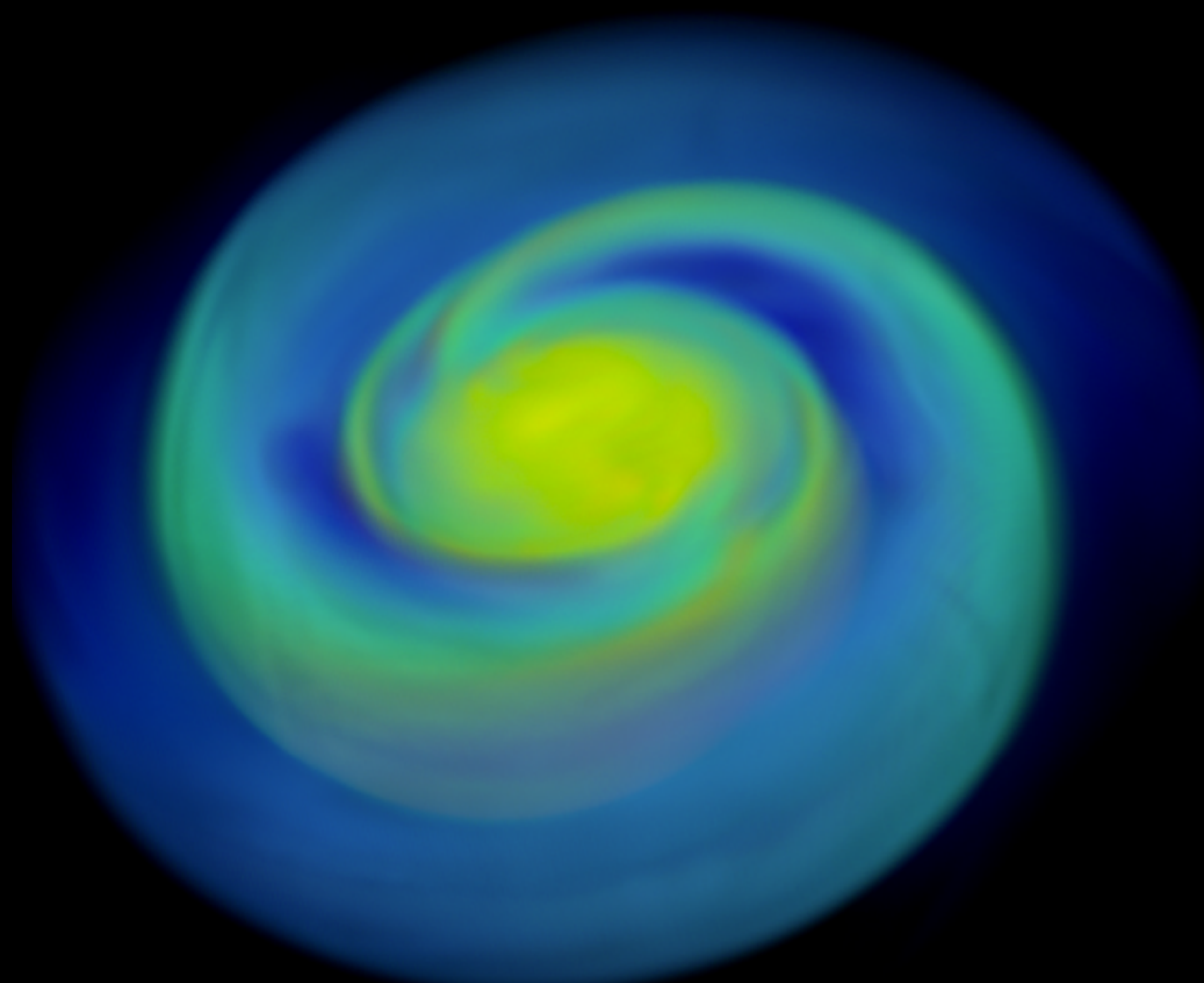
Numerical Simulations of Merging Neutron Stars



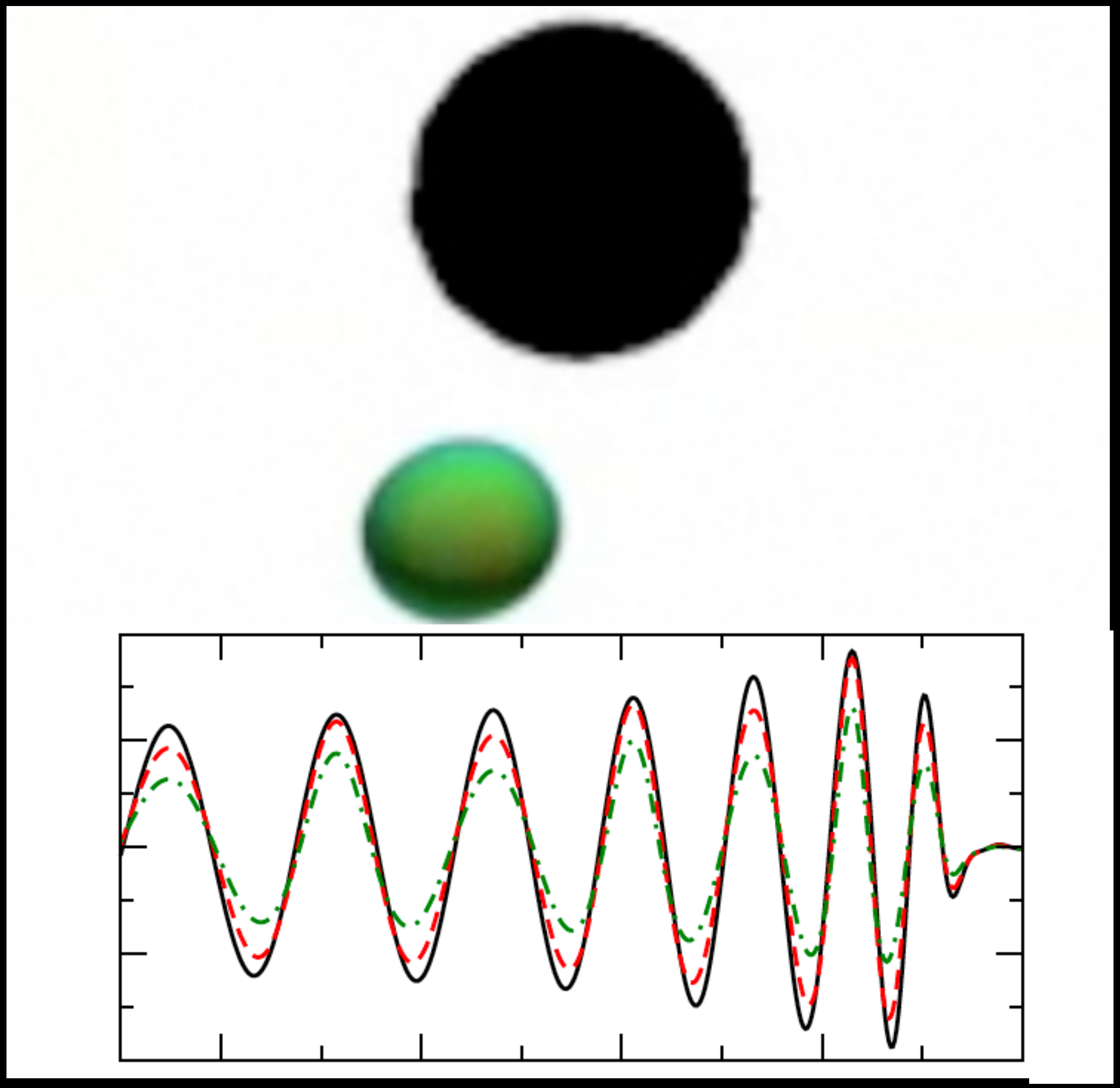
Francois Foucart (UNH)

YKIS - October 2019

Objectives of neutron star merger simulations

- **What we need from simulations depend on the signals we want to predict, and the desired accuracy**.
- In this talk:
  - Pre-merger GW signals in LIGO/Virgo
  - Post-merger EM signals (GRBs, kilonovae & their afterglows)
- Not covered:
  - GW signals from merger-ringdown
  - Pre-merger EM signals

