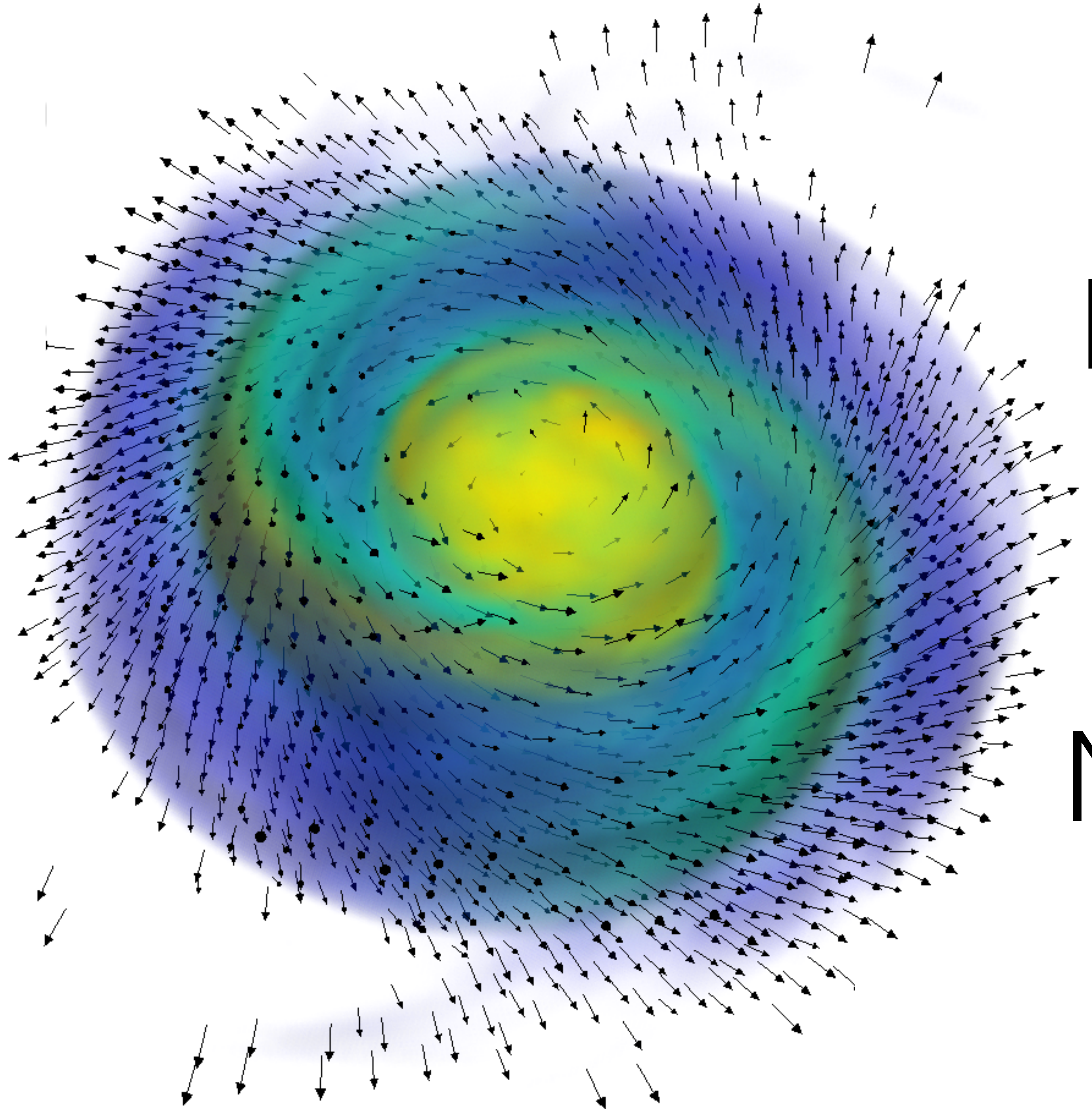
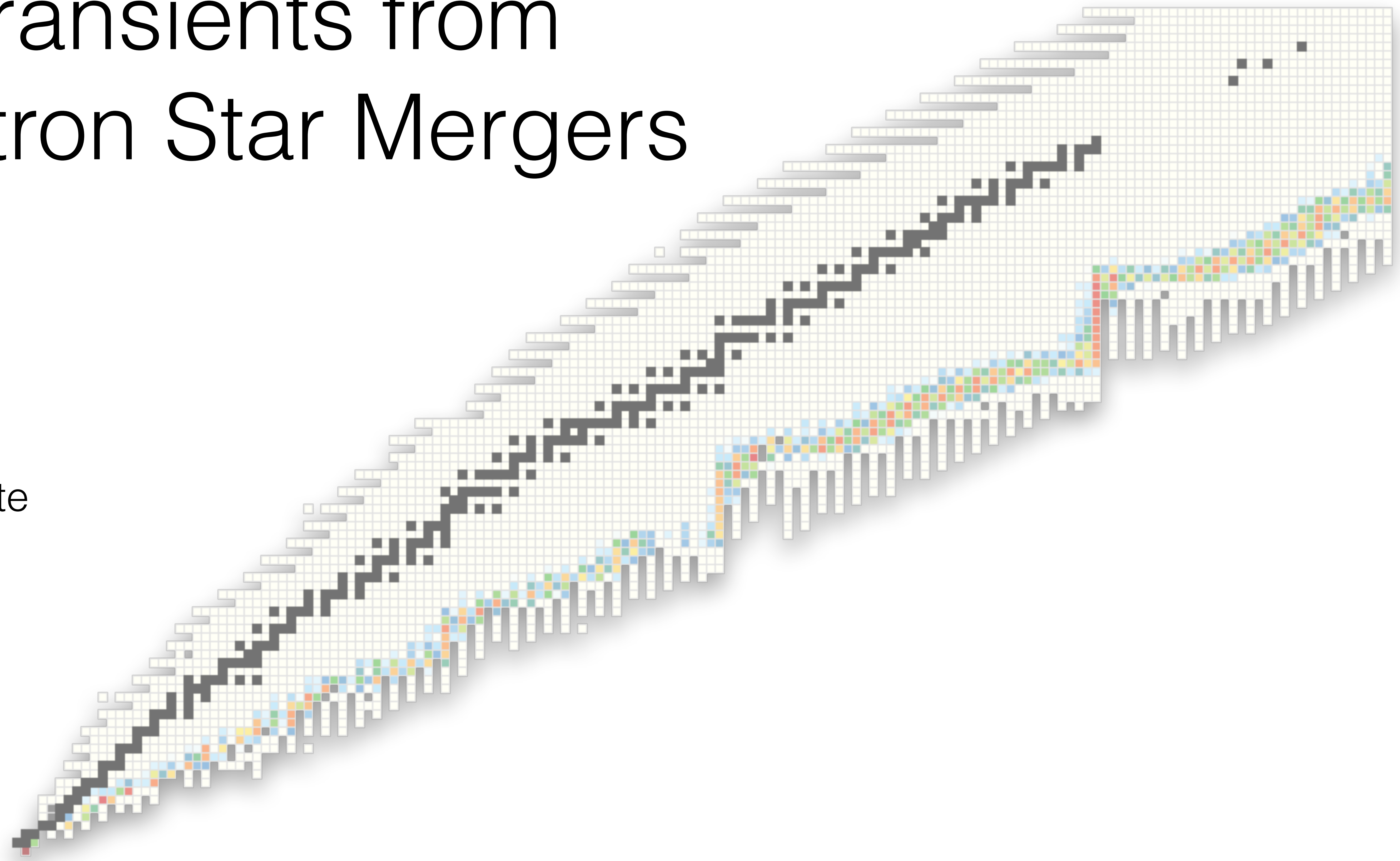


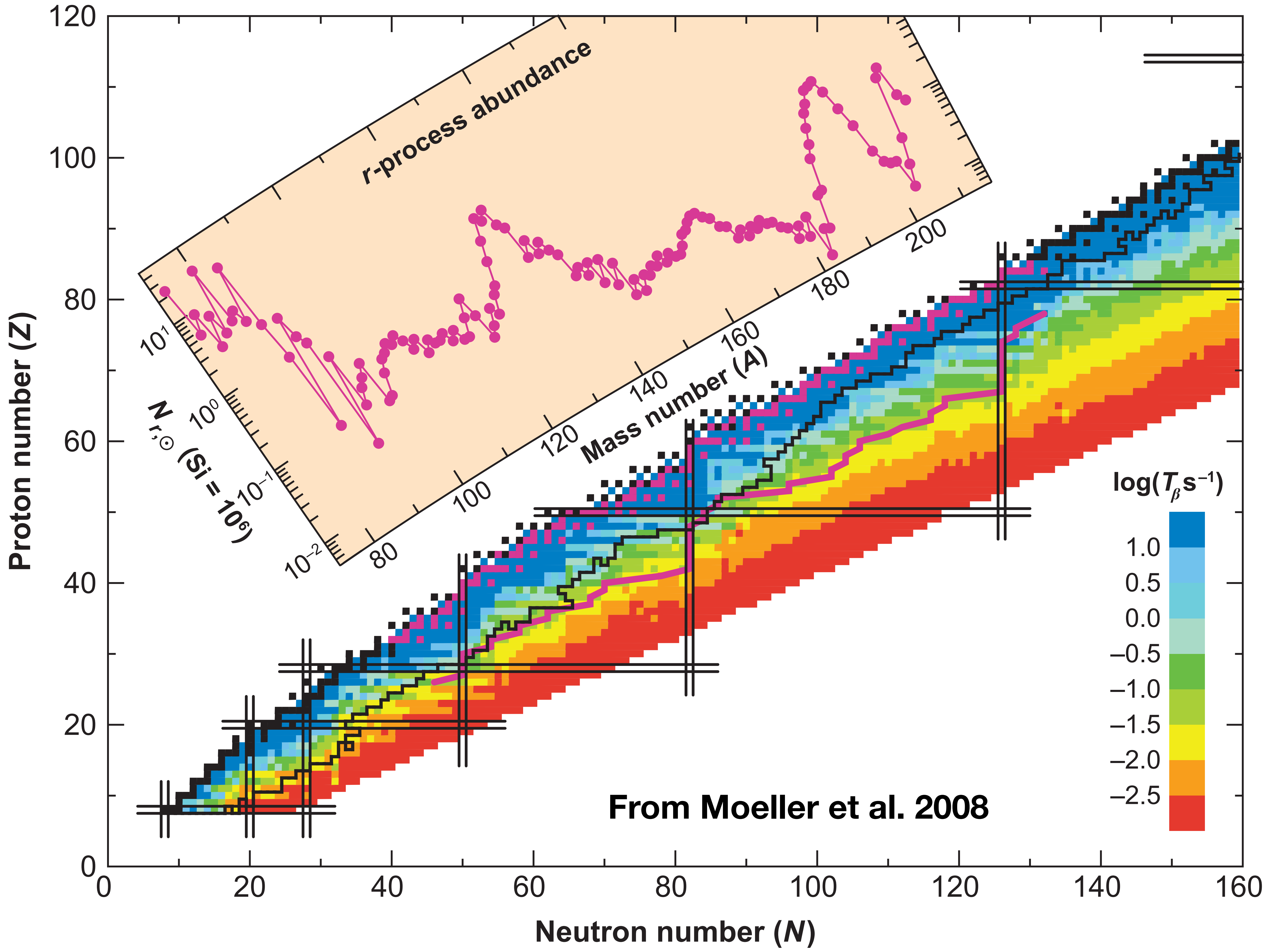
Nucleosynthesis and Electromagnetic Transients from Neutron Star Mergers



Luke Roberts
NSCL, Michigan State University

What is the source of the *r*-process nuclei?

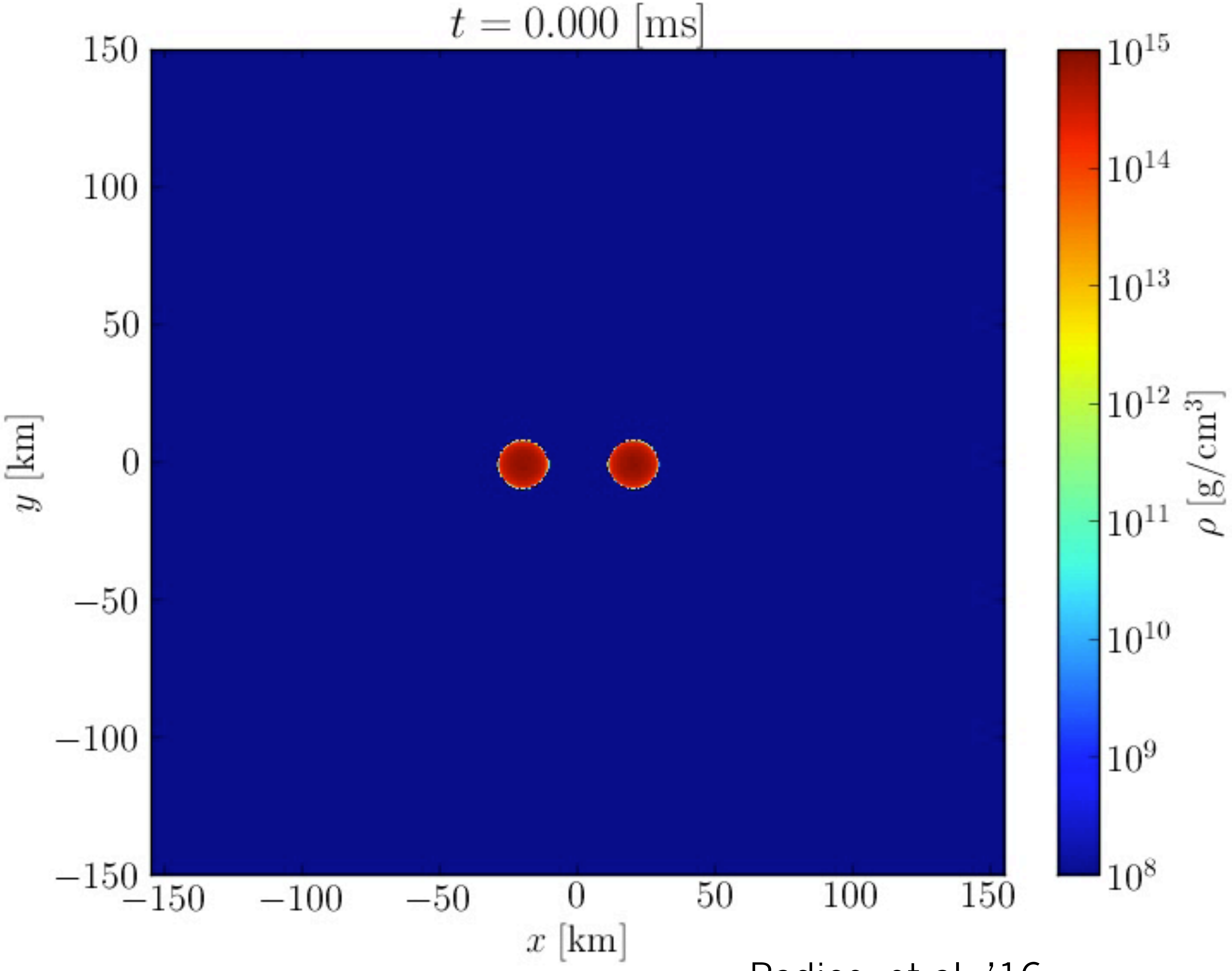
- *r*-process elements present in very low metallicity halo stars, suggesting it must be a primary process
- Abundance pattern of second and third peak *r*-process elements in low metallicity halo stars is remarkably similar to the pattern found in the sun
- Need lots of free neutrons
  - Site is one of the biggest questions of nuclear astrophysics
  - CCSNe have long been implicated as the site of the *r*-process
  - With GW170817, mounting evidence that NS mergers may be the site



