Nuclear Astrophysics: Lecture 2

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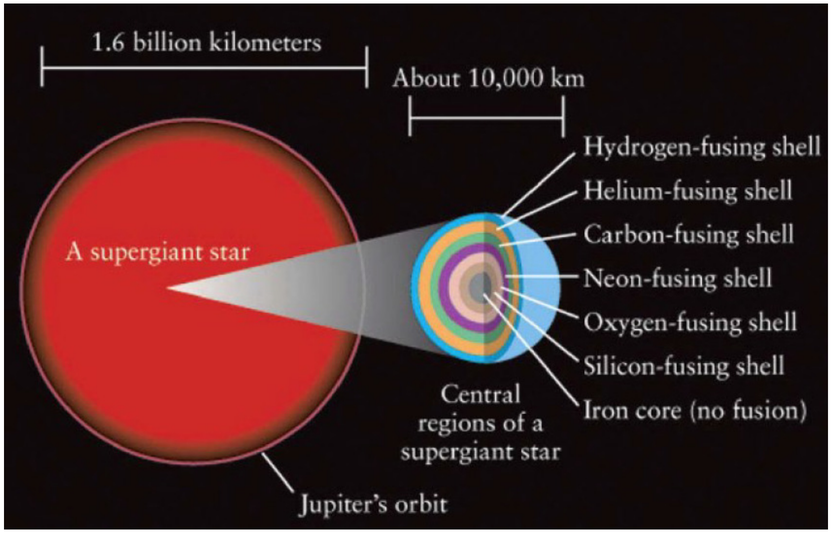
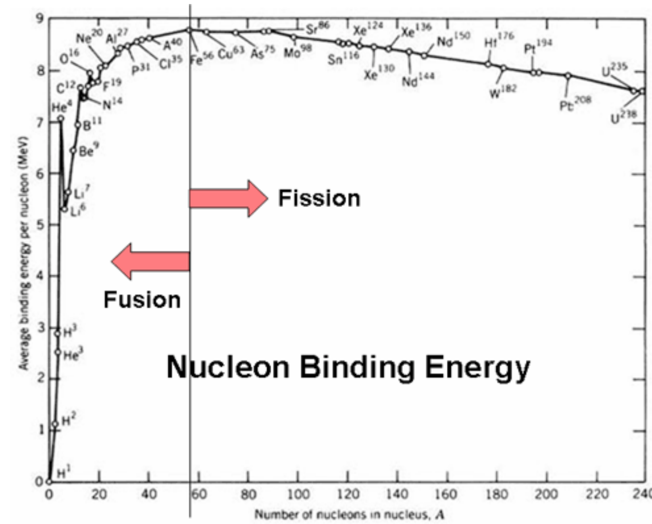
Lecture plan

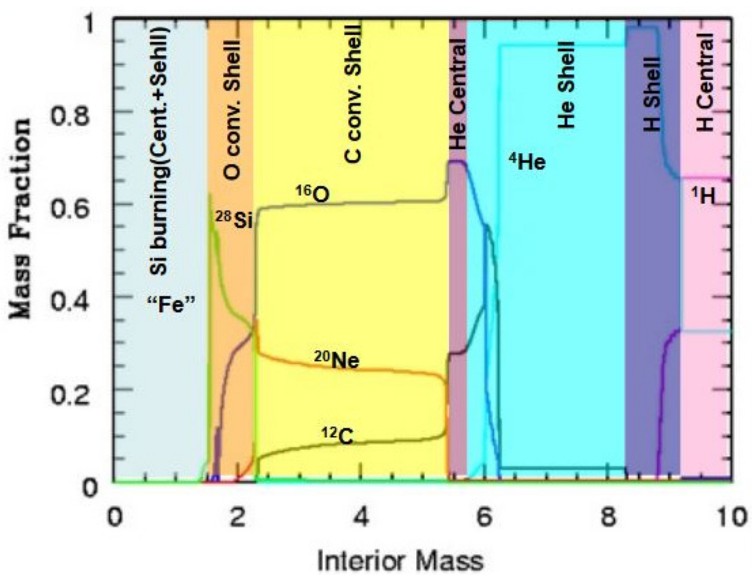
- Lecture 1
  - Solar system abundances
  - A tiny little bit of BBN
  - Hydrostatic nuclear burning
  - Thermonuclear reaction rates

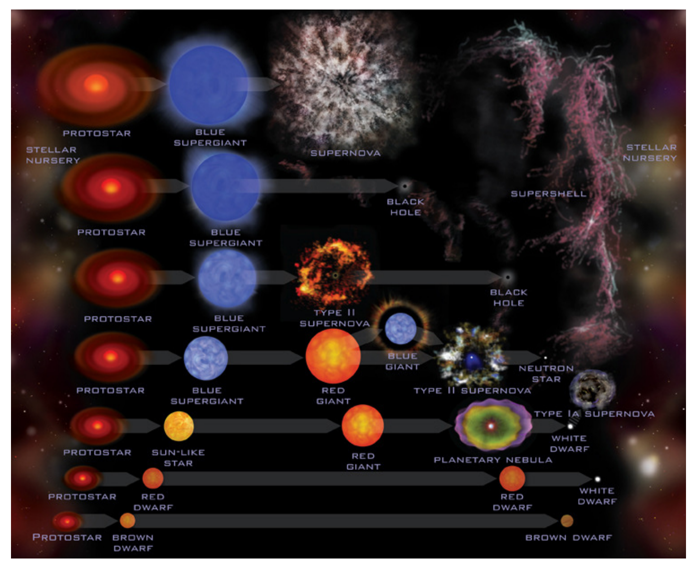
- Lecture 2
  - Supernovae
  - Explosive nuclear burning
  - Heavy element synthesis
  - Spectroscopy and metal-poor stars

Summary from lecture 1

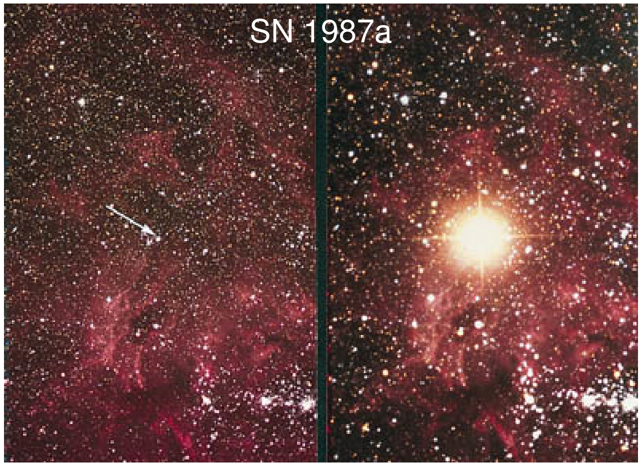


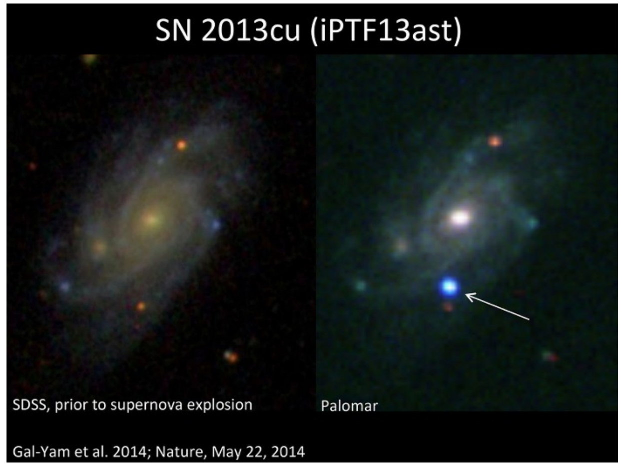


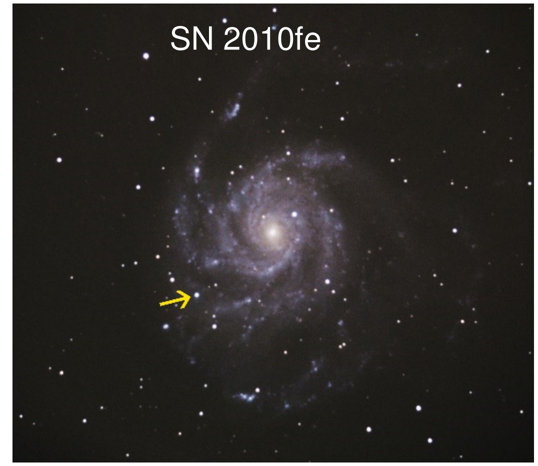


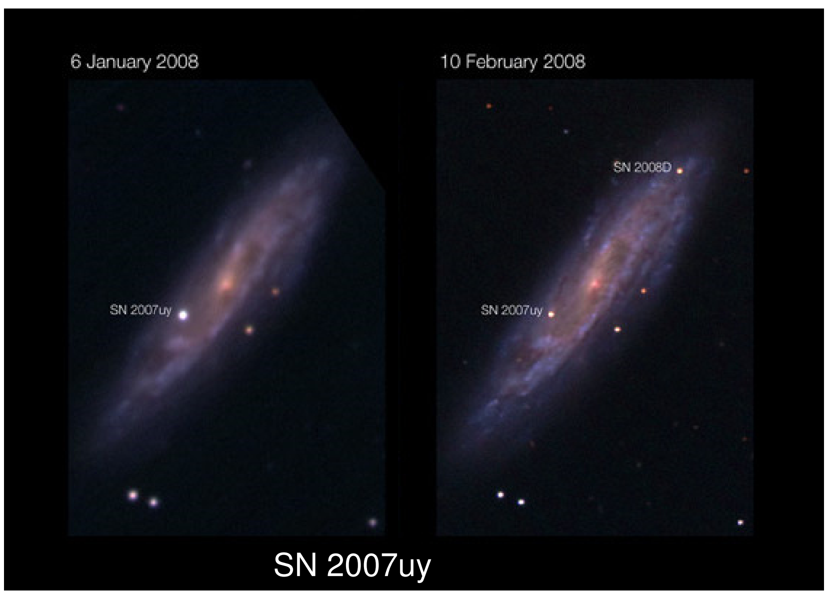


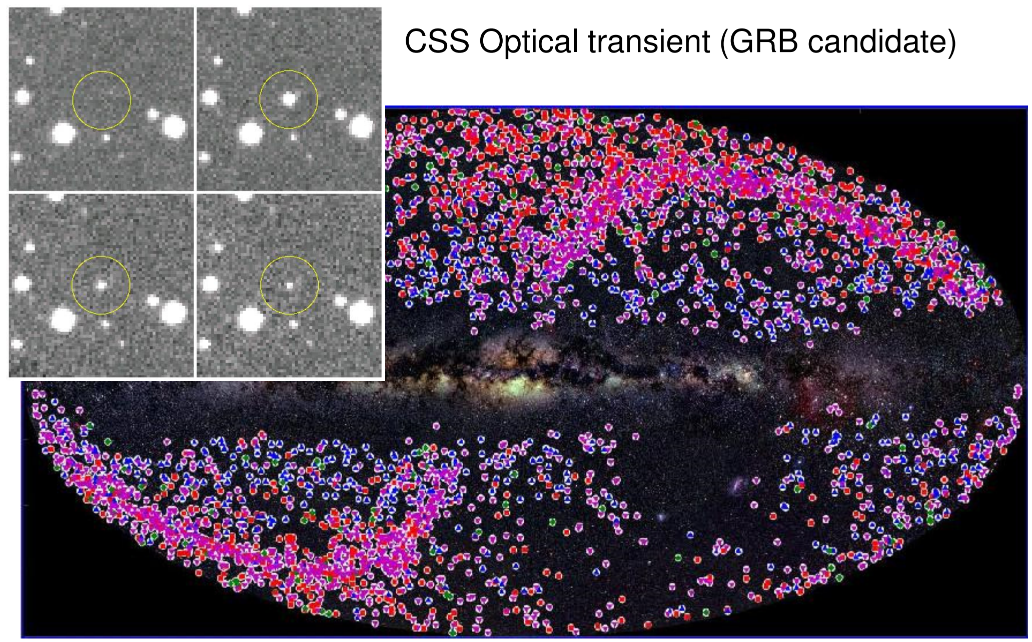
Supernovae









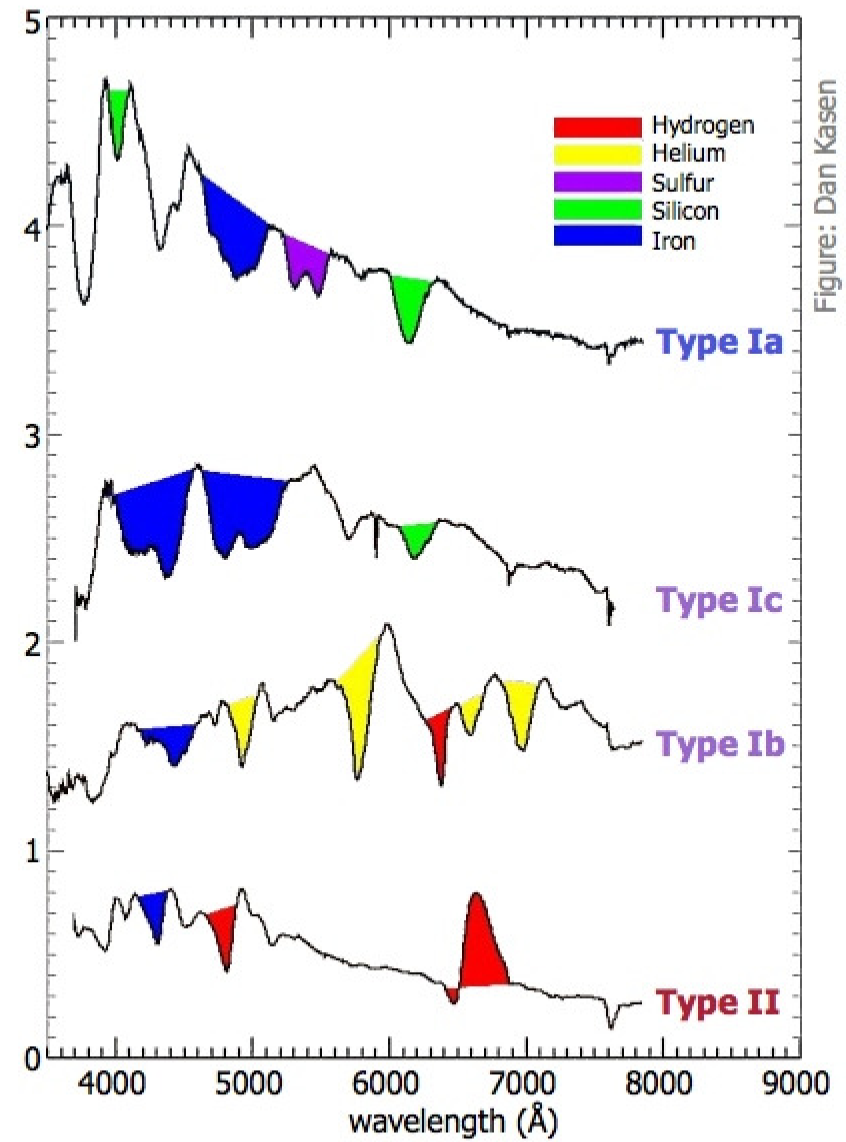


CSS Optical transient (GRB candidate)

Optical transients discovery by CRTS

Supernova Classification

- (Spectral) Appearance
  - Type I
    - Subtypes: a, b, c
  - Type II
- Mechanism:
  - Thermonuclear
  - Core-collapse
- Brightness
  - “normal”
  - superluminous



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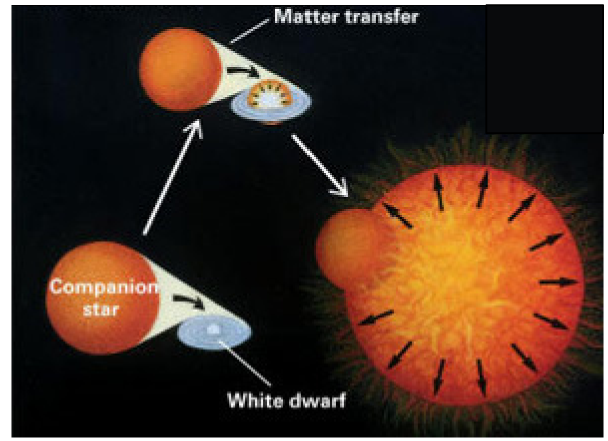
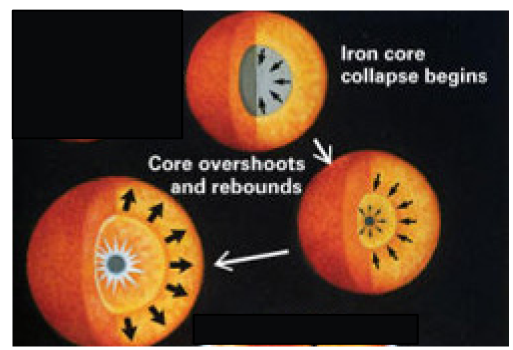
Thermonuclear SN



Core-collapse SN



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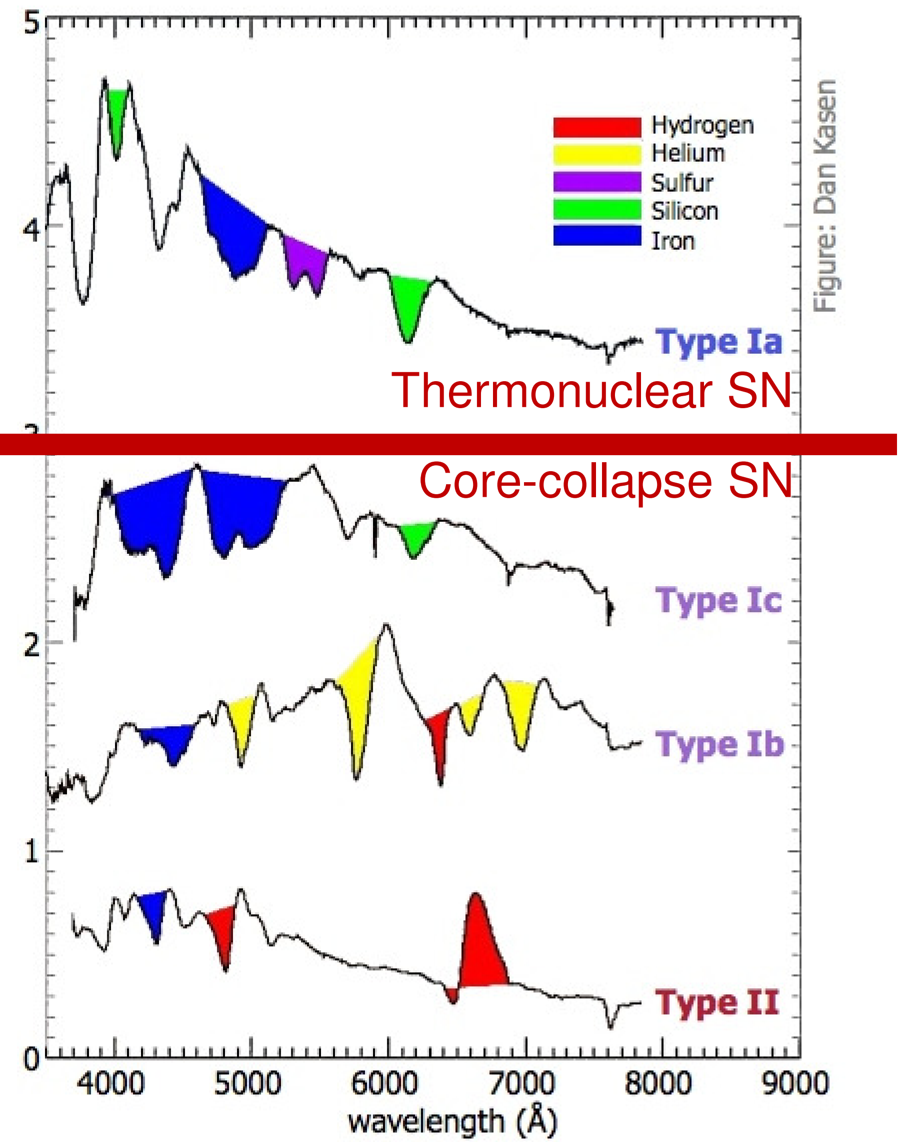

