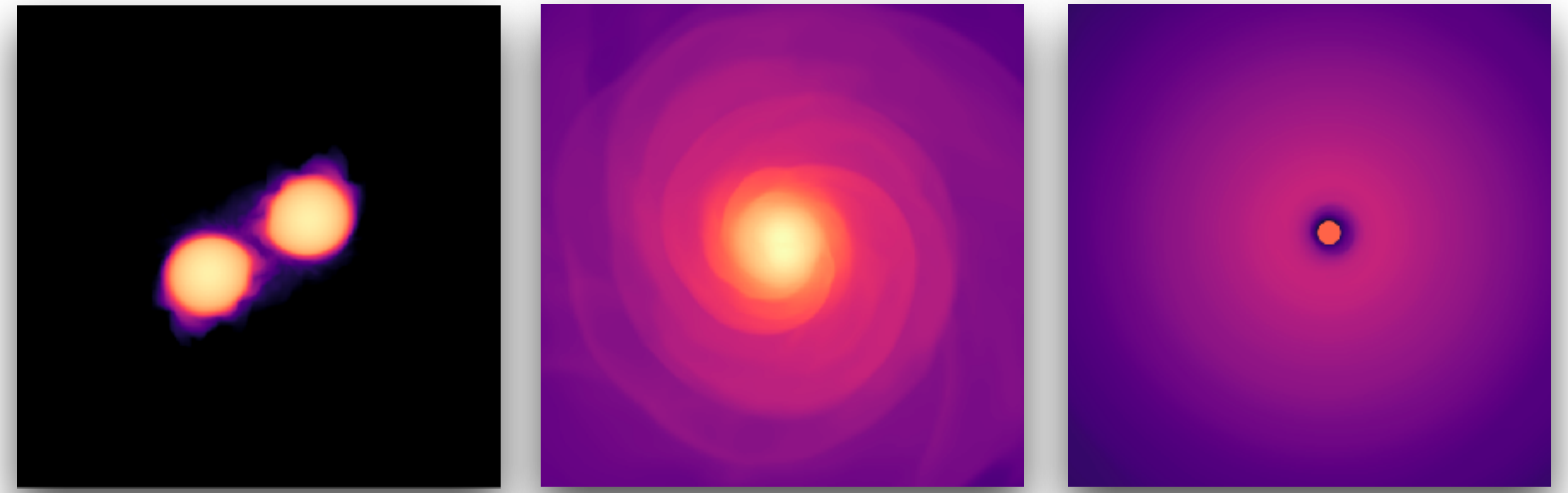
Magnetized BNS merger simulations & prospects of launching SGRB jets



Jay V. Kalinani

INAF, Astronomical Observatory of Padova, Italy

INFN, Padova, Italy

in collaboration with

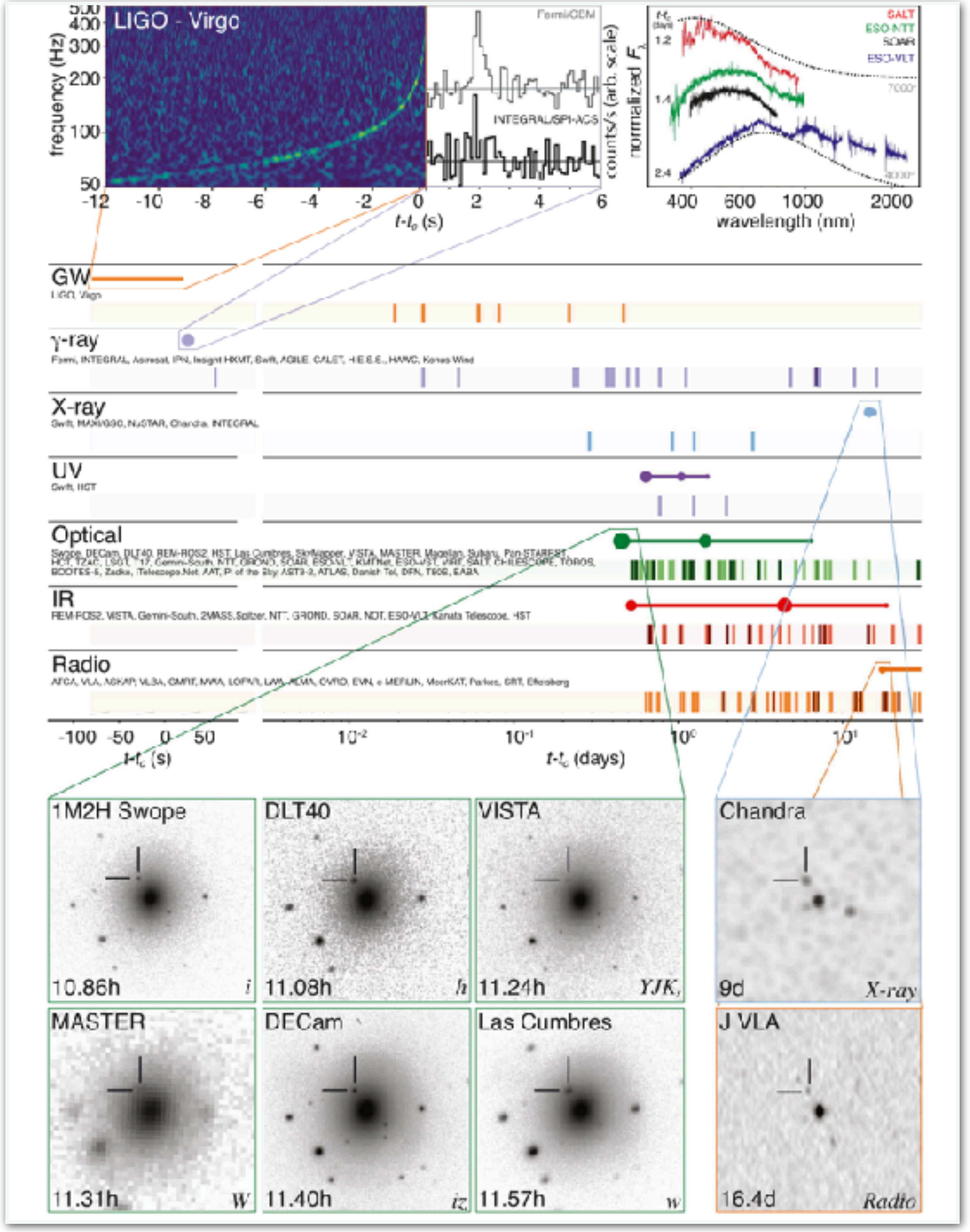
R.Ciolfi, B. Giacomazzo, F. Cipolletta, W. Kastaun, & others

