The r-process nucleosynthesis

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(cf A. Bauswein's talks for more details on the simulations)

Outline

1. R-process nucleosynthesis resulting from the NSM
   - Dynamical ejecta
   - Disk ejecta
2. Impact of neutrino absorption on the composition of the dynamical ejecta
3. Universality of the thermodynamic conditions in the dynamical ejecta
   - Sensitivity to the expansion timescales
   - Sensitivity to the initial Temperature

     → temperature processing of SPH simulations

     → Impact on abundance distribution and decay heat

     → Impact on a possible neutron-rich precursor

Systematic study of Neutron-star mergers

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

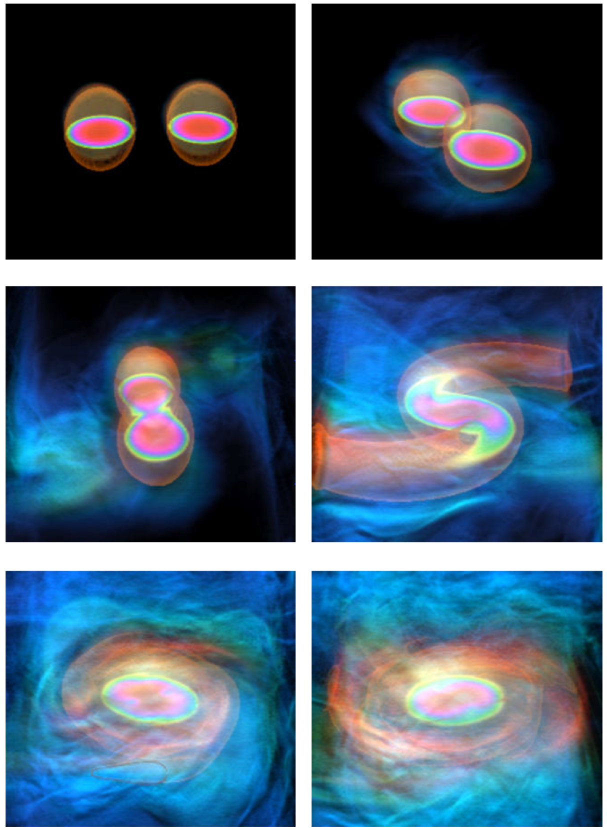
Various relativistic simulations for different binary systems :

- 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

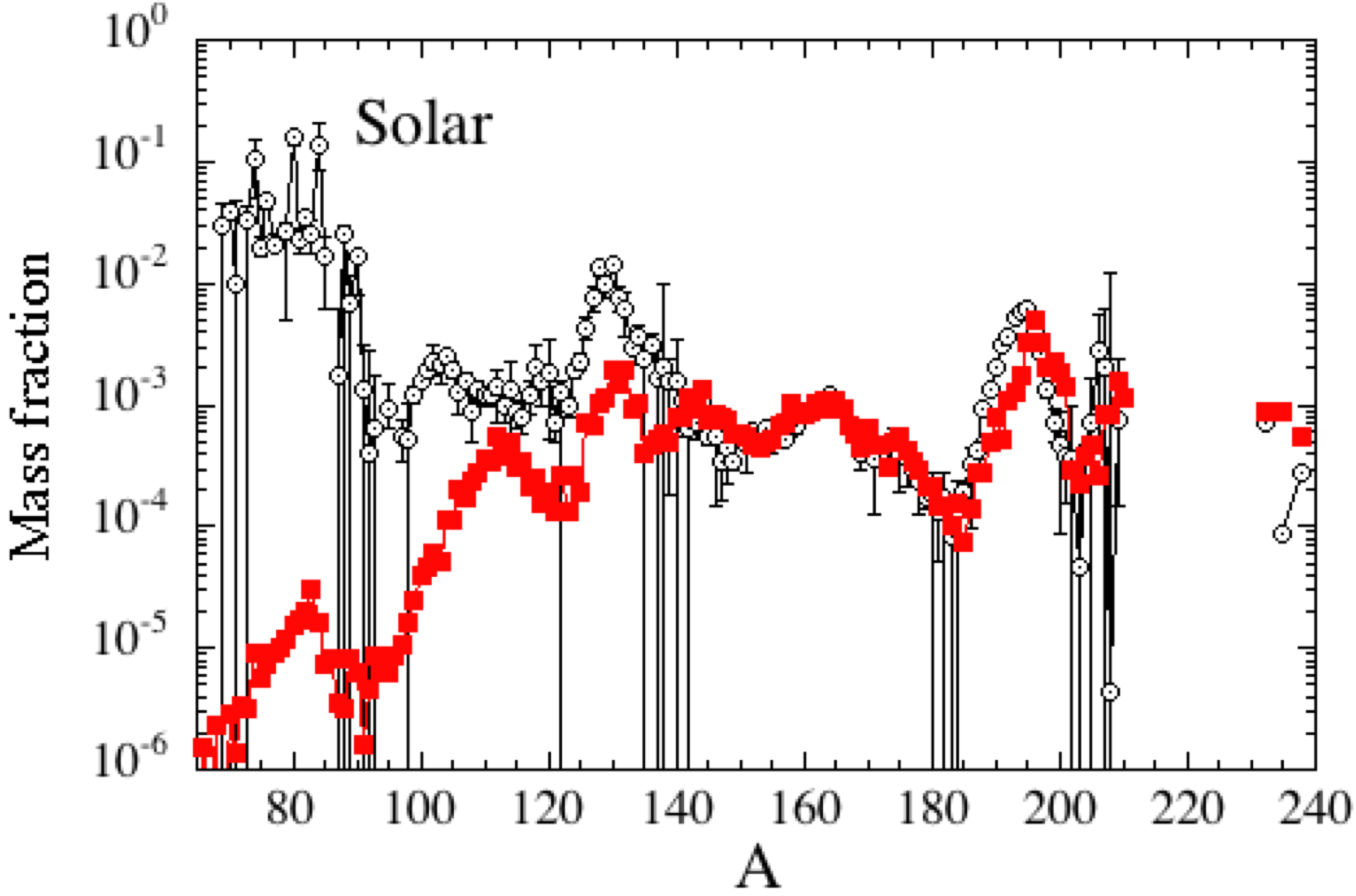
→ different luminosities of the optical transients 3 – 14 10^{41} erg/s



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

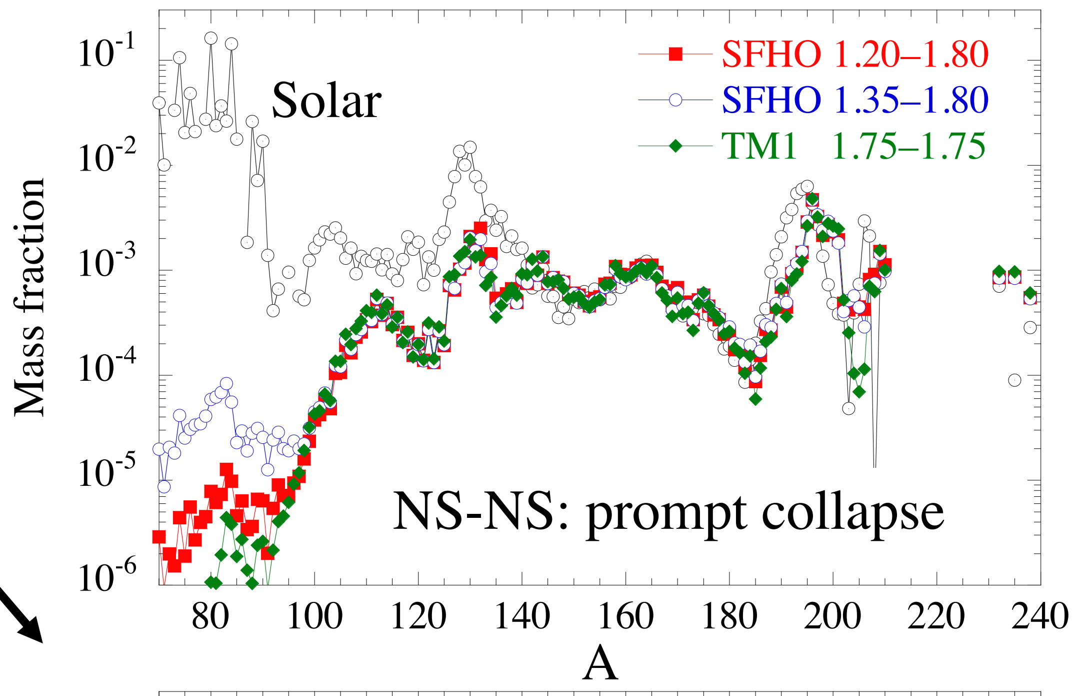
Systematic study of Neutron-star mergers

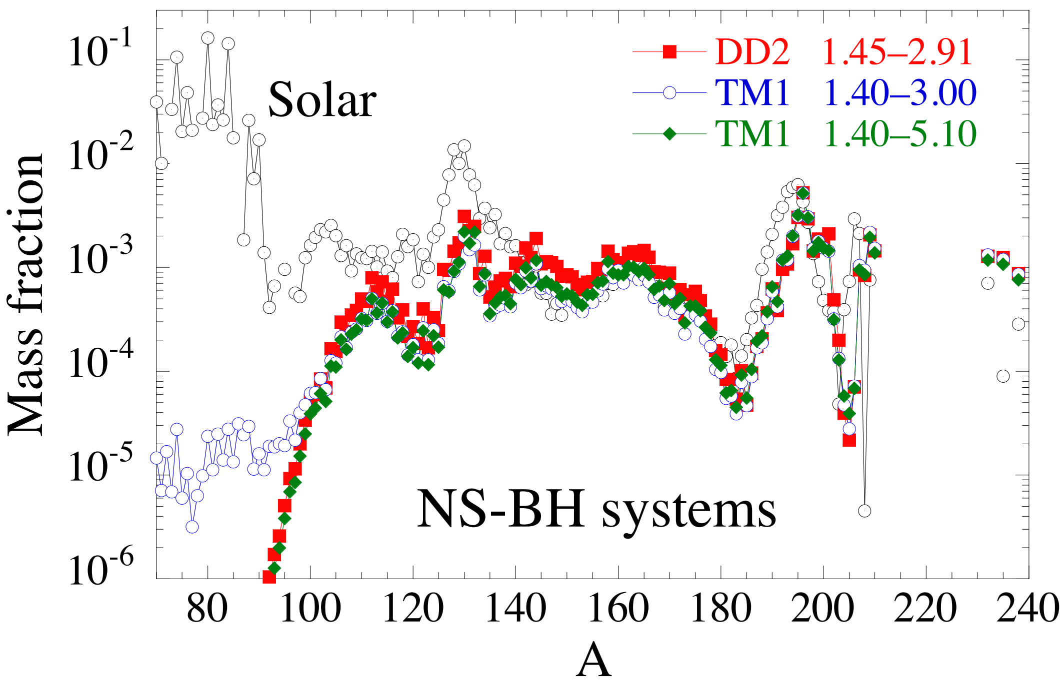
BUT *invariably*, more than 95 % of the ejected material is r-process with a distribution very similar to the solar r-abundance distribution (A>140)

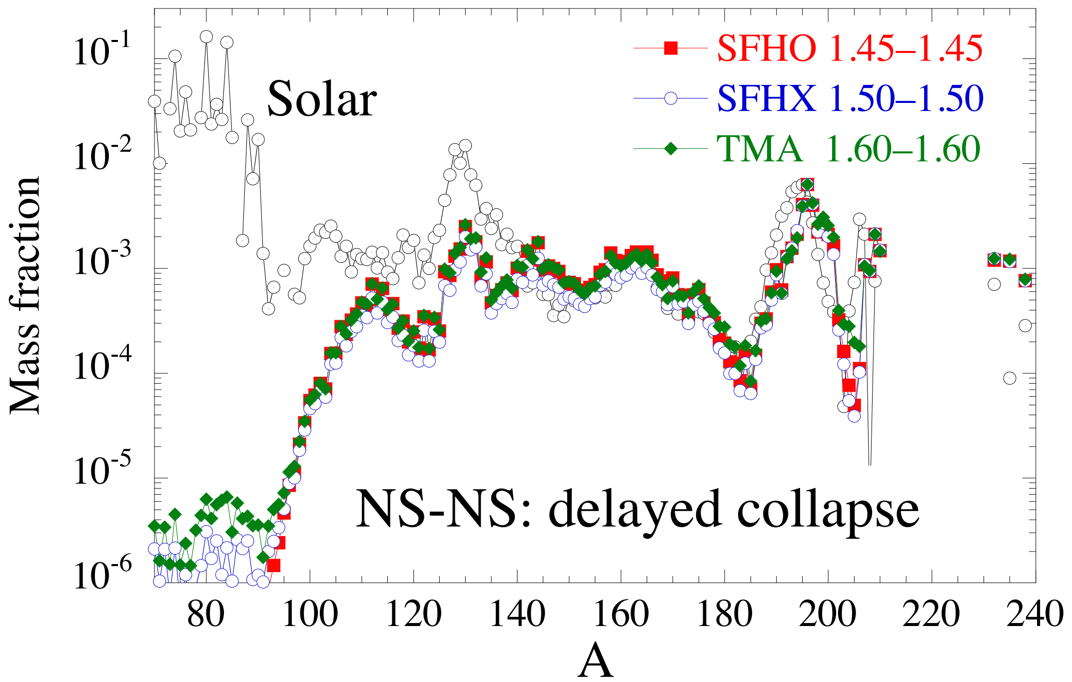


AND similar predictions, be it

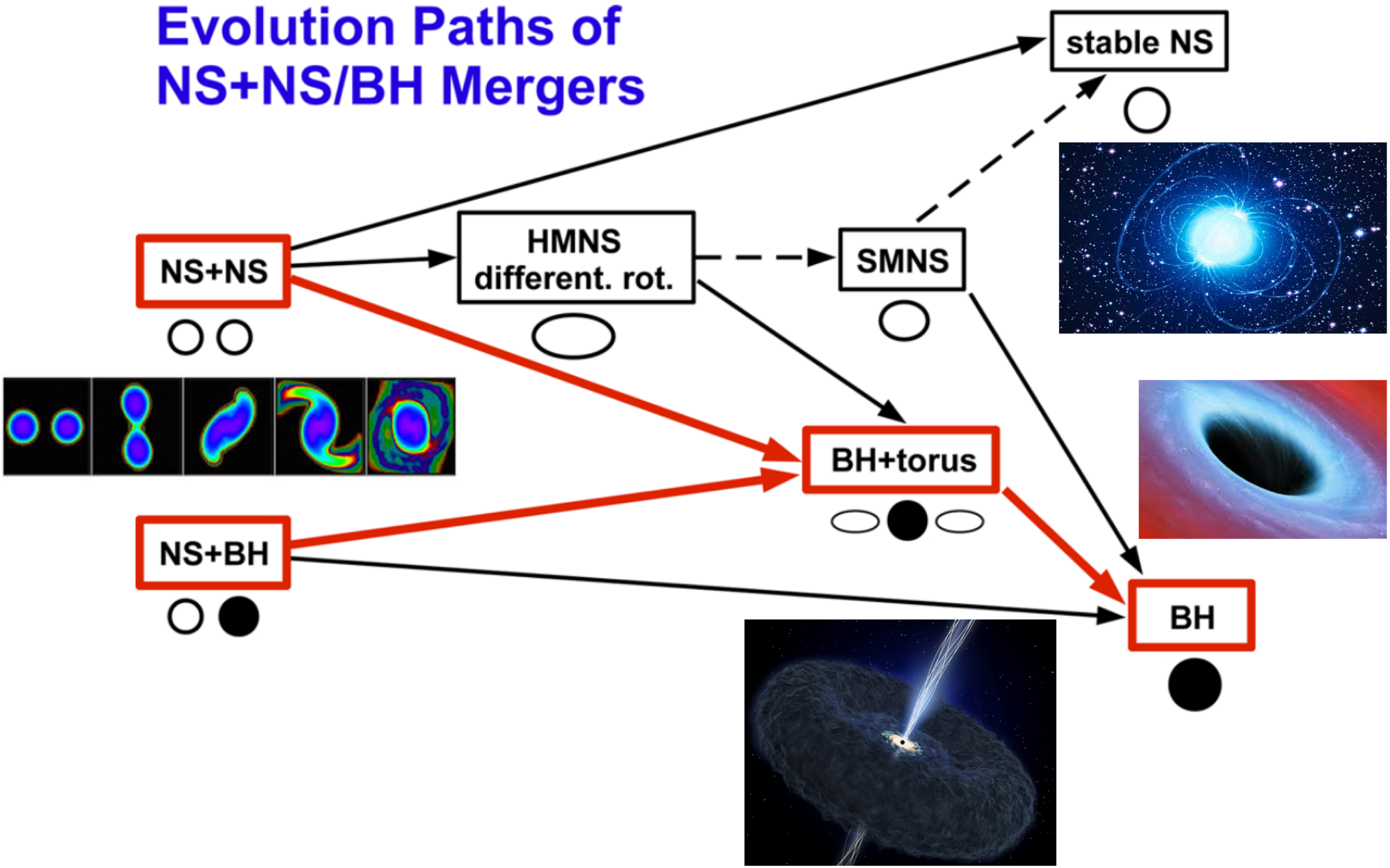
- a prompt collapse of NS-NS
- a delayed collapse of NS-NS
- a NS-BH system







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

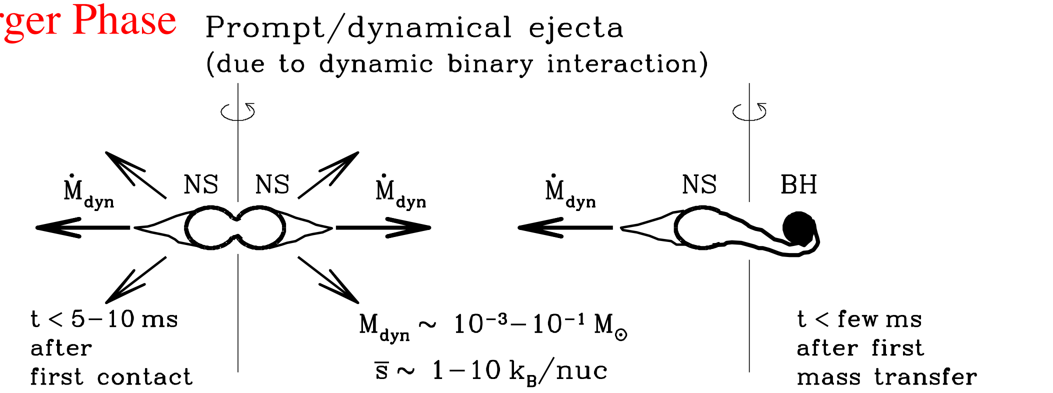

Evolution Paths of
NS+NS/BH Mergers
stable NS
NS+NS
HMNS
different. rot.
SMNS
BH+torus
NS+BH
BH

Neutron Star Mergers: a very rich r-process site

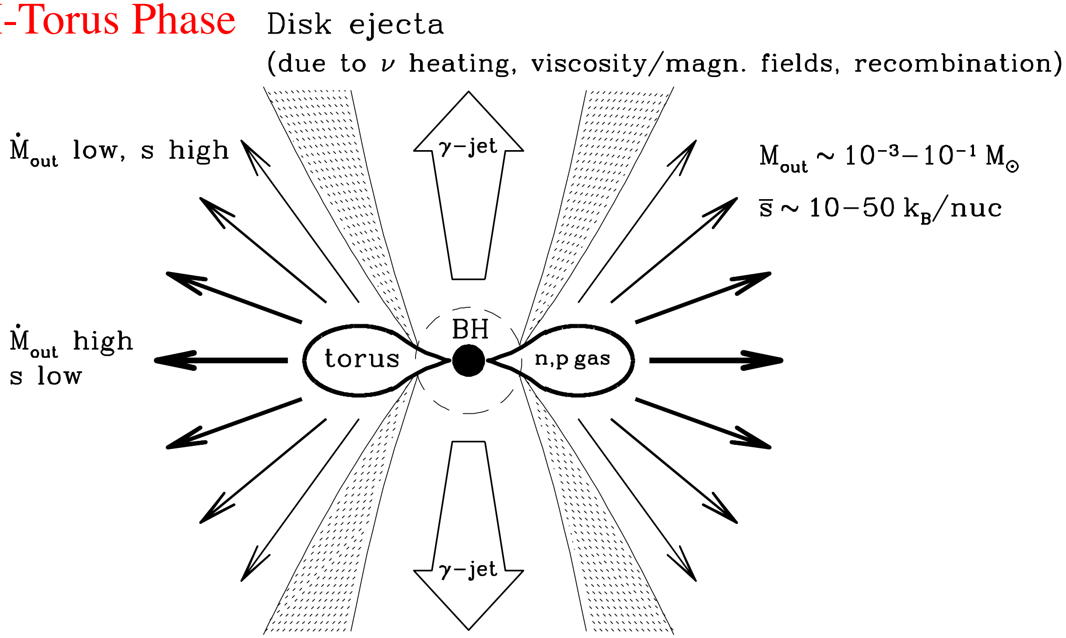
Hydrodynamical simulations : Just, Bauswein, Janka et al. MNRAS (2015)

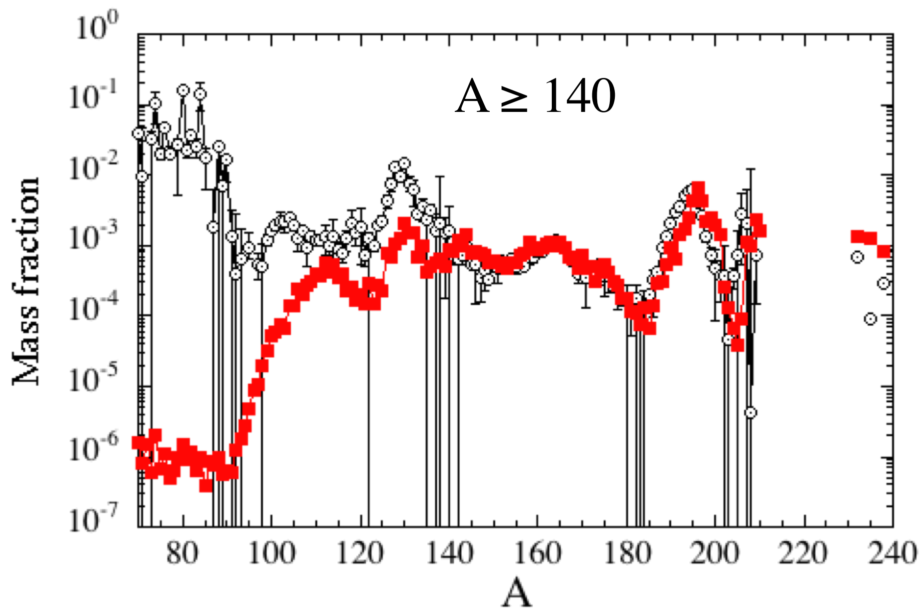
Mass loss phases during NS-NS and NS-BH merging

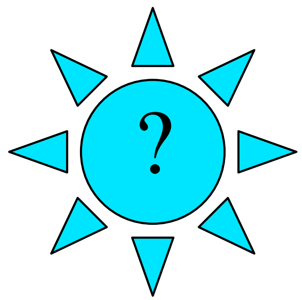
1. Merger Phase



2. BH-Torus Phase





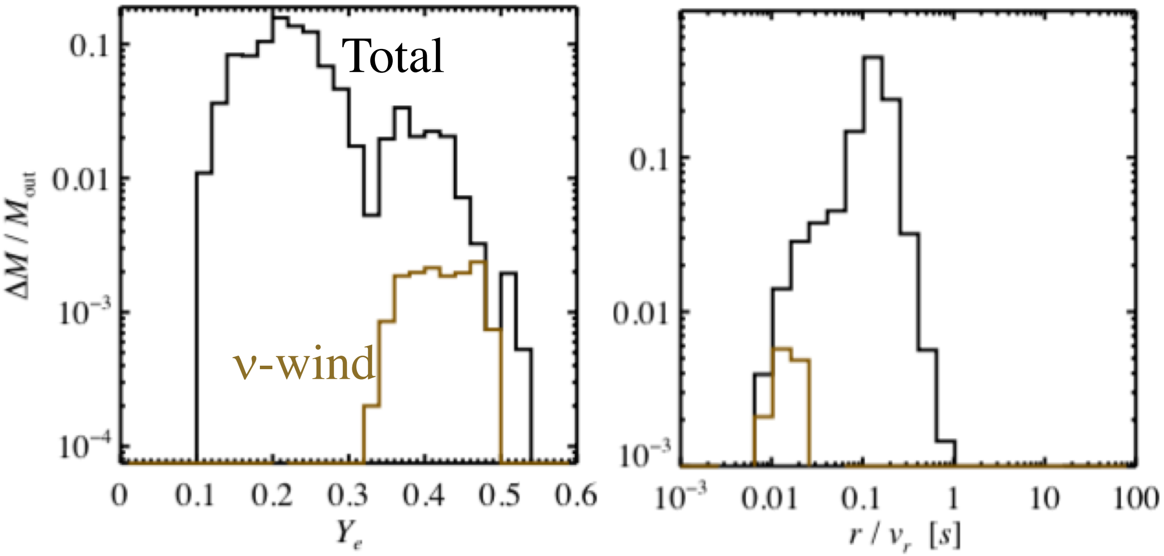


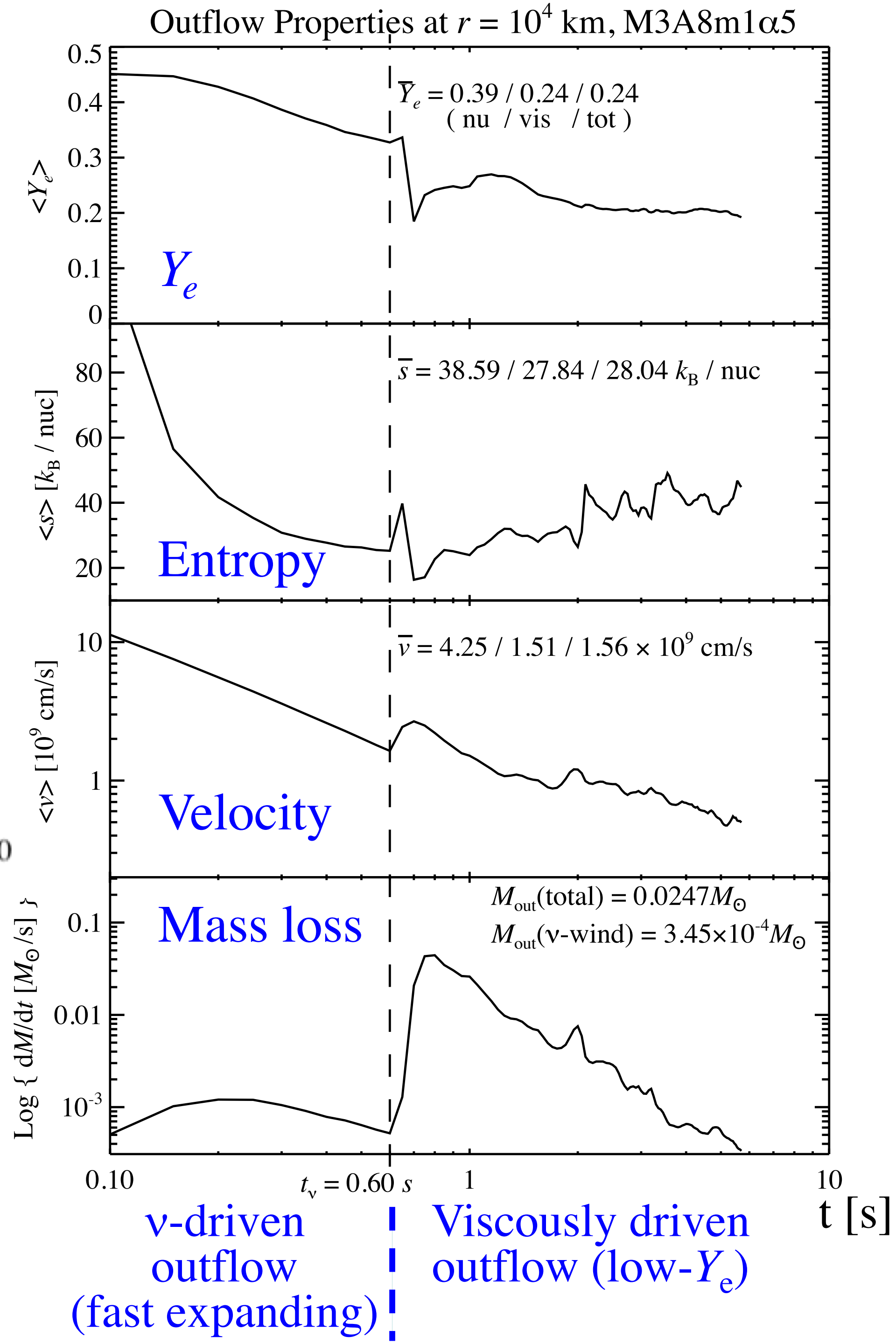
Properties of the disk ejecta

Ejected mass (ν-wind & viscous comp.)

$7\ 10^{-3} \leq M_{ej}[M_o] \leq 8\ 10^{-2}$

$M_{torus}=0.1M_o;\ M_{BH}=3M_o$





➡ **Nucleosynthesis corresponding to**

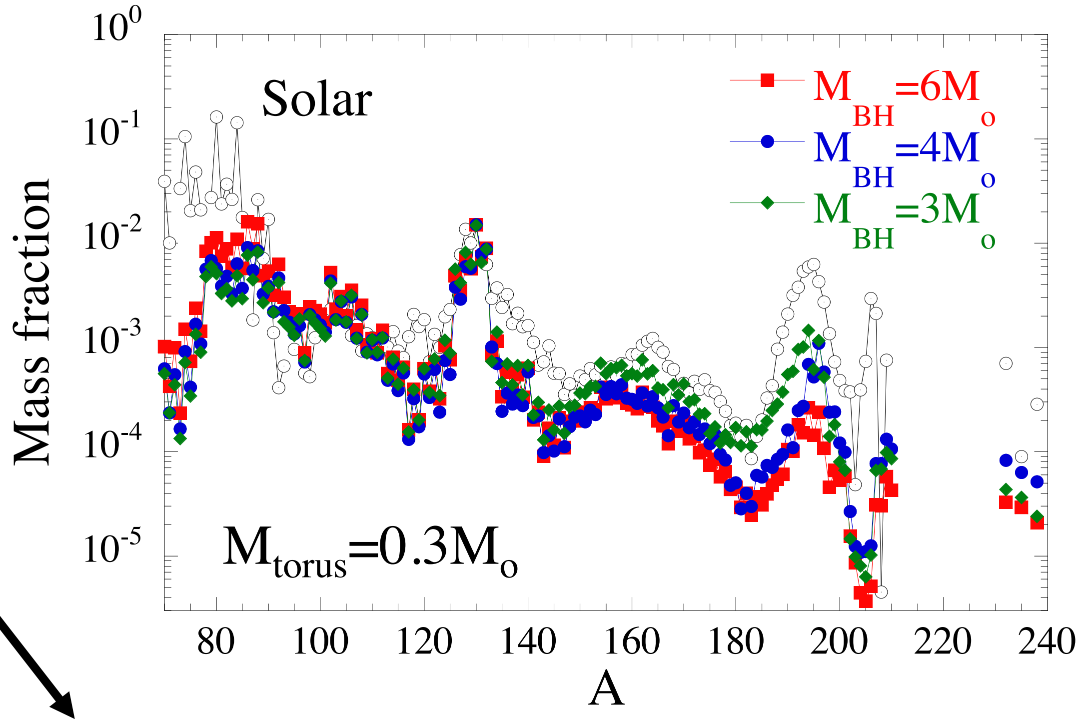
- **fast-expanding ν-wind**
- **low-Y_e viscous outflow**

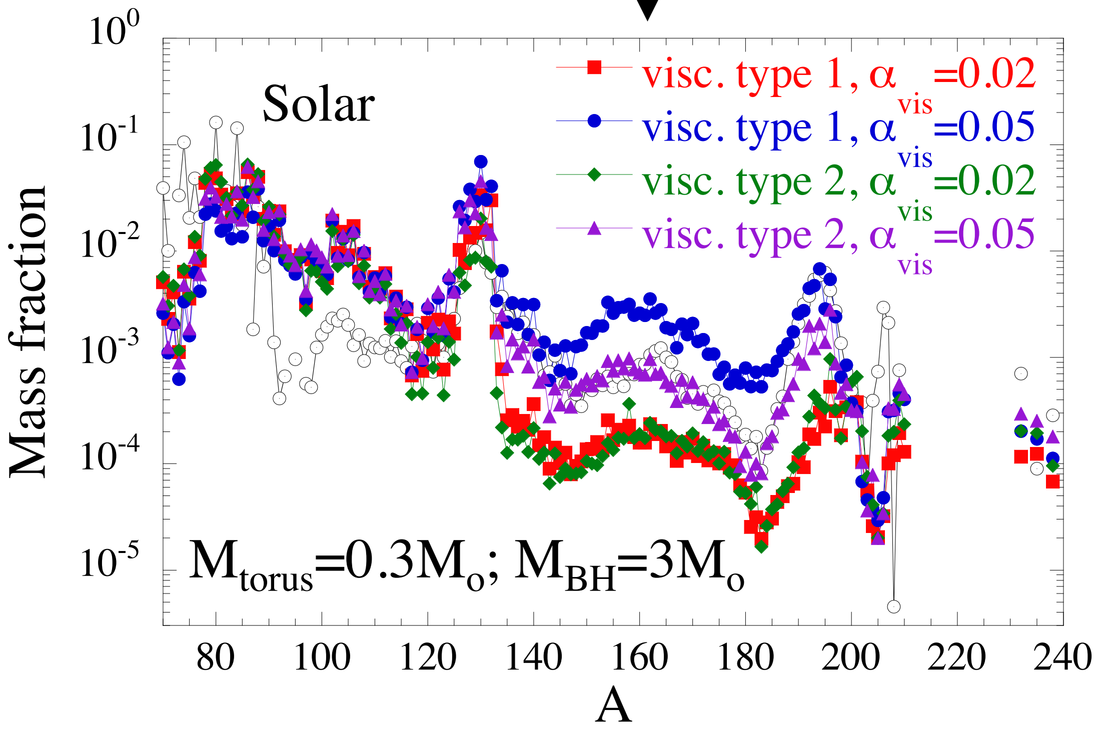
12 different hydro simulations

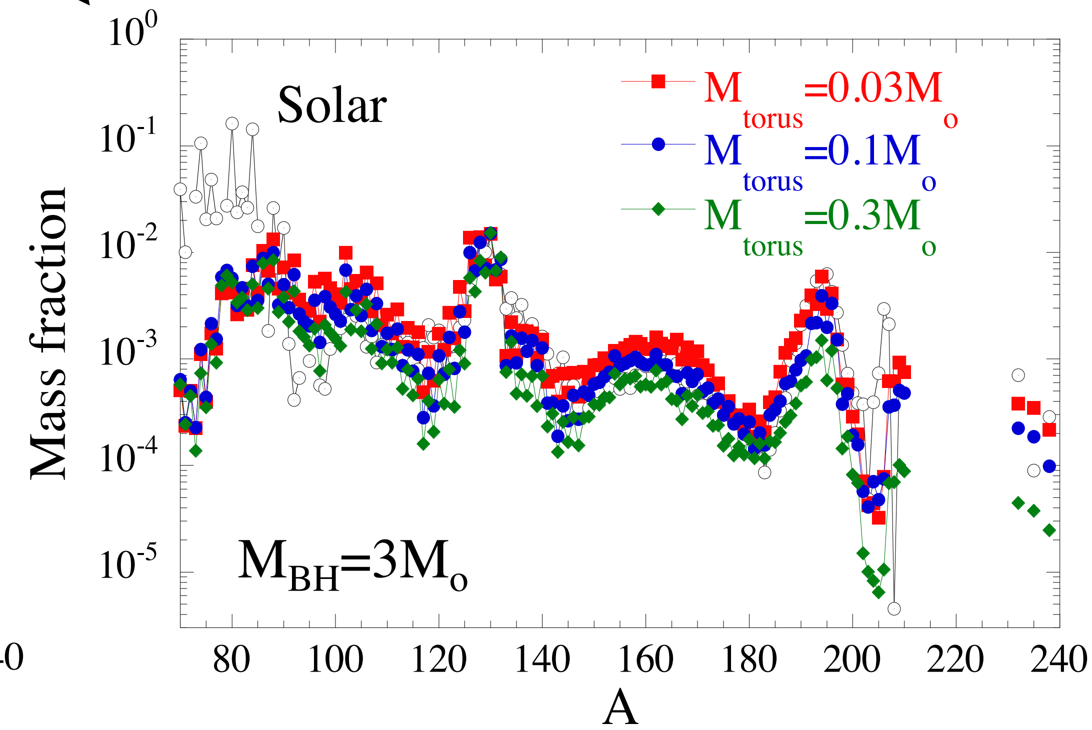
(O. Just, et al. 2015; see also Wu et al. 2016)

Abundance predictions sensitive to

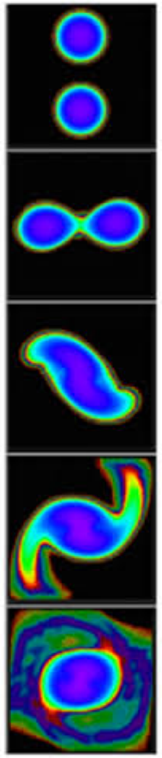
- Mass of the BH (same M_{torus})
- Mass of the torus (same M_{BH})
- Treatment of viscosity

