

# **Nucleosynthesis in Neutron Star Mergers**

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# Origin of the elements in the Universe ?

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**Frequently used fundamental physical constants**  
For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of  $^{133}\text{Cs}$

speed of light in vacuum	c	299 792 458 m s <sup>-1</sup>	(exact)
Planck constant	h	$6.6261 \times 10^{-34}$ J s	( $\hbar = h/2\pi$ )
elementary charge	e	$1.6022 \times 10^{-19}$ C	
electron mass	m <sub>e</sub>	$9.1094 \times 10^{-31}$ kg	
proton mass	m <sub>p</sub>	$1.6726 \times 10^{-27}$ kg	
fine-structure constant	$\alpha$	$1/137.036$	
Rydberg constant	R <sub>r</sub>	10 973 732 m <sup>-1</sup>	
R <sub>r,c</sub>	3.289 84 $\times 10^{15}$ Hz		
R <sub>r,hc</sub>	13.6057 eV		
Boltzmann constant	k	$1.3807 \times 10^{-23}$ JK <sup>-1</sup>	

U.S. DEPARTMENT OF COMMERCE  
Technology Administration  
National Institute of Standards and Technology

**Standard Reference Data Program**  
[www.nist.gov/srd](http://www.nist.gov/srd)

**VIII**

<b>He</b> Helium 4.00260 g/mol 24.6074
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**IIIB**    **IVB**    **VIB**    **VIB**    **VIIIB**

<b>5</b> $^1\text{P}_{0}$ <b>B</b> Boron 10.811 $1s^2 2s^2 2p^1$	<b>6</b> $^3\text{P}_0$ <b>C</b> Carbon 12.0107 $1s^2 2s^2 2p^2$	<b>7</b> $^1\text{S}_{1/2}$ <b>N</b> Nitrogen 14.00674 $1s^2 2s^2 2p^3$	<b>8</b> $^3\text{P}_2$ <b>O</b> Oxygen 15.9994 $1s^2 2s^2 2p^4$	<b>9</b> $^1\text{P}_{1/2}$ <b>F</b> Fluorine 18.99840 $1s^2 2s^2 2p^5$	<b>10</b> $^1\text{S}_{1/2}$ <b>Ne</b> Neon 20.1797 $1s^2 2s^2 2p^6$
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**13**  $^3\text{P}_{10}$   
**Al**  
Aluminum  
26.98154  
 $[Ne]3s^2 3p^1$

**14**  $^3\text{P}_0$   
**Si**  
Silicon  
28.0855  
 $[Ne]3s^2 3p^2$

**15**  $^1\text{S}_{1/2}$   
**P**  
Phosphorus  
30.97376  
 $[Ne]3s^2 3p^3$

**16**  $^3\text{P}_2$   
**S**  
Sulfur  
32.0666  
 $[Ne]3s^2 3p^4$

**17**  $^3\text{P}_{1/2}$   
**Cl**  
Chlorine  
35.45277  
 $[Ne]3s^2 3p^5$

**18**  $^1\text{S}_{1/2}$   
**Ar**  
Argon  
38.968  
 $[Ne]3s^2 3p^6$

**31**  $^3\text{P}_{10}$   
**Ga**  
Gallium  
69.723  
 $[Ar]3d^1 4s^2$

**32**  $^3\text{P}_0$   
**Ge**  
Germanium  
72.61  
 $[Ar]3d^1 4s^2 4p^2$

**33**  $^1\text{S}_{1/2}$   
**As**  
Arsenic  
74.92169  
 $[Ar]3d^1 4s^2 4p^3$

**34**  $^3\text{P}_2$   
**Se**  
Selenium  
79.956  
 $[Ar]3d^1 4s^2 4p^4$

**35**  $^3\text{P}_{1/2}$   
**Br**  
Bromine  
79.904  
 $[Ar]3d^1 4s^2 4p^5$

**36**  $^1\text{S}_{1/2}$   
**Kr**  
Krypton  
83.99  
 $[Ar]3d^1 4s^2 4p^6$

**51**  $^3\text{P}_2$   
**In**  
Indium  
114.818  
 $[Kr]4d^1 5s^2$

**52**  $^3\text{P}_0$   
**Sn**  
Tin  
118.710  
 $[Kr]4d^1 5s^2 5p^2$

**53**  $^3\text{P}_{1/2}$   
**Sb**  
Antimony  
121.760  
 $[Kr]4d^1 5s^2 5p^3$

**54**  $^1\text{S}_{1/2}$   
**I**  
Iodine  
126.90447  
 $[Kr]4d^1 5s^2 5p^5$

**55**  $^3\text{P}_{10}$   
**Xe**  
Xenon  
131.29  
 $[Kr]4d^1 5s^2 5p^6$

**81**  $^3\text{P}_{10}$   
**Tl**  
Thallium  
204.3633  
 $[Hg]6s^1$

**82**  $^3\text{P}_0$   
**Pb**  
Lead  
207.2  
 $[Hg]6s^1$

**84**  $^3\text{P}_{1/2}$   
**Bi**  
Bismuth  
208.98658  
 $[Hg]6s^1$

**85**  $^3\text{P}_{1/2}$   
**Po**  
Polonium  
(209)  
 $[Hg]6s^1$

**86**  $^1\text{S}_{1/2}$   
**Rn**  
Radium  
(222)  
 $[Hg]6s^1$

**For a description of the atomic data, visit [physics.nist.gov/atomic](http://physics.nist.gov/atomic)**

**Symbol**  
Ce  
[Xe]4f<sup>15</sup>d<sup>6</sup>s<sup>2</sup>  
5.5387

**Name**  
Cerium  
140.116  
[Xe]4f<sup>15</sup>d<sup>6</sup>s<sup>2</sup>

**Atomic Weight**  
140.116  
[Xe]4f<sup>15</sup>d<sup>6</sup>s<sup>2</sup>  
5.5387

**Ground-state Configuration**  
[Xe]4f<sup>15</sup>d<sup>6</sup>s<sup>2</sup>

**Ionization Energy (eV)**  
5.5387

**Atomic Number**  
58

**Ground-state Level**  
 $^1\text{G}_4$

**57**  $^3\text{D}_{10}$   
**La**  
Lanthanum  
138.9055  
 $[Xe]5d<sup>10</sup>6s<sup>2</sup>$

**58**  $^1\text{G}_4$   
**Ce**  
Cerium  
140.116  
 $[Xe]4f<sup>15</sup>d<sup>6</sup>s<sup>2</sup>$

**59**  $^1\text{I}_{12}$   
**Pr**  
Praseodymium  
140.90745  
 $[Xe]4f<sup>3</sup>5d<sup>1</sup>6s<sup>2</sup>$

**60**  $^3\text{I}_8$   
**Nd**  
Neodymium  
144.24  
 $[Xe]4f<sup>4</sup>6s<sup>2</sup>$

**61**  $^3\text{H}_{12}$   
**Pm**  
Promethium  
(145)  
 $[Xe]4f<sup>5</sup>6s<sup>2</sup>$

**62**  $^3\text{F}_0$   
**Sm**  
Samarium  
150.36  
 $[Xe]4f<sup>6</sup>6s<sup>2</sup>$

**63**  $^1\text{S}_{1/2}$   
**Eu**  
Europium  
151.984  
 $[Xe]4f<sup>7</sup>6s<sup>2</sup>$

**64**  $^3\text{D}_{10}$   
**Gd**  
Gadolinium  
157.25  
 $[Xe]4f<sup>8</sup>6s<sup>2</sup>$

**65**  $^3\text{H}_{12}$   
**Tb**  
Terbium  
158.92554  
 $[Xe]4f<sup>9</sup>6s<sup>2</sup>$

**66**  $^3\text{I}_8$   
**Dy**  
Dysprosium  
162.50  
 $[Xe]4f<sup>10</sup>6s<sup>2</sup>$

**67**  $^4\text{I}_{15/2}$   
**Ho**  
Holmium  
164.90352  
 $[Xe]4f<sup>11</sup>6s<sup>2</sup>$

**68**  $^3\text{H}_5$   
**Er**  
Erbium  
167.26  
 $[Xe]4f<sup>12</sup>6s<sup>2</sup>$

**69**  $^3\text{F}_{10}$   
**Tm**  
Thulium  
168.93421  
 $[Xe]4f<sup>13</sup>6s<sup>2</sup>$

**70**  $^1\text{S}_{1/2}$   
**Yb**  
Ytterbium  
173.04  
 $[Xe]4f<sup>14</sup>6s<sup>2</sup>$

**71**  $^3\text{D}_{10}$   
**Lu**  
Lutetium  
174.957  
 $[Xe]4f<sup>15</sup>6s<sup>2</sup>$

**89**  $^3\text{D}_{10}$   
**Ac**  
Actinium  
(227)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**90**  $^3\text{F}_0$   
**Th**  
Thorium  
232.0381  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**91**  $^4\text{K}_{15/2}$   
**Pa**  
Protactinium  
231.03588  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**92**  $^5\text{L}_{12}$   
**U**  
Uranium  
238.0289  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**93**  $^3\text{L}_{12}$   
**Np**  
Neptunium  
(237)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**94**  $^3\text{F}_6$   
**Pu**  
Plutonium  
(244)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**95**  $^3\text{S}_{1/2}$   
**Am**  
Americium  
(243)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**96**  $^3\text{D}_2$   
**Cm**  
Curium  
(247)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**97**  $^3\text{H}_{10}$   
**Bk**  
Berkelium  
(247)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**98**  $^3\text{I}_8$   
**Cf**  
Californium  
(251)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**99**  $^4\text{I}_{15/2}$   
**Es**  
Einsteinium  
(252)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**100**  $^3\text{H}_5$   
**Fm**  
Fermium  
(257)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**101**  $^2\text{F}_{15/2}$   
**Md**  
Mendelevium  
(258)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

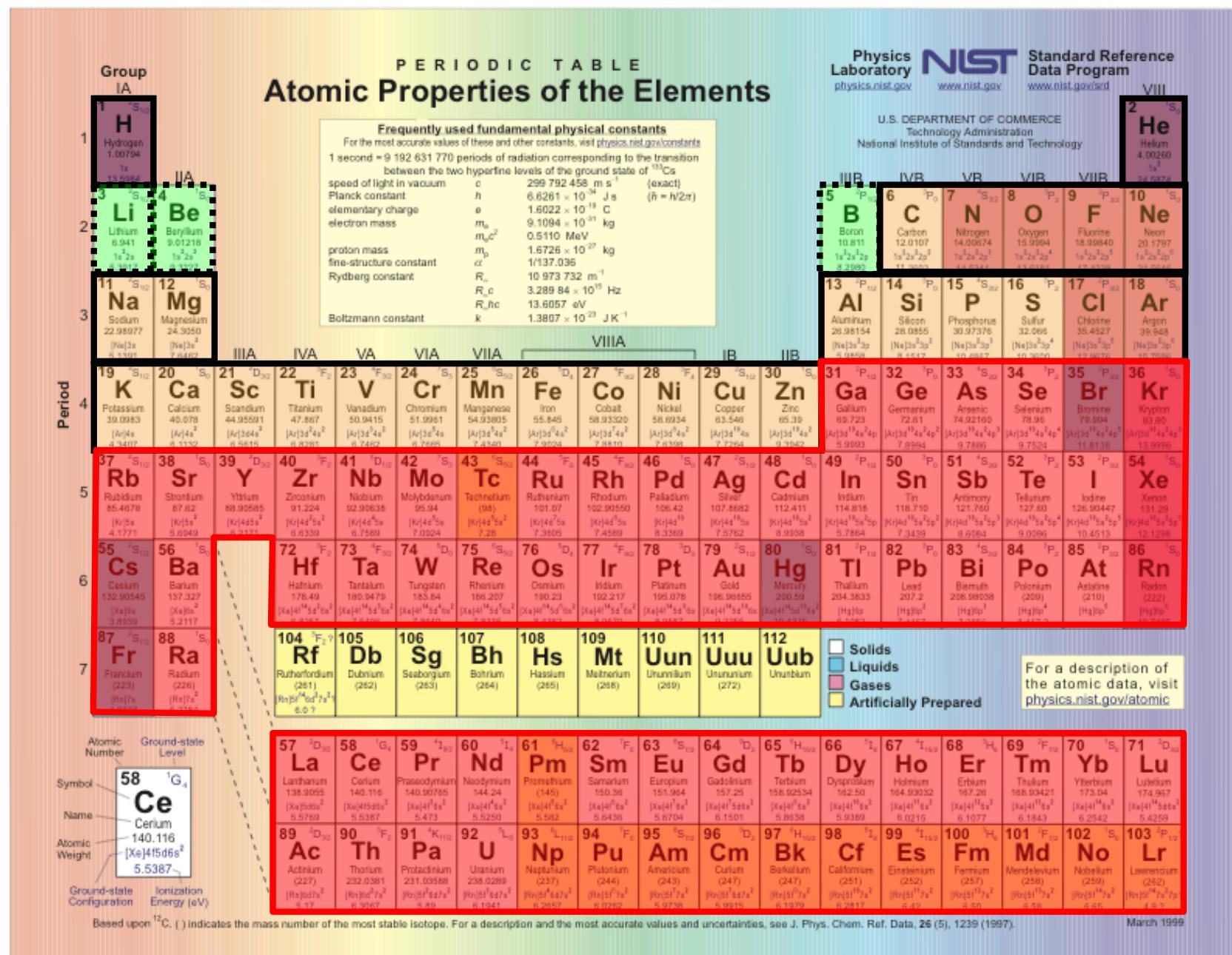
**102**  $^1\text{S}_{1/2}$   
**No**  
Nobelium  
(259)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

**103**  $^3\text{P}_{1/2}$   
**Lr**  
Lawrencium  
(262)  
 $[Ra]6d<sup>10</sup>7s<sup>2</sup>$

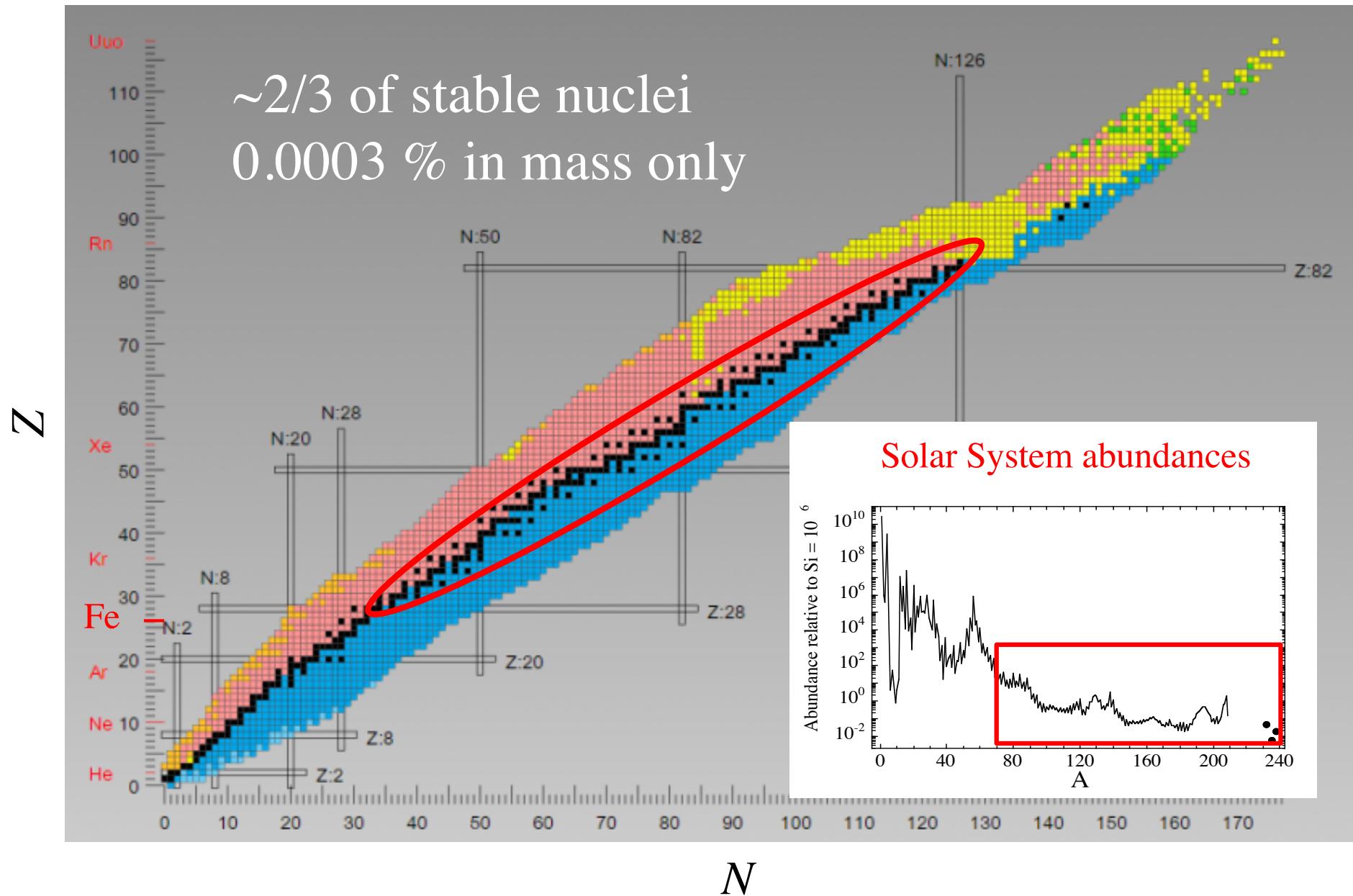
Based upon  $^{12}\text{C}$ . ( ) indicates the mass number of the most stable isotope. For a description and the most accurate values and uncertainties, see J. Phys. Chem. Ref. Data, **26** (5), 1239 (1997).

March 1999

# L'origine des éléments plus lourds que le Fer



# Nucleosynthesis of elements heavier than iron



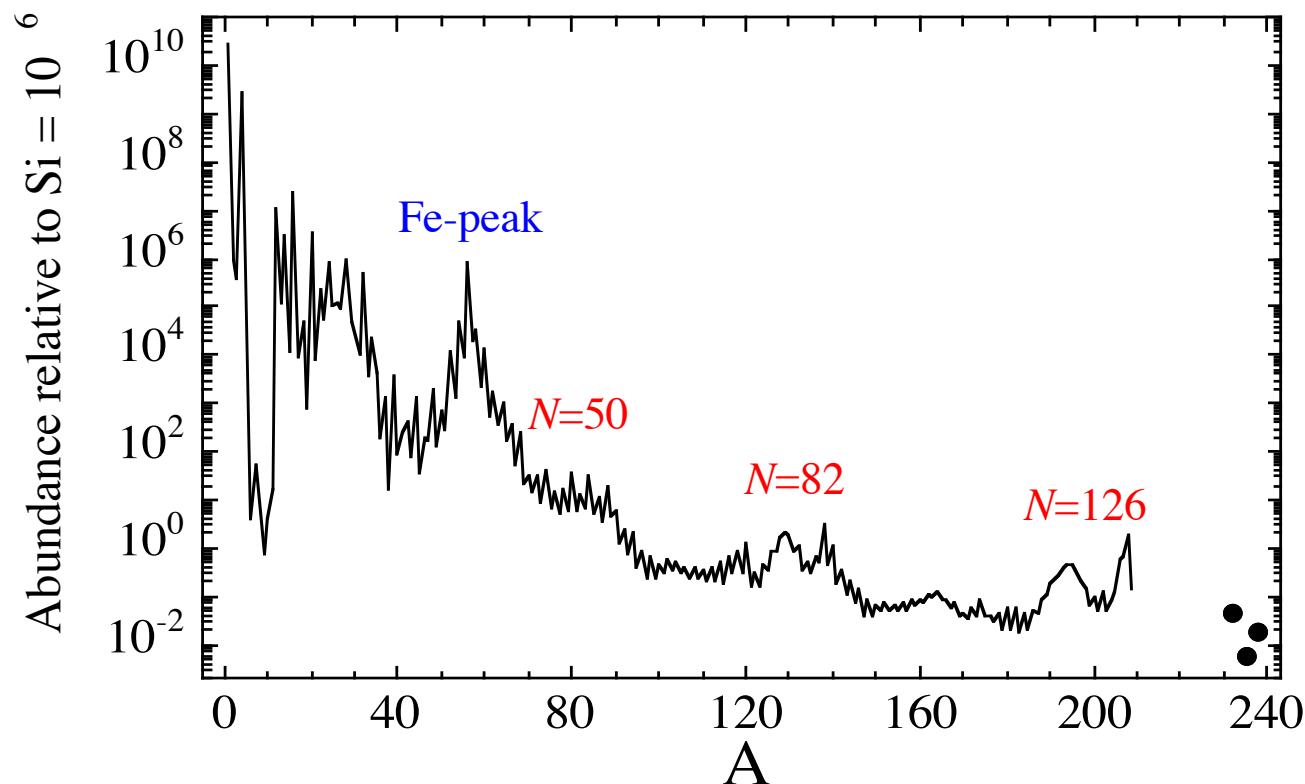
## The concept of synthesis by neutron captures

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

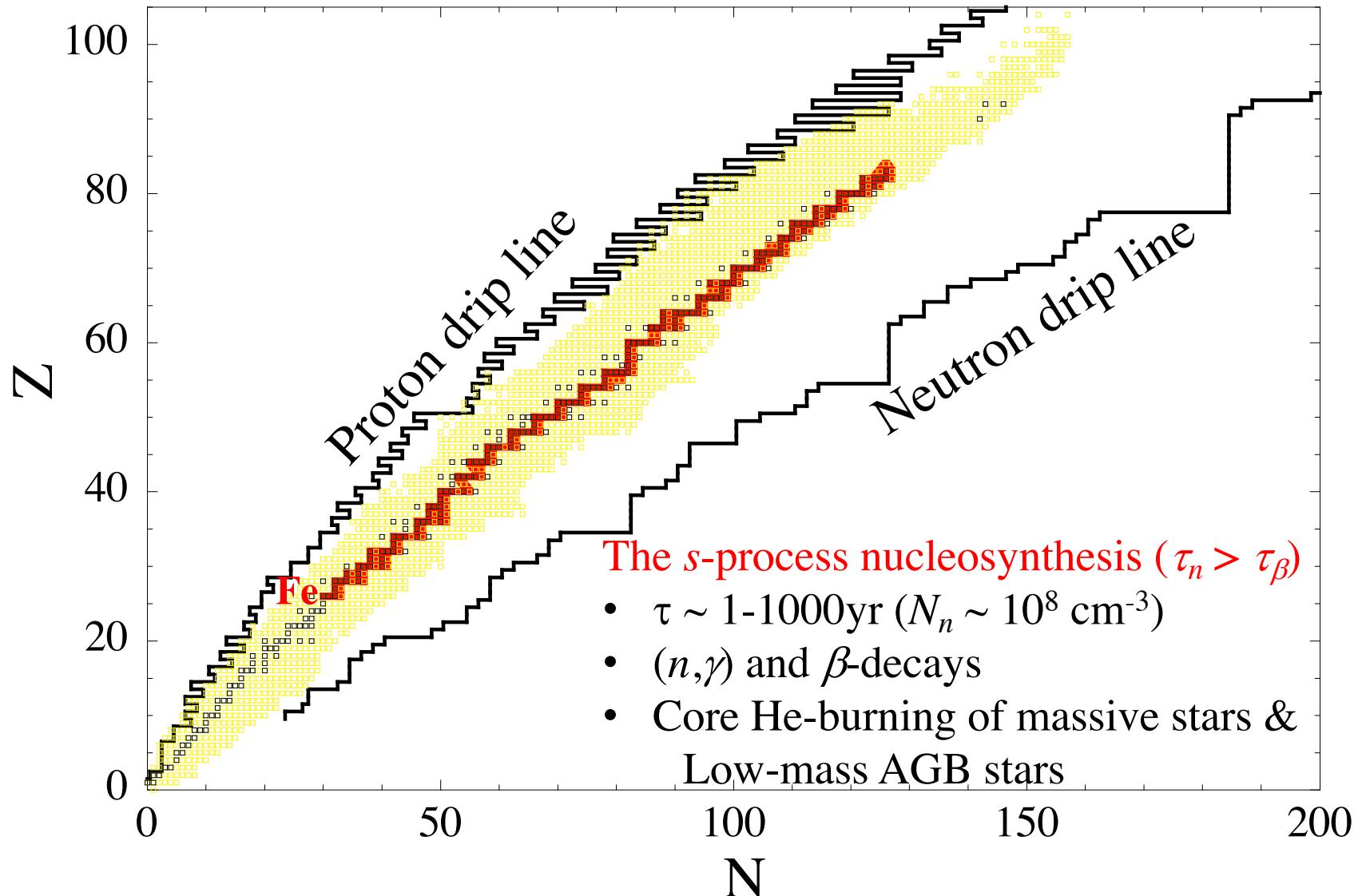
→ Charged-particle captures are inefficient to produce the bulk galactic  $A > 56$  nuclides

→ Use of NEUTRONS instead !

