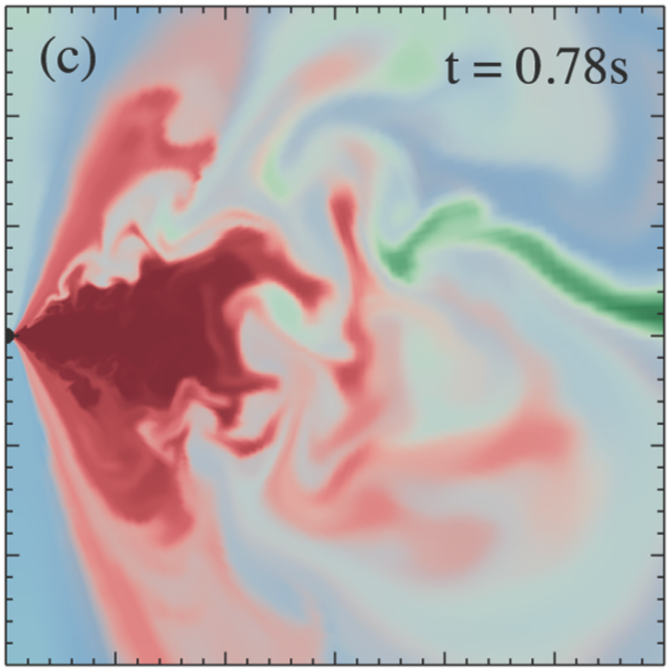
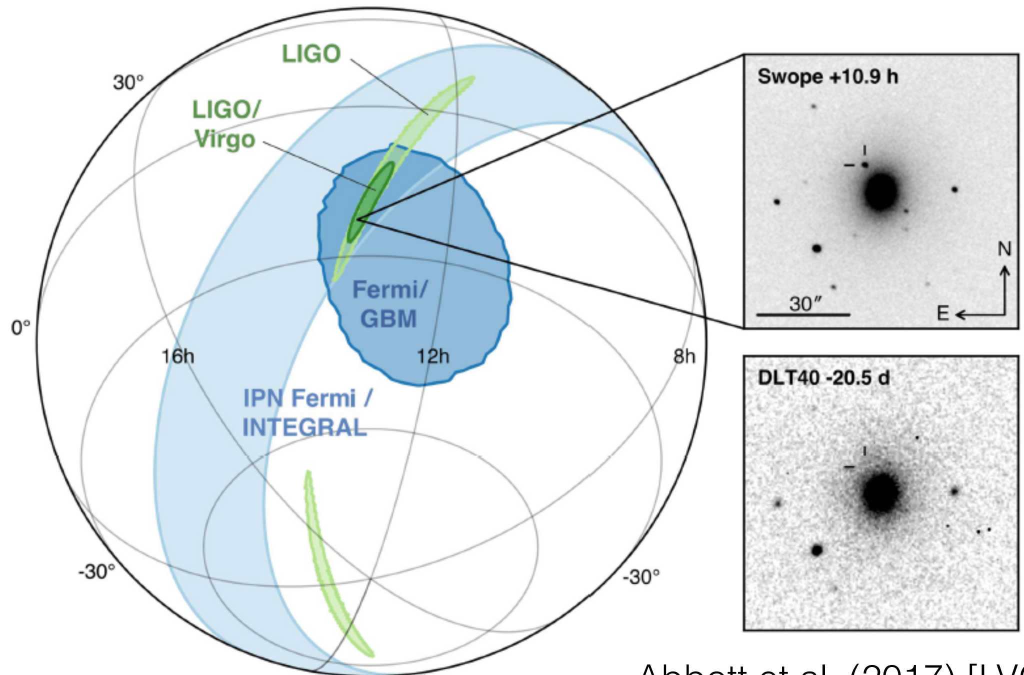




Abbott et al. (2017) [LVC]

Simulations of Post-Merger Evolution: Mass Ejection

Rodrigo Fernández (University of Alberta)

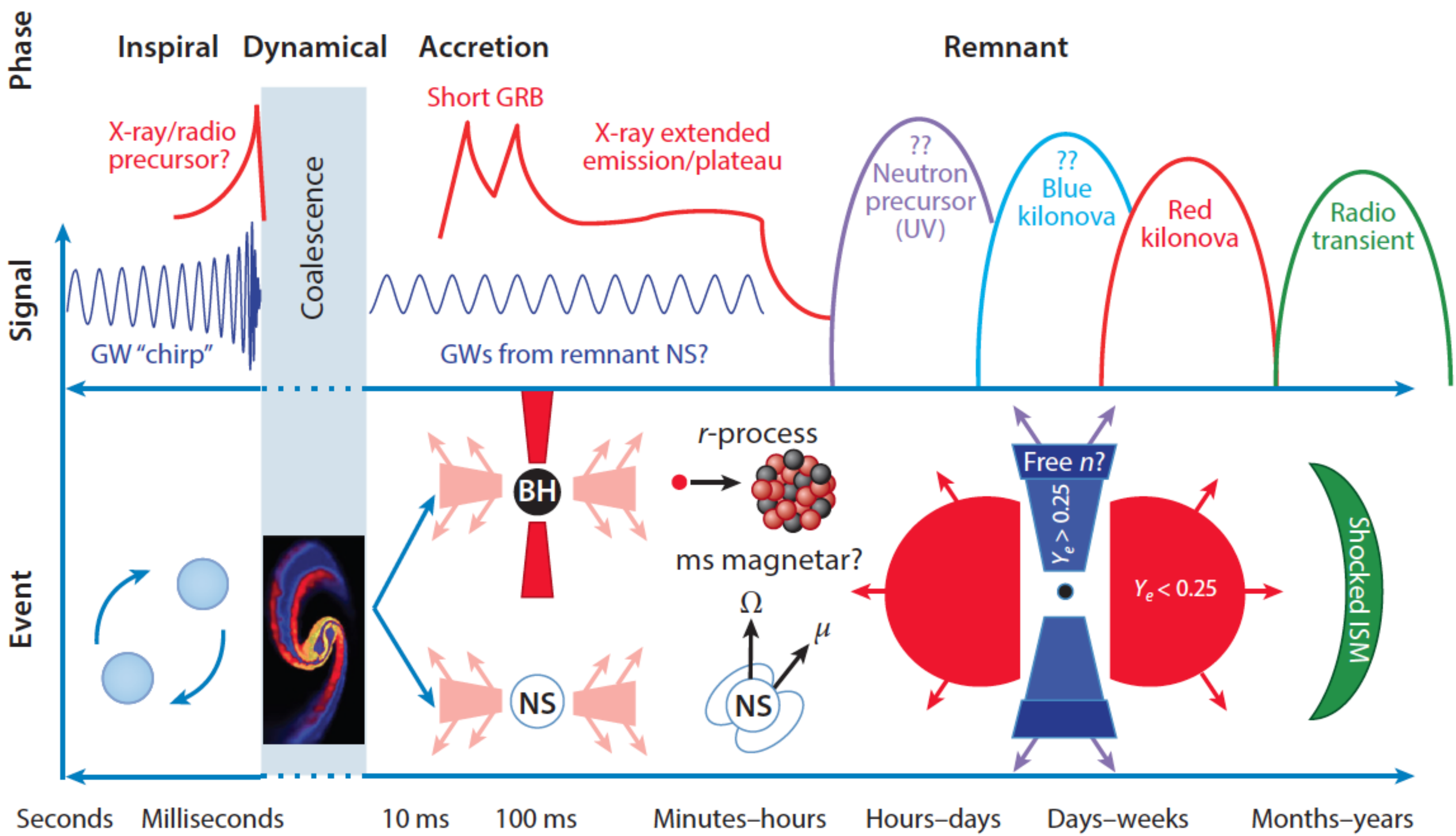
Overview

1. Timescales and processes

2. Accretion disk evolution

3. Challenges

Neutron Star Mergers



RF & Metzger (2016)

Reference Numbers

$$M \sim M_\odot = 2 \times 10^{30}\ \mathrm{kg}$$

GR:

$$r_g = \frac{GM}{c^2} \sim 1.5\ \mathrm{km}$$

$$R \sim 10\ \mathrm{km}$$

GWs:

$$t_{\mathrm{dyn}} = 2\pi \left(\frac{R^3}{GM}\right)^{1/2} \sim 10^{-3}\ \mathrm{s} \longrightarrow f_{\mathrm{GW}} \lesssim 1\ \mathrm{kHz}$$

$$\tau_\nu \sim \frac{R}{\ell_\nu} \sim \left(\frac{\varepsilon_\nu}{15\ \mathrm{MeV}}\right)^2 \left(\frac{\rho}{10^{11}\mathrm{g\ cm}^{-3}}\right)$$

