The fundamental role of fission during the r-process nucleosynthesis

S. Goriely (IAA-ULB)

Part I:

Introduction to the rapid neutron-capture process

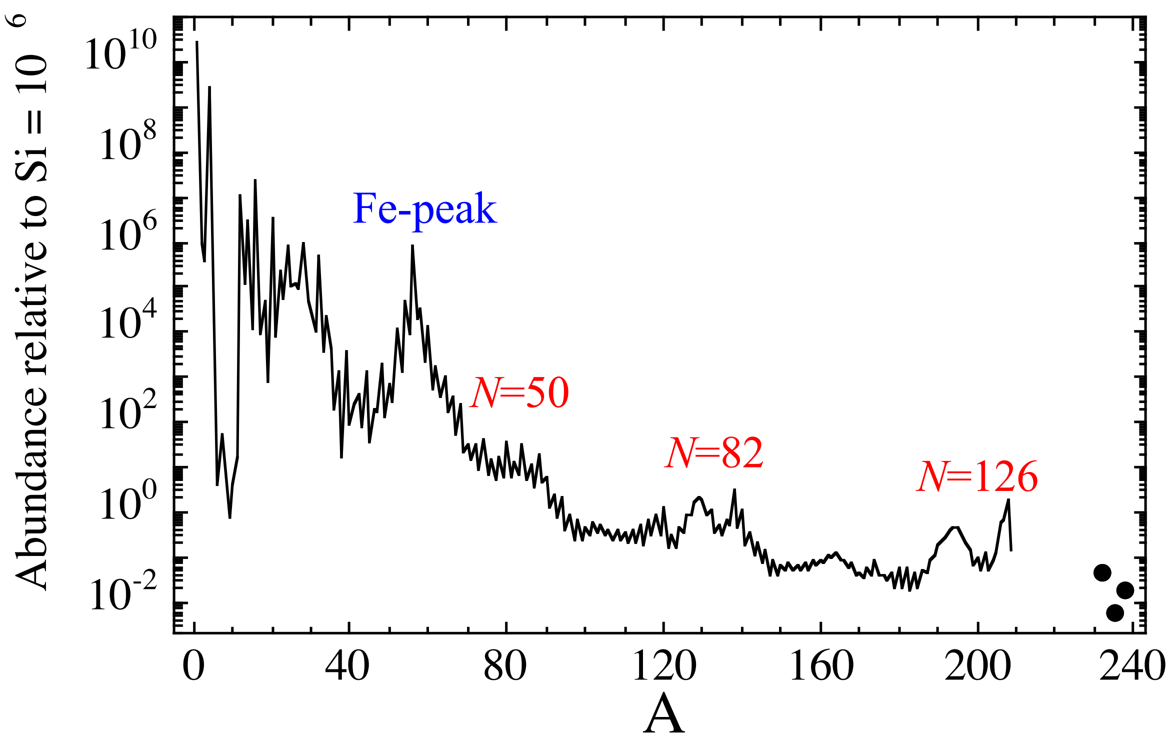
- Introduction to n-capture processes
- Some observations
- r-process in SNII, Collapsars, NSM
- Nuclear physics aspects & fission

The concept of synthesis by neutron captures

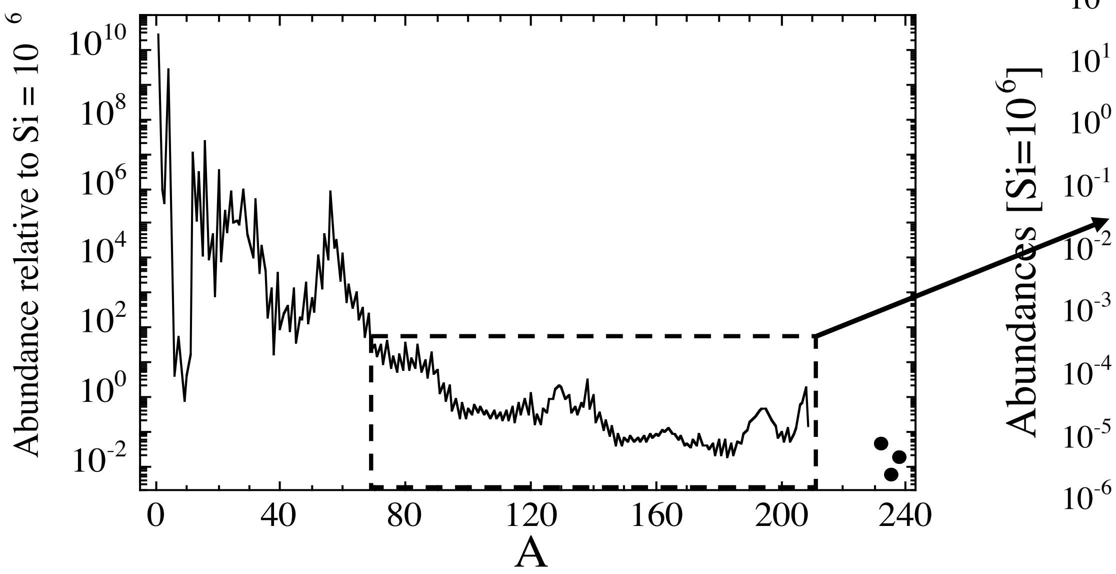
Charged-particle captures are inefficient to produce the bulk galactic $A > 56$ nuclides

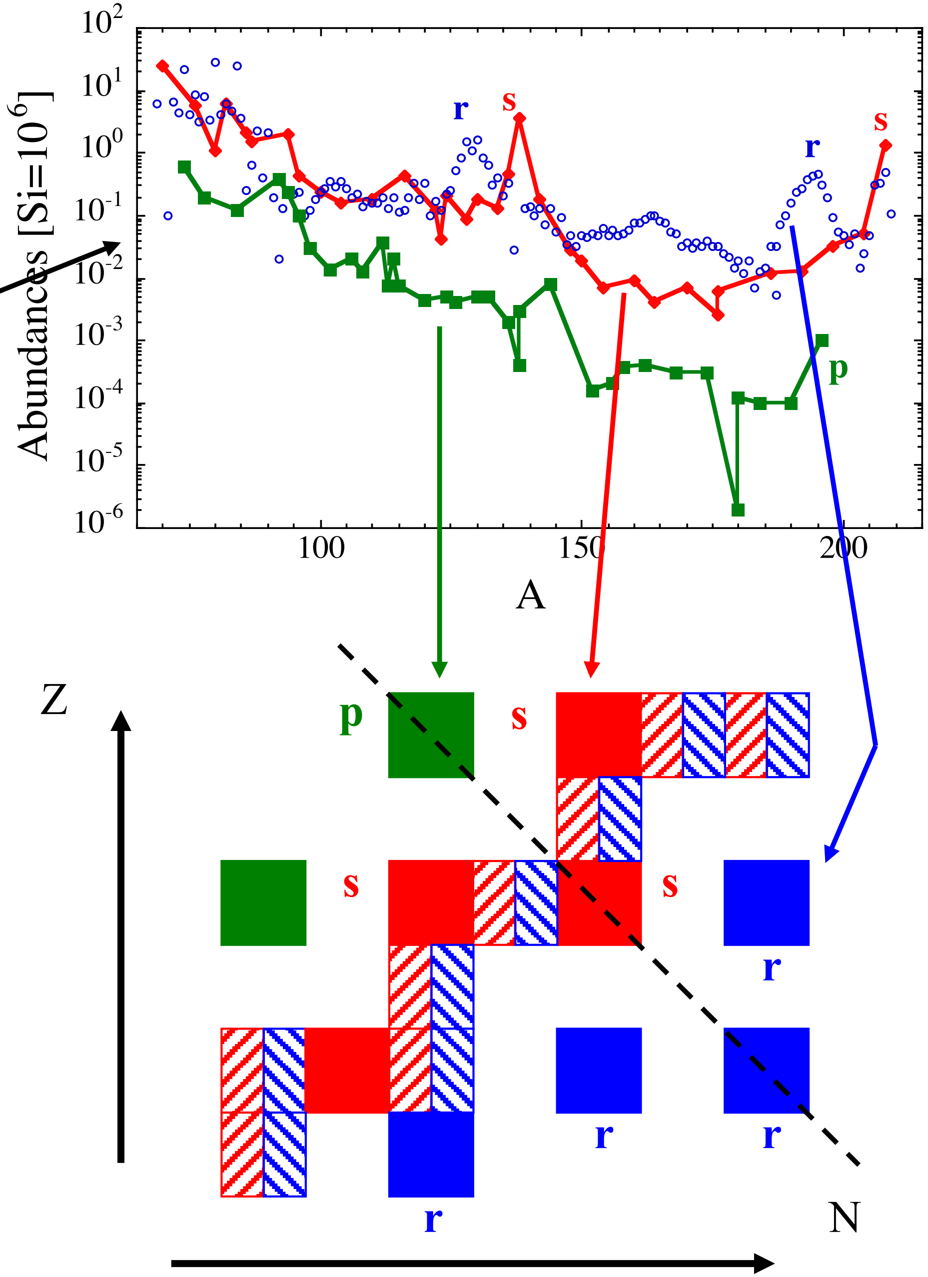
→ **Concept of NEUTRON Captures !**

- **No coulomb barrier**
- **Natural explanation for the peaks observed in the solar system abundances at neutron magic numbers *N*=50, 82 and 126**



Decomposition of the solar abundances

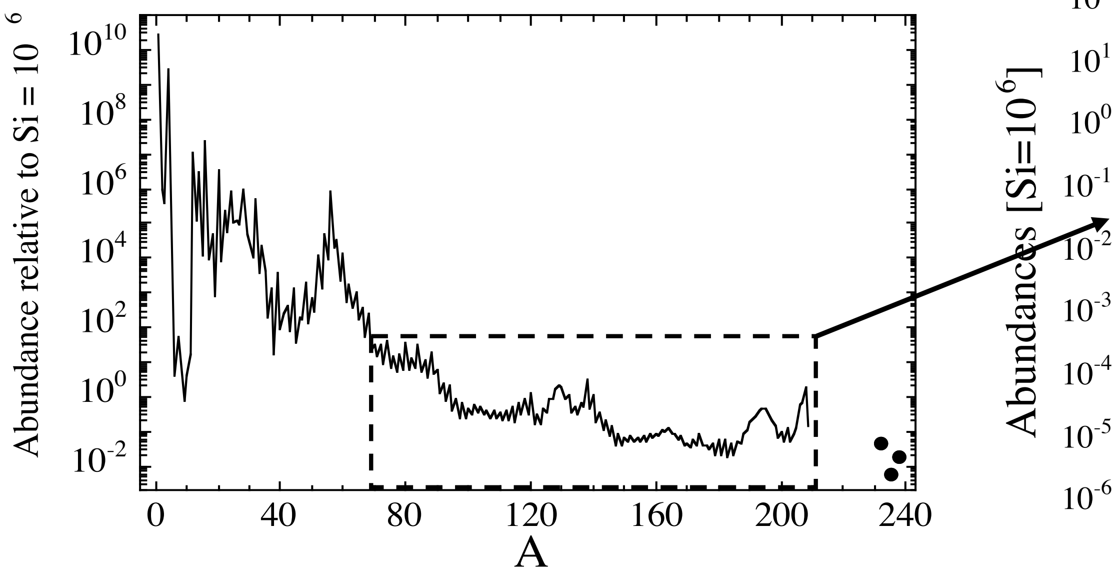


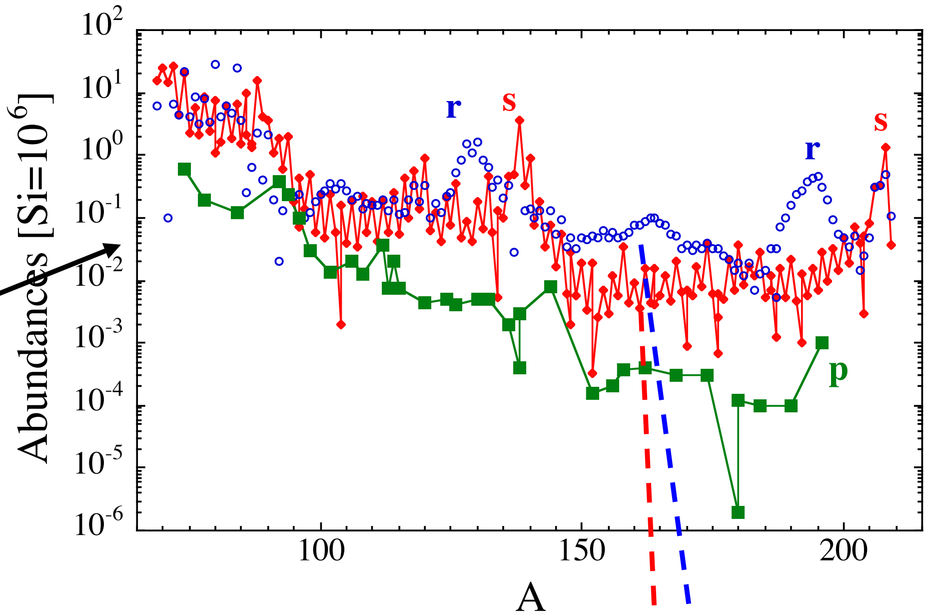


Separation of the stable nuclei into

- **Proton-rich isobars: p-nuclei**
- **Isobars at the bottom of the valley of β-stability: s-nuclei**
- **Neutron-rich isobars: r-nuclei**

Decomposition of the solar abundances





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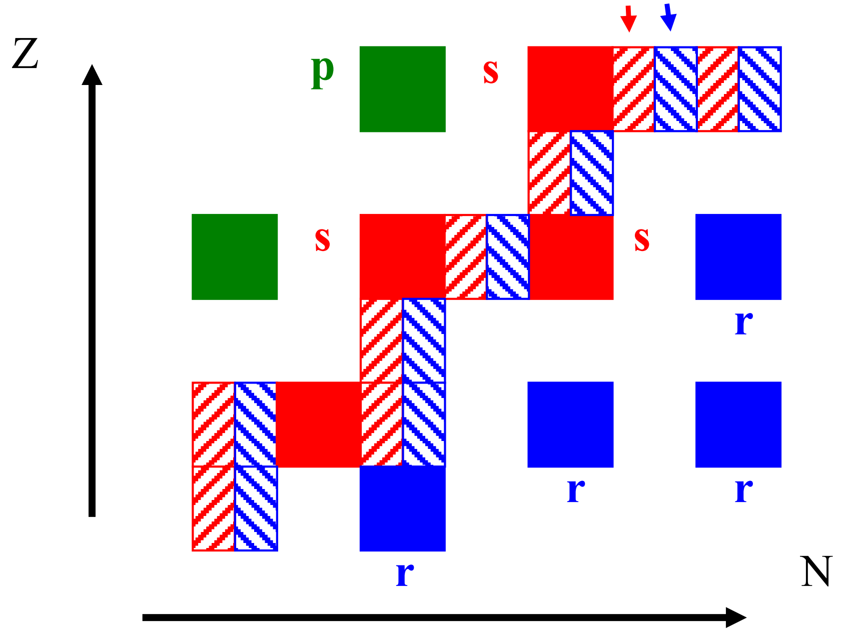
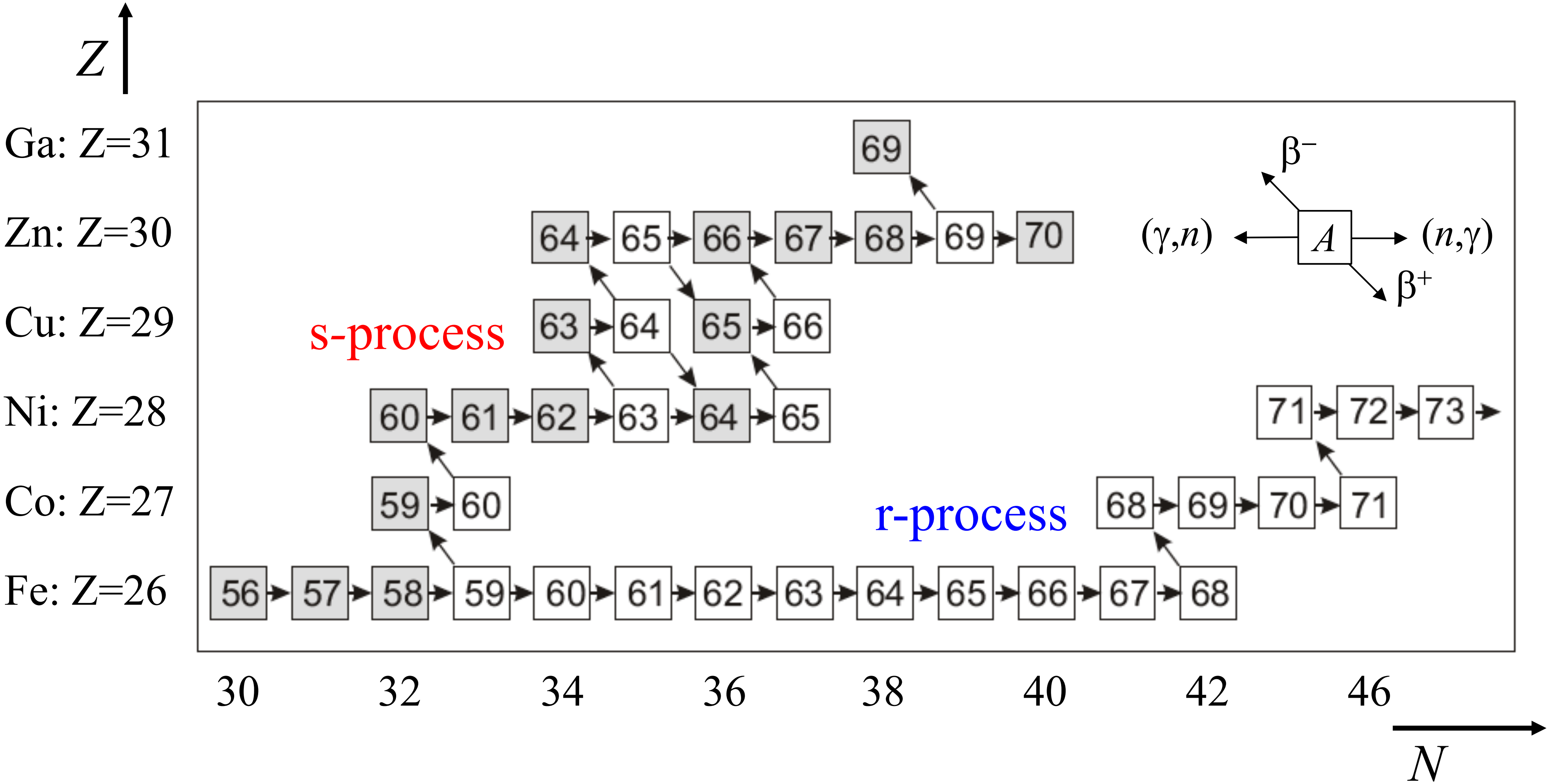


A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

Rapid neutron-capture process: $\tau_\beta >> \tau_n$

τ_n = lifetime against neutron capture
τ_β = lifetime against β^- decay



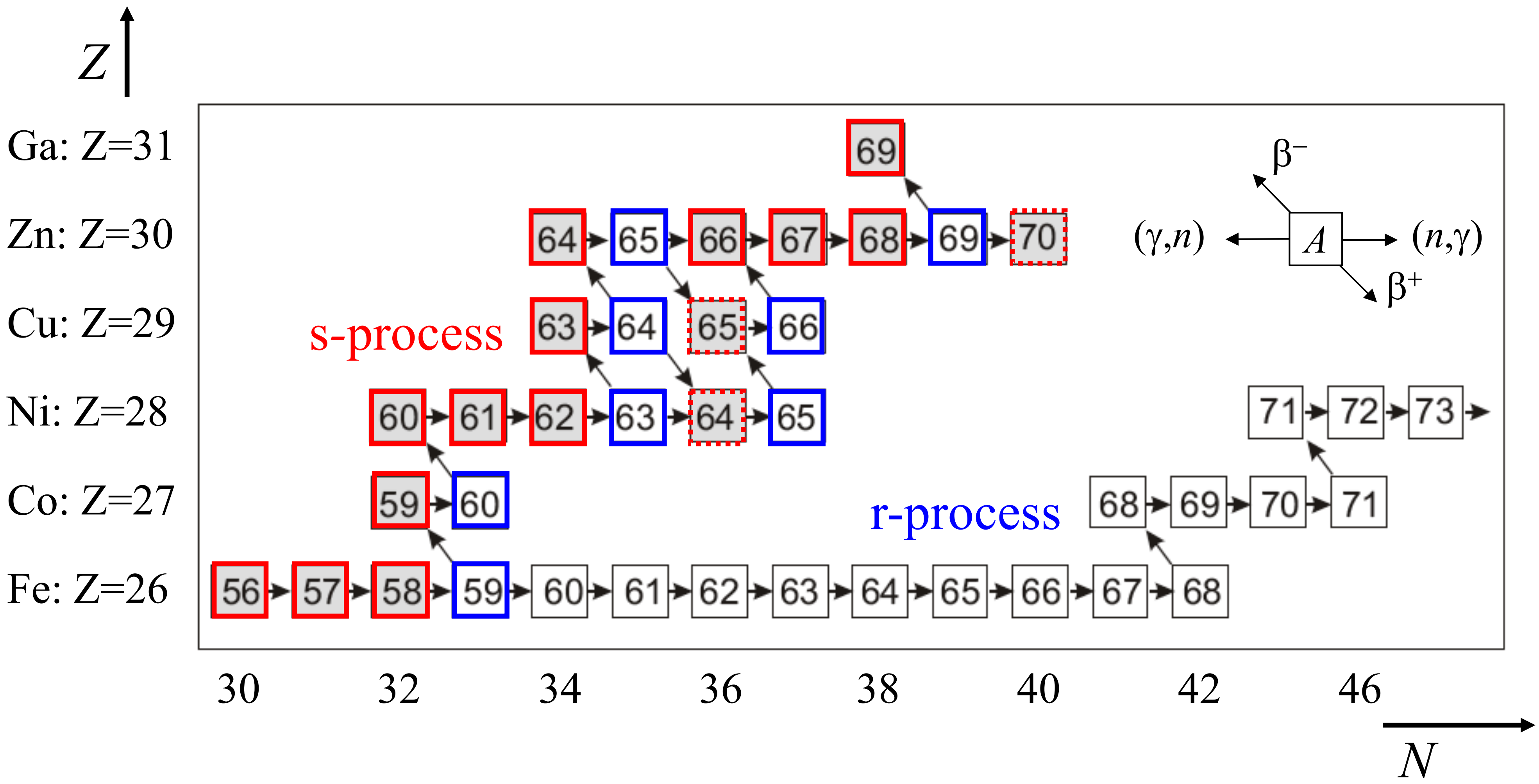
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

