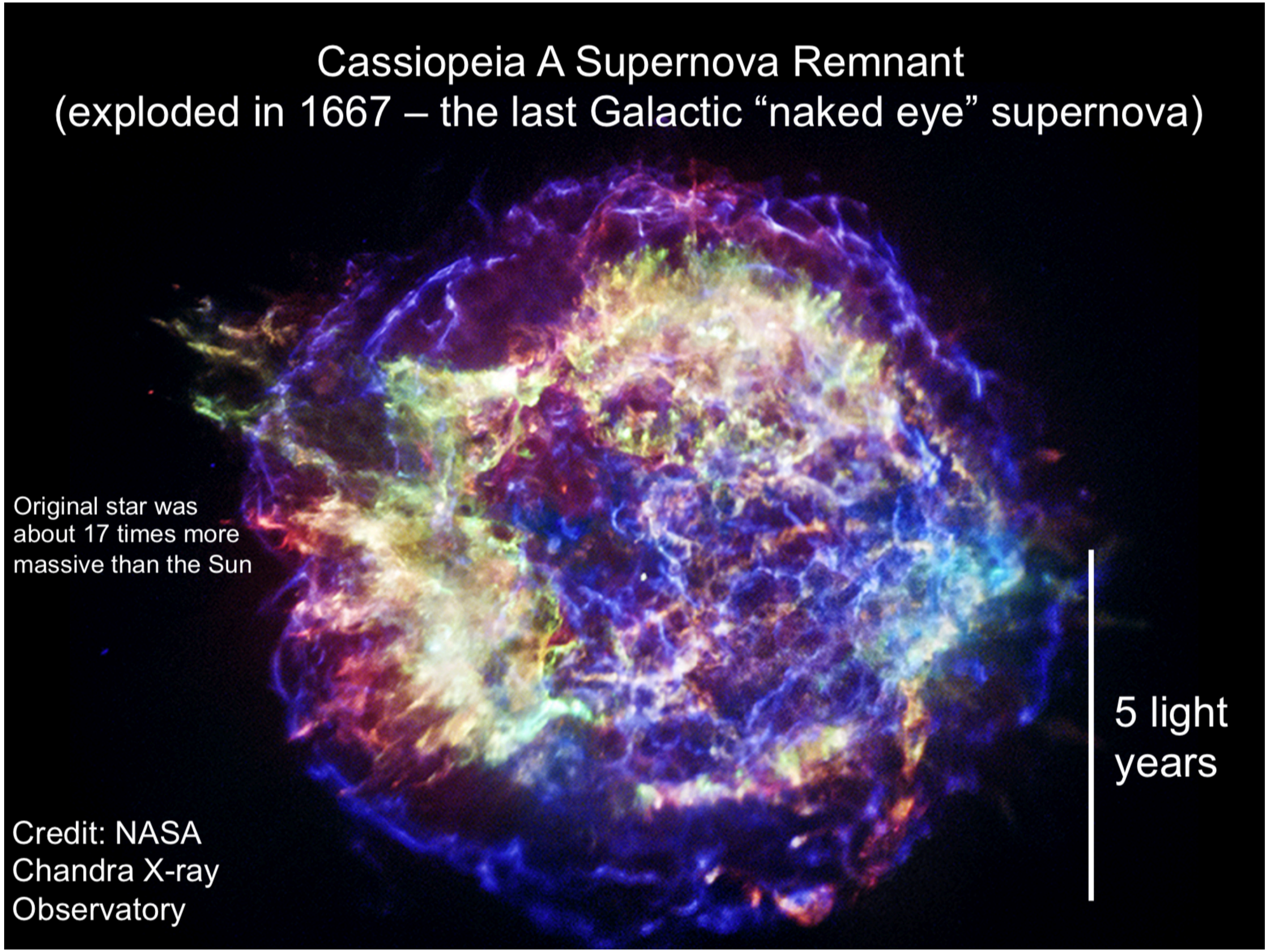
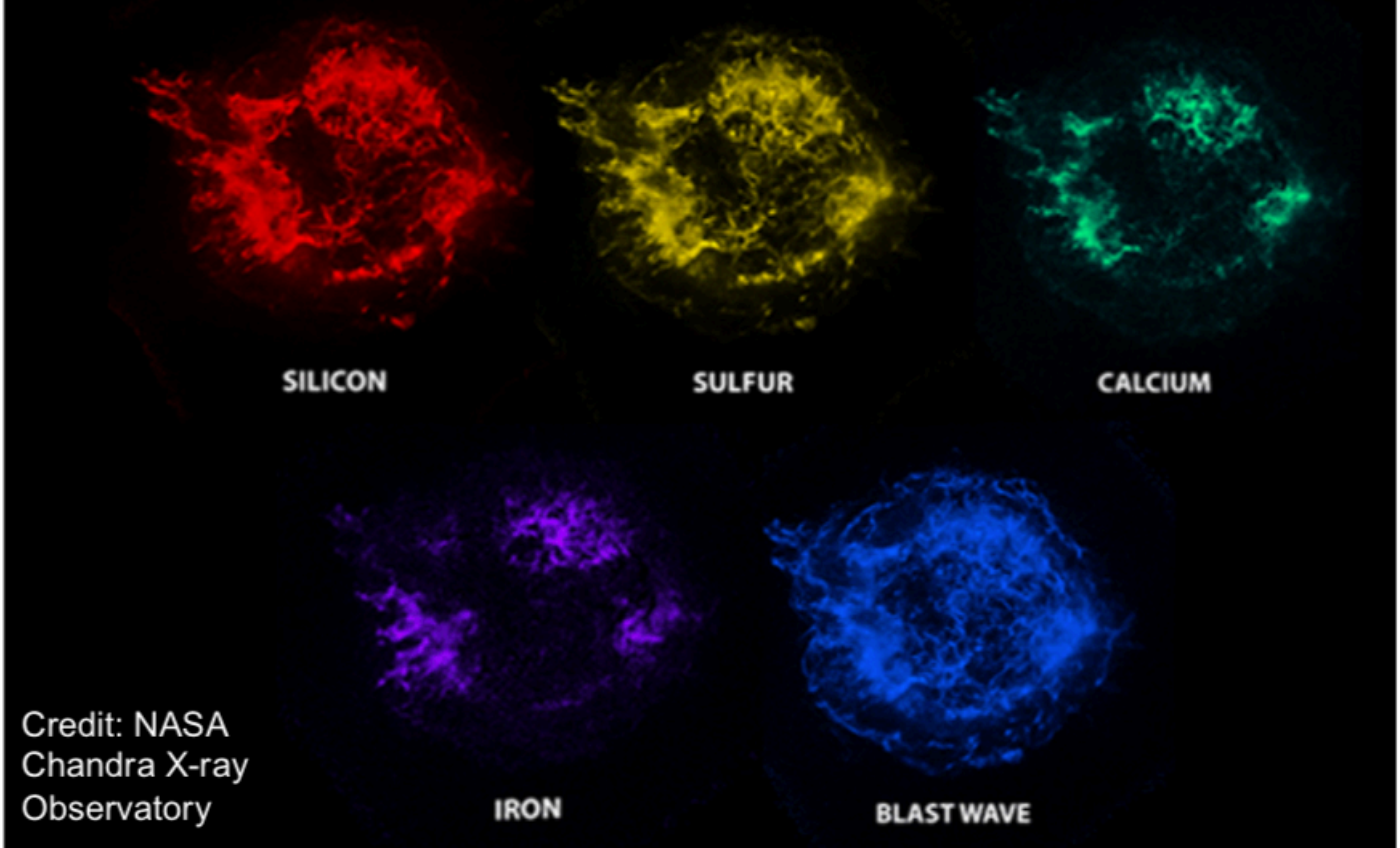
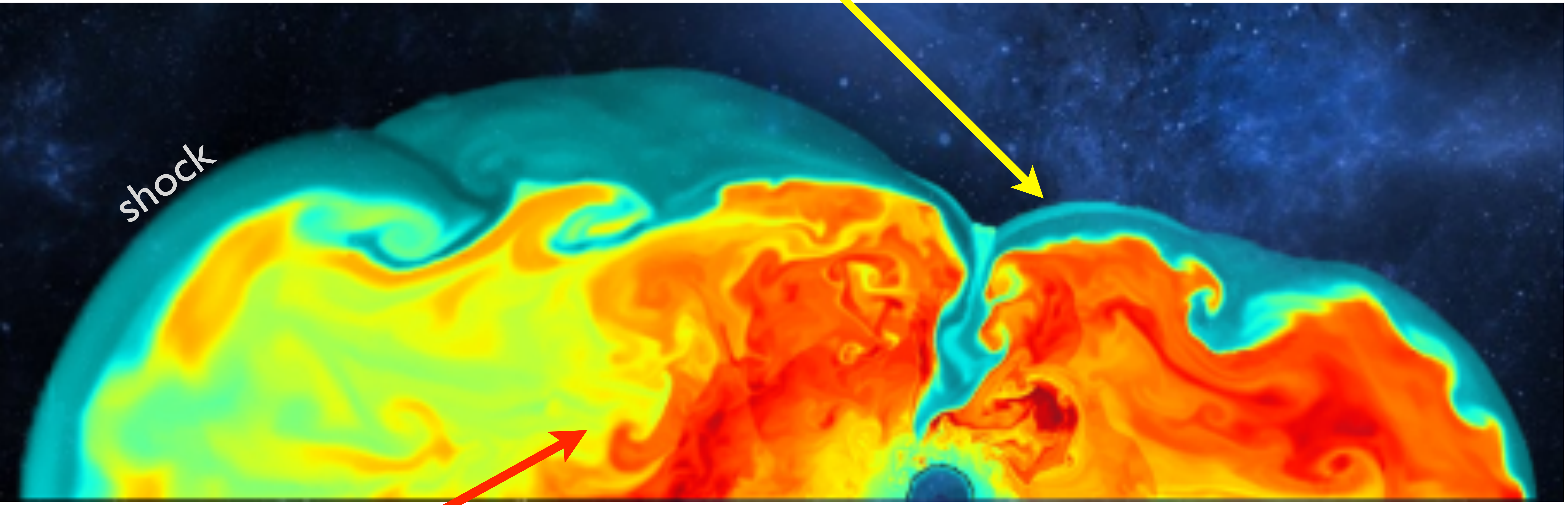
Day 4: Supernova nucleosynthesis




SILICON
SULFUR
CALCIUM
IRON
BLAST WAVE
Credit: NASA
Chandra X-ray
Observatory

Supernova nucleosynthesis

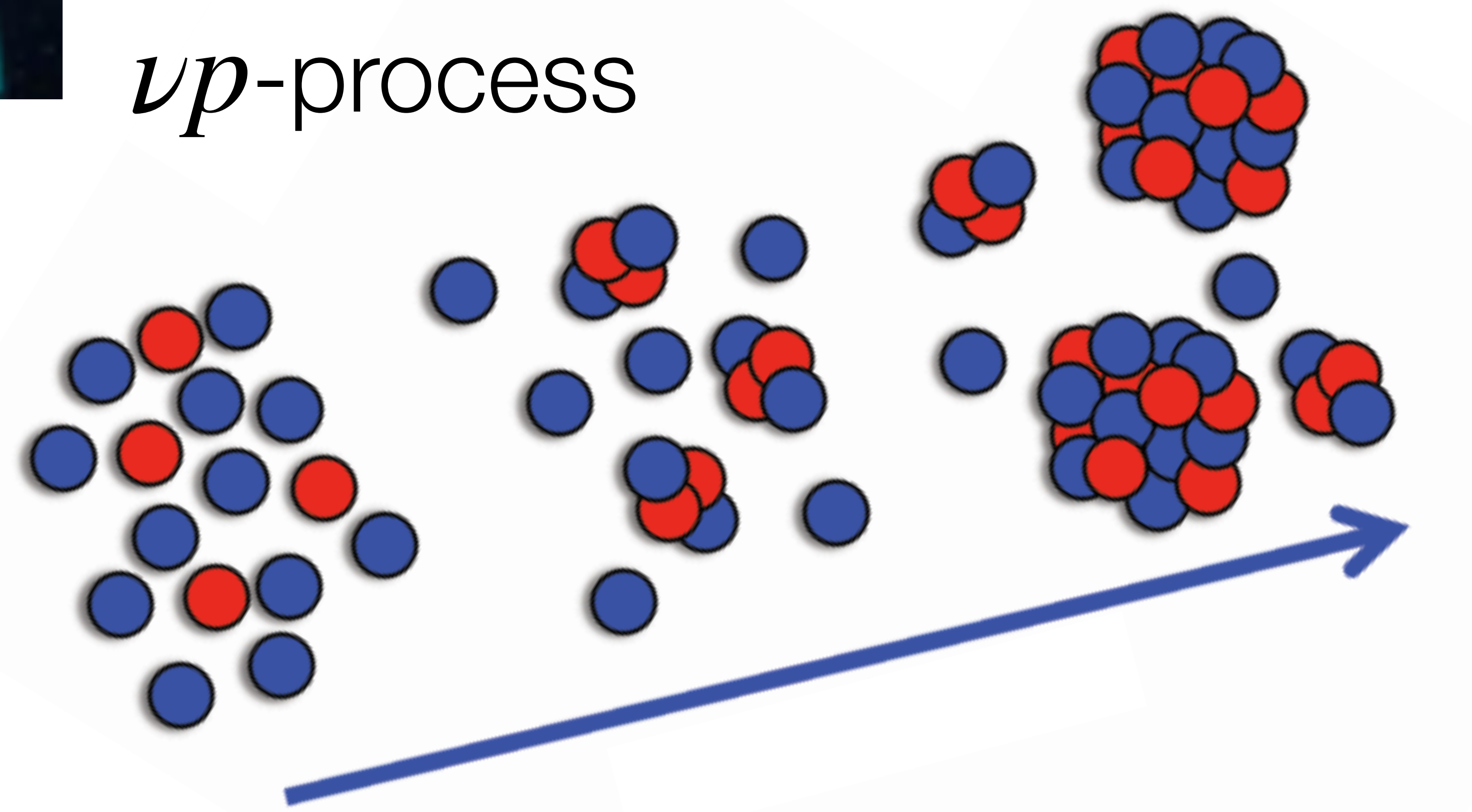
Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter



Nuclear statistical equilibrium (NSE)

charged particle reactions
α-process

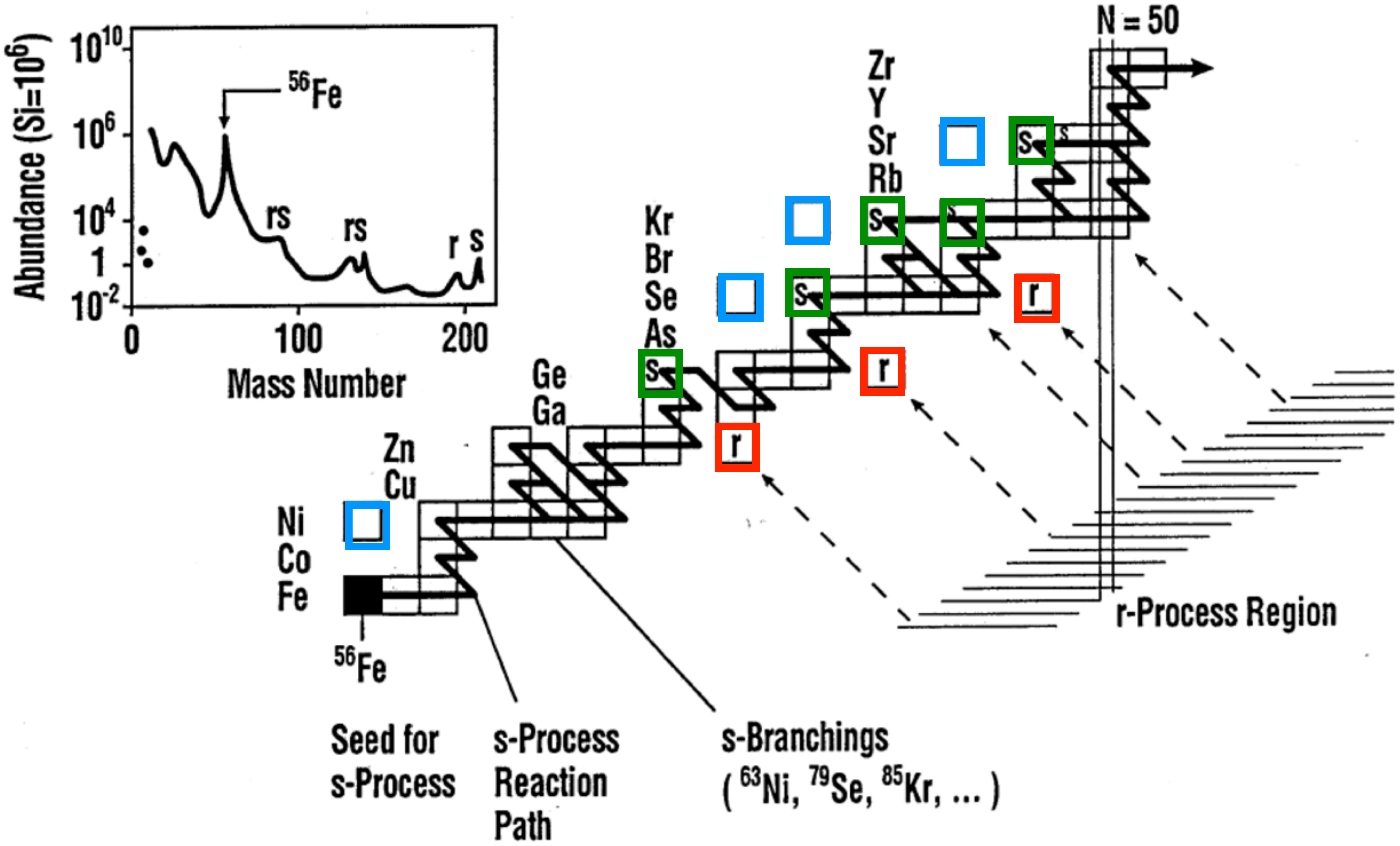
r-process
weak r-process
νp-process



neutrino-driven ejecta

Origin of heavy elements

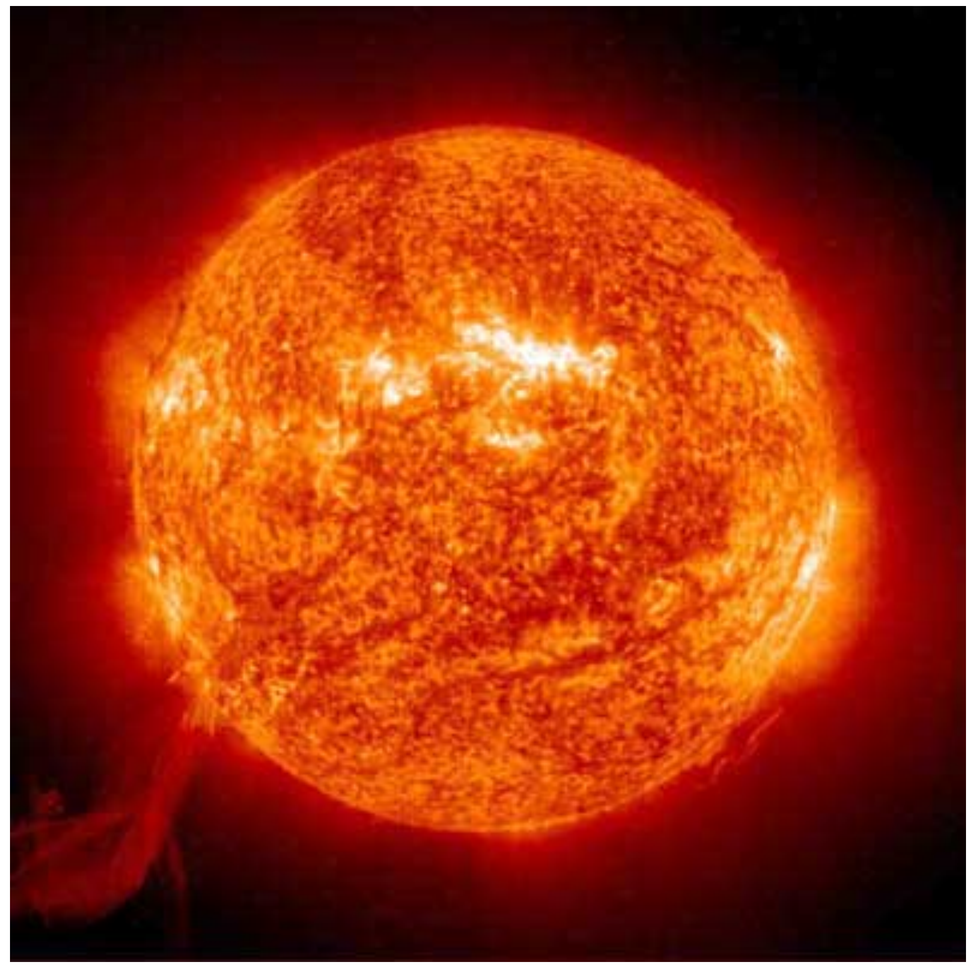
1. S-process
2. R-process
3. P-nuclei

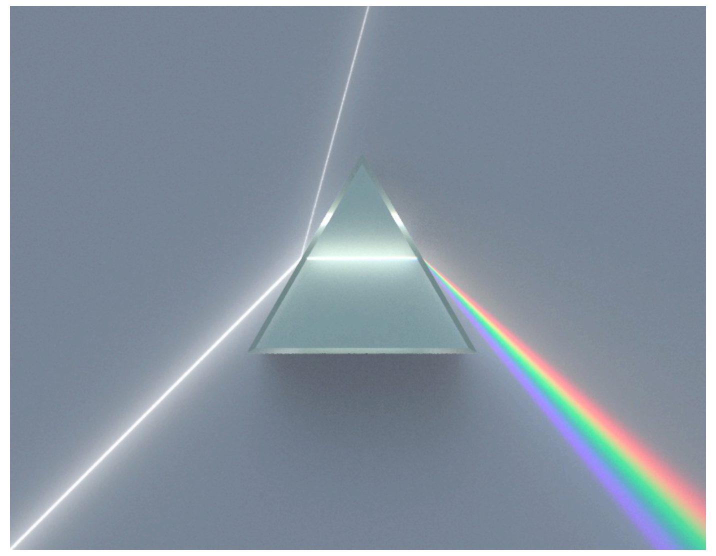


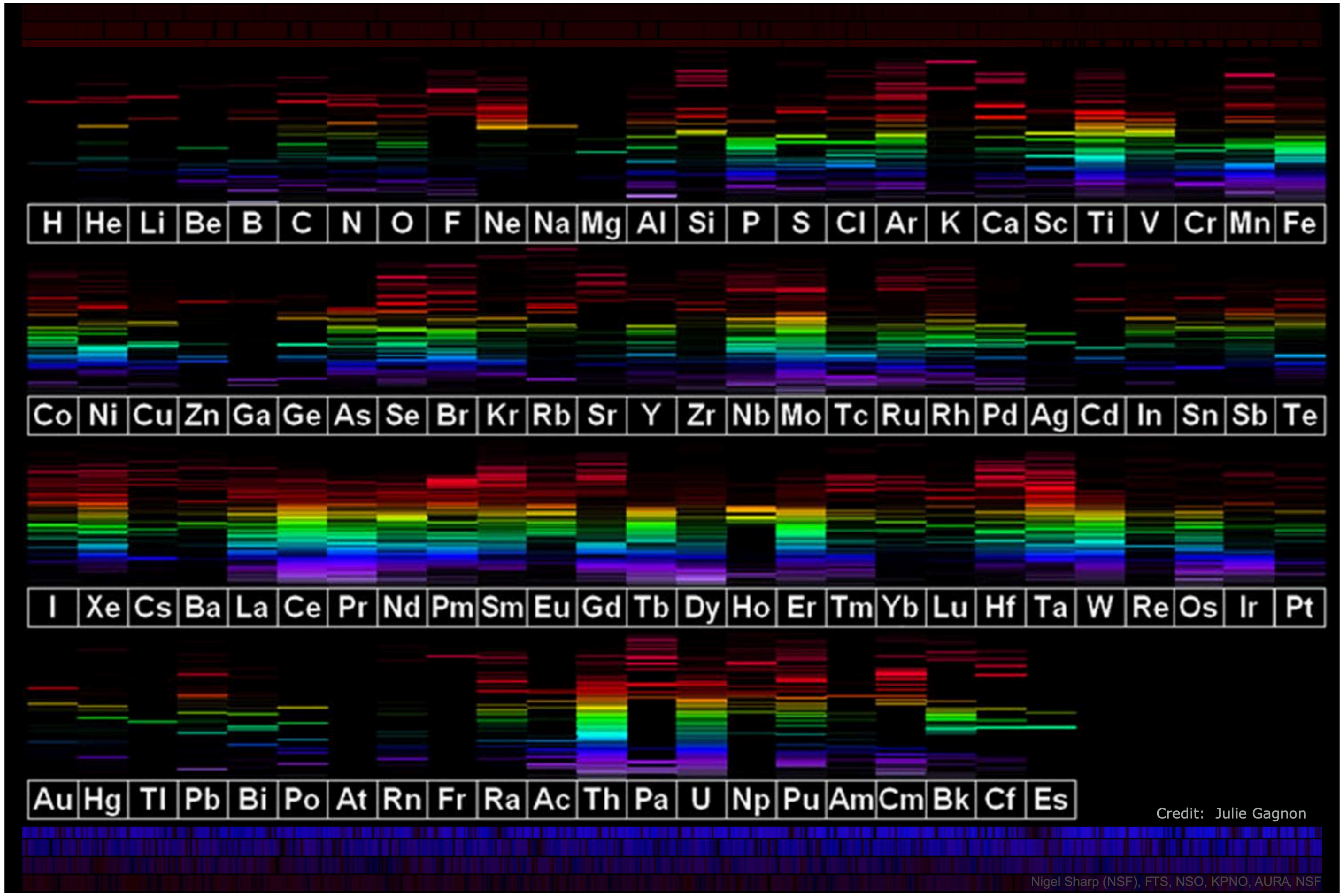
Solar system abundances

Solar photosphere and meteorites: chemical signature of gas cloud where the Sun formed

All nucleosynthesis processes







Solar system abundances

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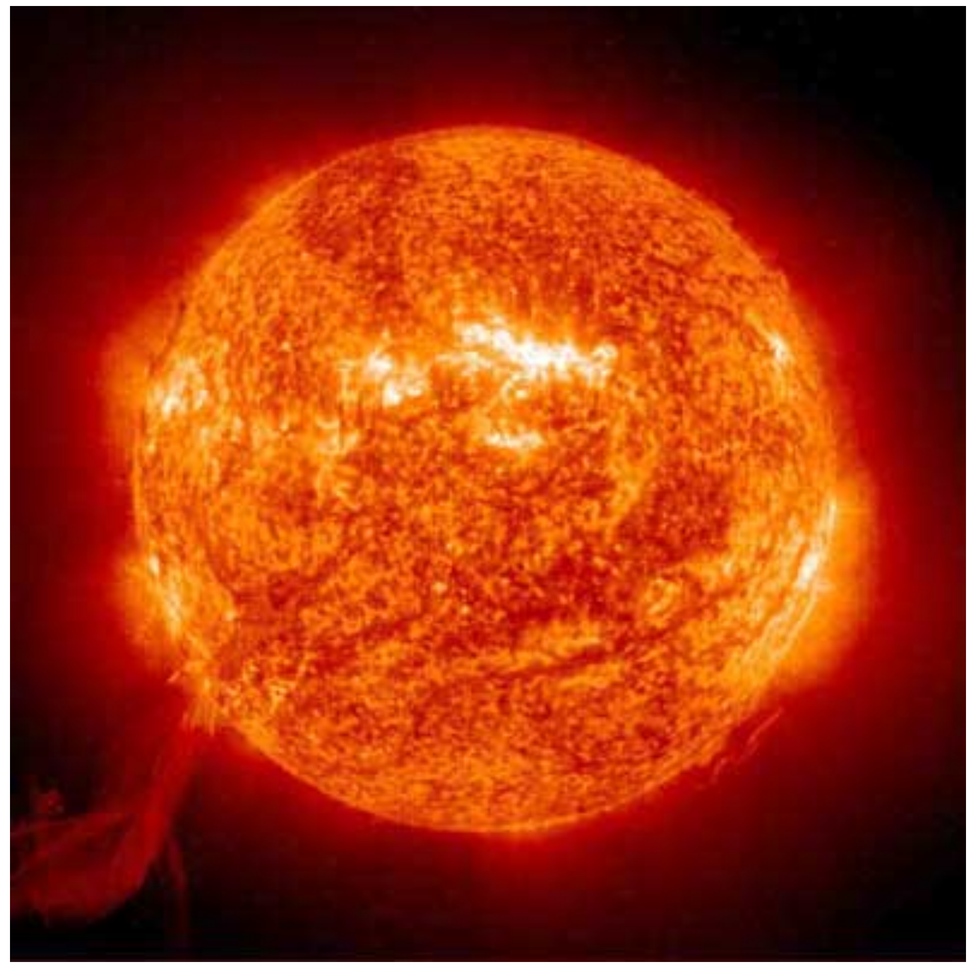
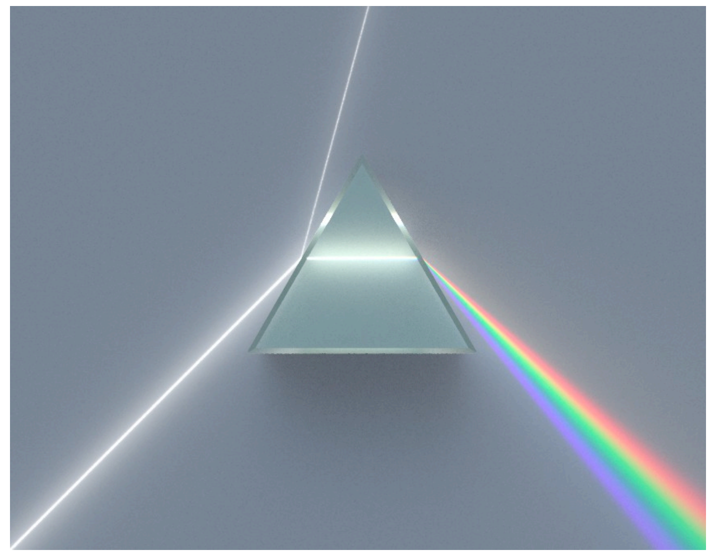
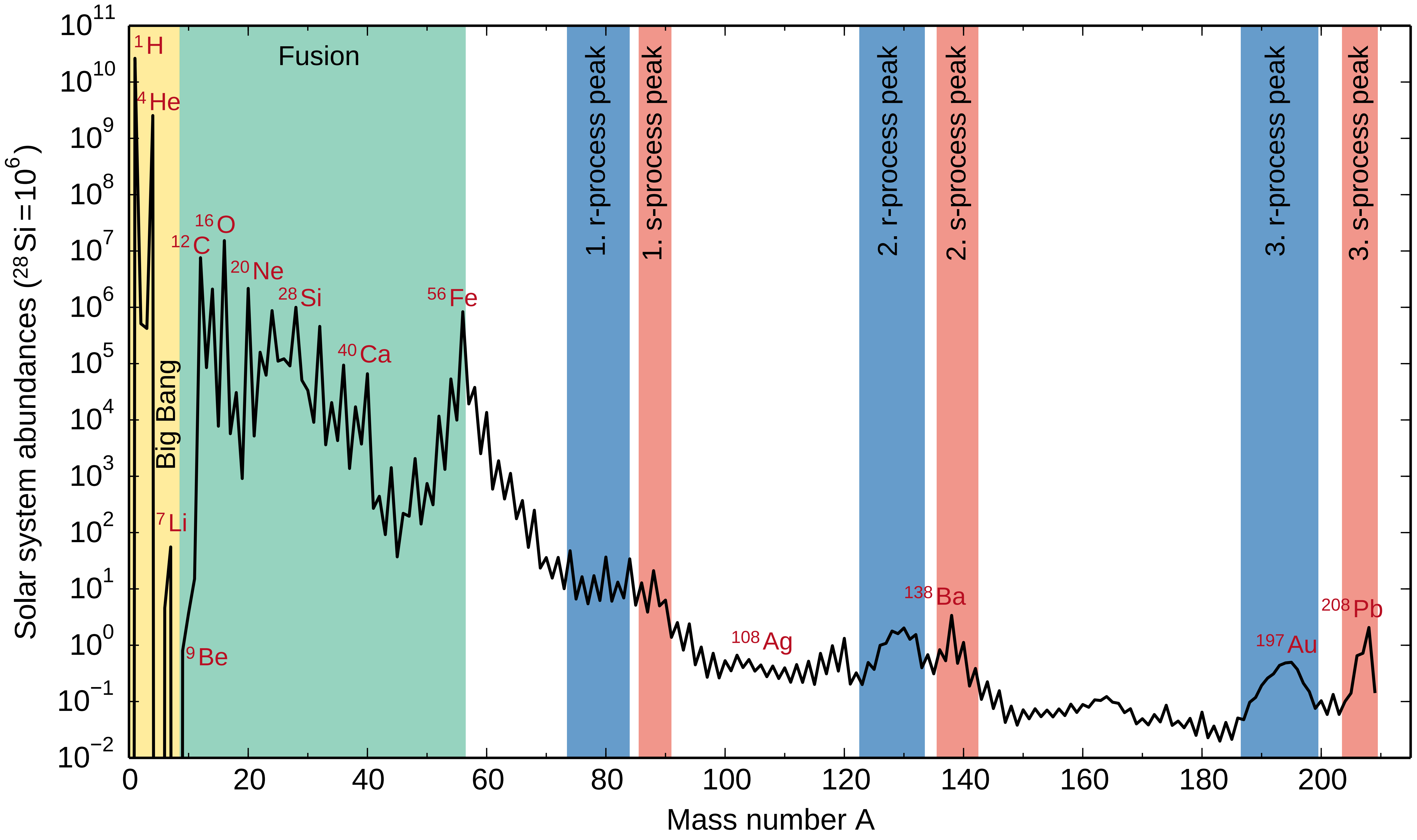
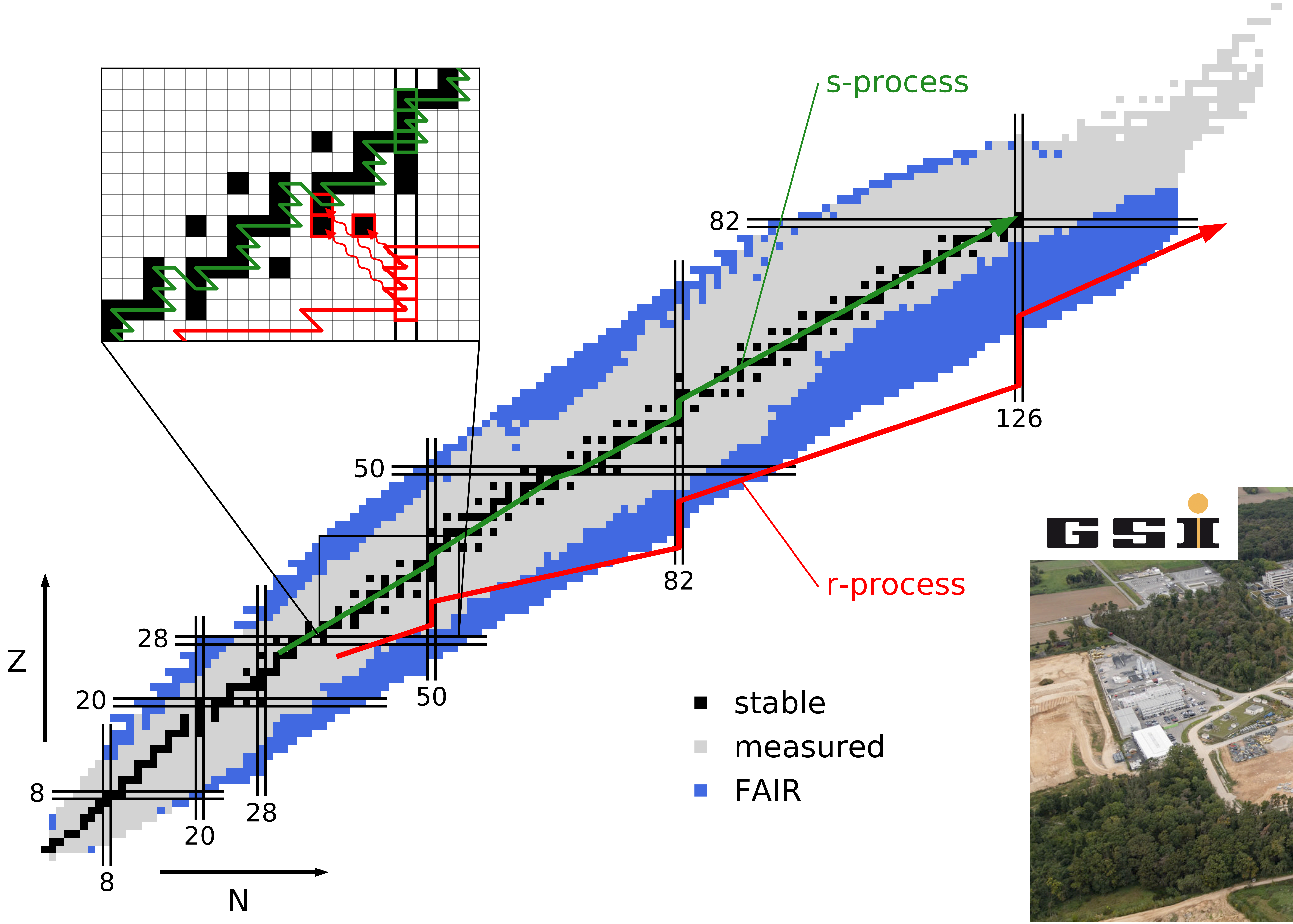






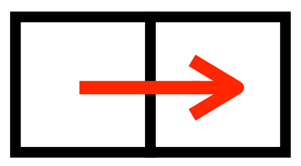
Neutron capture processes



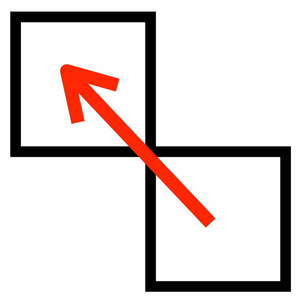
Heavy elements produced by Neutron capture processes: s-process and r-process

Neutron capture processes

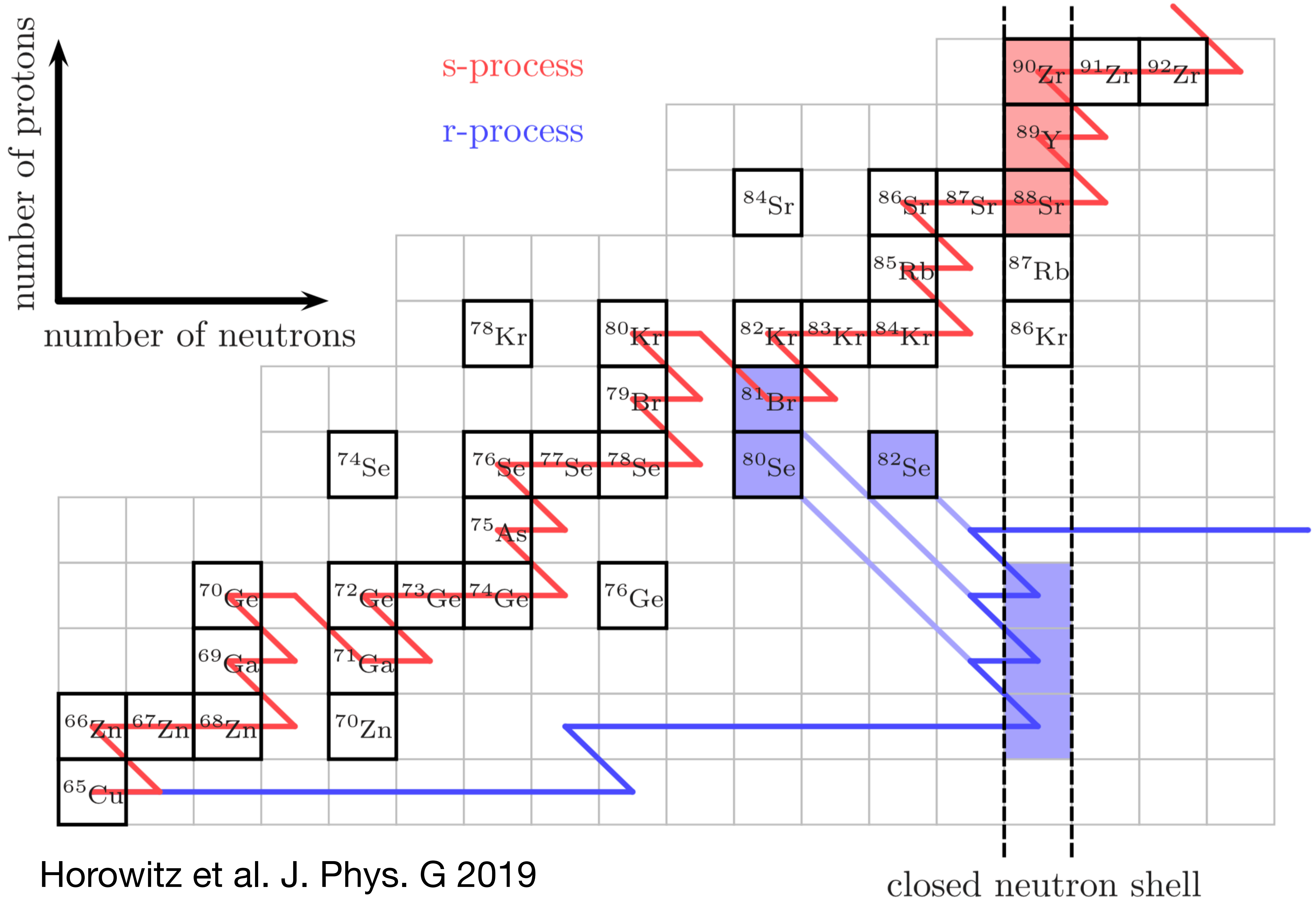
slow and rapid neutron capture compared to beta decay



neutron capture (n,γ):
(Z,A) + n → (Z,A+1) + γ

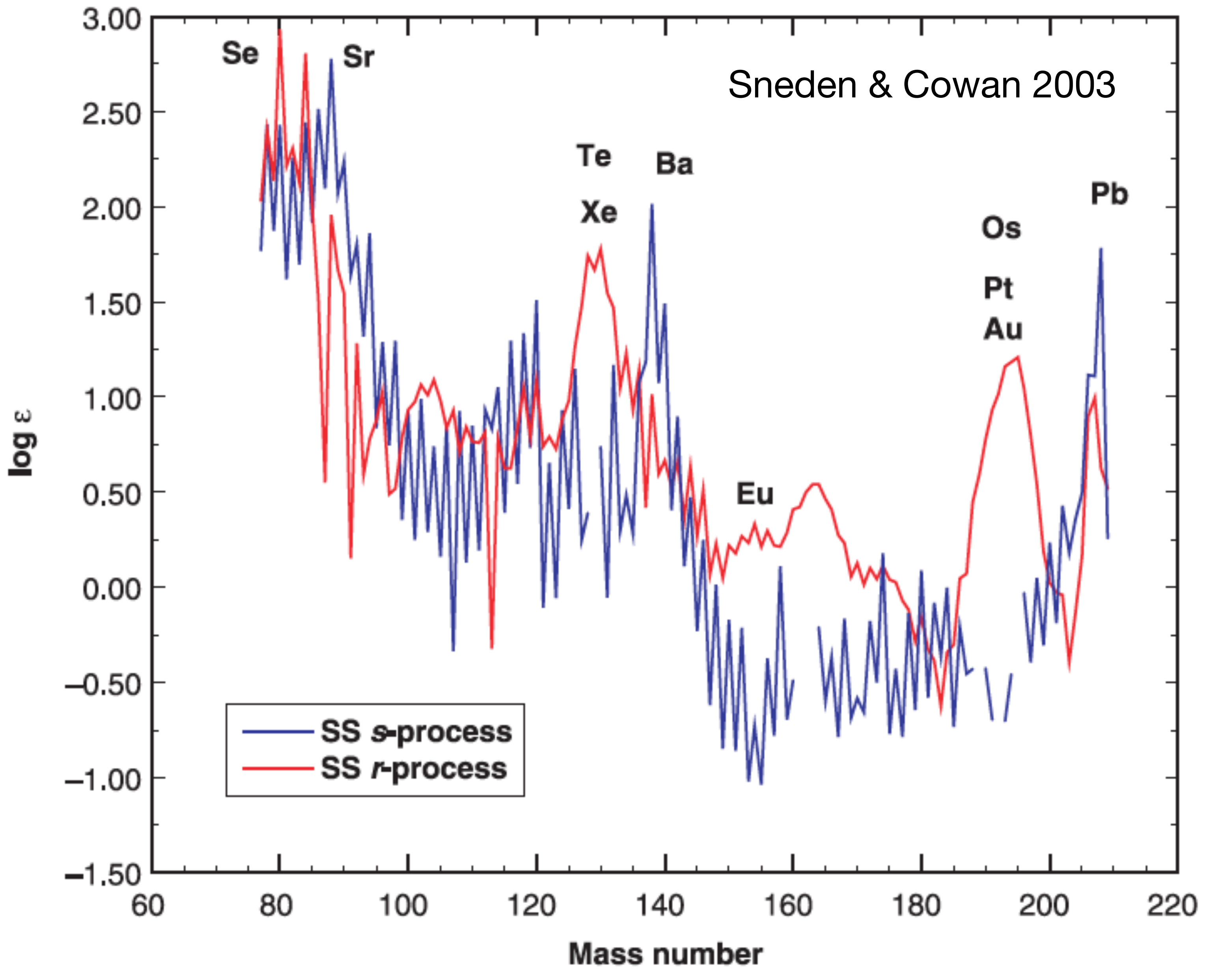


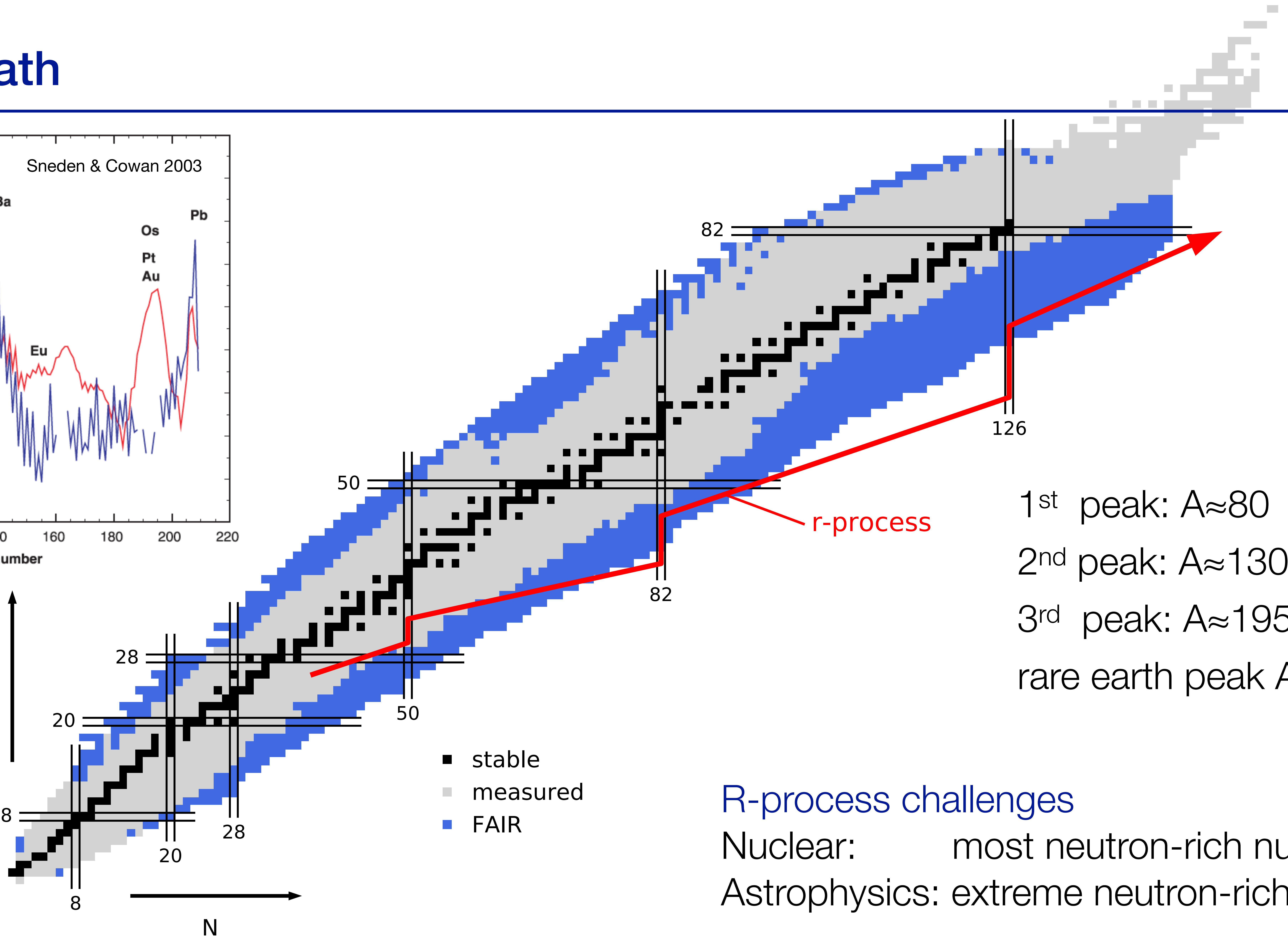
beta decay: (Z,A) → (Z+1,A)



Horowitz et al. J. Phys. G 2019

r-process path





1[st] peak: A≈80 → N=50

2[nd] peak: A≈130 → N=82

3[rd] peak: A≈195 → N=126

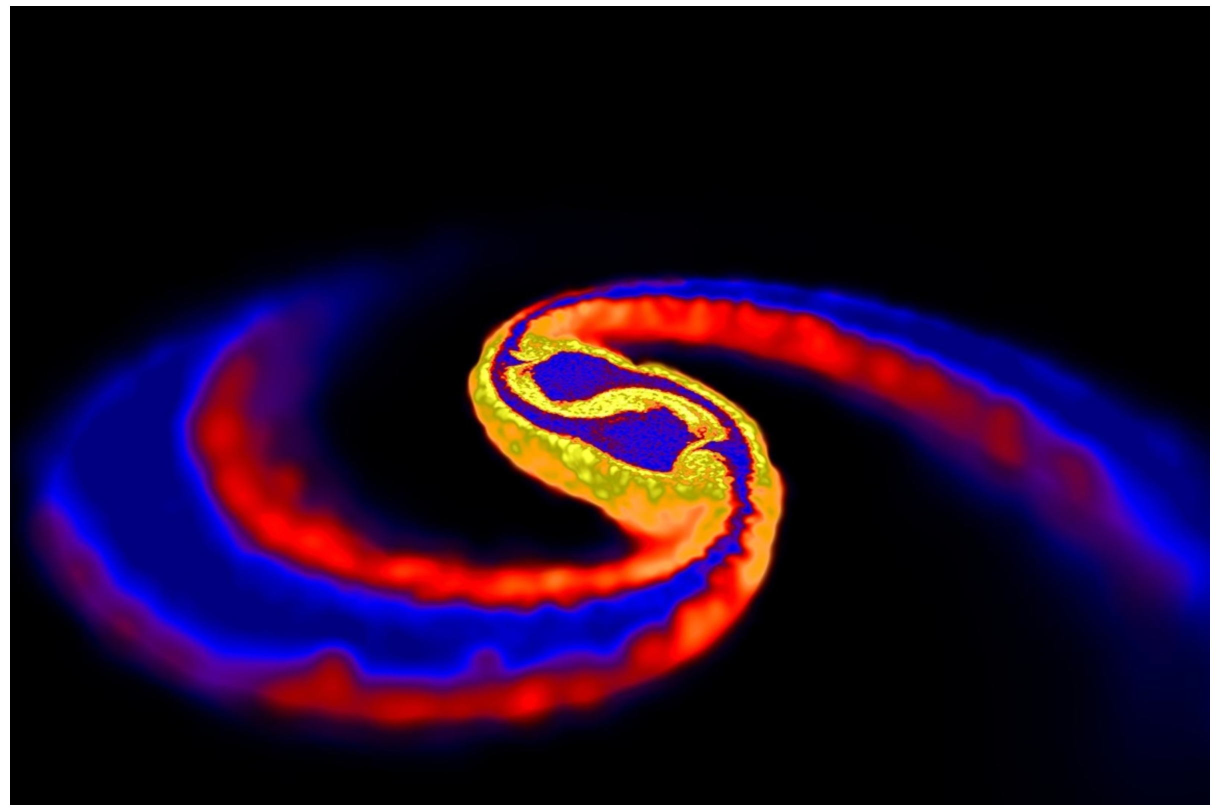
rare earth peak A≈165 → ?

