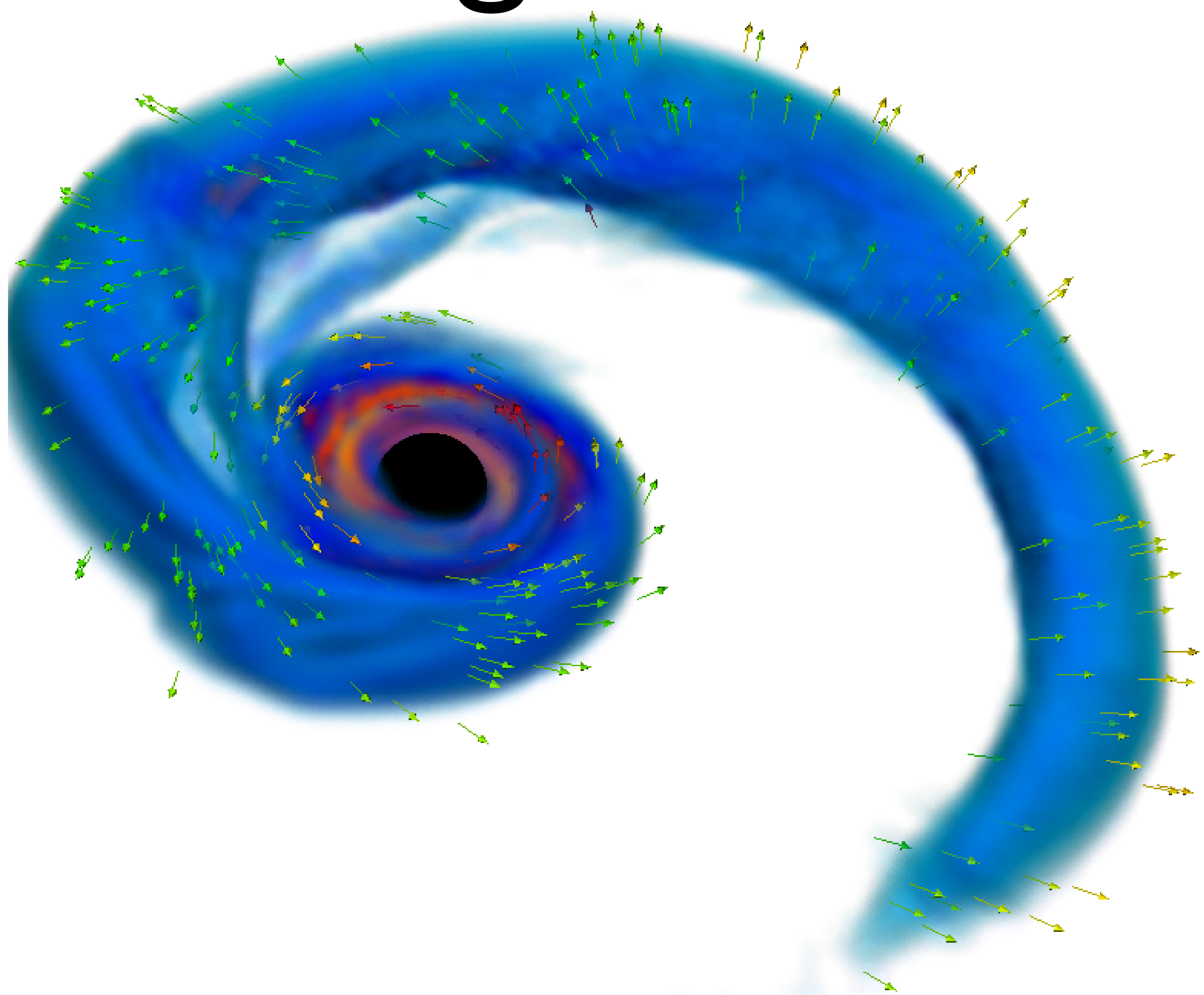
Microphysics for GR-Hydro merger simulations



Francois Foucart
Einstein Fellow
Lawrence Berkeley National Laboratory

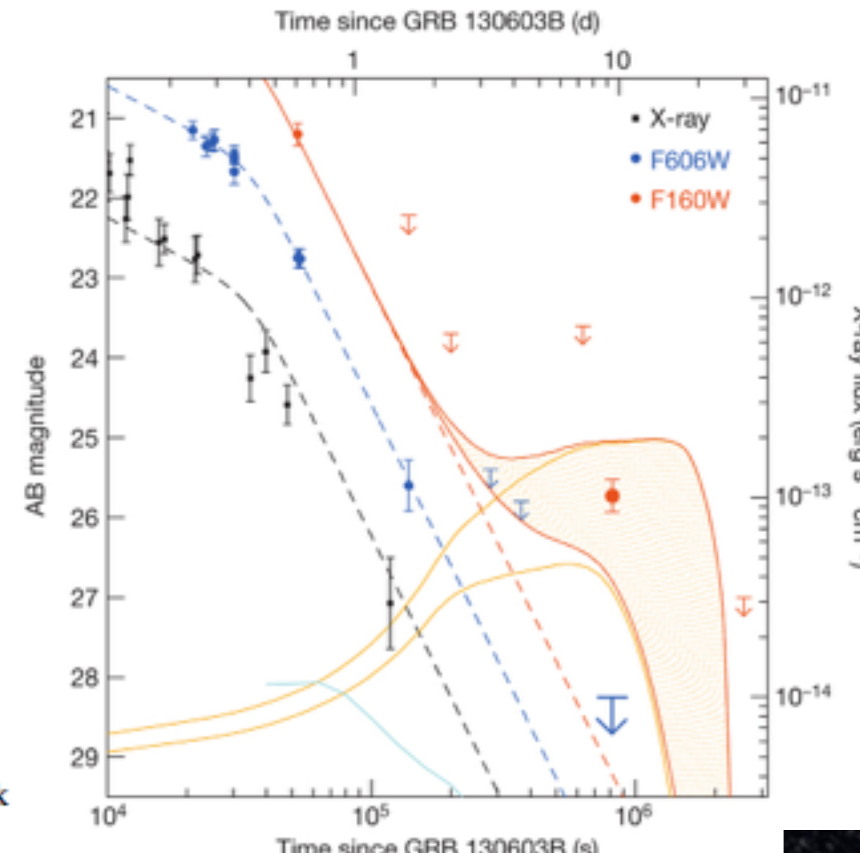
Hawaii 2014

Collaborators

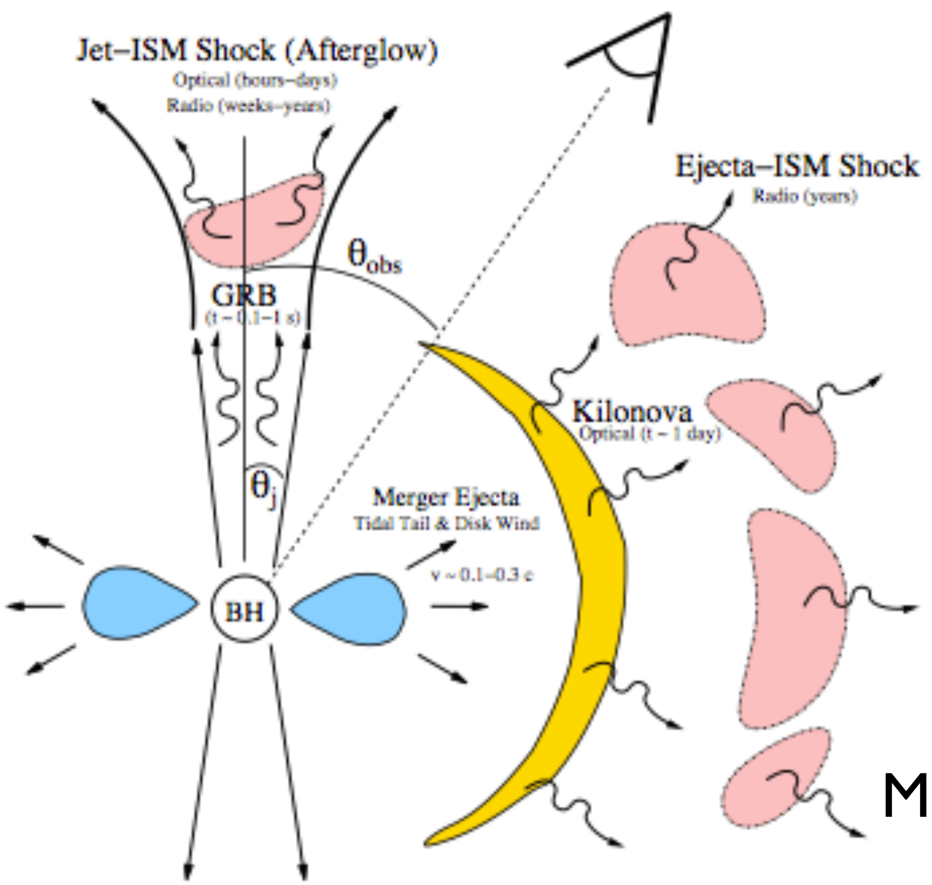
- Brett Deaton (WSU)
- Matt Duez (WSU)
- Evan O'Connor (UNC)
- Christian Ott (Caltech)
- Luke Roberts (Caltech)
- Lawrence Kidder (Cornell)
- Curran Muhlberger (Cornell)
- Harald Pfeiffer (CITA)
- Bela Szilagyi (Caltech)
- Mark Scheel (Caltech)

