NUCLEOSYNTHESIS OF HEAVY ELEMENTS IN EXTREMLY NEUTRON-RICH ENVIRONMENTS.

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- Introduction, history, conditions and nucleosynthesis' sites
- R-process nucleosynthesis and when it run?
- Overview – a look backward and forward
- evolution of the mainstream in the understanding of the r-process phenomena
- Fission: bifurcation of the r-process, fission cycling and formation of SHE
- Astrophysical sites for the r-process
- Remarks and Conclusions

Congress: important dates

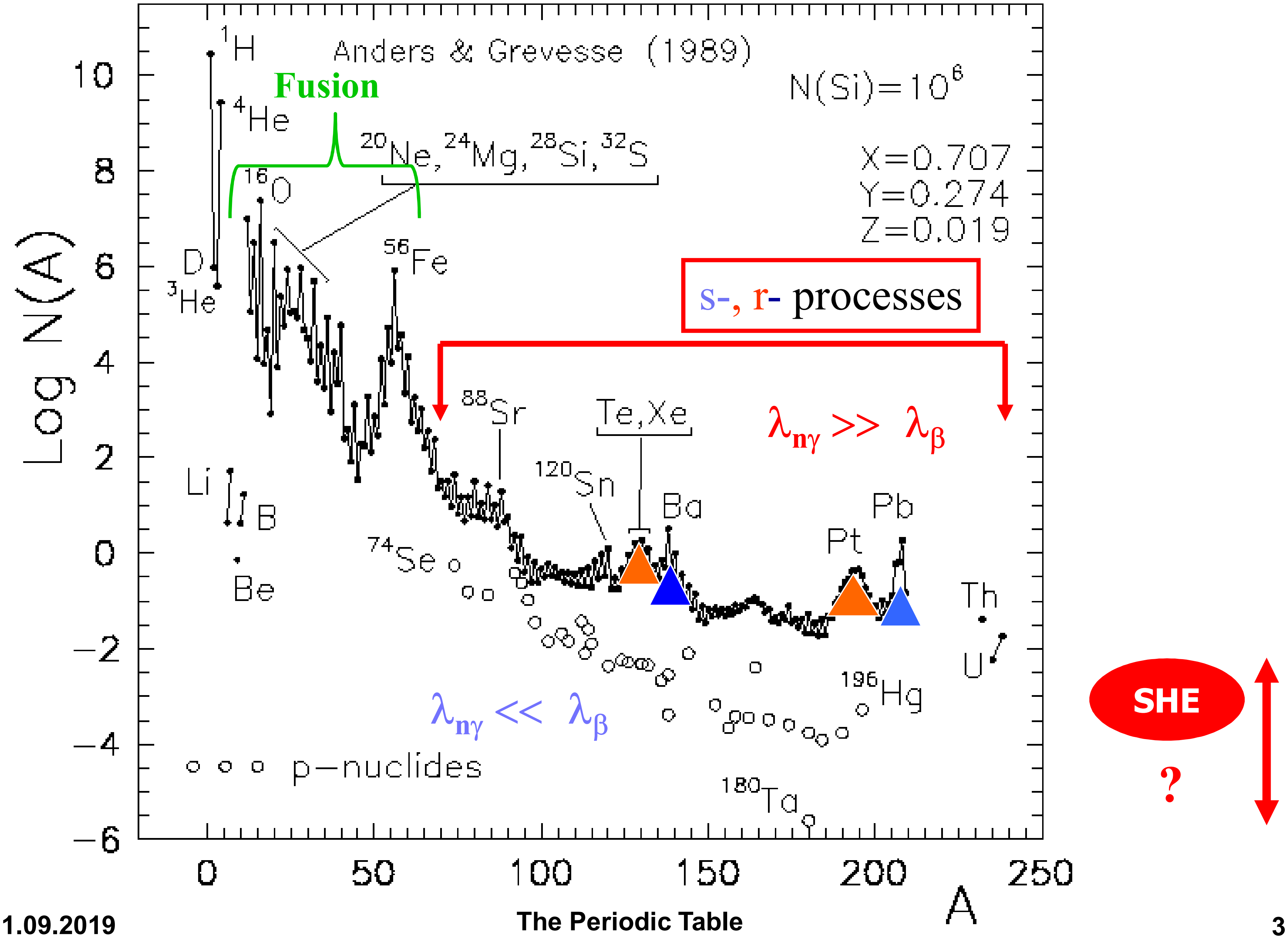
- 150 years of Periodic law
- 100 years since Rutherford in 1919 research

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H.$$

- the energy source in stars – thermonuclear reactions:
- **On the ideas of** Eddington **1920**

  1929 Atkinson, Houtermans, Gamow, Teller, Weizsacker

  1939 Bethe et al.
- BBFH 1957 – nucleosynthesis classification;
- SFC 1965 first calculations of the r-process 55 years
- 35-40 years of first propositions of NS+NS merger
- 20 years since first numerical NSM calculation



The Periodic Table

Nucleosynthesis beyond Fe-peak – r-process and s-process contributions $N_r = N_{ss} - N_s$

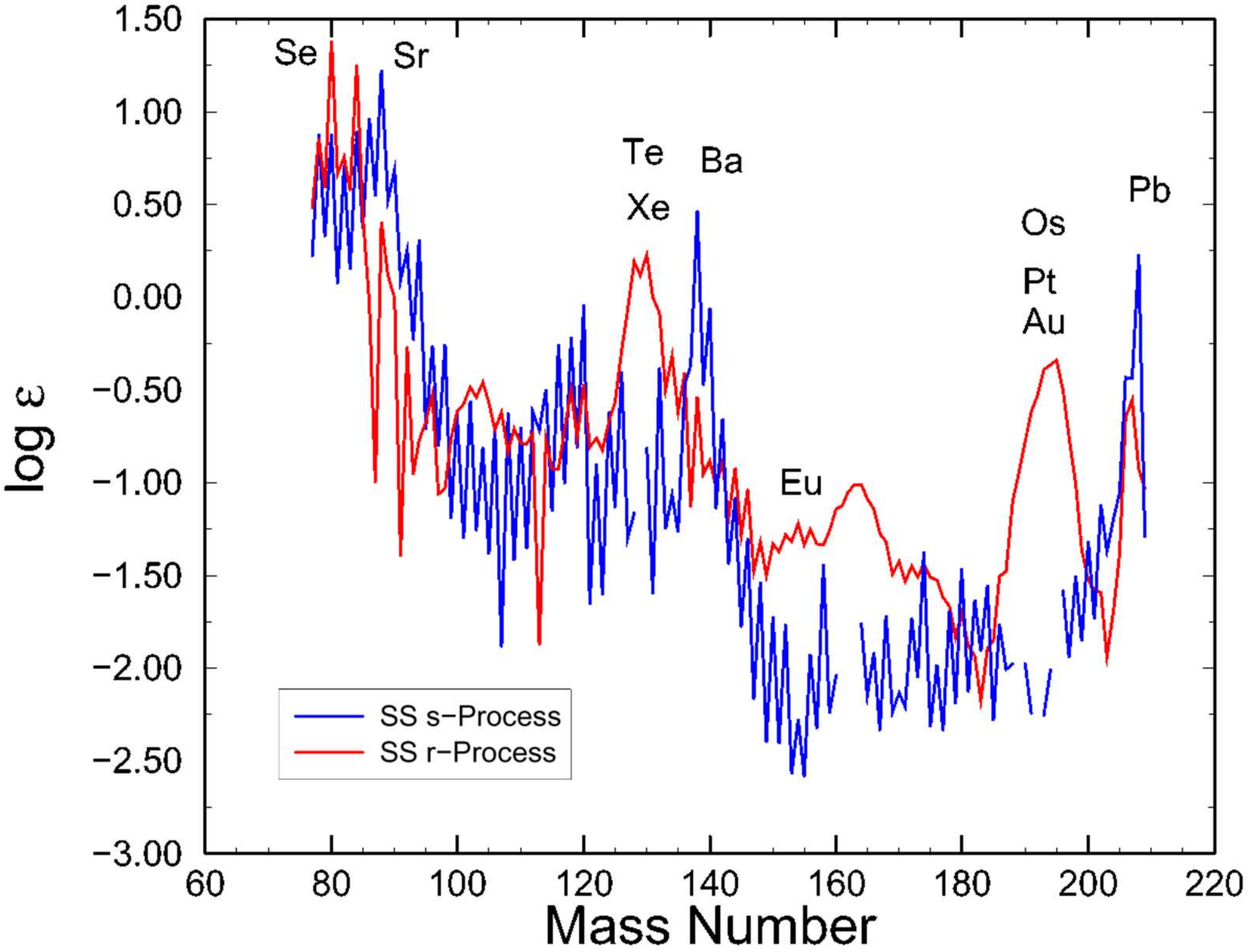
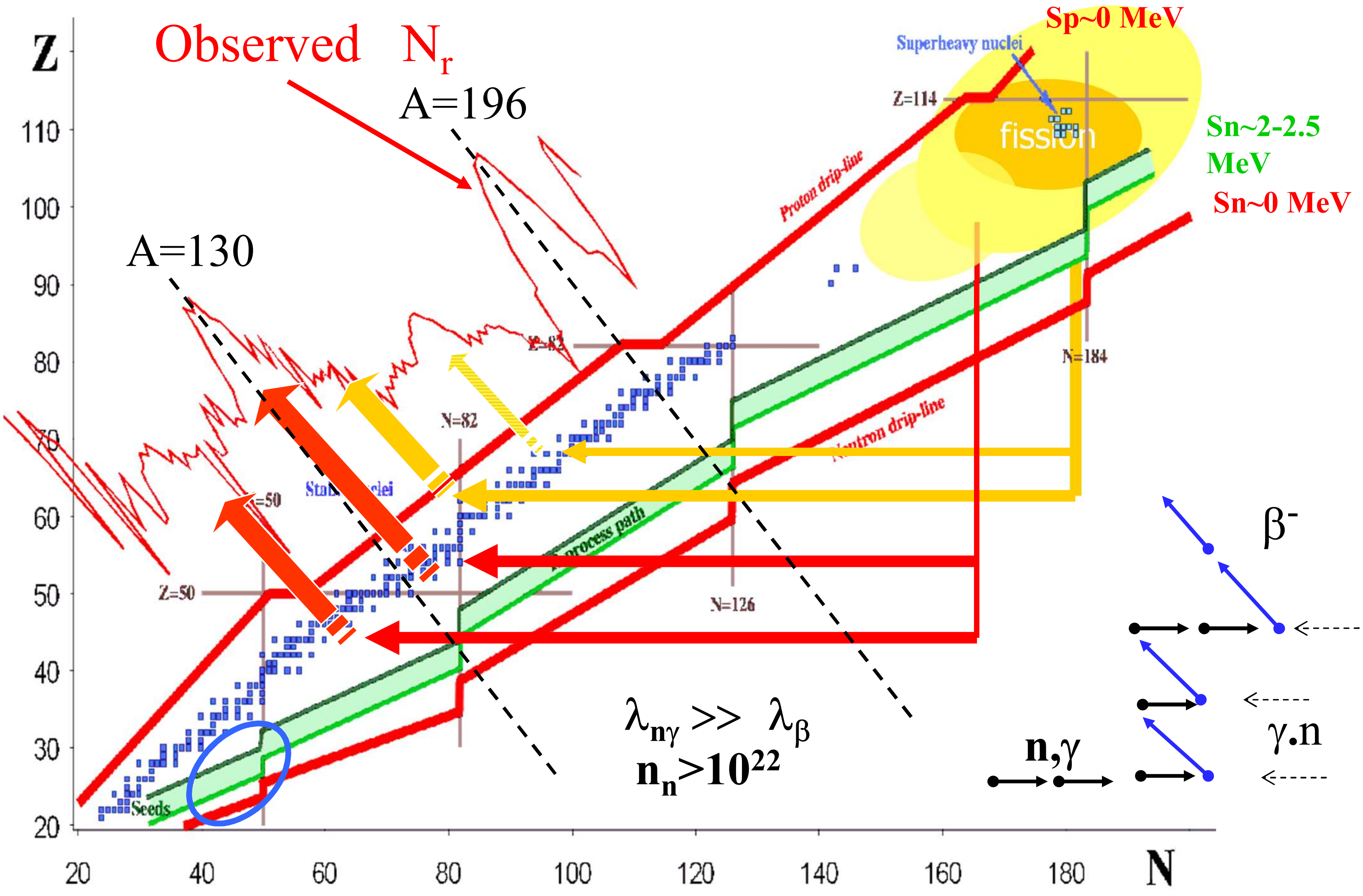


Figure from Cameron A.G.W. 1982

R-process under high neutron density environment – in NSM



Sites for the r-process –since BBFH up to 1999

Since work BBFH (1957) (nucleosynthesis classification) the main r-process site – SN explosion

He-flash – J.Cowan, A. G. W.Cameron, J.Truran, (1981)?