Inspiral

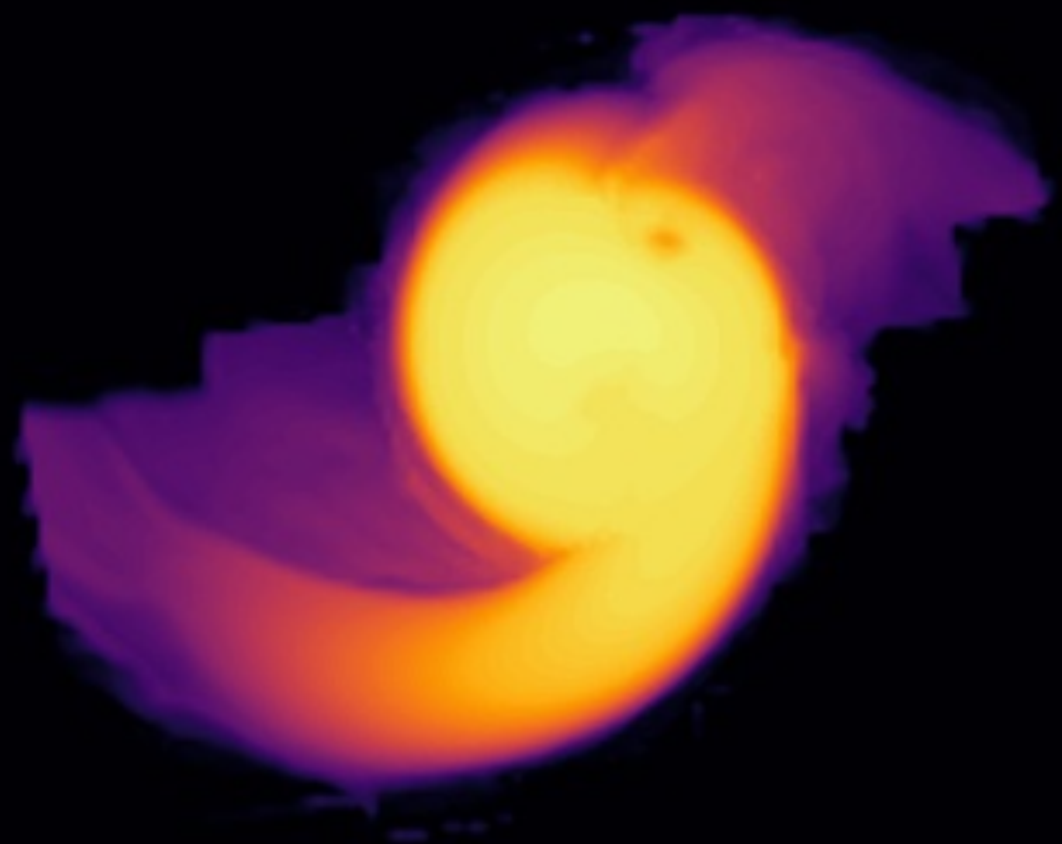


Timescale : 10-15 orbits for simulations… many more for observations

Important physics : General relativity + Hydro
+ Equation of state of Neutron Stars

What we need : high accuracy to calibrate/test models

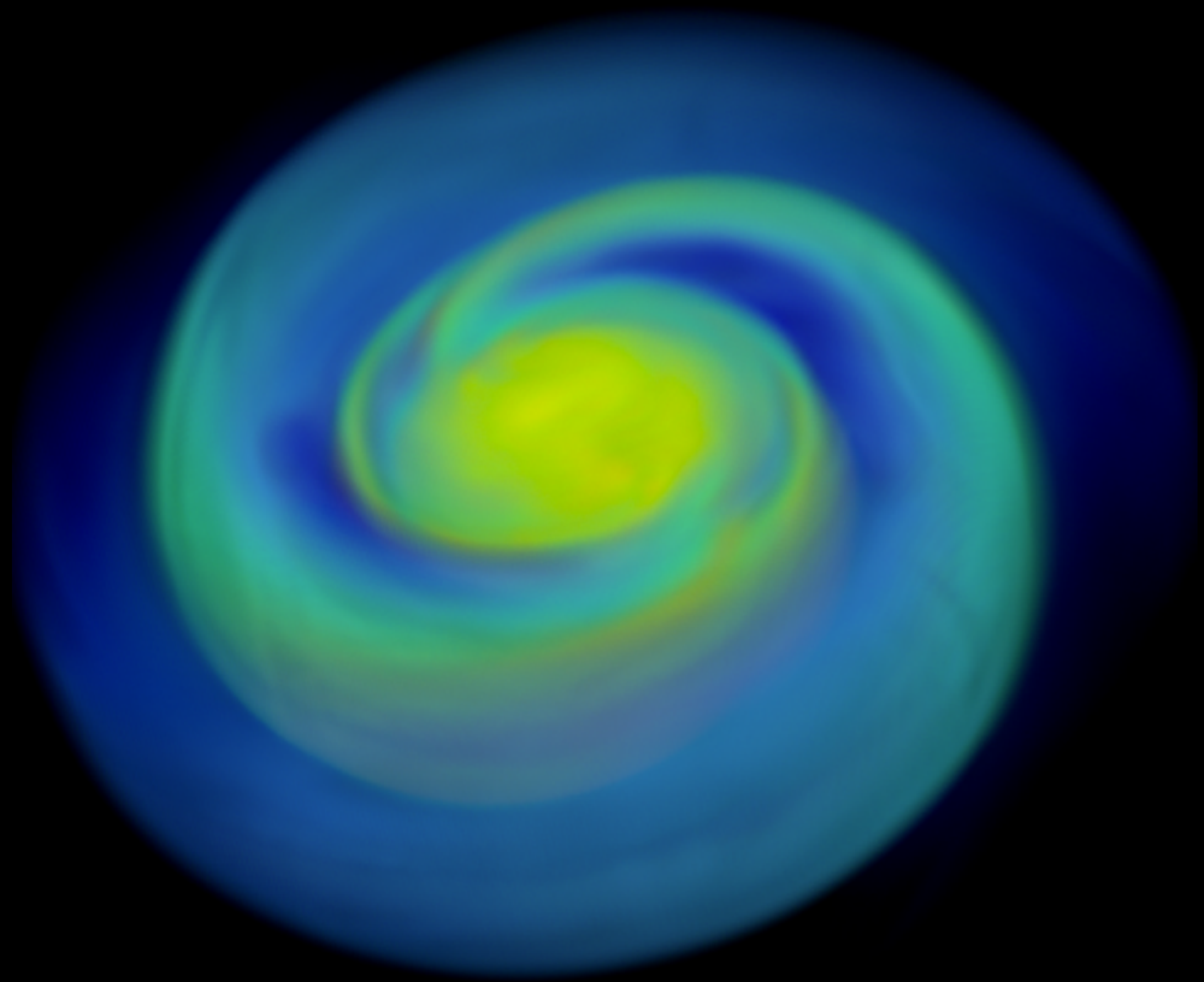
Merger



Timescale : Milliseconds

What we are looking for : BH/NS/Disk formation, dynamical ejecta

Post-merger disk & Outflows



Timescale : Seconds (<0.1s with 3D metric evolution)

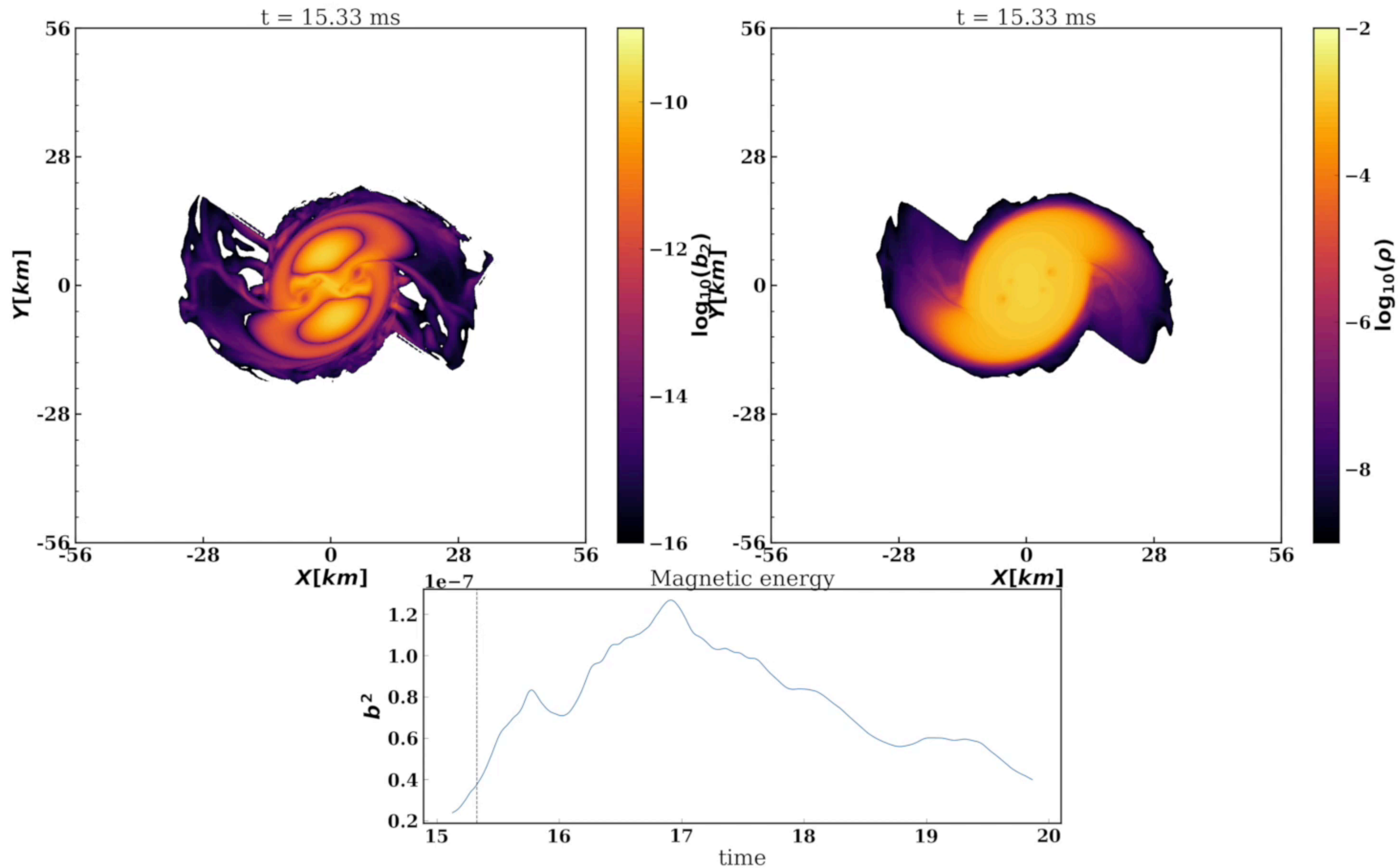
What we are looking for:
Disk outflows, jets

