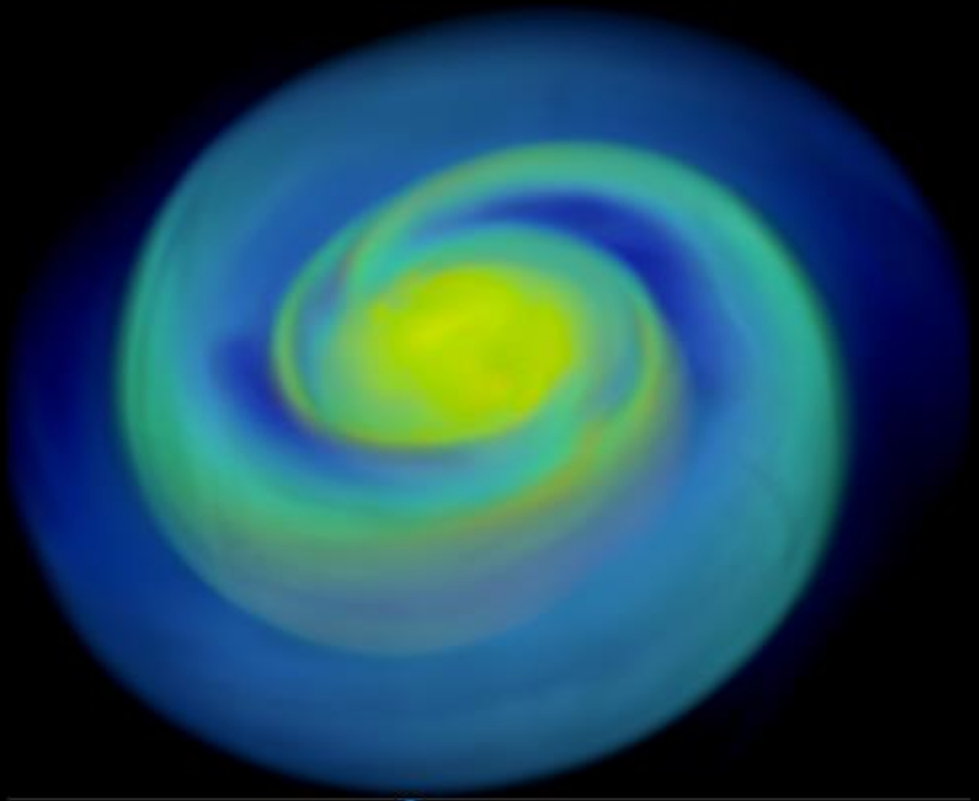
Simulations of Compact Binary Mergers From Gravity to Particles and Nuclear Physics Part II



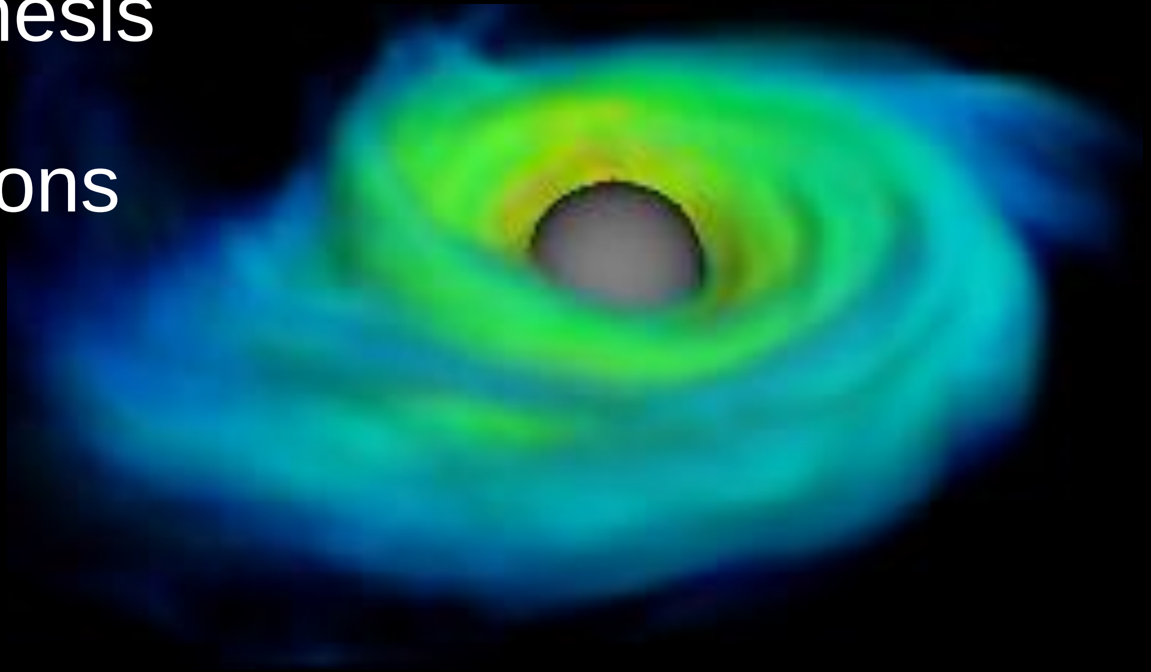
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Francois Foucart (University of New Hampshire)

