r-process nucleosynthesis in neutron star mergers and remnants

Meng-Ru Wu (Niels Bohr Institute)

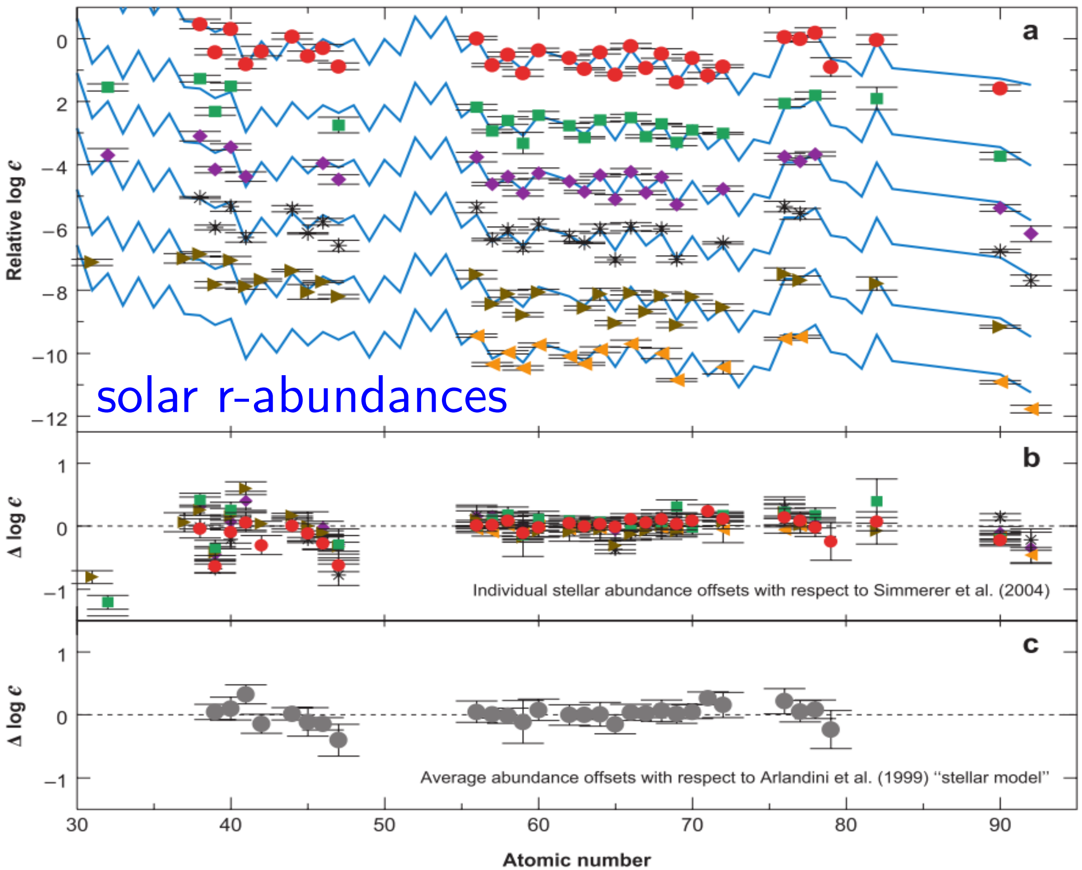
Neutron star mergers: From gravitational waves to nucleosynthesis
Hirschegg workshop, January 15-21, 2017, Hirschegg, Austria

Outline

- Introduction
- The dynamical ejecta from NS–NS(BH) mergers
- The outflow from the merger remnants: BH(NS) accretion disks
- Neutrinos flavor conversion in merger remnants
- Summary

collaborators:
G. Martínez-Pinedo, J. Mendoza-Temis, K. Langanke, A. Bauswein,T. Janka
R. Fernandez, B. Metzger, J. Barnes, D. Kasen, S. Rosswog, S. Giuliani
M. Frensel, C. Volpe, A. Perego, I. Tamborra

Observations of r-process elements



[Sneden et. al., ARA&A 46, 241 (2008)]

abundances of metal-poor stars

- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- BD+17°324817: Cowan et al. (2002)
- CS 31082-001: Hill et al. (2002)
- HD 221170: Ivans et al. (2006)
- HE 1523-0901: Frebel et al. (2007)

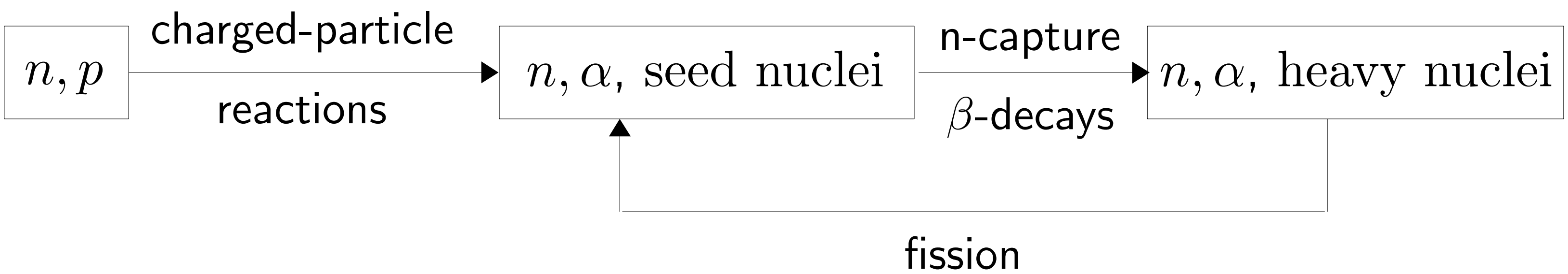
– Is the r-process enrichment in the early galaxies due to mergers?

[see Ji, Frebel, Chiti, Simon, Nature, 531 (2016) 610]

– are mergers the dominant source for the solar r-abundances?

[see Wallner+, Nature Commun. 6 (2015) 5956
Hotokezaka, Piran, Paul, Nature Phys. 11 (2015) 1042]

r-process nucleosynthesis



key quantity: the neutron-to-seed ratio, $R_{n/s}$, at the end of charged-particle processes

$$\langle A_{\rm heavy} \rangle \approx \langle A_{\rm seed} \rangle + R_{n/s}$$ assuming no fission occurs

- in a α-rich freeze-out environment, e.g., SN ν-wind,

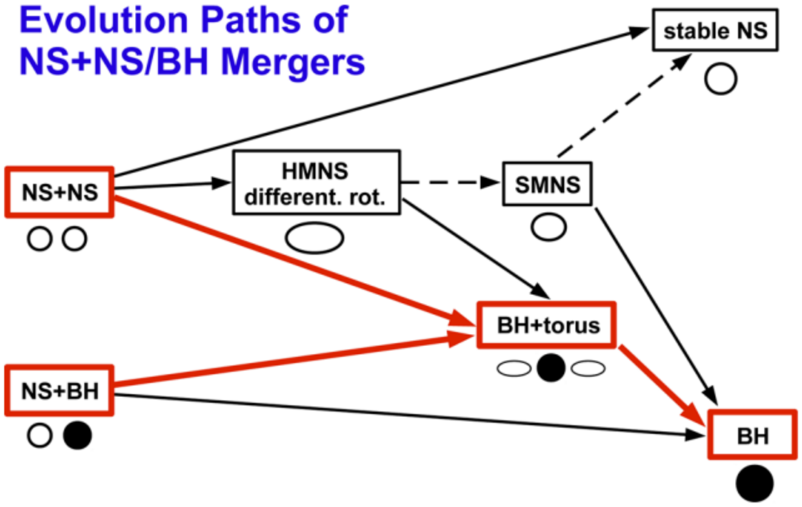
$$R_{n/s} \propto \frac{s^3}{\tau_{\rm dyn} Y_e^3}$$ [Hoffman+ 1997, Roberts+ 2010]

- Extremely n-rich and cold material such as dynamical merger ejecta,

$$R_{n/s} \propto Y_e^{-1}$$

$\rightarrow$ astrophysical conditions determine how far the r-process goes, nuclear physics determines the abundance distribution

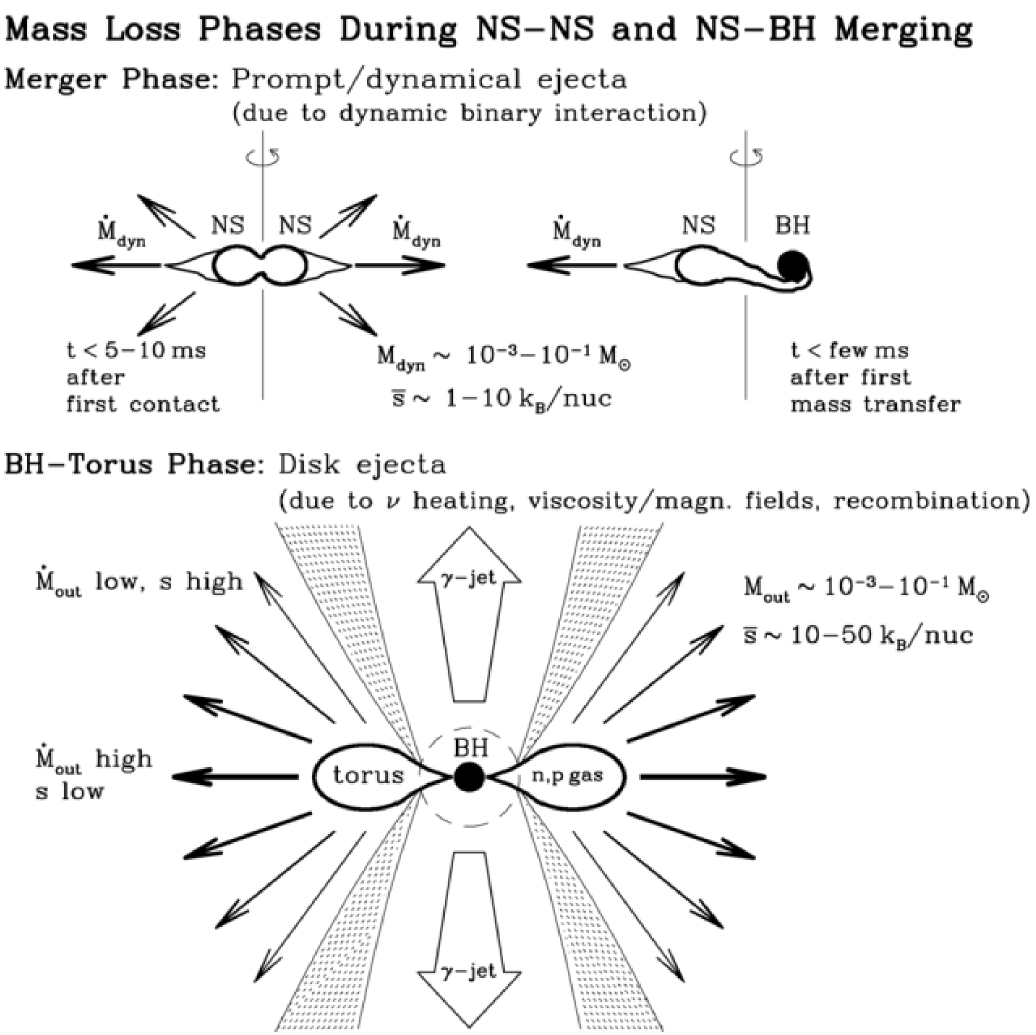
NS–NS and NS–BH mergers



[from Just+, MNRAS 448, 541 (2015)]