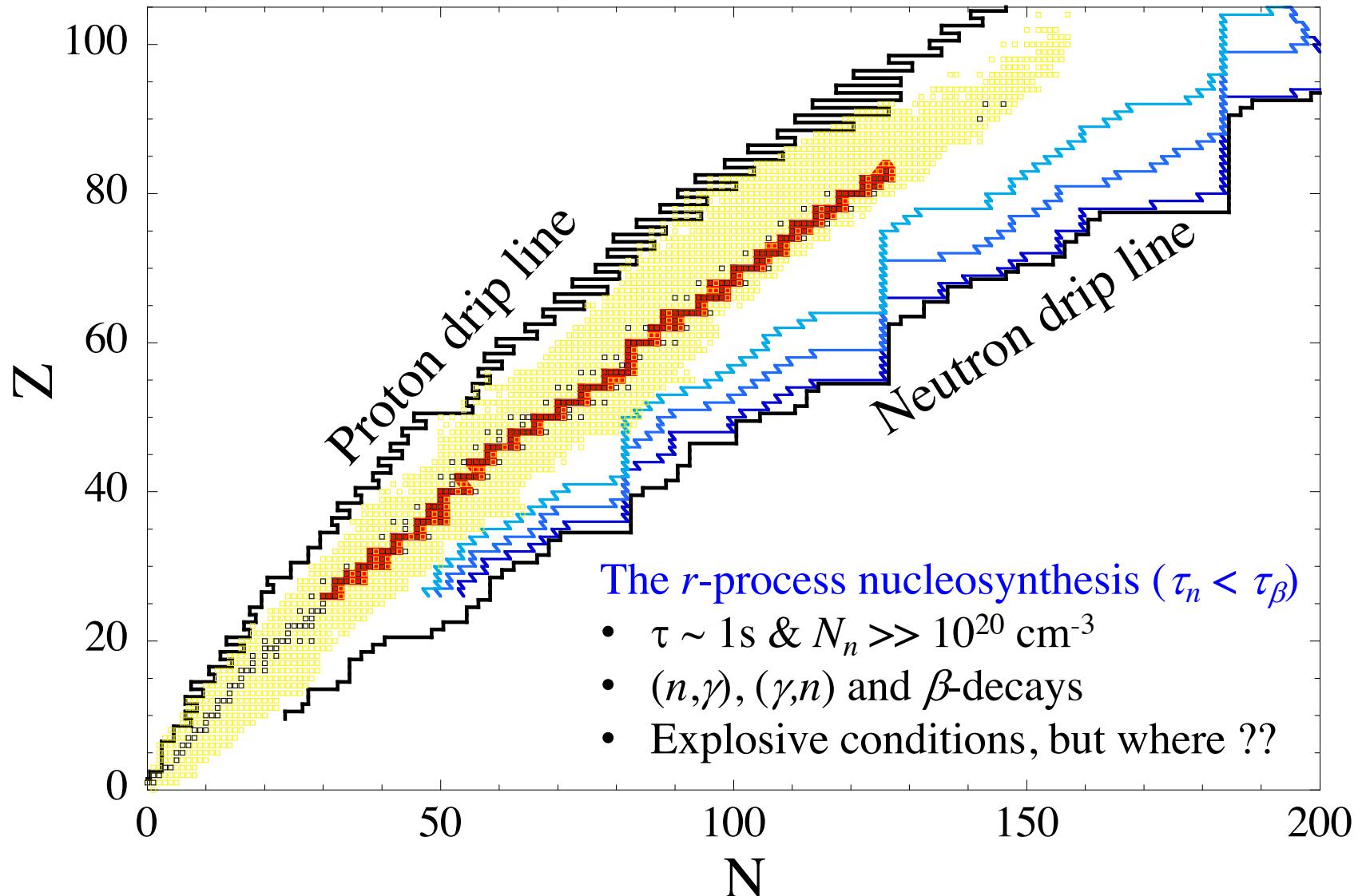
- No coulomb barrier
- Natural explanation for the peaks observed in the solar system abundances at neutron magic numbers  $N=50, 82$  and  $126$



# The *s*-process nucleosynthesis

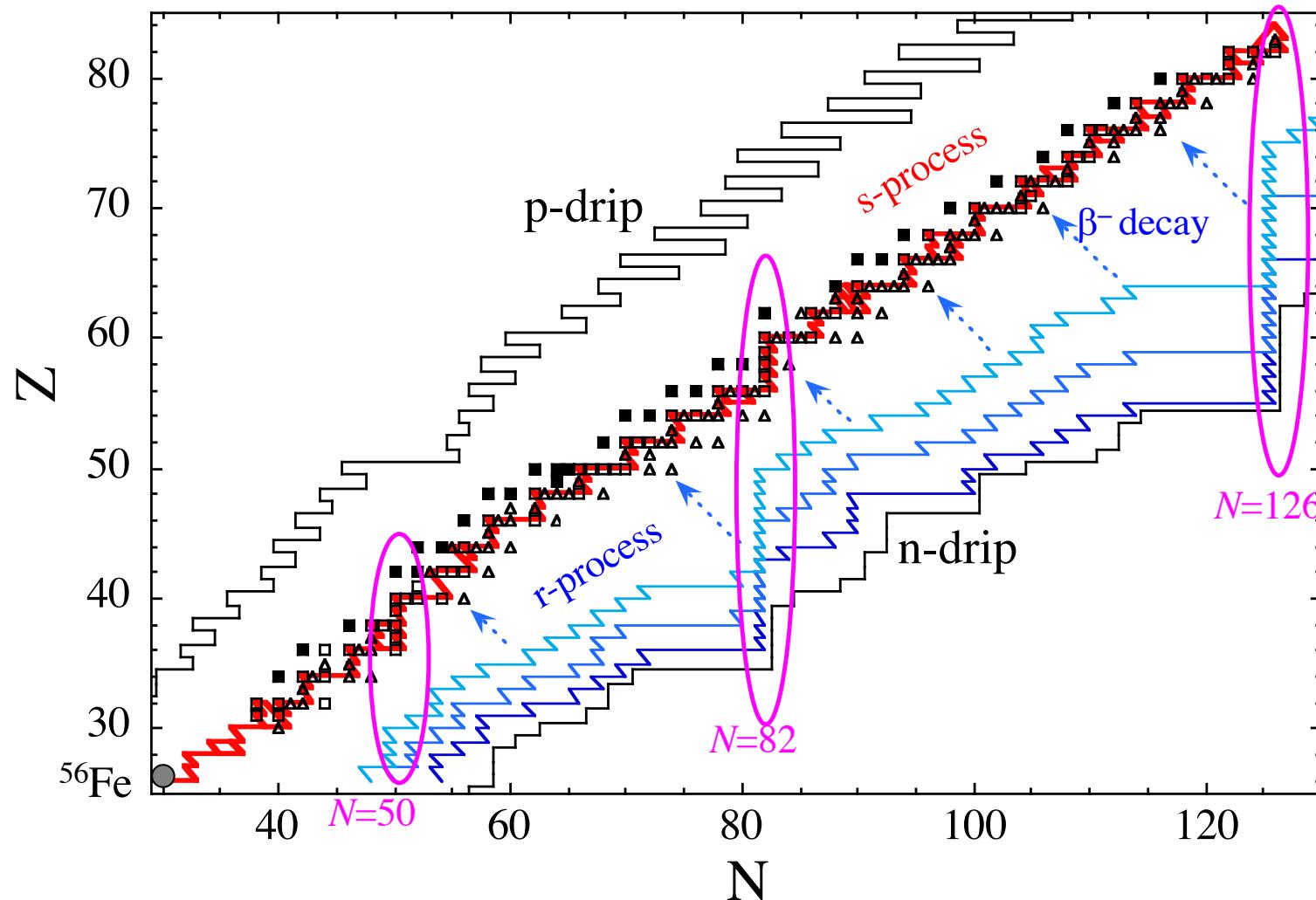


# The *r*-process nucleosynthesis



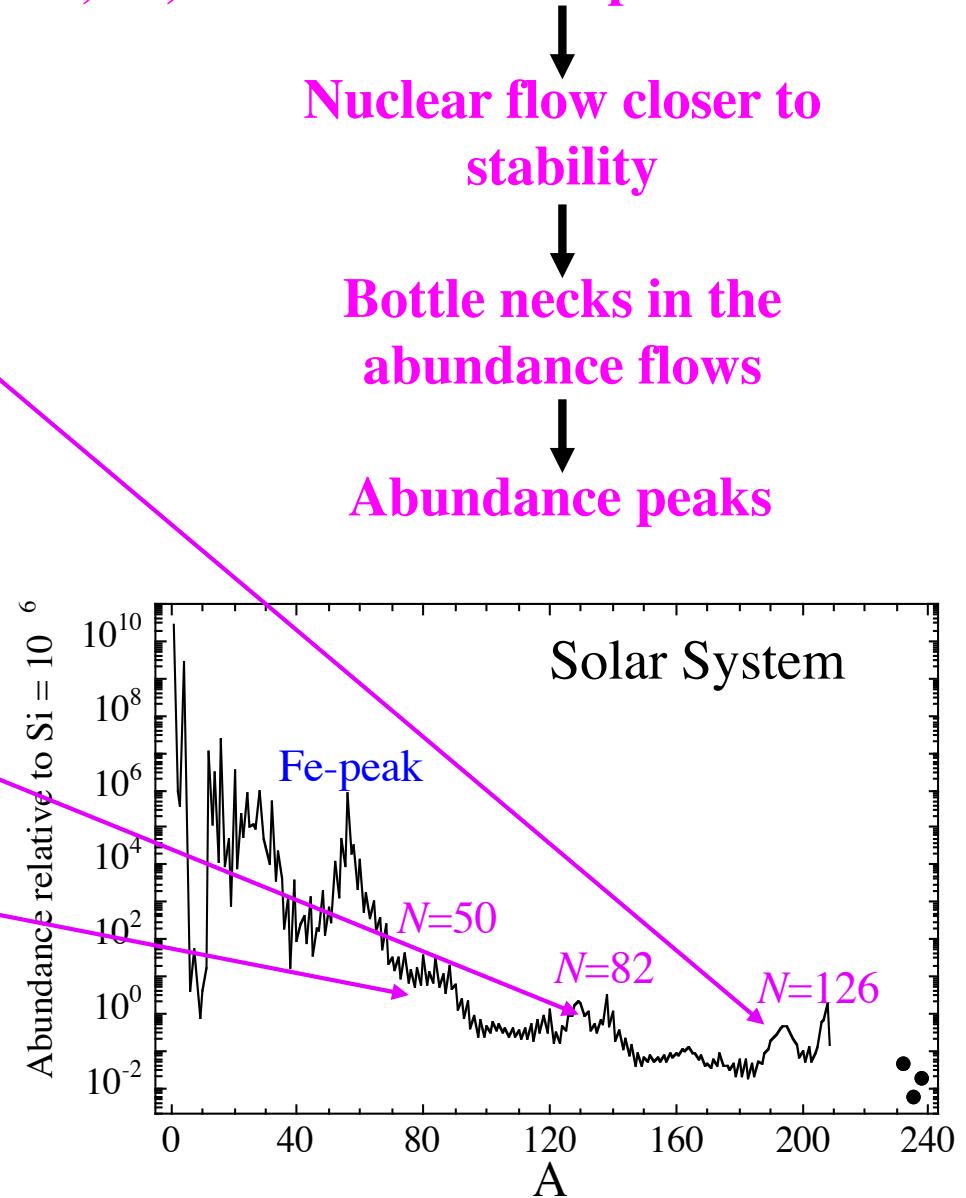
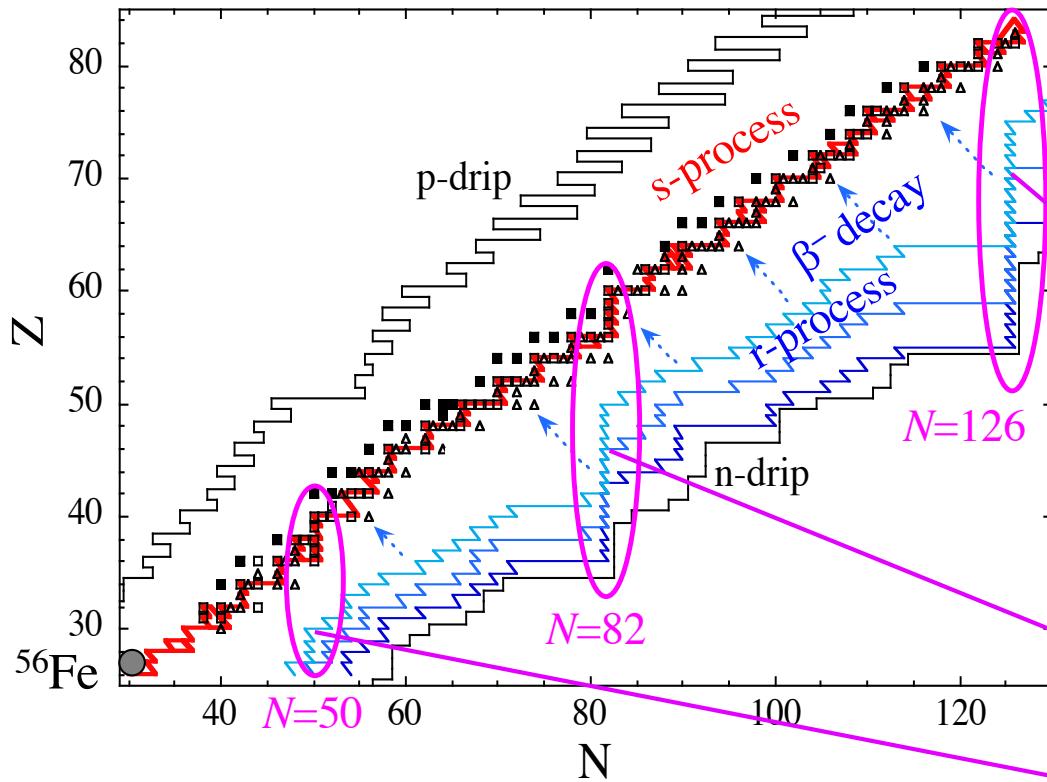
# A schematic representation of the s- and r-processes

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



# A schematic representation of the s- and r-processes

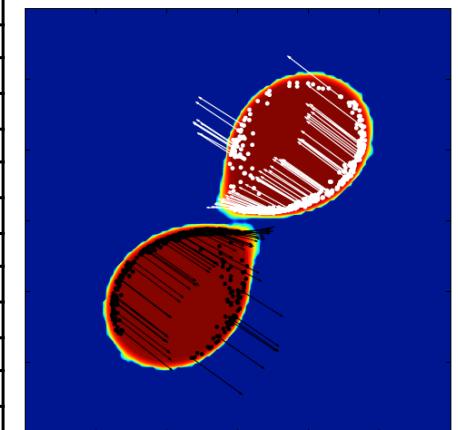
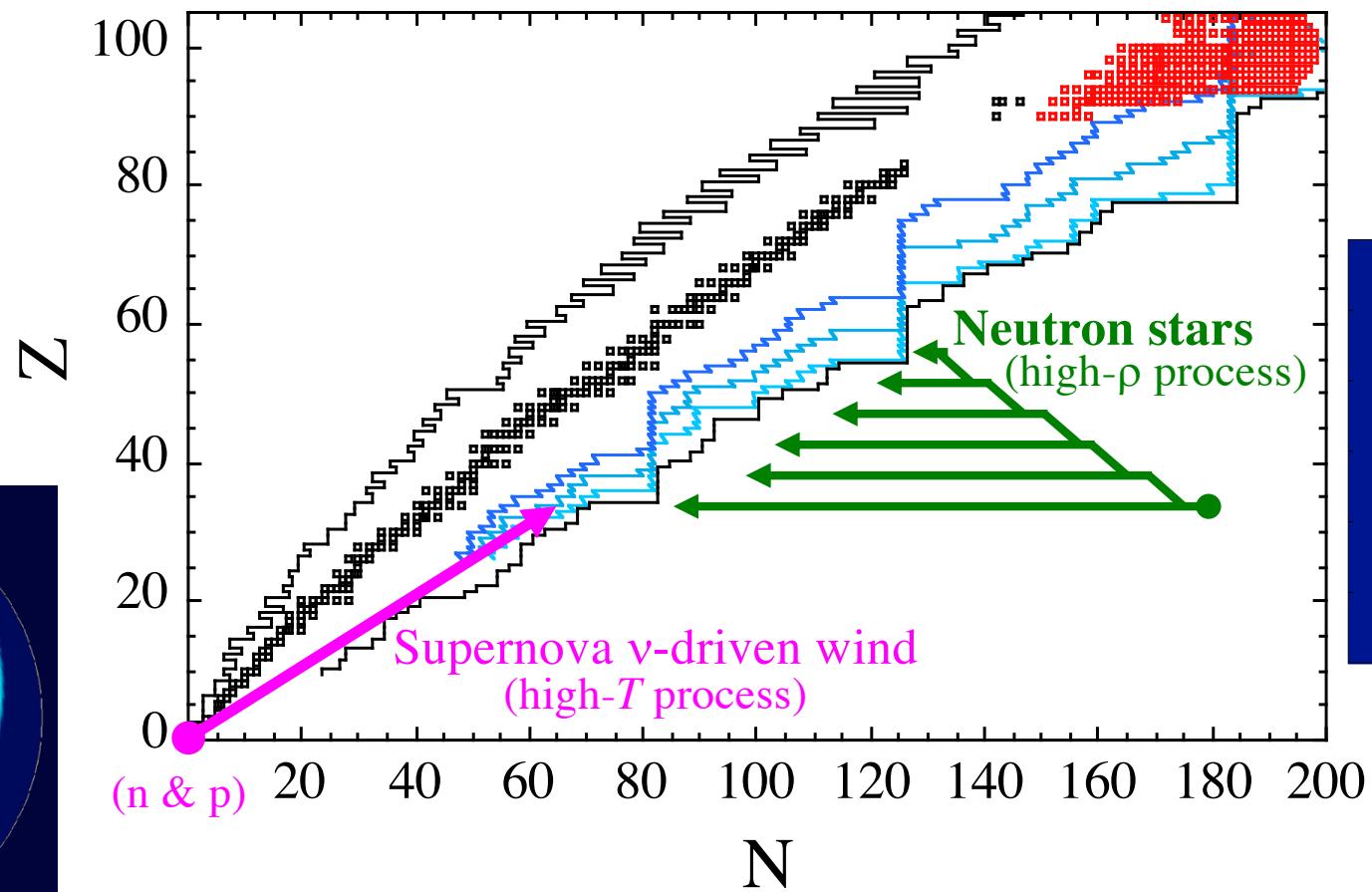
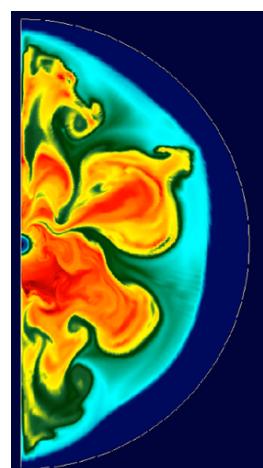
Closed shells at neutron magic numbers  $N=50, 82, 126 \rightarrow$  slow n-capture



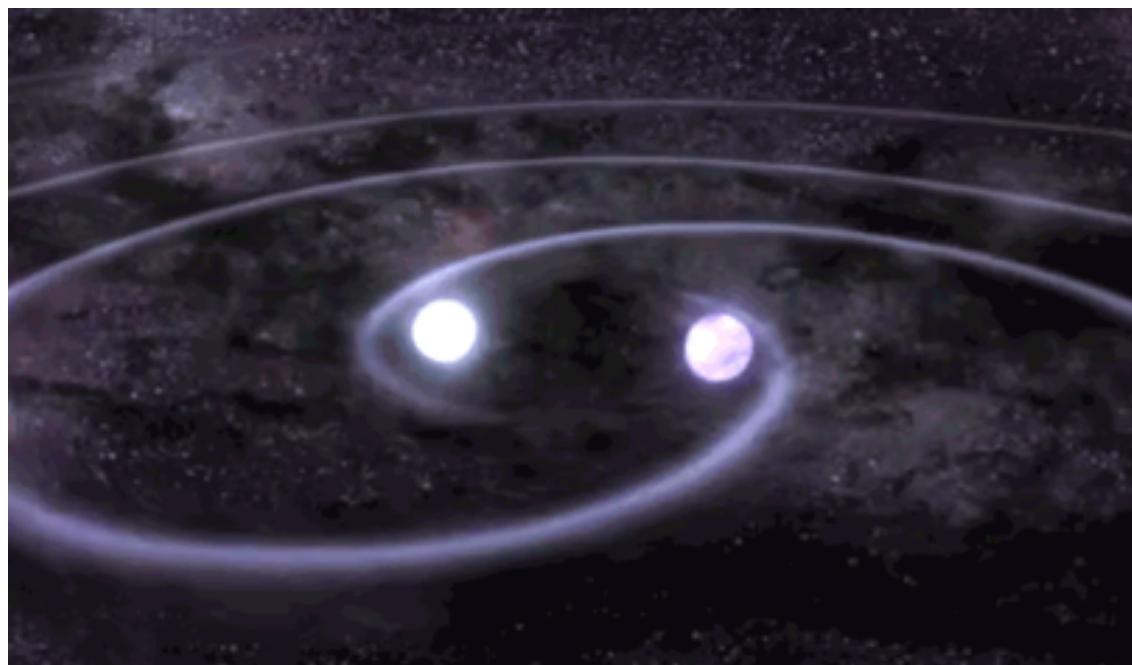
Nuclear flow closer to stability  
Bottle necks in the abundance flows  
Abundance peaks

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

one of the still unsolved puzzles in nuclear astrophysics

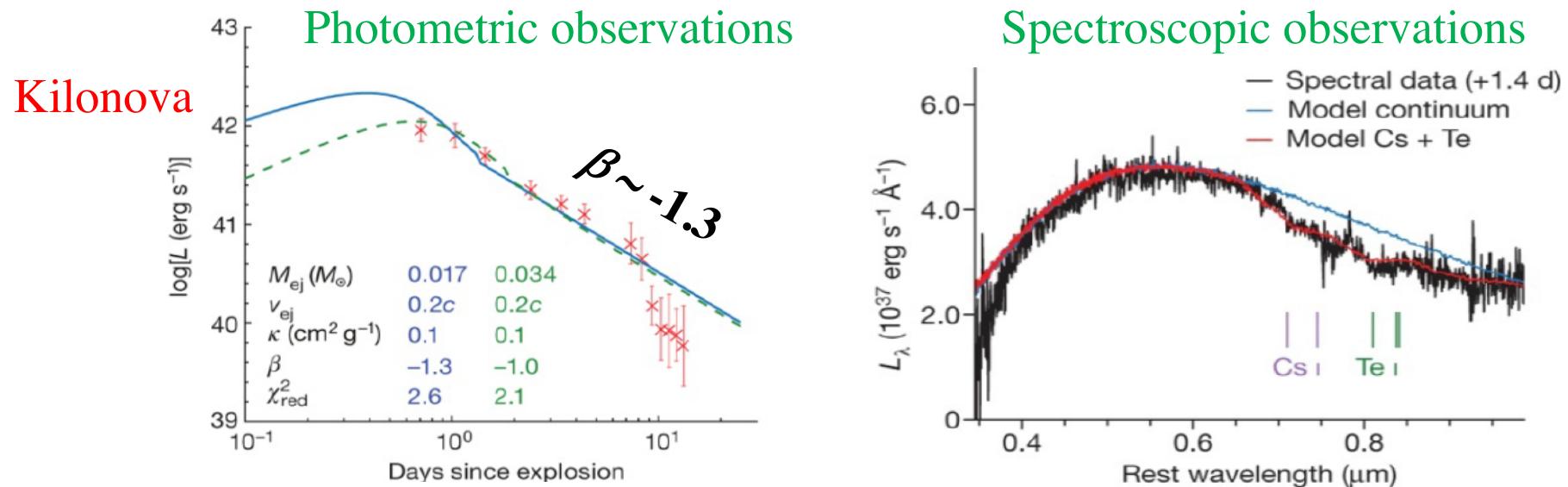


**New observational insight thanks  
to the observation of  
GW170817 binary NS merger  
and its optical counterpart  
AT2017gfo**



# The first analysis of the GW170817 light curve

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



- 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 :

