r-Process Nucleosynthesis (in neutron star mergers): Discussion session I

Friedrich-Karl Thielemann

Department of Physics and Gesellschaft für Schwerionenforschung (GSI)
University of Basel Darmstadt
Switzerland Germany

A bit of very early history on NS-mergers

- Lattimer & Schramm (1974/76) suggested neutron star – BH or implicitely als neutron star mergers as r-process sites

- Symbalisty & Schramm (1982) explicitely mentioned neutron star mergers as r-process sites

- Nucleosynthesis from the decompression of initially cold neutron star matter (Meyer & Schramm 1988, general decompression consideration)

- Nucleosynthesis, neutrino bursts & gamma-rays from coalescing neutron stars (Eichler, Livio, Piran, Schramm 1989, setting up the scheme)

- Merging neutron stars. 1. Initial results for coalescence of noncorotating systems (Davis, Benz, Piran, Thielemann 1994, estimate: obout $10^{-2} M_\odot$ of ejecta)

- Mass ejection in neutron star mergers (Rosswog, Liebendörfer, Thielemann, Davies, Benz, Piran 1999, $4 \times 10^{-3} - 4 \times 10^{-2}\ M_\odot$ get unbound in realistic simulations)

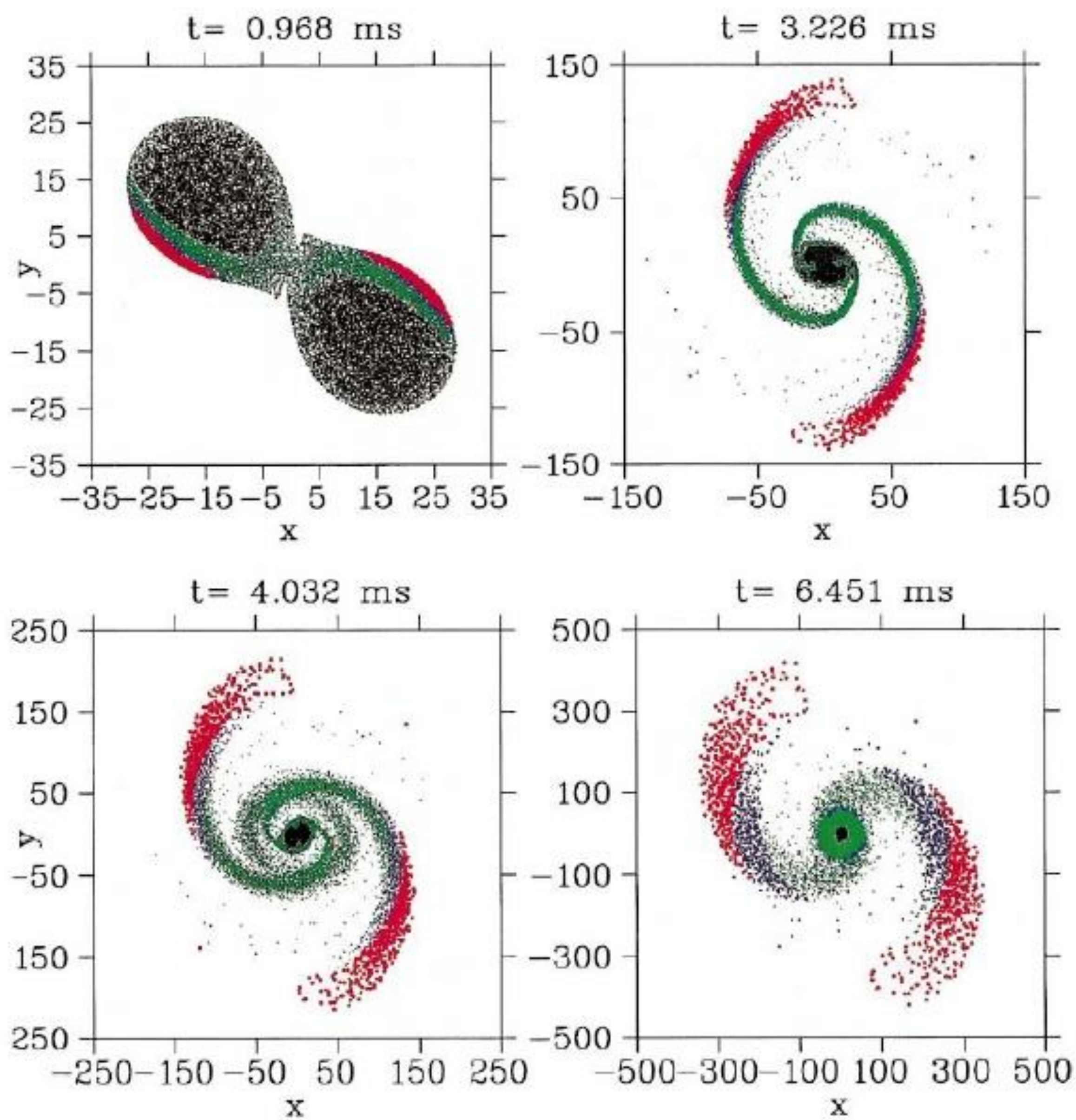
- r-Process in Neutron Star Mergers (Freiburghaus, Rosswog, Thielemann 1999, **first detailed abundance distribution prediction**)

Early and later SPH simulations

r -process site: NSMs and their «dynamic ejecta»

Rosswog et al.
A&A 341 (1999), 499

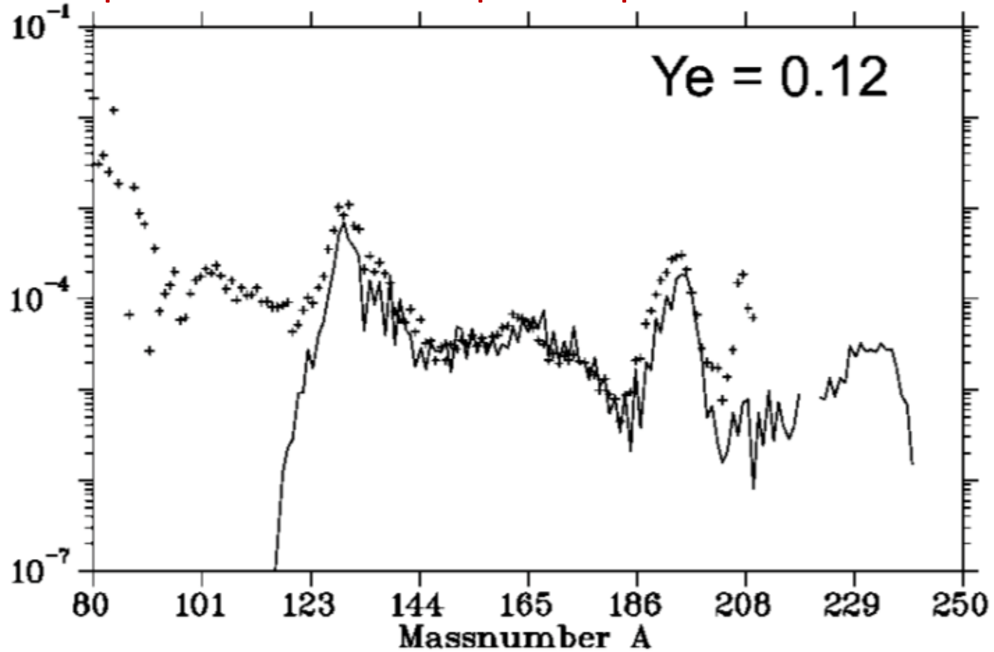
only tidal arm ejecta in early approaches



Newtonian SPH simulaton, FRDM mass model, assuming Ye of ejecta to be 0.12, simple fission description, symmetric fission for nuclei above A=250

Freiburghaus, Rosswog, Thielemann 1999

a huge neutron/seed ratio >200 permits neutron capture up to the actinides and beyond (+fission cycling).



Which improvements happened since then, how well do we understand things?

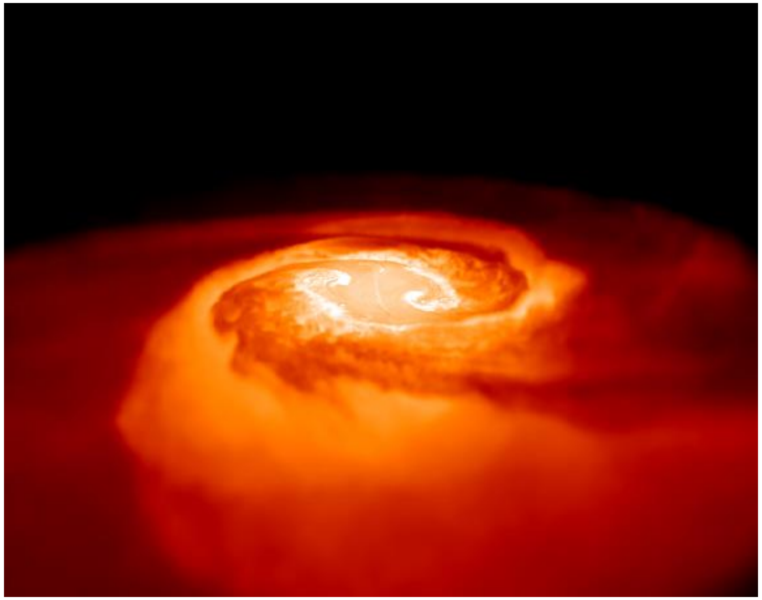
(a) Modelling: Highly increased resolution, (i) Newtonian, (ii) conformally flat, and (iii) fully relativistic simulations; How dramatic are the differences between (ii) and (iii). What is the impact of MHD?

(b) The role of nuclear input: EoS, improved mass models, half-lives, fission barriers, fission fragment distributions, neutrino interactions with matter

(c) What is the role of different substructures in the ejecta: (i) dynamic ejecta with tidal arm and polar ejecta from collsion, (ii) neutrino wind during hypermassive neutron star stage, (iii) disk outflows from BH accretion disk in late phases

---- How do these different aspects interact?

Modelling:
What is the structure of dynamic ejecta?

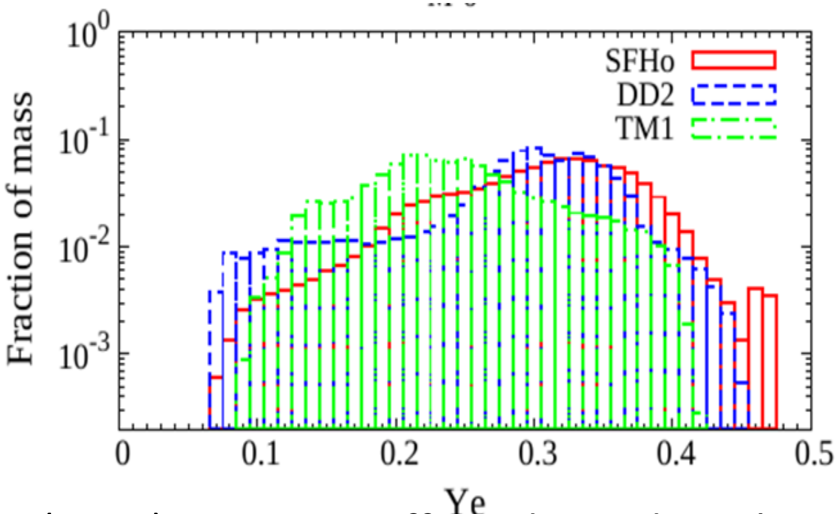


Rosswog et al. (2014)
Newtonian approaches seem not to show (polar) ejecta due to collisional compression

Relativistic approaches, like

- ***conformally flat*** treatments (starting with Oechslin+(2002), Bauswein, Janka, Just .. Garching) see these (polar) collosional ejecta due to deeper potential well in relativistic treatments and thus stronger collisions.