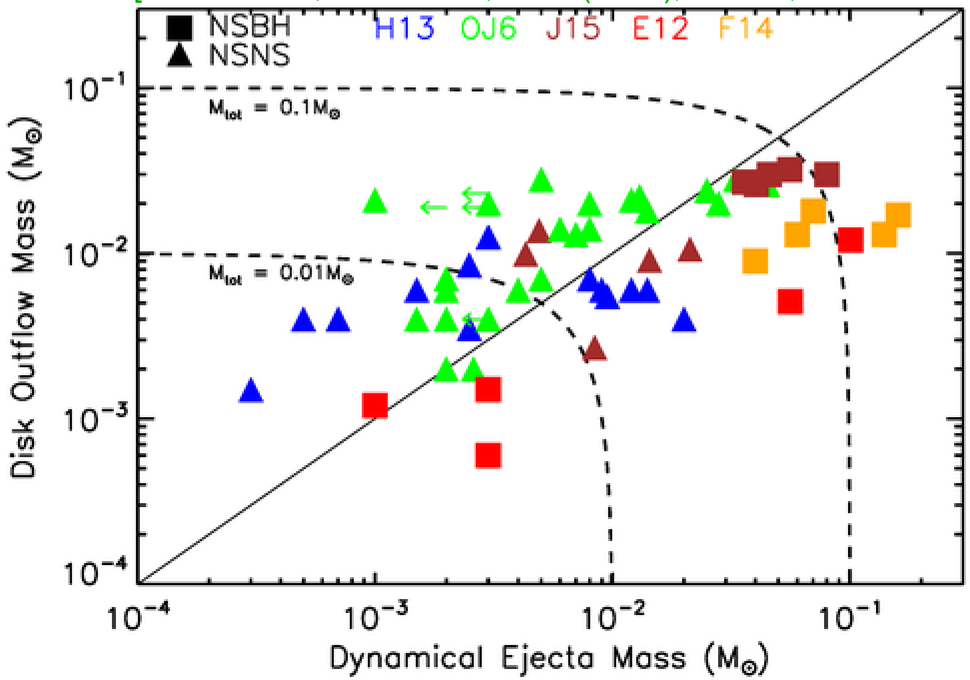
multiple mass ejection channels
due to different mechanisms

[from Just+, MNRAS 448, 541 (2015)]



Relative contribution

[Fernandez+, ANPRS 66, 2115 (2016); MRW+, MNRAS 463, 2323 (2016)]



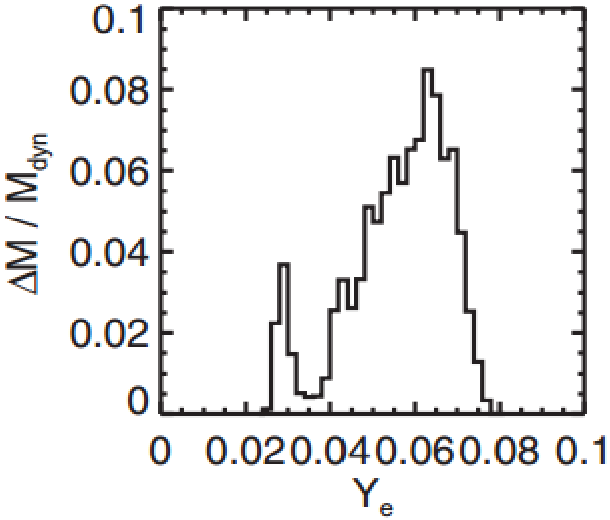
more dynamical ejecta in NS–BH cases while similar or disk-dominated ejecta in NS–NS cases

r-process in the dynamical ejecta – when neutrinos unimportant

[from Just+, MNRAS 448, 541 (2015)]

without weak interactions, Y_e distribute at $Y_e \lesssim 0.1$, resulting in nucleosynthesis outcome that is robust against:

- binary mass ratio
- adopted nuclear EoS



NS–BH
Eos: DD2

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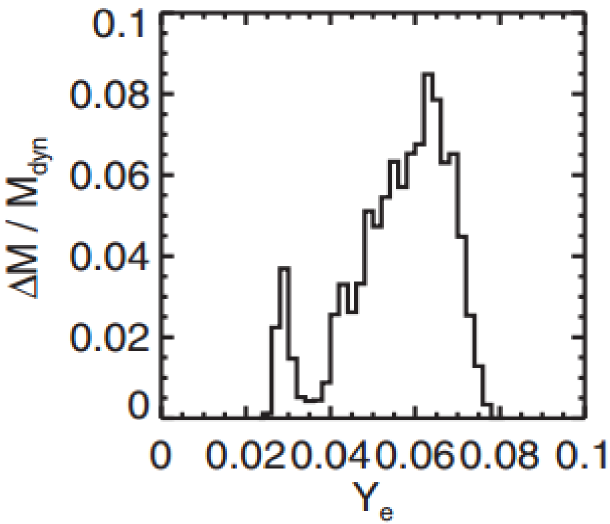

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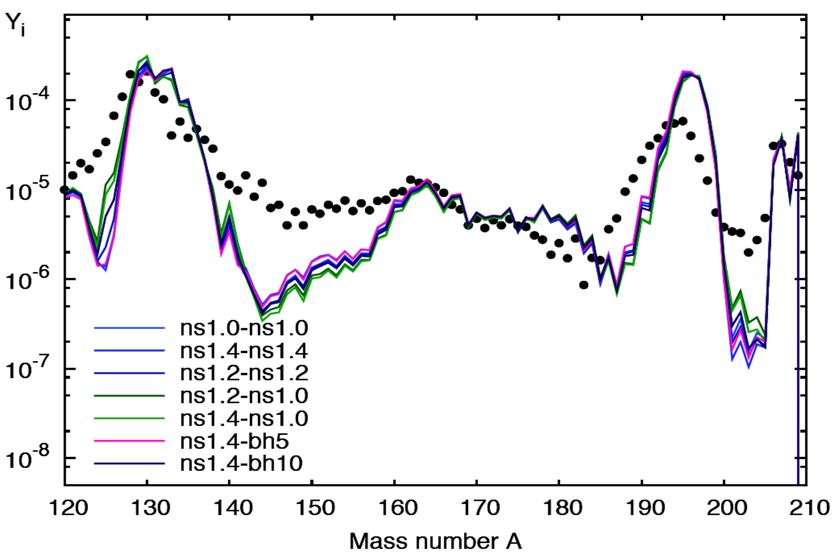

[Korobkin, Rosswog, Arcones, Winteler, MNRAS 426, 1940 (2012)]

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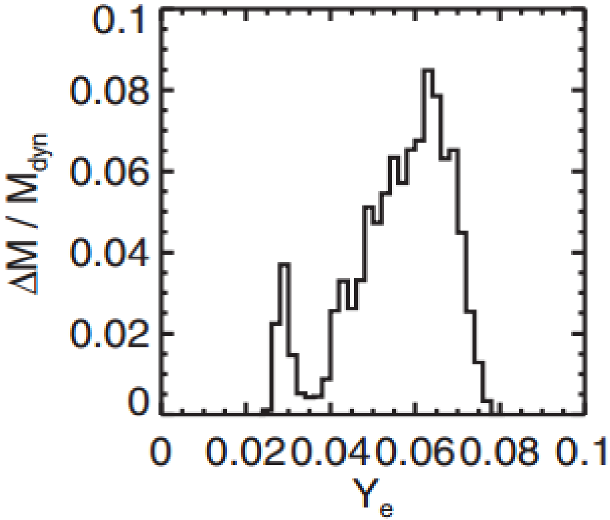

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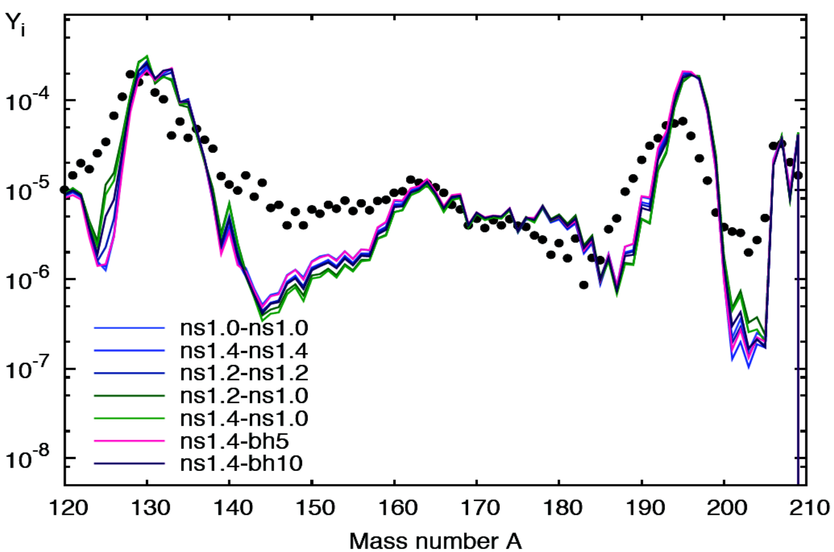

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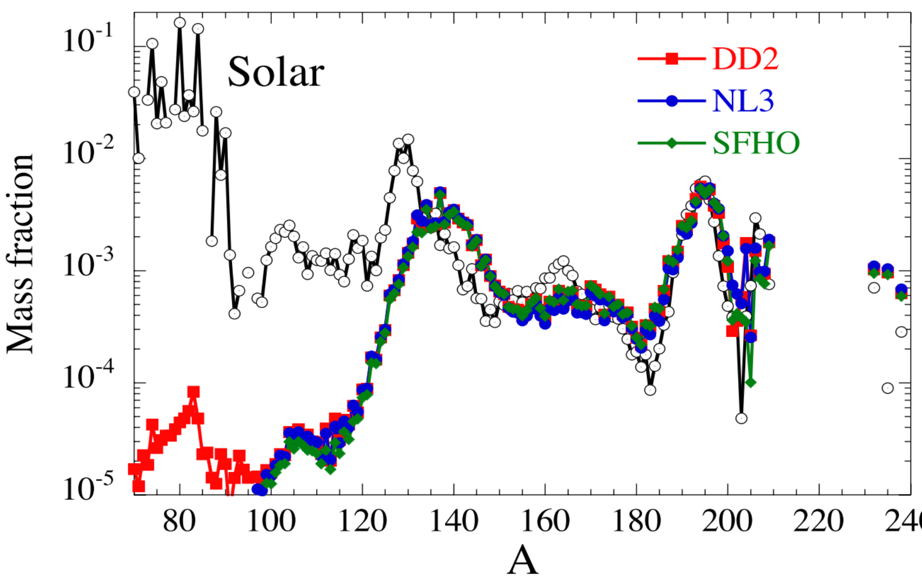
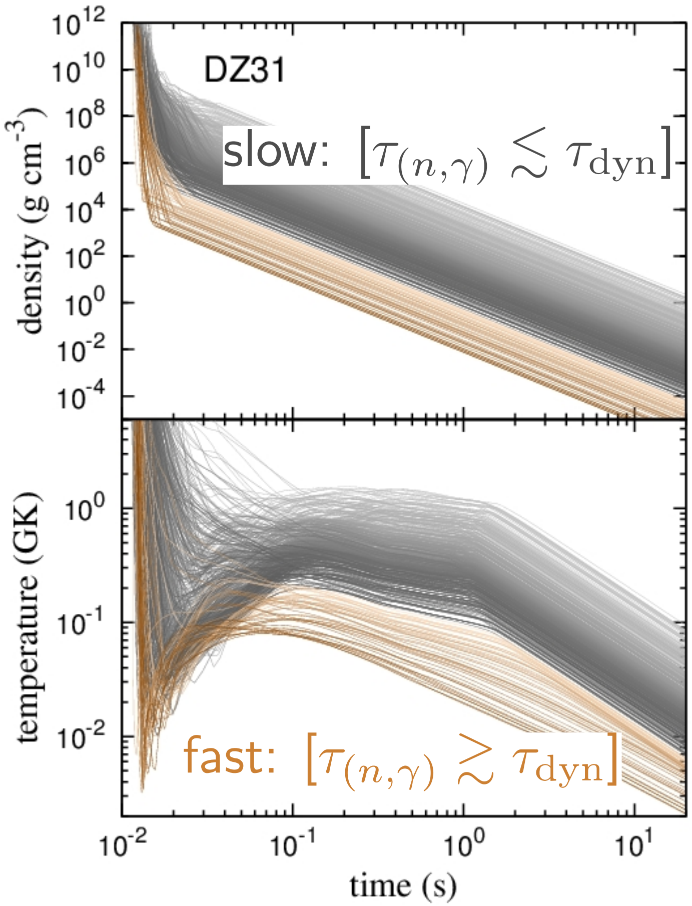


