Nucleosynthesis in Neutron Star Mergers

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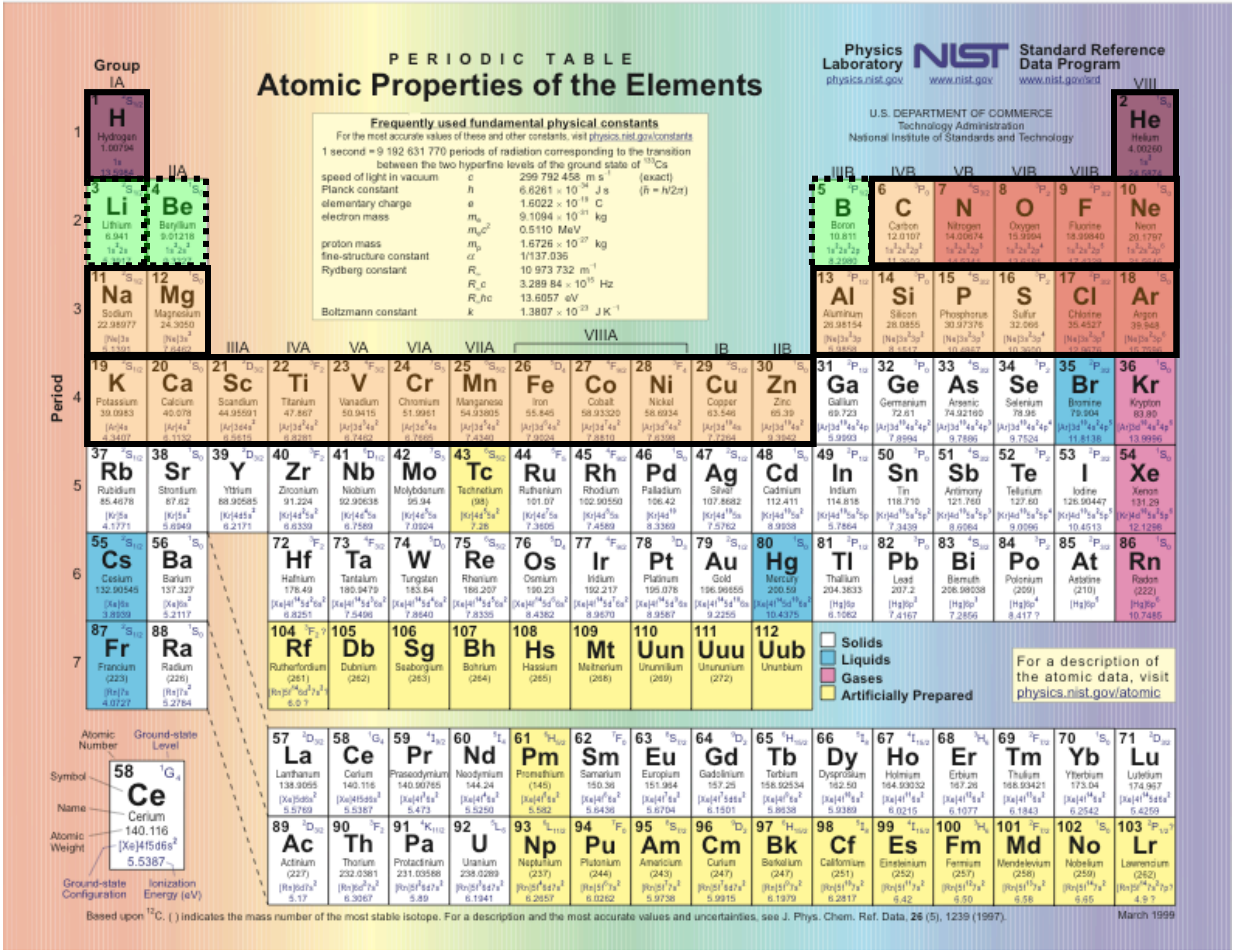
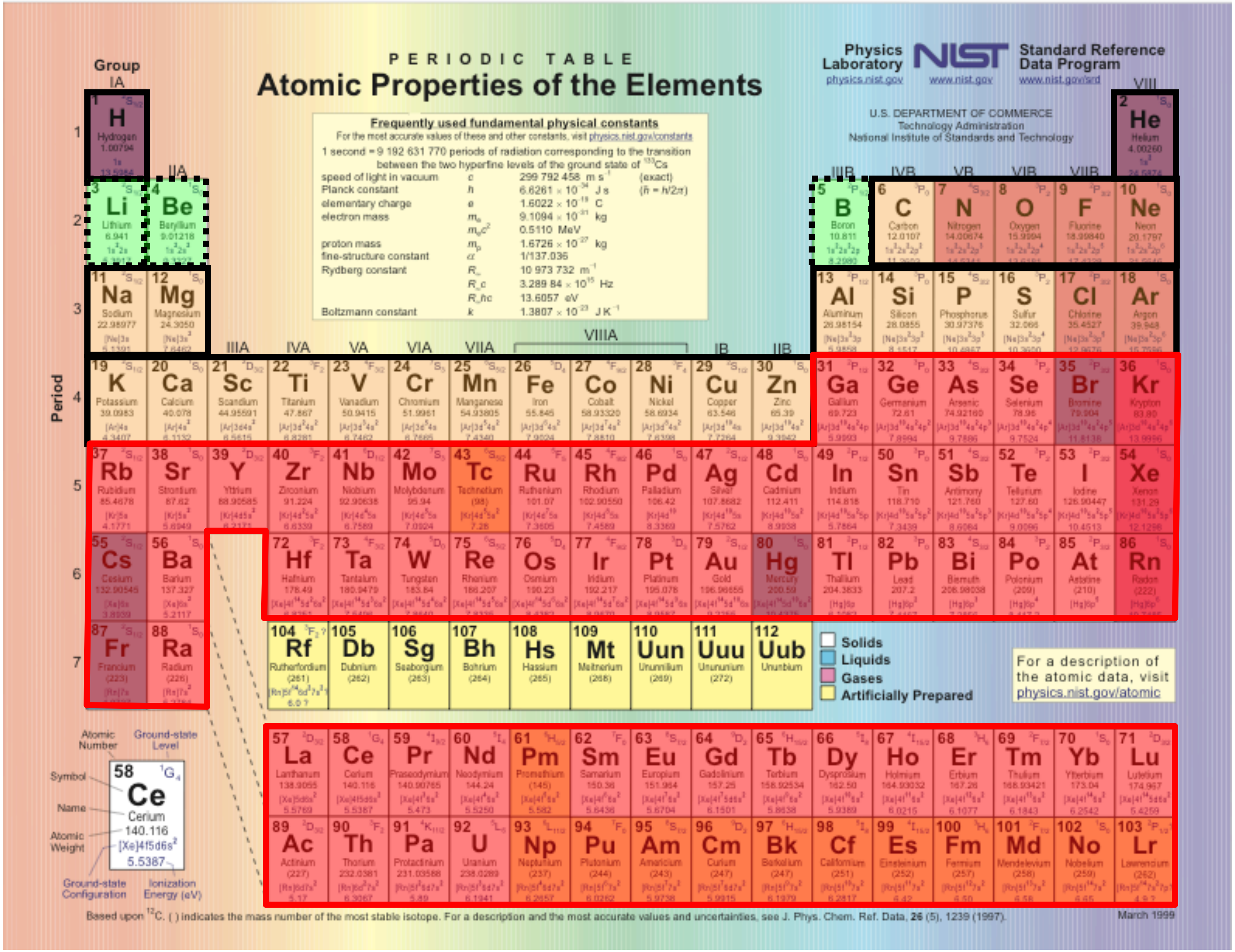
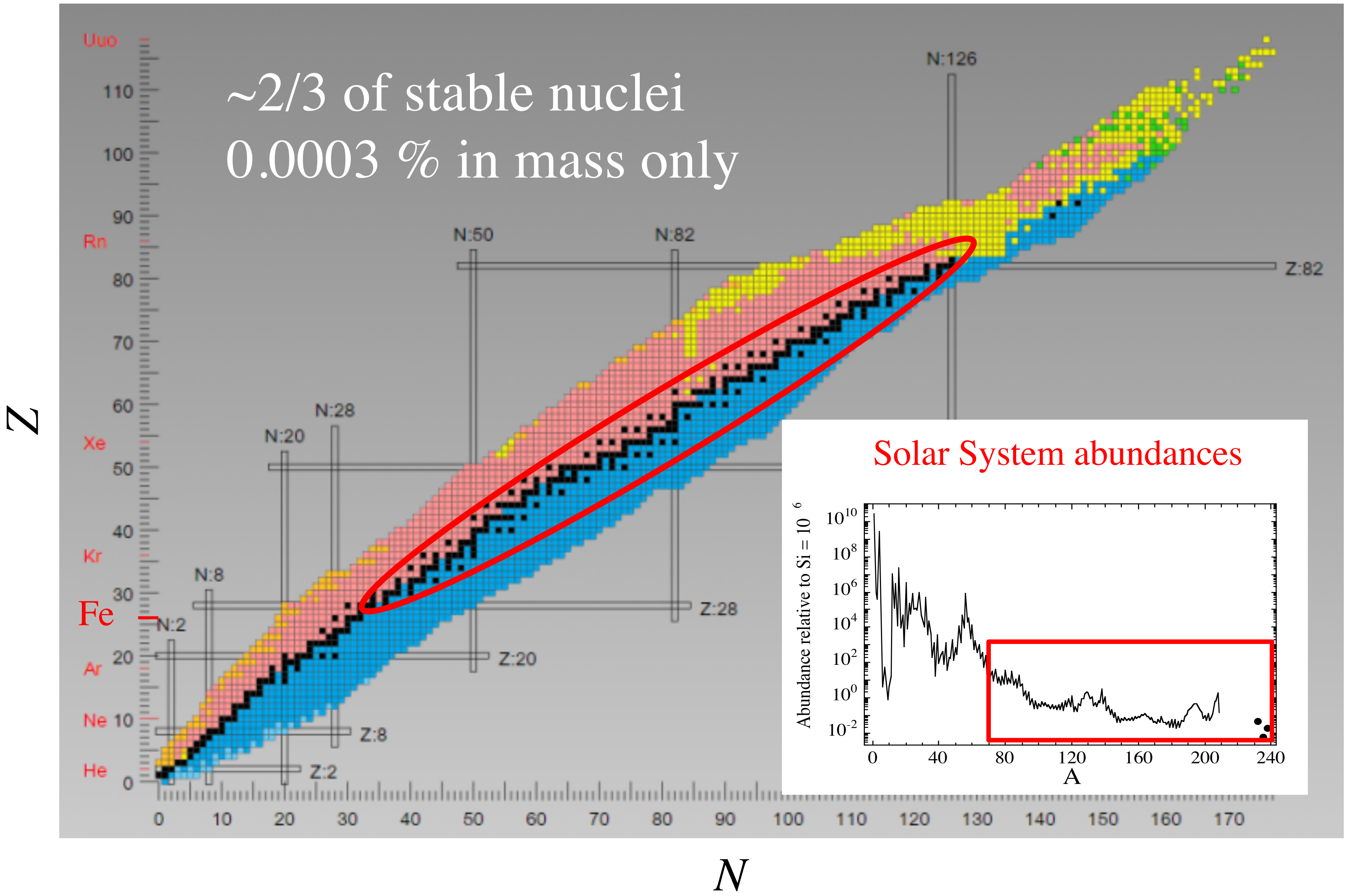
Origin of the elements in the Universe ?



L'origine des éléments plus lourds que le Fer



Nucleosynthesis of elements heavier than iron



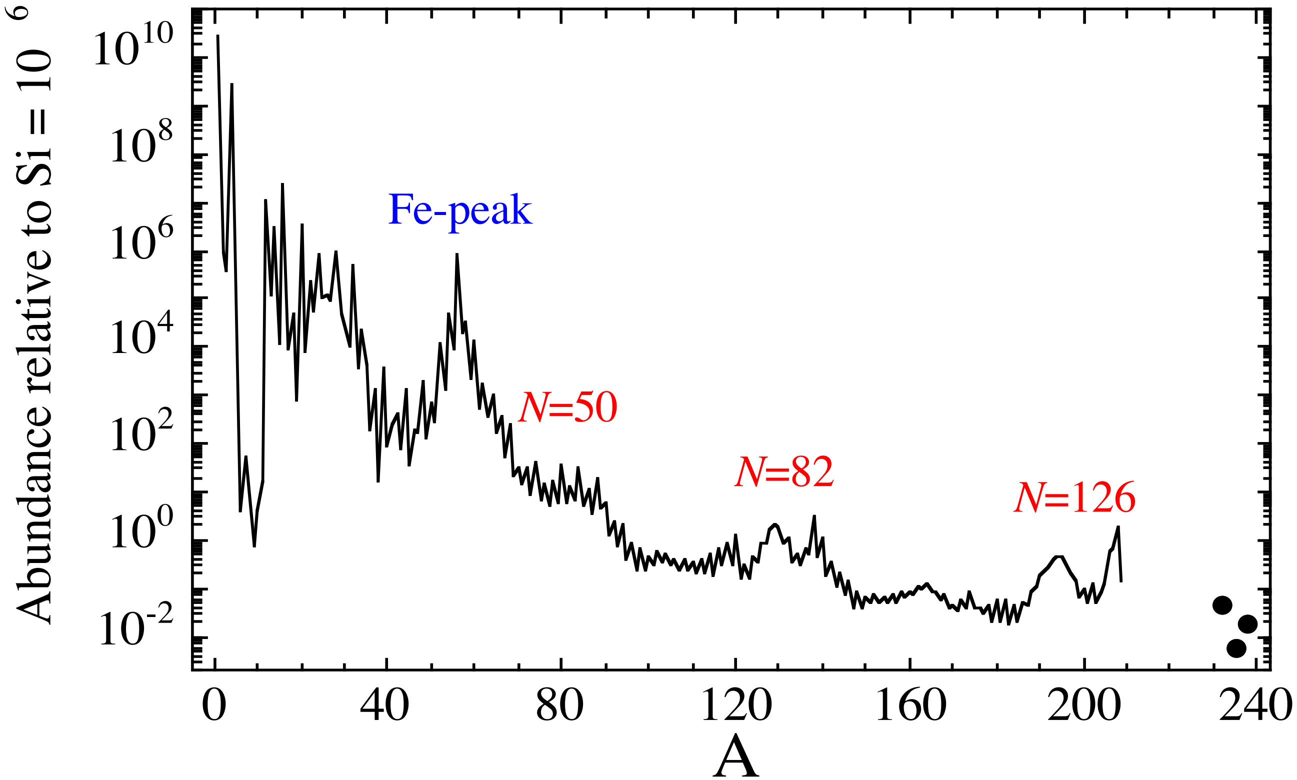
The concept of synthesis by neutron captures

$\tau_p(A>56)$ & $\tau_\alpha(A>56)$ >>> characteristic evolution lifetime of a star

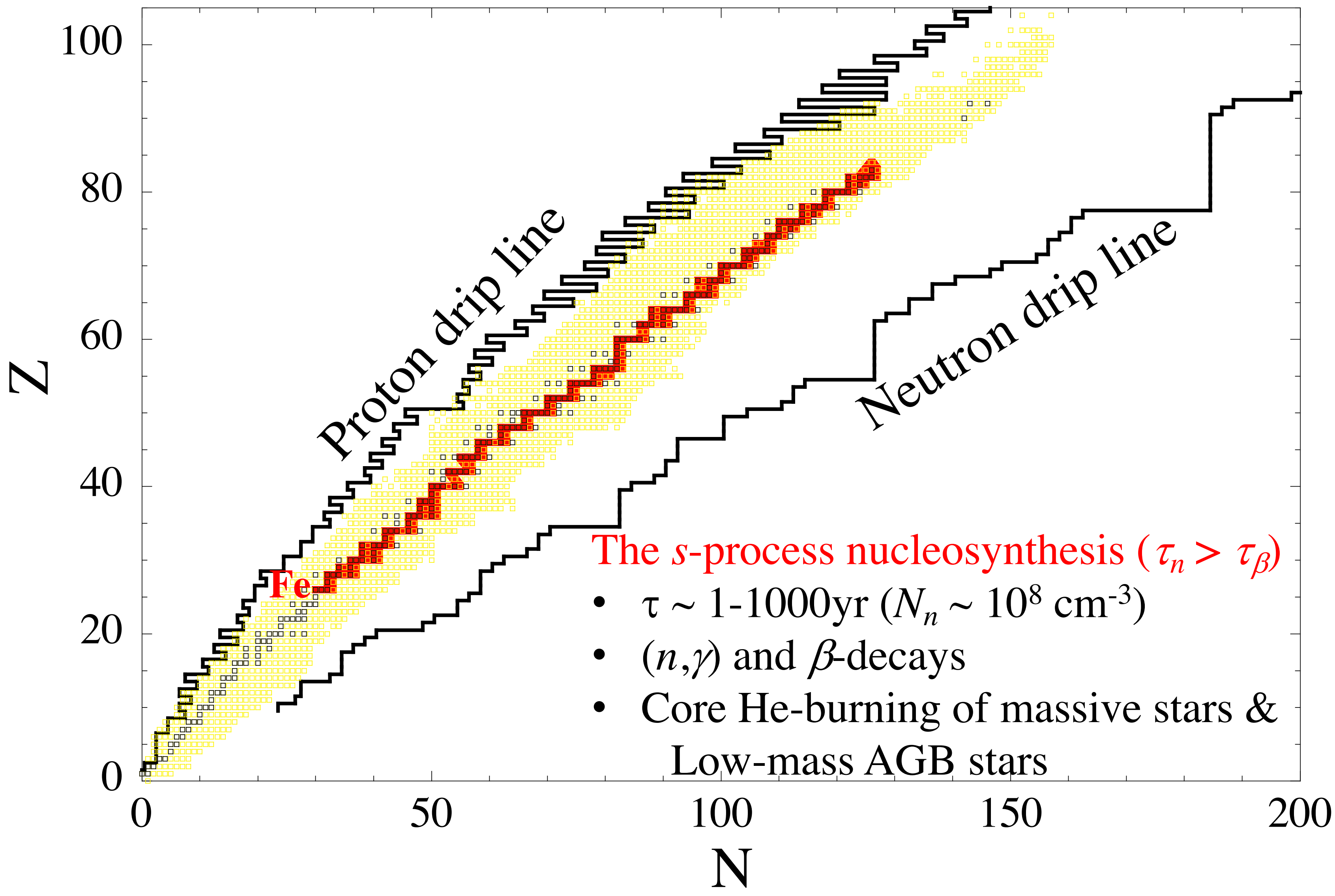
➡ Charged-particle captures are inefficient to produce the bulk galactic $A > 56$ nuclides

➡ **Use of NEUTRONS instead !**

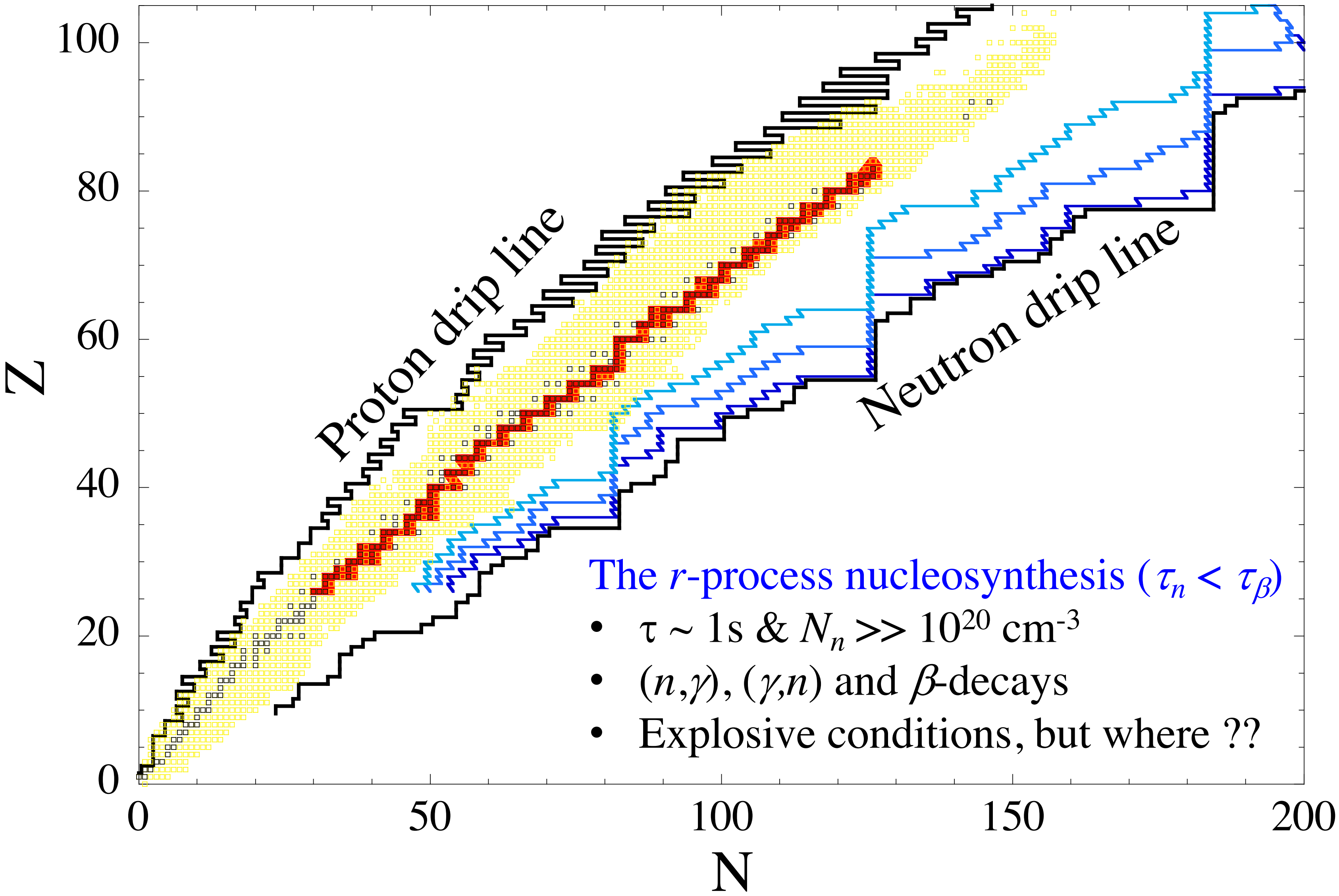
- **No coulomb barrier**
- **Natural explanation for the peaks observed in the solar system abundances at neutron magic numbers *N*=50, 82 and 126**