N_n~10^7-10^{11} cm^{-3} T~1-3 10^8K t_{irr}~ 10-10^4yr

τ_n = lifetime against neutron capture

τ_β = lifetime against β^- decay



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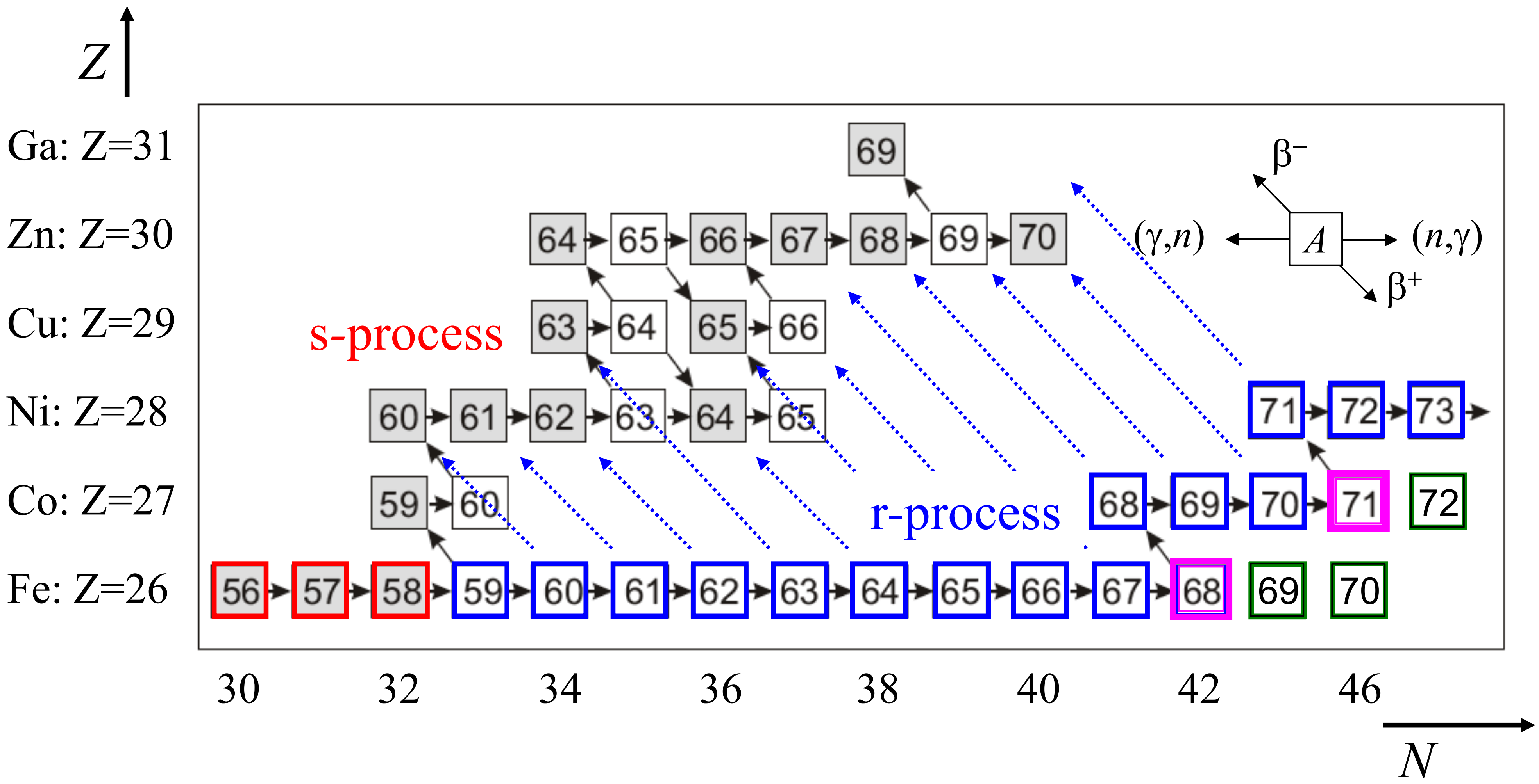
N_n~10^7-10^{11} cm^{-3} T~1-3 10^8K t_{irr}~ 10-10^4yr

Rapid neutron-capture process: $\tau_\beta >> \tau_n$

N_n>>10^{24} cm^{-3} T~1-2 10^9K t_{irr}~ 1s

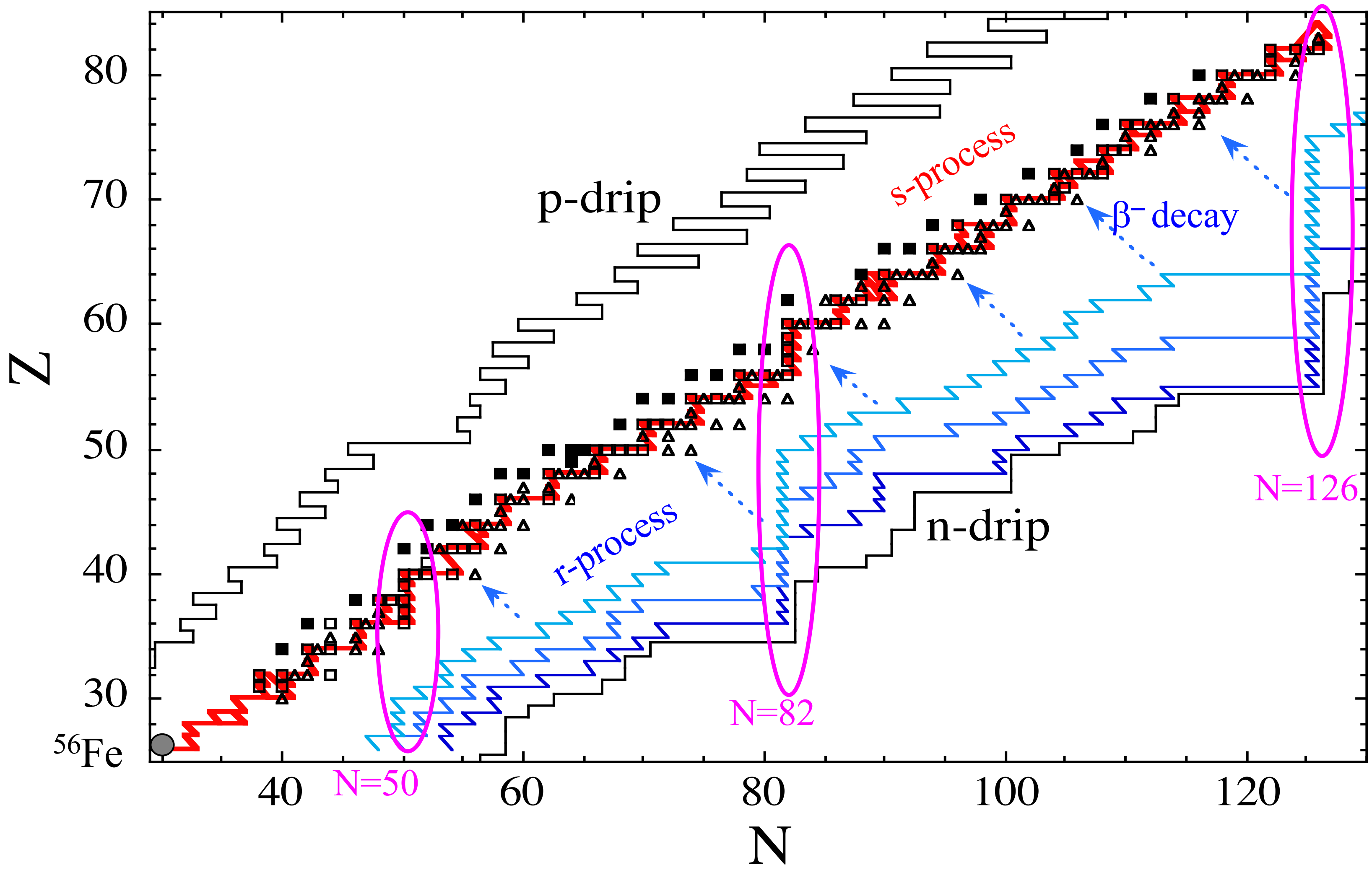
τ_n = lifetime against neutron capture

τ_β = lifetime against β^- decay

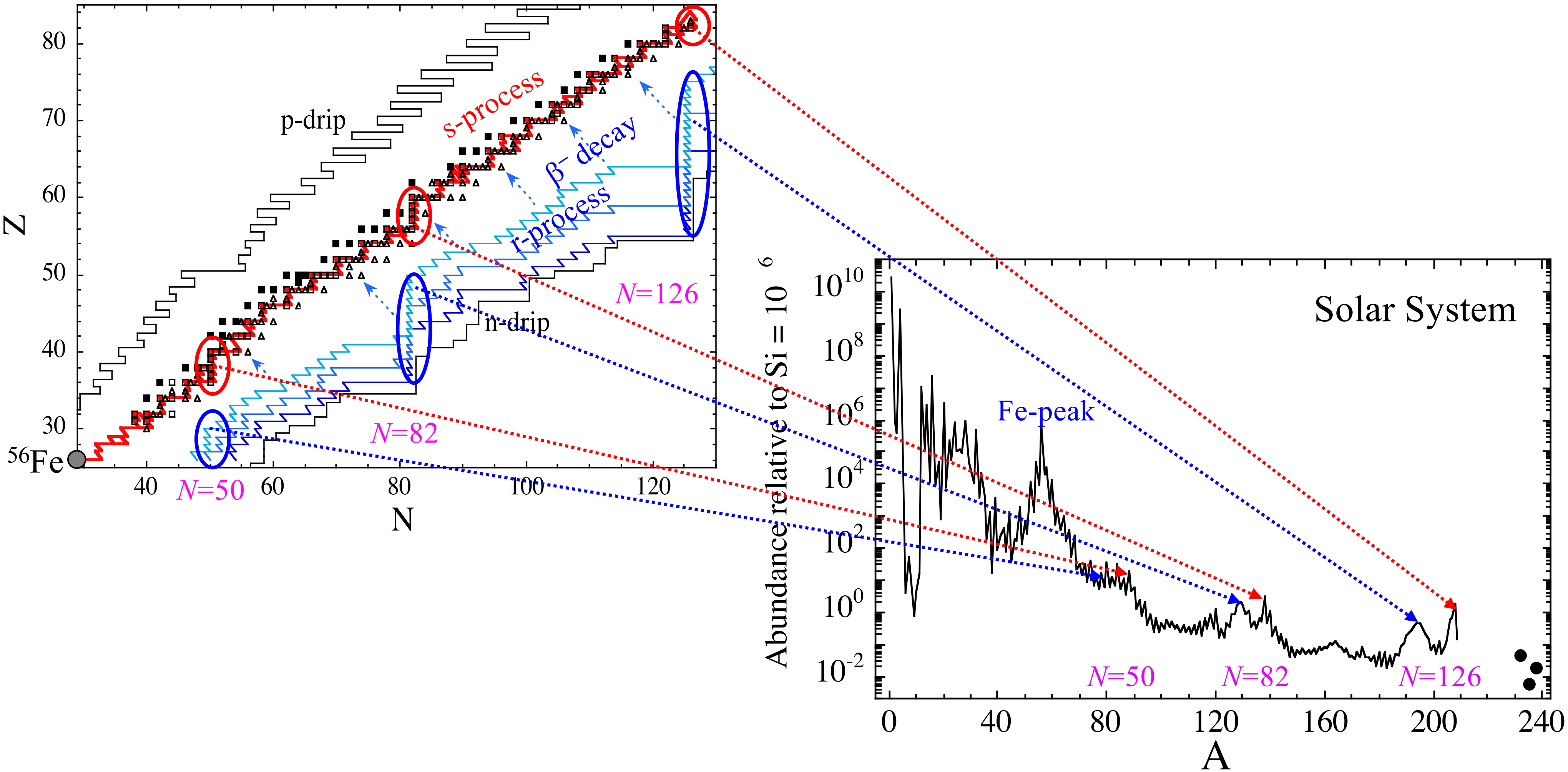


A schematic representation of the s- and r-processes

Closed shells at magic numbers *N*=50, 82, 126 —-> slow n-capture



The signature of nuclear properties in the double-peak pattern of the solar abundance distribution



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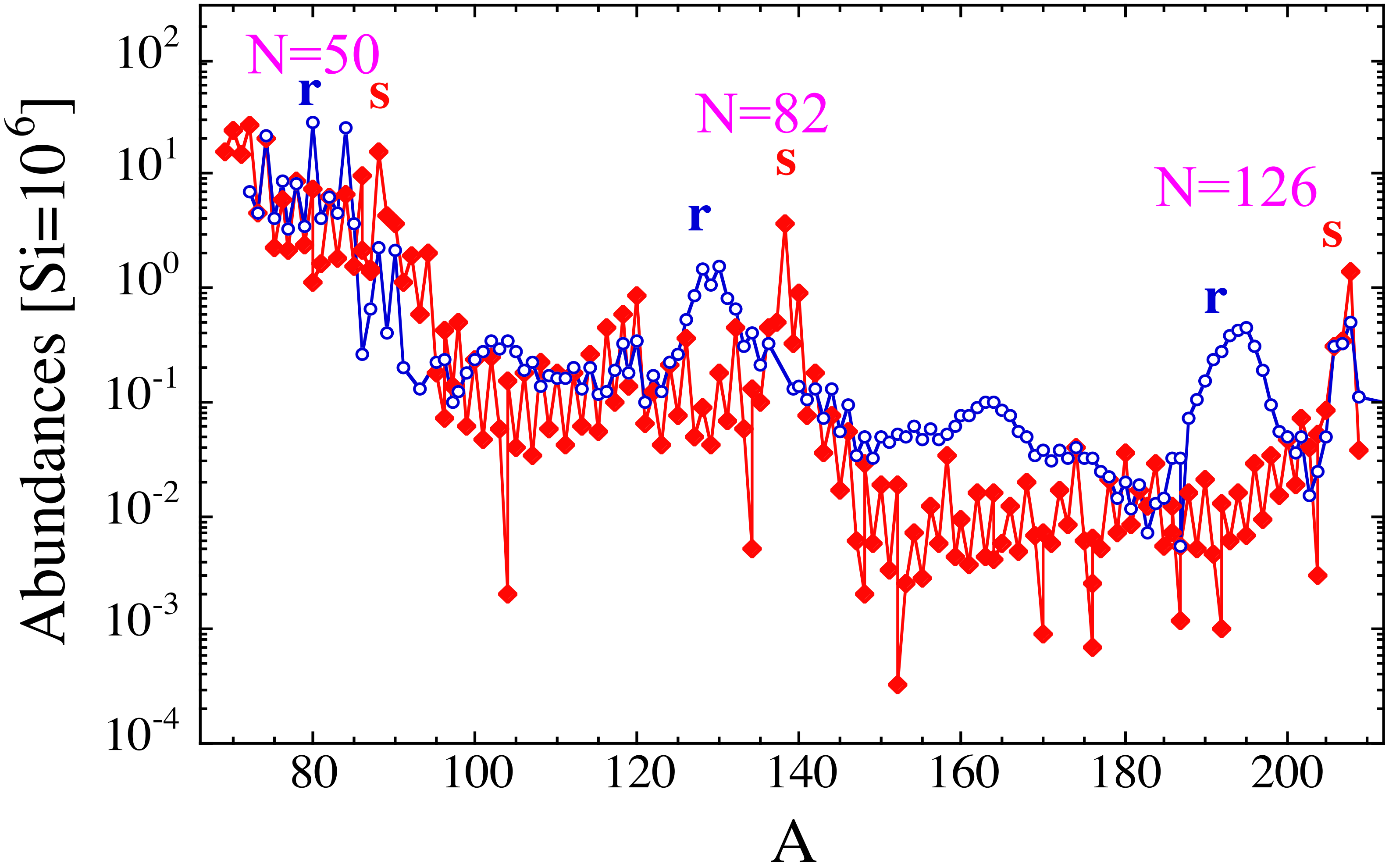
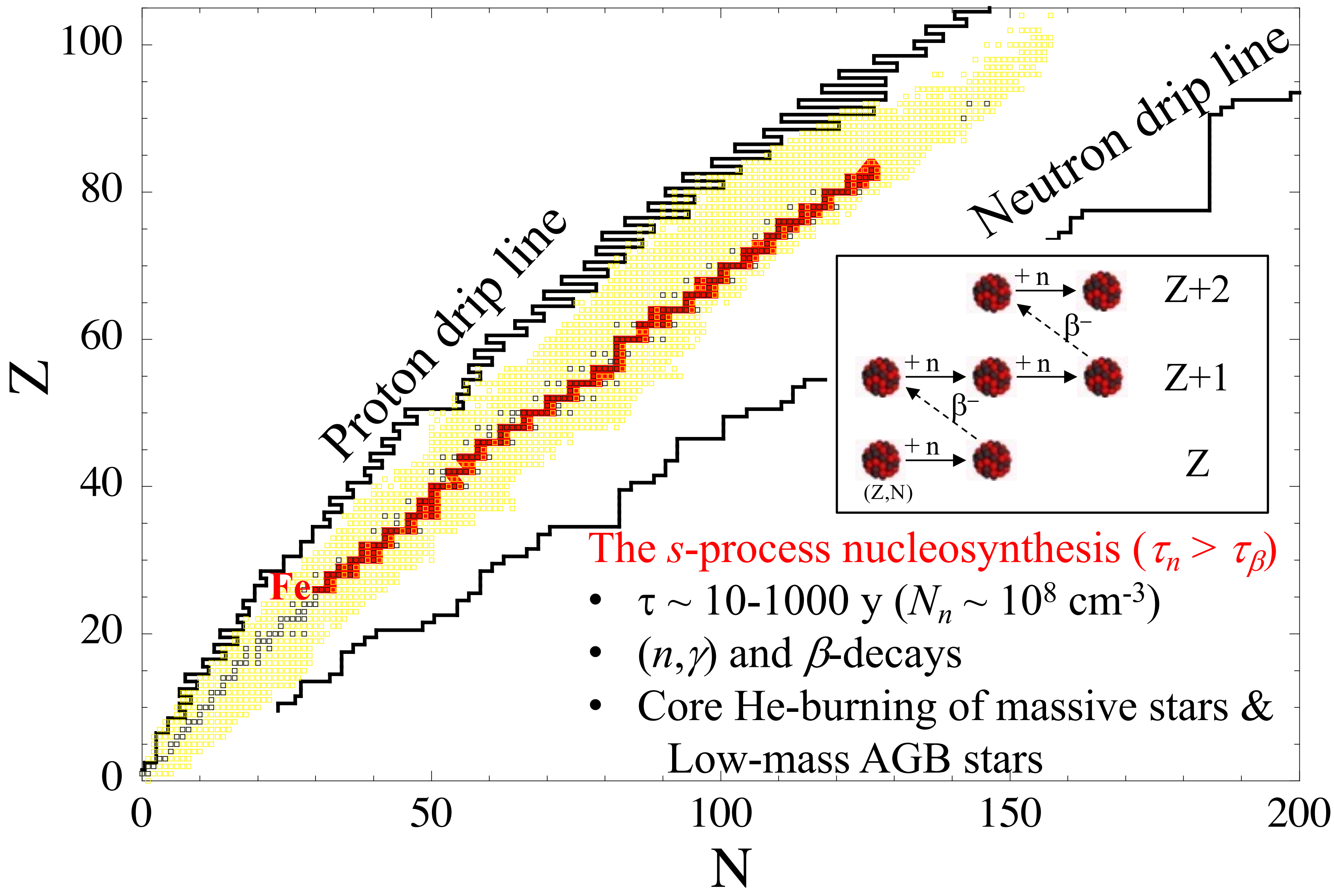
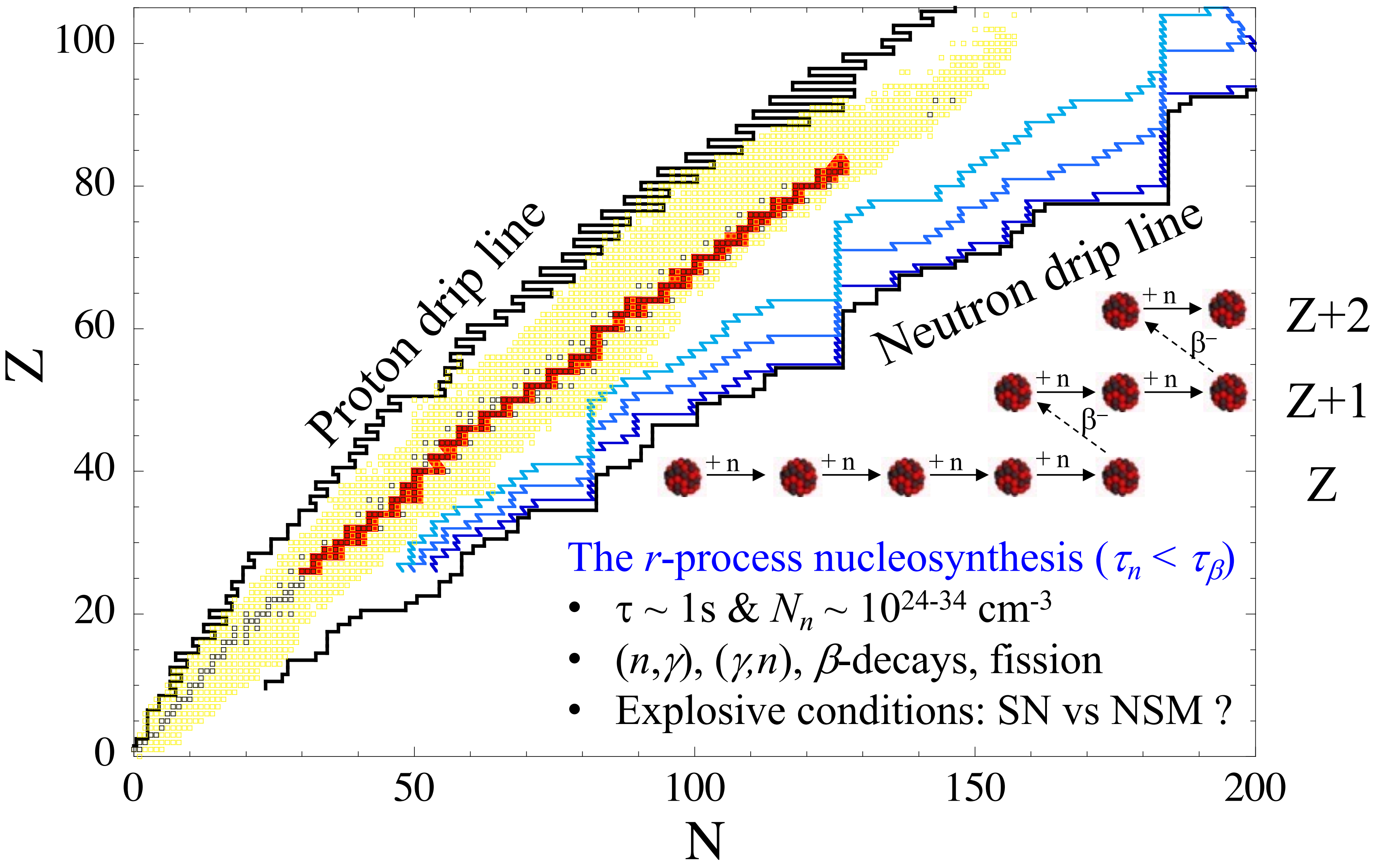


