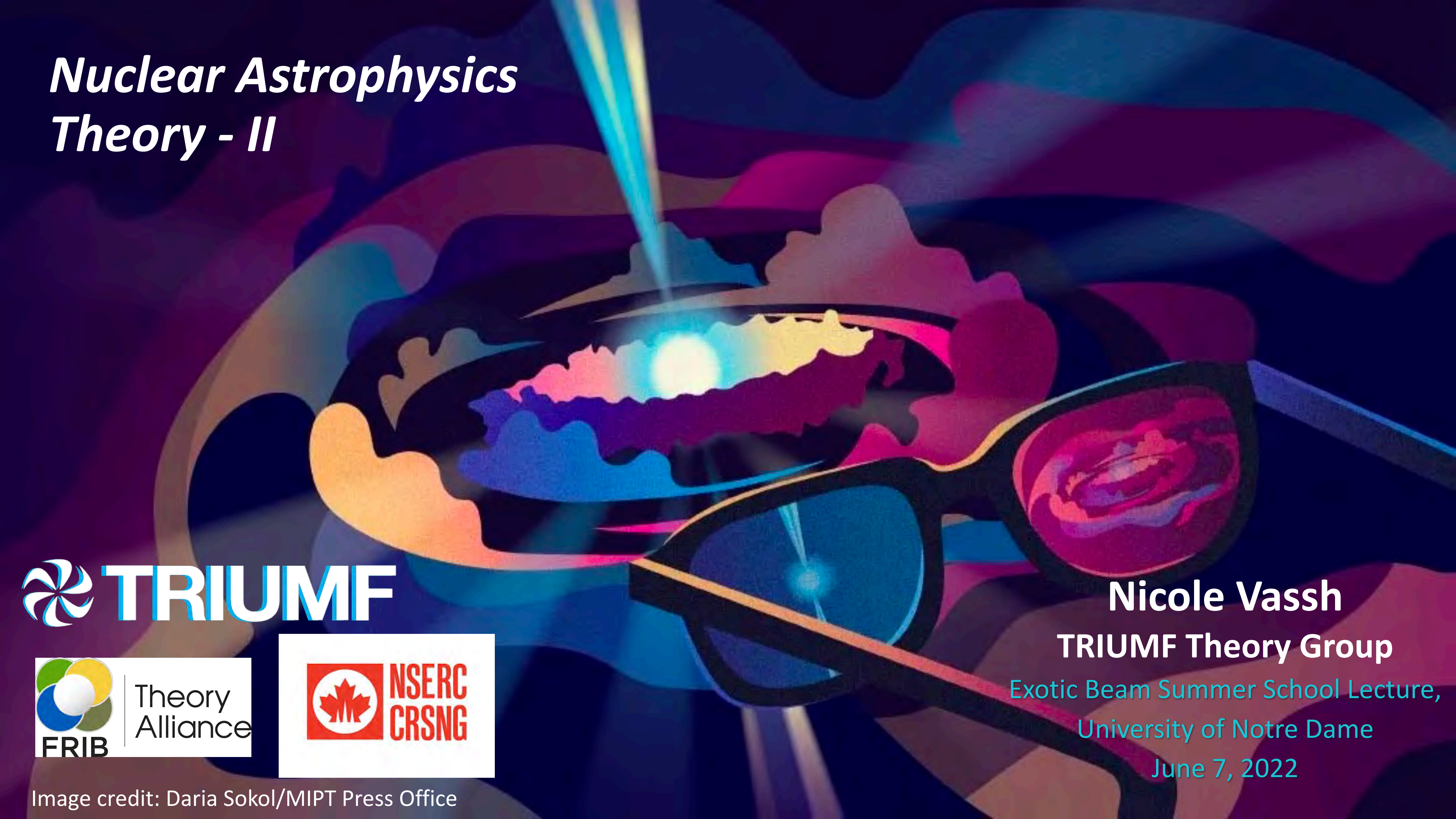

Nuclear Astrophysics Theory - II

Nicole Vassh

TRIUMF Theory Group

Exotic Beam Summer School Lecture,

University of Notre Dame

June 7, 2022

TRIUMF

FRIB Theory Alliance

NSERC CRSNG

Image credit: Daria Sokol/MIPT Press Office

Outline for lecture II

- Stellar burning and stellar evolution [3-9]
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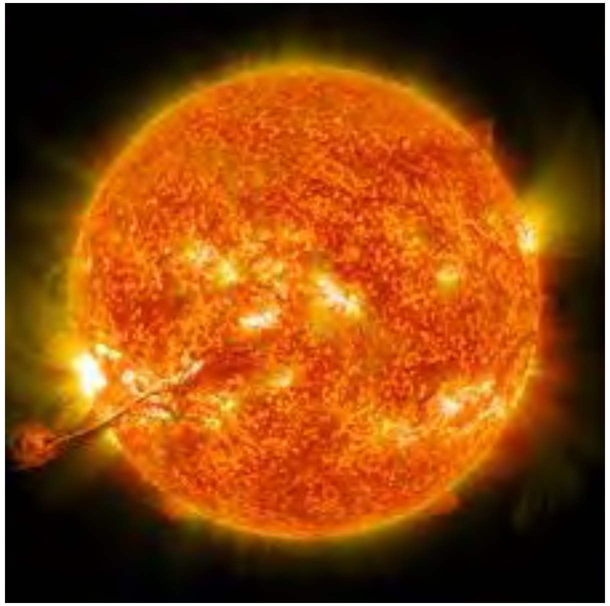
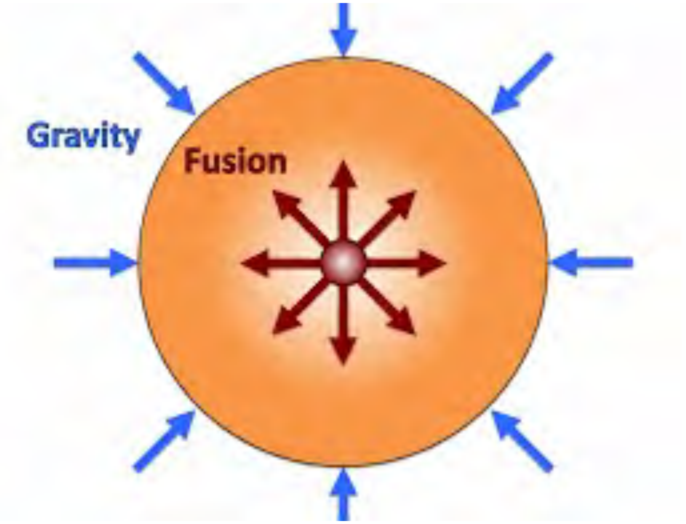
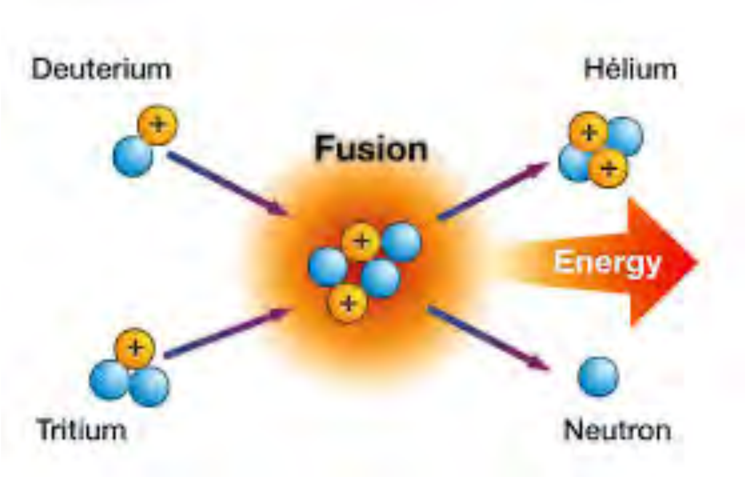
Stellar fusion







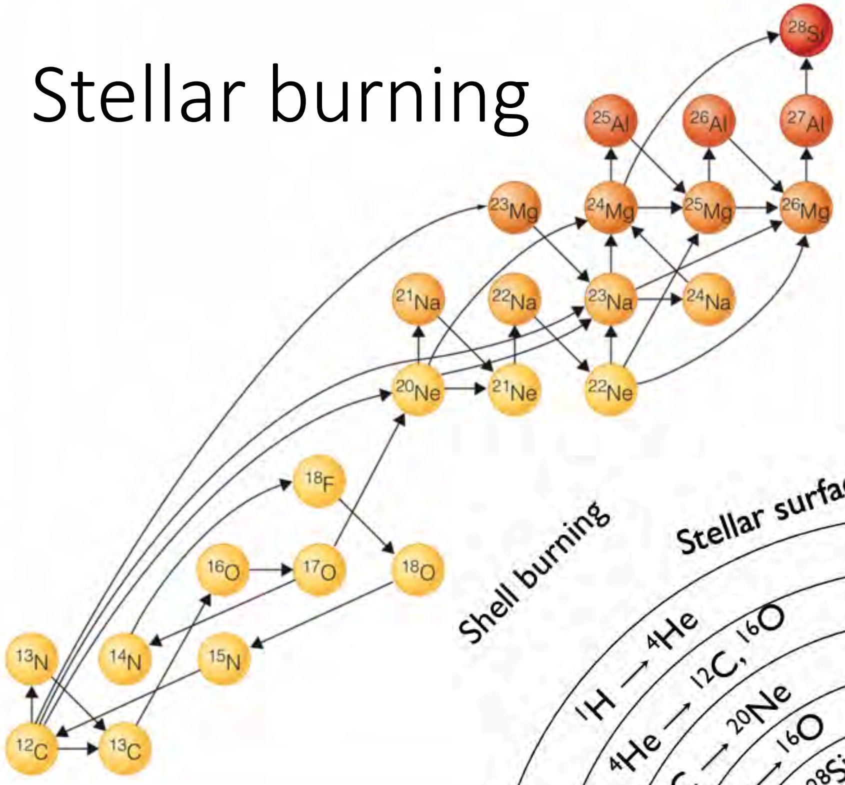
- The Sun was first a cloud of gas that underwent gravitational collapse, causing the core to become hot and dense enough* for fusion to begin
  *have to overcome the Coulomb barrier (proton repulsion)

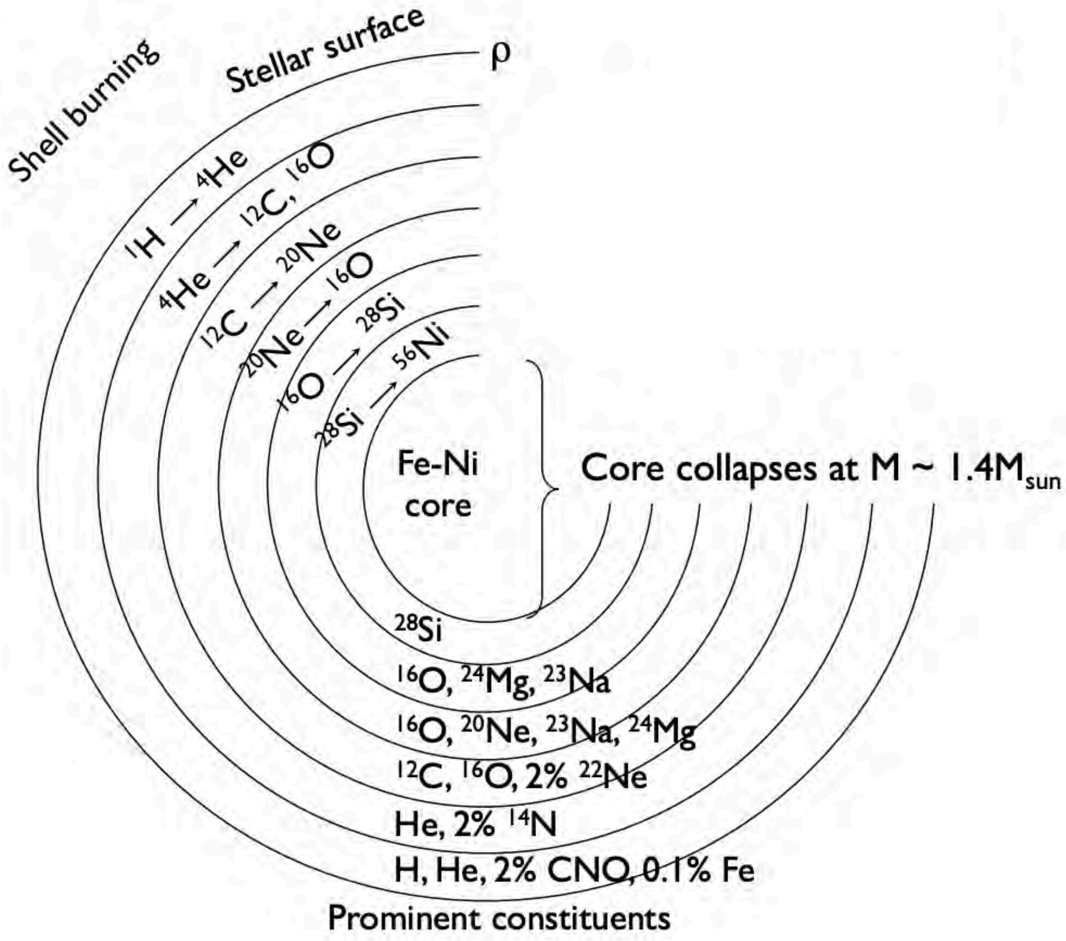
- The energy released by fusion provides an outward pressure, combating the gravitational inward pull

$$^{2}H + {}^{3}H \rightarrow {}^{4}He + n\ ,\ \ \mathrm{Q} = 17.6\ \mathrm{MeV}$$

Energy released by fusion ~10-30 MeV

Stellar burning



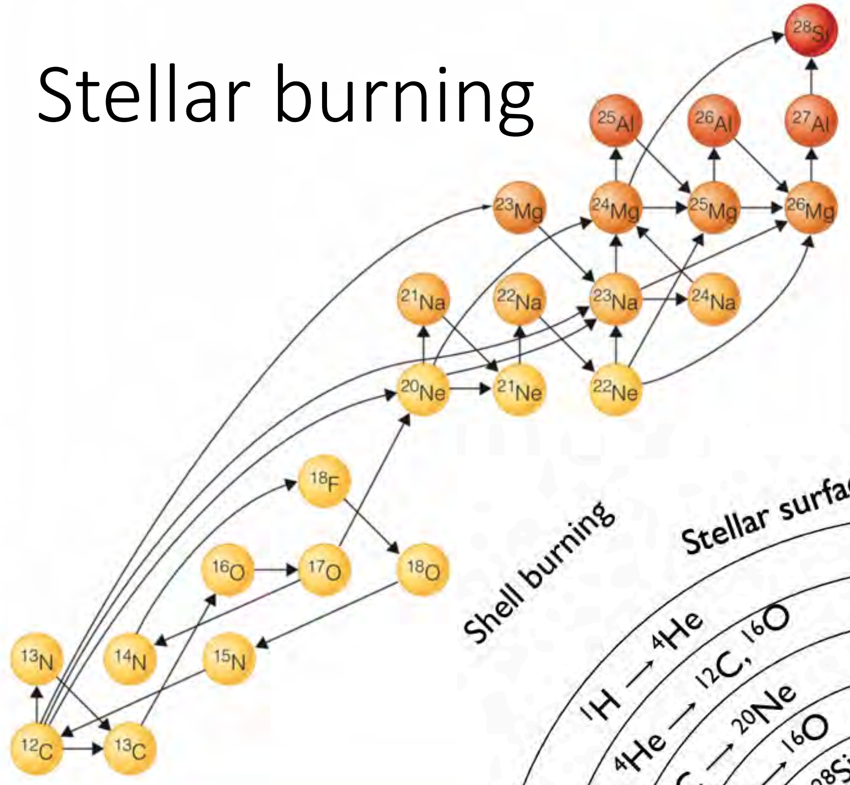


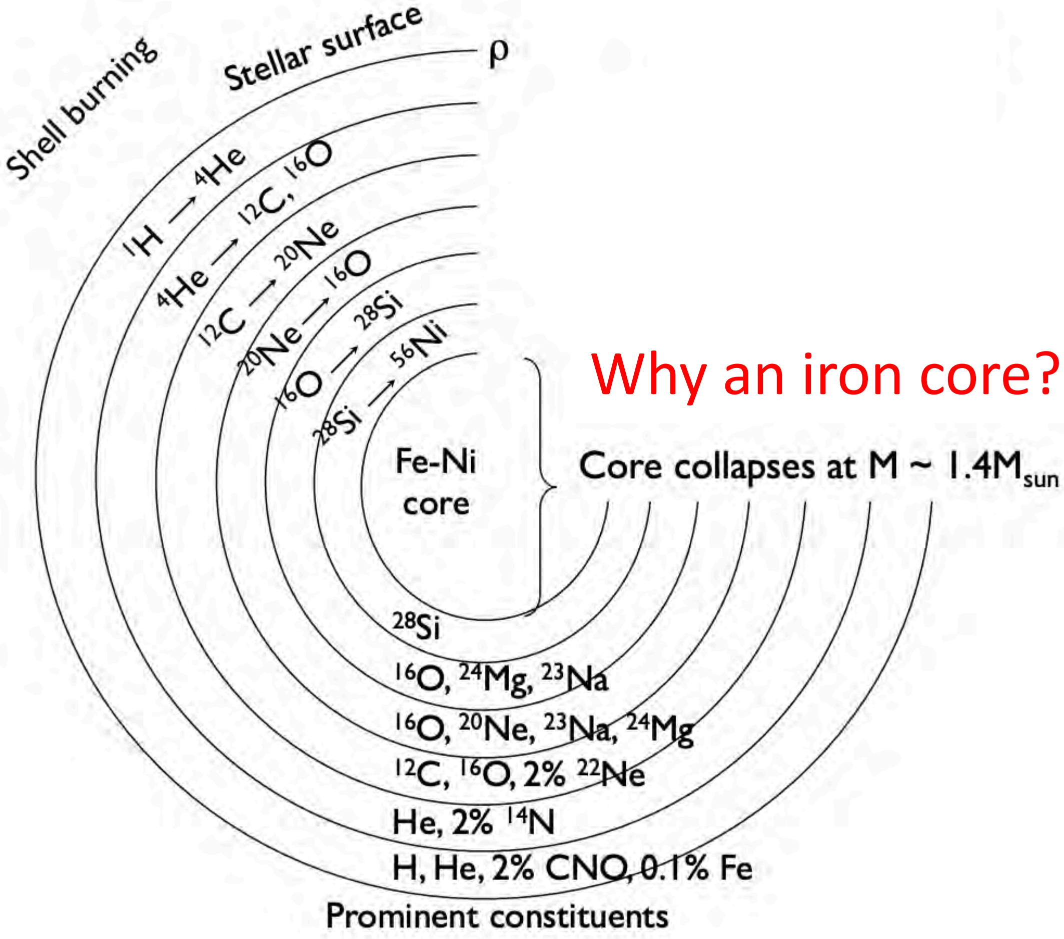
Stellar Nucleosynthesis

Evolutionary Time Scales for a 15 M_{sun} Star

Fused	Products	Time	Temperature
H	^{4}He	10^7 yrs.	4×10^6 K
^{4}He	^{12}C	Few X 10^6 yrs	1×10^8 K
^{12}C	^{16}O, ^{20}Ne, ^{24}Mg, ^{4}He	1000 yrs.	6×10^8 K
^{20}Ne +	^{16}O, ^{24}Mg	Few yrs.	1×10^9 K
^{16}O	^{28}Si, ^{32}S	One year	2×10^9 K
^{28}Si +	^{56}Fe	Days	3×10^9 K
^{56}Fe	Neutrons	< 1 second	3×10^9 K

Stellar burning





Why an iron core?

Stellar Nucleosynthesis

Evolutionary Time Scales for a 15 M_{sun} Star

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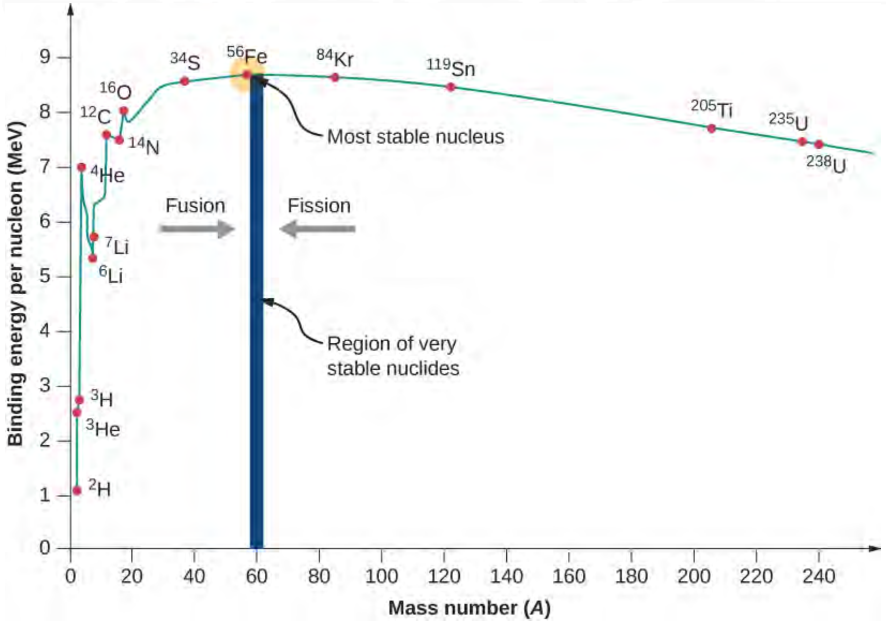


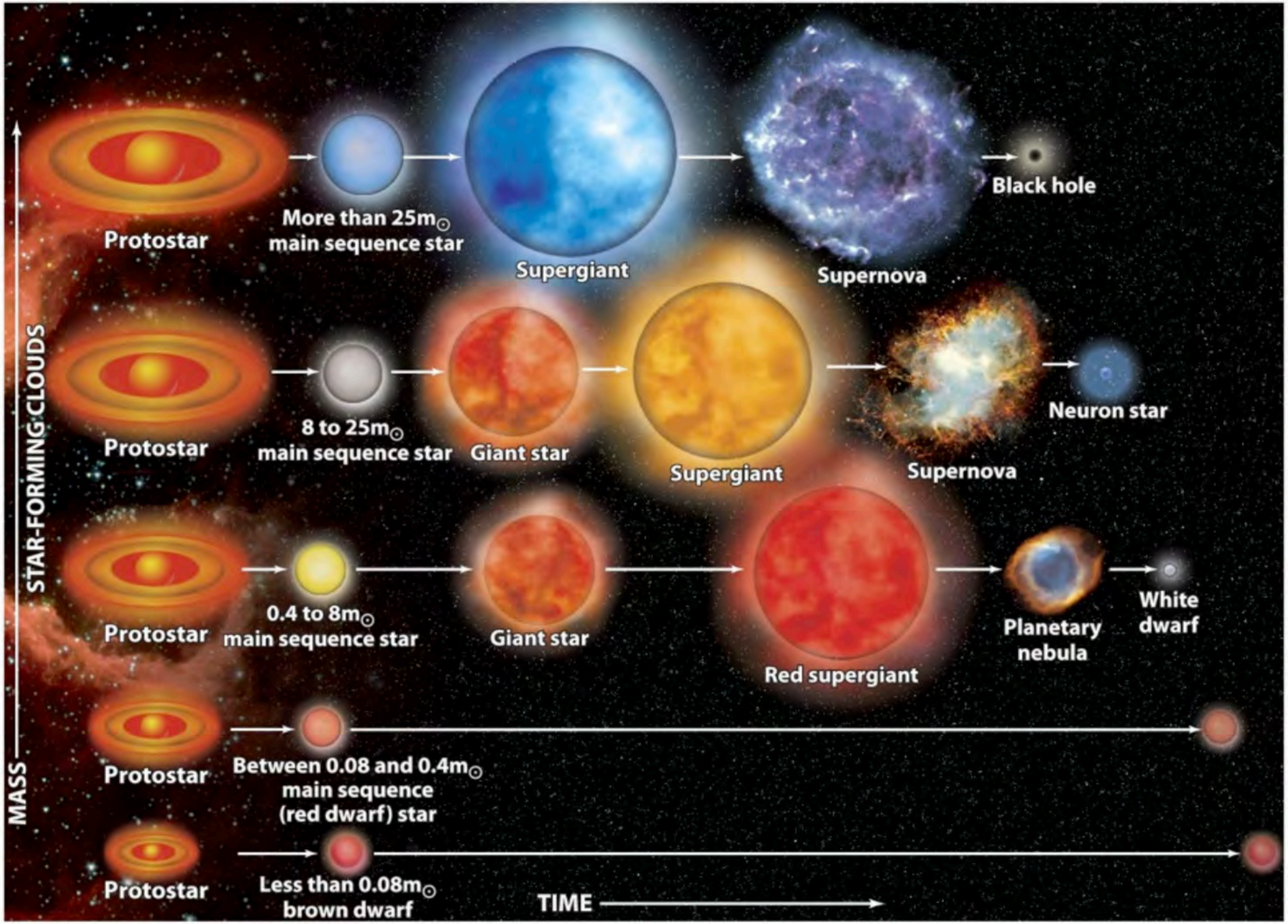


Figure 13-28a
Discovering the Universe, Eighth Edition

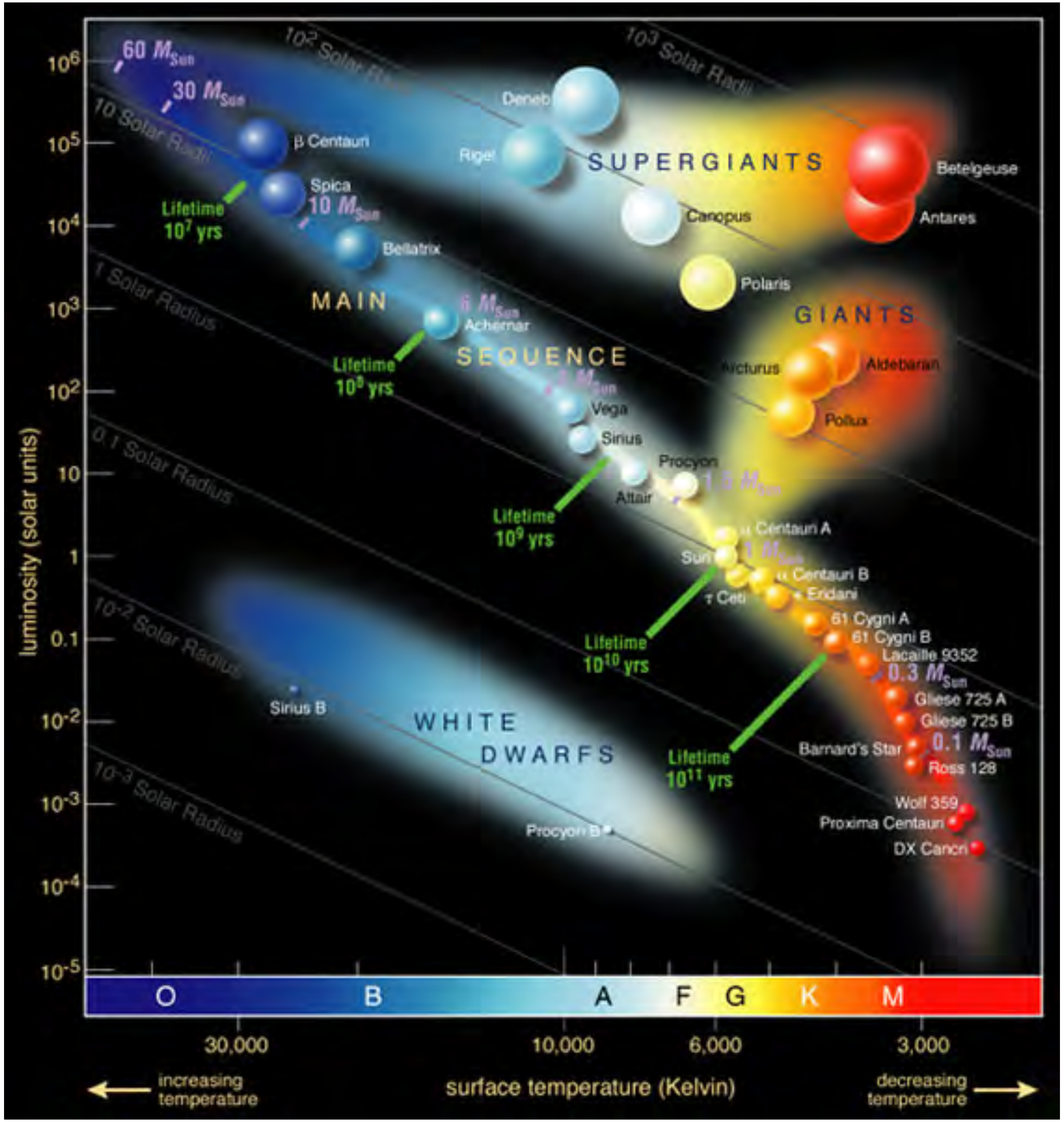
Neutron stars:
- Mostly neutrons, held up by neutron degeneracy pressure
- One teaspoon contains the mass of ~700 Great Pyramids
- ~10 mile diameter

C-O and O-Ne White dwarfs:
- Progenitor not able to proceed to fusion of heavier species, held up by electron degeneracy pressure
- ~200,000 times as dense as Earth with about same radius

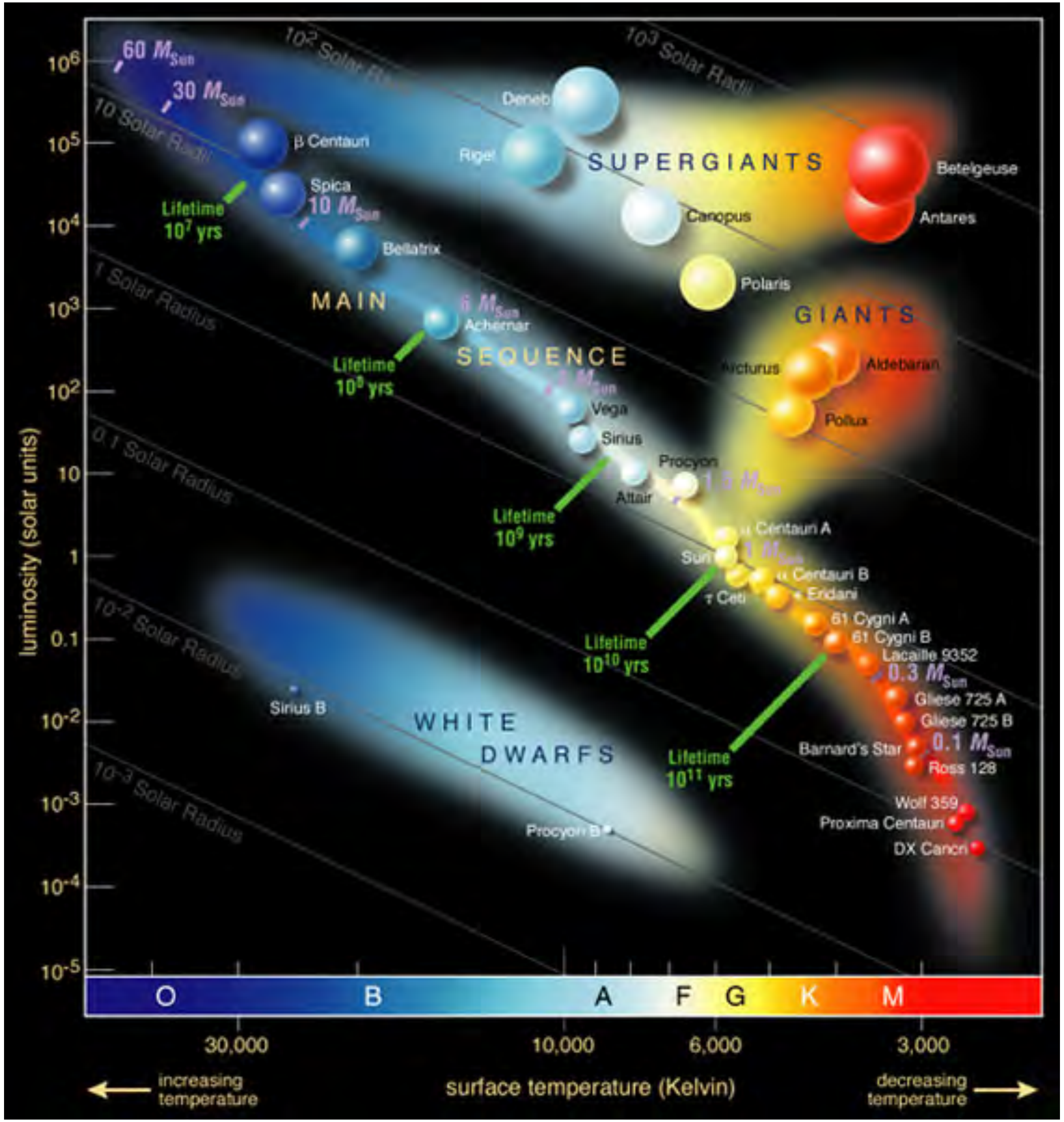
Red dwarf:
- Most common in Solar neighborhood
- Burn H but can't reach He burning

