Neutrino Interactions and Nucleosynthesis: Lecture 1

Sites and Conditions for heavy element synthesis

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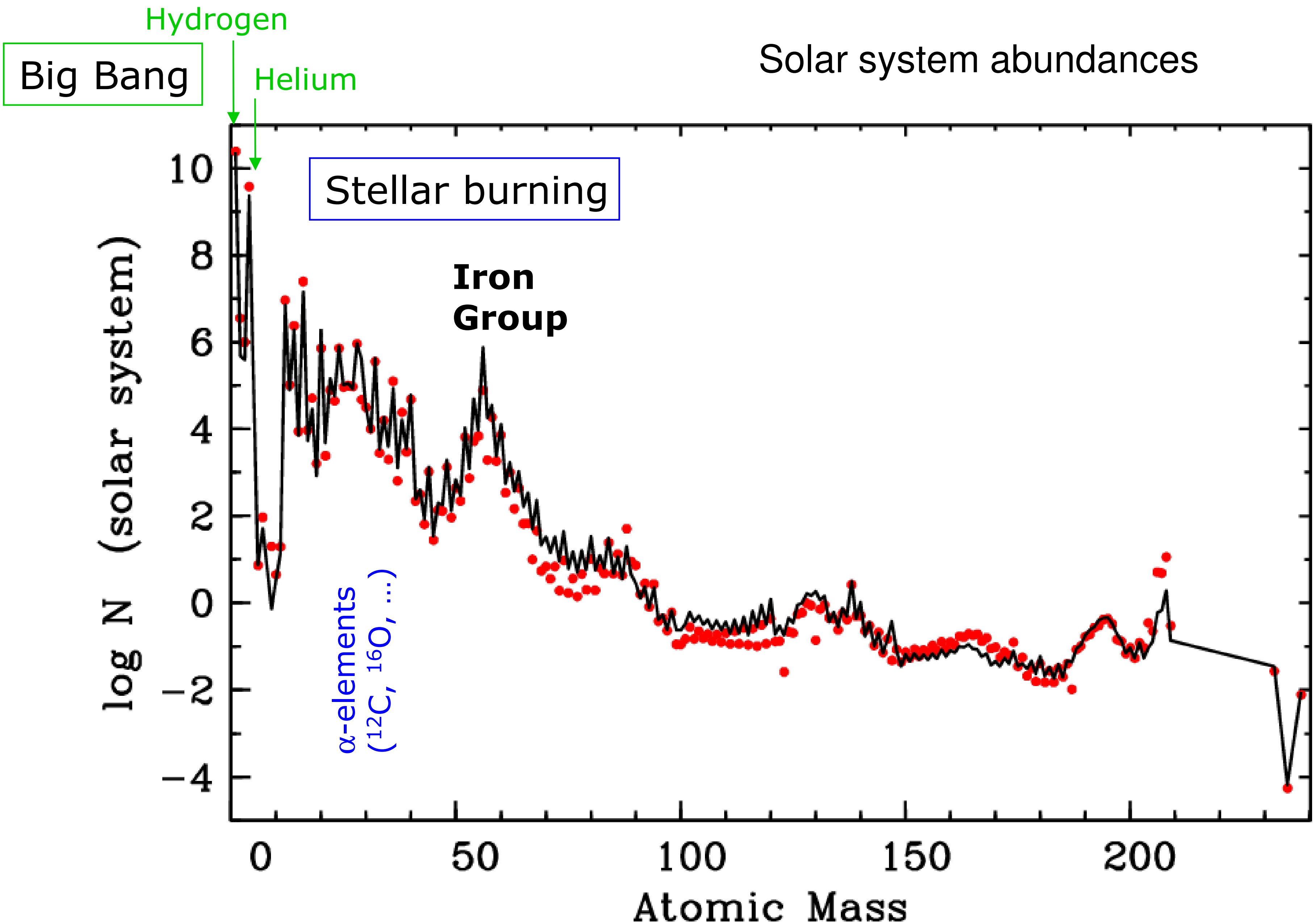
Lecture plan

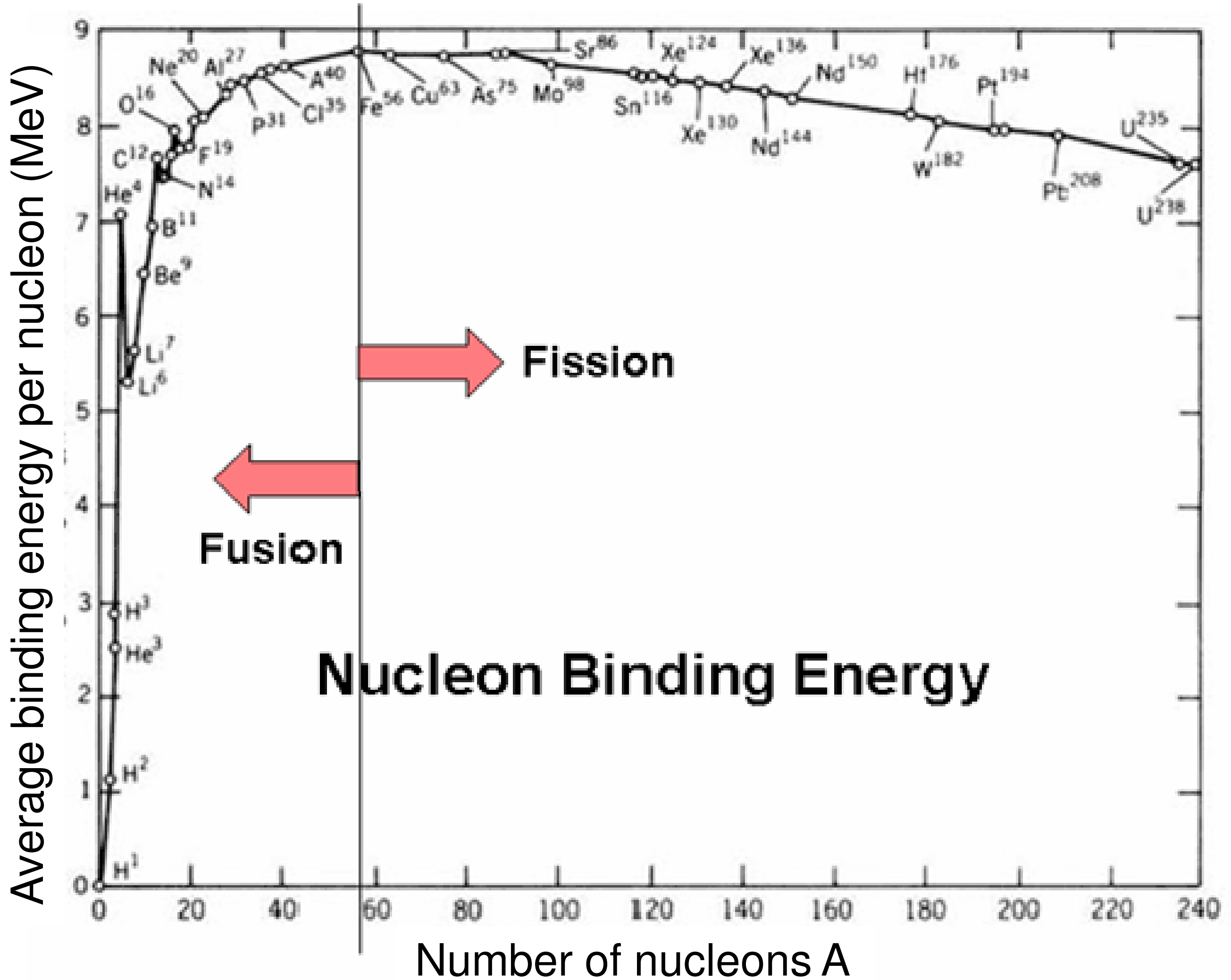
- Lecture 1
  - How to make heavy elements
  - Neutrinos set the conditions
  - Neutron-rich nucleosynthesis
  - Proton-rich nucleosynthesis