From Moeller et al. 2008

Merger Mass Ejection

- Dynamical Ejecta
  - Tidal Ejecta (BHNS)
  - GR -> matter ejected from collision region (NSNS)
- Disk winds
  (e.g. Surman et al. '08, Wanajo et al. '11)
- Disk outflows from viscous heating and alpha recombination
  (e.g. Fernandez & Metzger '13, Just '14)



Radice, et al. '16

Nuclear Evolution of the Ejecta

Dynamical Timescale for the Ejected Material:

$$\tau_{ej} \approx 10\ ms$$

Ejected Material is neutron rich:

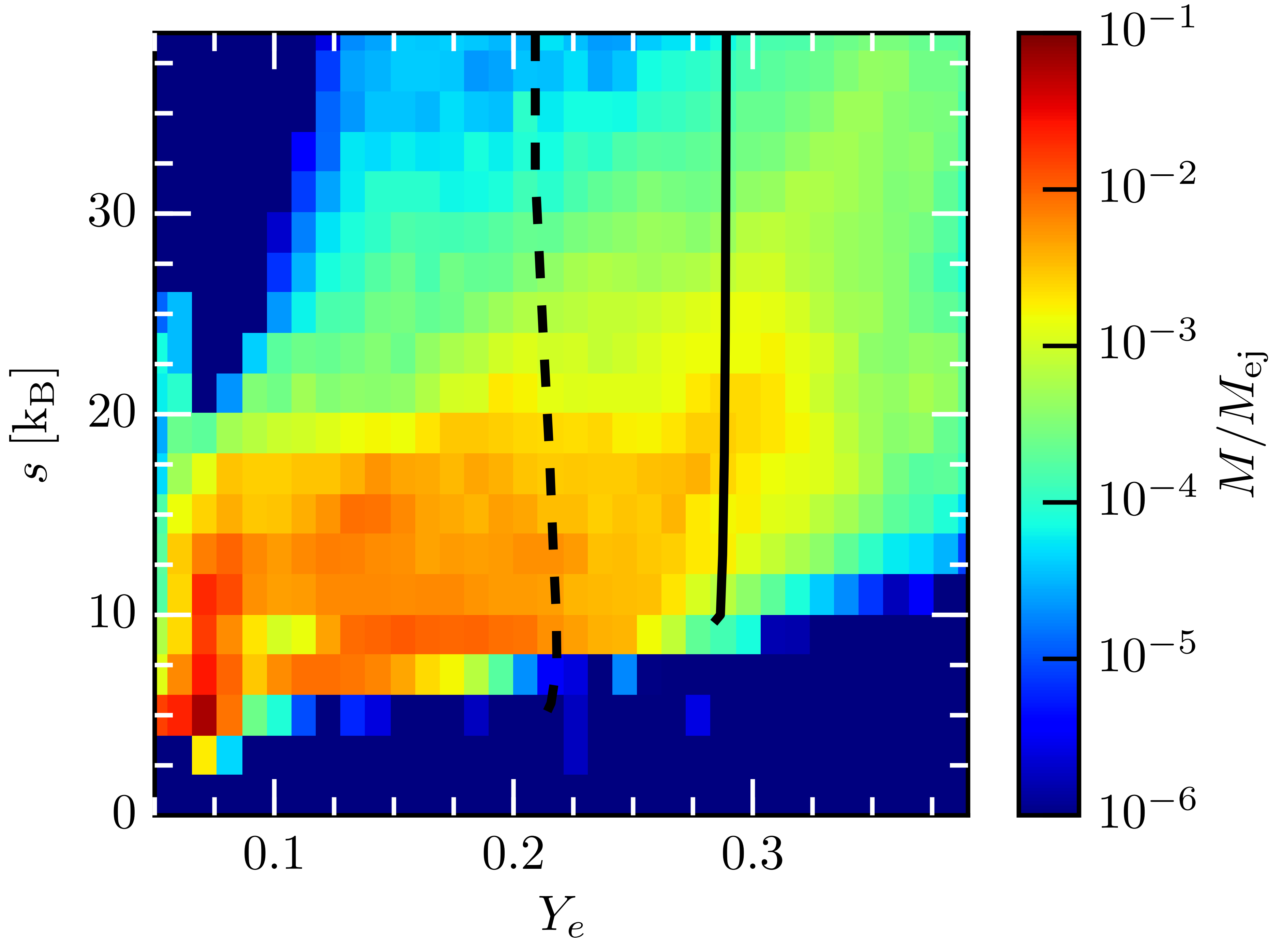
$$Y_e \sim 0.05 - 0.4$$

Low initial entropy:

$$S \sim 1 - 30$$

Which implies a neutron to seed ratio greater than 100

$$Y_e = 1 - \frac{n_{\rm neutrons,tot}}{n_{\rm baryons}}$$



Radice, et al. '16

see Lattimer & Schramm '76 and Freiberghaus et al. '99

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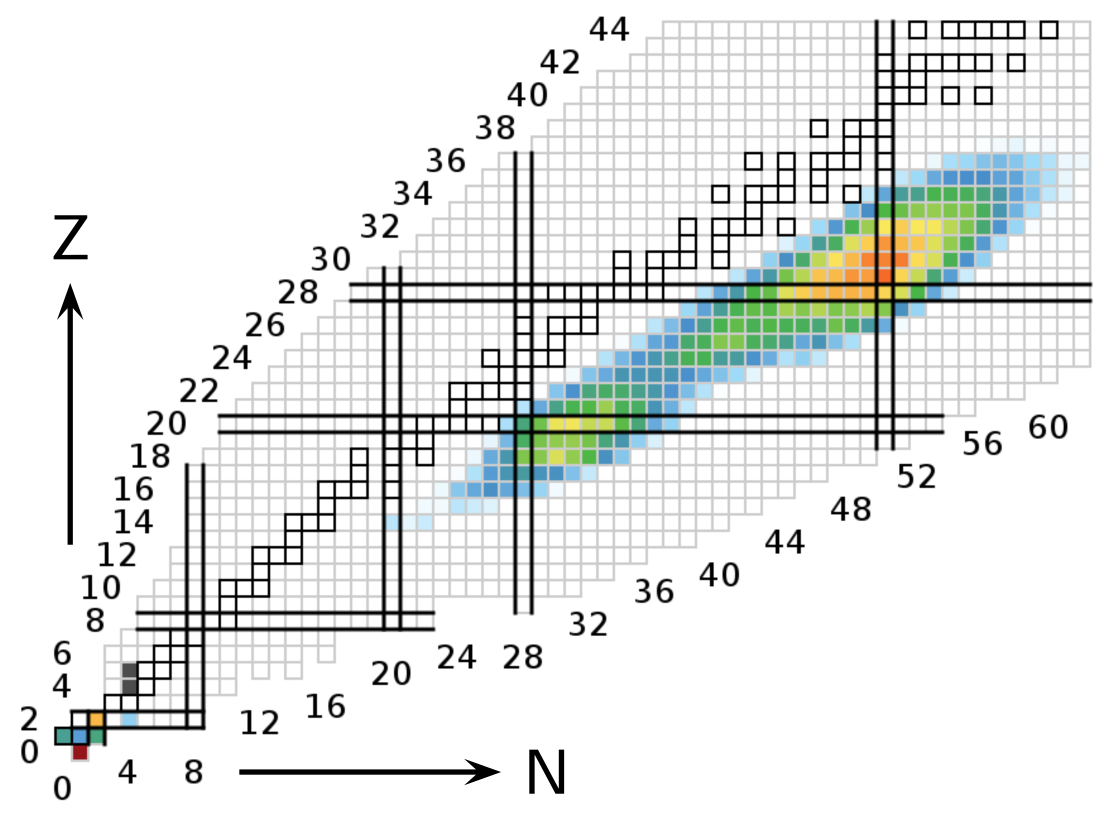
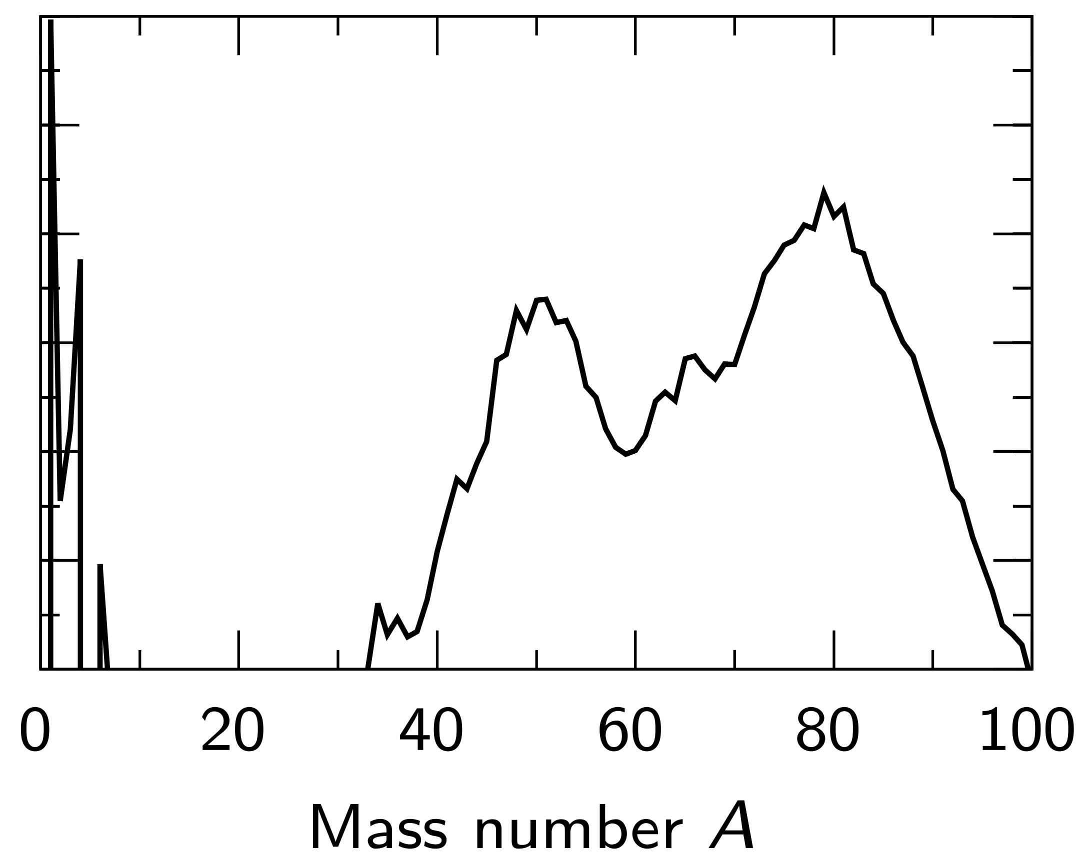
Initial distribution will be in NSE, clustered around doubly magic nuclei

T = 7.0 GK
$\rho = 2.2 \times 10^8$ g cm^{-3}
Y_e = 0.051





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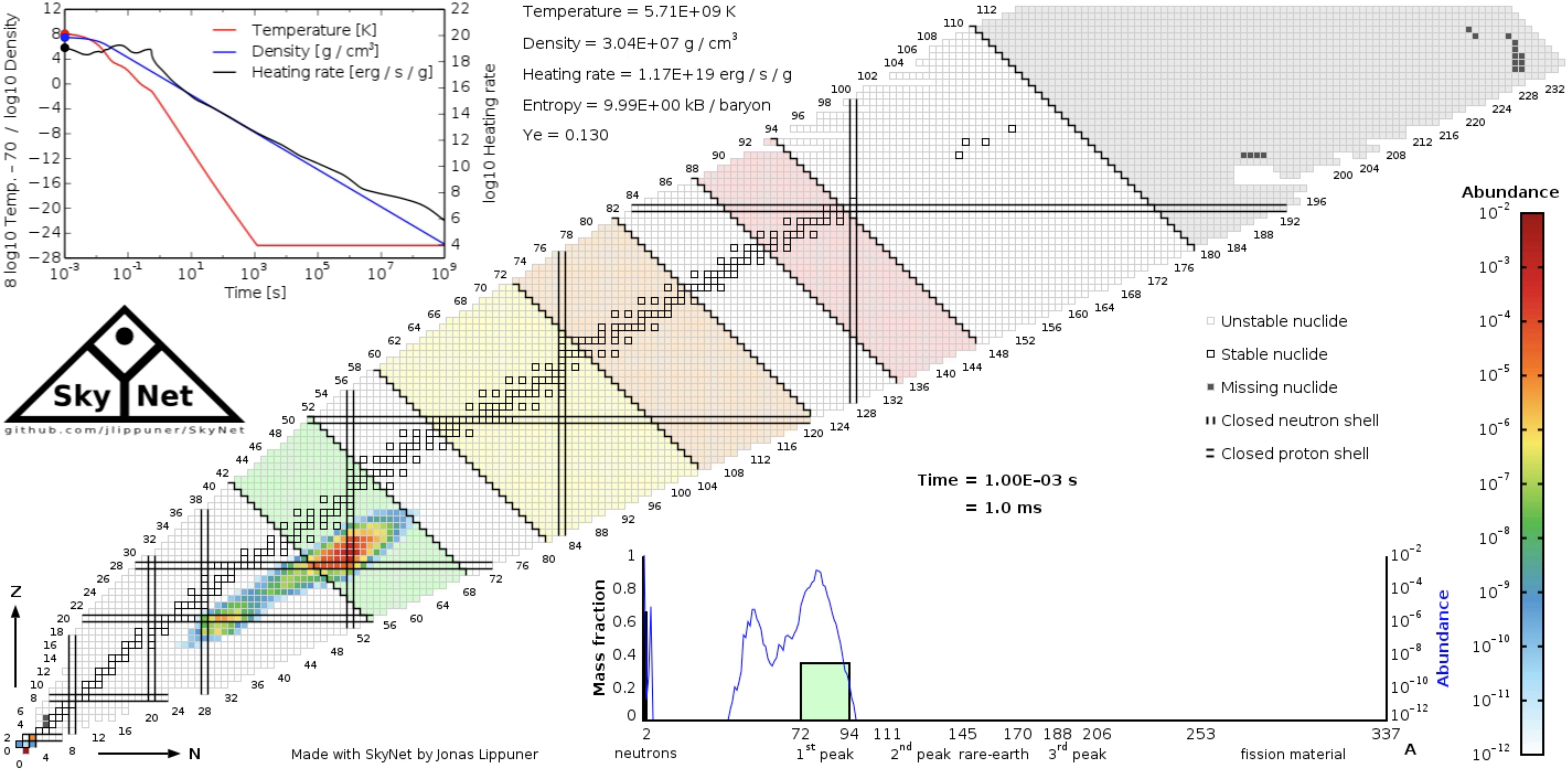
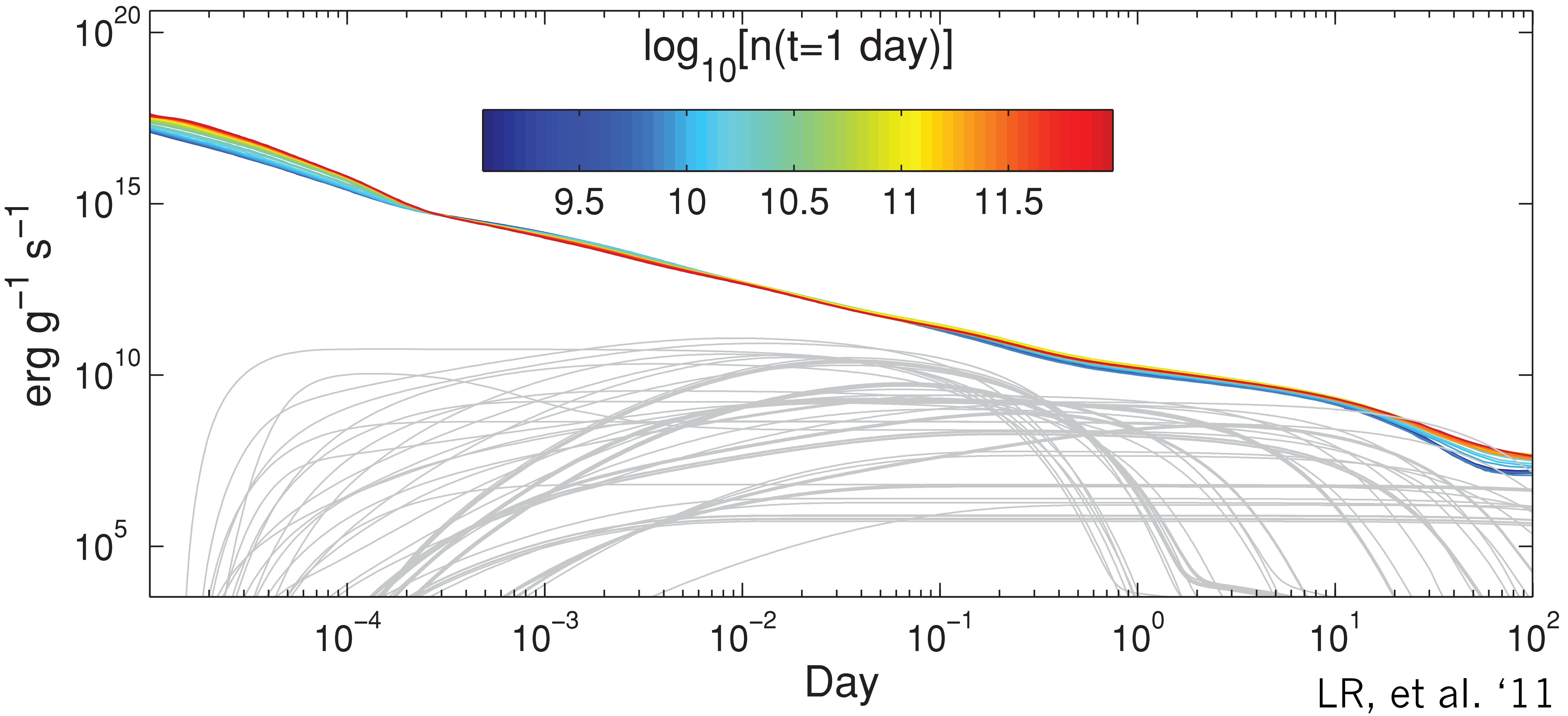