R-process challenges

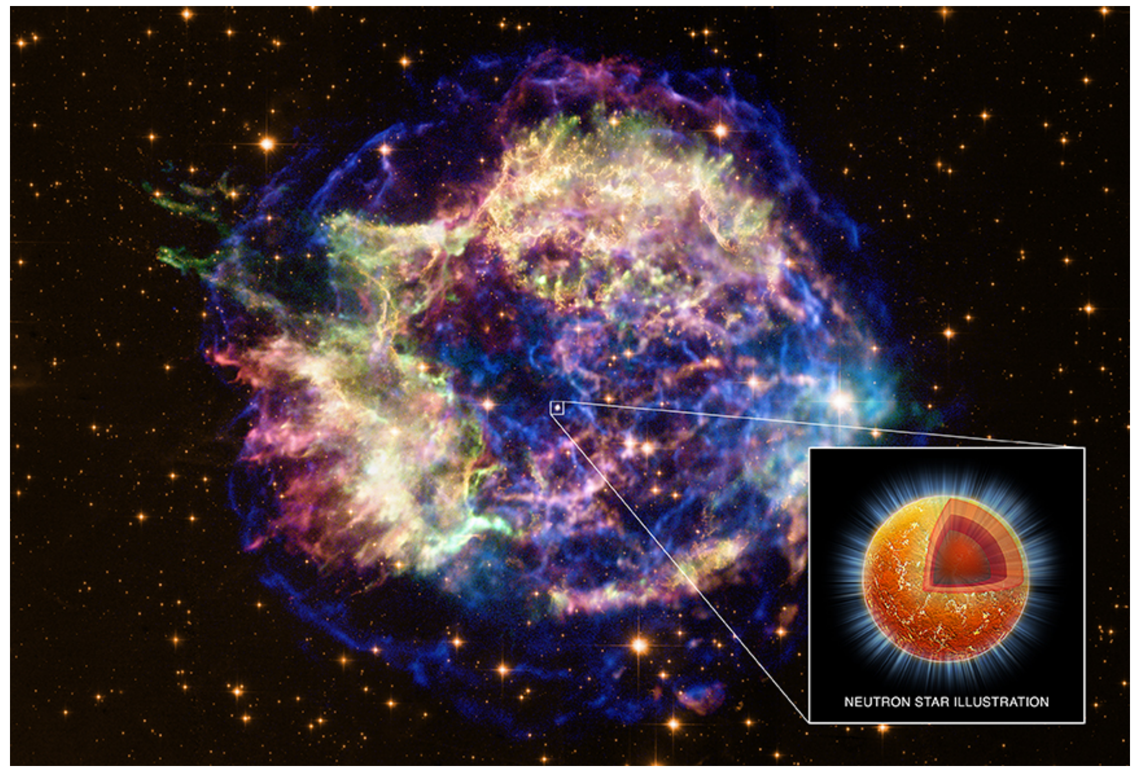
Nuclear: most neutron-rich nuclei

Astrophysics: extreme neutron-rich conditions

Nucleosynthesis calculations



Evolution of density, temperature and Y_e from astrophysical simulation or parametric model

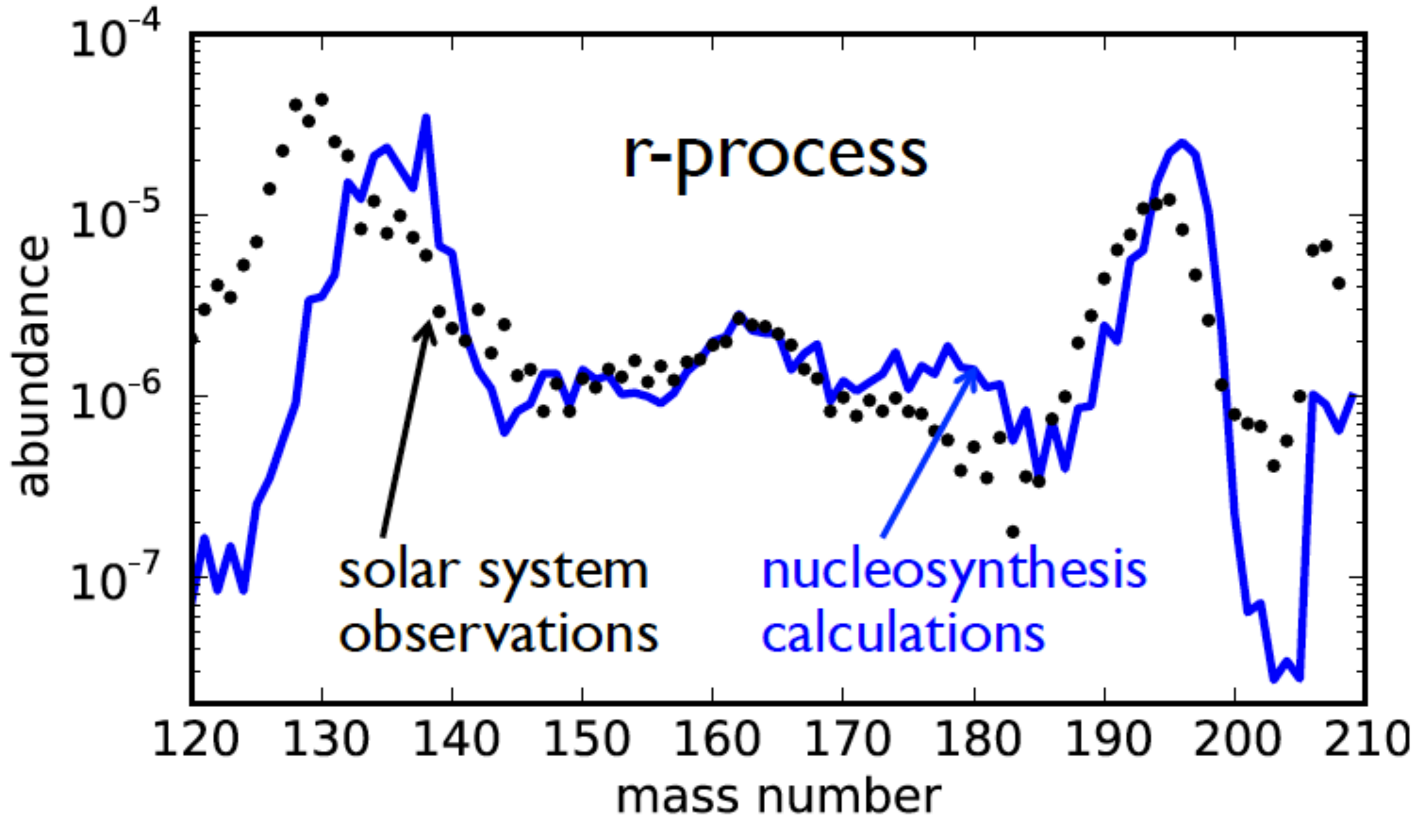


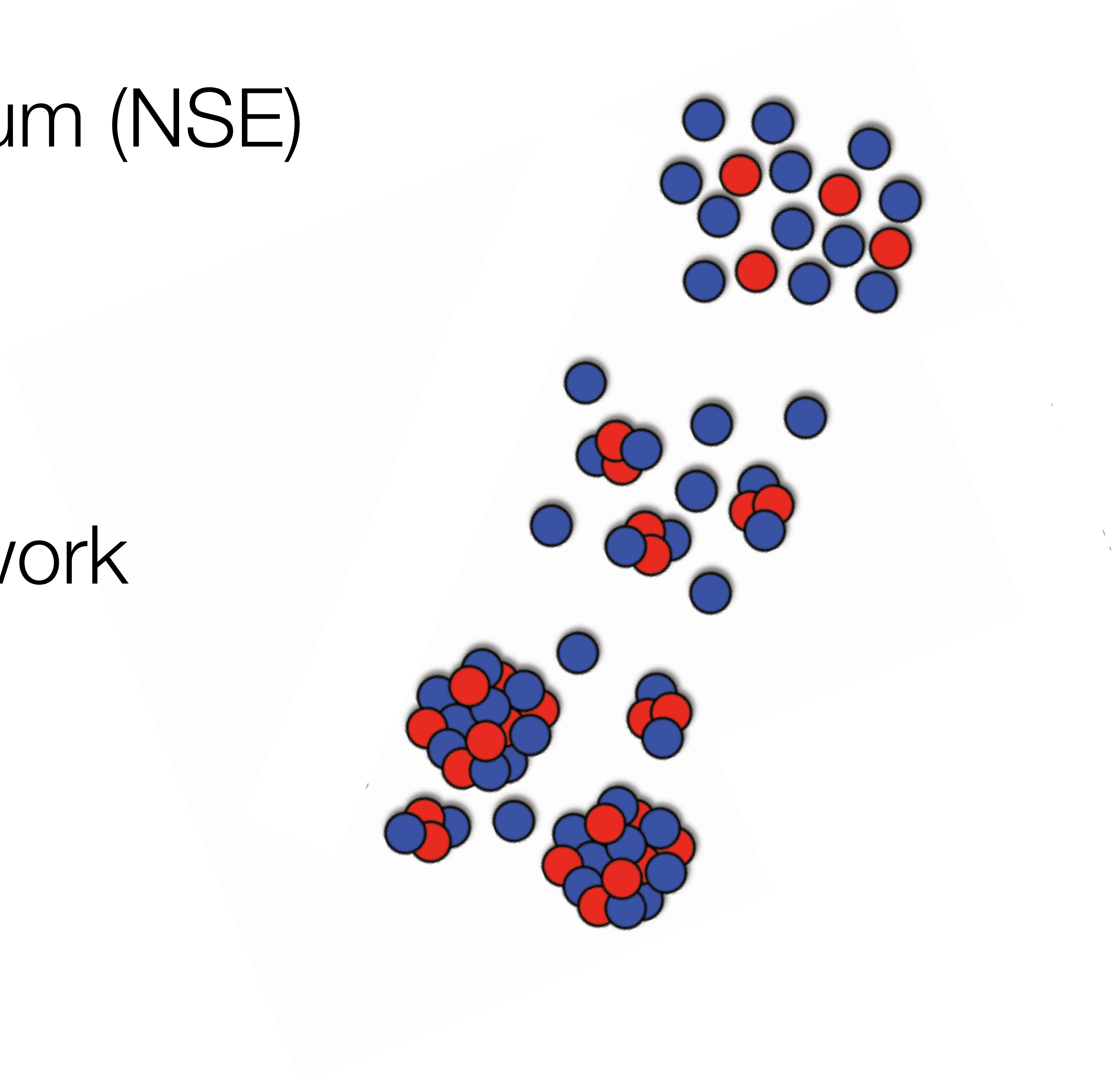
↓

Calculate initial composition:
high temperature ⇒ Nuclear Statistical Equilibrium (NSE)

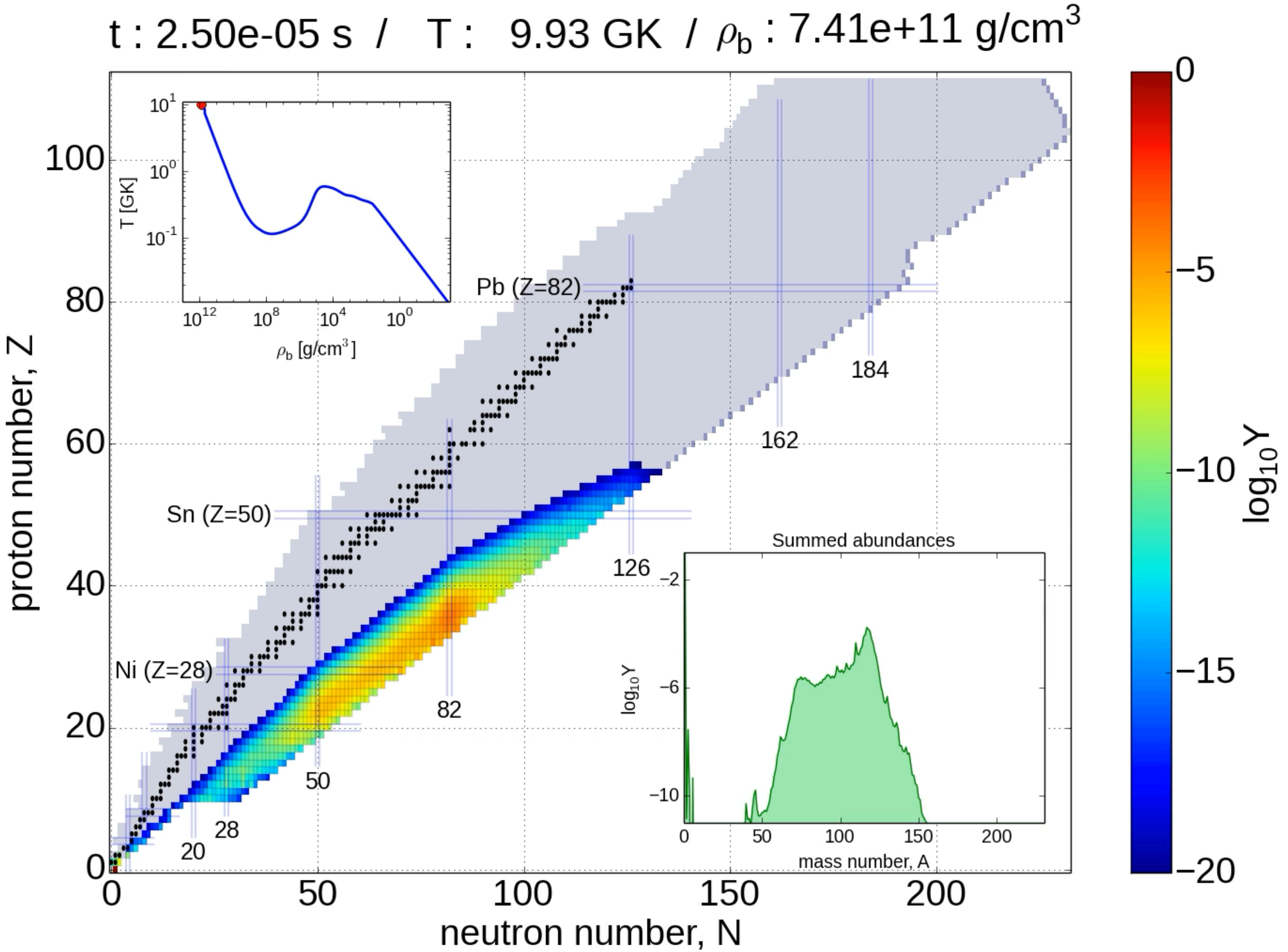
↓

Evolve composition using full reaction network

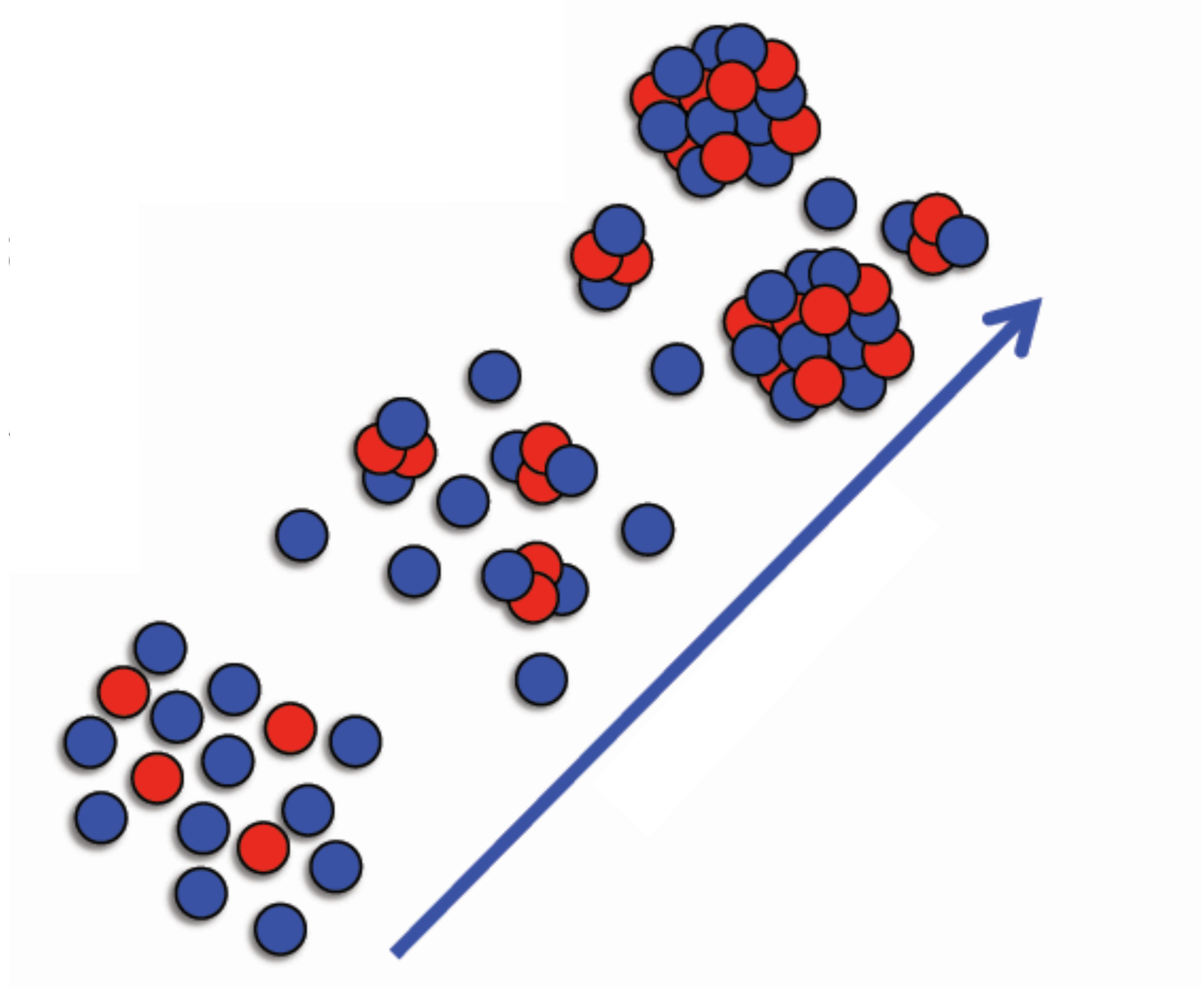




t : 2.50e-05 s / T : 9.93 GK / ρ_b : 7.41e+11 g/cm^3



r-process: required conditions



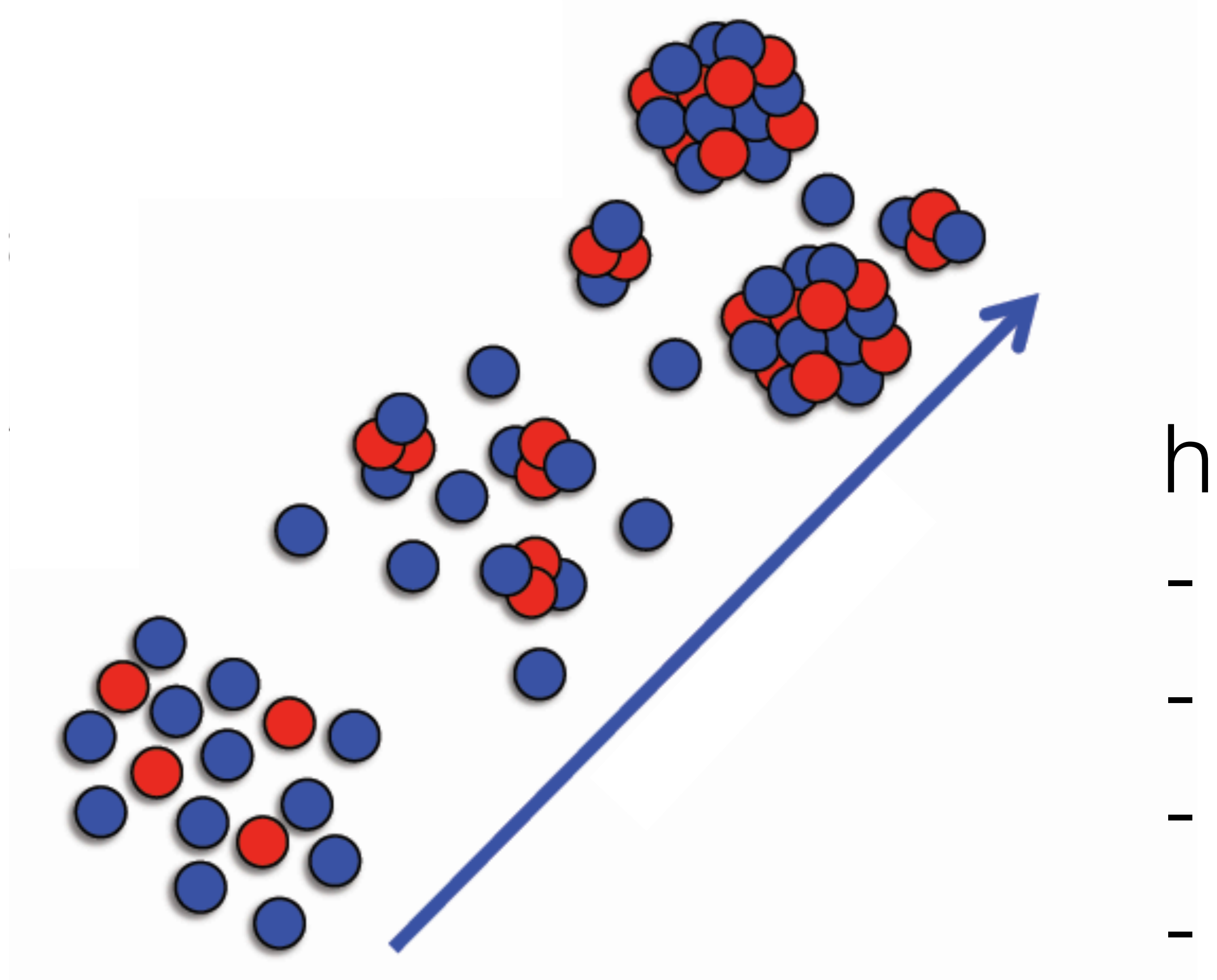
Seed nuclei capture neutrons faster than beta decay

$$\langle A_{\rm seed}\rangle + Y_n/Y_{\rm seed} = \langle A_{\rm r}\rangle$$

$$Y_n/Y_{\rm seed} > 100$$

- if seed nuclei were present: secondary process
- if seed nuclei are first produced: primary process

r-process: required conditions

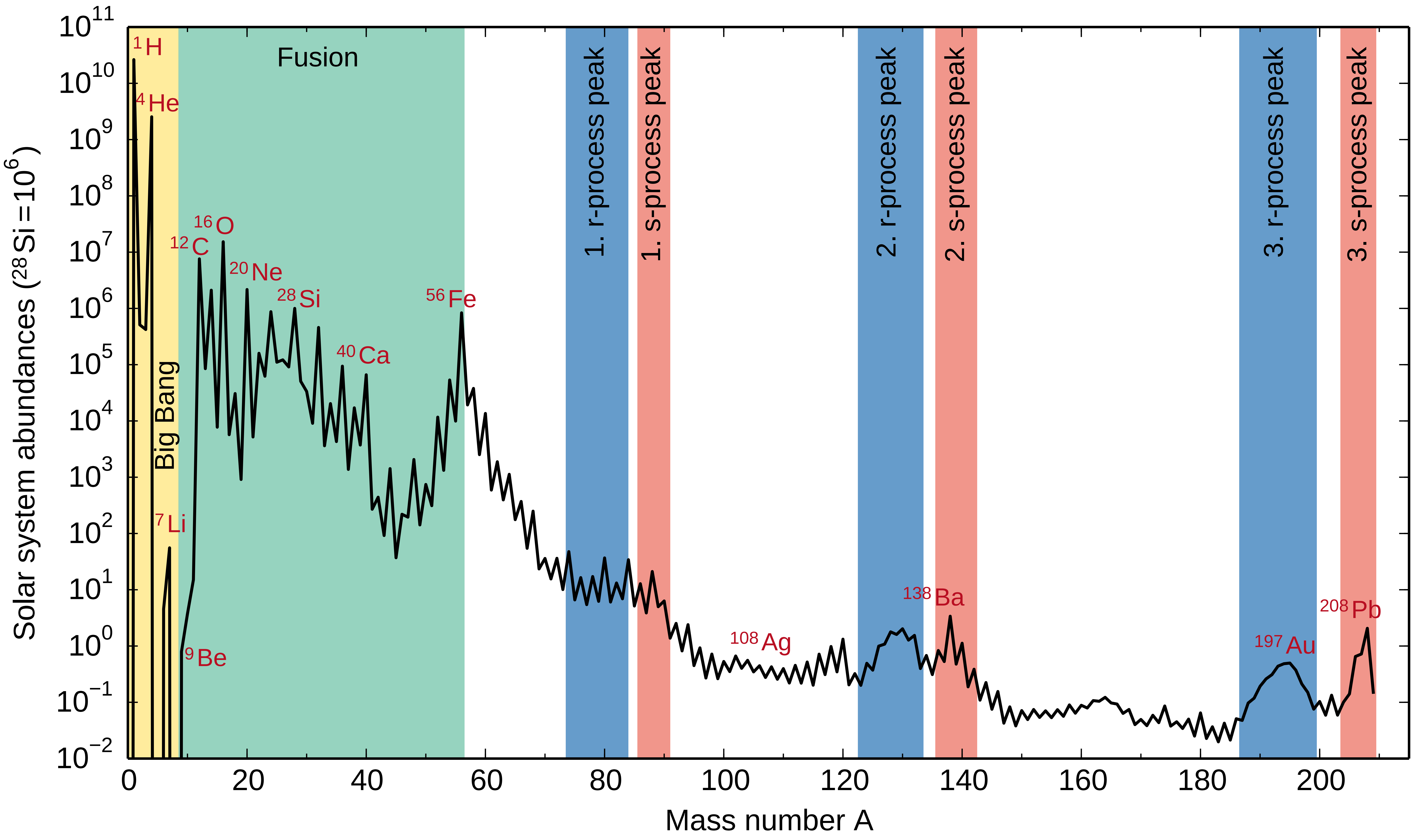


Primary r-process:

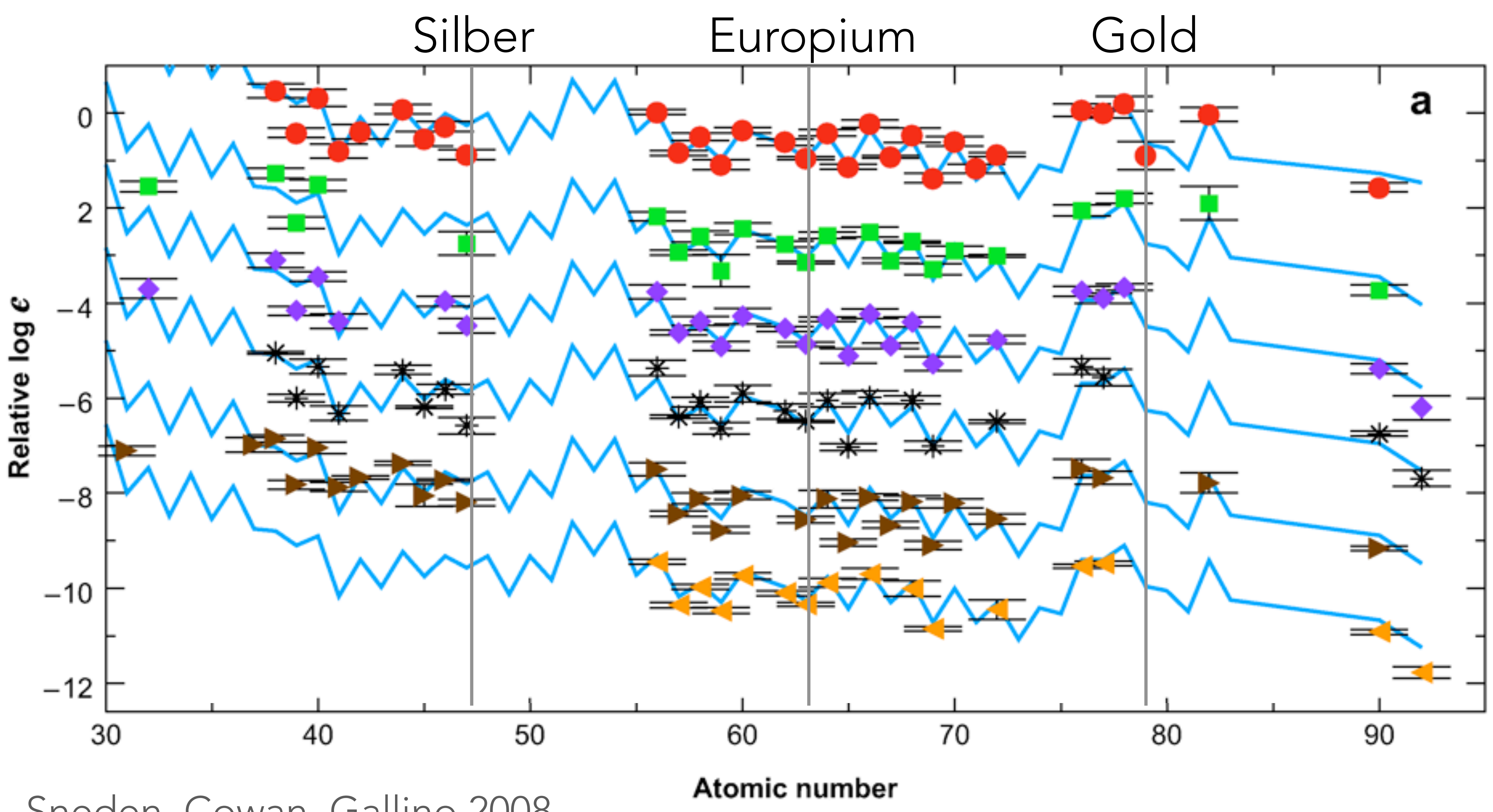
high entropy and Y_e~0.45:
- fast expansion starting at high temperatures (NSE)
- neutrons + protons form α-particles which recombine into seed nuclei
- α-rich freeze-out: 85% α-particles, 0.05% seeds, 0.1% neutrons
- sites: high entropy neutrino-driven ejecta (?)

low entropy and Y_e~0.1:
- fast expansion of high density neutron-rich matter
- neutron rich nuclei (drip line) in NSE and beta equilibrium, 99% neutrons
- sites: neutron star mergers, jets, accretion disks

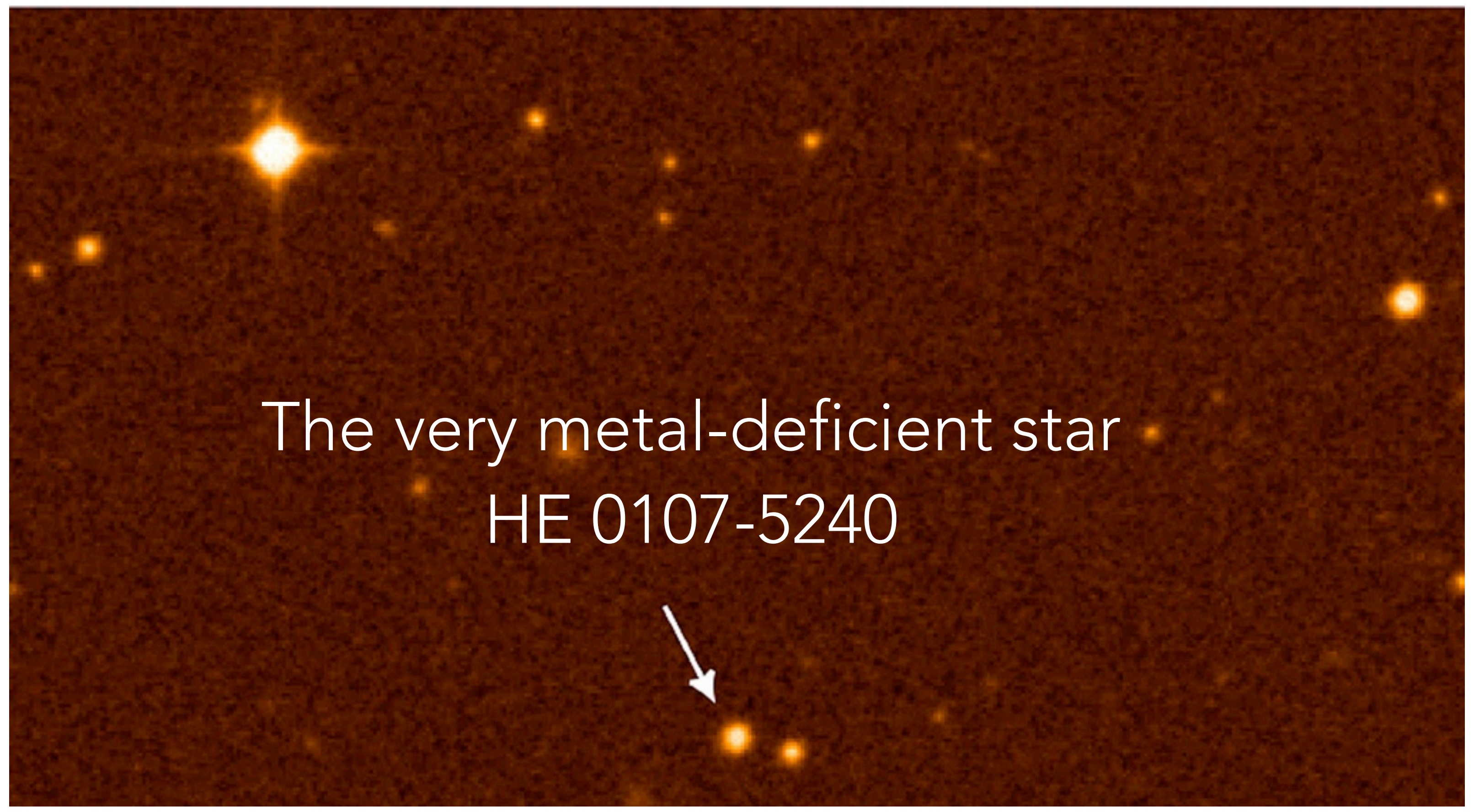
Heavy element: solar system



r-process: elemental abundances in the oldest stars



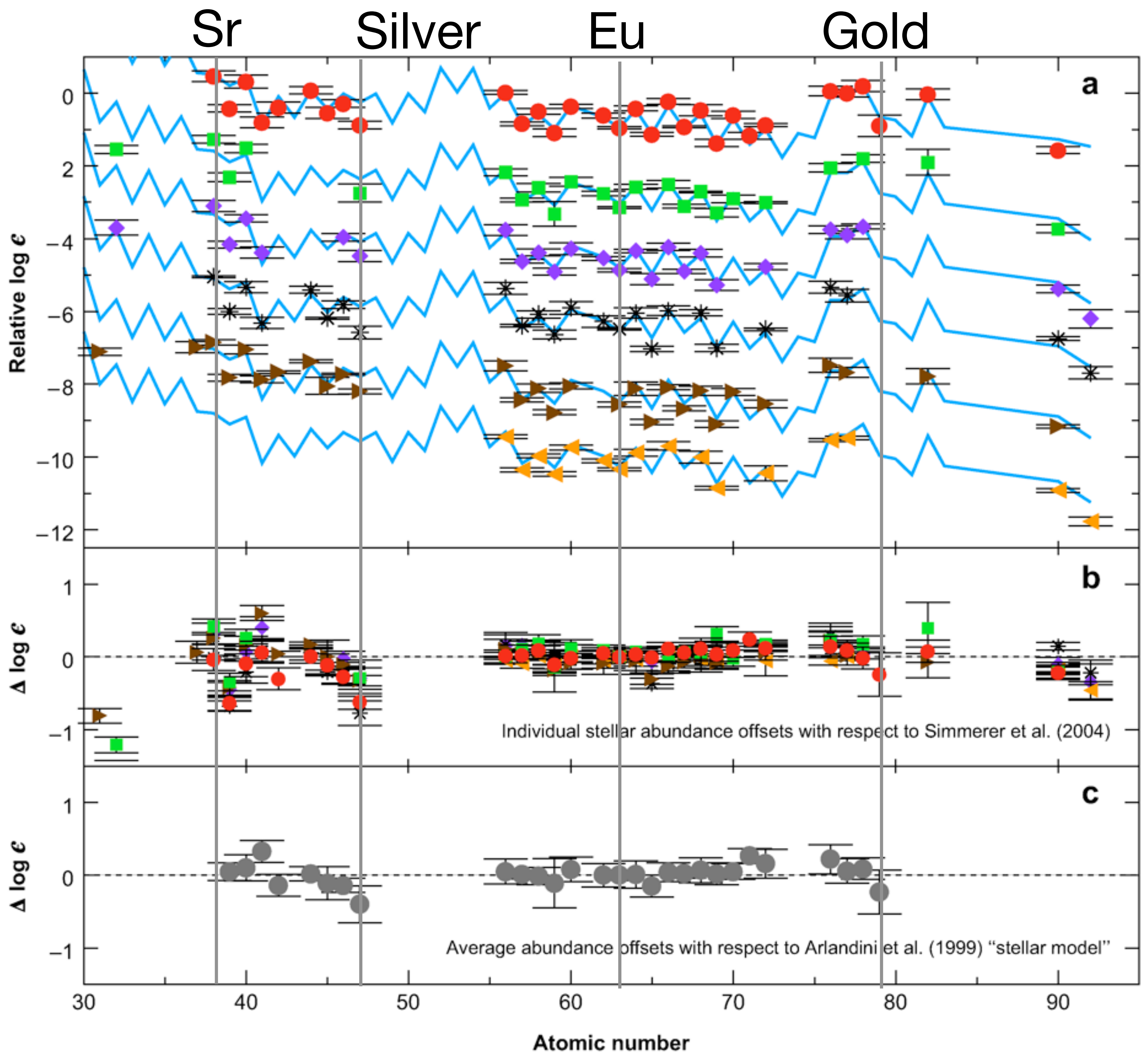
Sneden, Cowan, Gallino 2008



r-process in oldest stars and in Solar system same relative abundances:

Robust r-process

r-process: elemental abundances in the oldest stars



- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- BD+17°324817: Cowan et al. (2002)
- CS 31082-001: Hill et al. (2002)
- HD 221170: Ivans et al. (2006)
- HE 1523-0901: Frebel et al. (2007)

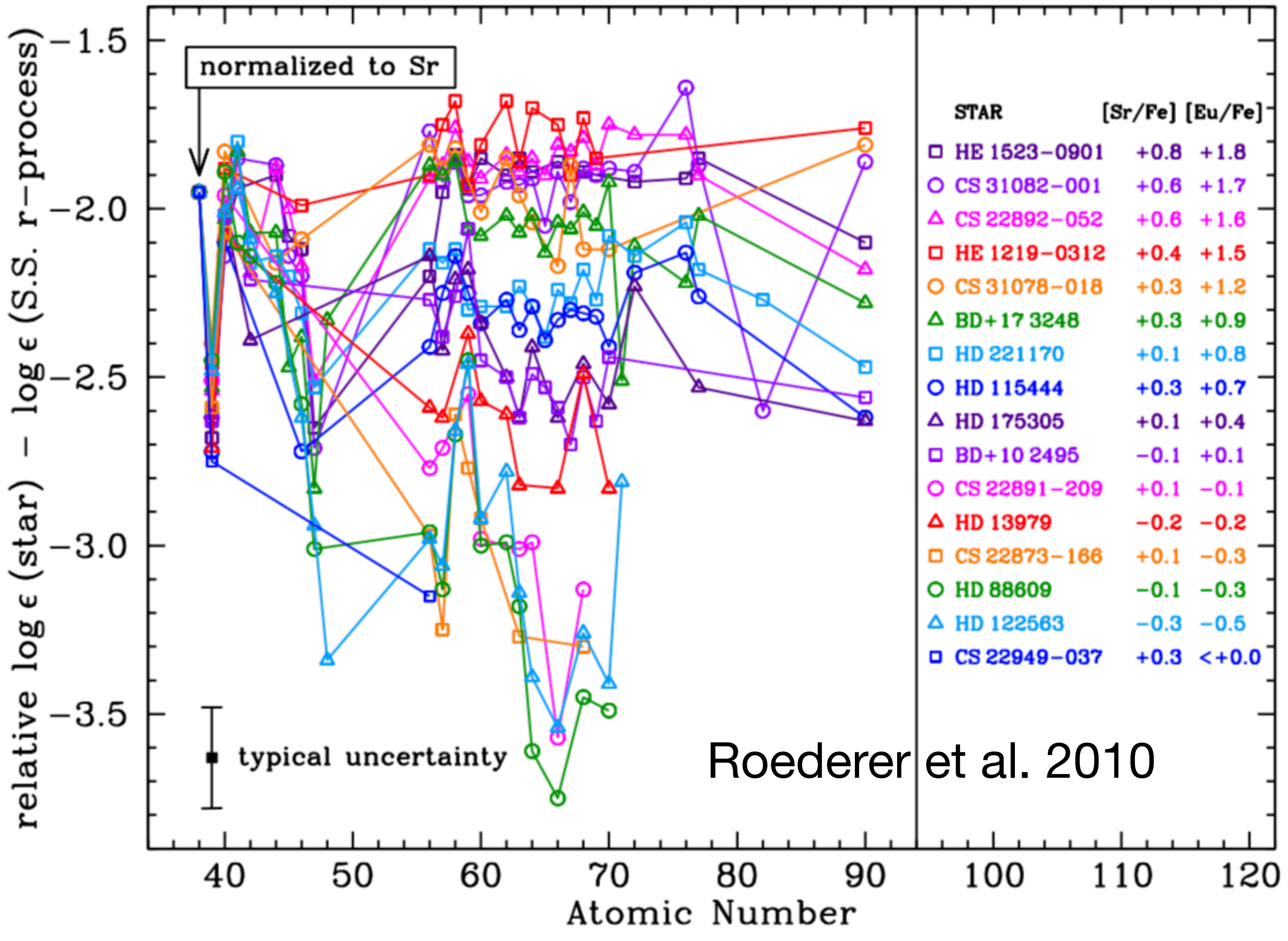
$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Sneden, Cowan, Gallino 2008

Abundances of r-process elements:
- ultra metal-poor stars and
- r-process solar system: N_{solar} - N_s