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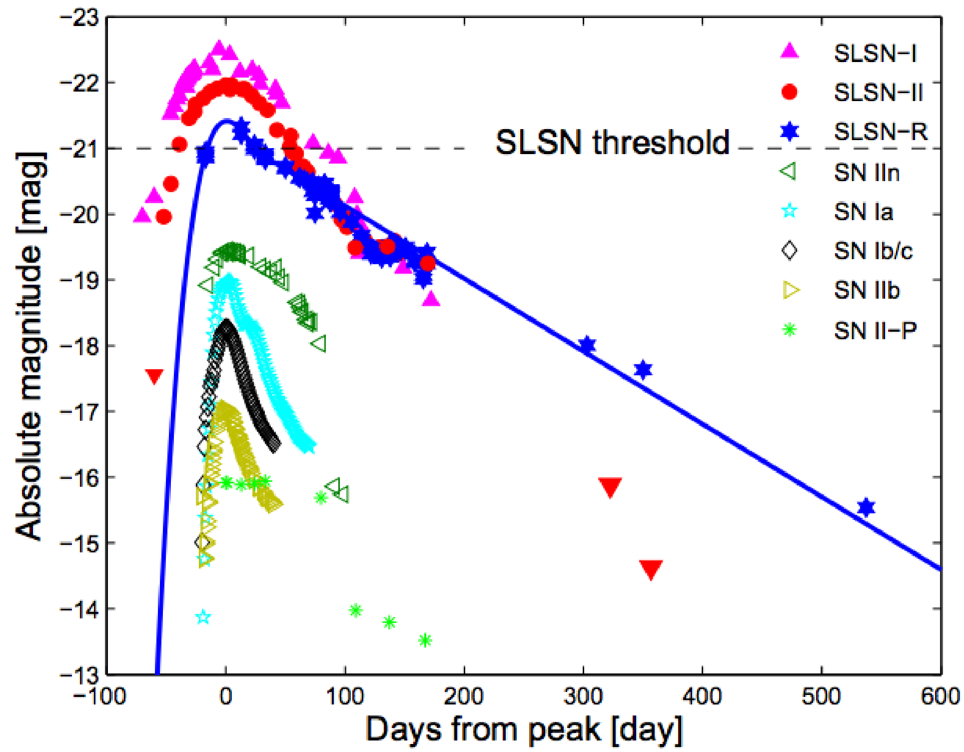
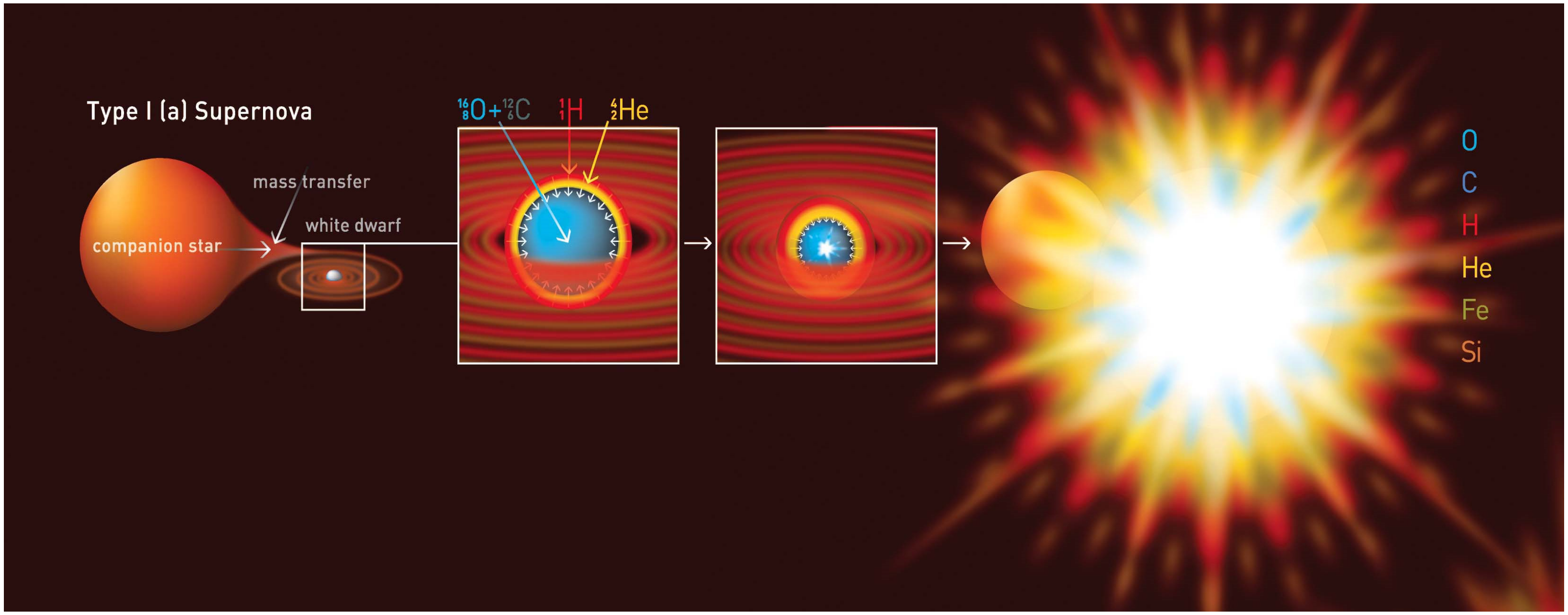
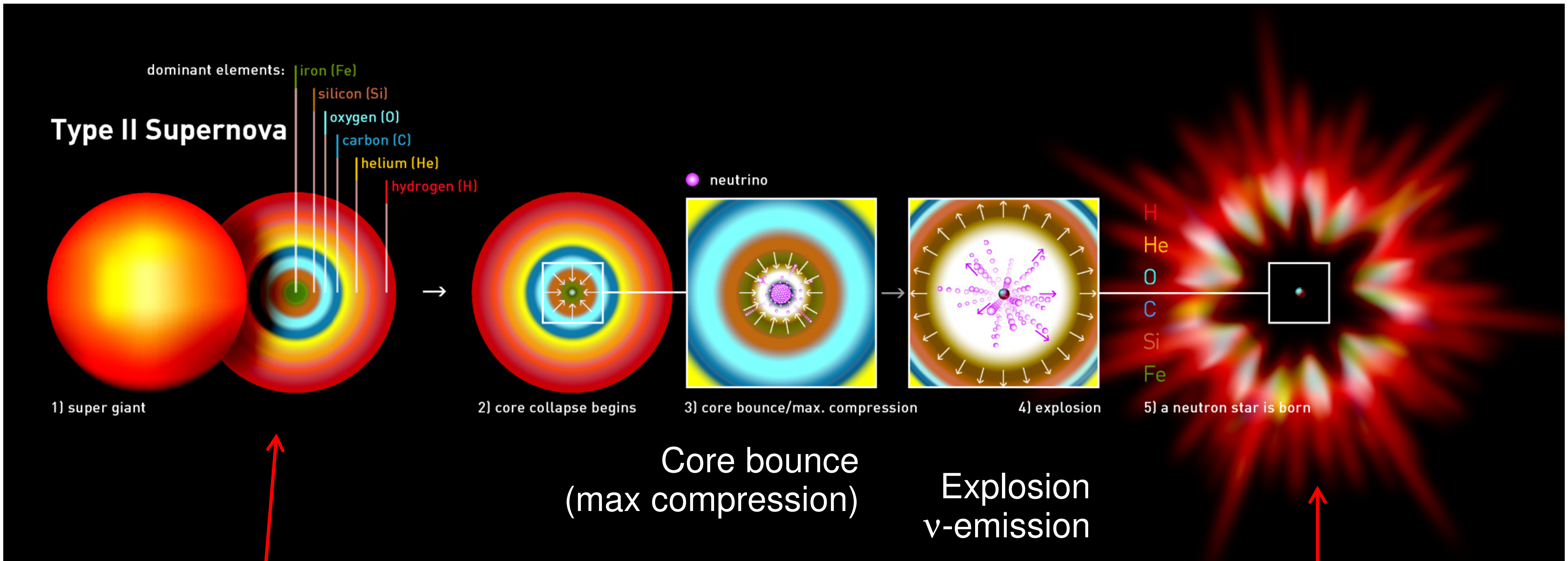


Type Ia supernovae



- White dwarf in a binary system with a …
  - Main-sequence star (single-degenerate scenario)
  - White dwarf (double-degenerate scenario)
- Synthesize mostly iron via explosive burning
  - About 2/3 of total iron is from type Ia SNe

Core-collapse supernovae (CCSNe)



Stellar burning
→ C, O
Weak s-process
→ heavy elements

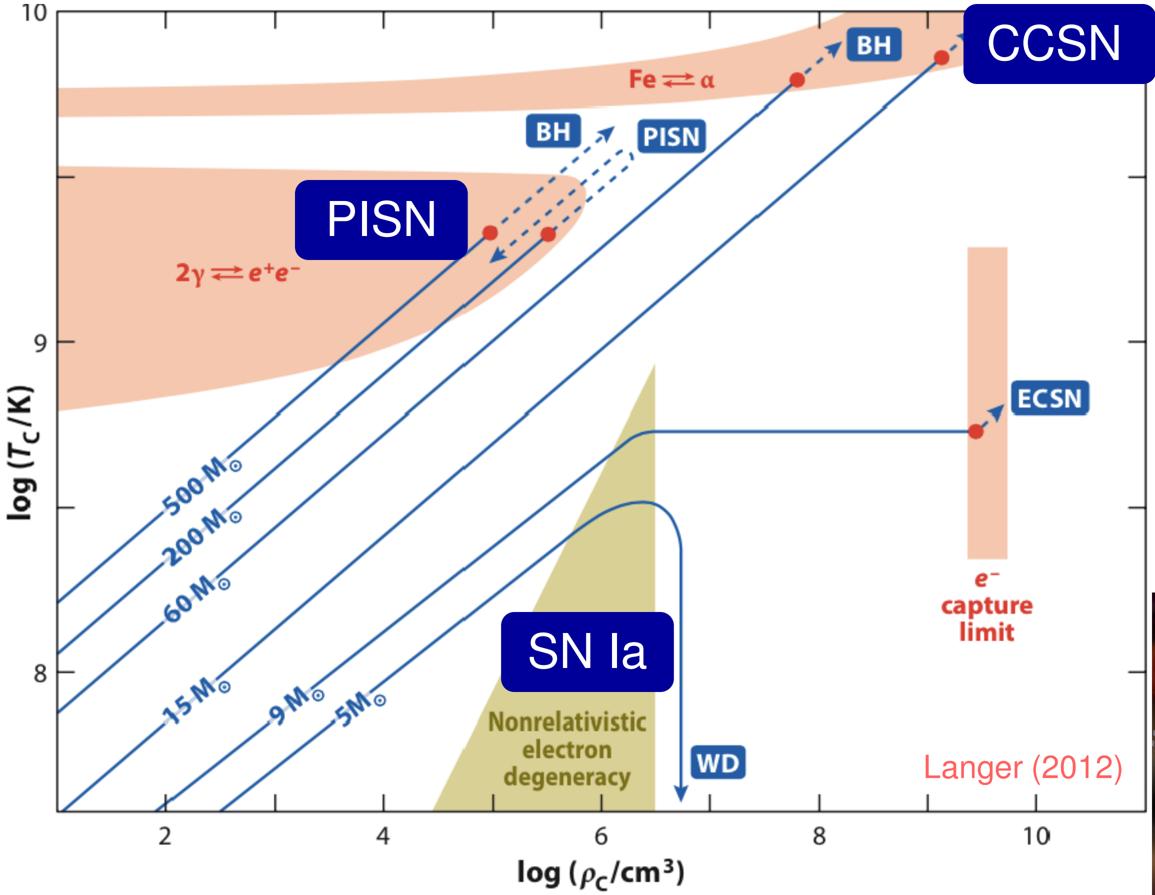
Explosion mechanism still not fully understood

Explosive burning
→ Si, S, Ca, Fe, Ni, Zn
νp-process
→ Sr, Y, Zr + Mo, Ru
r-process ???
γ-process
→ p-nuclides

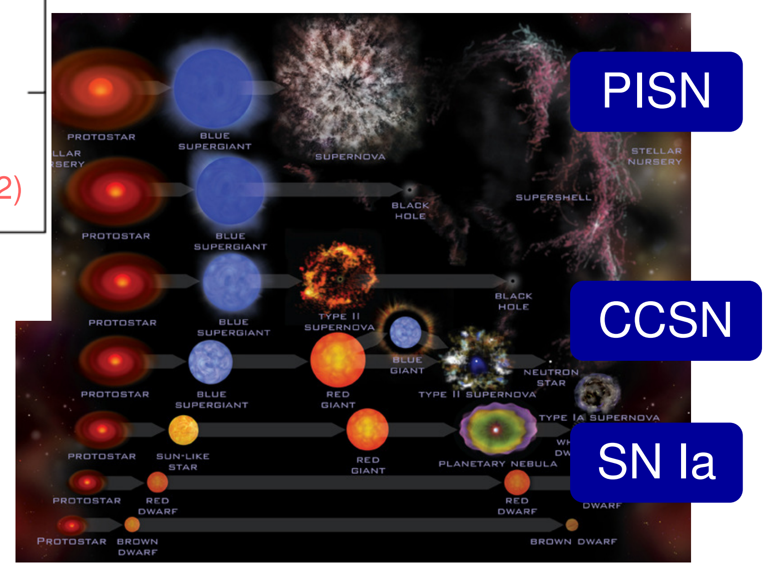
Pair-instability supernovae (PISNe)

- Also called: Pair-creation supernovae
- Very massive stars (>100 Msun)
- Oxygen-core becomes unstable via $2\gamma \rightarrow e^{+} + e^{-}$
  - Remove radiation pressure → core collapses → explosive oxygen burning reverses collapse → explosion

Supernovae

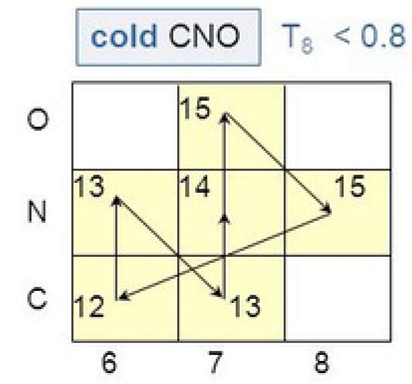


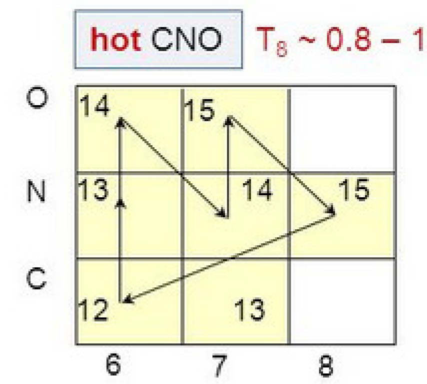
Supernovae happen when evolution reaches region of instability



Explosive nuclear burning

- Similar to hydrostatic burning, but
  - Shorter timescales
  - Higher temperatures
- H-burning:
  - Hot CNO-cycle (pp-chains are too slow), where $^{13}N(\beta)$ becomes $^{13}N(p,\gamma)$
- He-burning:
  - N-rich isotopes ^{15}O, ^{18}O, ^{19}F, ^{21}Ne
- C- and Ne-burning:
  - Simultaneously occurring

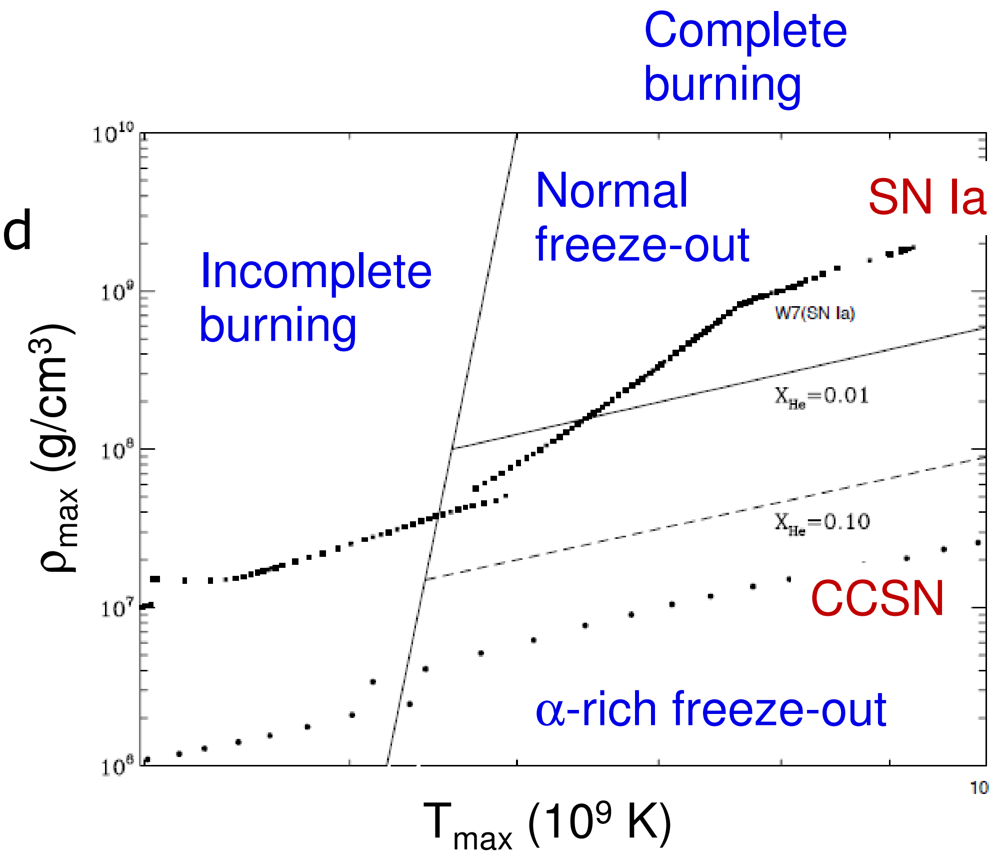




Explosive burning

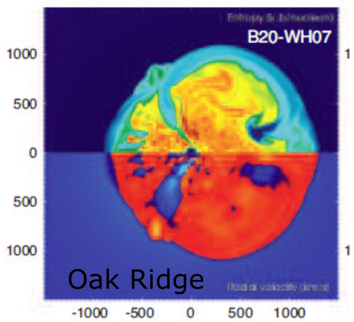
- O-burning:
  - Quasi-equilibrium (regions of equilibrium, connected by individual reactions)

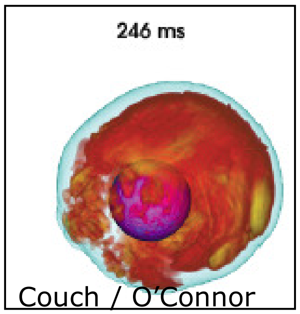
- Si-burning:
  - Details depend on peak temperature and peak density:

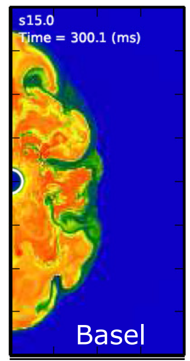


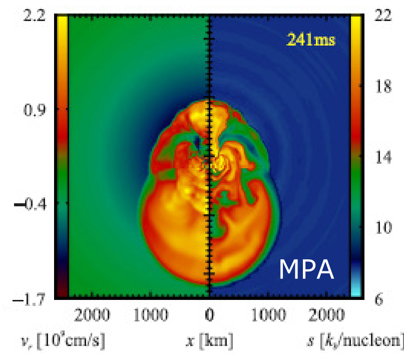
CCSN nucleosynthesis

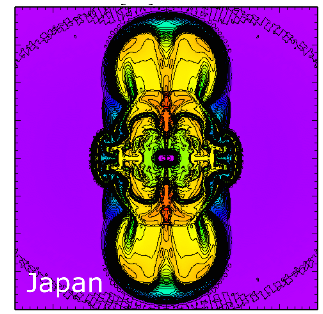
Simulations (computationally very expensive; not fully converged yet in outcome):





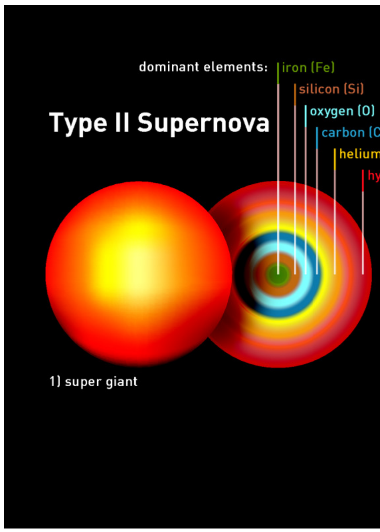






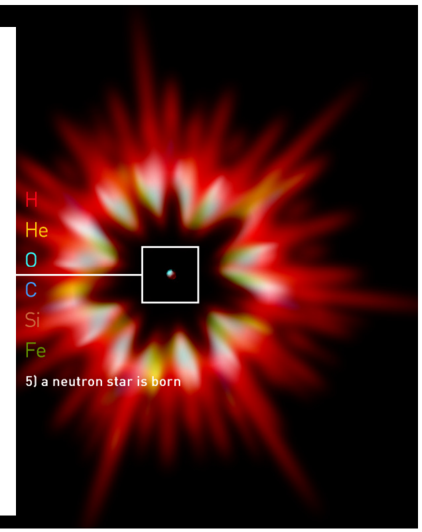
+ many more!