The *s*-process nucleosynthesis

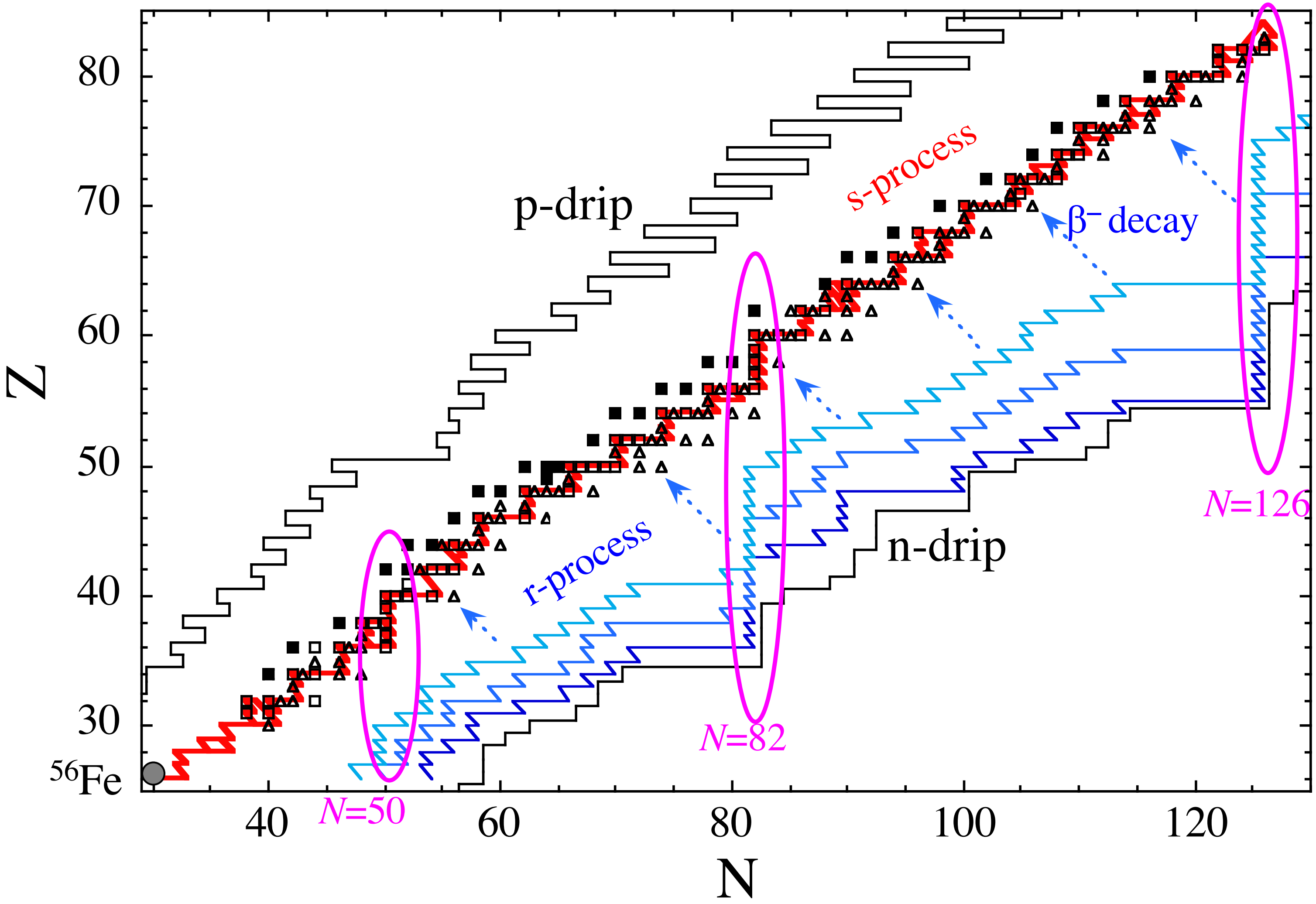


The *r*-process nucleosynthesis



A schematic representation of the s- and r-processes

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



A schematic representation of the s- and r-processes

Closed shells at neutron magic numbers N=50, 82, 126 → slow n-capture

↓

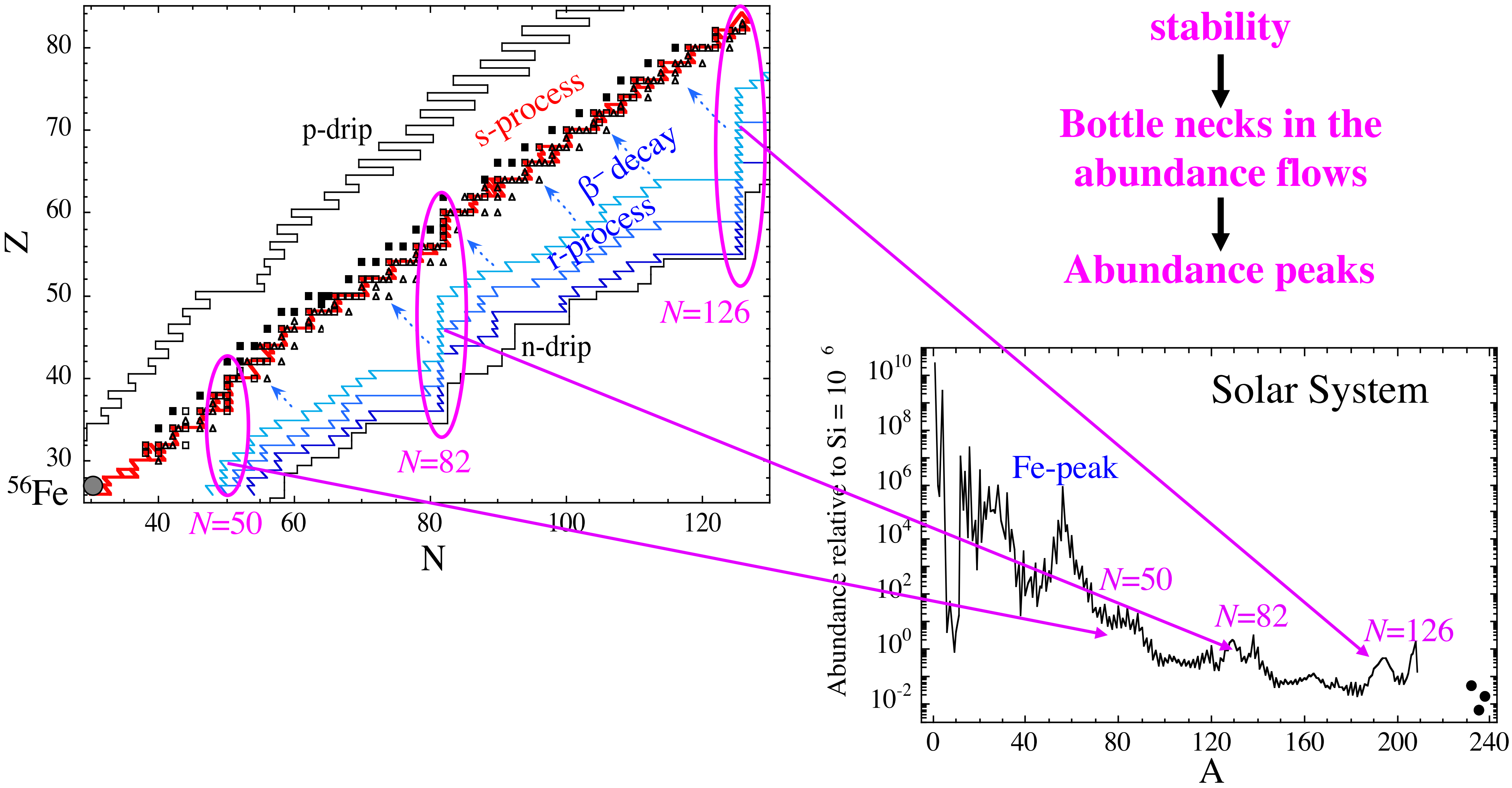
Nuclear flow closer to stability

↓

Bottle necks in the abundance flows

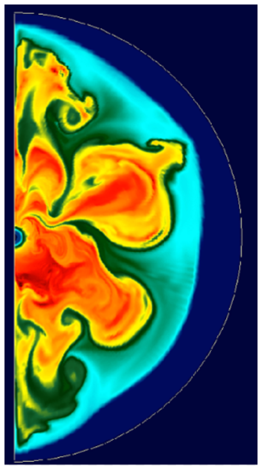
↓

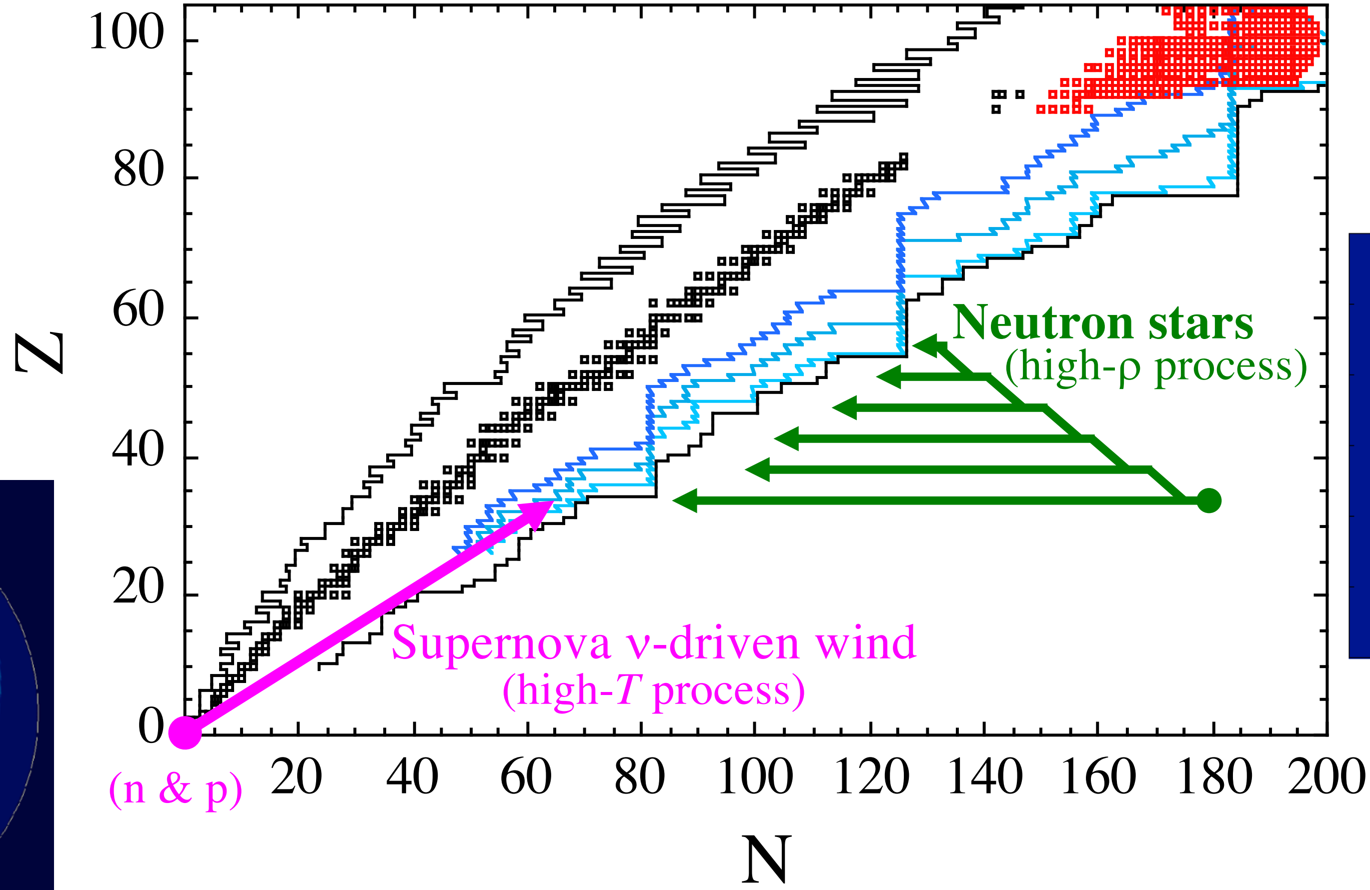
Abundance peaks

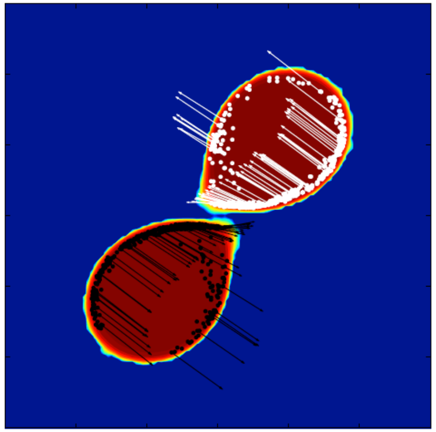


The r-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

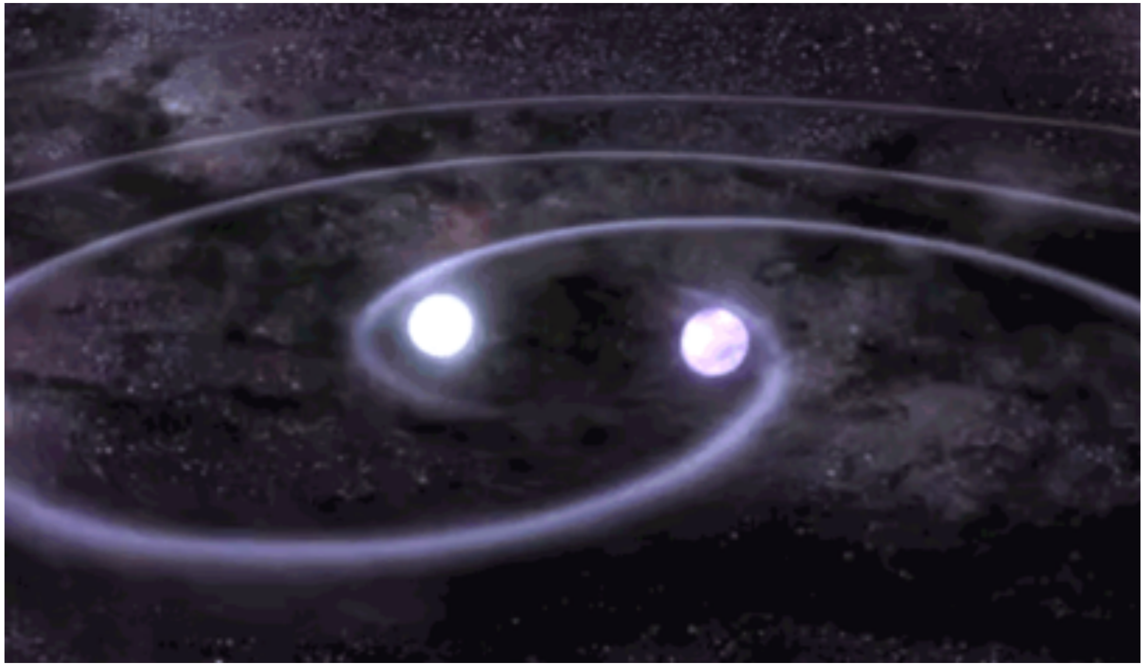
one of the still unsolved puzzles in nuclear astrophysics







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

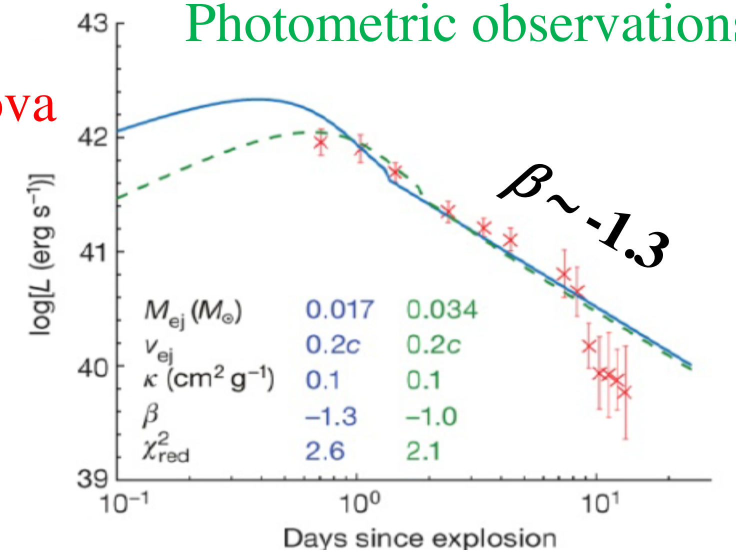


The first analysis of the GW170817 light curve

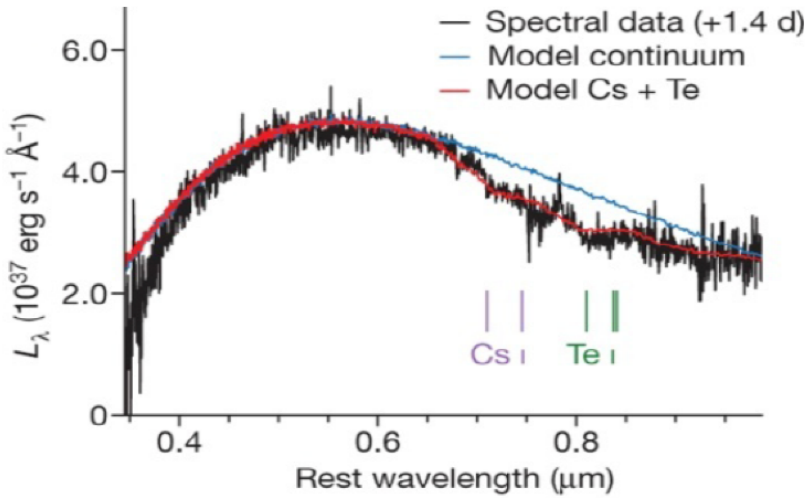
- The kilonova light curve is compatible with an overall ejecta mass ($M_{ej} \approx$ 0.03-0.06 $M_{\odot}$)
  - "Blue" A<140 component with $M_{ej} \approx$ 0.01-0.02 $M_{\odot}$ and $v_{ej} \approx 0.26c$
  - "Red" A>140 component with $M_{ej} \approx$ 0.02-0.05 $M_{\odot}$ and $v_{ej} \approx 0.15c$

Photometric observations

Kilonova



Spectroscopic observations



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

Systematic study of Neutron-star mergers

(Bauswein, Janka, Just, 2011, 2013, 2014, 2015, 2016)

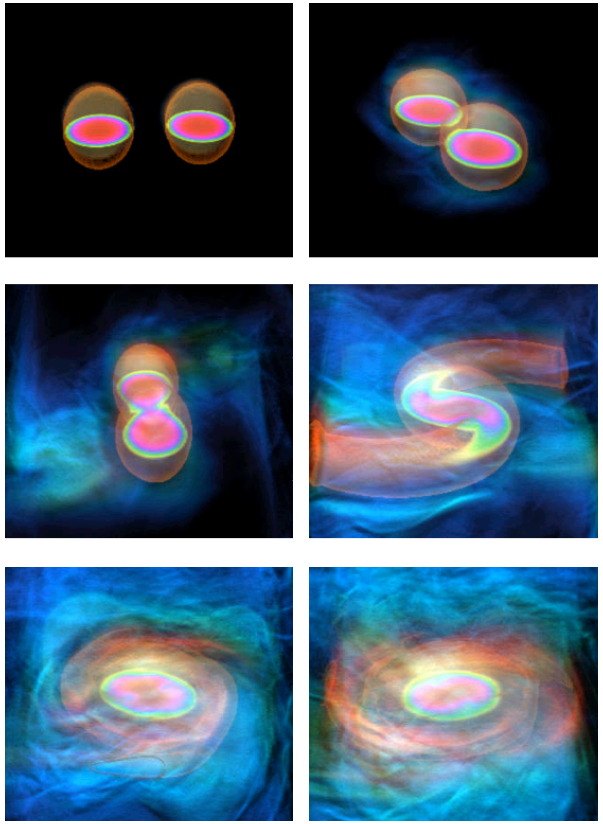
Various relativistic simulations for different binary systems :

- NS-NS systems: symmetric (e.g 1.35; 1.45; 1.6; 1.75 M_o)
  asymmetric (e.g 1.2–1.5 M_o; 1.2-1.8M_o; 1.35-1-8M_o)
- NS-BH systems: 1.1-1.45M_o NS with 2.3-7M_o BH (and spin α_{BH}=0-0.9)
- 40 different EoS with different stiffness (i.e. different NS compactness)

→ different amounts of mass ejected
$M = 10^{-3} – 2\ 10^{-2}\ M_o$

→ different ejecta velocities

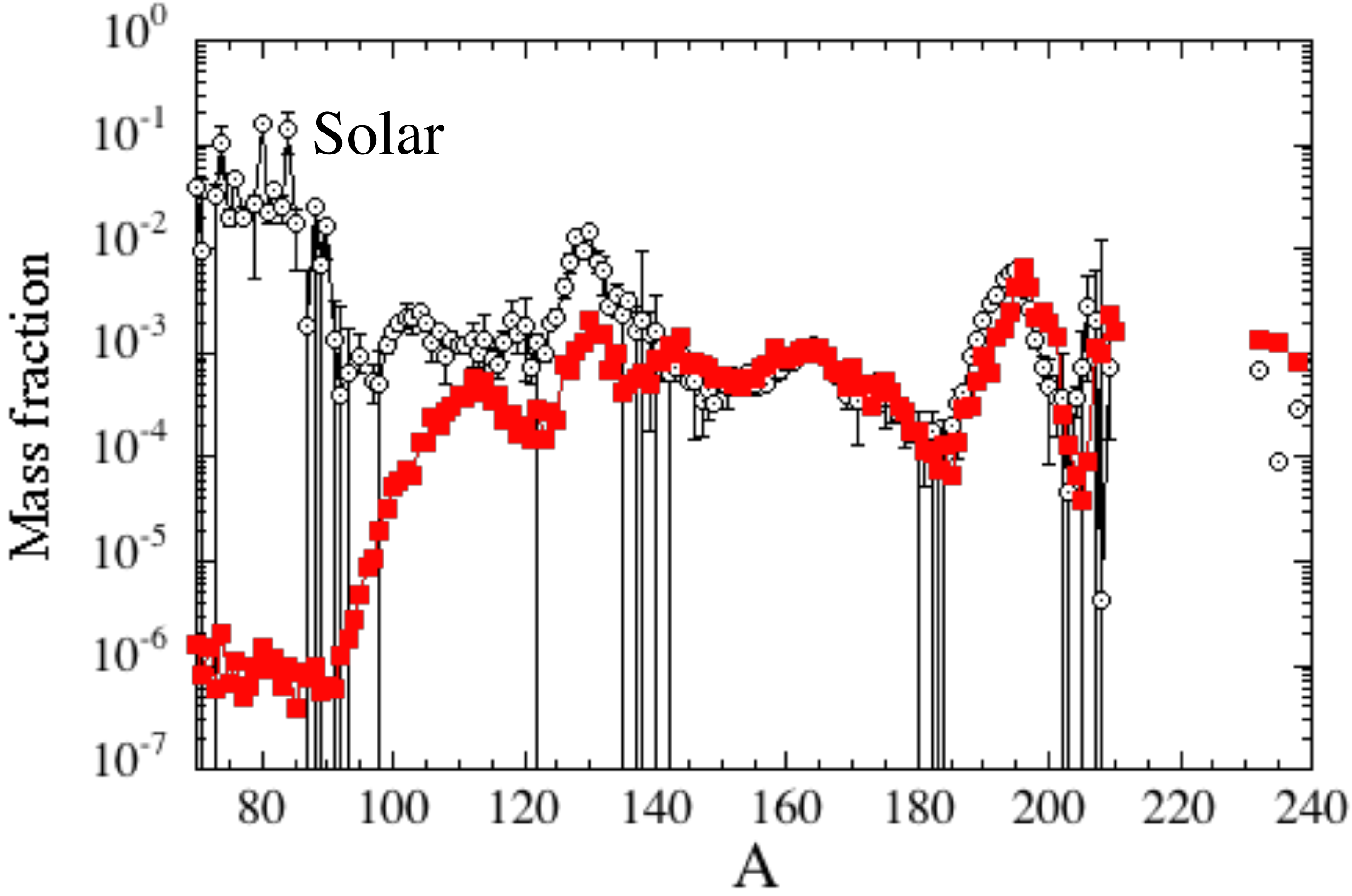
→ different luminosities of the optical transients 3 – 14 10^{41} erg/s