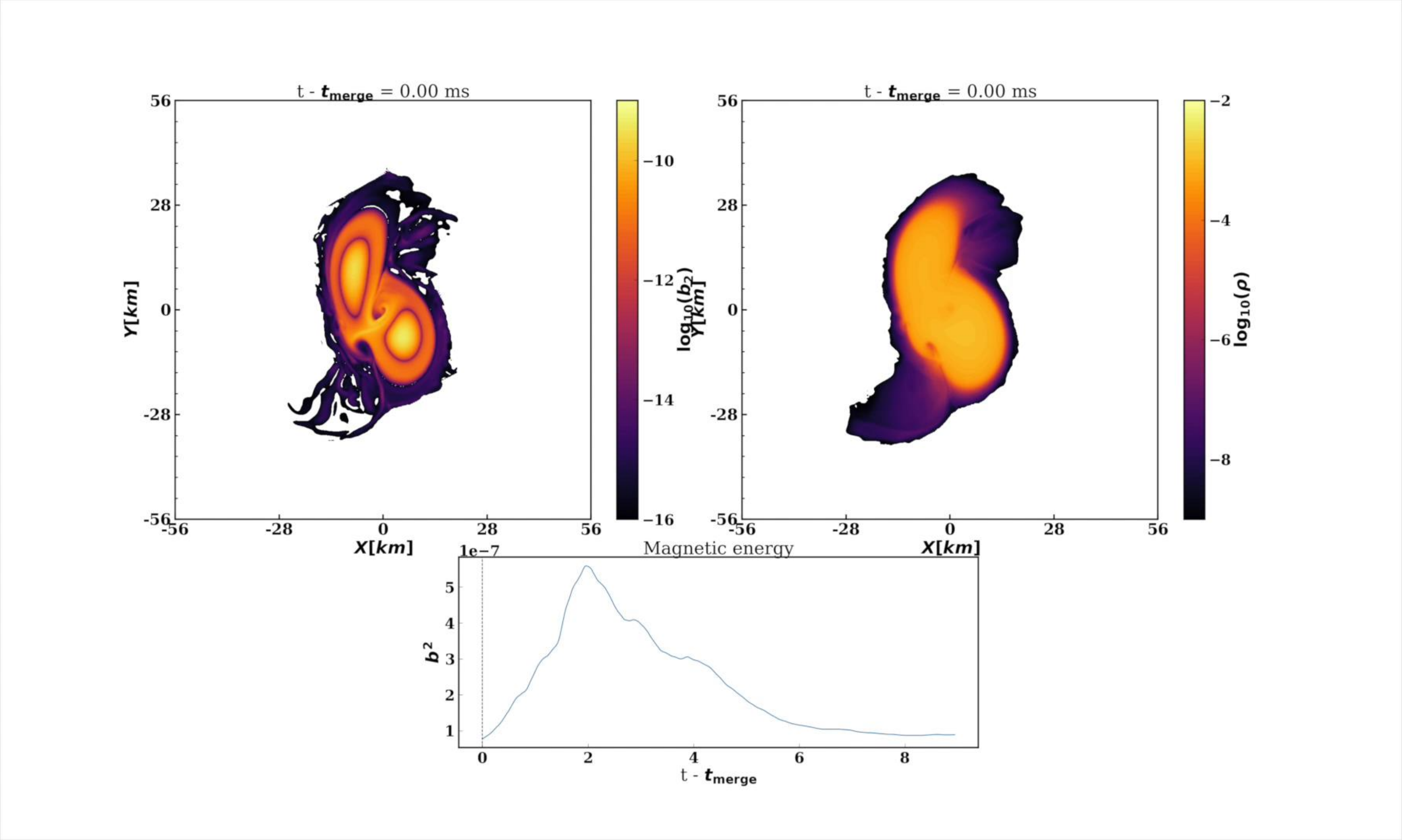
UIUC – May 21st 2022

Overview

- Kilonovae and r-process nucleosynthesis
- NS merger and post-merger simulations
  - Matter outflows
  - Neutrino physics in mergers