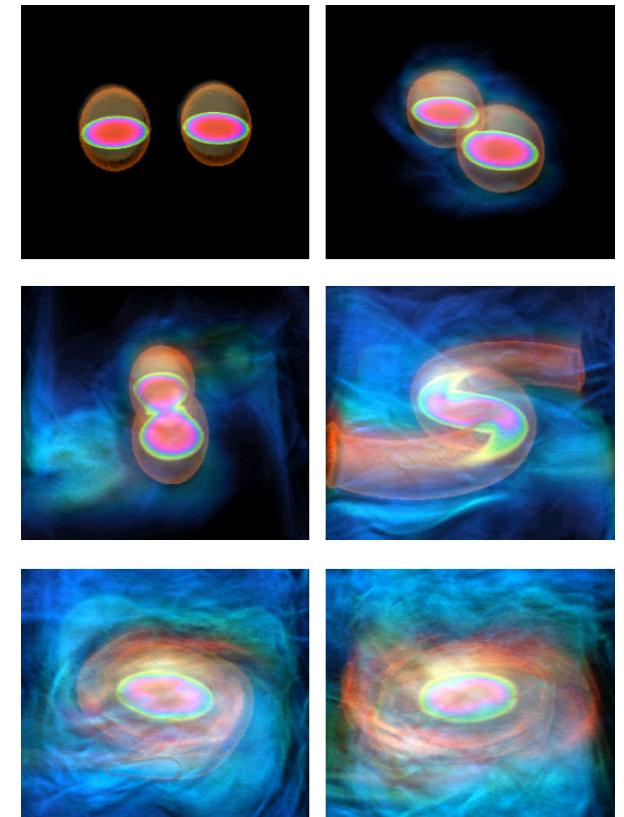
- NS-NS systems: symmetric (e.g 1.35; 1.45; 1.6; 1.75  $M_\odot$ )  
asymmetric (e.g 1.2–1.5  $M_\odot$ ; 1.2-1.8 $M_\odot$ ; 1.35-1-8 $M_\odot$ )
- NS-BH systems: 1.1-1.45 $M_\odot$  NS with 2.3-7 $M_\odot$  BH (and spin  $\alpha_{\text{BH}}=0-0.9$ )
- 40 different EoS with different stiffness (i.e.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

→ different amounts of mass ejected

$$M = 10^{-3} - 2 \cdot 10^{-2} M_\odot$$

→ different ejecta velocities

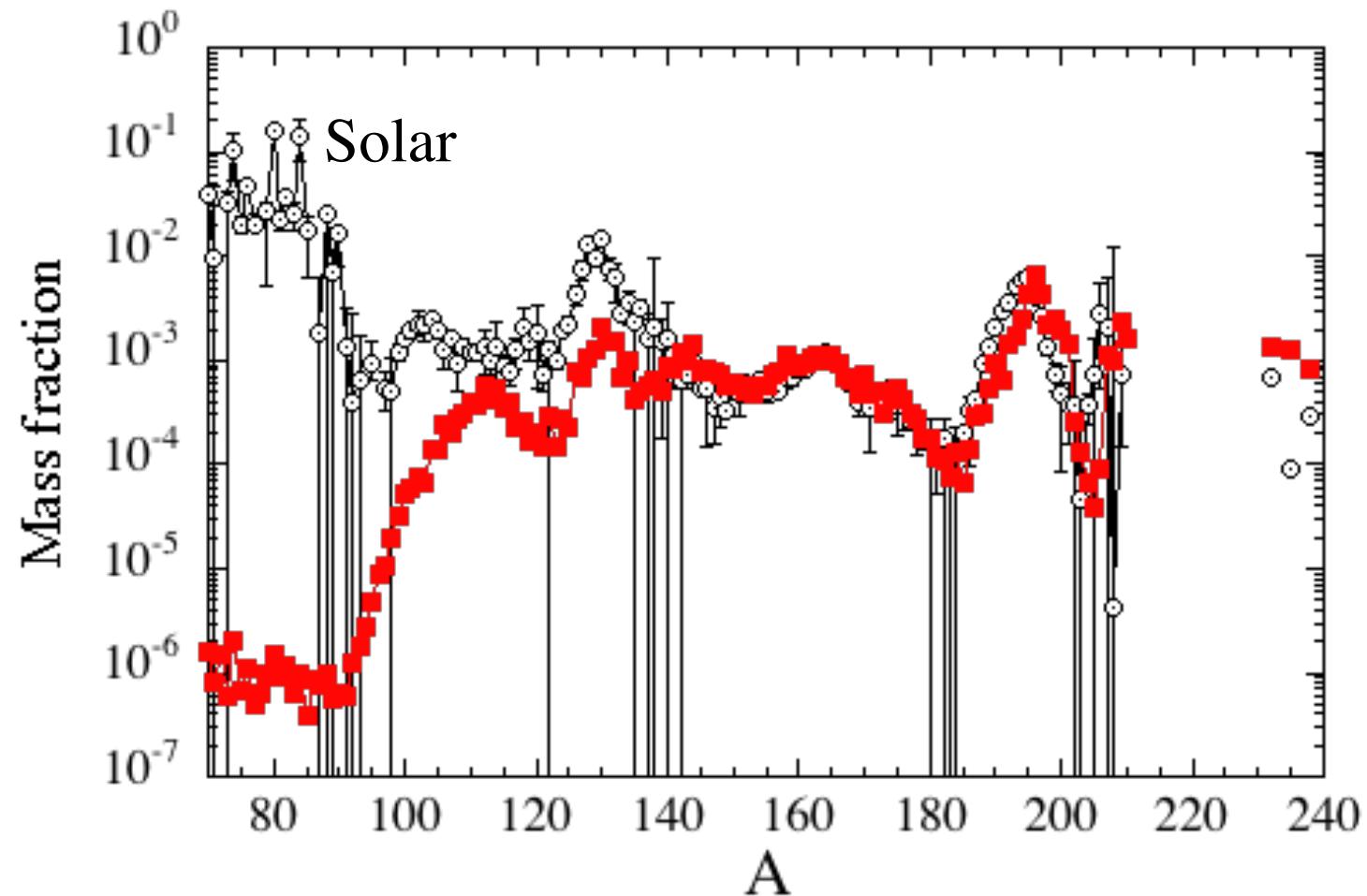
→ different luminosities of the optical  
transients  $3 - 14 \cdot 10^{41}$  erg/s

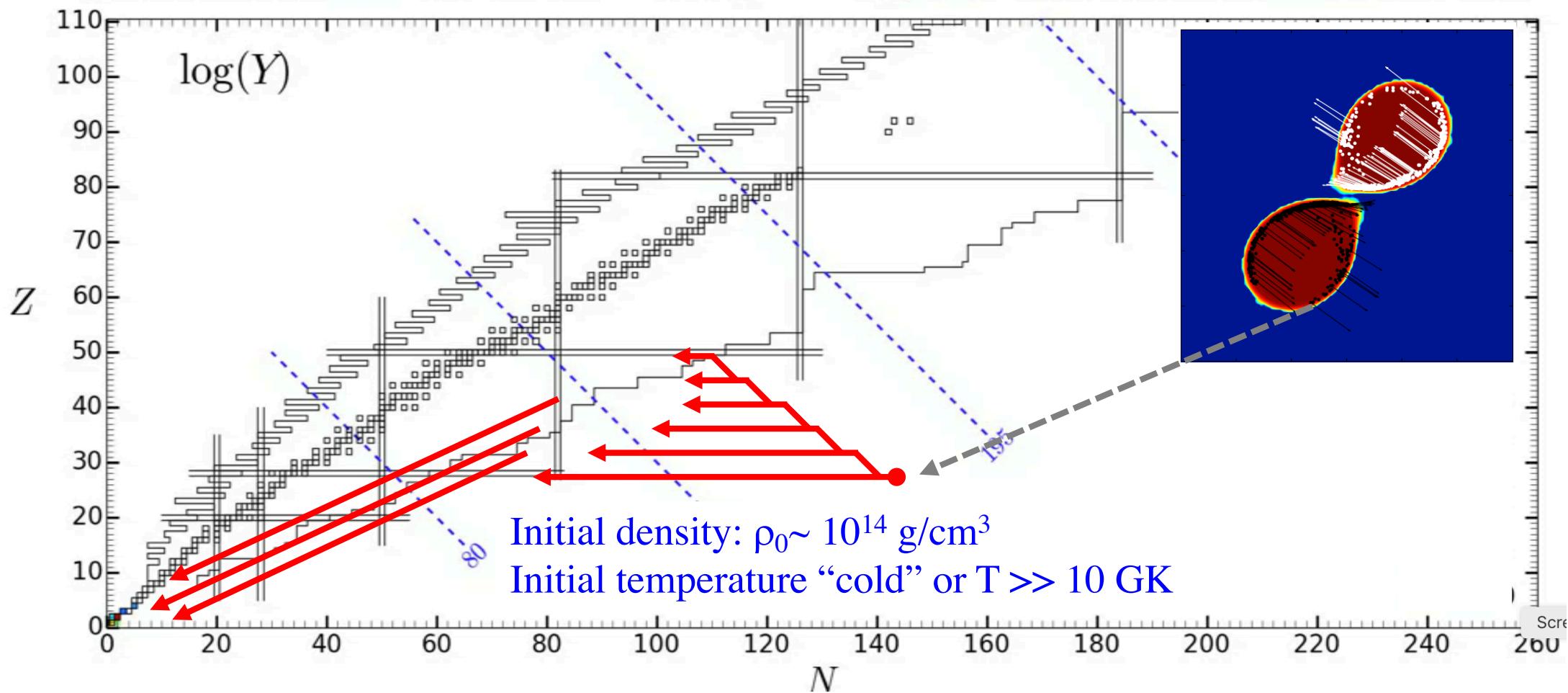


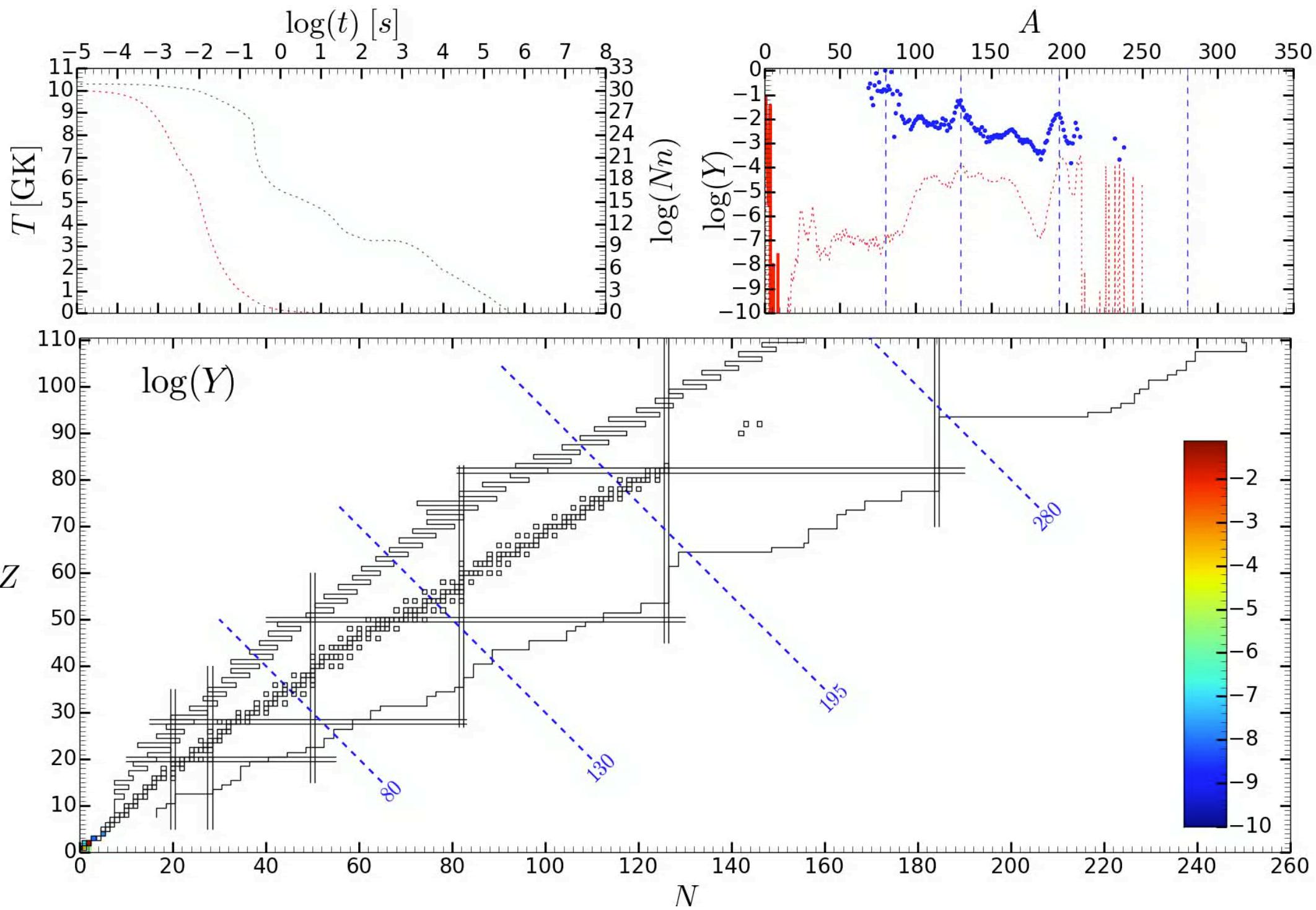
(see also e.g. Rosswog et al. 2013, 2014)

# 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 ( $A > 130-140$ )

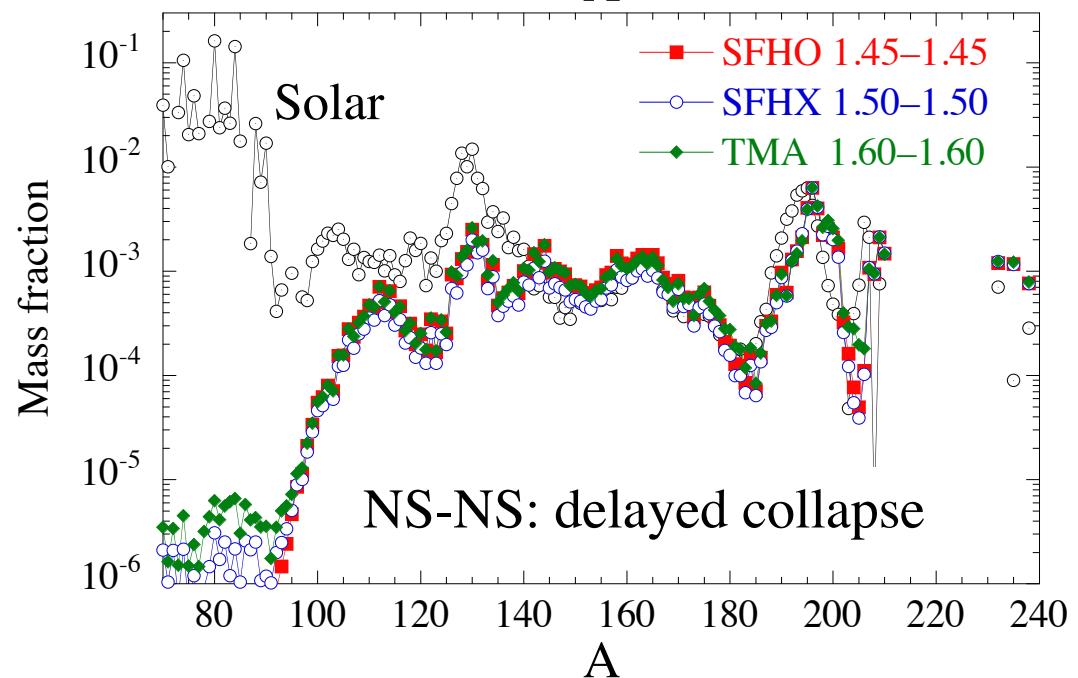
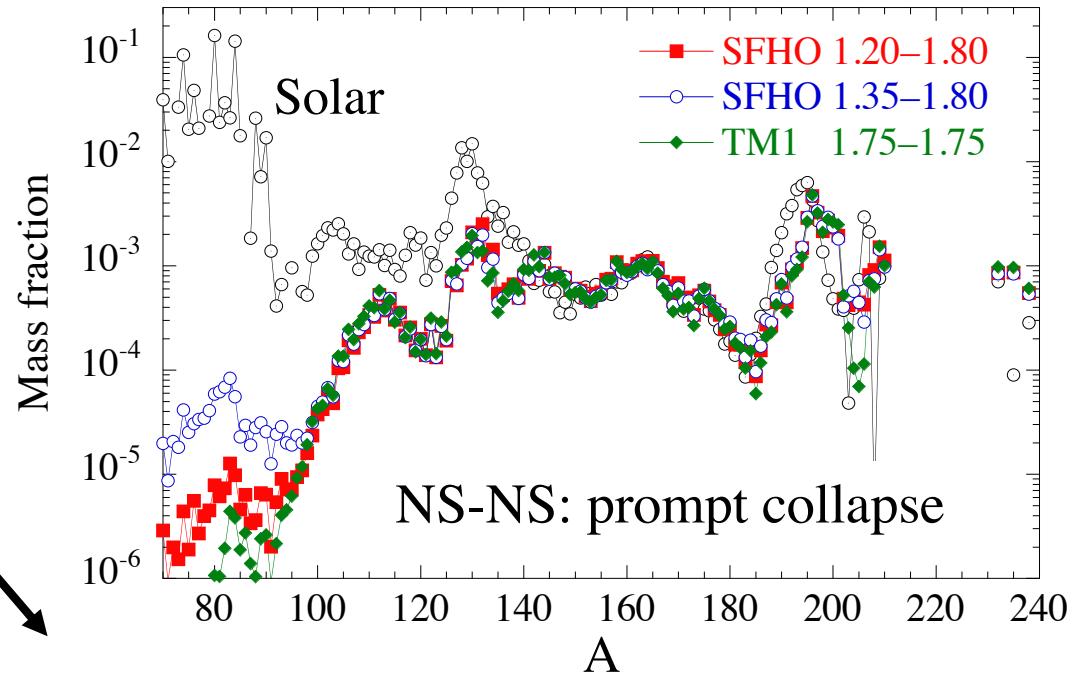
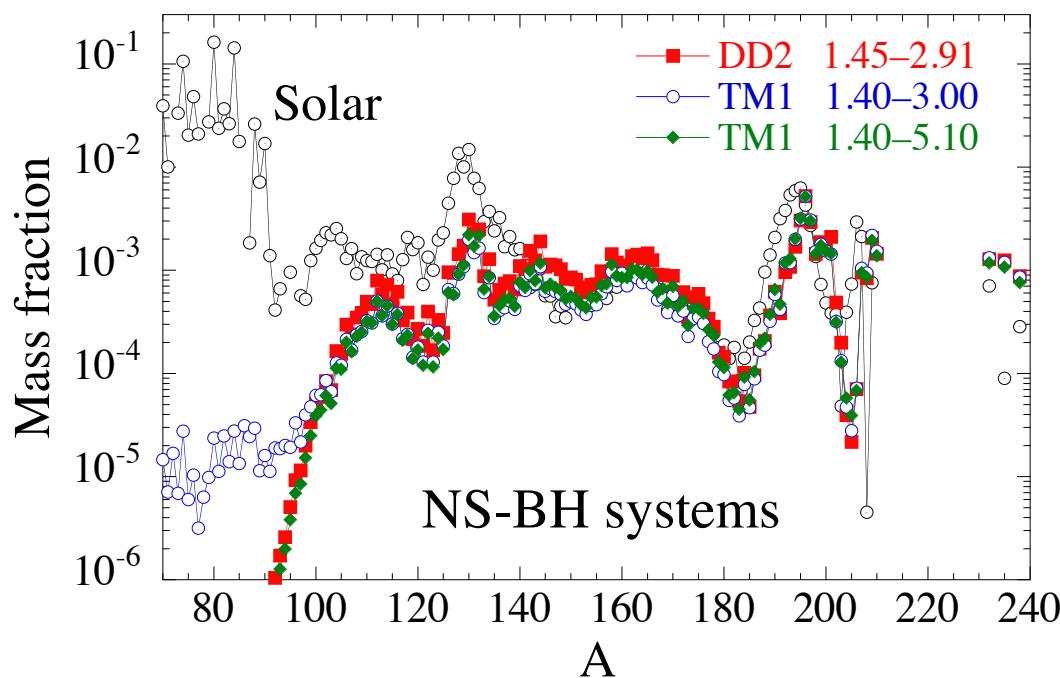






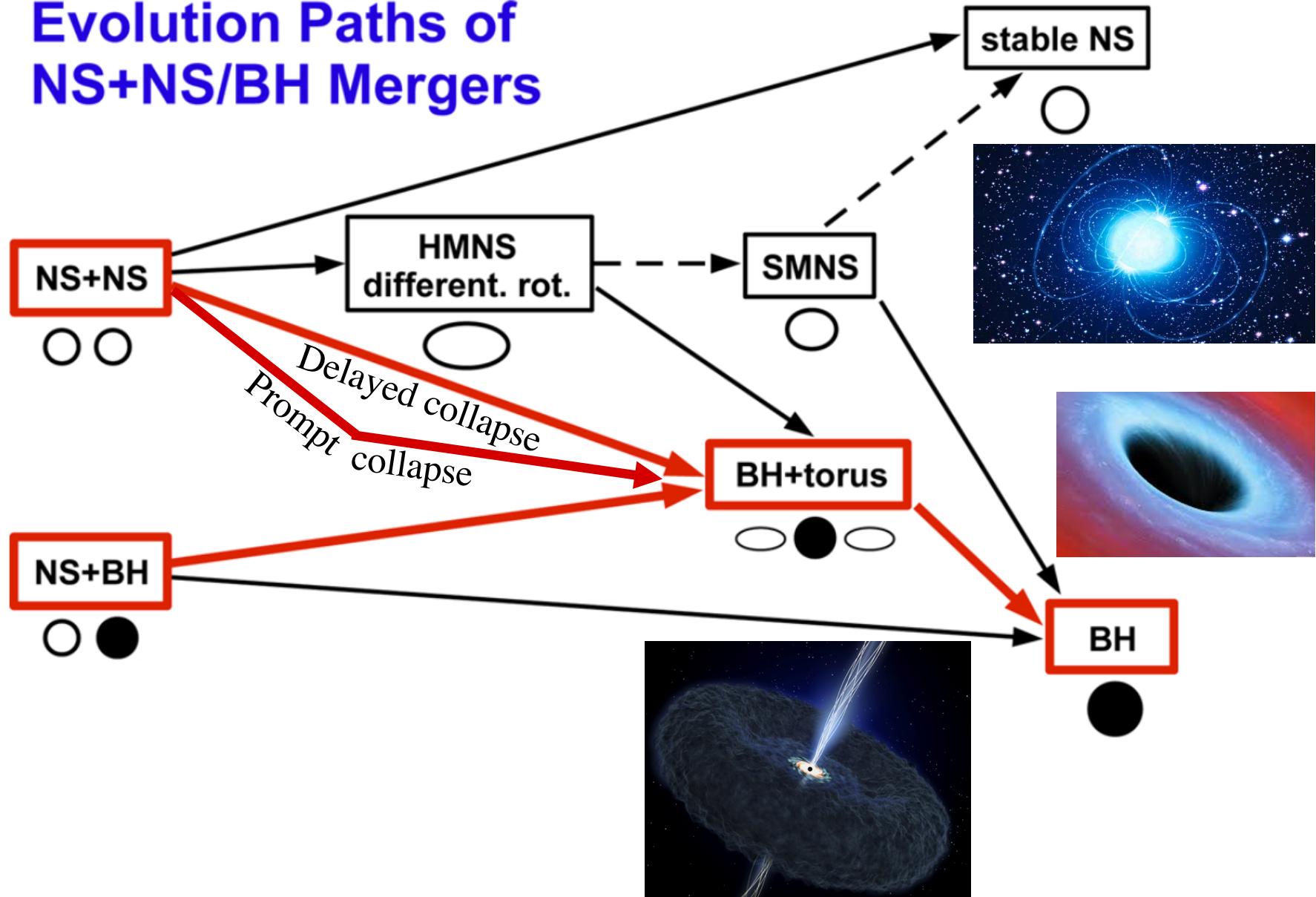
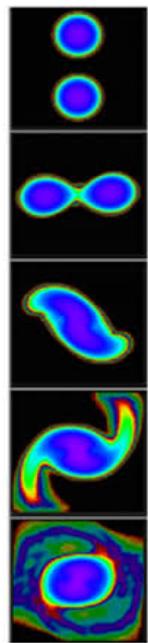
AND similar predictions, be it

