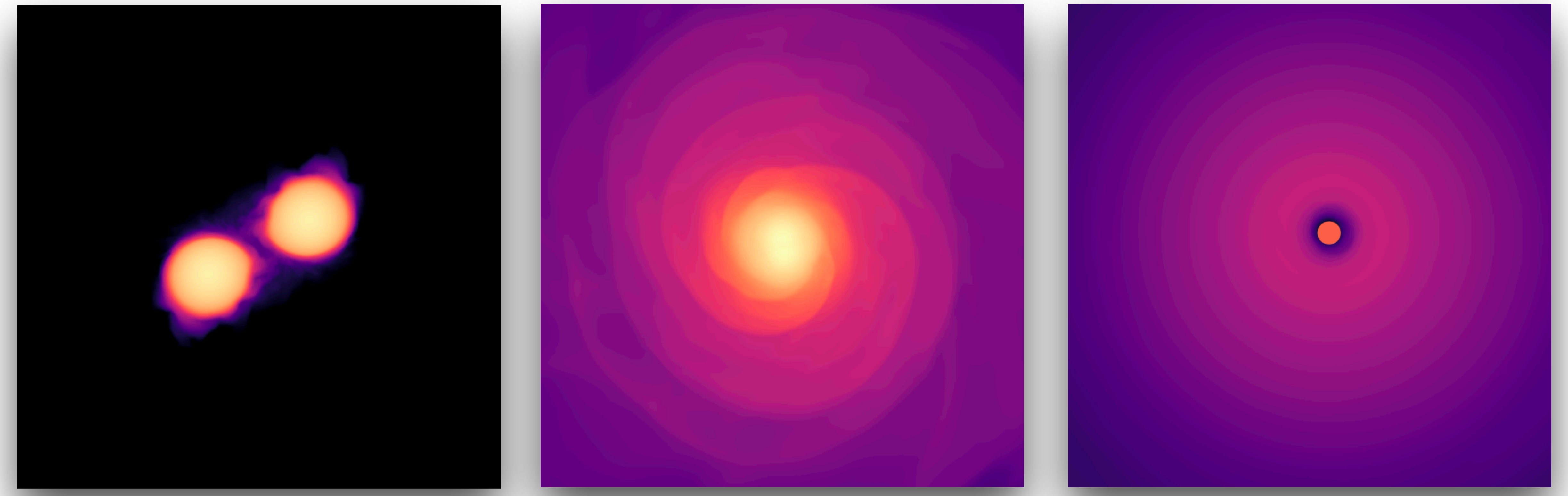
Binary Neutron Star Merger Simulations

Long-Lived Remnants, Short Gamma-Ray Bursts & Kilonovae



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in collaboration with

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INT 23-2: Astrophysical neutrinos and the origin of the elements

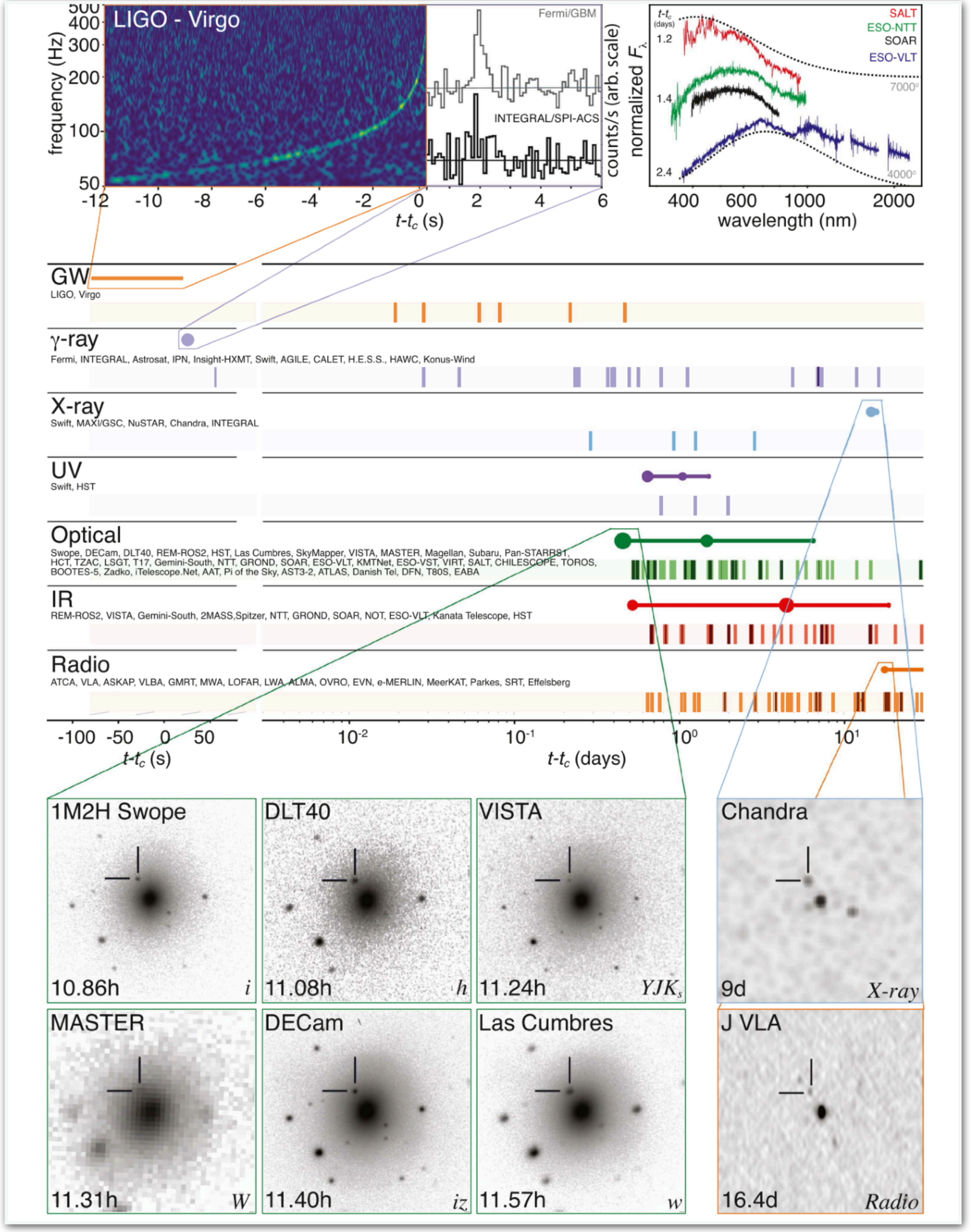
July 31 - Aug 4, Institute of Nuclear Theory, University of Washington

ROCHESTER INSTITUTE OF TECHNOLOGY R·I·T 1829

OSSERVATORIO ASTRONOMICO DI PADOVA

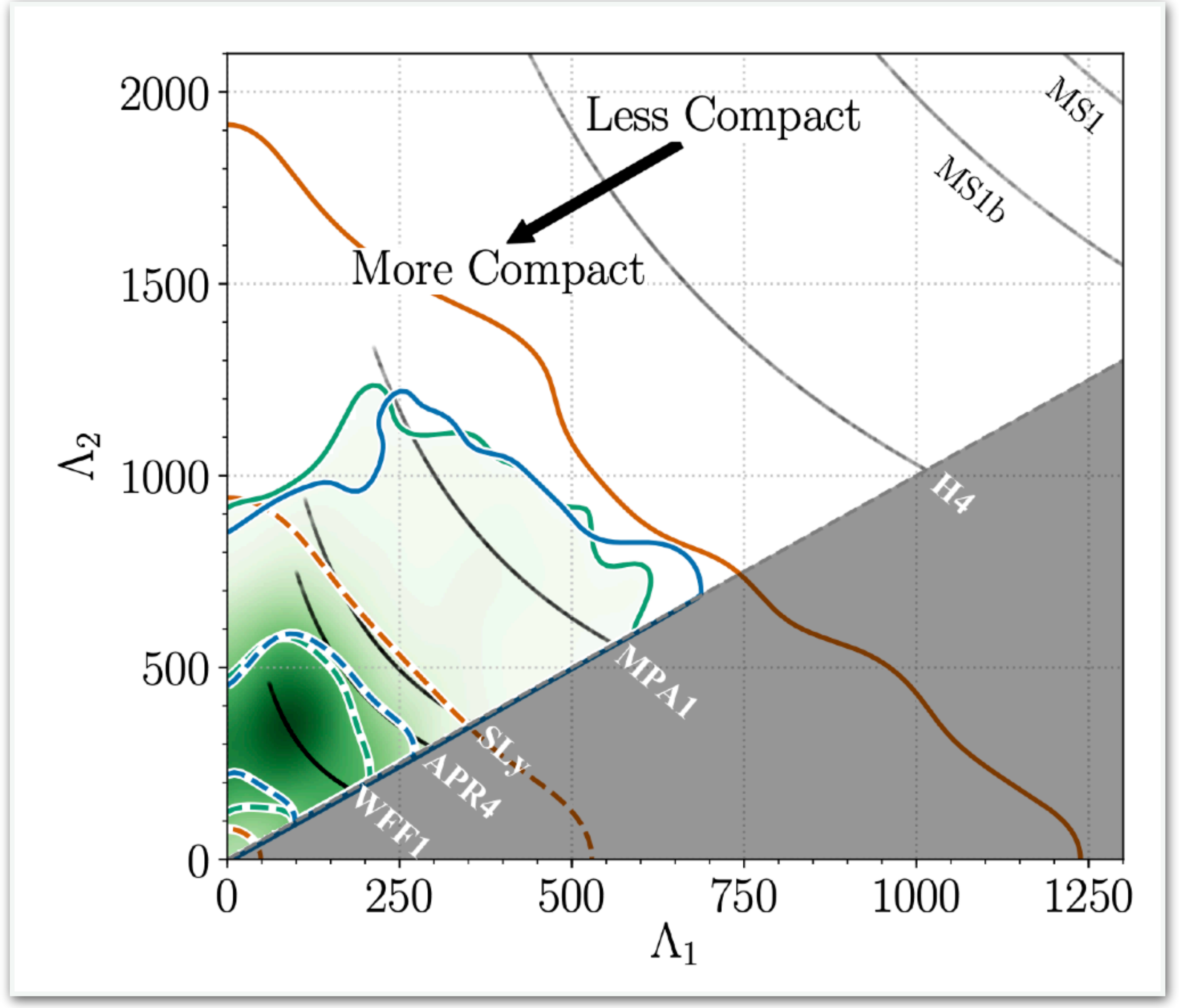
GW170817

GRB170817A + EM counterparts



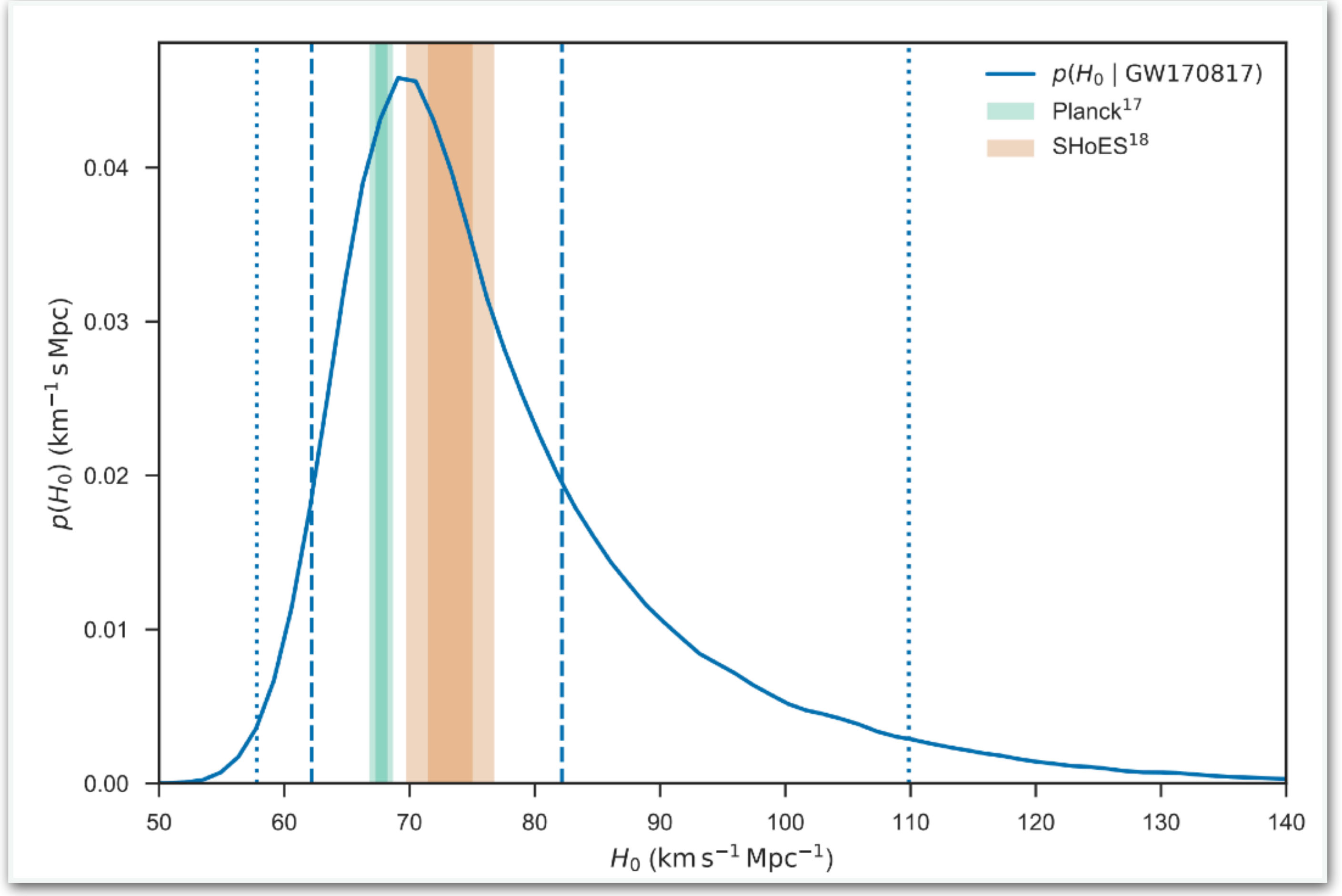
LVC+2017

EOS constraints



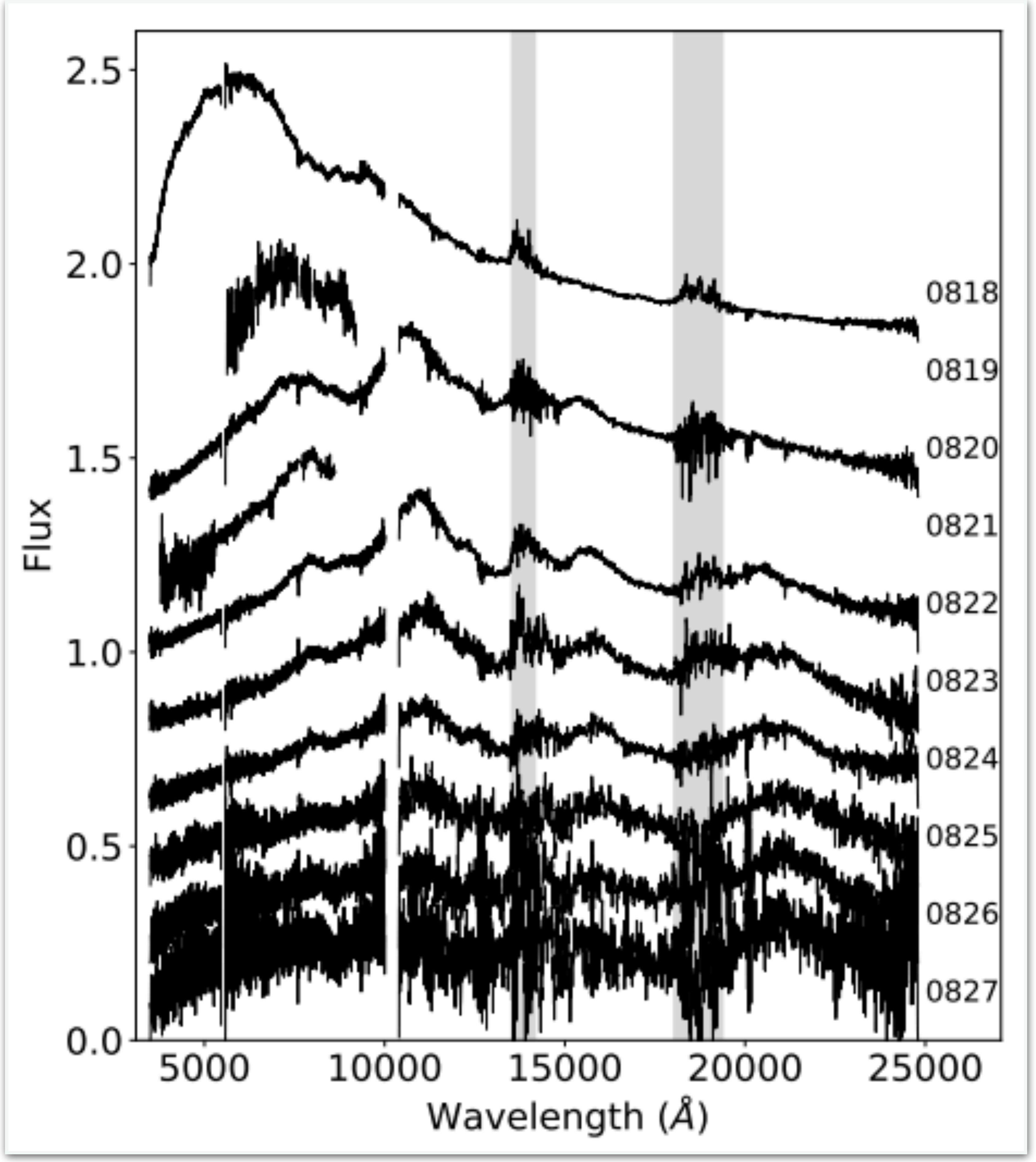
LVC+2018

H_0 measurement



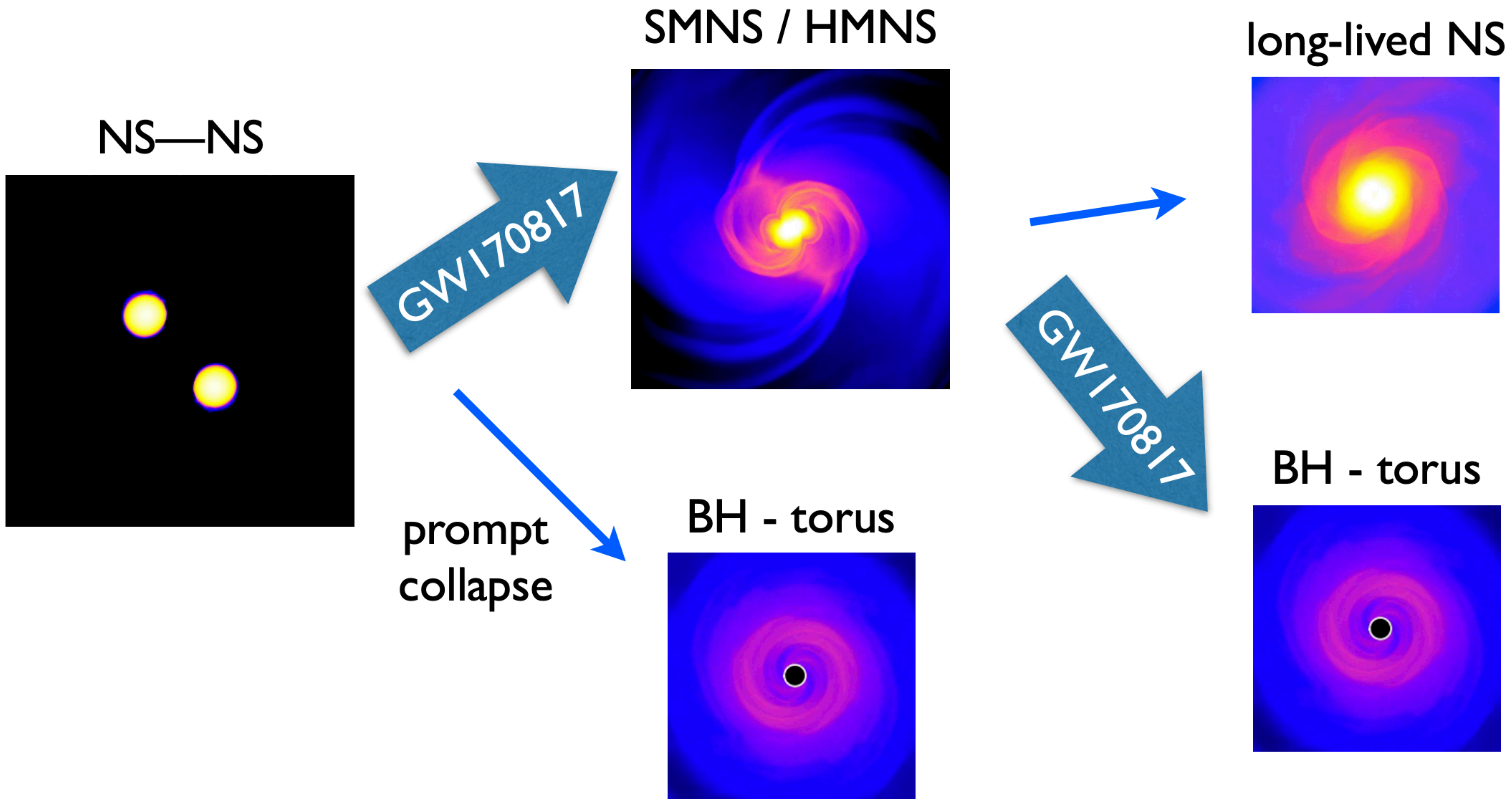
LVC+2017

AT2017gfo



Pian+2017

GW170817

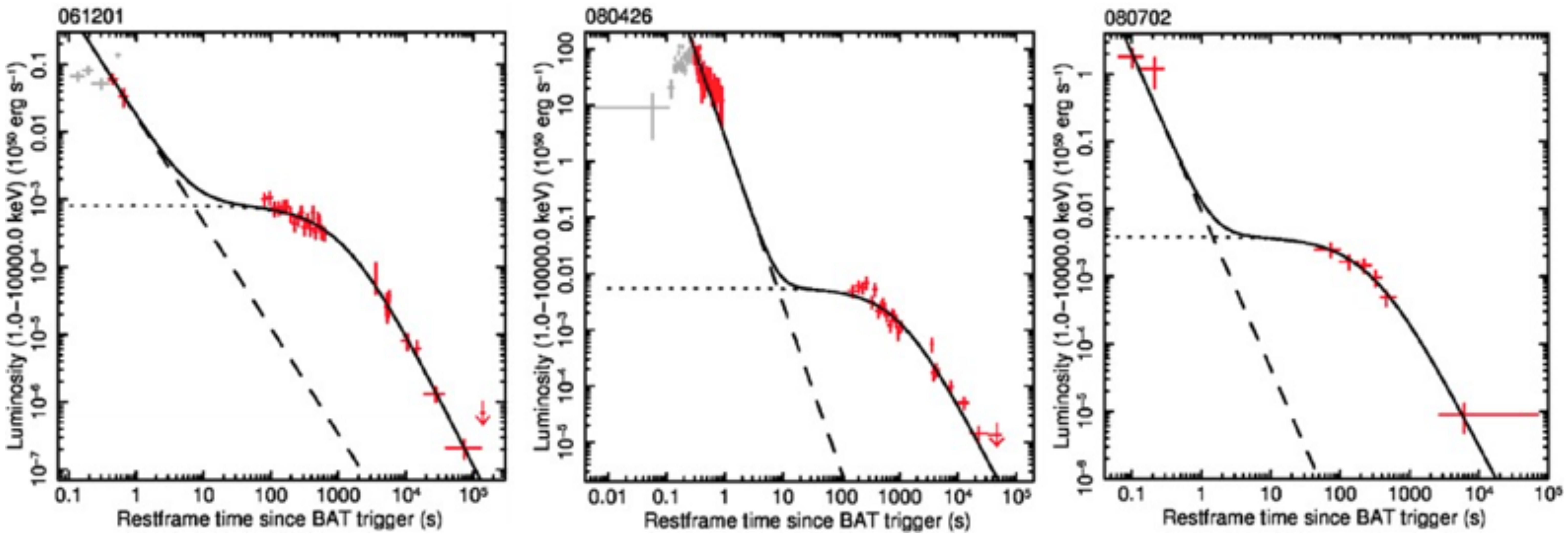


Siegel 2019

most-likely scenario of GW170817

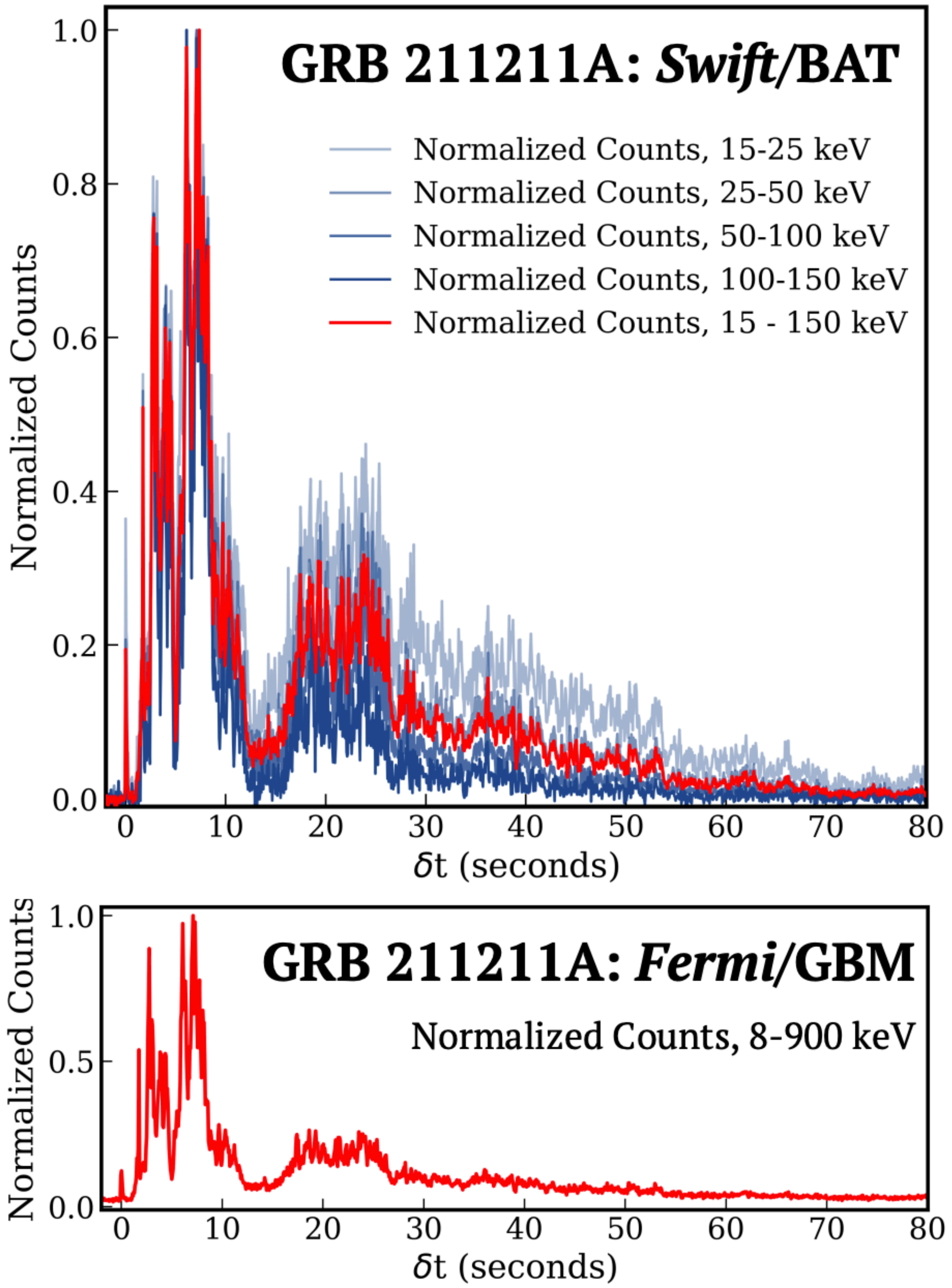
Magnetar engine for SGRB jets

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?

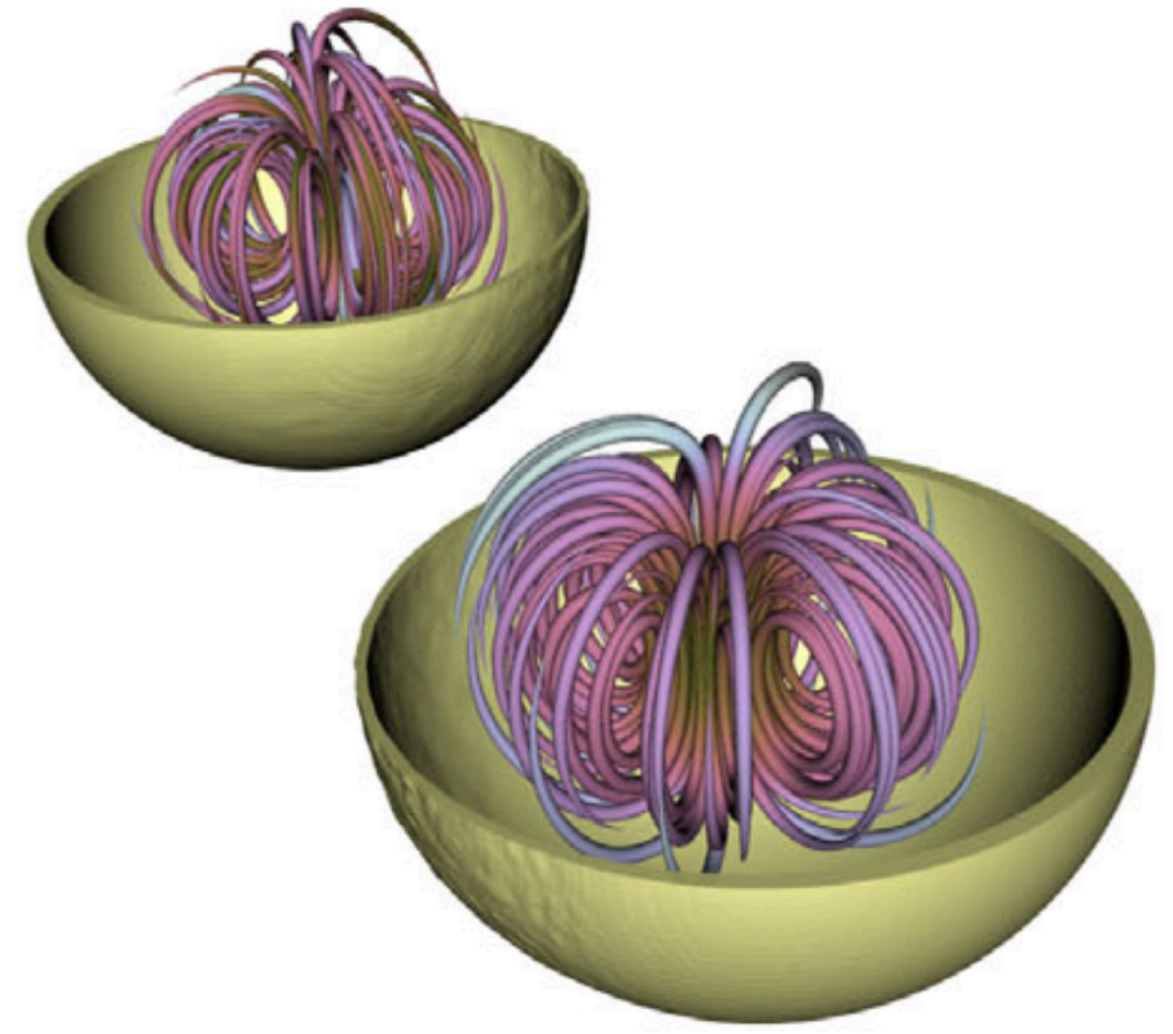
BNS simulations with WhiskyMHD

Physical & Numerical Setup

- Performed with Einstein Toolkit and WhiskyMHD code
- Equal-mass binary: $1.35 - 1.35\ M_{\odot}$
- APR4 EOS for nuclear matter
- LORENE: initial data for irrotational, quasi-circular binary
- Internal poloidal fields manually added: $B_{\rm max} = 10^{16}$ G

Why such a high magnetic field strength?