[Bauswein, Goriely, Janka, ApJ 773, 78 (2013)]

Variation in ejecta

[Mendoza-Temis et. al., PRC 92, 055805 (2015)]



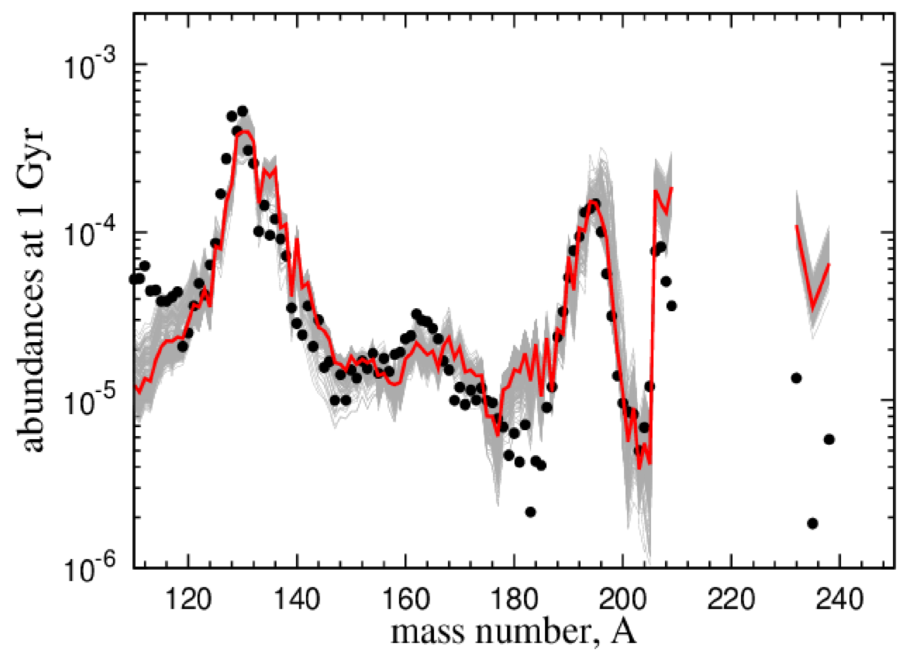
$1.35\ M_\odot - 1.35\ M_\odot$
from Bauswein+ 2013

slow ejecta:

– majority of the ejected mass ($\sim 90\%$ in this model)

– all neutrons are used out

– little variation among trajectories, due to the pile-up of fissioning nuclei



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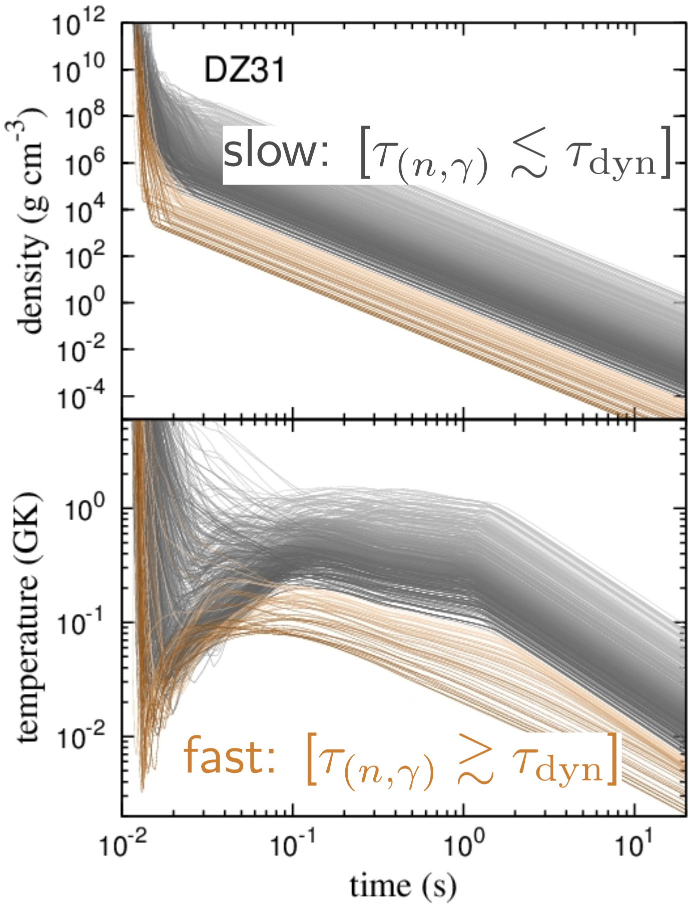


$1.35\ M_\odot - 1.35\ M_\odot$
from Bauswein+ 2013

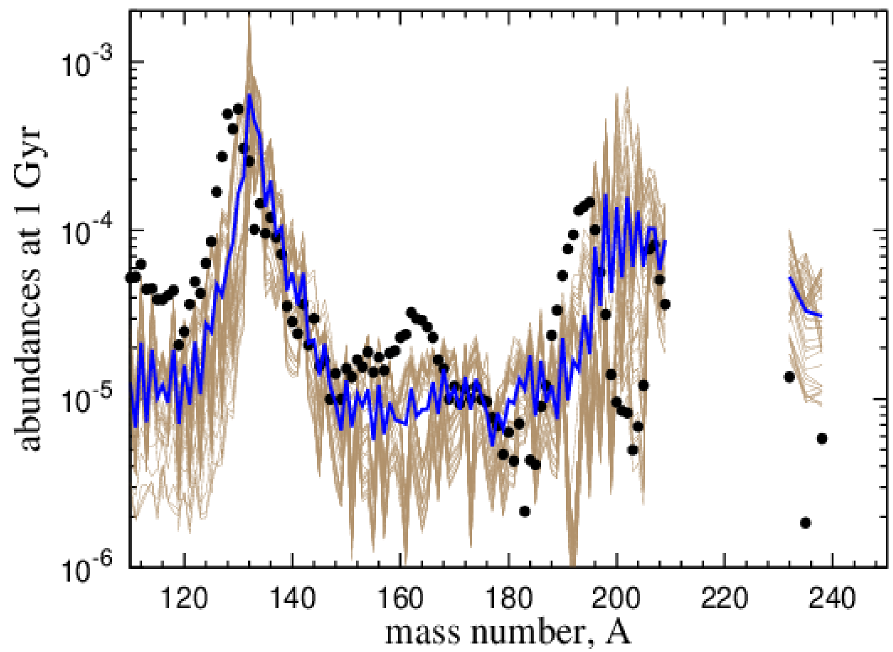
fast ejecta:

– $\sim 10\%$ in this model

– ~ 20–40% neutrons survive, may lead to blue kilonova precursor due to n-decay

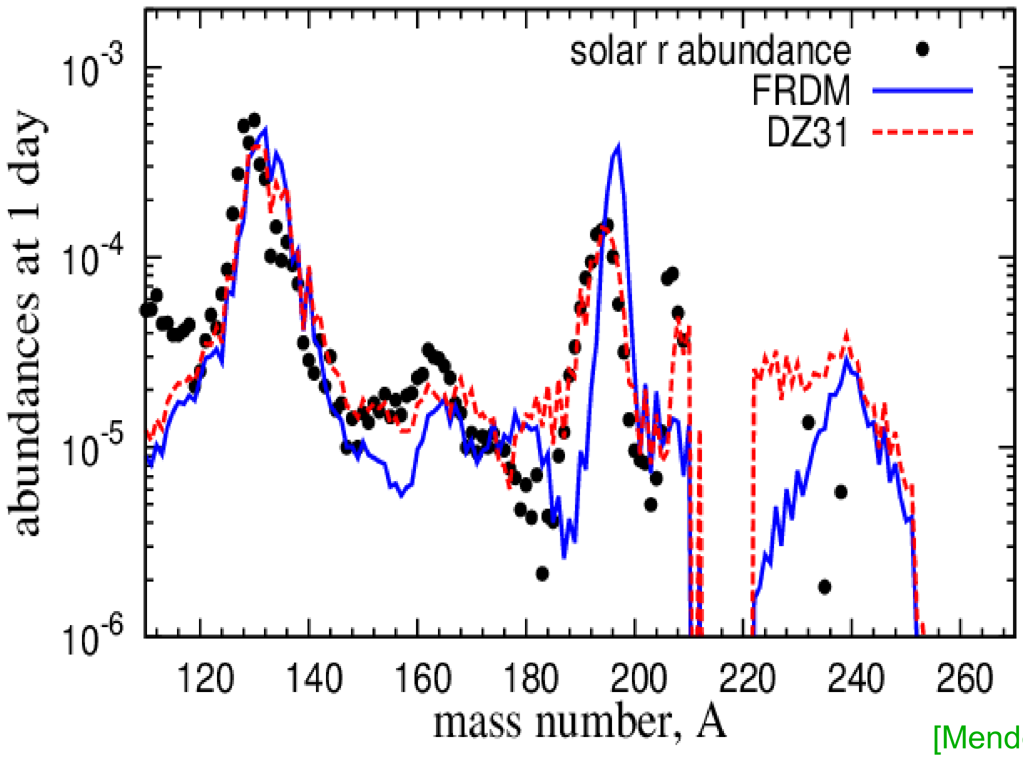
[Metzger et.al., MNRAS 446, 1115 (2015)]

– large variation among trajectories



Nuclear physics impact on dynamical ejecta

different nuclear masses (neutron capture and the inverse rates)