from Lippuner & LR, et al. ‘15

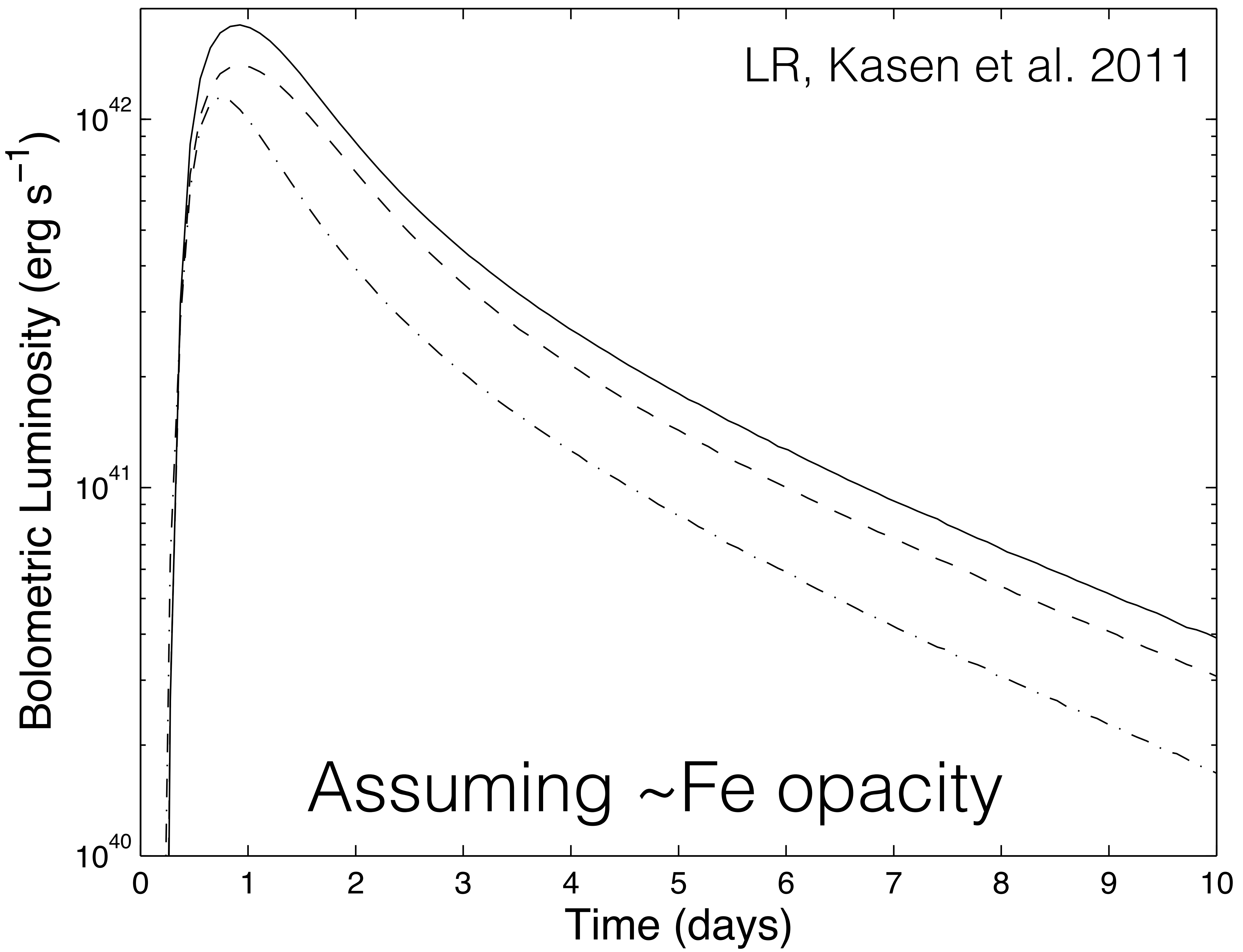
Nuclear Heating Rate

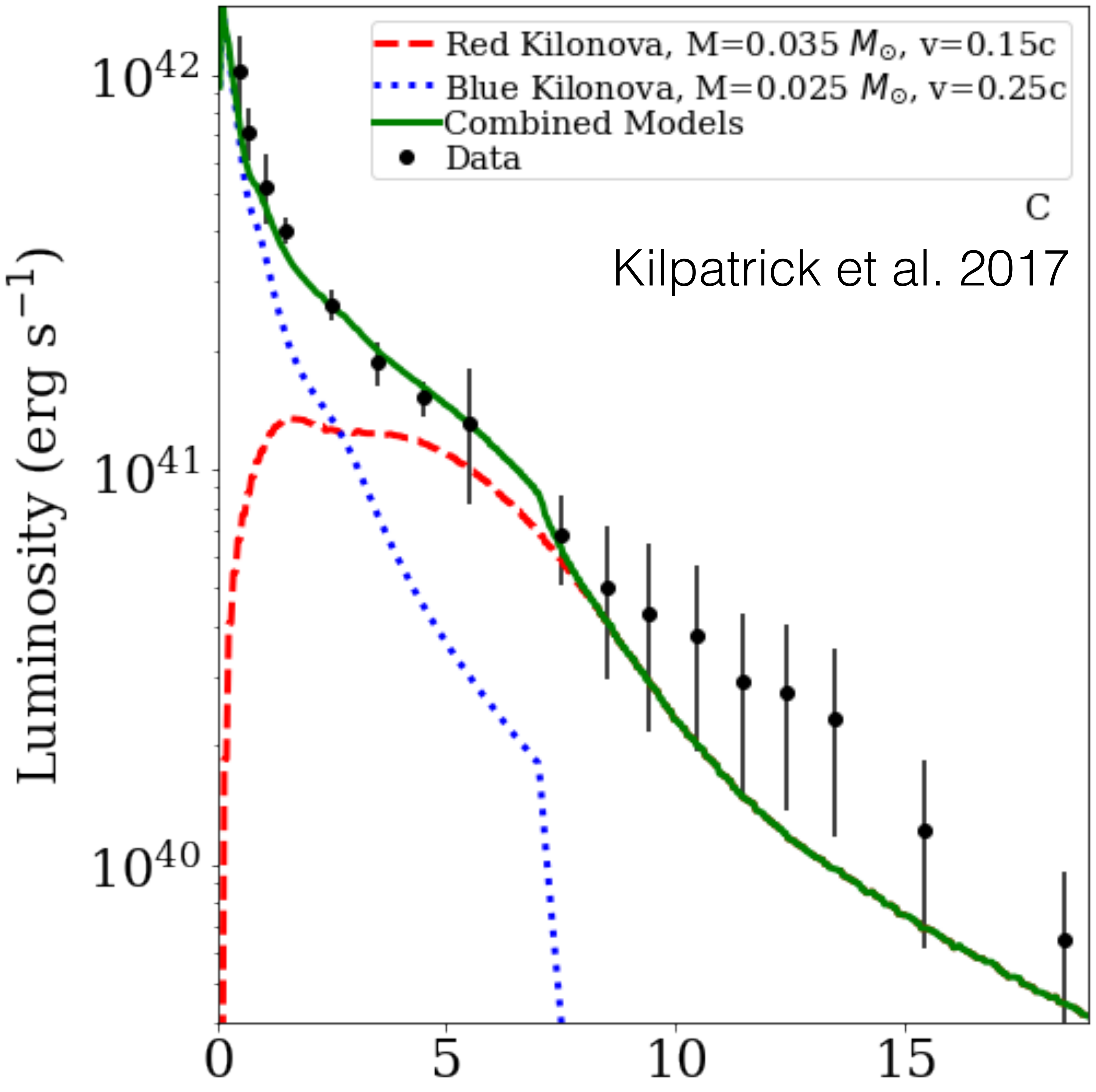


LR, et al. '11

- Power law heating rate (Metzger et al. '10, Roberts et al. '11, …)
- Larger number of isotopes involved, sum of numerous individual decays
- Beta-decays, alpha decays and fission

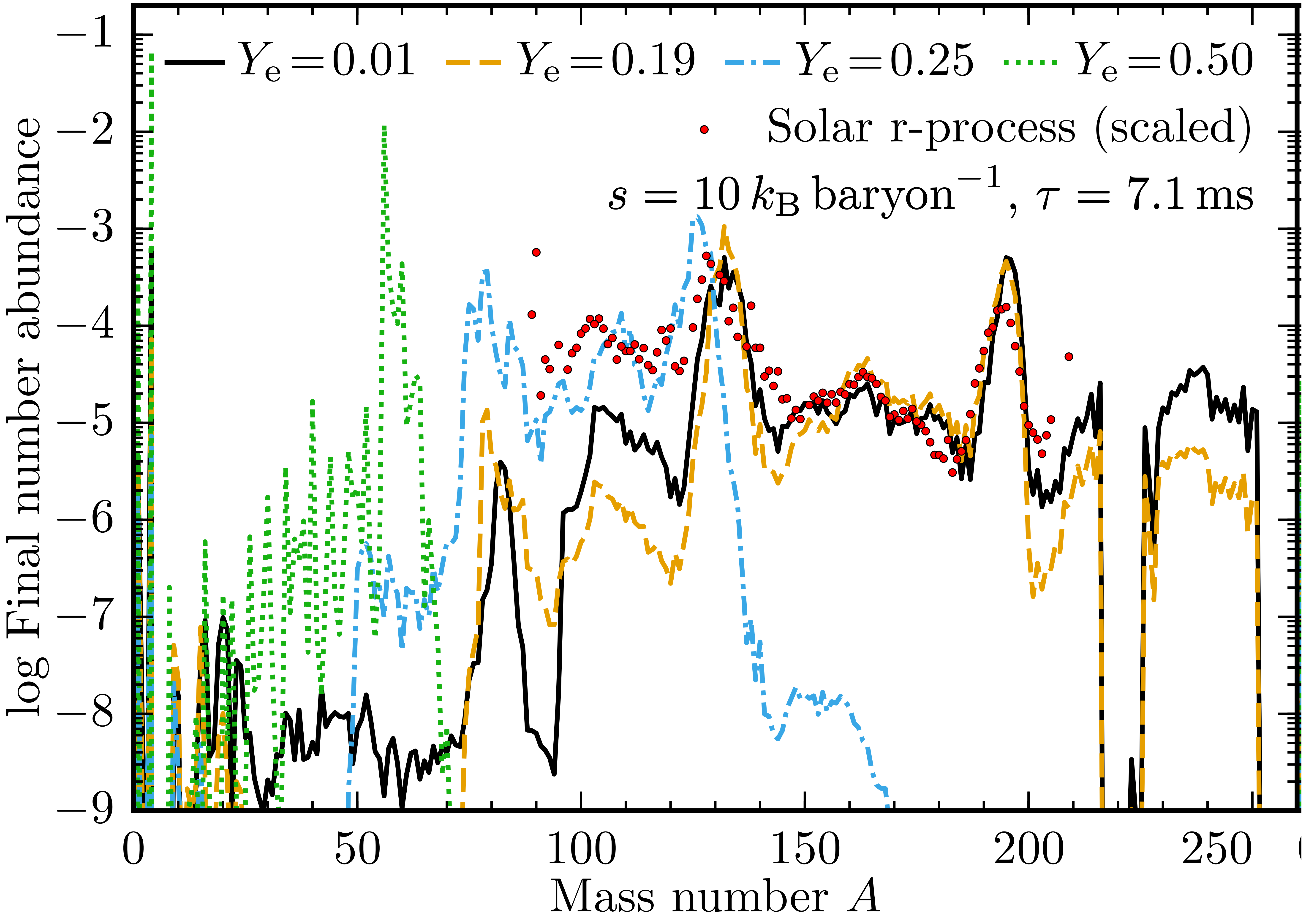
Electromagnetic displays from nuclear decay





Dependence of Nucleosynthesis on Initial Conditions

- Changing the electron fraction can substantially alter nucleosynthesis in neutron rich outflows
- Neutron rich nucleosynthesis is most sensitive to Y_e
- How far does nucleosynthesis get before neutron exhaustion?