- Lecture 2
  - Thermonuclear reaction networks
  - Nuclear inputs

Origin of elements



Nuclear binding energy

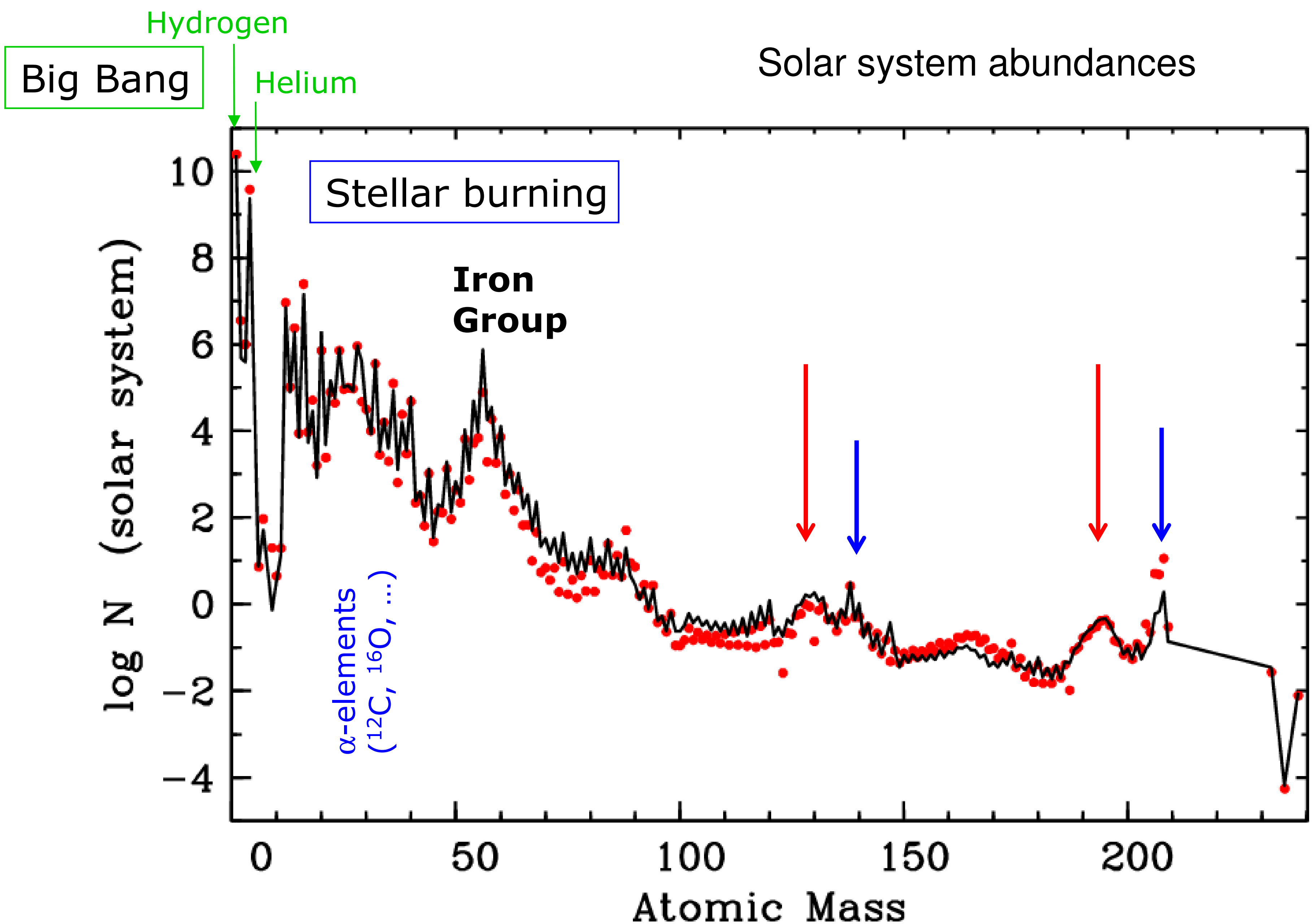


H → He → C → O → …. → Fe

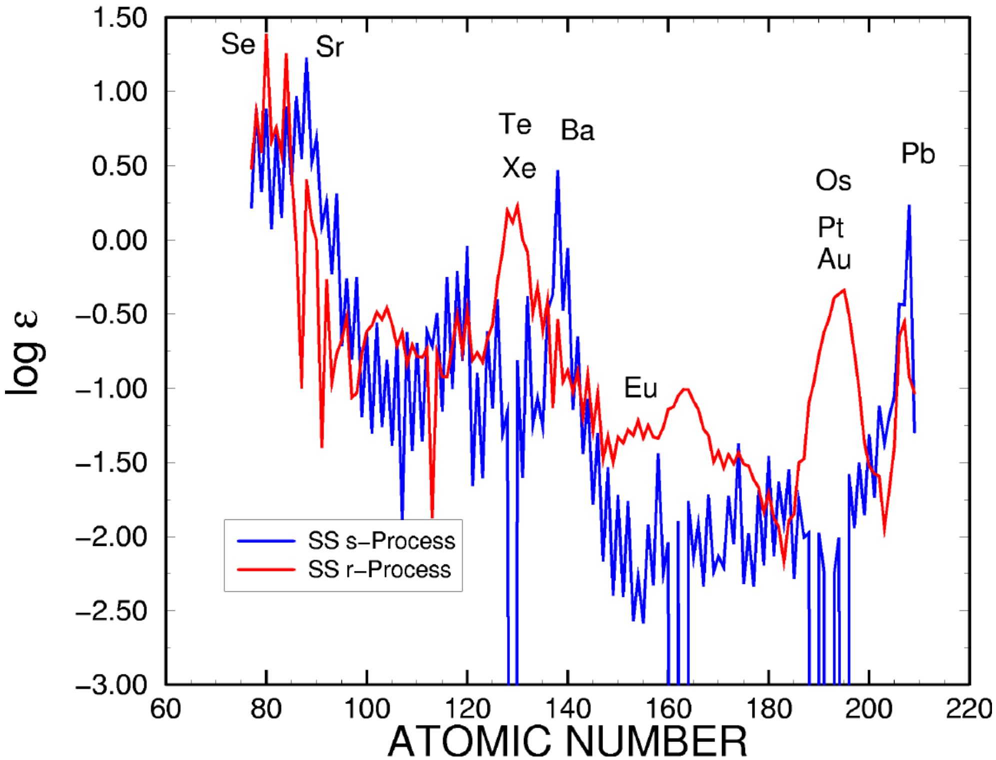
Nuclear fusion in stellar cores

Need mechanisms other than charged-particle fusion:
E.g. neutrons, photons, neutrinos

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

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

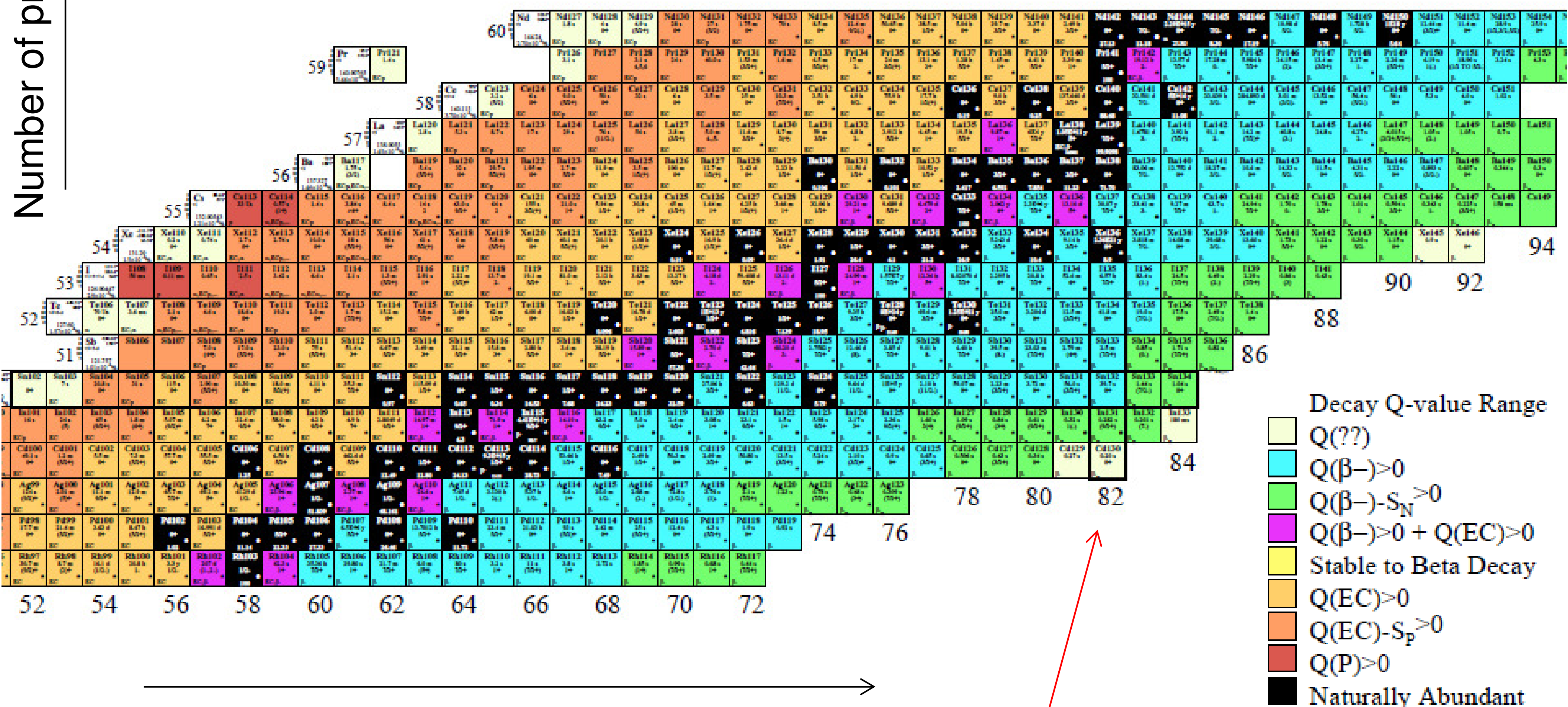
$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

