Nucleosynthesis in Neutron Star Mergers

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INT

Overview

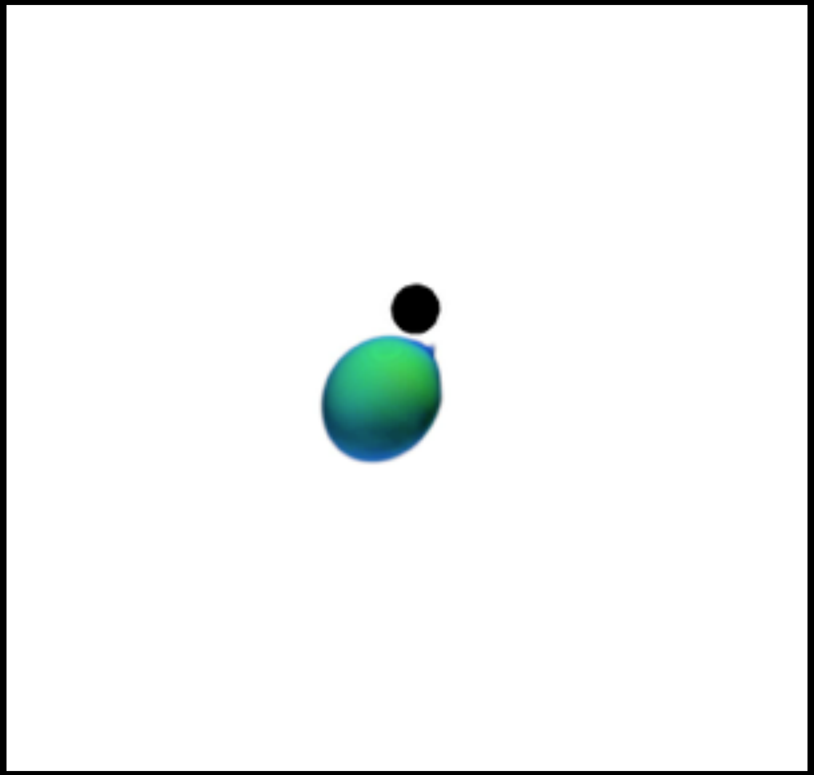
- Neutron star mergers: overview
- Nucleosynthesis in merger ejecta
- Outflow mechanisms in neutron star mergers
- From merger simulations to nucleosynthesis predictions

GW sources : Binaries

BH-BH

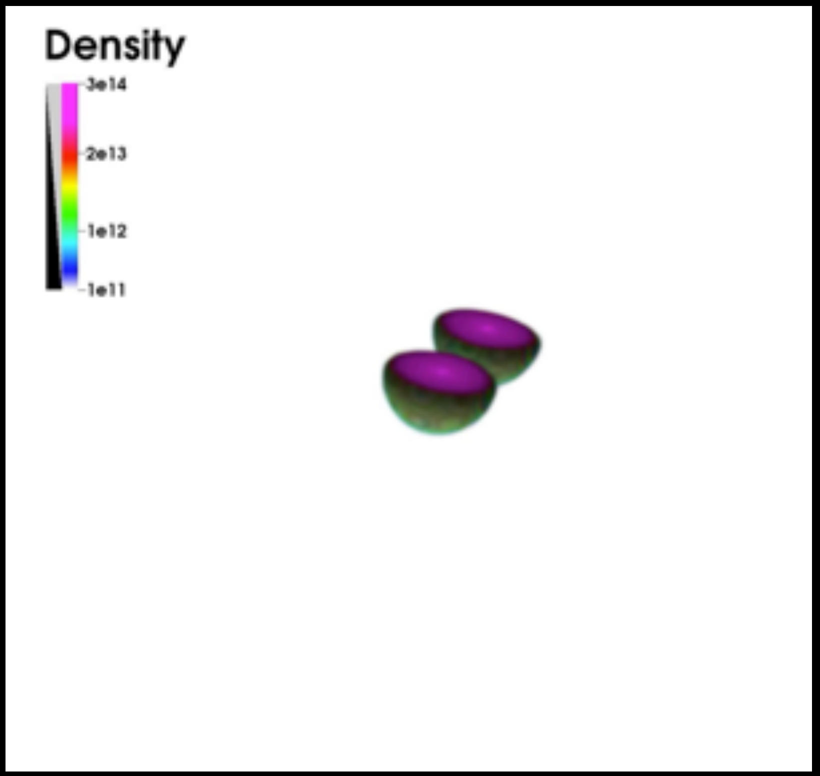
Movie : SxS Collaboration

BH-NS



Hinderer, .., FF et al. 2016

NS-NS



Foucart et al. 2016 (Movie: D. Faiez)

3 observations of BH-BH binaries already published, other systems expected in the coming years.
Still large uncertainties in event rates.

Merger Timeline

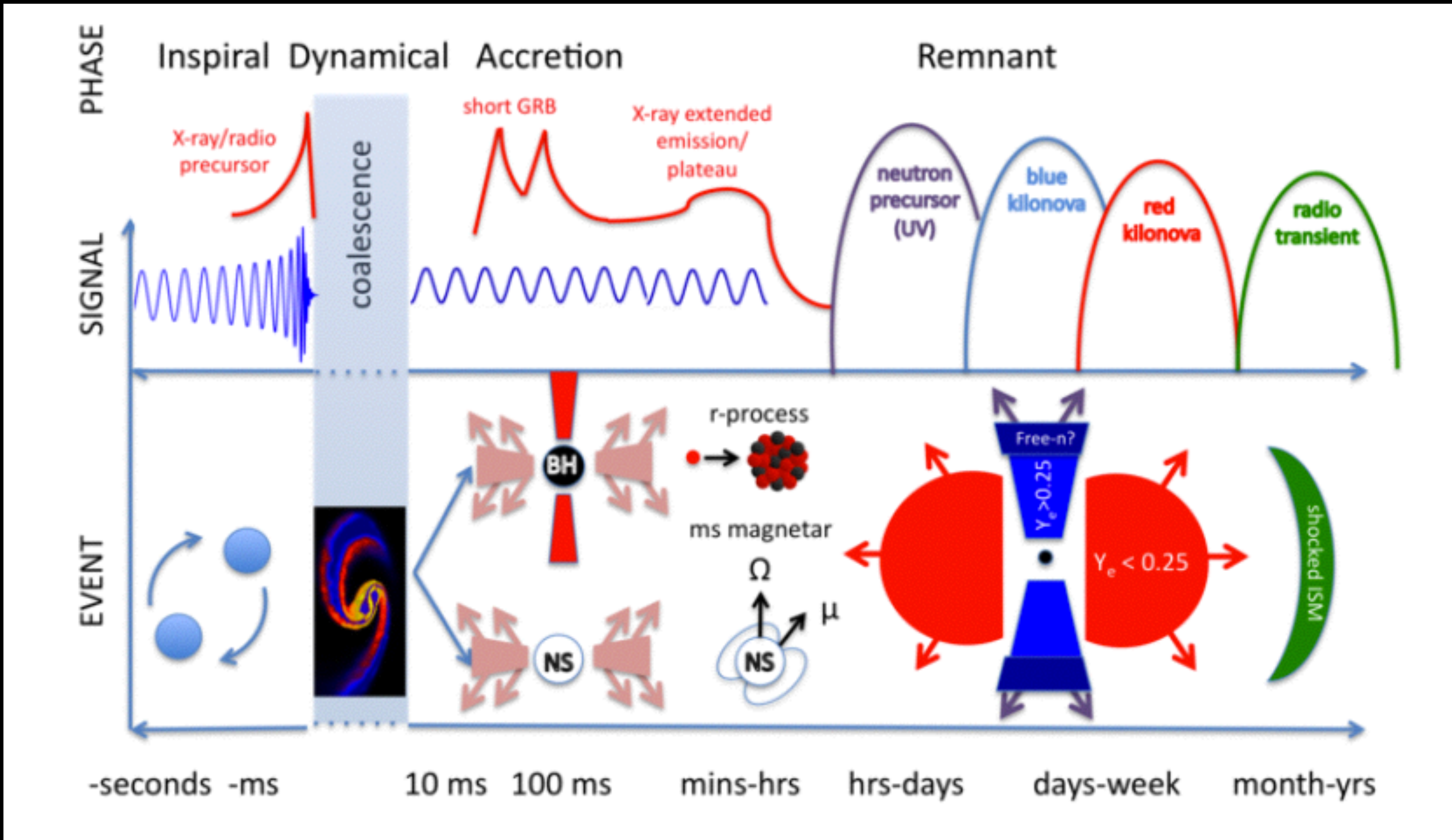
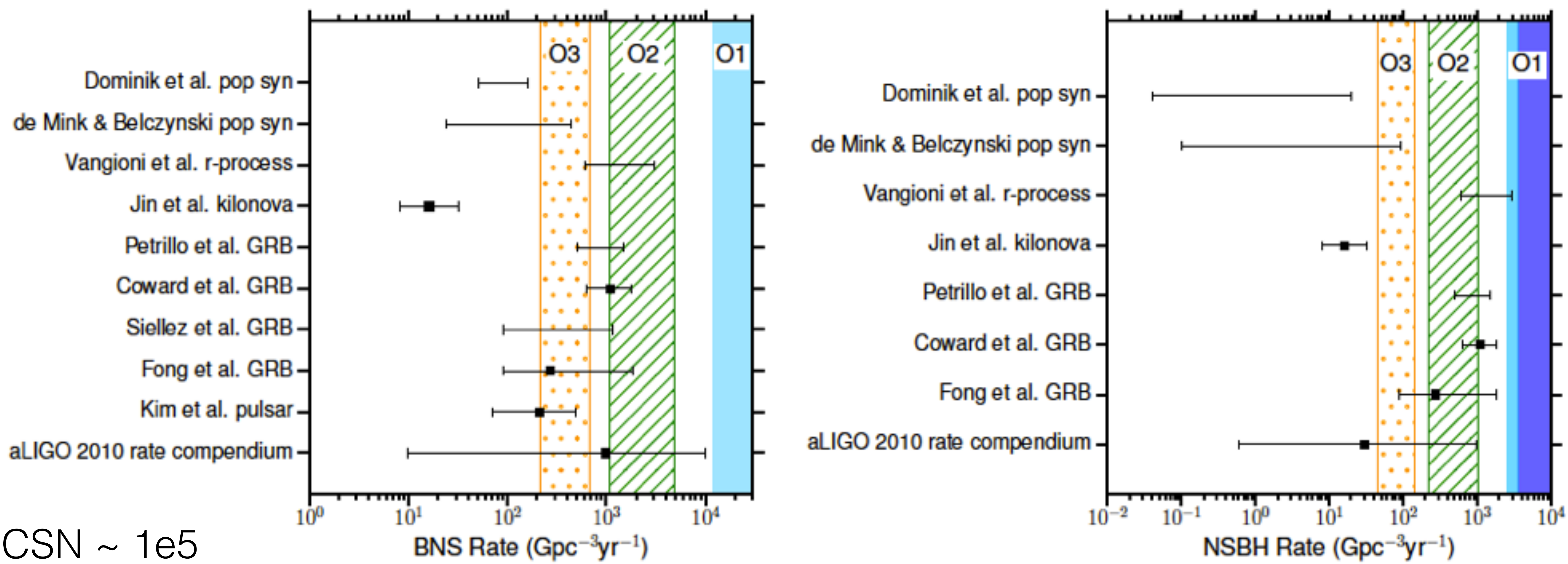