Explosions on NS crust, Chechetkin,Bisnovaty, UFN 1979

high entropy wind ("hot bubble") (Woosley et al.1992)

Explosion of a NS Just Below the Minimum Mass (1990)

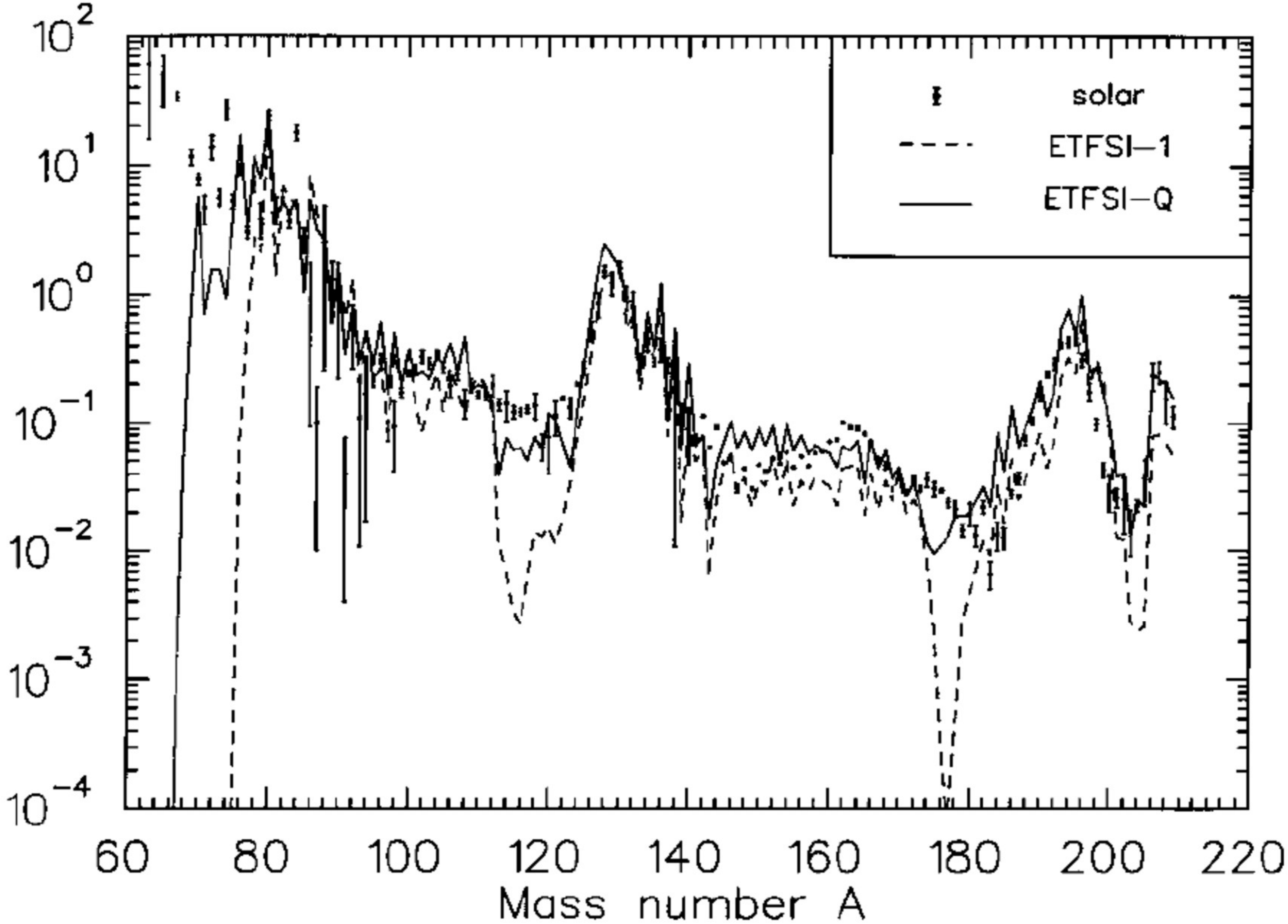
weak neutrino-induced r-process in SNII

Epstein, Colgate 1988; Nadezhin, Panov, 1992;
P. Banerjee, W. C. Haxton, Y.-Z. Qian, 2011

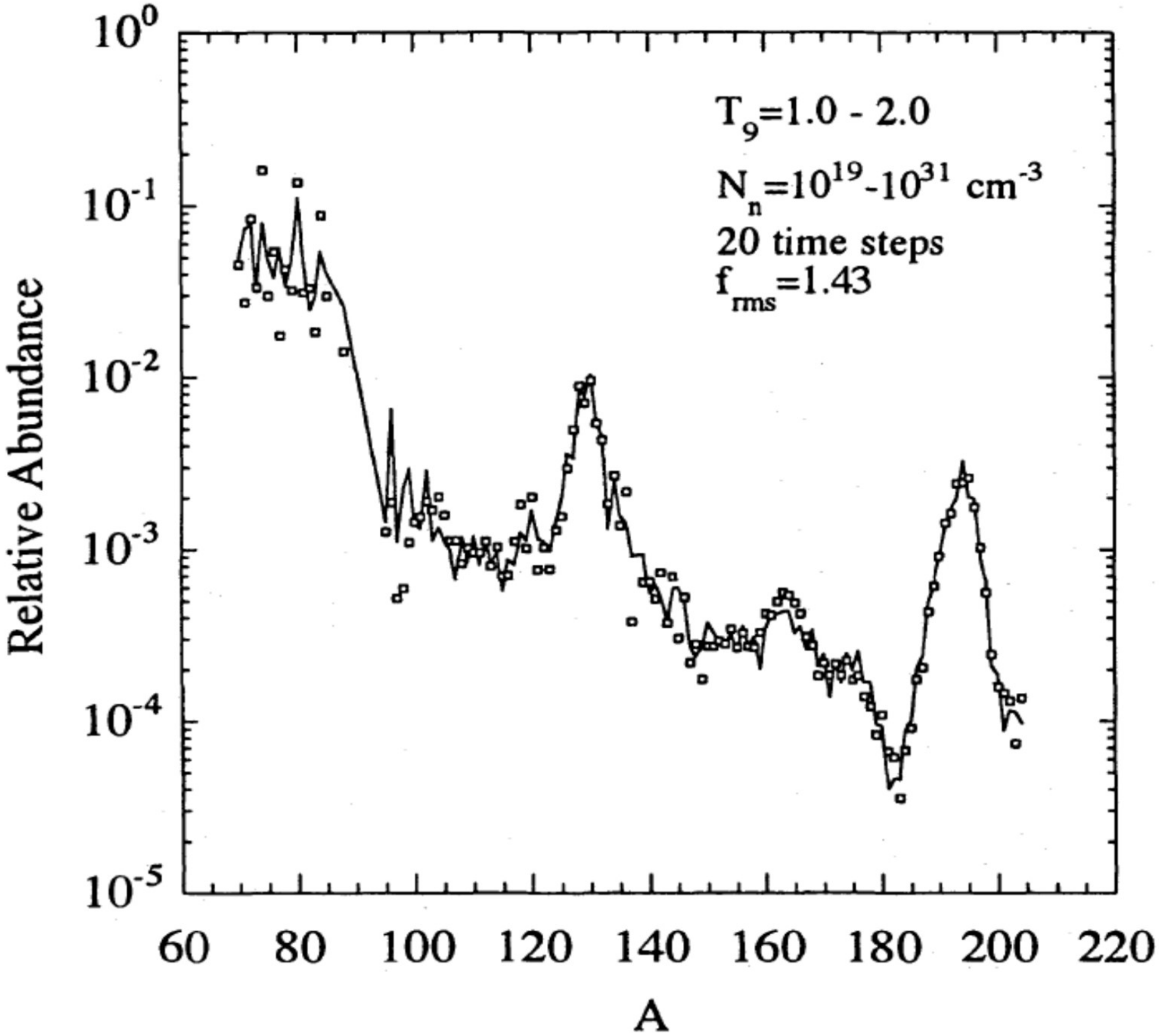
Wasserburg,Busso,Gallino AJ,466,1996: diverse SN

Merger close binary objects: Rosswog et al.1998/1999

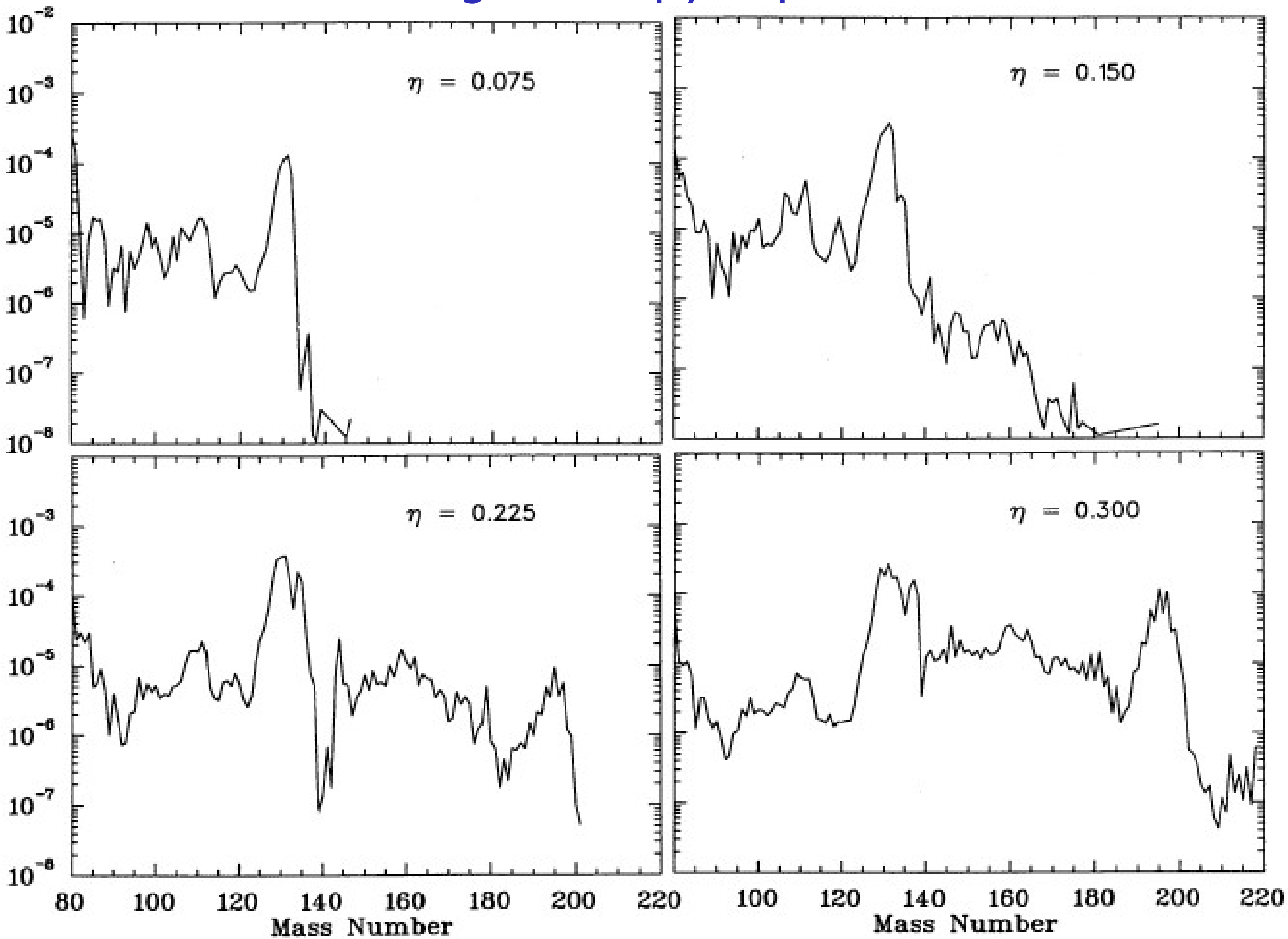
Sites: classical r-process 1<Sn<4.



Fits to r-process abundances (Thielemann et al. Acta Phisica 561 1998) obtained with 17 equidistant Sn(nn, T) components from 1 to 4 MeV canonical r-process (superposition of 10000 trajectories), Goriely & Arnould, AA 1996

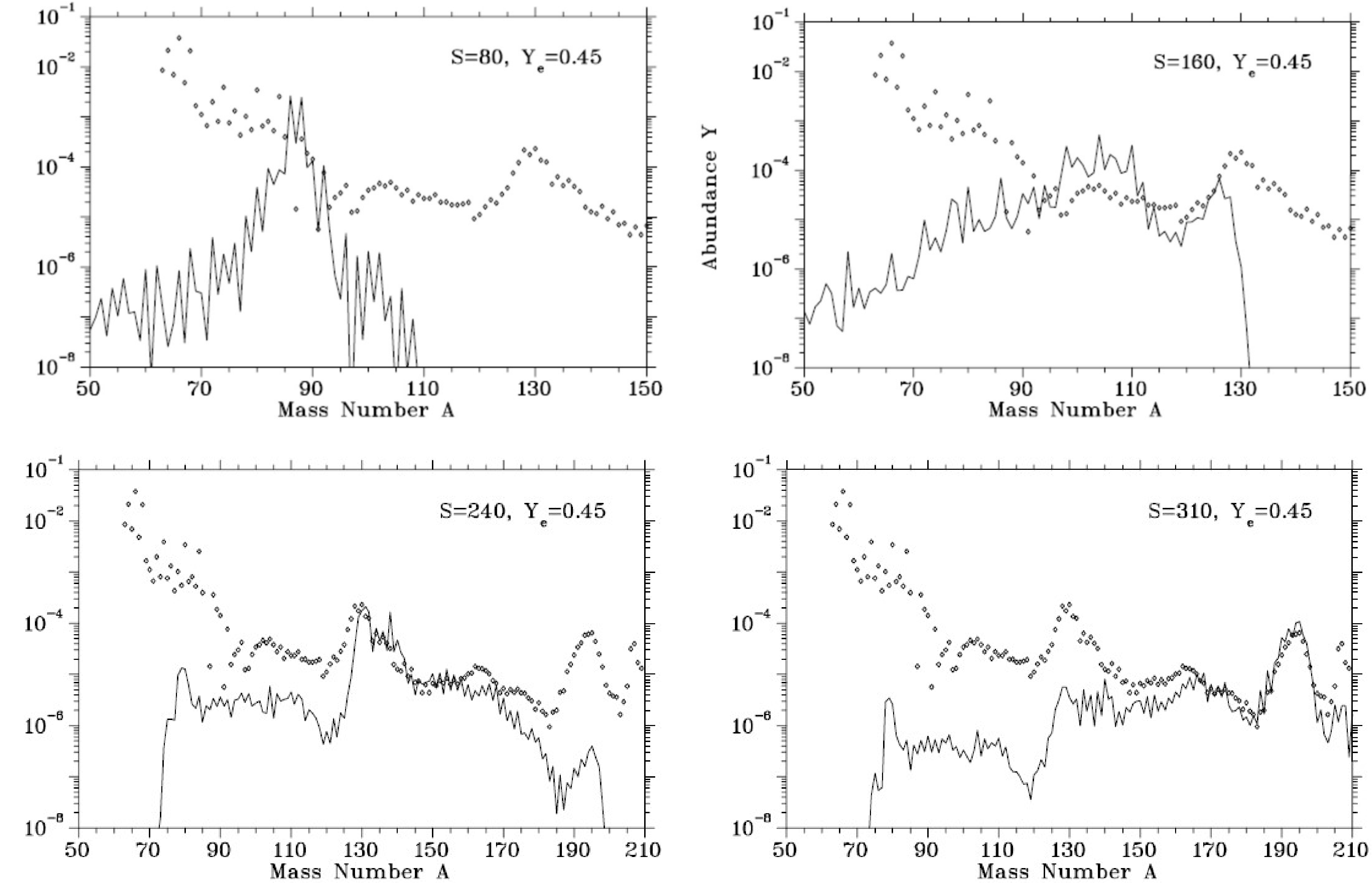


SN: high entropy supernova bubble.