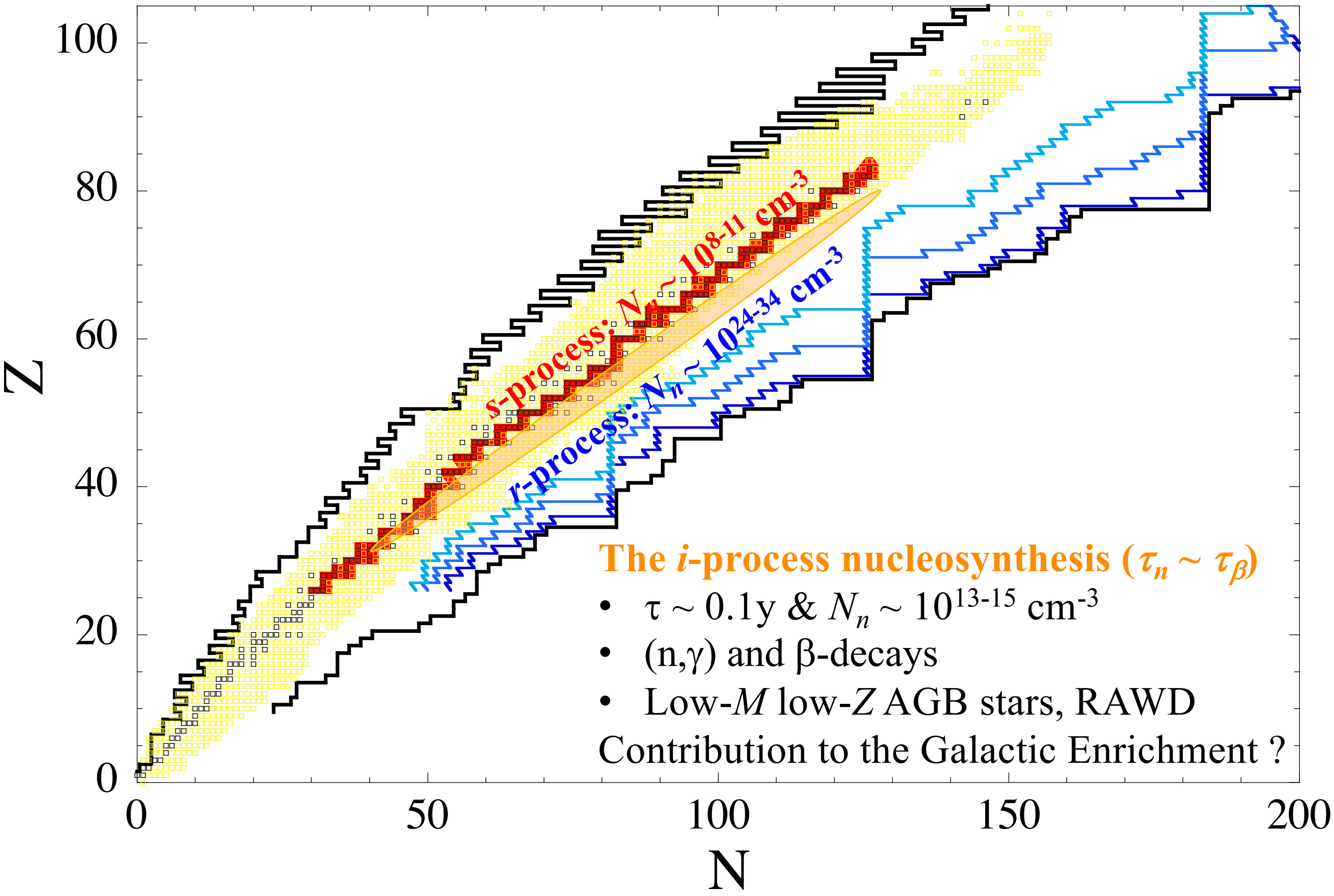
The *s*-process nucleosynthesis



The *r*-process nucleosynthesis



The intermediate neutron-capture process

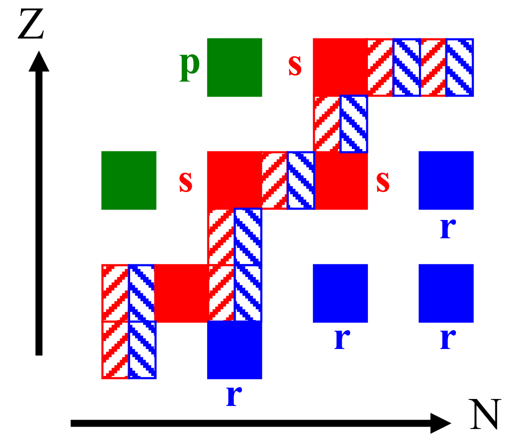


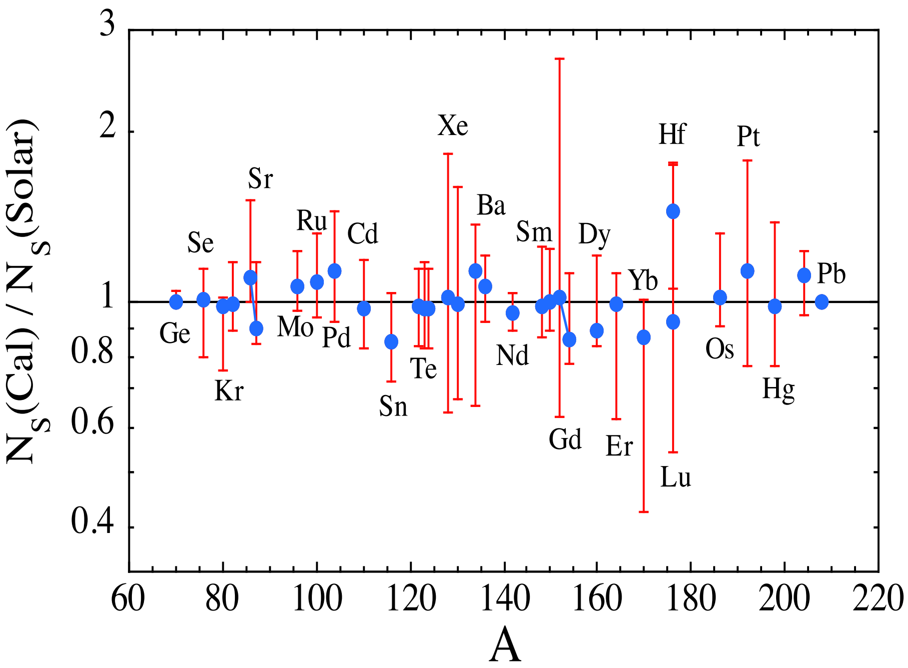
Decomposition of the solar abundances

Procedure for extracting the s-, r- and p-contributions from the SoS abundances

1. Select the ~33 s-only nuclides
2. Construct an s-process model to account *at best* for the SoS abundances of the s-only nuclides
3. Calculate the s-contribution to the s+r and s+p nuclides.
4. Estimate the SoS r- and p-abundances: $N_{r,p}(\mathrm{SoS}) = N_{tot}(\mathrm{SoS}) - N_s(\mathrm{SoS})$

Why starting from the s-process model ?
• nuclear physics input is based at large from experimental data
• the site-independent “canonical” s-process model reproduces most of the s-only SoS abundances within a few tens of a percent

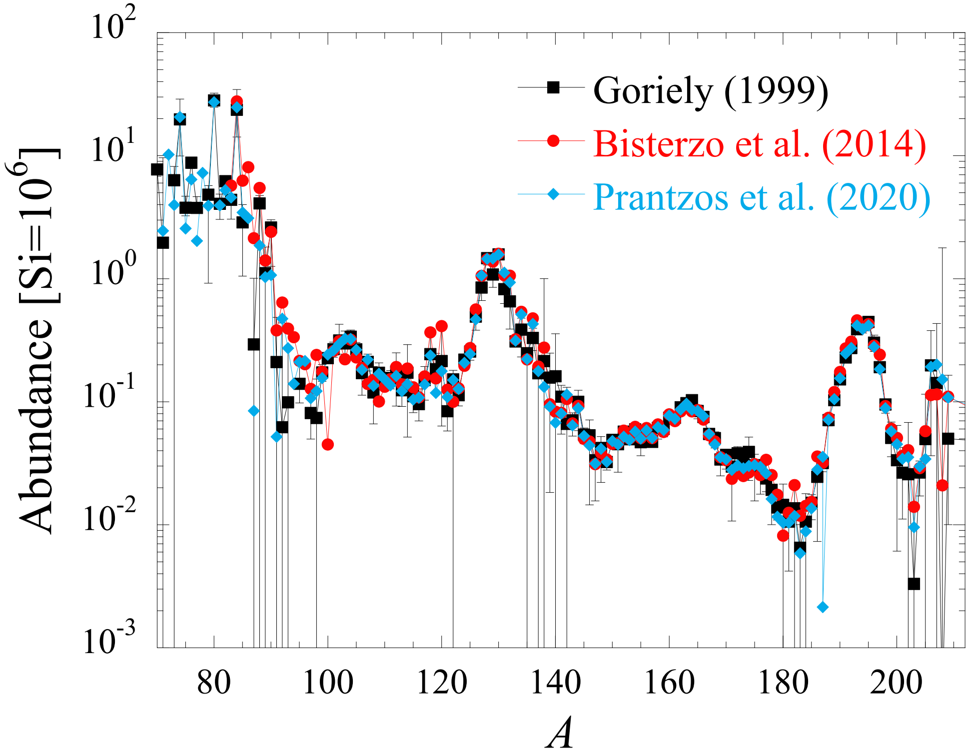




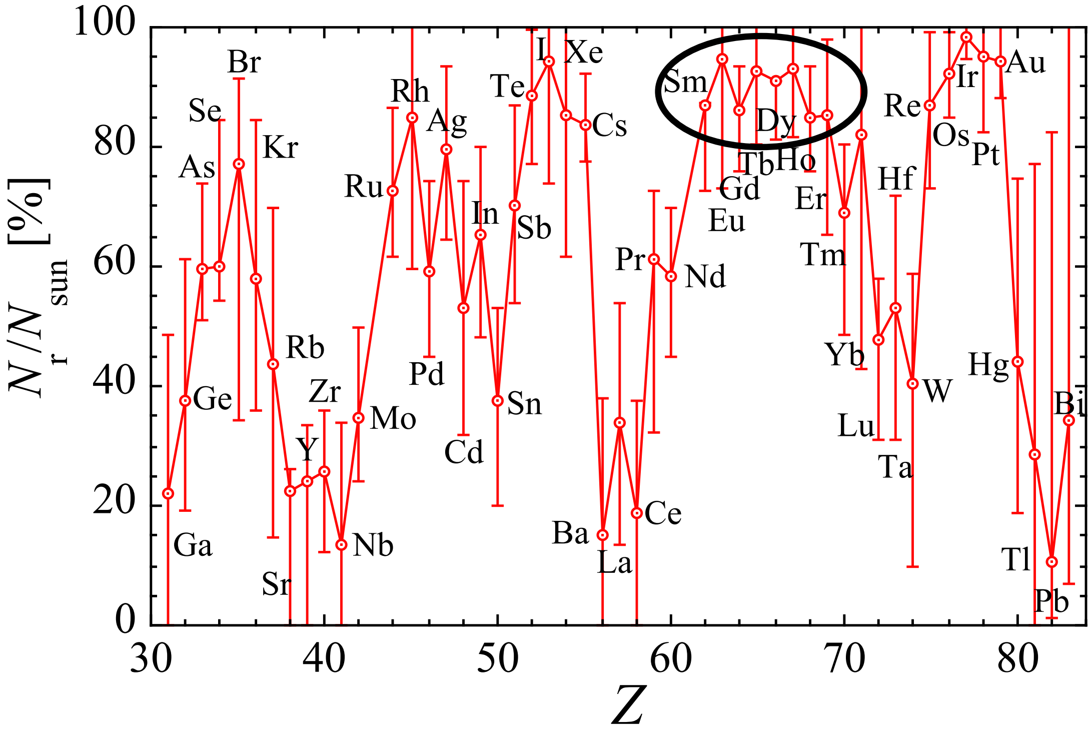
Uncertainties from meteoritic abundances, nuclear reaction and β-decay rates, s-process model

Decomposition of the solar abundances

Solar System nuclei
r-abundance distribution



r-contribution to the solar
elemental abundance



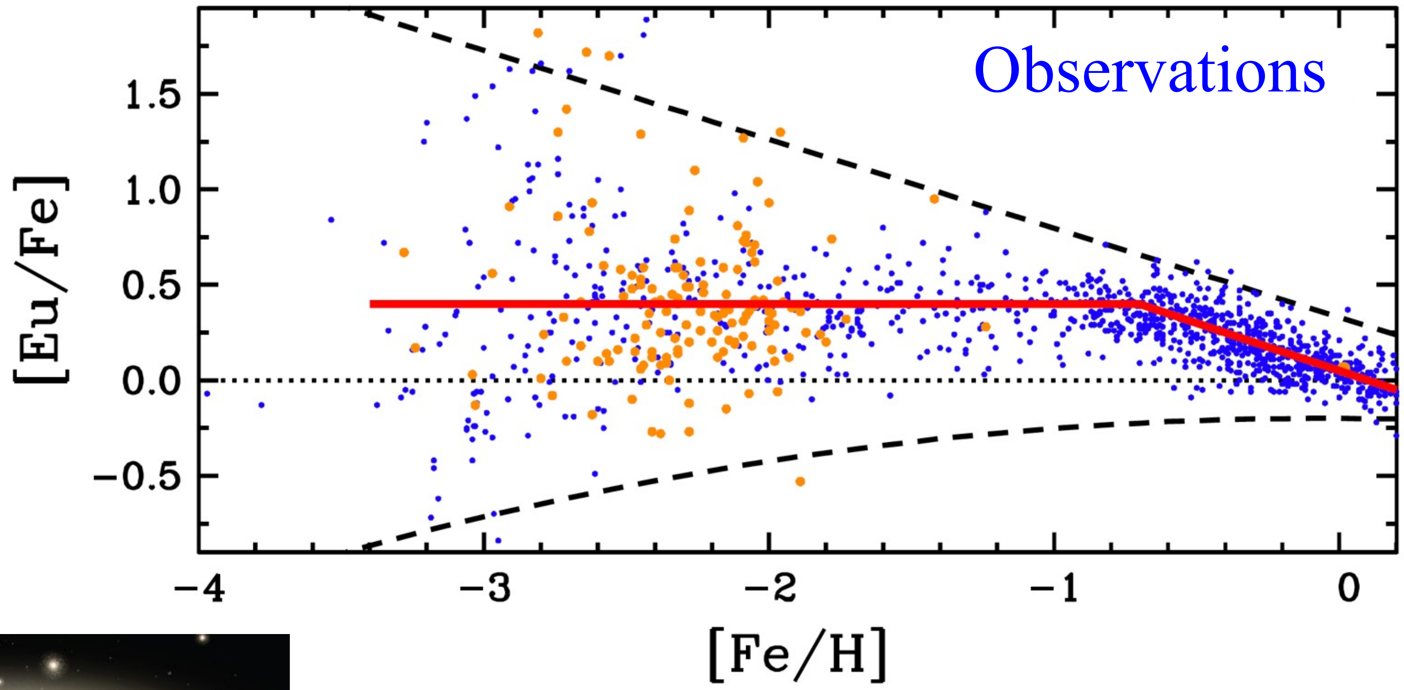
+ Th & U production

Observation of Eu

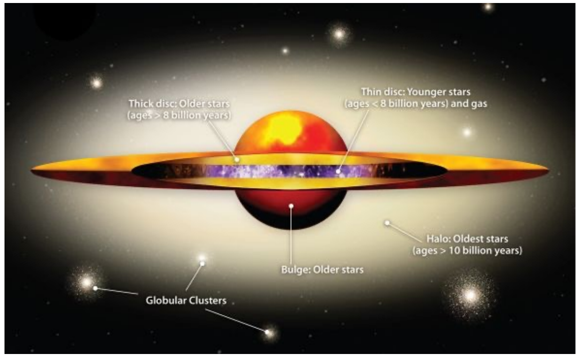
Chemical evolution of *r*-elements in the Galaxy

→ early enrichment of Eu (halo stars)

→ abundance scatter in low-metallicity stars



Cowan et al. (2021)



$[X/Y]=\log_{10}(X/Y)-\log_{10}(X/Y)_{\odot}$

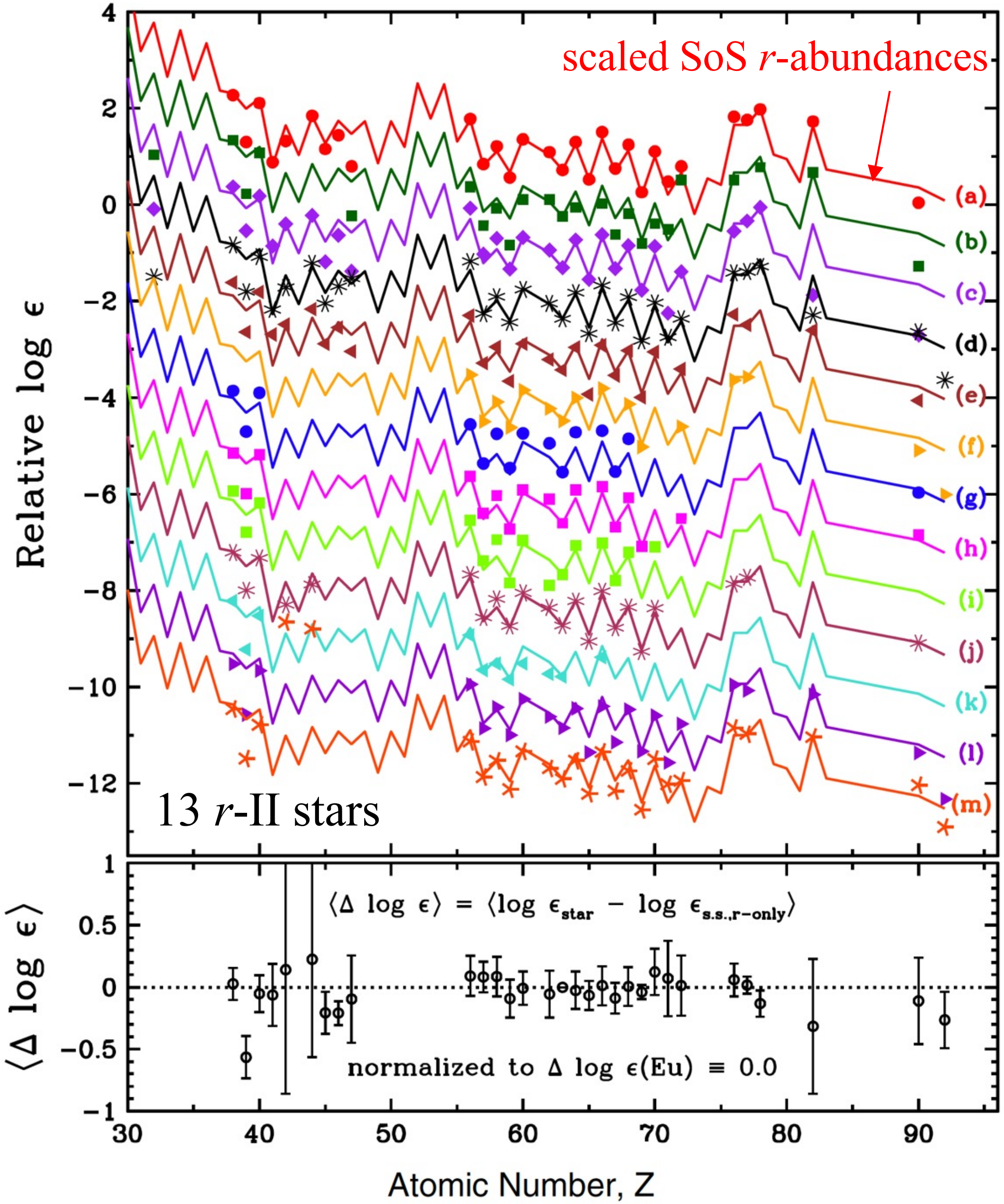
$[Fe/H]=\log_{10}(Fe/H)-\log_{10}(Fe/H)_{\odot}$

The r-process distribution in ultra-metal-poor stars

Low-metallicity r-process-rich stars (*r*-II: [Eu/Fe]>1) with elemental distributions matching the solar r-distribution

Universality of the r-process ?