Image: Fernandez & Metzger 2016

Event Rates

- Theoretically very uncertain
- Practically: to be determined by AdvLIGO observations



CCSN ~ 1e5

Image: LIGO 2016, ApJ

Nucleosynthesis Yields in Mergers

r-process abundances

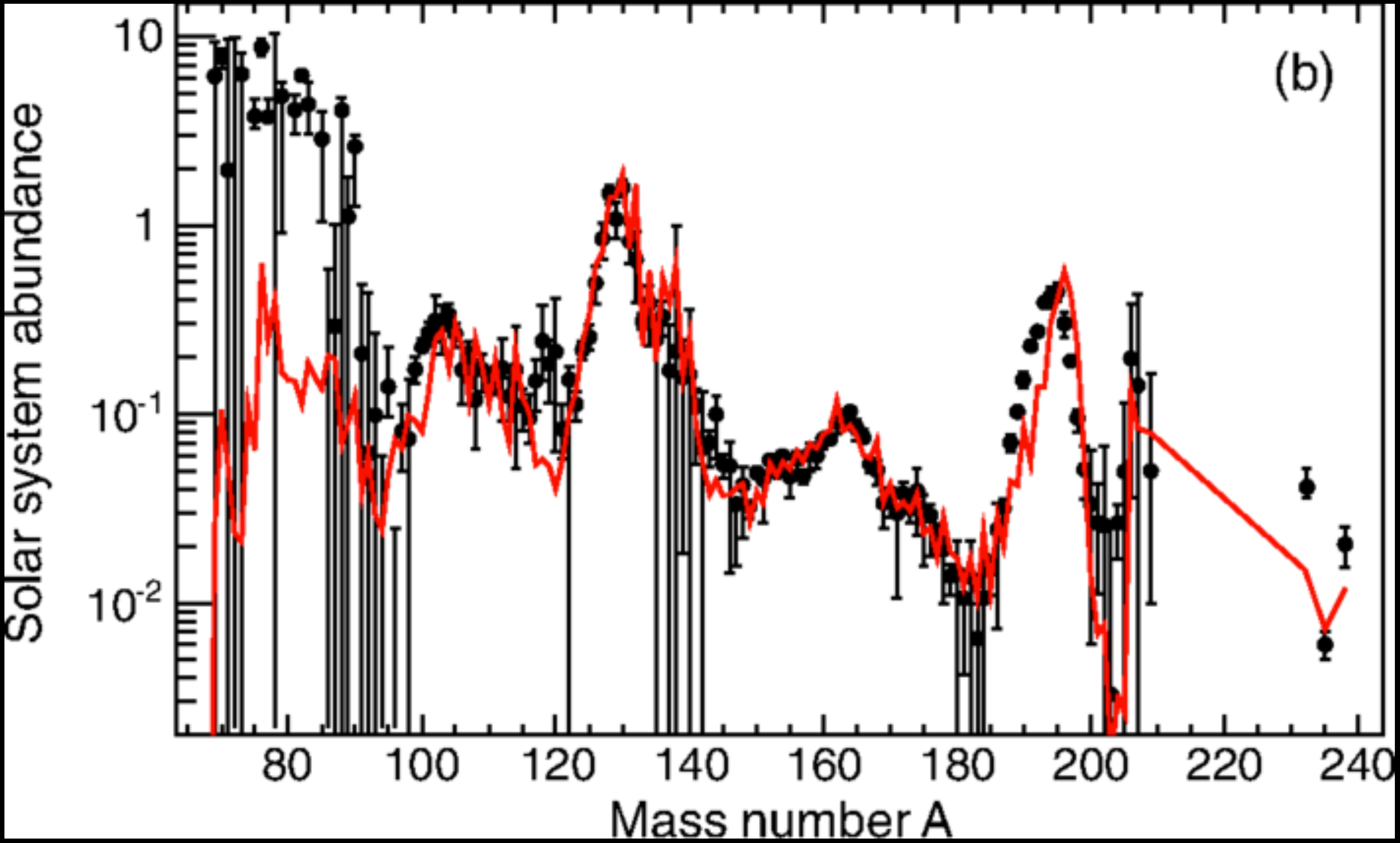
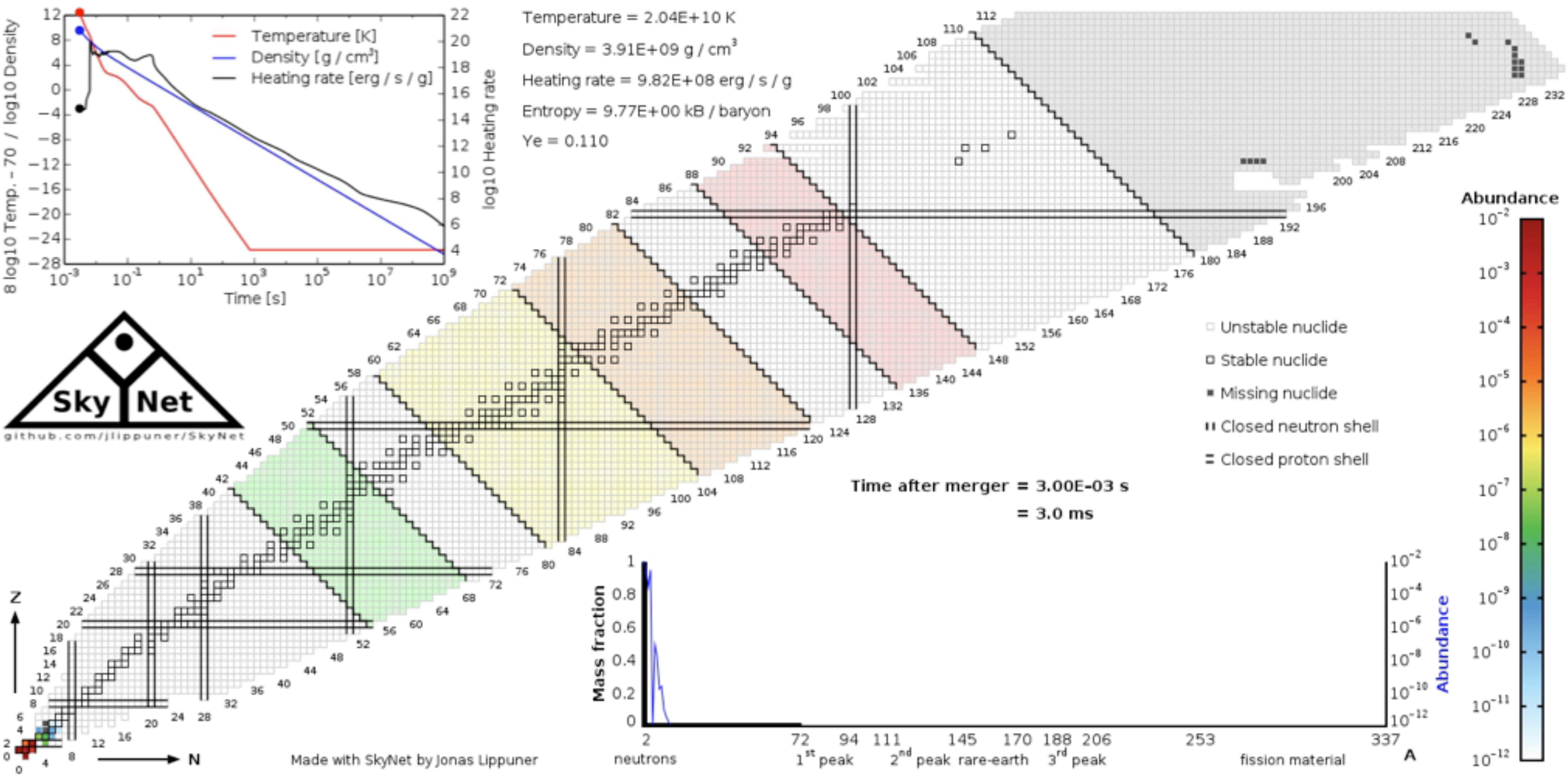