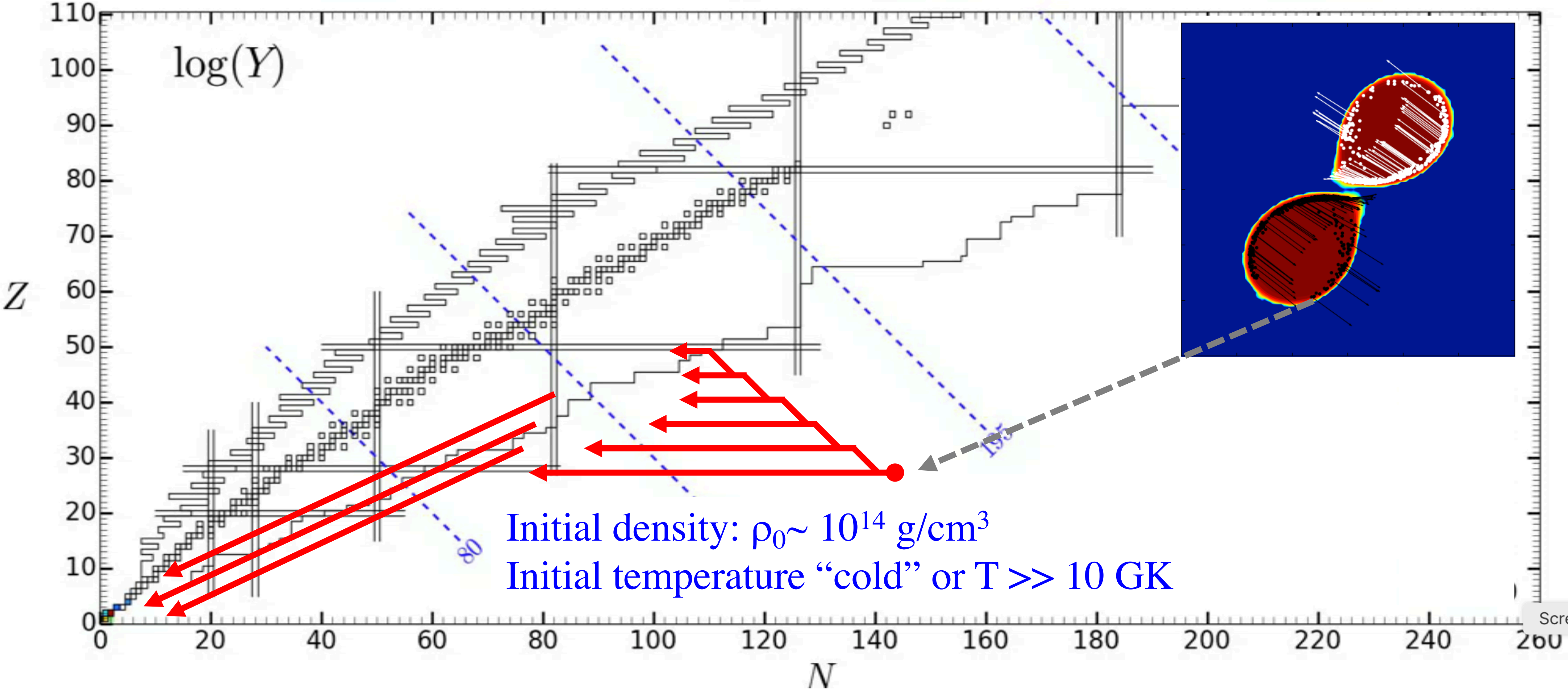


(see also e.g. Rosswog et al. 2013, 2014)

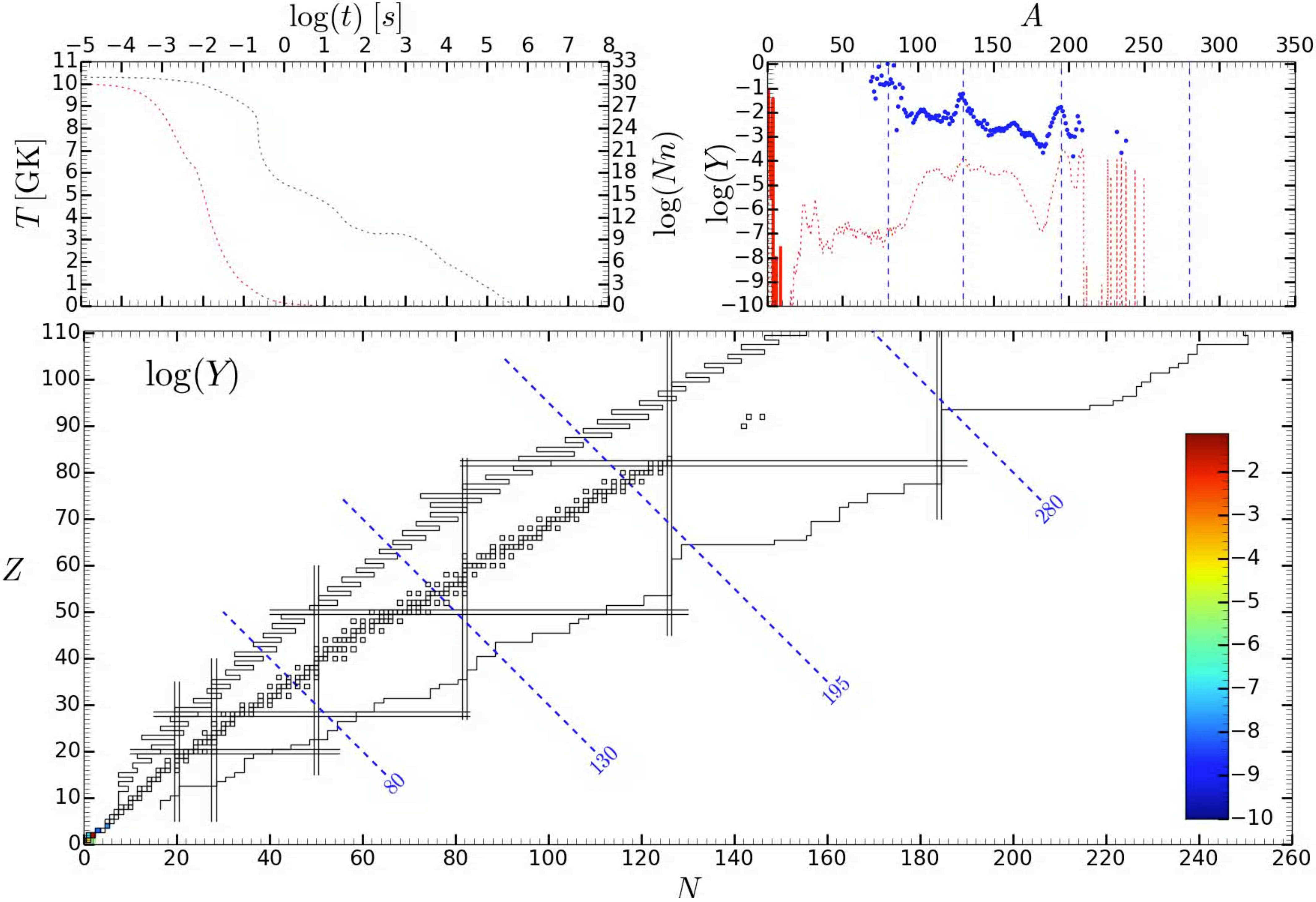
Systematic study of Neutron-star mergers

BUT *invariably*, more than 95 % of the ejected material is *r*-process with a distribution very similar to the solar r-abundance distribution (A>130-140)





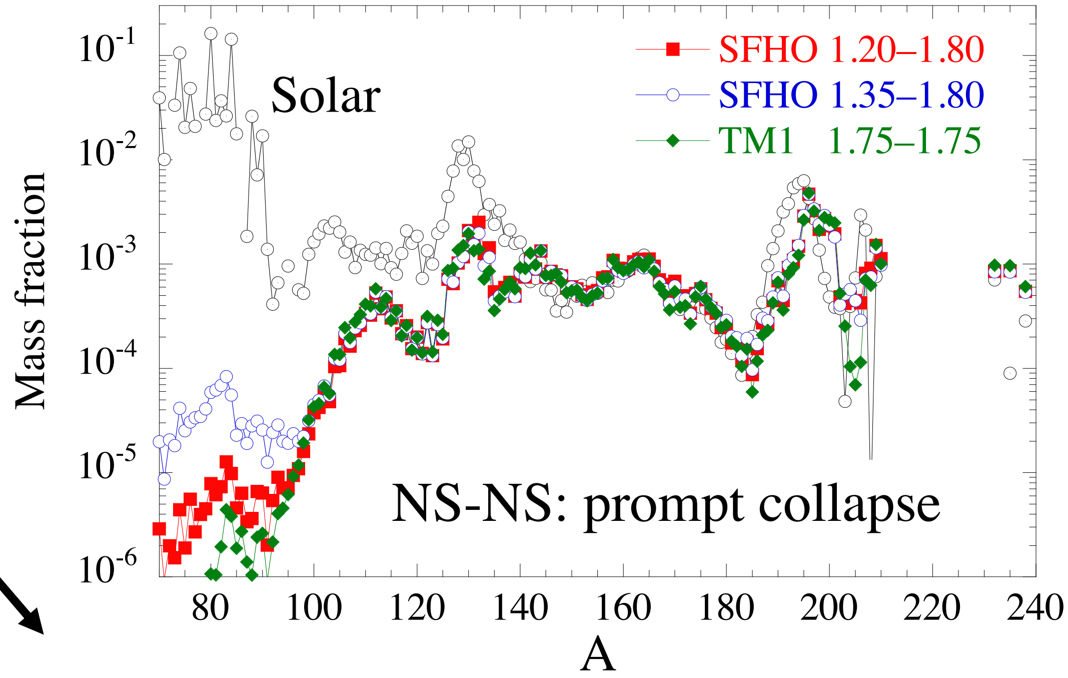
log(Y)
Z
N
80
135
Initial density: ρ0~ 10^14 g/cm^3
Initial temperature "cold" or T >> 10 GK

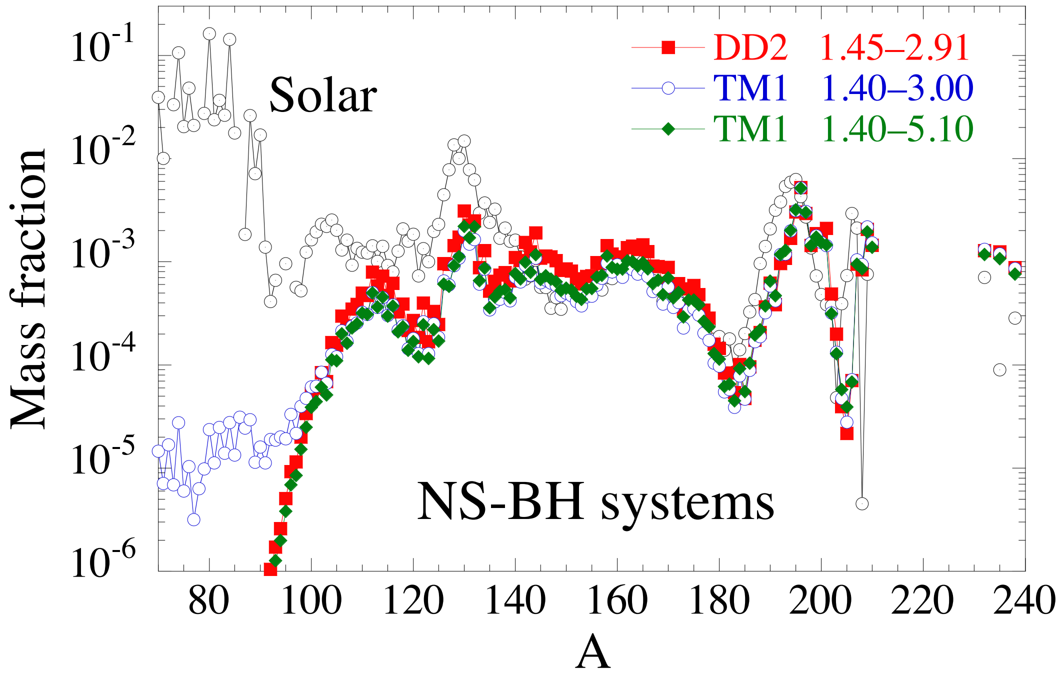


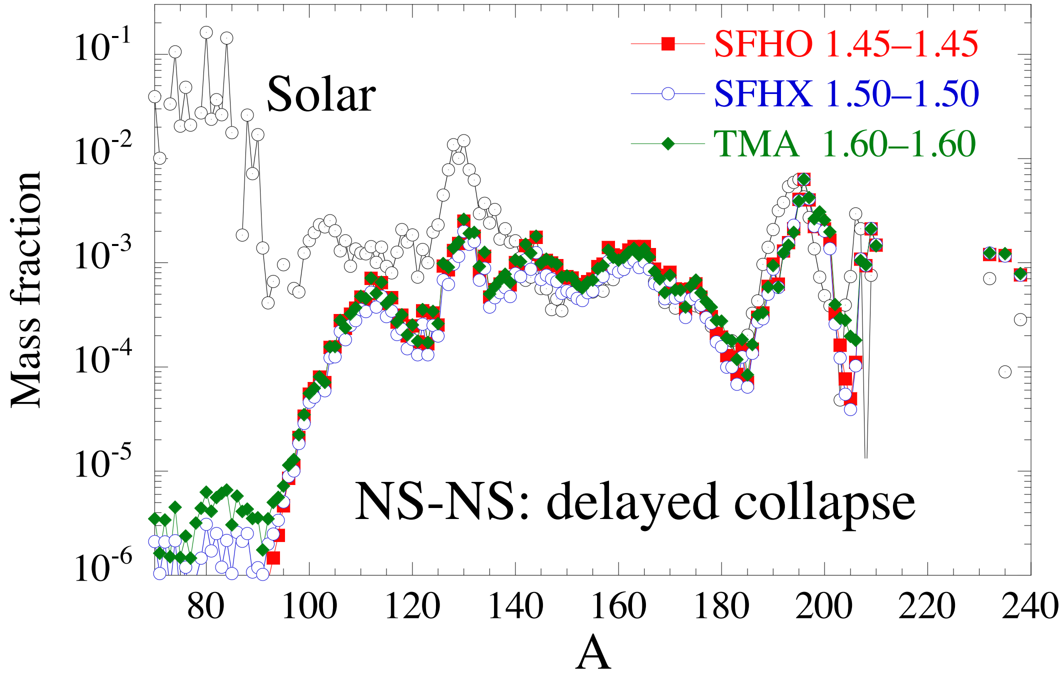
log(t) [s]
T [GK]
log(Nn)
A
log(Y)
log(Y)
Z
N
80
130
195
280

AND similar predictions, be it

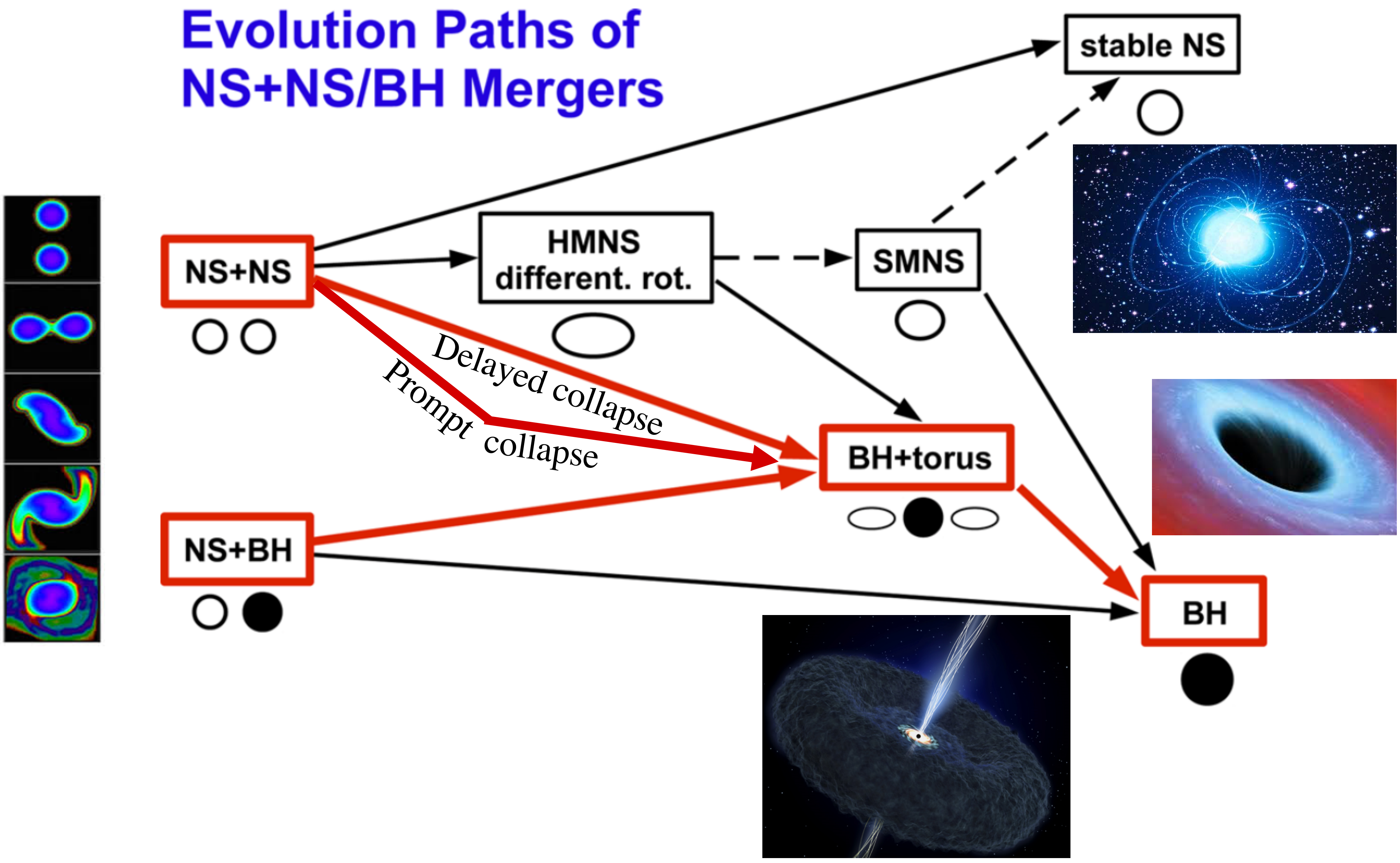
- a prompt collapse of NS-NS
- a delayed collapse of NS-NS
- a NS-BH system



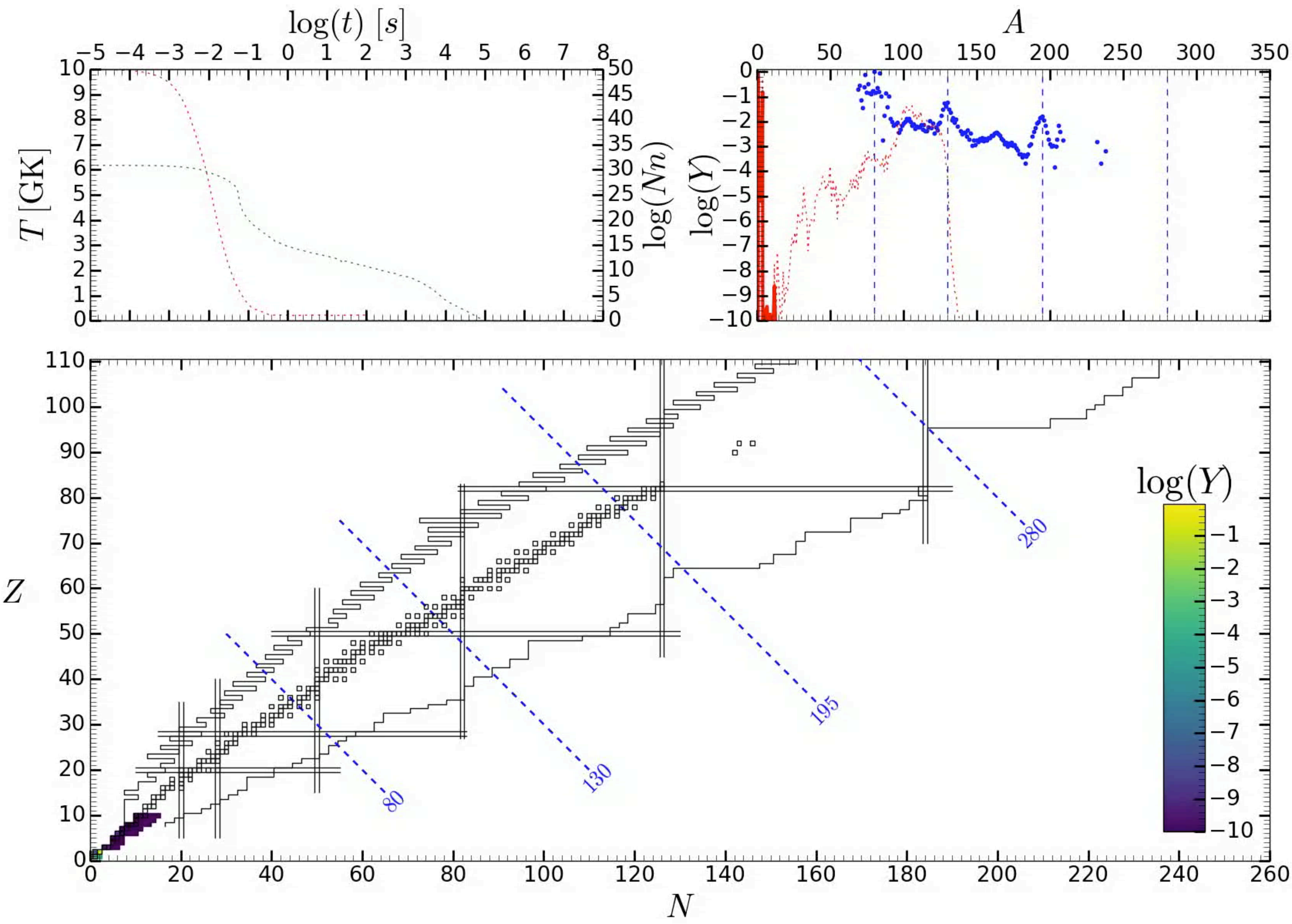




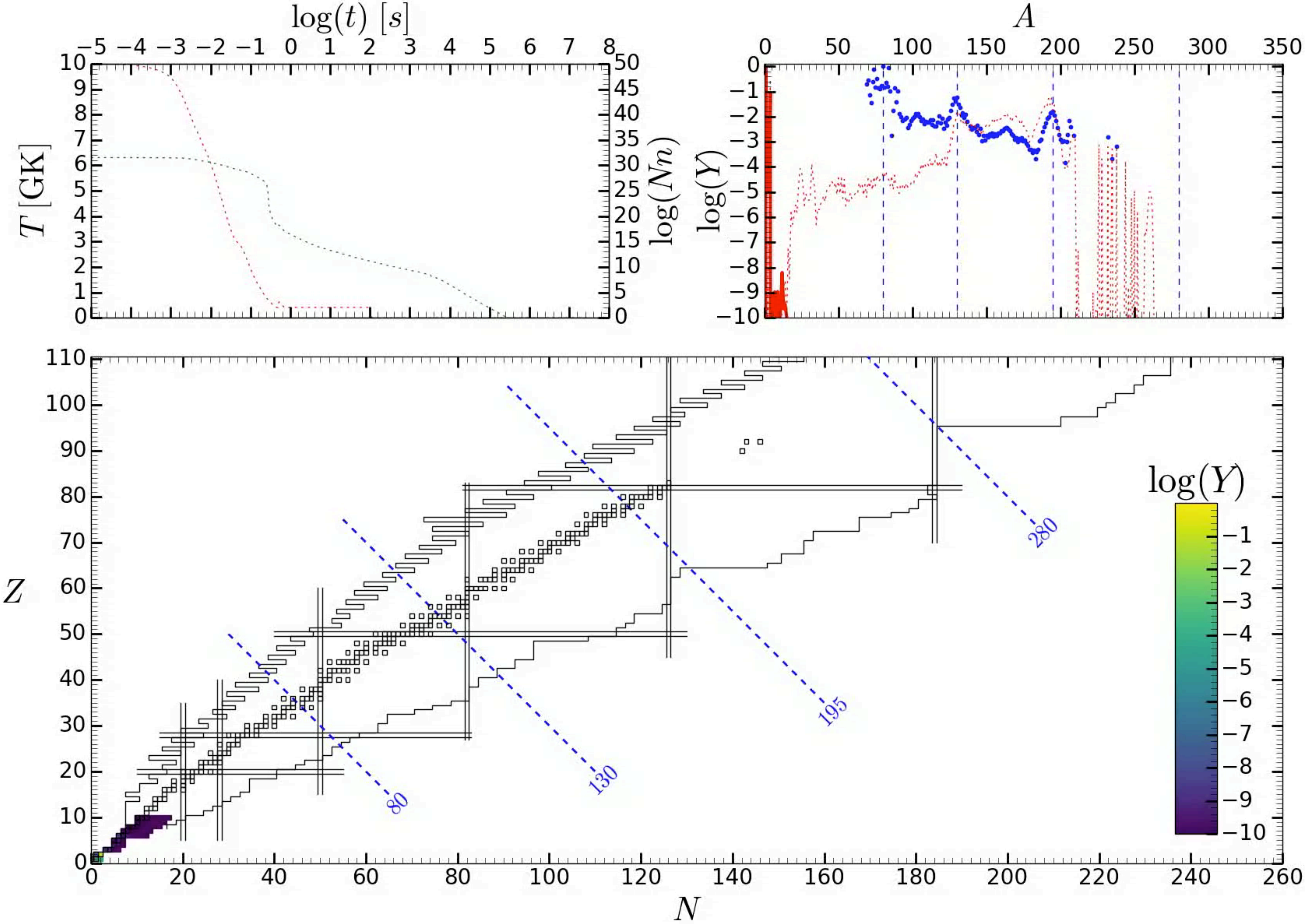
NS-NS or NS-BH mergers are robust site for the r-process (A>140)