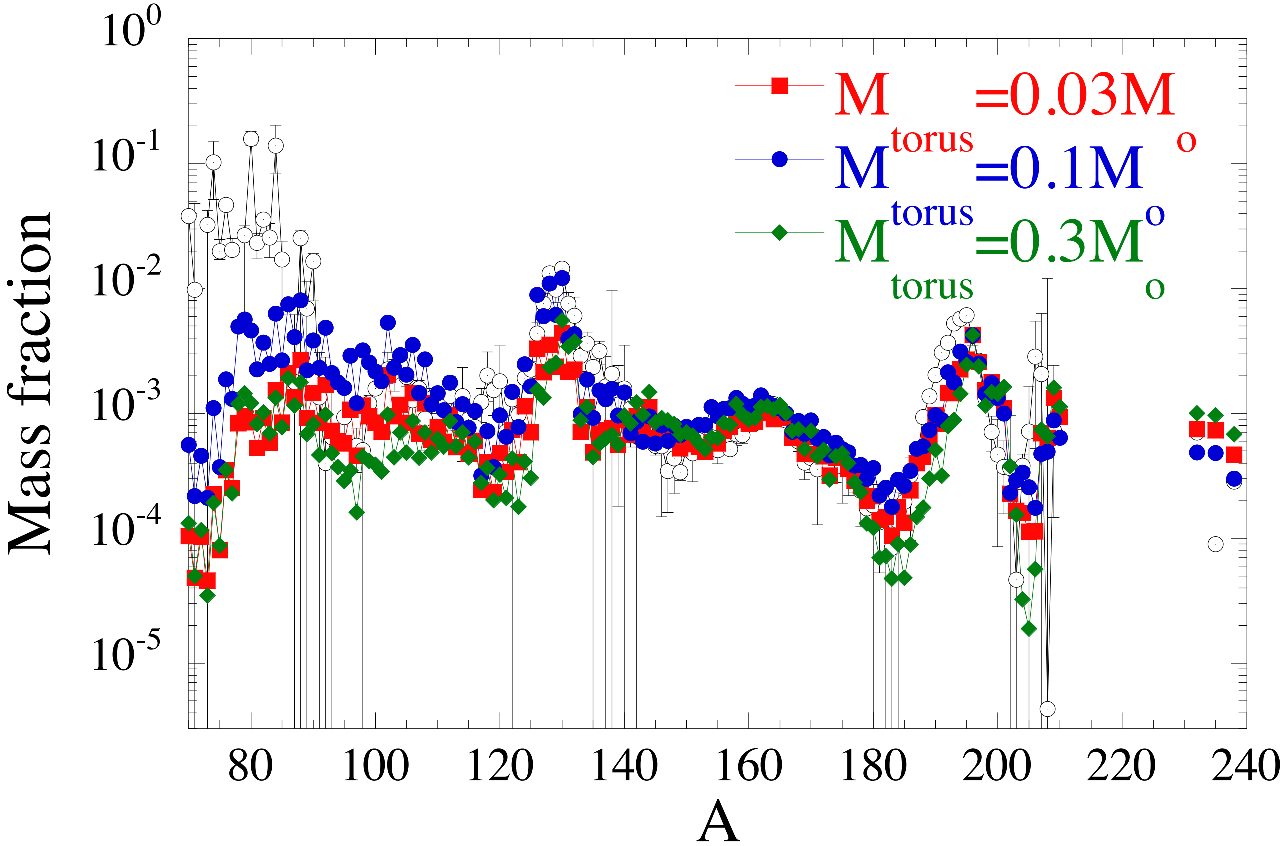


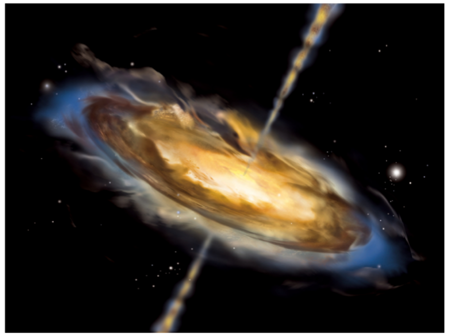




Mass-weighted *consistently* combined Dynamical + Disk ejecta



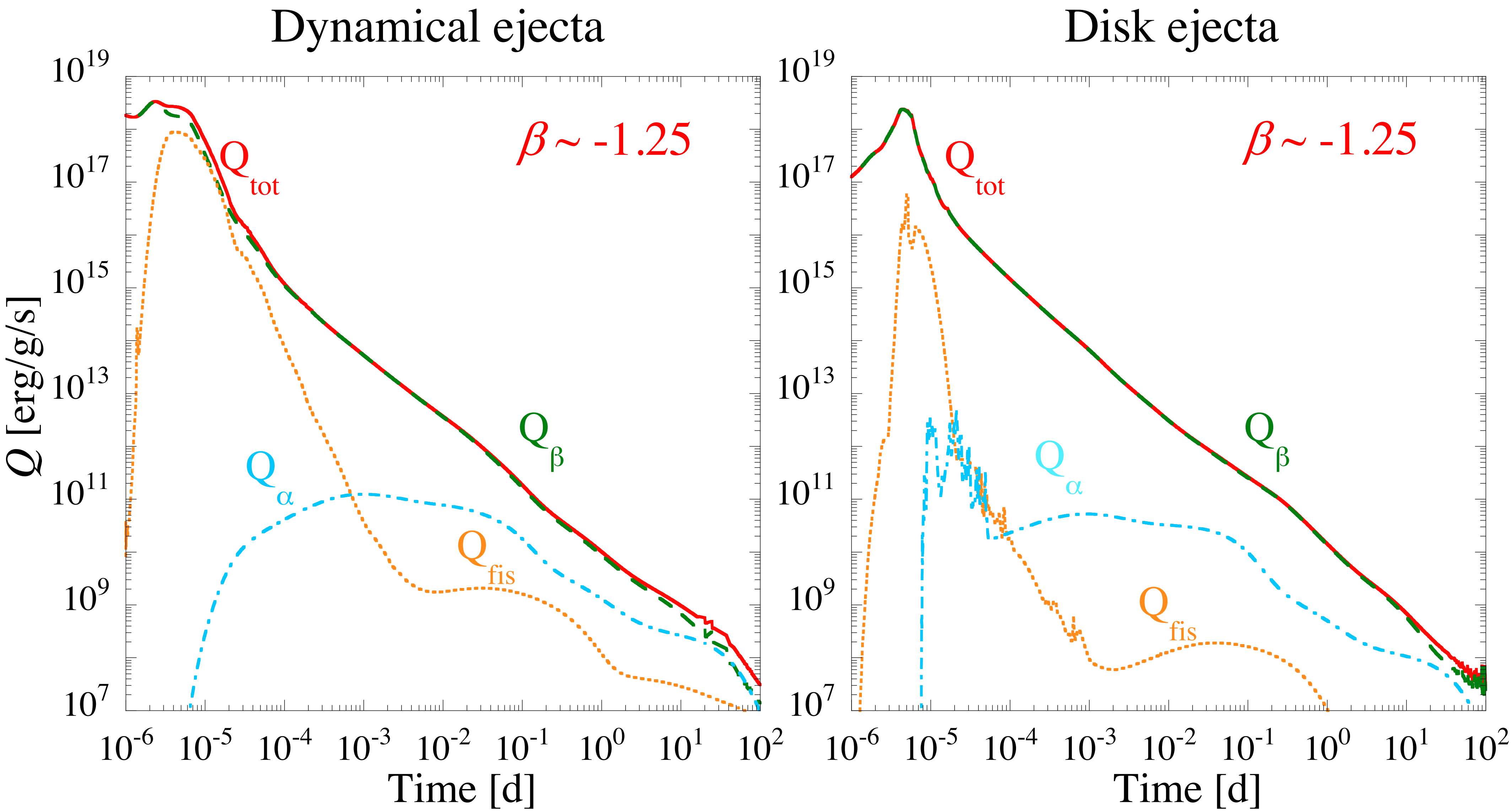




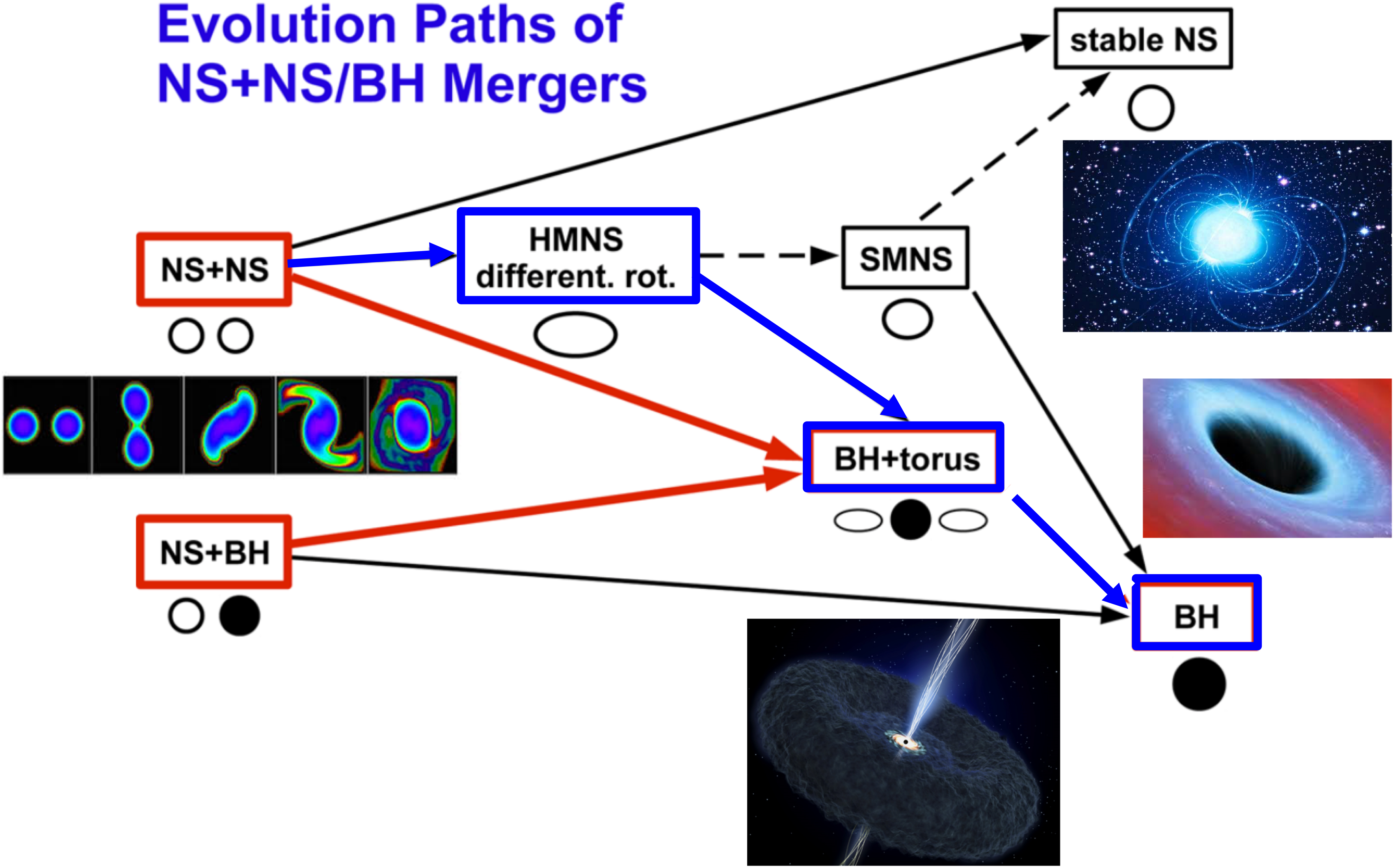
Robust production of all A ≥ 90 r-nuclei with a rather solar distribution.
Abundances for A ≤ 140 nuclei vary within typically a factor of 3

Total radioactive heating rate of the resulting Kilonova at late times

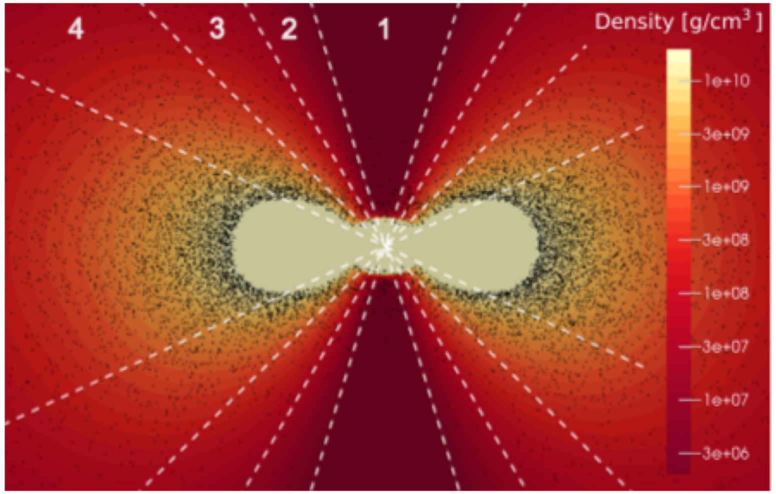
$$\boxed{Q_{tot}=Q_{\beta}+Q_{fis}+Q_{\alpha}}$$

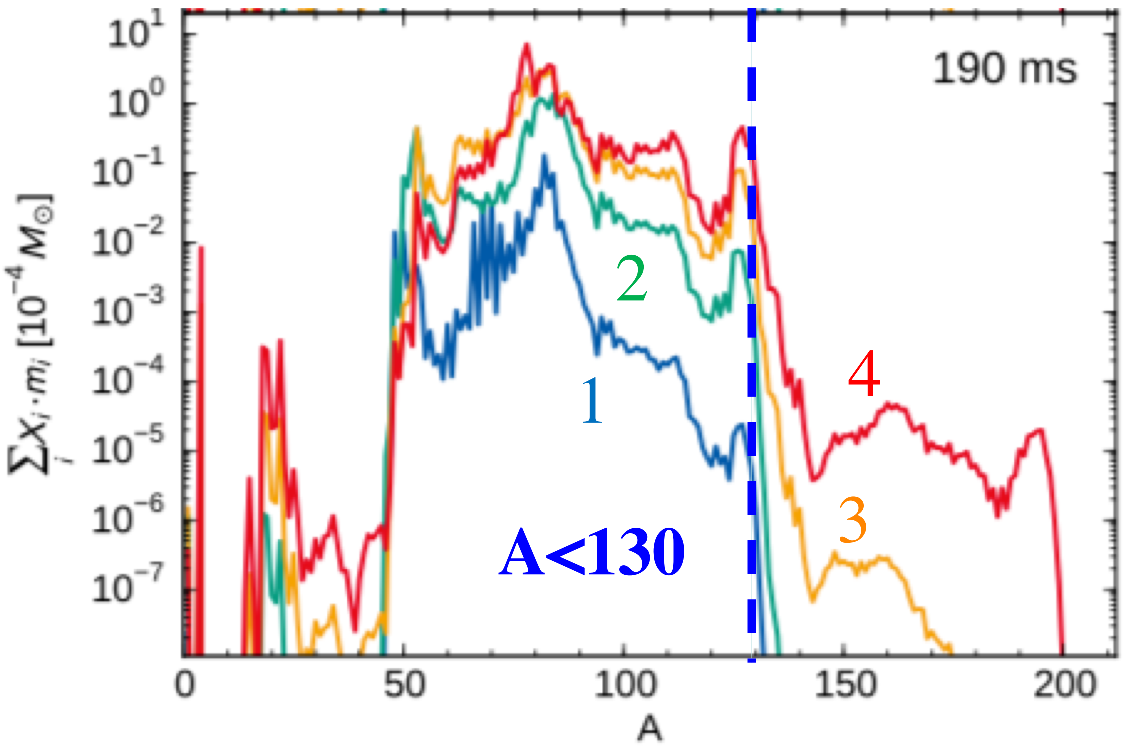


Evolution Paths of NS+NS/BH Mergers

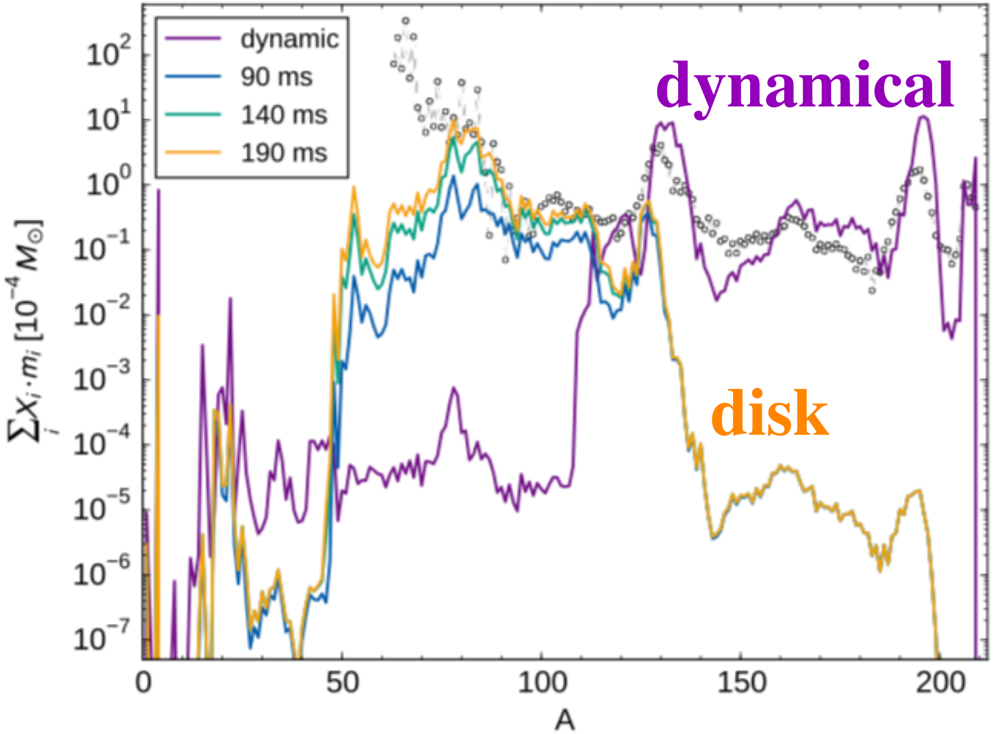


Composition of the matter ejected from a HMNS
(Perego et al. 2014; Martin et al. 2015)





Final composition (dynamical + disk)

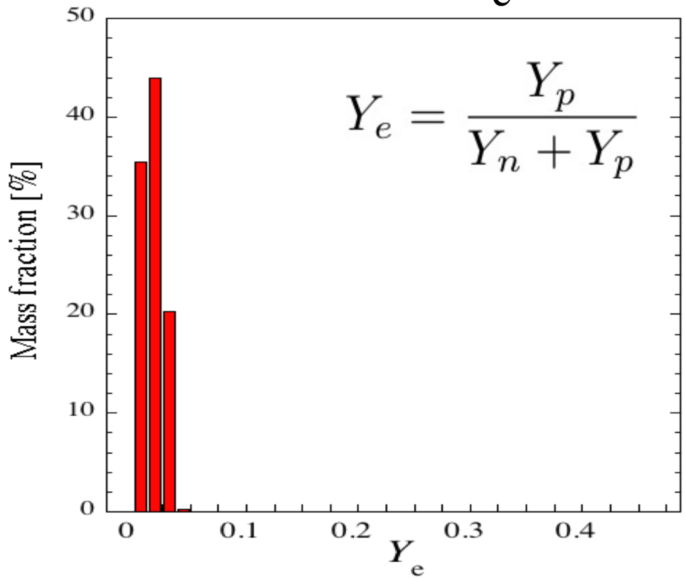


nucleosynthesis depends on the lifetime of the HMNS and the polar angle.

Still a major uncertainty affecting the nucleosynthesis in NS mergers:

electron (anti)neutrino absorption by free nucleons

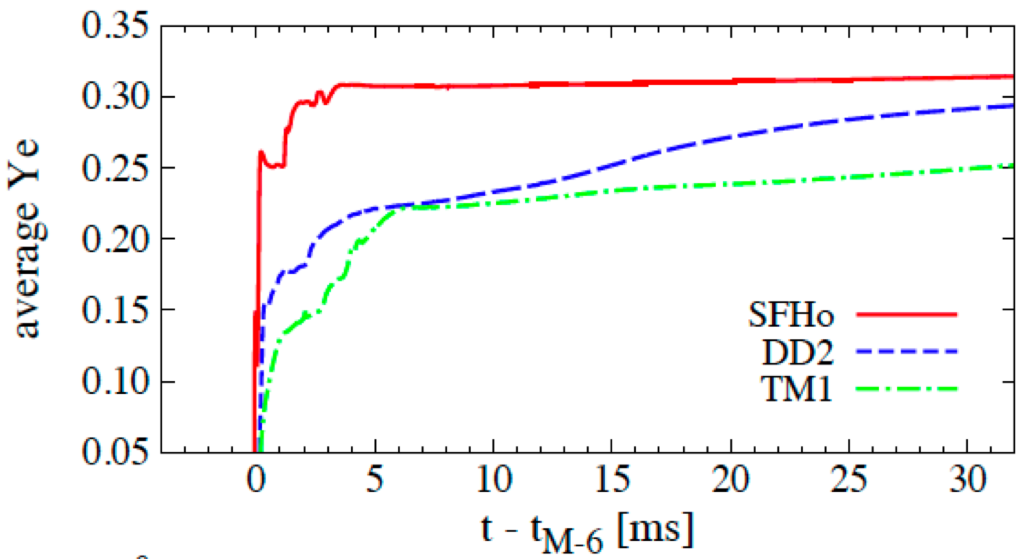
Initial Y_e

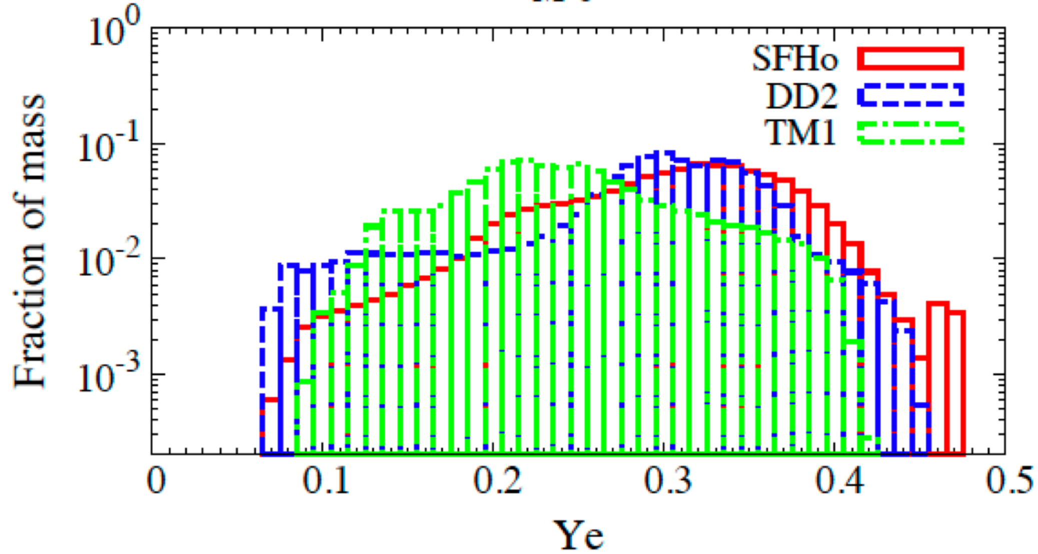


$$\nu_e + n \rightleftharpoons p + e^-$$

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

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





Also sensitive to the adopted EoS

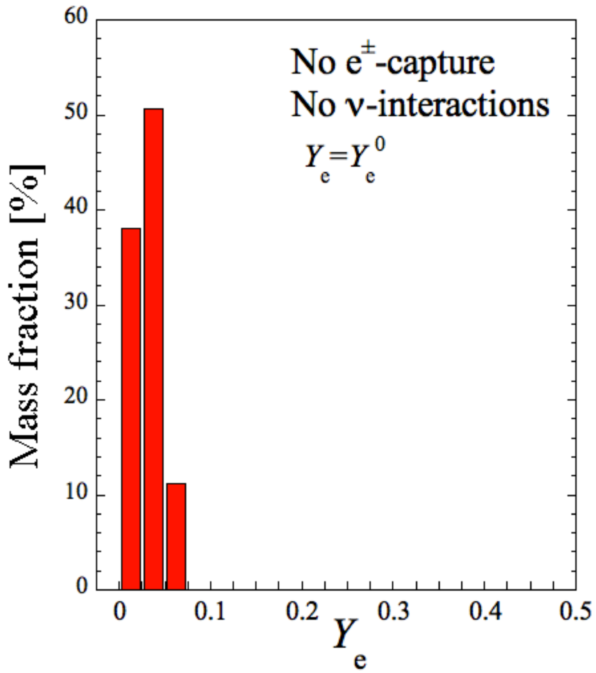
Wanajo et al. (2014); Sekiguchi et al. (2015)

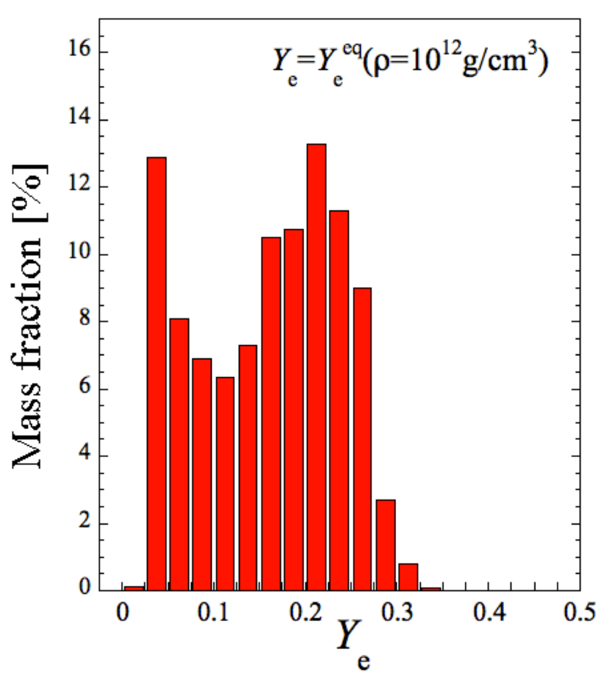
Initial *Ye* before r-processing

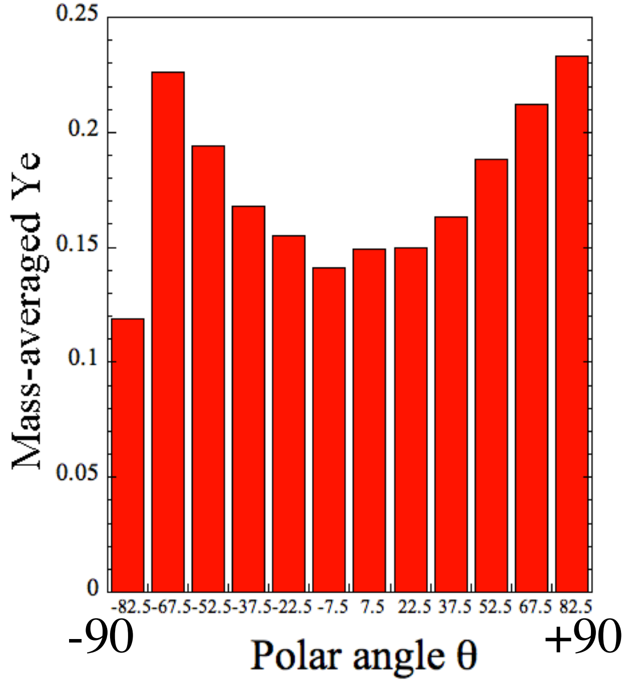
without ν-interaction

assuming equilibration at ρ=10^{12}g/cm^3

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







1.35 – 1.35 M$_o$ BNS

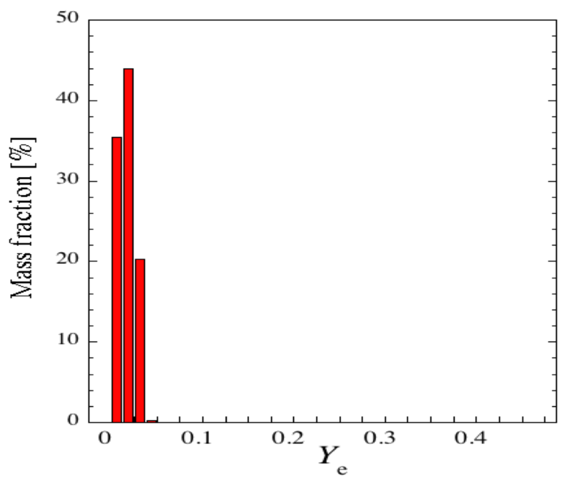
Sensitivity wrt e$^{\pm}$ capture and ν-interaction for different parametric properties of electron (anti)neutrinos: $L_{\nu e}$ and $\langle E_{\nu e}\rangle$

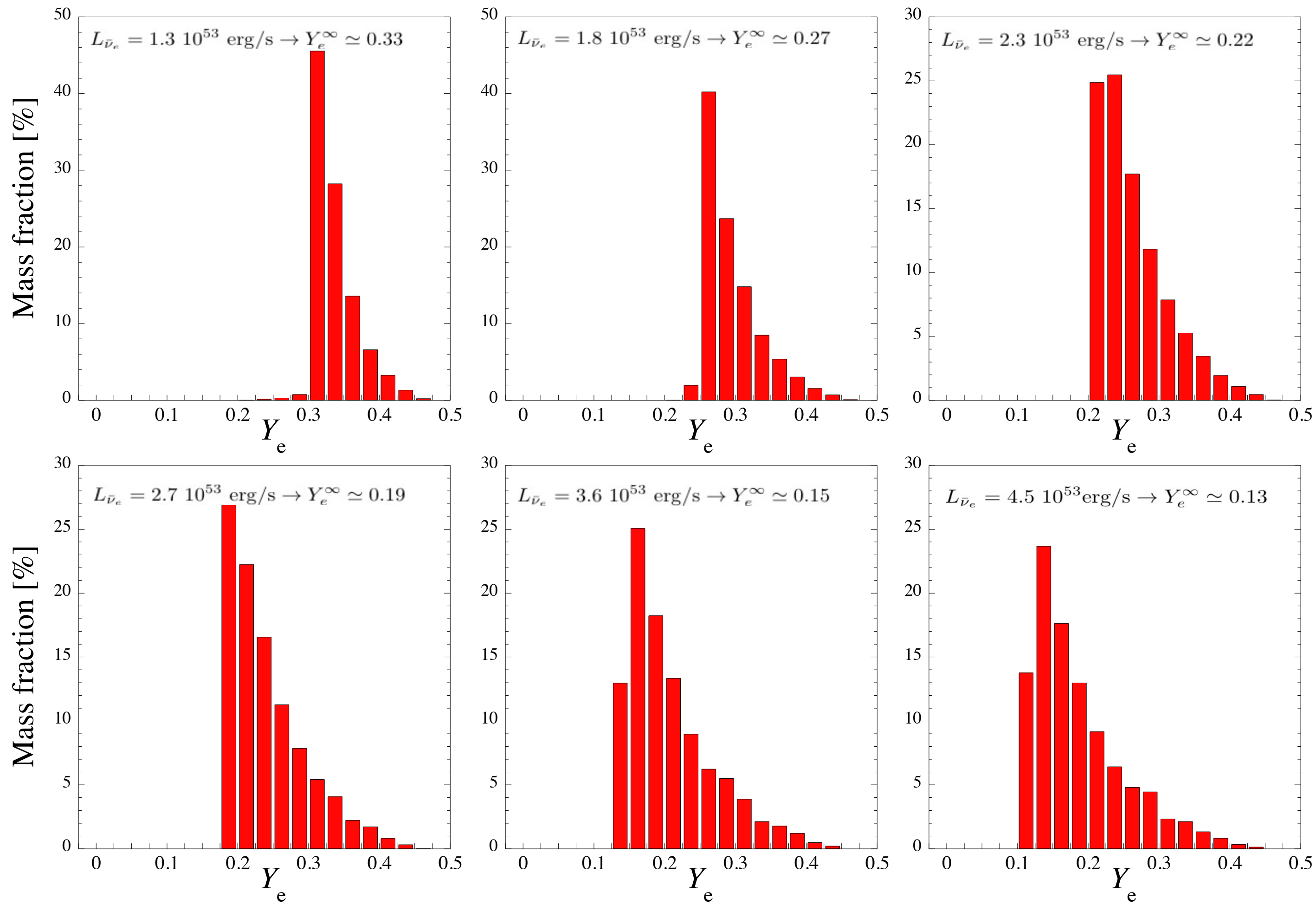
$$\nu_e + n \rightleftharpoons p + e^- \qquad \bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$\begin{cases} L_{\nu_e} = 0.6\ 10^{53}\mathrm{erg/s} \\ L_{\bar{\nu}_e} = L\ 10^{53}\mathrm{erg/s} \\ \langle E_{\nu_e}\rangle = 12\ \mathrm{MeV} \\ \langle E_{\bar{\nu}_e}\rangle = 16\ \mathrm{MeV} \end{cases}$$

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

without ν-interaction

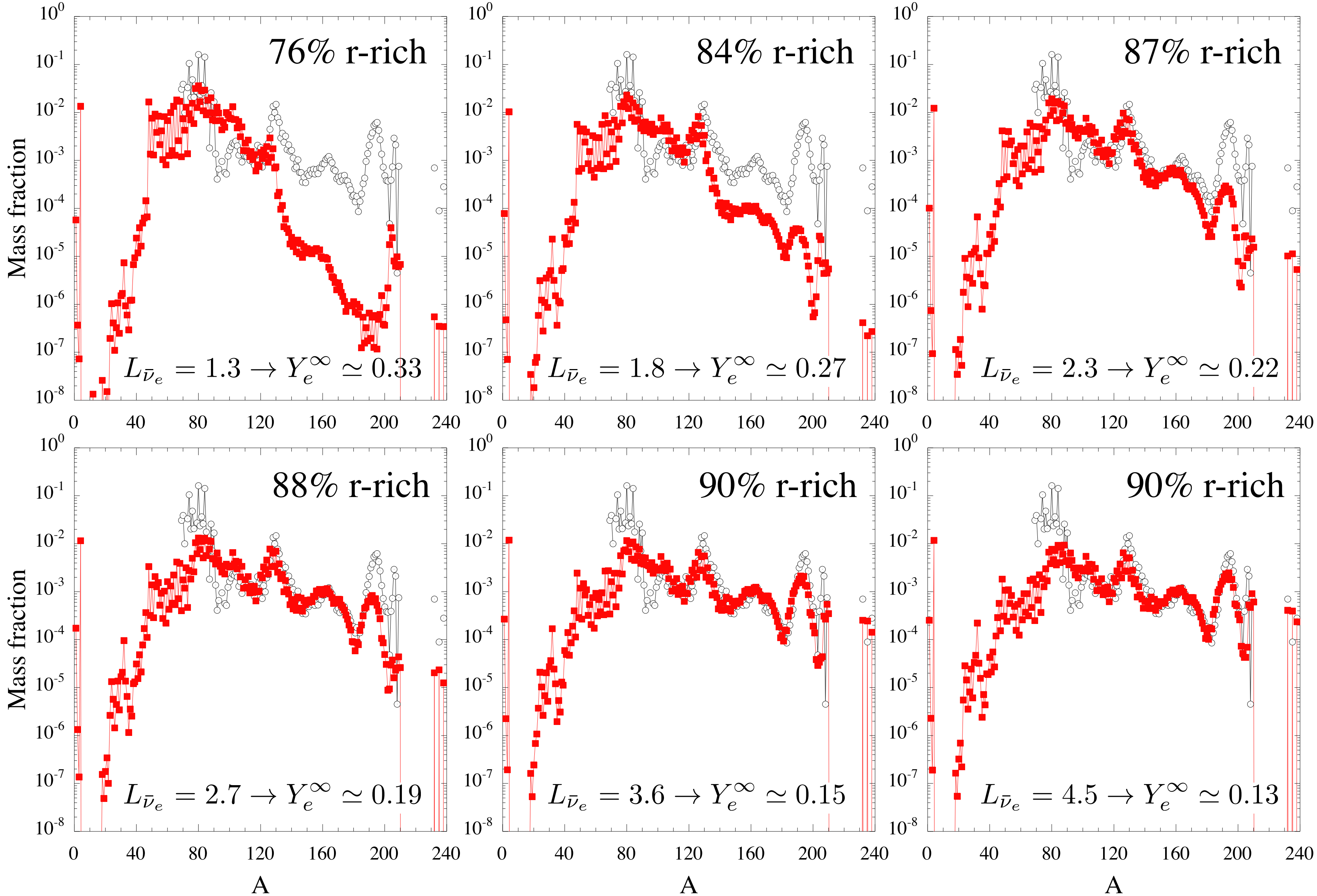




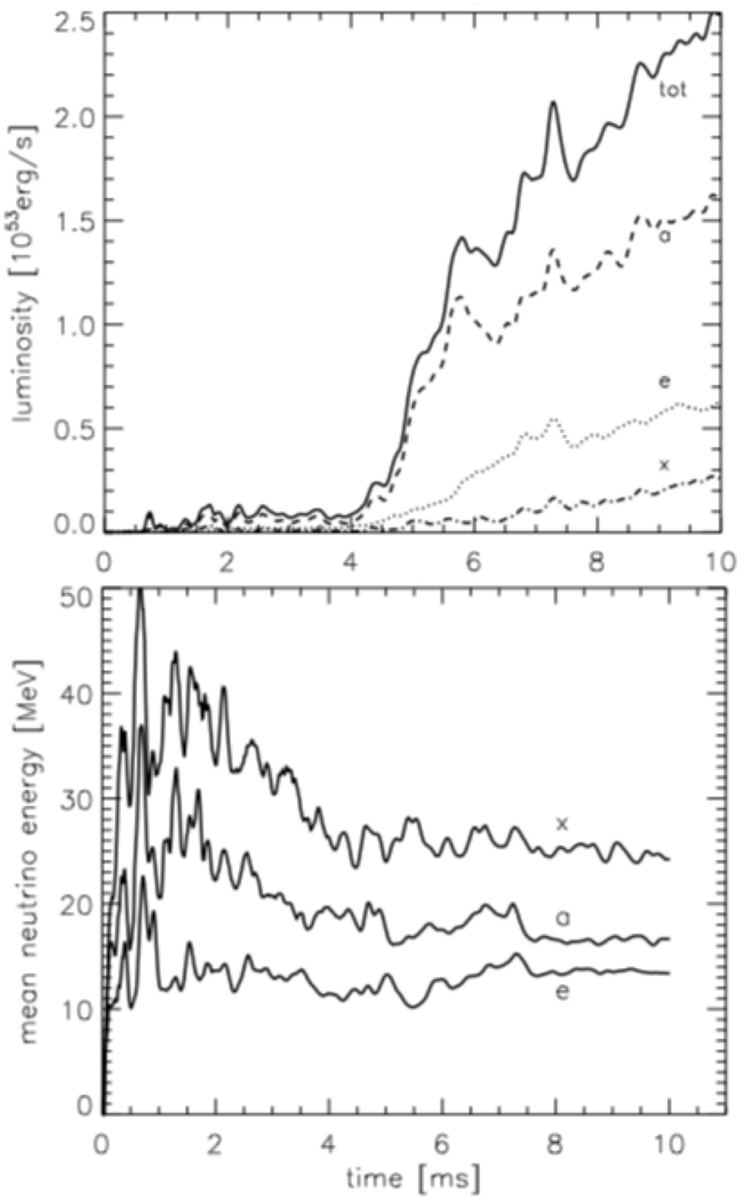
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$\left\{ \begin{array}{l} L_{\nu_e} = 0.6\ 10^{53}\mathrm{erg/s} \\ L_{\bar{\nu}_e} = L\ 10^{53}\mathrm{erg/s} \\ \langle E_{\nu_e} \rangle = 12\ \mathrm{MeV} \\ \langle E_{\bar{\nu}_e} \rangle = 16\ \mathrm{MeV} \end{array} \right.$$