Image: Lorusso et al. 2015

r-process nucleosynthesis and kilonovae

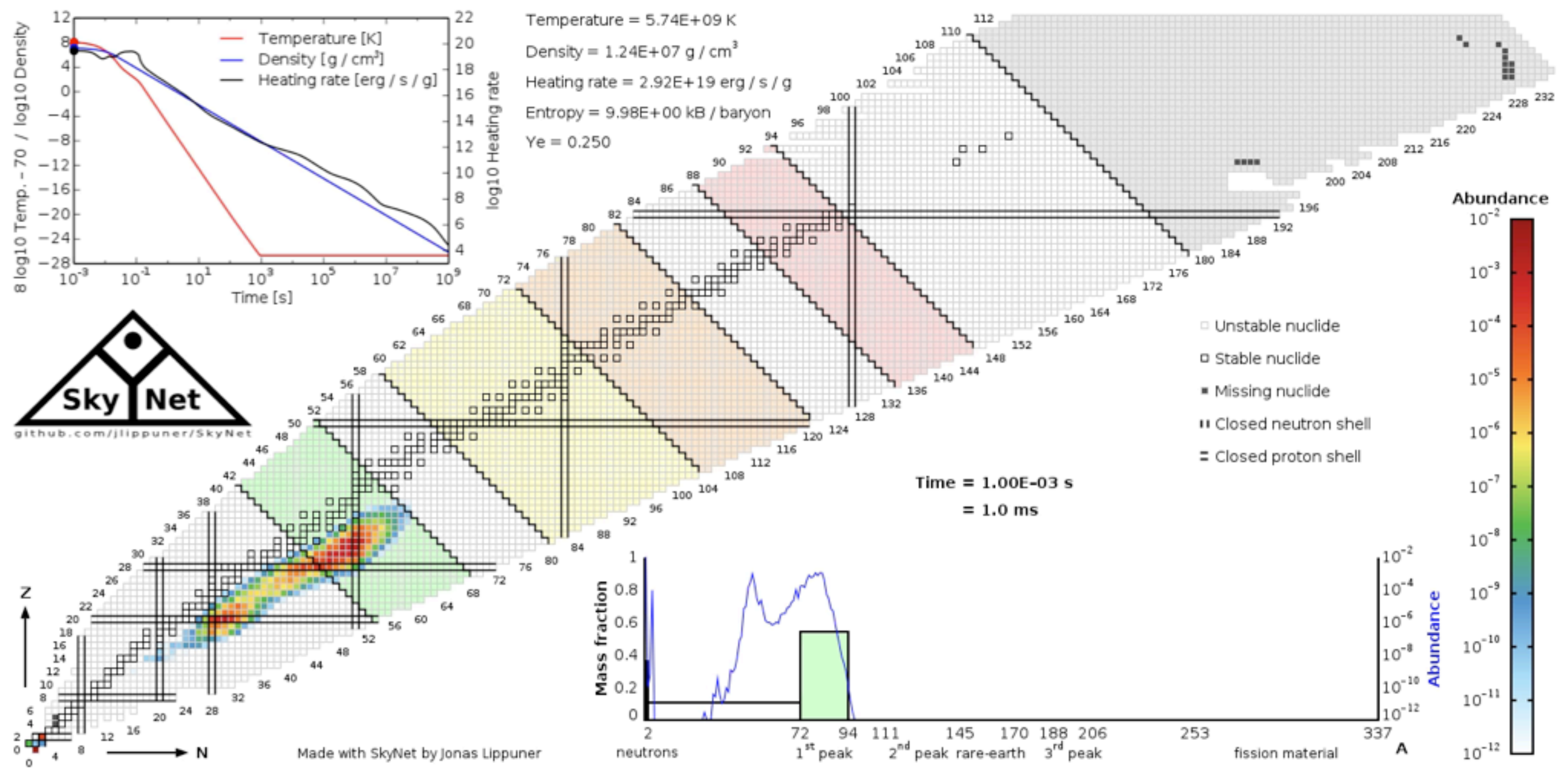
Nucleosynthesis in **neutron rich material** (e.g. tidal ejecta from BH-NS binary)



Visualization: Jonas Lippuner (Caltech), SkyNet code

Nucleosynthesis in neutron poor ejecta

Nucleosynthesis in “**neutron poor” material** (still 75% neutrons…)



Visualization: Jonas Lippuner (Caltech), SkyNet code

Important parameters

- Mass of ejected material
- Composition (e.g. electron fraction Y_e)
- Temperature/entropy of outflows
- Velocity / expansion timescale
- Mass model (not discussed here)
- Neutrino irradiation

Outflow mechanisms in NS Mergers

Outflow Mechanisms: Overview

- Dynamical Ejecta
  - Tidal disruption
  - Sheared/Shocked region in BNS mergers
- Disk outflows
  - Neutrino- and Magnetically-driven winds
  - Viscous outflows

Tidal disruption: BHNS Mergers:

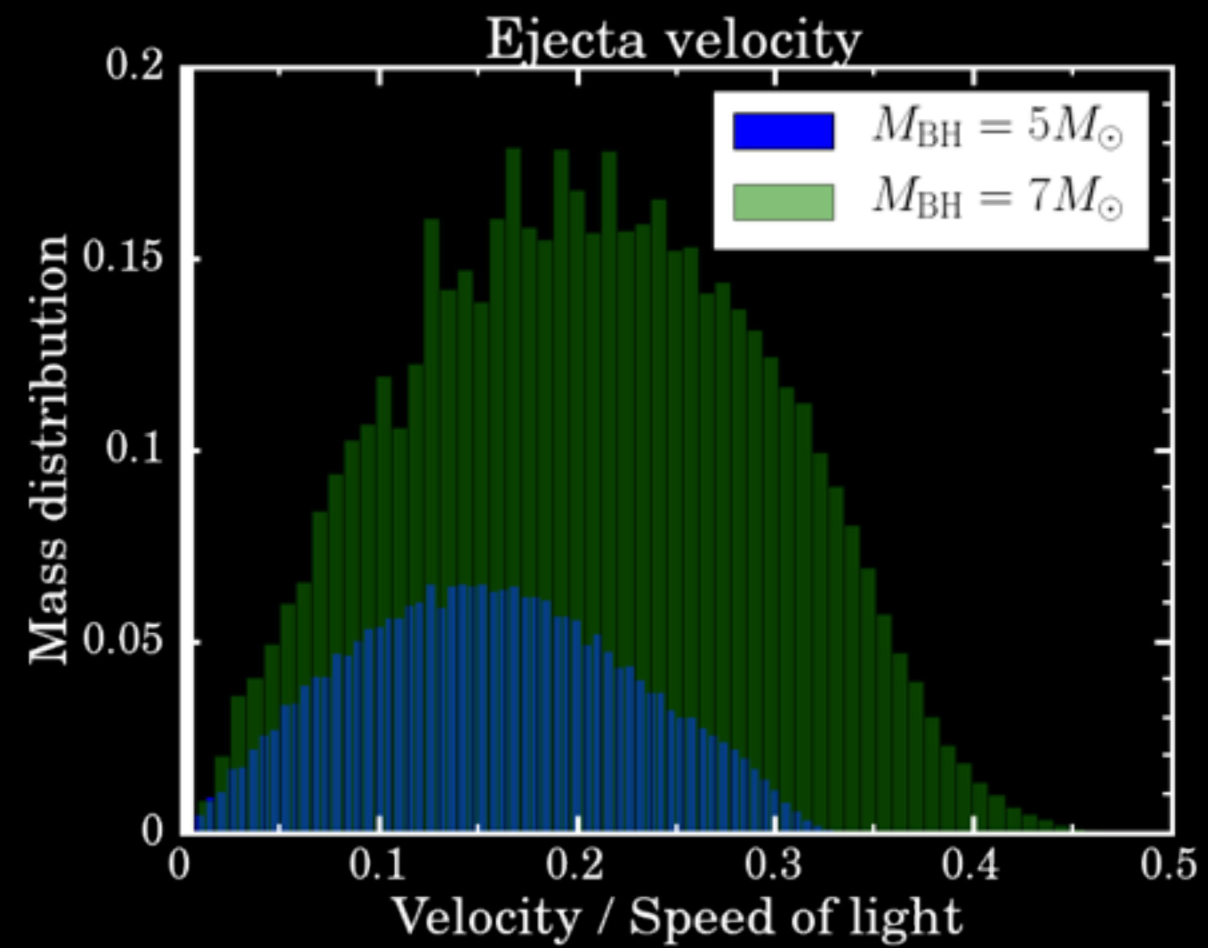
Cold

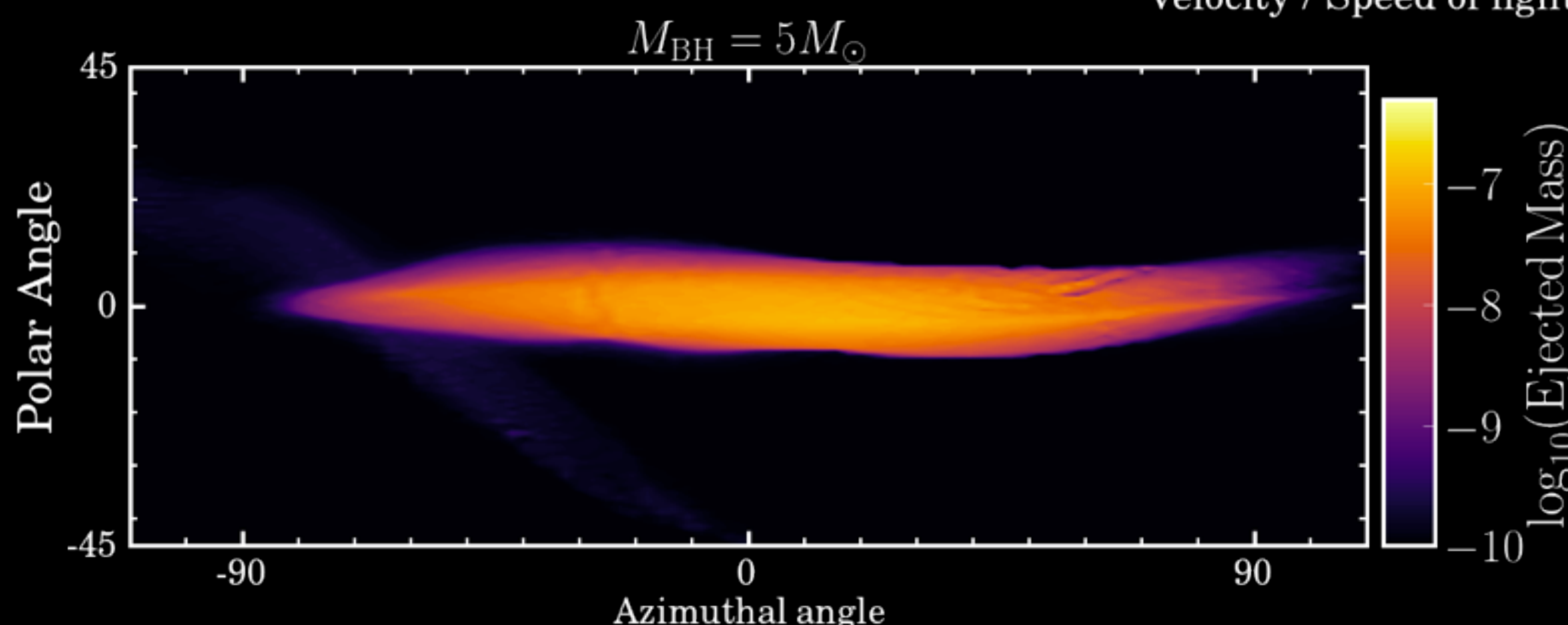
Neutron-rich

v/c ~ 0.2-0.3

M ~ 0.01-0.1 $M_\odot$

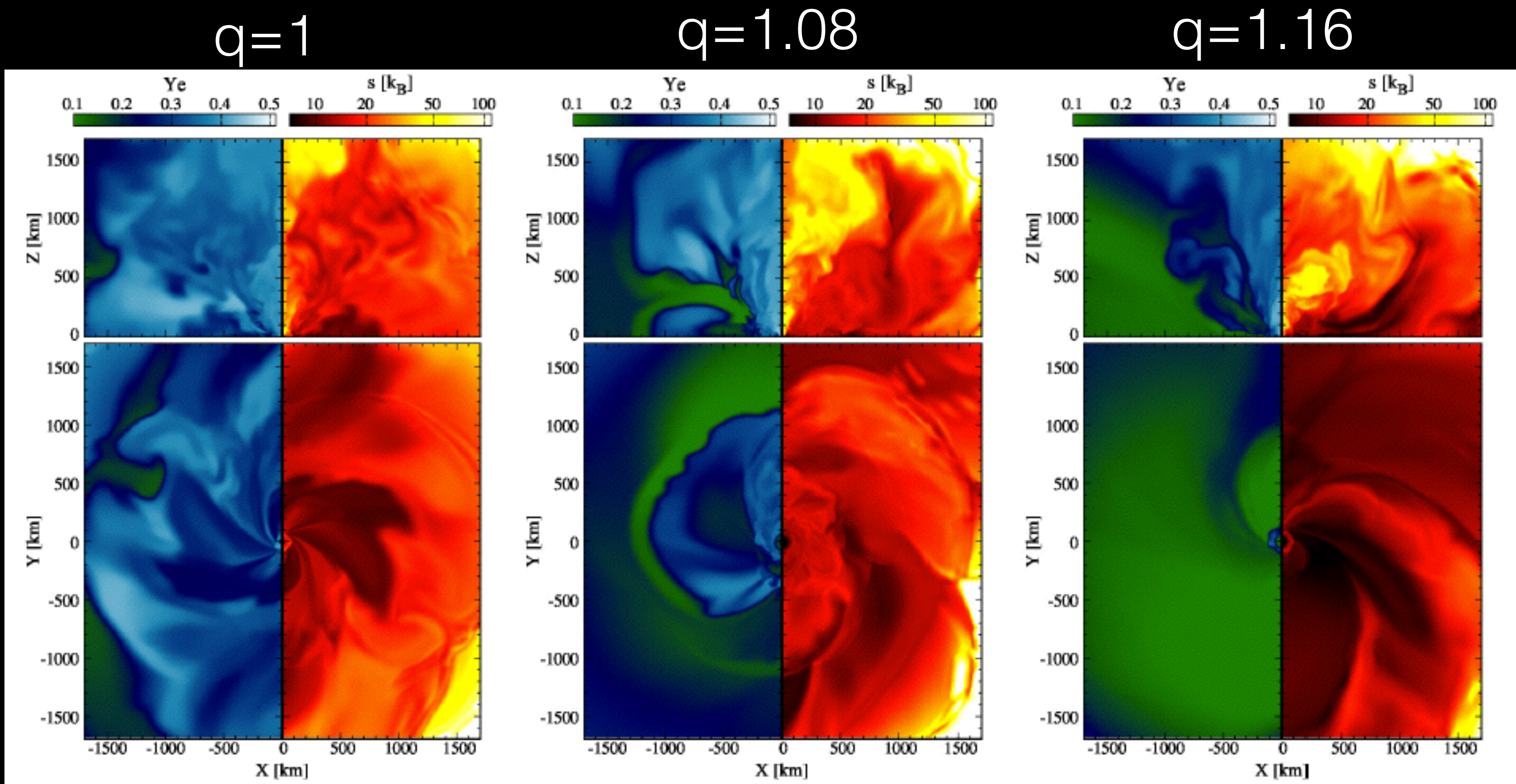
Anisotropic





Images: Foucart et al., 2017

BNS dynamical ejecta



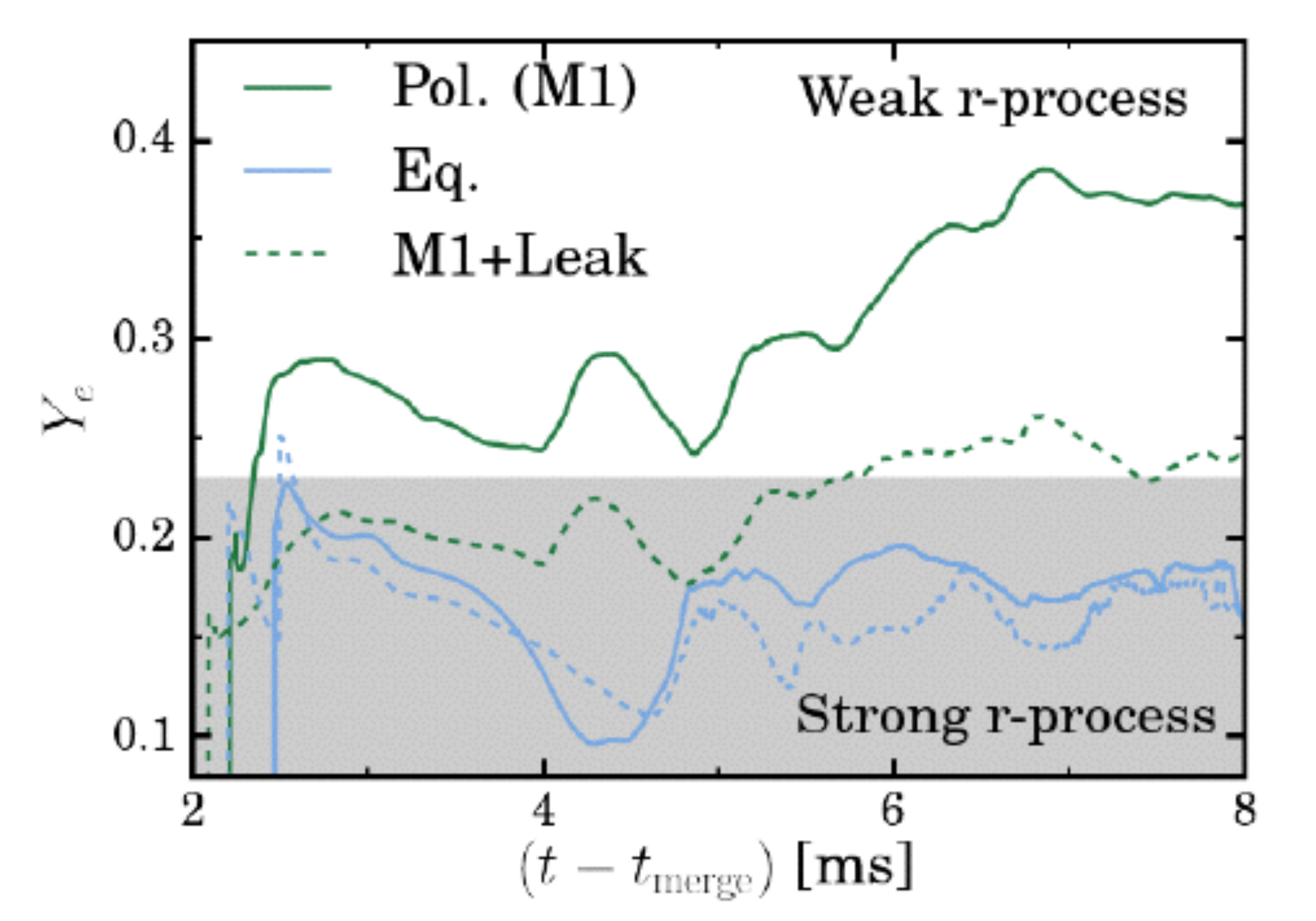
Images: Sekiguchi et al., 2016

Two components (at least): Cold & neutron-rich tidal ejecta, hot & neutron-poor shocked/wind ejecta

BNS dynamical ejecta

Outflow composition:

Impact of neutrino treatment

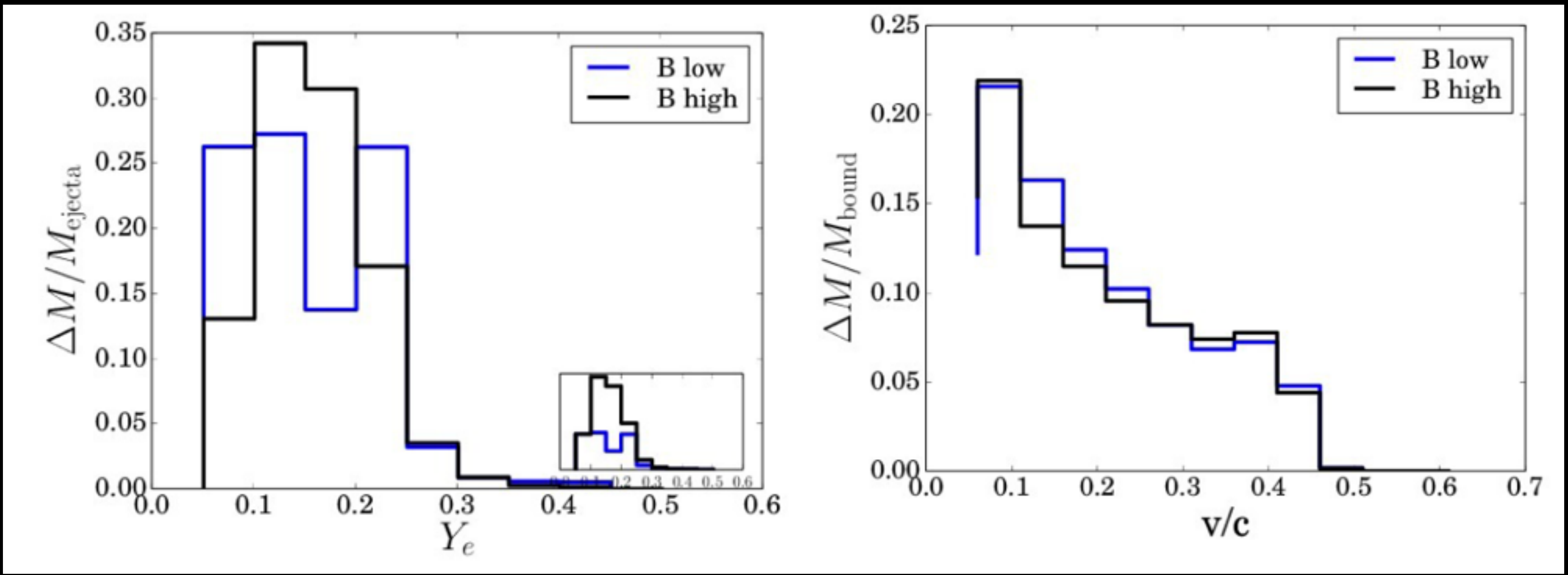


Images: Foucart et al., 2017

For equal mass binary, neutrino transport, no B-fields

BNS dynamical ejecta

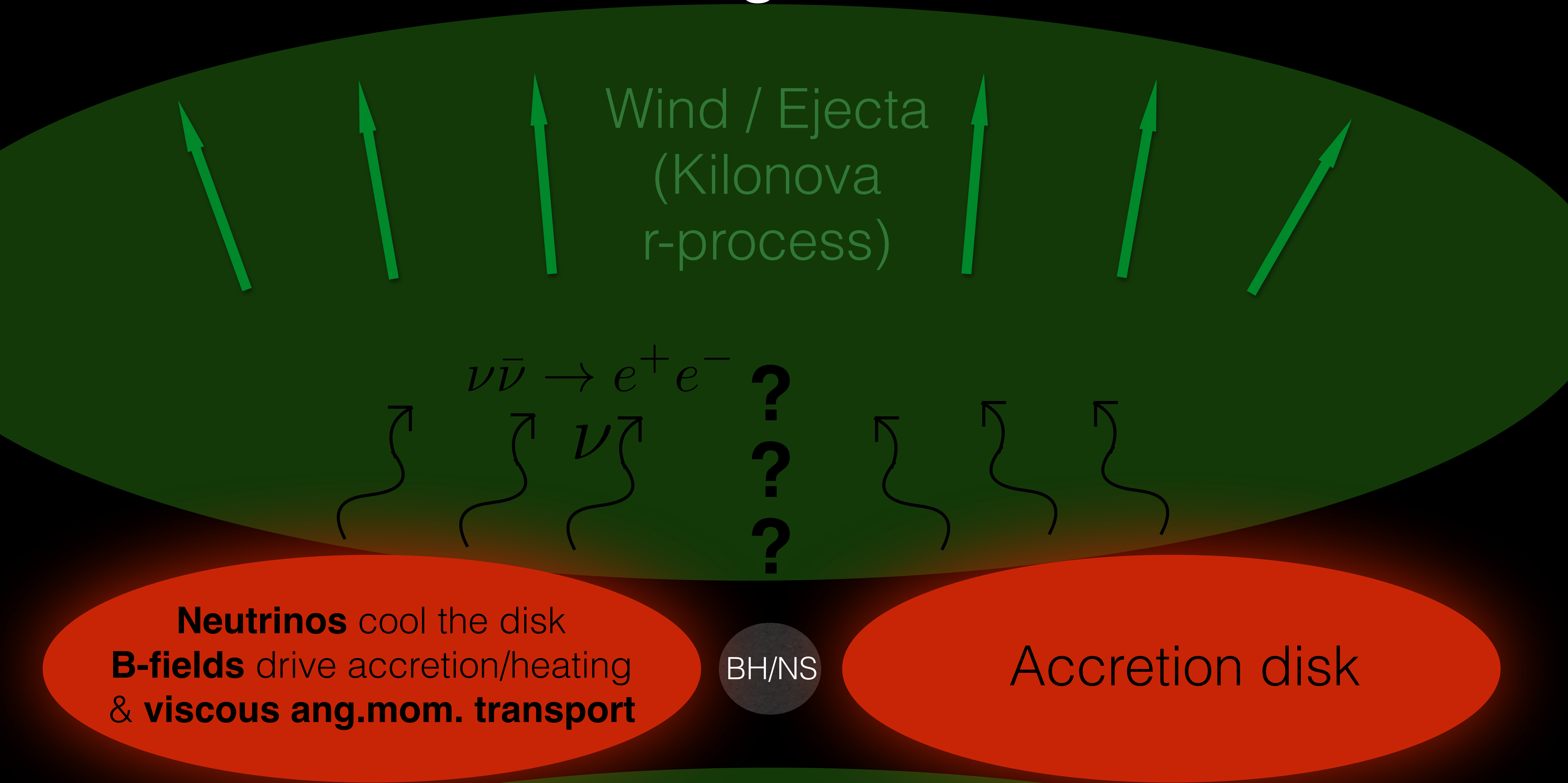
Impact of magnetic fields?



Images: Palenzuela et al., 2015

For equal mass binary, sub-grid model for B-field
Main difference: ~2x more mass ejection in strongly magnetized case

Post-merger remnant



Charged current reactions modify composition:

$$n + e^+ \leftrightarrow p + \bar{\nu}_e \text{ and } p + e^- \leftrightarrow n + \nu_e$$

Disk outflows - Viscous transport

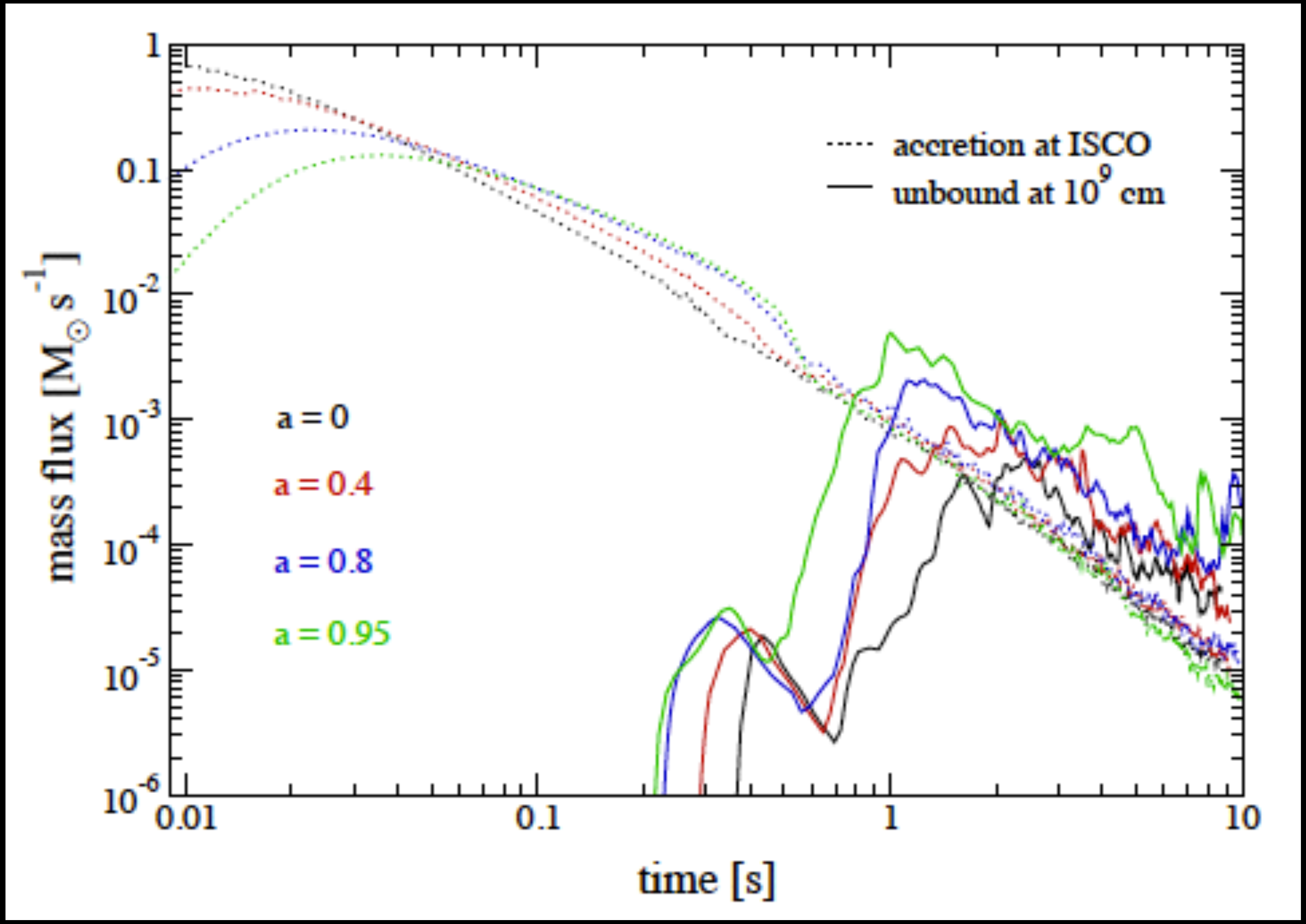


Image: Fernandez et al. 2014

Viscous transport / Recombination lead to
(5-20)% of disk mass being unbound, range of Y_e.
Results vary with disk compactness, BH spin
Require **long simulations** (>1s), and thus approximate physics

