Role of nuclear physics and neutrinos in the r-process in merger outflows

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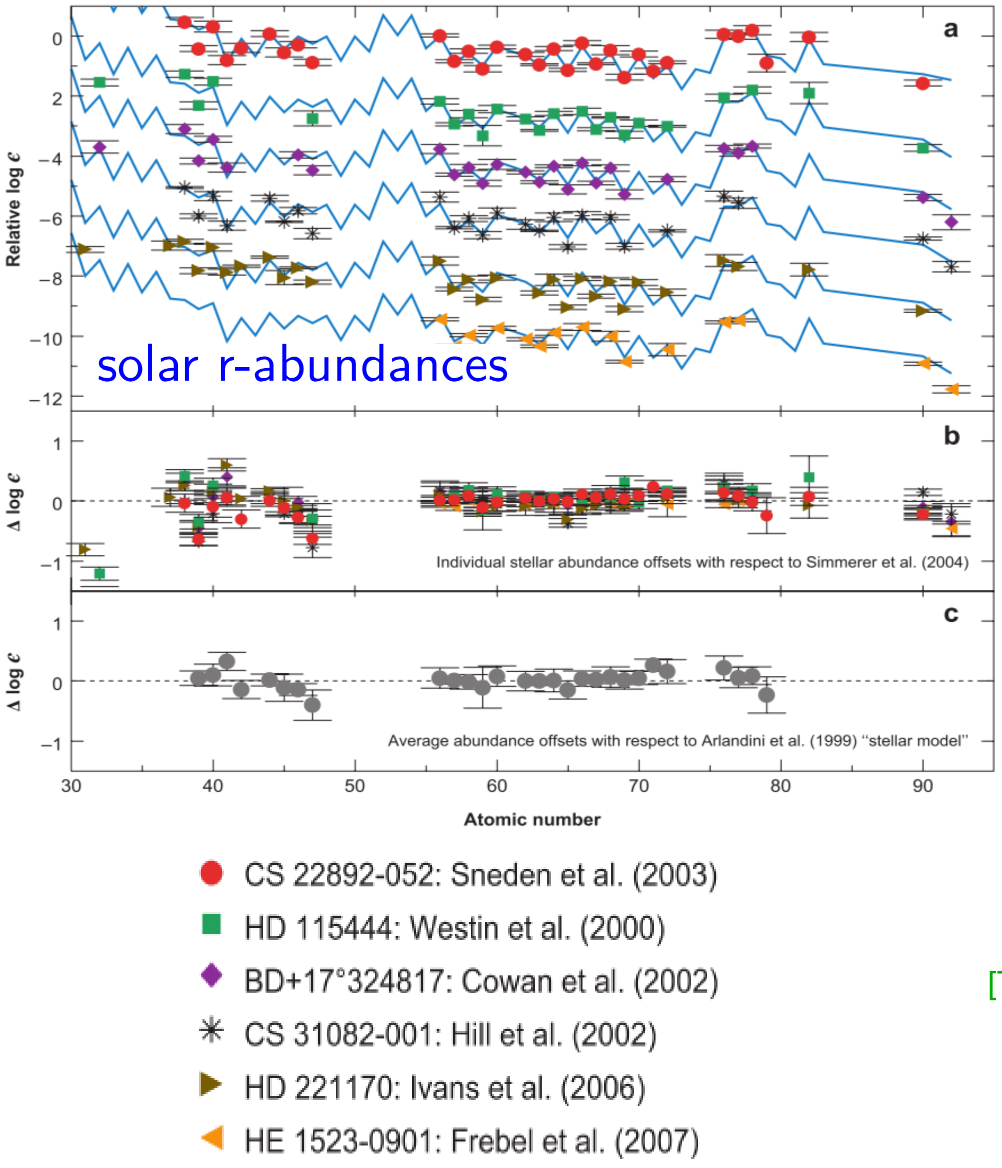
Observational Signatures of r-process Nucleosynthesis in Neutron Star Mergers
INT-17-2b Workshop, Seattle, USA, July 30 – August 4, 2017

Signature of the r-process

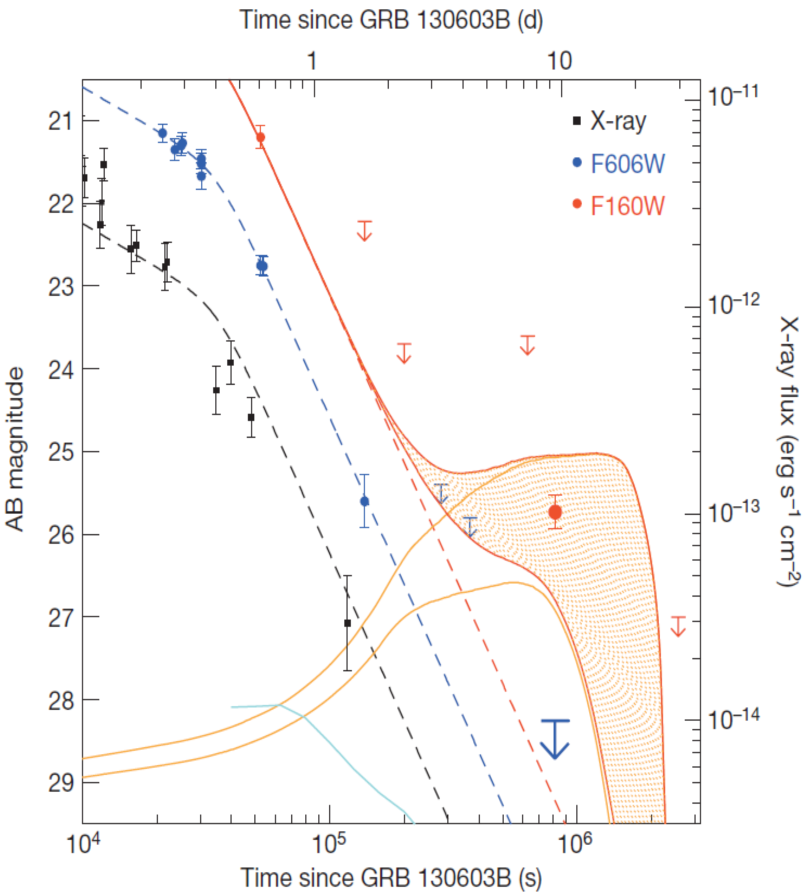
abundances in metal-poor stars & Solar system



solar r-abundances

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

kilonovae/macronovae
following sGRB

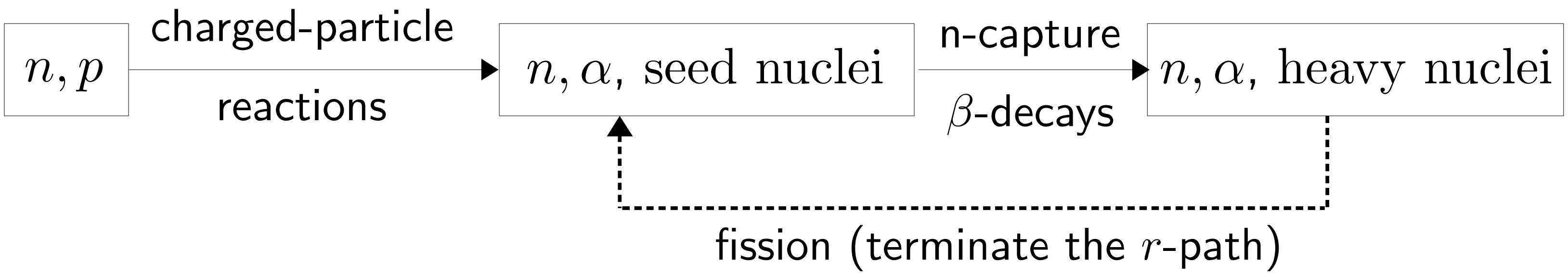


[Tanvir+ Nature 500 (2013) 547, Berger+ ApJL 774 (2013) 23]

other candidates, e.g.,
GRB060614 & GRB050709

[Yang+ 2015 & Jin+ 2016]

r-process nucleosynthesis – flow and nuclear physics



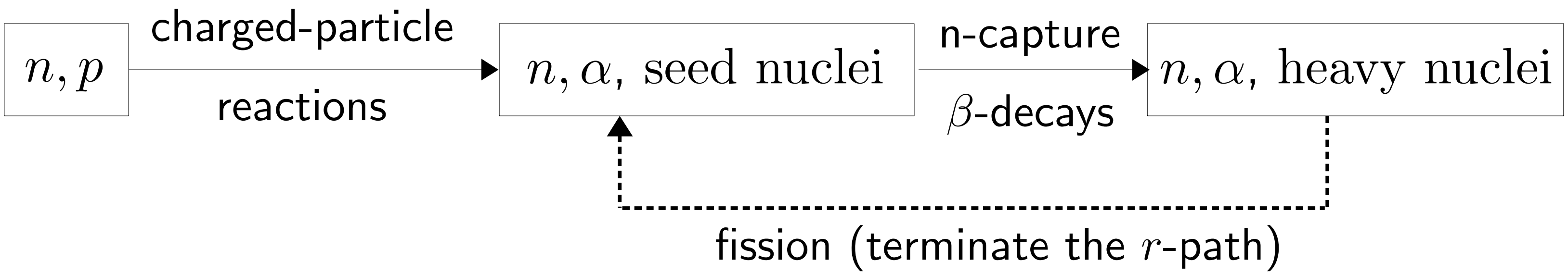
n, p charged-particle reactions → $n, \alpha,$ seed nuclei

$n, \alpha,$ seed nuclei n-capture β-decays → $n, \alpha,$ heavy nuclei

$n, \alpha,$ heavy nuclei → $n, \alpha,$ seed nuclei: fission (terminate the r-path)

- the neutron-to-seed ratio, $R_{n/s}$, governed by astrophysical conditions, determines how far the r-process goes

r-process nucleosynthesis – flow and nuclear physics



n, p

charged-particle

reactions

n, α, seed nuclei

n-capture

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- nuclear physics determines the abundance distribution