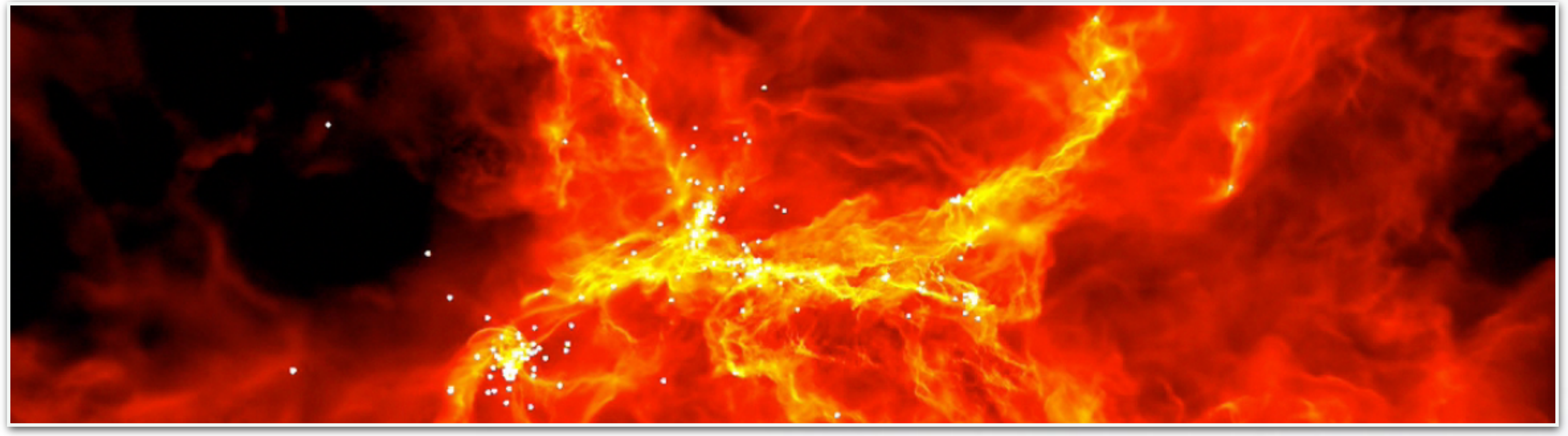
Robust r-process for 56<Z<83

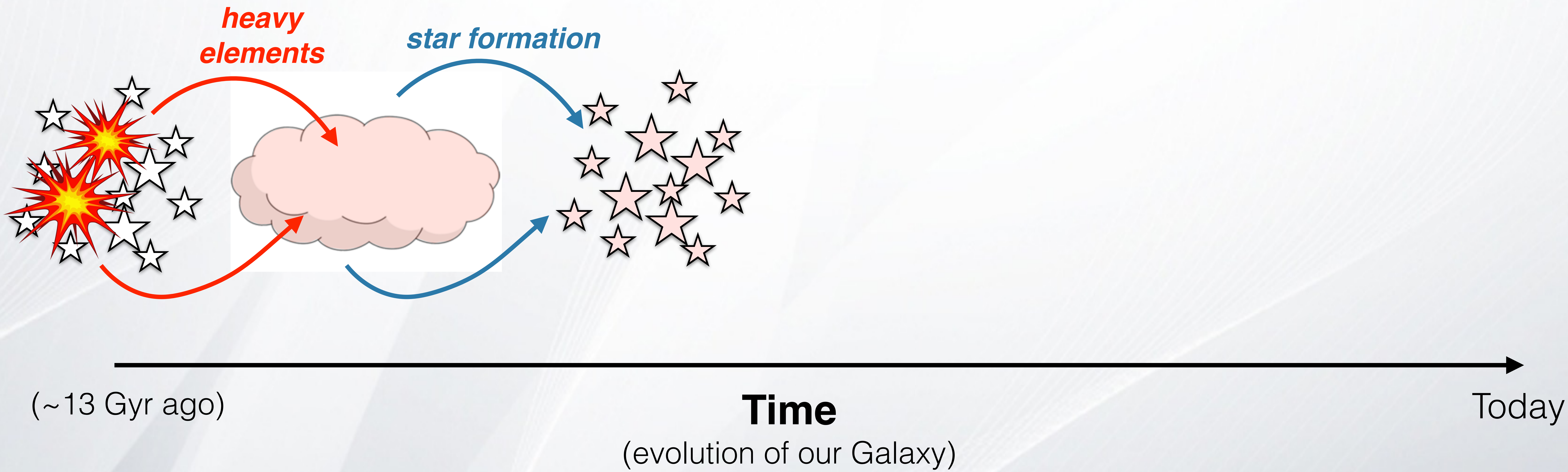
Scatter for lighter heavy elements, Z~40



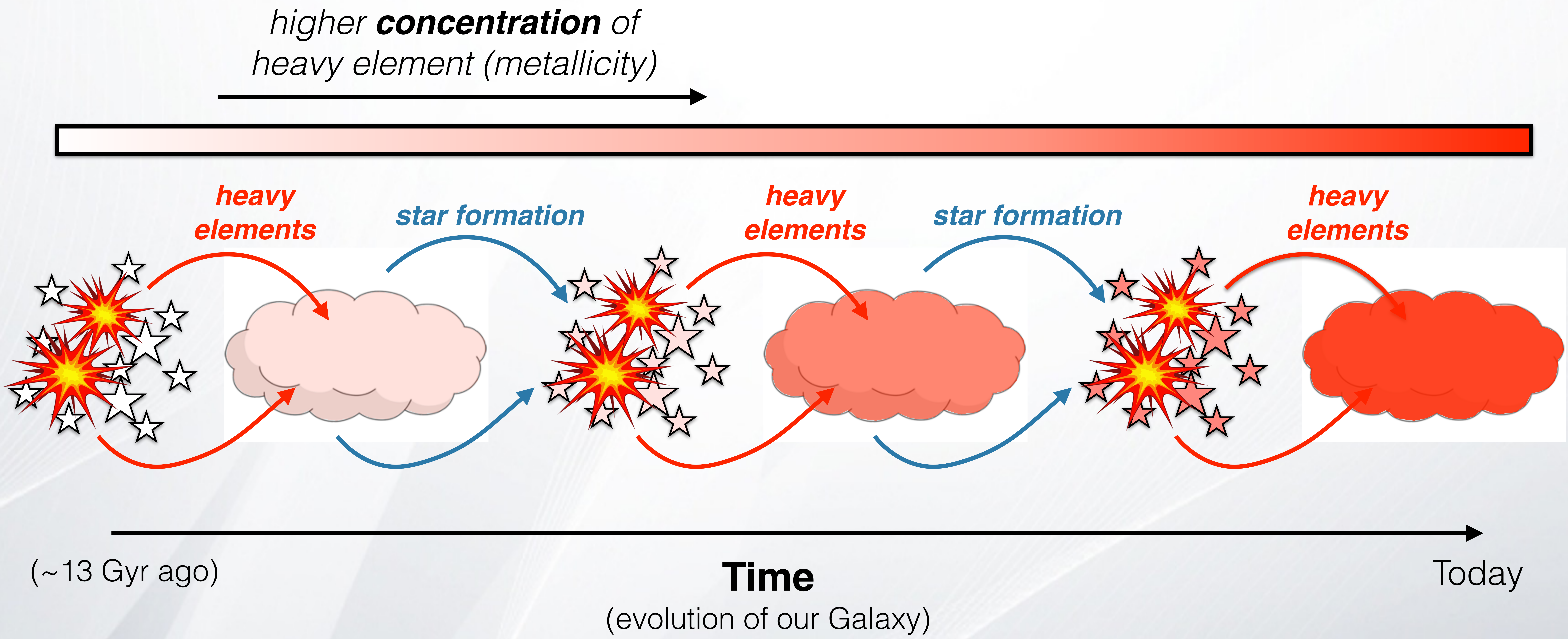
The Basics of Chemical Evolution

Benoit Côté





The Basics of Chemical Evolution



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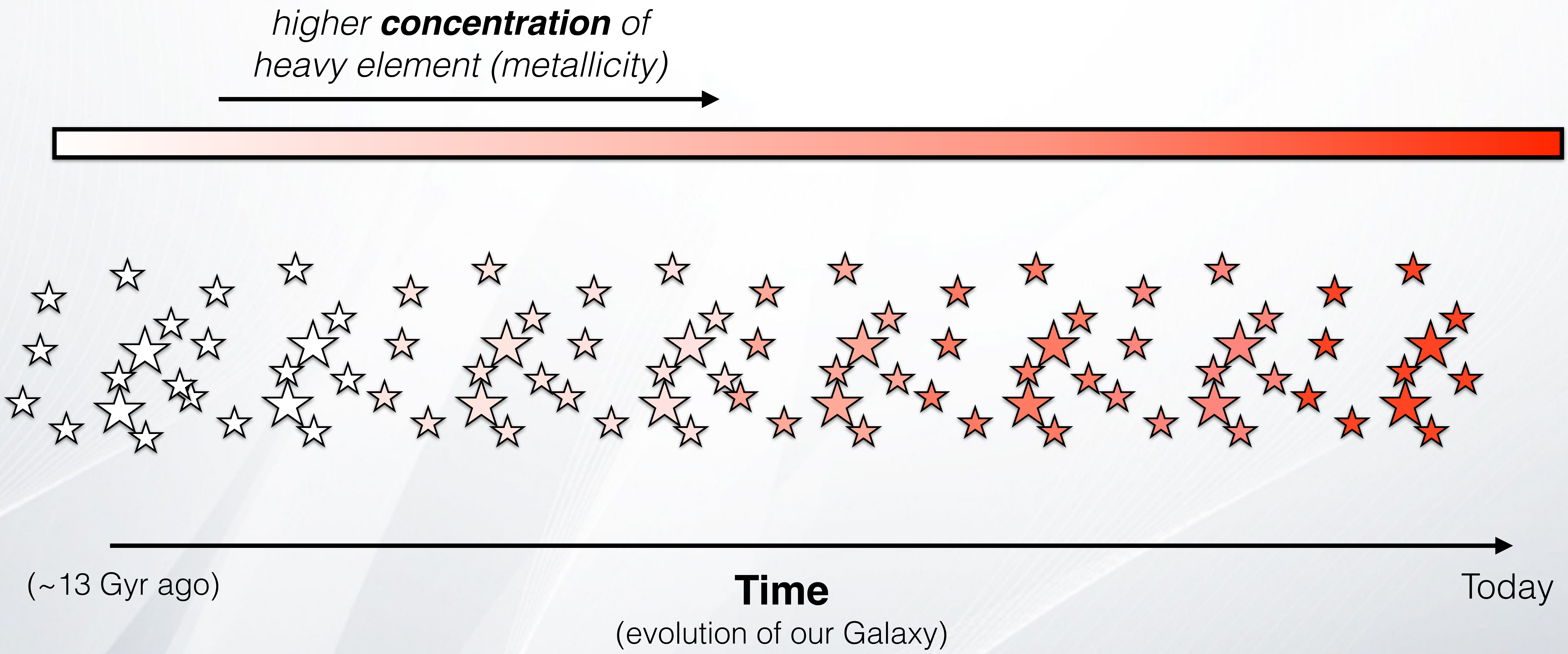
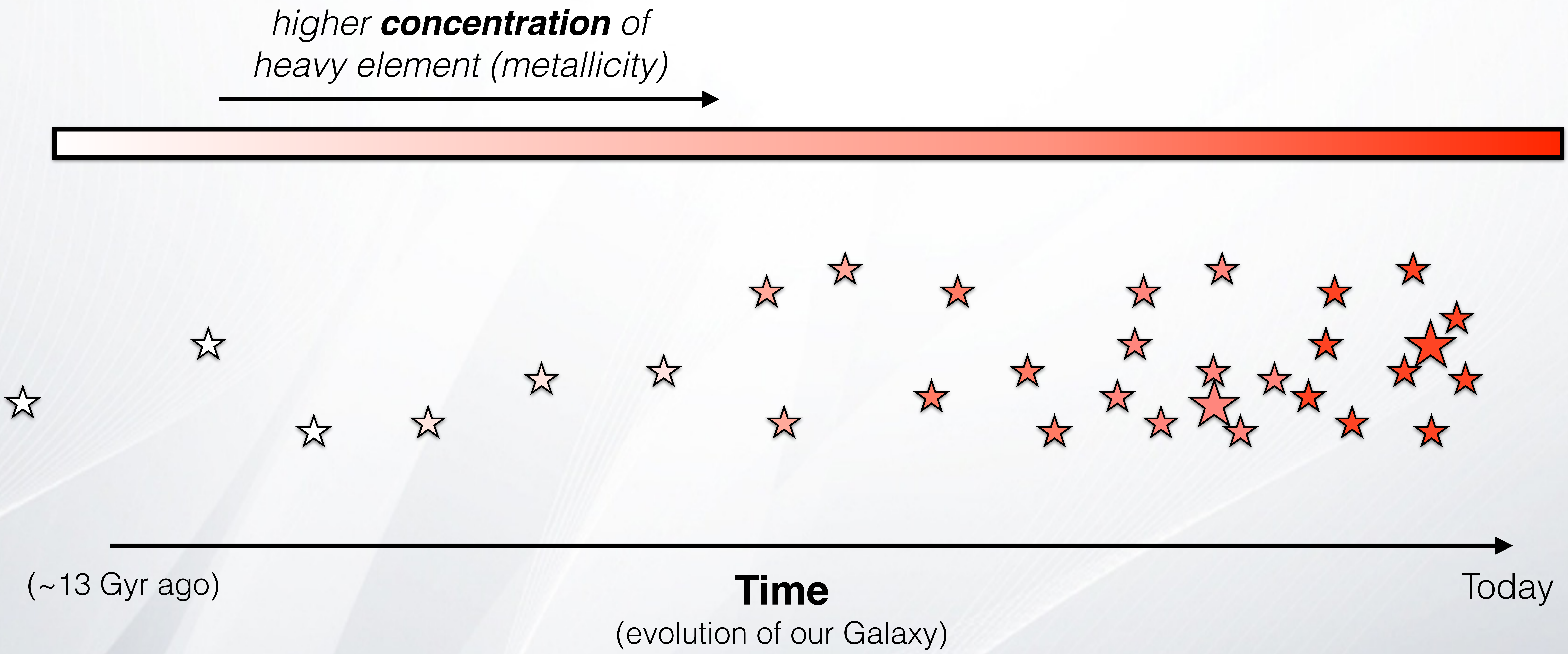


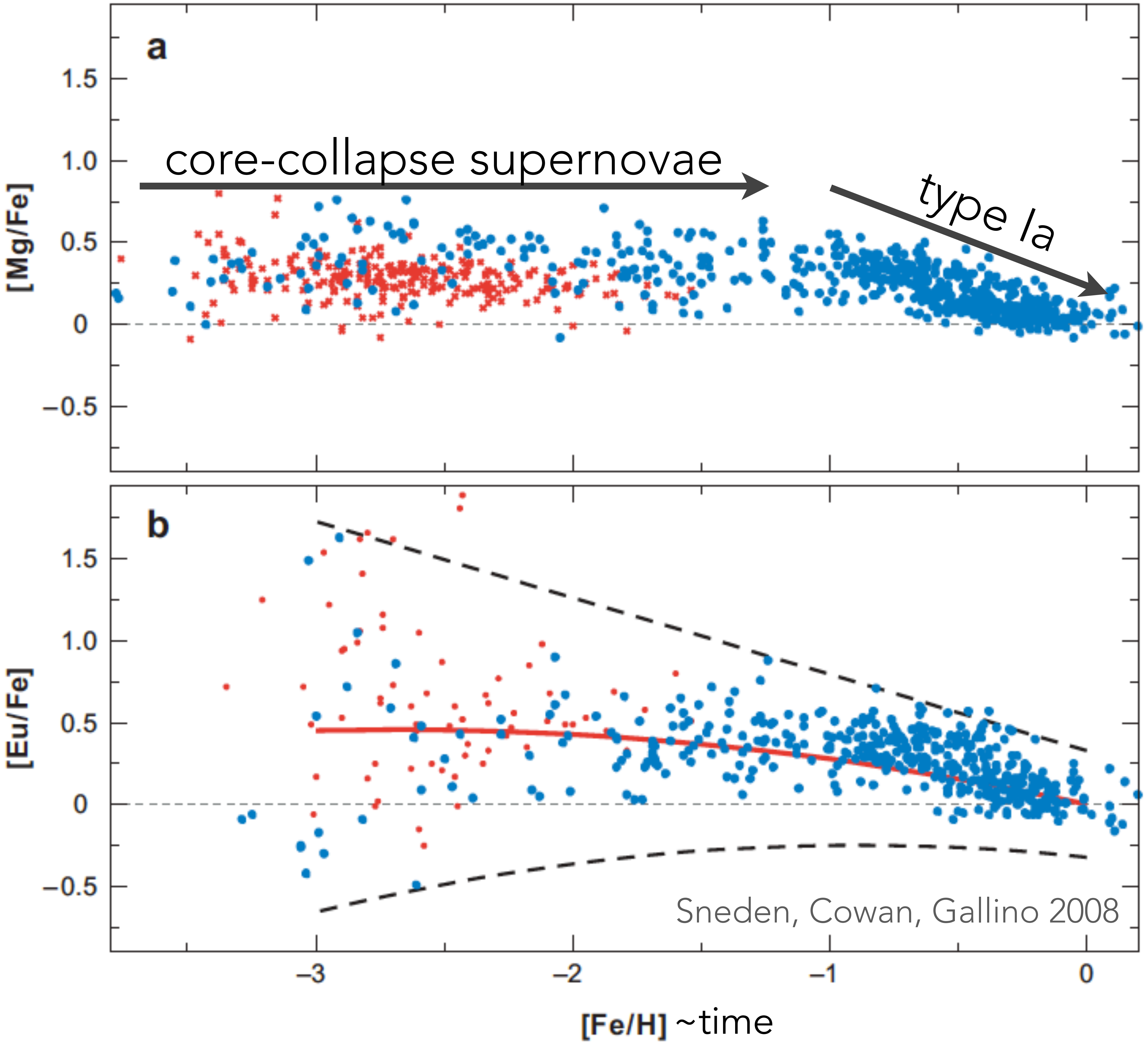
The Basics of Chemical Evolution



How to « Observe » Chemical Evolution?

Trends with metallicity [Fe/H]

$$[A/B] = \log_{10}(Y_A/Y_B)_* - \log_{10}(Y_A/Y_B)_\odot$$



Fe and Mg produced in same site: core-collapse supernovae

Type Ia supernova: thermonuclear explosion of a white dwarf -> late Fe contribution

Eu: typical r-process element

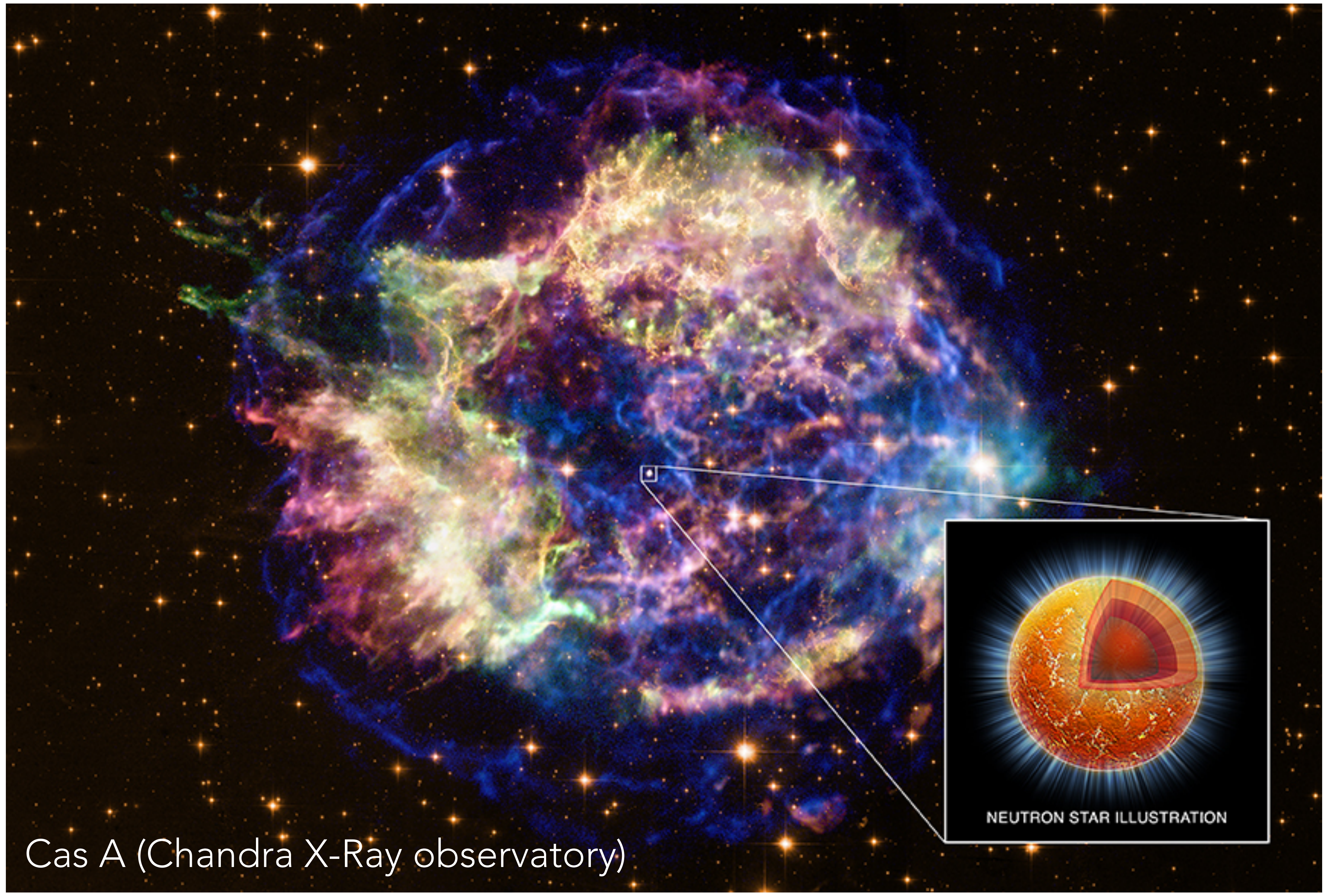
Scatter at low metallicities: rare and early event

Origin of heavy elements?

Rapid neutron capture process

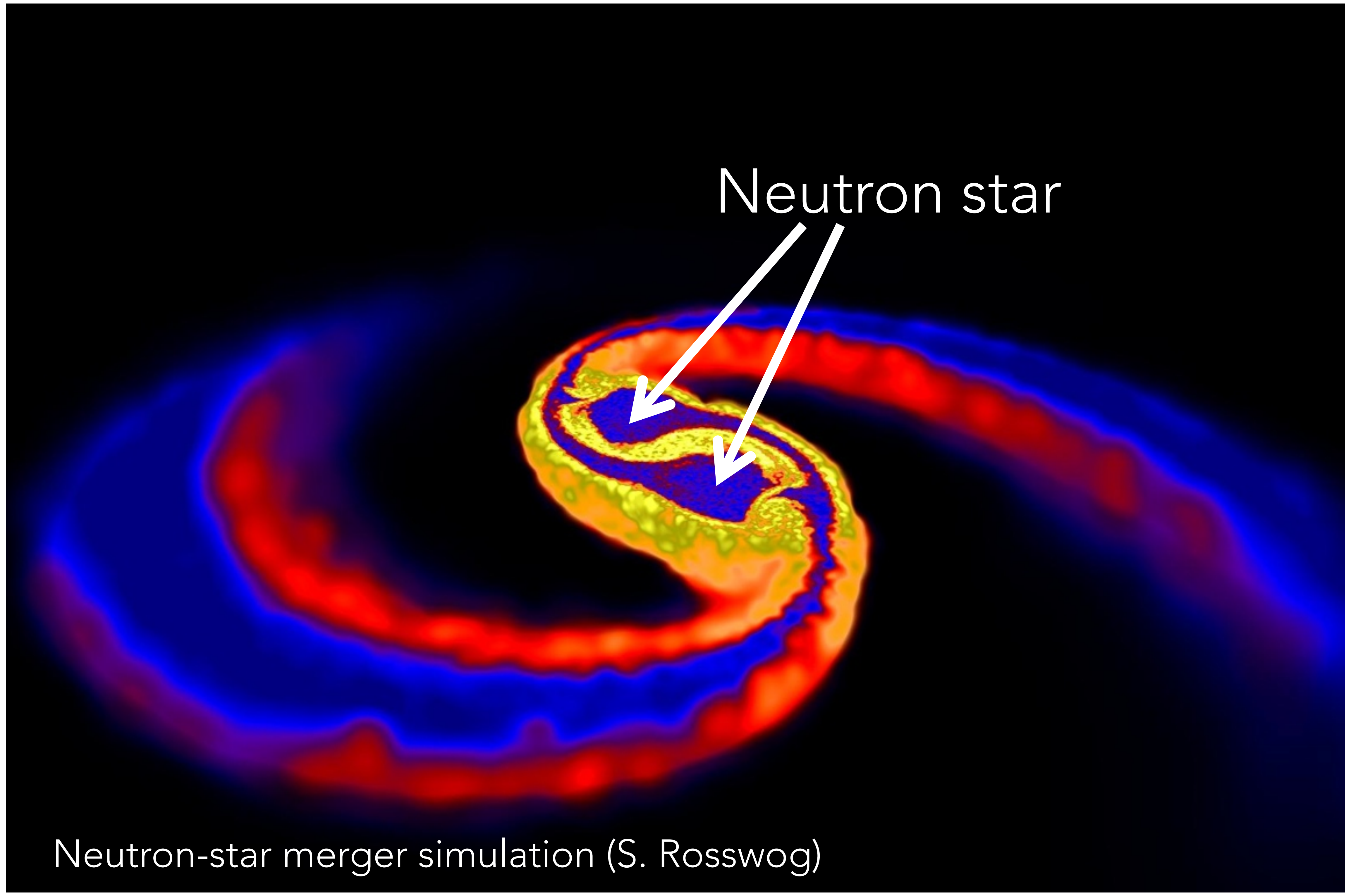
Explosive and high neutron densities

Supernova



Cas A (Chandra X-Ray observatory)

Neutron star mergers

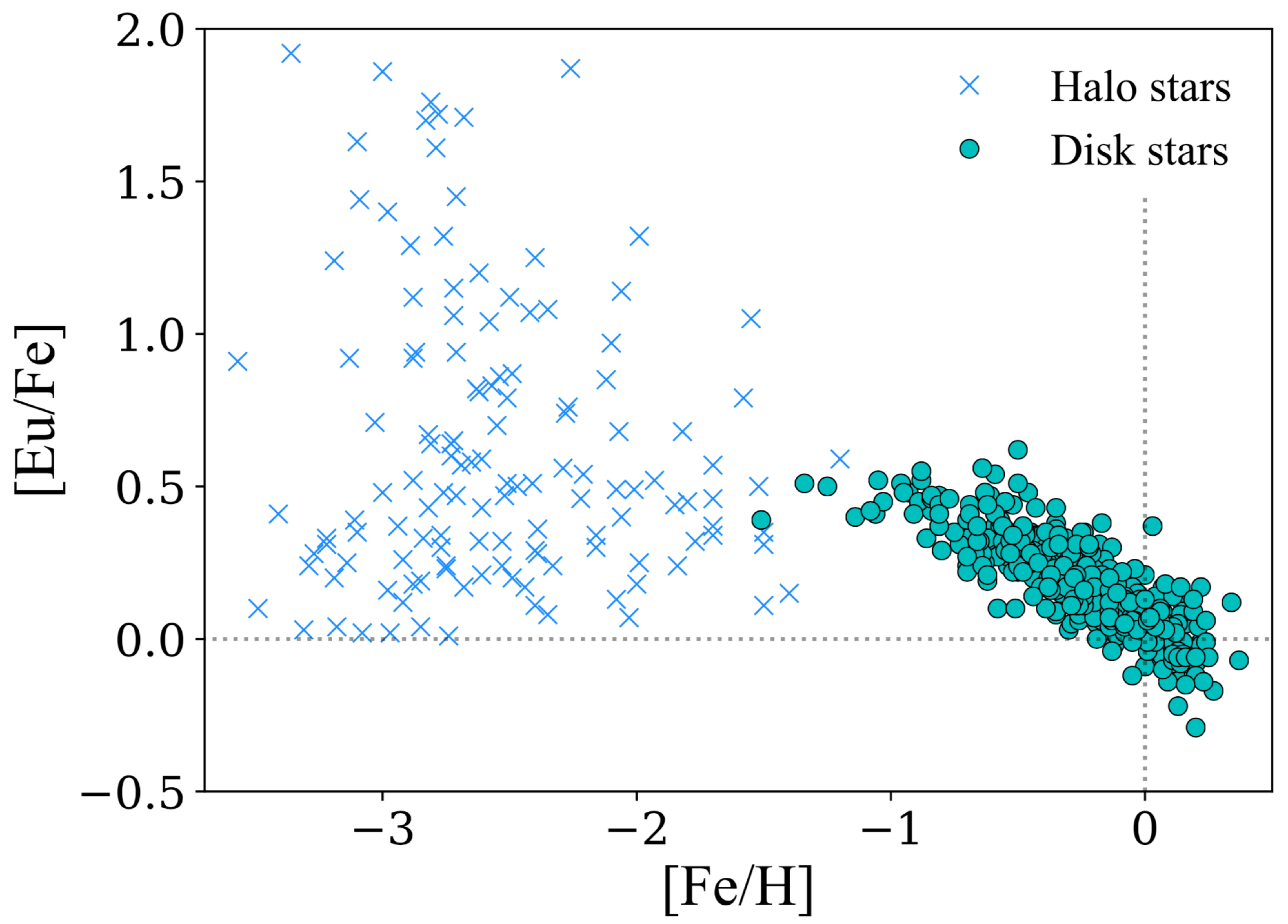


Neutron-star merger simulation (S. Rosswog)

Observations and galactic chemical evolution

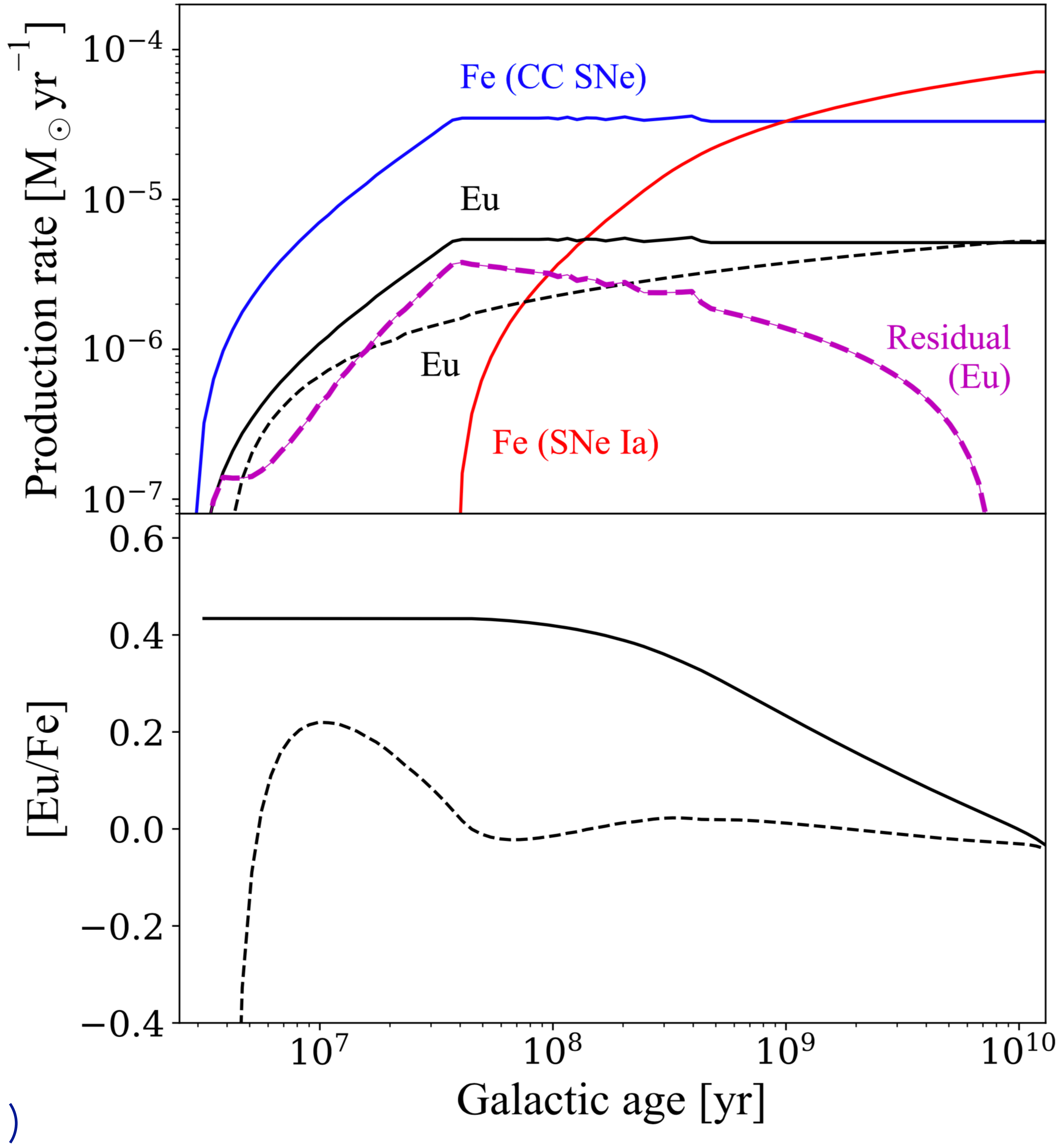
Evolution with time (or metallicity) -> Galactic Chemical Evolution (GCE)

-> r-process sites: mergers vs. supernovae



Matteucci et al. MNRAS (2014), Côté et al. ApJ (2019), Molero et al. MNRAS (2021)

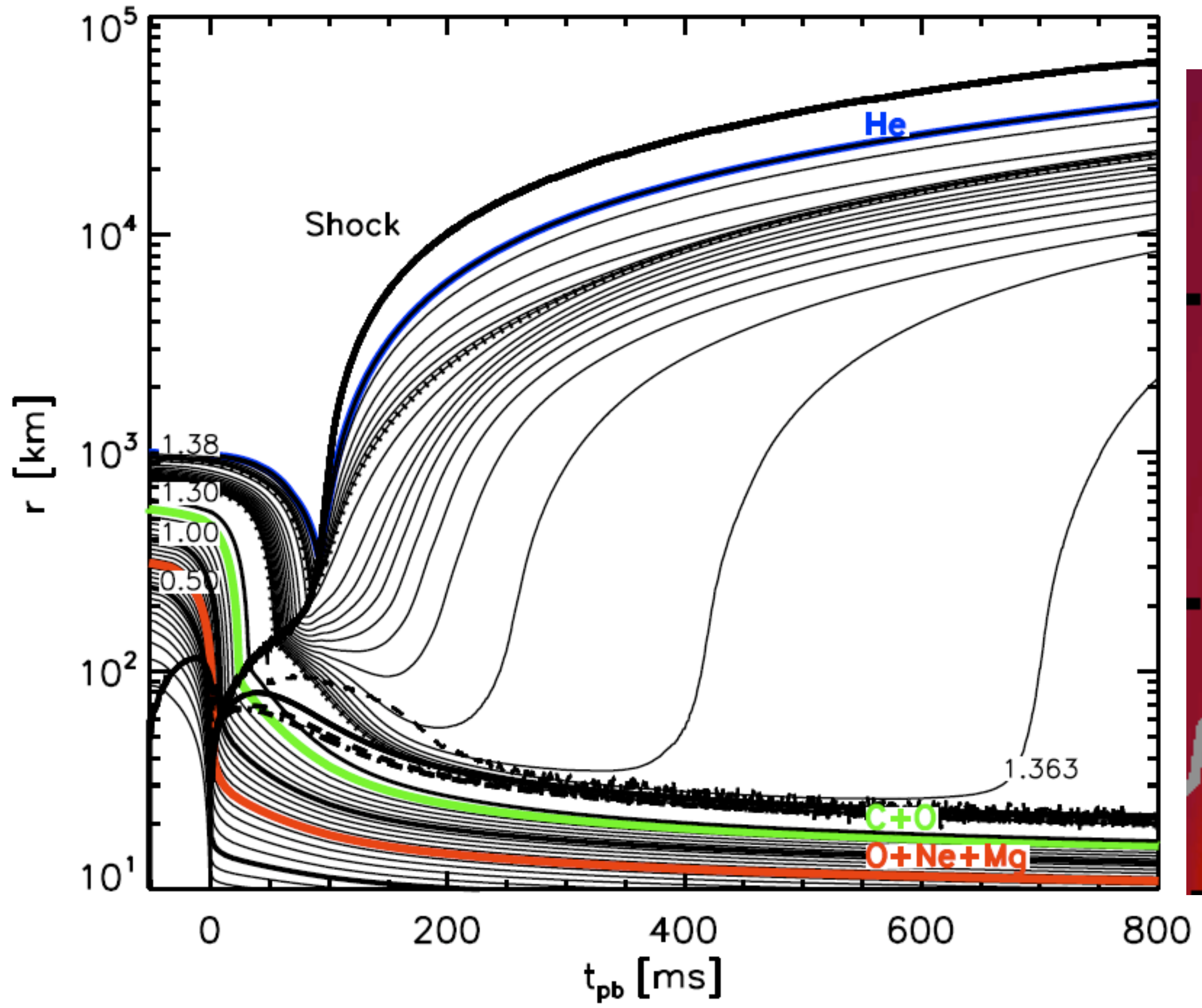
Côté et al. ApJ (2019)

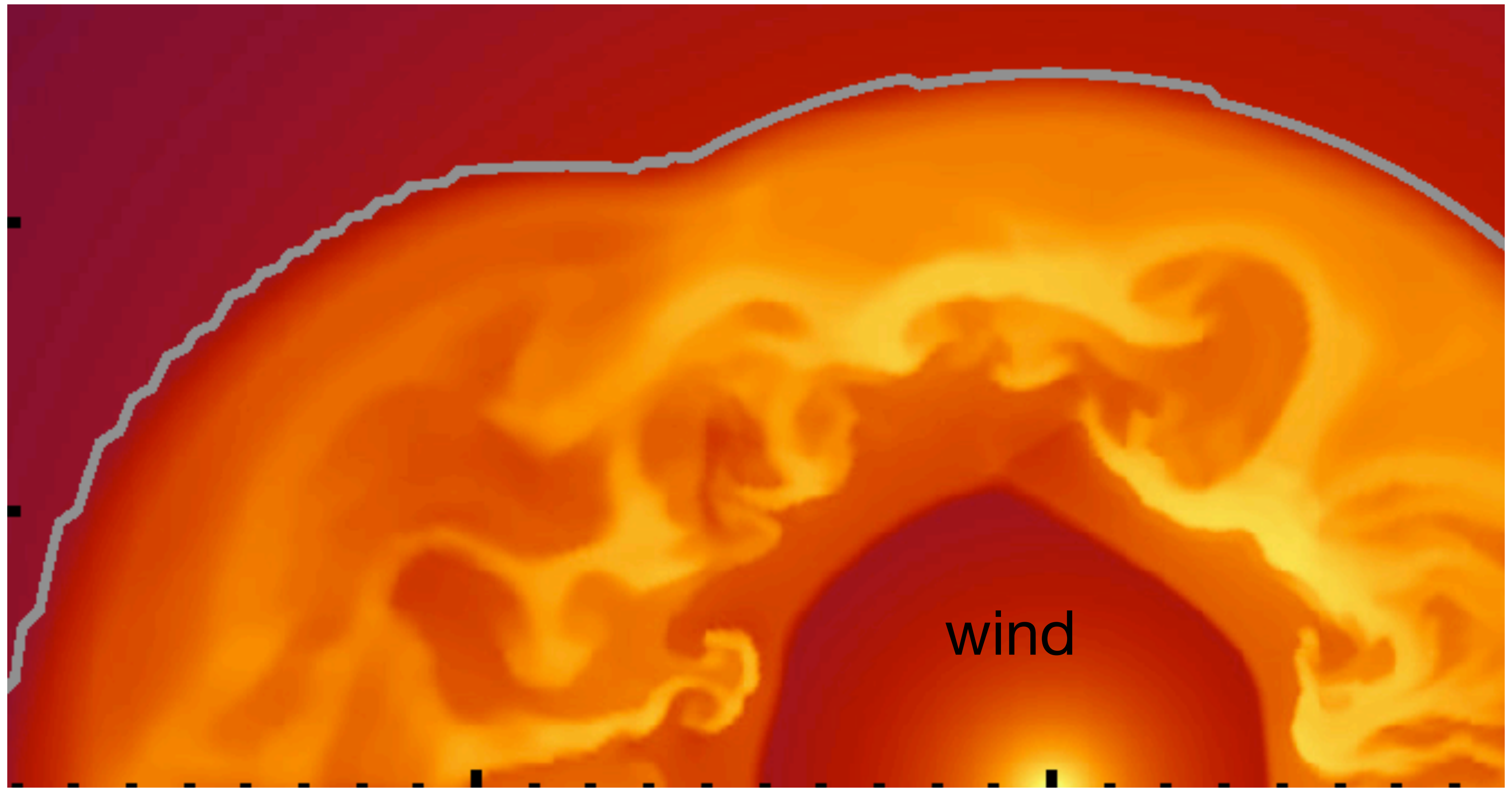


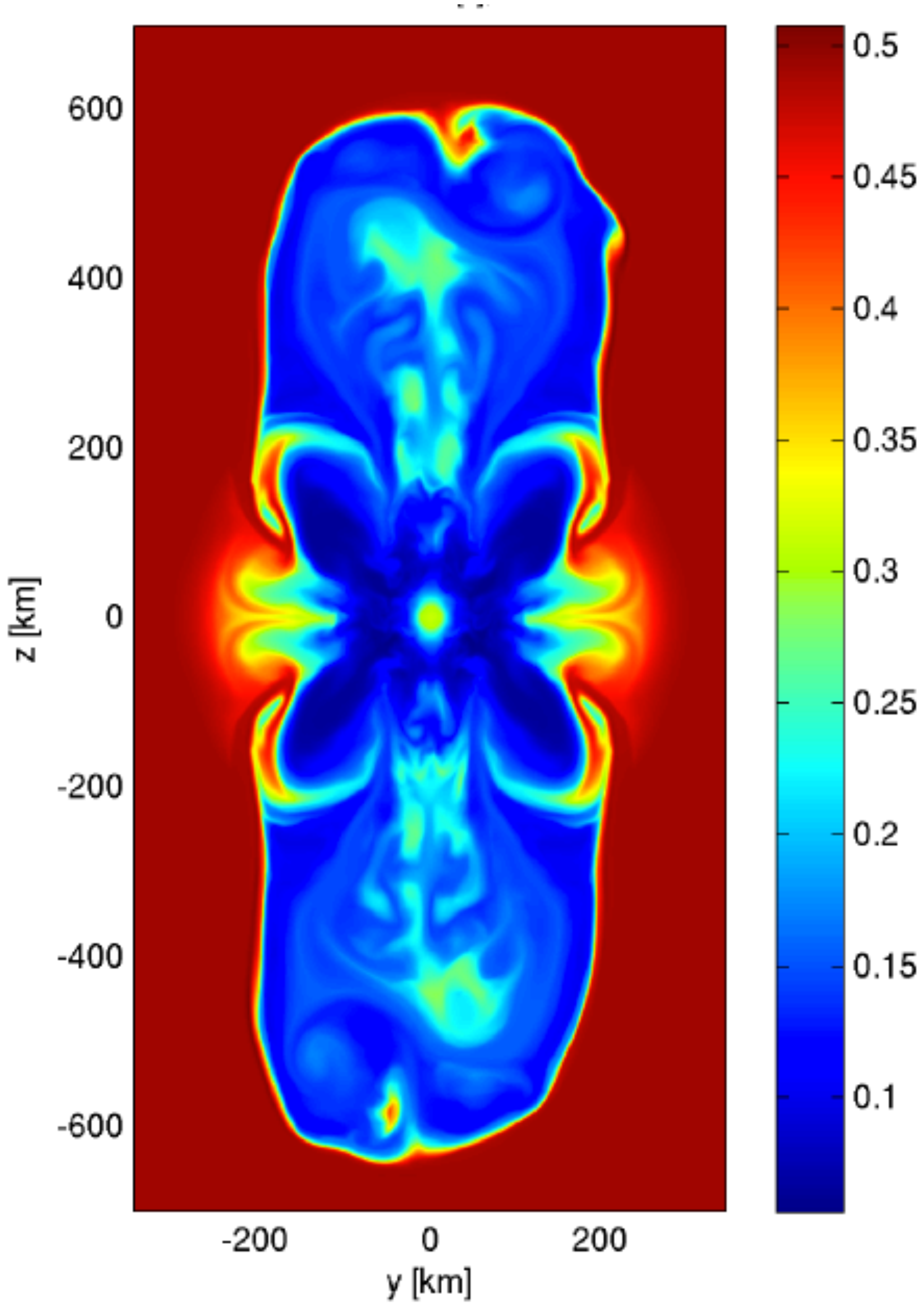
Nucleosynthesis in supernova: r-process

(B²FH 1957)

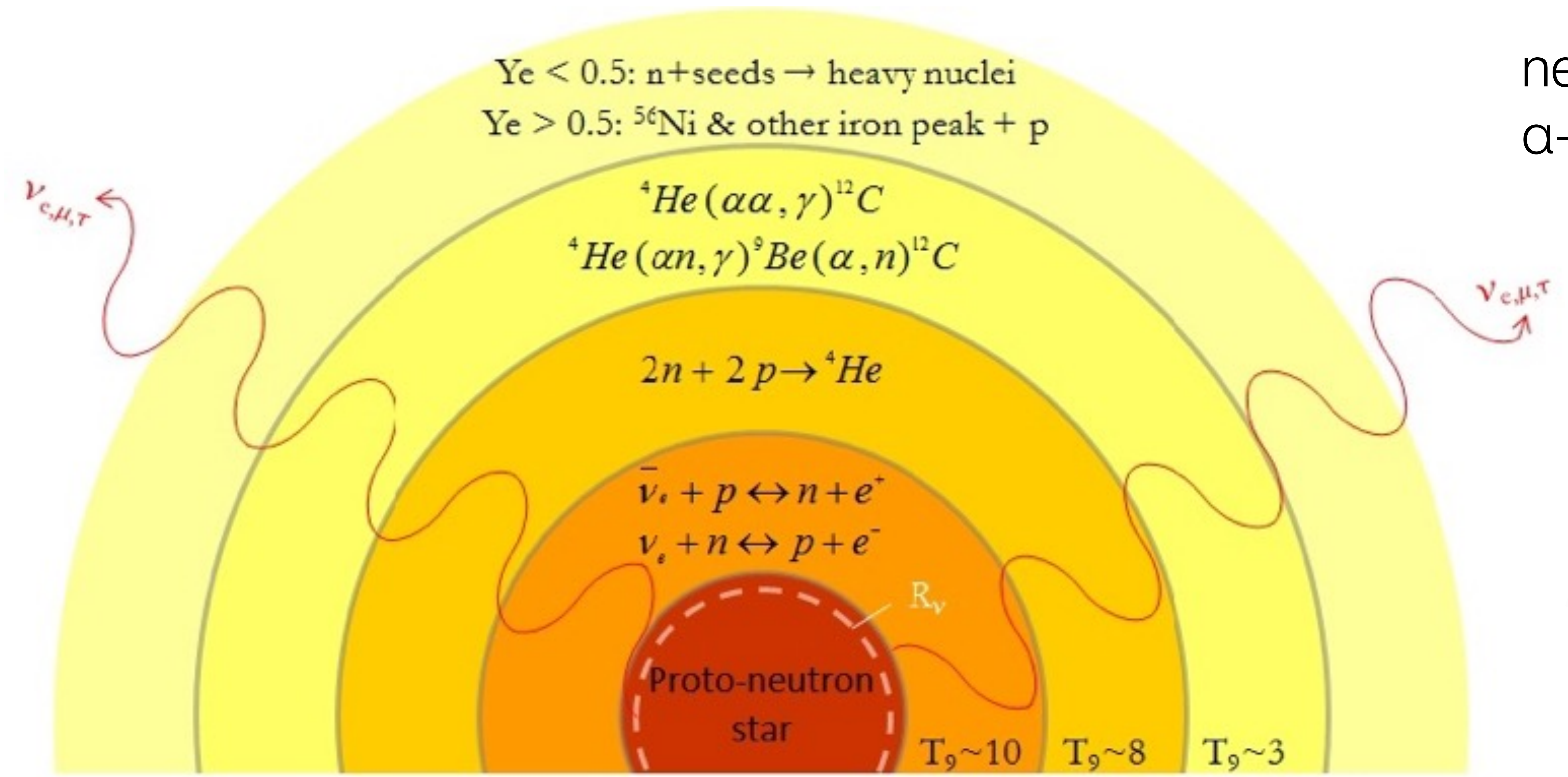
- Supernovae suggested by B2FH in 1957
- Prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
- Neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994)
- Magneto-rotational supernova (Winteler et al. 2012)