Textbook:



Reality:

- We observe stars and SNe
- We still do not fully understand the explosion mechanism despite 60+ years of research

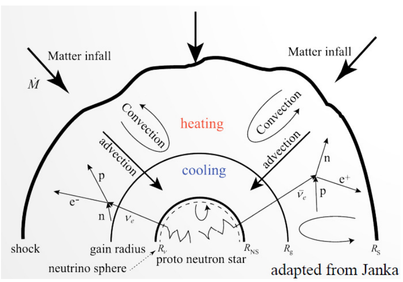


Practical approach:

- Add energy to pre-collapse star to trigger explosion (piston, thermal bomb, neutrinos)
- But: Ignores some physics (collapse, bounce, neutrinos, NS/BH formation, etc)

Modelling of CCSN nucleosynthesis

- Piston / thermal bomb — Woosley&Weaver 95, Rauscher+02; Thielemann+96, Limongi & Chieffi 06, Umeda&Nomoto 08
- Neutrinos methods
  - Light bulb — Iwakami+09, Yamamoto+13
  - Modified neutrino reactions — Frohlich+06, Fischer+10
  - Parameterized PNS contraction — Ugliano+12, Ertl+15, Sukhbold+16
  - **PUSH method** — Perego, Hempel, CF, Ebinger, et al 2015)
    → Based on neutrino-driven mechanism
    (use neutrinos to obtain explosion)
    → Preserve Ye evolution
    (no modification of ν_e-transport)
    → Nuclear EOS and PNS evolution included

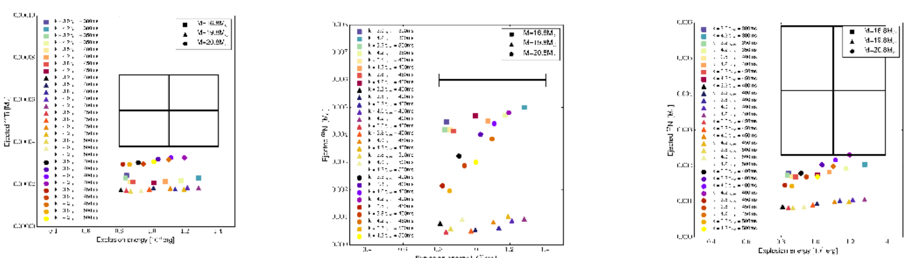


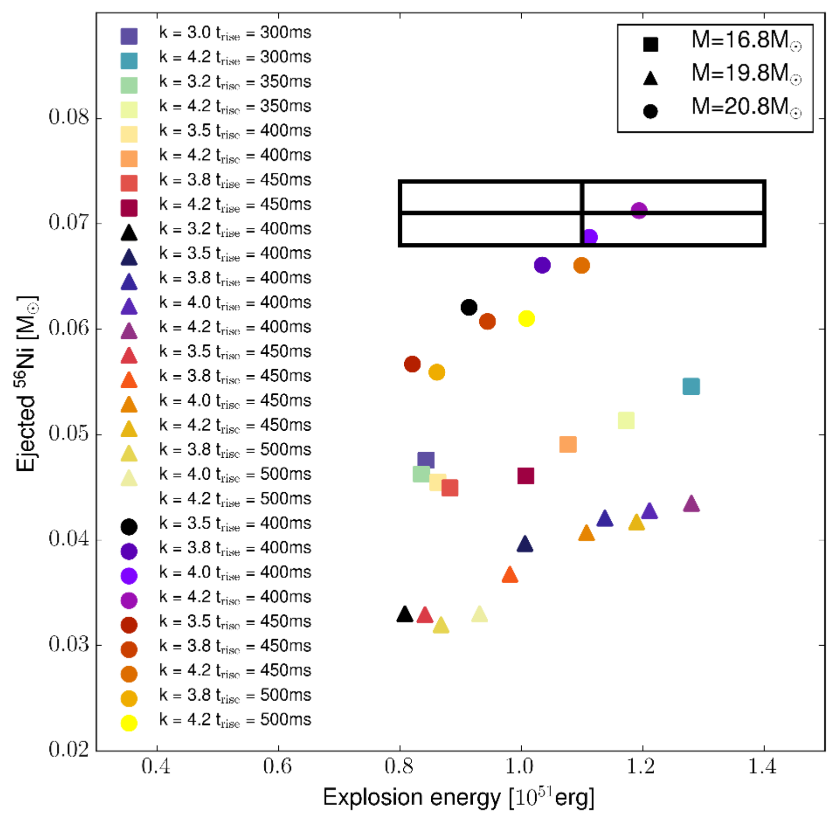
Results using the PUSH method

- Calibrated against SN 1987A
  - Progenitor mass, explosion energy, Ni and Ti ejecta

E_{expl}	$(1.1 \pm 0.3) \times 10^{51}$ erg
m_{prog}	18-21$M_\odot$
$m(^{56}Ni)$	(0.071 ± 0.003) $M_\odot$
$m(^{57}Ni)$	(0.0041 ± 0.0018) $M_\odot$
$m(^{58}Ni)$	0.006 $M_\odot$
$m(^{44}Ti)$	$(0.55 \pm 0.17) \times 10^{-4}$ $M_\odot$

Seitenzahl+ 14, Fransson & Kozma 02, Blinnikov+ 00

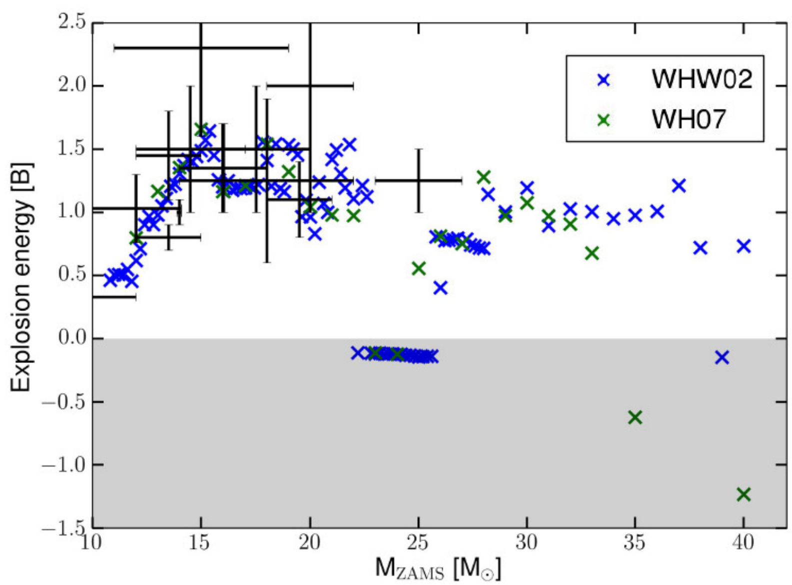


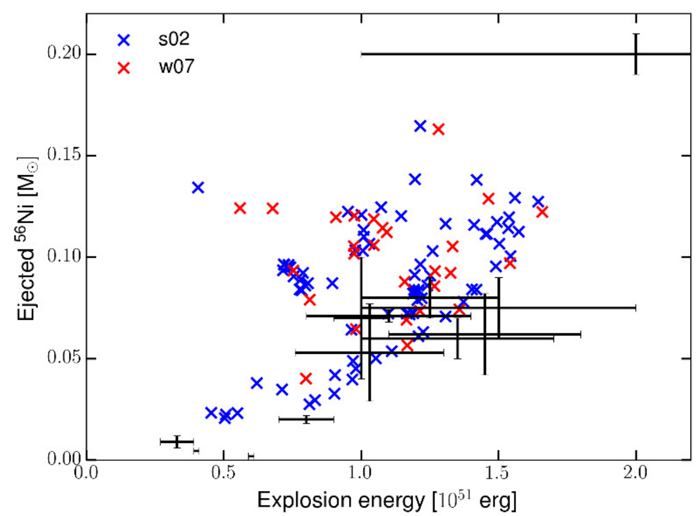


Ebinger+ (in prep)

Results using the PUSH method

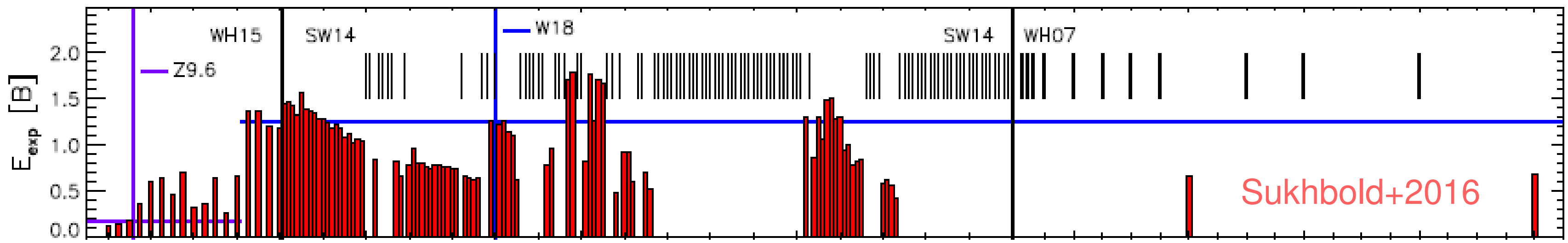
- Calibrated against SN 1987A
  - Progenitor mass, explosion energy, Ni and Ti ejecta
- Applied to models from 11 Msun to 40 Msun
  - Predict some explosions and some BHs

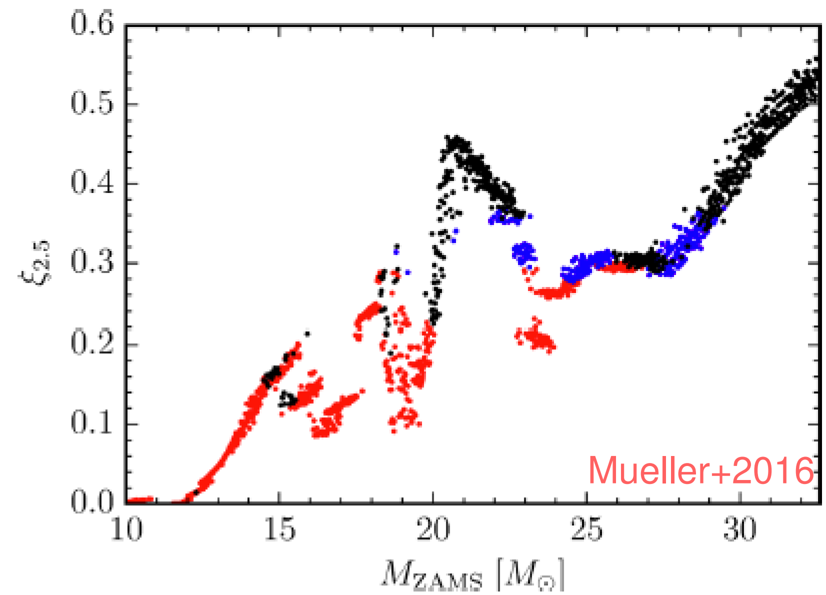


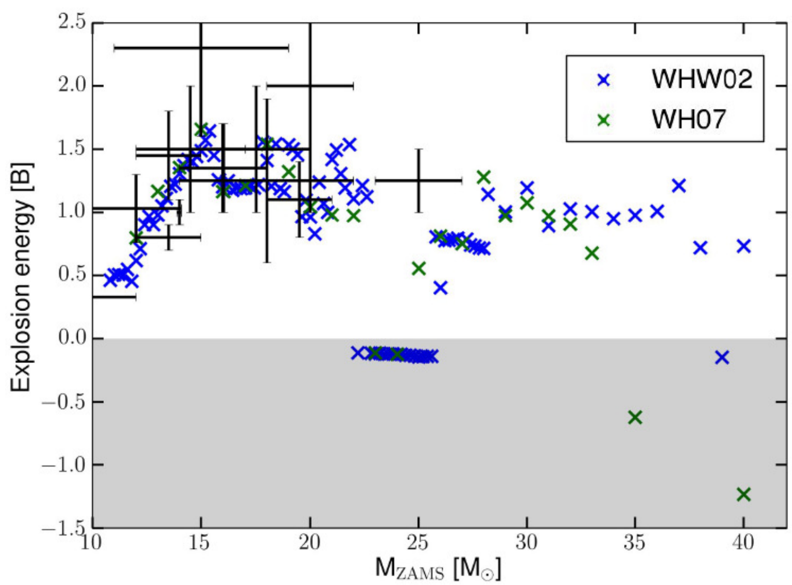


Ebinger+ (in prep)

Comparison to other methods







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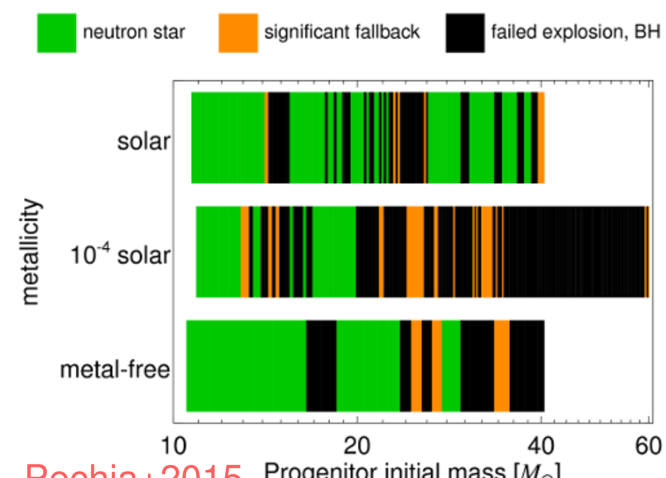


Pechja+2015

Results using the PUSH method

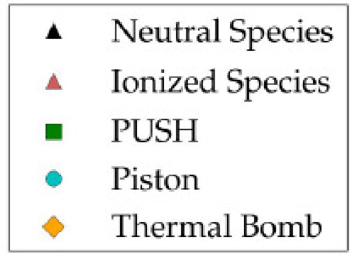
- Calibrated against SN 1987A
  - Progenitor mass, explosion energy, Ni and Ti ejecta

- Applied to models from 11 Msun to 40 Msun
  - Predict some explosions and some BHs

- Nucleosynthesis predictions
  - Better match to observations than piston models

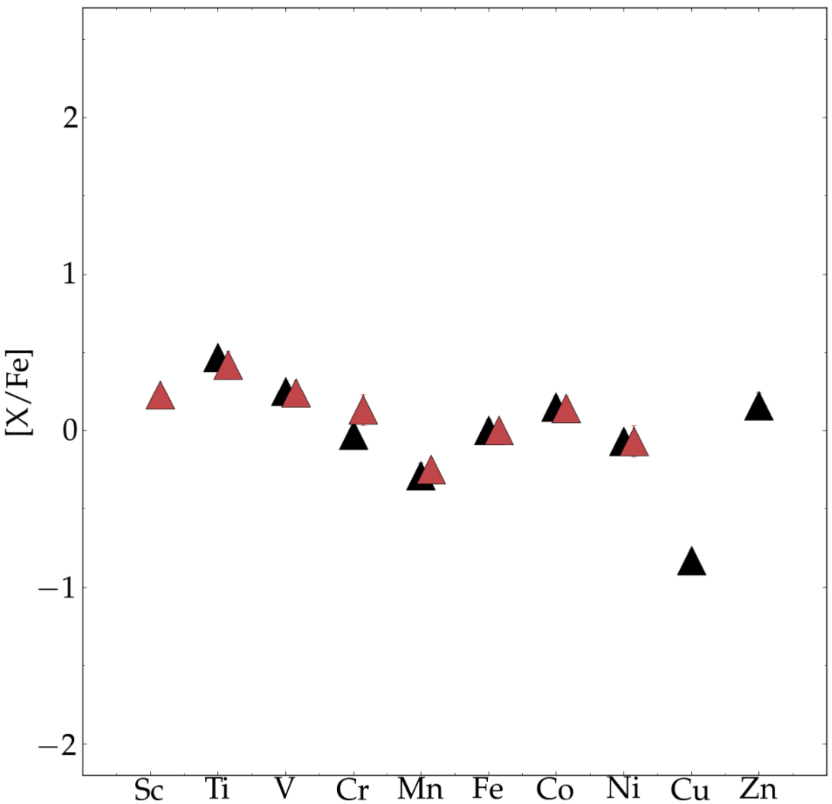
Metal-poor star HD 84937

$$\left[\frac{X}{X_{\mathrm{Fe}}}\right] = \log\left(\frac{X}{X_{\mathrm{Fe}}}\right) - \log\left(\frac{X}{X_{\mathrm{Fe}}}\right)_{\odot}$$



Sneden+16

Sanjana+ (in prep)



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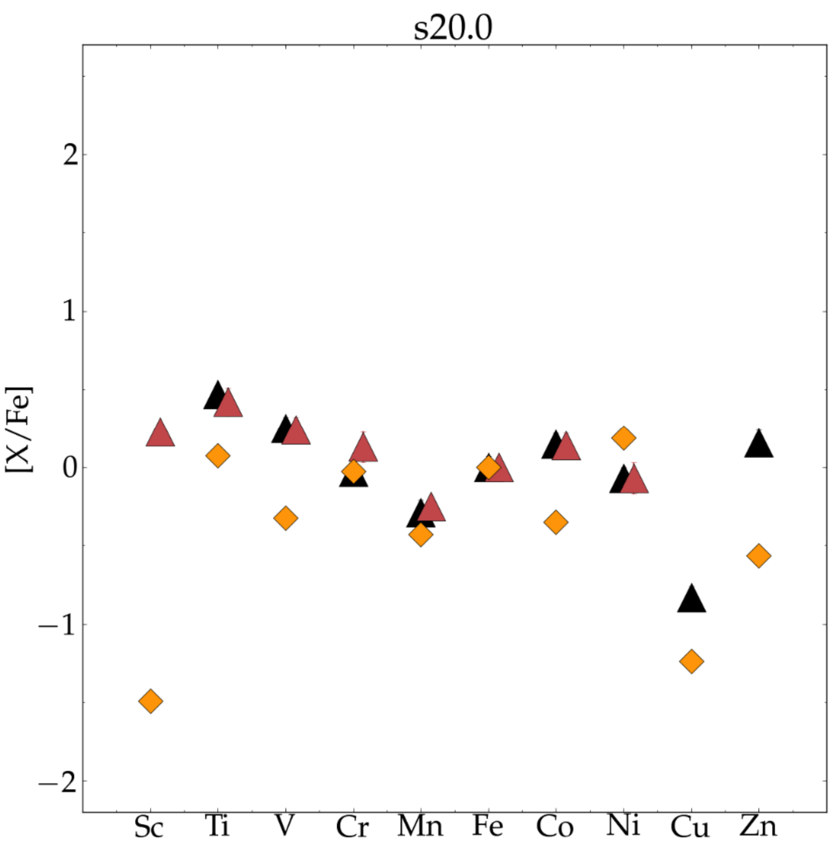
Neutral Species
Ionized Species
PUSH
Piston
Thermal Bomb

Sneden+16

Sanjana+ (in prep)



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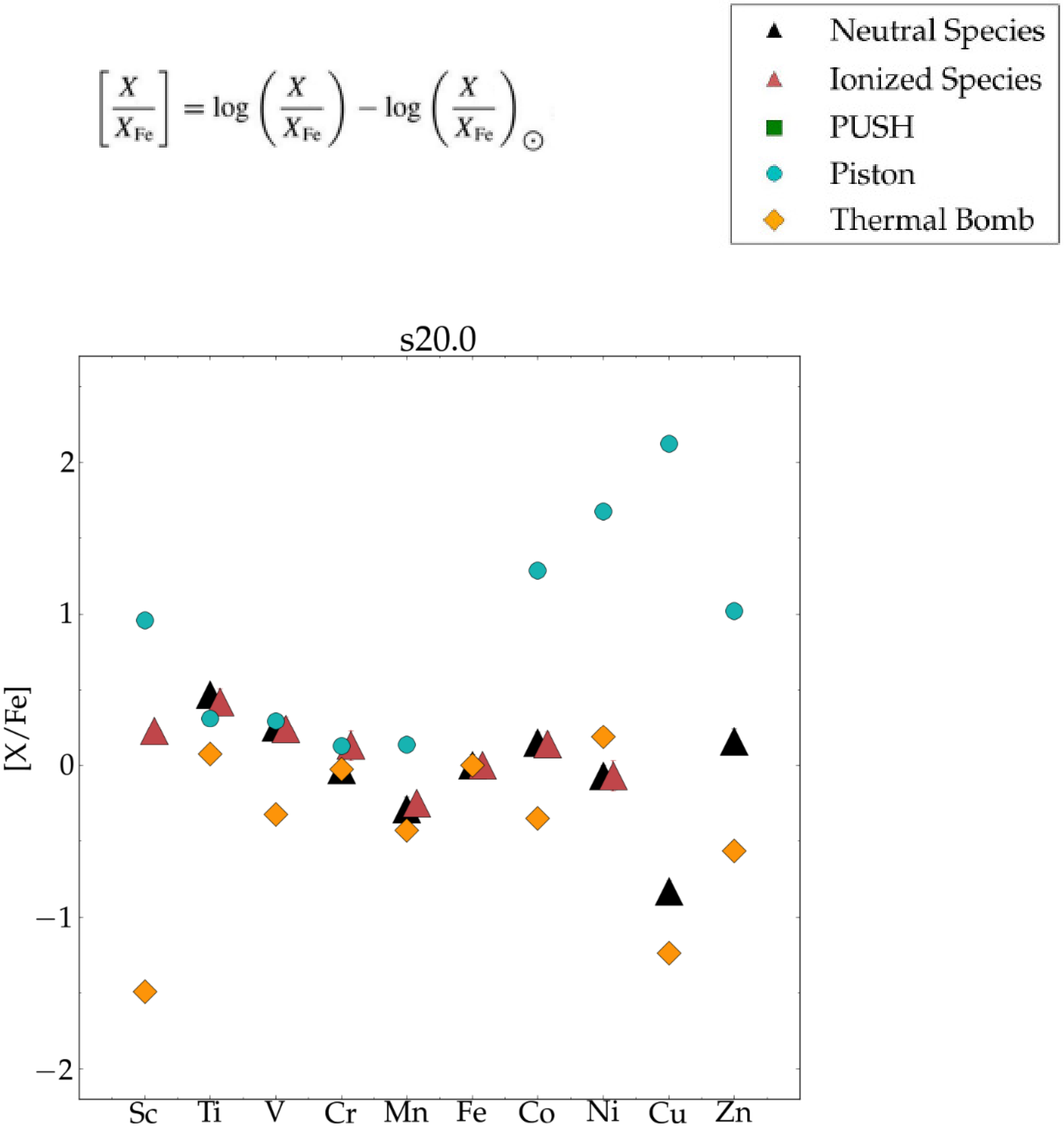