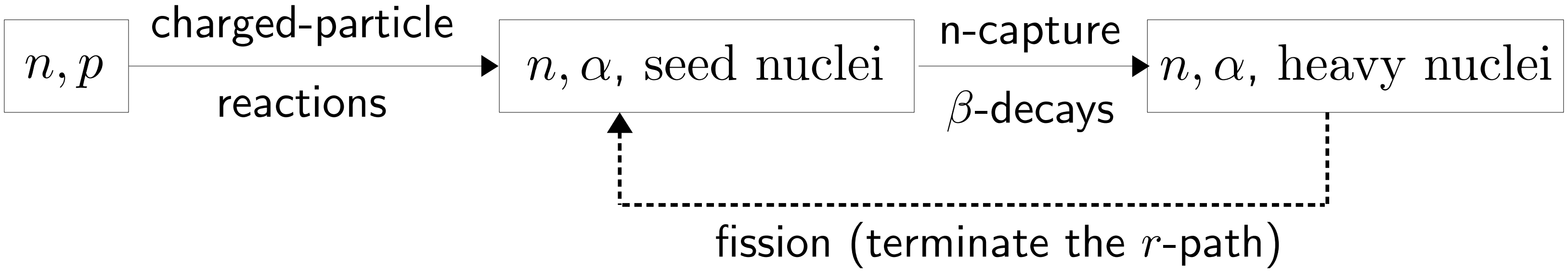
→ neutron separation energies (masses) determine the path

→ β-decay rates determine the relative abundances along the path

→ neutron capture rates and β-decay rates determine details of freeze-out

→ fission distributions can largely shape the pattern if fissioning nuclei dominate

r-process nucleosynthesis – flow and nuclear physics



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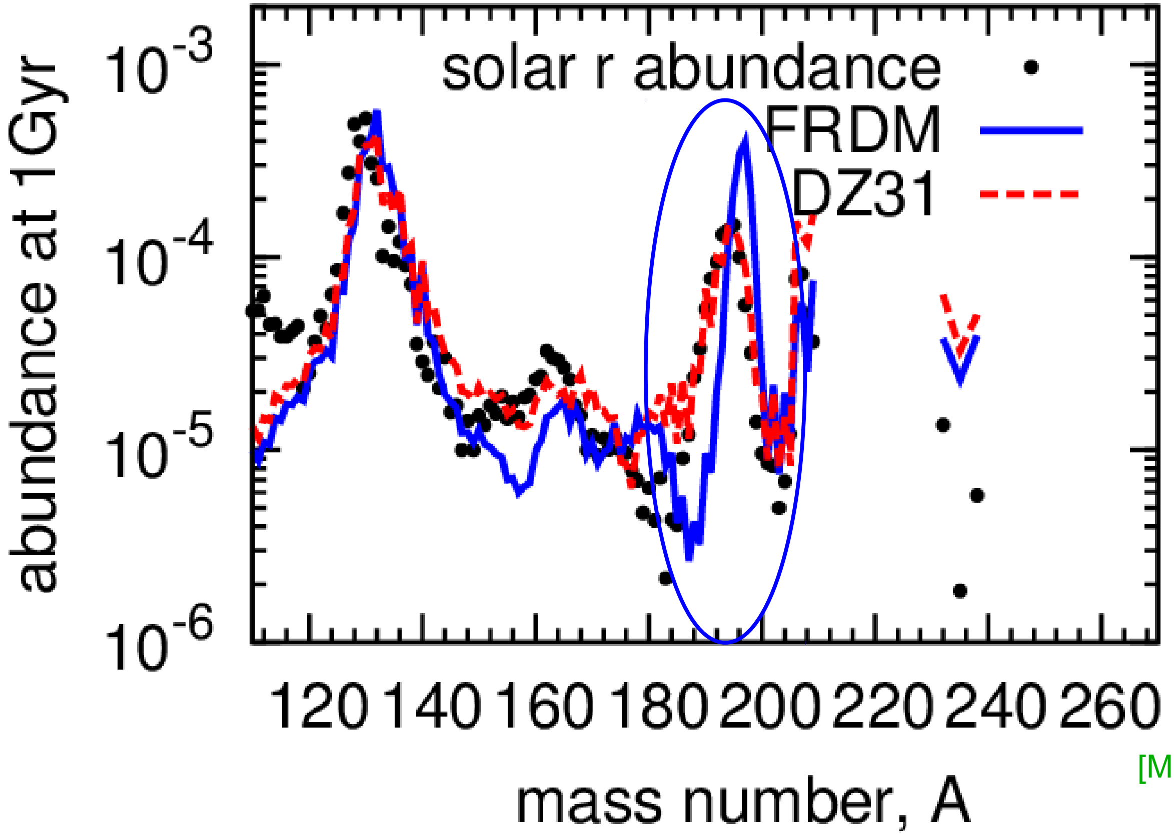
energy release during AND after the r-process are both relevant

Nuclear physics impact on low Y_e ejecta – mass model

- dynamical ejecta from simulation of $1.35\ M_\odot - 1.35\ M_\odot$ model from Bauswein+ 2013, $0.01 < Y_{e,\mathrm{init}} < 0.06$



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

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

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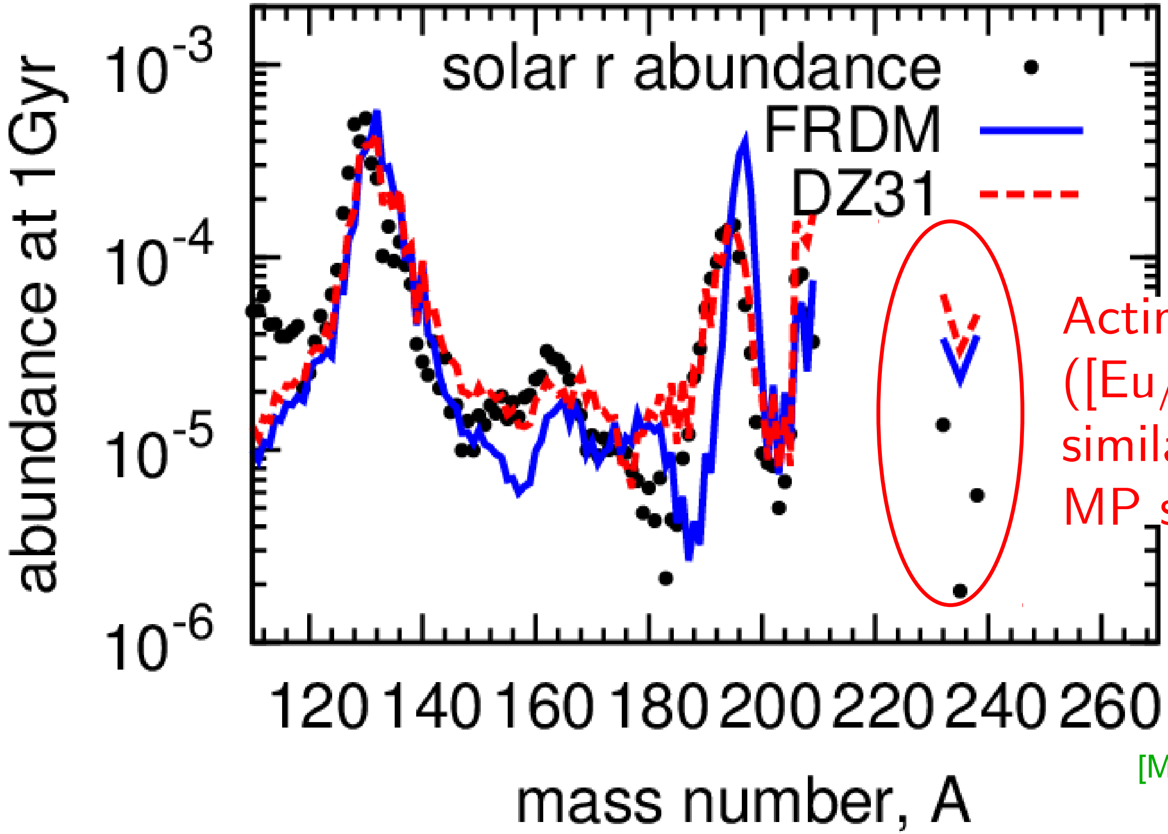


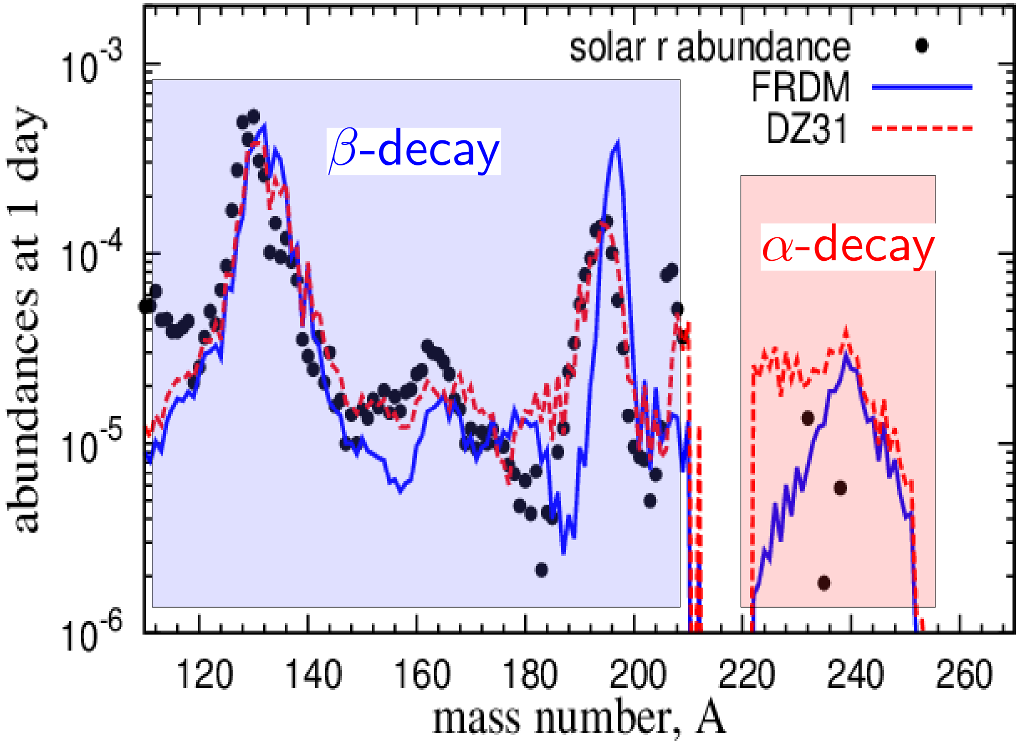
Actinide boosted!
([Eu/Th]≈ -0.3 at 13Gyr)
similar to the mostly-boosted MP star