- ***Fully relativistic*** GR treatments (starting with Shibata & Uryu (2000) and now a truely extended community (see yesterday's talk by S. Bernuzzi and the discussion session by Shibata as well as Rezolla and Perego) clearly see this part of the ejecta structure which has a dramatic impact on the nucleosynthesis in dynamic ejecta

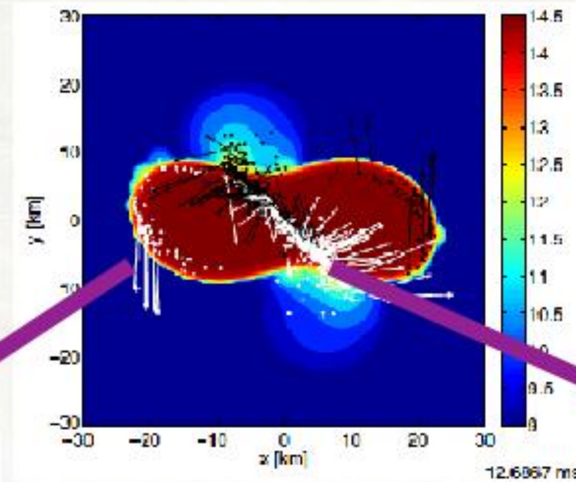


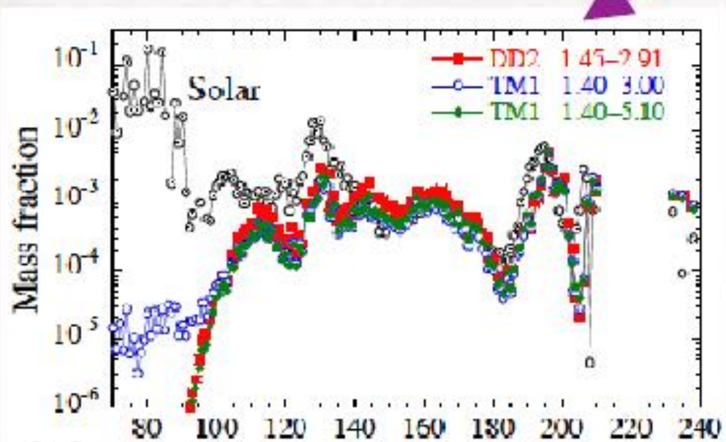
Sekiguchi+ (2015), strong Ye effect, depending also in EoS

Prompt / dynamical Ejecta

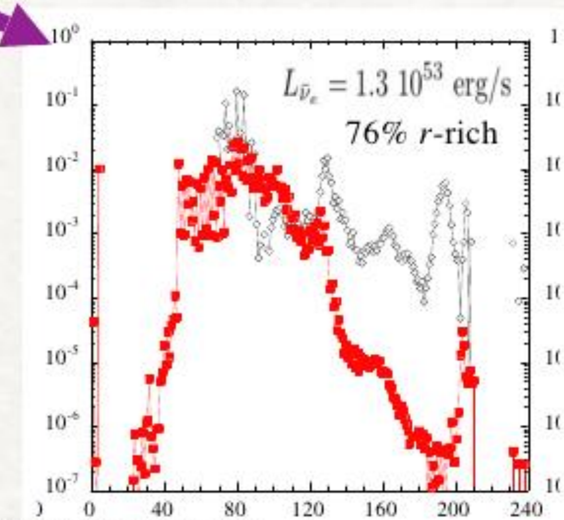
(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16)

from Just (2018) Shanghai talk





(OJ, Bauswein, Ardevol, Goriely, Janka '15)

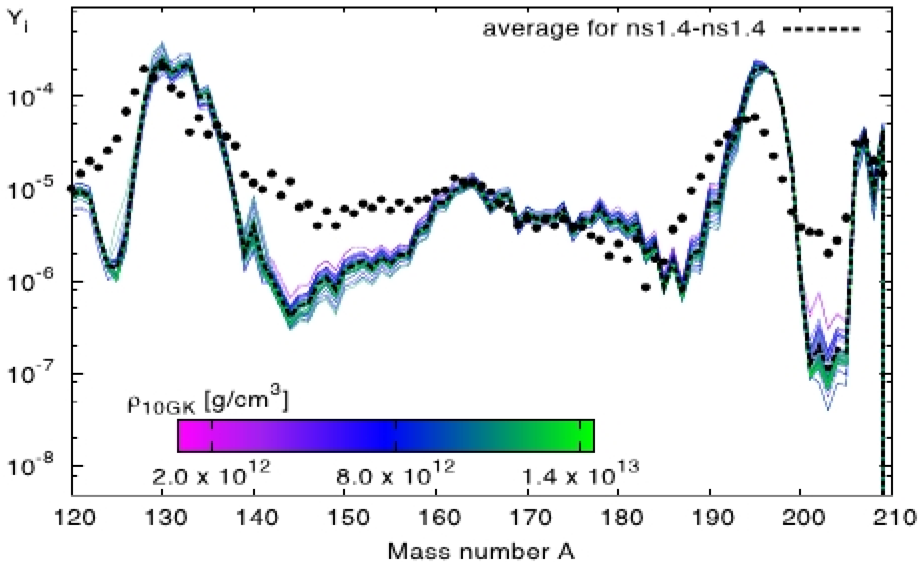


(Goriely et al '15+'18)

from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

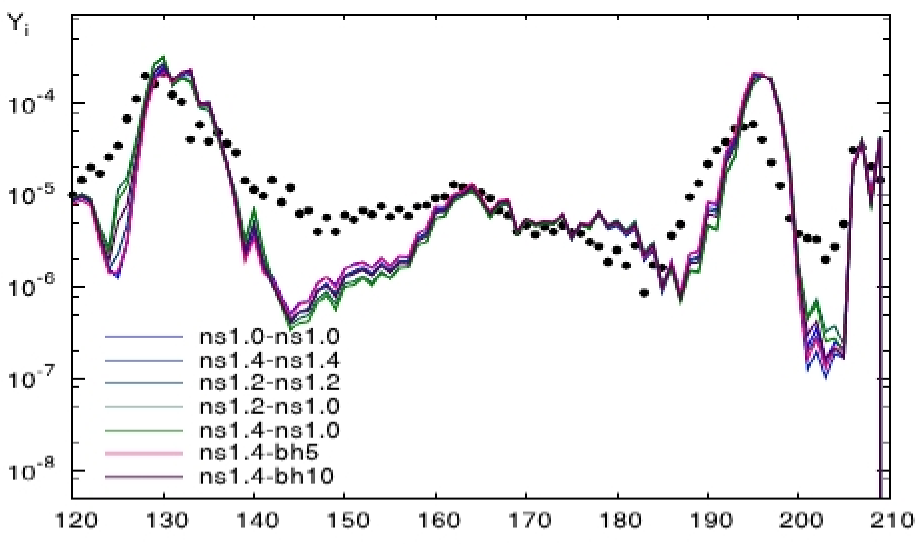
from collision shock
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

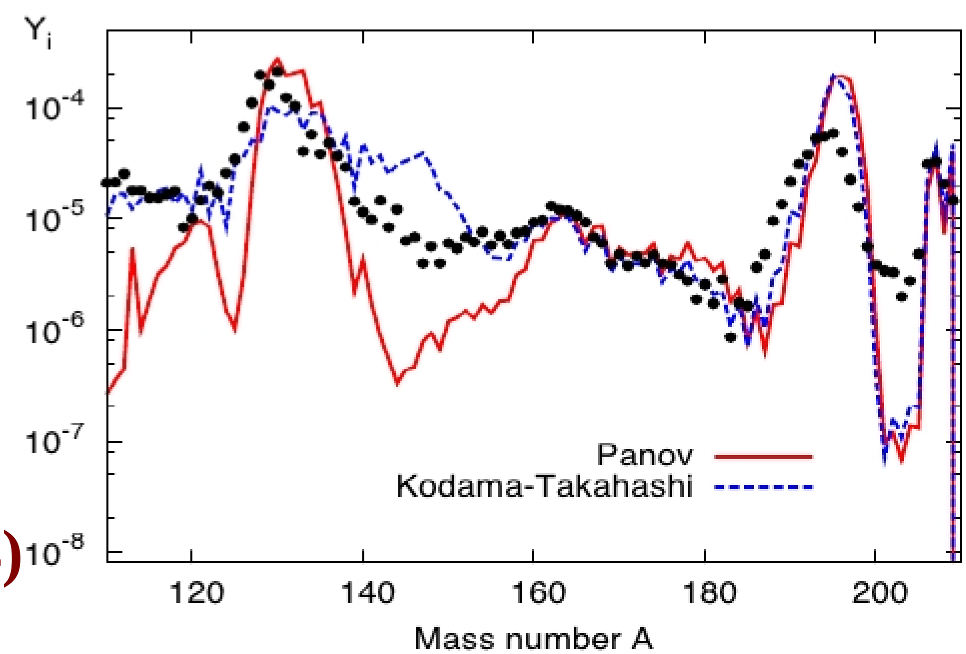
Nuclear Input:
Dependence on Fission Probabilities and Yields



Dynamic neutron star merger ejecta in non-relativistic calculations (Korobkin et al. 2012, see also Rosswog + 2014)

fission yields affect abundances below A=165, the third peak seems always shifted to heavier nuclei





Ejected mass of the order 10 $^{-2}$ M $_{sol}$
conditions very neutron-rich (Ye=0.04)
[all related to dynamic ejecta]

After charged-particle freeze-out quasi-equilibrium clusters emerge along isotopic chains, leading to (n,γ)-(γ,n) equilibrium which is in place up to about 1s (Eichler et al. 2015)