Magnetic fields in mergers

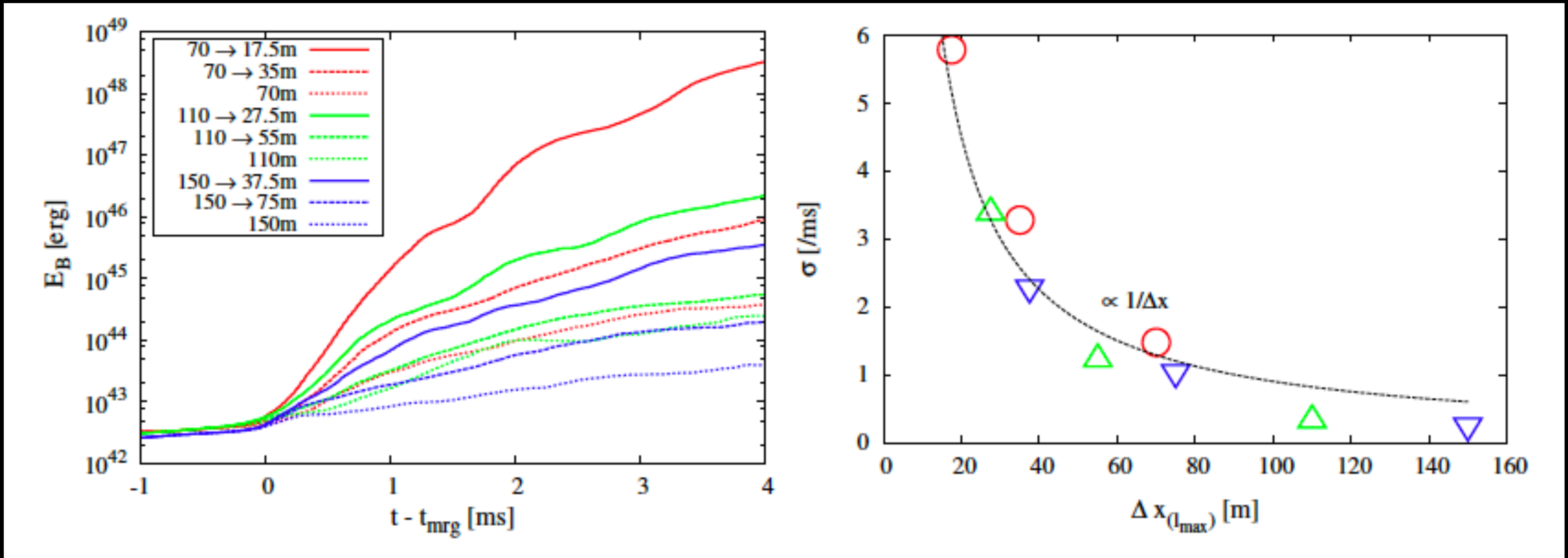
- Merger: growth of B-field driven by Kevin-Helmoltz (shear instability)
- Post-merger: turbulence in disk (and maybe NS) driven by magnetorotational instability
- Responsible for
  - Angular momentum transport
  - Disk outflows (from 10ms-10s scales…)
  - Jets
- Can we get *large scale poloidal* B-fields (dynamo)?

Magnetic fields in mergers : Kevin-Helmoltz instability

Movie : A. Chernoglazov (UNH)



Magnetically-driven turbulence

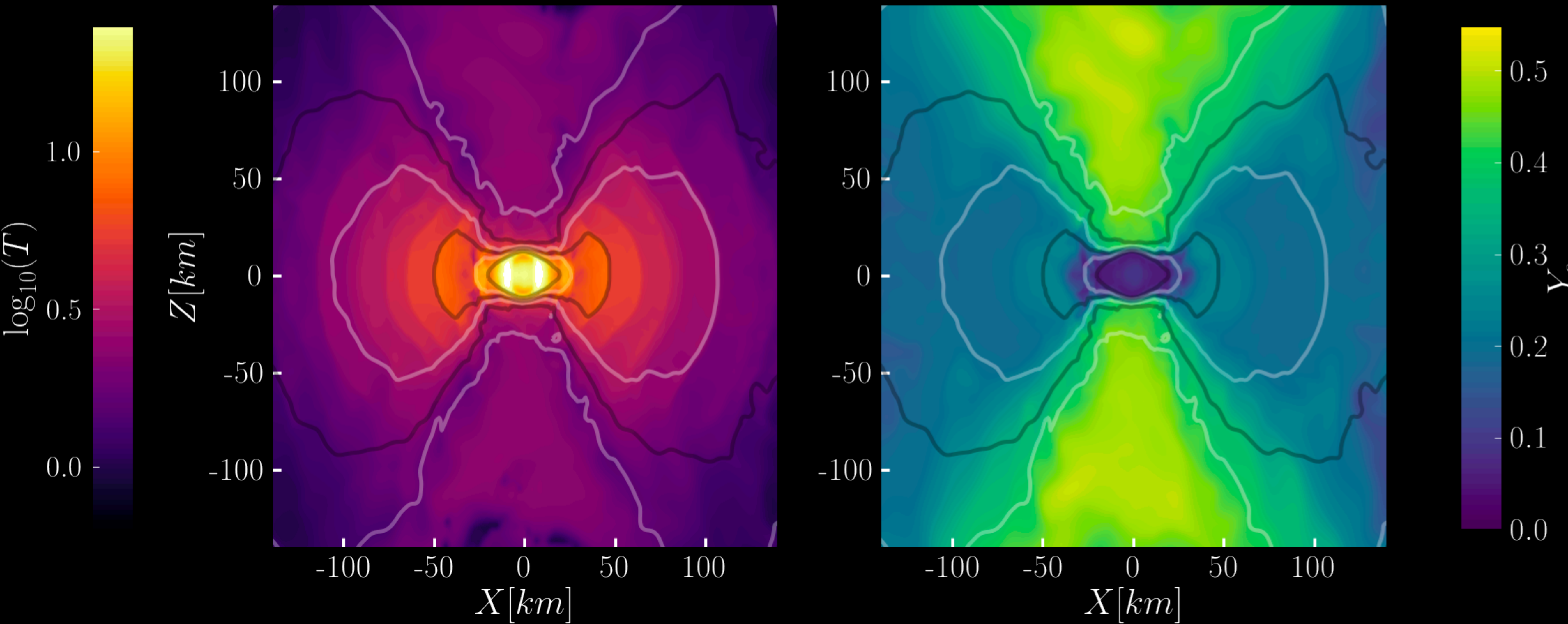


Images : Kiuchi+ 2015

- Current simulations capture instabilities, but not full growth from realistic field strengths
- Starting from large initial B-field leads to different saturation levels / large-scale structure
- What about the large-scale structure of the B-field?
- Alternative: viscous models (Radice; Shibata+)

Neutrinos in mergers

Neutron Star Merger remnant (Foucart+2019)



(1) Neutrinos cool the disk

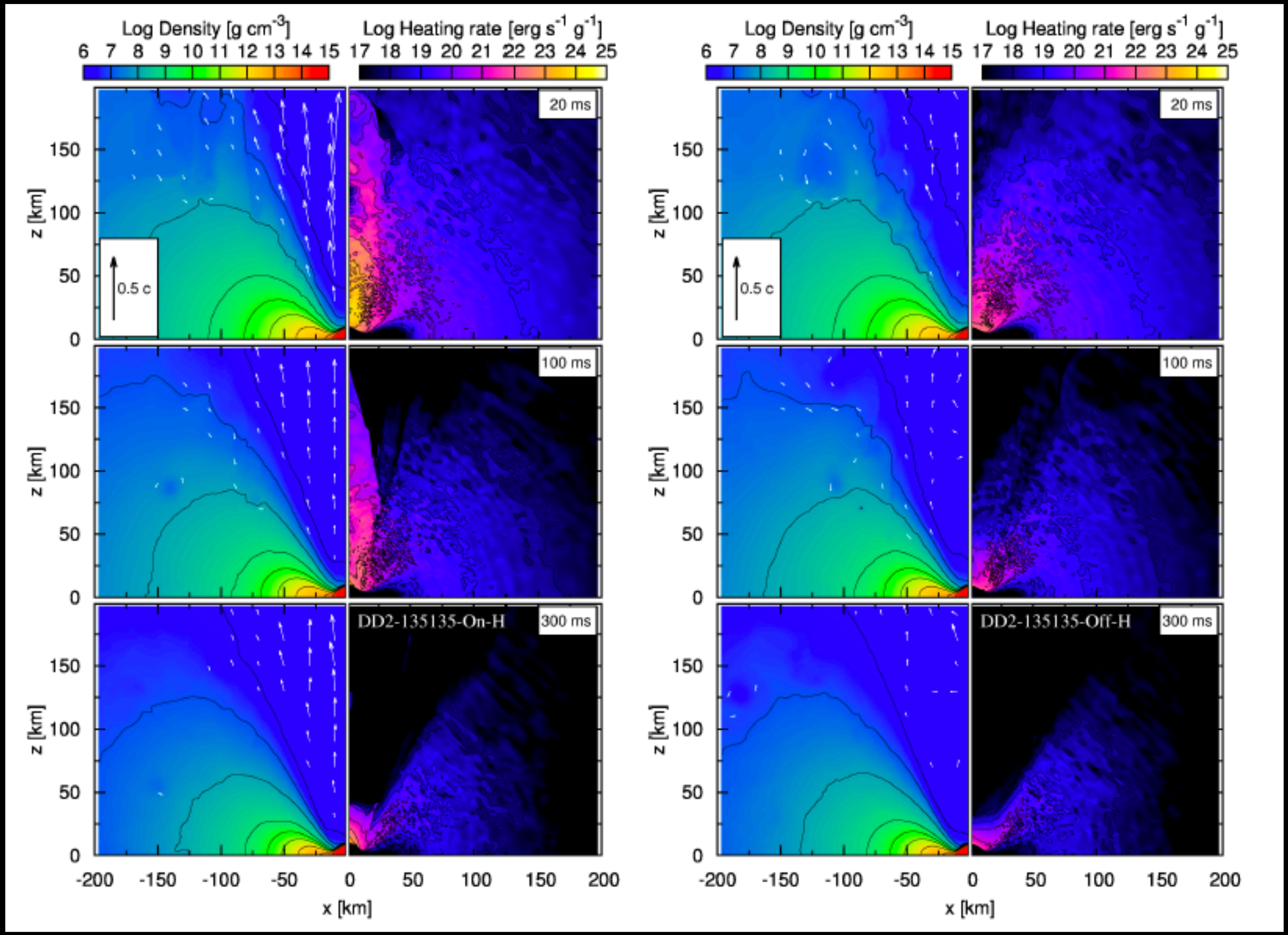
(2) Neutrinos drive polar outflows (subdominant…)