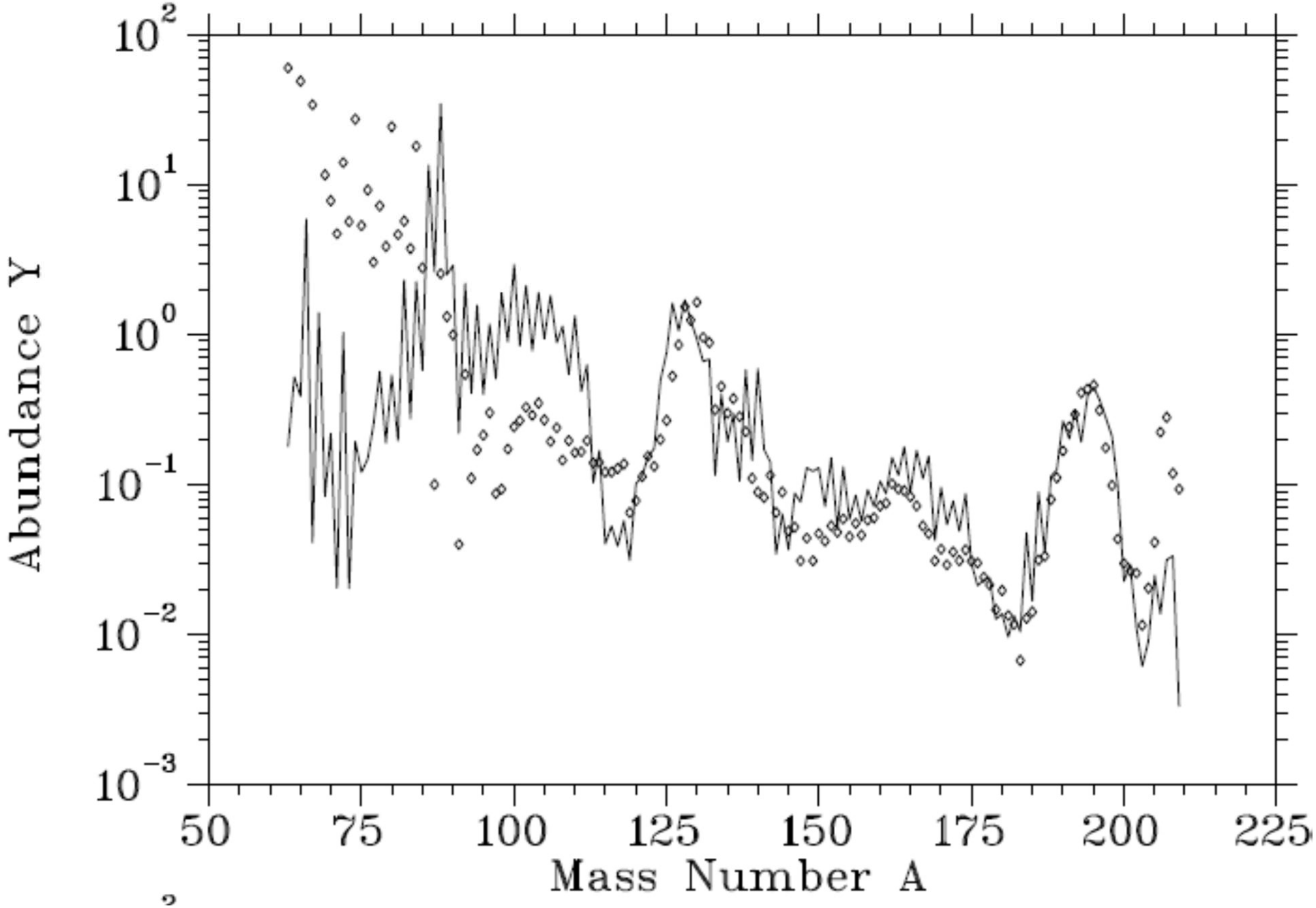


Meyer et al 1992, AJ,399, different , \etta=1-2Ye; Ye=0.35 – 0.46

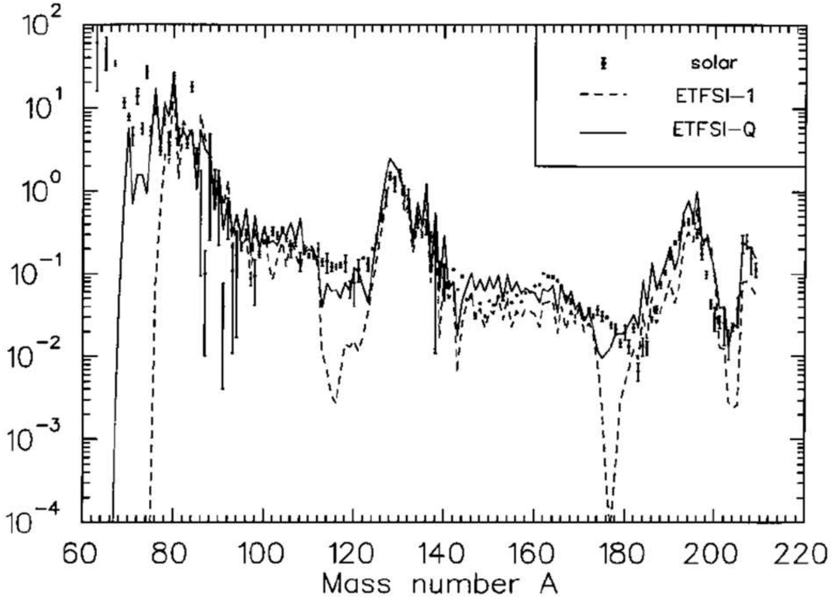
SN: adiabatic expansion model.

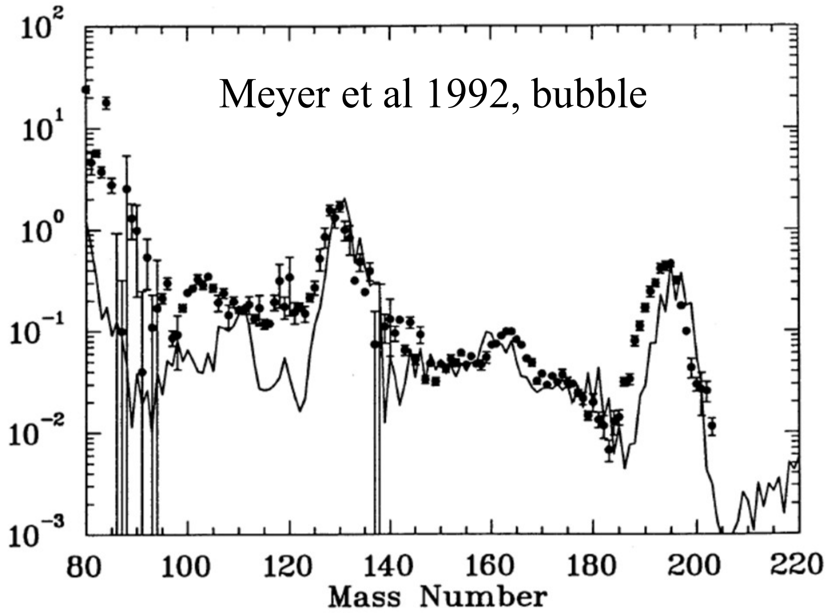


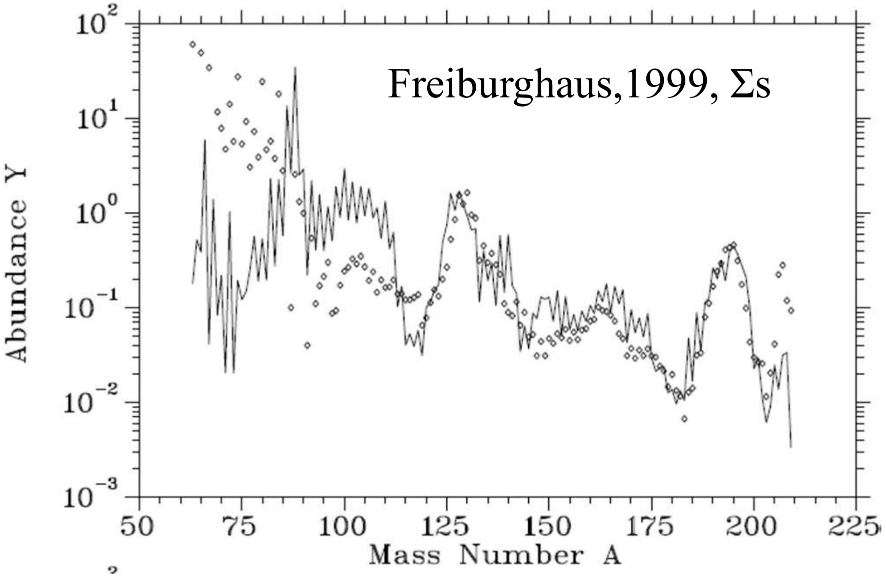
Simulation of r-process conditions for the high-entropy neutrino wind in SNe II. Ye=0.45, superposition of entropies: 130<s<350

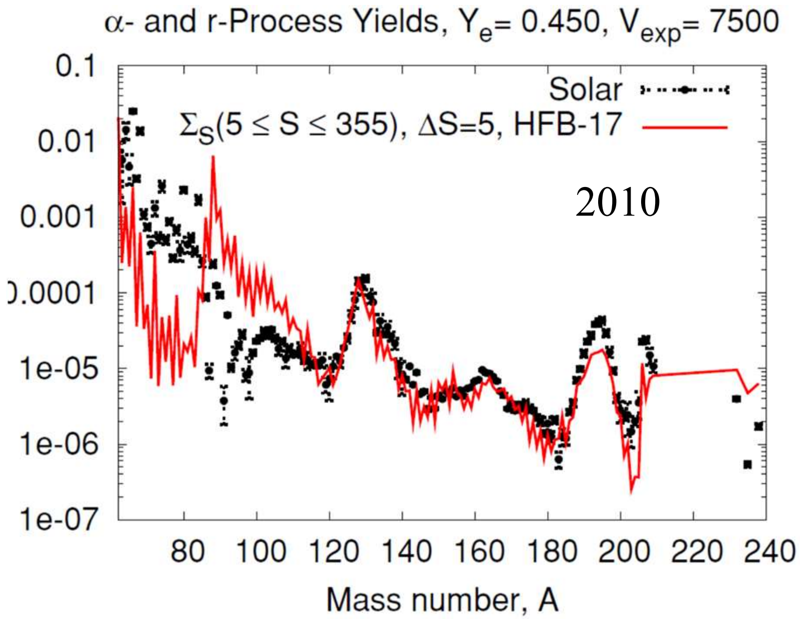


Parametrical study of the r-process conditions in SN (1992-2010)









Which Conditions are necessary for the r-process processing, and r-process modelling?