Observing Mergers

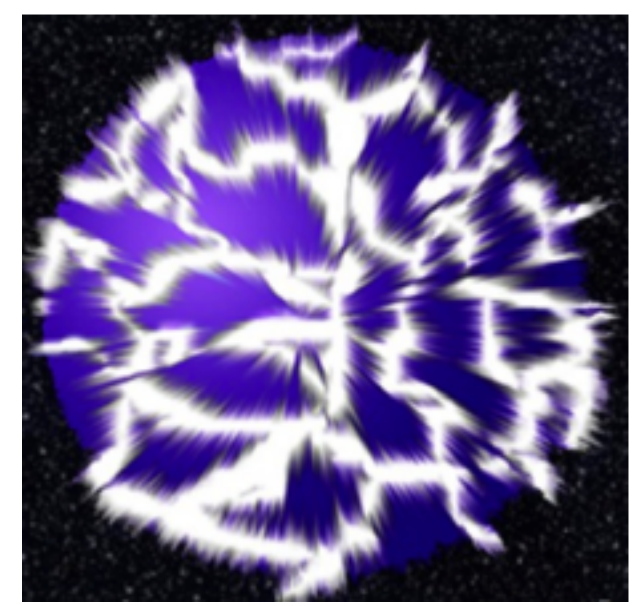
LIGO Livingston



Tanvir et al. 2013



Metzger & Berger 2012



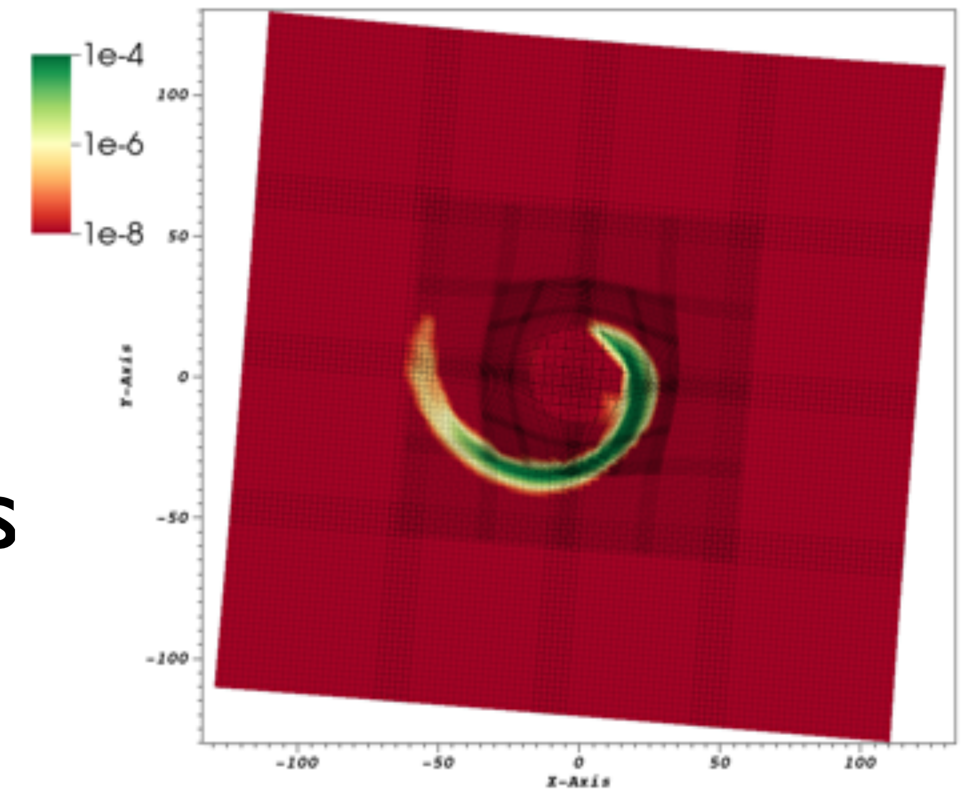
Tsang et al. 2012

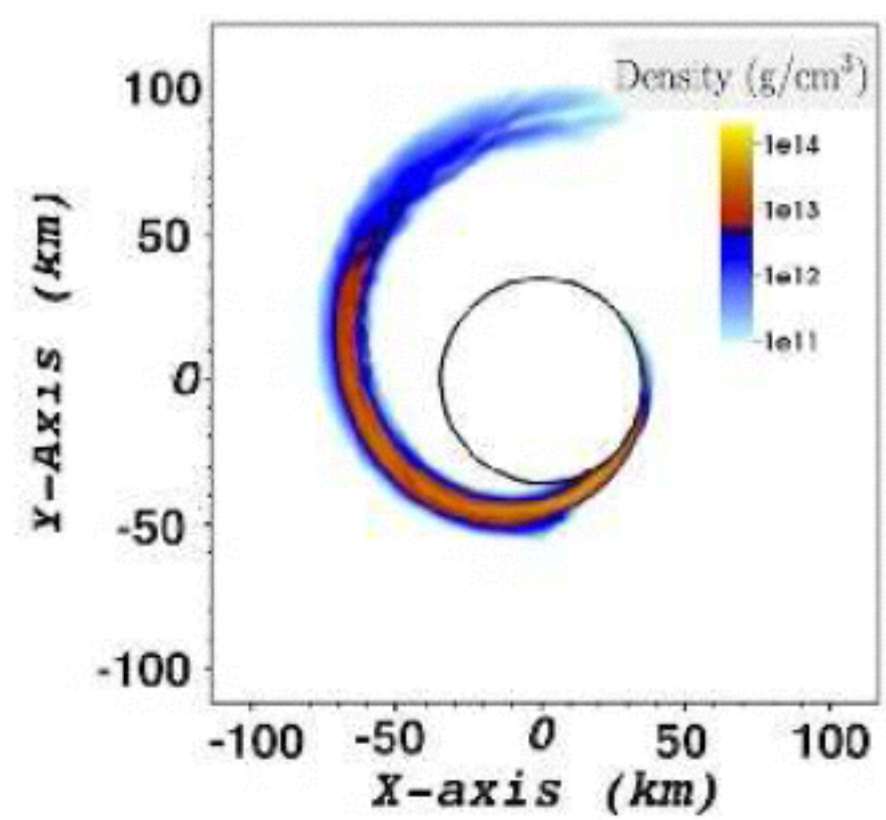
Important Physics

- General Relativity + Hydrodynamics
- Magnetic Fields
- Neutrino Radiation
- Equation of state of dense matter $P(\rho,T,Y_e)$
- Nuclear reactions in disk / outflows

Challenges: GR-Hydro

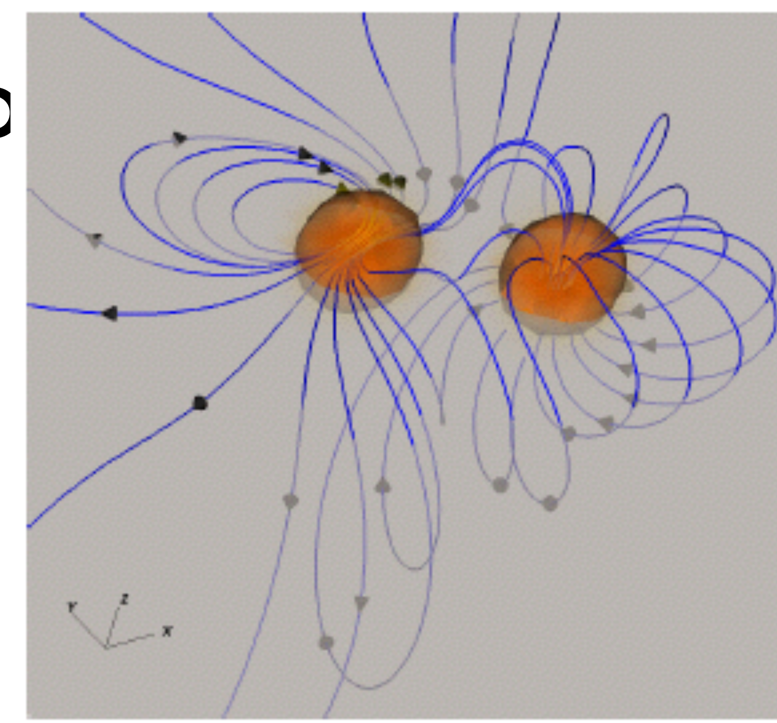
- Formulation of Einstein's equations
  - BSSN, Generalized Harmonics
- Shock capturing schemes in GR
- Highly relativistic flows
- Scales to resolve (density, distances)
- ~10^5 CPU-hrs





Challenges: B-fields

- Ideal MHD: resolve growth of instabilities (e.g. MRI grows on short length scales)
  - ~10^7 CPU-hrs
- Magnetically dominated regime in lo density regions
  - Atmosphere treatment
- Reconnection, current sheets