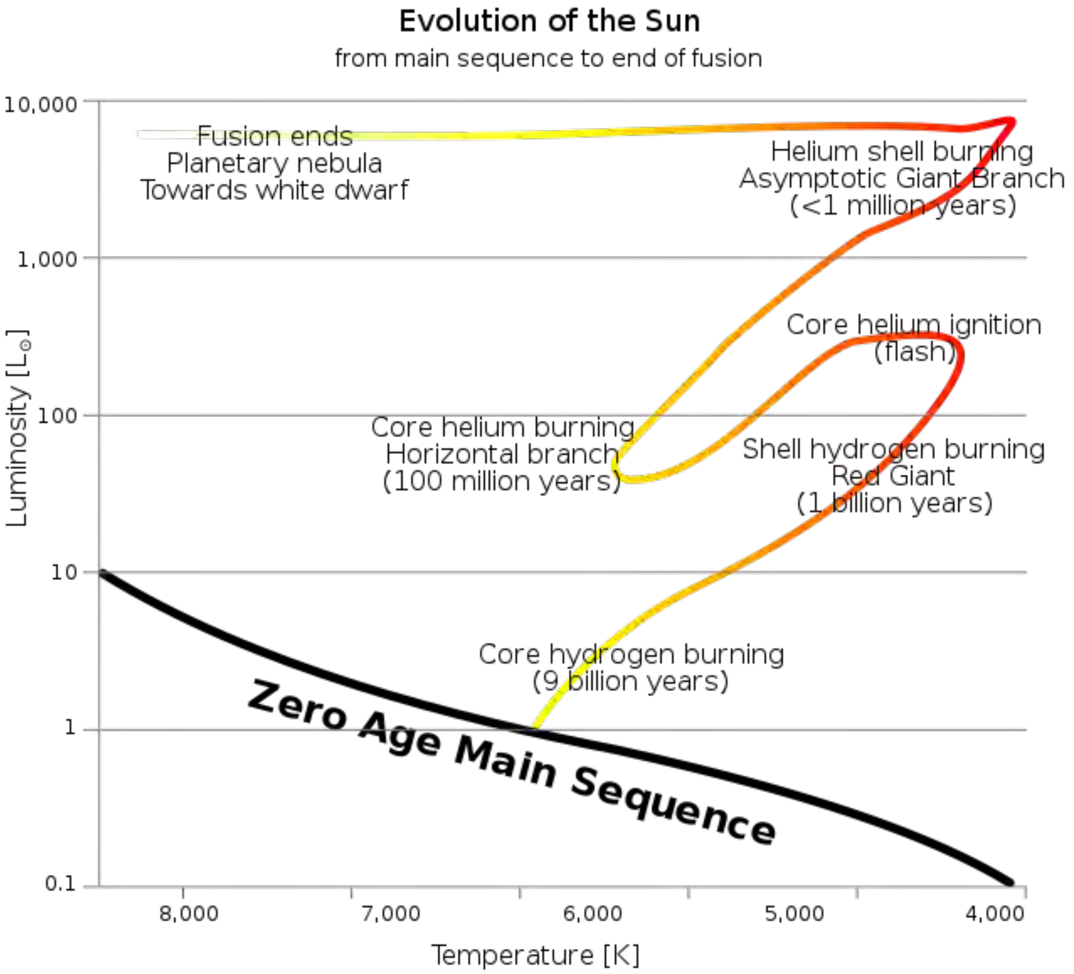
Brown dwarf: Not able to burn H

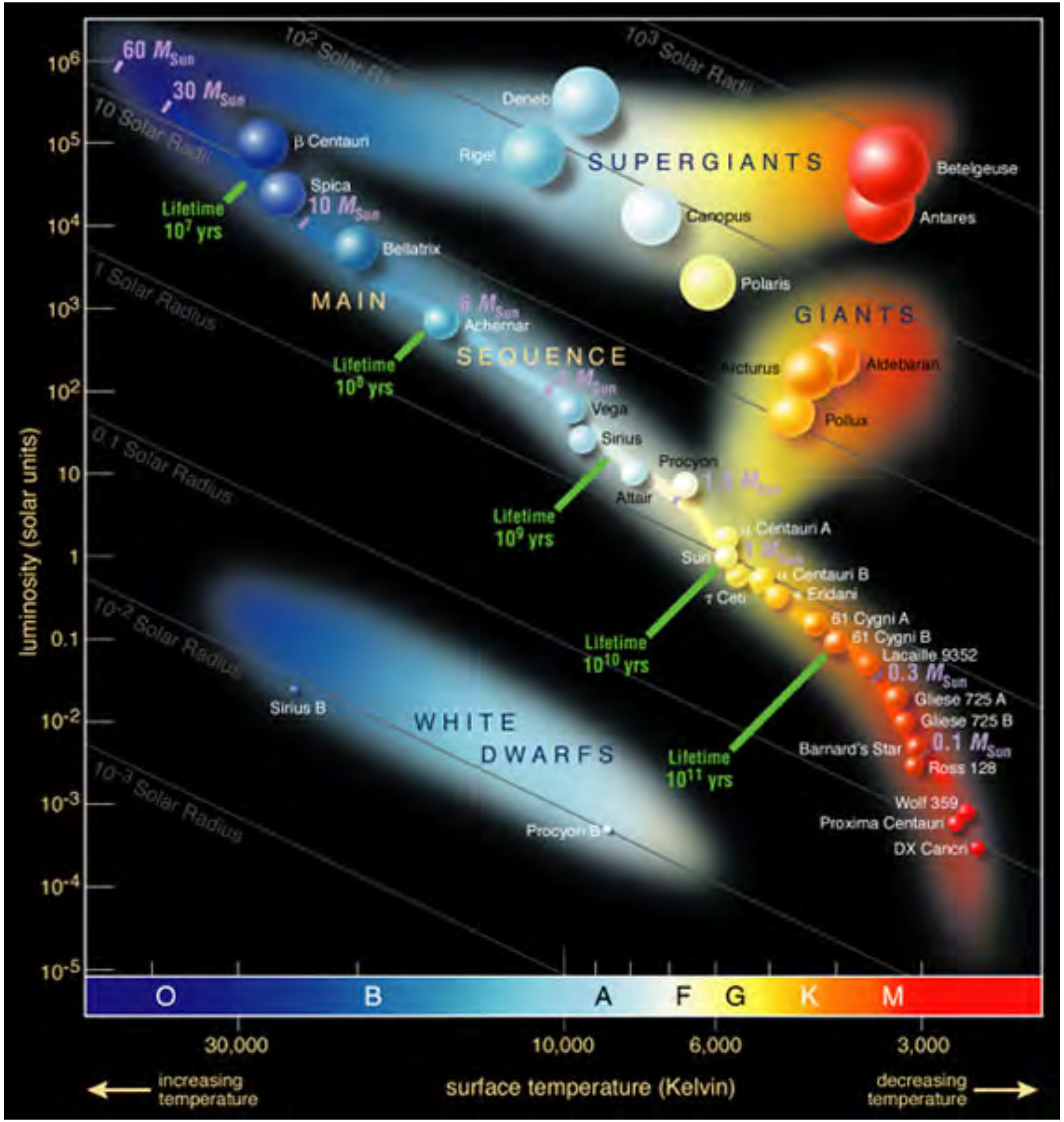
Hertzsprung-Russell (HR) Diagrams



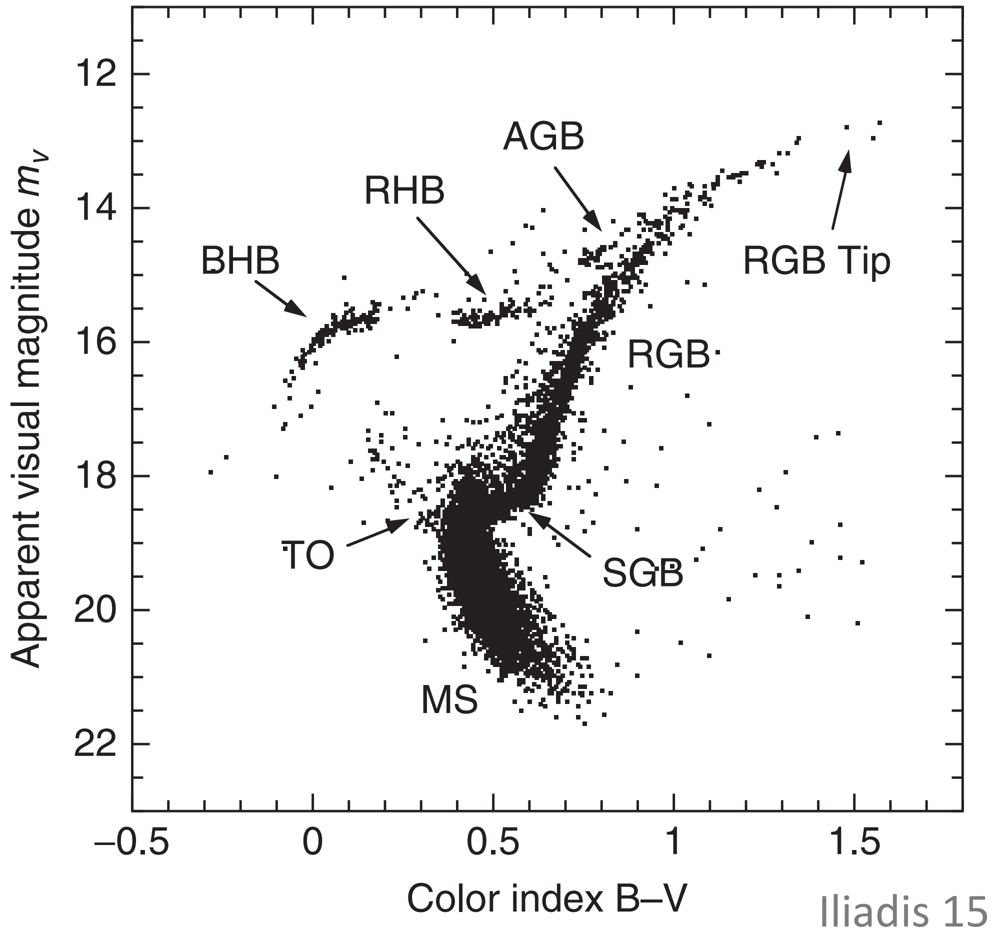
Hertzsprung-Russell (HR) Diagrams







Hertzsprung-Russell (HR) Diagrams



Iliadis 15

Stars in globular cluster M 3: these all formed around the same time and some have moved on to later stages, most still in hydrogen burning phase on main sequence

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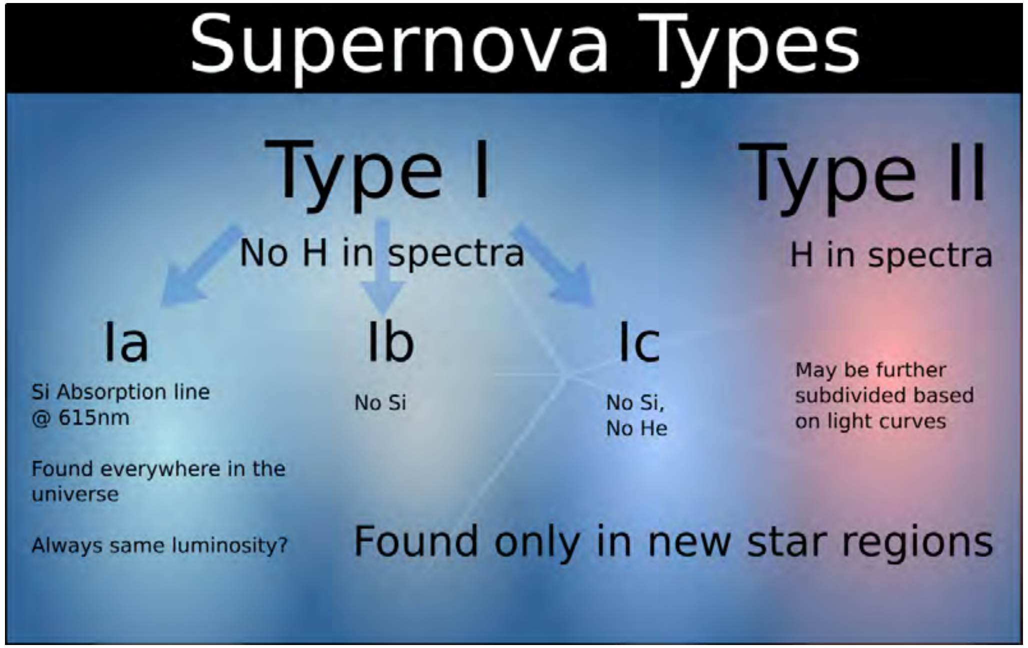
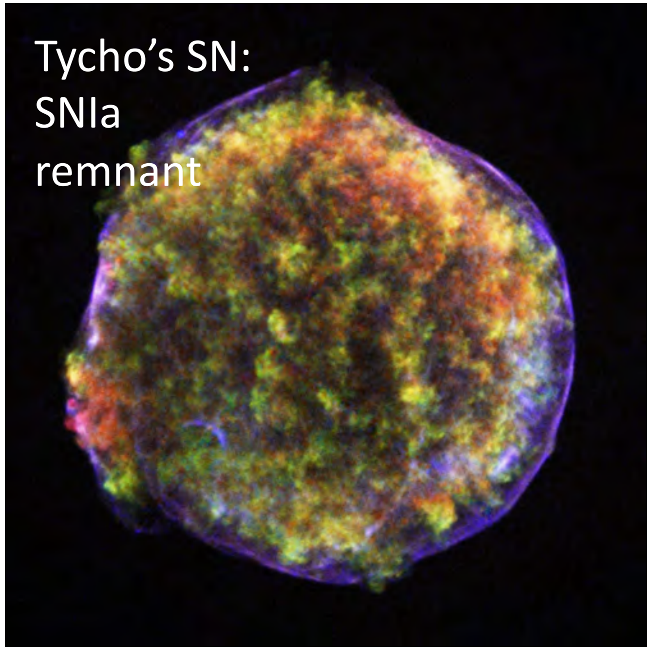
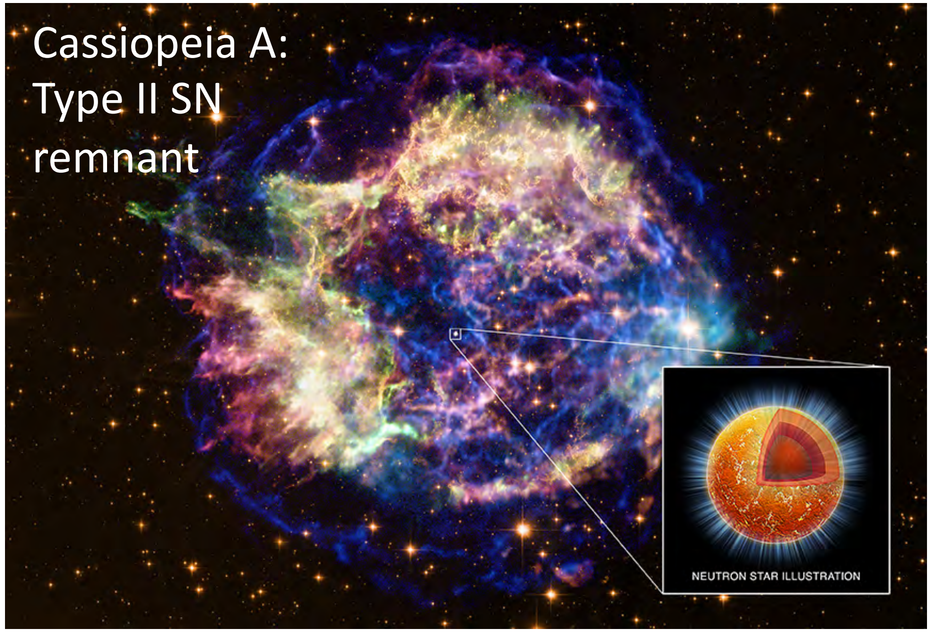
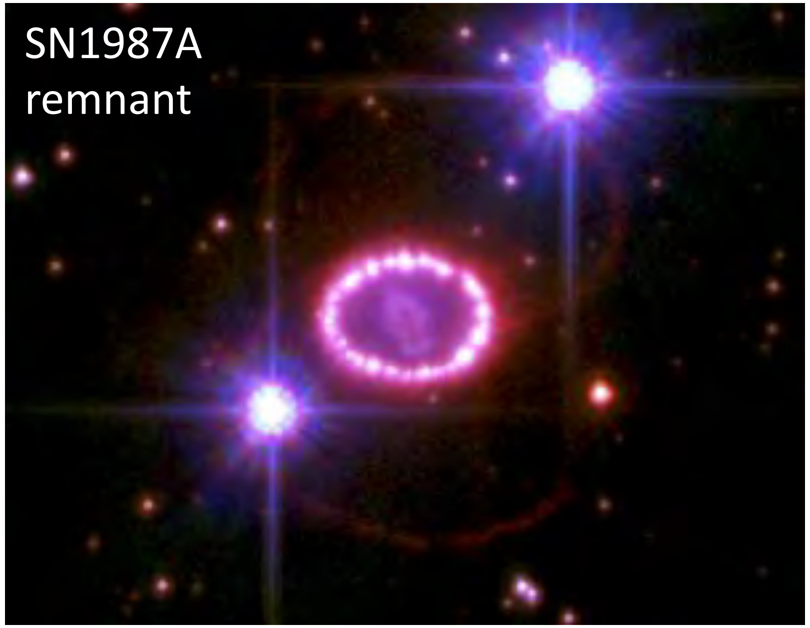

Supernova Types
Type I
No H in spectra
Type II
H in spectra
Ia
Si Absorption line
@ 615nm
Found everywhere in the universe
Always same luminosity?
Ib
No Si
Ic
No Si,
No He
May be further subdivided based on light curves
Found only in new star regions

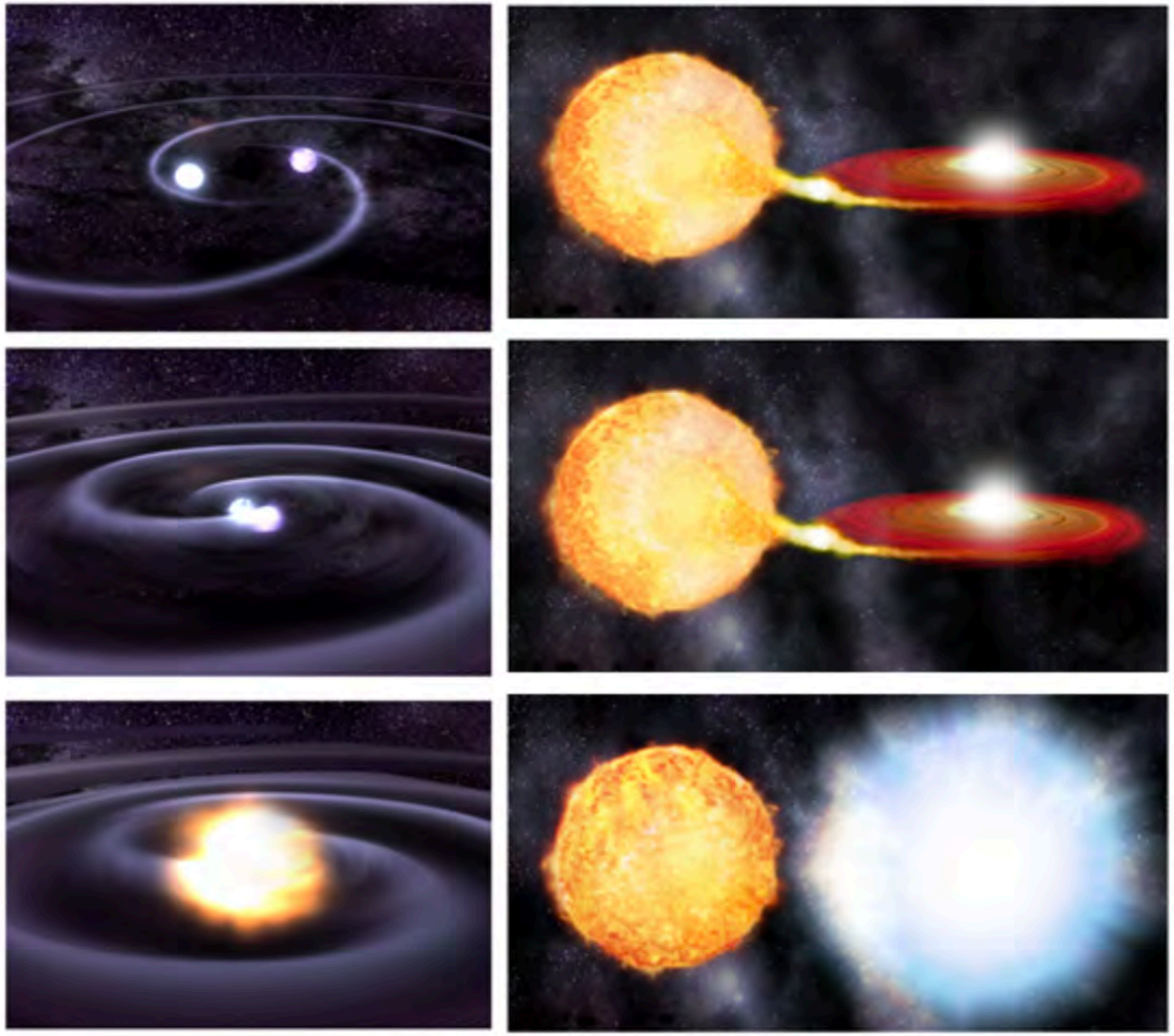

Tycho's SN:
SNIa
remnant


Cassiopeia A:
Type II SN
remnant
NEUTRON STAR ILLUSTRATION


SN1987A
remnant

Thermonuclear Supernovae (Type Ia)

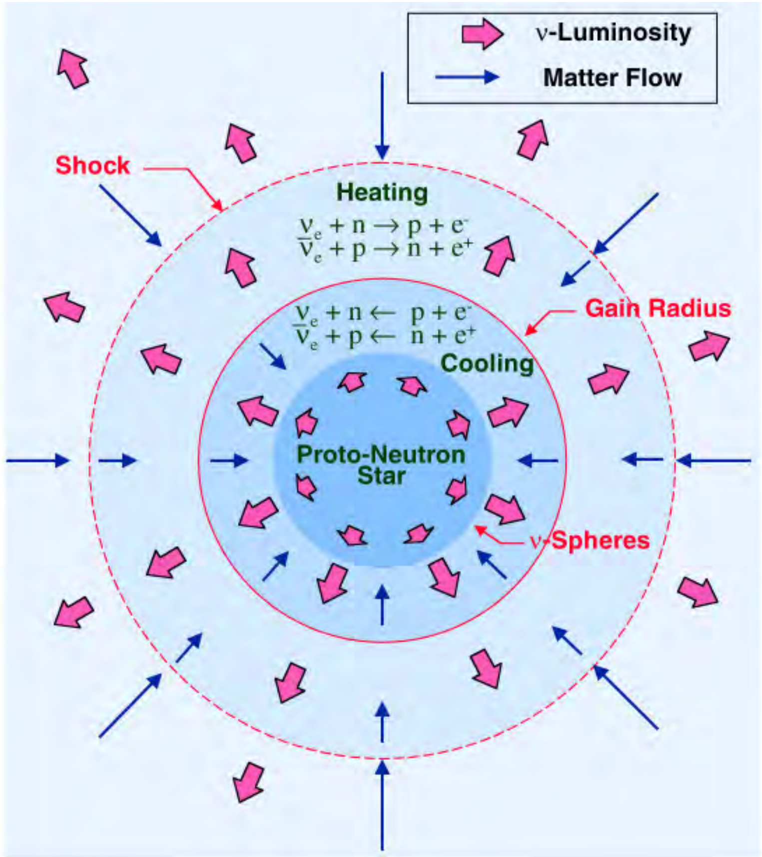
Double degenerate model   Single-degenerate model



- 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 $M_\odot$

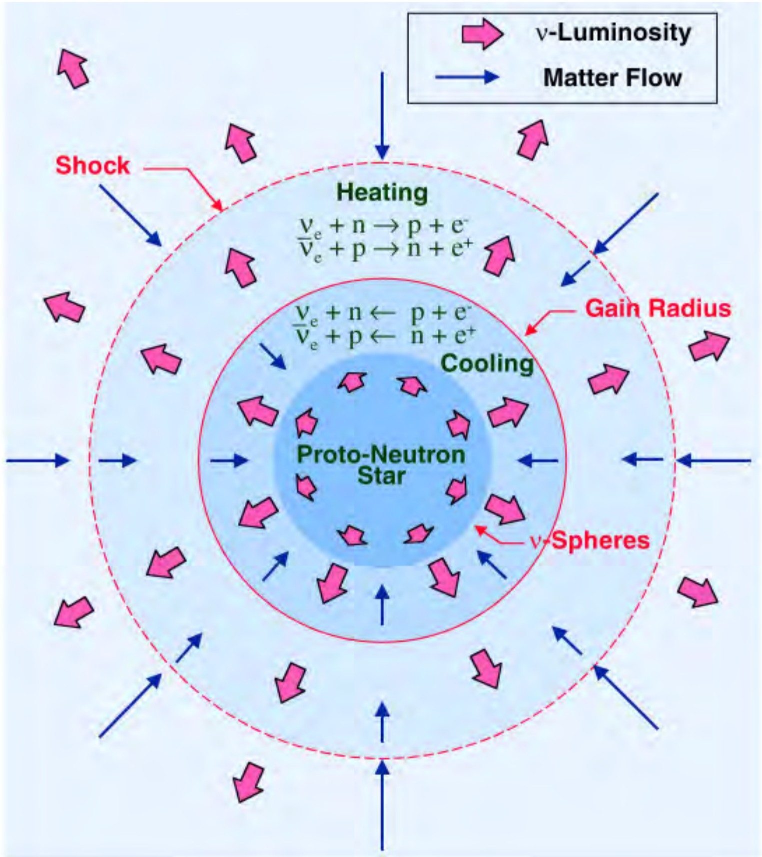
- Double-degenerate model:
  - Two C-O white dwarfs merge due to gravitational wave radiation, triggering explosion
  - Does not easily explain similar peak luminosity of SN-Ia due to wide range of ^{56}Ni production

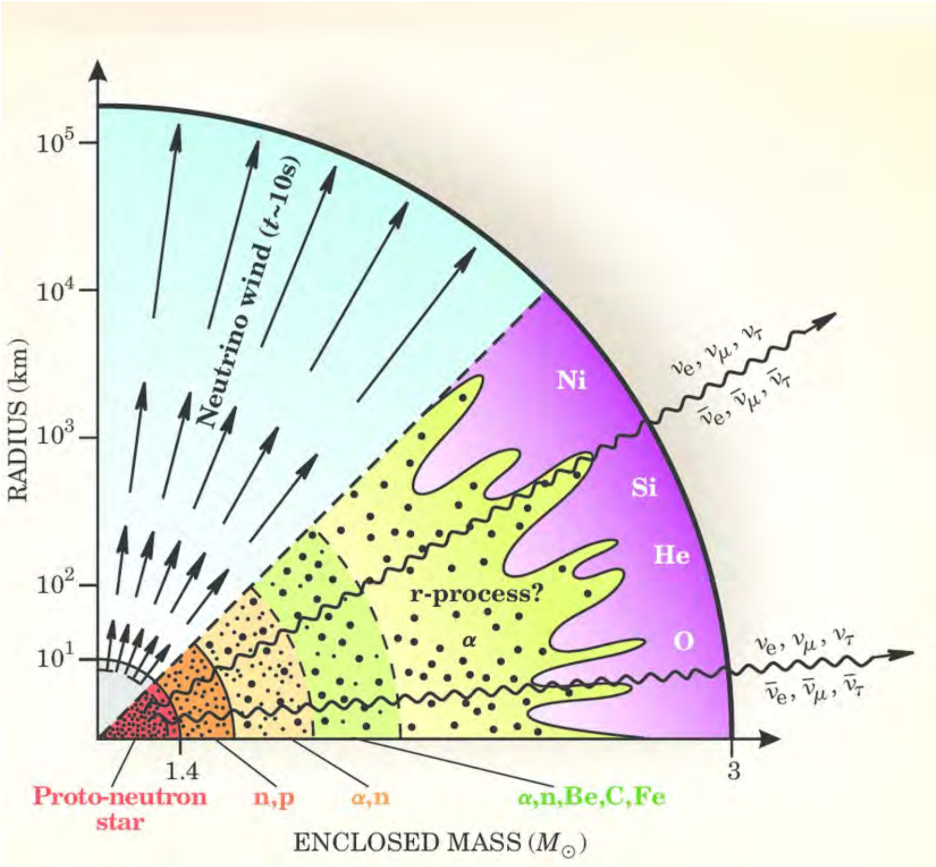
Core-collapse SN and neutrino-driven winds



- 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

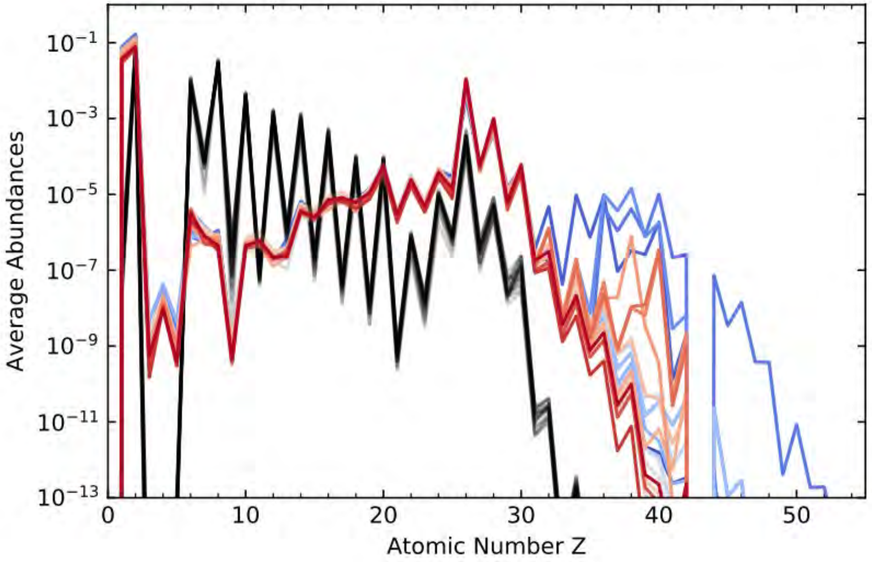
- The proto-neutron star cools through neutrino emission (99% star's binding energy released as ν)
- Cooling via *Urca processes* (lepton + baryon → baryon + ν) as well as $e^+e^- \rightarrow \nu_l\bar{\nu}_l$ where $l = e, \mu, \tau$