Neutrinos

$$\frac{kT_{\mathrm{vir}}}{m_n} \sim \frac{GM}{R}$$

$$\downarrow$$

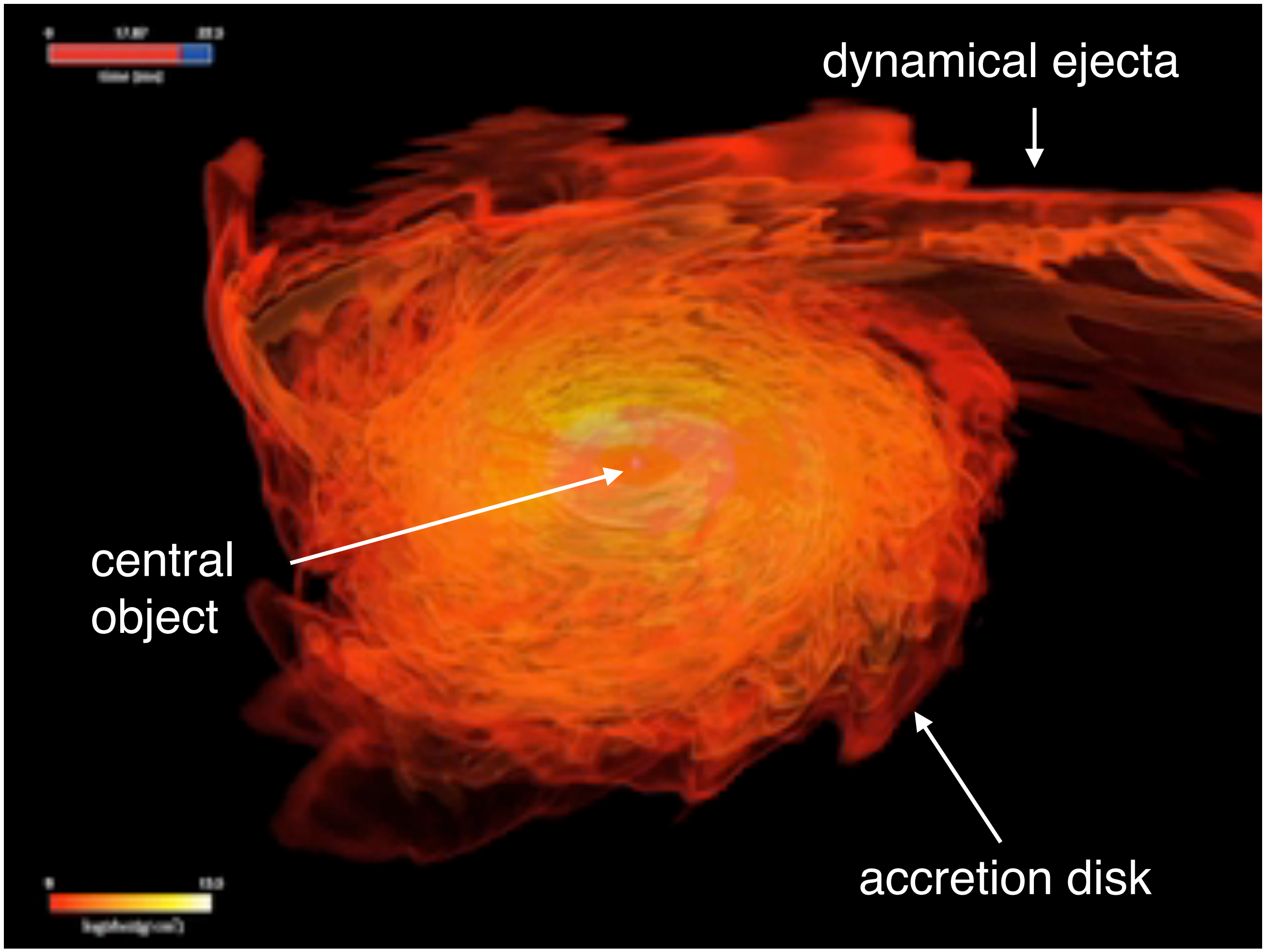
$$kT_{\mathrm{vir}} \sim 100\ \mathrm{MeV}$$

$$\bar{\rho}_{\mathrm{NS}} \sim \frac{M}{R^3} \sim 10^{15}\ \mathrm{g\ cm}^{-3}$$

Nuclear physics

Dynamical Phase: Merger

Unequal mass NS-NS merger:



Rezzolla+ (2010)

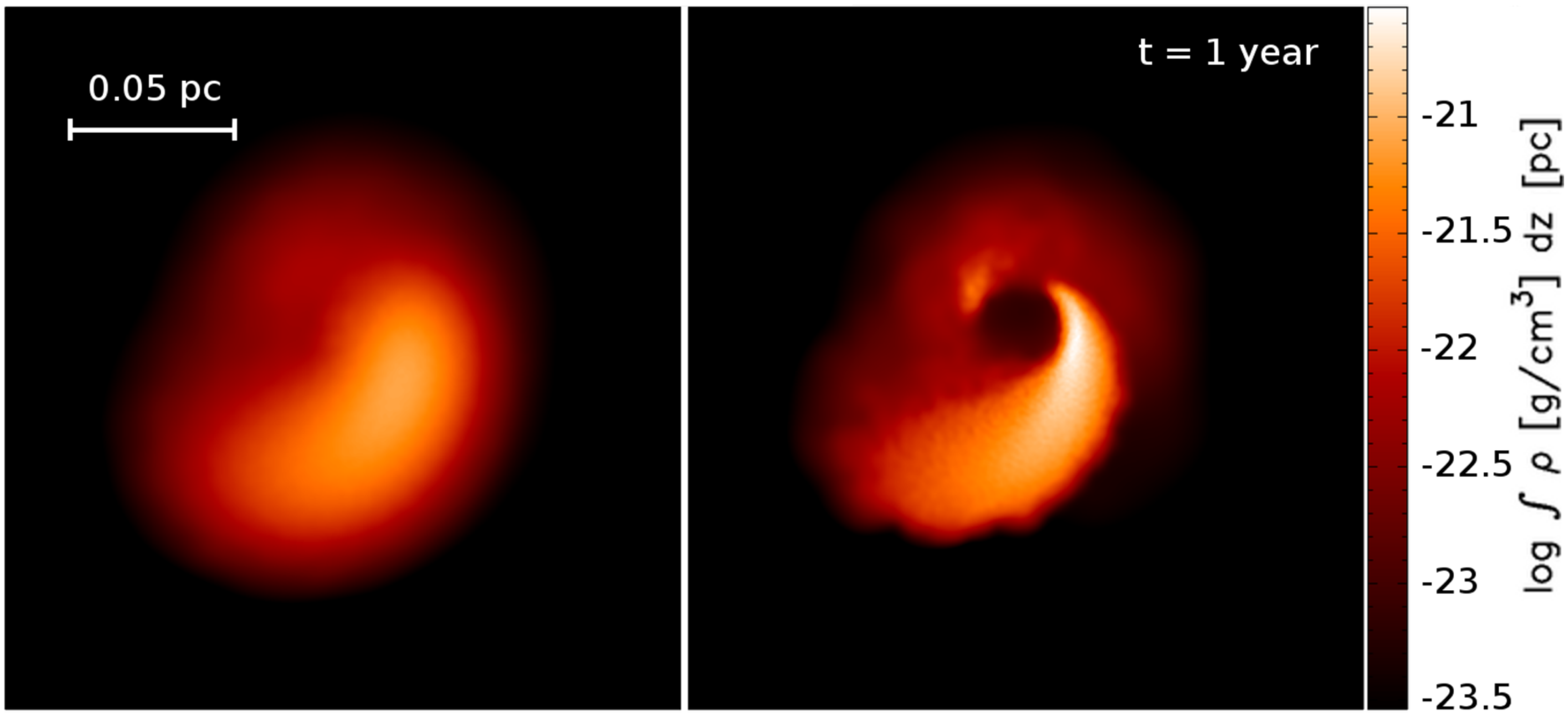
Phases:

- inspiral
- merger
- remnant + ejecta
- relativistic jet (?)

Large body of work:

MPA, Kyoto, Caltech-Cornell-CITA
Princeton, Frankfurt, Trento,
Stockholm, Illinois, Perimeter, etc.

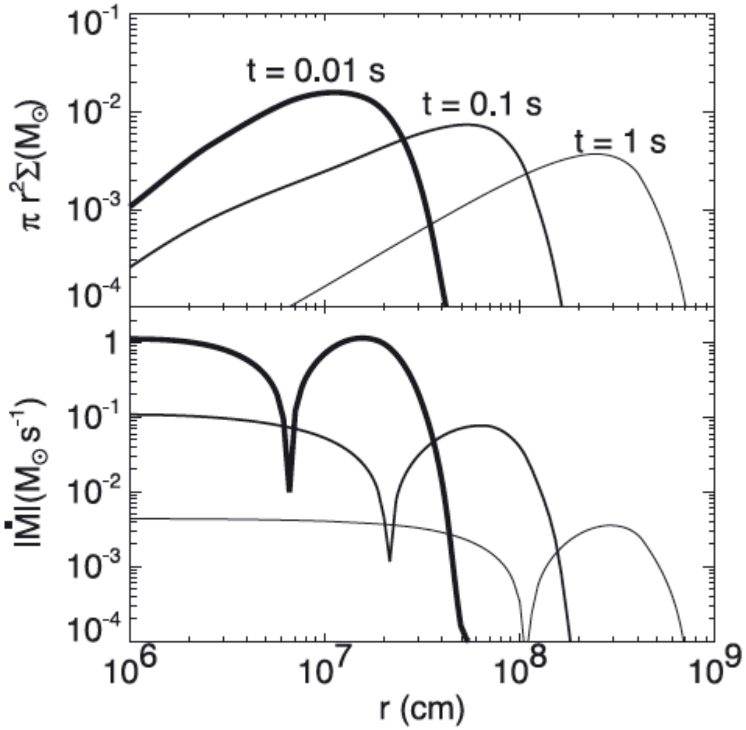
Late-time dynamical ejecta



Rosswog+ (2014)

Disk evolution

Evolution of surface density and accretion rate



Metzger+ (2008)

also Popham+ (1999), Chen & Beloborodov (2003)

$$t_{\rm orb} \simeq 3R_{50}^{3/2}M_3^{-1/2}\ {\rm ms}$$

$$t_{\rm visc} \simeq 1\alpha_{0.03}^{-1}R_{50}^{3/2}M_3^{-1/2}\,(H/3R)\ \ {\rm s}$$

$$t_{\rm therm} \simeq \frac{c_s^2}{v_K^2}t_{\rm visc} \lesssim t_{\rm visc}$$

- Disk evolves on timescales long compared to the dynamical (orbital) time, due to viscous processes
- Weak interactions freeze-out as the disk spreads viscously: final Ye
- Gravitationally-unbound outflows driven by:

  - Neutrino heating (on thermal time)

    Ruffert & Janka (1999), Dessart+ (2009)

  - Viscous heating and nuclear recombination (on viscous time)

    $$\frac{E_\alpha}{GM_{\rm BH}/R} \simeq 1R_{600}M_3^{-1}$$ Metzger+ (2009)

  - MHD stresses

    Kiuchi (2015), Siegel (2017)