Evolution Paths of NS+NS/BH Mergers
stable NS
HMNS
different. rot.
SMNS
NS+NS
Delayed collapse
Prompt collapse
BH+torus
NS+BH
BH



log(t) [s]
T [GK]
log(Nn)
A
log(Y)
Z
N
log(Y)
80
130
195
280



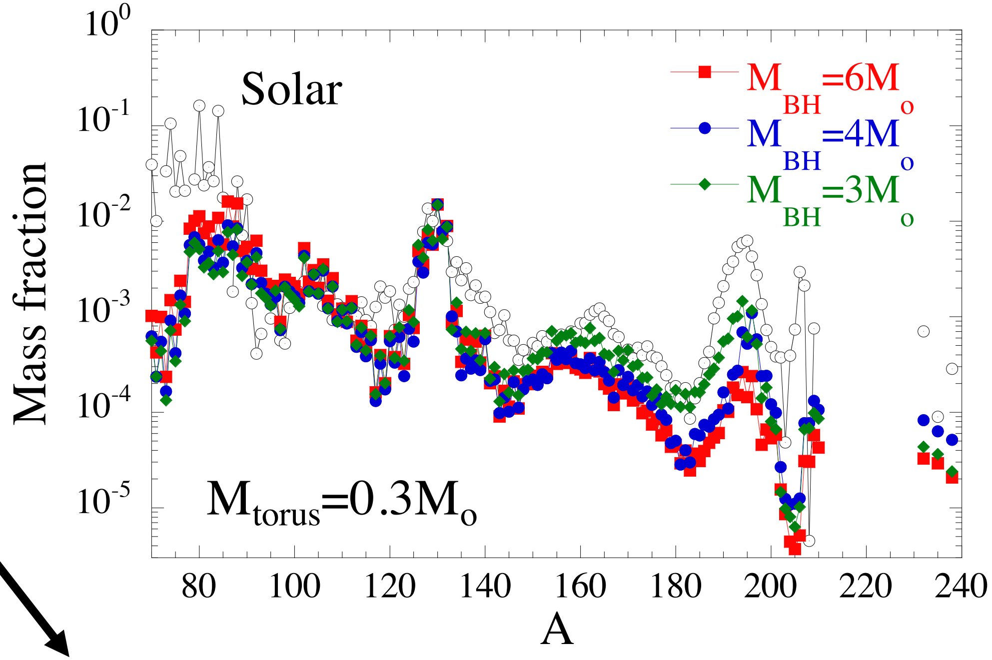
log(t) [s]
T [GK]
log(Nn)
A
log(Y)
Z
N
log(Y)
80
130
195
280

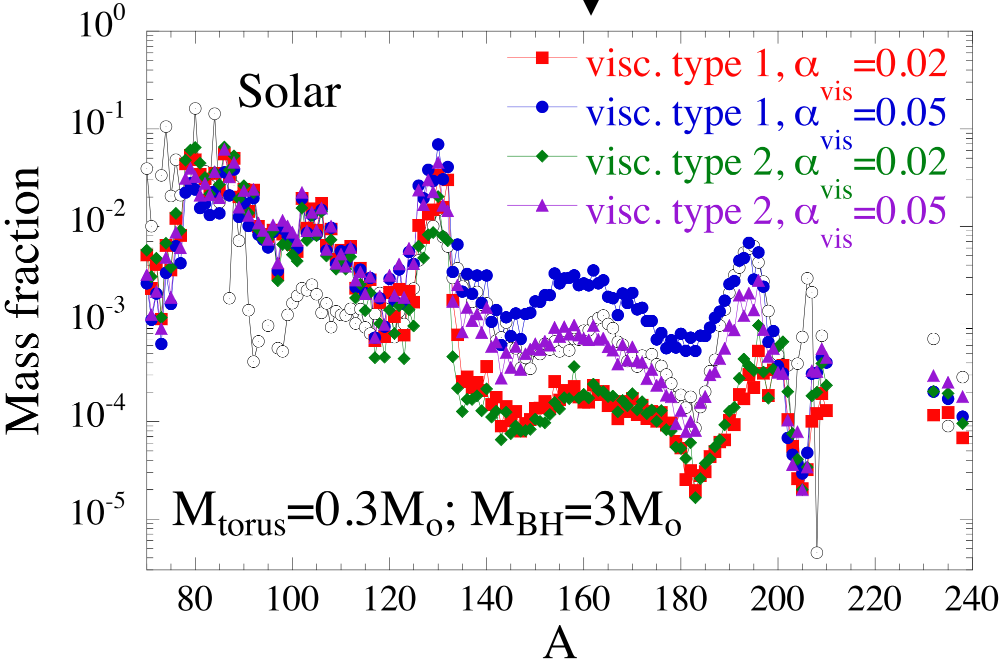
Different hydrodynamical simulations

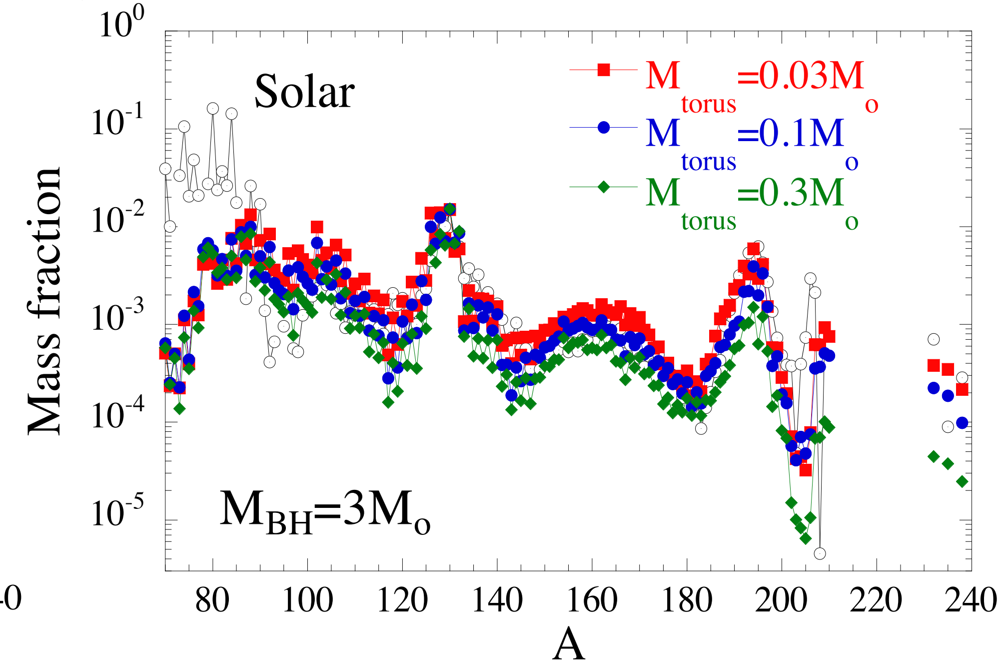
(Just, et al. 2015; Wu et al. 2016)

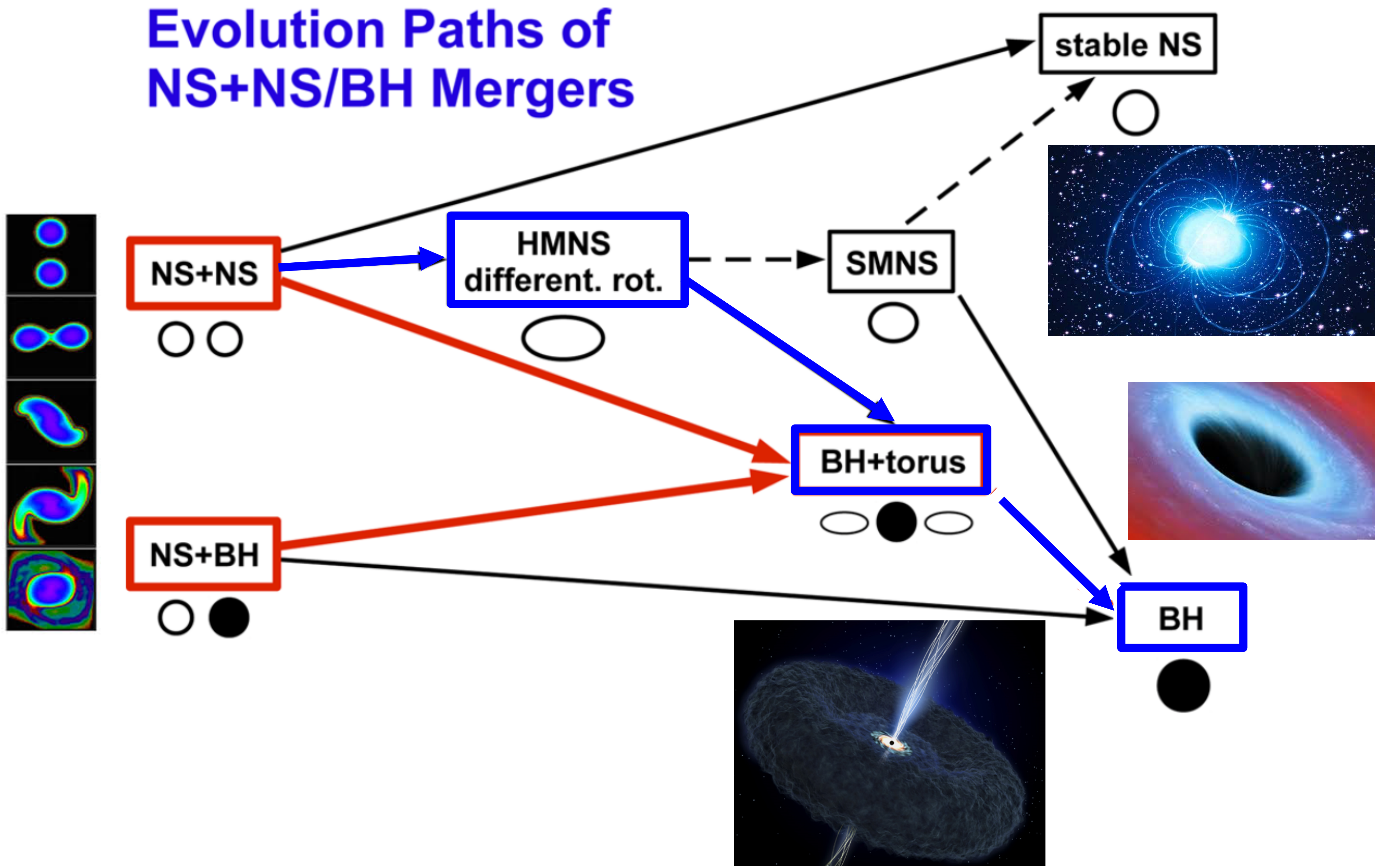
Abundance predictions sensitive to

- Mass of the BH (same M_{torus})
- Mass of the torus (same M_{BH})
- Treatment of viscosity



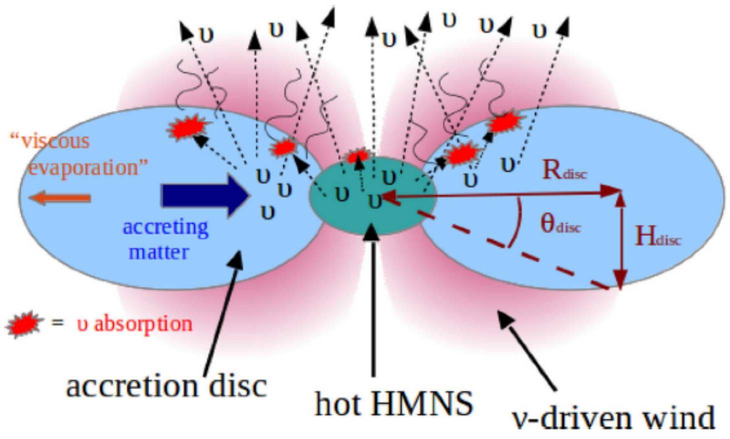


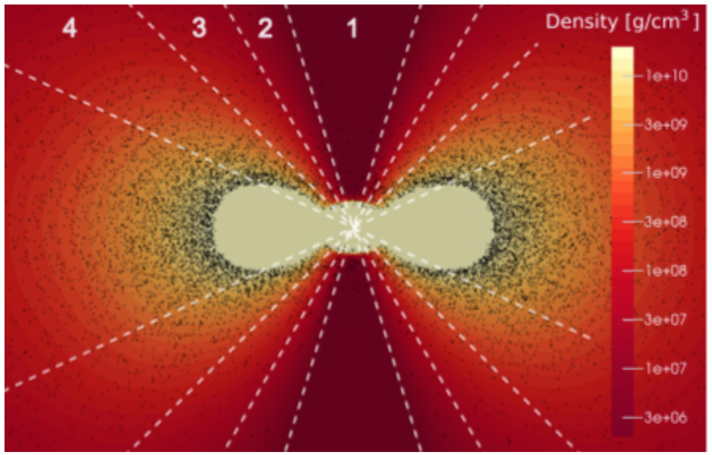


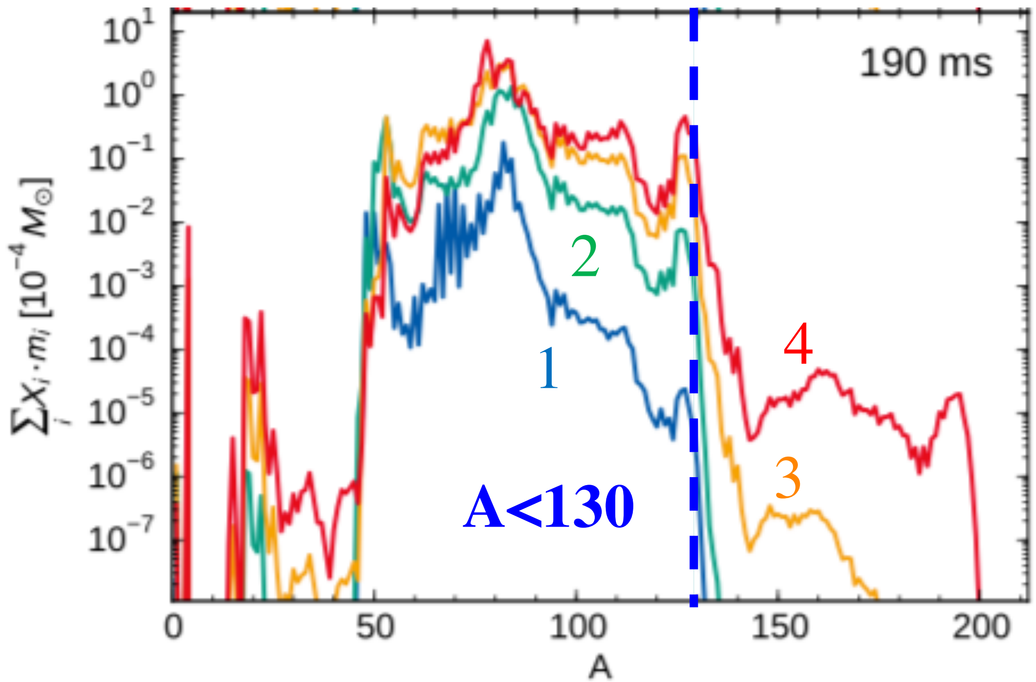

Evolution Paths of
NS+NS/BH Mergers
stable NS
NS+NS
HMNS
different. rot.
SMNS
BH+torus
NS+BH
BH

Composition of the matter ejected from a HMNS

(Perego et al. 2014; Martin et al. 2015, Wu et al. 2016, Lippuner et al. 2017)





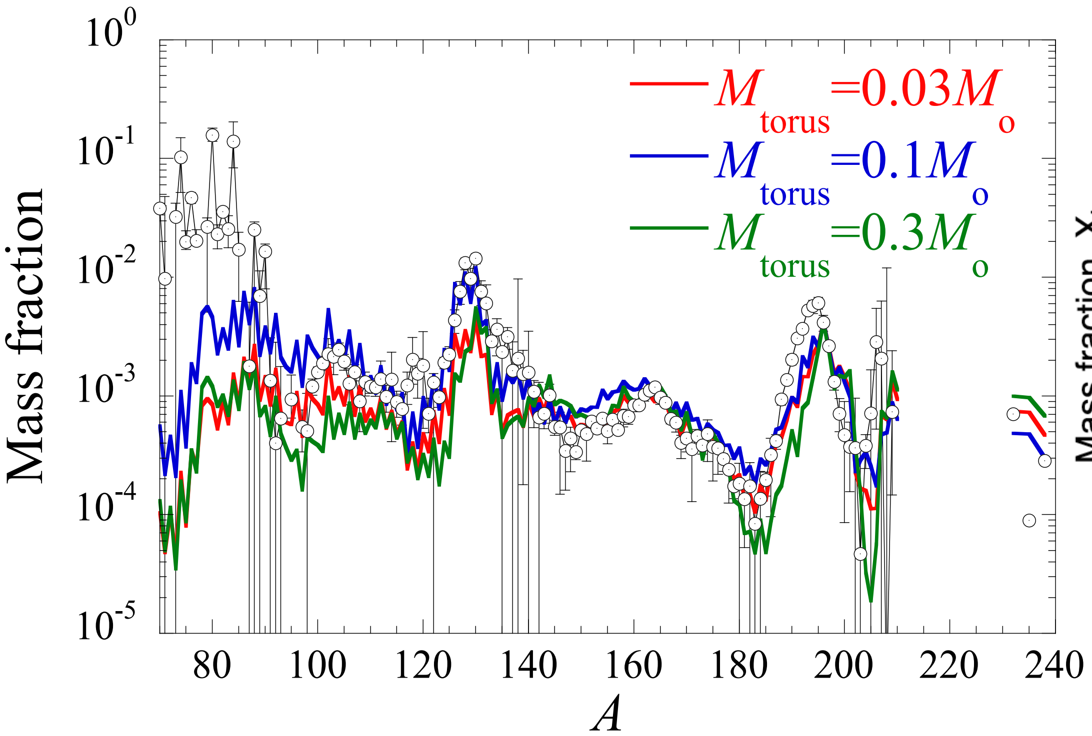


Nucleosynthesis of A<130 r-nuclei though depends on the lifetime of the HMNS and the polar angle.

Final abundance distributions from Binary Neutron Star Mergers

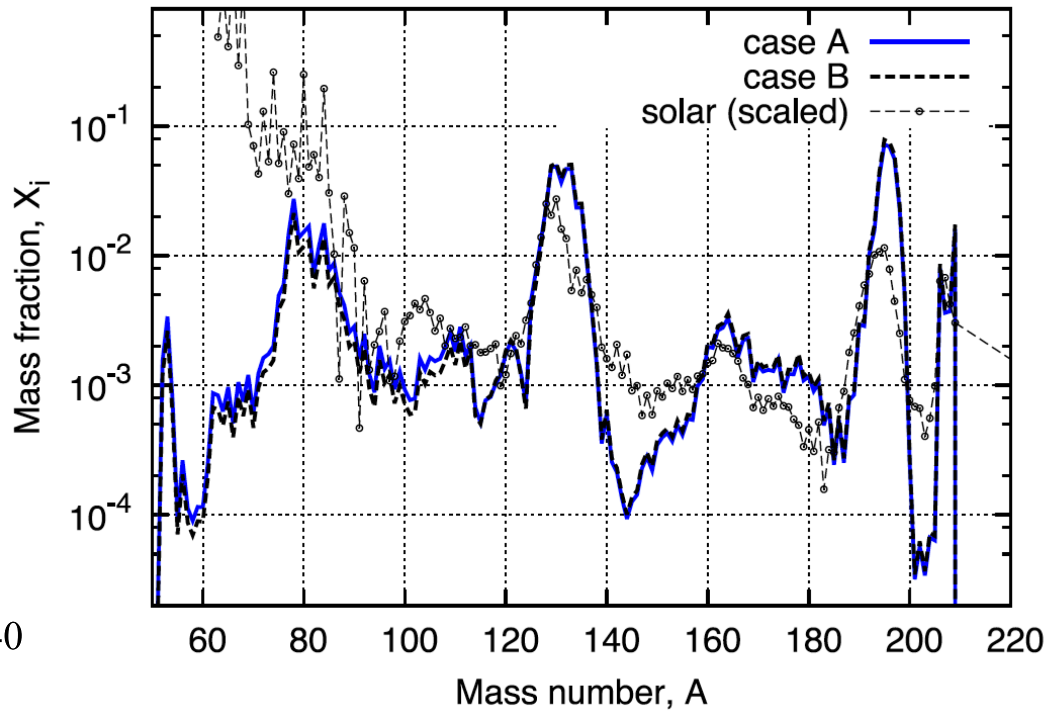
Dynamical + BH-Torus system

Just et al. (2015)



Dynamical + HMNS system

Perego et al. (2014); Martin et al. (2015)