  - General relativistic neutrino transport



Neutron Star-Neutron Star Mergers



Movie: Sasha Chernoglazov

Neutron Star Binaries: Electromagnetic Signals

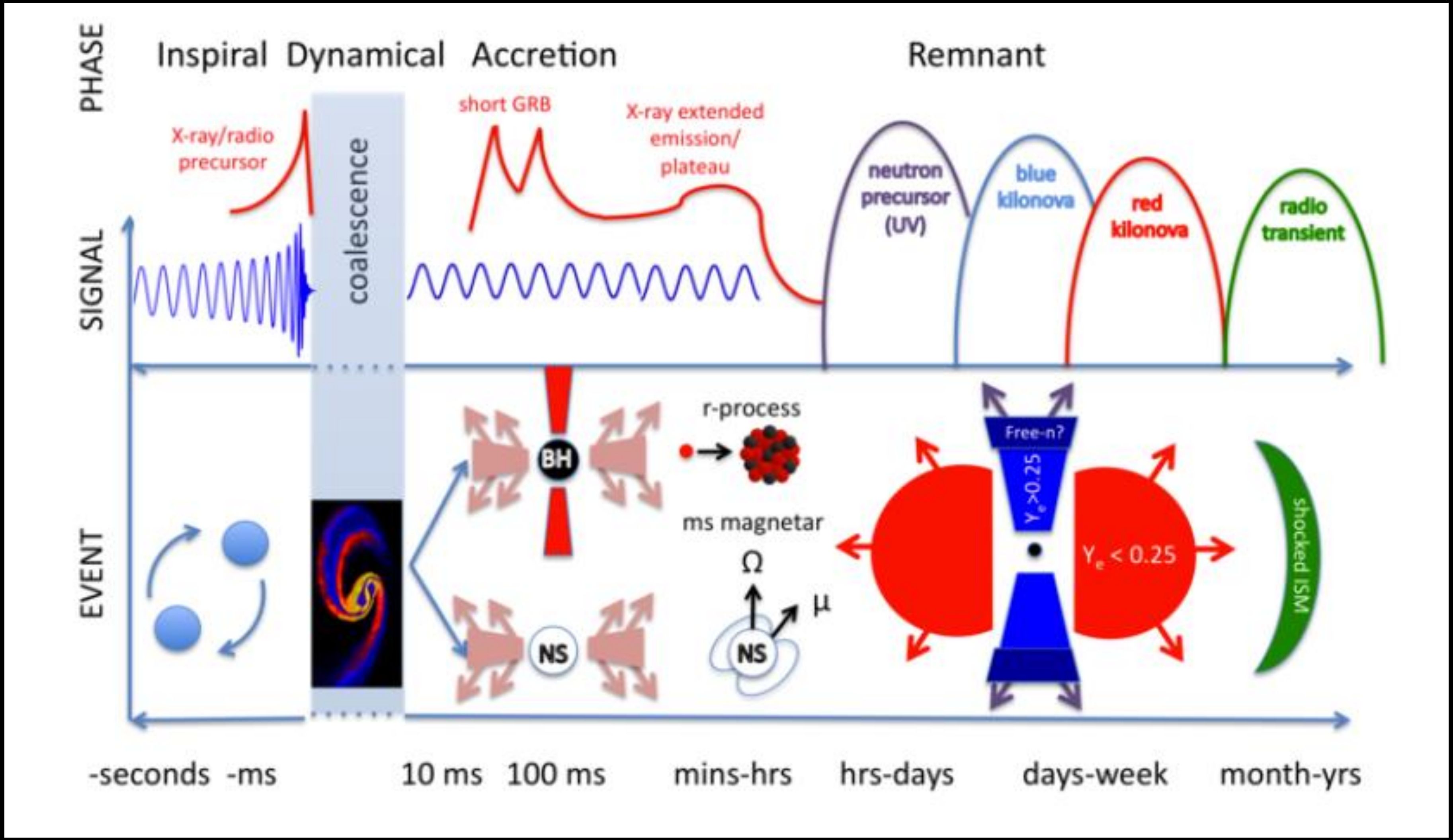
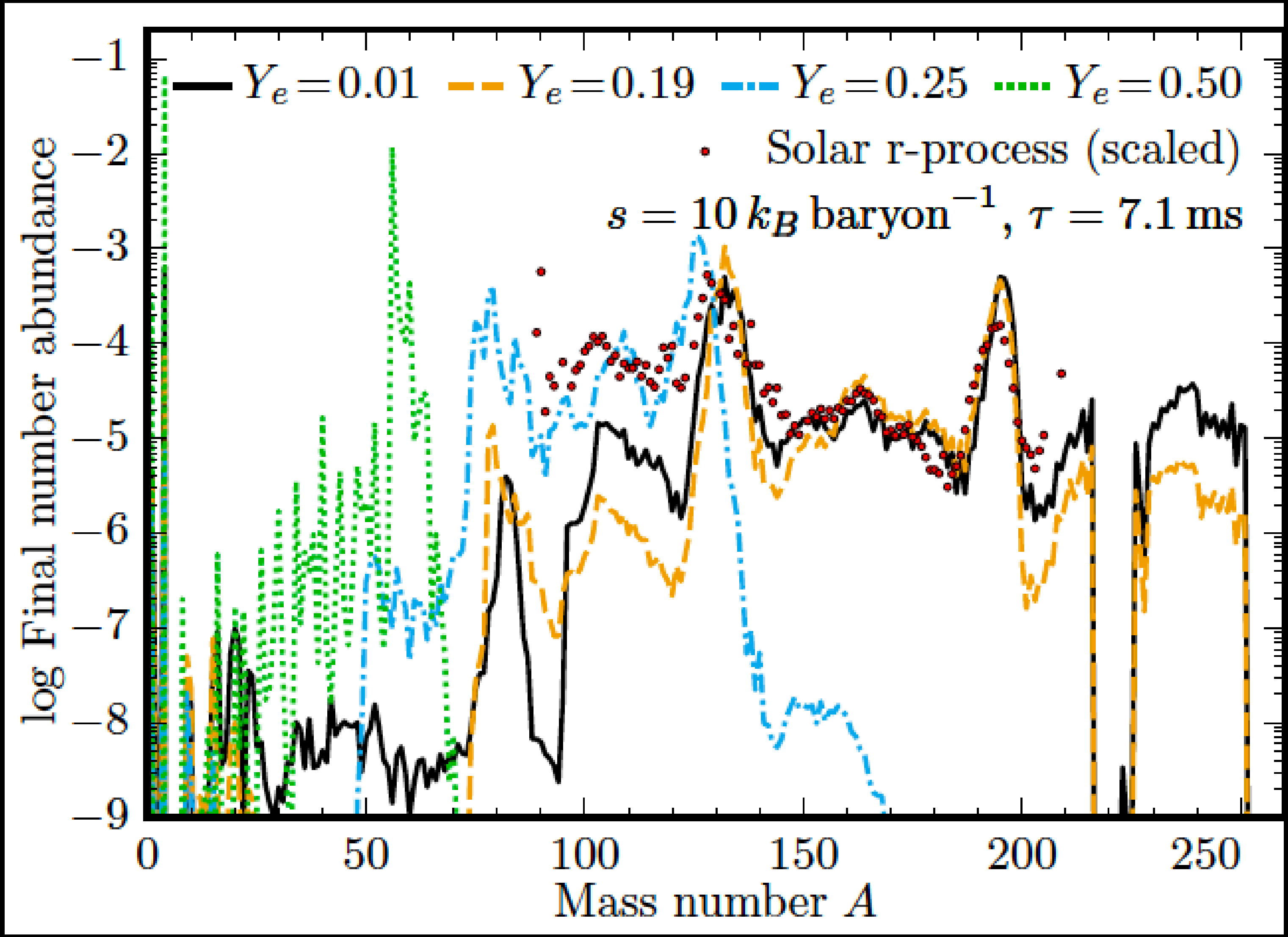


