The r-process nucleosynthesis

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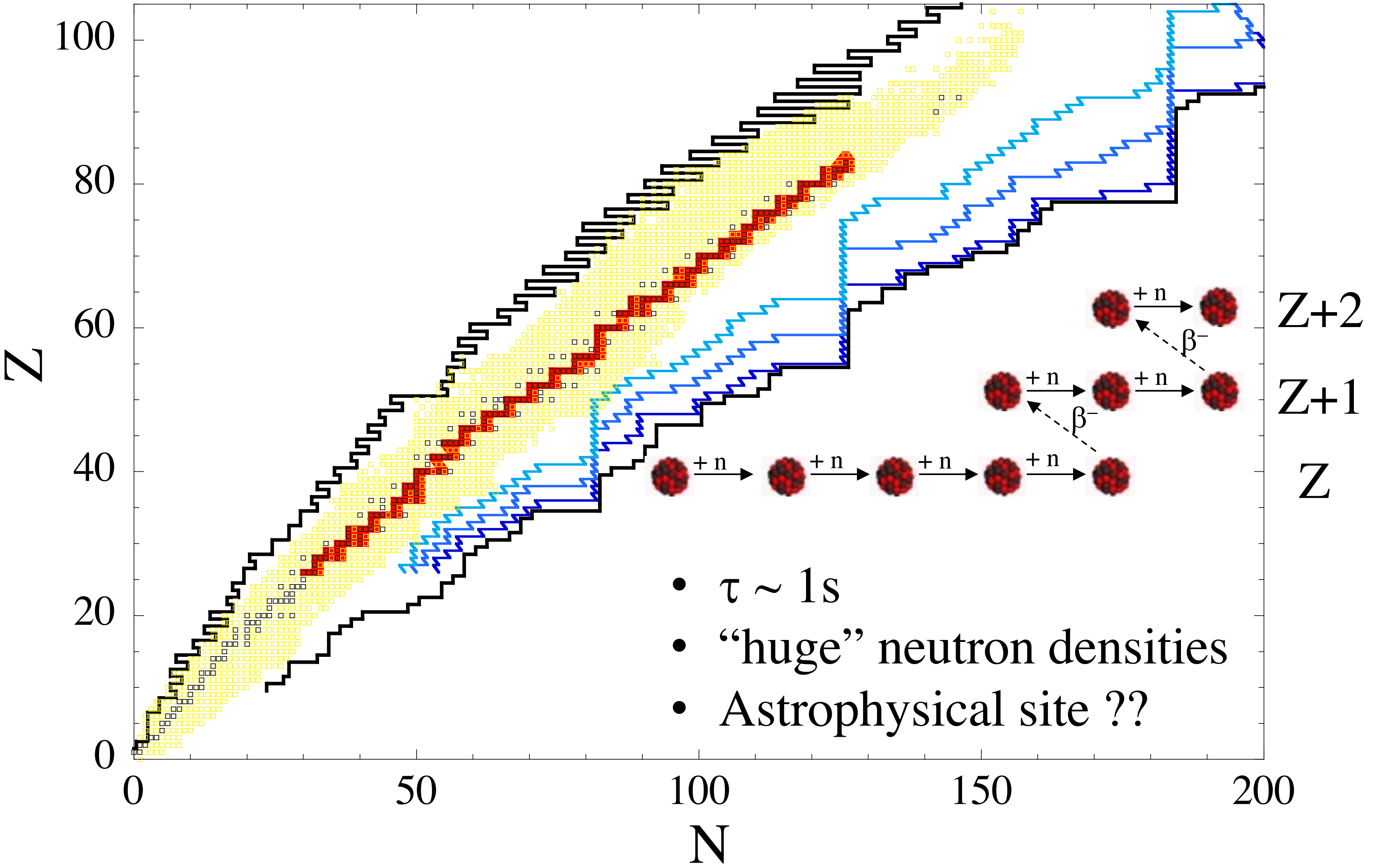
The rapid neutron-capture process (r-process) of nucleosynthesis



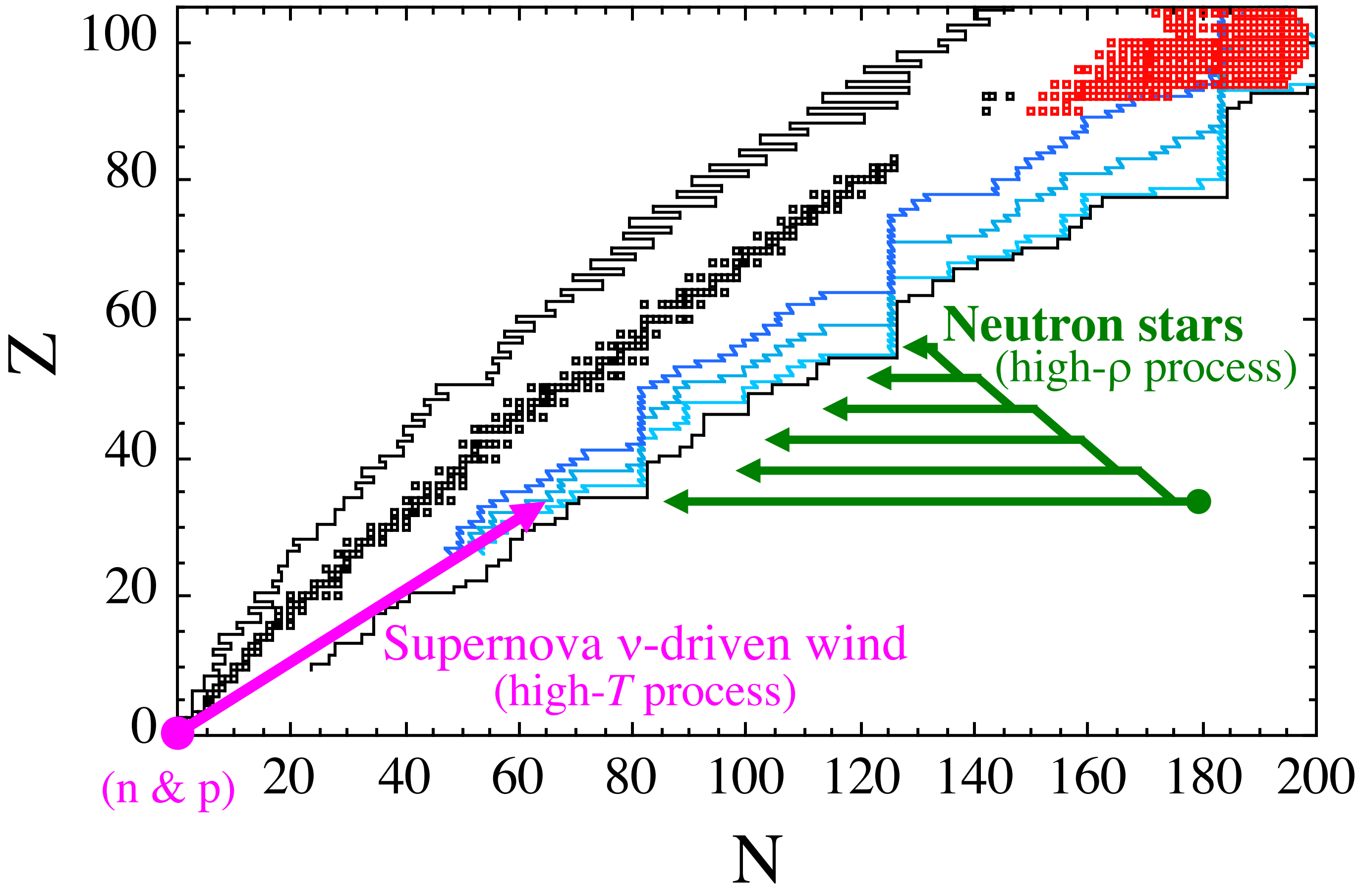
- τ ~ 1s
- “huge” neutron densities
- Astrophysical site ??

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

Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as

one of the top 11 questions in Physics and Astronomy

("Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century": 2003,
National research council of the national academies, USA)

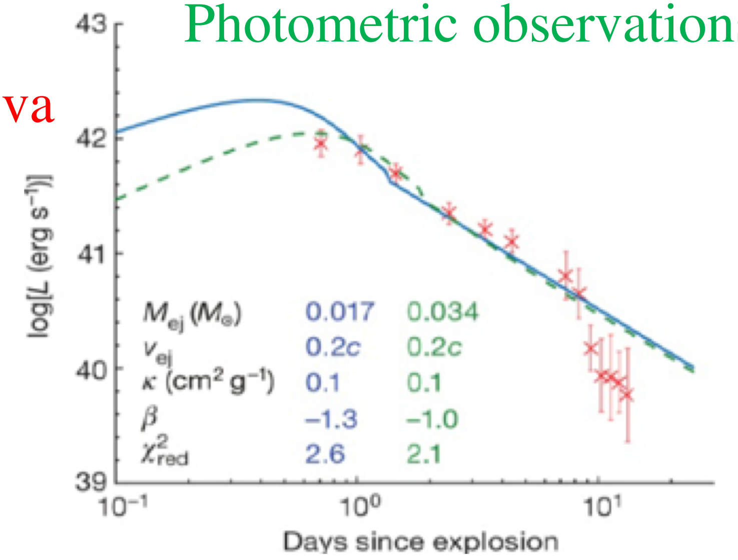


The first analysis of the GW170817/AT2017fgo light curve

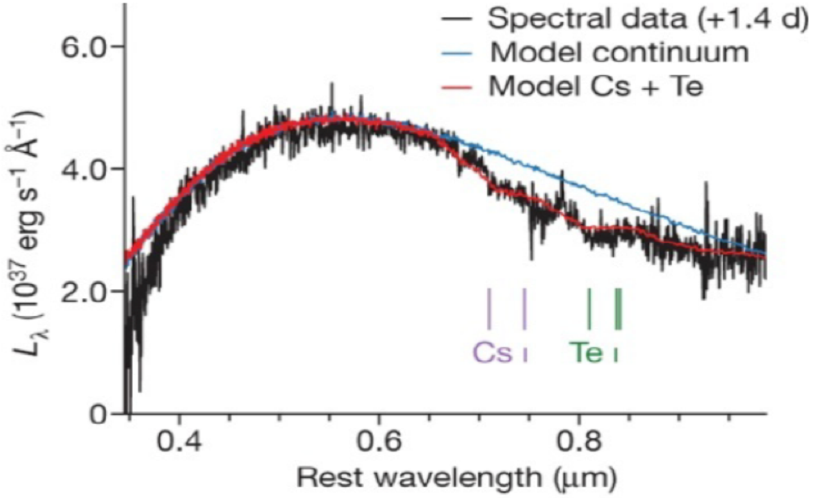
- The kilonova light curve is compatible with an overall ejecta mass ($M \approx 0.065\ M_\odot$)
  - "Blue" *lanthanide-free* component with $M_{ej} \approx 0.019\ M_\odot$ & $v_{ej} \approx 0.26c$
  - "Red" *lanthanide-rich* component with $M_{ej} \approx 0.046\ M_\odot$ & $v_{ej} \approx 0.15c$

Kilonova

Photometric observations



Spectroscopic observations



- The ejected mass and a 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, SG, Janka, Just, 2011, 2013, 2014, 2015)

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
$M = 10^{-3} – 2\ 10^{-2} M_o$

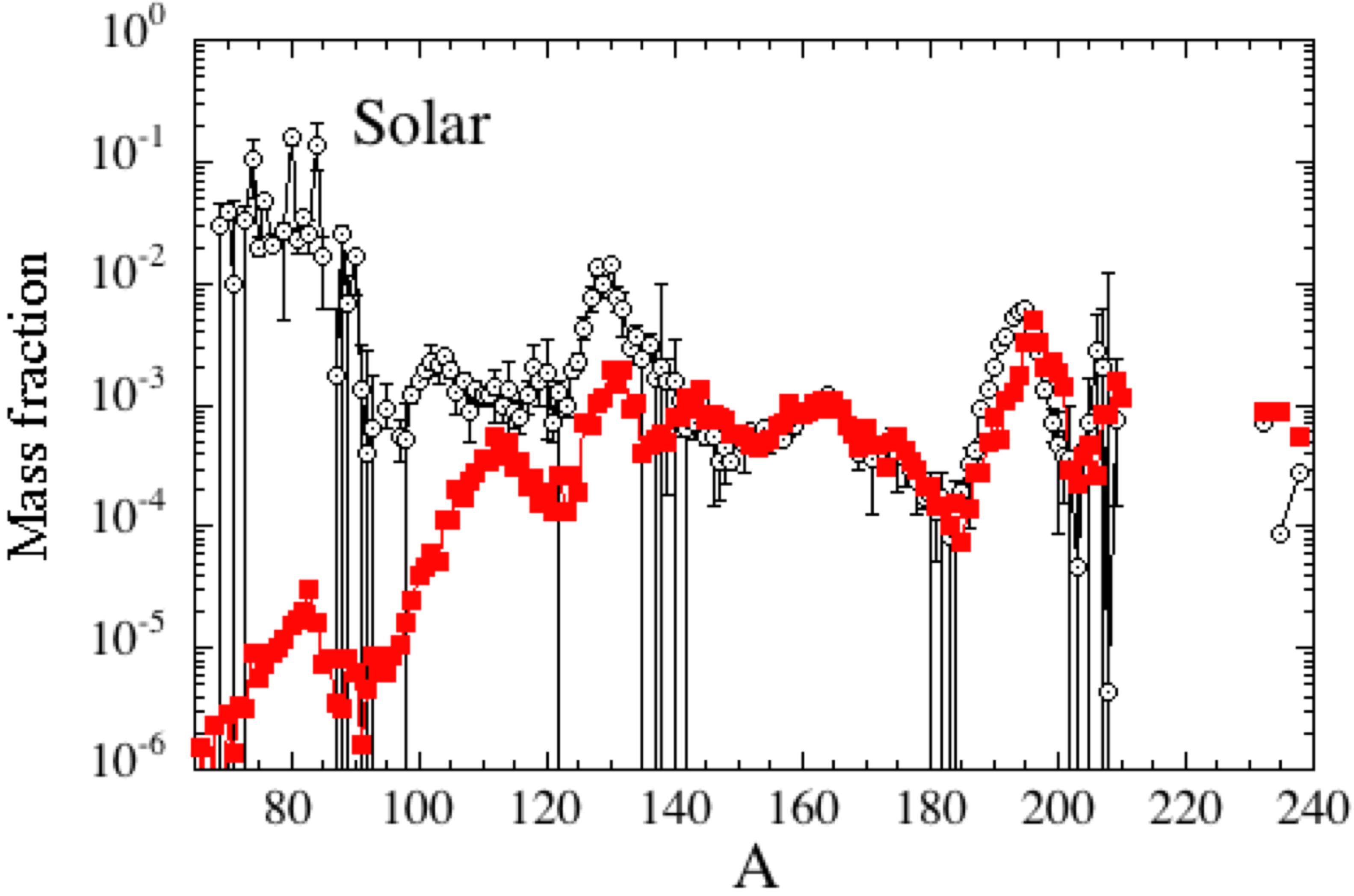
→ different ejecta velocities
$v/c = 0.1 - 0.4$