Ponce *et al* 2014

Challenges: Neutrinos

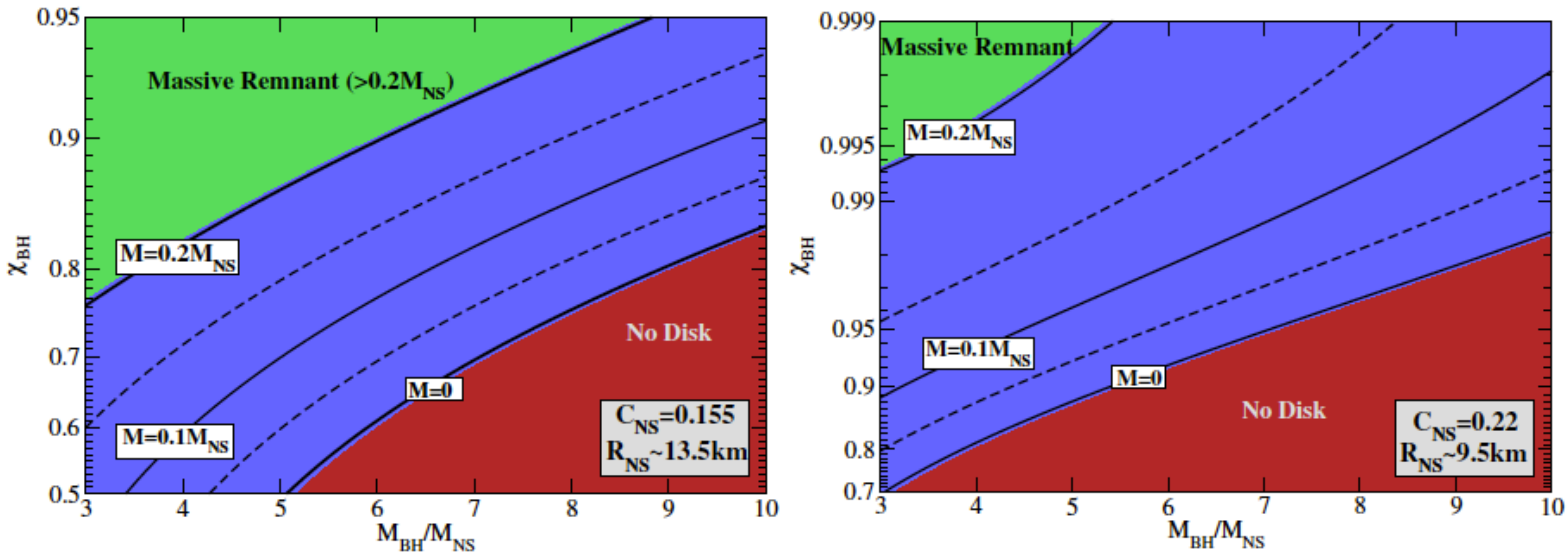
- 6+1-D problem (t, **x**, **p**) => High CPU-cost
  - $$p^\alpha \left[\frac{\partial f_\nu}{\partial x^\alpha} - \Gamma^\beta{}_{\alpha\gamma}\, p^\gamma \frac{\partial f_\nu}{\partial p^\beta}\right] = \left[\frac{df_\nu}{d\tau}\right]_{\rm coll}$$
- Stiff equations: absorption in optically thick regions, redshift terms
- Simplified formalisms exist, but only order-of-magnitude accurate (or with known artifacts)
- See simulations later in this talk…

Results

Results

BH-NS "Disruption Line"

Foucart 2012



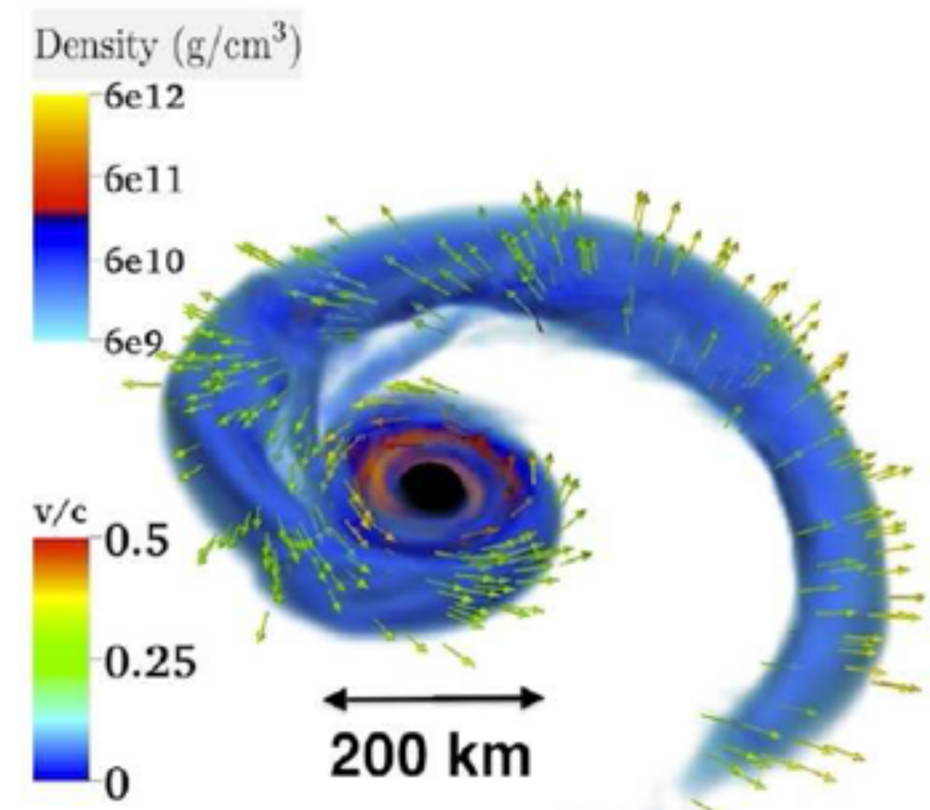
Approximate disruption condition from NR simulations:

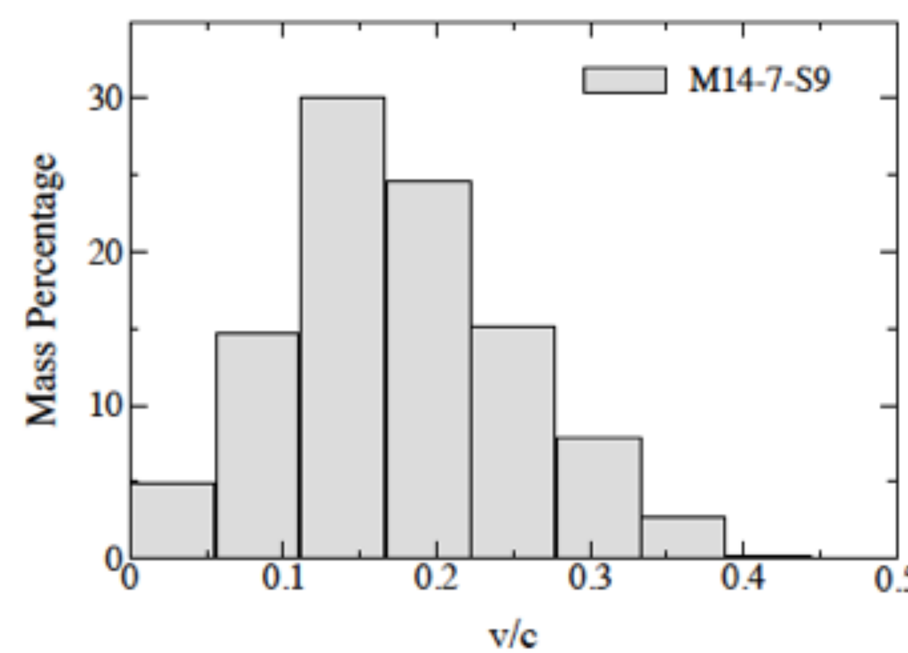
$$C_{NS} \lesssim \left(2 + 2.14 q^{2/3} \frac{R_{ISCO}}{6 M_{BH}}\right)^{-1}$$

BhNs Mergers: Outflows

Foucart et al. 2013/4; Kyutoku et al. 2013; Lovelace et al. 2013, Deaton et al. 2013; Hotokezaka et al. 2014

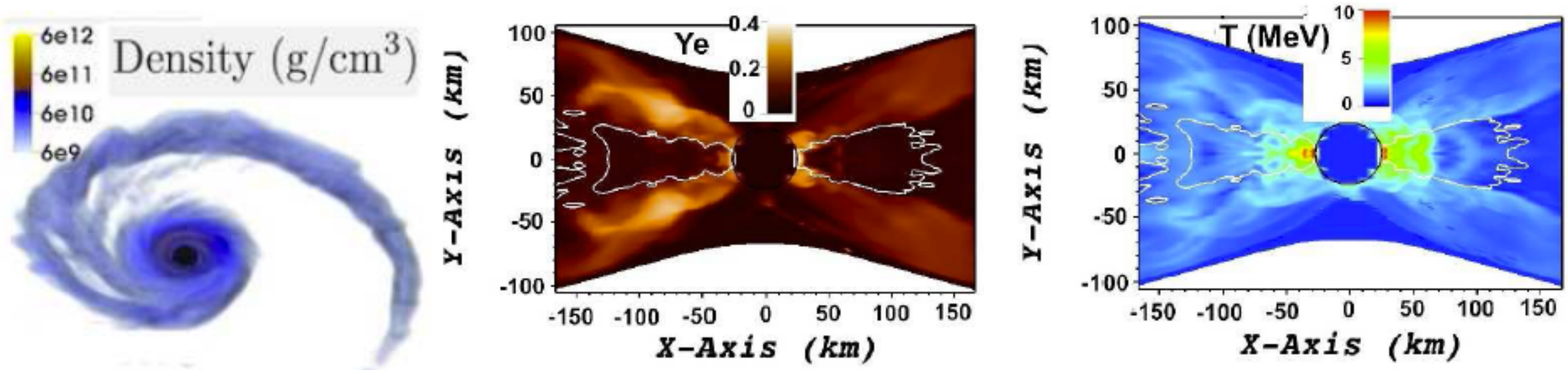
- NS disruption:
  - More ejecta than NS-NS
  - Anisotropic => kicks
  - Low T, neutron rich
  - Strong r-process
- Disk outflows (e.g. Fernandez & Metzger 2014)
  - Probably subdominant