Equations

mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$\rho :$ density

$\mathbf{v} :$ velocity

momentum conservation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p = -\nabla \Phi + \frac{1}{\rho}\nabla \cdot \mathbb{T}$$

gas pressure

gravity

angular mom. transport

$p :$ pressure

energy conservation:

$$\frac{De_{\rm int}}{Dt} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = \frac{1}{\rho^2 \nu}\mathbb{T} : \mathbb{T} + Q_{\nu,\rm abs} - Q_{\nu,\rm em}$$

viscous heating

neutrino heating

neutrino cooling

$e_{\rm int} :$ int. energy

lepton # conservation:

$$\frac{DY_e}{Dt} = \Gamma_{\nu,\rm abs} + \Gamma_{\nu,\rm em}$$

neutrino absorption

neutrino emission

EOS:

$$p = p(\rho, e_{\rm int}, Y_e)$$

$$Y_e = \frac{n_e}{n} = \frac{n_e}{\rho / m_n}$$

$Y_e :$ electron fraction

Equations

mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

hydrodynamics: FLASH

momentum conservation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p = -\nabla\Phi + \frac{1}{\rho}\nabla \cdot \mathbb{T}$$

gas pressure

gravity

angular mom. transport

pseudo-Newtonian gravity

energy conservation:

$$\frac{De_{\rm int}}{Dt} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = \frac{1}{\rho^2 \nu}\mathbb{T} : \mathbb{T} + Q_{\nu,\rm abs} - Q_{\nu,\rm em}$$

viscous heating

neutrino heating

neutrino cooling

α-viscosity

lepton # conservation:

$$\frac{DY_e}{Dt} = \Gamma_{\nu,\rm abs} + \Gamma_{\nu,\rm em}$$

neutrino absorption

neutrino emission

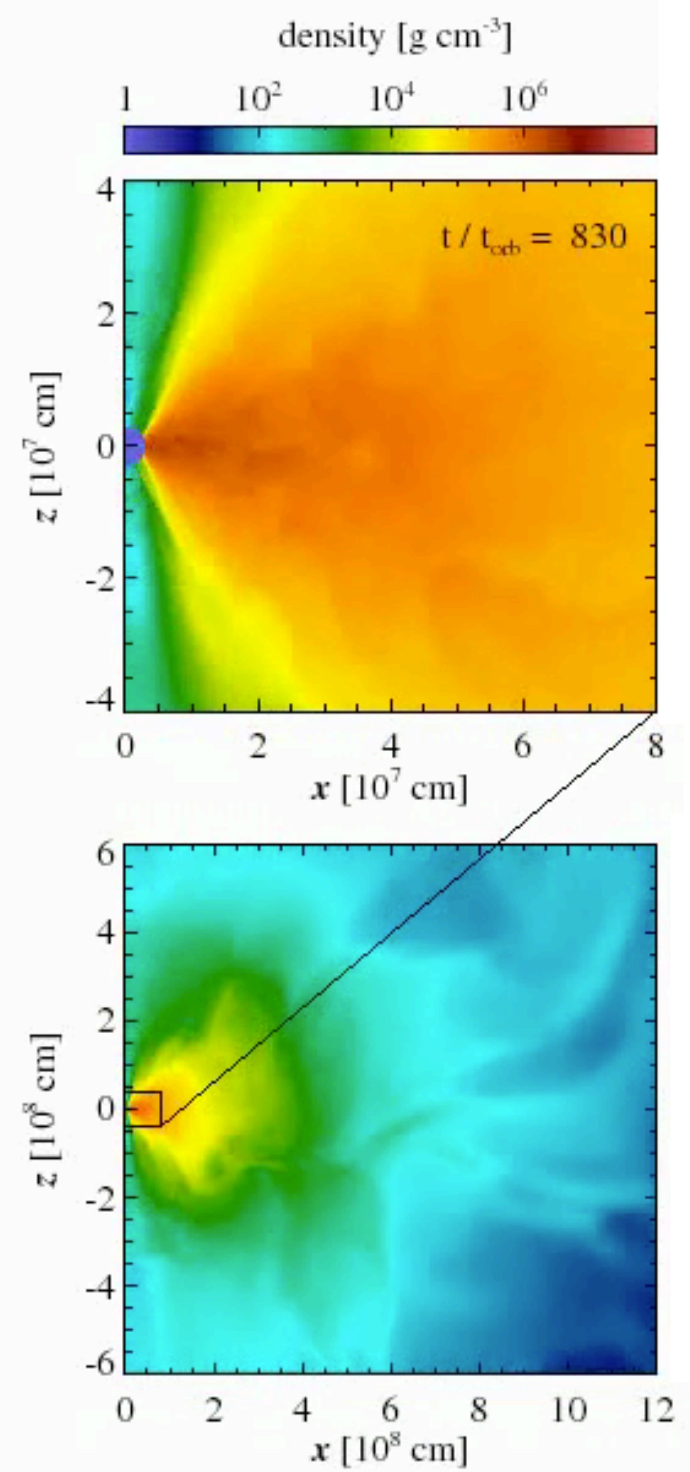
neutrino leakage

lightbulb self-irradiation

EOS:

$$p = p(\rho, e_{\rm int}, Y_e) \qquad Y_e = \frac{n_e}{n} = \frac{n_e}{\rho/m_n}$$

Helmholtz EOS



Wind from remnant accretion disk

- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10-20% of initial disk mass ejected, ~1E-3 to 1E-2 solar masses
- Material is neutron-rich (Ye ~ 0.2-0.4)
- Wind speed (~0.05c) is slower than dynamical ejecta (~0.1-0.3c)

RF & Metzger (2013), MNRAS

Just et al. (2015), MNRAS

RF et al. (2015), MNRAS

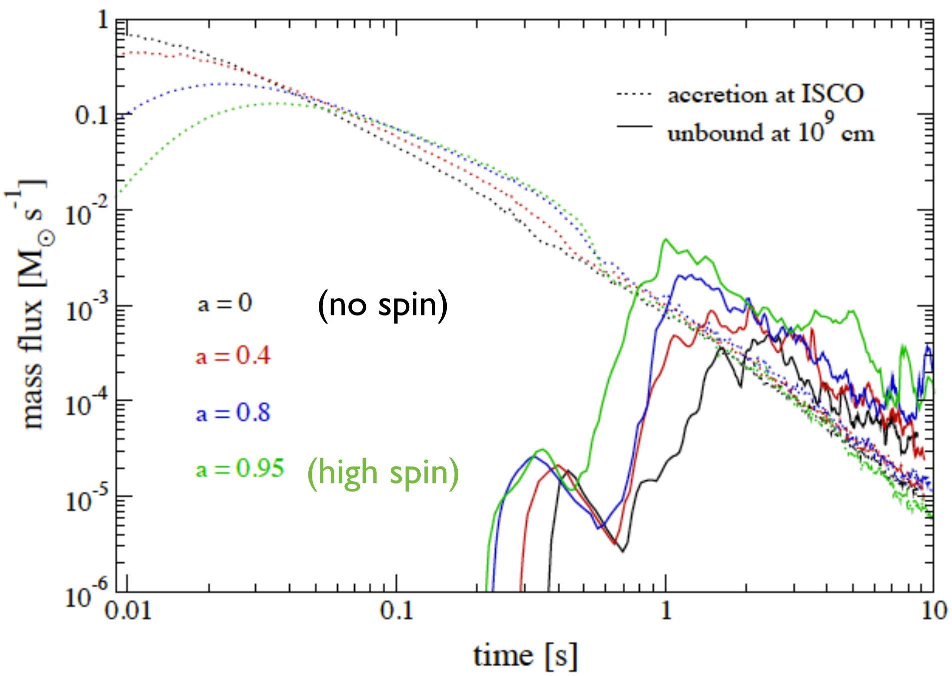
Setiawan et al. (2005)

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)

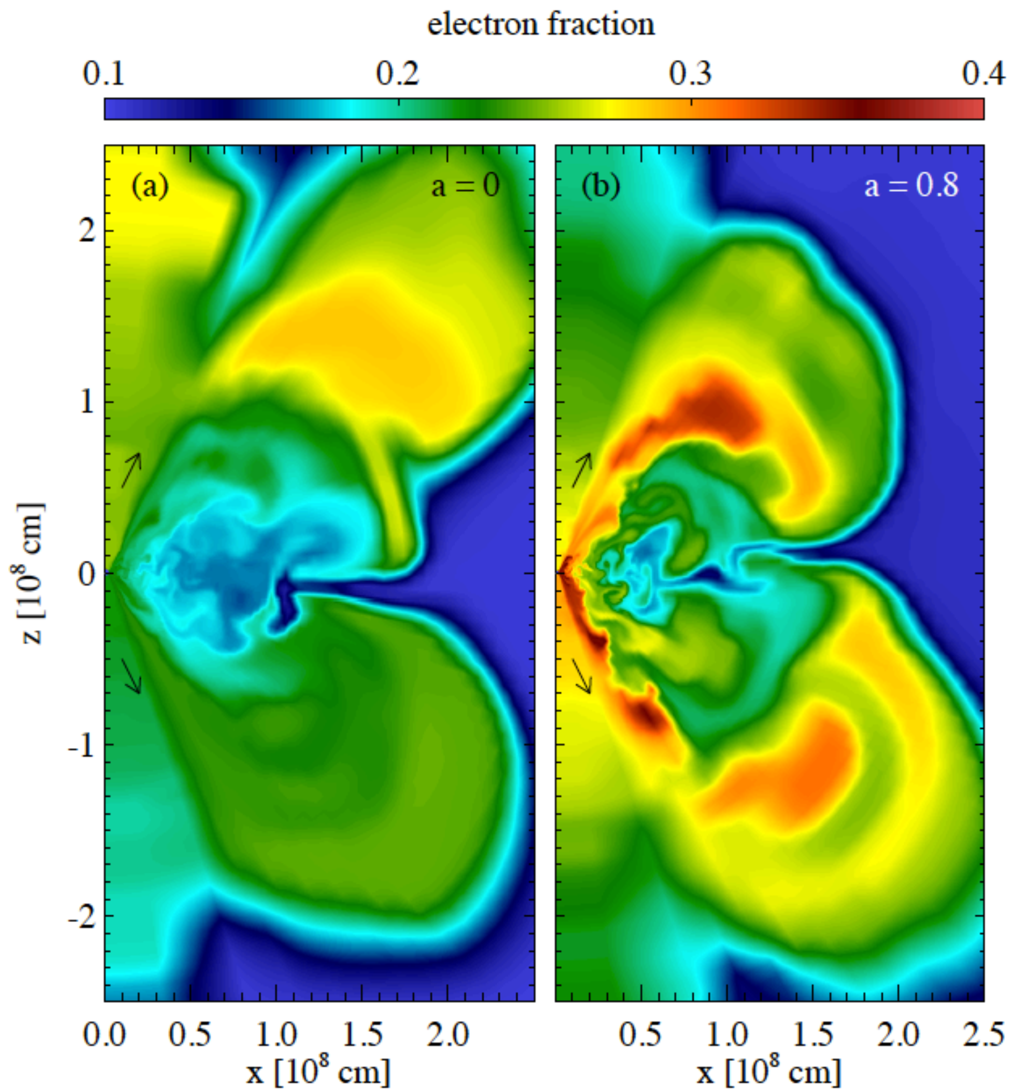
Metzger (2009)

Effect of BH spin on disk wind

Mass ejection as a function of time (solid lines):