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

(see also e.g. Korobkin et al. 2012)

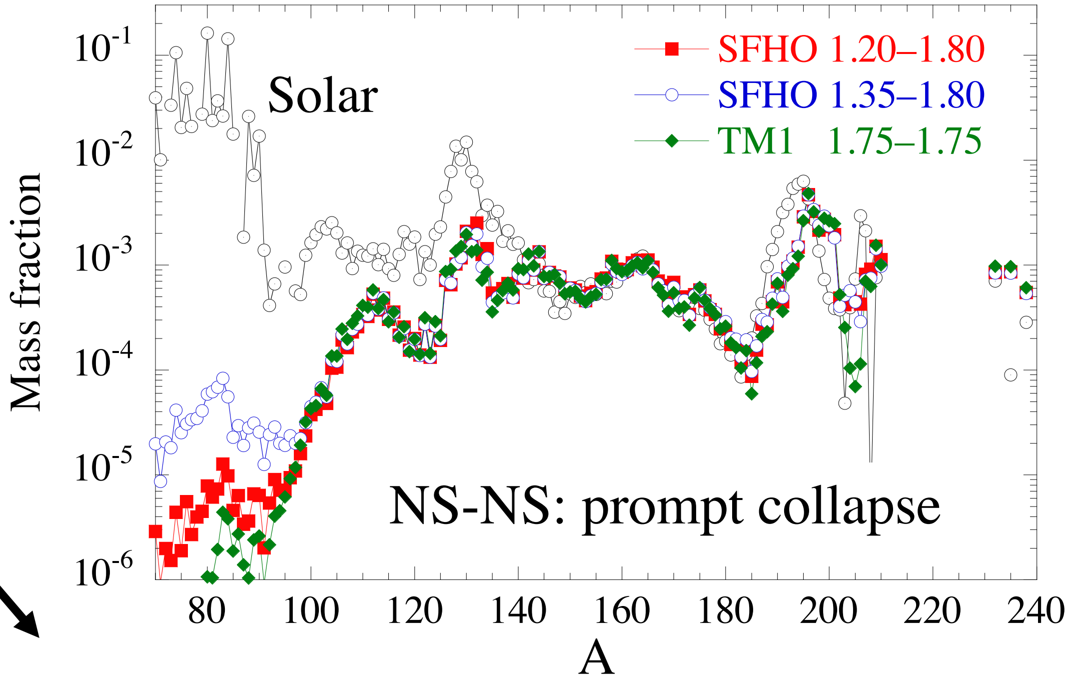
Systematic study of Neutron-star mergers

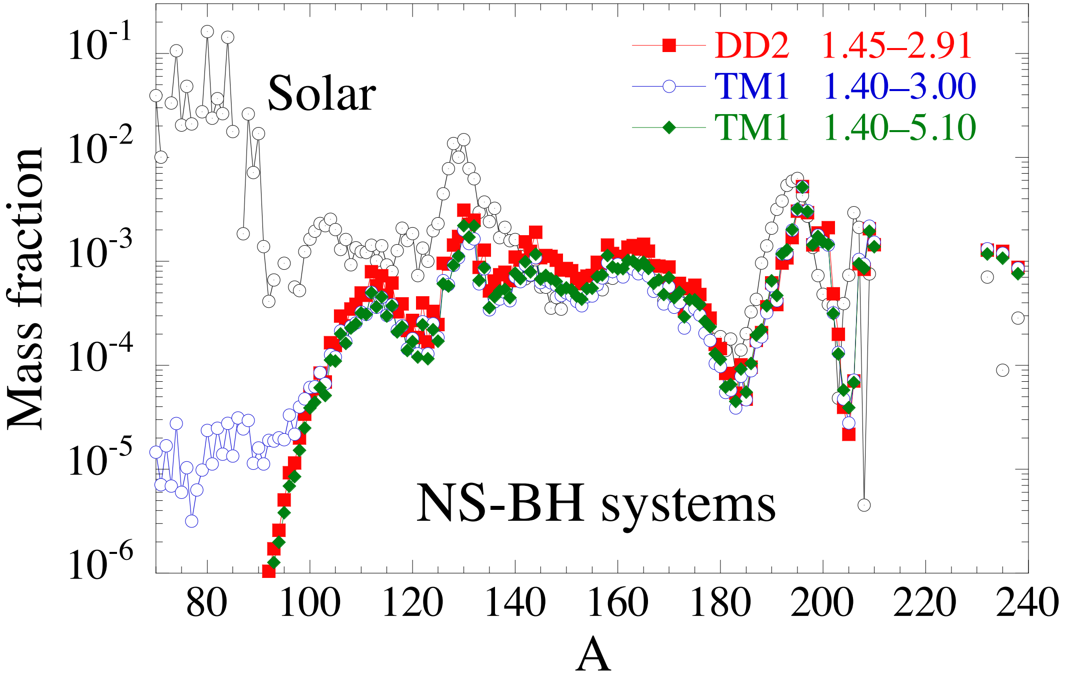
BUT *invariably*, more than 95 % of the ejected material is r-process with a distribution very similar to the solar r-abundance distribution (A>140)

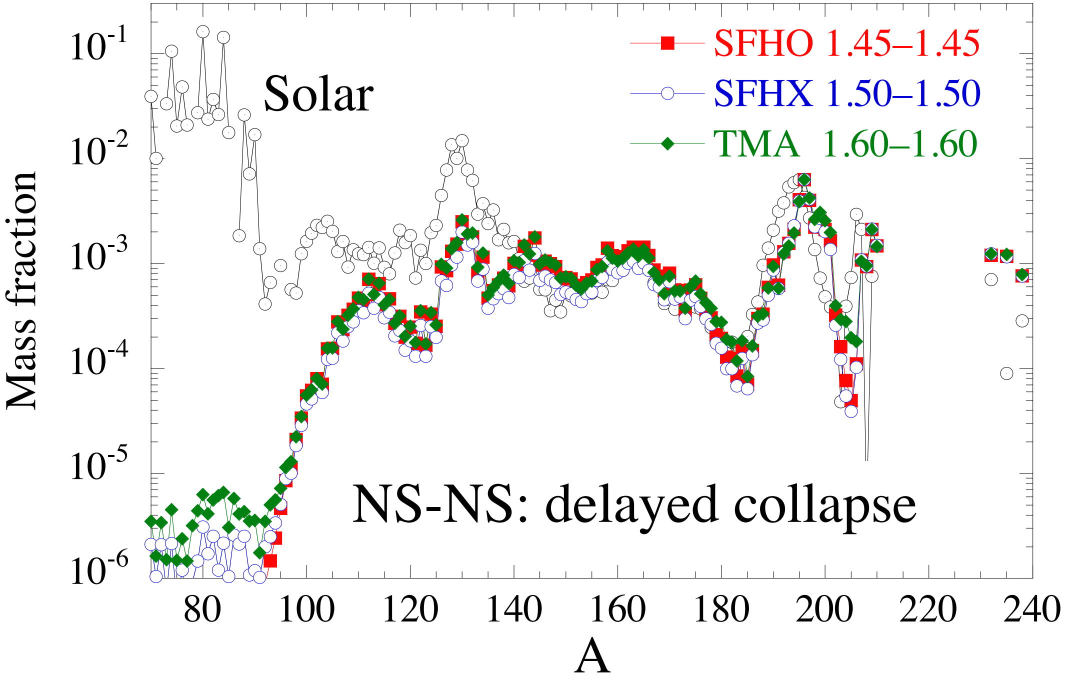


AND similar predictions, be it

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

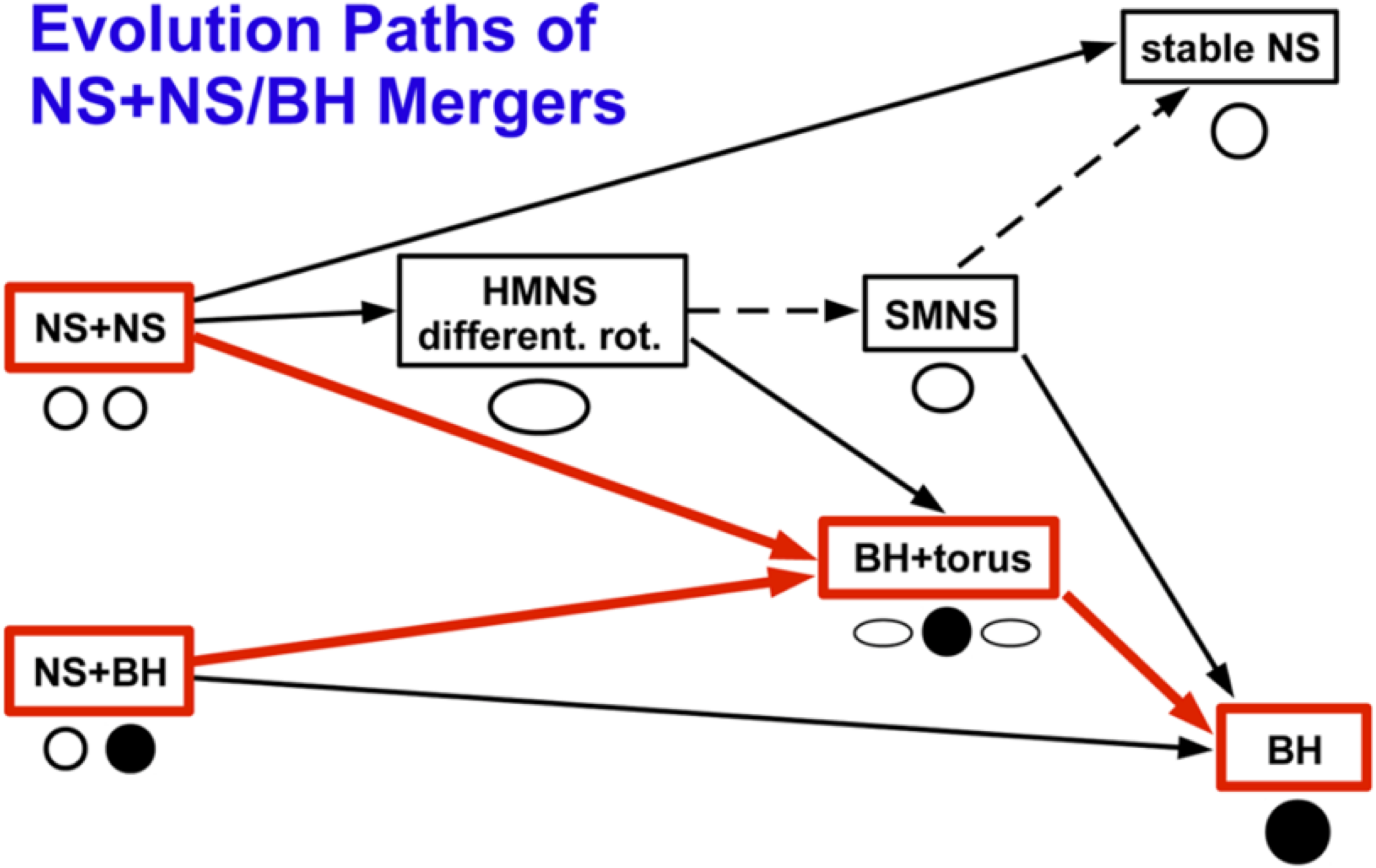






NS-NS or NS-BH mergers are robust site for the r-process (A>140)

Evolution Paths of NS+NS/BH Mergers



NS+NS

HMNS
different. rot.