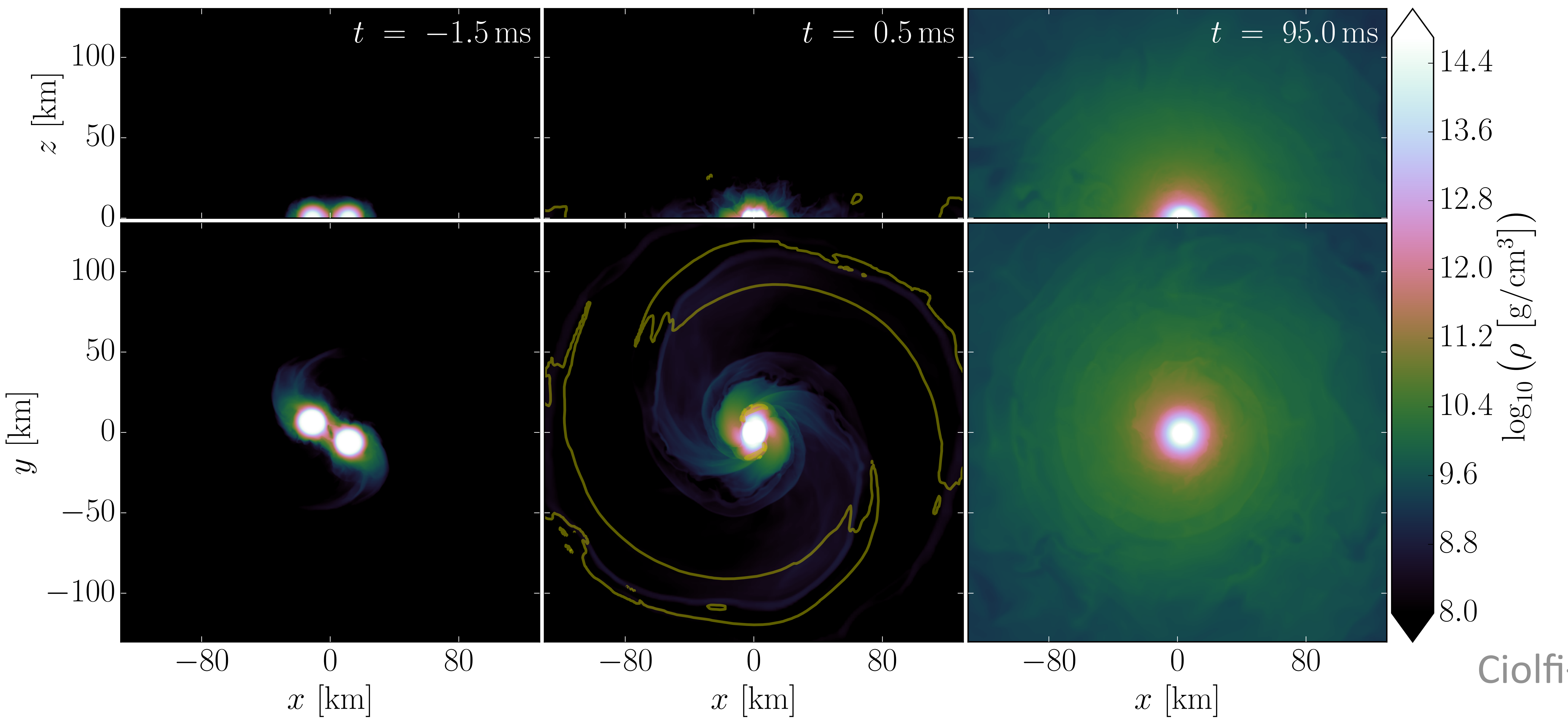
- to compensate for insufficient resolution
- to study highly magnetised post-merger system
- more favourable conditions for possible jet formation



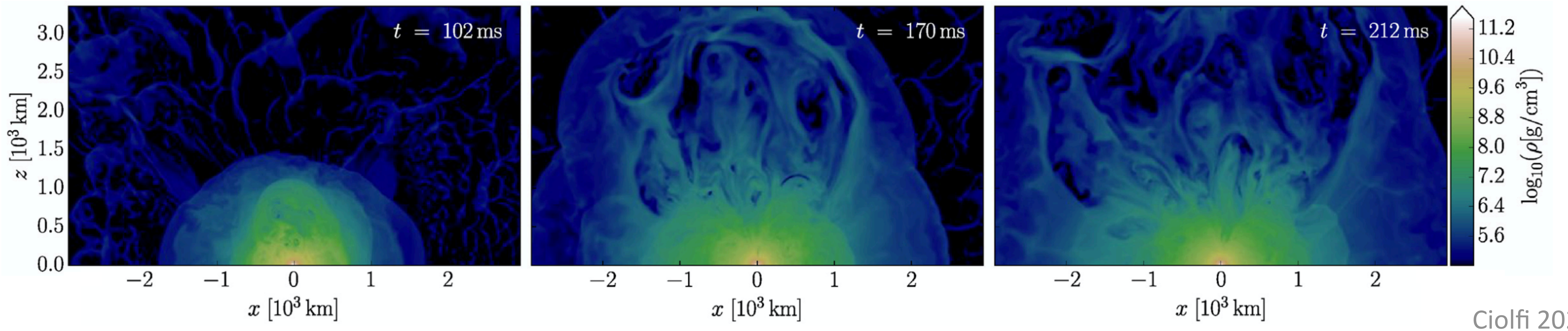
Kawamura+2016

BNS with WhiskyMHD

Merger produces a differentially rotating, metastable SMNS

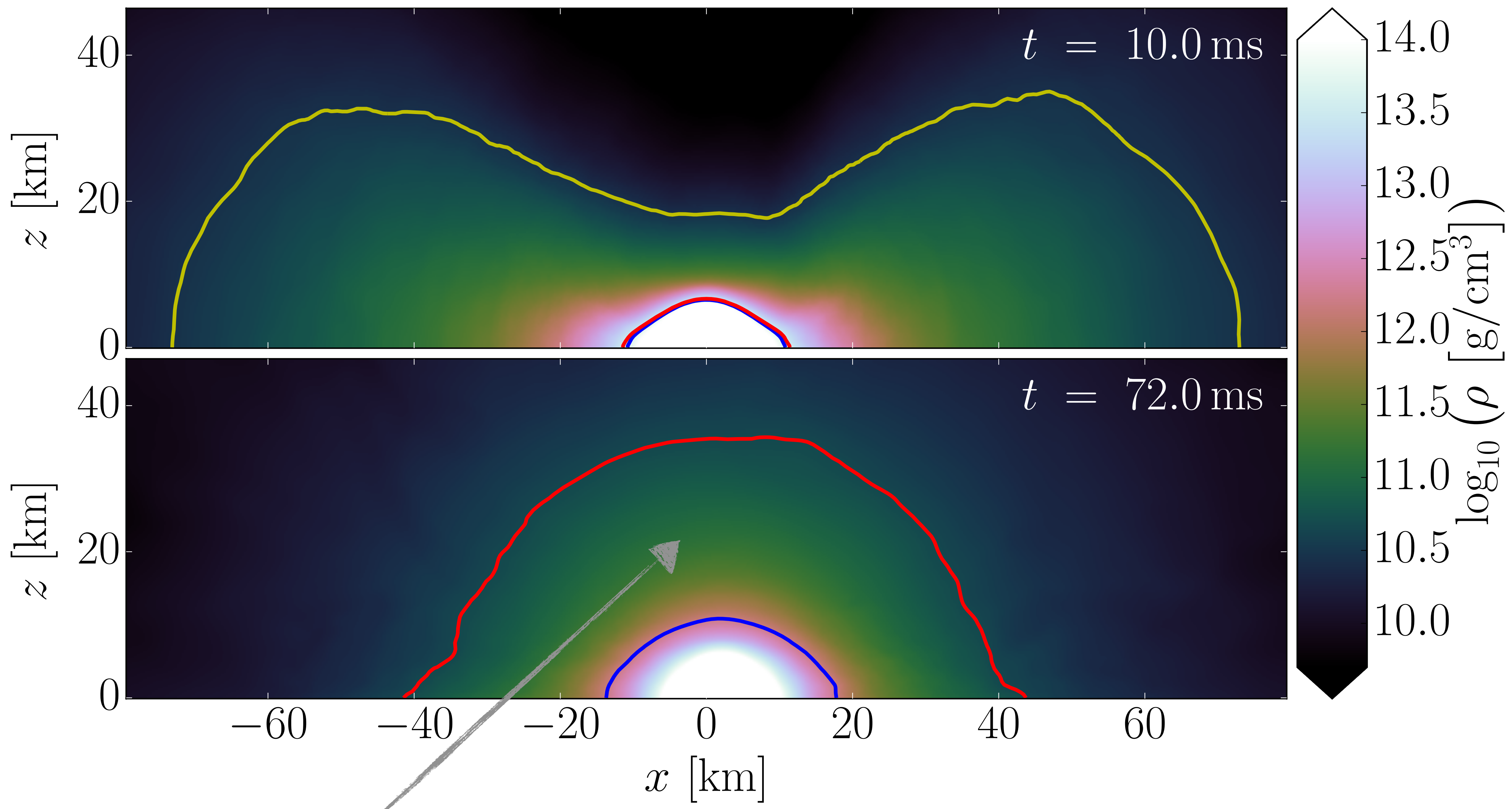


Ciolfi+2019



Ciolfi 2020

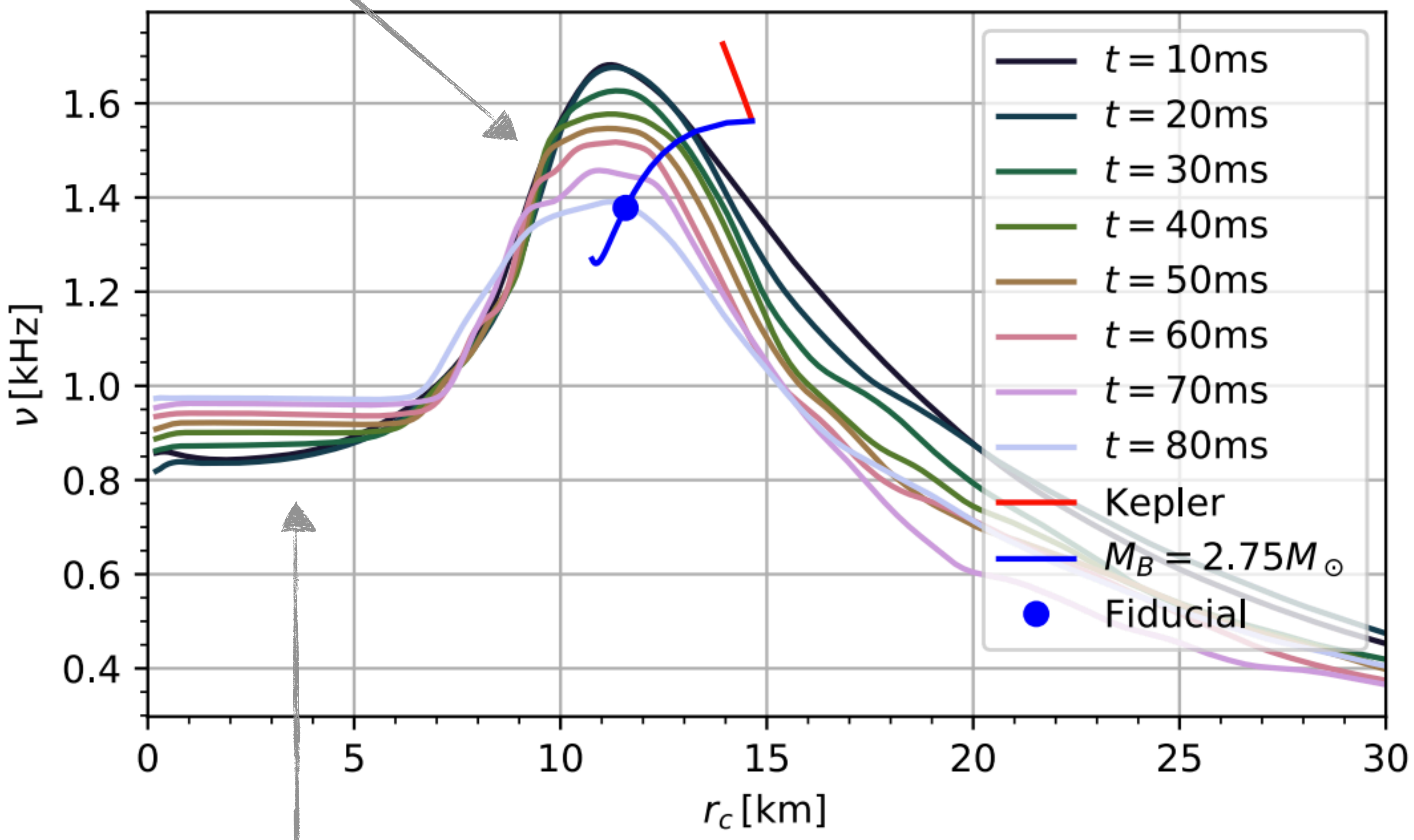
Remnant Structure & Rotation Profile



Magnetized Ejecta "Bubble"

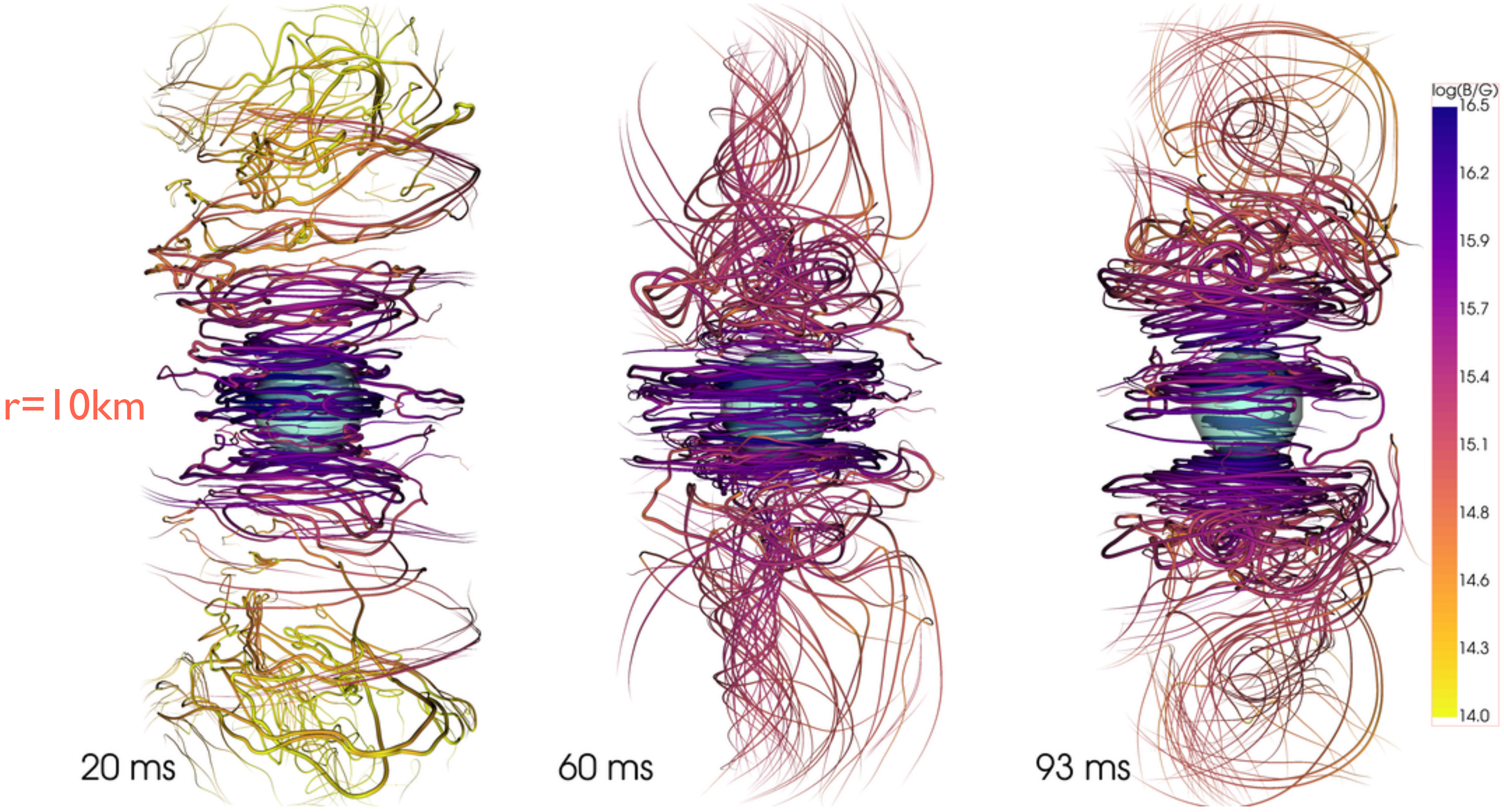
Faster envelope "differential" rotation

Ciolfi+2019



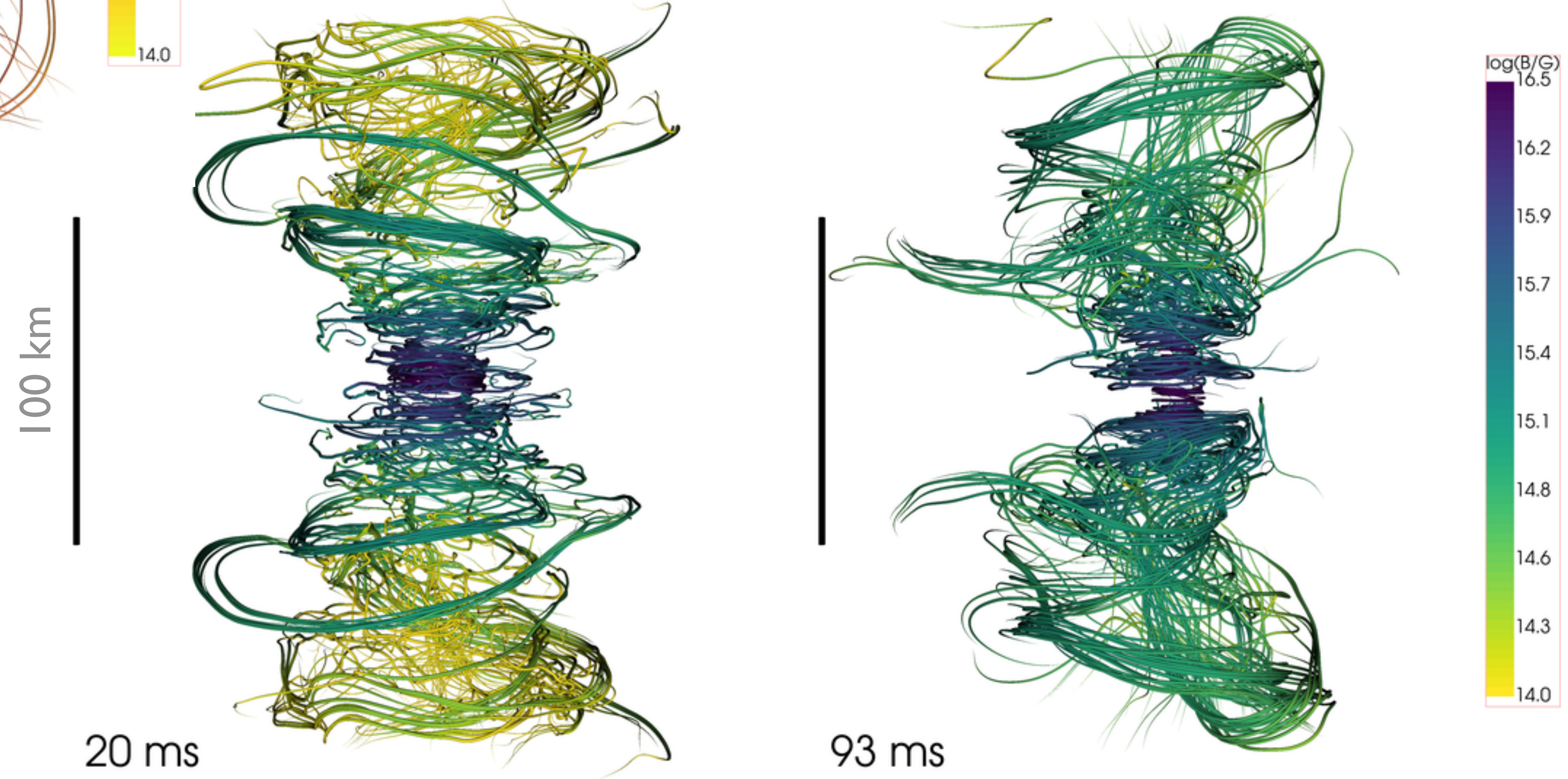
Slower core "uniform" rotation

Field-line Topology

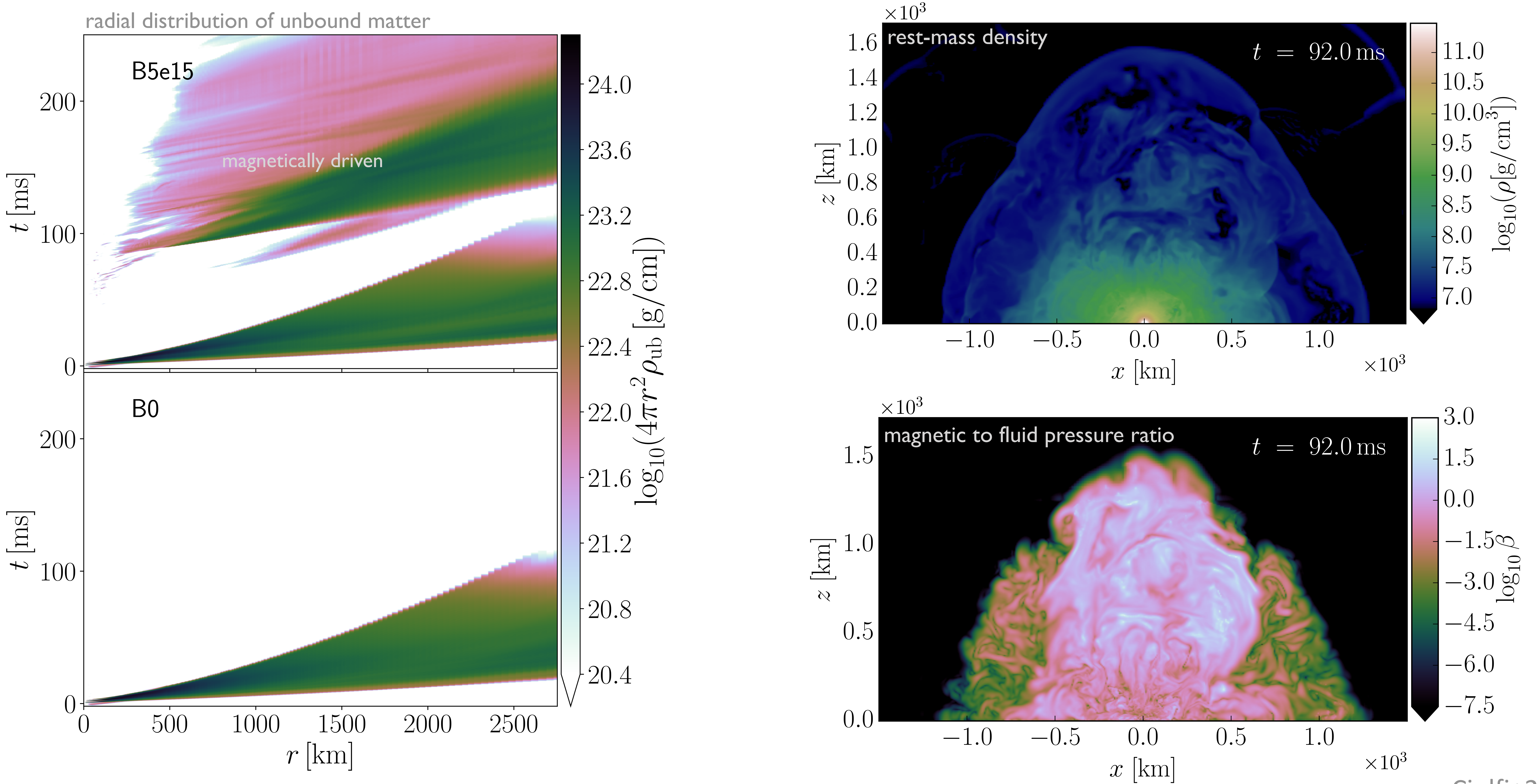


toroidal + poloidal field amplification

emergence of a global magnetic field



Baryon Pollution Problem

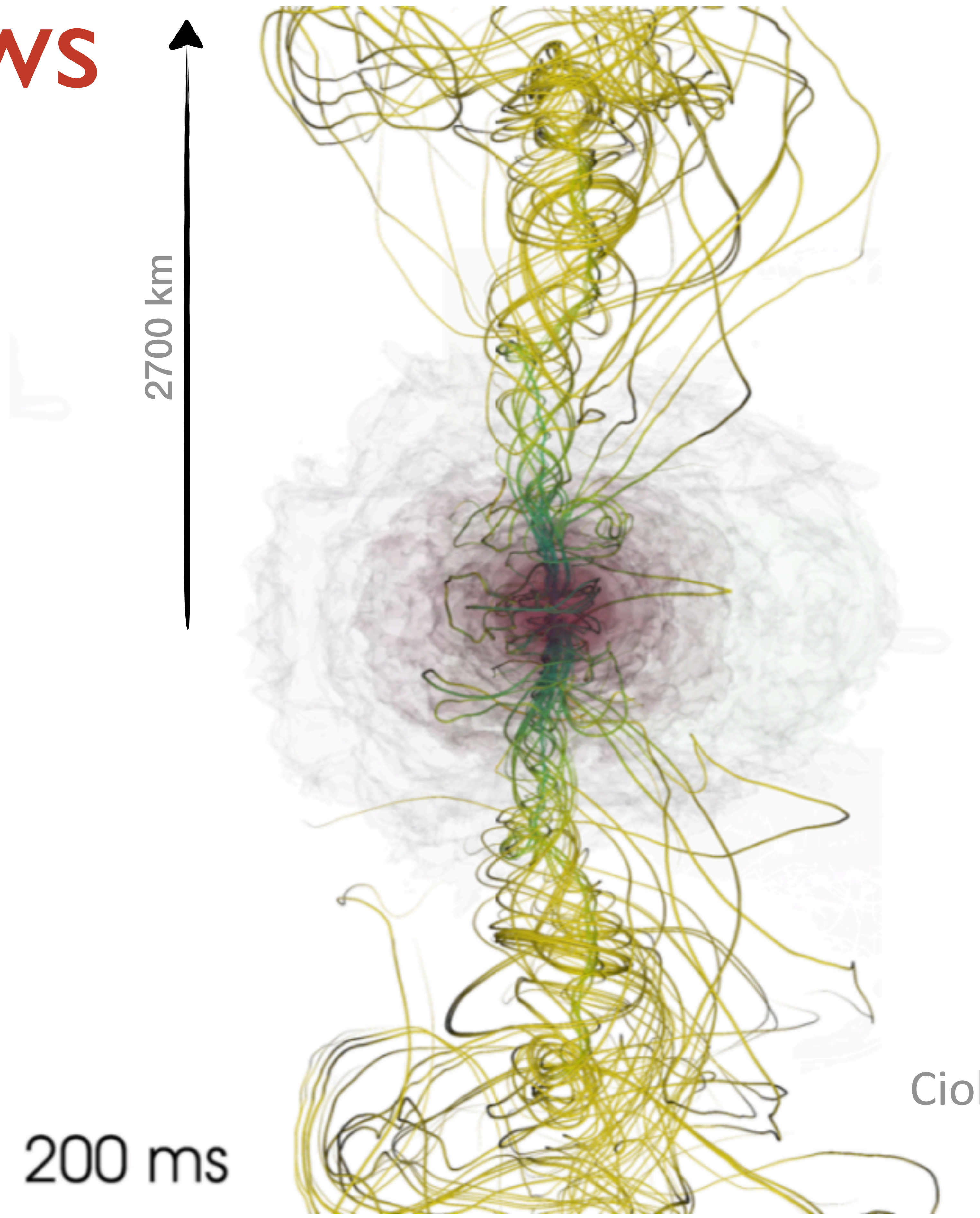


Ciolfi+2019

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

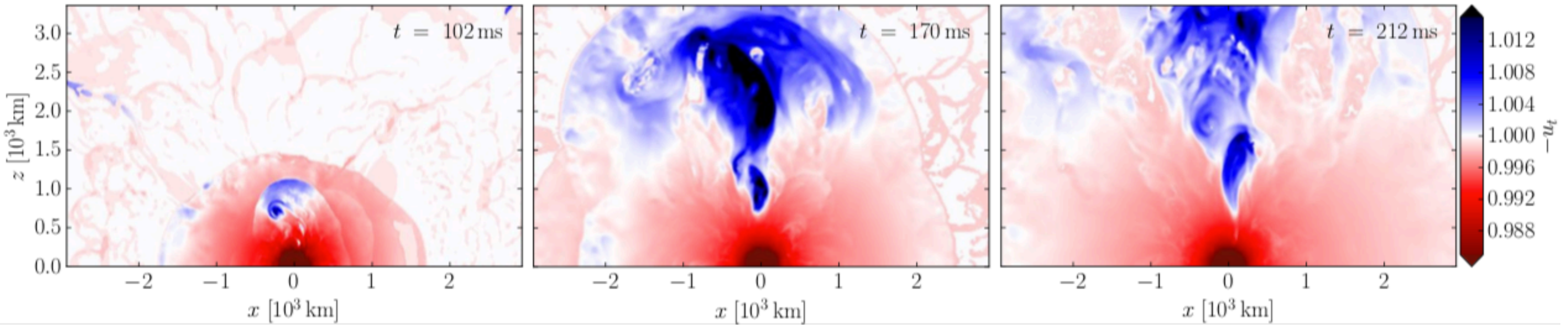
what it has

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

what it needs

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

Matter unbound when $u_t \leq -1$



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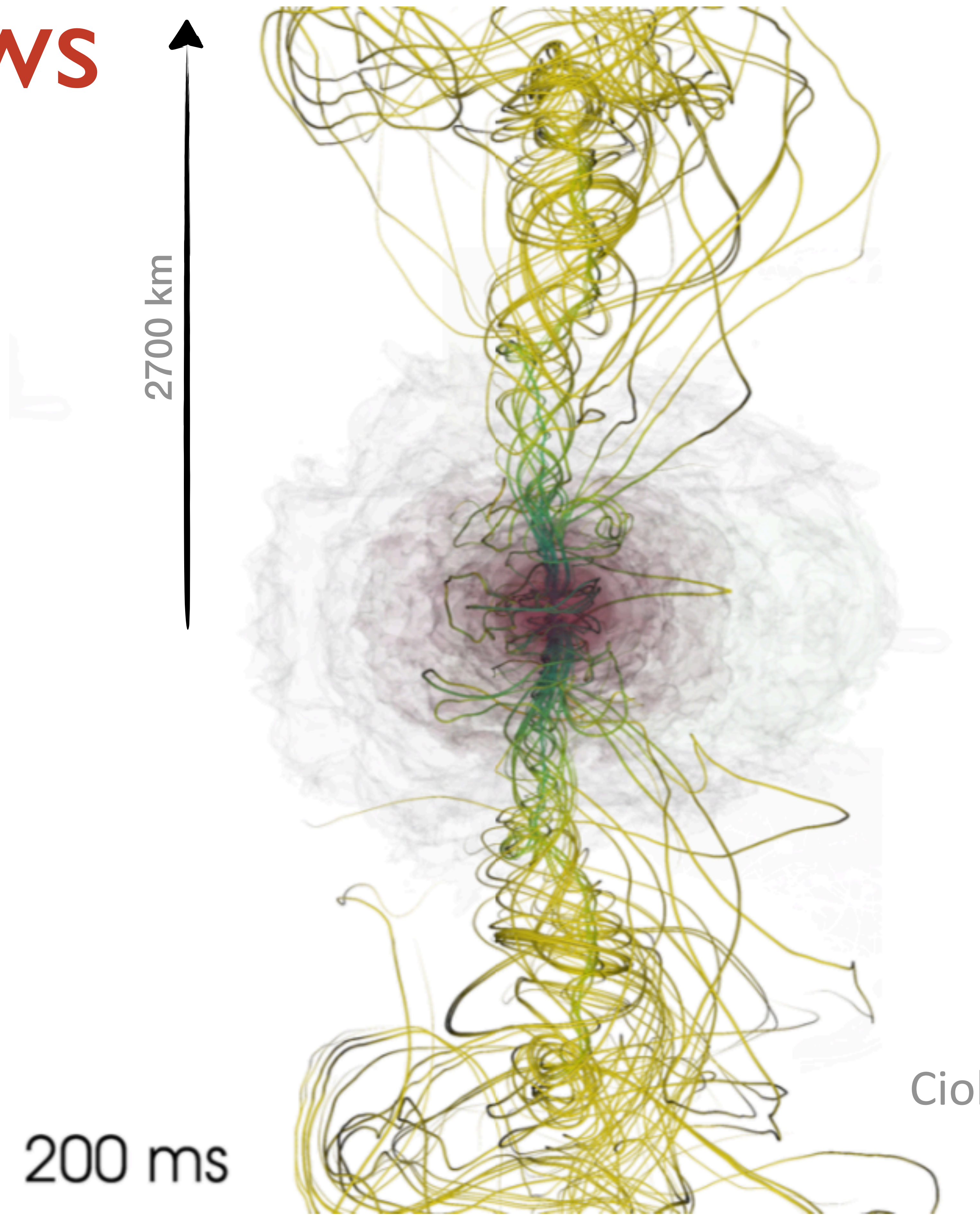