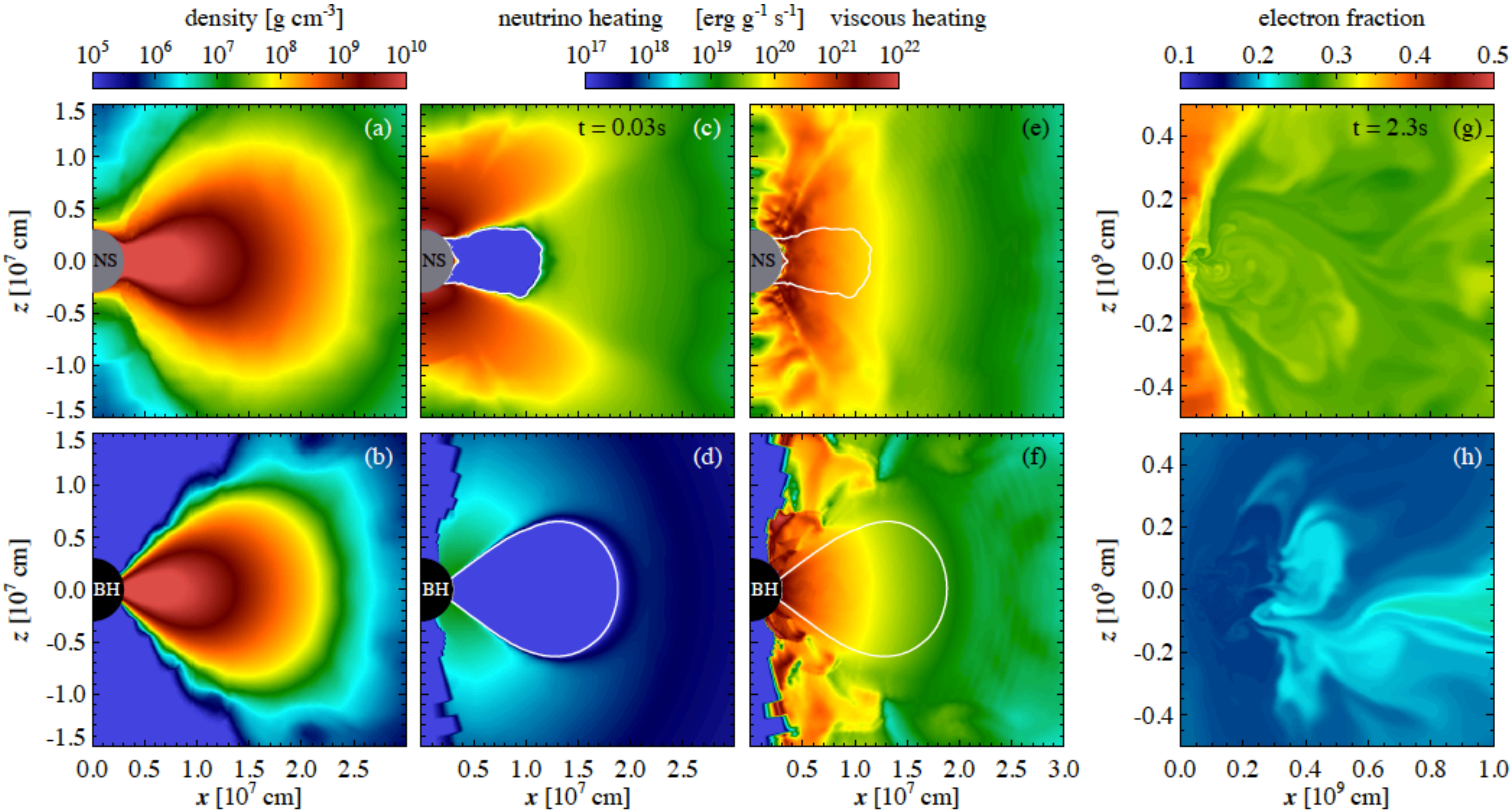


RF, Kasen, Metzger, Quataert (2015), MNRAS



see also Setiawan+2006, Shibata+ 2007
Just et al. 2015

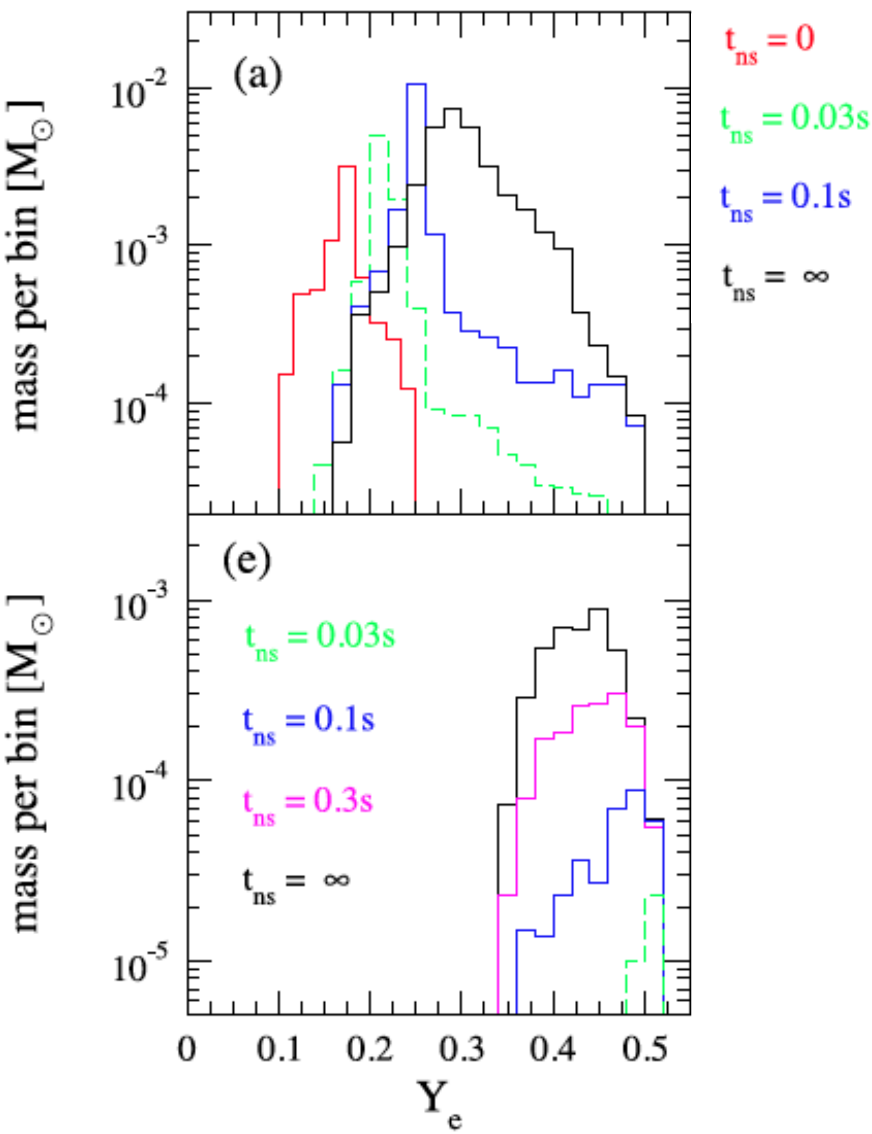
Hypermassive NS versus BH



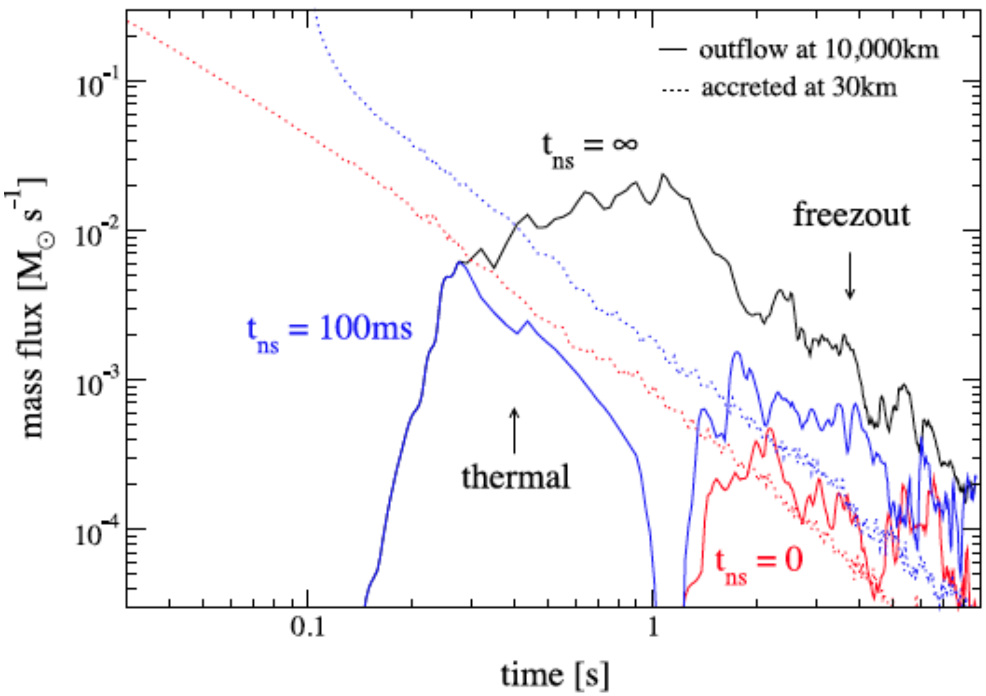
See also: Dessart+ (2009) Martin+ (2015)
Perego+ (2014) Fujibayashi+ (2017a,b)

Metzger & RF (2014)

Disk around HMNS



Varying HMNS lifetime:



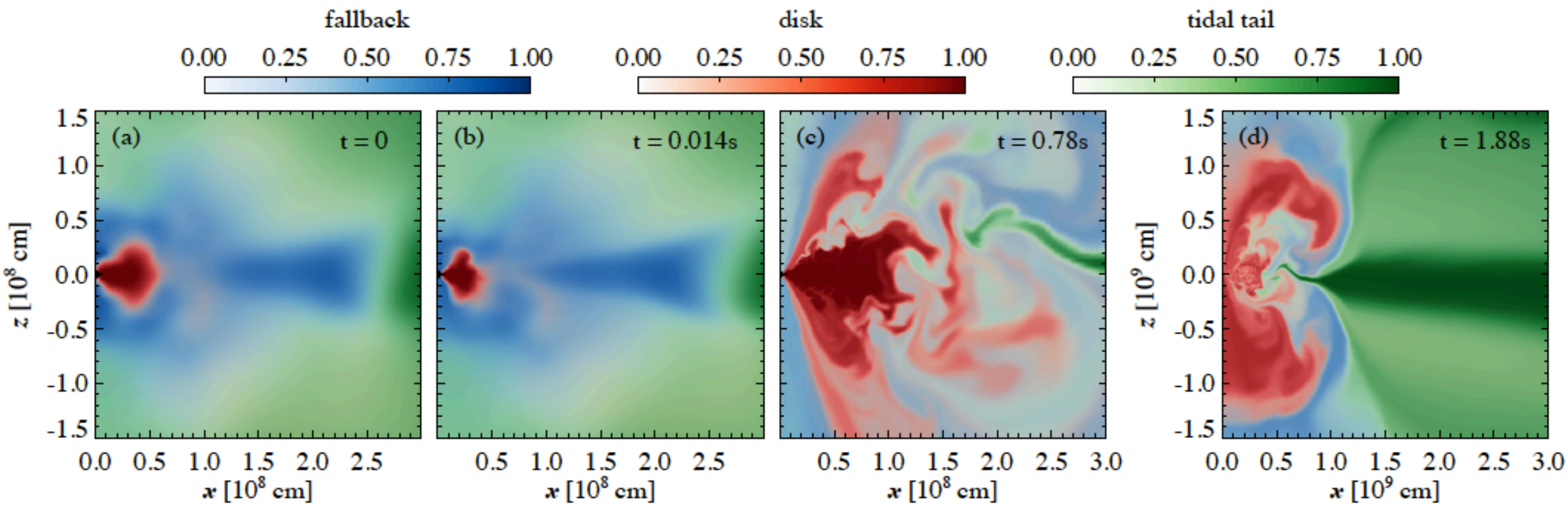
Metzger & RF (2014)