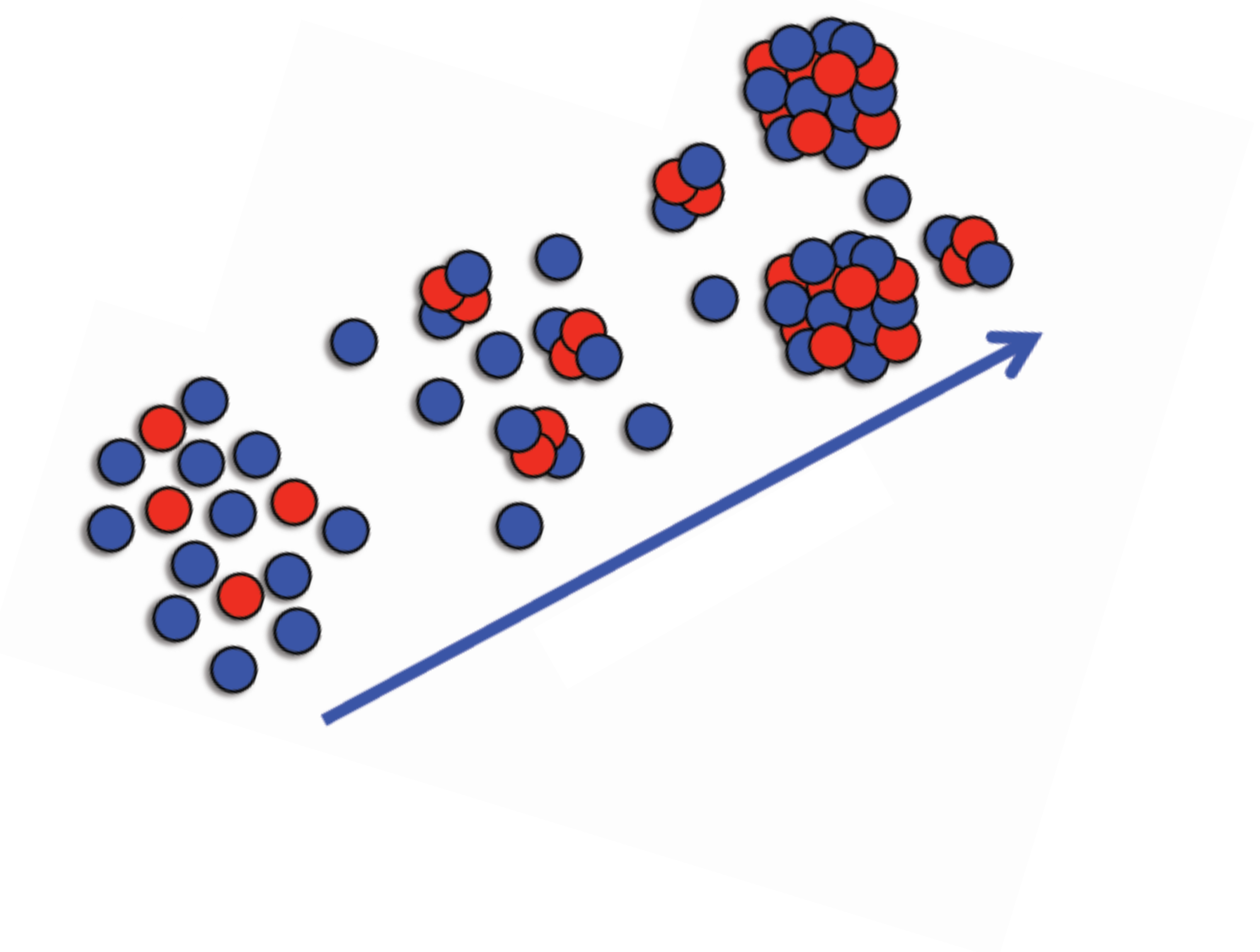




Neutrino-driven wind



neutrons and protons form α-particles
α-particles recombine into seed nuclei



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

NSE → charged particle reactions / α-process → r-process
weak r-process
νp-process

Neutrino-driven wind parameters

r-process ⇒ high neutron-to-seed ratio (Y_n/Y_{seed}~100)

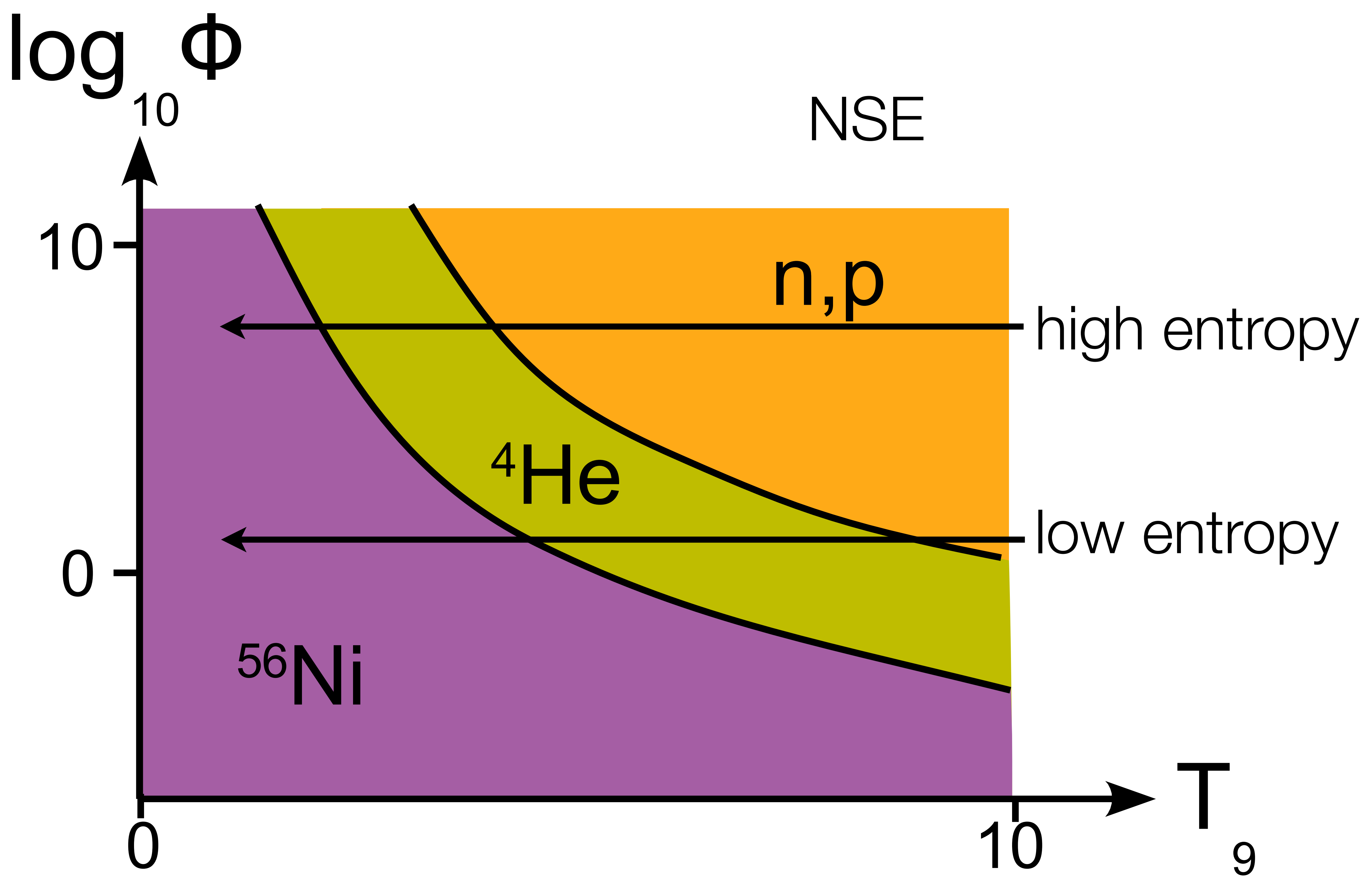
- Short expansion time scale to inhibit α-process and formation of seed nuclei
- High entropy is equivalent to high photon-to-baryon ratio: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e<0.5$

Photon-to-baryon ratio:

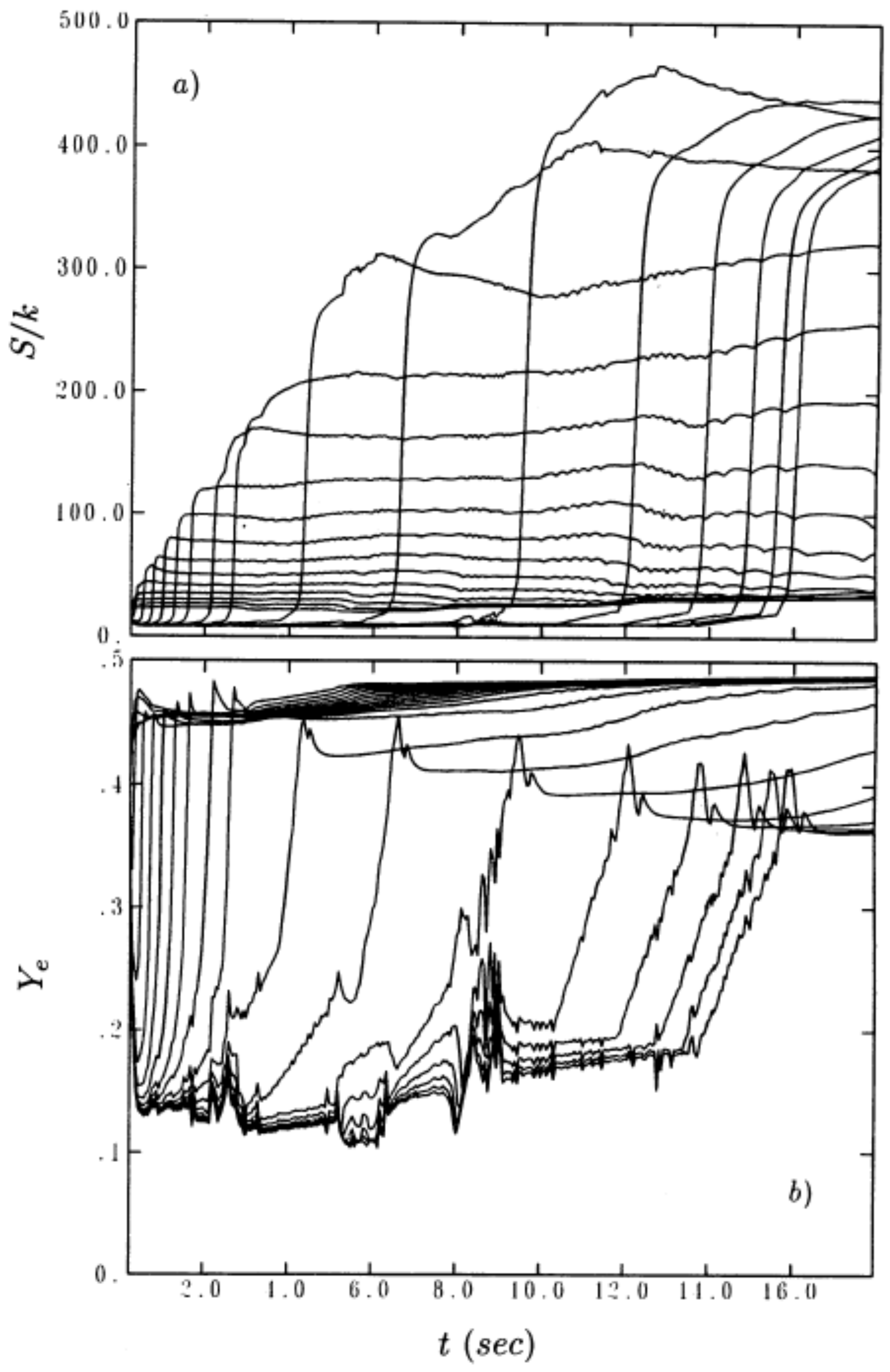
$\Phi = n_\gamma / (\rho N_A) \propto (kT^3) / (\rho N_A)$

Entropy per baryon in relativistic gas:

$s \propto (kT^3) / (\rho N_A) \Rightarrow s = 10/\Phi$



Neutrino-driven wind and r-process



Meyer et al. 1992 and Woosley et al. 1994:
r-process: high entropy and low Y_e

Witti et al., Takahasi et al. 1994 needed factor 5.5 increased in entropy

Qian & Woosley 1996: analytic model

$$\dot{M} \propto L_\nu^{5/3}\,\epsilon_\nu^{10/3}\,R_{ns}^{5/3}\,M_{ns}^{-2}\,,$$
$$s \propto L_\nu^{-1/6}\,\epsilon_\nu^{-1/3}\,R_{ns}^{-2/3}\,M_{ns}\,,$$
$$\tau \propto L_\nu^{-1}\,\epsilon_\nu^{-2}\,R_{ns}\,M_{ns}\,.$$

Thompson, Otsuki, Wanajo, ... (2000-...) parametric steady state winds

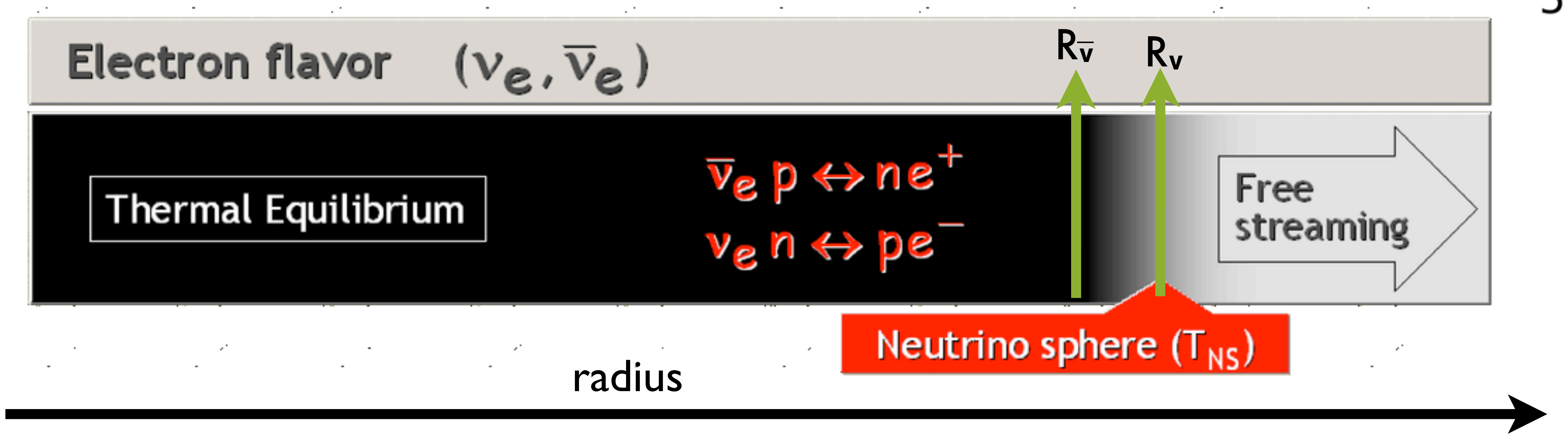
Electron fraction

depends on supernova neutrino transport and neutrino interactions in outer layers of neutron star

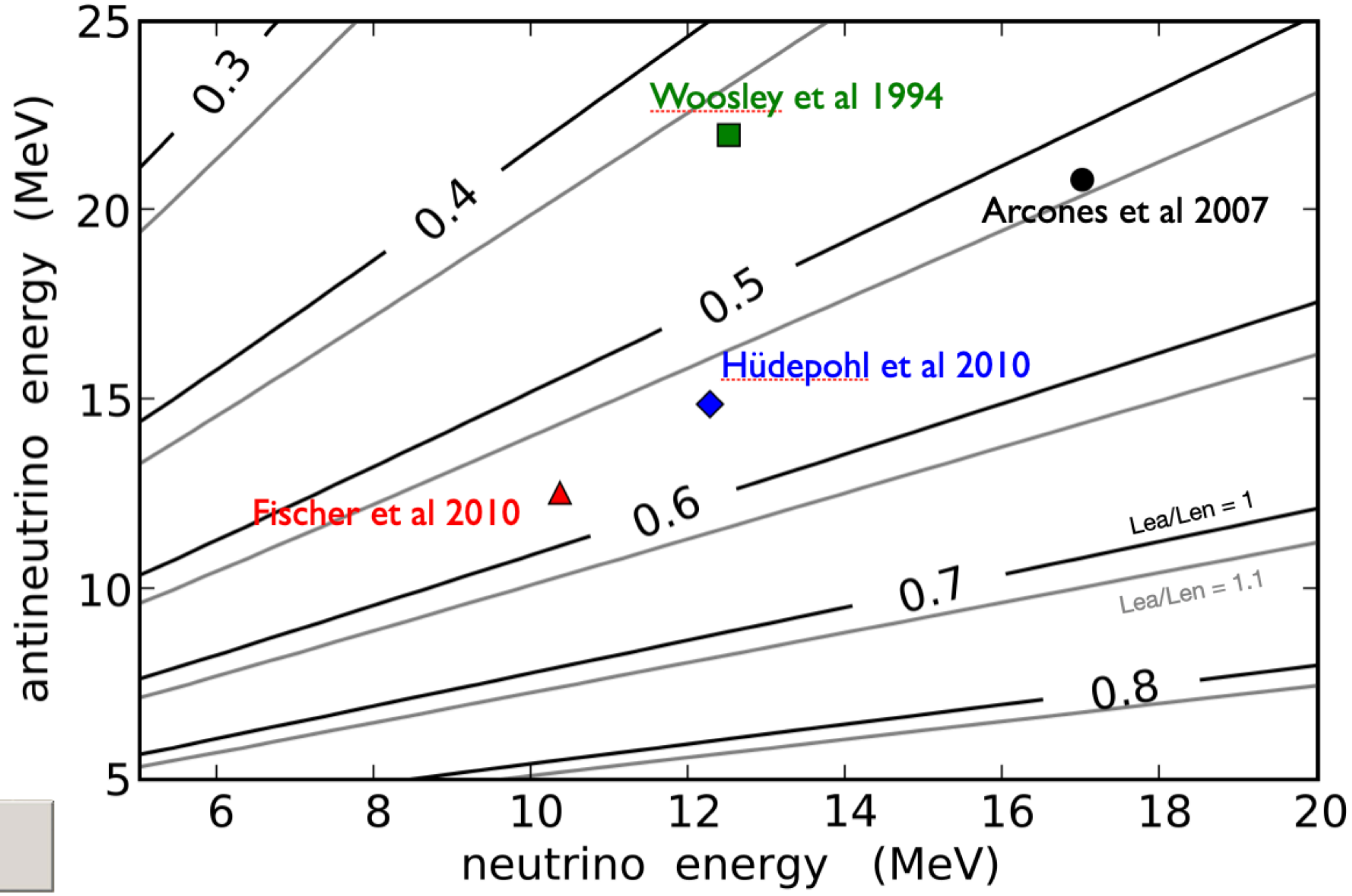
$$Y_e \approx \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e})}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e})}\right]^{-1}$$

($\Delta = m_n - m_p$)

Neutrino energies determined by neutrinosphere

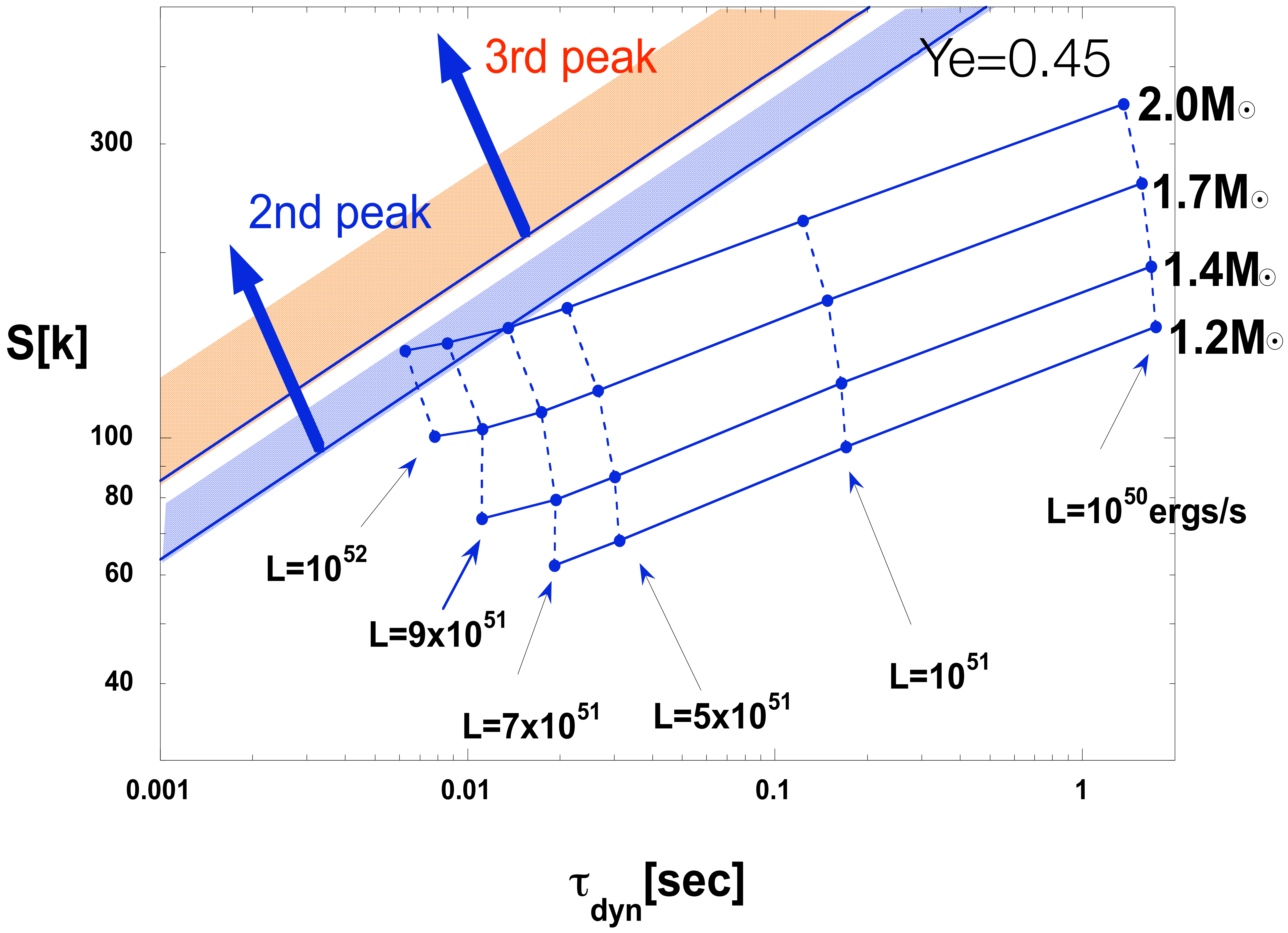


$Y_e < 0.5$ if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} \gtrsim 4\Delta \approx 5$ MeV



Neutrino-driven wind parameters and r-process

Necessary conditions identified by steady-state models (e.g., Otsuki et al. 2000, Thompson et al. 2001)



Otsuki et al. 2000

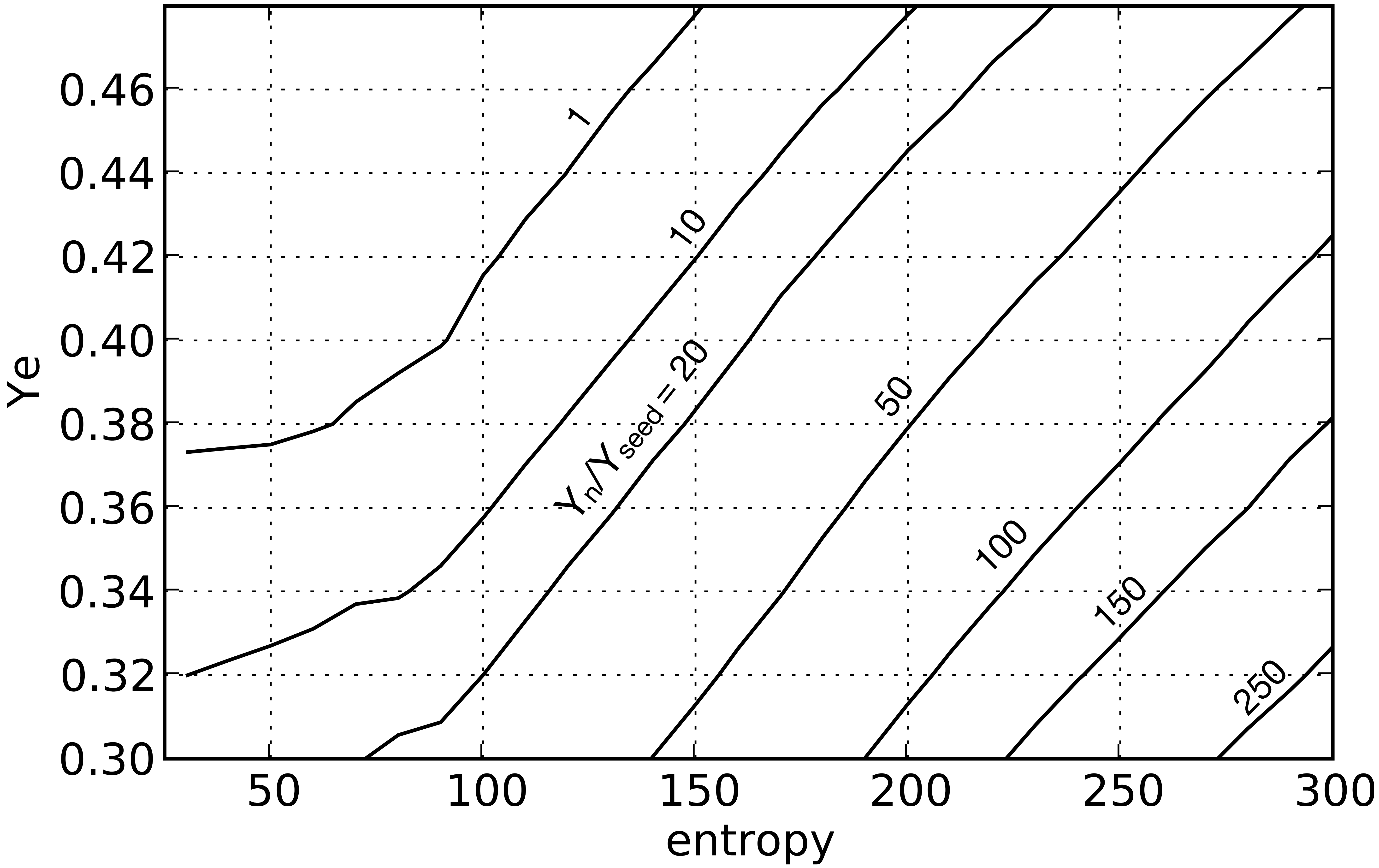
Neutrino-driven wind parameters and r-process

Necessary conditions identified by steady-state models (e.g., Otsuki et al. 2000, Thompson et al. 2001)

Conditions were not realized in simulations
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, …)

S_{wind} = 50 - 120 k_B/nuc
τ = few ms
Y_e > 0.5?

Additional ingredients: wind termination, extra energy source, rotation and magnetic fields, neutrino oscillations



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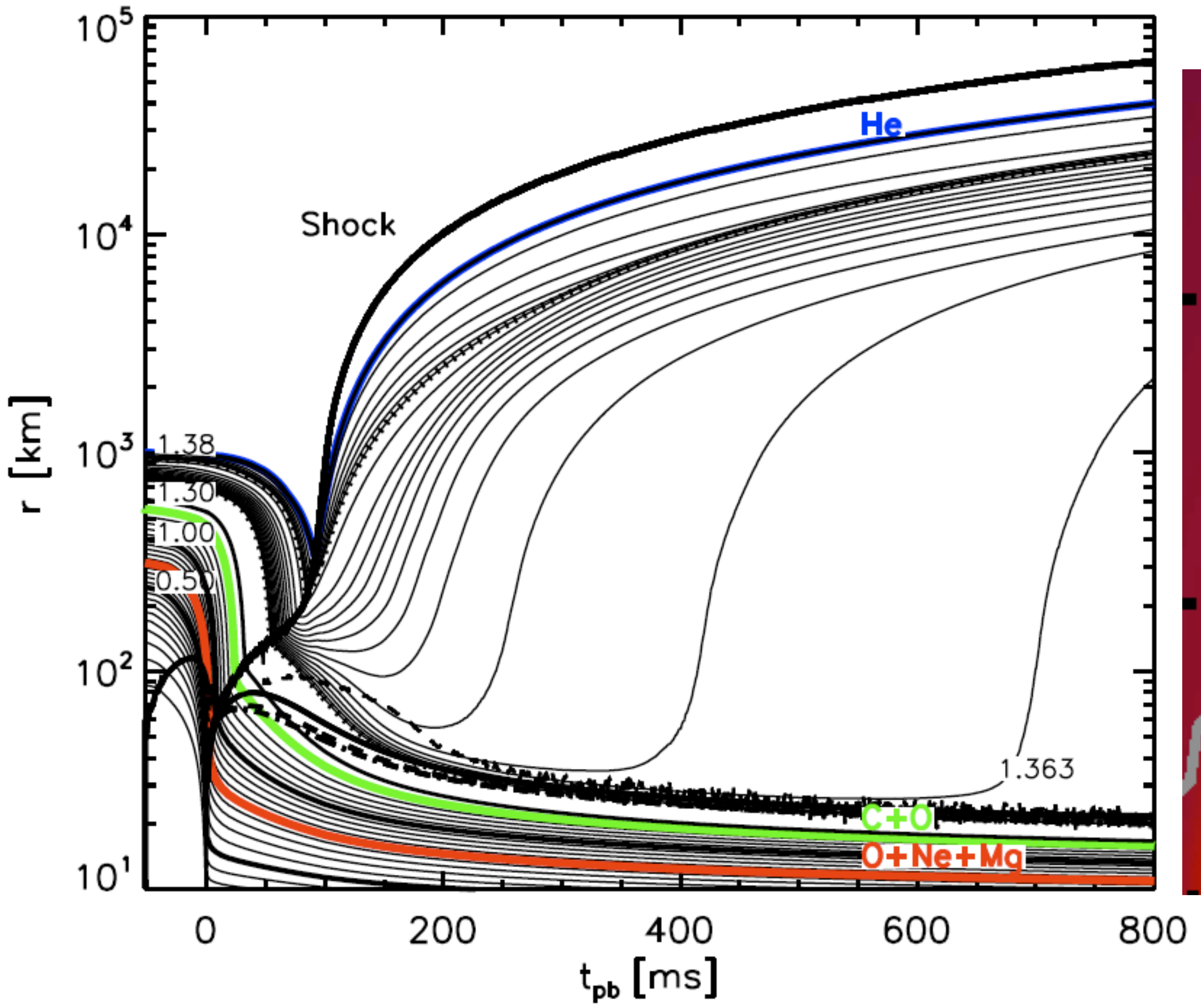
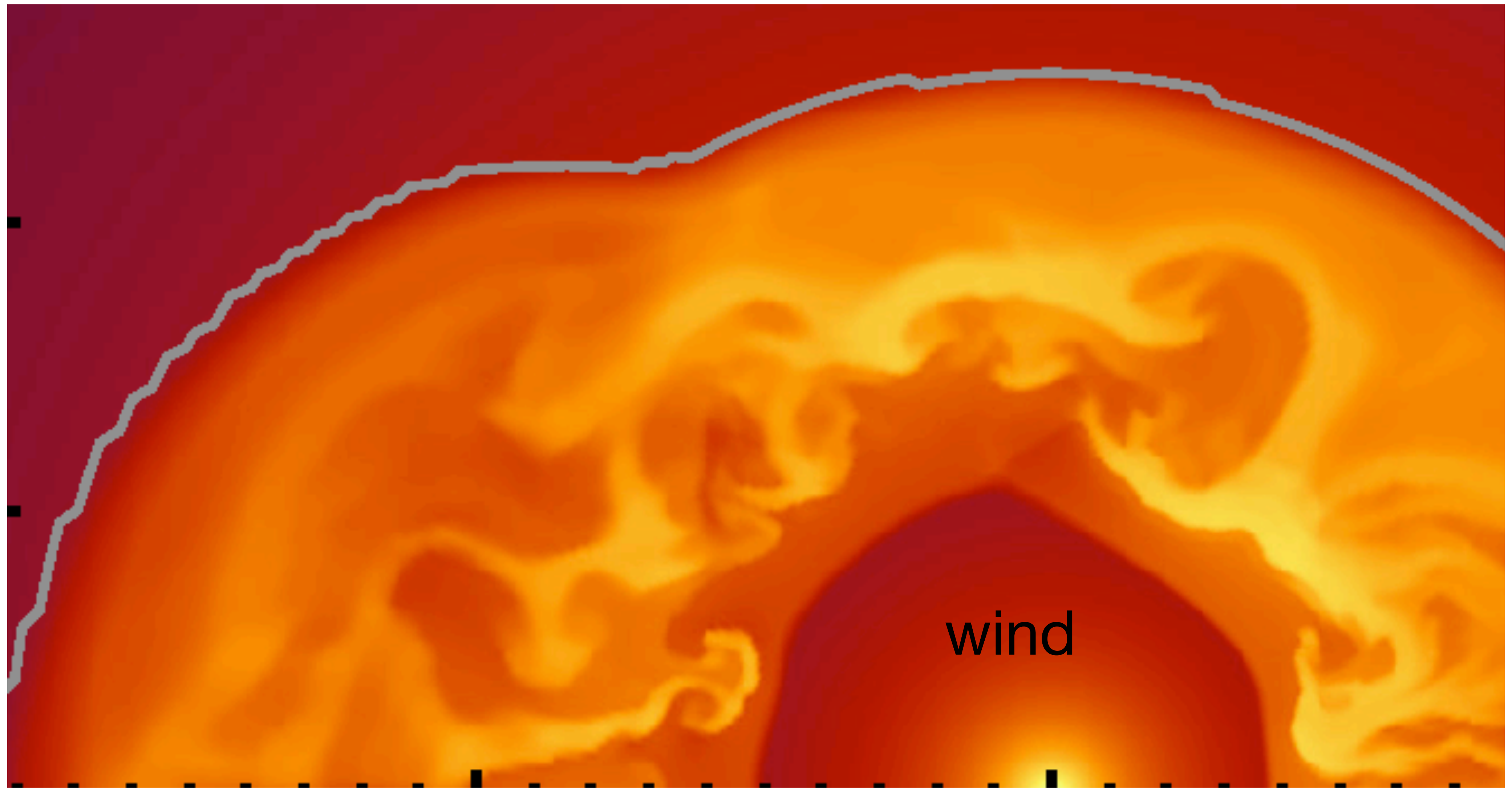
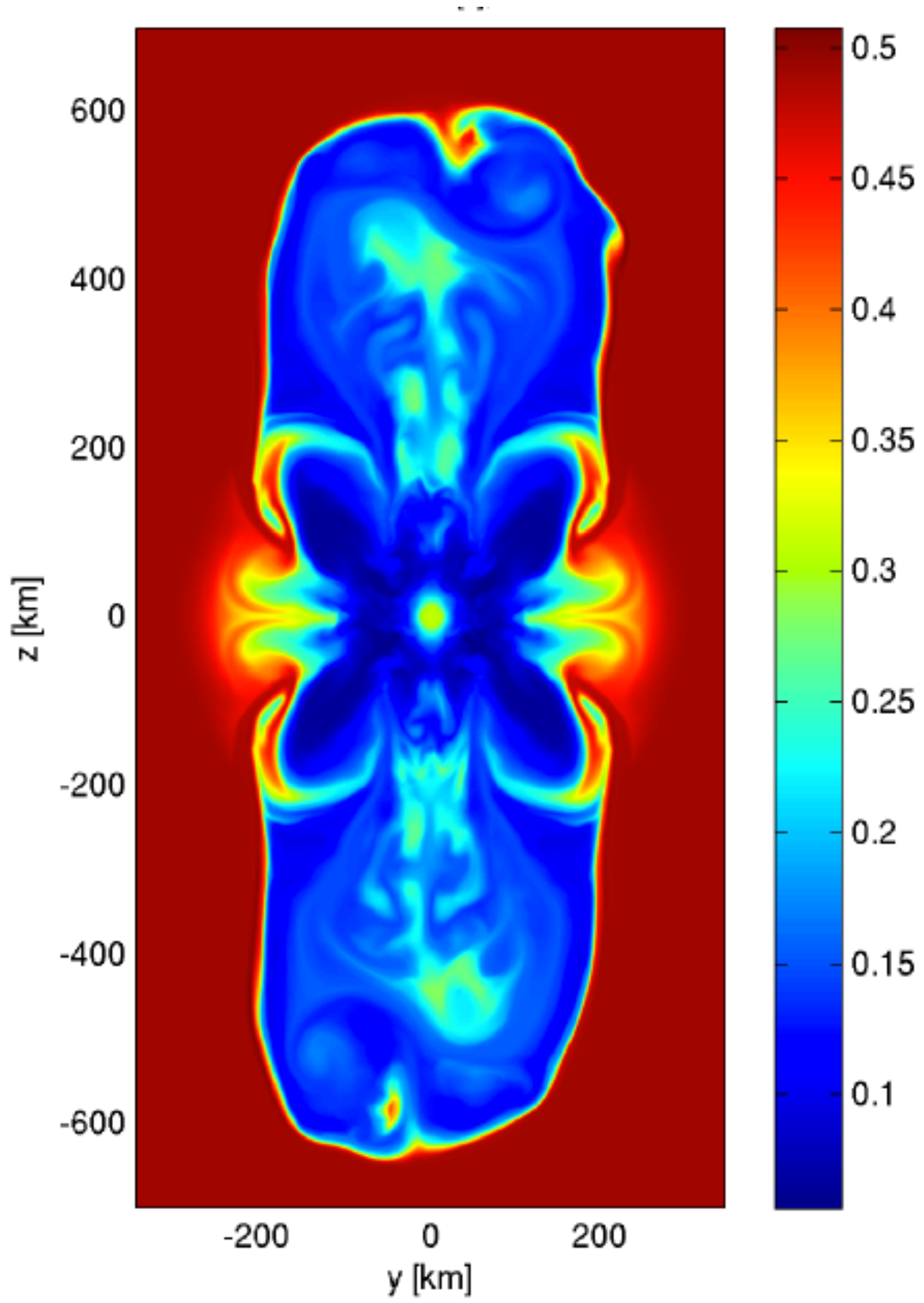






Magneto-rotational supernova (MR-SN)

→ Moritz Reichert lecture

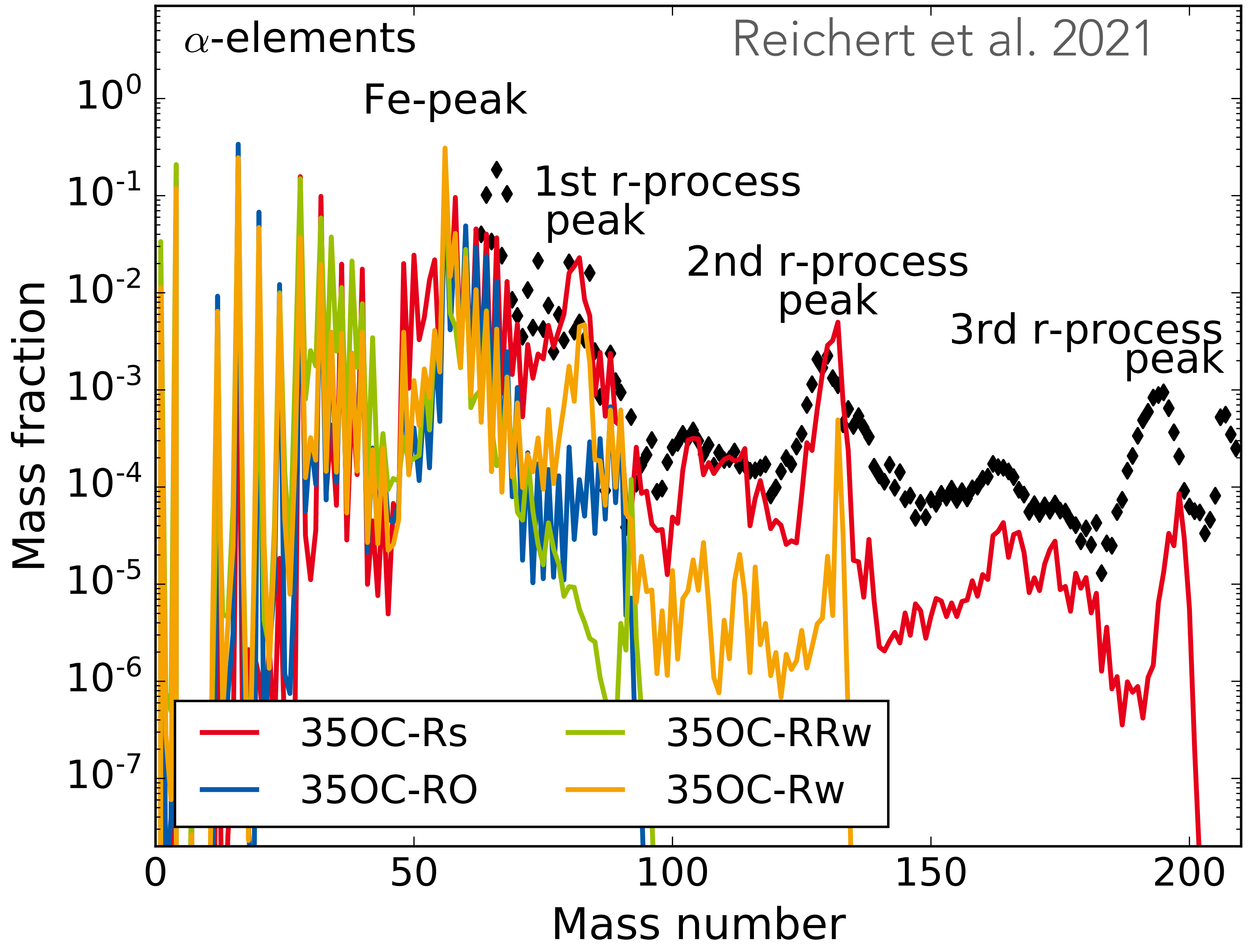
Neutron-rich matter ejected by strong magnetic field (Cameron 2003, Nishimura et al. 2006)

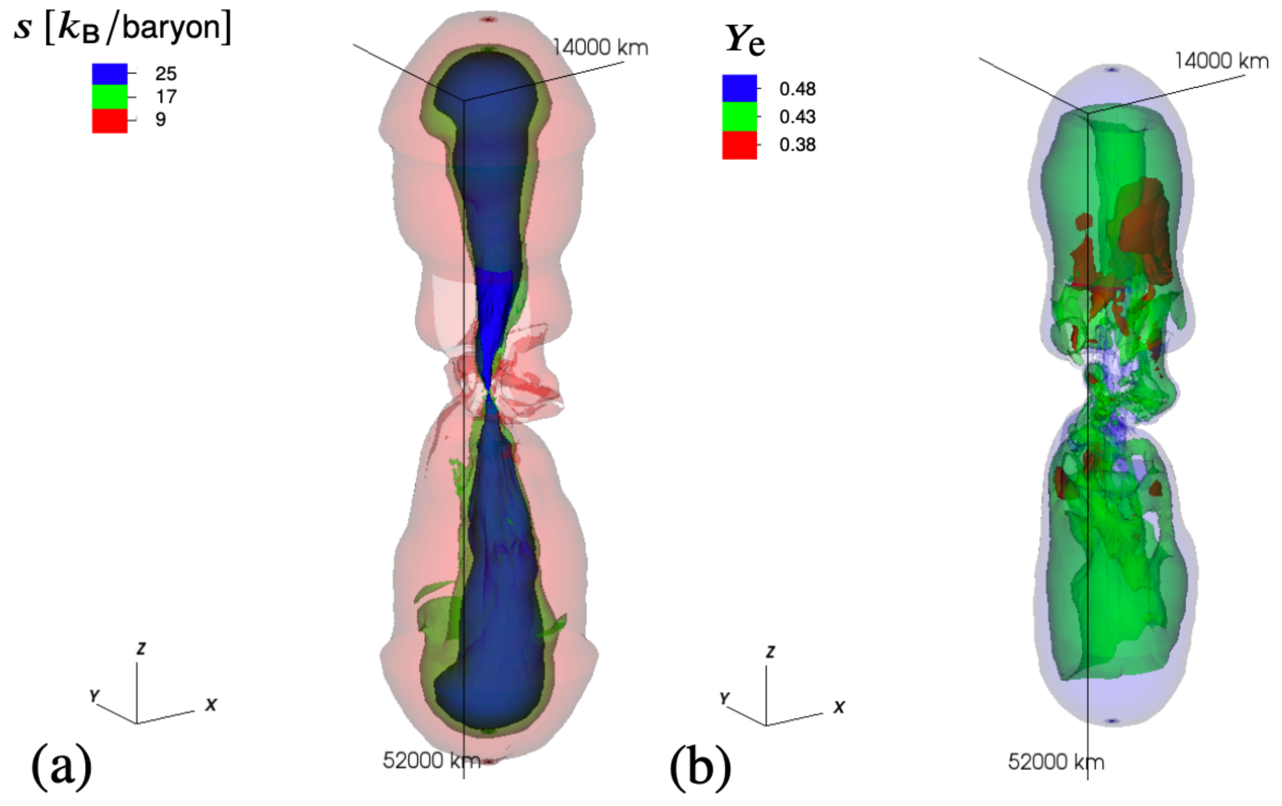
2D and 3D + parametric neutrino treatment
(Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018)