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

- remain actinide boosted with $Y_e \lesssim 0.125 - 0.175$
- depending on the β-decay lifetime prediction of actinides

Nuclear physics impact on low Y_e ejecta – mass model

At kilonova time, large difference for $220 \lesssim A \lesssim 240$



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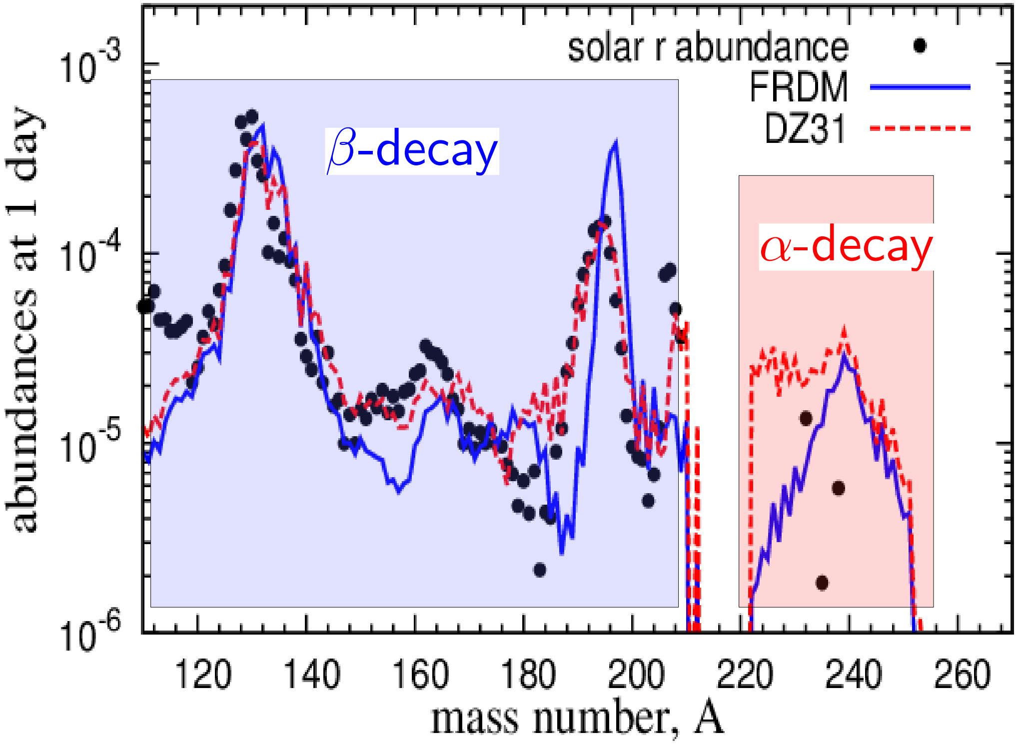
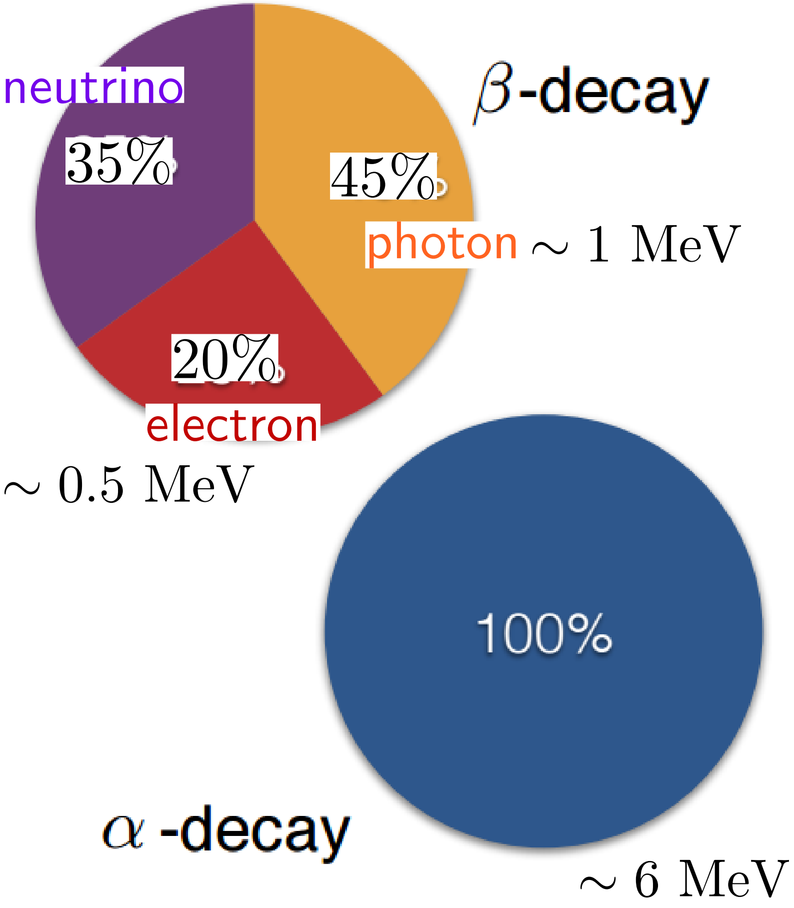
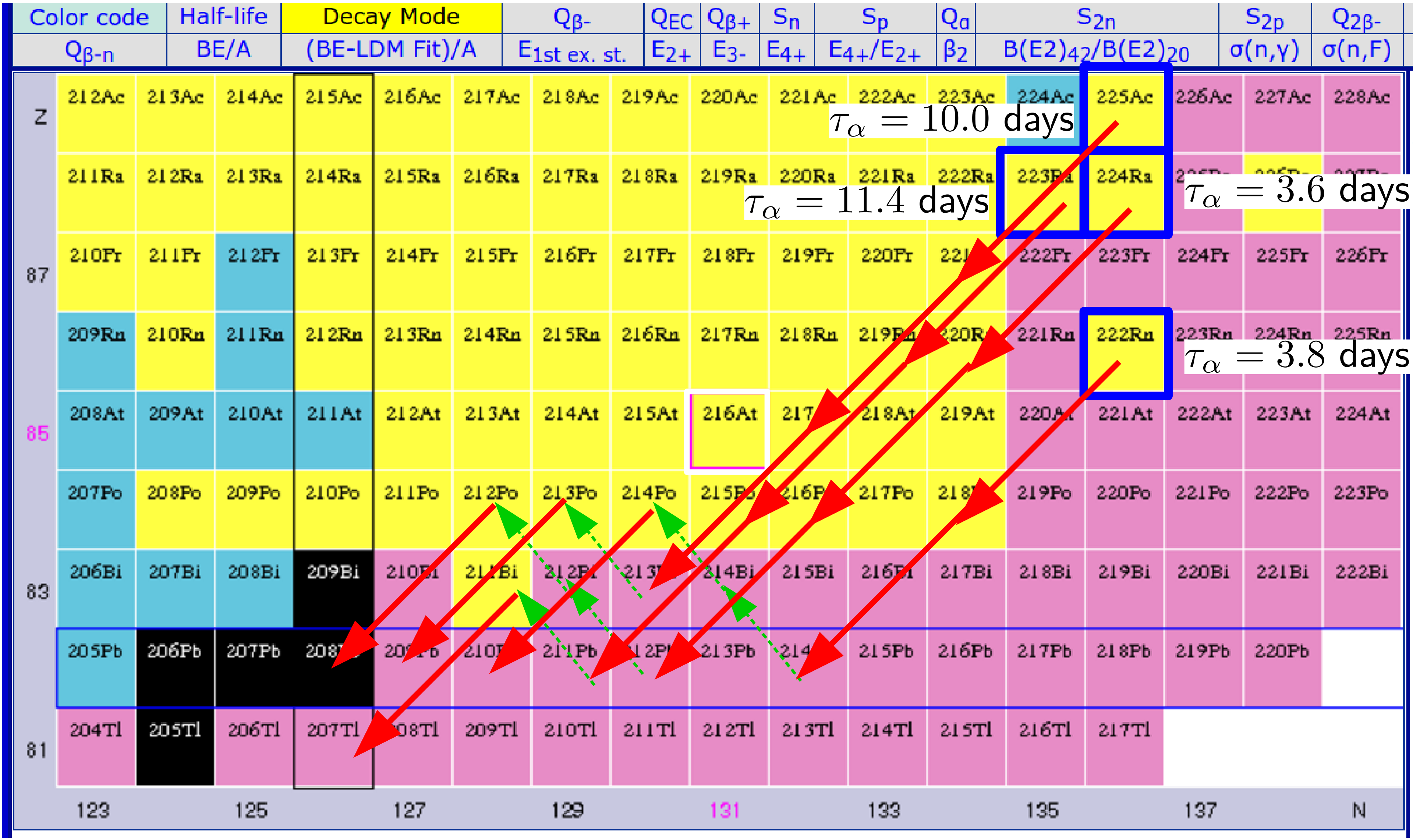




[Hotokezaka+2016, Barnes+2016]

Relevant α-decays



Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$
$Q_{\beta\text{-}n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$