(3) Neutrino absorption / Antineutrino emission increase Y_e of outflows

(4) Pair annihilation deposits energy in polar regions

Pair annihilation **(NSNS)**

With annihilation | Without annihilation



Images: Fujibayashi et al., 2017

Neutrino Radiation Transport

High cost: (6+1)D problem

$$f_{(\nu)} = f(t, x^i, p^\alpha)$$

and complex collision terms, e.g.

Inelastic scattering

Neutrino-antineutrino annihilation

- Now: Approximate methods
  - Leakage [Ruffert+1997, Rosswog & Liebendorfer 2003]
  - 'Moment schemes' [Wanajo+2014, Sekiguchi+, Foucart+]

- Desired: Solutions to Boltzmann's equation
  - Monte-Carlo methods [Foucart+2018, Miller+2019]
  - Full discretization

Neutrinos in mergers

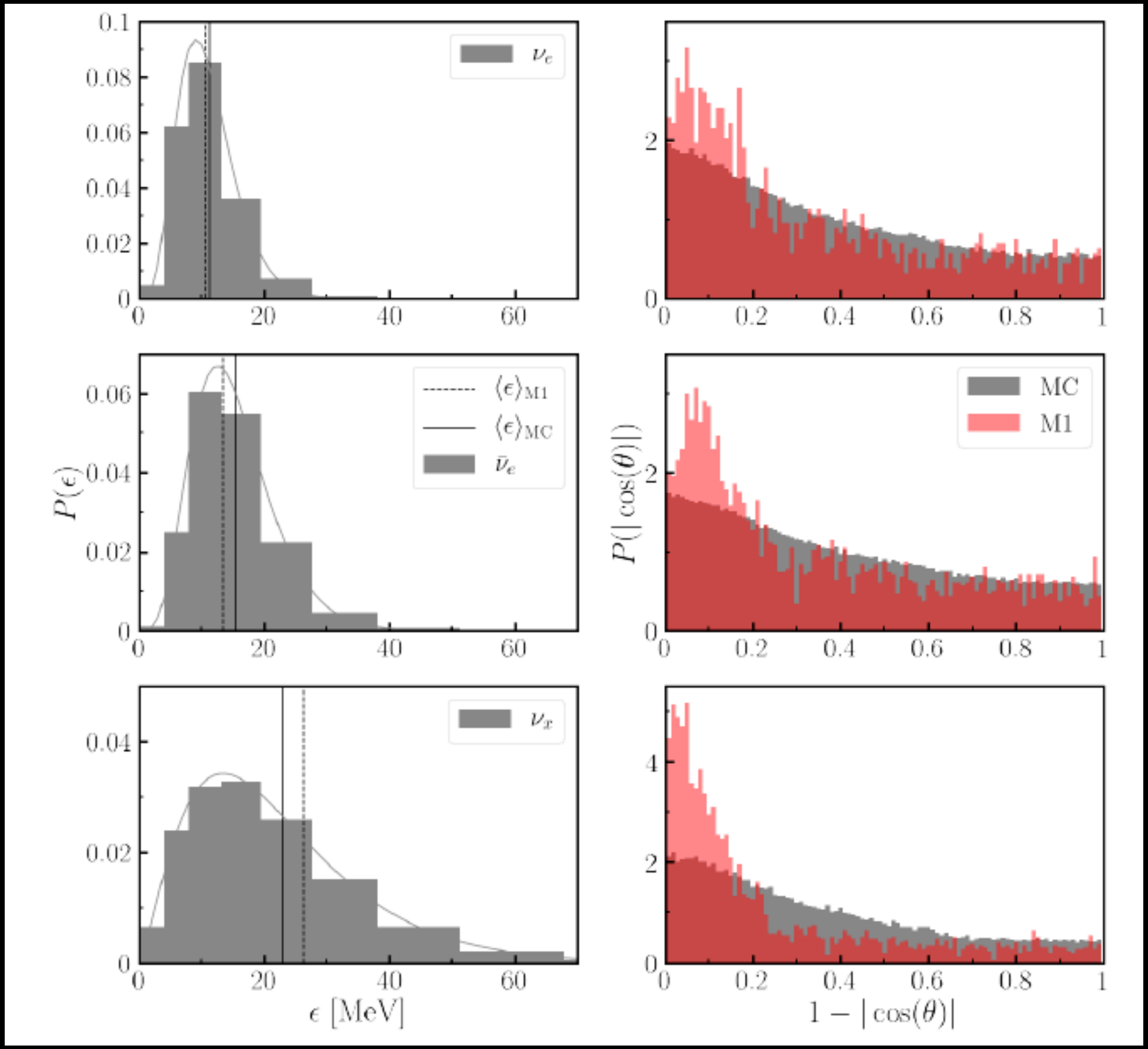
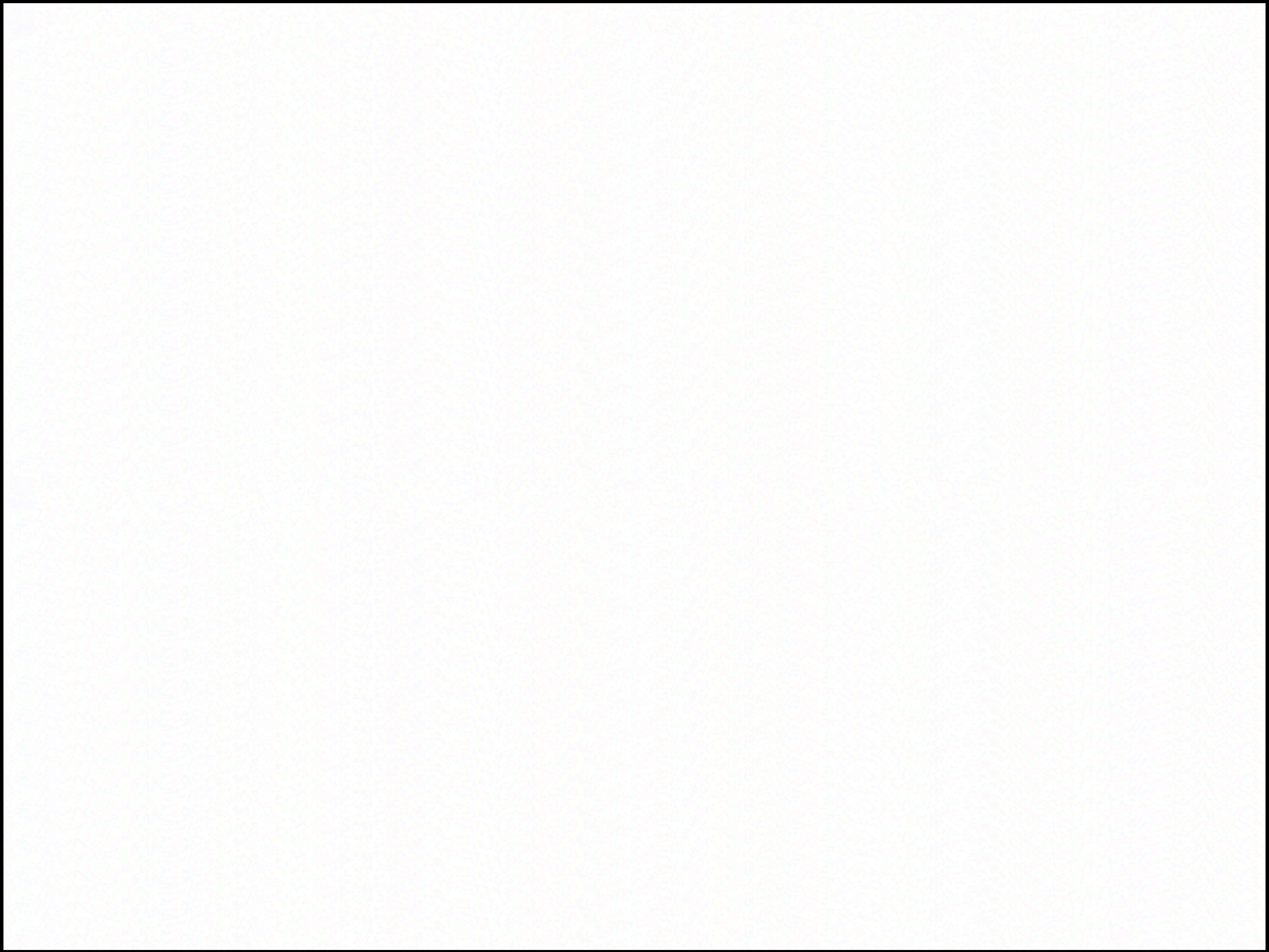
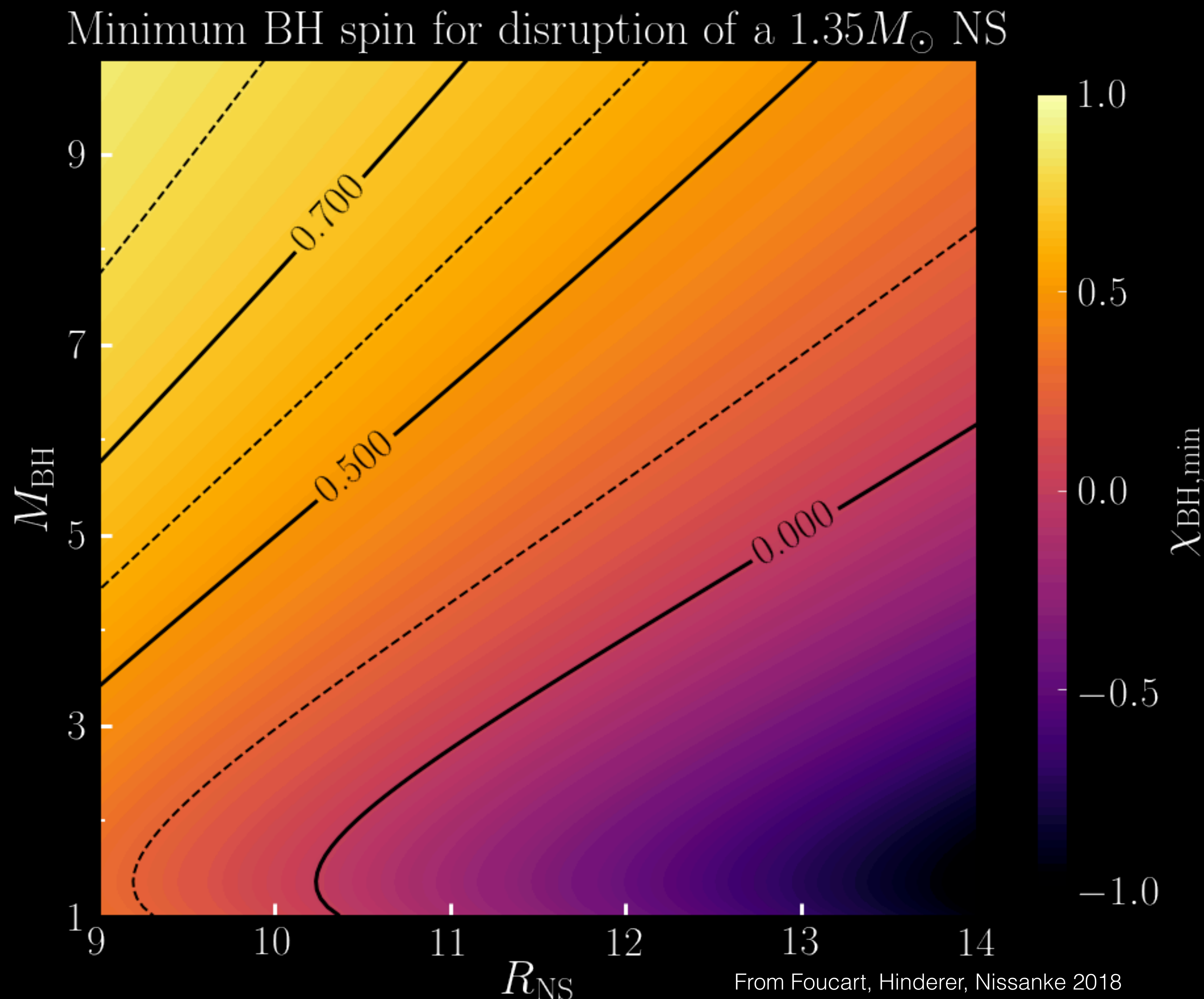