SMNS

stable NS

BH+torus

NS+BH

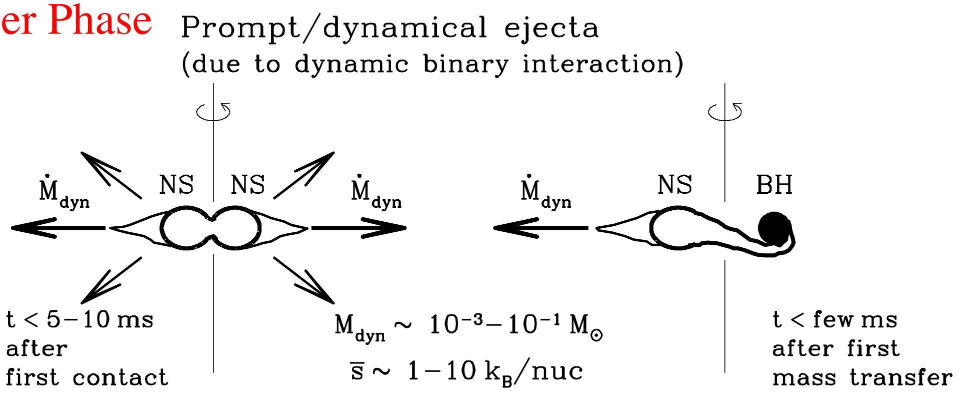
BH

Neutron Star Mergers: a very rich r-process site

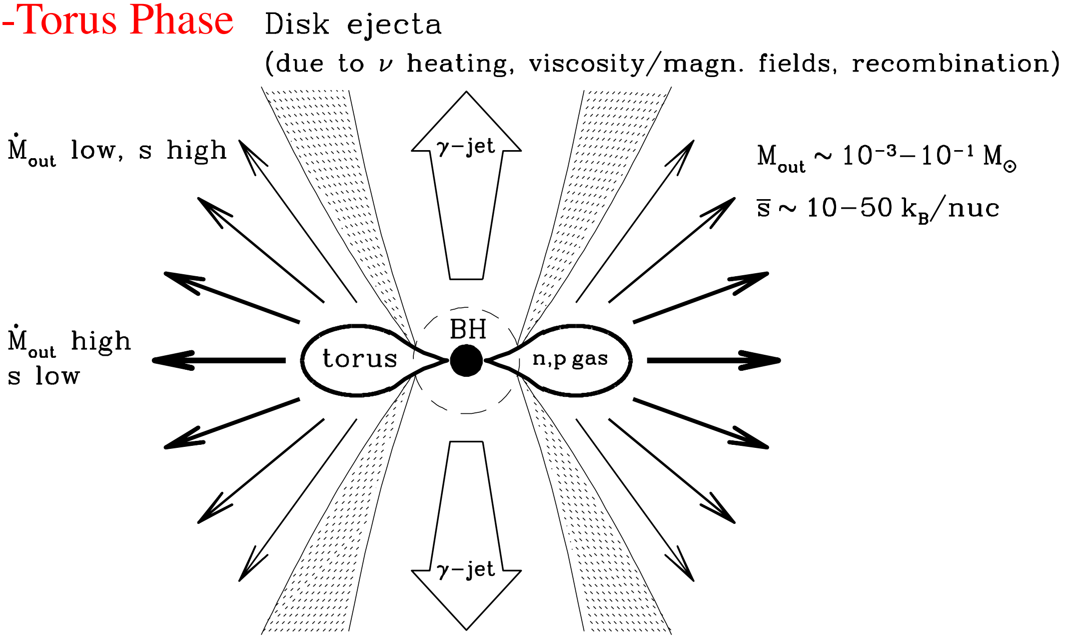
Hydrodynamical simulations : Just, Bauswein, Janka et al. MNRAS (2015)

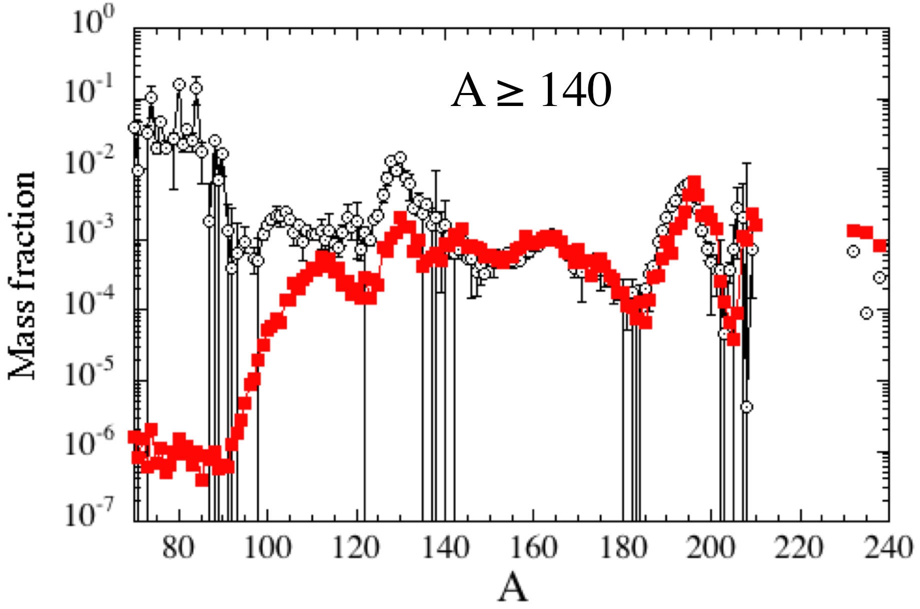
Mass loss phases during NS-NS and NS-BH merging

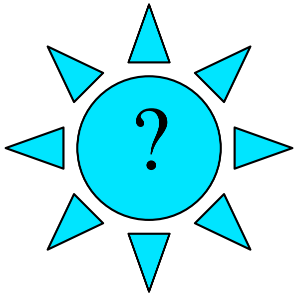
1. Merger Phase



2. BH-Torus Phase





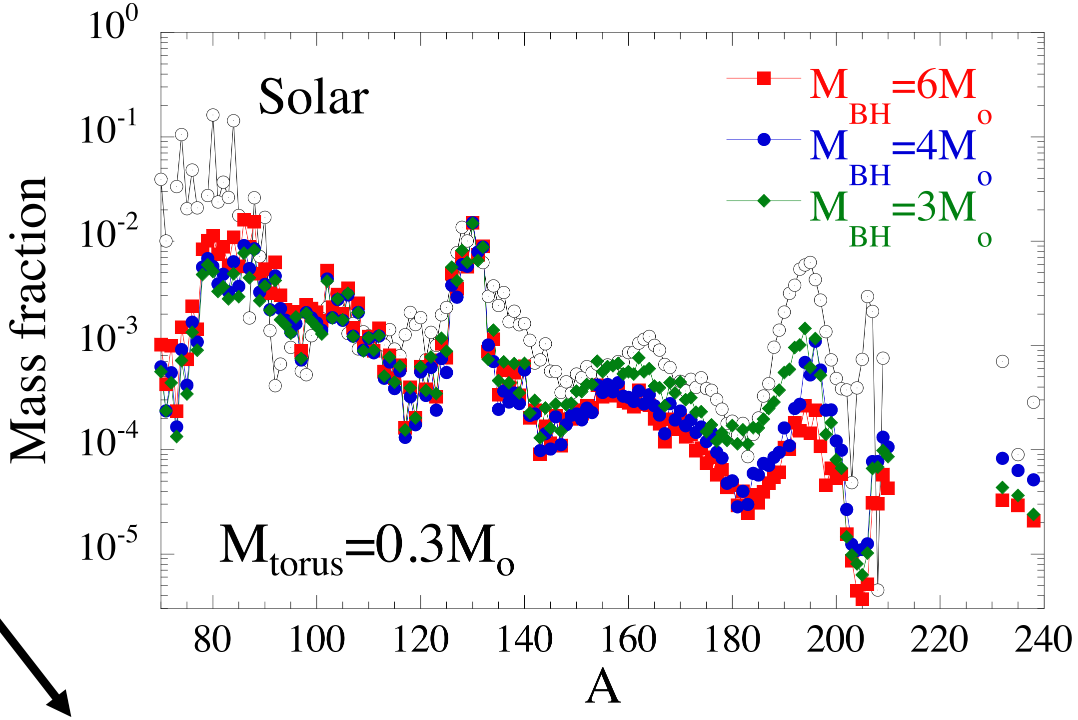


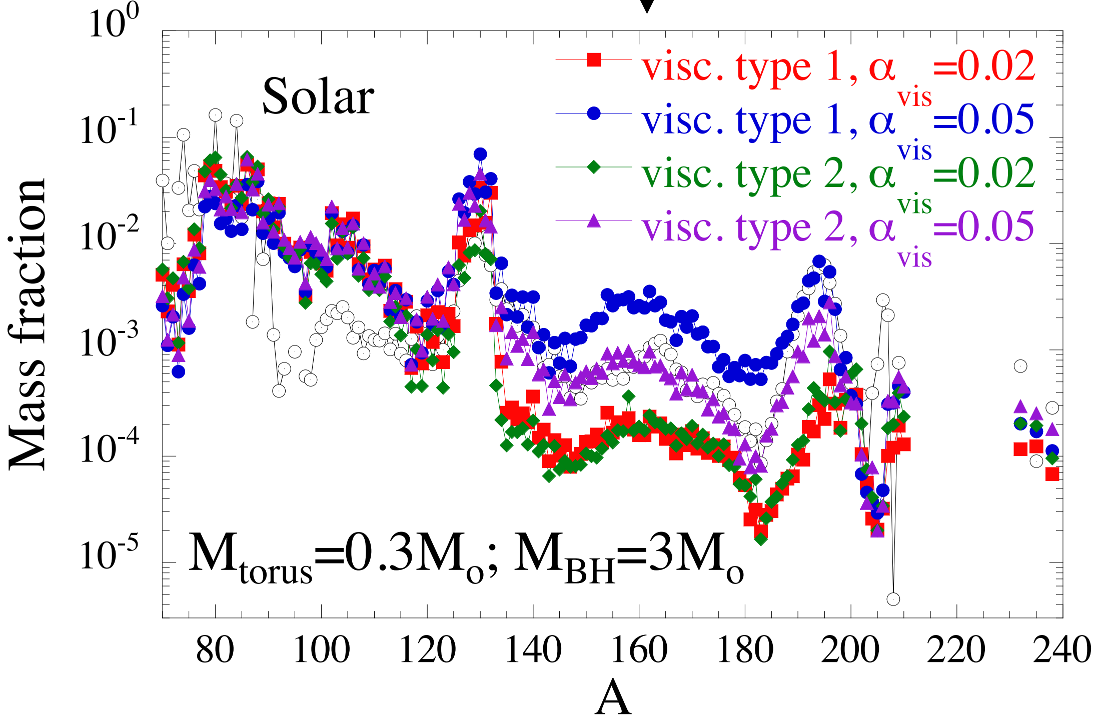
12 different hydro simulations

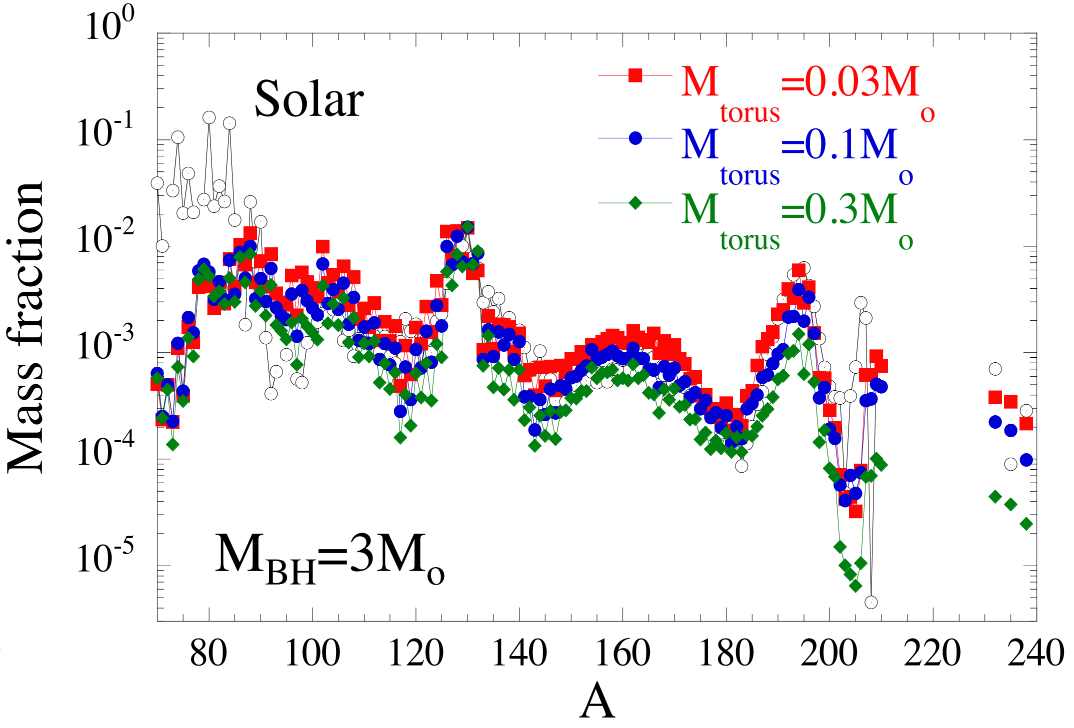
(O. Just, et al. 2015; see also Wu et al. 2016)