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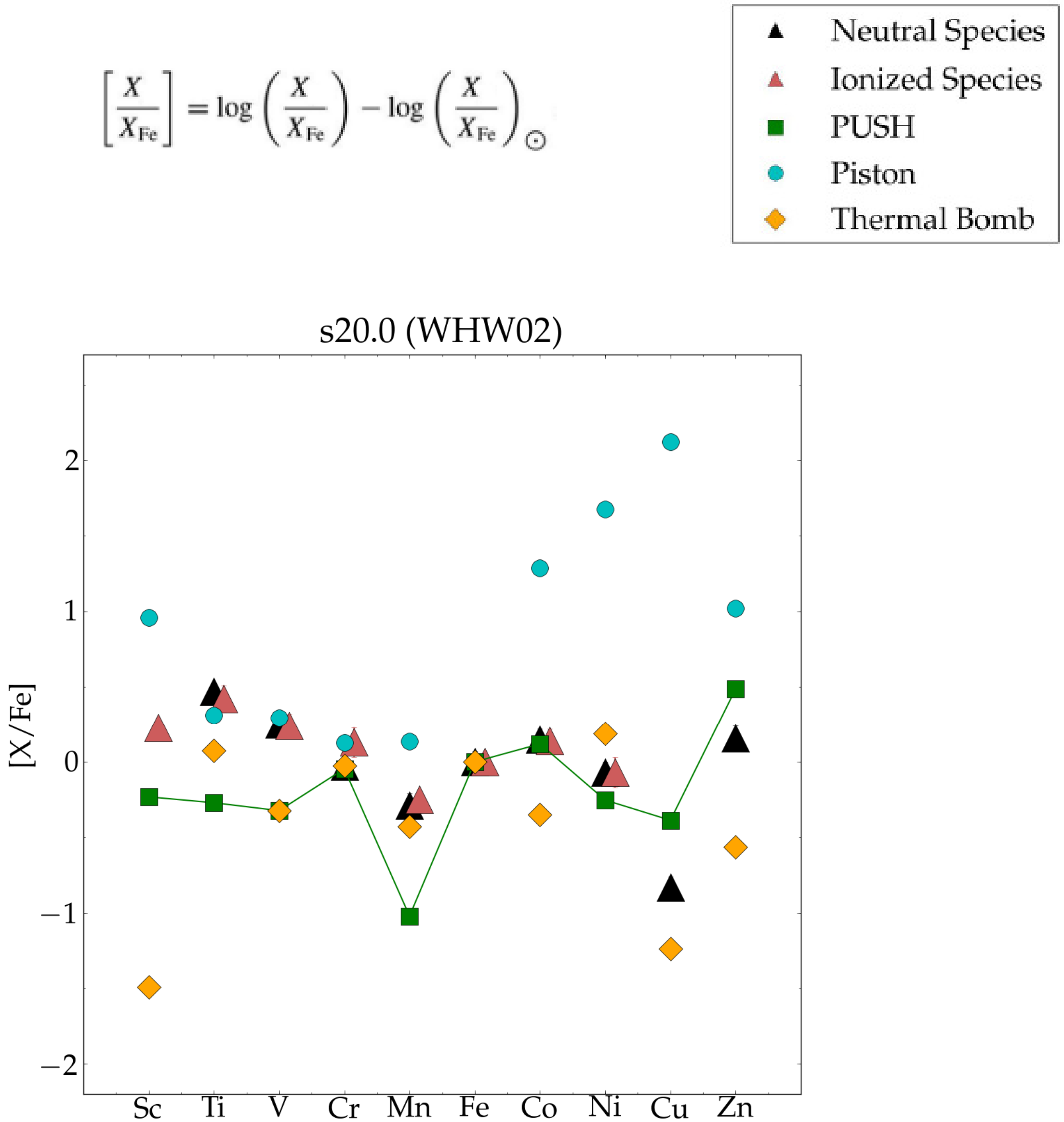

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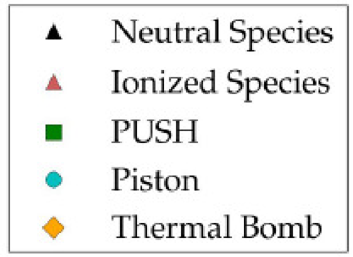

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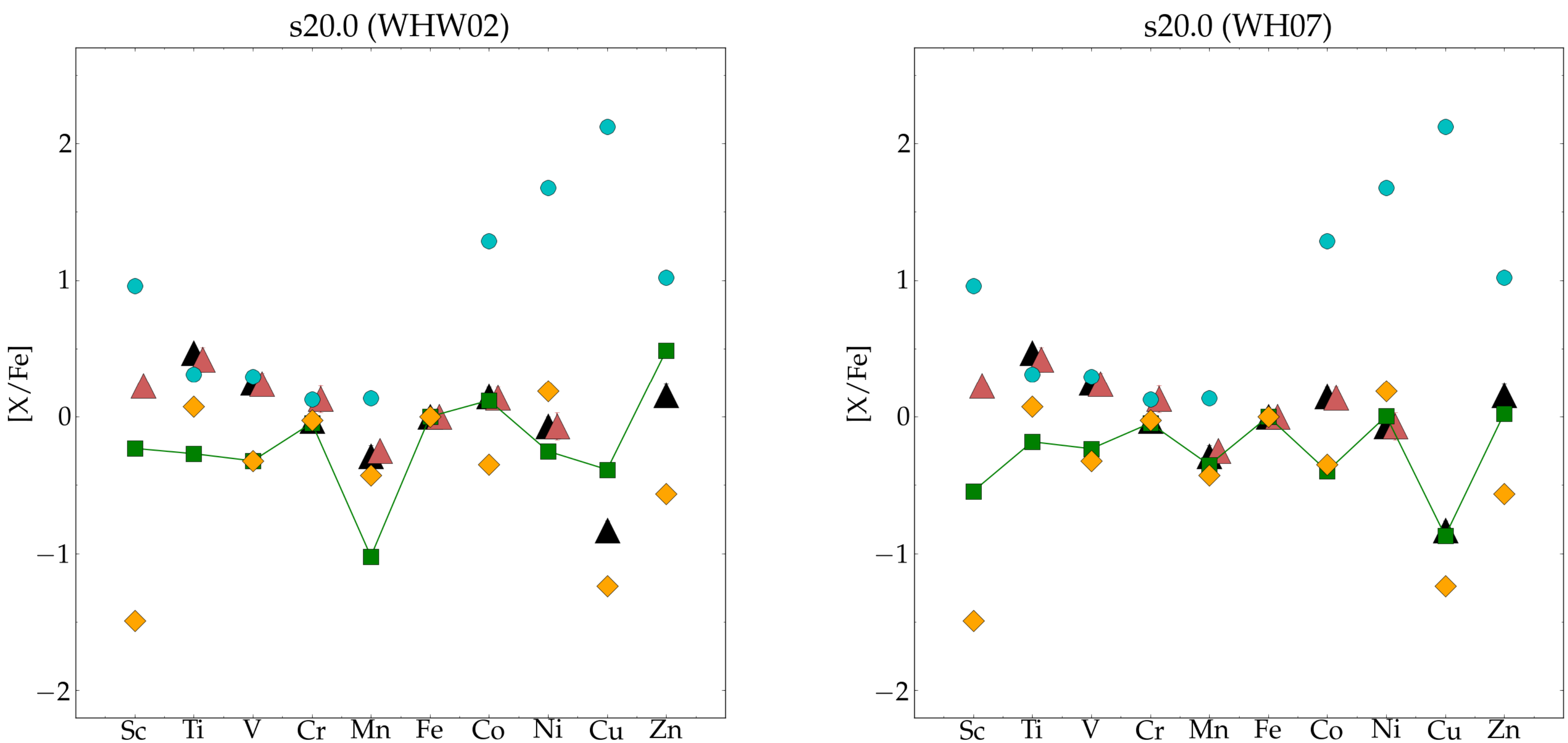
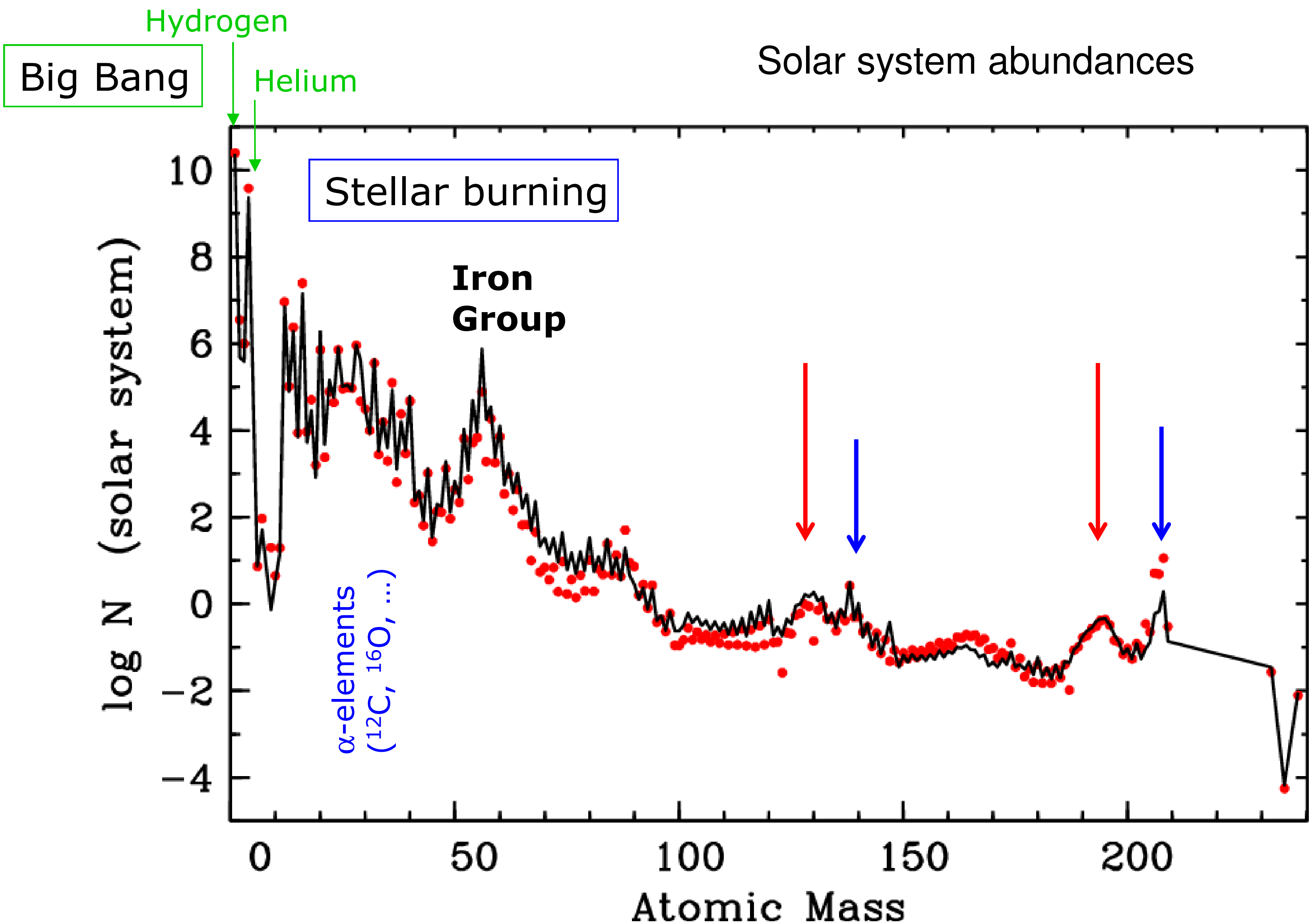
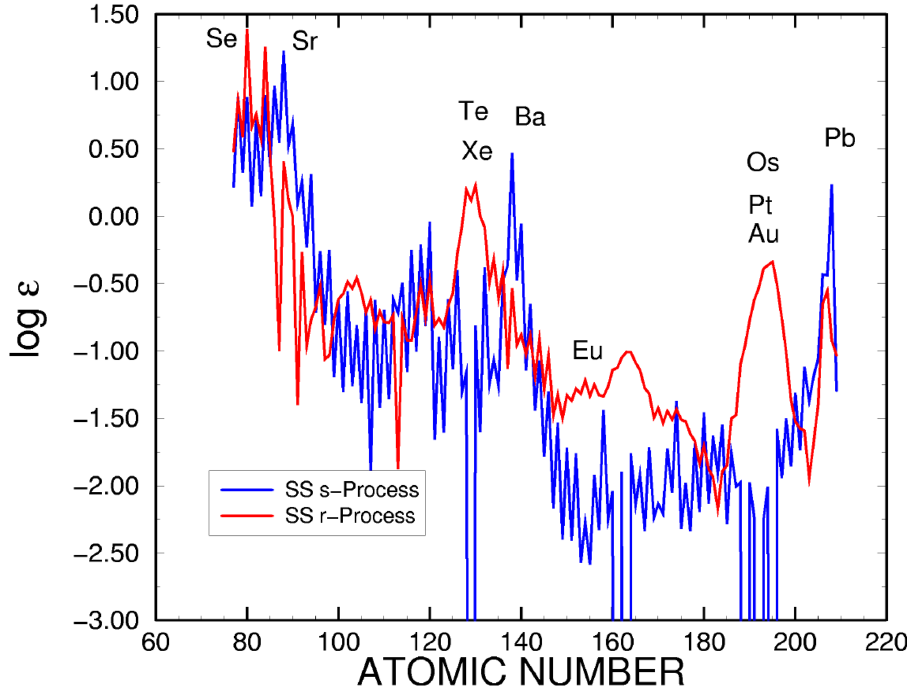


Origin of elements



Neutron-capture processes



heavy elements are made by

slow ($\tau_\beta/\tau_n<1$)

and

fast ($\tau_\beta/\tau_n>1$)

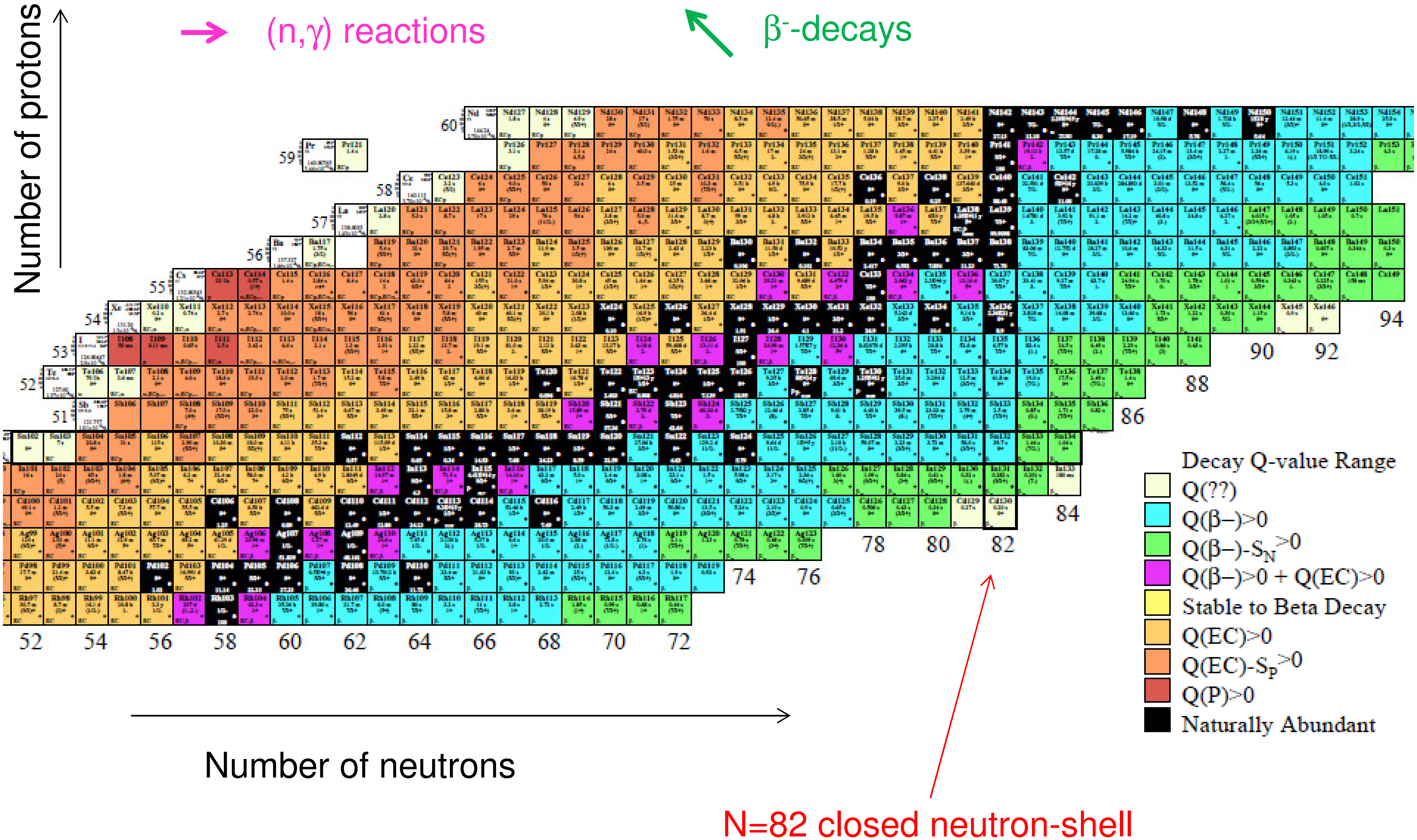
neutron-capture events

- Sequences of (n,γ) reactions and β^-decays

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

Neutron-capture paths



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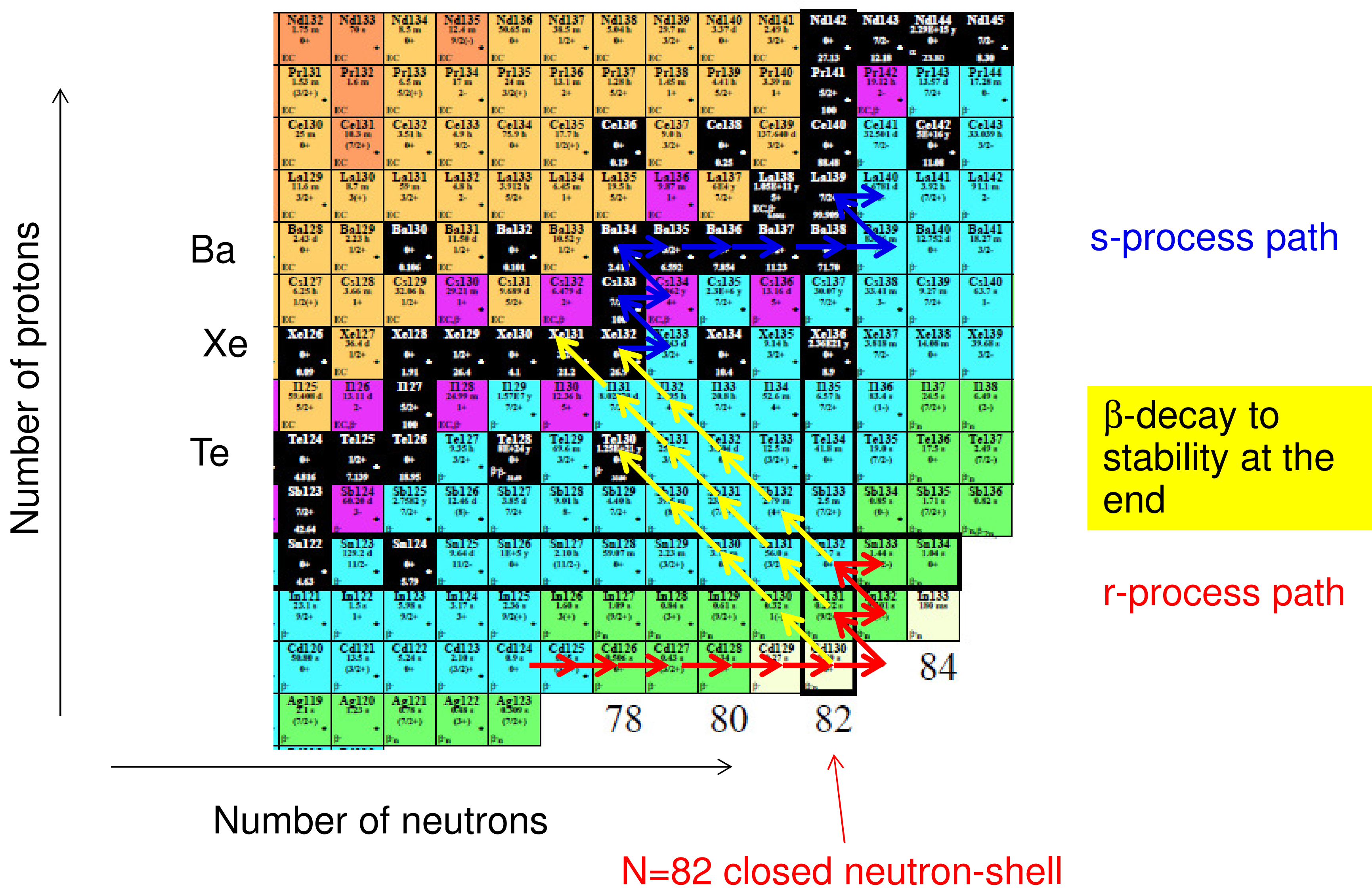
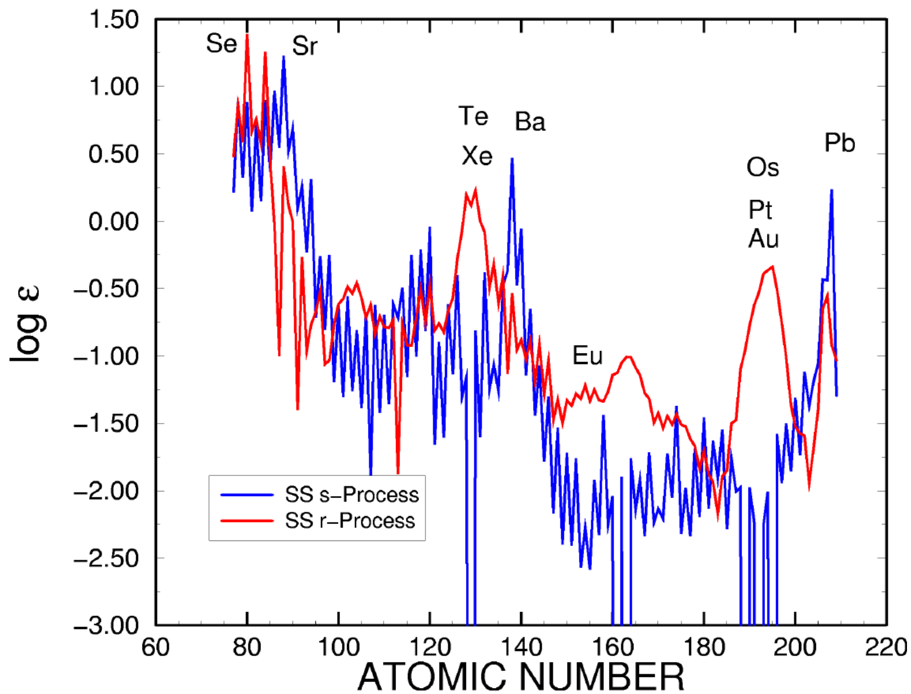


