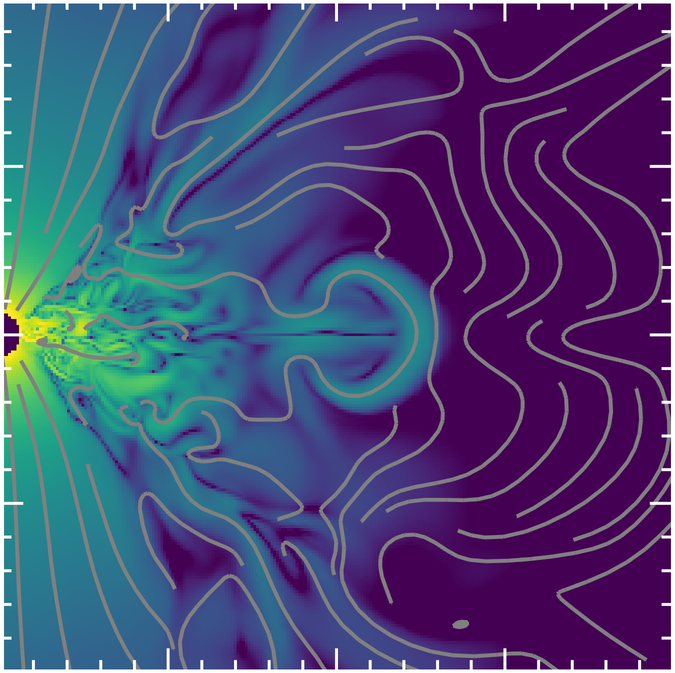
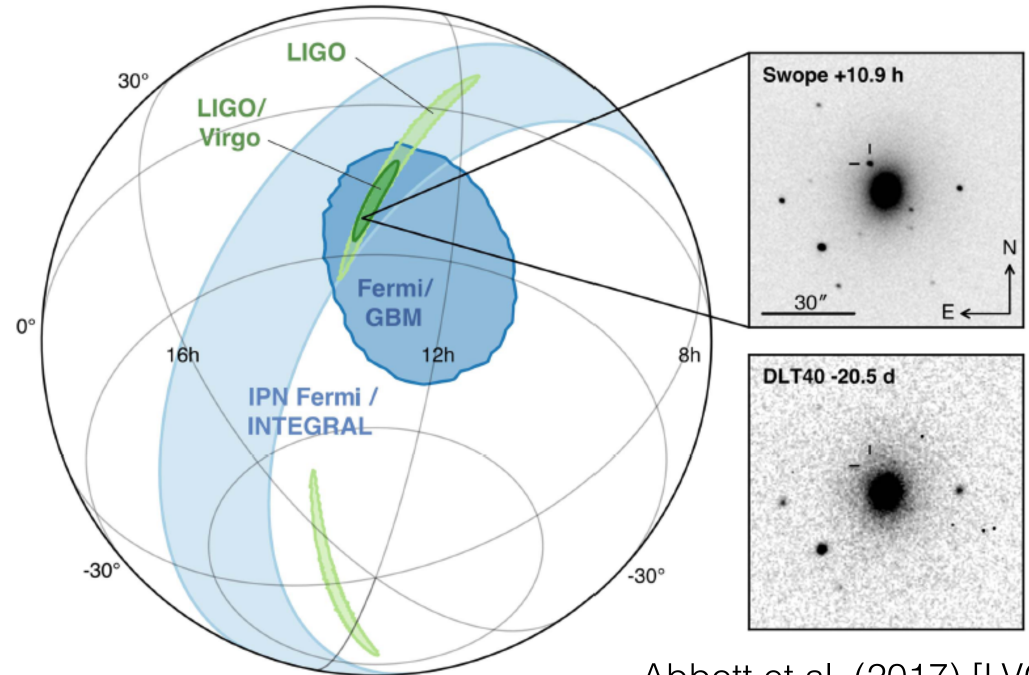




Abbott et al. (2017) [LVC]

Mass Ejection from NS merger accretion disks

Rodrigo Fernández (University of Alberta)

w/ Fahlman (UAlberta), Tchekhovskoy + Christie + Lalakos (Northwestern),
Foucart (UNH), Kasen + Quataert (Berkeley), Metzger (Columbia),

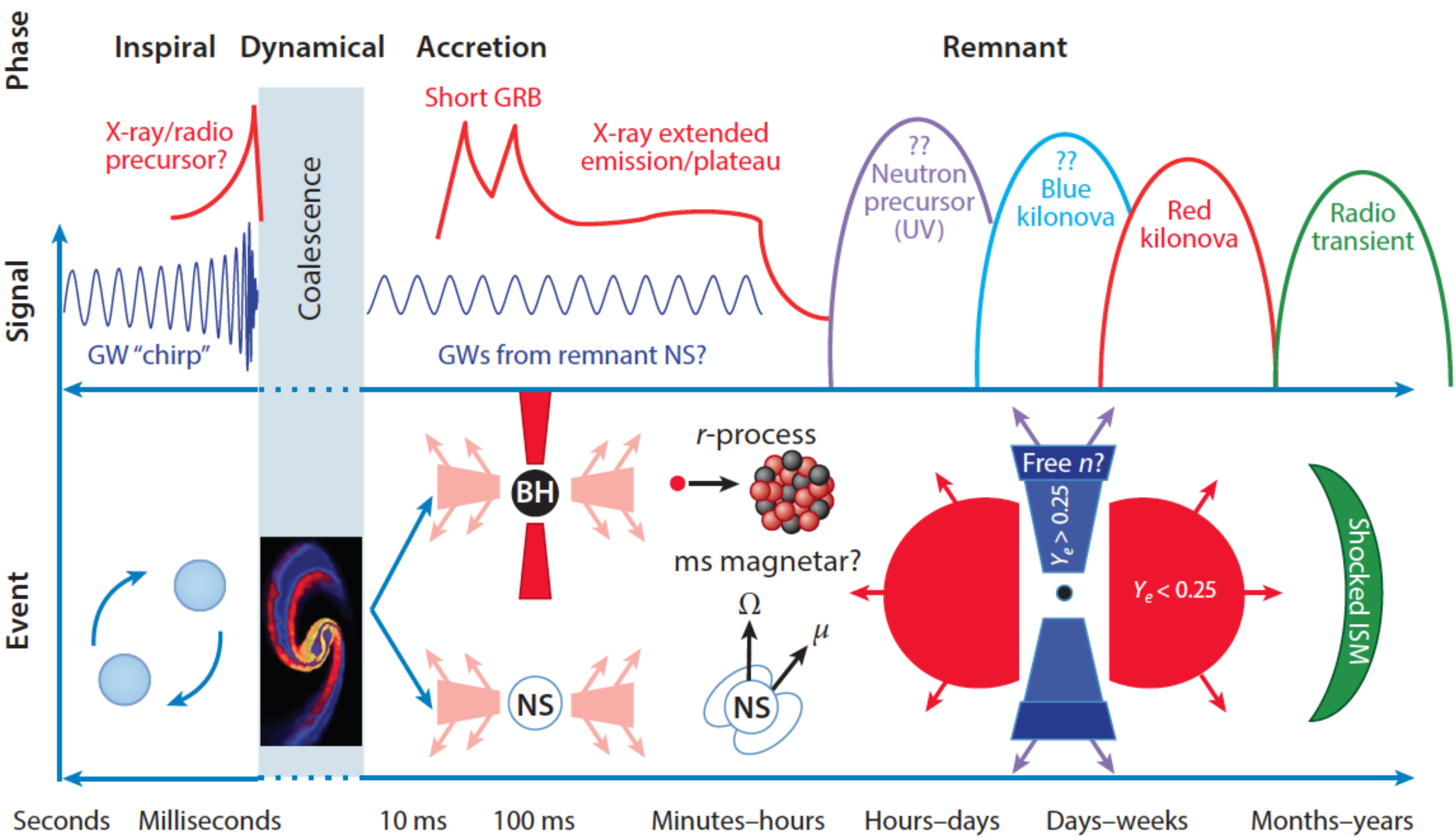
Overview

1. HMNS disk outflows & GW170817

2. Mass ejection from disks in GRMHD

3. Jets from NS merger disks in GRMHD

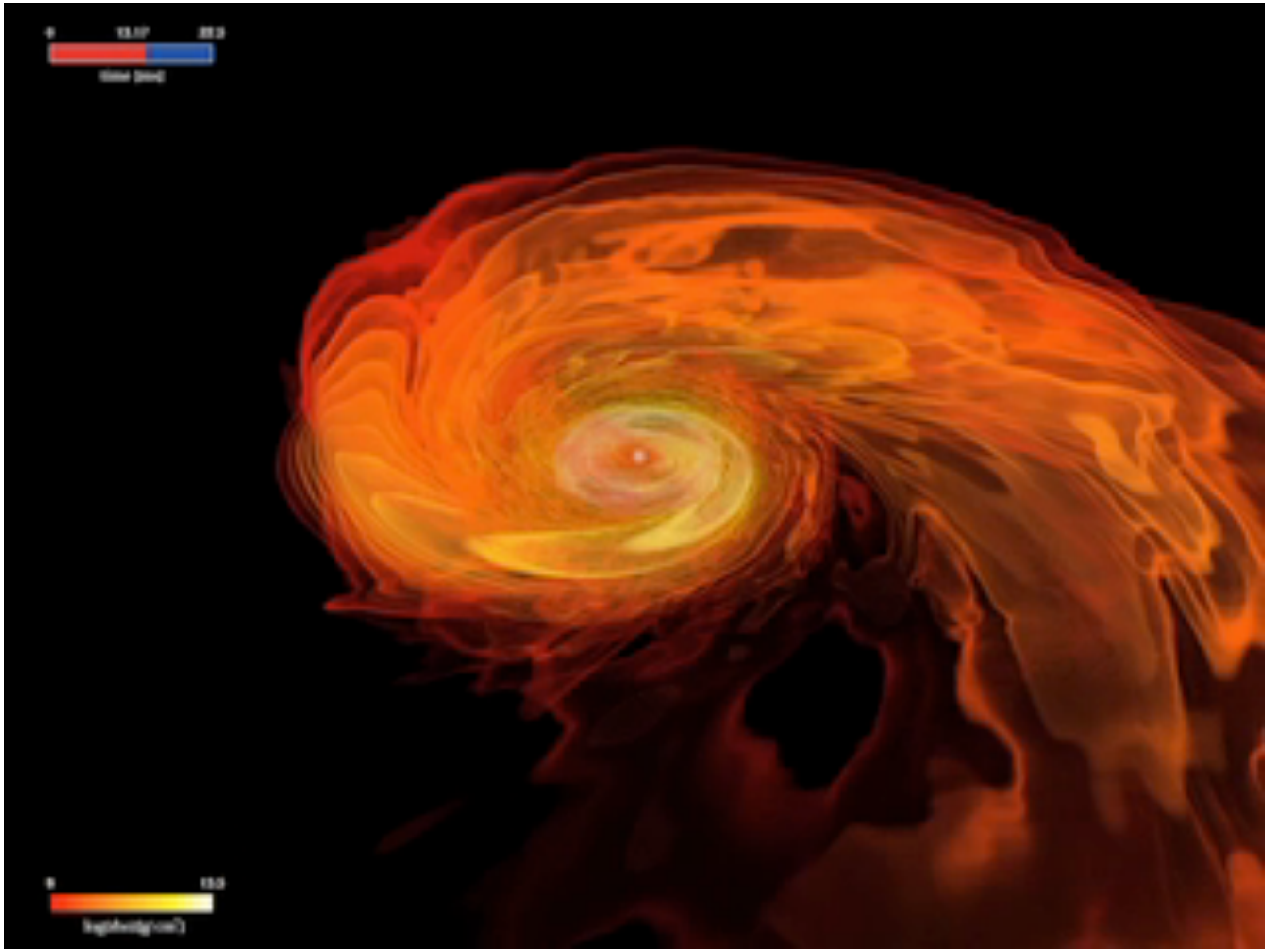
Neutron Star Mergers



RF & Metzger (2016)