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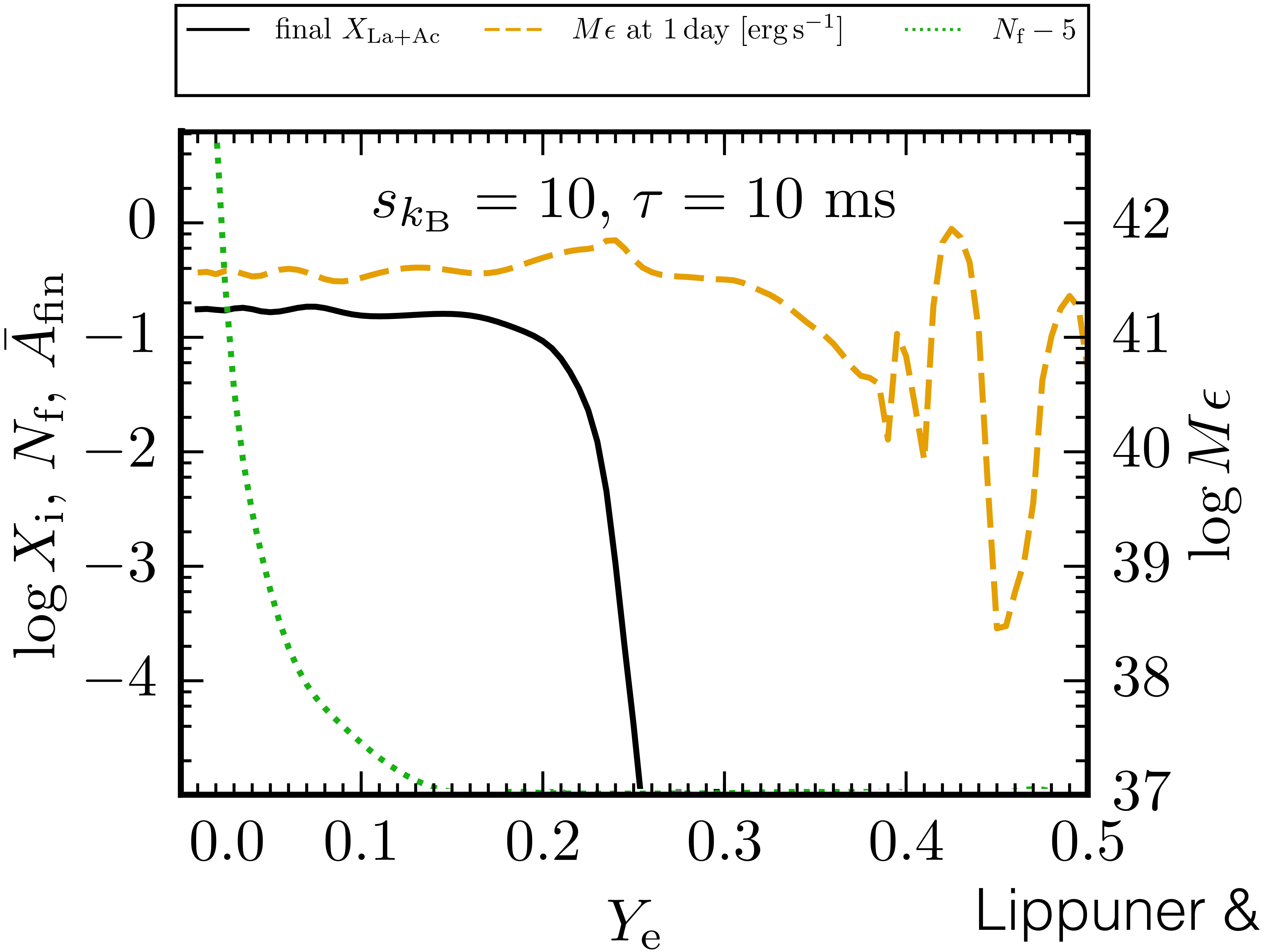
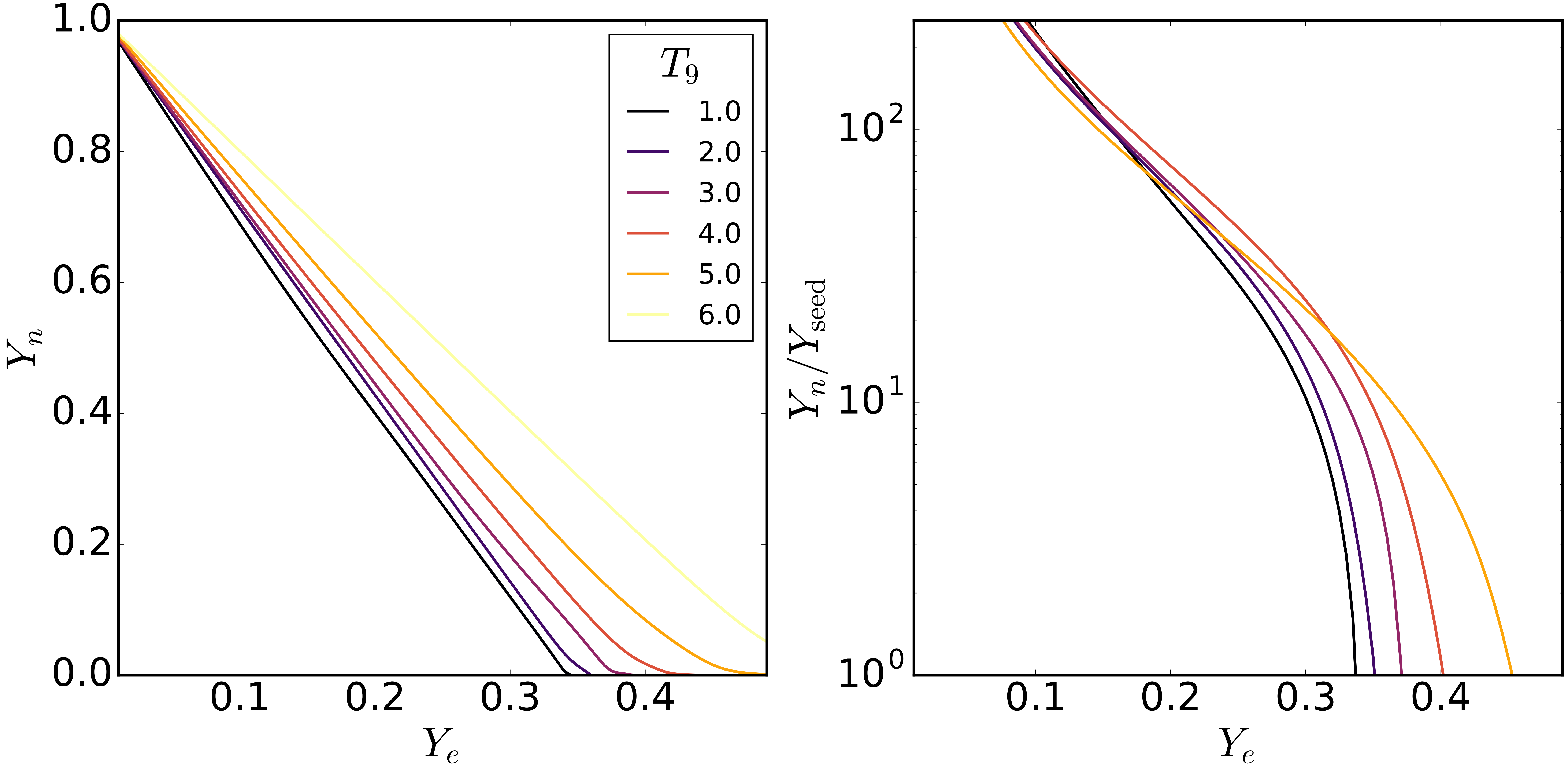


Lippuner & Roberts (2015)

Neutron-to-Seed Ratio of initial NSE distributions



Can trace Ye cutoff back to the initial conditions

Setting Y_e in the Ejecta

Evolution of the electron fraction is governed by

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + ...$$

$$Y_e(t) \approx Y_{e,0}\exp(-t/\tau_w) + [1 - \exp(-t/\tau_w)]Y_{e,eq}$$

where

$$\tau_w = [\lambda_{e^-} + \lambda_{e+} + \lambda_{\nu_e} + \lambda_{\bar{\nu}_e}]^{-1}$$

$$Y_{e,eq} = \frac{\lambda_{\nu_e} + \lambda_{e+}}{\lambda_{\nu_e} + \lambda_{e+} + \lambda_{\bar{\nu}_e} + \lambda_{e-}}$$

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Characteristic Rates:

$$\lambda_{e^-p} \approx \lambda_{e^+n} \approx 0.448 T_{\mathrm{MeV}}^5 \ \mathrm{s}^{-1}$$

$$\lambda_{\nu_e n} \approx 4.83 L_{\nu_e,51}\left(\epsilon_{\nu_e,\mathrm{MeV}} + 2\Delta_{\mathrm{MeV}} + 1.2\frac{\Delta_{\mathrm{MeV}}^2}{\epsilon_{\nu_e,\mathrm{MeV}}}\right) r_6^{-2} \ \mathrm{s}^{-1}$$

$$\lambda_{\bar{\nu}_e p} \approx 4.83 L_{\bar{\nu}_e,51}\left(\epsilon_{\bar{\nu}_e,\mathrm{MeV}} - 2\Delta_{\mathrm{MeV}} + 1.2\frac{\Delta_{\mathrm{MeV}}^2}{\epsilon_{\bar{\nu}_e,\mathrm{MeV}}}\right) r_6^{-2} \ \mathrm{s}^{-1}$$

Weak Interactions in NS Mergers

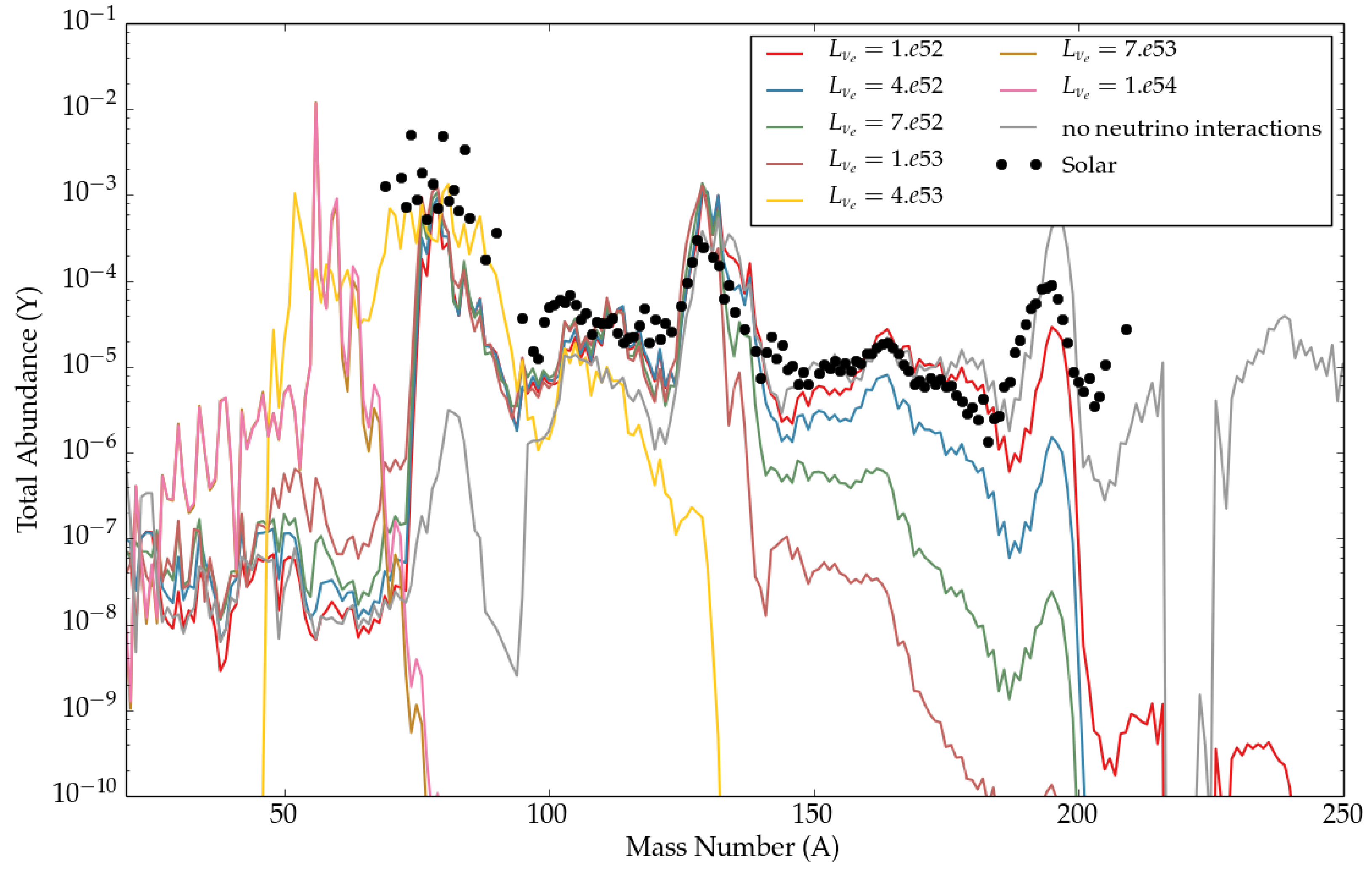
See Wanajo et al. (2014) and
Goriely et al. (2015)

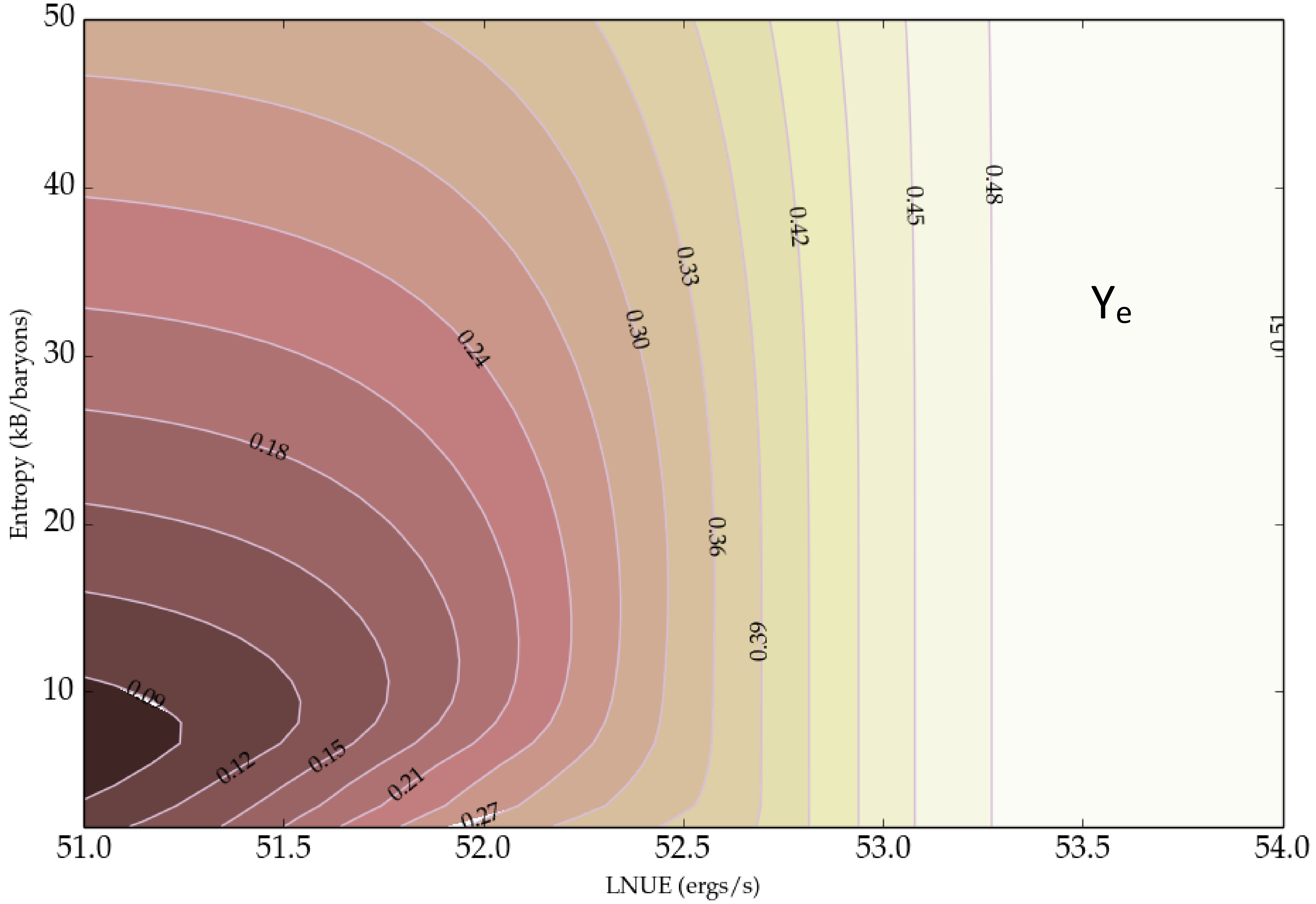
Destroy neutron at early times in hot,
neutrino rich environment
at early times via:

$$\{\nu_e, e^+\} + n \rightarrow p + \{e^-, \bar{\nu}_e\}$$

NSE favors more seed nuclei, fewer neutrons,
thereby gives lower neutron to seed ratio