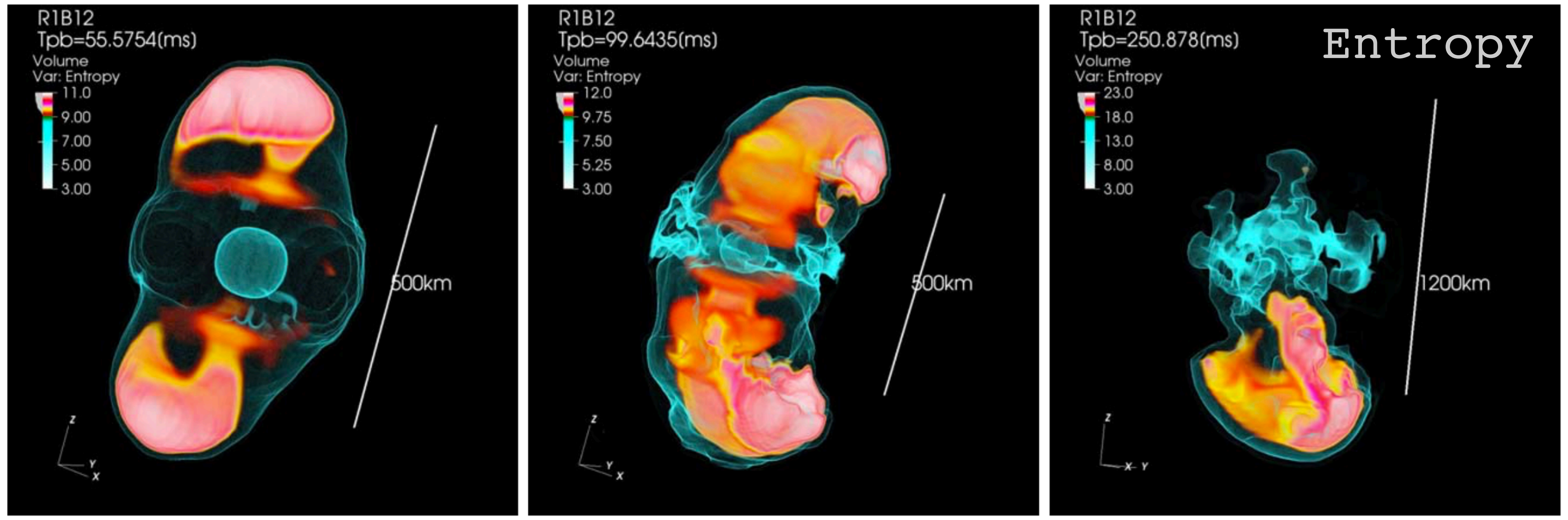
Nucleosynthesis based on simulations with accurate neutrino transport (Obergaulinger & Aloy 2017)

Weak r-process, νp-process, r-process (Reichert et al. 2021, 2023, 2024)

First 3D simulations with accurate neutrino transport
(Obergaulinger et al. 2020, Kuroda et al. 2020)

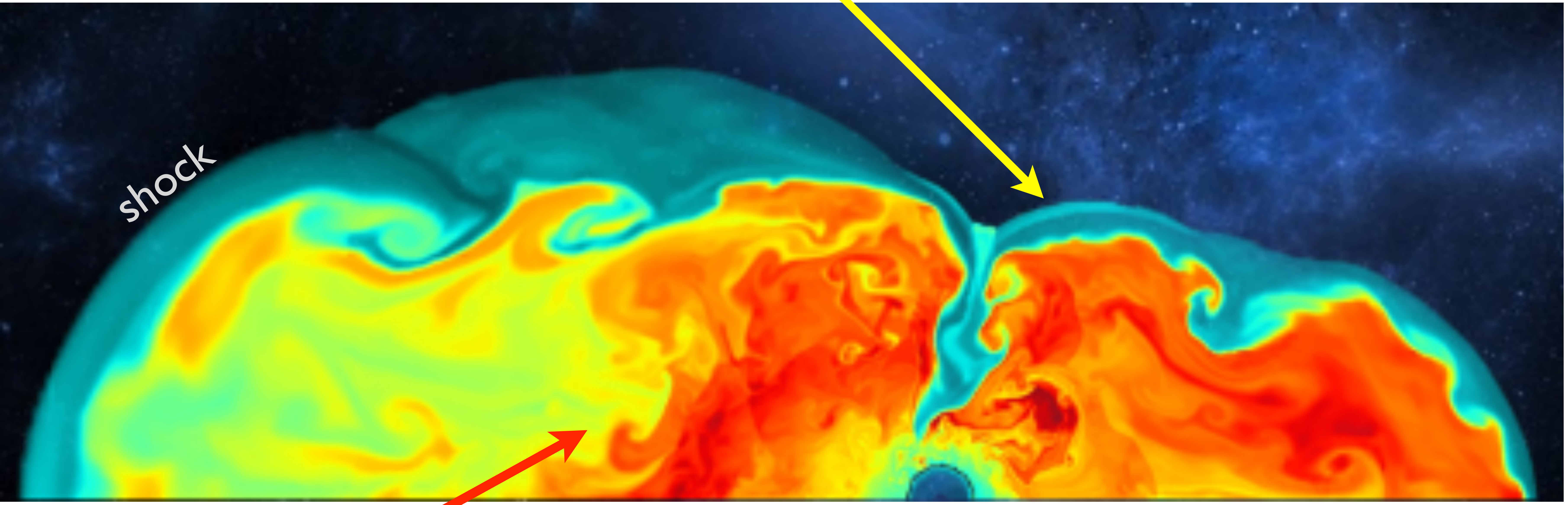






Supernova nucleosynthesis

Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter



neutrino-driven ejecta

Nuclear statistical equilibrium (NSE)

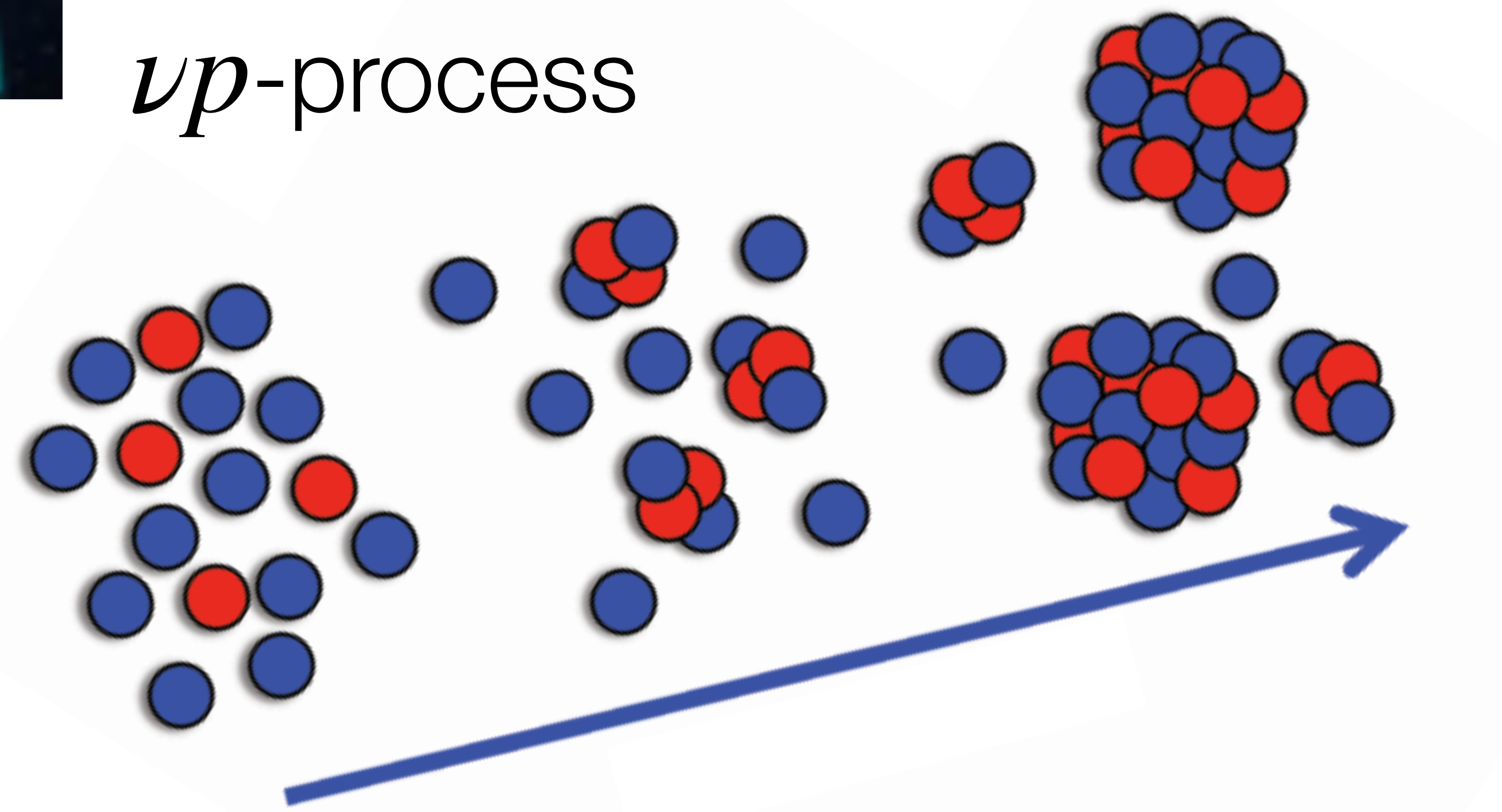
charged particle reactions

α-process

~~r-process~~

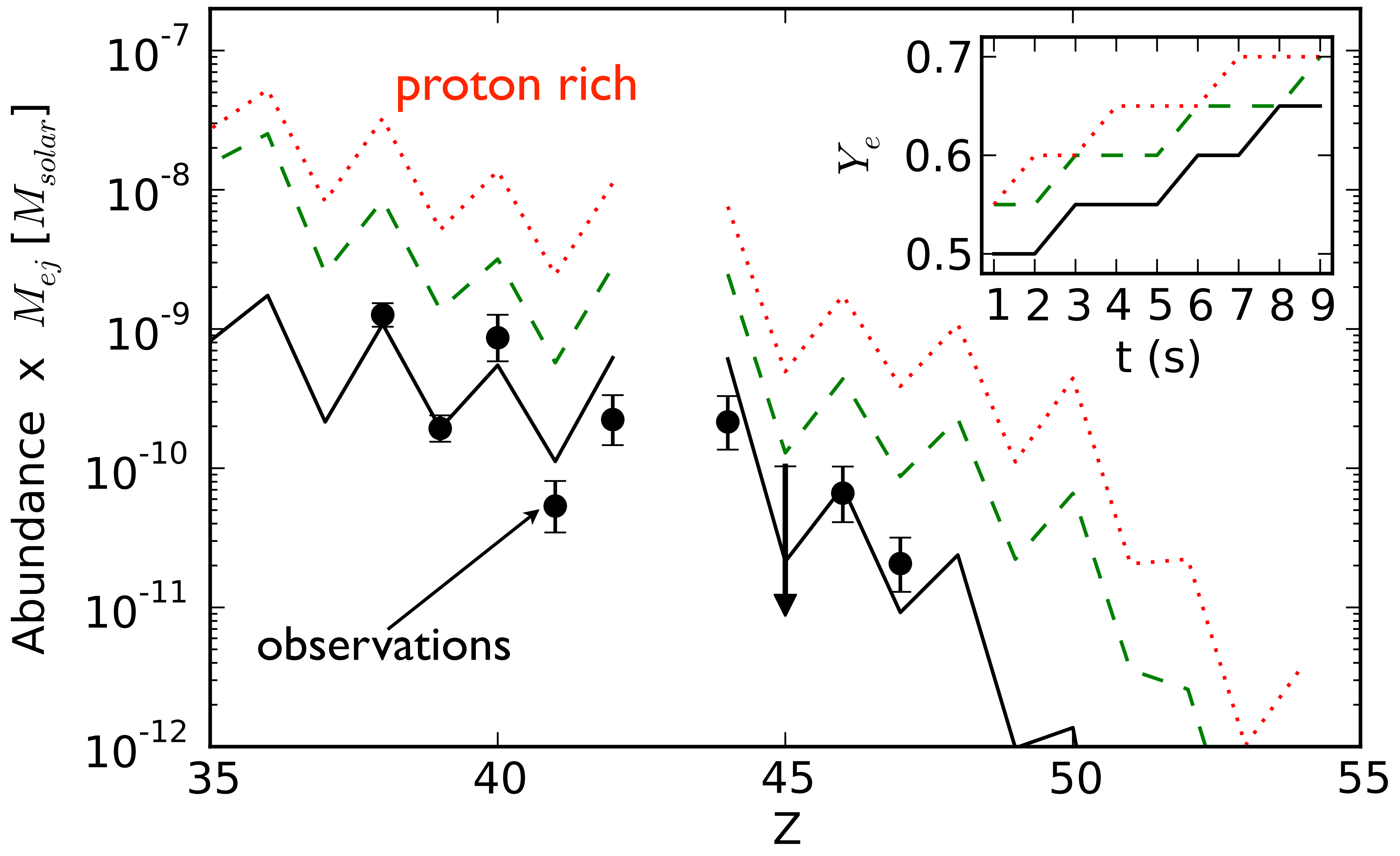
weak r-process

νp-process

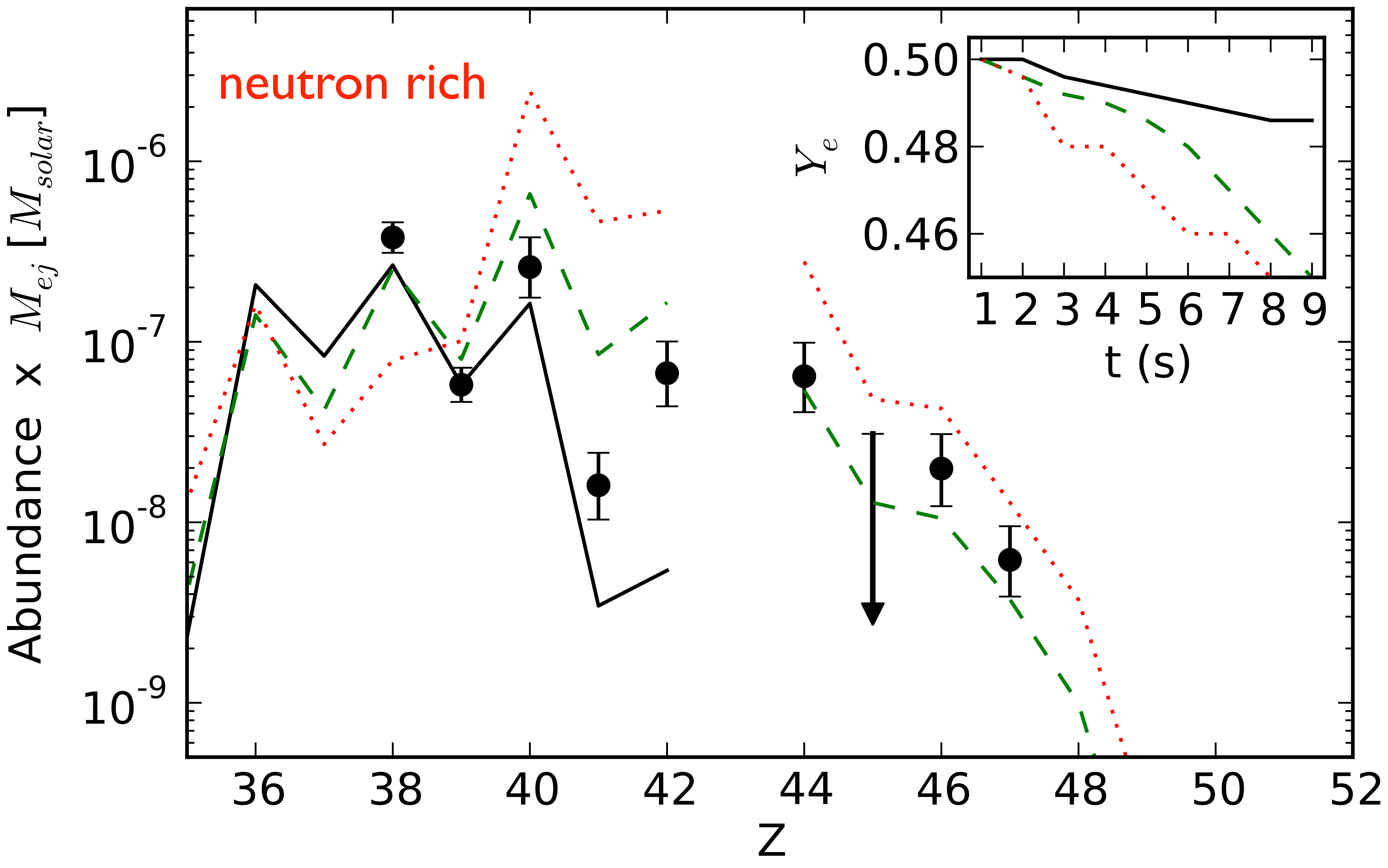


Lighter heavy elements (Sr to Ag)

Proton-rich: νp-process



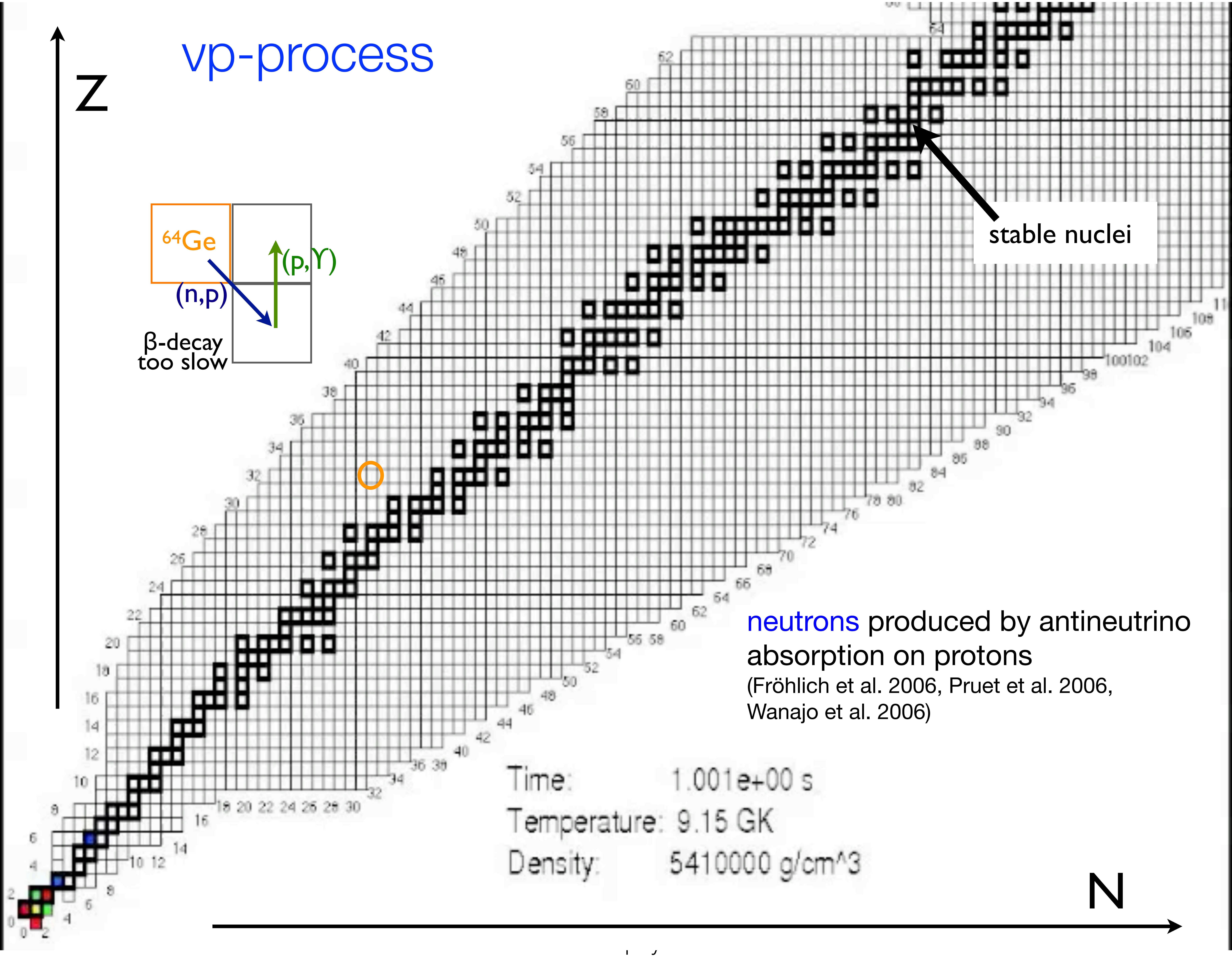
Neutron-rich: weak r-process



Observation pattern reproduced
Production of p-nuclei

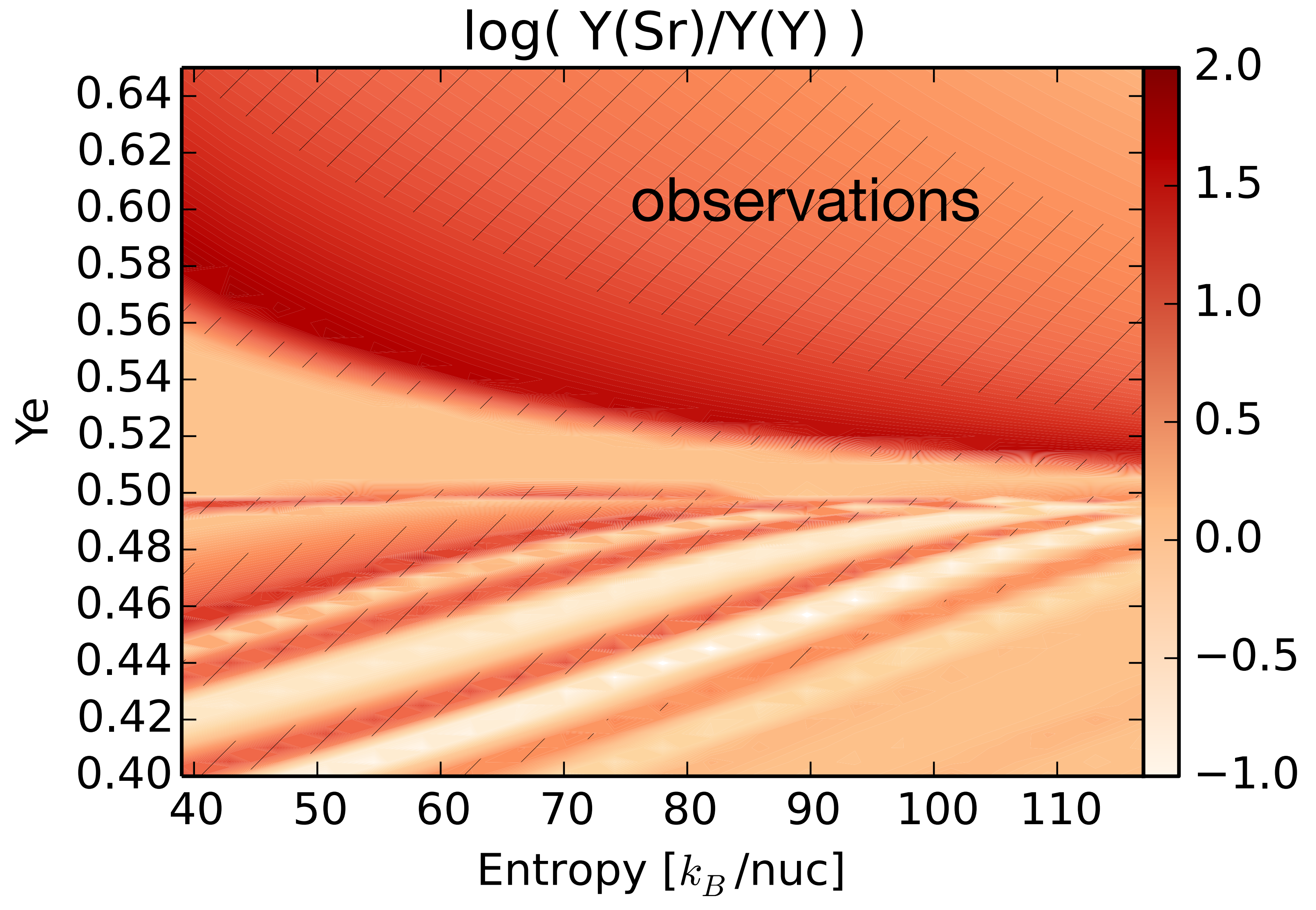
Overproduction at A=90 (N=50)
→ only a fraction of neutron-rich ejecta
(Hoffman et al. 1996)

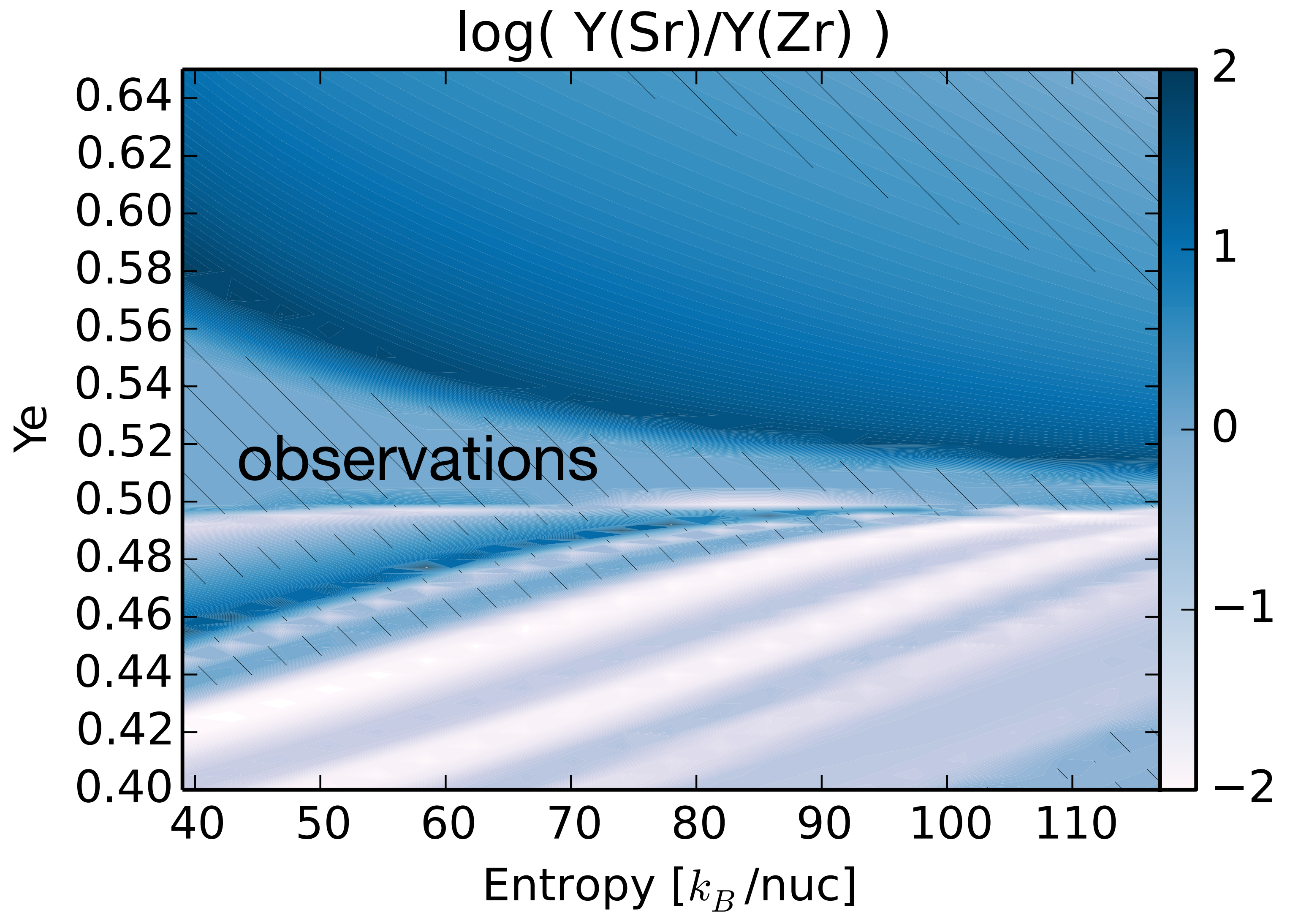
Arcones & Montes, ApJ (2011), Arcones & Bliss, J.Phys. G (2014), Bliss, Arcones, Qian, ApJ (2018)



νp-process
Z
N
⁶⁴Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
neutrons produced by antineutrino absorption on protons
(Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)
Time: 1.001e+00 s
Temperature: 9.15 GK
Density: 5410000 g/cm^3

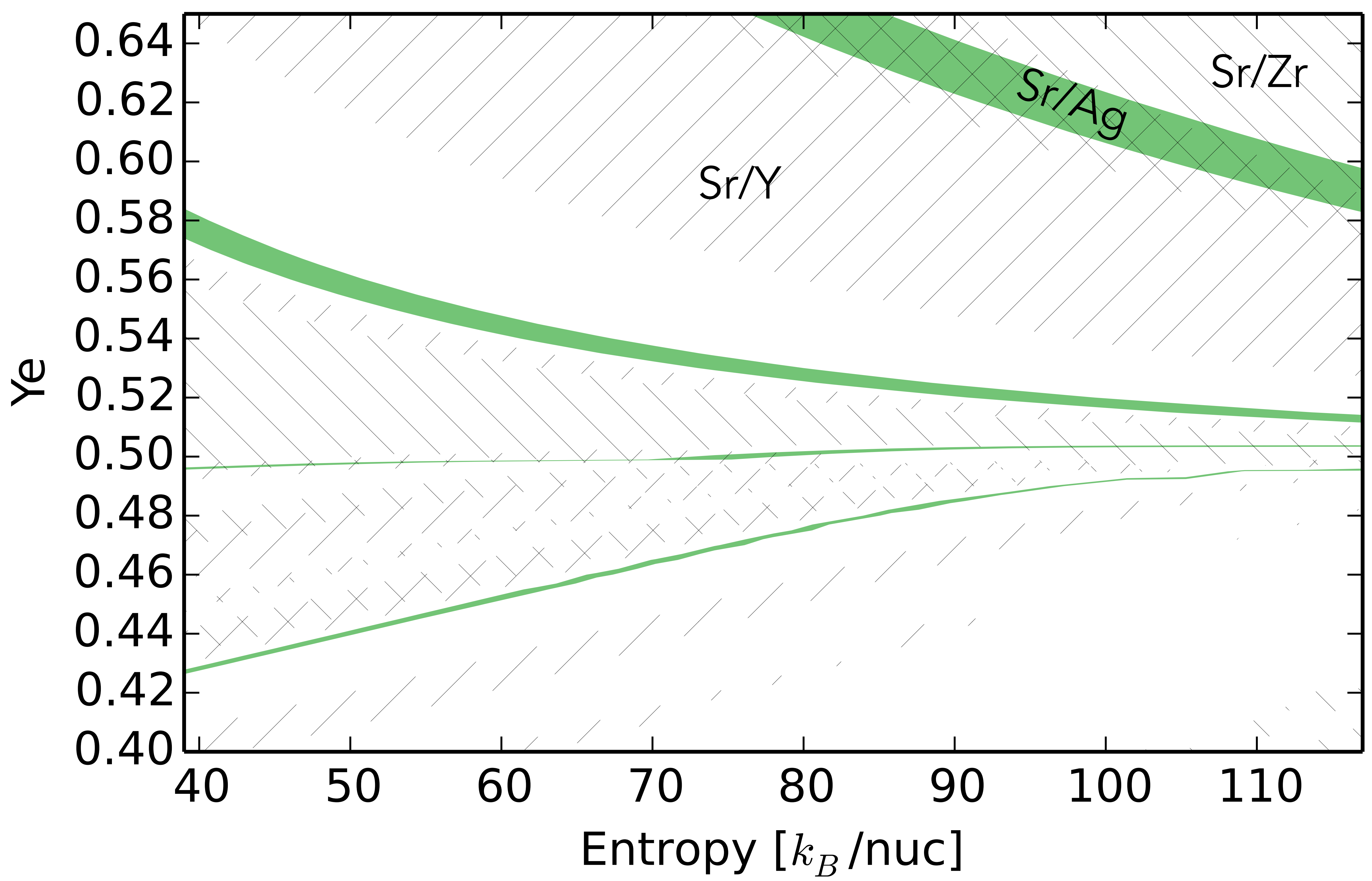
Constraints from observations





Observation of abundance ratios can constrain conditions in supernova explosions:

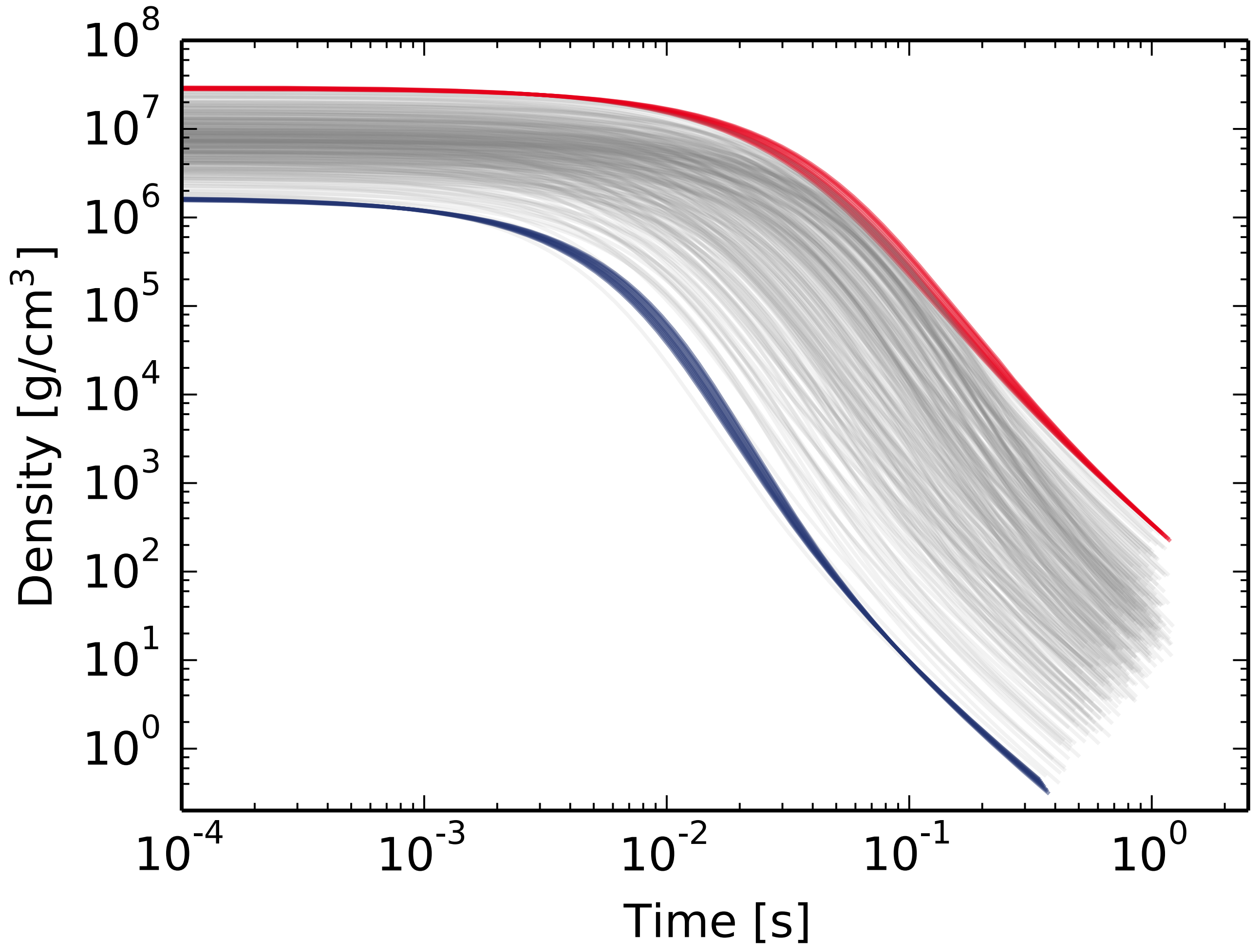
Proton vs. Neutron rich → neutrino energies and luminosities

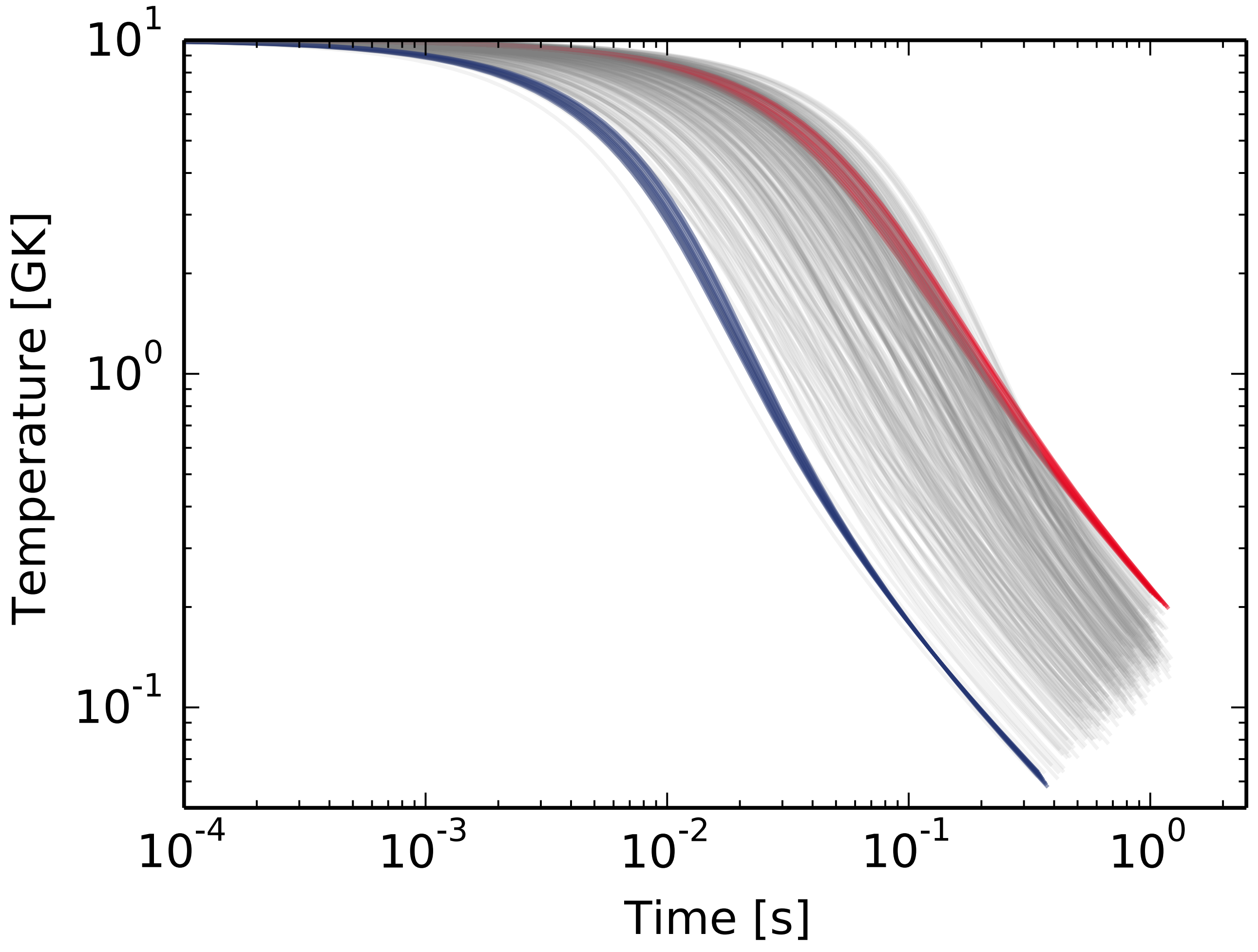


Astrophysics uncertainties/variability

Bliss, Witt, Arcones, Montes, Pereira (2018)

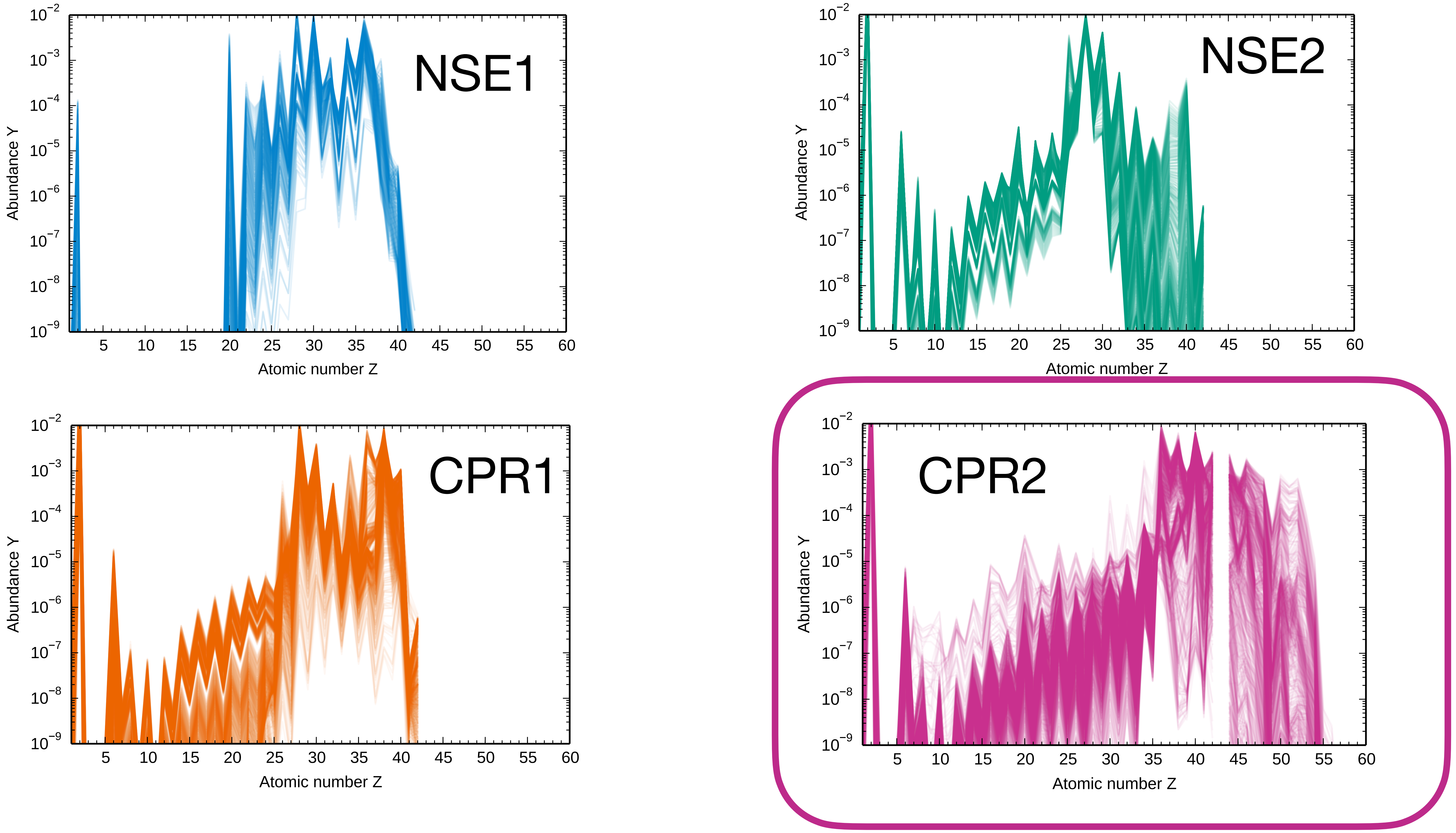
Steady-state model: all possible conditions and nucleosynthesis pattern in neutrino-driven ejecta





Based on Otsuki et al. 2000: study of 3 000 trajectories

Four characteristic patterns

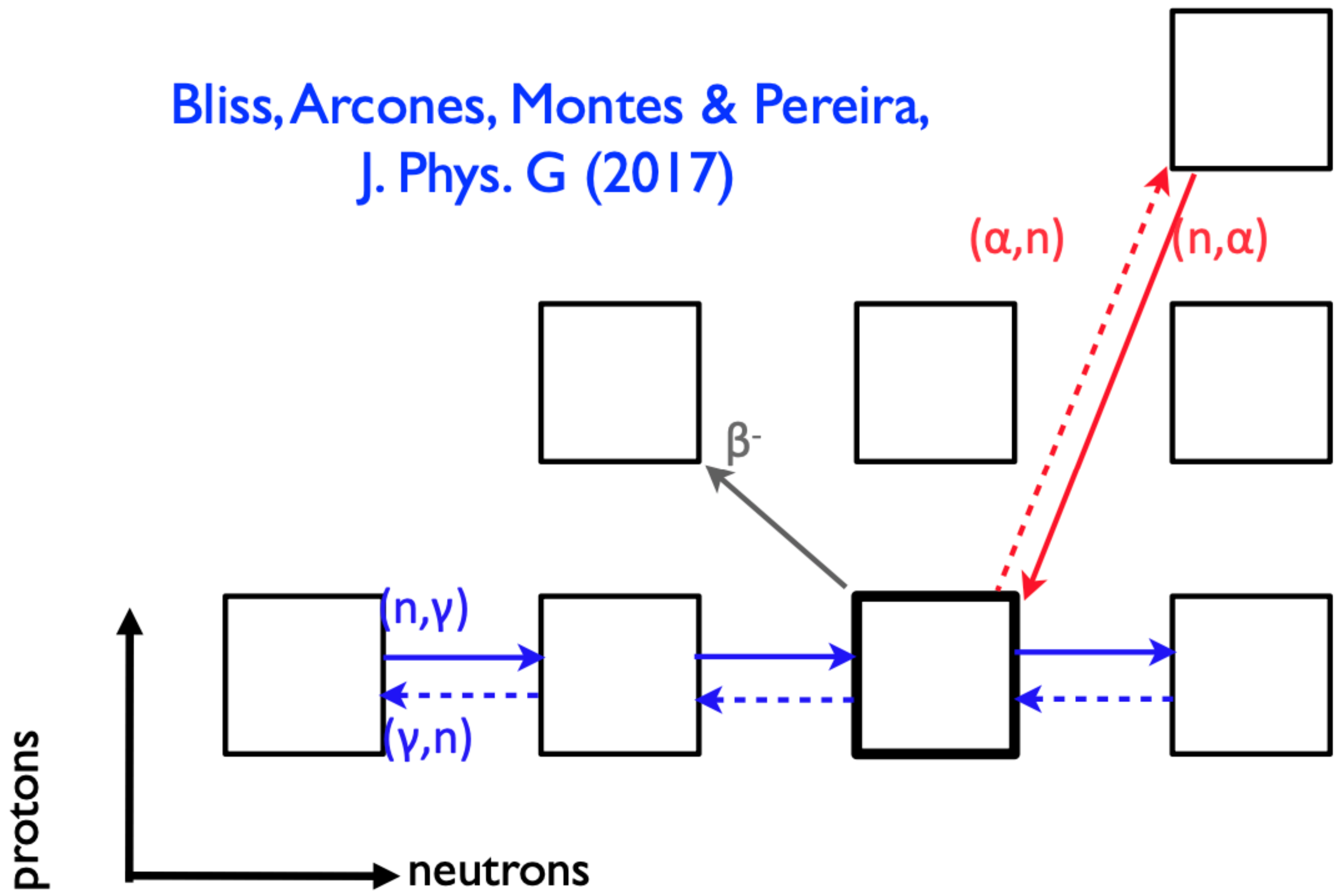


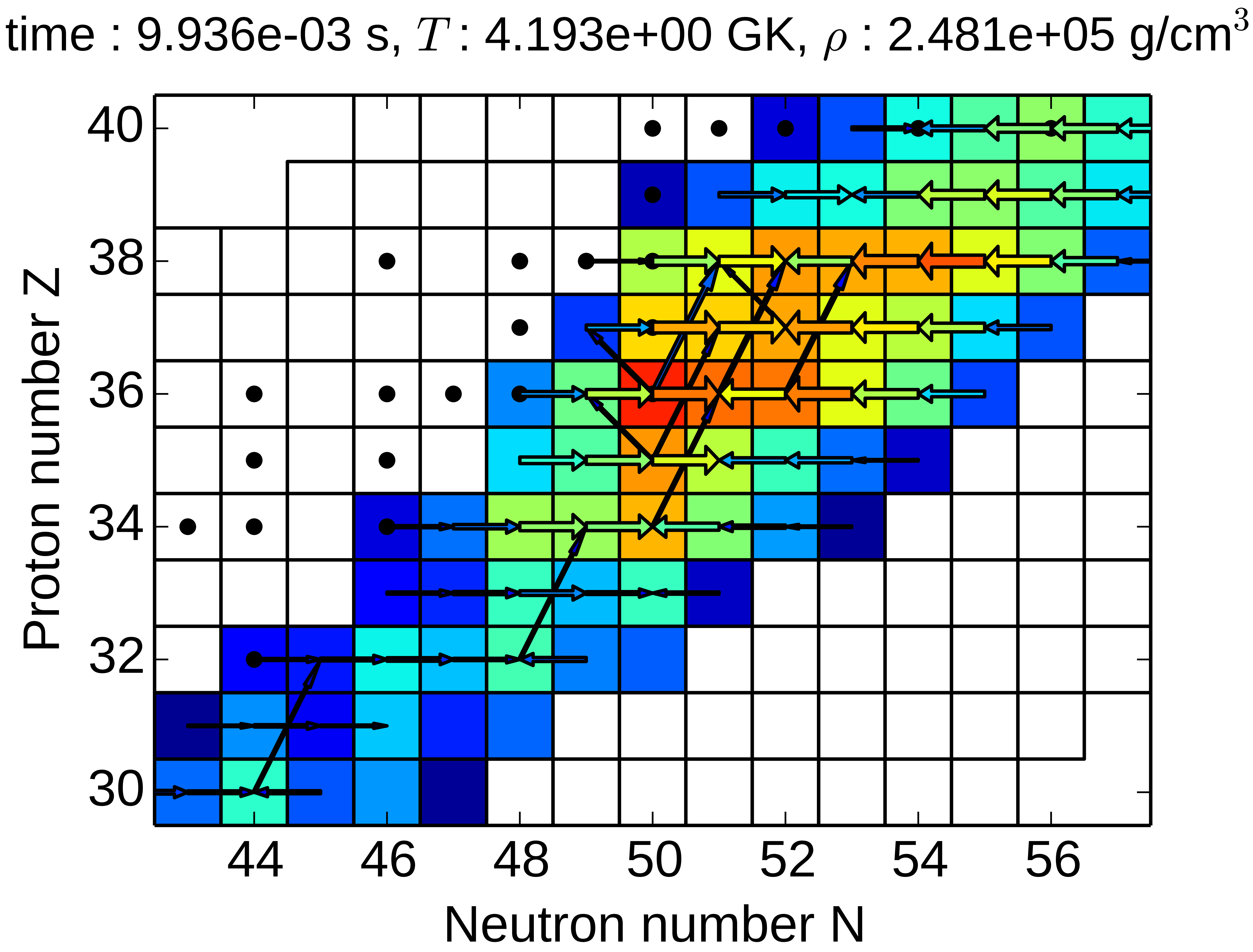
Nuclear physics uncertainty

Path close to stability:

- masses and beta decays known
- beta decays slow
- $(\alpha$,n) reactions move matter to higher Z

Bliss, Arcones, Montes & Pereira, J. Phys. G (2017)



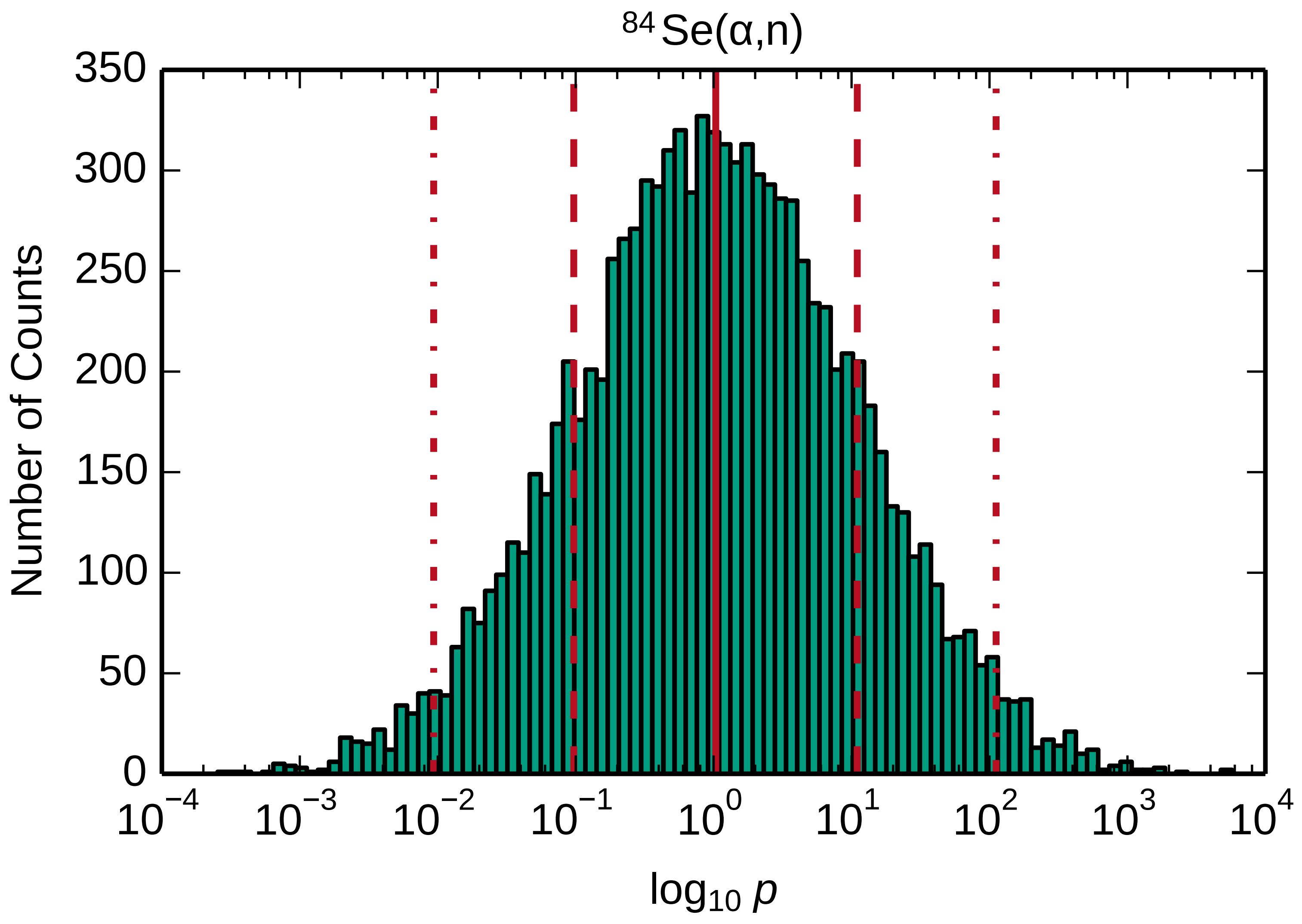


Sensitivity study

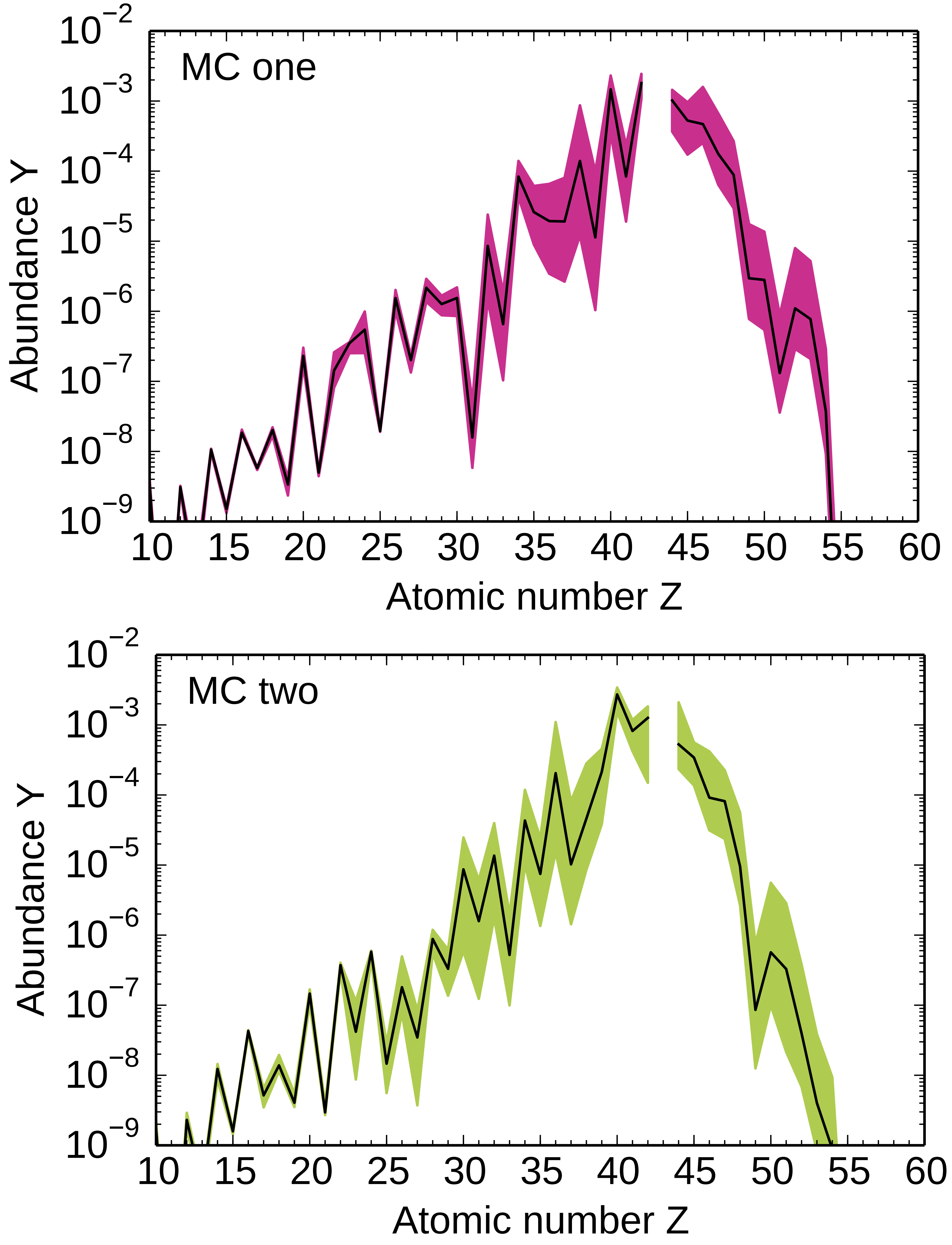
Bliss et al., PRC (2020)

Independently vary each (α,n) reaction rate between Fe and Rh by a random factor

Include theoretical and experimental uncertainties
→ log-normal distributed rates (μ = 0, σ = 2.3)

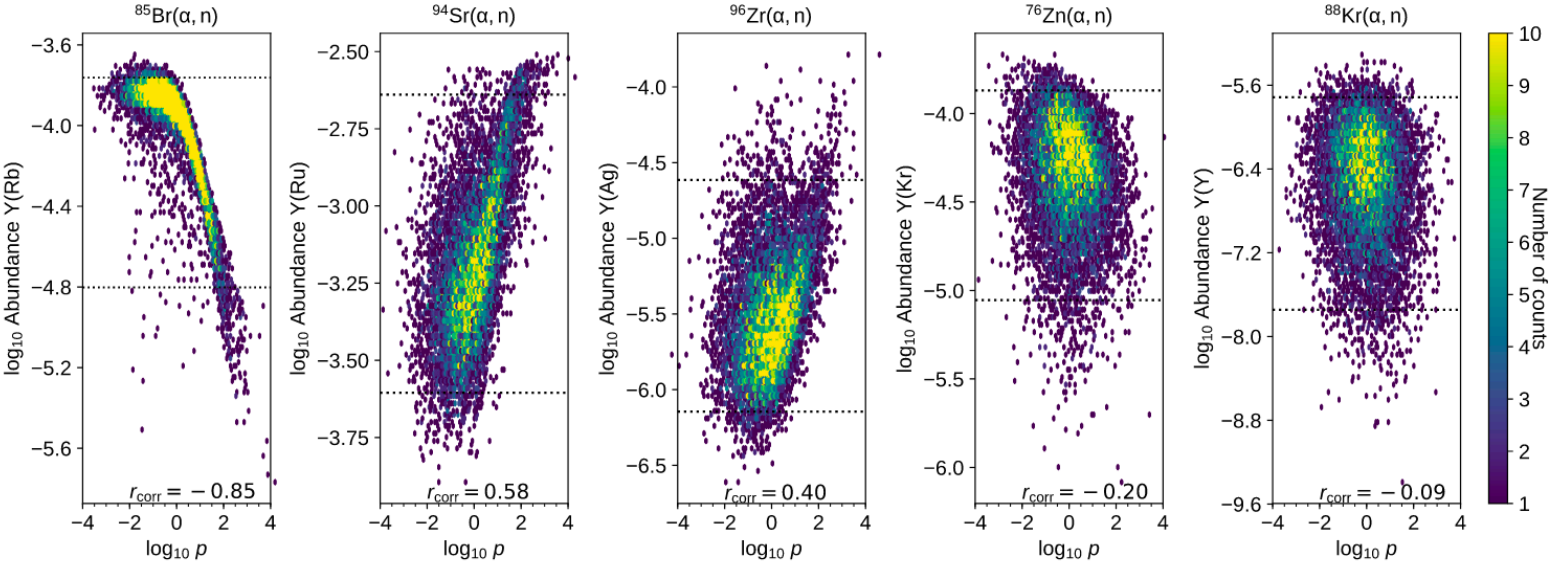


36 representative trajectories of group CPR2,
10 000 Monte Carlo runs



Sensitivity study: key reactions

Bliss et al., PRC (2020)



Spearman rank order correlation

$$\rho_{\text{corr}} = \frac{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)\left(R(y_i) - \overline{R(y)}\right)}{\sqrt{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)^2}\sqrt{\sum_{i=1}^{n}\left(R(y_i) - \overline{R(y)}\right)^2}}$$

→ Monotonic changes

→ $-1 \leq \rho_{\text{corr}} \leq +1$

Sensitivity study: key reactions

Bliss et al., PRC (2020)

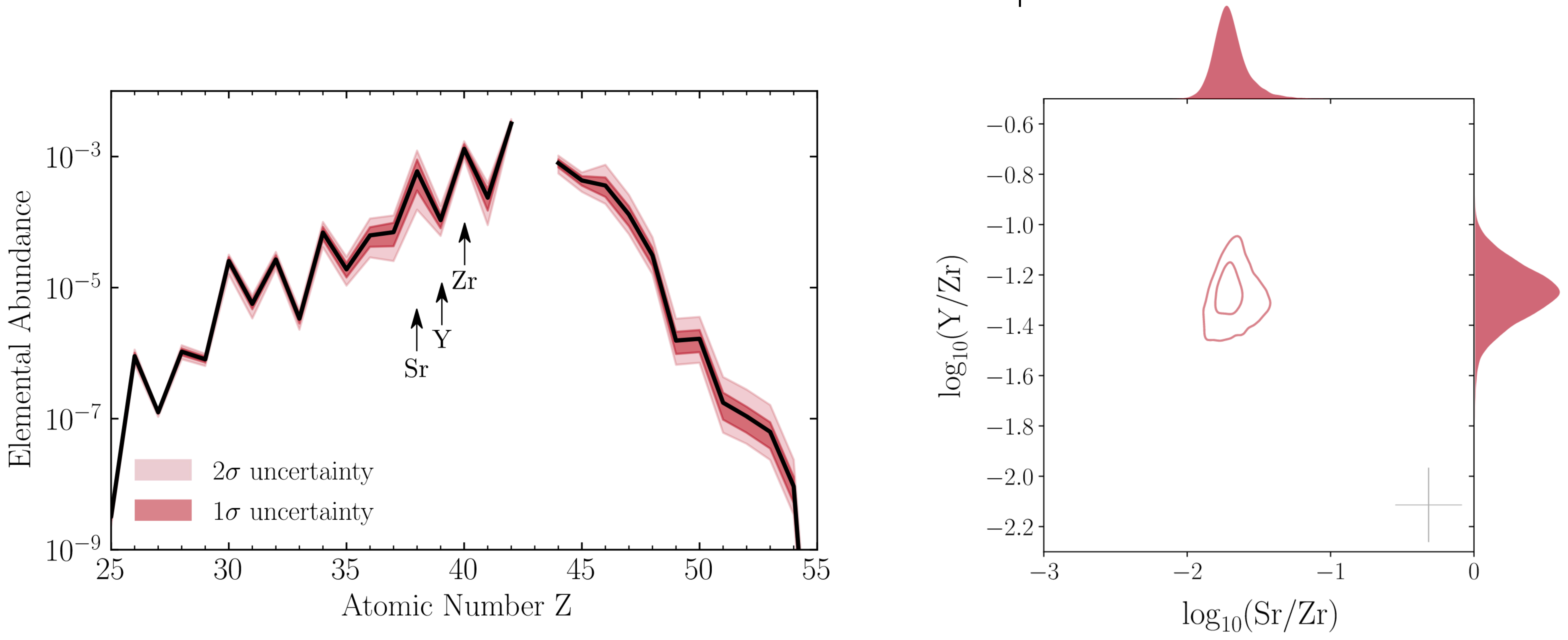
Key reactions ⇒ large correlation + significant impact on abundance for several astro conditions

Reaction	Z	MC tracers
$^{59}Fe(\alpha, n)^{62}Ni$	39 – 42, 45	34, 36
$^{68}Fe(\alpha, n)^{71}Ni$	36, 37	3
$^{63}Co(\alpha, n)^{66}Cu$	39–42, 45	20, 34, 36
$^{71}Co(\alpha, n)^{74}Cu$	36, 37	3
$^{74}Ni(\alpha, n)^{77}Zn$	36–42	2, 3, 17, 18, 32
$^{76}Ni(\alpha, n)^{79}Zn$	36–42	2, 3, 18, 32
$^{67}Cu(\alpha, n)^{70}Ga$	47	35
$^{77}Cu(\alpha, n)^{80}Ga$	37	3
$^{72}Zn(\alpha, n)^{75}Ge$	39–42	36
$^{76}Zn(\alpha, n)^{79}Ge$	36, 37–42	2, 3, 17, 18, 32
$^{78}Zn(\alpha, n)^{81}Ge$	36, 37–42	2, 3, 17, 18, 32
$^{79}Zn(\alpha, n)^{82}Ge$	36, 37–42	2, 3, 18, 32
$^{80}Zn(\alpha, n)^{83}Ge$	36, 37, 39–42	2, 3, 18, 32
$^{81}Ga(\alpha, n)^{84}As$	36, 38, 39, 41	17, 32
$^{78}Ge(\alpha, n)^{81}Se$	39–42	36
$^{80}Ge(\alpha, n)^{83}Se$	36–39, 42	28, 33, 36
$^{82}Ge(\alpha, n)^{85}Se$	36–39, 41	11, 17, 19, 27, 28, 33
$^{83}As(\alpha, n)^{86}Br$	36, 37, 41	11, 26, 27, 28, 33
$^{84}Se(\alpha, n)^{87}Kr$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 20, 22, 23, 24, 26, 27, 28, 29, 30, 31, 33, 34, 36
$^{85}Se(\alpha, n)^{88}Kr$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31
$^{85}Br(\alpha, n)^{88}Rb$	37–39	6, 7, 8, 9, 10, 22, 23, 24, 26, 28, 29, 30, 31
$^{87}Br(\alpha, n)^{90}Rb$	37, 39	6, 9, 10, 29, 31
$^{88}Br(\alpha, n)^{91}Rb$	39	26
$^{86}Kr(\alpha, n)^{89}Sr$	38–42, 44, 45, 47	4, 5, 7, 8, 13, 14, 15, 16, 20, 24, 25, 33, 34, 35

Comparison to observations

Psaltis et al., ApJ (2022)

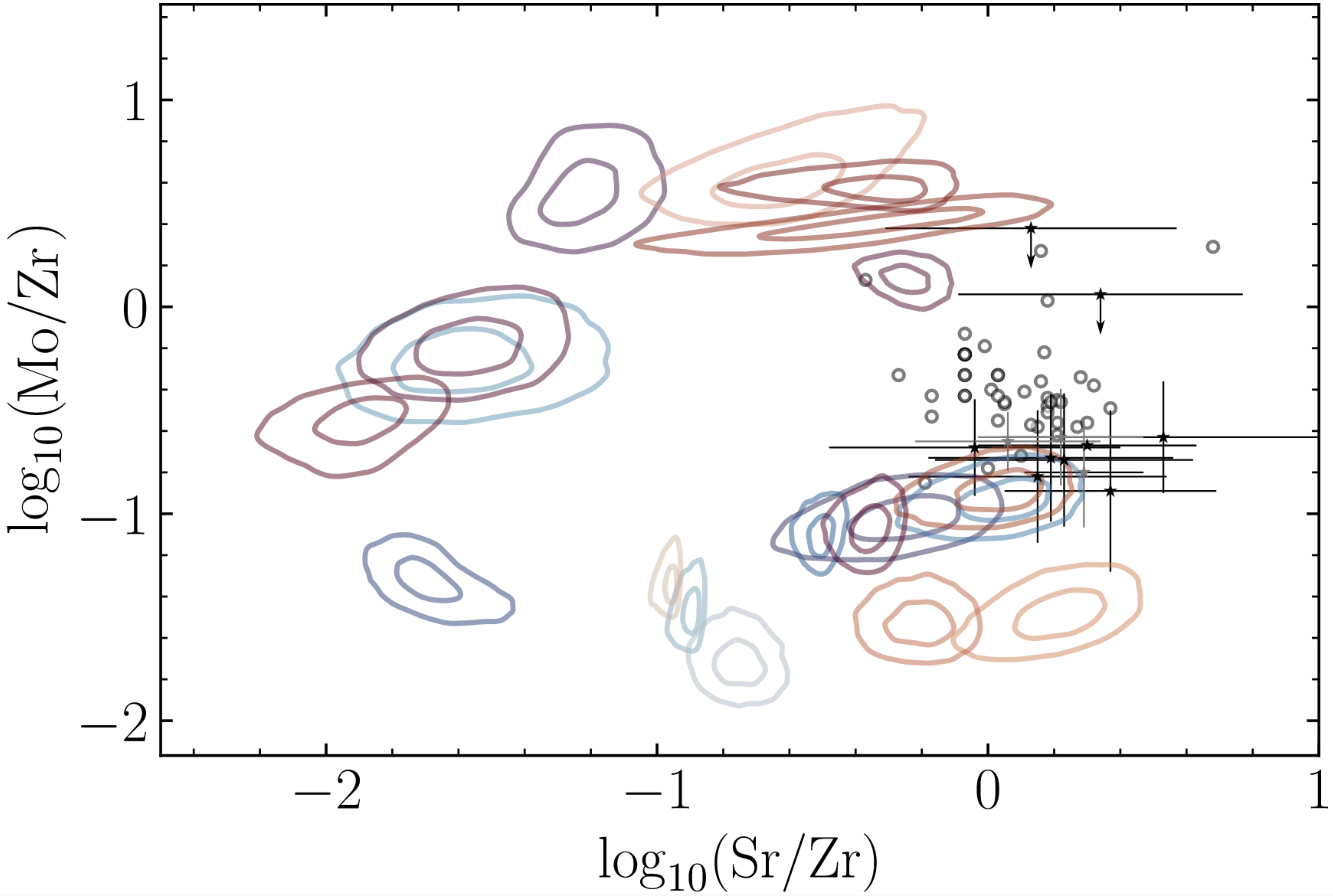
Abundance with uncertainties for several astro conditions ⟶ compare abundance ratios



Comparison to observations

Psaltis et al., ApJ (2022)

Abundance with uncertainties for several astro conditions ⟶ compare abundance ratios



What has been measured so far?

- ^{86}Kr(α, n), ^{96}Zr(α, n) and ^{100}Mo(α, n) at ATOMKI

  G.G. Kiss et al., Astrophys. J **908**, 202 (2021) • T.N. Szegedi et al., Phys. Rev. C **104**, 035804 (2021)

- ^{75}Ga(α, n), ^{85,86}Kr(α, xn), ^{85}Br(α, xn) at NSCL/FRIB (HabaNERO/SECAR)

  F. Montes, J. Pereira et al.

- ^{86}Kr(α, xn), ^{87}Rb(α, xn), ^{88}Sr(α, xn), ^{100}Mo(α, xn) at Argonne (MUSIC)

  M. L. Avila, C. Fougères et al.

  W. J. Ong et al., Phys. Rev. C **105**, 055803 (2022)

- ^{86}Kr(α, n) and ^{94}Sr(α, n) at TRIUMF (EMMA)

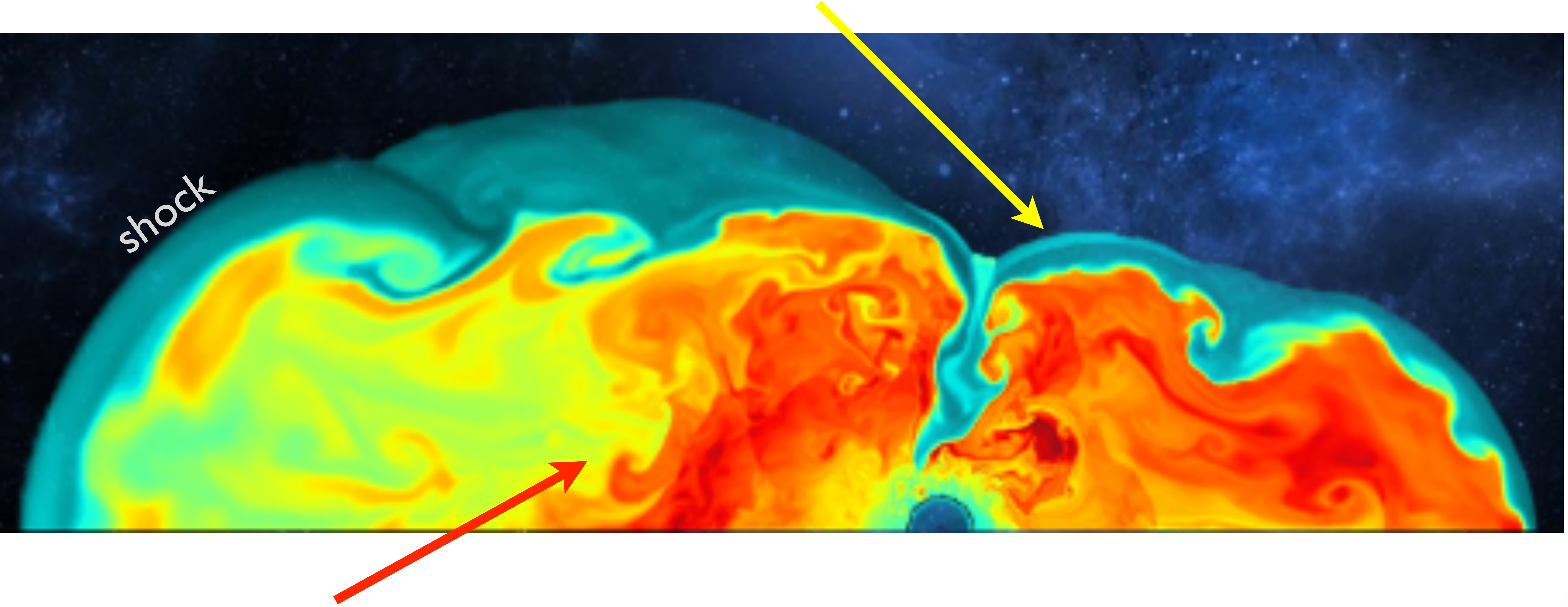
  C. Aa. Diget, A. M. Laird, M. Williams et al.

  C. Angus *et al.*, EPJ Web of Conferences, NPA-X (2023)

Thanassis Psaltis

Supernova nucleosynthesis

Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter

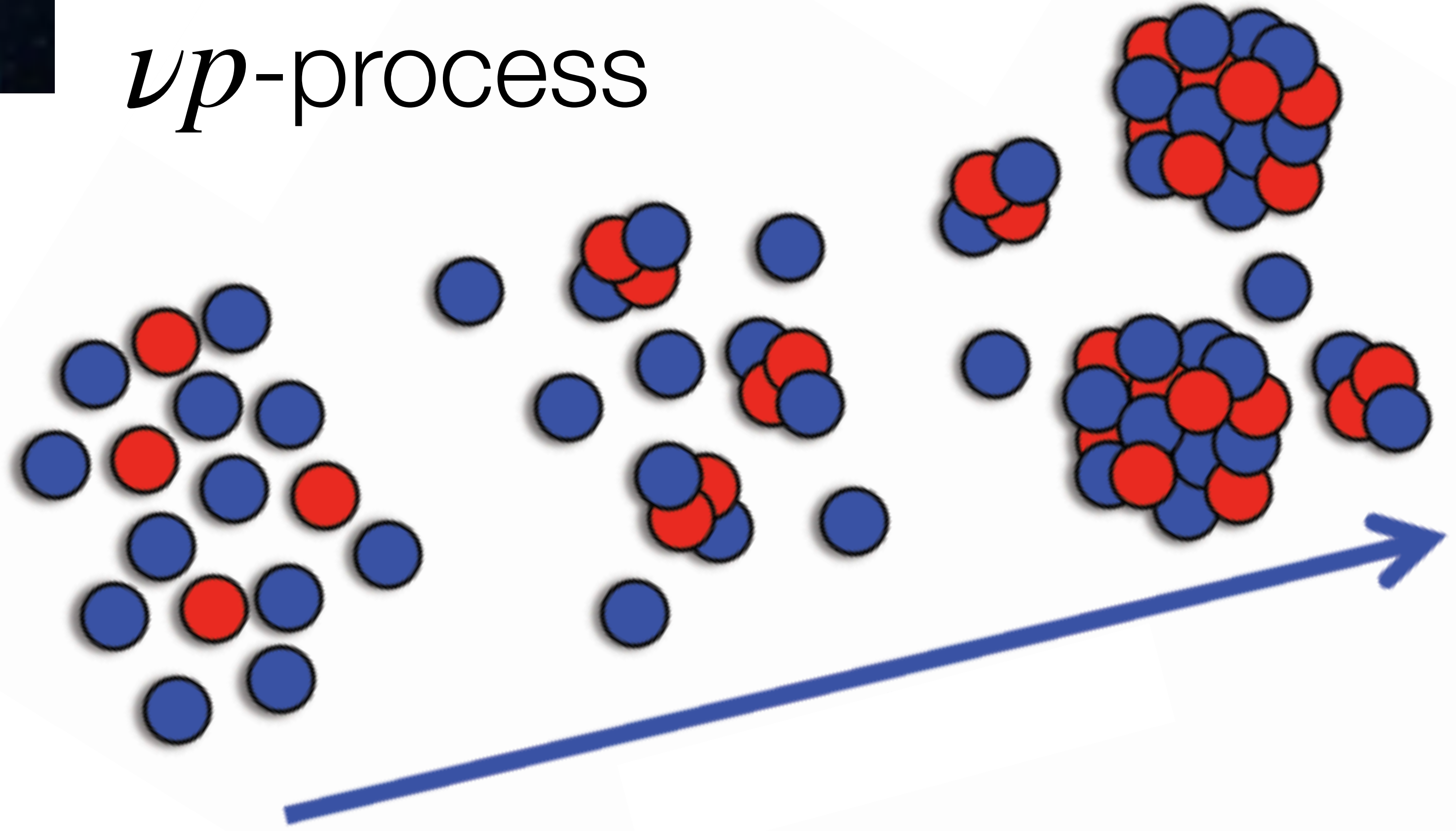


neutrino-driven ejecta

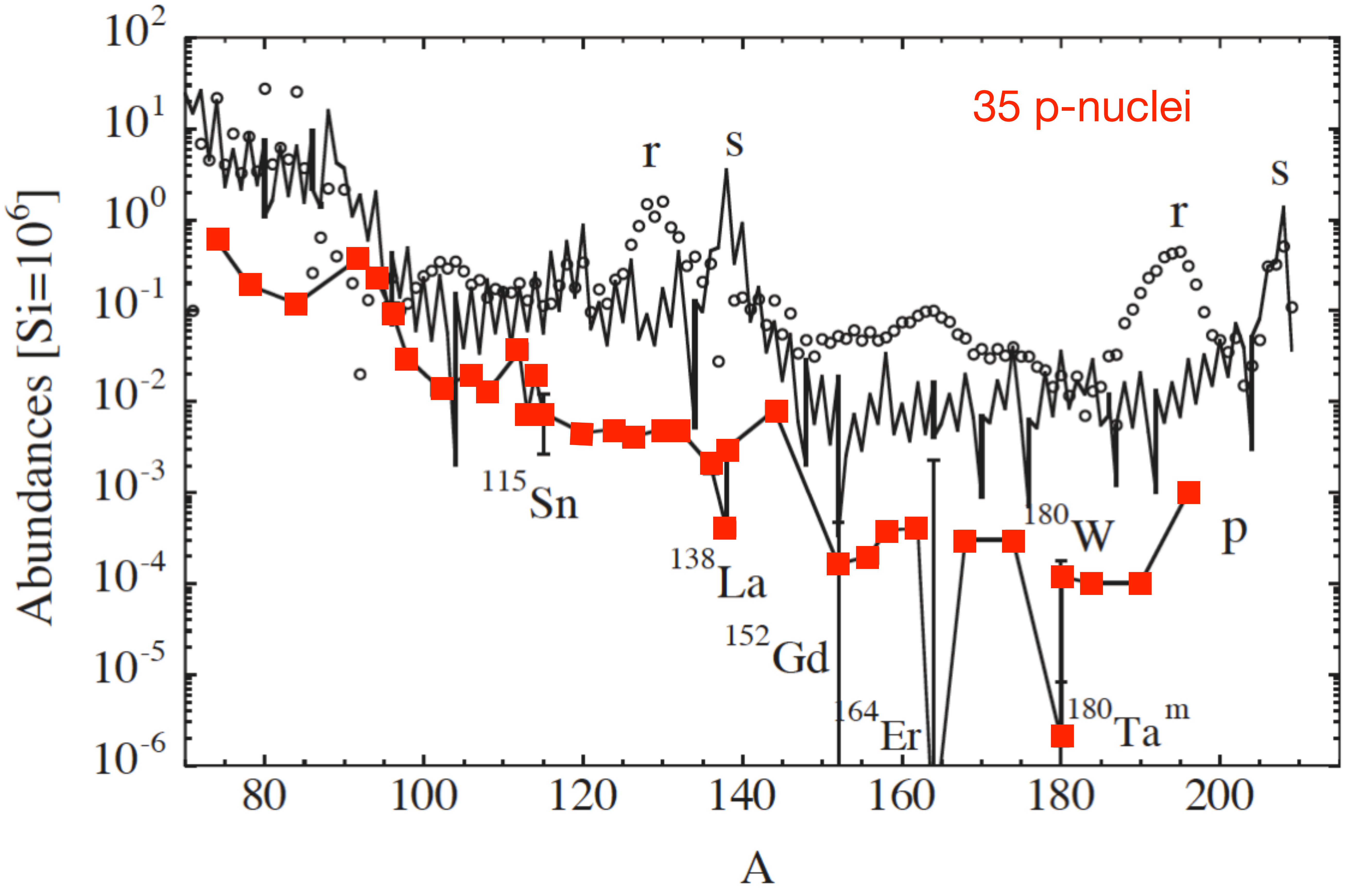
Nuclear statistical equilibrium (NSE)

charged particle reactions
α-process

r-process
weak r-process
νp-process



P nuclei



P-process and νp-process

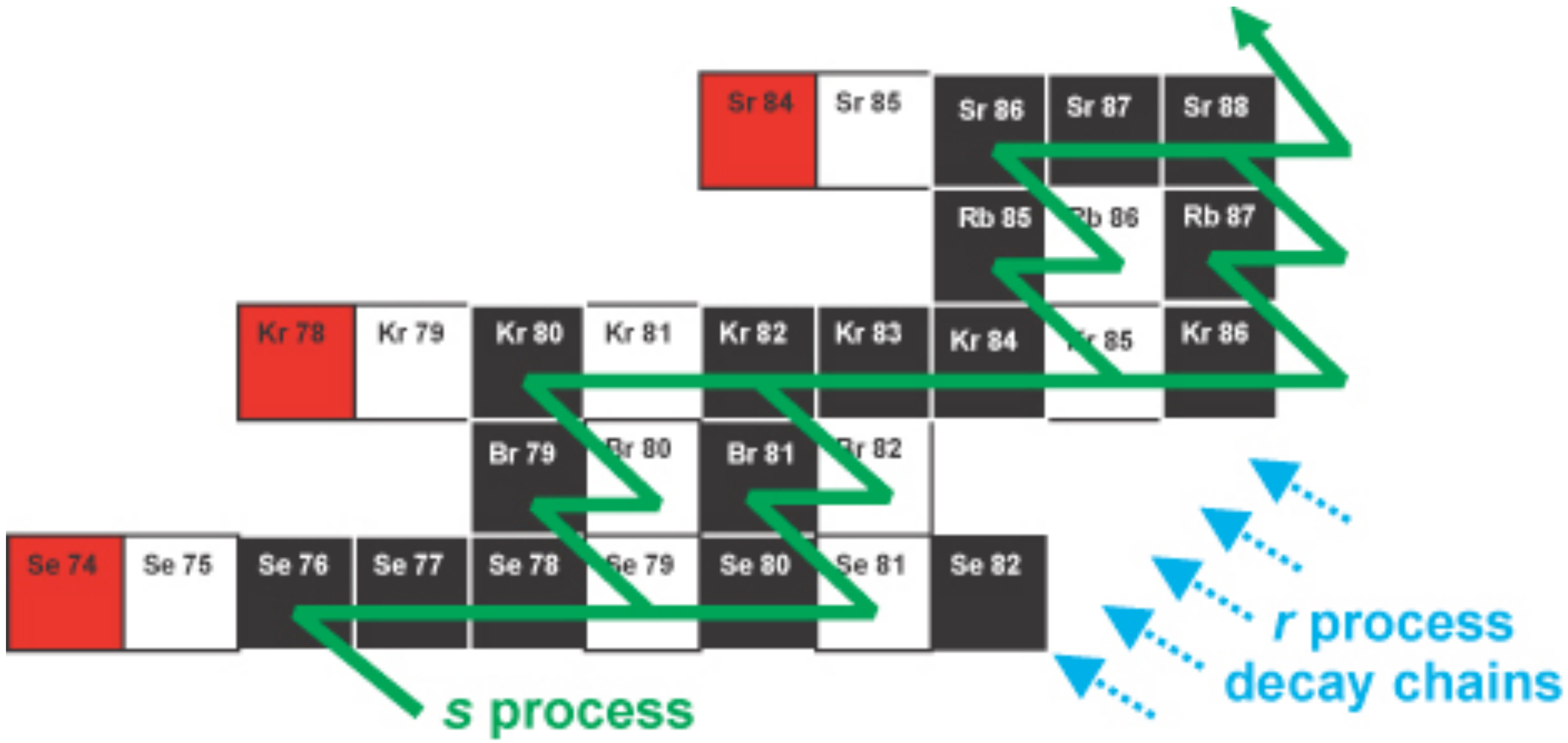
M. Arnould, S. Goriely / Physics Reports 384 (2003) 1–84 9

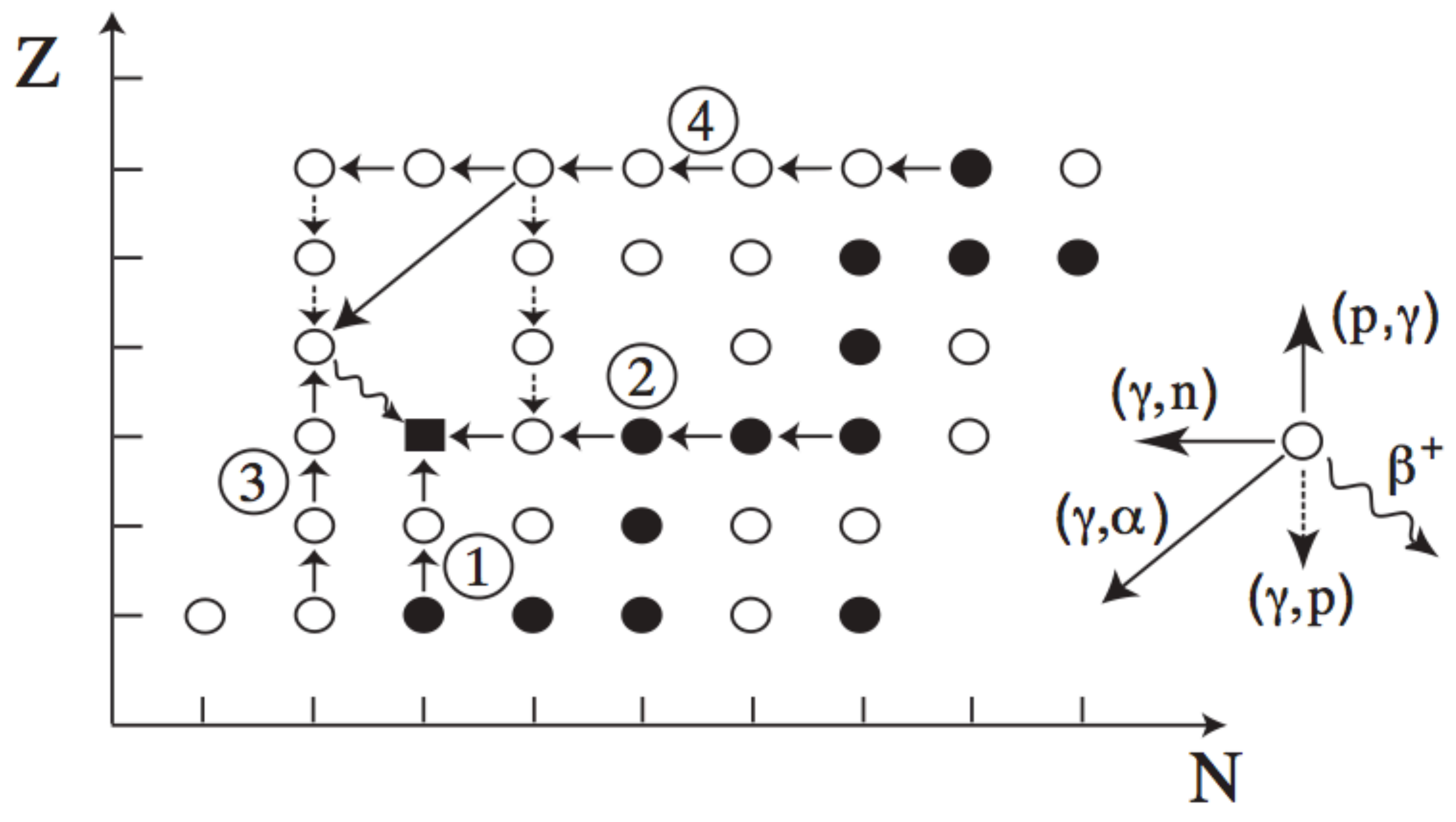
Table 1
List of the species commonly classified as p-nuclides, with their solar system abundances relative to 10^6 Si atoms proposed by two compilations [13,15]

Nucleus	Anders and Grevesse [13]	Error (%)	Palme and Beer [15]	Error (%)
^{74}Se	0.55	6.4	0.6	5
^{78}Kr	0.153	18	0.19	—
^{84}Sr	0.132	8.1	0.12	5
^{92}Mo	0.378	5.5	0.38	5
^{94}Mo	0.236	5.5	0.23	5
^{96}Ru	0.103	5.4	0.1	10
^{98}Ru	0.035	5.4	0.03	10
^{102}Pd	0.0142	6.6	0.014	10
^{106}Cd	0.0201	6.5	0.02	10
^{108}Cd	0.0143	6.5	0.014	10
^{113}In	0.0079	6.4	0.008	10
^{112}Sn	0.0372	9.4	0.036	10
^{114}Sn	0.0252	9.4	0.024	10
^{115}Sn	0.0129	9.4	0.013	10
^{120}Te	0.0043	10	0.0045	10
^{124}Xe	0.00571	20	0.005	—
^{126}Xe	0.00509	20	0.004	—
^{130}Ba	0.00476	6.3	0.005	5
^{132}Ba	0.00453	6.3	0.005	5
^{138}La	0.000409	2	0.0004	5
^{136}Ce	0.00216	1.7	0.002	5
^{138}Ce	0.00284	1.7	0.003	5
^{144}Sm	0.008	1.3	0.008	5
^{152}Gd	0.00066	1.4	0.001	5
^{156}Dy	0.000221	1.4	0.0002	5
^{158}Dy	0.000378	1.4	0.0004	5
^{162}Er	0.000351	1.3	0.0004	5
^{164}Er	0.00404	1.3	0.0042	5
^{168}Yb	0.000322	1.6	0.0003	5
^{174}Hf	0.000249	1.9	0.0003	5
^{180}Ta	2.48e-06	1.8	2.00e-06	10
^{180}W	0.000173	5.1	0.0002	7
^{184}Os	0.000122	6.3	0.0001	5
^{190}Pt	0.00017	7.4	0.0001	10
^{196}Hg	0.00048	12	0.001	20

P-process

Transformation of pre-existing s- or r-nuclei by photodisintegrations when T increases complemented by neutron and proton captures





- supernova shock
- type Ia supernovae

Arnould & Goriely 2003

P-process

Photodisintegrations depend on temperature:

$T \geq 1.5 \times 10^9\,\mathrm{K}$ required for photodisintegration,

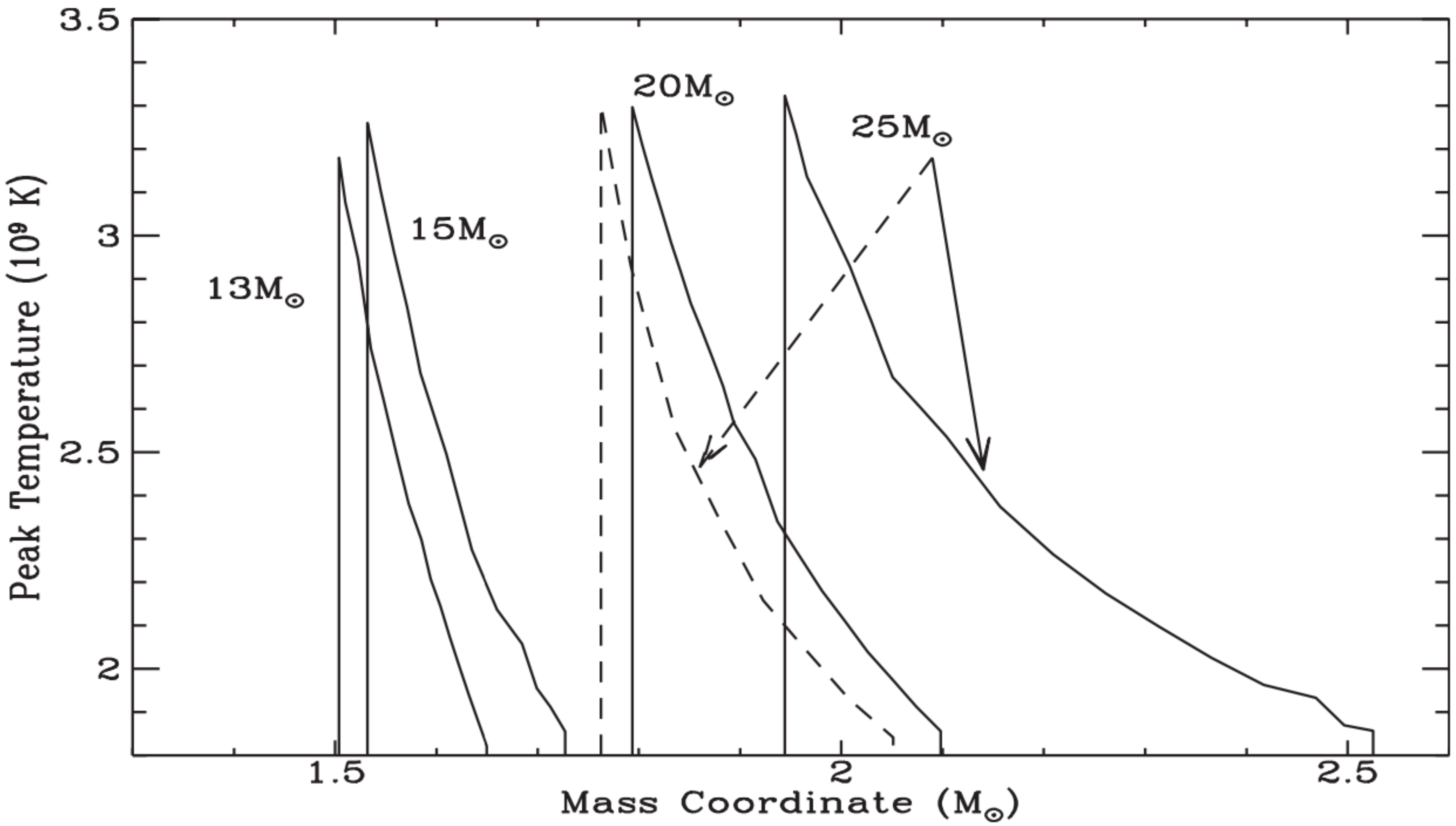
but not exceed $3.5 \times 10^9\,\mathrm{K}$ to prevent reaching NSE and produce Fe group nuclei