EMMI+IReNA GSI Workshop

Oct 17-20, 2022

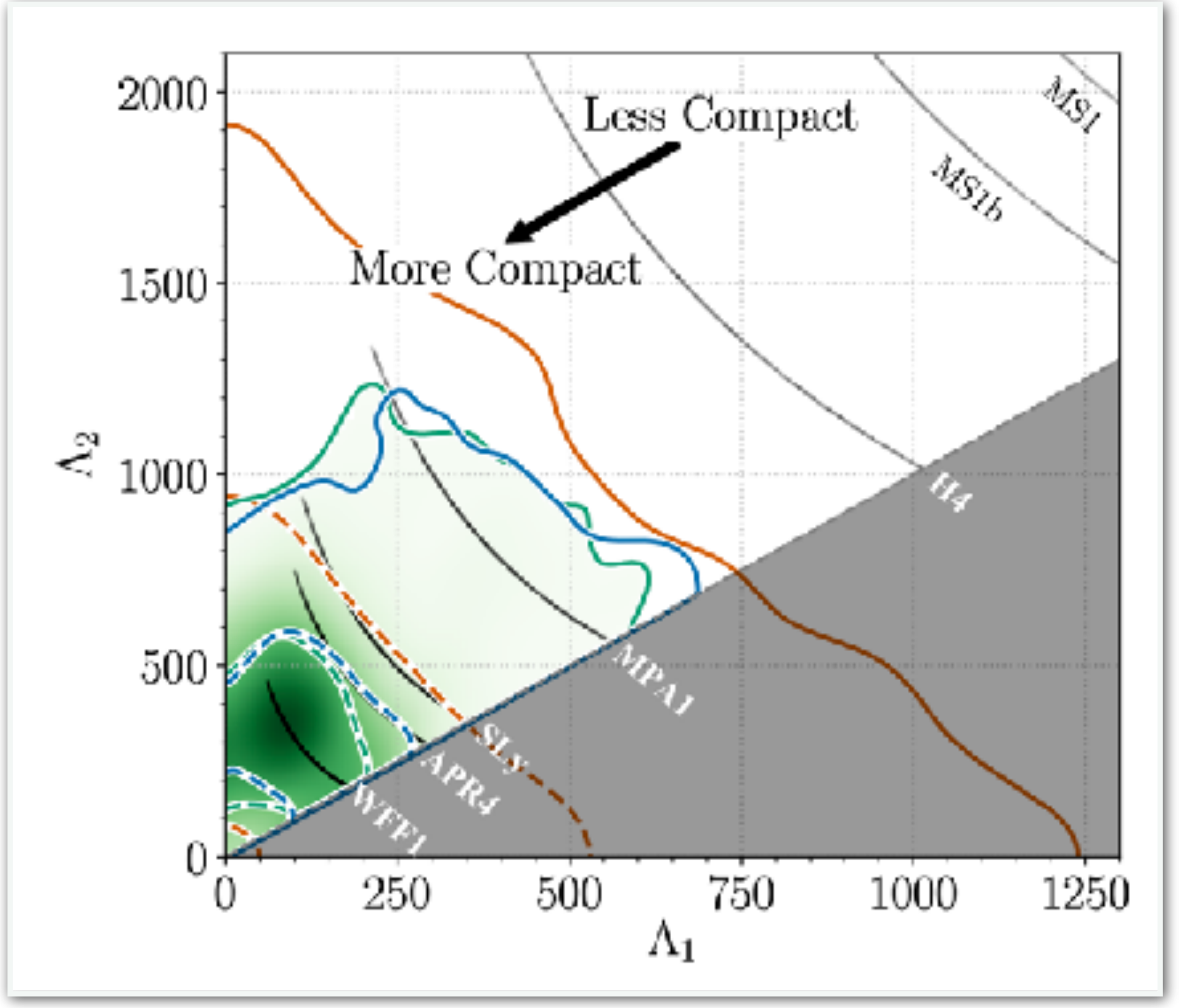
GW170817

GRB170817A + EM counterparts



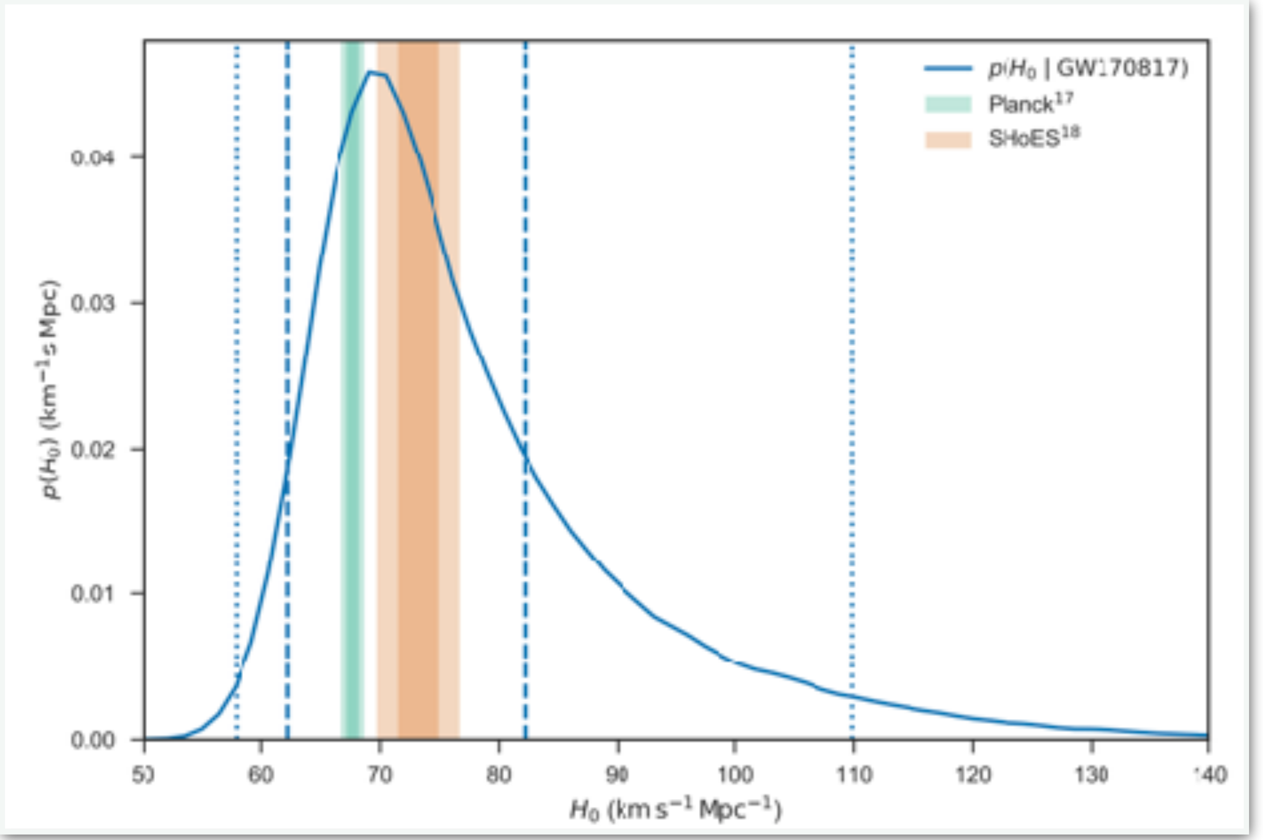
LVC+2017

EOS constraints



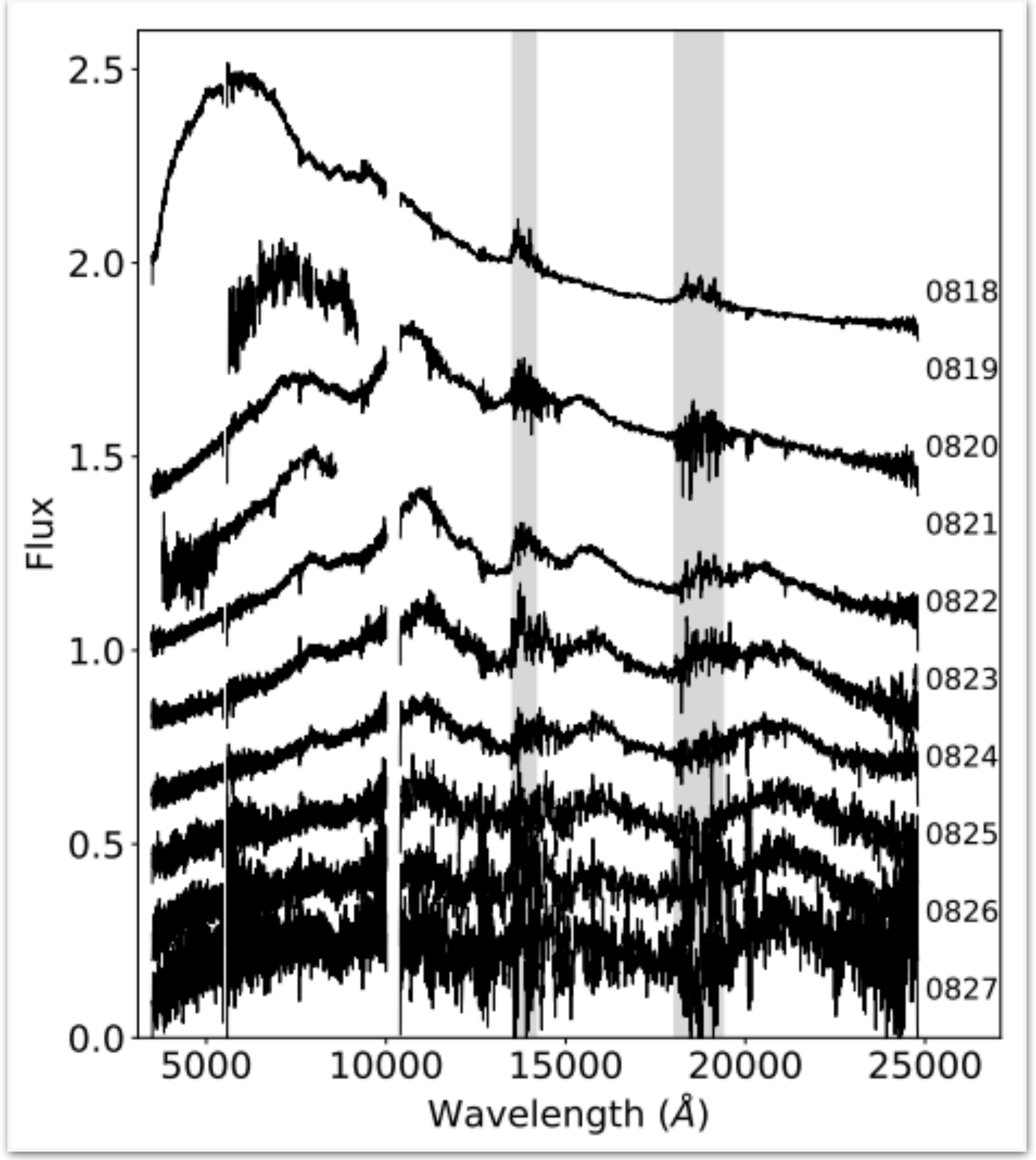
LVC+2018

H_0 measurement



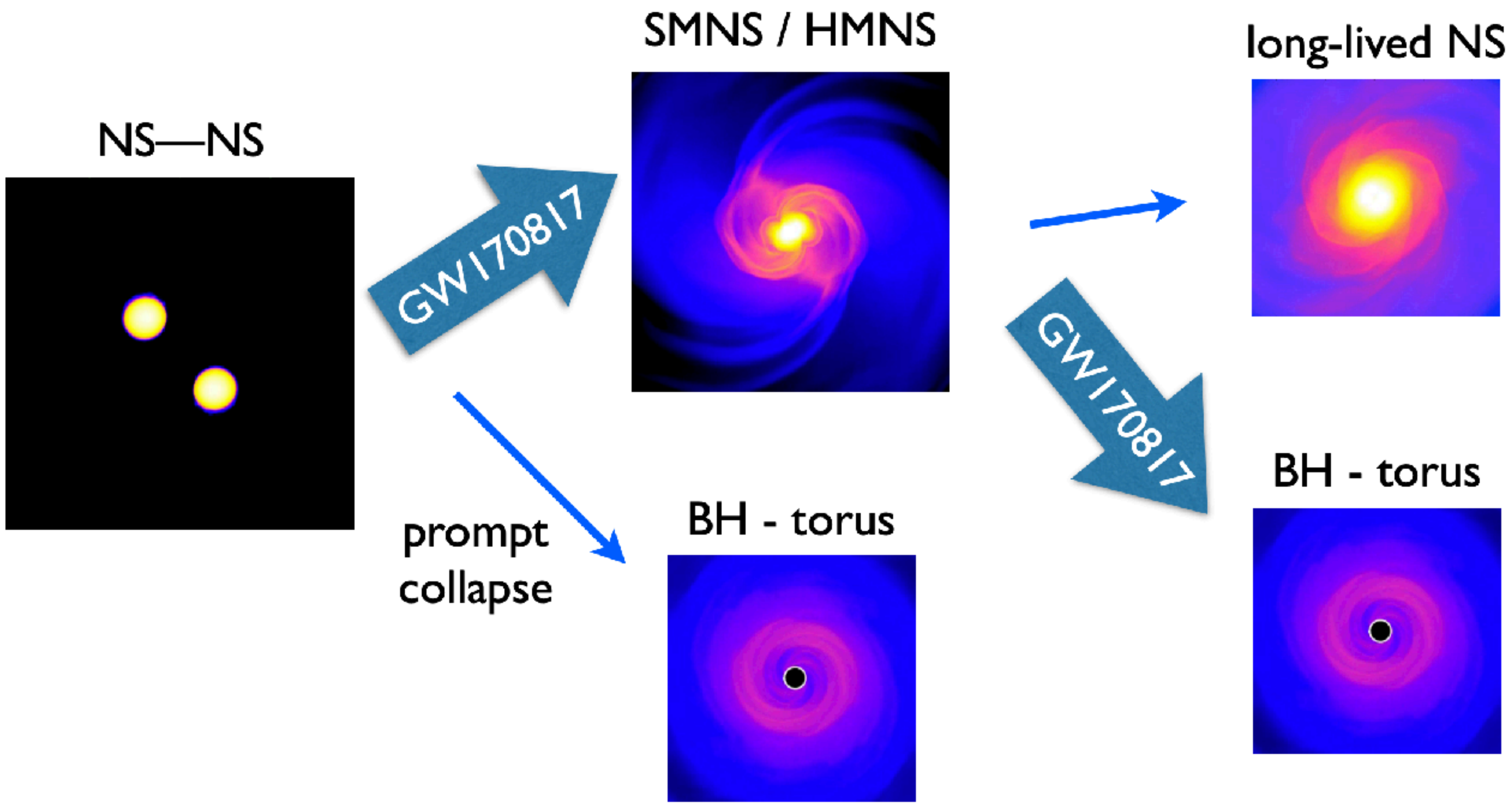
LVC+2017

AT2017gfo



Pian+2017

GW170817

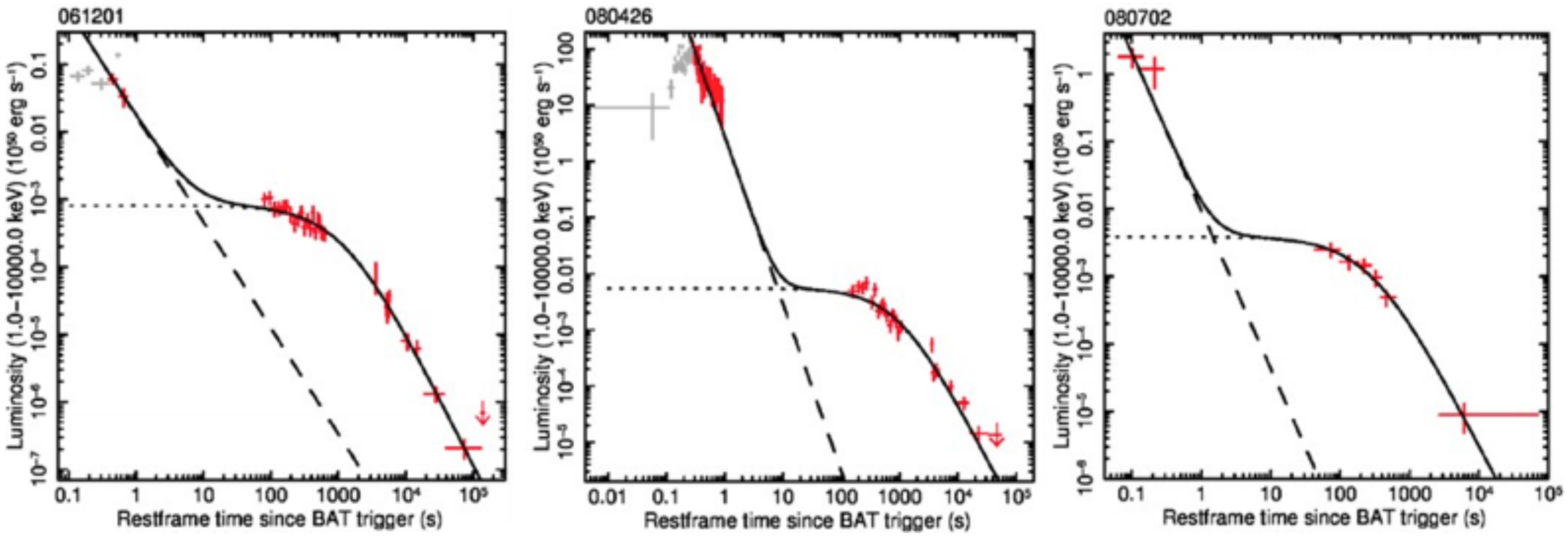


Siegel 2019

most-likely scenario of GW170817

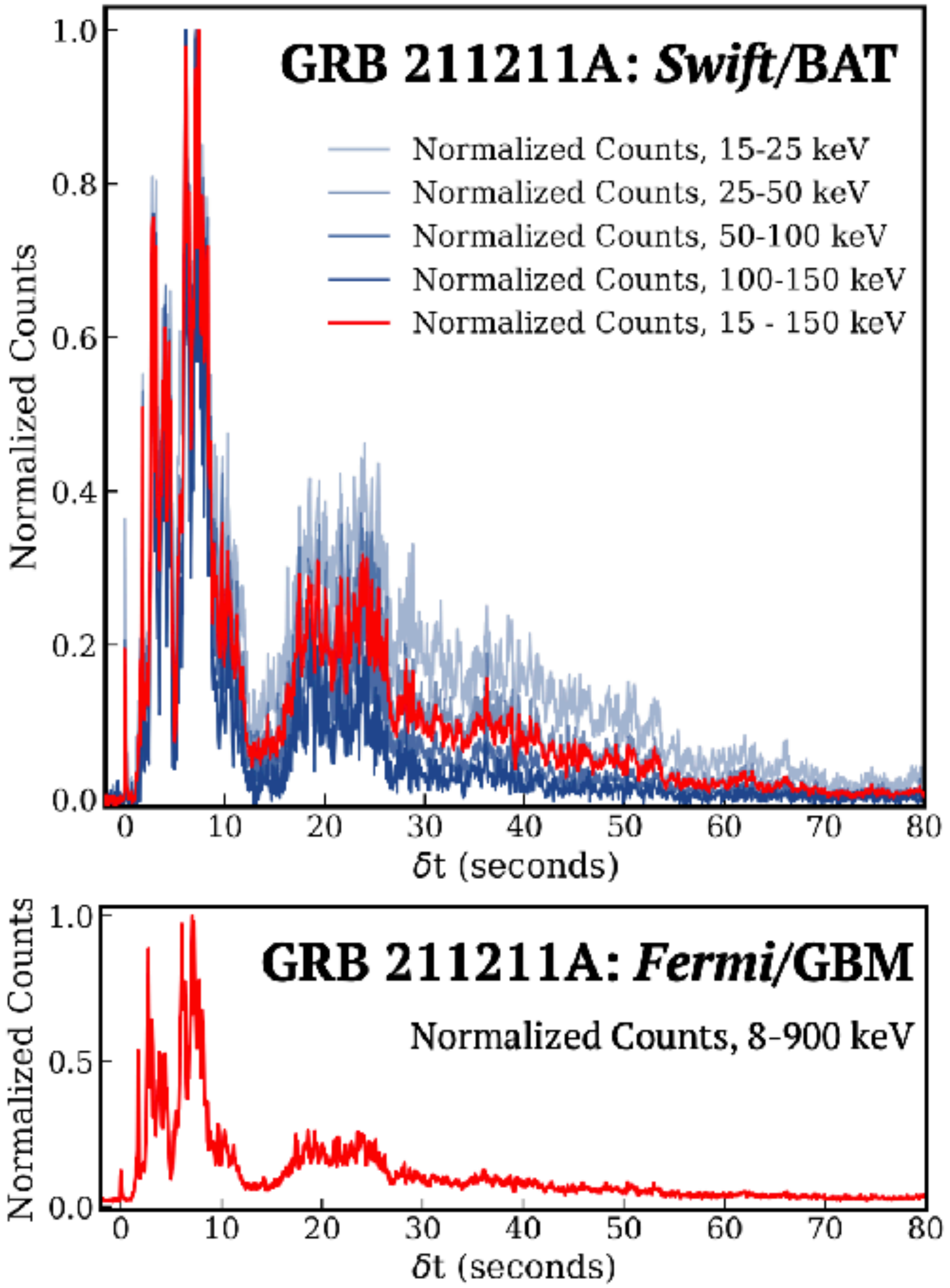
Magnetar Scenario

Characteristic X-ray plateaus in SGRB afterglows



Rowlinson+2017

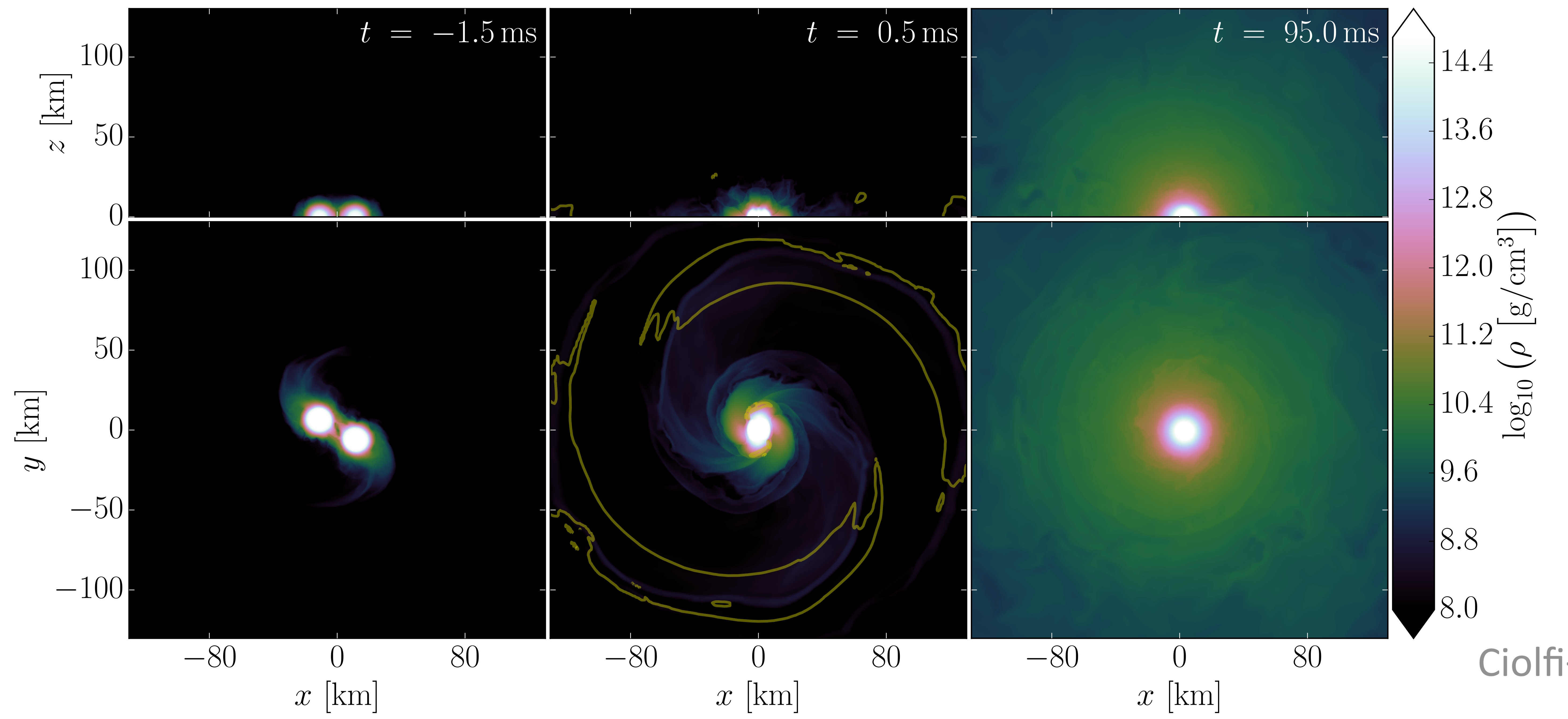
Extended emissions from SGRBs



Rastinejad+2022

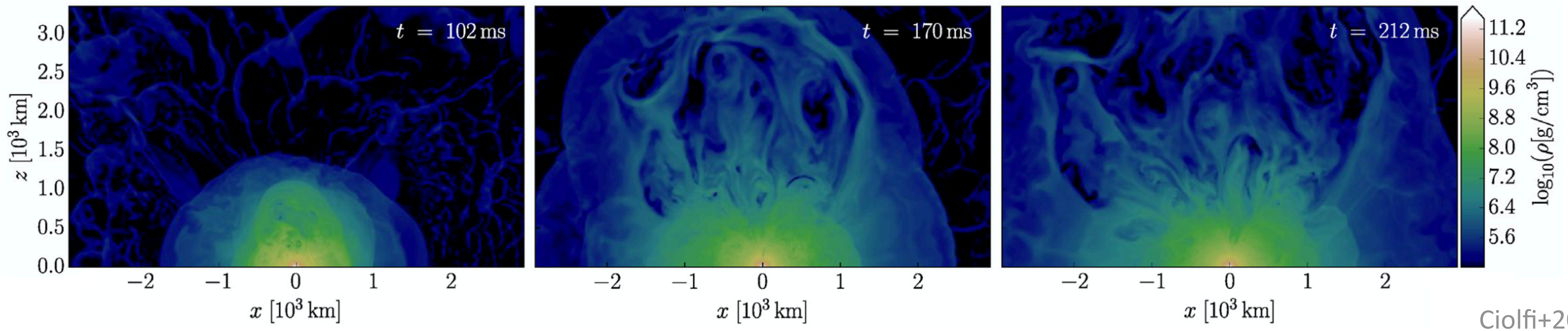
Open question: can a MNS remnant power a SGRB jet?

BNS with WhiskyMHD



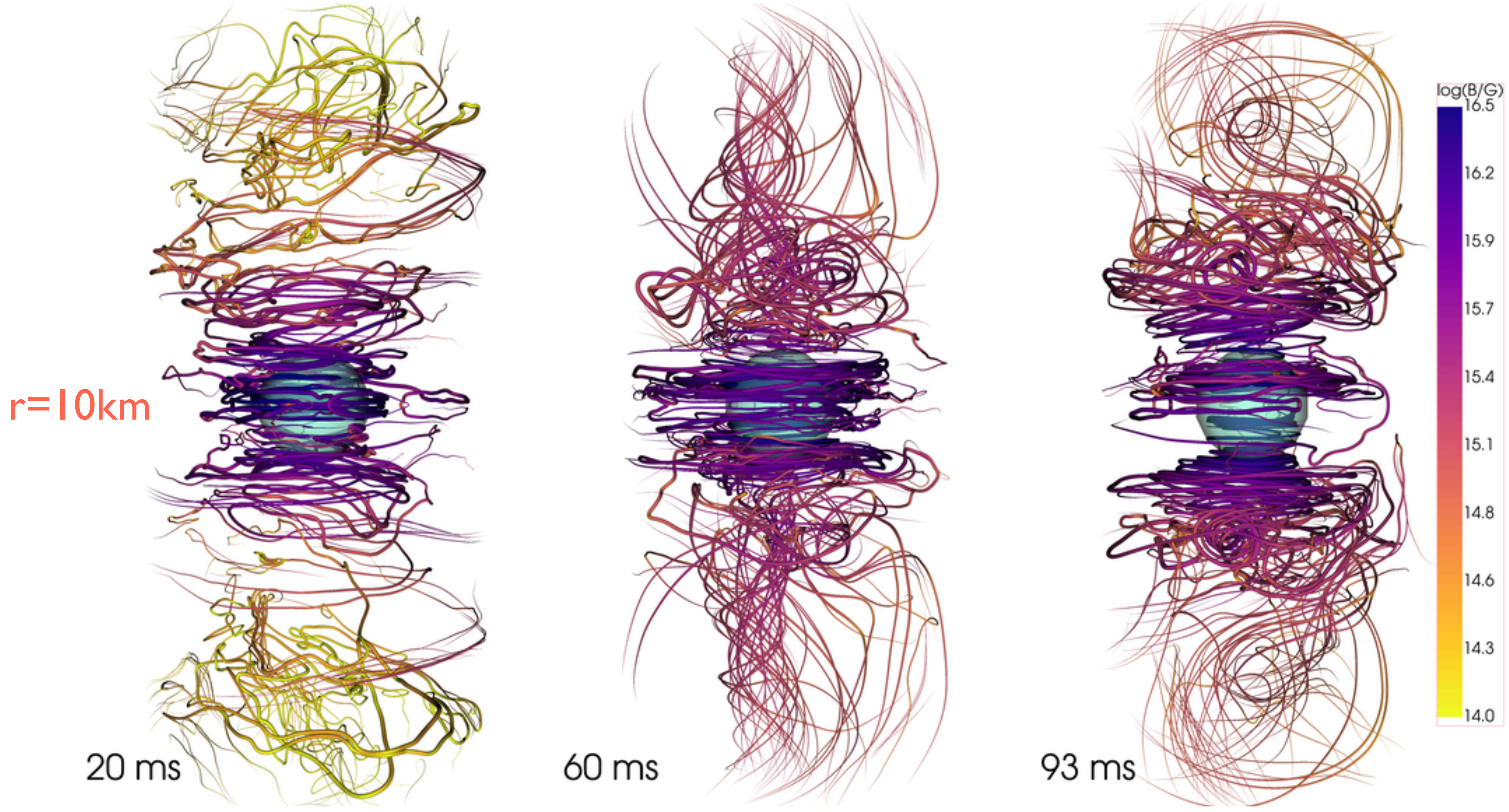
Merger produces a differentially rotating, metastable SMNS