Incomplete r-process, material builds up at first
peak



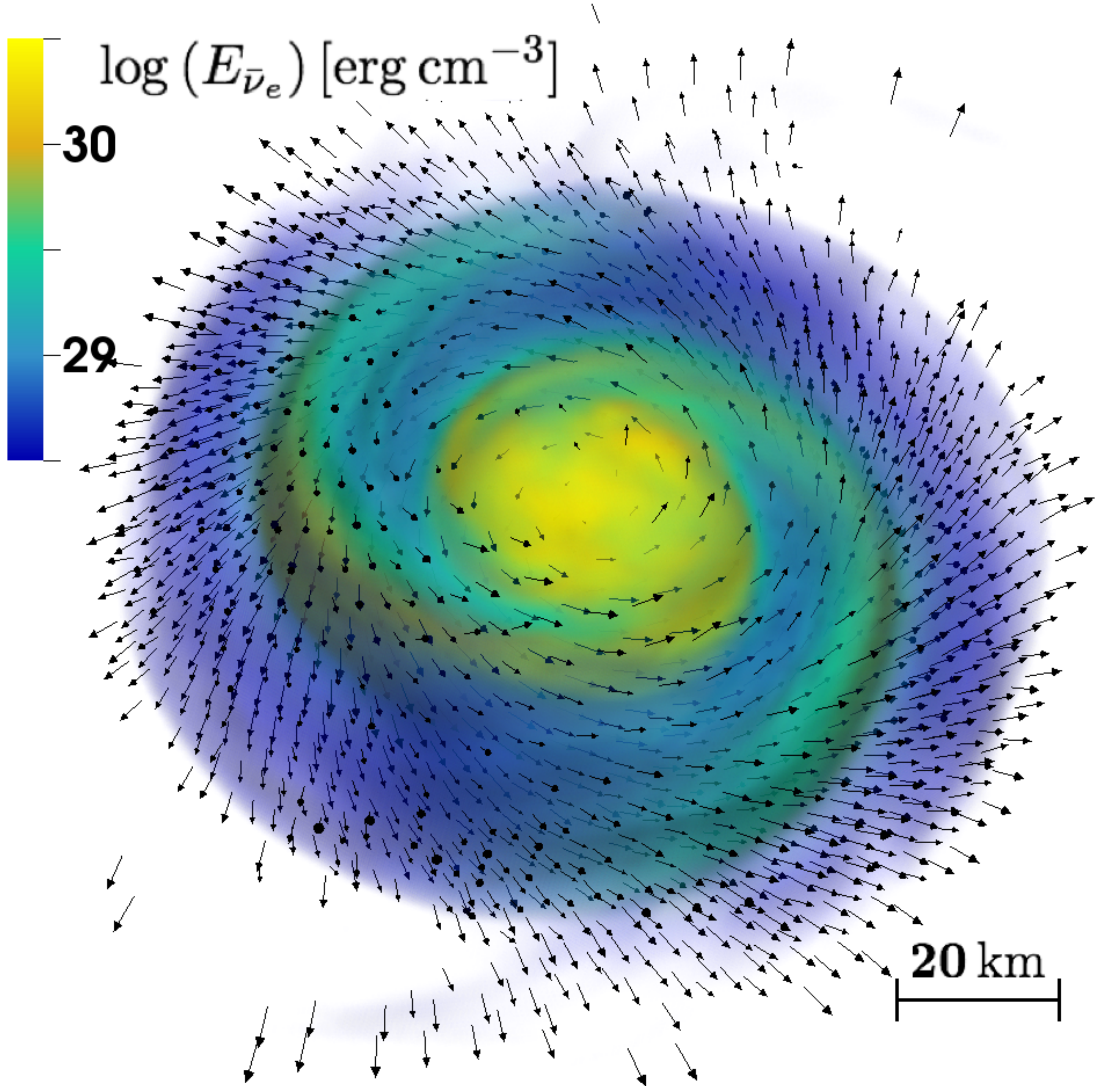


From summer student Sandra Ning

Neutrino Transport in the Ejecta

see Wanajo, et al. ’14, Radice et al. 16, Palenzuela et al. 16

- Large neutrino luminosities provided by central remnant of the NS merger
- Hierarchy of neutrino energies similar to proto-NS neutrino emission because neutrino decoupling physics is similar



Foucart, O’Connor, LR et al. ’16

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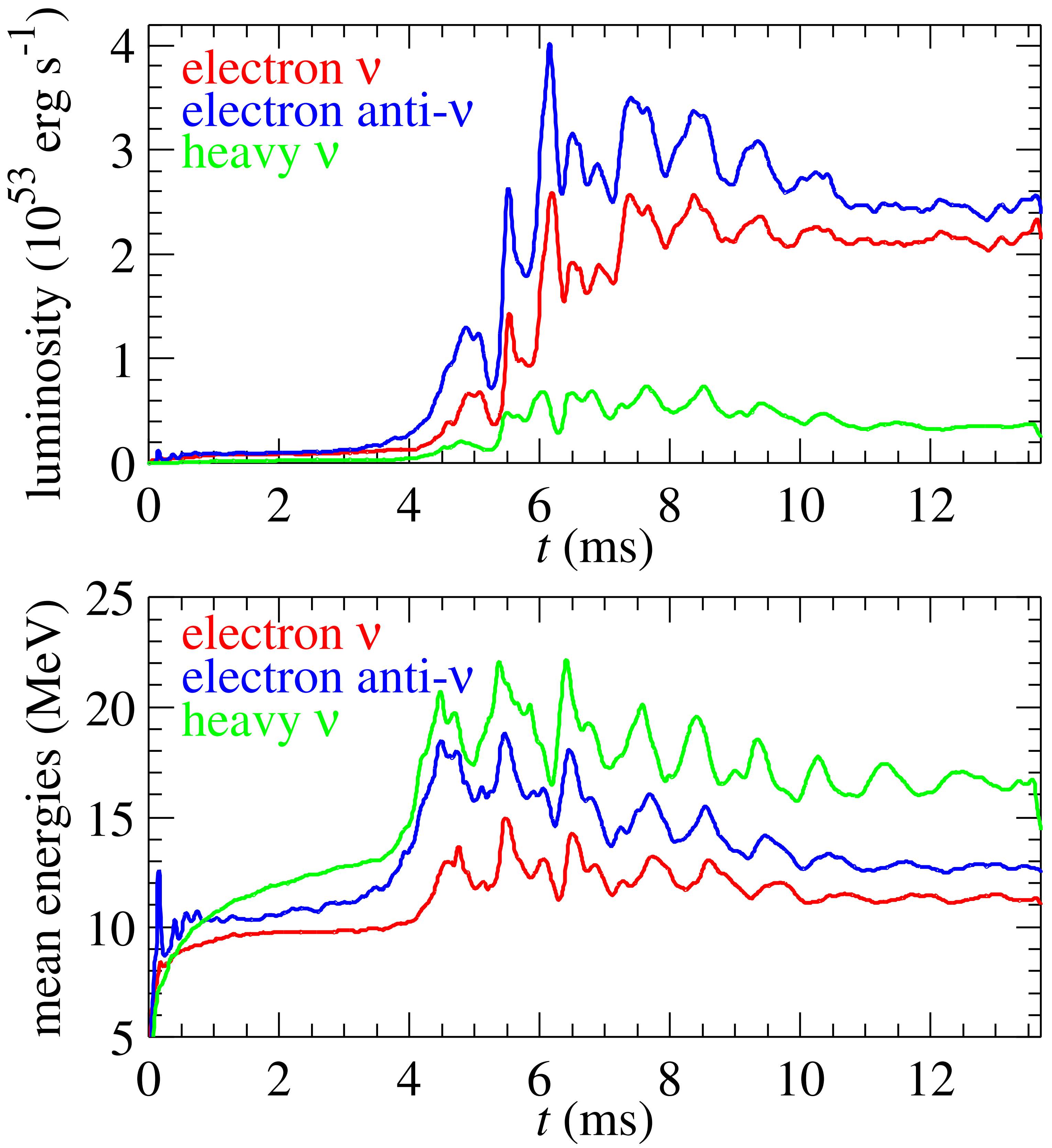

from Wanajo (2014)

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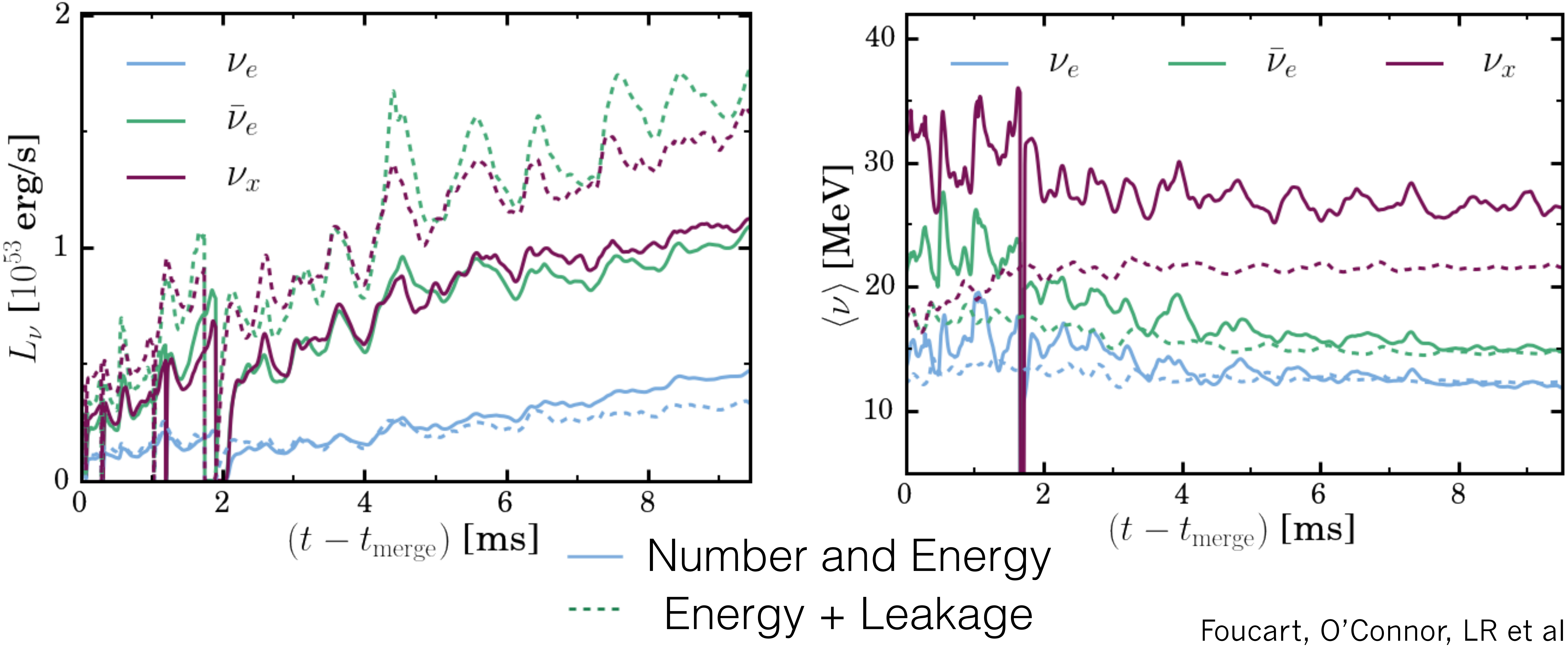

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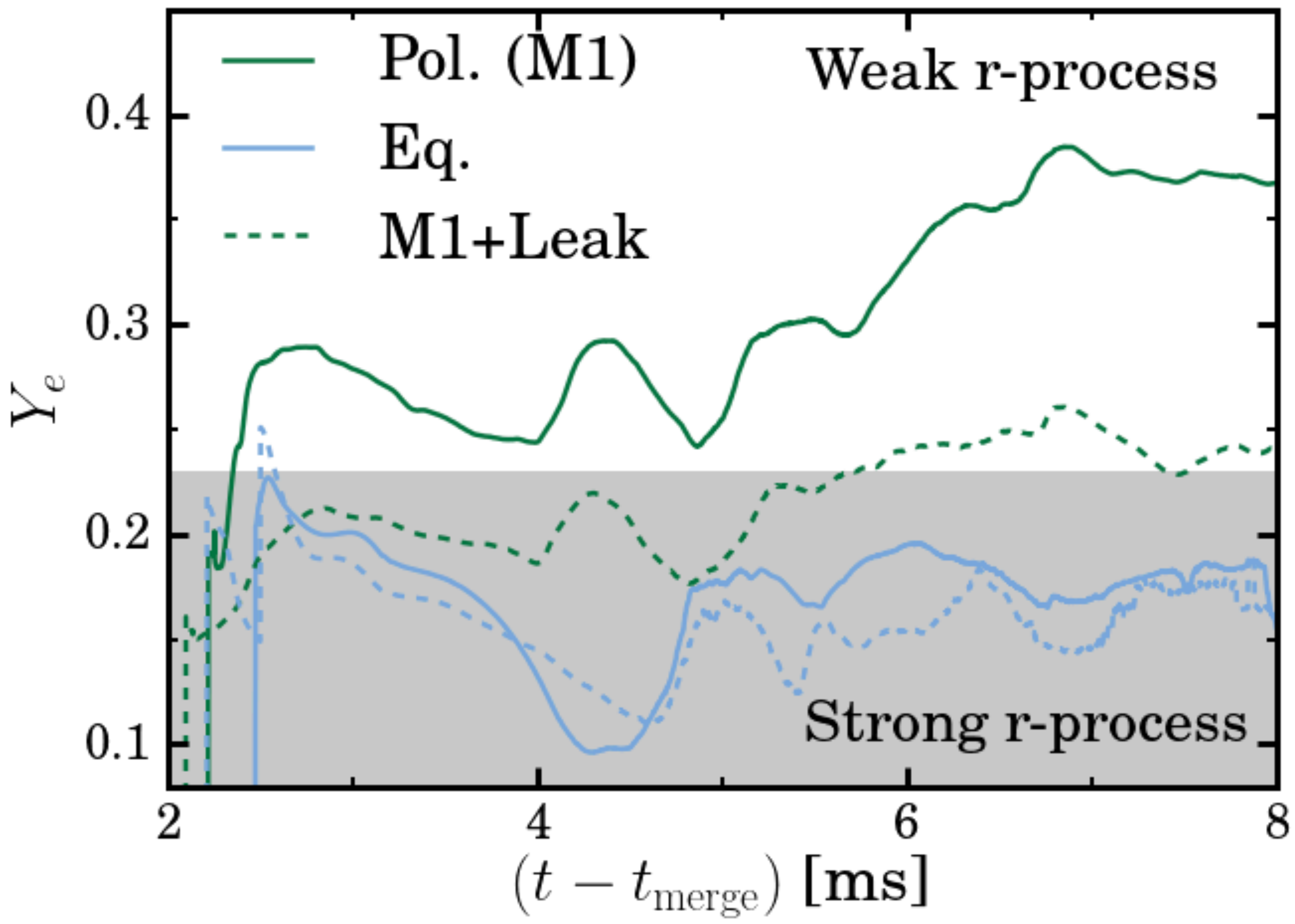
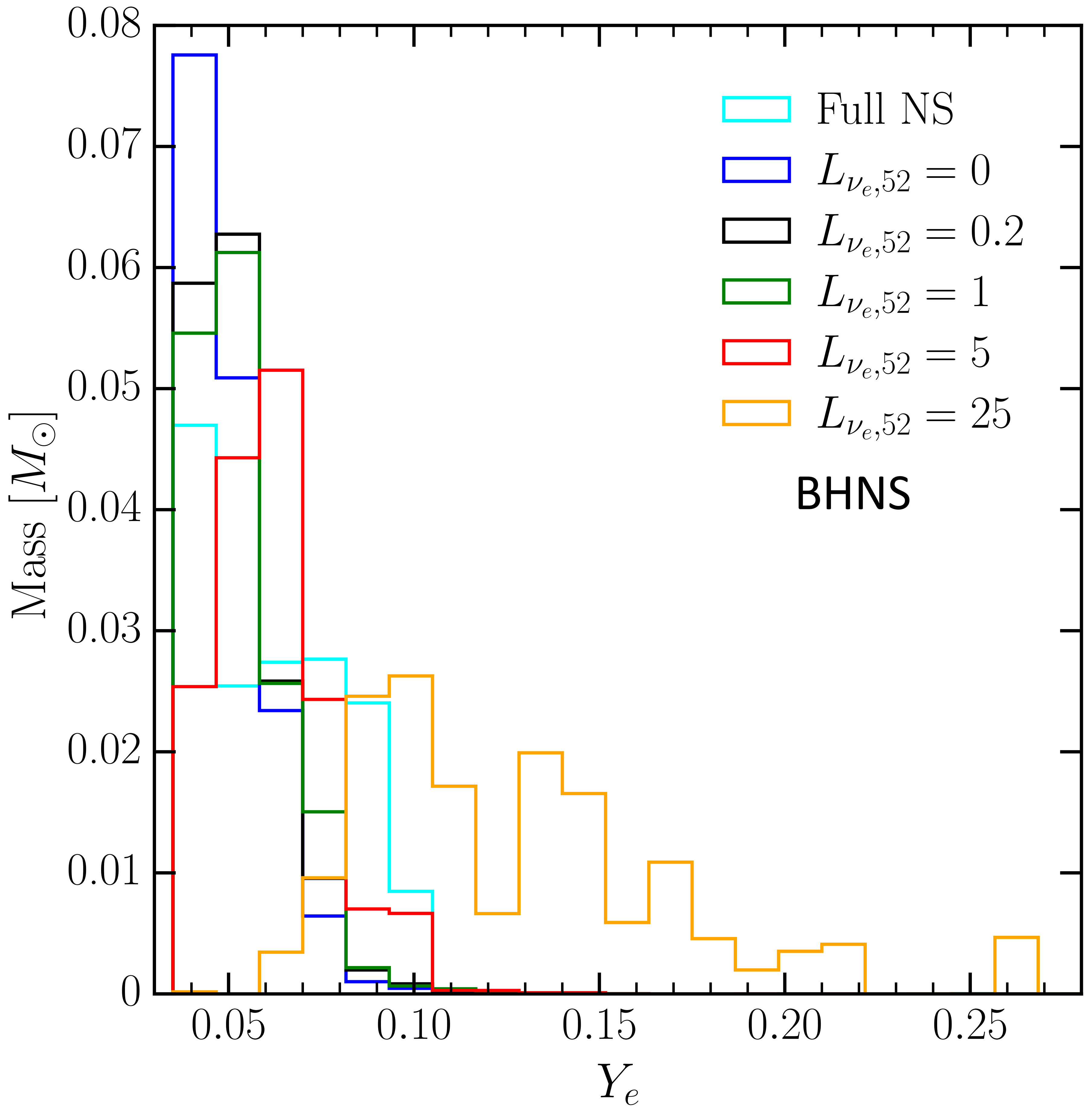