Image: Fernandez & Metzger 2016

R-Process nucleosynthesis



Y_e= Electron Fraction
= (#protons)/(#nucleons)

Image: Lippuner & Roberts 2015

Kilonovae lightcurves

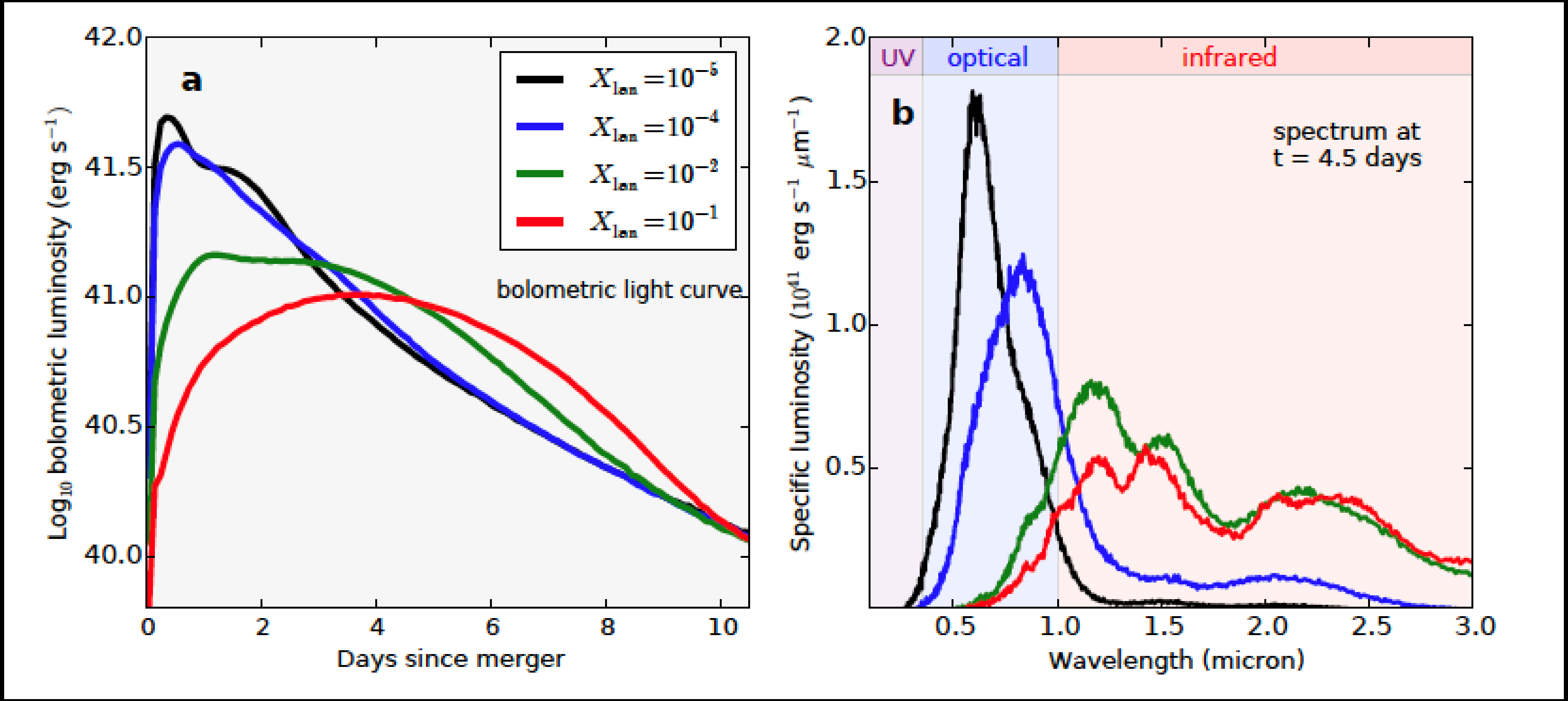


Image: Kasen *et al* 2017

Matter outflows in NSNS/BHNS Mergers

Matter Outflows

Decent *qualitative* understanding of outflow processes

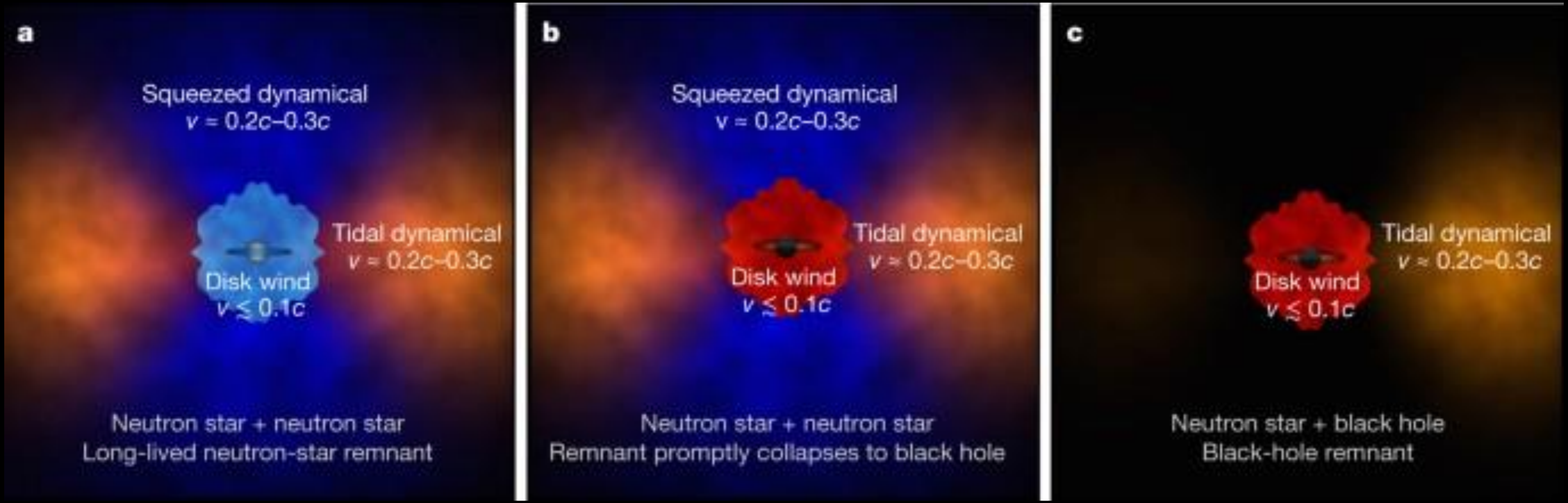
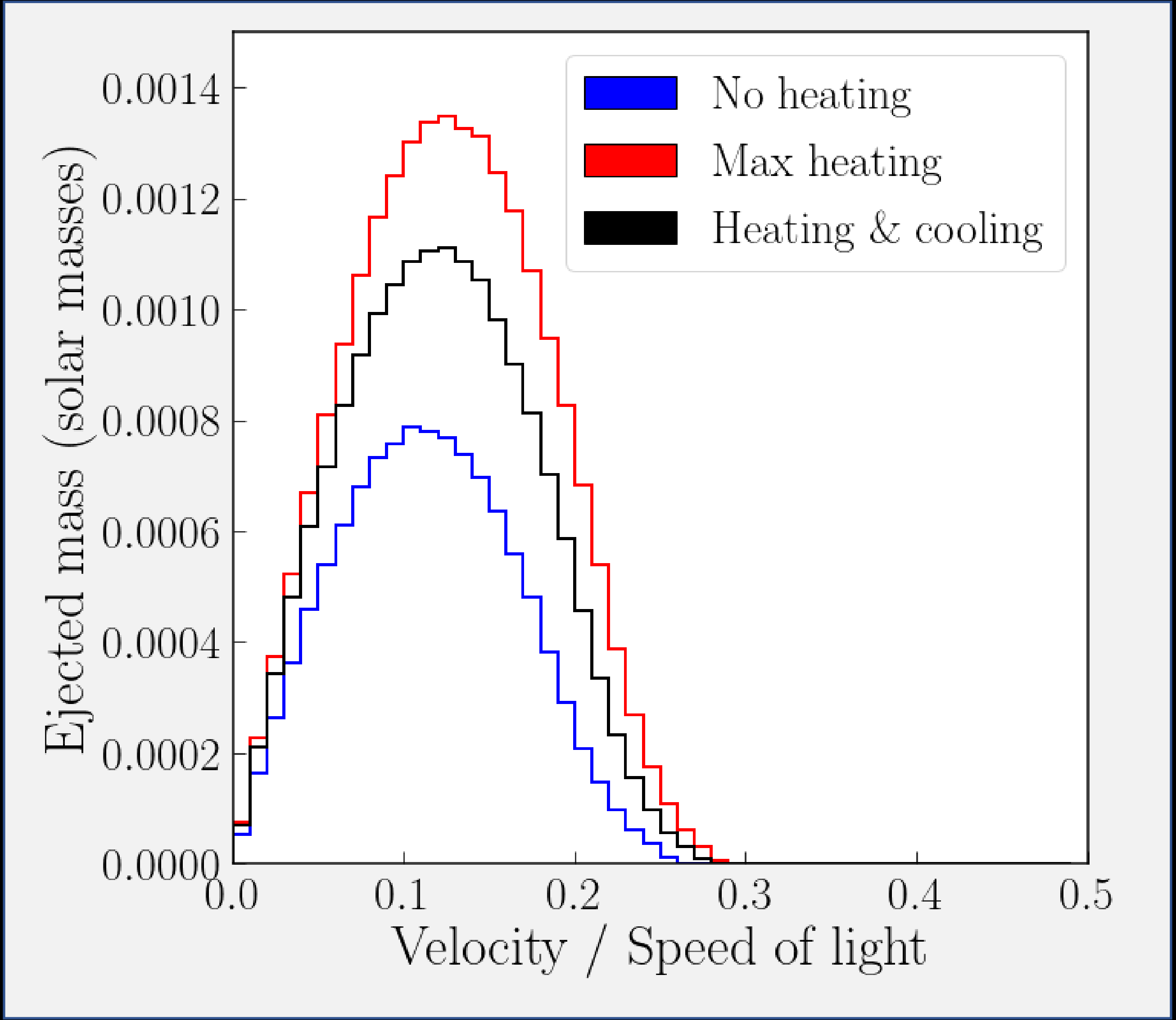


Image: Kasen *et al* 2017

Matter Outflows – Dynamical Ejecta

Difficulties:

- **What happens after simulations end?**
- Energy gain/loss from r-process / neutrinos
  - Example: mass ejected in an asymmetric NSNS merger (see Fig), Foucart+ in prep.



Matter Outflows – Post-Merger Ejecta

Difficulties:

- No reliable predictions for disk properties determining mass ejection (B-field, compactness)
- Approximate neutrino transport
- Very few long, 3D post-merger simulations