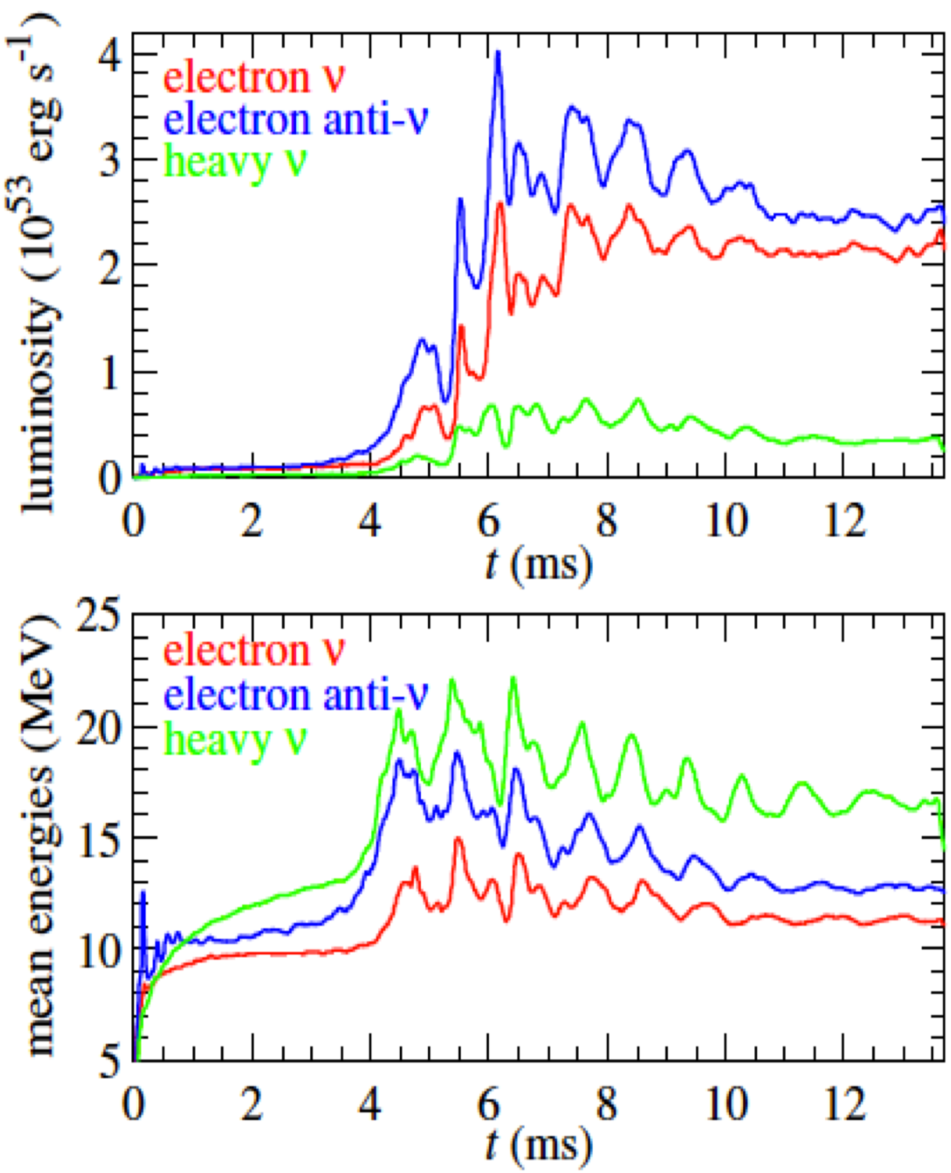
$$Y_e^{\nu\infty} \simeq \frac{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr}}{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr} + L_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle f_{\bar{\nu}_e}^{mr}}$$



Ruffert & Janka (2001)

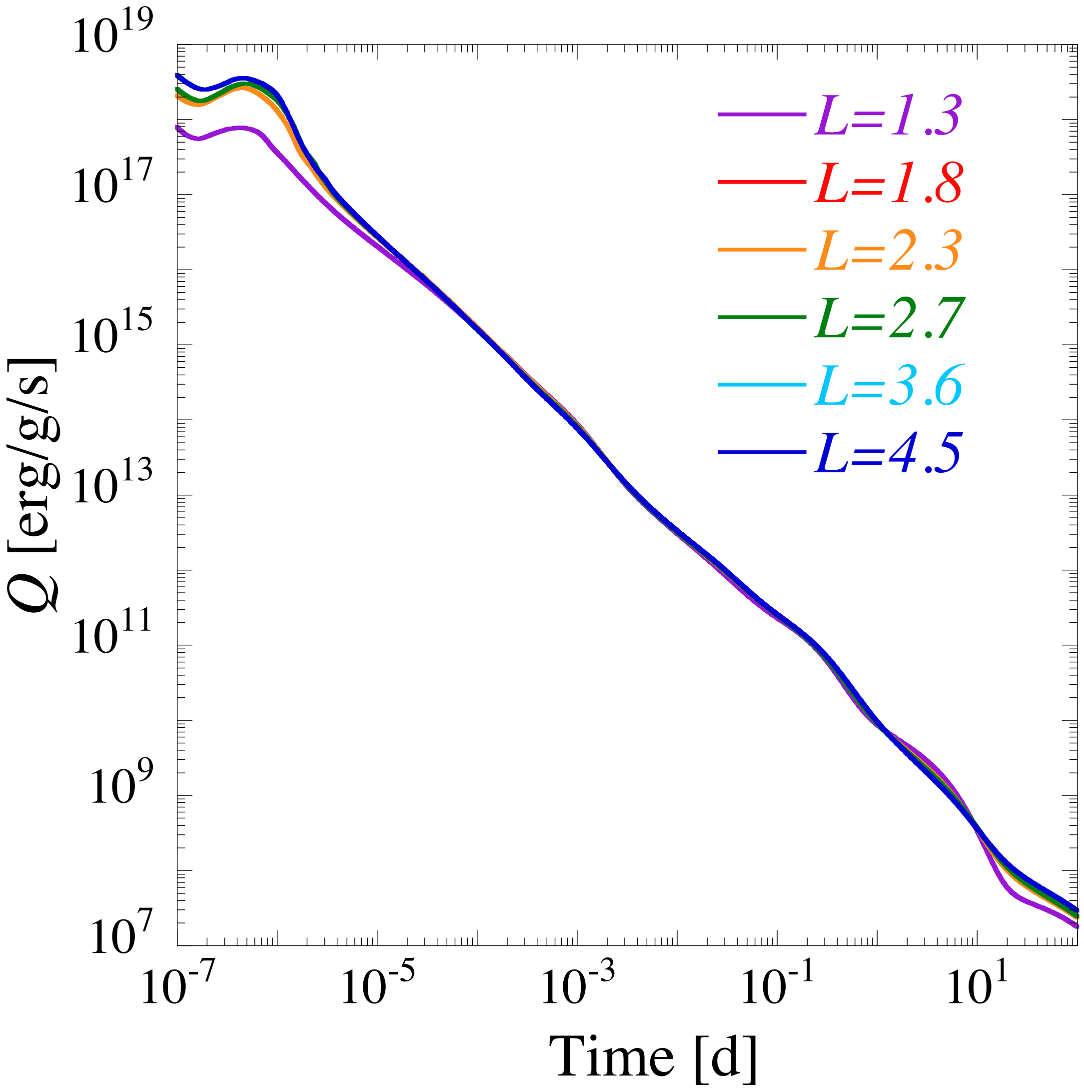


Wanajo et al. (2014)



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

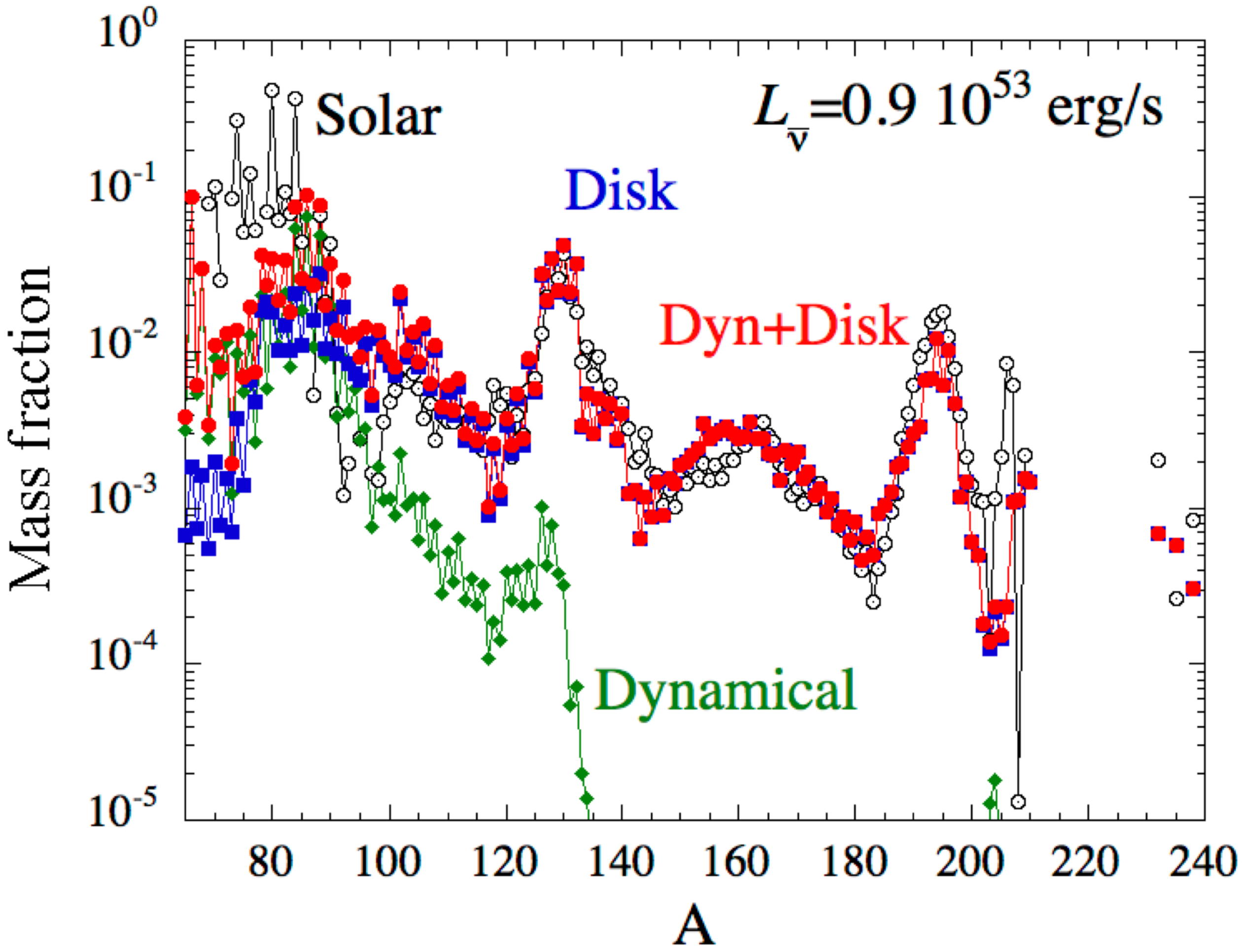
$$\Rightarrow \left\{ \begin{array}{l} L_{\nu_e} = 0.6\ 10^{53}\mathrm{erg/s} \\ L_{\bar{\nu}_e} = L\ 10^{53}\mathrm{erg/s} \\ \langle E_{\nu_e} \rangle = 12\ \mathrm{MeV} \\ \langle E_{\bar{\nu}_e} \rangle = 16\ \mathrm{MeV} \end{array} \right. \Rightarrow Y_e^{\nu\infty} \simeq \frac{L_{\nu_e}\langle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



Similar radioactive heating rate

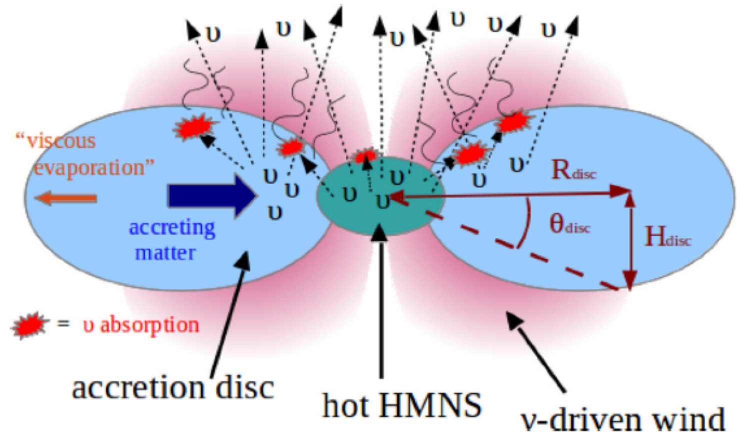
Possibility for the Kilonova to result from

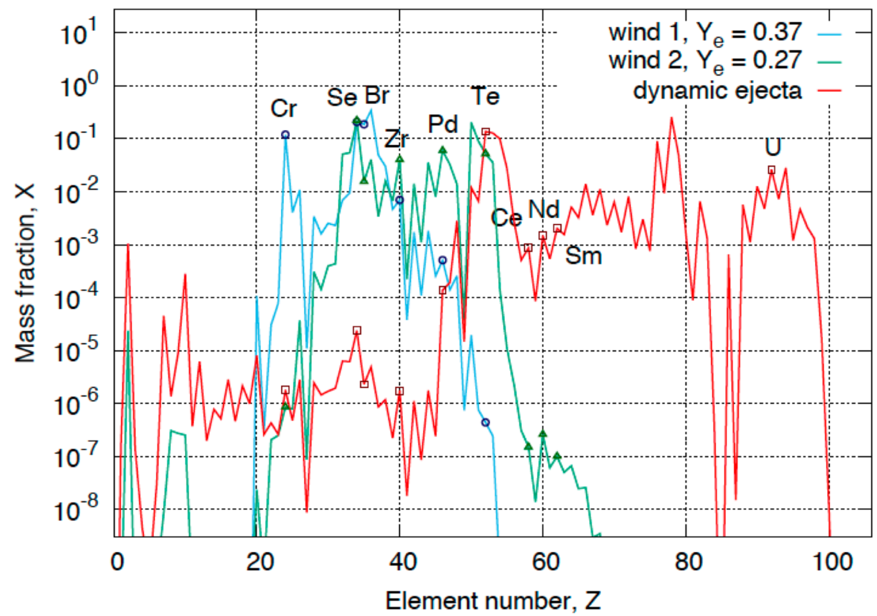
- a lanthanide-*free* dynamical ejecta (if $L_{\bar{\nu}_e} \lesssim 3 \times L_{\nu_e}$)
- a lanthanide-*rich* disk ejecta

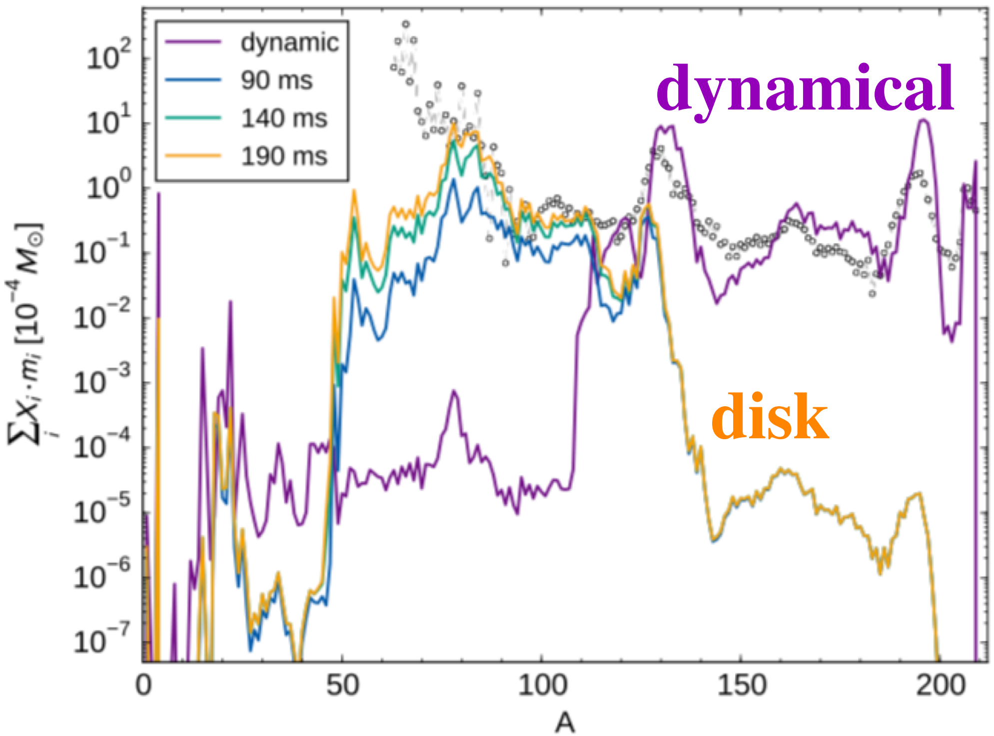


with $M_{\rm dyn} \sim M_{\rm disk}$ but $v_{\rm dyn} \sim$ 4-7 x $v_{\rm disk}$

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







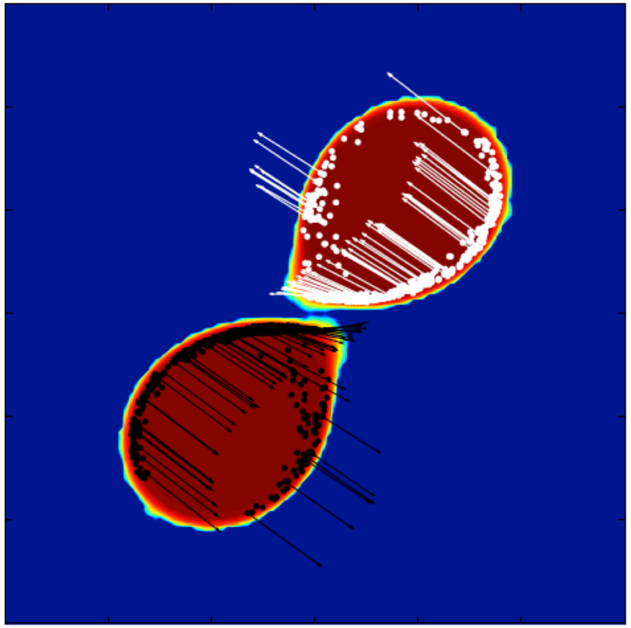
- a lanthanide-*rich* dynamical ejecta
- a lanthanide-*free* disk ejecta

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

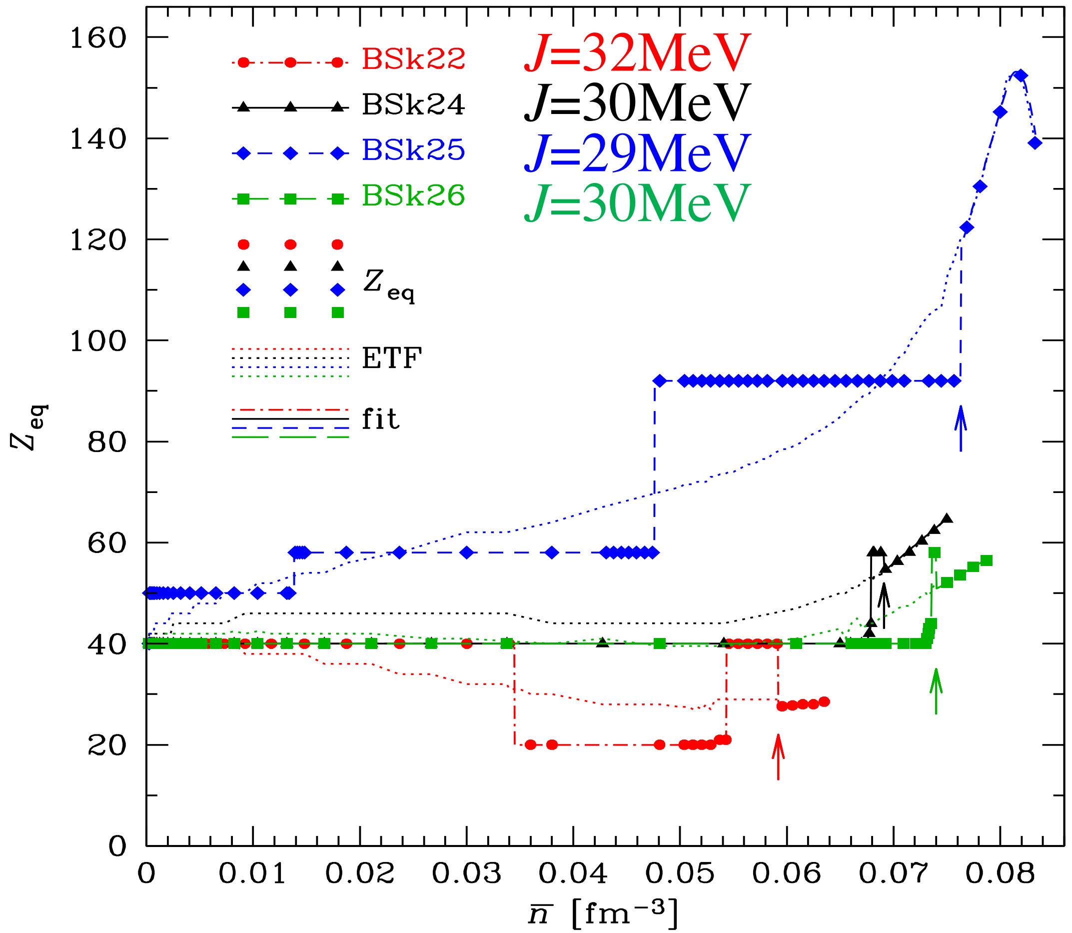
How universal are the thermodynamic conditions during the NSM decompression ?

About 1000-7000 mass elements ejected in the SPH simulations

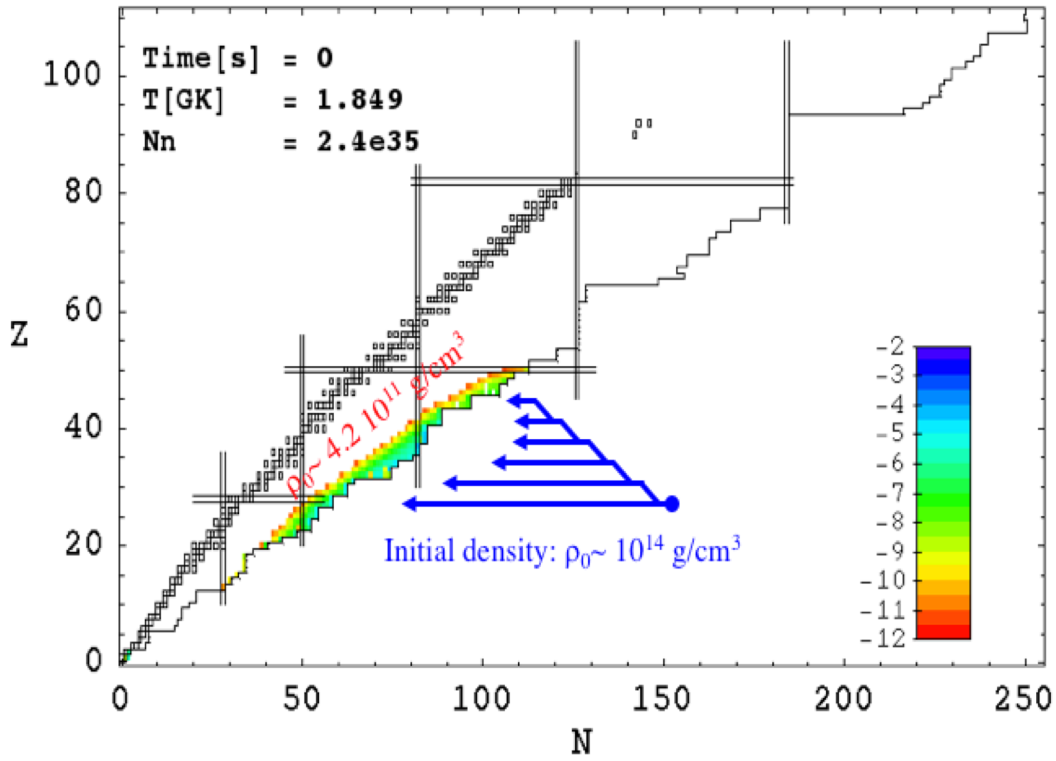
Each mass element has a specific density and temperature history



Sensitivity of the inner crust composition to the symmetry energy



Possible β-decay of the inner crust material (with change of Y_e)



cf Sumiyoshi et al. (1998)

Network calculations based on the MPA NS-NS merger simulations

- Density profiles from hydrodynamical simulations (SPH trajectories)

$$\rho(t{=}0) \;\leq\; \rho_{\mathrm{drip}} = 4.2\ 10^{11}\,\mathrm{g/cm^3} \qquad \text{if } T \leq 10^{10}\mathrm{K}$$

$$= \;\rho(T{=}10^{10}\mathrm{K}) \qquad \text{if } T \geq 10^{10}\mathrm{K}$$

At late times, a constant velocity expansion is assumed

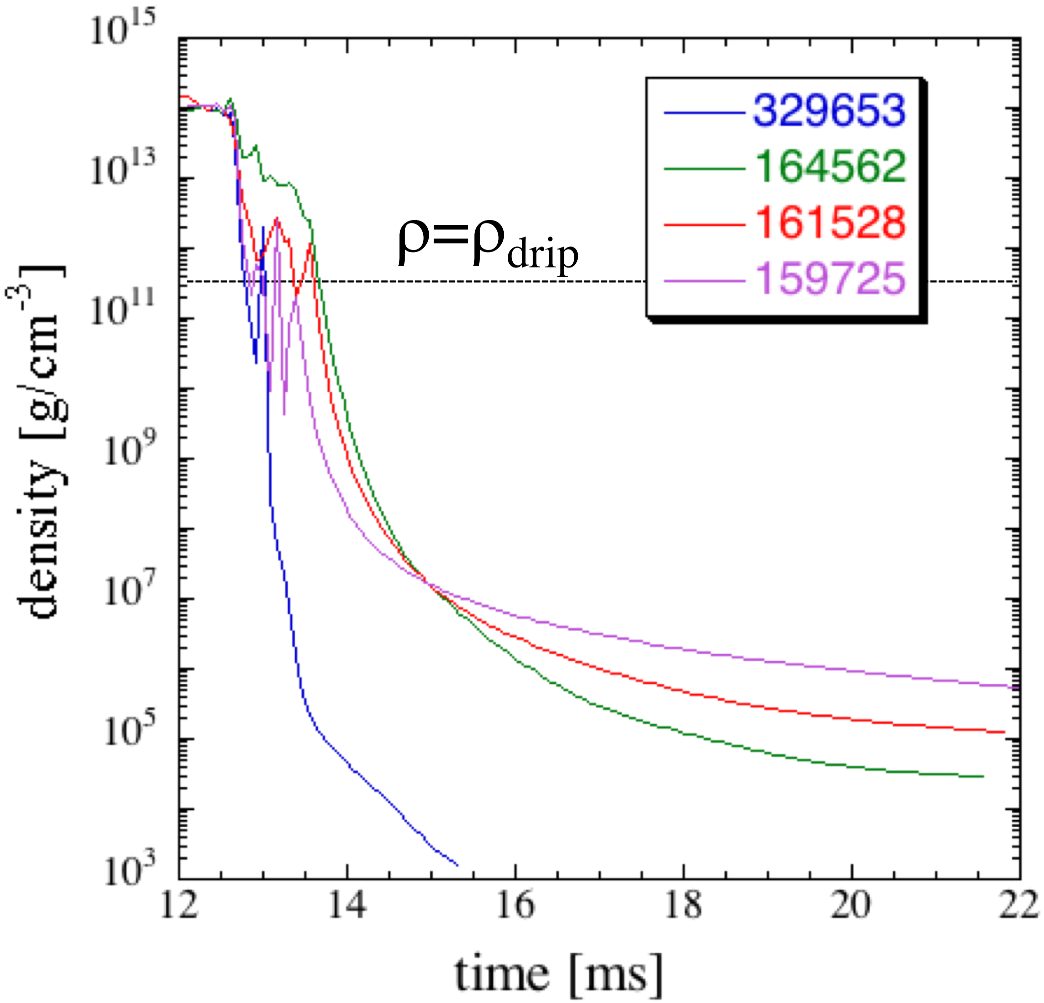
$$\rho[t > t_{\mathrm{max}}(\mathrm{simulation})]:\ \rho \propto \frac{1}{t^3}$$

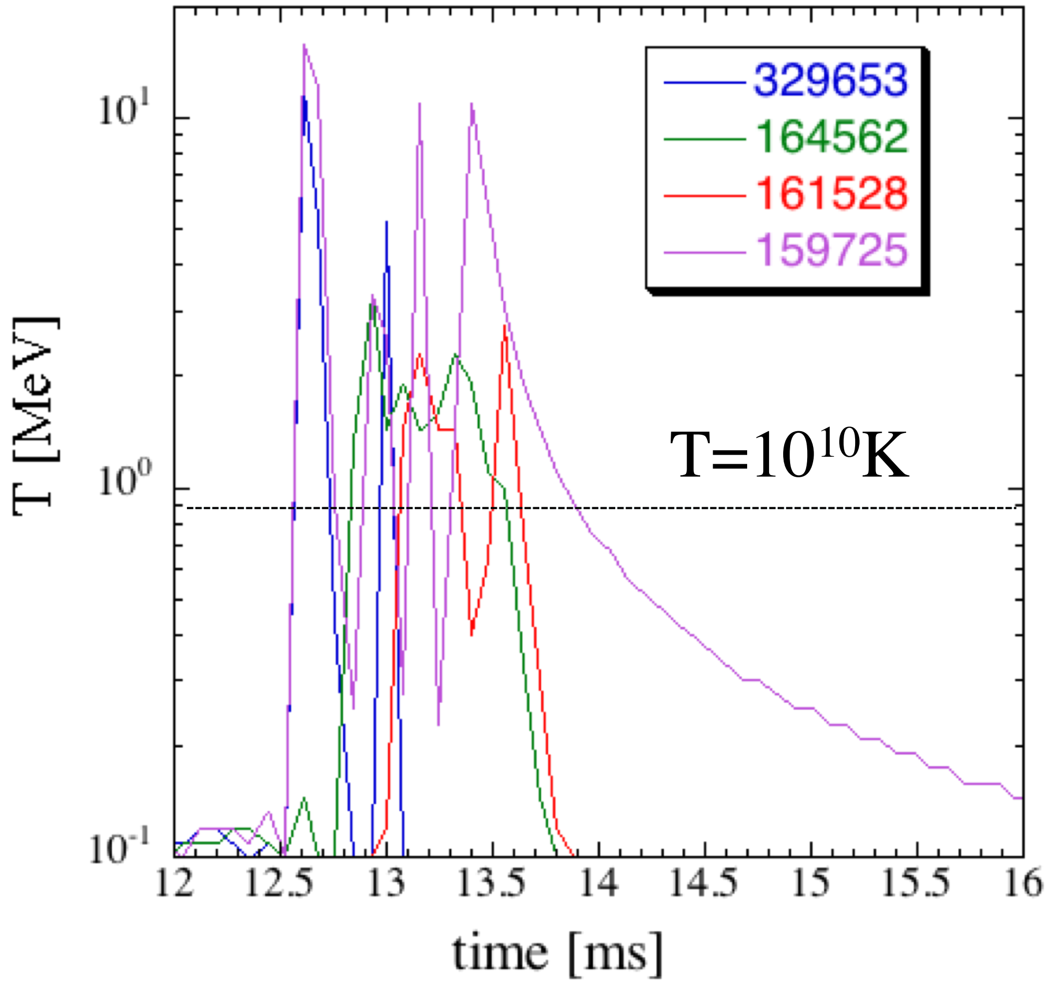
- Temperature profile from trajectories followed by thermodynamic laws for time such that $T \leq 10^{10}$K (heating by β and nuclear reactions)

- Initial composition: NSE at T=10^{10}K; $\rho = \rho(T{=}10^{10}\mathrm{K})$; Y_e=$Y_e(T{=}10^{10}\mathrm{K})$

About a few thousands mass elements ejected in the SPH simulations

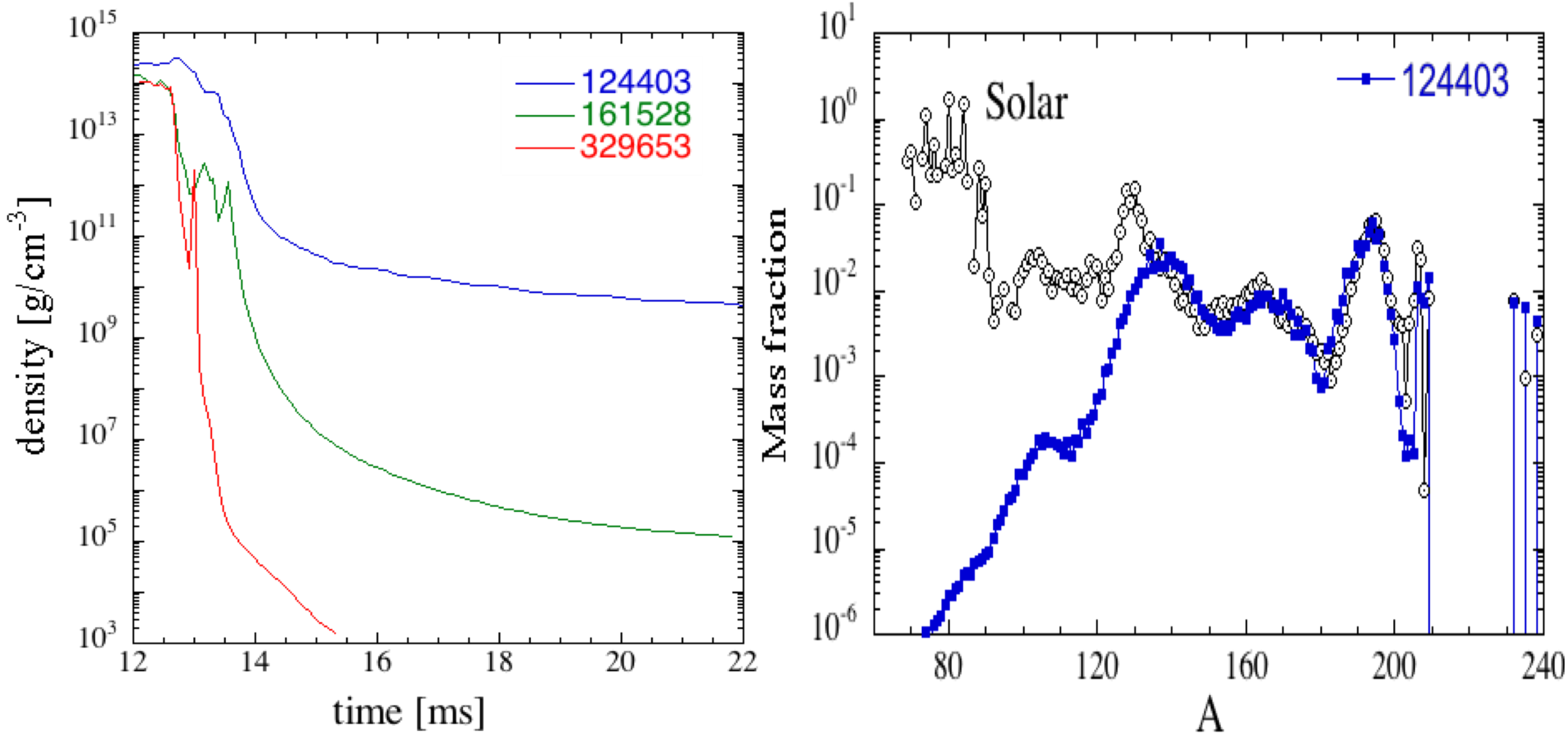
Each mass element has a specific density and temperature history