Abundance predictions sensitive to

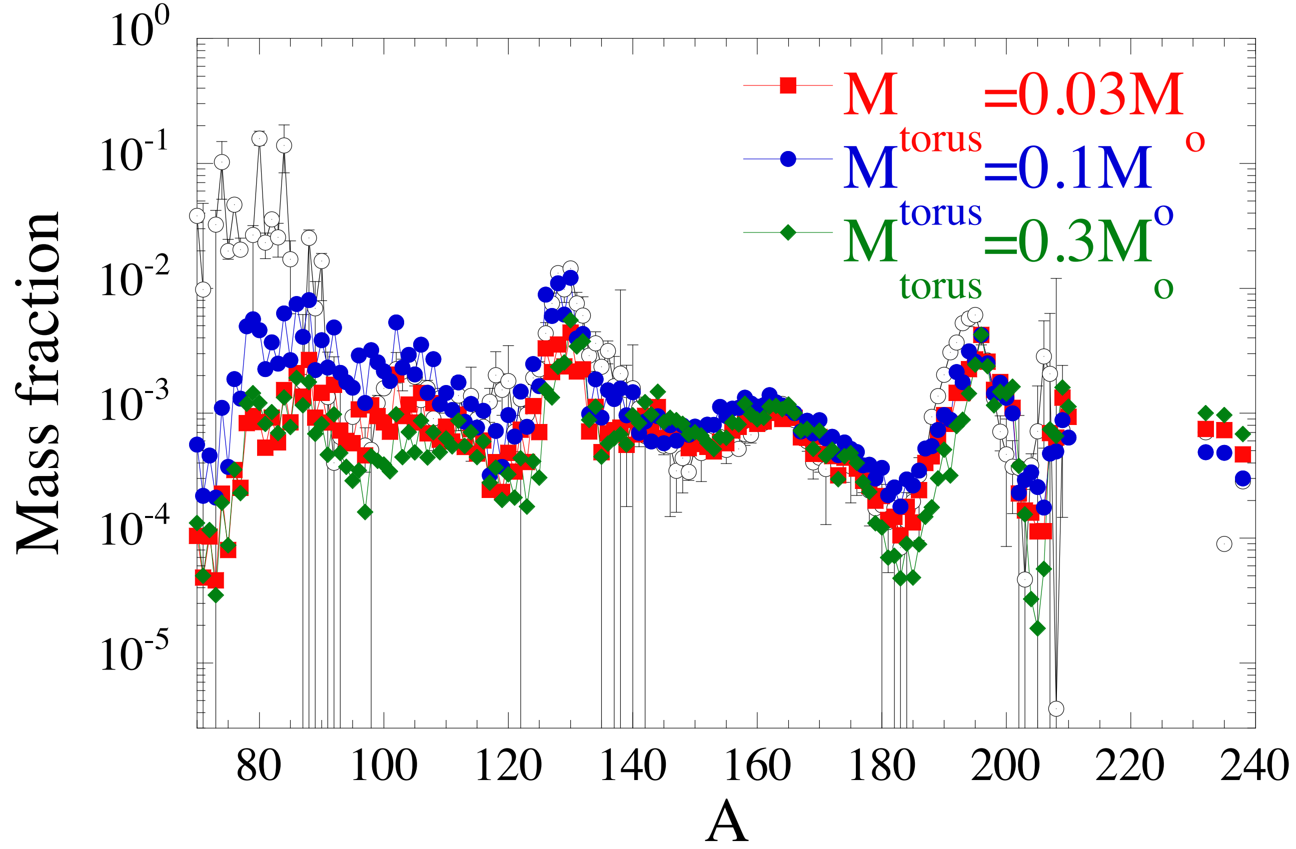
- Mass of the BH (same M_{torus})
- Mass of the torus (same M_{BH})
- Treatment of viscosity







Mass-weighted *consistently* combined Dynamical + Disk ejecta

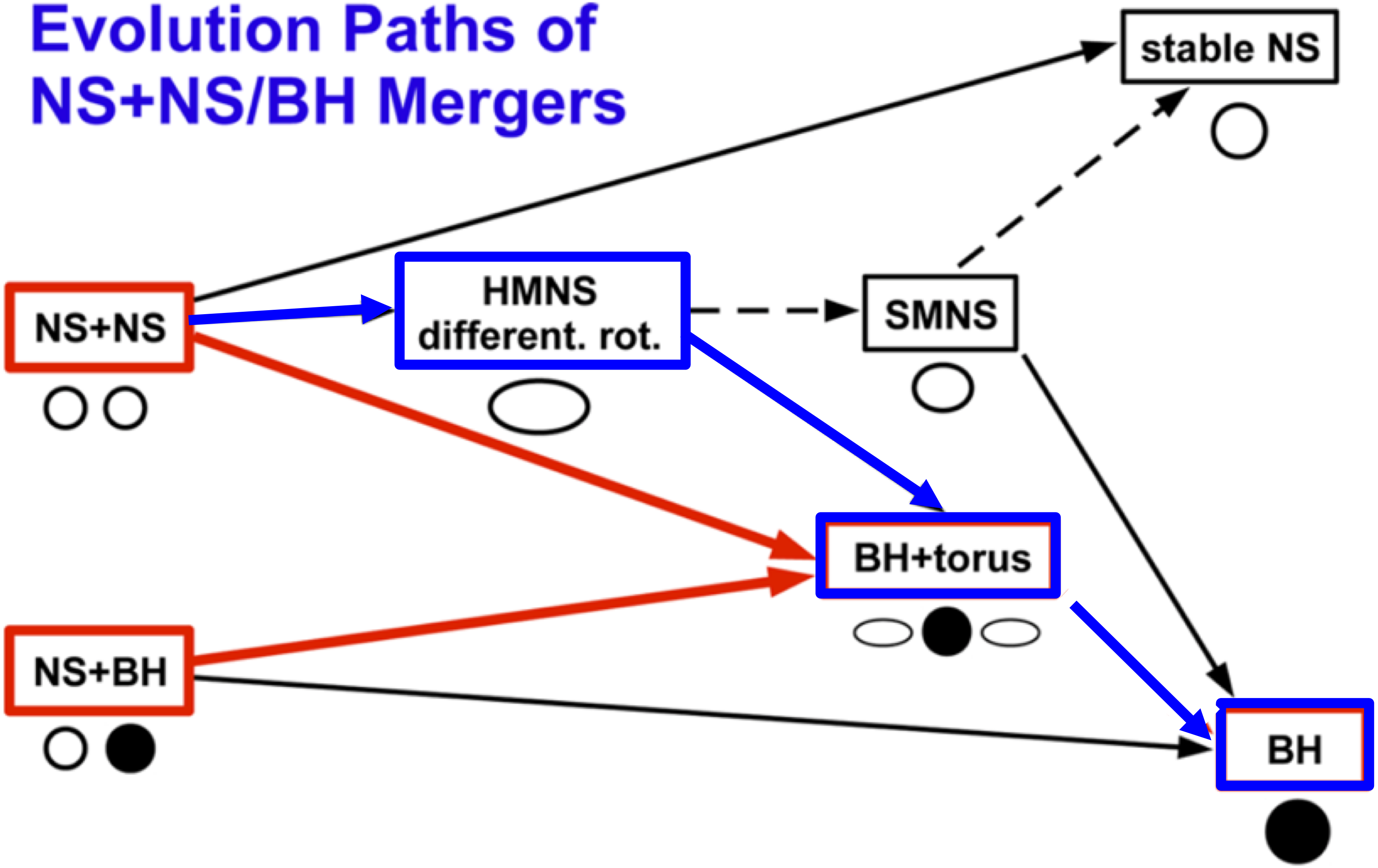


Robust production of all A ≥ 90 r-nuclei with a rather solar distribution.

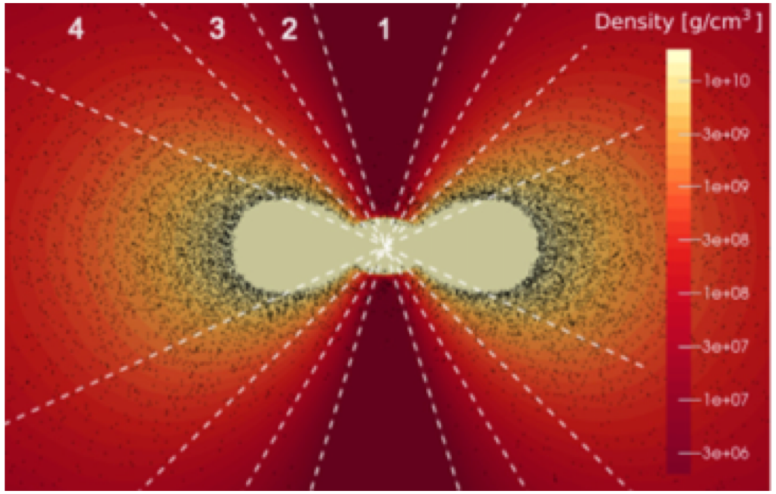
Abundances for A ≤ 140 nuclei vary within typically a factor of 3

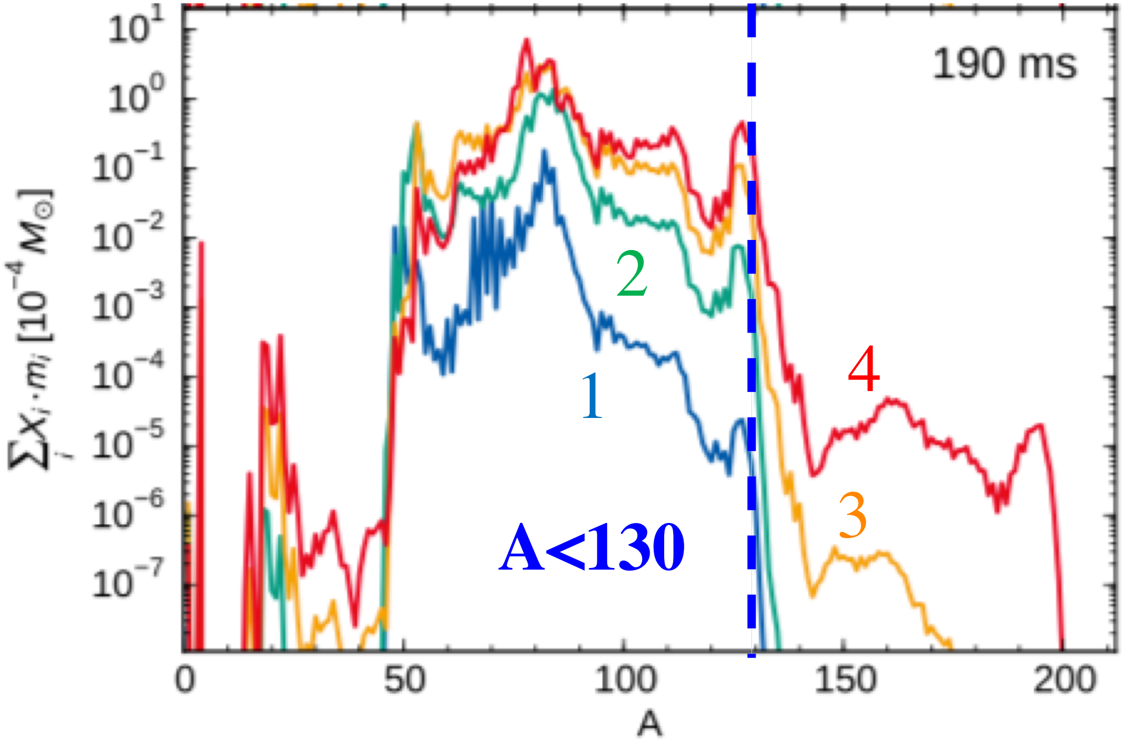
NSM *may* be a dominant site for the r-process nucleosynthesis

Evolution Paths of NS+NS/BH Mergers

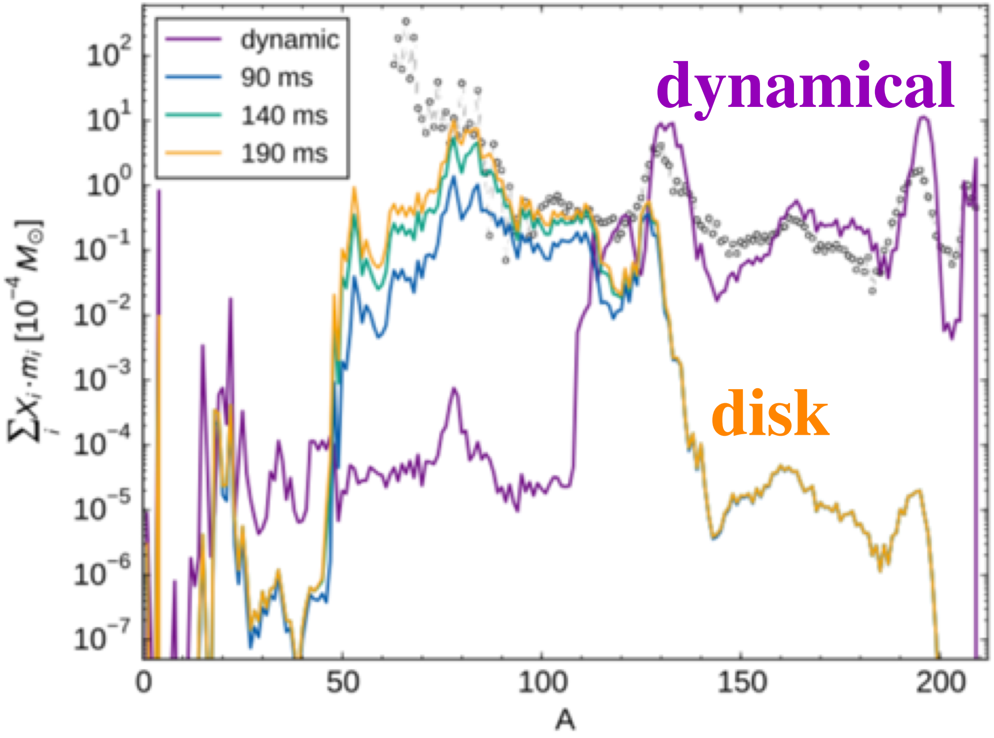


Composition of the matter ejected from a HMNS (Perego et al. 2014; Martin et al. 2015)