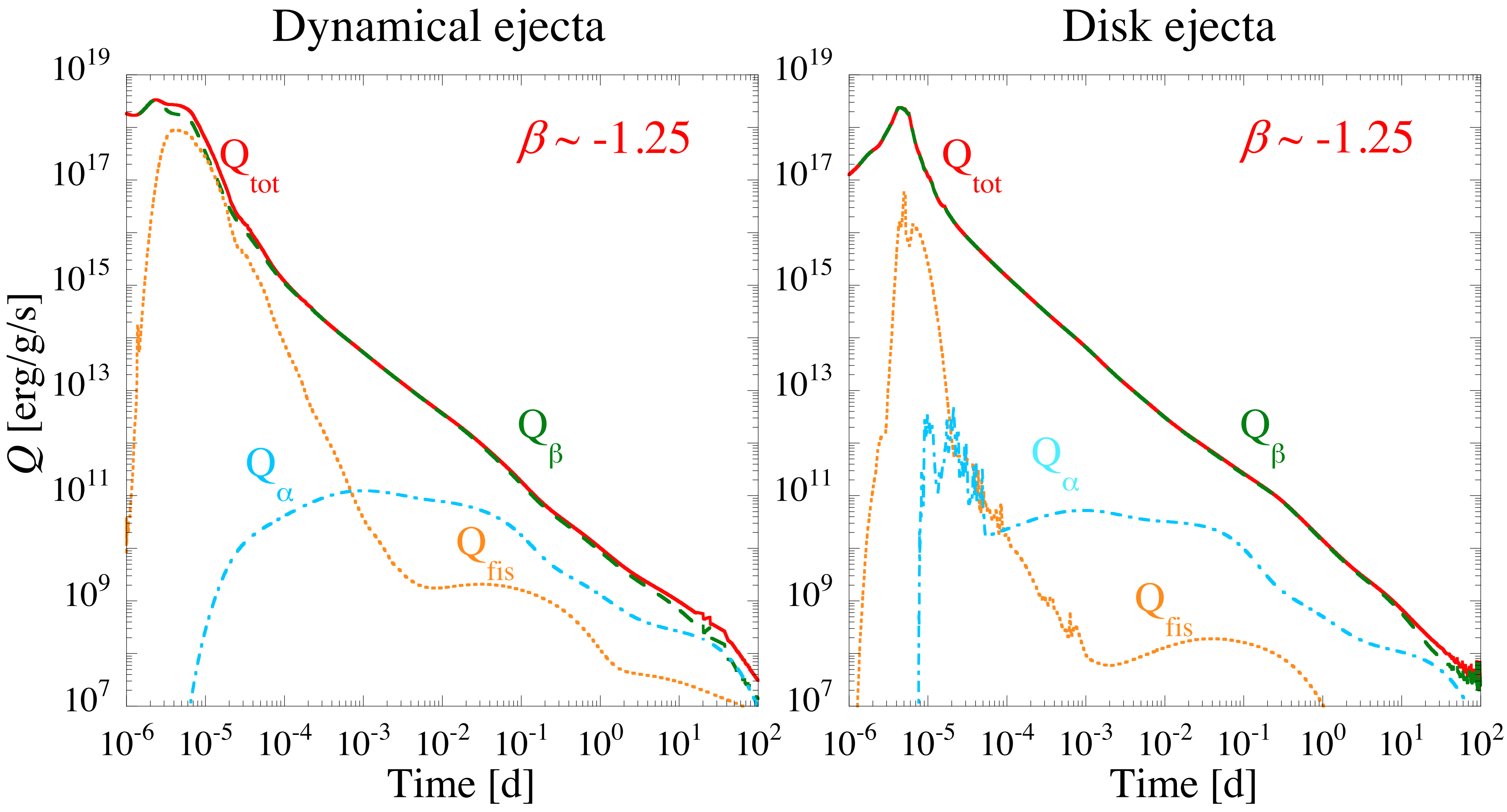


Robust production of all A ≥ 90 *r*-nuclei with a rather solar distribution

Two contributions : Dynamical & Disk ejecta (~ same mass; $v_{dyn} > v_{disk}$)

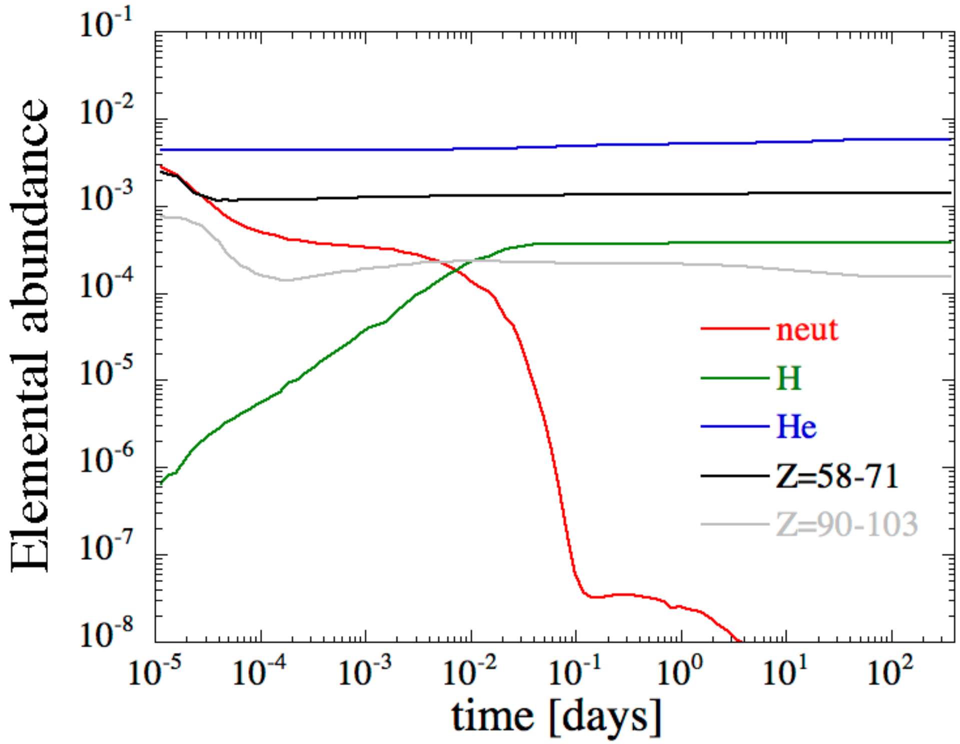
Total radioactive heating rate of the resulting Kilonova at late times

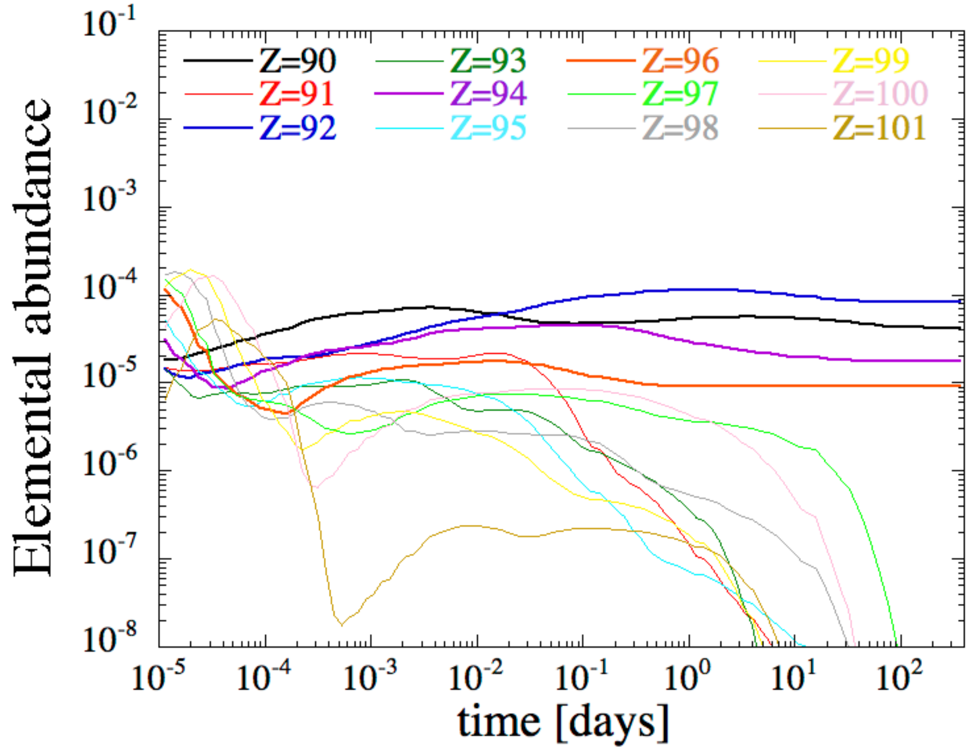
$$Q_{tot}=Q_{\beta}+Q_{fis}+Q_{\alpha}$$



Elemental abundances expected in the dynamical ejecta

Dynamical ejecta





Significant production of lanthanides and actinides (if neutrino interactions are negligible)

Very much dependent on the description of fission processes → Possible production of superheavy elements ?

Some open questions on the r-process in NSM remain …

- Impact of neutrinos & EC on the neutron richness during dynamical ejection

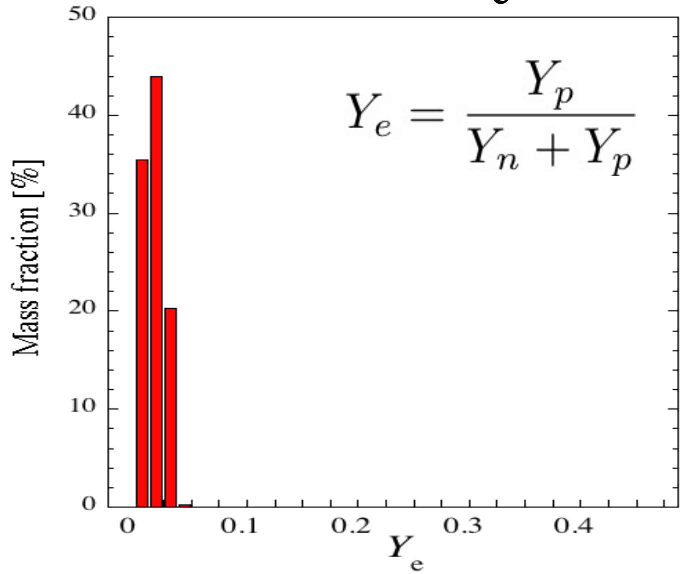
$$\nu_e + n \rightleftharpoons p + e^-$$

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

Still a major uncertainty affecting the nucleosynthesis in NS mergers:

electron (anti)neutrino absorption by free nucleons

Initial Y_e

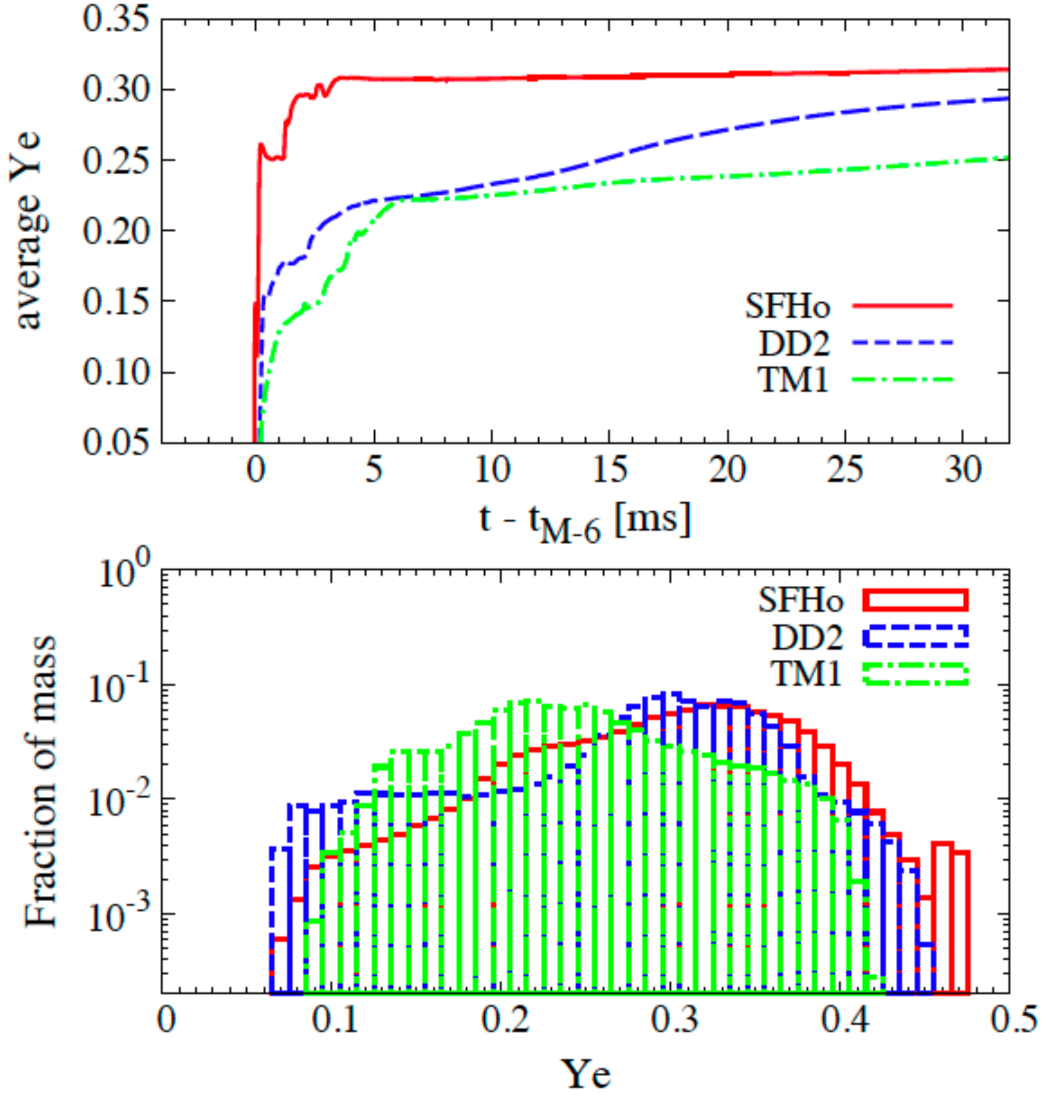


$$\nu_e + n \rightleftharpoons p + e^-$$

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

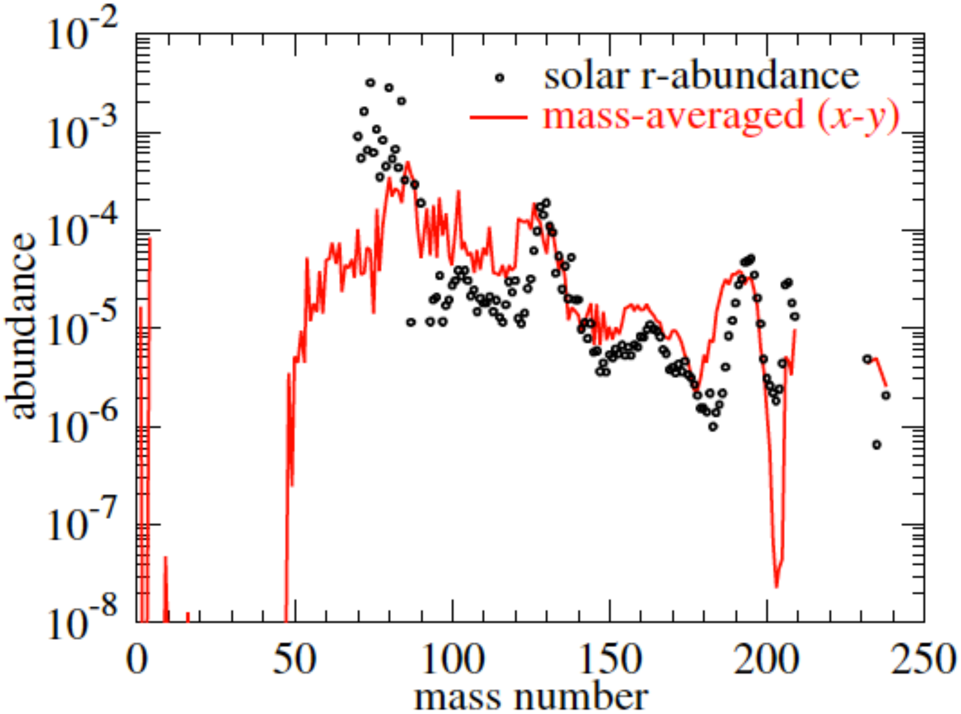
$$Y_e^{\nu\infty} \simeq \frac{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{mr}}{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{mr} + L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle f_{\bar{\nu}_e}^{mr}}$$

Also sensitive to the adopted EoS

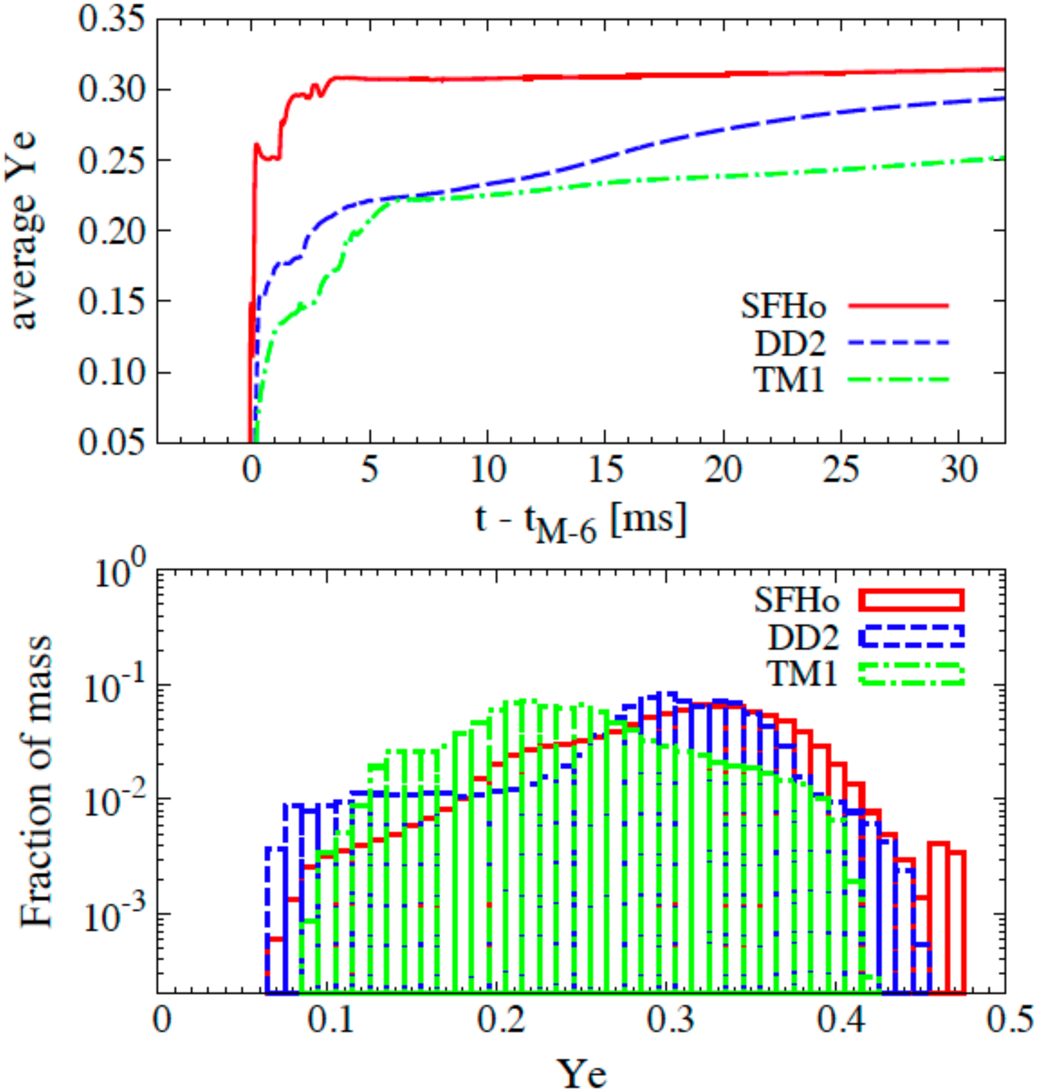


Wanajo et al. (2014); Sekiguchi et al. (2015)

Still a major uncertainty affecting the nucleosynthesis in NS mergers:
electron (anti)neutrino absorption by free nucleons



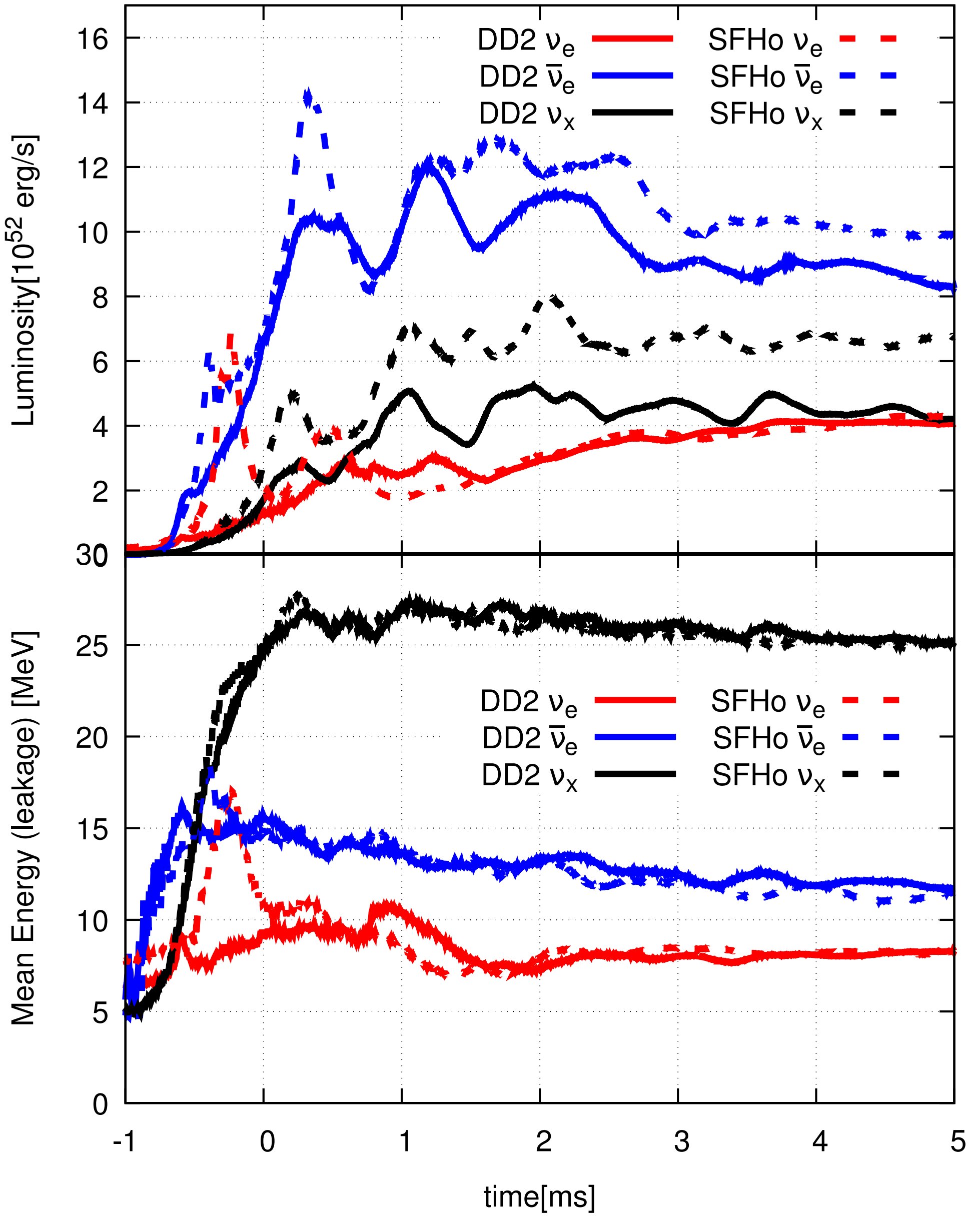
Production of A<140 nuclei in the dynamical ejecta



Wanajo et al. (2014); Sekiguchi et al. (2015)