Mean differences with respect to the solar r-abundance distribution

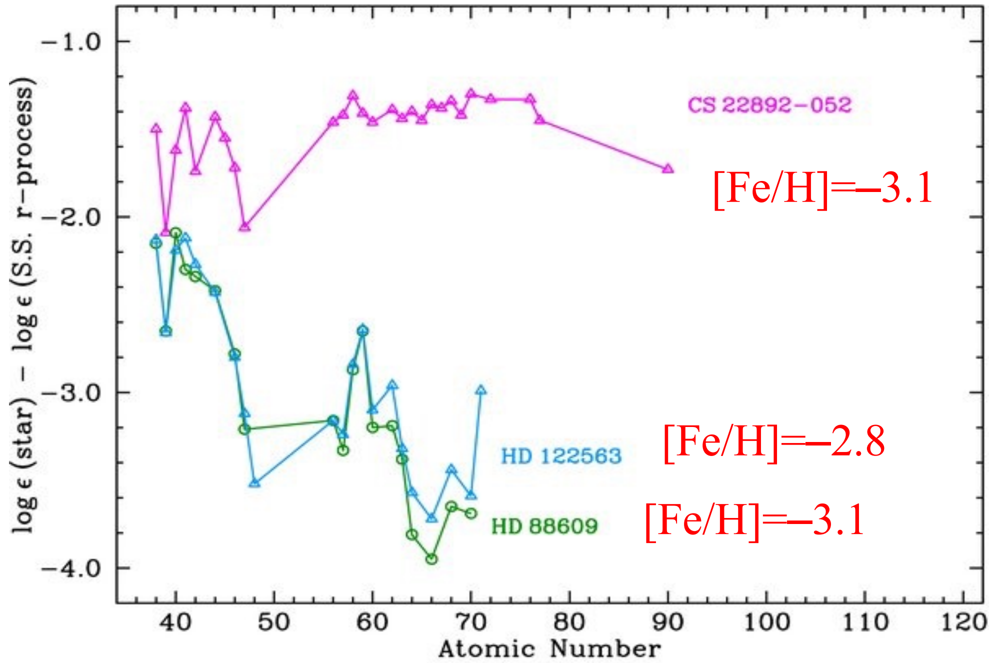


Cowan et al. (2021)

The r-process distribution in ultra-metal-poor stars

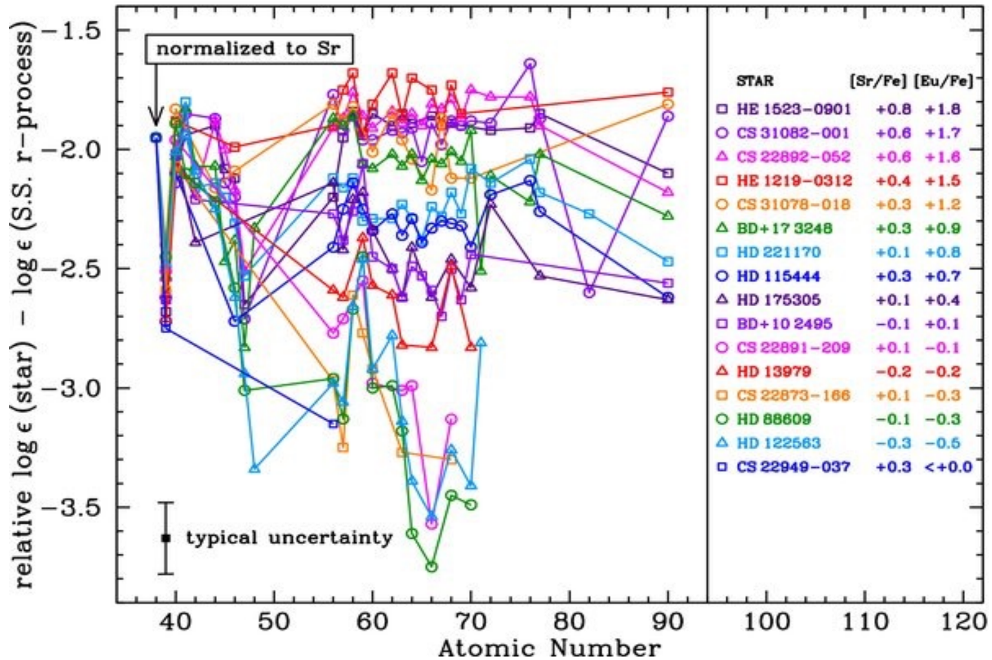
Differences between the SS r-process and stellar abundances in metal-poor stars

Honda et al (2007)



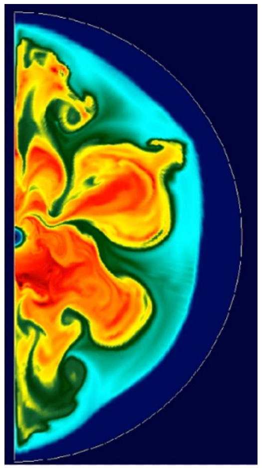
Continuous distribution of r-abundance patterns in metal poor stars falling between two extreme cases: CS22892-052 and HD88609/HD122563

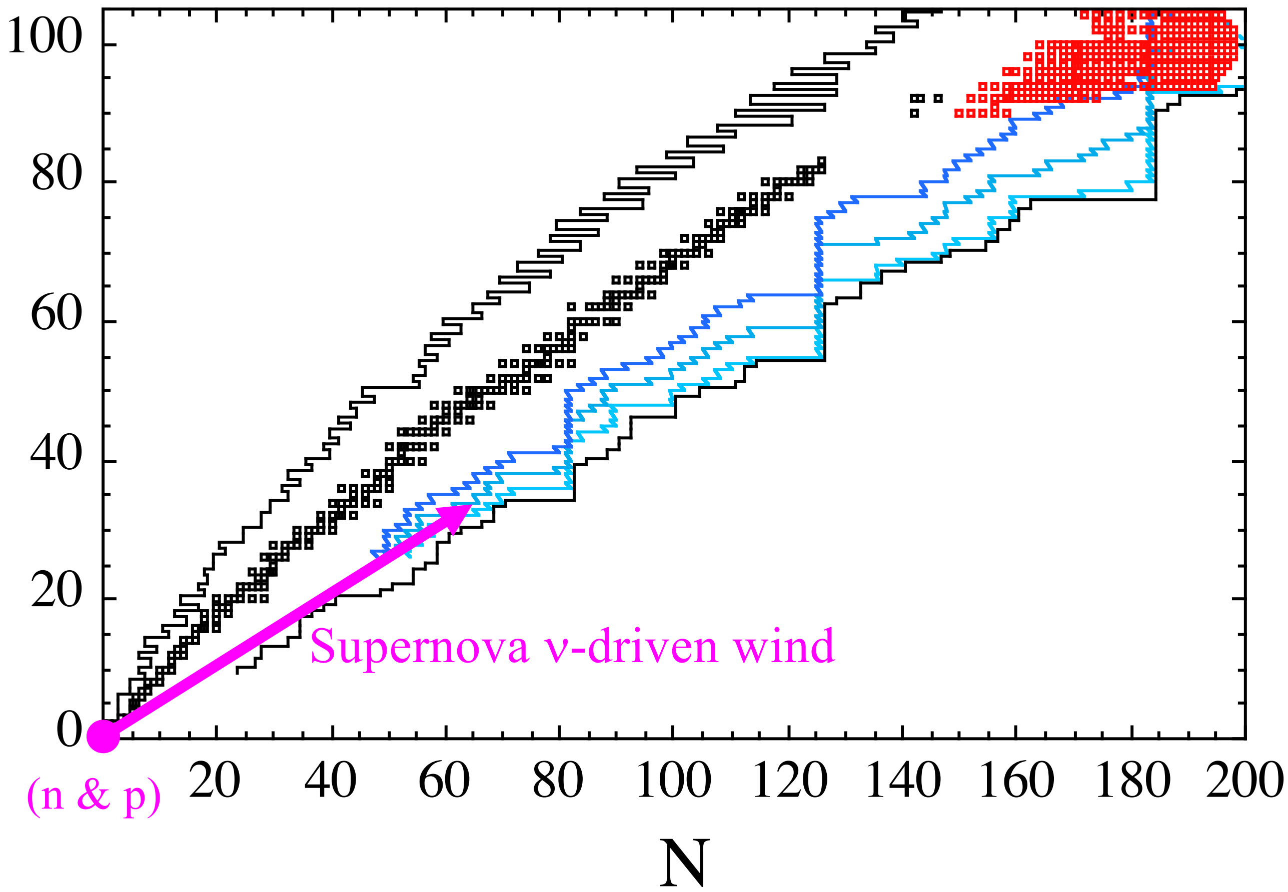
Roederer et al (2010)



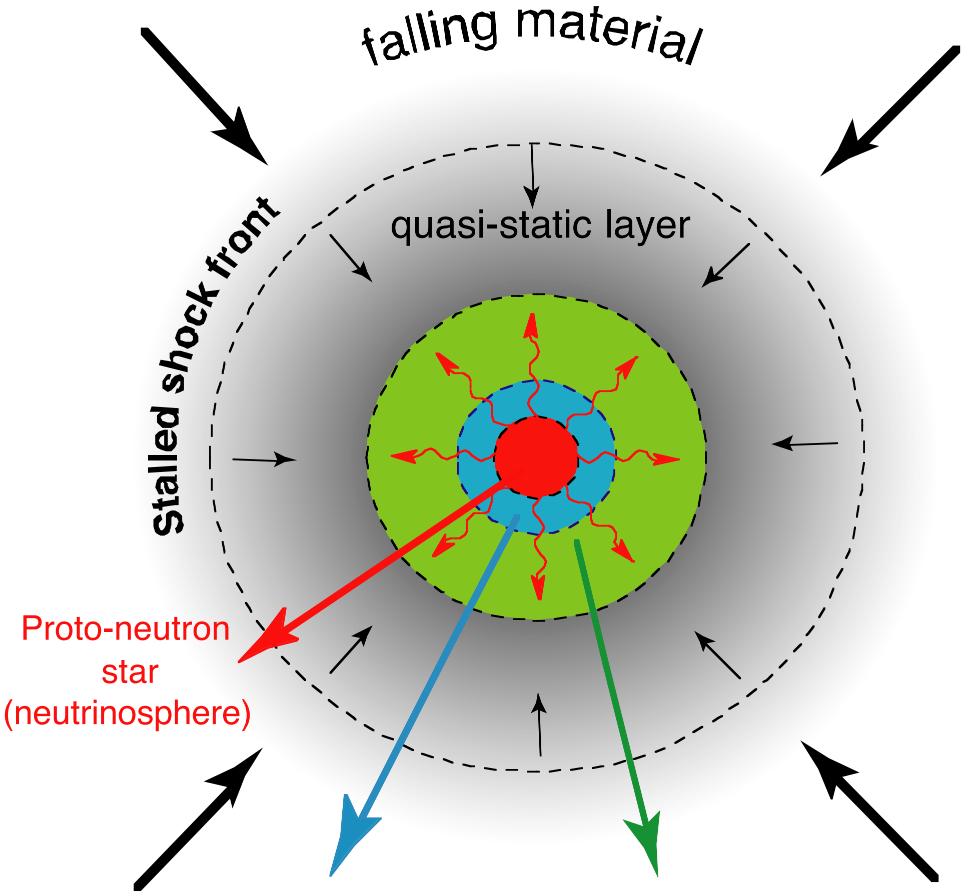
The *r*-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics





Nucleosynthesis in the ν-driven wind



Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6 \mathrm{g/cm}^3$

↓ NSE

^{4}He recombination

↓ $\alpha\alpha n$-^{9}Be(α,n)

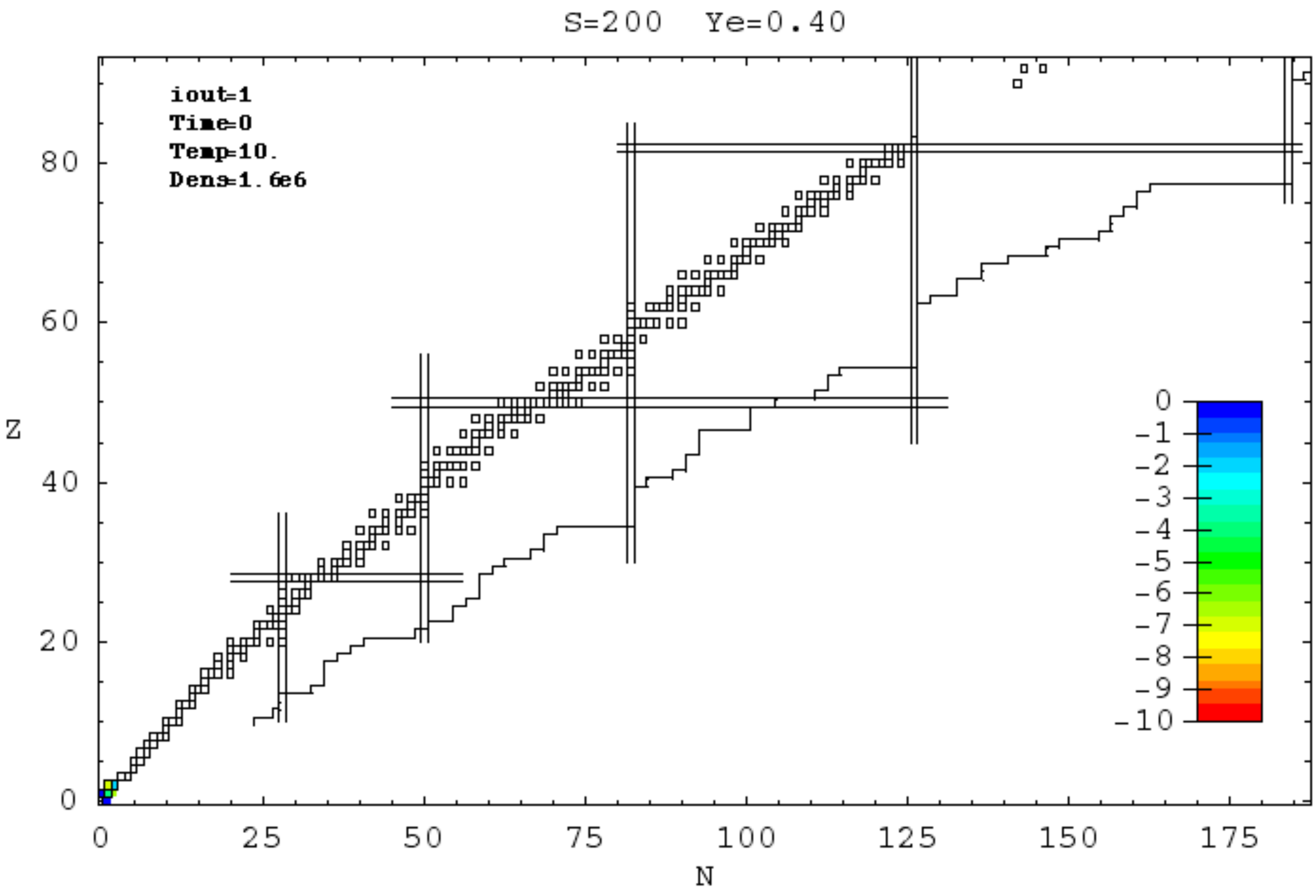
^{12}C bottleneck

↓ (α,γ) & (α,n)

$60 \leq A \leq 100$ seed

↓ (n,γ) & (γ,n) + β-decays

r-process


S=200 Ye=0.40
iout=1
Time=0
Temp=10.
Dens=1.6e6
Z
N
0
20
40
60
80
0
25
50
75
100
125
150
175
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

→ the r-process yields highly sensitive to

- the entropy $S \propto T^3 / \rho$
- the electron fraction $Y_e = Y_p/(Y_p + Y_n)$
- the expansion timescales τ_{dyn}

Typical conditions in the ν-driven wind

$$S \propto \frac{T^3}{\rho} \leq 100$$

$$Y_e = \frac{Y_p}{Y_p + Y_n} \simeq 0.47 - 0.6$$

$$\tau_{dyn} = 100\text{ms}$$

No r-process in realistic hydrodynamical simulations:

Conditions for a successful r-process (high N_n/N_{seed})

- High entropy wind (high-T, low-ρ) → Increase S — $S \sim 500$
- Low-Y_e wind (n-rich matter) → Lower Y_e — $Y_e \sim 0.3$
- Fast expanding wind → Lower τ_{dyn} — $\tau_{dyn} \sim 10\text{ms}$

The important role of the electron fraction

$$Y_e = \frac{Y_p}{Y_p + Y_n}$$

pure neutron matter	→ Y_e=0
NS inner crust	→ Y_e~0.05 – 0.10
Symmetric matter (Z=N)	→ Y_e = 0.5
Core-Collapse supernova	→ $0.47 \leq Y_e \leq 0.6$?

In hot & dense environment, Y_e is modified by charged-current ν-interactions

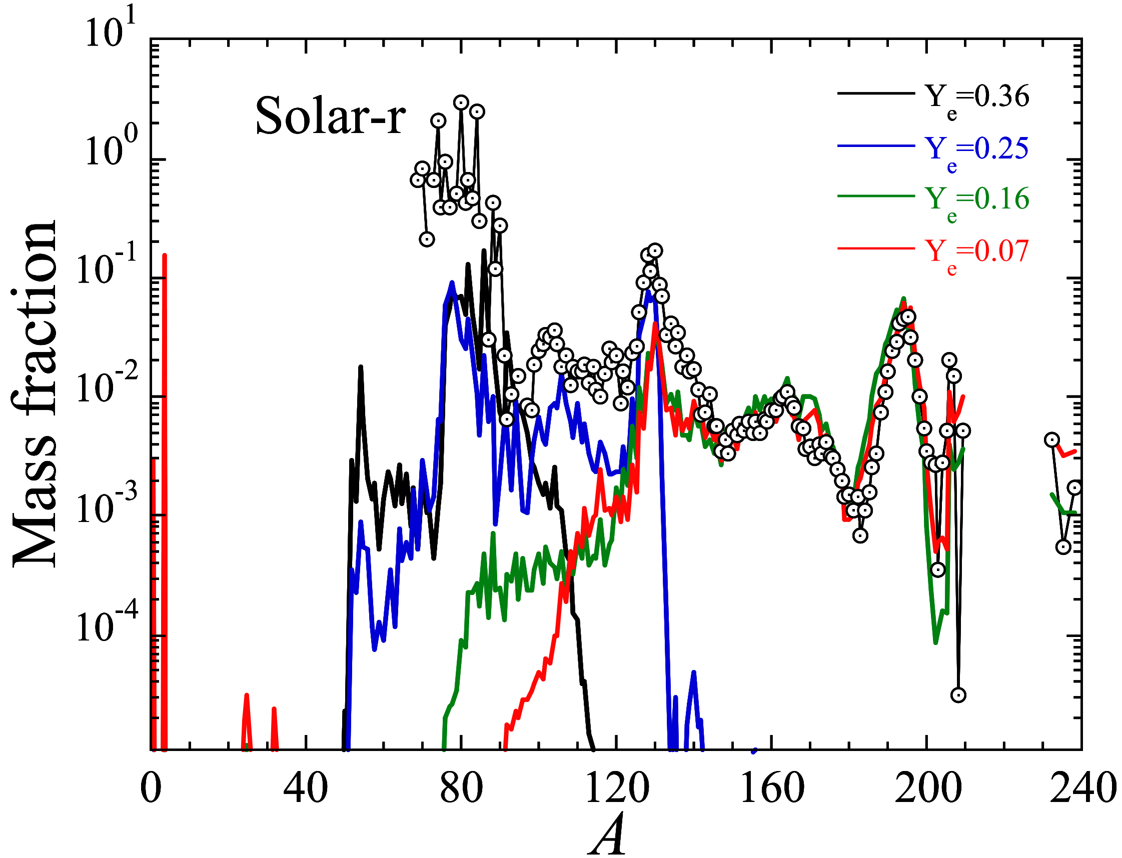
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

both ν-emission and ν-absorption need to be included

Extreme complexities of 3D energy-dependent neutrino transport in relativistic environments, with the neutrino opacities of dense, potentially highly magnetized matter and with neutrino-flavour oscillations at rapidly time-variable, largely aspherical conditions of neutrino emission

→ Many approximation used (often neglecting ν-absorption)

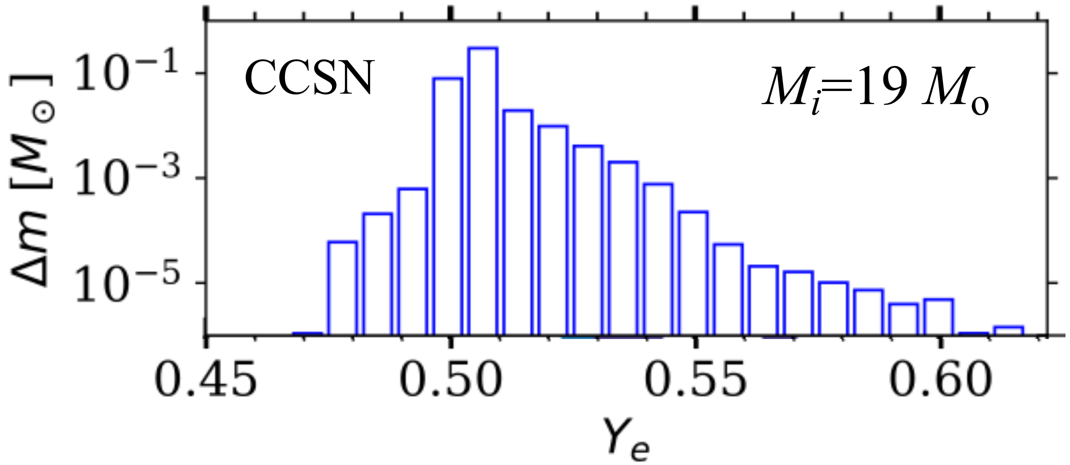
The important role of the electron fraction



The smaller the Y_e,
→ the more free neutrons
→ the stronger the r-process
(Only $Y_e \lesssim 0.15$ trajectories produce actinides)

But in a given site, there is a full distribution of initial Y_e

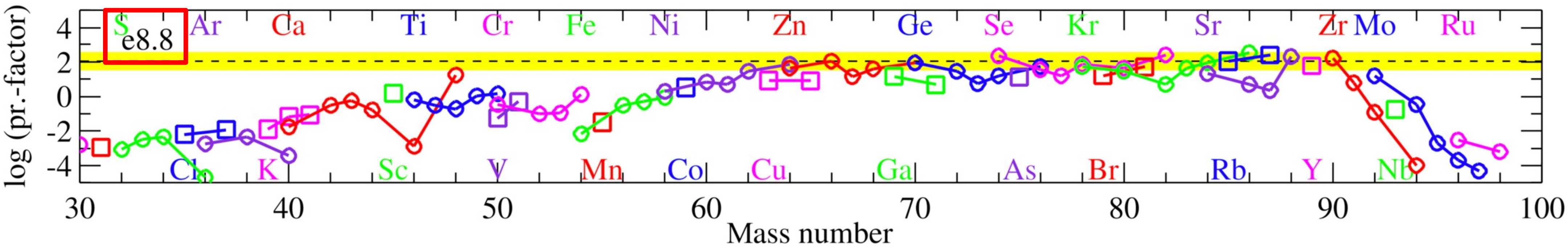
- sensitive to ν-interaction
- sensitive to EoS



Self-consistent 2D hydrodynamical (successful) explosions

Wanajo, Müller, Janka, Heger, 2018
Wang & Burrows, 2023

- Electron-Capture Supernova ($M_i \sim 8.8 M_o$) → production of n-rich up to ~Zr



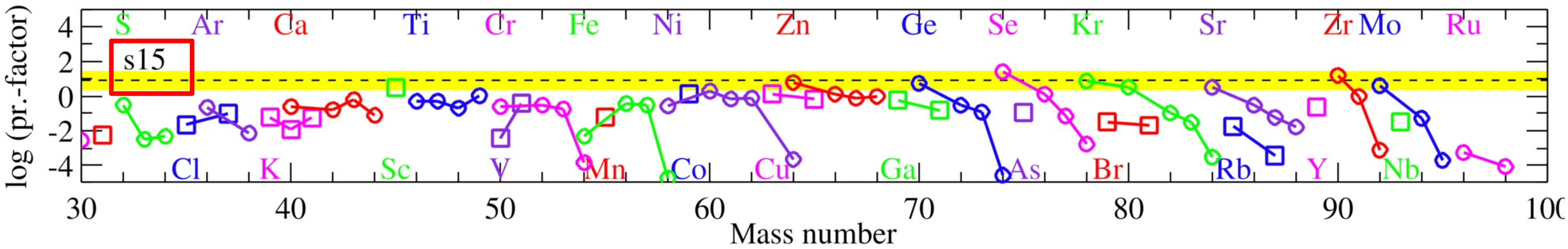
$8.5 \lesssim M \lesssim 10\ M_o$

→ fast shock expansion
→ Y_e remains low ($Y_e > 0.4$)
→ an α-rich freeze out from NSE (not n-cap process !)
→ possible production up to ~ Zr
→ contribution to the Galactic enrichment ?