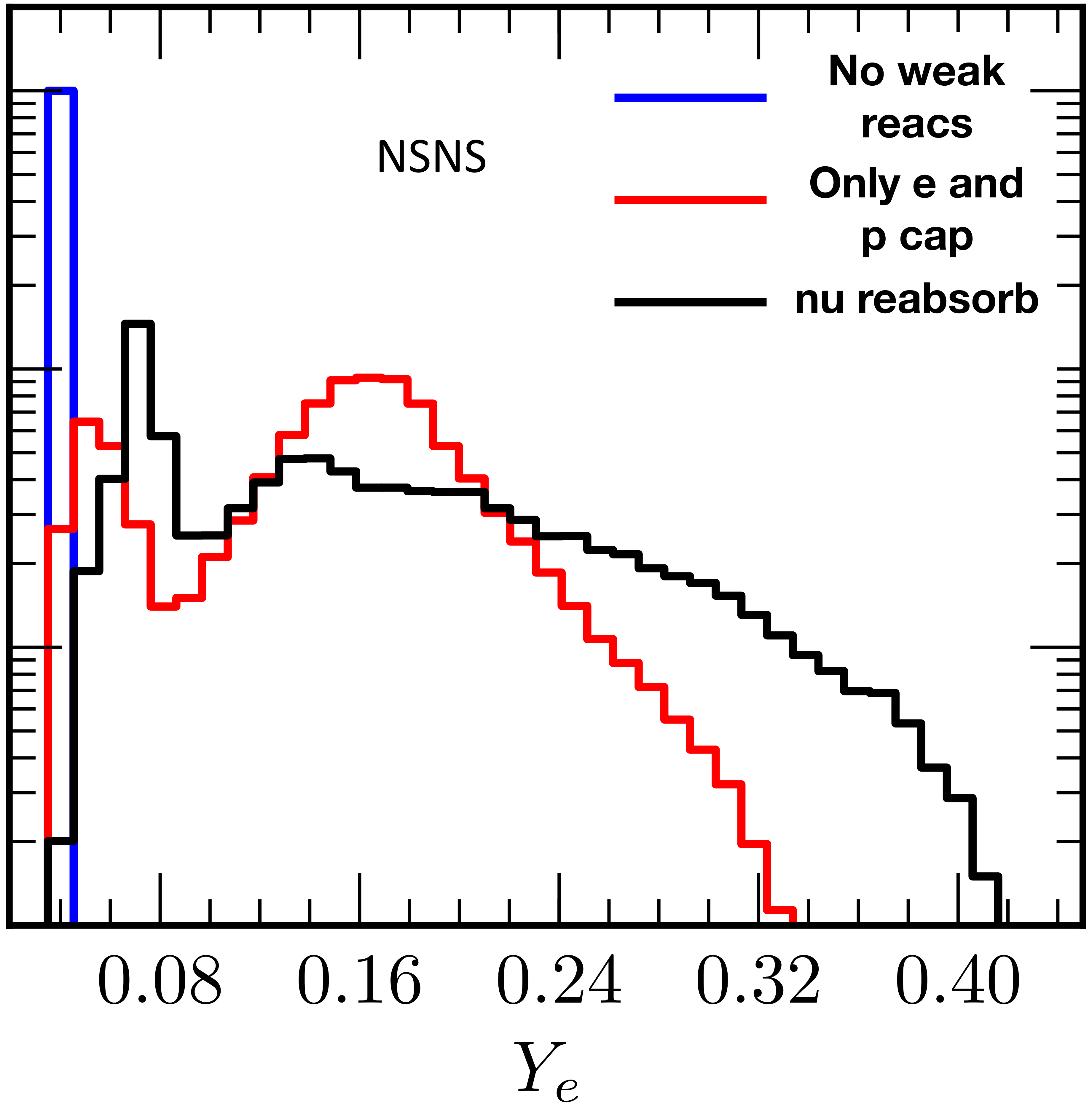
$$\{\nu_e, e^+\} + n \rightarrow p + \{e^-, \bar{\nu}_e\}$$