Constraints:

- abundant enough seed nuclei,
- high enough temperatures,
- short enough time scales for the hot phases,
- protons if (p,γ) contribute

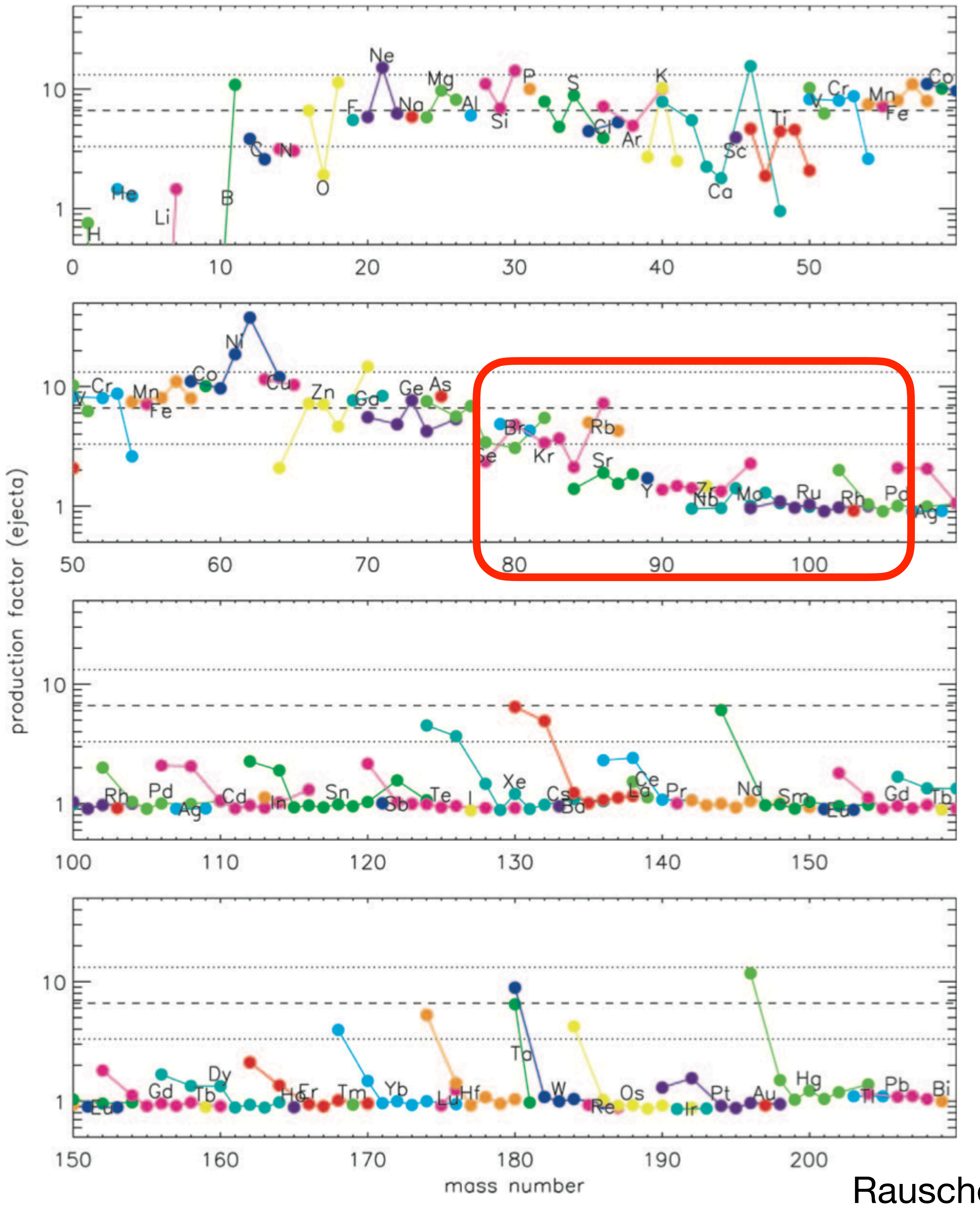
Possible astrophysical sites:

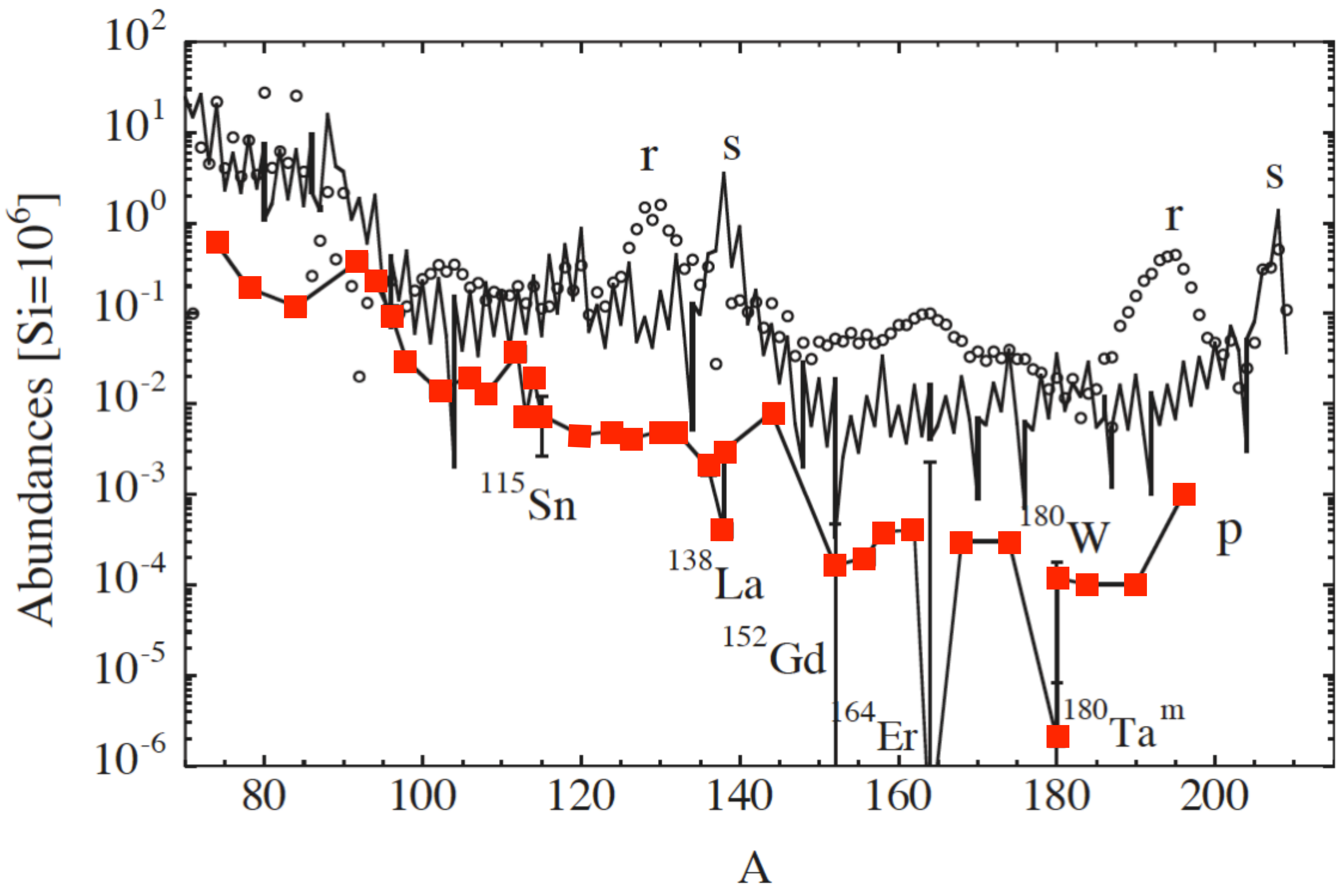
- core-collapse supernova shock
- Type Ia supernovae



P-process

core-collapse supernova

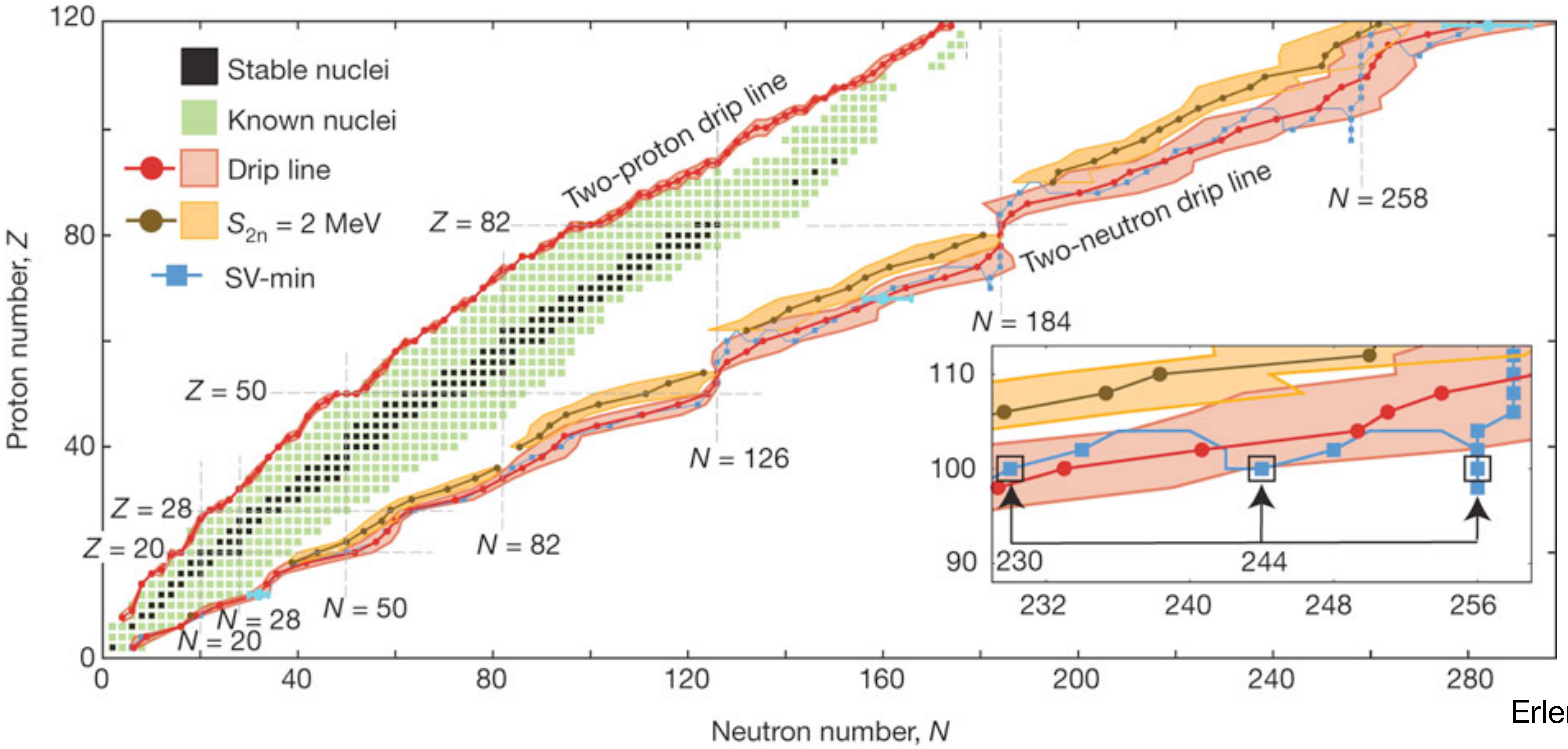




Rauscher et al. 2002

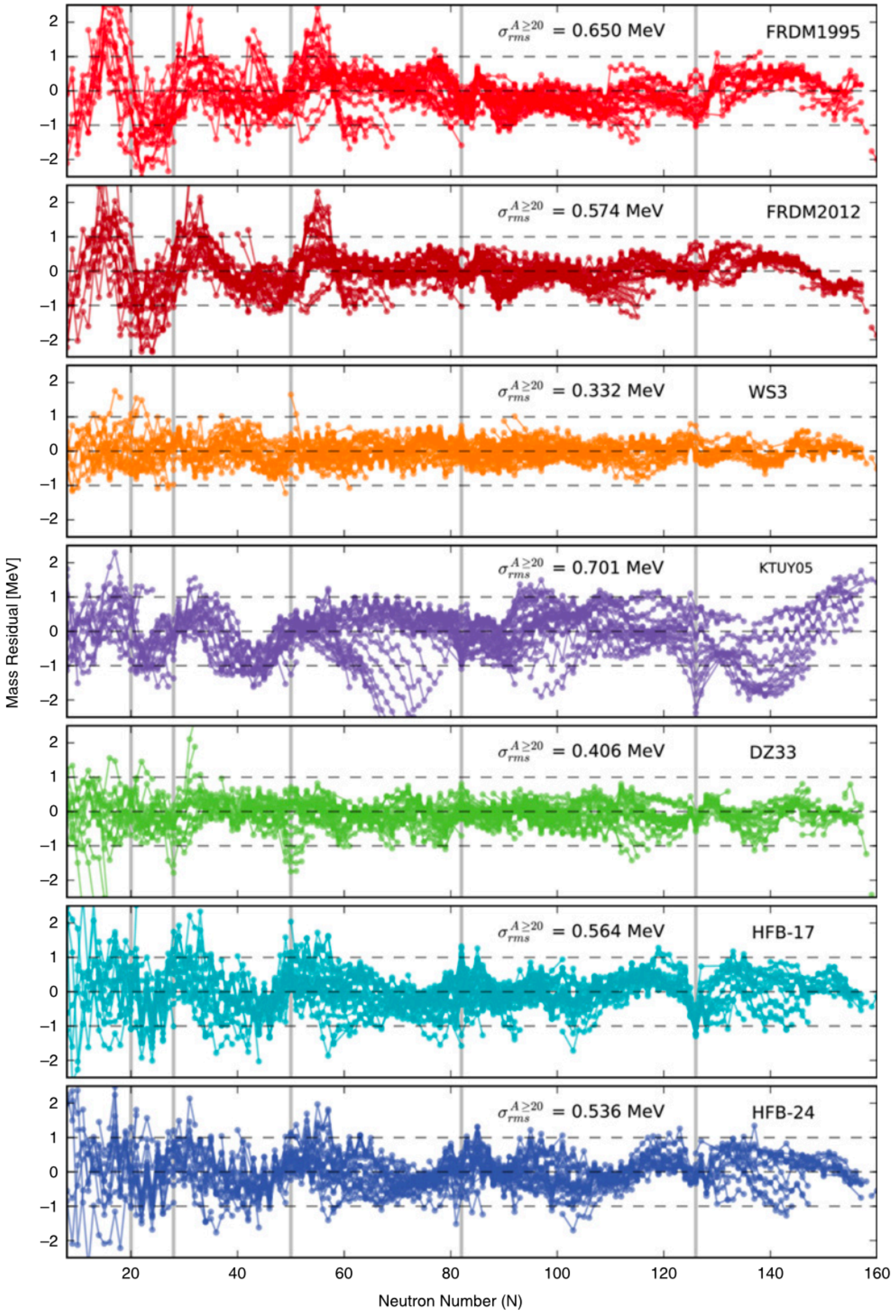
5.2 r-process: nuclear physics input

nuclear masses, beta decay, reaction rates (neutron capture), fission

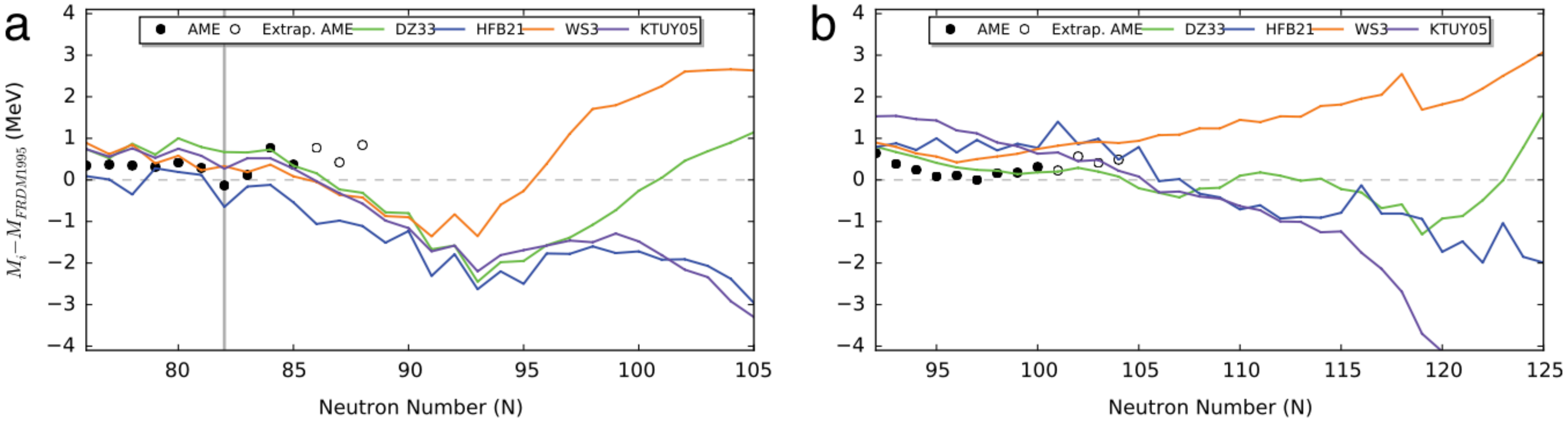


Erler et al. (2012)

5.2 r-process: nuclear masses



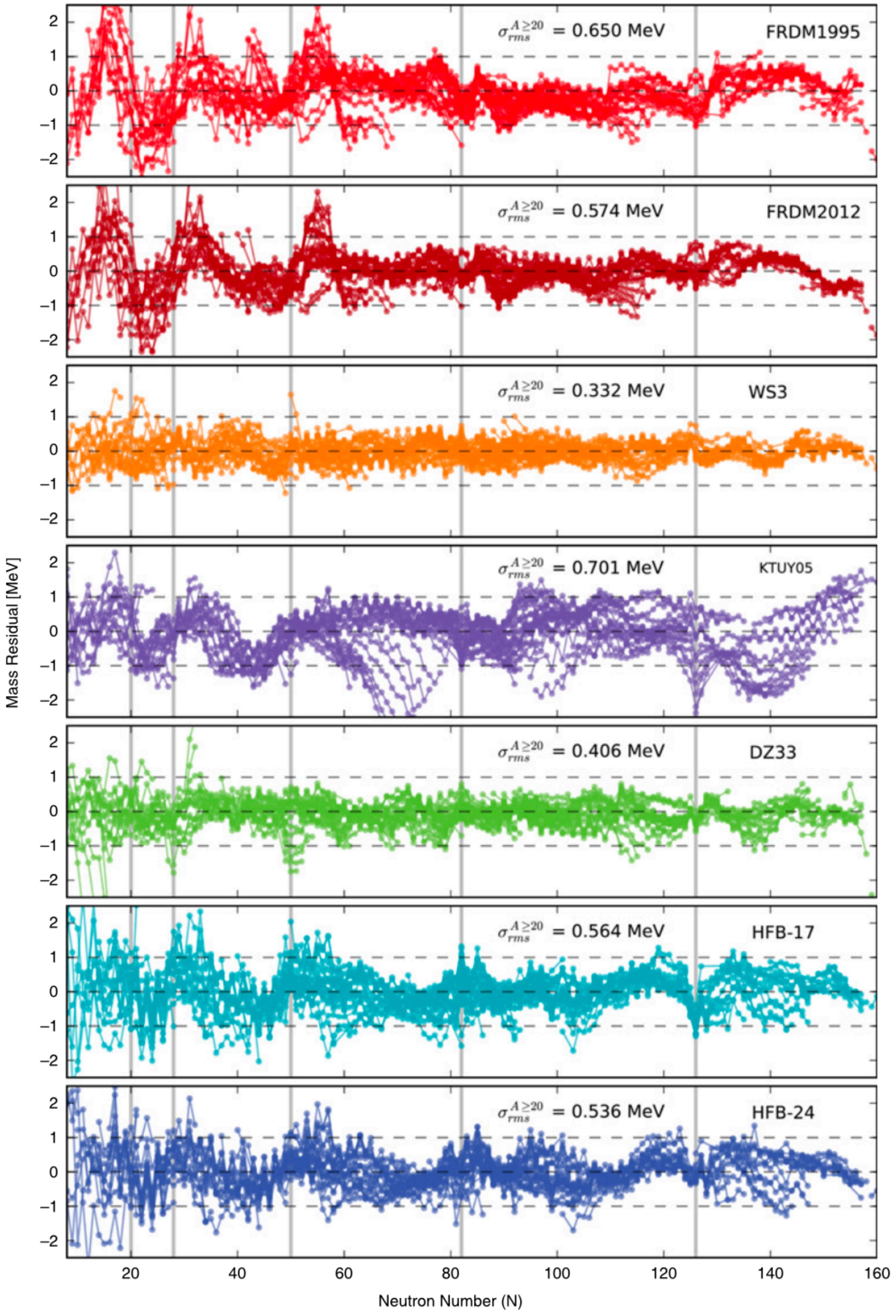
seven commonly used mass models compared to the latest measured masses found in the 2012 Atomic Mass Evaluation (AME2012).



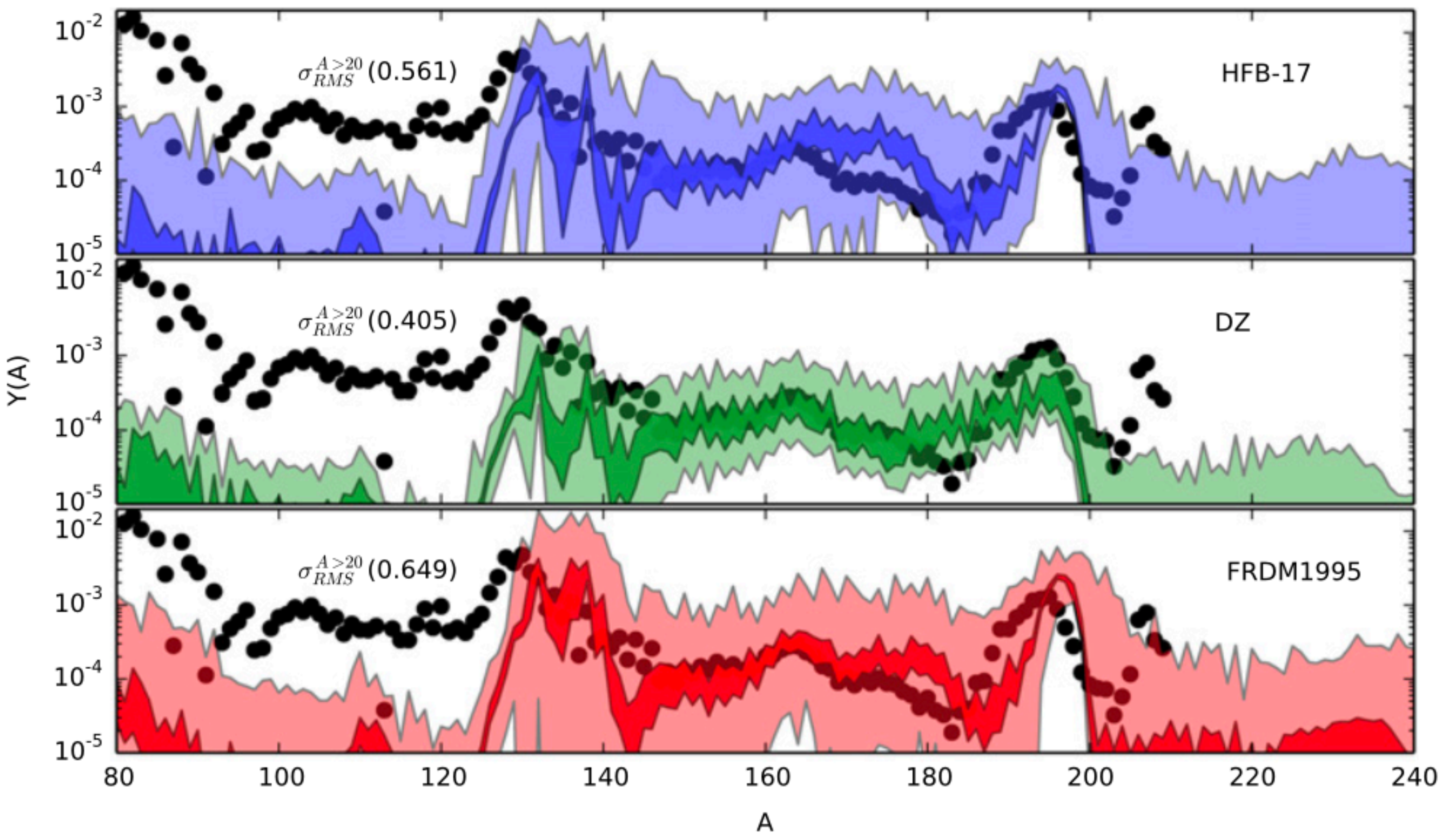
Sn (Z=50)

Eu (Z=63)

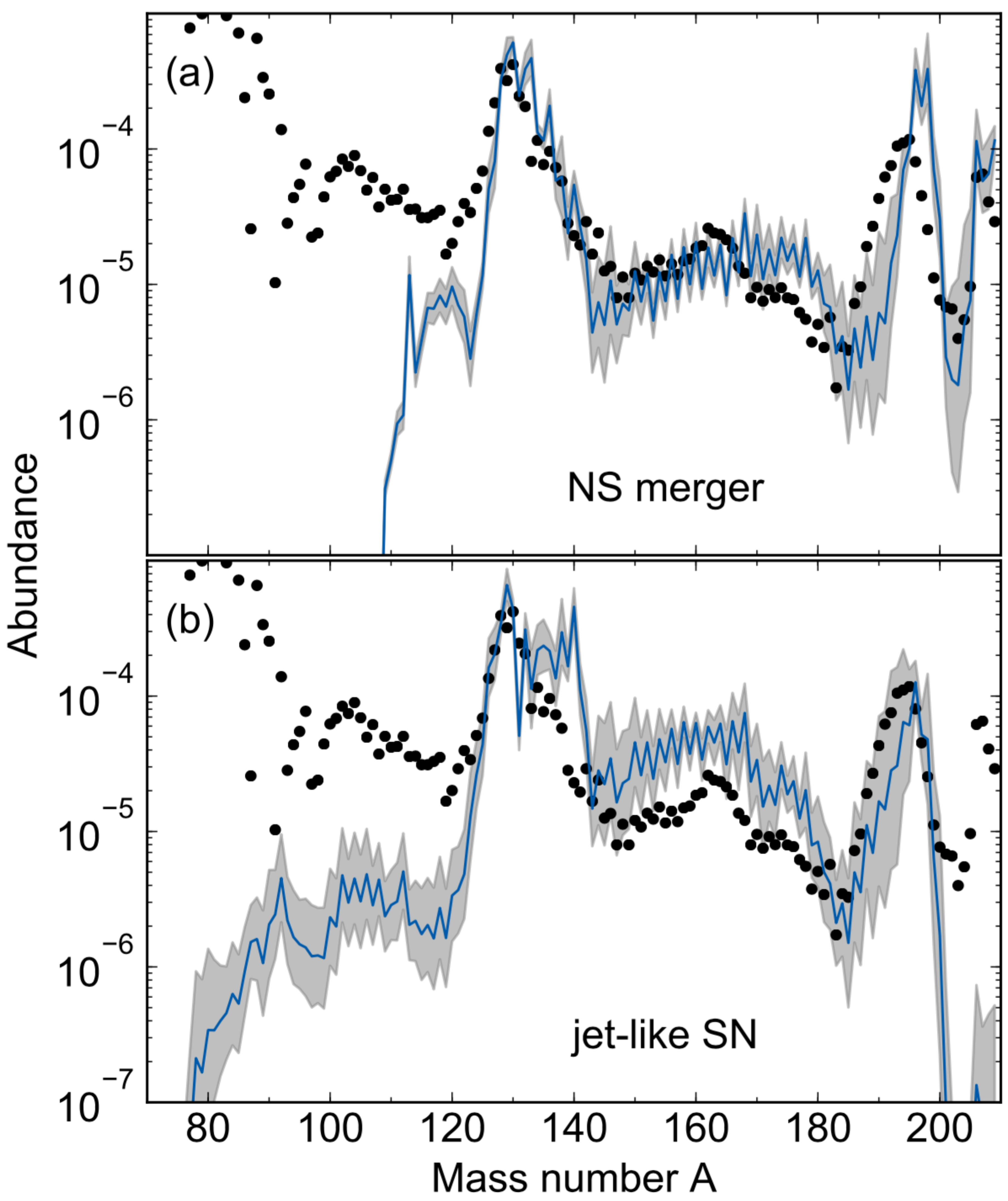
5.2 r-process: nuclear masses



M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126



5.2 r-process: nuclear masses



Abundances based on density functional theory
- six sets of different parametrisation (Erler et al. 2012)
- two realistic astrophysical scenarios

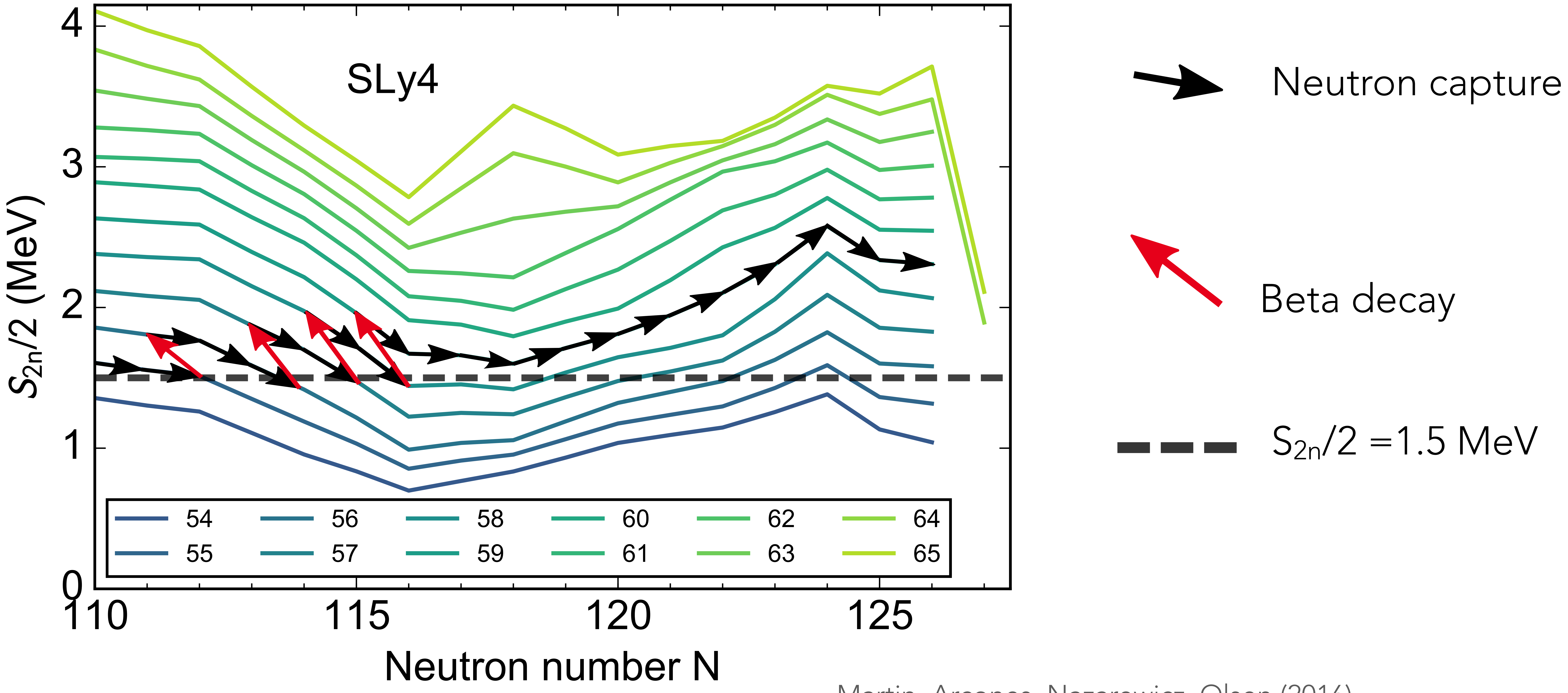
First systematic uncertainty band for r-process abundances

Uncertainty band depends on A,
in contrast to homogeneous band for all A

Martin, Arcones, Nazarewicz, Olsen (2016)

Two neutron separation energy

Nucleosynthesis path at constant S_n: (n,γ)-(γ,n) equilibrium

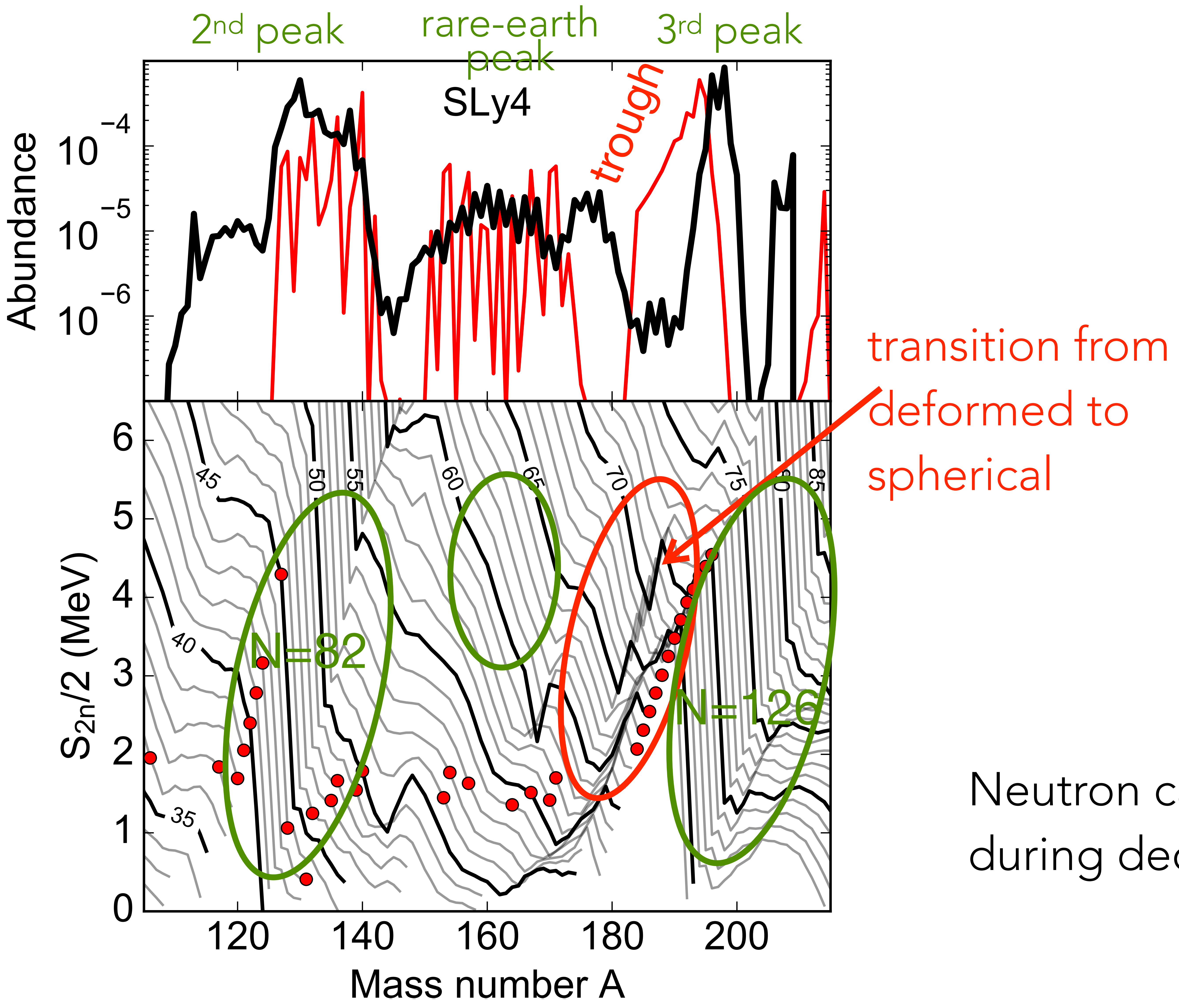


Martin, Arcones, Nazarewicz, Olsen (2016)

Two neutron separation energy -> abundances

Abundances

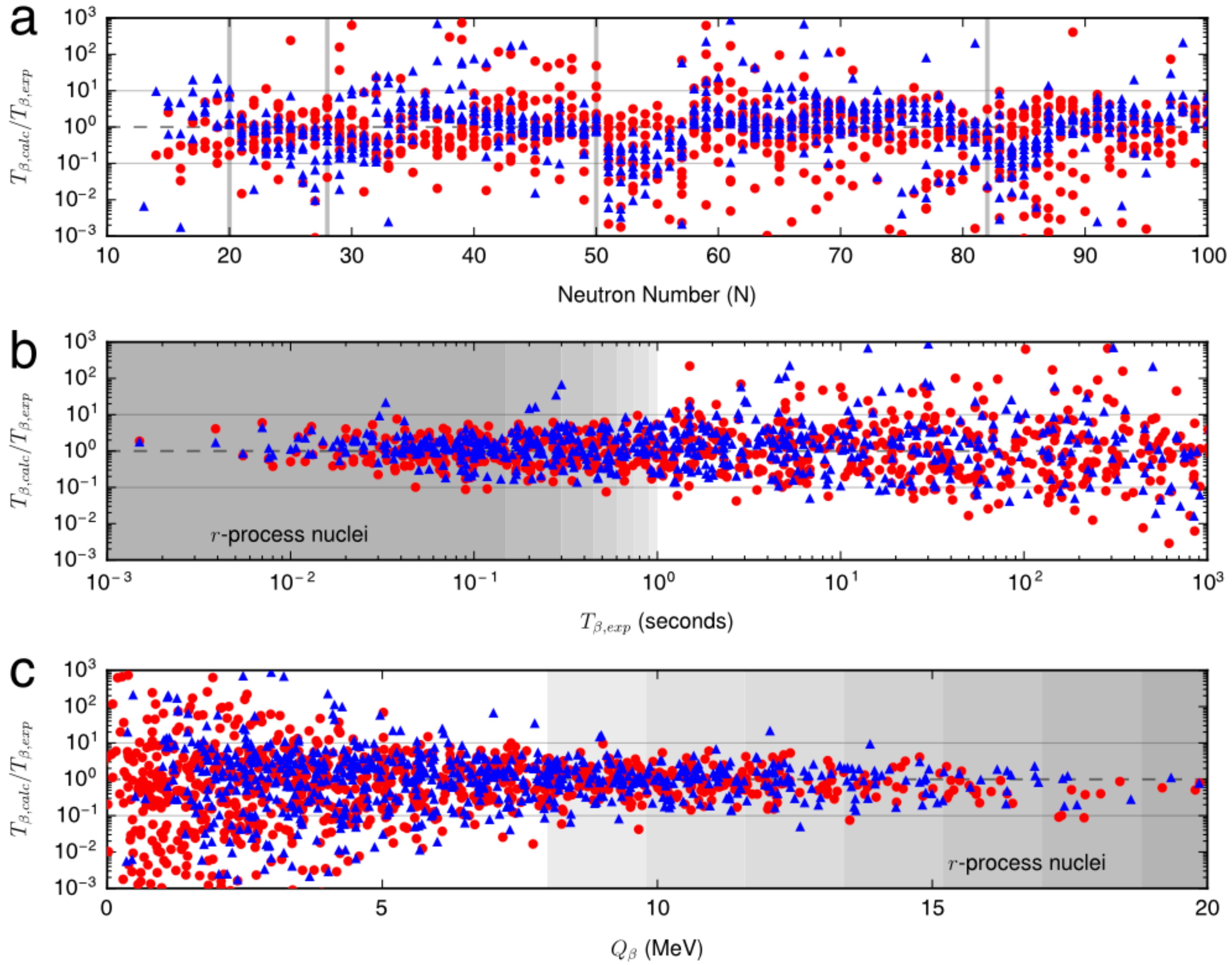
Nuclear properties



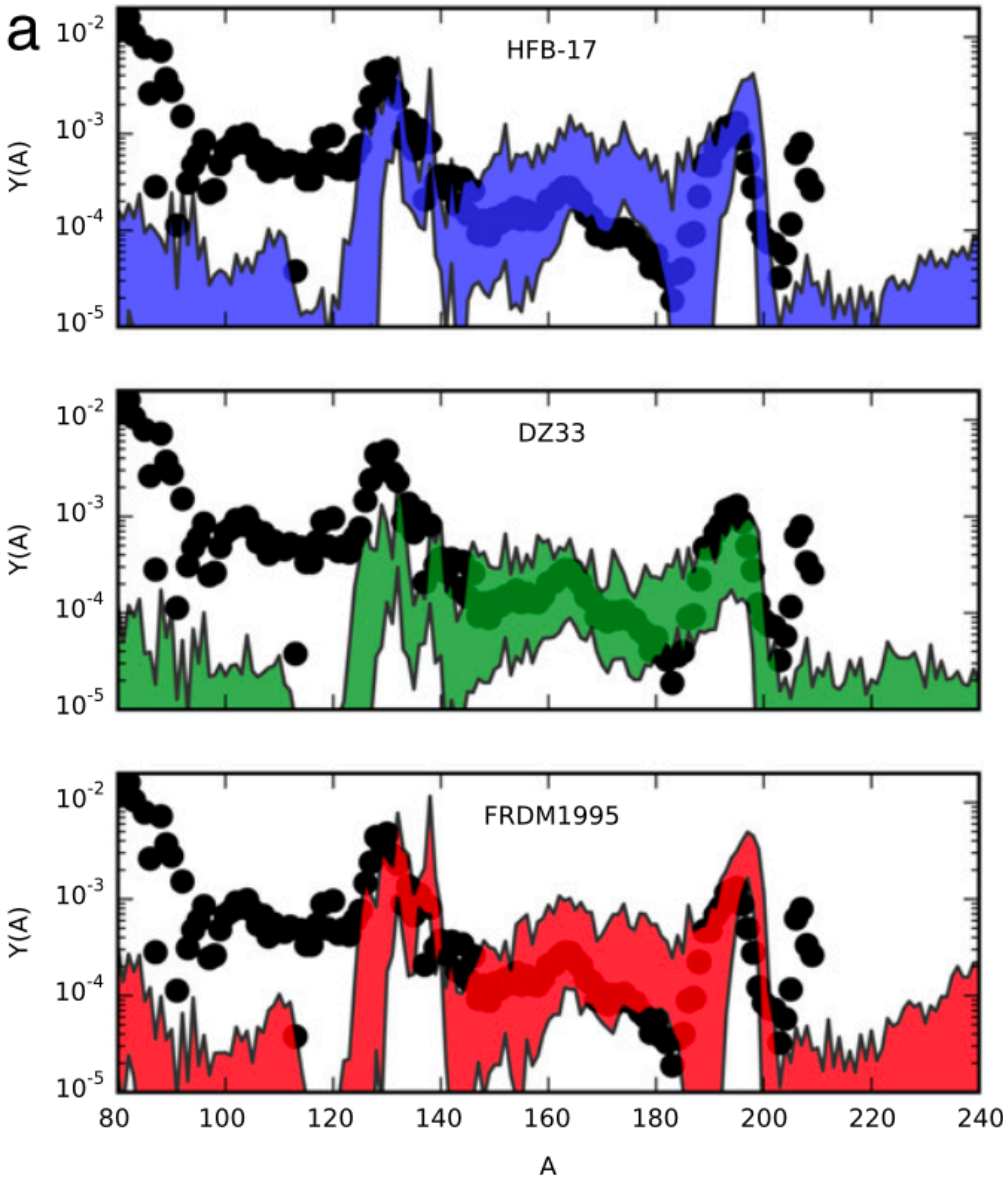
Neutron capture are critical during decay to stability!