Z	212Ac	213Ac	214Ac	215Ac	216Ac	217Ac	218Ac	219Ac	220Ac	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac
	211Ra	212Ra	213Ra	214Ra	215Ra	216Ra	217Ra	218Ra	219Ra	220Ra	221Ra	222Ra	223Ra	224Ra	2	[illegible]	[illegible]
87	210Fr	211Fr	212Fr	213Fr	214Fr	215Fr	216Fr	217Fr	218Fr	219Fr	220Fr	221	222Fr	223Fr	224Fr	225Fr	226Fr
	209Rn	210Rn	211Rn	212Rn	213Rn	214Rn	215Rn	216Rn	217Rn	218Rn	219R	220R	221Rn	222Rn	223Rn	224Rn	225Rn
85	208At	209At	210At	211At	212At	213At	214At	215At	216At	217	218At	219At	220A	221At	222At	223At	224At
	207Po	208Po	209Po	210Po	211Po	212Po	213Po	214Po	215P	216P	217Po	218	219Po	220Po	221Po	222Po	223Po
83	206Bi	207Bi	208Bi	209Bi	210Bi	211Bi	212Bi	213	214Bi	215Bi	216Bi	217Bi	218Bi	219Bi	220Bi	221Bi	222Bi
	205Pb	206Pb	207Pb	208	209Pb	210	211Pb	212P	213Pb	214	215Pb	216Pb	217Pb	218Pb	219Pb	220Pb	
81	204Tl	205Tl	206Tl	207Tl	08Tl	209Tl	210Tl	211Tl	212Tl	213Tl	214Tl	215Tl	216Tl	217Tl			
	123		125		127		129		131		133		135		137		N

$\tau_\alpha = 10.0$ days

$\tau_\alpha = 11.4$ days

$\tau_\alpha = 3.6$ days

$\tau_\alpha = 3.8$ days

Nuclear physics impact on low Y_e ejecta – mass model

- α decays may release similar amount of energy as β decays per second, sensitively depending on the adopted nuclear mass model

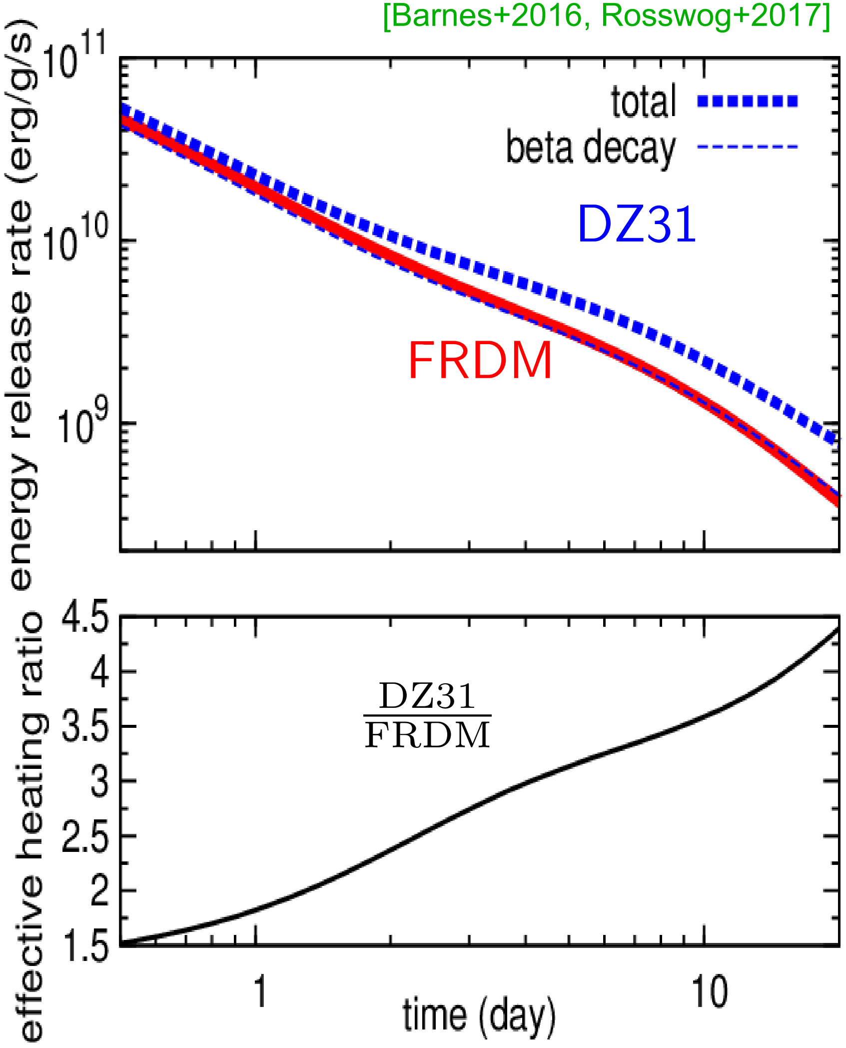
- α & β particles thermalize in a similar way while γ-ray thermalization quickly become inefficient

[Hotokezaka+2016, Barnes+2016]

effective heating $\sim \dot{Q}_\alpha + 0.2\dot{Q}_\beta$

(fission ignored)

[Barnes+2016, Rosswog+2017]



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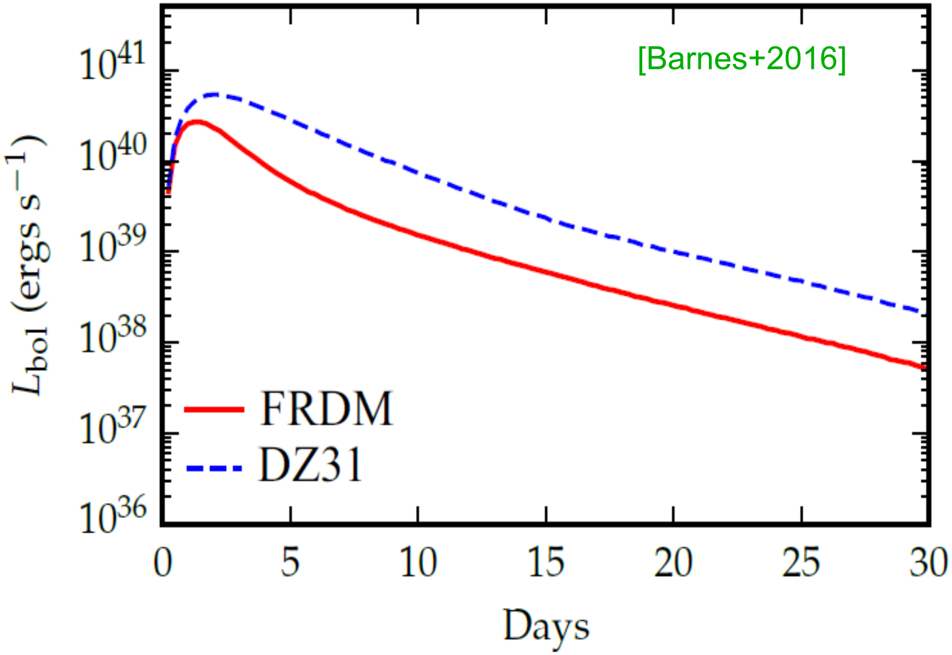
$M_{\rm ej} = 5 \times 10^{-3}\ M_\odot,\ v_{\rm ej} = 0.2c$



(see also Rosswog+ 2017 for models with different $M_{\rm ej}$, $v_{\rm ej}$)

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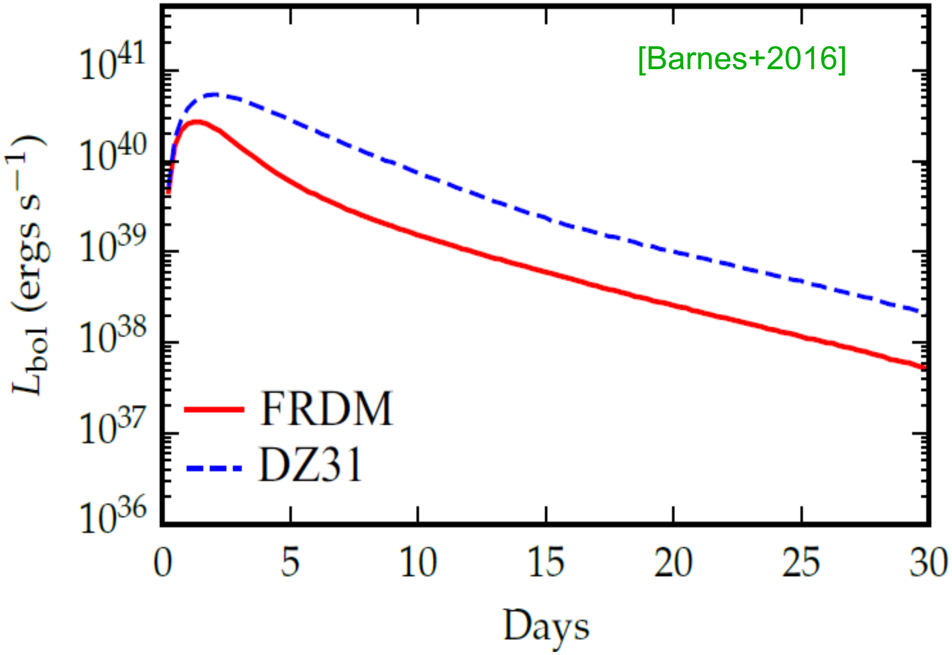

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α-heating may become dominant for ejecta with $Y_e \lesssim 0.15$, smaller enhancement in disk outflow or if neutrinos increase Y_e of dynamical ejecta substantially

**fission? If nuclei with $A \gtrsim 260$ can survive...

Neutron-decay powered pre-cursor?