Neutron-capture processes



heavy elements are made by

slow ($\tau_\beta/\tau_n<1$)

and

fast ($\tau_\beta/\tau_n>1$)

neutron-capture events

- Sequences of (n,g) reactions and β^-decays

$$A(Z,N)+n \leftrightarrow A+1(Z,N+1)+\gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1)+e^- + \bar{\nu}_e$$

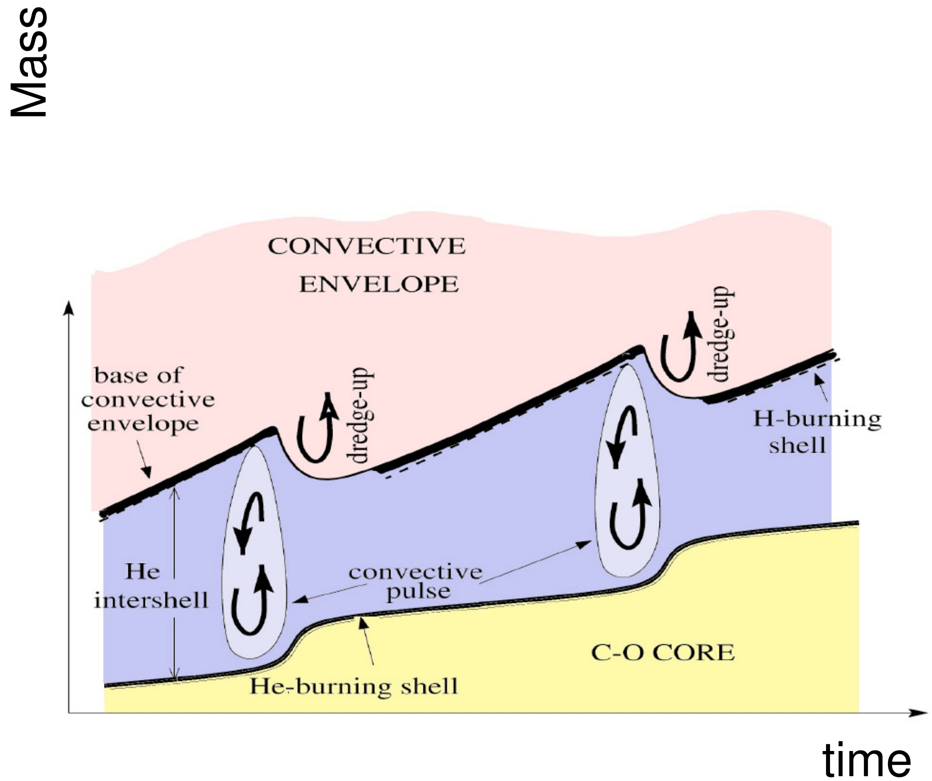
- Closed neutron-shells give rise to the peaks at Te,Xe / Ba and at Os,Pt,Au / Pb

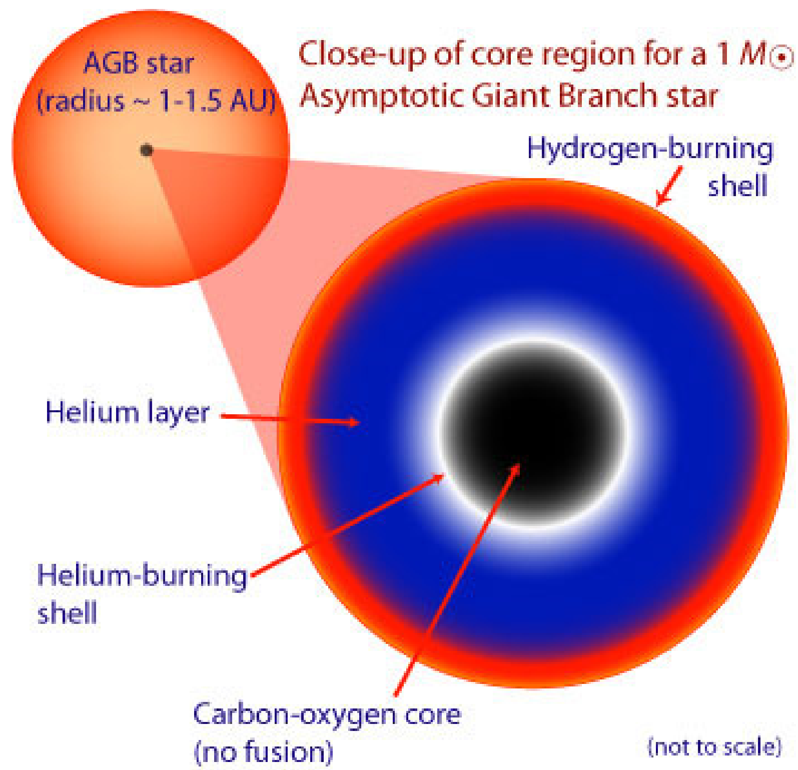
The s-process

- Secondary process
  → neutron captures on pre-existing Fe-group nuclei
- Strong s-process (up to Pb)
  -
- Weak s-process (truncated at Z~60)

The strong s-process

- He-shell flashes in AGB stars



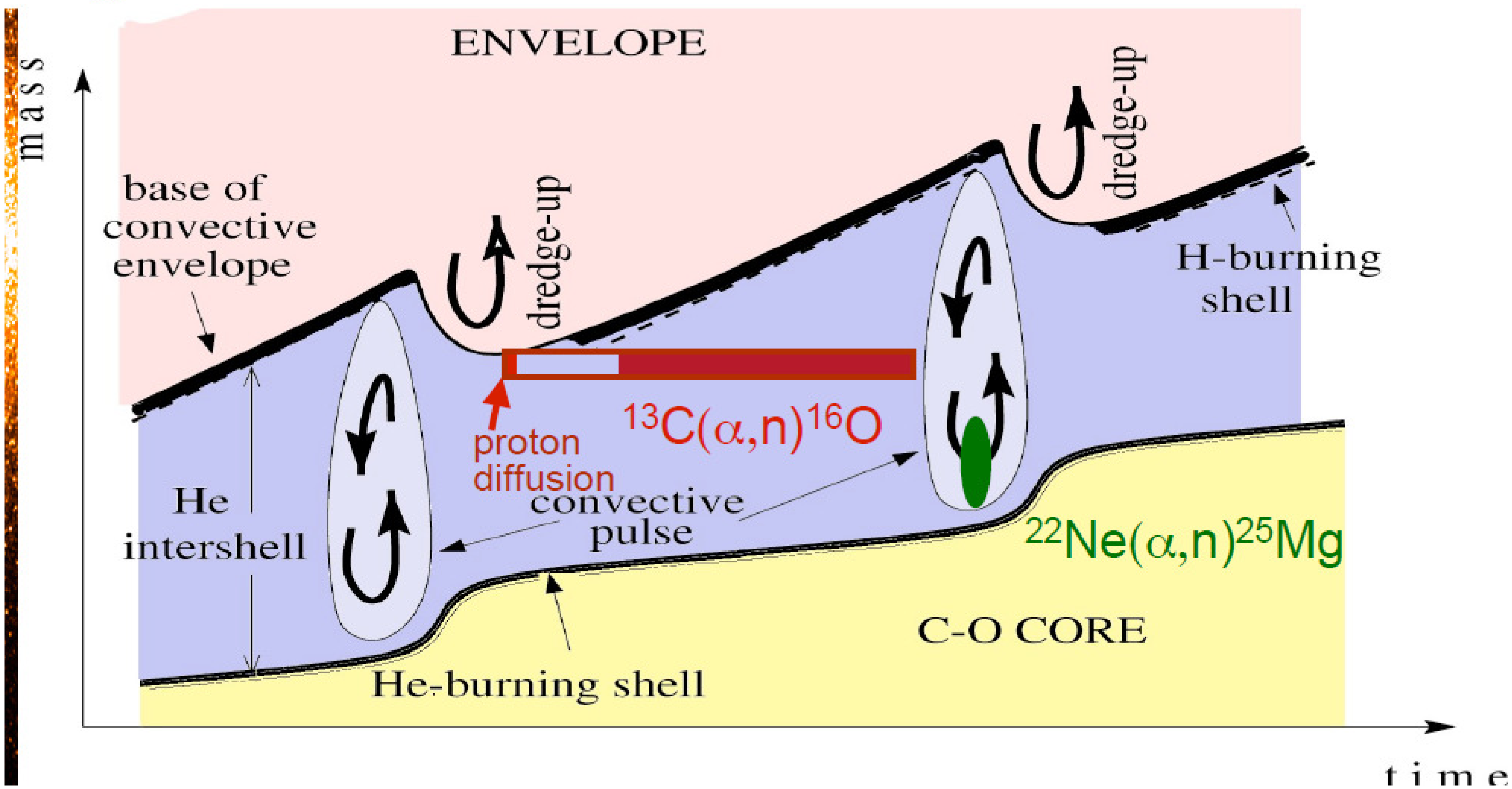


Strong s-process

Low mass AGBs | Intermediate mass AGBs

Lower temperature ~4.5 $M_\odot$ Higher temperature

Larger intershell mass | Smaller intershell mass



Slide from Karakas & Lugaro

The s-process

- Secondary process
  → neutron captures on pre-existing Fe-group nuclei

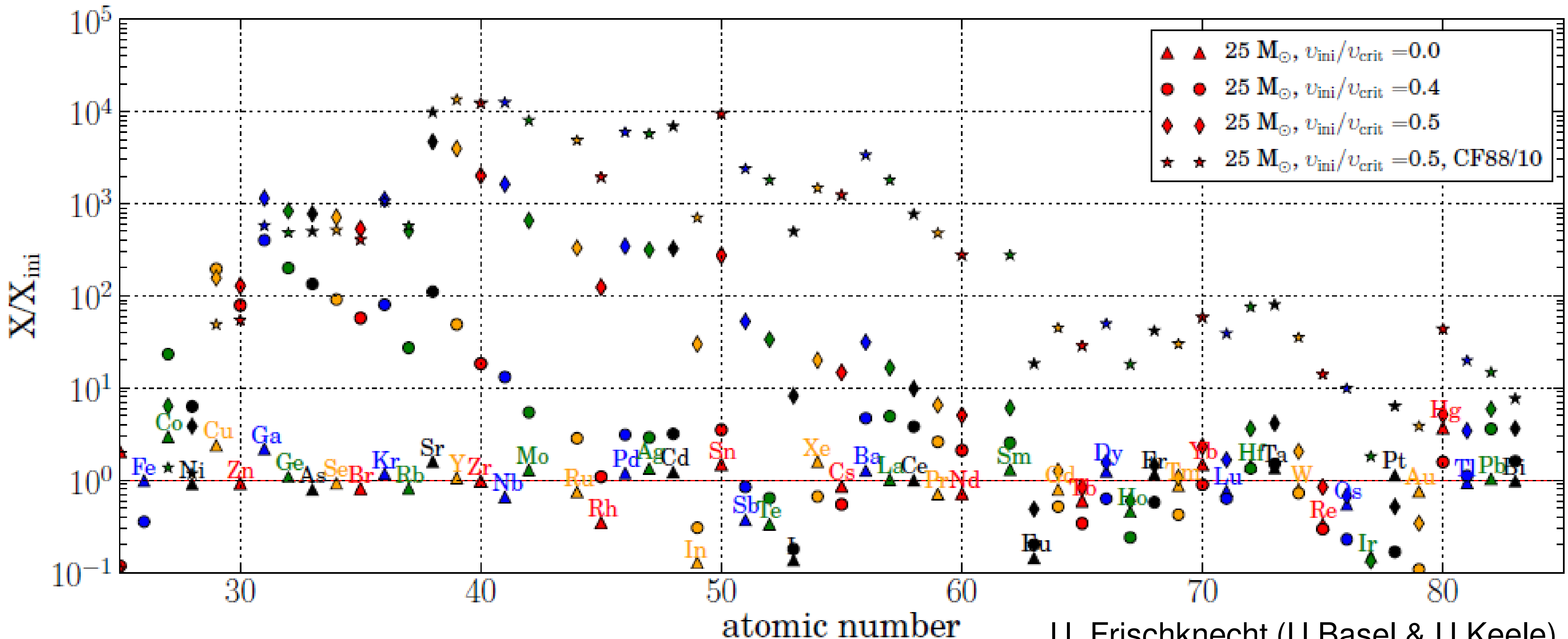
- Strong s-process (up to Pb)
  - He-shell flashes in AGB stars
  - Protons are mixed from H-shell; produce ^{13}C
  - During He-burning: $^{13}C + \alpha \rightarrow {}^{16}O + n$
    → strong neutron source

- Weak s-process (truncated at Z~60)
  - Core burning in massive stars:
    - He-burning ($1\text{-}2 \times 10^8$K) $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$
    - C-burning ($6\text{-}8 \times 10^8$K) $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$
      $^{13}C(\alpha,n)^{16}O$

p from $^{12}C(^{12}C,p)\,^{23}Na$
α from $^{12}C(^{12}C,\alpha)\,^{20}Ne$

The weak s-process

Overproduction factors of 25 $M_\odot$ models with Z$= 10^{-5}$ ([Fe/H] $= -3.8$)



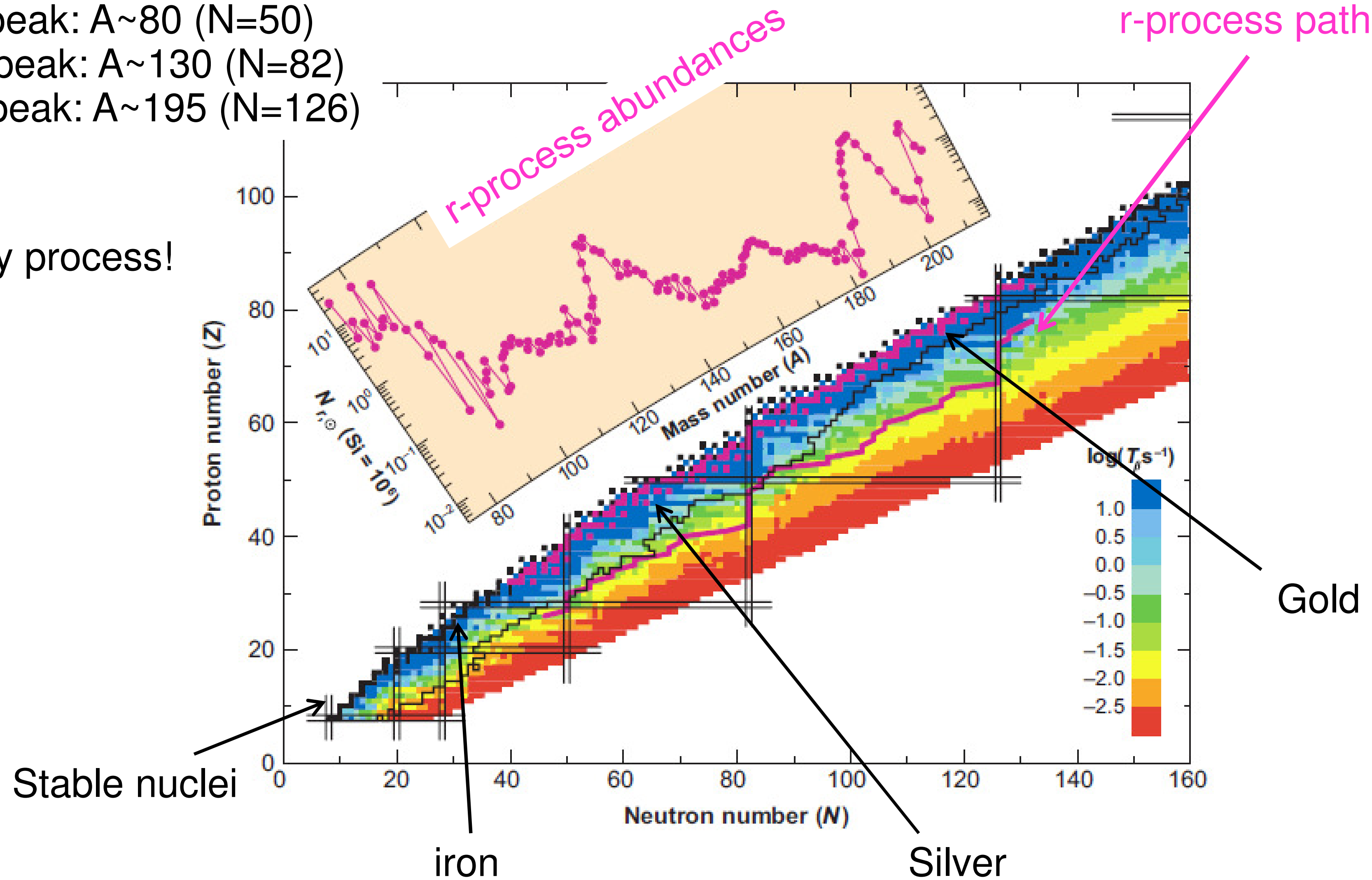
U. Frischknecht (U Basel & U Keele)

➔ Seed nuclei and neutron sources are secondary,
neutron poisons are primary!

The r-process

1st peak: A~80 (N=50)
2nd peak: A~130 (N=82)
3rd peak: A~195 (N=126)

Primary process!

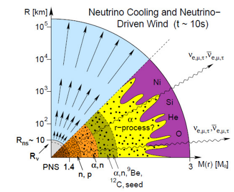


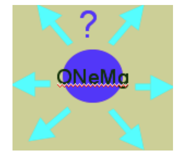
The r-process site

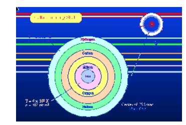
- Most important criteria for an r-process site:
  - High neutron density
  - Eject material
- Neutron sources:
  - Neutrons in nuclei (must be liberated)
  - Neutron stars
  - Made through weak reactions
- Conditions:
  - High entropy, alpha-rich freeze-out
  - Low entropy, normal freeze-out with very low Ye

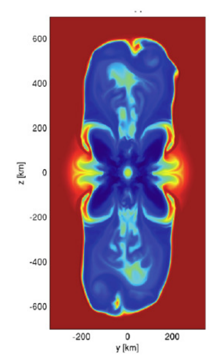
The r-process site(s)

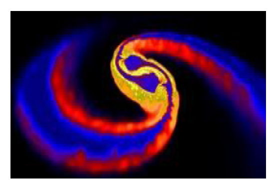
- Neutrino-driven wind in CCSNe
- ONeMg core collapse
- Quark-hadron phase transition
- Explosive He-burning in outer shells
- Charged-current neutrino interactions in outer shells
- Polar jets from rotating CCSNe
- Neutron-star mergers
- BH accretion disks







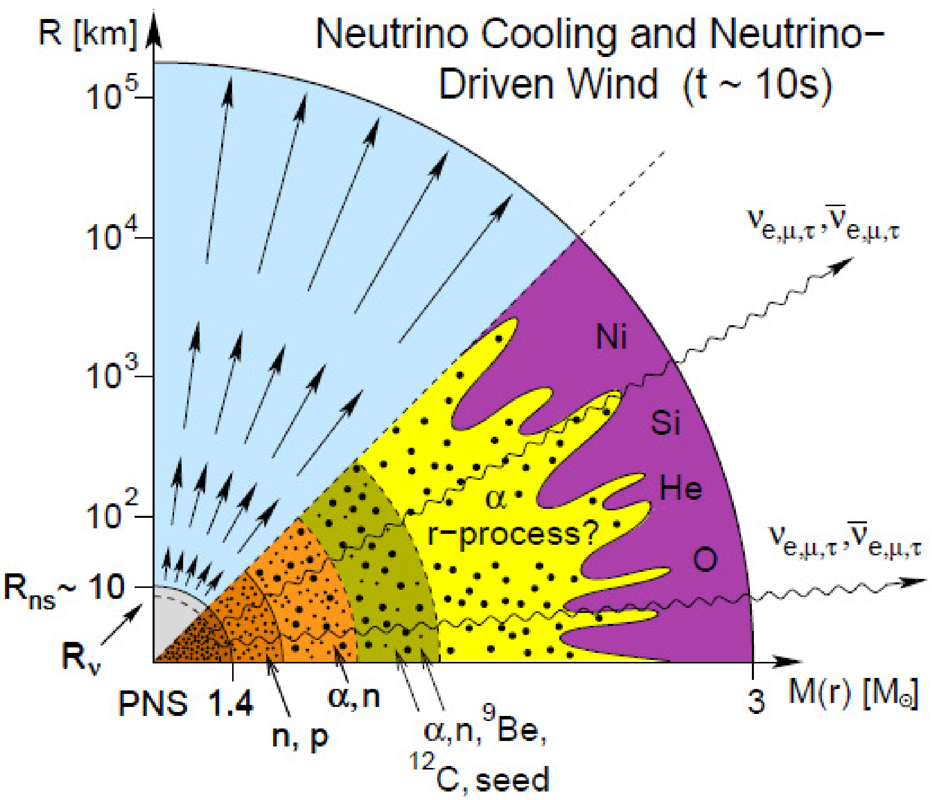


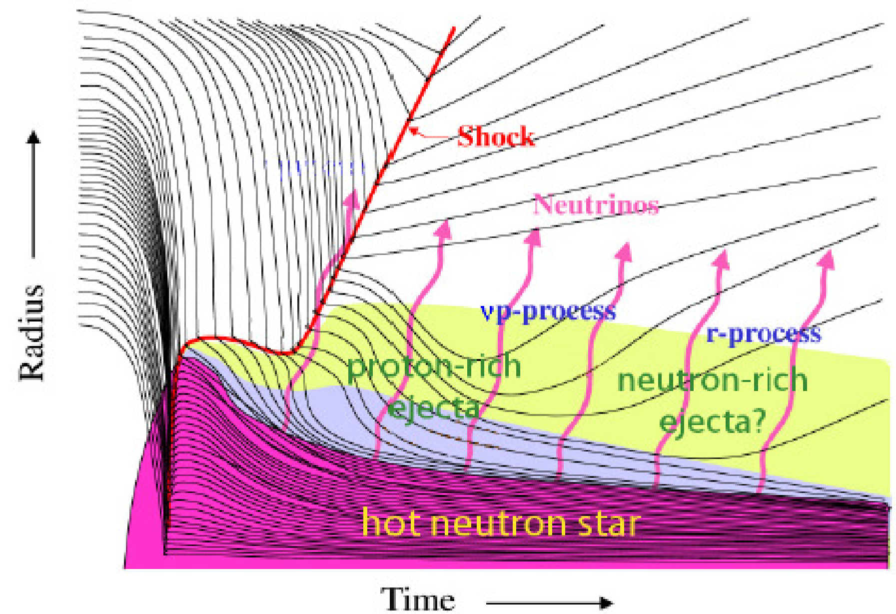


The r-process site(s)