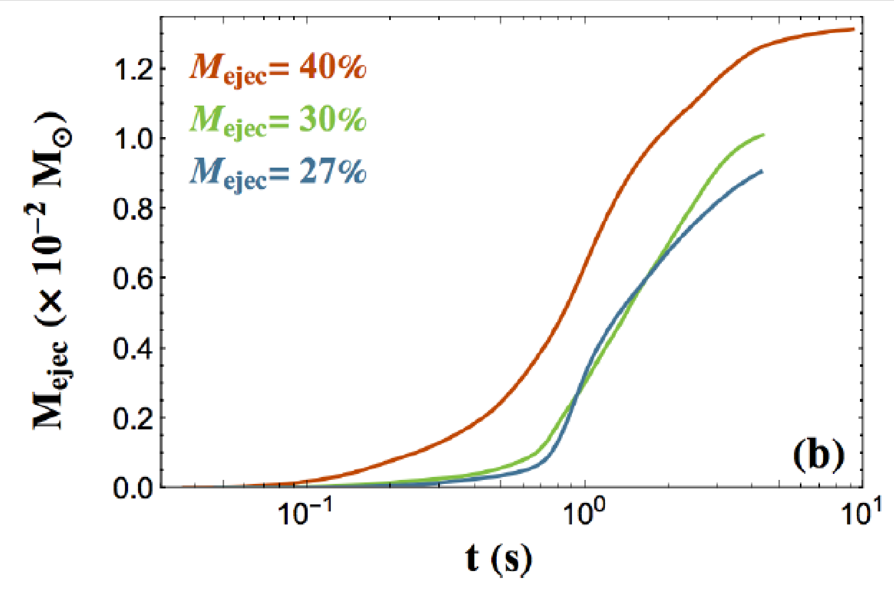


Image: Christie+ 2019

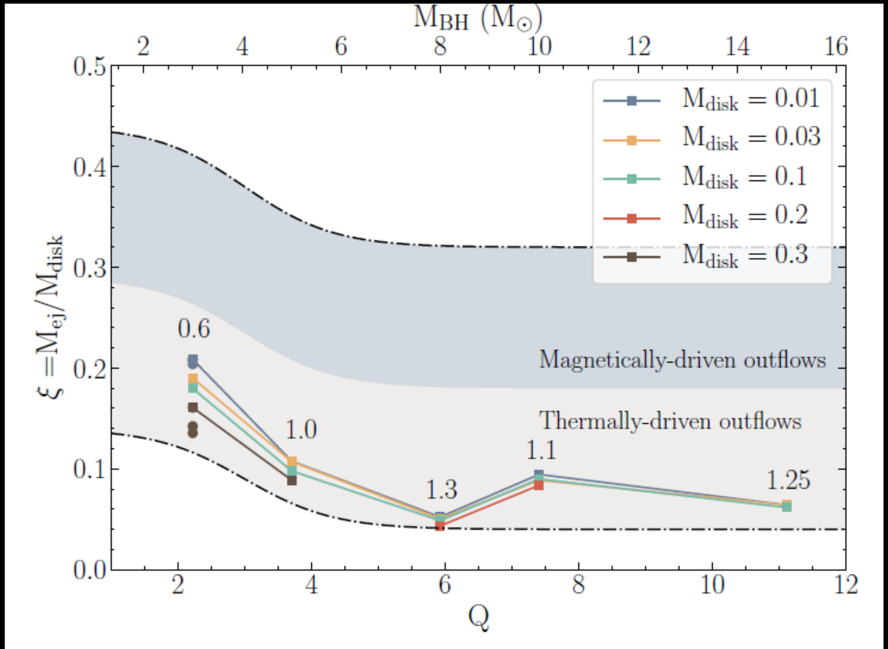


Image: Raaijmakers+2022

Matter Outflows: Modeling

Difficulties:

- Large disagreement between models fitted to numerical simulations, depending on the chosen functional form of the model (Henkel+ in prep), and the microphysics of calibration simulations (Nedora+2020)!

Predicted disk mass for system with GW170817’s chirp mass

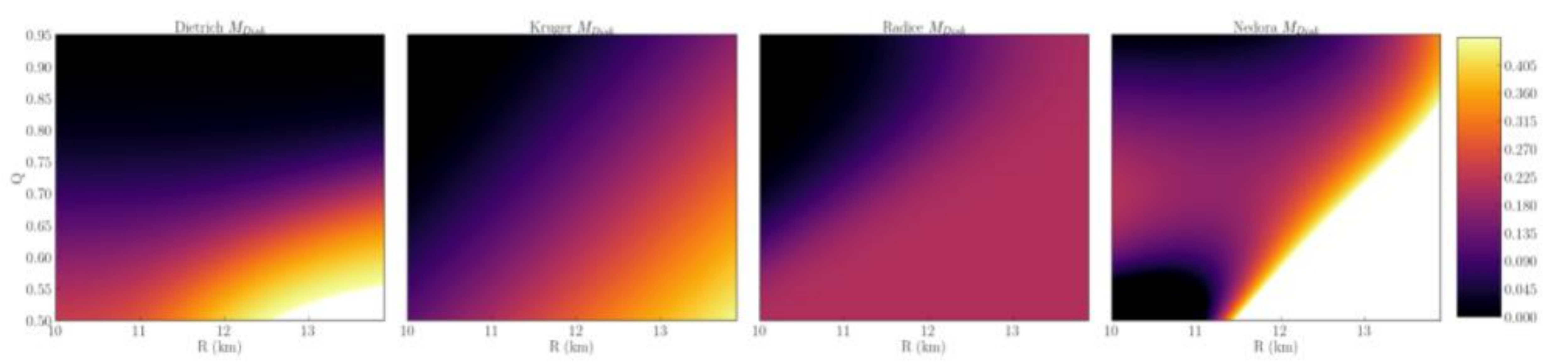
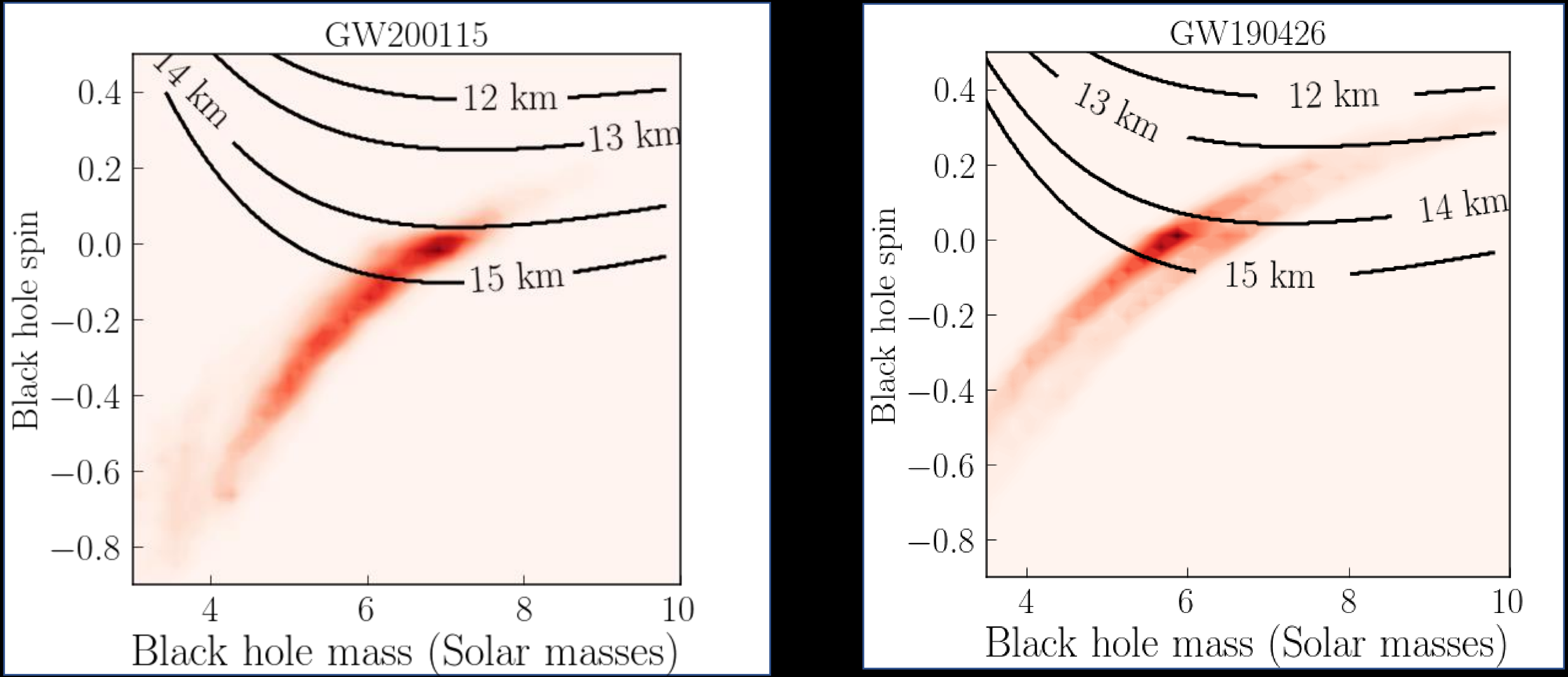


Image: Amelia Henkel, UNH

BHNS: Better understood… but less useful?