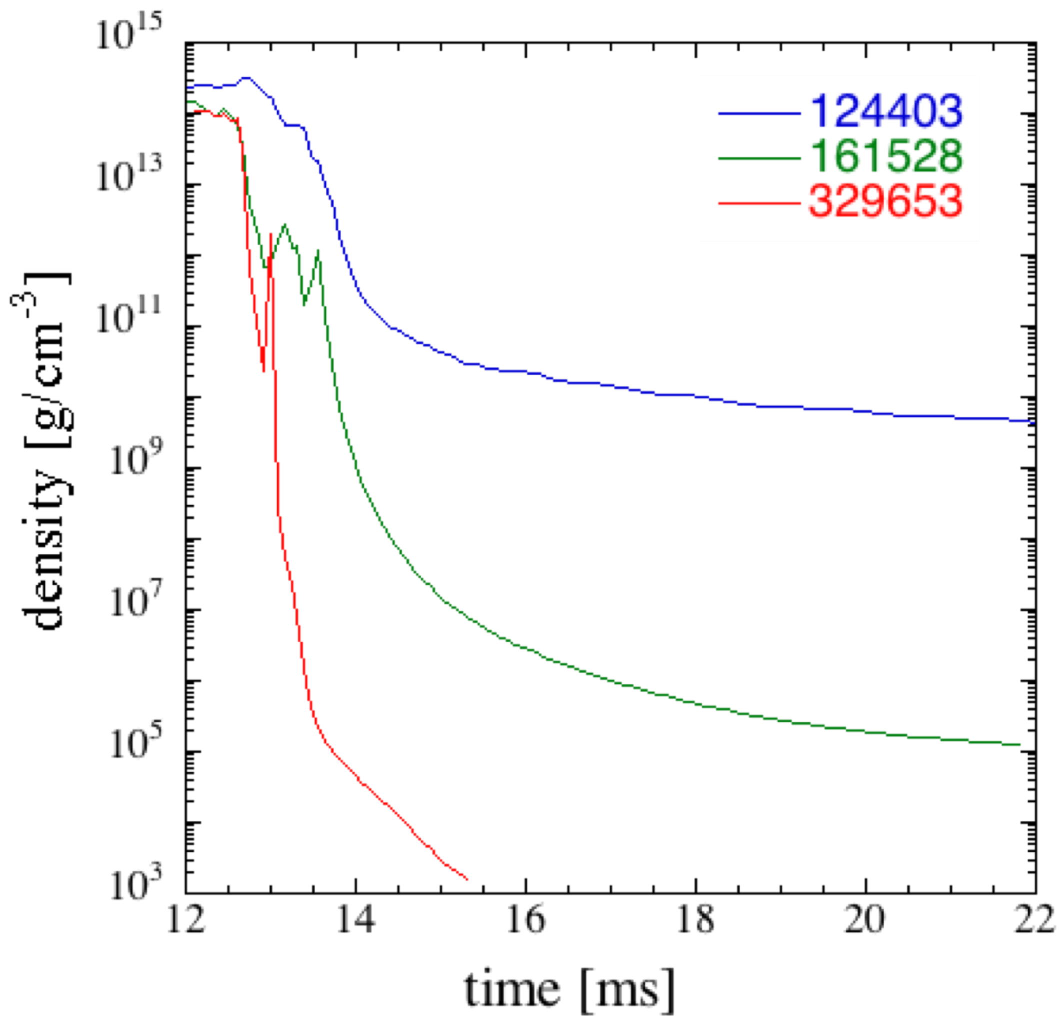


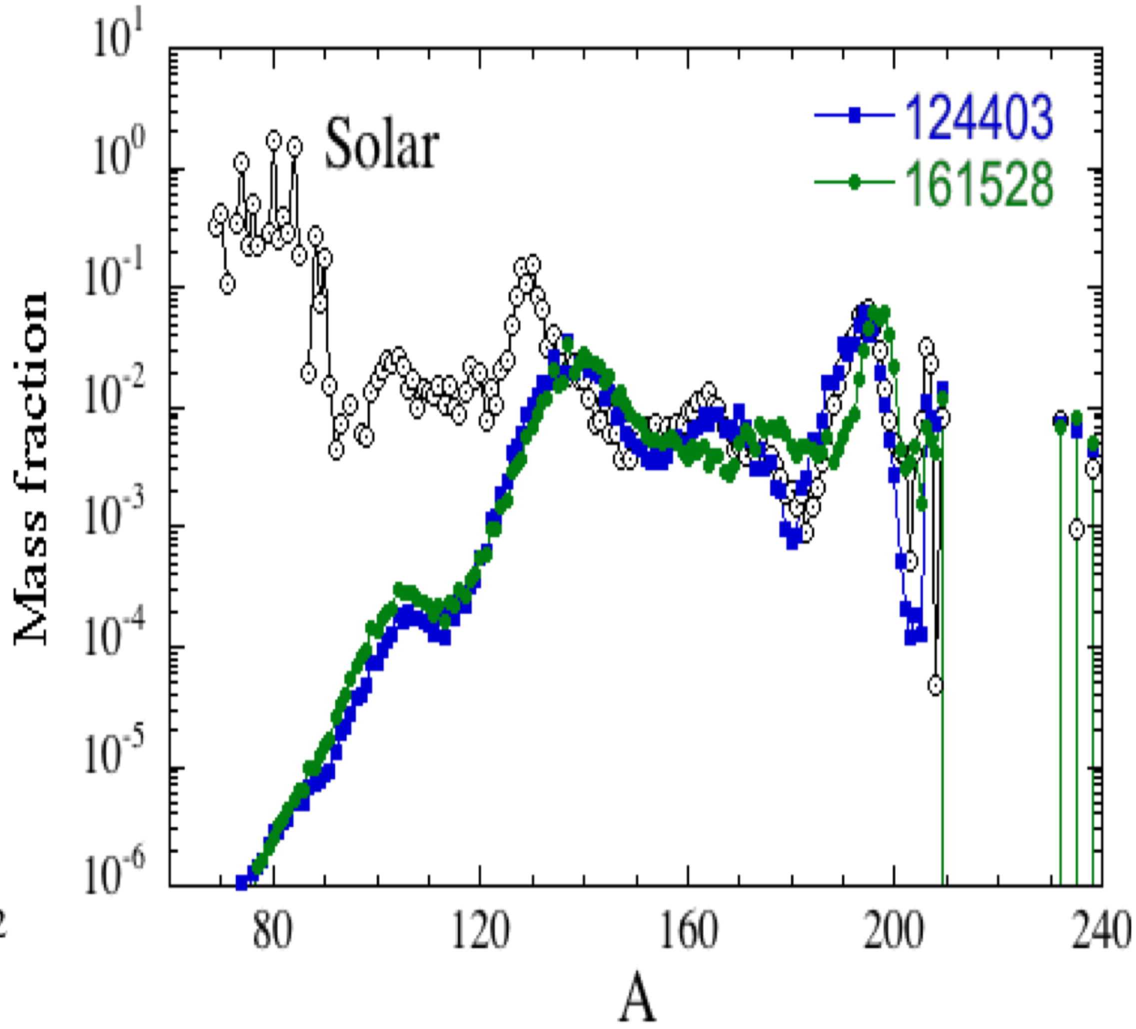
Different entropies S and different expansion timescales τ

mass elements with different expansion timescales

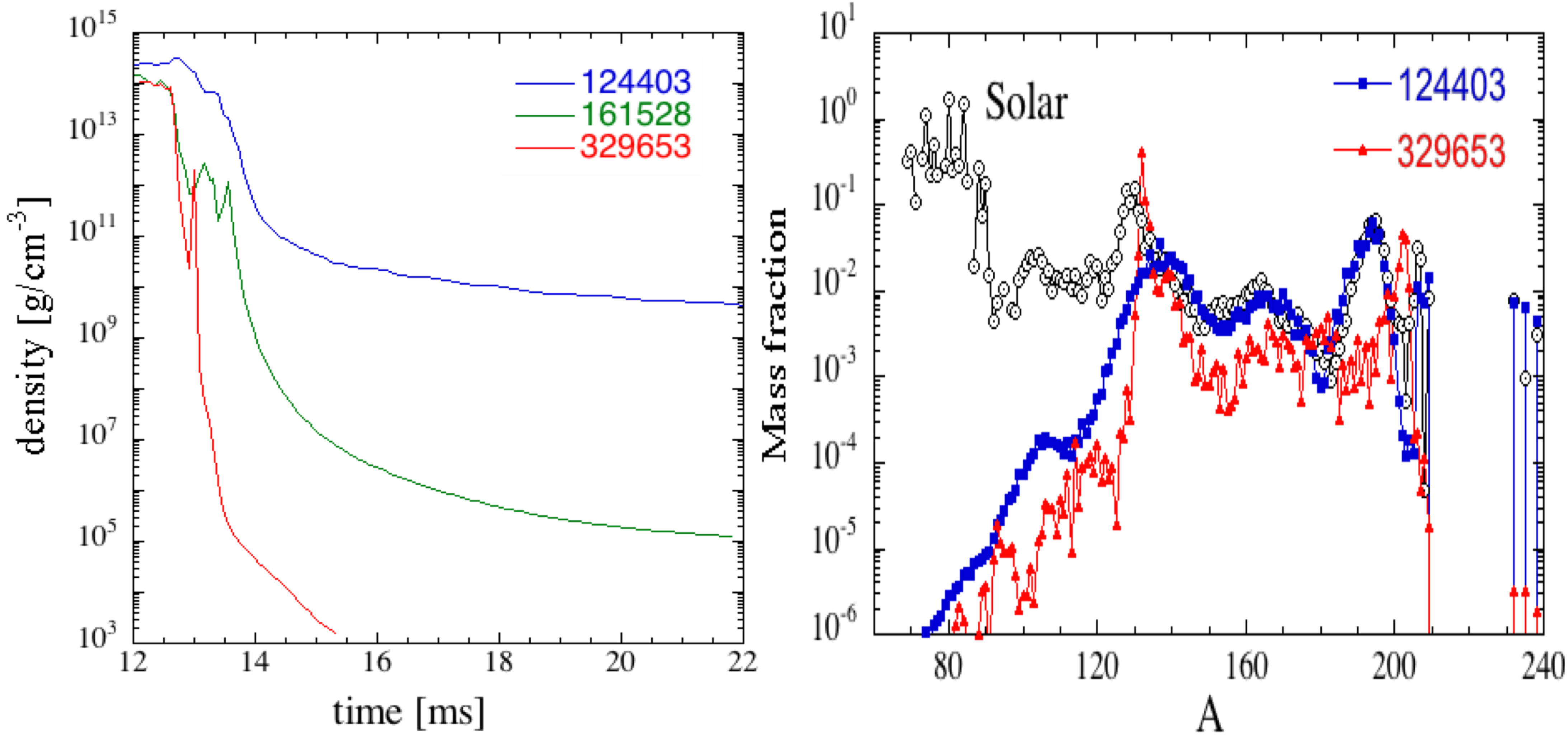


mass elements with different expansion timescales





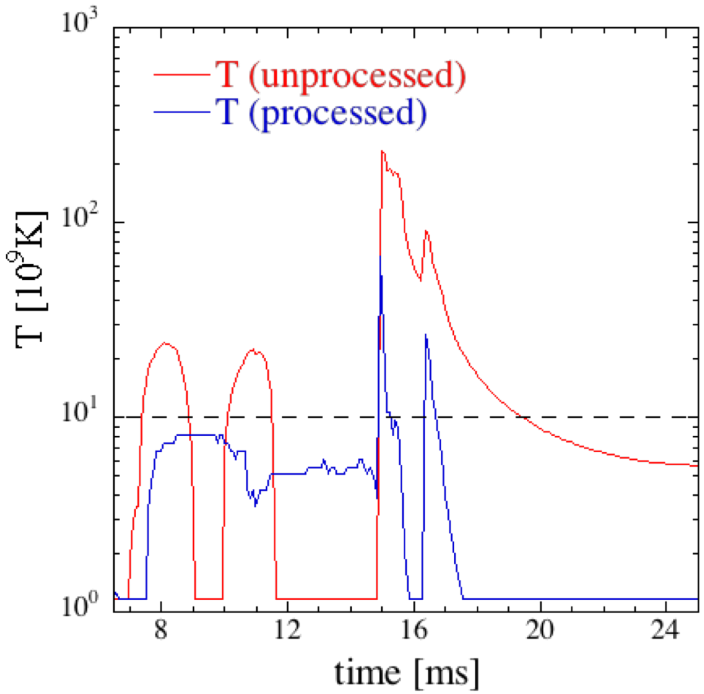
mass elements with different expansion timescales



Temperature evolution and decay heat

Determination of the temperature of each trajectory within SPH simulations - 2 variants:

1) without T-processing: the original T determination including « artificial heating »
2) With T-processing: Post-processing of the temperature, i.e.
   --> assume constant specific entropy in absence of shocks
   --> follow evolution of fluid element and identify shocks
   --> if shock detected, then increase entropy
   --> From the EoS, determine the new temperature based on post-processed entropy

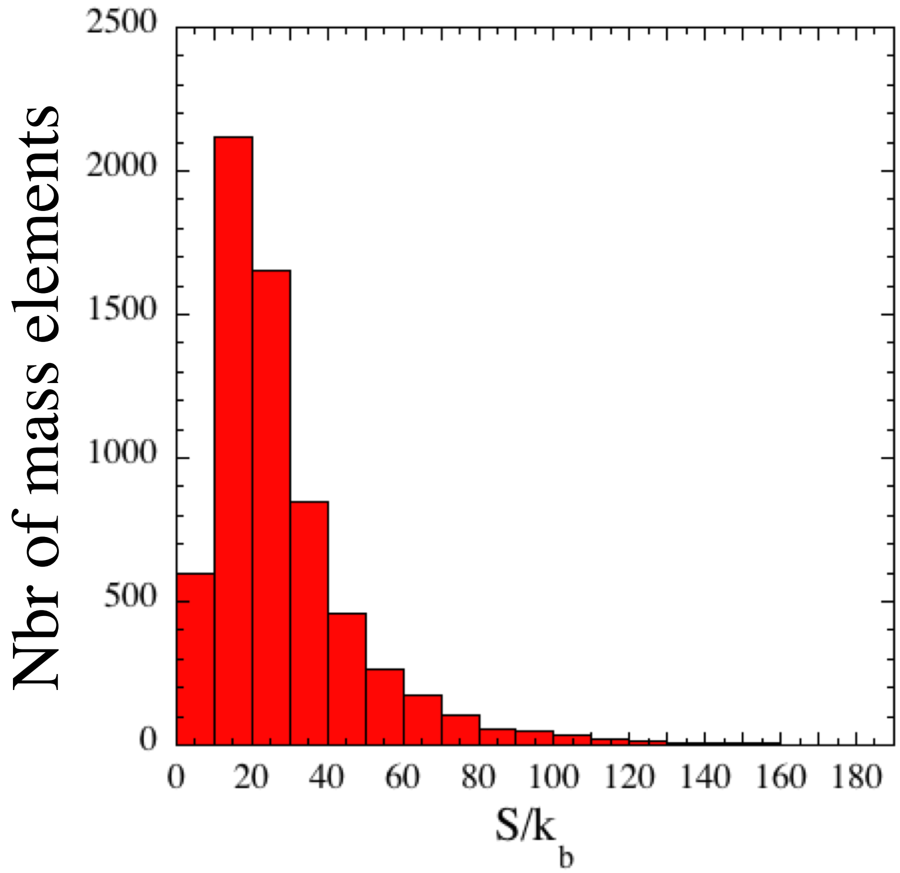


(trajectory 0489807)

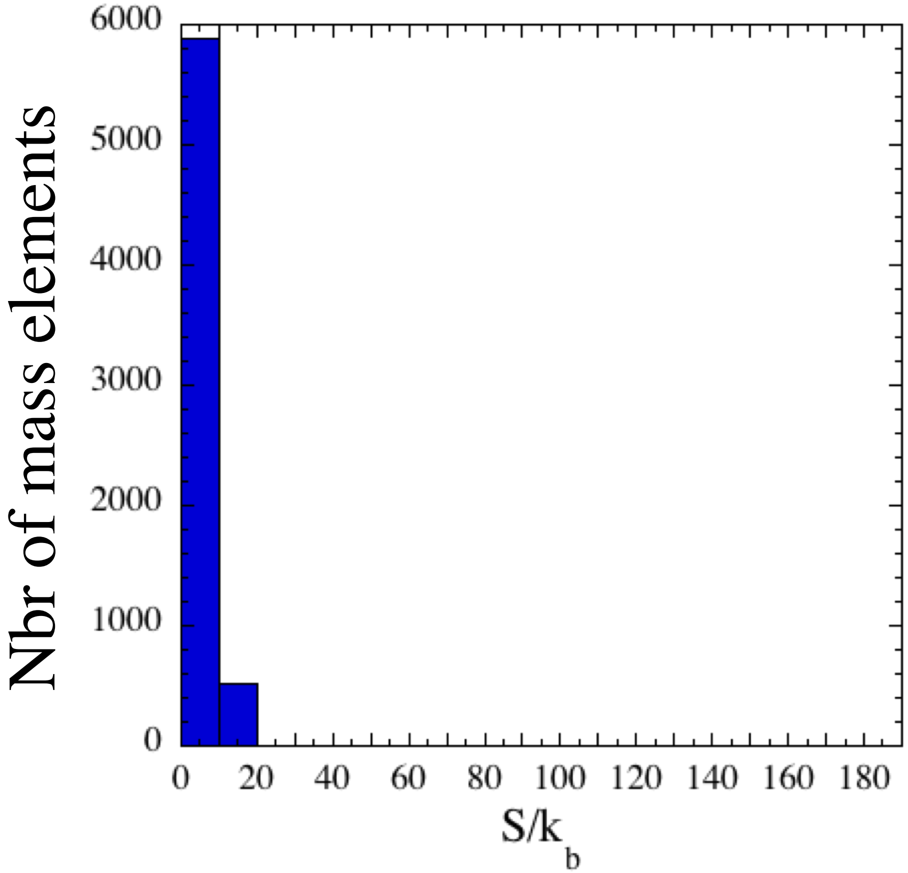
And for $t > t_0$: determination of the temperature evolution on the basis of the nuclear energy produced Q_{nuc} by β-decay and fission

Distribution of initial entropies for the 6423 ejected ‘particles’

Without T-processing



With T-processing

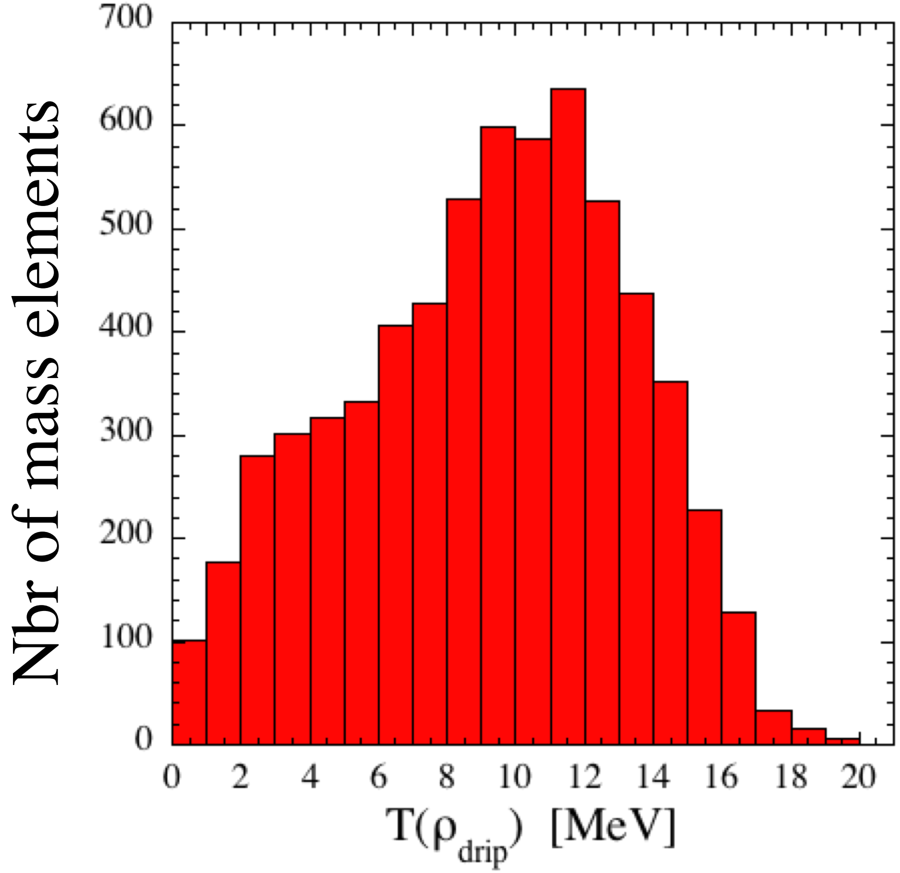


(Entropies calculated when T decreases below T=10^{10}K)

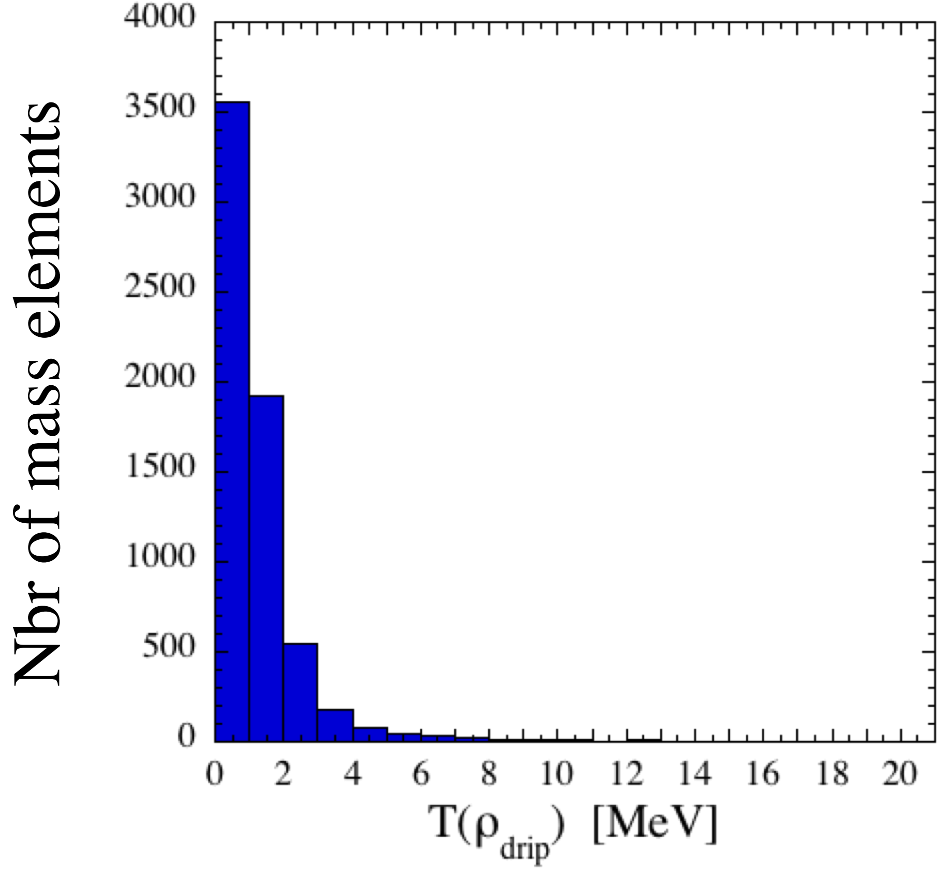
DD135135_wdl_1000Kav15

Distribution of the *T* at the drip density for the 6423 ejected ‘particles’

Without T-processing

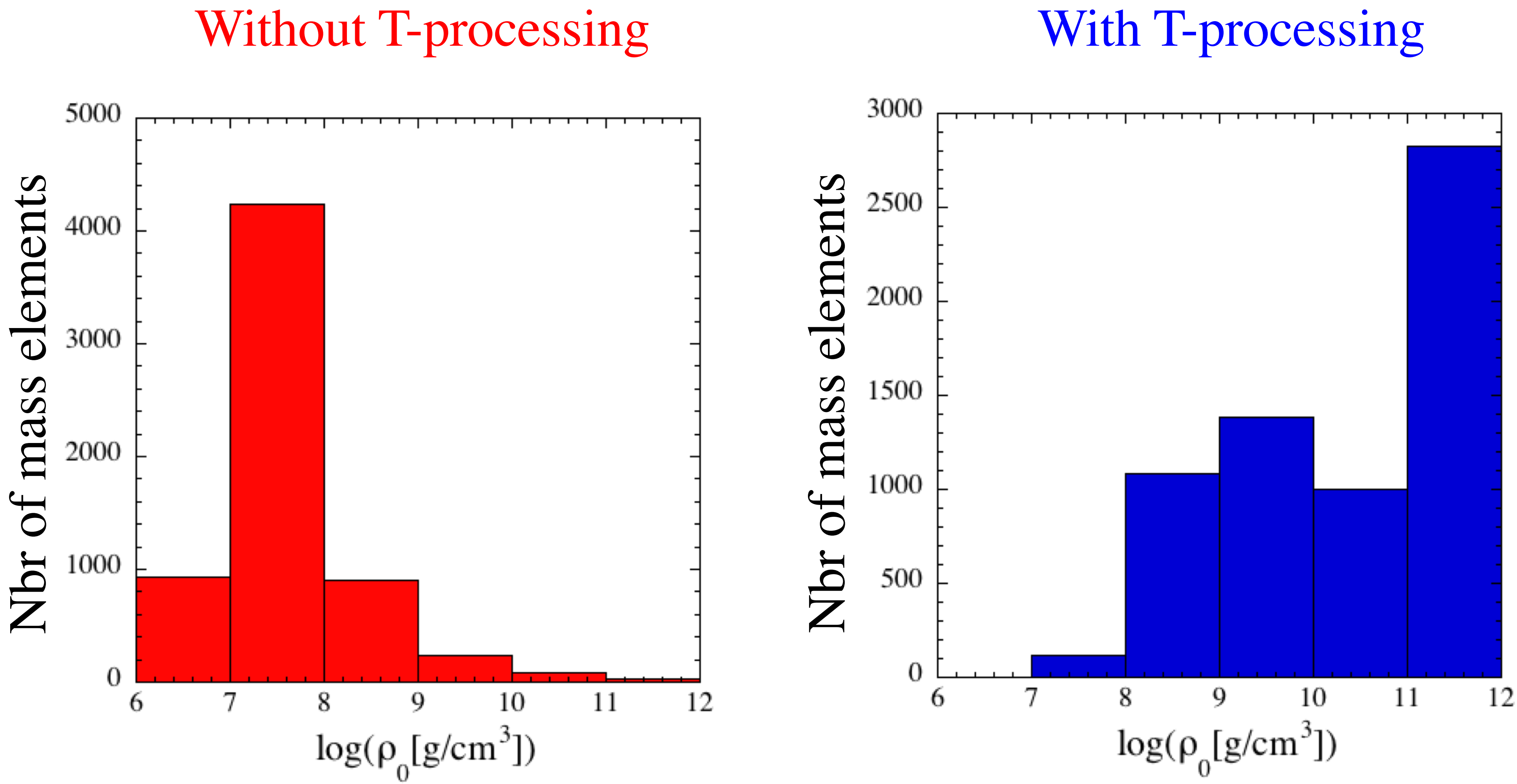


With T-processing



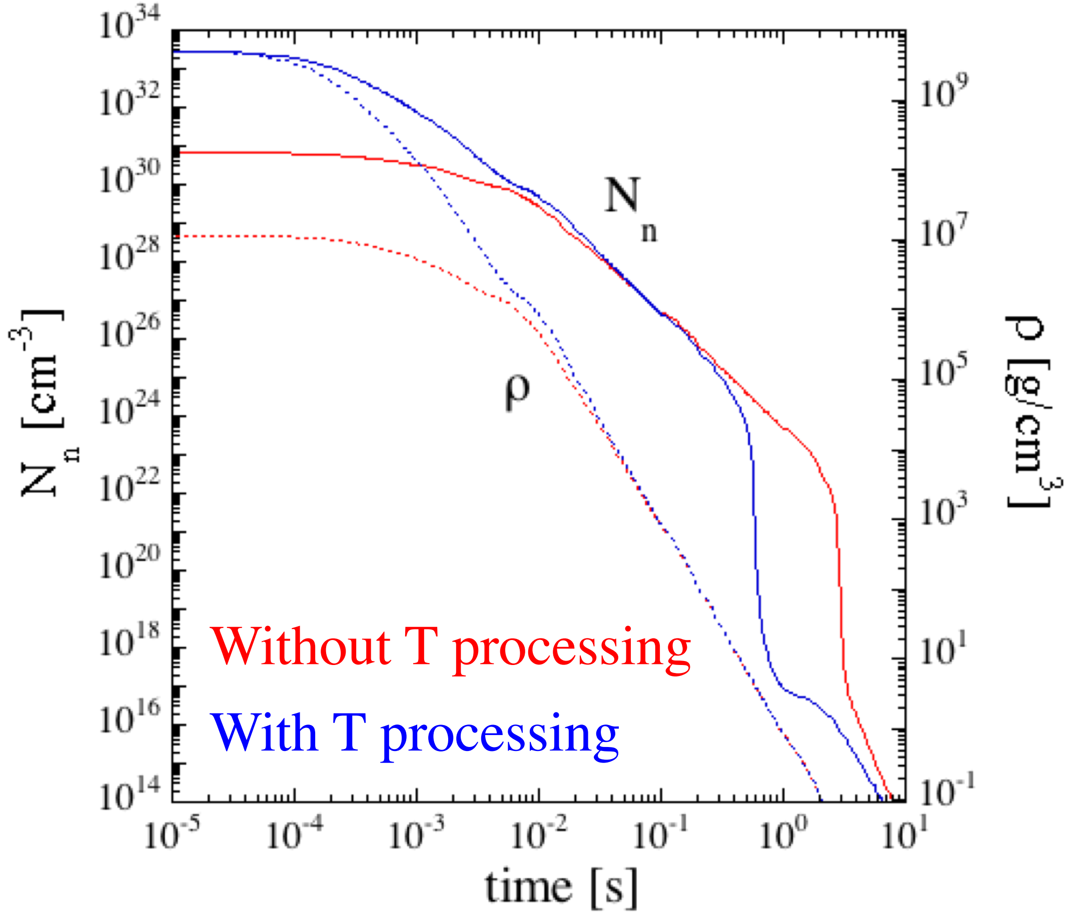
DD135135_wdl_1000Kav15

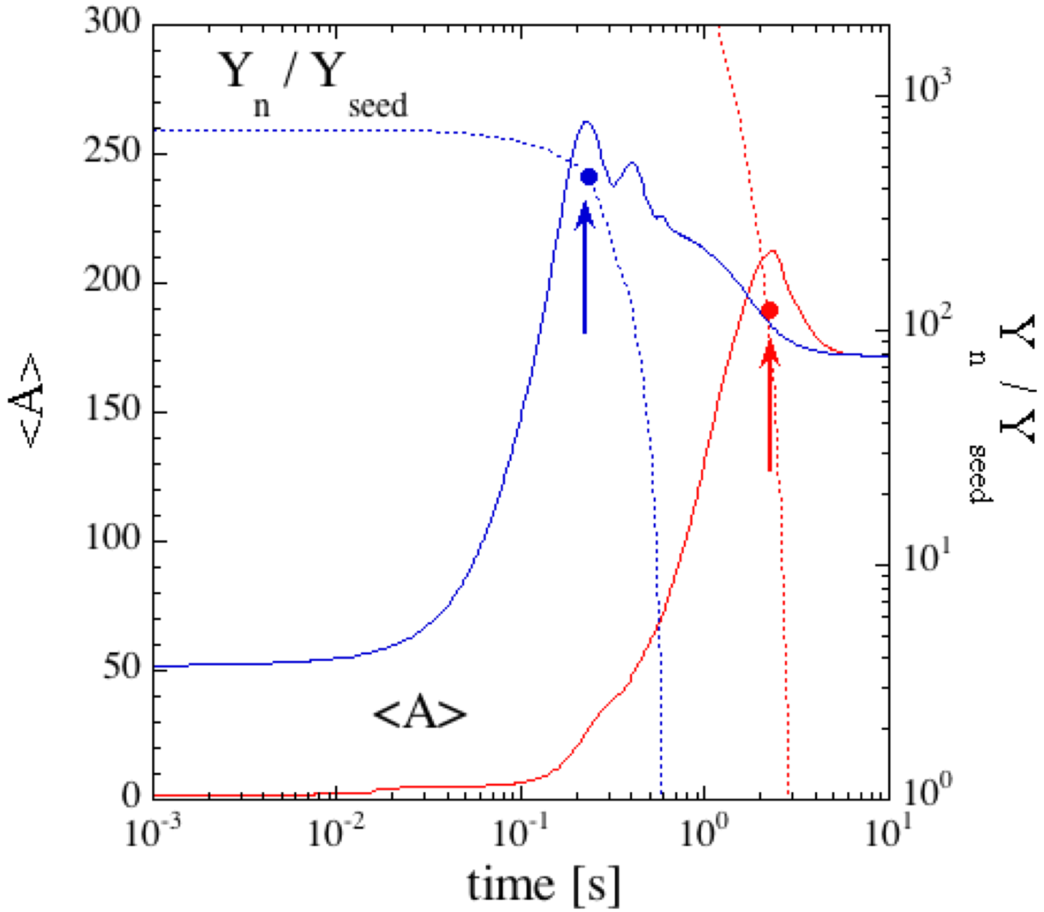
Distribution of the initial density $\rho_0(T=10^{10}\mathrm{K})$ for the 6423 ejected 'particles'



DD135135_wdl_1000Kav15

Evolution of specific properties for a given ejected 'particles'



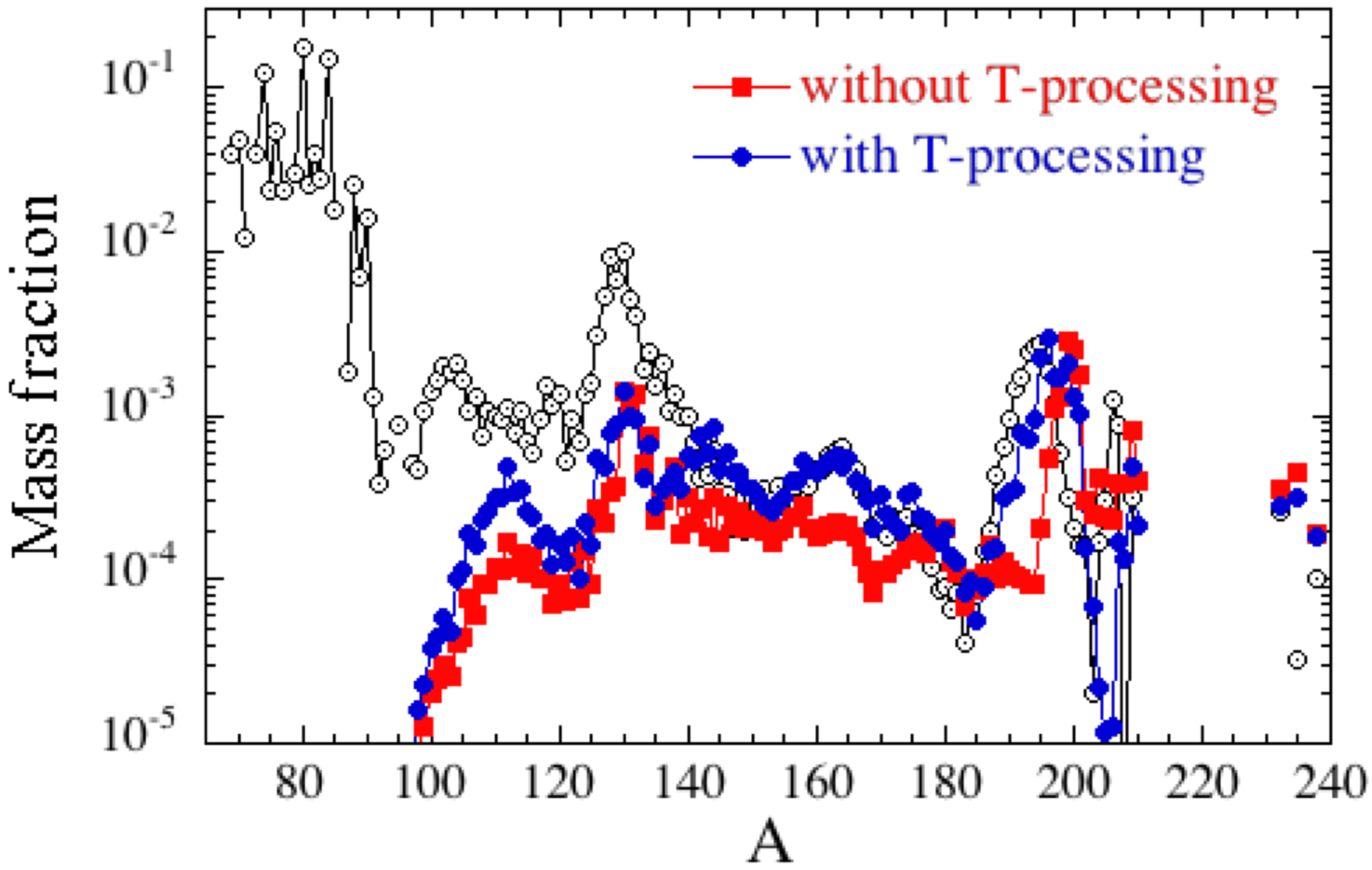


(seed : A≥12)