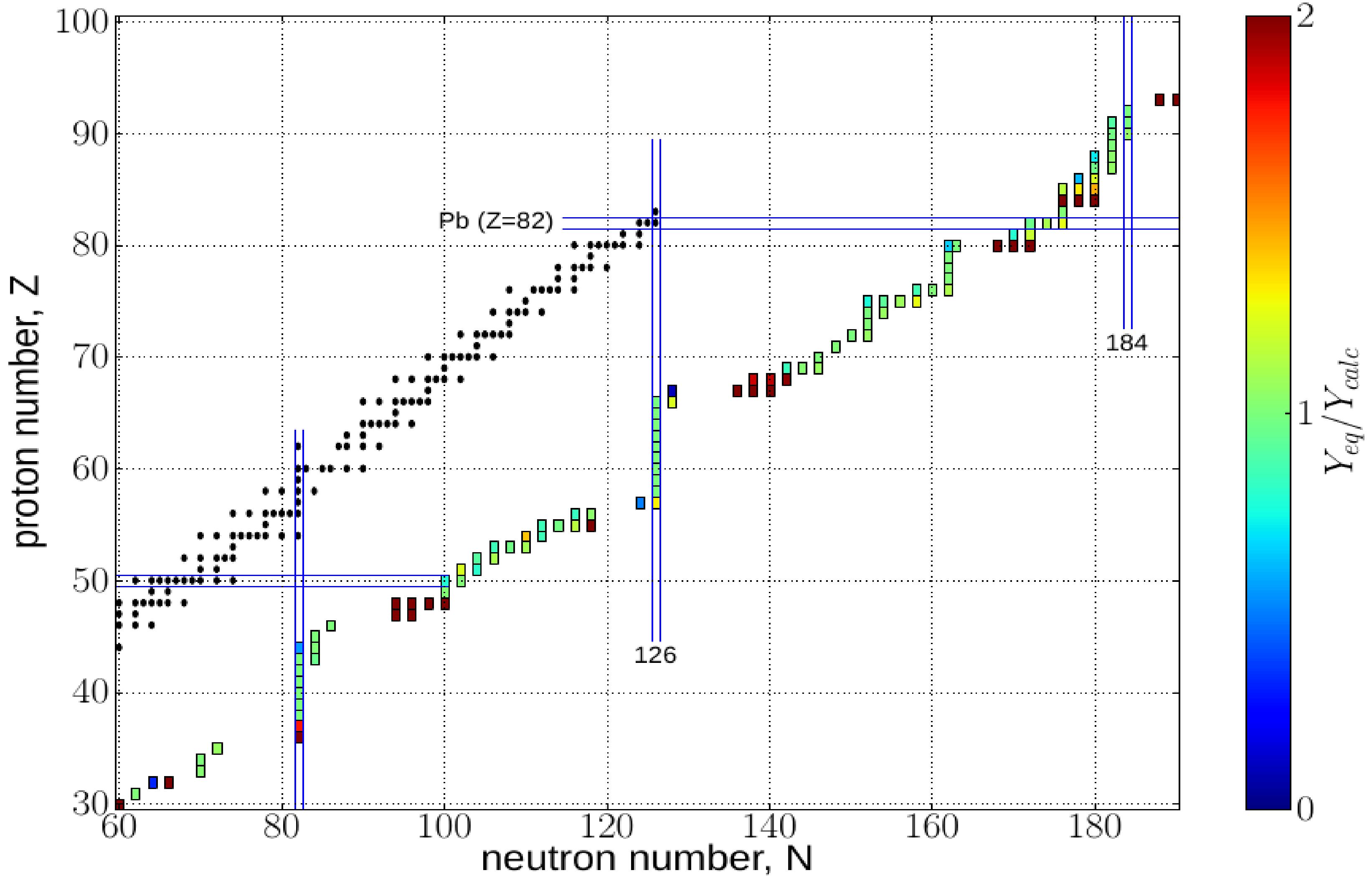
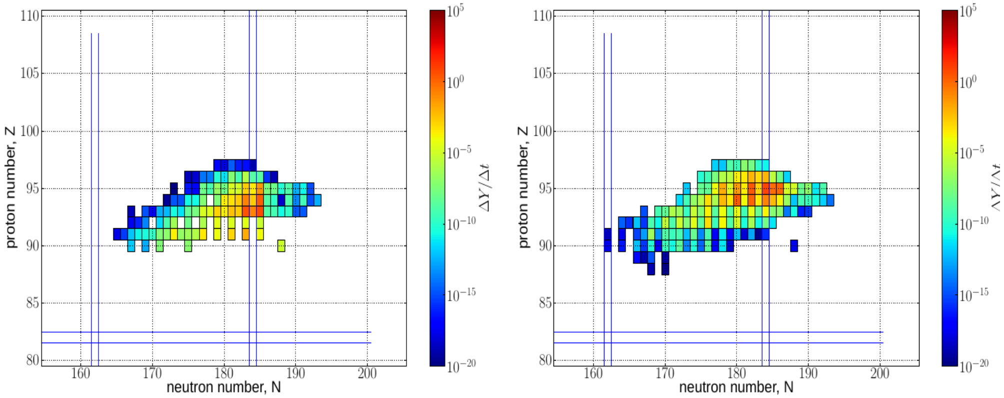
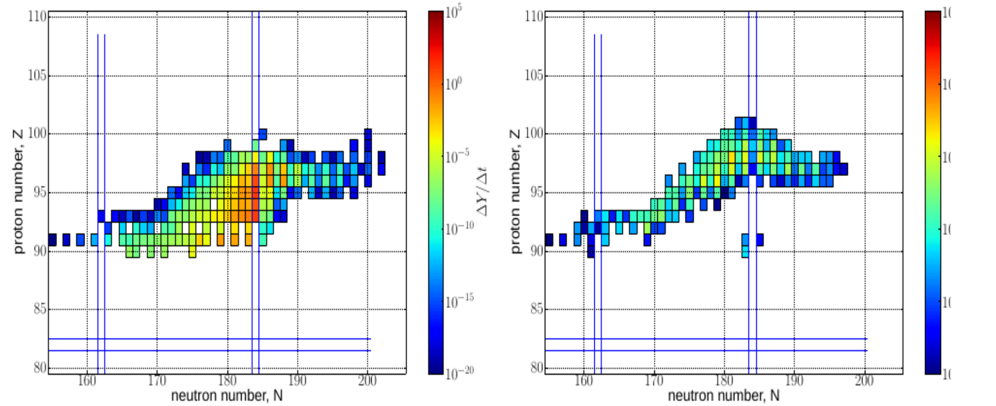


Fig. 7.—: Comparison of abundances from our calculations with (n,γ)-(γ,n) equilibrium abundances on the r-process path for the FRDM mass model. The colours show the factor Y_{eq}/Y_{calc}. Only the most abundant nuclei are shown for each isotopic chain. See text for details.

(n,f), (β,f) and fission yield distribution FRDM/TF and HFB-14/ETFSI (Eichler et al. 2015)

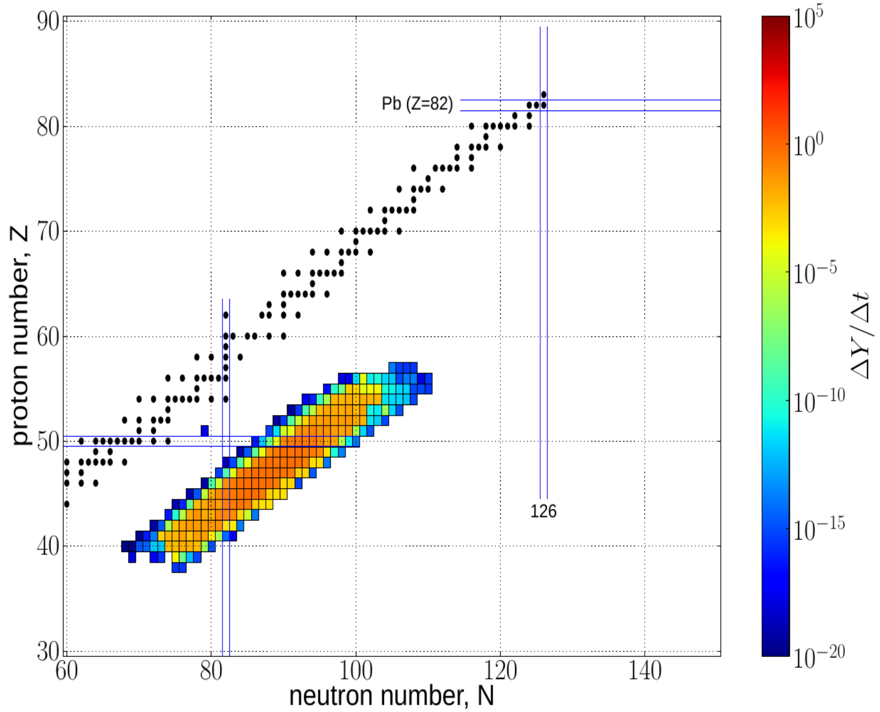


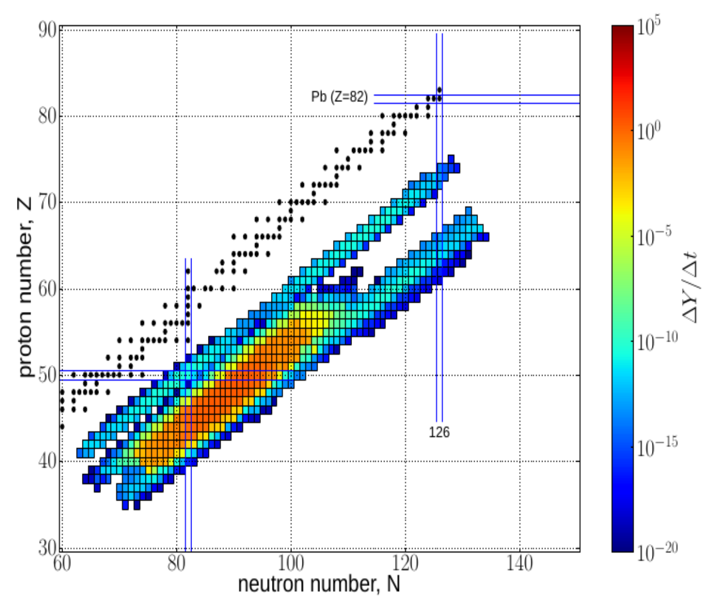


(a) β-delayed fission

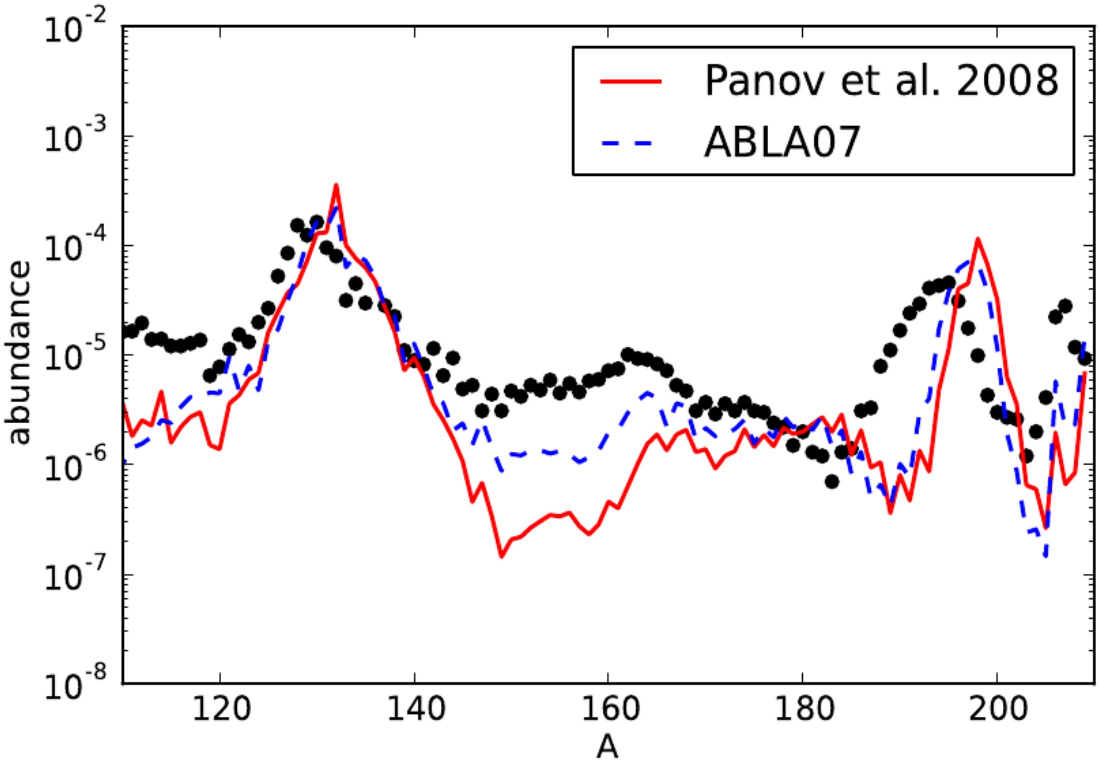
(b) neutron-induced fission

N=184 shell closure important!!