Foucart, O'Connor, LR et al. '16

Dynamical Ejecta in BHNS mergers vs NSNS mergers

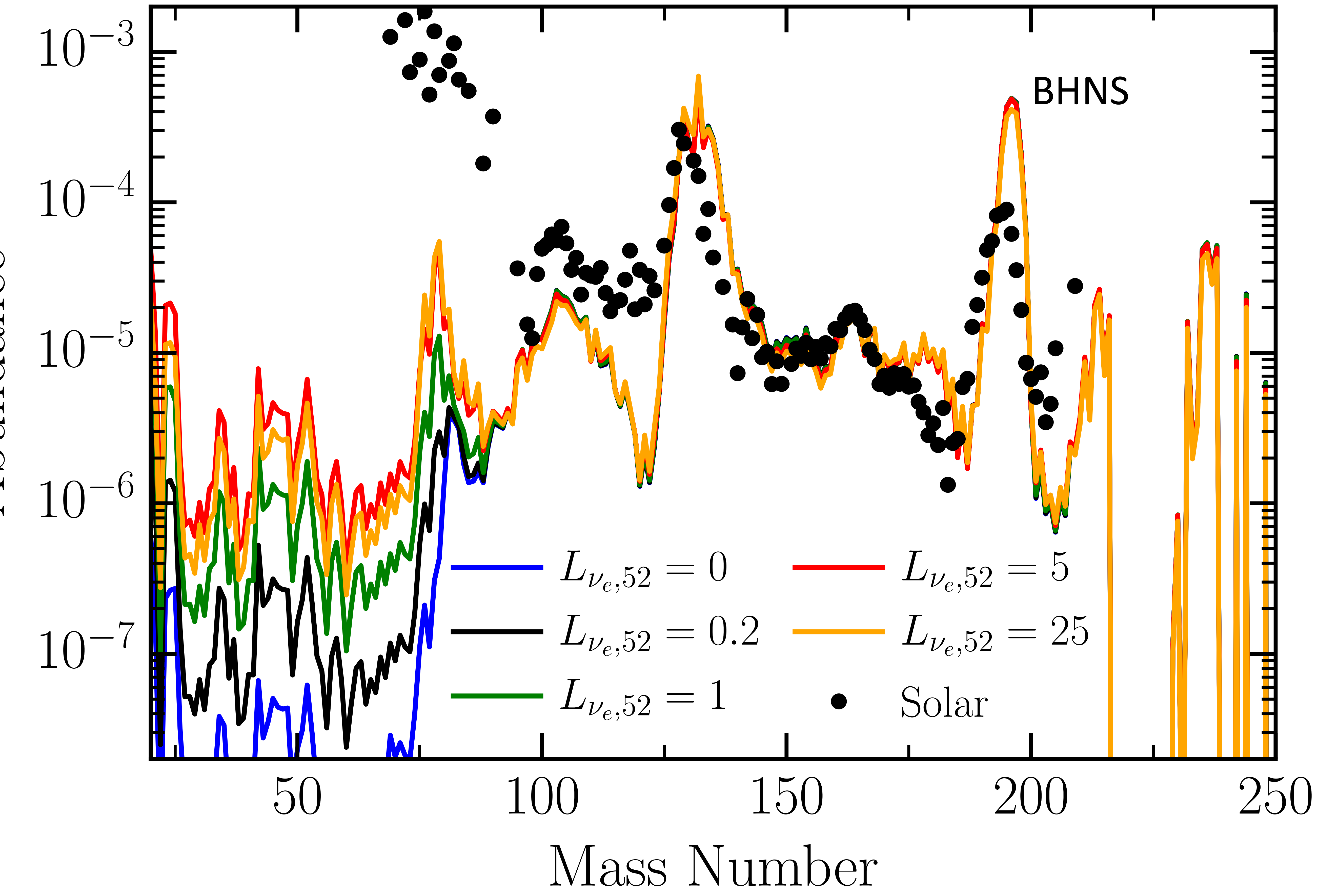


LR, et al. '16

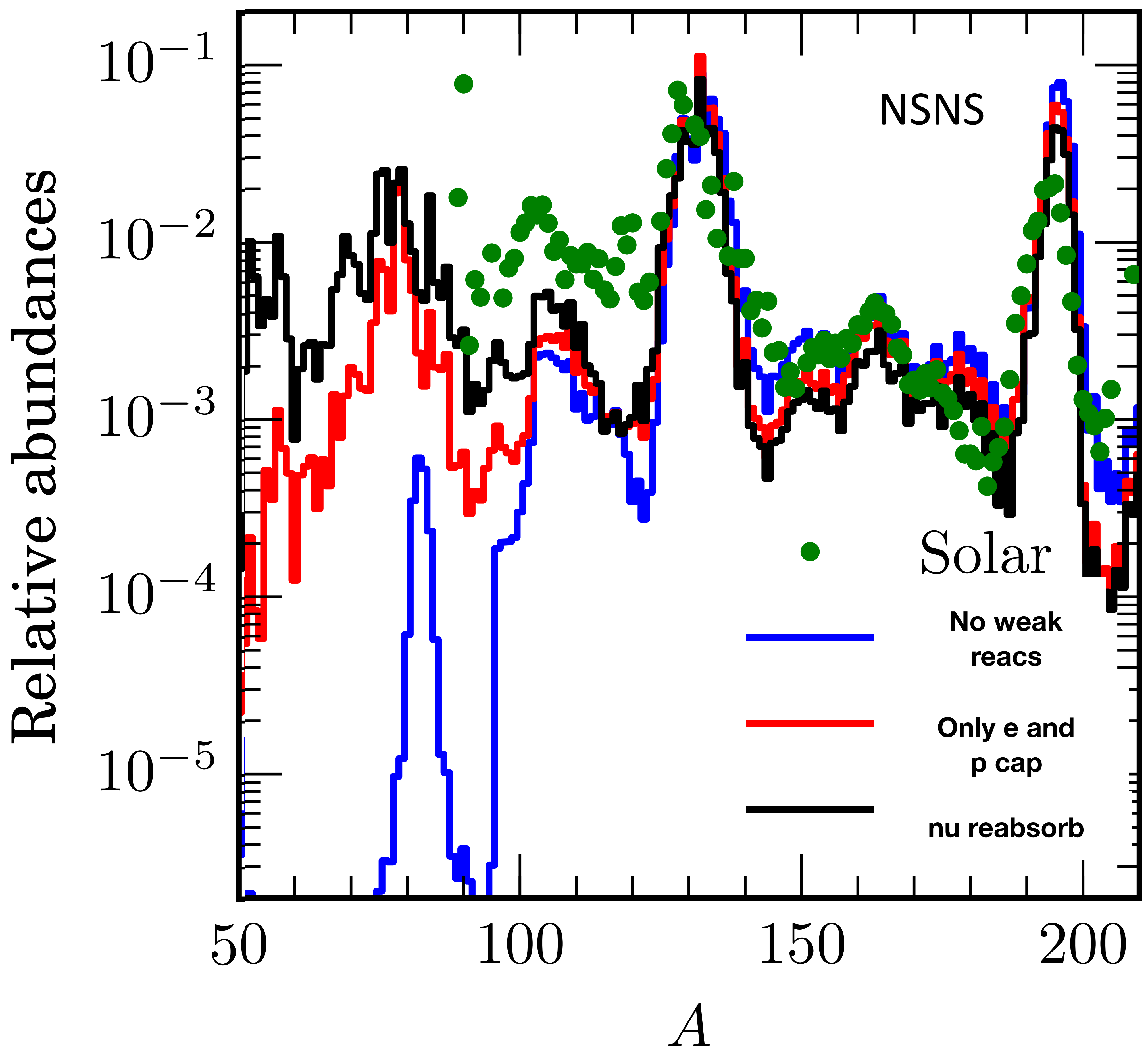


Radice, ..., LR et al. '16

Ejecta Composition



LR, et al. '16



Radice, ..., LR et al. '16

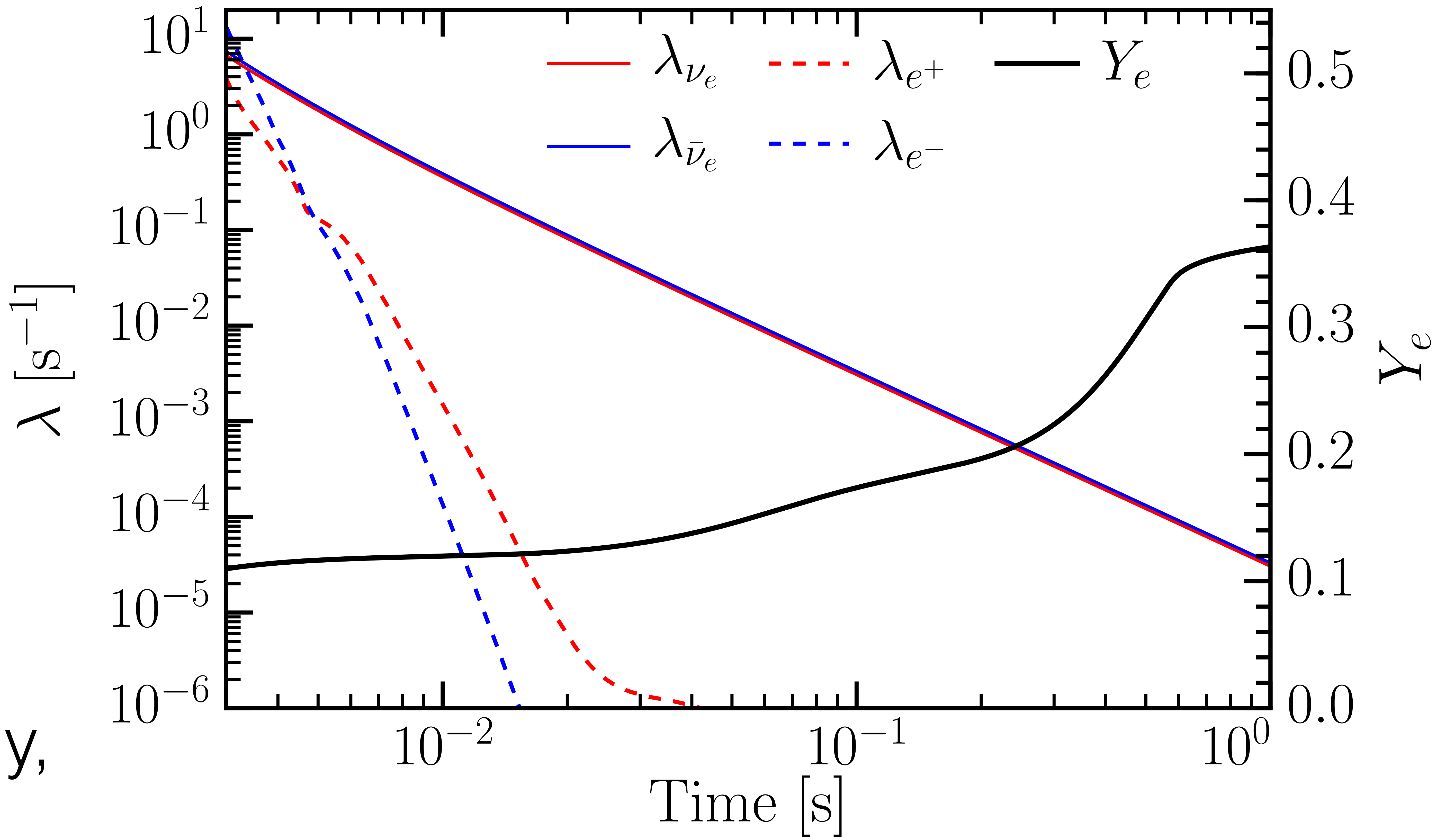
Weak interactions in BHNS dynamical ejecta

Low entropy tidal ejecta -> small electron/positron capture rates

Neutrino reactions are somewhat faster

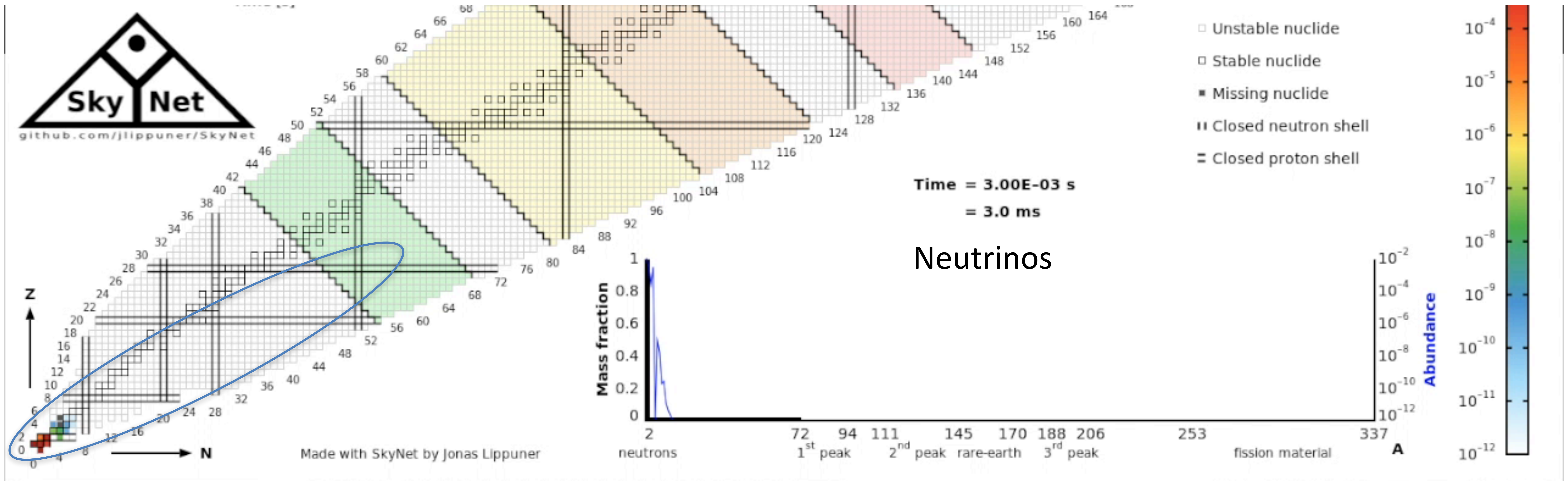
$$\tau_\nu(r) \approx 67.8\,\mathrm{ms}\left(\frac{r}{250\,\mathrm{km}}\right)^2 L_{\nu_e,53}^{-1} T_{\nu_e,5}^{-1}$$

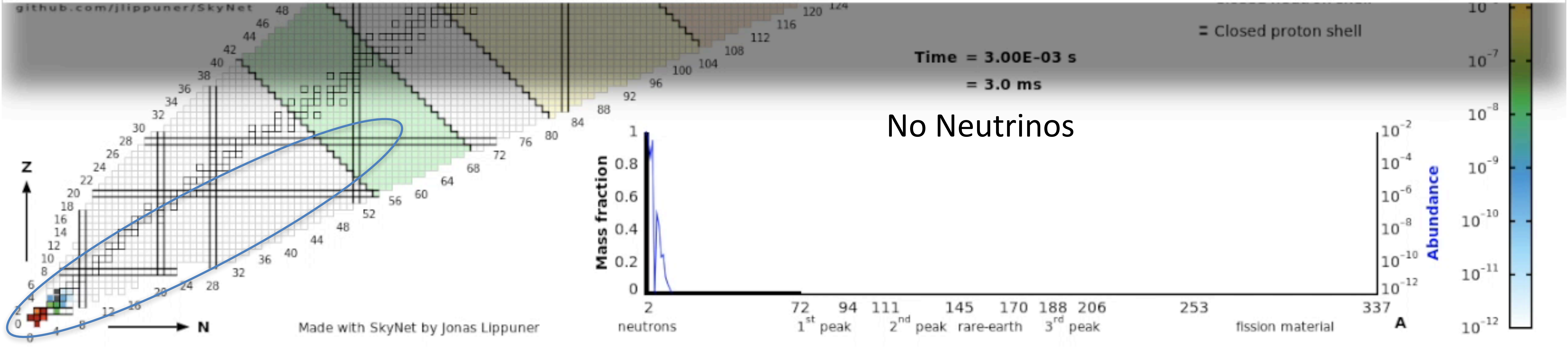
Still to slow to impact Y_e significantly, but can impact the first peak nucleosynthesis in the dynamical ejecta



LR, et al. '16

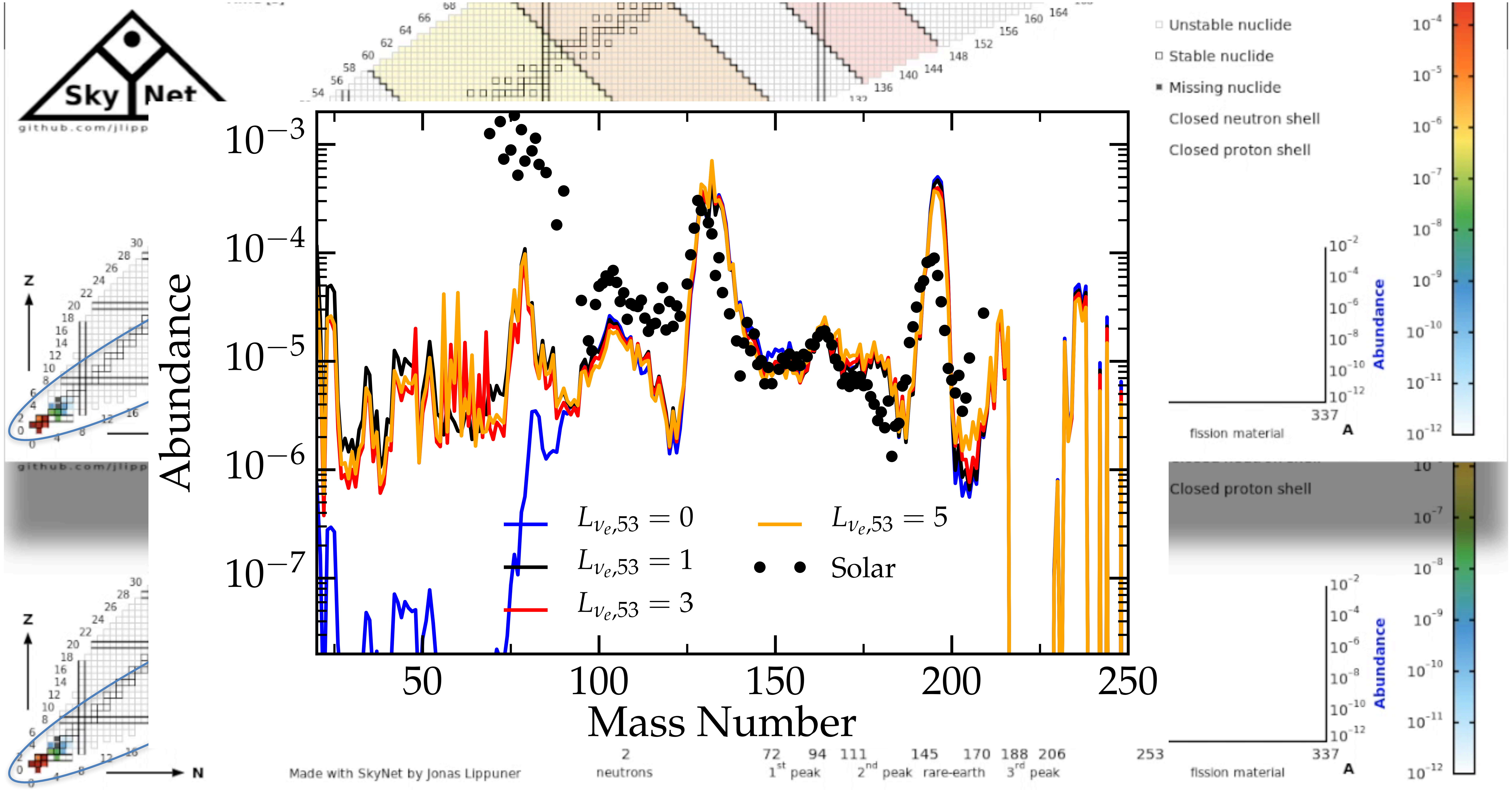
First r-Process Peak Production in BHNS Mergers





$\nu_e + n \to p + e^-$ $2p + 2n \to \alpha$ $3\alpha + n \to^{12} C + n$ $^{12}C + n...$

First r-Process Peak Production Method 2

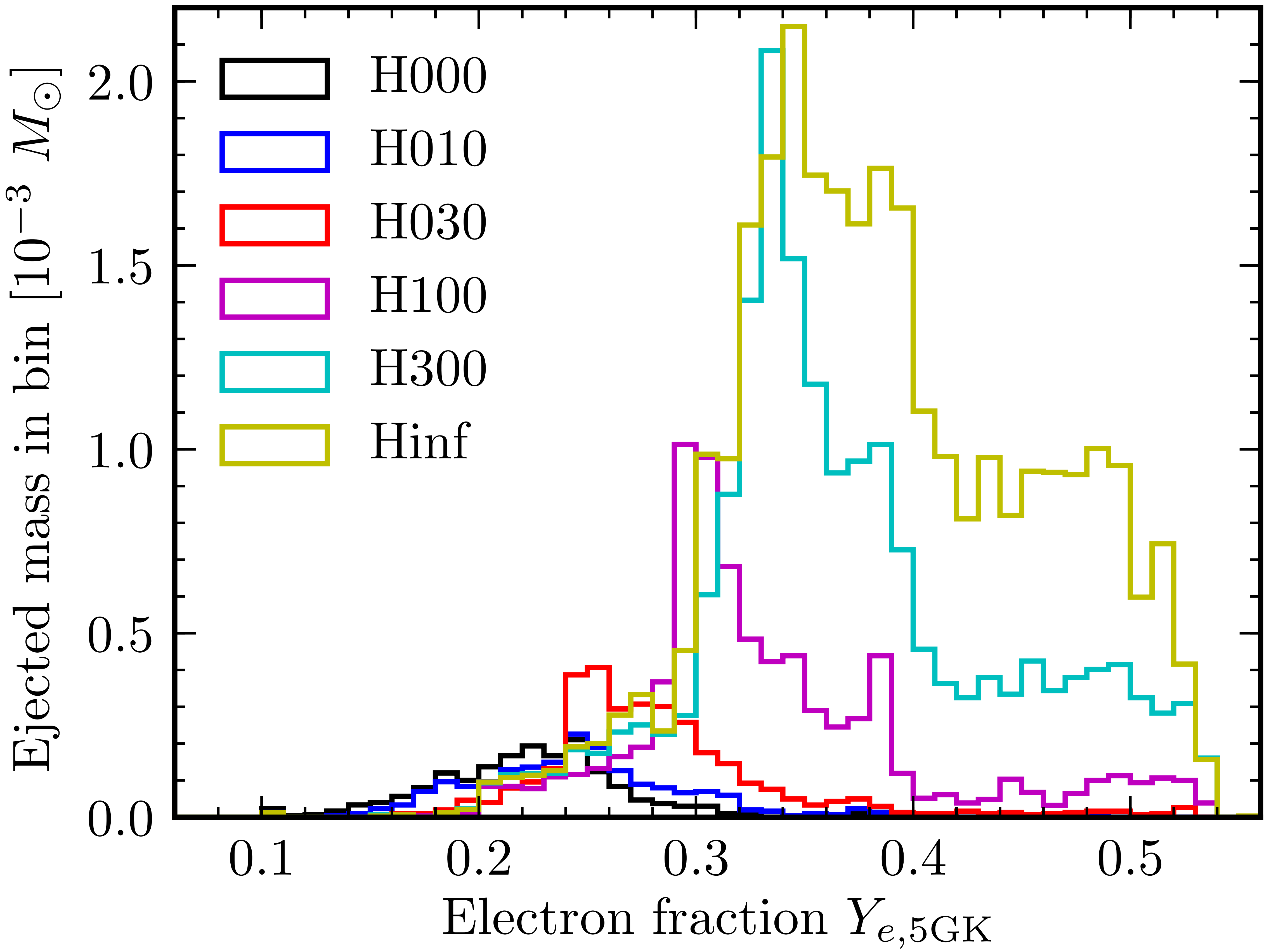


$\nu_e + n \rightarrow p + e^-$ $\quad 2p + 2n \rightarrow \alpha$ $\quad 3\alpha + n \rightarrow ^{12}C + n$ $\quad ^{12}C + n...$

Disk ejecta

see e.g. Metzger & Fernandez 14, Just et al. 15, Siegel & Meter 2018

- Material in the remnant disk also experiences a large number of weak interactions, beta-equilibrates
- Broad range of Y_e, depending on the lifetime of the hyper-massive neutron star
- Ratio of weak to strong r-process sensitive to the lifetime of the central object



from Lippuner, Fernandez, LR, et al. (2017)