DD135135_wdl_1000Kav15

(trajectory 0489807)

Final abundances from a representative ejected ‘particles’



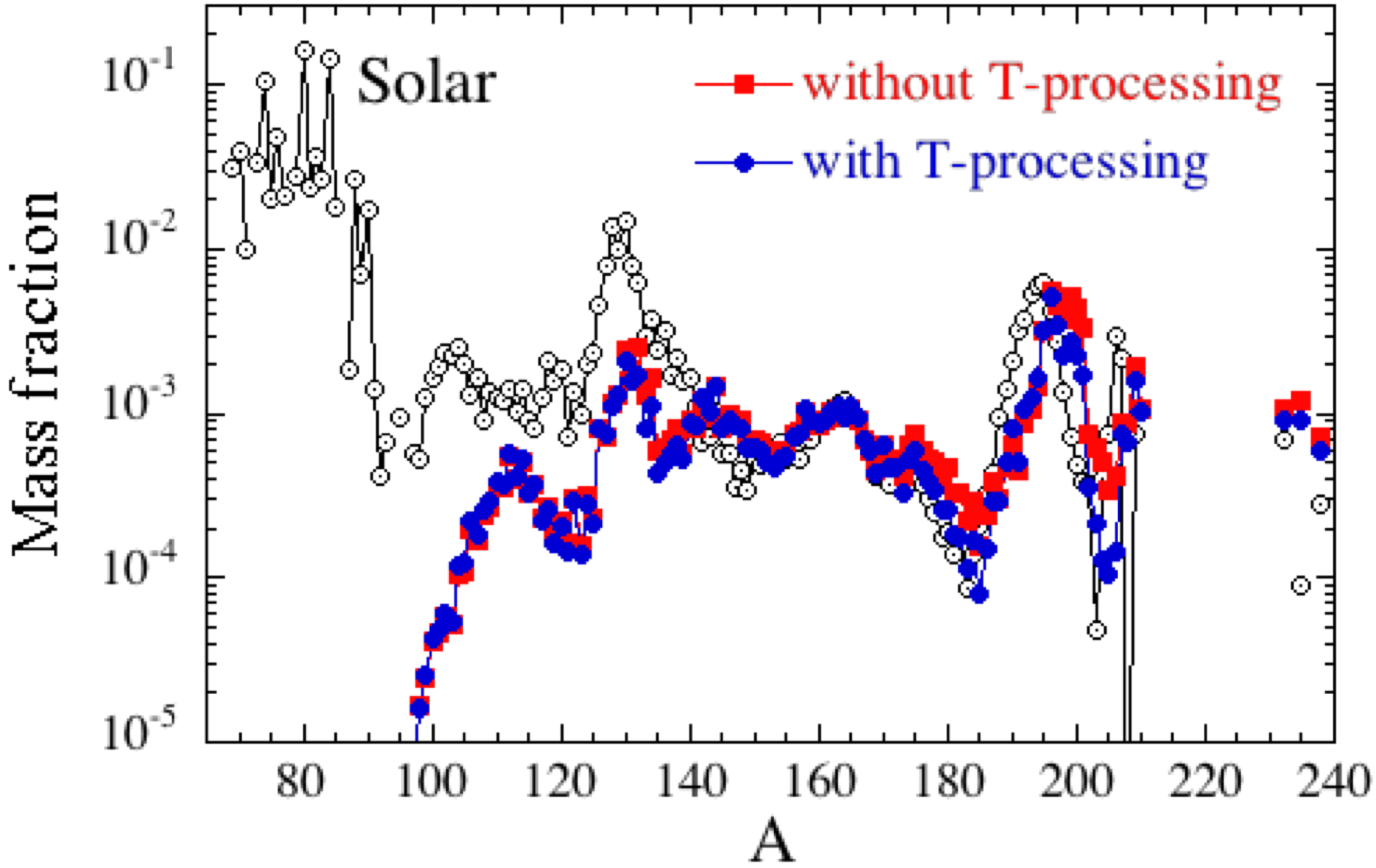
Without T processing : S_0=40

With T processing: S_0=6.4

DD135135_wdl_1000Kav15

(trajectory 0489807)

Final mass-averaged abundances for a large sample of ejected 'particles'



87% r-process

98% r-process

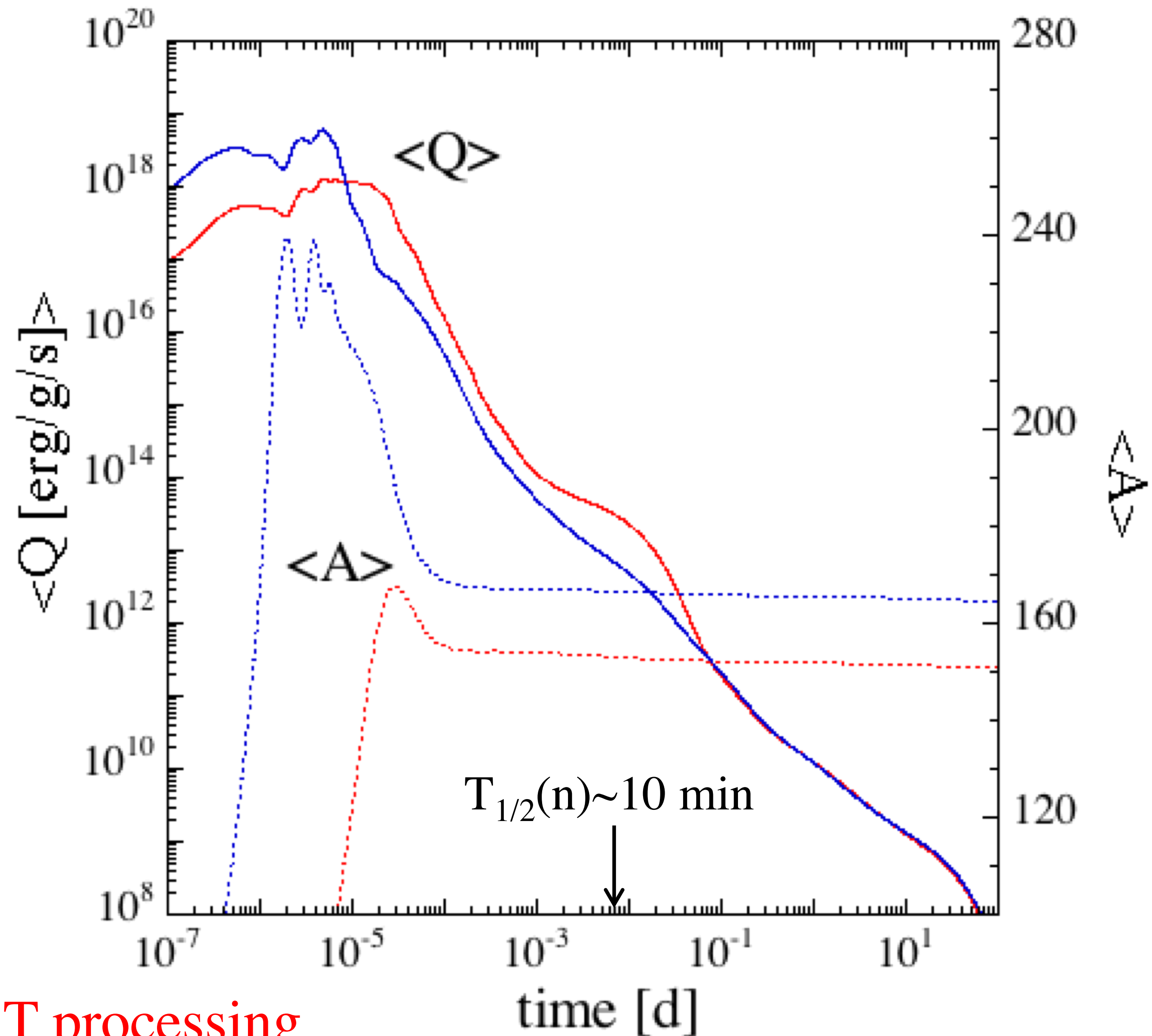
left-overs: H(n), ^{2}H, ^{4}He

Without T processing

With T processing

DD135135_wdl_1000Kav15

Final mass-averaged decay heat



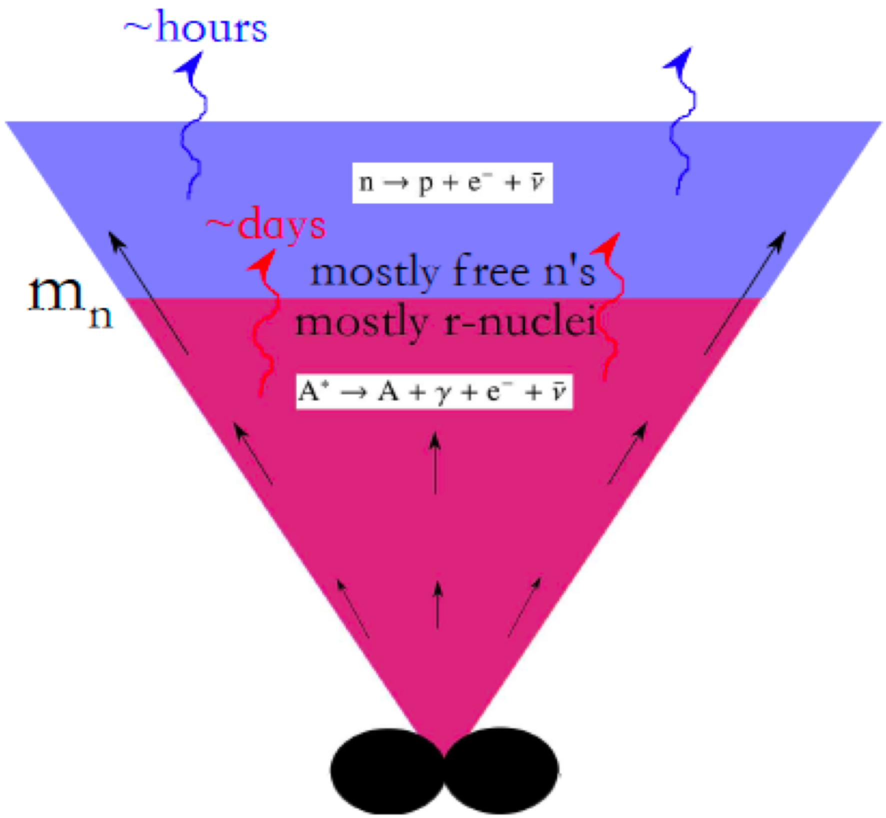
Without T processing

With T processing

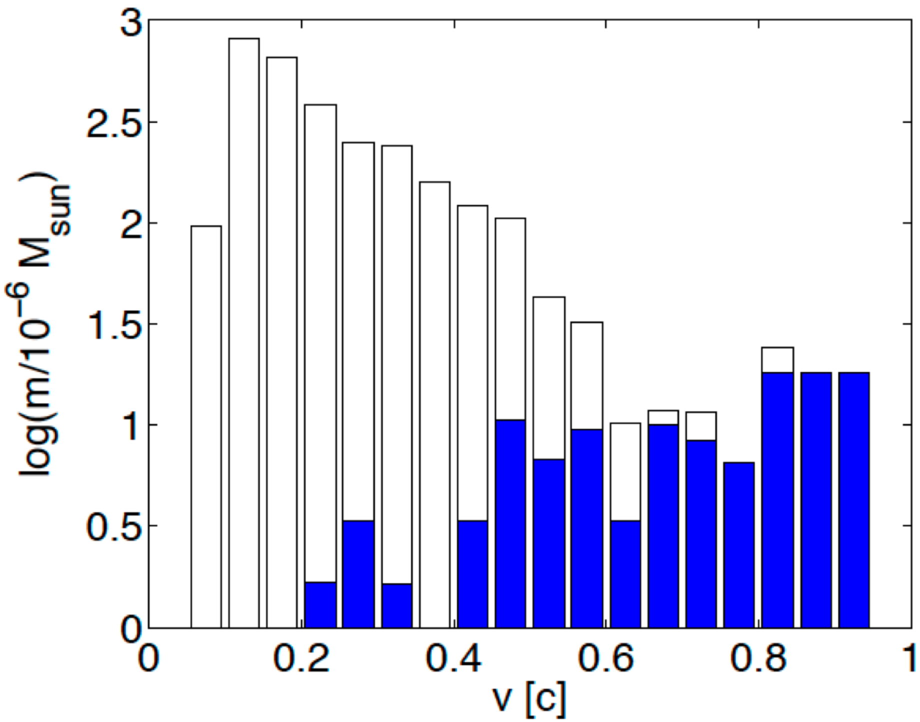
DD135135_wdl_1000Kav15

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



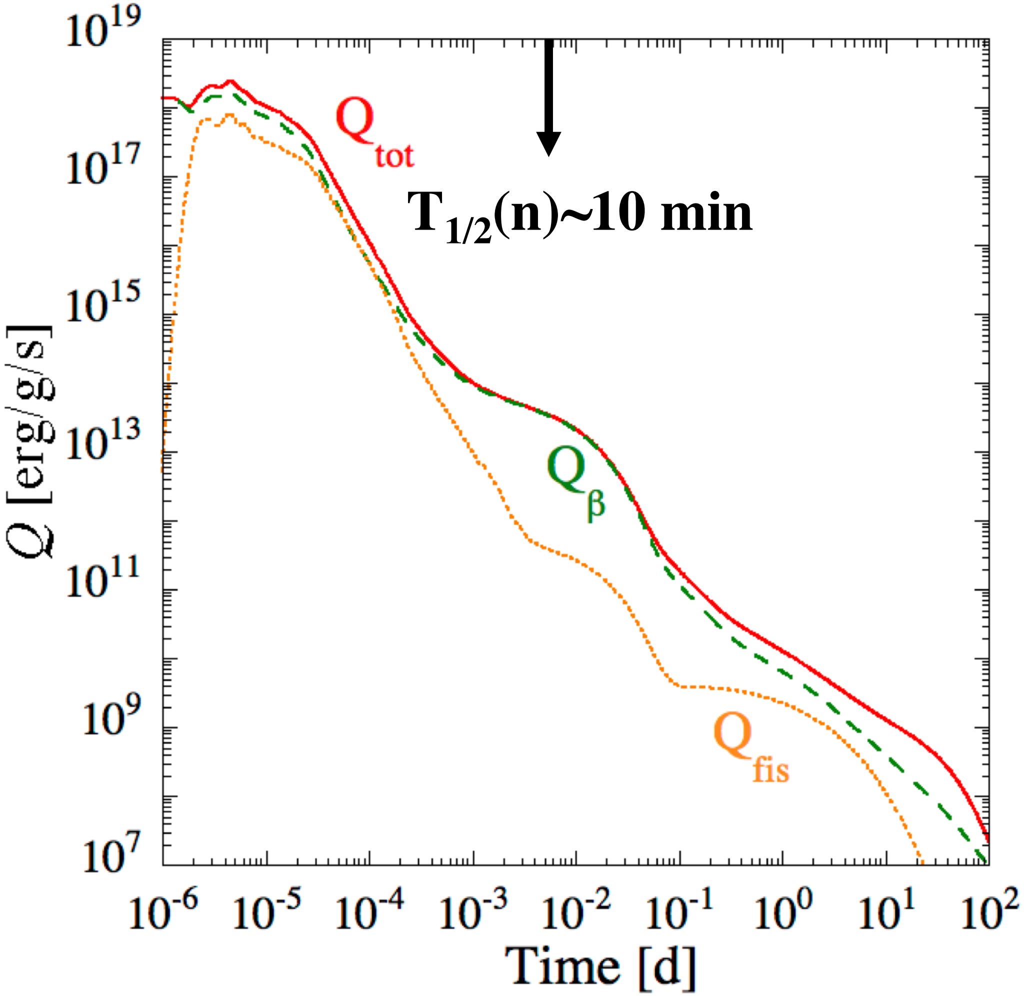
~ a few % of the total mass ejected as free neutrons



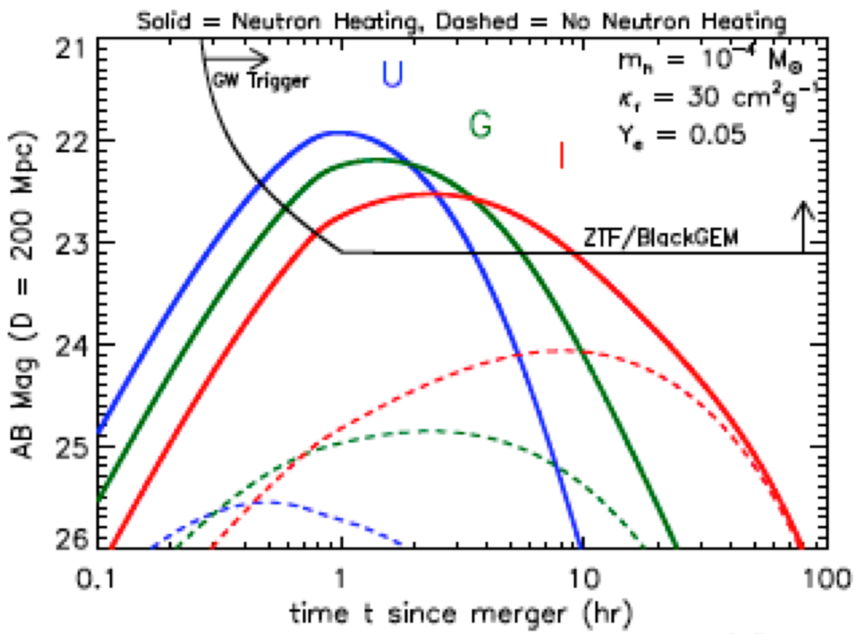
→ Potential counterpart to the gravitational wave source

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. $L_{tot} \sim 10^{41}$ erg/s



Metzger et al. (2014)

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

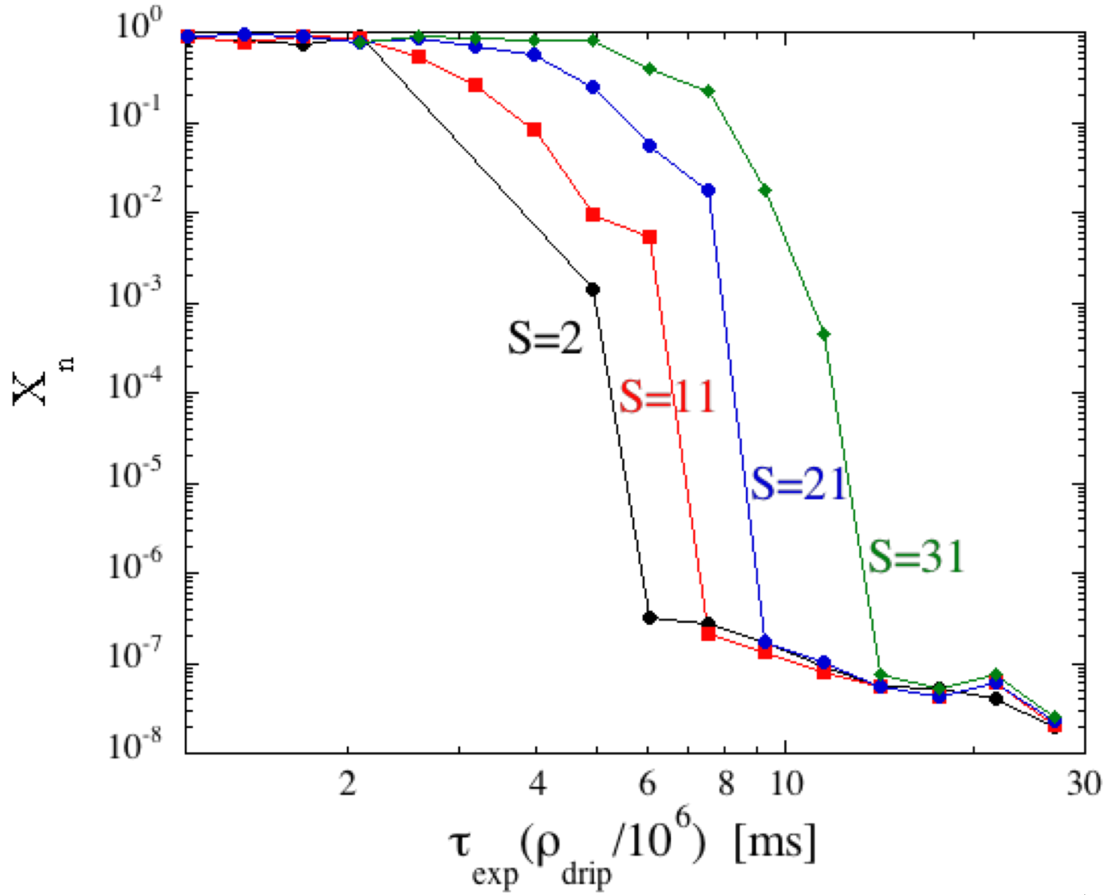
Free neutron ejection is found to be sensitive to

- *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 many uncertainties to estimate reliably free neutron ejection

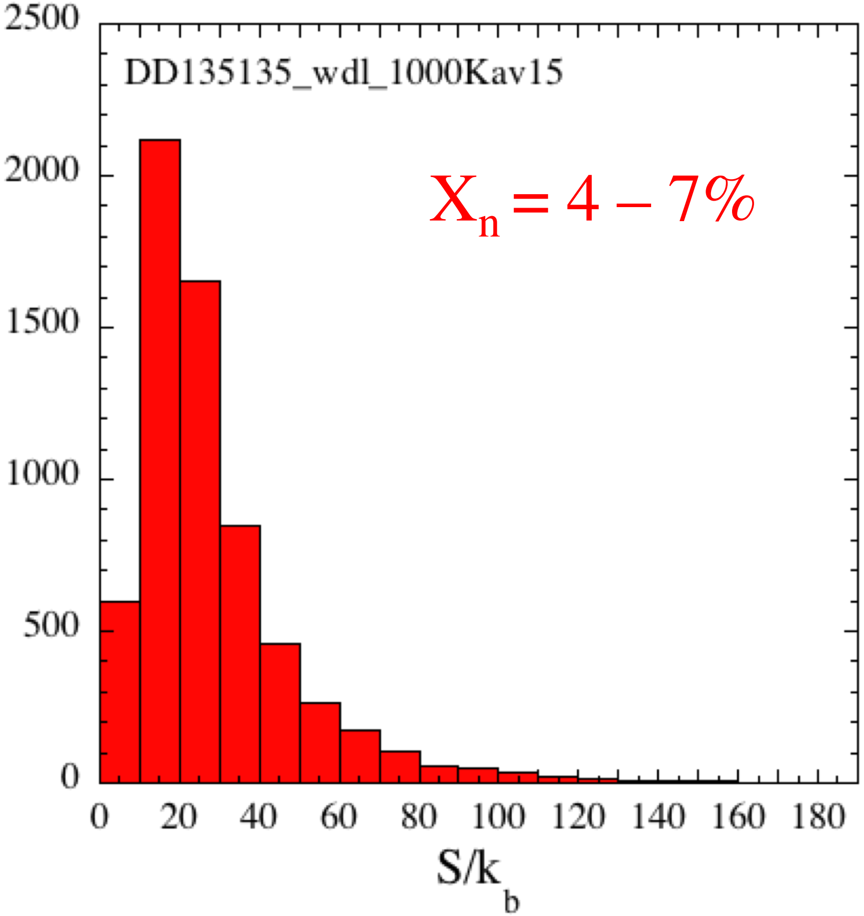
Free neutron ejection is found to be sensitive to

- *Expansion timescale*: the faster the ejection, the less efficient the neutron captures
- *Initial entropy*: the highest the entropy, the less effective is the rebuilding of heavy nuclei from neutrons and protons

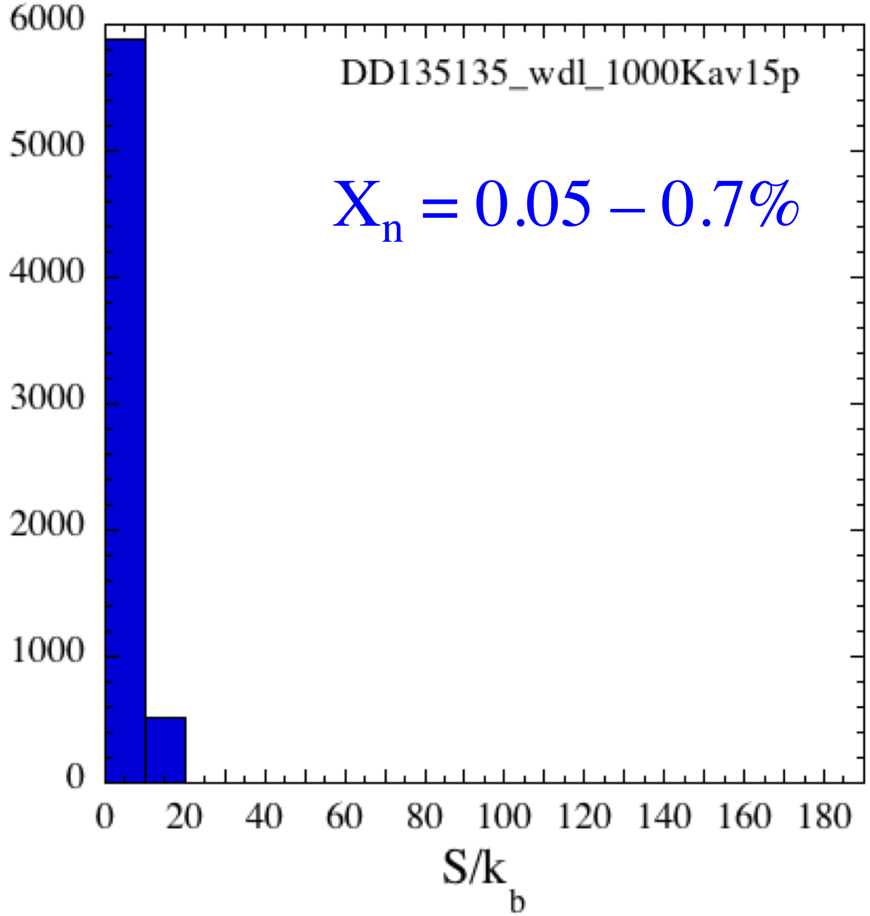


DD135135_std_1000Kav15

without T-processing



with T-processing



Conclusions

The astrophysical site for the r-process remains puzzling despite the remarkable observation of GW170817/ AT2017fgo

Favour nowadays to Compact Object Mergers (NS-NS;NS-BH)

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

But still some major open questions, in particular:

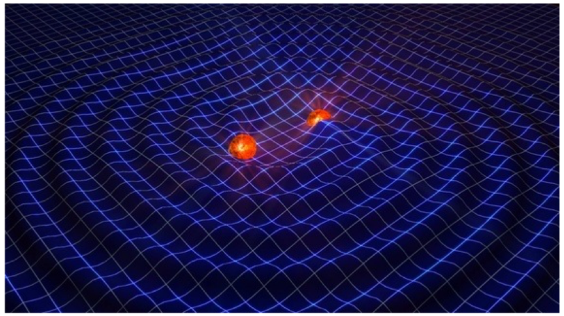
- Description of the hydrodynamical conditions (expansion timescales: Newtonian vs Relativistic simulations)
- Description of the thermodynamic conditions, in part. initial T
- Neutrino absorption affecting the composition of the dyn. ejecta (+ possible neutrino oscillation)

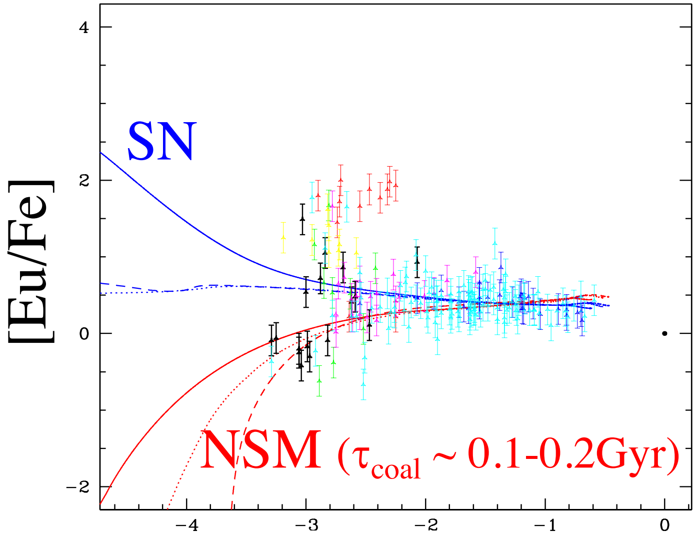
Still major astrophysical questions to be answered, including

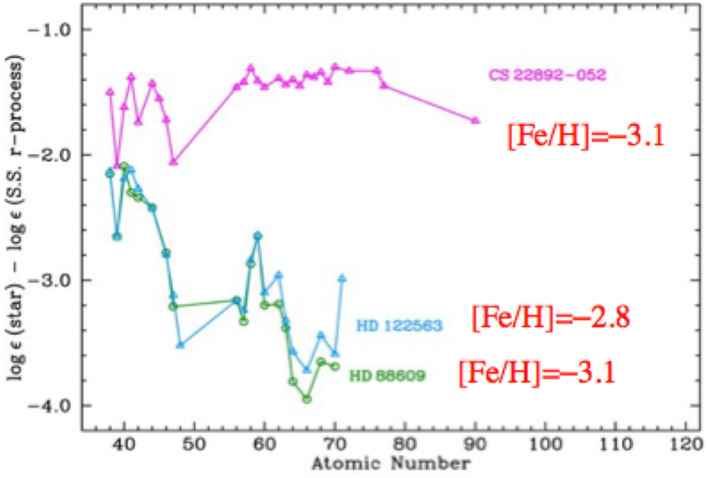
- Impact of neutrinos on the neutron richness during dynamical ejection

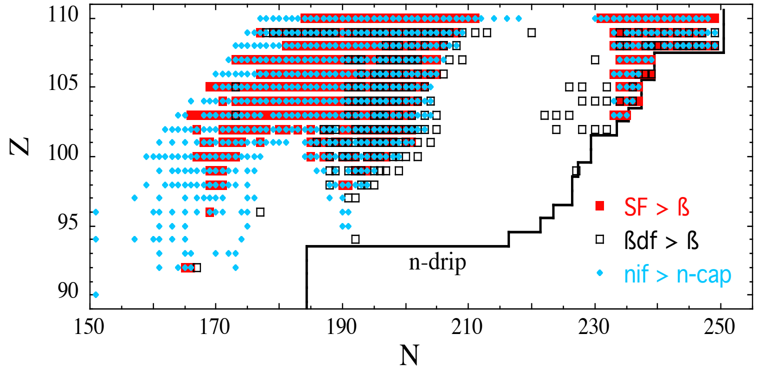
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

- 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





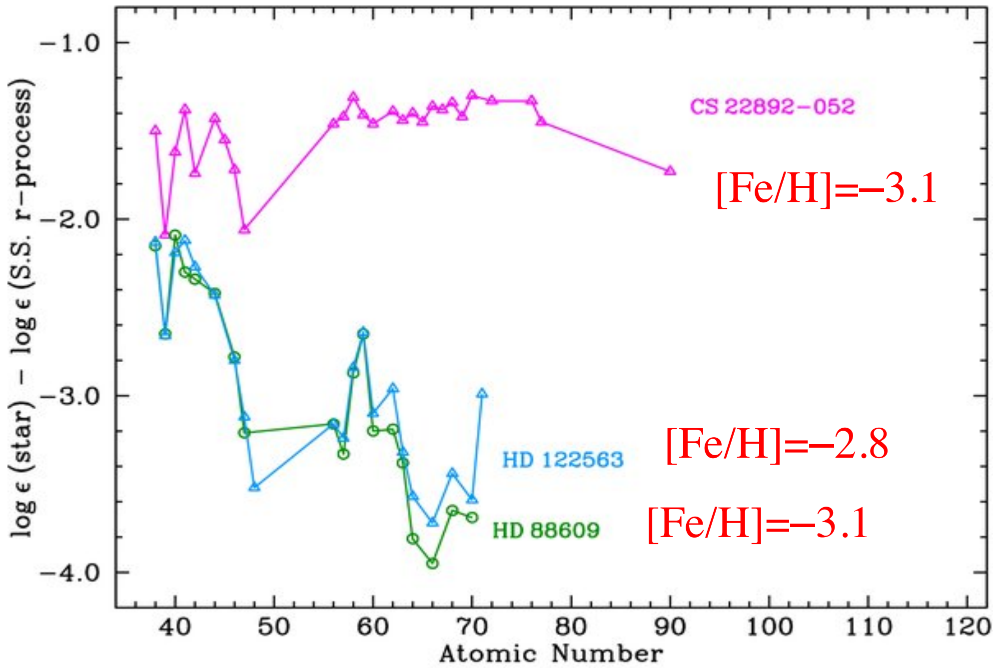




The r-process distribution in ultra-metal-poor stars

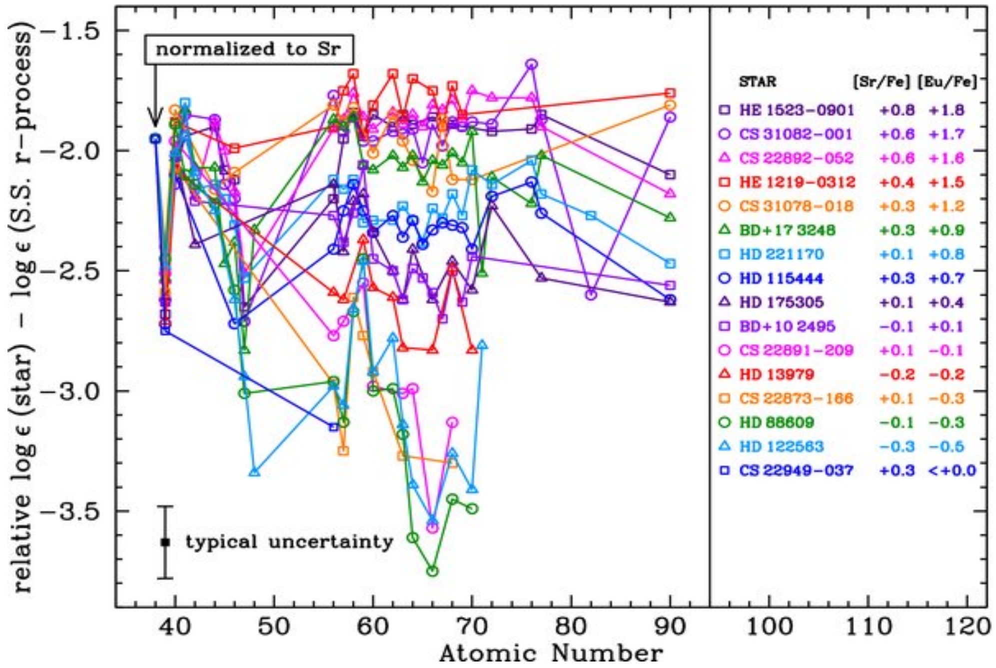
Differences between the SS r-process and stellar abundances in metal-poor stars