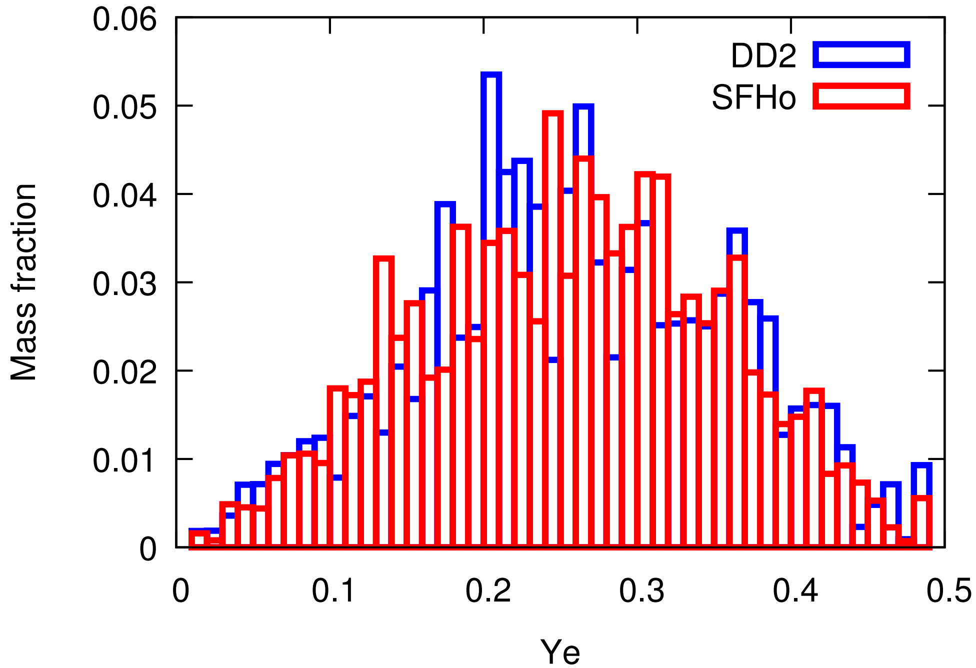
Improved Leakage-Equilibration-Absorption scheme (ILEAS)

R. Ardevol-Pulpillo, H.-T Janka, O. Just, A. Bauswein, MNRAS 485, 4754 (2019)



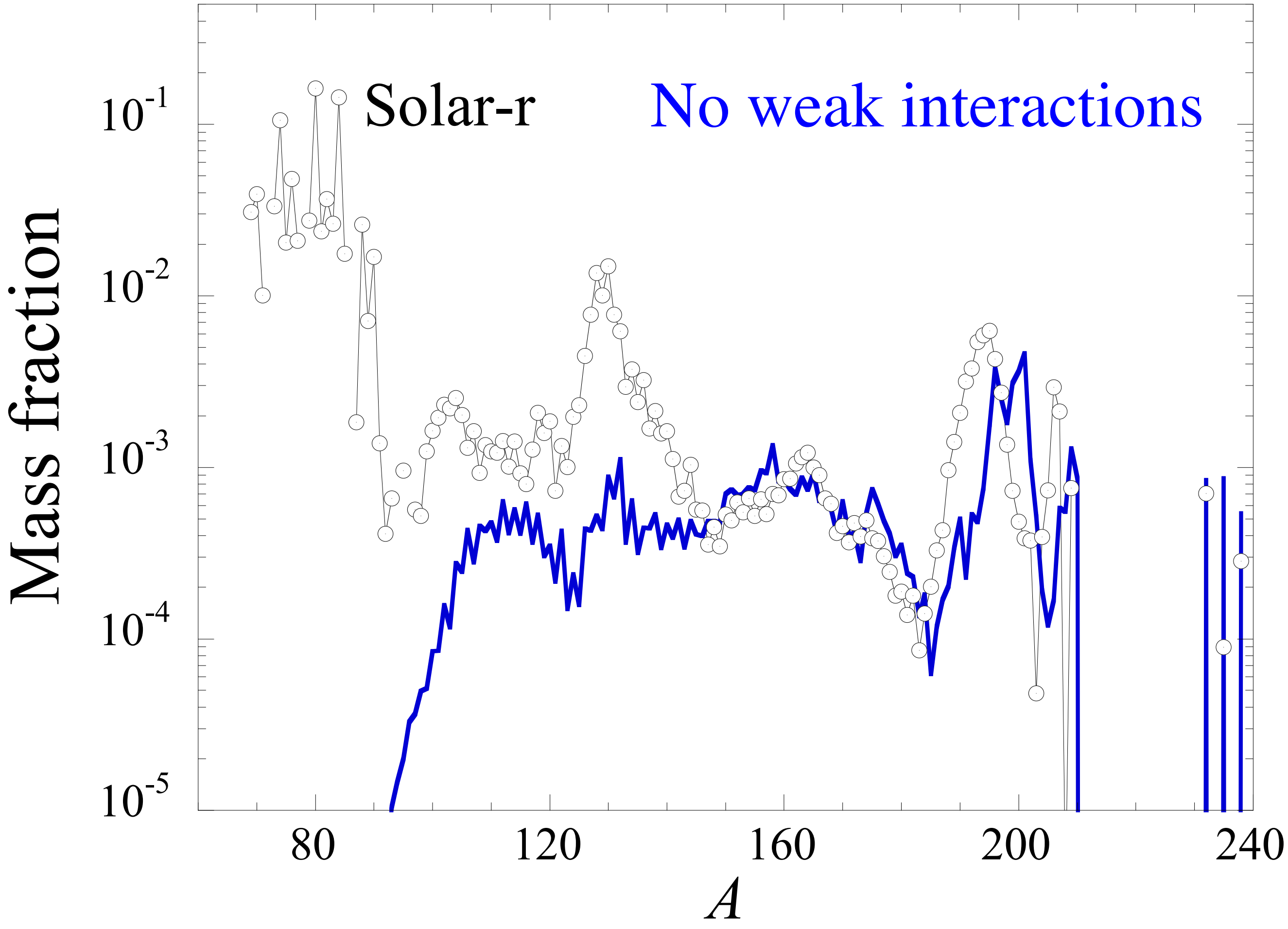
1.35-$1.35 M_o$ NS binary systems

Resulting Y_e of the ejected material



$< Y_e > \sim 0.26$

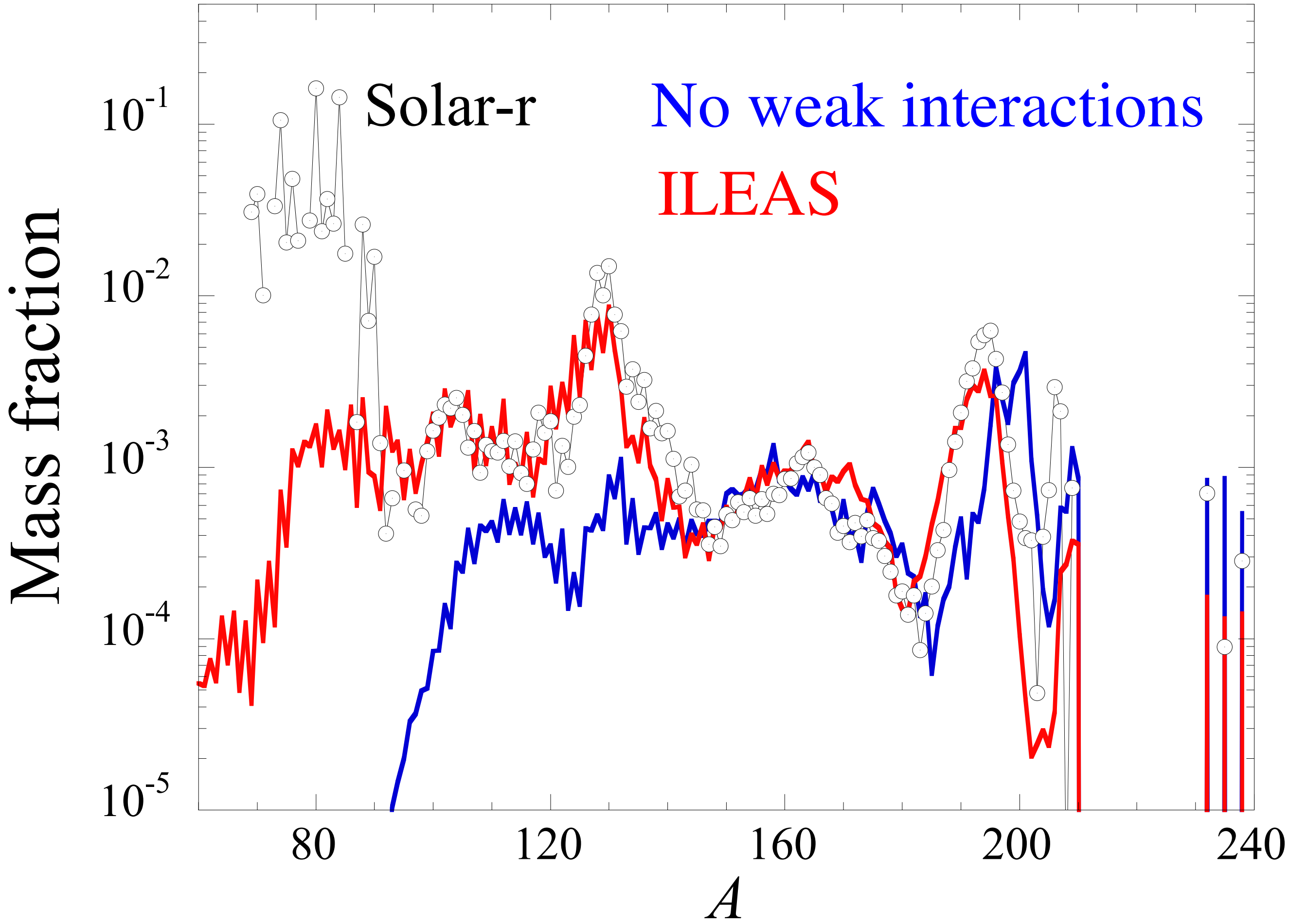
ILEAS predictions for NS-NS mergers



1.35-1.35 M_o

Production of *A*<140 nuclei in the dynamical ejecta

ILEAS predictions for NS-NS mergers



1.35-1.35 M_o

Production of 90 < *A* < 140 nuclei in the dynamical ejecta

Some open questions on the r-process in NSM remain …

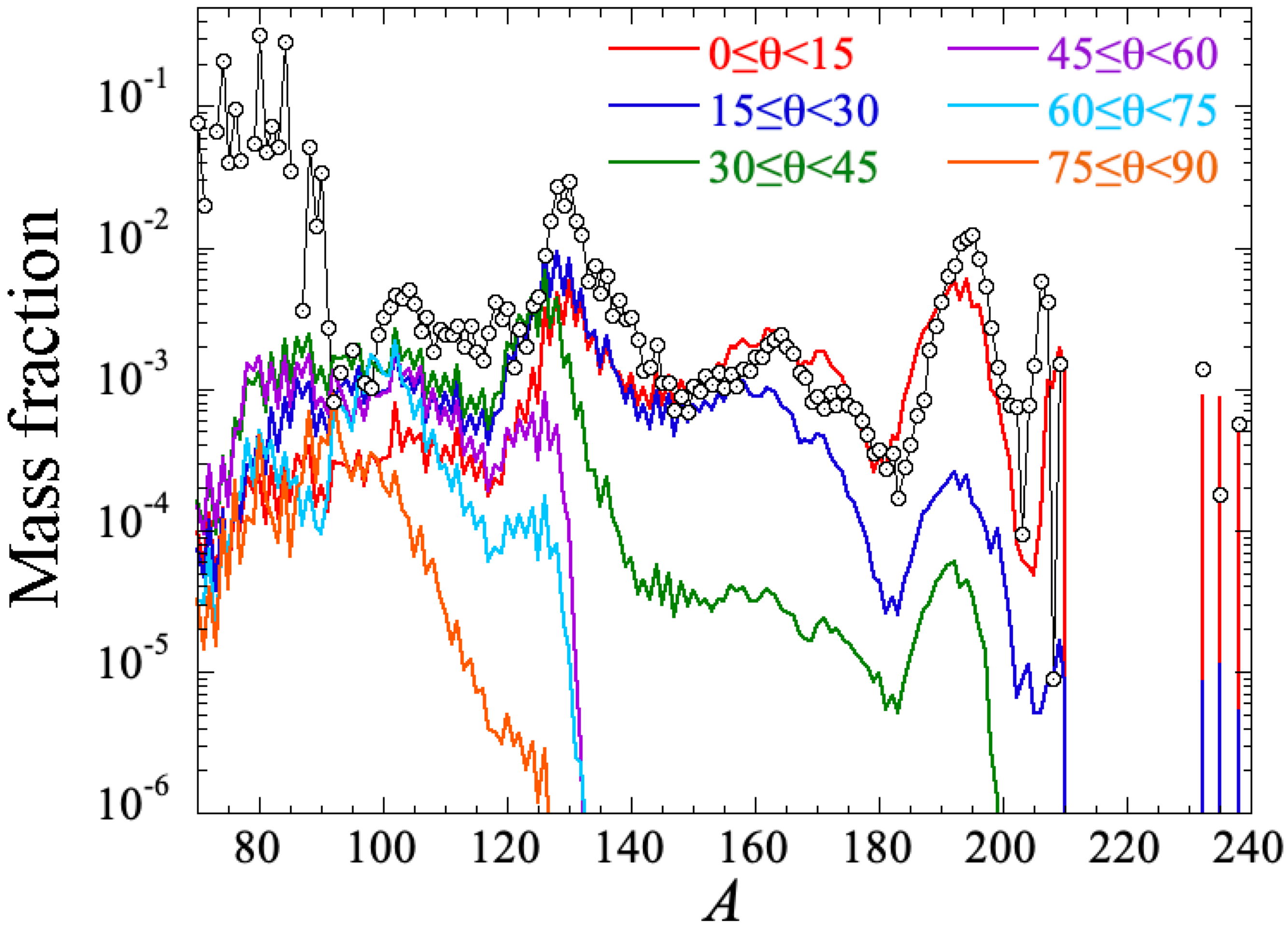
- Impact of neutrinos & EC on the neutron richness during dynamical ejection

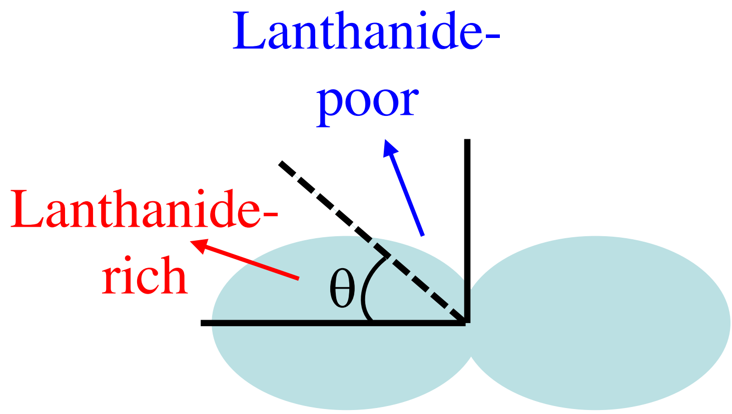
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

- Angular and velocity distribution of the ejecta

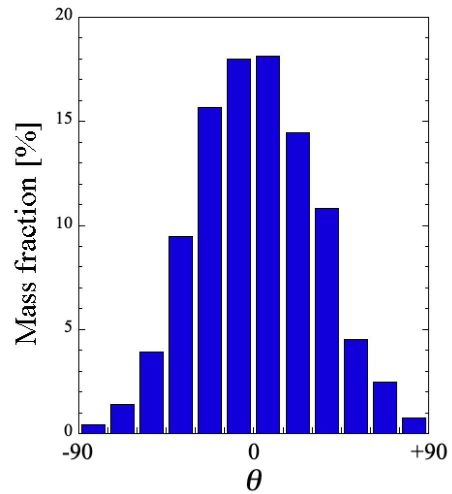
Angular distribution of the dynamical ejecta composition

1.35-1.35M_{o} NS prompt ejecta (with ILEAS ν-interactions)



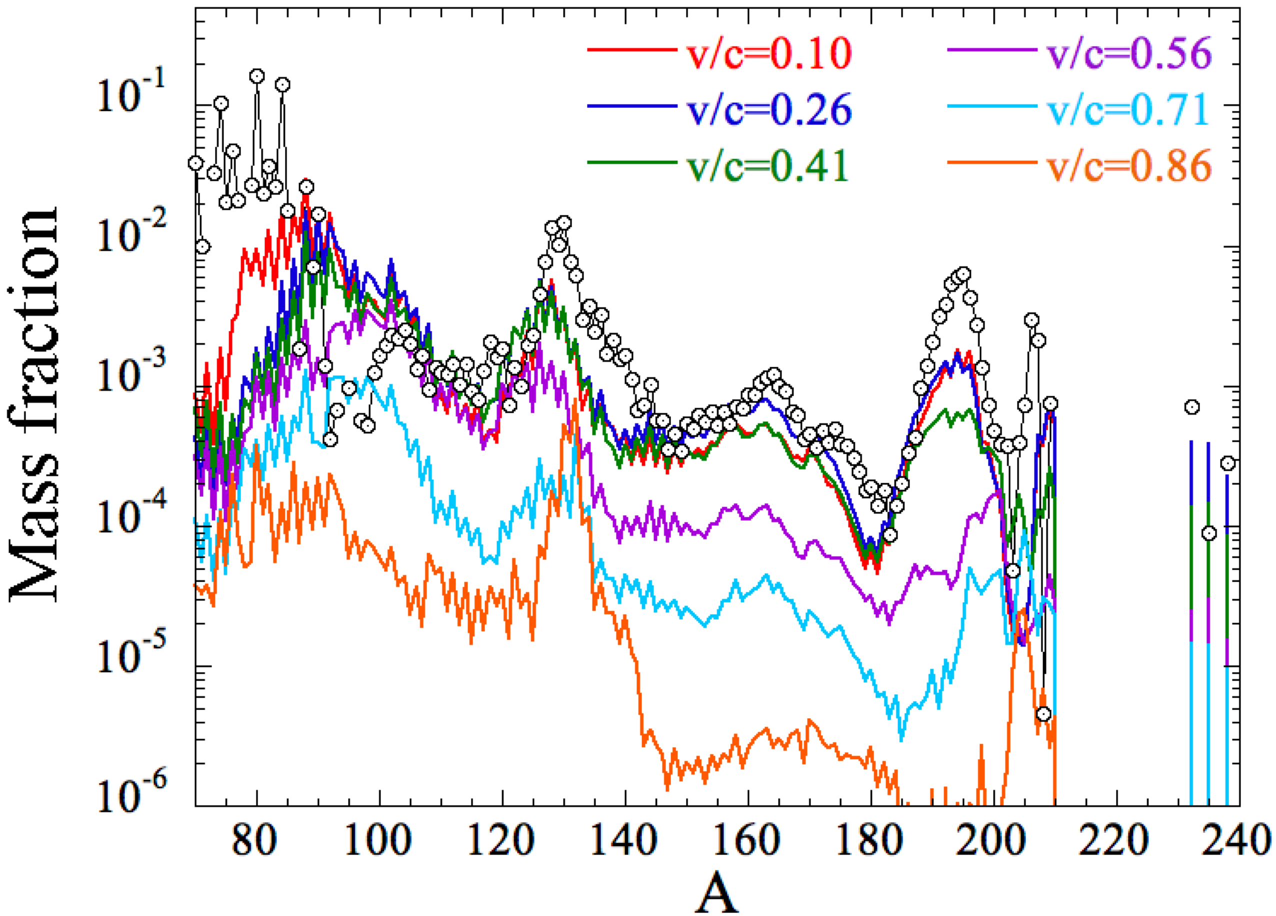


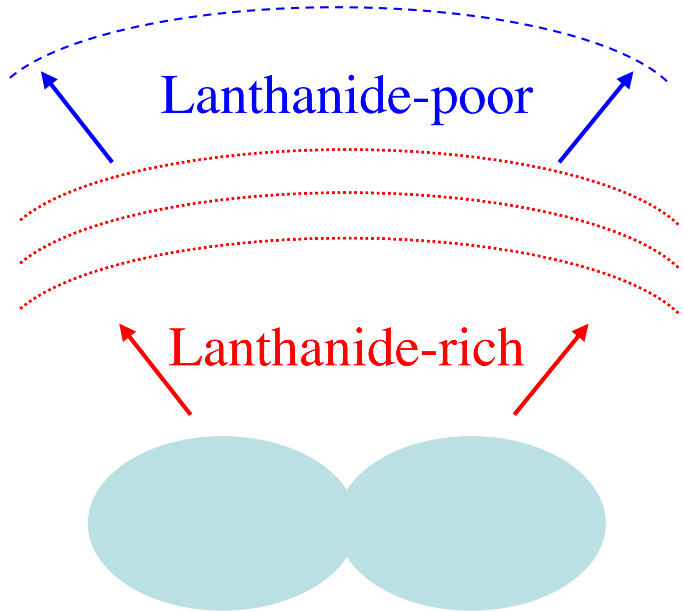
GW170817: $\theta_{obs} \sim 57 – 79^{o}$
(off-axis : $\theta' \sim 11\text{-}33^{o}$)

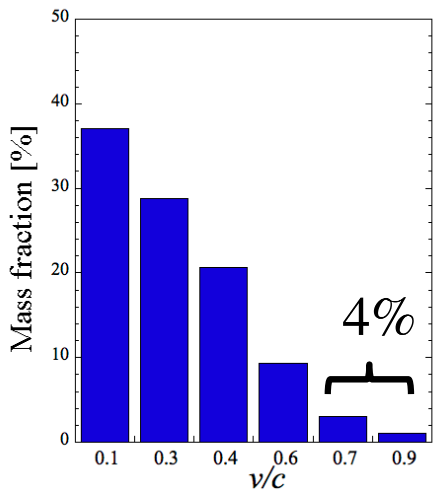


Velocity distribution of the ejected matter

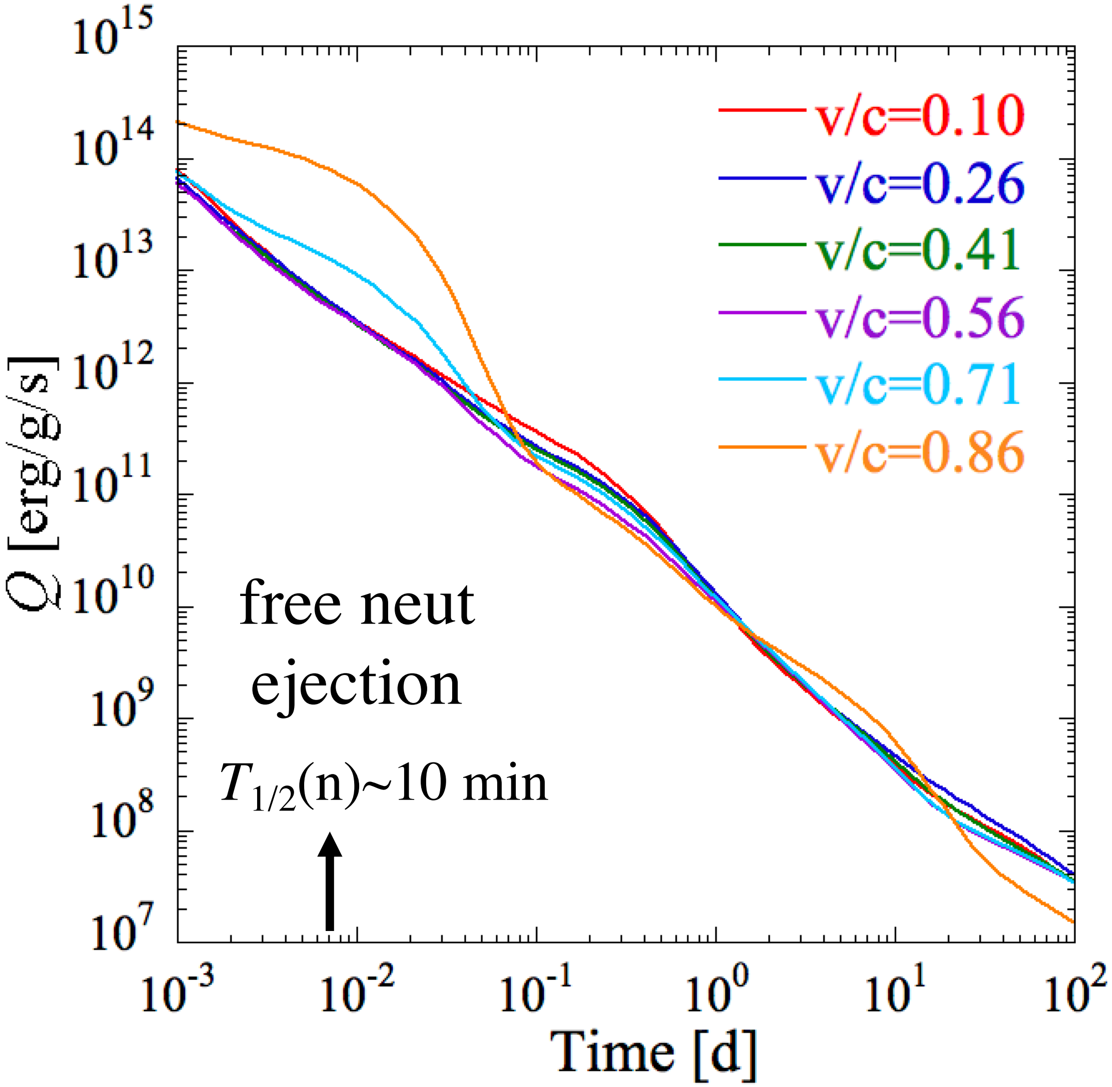
1.35-1.35M_o NS prompt ejecta (with EC; no ν-interactions)