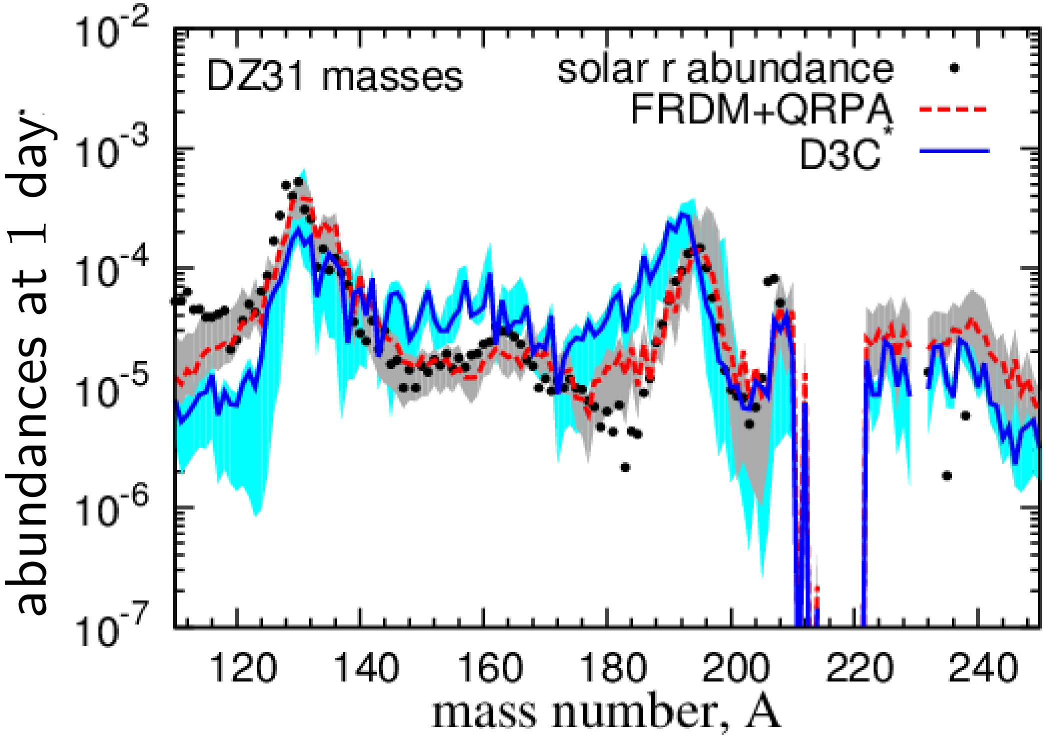
[Mendoza-Temis+, PRC 92, 055805 (2015)]

- different 3rd peak position and height due to the difference of neutron separation energies slightly above N=126 shell closure

- large difference in $A = 220 - 240$ at the kilonova relevant time, affecting the predicted lightcurves due to nuclei that α-decay [Barnes+ 2016, Rosswog+ 2016]

Nuclear physics impact on dynamical ejecta

different β-decay rates



- higher 3rd peak, lower 2nd peak for the model with faster β-decays (particularly at $A > 200$). [See also Eichler+ 2015]
- larger spread among trajectories.

role of fission rates and distribution?

Effect of neutrinos on dynamical ejecta

the neutrino interaction timescale and the dynamical timscale of the ejecta can be comparable, for ejecta NOT in the equatorial plane.

$$\frac{1}{r_{\nu\mathrm{N}}} \approx 1 \text{ ms} \left(\frac{10^{53}\mathrm{erg/s}}{L_\nu}\right) \left(\frac{r}{100\mathrm{km}}\right)^2 \left(\frac{10\mathrm{MeV}}{\langle E_\nu \rangle}\right)$$

$$\tau_{\mathrm{dyn}} \approx 1.7 \text{ ms} \left(\frac{r}{100\mathrm{km}}\right) \left(\frac{0.2c}{v_{\mathrm{ej}}}\right)$$

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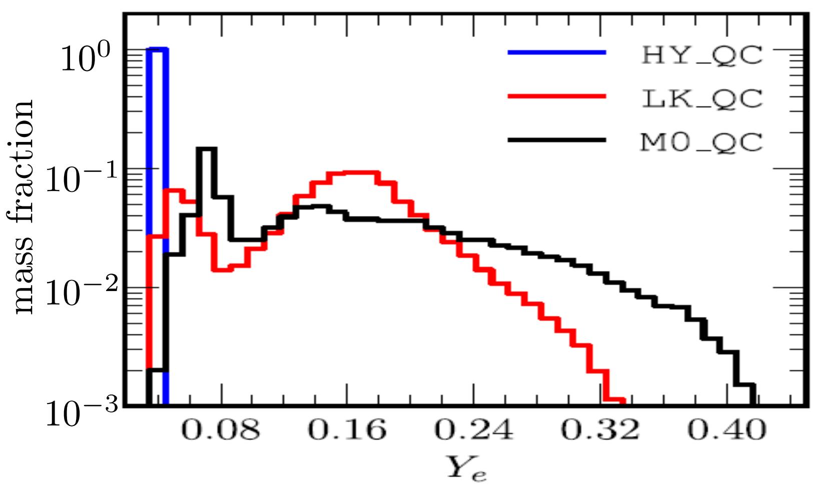
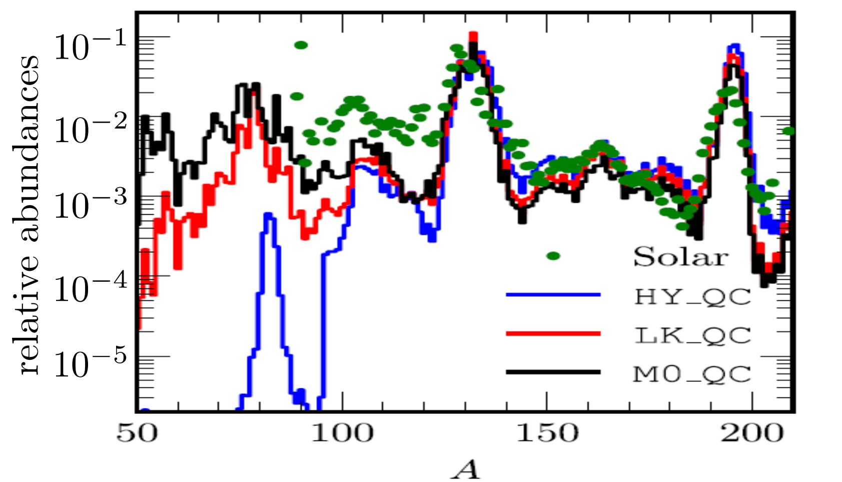
Y_e in dynamical ejecta can be significantly larger for NS–NS mergers [see e.g., Wanajo+ 2014, Sekiguchi+ 2016, Radice+ 2016]



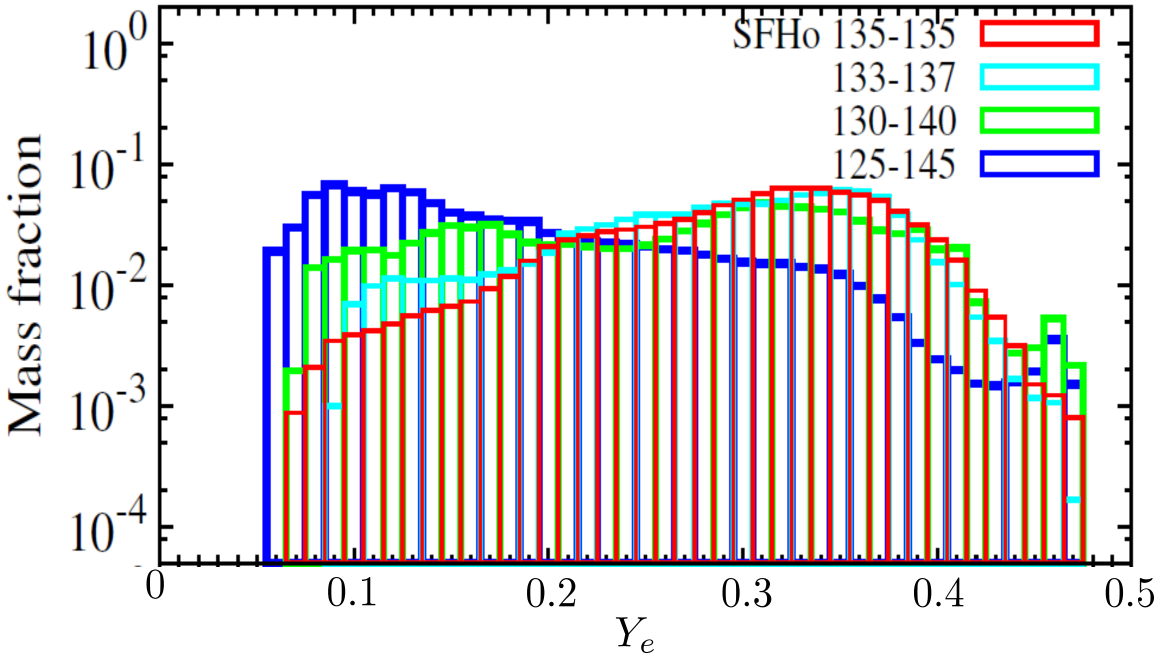


[Radice+, MNRAS 460, 3255 (2016)]

Effect of neutrinos on dynamical ejecta

do we still have the robustness of heavy r-abundances against variation of astrophysical condition?

[Sekiguchi+, PRD 93, 124046 (2016)]



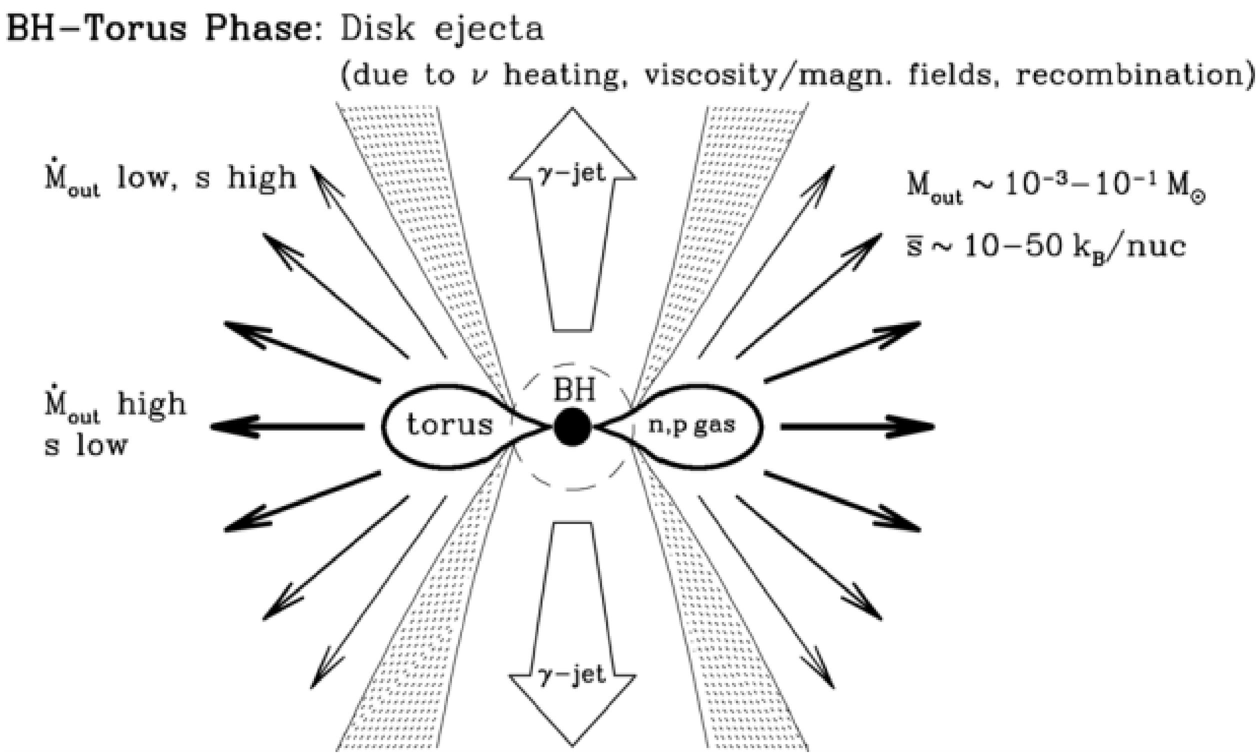
- neutrino transport? flavor conversions?...