Ciolfi+2019



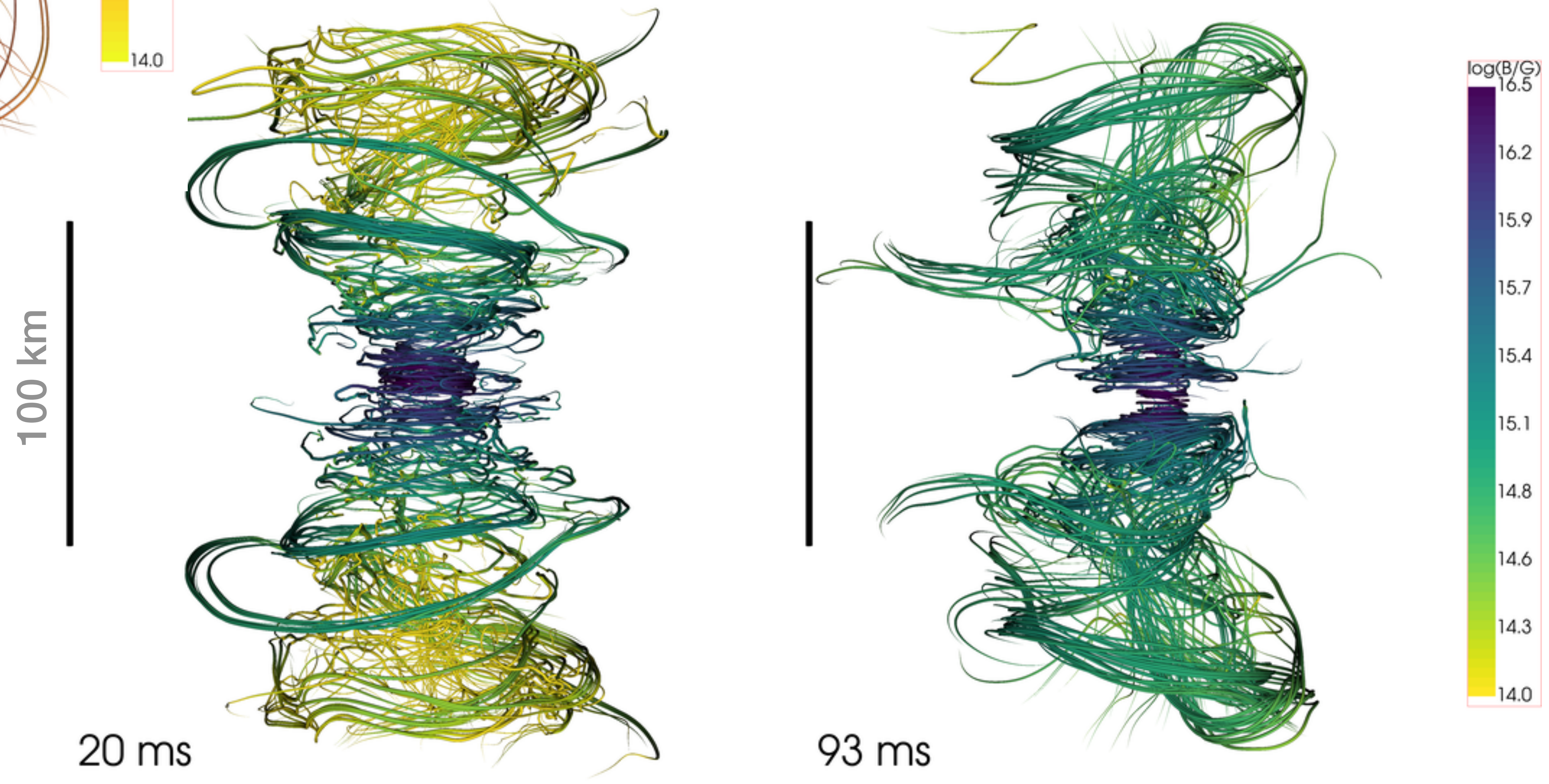
Ciolfi+2020

Field-line Geometry

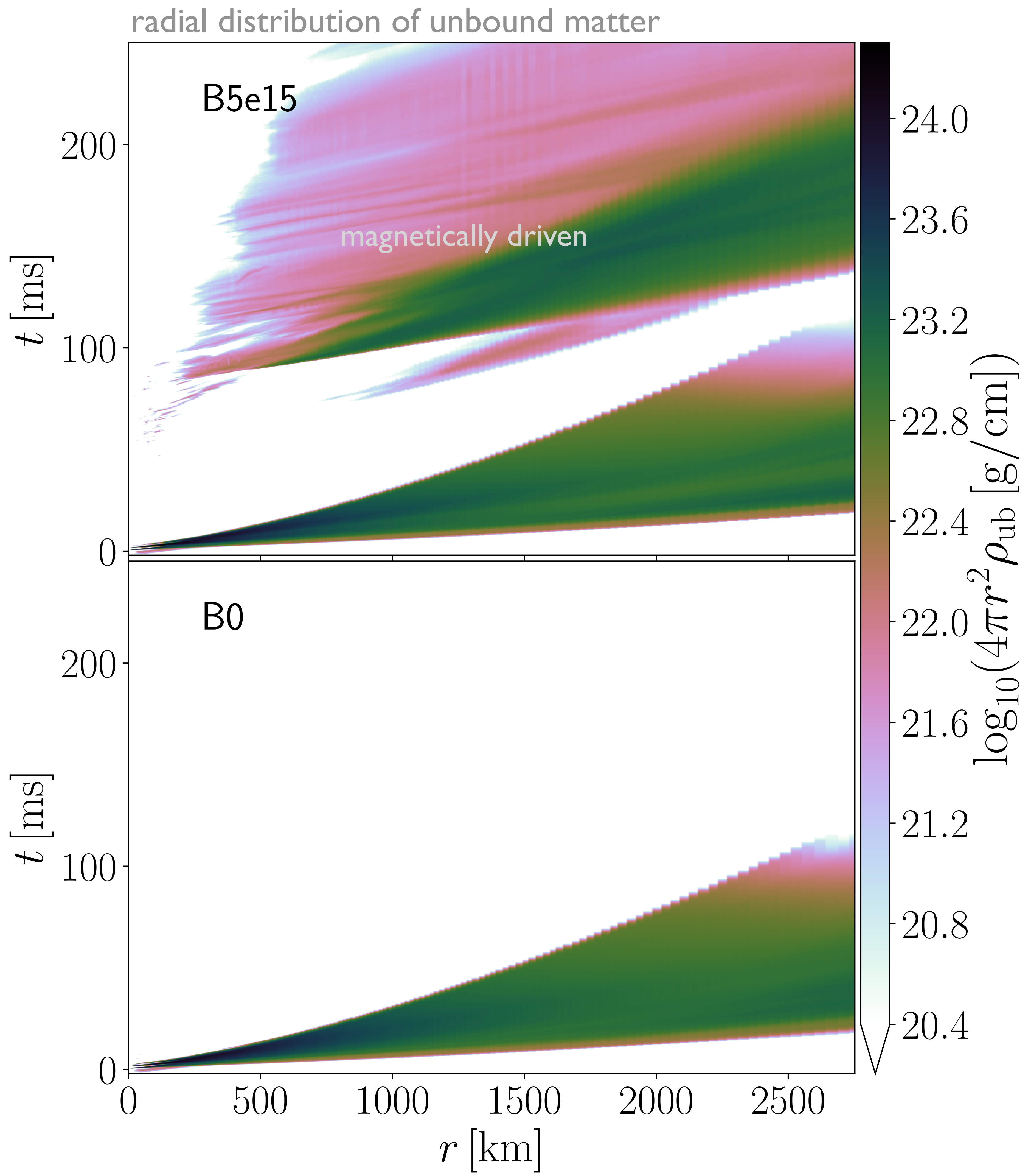


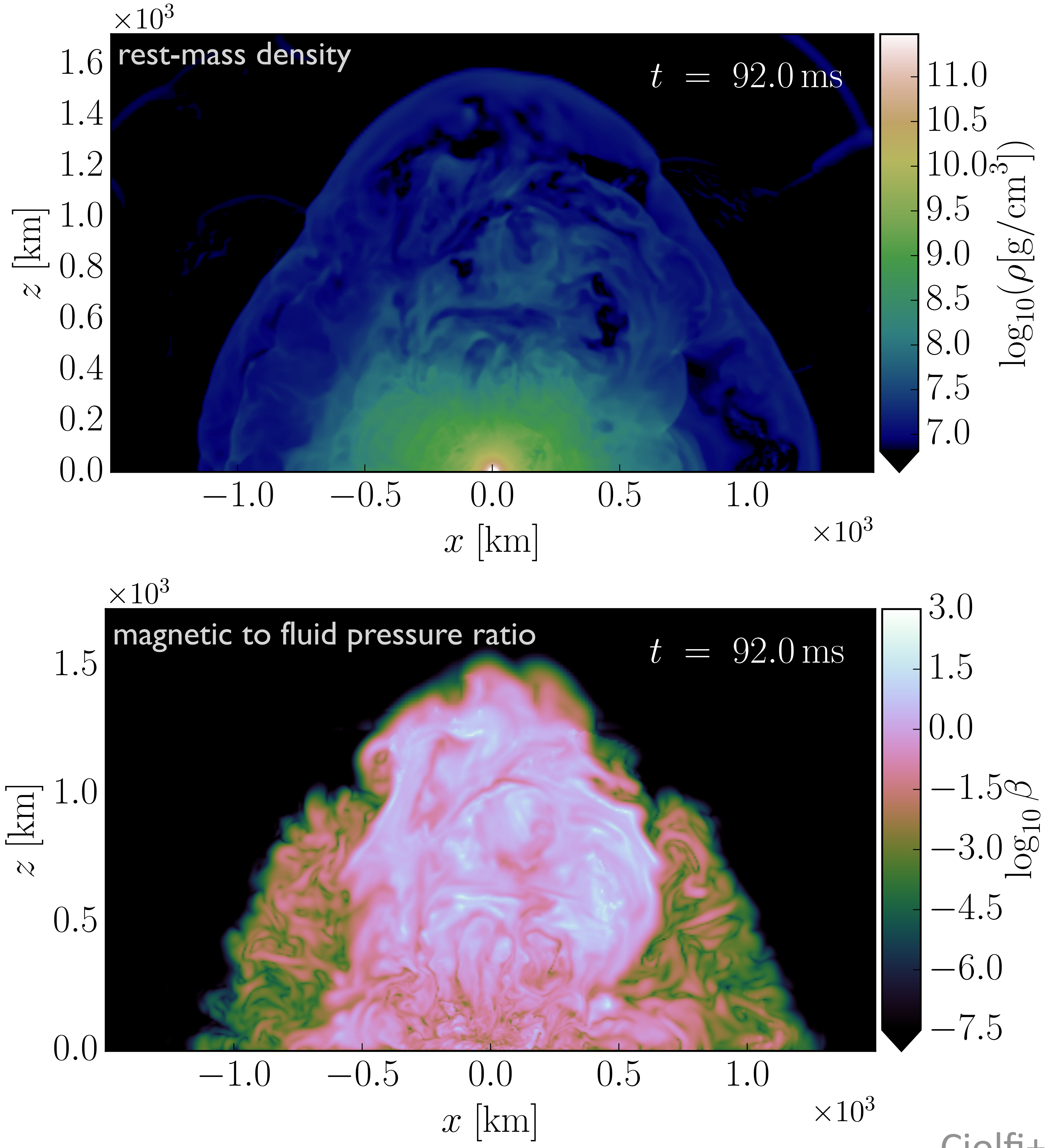
toroidal + poloidal field amplification

emergence of a global magnetic field



Baryon Pollution Problem



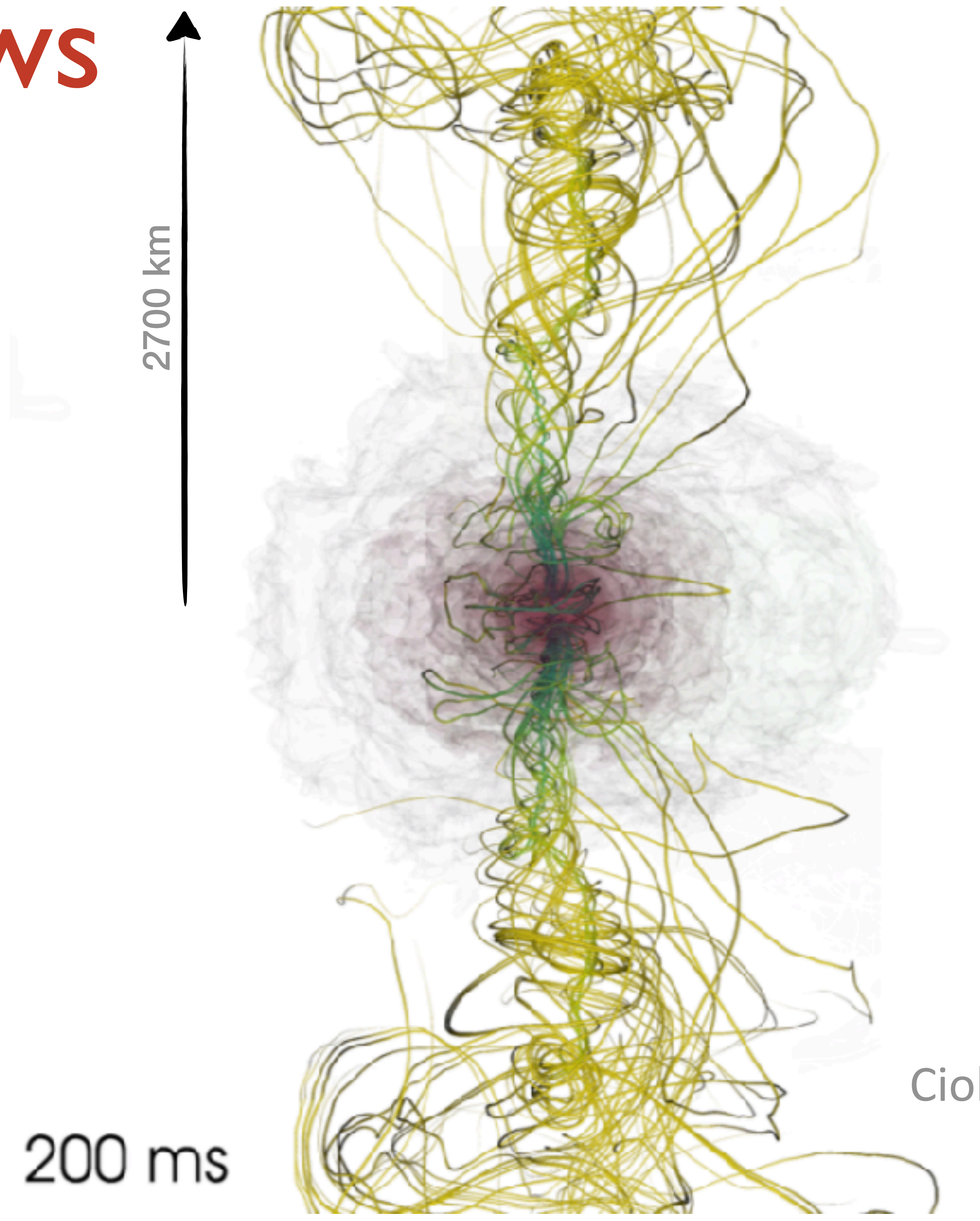


Ciolfi+2019

potential obstacle for jet launching

Collimated Outflows

- Jet-like helical structure emerges
- Isotropic matter distribution (no accretion disk)
- Breaking out around 170 ms
- Radial velocities reach 0.2-0.3c



Ciolfi 2020

Compatibility with GRB 170817A

- Not enough jet core energy
- Outflow too heavy

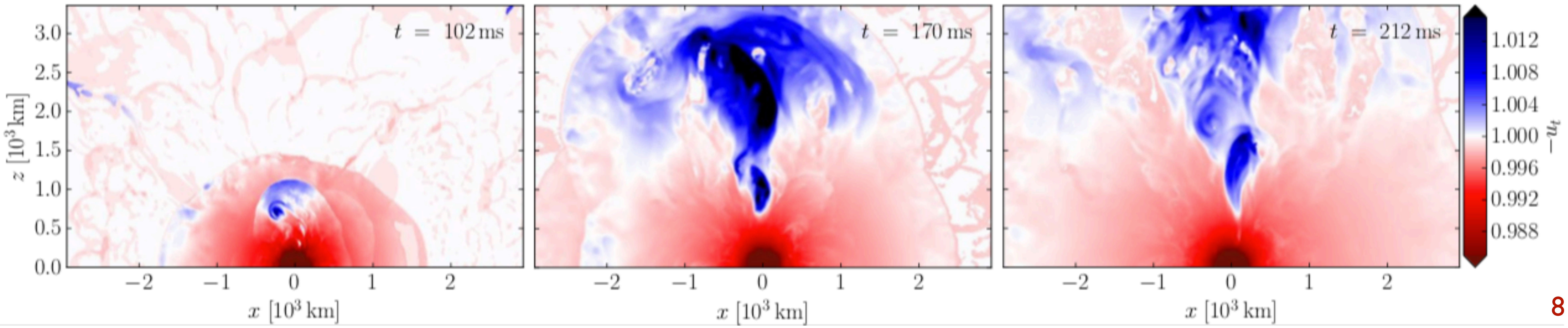
what it has

$\Gamma \lesssim 1.05,\ v \lesssim 0.3c$

what it needs

$\Gamma \gtrsim 10,\ v \gtrsim 0.995c$

Matter unbound when $u_t \leq -1$



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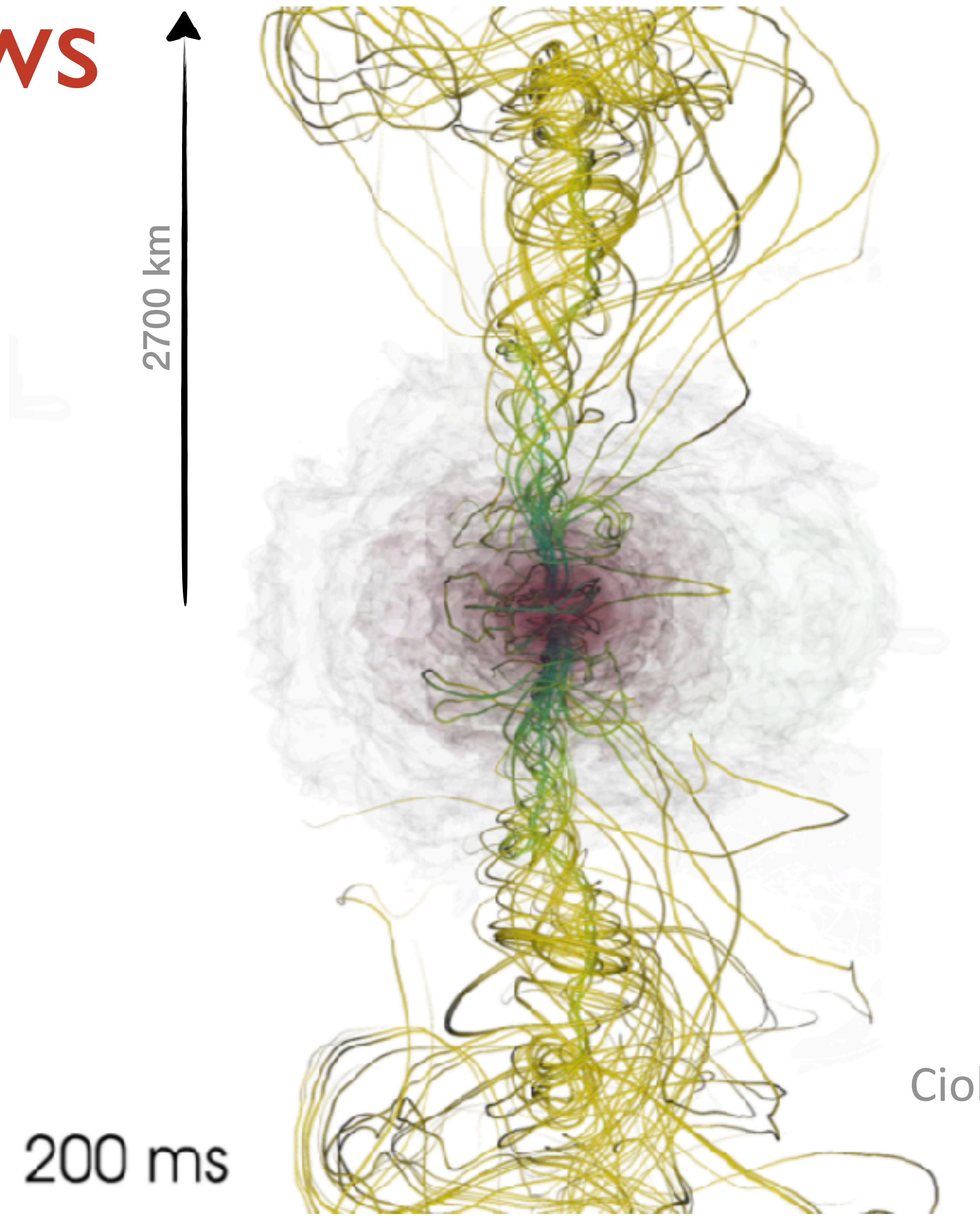

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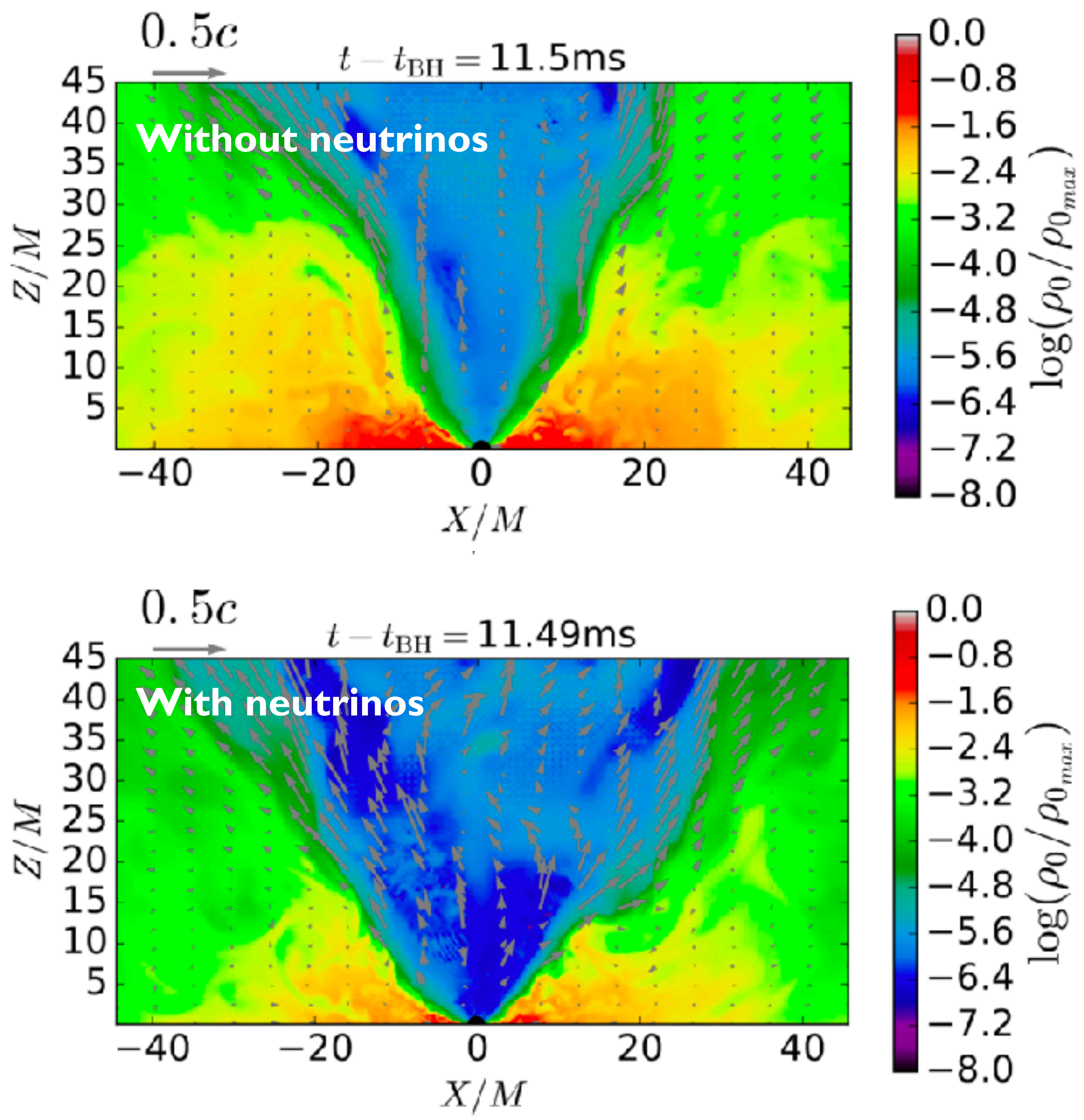
Magnetar scenario disfavoured for producing a SGRB jet