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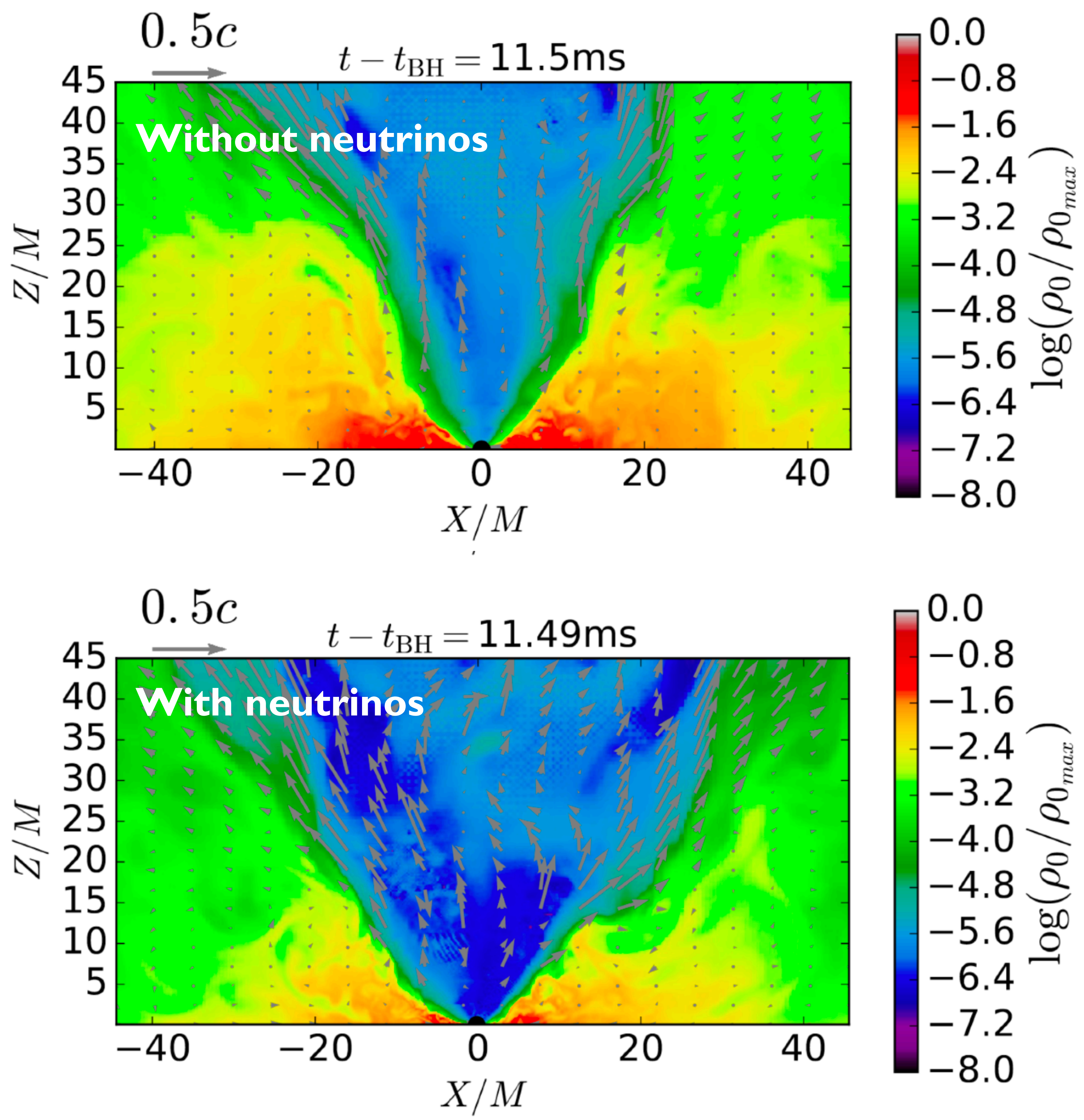
Magnetar scenario disfavoured for producing a SGRB jet

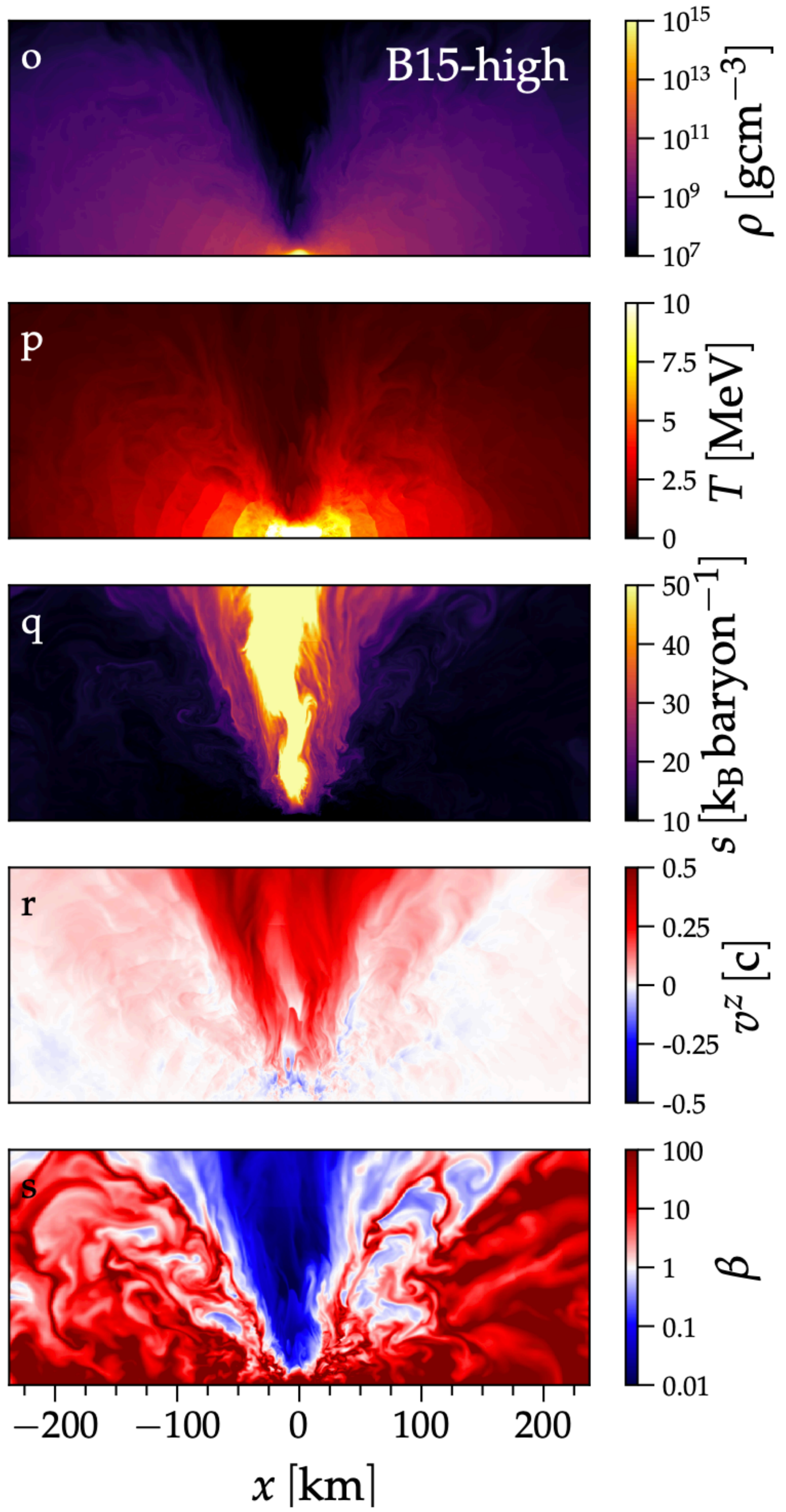
Role of Neutrinos

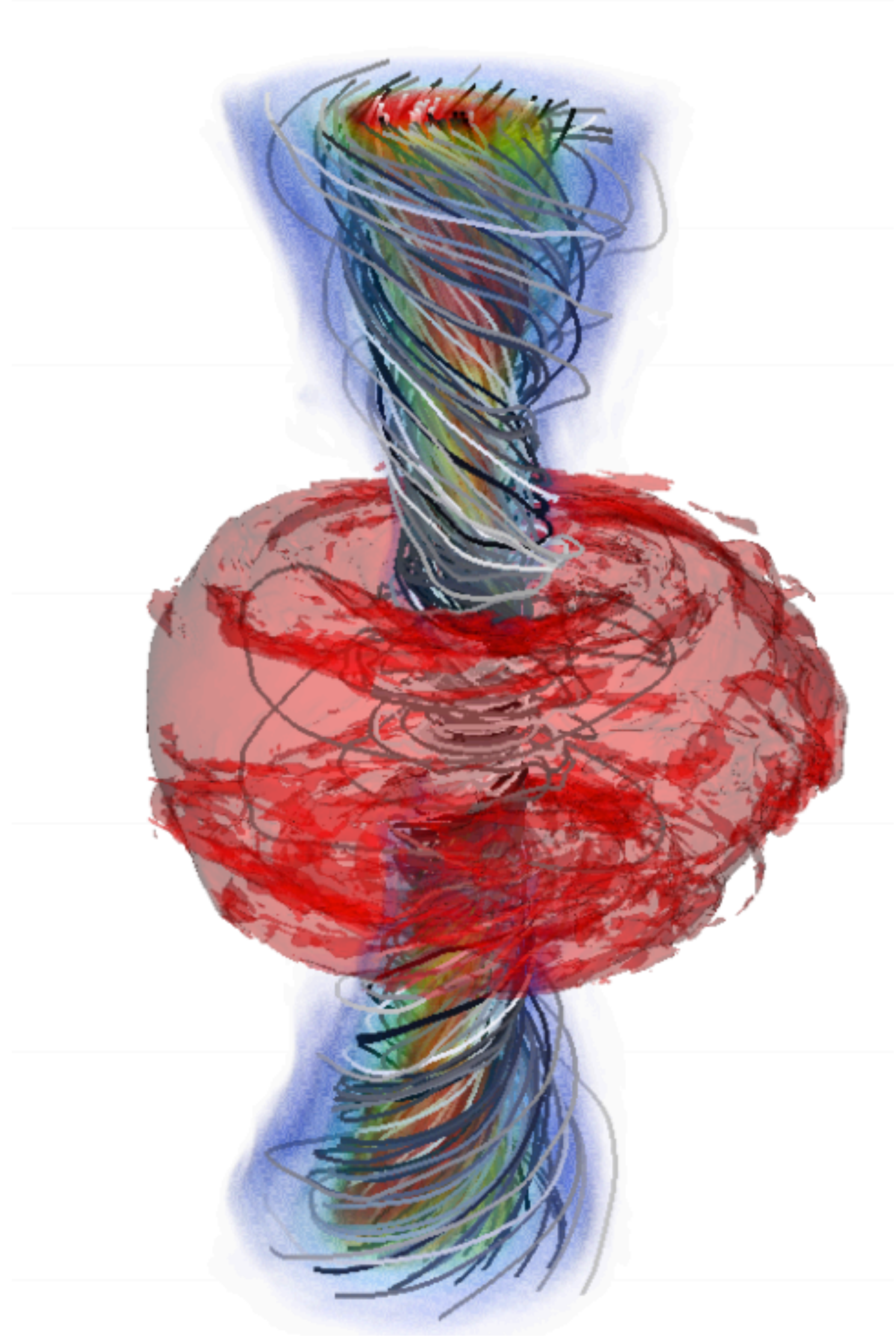
BH + disk



Sun+2022

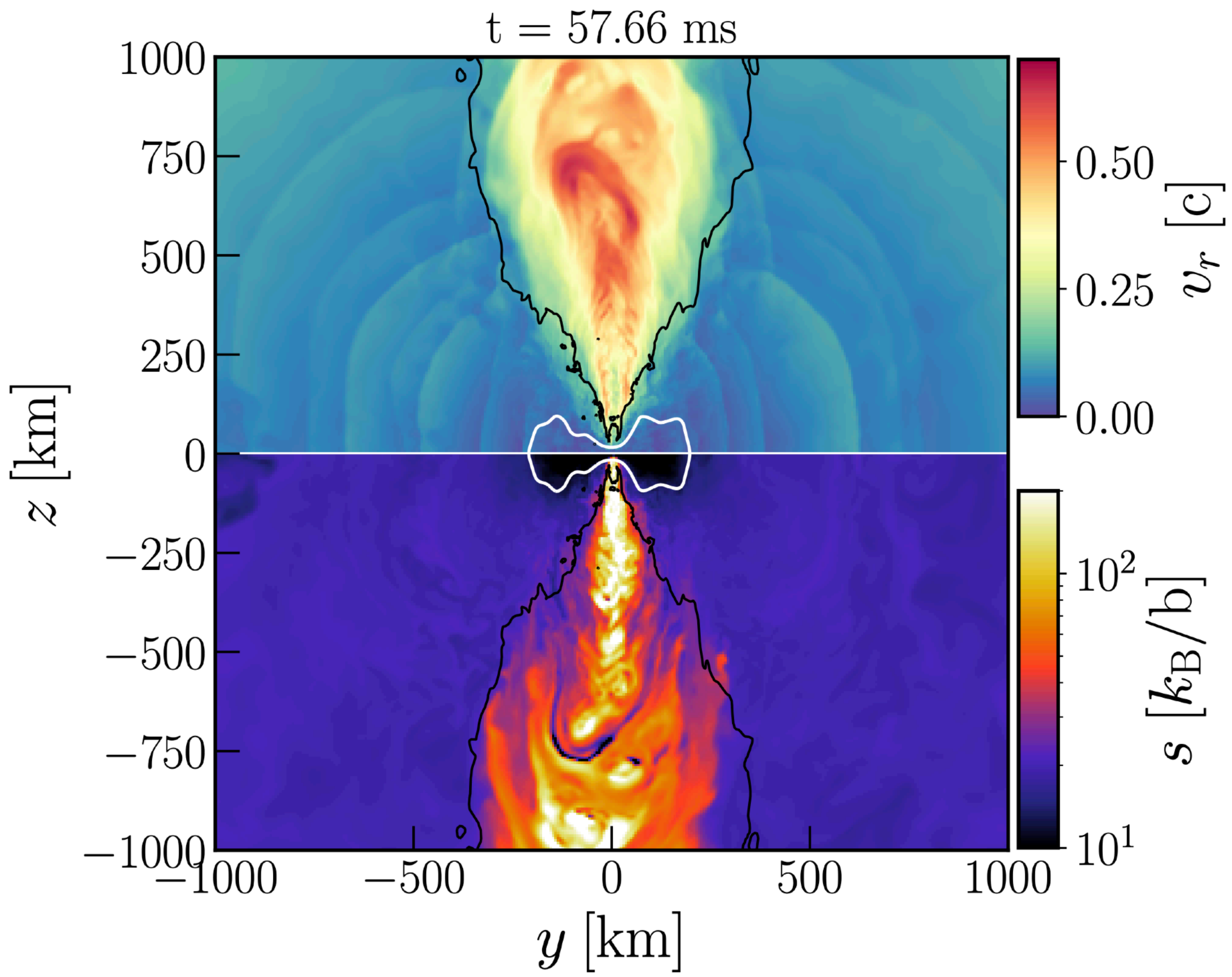
Magnetar with neutrinos BUT
large poloidal field placed later by hand



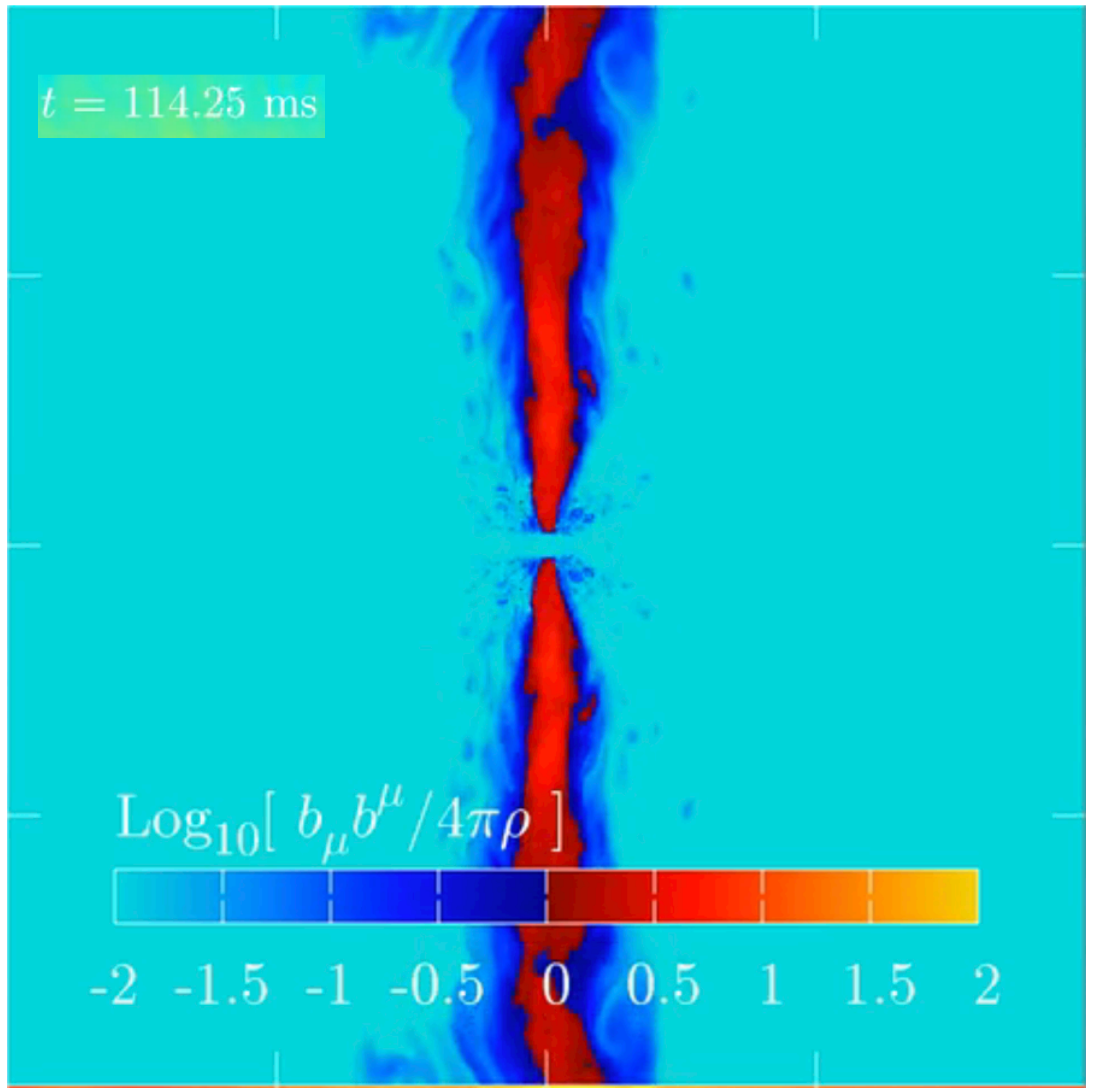


Moesta+2020

Role of Neutrinos



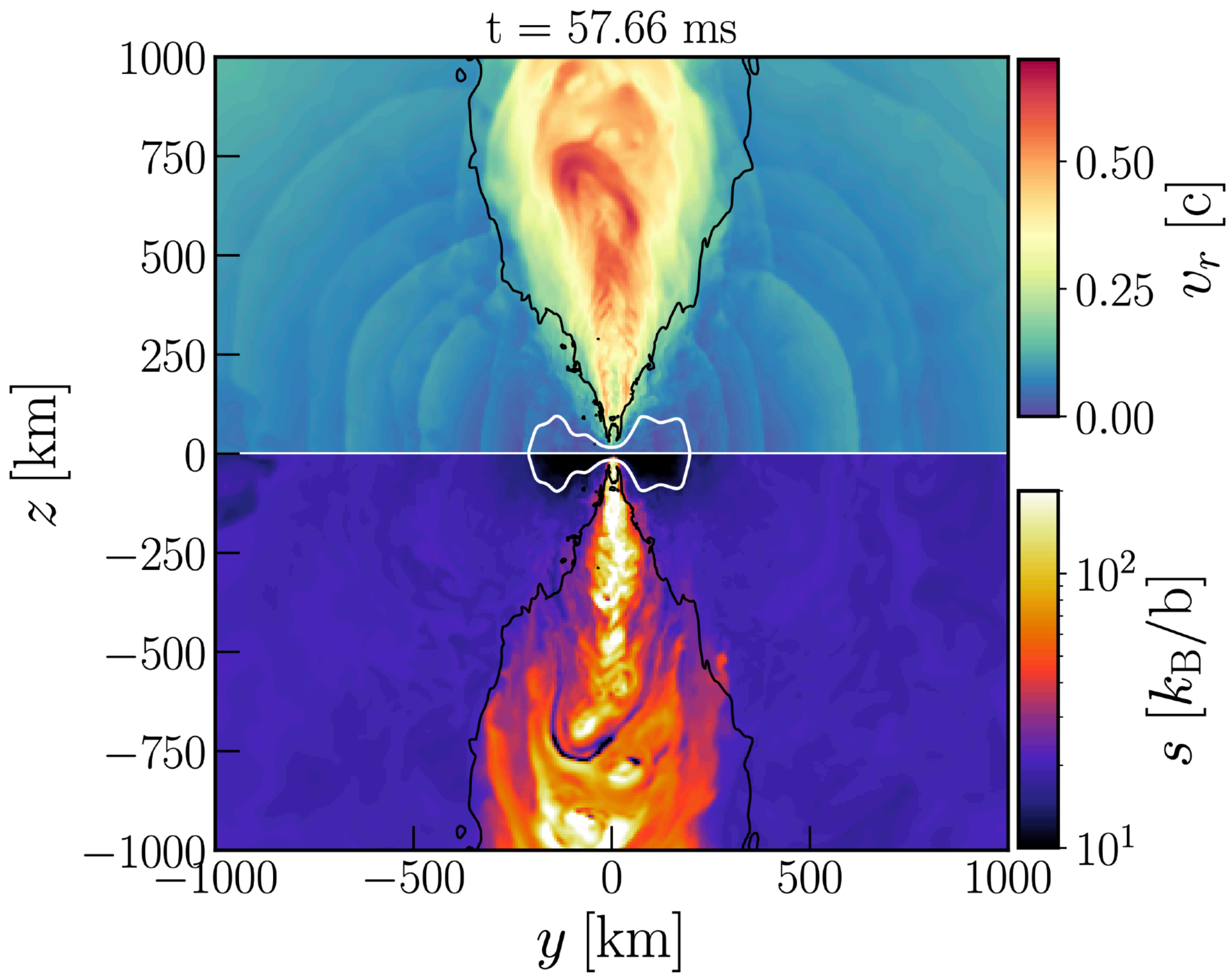
Combi+2023



Kiuchi+2023

$\Delta x_{\mathrm{finest}} = 12.5$ m

Role of Neutrinos



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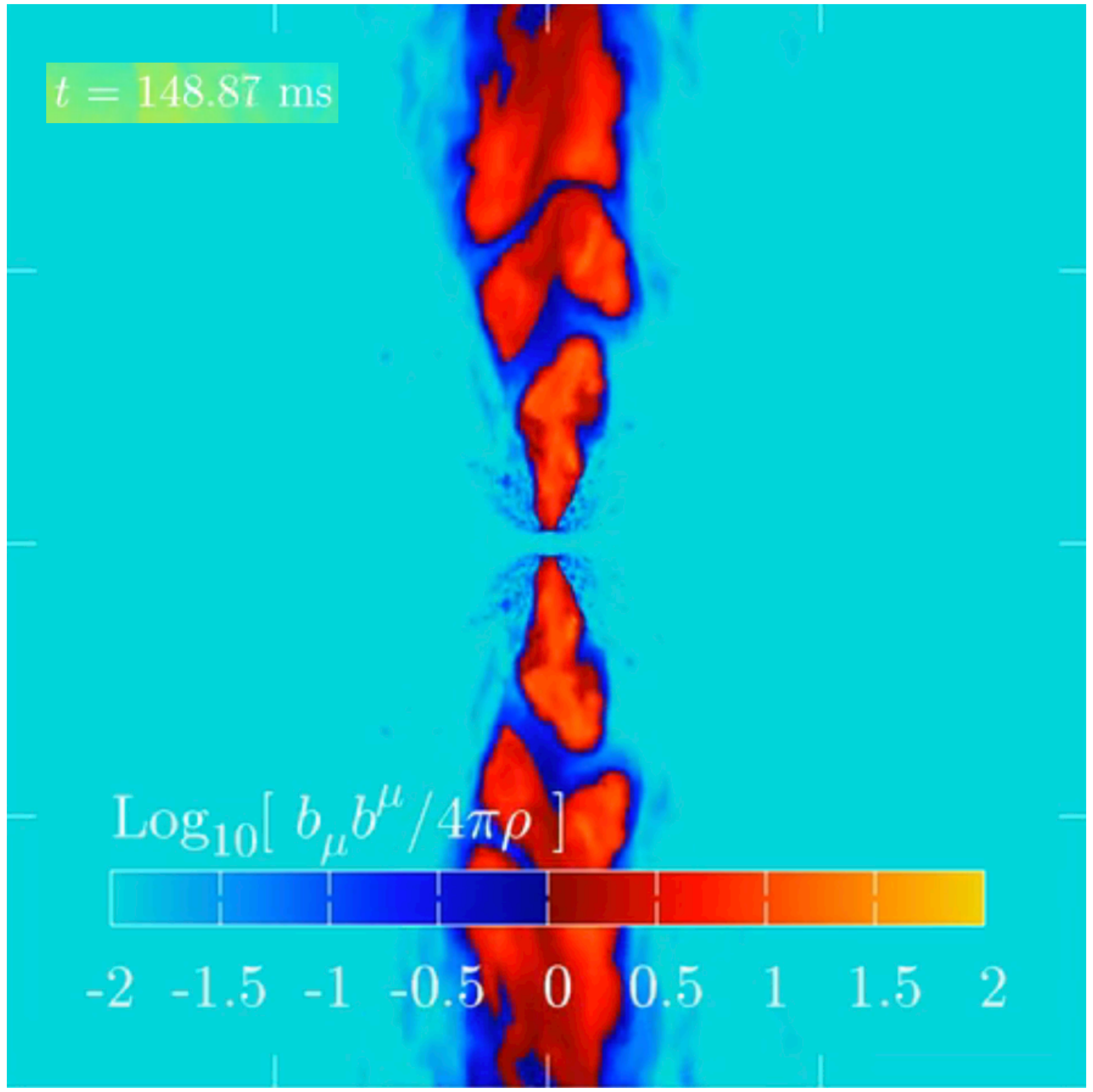


Kiuchi+2023

$\Delta x_{\rm finest}$ = 12.5 m

Open problem: complex interplay between continuous MNS outflows and neutrinos

The Blue Kilonova

- GW170817 accompanied by electromagnetic transient AT2017gfo
- **Smoking gun evidence:** *BNS mergers produce radioactively powered kilonovae*

AT2017gfo shows at least two distinct components

Blue component

-peaks about 1 day after merger

-lanthanide poor (lower opacities)

-ejecta velocities: about **0.2-0.3c**

-ejecta mass: about **0.015-0.025 M_{sun}**

-source: **magnetically driven MNS winds?**

Red component

-peaks several days after merger

-lanthanide rich (higher opacities)

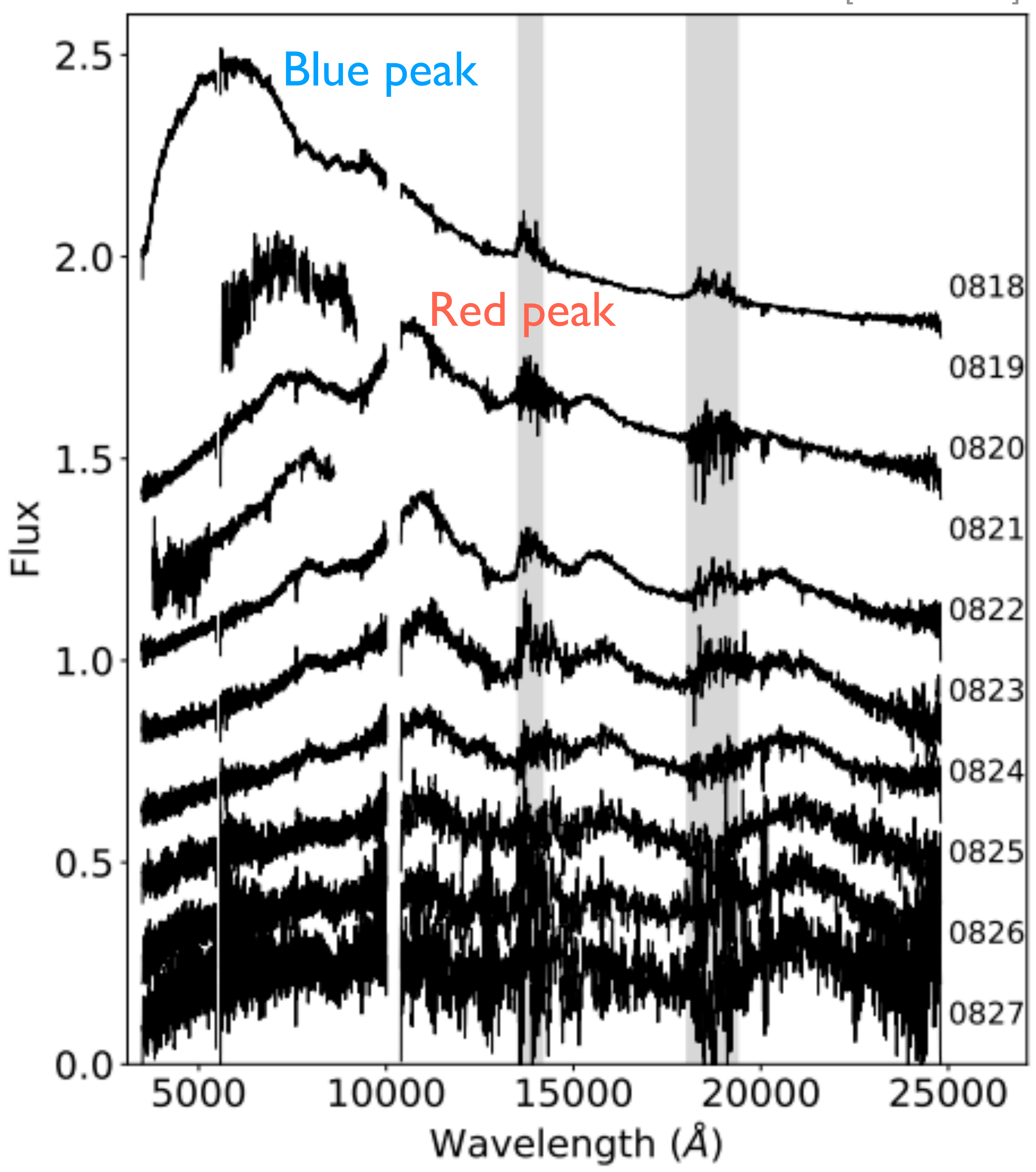
-ejecta velocities: about **0.1c**

-ejecta mass: about **0.05 M_{sun}**

-source: post-merger disk winds

[Perego+2014, Siegel & Metzger 2017a,b,....]

