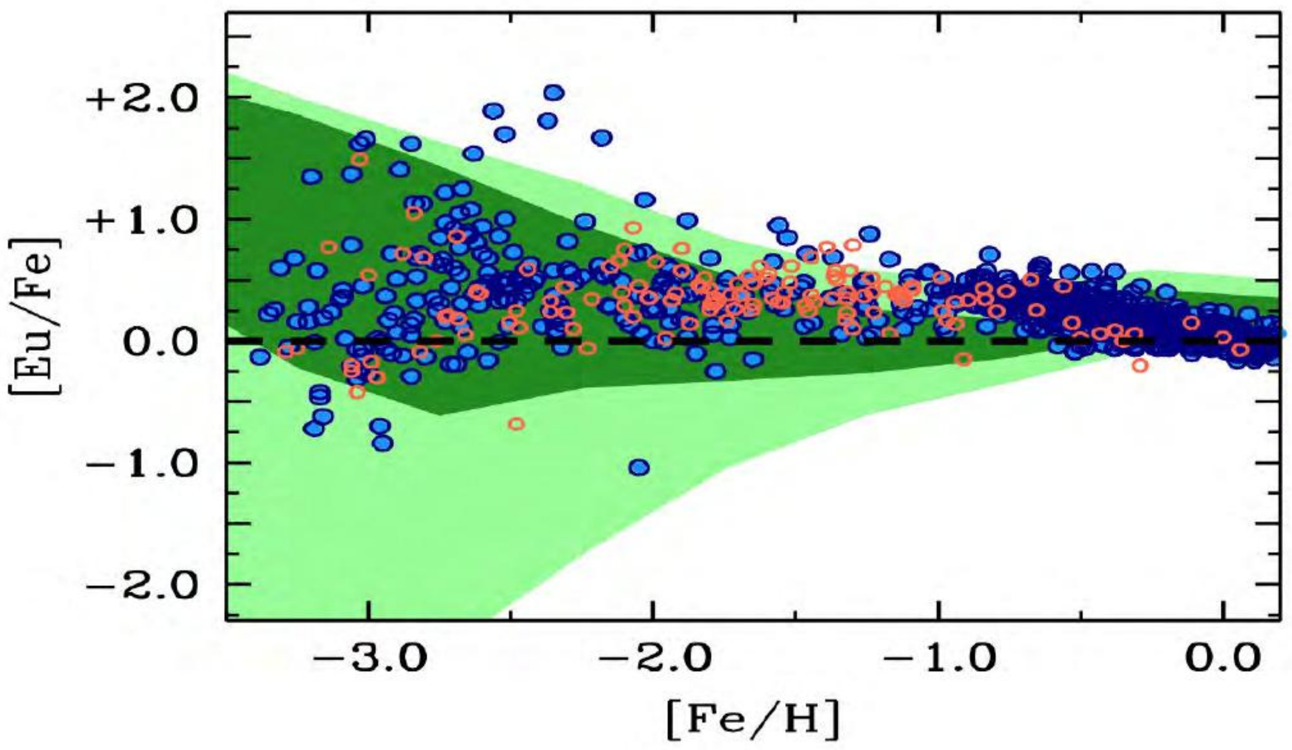
~ average ISM abundances

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



Mathews & Cowan 90

Neutron Star Mergers only

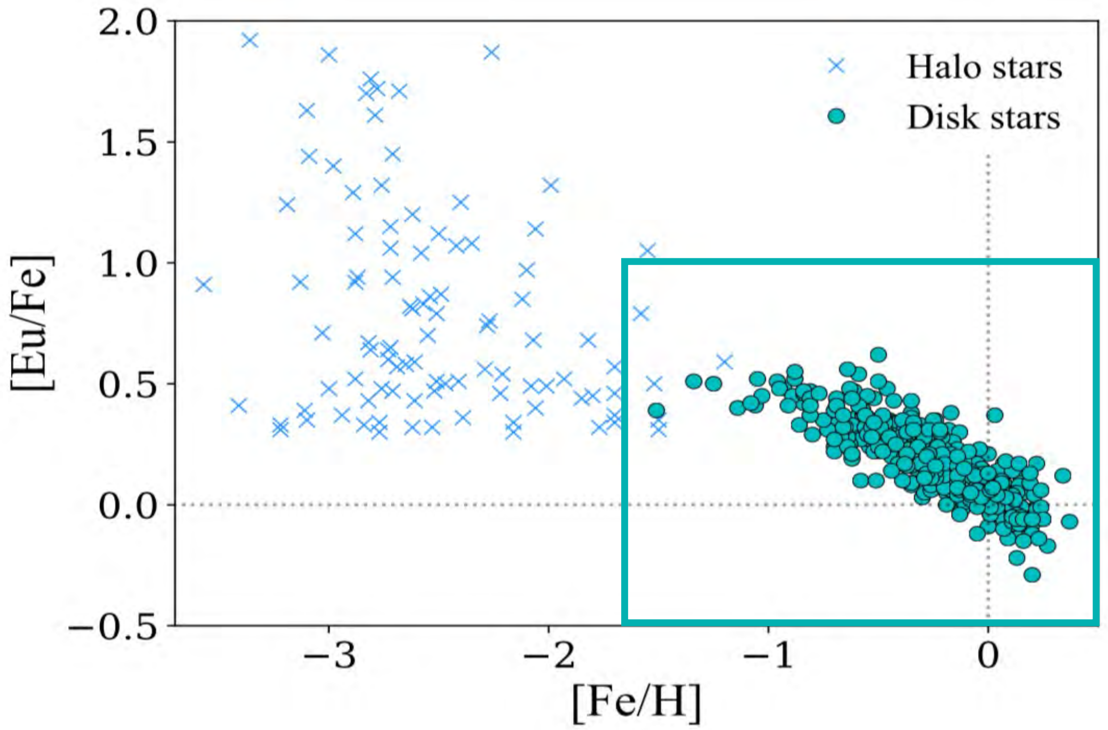