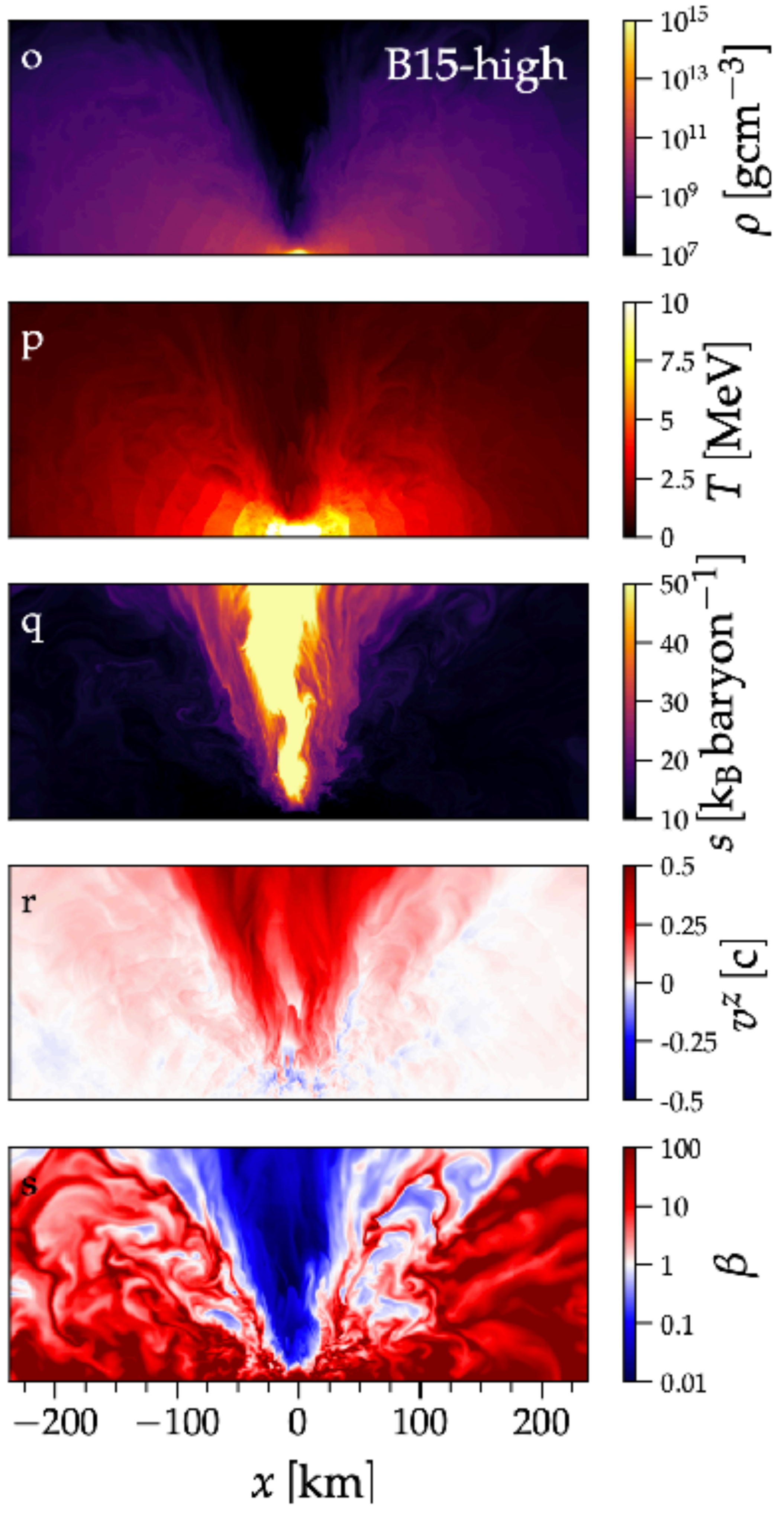
Role of Neutrinos

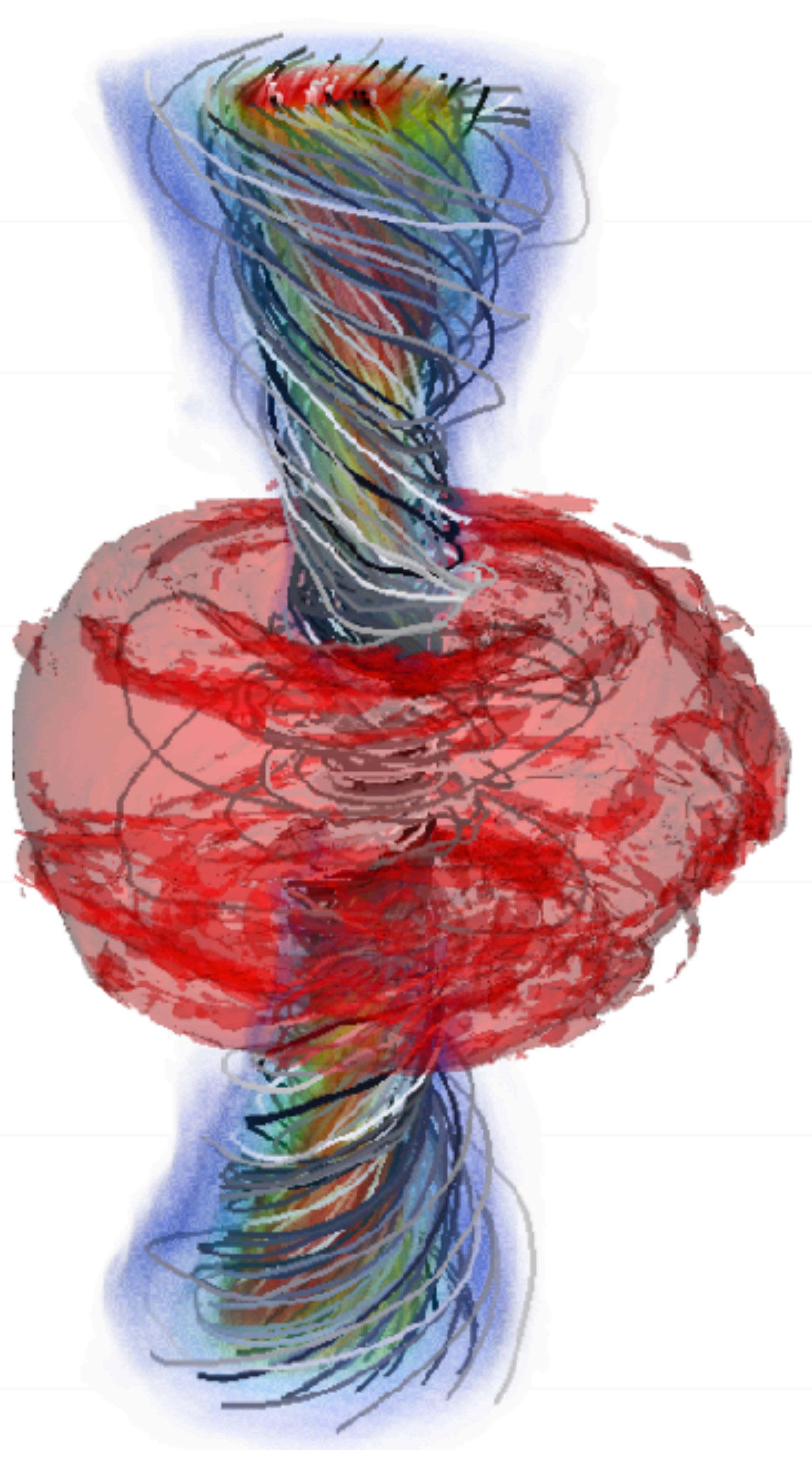
BH + disk



Sun+2022

Magnetar with neutrinos BUT
large poloidal field placed later by hand



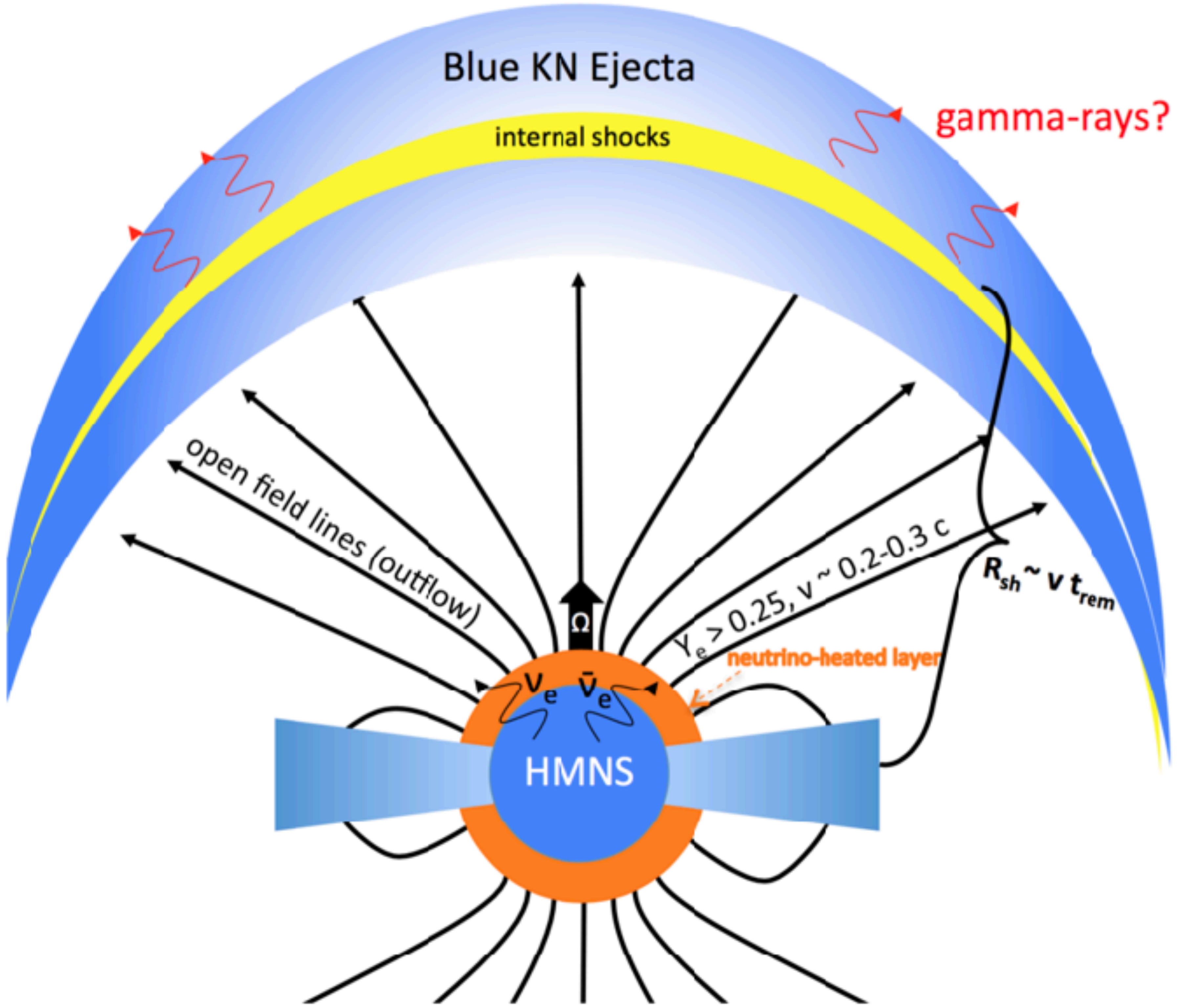


Moesta+2020

Open problem: complex interplay between continuous MNS outflows and neutrinos

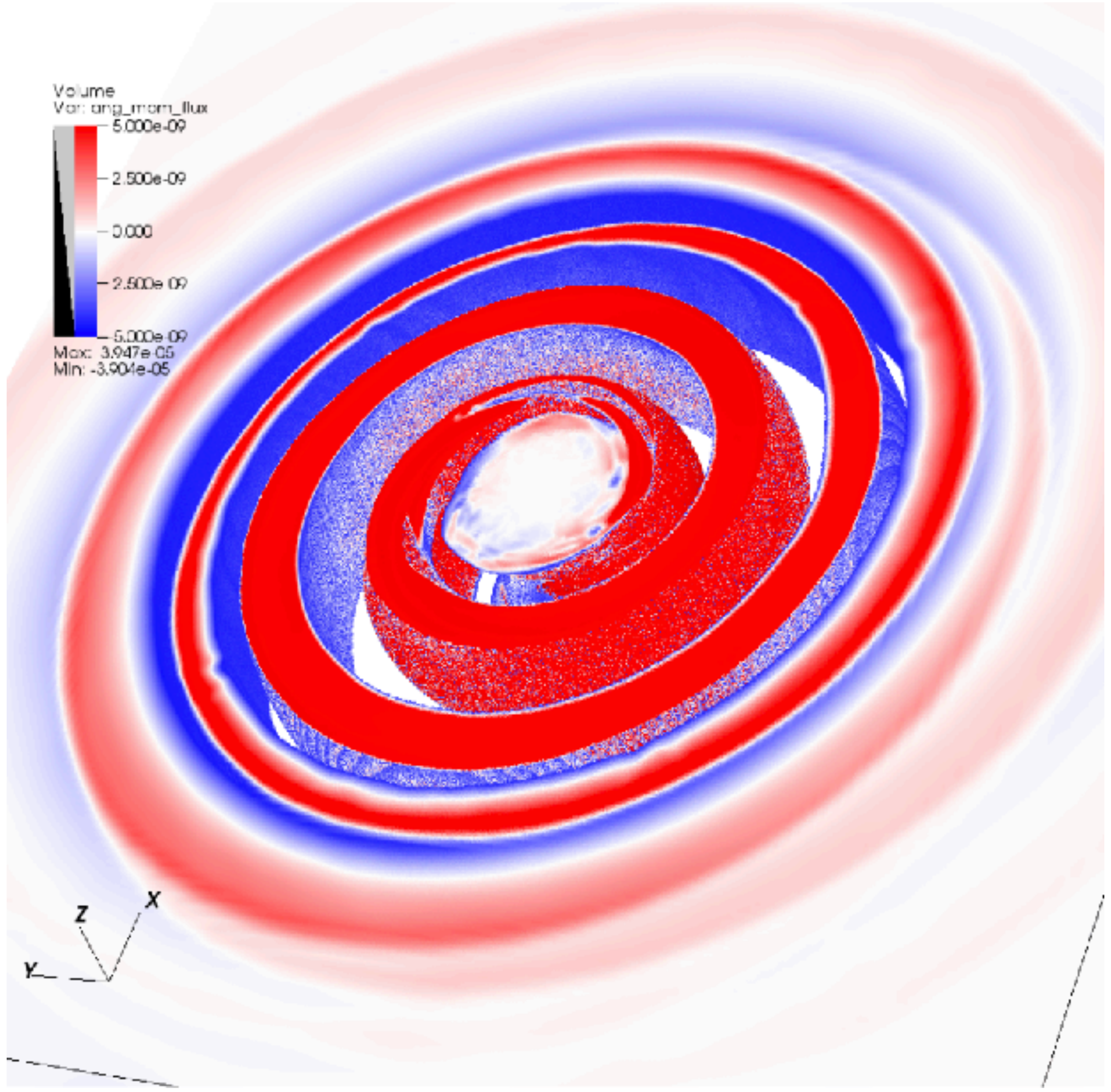
The Blue Kilonova

Magnetised winds from MNS remnant



Metzger+2018

Spiral density-wave winds

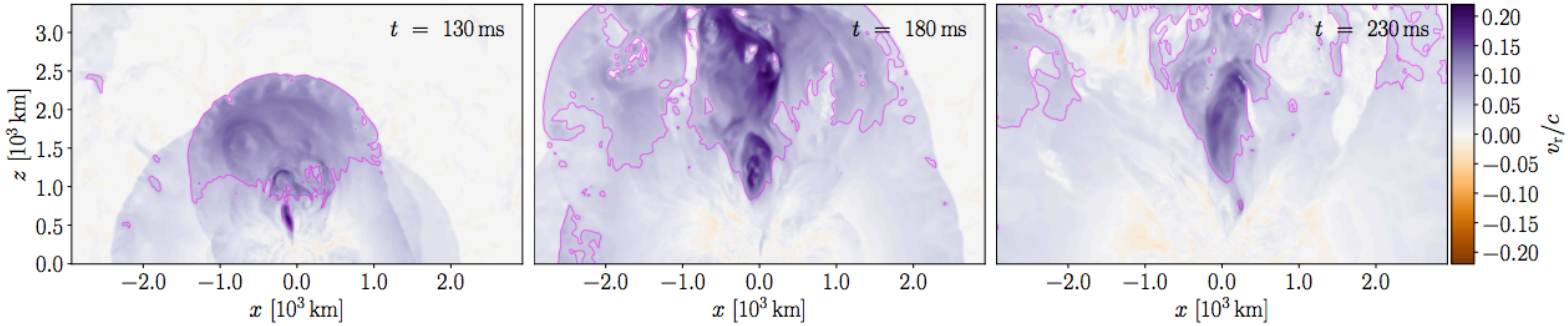


Nedora+2019

Open question: source of the blue kilonova component?

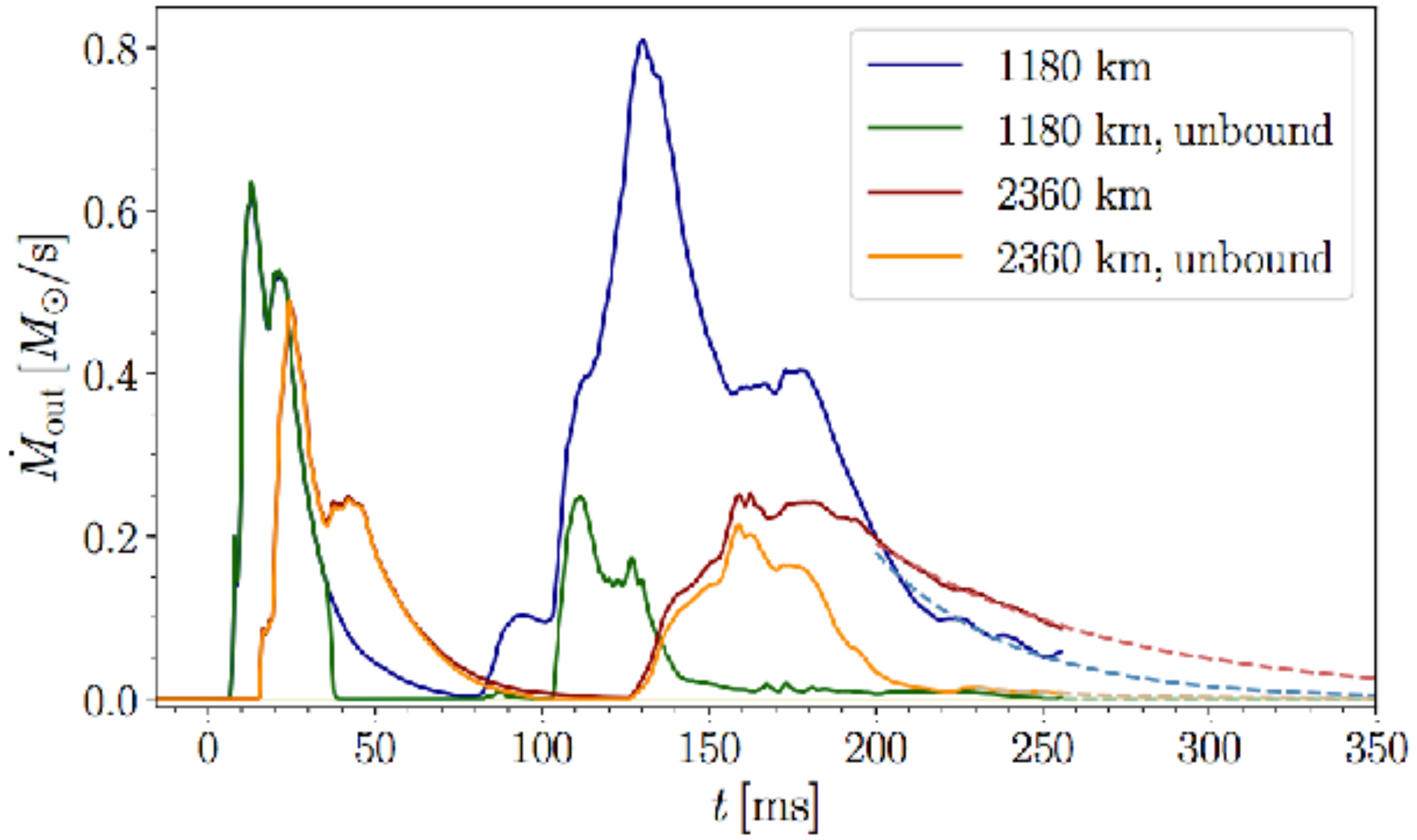
Ciolfi, Kalinani 2020

Radial velocity

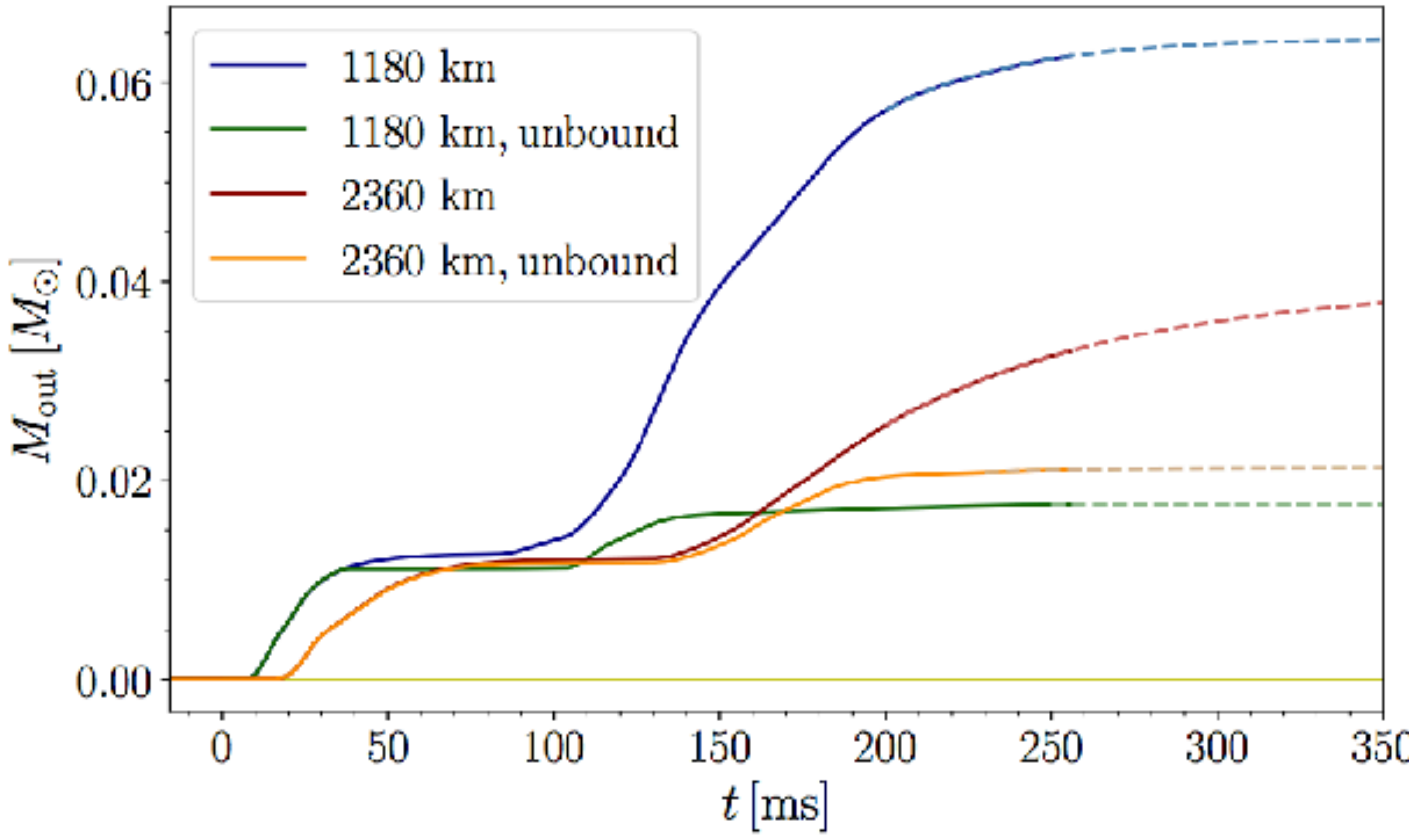


ejecta velocities reach about **0.2-0.22c**

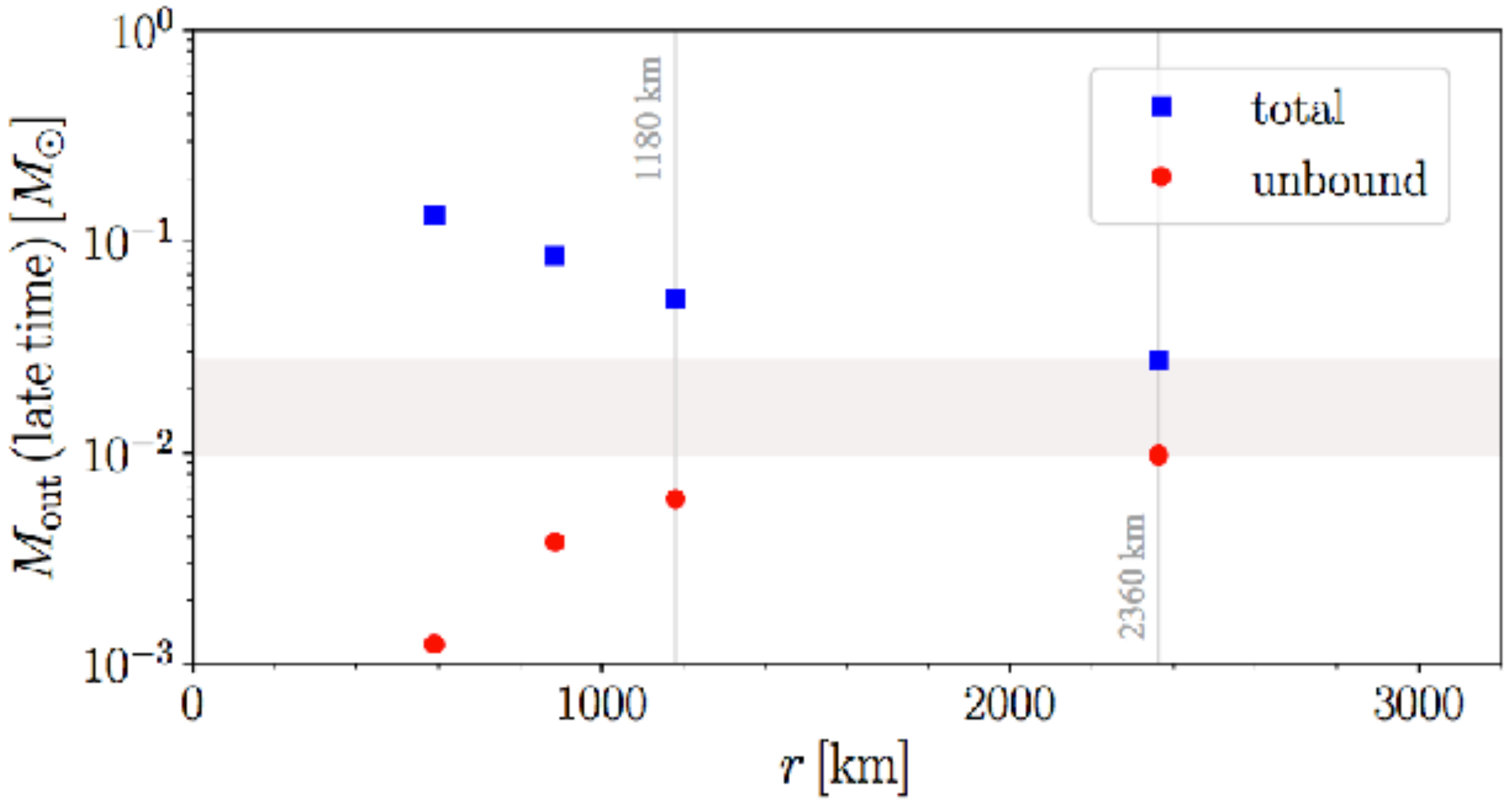
Mass outflow rate evolution



Mass outflow evolution



Radial distribution of mass outflow



total unbound ejecta mass reaches about **0.01-0.028 Msun**

Ejecta velocities and mass consistent with blue kilonova

The Spritz code: GRMHD with Neutrino Leakage

Cipolletta+2020, Cipolletta+2021

Version 1.0:

- Derived from parent WhiskyMHD code
- Works within Einstein Toolkit framework
- Staggered vector potential evolution
- Support for ideal gas and polytropic EOS

Version 2.0:

- Support for microphysical EOS
- ZelmaniLeak neutrino leakage scheme [Ott+2012]
- Evolution equation of electron fraction
- Higher order schemes: WENOZ with HLLE4 and HLLE6
- Publicly available on Zenodo: 10.5281/zenodo.4350072