Self-consistent 2D hydrodynamical (successful) explosions

Wanajo, Müller, Janka, Heger, 2018
Wang & Burrows, 2023

- Core-Collapse Supernovae (M_i = 11-15-27M_o) → production of p-rich up to ~Mo



M ≳ 10 M_o → slow shock expansion
→ effective neutrino interactions → $Y_e \gtrsim 0.5$
→ production of p-isotopes
→ contribution to the Galactic enrichment ?

2D/3D MHD jet-like explosion of rapidly rotating magnetically driven core-collapse supernovae

(Winteler et al. 2012; Mösta et al. 2014; Nishimura et al. 2015)

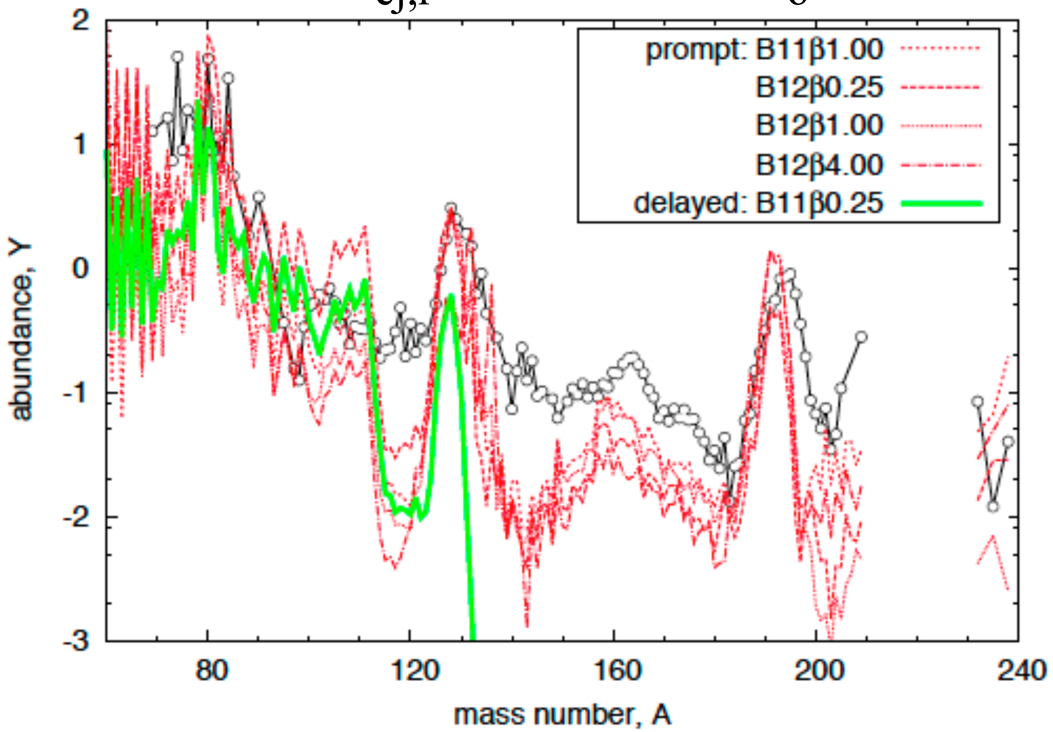
Pre-collapse core "assumed" to have **strong** initial magnetic fields and rapid rotation → highly magnetized NS with $B \sim 10^{15}$G

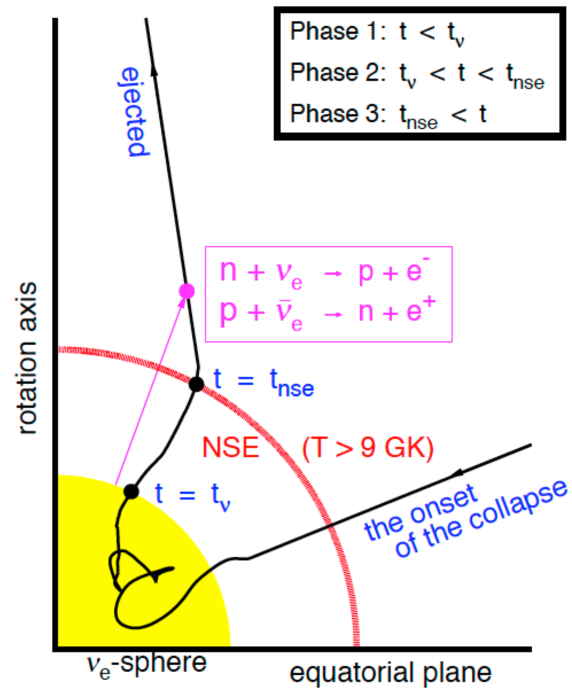
Rare events $P \sim 0.01–0.1\%$ of all SNe

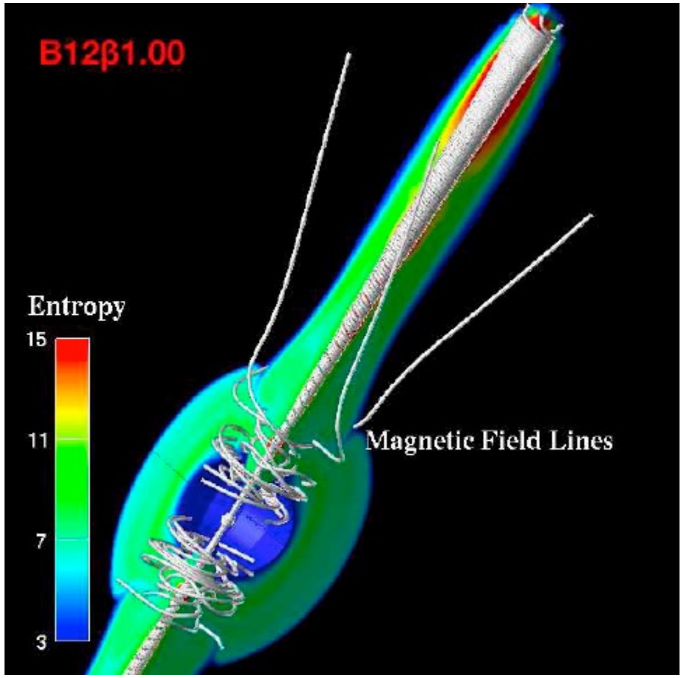
$B_0 = 10^{11}$ G → Synthesis up to $A \sim 130$

$B_0 = 10^{12}$ G → Synthesis up to Th/U

$M_{ej,r} \sim 1\text{-}2\ 10^{-2}\ M_o$





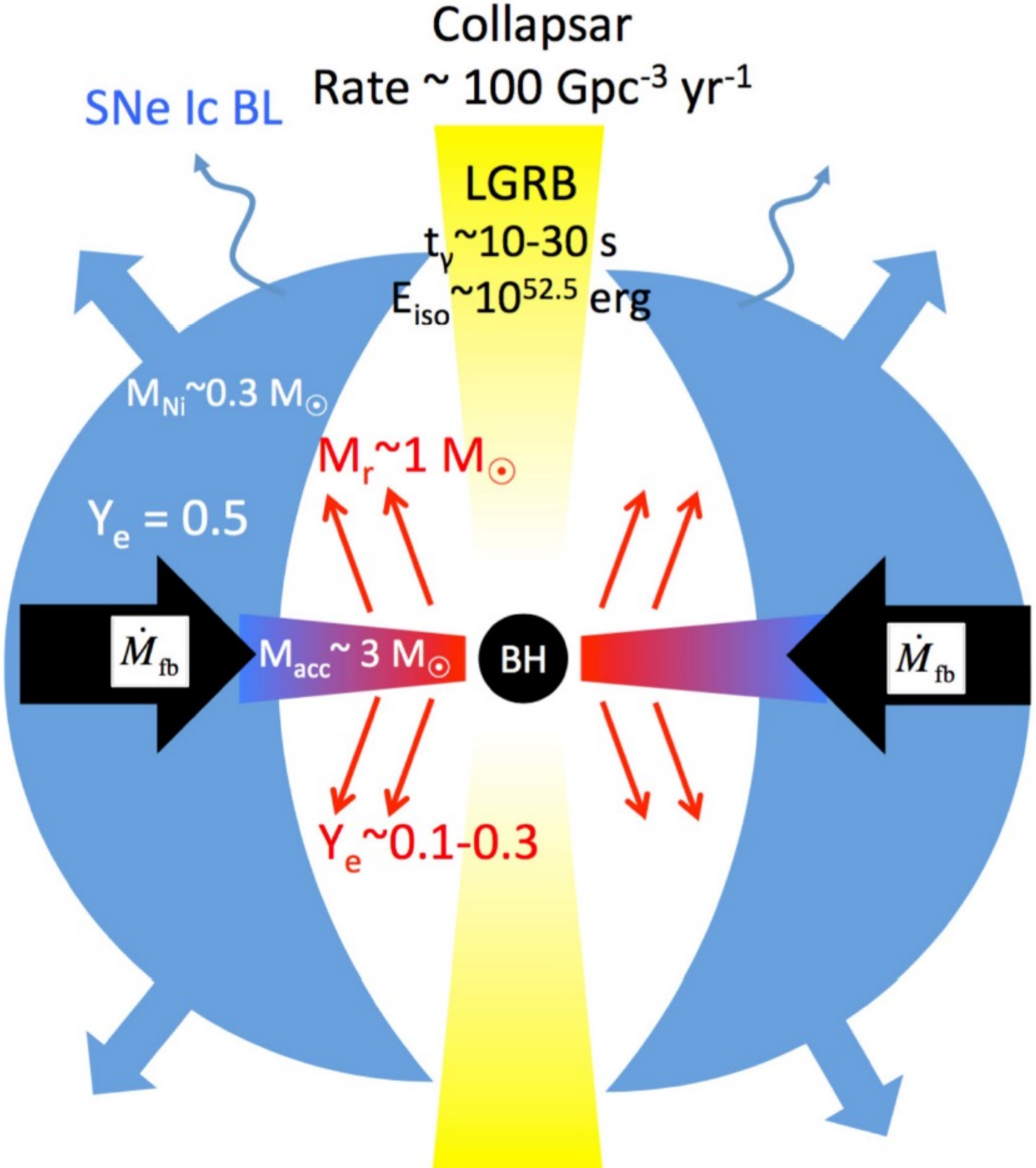


Collapsar = Collapse of rapidly rotating massive stars ($M > 20 M_\odot$)

- Failed explosion with direct collapse to a BH
- Weak explosion with the proto-NS collapsing due to fallback material

Rapid rotation of the infalling material leading to the formation of a massive accretion disk around the BH

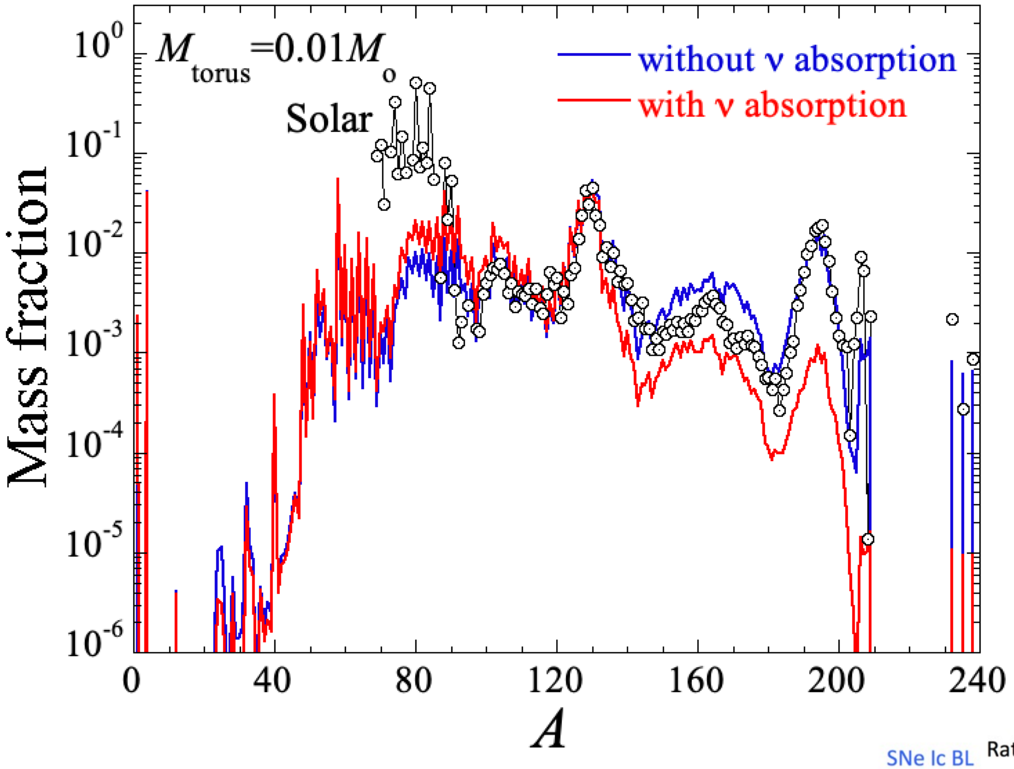
Generation of long GRB & SN Ic

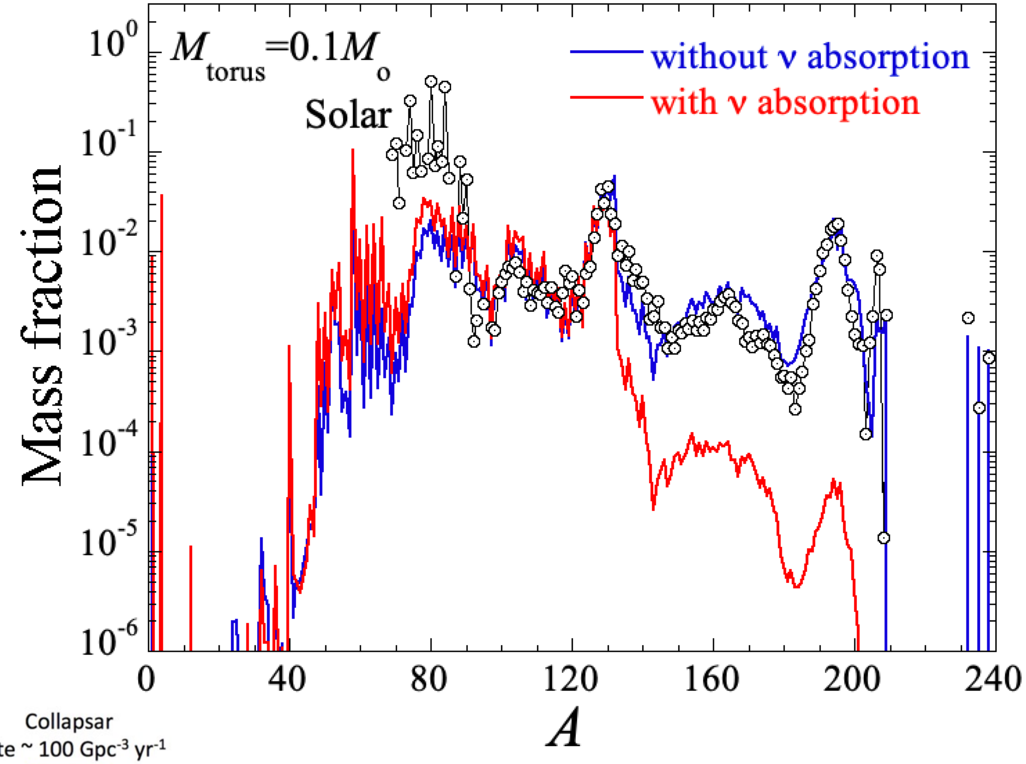


Long γ-ray bursts

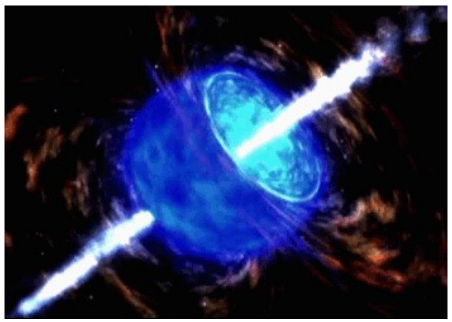
Siegel et al. (2019)

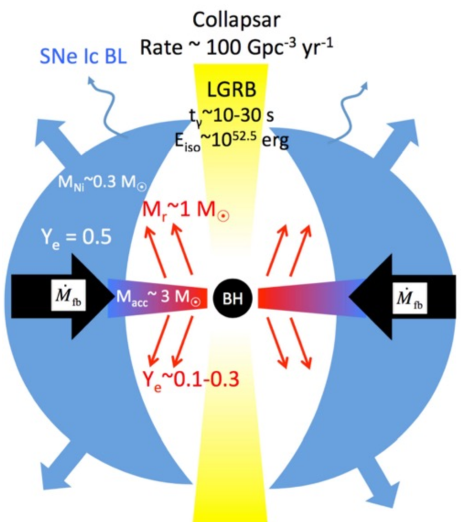
Impact of ν-absorption on the composition of matter ejected from ν-cooled BH accretion disks





Just et al. (2021)





Conclusions for Core-Collapse Supernovae:

- no ab-initio conditions from state-of-the-art SN models for a successfull efficient r-process
- (Y_e, S, τ_{exp}) conditions lead at most to the Zr production
- More hope in collapsars ? Still unclear due to uncertainties affecting ν-interactions
- No observation of r-element tracers in exploding SNe
  (in particular, the brightest GRB221009A, Blanchart et al. 2024)

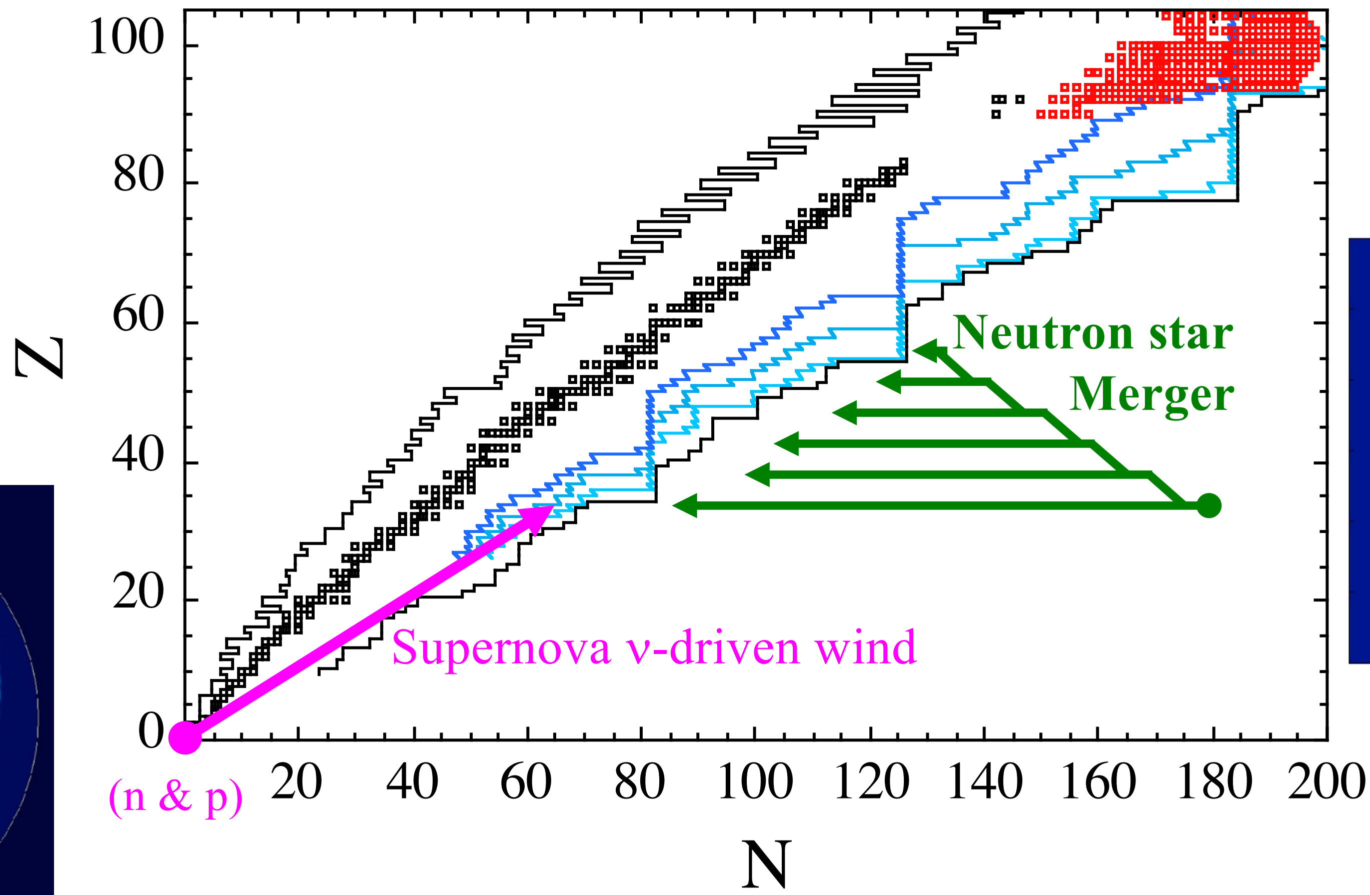
→ role of fission in CCSN cannot be easily assessed
(parametric approach, most probably unrealistic)

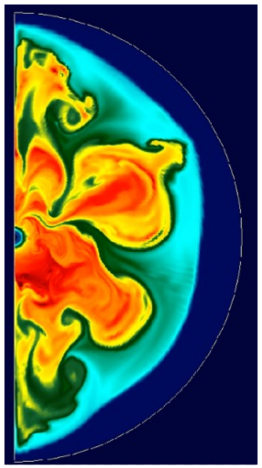
→ requires more hydrodynamical studies

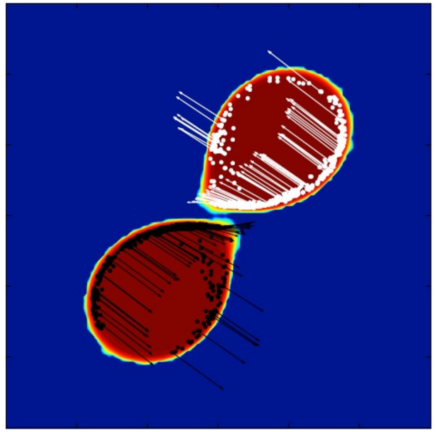
→ maybe CCSN will turn out to be a major r-process site !!