- Neutrino-driven wind in CCSNe — No?!
- ONeMg core collapse — weak
- Quark-hadron phase transition — If? Weak!
- Explosive He-burning in outer shells — ???
- Charged-current neutrino interactions in outer shells — Abundance pattern??
- Polar jets from rotating CCSNe — Promising; initial conditions??
- Neutron-star mergers
- BH accretion disks

Neutrino-driven winds in CCSNe





T = 10-8 GK → T = 8 - 2 GK → T < 3 GK

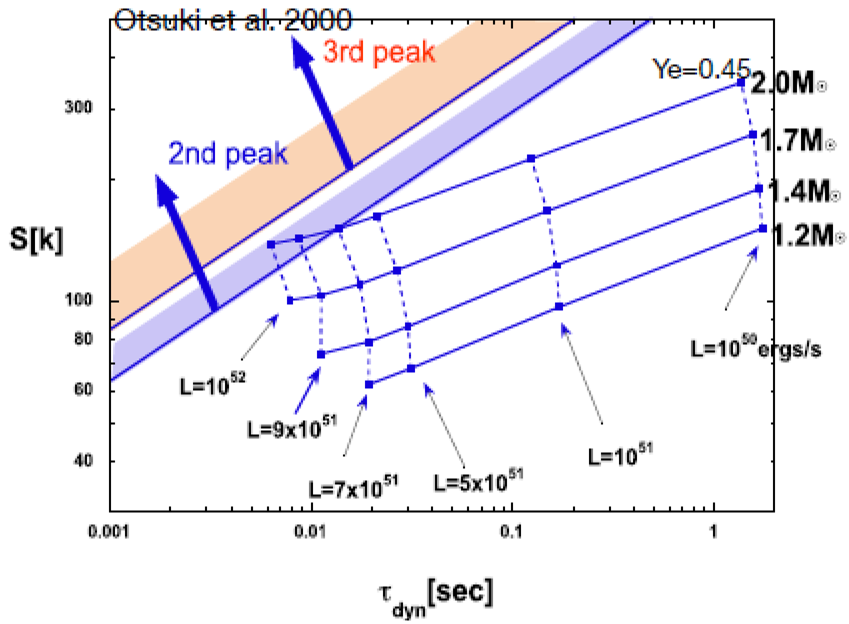
NSE

charged-particle reactions;
α-process

(weak) r-process
νp-process

Wind conditions for r-process

- High neutron-to-seed ratio: $Y_n/Y_{seed} \sim 100$
- Short expansion timescale: 10^{-3} to 1 second
  → inhibits formation of nuclei through α-process
- High entropy: $s/k_B \sim 20 - 400$
  → many free nucleons
- Moderately low electron fraction: Ye<0.5

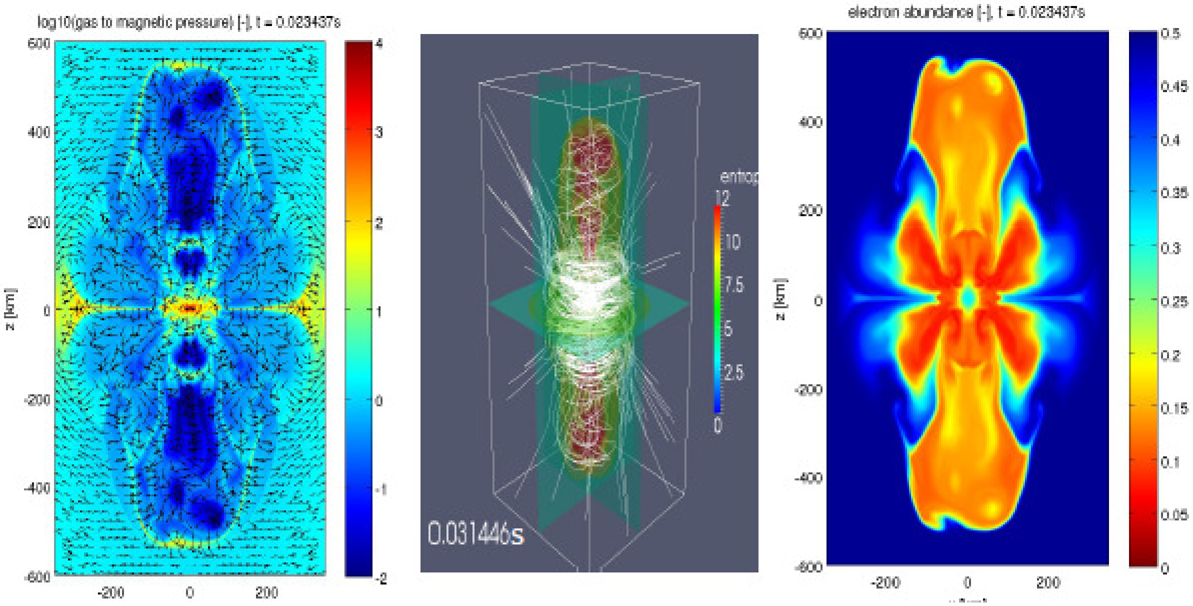


BUT: Conditions not realized in recent simulations

Simulations find:
τ ~ few milliseconds
s ~ 50-120 k_B/nuc
Ye ~ 0.4 – 0.6

→ Additional ingredients??

Magneto-rotational SNe



3D collapse of fast rotator with strong magnetic fields:

15 Msun progenitor
Shellular rotation with period of 2s at 1000km
Magnetic field in z-direction of 5 x 10^{12} G

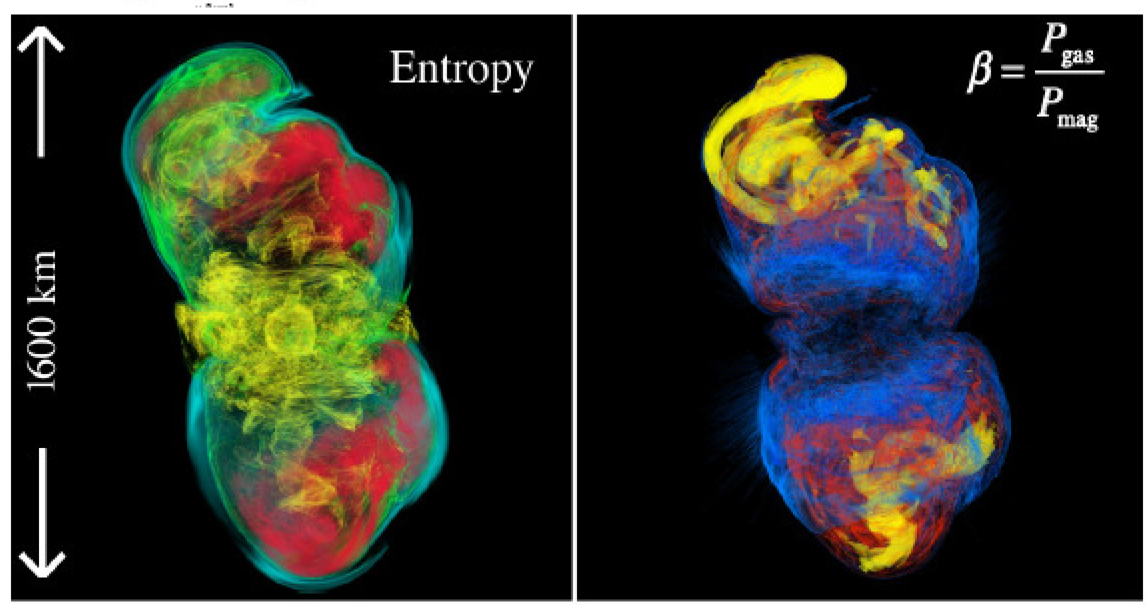
Kaeppeli, Winteler, Liebendoerfer 2014
Eichler+2014 (nucleosynthesis)

3D collapse of fast rotator with strong magnetic fields:

25 Msun progenitor

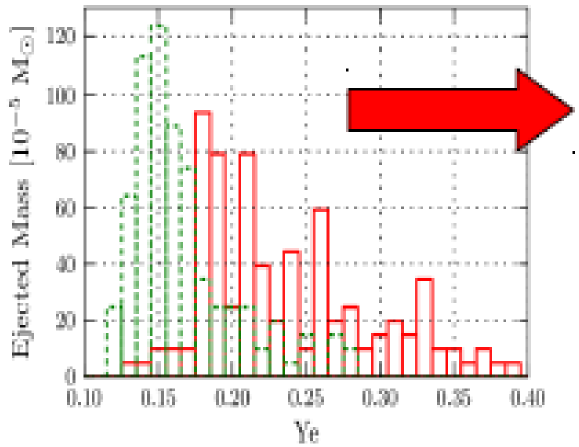
Magnetic field in z-direction of 10^{12} G

Moesta+2014

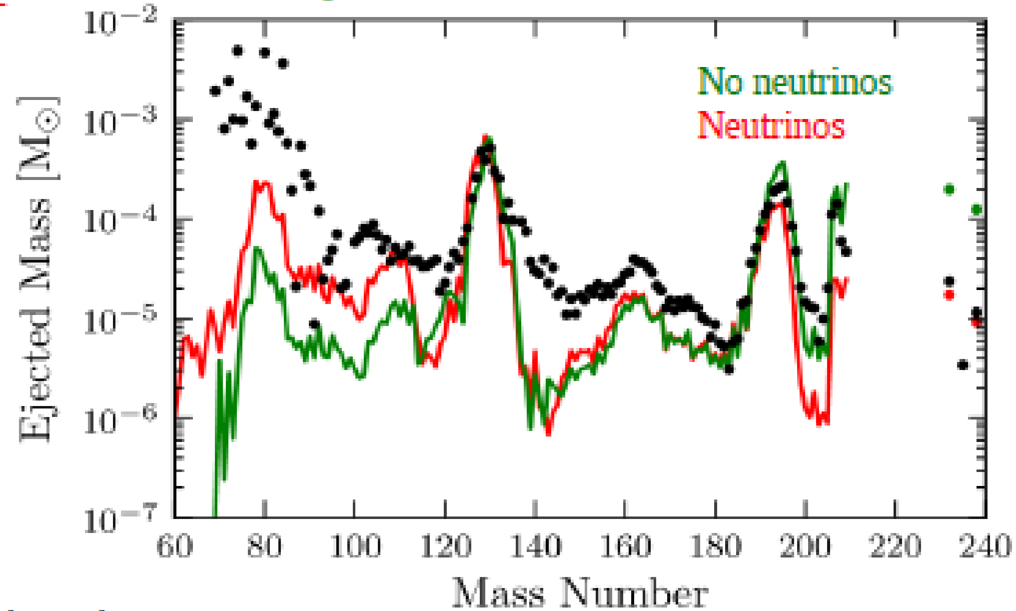


Nucleosynthesis from rot. CCSNe

From fast rotators with strong magnetic fields, i.e polar jets



neutrino effect small opposite to neutrino wind with slow expansion velocities



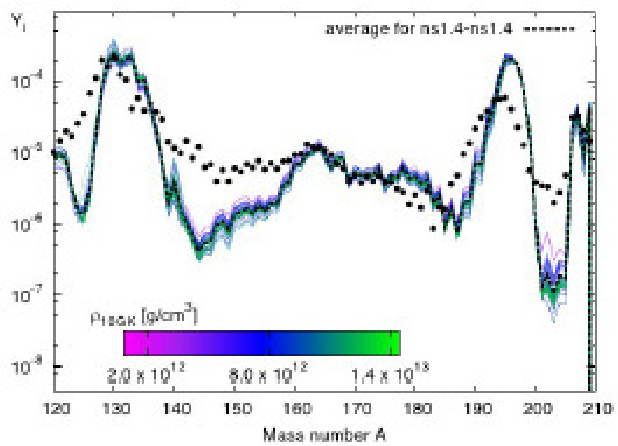
- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

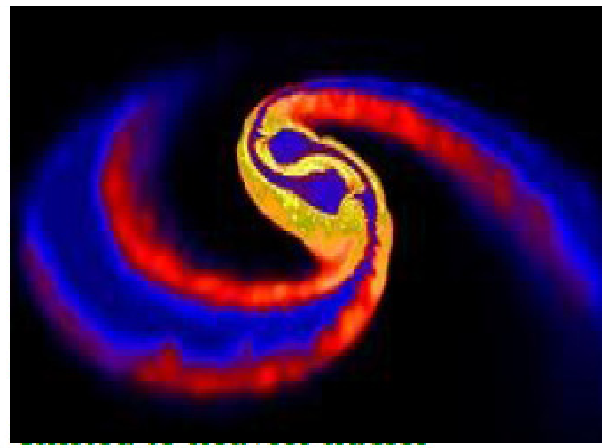
similar to mergers!!!

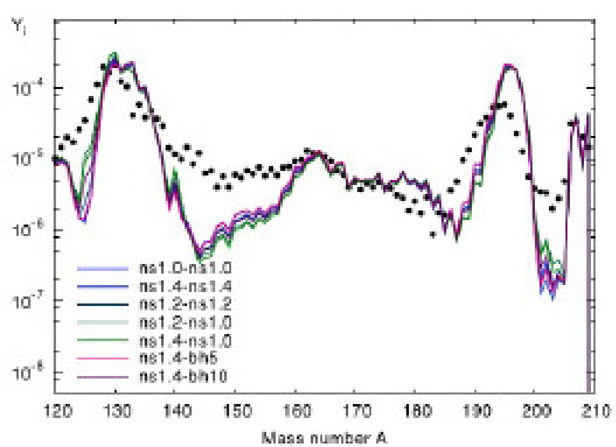
$$M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_{\odot}$$

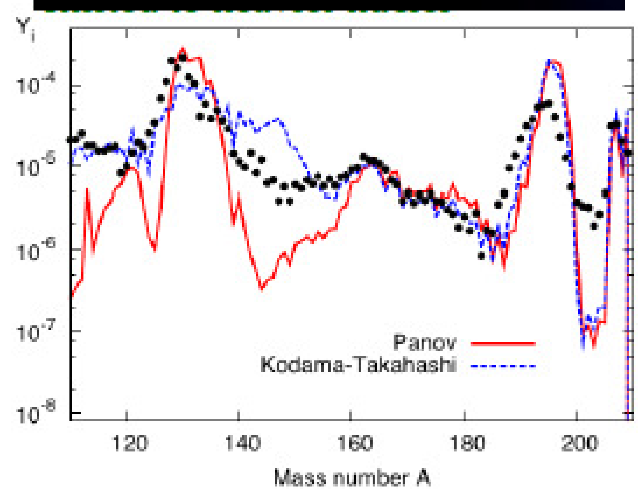
Neutron-star mergers

- 3^{rd} peak always shifted to heavier nuclei (trajectories too neutron-rich)





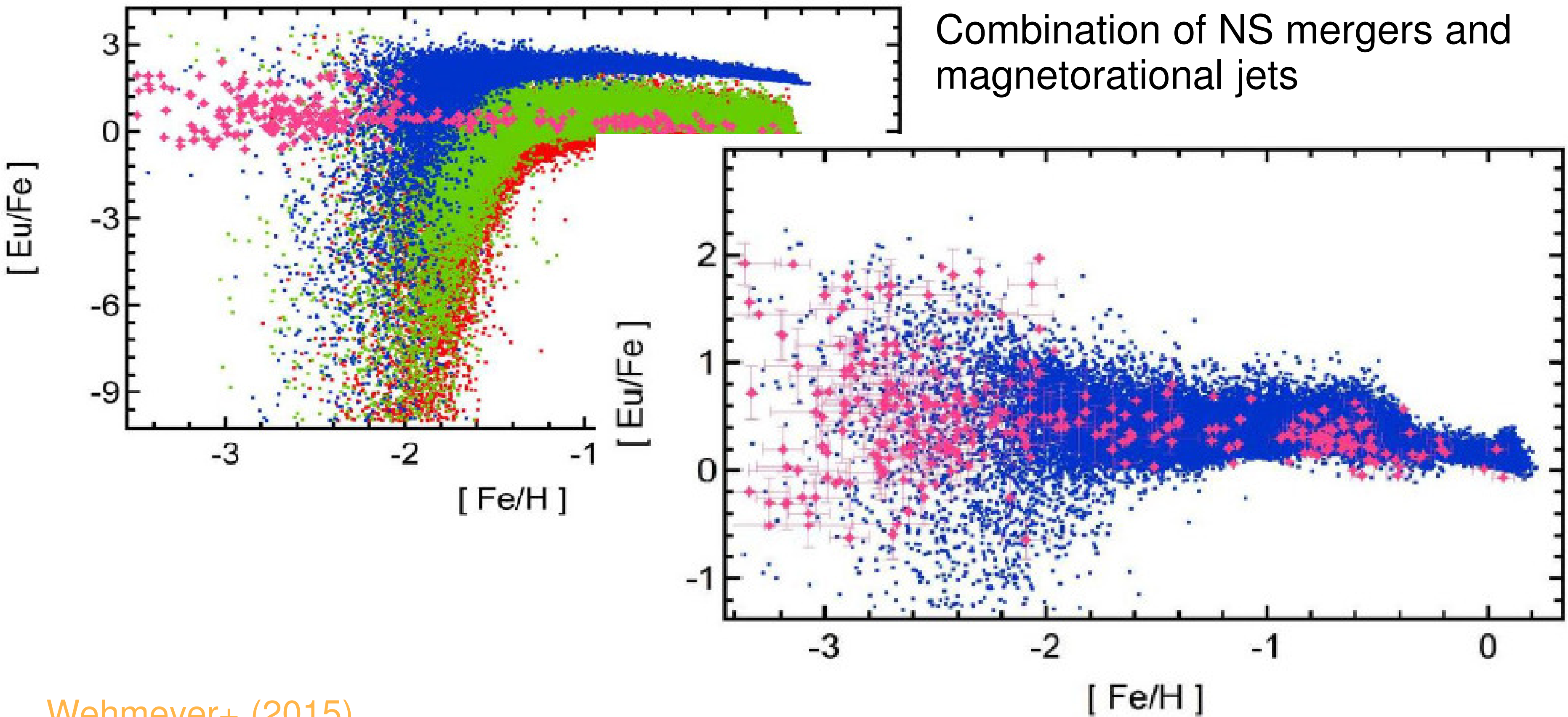




Chemical evolution

Magenta: data
No magnetorotational jets
Green/red: different merging time scales
Blue: higher merger rate

Combination of NS mergers and magnetorational jets

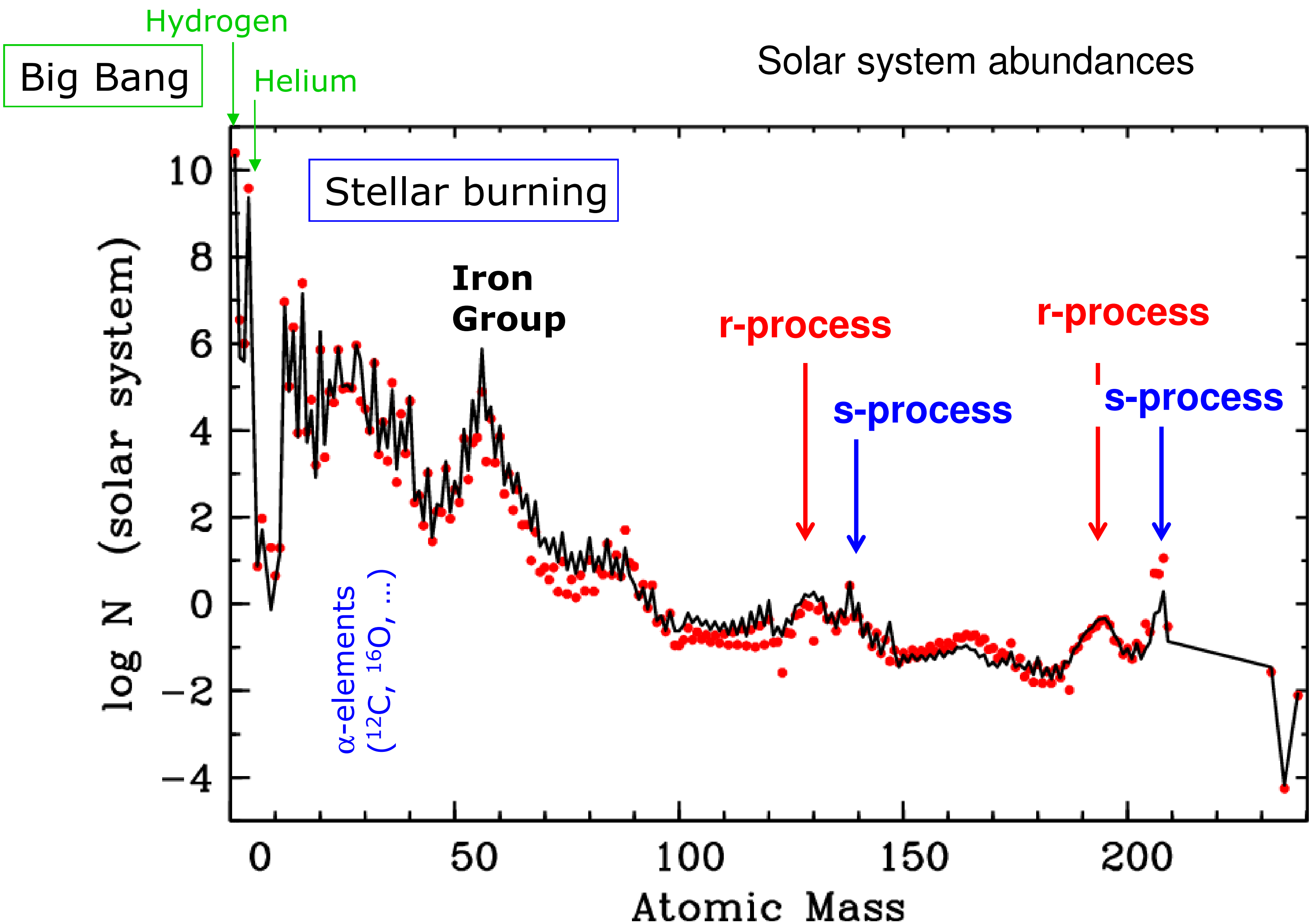


Wehmeyer+ (2015)