RePrimAnd C2P scheme in Spritz

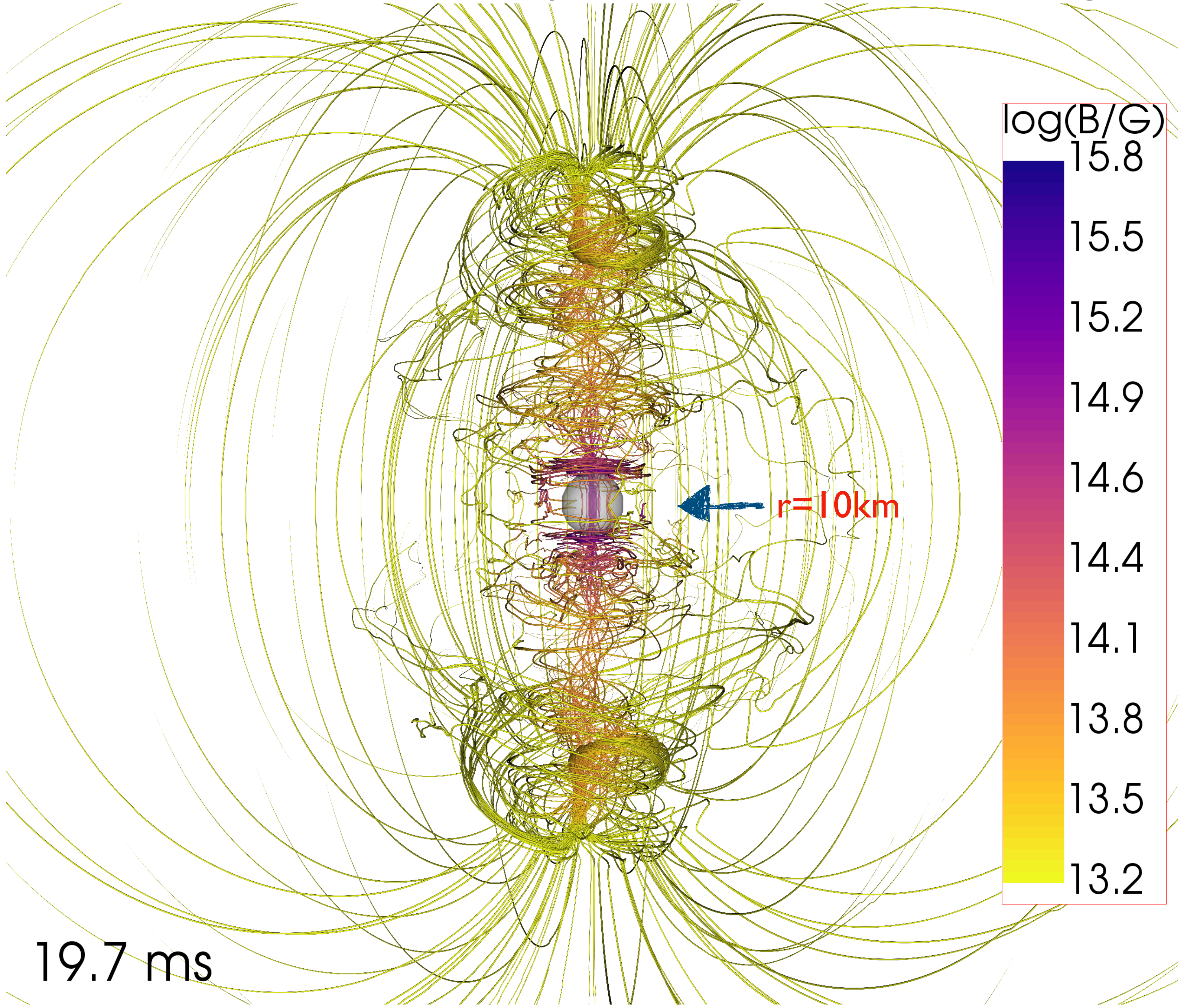
Scheme features: Kastaun+2021

- Uses root-bracketing scheme
- Alway converges to a unique solution
- Fine grained error policies
- EOS-agnostic
- Publicly available library with an EOS-framework on Zenodo: wokast/RePrimAnd

Implementation in Spritz: Kalinani+2022

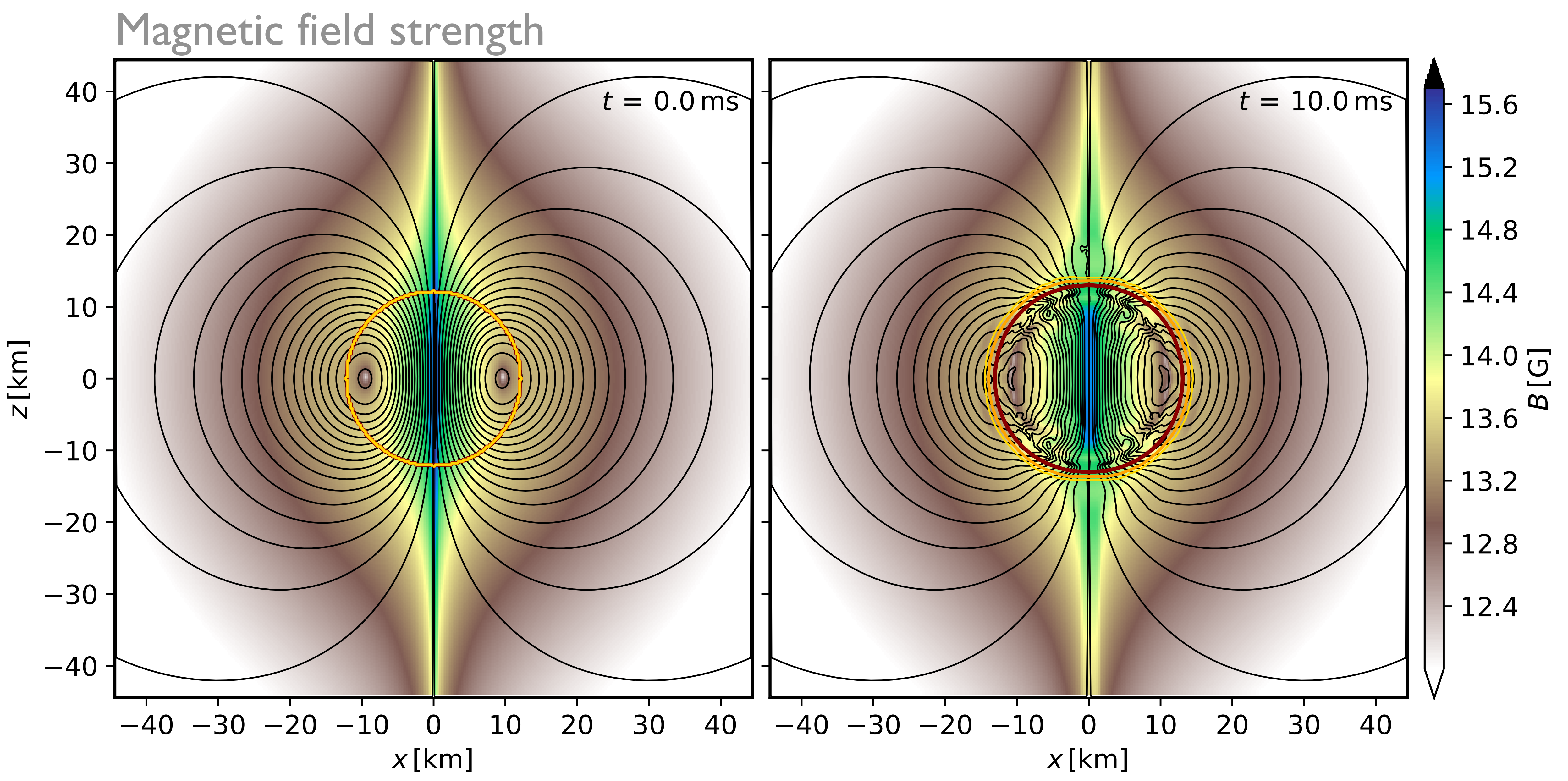
- Integrated RePrimAnd library into Einstein Toolkit
- Added option in Spritz to use C2P from RePrimAnd
- Defined and enforced validity range for EOS
- Different error policies within BHs
- Support for fully tabulated EOS underway

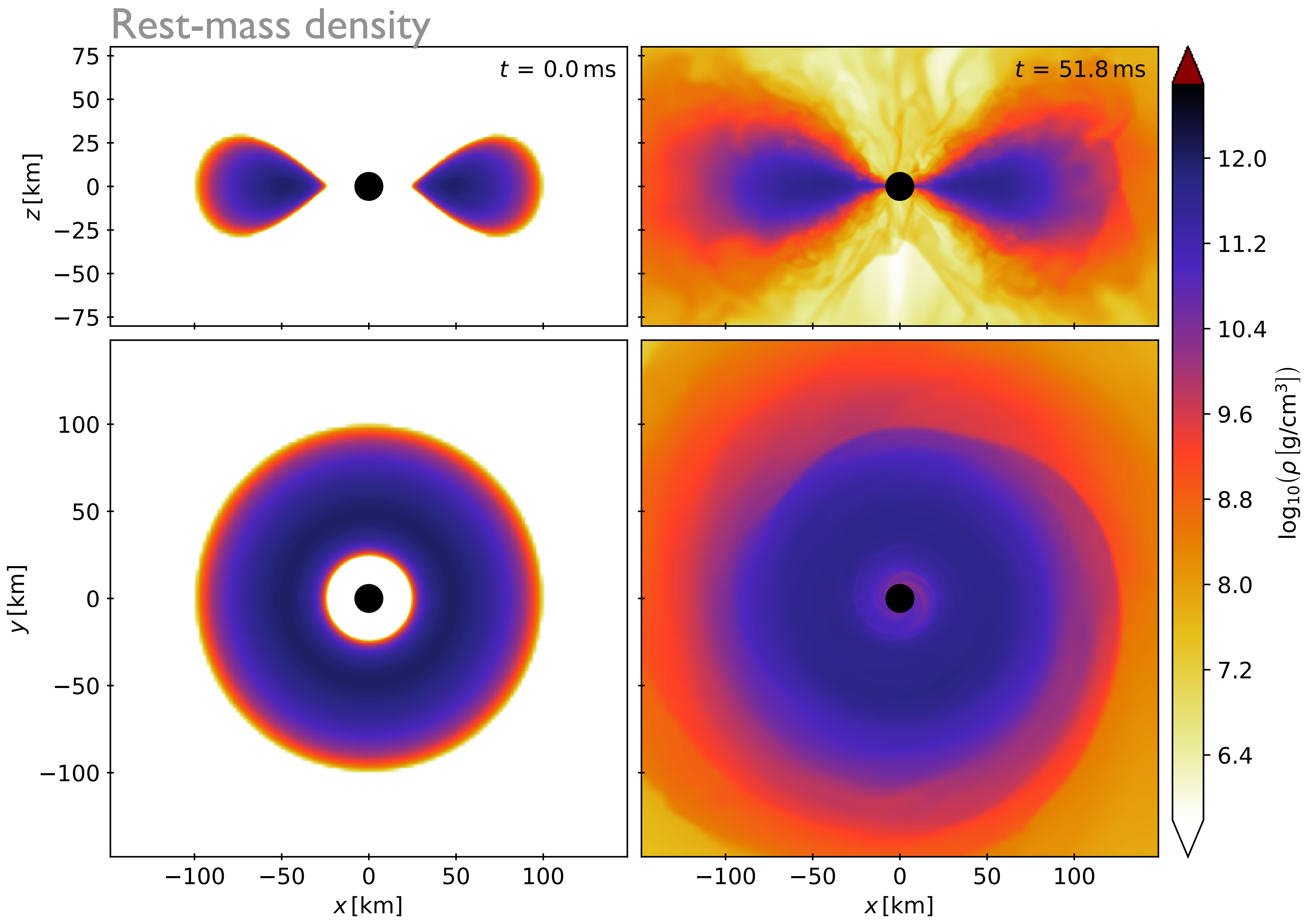
Dipolar field painted on a rotating NS



3D tests in GRMHD:

- TOV star with internal magnetic field
- NS with external dipolar magnetic field
- Rotating magnetised NS
- Rotating magnetised NS collapse to BH
- Fishbone-Moncrief BH-accretion disk