Accretion Disks

Foucart et al 2014

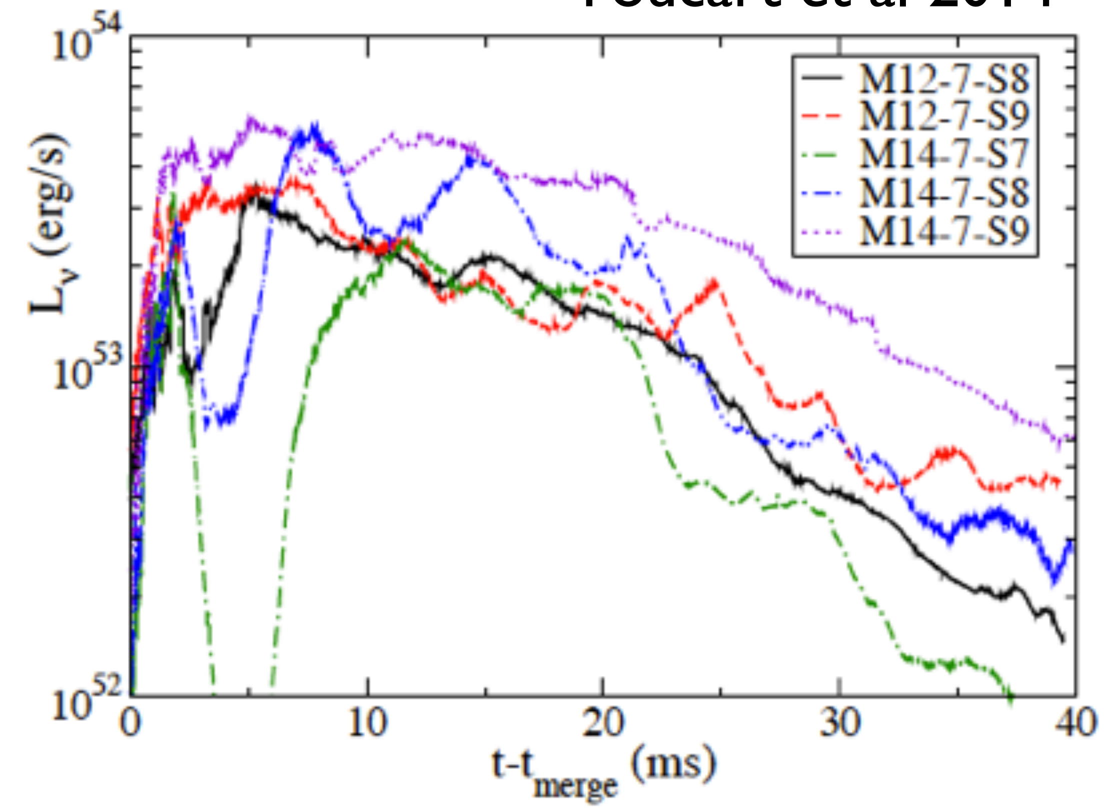


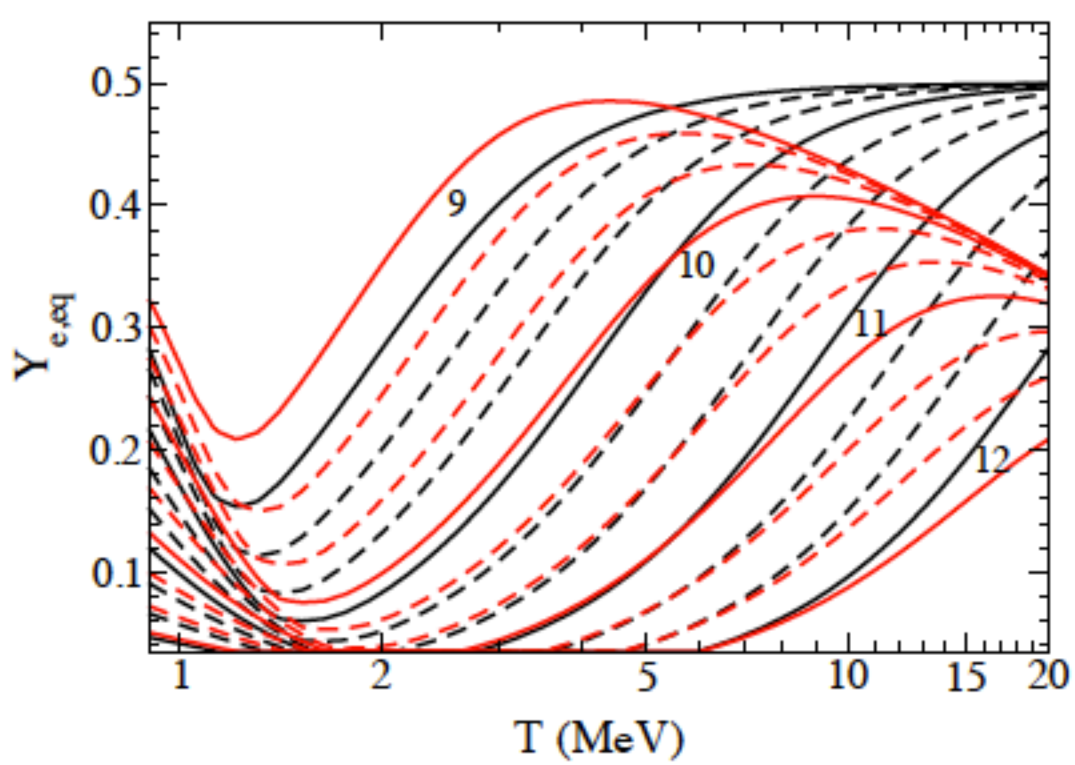
- Massive dynamical ejecta
- Disk with T~5-10 MeV
- Core neutron rich, Ye<0.1
  - But Ye~0.2-0.4 in low-density regions

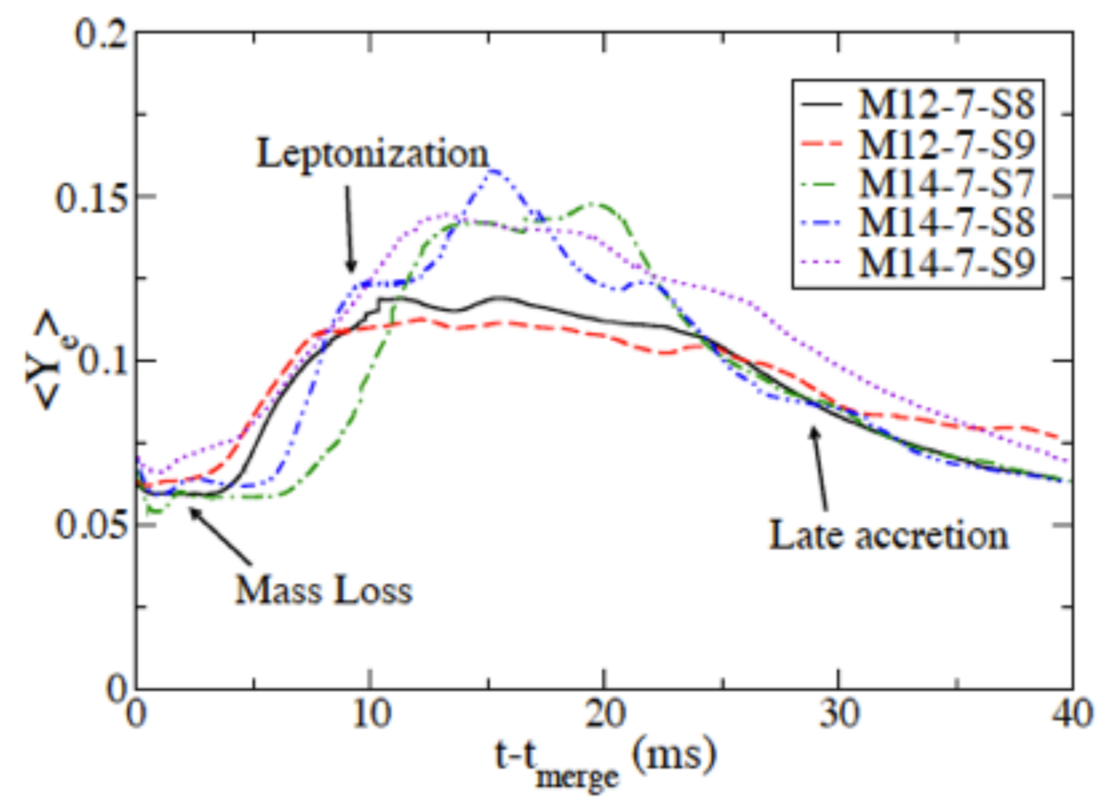
Neutrino Emission

- No impact before merger
- Main source of cooling
- Energy deposition
- Sets Ye in disk / outflow