Seeds, A~40-100; neutron source(?)or strong fraction of neutrons with n_n/seed>20 (150); T9<1.5; $\rho < \sim 10^8$ g/cm^3;

Classical r-process;

Dynanical models:

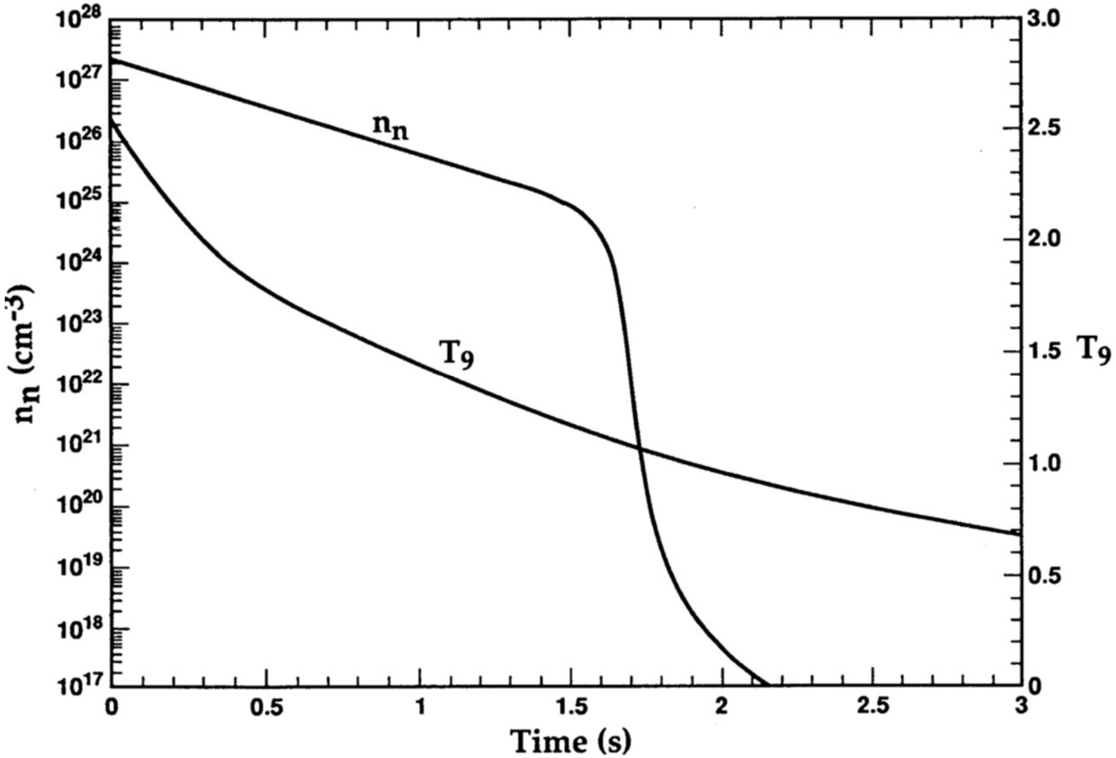
Different high entropy wind scenario:

τ_R<~1c; entropy s>150,

τ_{hyd}<10mc, Ye<0.46;

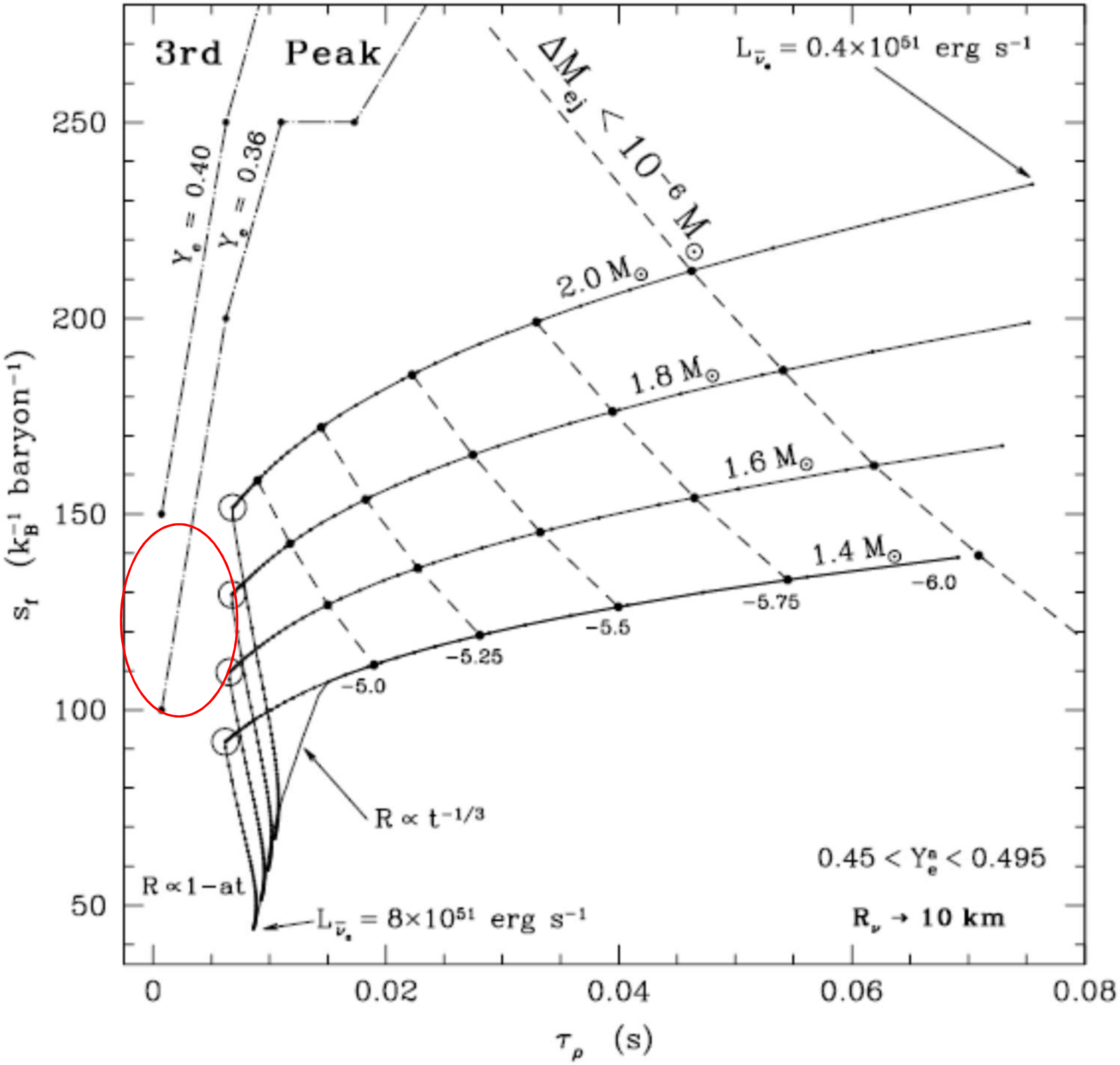
Thompson et al. AJ 562, 2001;

Panov, Janka, AA 2009



Meyer et al. AJ 1992; Woosley 1994

Sites: Proto-neutron star winds



<=
T. A. Thompson, A. Burrows, B. S. Meyer, (AJ, 562:887) 2001 found that winds with S<150, tau<1.3 ms, and 0.47<Ye <0.495 can generate third-peak r- process elements.

Panov, Janka, A&A 494, 829 (2009) (with boundary P) 3d peak: s>100, τ<5ms, Ye <0.46

Final stages of compact binary systems (NS+NS, NS+BH) evolution

Since BBFH the majority of sites for the r-process were connected with SNe explosion: But (T. Fischer et al.2010; L. Hudepohl et al. 2010): Ye>0.5 and formation A>90 is hardly possible from today understanding.

NS+BH – Lattimer J. M., Schramm D. W. AJ., 1974, 192, L145.

NS+NS: - Clark, Eardley, AJ, 215 (1977) p. 311

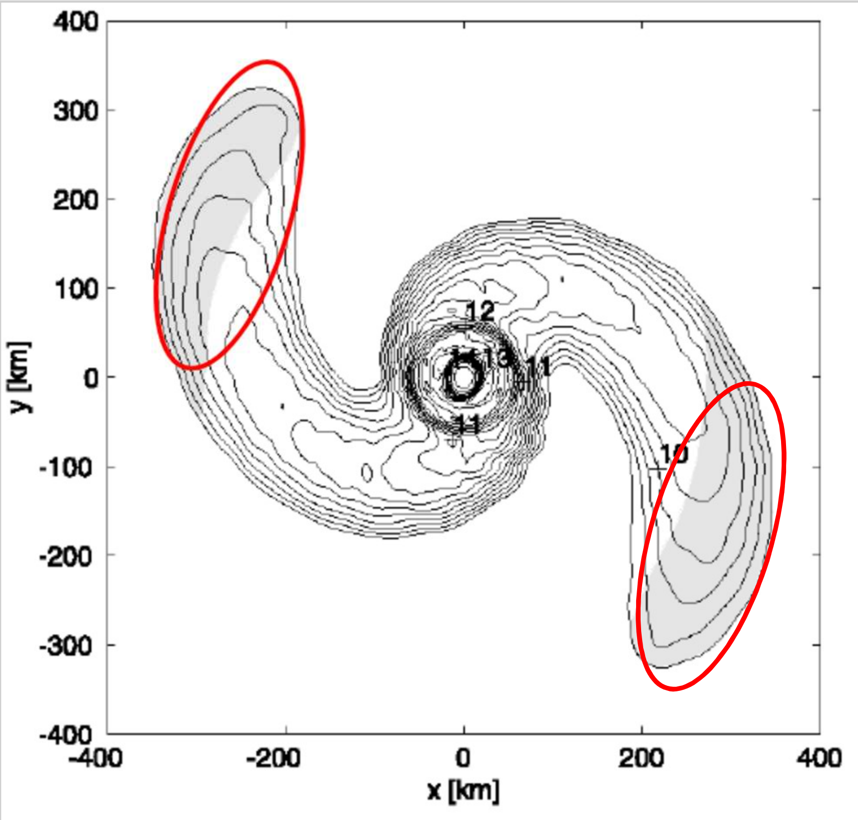
-Blinnikov, Novikov, Perevodchikova, Polnarev, A.Lett. (1984) considered **the evolution of NS+NS or NS+BH. It was shown** that the matter outflow from the neutron star results in quasi-static evolution of the star until **M_min ≈ 0.09Msun and then the explosion.**

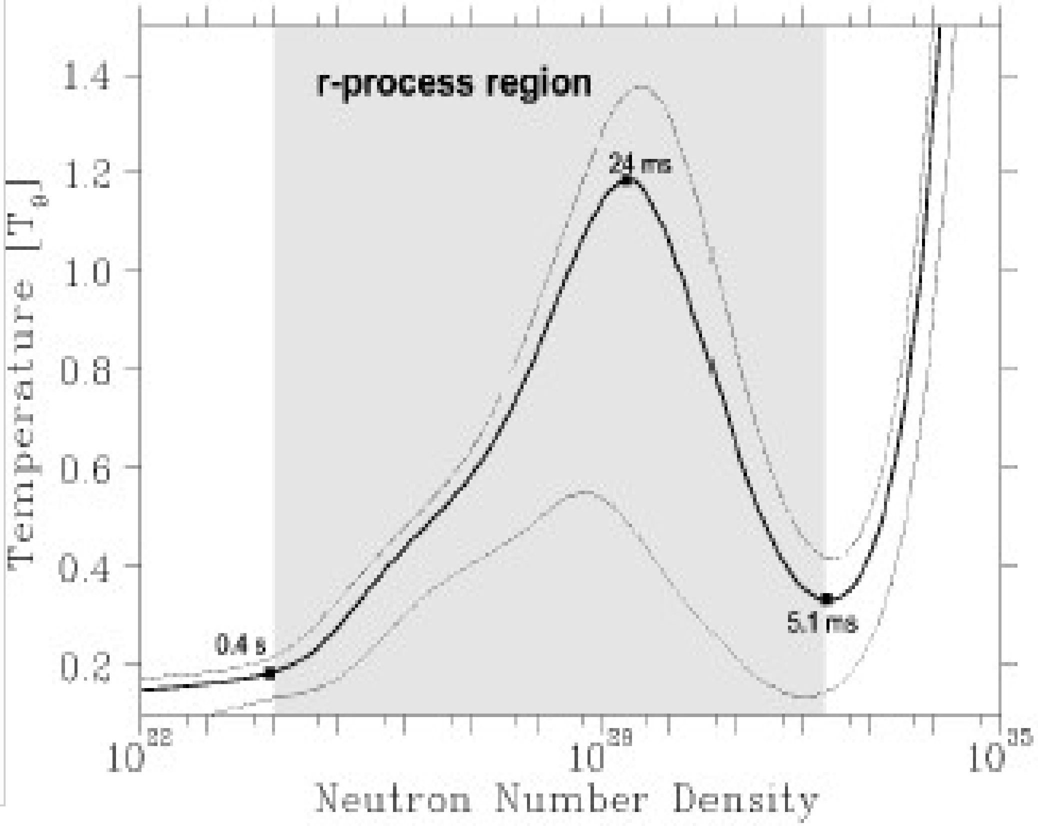
-Symbalisty&Schramm,1982 discuss collision NS+NS in close binary system and resulting ejecta as r-process site;

Rosswog et al. Astron. Astrophys. 341, 499–526 (1999)

The main and new result is "that for the realistic LS-EOS between $4\cdot10^{-3}$M and $4\cdot10^{-2}$M of material become unbound. If, large parts of this matter consist of r-process nuclei, neutron star mergers could account for the whole observed r-process material in the Galaxy. "

Neutron Star Merger scenario.