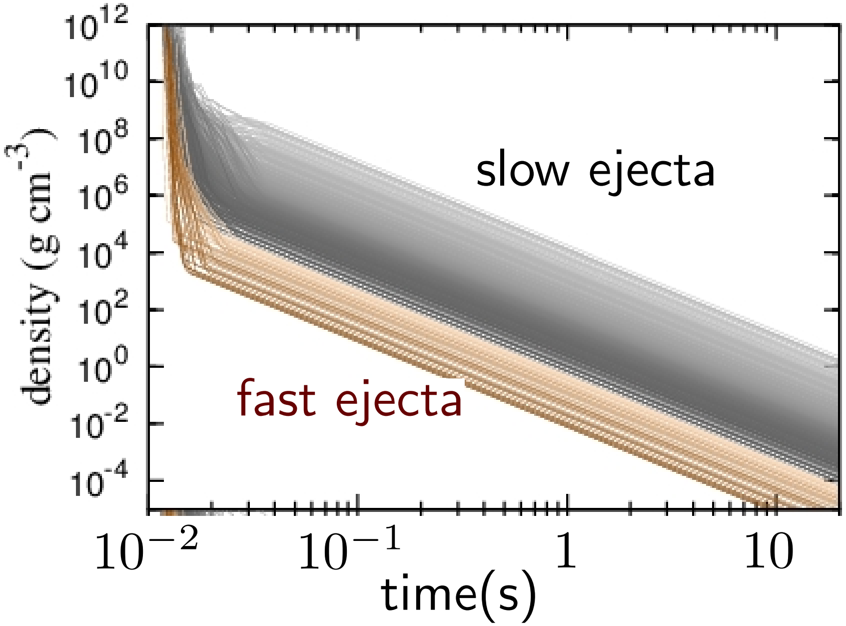
- for $\sim 90\%$ of the ejecta, neutrons are used out during the r-process time scale ~ 1 second $(\tau_{(n,\gamma)} \lesssim \tau_{\rm dyn})$
$\rightarrow$ normal r-process

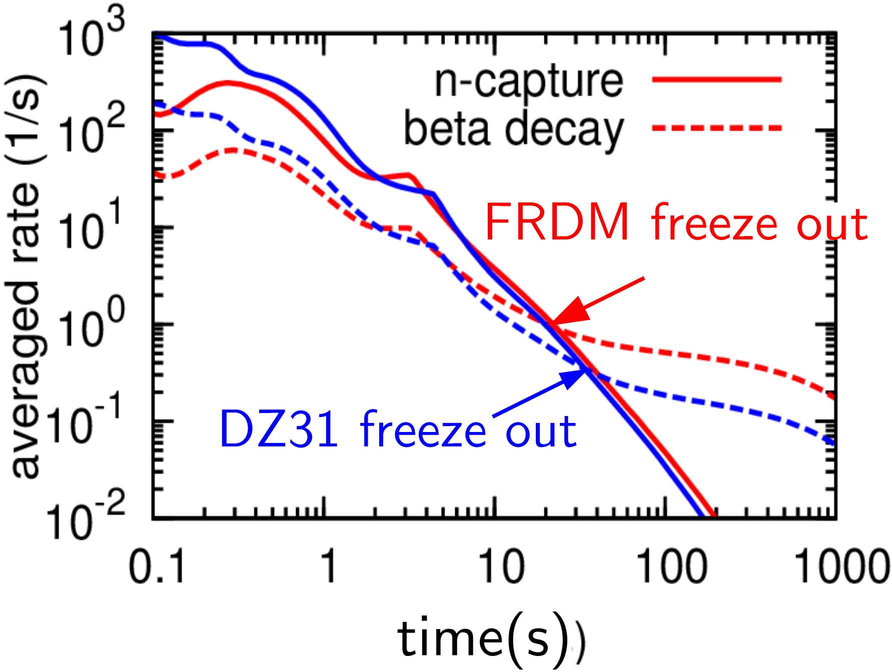
- $\sim 10\%$ of the ejecta expands very fast so that free neutrons left at the end of the r-process ("not-so-rapid" r-process)
$\rightarrow$ kilonova pre-cursor?

[Metzger+2015, Goriely+ 2015]

- unused amount of neutrons depends on the mass model again:
$\sim 40\%$ with FRDM and
$\sim 20\%$ with DZ31 at $t \approx 20$ s

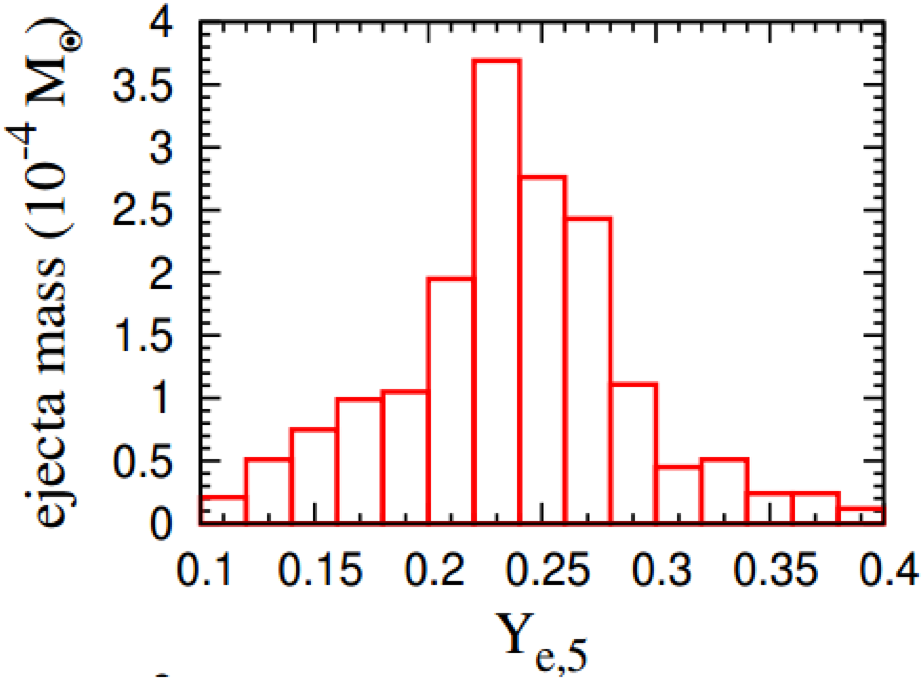
[Mendoza-Temis+, PRC 92, 055805 (2015)]

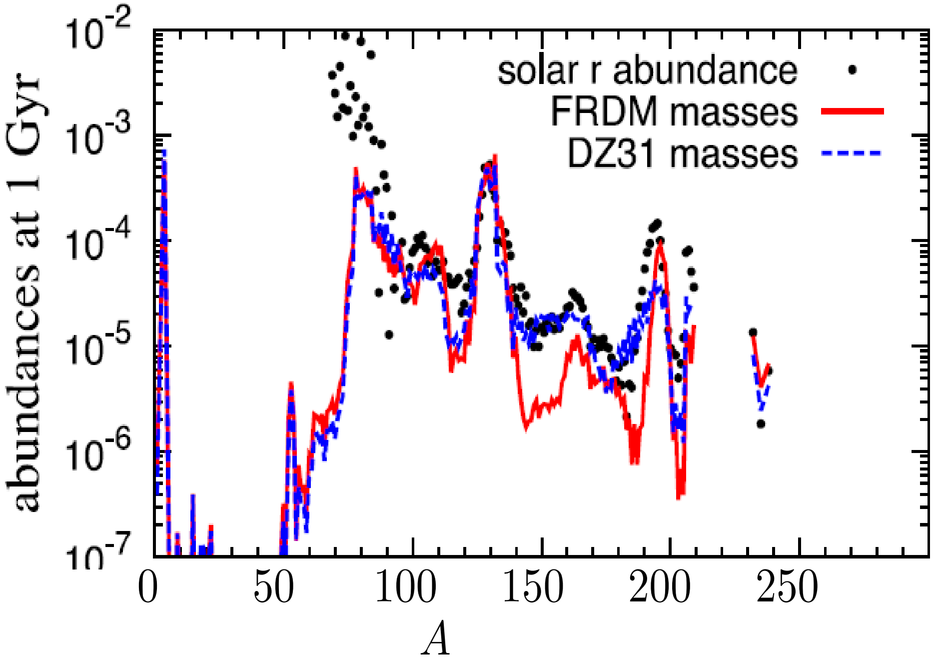




BH-disk ejecta

– α-disk simulation from Fernandez, similar to Fernandez & Metzger 2013, $\mathrm{M_{BH}} = 3M_\odot$, $\mathrm{M_{disk}} = 0.03M_\odot$, $R_0 = 50$ km, $Y_{e,0} = 0.1$, $s_0/k_B/\mathrm{nuc} = 8$, $\alpha = 0.03$, $\chi_{\mathrm{BH,spin}} = 0$

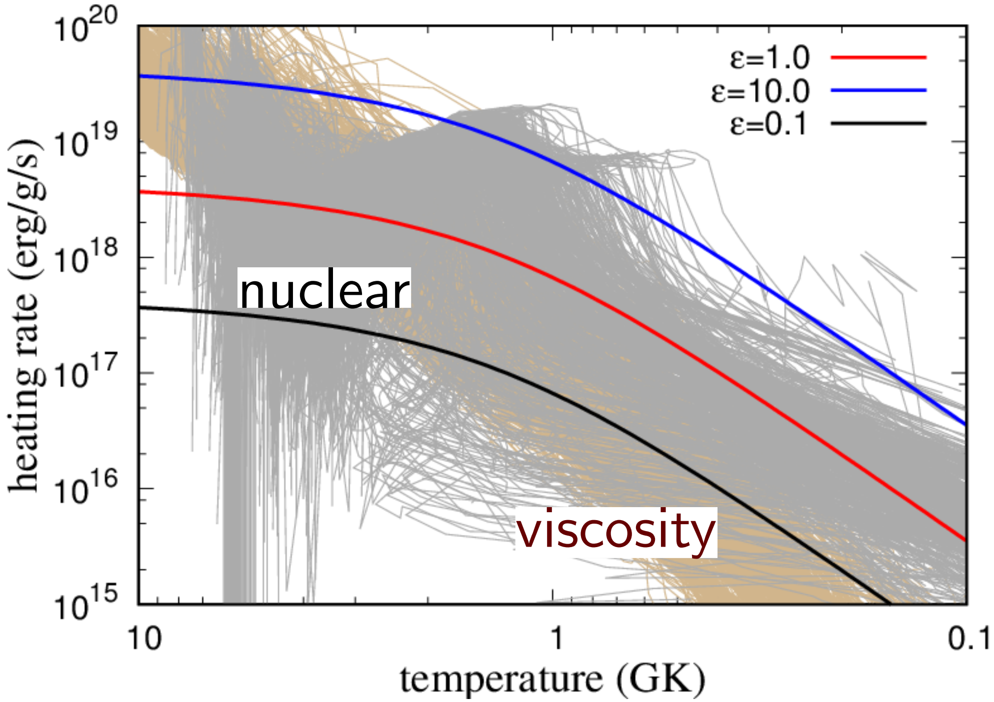




[MRW, Fernandez, Martinez-Pinedo, Metzger, MNRAS 463, 2323 (2016)]

Nuclear energy release beyond α-formation?