(c) fission fragments

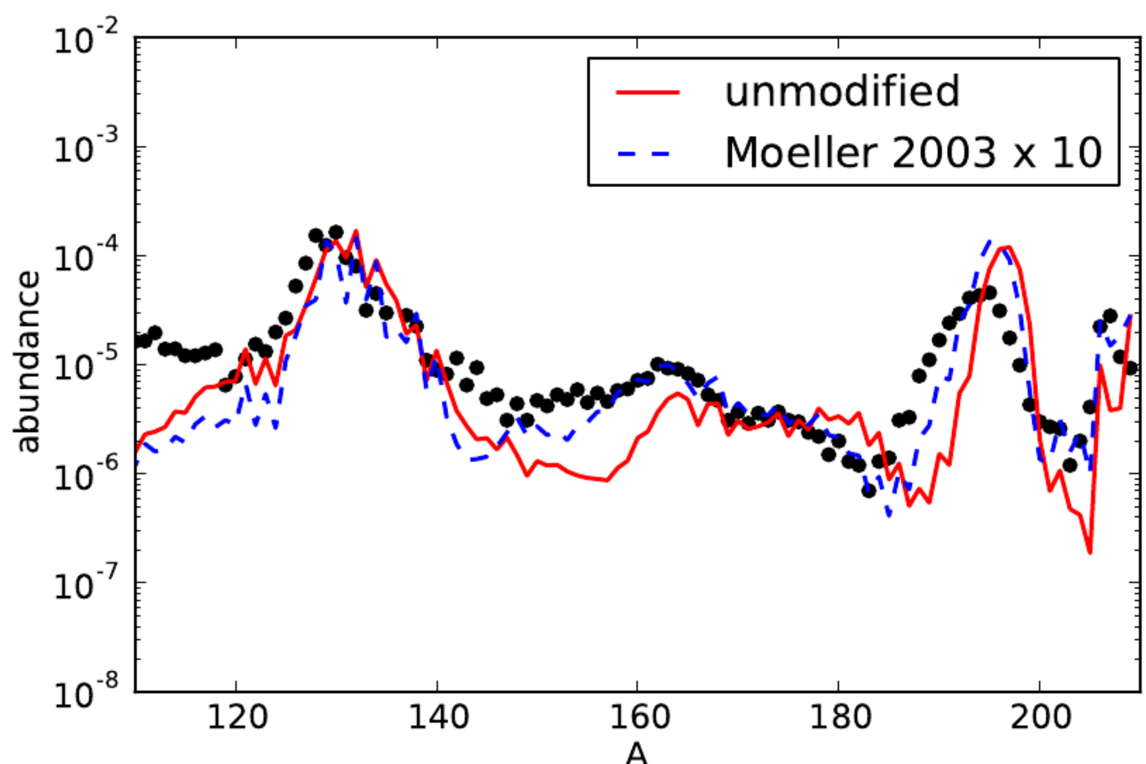


Eichler et al. (2015)

Variations in fission yield distributions (ABLA from Kelic et al. GSI).

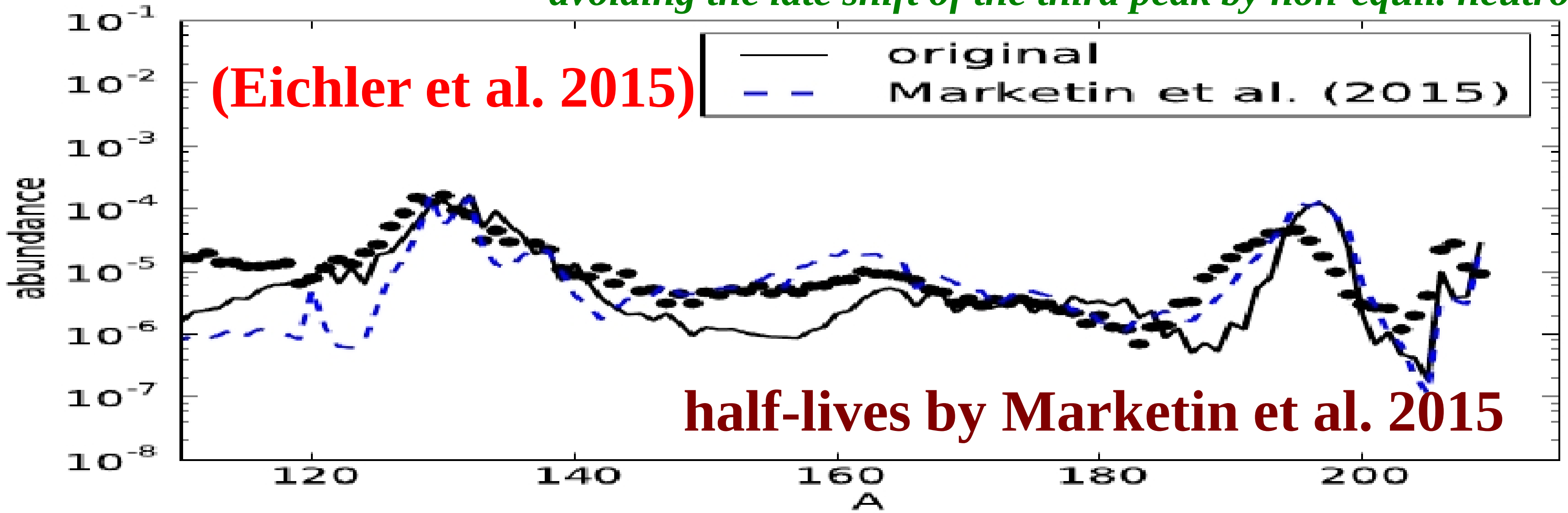
Fills somewhat A=140-160 gap and moves A=195 peak down slightly (related to fission yield distribution and corres-ponding neutron emission)

The final abundance pattern also depends at what time the neutron capture from fission neutrons occurs. If still n,γ-γ,n equilibrium persists, the fit is better than with late neutron capture in a type of n-process. The first is the case if beta-decay rates above Z=80 are faster (recent evidence)..



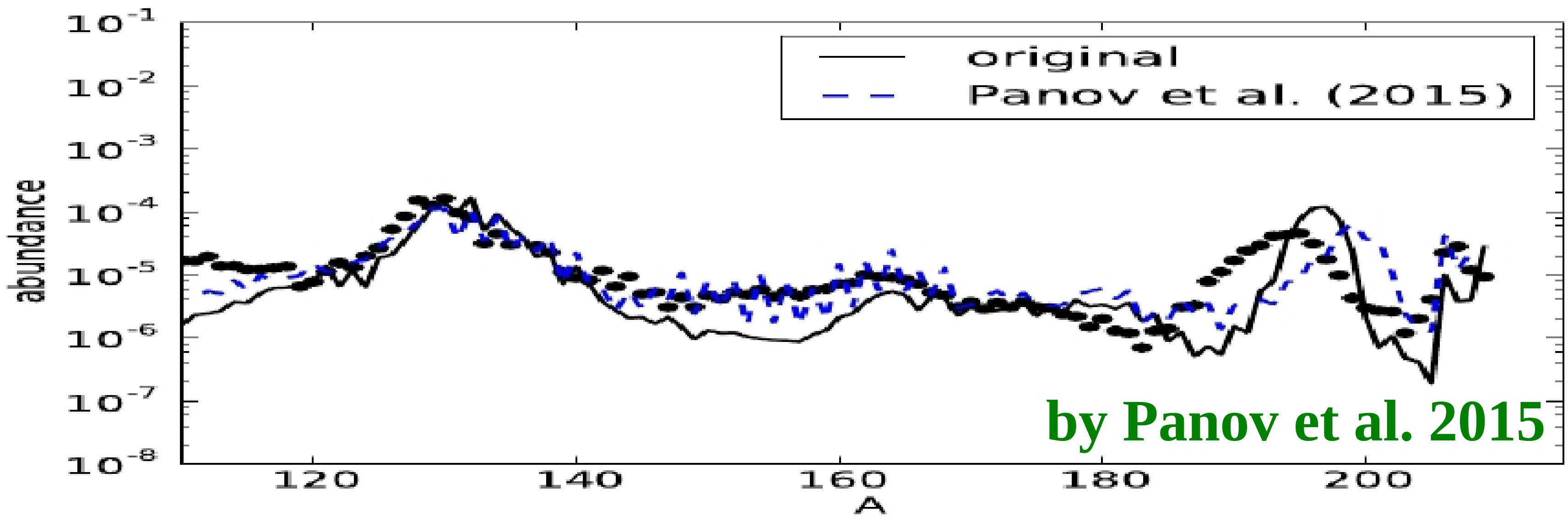
Exploring variations in beta-decay rates and fission fragment distributions

Shorter half-lives of heavies release neutrons (from fission/fragments) earlier *(still in n,γ - γ,n equilibrium) ,*
avoiding the late shift of the third peak by non-equil. neutron captures???



Similar results seen in Caballero et al. (2014), due to DF3 half-lives (Borzov 2011)

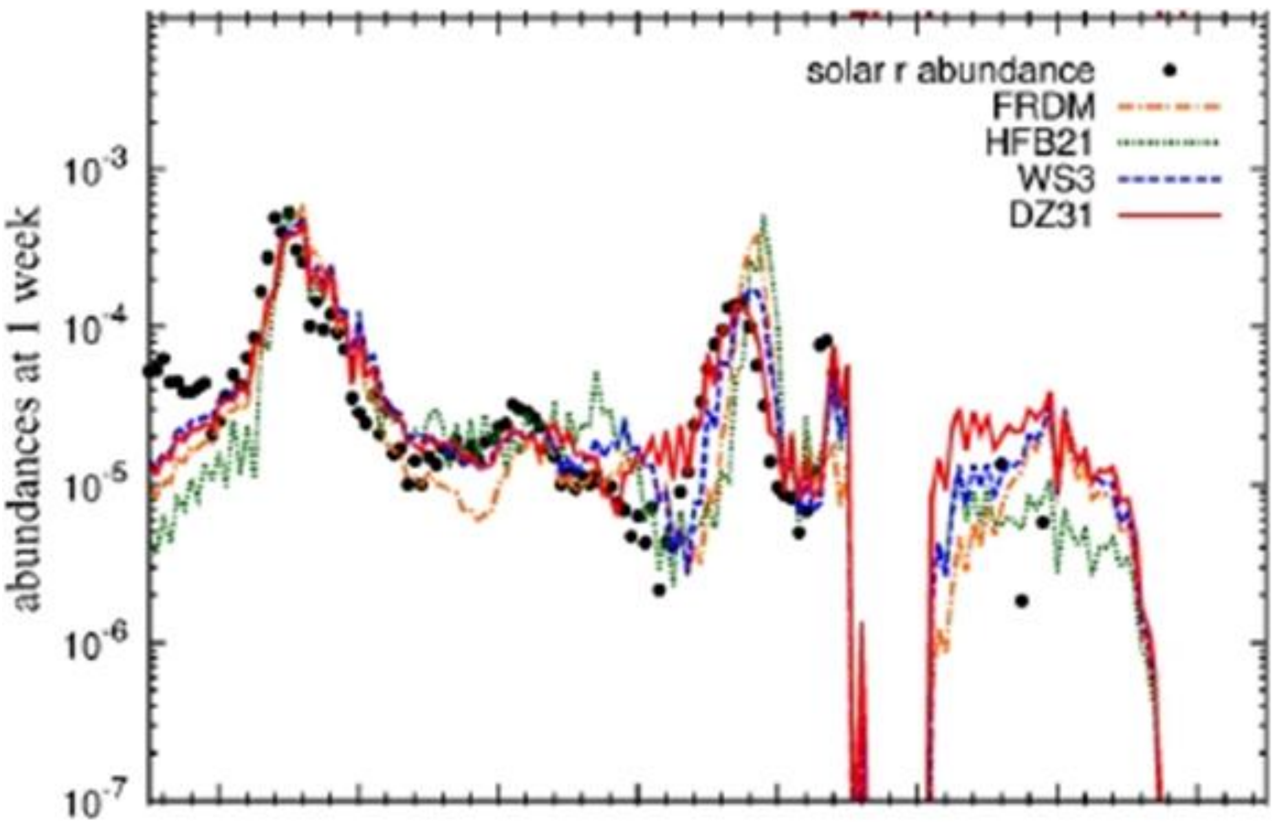
(a) FRDM, Marketin (2015)