5.2 r-process: beta decay

M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126



red circles = FRDM1995 + QRPA
blue triangles = KTUY05 + gross theory

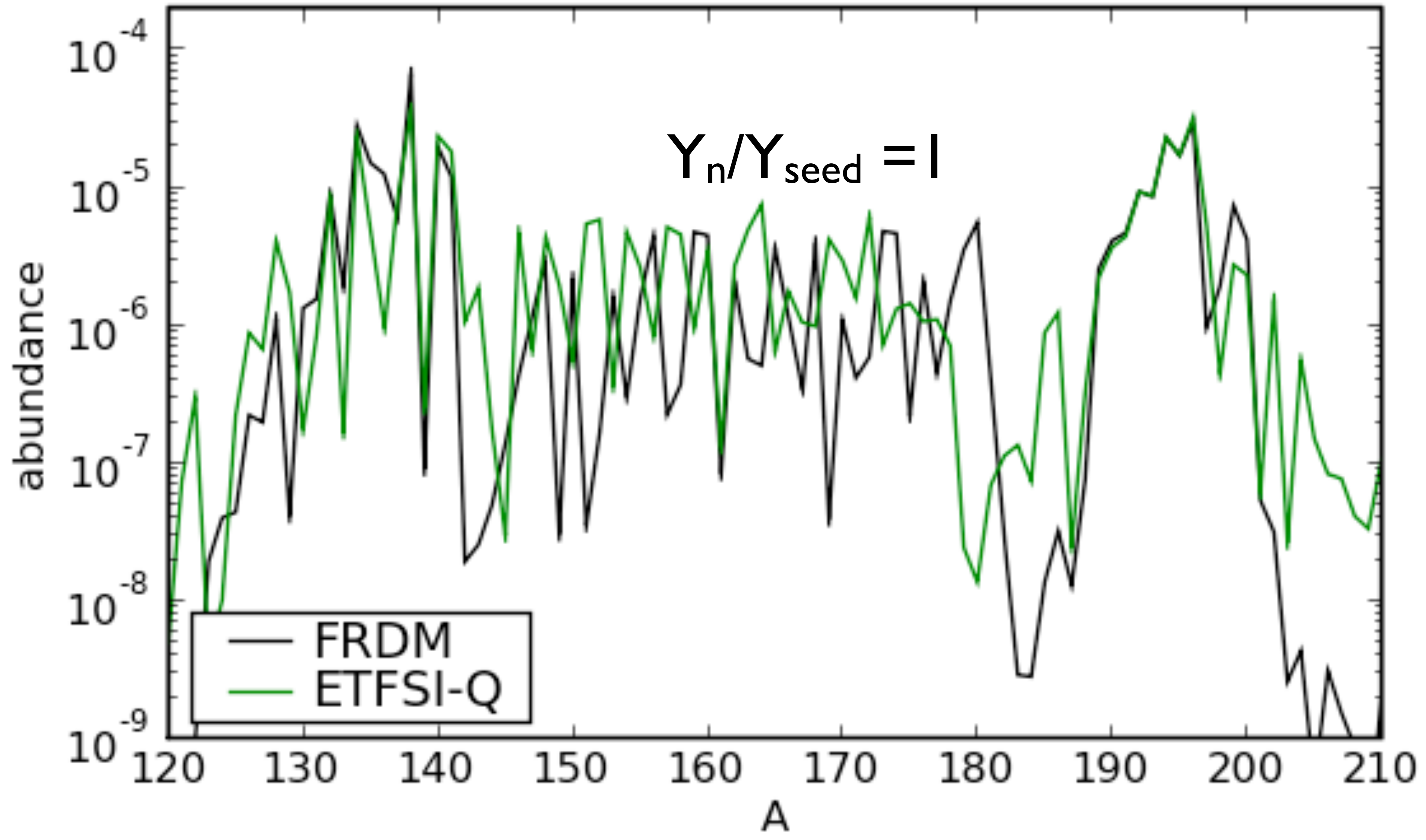


5.2 r-process: decay to stability

Abundances at freeze-out (Y_n/Y_{seed}=1): odd-even effects

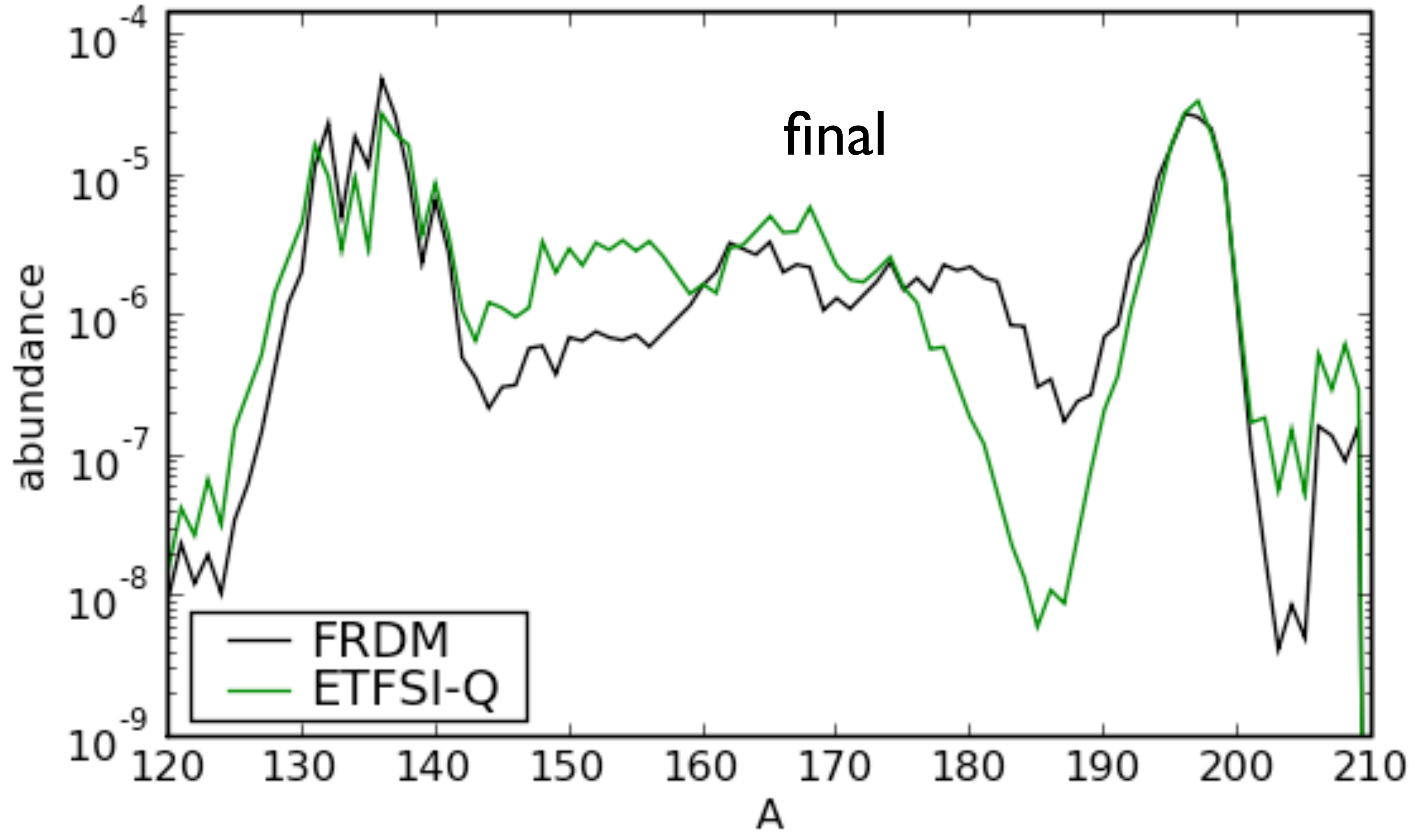
Final abundances are smoother like solar abundances.

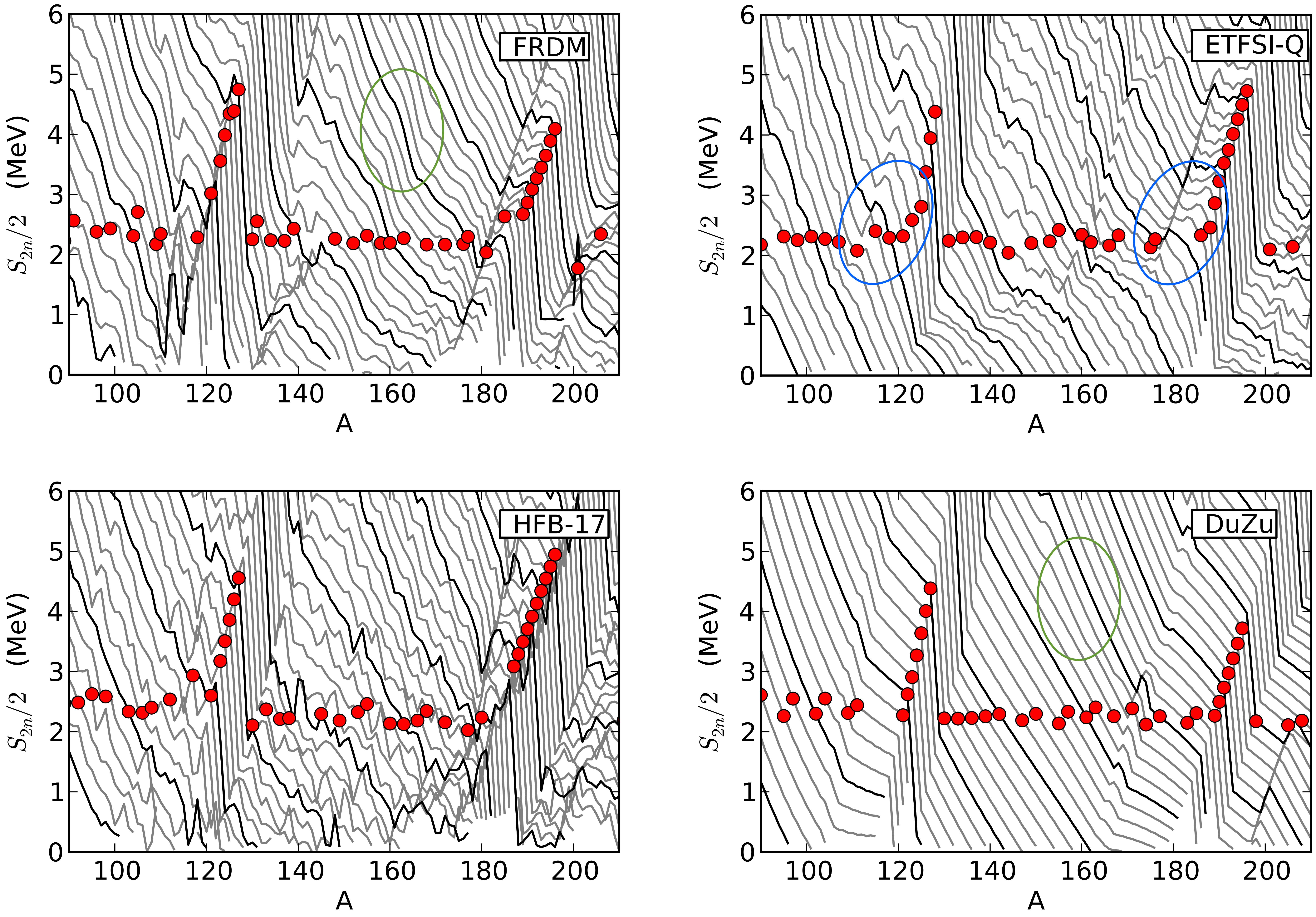
Why does the abundance pattern change?



Classical r-process (waiting point approximation):
beta-delayed neutron emission

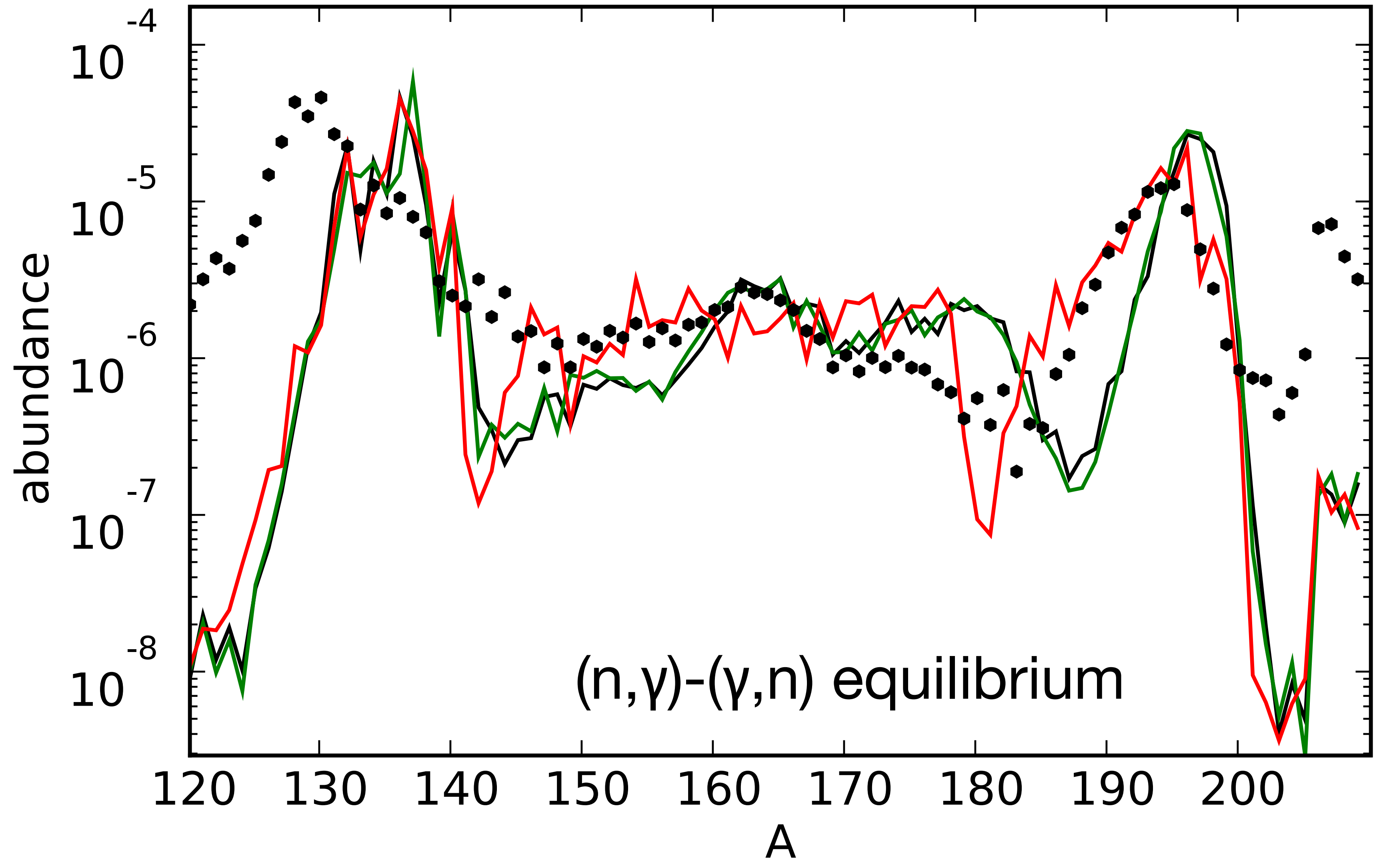
Dynamical r-process:
neutron capture and beta-delayed neutron emission





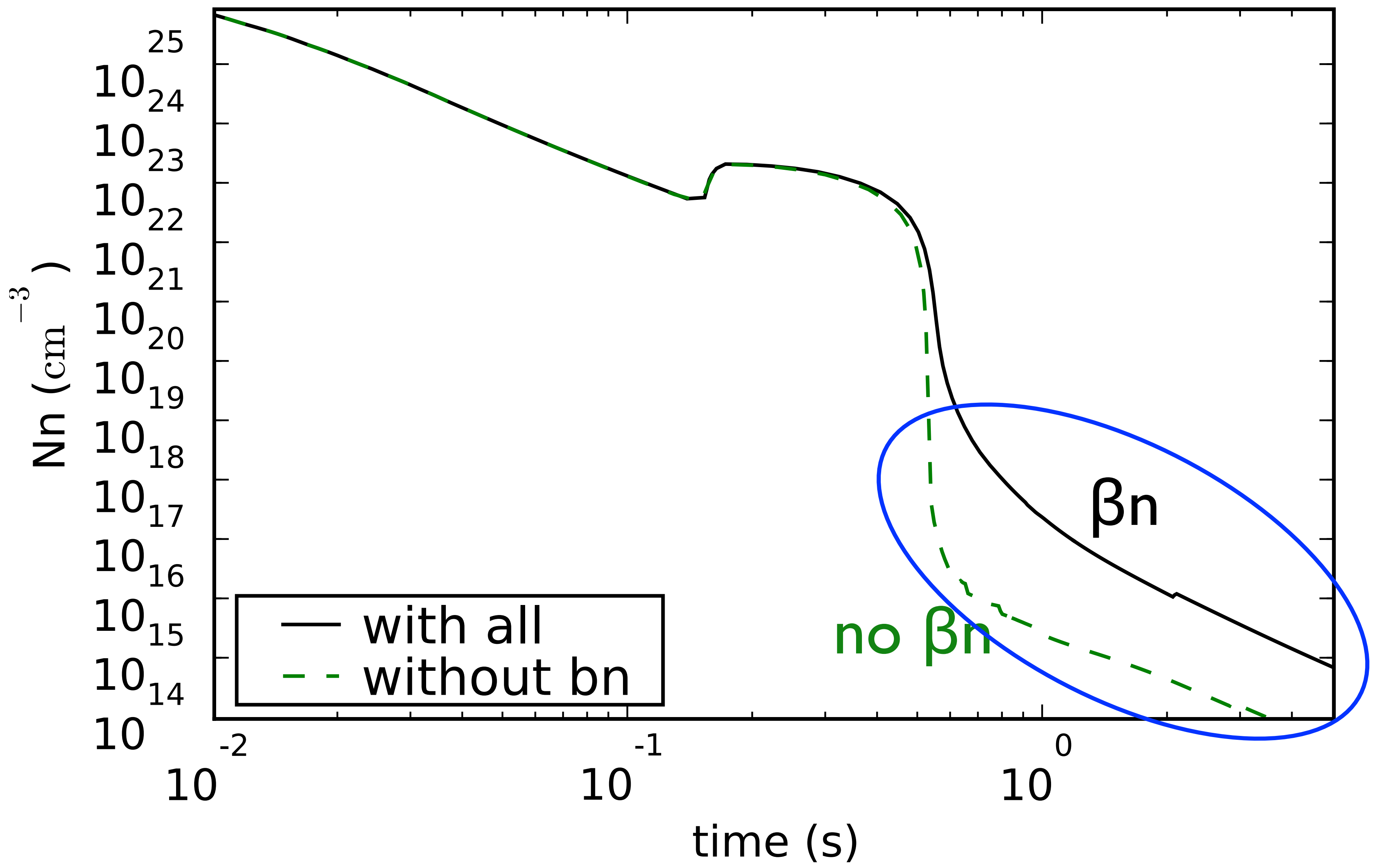
FRDM
ETFSI-Q
HFB-17
DuZu
$S_{2n}/2$ (MeV)
A

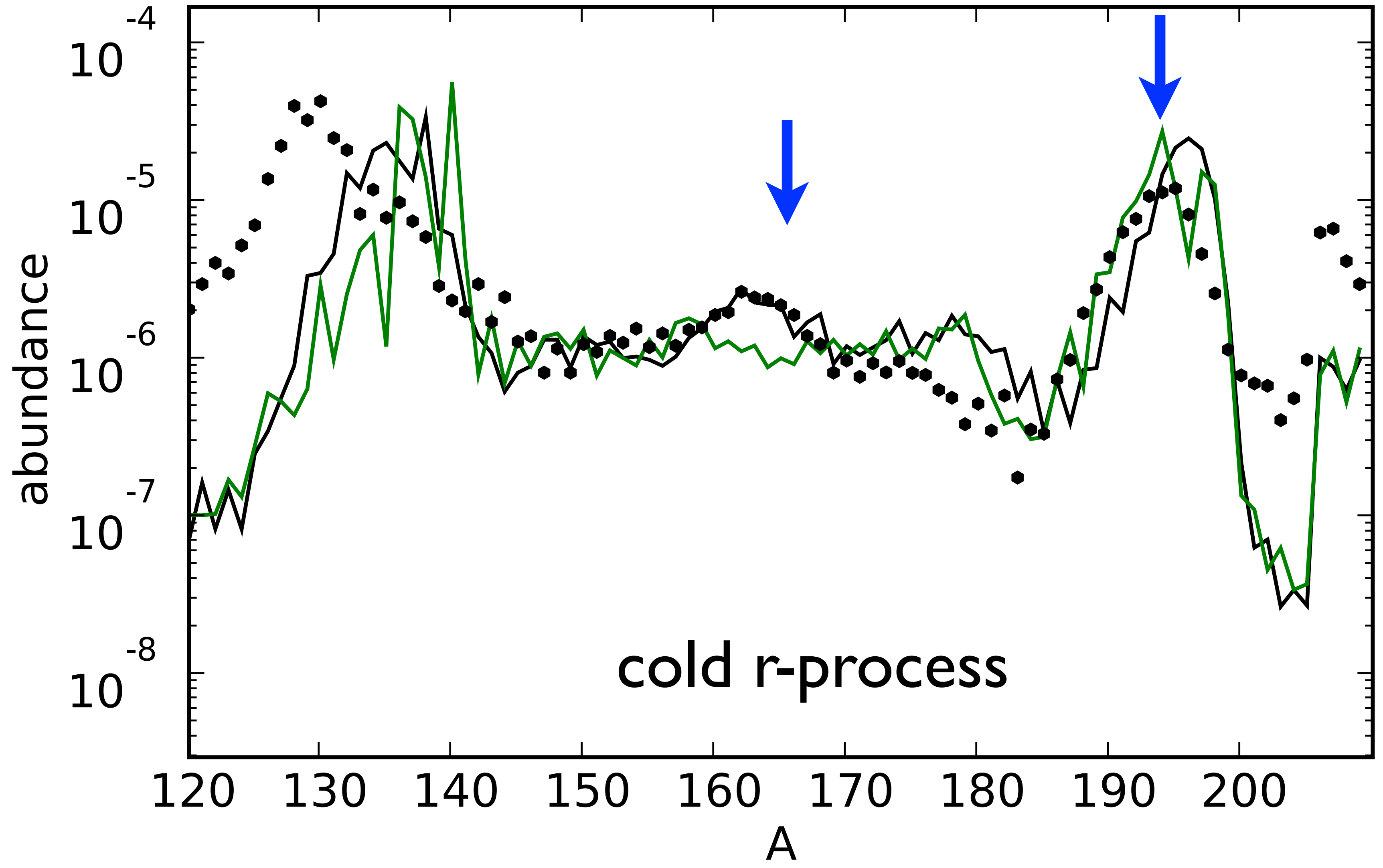
5.2 r-process: decay to stability



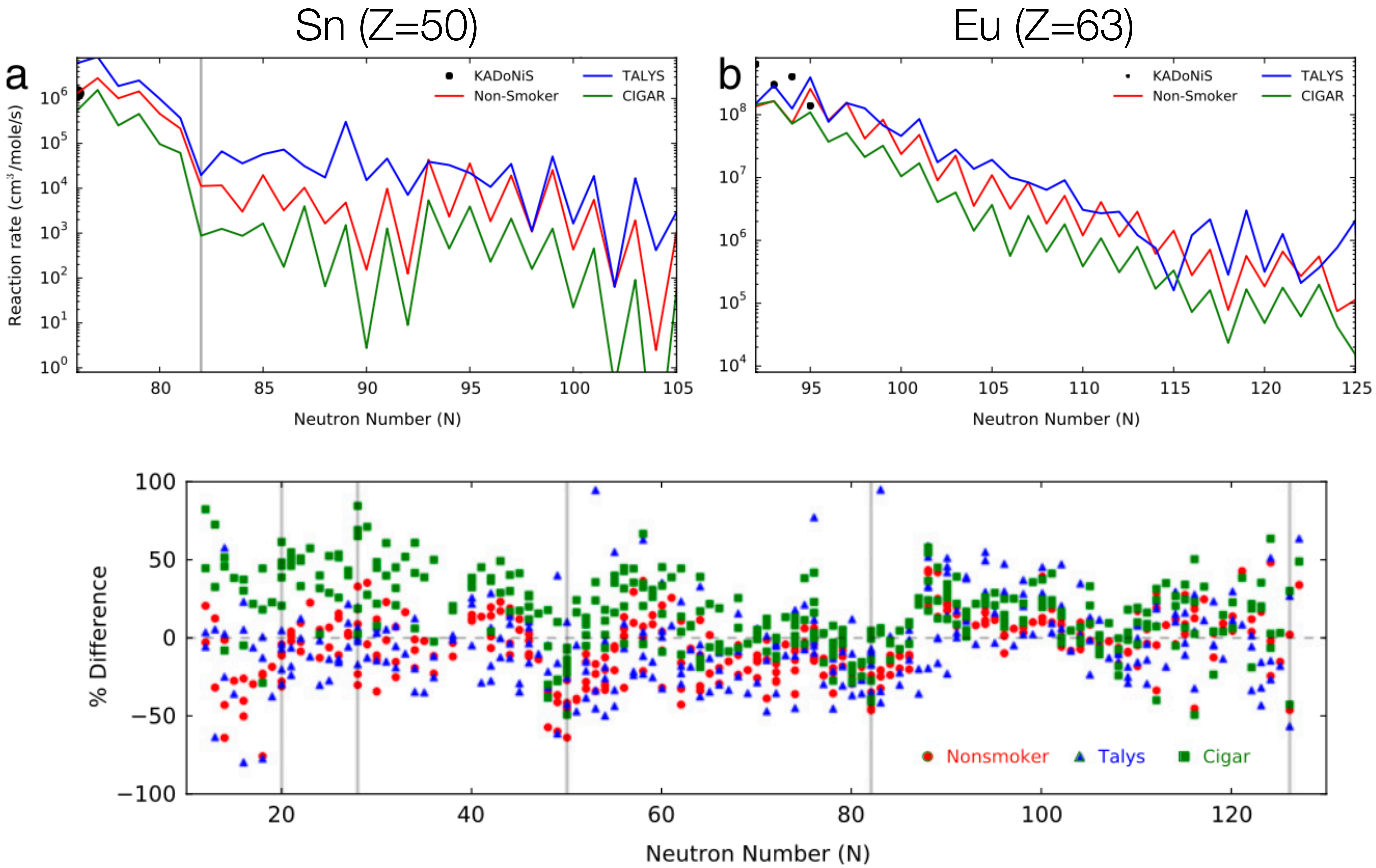
Final abundances
with and without beta-delayed neutron emission and with and without neutron captures after freeze-out

Beta-delayed neutron emission supply neutrons



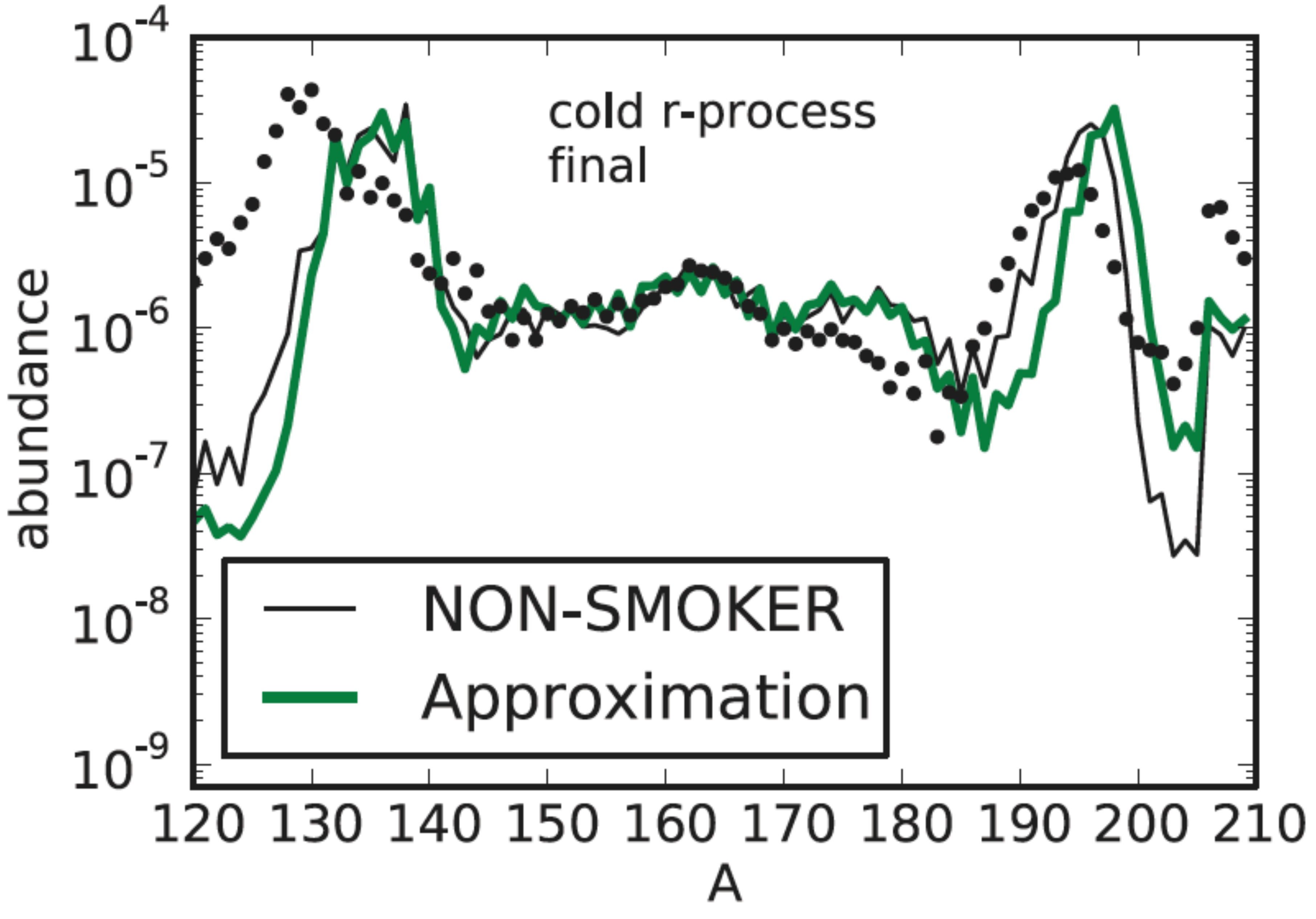


5.2 r-process: neutron captures

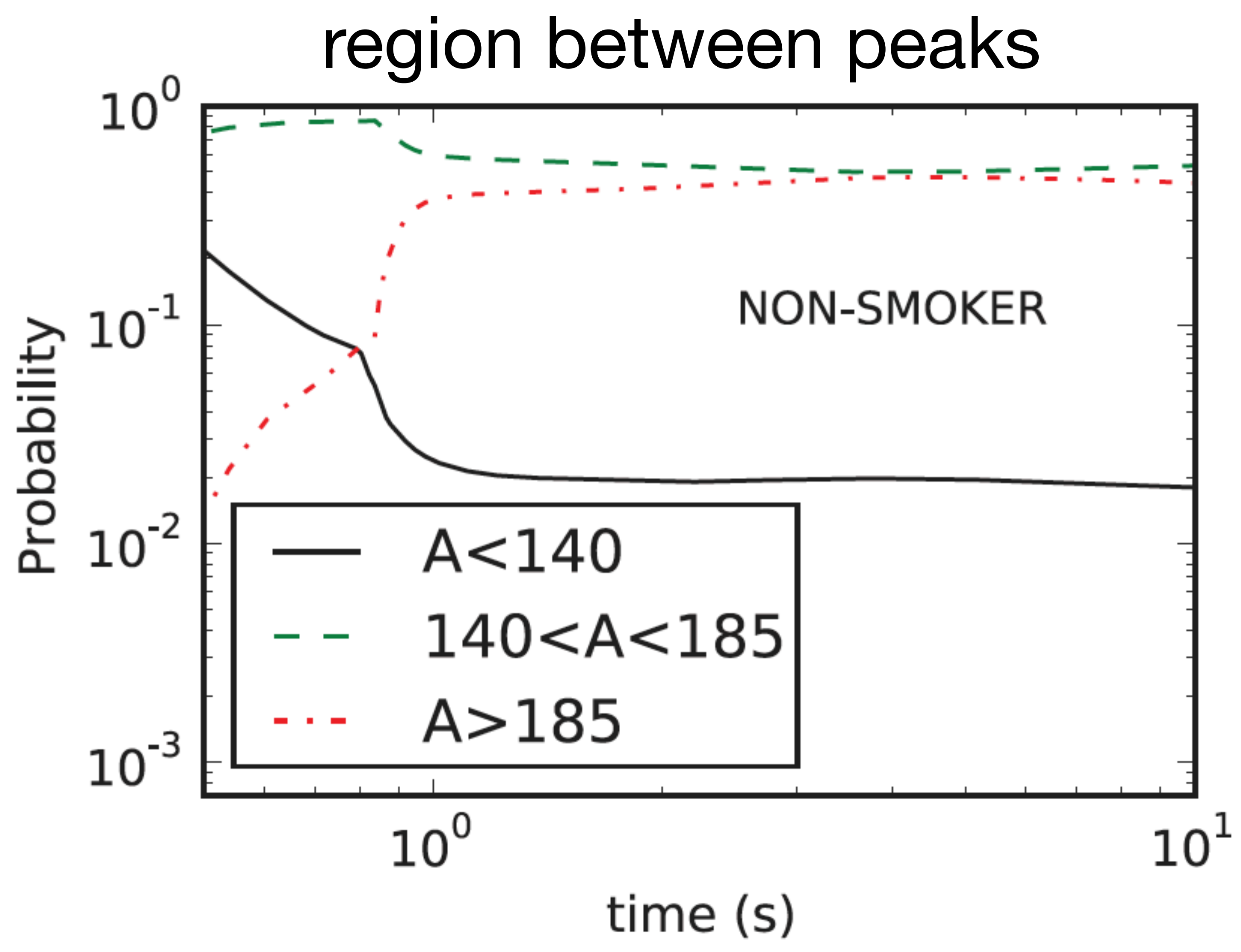


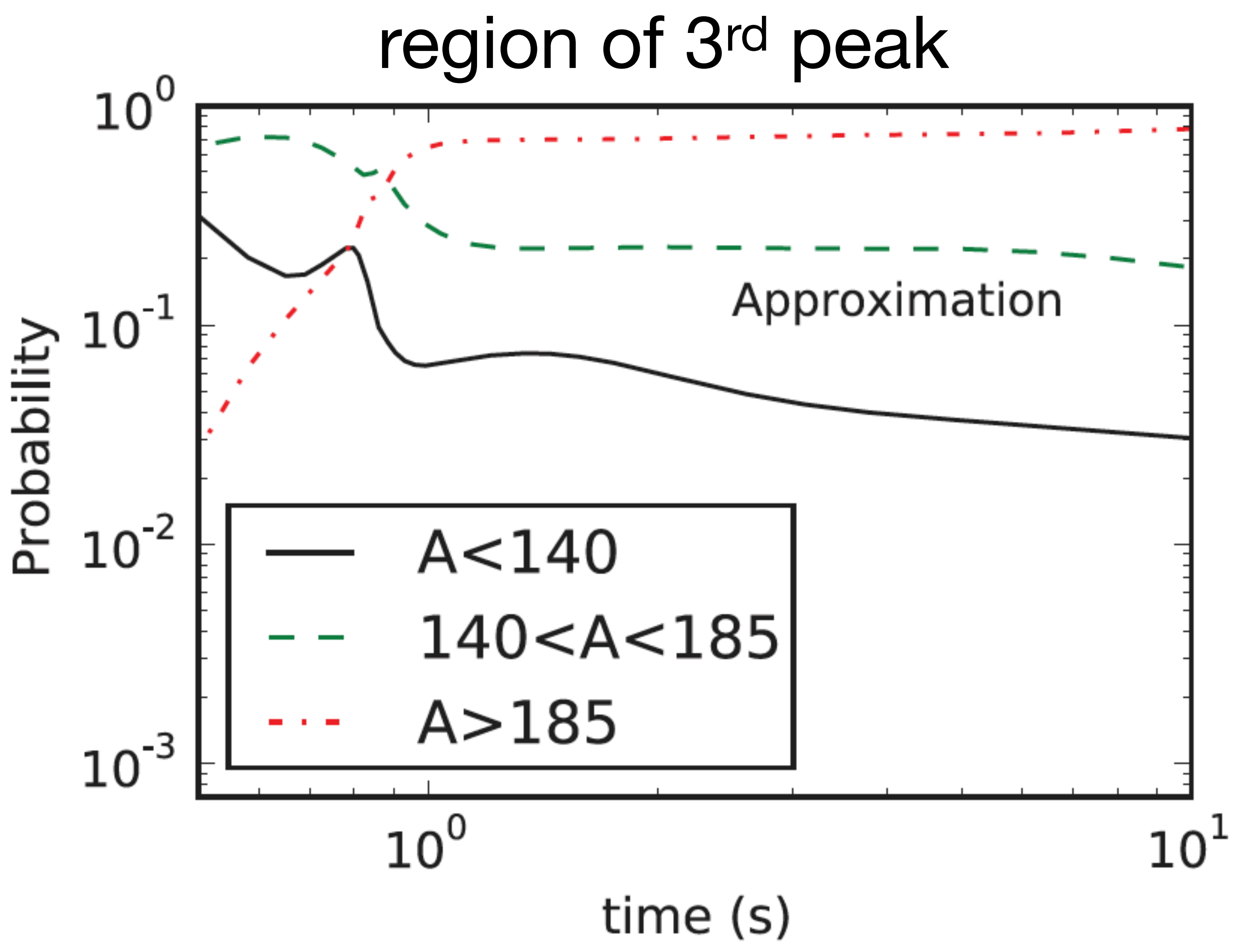
5.2 r-process: neutron captures

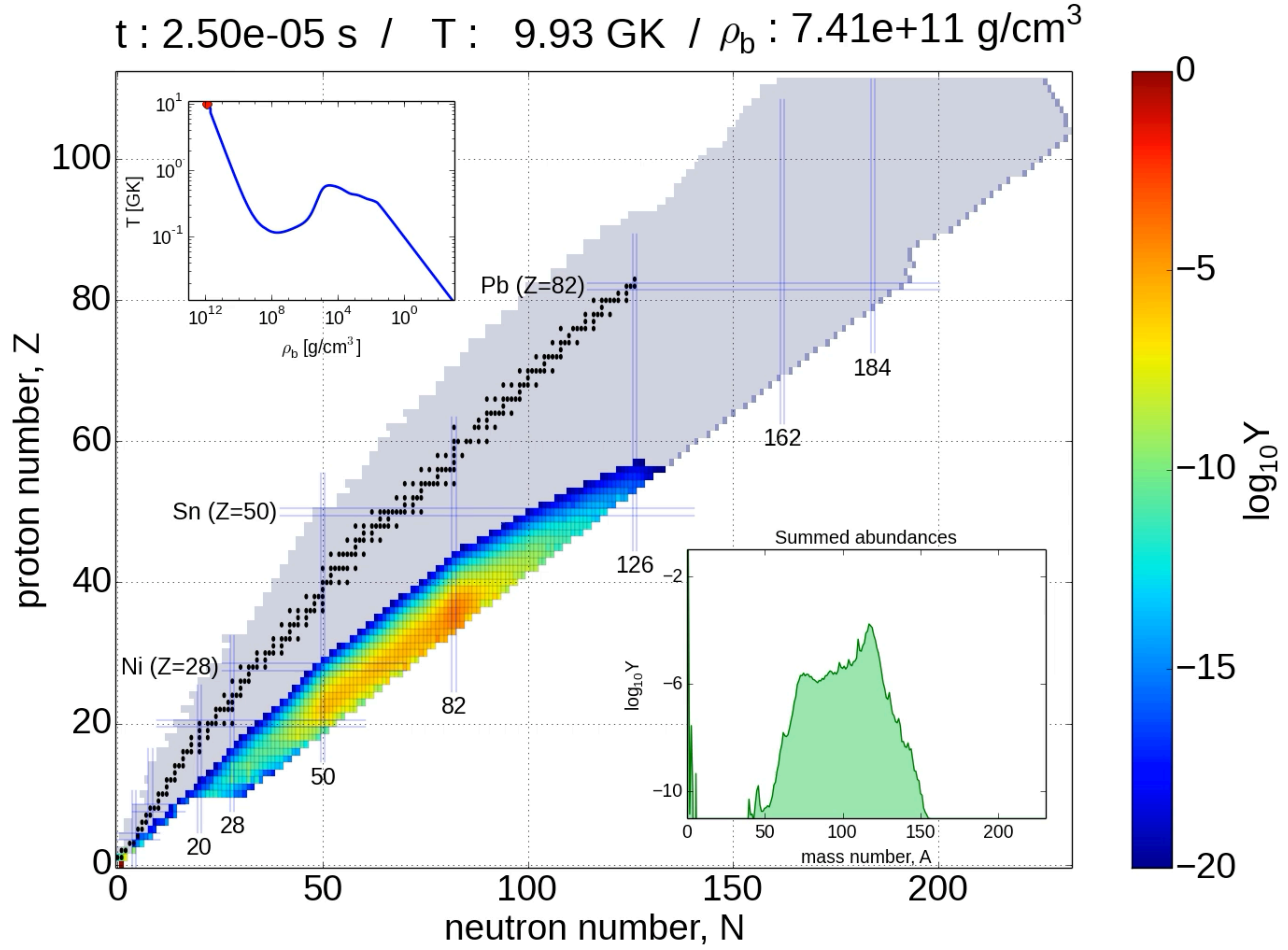
Compare neutron capture calculations



Neutron capture probability:

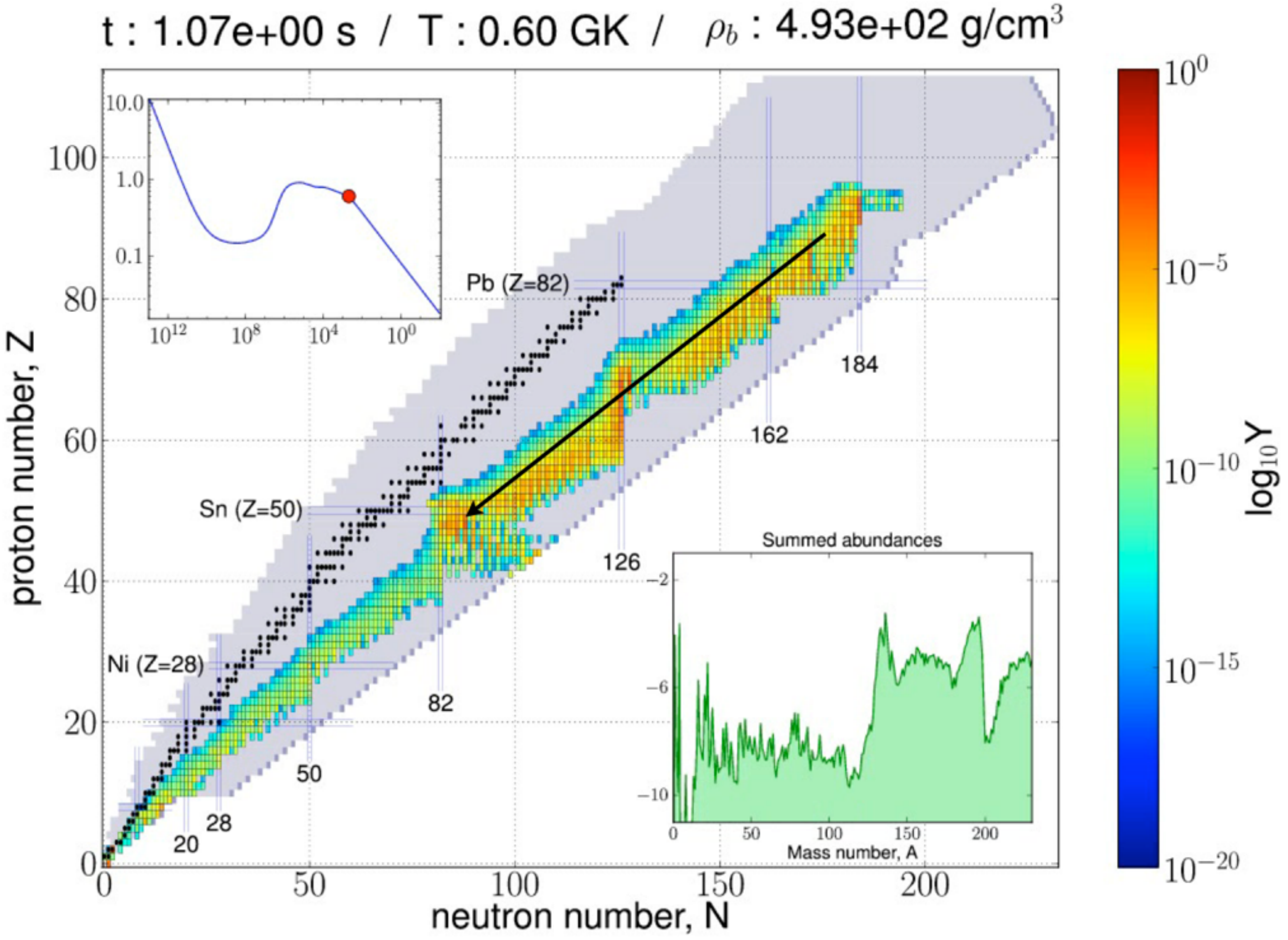


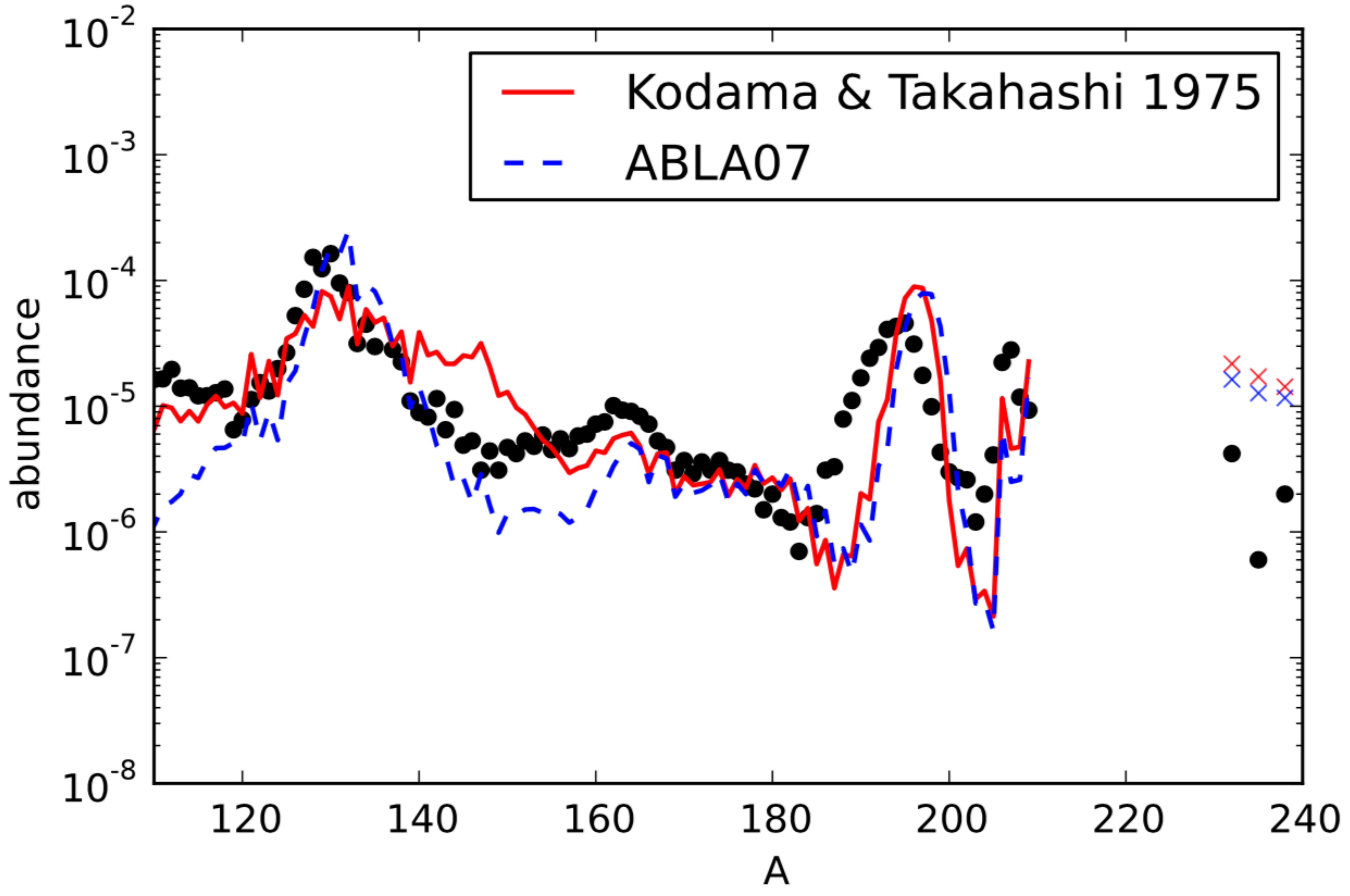




t : 2.50e-05 s / T : 9.93 GK / ρ_b : 7.41e+11 g/cm^3
proton number, Z
neutron number, N
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
20
28
50
82
126
162
184
T [GK]
ρ_b [g/cm^3]
Summed abundances
$\log_{10}$Y
mass number, A
$\log_{10}$Y

Fission: barriers and yield distributions





2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, neutron captures

Eichler et al. (2015), Eichler et al. (2019)