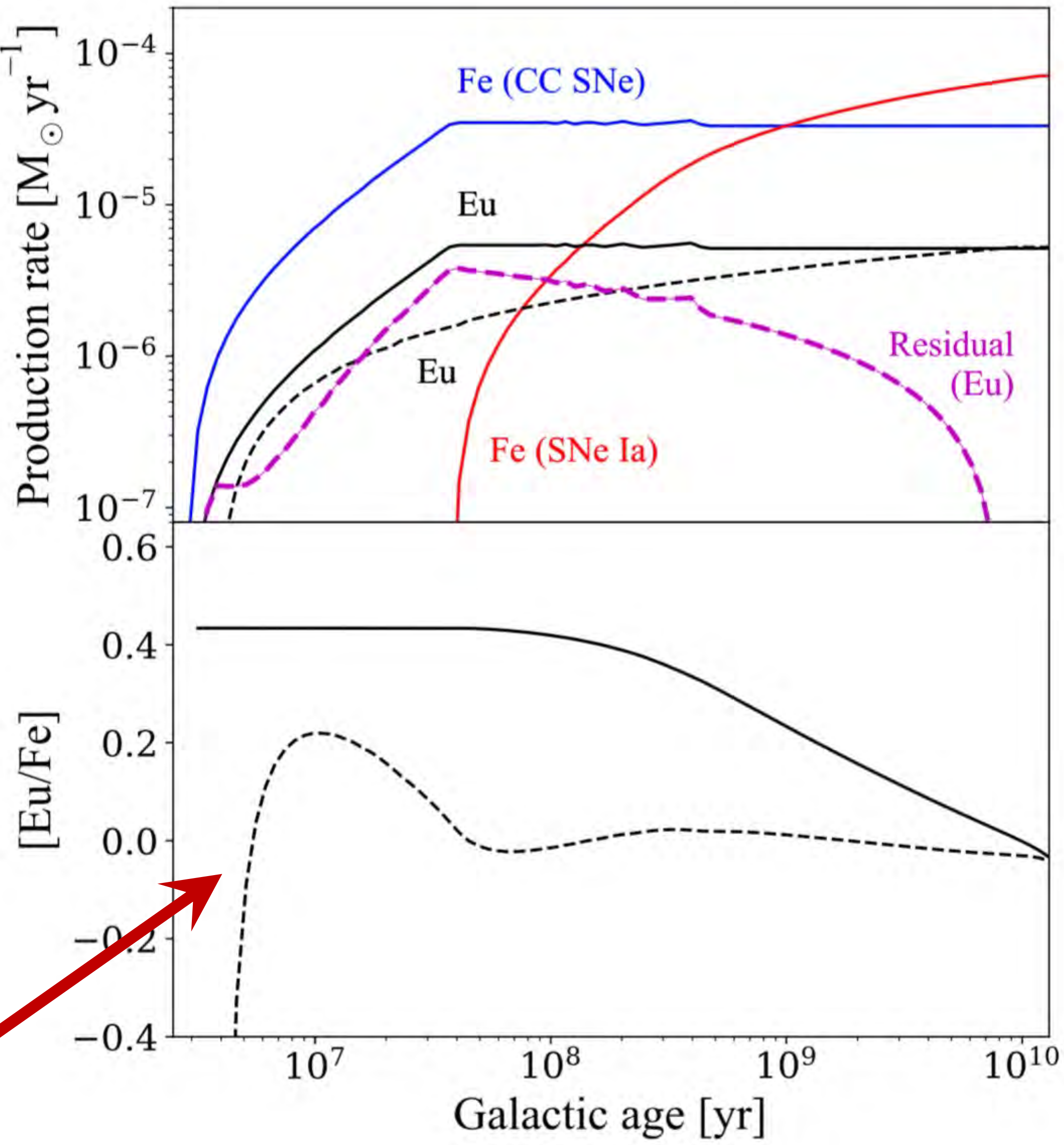
Shen+15

*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

Could NSMs be the only *r*-process source? Consider [Eu/Fe] again but now 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