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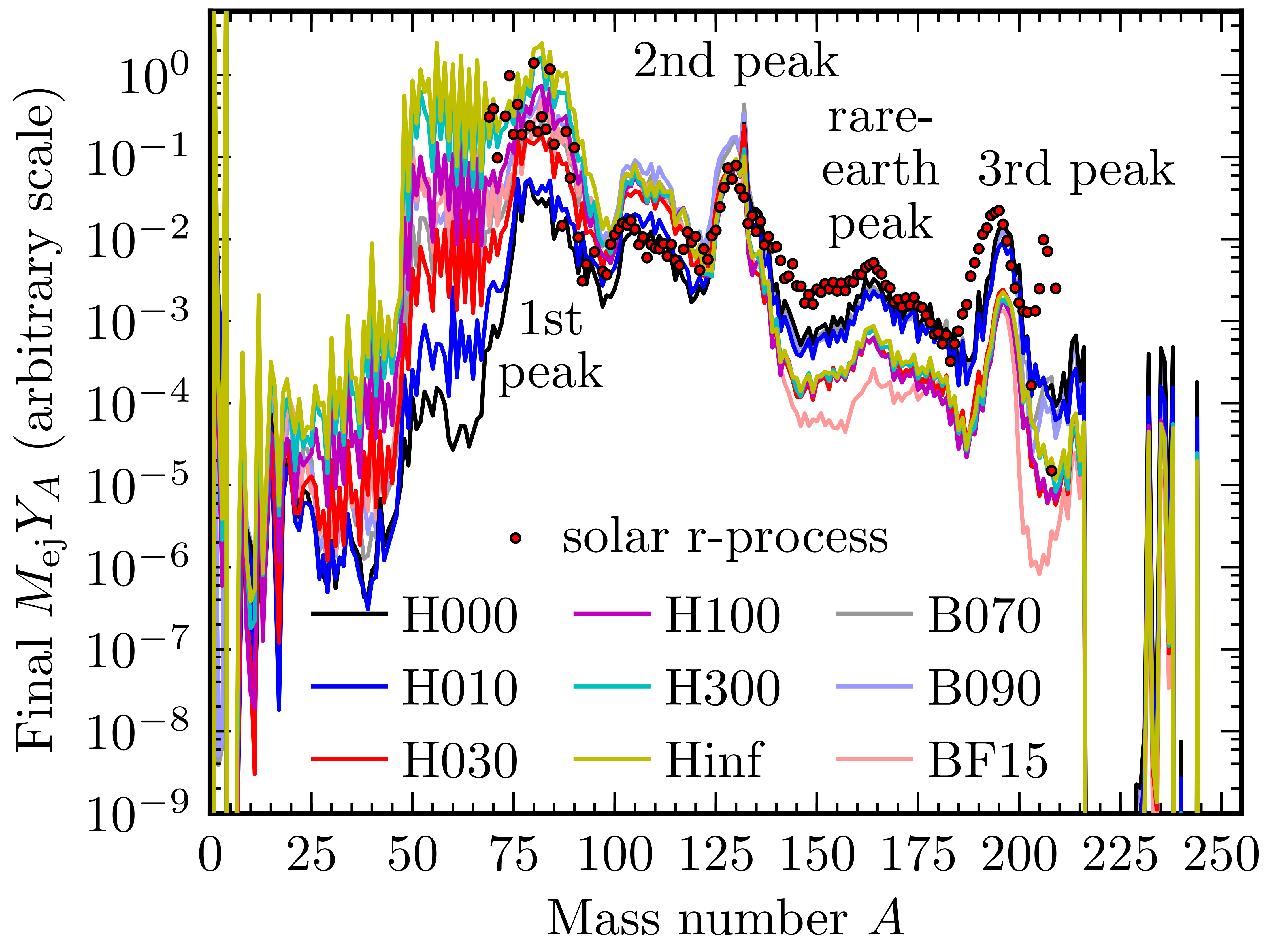
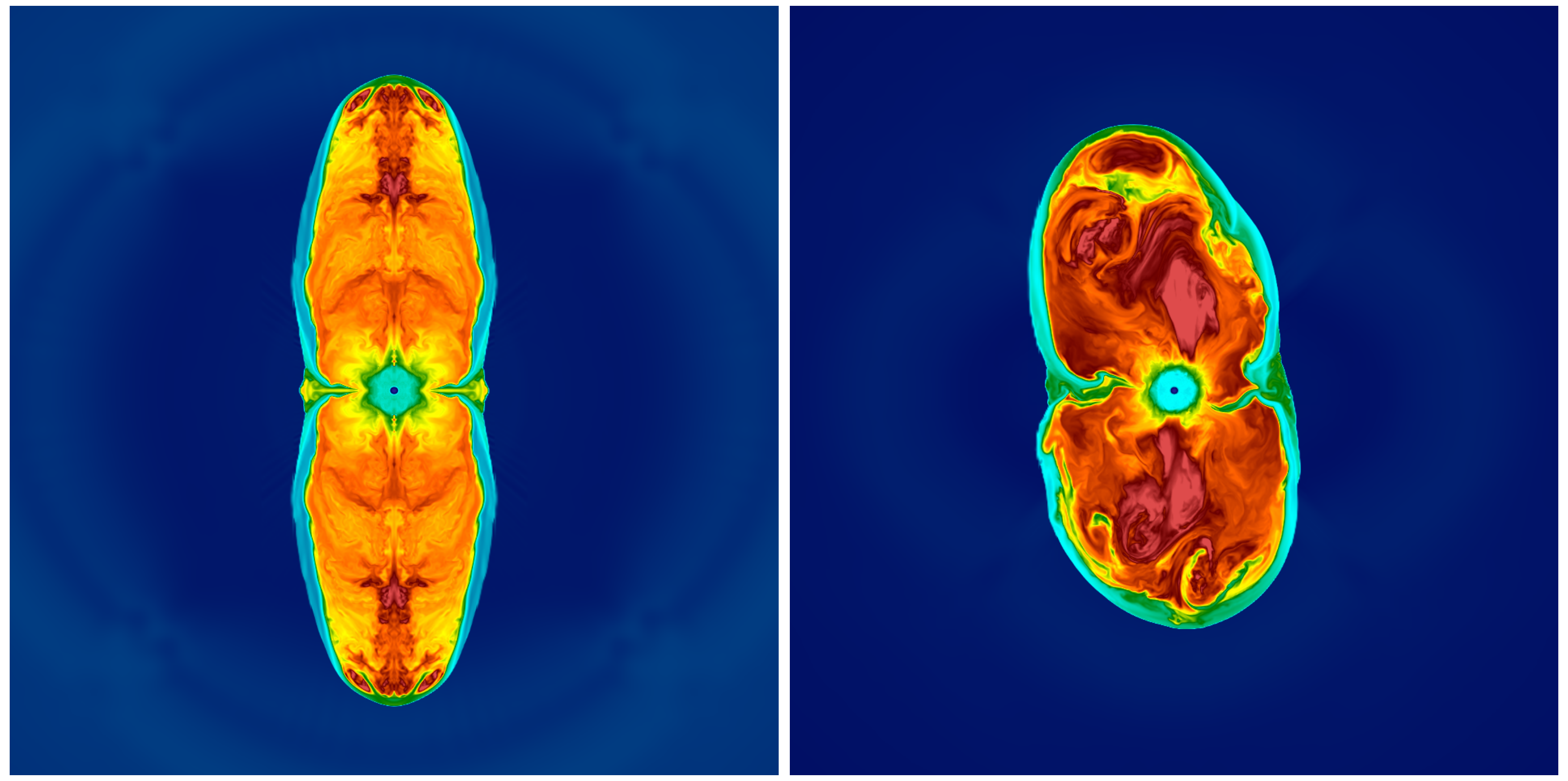


from Lippuner, Fernandez, LR, et al. (2017)

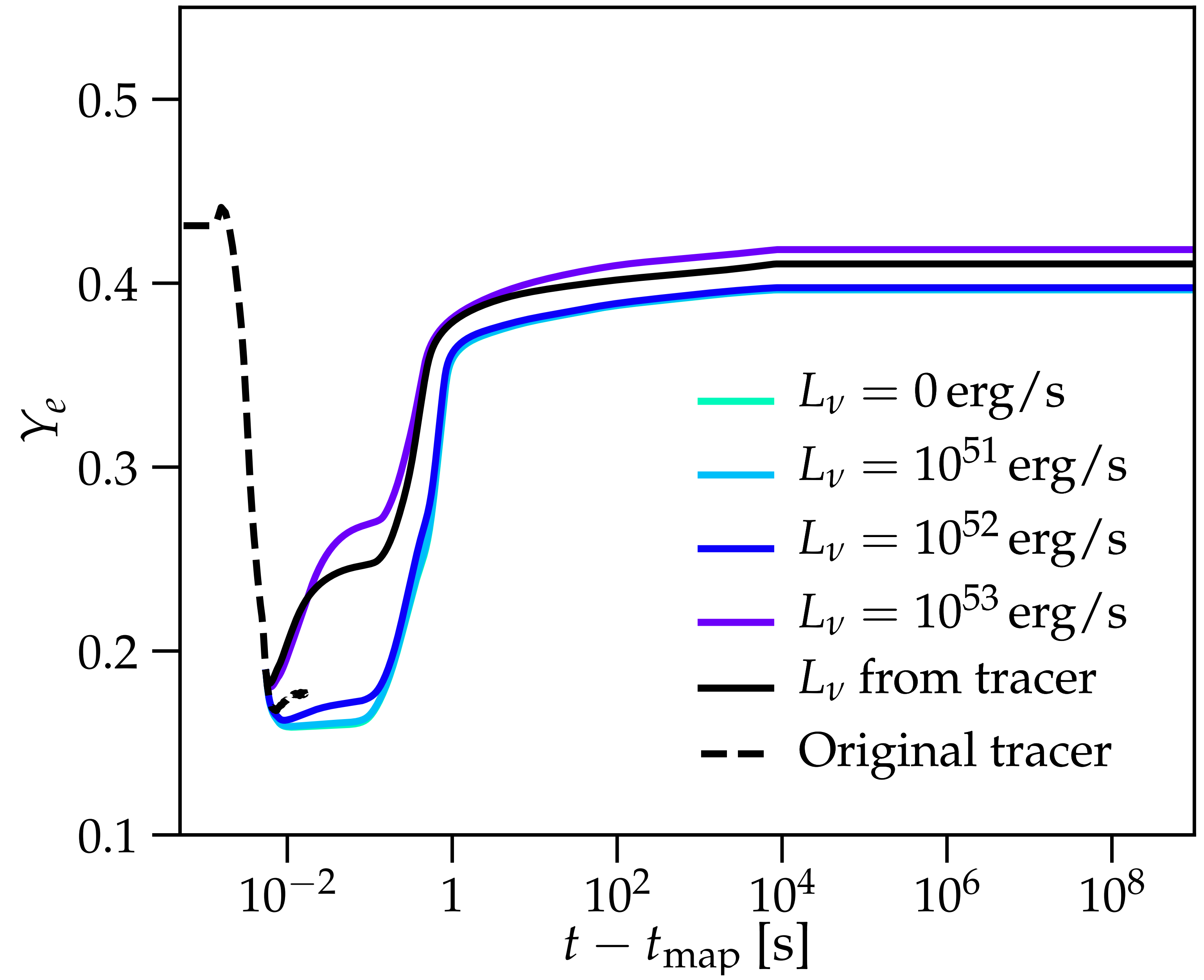
Jet Driven Supernovae

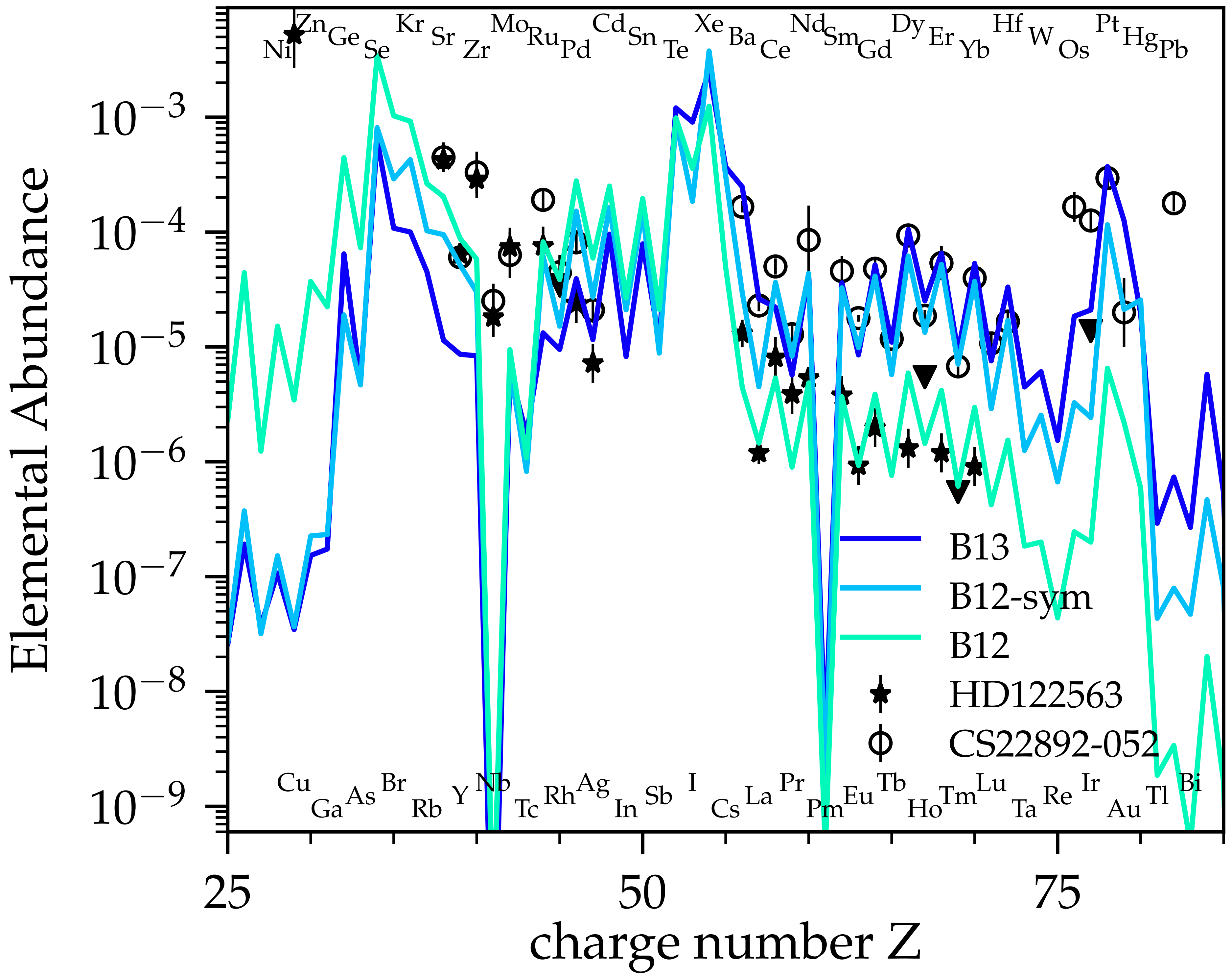
see Winteler et al. 2012, Nishimura et al. 2015, Moesta et al. 2018

Moesta, LR, et al. (2018)



- Rapidly rotating, magnetized SNe
- Full 3D Dynamics also important here
- Kink instabilities in jet significantly change dynamics and impact nucleosynthesis





Summary and Outlook

- Y_e distribution of the ejecta determining factor in the final composition and properties of the transient
- Weak interactions play a substantial role in setting the initial conditions for nucleosynthesis
- Going forward need better treatment of neutrinos during the dynamical phase -> important to setting the electron fraction distribution via weak interactions
- Sensitivity of r-process nucleosynthesis to input nuclear data of nuclear reaction network calculations. How well is the lanthanide cutoff Y_e known?
- Still some possible SN sites of the r-process
- Hopefully observe a BHNS merger