Dynamical Phase: Merger

Unequal mass NS-NS merger:



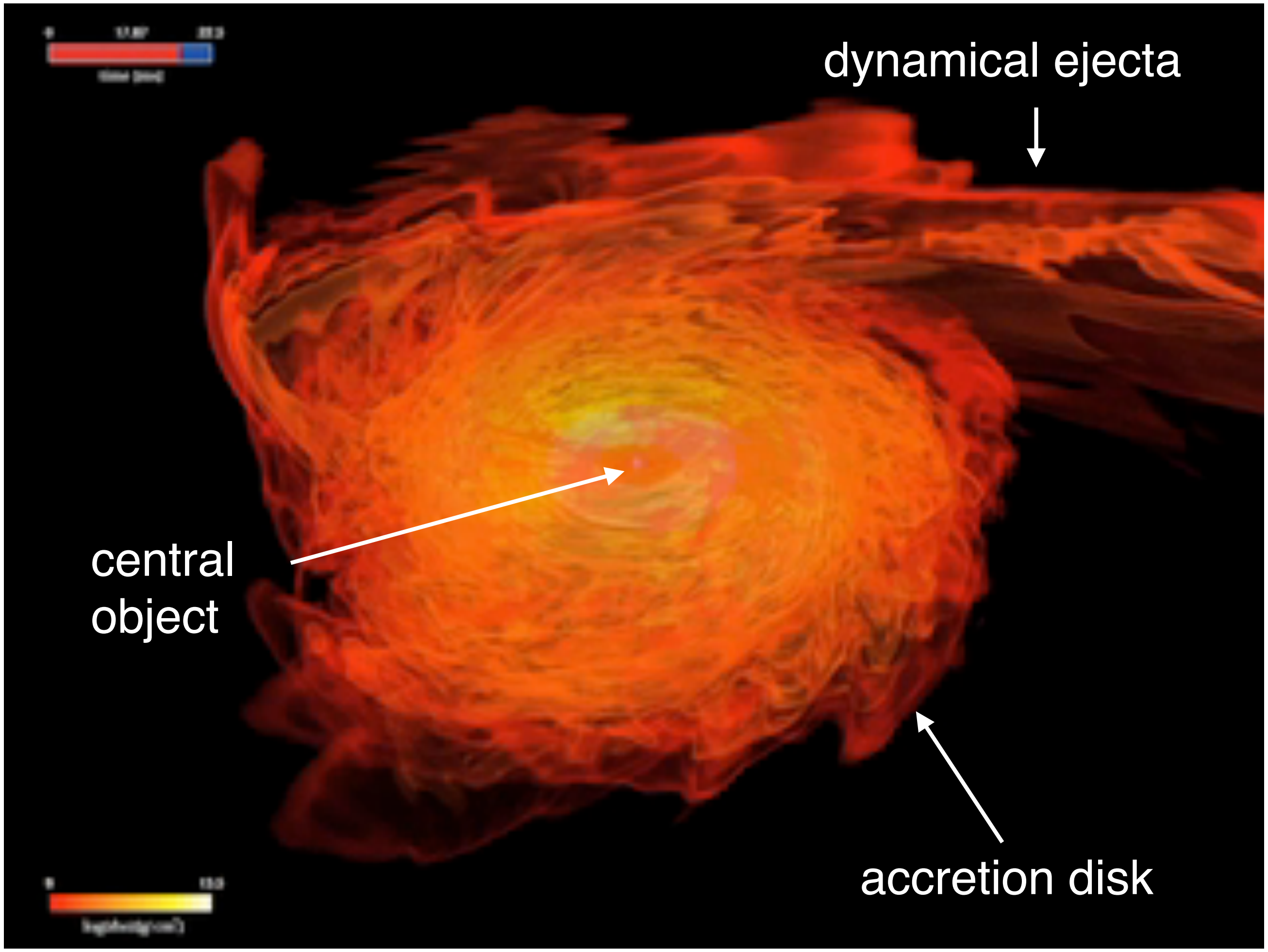
Rezzolla+ (2010)

Phases:

- inspiral
- merger
- remnant + ejecta

Dynamical Phase: Merger

Unequal mass NS-NS merger:



Rezzolla+ (2010)

Phases:

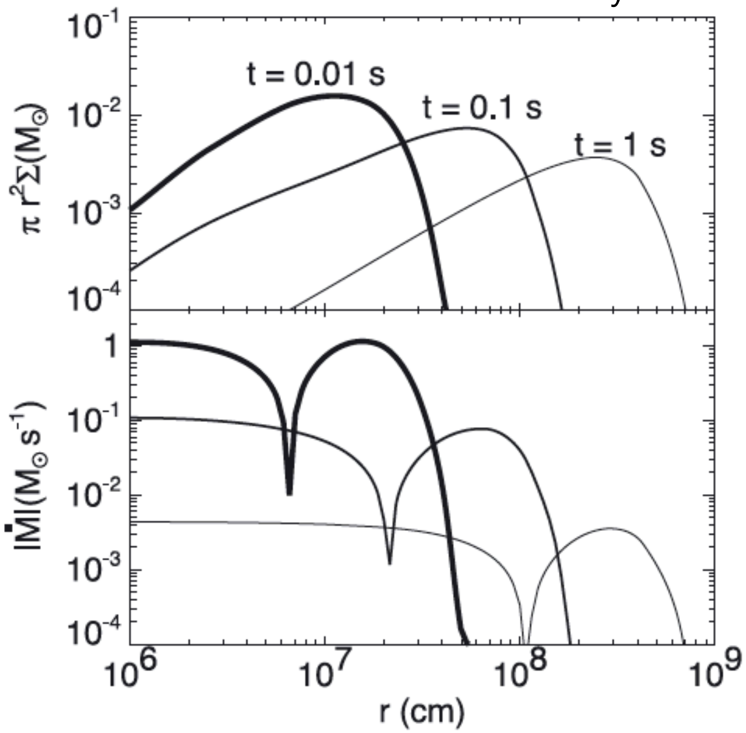
- inspiral
- merger
- remnant + ejecta
- relativistic jet (?)

Large body of work:

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

Disk evolution

Evolution of surface density and accretion rate



Metzger+ (2008)

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

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

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

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

- 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)

$$\frac{E_\alpha}{GM_{\rm BH}/R} \simeq 1 R_{600} M_3^{-1}$$

  - MHD stresses

Equations for Newtonian hydro case (simplest)

mass conservation:

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

ρ : 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

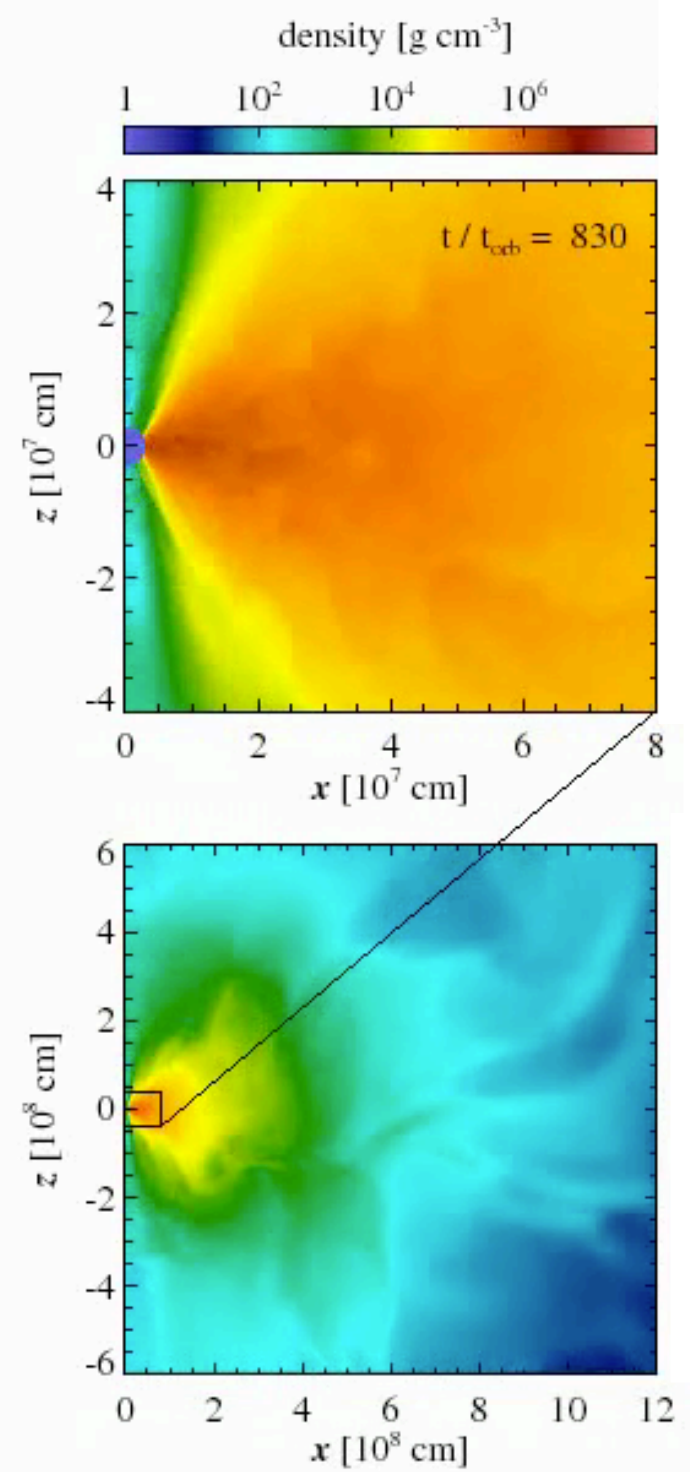
EOS:

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

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

Y_e : electron fraction

(nuclear statistical equilibrium: nuclear binding energy)



Wind from remnant accretion disk

- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- If BH-disk, eject fraction ~10-20% of initial disk mass, more if HMNS-disk
- Material is neutron-rich (Ye ~ 0.2-0.4), mostly light r-process, some light dep. on parameters
- Mass-averaged wind speed (~0.05c) is slower than dynamical ejecta (~0.1-0.3c)

RF & Metzger (2013), MNRAS

Just et al. (2015), MNRAS

Perego+(2014)

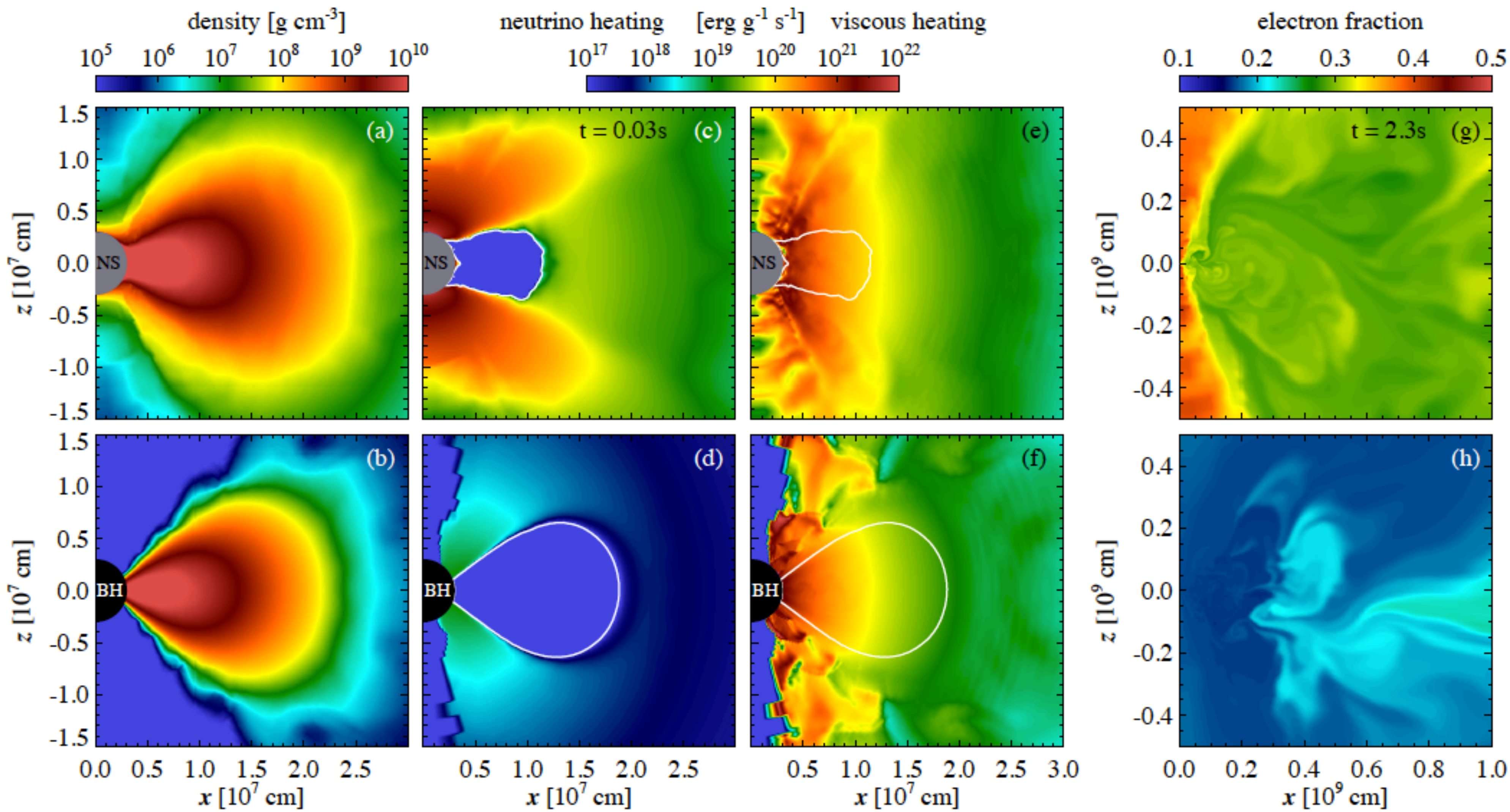
Fujibayashi+(2017)

Setiawan et al. (2005)

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

Metzger (2009)

Hypermassive NS versus BH

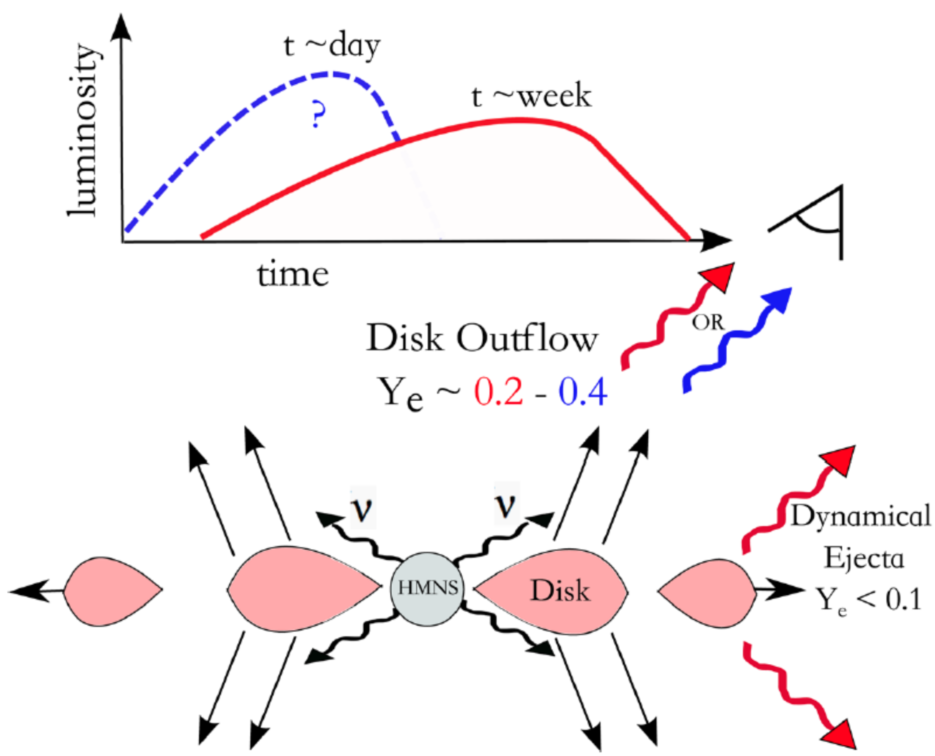


See also: Dessart+ (2009) Martin+ (2015) Metzger & RF (2014)

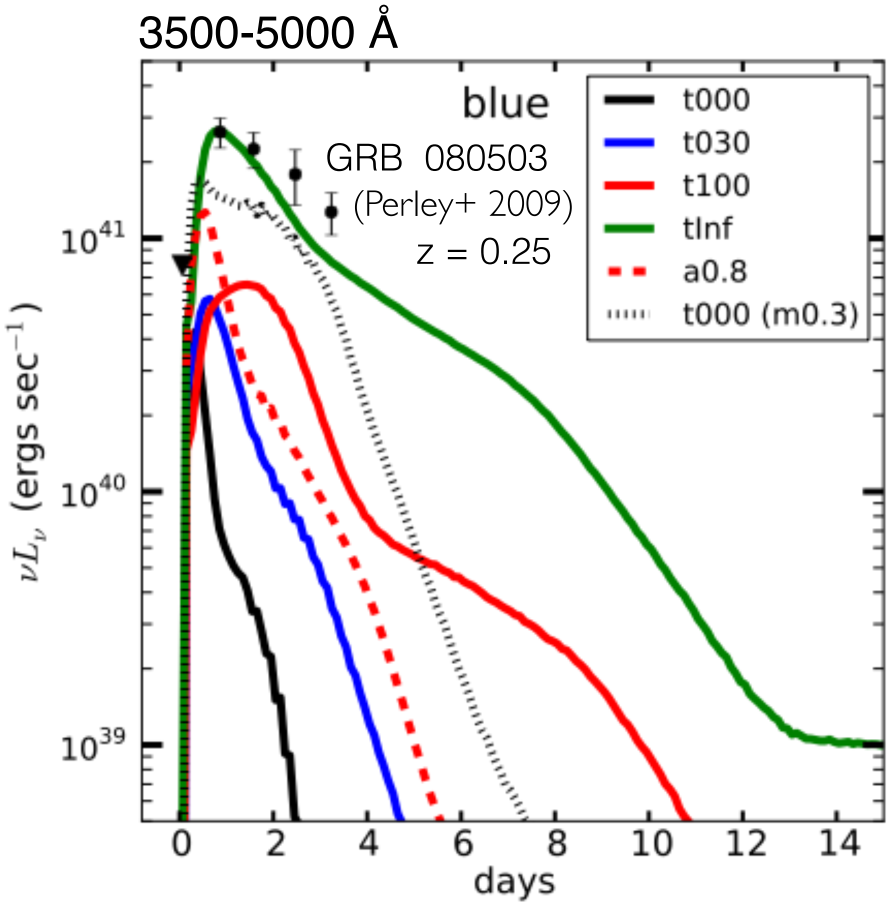
Perego+ (2014) Fujibayashi+ (2017a,b)

HMNS lifetime and kilonova

Longer lifetime → more neutrino irradiation → less neutrons → smaller opacity → bluer emission



Metzger & RF (2014)