Hard to get to speeds larger than about 0.1c, however (in light of blue kilonova from GW170817)

e.g. Metzger et al. (2018)

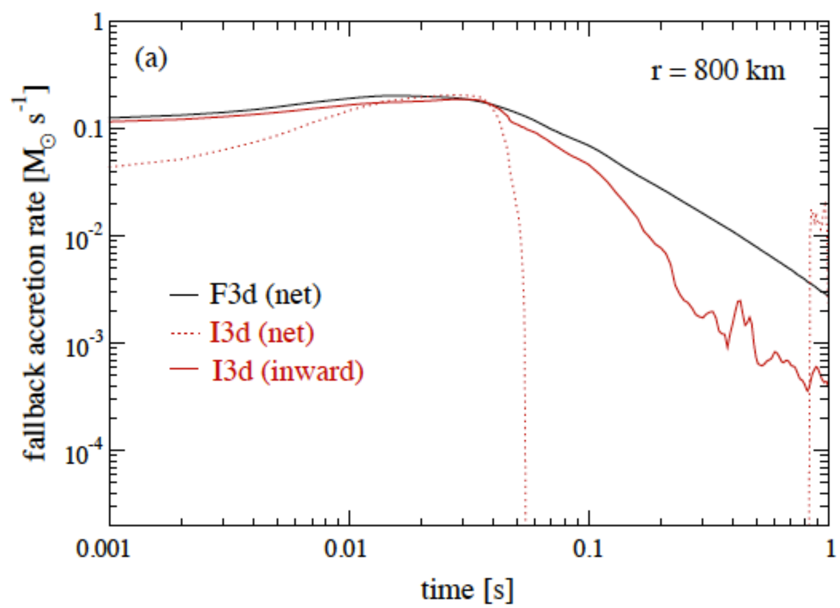
Interplay of disk wind and dynamical ejecta

Mapping from Newtonian BH-NS merger simulation (Rosswog) onto 2D disk code

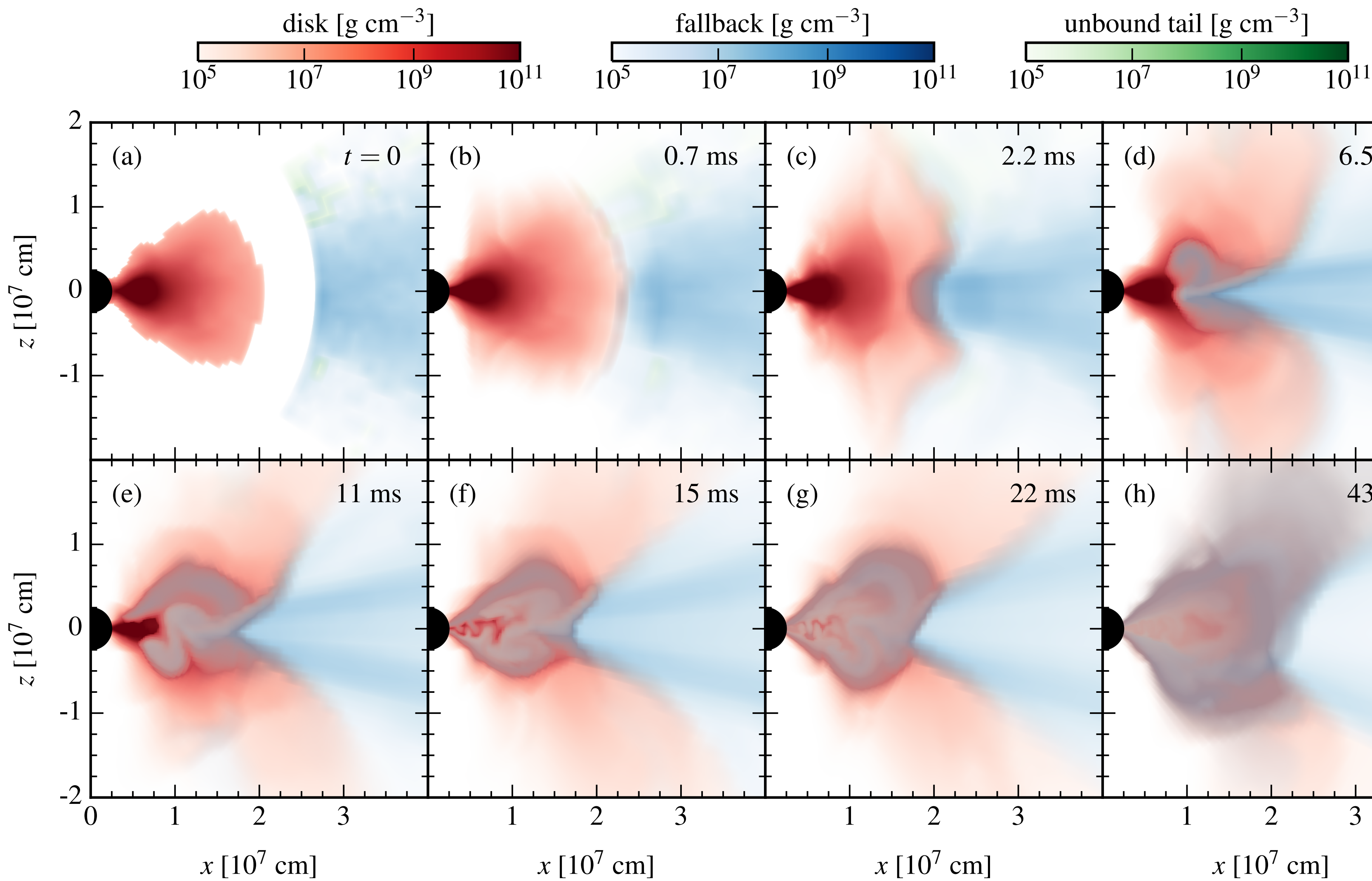


Disk wind can suppress fallback accretion: implications for the late-time emission from GRBs (BH-NS)

RF, Quataert, Schwab, Kasen & Rosswog (2015)



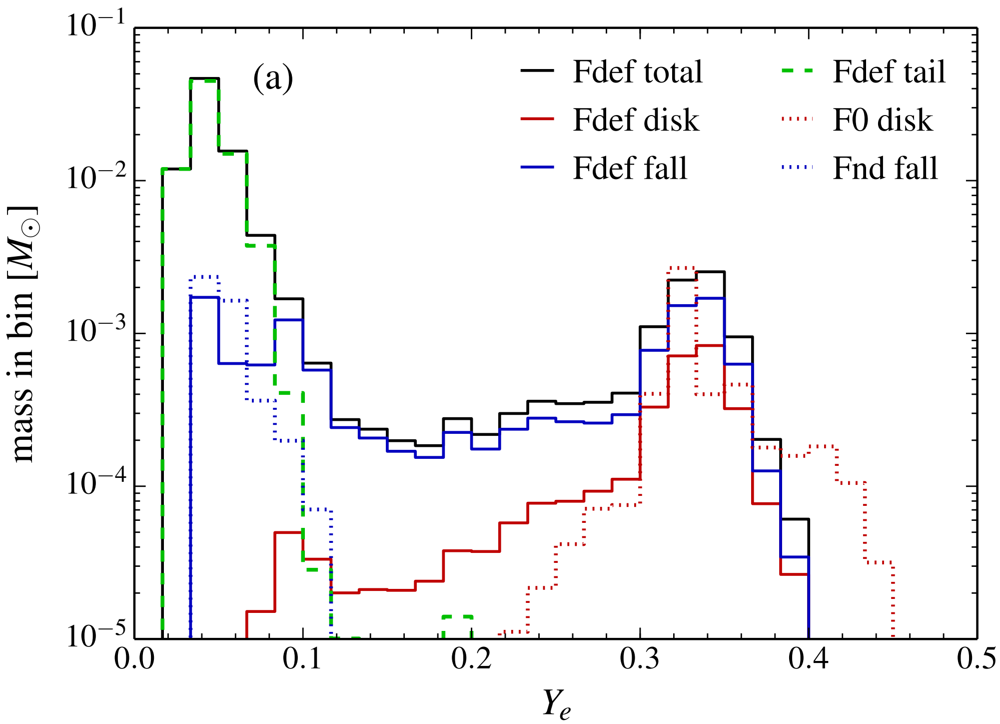
Interplay of disk wind and dynamical ejecta



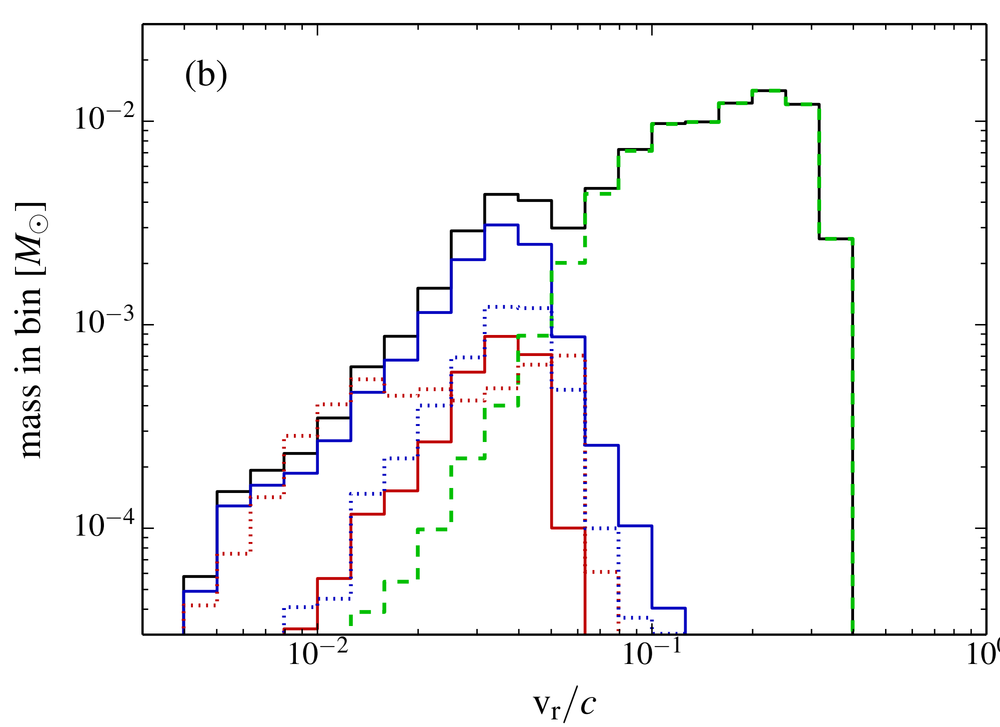
RF, Foucart, Kasen, Lippuner, et al. (2017)