The *r*-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

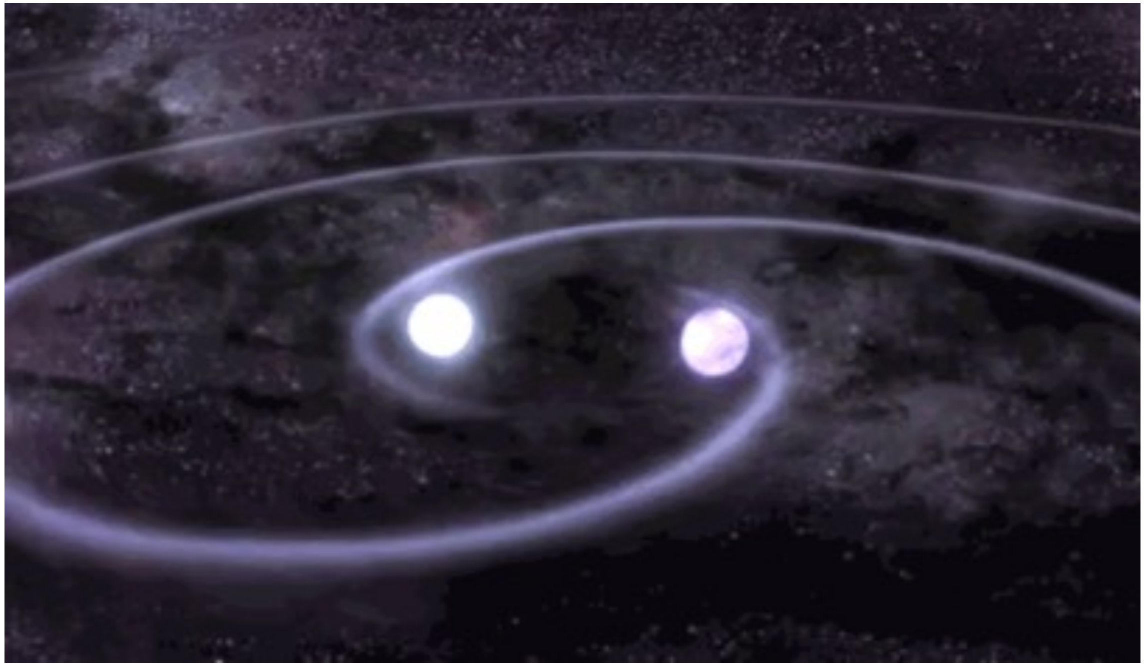
one of the still unsolved puzzles in nuclear astrophysics





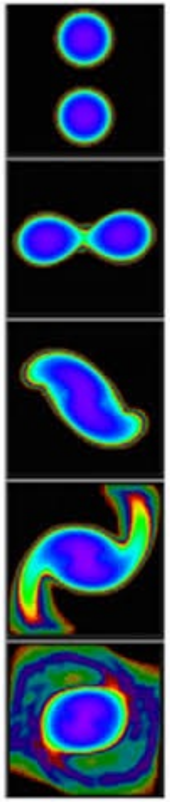


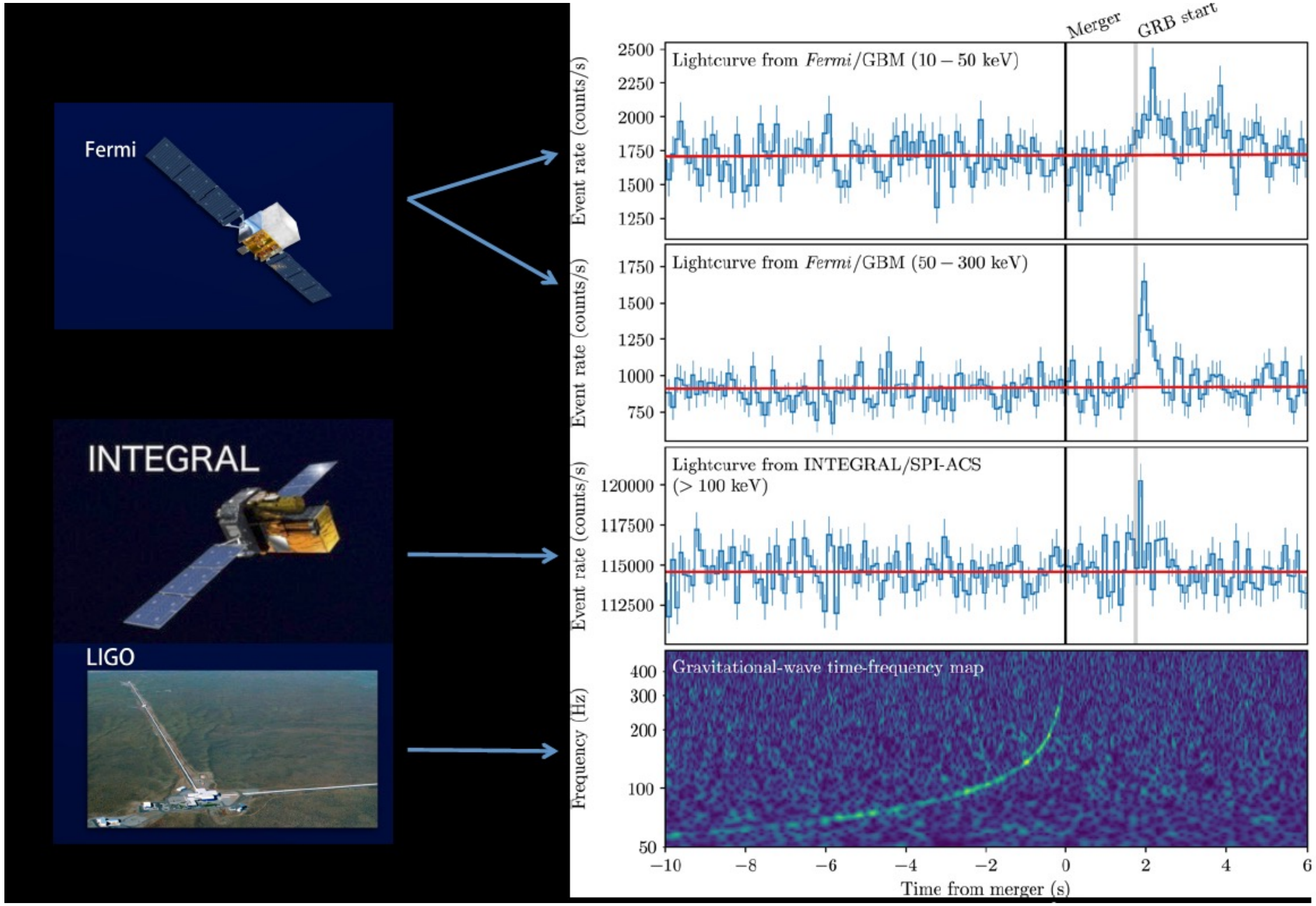
New observational insight thanks to the detection of GW170817 binary NS merger and its optical counterpart AT2017gfo



On August 17, 2017

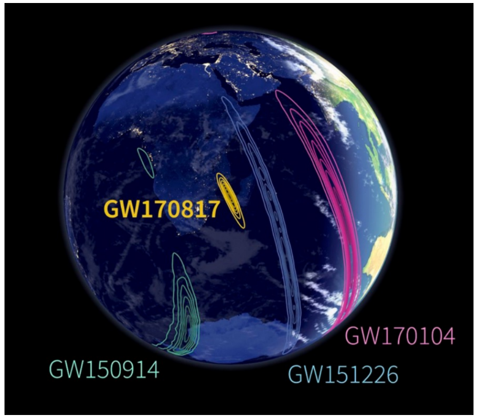
First detection of binary NS merger

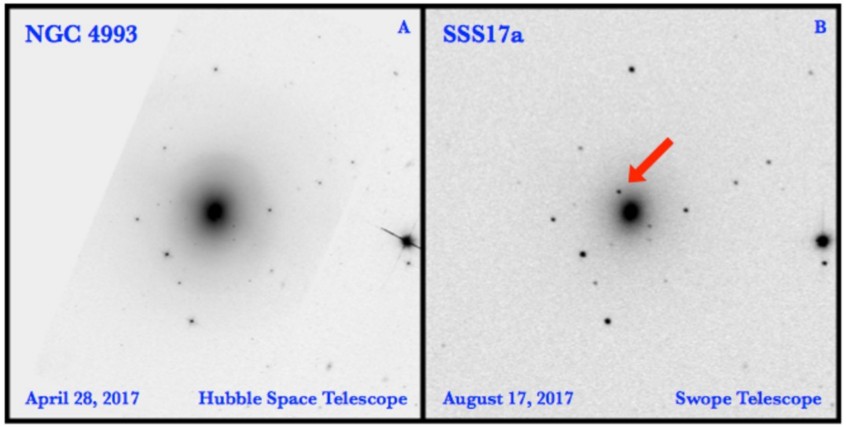




11h after

OPTICAL



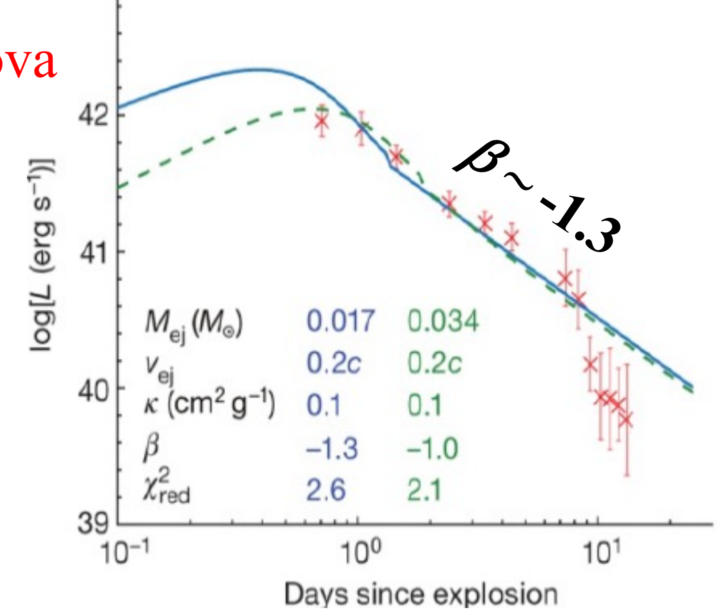


The analysis of the GW170817 light curve

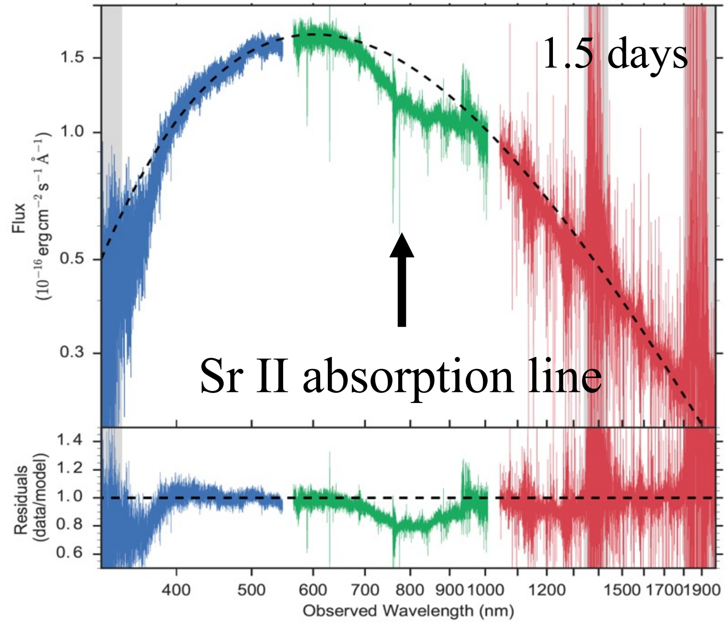
- The kilonova light curve is compatible with an ejecta mass ($M_{ej} \approx$ 0.03-0.06 $M_\odot$)
  - "Blue" A<140 component with $M_{ej} \approx$ 0.01-0.02 $M_\odot$ and $v_{ej} \approx 0.26c$
  - "Red" A>140 component with $M_{ej} \approx$ 0.02-0.05 $M_\odot$ and $v_{ej} \approx 0.15c$

Kilonova

Photometric observations

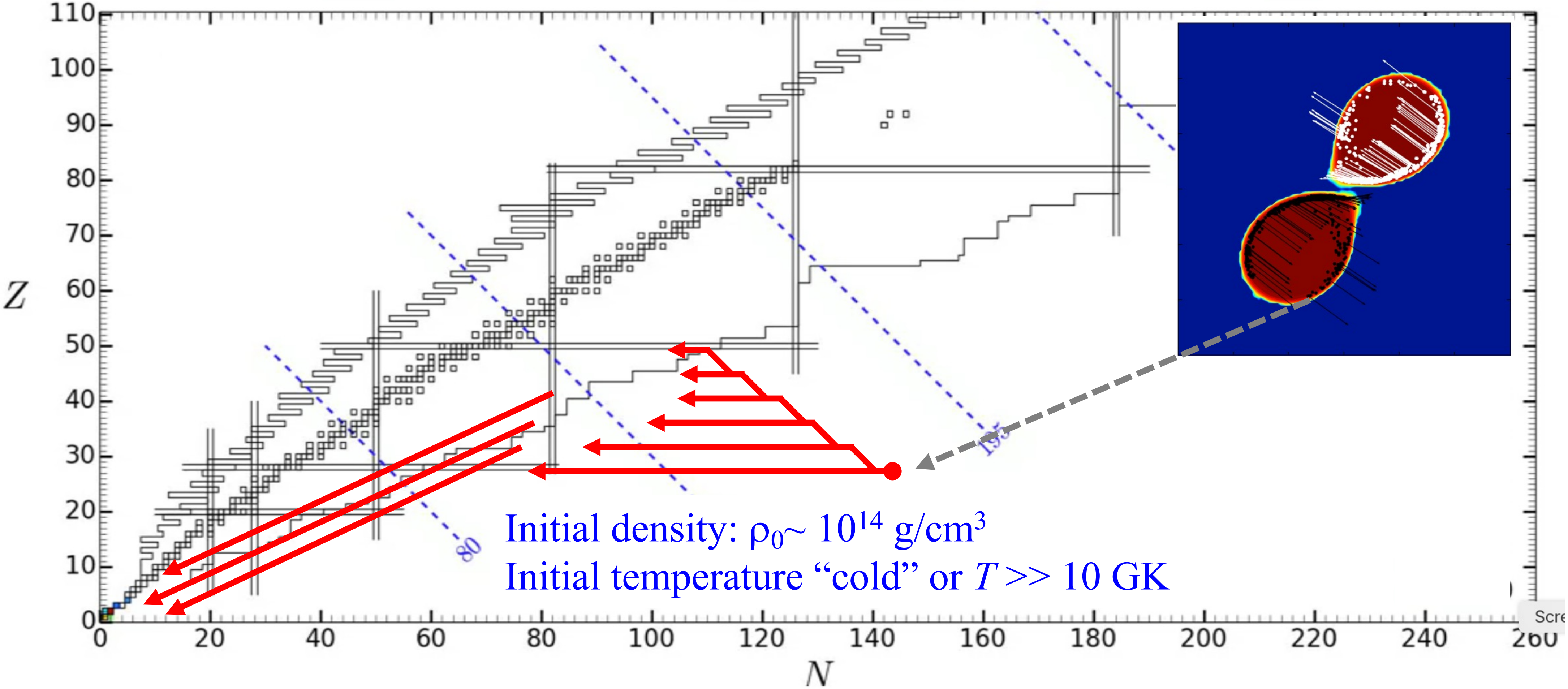


Spectroscopic observations

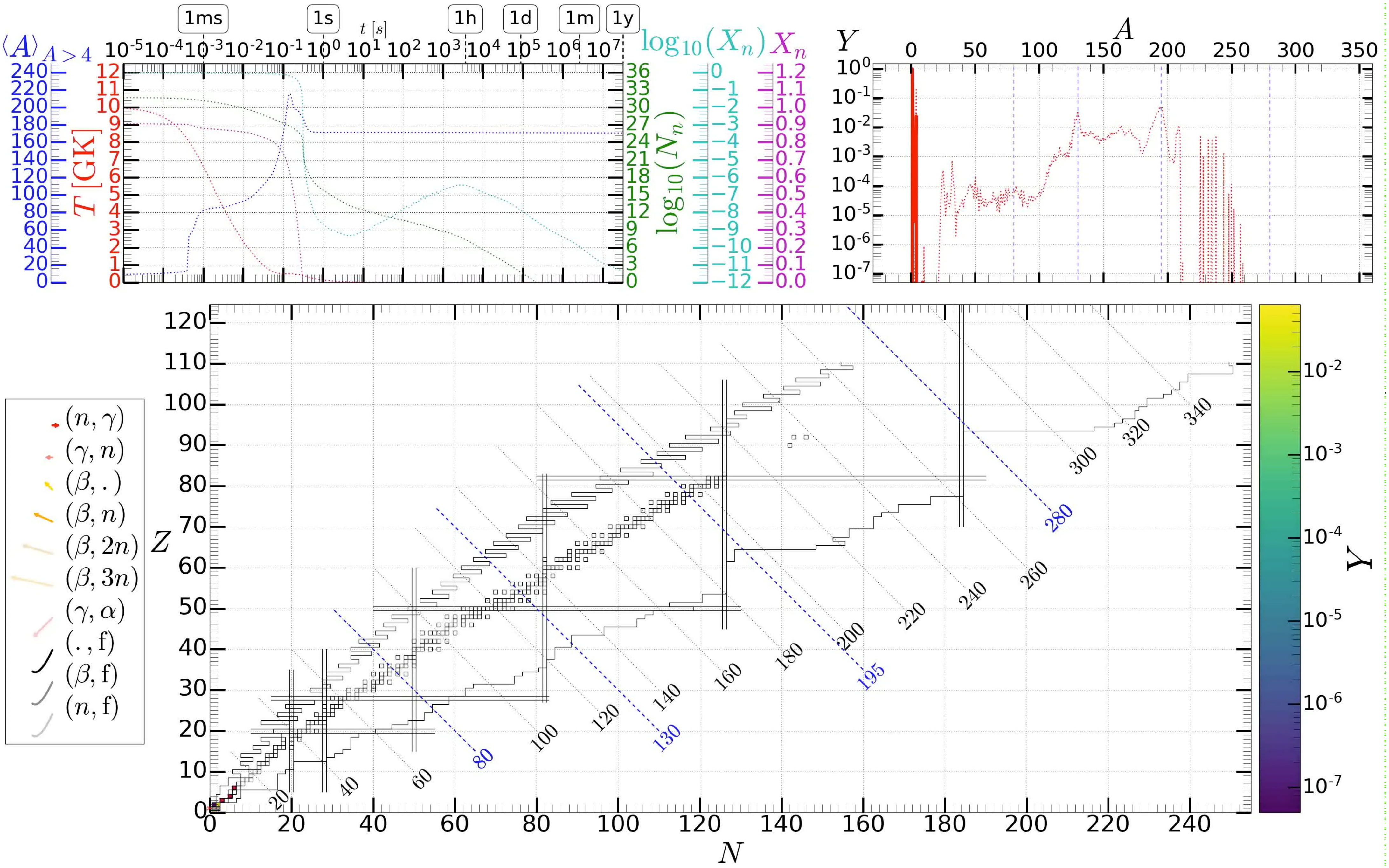


Watson et al. (2019)

- The ejected mass and new merger rate inferred from GW170817 imply that NS mergers are a dominant source of r-process production in the Universe.