Foucart et al 2014

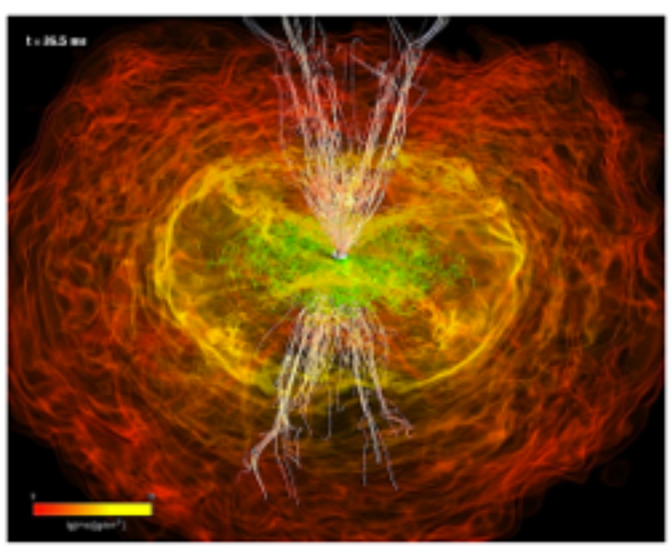




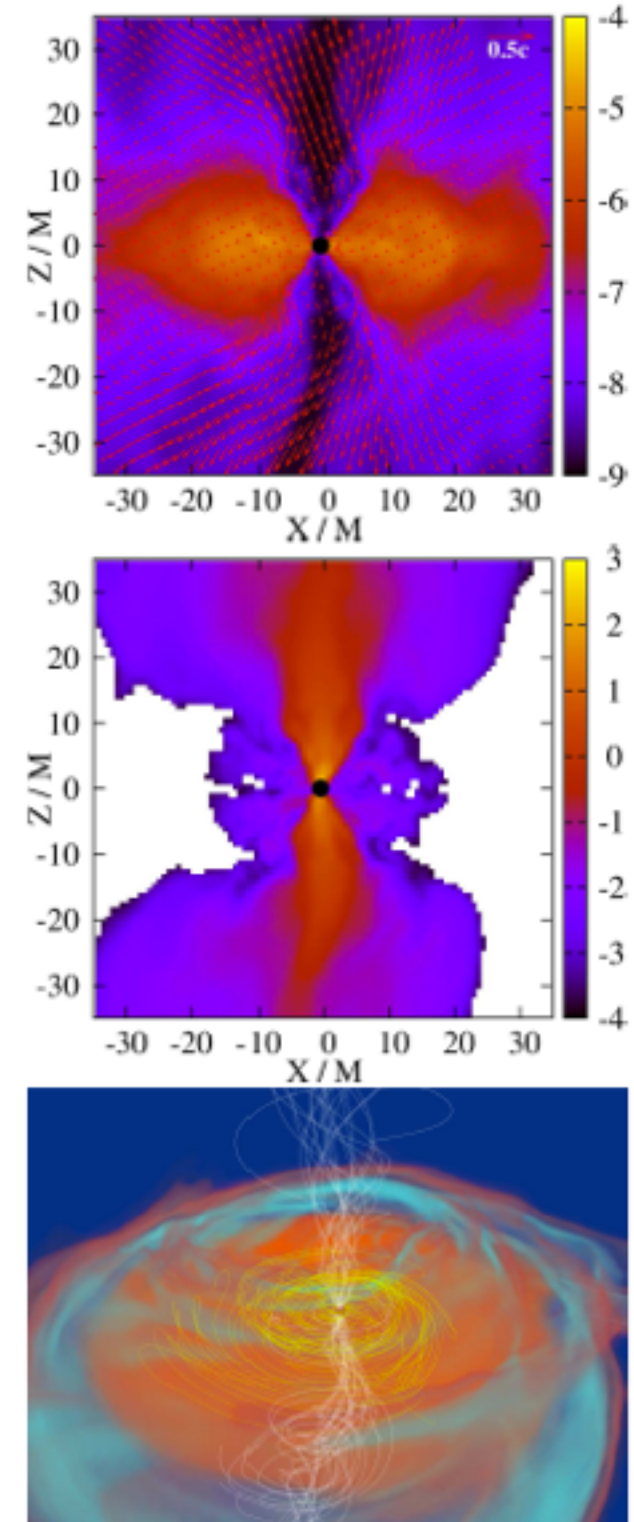


Magnetic fields - Jets?

- Dynamically not important before merger
  - EM precursors?
- Critical post-merger (MRI, jets, winds)
- Hard to resolve numerically



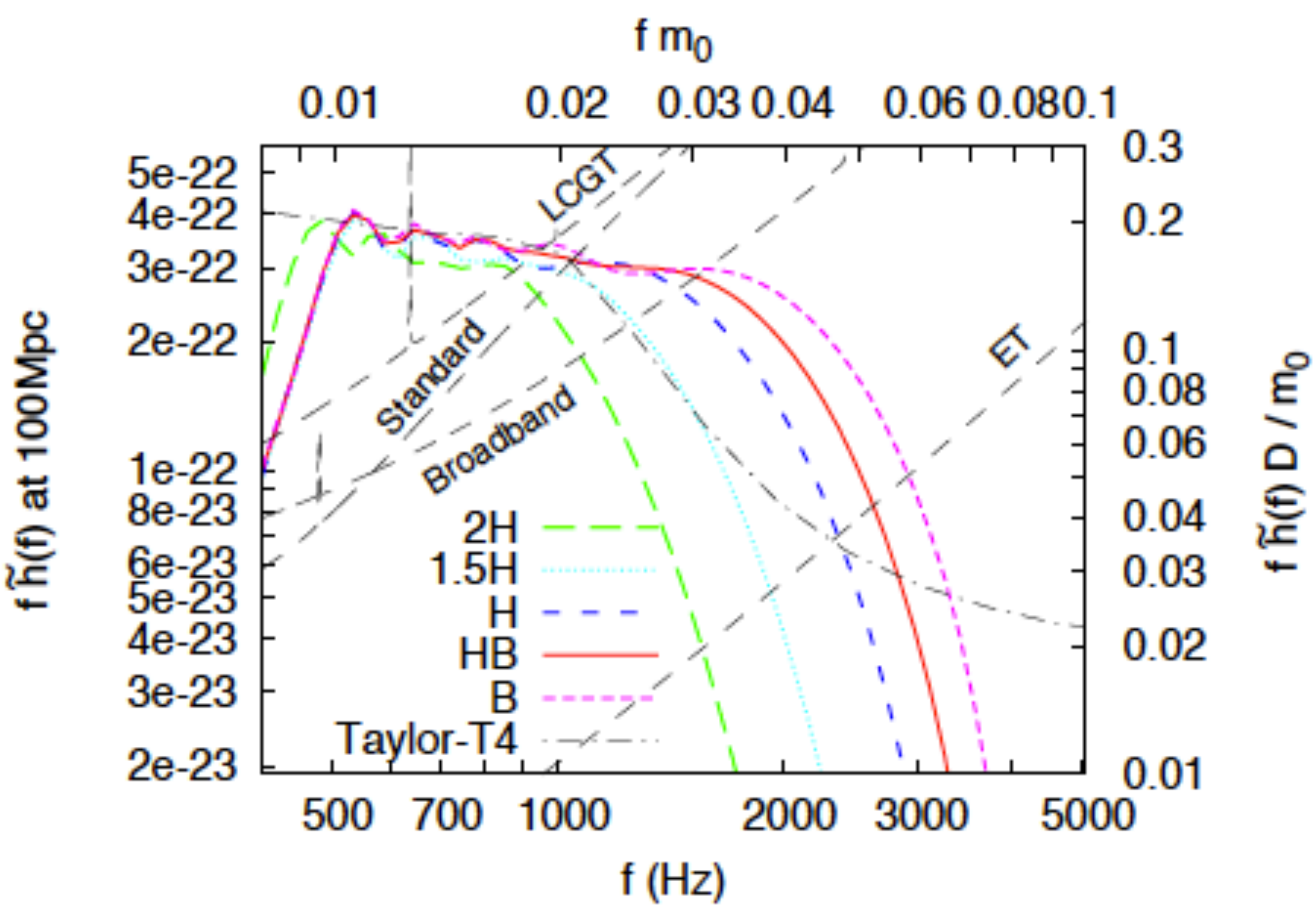
Rezzolla et al. 2011



Etienne et al 2012

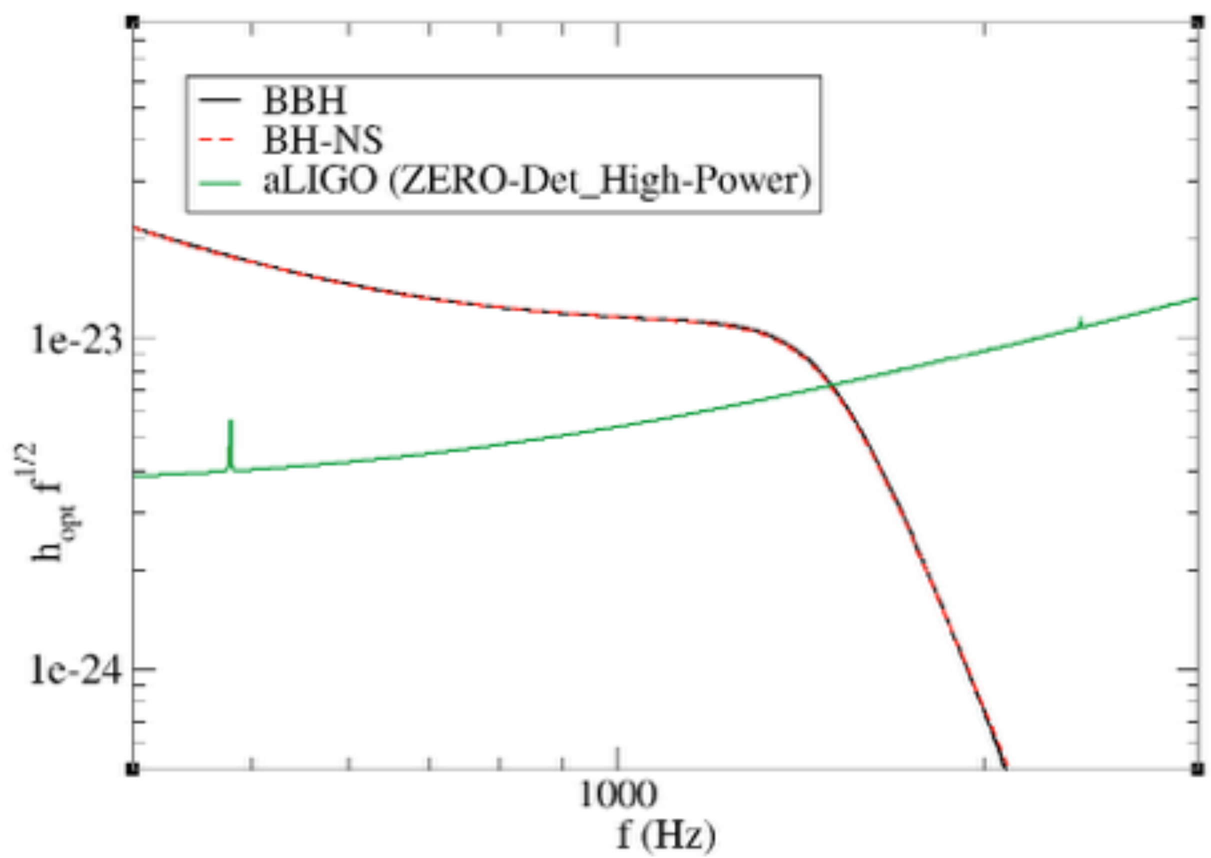
Gravitational Waves

GW signal - low mass



Kyutoku et al. 2011

GW signal - high mass



Foucart et al 2013

- Finite size effects matter for low mass systems / high spins
- Weak effects for “typical” NS-BH system