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

Roederer et al (2010)
ApJ 724, 975

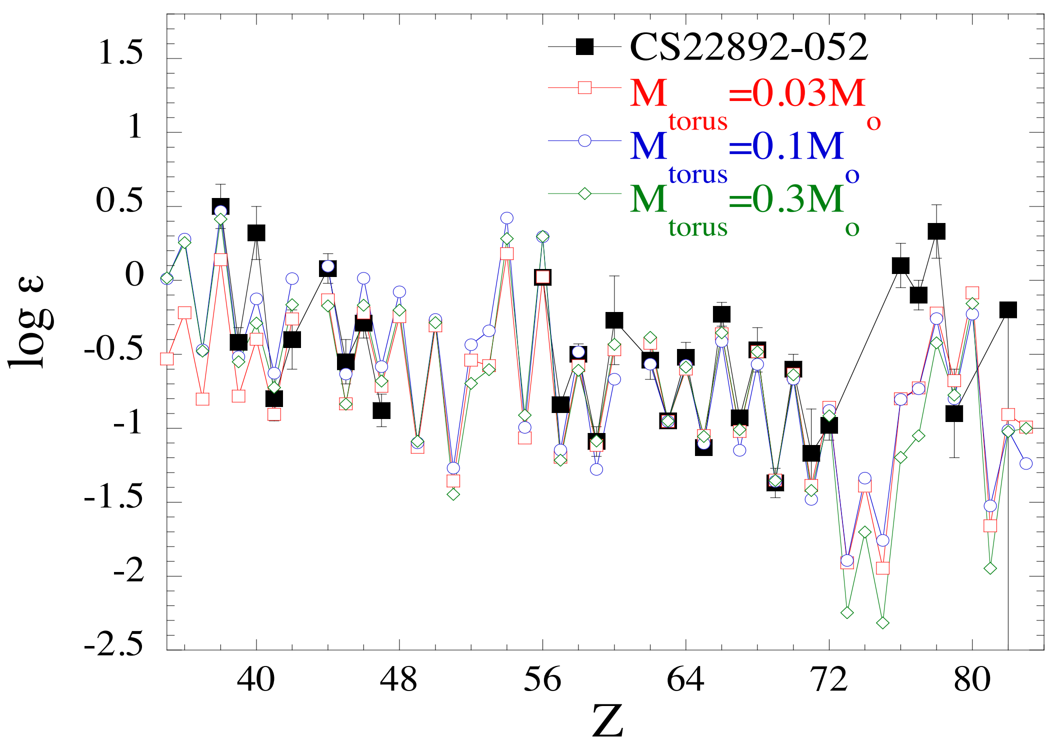


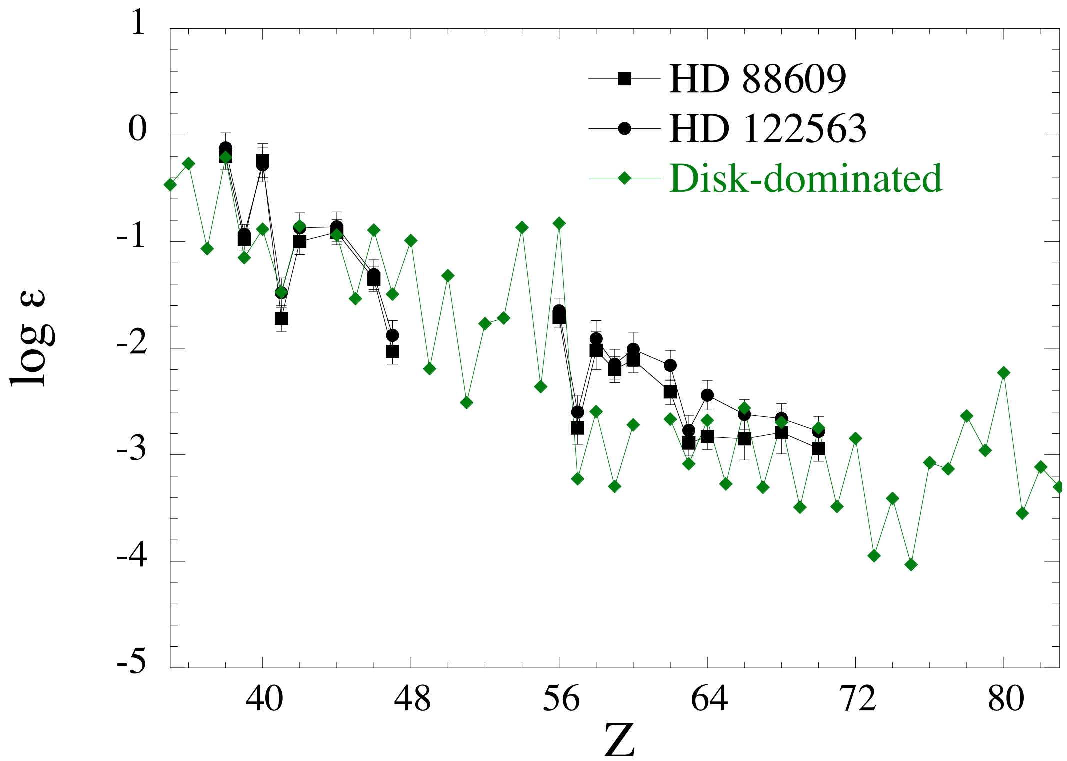
Comparison with observation in low-metallicity r-process-rich stars

2 extreme cases

Main trend: rather solar-like distribution

Stars deficient in heavy r elements





Dynamical + Disk ejecta (mass averaged)

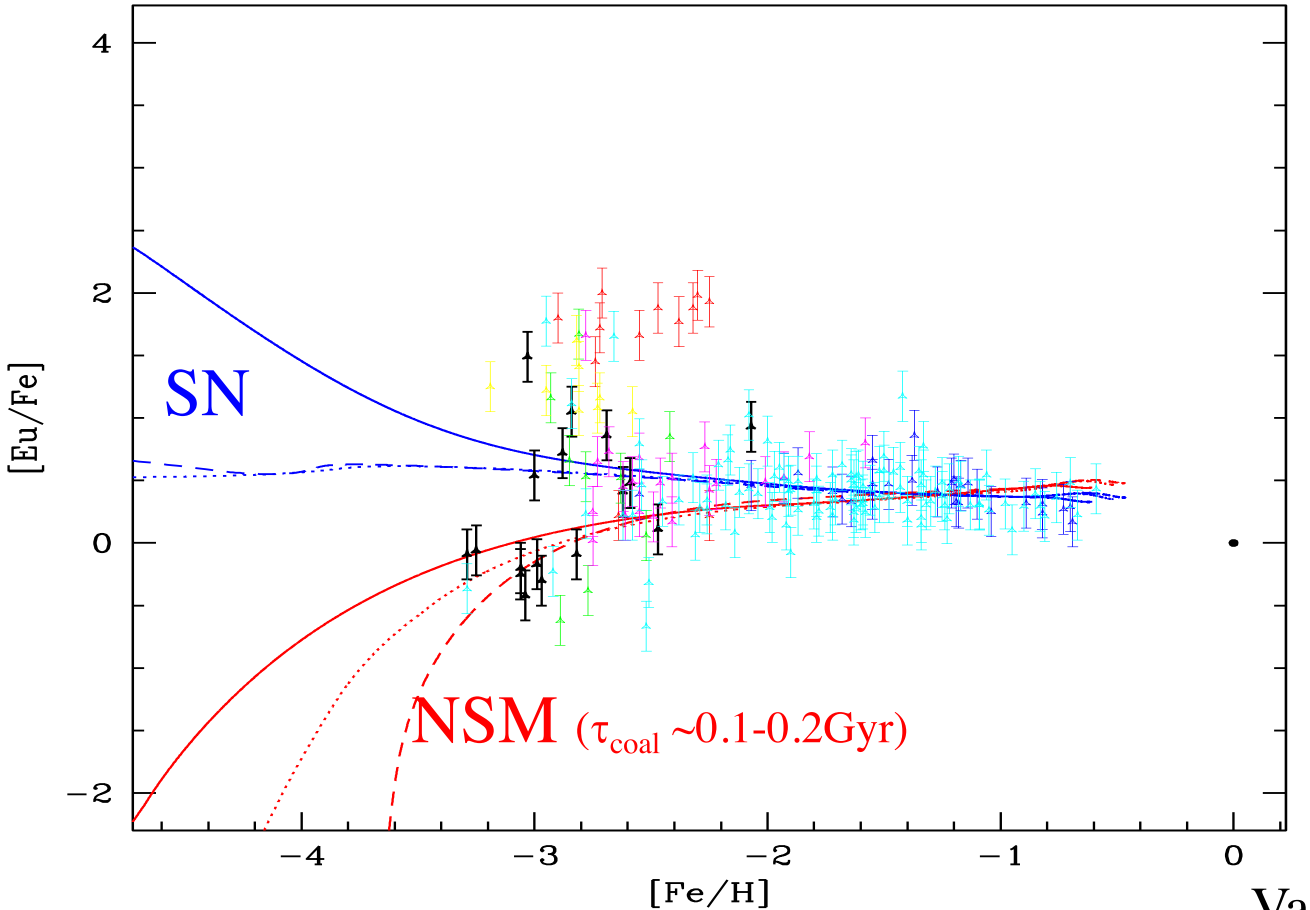
- for 56 ≤ Z ≤ 76 : « Universal » solar-like distribution
- for Z < 56 : Deviation wrt solar (0.5dex)

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

- Asymmetric ejecta
- Small ejecta (NS accreted by the BH)
- Or ν-nucleon interaction !!

Cosmic & Galactic Chemical Evolution Models

The SN vs NSM imprint at very low-metallicities

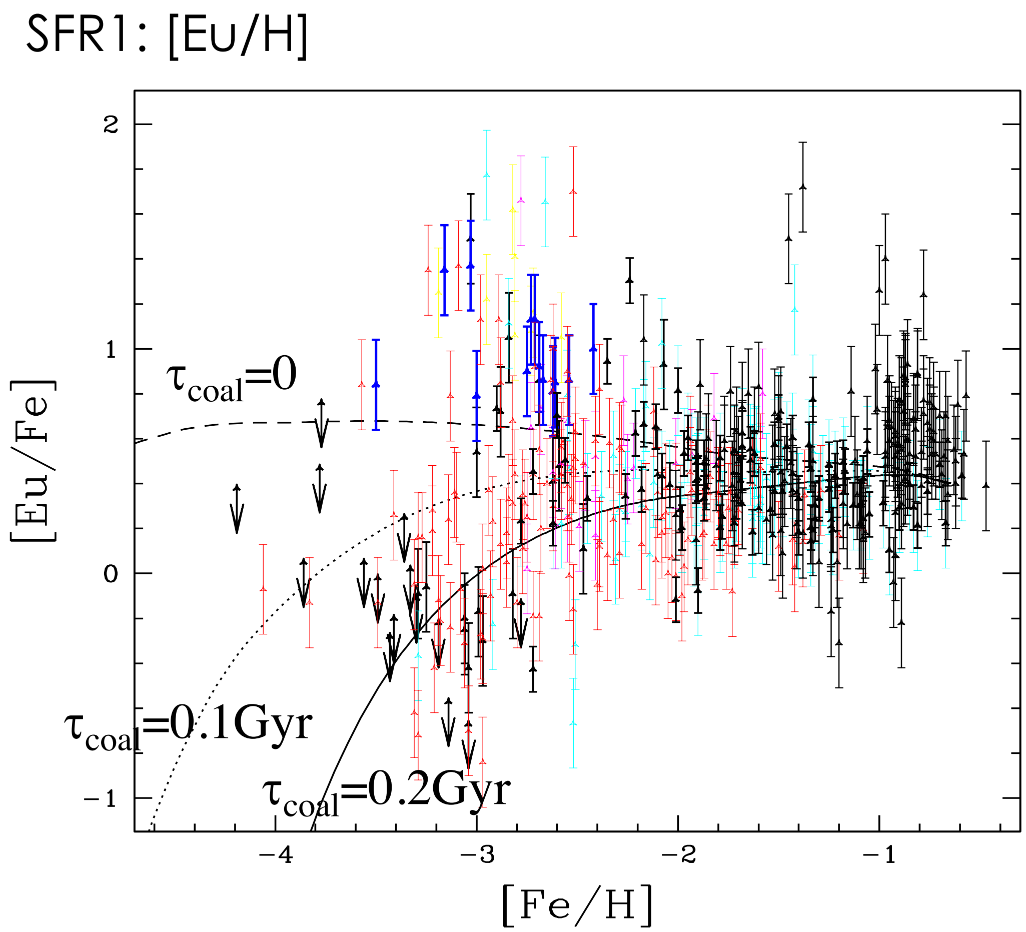


Vangioni et al. (2015)

Cosmic chemical evolution based on a hierarchical model for structure formation

Eu evolution: NSM scenario with 7 10^{-5} $M_\odot$ to 2 10^{-4} $M_\odot$ per merger

Constraint on the coalescence timescale

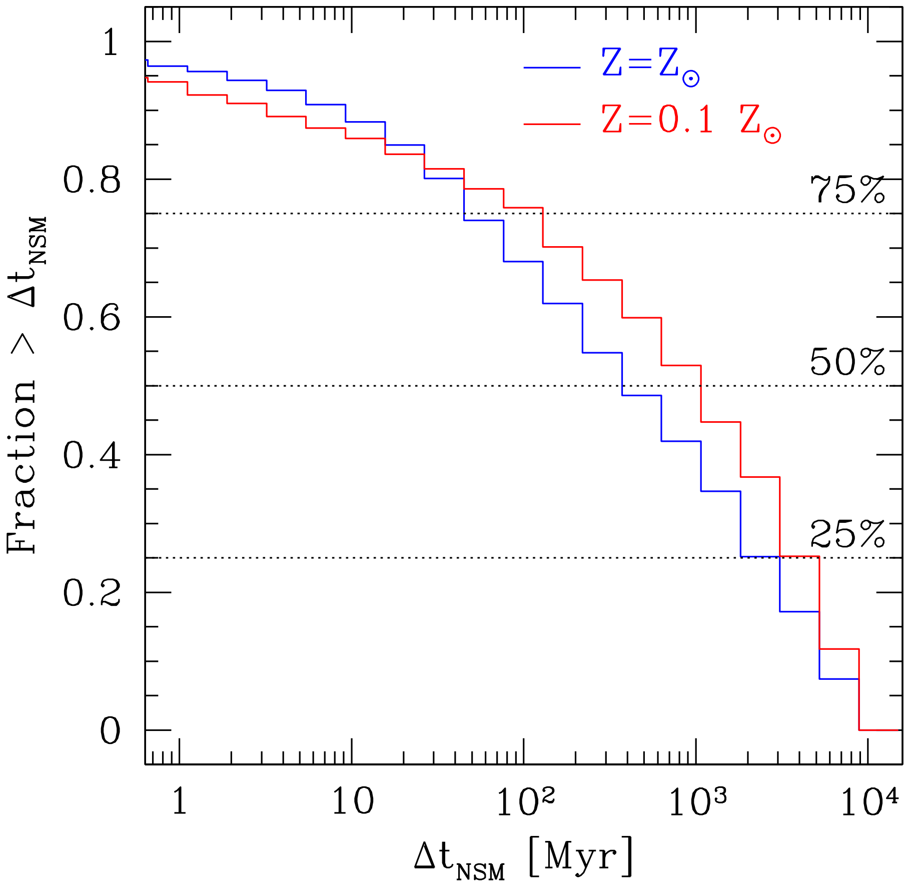


Vangioni et al. (2015)

Cosmic chemical evolution based on a hierarchical model for structure formation

On the basis of realistic estimates of the coalescence timescales estimate

Updated version of the population synthesis model (Belczynski et al. 2015)



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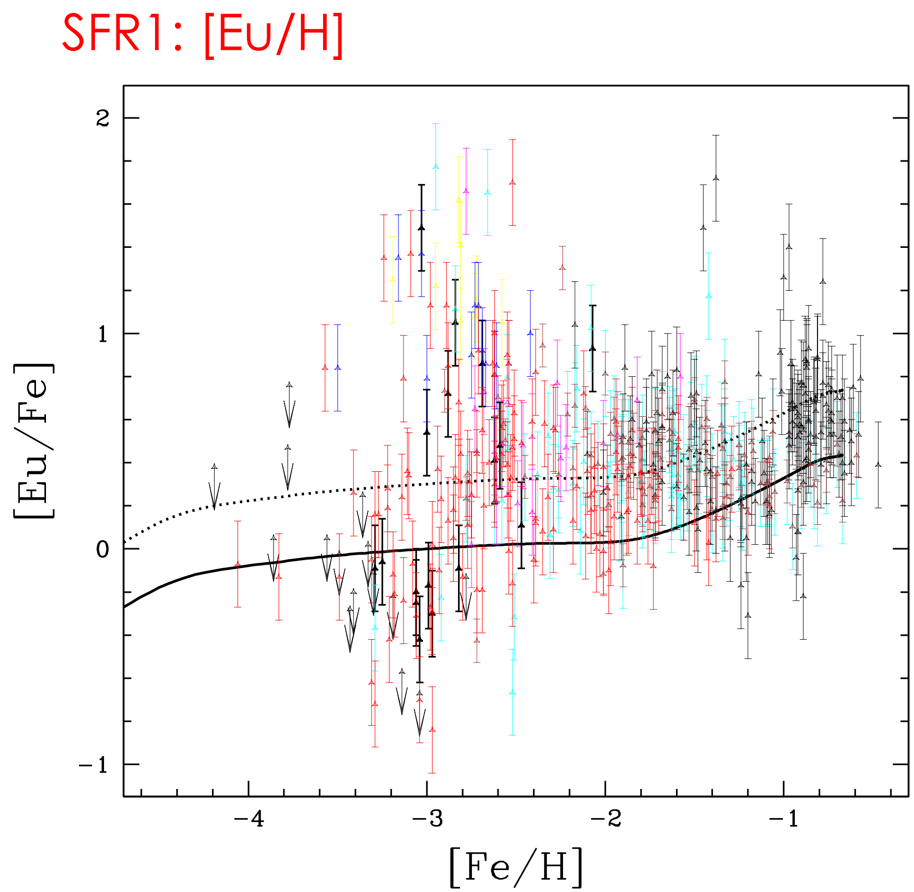
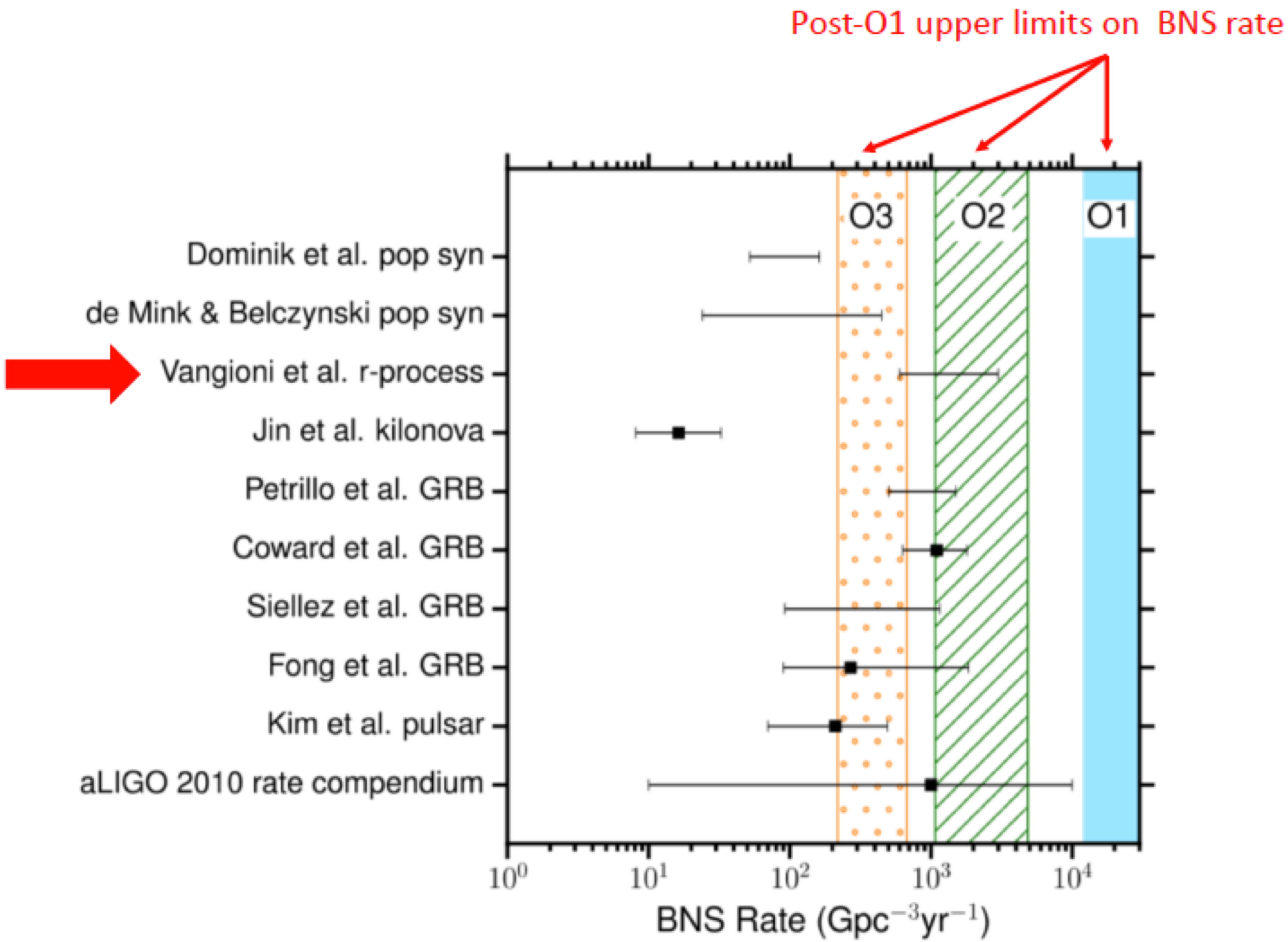


For 2 fractions of NS binaries

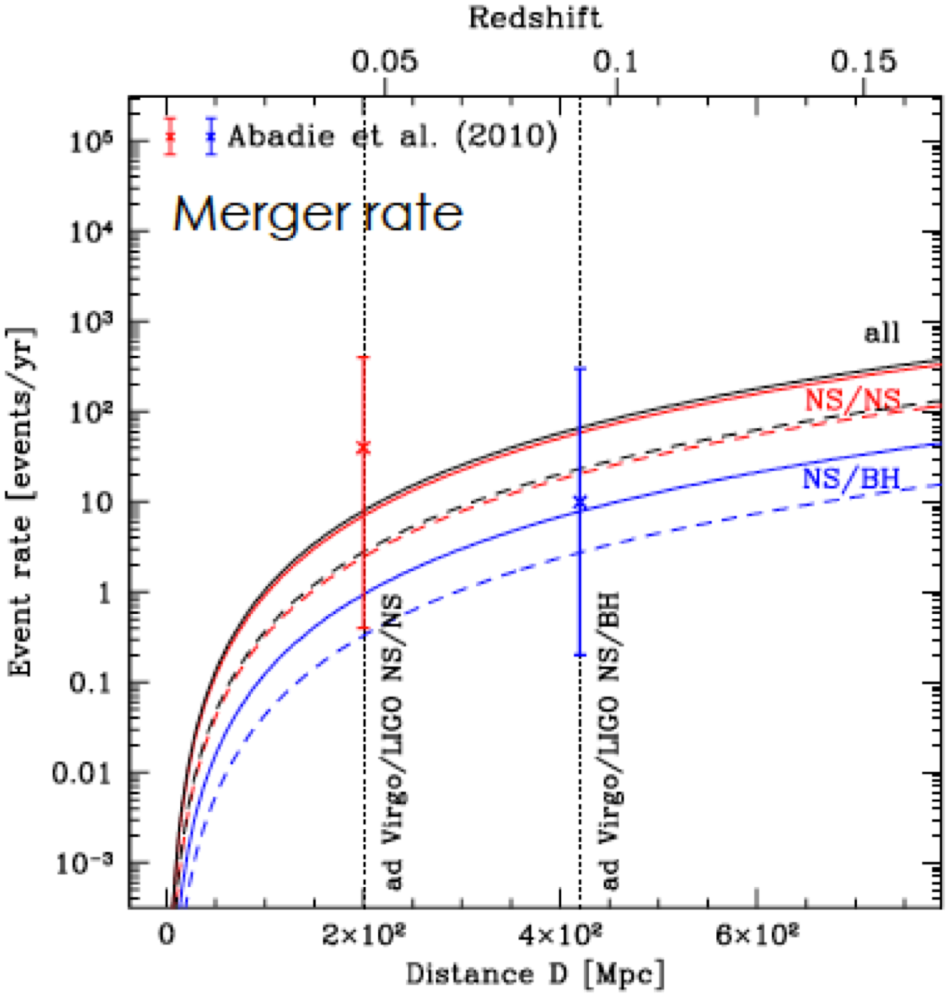
Merger rate: BNS

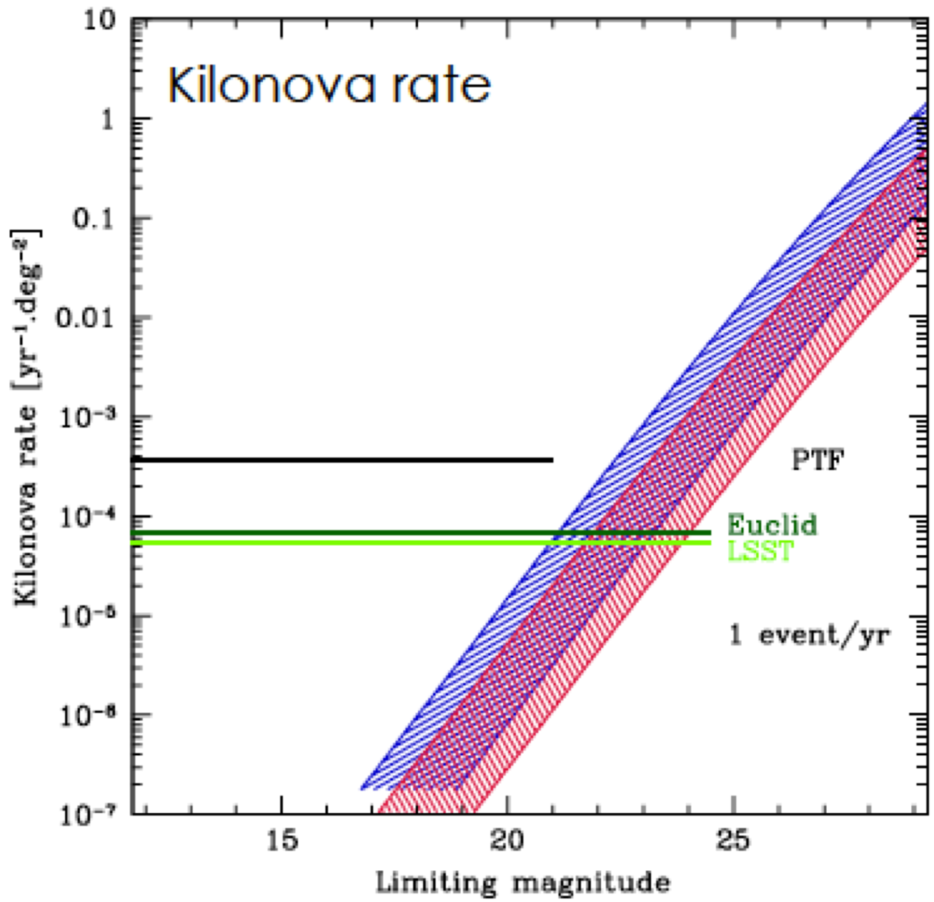


Abbott et al. 2016, post-O1

Merger rate: BNS

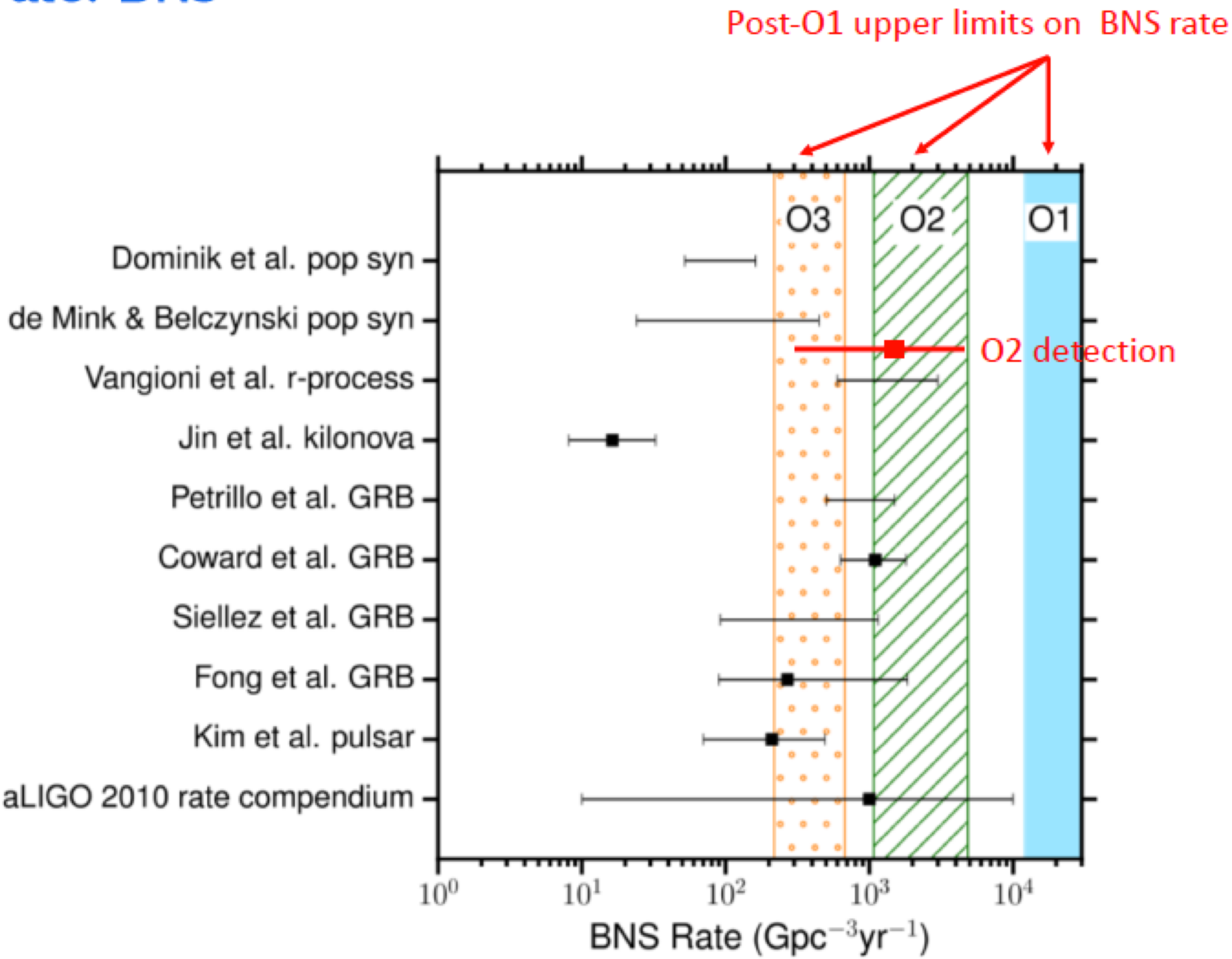
- **Model:** estimate the BNS rate assuming that most of the r-process elements are produced by NS+NS mergers
- **Observations:** Eu measured in metal-poor halo stars in the Milky Way = tracer of the time evolution of the r-process





Vangioni, Goriely, Daigne, François & Belczynski (2016)

Merger rate: BNS



Abbott et al. 2016, post-O1

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 !

CONCLUSIONS

Compact Object Mergers (NS-NS;NS-BH) : recent robust hydrodynamical simulations

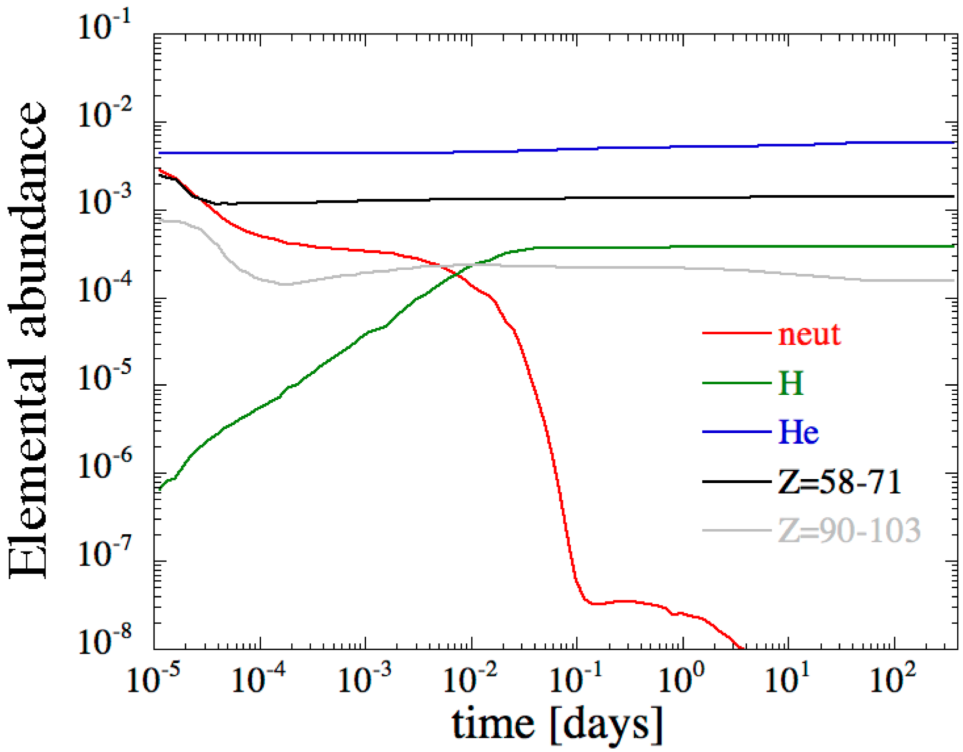
- Successful solar-like r-process for $A \geq 90$ nuclei with contribution from both Dynamical $A \geq 140$ and Disk ejecta $A \geq 90$
- Can explain the Galactic amount of r-nuclei
- Possible ejections of free neutrons with observable blue signal

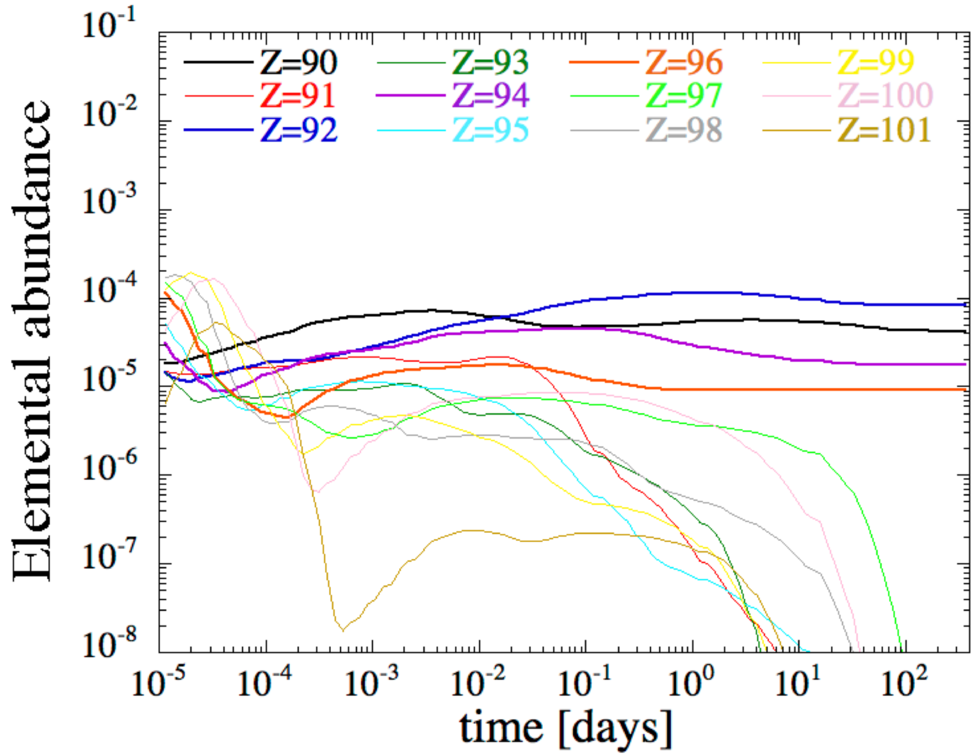
But we need

- to confirm Galactic/Cosmic Chemical Evolution
- to investigate neutrino effects in relativistic models
- to improve nuclear physics input
- to confirm the ejection of precursor free neutrons

Elemental abundances expected in the dynamical ejecta

Dynamical ejecta



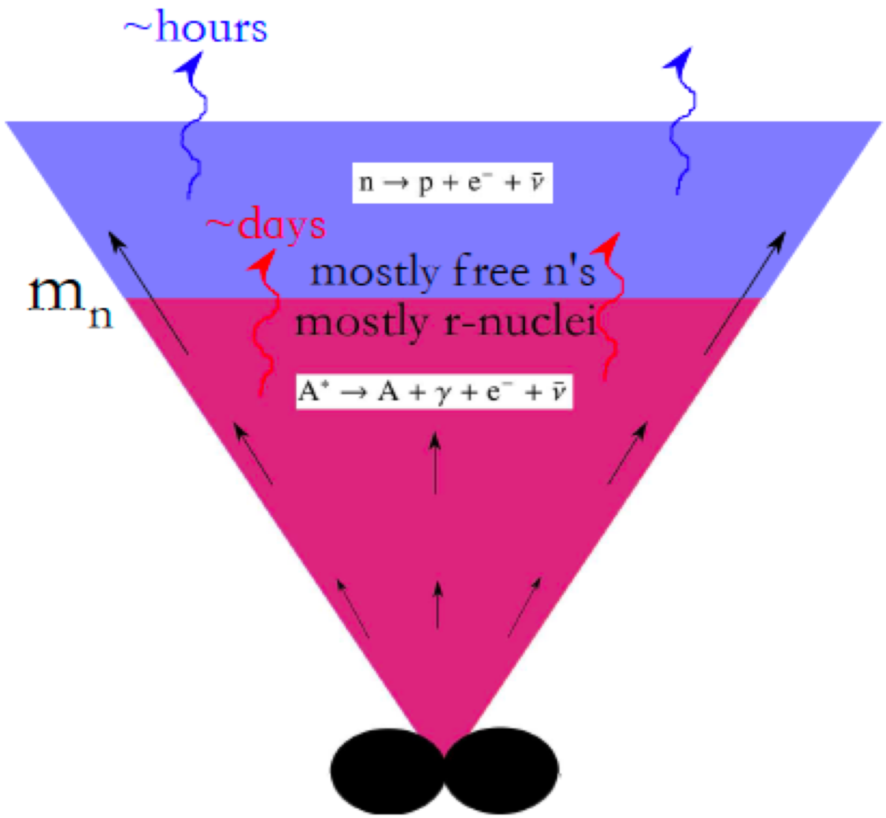


Significant production of lanthanides and actinides
(if neutrino interactions are negligible)

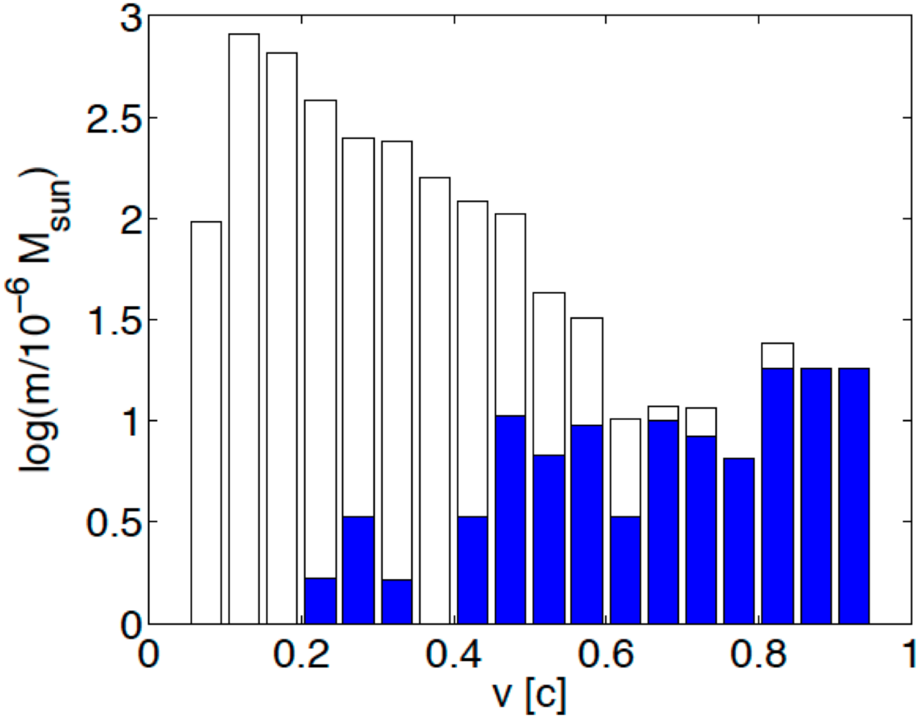
Very much dependent on the nuclear physics treatment of fission – Possible production of superheavy elements ?