Longer half-lives give the opposite effect

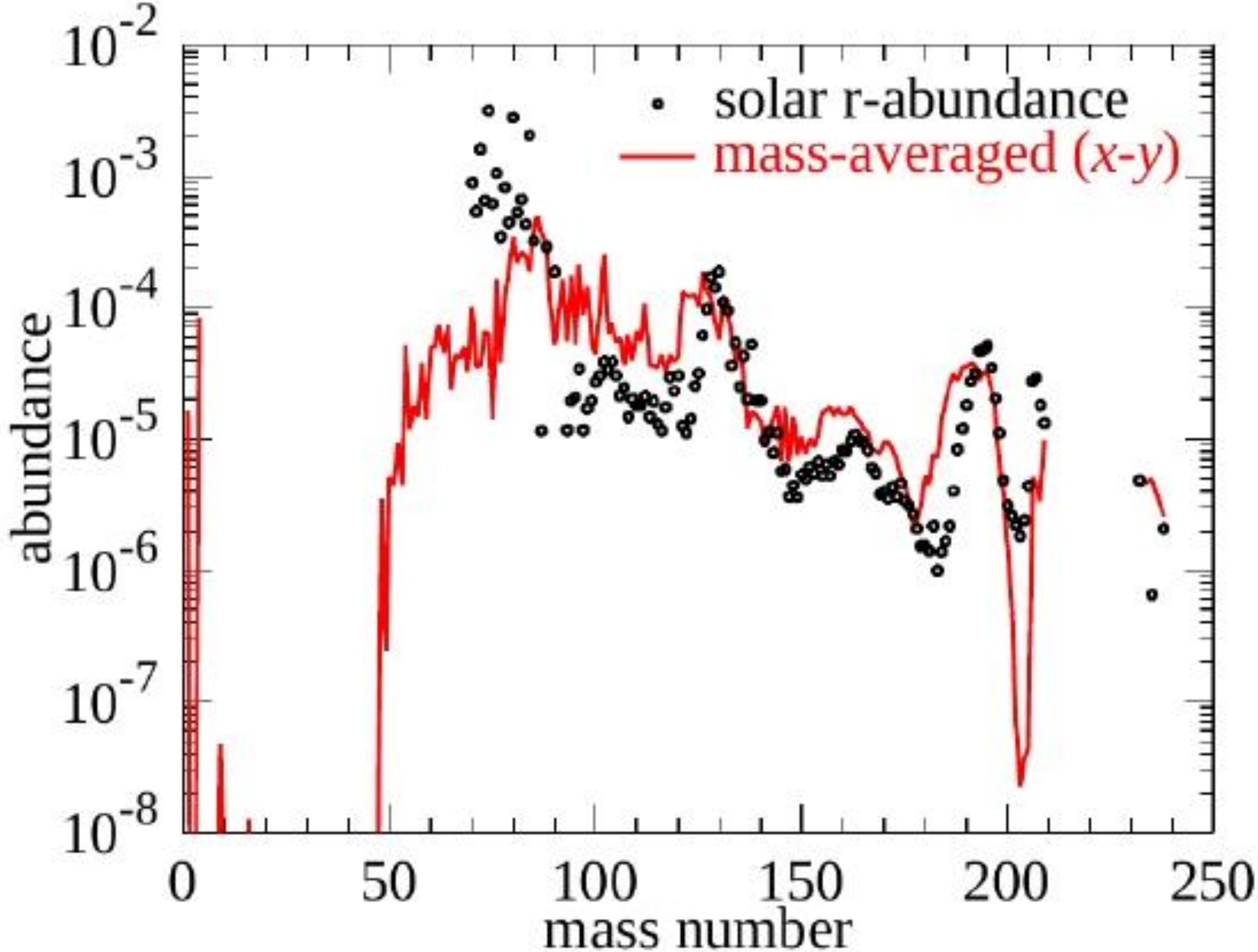
(c) FRDM, Panov (2015)

Mass Model Dependence (utilizing dynamic ejecta within conformally flat approach)



Variations based on different nuclear mass models.
Mendoza-Temis, Wu, Langanke, Martinez-Pinedo, Bauswein, Janka (2015)

General relativistic calculations (based on the Sekiguchi et al. calculations), find higher Ye’s, but also changed positions of the r-process peaks **(Wanajo et al. 2014)**

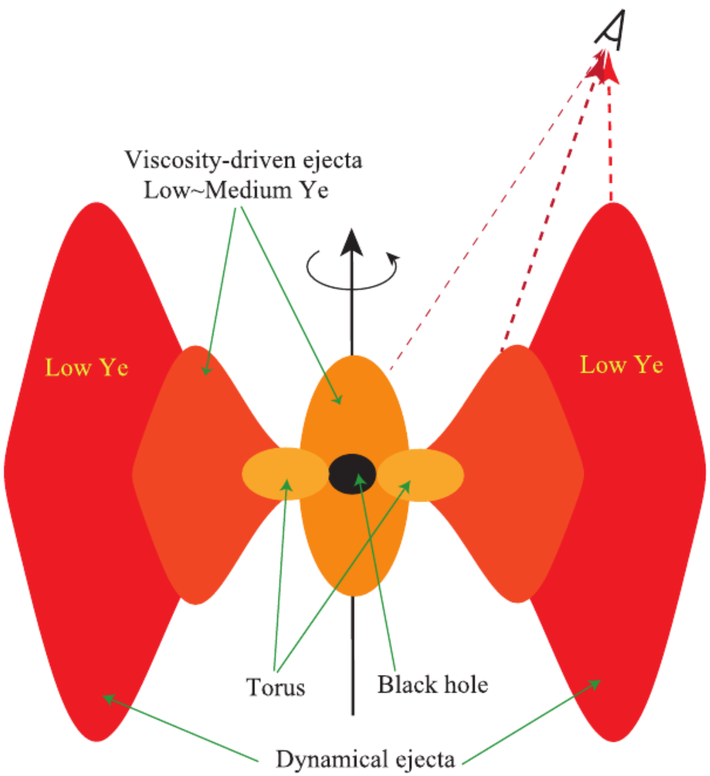


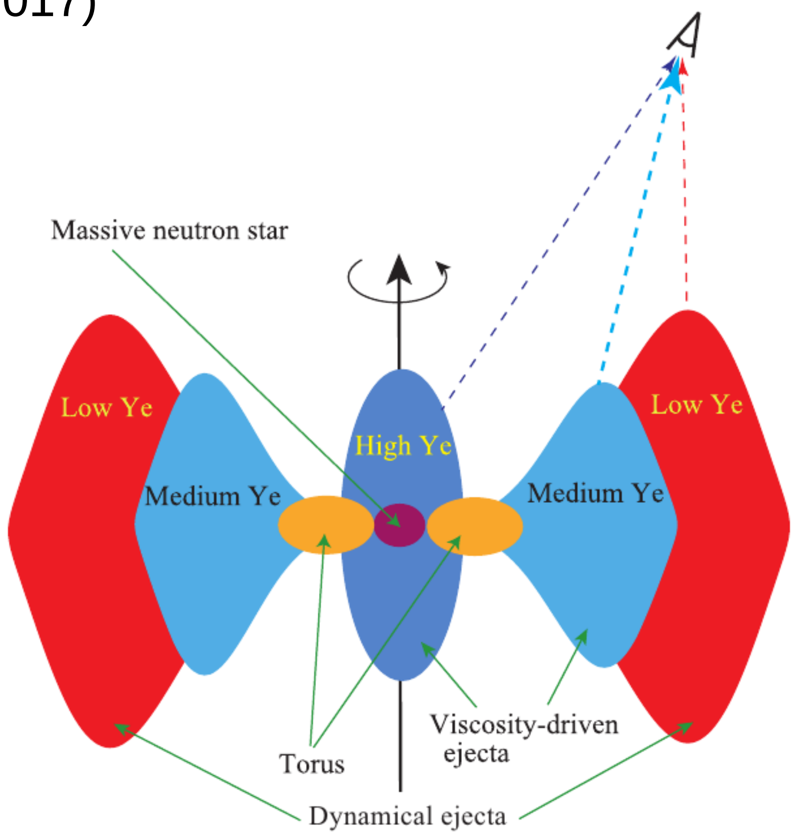
The EoS:

1. Effect on dynamic ejecta from collision (discussed before)

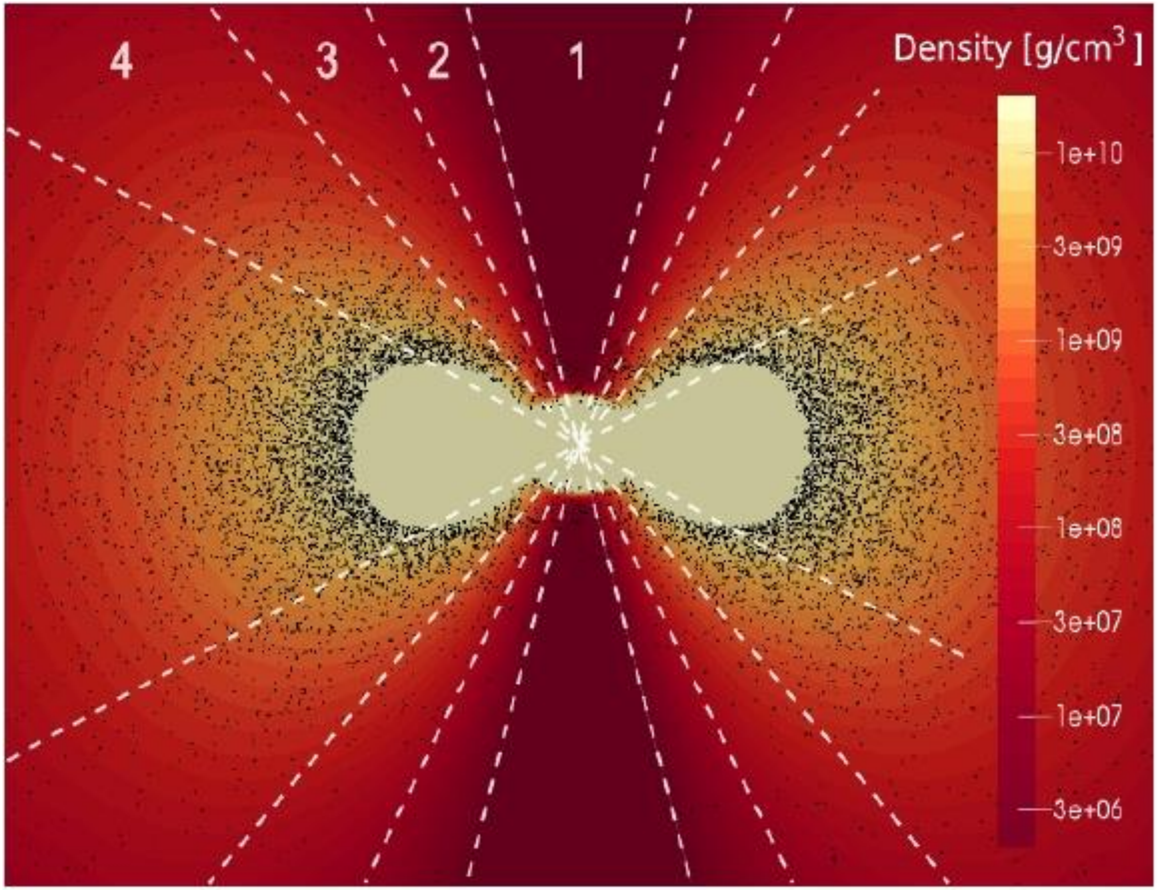
2. Effect on structure of ejecta, the duration of a neutrino wind (does a black hole form and when?)