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

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



All exploding 15 $M_\odot$ models

Witt+21; see also Bliss+18

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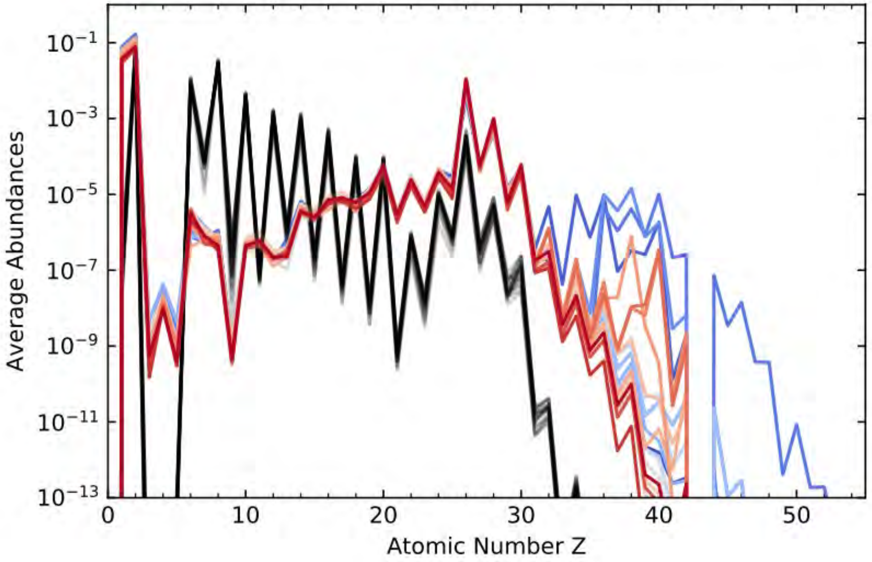

All exploding 15 $M_\odot$ models

Witt+21; see also Bliss+18

"SWASI" analog of the **SASI (Standing Accretion Shock Instability) in CCSNe** – non-radial perturbations amplify leading to convective motion which impacts how the shock can move out

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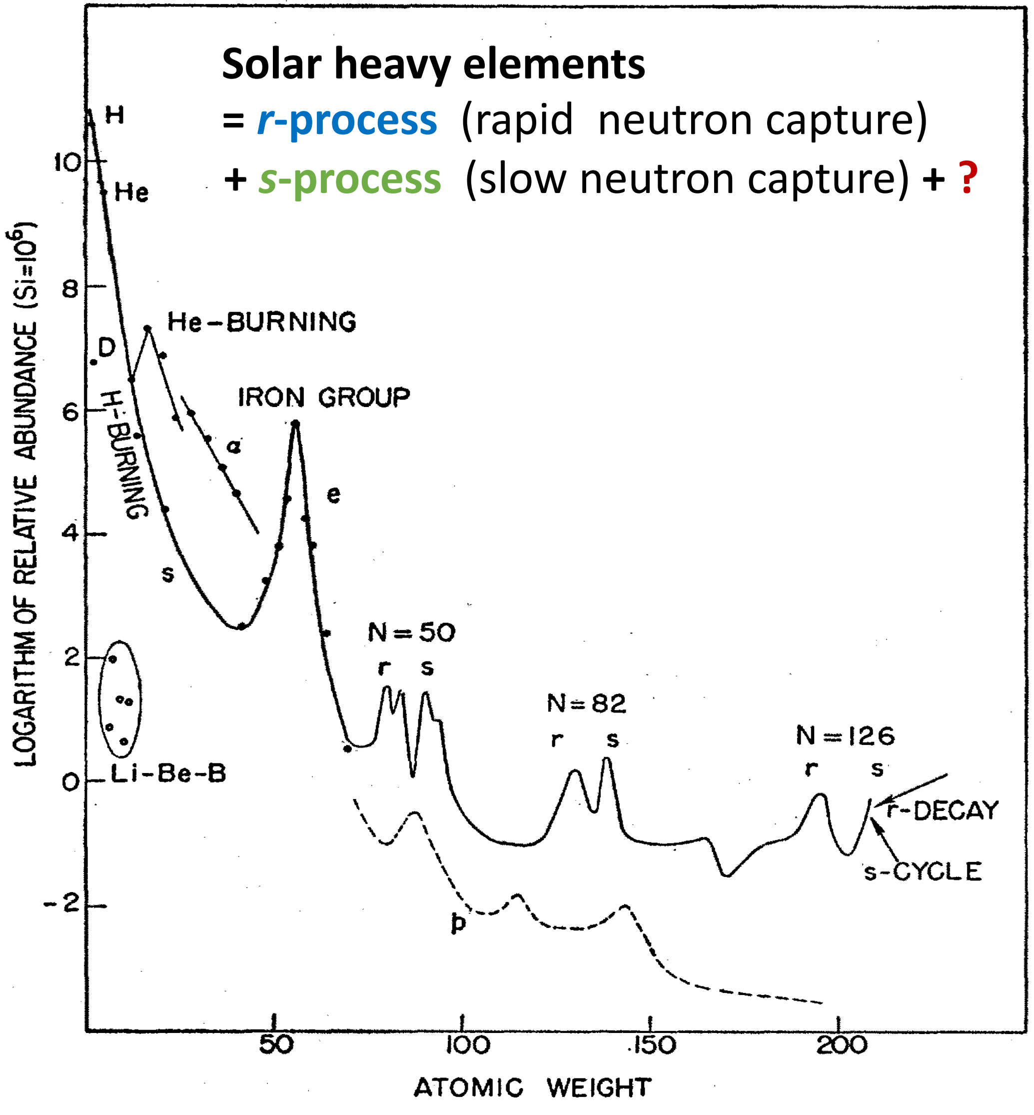
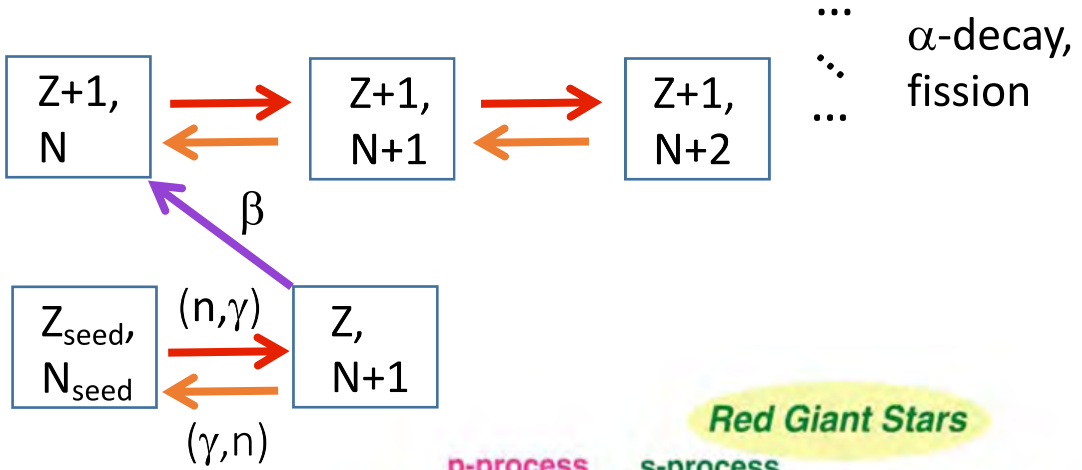
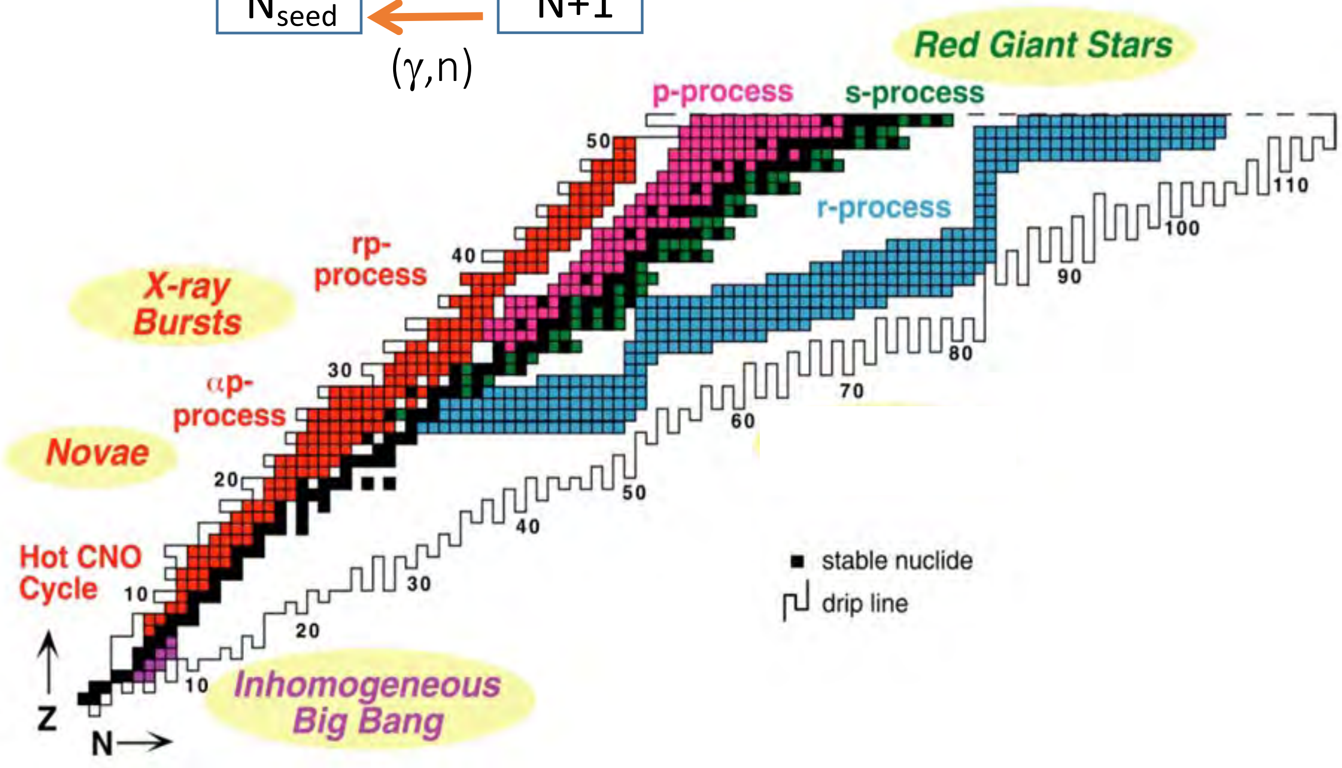
Neutron capture processes to make the heaviest elements



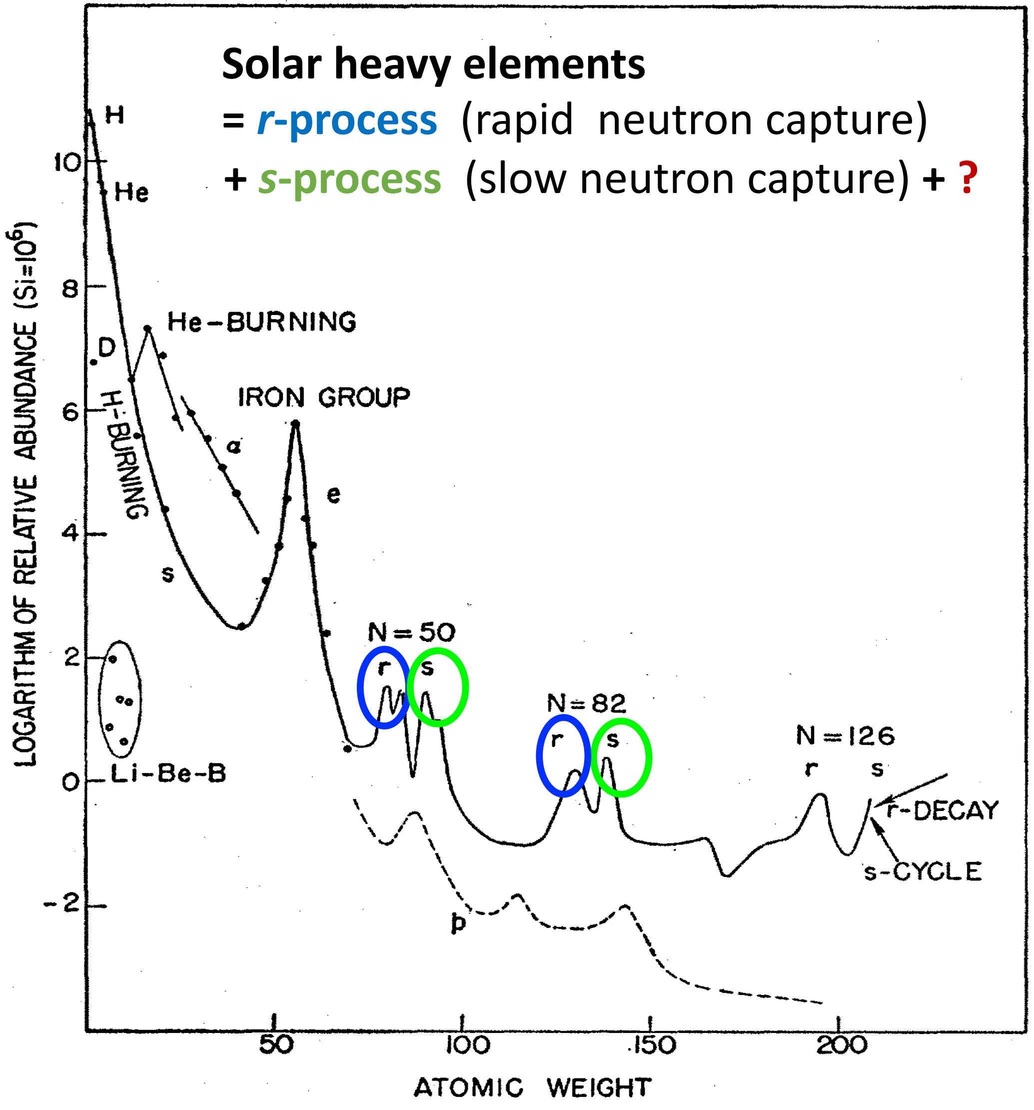
Burbidge, Burbidge, Fowler, and Hoyle (B^{2}FH) (1957)





Smith&Rehm 01

Neutron capture processes to make the heaviest elements



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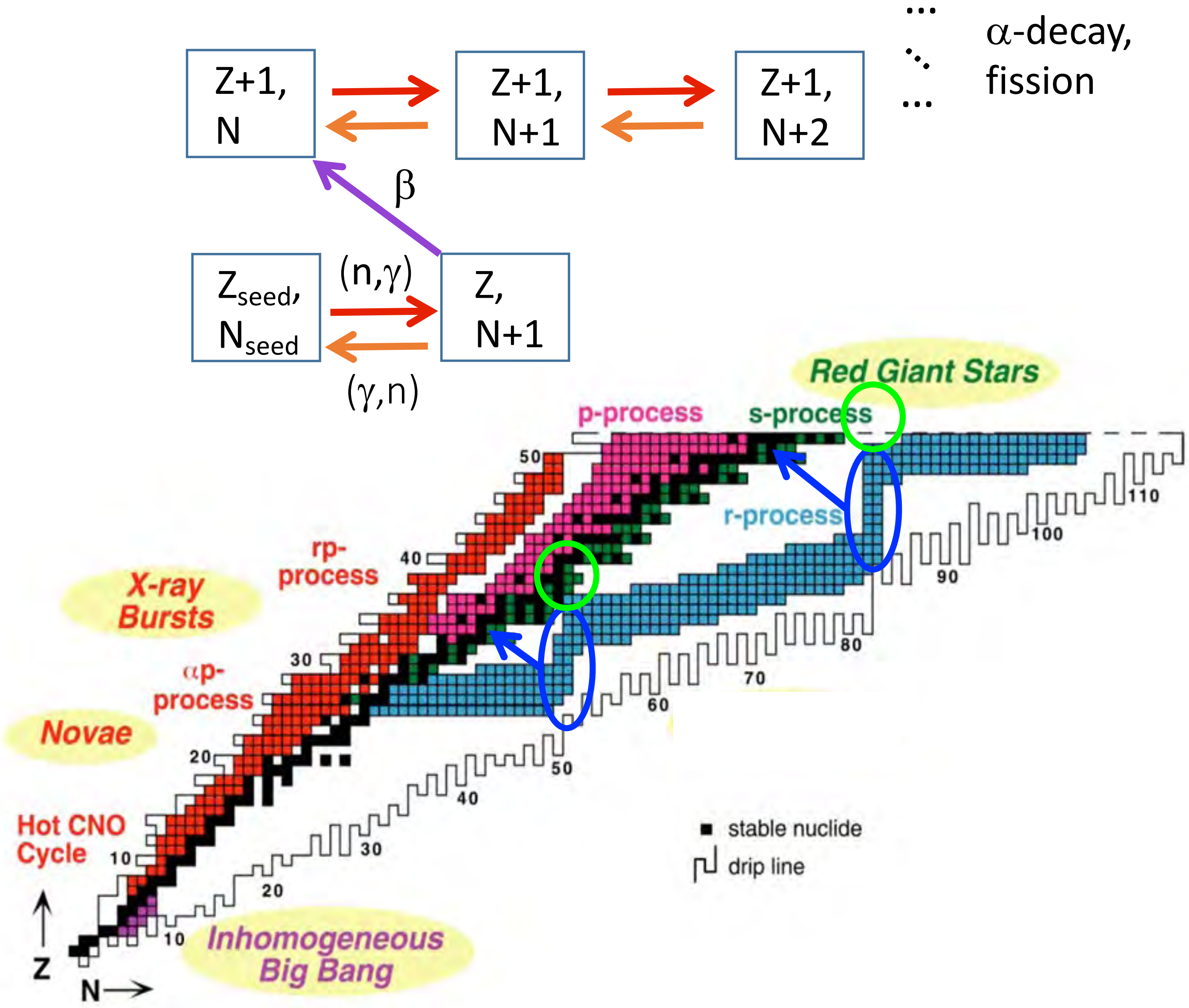

Smith&Rehm 01

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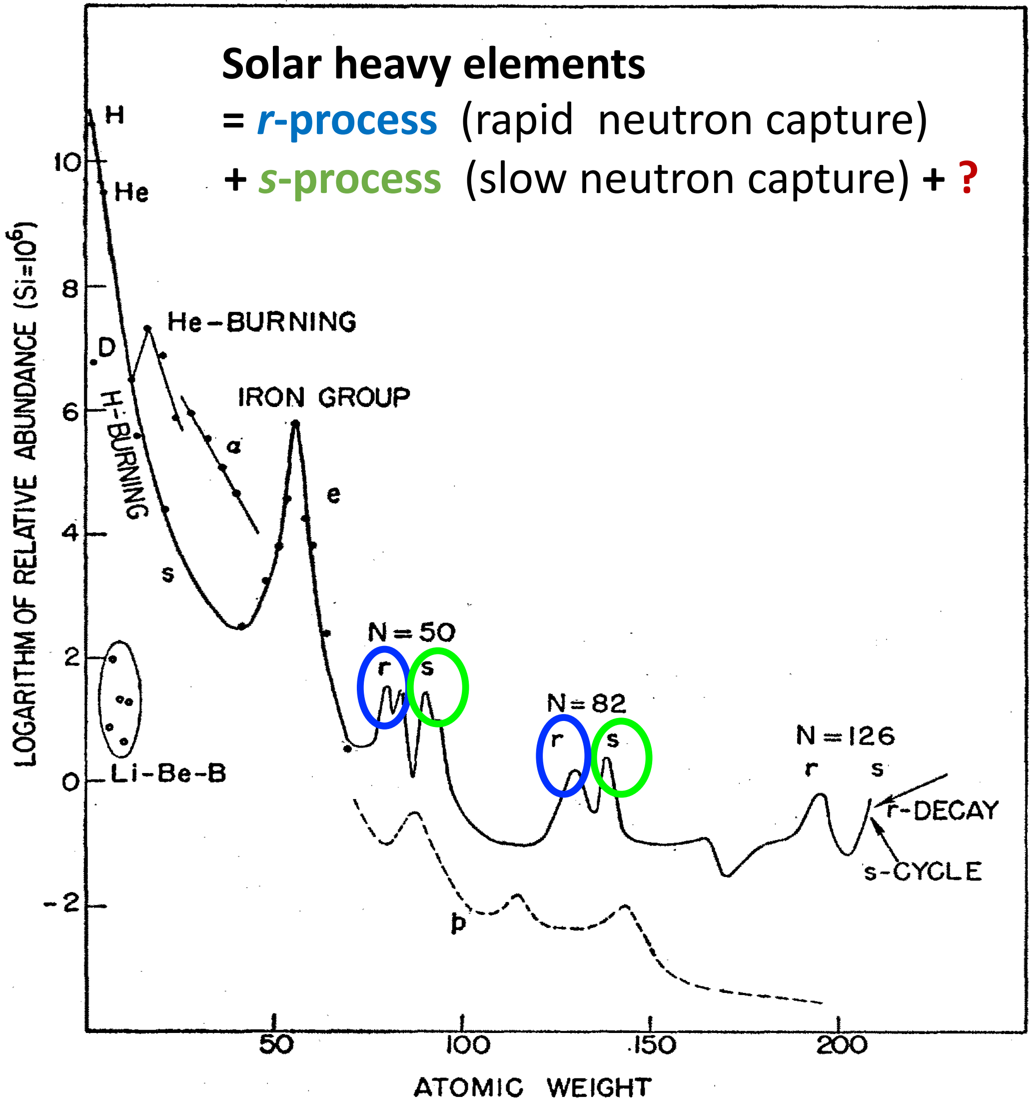
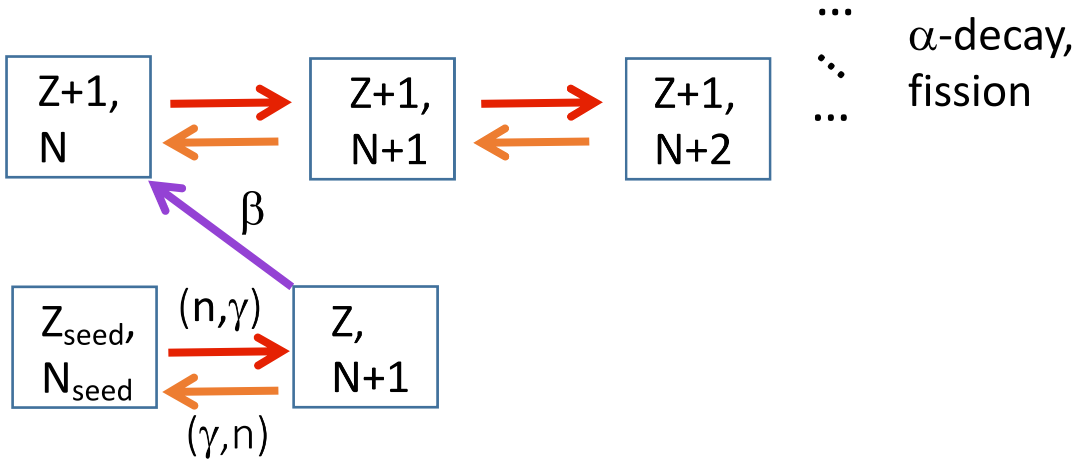
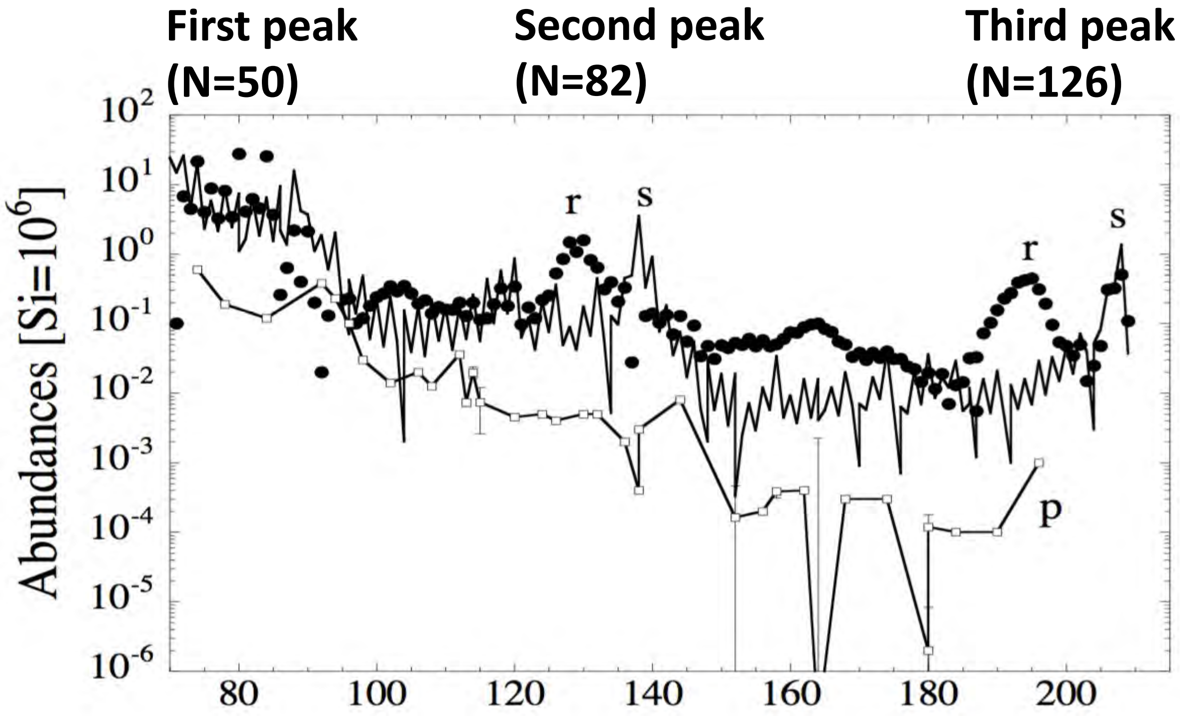


Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)





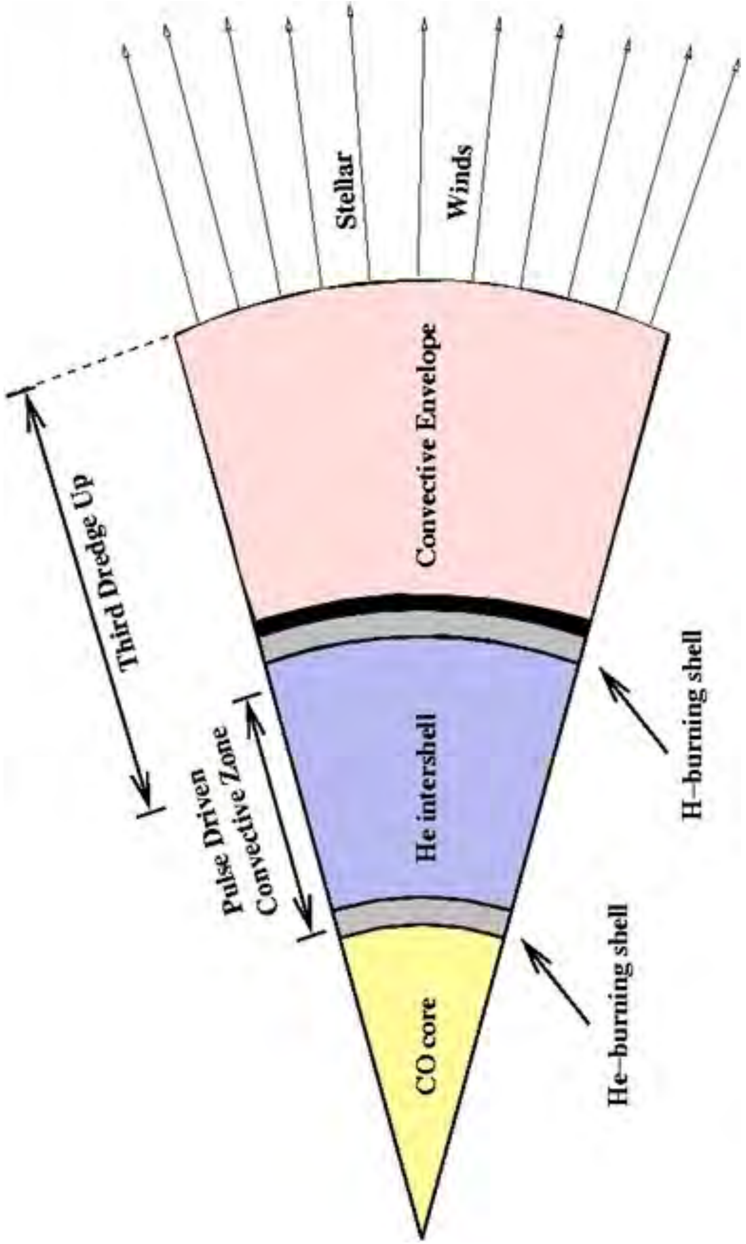
Arnould+07

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

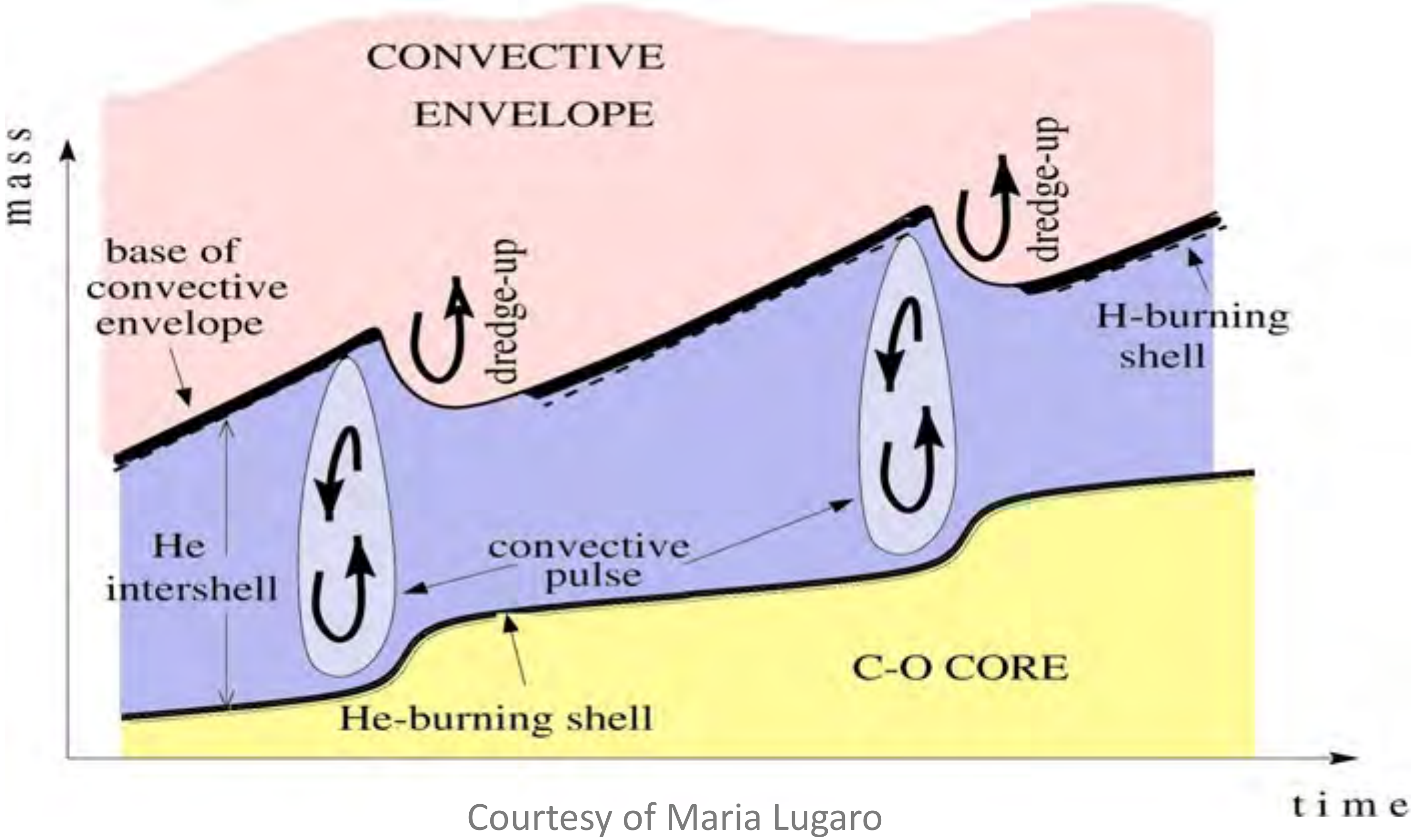


Where do the neutrons come from?