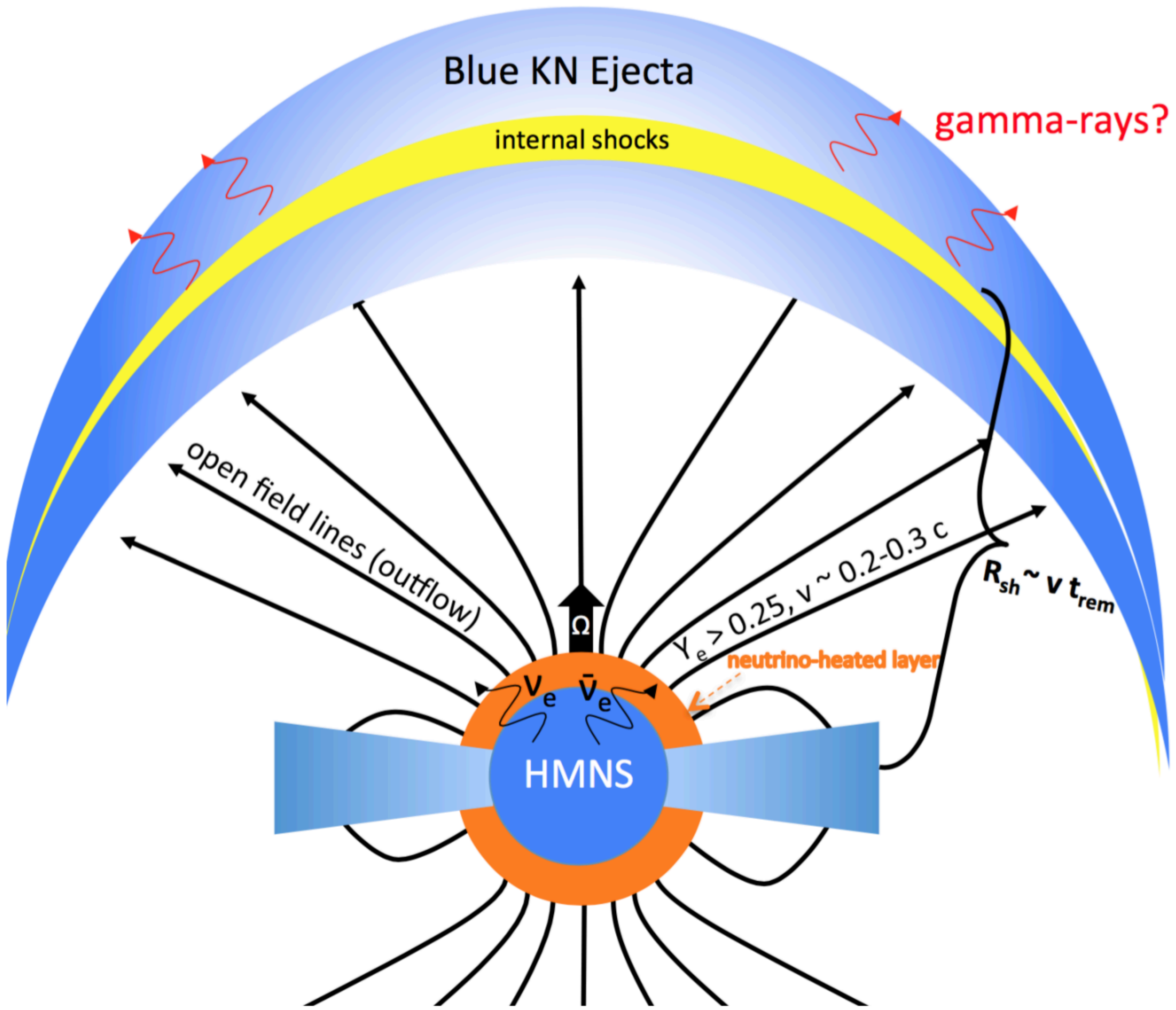
[Pian+2017]



Time-evolution of AT2017gfo spectra

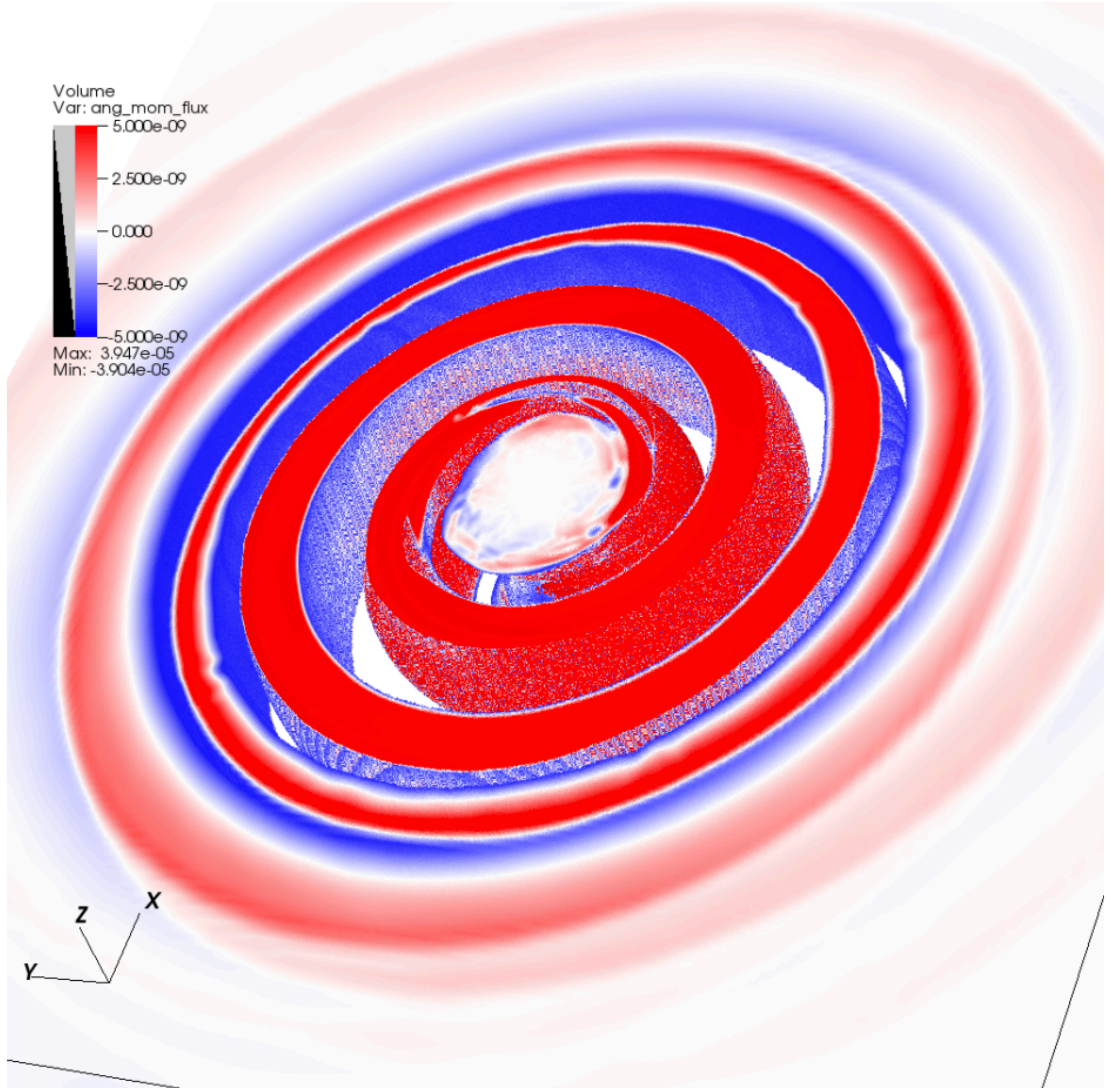
The Blue Kilonova

Magnetised winds from MNS remnant



Metzger+2018

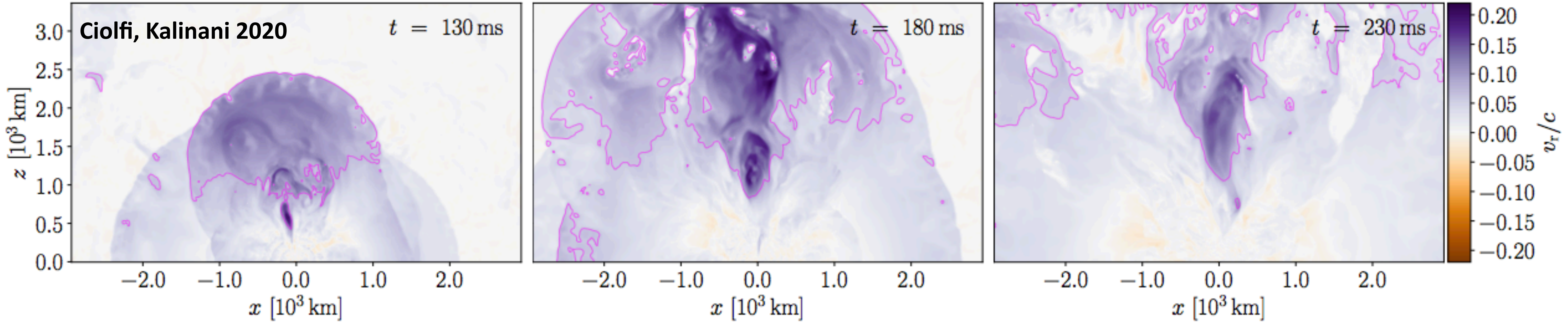
Spiral density-wave winds



Nedora+2019

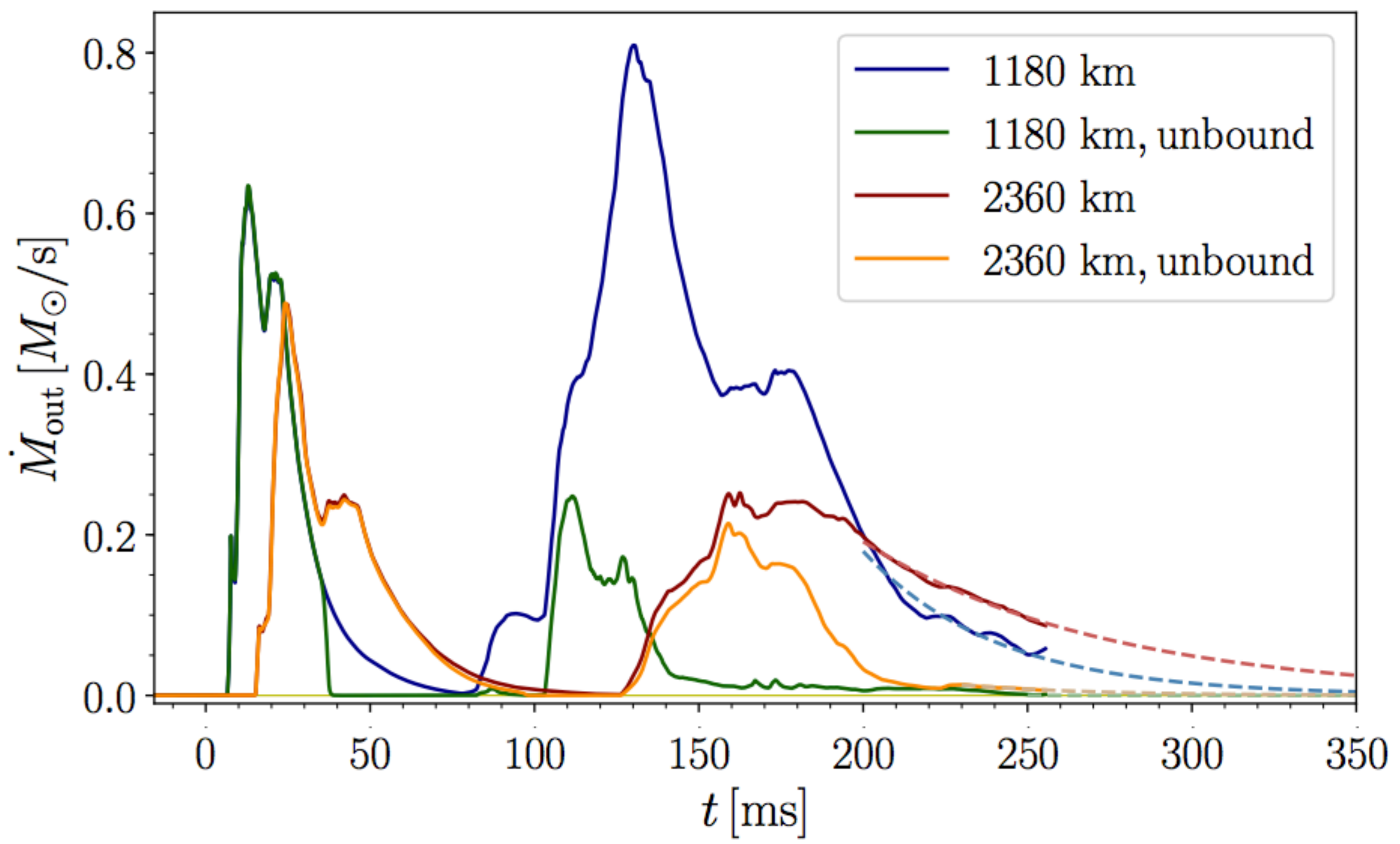
Open question: source of the blue kilonova component?

Radial velocity

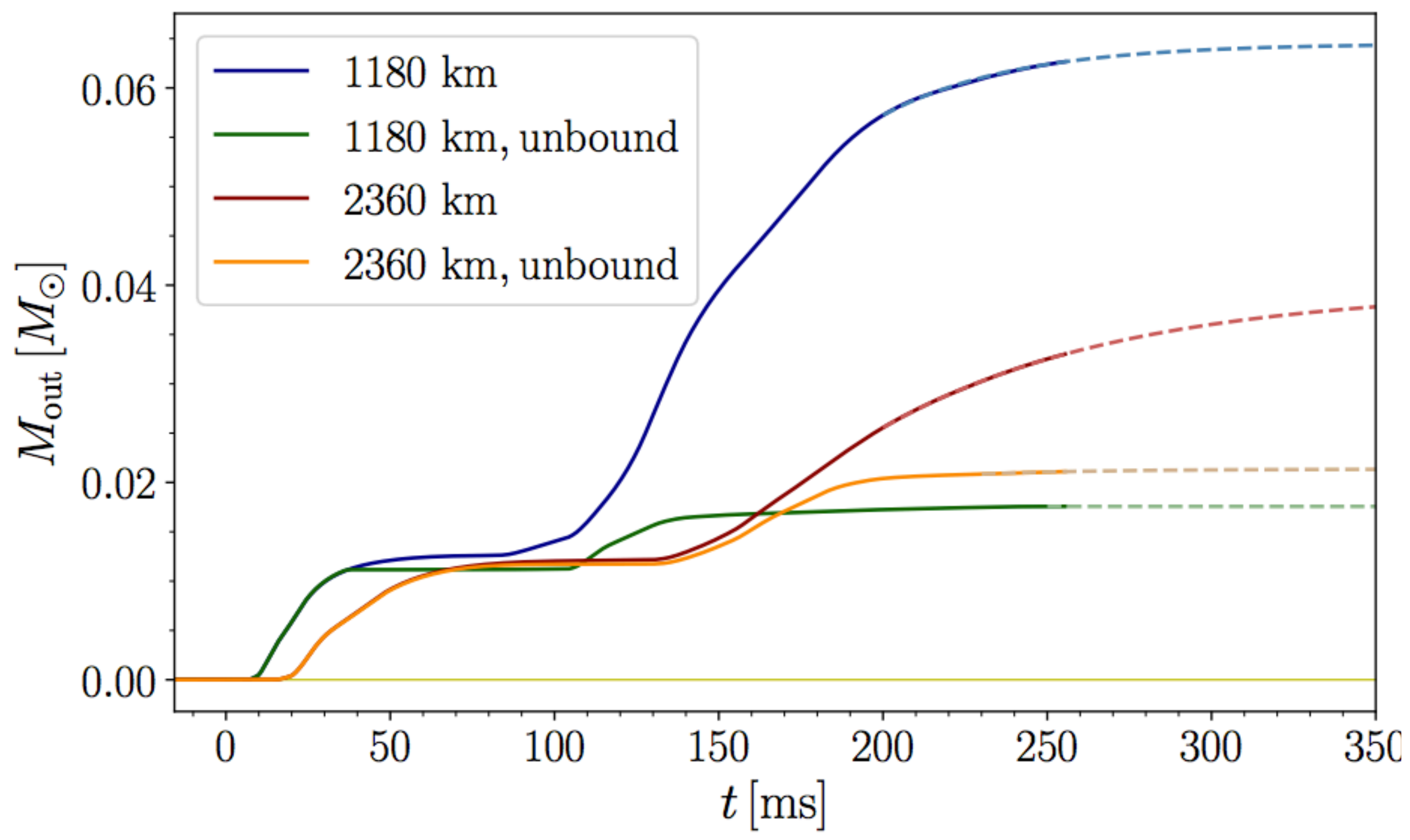


ejecta velocities reach about **0.2-0.22c**

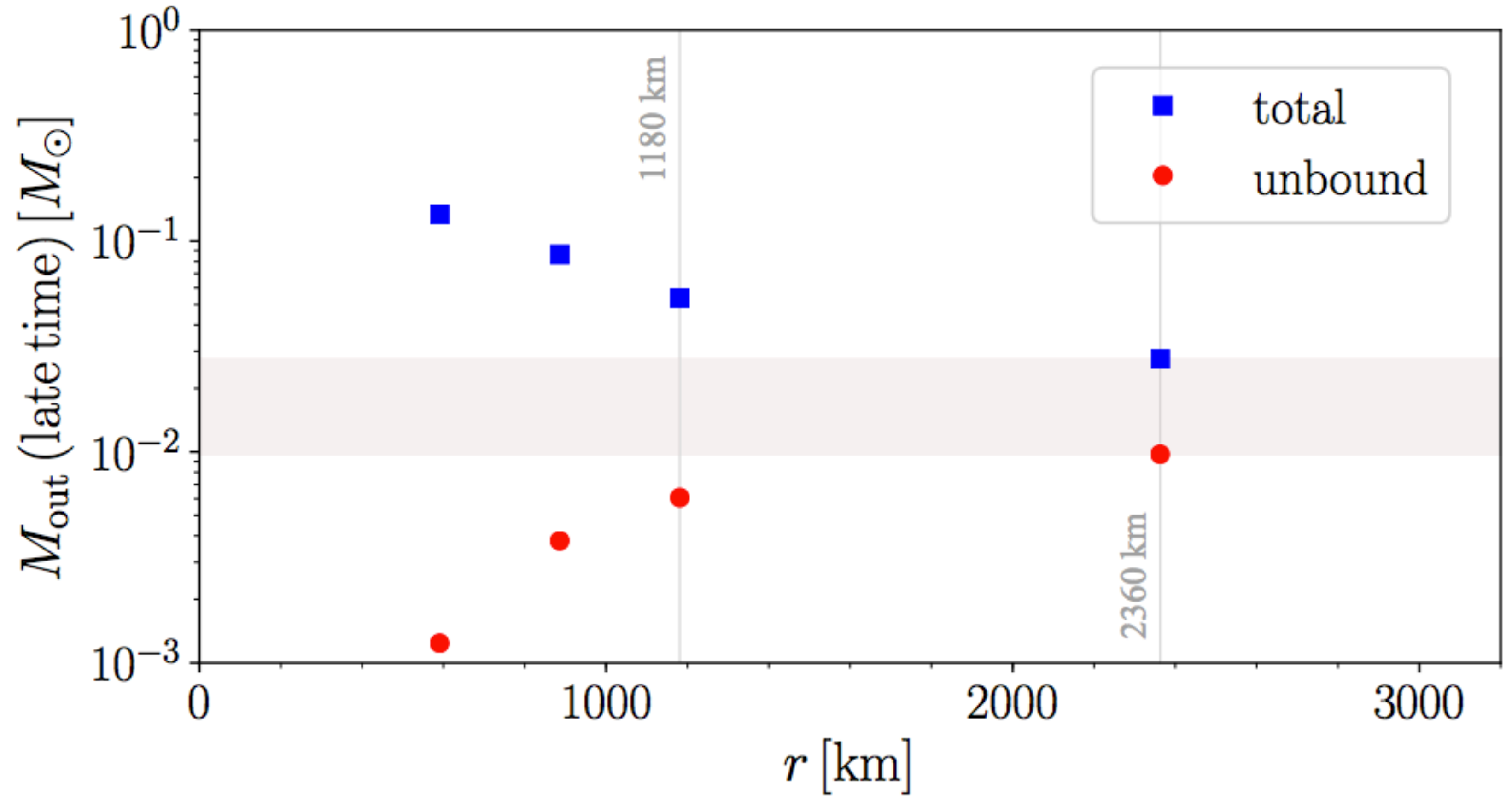
Mass outflow rate evolution



Mass outflow evolution



Radial distribution of mass outflow

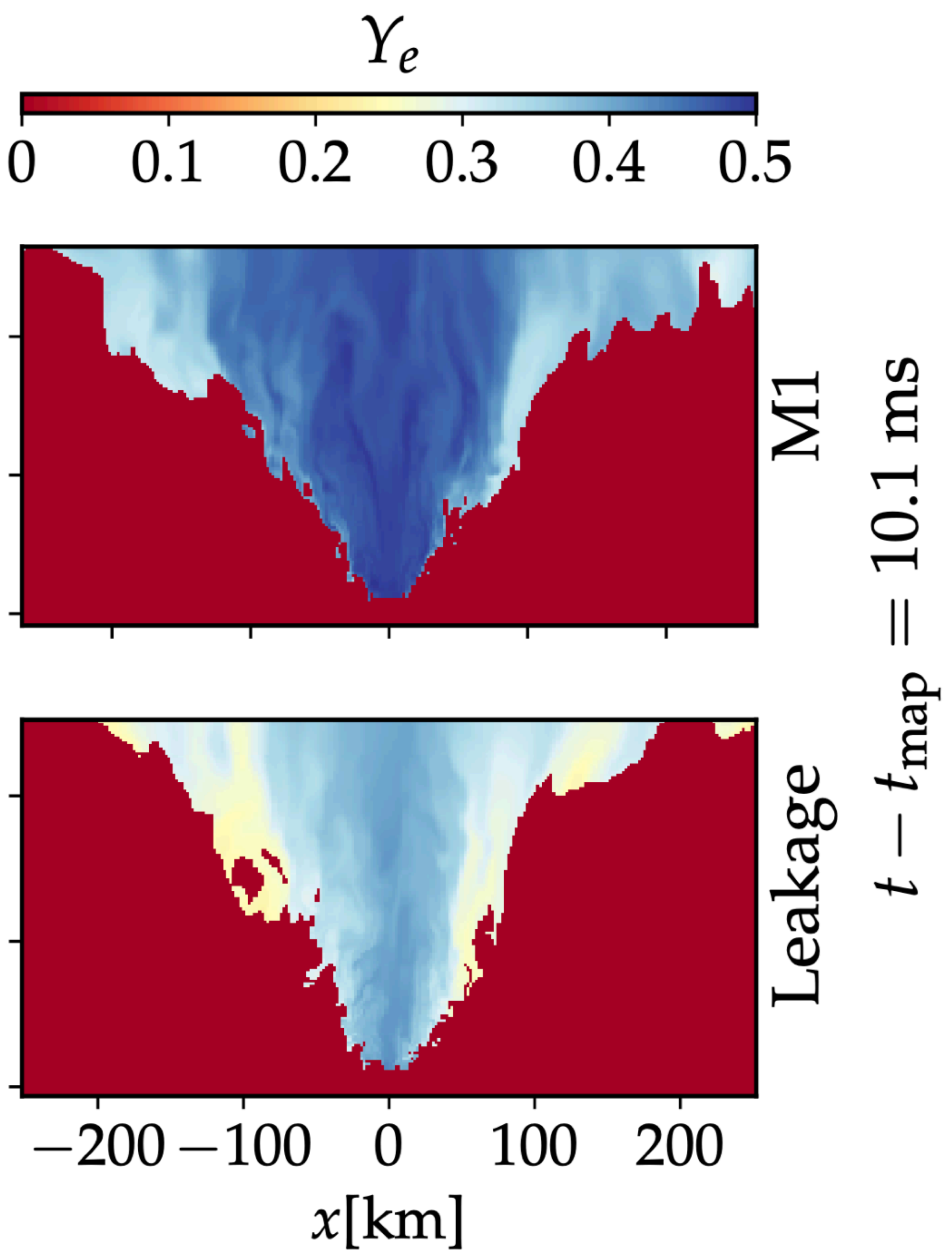


total unbound ejecta mass reaches about **0.01-0.028 Msun**

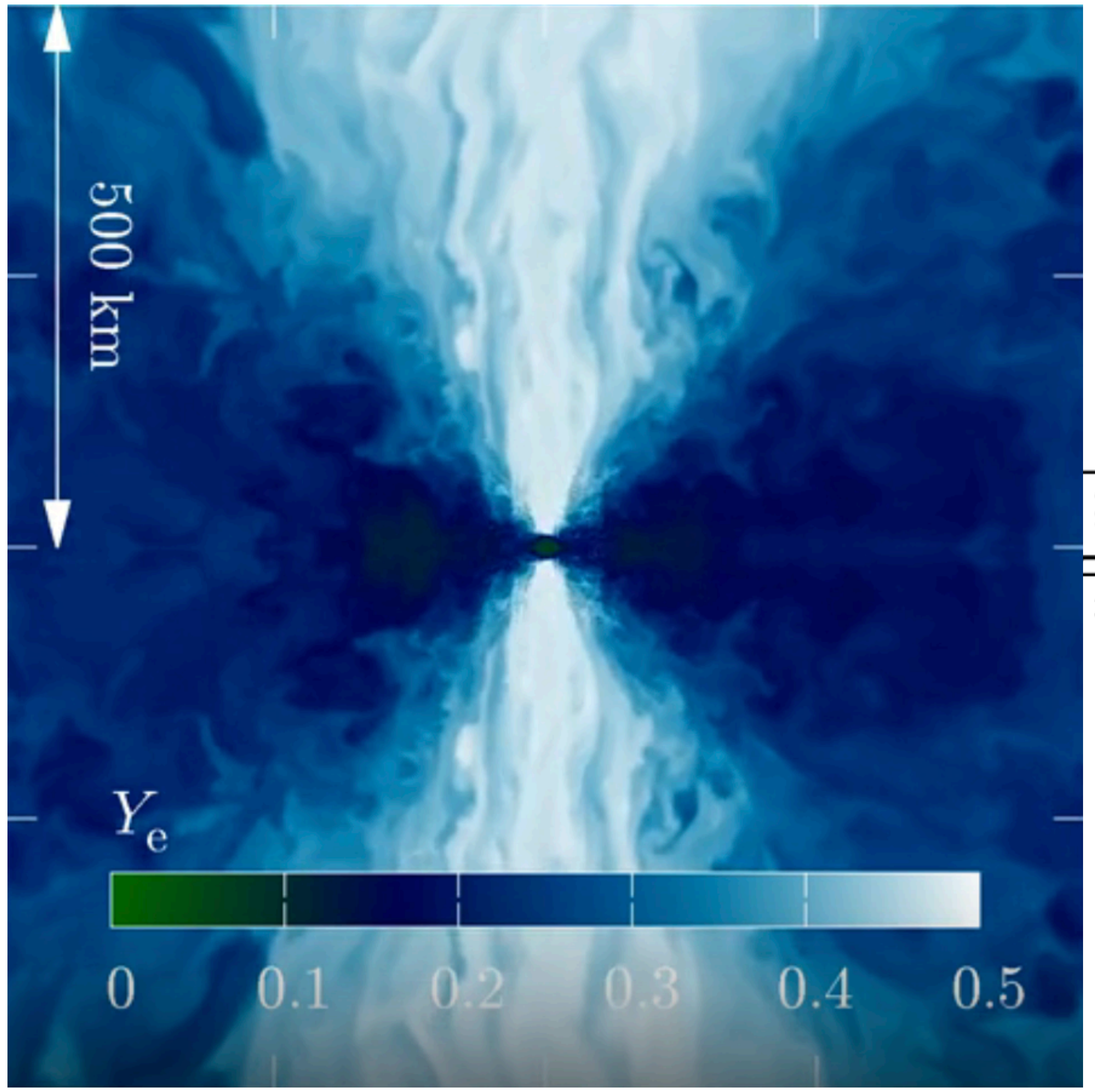
Ejecta velocities and mass consistent with blue kilonova