Energy ~ 3 MeV/nucleon is released from a net reaction of $20n + 15\alpha \rightarrow {}^{80}$Zn



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

$$\langle \dot{q} \rangle(\langle T \rangle) = 2.5 \times 10^{19}\, \varepsilon \left[\frac{1}{\pi} \arctan\left(\frac{\langle T \rangle}{1.1\ \mathrm{GK}} \right) \right]^{5/2} \mathrm{erg\ g^{-1}\ s^{-1}} \quad \text{for } T < 6 \text{ GK}$$

$\sim$ more "ejecta" for $\varepsilon = 1.0$ in a BH–disk simulation, and cure some strange abundance anomaly

How important neutrinos are in merger ejecta?

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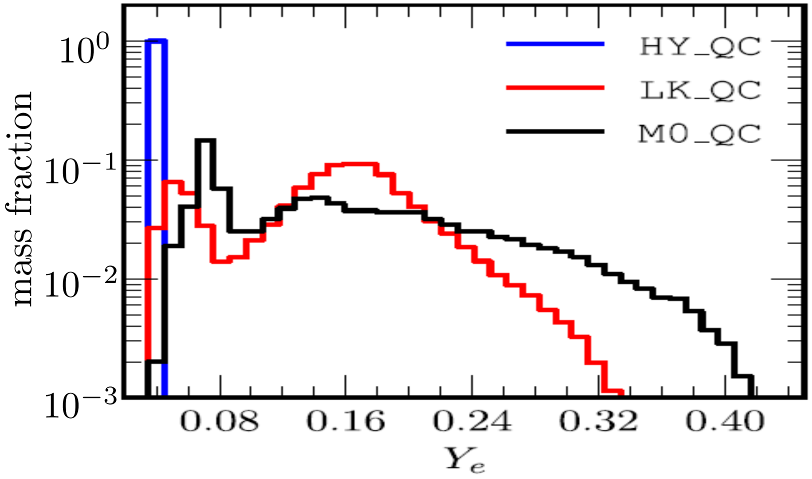
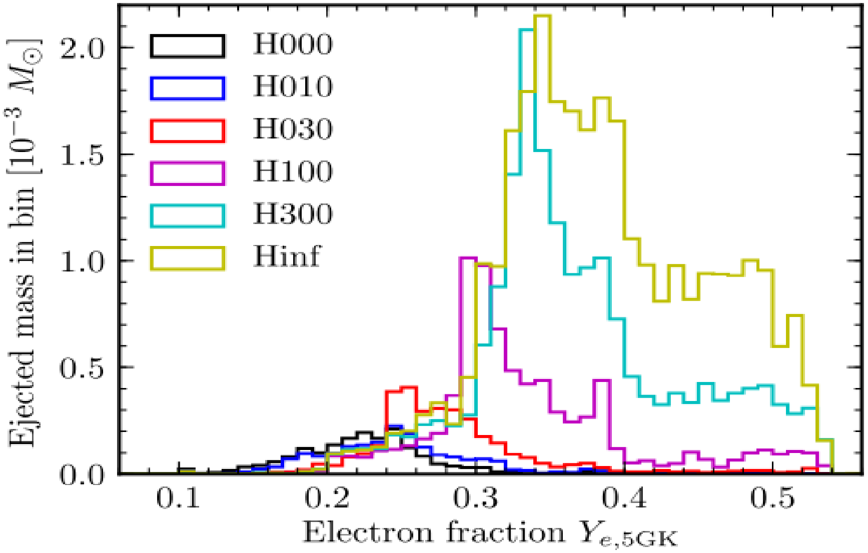
BNS dynamical ejecta:

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

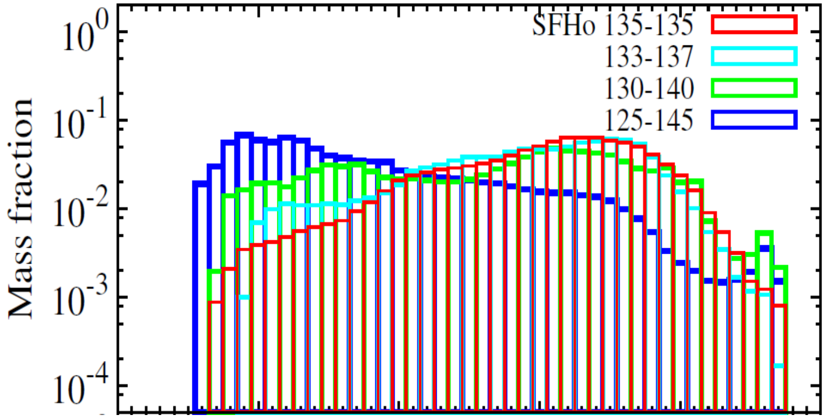


disk ejecta:

[Lippuner+, 1703.06216]

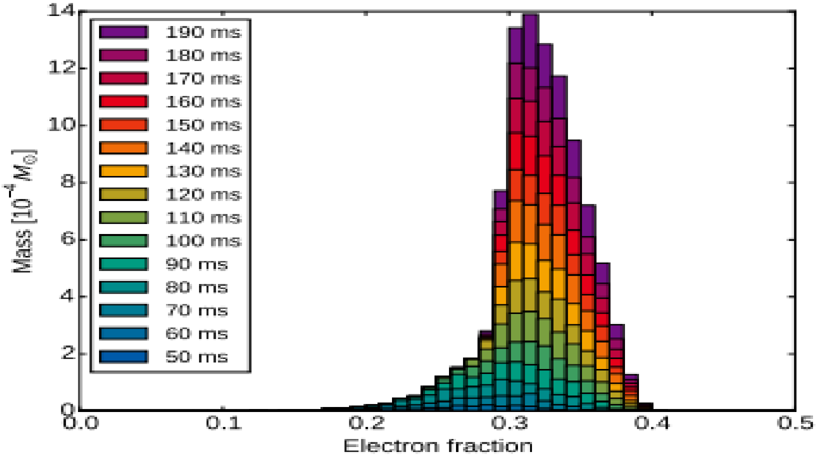


[Sekiguchi+, PRD 93, 124046 (2016)]



ν-driven wind:

[Perego+ 2014,2015]



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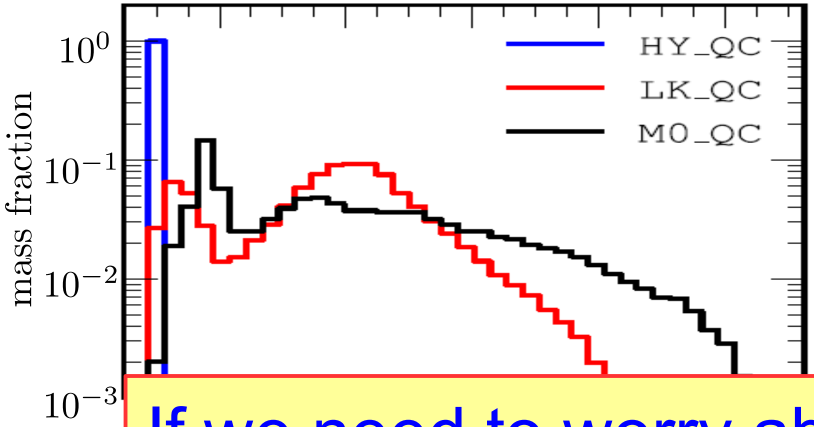

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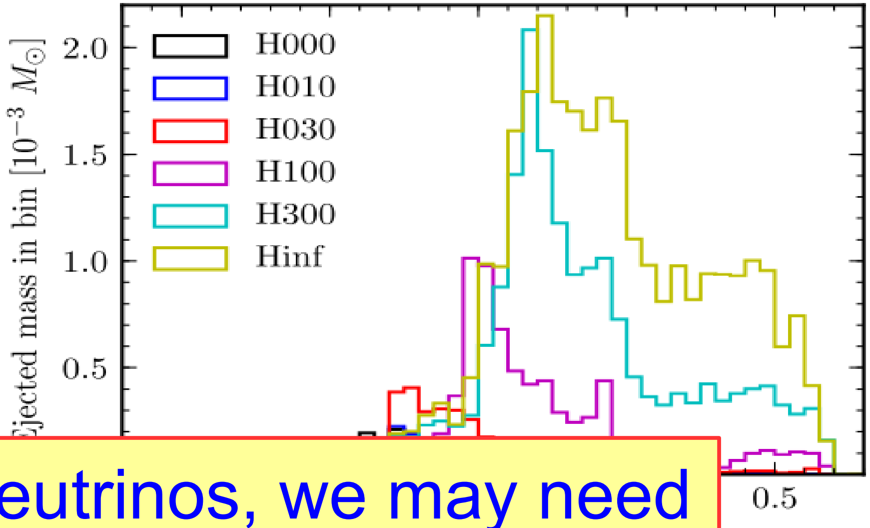
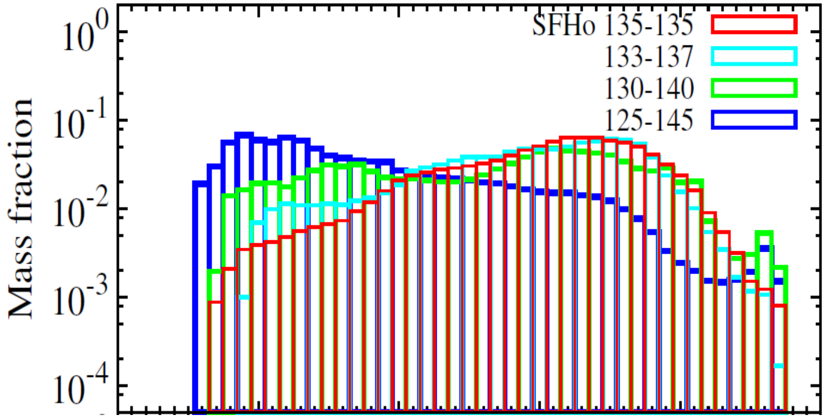
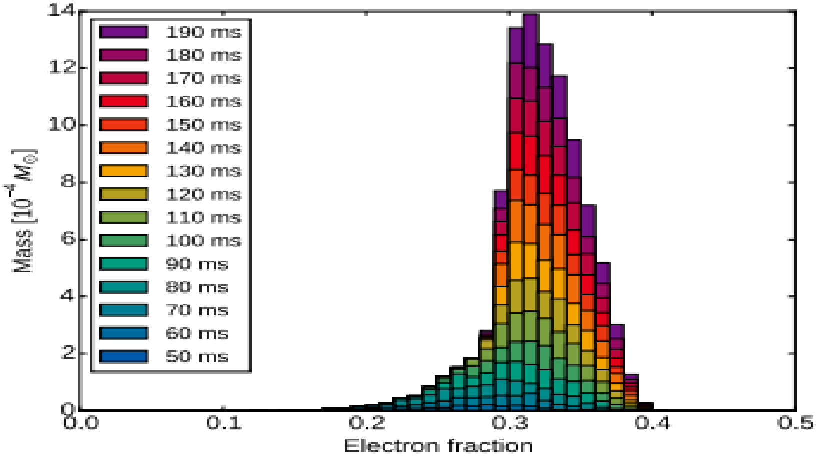