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

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

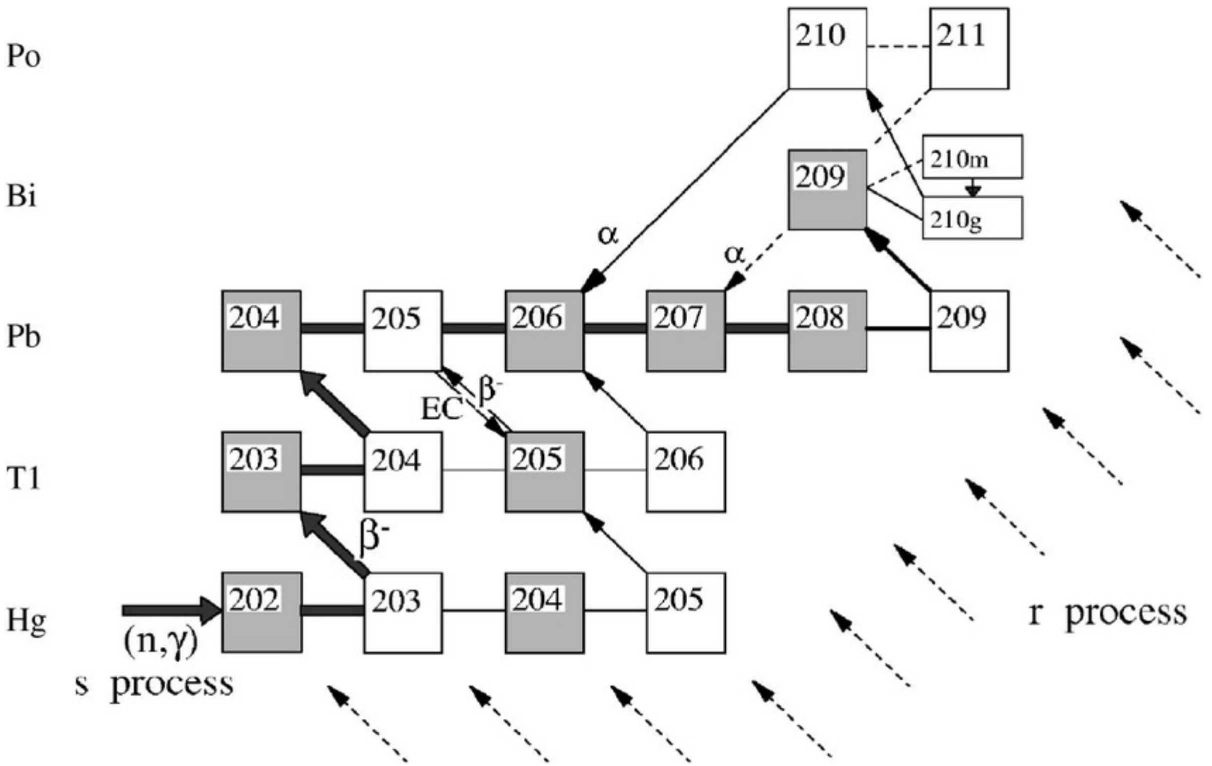
$$^{13}C(\alpha,\boxed{n})^{16}O$$



Courtesy of Maria Lugaro

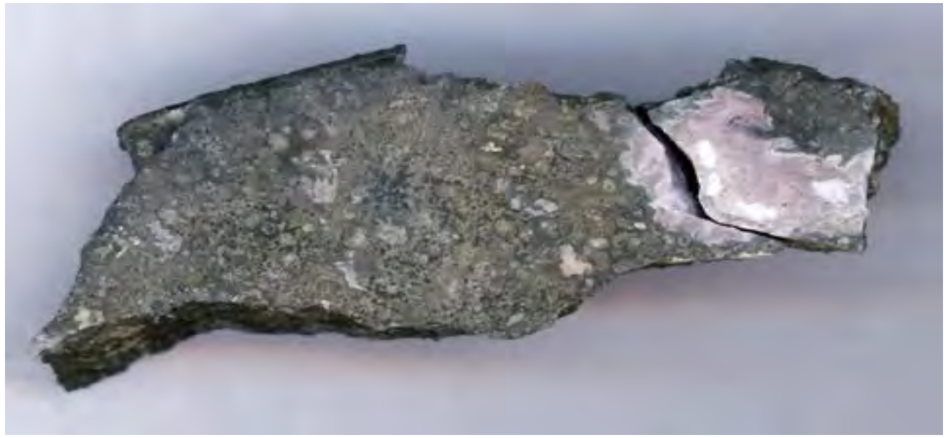
How do we know there is an *r*-process? Actinides (Z=89-103)

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

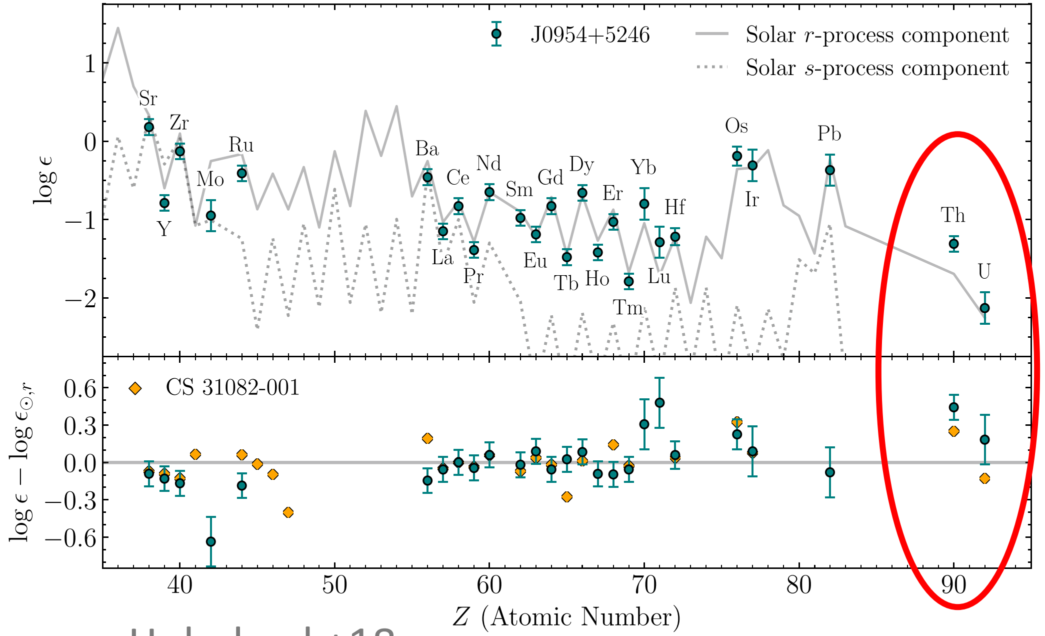


Ratzel+04

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

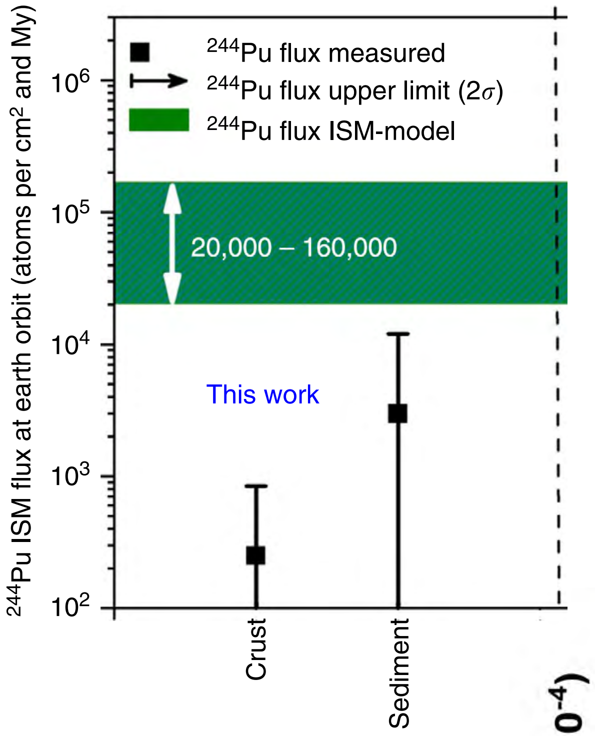


Actinide boost stars compared to solar



Holmbeck+18

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

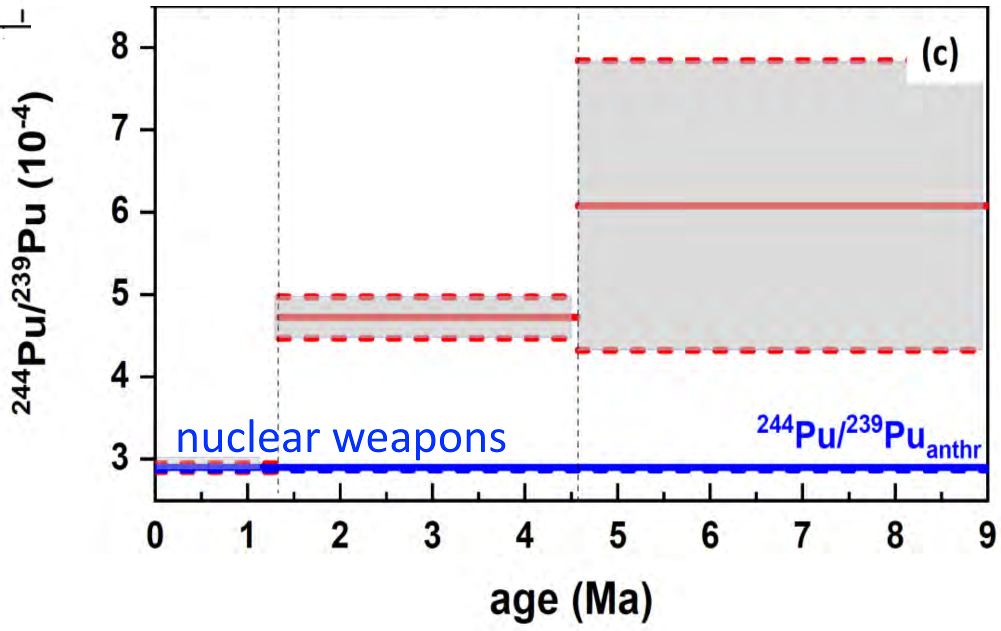


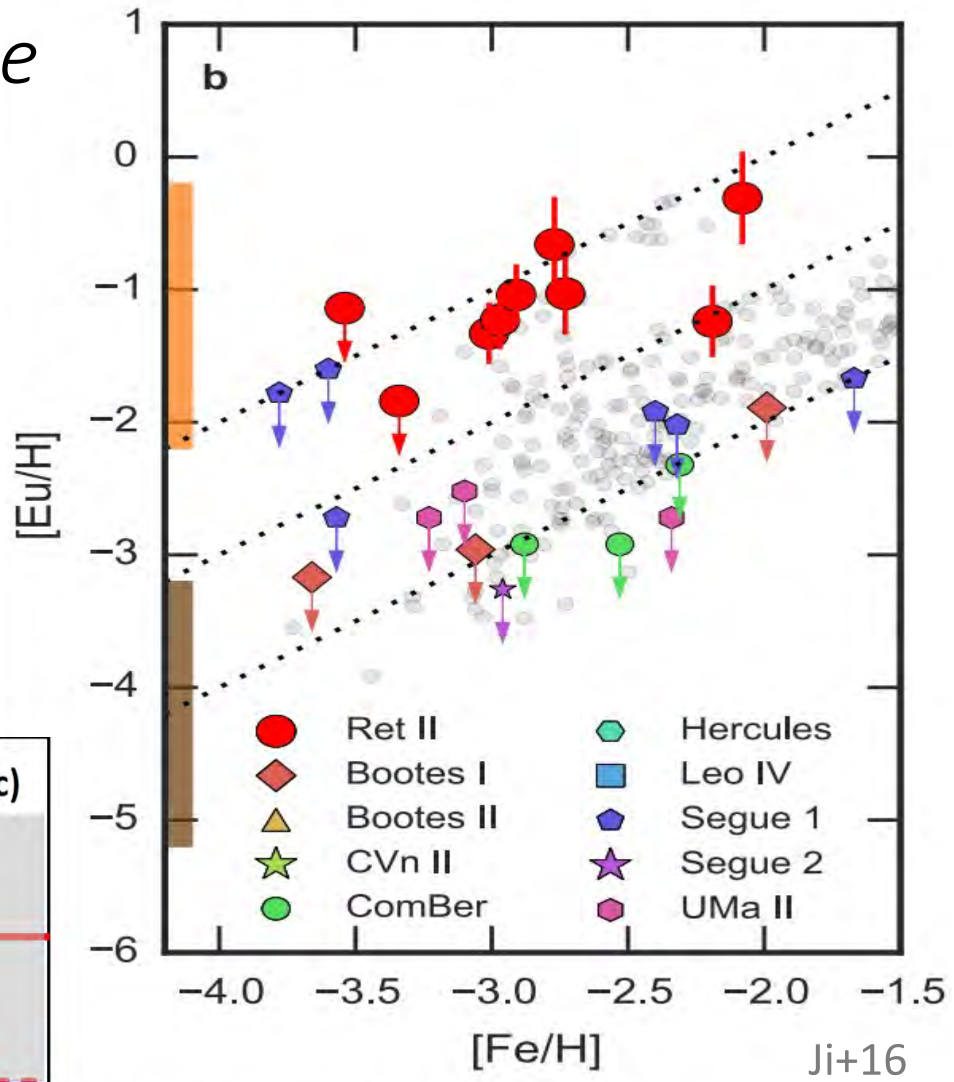
Pu-244 in deep-sea ocean crusts compared to a model which assumes a source as frequent as supernova

Wallner+15

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

Wallner+21



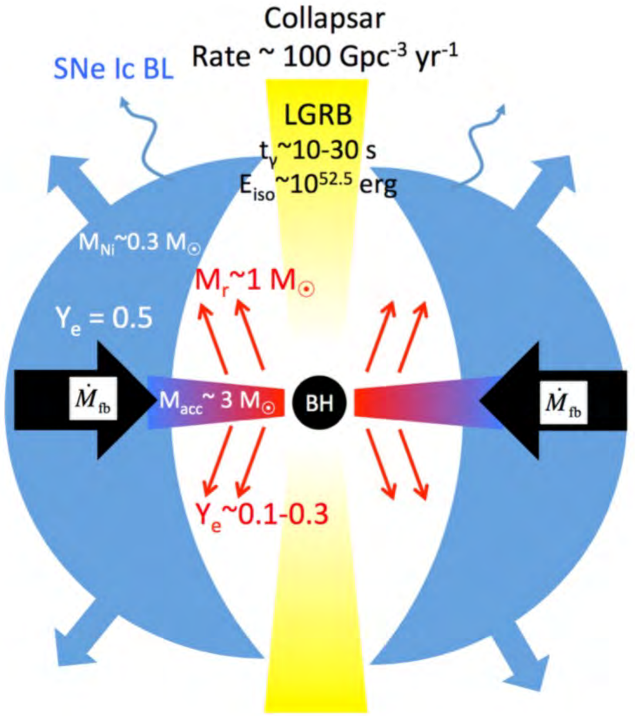


Ji+16

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

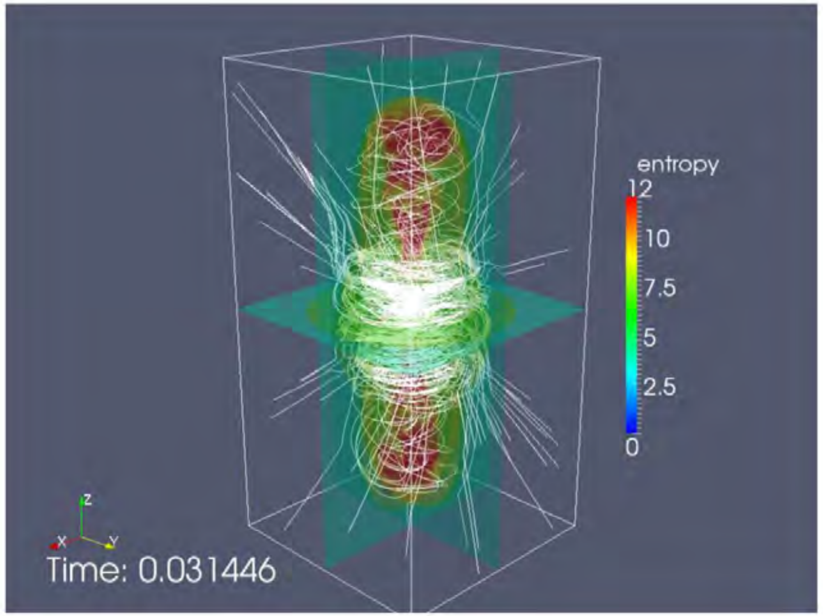
Some candidate sites for *r*-process element production

Collapsar disk winds



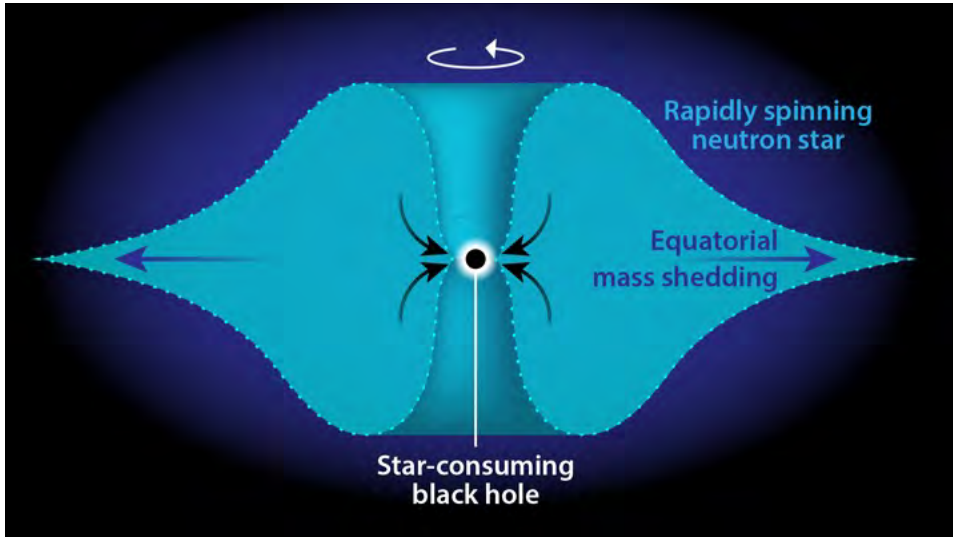
Siegel+18; see also McLaughlin&Surman 05, Miller+19

Magneto-rotationally driven (MHD) supernovae



Winteler+12; see also Mosta+17

Primordial black hole + neutron star

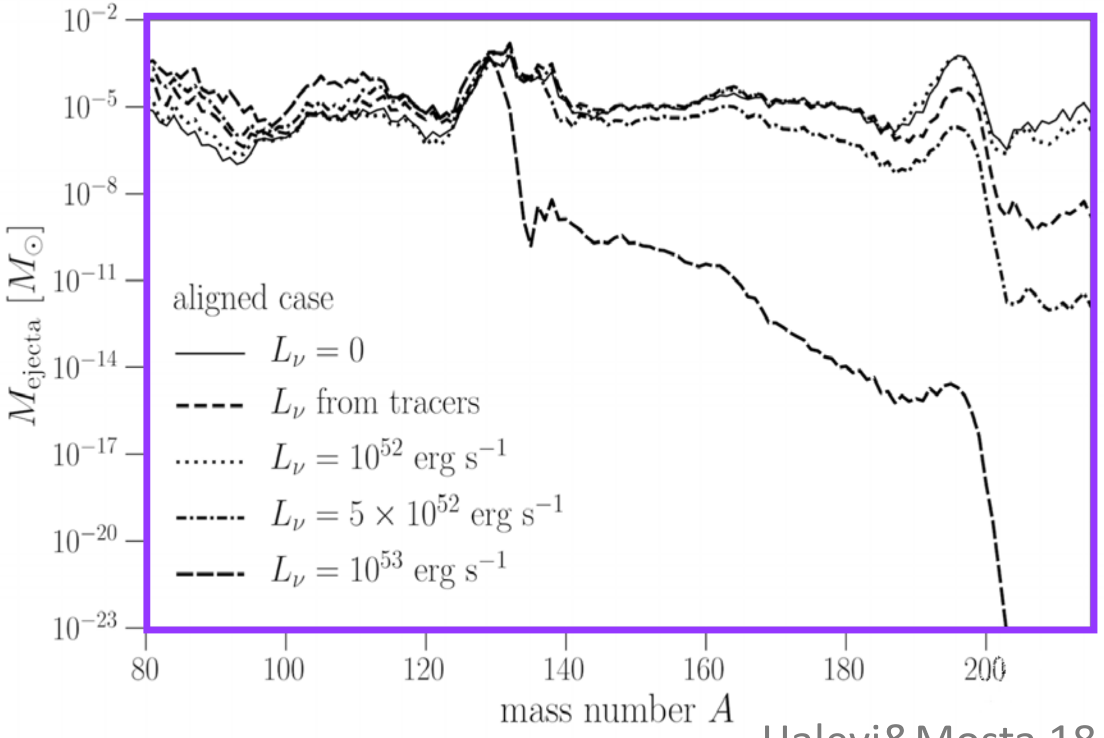


Credit: APS/Alan Stonebraker, via *Physics*

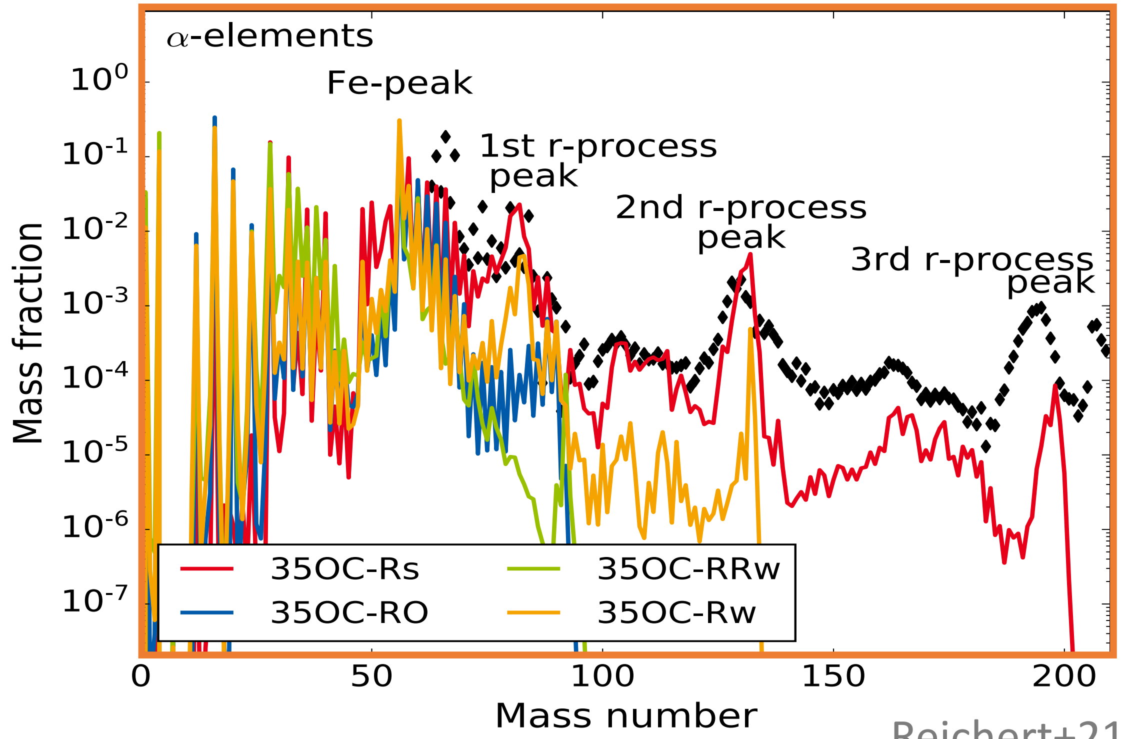
Fuller+17

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)

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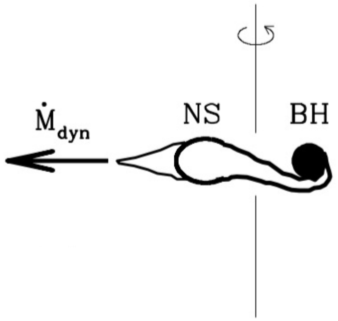
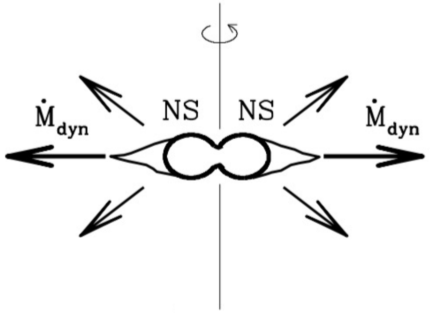
Neutron star mergers and the *r* process: a bit of history

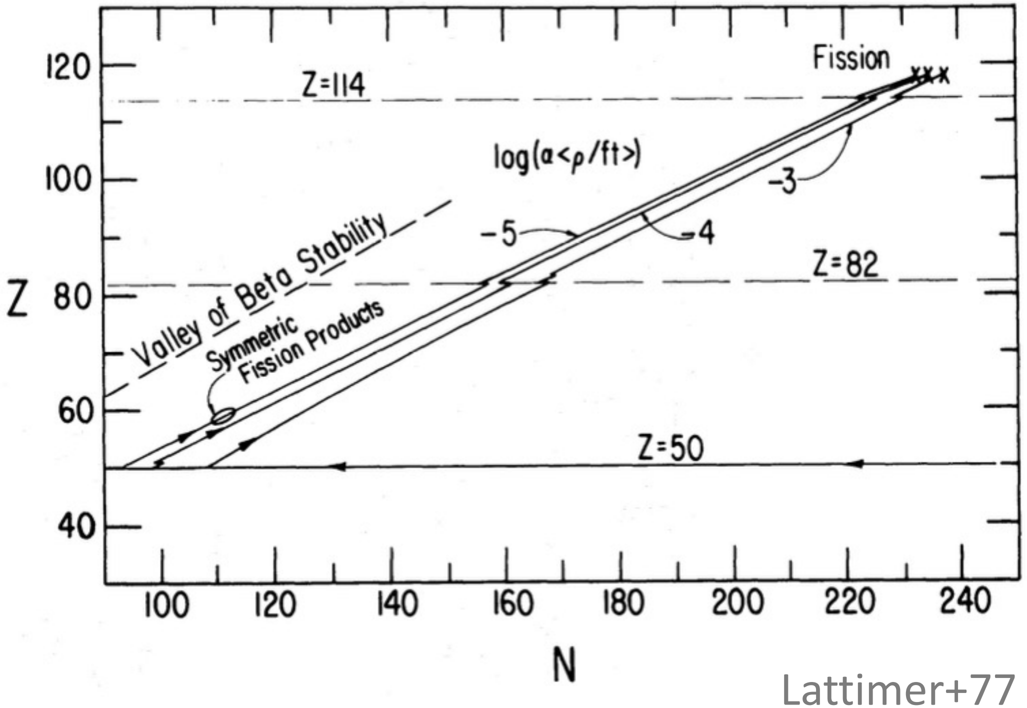
Neutron-rich ejecta from neutron stars
> 40 years ago



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

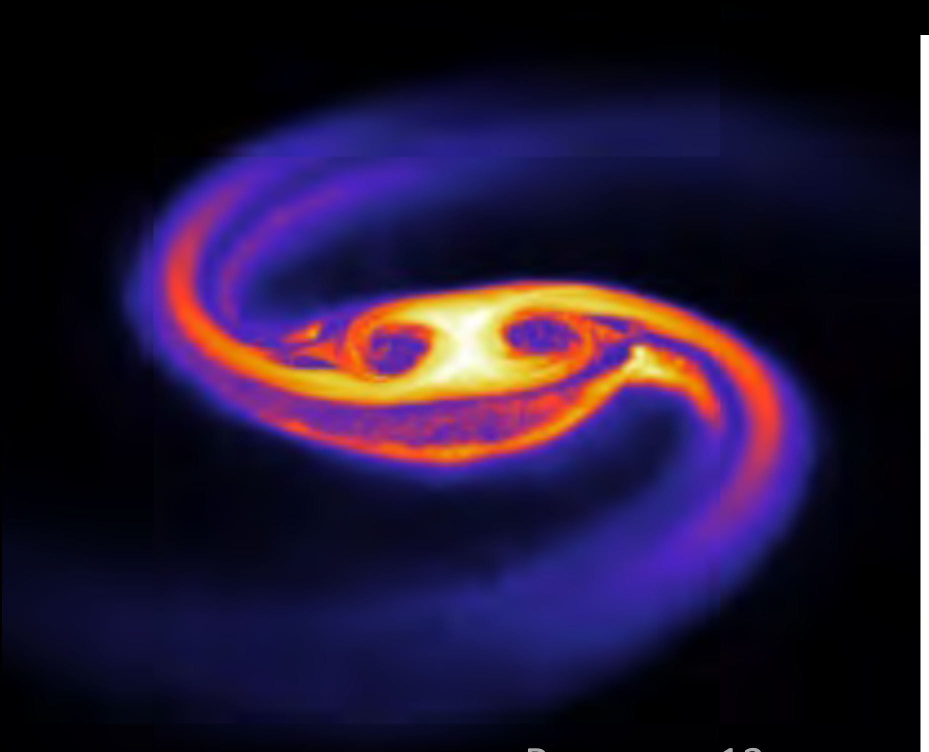


Lattimer+ (1977): initially cold, expanding neutron star matter → fission cycling *r* process capable of super heavy element formation