The Blue Kilonova

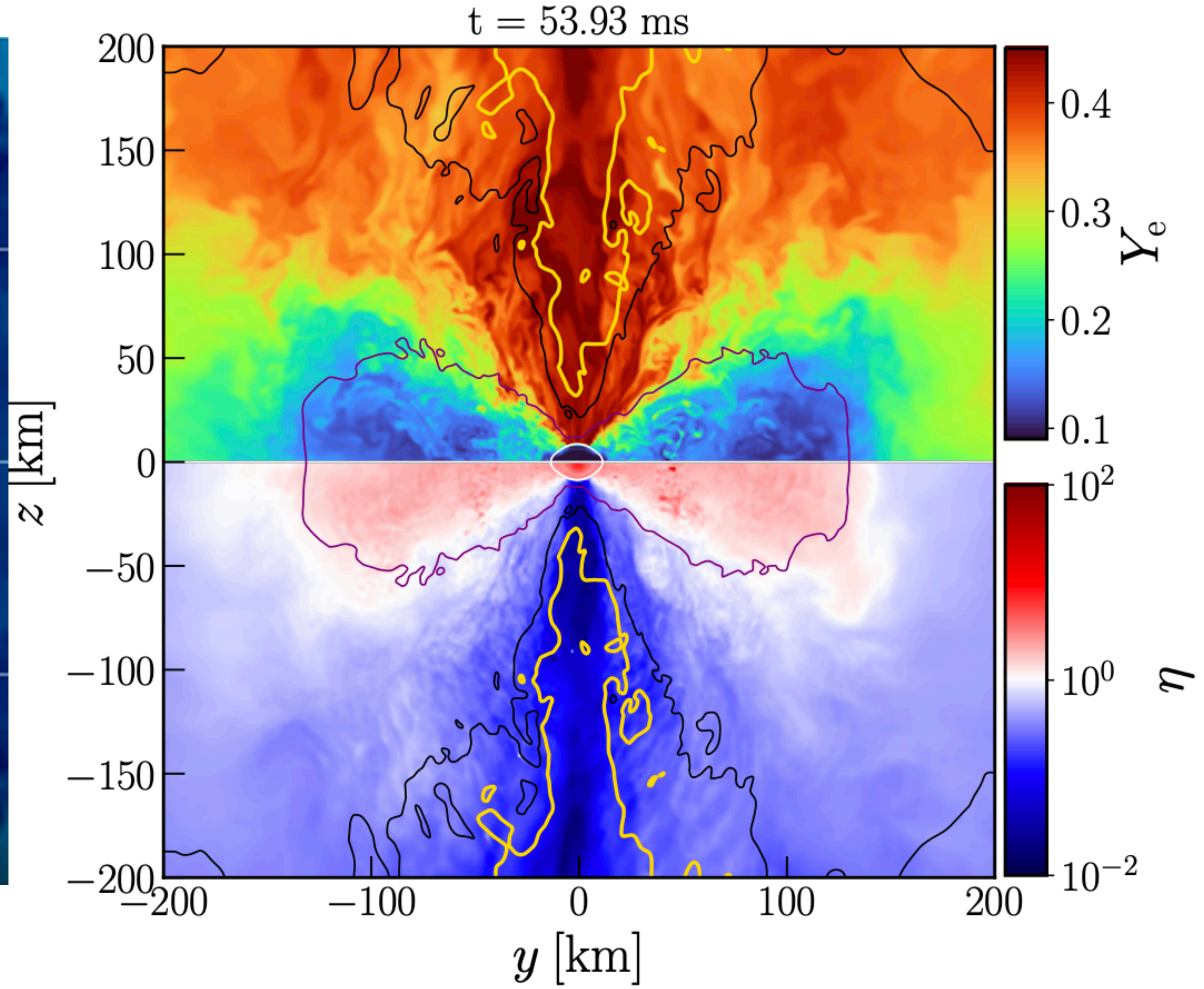
Curtis+2023



Kiuchi+2023



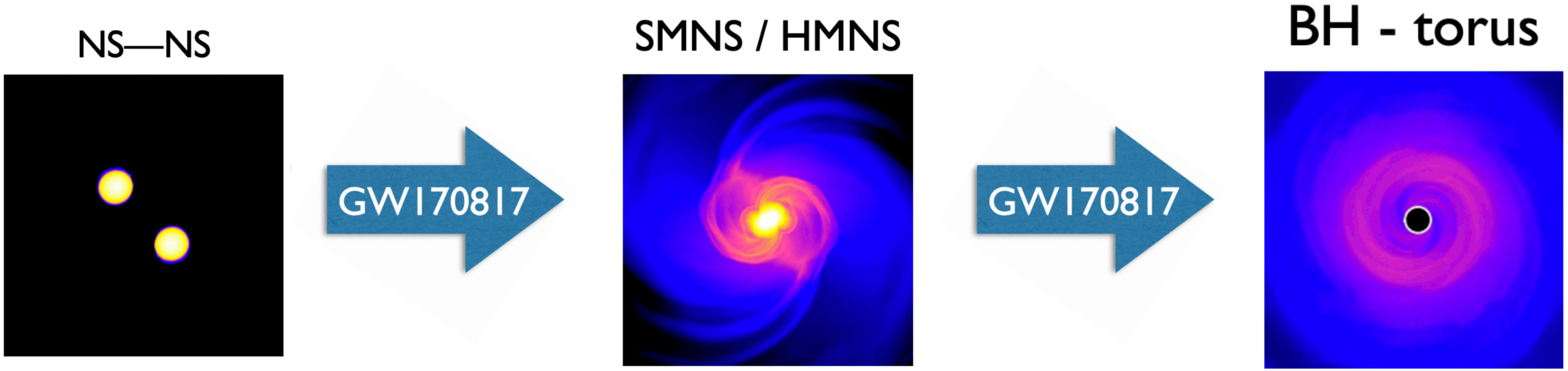
Combi+2023



Polar outflows

Disk outflows

GW170817



Pre-cursor magnetized flares from MNS remnant (and disk?) drive the blue kilonova

Disk outflows drive the red kilonova

SGRB jet launched via Blandford-Znajek mechanism

most-likely scenario of GW170817

WhiskyMHD

- ✗ Staggered vector potential evolution
- ✗ Handling magnetised BH-disk environments
- ✗ Support for composition-dependent finite temperature tabulated EOS
- ✗ Implementation for evolution of electron fraction
- ✗ Neutrino transport
- ✗ Higher order numerical schemes

BNS simulations with Spritz

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

The Spritz code: GRMHD with Neutrino Leakage

Cipolletta+2020, Cipolletta+2021

Version 1.0:

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- Works within Einstein Toolkit framework
- Staggered vector potential evolution
- Support for ideal gas and polytropic EOS

Version 2.0:

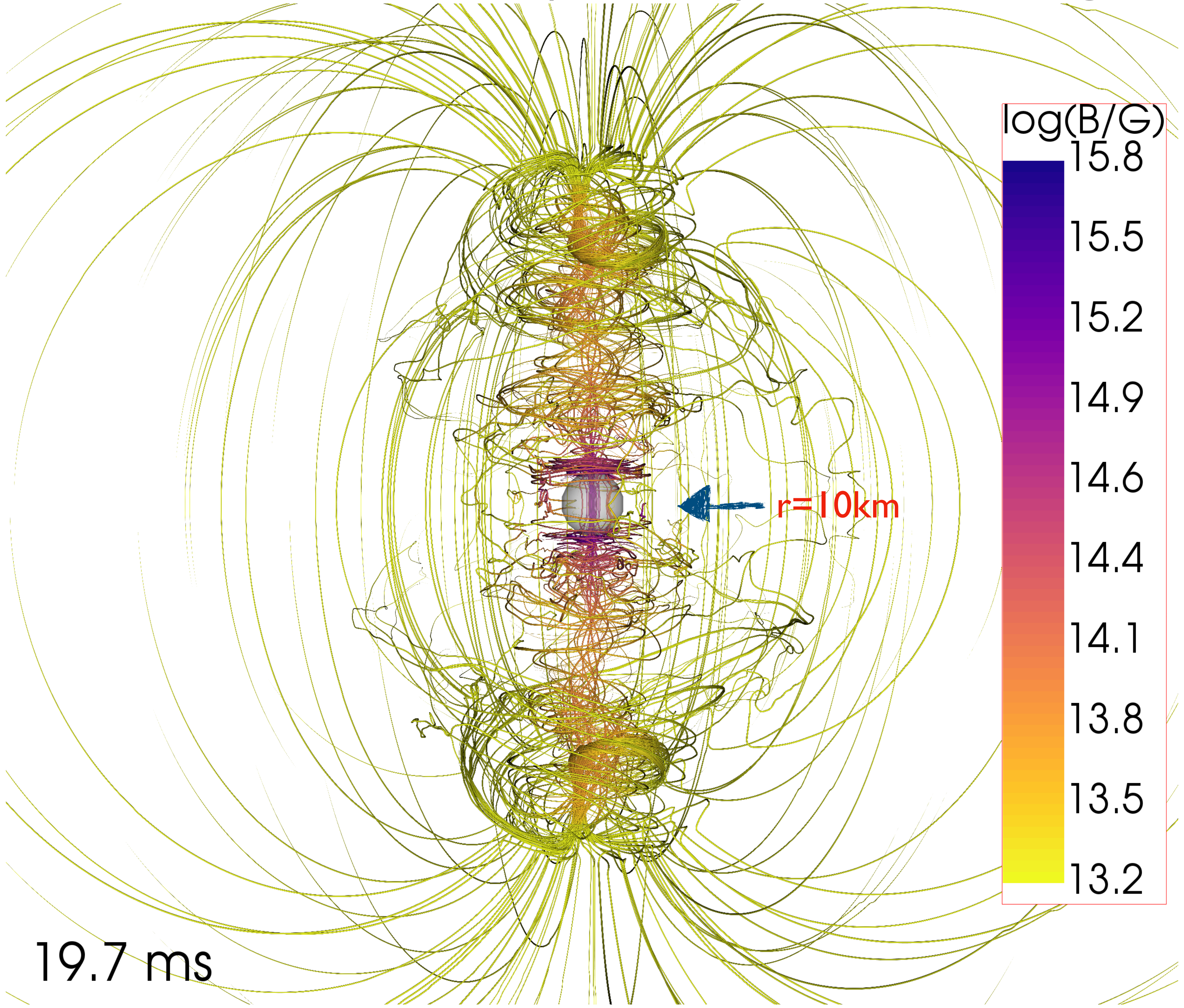
- Support for microphysical EOS
- ZelmaniLeak neutrino leakage scheme [Ott+2012]
- Evolution equation of electron fraction
- Higher order schemes: WENOZ with HLLE4 and HLLE6
- Publicly available on Zenodo: 10.5281/zenodo.4350072

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

Dipolar field painted on a rotating NS



RePrimAnd C2P scheme in Spritz

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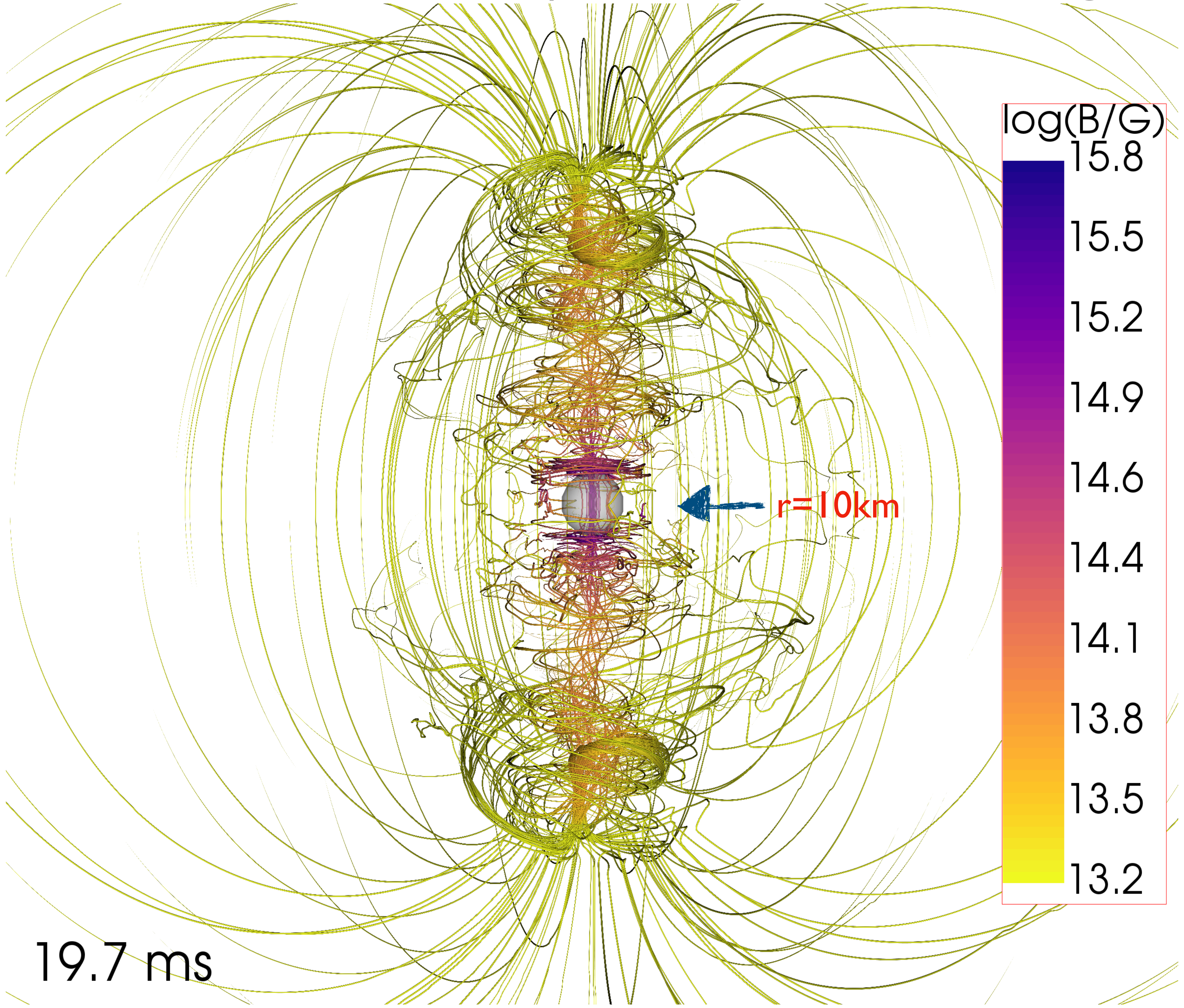
- Publicly available library with an EOS-framework on Zenodo: wokast/RePrimAnd

Implementation in Spritz: Kalinani+2022

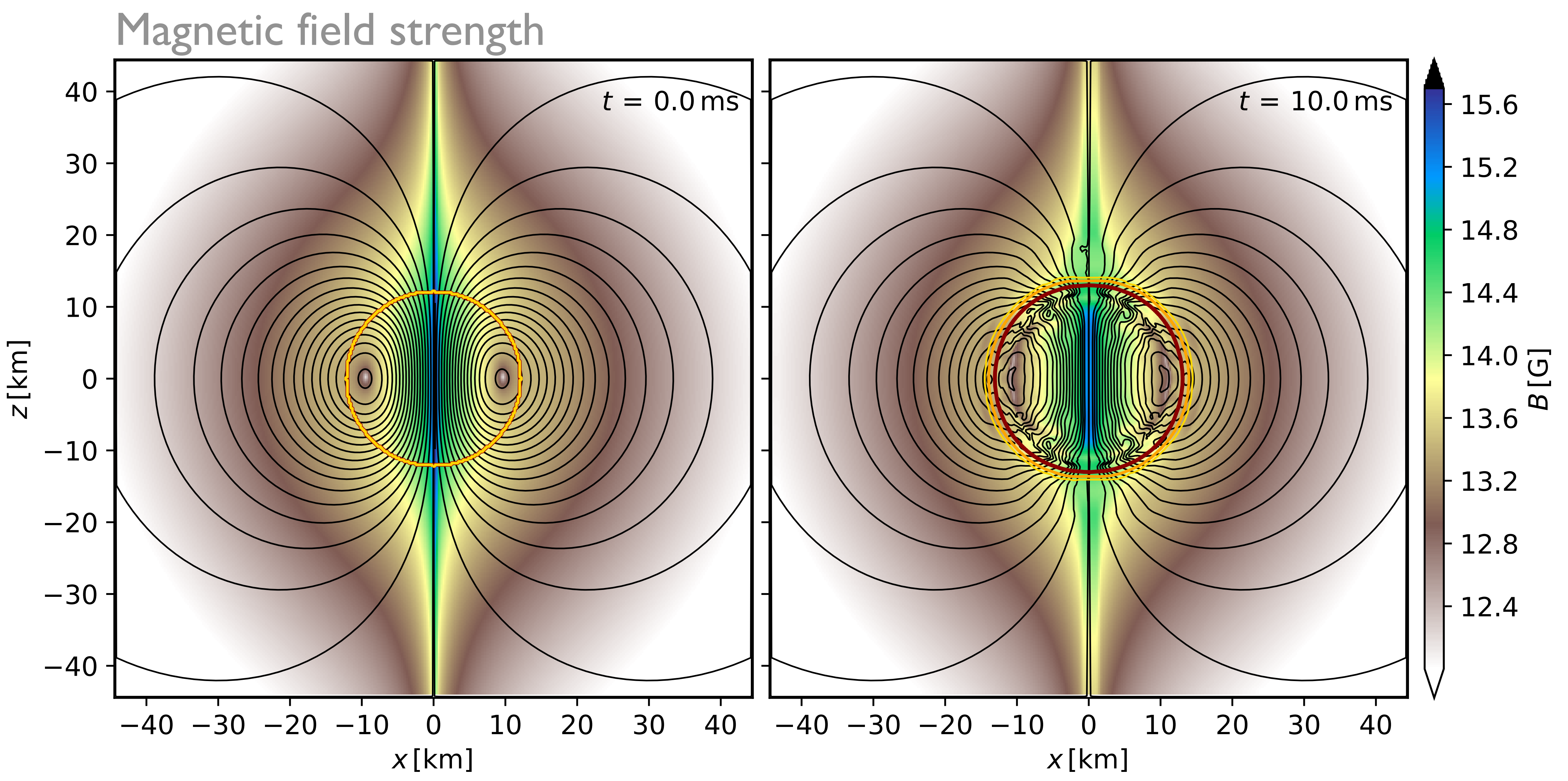
- Integrated RePrimAnd library into Einstein Toolkit
- Added option in Spritz to use C2P from RePrimAnd
- Defined and enforced validity range for EOS
- Different error policies within BHs
- Support for fully tabulated EOS underway

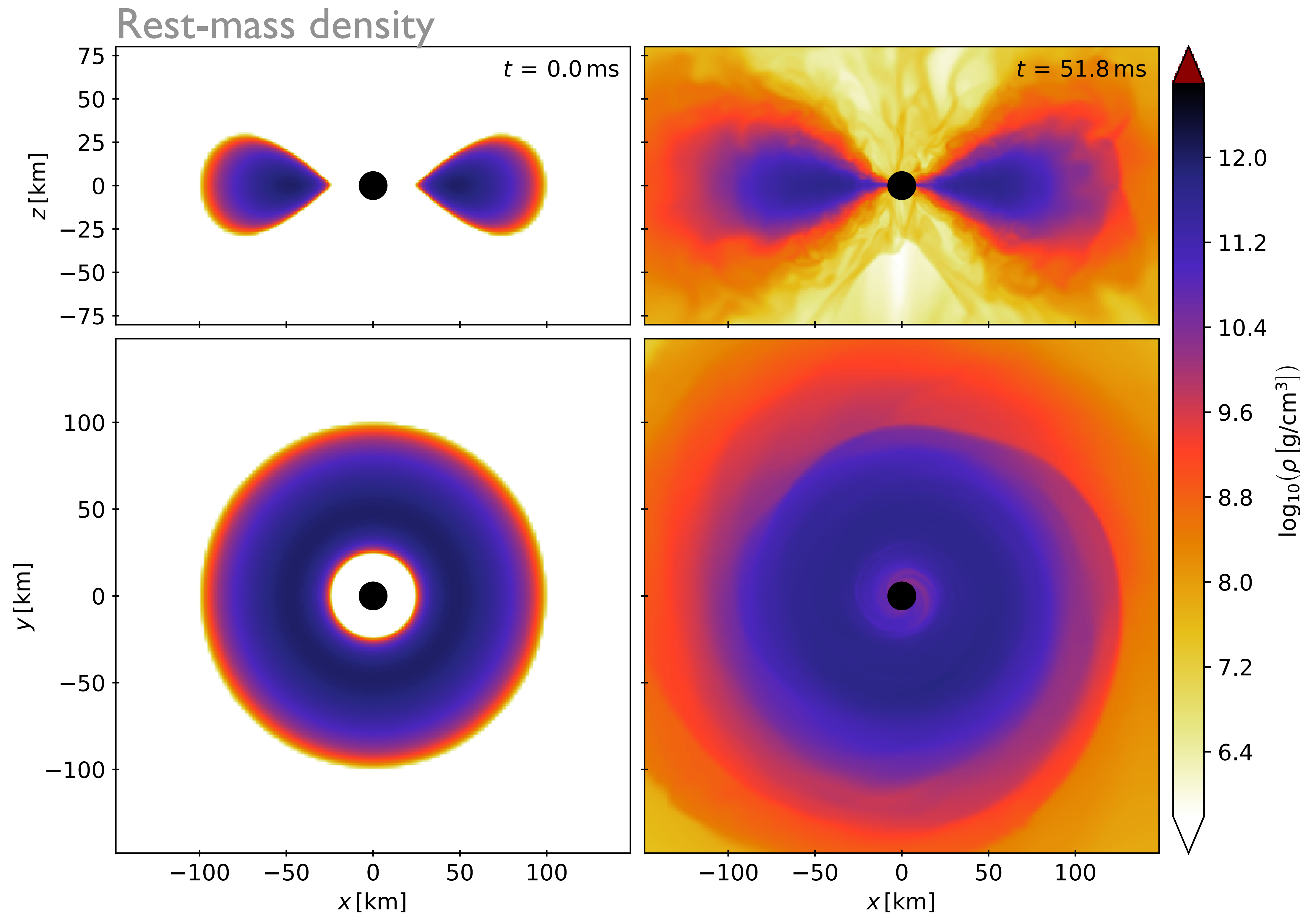
Dipolar field painted on a rotating NS



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

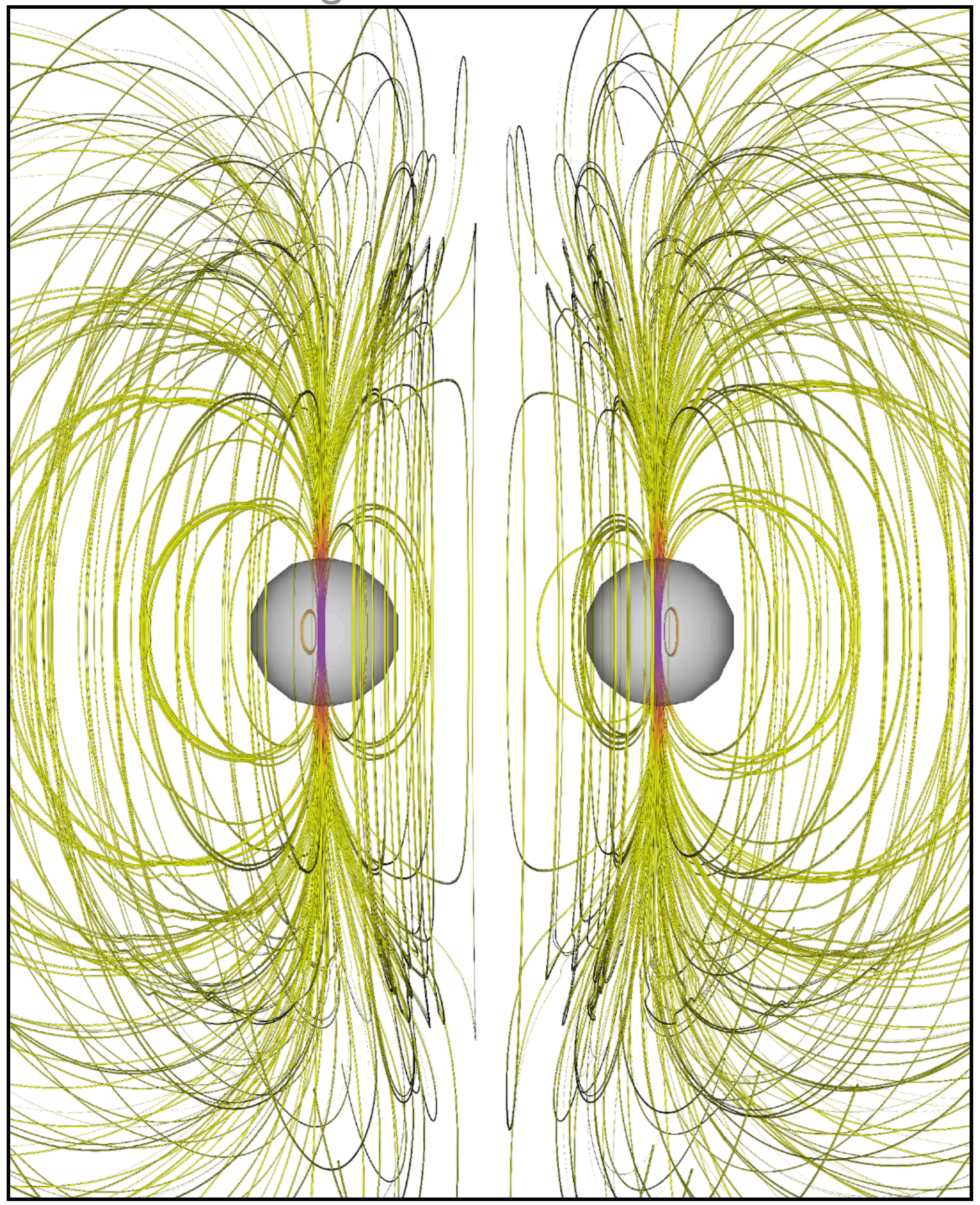




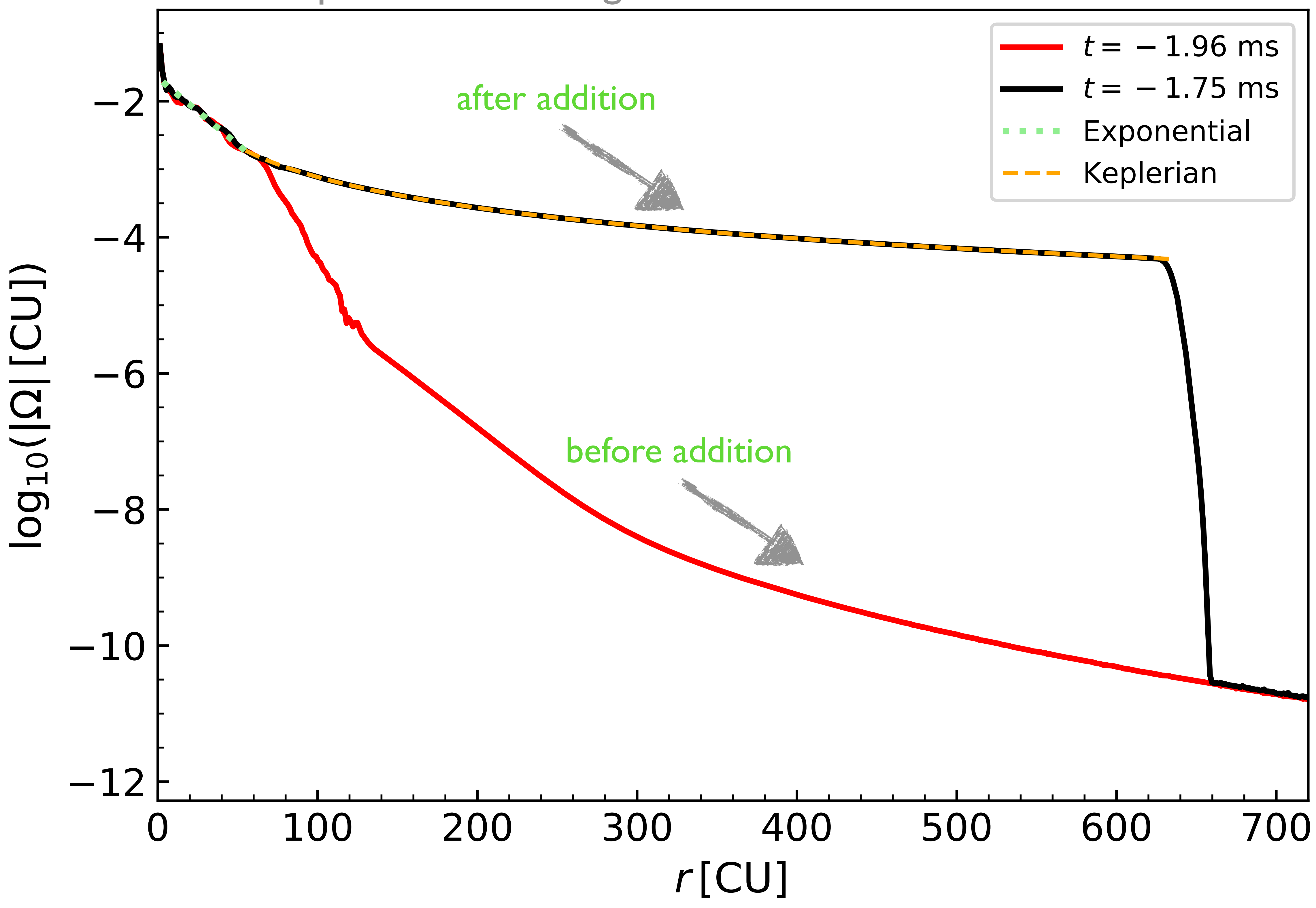
BNS with Spritz using RePrimAnd

Kalinani+ in prep

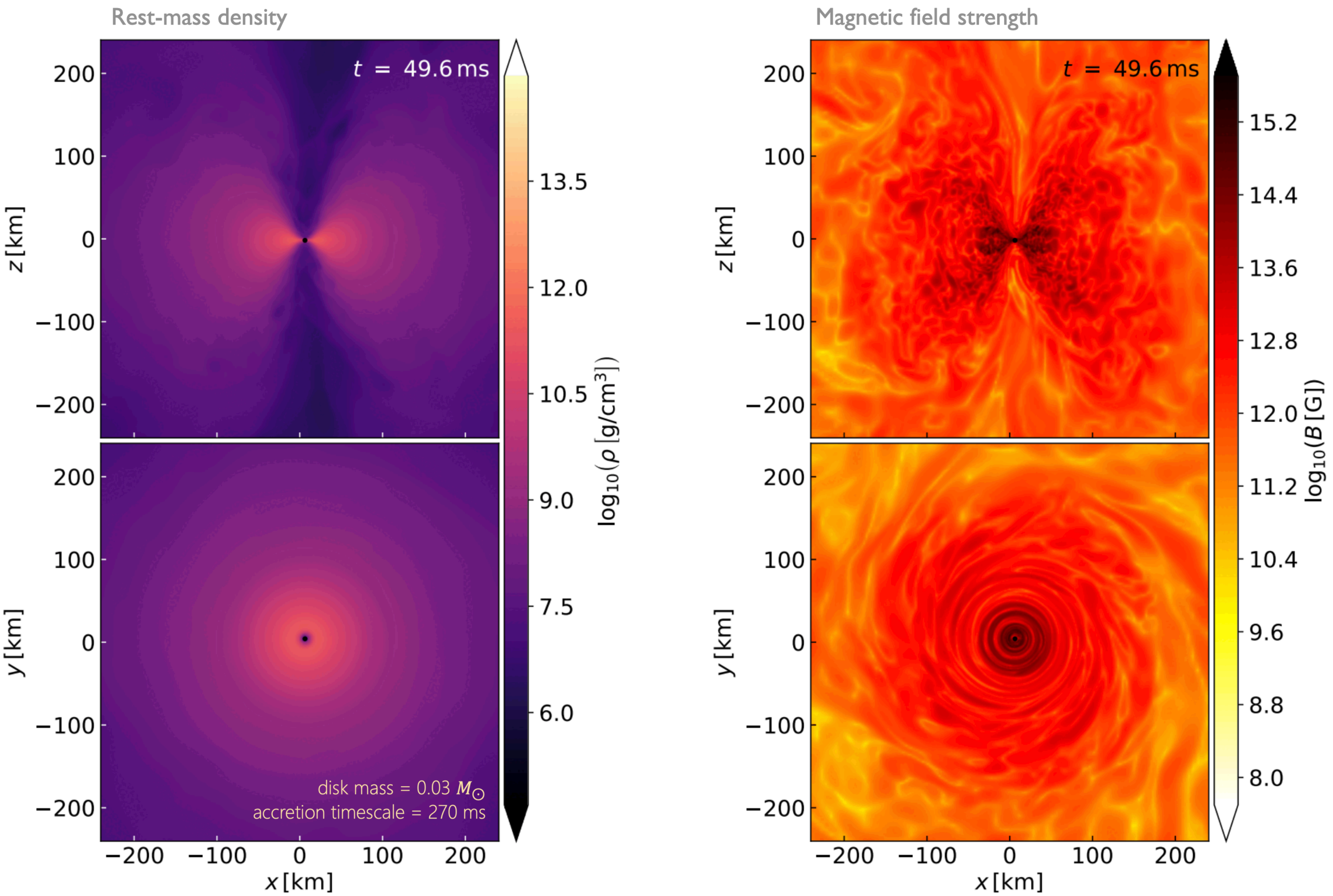
Initial field configuration



Rotation profile of added gas



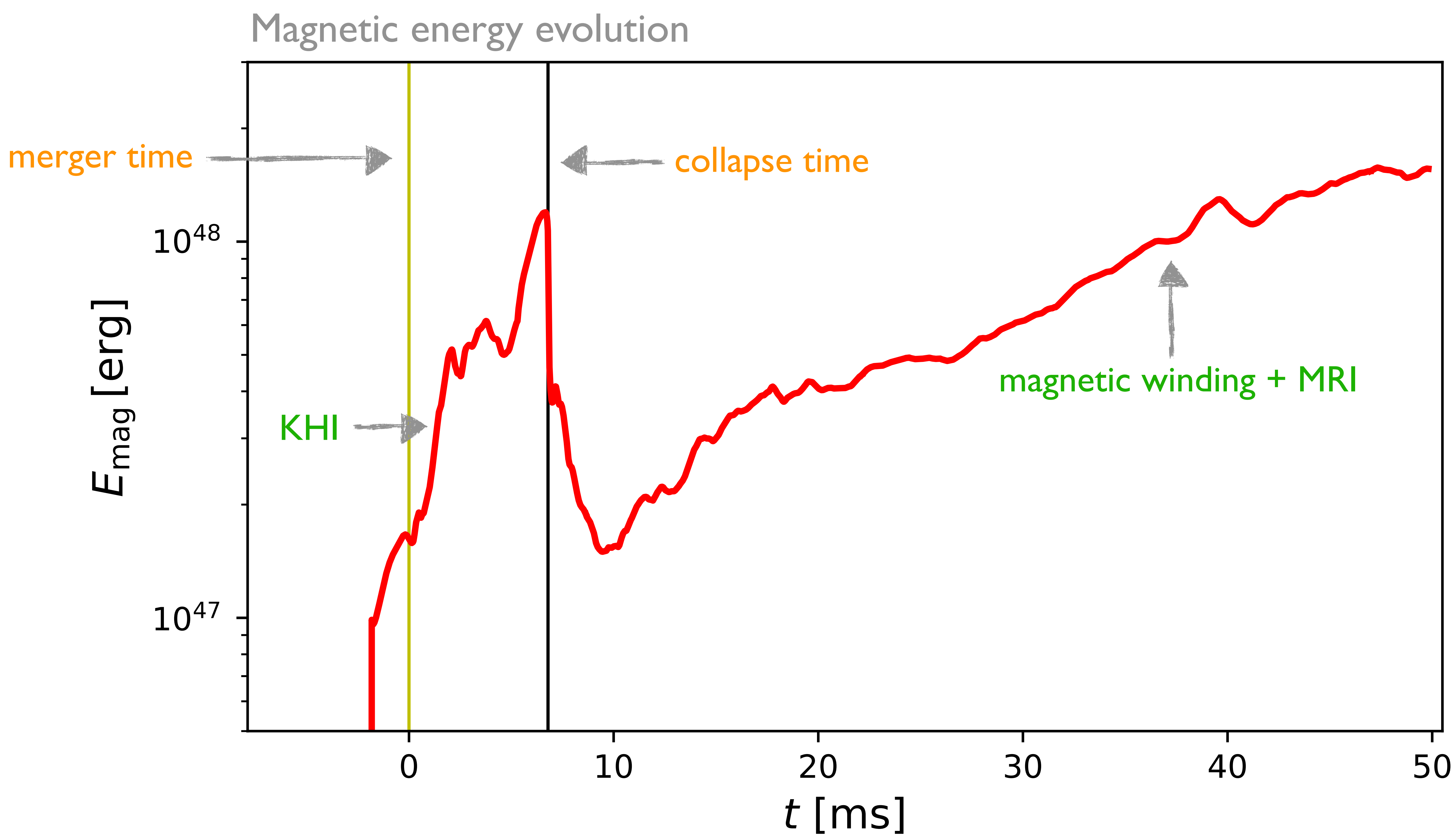
- Equal mass system ($1.5\,\mathrm{M}_\odot$ each) [Ruiz+2016]
- Ideal gas EOS for evolution
- Dipolar magnetic fields added after two orbits with $B_{\mathrm{max}} = 10^{16}$ G
- Addition of co-rotating material ($M < 0.001\,\mathrm{M}_\odot$)