Image: Foucart+2019

Neutron Star merger dynamics

BH-NS mergers : Potential outcomes

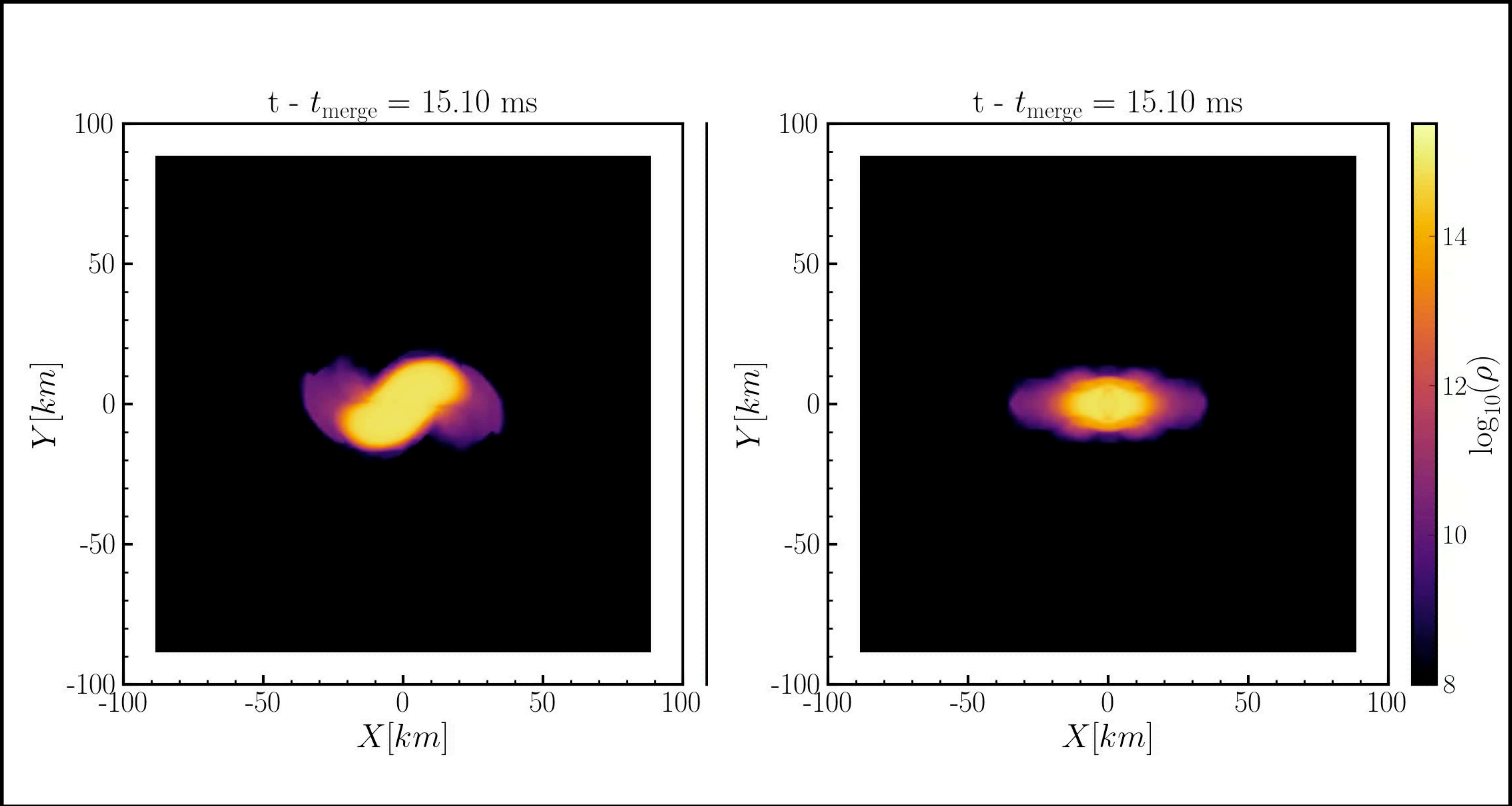




From Foucart, Hinderer, Nissanke 2018

NS-NS mergers

(1.36Msun + 1.36Msun) merger of 10.6km stars



From Foucart+, in prep

NS-NS merger : Types of remnants

Outcome of merger <-> [Total mass of binary] / [Maximum mass of NS]