Neutron-capture paths

→ (n,γ) reactions

↖ β⁻-decays

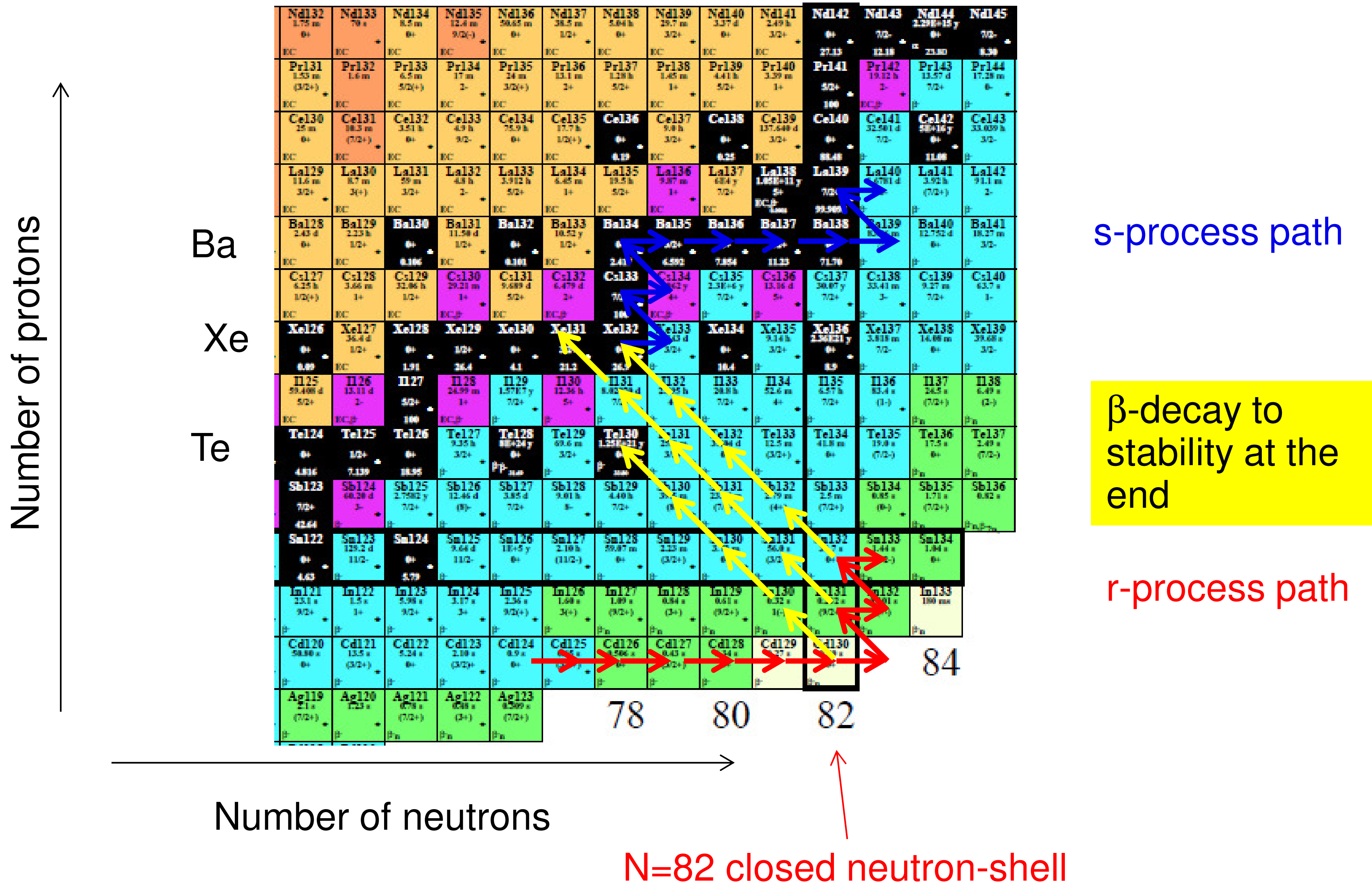
Number of protons



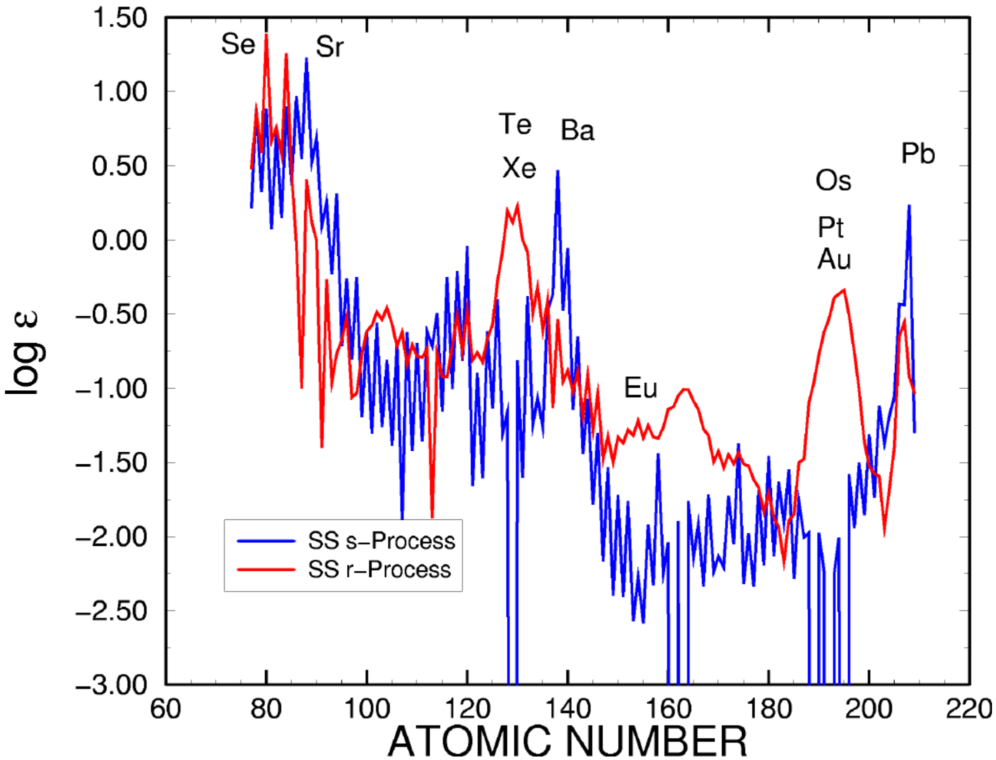
Number of neutrons

N=82 closed neutron-shell

Neutron-capture paths



Neutron-capture processes



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

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

- 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

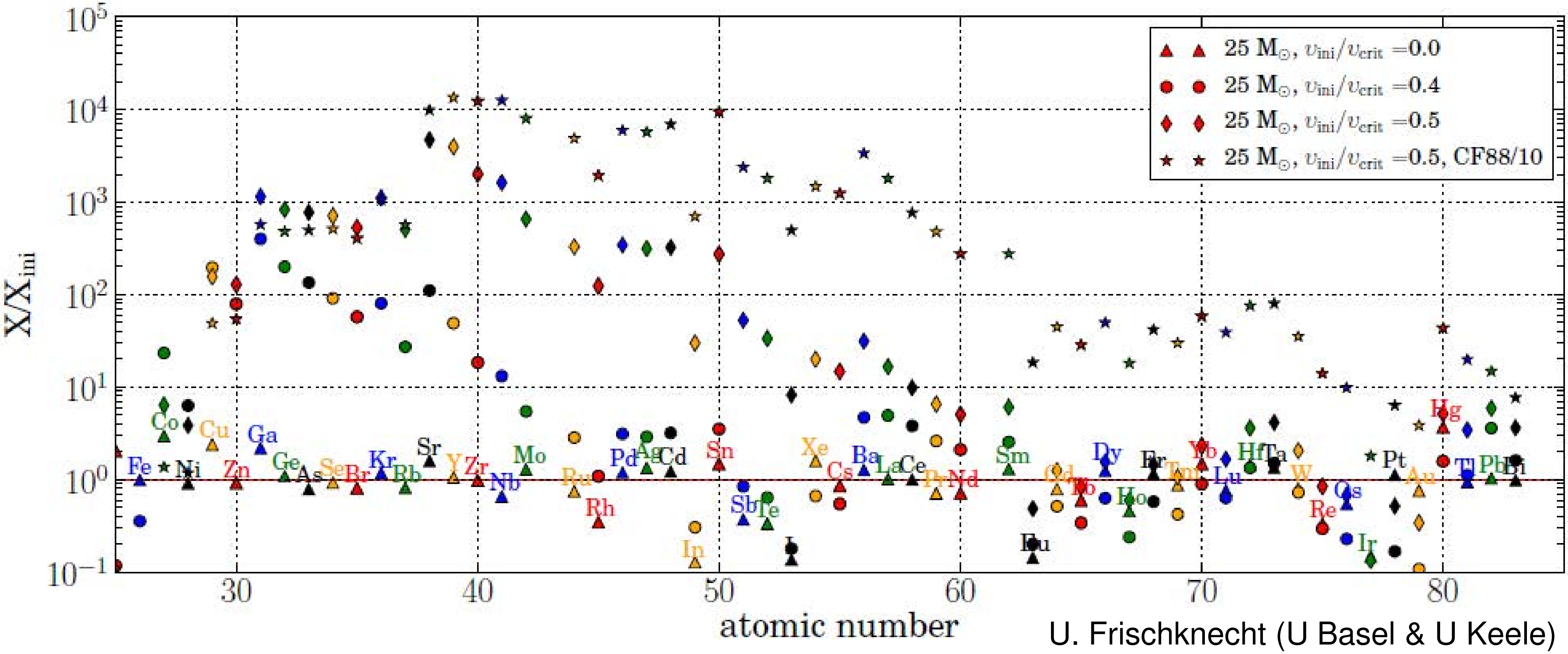
- Strong s-process (up to Pb)
  - He-shell flashes in AGB stars
  - Protons are mixed from H-shell; produce ^{13}C
  - During He-burning: $^{13}C + a \rightarrow {}^{16}O + n$
    → strong neutron source

- 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)



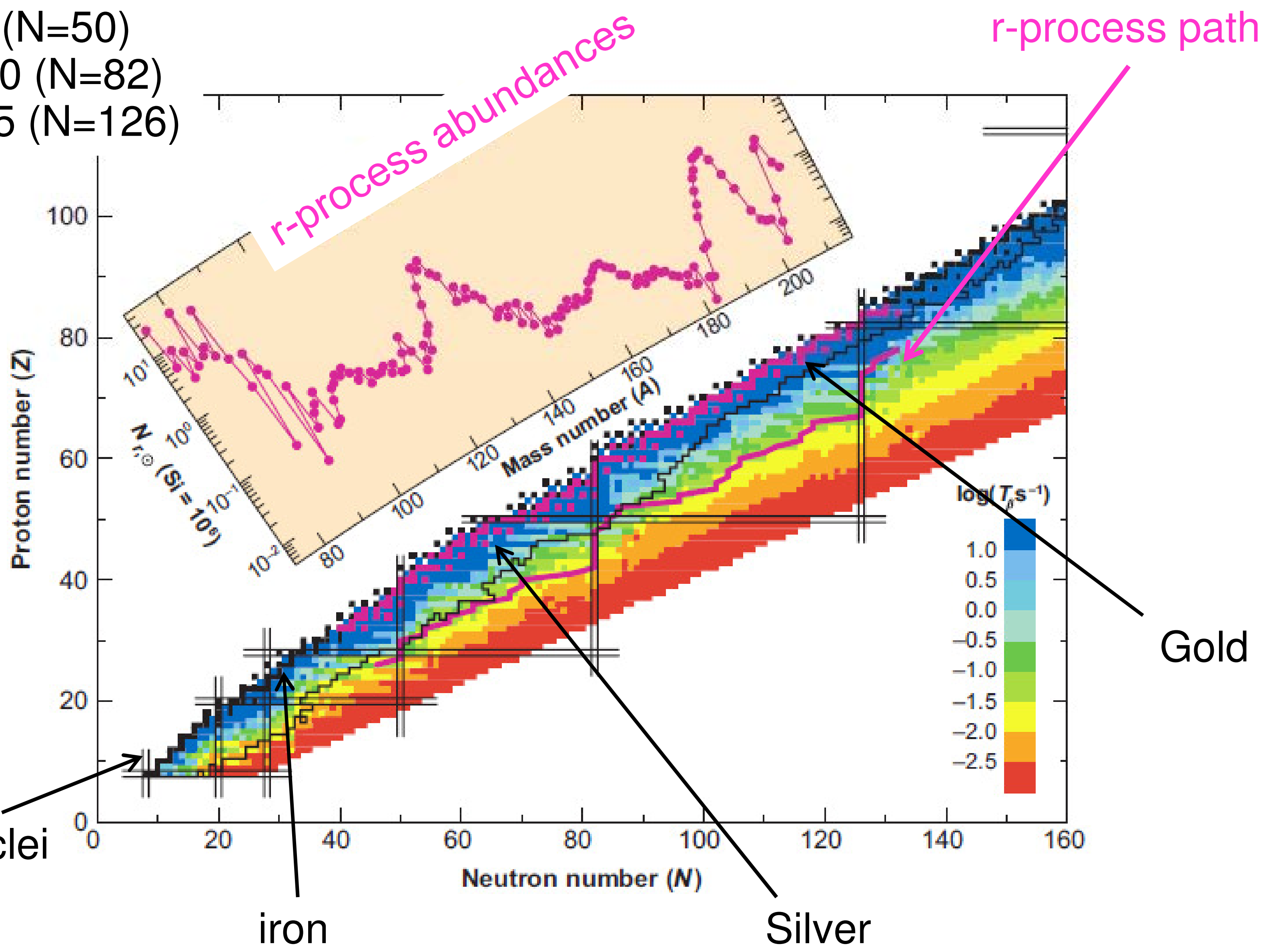
U. Frischknecht (U Basel & U Keele)

➔ 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!

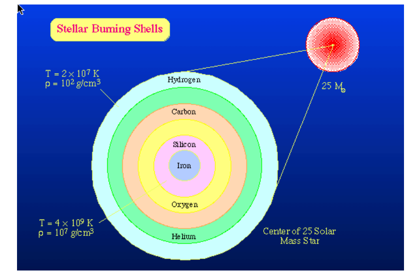


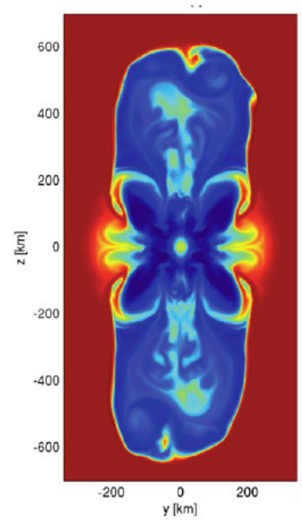
The r-process site

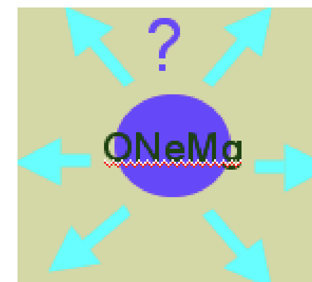
- Most important criteria for an r-process site:
  - High neutron density
  - Eject material
- Neutron sources:
  - Neutrons in nuclei (must be liberated)
  - Neutron stars
  - Made through weak reactions
- Conditions:
  - High entropy, alpha-rich freeze-out
  - Low entropy, normal freeze-out with very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

The r-process site(s)

- Neutrino-driven wind in CCSNe
- He-shell of CCSNe
- Jets from CCSNe
- Accretion disks from CCSNe
- ONeMg core collapse