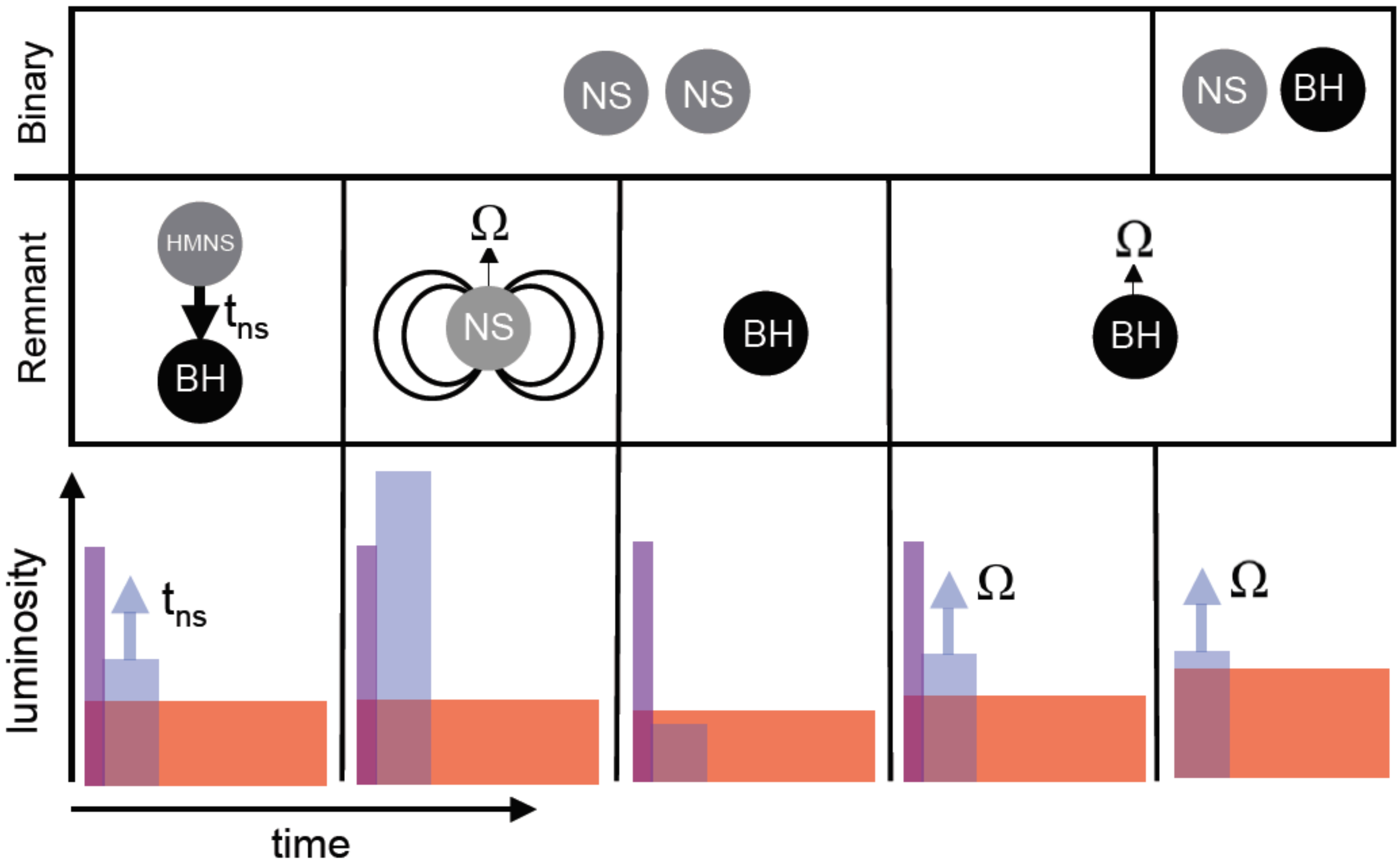


Kasen, RF, & Metzger (2015)

Diversity of Outcomes & Transients

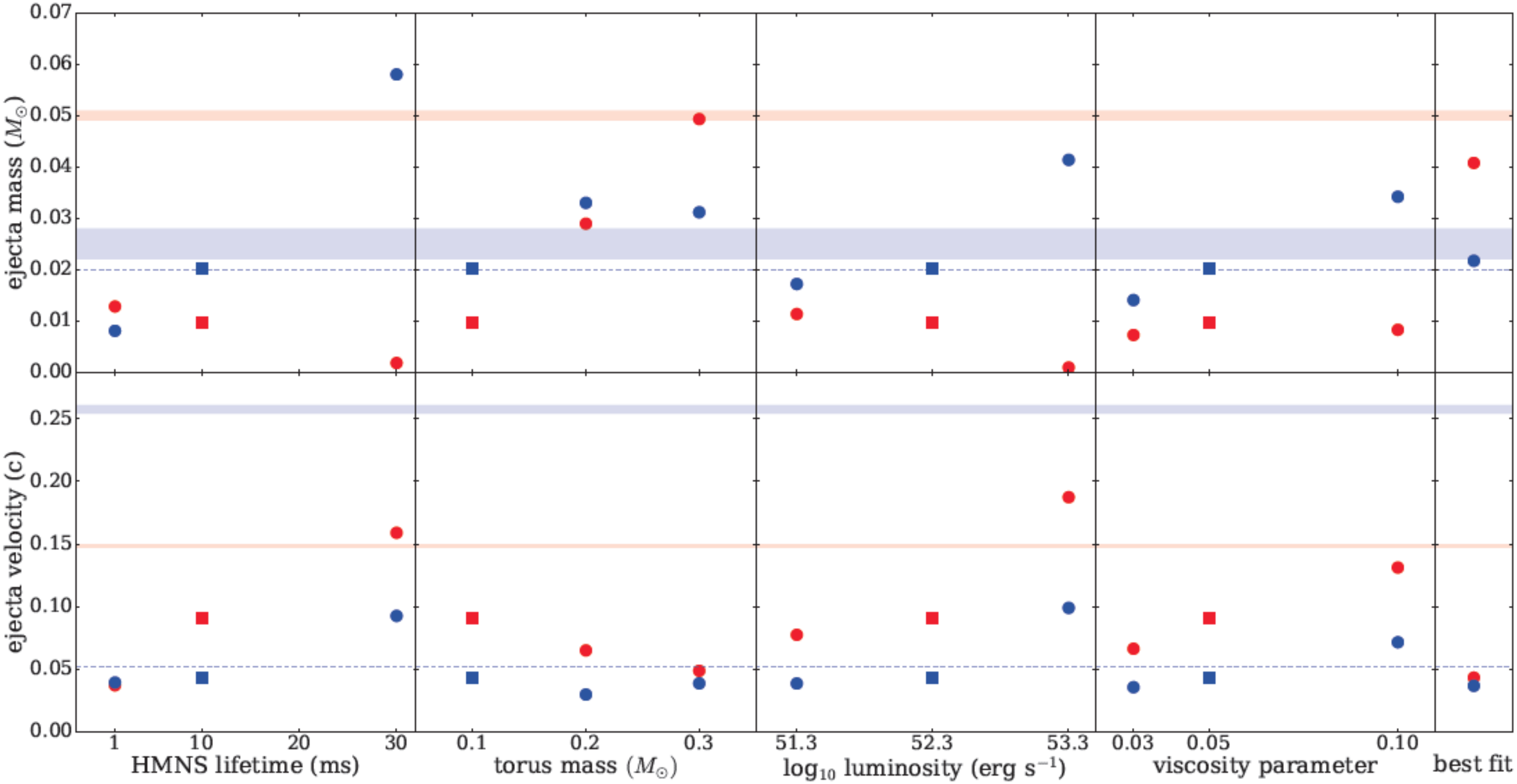
(Metzger+ 2015)

UV (n-precursor) optical (disk wind) infrared (disk wind + dynamical)



Kasen, RF, & Metzger (2015)

HMNS disk outflow & GW170817

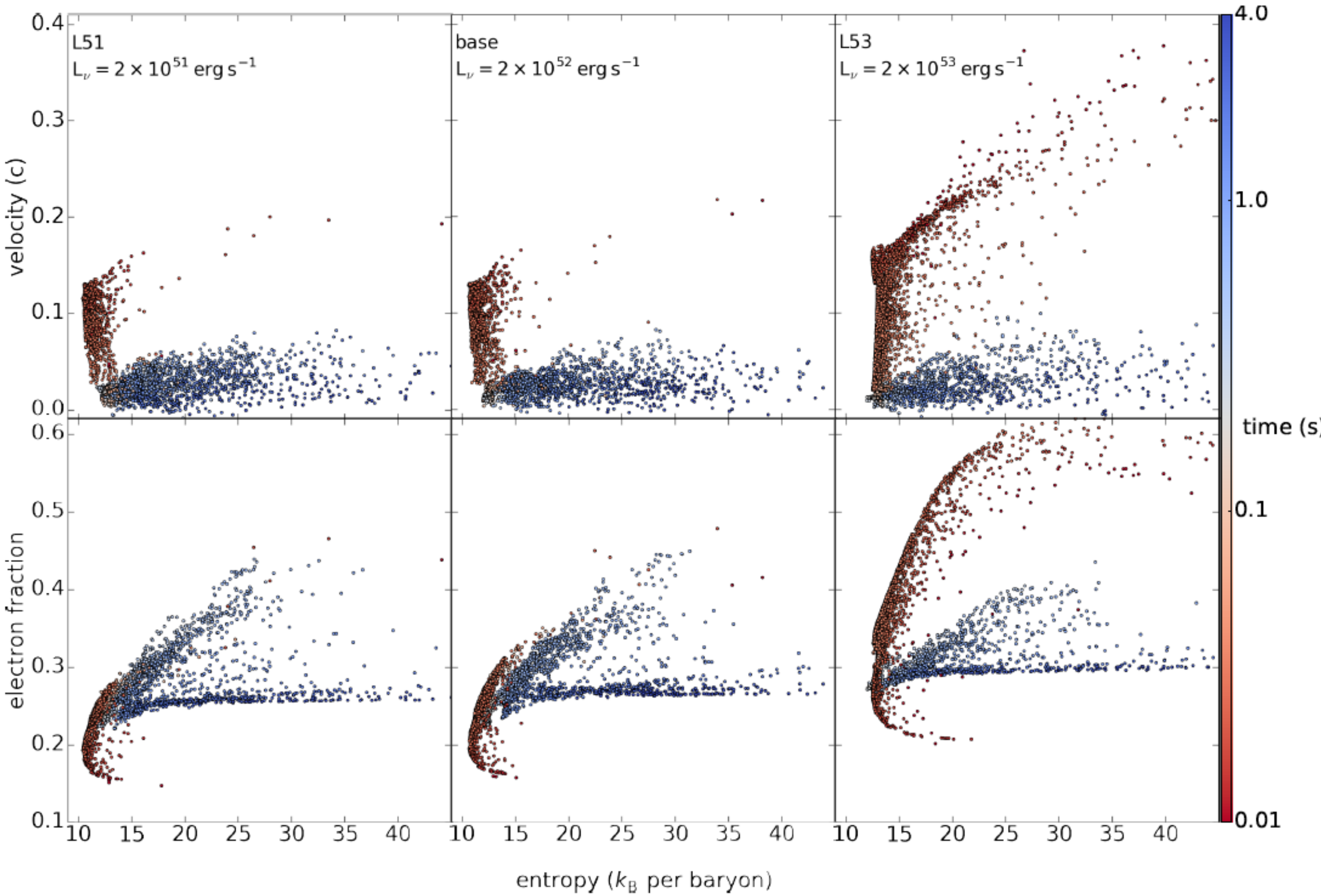


Two-component kilonova fit from Villar+ (2017)

also: Fujibayashi+ (2017), Kawaguchi+(2018)

Fahlman & RF (2018)

HMNS disk outflow & GW170817



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

Fahlman & RF (2018)

HMNS disk outflow & GW170817

Disk with viscous hydro + neutrino heating: mass-averaged velocity is < 0.15c for physically plausible parameters

Possible resolutions:

1) Use composite ejecta for kilonova model (e.g. Kawaguchi+2018)

2) Magnetic stresses (e.g. Metzger+2018)

3) Enhancement of dynamical ejecta (e.g. Radice+2018)

4) Other models for blue kilonova (e.g., Piro & Kollmeier, Waxman, etc.)