Neutrino Treatment

- Leakage (Deaton et al. 2013, Foucart et al. 2014)
  - Cooling only, possibly ad-hoc heating
- Moment Scheme (from Shibata et al. 2011)
  - Closure, Crossing beams, Stiff equations
- Radiation Transport
  - Very expensive…

Moment Formalism

$$T^{\mu\nu} = En^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + P^{\mu\nu}$$

$$\begin{aligned}
\partial_t \tilde{E} &+ \partial_j(\alpha \tilde{F}^j - \beta^j \tilde{E}) \\
&= \alpha(\tilde{P}^{ij} K_{ij} - \tilde{F}^j \partial_j \ln\alpha - \tilde{S}^\alpha n_\alpha) \\
\partial_t \tilde{F}_i &+ \partial_j(\alpha \tilde{P}_i^j - \beta^j \tilde{F}_i) \\
&= (-\tilde{E}\partial_i \alpha + \tilde{F}_k \partial_i \beta^k + \frac{\alpha}{2} \tilde{P}^{jk} \partial_i \gamma_{jk} + \alpha \tilde{S}^\alpha \gamma_{i\alpha})
\end{aligned}$$

$$\tilde{S}^\alpha = \sqrt{\gamma}\,(\eta u^\alpha - \kappa_a J u^\alpha - (\kappa_a + \kappa_s) H^\alpha)$$

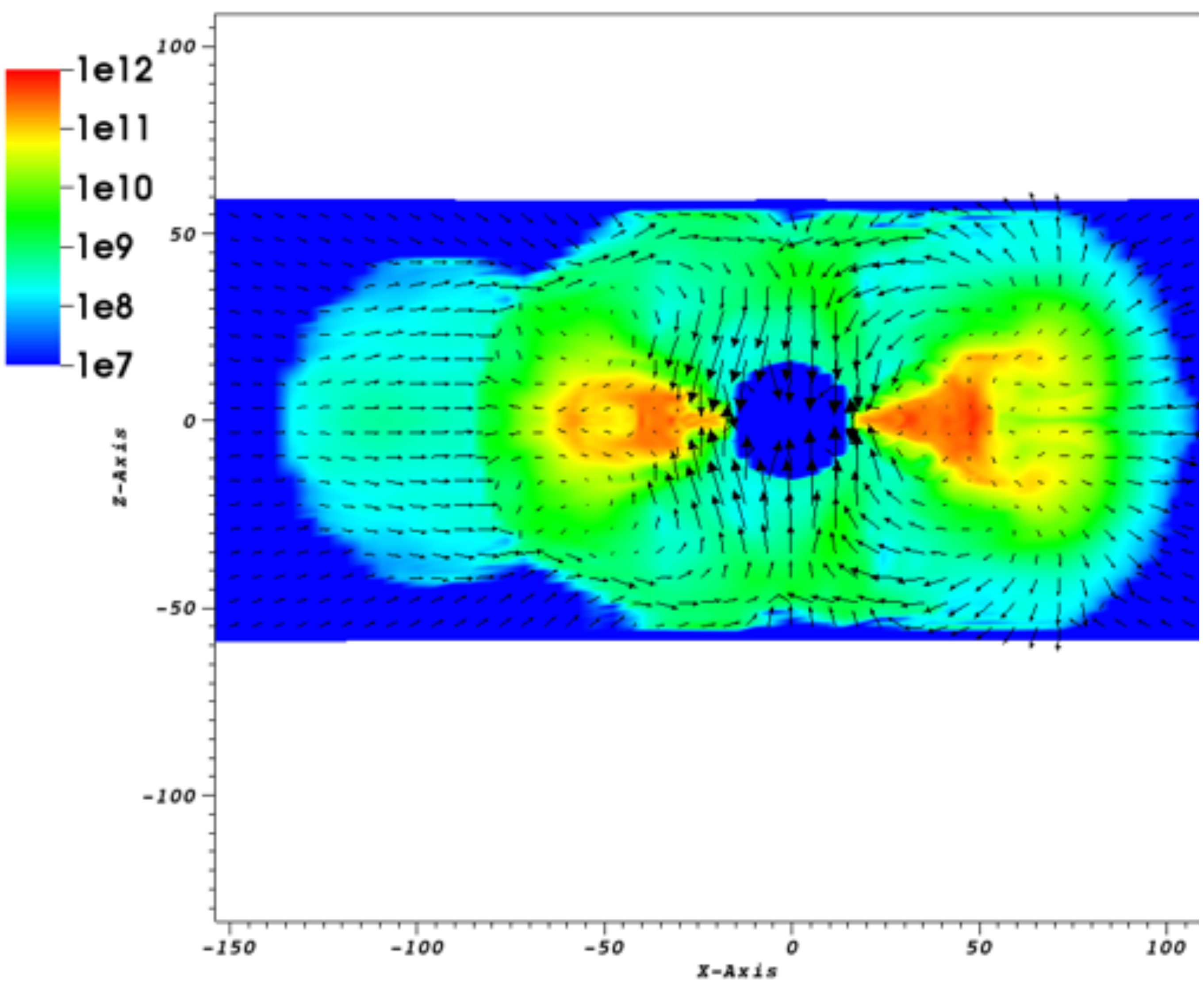
$$P^{ij} = \frac{3\chi(\zeta) - 1}{2} P^{ij}_{\text{thin}} + \frac{3(1 - \chi(\zeta))}{2} P^{ij}_{\text{thick}}$$

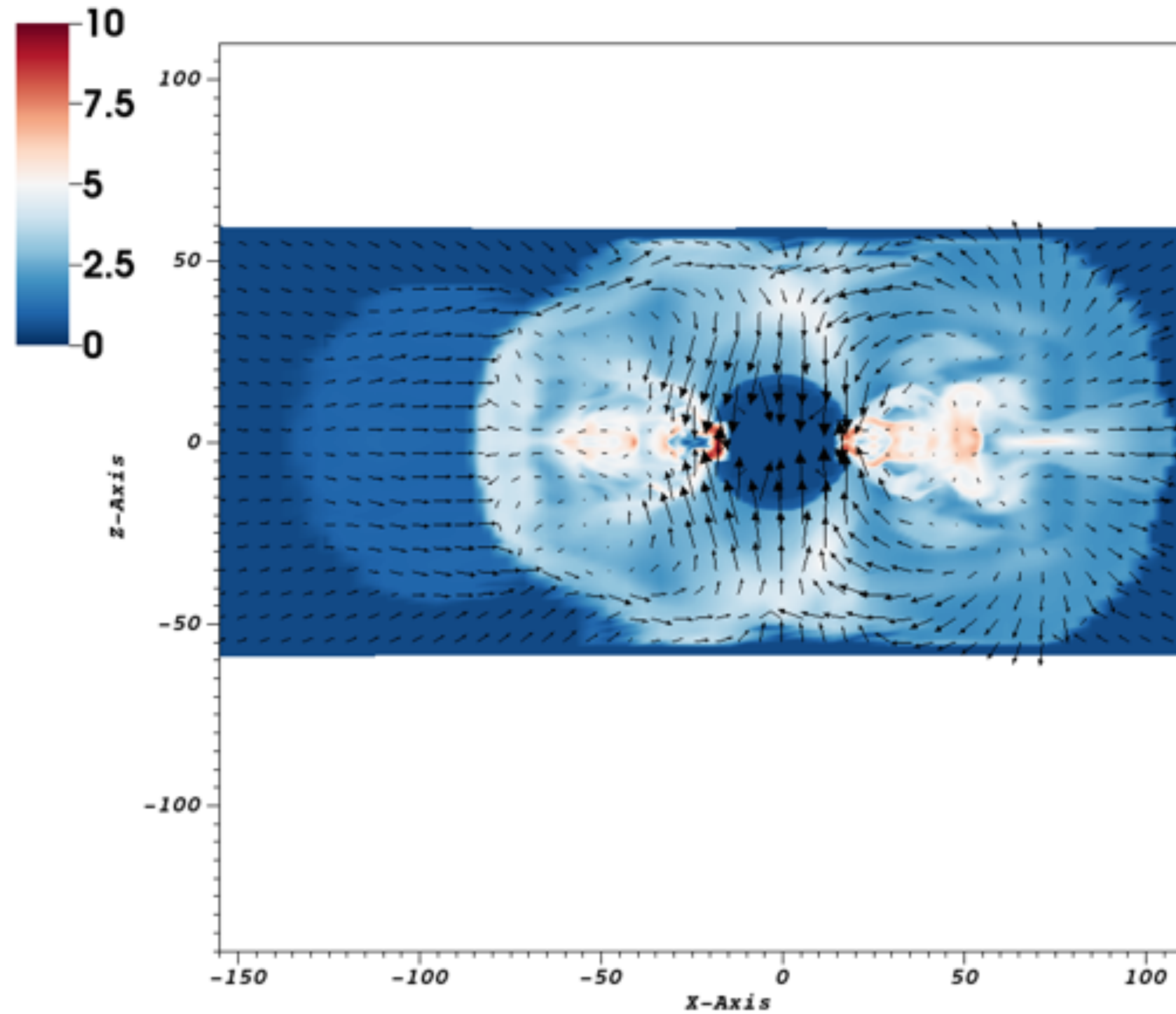
- Issues:
  - Closure!
  - Grey approx.
  - Stiff terms