r-process in the remnant outflow

After the dynamical ejecta, more material can be driven off from the remnant massive NS–disk or BH–torus system by:

– neutrino heating [see e.g., Dessart+ 2009, Perego+ 2014]

– viscous heating + nuclear recombination
[see e.g., Fernandez+ 2013-2016, Just+ 2016]



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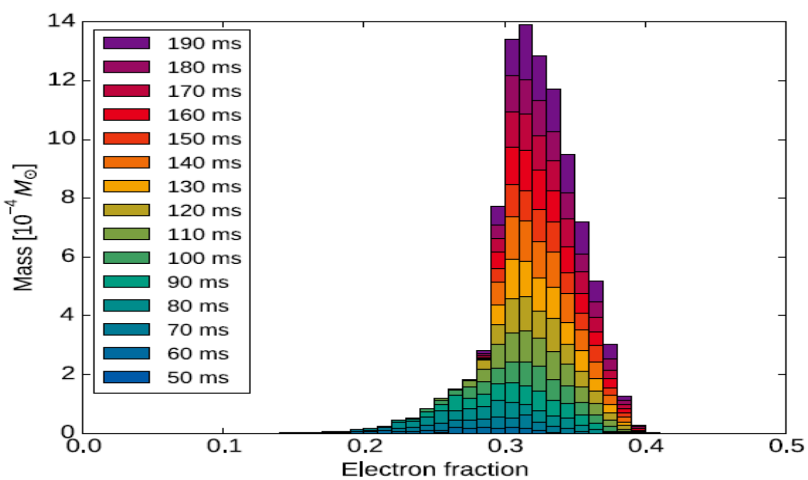
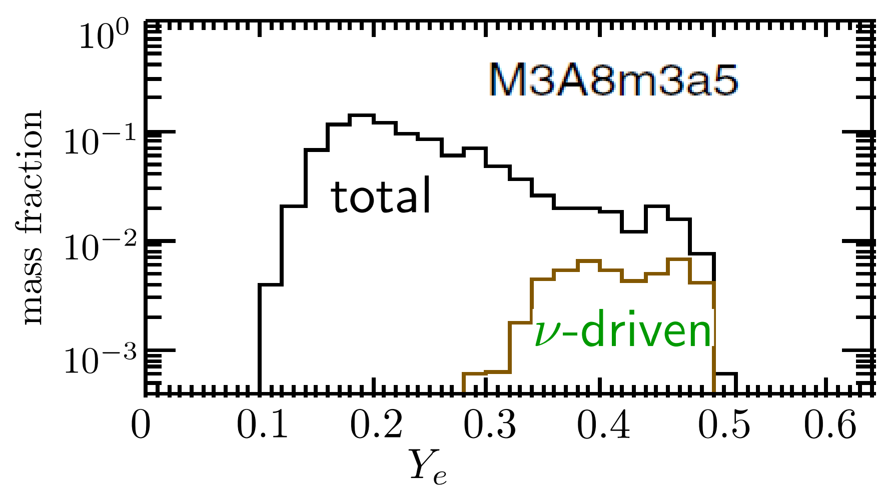
→ higher Y_e of the ejecta as weak interactions rise Y_e to their nearly-equilibrium values for a large part of the ejecta

[Martin+, ApJ 813, 2 (2015)]



MNS(2.5M$_\odot$)+disk(0.19M$_\odot$)

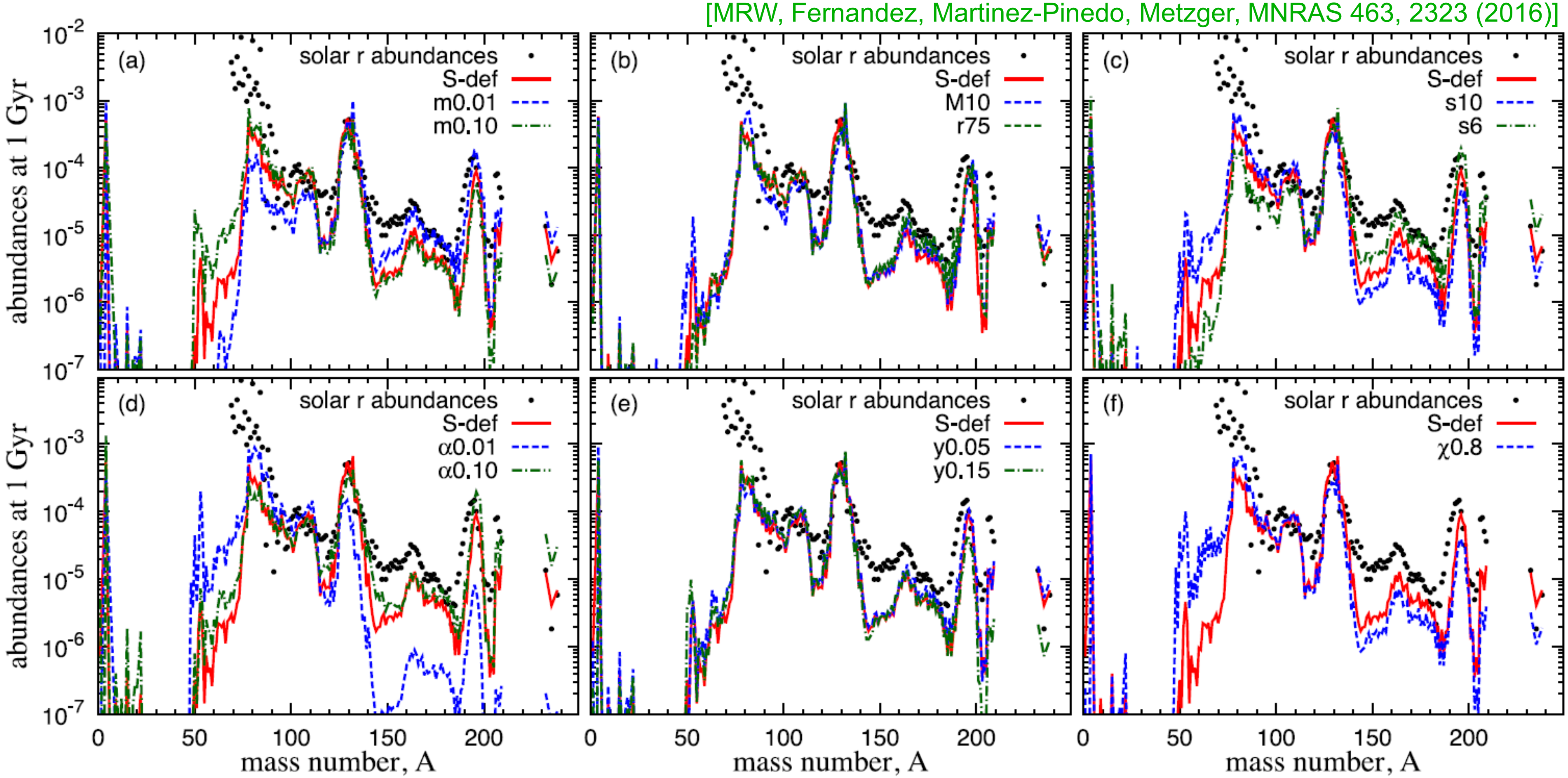
[Just+, MNRAS 448, 541 (2015)]



BH(3M$_\odot$,$\chi = 0.8$)+torus

Dependence on the Initial condition of BH–torus system

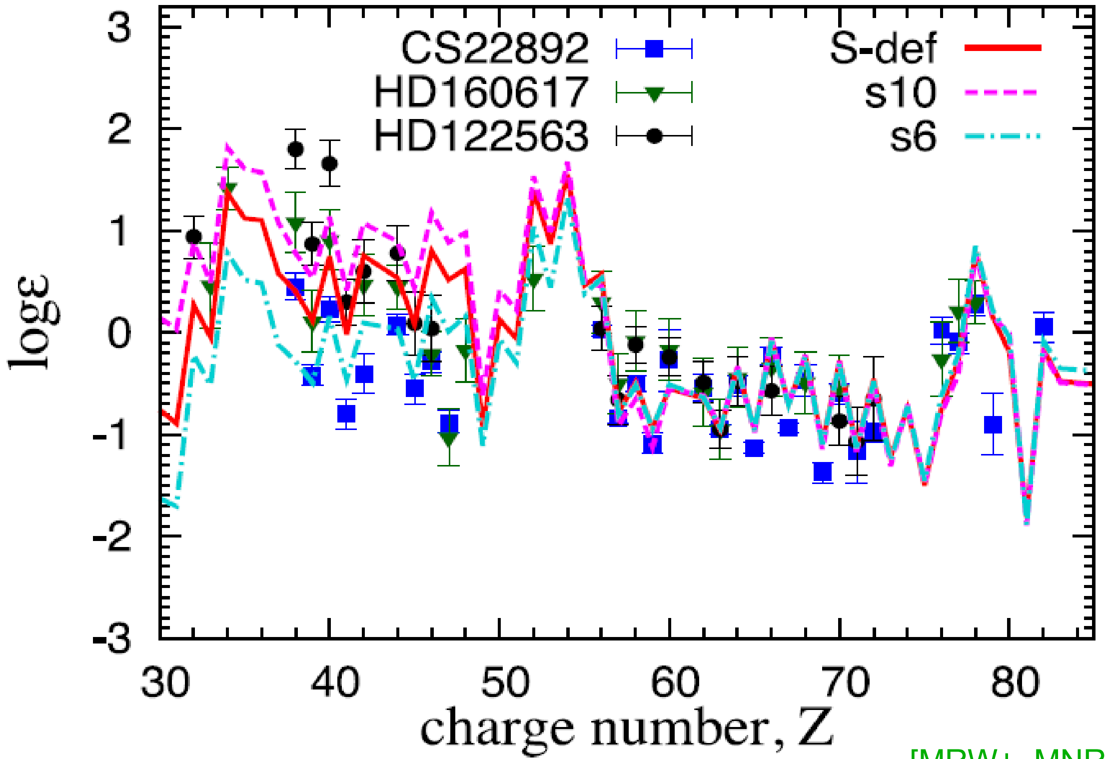
[MRW, Fernandez, Martinez-Pinedo, Metzger, MNRAS 463, 2323 (2016)]



viscosity being the most relevant,
BH-spin, disk mass, and disk entropy are also important

[S-def: $\mathrm{M_{BH}} = 3M_\odot$, $\mathrm{M_{disk}} = 0.03M_\odot$, $R_0 = 50$ km, $Y_{e,0} = 0.1$, $s_0/k_B/\mathrm{nuc} = 8$, $\alpha = 0.03$, $\chi_{\mathrm{BH,spin}} = 0$]