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



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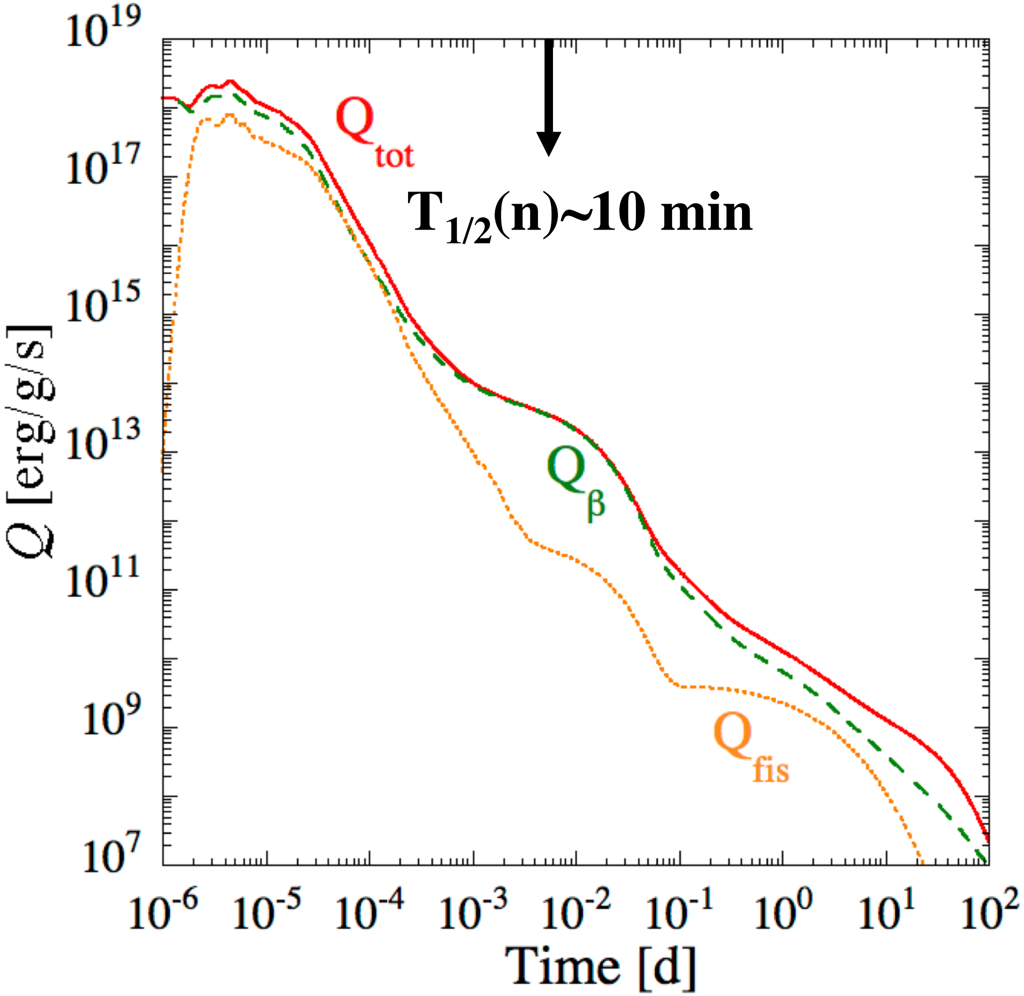
On the possible fast ejection of free neutrons

Final mass-averaged decay heat of the dynamical ejecta



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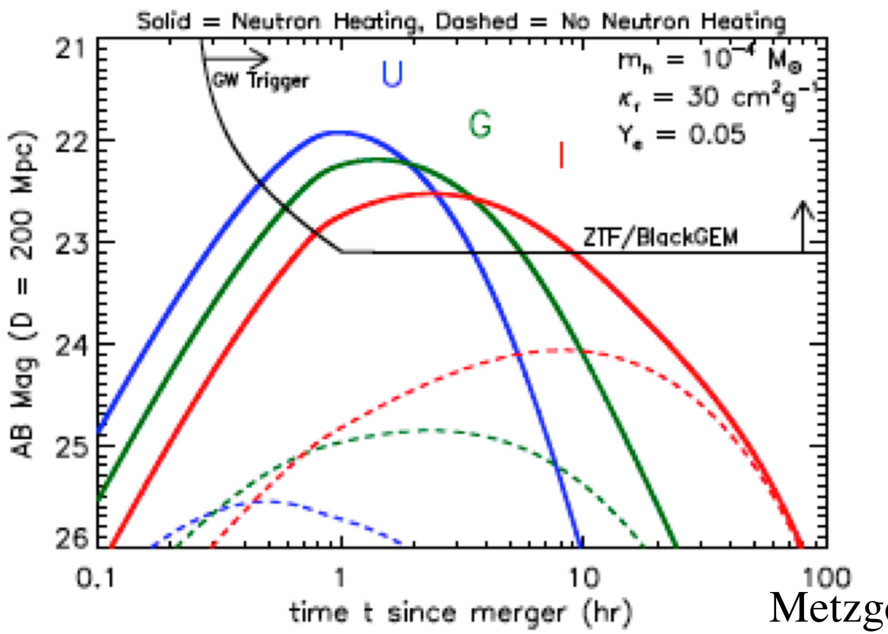

Metzger et al. (2014)

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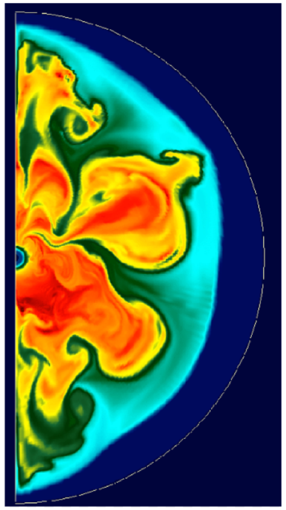
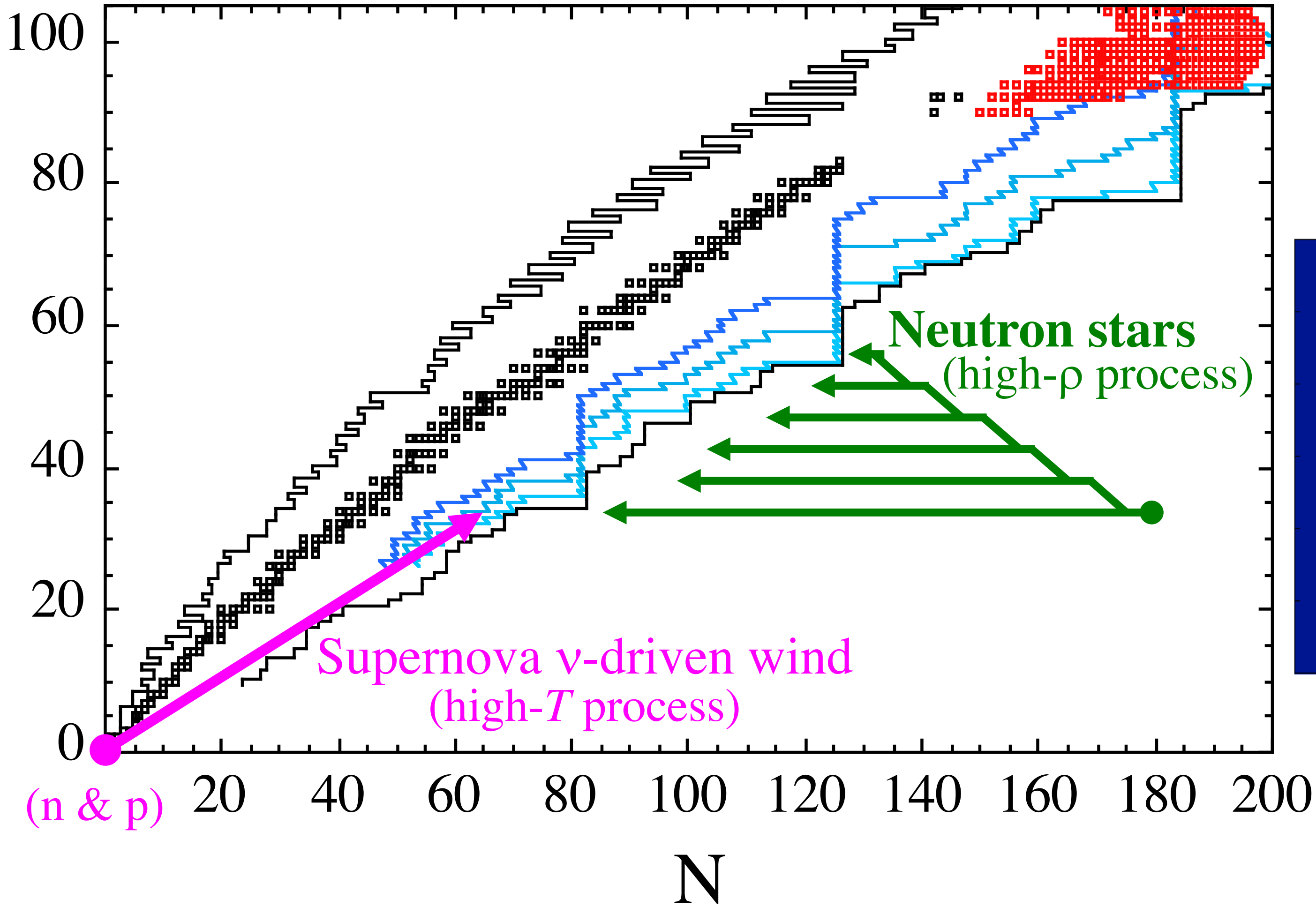
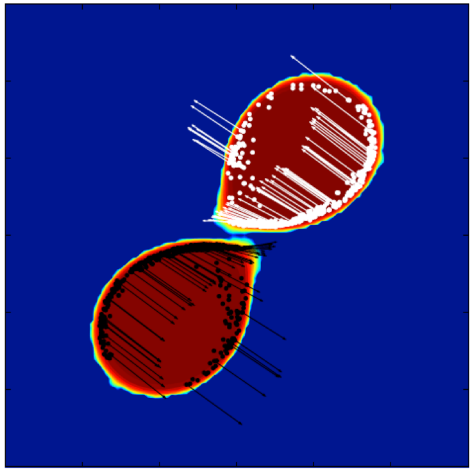
- *The neutrino interactions*: the stronger the weak interactions with nucleons, the smaller the amount of free neutrons left

The now-favoured r-process scenario: the decompression of NS matter

(initial conditions: high-density matter)

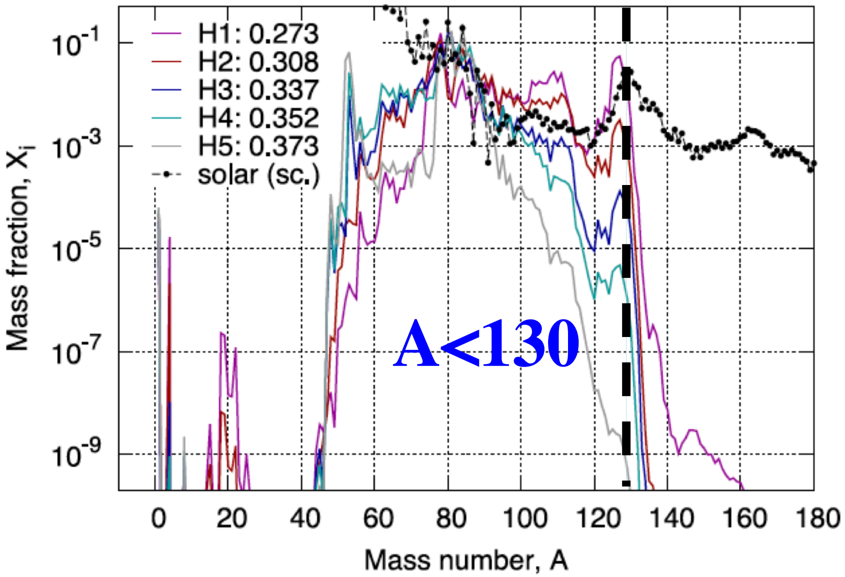


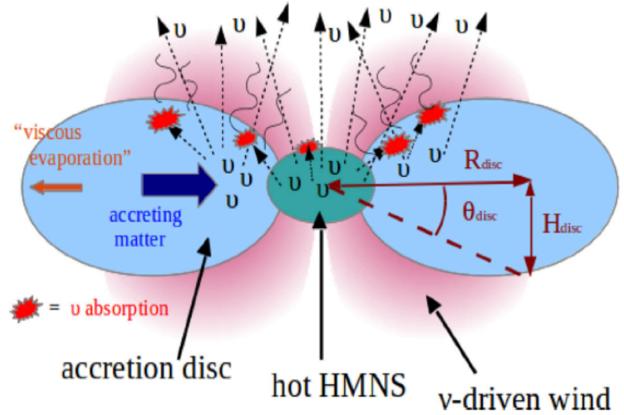




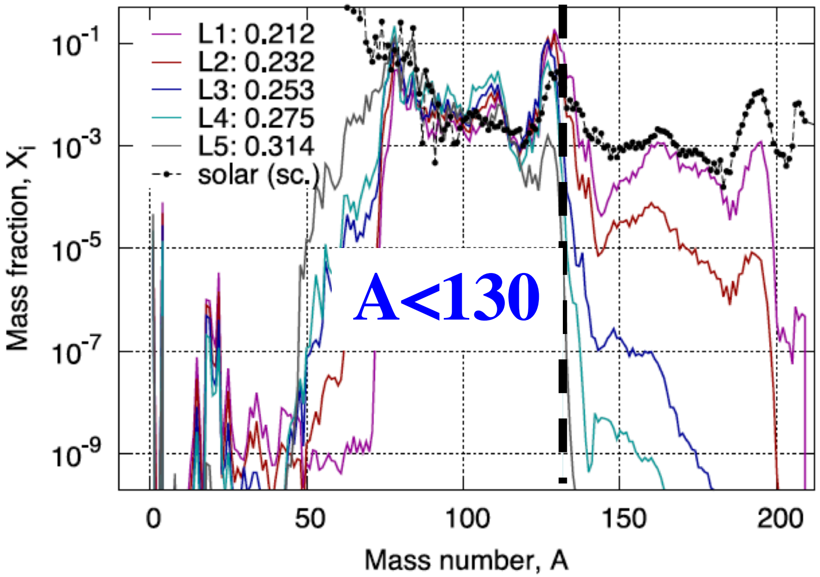
Composition of the matter ejected from a HMNS (Perego et al. 2014; Martin et al. 2015)

High latitudes

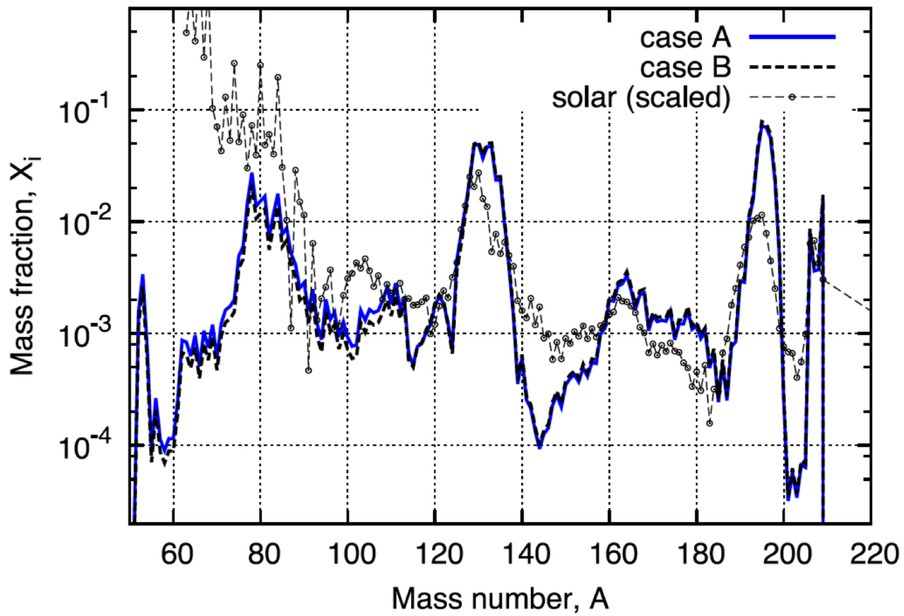




Low latitudes



Final composition (dynamical + disk)



Network calculations based on the MPA NS-NS merger simulations

- Density profile from SPH trajectories

$$\rho(t=0) \le \rho_{drip} = 4.2\ 10^{11} \mathrm{g/cm^3} \qquad \text{if } T \le 10^{10}\mathrm{K}$$

$$= \rho(T=10^{10}\mathrm{K}) \qquad \text{if } T \ge 10^{10}\mathrm{K}$$

At late times, a constant velocity expansion is assumed

$$\rho[t > t_{max}(\text{simulation})]: \quad \rho \propto \frac{1}{t^3}$$

- Temperature profile from trajectories followed by thermodynamic laws for time such that $T \le 10^{10}$K (heating by β-decay and fission)

- Initial composition: NSE at $T=10^{10}$K; $\rho = \rho(T=10^{10}\mathrm{K})$; $Y_e = Y_e(T=10^{10}\mathrm{K})$

- Nuclear input:
  - HFB-21 masses and *corresponding* reaction rates (TALYS)
  - GT2+HFB-21 β-decay rates
  - Full fission processes for Z_{max}=90-110 with HFB-14 nuclear inputs & SPY (Saclay) fission fragment distributions

STILL MANY OPEN QUESTIONS FOR THE NEXT DECADE

- **The reaction model**
  - **CN vs Direct capture for low-S_n reactions**
- **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

Conclusions

Astrophysics simulations are now able to provide consistent robust nucleosynthesis models for the r-process
(3D relativistic hydro simulations of the NS Mergers and BH-torus phases)

Calculated r-abundance distributions remain essentially affected by

- **β-decay: better than factor 1.5**
- **neutron capture (nuclear input models as well as reaction models: CN, DC): better than factor 2 around S_n~2-3MeV, 10 at drip lines ?**
- **Fission probabilities (barriers within ~ few 100keVs) and fission fragment distributions**

The best Nuclear Physics input should be provided

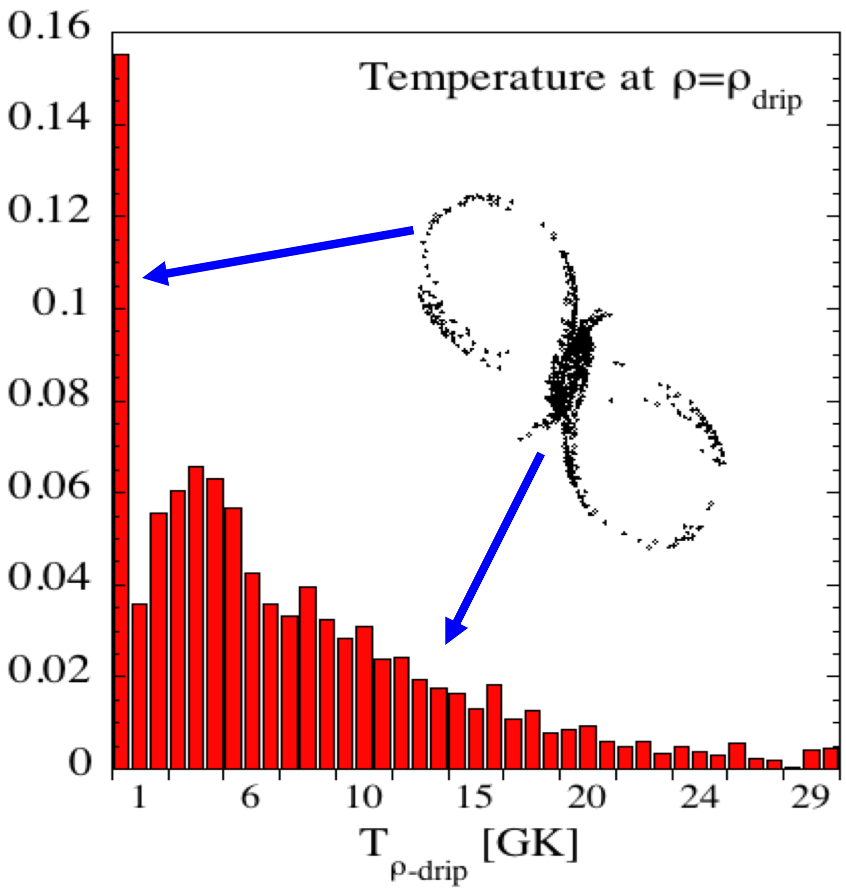
- **More theoretical work based on "MICROSCOPIC" approaches**
- **Consistent estimate of the model & parameter uncertainties**

That should keep us busy for the next decade… for sure…

Characteristics of the ejected "particles" from NS merger

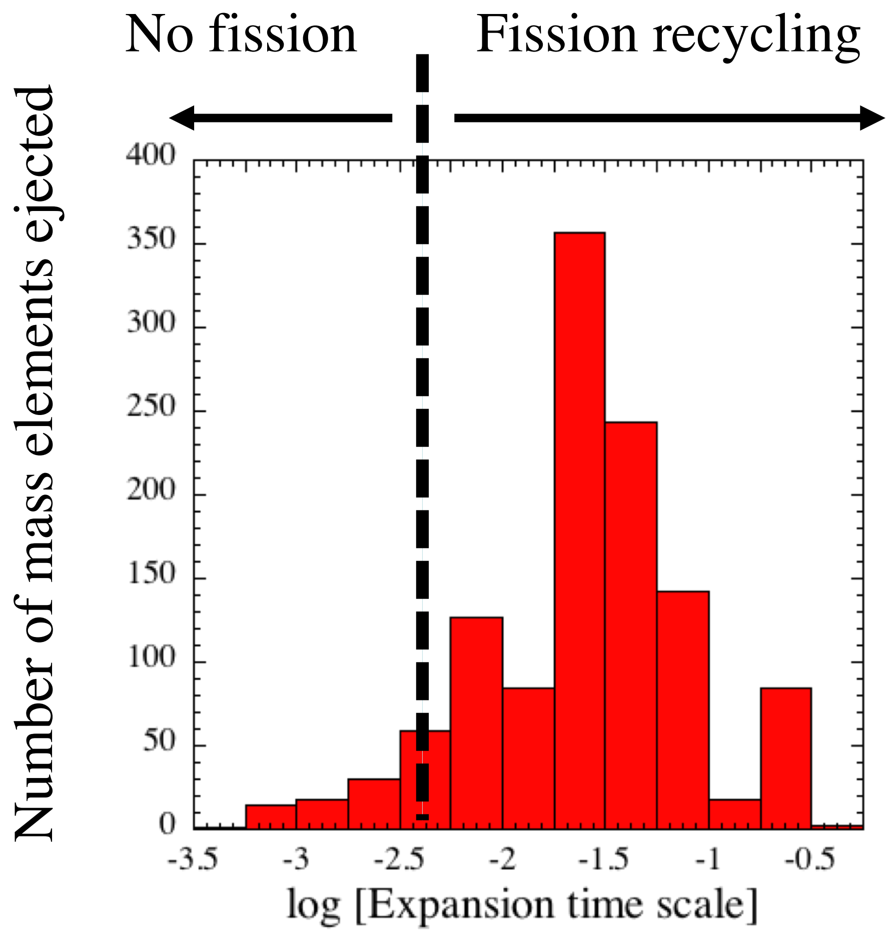
Material initially from the inner crust $\rho \sim 10^{14}$ g/cm^3 ; $Y_e \sim 0.01$-0.05

Temperatures reached during the decompression

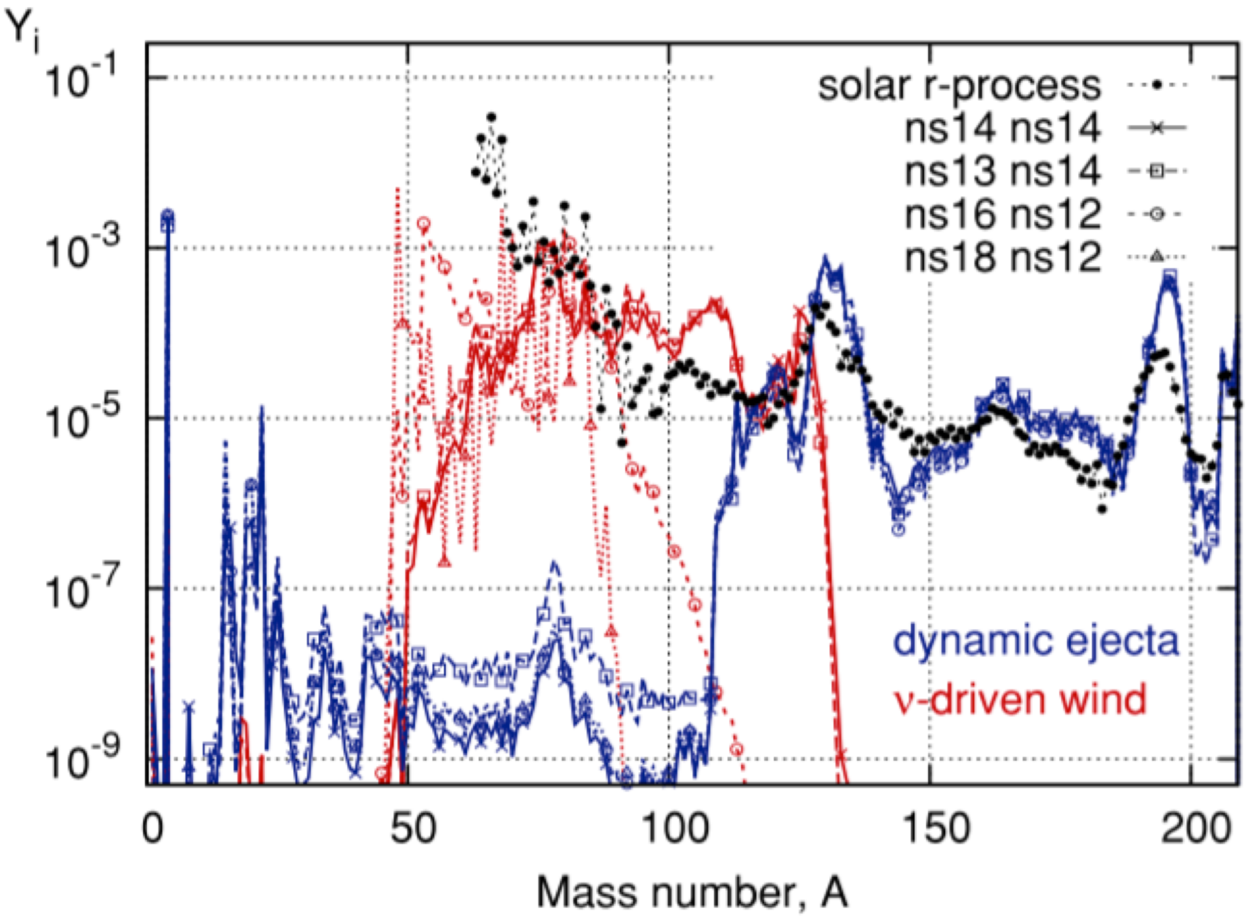


Expansion timescales

Time required to reach $\rho_{drip}/10^6$

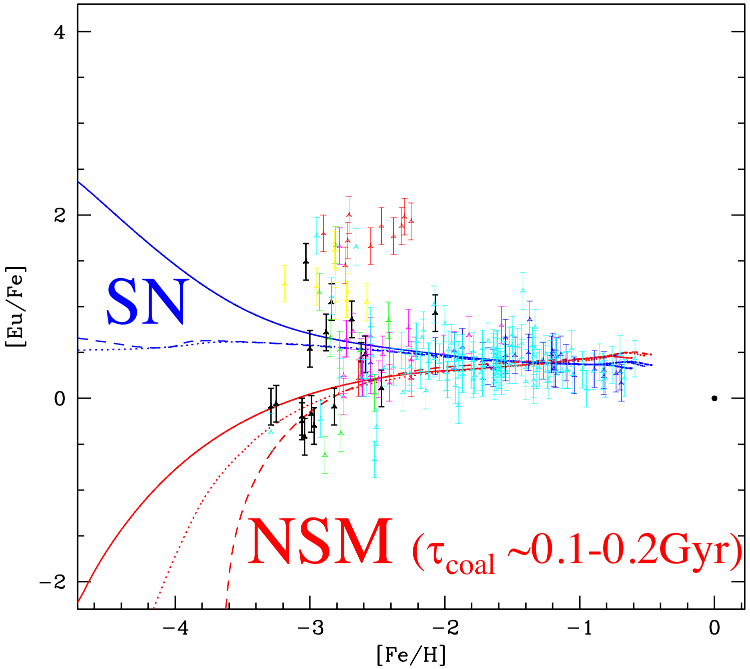


A relatively different result in comparison with the ejecta from a HMNS (Rosswog et al. 2014)



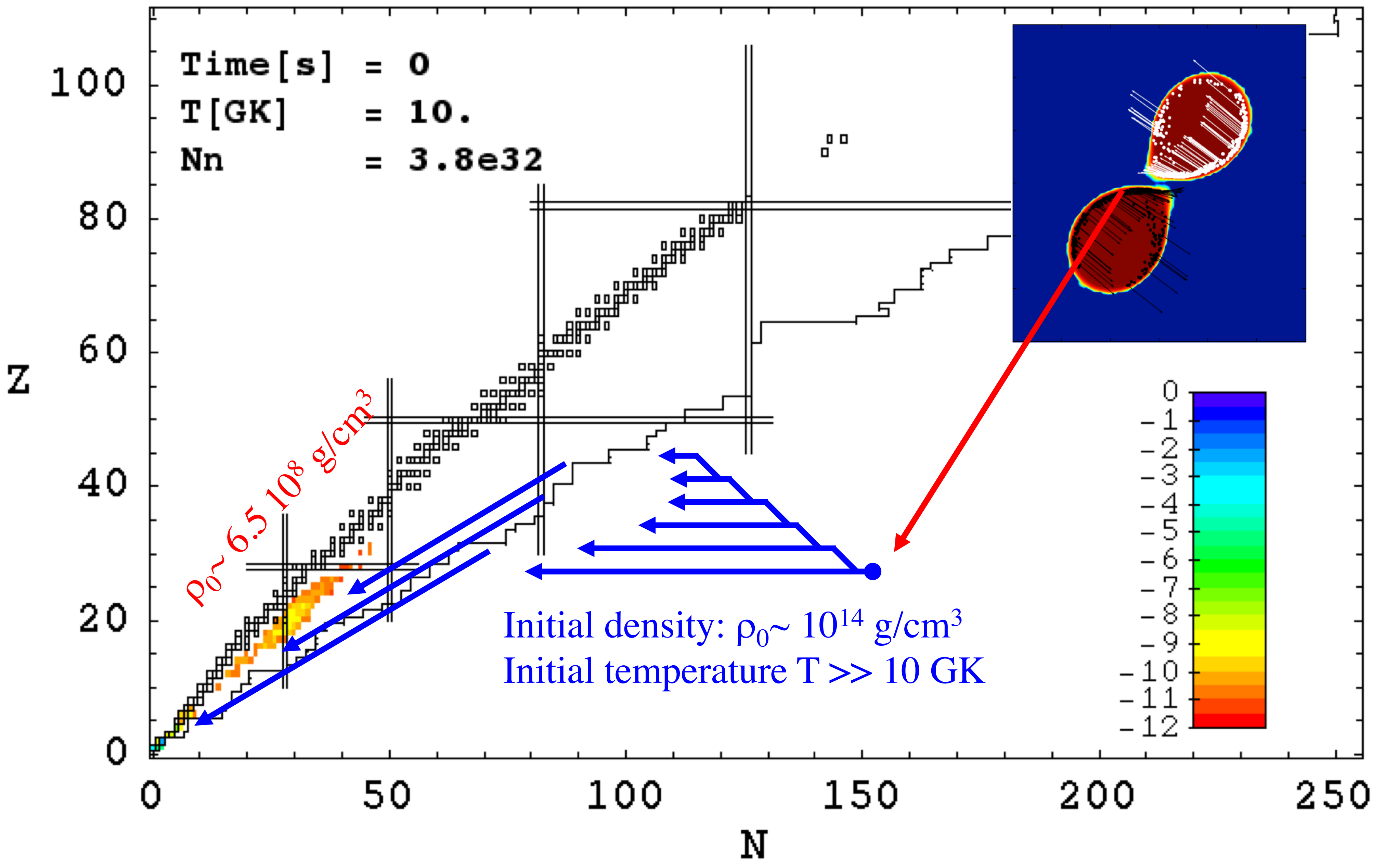
Cosmic & Galactic Chemical Evolution Models

On the basis of Galactic chemical evolution model, including cosmological zoom-in simulations, & cosmological evolution model using a hierarchical model for structure formation