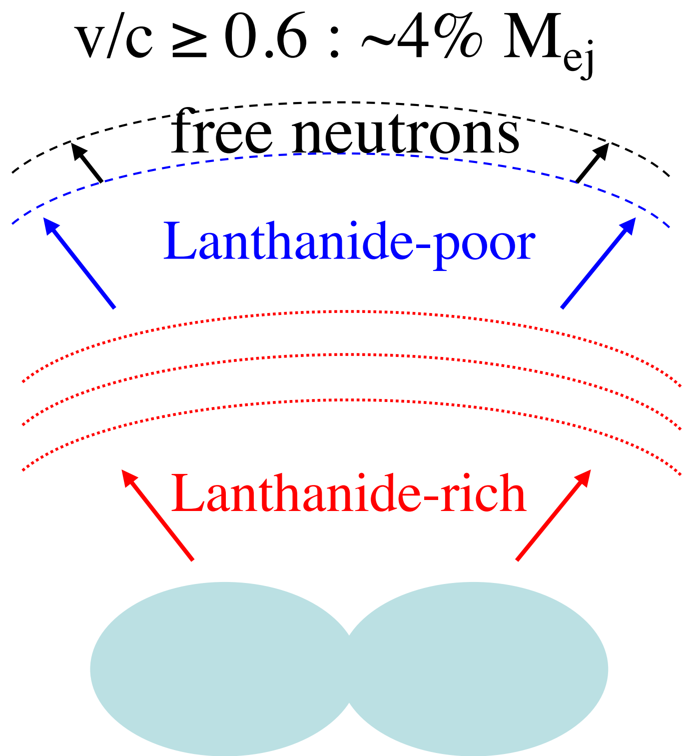






Velocity distribution of the energy release



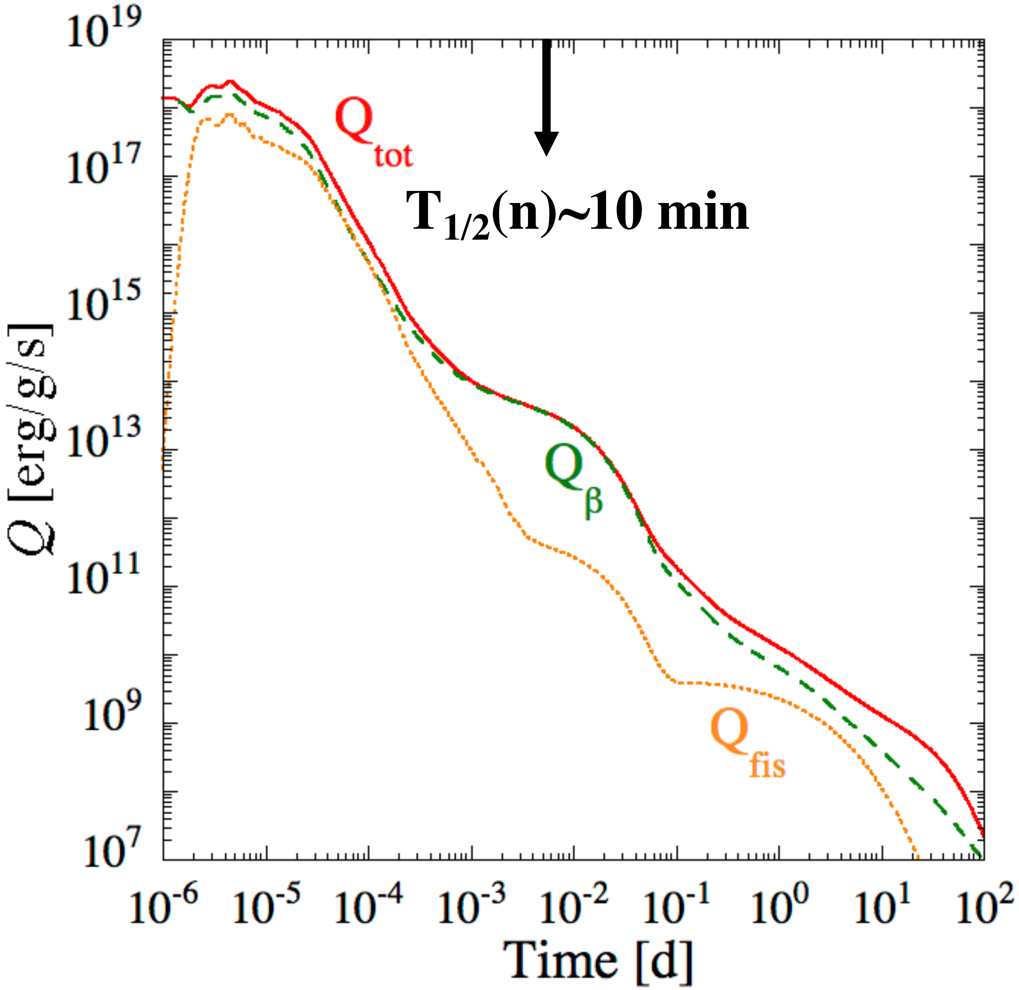


Free n emission sensitive to

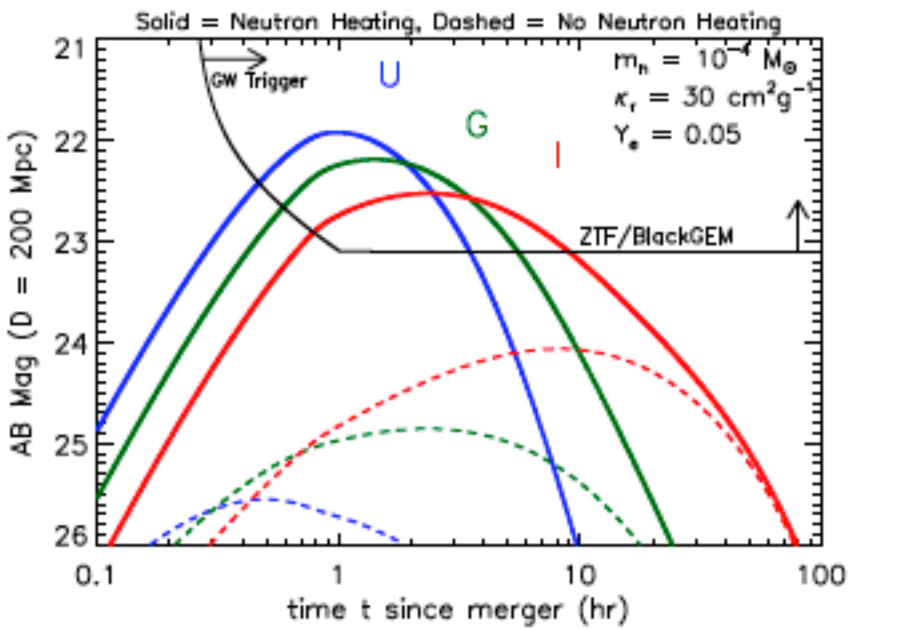
- Initial velocity & entropy
- EOS
- Mass asymmetry

On the possible fast ejection of free neutrons

Final mass-averaged decay heat of the dynamical ejecta



The β-decay of free neutrons may power a 'precursor' to the main kilonova emission: peak on a timescale of ~ few hours at U-band magnitude ~ 22 (at 200 Mpc), i.e. $L_{tot} \sim 10^{41}$ erg/s



Metzger et al. (2014)

Some open questions on the r-process in NSM remain …

- Impact of neutrinos & EC on the neutron richness during dynamical ejection

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

- Angular and velocity distribution of the ejecta

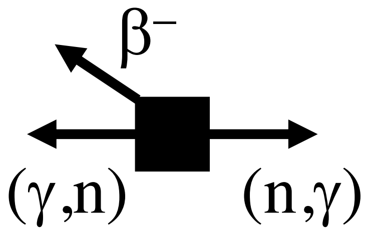
- Nuclear Physics aspects

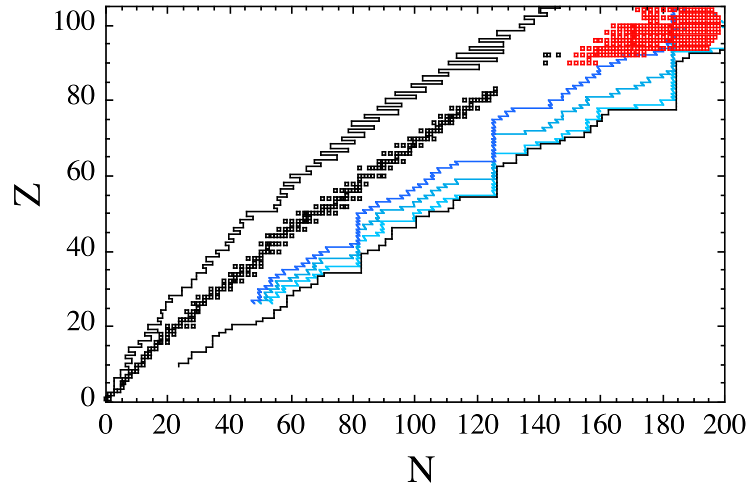
Another uncertainty: nuclear physics input

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

Main needs

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





Nucleosynthesis requires RATES for some 5000 nuclei !

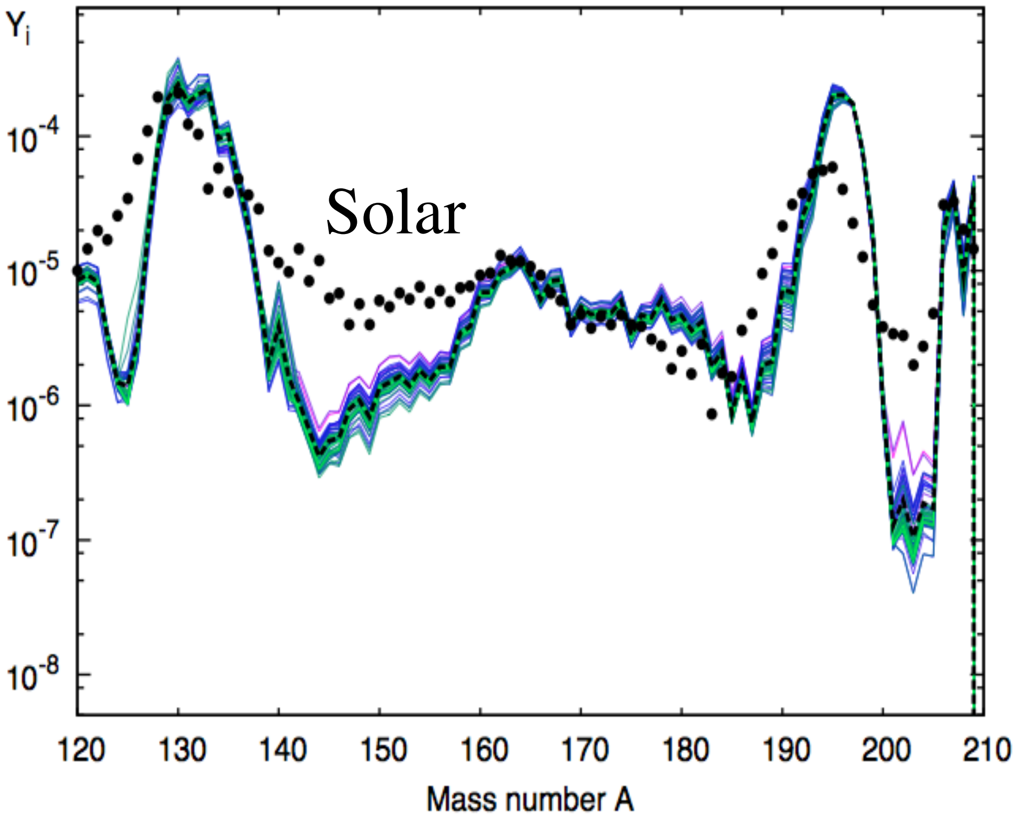
(and not only masses or β-decay along the oversimplified so-called "r-process path")

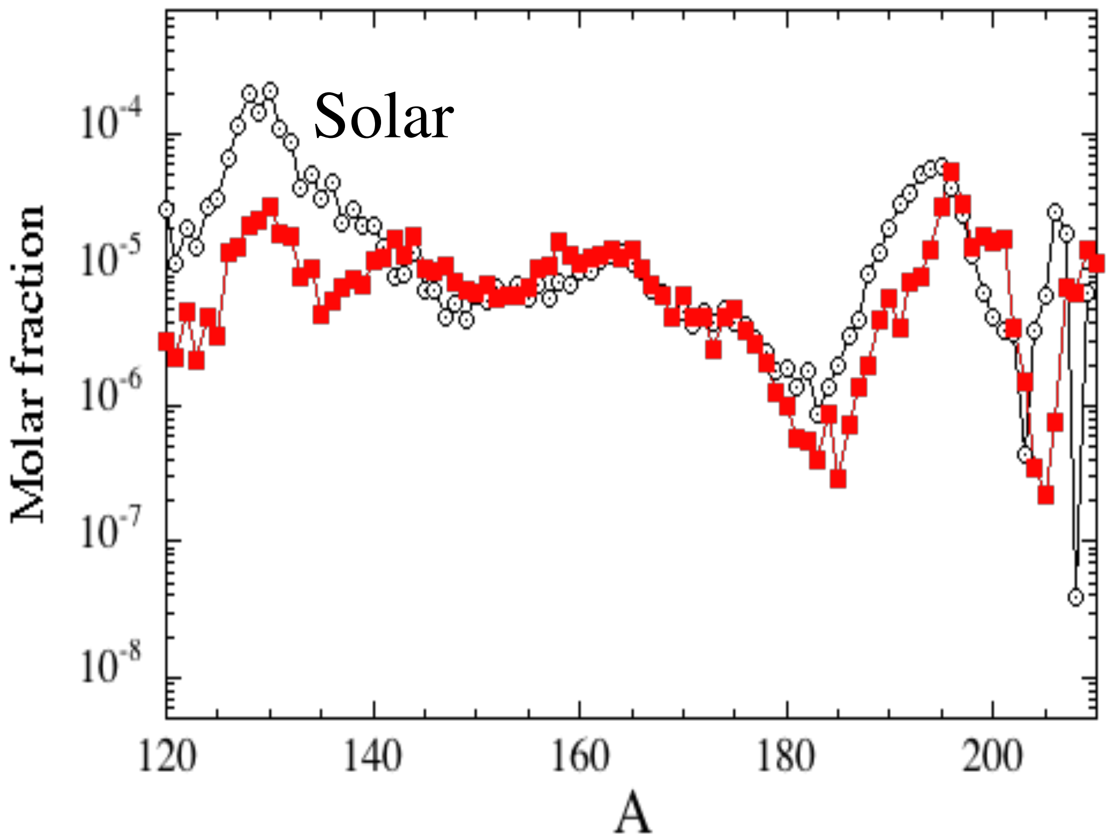
⇒ simulations rely almost entirely on theoretical predictions

In turn, theoretical models are tuned on available experimental data

Ongoing progress on both theoretical and experimental sides

Differences due to different Nuclear Physics inputs
(same trajectories for the prompt ejecta)





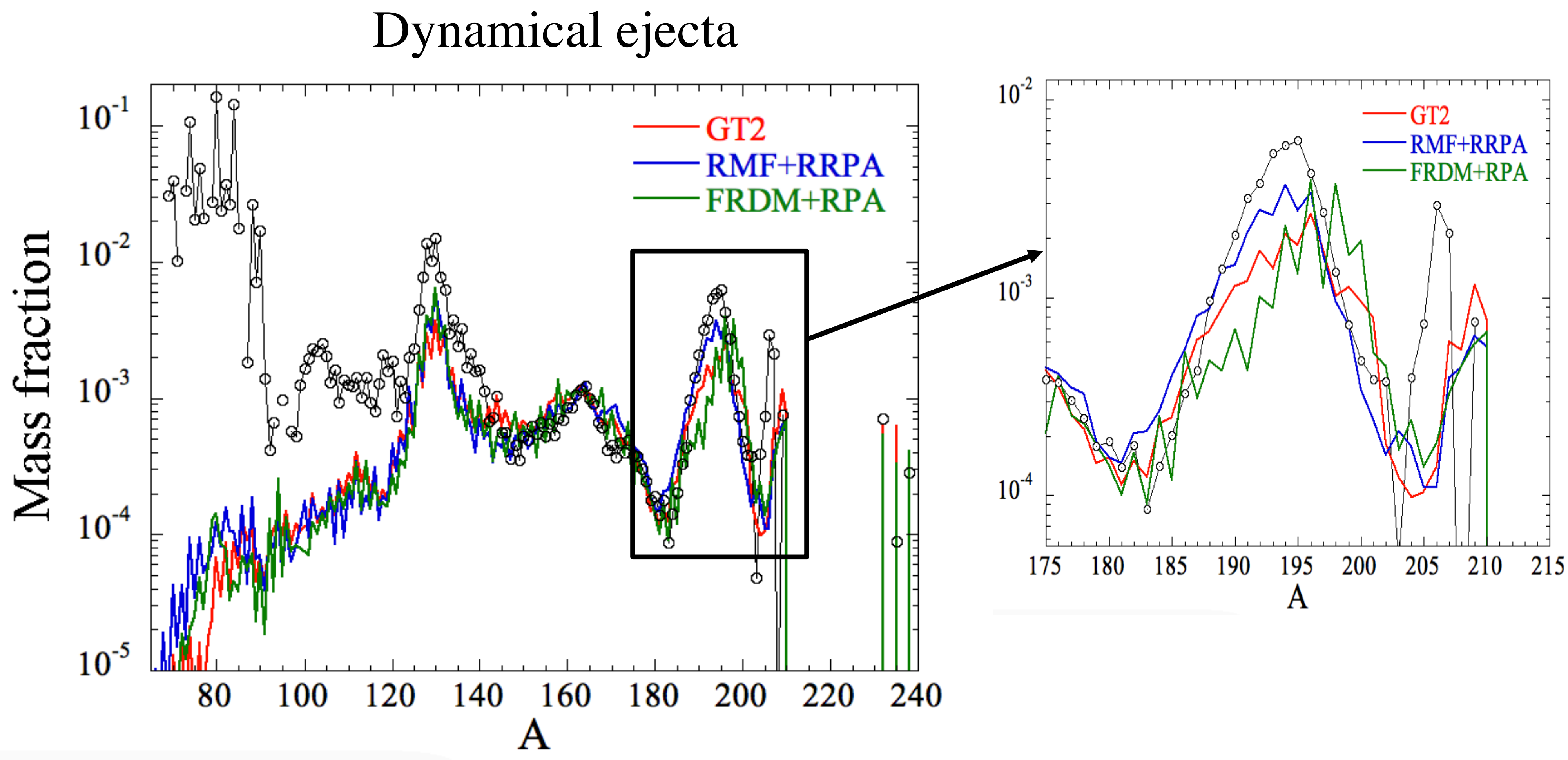
STILL MANY OPEN QUESTIONS

- **The reaction model**
  - **CN vs Direct capture for low-S_n & Isolated Resonance Regime**
- **Nuclear inputs to the reaction model** (almost no exp. data !)
  - **GS properties:** masses (correlations - GCM, odd-nuclei)
  - **E1-strength function:** GDR tail, PR, ε_γ=0 limit, *T*-dep, PC
  - **Nuclear level Densities (at low *E*):** *J*- and π-description, pairing, shell and collective effects & damping
  - **Optical potential:** the low-*E* isovector imaginary component
  - **Fission:** fission paths, NLD at the saddle points, FFD
- **The β-decay rates**
  - **Forbidden transitions, deformation effects, odd-nuclei, PC**

We are still far from being capable of estimating ***reliably*** the radiative neutron capture and β-decay of exotic n-rich nuclei
(and fission properties even for known nuclei)

Models exist, but corresponding uncertainties are usually not estimated

Impact of β-decay rates on the r-process nucleosynthesis in NS mergers



Large impact of the β-decay rate – set the synthesis timescales

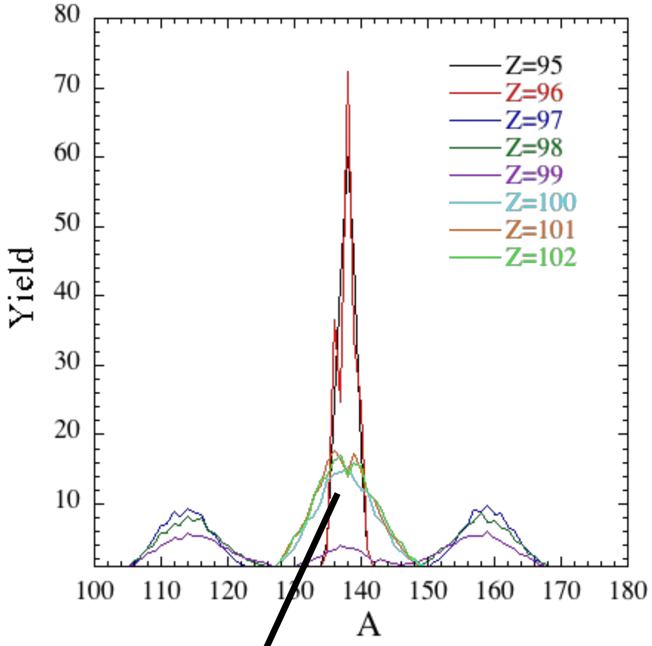
→ Need *deformed* "microscopic" calculation (MF+QRPA) including GT+FF transitions, odd nuclei, PC, ….