Disk outflows - MHD Effects

One 3D GRMHD + neutrino leakage simulation
of an (idealized) post-merger remnant [Siegel & Metzger 2017]
Other results use alpha-viscosity / 2D / no neutrinos

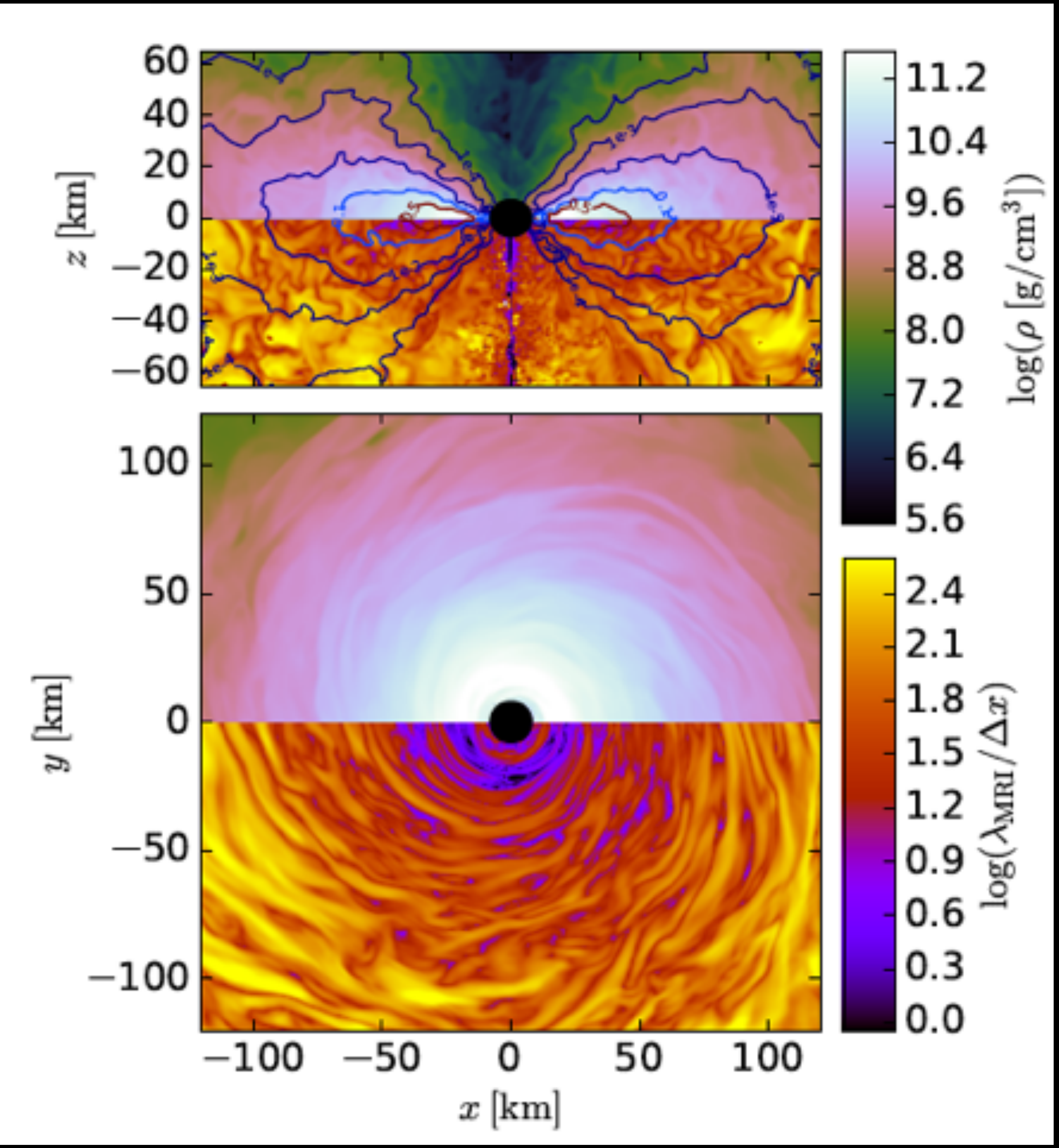


Image: Siegel & Metzger, 2017

<u>Many open questions:</u>

Impact of initial conditions (?)

Impact on mass outflows (~x2 compared to alpha-disk, ~20% of disk mass?)

Impact on nucleosynthesis (need better neutrino scheme)

Disk outflows - Neutrino Effects

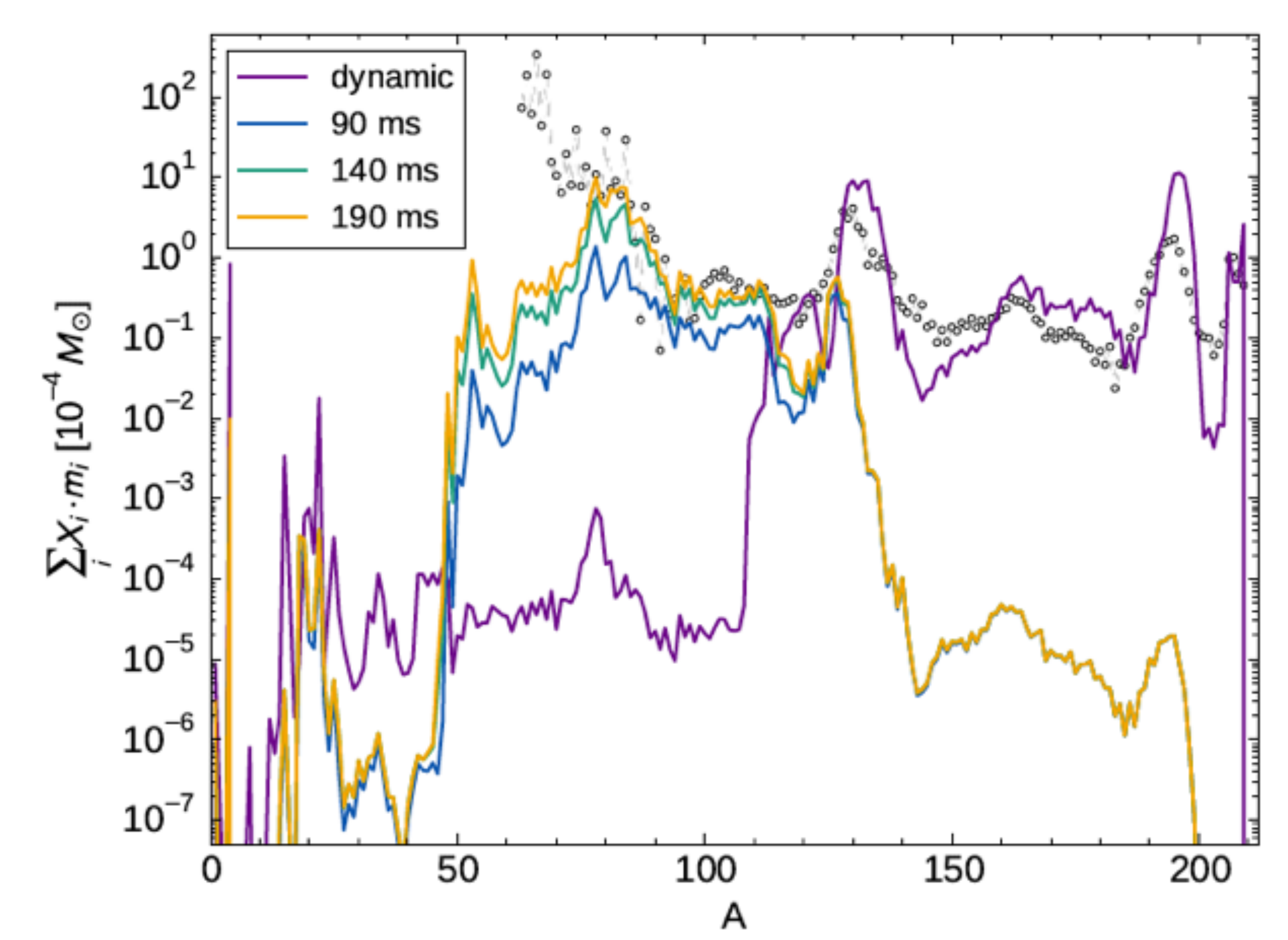


Image: Martin et al. 2015

Weak r-process in neutrino-driven wind

Generally less massive than MHD wind - **what happens when we have both neutrinos and MHD**?