M1 Results

- Global properties similar to leakage results

9ms after merger:

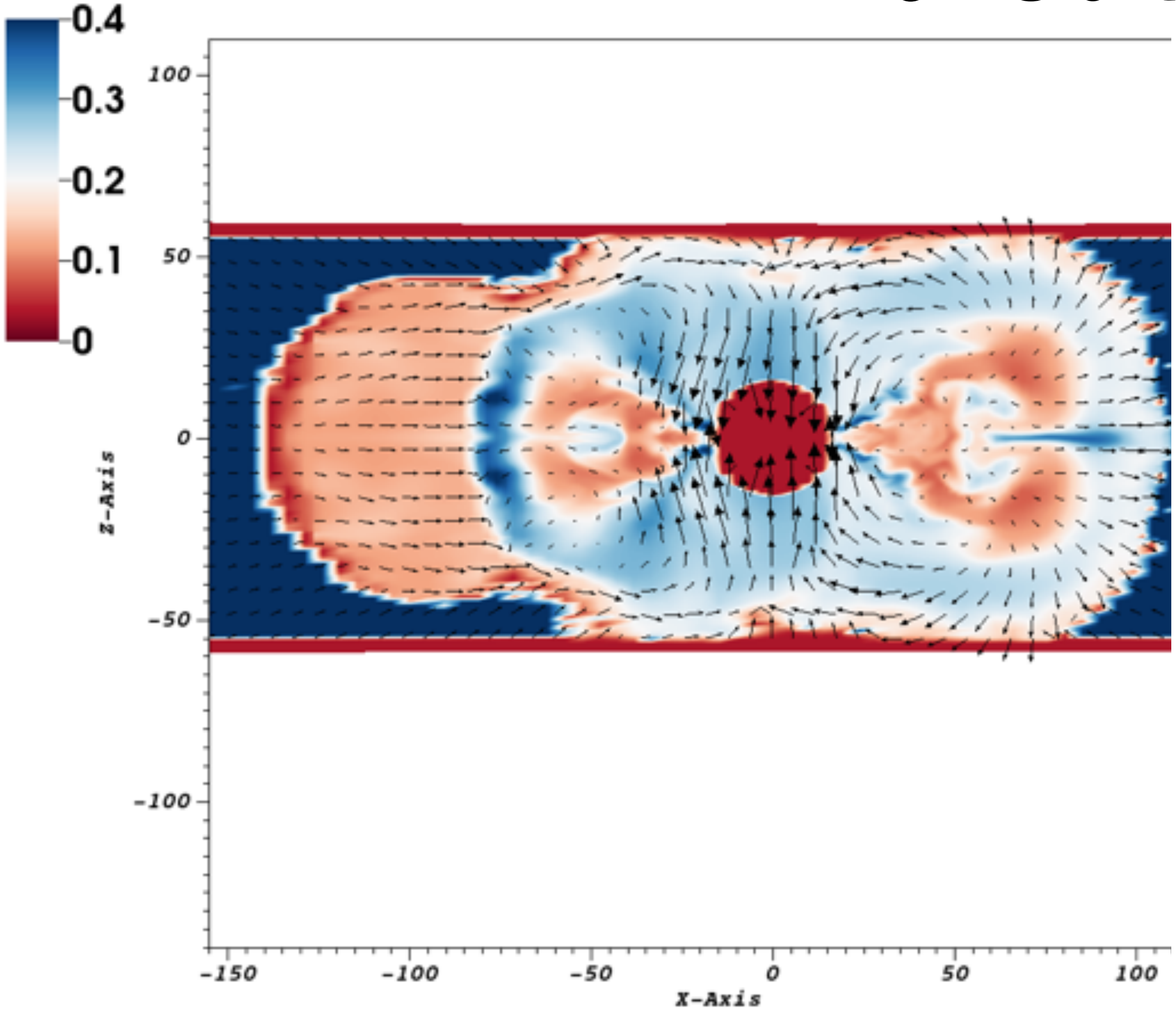


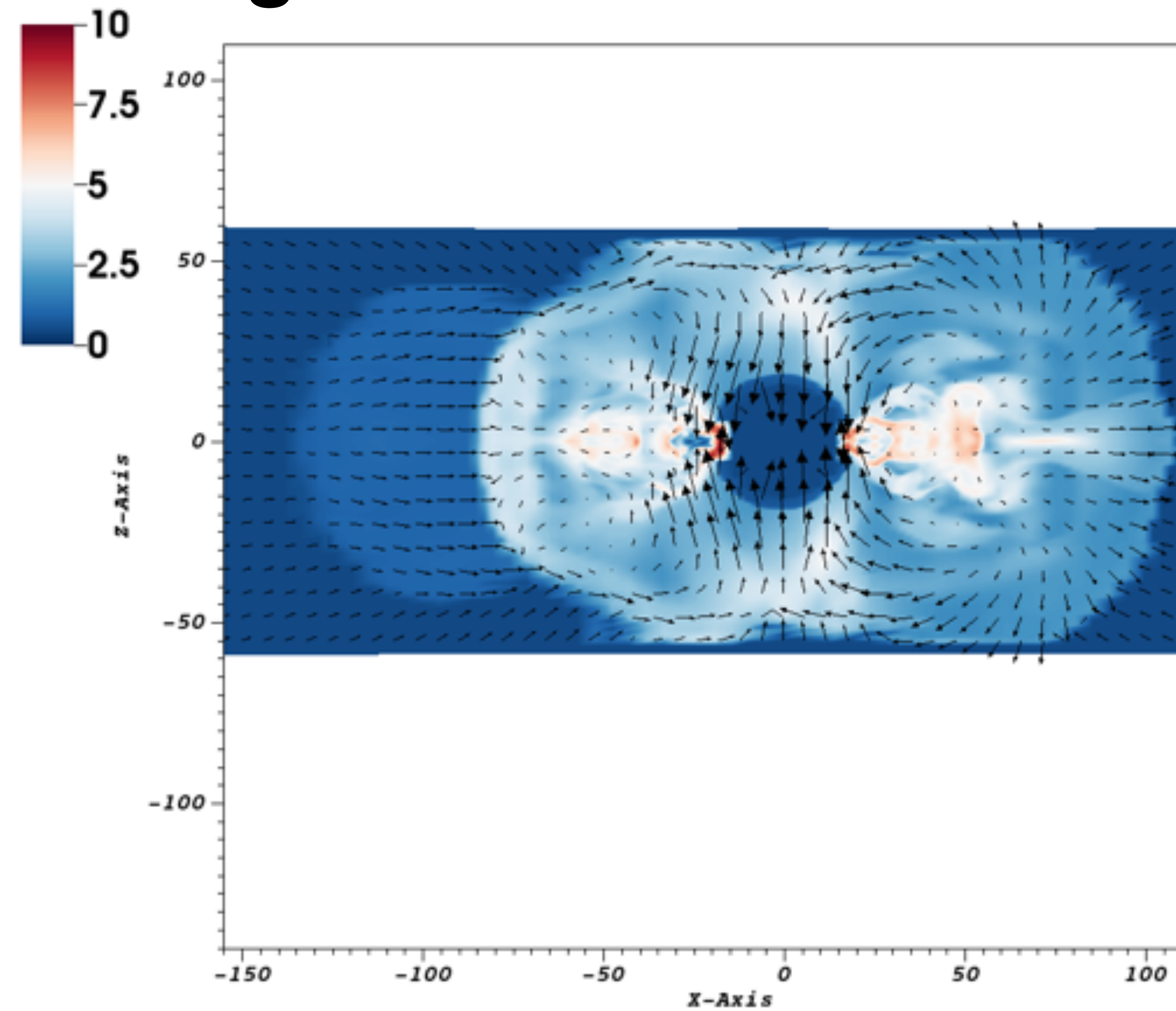


M1 Results

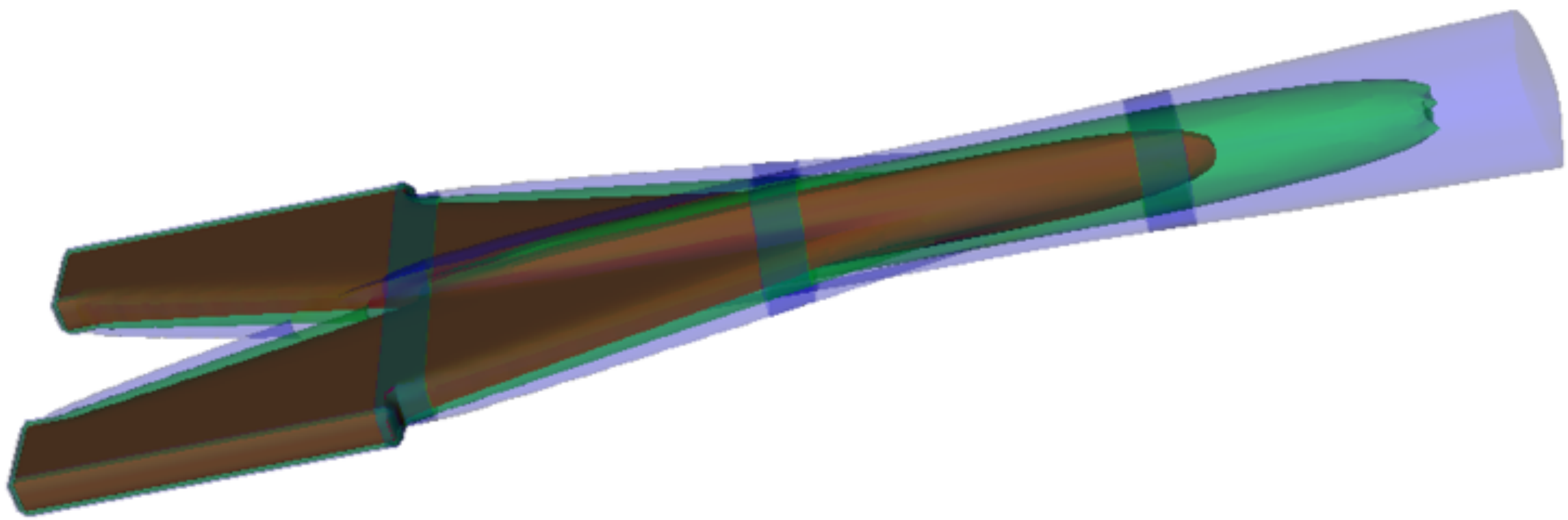
- Global properties similar to leakage results

9ms after merger:





M1 Problems

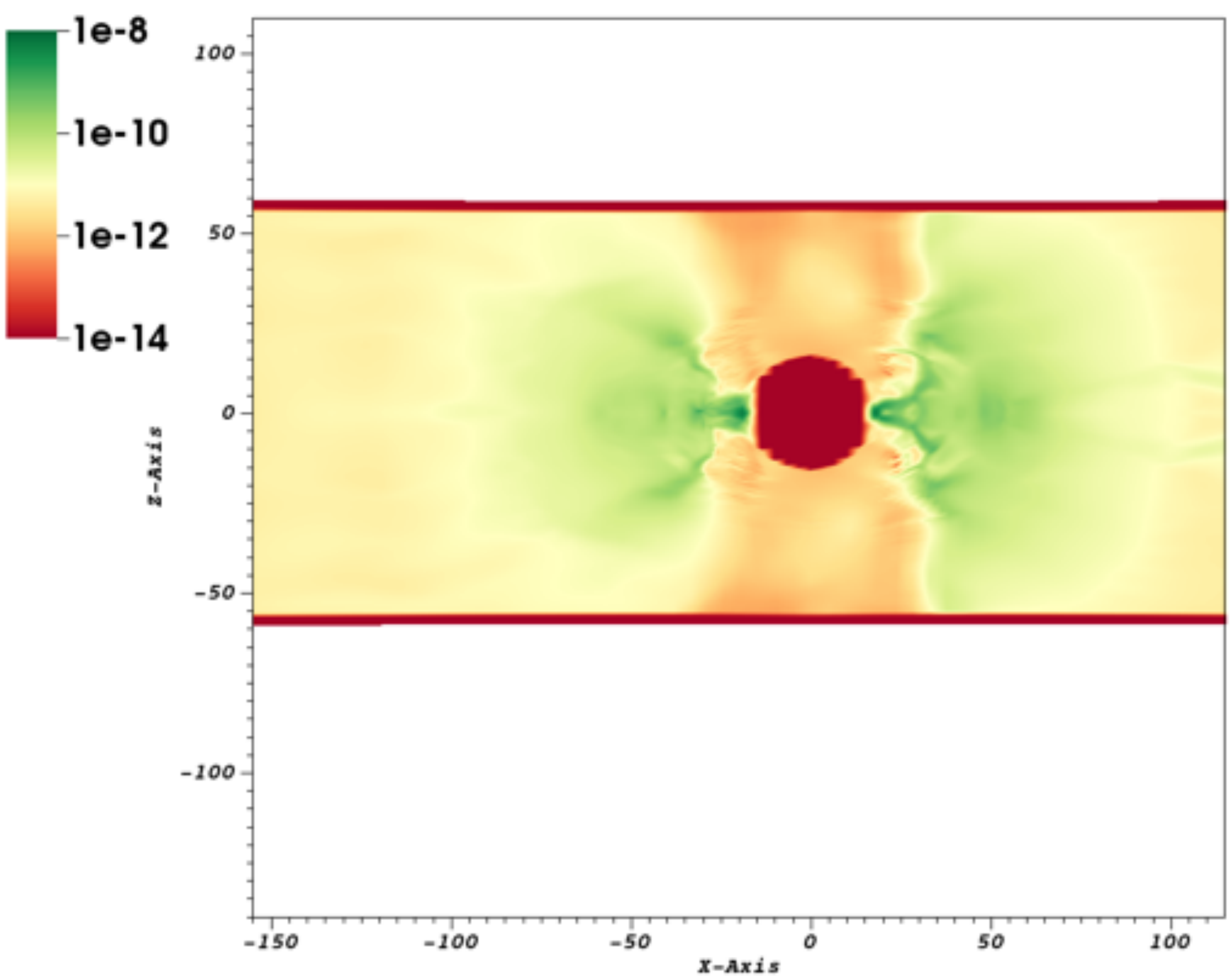