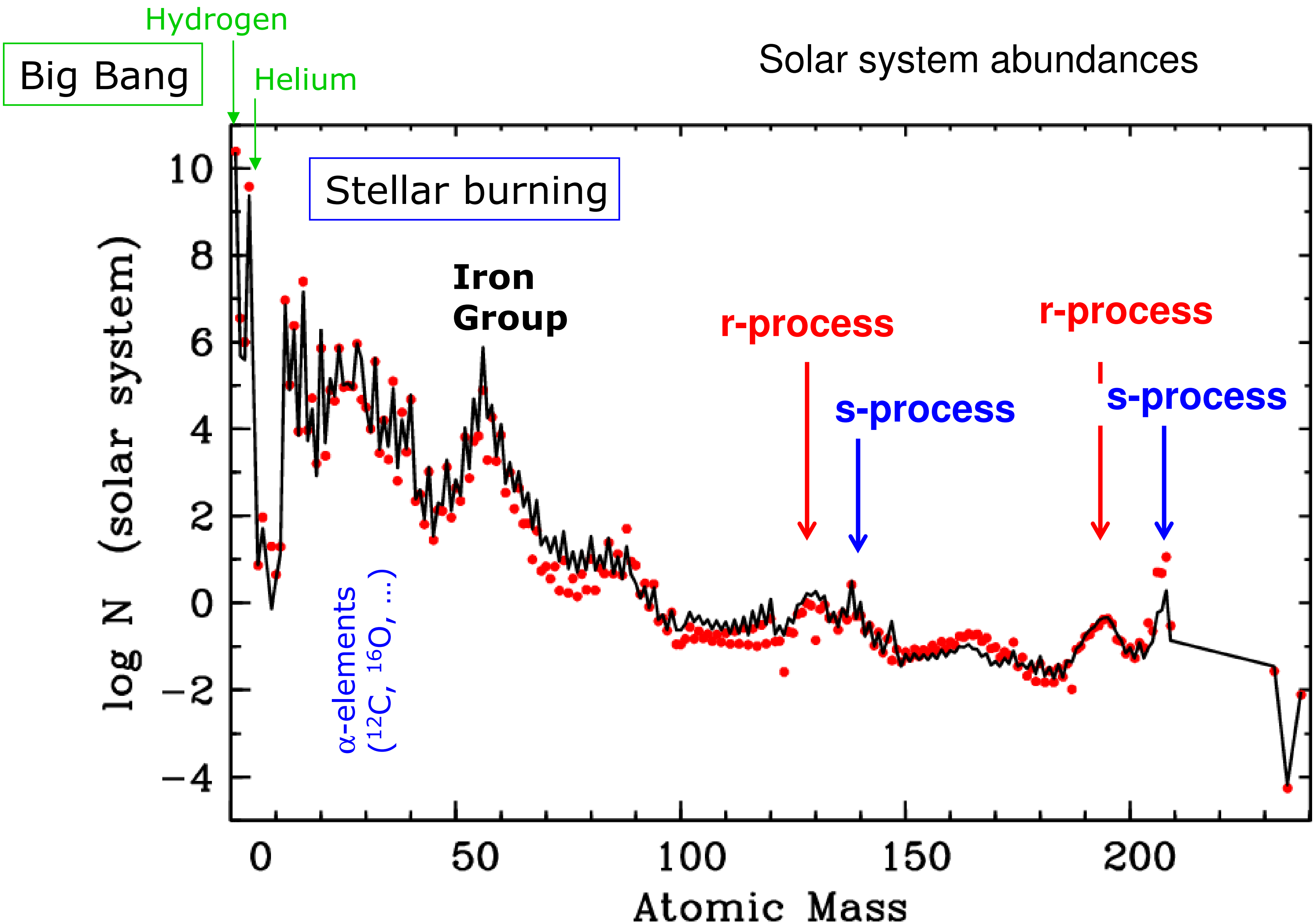




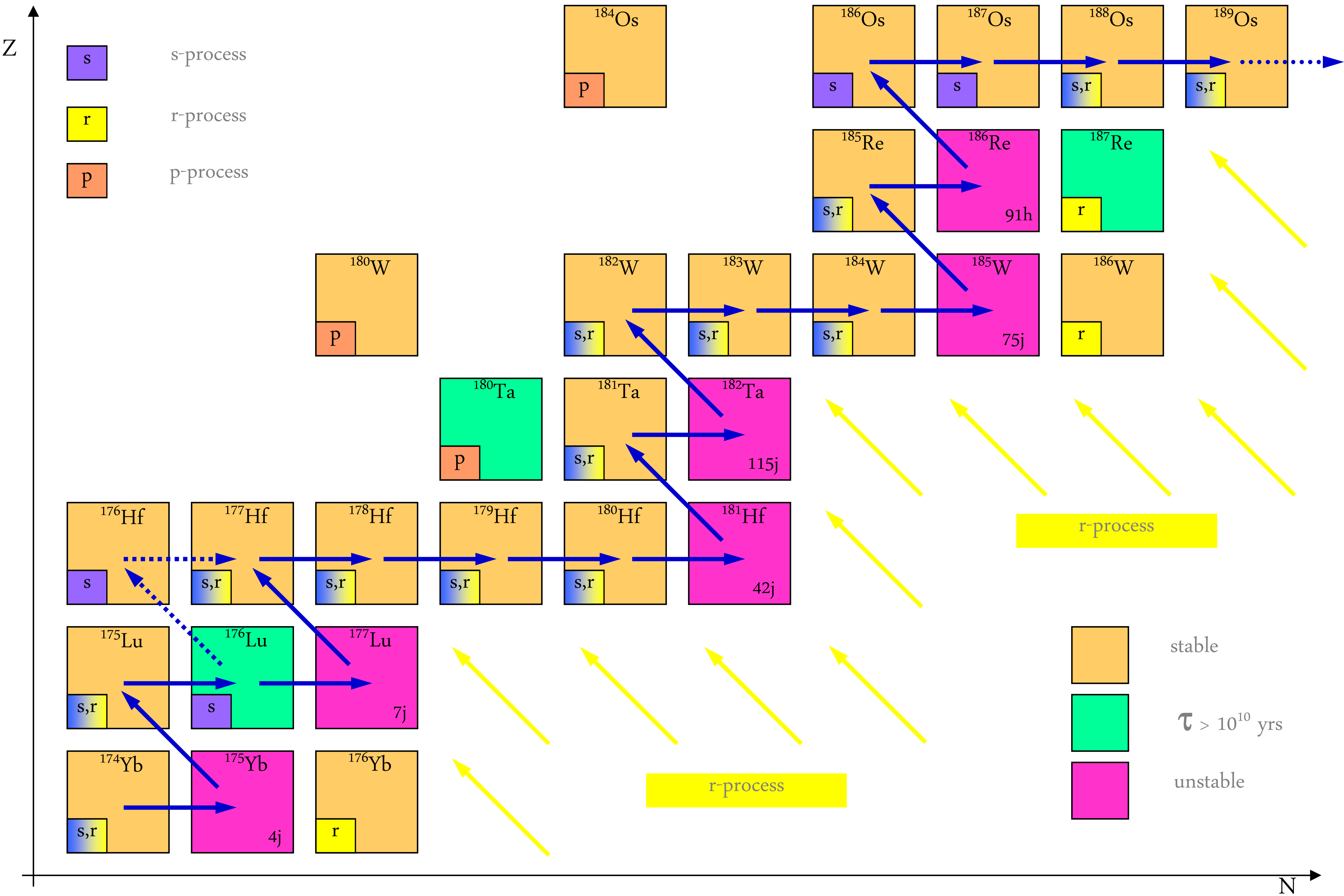
- Tidal ejection of matter from NS mergers
- Accretion disk outflows from compact object mergers (NSNS or NSBH)
- Shocked ejecta from compact object mergers

- Neutrino flavor oscillations in CCSNe

Origin of elements

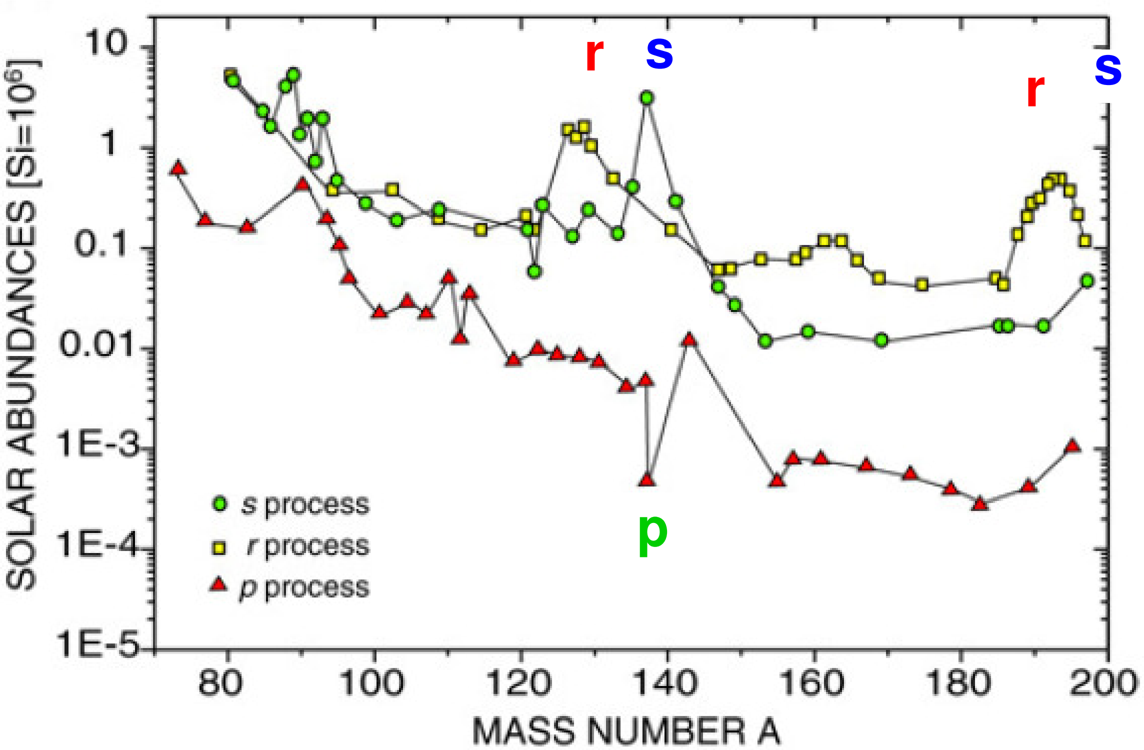


The neutron-capture processes



The p-process (for the p-nuclei)

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

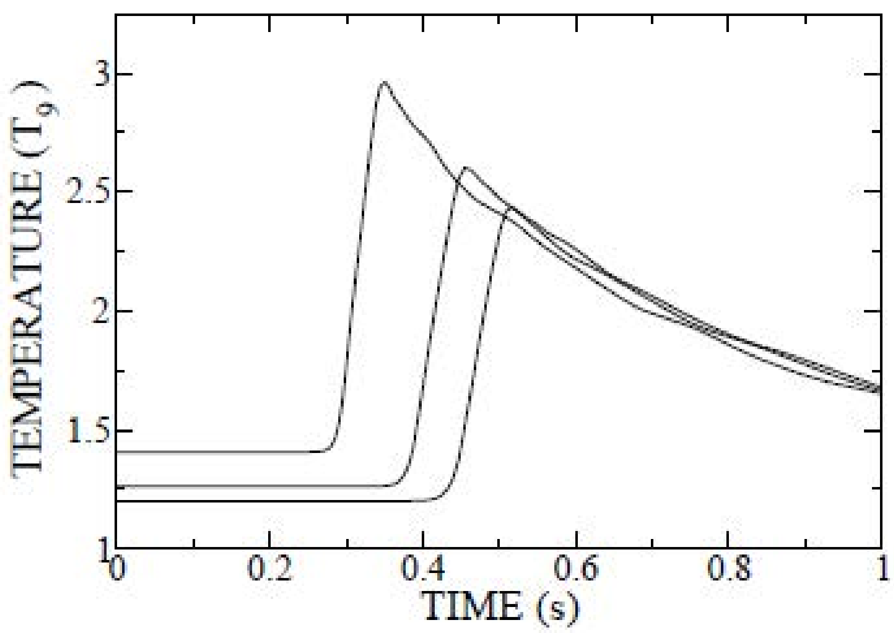


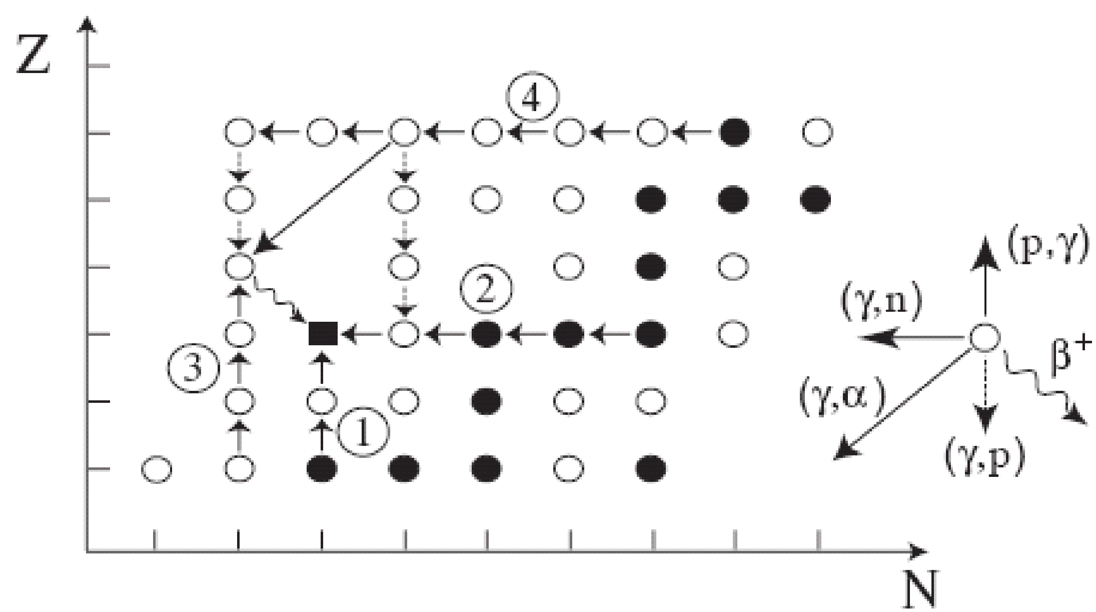
Now understood to be several processes:

- **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





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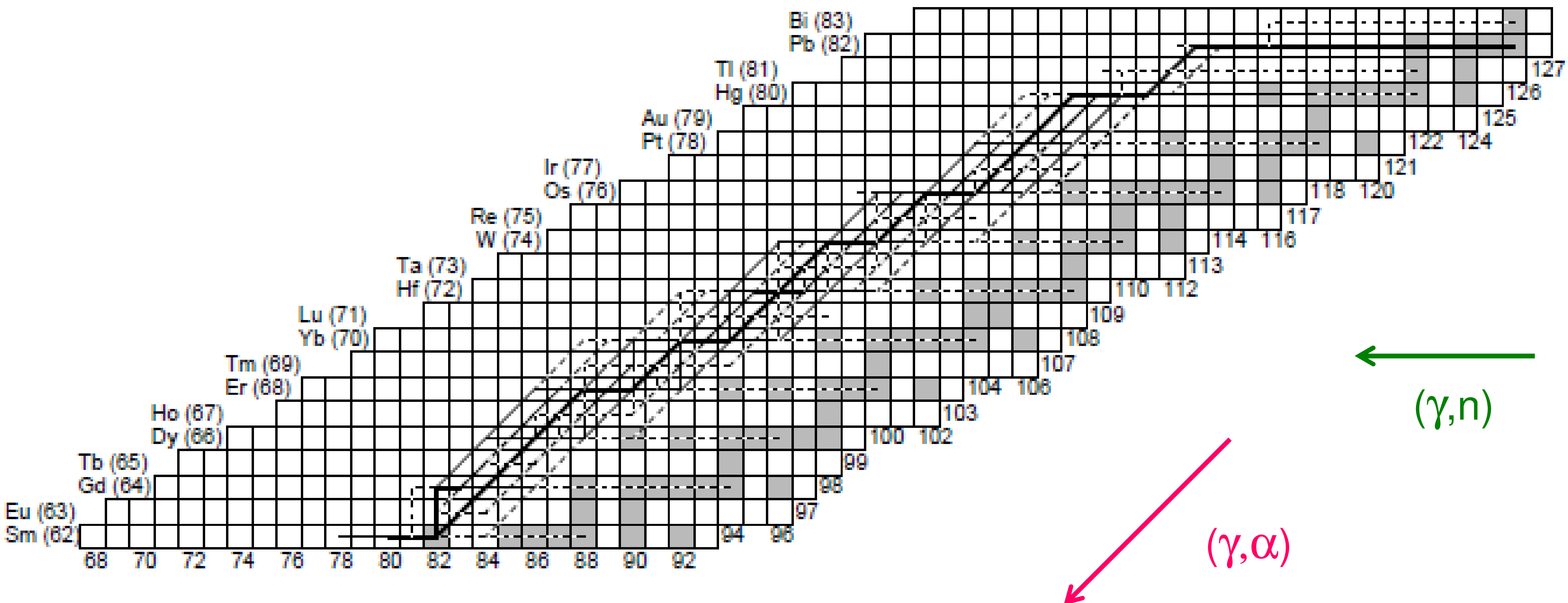
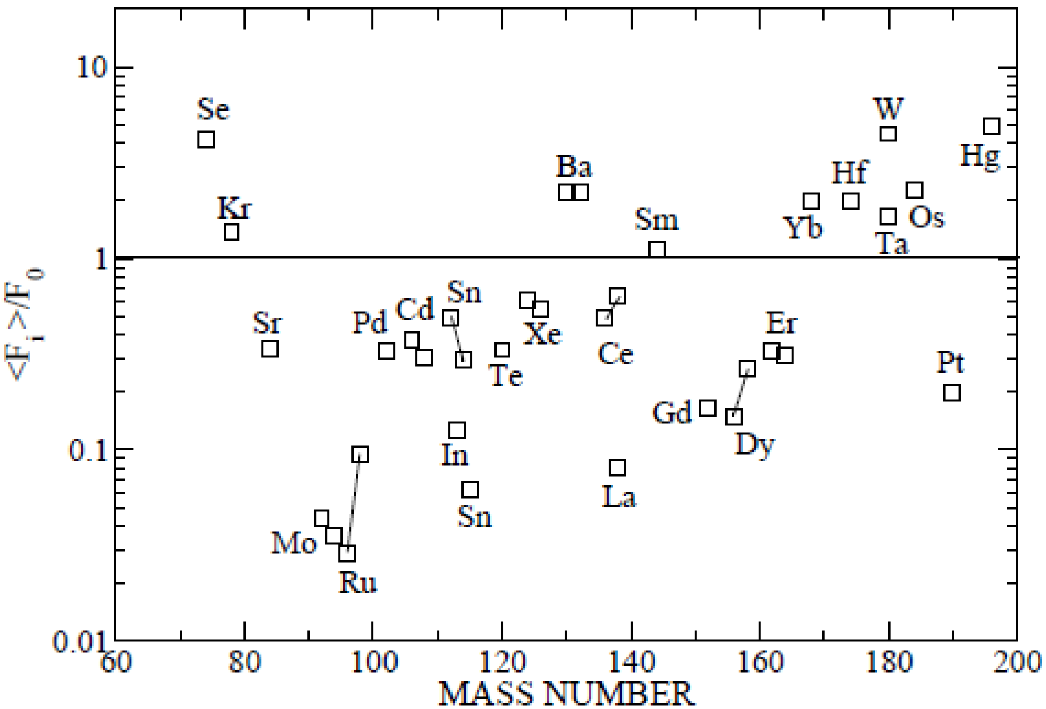


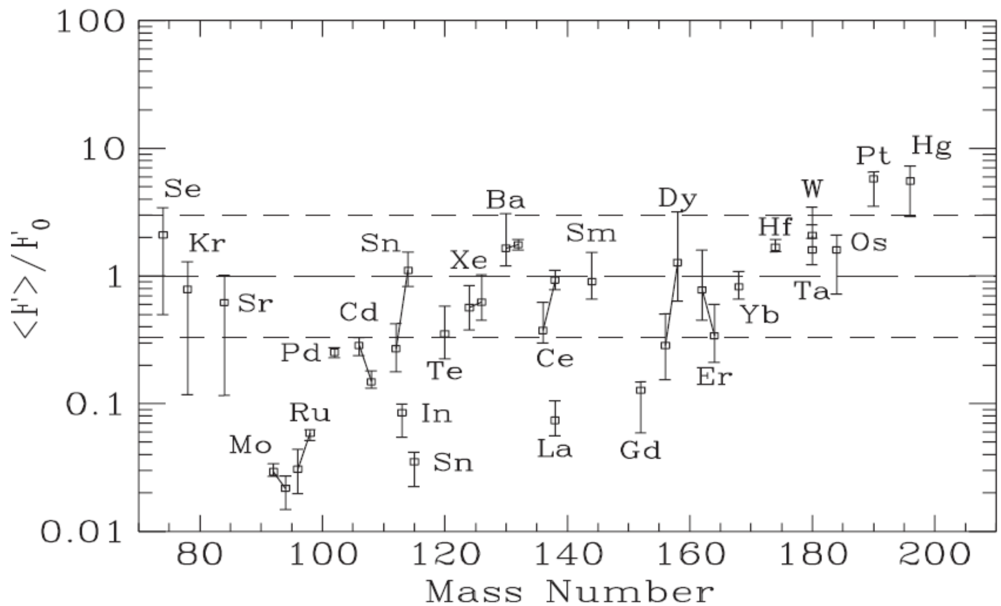
Rapp et al (2006)

The γ-process

- Predicted p-nuclei overproduction



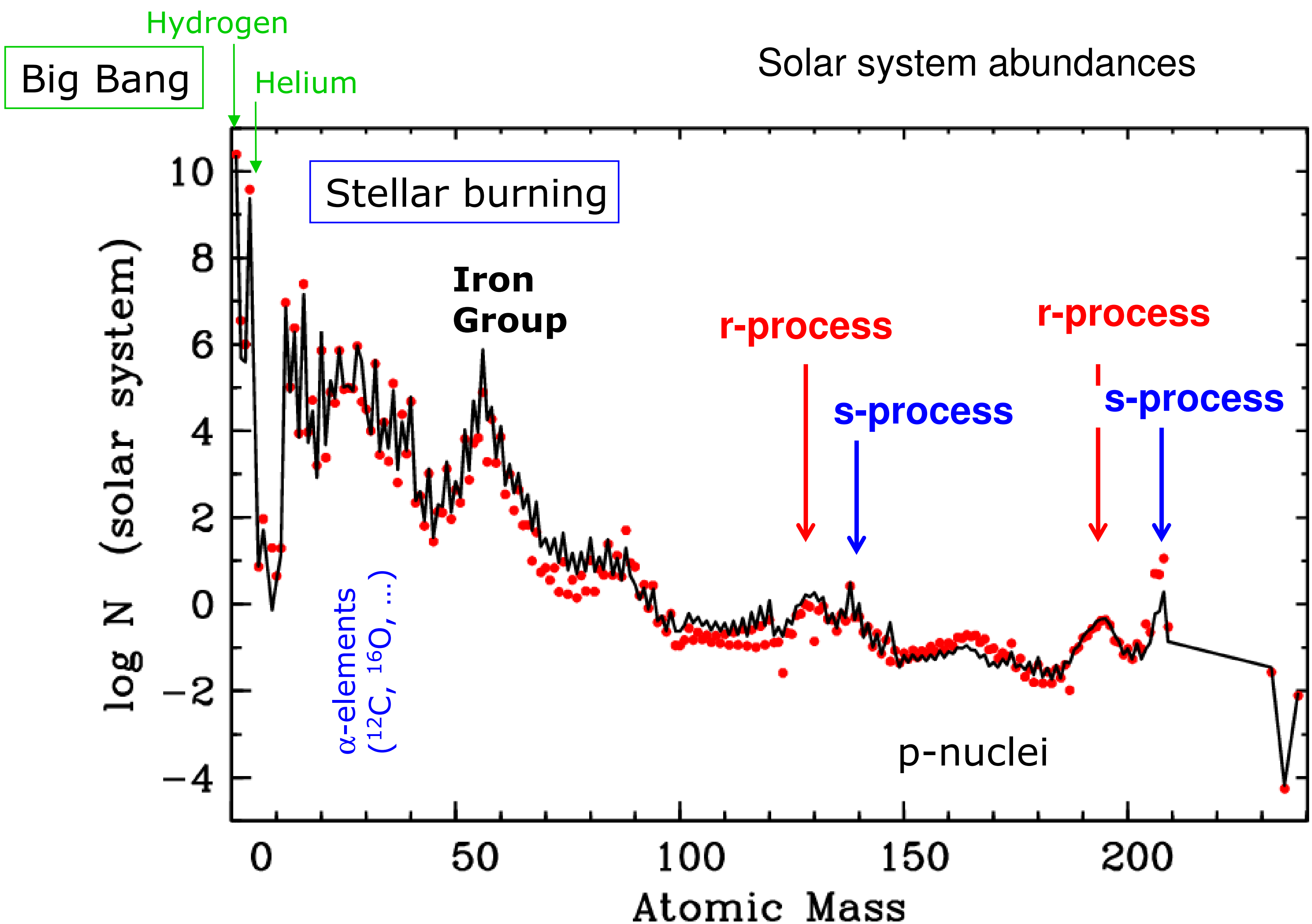
Rapp et al (2006)



Arnould & Goriely (2003)