Outflow models

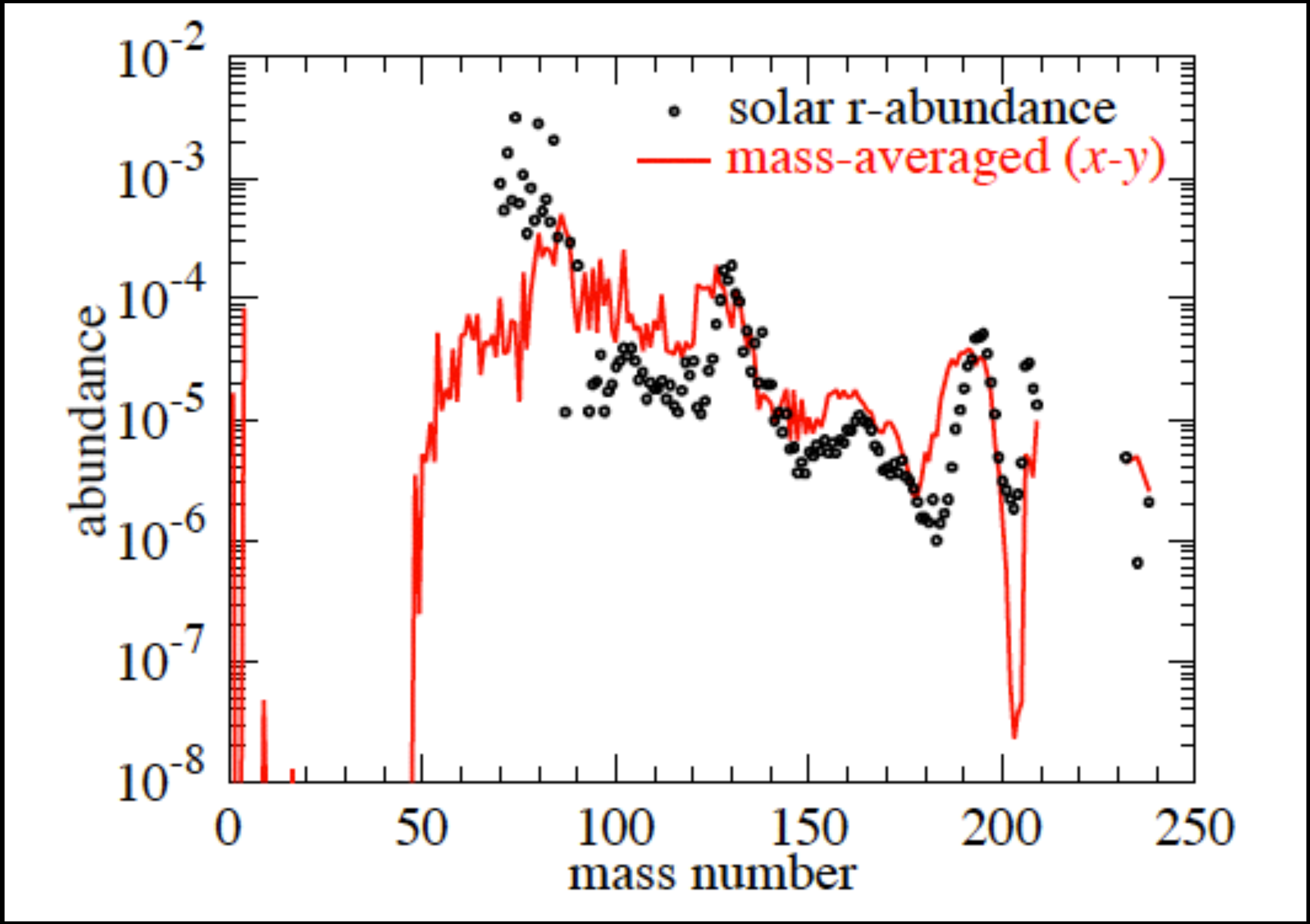
- Dynamical ejecta: Fitting formulae
  - BHNS : ejecta and disk mass estimates, ~10% error (Kawaguchi et al. 2016, Foucart 2012)
  - BNS : O(1) uncertainties (Dietrich & Ujevic 2017), Y_e modeling insufficient
- Disk outflows: Qualitative impact of important parameters
  - Need to connect to binary properties
  - Most simulations use idealized initial conditions
  - Many uncertainties due to missing physics (neutrinos, MHD)

Nucleosynthesis predictions

Overview of modeling effort

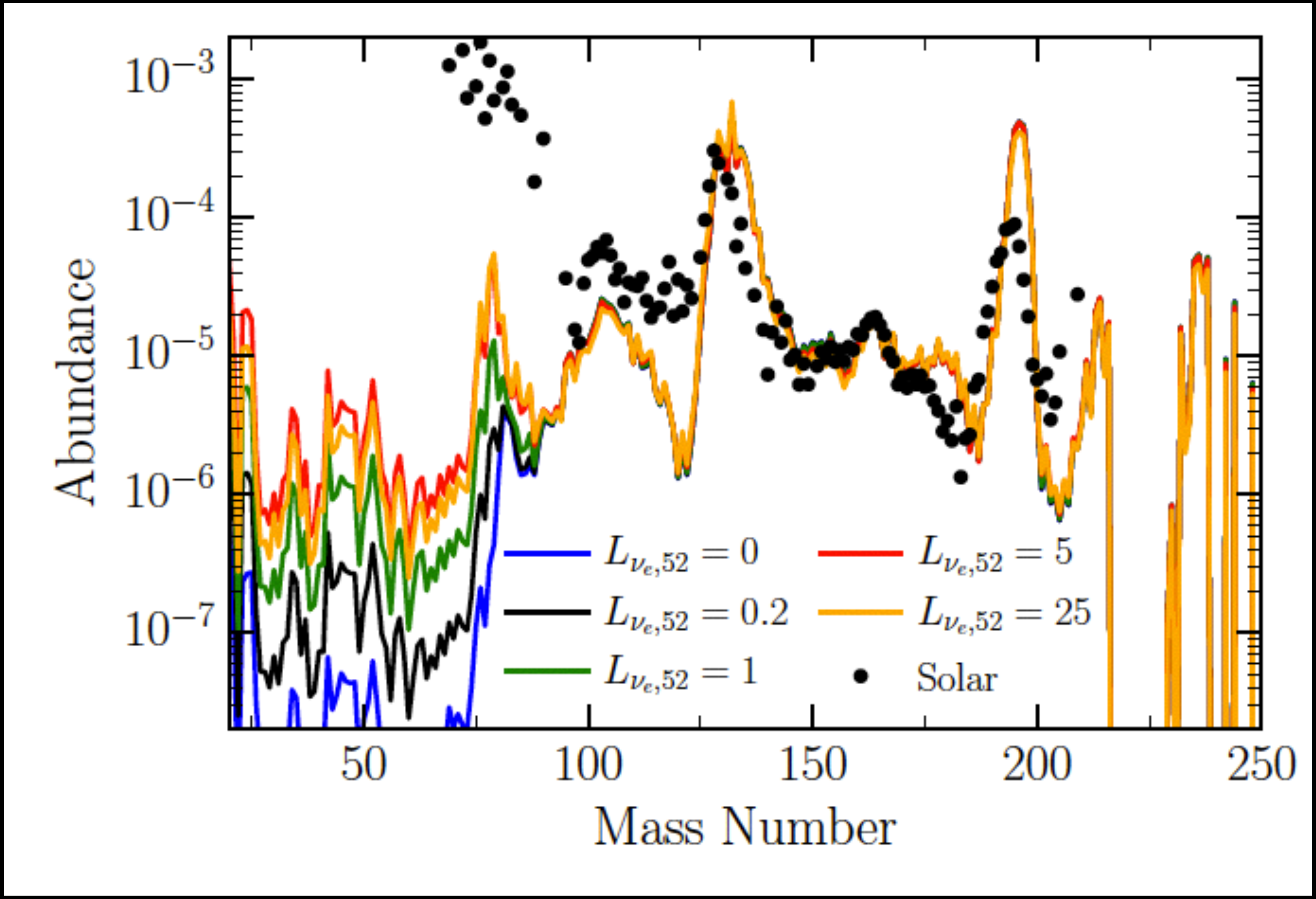
- From ejecta models to r-process yields
  - Parametrization of r-process outcome: strong vs weak r-process, lanthanide yields (Lippuner & Roberts 2016)
  - Yields otherwise calculated for a few specific simulations, most often with only dynamical or disk ejecta

Selected results: Wanajo et al. 2014



Dynamical ejecta from a single BNS merger *could* provide r-process yields with solar abundances (requires neutrino transport)