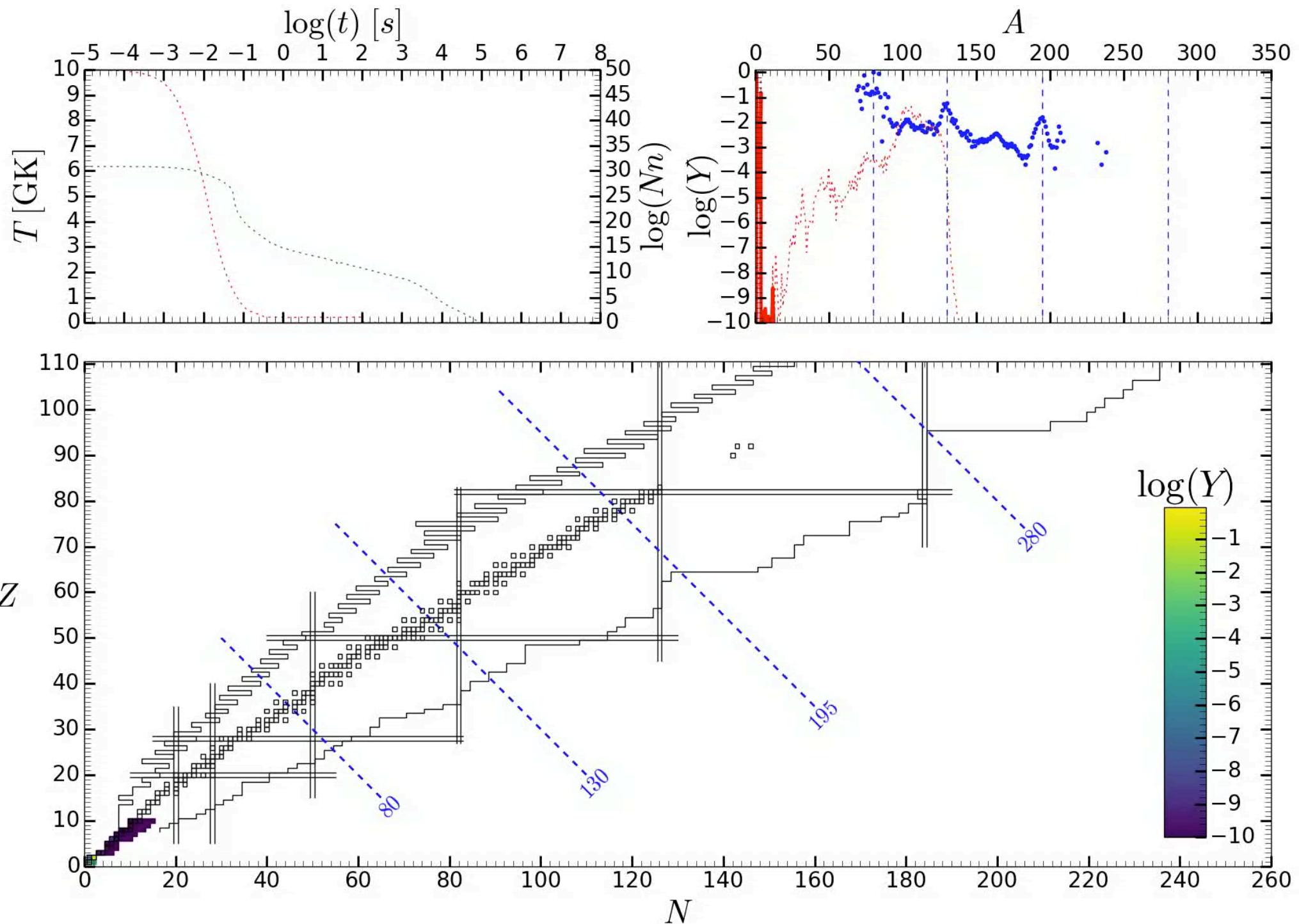
- a prompt collapse of NS-NS
- a delayed collapse of NS-NS
- a NS-BH system

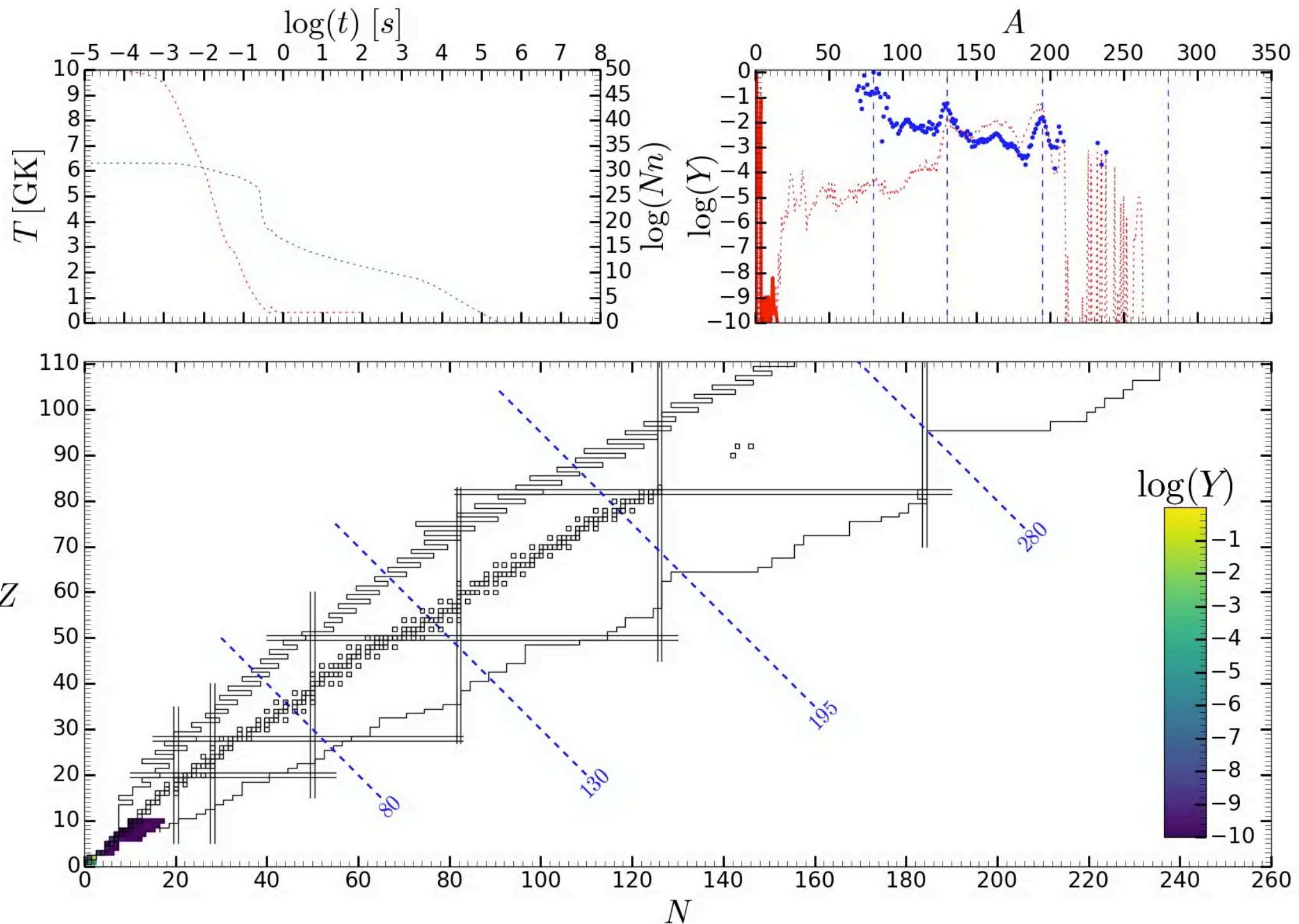


NS-NS or NS-BH mergers are robust site for the r-process ( $A>140$ )

# Evolution Paths of NS+NS/BH Mergers





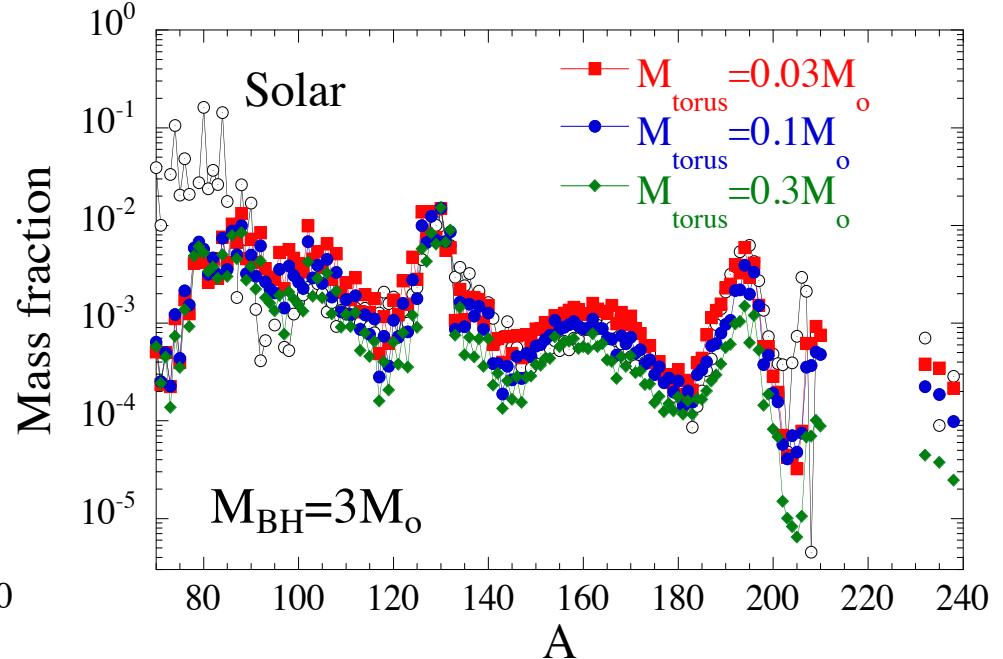
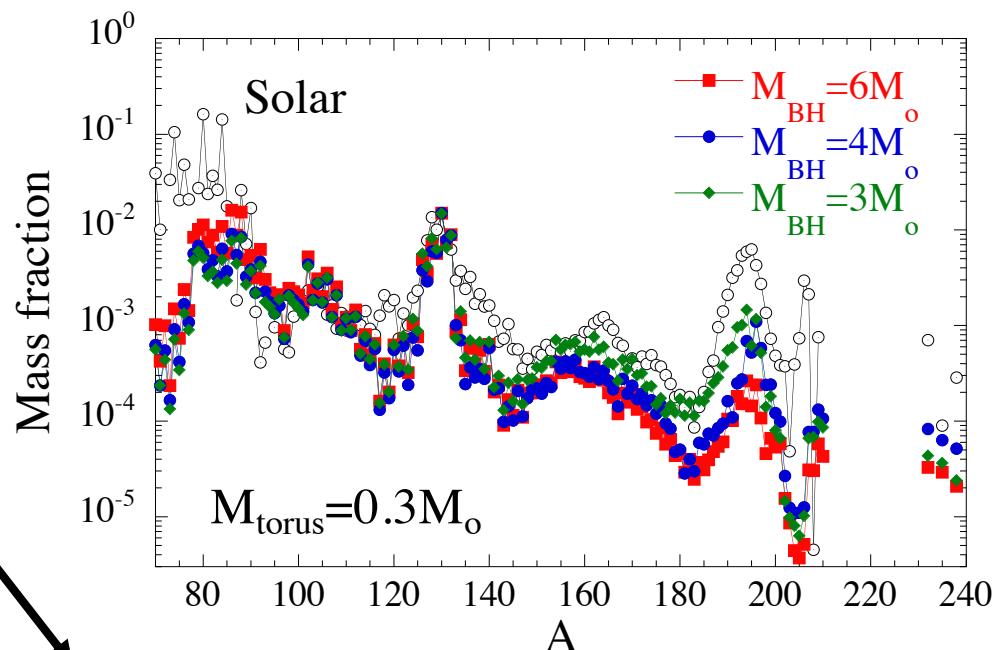
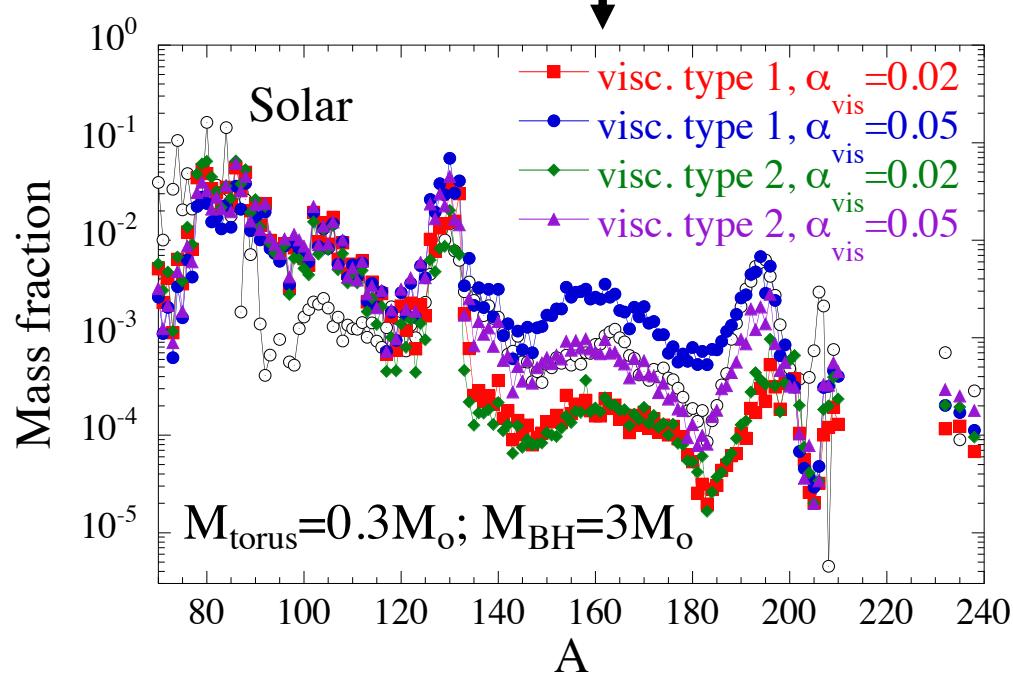


## Different hydrodynamical simulations

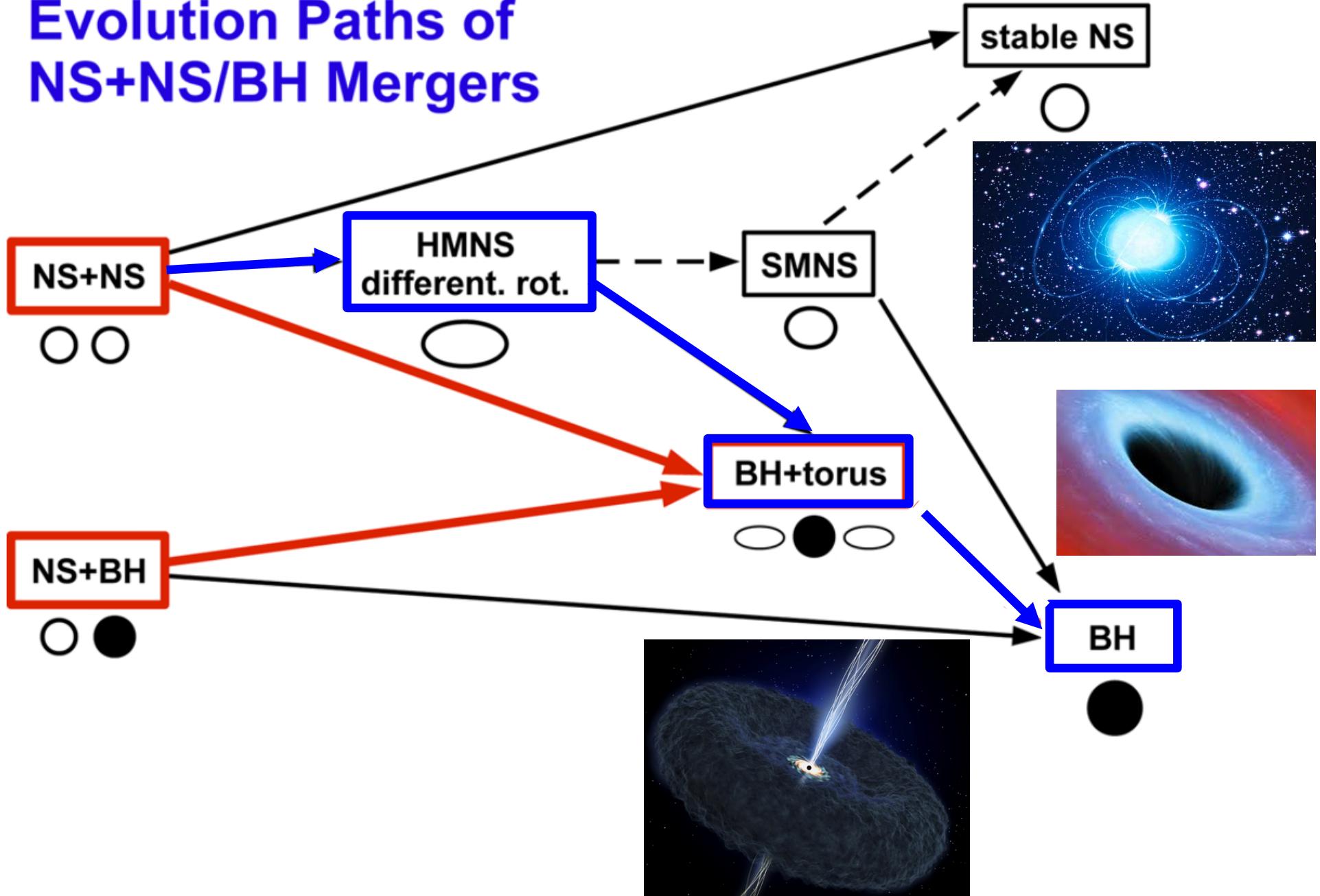
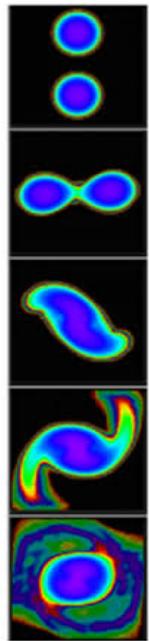
(Just, et al. 2015; Wu et al. 2016)

Abundance predictions sensitive to

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

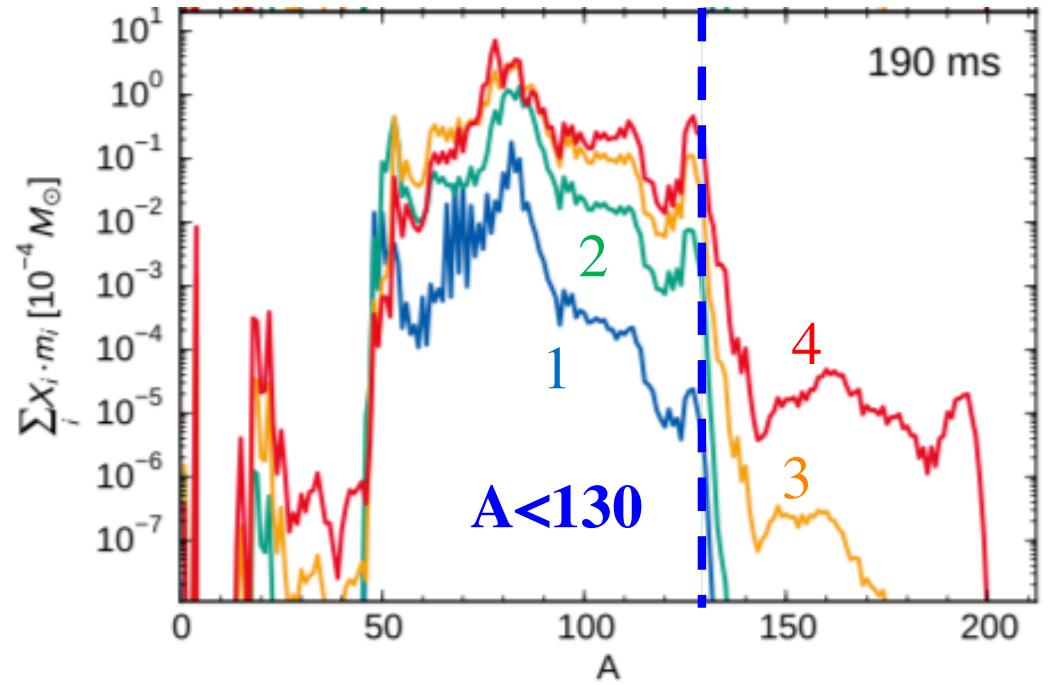
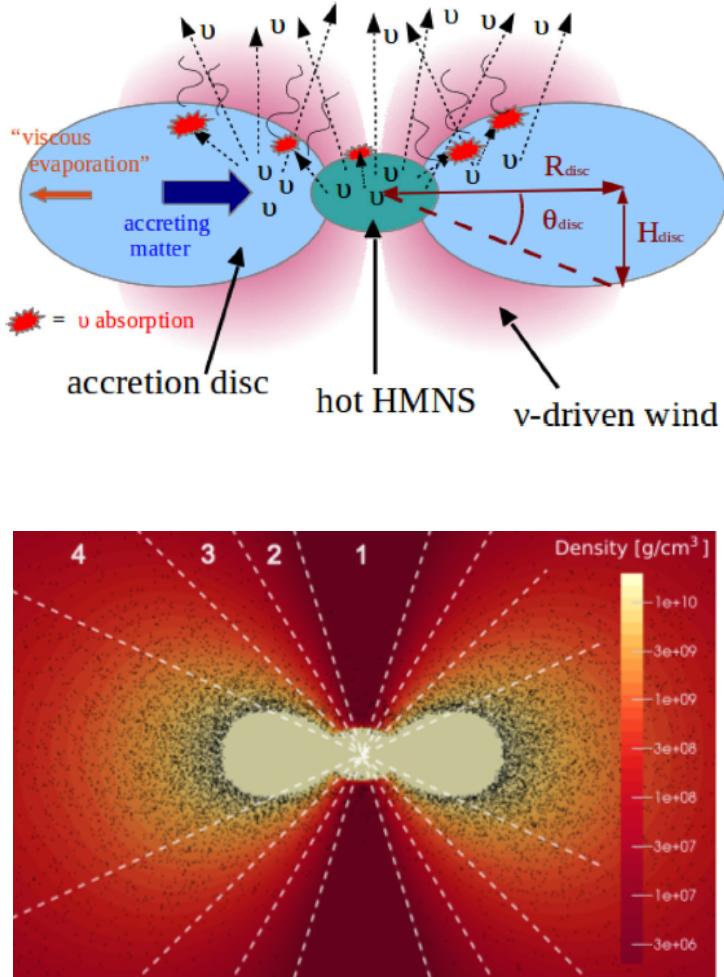


# Evolution Paths of NS+NS/BH Mergers



# Composition of the matter ejected from a HMNS

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

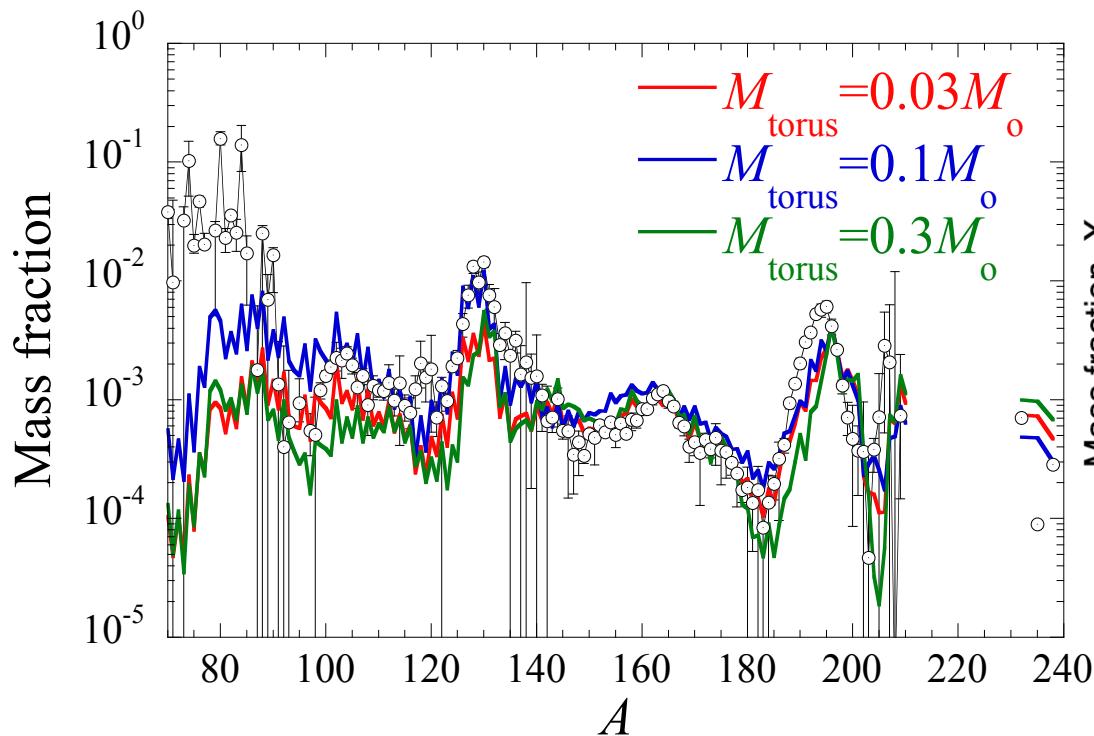


Nucleosynthesis of  $A < 130$  r-nuclei  
though depends on the lifetime of the  
HMNS and the polar angle.