GRMHD evolution of BH disks

Use HARM, extended to 3D and parallelized with MPI

Parameterized neutrino cooling and nuclear recombination, gamma-law EOS, Kerr metric

Black hole mass: $3M_{sun}$, spin = 0.8

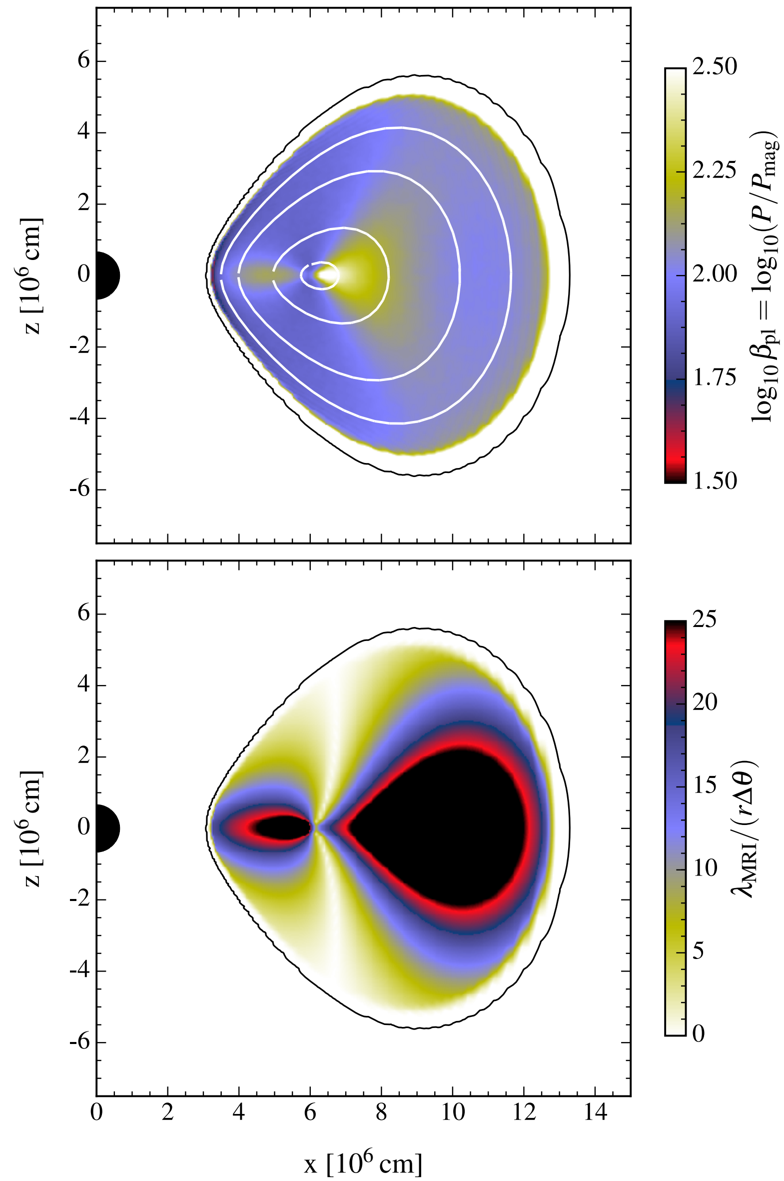
Start from equilibrium torus, constant Ye=0.1, entropy, and angular momentum, M_{disk}=0.03M_{sun}

Impose strong initial poloidal field, fully resolve MRI in equatorial plane

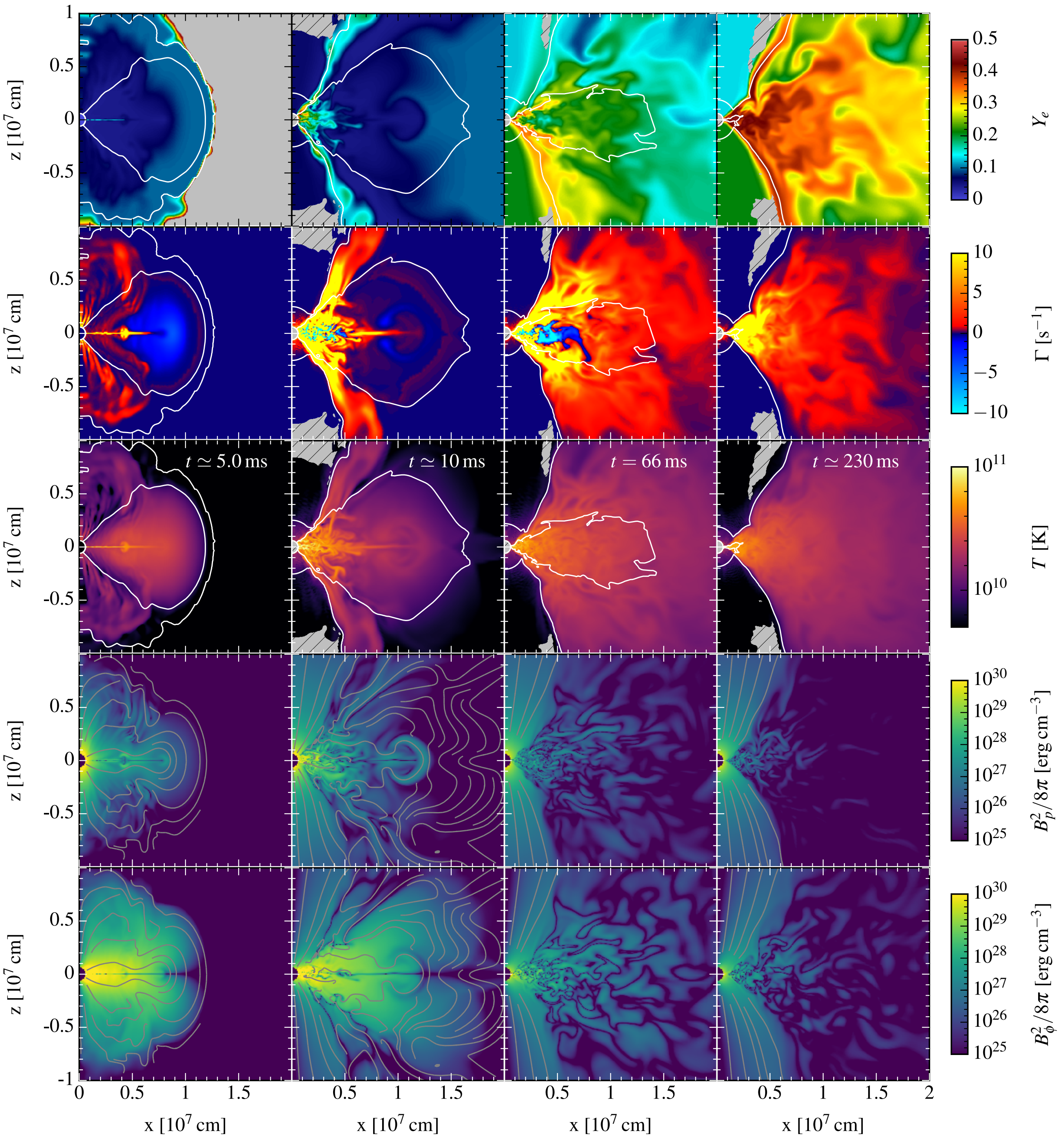
Compare with hydro models with identical microphysics

see also work by Siegel & Metzger (2017,2018), and Miller+2019

Shibata+ (2007,2012), Janiuk+(2013), Nouri+ (2017)



RF, Tchekhovskoy, Quataert, Foucart, & Kasen (2019)



GRMHD

Development of MRI starts accretion

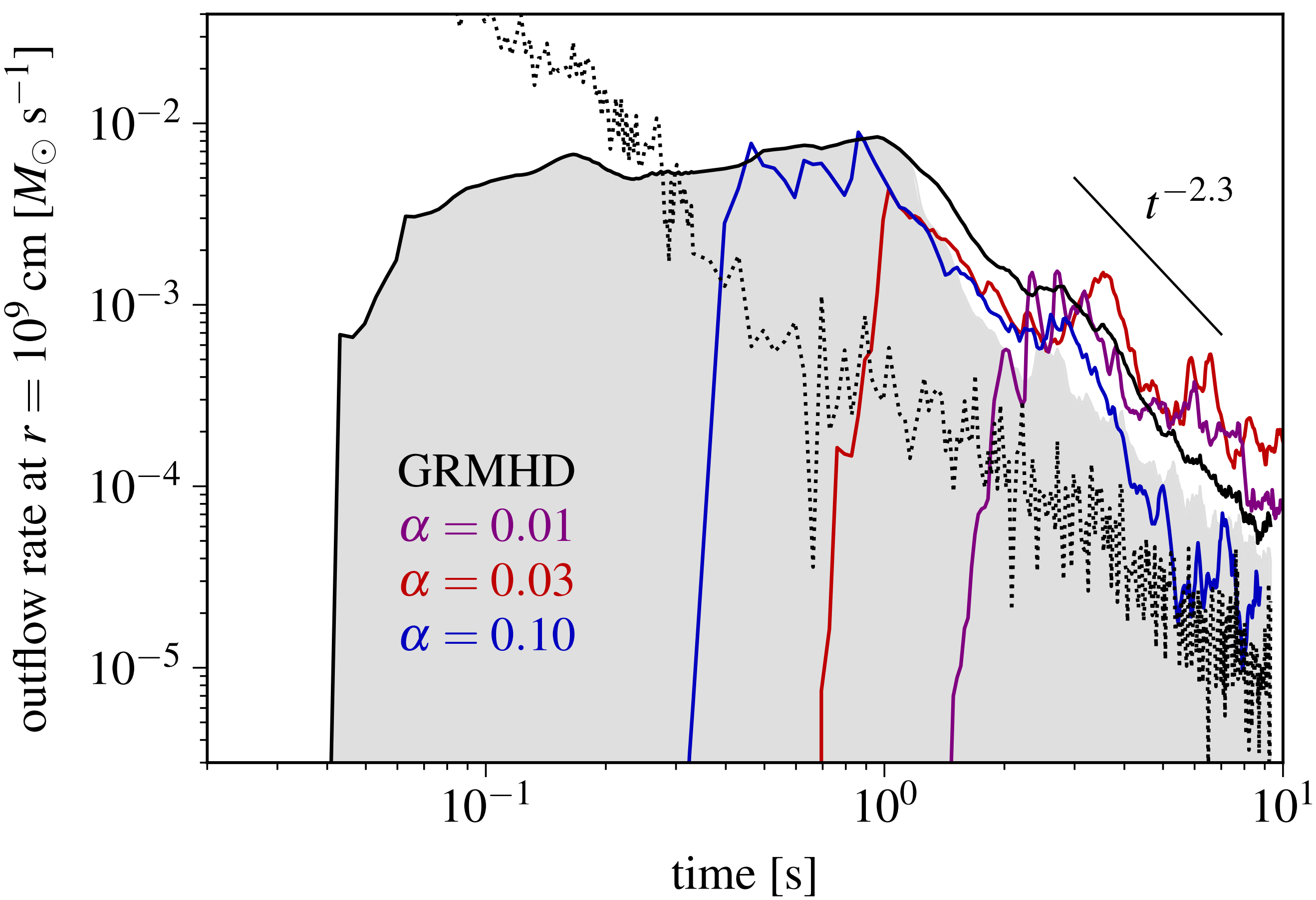
Magnetic field winding and amplification launch relativistic outflow over first few orbits