Interplay of disk wind and dynamical ejecta

Electron fraction distribution:



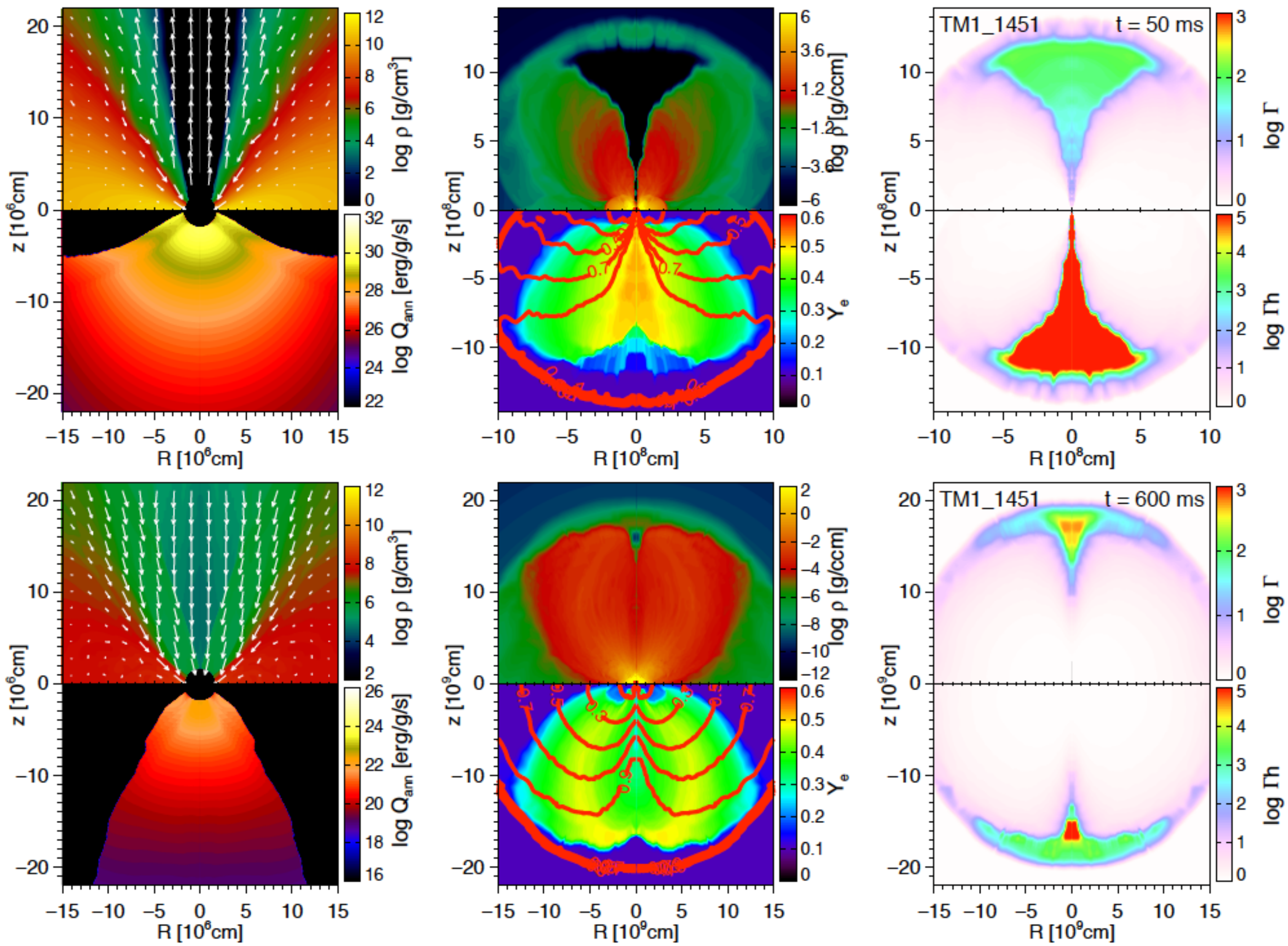
Radial velocity distribution:



RF, Foucart, Kasen, Lippuner, et al. (2017)

SGRB jet: neutrino pair annihilation

Energy injection weak, and jet has trouble breaking out of dynamical ejecta for NS-NS mergers



Only BH-NS successful

Just+ (2016)

See also:

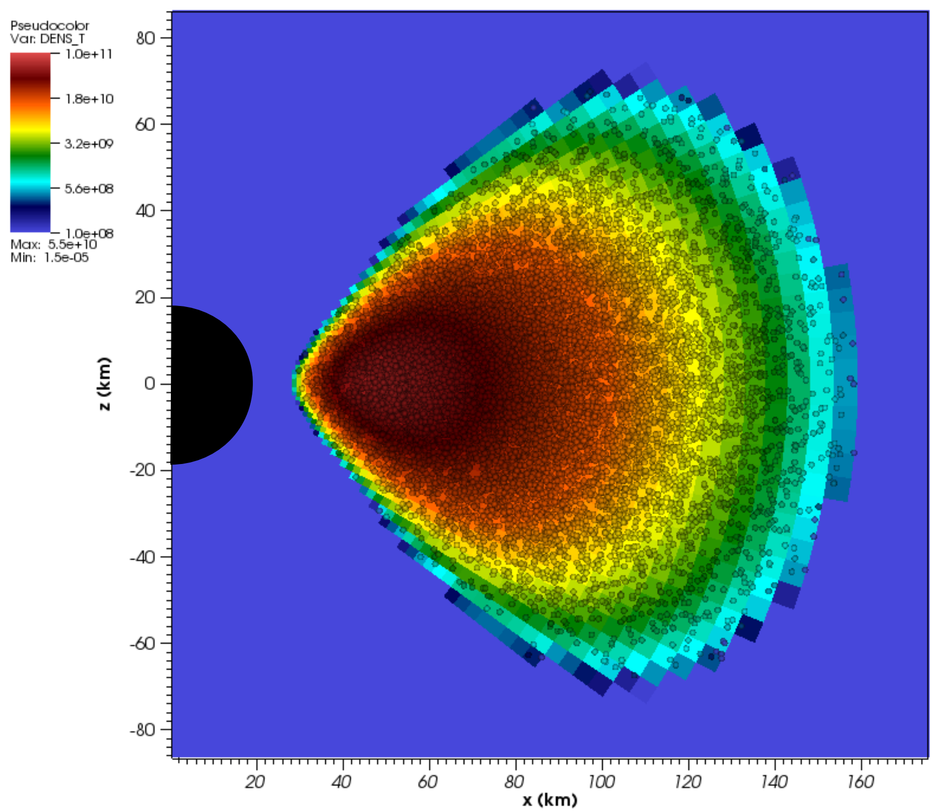
Dessart+ (2009) Richers+ (2015) Perego+ (2017)

Collimation:

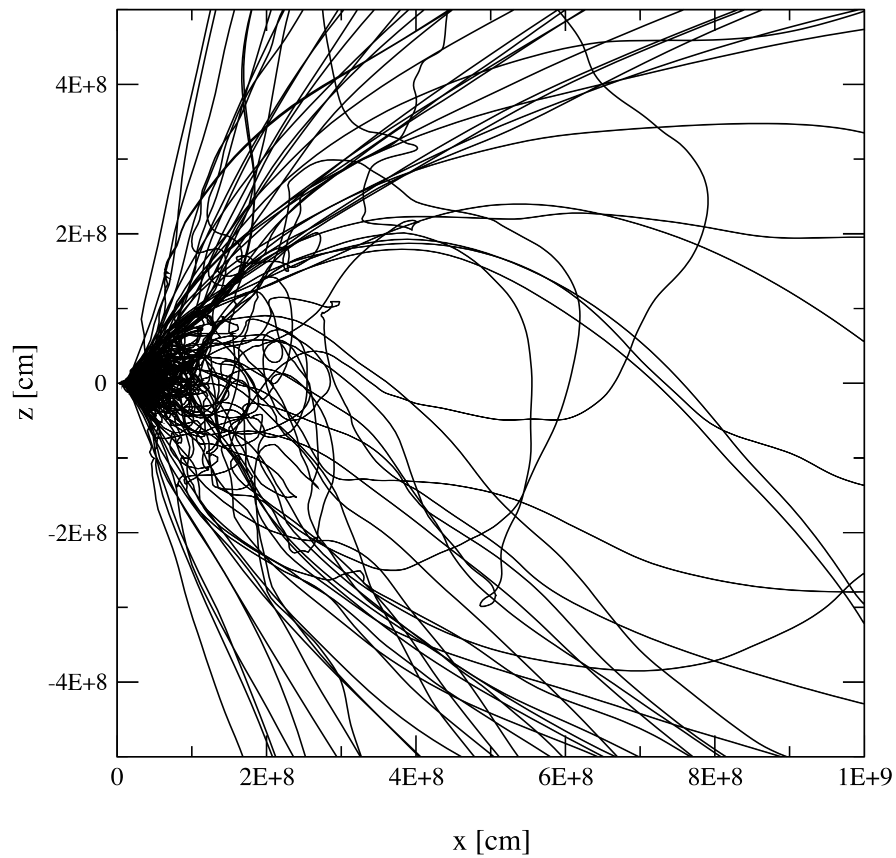
Nagakura+ (2014) Duffell+ (2015) Murguia-Berthier+ (2016)