# Final abundance distributions from Binary Neutron Star Mergers

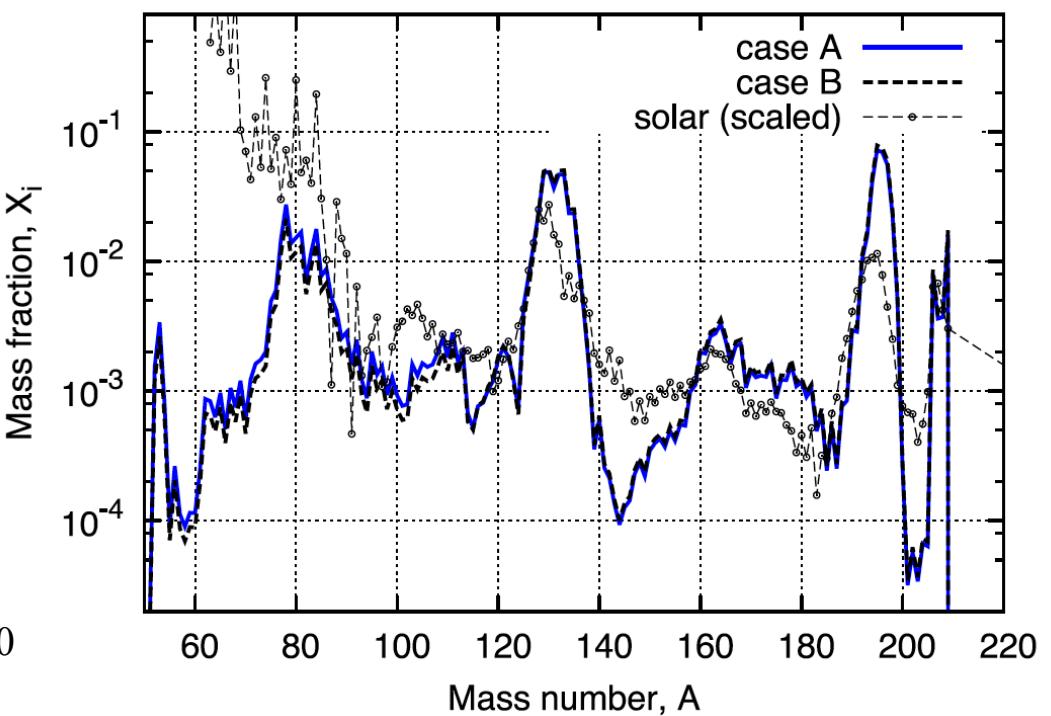
## Dynamical + BH-Torus system

Just et al. (2015)



## Dynamical + HMNS system

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

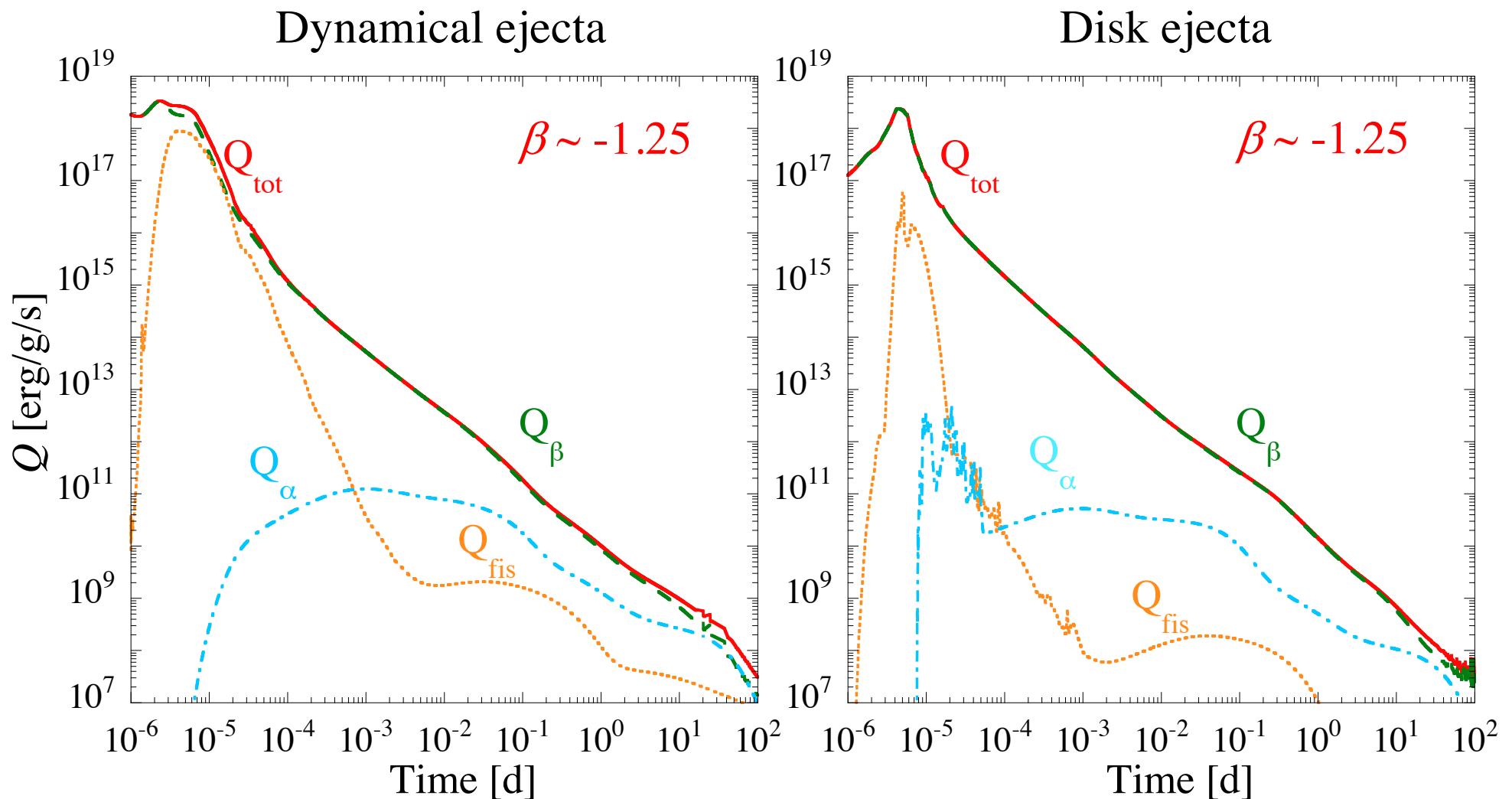


Robust production of all  $A \geq 90$   $r$ -nuclei with a rather solar distribution

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

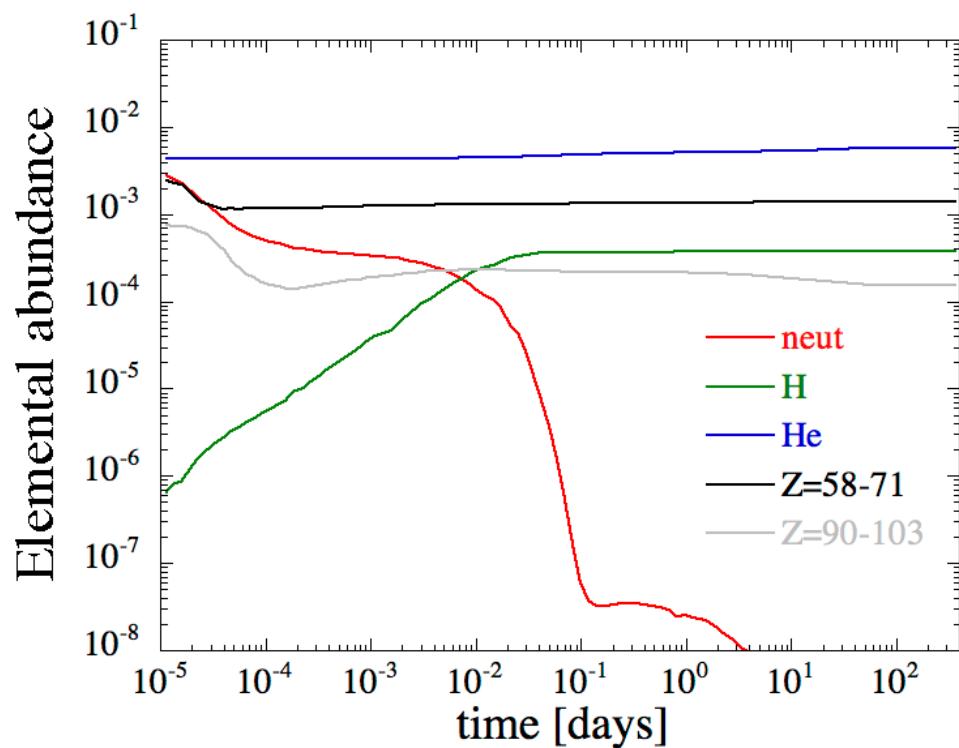
## Total radioactive heating rate of the resulting Kilonova at late times

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

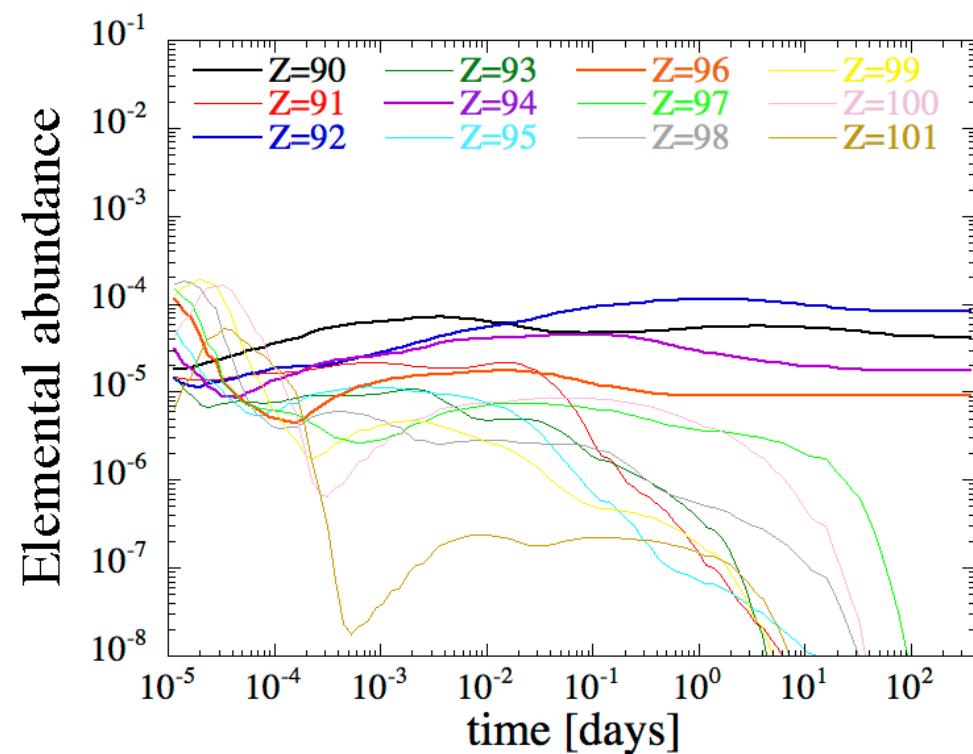


# Elemental abundances expected in the dynamical ejecta

## Dynamical ejecta



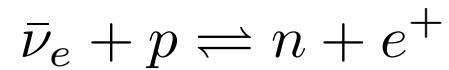
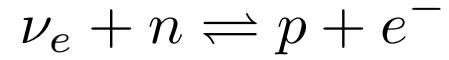
Significant production of lanthanides  
and actinides  
(if neutrino interactions are negligible)



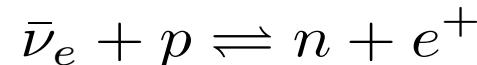
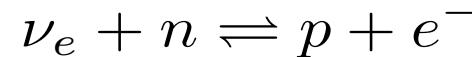
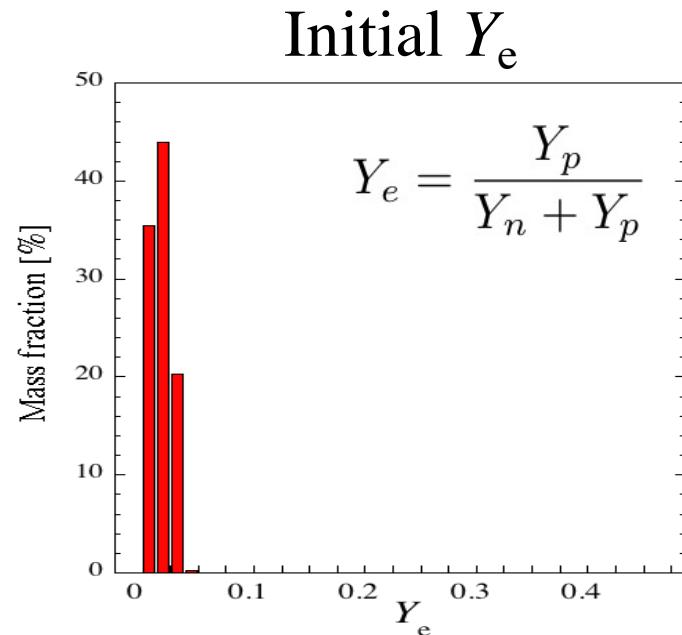
Very much dependent on the  
description of fission processes  
→ Possible production of  
superheavy elements ?

## Some open questions on the r-process in NSM remain ...

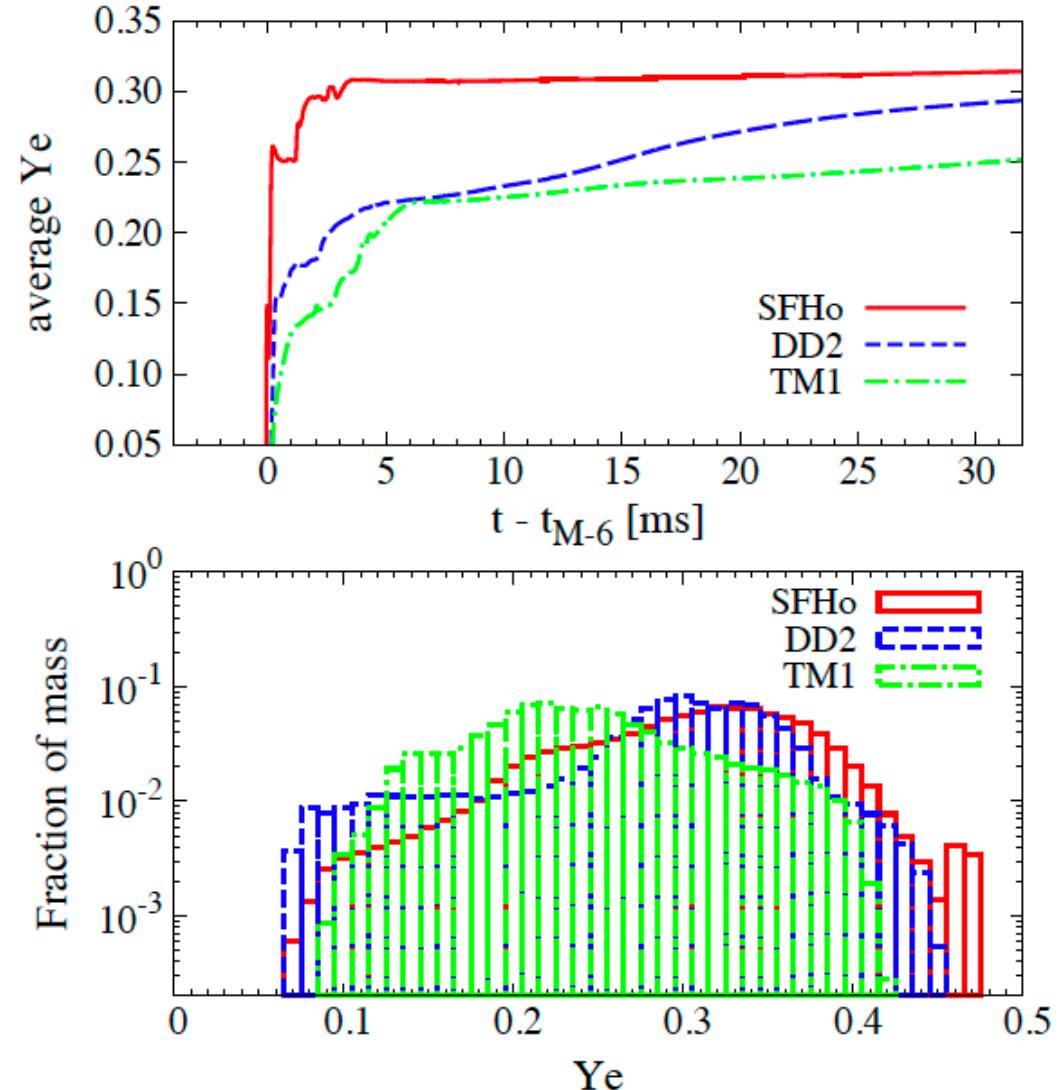
- Impact of neutrinos & EC on the neutron richness during dynamical ejection



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



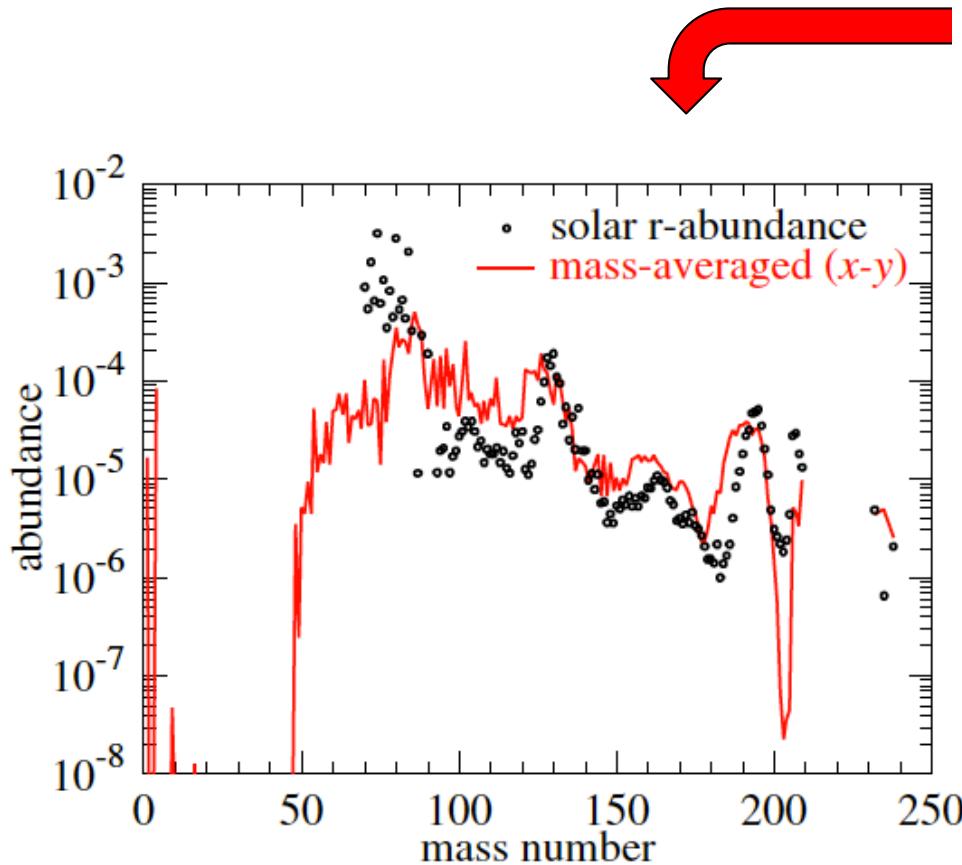
$$Y_e^{\nu\infty} \sim \frac{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr}}{L_{\nu_e} \langle E_{\nu_e} \rangle f_{\nu_e}^{mr} + L_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle f_{\bar{\nu}_e}^{mr}}$$



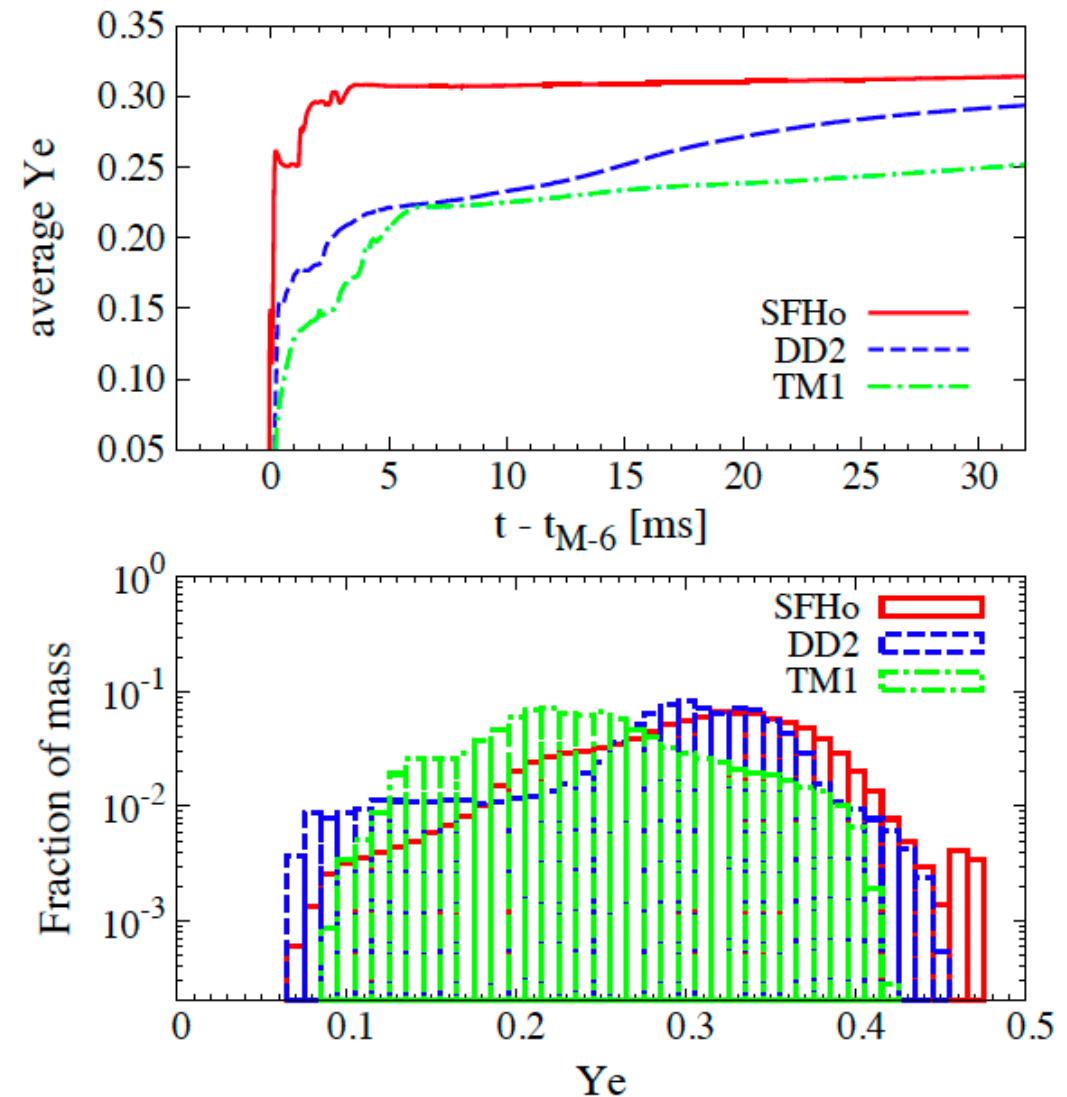
Also sensitive to the adopted EoS

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**



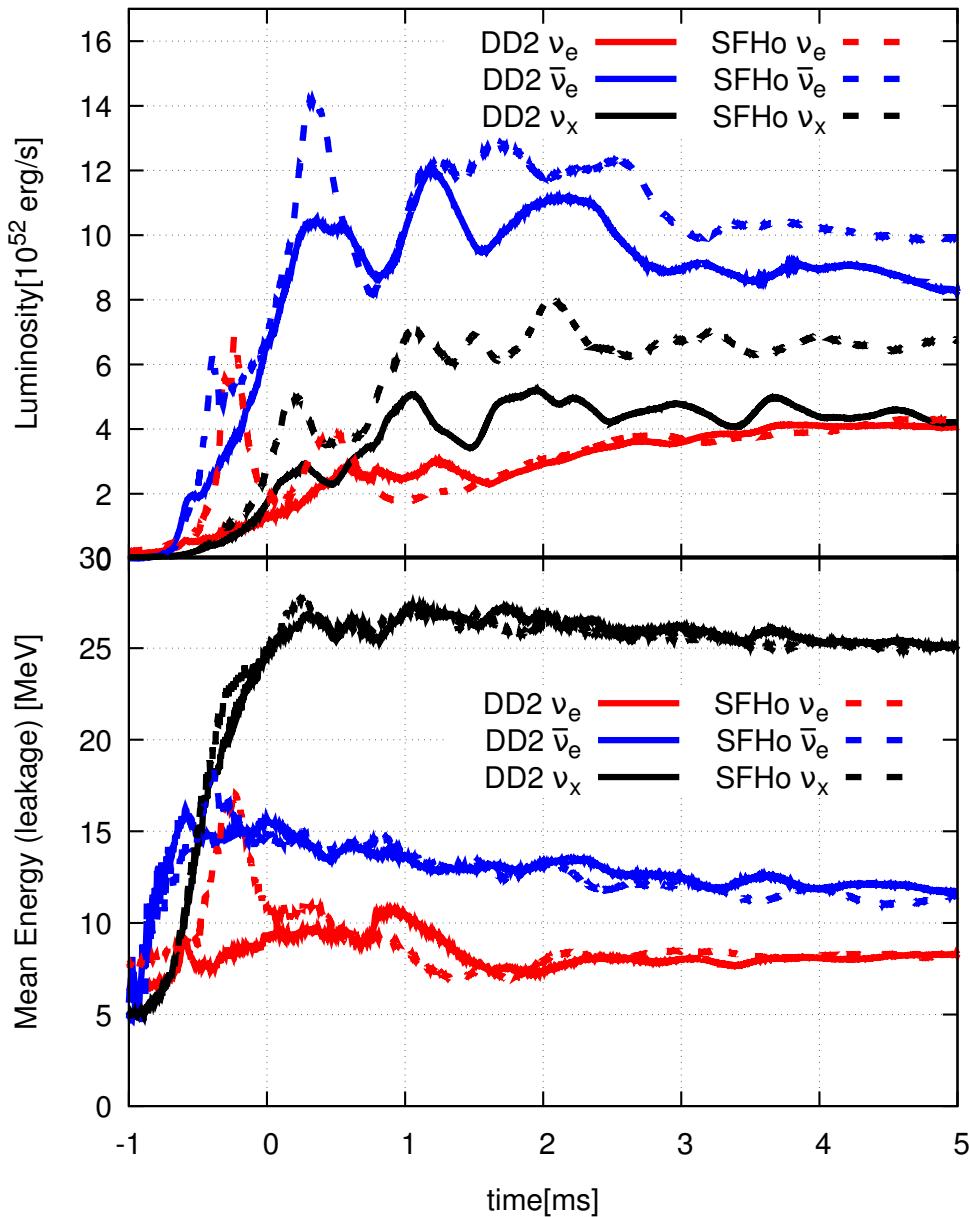
Production of  $A < 140$  nuclei  
in the dynamical ejecta