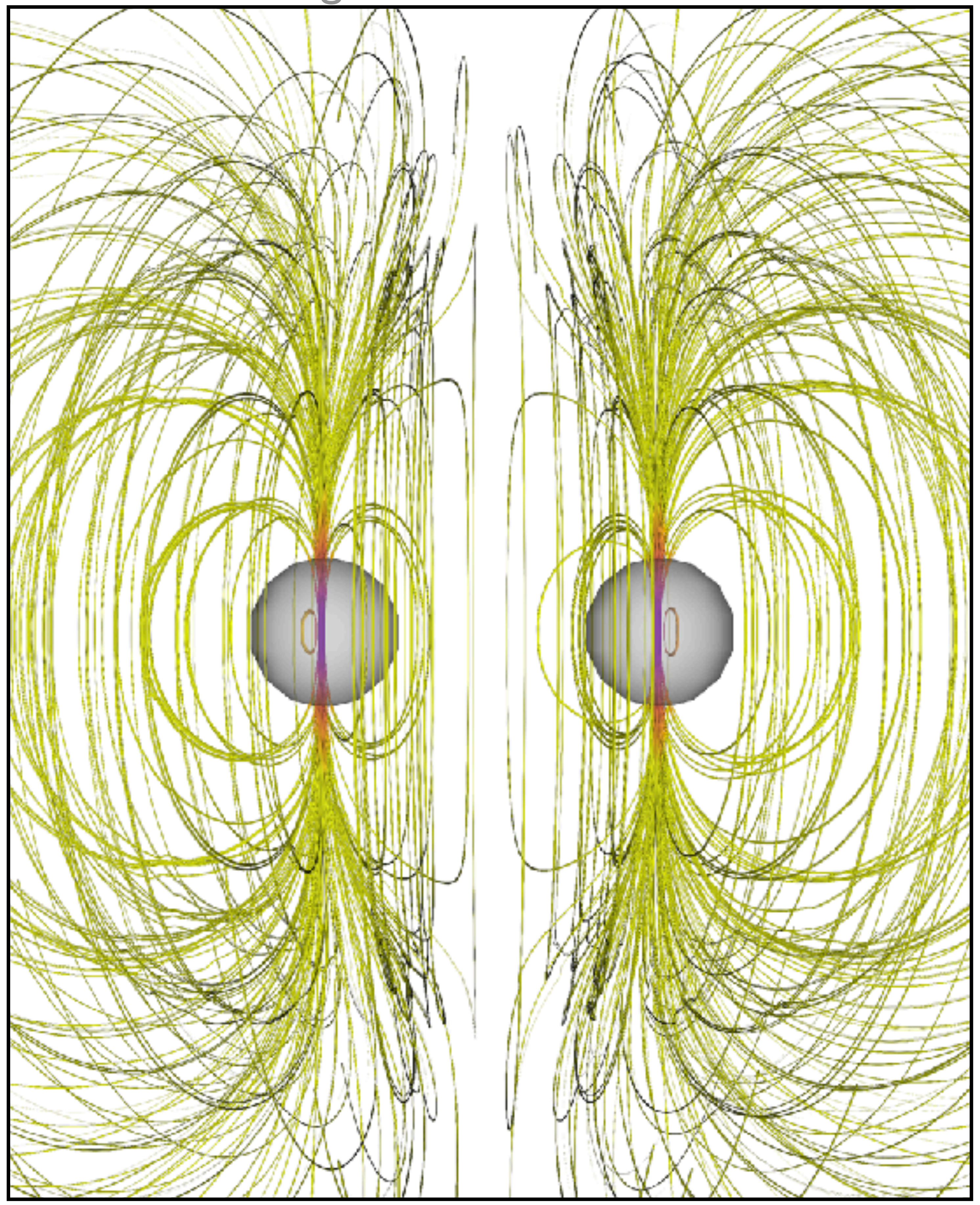




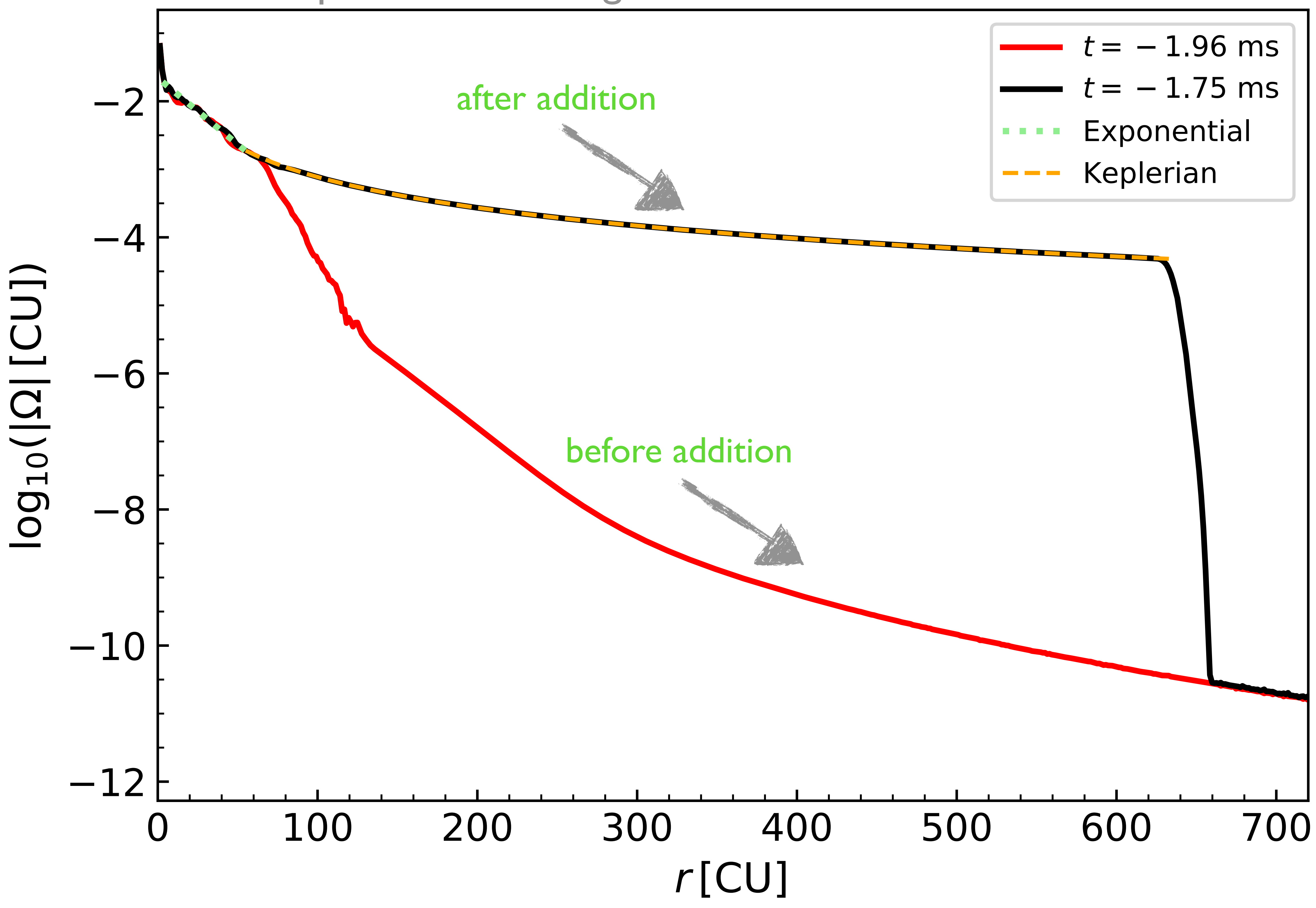
BNS with Spritz using RePrimAnd

Kalinani+ in prep

Initial field configuration

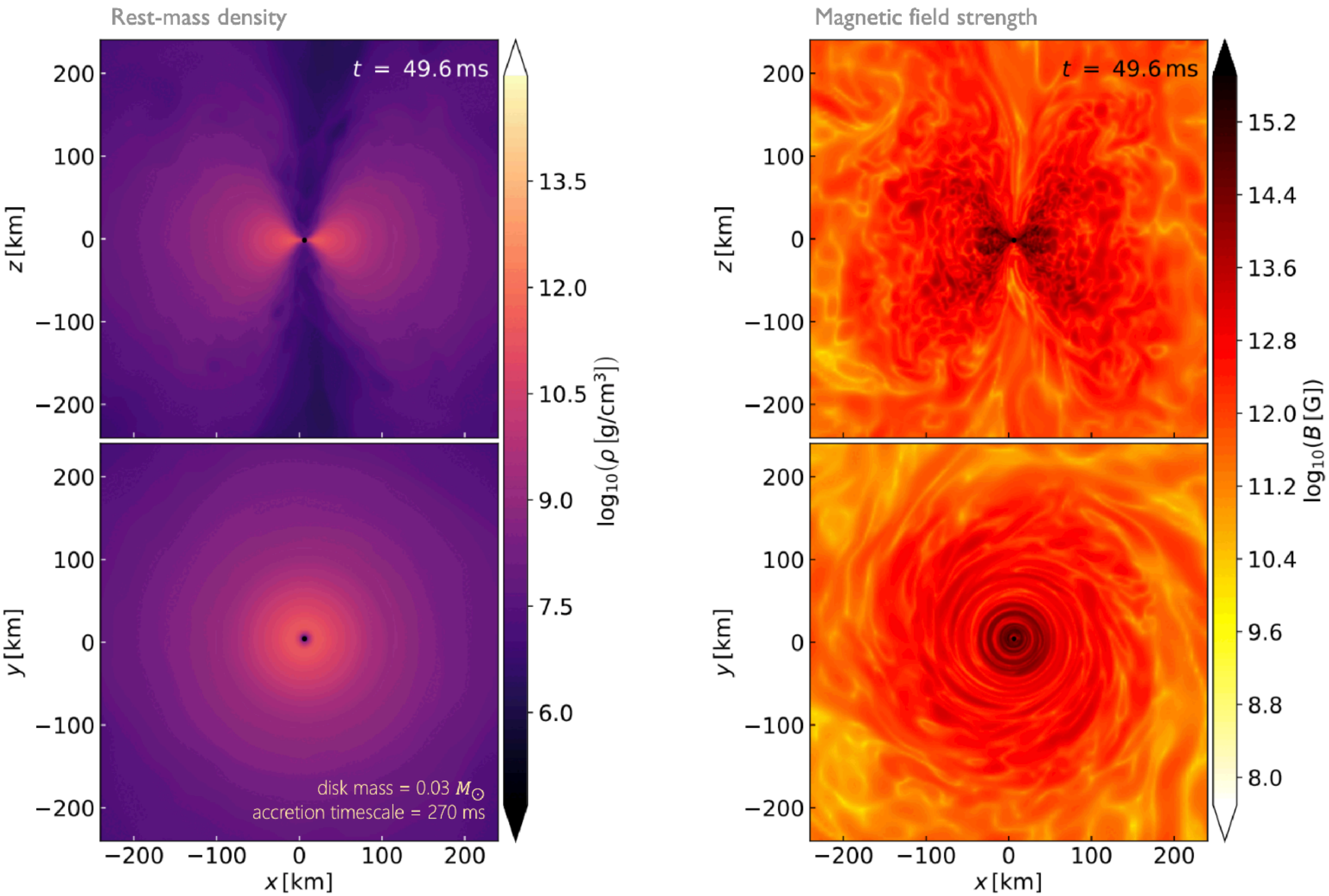


Rotation profile of added gas



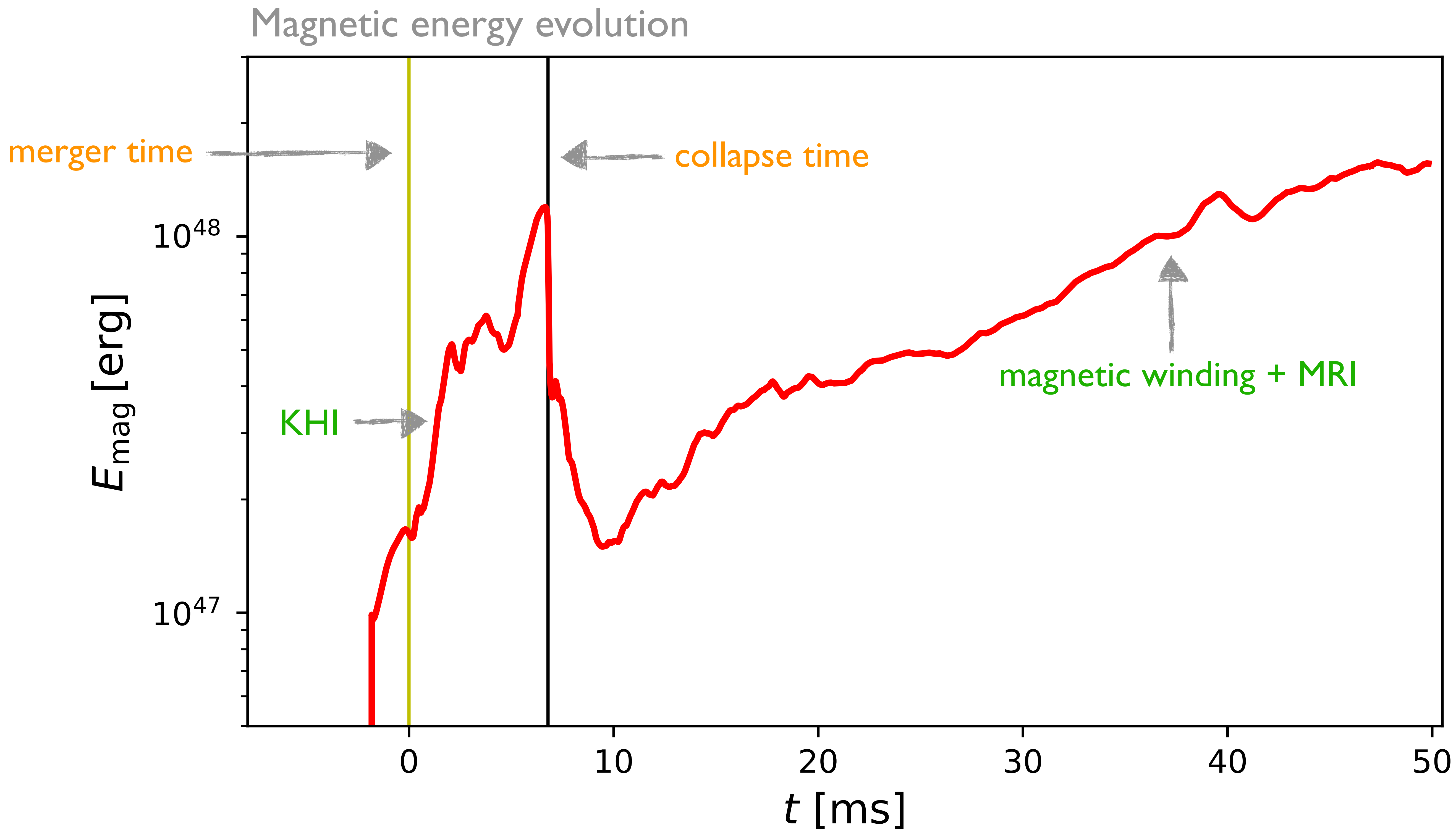
- Equal mass system ($1.5\,\mathrm{M}_\odot$ each) [Ruiz+2016]
- Ideal gas EOS for evolution

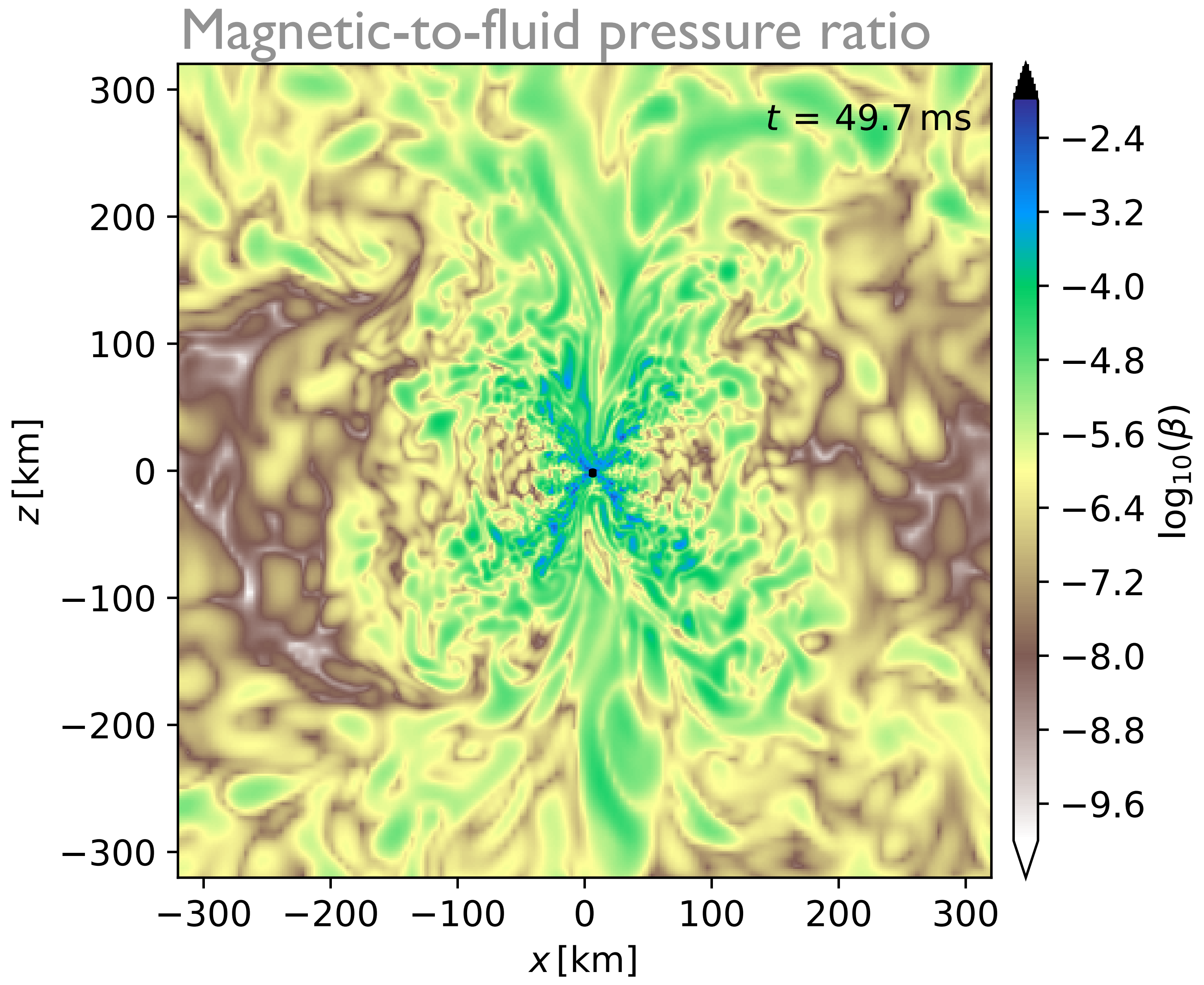
- Dipolar magnetic fields added after two orbits with $B_{\rm max} = 10^{16}$ G
- Addition of co-rotating material ($M < 0.001\,\mathrm{M}_\odot$)

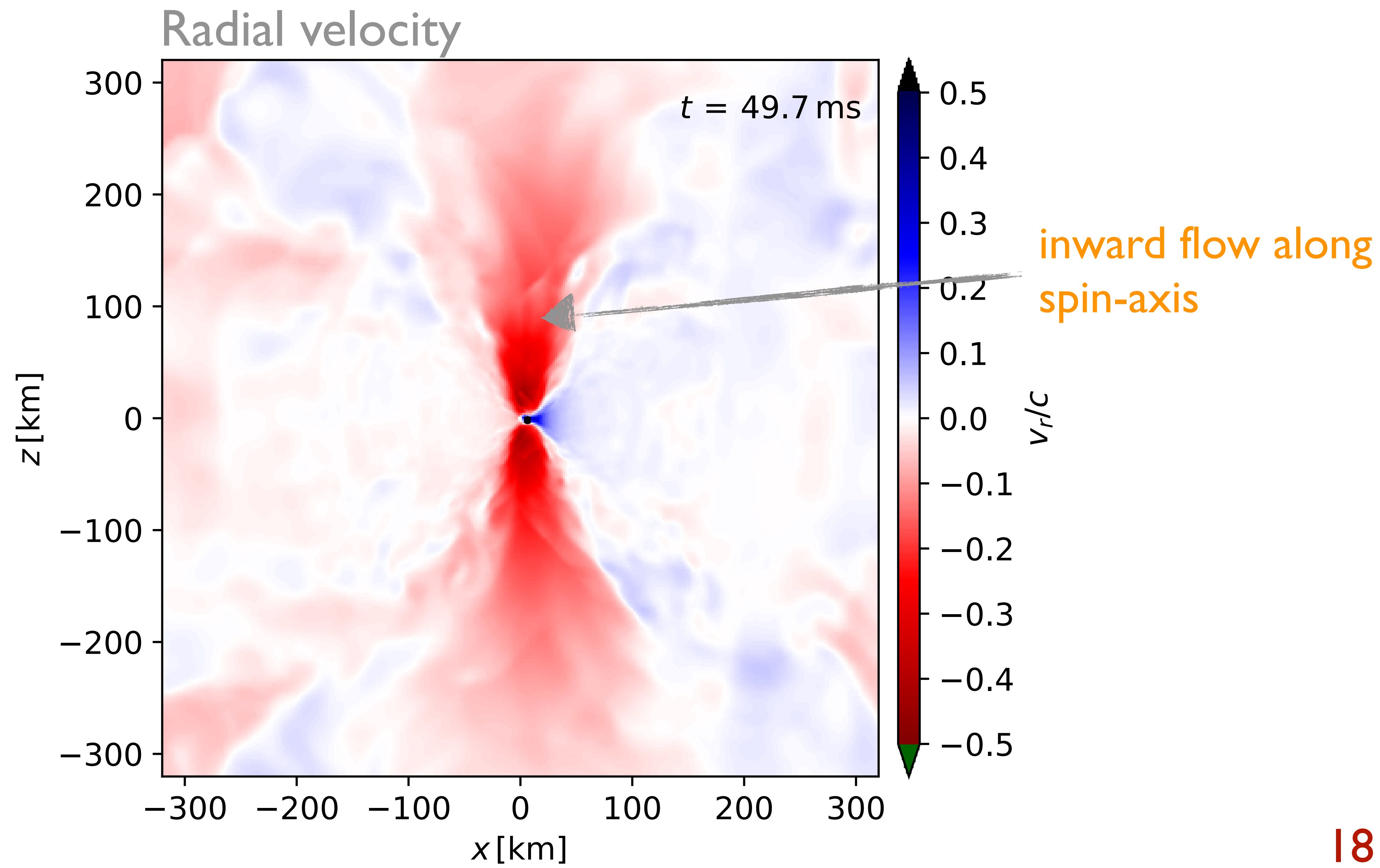

Rest-mass density
Magnetic field strength
t = 49.6 ms
t = 49.6 ms
disk mass = 0.03 $M_\odot$
accretion timescale = 270 ms
$\log_{10}(\rho\,[\mathrm{g/cm^3}])$
$\log_{10}(B\,[\mathrm{G}])$
z [km]
y [km]
x [km]
13.5
12.0
10.5
9.0
7.5
6.0
15.2
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0

Magnetic Field Geometry

Magnetic Field Evolution



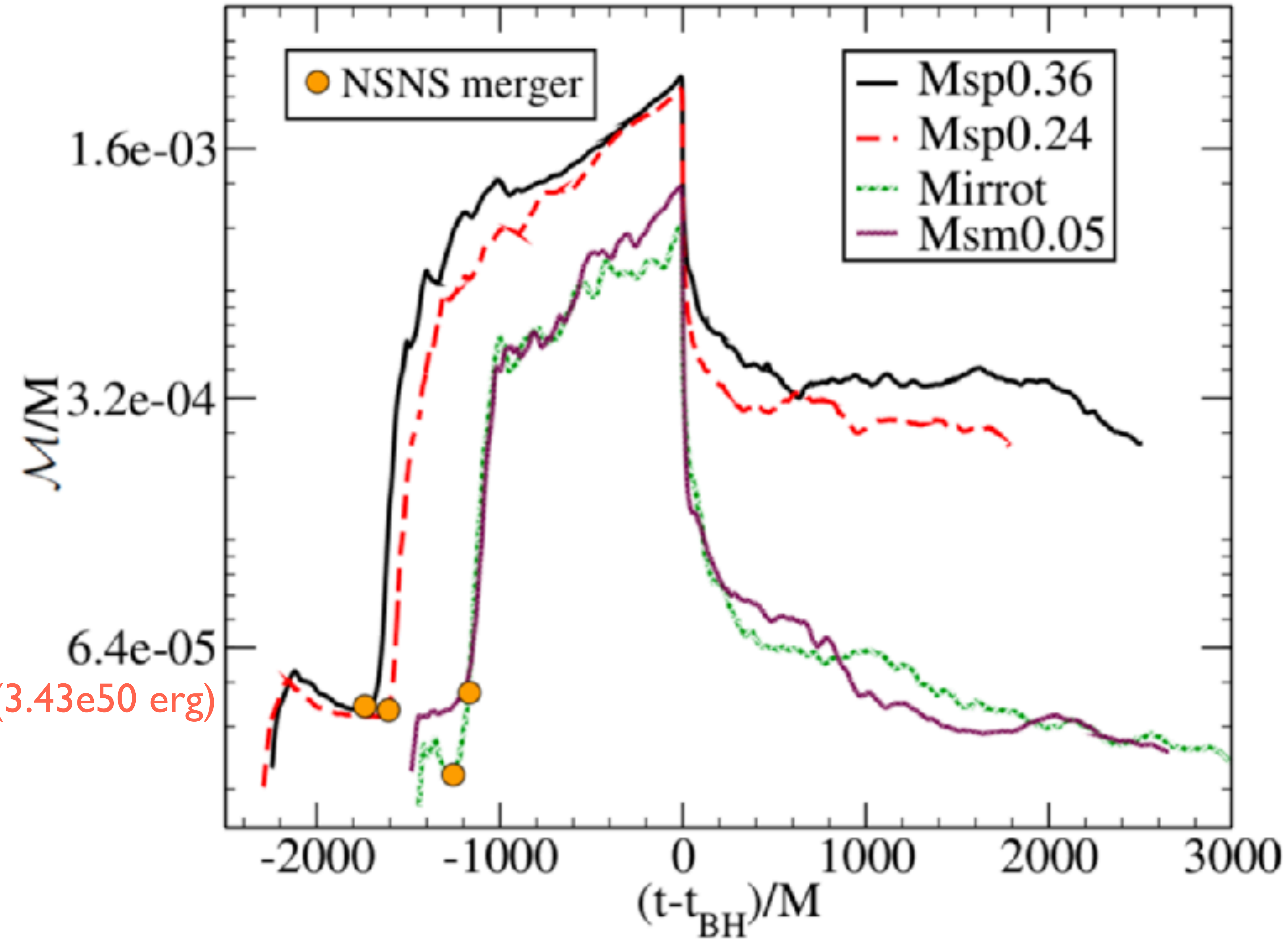




- Magnetic energy still growing; not enough to power a relativistic jet *yet*
- Funnel along spin-axis fluid pressure dominated

	Ruiz+2016	This work
Initial magnetic energy	> 1E49 erg	~ 1E47 erg
Initial magnetic-to-fluid pressure ratio	3.125E-03	1.7E-05
Grid-resolution	LR ~ 227 m HR ~ 152 m	~ 354 m Finer reflevel (~177m) activated before collapse
Computation of electric field	UCT-HLL scheme (IllinoisGRMHD)	Flux CT method
KO dissipation on vector potential	No	Yes

Magnetic energy evolution

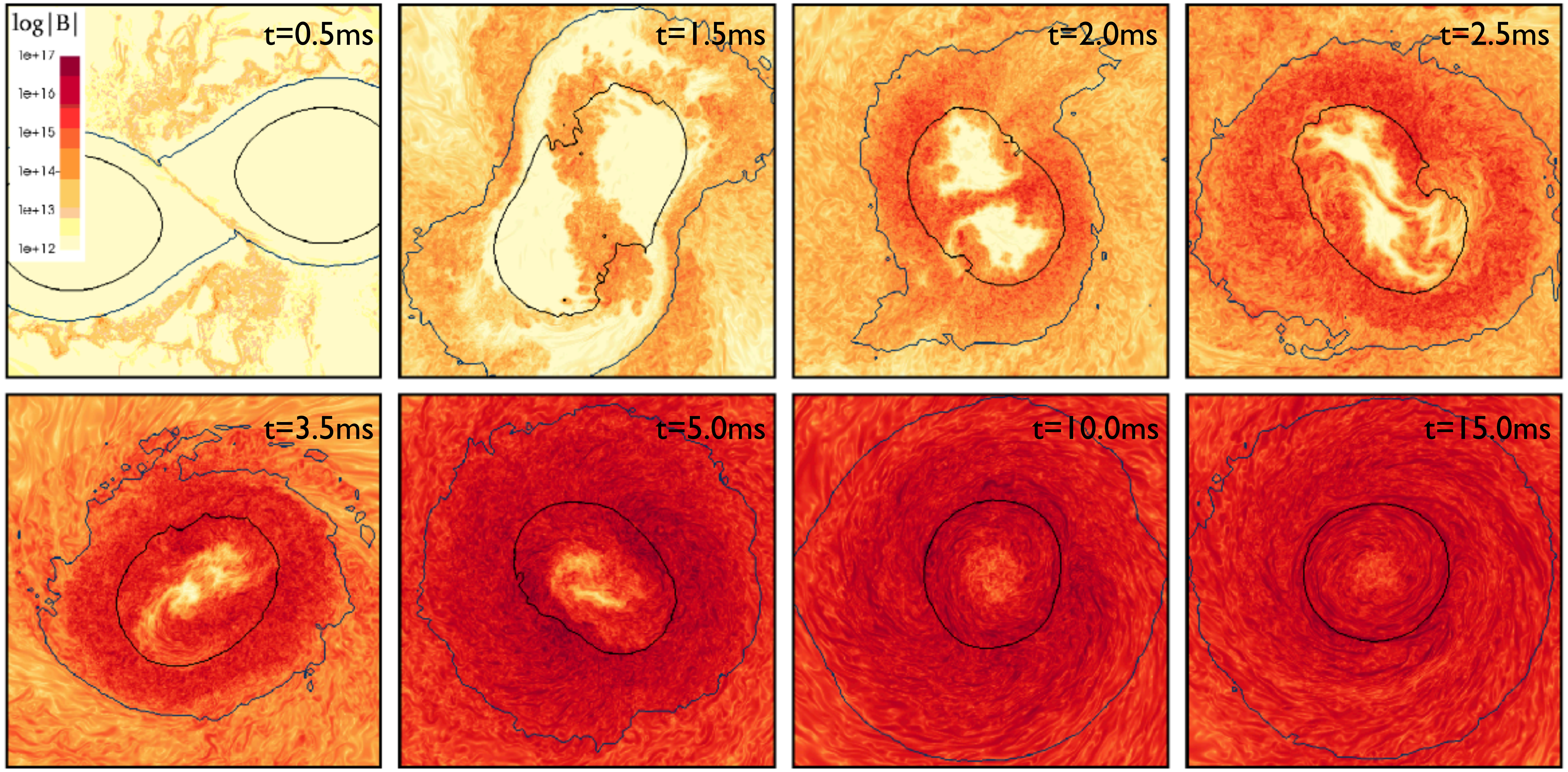


Ruiz+2019

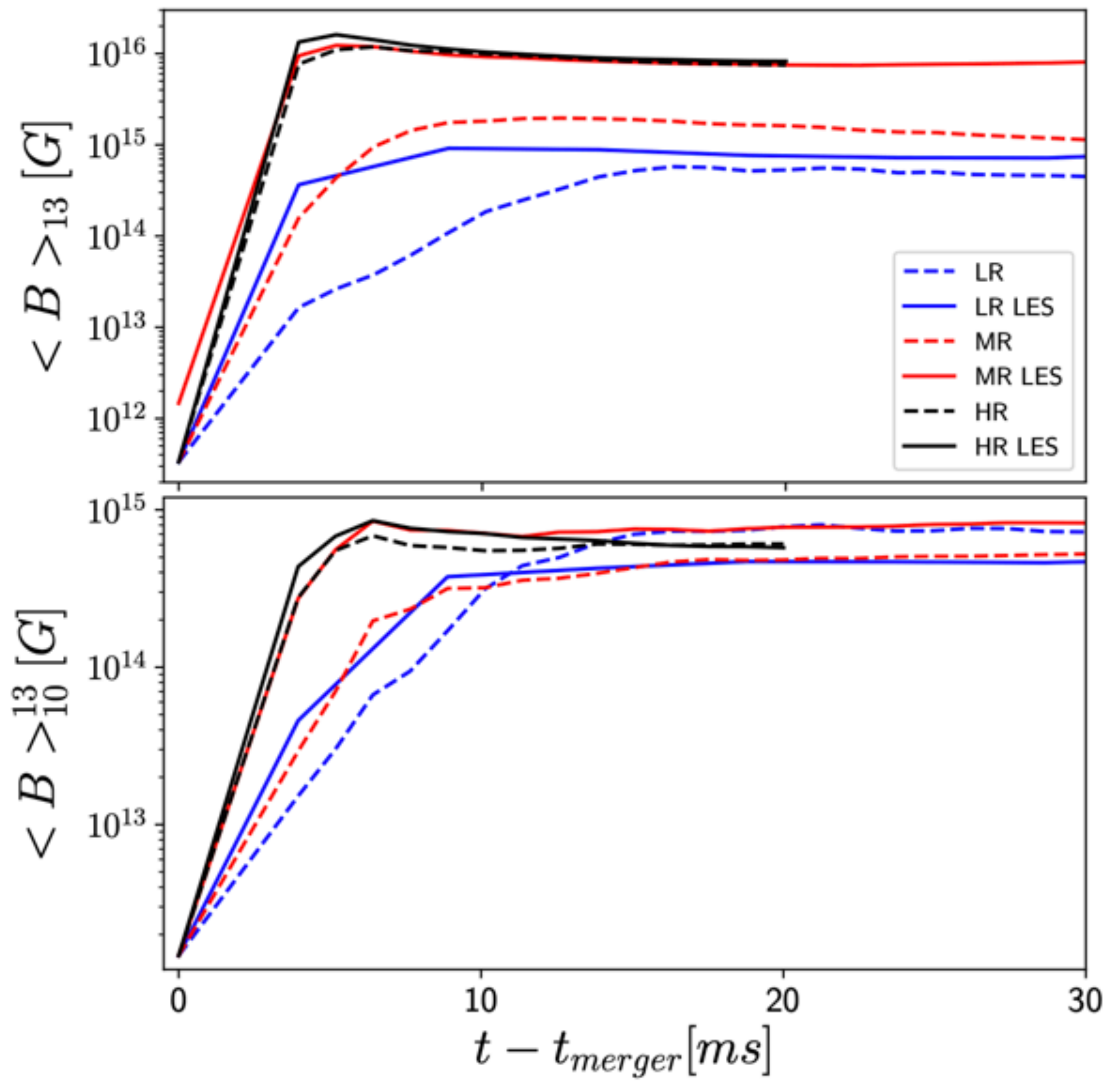
Questions:

- Dependence of jet formation on initial magnetic energy?
- Are such initial field strengths physically reasonable?