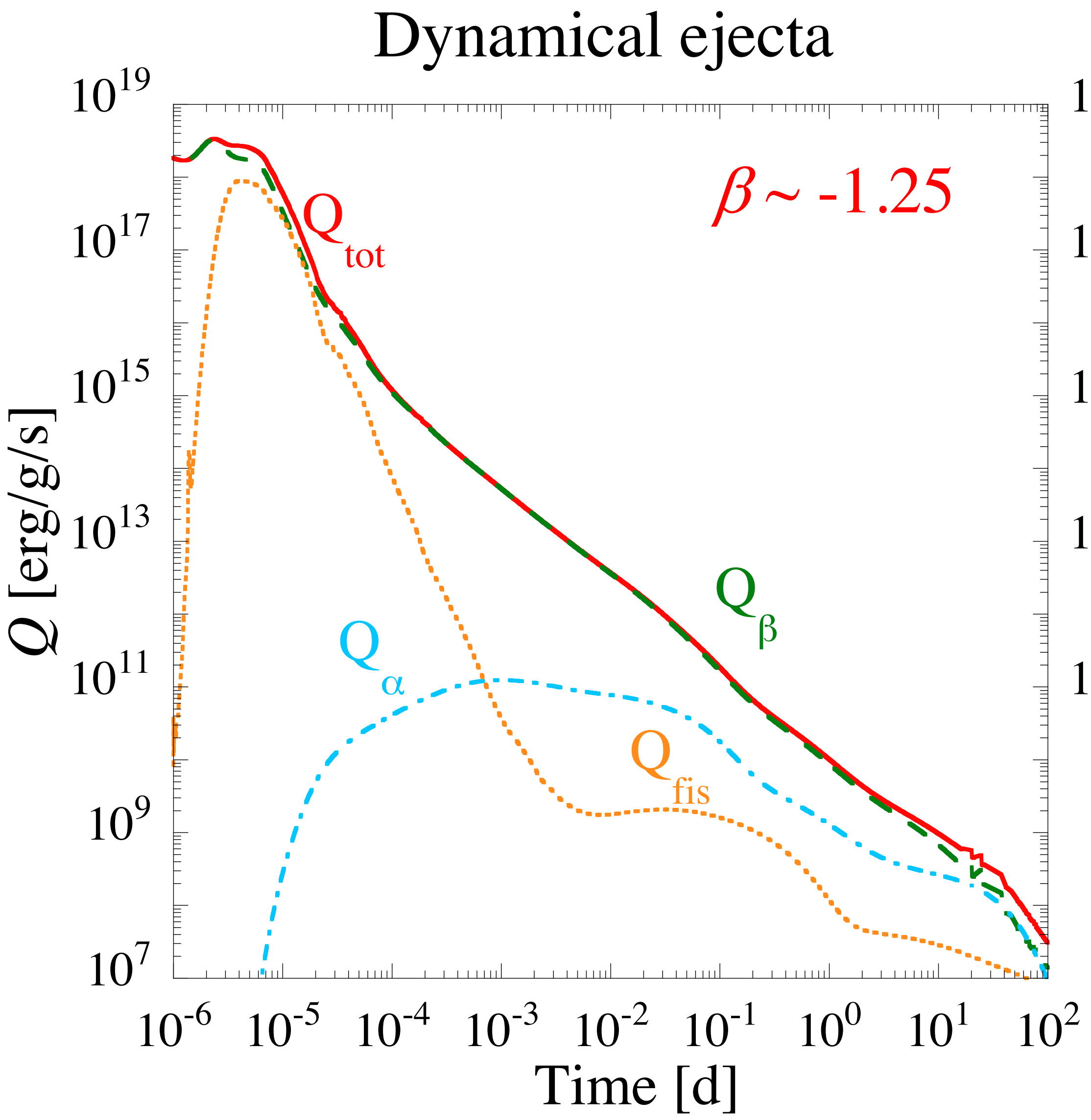
Final composition (dynamical + disk)

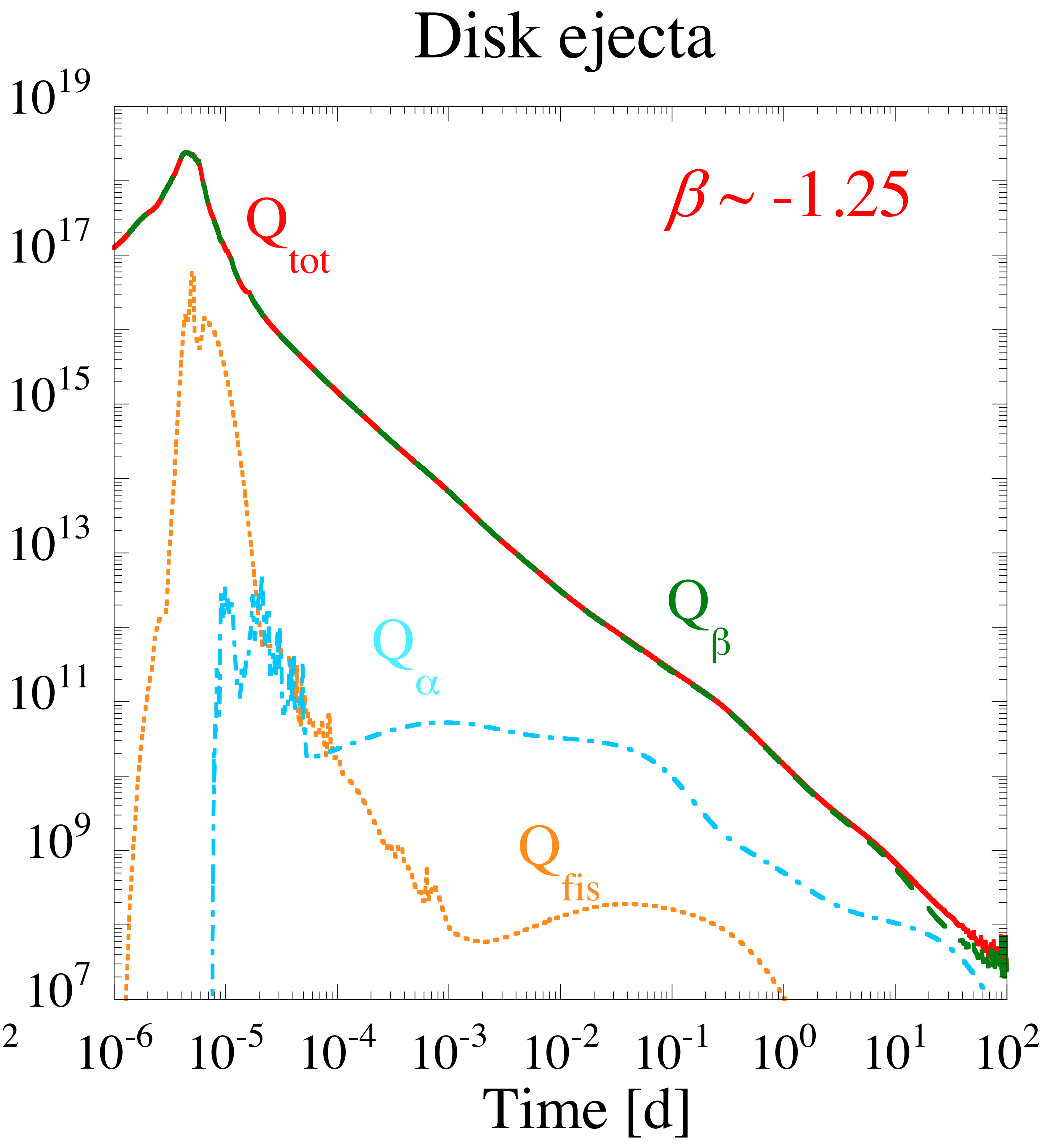


nucleosynthesis depends on the lifetime of the HMNS and the polar angle.

Total radioactive heating rate of the resulting Kilonova

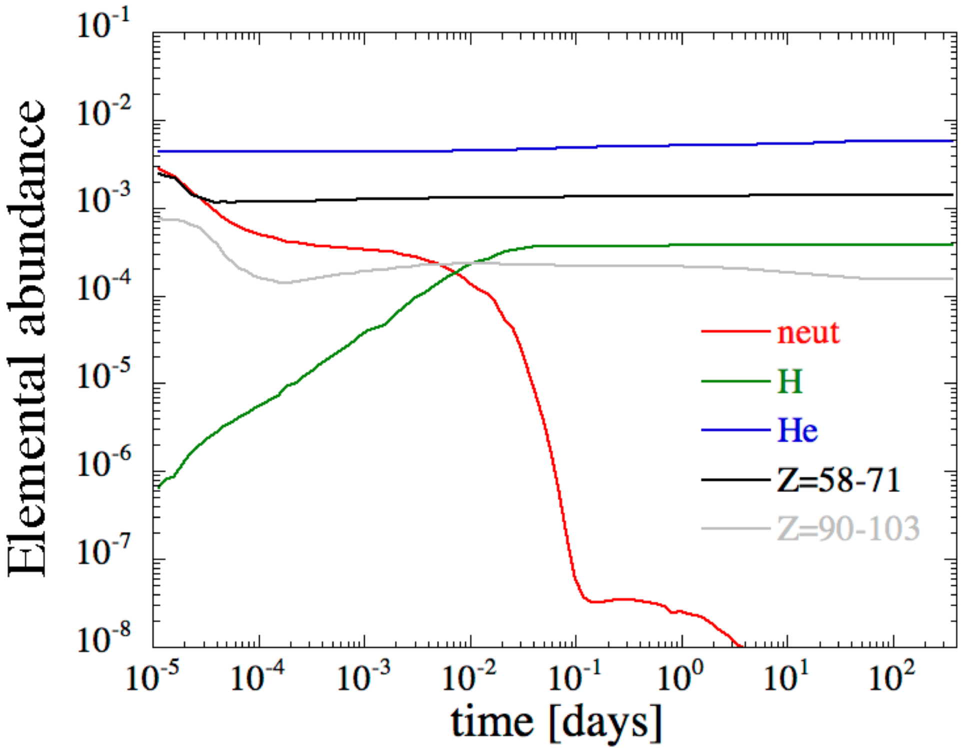
$$\boxed{Q_{tot}=Q_{n,\gamma}+Q_{\gamma,n}+Q_{\beta}+Q_{fis}+Q_{\alpha}}$$