Rest-mass density
Magnetic field strength
t = 49.6 ms
t = 49.6 ms
z [km]
y [km]
x [km]
x [km]
200
100
0
−100
−200
log10(ρ [g/cm^3])
13.5
12.0
10.5
9.0
7.5
6.0
disk mass = 0.03 M⊙
accretion timescale = 270 ms
log10(B [G])
15.2
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0

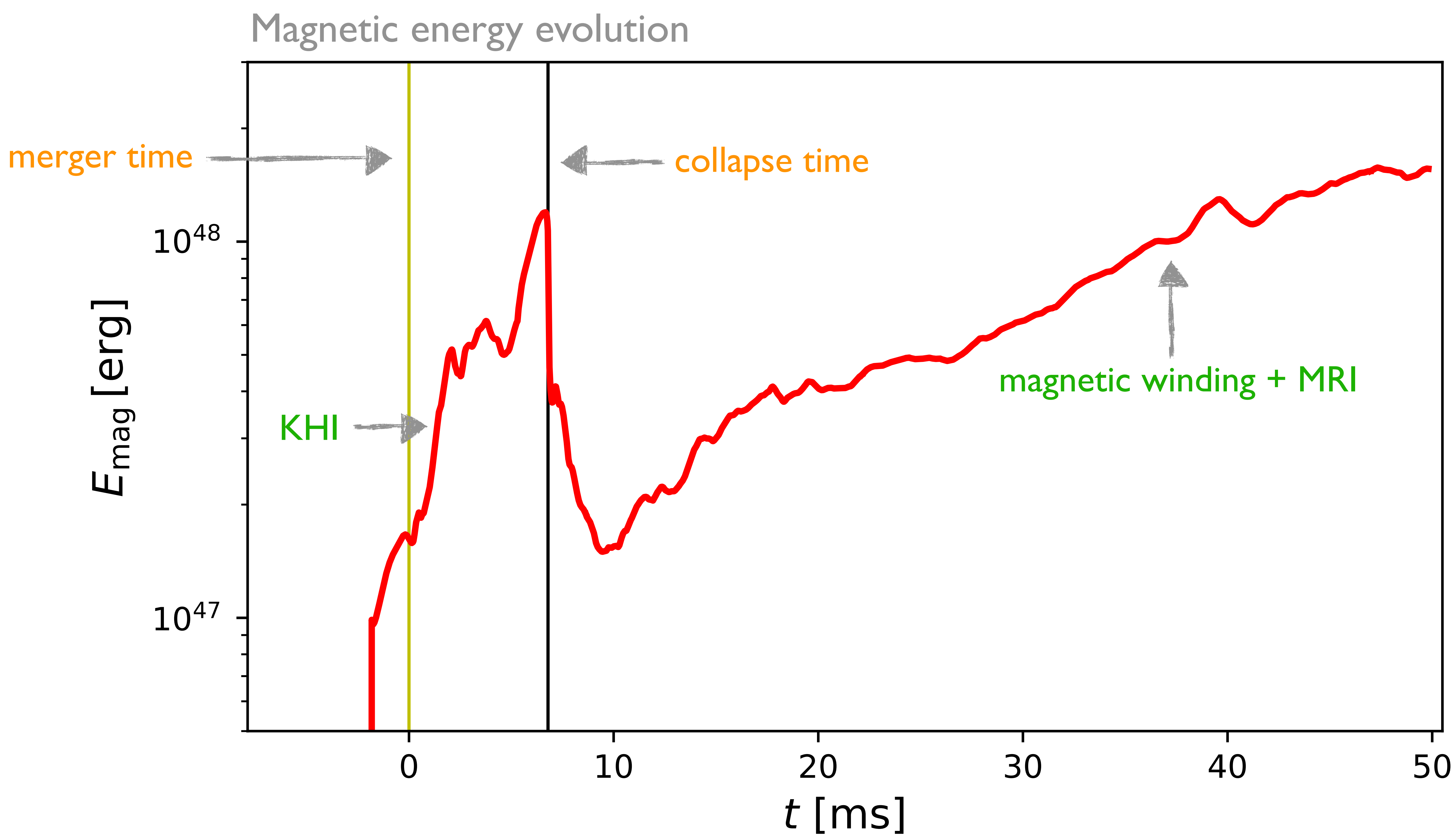
Magnetic Field Geometry

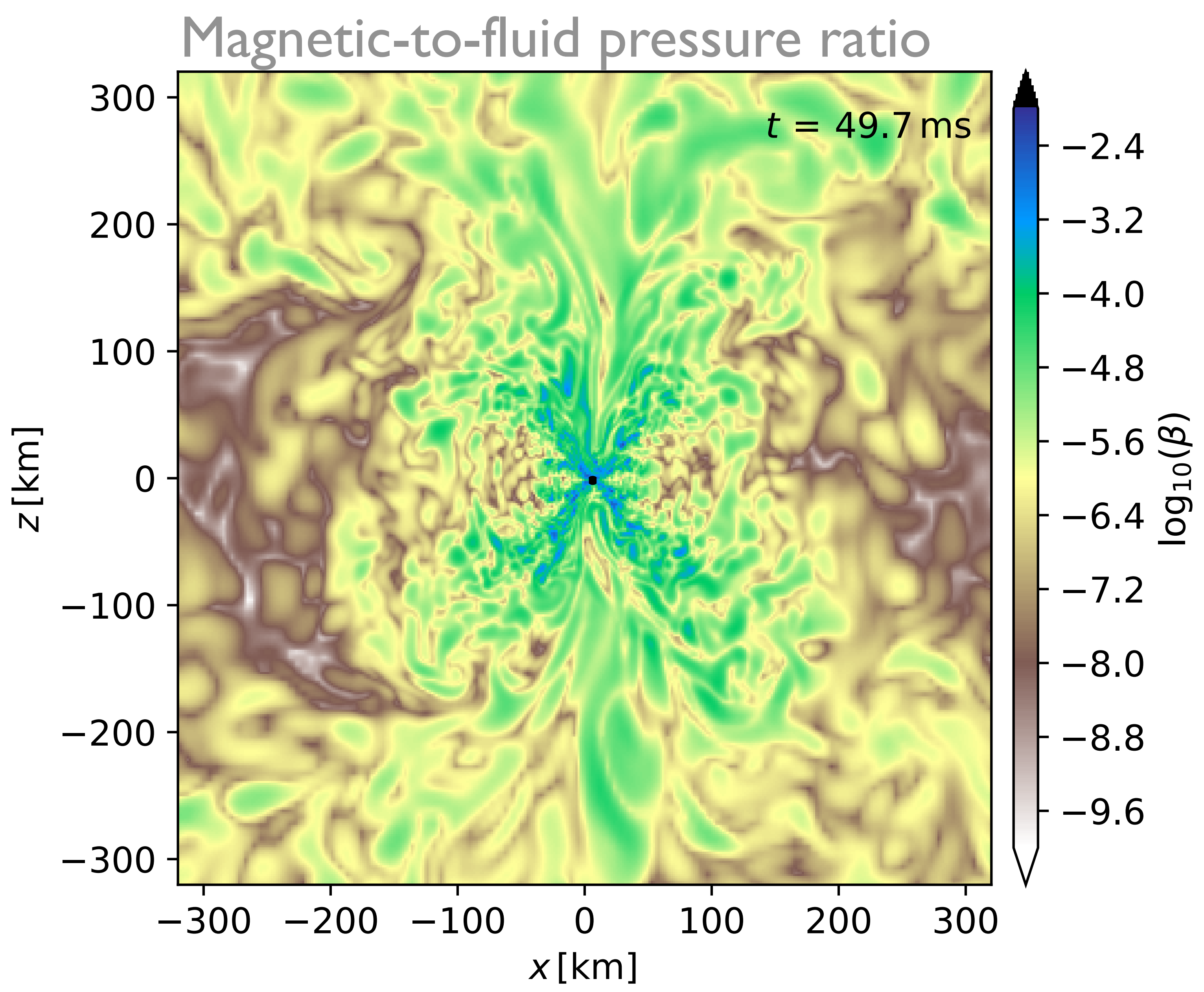
Magnetic Field Evolution

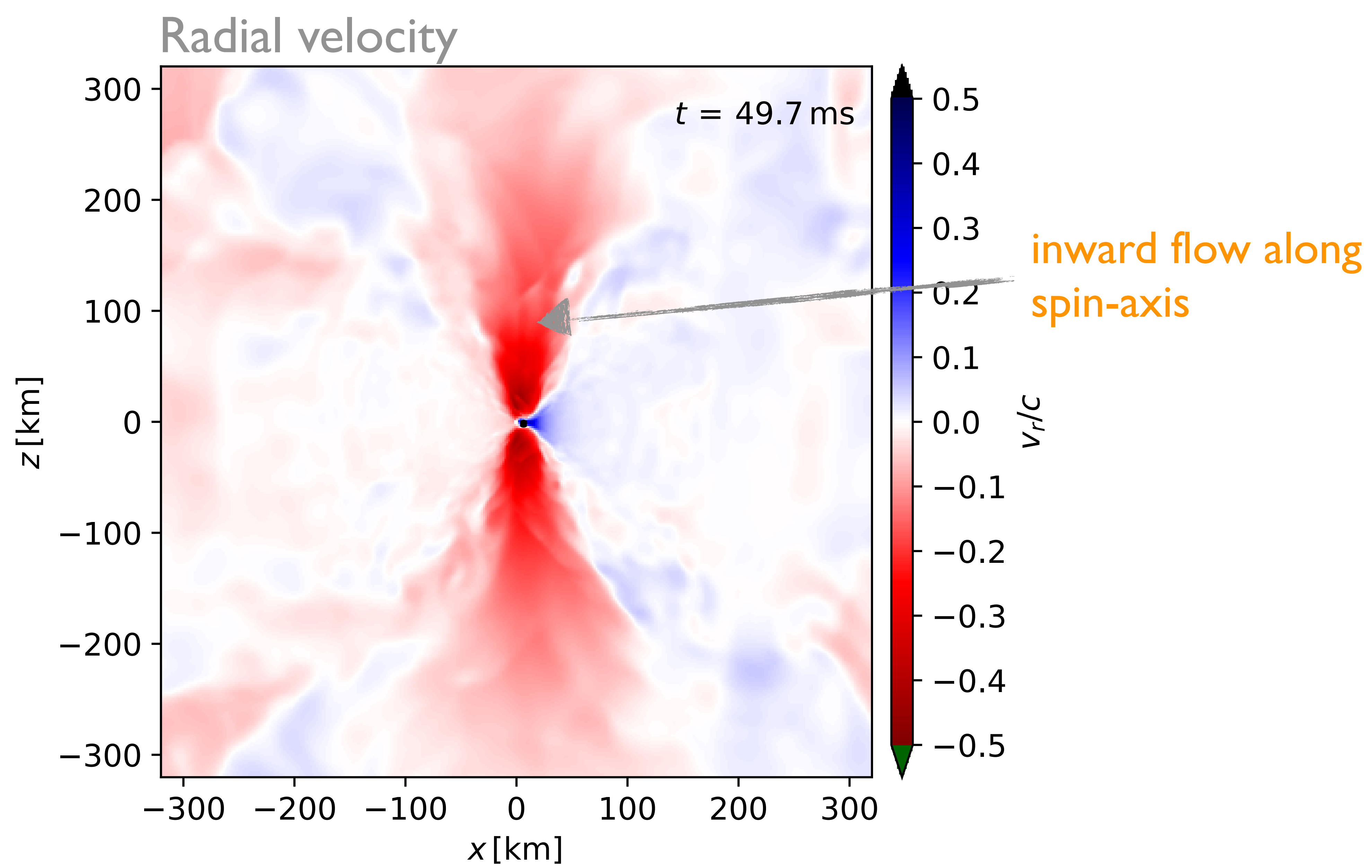


- Magnetic energy still growing; not enough to power a relativistic jet *yet*
- Funnel along spin-axis fluid pressure dominated

Magnetic Field Evolution



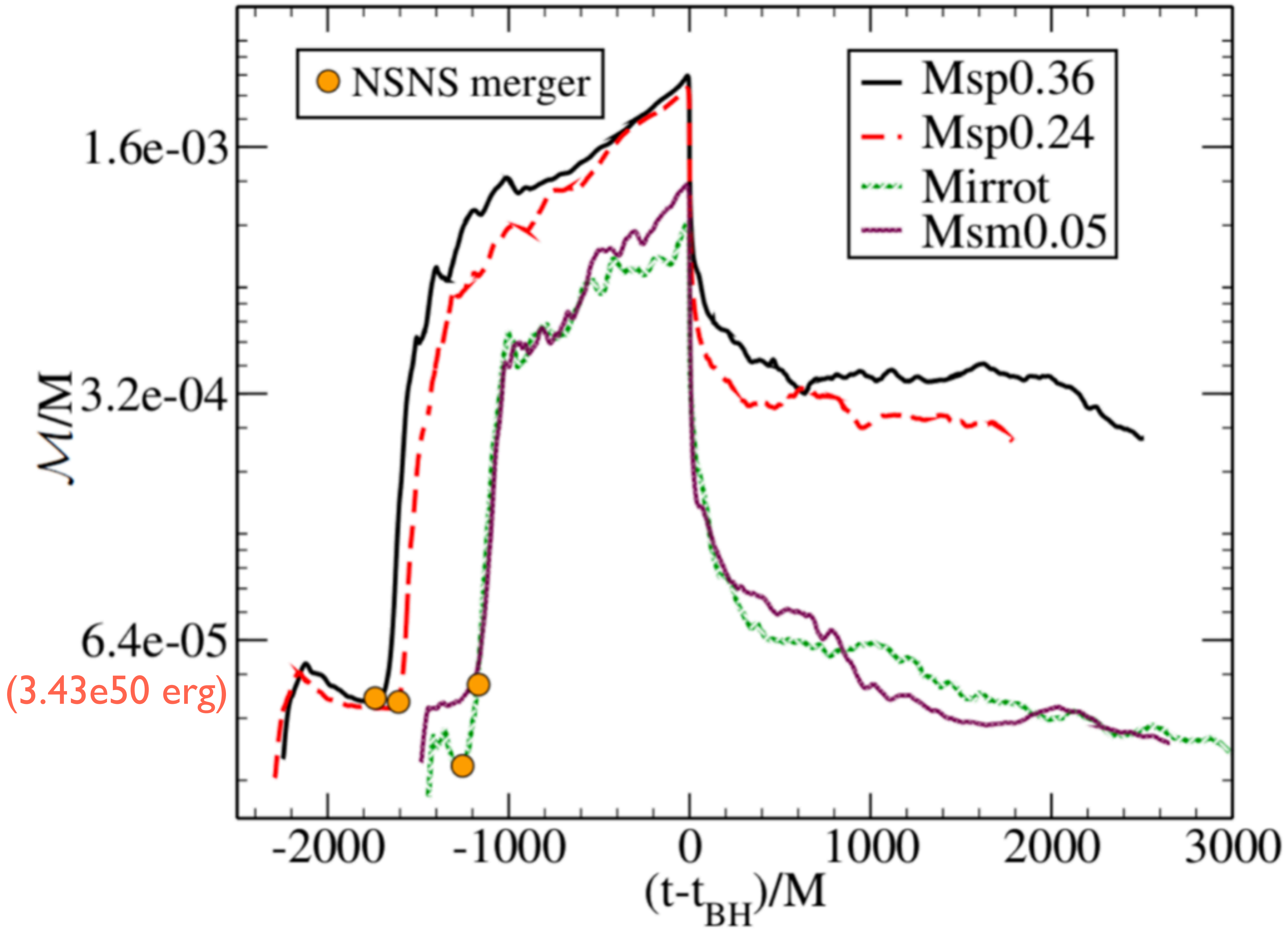




- Magnetic energy still growing; not enough to power a relativistic jet *yet*
- Funnel along spin-axis fluid pressure dominated

	Ruiz+2016	This work
Initial magnetic energy	~ 1e50 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

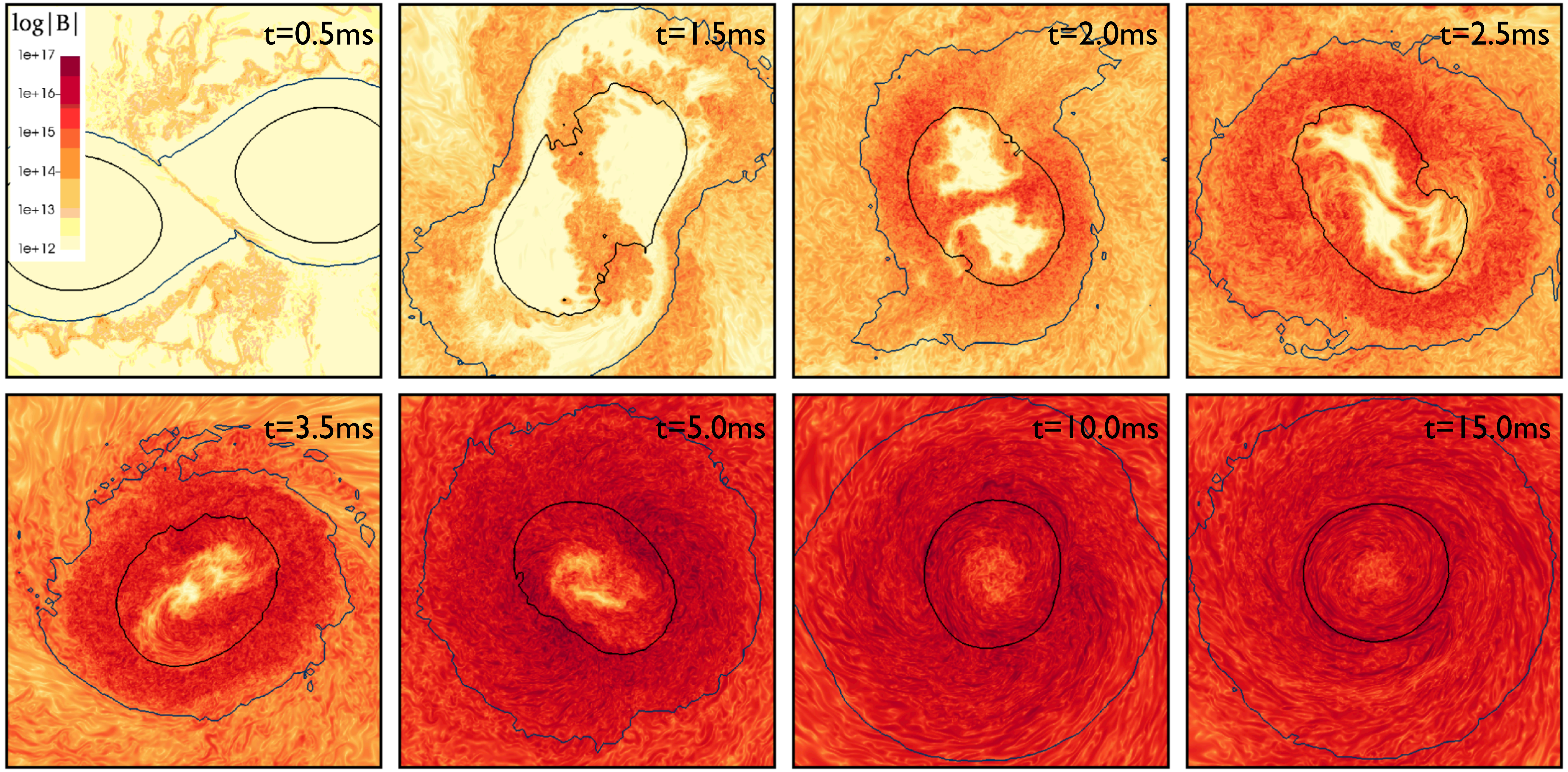
Magnetic energy evolution



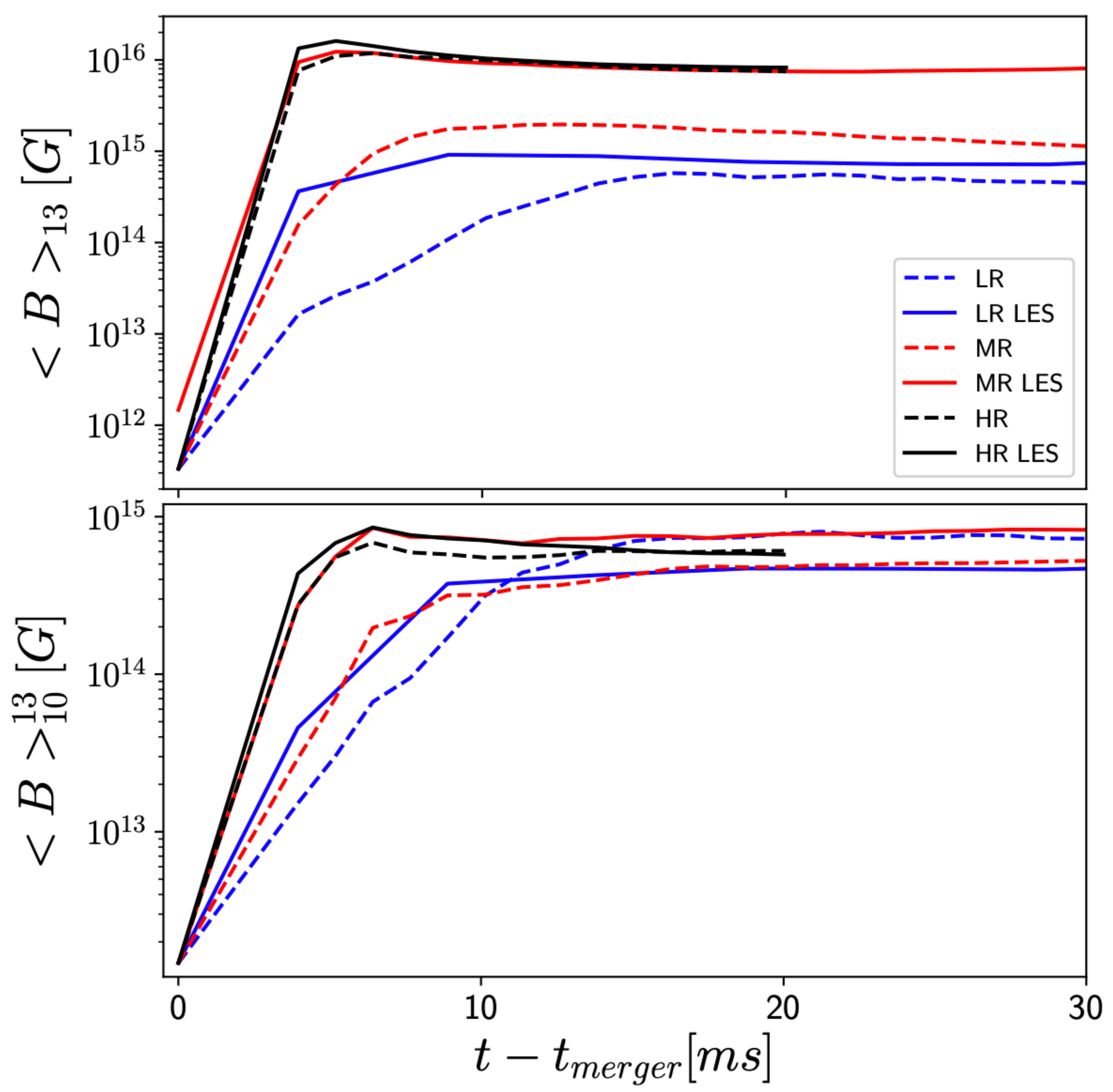
Ruiz+2019

Question: Dependence of jet formation on initial magnetic energy?

Large-Eddy Simulations



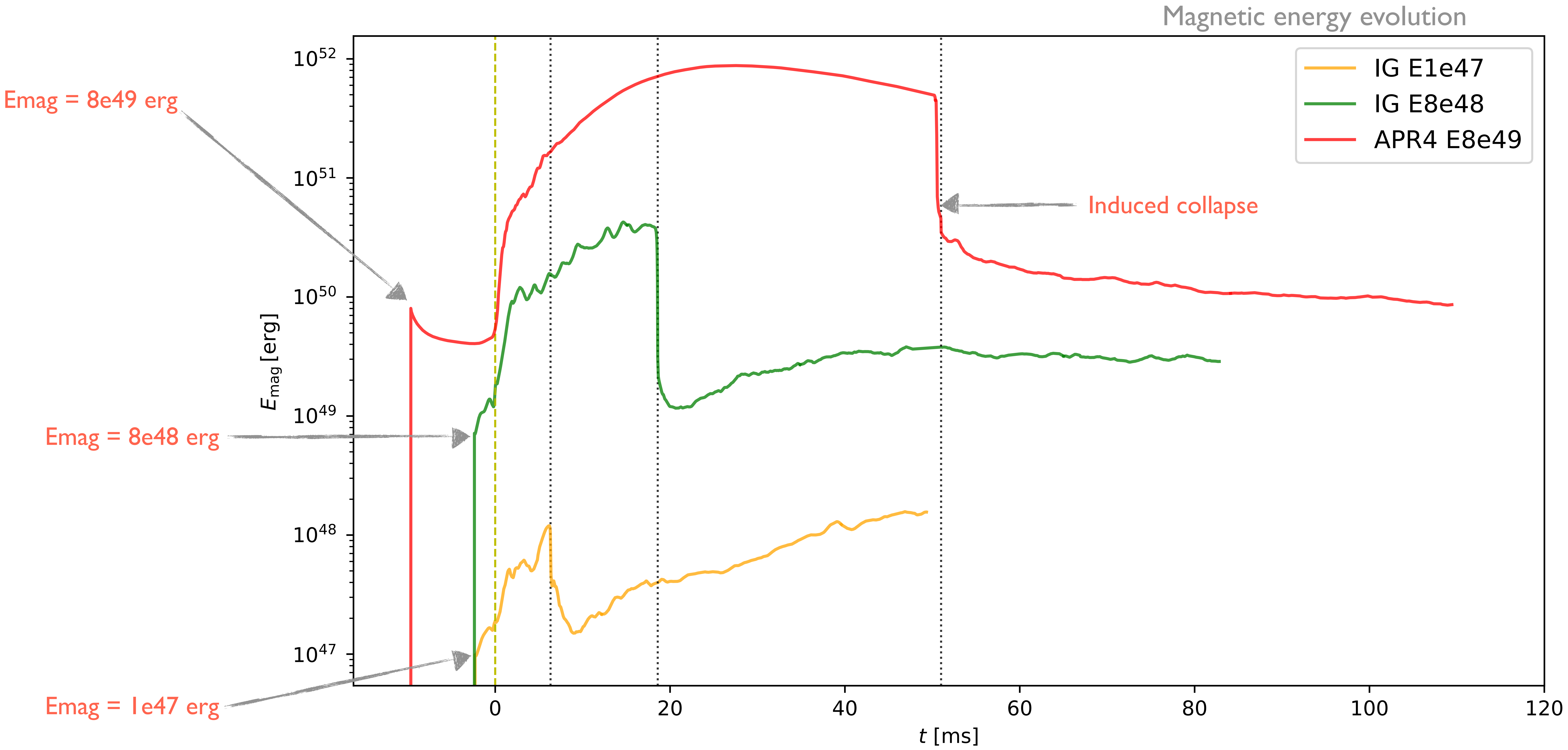
Palenzuela+2021



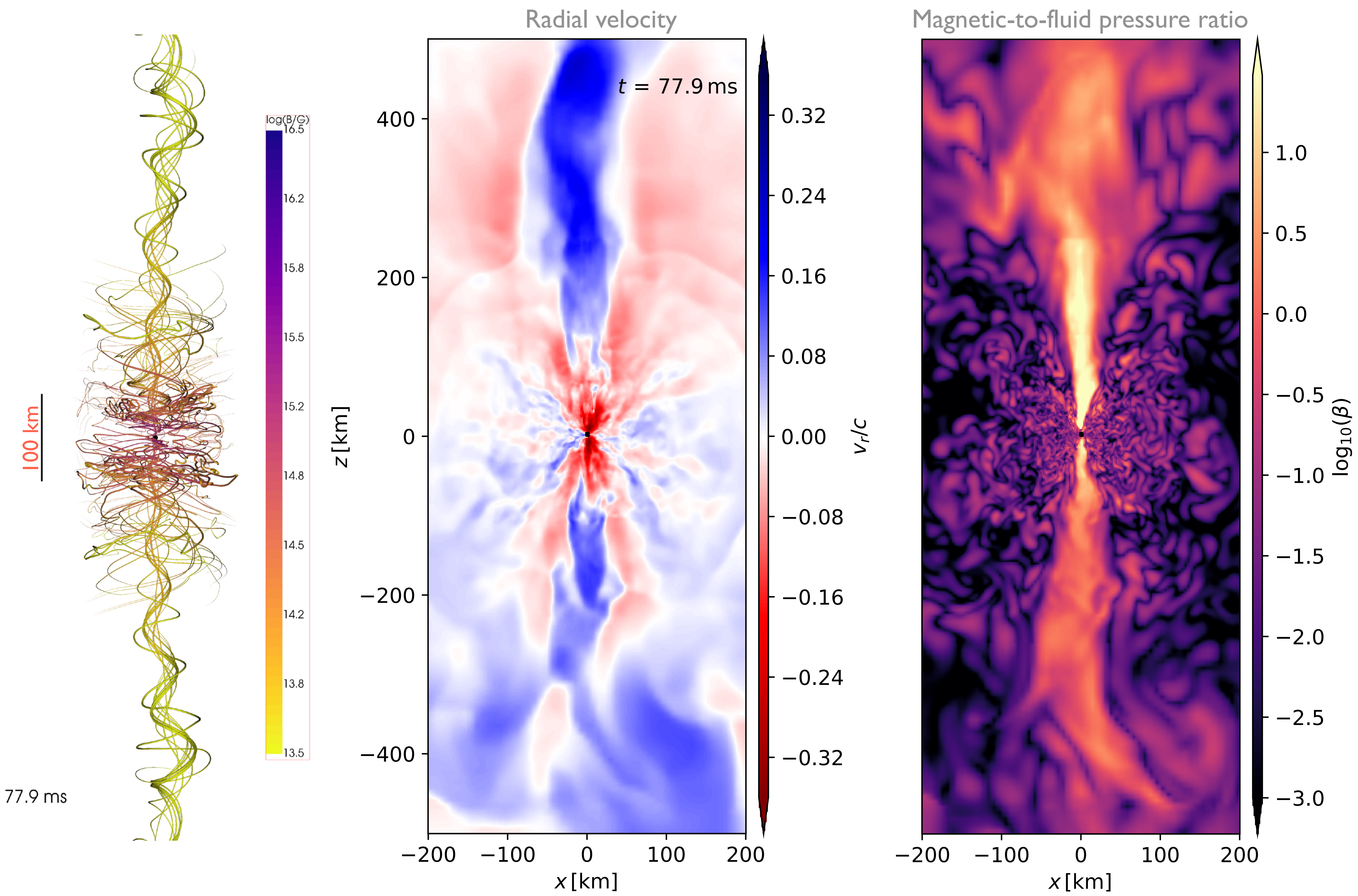
- Convergent results for MR-LES (dx=60m) case in comparison with HR (dx=30m) one