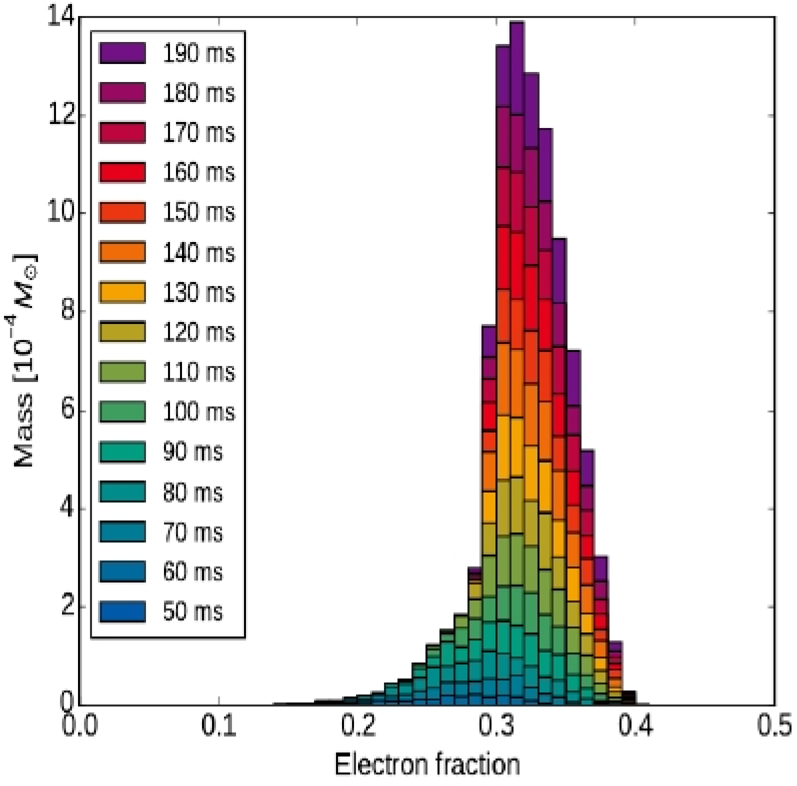
Shibata+(2017)





Neutrino Wind Contribution before BH formation (Perego et al. 2014, Martin et al. 2015)





Ye in neutrino wind

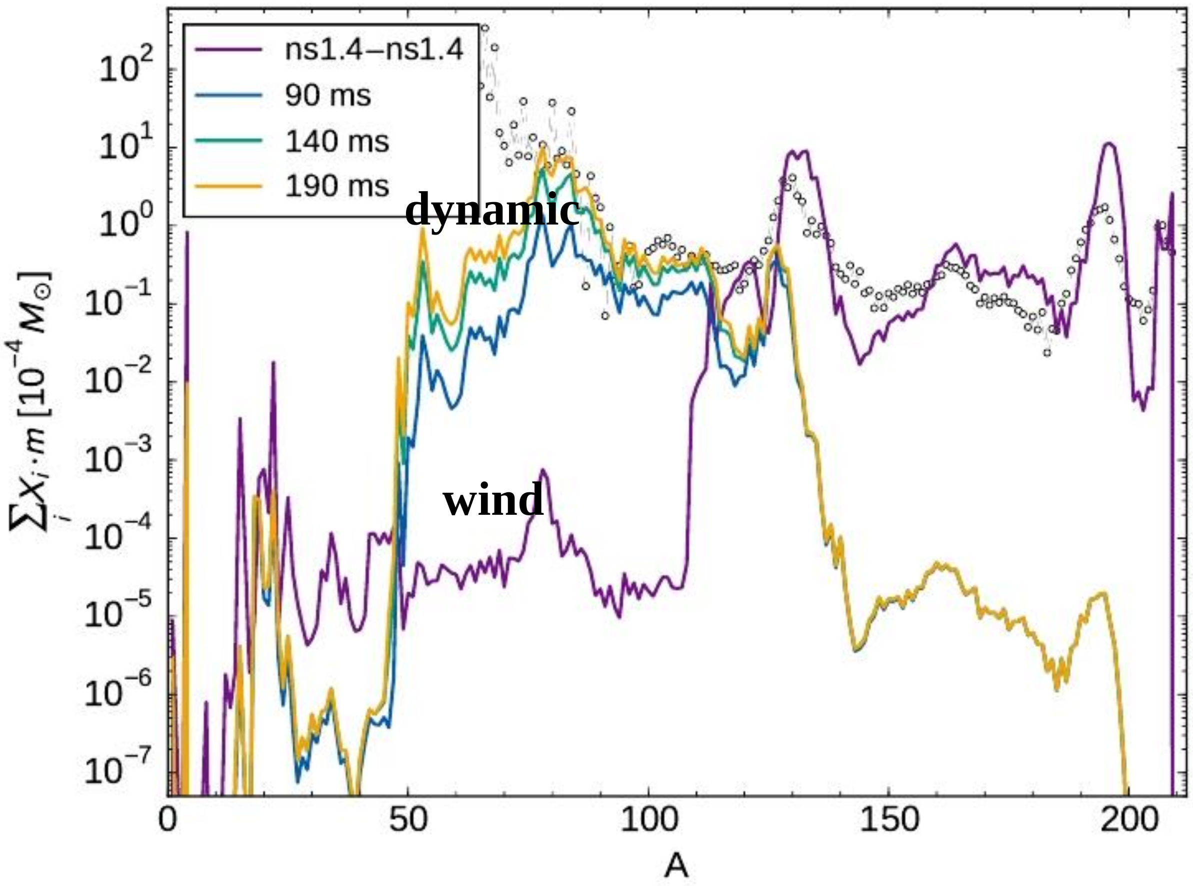
Neutrino interactions with matter (as in supernovae) increase Ye as

$\nu + n \to p + e^-$ wins over $\bar{\nu} + p \to n + e^+$

There exist possibly additional effects via neutrino oscillations (Zhu+16, Frensel+17, Wu+17)

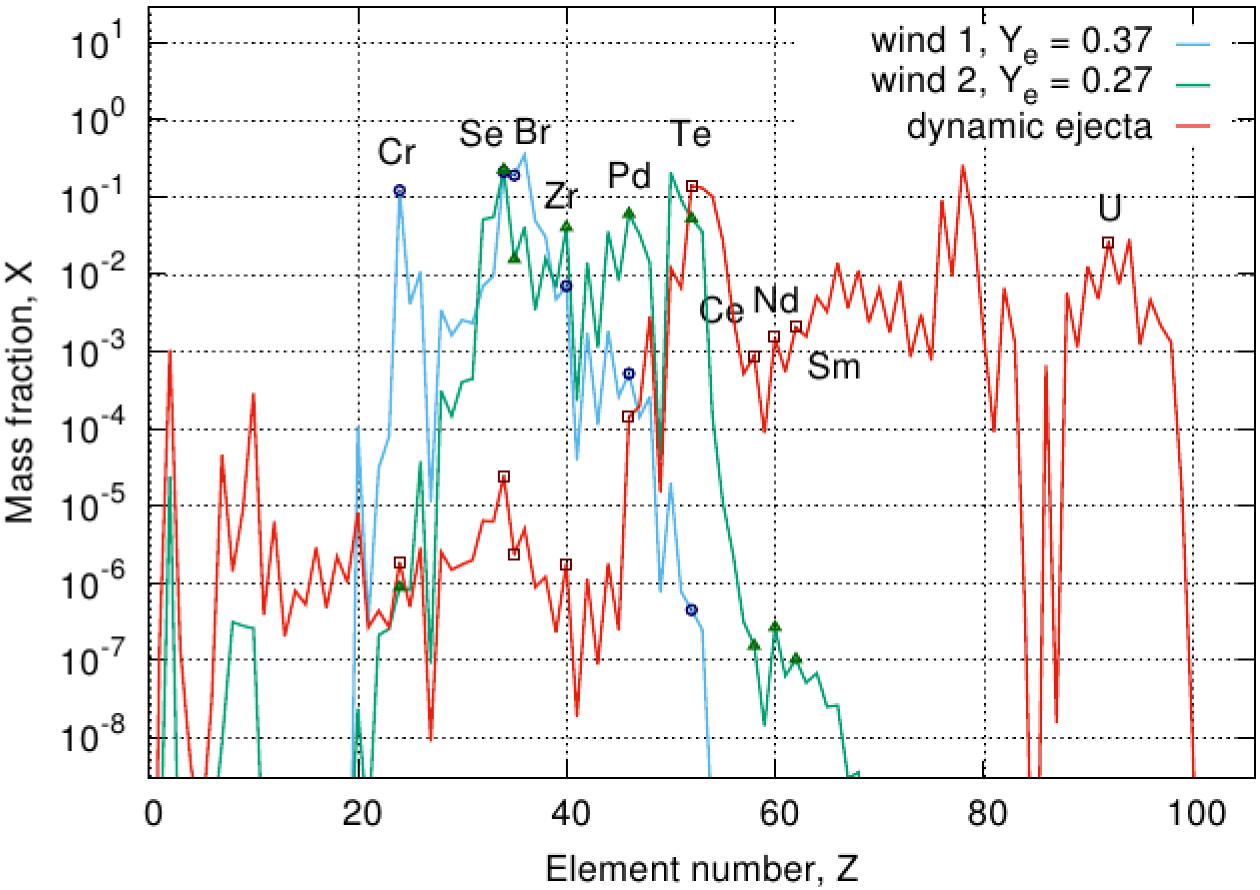
After dynamic ejection of matter, the hot, hypermassive neutron star (before – possibly and with which delay - **collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014), Martin et al. (2015)**