Dynamical ejecta

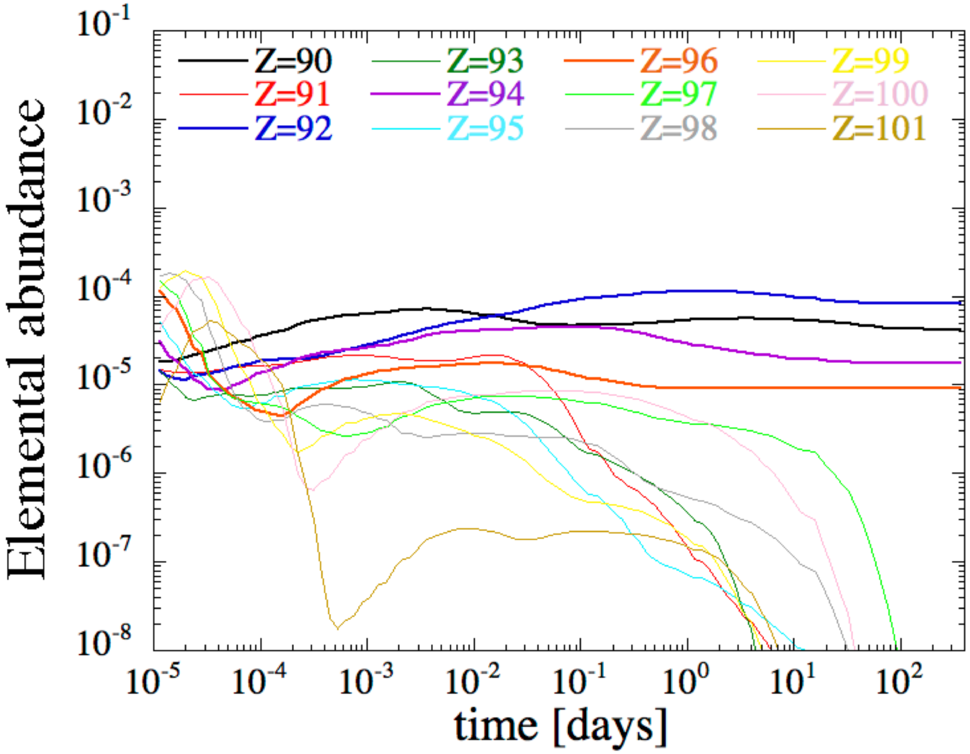

Disk ejecta

Elemental abundances expected in the dynamical ejecta

Dynamical ejecta



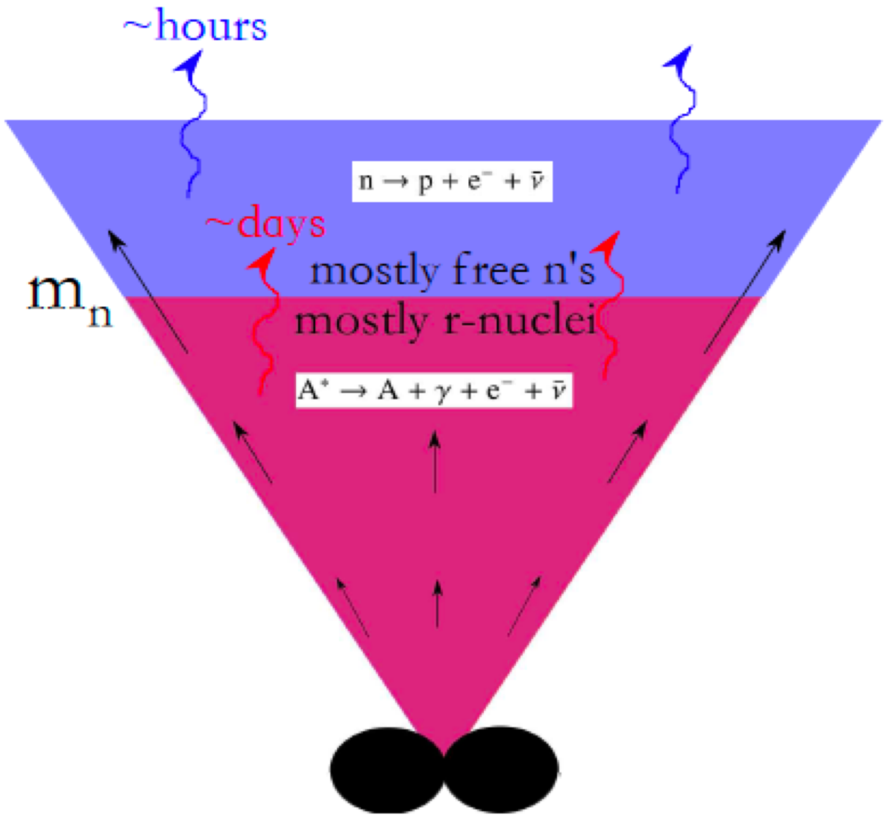
Significant production of lanthanides
and actinides
(if neutrino interactions are negligible)



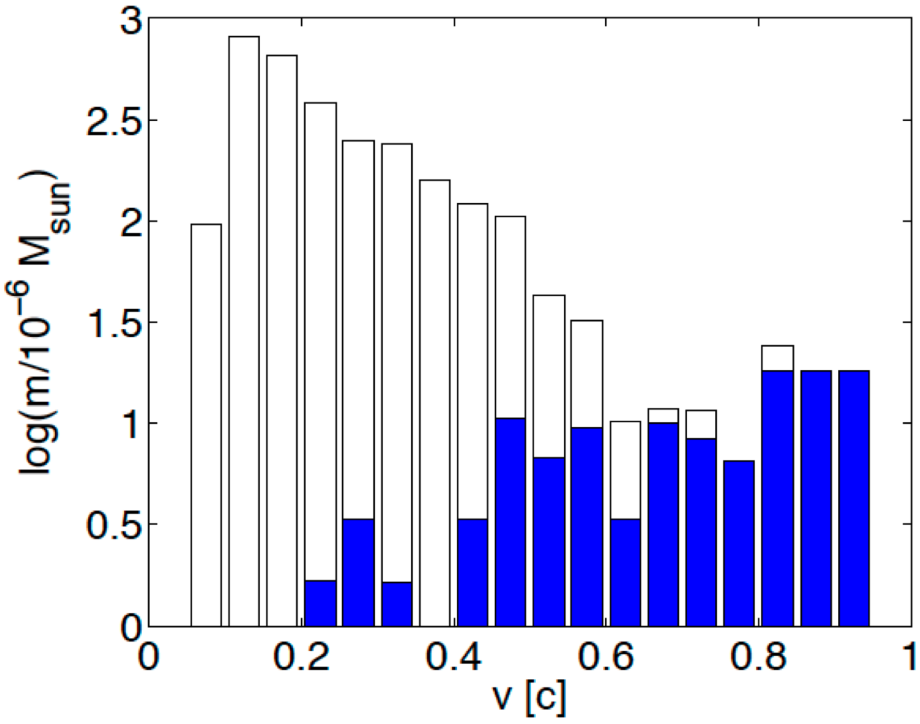
Very much dependent on the
nuclear physics treatment of
fission – Possible production
of superheavy elements ?

On the possible fast ejection of free neutrons

Small fraction of the ejected mass (a few % or ~$10^{-4}M_o$) possibly made of free neutrons



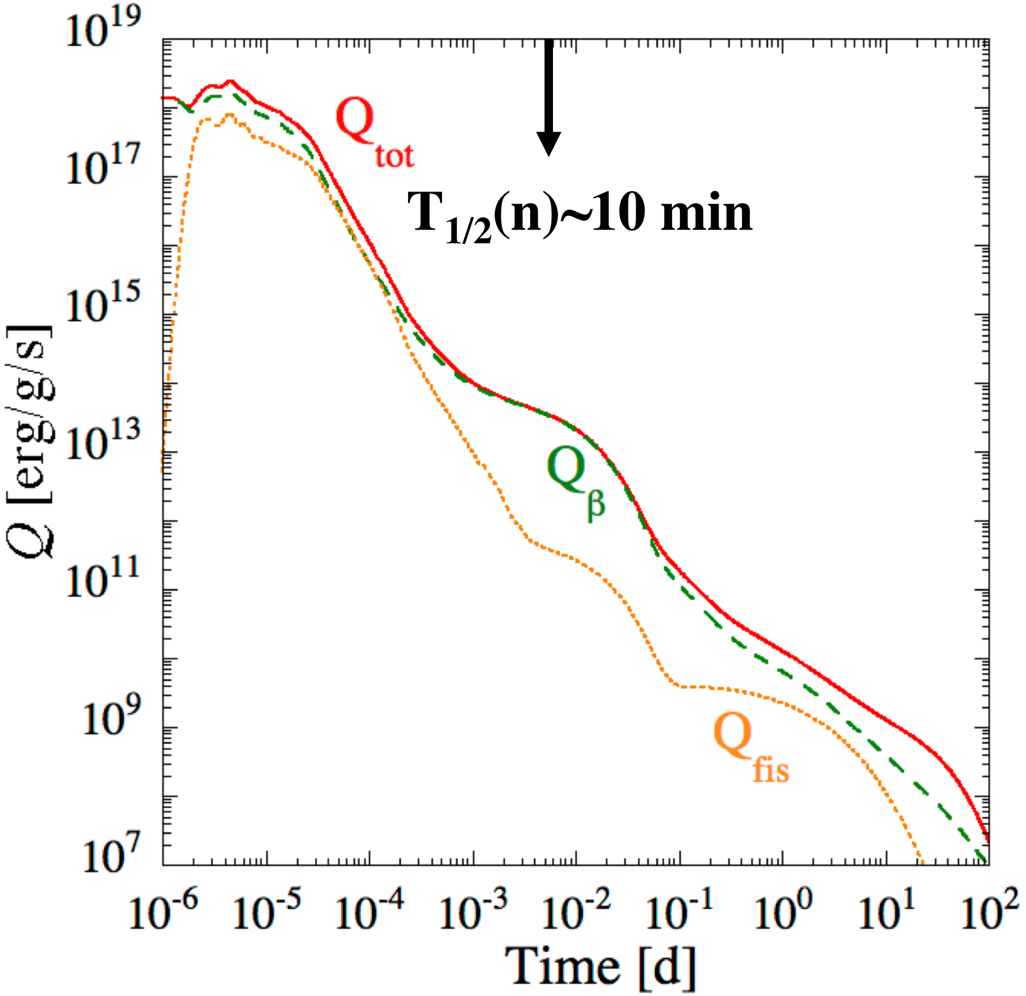
~ a few % of the total mass ejected as free neutrons



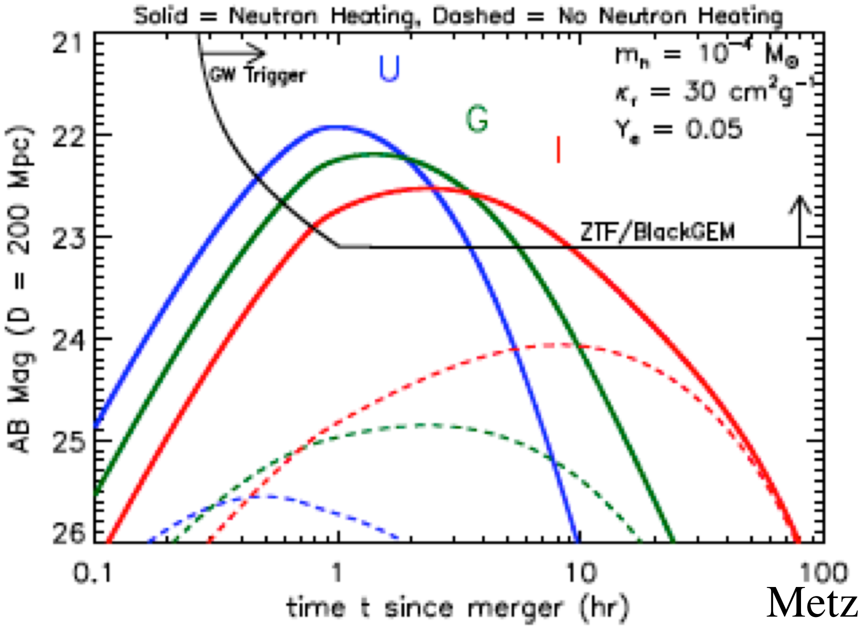
→ Potential counterpart to the gravitational wave source

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} ~ 10^{41} erg/s



Metzger et al. (2014)

But how reliable is the estimated amount of ejected free neutrons ??

Free neutron ejection is found to be sensitive to

- *The NS-NS system* : the higher the asymmetry, the more fast-expanding material
- *The EoS*: the softer the EoS, the stronger the shock-heated outflows
- *Late time extrapolation* of the density evolution $\rho \propto t^{-3}$
- *Initial velocities*: the faster the ejection, the less efficient the neutron captures (Relativistic vs Newtonian models)
- *Initial entropies*: the highest the entropy, the longer it takes to rebuild heavy nuclei from neutrons and protons
- *The neutrino interactions*: the stronger the weak interactions with nucleons, the smaller the amount of free neutrons left

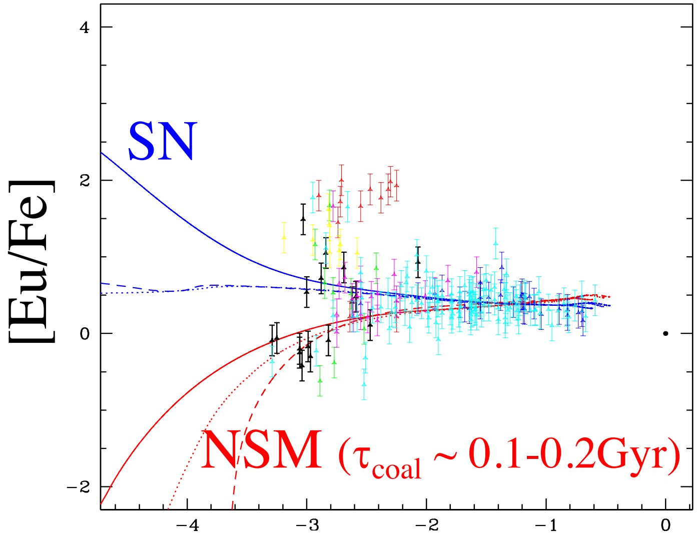
Still major astrophysical questions to be answered, including

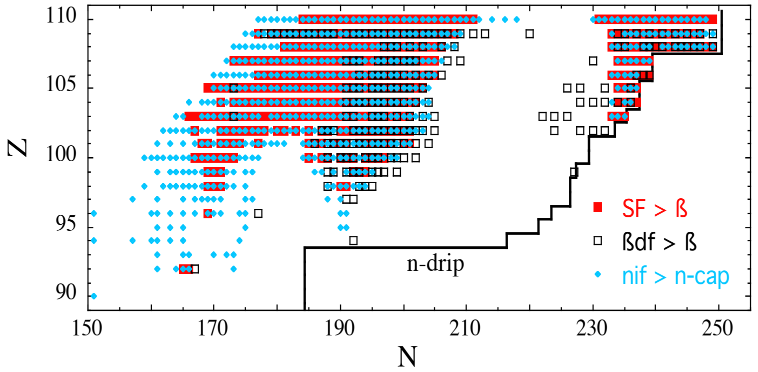
- Impact of neutrinos on the neutron richness during dynamical ejection