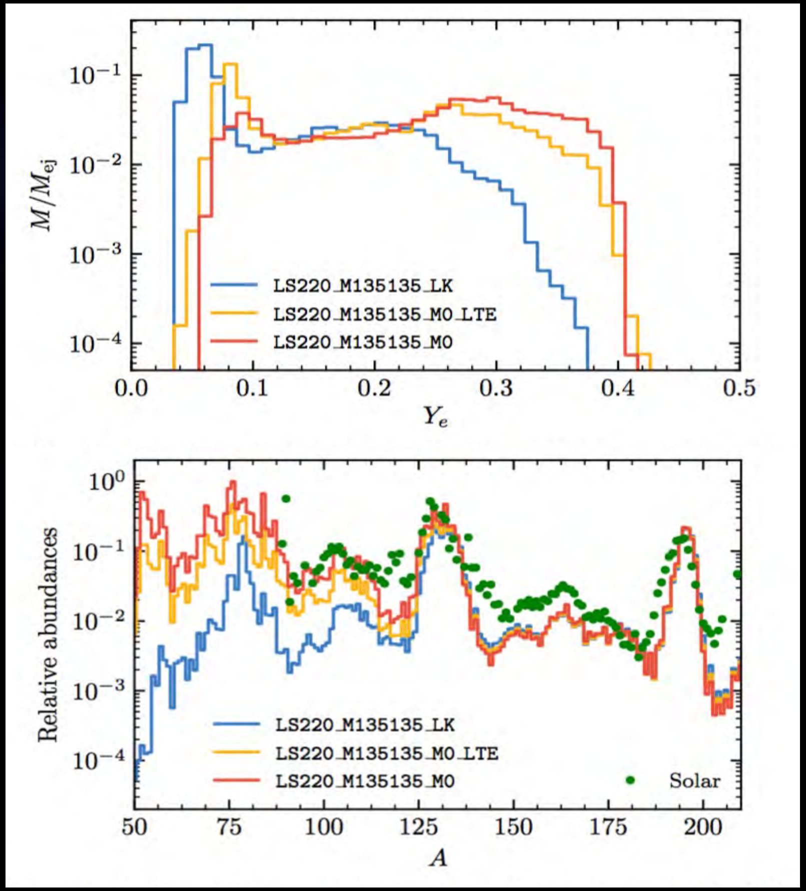
Lattimer+77

NSM dynamical ejecta



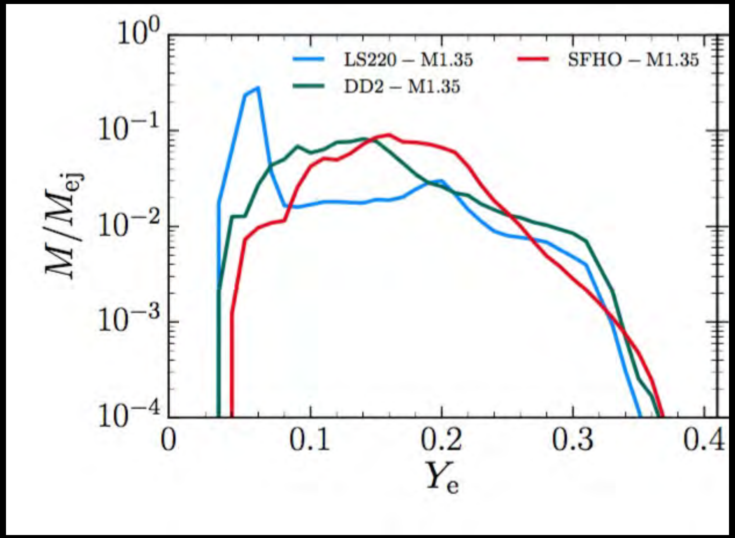
Rosswog+13

Effect of neutrinos



Radice+19; see also Perego+19

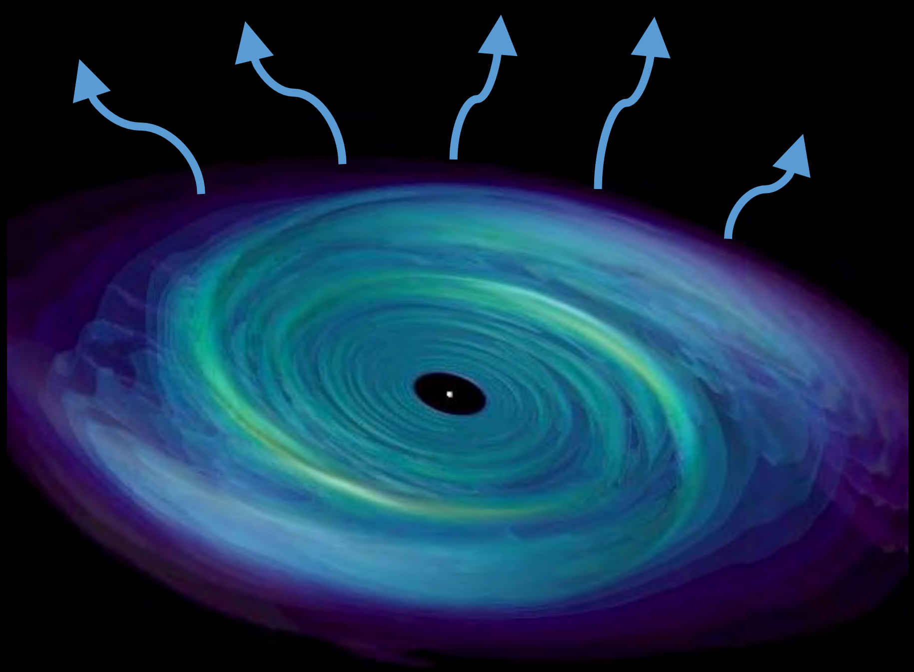
Equation of state



Bovard+17

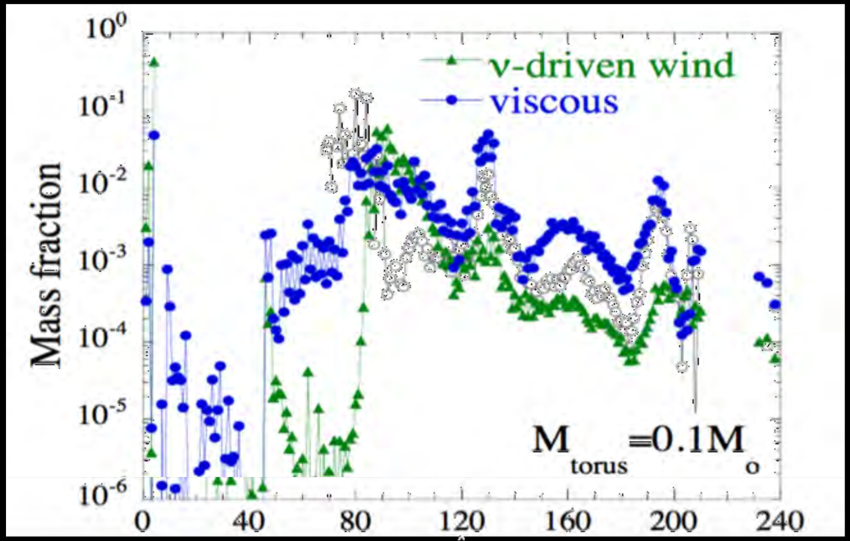
See also Wanajo+14, Vincent+19, Foucart+20….

Post-merger disk ejecta

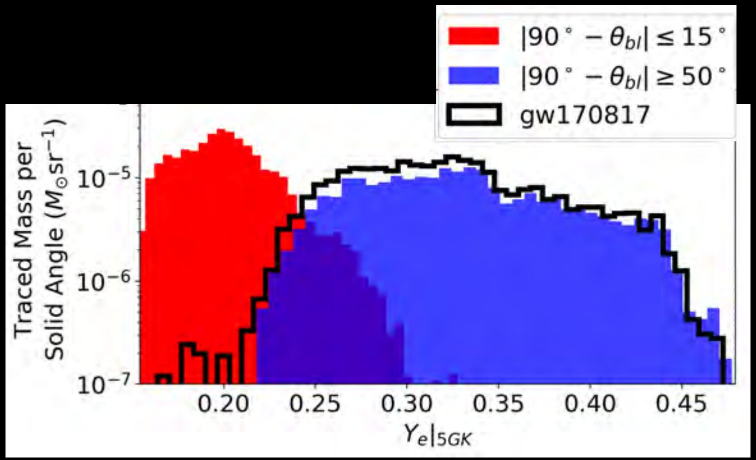


Owen&Blondin 05

Neutrino driven vs viscous

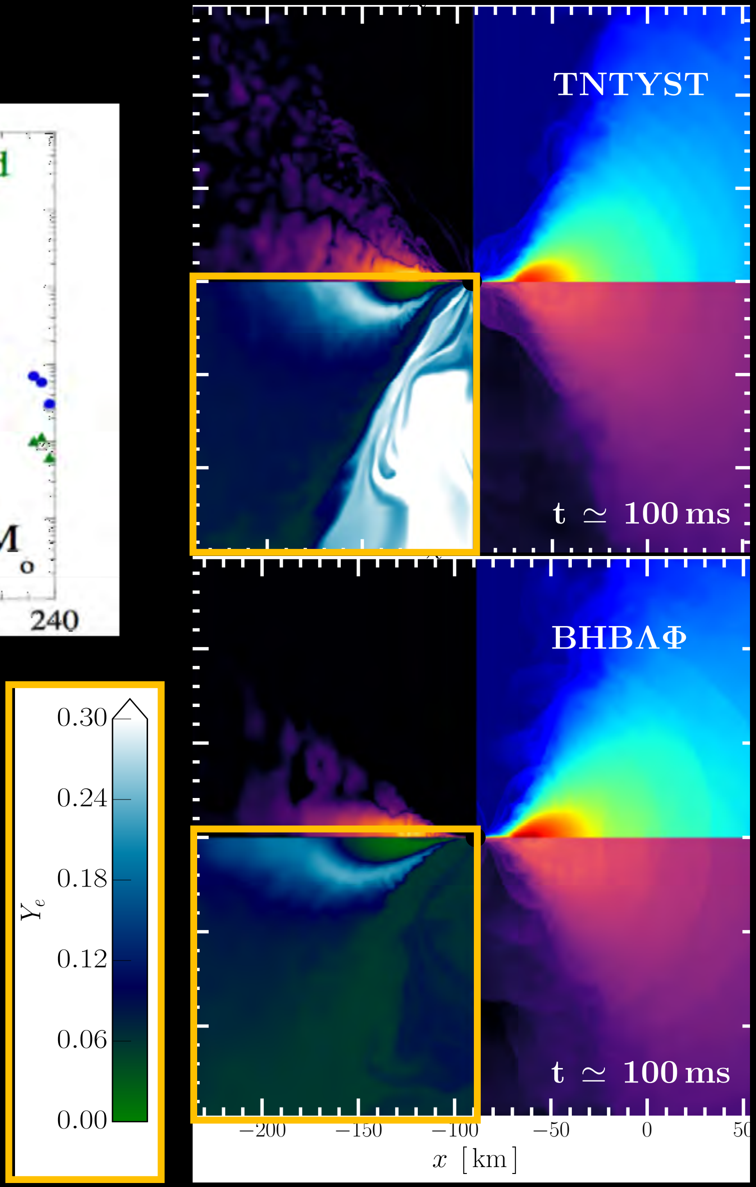


Just+16



Miller+19

Equation of state

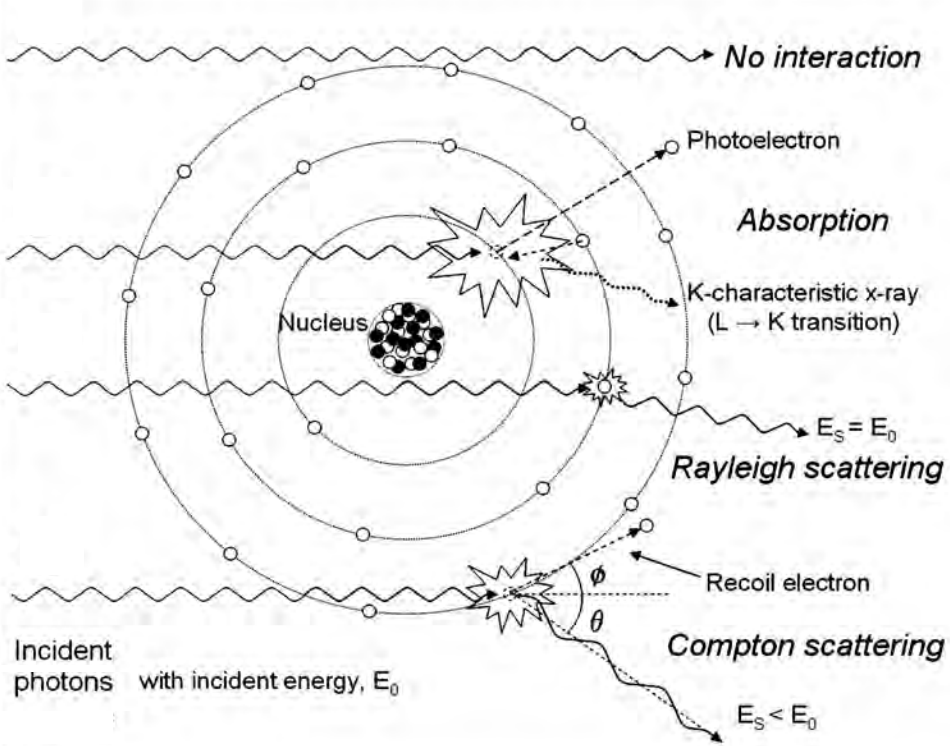


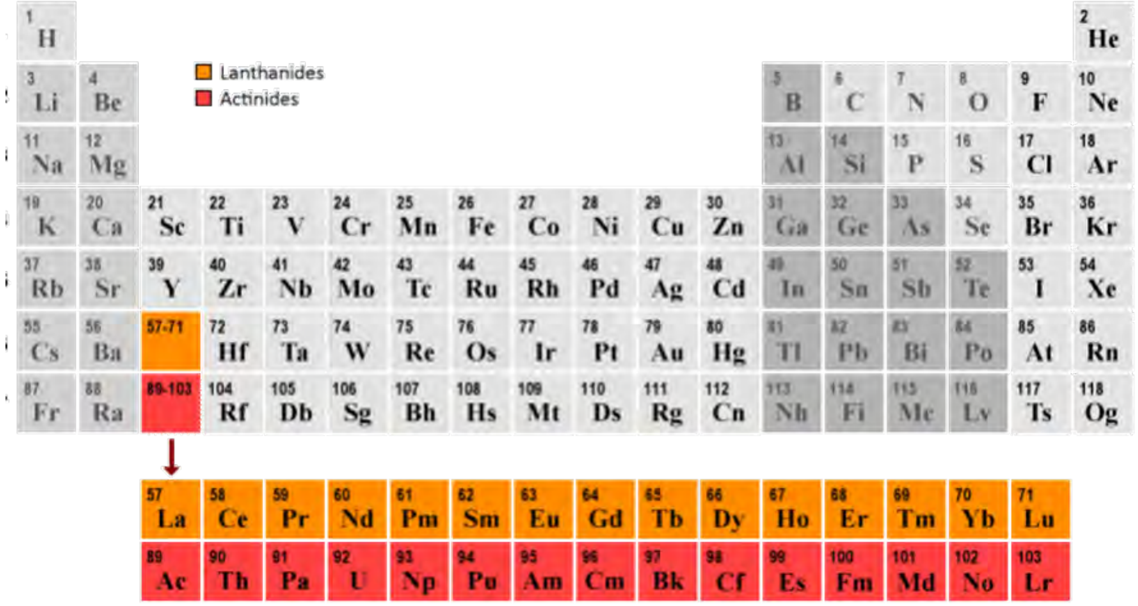
Most+21

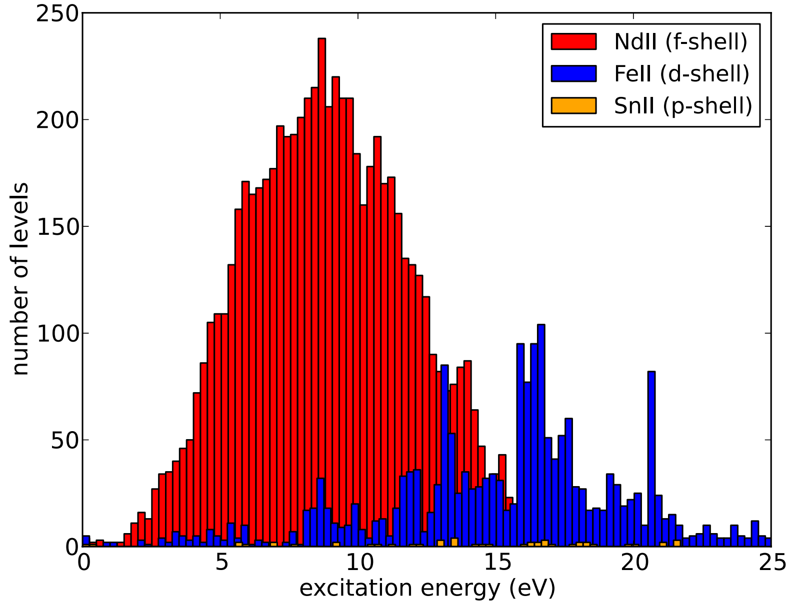
GW170817 & AT2017gfo: photon opacity

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



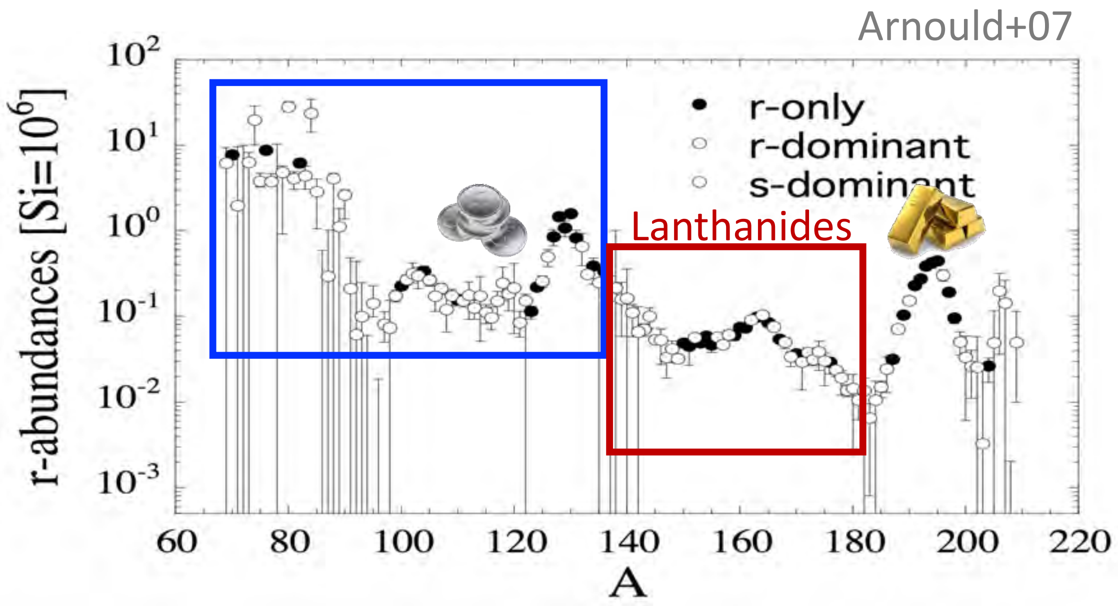




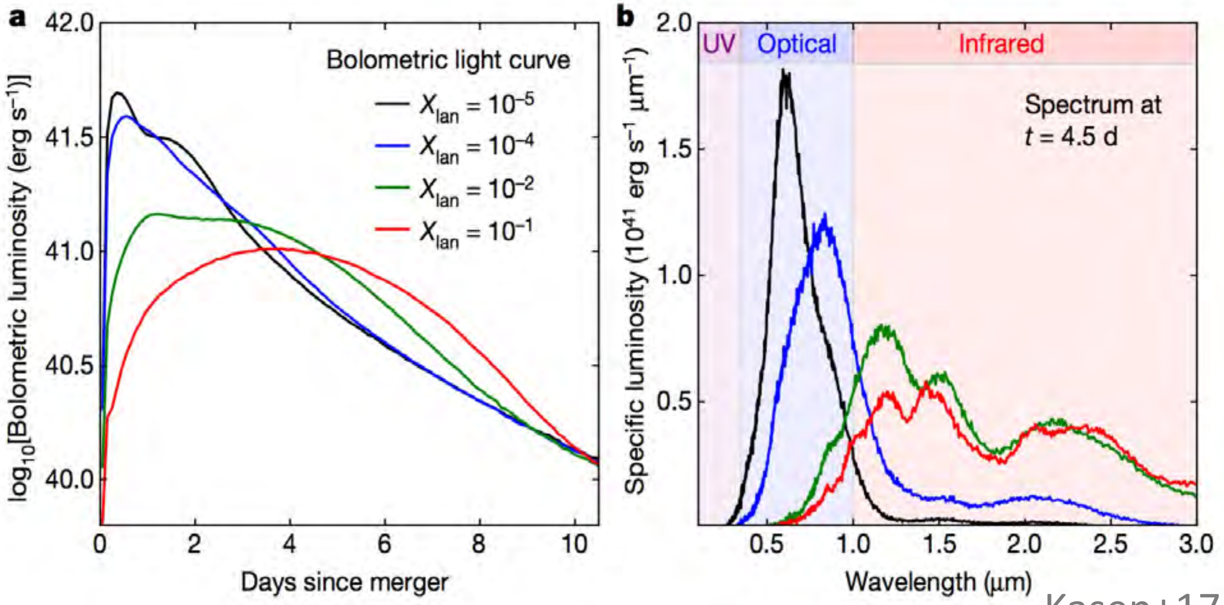
Kasen+13; see also Fontes+20, Tanaka+20

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

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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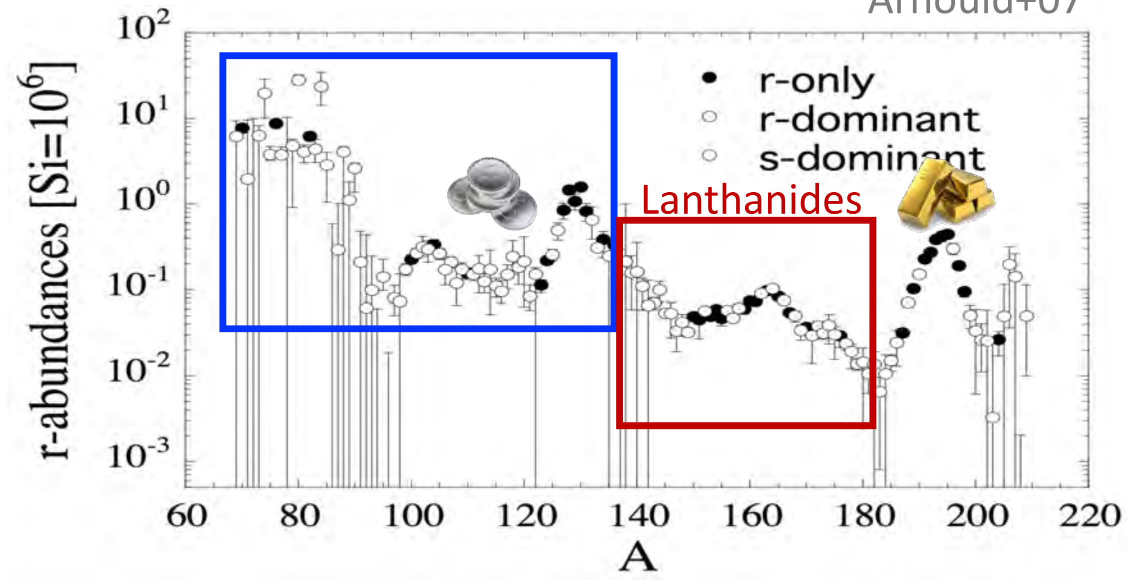

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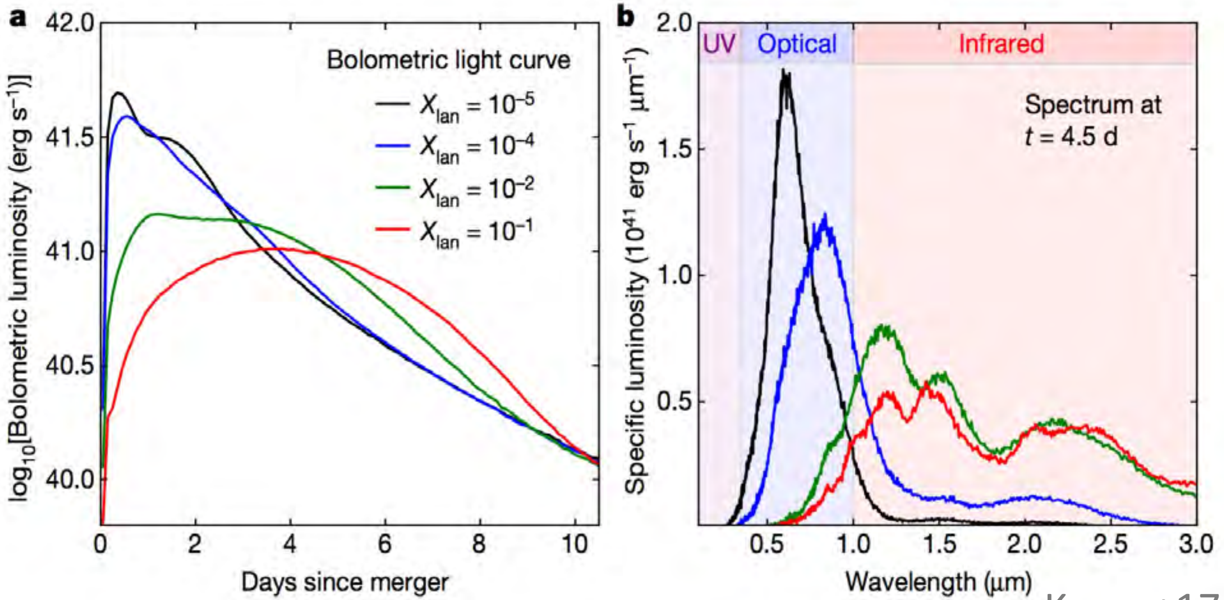
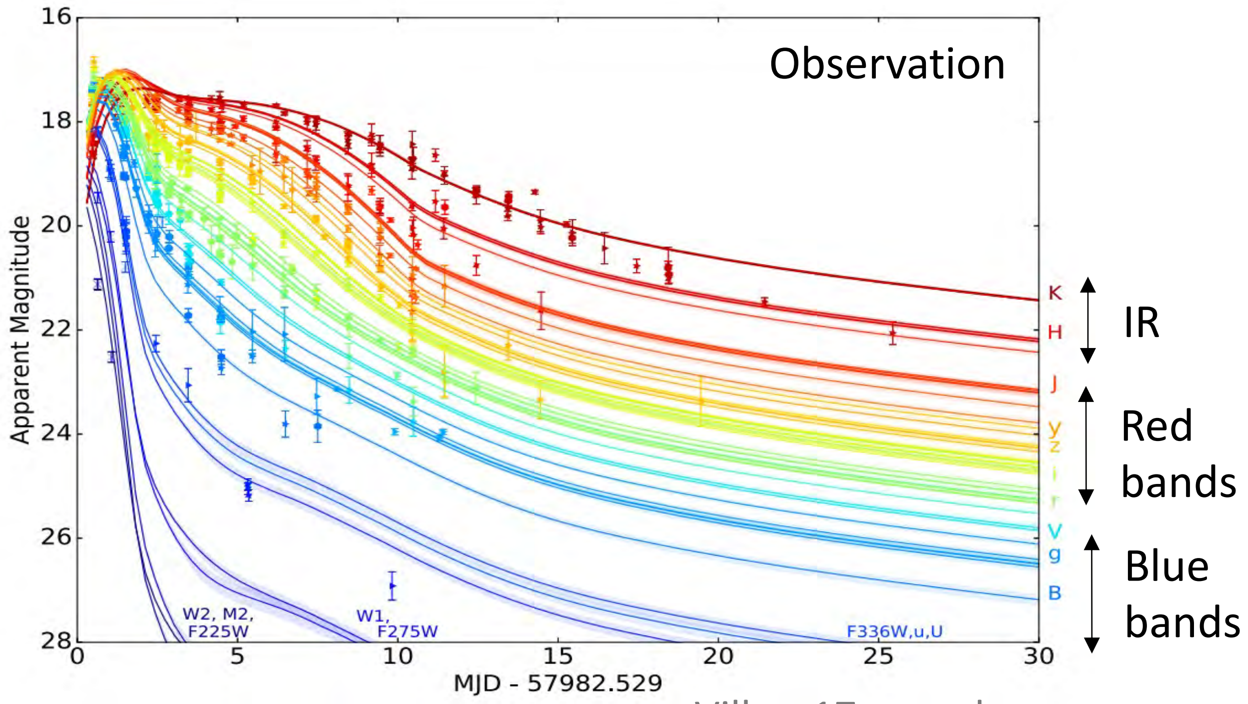


Kasen+17

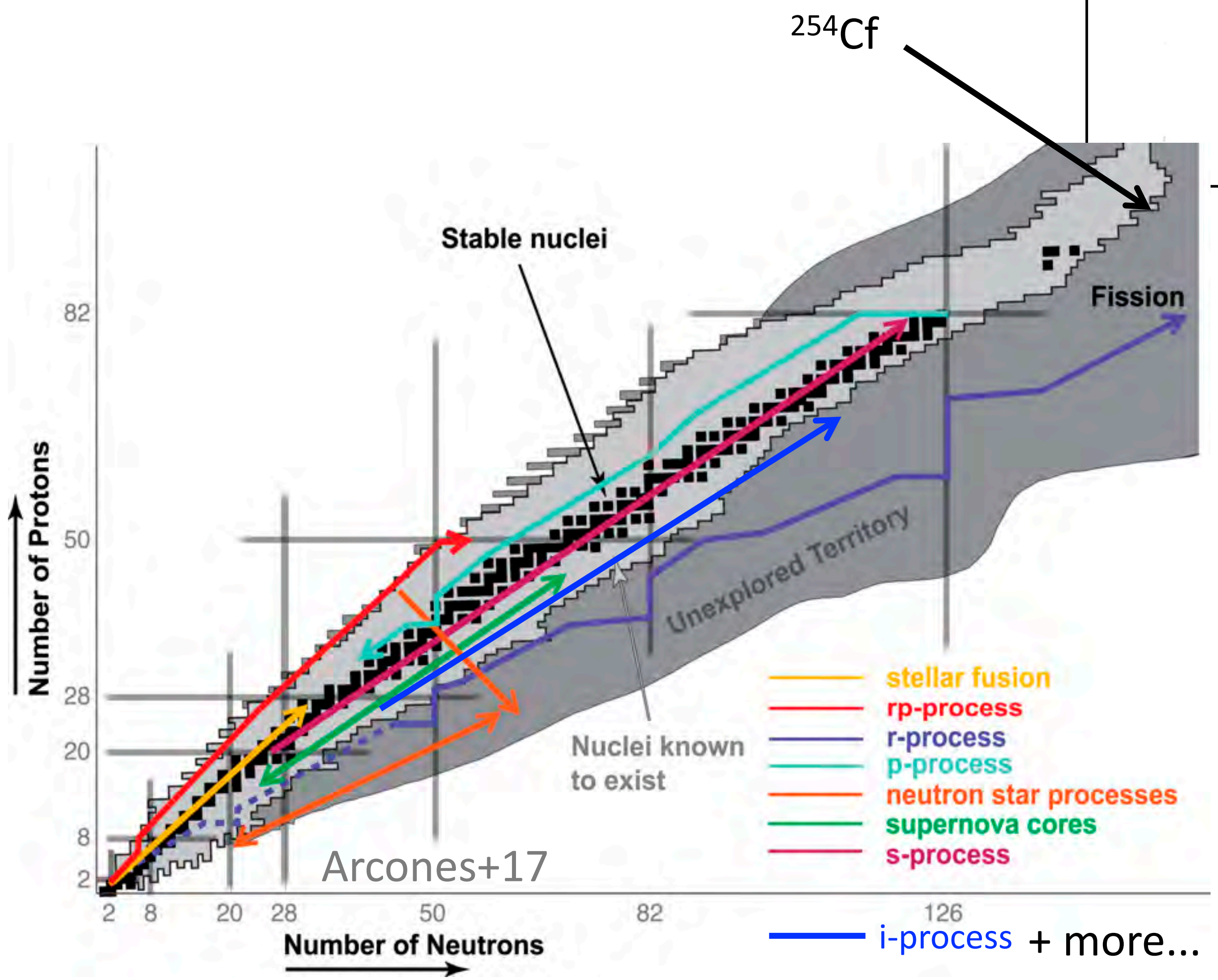
Observation



Days

Villar+17; see also Cowperthwaite+17

Are actinides produced in NSMs?