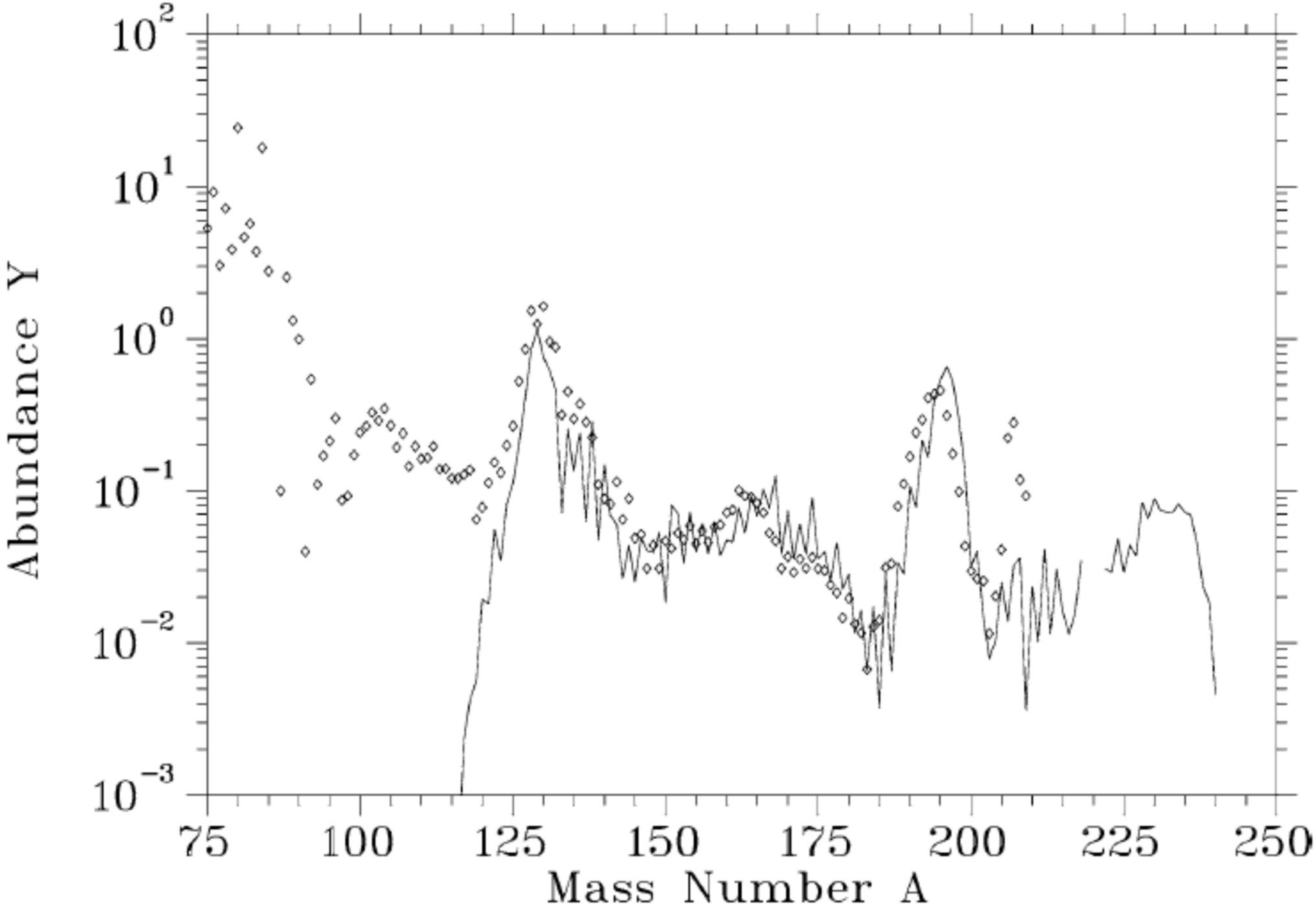


Neutron star merger scenario - $T_9(t)$, $Y_n(t)$, $\rho(t)$

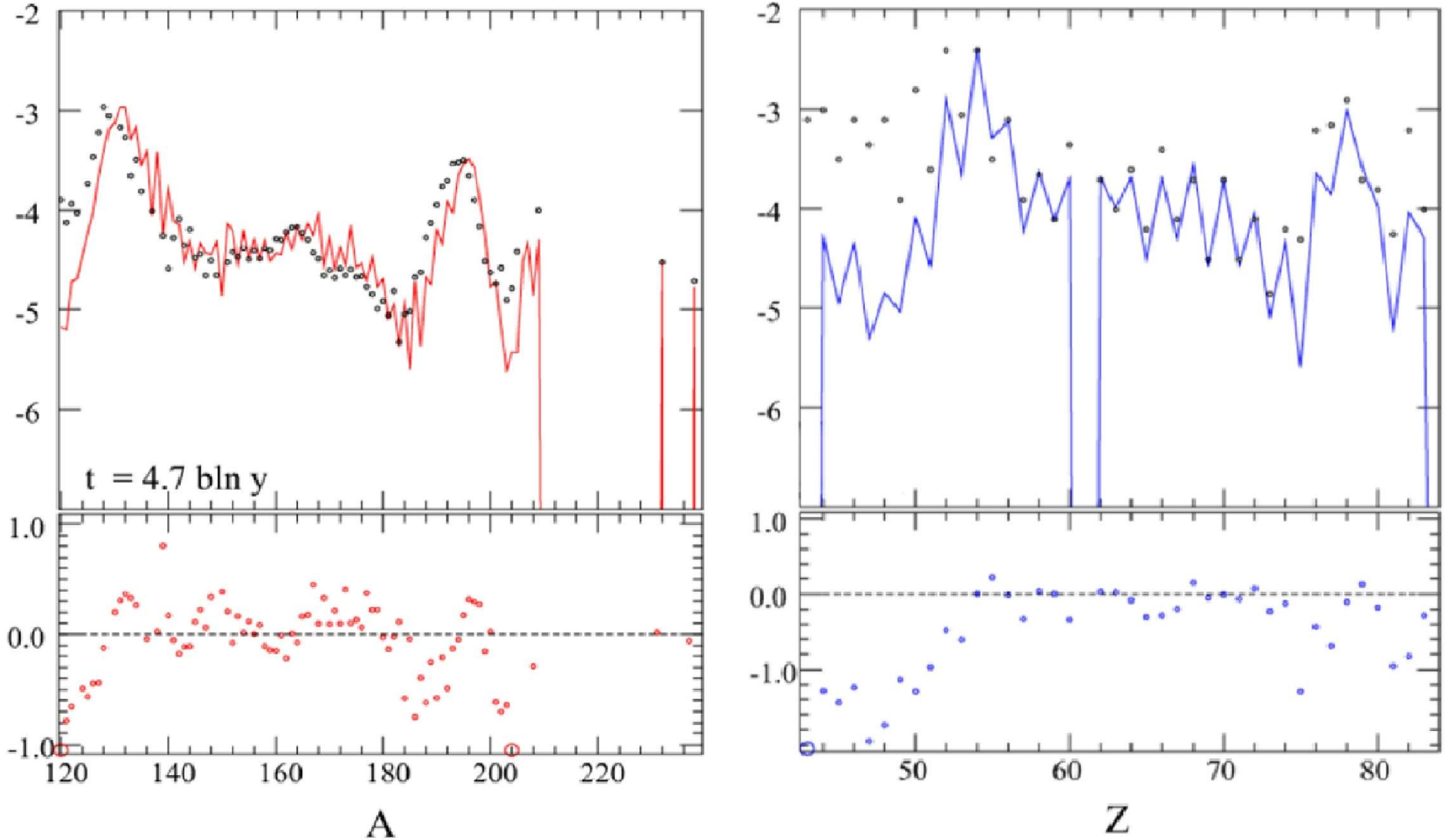
Rosswog et al Astron. Astrophys. 341, 499 (1999)

Freiburghaus et al. AJ 525 (1999) $0.01 < Y_e < 0.20$

NSM, superposition of $\sum Y_A(Ye)$ for $0.08<Ye<0.14$



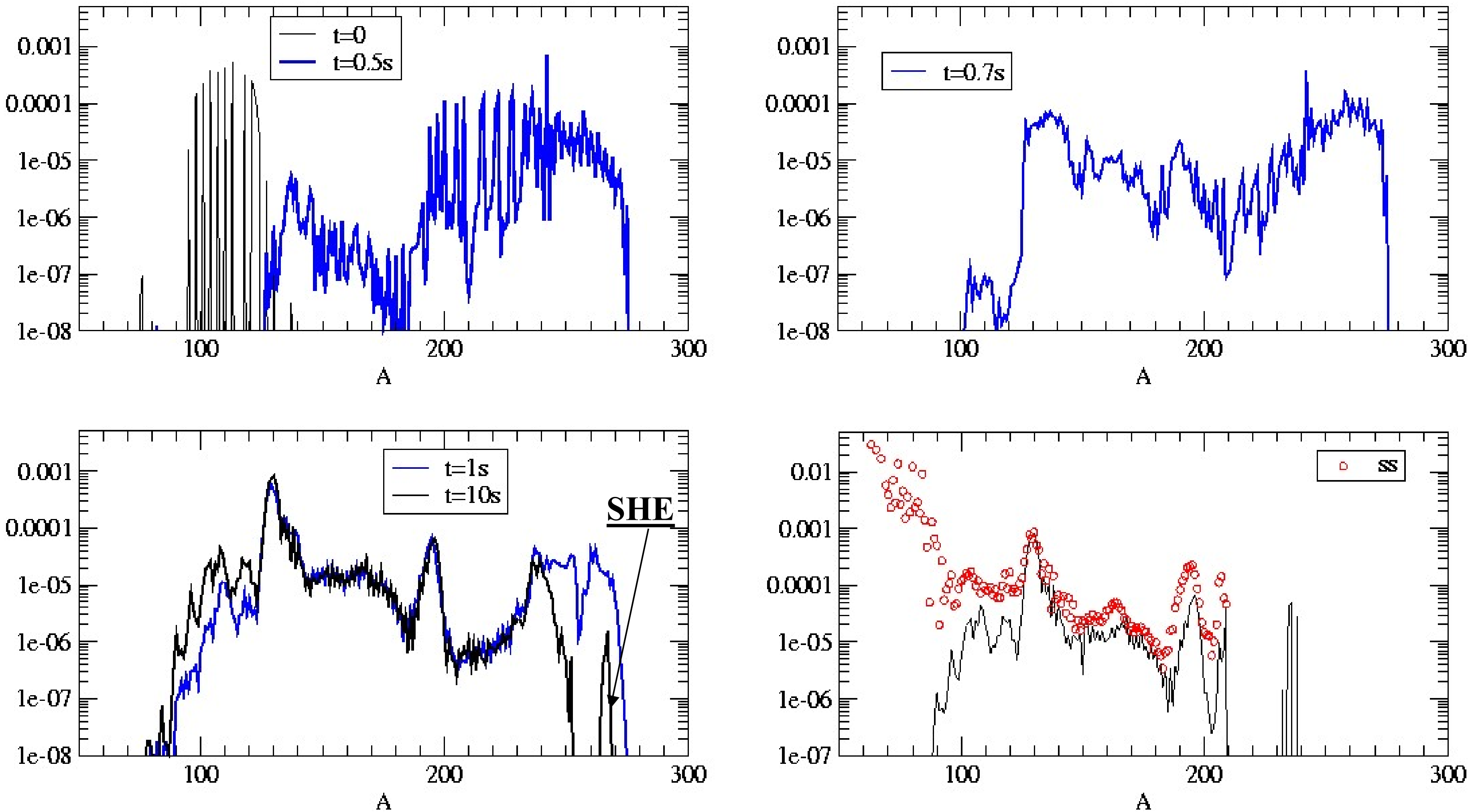
r-process in NSM ejecta for Y_e=0.1 (Panov et al. 1999,2011)



NSM input from Freiburghause,Rosswog,Thielemann 1999

NSM: nucleosynthesis wave propagation and fission cycling

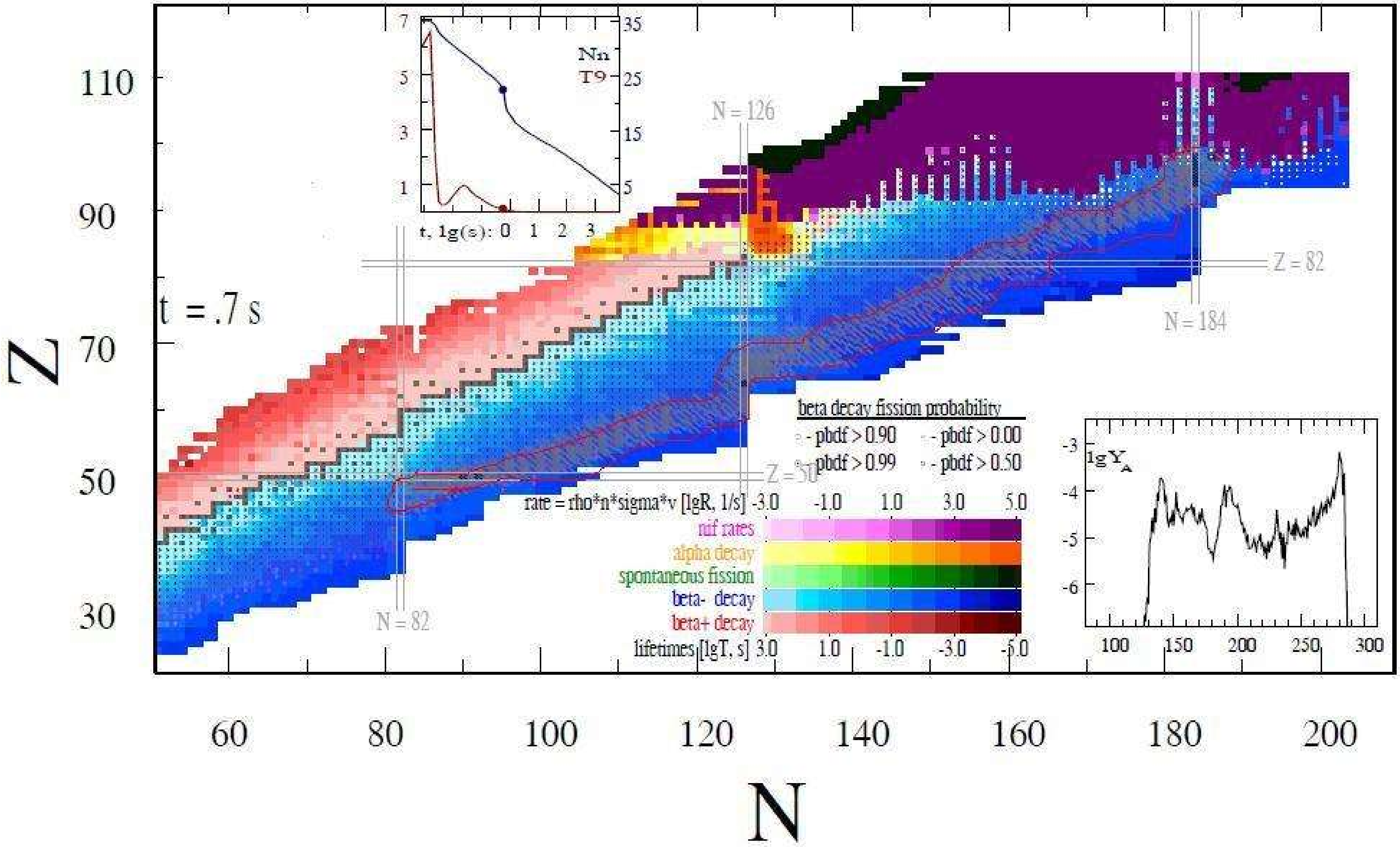
Klapdor, Metzinger, Thielemann, 1983. Beta-delayed fission: Z>92, A~260