MRI increases heating and equilibrium Ye

RF, Tchekhovskoy, et al. (2019)

GRMHD: strong poloidal vs hydro

Outflow at r=10^9 cm

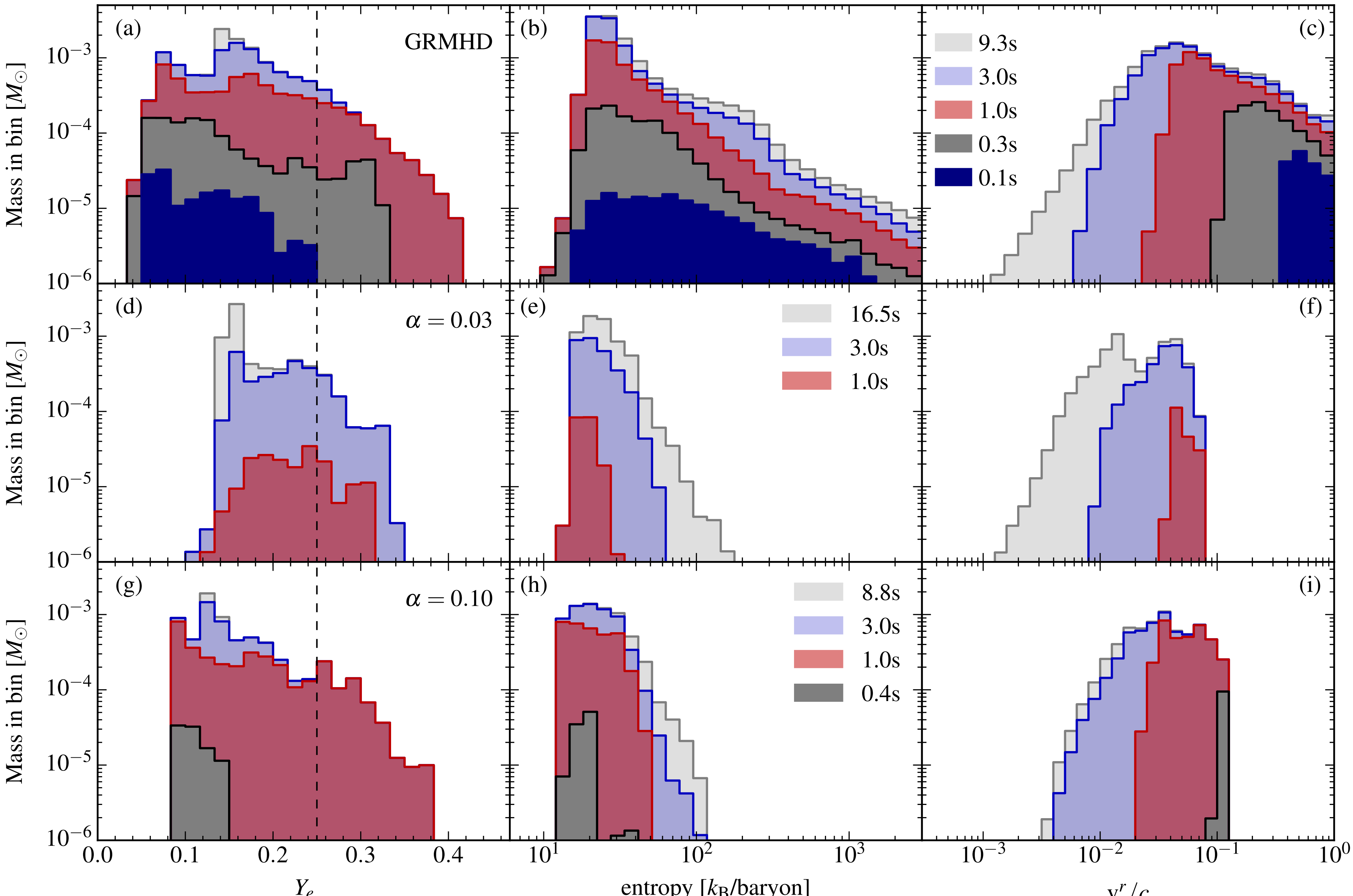


RF, Tchekhovskoy, et al. (2019)

GRMHD outflow ejects twice more mass than equivalent hydro model

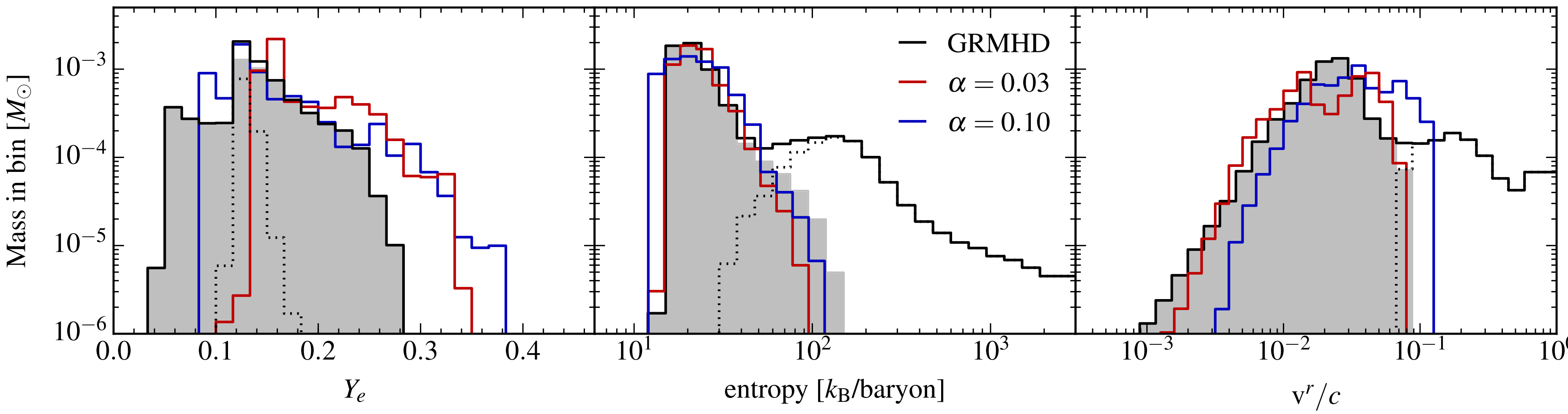
50% of the mass is ejected before 1s

Late-time behavior is similar to hydro: shared mass ejection mechanism



RF, Tchekhovskoy, et al. (2019)

GRMHD: advective phase

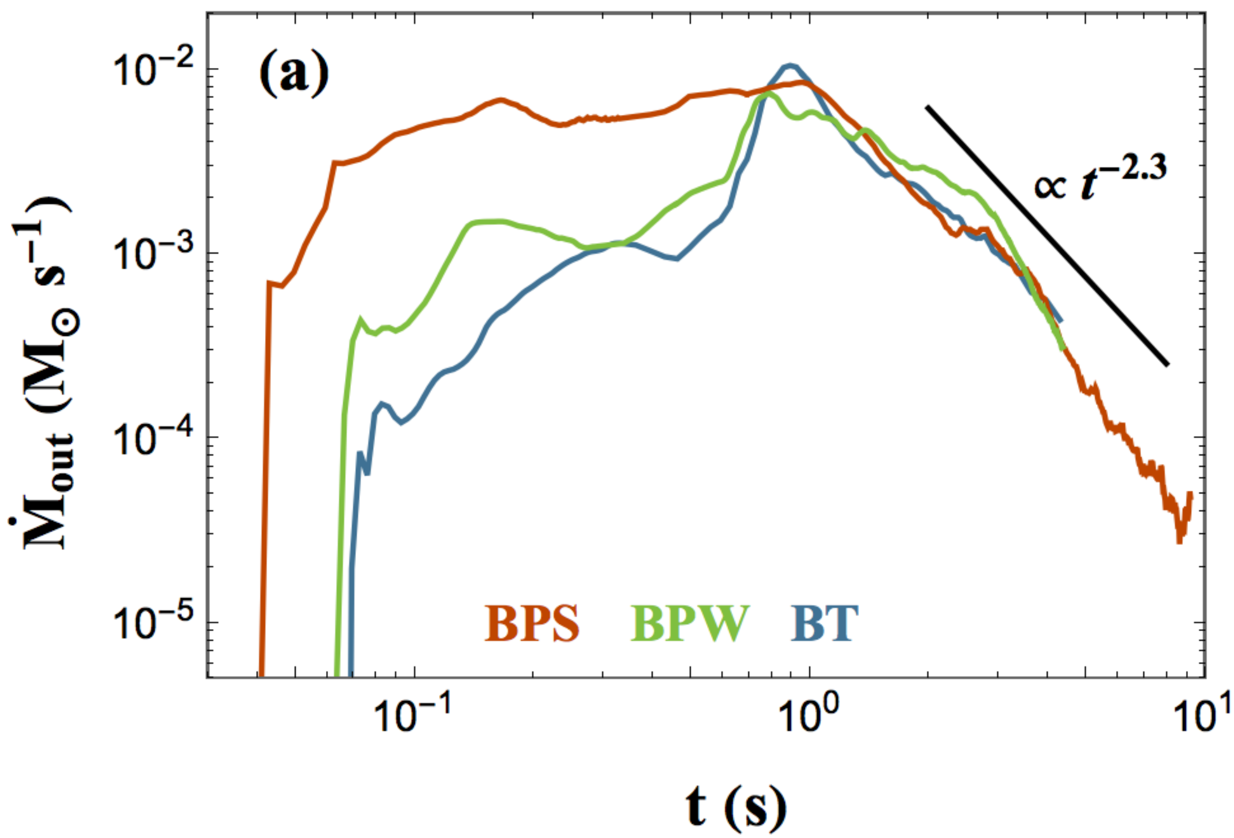


RF, Tchekhovskoy, et al. (2019)

Restricting late-time GRMHD outflow to t > 1s and v < 0.1c shows good agreement with purely hydrodynamic models (pseudo-Newtonian: physics set far from the BH)

Underlying physical mechanism should be the same: freezout of weak interactions (no cooling), with energy deposition from viscous / MRI heating and nuclear recombination, slow speeds

GRMHD: toroidal vs poloidal



New simulations with weak poloidal field and also toroidal field.