Elemental abundances vs. metal poor stars



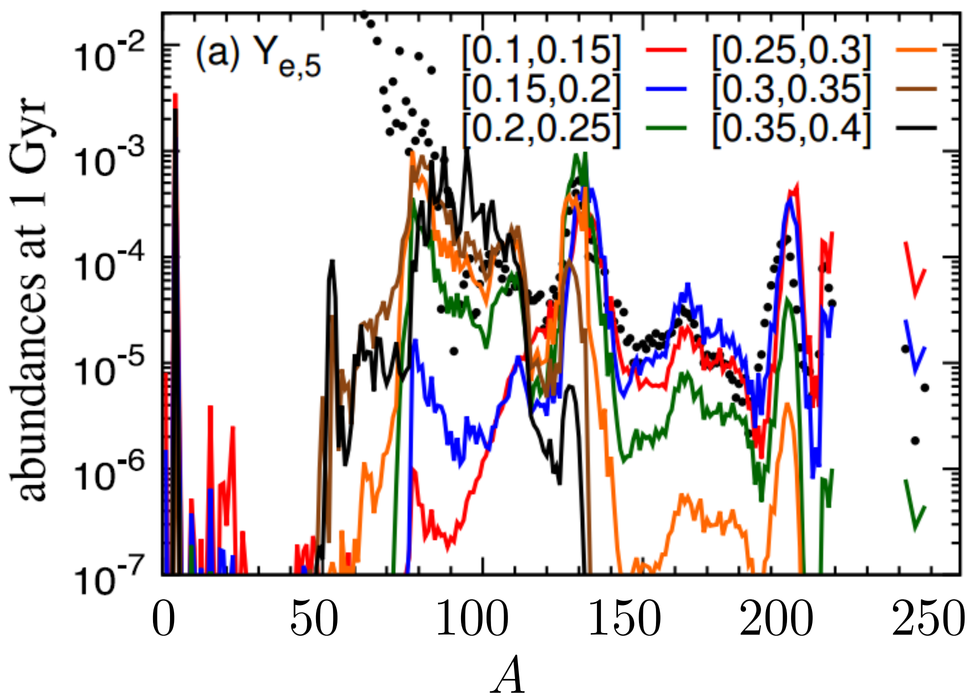
[MRW+, MNRAS 463, 2323 (2016)]

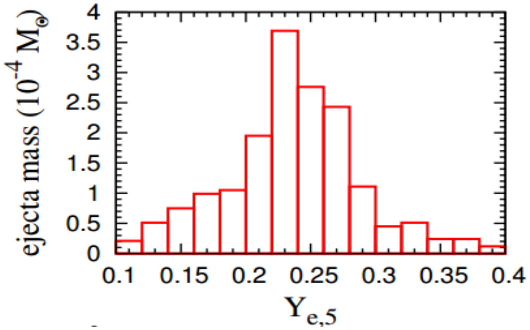
Can mergers & remnants account for the variations seen in metal-poor stars?

[see also Just+, MNRAS 448, 541 (2015)]

Dependence on the properties of the ejecta

Y_e being the most relevant quantity



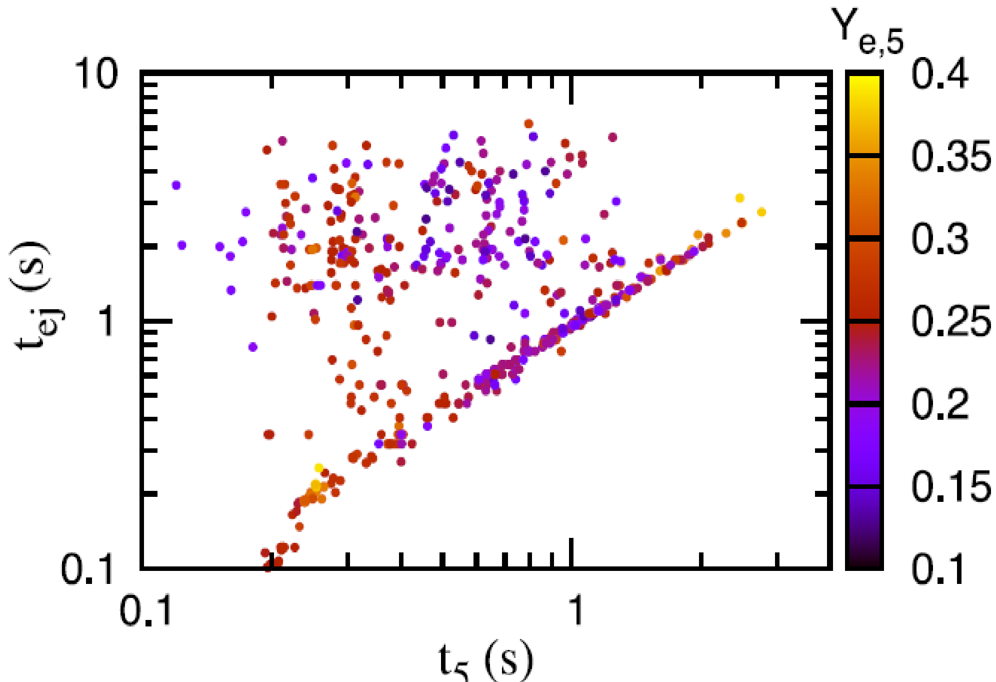


[MRW+, MNRAS 463, 2323 (2016)]

outcome insensitive to other quantities such as the ejection angle and the ejecta velocity.

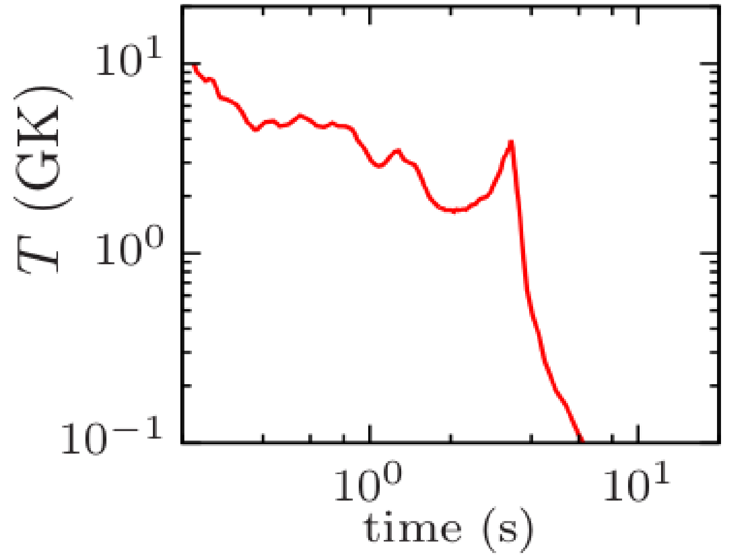
Anomaly of convective disk

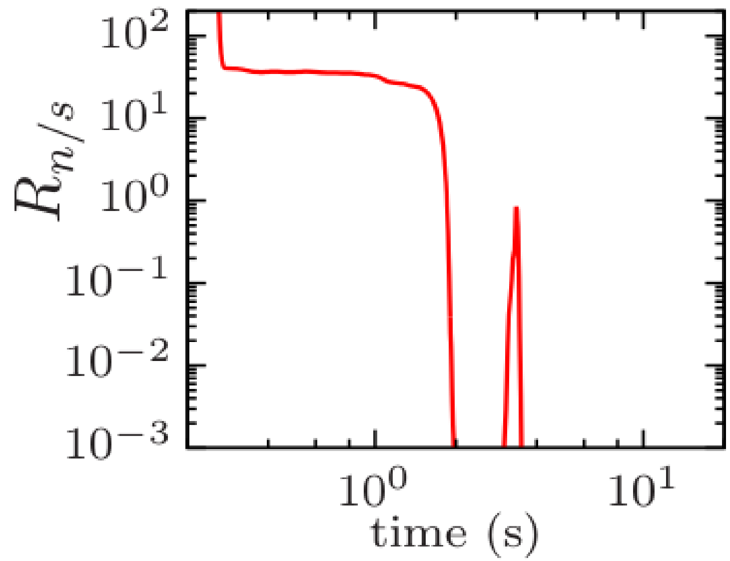
- large convective current may develop in the α-viscosity disk
- ejecta can be reheated at late evolution stage to increase T from $T \lesssim 1$ GK to $T \gtrsim 3$ GK
- neutrons are photo-dissociated during decay of r- nuclei at $t \gtrsim 1$ s



[MRW+, MNRAS 463, 2323 (2016)]

→ pile up of doubly-magic ^{132}Sn

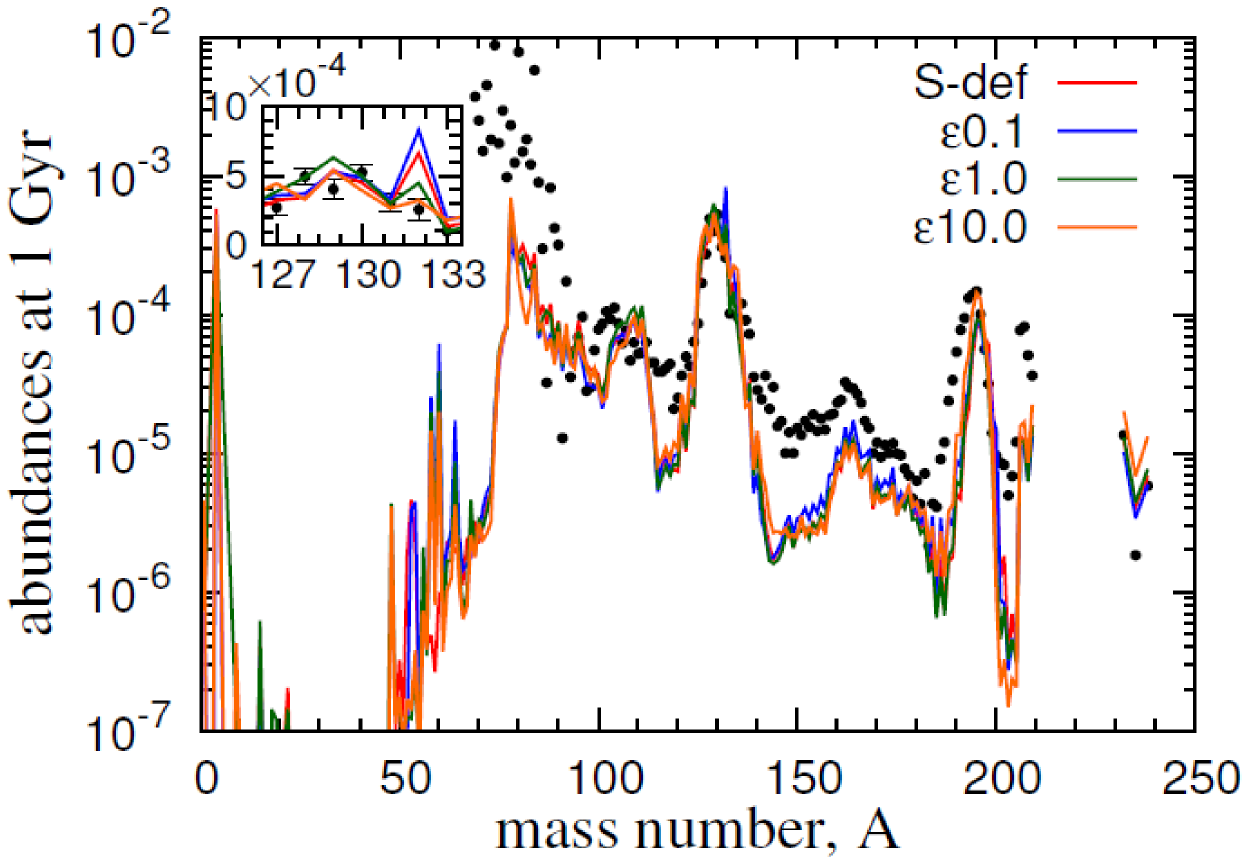




Anomaly of convective disk

Anomalously high abundance of ^{132}Sn:

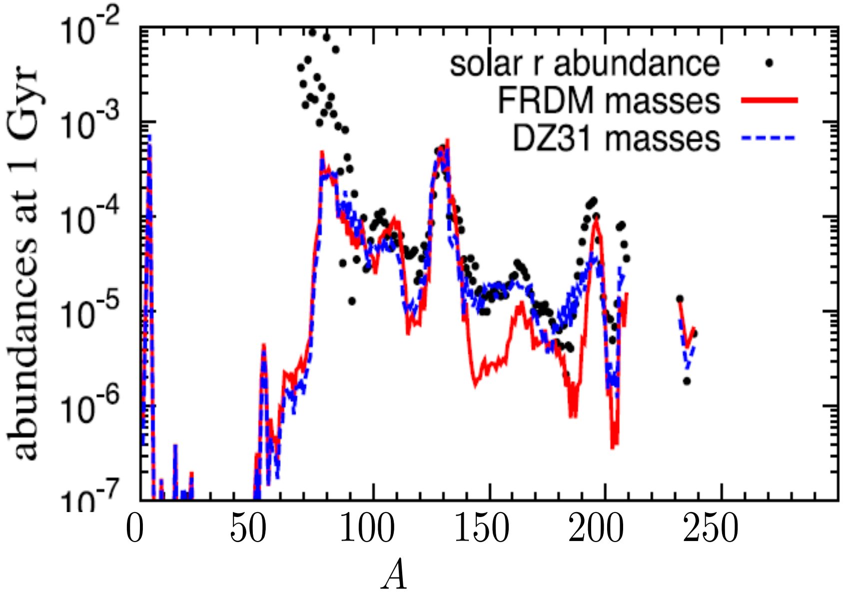
[MRW+, MNRAS 463, 2323 (2016)]



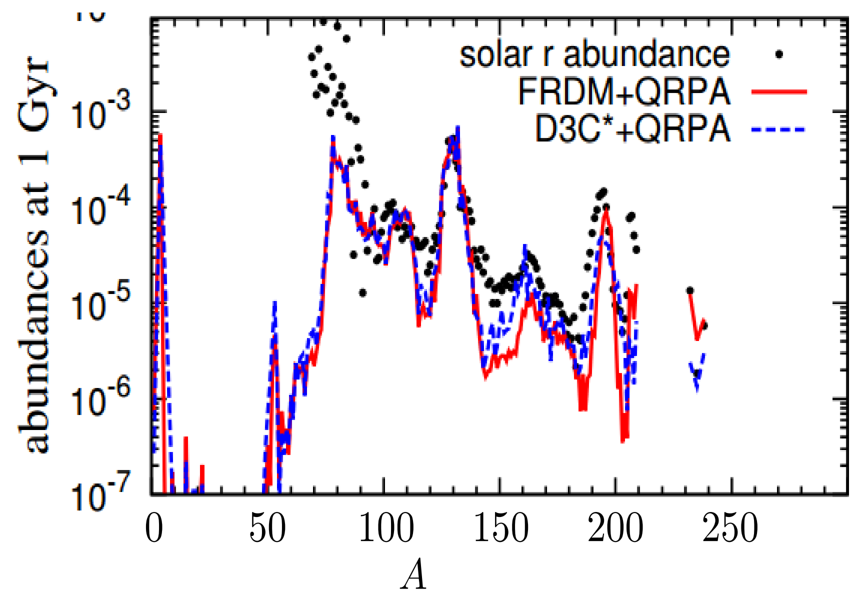
- inclusion of nuclear energy release beyond ^{4}He formation
- large or small viscosity may relieve this

Nuclear physics impact on BH-torus outflow

different nuclear masses



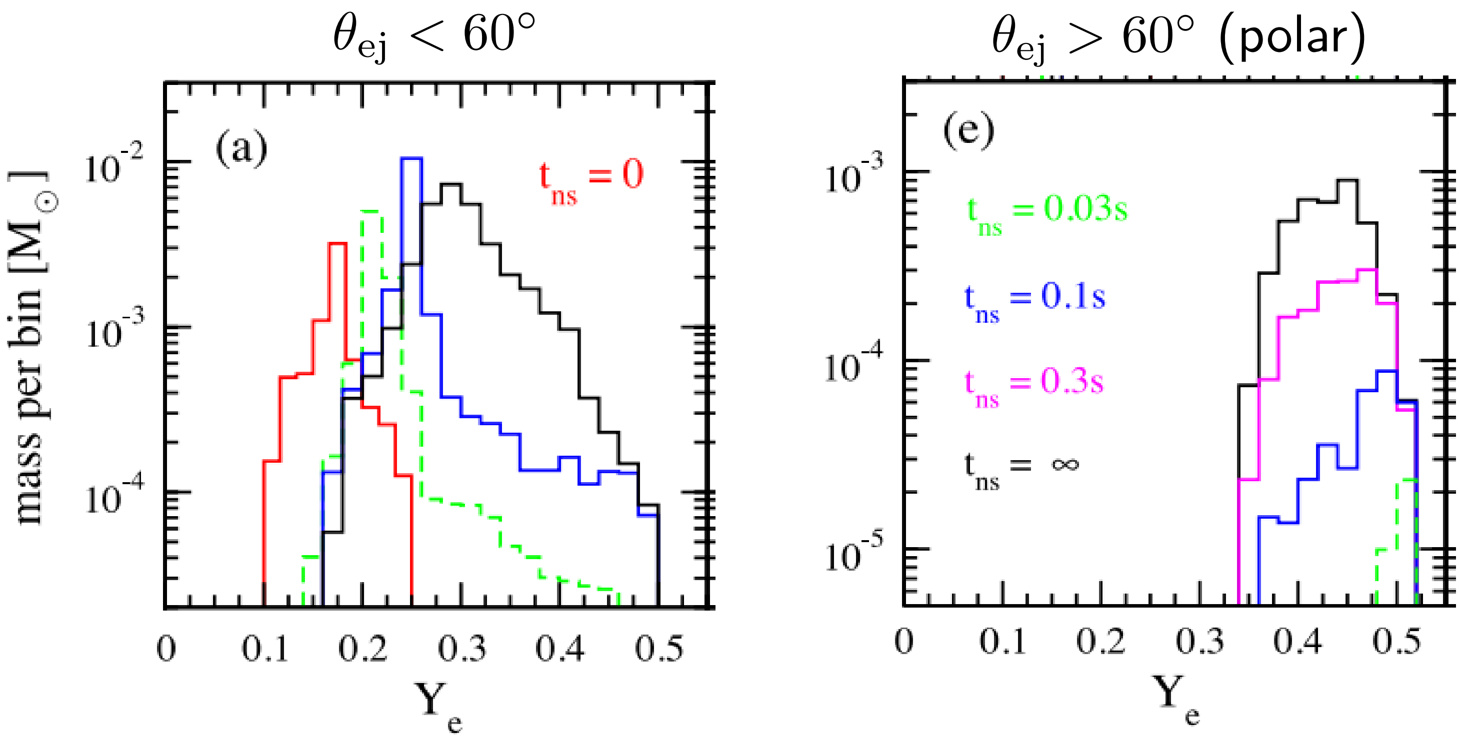
different β-decay rates



[MRW+, MNRAS 463, 2323 (2016)]

nuclear physics again can affect the resulting abundances despite much less neutron-rich

Effect of neutrinos from massive NS?



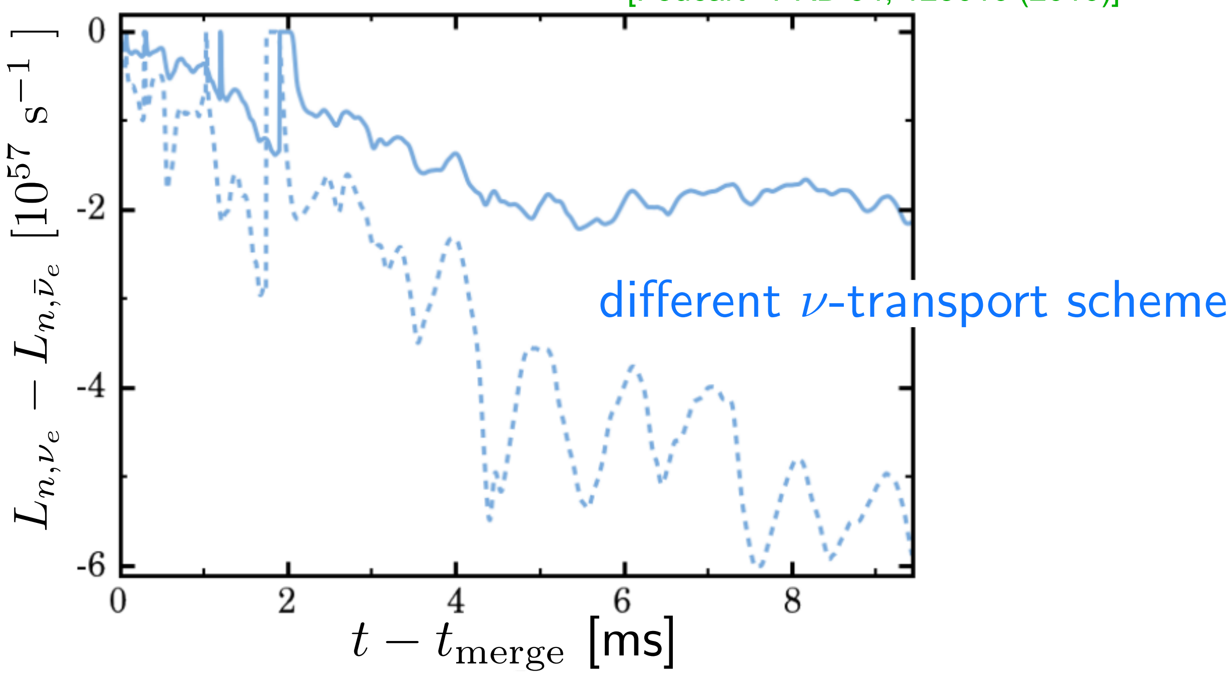
[Metzger & Fernandez, MNRAS 441, 3444 (2014)]

- life-time of the massive neutron star?
- neutrino transport? flavor conversions?...