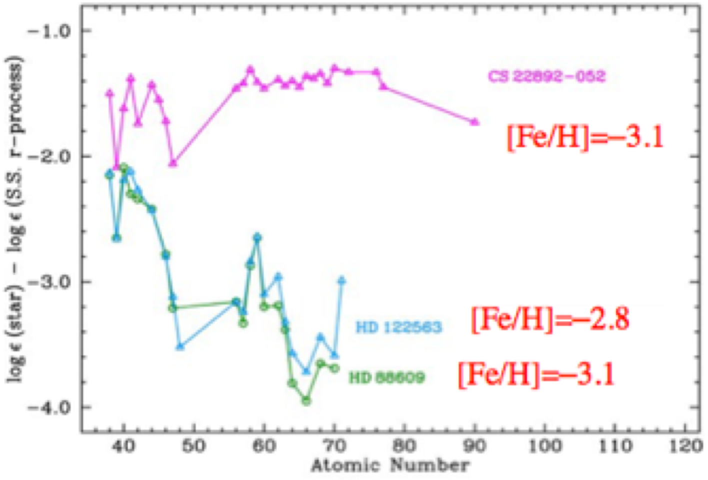
$$\nu_e + n \rightleftharpoons p + e^-$$

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

- Frequency and properties of NS binary systems (in part, coalescence time)
- Chemical evolution of r-nuclei in the Galaxy
- Comparison with spectroscopic observation, in particular with r-enrichment in old (ultra-metal-poor) stars
- Nuclear Physics Aspects

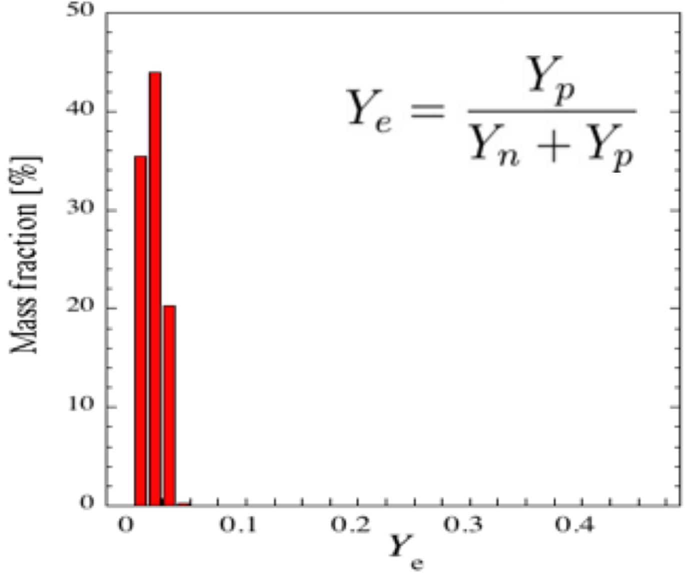






Still a major uncertainty affecting the nucleosynthesis in NS mergers: electron (anti)neutrino absorption by free nucleons

Initial Y_{e}



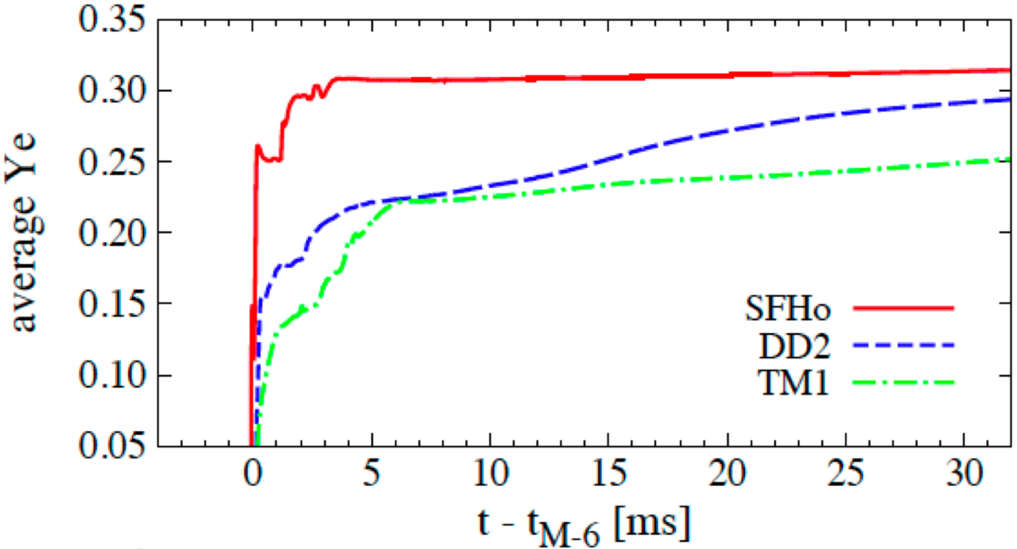
$$Y_e = \frac{Y_p}{Y_n + Y_p}$$

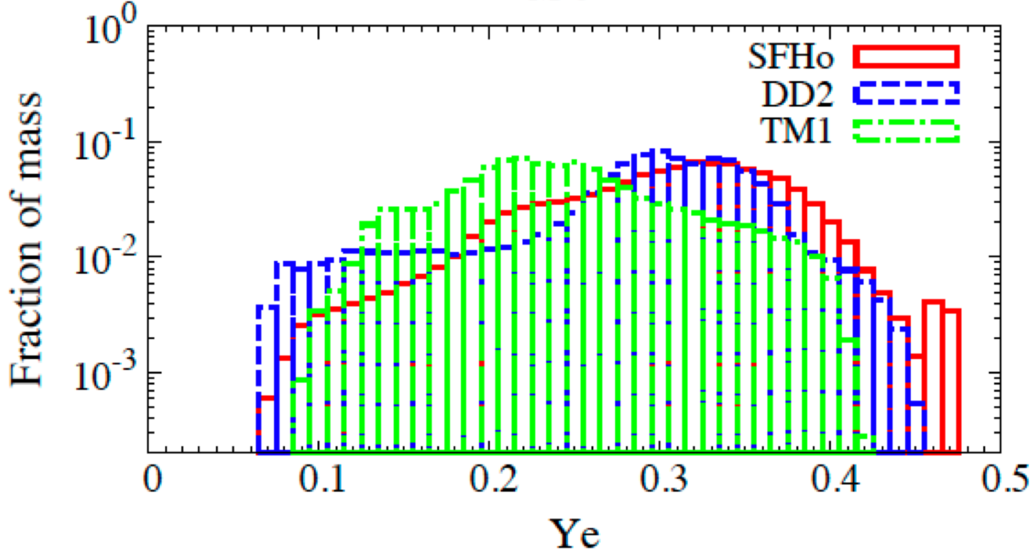
$$\nu_e + n \rightleftharpoons p + e^-$$

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

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

Also sensitive to the adopted EoS

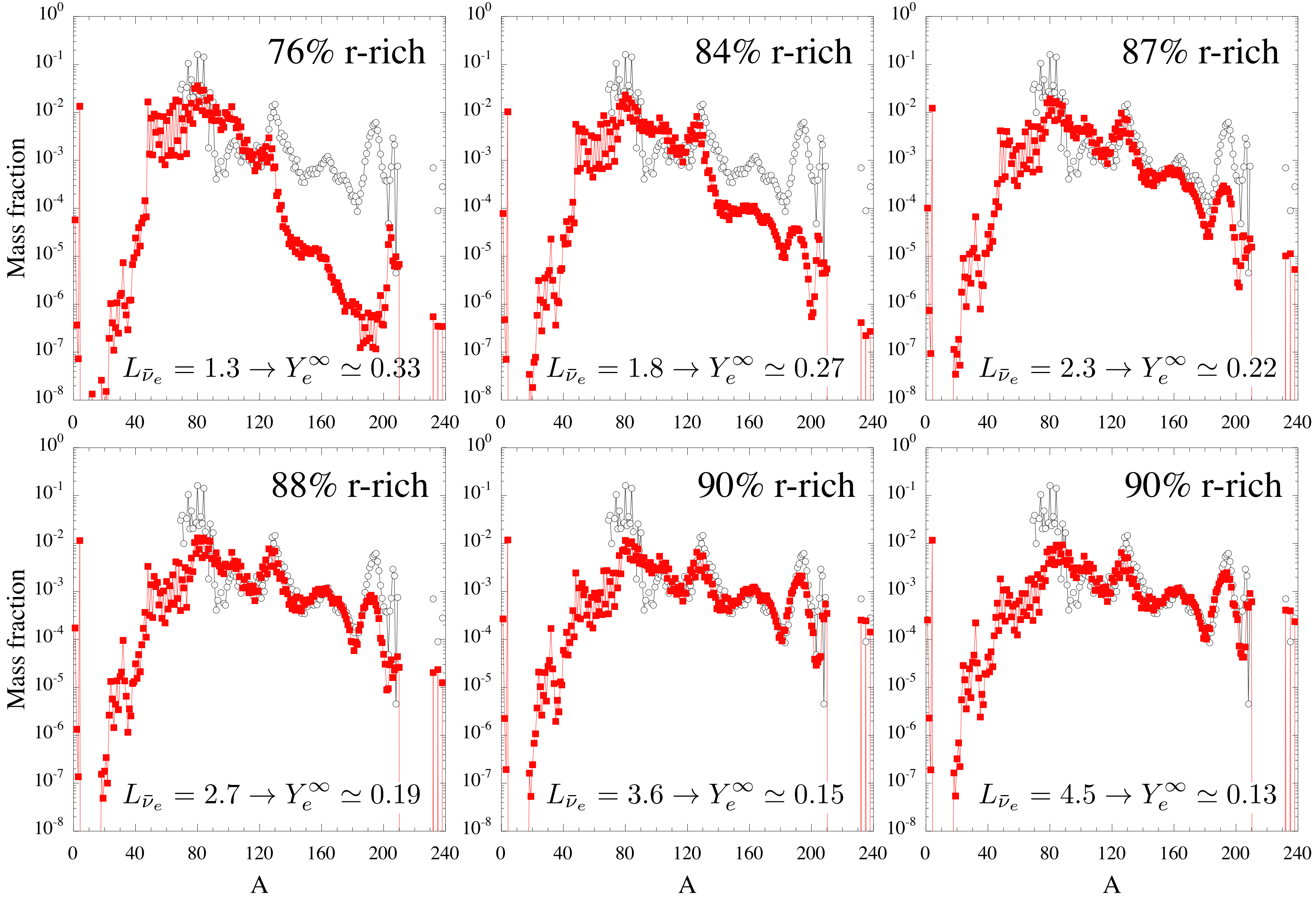




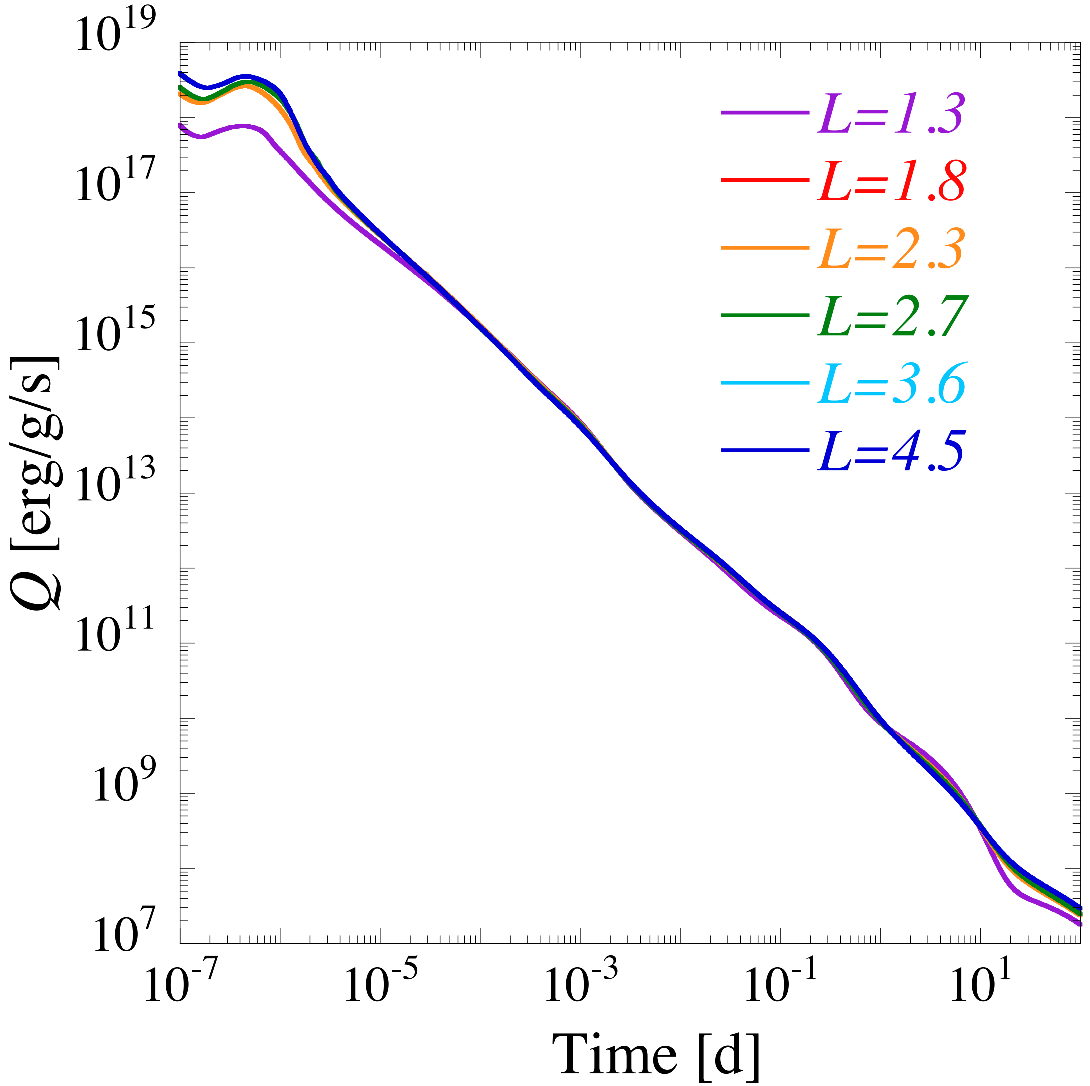
Wanajo et al. (2014); Sekiguchi et al. (2015)