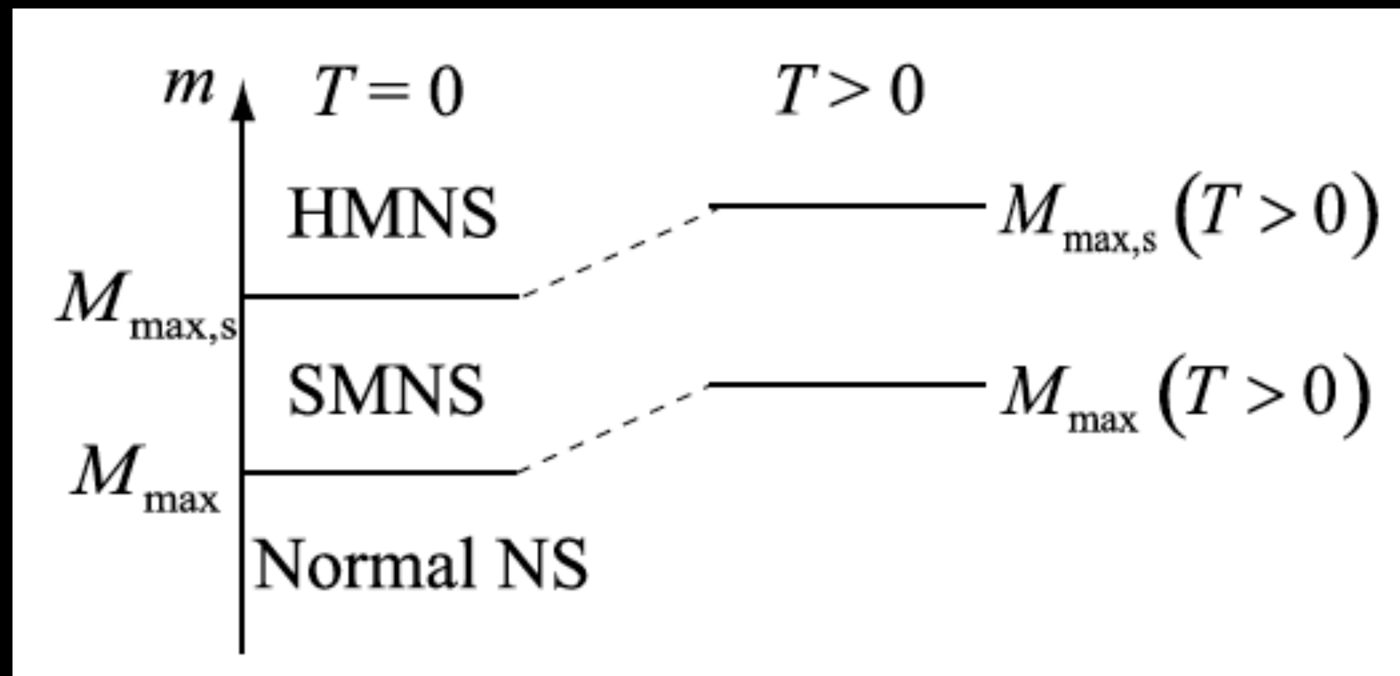


Image: Hotokezaka+ 2013

Case 1:	Case 2:	Case 3:
Long -lived NS remnant	Short -lived NS remnant	BH remnant
$M<1.2M_{max}$	$1.2M_{max}<M<1.4M_{max}$	$1.4M_{max}<M$

Precise lifetime depends on cooling / angular momentum transport timescales

Mass threshold for prompt collapse: Bauswein+2013

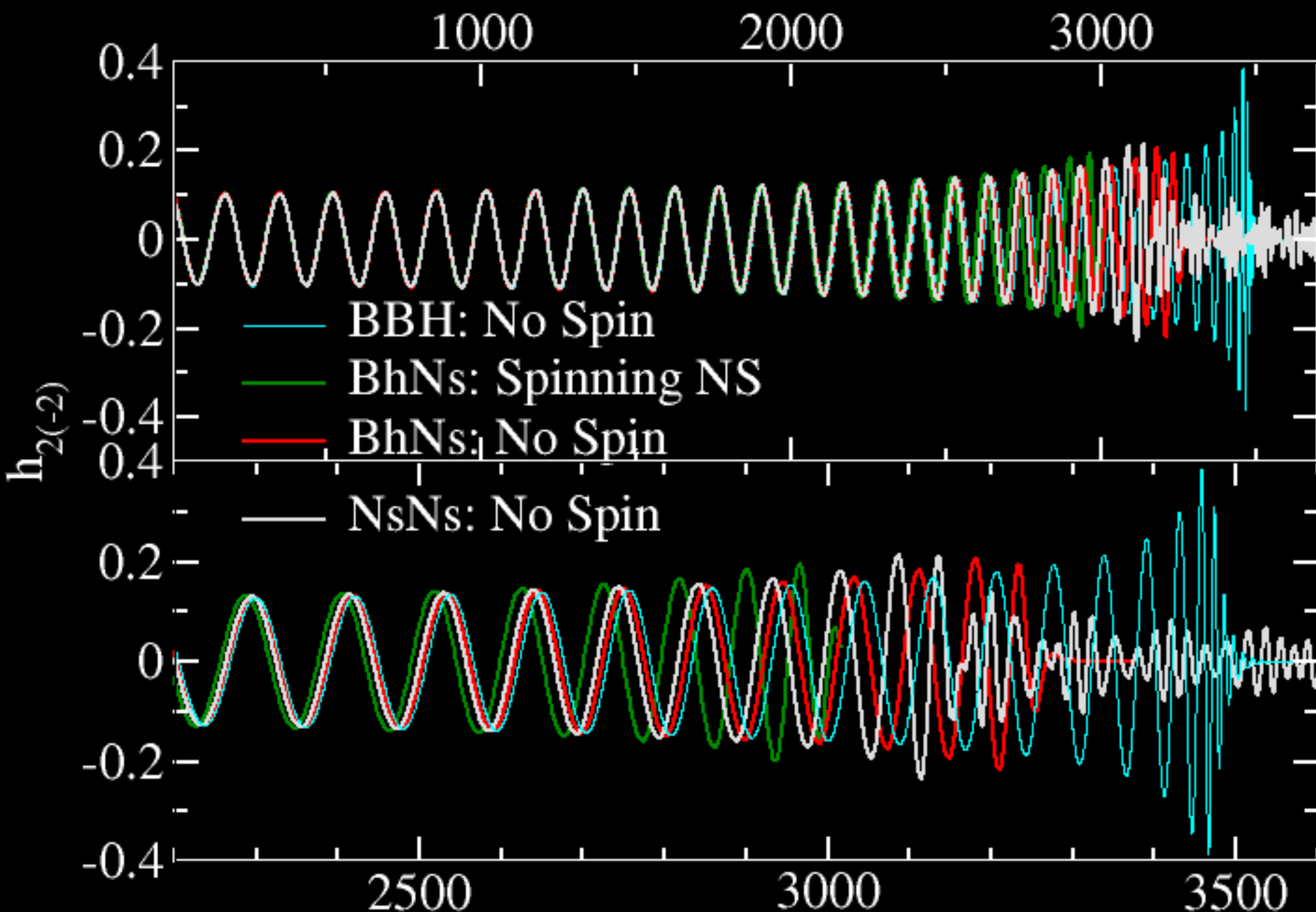
Merger remnant : observational consequences

- BHNS mergers :
  - No disruption = No post-merger EM counterpart
- NSNS mergers :
  - Rapid collapse = very little disk/ejecta mass available to power post-merger signals for q~1
    - More matter can remain for asymmetric binaries (Kiuchi+) -> Mass ratio effects need to be better explored.
  - A long-lived, strongly magnetized neutron star will have observable consequences (see B. Zhang's talk)