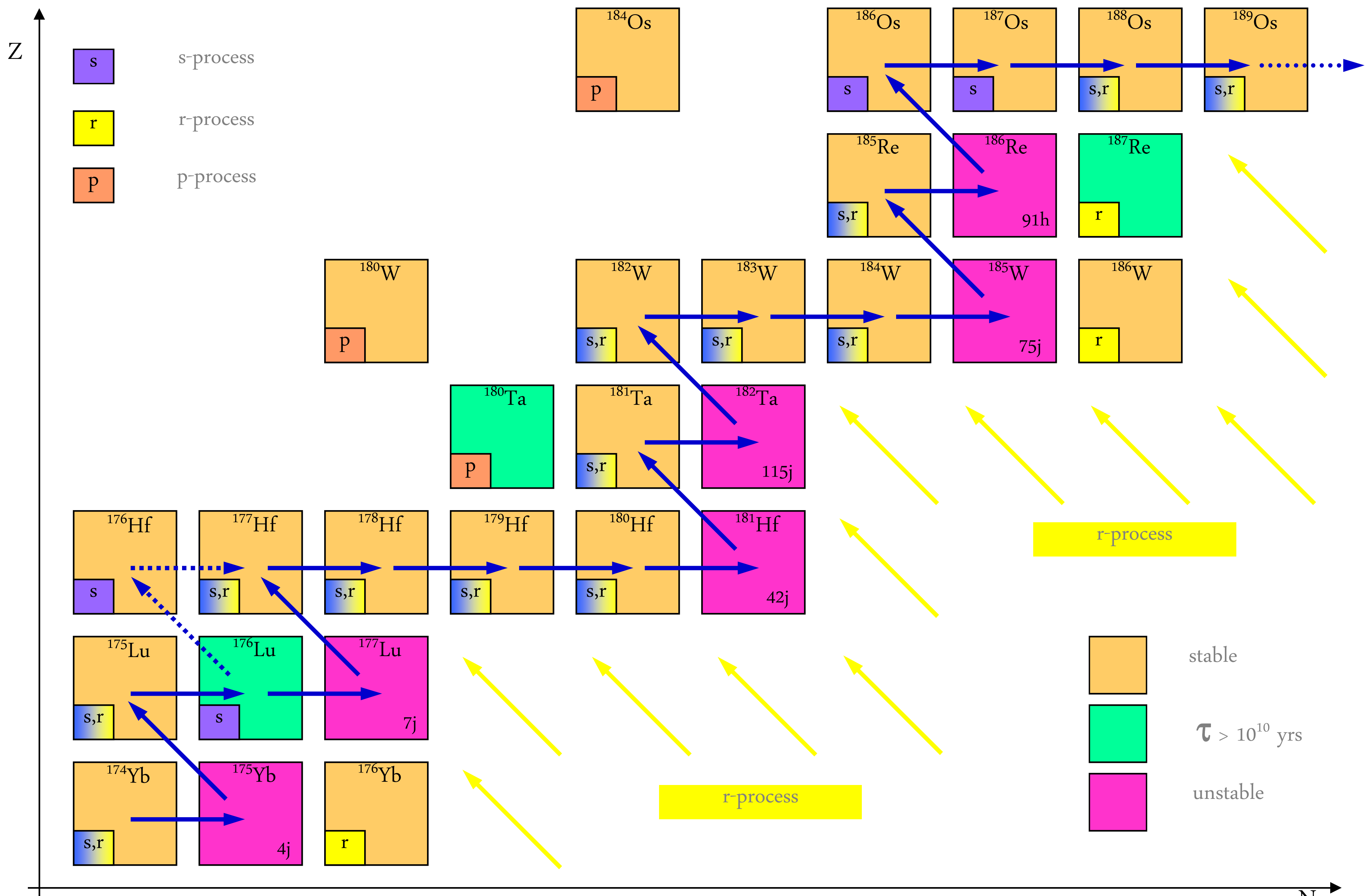
The r-process site(s)

- Neutrino-driven wind in CCSNe — No?!
- ONeMg core collapse — weak
- Quark-hadron phase transition — If? Weak!
- Explosive He-burning in outer shells — ???
- Charged-current neutrino interactions in outer shells — Abundance pattern??
- Polar jets from rotating CCSNe — Promising; initial conditions??
- Neutron-star mergers — Will results hold with improved simulations??
- BH accretion disks

Origin of elements

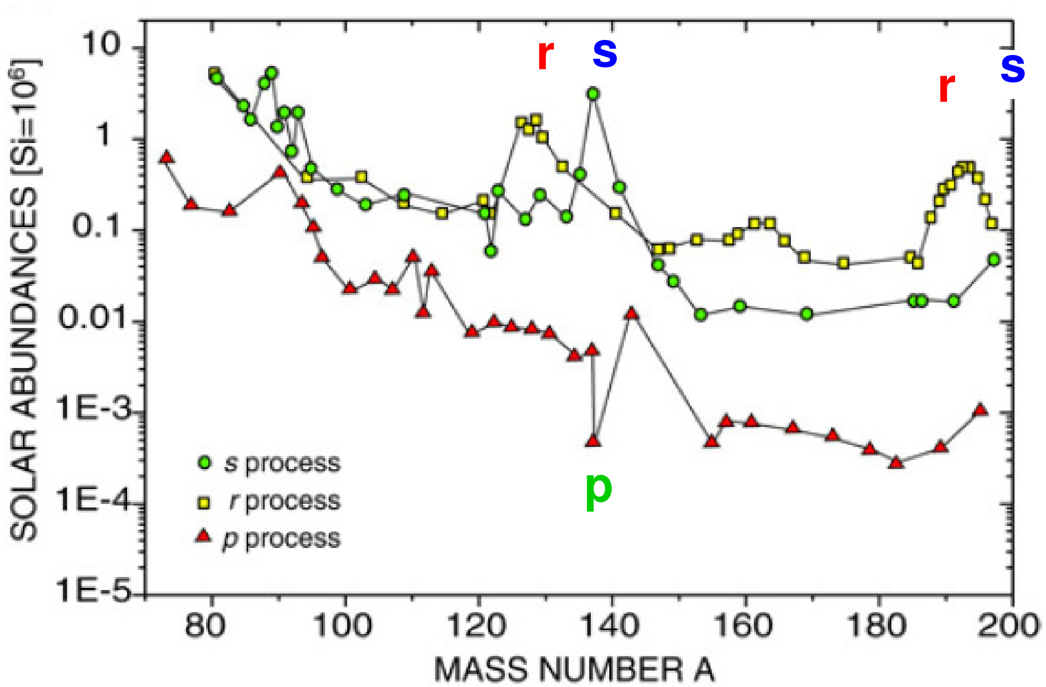


The neutron-capture processes



The p-process (for the p-nuclei)

Suggested by Arnould (1976) and Woosley&Howard (1978)

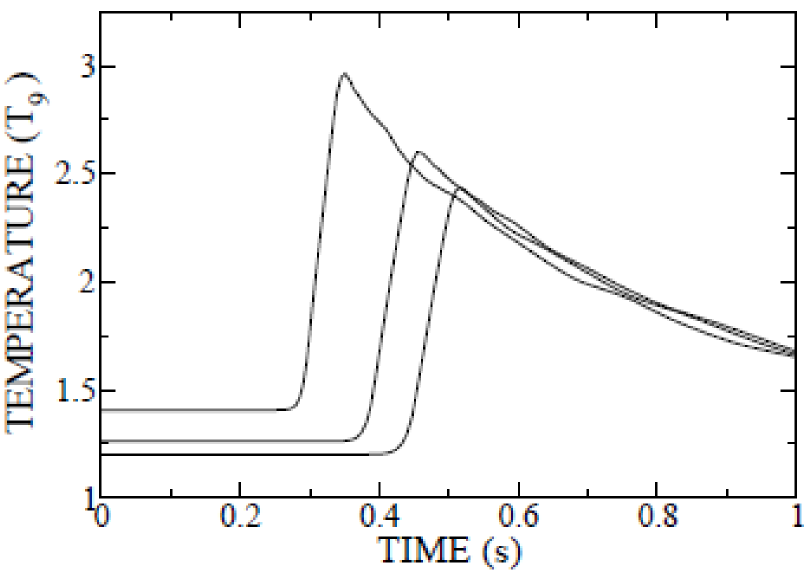


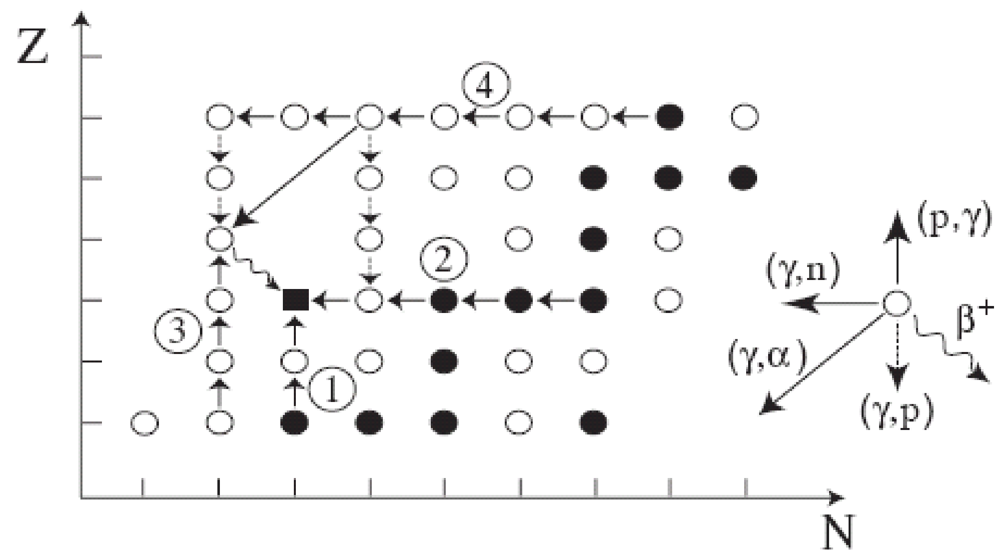
Now understood to be several processes:

- **γ-process**: photodisintegration of pre-existing heavy nuclei
- **ν-process**: (ν, ν') or (ν,e-)
- **νp-process**: p(ν,e+)n followed by (n,p)

The γ-process

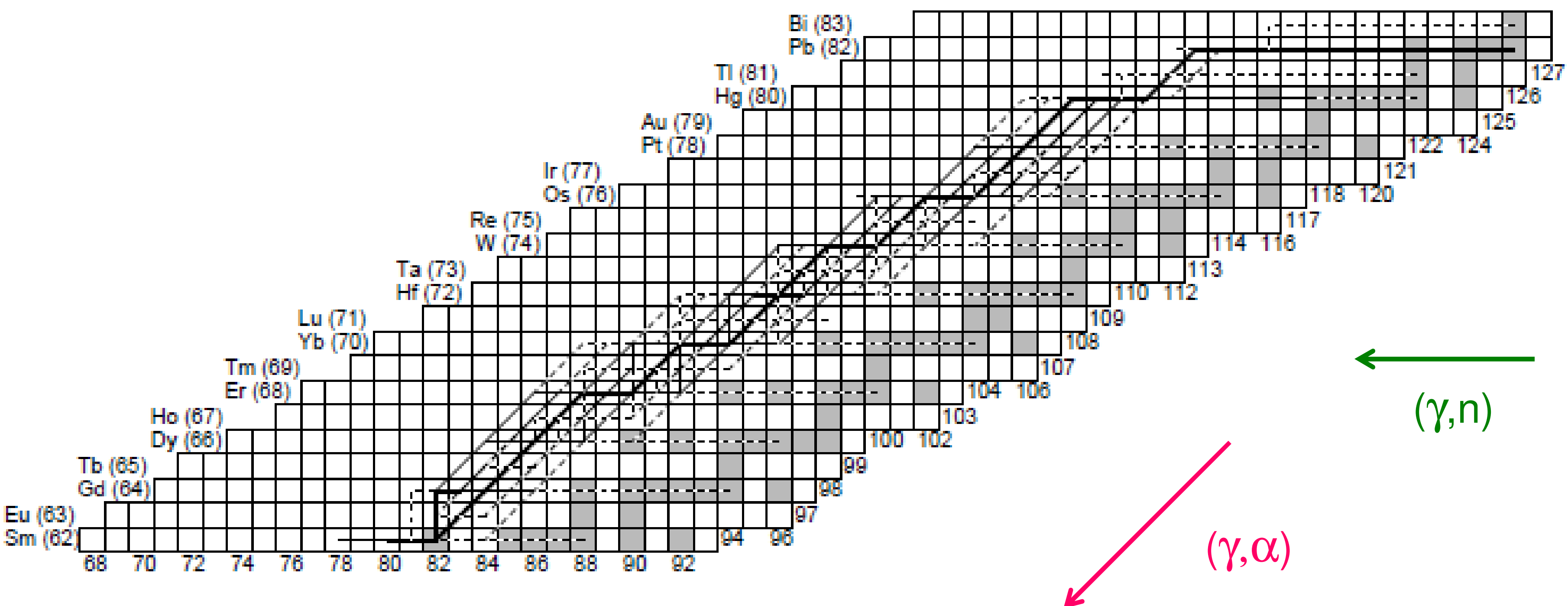
- Photodisintegrations of pre-existing heavy (s-process) nuclei
  - In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of 2-3 10^9K





The γ-process

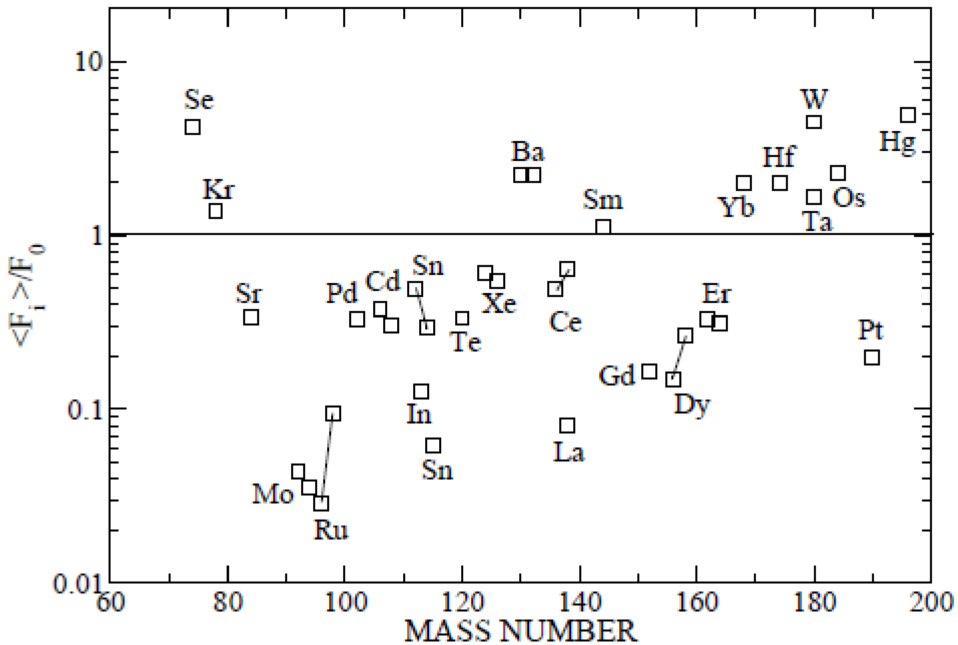
- Photodisintegrations of pre-existing heavy nuclei (from previous s-process event)
  - In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of 2-3 10^9K



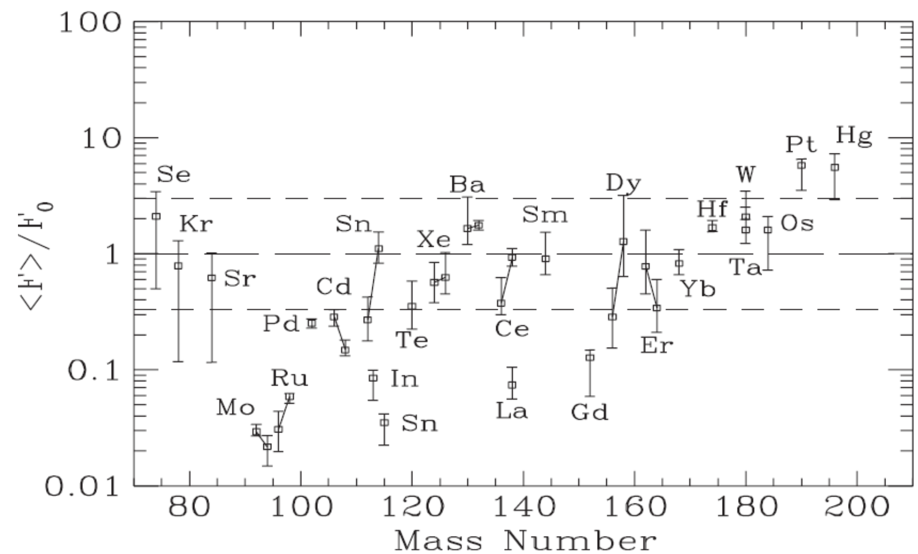
Rapp et al (2006)

The γ-process

- Predicted p-nuclei overproduction



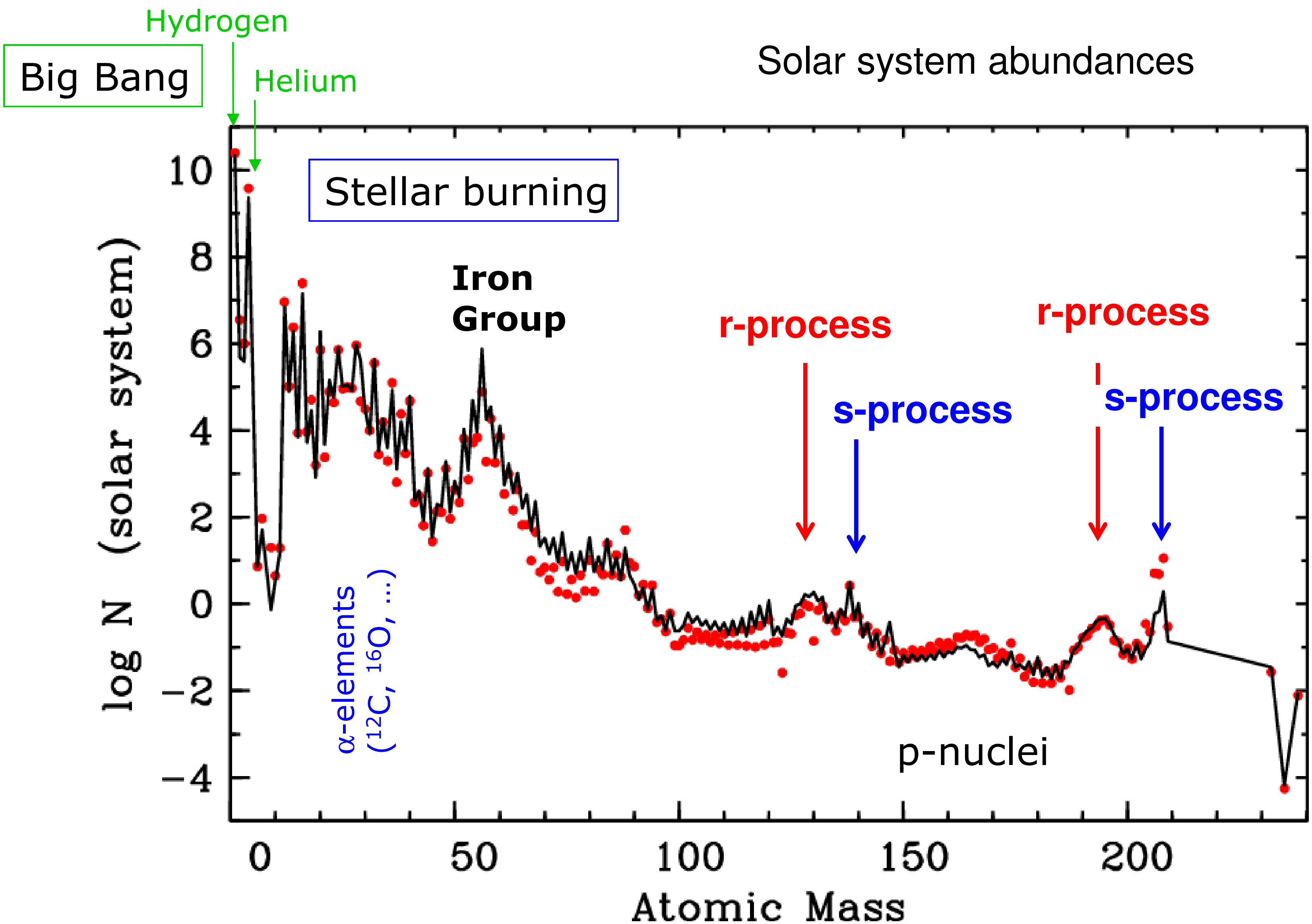
Rapp et al (2006)