Neutrino physics – flavor conversion

protonization of the merger remnant $\leftrightarrow$ negative neutrino lepton number

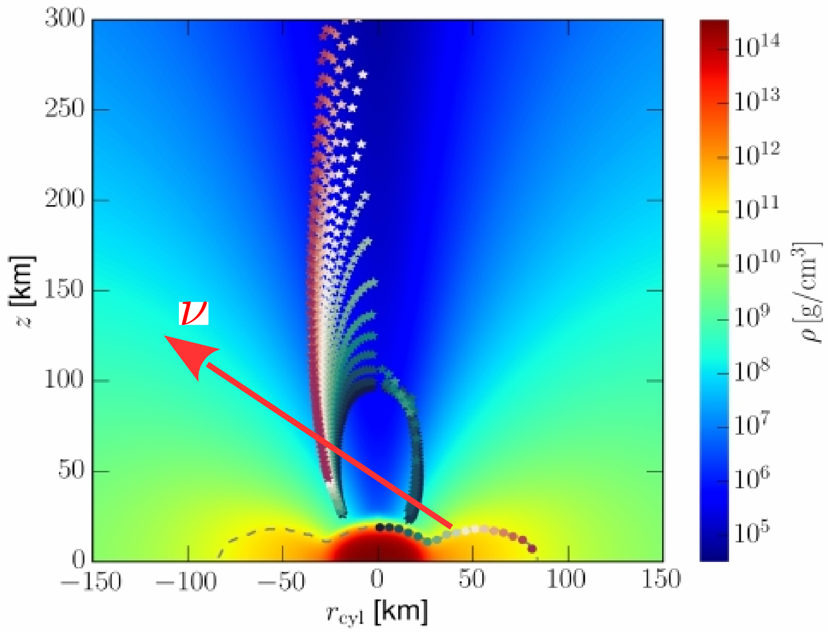
[Foucart+ PRD 94, 123016 (2016)]

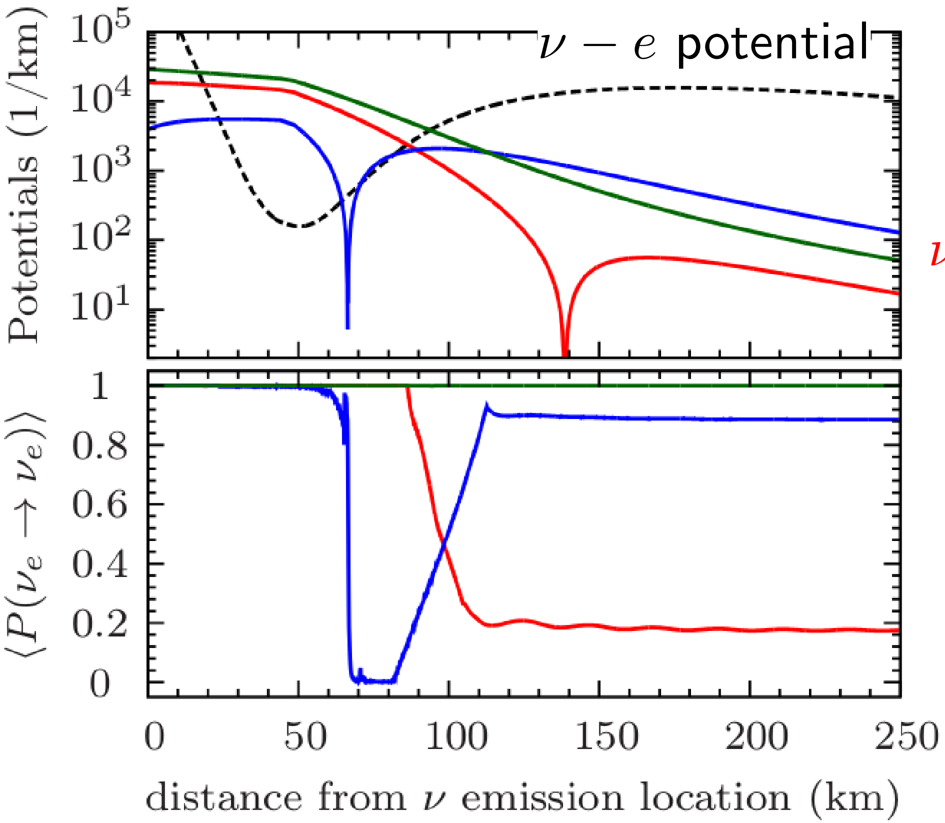


$\rightarrow$ potential ν flavor transformation above remnants through the matter-neutrino resonance when the $\nu - e$ and $\nu - \nu$ interacting potentials nearly cancel [Malkus+, Vaananen+, MRW+, Zhu+, Frensel+,..., see Gail's talk]

Neutrino physics – flavor conversion

The exact outcome of such conversion can be sensitive to the leptonization rates:





$\nu - \nu$ potentials with:

- L_ν at infinity from Perego+ 2014
- L_ν at ν surface from Perego+ 2014
- L_ν at infinity from Foucart+ 2016

[Frensel+, to appear in PRD (2017), ariXiv:1607.05938]

Neutrino physics – flavor conversion

Full EoM: $(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}})\varrho(\mathbf{x}, \mathbf{p}, t) = -i[H(\mathbf{x}, \mathbf{p}, t), \varrho(\mathbf{x}, \mathbf{p}, t)]$

$H(\mathbf{x}, \mathbf{p}, t) \subset \sum_{\mathbf{p}'}(\varrho(\mathbf{x}, \mathbf{p}', t) - \bar{\varrho}^*(\mathbf{x}, \mathbf{p}', t))(1 - \mathbf{v} \cdot \mathbf{v}') \to \text{non-linear coupling}$

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Imposing symmetries of the system help to reduce the dimension of the problem:

– spherical symmetry $\rightarrow \varrho(r, \theta_{\mathrm{em}}, |\mathbf{p}|, t)$

– stationarity $\rightarrow \varrho(r, \theta_{\mathrm{em}}, |\mathbf{p}|)$, ν-bulb model (multi-angle) [Duan+ 2006]

– single-angle approximation$\rightarrow \varrho(r, |\mathbf{p}|)$, might be fine if flavor conversion far away from the source

Neutrino physics – flavor conversion

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In NS(BH)-disk case, only cylindrical symmetry is present

$\rightarrow \varrho(x,z,\theta,\phi,|\mathbf{p}|)$

– single-trajectory approximation $\rightarrow \varrho(d,r_{\mathrm{em}},\theta,\phi,|\mathbf{p}|)$ this actually "decouples" the flavor evolution of neutrinos with different momenta

Neutrino physics – flavor conversion

"fast" conversion can happen extremely close to the ν surfaces, driven by the local angular distribution of neutrino lepton number

[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016]

Neutrino physics – flavor conversion

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Solving the full EoM is cubersome, but one can linearize the EoM and analyze locally how off-diagonal term in ϱ evolves in linear regime.

[Banerjee+ 2011, Raffelt+ 2013, Izaguirre+ 2017...]

If the off-diagonal term grows exponentially $\leftrightarrow$ flavor conversion happens at the time/length scale of the exponent

Neutrino physics – flavor conversion

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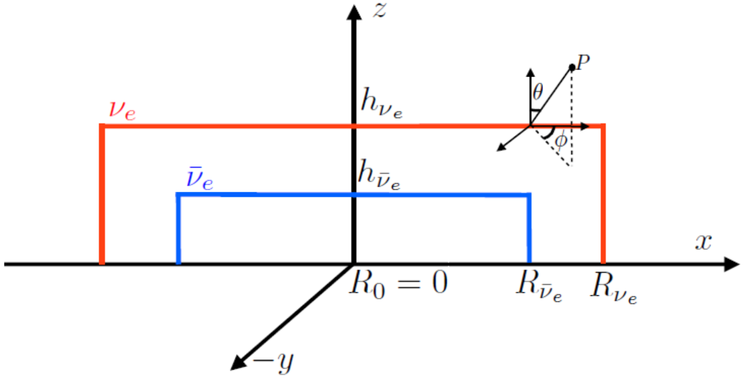
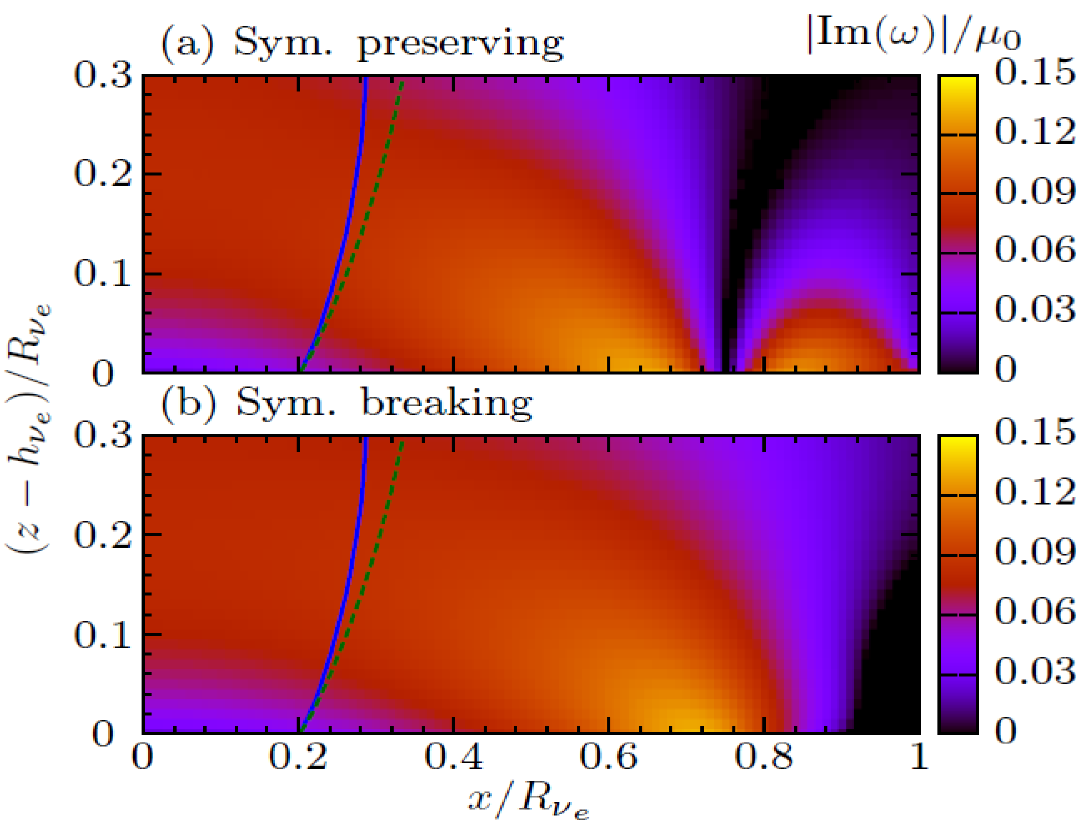
[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016]





$\mathrm{Im}(\omega)$: rate of flavor conversion in the linear regime

$$\mu_0 \approx 4.25\ \mathrm{cm}^{-1} \times \left(\frac{L_{\nu_e}}{10^{53}\mathrm{erg/s}}\right)\left(\frac{10\mathrm{MeV}}{\langle E_{\nu_e}\rangle}\right)\left(\frac{100\mathrm{km}}{R_{\nu_e}}\right)^2$$

[MRW & Tamborra, in preparation]

$$L_{n,\bar{\nu}_e}/L_{n,\nu_e} = 1.35,\ R_{\bar{\nu}_e} = 0.75 R_{\nu_e},\ h_{\nu_e}/R_{\nu_e} = h_{\bar{\nu}_e}/R_{\bar{\nu}_e} = 0.25.$$

Summary & discussions

- NH–NS/BH mergers can produce the whole range of r-process nuclides with (the combination of) different components of ejecta. Can the variations simultaneous account for the observed robustness of heavy r abunadnces and the variations of light r abundances?
- The dynamical ejecta can always reach the 3rd peak and above. Influence of neutrinos determines how much $A < 120$ can be synthesized.
- The disk outflow can potentially produce all r-nuclei from $A \approx 80$ to U and Th. Viscosity and the life time of the massive NS are the big unknowns.
- Nuclear physics affects the detail abundances in several ways and may even play roles in the kilonova/macronova lightcurves.
- Neutrino flavor conversion will likely occur in the merger remnants. Fast conversions may change the MNR paradigm and change the role of neutrinos on nucleosynthesis and jet dynamics (if any).