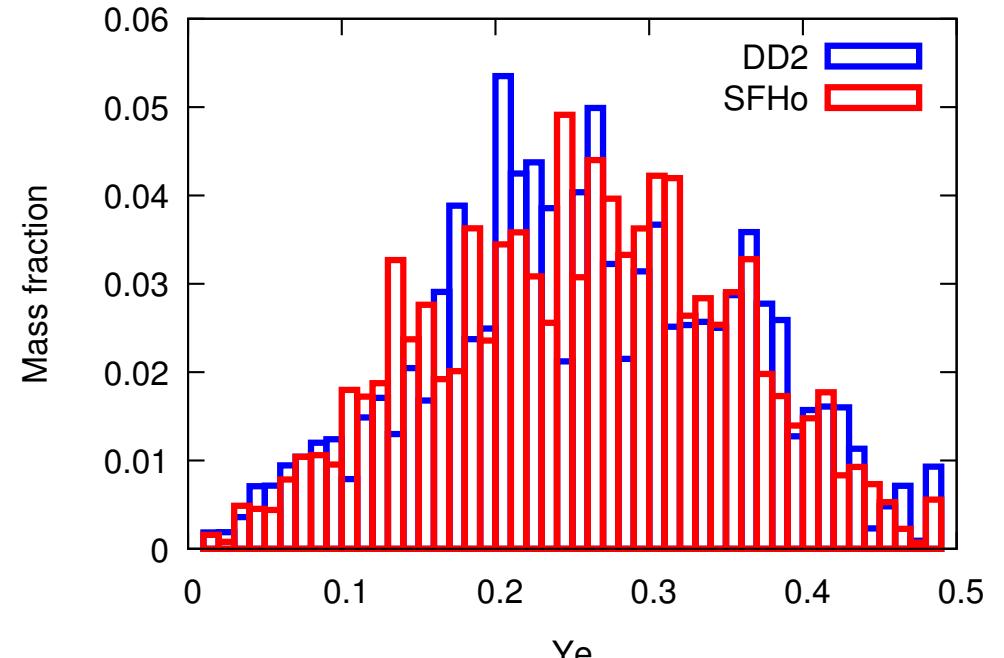
Wanajo et al. (2014); Sekiguchi et al. (2015)

# Improved Leakage-Equilibration-Absorption scheme (ILEAS)

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

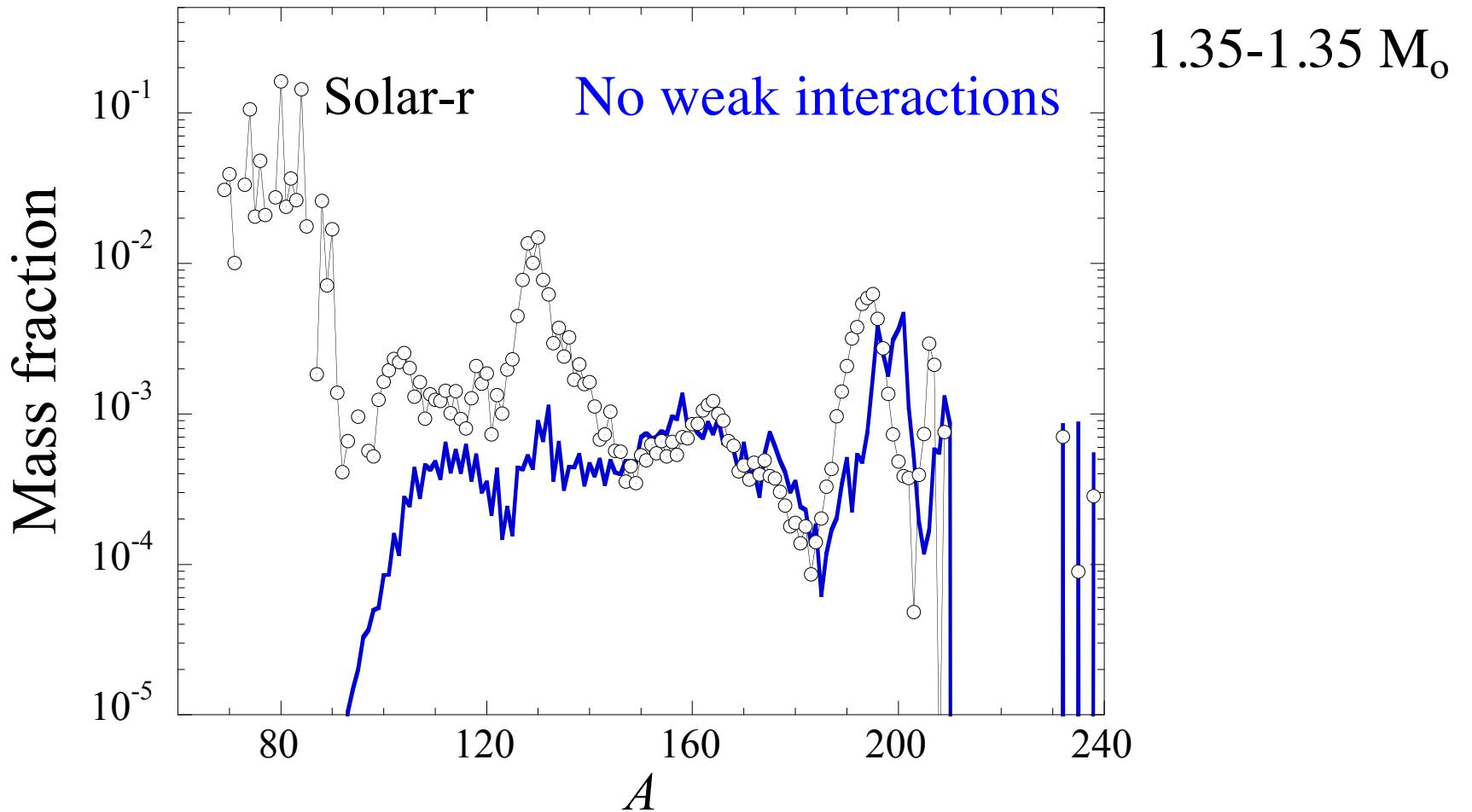


$1.35-1.35M_\odot$  NS binary systems  
Resulting  $Y_e$  of the ejected material



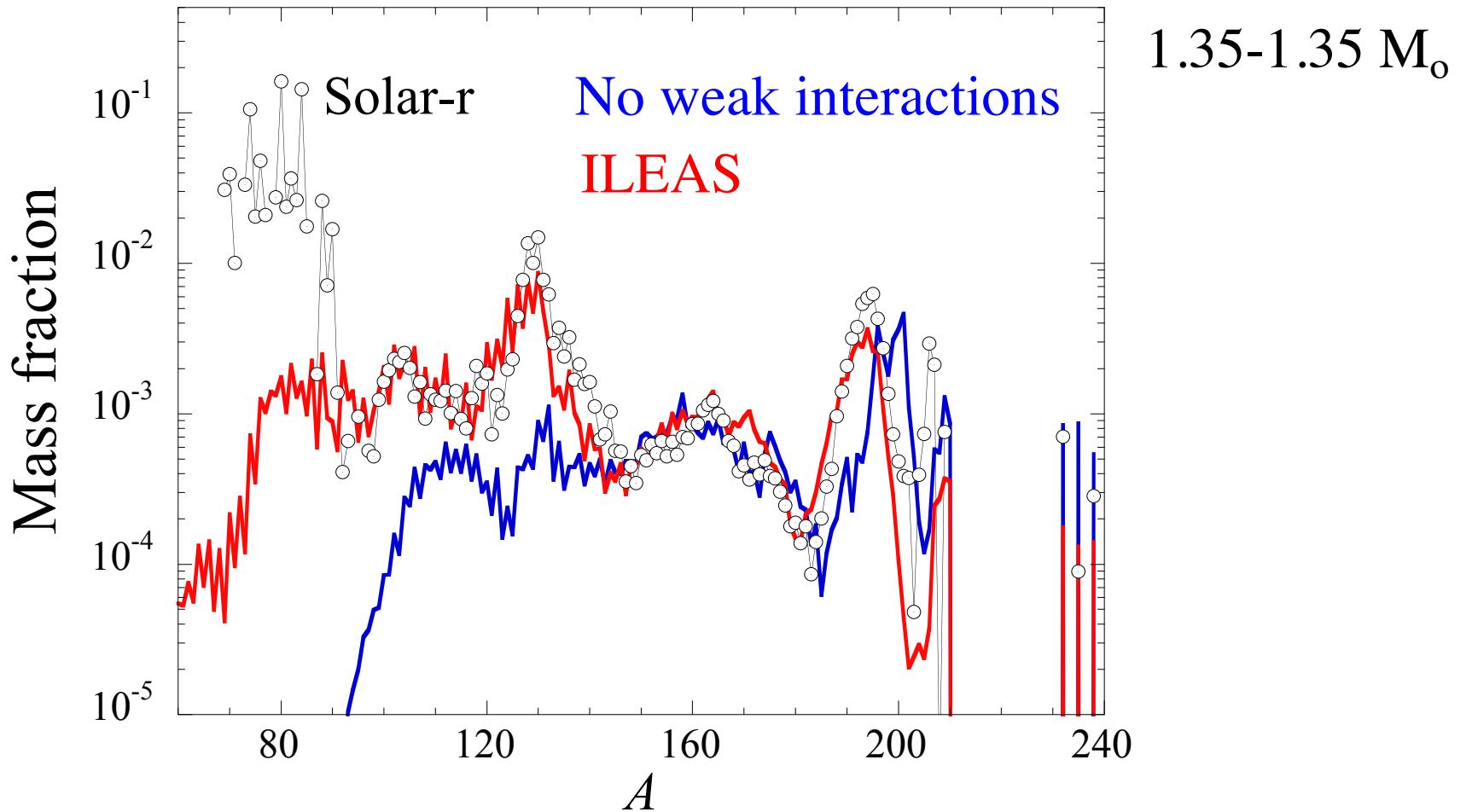
$$\langle Y_e \rangle \sim 0.26$$

# ILEAS predictions for NS-NS mergers



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

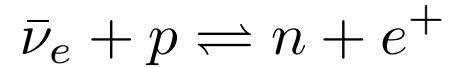
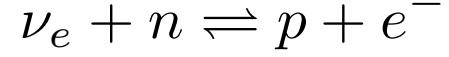
# ILEAS predictions for NS-NS mergers



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

## Some open questions on the r-process in NSM remain ...

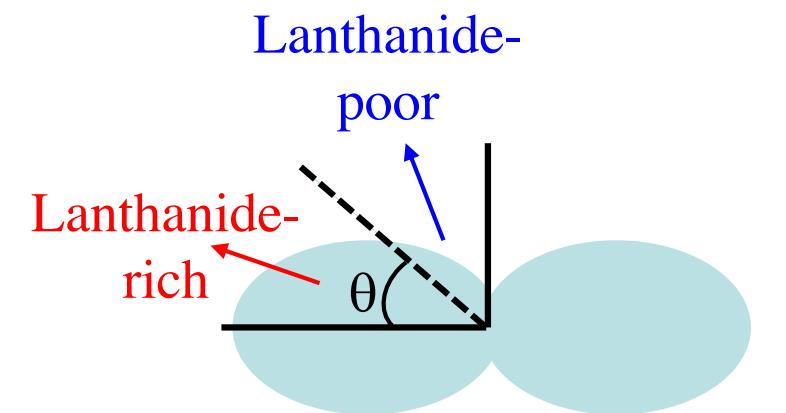
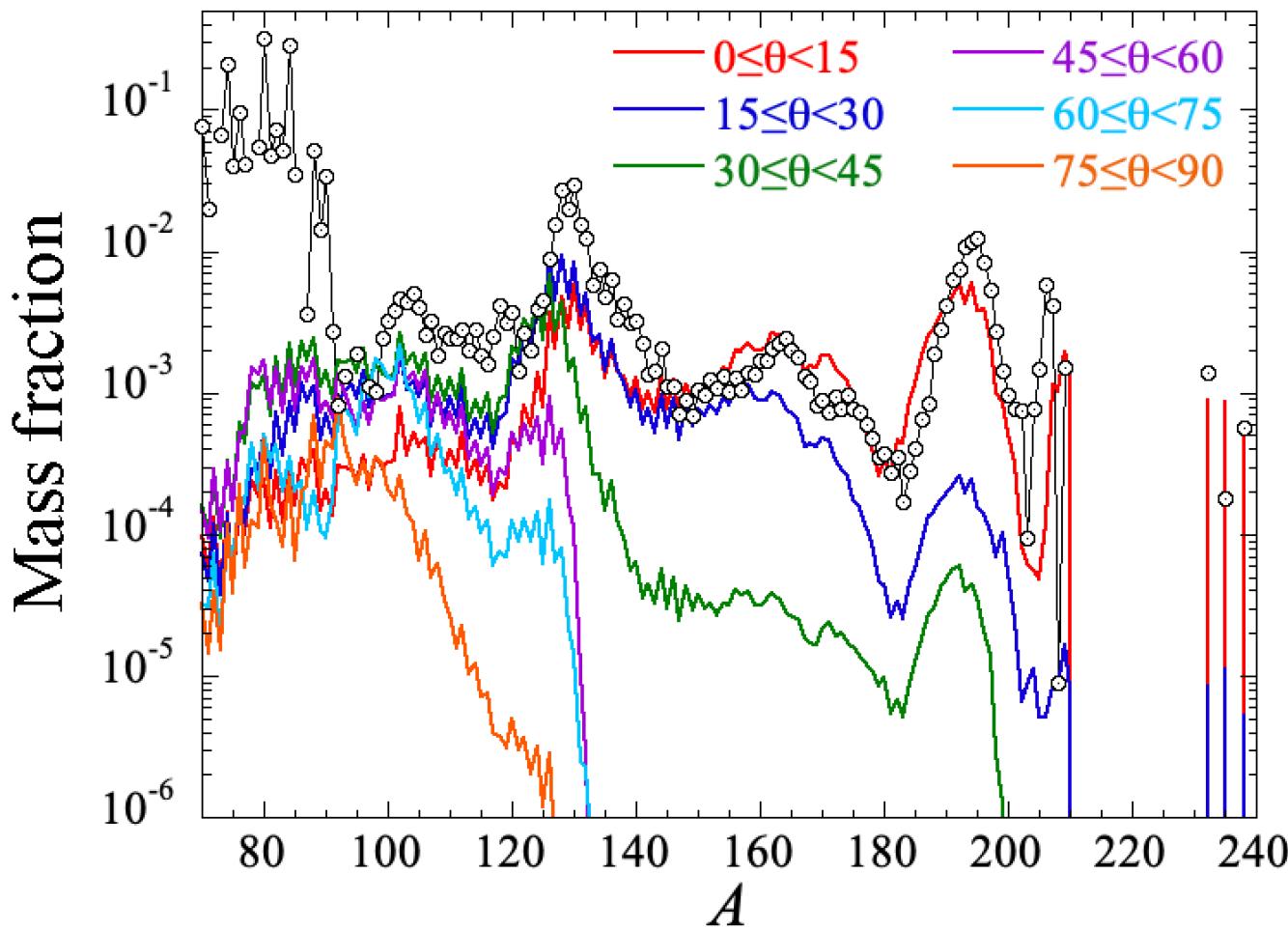
- Impact of neutrinos & EC on the neutron richness during dynamical ejection



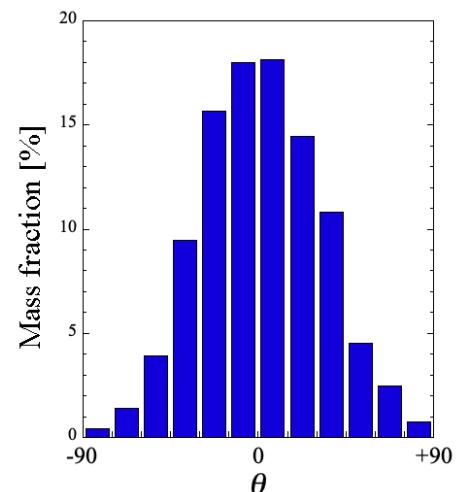
- Angular and velocity distribution of the ejecta

# Angular distribution of the dynamical ejecta composition

1.35-1.35M<sub>o</sub> NS prompt ejecta (with ILEAS ν-interactions)

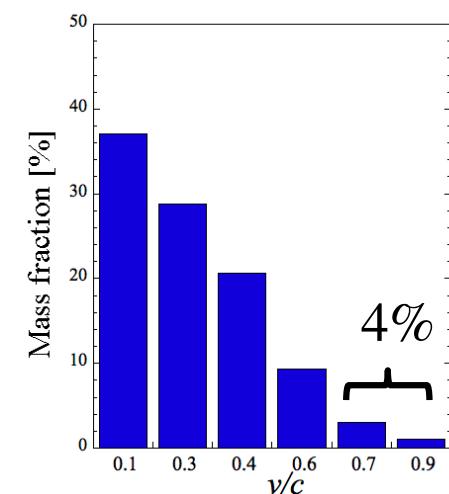
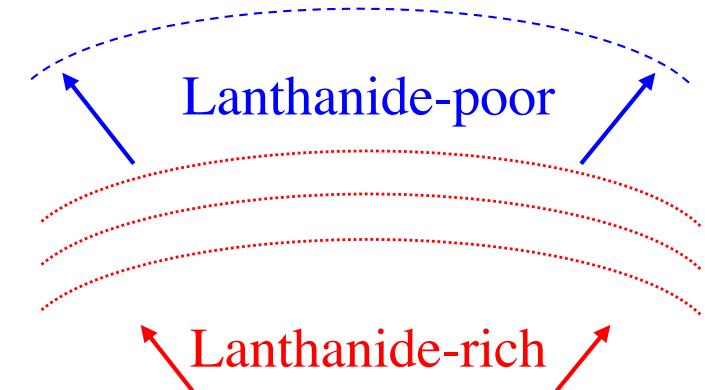
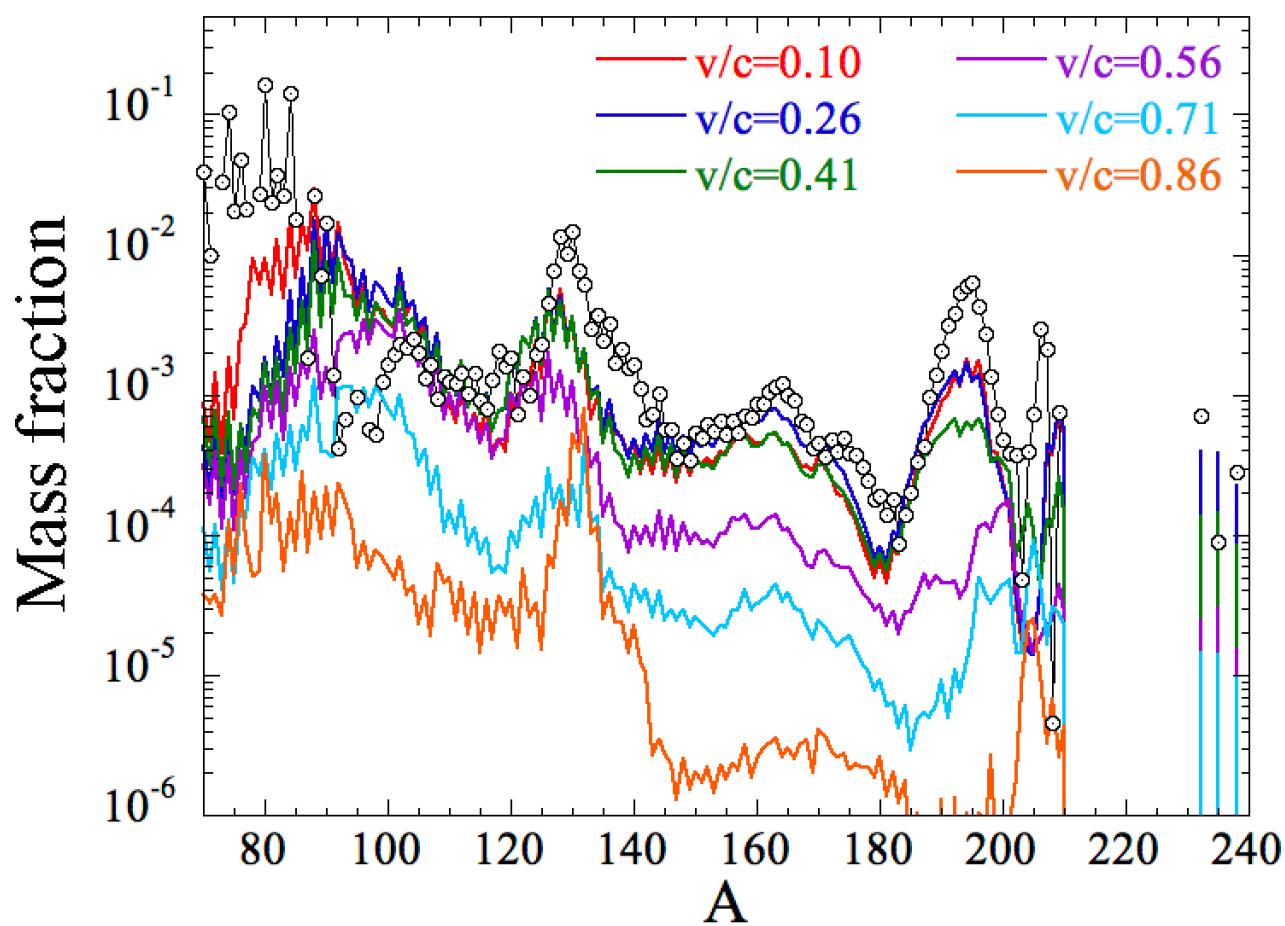