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*

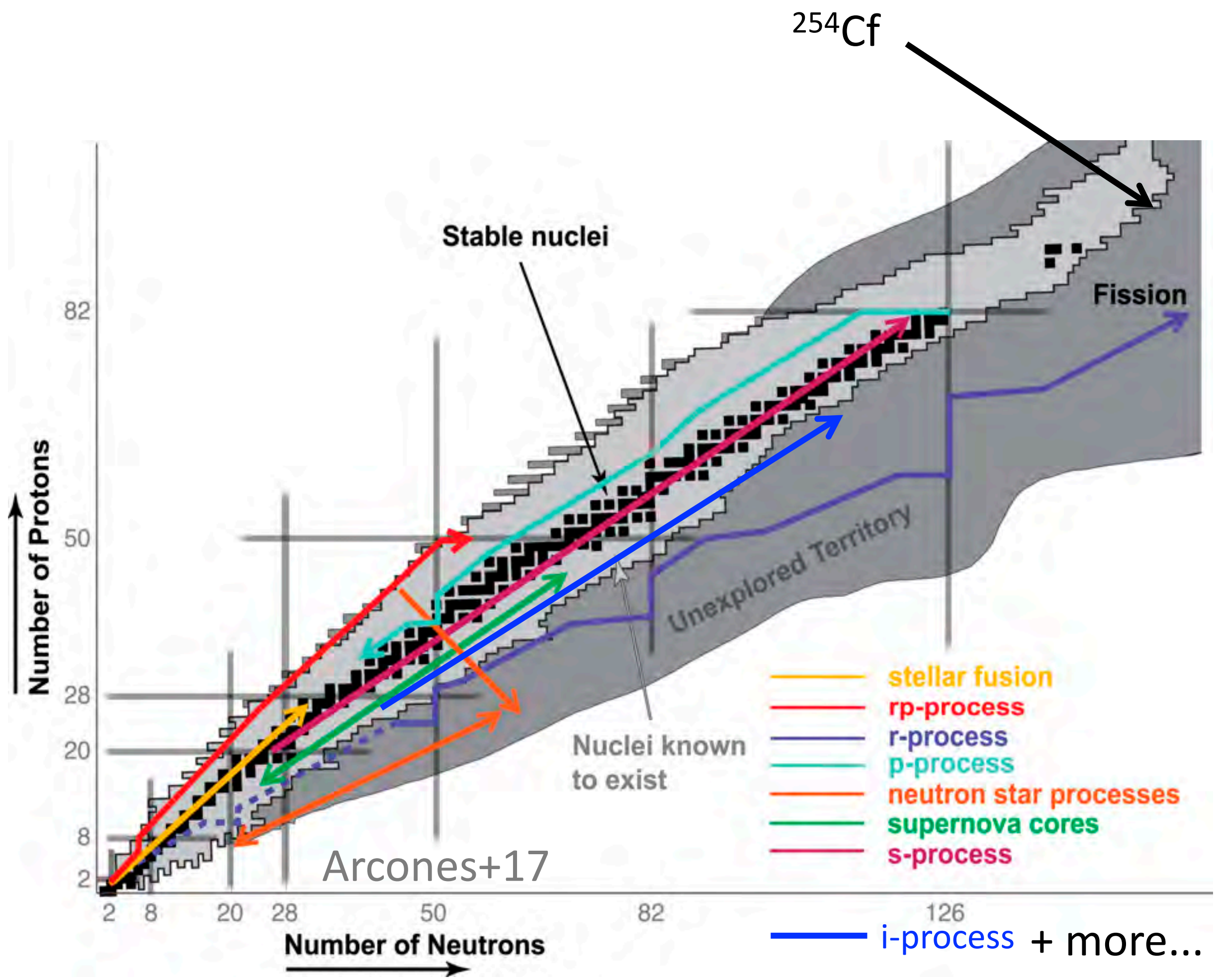
AND

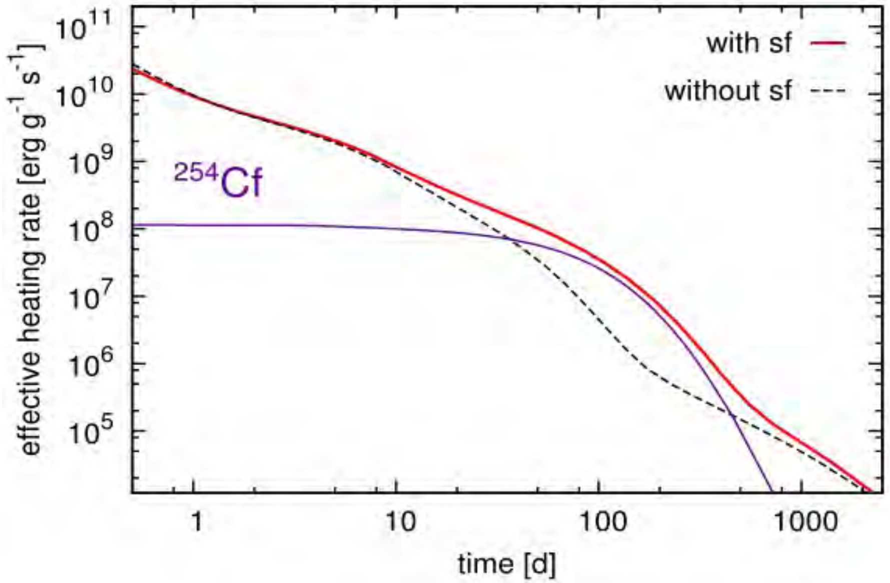
E. M. BURBIDGE, R. F. CHRISTY, AND W. A. FOWLER, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

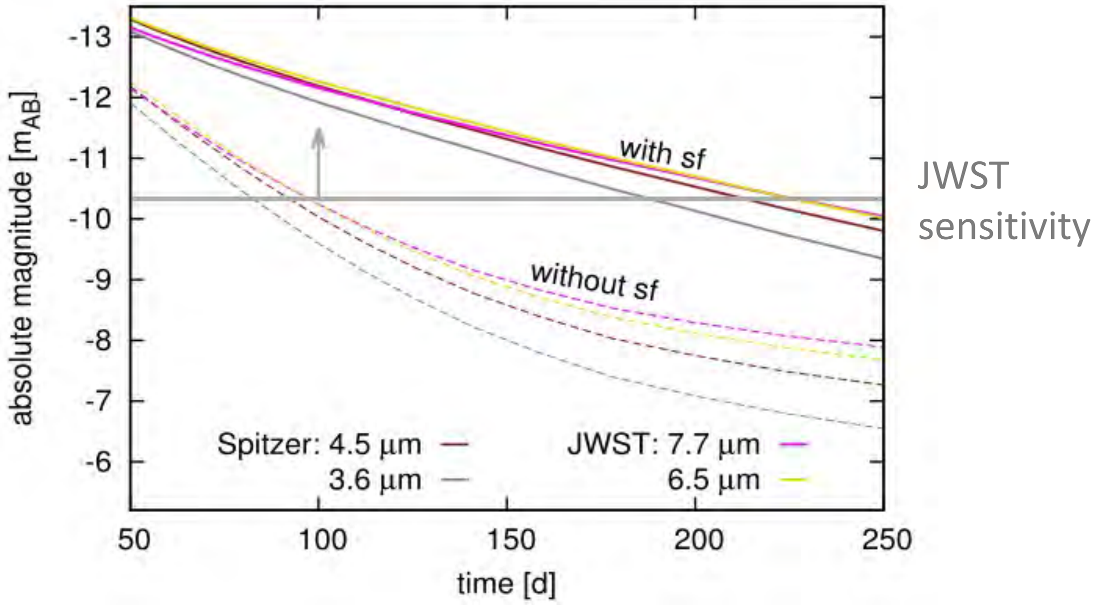
(Received May 17, 1956)

W. W. Girdner/Caltech Archives

Are actinides produced in NSMs?



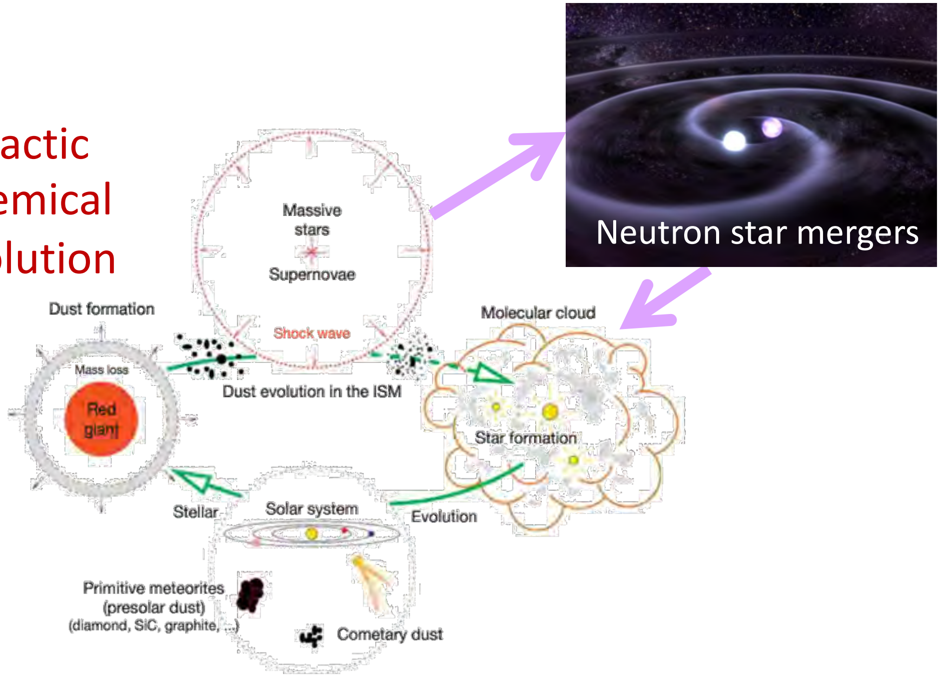




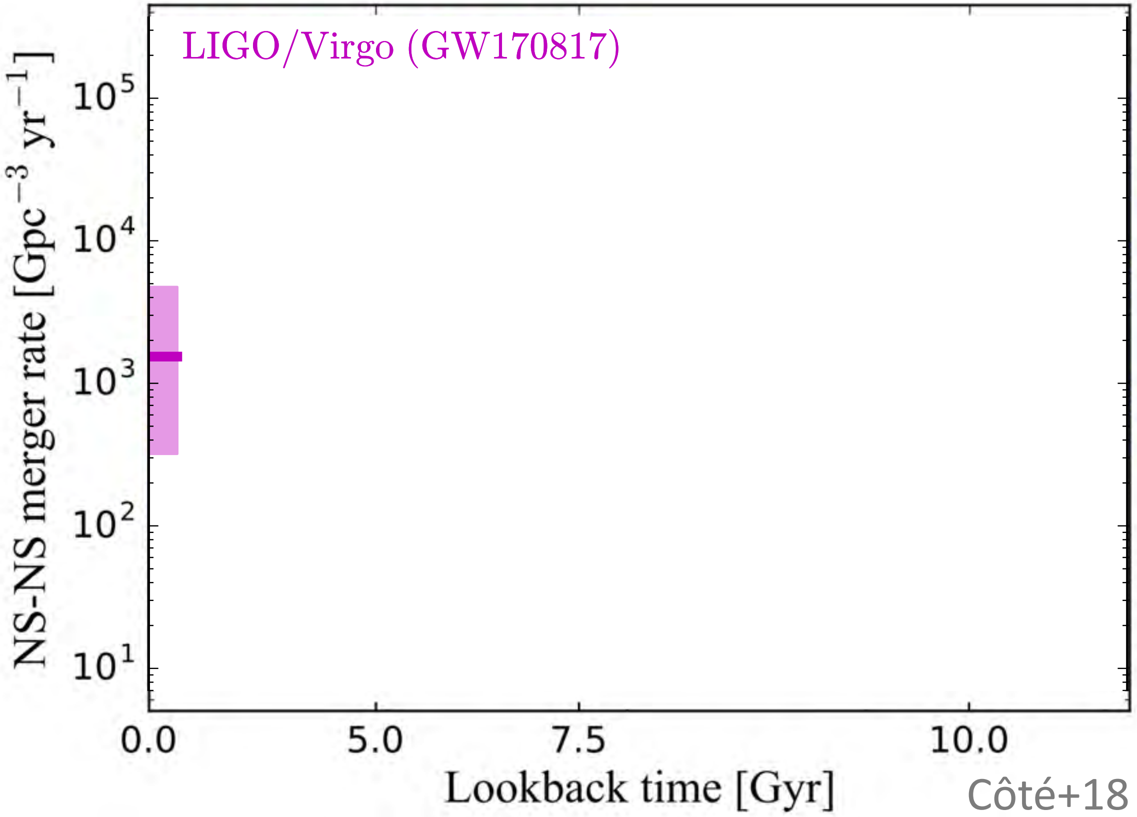
Zhu+18; see also Wu+19

Do binary NSMs make enough heavy elements?

Galactic Chemical Evolution



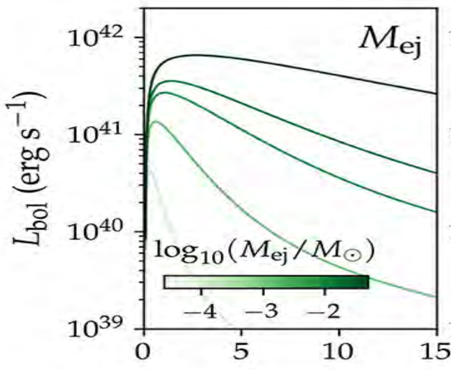
Palm+14



Côté+18

Do binary NSMs make enough heavy elements?

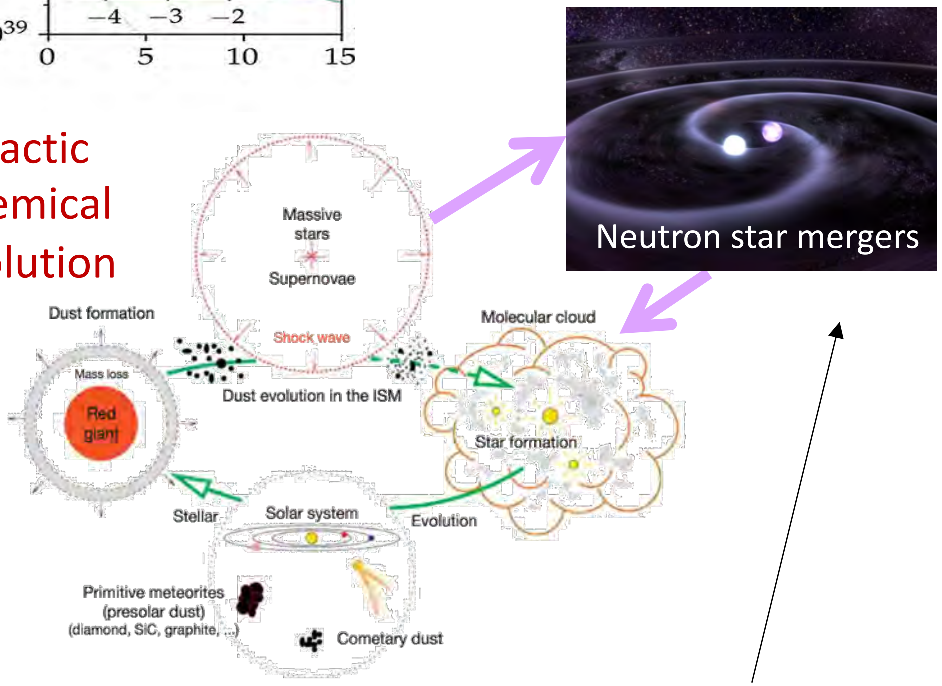
Barnes 20



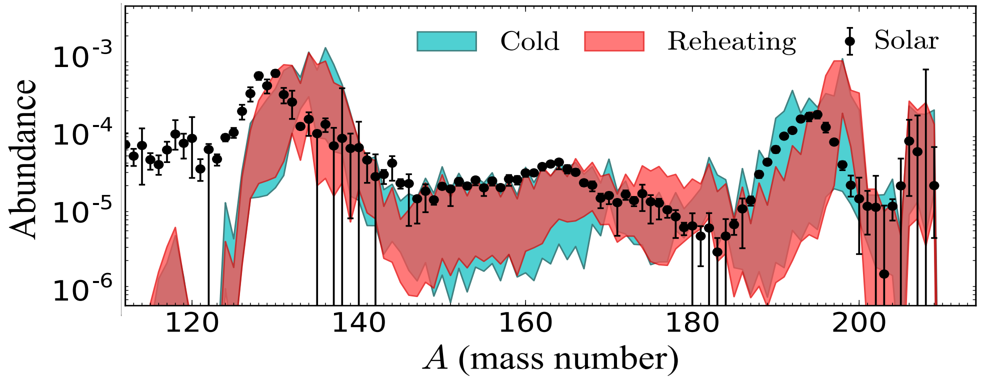
Light Curves

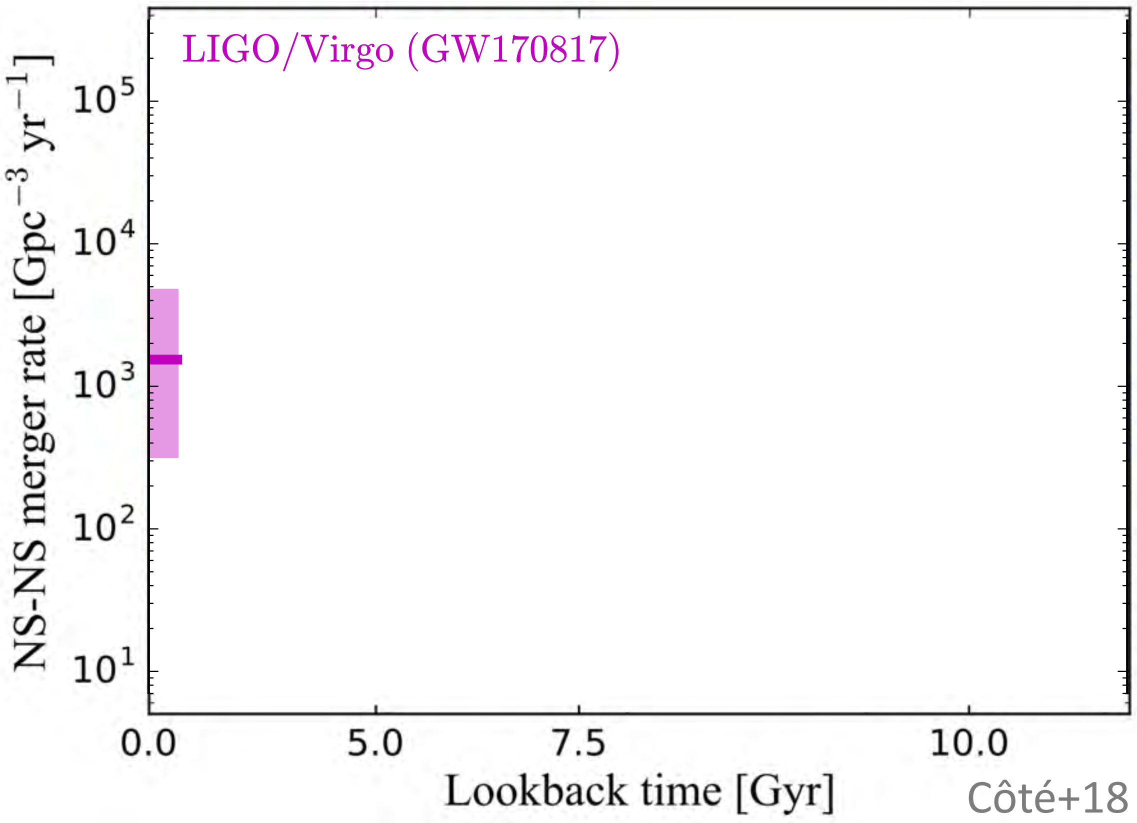
Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution



Palm+14





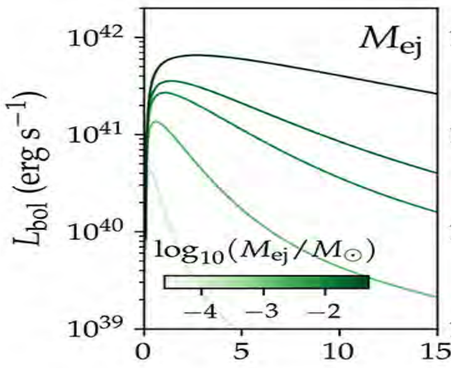
Côté+18

Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models

Do binary NSMs make enough heavy elements?

Barnes 20



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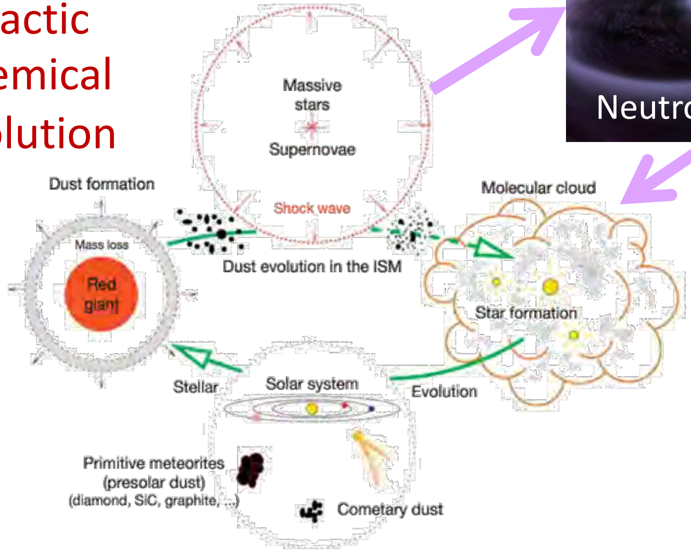
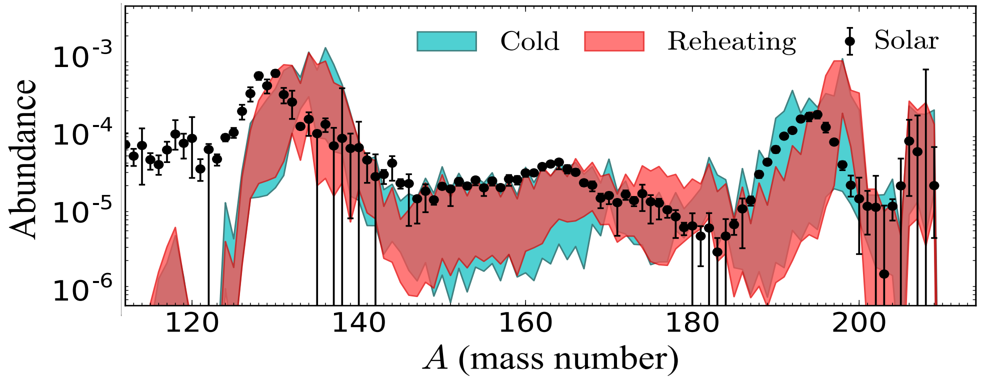


Palm+14



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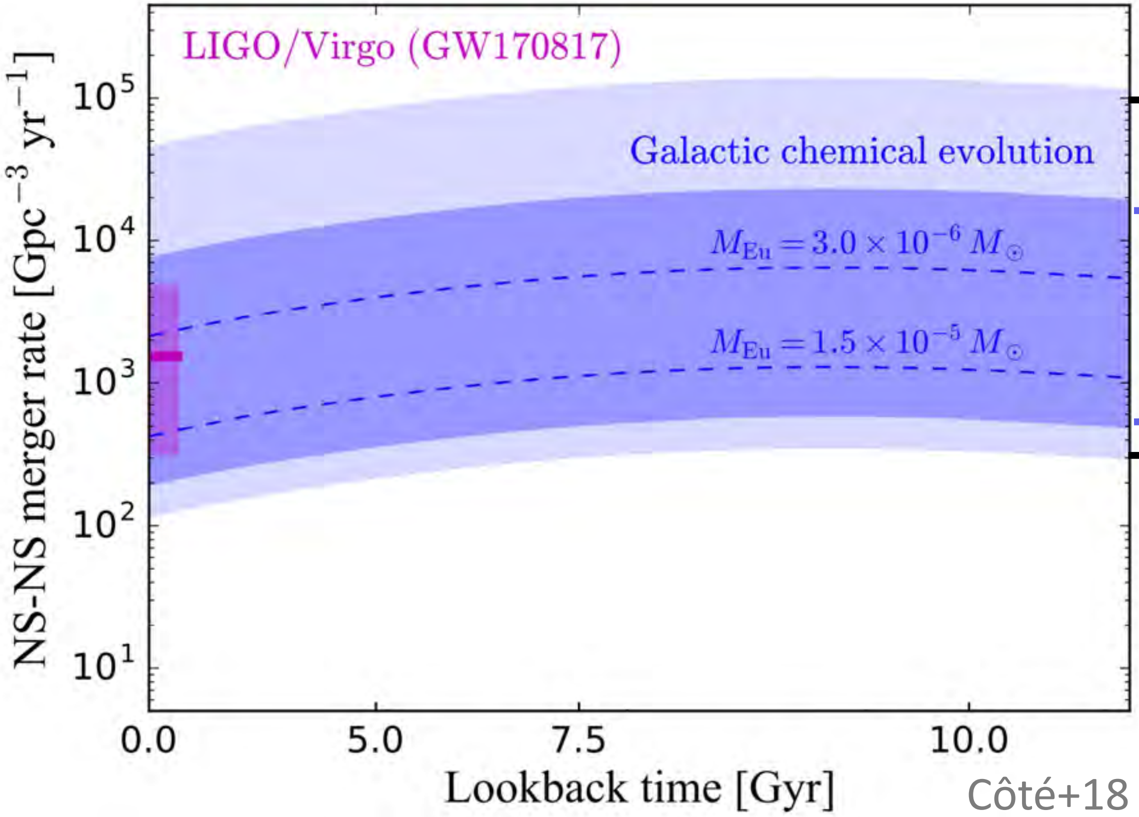


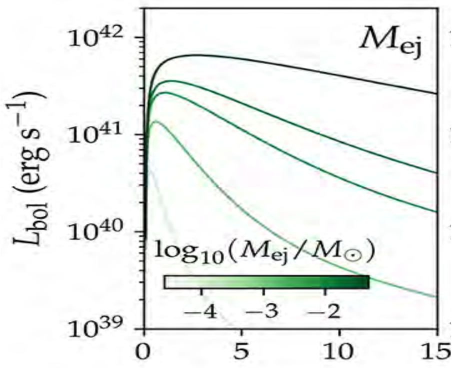
Côté+18

GCE with Solar Abund.

nuclear physics uncertainties

Do binary NSMs make enough heavy elements?

Barnes 20



Light Curves

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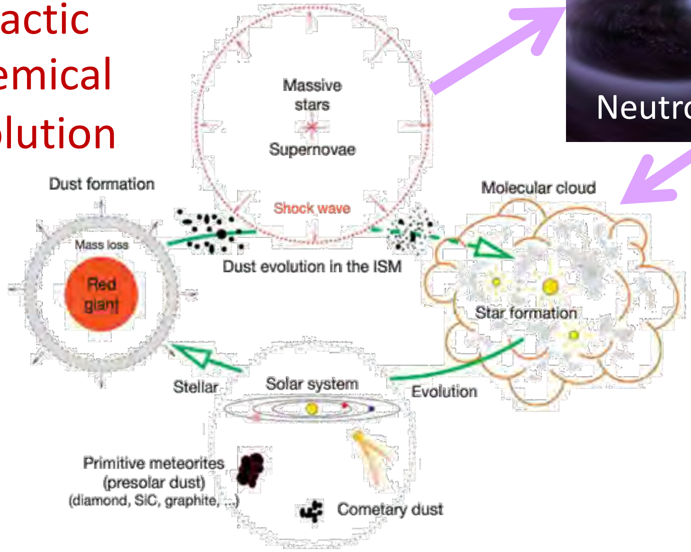
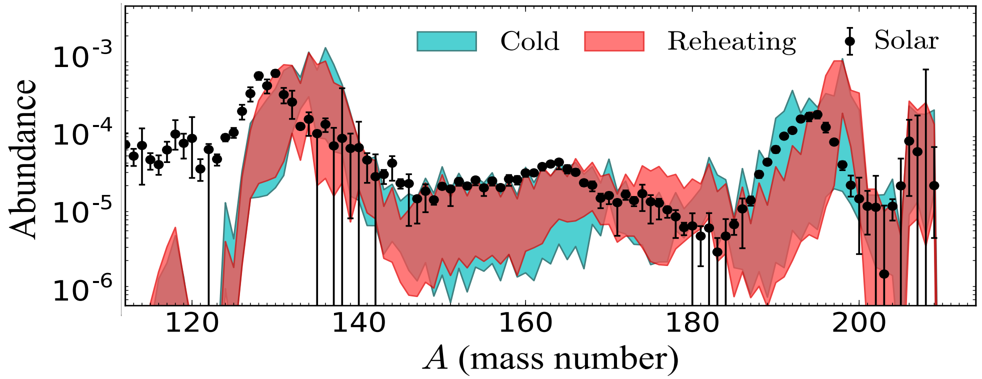
Galactic Chemical Evolution

Palm+14





Nucleosynthesis Predictions

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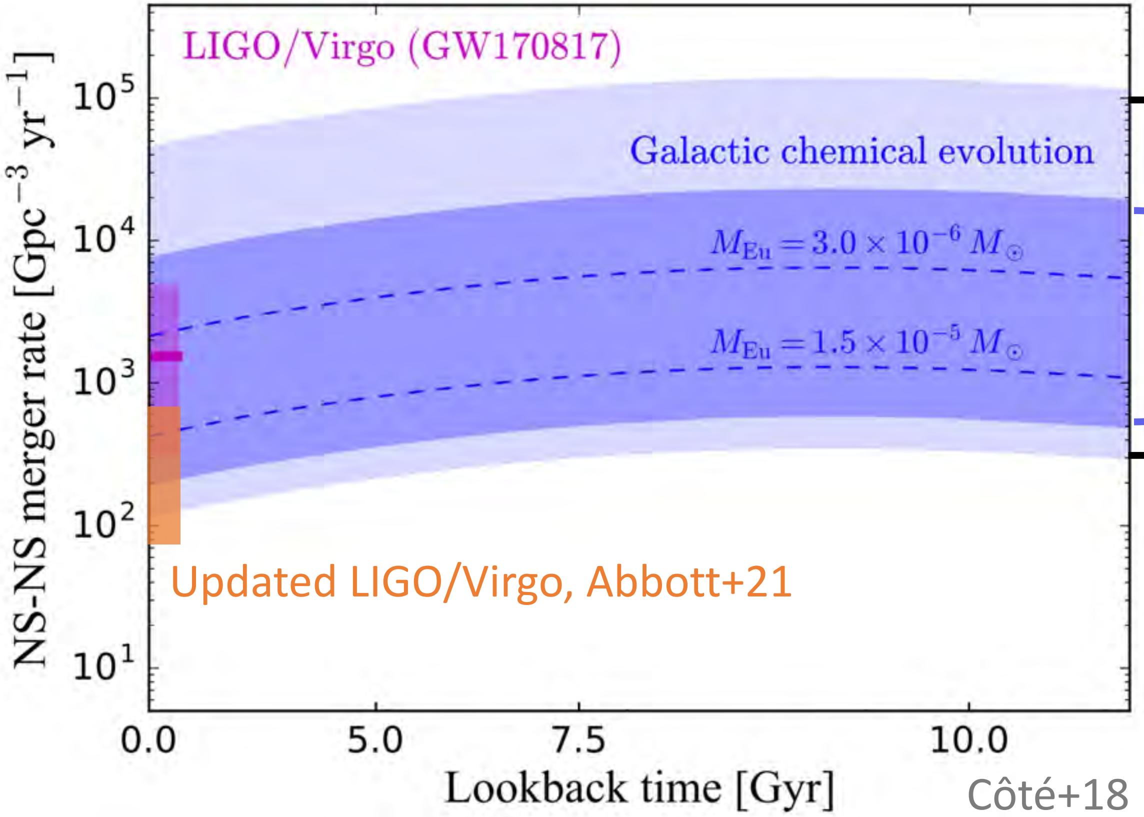