Nucleosynthesis with Tracer Particles

Passive tracers follow density distribution



Disk is convective

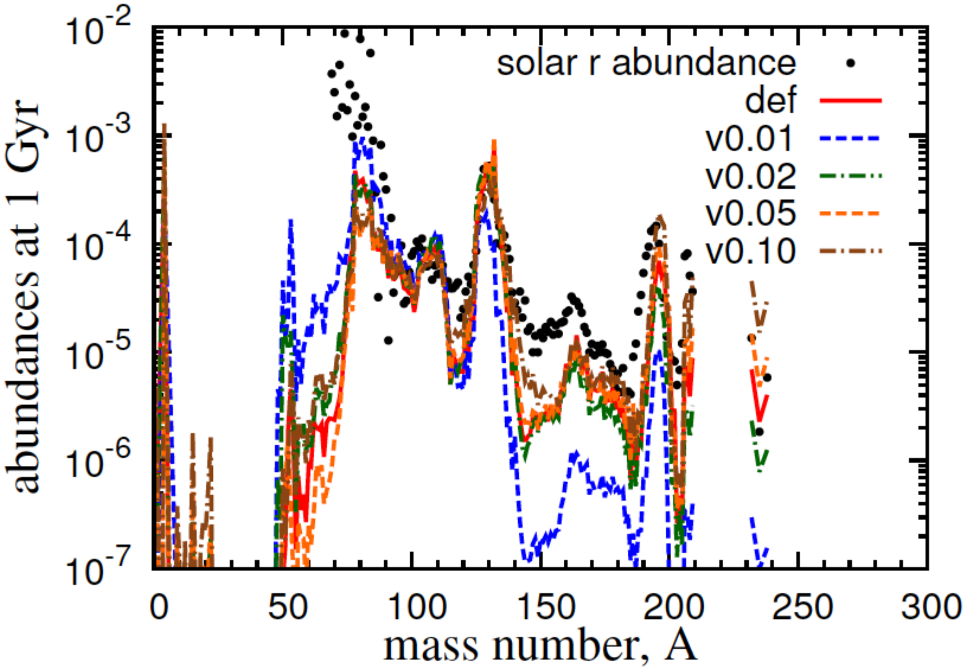


M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

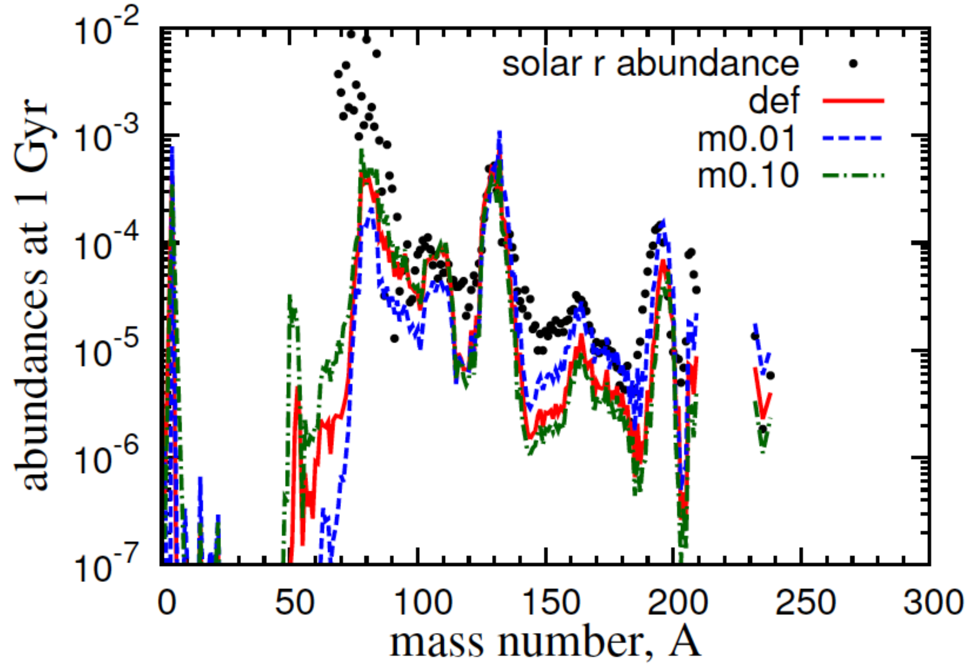
- Nuclear network: ~7000 isotopes, include neutrino effects
- Non-spinning BH, parameter dependencies

Black Hole Accretion Disks

Varying disk viscosity:



Varying disk mass:

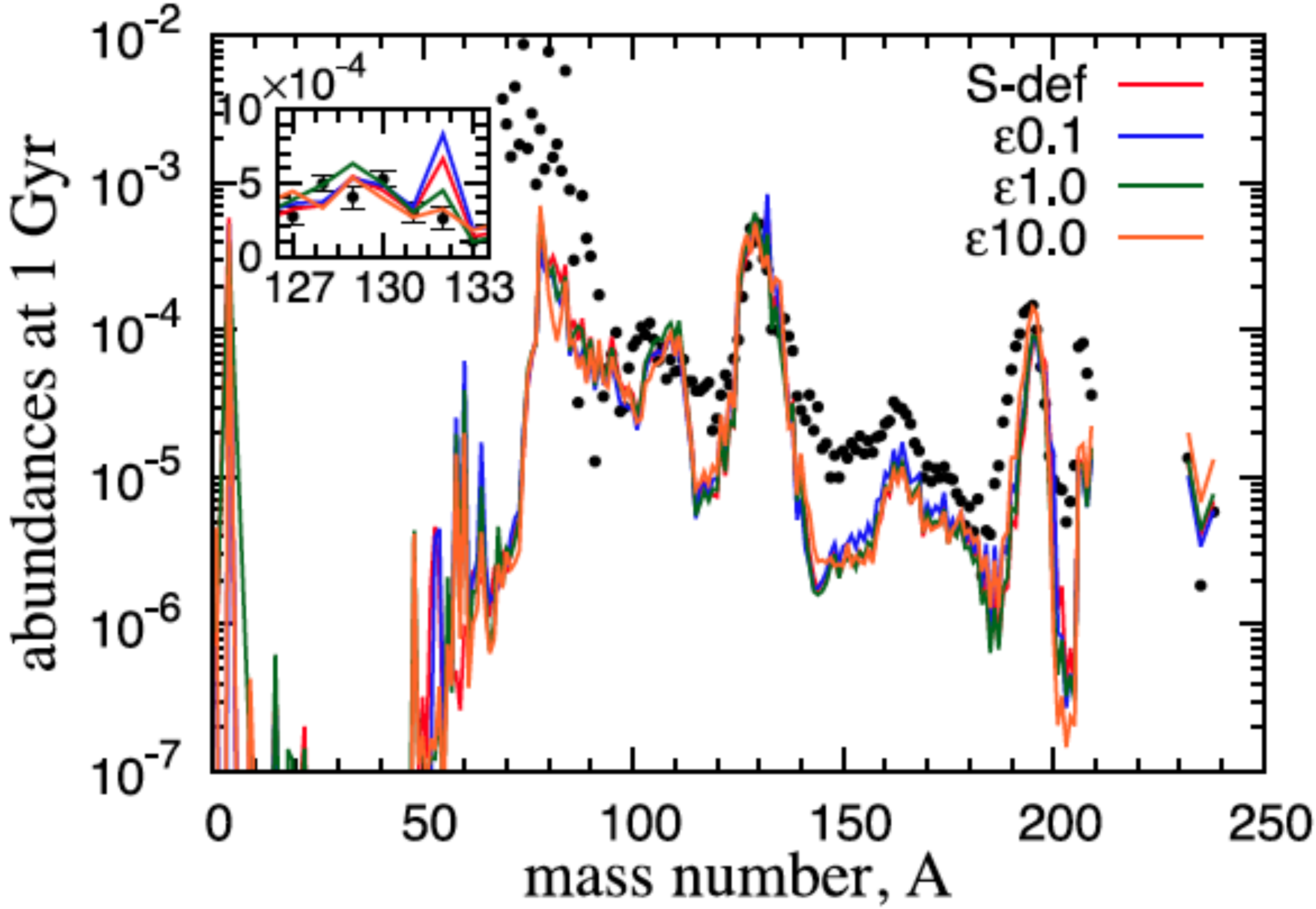


M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

- Most sensitive to viscosity: expansion time vs weak interaction time
- Also sensitive to disk mass and degeneracy: neutrinos & equilibrium Ye

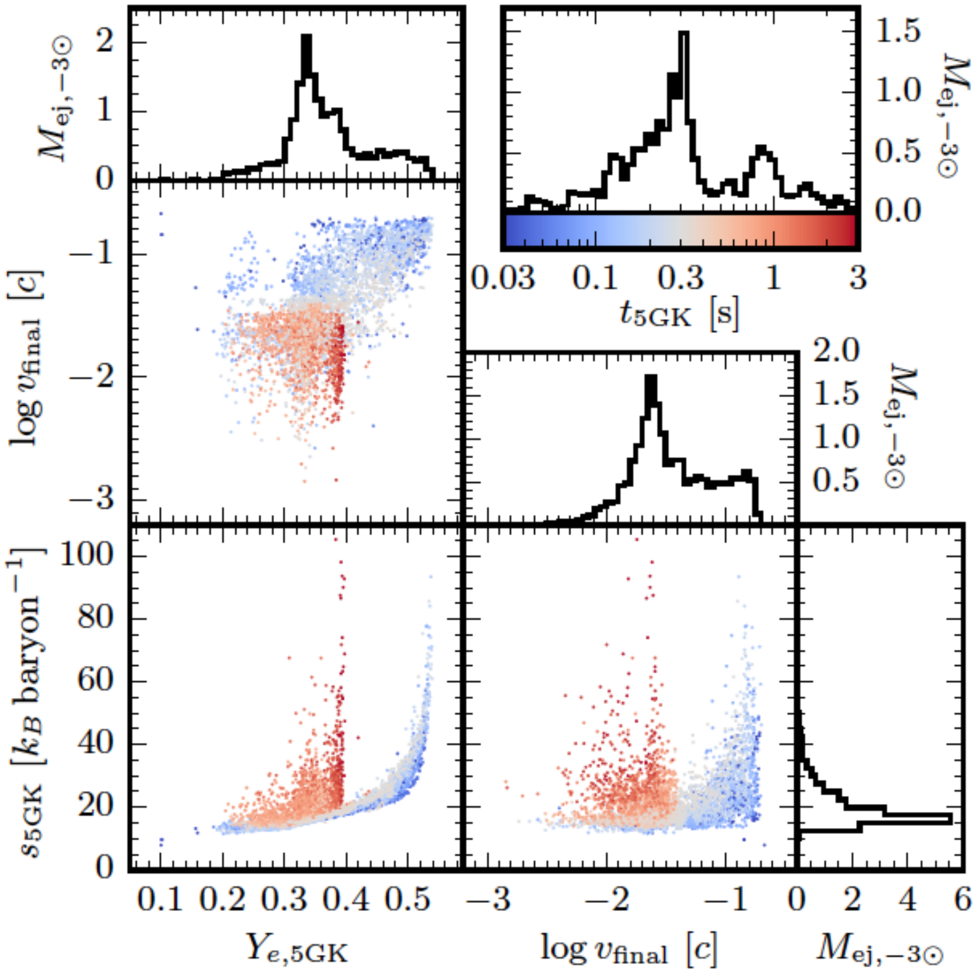
- Not very sensitive to initial Ye
- See also Just et al. 2015