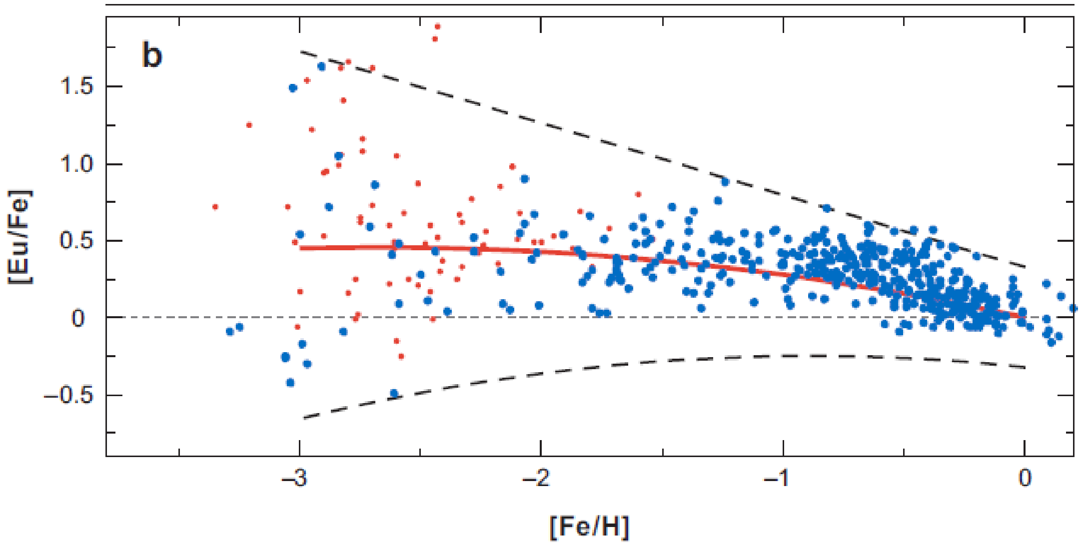
Arnould & Goriely (2003)

→ Underproduction of light p-nuclei

Origin of elements

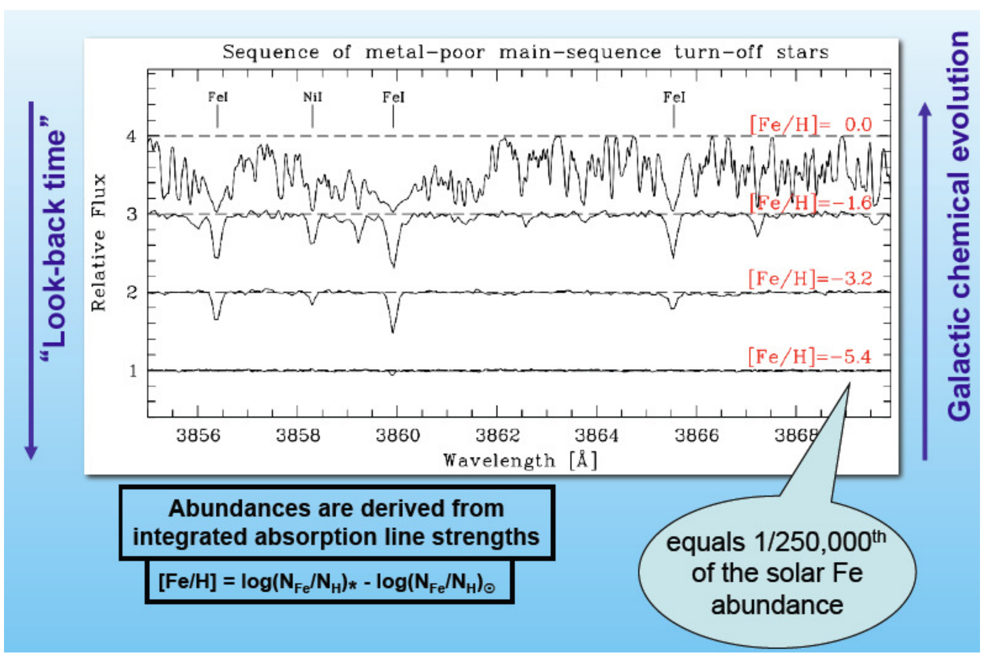


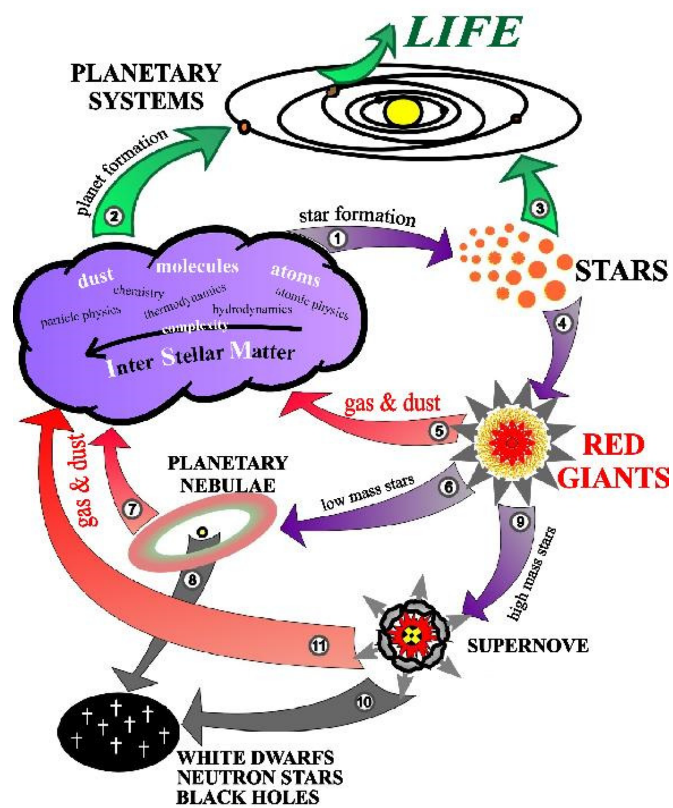
Trends with metallicity



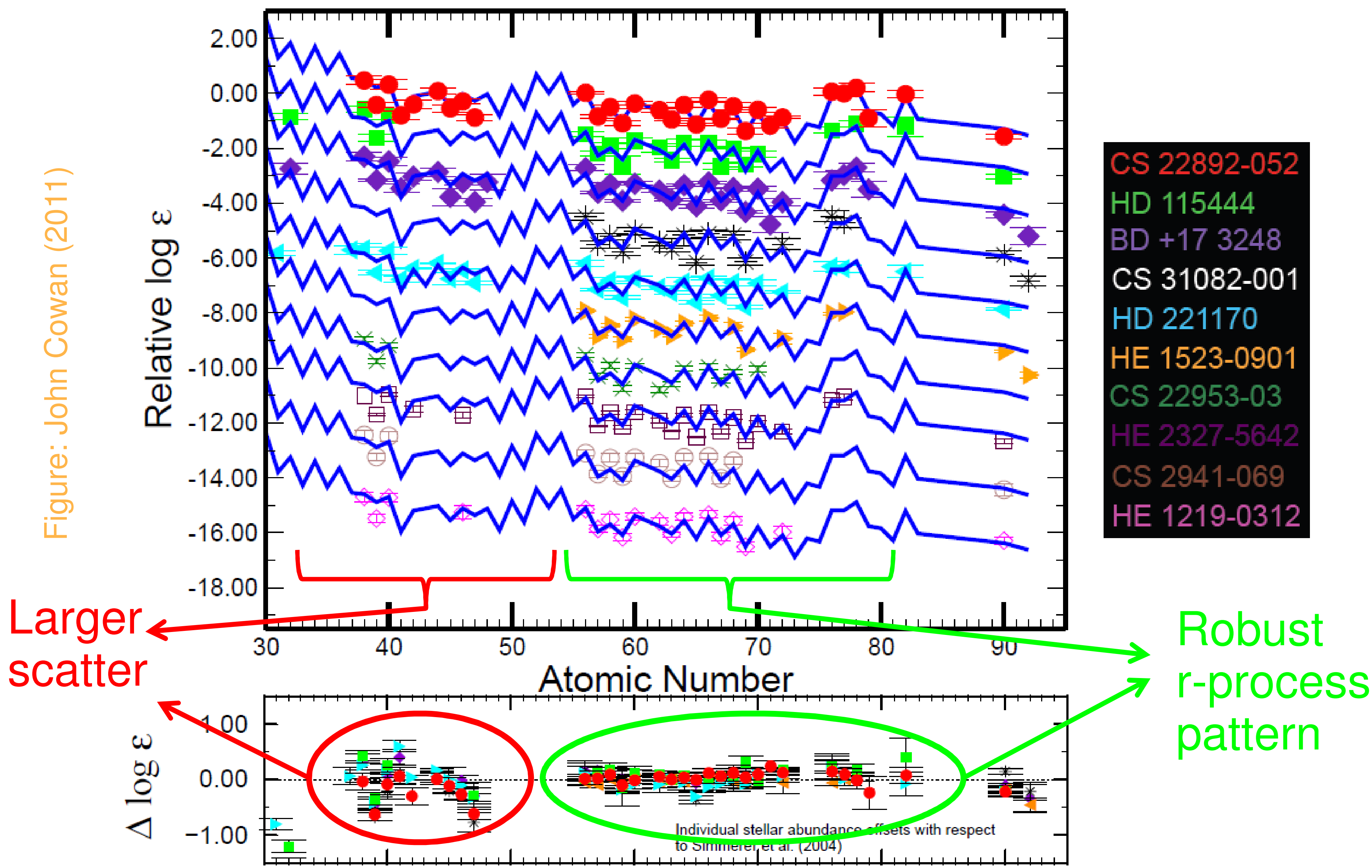
Significant scatter at low metallicities

r-process is rare in early Galaxy



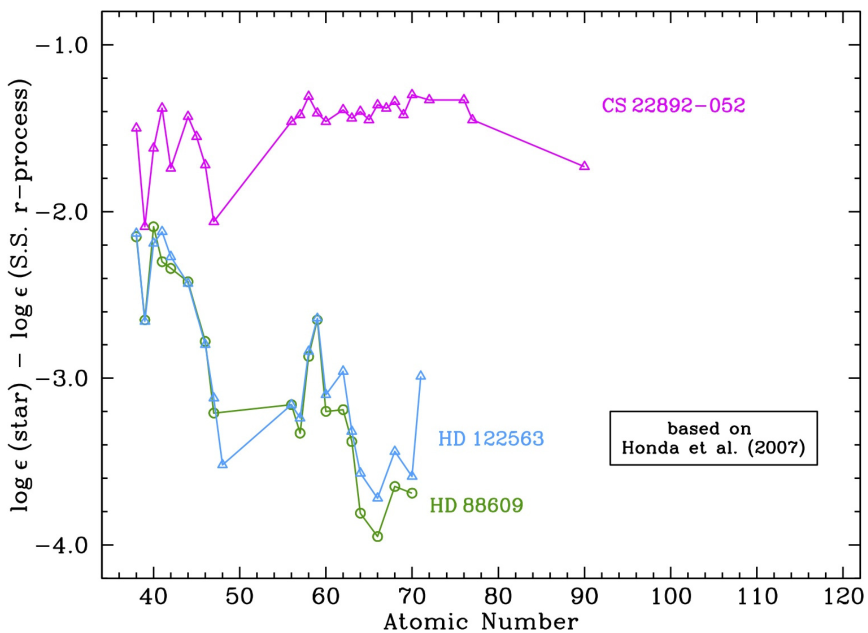


The oldest observed stars



LEPP: Lighter Element Primary Process

- Observations of halo stars indicate two "r-process" sites:
  - Main r-process
  - Stellar LEPP / weak r-process



Stars with high enrichment in heavy r-process abundances

Stars with low enrichment in heavy r-process abundances

LEPP: Lighter Element Primary Process

- Observations of halo stars indicate two "r-process" sites:
  - Main r-process
  - Stellar LEPP / weak r-process

- Solar LEPP

  Travaglio et al (2004): LEPP (solar LEPP)
  - Explains underproduction of "s-only" isotopes from Mo to Xe
  - Contributes 20-30% of solar Sr, Y, Zr
  - Solar abuns = r-process + s-process + LEPP

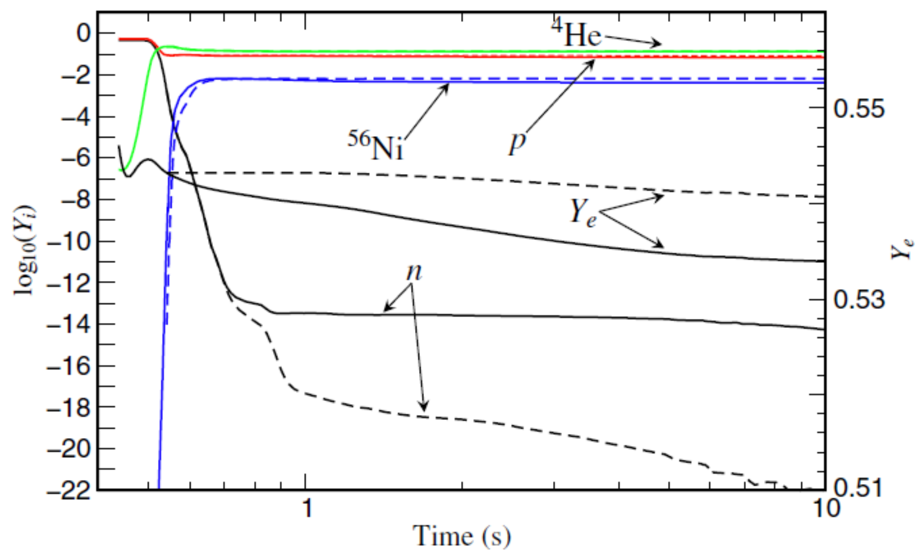
- Stellar LEPP

  Montes et al (2007)
  - Same as solar LEPP?

The νp-Process

- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow β decays, e.g. τ(64Ge)
- Neutron source:

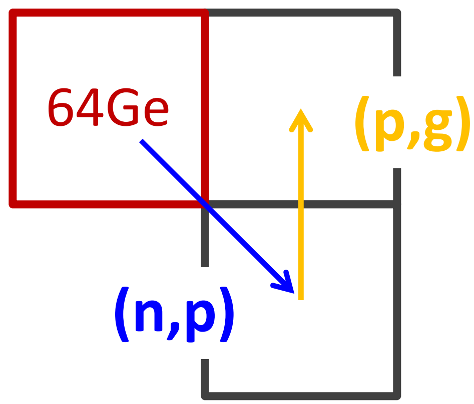
$$\overline{\nu}_e + p \rightarrow n + e^+$$

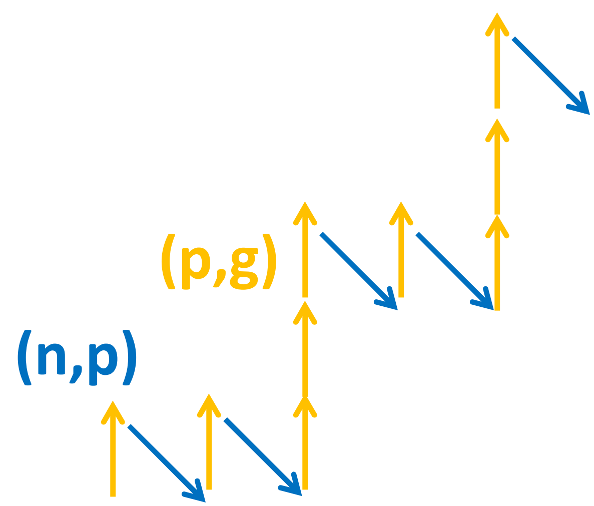


Frohlich et al (2006)

- Antineutrinos help bridging long waiting points via (n,p) reactions:

64Ge (n,p) 64Ga
64Ga (p,γ) 65Ge





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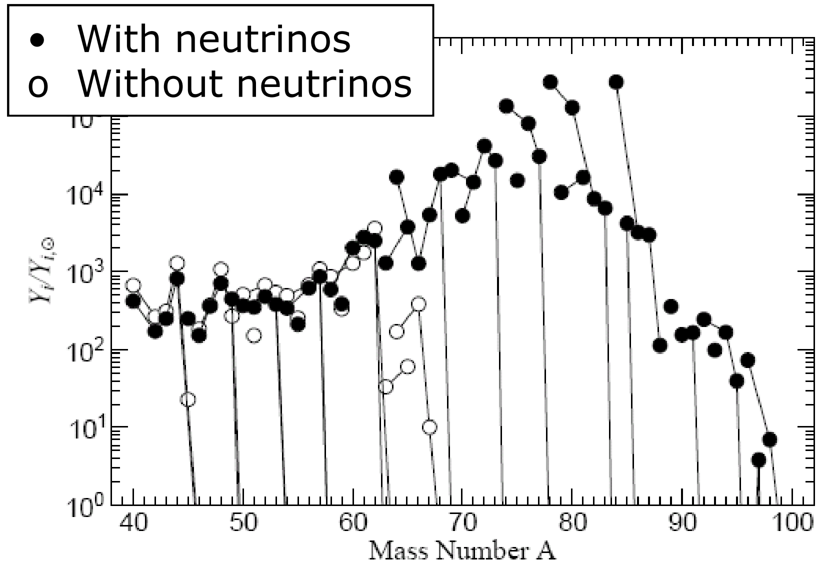

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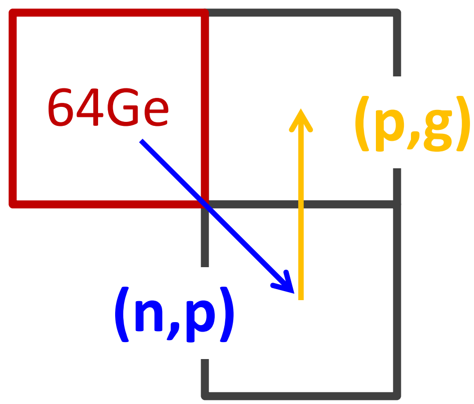
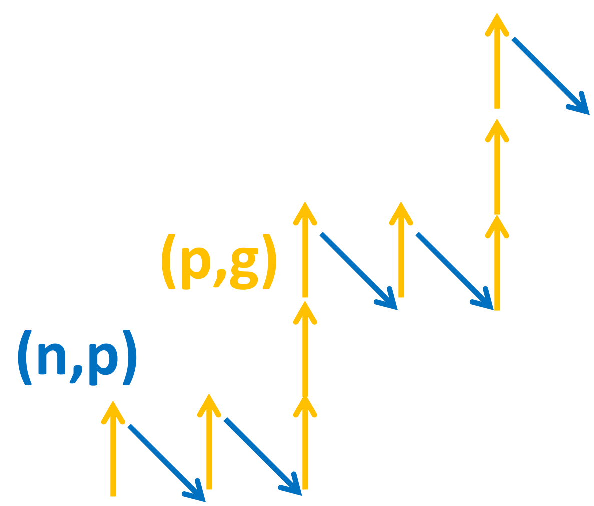
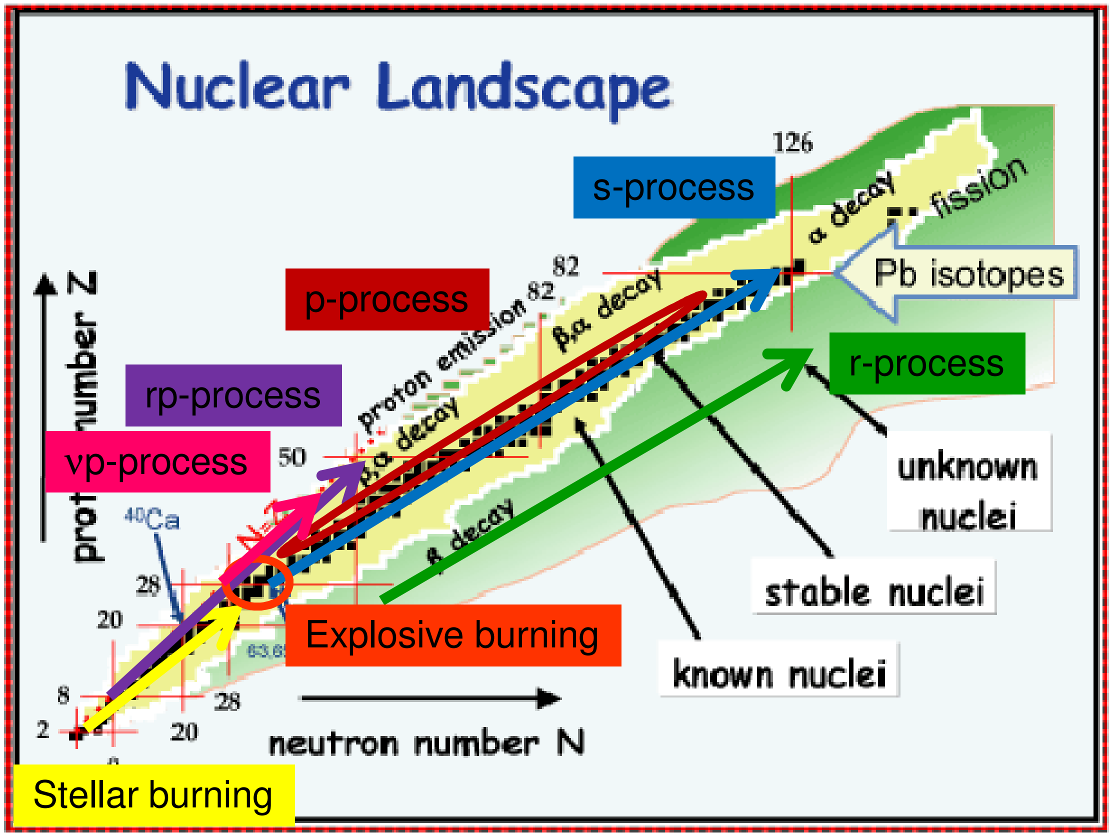




Heavy element synthesis inventory

- s-process
  - Secondary process; in AGB stars up to Pb or in massive stars as weak s-process
- γ-process
  - Secondary process; underproduction of light p-nuclei
- r-process
  - Primary process; probably some combination of MHD SNe and NS-mergers?
  - ???
- νp-process
  - In proton-rich neutrino winds

Summary



Astrophysical sites:

- Stellar evolution of low-mass and massive stars
- AGB stars (main s-process)
- core He-burning of massive stars (weak s-process)
- Supernovae (explosive burning)
- CC supernovae (γ-process)
- CC supernovae (νp-process)
- Jets in magn-rot. SNe (r-process)
- NS mergers (r-process)
- X-ray bursts (rp-process)