Promising alternative to simulations with high initial magnetic fields

Latest Simulations



Ideal Gas E8e48

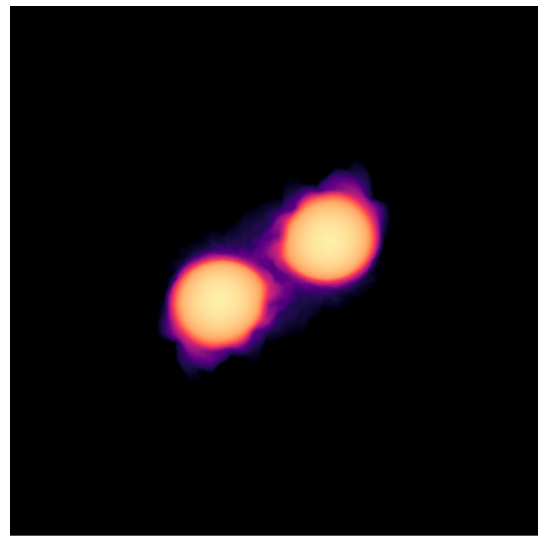


APR4 E8e49

500 km
105.3 ms
log(B/G)
16.5
16.2
15.8
15.5
15.2
14.8
14.5
14.2
13.8
13.5
Radial velocity
t = 105.30 ms
600
400
200
0
−200
−400
−600
z [km]
0
200
x [km]
0.32
0.24
0.16
0.08
0.00
−0.08
−0.16
−0.24
−0.32
v_r
Magnetic-to-fluid pressure ratio
3.2
2.4
1.6
0.8
0.0
−0.8
−1.6
−2.4
−3.2
log10(β)
Magnetization
2.4
1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8
−2.4
log10(b²/(2ρ))

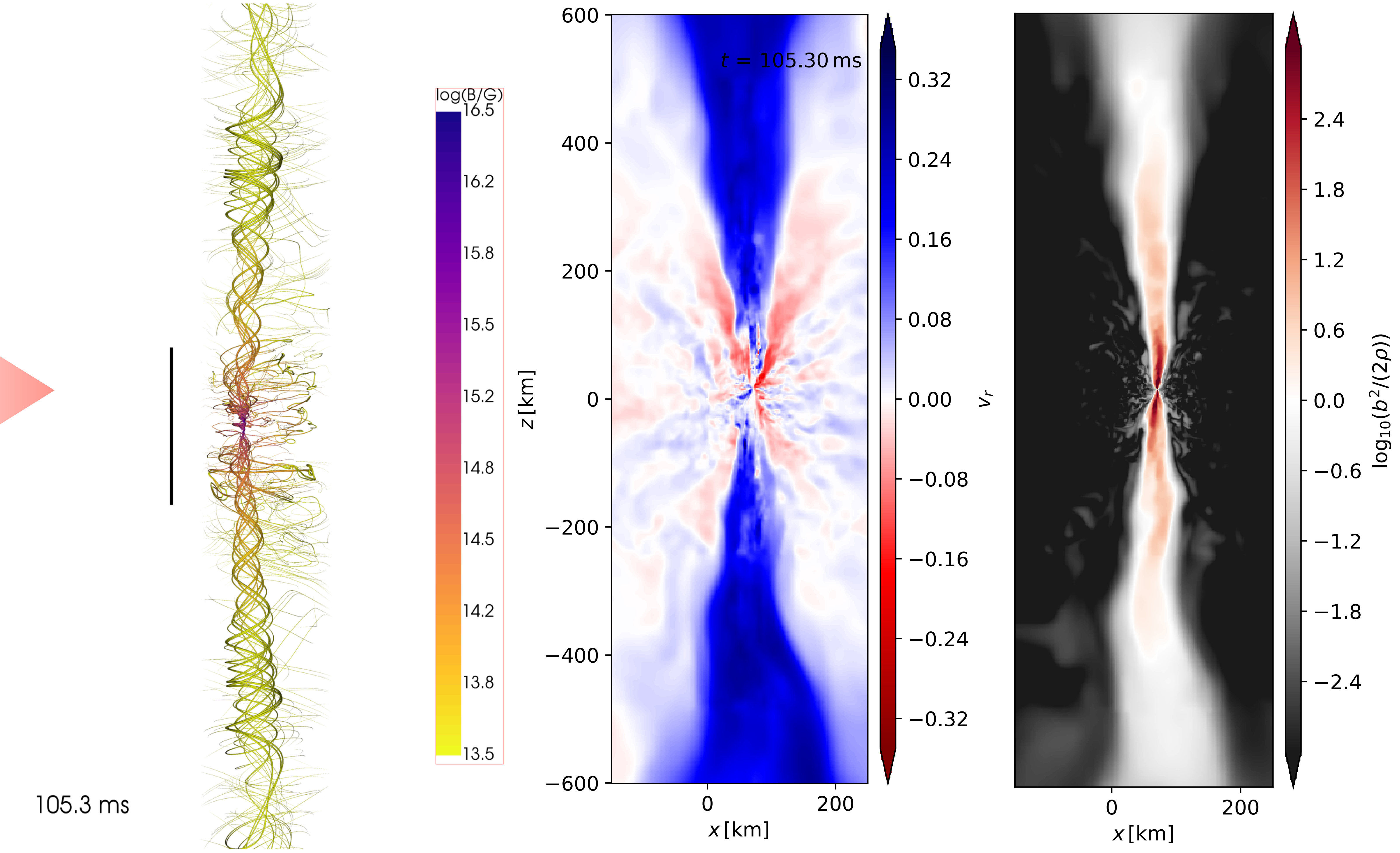
Towards end-to-end modelling

Merger



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

Jet production

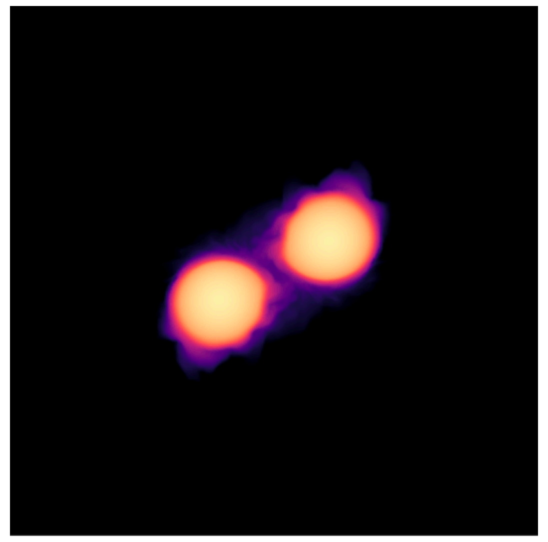


Time-scale ~ 100 ms
Length-scale ~ 1000 km

BNS merger simulations with Spritz

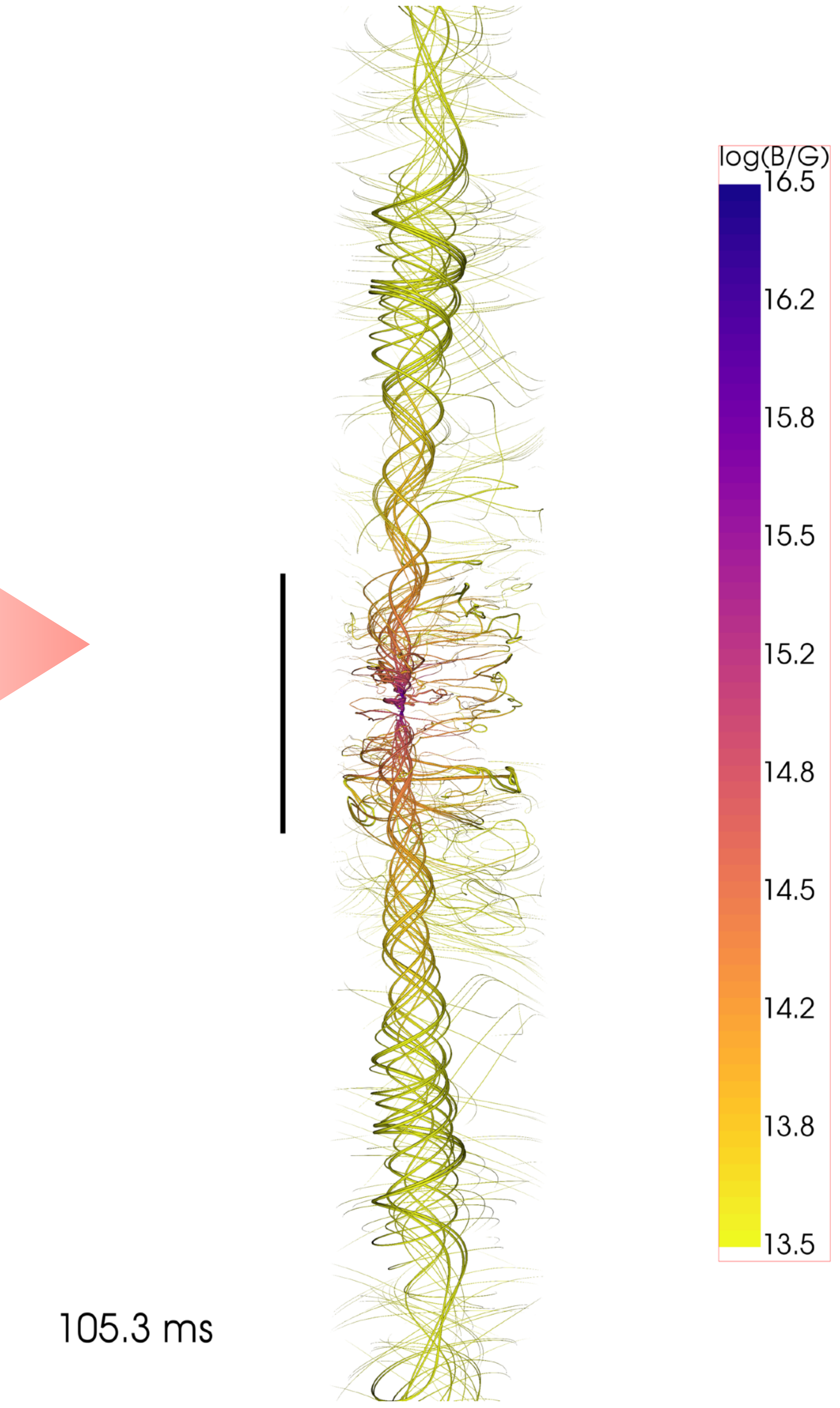
Towards end-to-end modelling

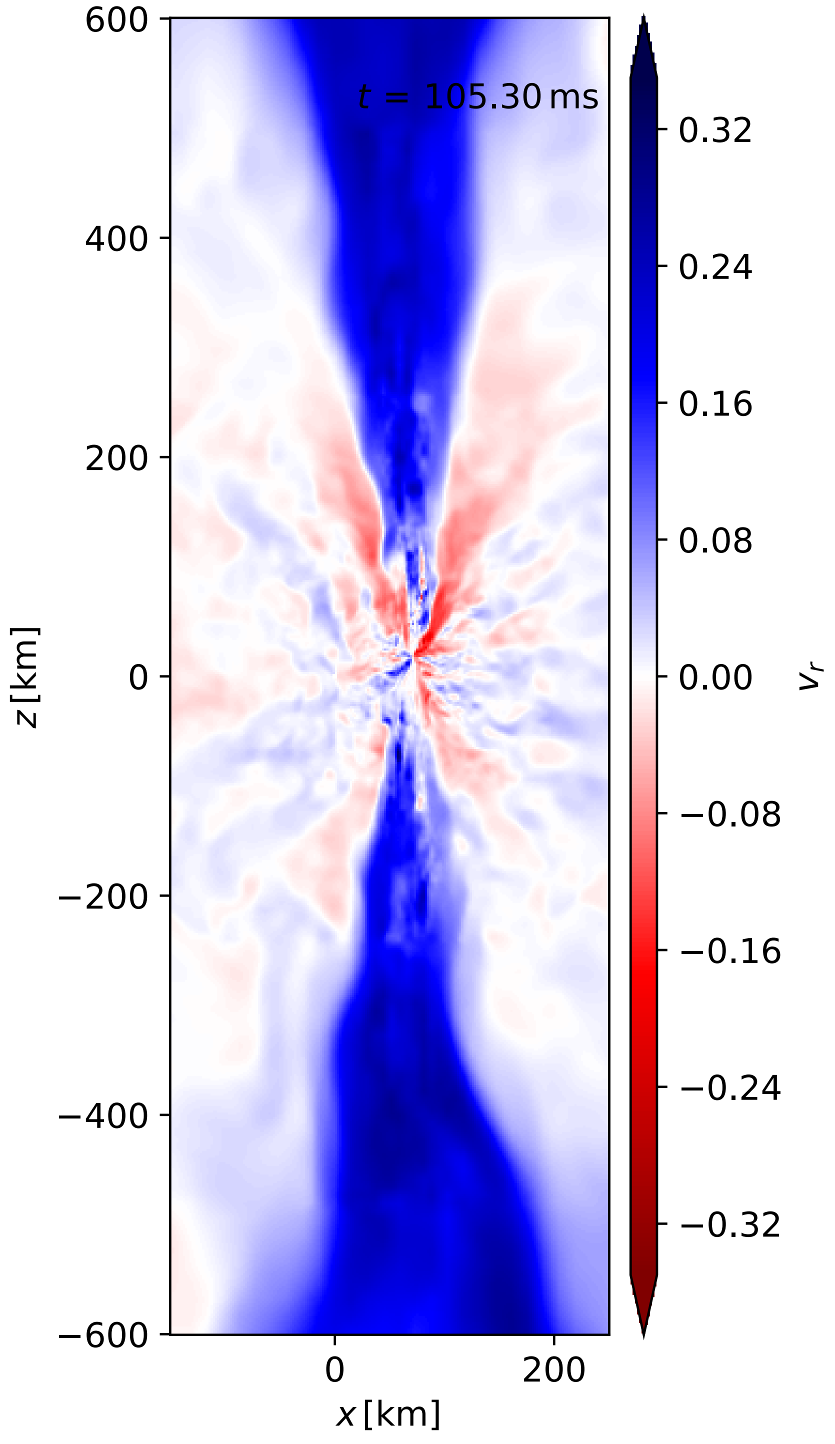
Merger

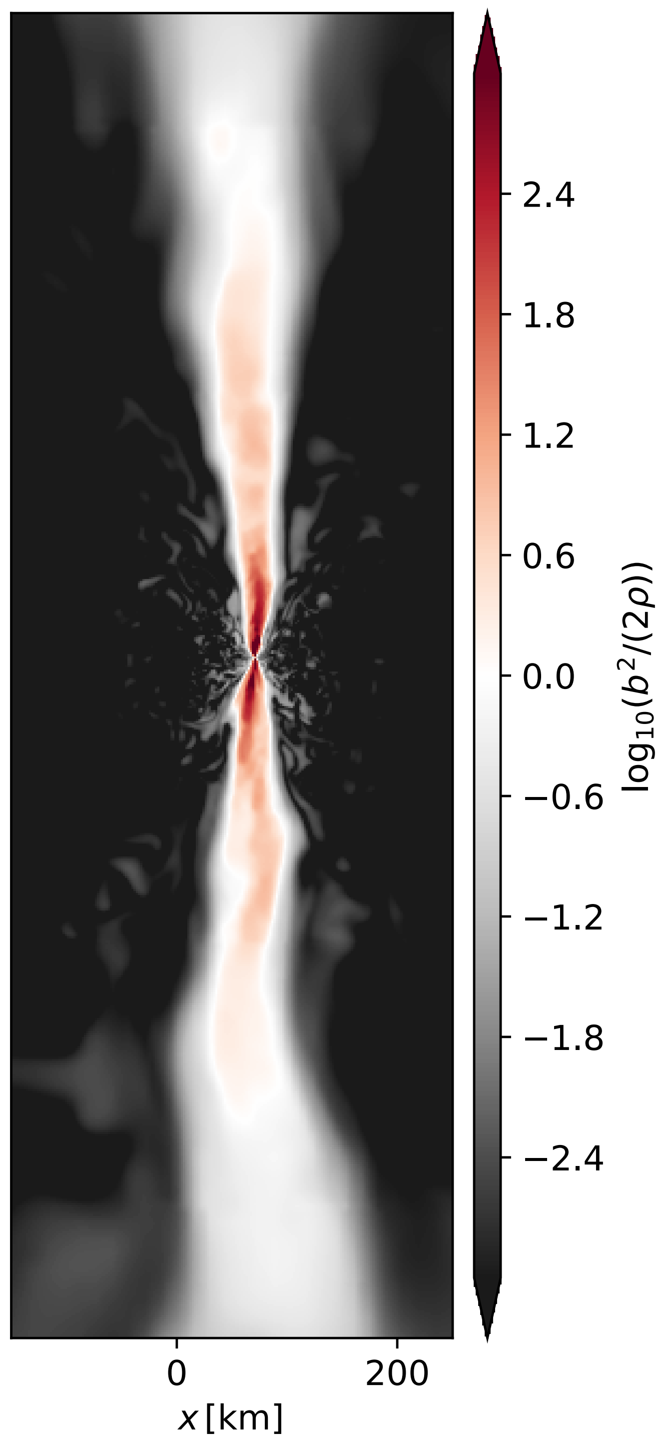


Time-scale ~ 10 ms
Length-scale ~ 100 km

Jet production

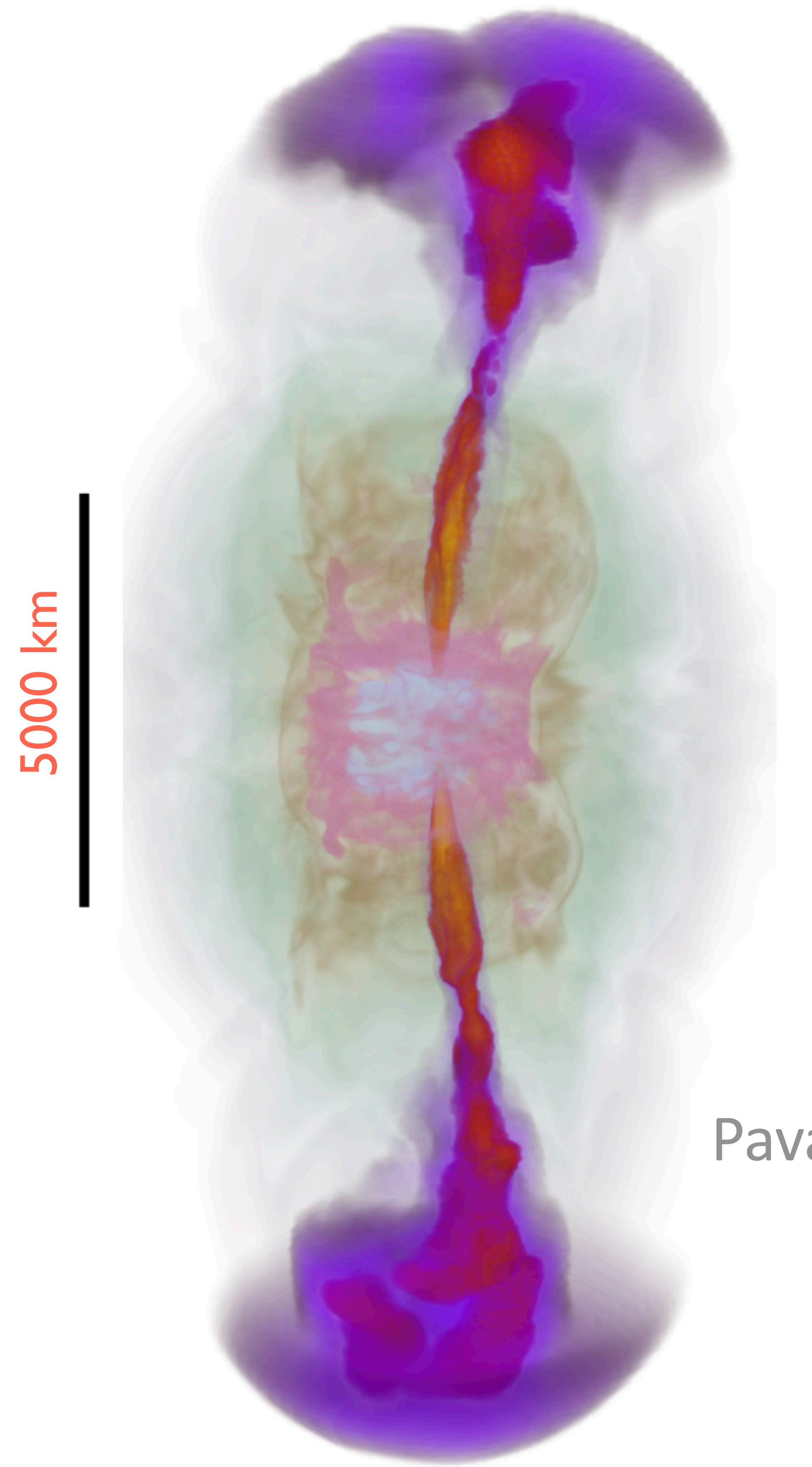






Time-scale ~ 100 ms
Length-scale ~ 1000 km

Jet propagation



Pavan+2023

Time-scale ~ 1-10s
Length-scale ~ 10000 km

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 disk 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:

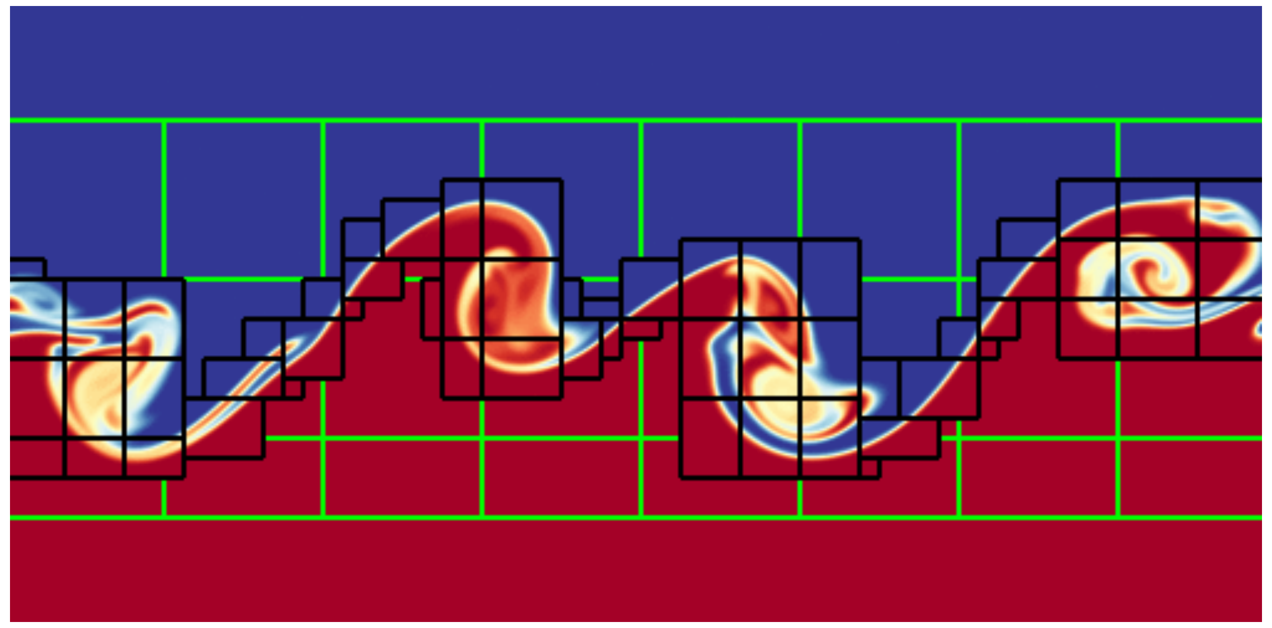
- Temperature and composition dependent EOSs
- Neutrino radiation
- NS spins

AsterX: a new open-source GPU-accelerated GRMHD code for dynamical spacetimes

Jay V. Kalinani
Center for Computational Relativity and Gravitation, RIT

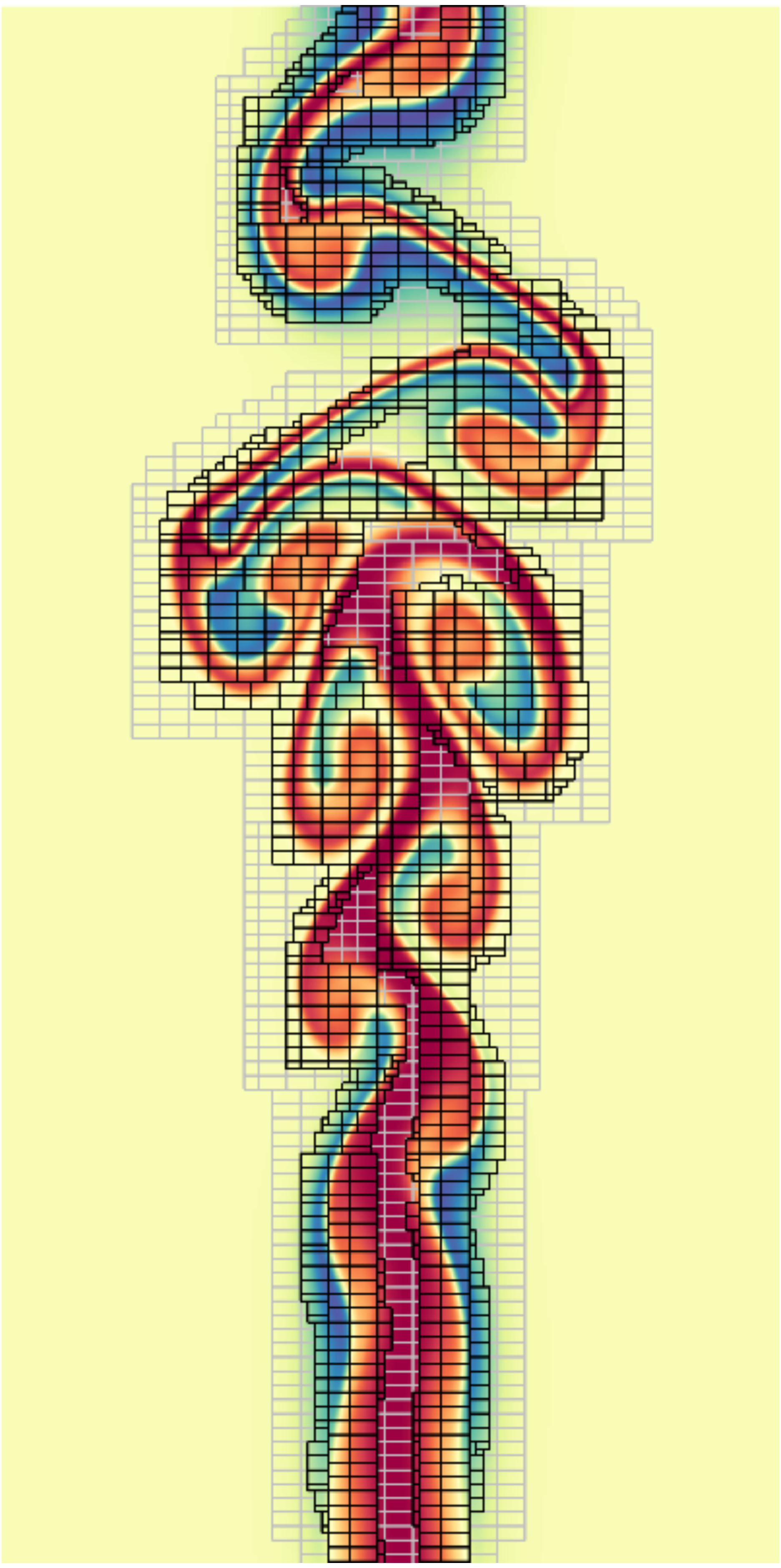
in collaboration with
F. Armengol, S. Brandt, M. Campanelli, R. Ciolfi, L. Ennoggi, B. Giacomazzo,
R. Haas, L. Ji, L.T. Sanches, E. Schnetter, J. Tsao, Y. Zlochower