Minimum radius required for tidal disruption



Combining public data from the LVC with results from Foucart+2018

Conclusions #1

- Decent ***qualitative*** understanding of outflows and relevant physics
- NSNS systems difficult to model ***quantitatively*** with acceptable accuracy
  - We can only rely on our results in `physically obvious' corners of the parameter space
  - **Much remains to be done to reliably predict mass & composition of outflows for both merger and post-merger ejecta!**
- Tidal ejecta and disk formation reasonably well modeled for BHNS systems
  - … but most BHNS merger may not eject any matter ☹
  - And post-merger outflows are still difficult to model

Neutrino transport in NSNS/BHNS Mergers

Role of neutrinos in mergers

- *Cool* post-merger remnants
- *Heat outflows* in post-merger remnants
- Drive *changes of composition* in matter
- Deposit energy in polar regions

Crucial to understand kilonovae, r-process nucleosynthesis, and maybe GRBs

Neutrino Transport Problem

Difficulties:

- Solve (6+1)D Boltzmann equation for distribution function $f_{(\nu)}(t, x^i, p^\mu)$ for each neutrino species
- Coupling between different momenta (scattering), different species (pair annihilation, oscillations)
- Stiff coupling to fluid properties (temperature, composition)

Current strategies

Approximate methods: Cooling function, Leakage, Moments

(Towards) full transport: Monte-Carlo, Spectral, Finite Difference

Methods mostly borrowed from SNe & Accretion disk communities

Moment Schemes: Formalism

Main Idea:

- Evolve moments of $f_{(v)}$, e.g. energy density, momentum density.
- Boltzmann's equations => *Conservative* system of equations for the moments
  - Very similar to conservative equations for MHD system!

Challenges:

- Choice of closure for higher-order moments not evolved
- For grey schemes , choice of energy spectrum
- Implicit timestepping needed for stiff fluid-neutrino coupling (Foucart+), or hybrid moment-leakage schemes (Sekiguchi+, Radice+)

Moment Schemes: Results

- *Main Result*: Much broader composition for hot outflows
  - Absorption of neutrinos in outflows from NSNS collision and/or MHD-driven wind allows for high-Y_e ejecta, <u>*optical kilonovae, and low-mass r-process elements*</u>

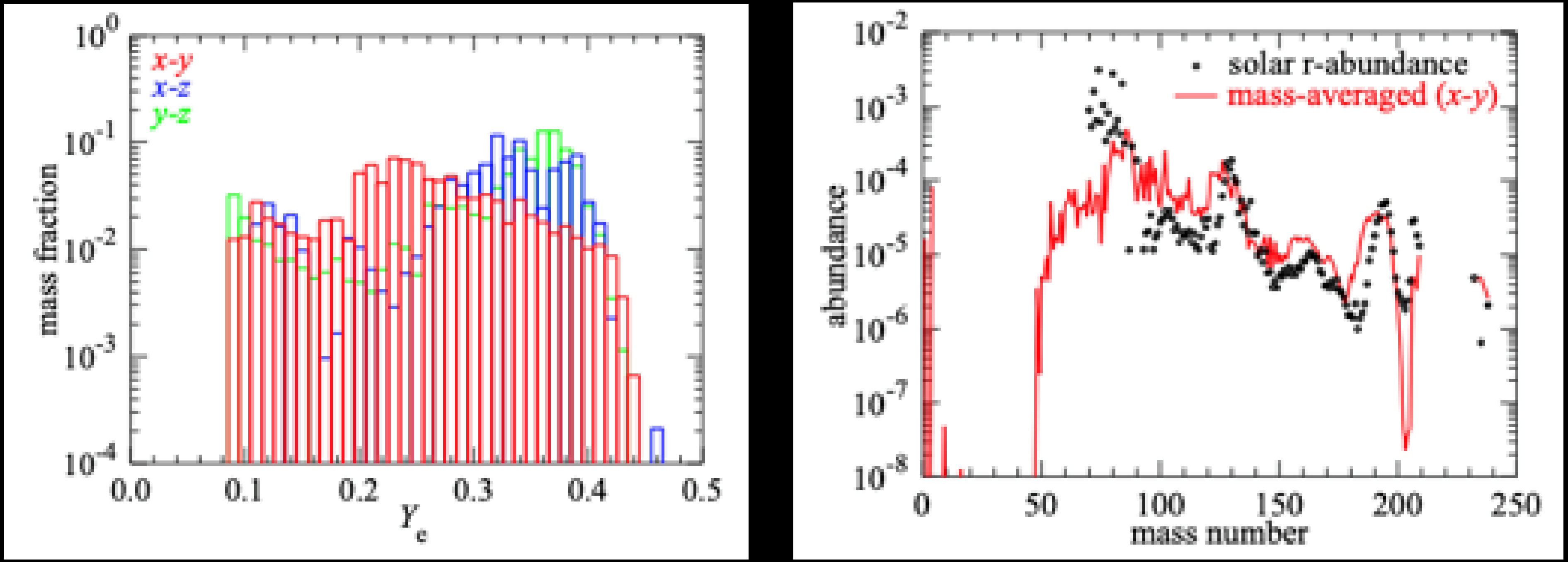


Image: Wanajo *et al* (2014)

Moment Schemes: Limitations

Standard pressure closure unable to handle crossing neutrinos

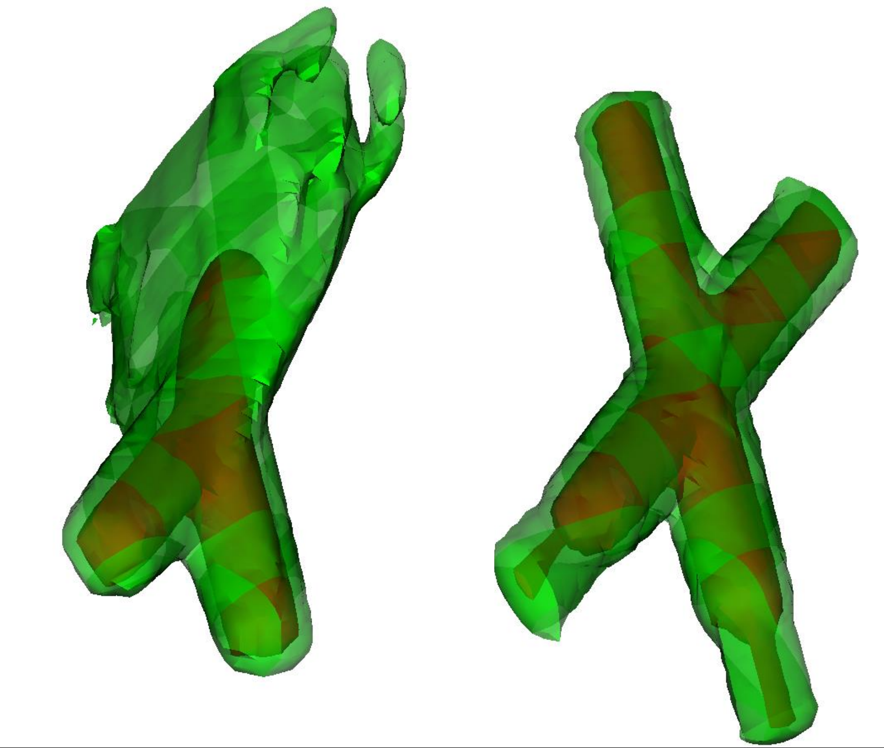


Image: Foucart *et al* (2018)