GW170817:  $\theta_{\text{obs}} \sim 57 - 79^\circ$   
(off-axis :  $\theta' \sim 11 - 33^\circ$ )

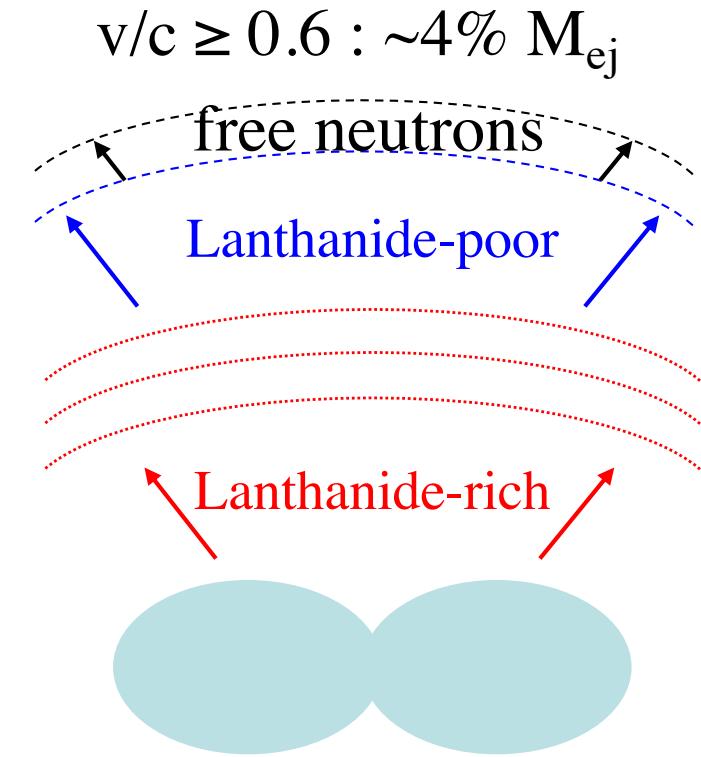
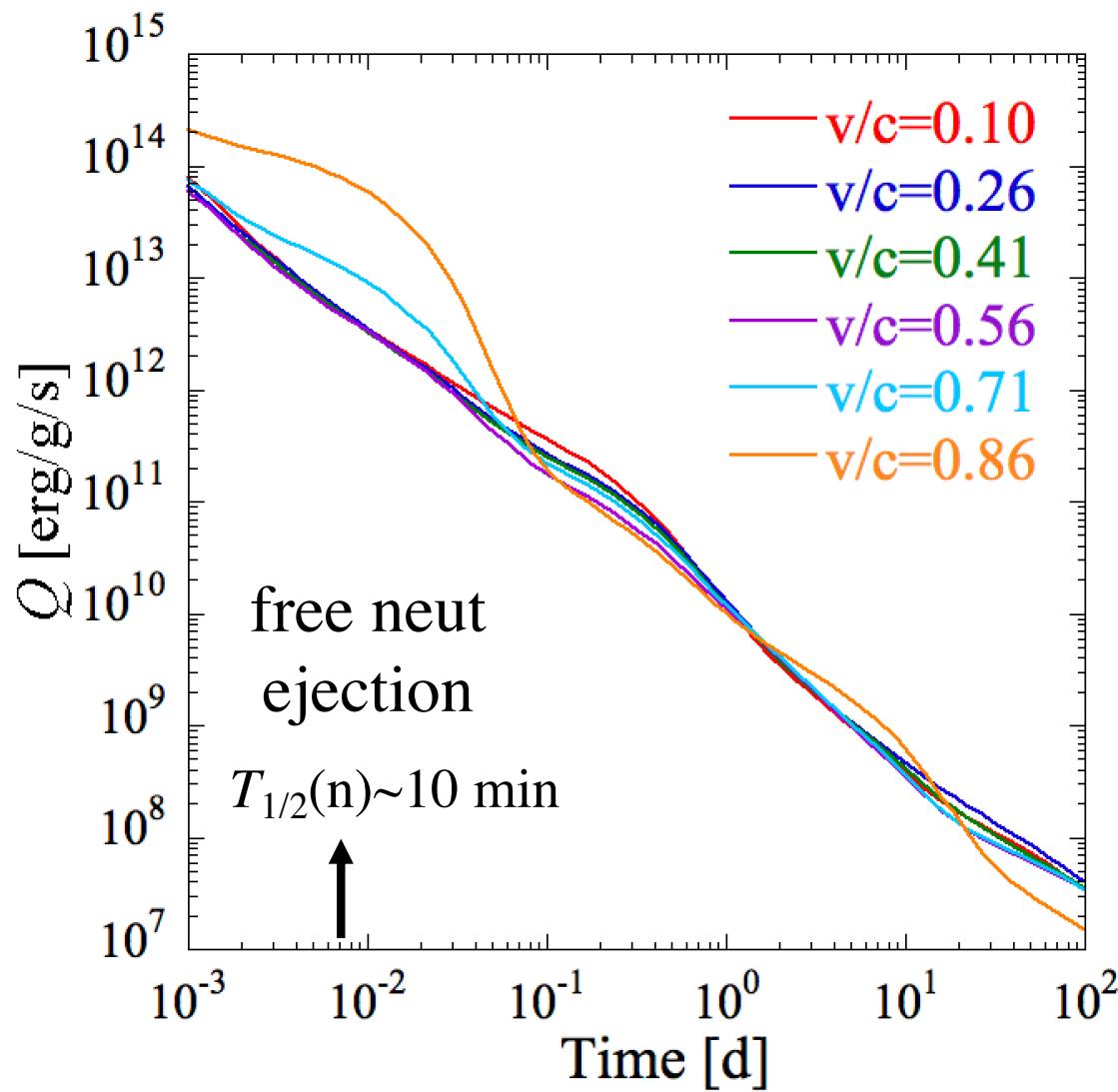


# Velocity distribution of the ejected matter

1.35-1.35M<sub>o</sub> NS prompt ejecta (with EC; no ν-interactions)



# Velocity distribution of the energy release

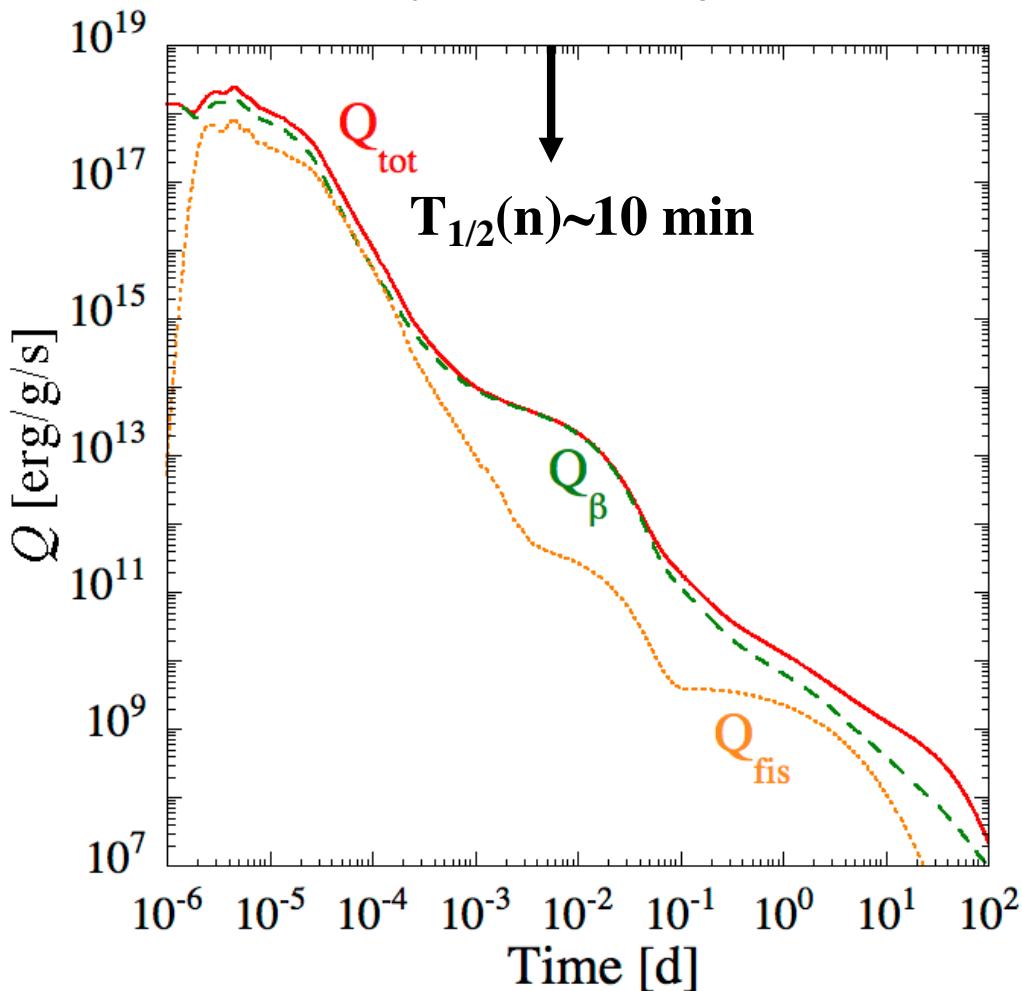


Free n emission sensitive to

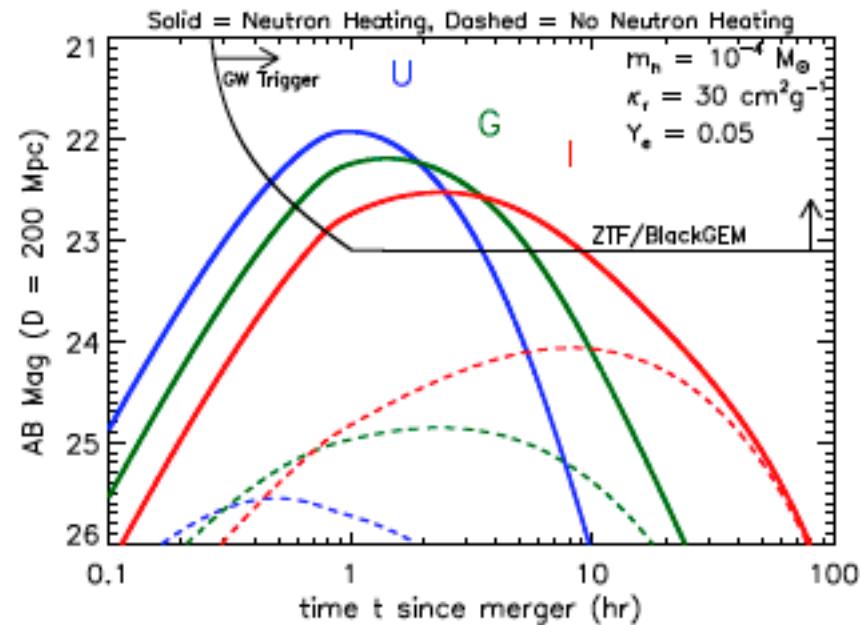
- Initial velocity & entropy
- EOS
- Mass asymmetry

# On the possible fast ejection of free neutrons

Final mass-averaged decay heat of the dynamical ejecta



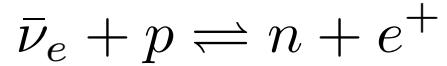
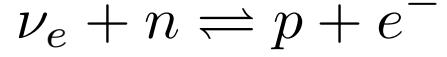
The  $\beta$ -decay of free neutrons may power a ‘precursor’ to the main kilonova emission: peak on a timescale of  $\sim$  few hours at U-band magnitude  $\sim 22$  (at 200 Mpc), i.e.  $L_{\text{tot}} \sim 10^{41} \text{ erg/s}$



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



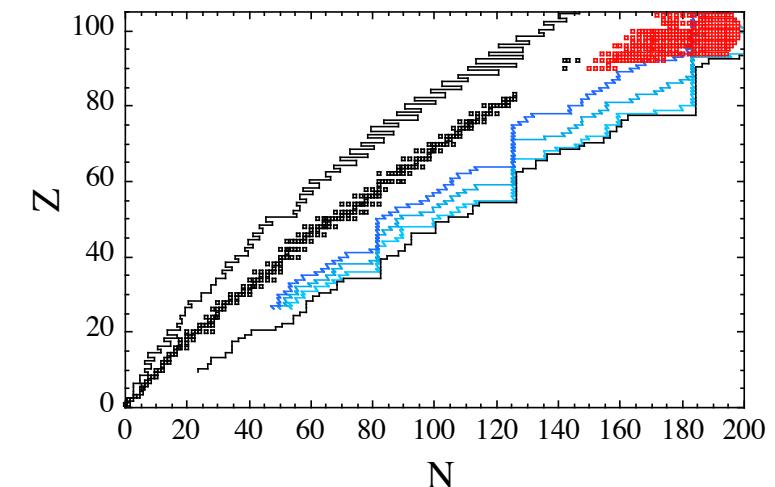
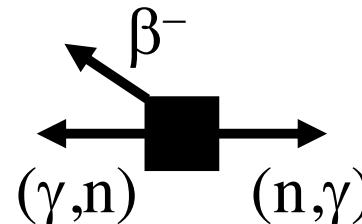
- Angular and velocity distribution of the ejecta
- Nuclear Physics aspects

# Another uncertainty: nuclear physics input

(n, $\gamma$ ) – ( $\gamma$ ,n) –  $\beta$  competition & Fission

Main needs

- $\beta$ -decay rates
- (n, $\gamma$ ) and ( $\gamma$ ,n) rates
- Fission (nif, sf,  $\beta$ df) rates
- Fission Fragments Distributions



Nucleosynthesis requires RATES for some 5000 nuclei !

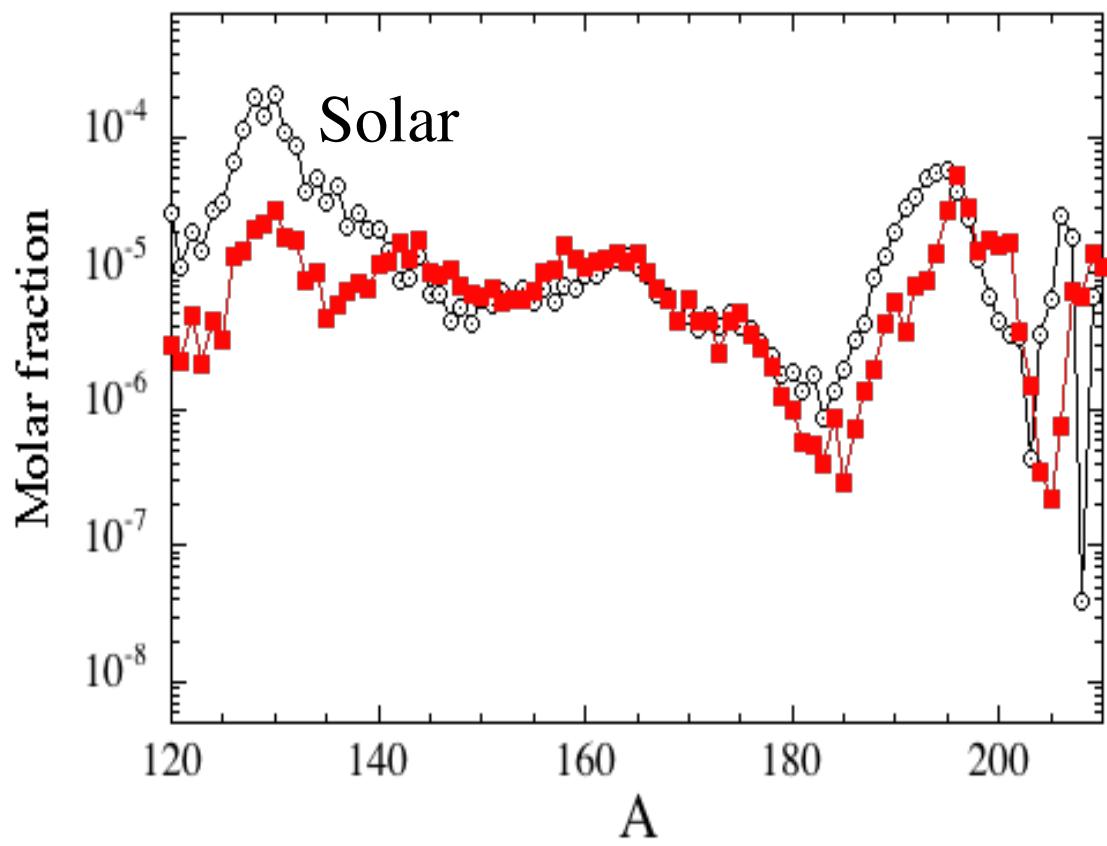
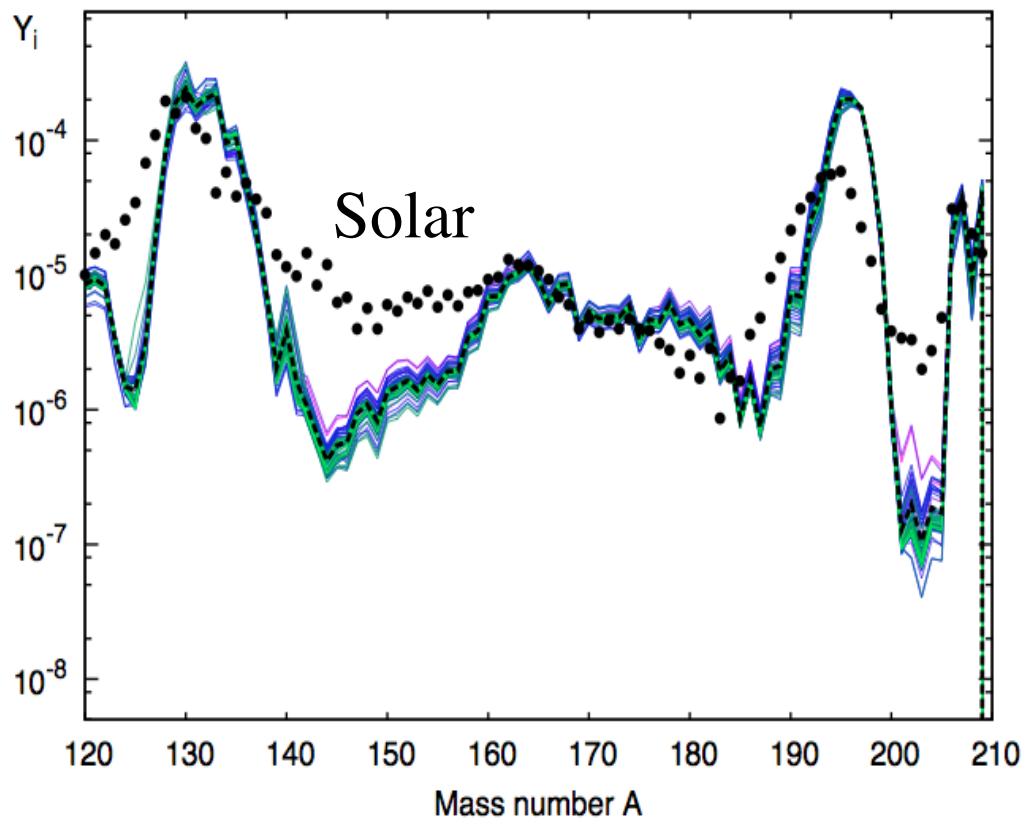
(and not only masses or  $\beta$ -decay along the oversimplified so-called “r-process path”)

→ 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

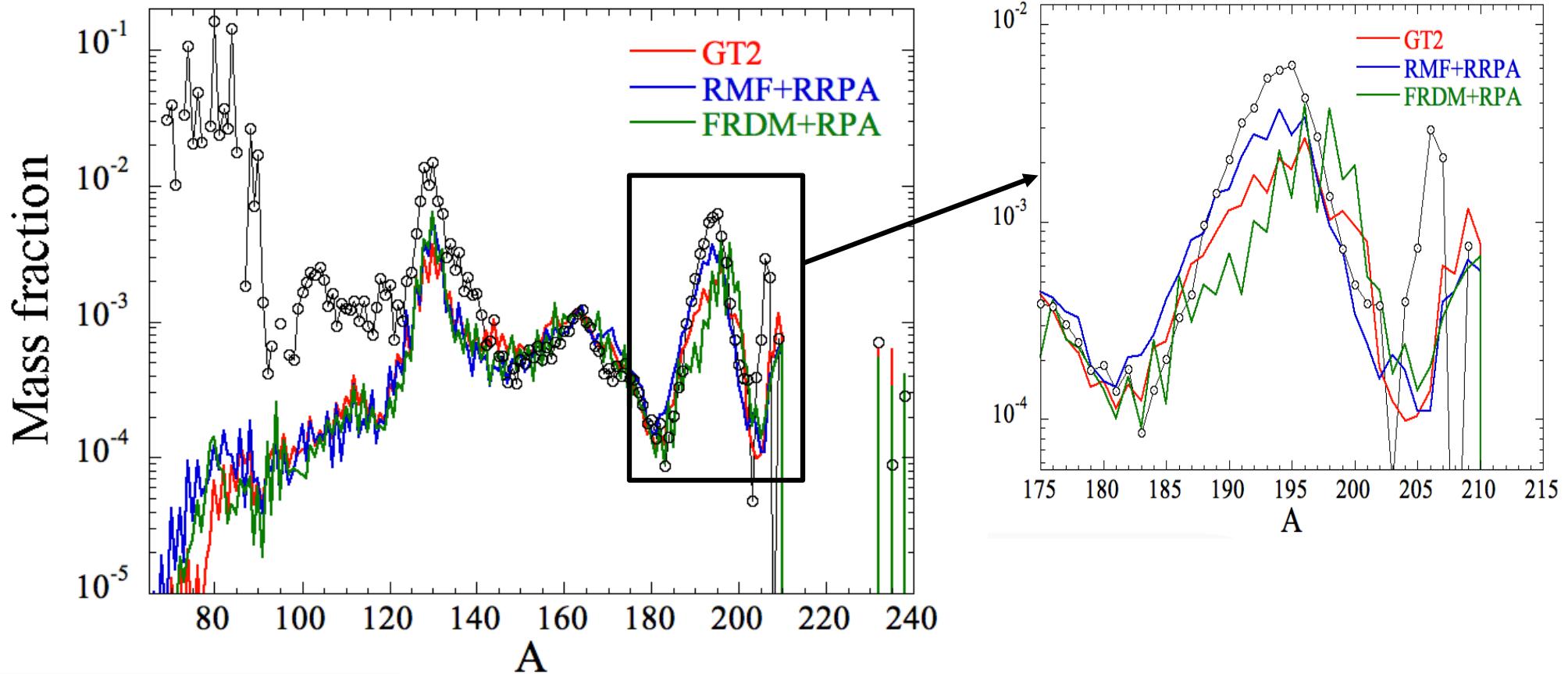
- The reaction model
  - CN vs Direct capture for low- $S_n$  & Isolated Resonance Regime
- Nuclear inputs to the reaction model (almost no exp. data !)
  - GS properties: masses (correlations - GCM, odd-nuclei)
  - E1-strength function: GDR tail, PR,  $\varepsilon_\gamma=0$  limit,  $T$ -dep, PC
  - Nuclear level Densities (at low  $E$ ):  $J$ - and  $\pi$ -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  $\beta$ -decay rates
  - Forbidden transitions, deformation effects, odd-nuclei, PC