Large-Eddy Simulations



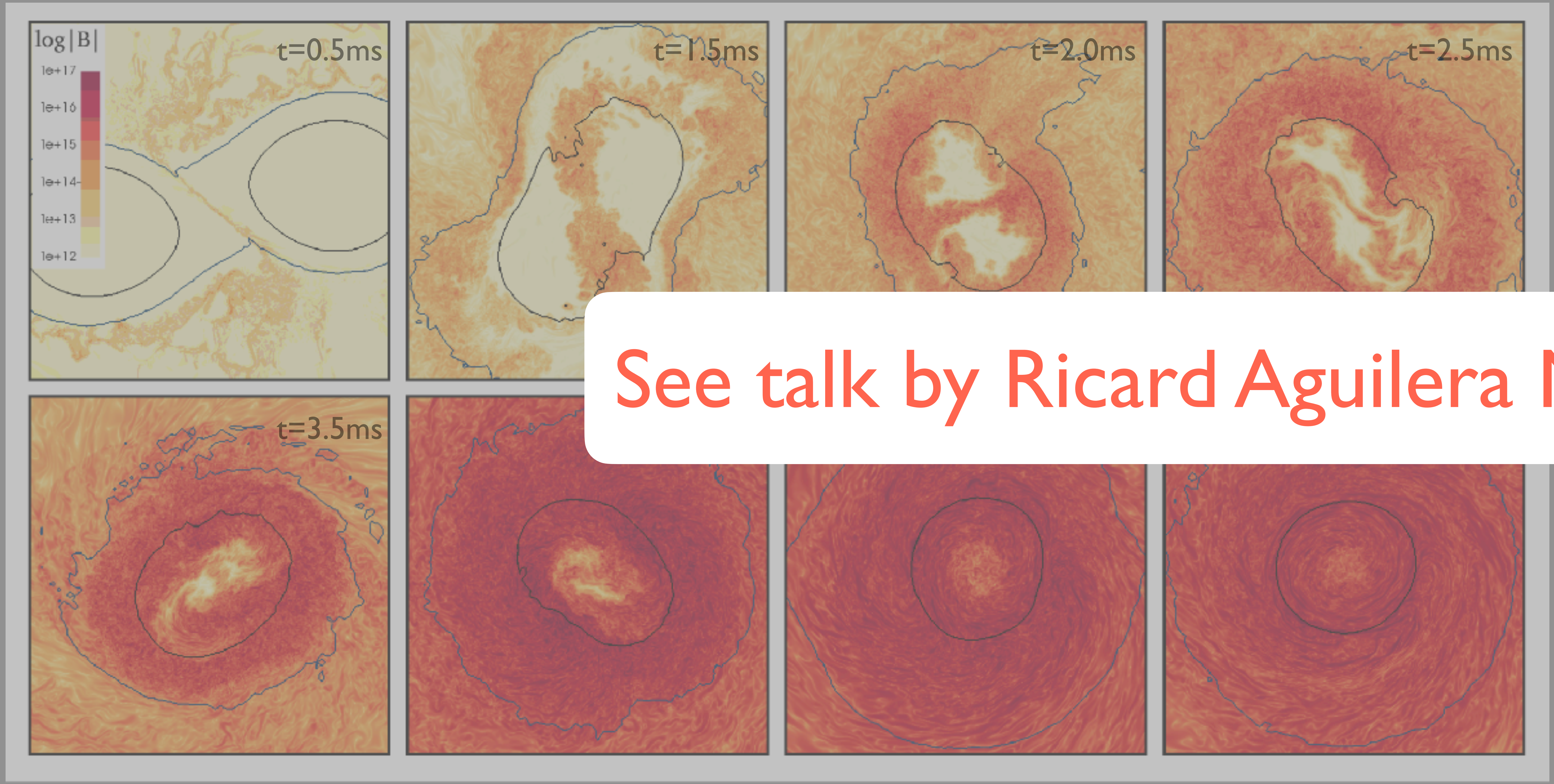
Palenzuela+2021

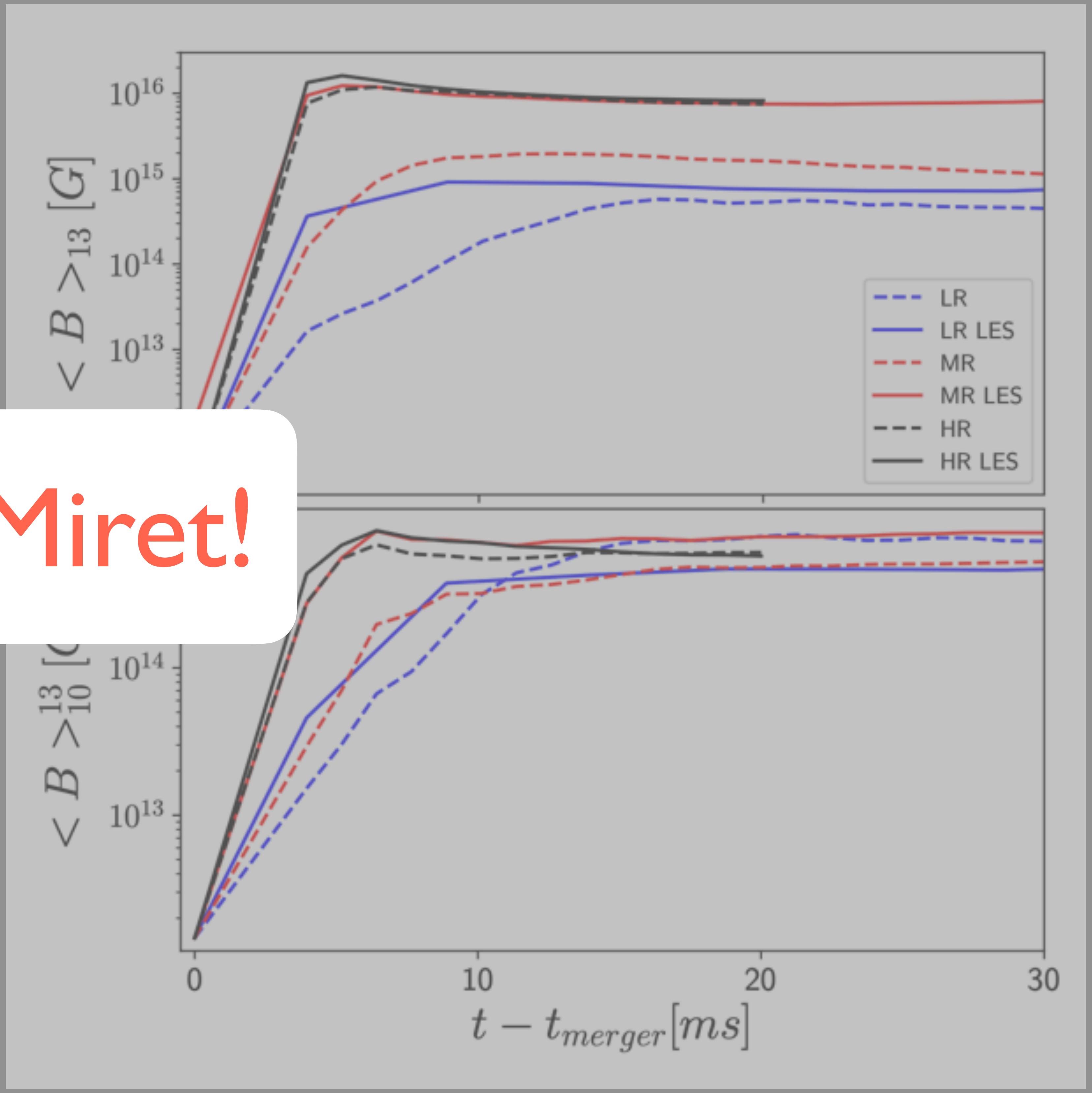


- Convergent results for MR-LES (dx=60m) case in comparison with HR (dx=30m) one

Promising alternative to simulations with high initial magnetic fields

Large-Eddy Simulations





See talk by Ricard Aguilera Miret!

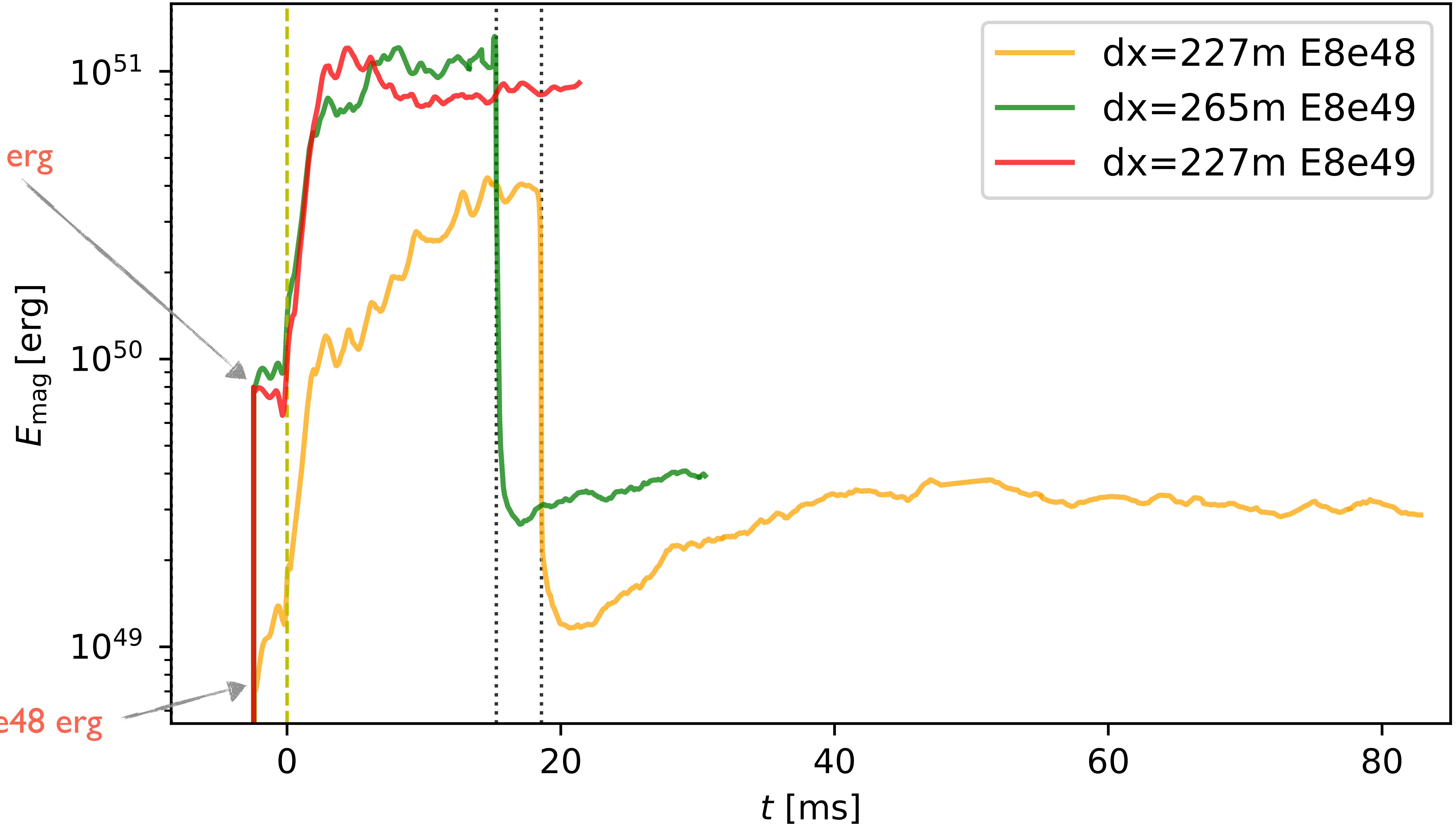
- Convergent results for MR-LES (dx=60m) case in comparison with HR (dx=30m) one