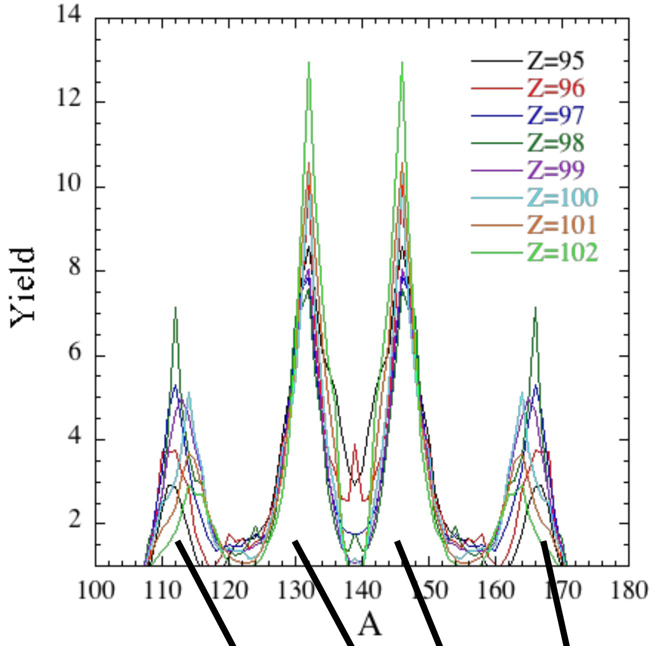
Sensitivity of dynamical composition to the fission fragment distribution

along the A=278 isobar (from the N=184 closed shell)

GEF v1.4
K. Schmidt et al. (2013)

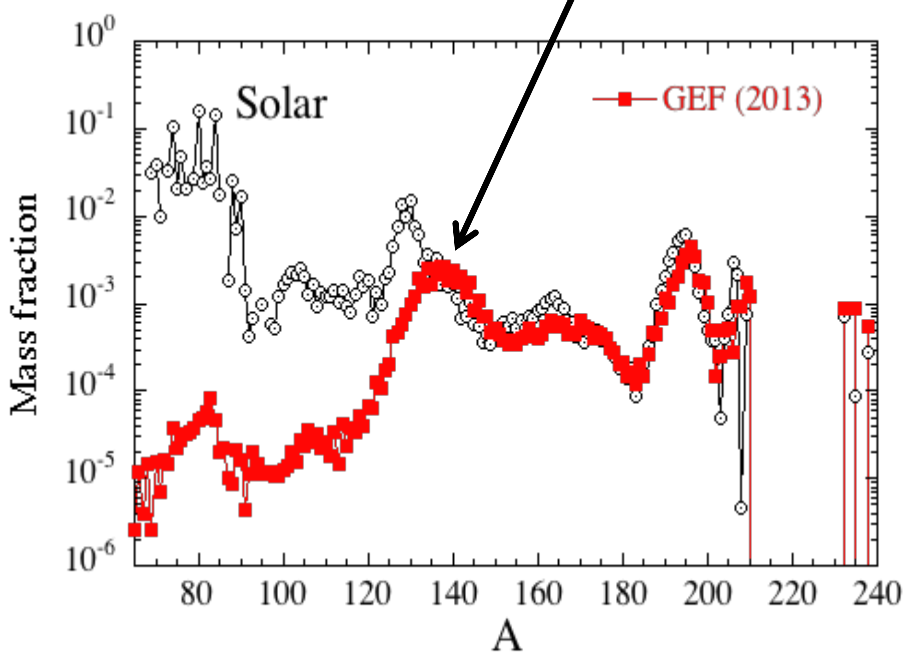
Semi-empirical mic-mac Scission Point model

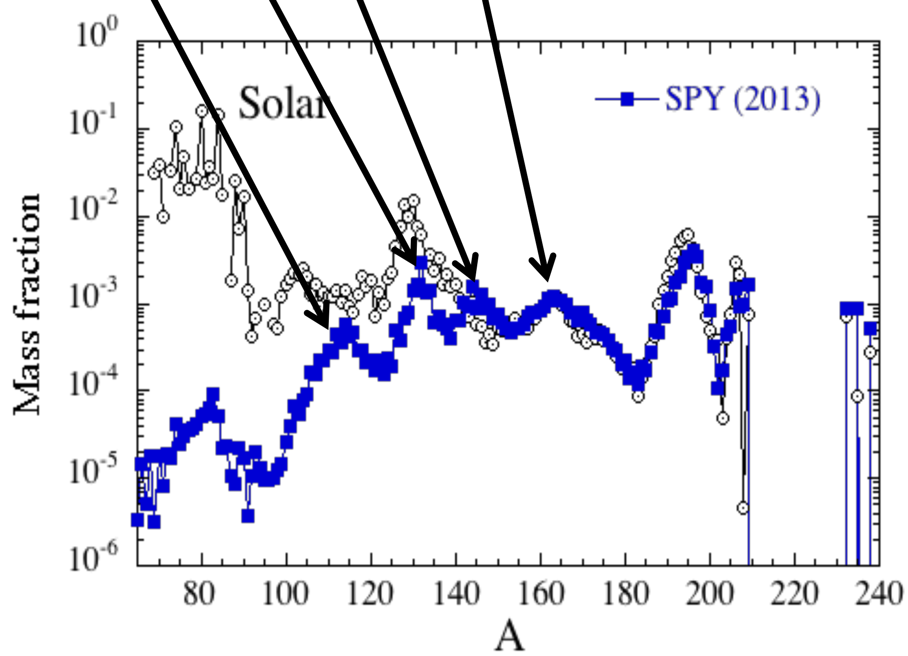




SPY:
S. Panebianco et al. (2013)

Parameter-free Scission Point model based on D1S potential energy surfaces





Some open questions on the r-process in NSM remain …

- Impact of neutrinos & EC on the neutron richness during dynamical ejection

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

- Angular and velocity distribution of the ejecta
- Nuclear Physics aspects
- Frequency and properties of NS binary systems (in part, coalescence time)

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

1. 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)

Conclusion in term of amount of r-enrichment:

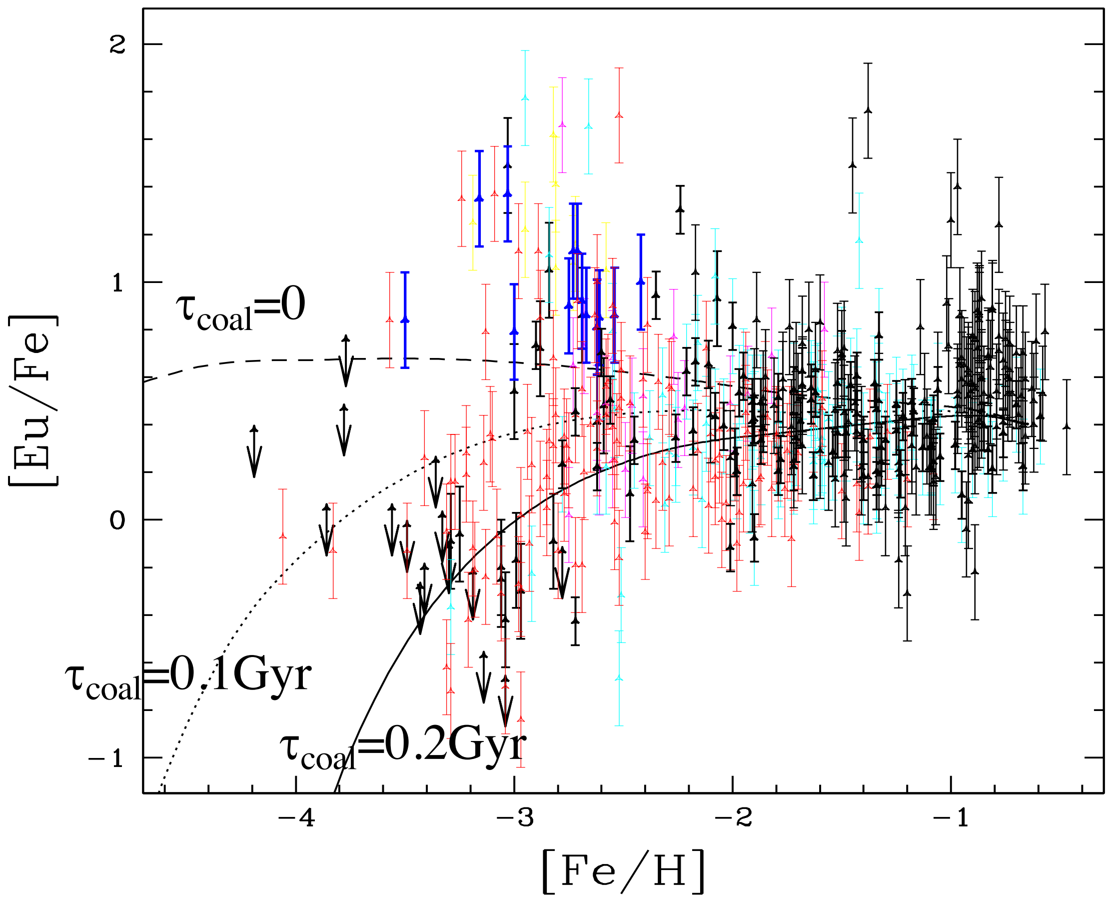
If GW170817 is statically a representative event, NS mergers are likely to be the main r-process site in the Milky Way and possibly in other galaxies.

Challenges for r-process in NS mergers

Chemical Evolution of r-elements in the Galaxy (halo stars)

→ early enrichment of Eu

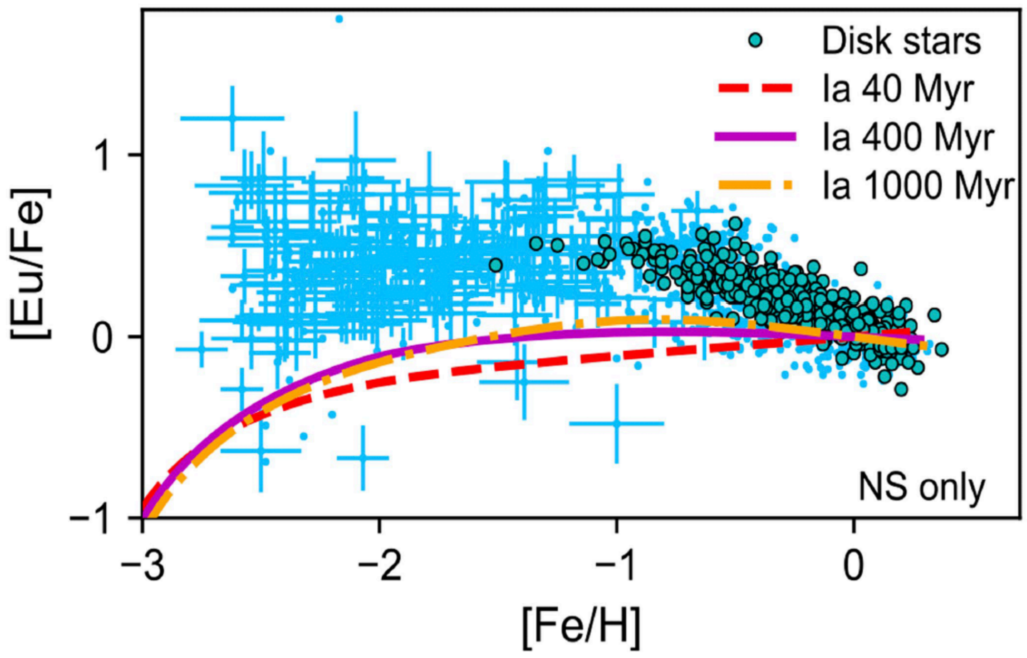
→ abundance scatter in low-metallicity stars



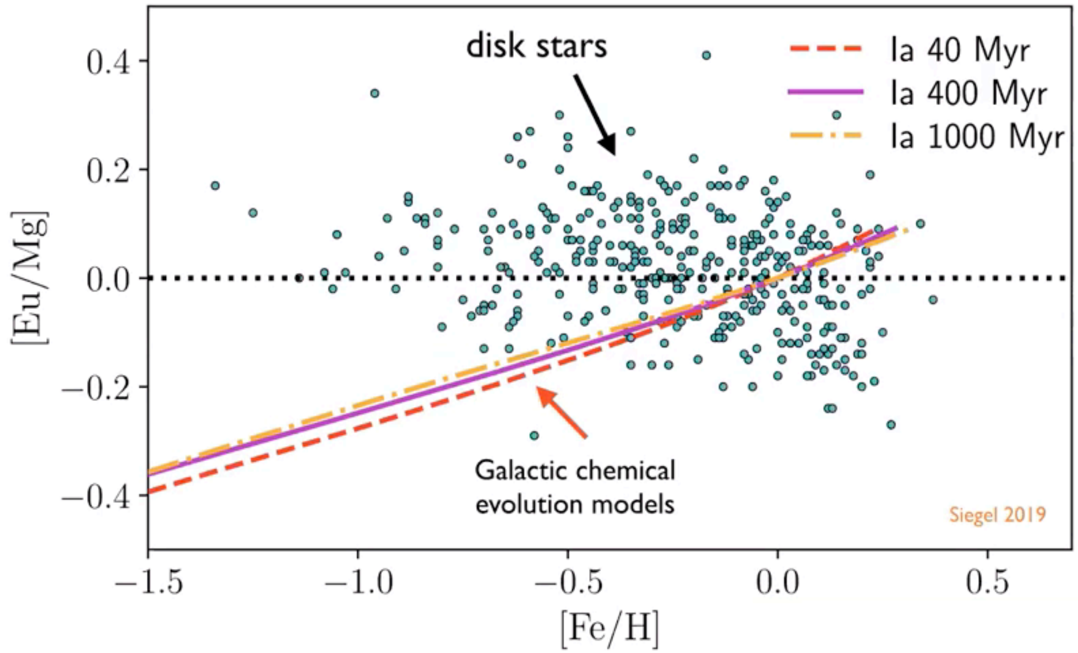
Vangioni et al. (2015)

Challenges for r-process in NS mergers

r-process vs Fe evolution
for disk stars



r-process vs α-elements
evolution for disk stars



Coté et al. (2018)
Siegel et al. (2019)

Some open questions on the r-process in NSM remain …

- Impact of neutrinos & EC on the neutron richness during dynamical ejection

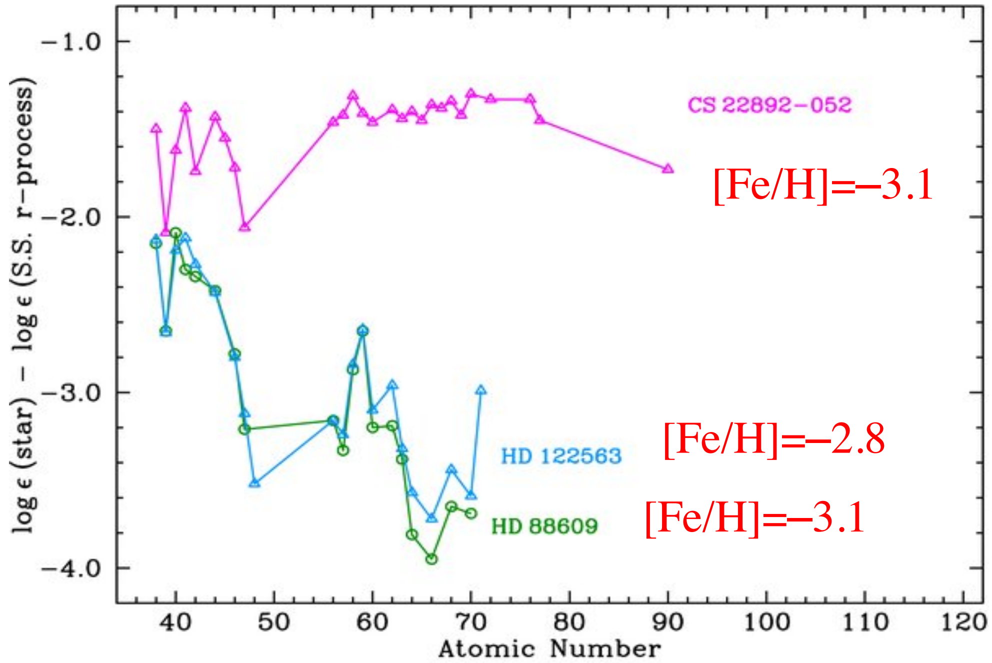
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

- Angular and velocity distribution of the ejecta
- Nuclear Physics aspects
- Chemical Evolution of the Galaxy
- Comparison with spectroscopic observation, in particular with *r*-enrichment in old (ultra-metal-poor) stars, ultra-faint dwarf galaxies, globular clusters, …

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

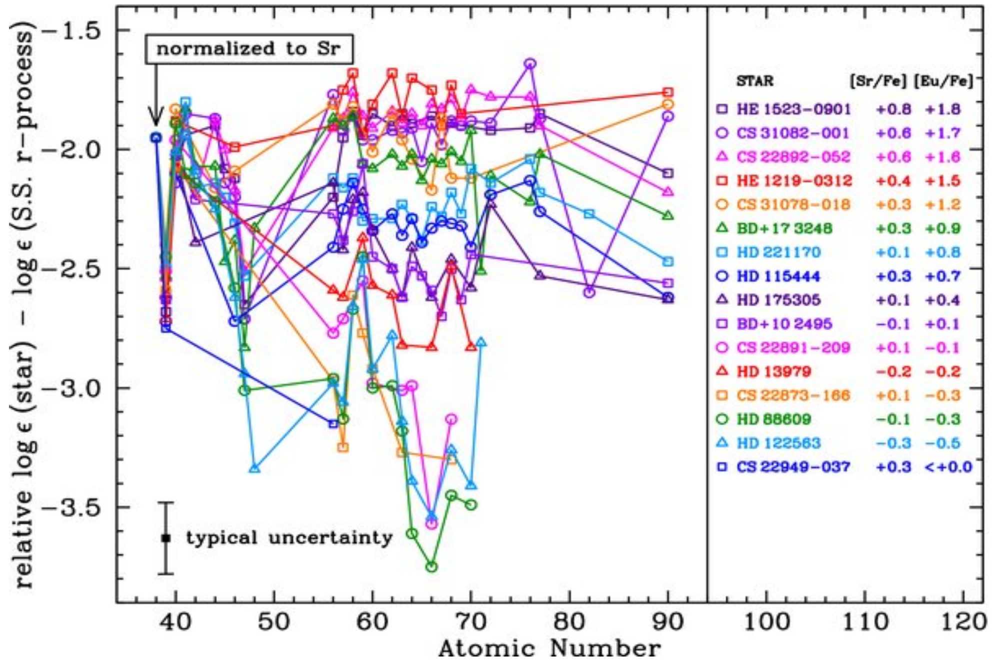
Differences between the SS r-process and stellar abundances in metal-poor stars

Honda et al (2007)
ApJ 666, 1189



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

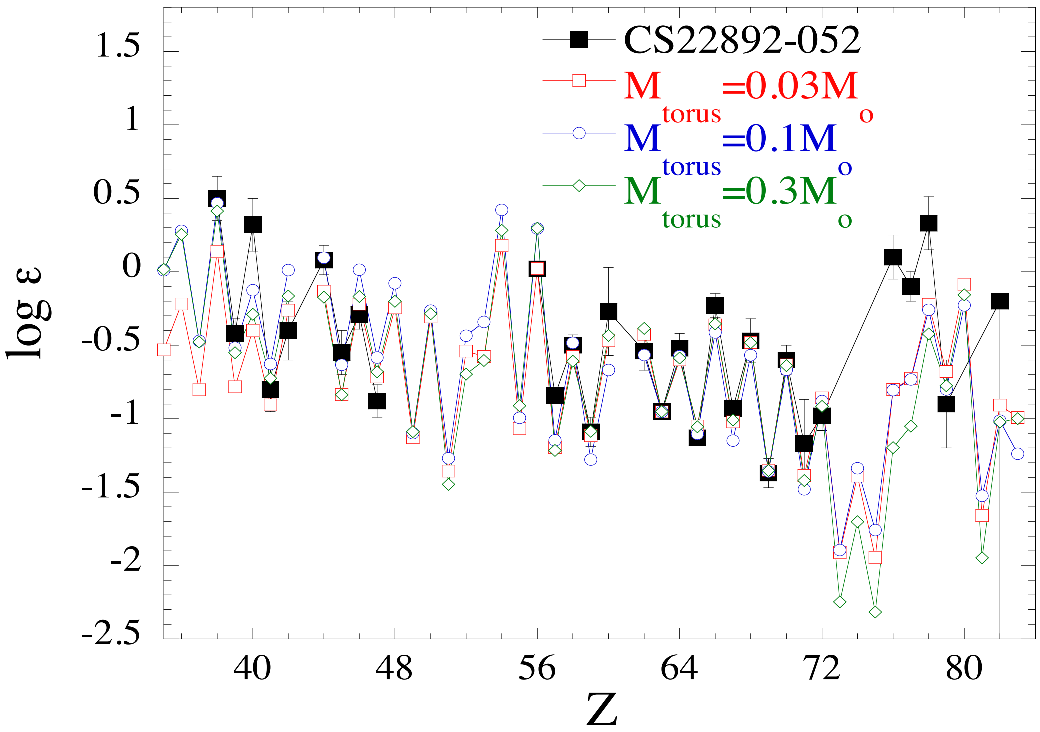
Roederer et al (2010)
ApJ 724, 975



Comparison with observation in low-metallicity r-process-rich stars

2 extreme cases

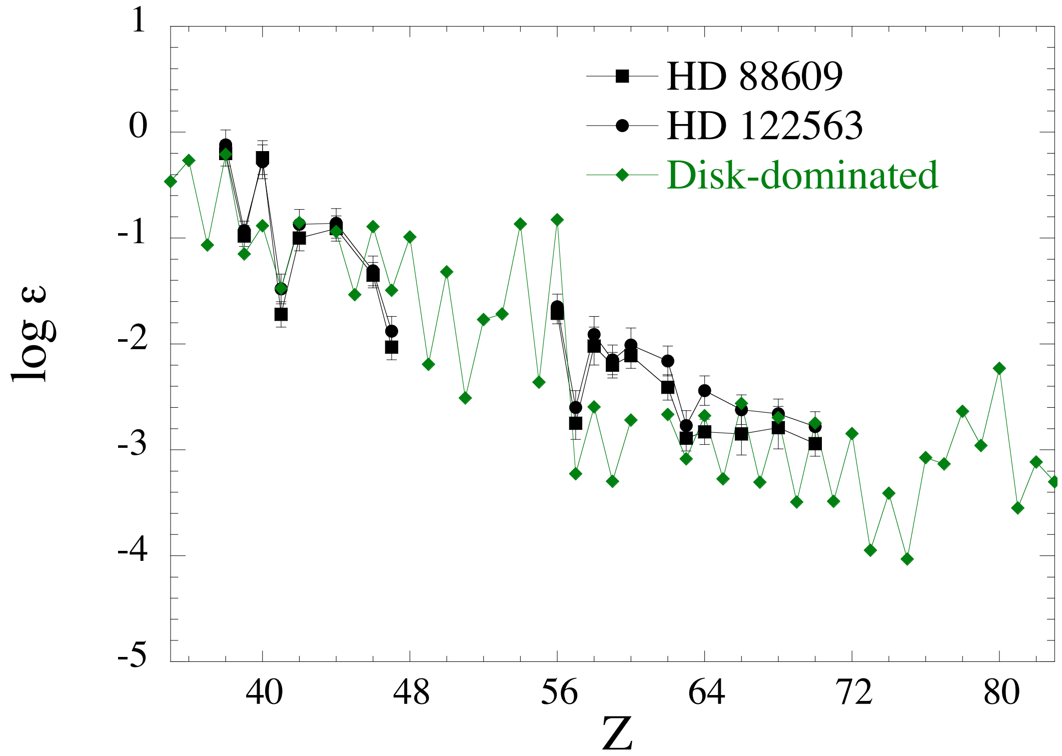
Main trend: rather solar-like distribution



Dynamical + Disk ejecta (mass averaged)

- for 56 ≤ Z ≤ 76 : « Universal » solar-like distribution
- for Z < 56 : Deviation wrt solar (0.5dex)

Star deficient in heavy r elements



Suppressed dynamical ejecta (only ~1%) in particular for NS-BH systems

- Asymmetric ejecta
- Small ejecta (NS accreted by the BH)

Conclusions

The astrophysical site for the *r*-process remains puzzling !

Compact Object Mergers (NS-NS;NS-BH) :

- First analysis of GW170817 compatible with *r*-process
- Recent robust hydrodynamical simulations
  Successful solar-like *r*-process for $A \geq 90$ nuclei from Dynamical and Disk ejecta

But still some major open questions, in particular

- Neutrino effects in relativistic models
- Angle and velocity dependence
- Nuclear physics inputs
- Chemical evolution of the Galaxy