→ Underproduction of light p-nuclei

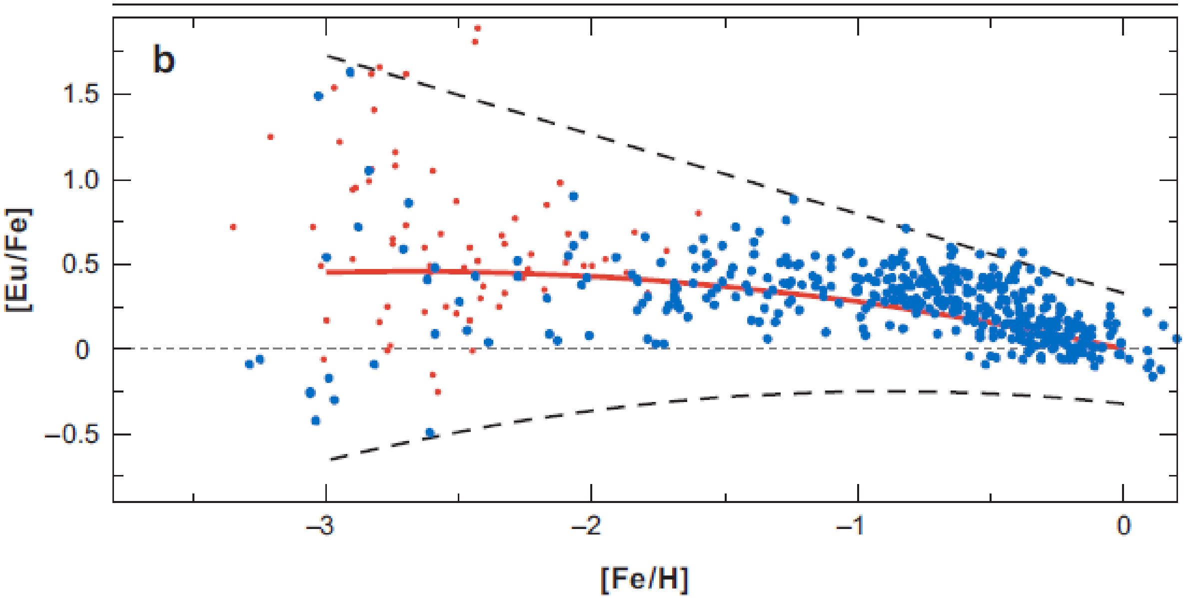
Origin of elements



Observations

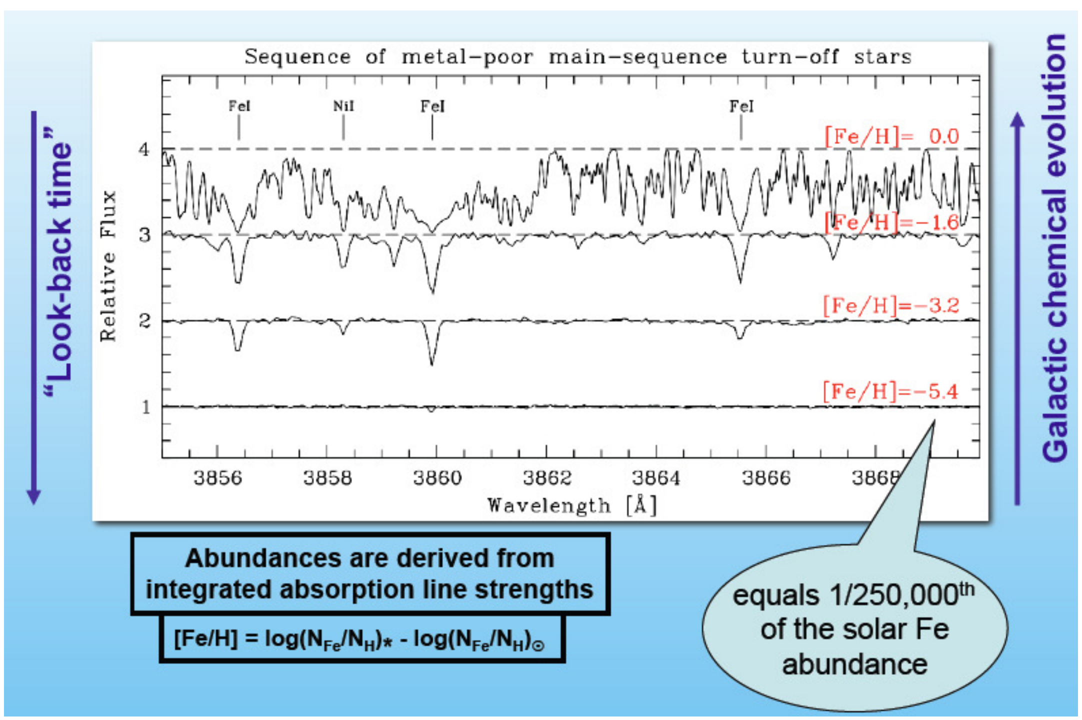
- What old (metal-poor) stars tell us

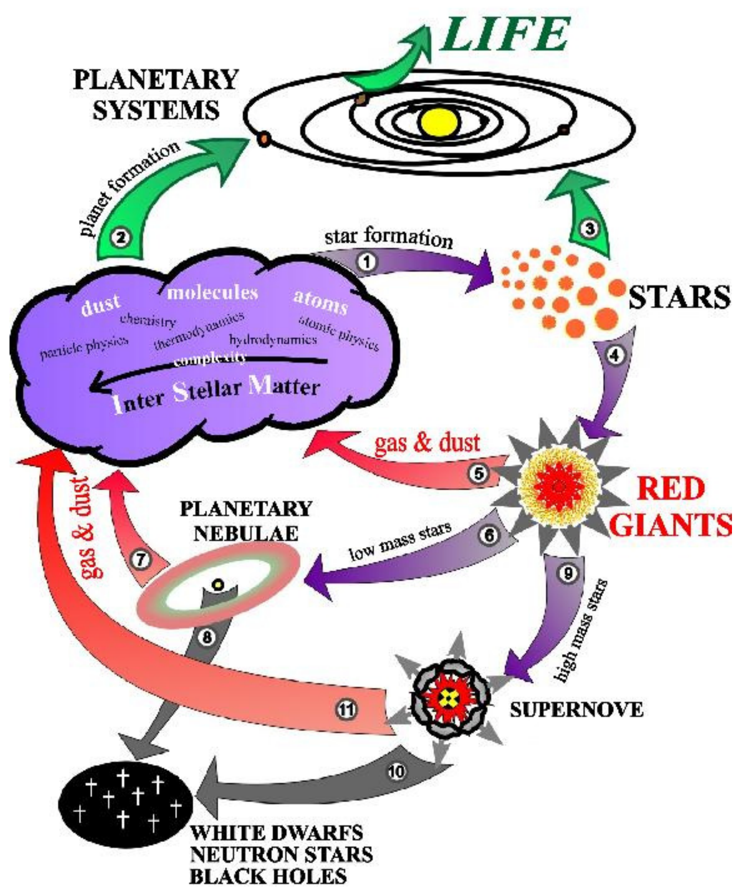
Trends with metallicity



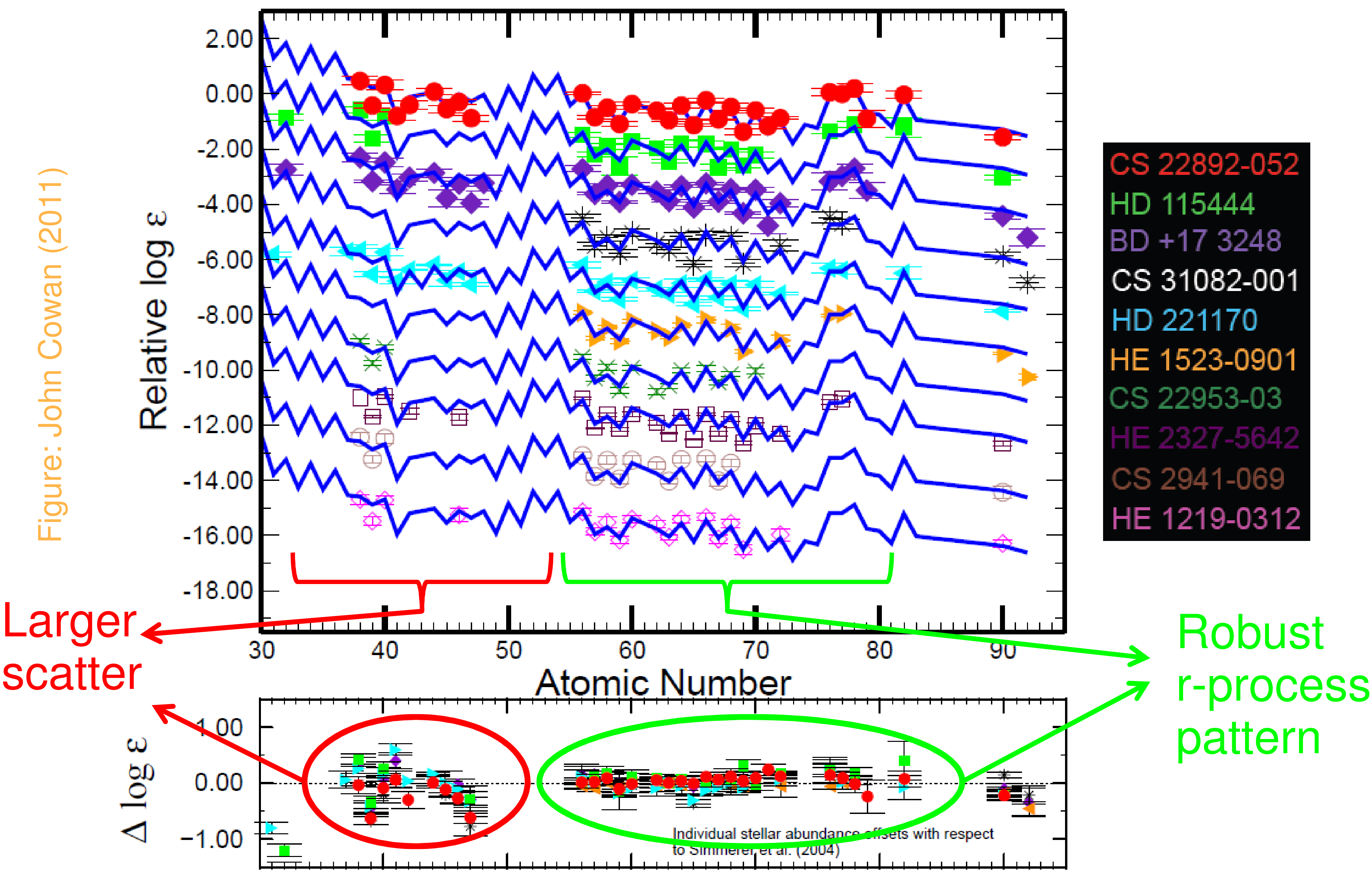
Significant scatter at low metallicities

r-process is rare in early Galaxy



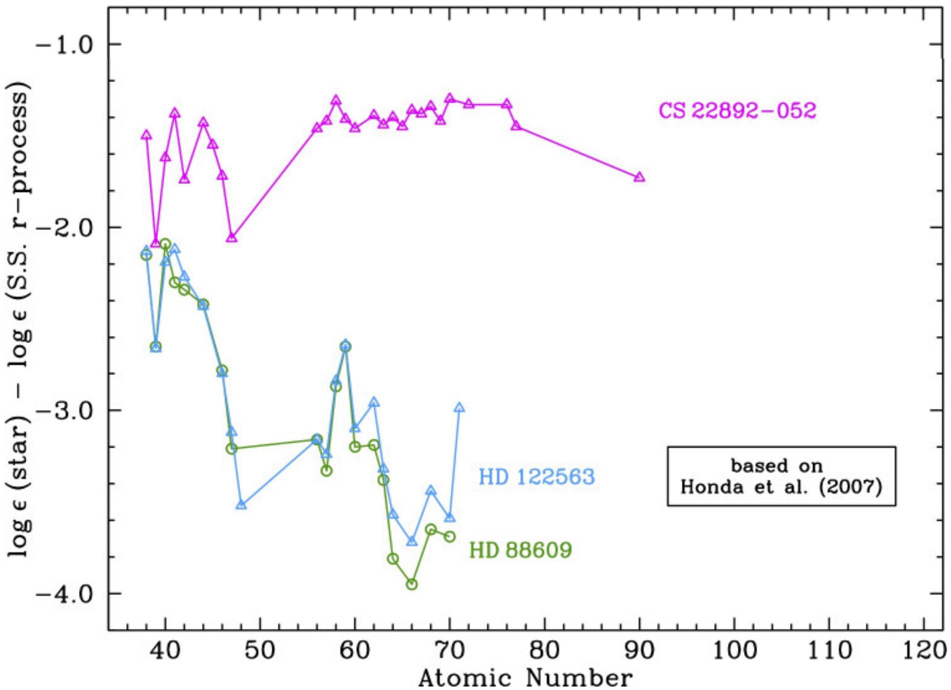


The oldest observed stars



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

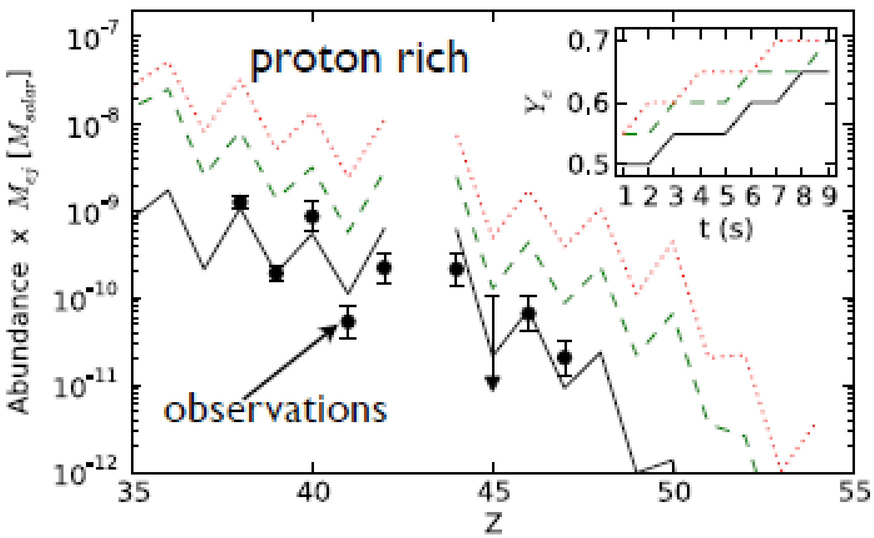
- Observations of halo stars indicate two "r-process" sites:
  - Main r-process
  - Stellar LEPP / weak r-process
- Solar LEPP

  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

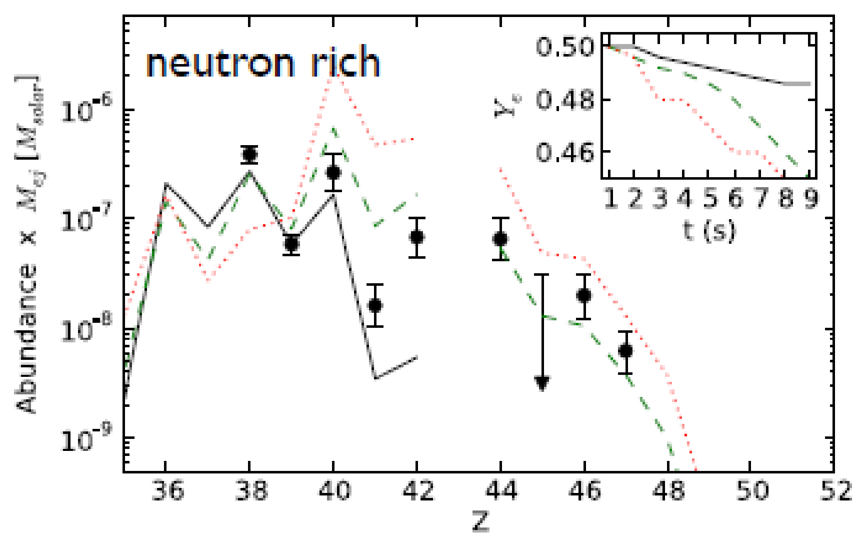
  Montes et al (2007)
  - Same as solar LEPP?