Modeling Gravitational Wave Signals

Gravitational wave signal : Dephasing

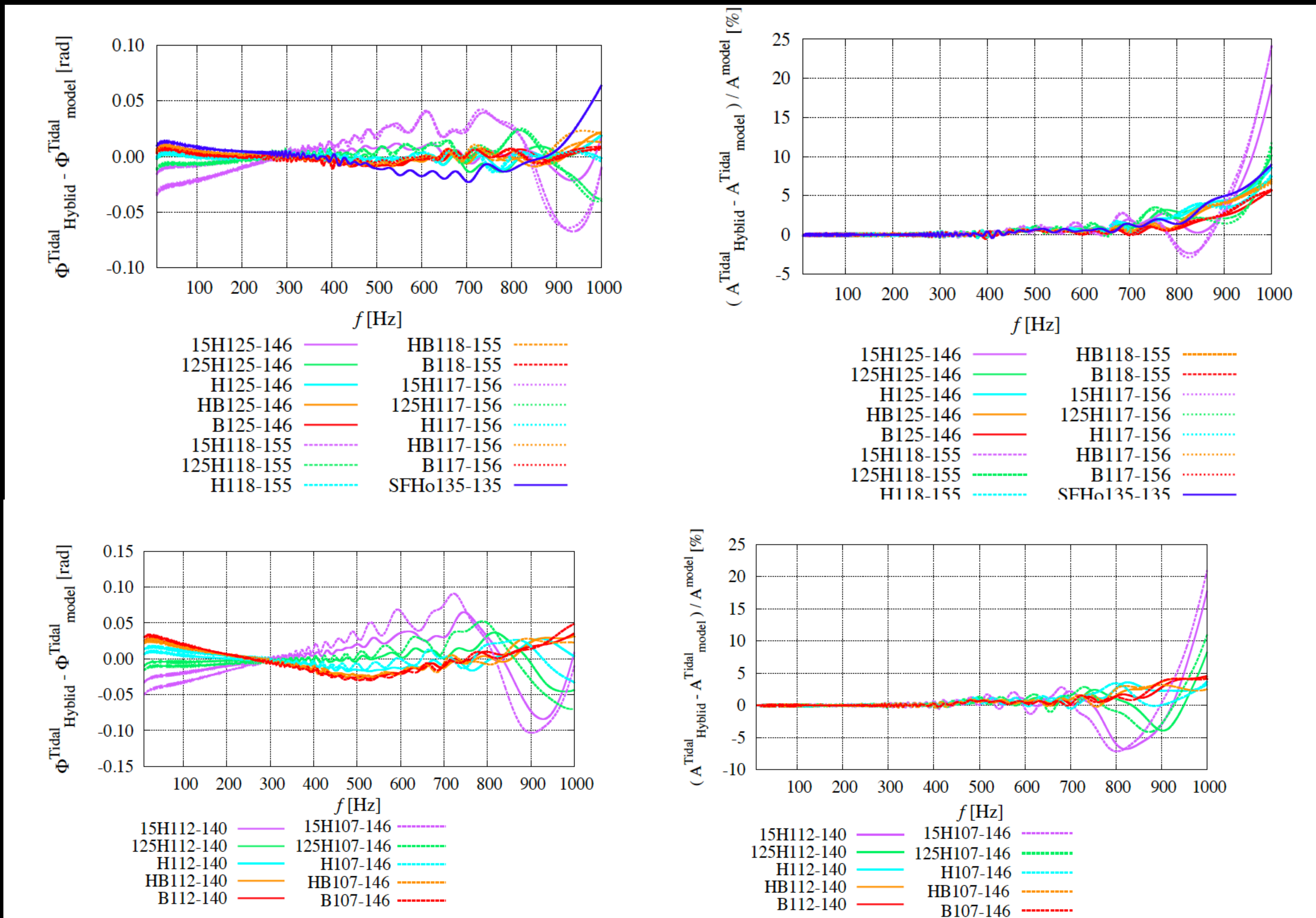
Equal mass systems, NS radius = 14.4km



Status of simulations

- Multiple codes with sub-radian accuracy for NSNS/BHNS waveforms
  - e.g. SACRA, THC, SpEC, BAM (see also CORE, SACRA, SxS waveform databases)
  - Finite size effects on the phase of the inspiral waveform can be tested to (0.1-0.5) rad, over 10-15 orbits… is this enough?

Gravitational wave signal : Model consistency



Gravitational wave signal : Model accuracy

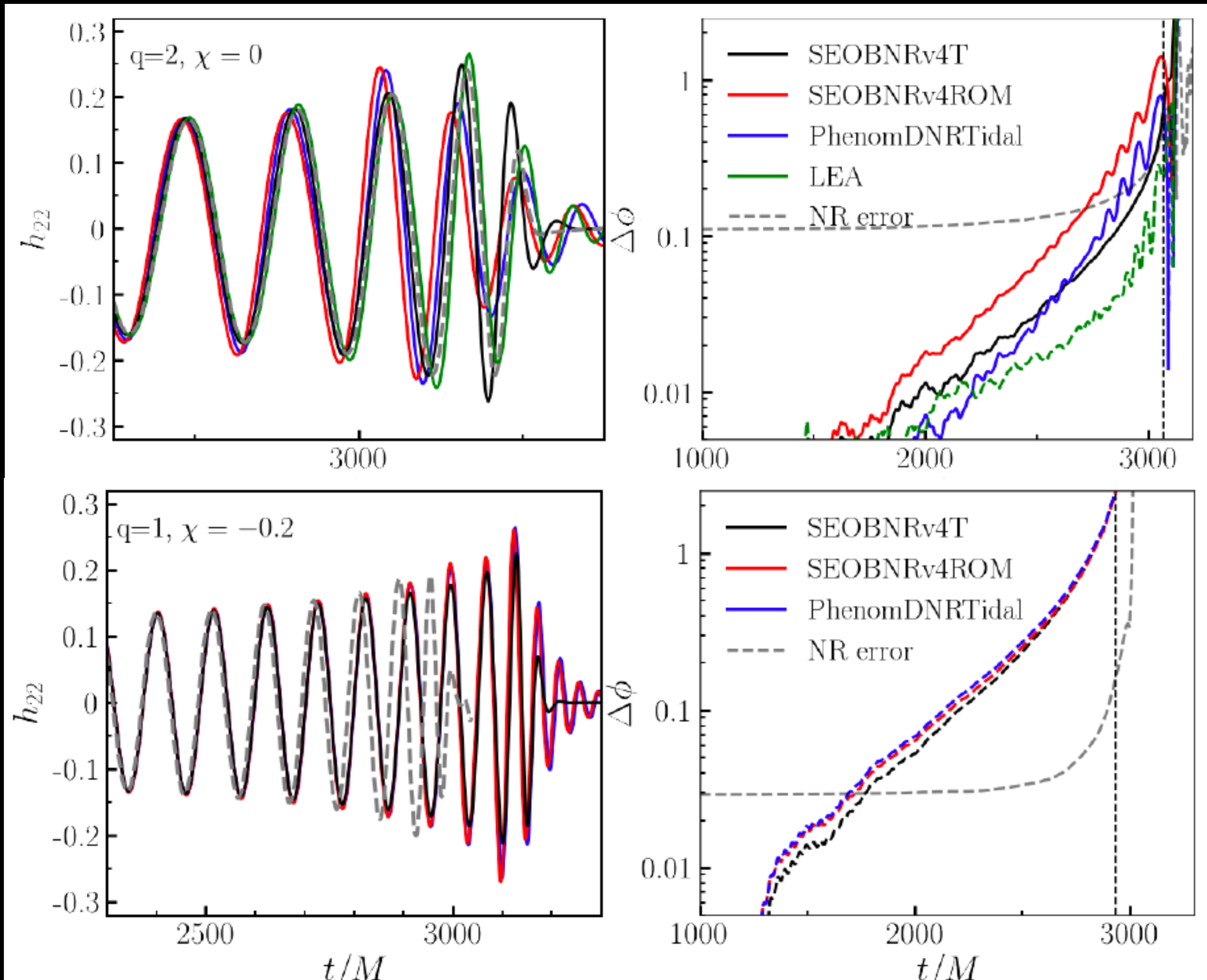


Image: Foucart, Duez, Hinderer+2019

Modeling Electromagnetic Signals:

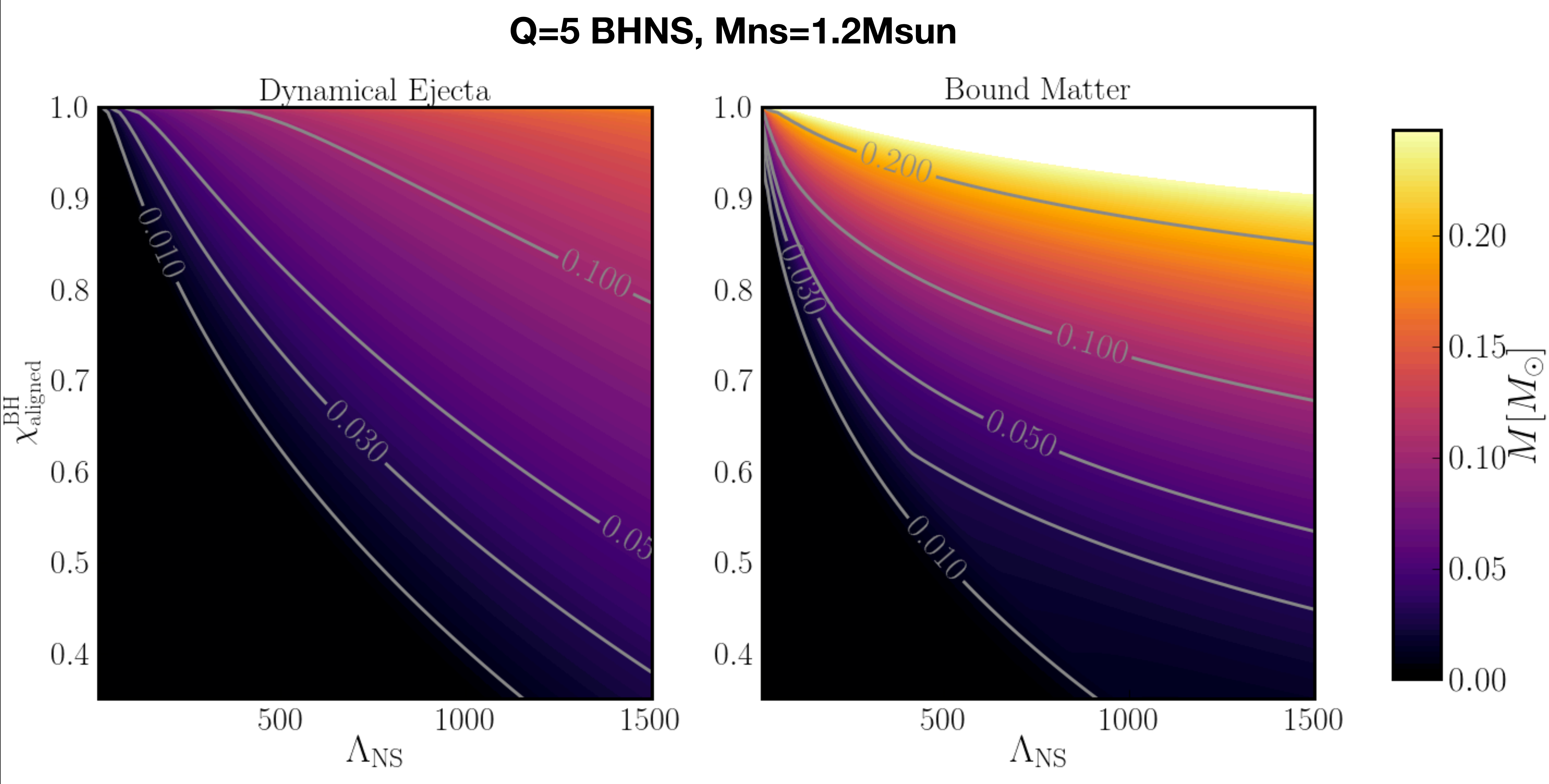
Mergers and Outflows

BHNS Outflows

- Dynamical ejecta [1ms post-merger]
- Early post-merger magnetically driven winds [1ms-1s post-merger]
- Long-term ‘viscous’ outflows [1s-10s post-merger]