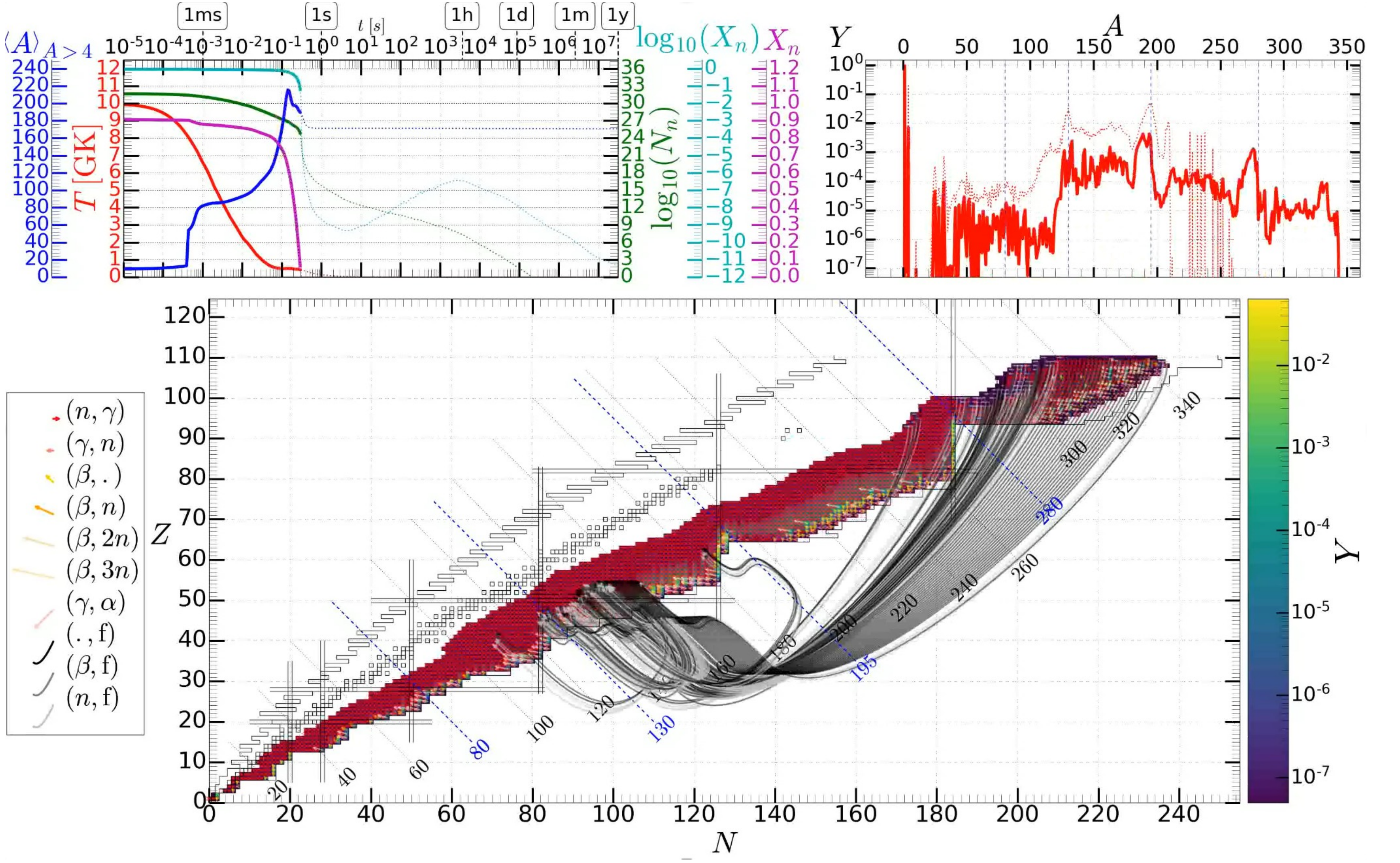


Z
N
80
135
Initial density: $\rho_0 \sim 10^{14}$ g/cm^3
Initial temperature "cold" or $T >> 10$ GK



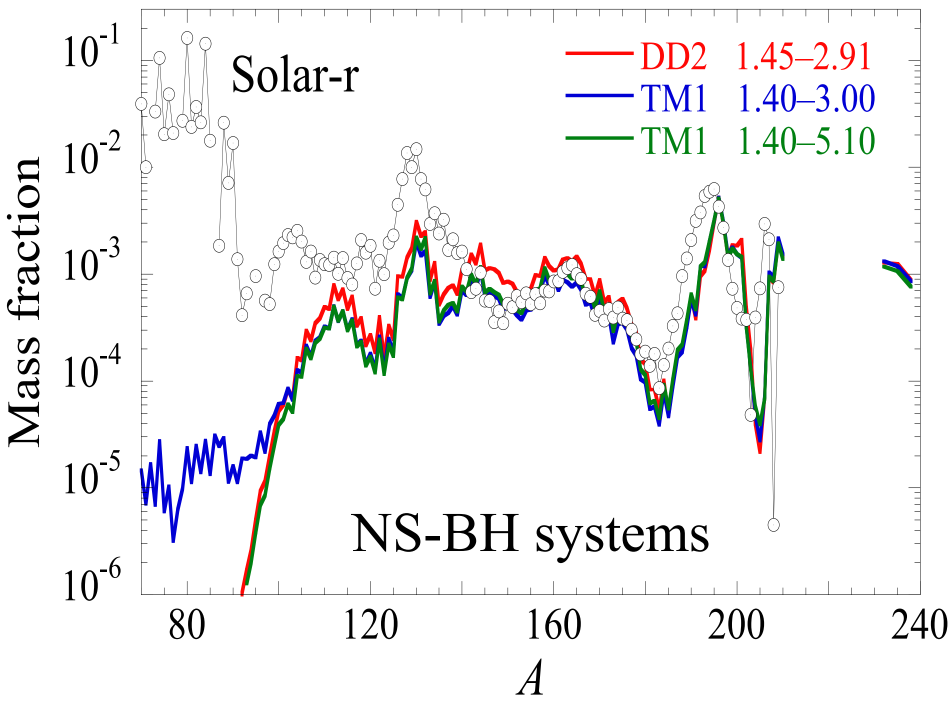
1ms
1s
1h
1d
1m
1y
t [s]
⟨A⟩ A > 4
T [GK]
log10(N_n)
log10(X_n)
X_n
Y
A
Z
N
(n, γ)
(γ, n)
(β, .)
(β, n)
(β, 2n)
(β, 3n)
(γ, α)
(., f)
(β, f)
(n, f)

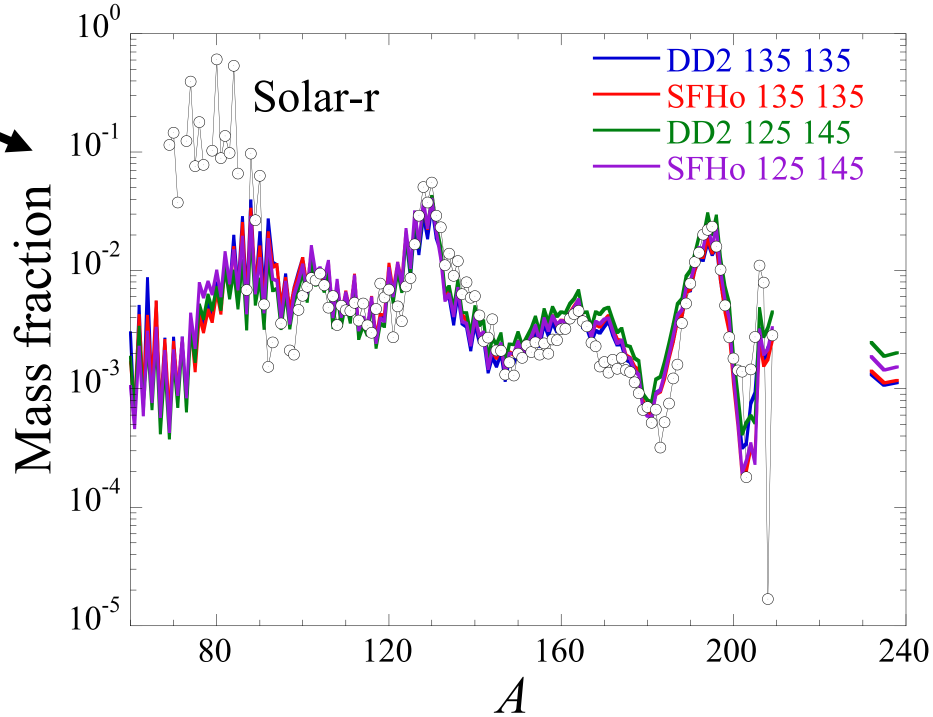
After a few hundred ms...



Dynamical ejecta: very much dependent on the impact of neutrinos

- a delayed collapse of NS-NS
- a NS-BH system



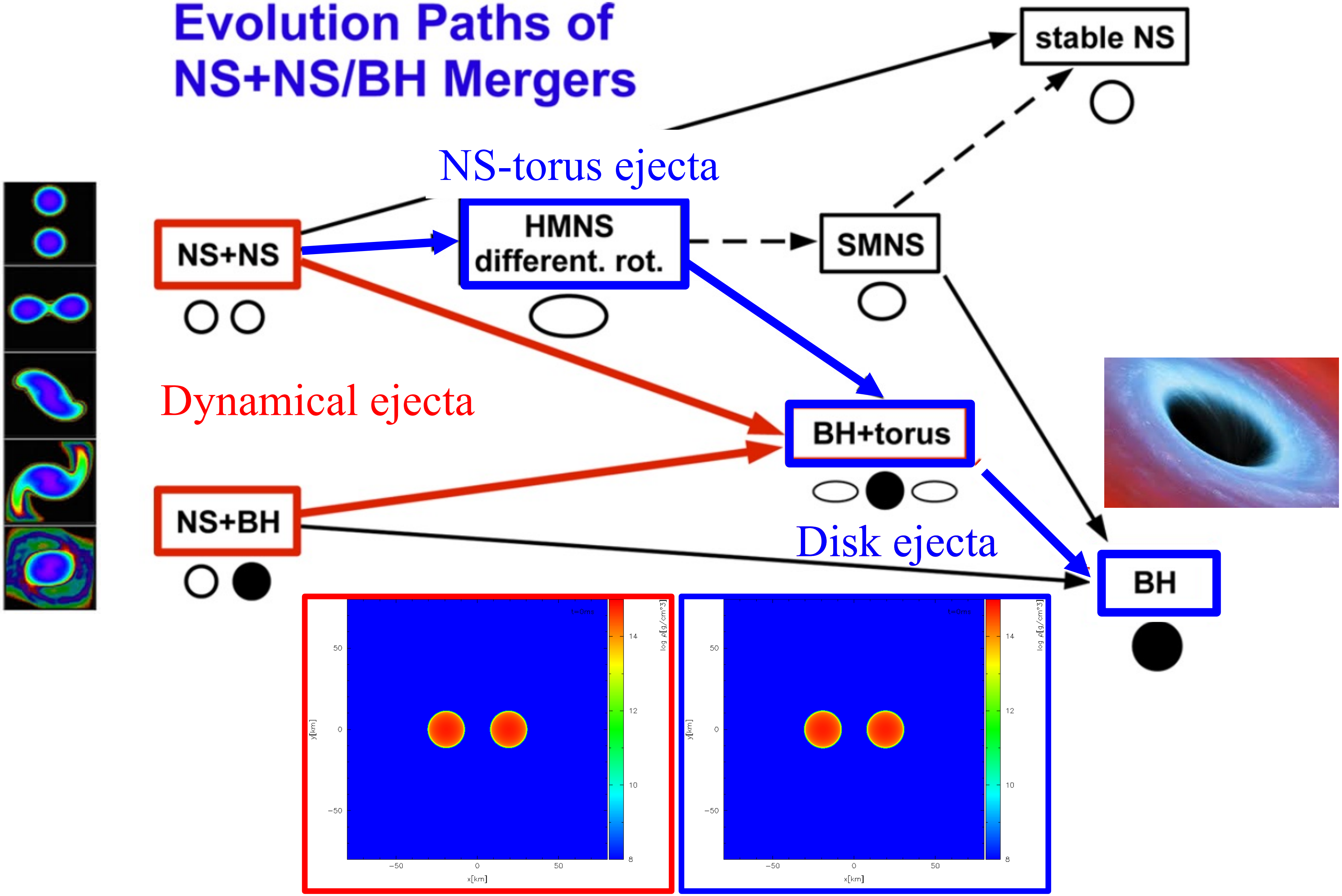


Major impact of ν-interactions

$$\nu_e + n \rightleftharpoons p + e^-$$

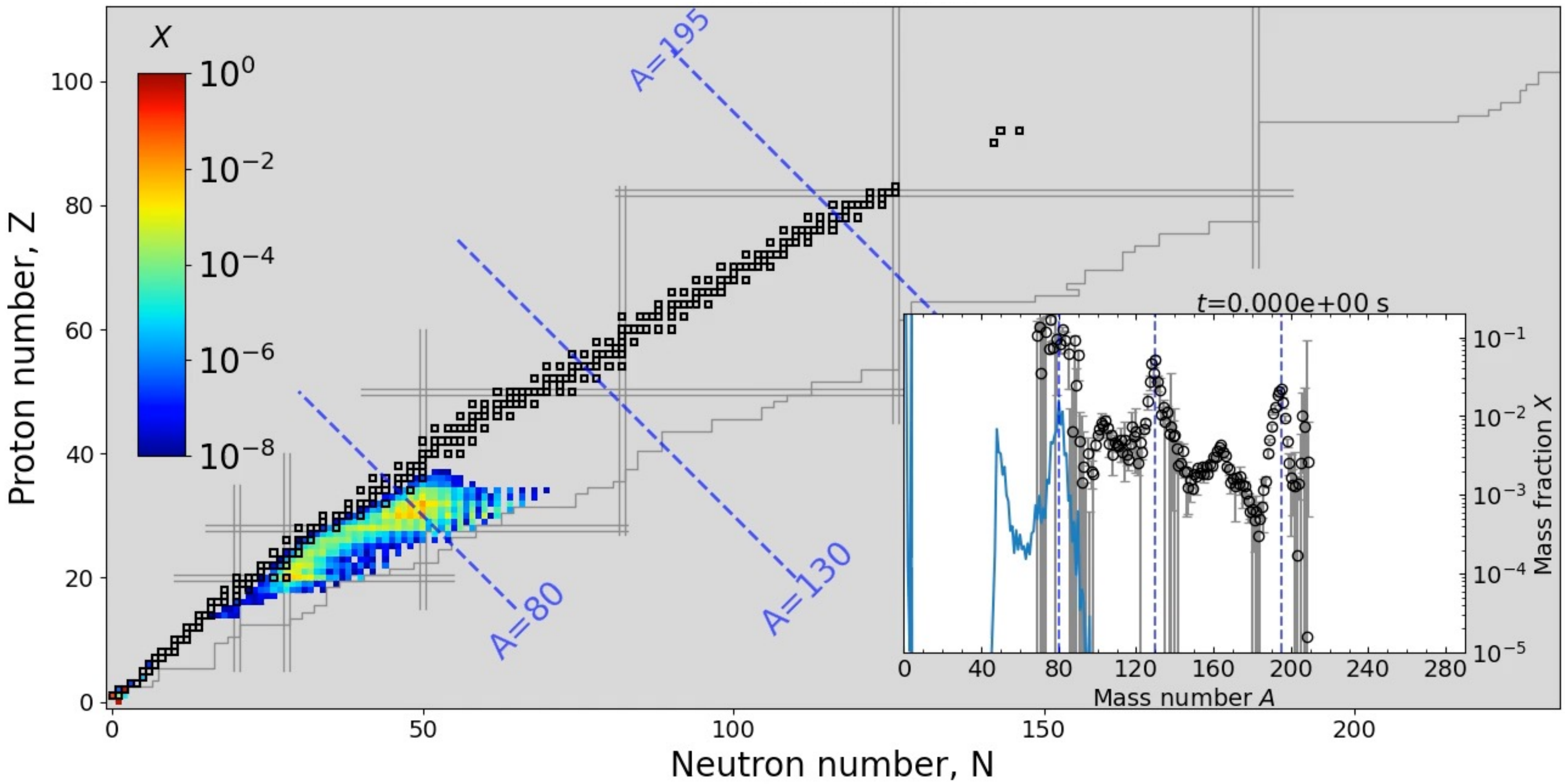
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

Evolution Paths of NS+NS/BH Mergers

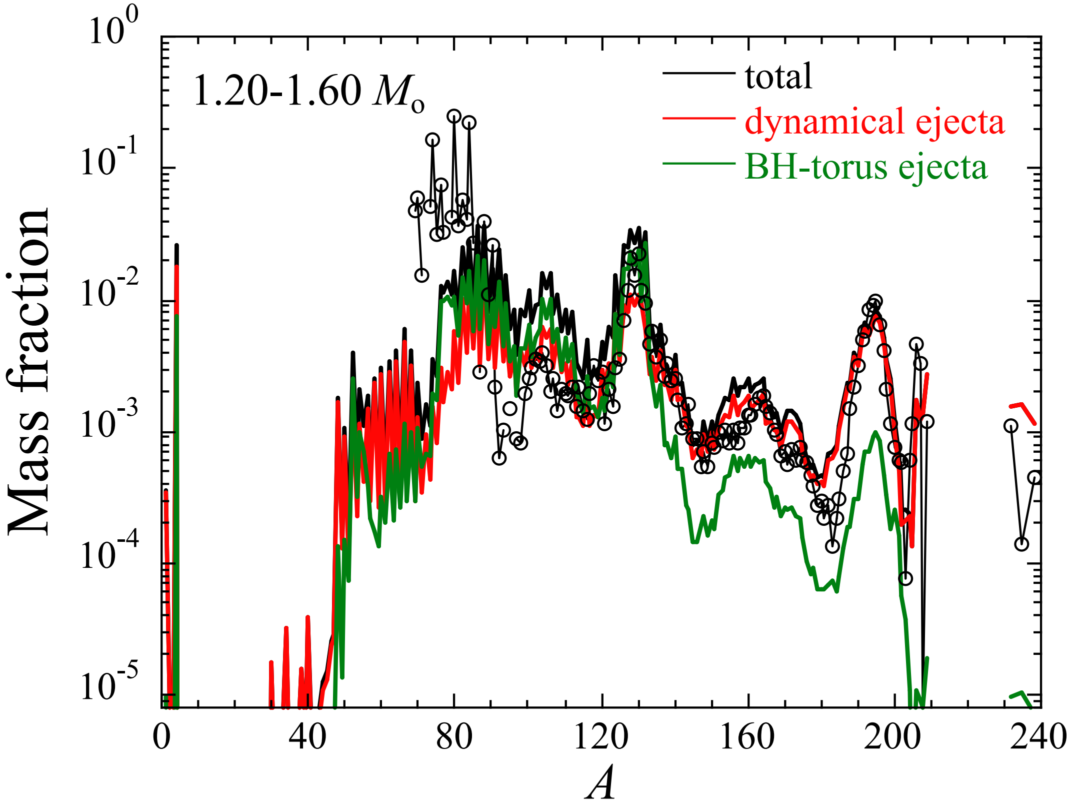


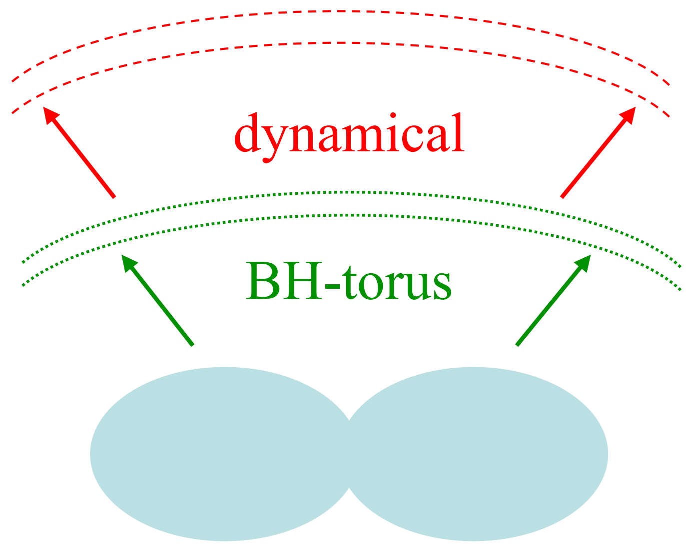
Each of these phases (Dyn, NS-torus, BH-torus) is accompanied with mass ejection

Time evolution of the composition of matter ejected from a 1.20 – 1.60M_o NSM (7234 trajectories from dynamical + BH-Torus winds – Just et al. 2023)



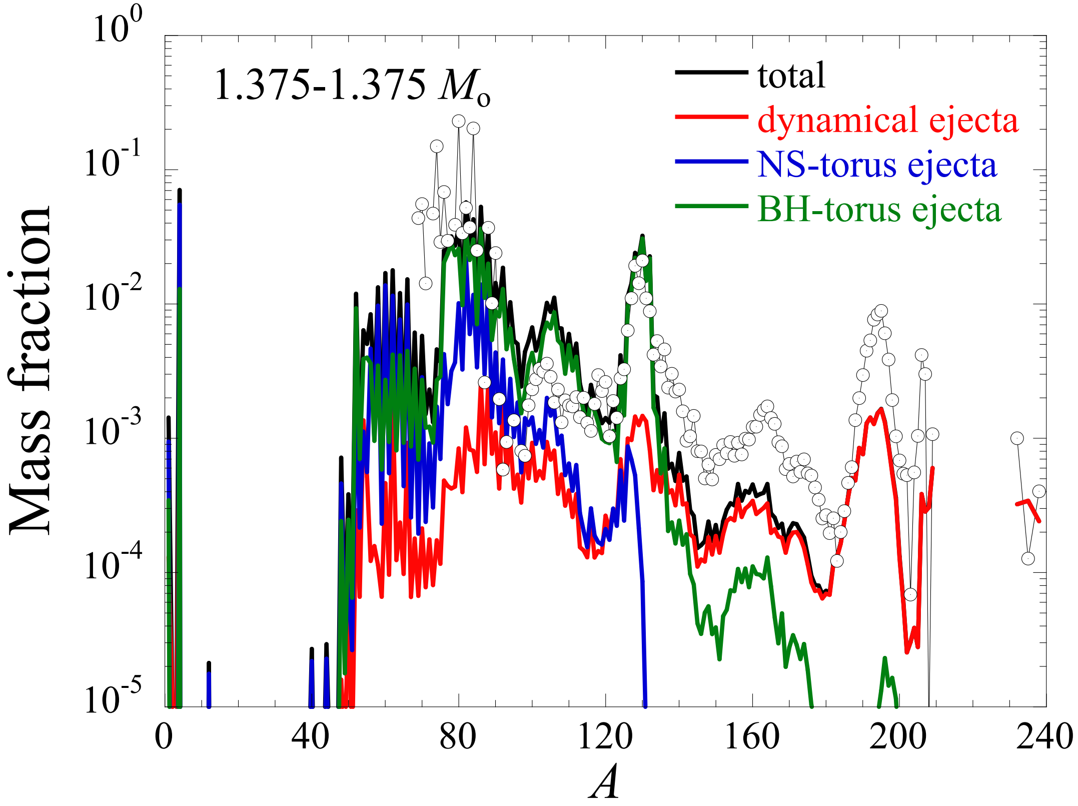
Properties of the ejecta for a prompt collapse