If we need to worry about neutrinos, we may need to worry about their flavor conversion...

015]





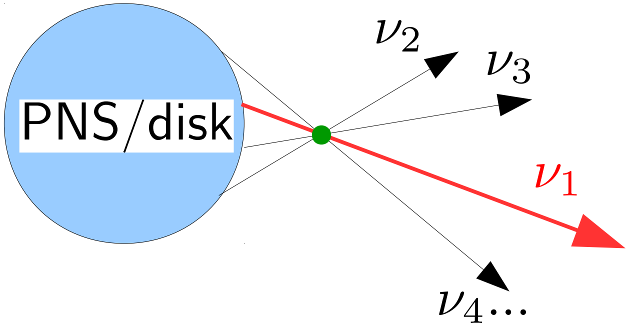
Neutrino physics – flavor conversion

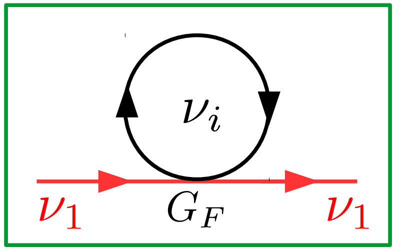
In the regime where neutrinos ∼ free-stream

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

ϱ: flavor density matrix, $= \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{pmatrix}$

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





→ many-body quamtum system in "strong" coupling regime $(G_F n_\nu \gg \frac{\delta m^2}{2E_\nu})$

Neutrino physics – flavor conversion

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

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Solving the full EoM is cubersome, but one can linearize the EoM and analyze locally how the plane-wave (Fourier) mode of the off-diagonal term in ϱ evolves in linear regime. [Izaguirre+ 2017, Capozzi+ 2017]

Complex frequency solution in the dispersion relation of the plane-wave $\leftrightarrow$ "flavor instability" leads to flavor conversion

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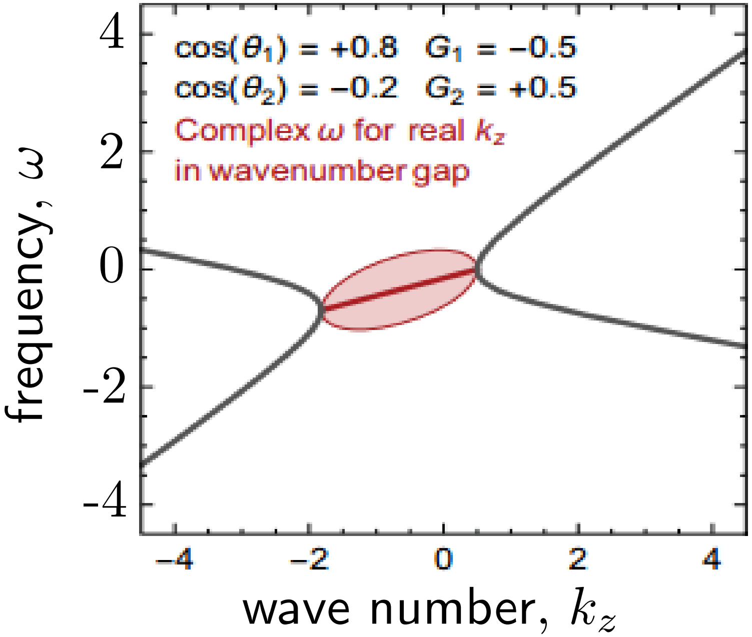

[Izaguirre+, PRL 118, 021101 (2017)]

"fast" conversion can happen extremely close to the ν surfaces, provided that local angular distribution of neutrino lepton number has a "crossing" (more $\bar{\nu}_e$ than ν_e in some solid angle range, while more ν_e than $\bar{\nu}_e$ in other range)

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

Neutrino physics – flavor conversion

Why is this particularly revelant for merger remnants?

Becuse they protonize, i.e., more $\bar{\nu}_e$ emission than ν_e [Foucart+, Perego+, Janka+,...]

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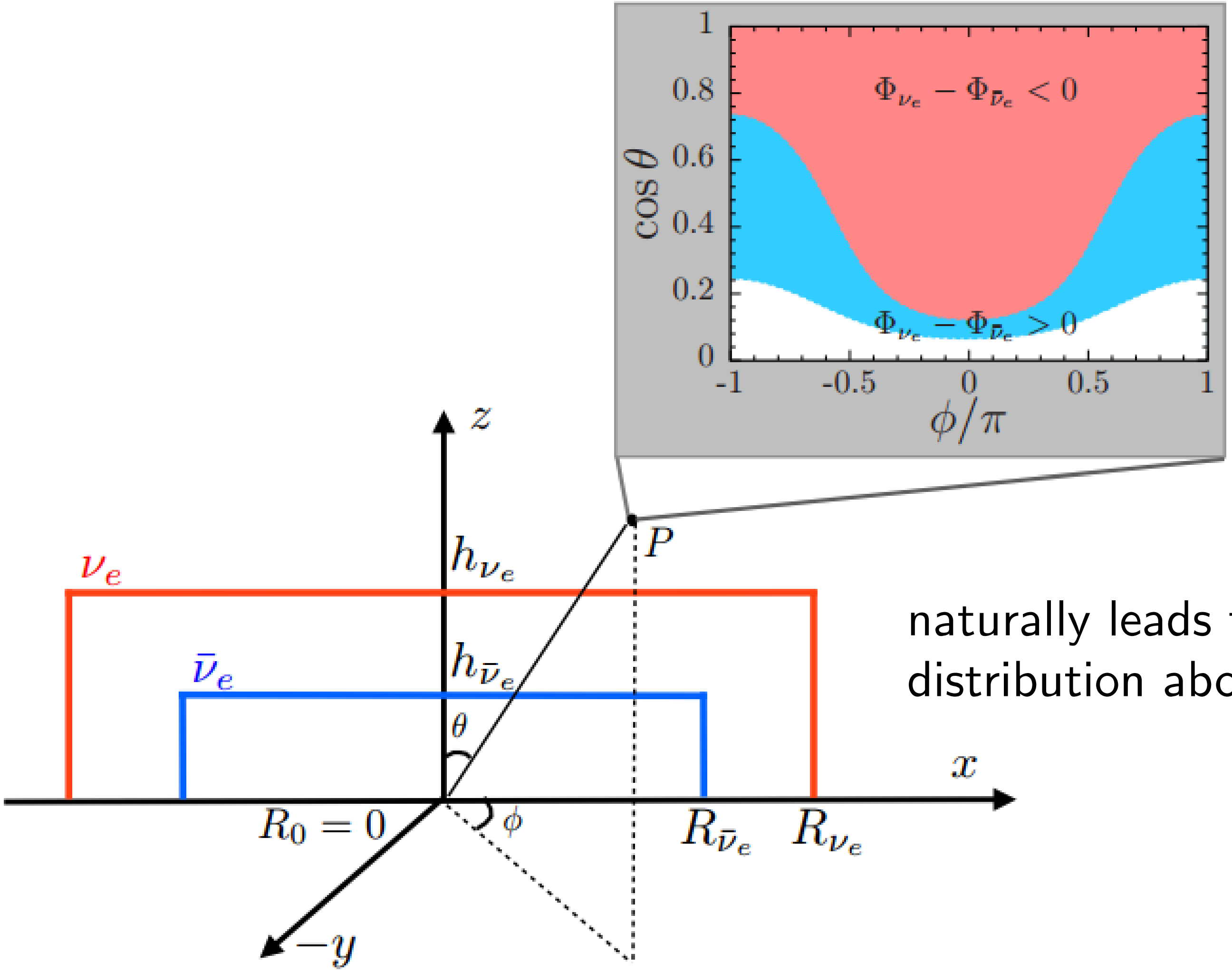
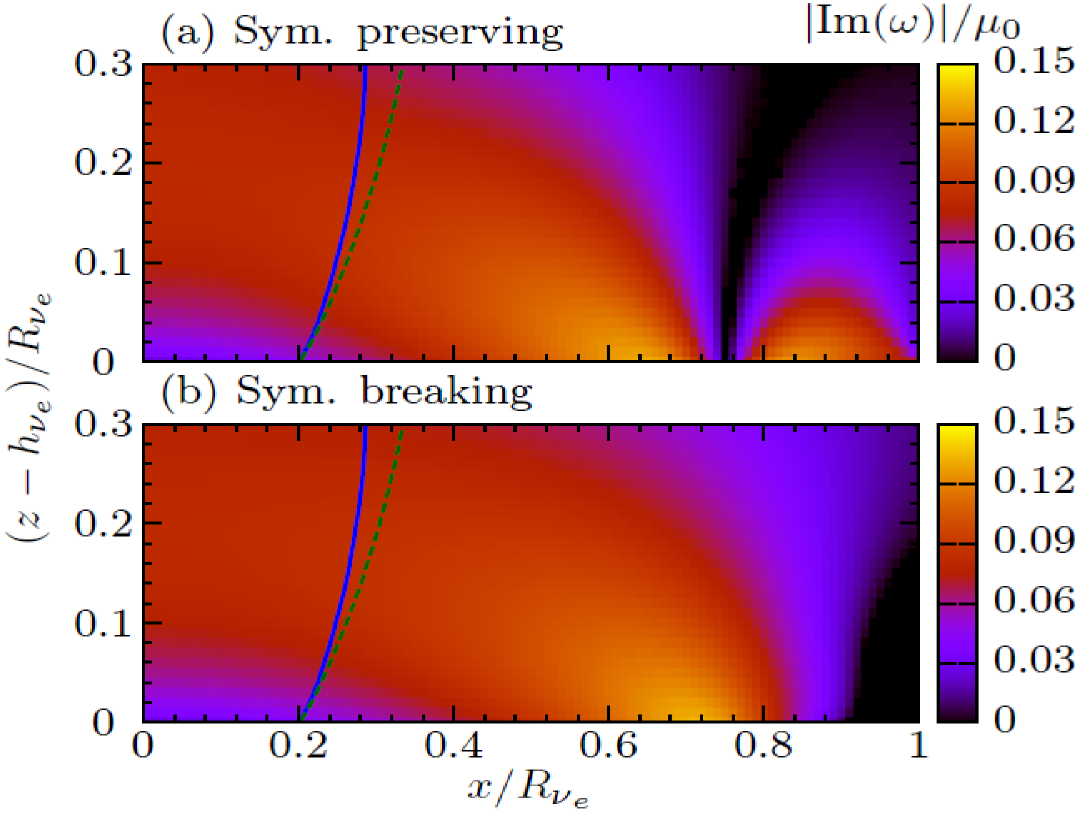