Energy closure leads to inaccurate outflow composition

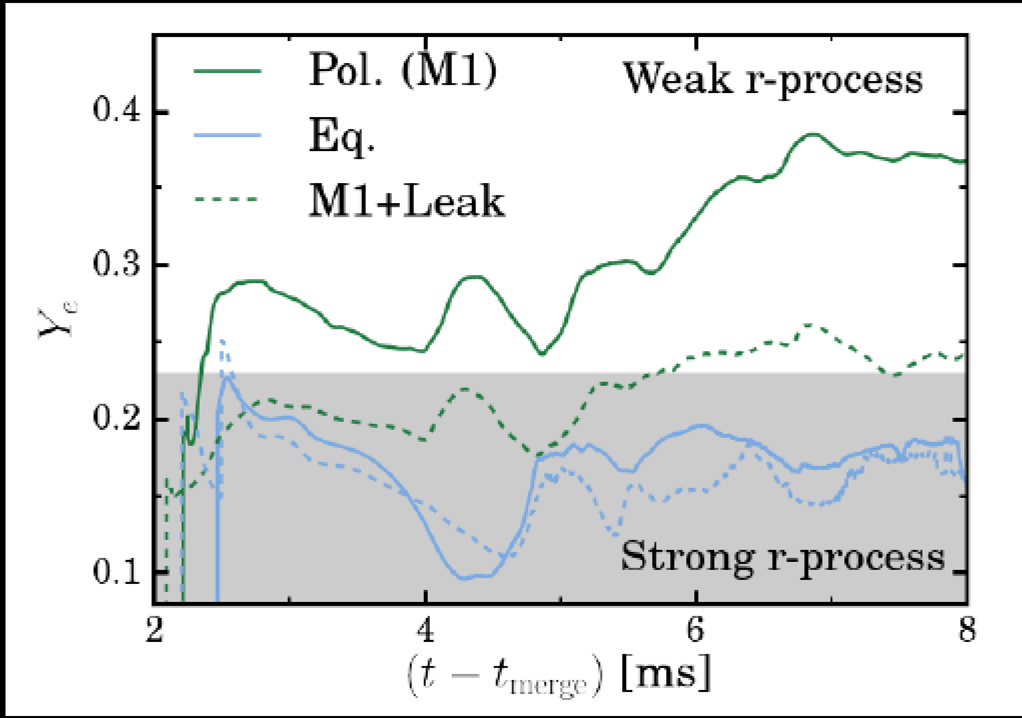


Image: Foucart *et al* (2017)

Monte-Carlo Transport: Formalism

- Sample distribution $f_{(\nu)}$ using superparticles / packets.
- Packets are emitted / transported / scattered / absorbed as individual neutrinos
- Very efficient method *at low-resolution in high-dimensional spaces*

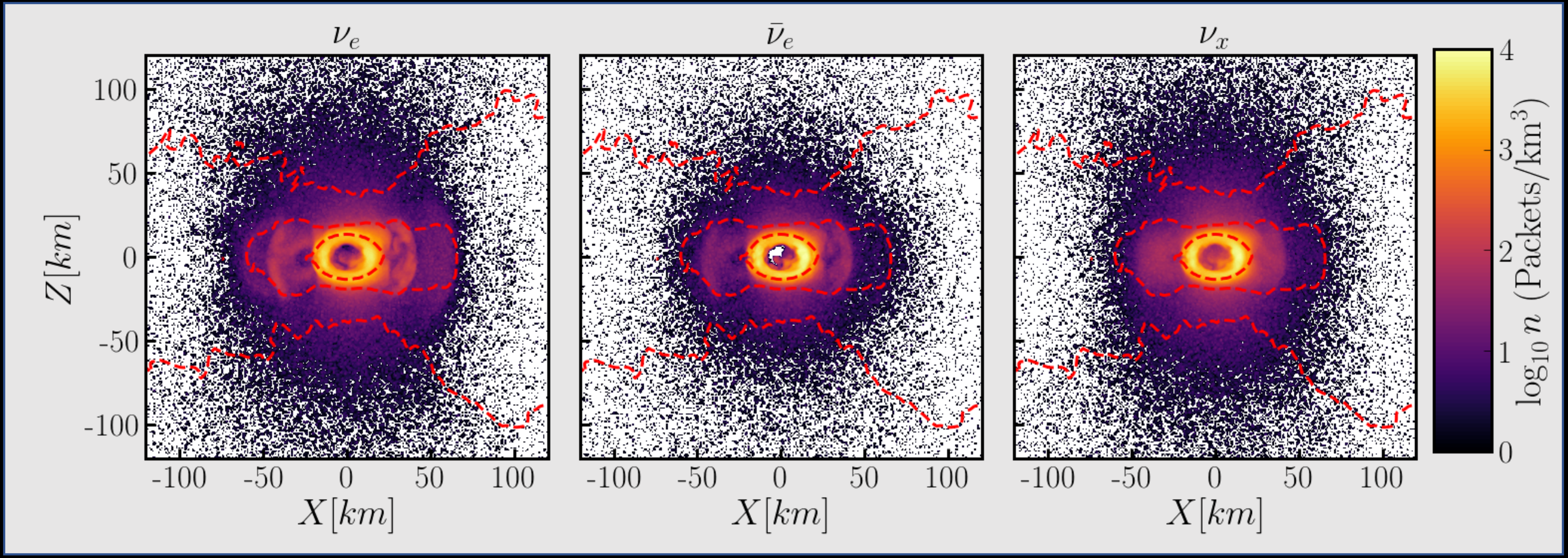


Image: Foucart *et al* (2020)

Monte-Carlo: Implementation Issues

High absorption / scattering opacities expensive to handle without corrections.

SpEC choices:

- High scattering opacity as diffusion instead of many individual scatterings
- High absorption opacity using implicit Monte-Carlo

Stiff coupling to fluid in high opacity regions: also fixed by use of implicit MC

Parallelization difficult due to inhomogeneous distribution of packets

For details see our code papers:
Foucart 2018 (MNRAS 475:4186) and Foucart+ 2021 (ApJ 920:82)

Monte-Carlo Transport: Results

Difference between M1 and MC methods : 10% relative errors (10^8 packets)