LEPP: Lighter Element Primary Process

- Some amount of proton-rich ejecta from CCSN neutrino-driven winds is needed to be compatible with observations



Observed pattern reproduced
Production of p-nuclei



Overproduction of A=90 (N=50)
→ Only a fraction of neutron-rich ejecta (Hoffman et al 1996)

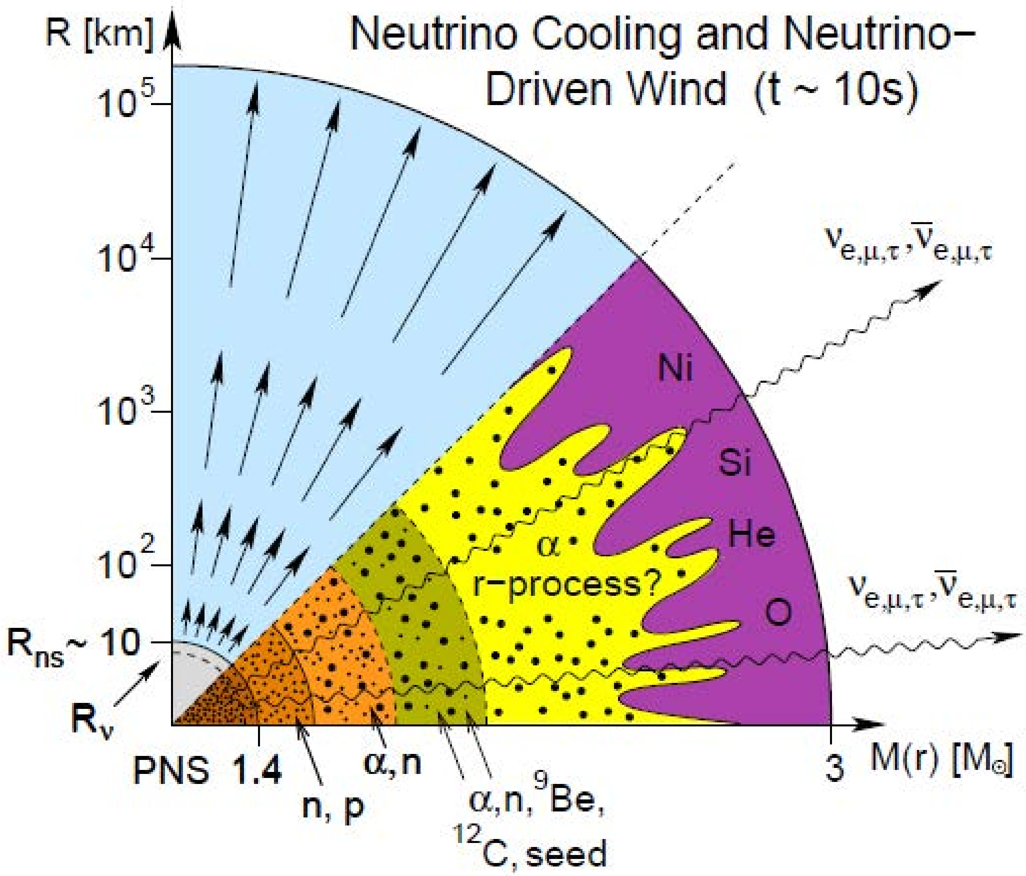
Arcones & Montes (2011)

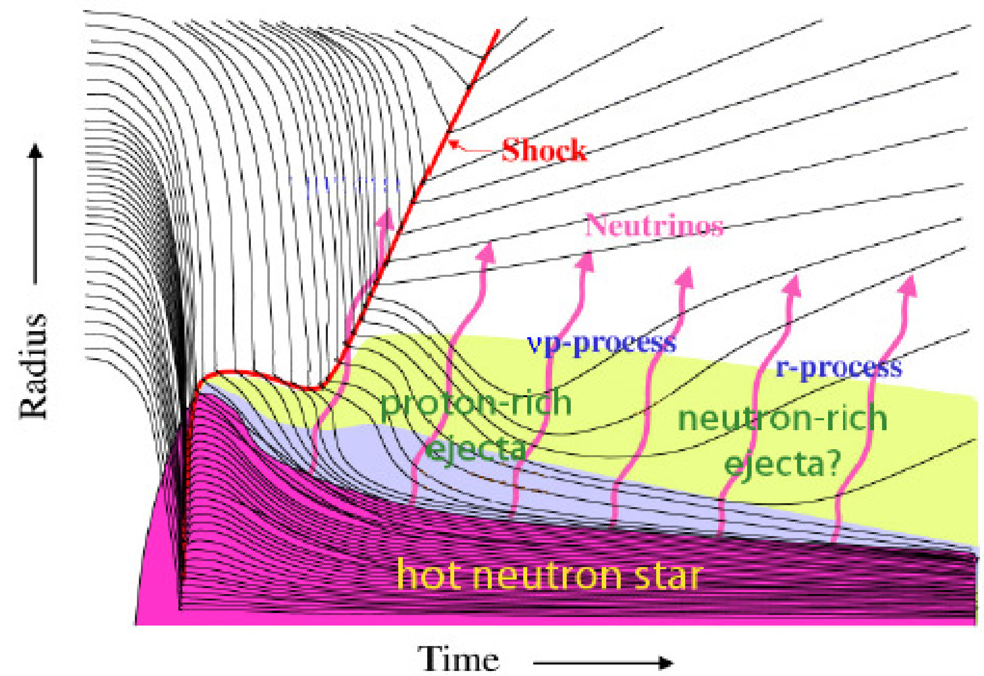
Neutrino-driven winds

- Core-collapse supernovae explode early
- Conditions of neutrino-driven wind

→ ideal site for the r-process ?!

Neutrino-driven winds in CCSNe





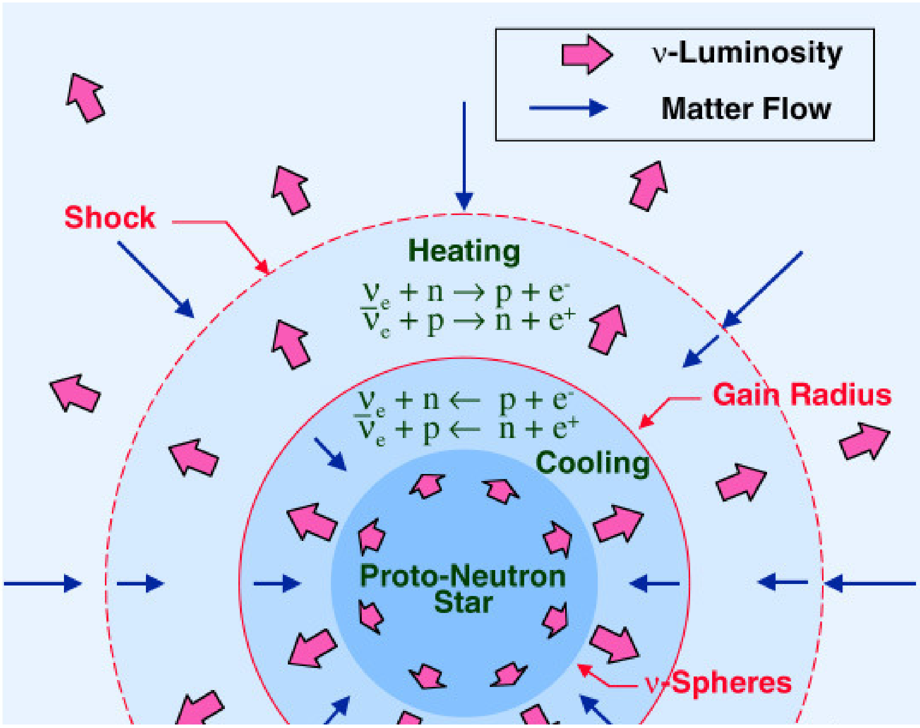
T = 10-8 GK → T = 8 - 2 GK → T < 3 GK

NSE

charged-particle reactions;
α-process

(weak) r-process
νp-process

Neutrinos from CCSNe



ν-spheres:
- where neutrinos decouple
  → sets neutrino energies
- Deeper inside for μ/τ neutrinos
  → larger energies (20-30 MeV)
    - $\bar{\nu}_e$: 13-19 MeV
    - ν_e: 8-13 MeV

Effects of neutrinos

Heating:

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

Opacity:

$$\nu_e + A' \leftrightarrow A + e^-$$
$$\nu + N \leftrightarrow \nu + N$$
$$\nu + A \leftrightarrow \nu + A$$

Thermalization:

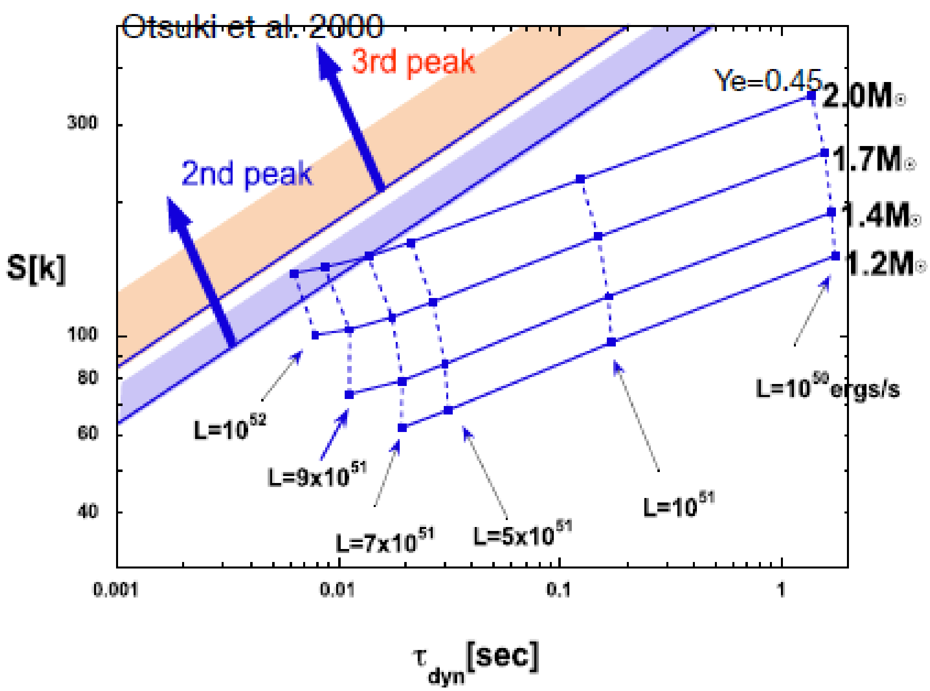
$$\nu + e^- \leftrightarrow \nu + e^-$$
$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$

Source terms (all flavors):

$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$
$$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$$

Wind conditions for r-process

- High neutron-to-seed ratio: Y_n/Y_{seed} ~ 100
- Short expansion timescale: 10^{-3} to 1 second
  → inhibits formation of nuclei through α-process
- High entropy: s/k_B ~ 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??