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

$$\Rightarrow \left\{ \begin{array}{l} L_{\nu_e} = 0.6\ 10^{53}\mathrm{erg/s} \\ L_{\bar{\nu}_e} = {\color{red}L}\ 10^{53}\mathrm{erg/s} \\ \langle E_{\nu_e}\rangle = 12\ \mathrm{MeV} \\ \langle E_{\bar{\nu}_e}\rangle = 16\ \mathrm{MeV} \end{array} \right. \Rightarrow Y_e^{\nu\infty} \simeq \frac{L_{\nu_e}\langle E_{\nu_e}\rangle f^{mr}_{\nu_e}}{L_{\nu_e}\langle E_{\nu_e}\rangle f^{mr}_{\nu_e} + L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle f^{mr}_{\bar{\nu}_e}}$$



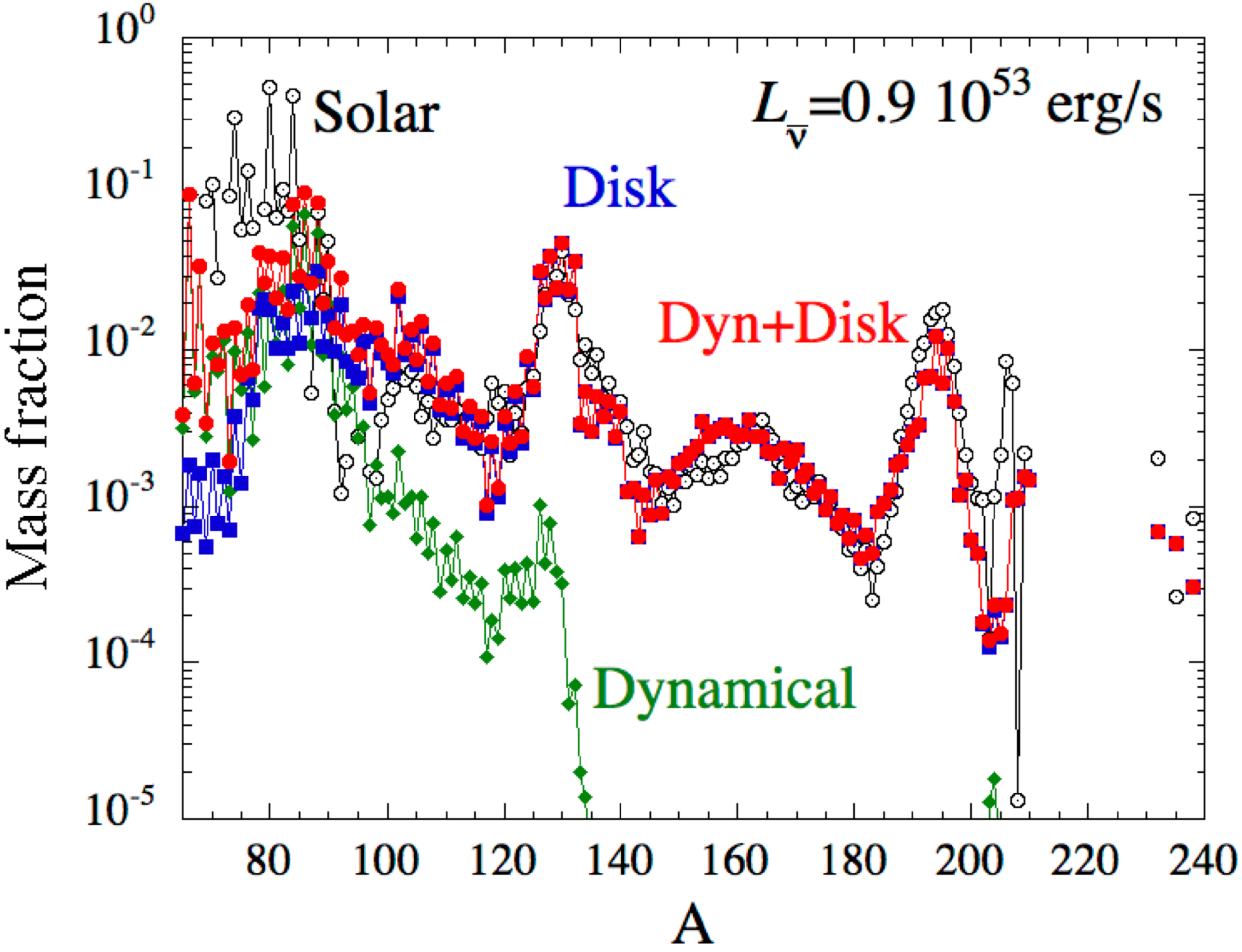
$$\begin{aligned} \nu_e + n &\rightleftharpoons p + e^- \\ \bar{\nu}_e + p &\rightleftharpoons n + e^+ \end{aligned} \Rightarrow \left\{ \begin{aligned} L_{\nu_e} &= 0.6\ 10^{53}\mathrm{erg/s} \\ L_{\bar{\nu}_e} &= L\ 10^{53}\mathrm{erg/s} \\ \langle E_{\nu_e} \rangle &= 12\ \mathrm{MeV} \\ \langle E_{\bar{\nu}_e} \rangle &= 16\ \mathrm{MeV} \end{aligned} \right. \Rightarrow Y_e^{\nu\infty} \simeq \frac{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr}}{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr} + L_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle f_{\bar{\nu}_e}^{mr}}$$



Similar radioactive heating rate

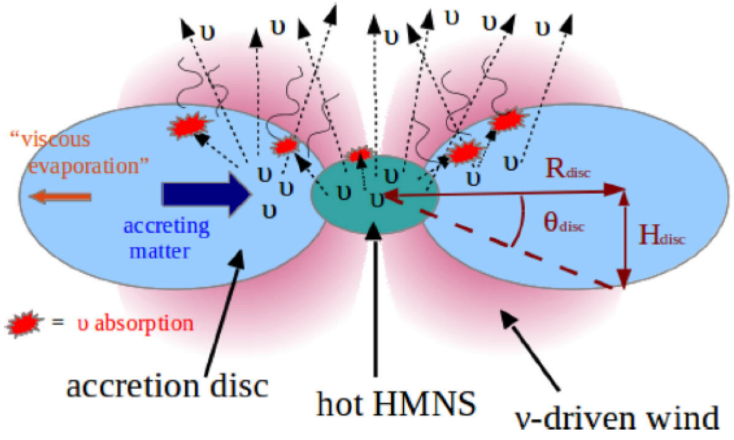
Possibility for the Kilonova to result from

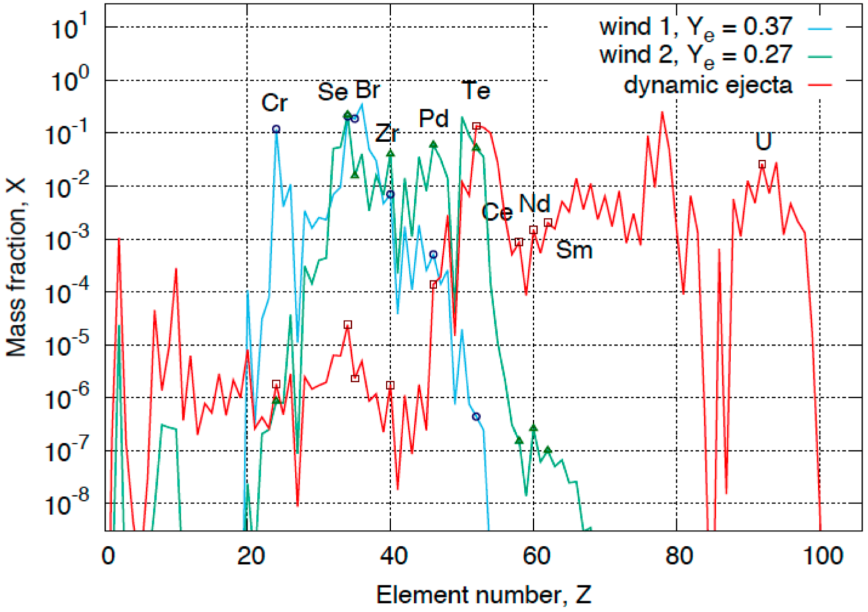
- a lanthanide-*free* dynamical ejecta (if $L_{\bar{\nu}_e} \lesssim 3 \times L_{\nu_e}$)
- a lanthanide-*rich* disk ejecta

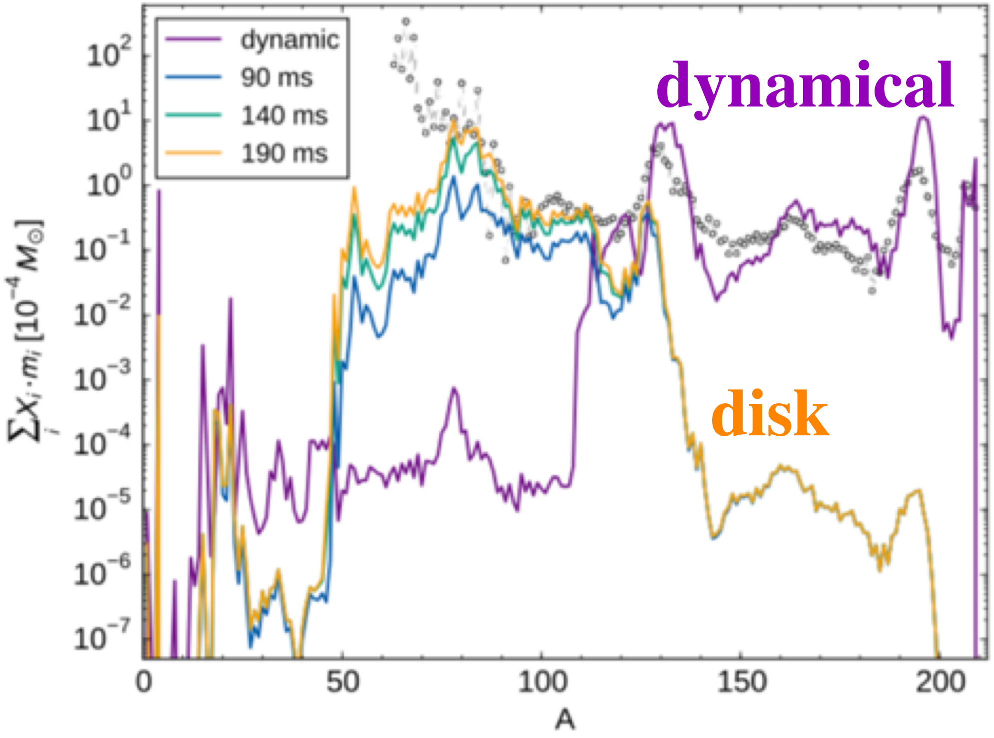


with $M_{\mathrm{dyn}} \sim M_{\mathrm{disk}}$ but $v_{\mathrm{dyn}} \sim$ 4-7 x v_{disk}

A relatively different conclusion obtained with the HMNS ejecta (Perego et al. 2014; Martin et al. 2015; Wollaeger et al. 2018)







- a lanthanide-*rich* dynamical ejecta
- a lanthanide-*free* disk ejecta

with $M_{\rm dyn} \sim M_{\rm disk}$ but $v_{\rm dyn} \sim 4\text{-}7 \times v_{\rm disk}$

Conclusions

The astrophysical site for the r-process remains puzzling !

- **Supernovae** : favorite sites for decades (GCE), but so far fail to produce a successful r-process

  → Need to solve the explosion mechanism first; may still be viable
- **Compact Object Mergers (NS-NS;NS-BH)** : GW170817

  recent robust hydrodynamical simulations
  - Successful solar-like r-process for A ≥ 90 nuclei with contribution from Dynamical A≥140 and Disk ejecta A≥90
  - Can explain the Galactic amount of r-nuclei
  - Galactic/Cosmic Chemical Evolution to be confirmed
  - Favoured by some observations (ultrafaint dwarf Galaxies, 244Pu in crust and sediment samples, …)
  - Possible ejections of free neutrons with observable blue signal

  But still some major open questions, in particular neutrino effects in relativistic models !