Can’t handle crossing beams!

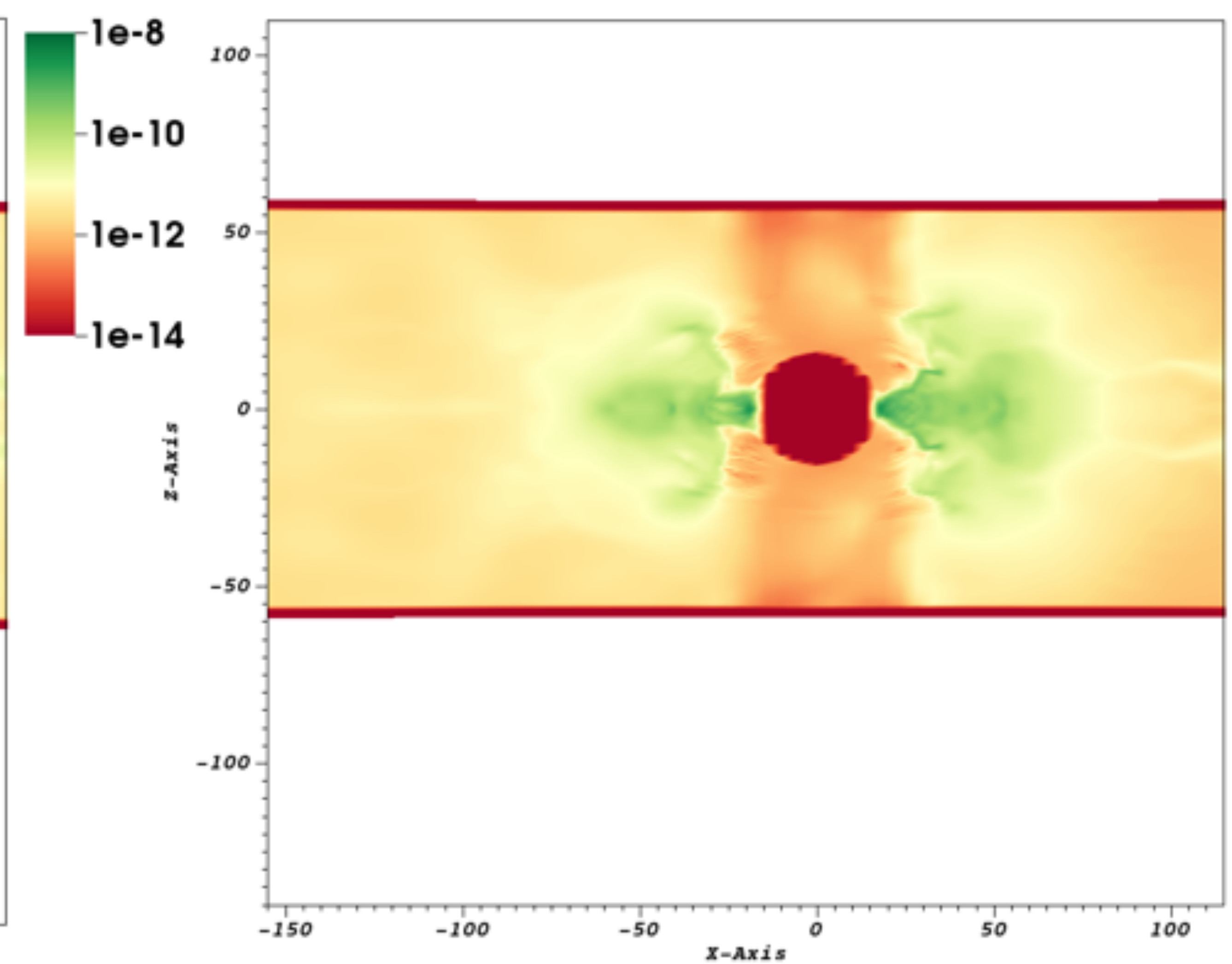
M1 Results

9ms after merger:

Antineutrinos



Neutrinos



Conclusions

- Can predict disruption / global properties
- GW not as promising as BNS
  - Work still necessary on modeling
- Improved microphysics
  - Can we get a jet?
  - Neutrino energy deposition?
  - Wind & Composition?