abundances



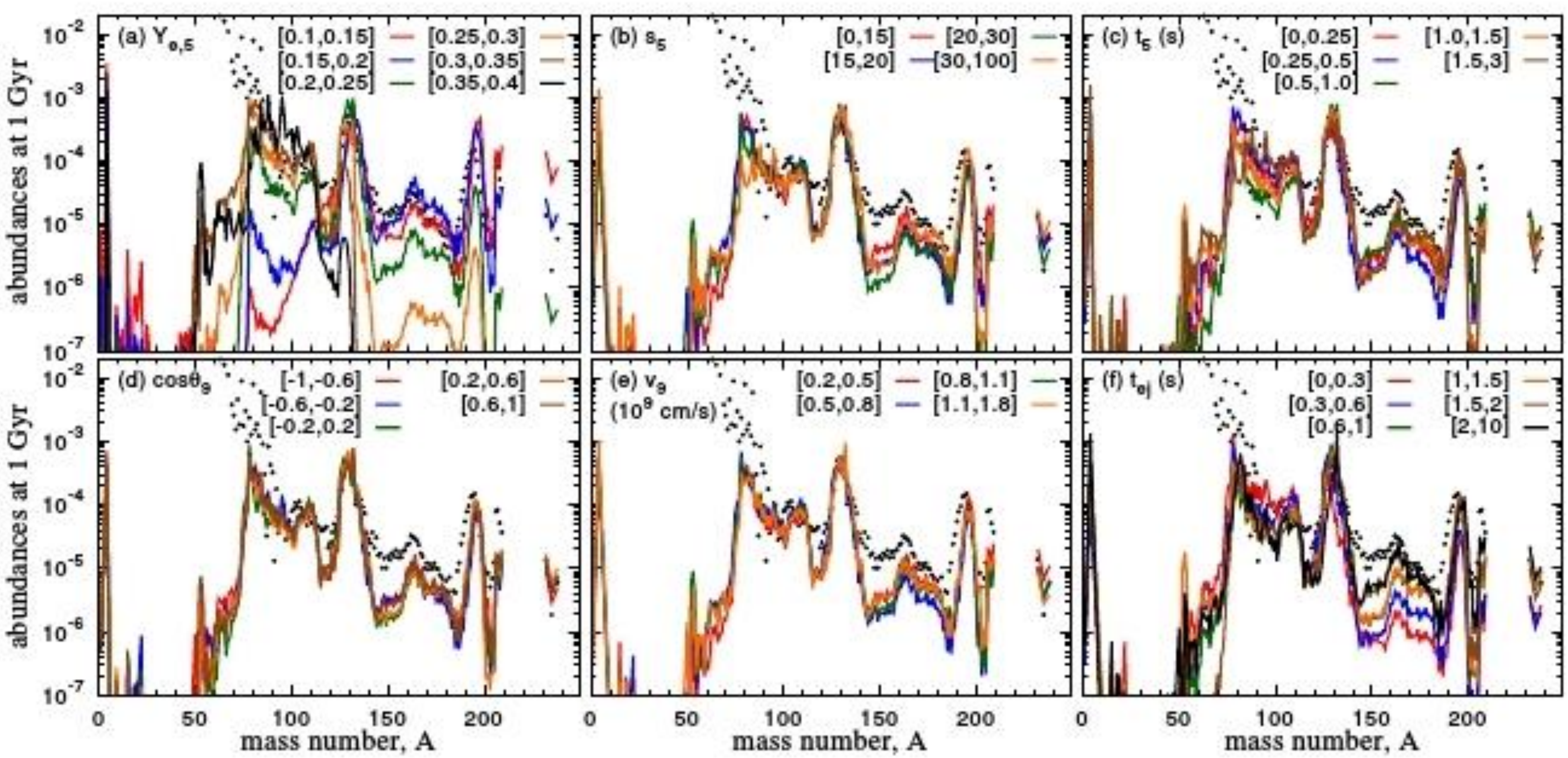
Martin et al. (2015) with neutrino wind contributions, here still combined with composition of dynamic ejecta of Korobkin+ (2012) with their known deficiences.

Another result from the Los Alamos group (Wollaeger et al. 2017)



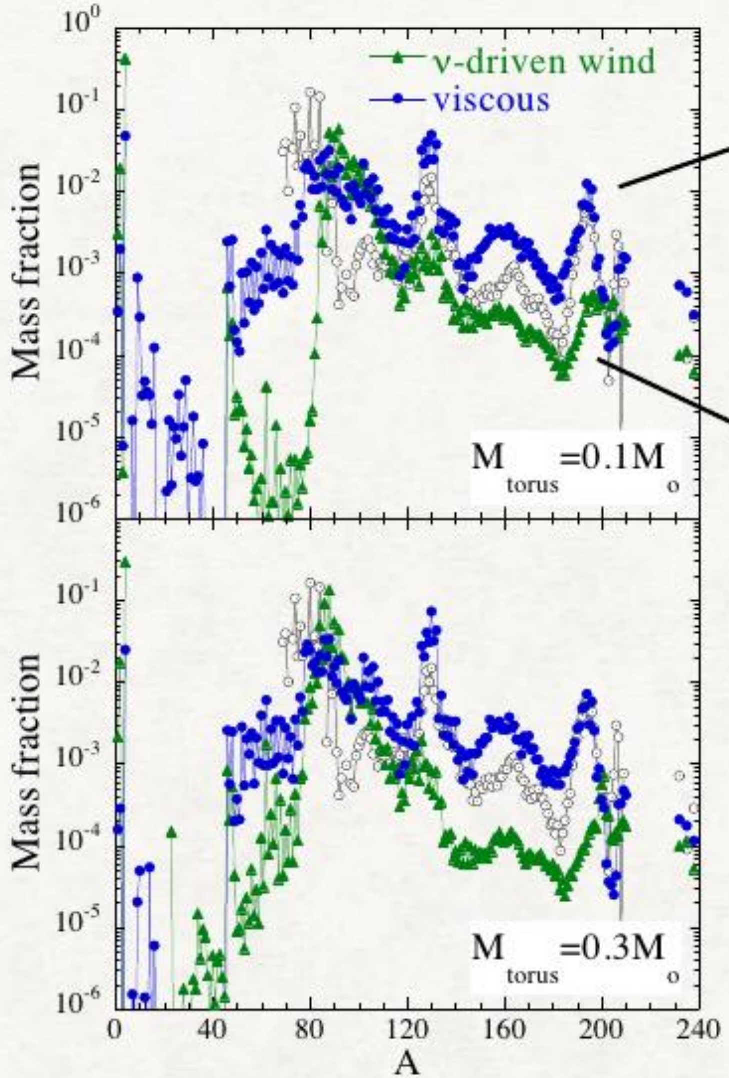
Another Substructure of Ejecta: Nucleosynthesis from BH accretion disks (after merger and BH formation, but without dynamical ejecta)

Variations in BH mass, spin, disk mass, viscosity, entropy in alpha-disk models: r-process nuclides up to lanthinides and actinides *can* be produced.



Wu, Fernandez, Martinez-Pinedo, Metzger (2016)

Nucleosynthesis yields of BH-torus ejecta



viscous outflows:
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

neutrino-driven outflows:
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

from Just (2018)
Shangai talk

(similar qualitative tendency for outflows from a HMNS-torus system, e.g. Fujibayashi '17, Perego '14) from Lippuner et al. (2017), with varying system properties related to Hypermassive neutron star lifetimes

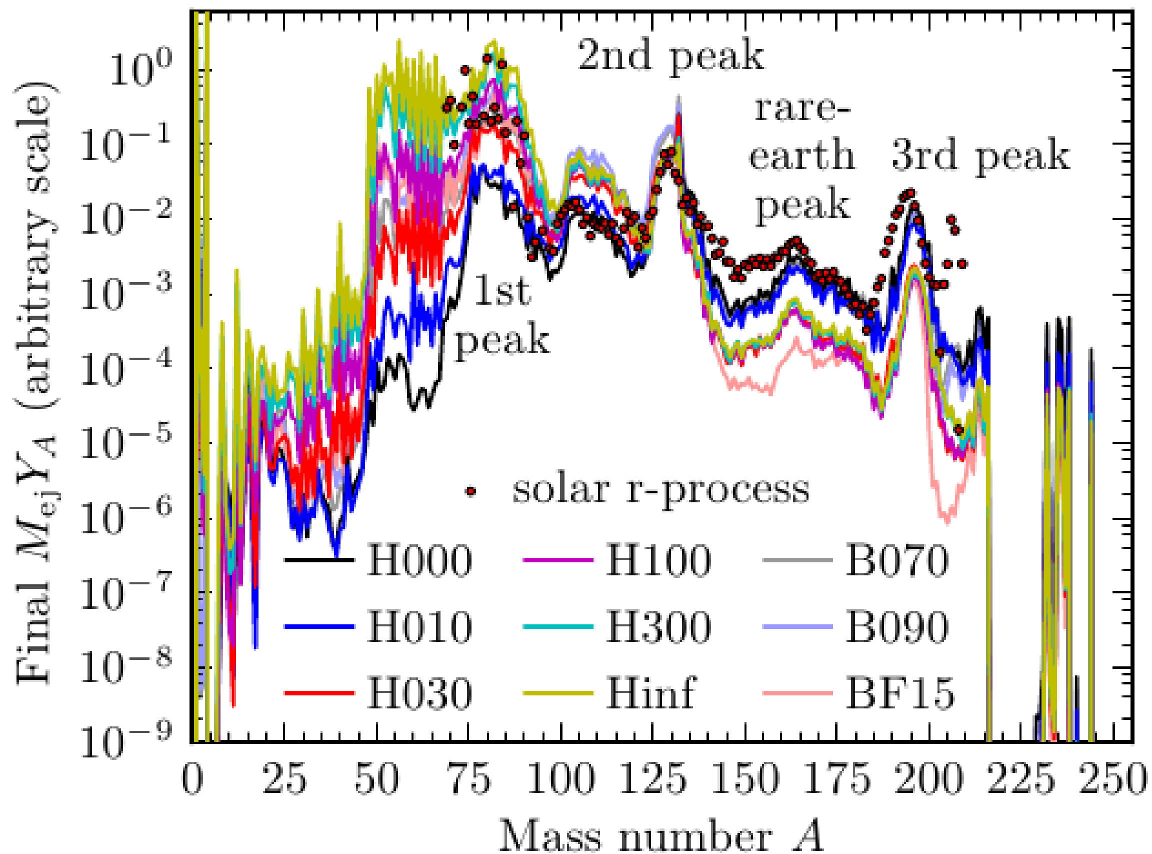


Figure 4. Final trajectory-averaged abundances as a function of mass number, scaled by the total ejecta mass, for all models with non-zero viscosity. The observed solar r-process abundances (Arnould et al. 2007) are scaled to match the second peak of the HMNS models at $A = 130$ (none of the abundances from our models have been scaled).