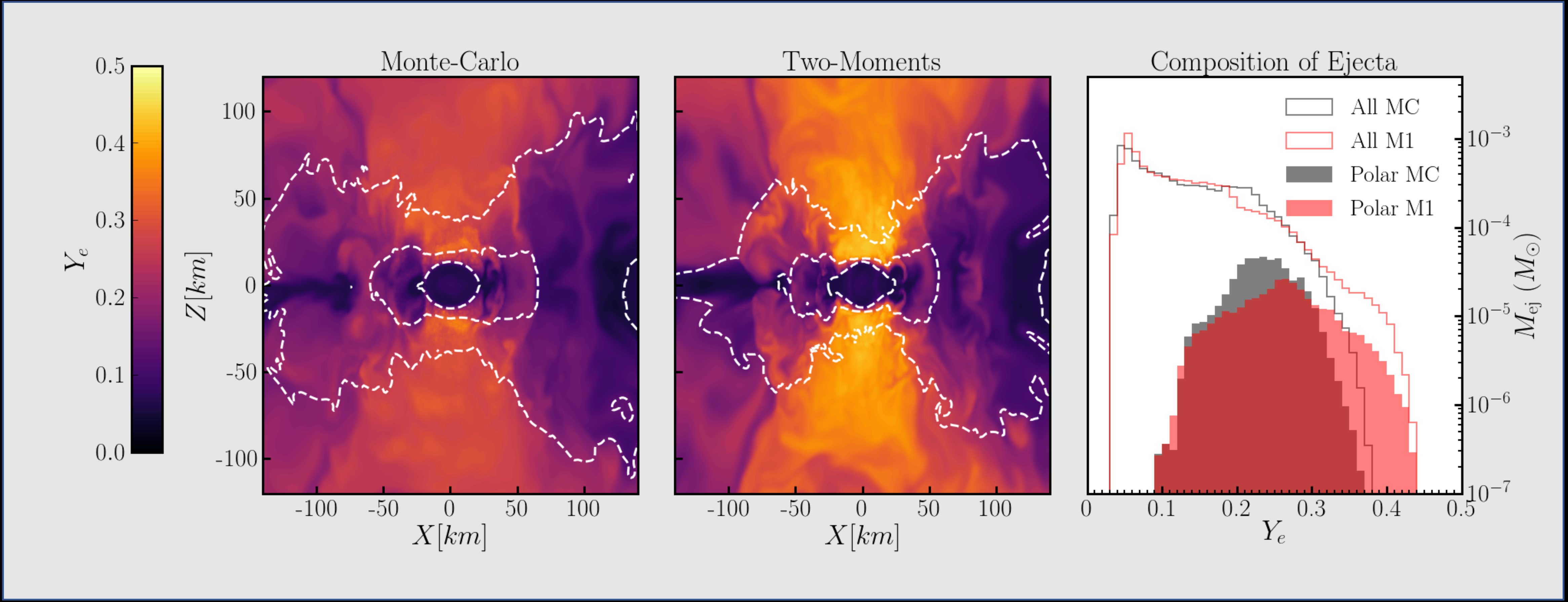
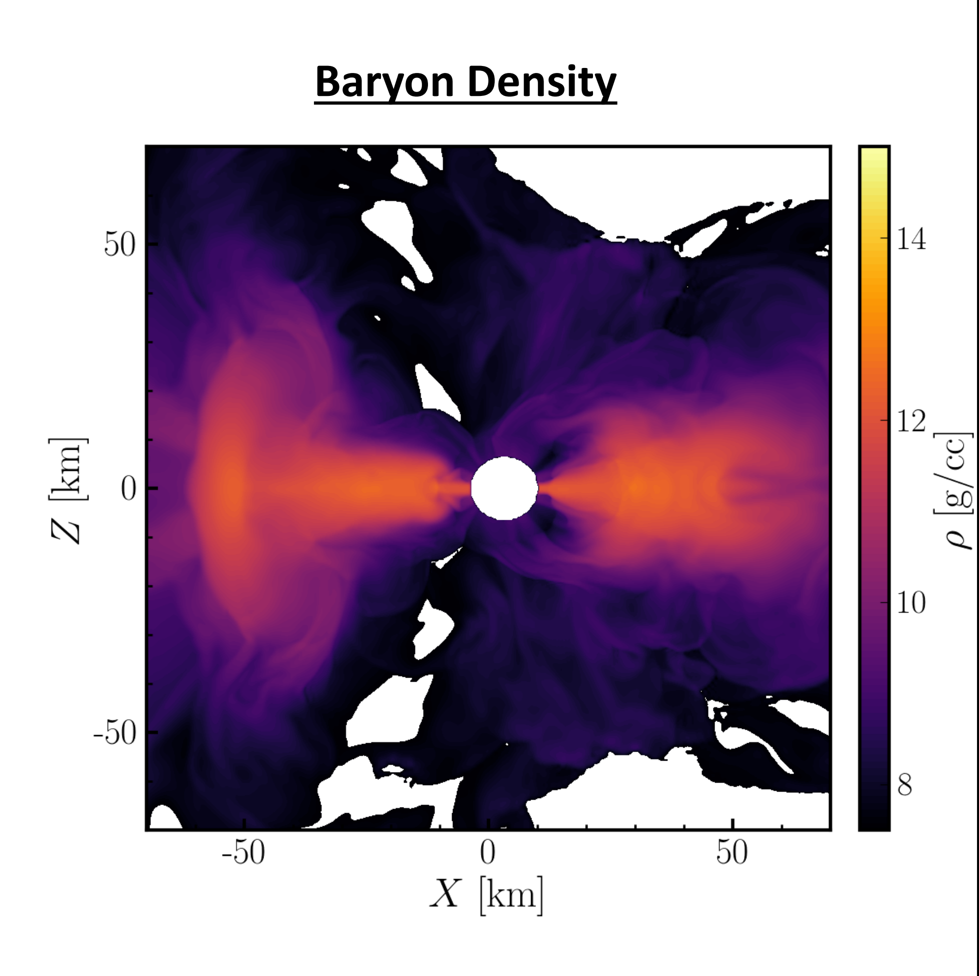


Image: Foucart *et al* (2020)

Collapsing NSNS mergers

Low-luminosity system => Stable evolution with just 10^6 packets per species!



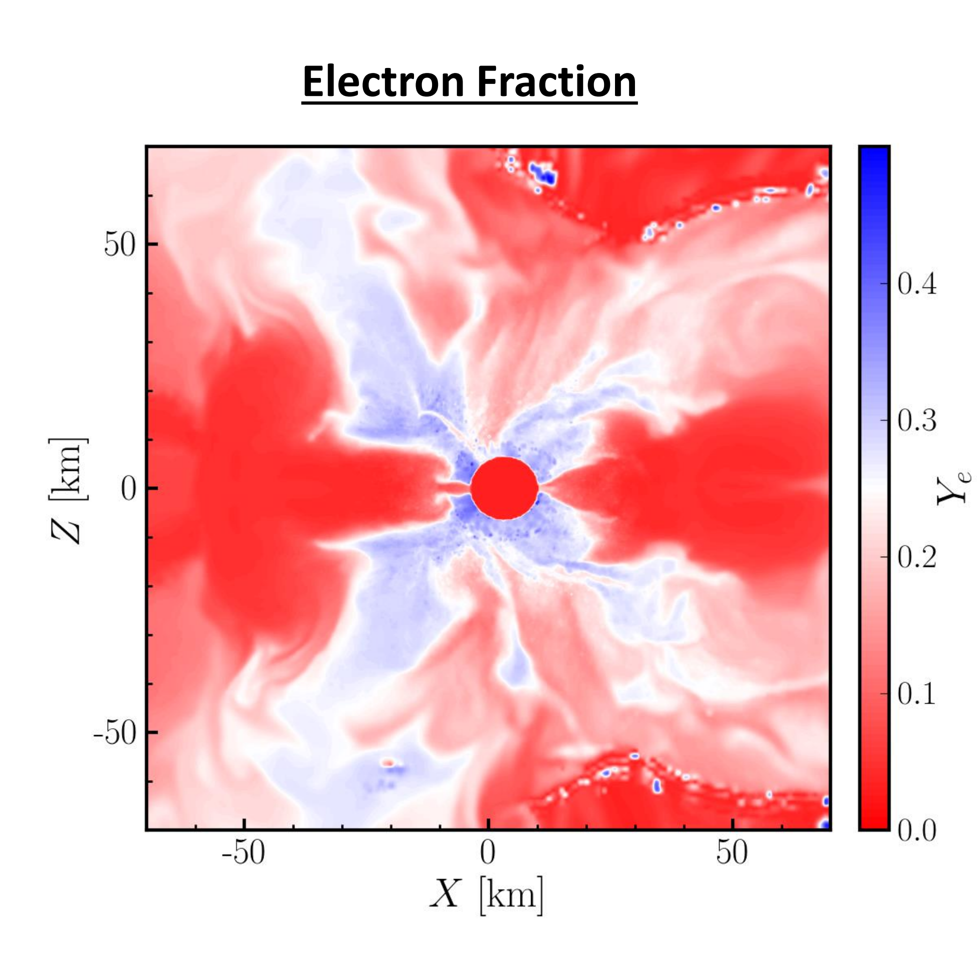


Image: Foucart *et al* (in prep); 6ms post-collapse for q=1.7 LS220

Conclusions #2

- Rapid progress in neutrino transport over the last decade
  - Moment methods (Sekiguchi+, Foucart+, Radice+)
  - Monte-Carlo methods (Foucart+, Miller+)
- What do we still need to do?
  - Oscillations only accessible in post-processing (with difficulties…), pair annihilation still largely untested
  - Dependence in the choice of included reactions, neutrino physics,… remain poorly studied
  - Parameter space coverage for BHNS / NSNS (In progress)