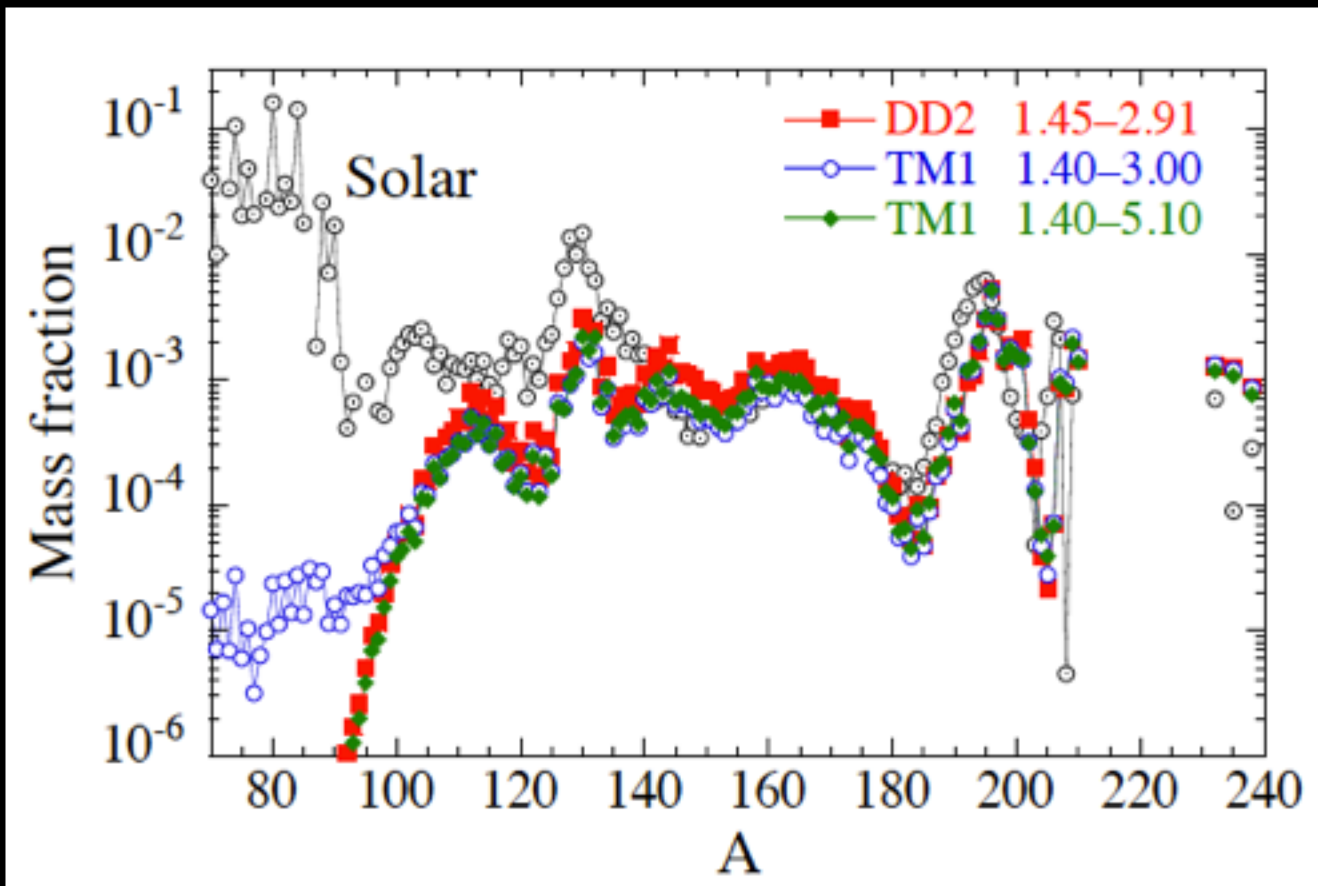
Selected results: Roberts et al. 2016



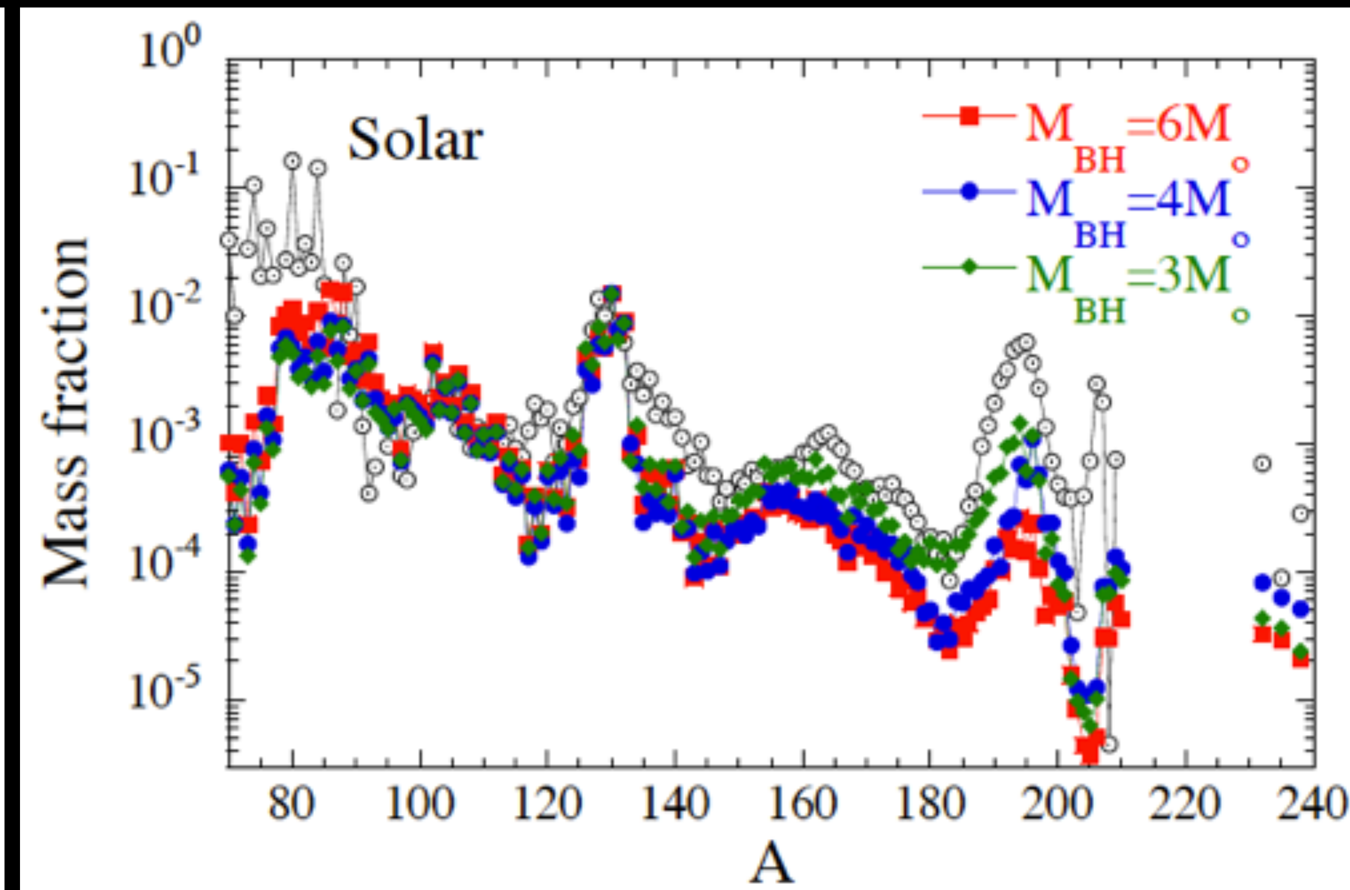
Dynamical ejecta from NSBH simulations:
Strong r-process, very mild neutrino effects

Selected results: Just et al. 2015

Dynamical ejecta

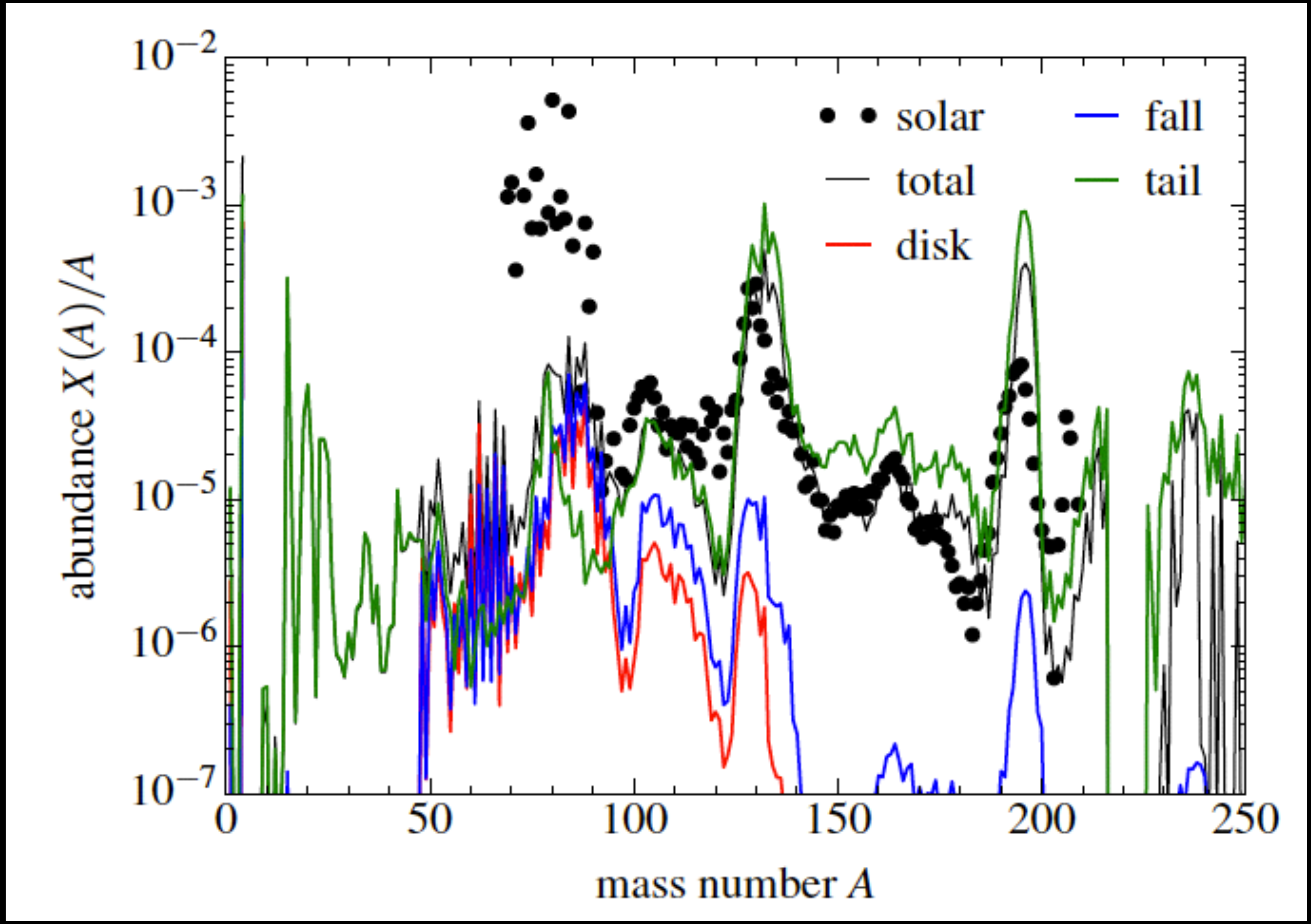


Neutrino-driven wind



(Pseudo)-Newtonian simulations of NS mergers with neutrino transport
Strong r-process in dynamical ejecta, broader distribution
of elements in disk outflows

Selected results: Fernandez et al. 2017



Relativistic NSBH merger simulation + pseudo-Newt. disk evolution
Similar trend, but dynamical ejecta dominates disk outflows

Conclusions

- Neutron star mergers robustly produce heavy r-process elements
- Production of lighter elements is more uncertain
  - Depends on binary type and parameters
  - Impacted by neutrino physics
- Simulations are *beginning* to provide models for the ejecta
  - Reliability of models still limited by incomplete physics
  - Very few results combine all ejecta components
- Not in this talk: nuclear physics uncertainties