Outflow obtained in all cases, but prompt component increases with strength of initial poloidal field

Christie, Lalakos, Tchekhovskoy, RF, Foucart, Quataert, & Kasen (2019)

(same run as RF+2019)

Model Name	Field Geometry	Max Field Strength (G)	Duration, t_{max} (s)	(10^5 r_g/c)	Initial plasma $\langle\beta\rangle$
BPS	Poloidal	1.1×10^{14}	9.2	6.2	100
BPW	Poloidal	3.6×10^{13}	4.4	3	850
BT	Toroidal	4.7×10^{14}	4.3	2.9	5

GRMHD: poloidal, toroidal & hydro

	Model Name	$M_{\rm ejec}$ (%)	$M_{\rm ejec}$ $(10^{-2}\,M_\odot)$	$\langle v_r \rangle$	$\langle Y_{\rm e} \rangle$
GRMHD	BPS	40	1.3	0.18	0.16
	BPW	30	0.99	0.08	0.19
	BT	27	0.89	0.05	0.18
Hydro	$\alpha = 0.1$	22	0.67	0.05	0.17
	$\alpha = 0.03$	21	0.63	0.03	0.20
	$\alpha = 0.01$	16	0.48	0.03	0.26

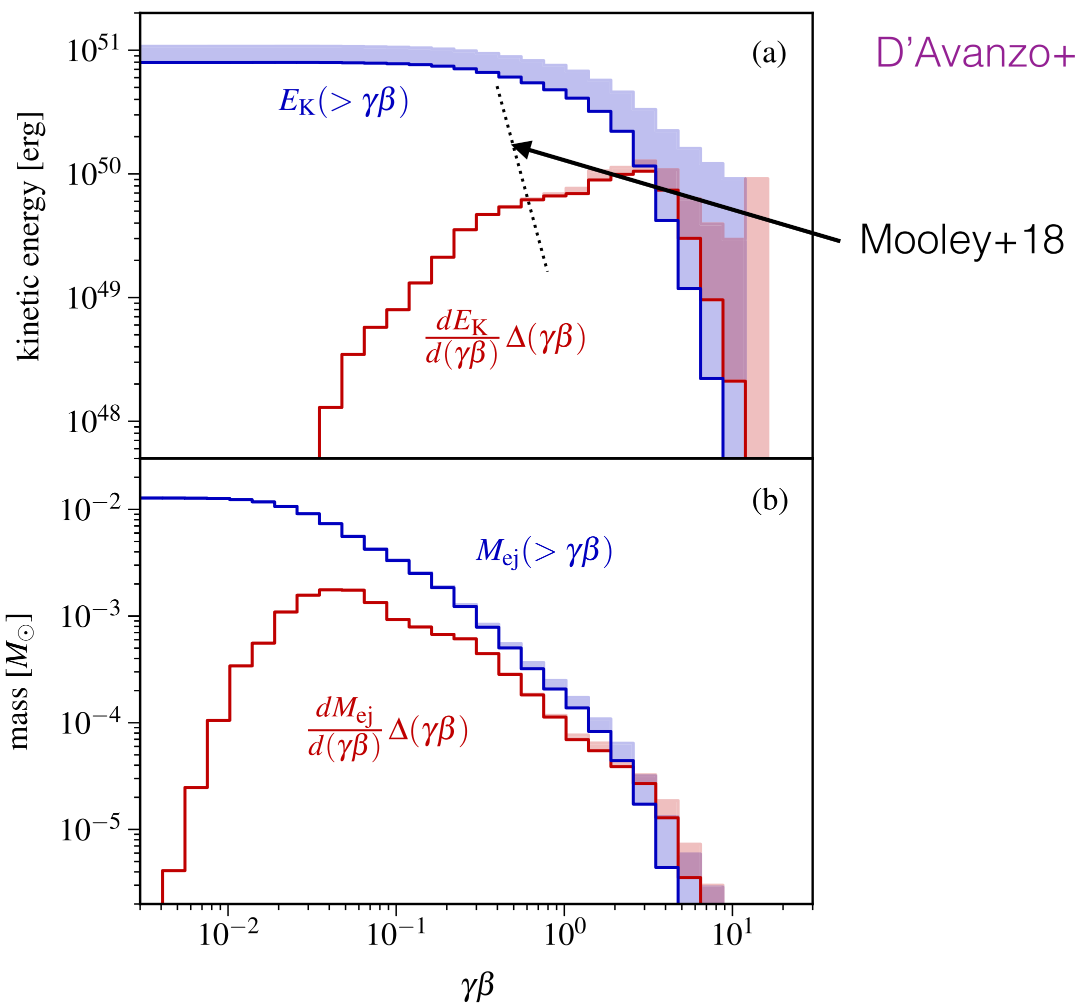
Main caveat: Ye set only by neutrino cooling

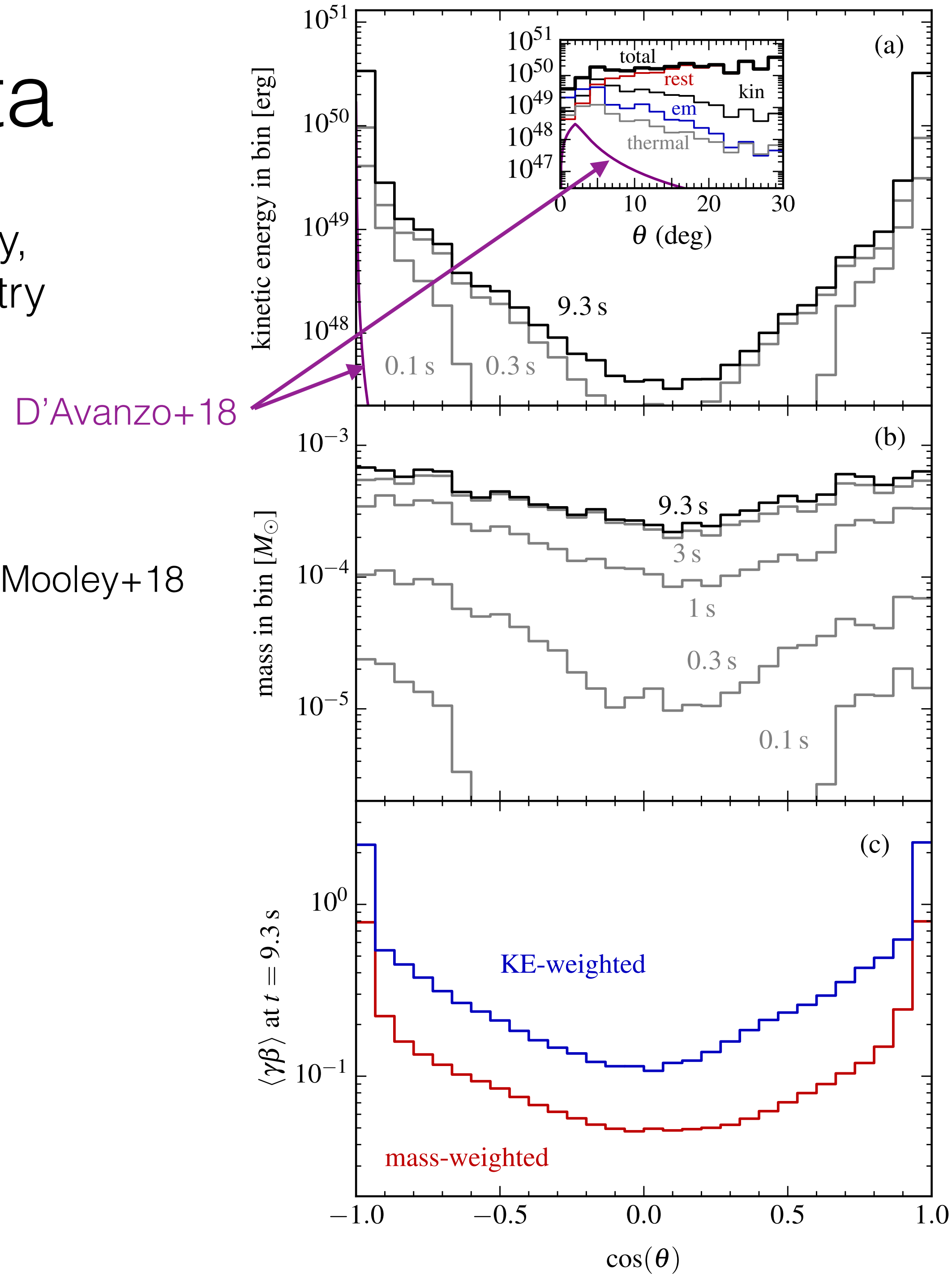
Christie, Lalakos, Tchekhovsoy, RF+ (2019)

RF, Tchekhovskoy+ (2019)