naturally leads to crossing in angular distribution above the merger remnant

[MRW & Tamborra, PRD 95, 103007, 2017]

Neutrino physics – flavor conversion

$L_{n,\bar{\nu}_e}/L_{n,\nu_e} = 1.35,\ R_{\bar{\nu}_e} = 0.75 R_{\nu_e},\ h_{\nu_e}/R_{\nu_e} = h_{\bar{\nu}_e}/R_{\bar{\nu}_e} = 0.25,\ \vec{k} = 0.$



[MRW & Tamborra, PRD 95, 103007, 2017]

Im(ω): growth rate of flavor mixing in the linear regime

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

fast flavor conversion condition exists everywhere above the remnant

Does the picture remain beyond the toy model?

Does this lead to flavor equipartition among flavors? if so, nucleosynthesis?

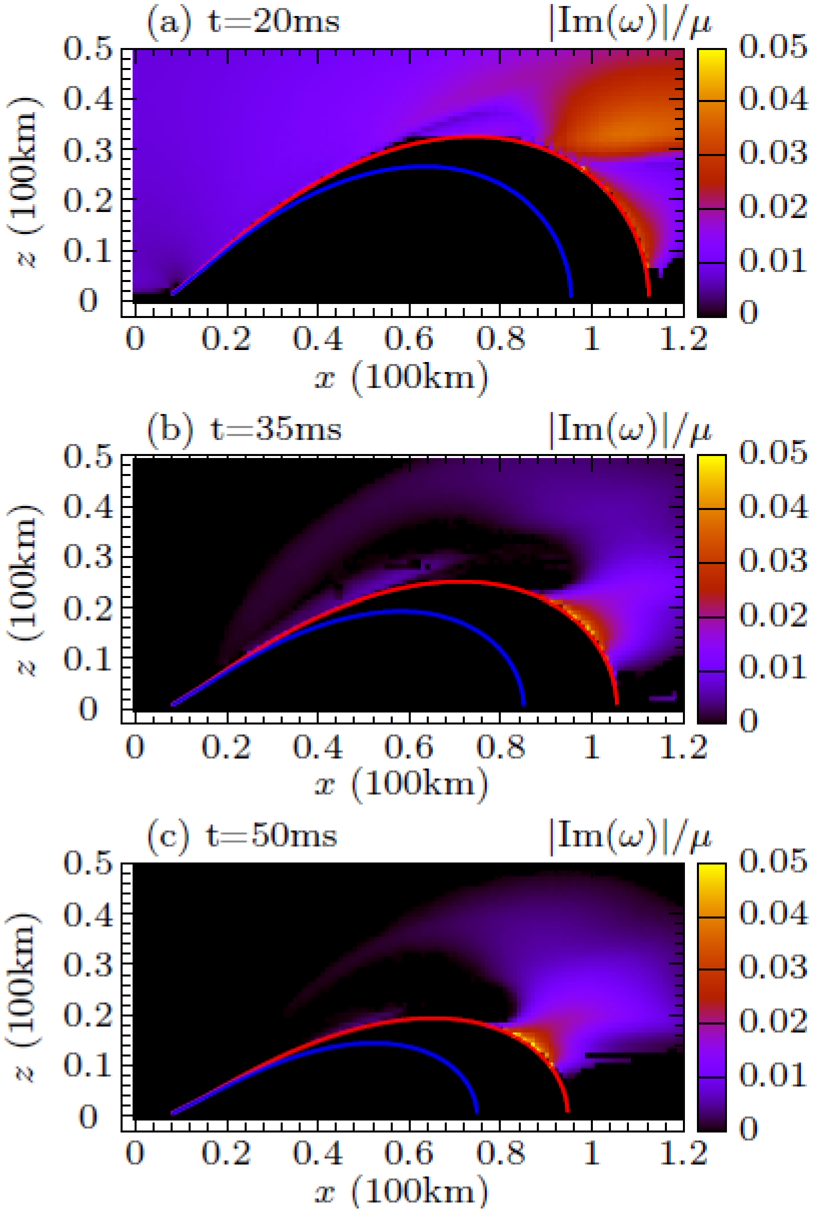
Neutrino physics – flavor conversion

- $3M_\odot$ BH + $0.3M_\odot$ torus model from Just+ 2015

- torus protonizes during the first ~ 100 ms, i.e., more $\bar{\nu}_e$ over ν_e emission

- funnel region has ν_e over $\bar{\nu}_e$ excess, after ~ 30ms, unstable region gets smaller afterwards

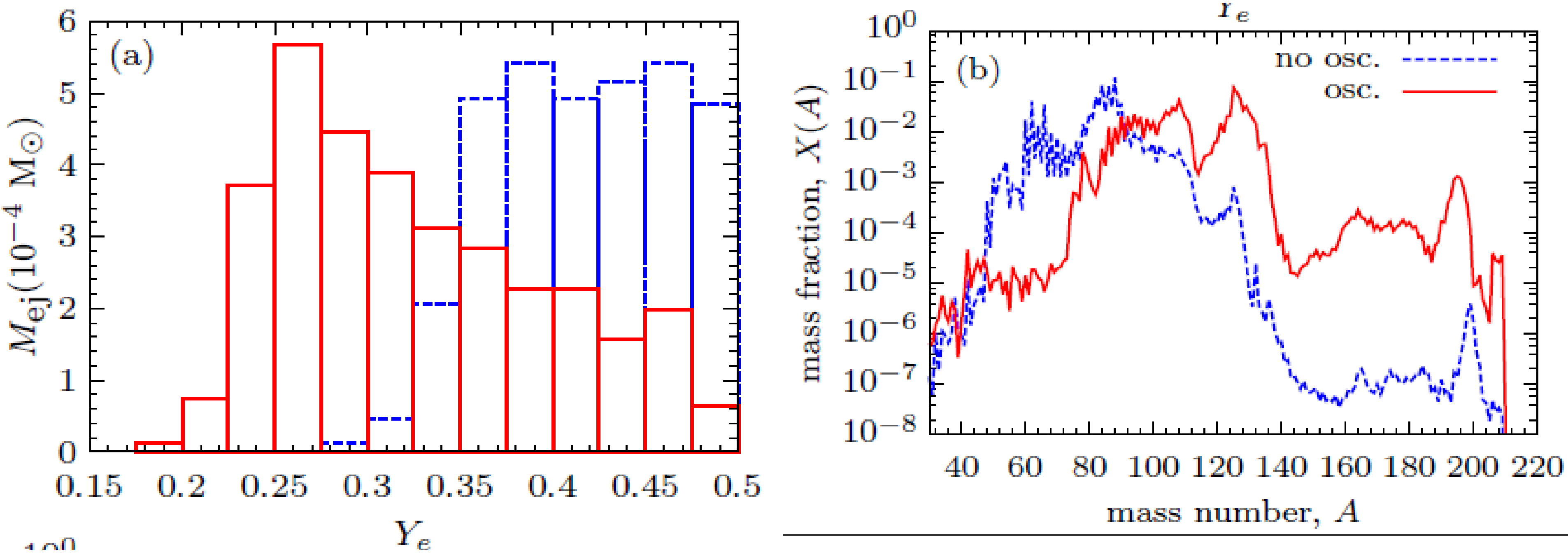
- Still, most of ν-driven ejecta exposed to neutrinos going through the unstable region



[MRW, Tamborra, Just, Janka, in preparation]

Neutrino physics – flavor conversion

if flavor equipartition occurs due to fast flavor conversion:



[MRW, Tamborra, Just, Janka, in preparation]

- NS–disk system and dynamical ejecta?
- Any observational consequence?
- If no fast conversion, matter-neutrino-resonances?

Summary

- Properties of neutron-rich nuclei play important roles in r-process abundance distribution, including the actinide abundances and the kilonova heating rates, particularly for low Y_e ejecta.
- Fast neutrino flavor conversion (centimeter to meter scale!) will likely occur in the merger remnants due to the crossing of local angular $\nu_e - \bar{\nu}_e$ distribution. More effort needed to understand the exact outcome but a flavor equipartition may change Y_e of the ejecta significantly.