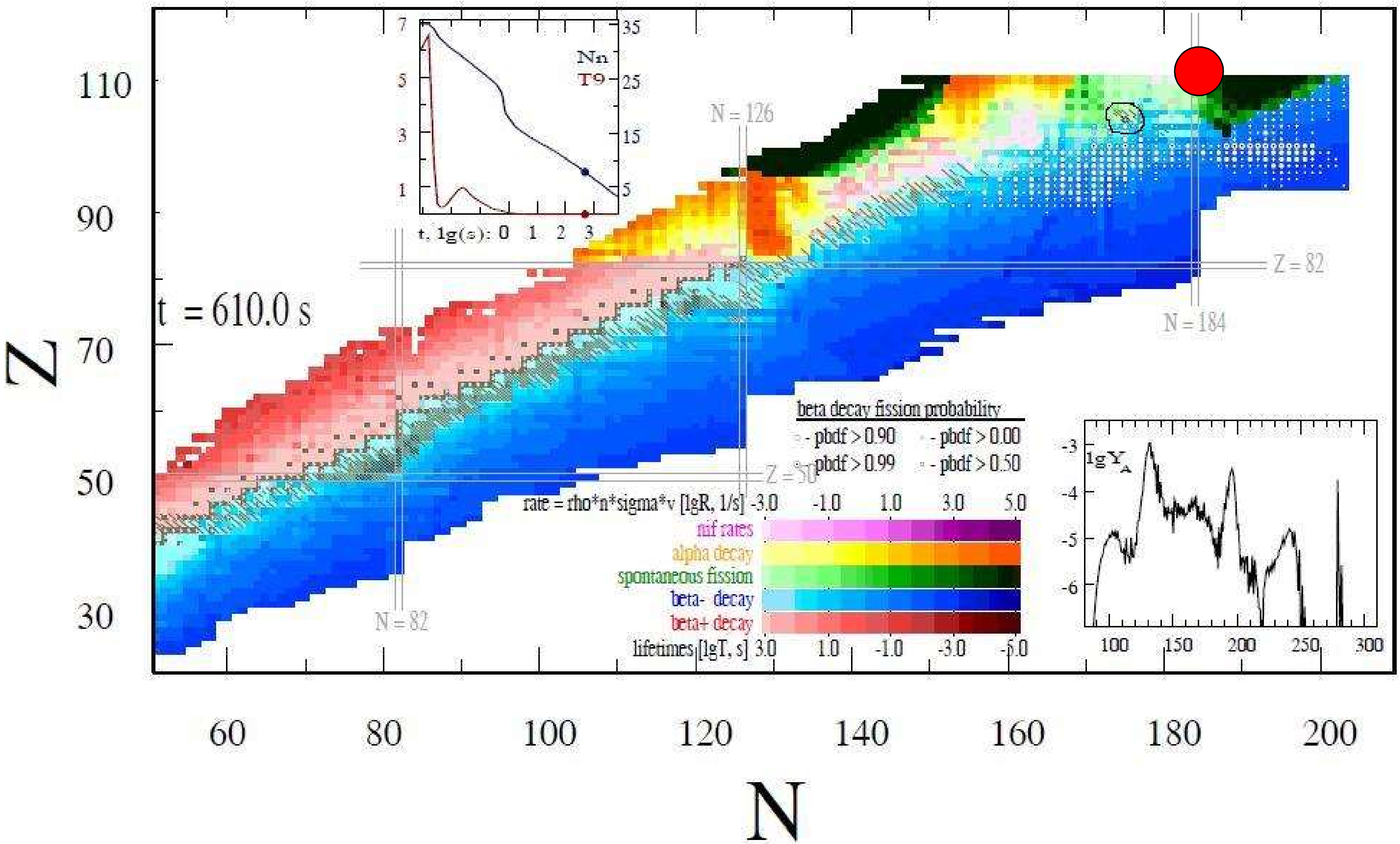
Y(A) with (n,f): Panov et al. 2002, 2005, 2010; $n_{cycl} = (\log_2(\Sigma Y_f/\Sigma Y_{in})) \sim 1$

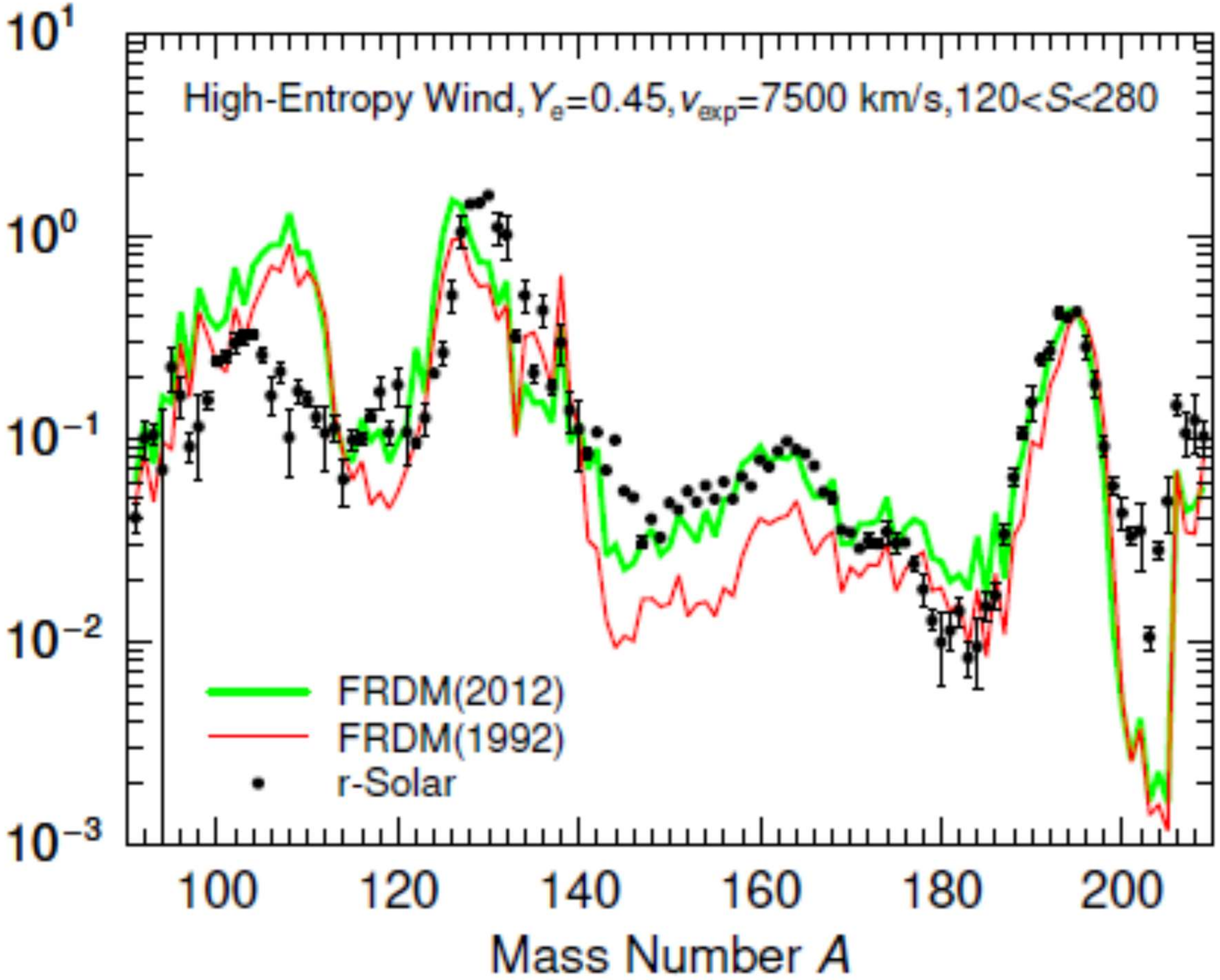
Trajectory Ye=0.1 from Freiburghause, Rosswog, Thielemann, 1999