Relativistic Ejecta

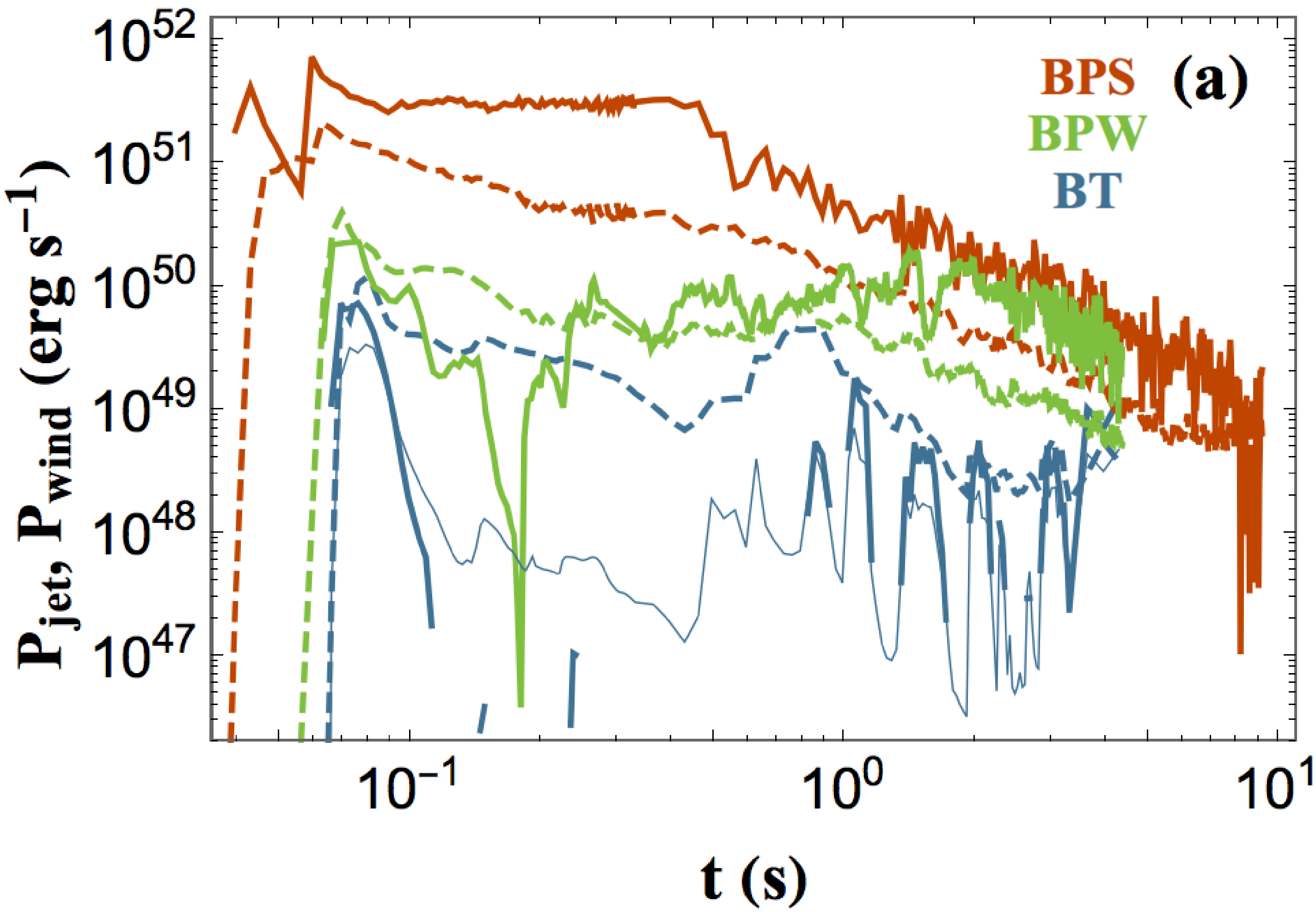
More than enough Kinetic Energy, depending on initial field geometry





RF, Tchekhovskoy+ (2019)

GRMHD: toroidal field also yields jet



jet (solid)

$$-\frac{T^r_t}{\rho u^r} > 2$$

wind (dashed)

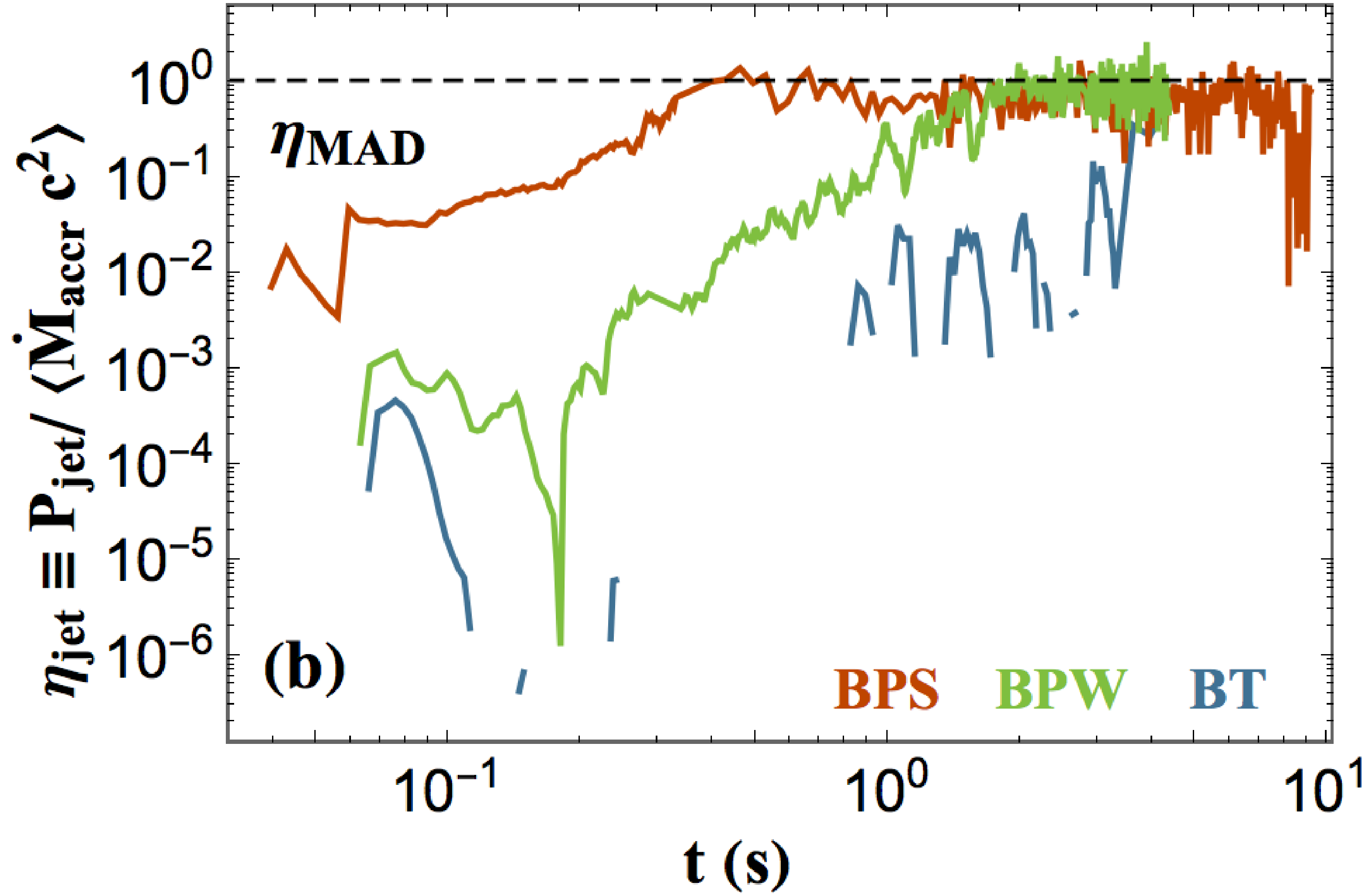
$$-\frac{T^r_t}{\rho u^r} < 2$$

(c = 1)

Christie, Lalakos, Tchekhovsoy, RF+ (2019)

GRMHD: toroidal field also yields jet

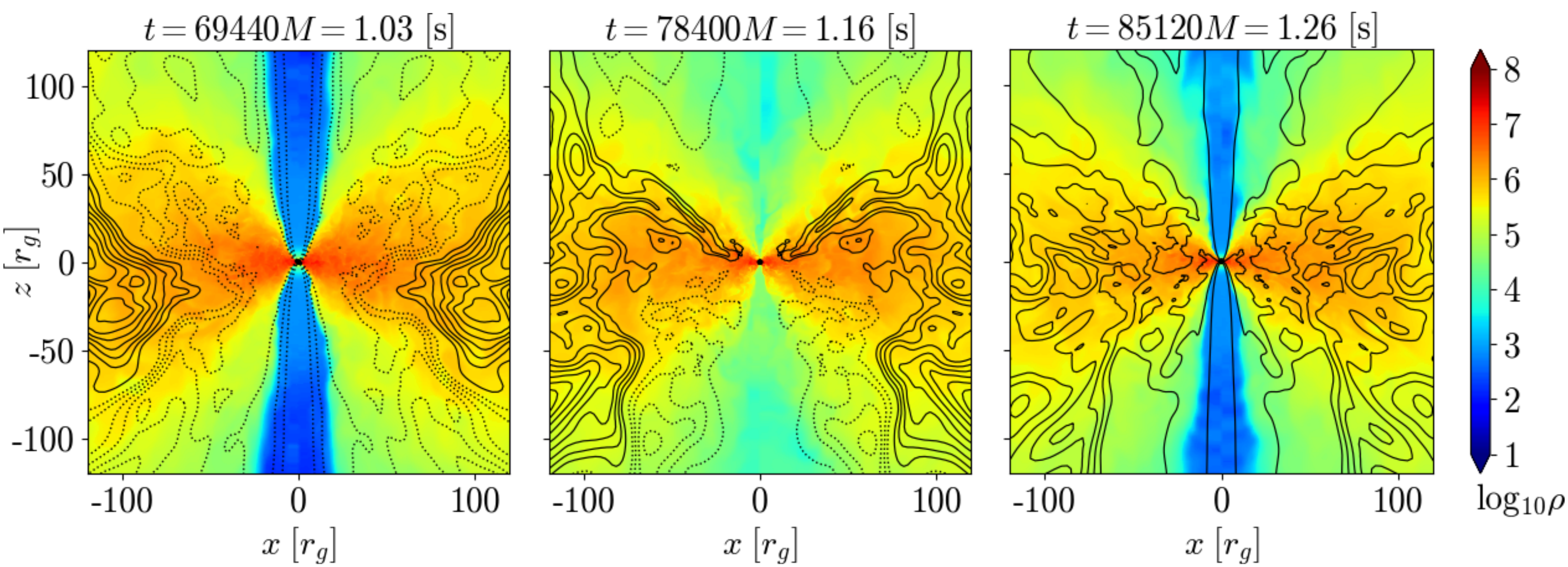
MAD: magnetically arrested disk



Christie, Lalakos, Tchekhovsoy, RF+ (2019)

GRMHD: toroidal initial field

Toroidal field undergoes flips in polarity: intermittent jet



Christie, Lalakos, Tchekhovsoy, RF+ (2019)

see also Liska+18

GRMHD: cumulative jet energies

Model Name	$E_{\rm jet}$ (10^{50} erg)	$E_{\rm iso}$ (10^{52} erg)	$\langle\theta_{\rm jet}\rangle$ (°)
BPS	25	22	13
BPW	3.9	3.6	6.4
BT	0.2	1.3	4.6

Christie, Lalakos, Tchekhovsoy, RF+ (2019)

Pending Issues in Disk Modeling

1) Improve neutrino transport (with GRMHD): outflow composition

2) HMNS disk in MHD (long-term)

3) Realistic initial conditions for magnetic field and matter

Summary

1. HMNS disks evolved in hydrodynamics + viscosity + neutrino heating cannot reproduce blue kilonova from GW170817 if fitting observations with two-component fit (need MHD, composite ejecta, or enhanced dynamical ejecta)

2. GRMHD simulations show that magnetic stresses can enhance mass ejection above weak freezout (hydro), effect is dependent on the strength of the initial poloidal field.

3. Disks with initial magnetic fields mostly toroidal can also produce a jet, although power is intermittent due to field reversals

Thanks to:

UNIVERSITY OF ALBERTA

NSERC CRSNG

NERSC

U.S. DEPARTMENT OF ENERGY | Office of Science

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