Promising alternative to simulations with high initial magnetic fields

Latest Simulations

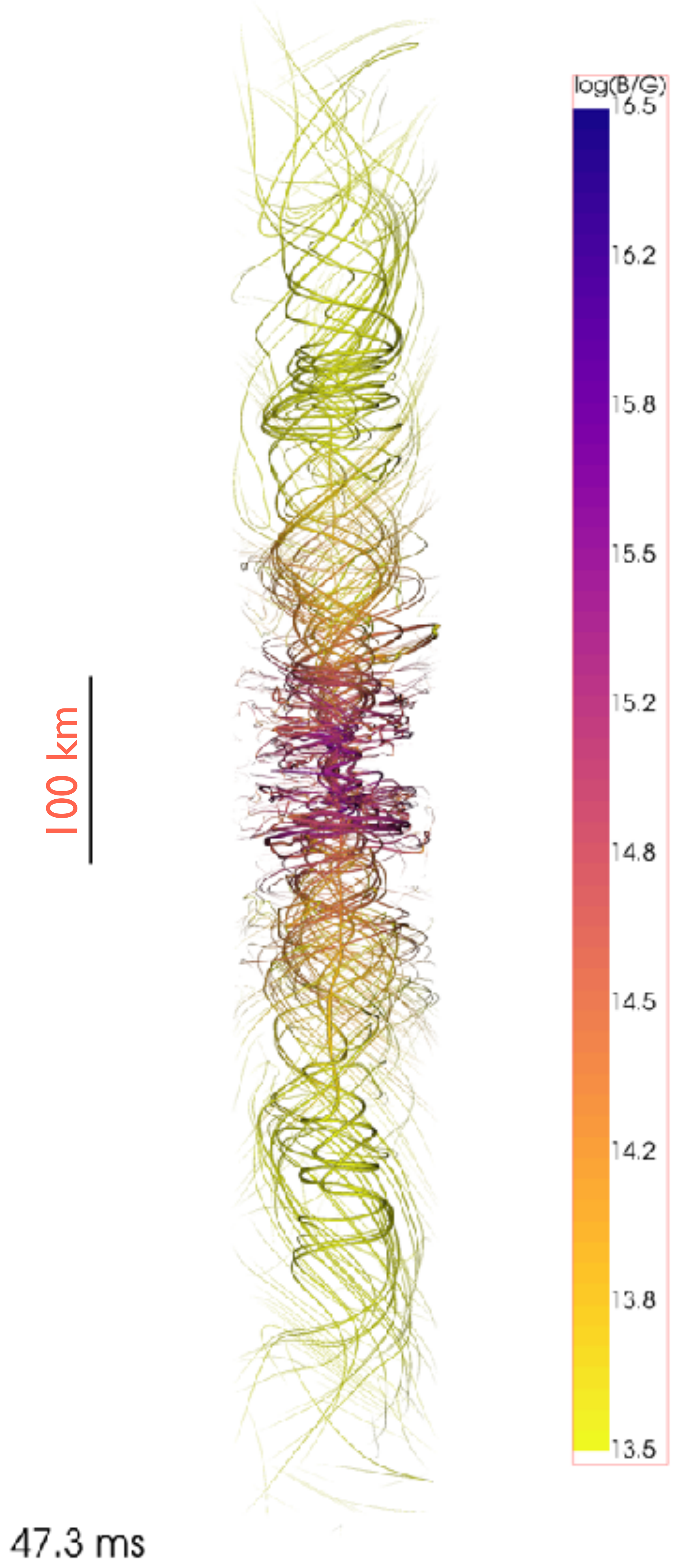
Magnetic energy evolution

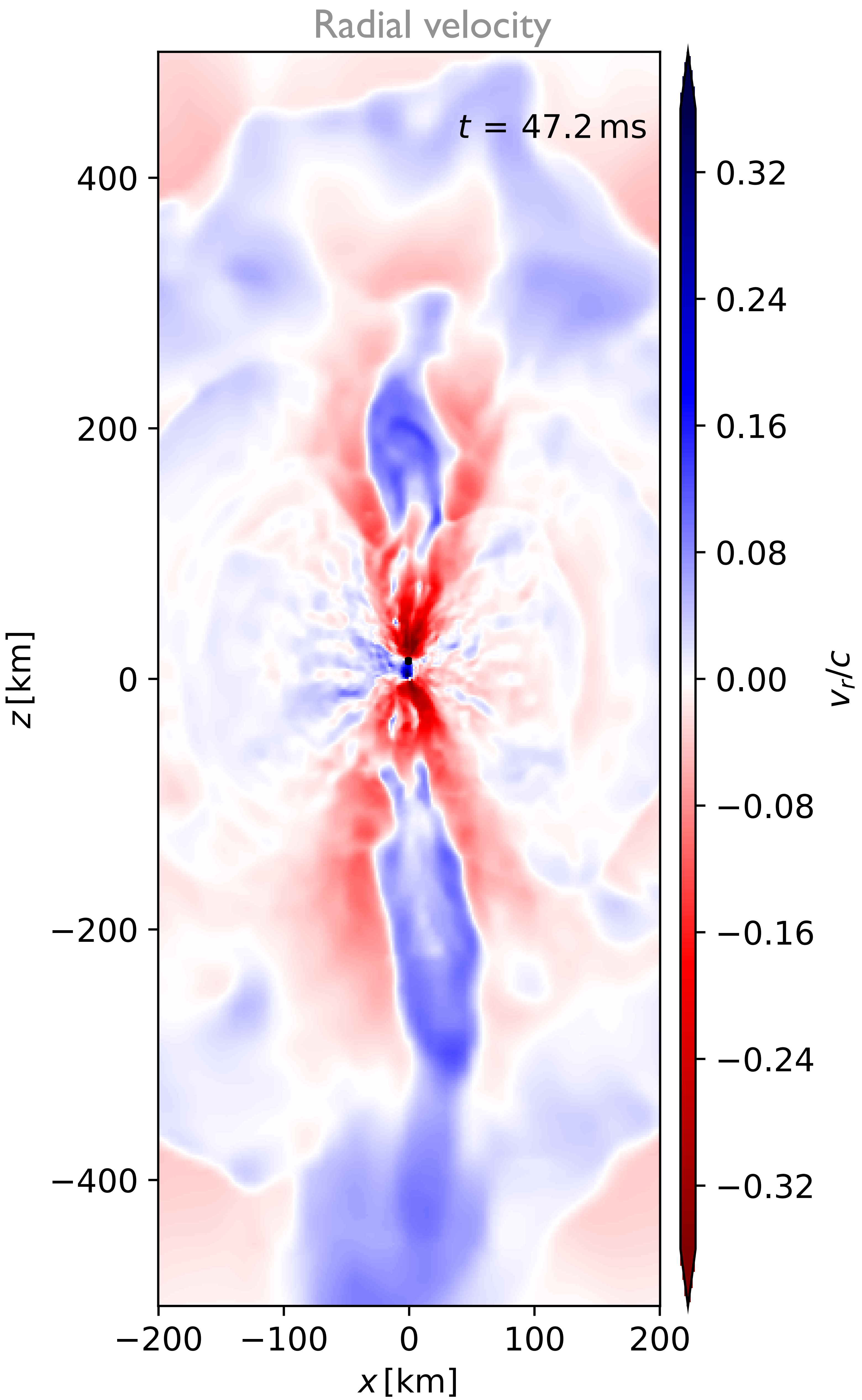
Emag ~ 8e49 erg

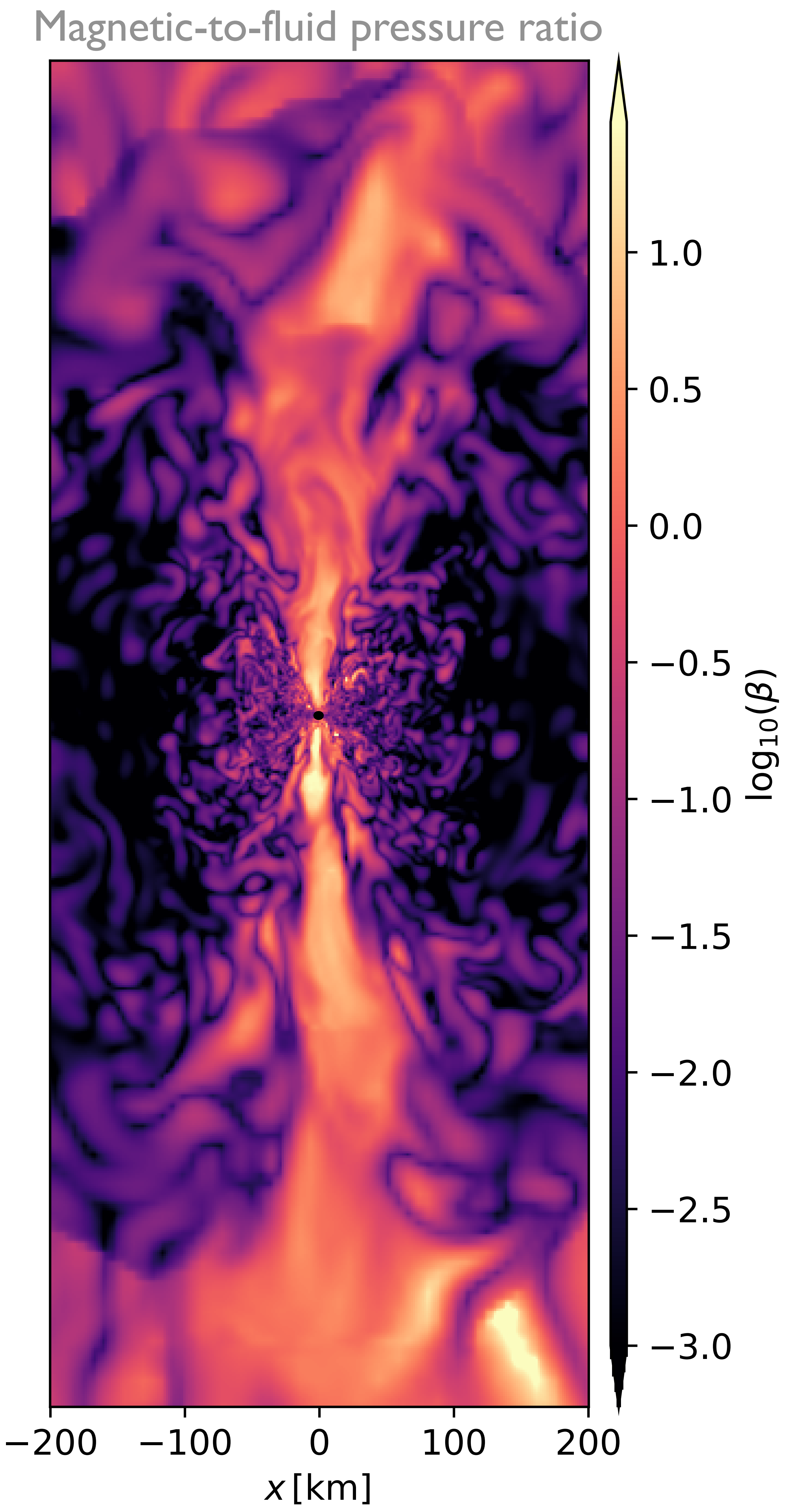


Emag ~ 8e48 erg

Latest Simulations







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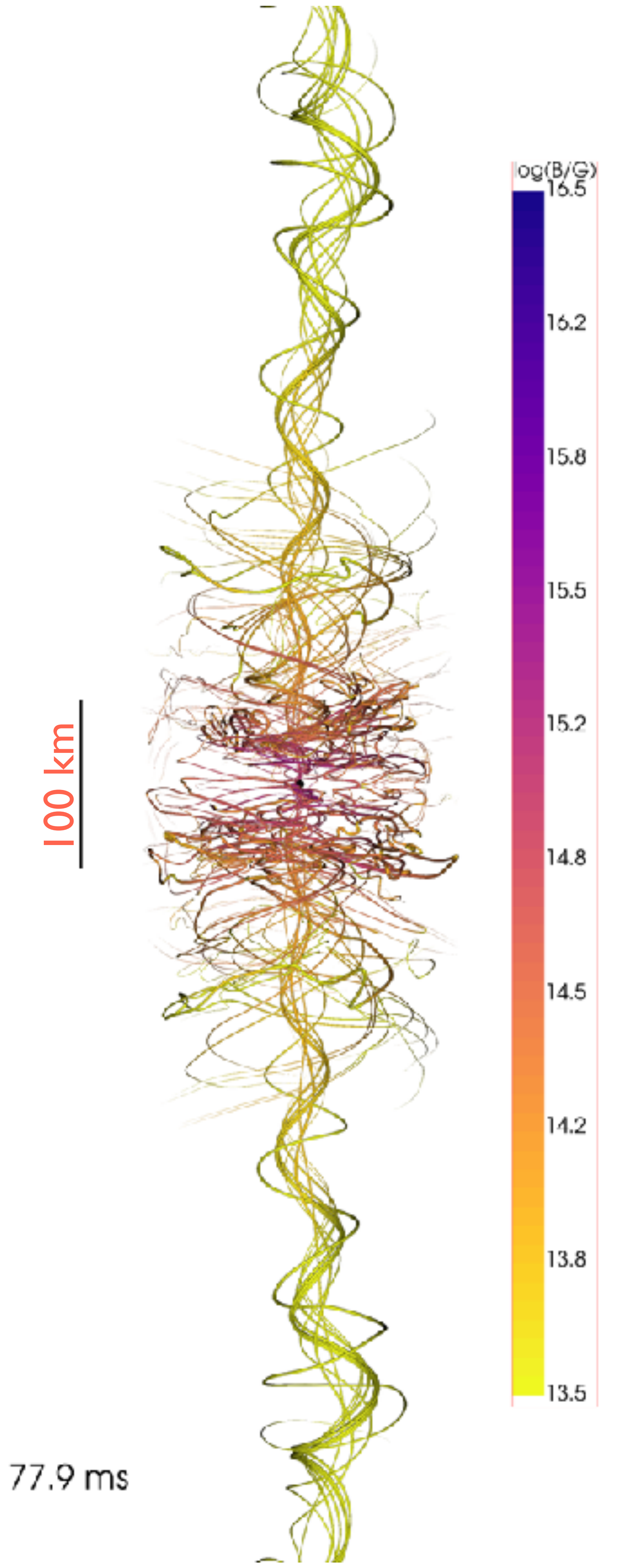
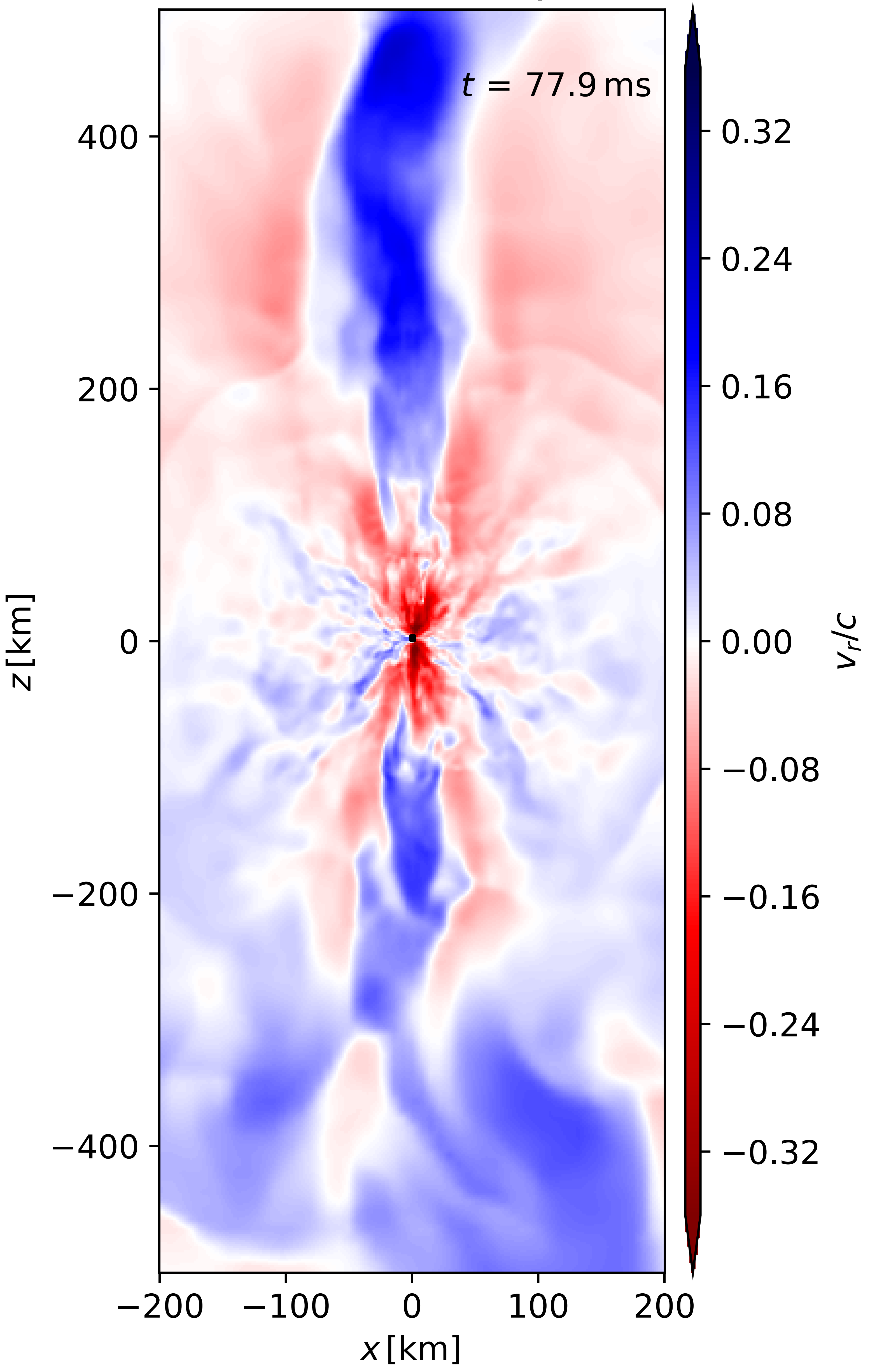
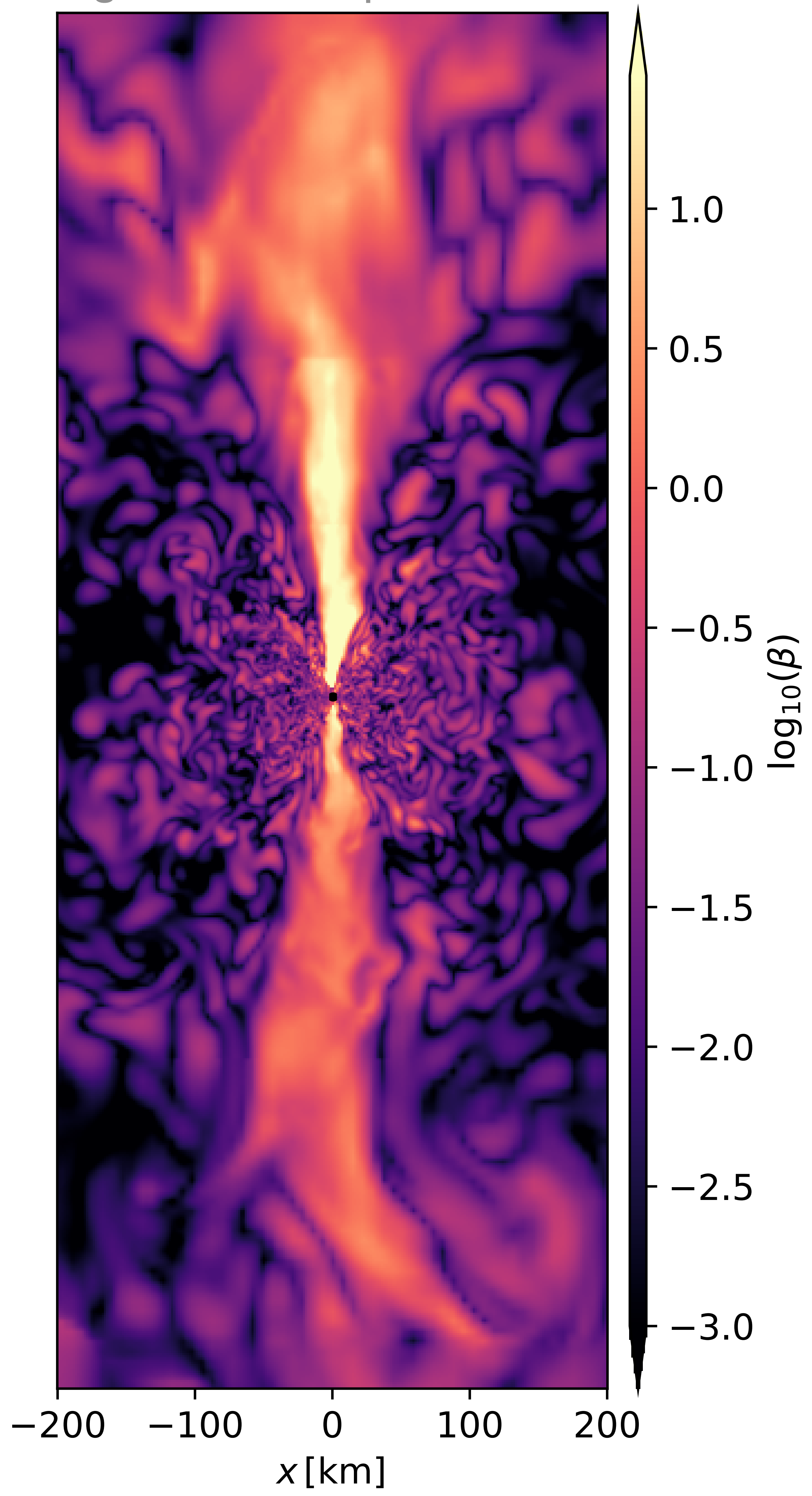


Radial velocity



Magnetic-to-fluid pressure ratio



Other Ongoing Spritz Applications

- *Spritz vs IGM* code comparison project based on BNS simulations
  Lorenzo Ennoggi (RIT, USA)

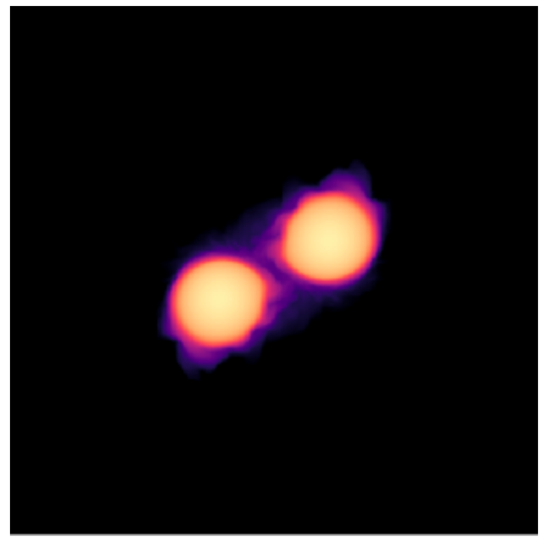
- BNS simulations with BLhot EOS using Lorene ID
  Alberto Ghedin, Alice Gambaro (University of Milano - Bicocca, Italy)

- BNS simulations with BLhot EOS using Kadath ID
  Paolo Garimberti (University of Milano - Bicocca, Italy)

- BH-NS simulations (*Spritz vs WhiskyTHC*) with DD2 EOS using Kadath ID
  Rahime Matur (Ege University, Turkey)

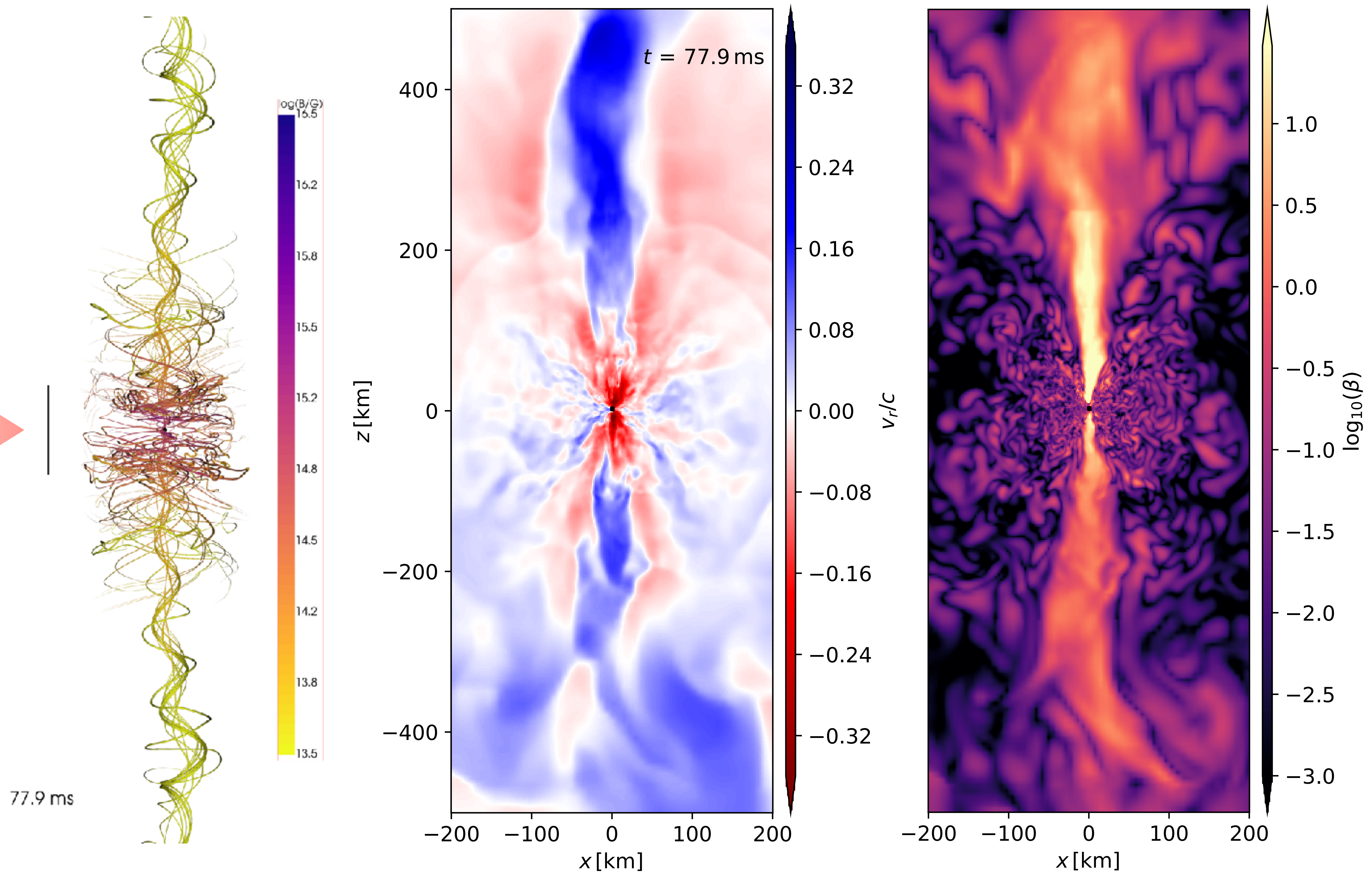
Towards end-to-end modelling

Merger



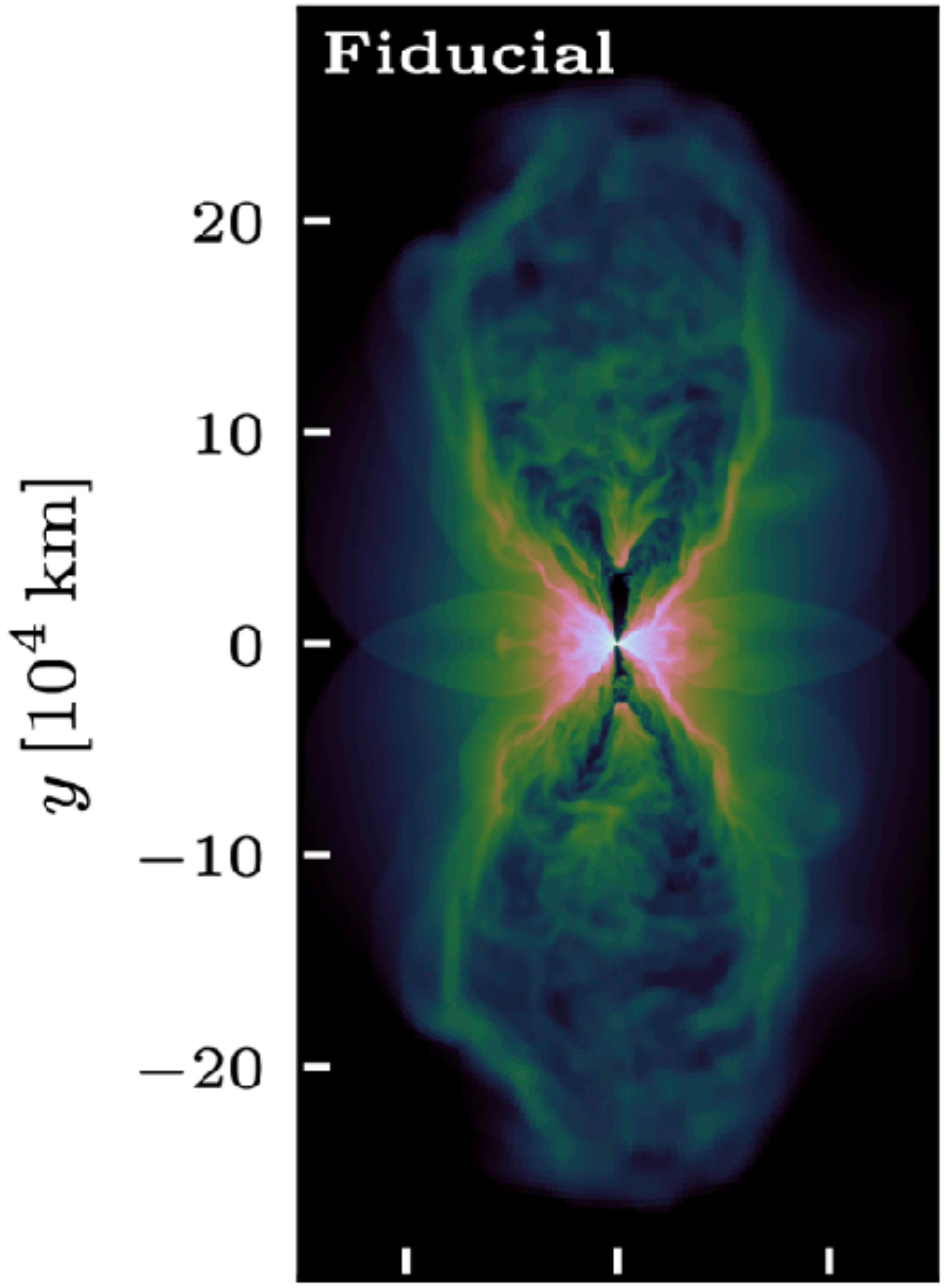
Time-scale ~ 10 ms
Length-scale ~ 100 km

Jet production



Time-scale ~ 100 ms
Length-scale ~ 1000 km

Jet propagation



Time-scale ~ 1000 ms
Length-scale ~ 10000 km

Pavan+2021

BNS merger simulations with Spritz → RMHD jet simulations with PLUTO

Summary

- **Magnetar scenario:** fight between baryon pollution vs neutrino radiation still needs resolve
- **Blue kilonova:** sourced by magnetized MNS winds (and spiral wave winds?)
- **Spritz:** a new state-of-the-art GRMHD code with neutrino emission/reabsorption
- **RePrimAnd C2P:** an accurate, efficient and robust scheme
- **First BNS simulations with Spritz+RePrimAnd:** able to evolve magnetised BH-disk environments
- **Incipient jet formation with BH-disk:** require very high initial magnetic energy for adopted grid-res.

Future exploration:

- Temperature and composition dependent EOSs
- Neutrino radiation
- NS spins

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Thank you for your attention!