Resulting sites



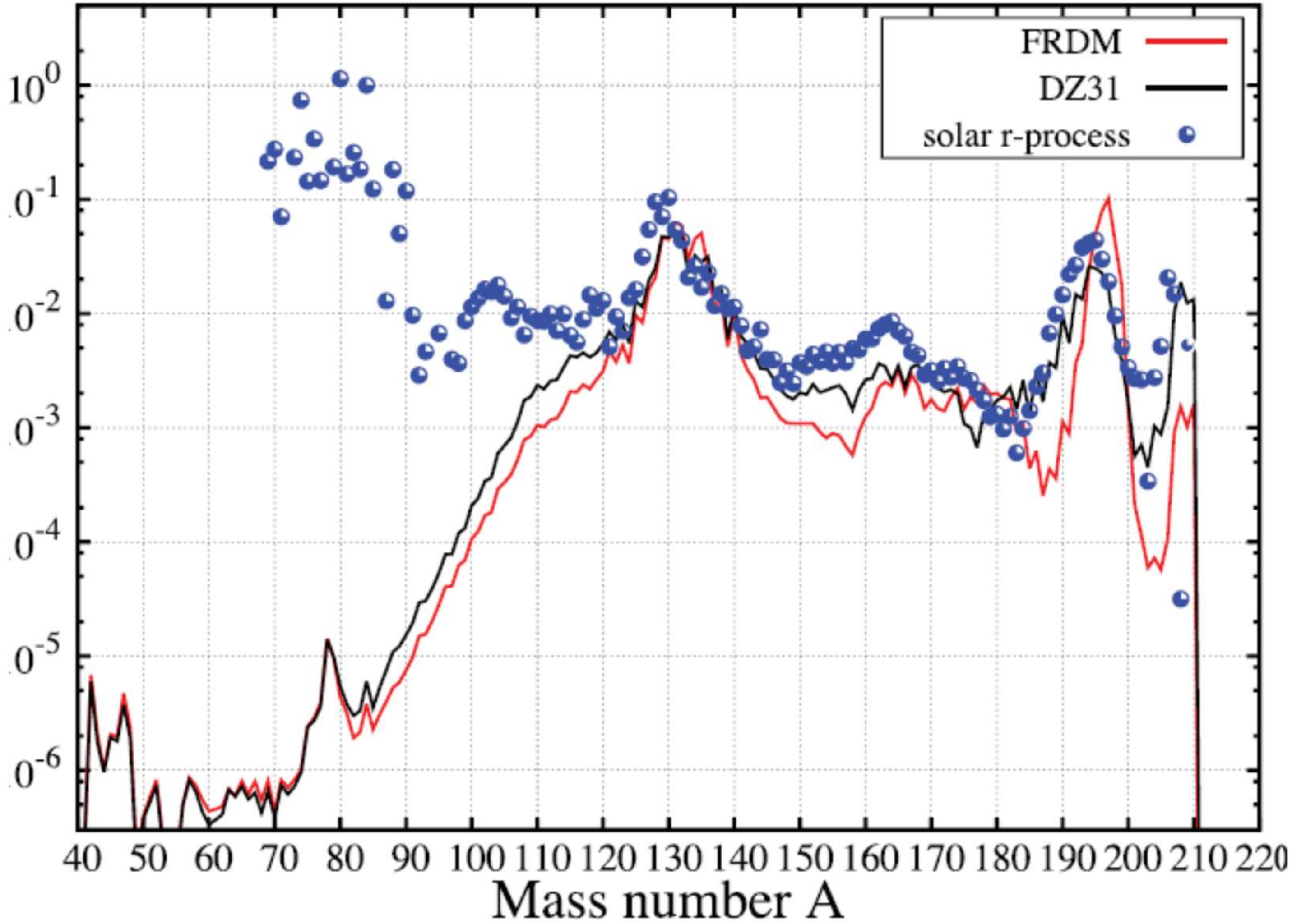
Resulting sites



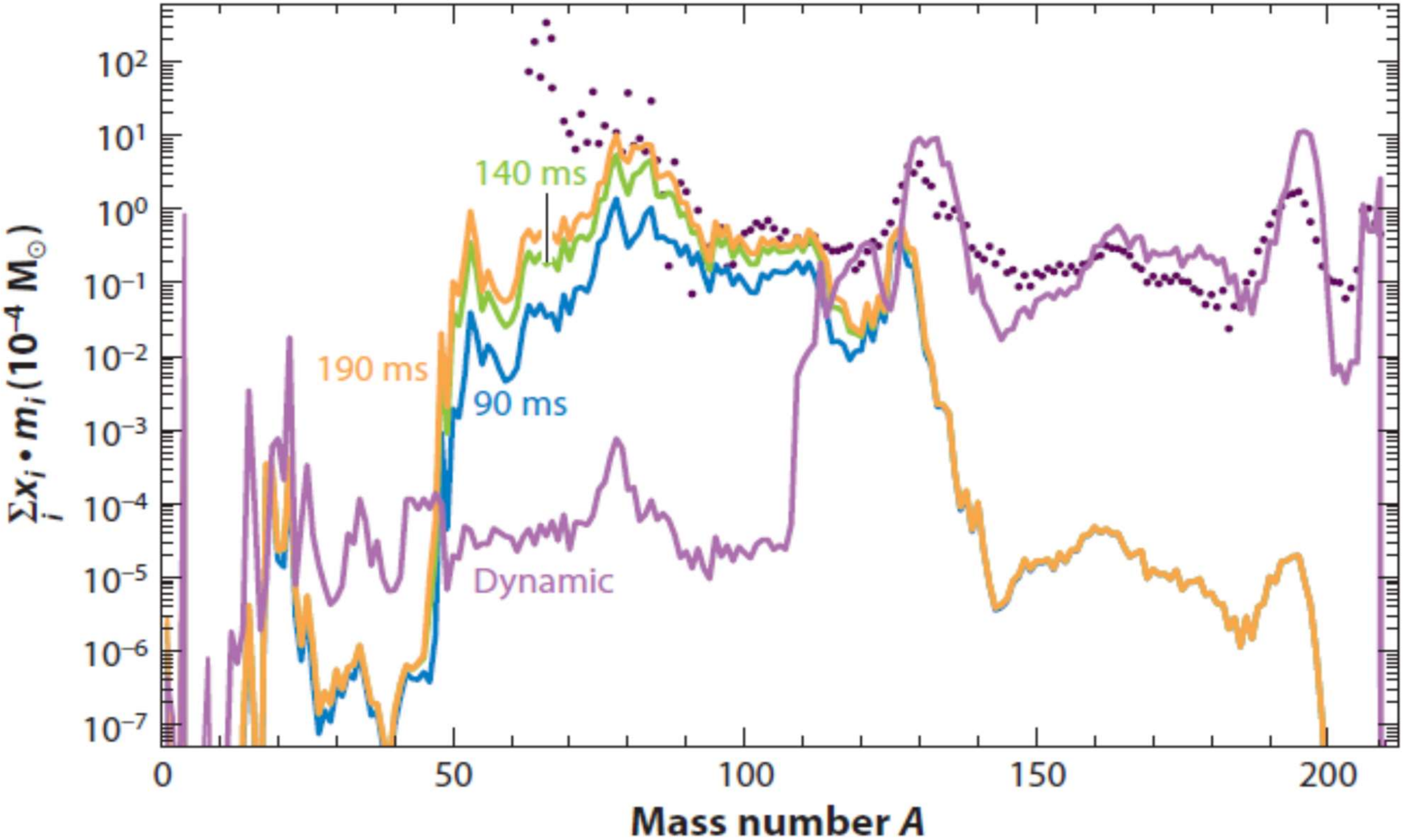


Ya with diff. FRDM masses (Figure from review Cowan et al. 2019)

Resulting element distribution for dynamic ejecta
S Rosswog, et al. Class. Quantum Grav. 34, 2017

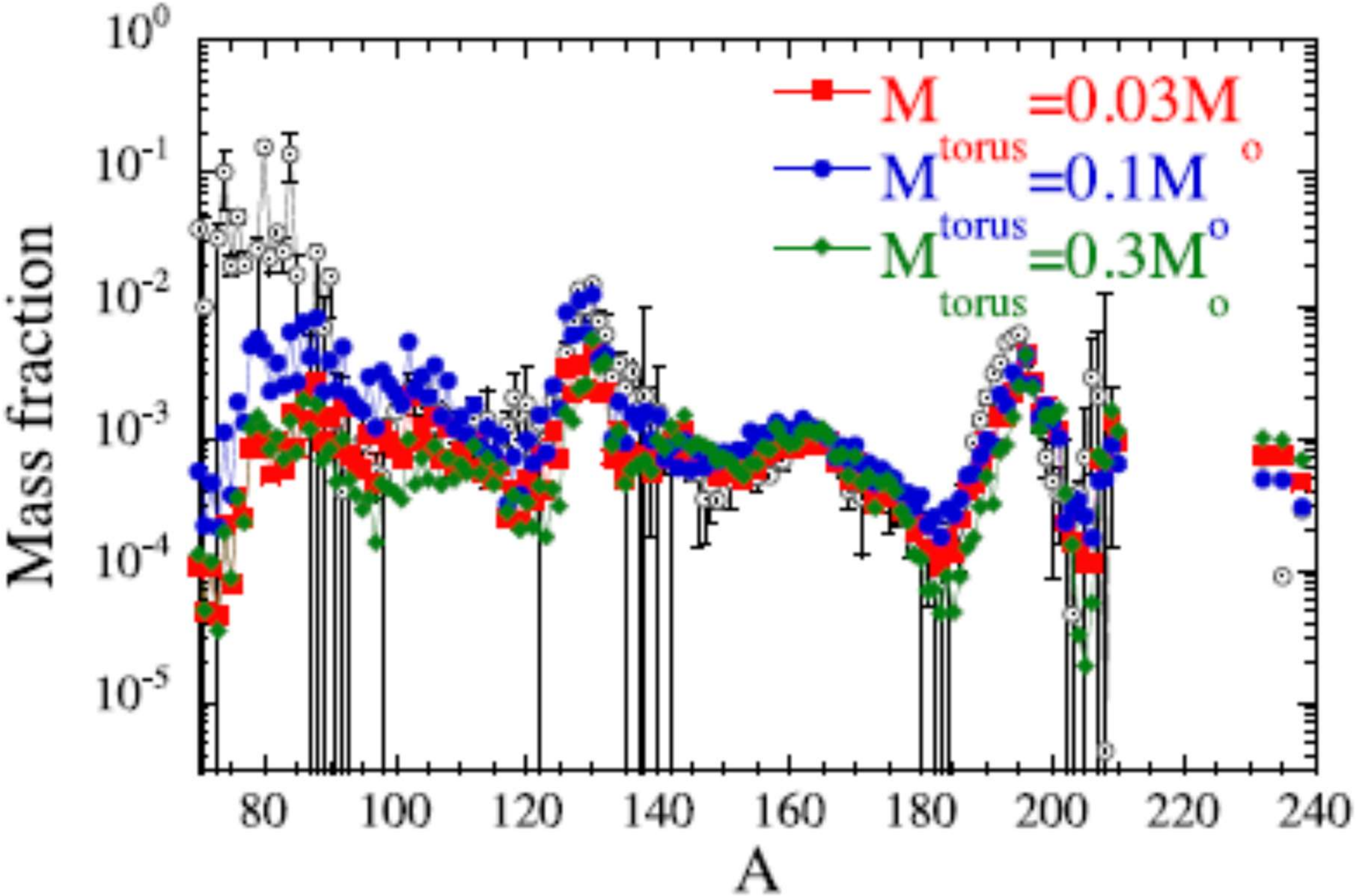


The neutrino wind contribution (Martin, et al. AJ. 813 (2015)). Dynamic ejecta (Korobkin, Rosswog, et al.MNRAs,426,2012)



Modified Figure (Martin et al.2015) from Cowan et al. RMP, 2019

Combined mass fractions produced by the dynamical ejecta and disk wind for 3 disk masses from Just et al. (MNRAS 448,2015) were discussed by R. Fern´andez, B.Metzger, ARNPS 66, 2016.



https://www.ligo.caltech.edu/page/press-release-gw170817

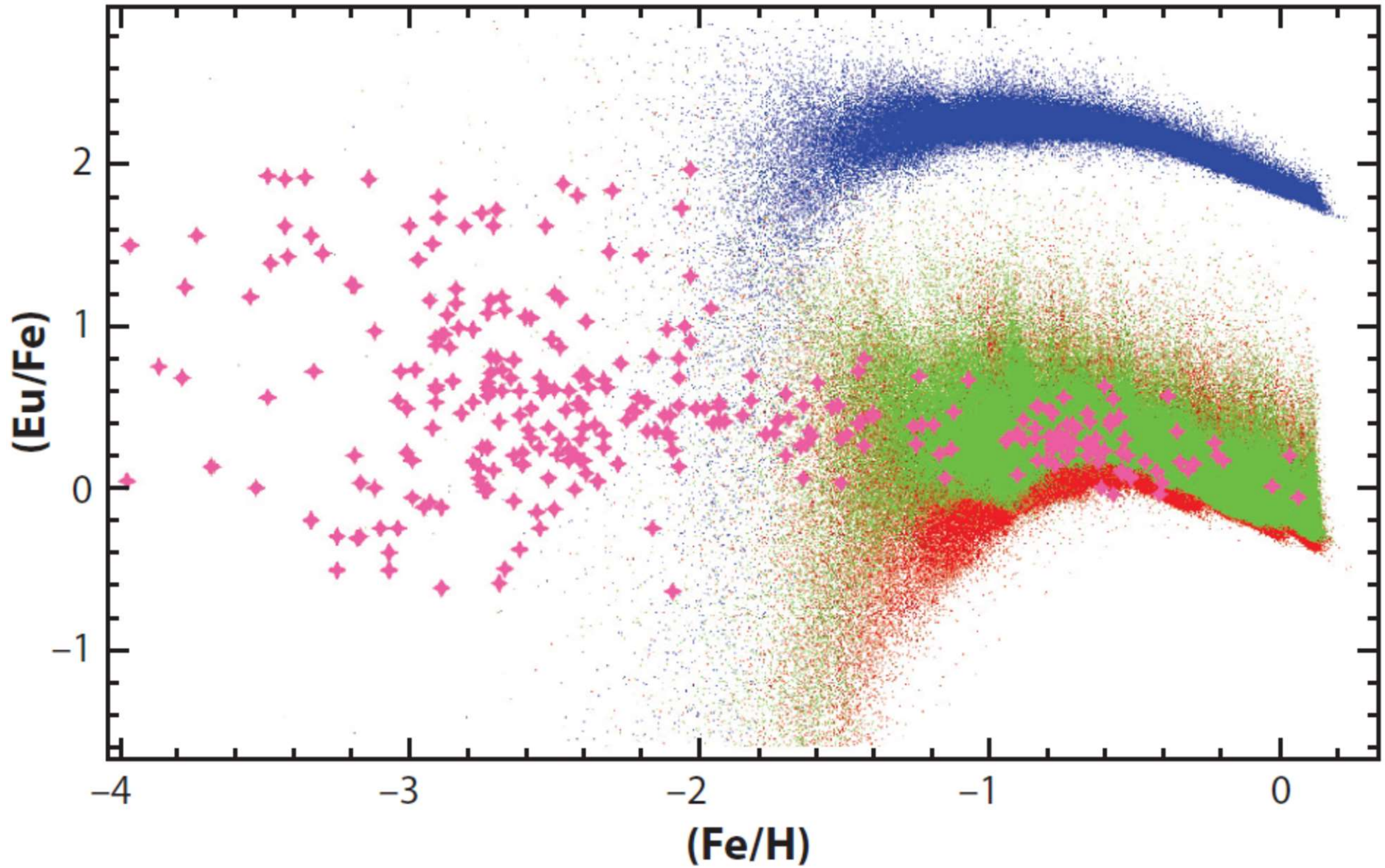
THE EMERGENCE OF A LANTHANIDE-RICH KILONOVA FOLLOWING THE MERGER OF TWO NEUTRON STARS

Tanwir,..Korobkin, ..Rosswog….