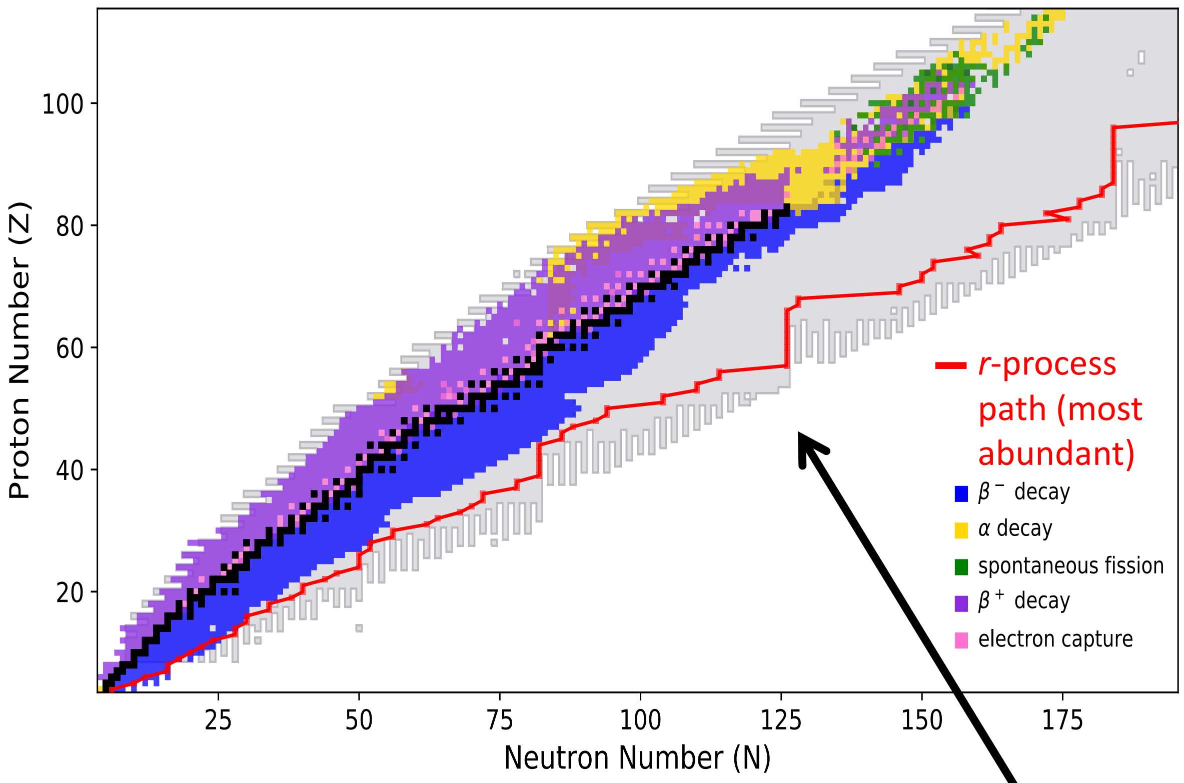
Côté+18

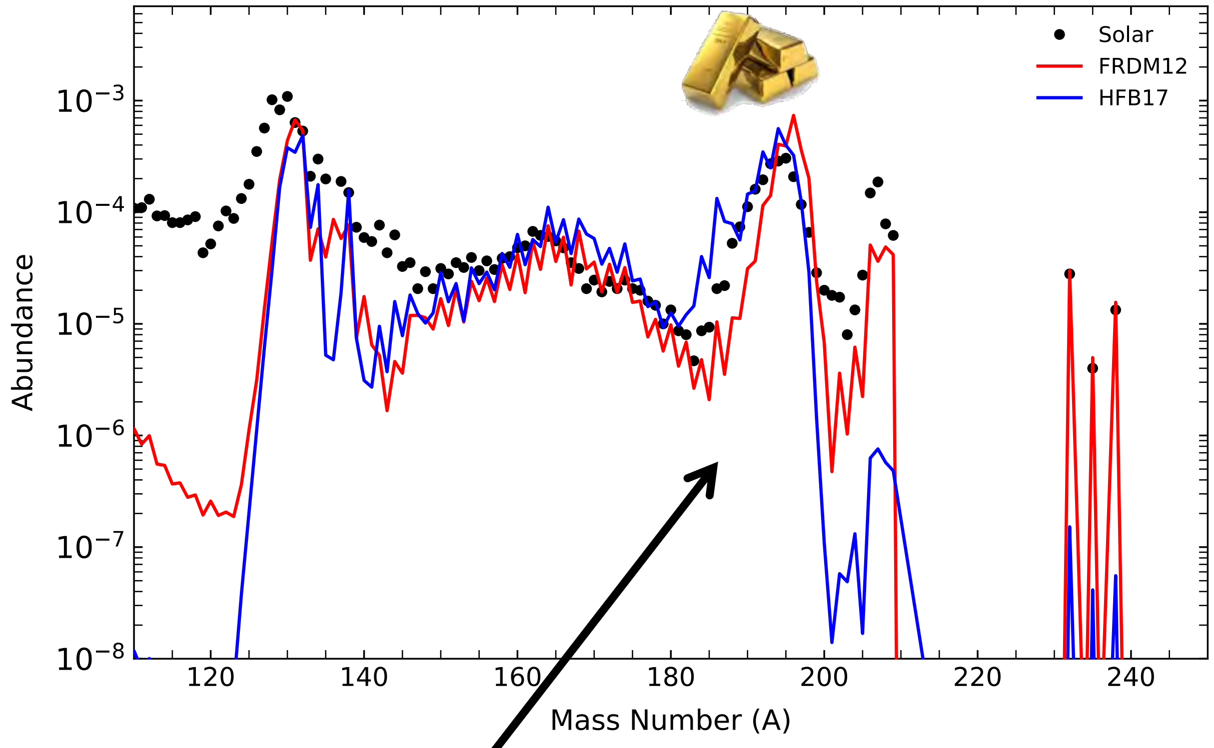
GCE with Solar Abund.

nuclear physics uncertainties

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

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

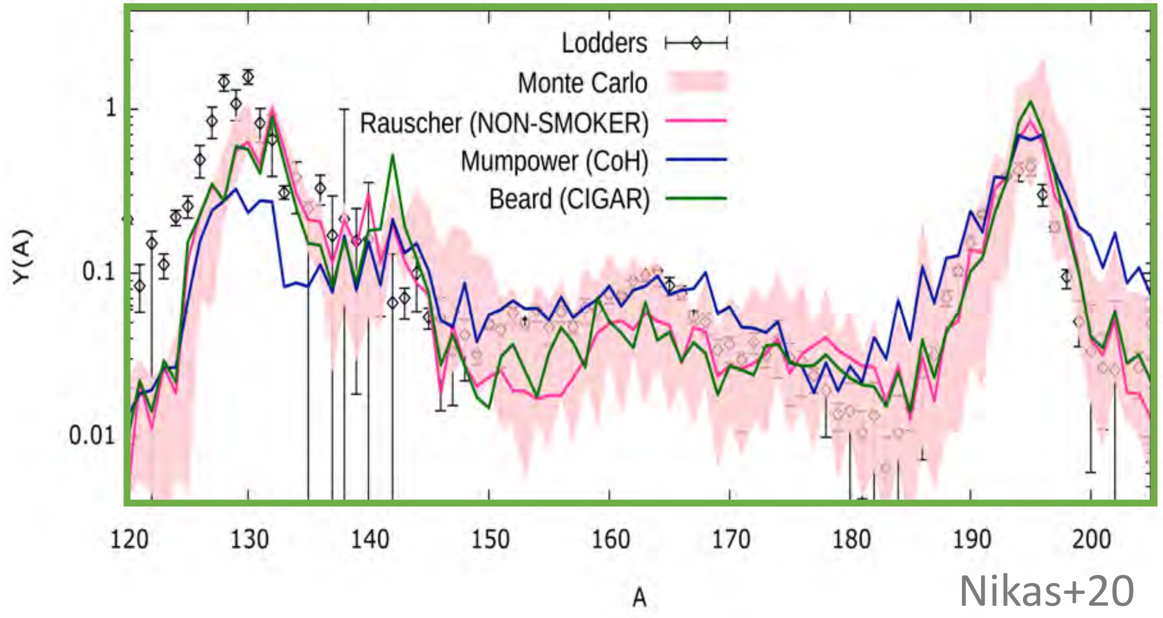




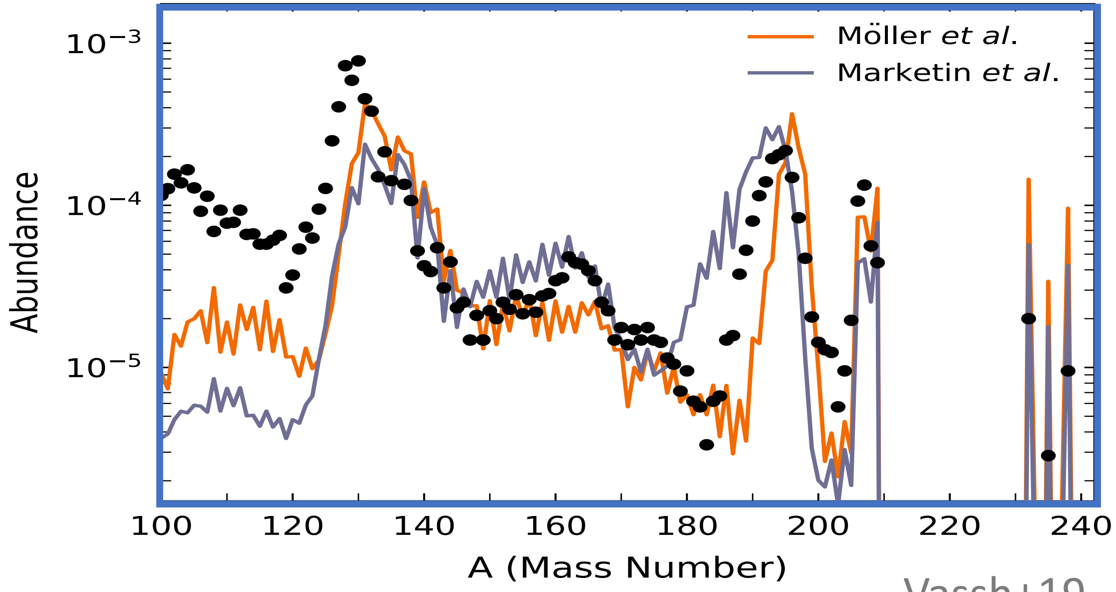
- Little to no experimental data on the neutron-rich side at N=126; nuclear mass models predict different shell closure strengths and thus different amounts of elements like gold and platinum

- The N=126 shell closure is the "gateway" to the actinides and thus affects how strongly elements like uranium-238 are produced

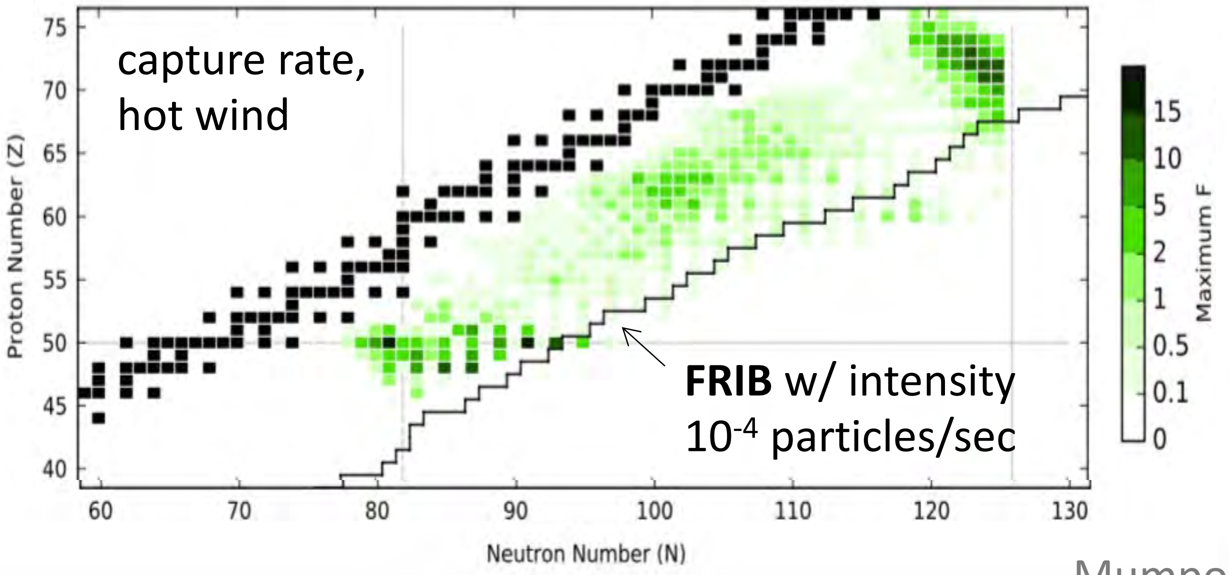
Sensitivity of *r*-process abundances to neutron capture and β-decay

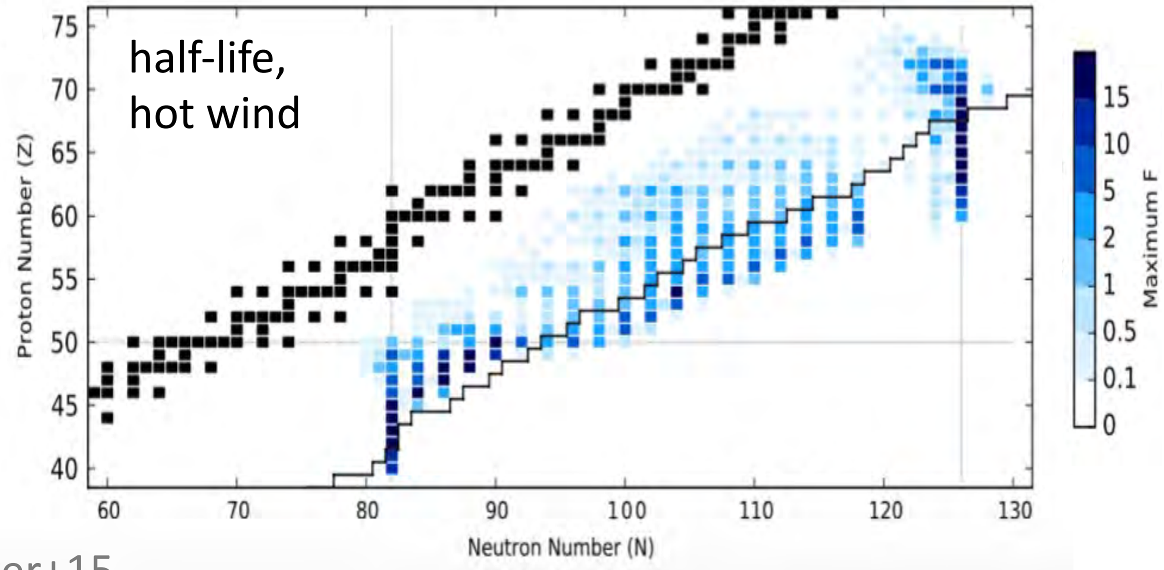


Nikas+20



Vassh+19





Mumpower+15

Spotlight on impact of nuclear masses

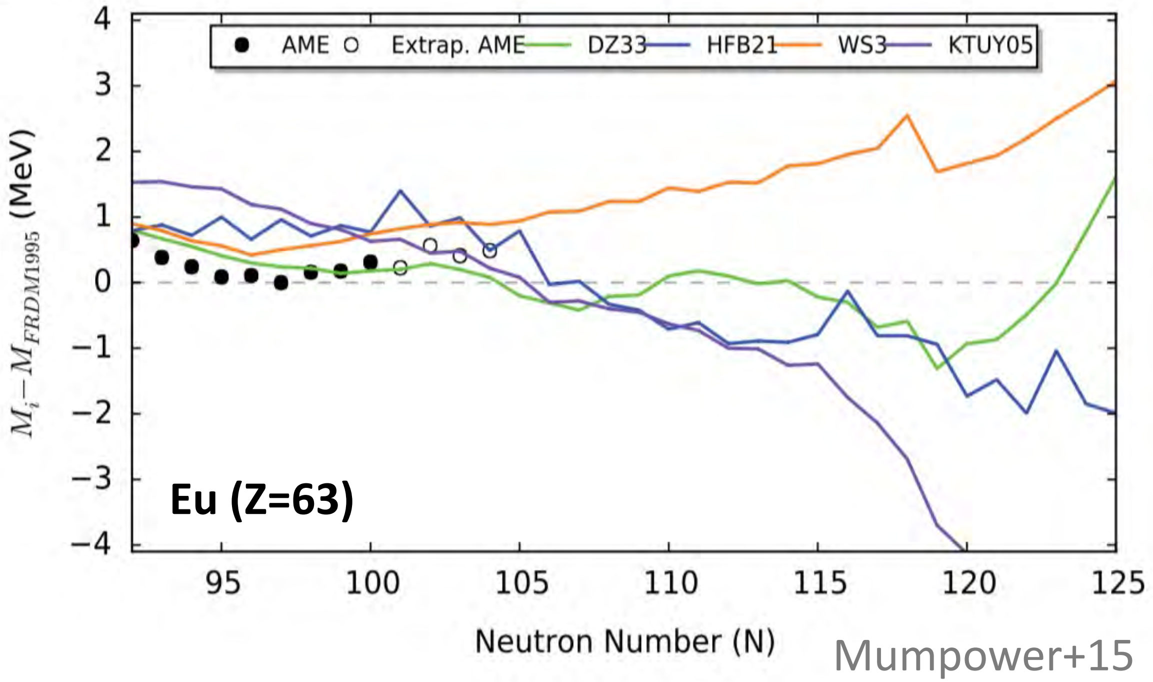
Masses determine key quantities that go into calculating capture and decay rates; for instance:

Neutron capture rates depend on

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

β⁻-decay rates depend on

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



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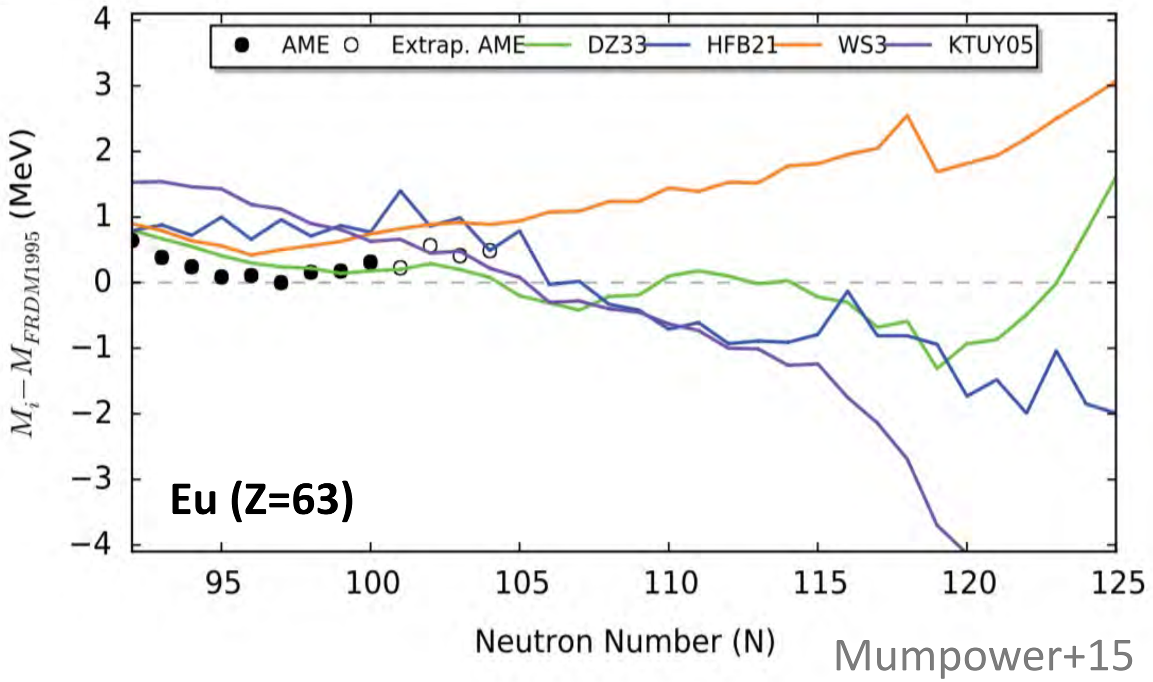
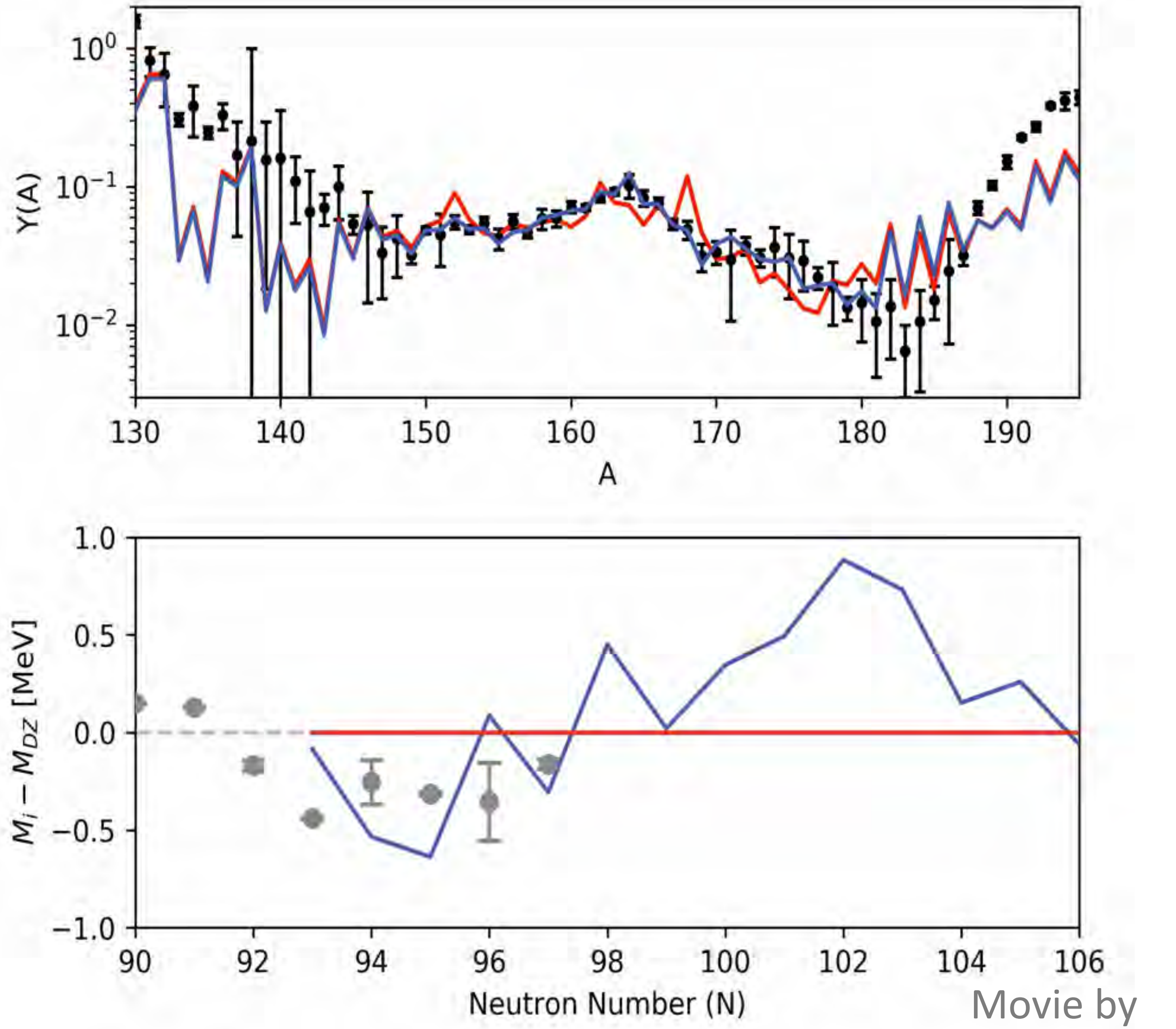


Mumpower+15

MCMC predictions for neutron-rich rare-earth masses



Movie by N. Vassh

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

Spotlight on impact of nuclear masses

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

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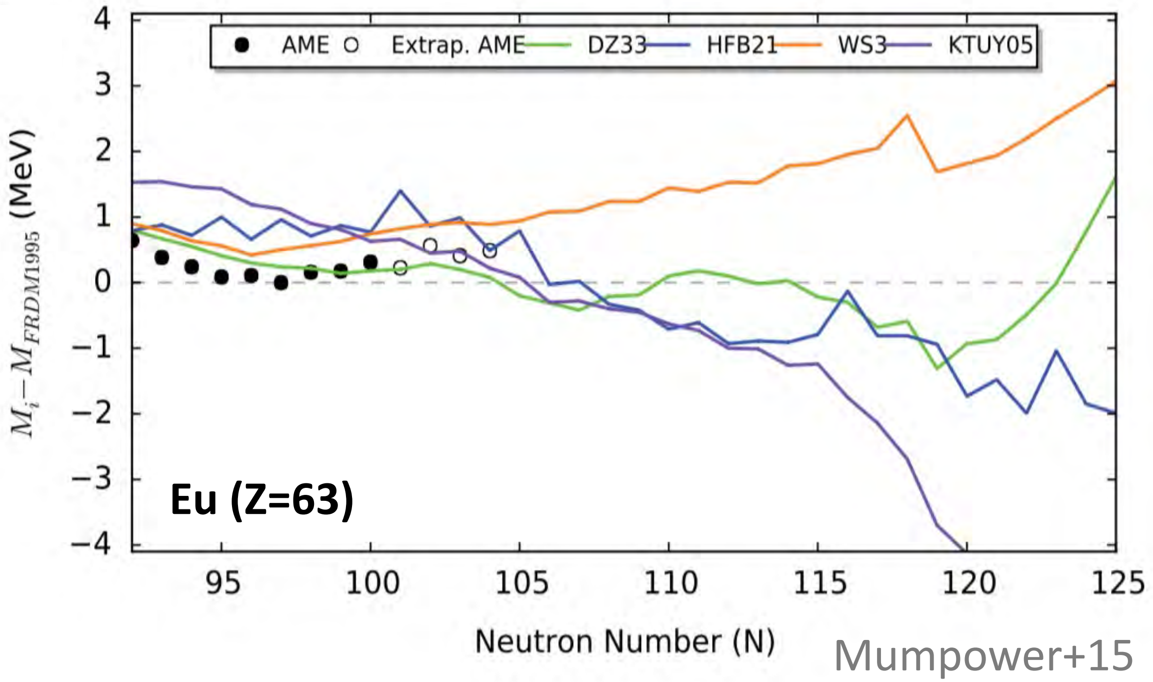
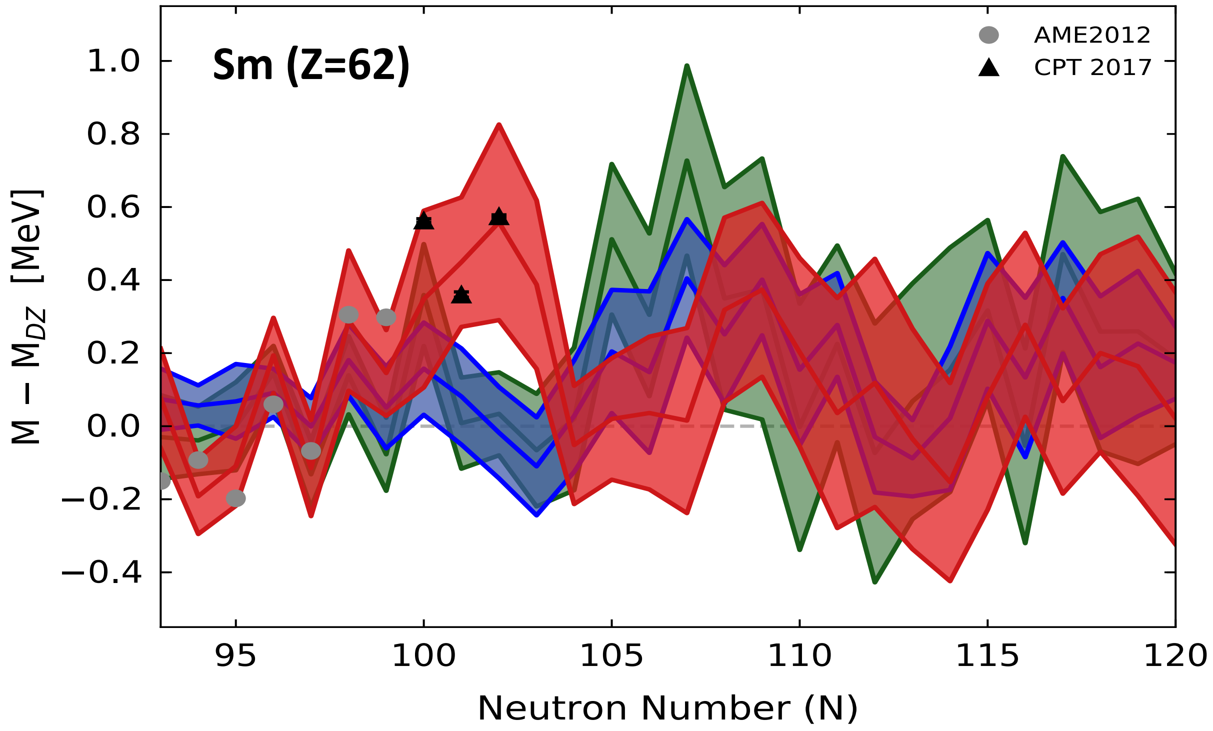


Mumpower+15

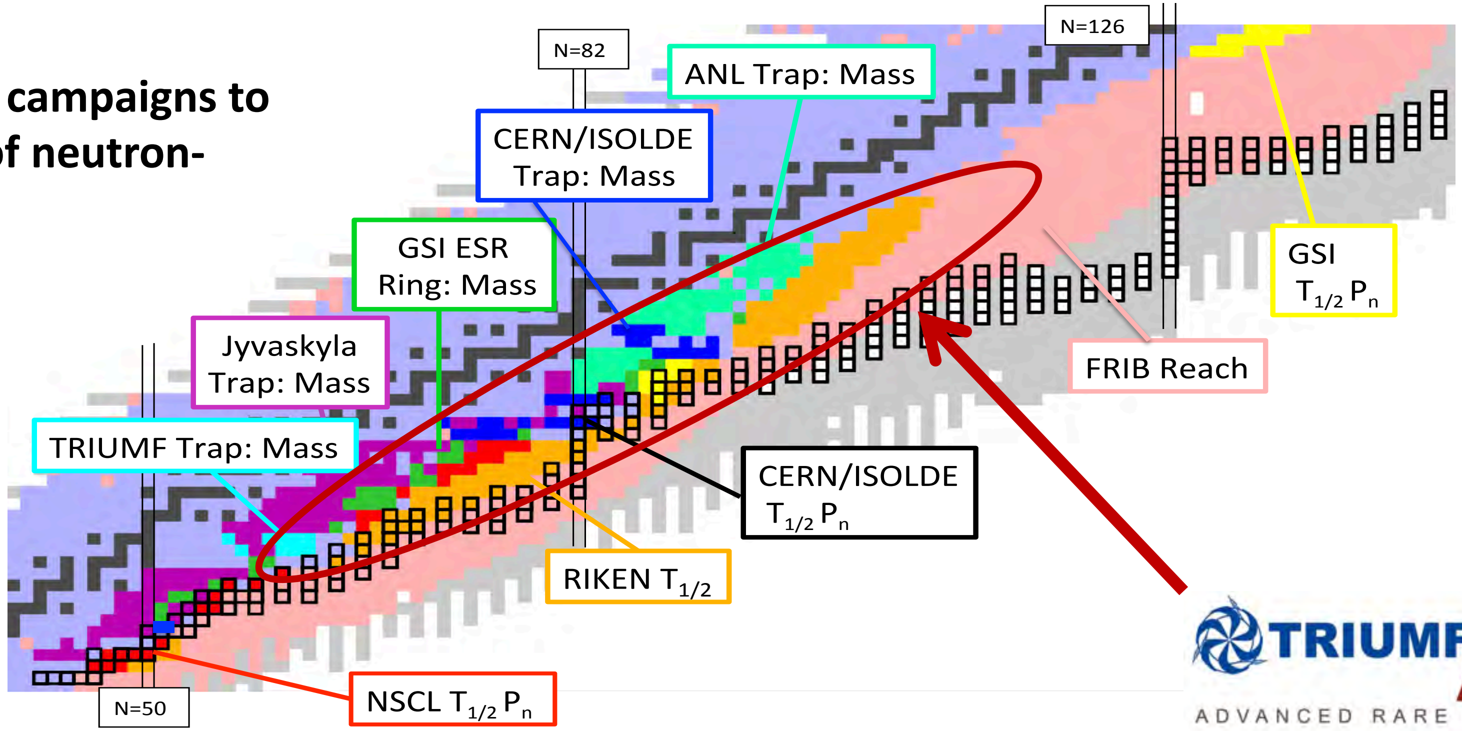
MCMC results in
moderately neutron-rich outflows