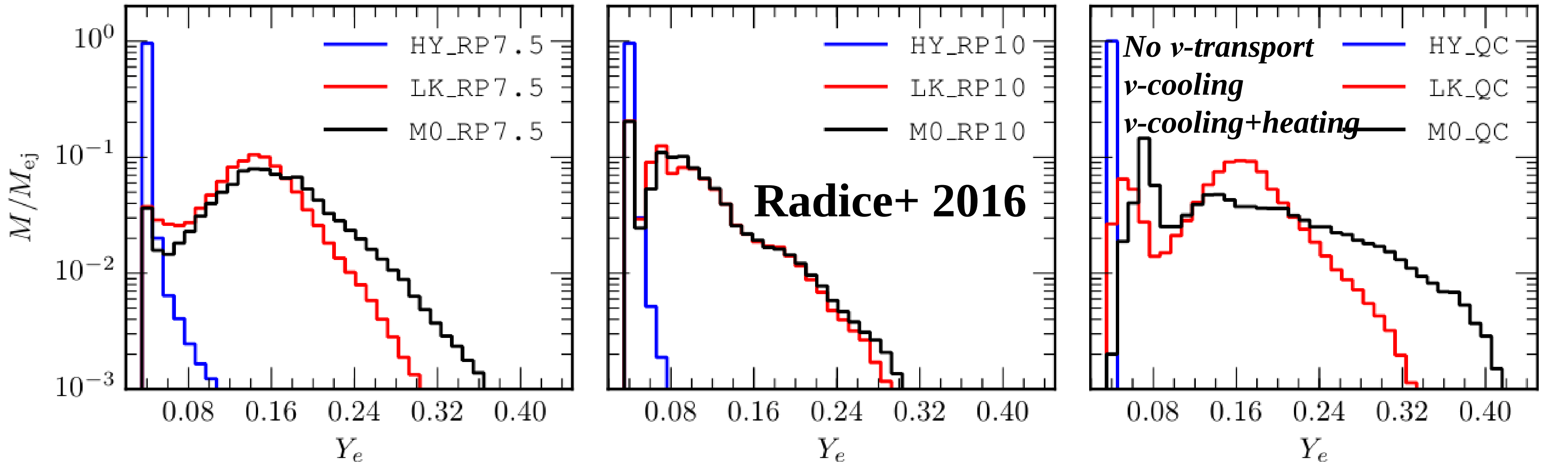
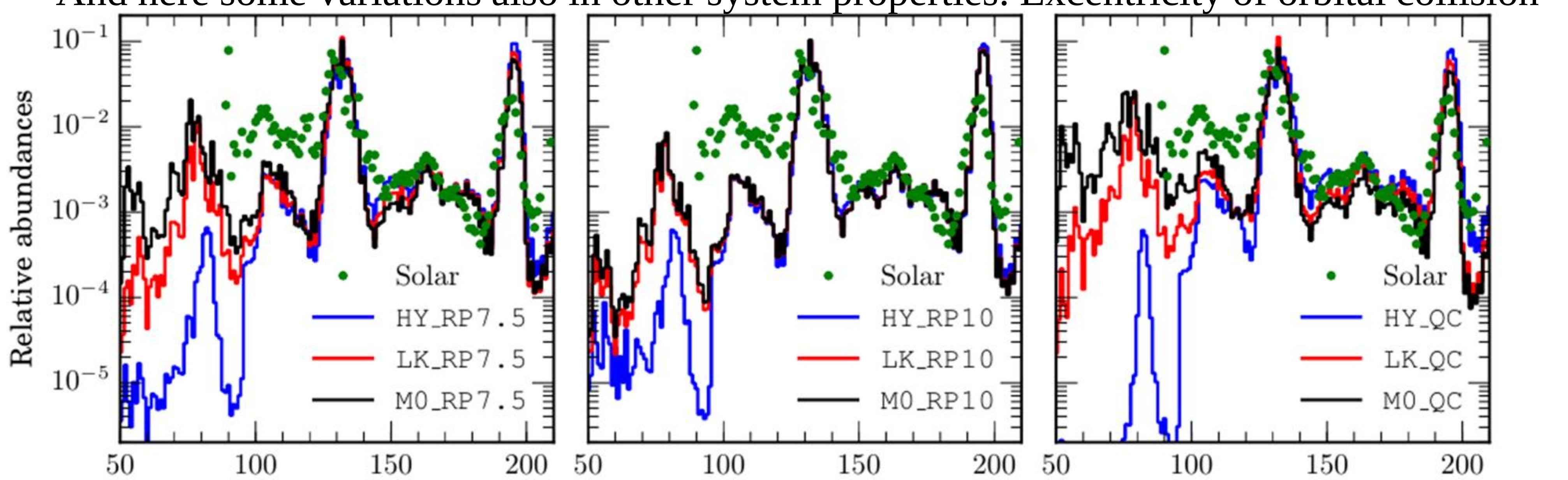
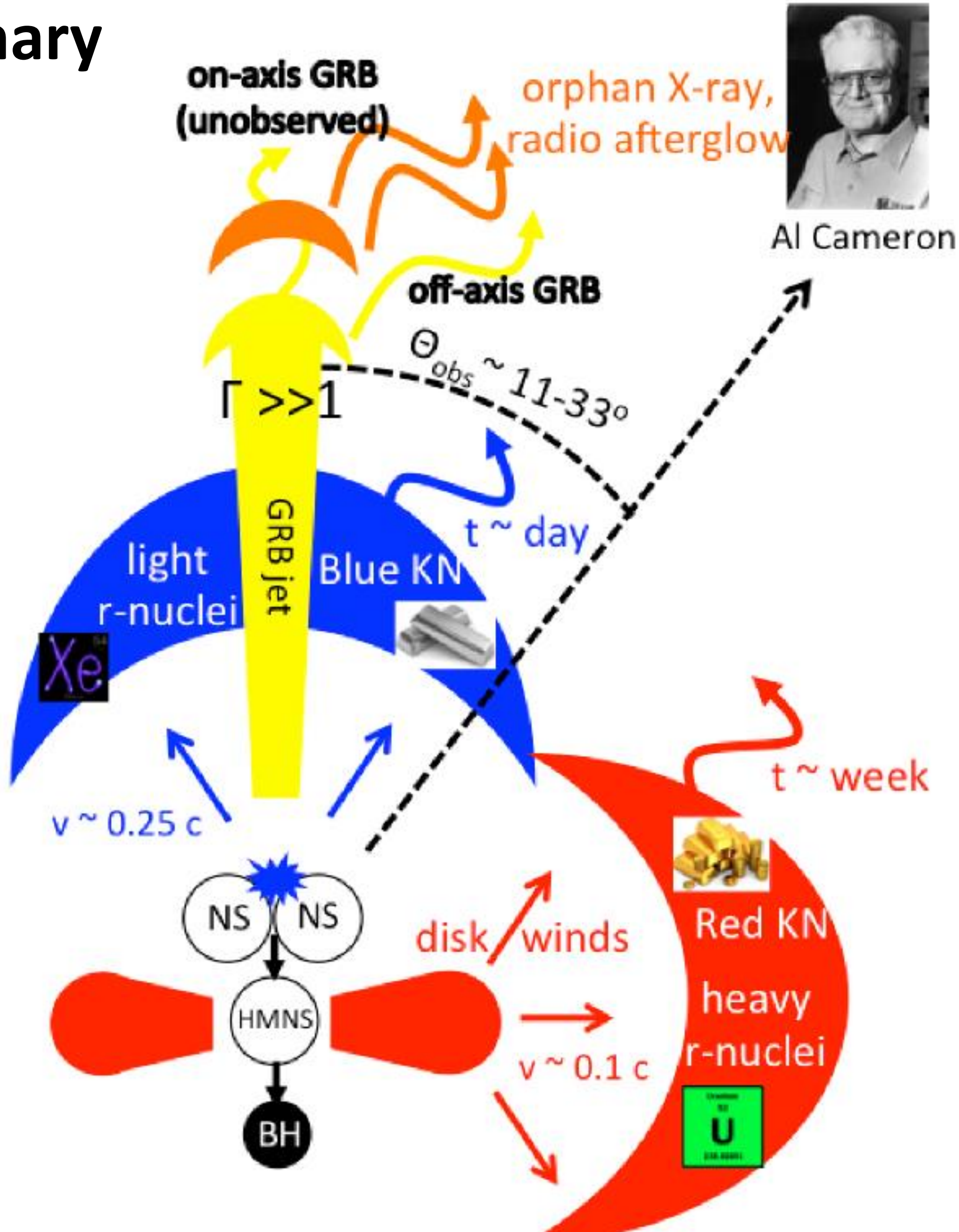


Figure 7. Electron fraction (*top row*), specific entropy per baryon (*second row*), asymptotic velocity (*third row*), and angular distribution (*bottom row*) of the ejecta. θ is the angle from the orbital plane. The first, second, and third columns show results from models `RP7.5`, `RP10`, and `QC` respectively. For each configuration we consider three different levels of microphysical description: pure hydrodynamics (`HY`), neutrino cooling (`LK`), or neutrino cooling and heating (`M0`). The histograms are computed from the mass fraction of the matter crossing a spherical surface at radius $r = 200\ M_\odot \simeq 295$ km with positive specific energy (*i.e.*, with $u_t \leqslant -1$). The bump in the angular distribution at $\theta = 45^\circ$ is a numerical artefact generated by our Cartesian simulation grid.

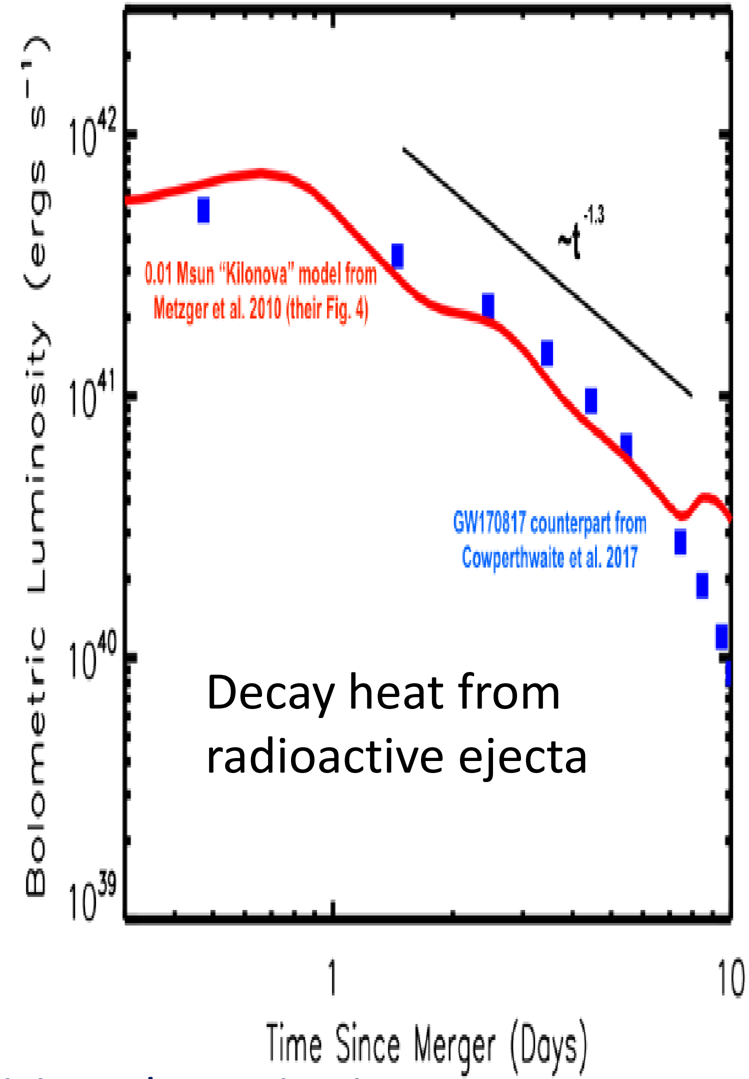
And here some variations also in other system properties: Excentricity of orbital collision



Summary



Metzger, Martinez-Pinedo et al. (2010)



Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation

We need to understand the modeling and nuclear uncertainties as well as the system properties