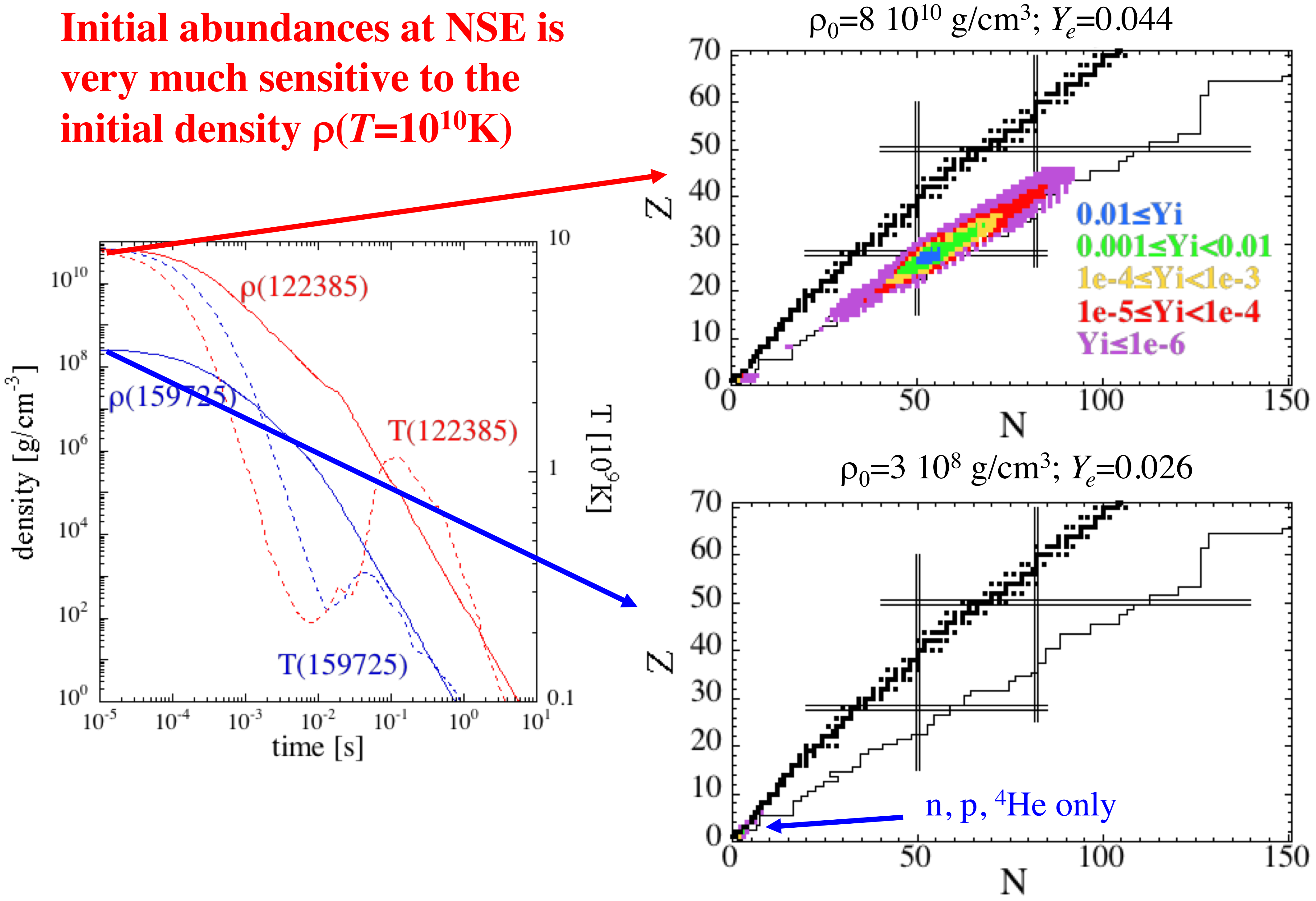
IT HAS BEEN CONCLUDED

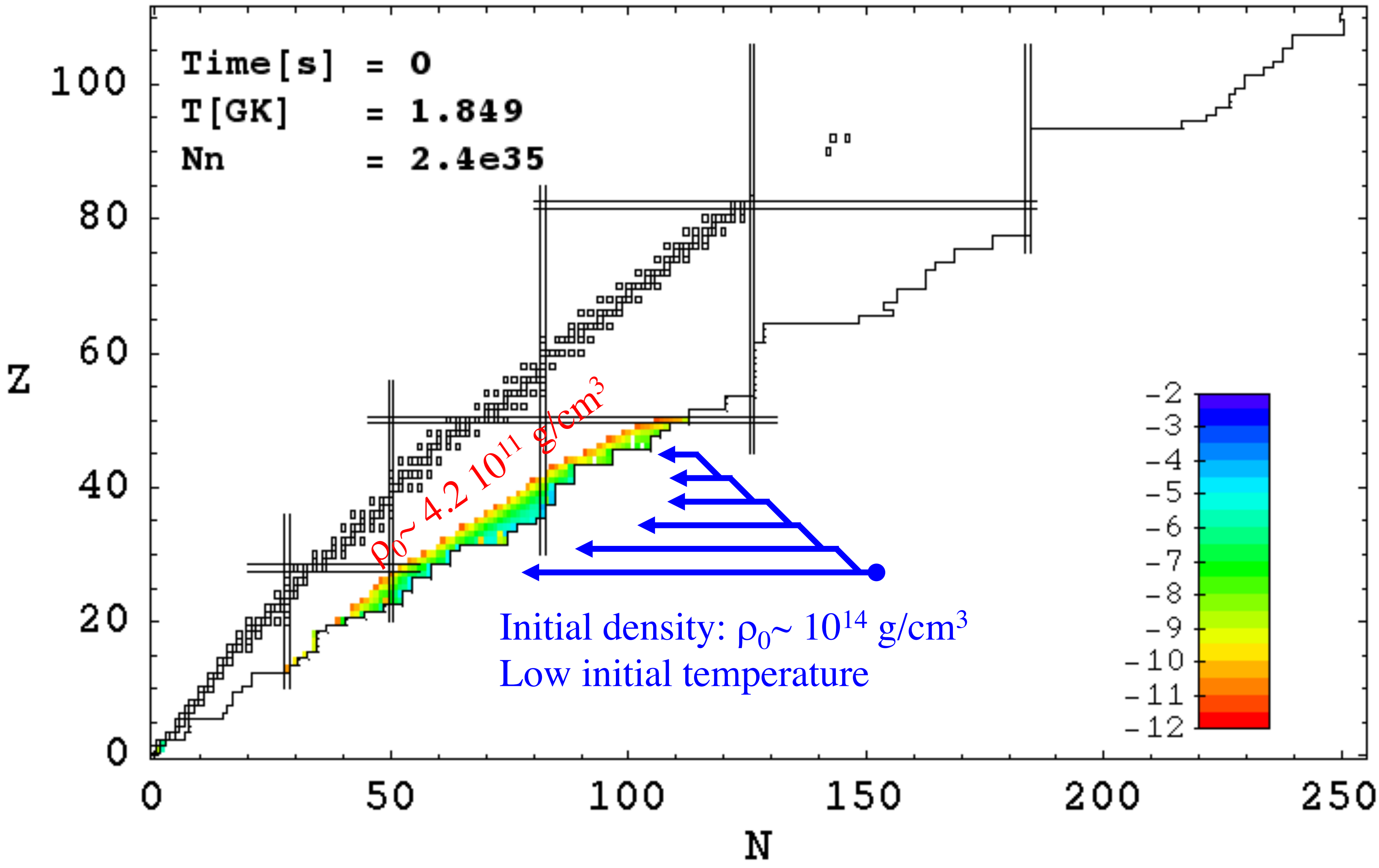
- Matteuci et al. (2014) « NSM can be entirely responsible for the production of Eu in the Galaxy if τ_{coal} ~1Myr »
- Mennekens et al. (2014) conclude « that except for the earliest evolutionary phase of the Galaxy (~the first 100 Myr), double compact star mergers may be the major production sites of r-process elements »
- Vangioni et al. (2015): « the Eu cosmic evolution tends to **favour NSM as the main astrophysical site** for the r process »
- Tsujimoto et al. (2014) « results demonstrate that NSM occuring at Galactic rate of 12-23Myr^{-1} are the **main site of r-process elements** »
- Van de Voort et al. (2014) « Overall, results are consistent with **NS mergers being the source** of most of the r-process nuclei in the Universe. »
- Shen et al. (2014) « argue that **compact binary mergers could be the dominant source** of r-process nucleosynthesis in the Galaxy »



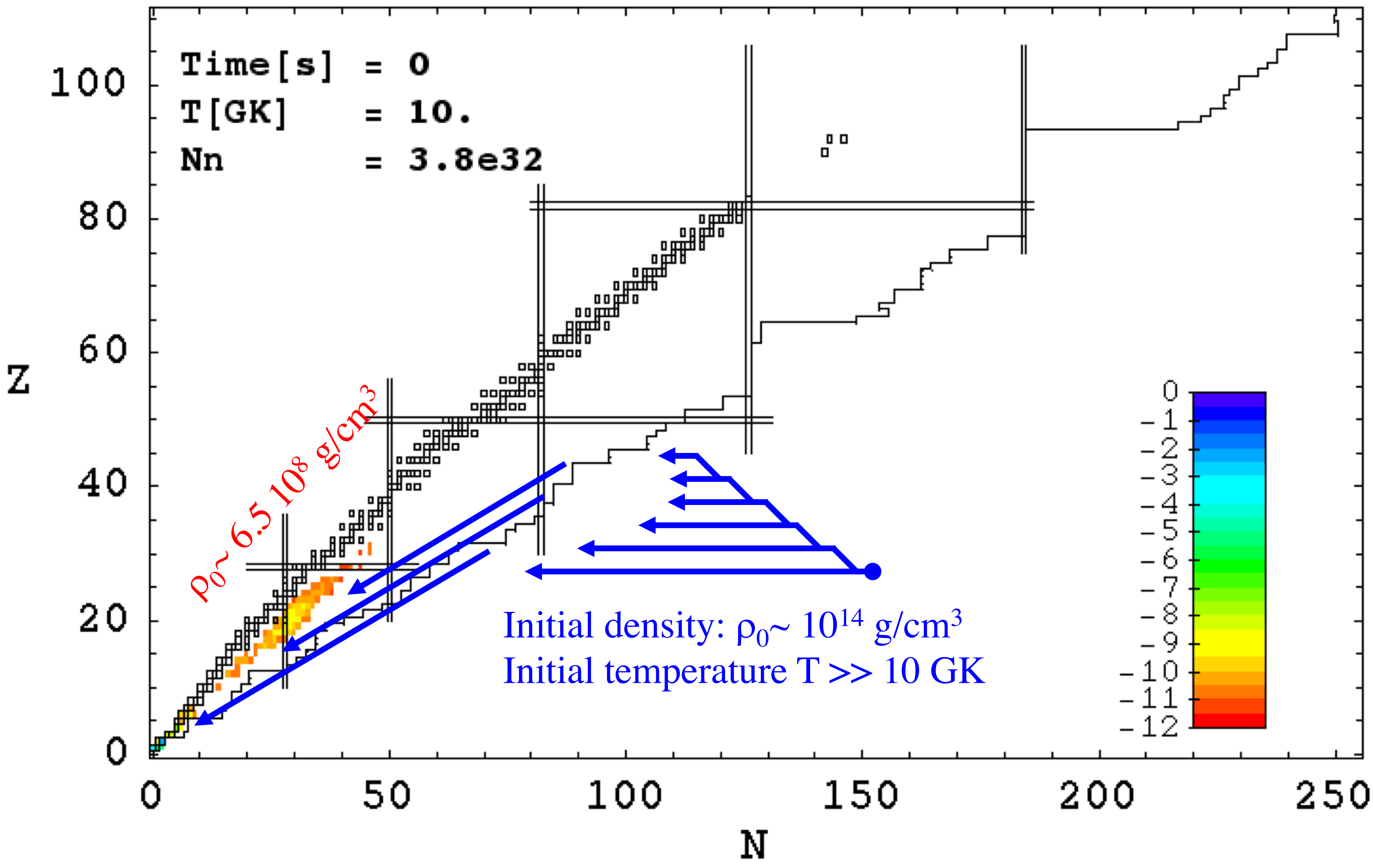
Time[s] = 0
T[GK] = 10.
Nn = 3.8e32
$\rho_0 \sim 6.5\ 10^8$ g/cm^3
Initial density: $\rho_0 \sim 10^{14}$ g/cm^3
Initial temperature T >> 10 GK
Z
N
0
20
40
60
80
100
0
50
100
150
200
250
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12

Initial abundances at NSE is very much sensitive to the initial density $\rho(T=10^{10}\mathrm{K})$



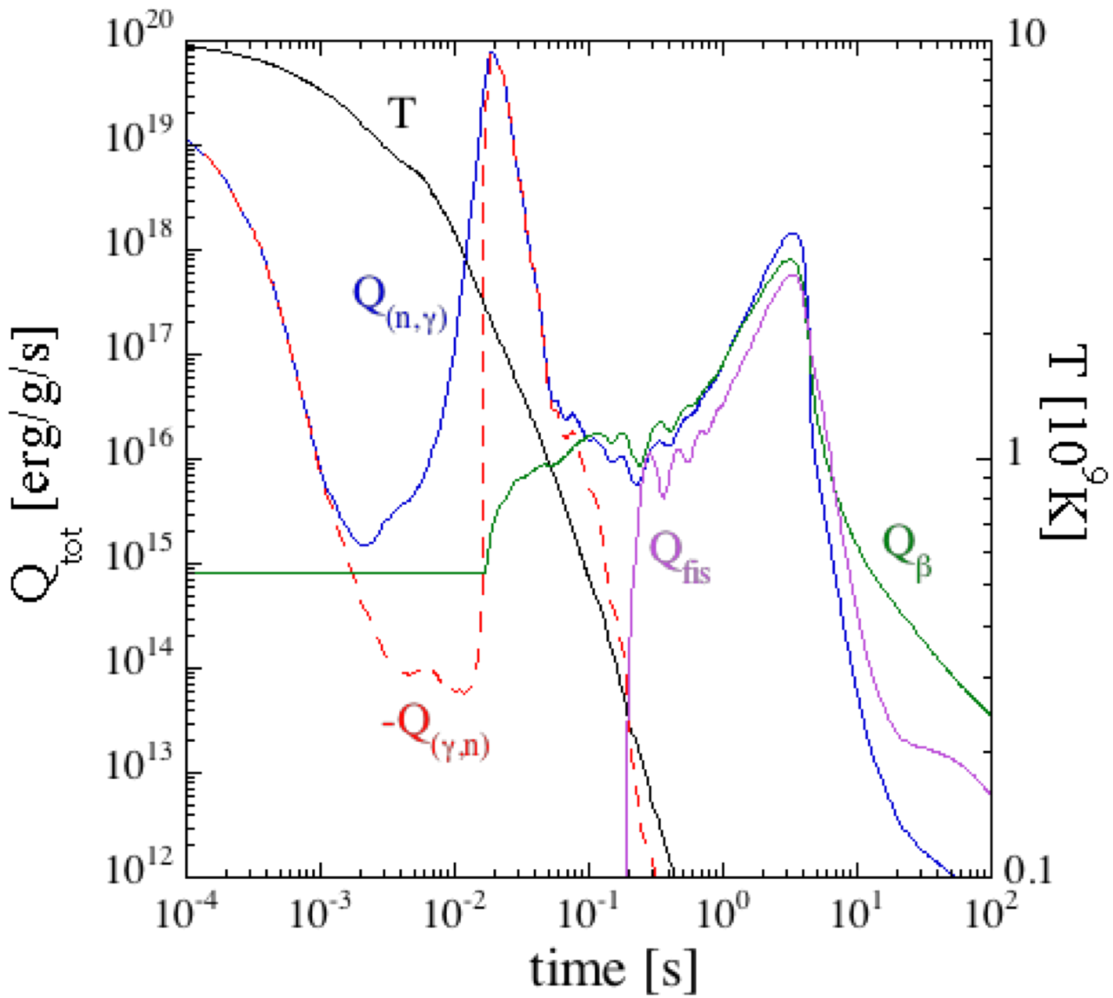


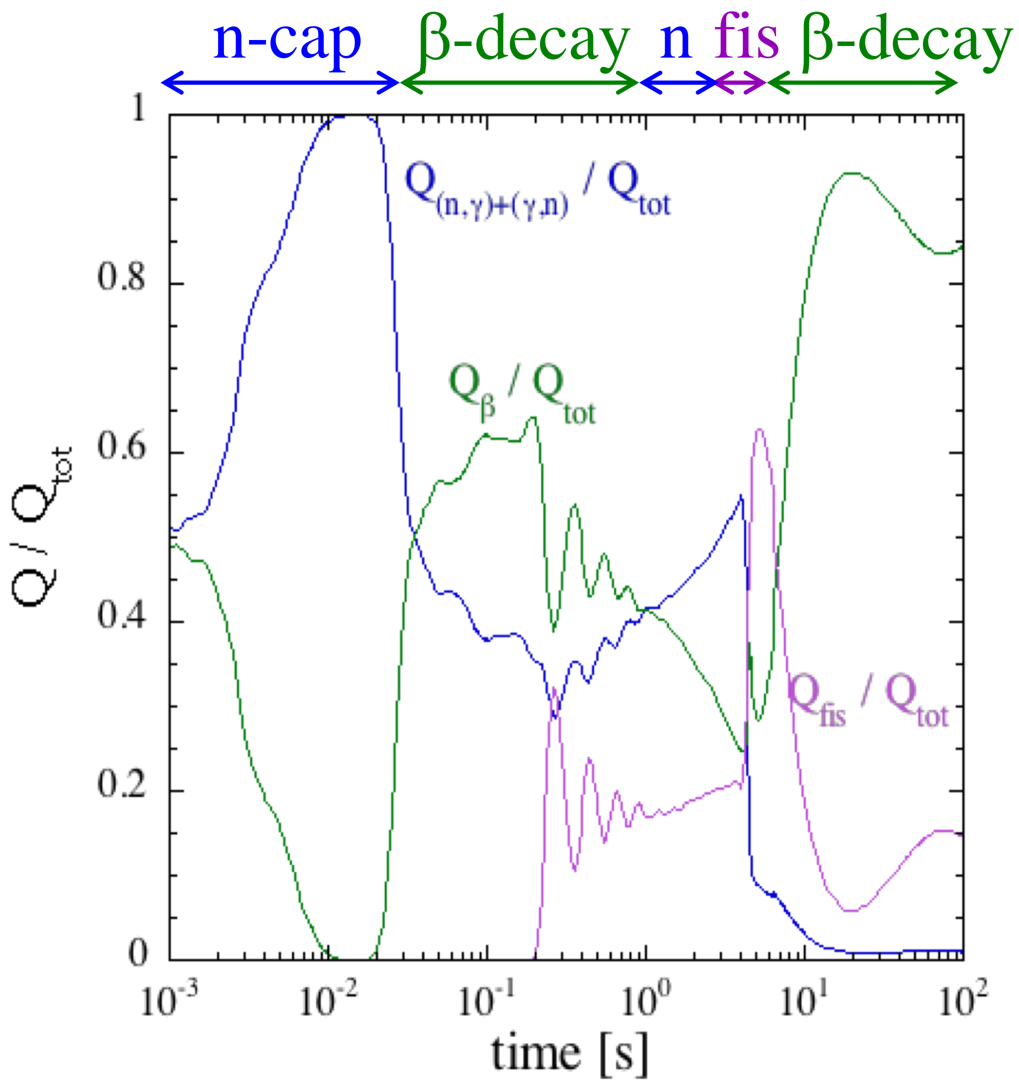
Time[s] = 0
T[GK] = 1.849
Nn = 2.4e35
ρ_0~ 4.2 10^{11} g/cm^3
Initial density: ρ_0~ 10^{14} g/cm^3
Low initial temperature
Z
N
0
50
100
150
200
250
20
40
60
80
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12



Time[s] = 0
T[GK] = 10.
Nn = 3.8e32
Z
N
$\rho_0 \sim 6.5\ 10^8$ g/cm^3
Initial density: $\rho_0 \sim 10^{14}$ g/cm^3
Initial temperature T >> 10 GK

Evolution of the decay heat in the dynamical ejecta



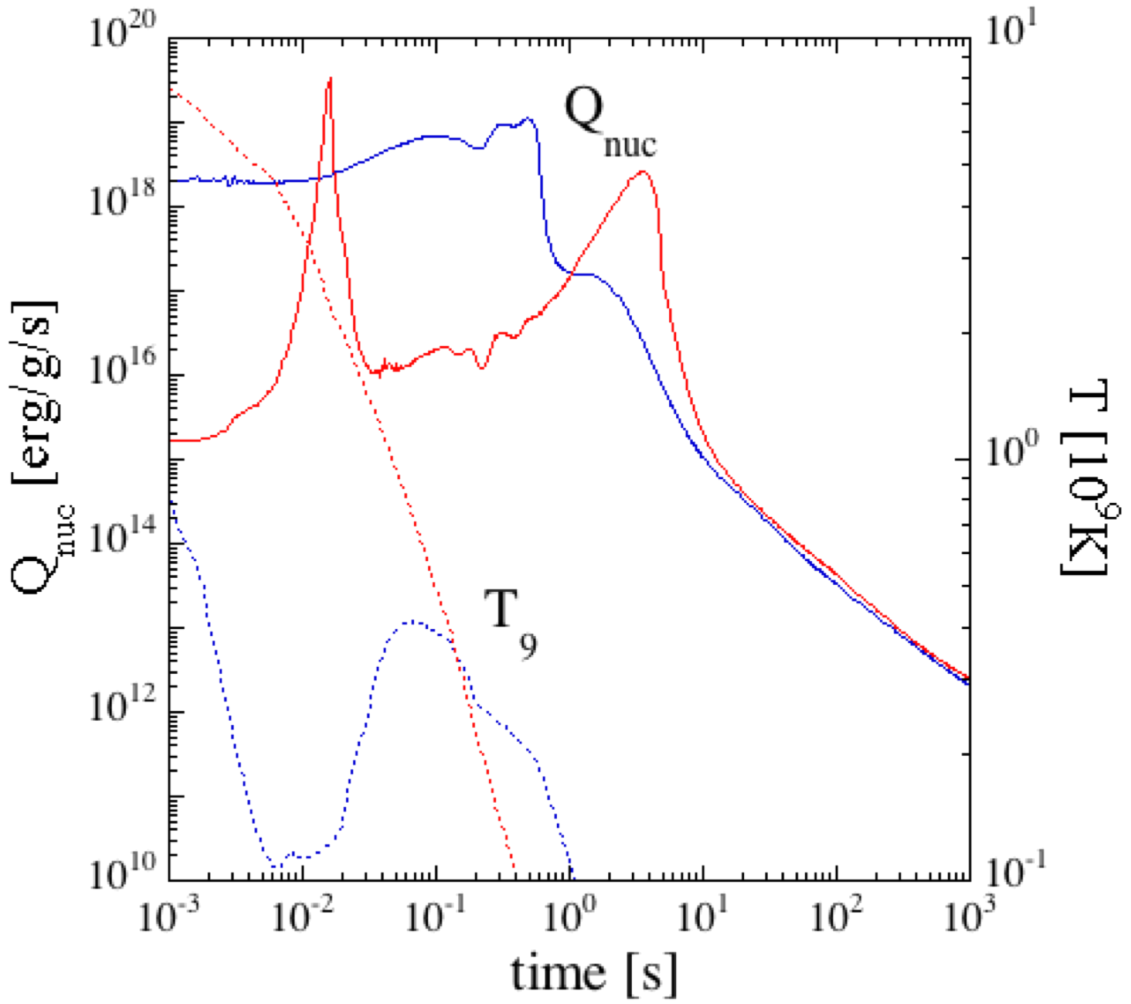


$\boxed{Q_{tot}=Q_{n,\gamma}+Q_{\gamma,n}+Q_\beta+Q_{fis}+Q_\alpha}$

DD135135_wdl_1000Kav15

(trajectory 0489807)

Evolution of specific properties for a given ejected 'particles'



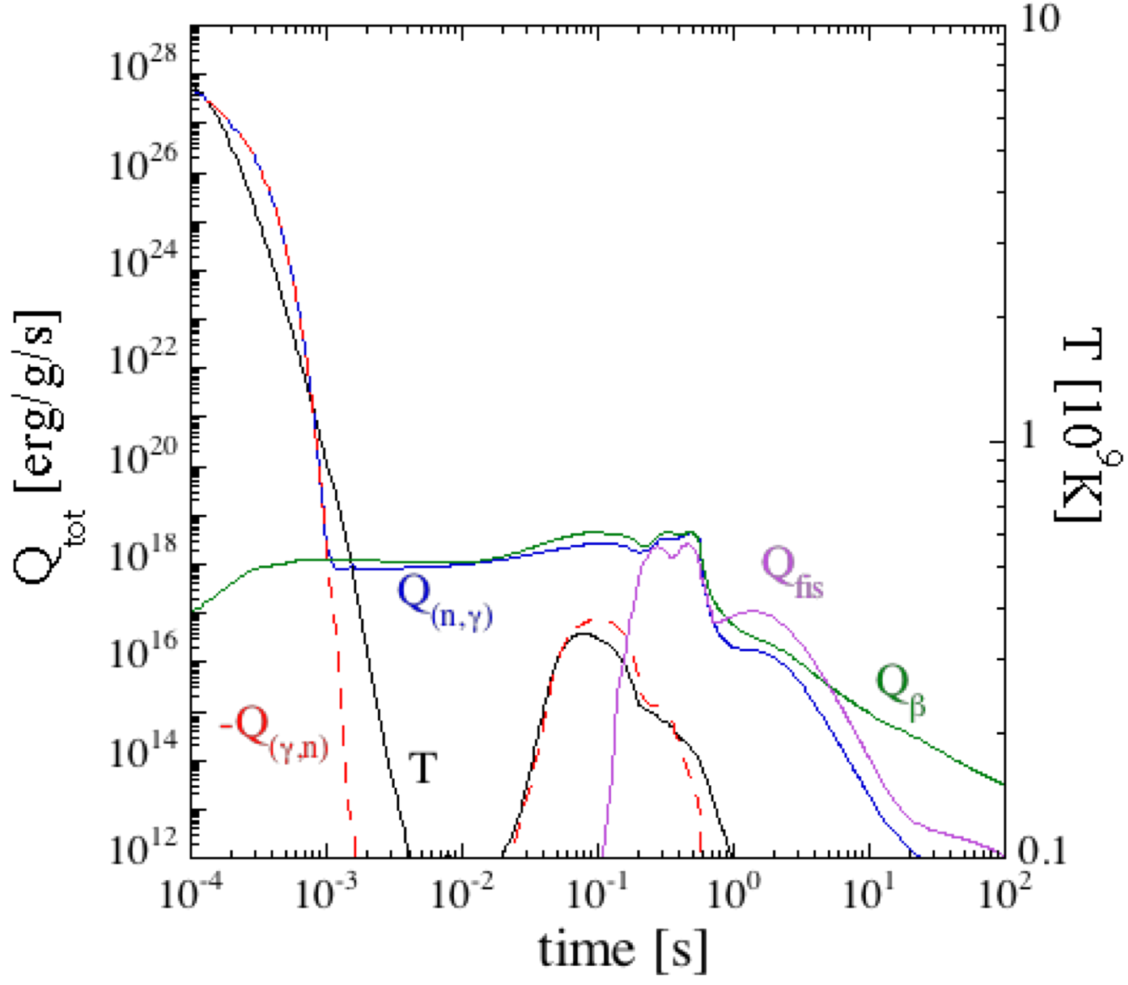
Without T processing

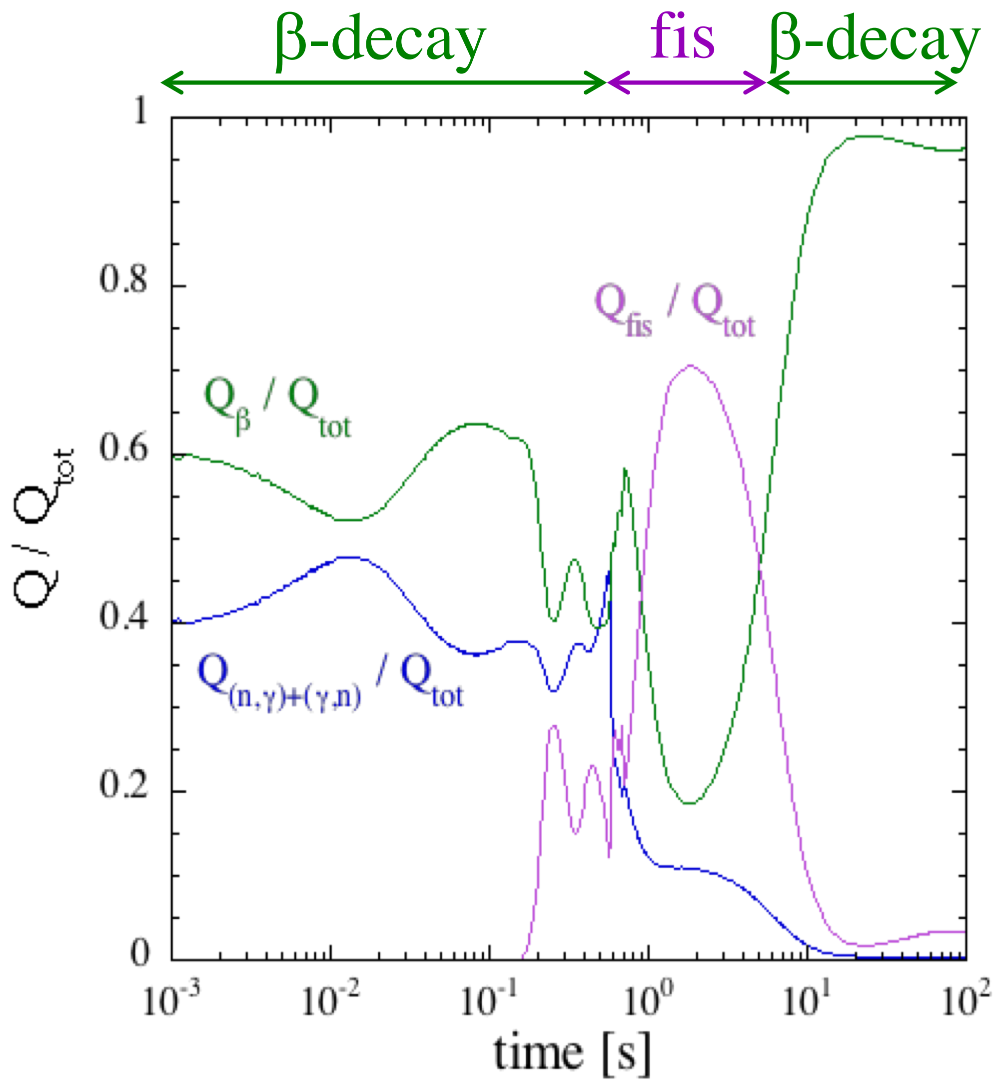
With T processing

DD135135_wdl_1000Kav15

(trajectory 0489807)

Evolution of the decay heat (for a given T-processed case)



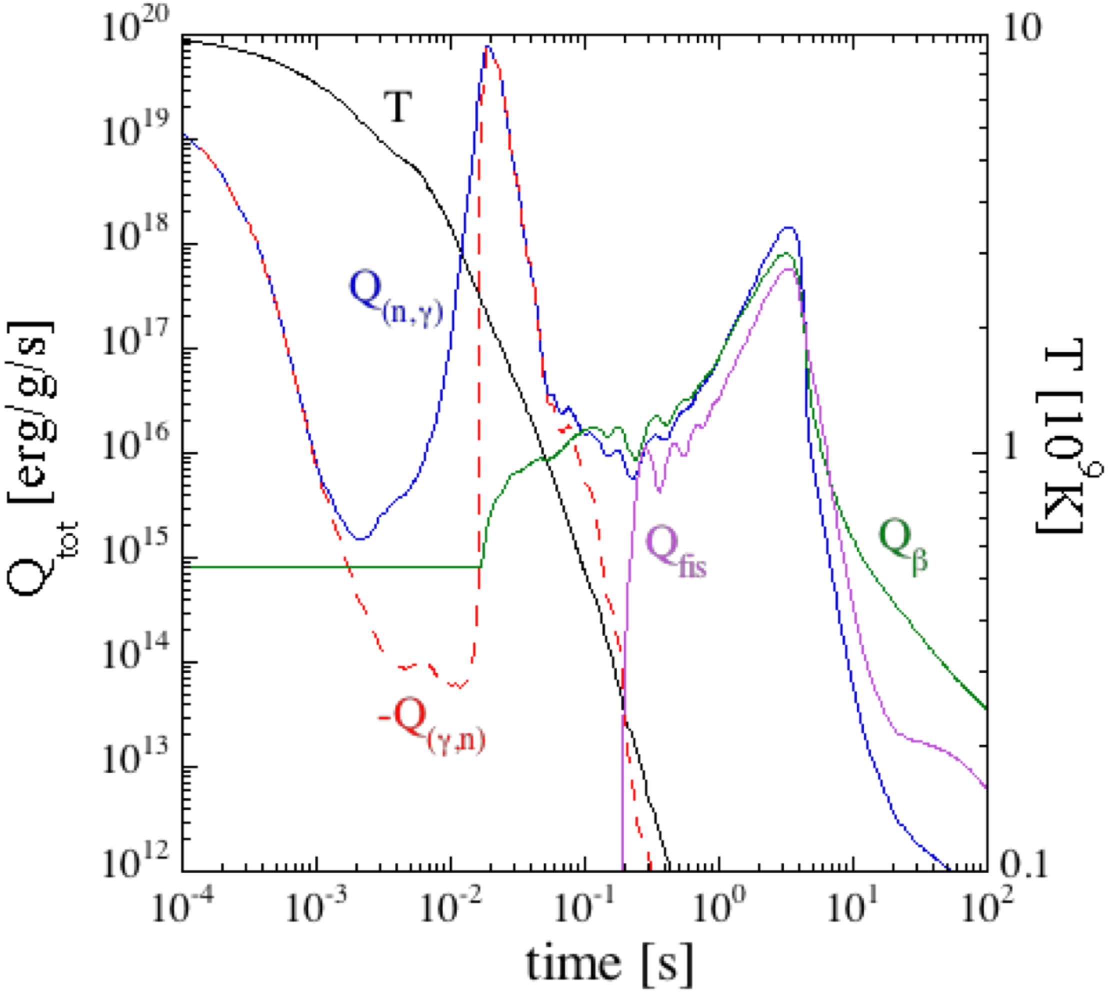


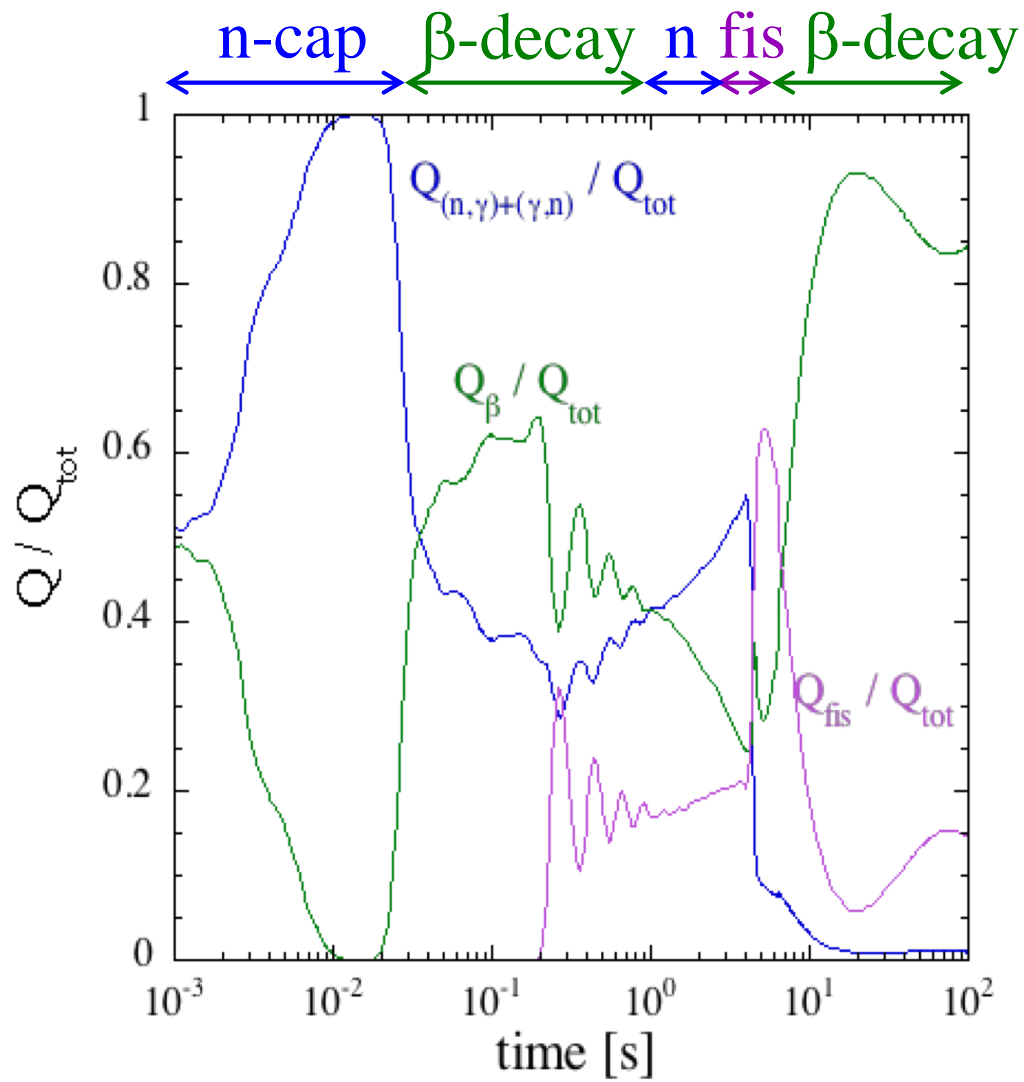
$$\boxed{Q_{tot}=Q_{n,\gamma}+Q_{\gamma,n}+Q_\beta+Q_{fis}+Q_\alpha}$$

DD135135_wdl_1000Kav15p

(trajectory 0489807)

Evolution of the decay heat (for a given T-unprocessed case)





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

DD135135_wdl_1000Kav15

(trajectory 0489807)