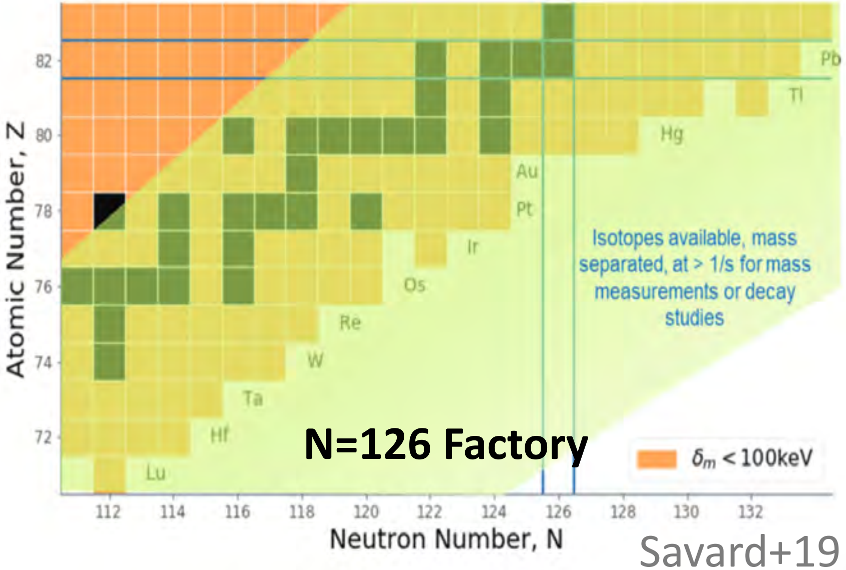
Neutron star merger accretion disk winds with:
Hot = extended (n,γ)⇆(γ,n) equilibrium
Cold = photodissociation falls out early

Vassh+21 (ApJ 907, 98)

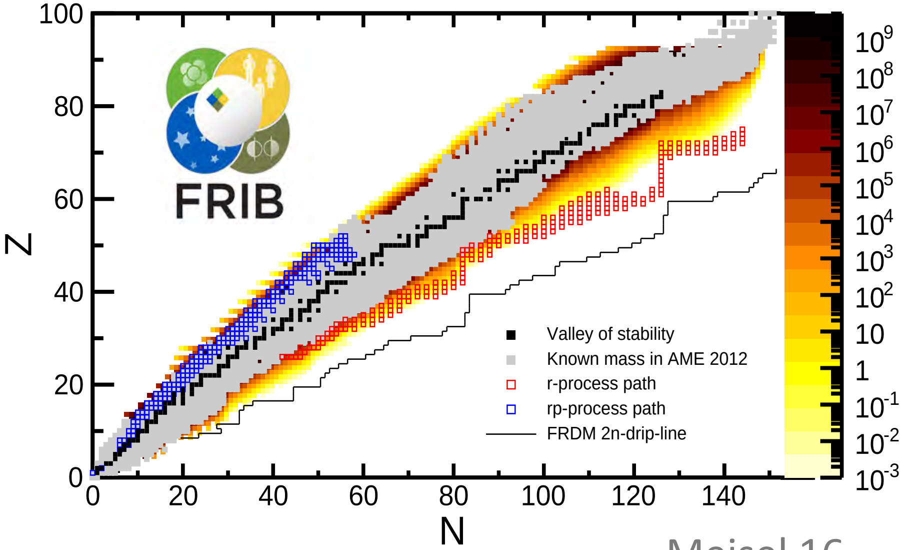
Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives,
reaction rates…



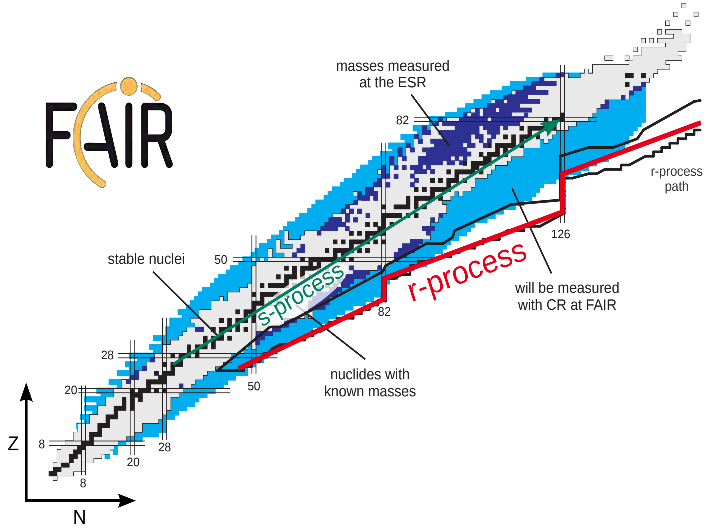
Horowitz+18



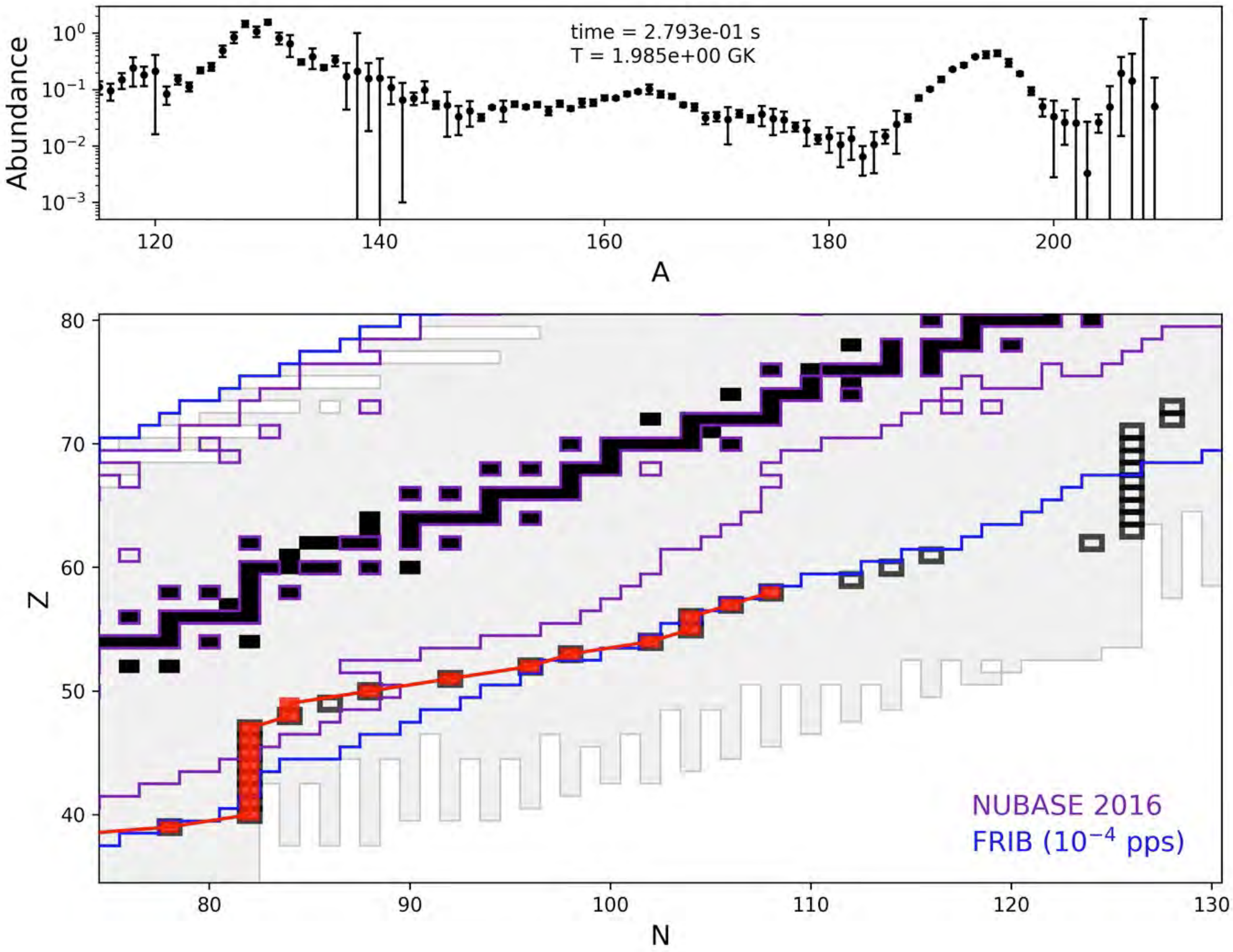
Savard+19



Meisel 16



Future experiment meets the *r*-process path



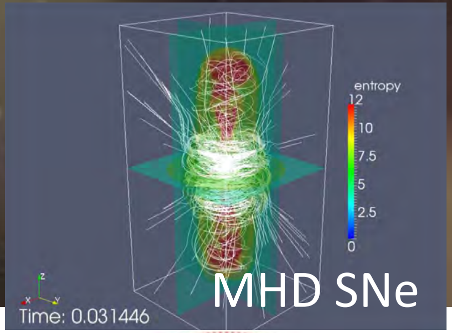
*reach of future experiment in key regions impacting the evolution of abundances (note moderately n-rich conditions used here)

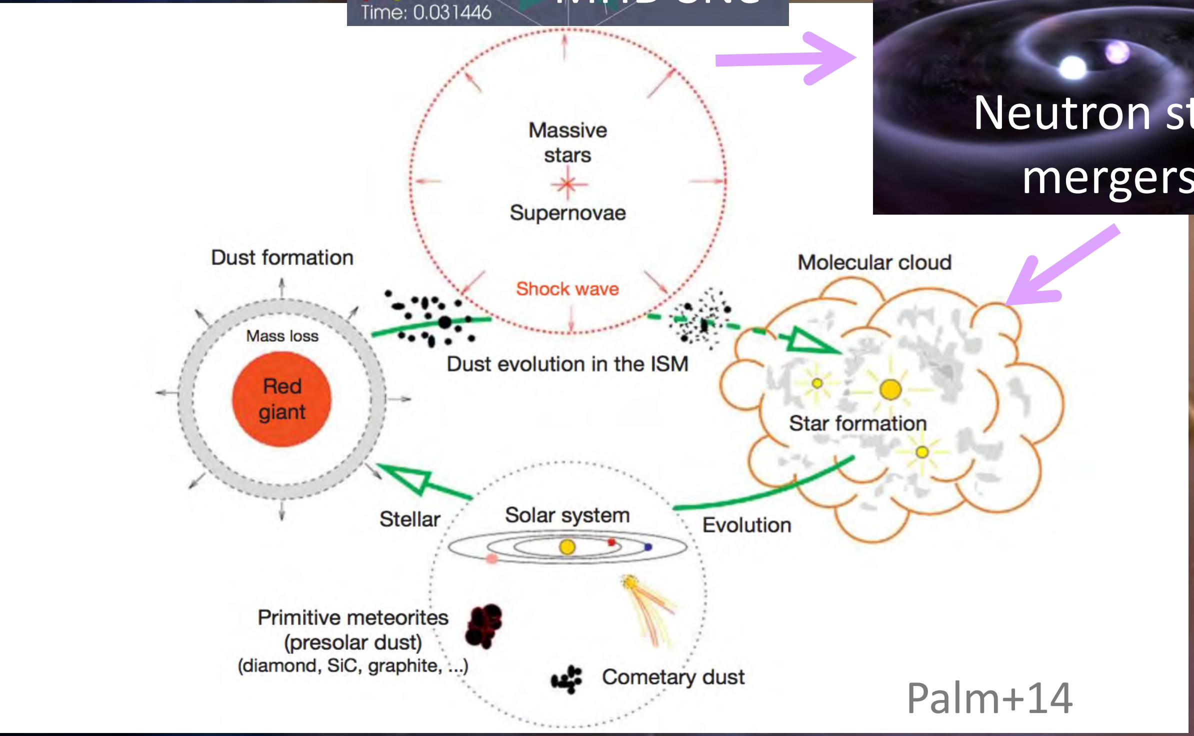
Movie by N. Vassh

Outline for lecture II

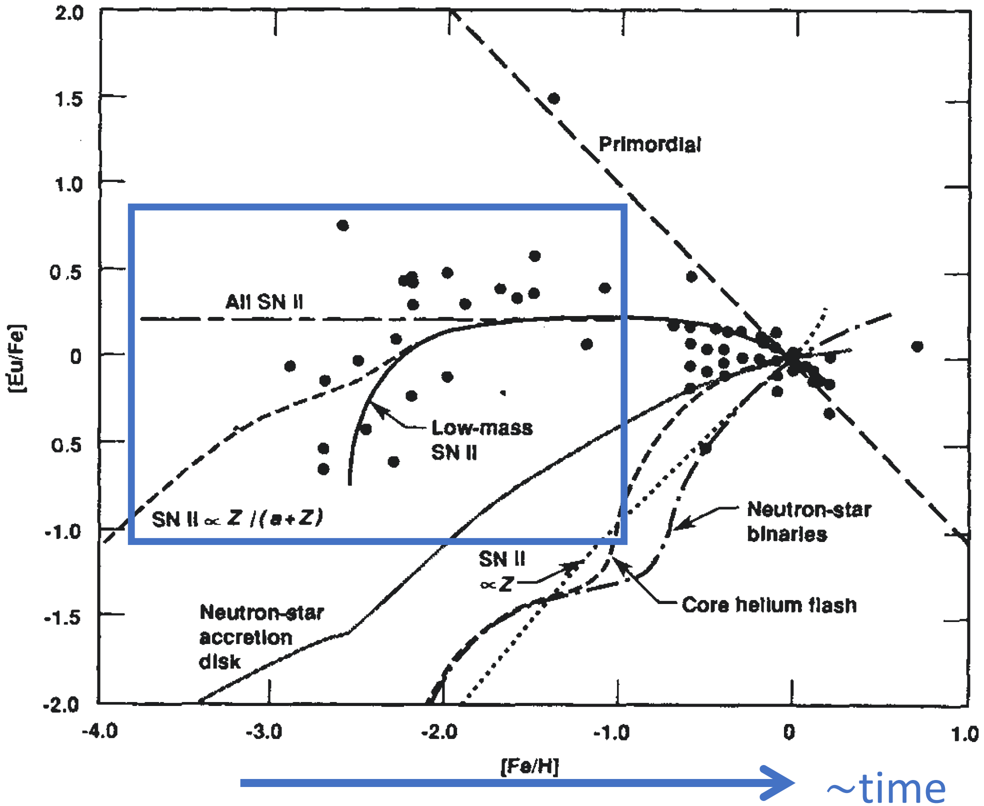
- Stellar burning and stellar evolution [3-9]
- Supernovae: types and nucleosynthesis [11-16]
- Making the heaviest elements: neutron capture nucleosynthesis [18-26]
- Neutron star mergers: gravitational waves, kilonovae, and nucleosynthesis [28-46]
- Galactic chemical evolution [49-51]

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





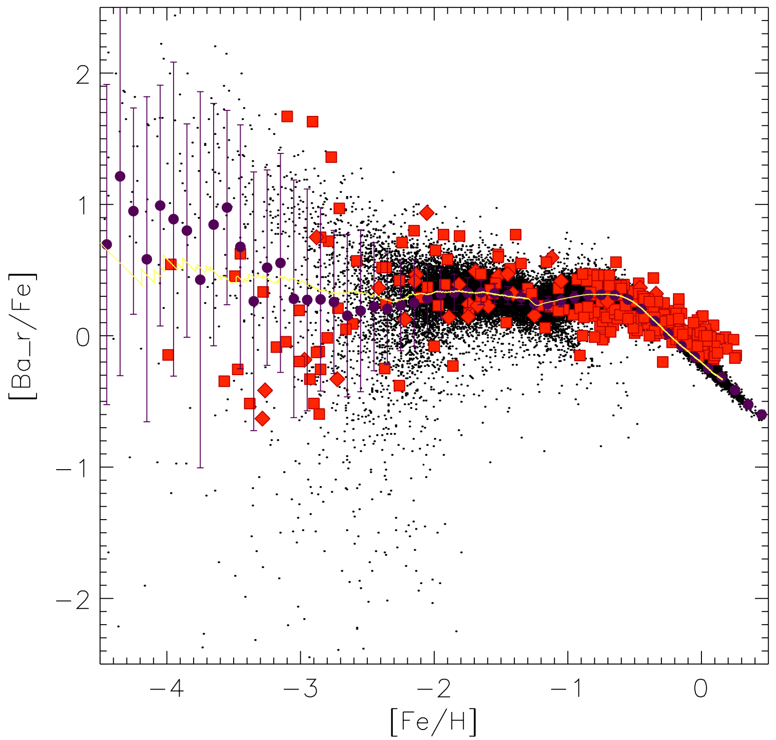
Supernovae as the *r*-process source?
Galactic chemical evolution (GCE) and low metallicity stars



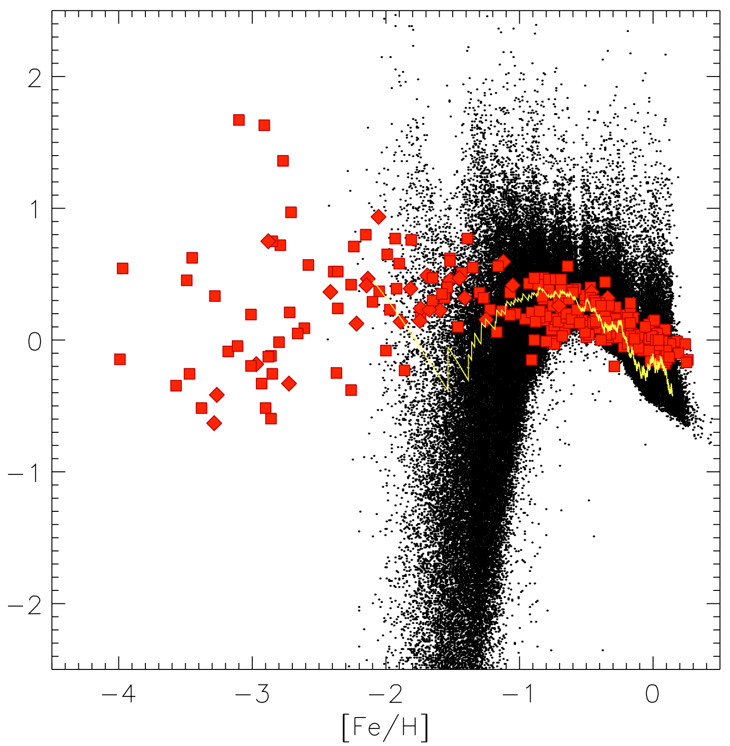
~time

Mathews & Cowan 90

Type II Supernova



Neutron Star Mergers



Argast+04

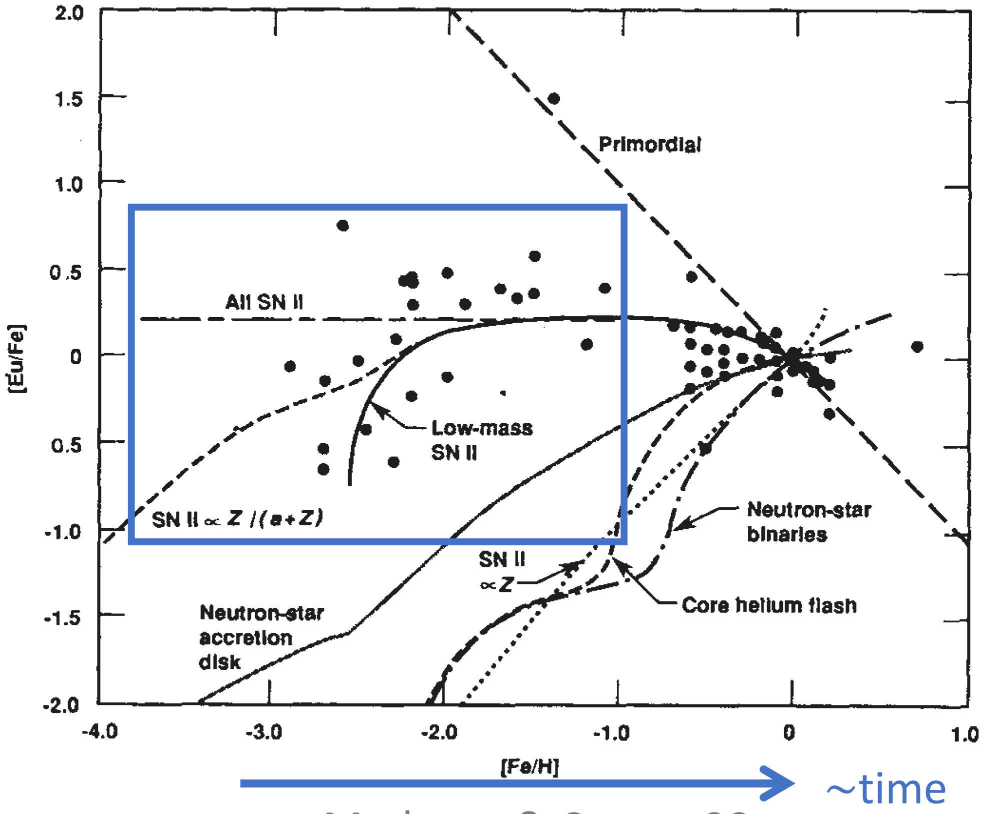
*The stars in the box seem to be more consistent with supernovae since neutron stars take time to merge

◆ ■ observations

● • model stars

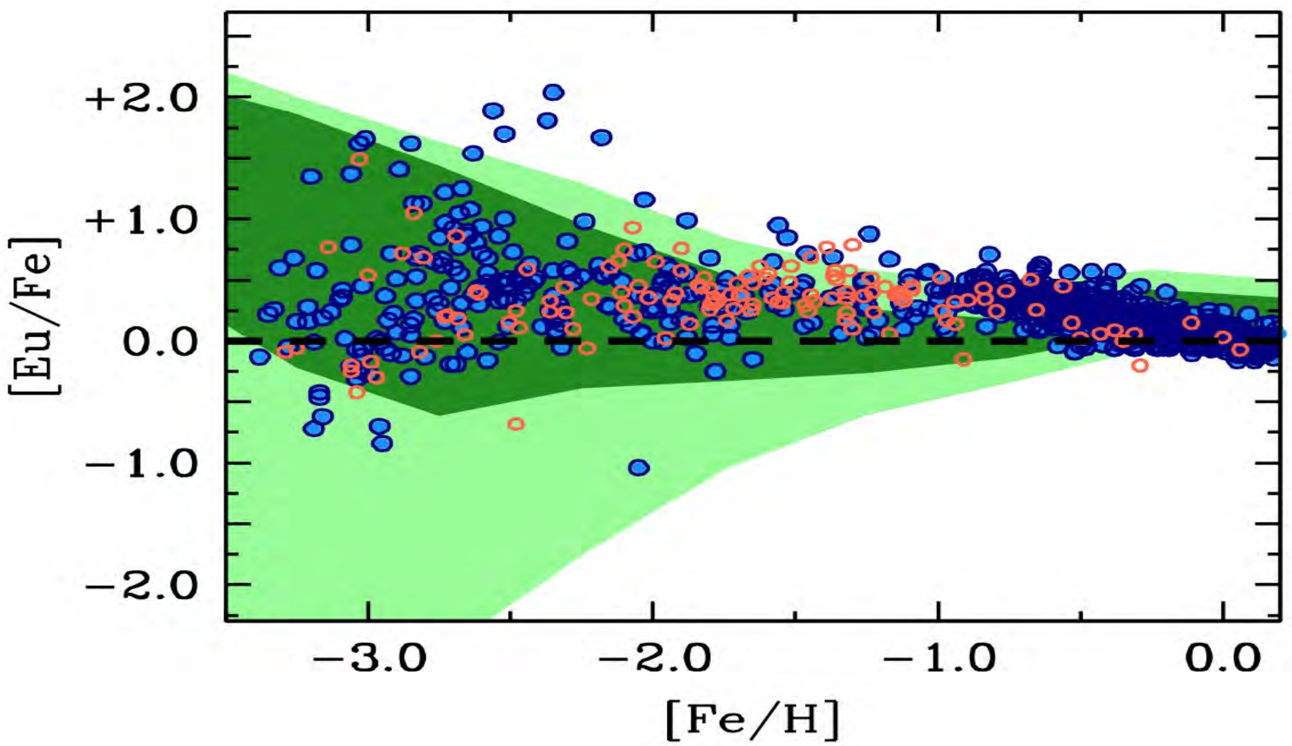
~ average ISM abundances

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



Mathews & Cowan 90

Neutron Star Mergers only

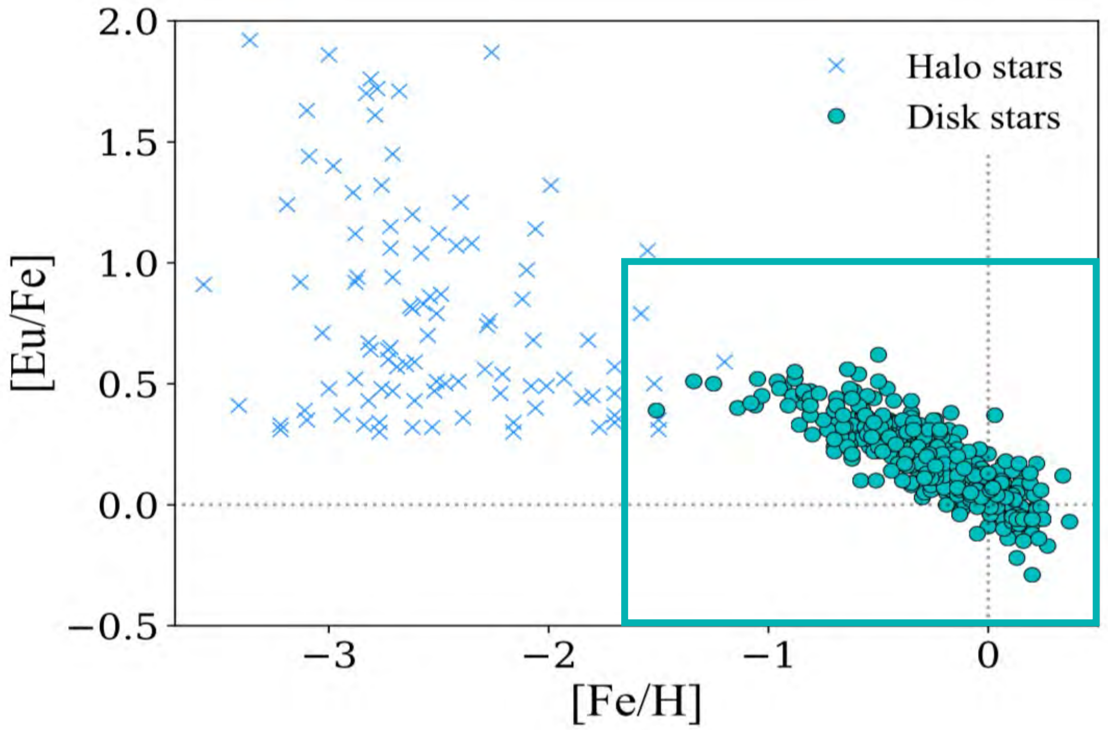


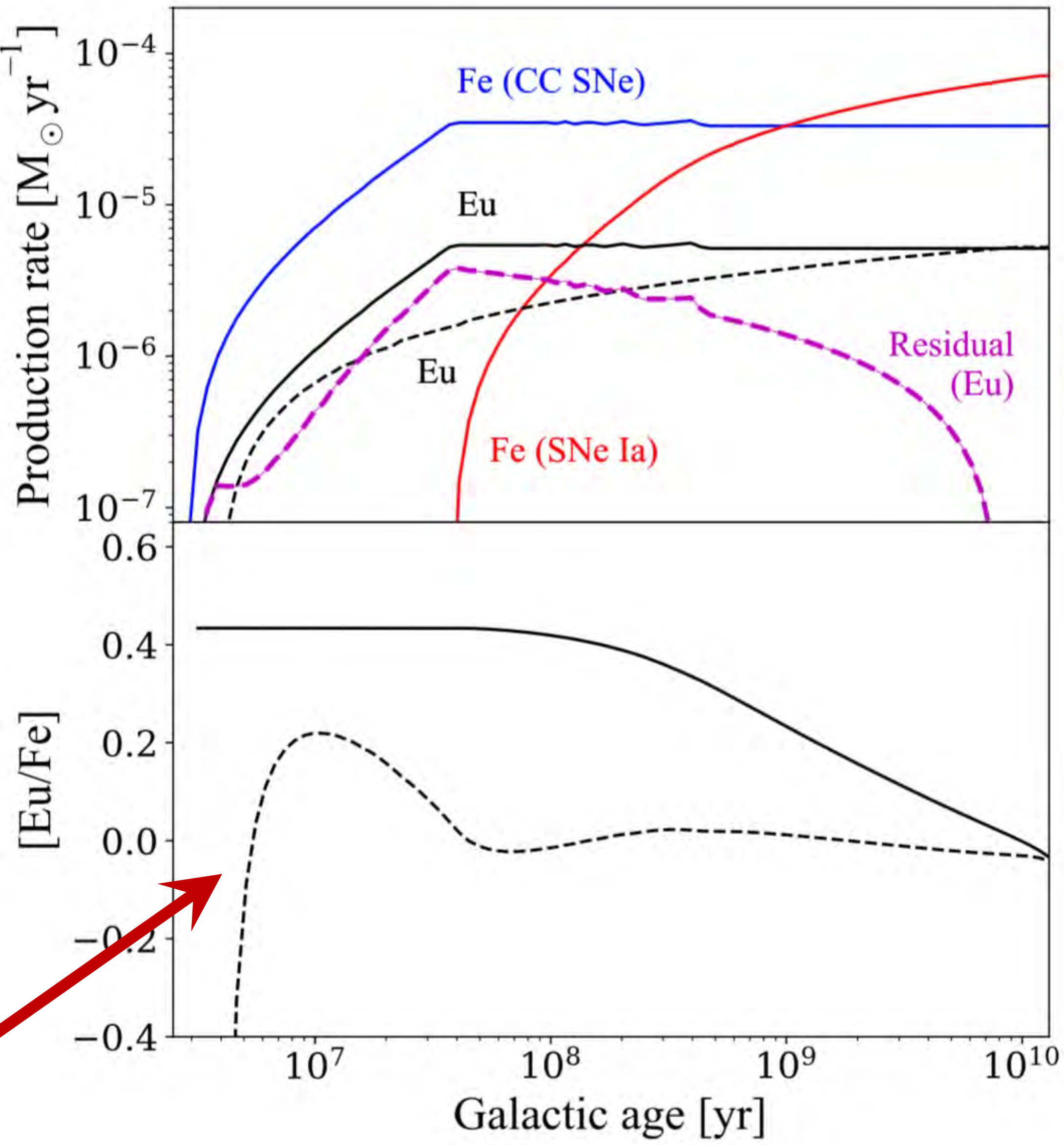
Shen+15

*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