- If neutrino-driven winds from CCSNe (currently) cannot produce an r-process, what can they do?

Electron fraction in neutrino-winds

- Electron fraction Ye: set by weak interactions

$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\overline{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$

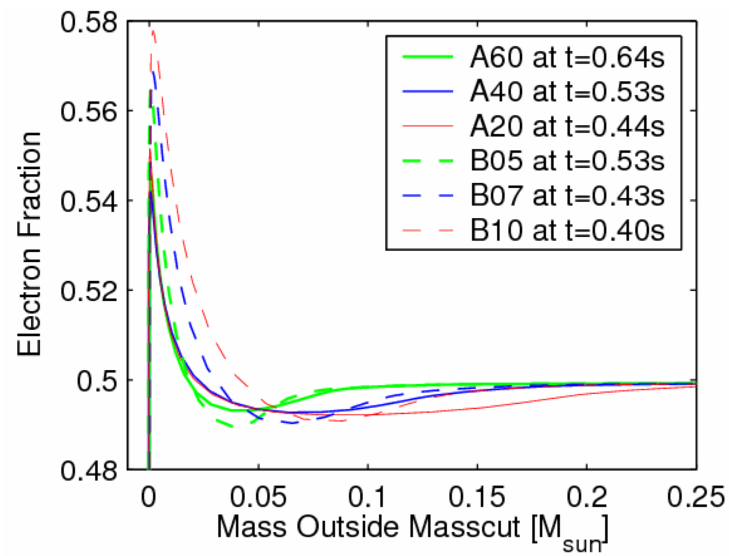
$$Y_e = \frac{Y_p}{Y_p + Y_n} = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e, p}}{\lambda_{\nu_e, n}}}$$

  - Luminosity ratio $L_{\bar{\nu}_e} / L_{\nu_e}$
  - Difference in neutrino energies: $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e}$
    - Proton-rich if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2) \approx 5.2\mathrm{MeV}$
  - Details of nuclear physics (nuclear potentials, etc)
    - EOS treats neutrons and protons as non-interacting particles in mean field potential → need to be consistent
    - Up to 10 MeV difference in neutrino energies

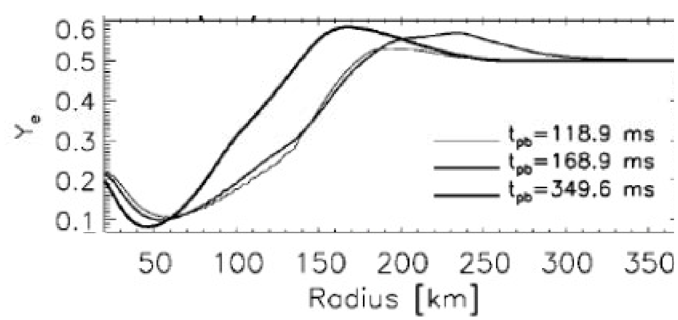
Proton-rich winds

Ye>0.5 is generic result of simulations with elaborate ν-transport

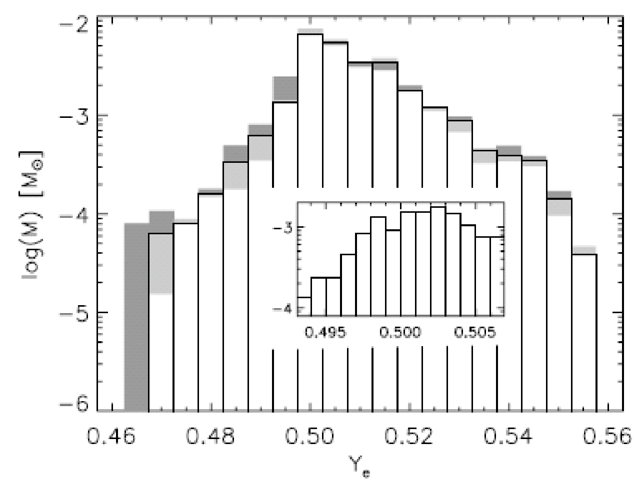
$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\bar{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$



Liebendörfer et al (2001)
Frohlich et al (2006)



Rampp & Janka (2000)



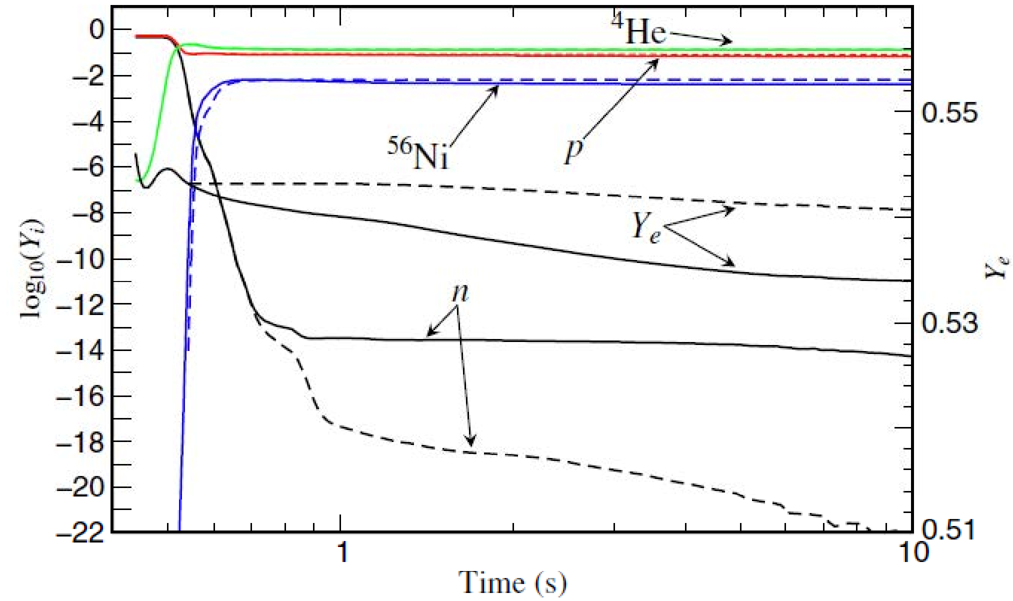
Buras et al (2006)

- If the neutrino flux is sufficient (scales $1/r^2$):
- High density / low temperature → high E_F for electrons → e-captures dominate → n-rich
- If electron degeneracy lifted for high T → ν_e-captures dominate → due to n-p mass difference, p-rich composition

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:

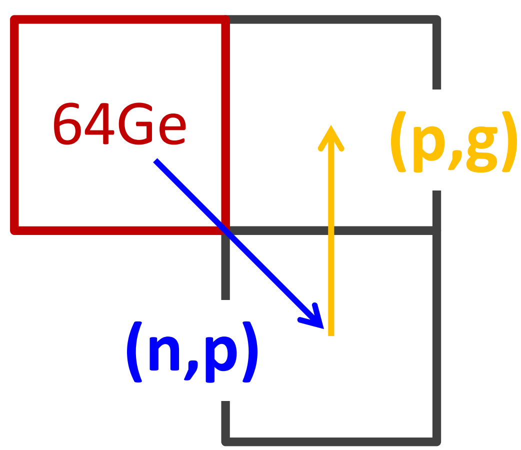
$$\overline{\nu}_e + p \rightarrow n + e^+$$

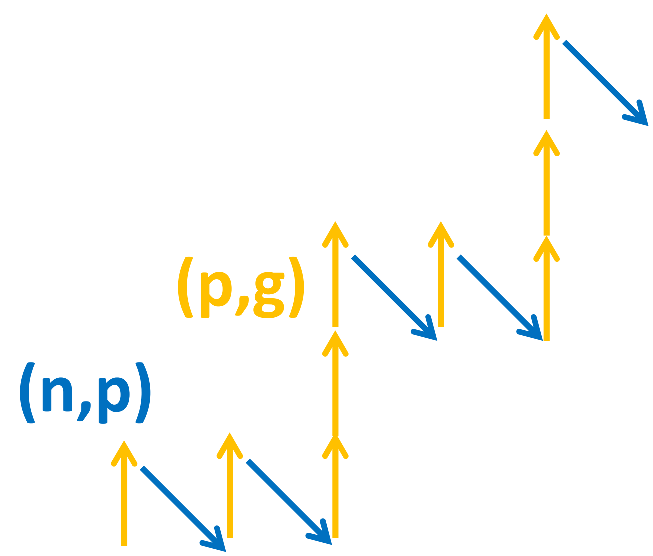


Frohlich et al (2006)

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

64Ge (n,p) 64Ga
64Ga (p,γ) 65Ge





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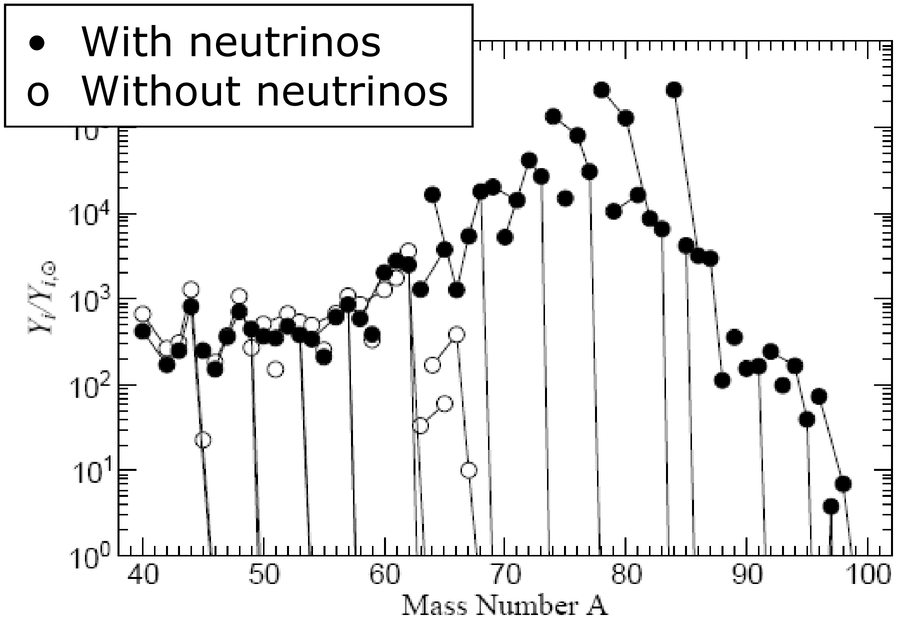

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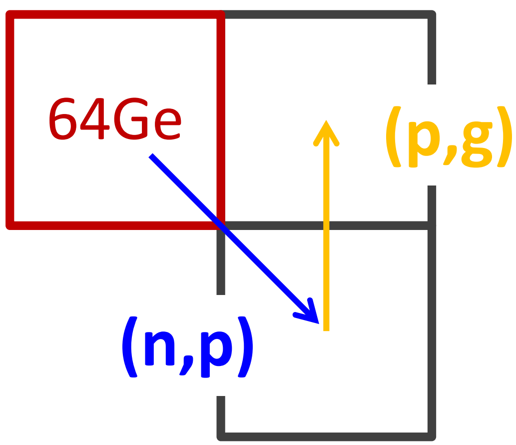

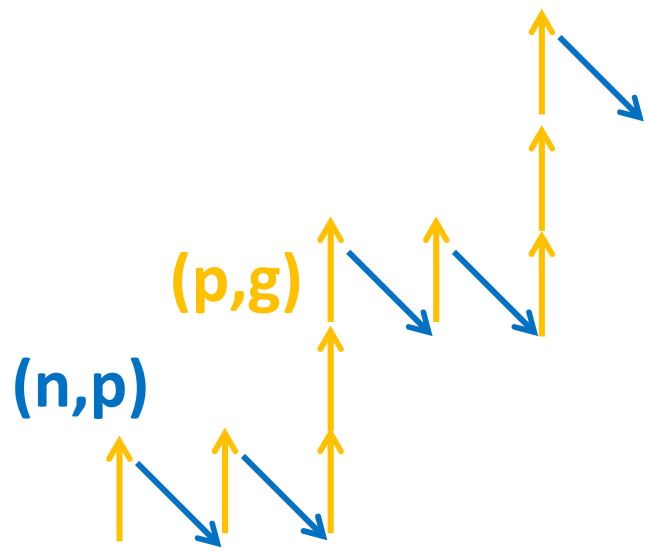

Heavy element synthesis inventory

- 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; in neutrino-driven winds from CCSNe?
  - ???
- νp-process
  - In proton-rich neutrino winds