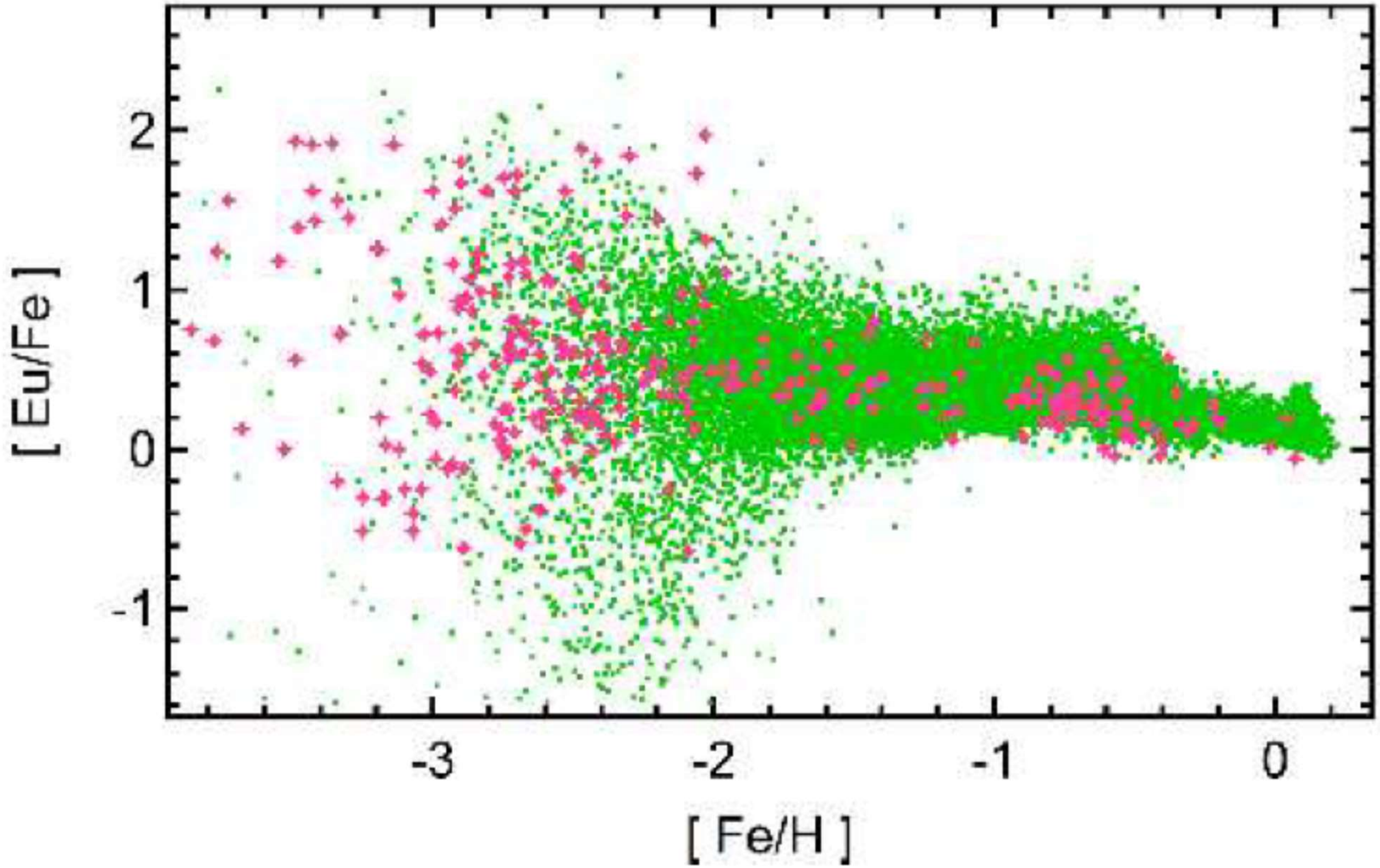
2017arXiv171005455T 16.October 2017

We report the discovery and monitoring of the near-infrared counterpart (AT2017gfo) of a binary neutron-star merger event detected as a gravitational wave source by Advanced LIGO/Virgo (GW170817) and as a short gamma-ray burst by Fermi/GBM and Integral/SPI-ACS (GRB 170817A). The evolution of the transient light is consistent with predictions for the behavior of a \kilonova/macronova", powered by the radioactive decay of massive neutron-rich nuclides created via r-process nucleosynthesis in the neutron-star ejecta. In particular, evidence for this scenario is found from broad features seen in Hubble Space Telescope infrared spectroscopy, similar to those predicted for lanthanide dominated ejecta, and the much slower evolution in the near-infrared Ks-band compared to the optical. This indicates that the late-time light is dominated by high-opacity lanthanide-rich ejecta, suggesting nucleosynthesis to the 3rd r-process peak (atomic masses A□ 195). This discovery confirms that neutron-star mergers produce kilo-/macronovae and that they are at least a major - if not the dominant - site of rapid neutron capture nucleosynthesis in the universe.

Influence of the coalescence timescale and neutron star merger probability on Eu abundances in galactic chemical evolution. The magenta stars represent observations.



Evolution of Eu-abundances in galactic chemical evolution models,



including both magneto-rotational SNe and NSMs as r-process sites (figures from Wehmeyer et al., MNRAS 452, 2015)

conclusion remarks

The first observation of the r-process site (GW170817) in 2017, confirmed that neutron star mergers are probably the most important site for the r-process:

- models of compact binary mergers indicate that they can be sites of the main r-process
- The magneto-rotational core-collapse supernovae could lead to neutron stars with huge magnetic fields – the existed models show r-process matter ejected in polar jets;
- further understanding and modelling of the evolution of massive stars are needed for understanding whether the neutron rich matter available for the r-process can be formed in these massive stars.
- Some supernovae, where weak r-process can be supported with formation of nuclei with A<150, also can exist.

conclusion remarks

Strong efforts to improve different nuclear data are needed:

- predictions of nuclear masses as well as fission barriers;
- properties of neutron-rich nuclei far from stability:
- beta-decay properties and alpha-decays;
- spontaneous and neutron-induced fission as well as fission cycling, leading to new seed nuclei (fission products) and mass distribution of fission products;
- neutron captures, including direct capture, - the main engine for the r-process.

Thank you !

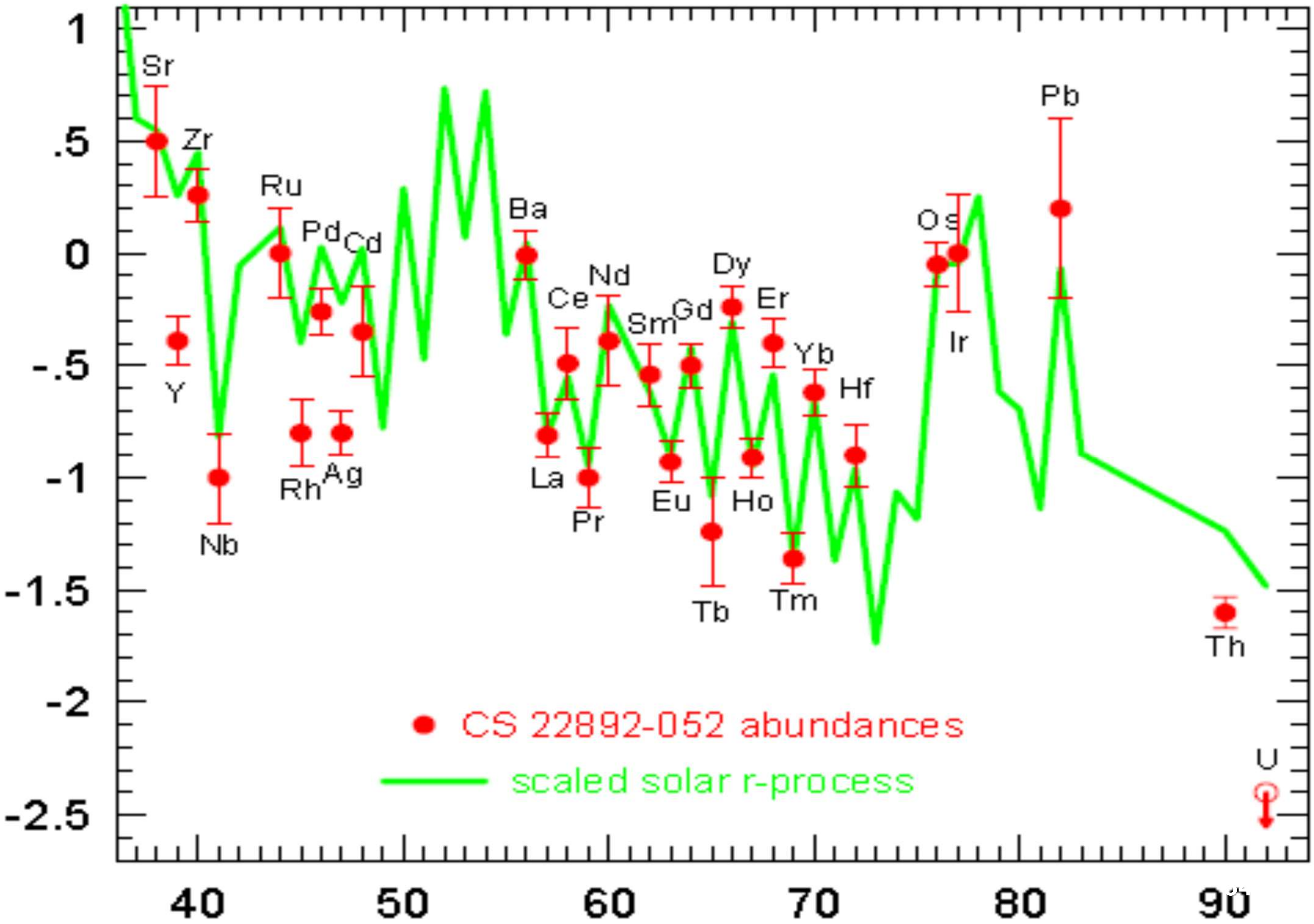
- Participants for attention
- colleagues - for collaboration

Now it was known 118 Chemical Elements. Louis de Broglie and Lavoisier proposed (instead of Aristotle’s 4 entities: air, fire, ground, water) corpuscular theory; then Dalton in XIX start to consider Ch.E. on the basis of atom-molecular theory, adopted by community in 1960. And periodic law was published in 1869.

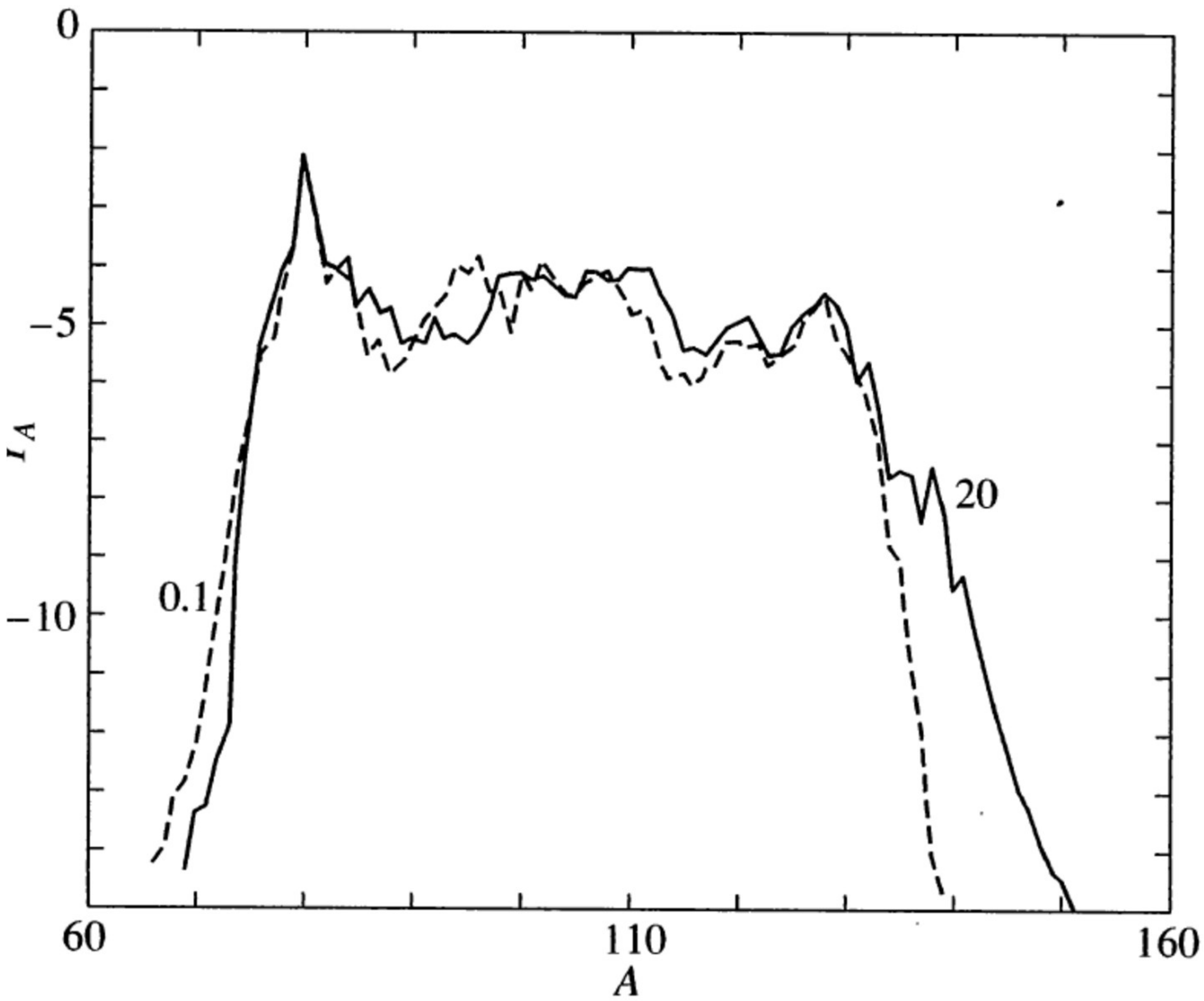
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	105	106	107	108	109	110	111	112	113	114	115	116		118
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

In ancient world it was known up to 11 elements C,S,Fe,Cu,As,Ag, Sn, Sb, Au,Hg,Pb. In 1869 63 Chemical Elements were known.

Sneden, Cowan et al. The Astrophysical Journal, 591, 613–633, 2003 ([Fe/H] = –3.1)



NSE, seed nuclei



Panov, Chechetkin, Astronomy Letters, 2002;
Etta=(N-Z)/A=1-2Ye=0.28;   Ye=0.36, T_9~5, ρ~10^9