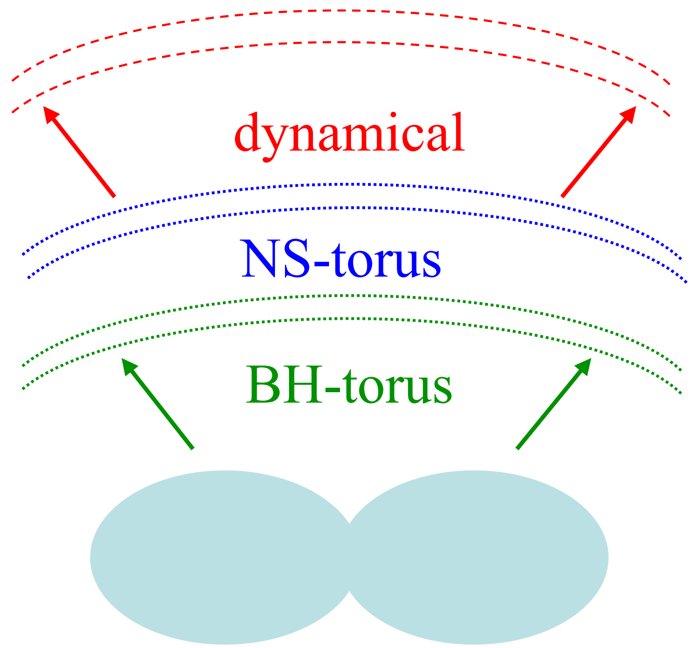




	total	dynamical	NS-torus	BH-torus
M_{ej} [M_o]	0.024	0.012	0.0	0.012
$<Y_e>$	0.27	0.26	0.0	0.28
v_{ej} [c]	0.14	0.24	0.0	0.05

Properties of the ejecta for a delayed collapse (symmetric system)

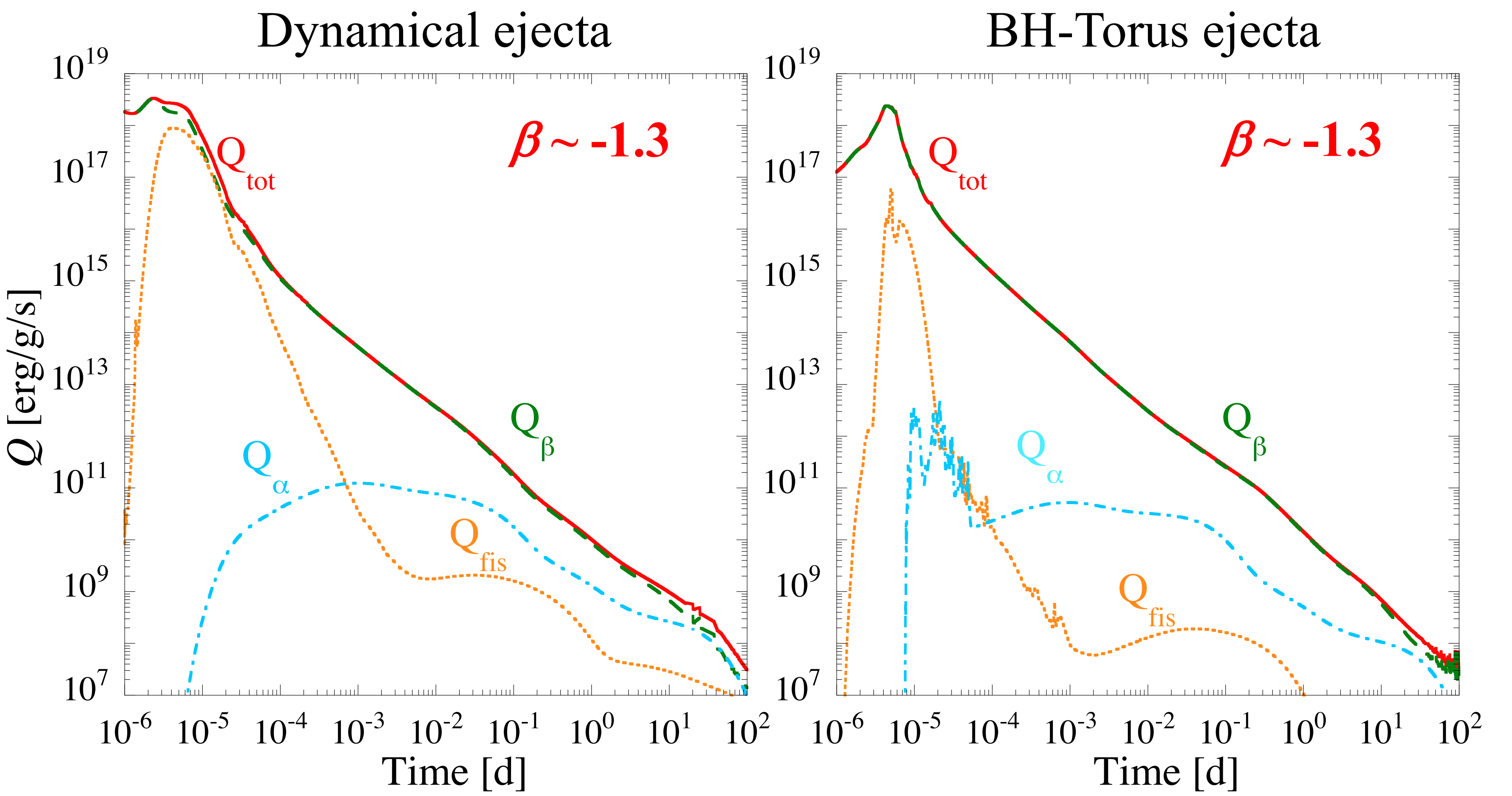




	total	dynamical	NS-torus	BH-torus
M_{ej} [M_o]	0.073	0.006	0.020	**0.047**
$<Y_e>$	0.33	0.24	0.41	0.30
v_{ej} [c]	0.11	**0.22**	0.18	0.06

Total radioactive heating rate of the resulting Kilonova at late times

$$Q_{tot}=Q_{\beta}+Q_{fis}+Q_{\alpha}$$

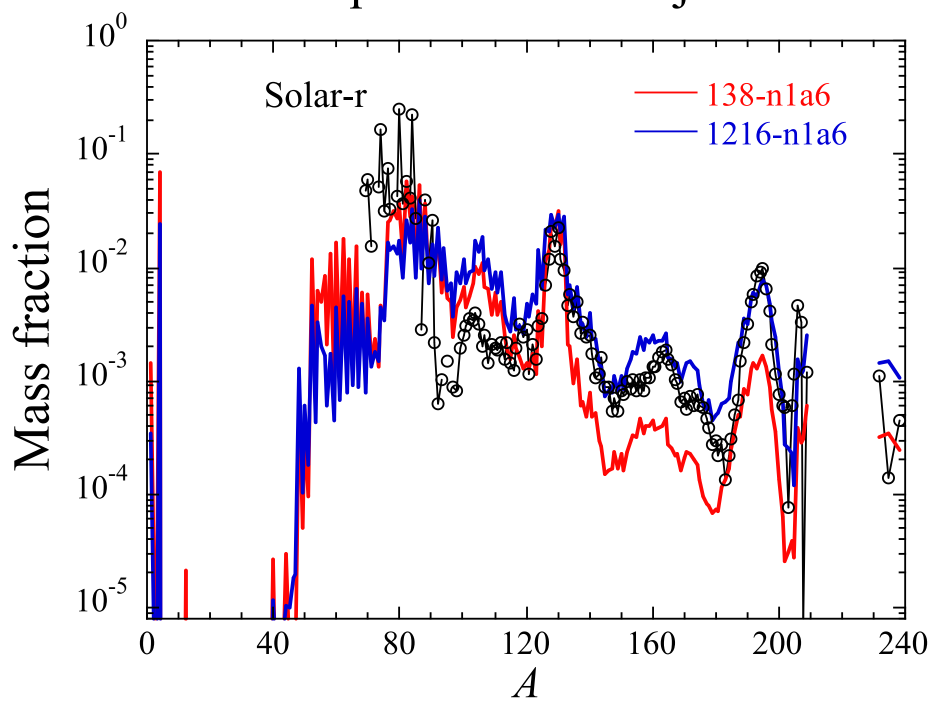


End-to-End Hydrodynamical Simulations from Just et al. (2023)

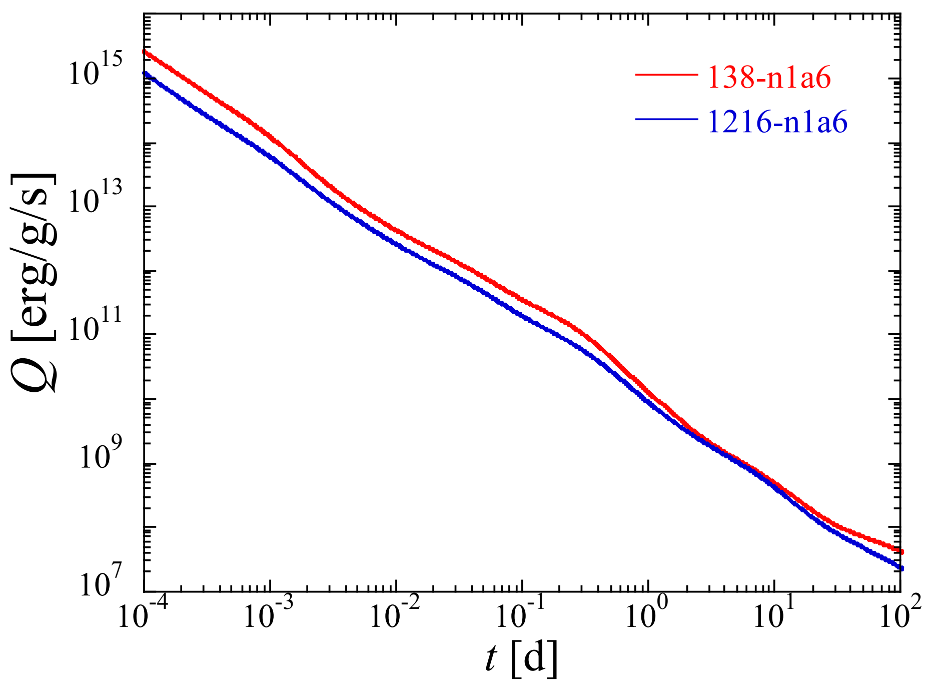
Delayed collapse: 1.375 – 1.375 M_o

Prompt collapse: 1.20 – 1.60 M_o

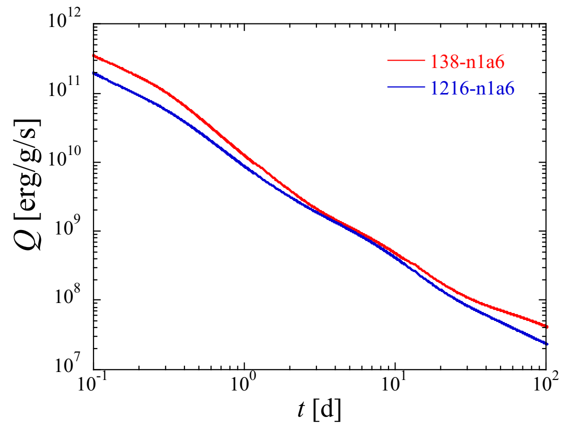
Composition of the ejecta



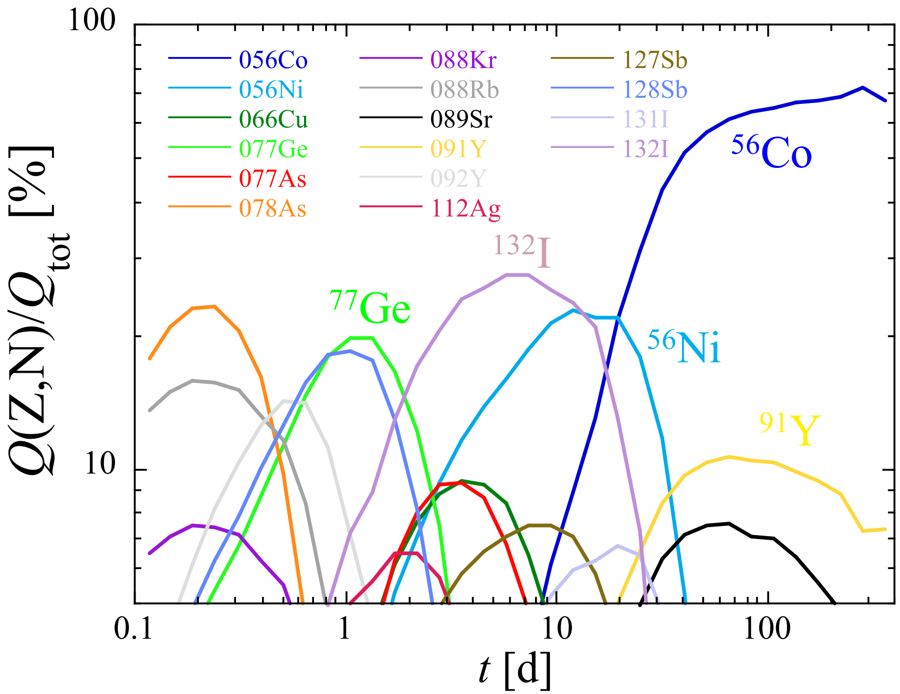
Radioactive decay heat



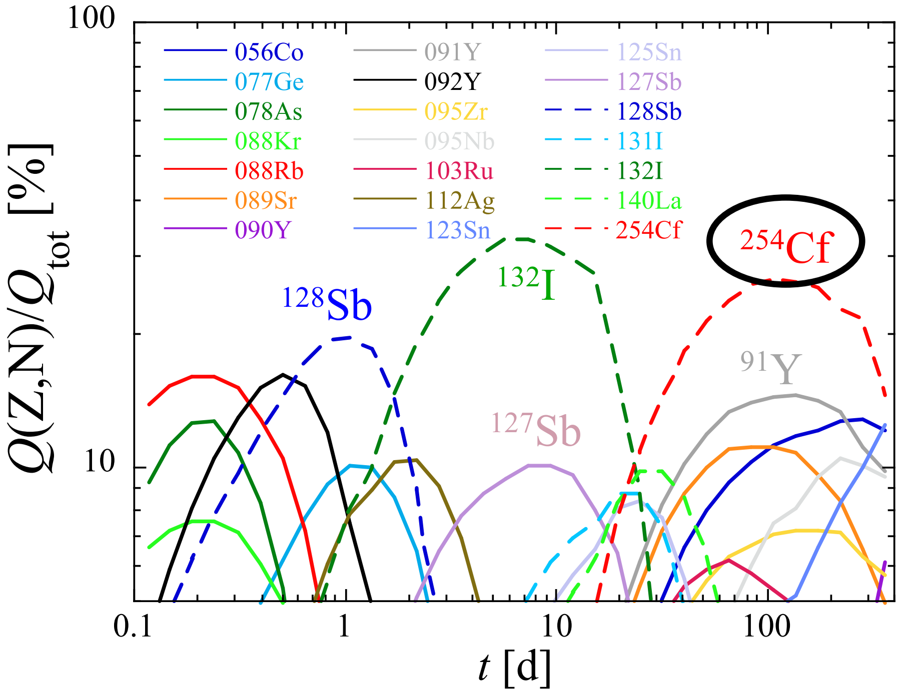
Major contributors to the decay heat



Delayed collapse: 1.375 – 1.375 M_o



Prompt collapse: 1.20 – 1.60 M_o



Relevance of NS-NS mergers as a plausible astrophysical site for the *r*-process

Total amount of *r*-process in the Galaxy

- $M_{Gal} \sim 6\ 10^{10}\ M_o$ of baryons
- $X_o(Eu) \sim 3.7\ 10^{-10}\ M_o$

} → $M_{Gal}(Eu) \sim 22\ M_o$

- NS-NS yield of Europium : $Y_{Eu} \sim 7\ 10^{-5} – 2\ 10^{-4}\ M_o$ (Dynamical+Disk)

→ NS-NS rate to produce the Galactic Eu during 13 Gyr

Rate ~ 8 – 20 Myr^{-1}

Compatible with current estimates

Rate ~ 2 – 210 Myr^{-1} from poputation synthesis models (e.g. Chruslinska et al, 2018)

~ 5 – 495 Myr^{-1} from Galactic Chemical Evolution models constrained by GW170817 observation (e.g. Coté et al, 2018)

~ 0 – 52 Myr^{-1} after no more BNS observation in Ligo-Virgo O4 run (?)

Conclusion in term of amount of *r*-enrichment:

If GW170817 is statistically a representative event, NS mergers are likely to be a (the) main *r*-process site in the Milky Way and possibly in other galaxies... BUT....

Conclusions for Neutron Star Mergers:

- State-of-the-art multi-D hydro model available
- Favourable (Y_e, S, $\tau_{\exp}$) conditions in dynamical & post-merger ejecta for a successful r-process
- Prediction of solar-like abundance distribution, though vary with progenitor properties
- Astrophysics uncertainties still affecting hydro model (ν-absorption, viscosity, ...)
- Observational confirmation (GW170817; more to come ?), though not many NS-NS systems observed since...

→ role of fission in NSM can be assessed in multi-zone models (a consistent propagation to r-process still difficult)

→ Some observational constraints difficult to be met

→ Still unclear if NSM is the major r-process site !!

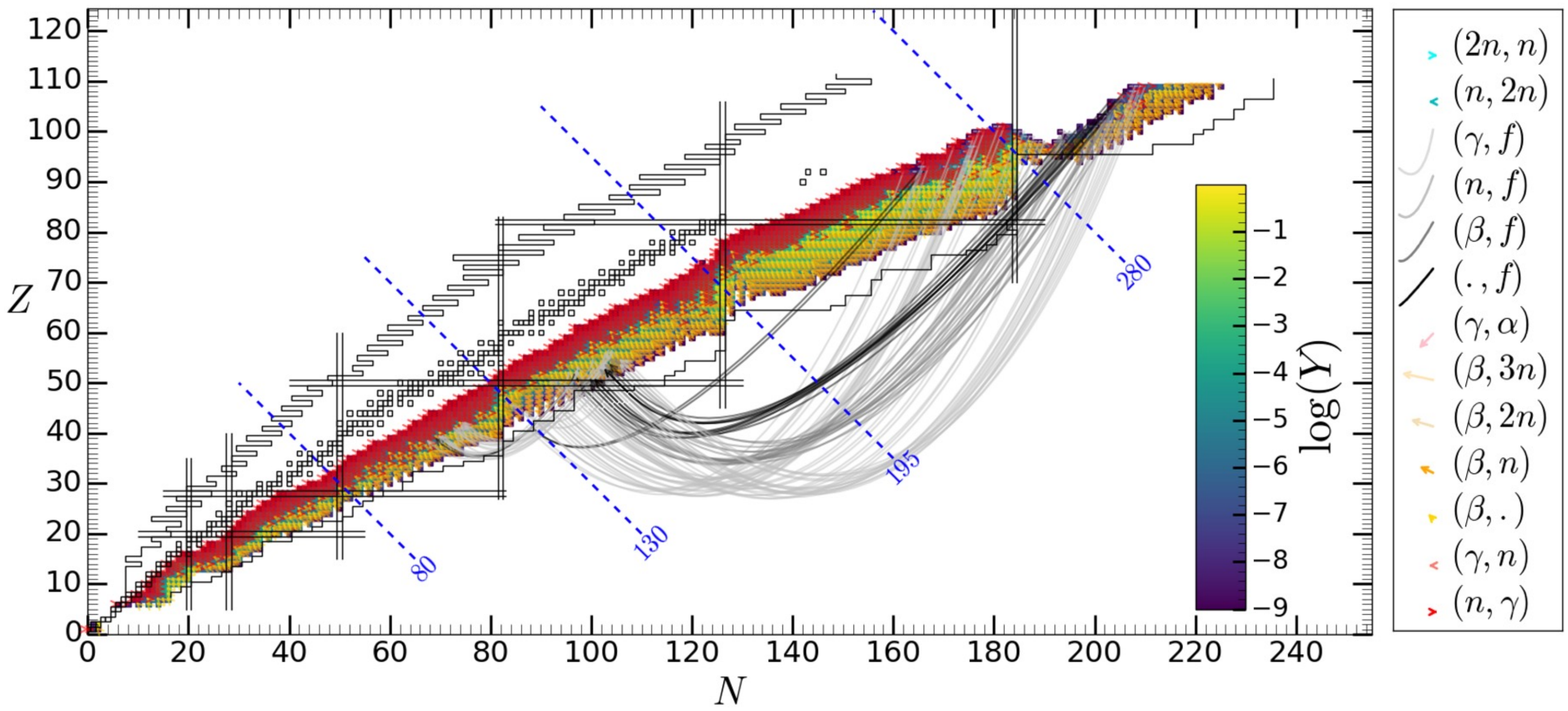
Another uncertainty: nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

- β-decay rates
- (n,γ) and (γ,n) rates
- Fission (nif, sf, βdf) rates
- Fission Fragments Distributions

} Still many open questions

some 5000 nuclei with $Z \leq 110$ involved on the n-rich side



THANK YOU
FOR
YOUR ATTENTION