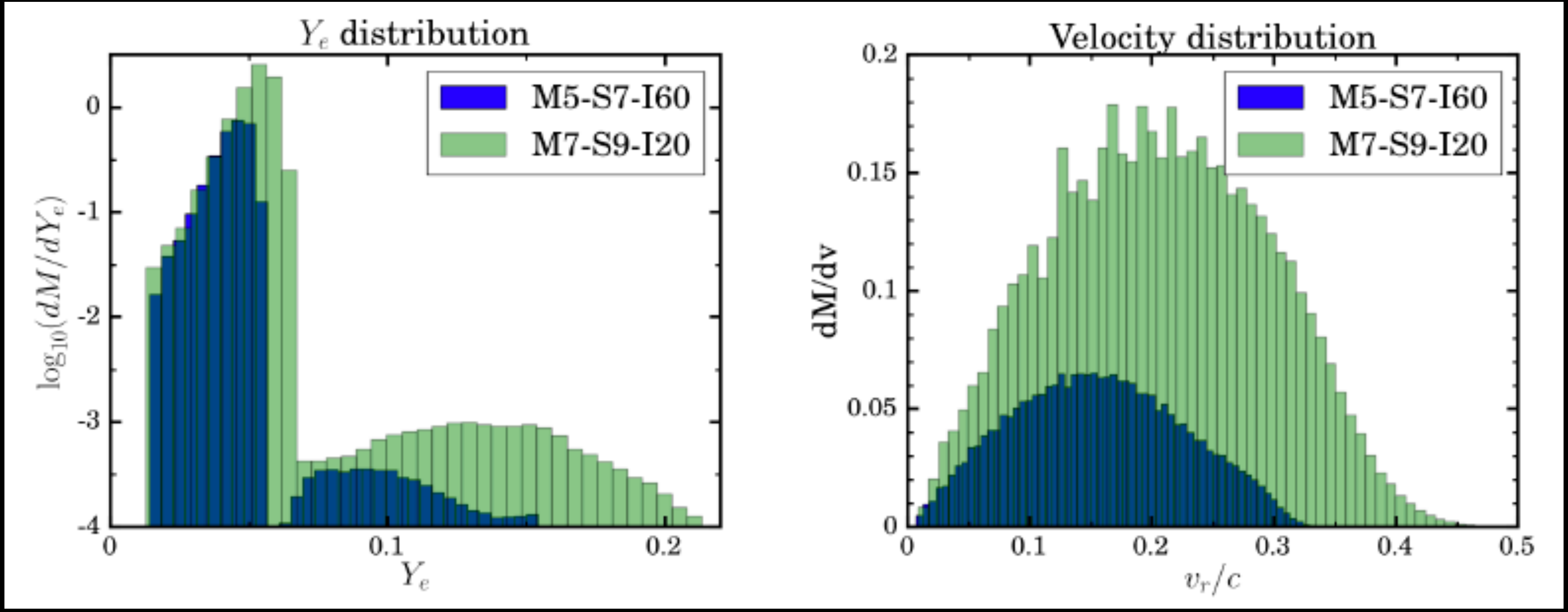
BHNS post-merger remnant

Foucart, Hinderer, Nissanke 2018; Kawaguchi+2016; Kruger+ in prep



Dynamical Ejecta

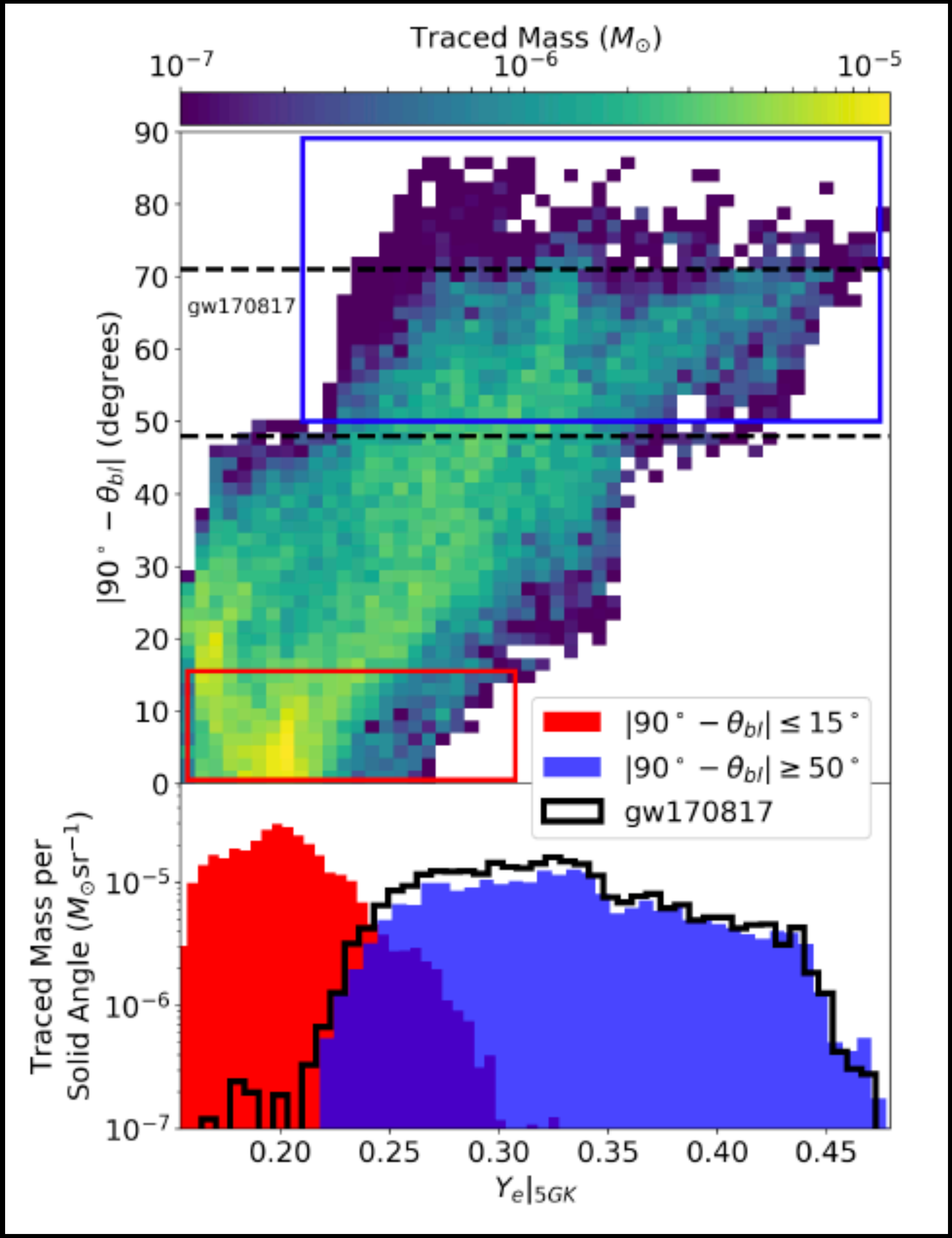
- Cold, neutron-rich, equatorial and asymmetric
  - Should lead to strong r-process (lanthanide production), infrared kilonova
- Typically (0.01-0.1)$M_\odot$, possibly more for near-extremal spins [Kawaguchi+2016]
  - Out-of-NSE physics desirable improvement to predict M,v



Foucart et al., PRD (2017)

Early post-merger ejecta

- Magnetically-driven and neutrino irradiated
- (10-25)% of disk mass ejected [Siegel & Metzger 2017, Fernandez+2018, Miller+2019, Christie+2019]
- **Broad range of composition and velocity** for the outflows
- High uncertainty in magnetic field, neutrino effects



J. Miller et al. 2019

Late post-merger ejecta

- Driven by MHD instability (MRI) and ^{4}He recombination
- (5-25)% of disk mass ejected (Fernandez+201x, Just+2014)
- B**road range of composition** and **low velocities** (~0.05c)
- See previous talk…

NSNS Outflows

- Main differences with BHNS mergers:
  - Hot dynamical ejecta from core-bounce
    - ~100% uncertainty in unbound mass, disk mass [Dietrich & Ujevic 2017, Radice+2018, Coughlin+2018]
  - Mass ejection during angular momentum redistribution in NS
  - Greater wind irradiation if we have a NS remnant
- **Extreme caution currently necessary when modeling kilonovae**

Conclusions

- Numerical relativity helps us understand observable properties of NSNS/BHNS mergers
- Qualitative understanding of the merger outcome and outflow processes fairly well under control
- B-field and neutrino modeling has made significant progress, but remain important limiting factors in GW/EM models of NS mergers
- **Given the complexity of these systems, improving models requires collaborative efforts involving the numerical and analytical relativity communities, GW & EM observers, theoretical astrophysicists, and nuclear physicists**