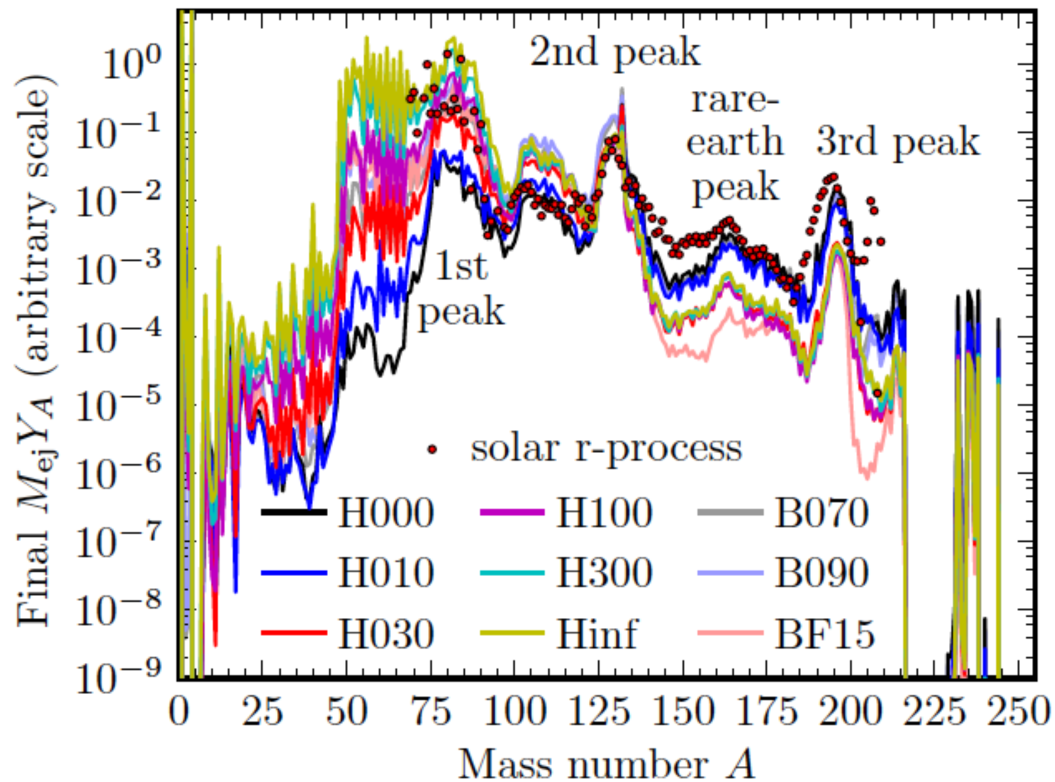
Black Hole Accretion Disks



M-R Wu, RF, Martinez-Pinedo & Metzger (2016)

HMNS disks





Lippuner, RF, Roberts, et al. (2017)

Pending Issues in Disk Modeling

1) Include magnetic fields (in progress)

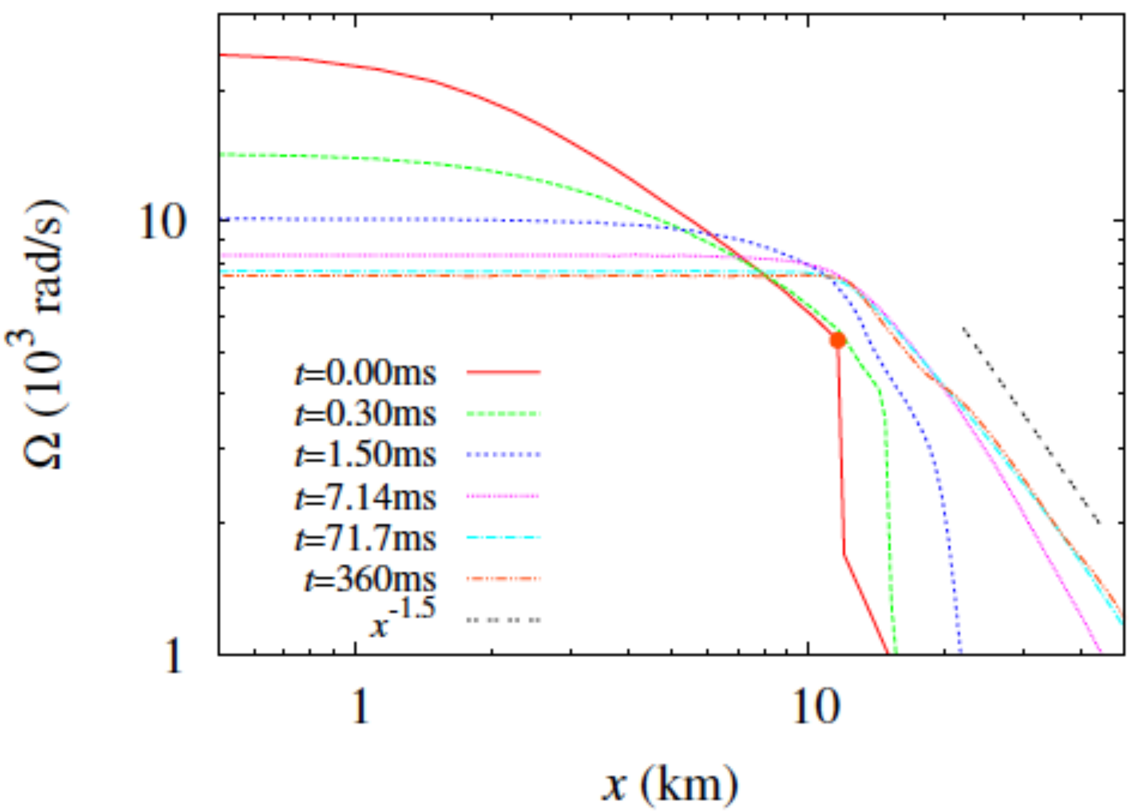
Siegel & Metzger (2017), Nouri et al. (2017)

2) Improve neutrino transport: outflow composition

Just et al. (2015), Fujibayashi et al. (2017), Foucart et al. (2018)

3) Realistic initial conditions for magnetic field and matter, interplay with dynamical ejecta

HMNS evolution with viscosity



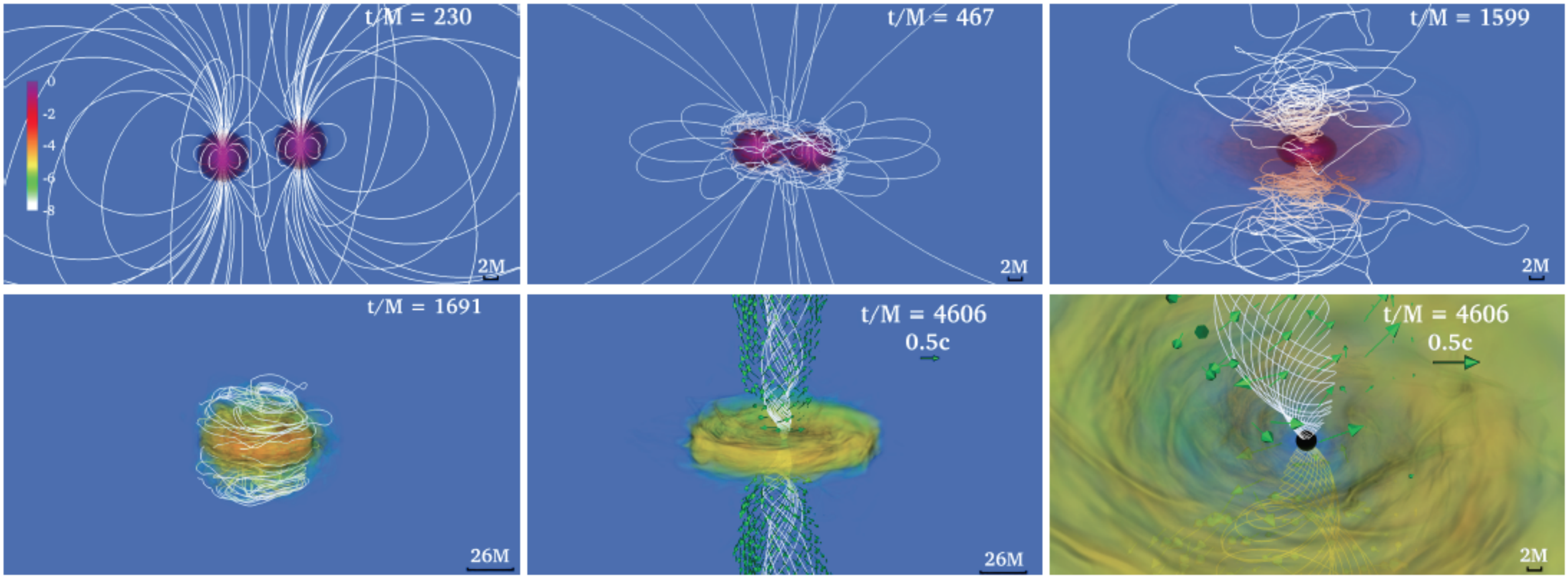
Angular velocity profile inside the HMNS changes from differential to uniform over ~10ms. Large release of energy, and driving of an outflow.

Previous work had not included viscosity for the internal HMNS evolution.

Shibata et al. (2017), Fujibayashi et al. (2017)

SGRB jet: MHD

Winding of toroidal field and buildup of magnetic pressure around rotation axis.



Ruiz+ (2016)

In BH-NS, it requires the NS to have an external poloidal field Paschalidis+ (2015)

See also: Rezzolla+ (2011) Kiuchi+ (2015) Kawamura+ (2016)

Summary

1. Accretion disks formed in NS mergers can eject significant amounts of mass, reprocessed by neutrinos and hence with different composition than bulk of dynamical ejecta

2. Outstanding issues in post-NS-merger modeling: GRMHD, neutrino transport, and realistic initial conditions including dynamical ejecta

Thanks to:

UNIVERSITY OF ALBERTA

NSERC CRSNG

NERSC

U.S. DEPARTMENT OF ENERGY | Office of Science

compute canada | calcul canada

WESTGRID