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

Models exist, but corresponding uncertainties are usually not estimated

# Impact of $\beta$ -decay rates on the r-process nucleosynthesis in NS mergers

## Dynamical ejecta



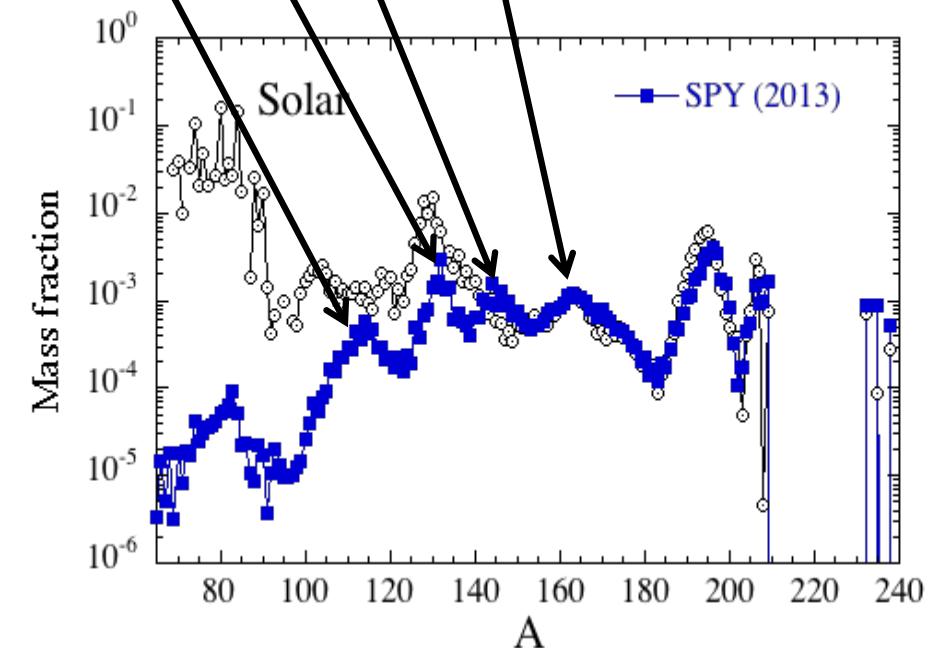
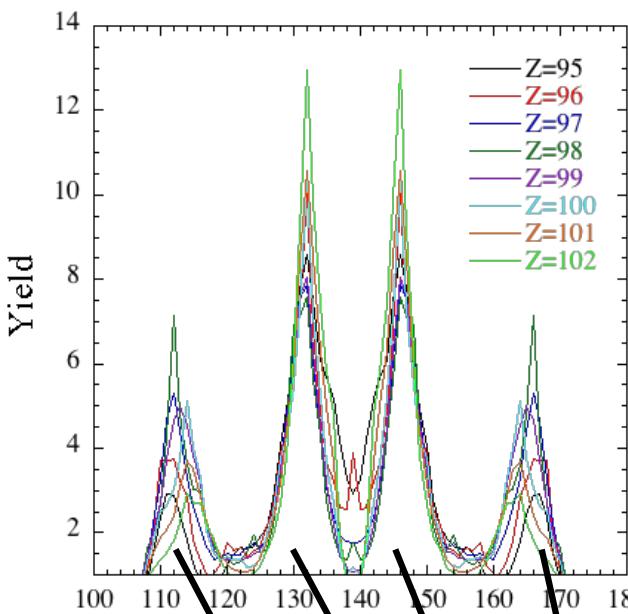
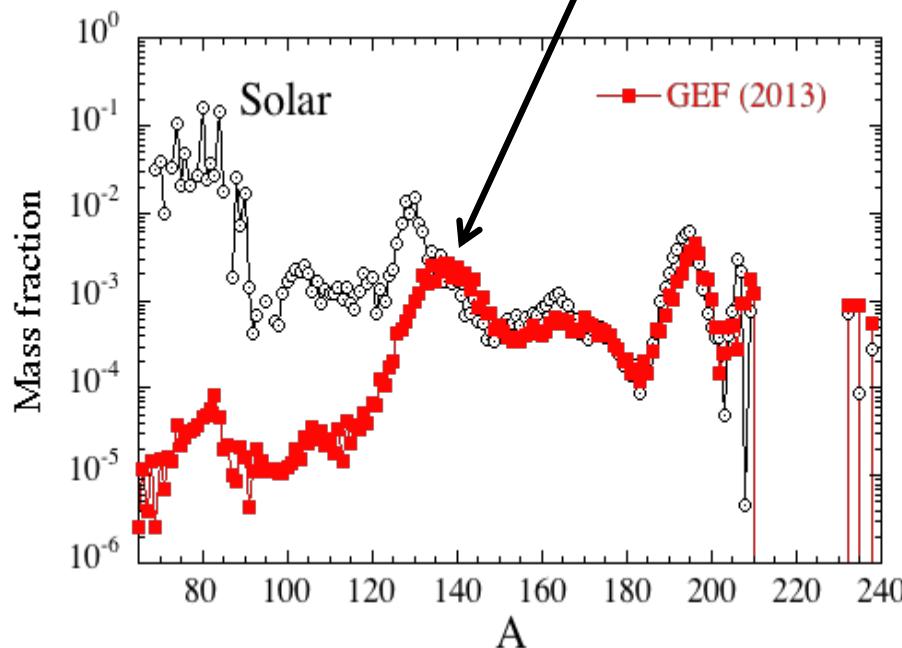
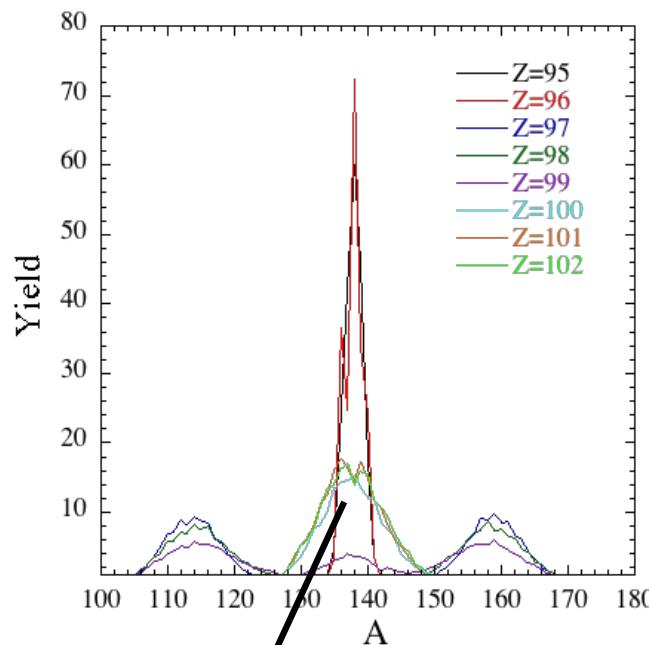
Large impact of the  $\beta$ -decay rate – set the synthesis timescales

→ 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

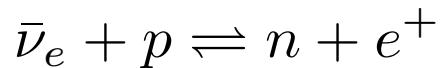
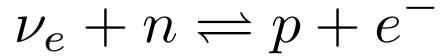


SPY:  
S. Panebianco  
et al. (2013)

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



- 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

- $M_{\text{Gal}} \sim 6 \cdot 10^{10} M_{\odot}$  of baryons
- $X_{\odot}(\text{Eu}) \sim 3.7 \cdot 10^{-10} M_{\odot}$
- NS-NS Yield of Europium :  $Y_{\text{Eu}} \sim 7 \cdot 10^{-5} - 2 \cdot 10^{-4} M_{\odot}$  (Dynamical+Disk)

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

$$\text{Rate} \sim 8 - 20 \text{ Myr}^{-1}$$

Compatible with current estimates

Rate  $\sim 2 - 210 \text{ Myr}^{-1}$  from population synthesis models (e.g. Chruslinska et al, 2018)  
 $\sim 5 - 495 \text{ Myr}^{-1}$  from Galactic Chemical Evolution models constrained by  
GW170817 observation (e.g. Coté et al, 2018)

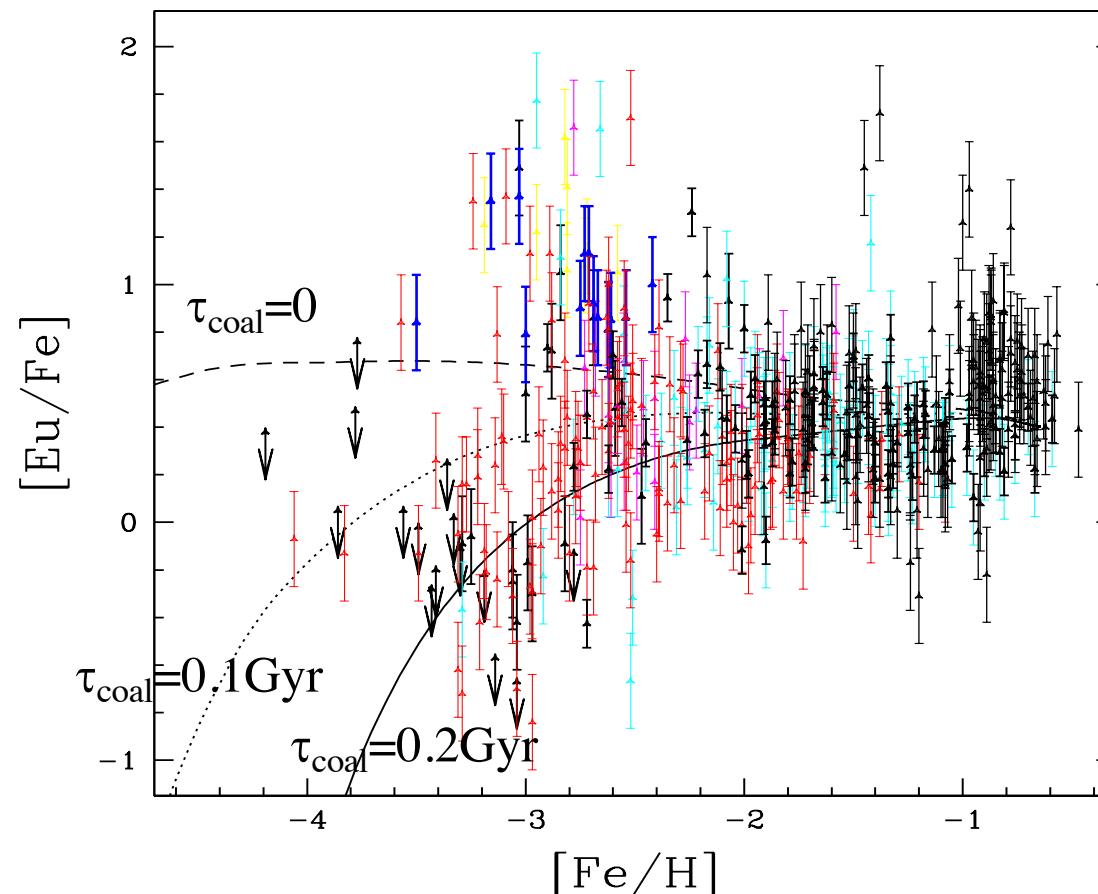
**Conclusion in term of amount of r-enrichment:**

If GW170817 is statistically 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

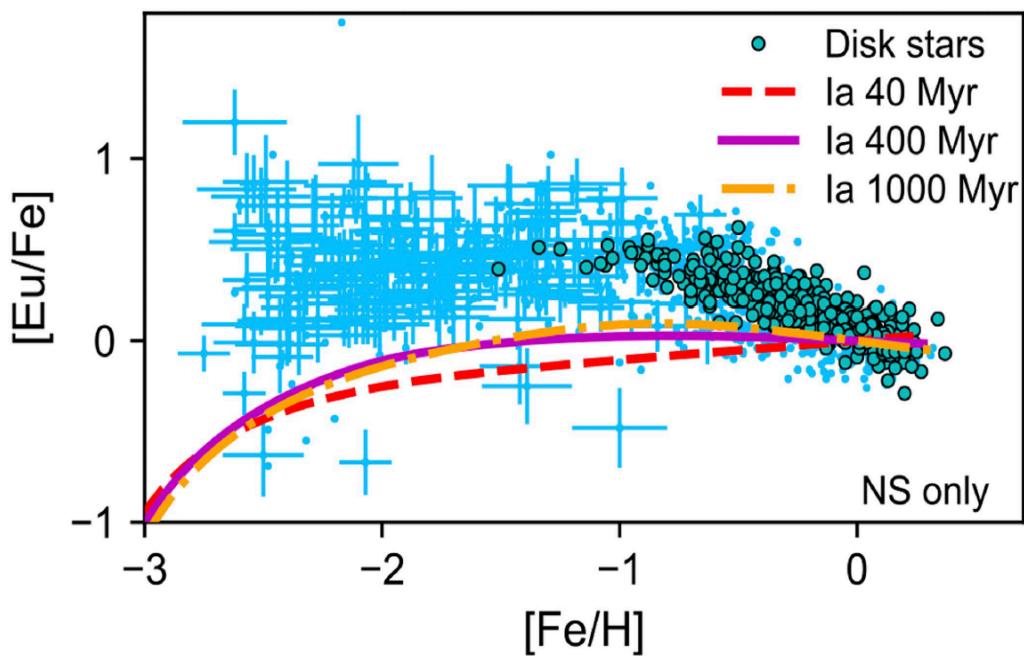
Chemical Evolution of r-elements in the Galaxy (halo stars)

- early enrichment of Eu
- abundance scatter in low-metallicity stars

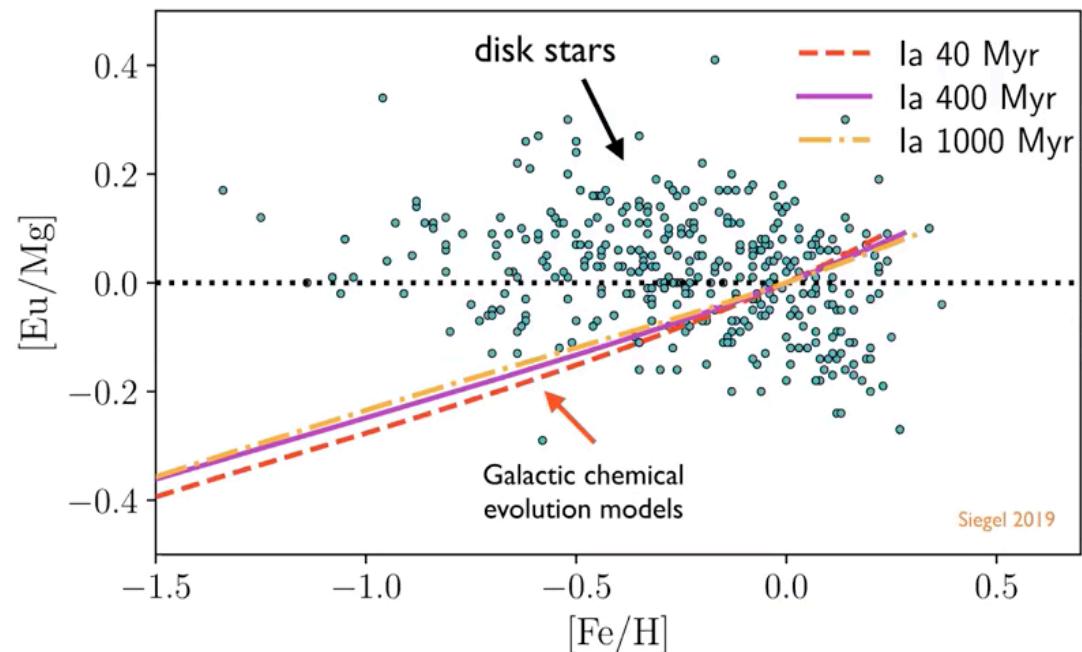


# Challenges for r-process in NS mergers

r-process vs Fe evolution  
for disk stars



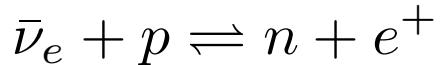
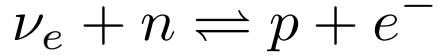
r-process vs  $\alpha$ -elements  
evolution for disk stars



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



- 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, ...

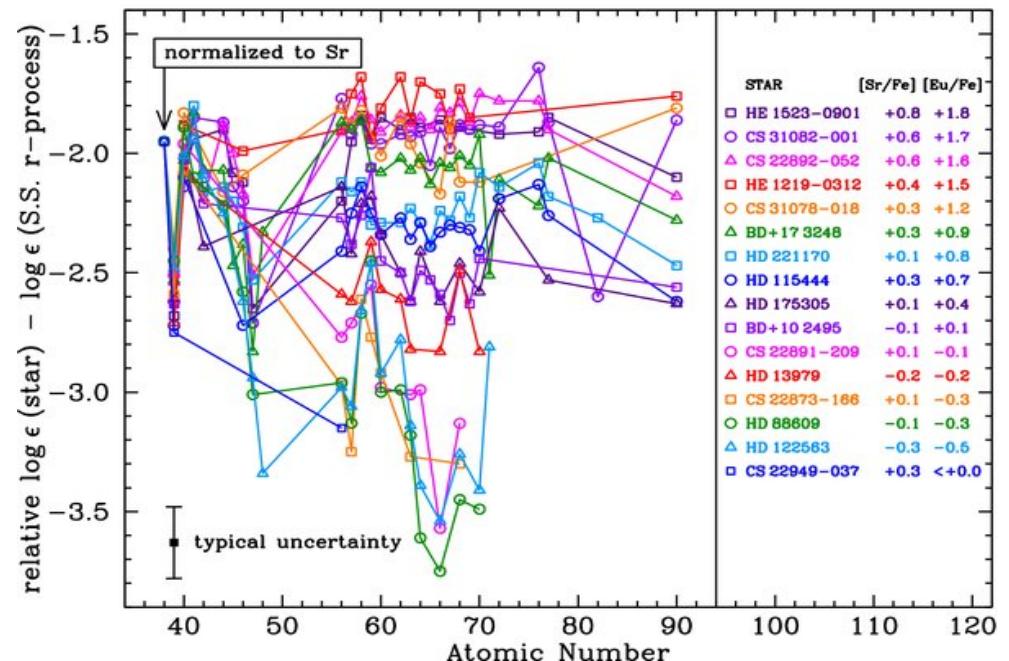
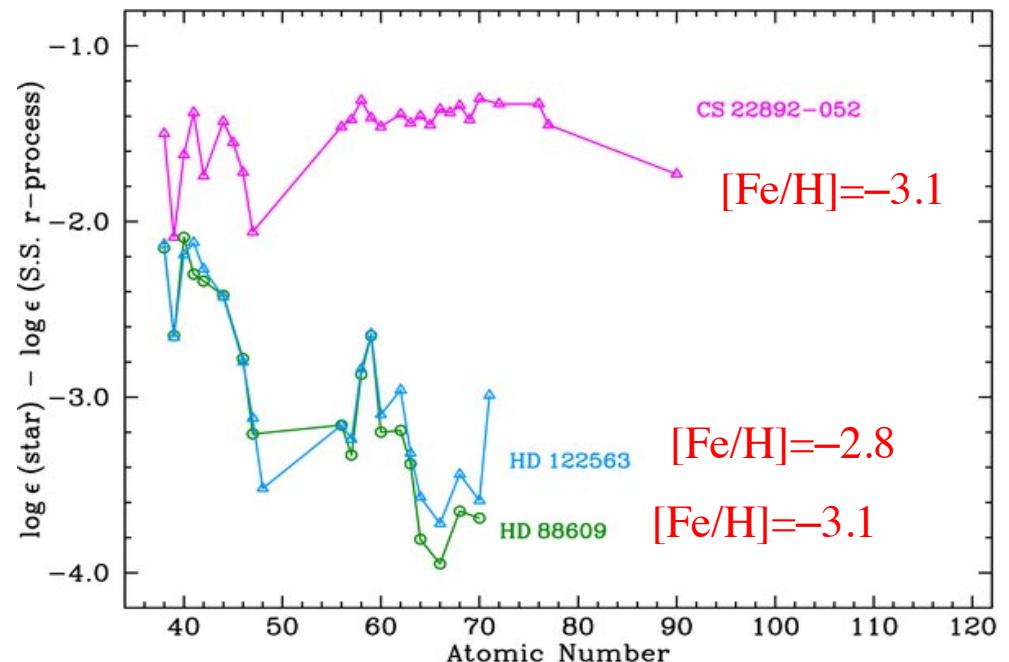
# The r-process distribution in ultra-metal-poor stars

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

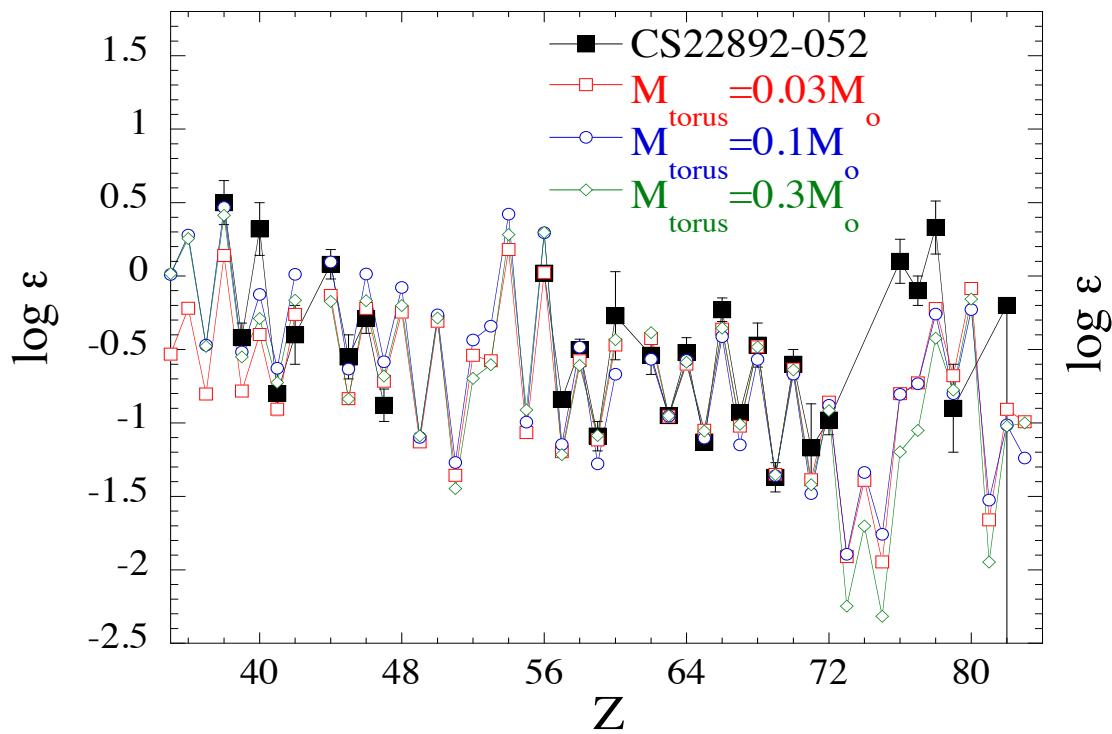


# Comparison with observation in low-metallicity r-process-rich stars

2 extreme cases



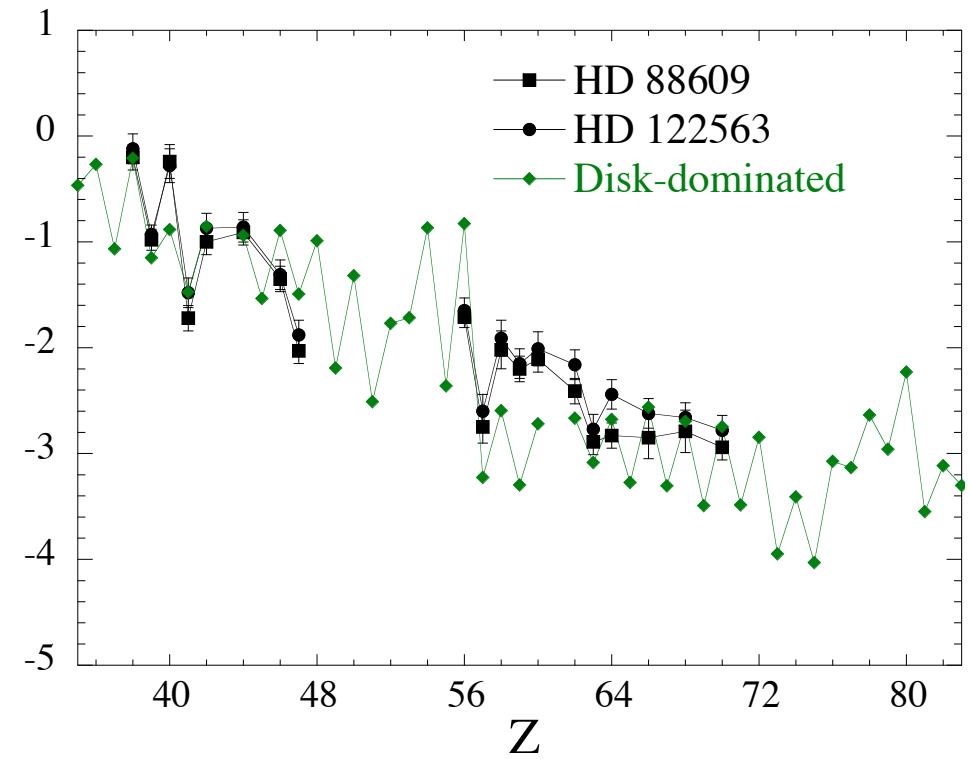
Main trend: rather solar-like distribution



Dynamical + Disk ejecta (mass averaged)

- for  $56 \leq Z \leq 76$  : « 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