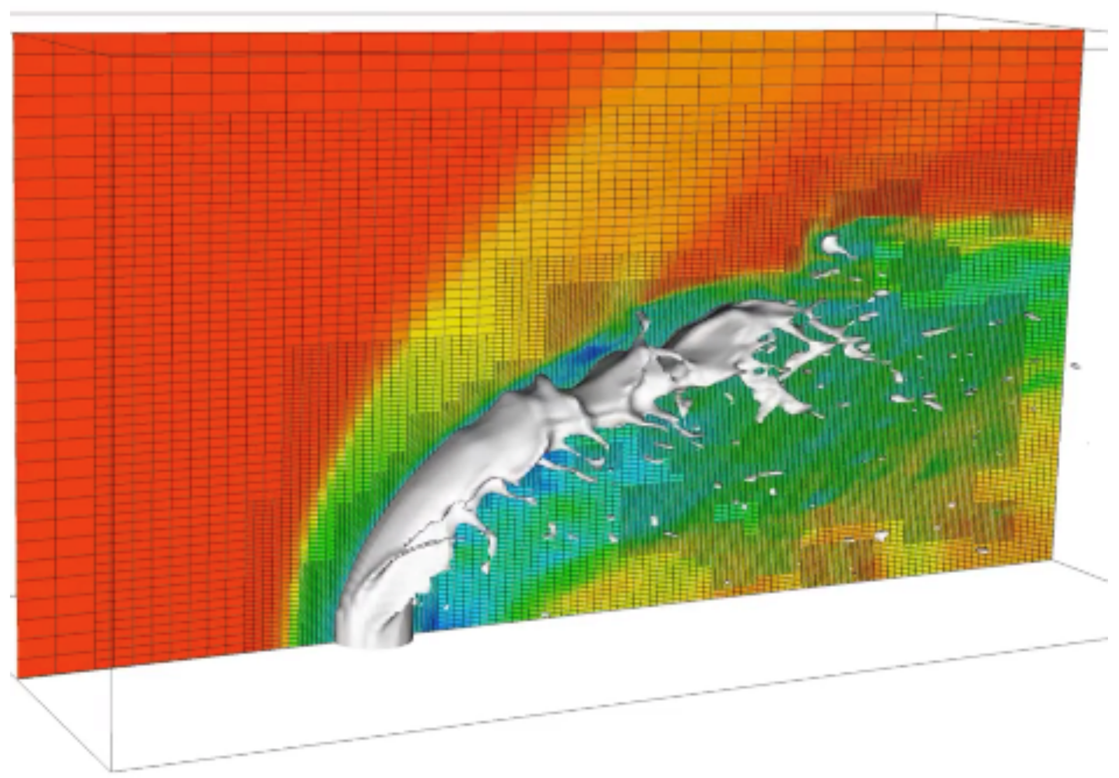
AMReX

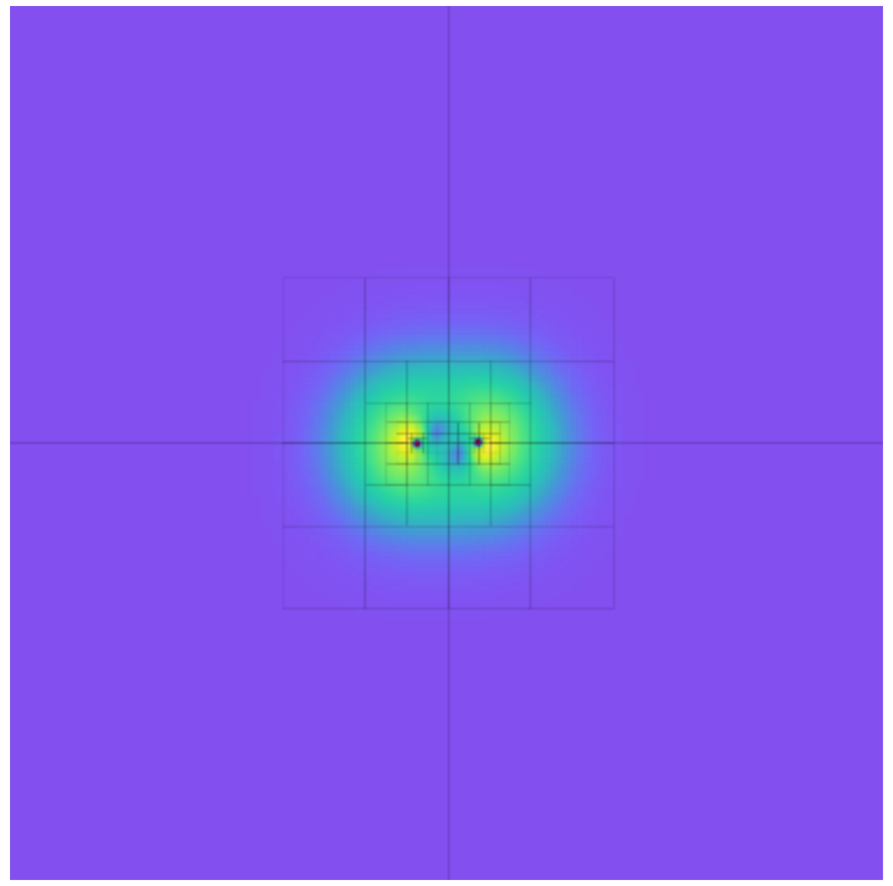


AMReX

- Software framework for massively parallel, block-structured adaptive mesh refinement (AMR) applications
- Developed at **LBNL**, **NREL** and **ANL** as a part of DOE's Exascale Computing Project
- **Key features:**
  - C++ and Fortran interfaces
  - 1-, 2- and 3-D support
  - Support for cell-, face-, vertex-, edge-centered data
  - Support for hyperbolic, parabolic, and elliptic solvers
  - Optional subcycling in time for time-dependent PDEs
  - Support for particles
  - **Performance portability**: parallelization via flat MPI, OpenMP, hybrid MPI/OpenMP, hybrid MPI/(**CUDA** or **HIP** or DPC++)
  - Parallel I/O



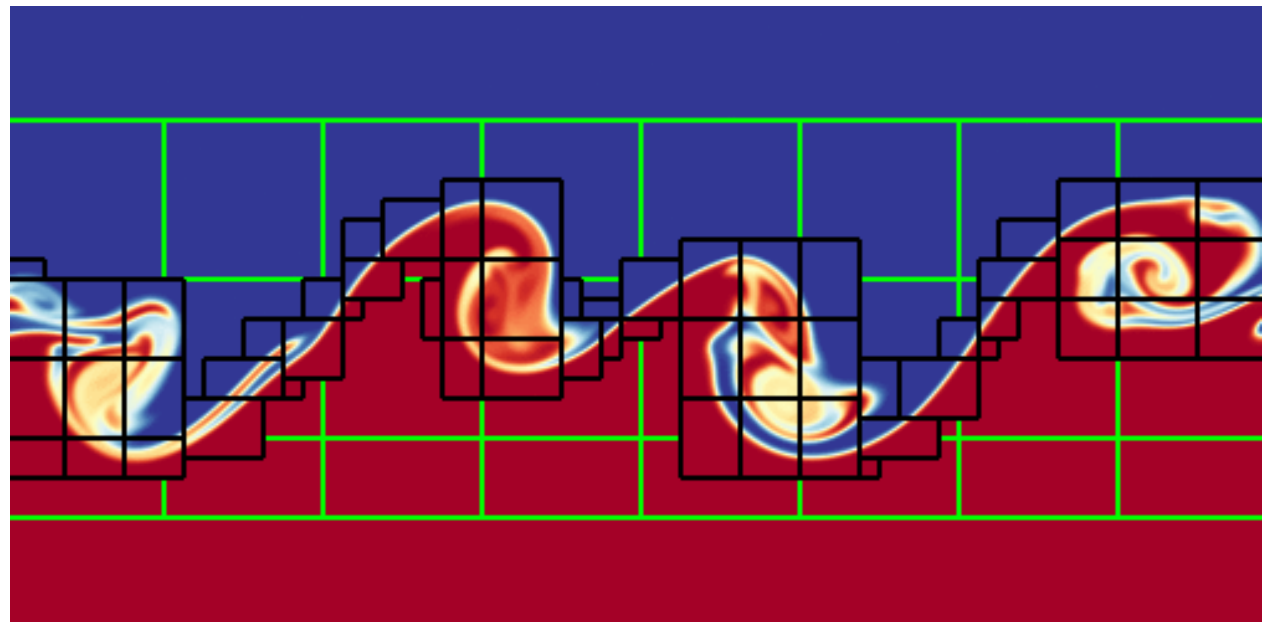


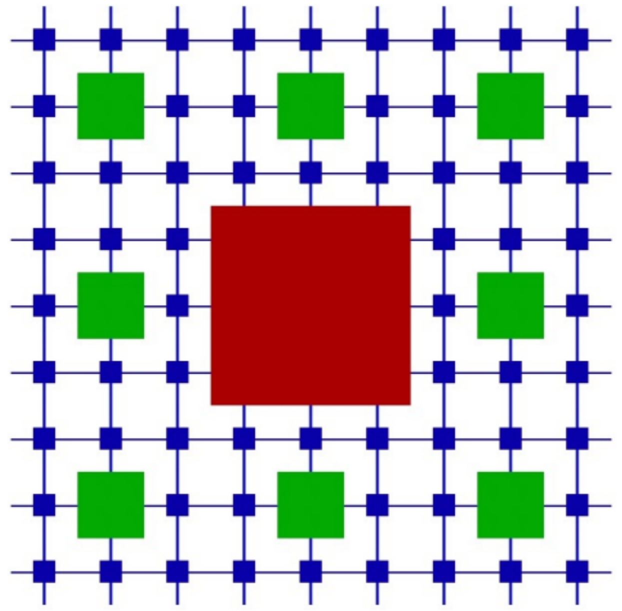


Taken from https://amrex-codes.github.io/amrex/

AMReX

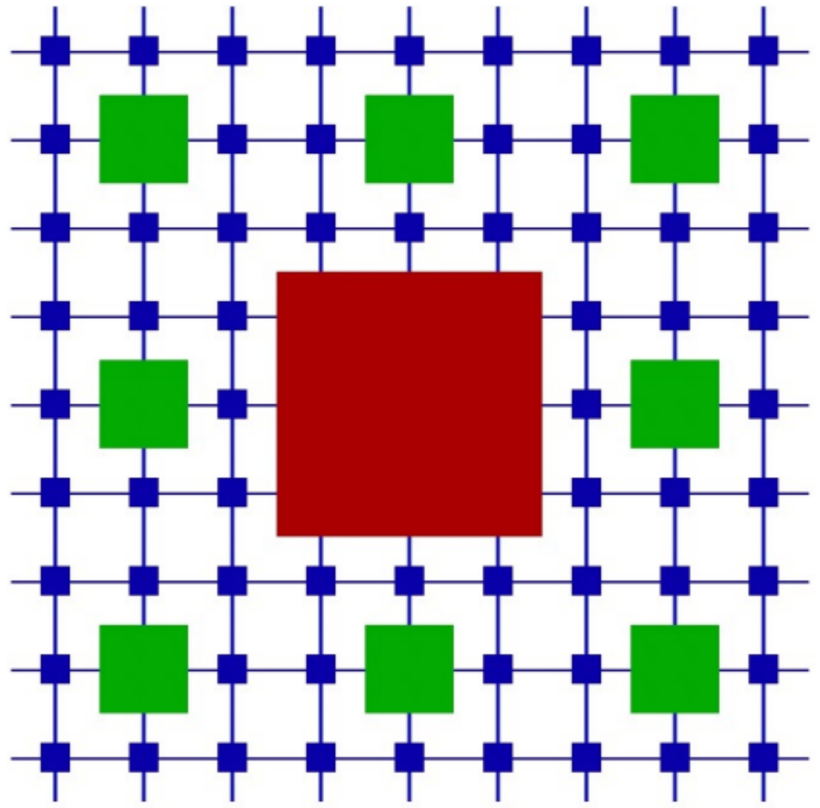
CarpetX

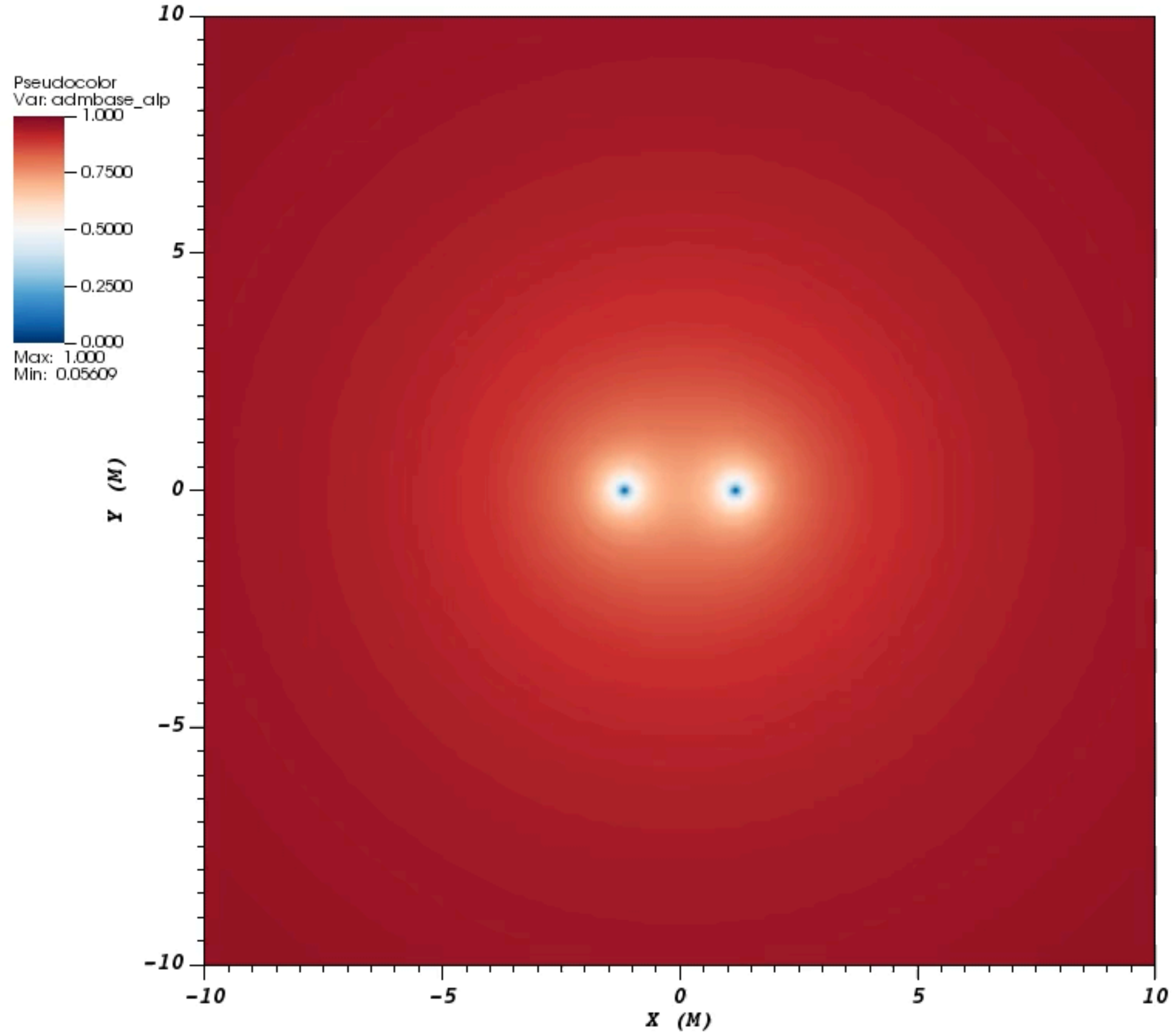




CarpetX: a new driver for the Einstein Toolkit

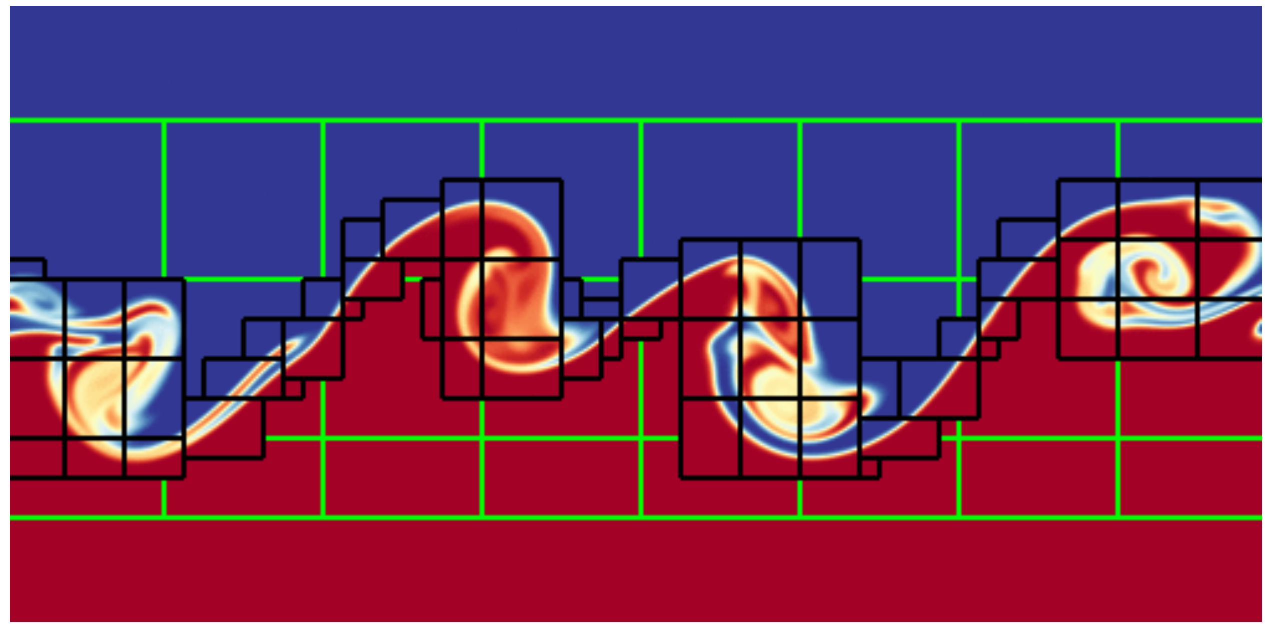
- **Support for accelerators (e.g. GPUs)**
- AMR based on local criteria
- Scalable → Exascale
- Hydro refluxing
- Elliptic solvers
- I/O in HDF5 (Silo, openPMD) or ASCII
- GitHub: https://github.com/eschnett/CarpetX
- Applications:
  - **WaveToyX:** solves a scalar wave equation
  - **Z4c:** Einstein field equations in vacuum
  - **GRaM-X:** a new GRMHD code [Shankar et al. 2022]



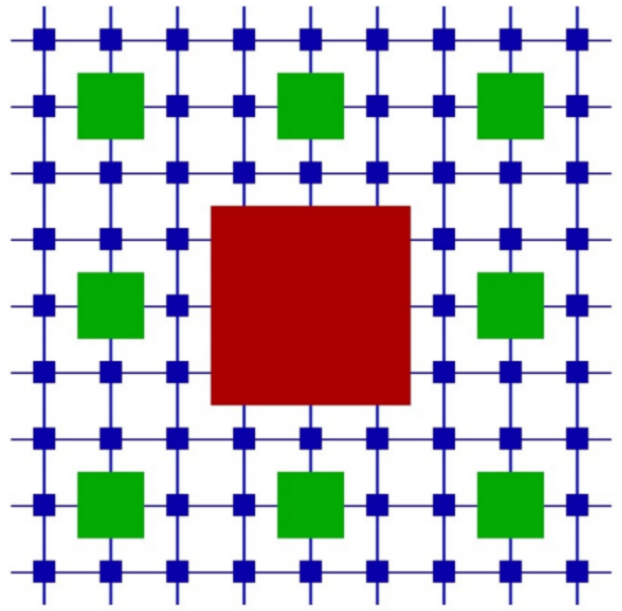


BBH merger simulations by
Allen Wen (RIT)

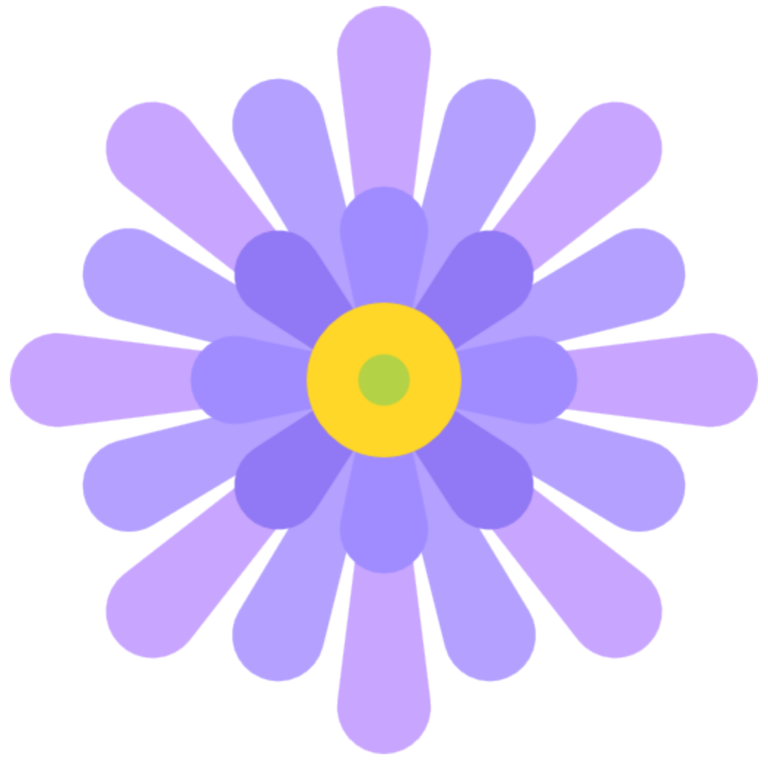
AMReX



CarpetX



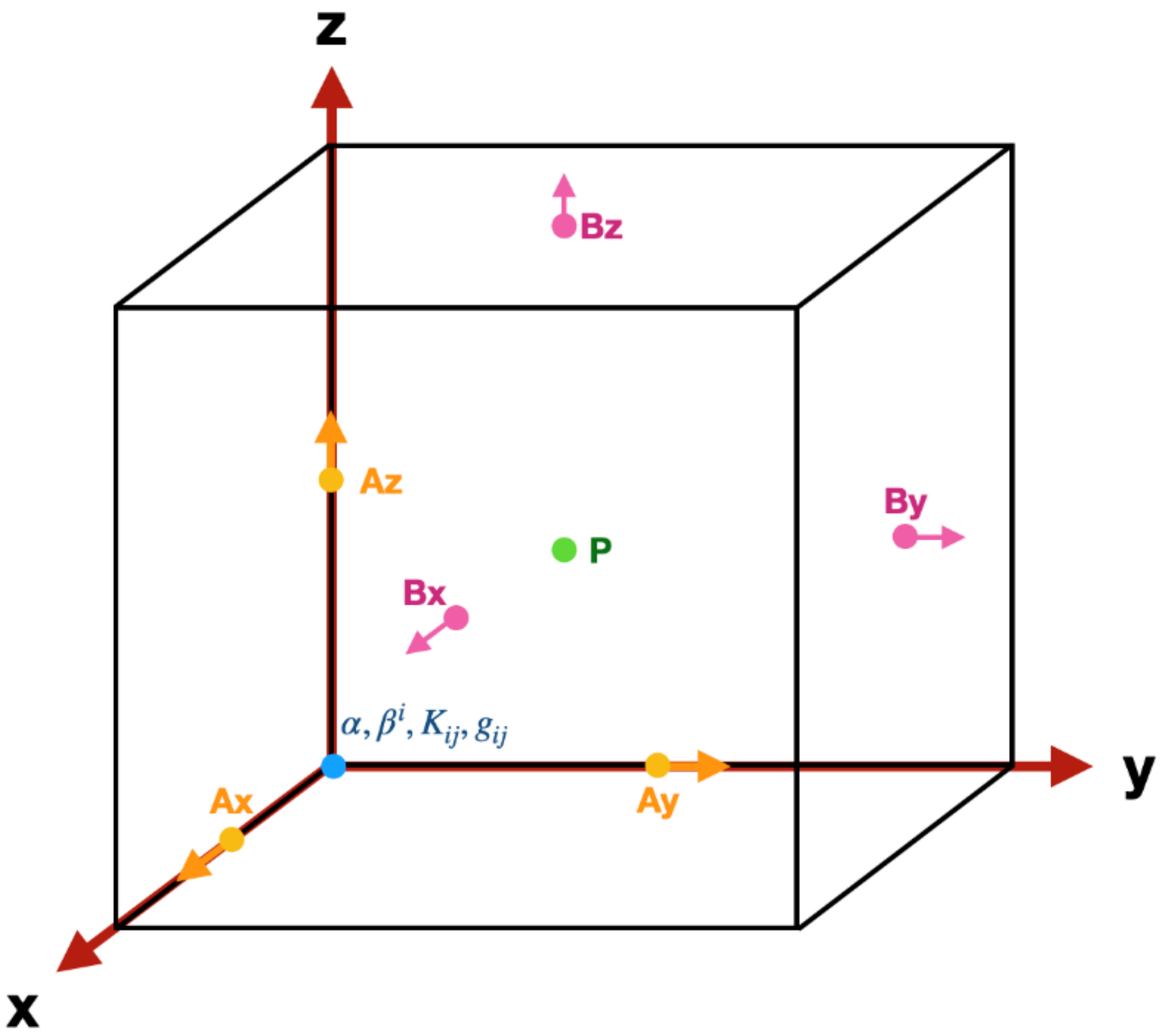
AsterX



AsterX: General Relativistic MHD code

Heavily derived from the Spritz code

- ReconX:
  - MinMod (TVD)
  - Piecewise Parabolic Method (PPM)
  - WENO-Z (weighted essentially non-oscillatory)-Z
  - MP5 (5th order monotonicity-preserving)
- Flux solvers:
  - Lax-Friedrichs
  - HLLE
- Con2PrimFactory:
  - 2D Noble et al.
  - 1D Palenzuela et al.
  - 1D RePrimAnd (only CPU-compatible)
  - 3D Anton et al.
  - 1D Newman & Hamlin



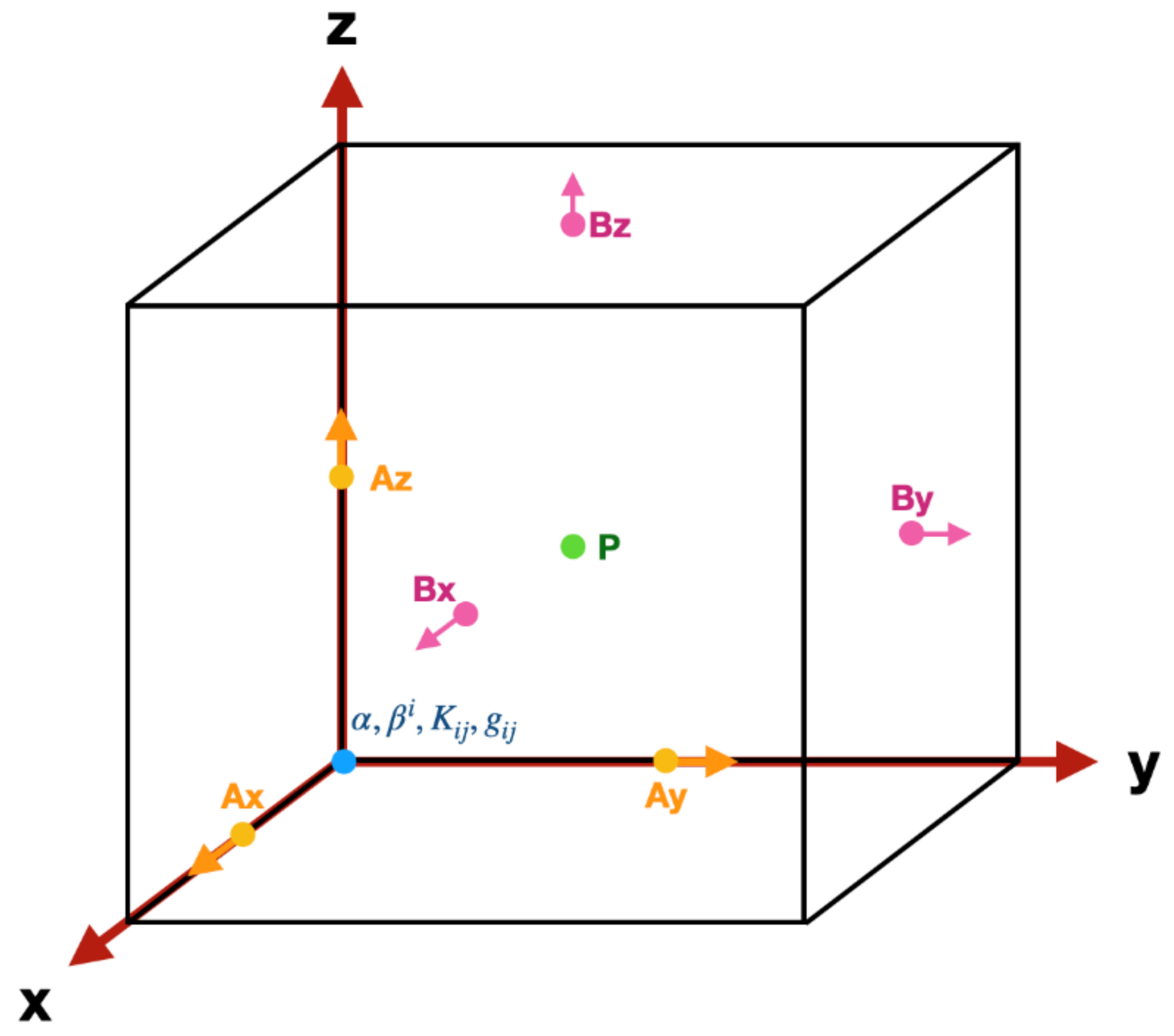
Locations of different grid-functions in a grid-cell

AsterX: General Relativistic MHD code

Heavily derived from the Spritz code

- EOSX:
    - Analytical: Ideal gas, Polytropic
    - Hybrid
    - Finite temperature tabulated
- Vector potential evolution:
    - Flux CT
    - Upwind CT (HLLE)
- GitHub:

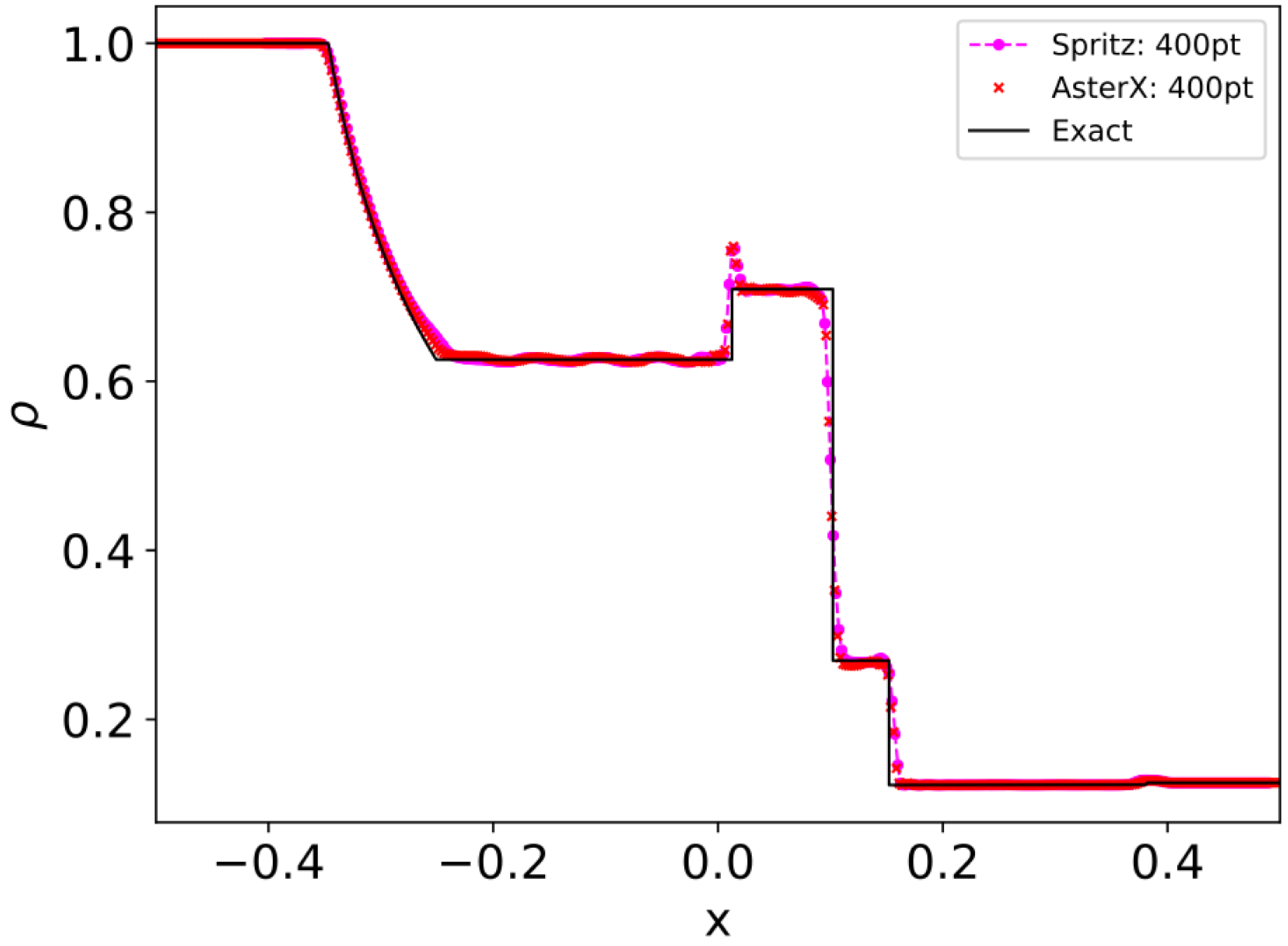
  https://github.com/jaykalinani/AsterX



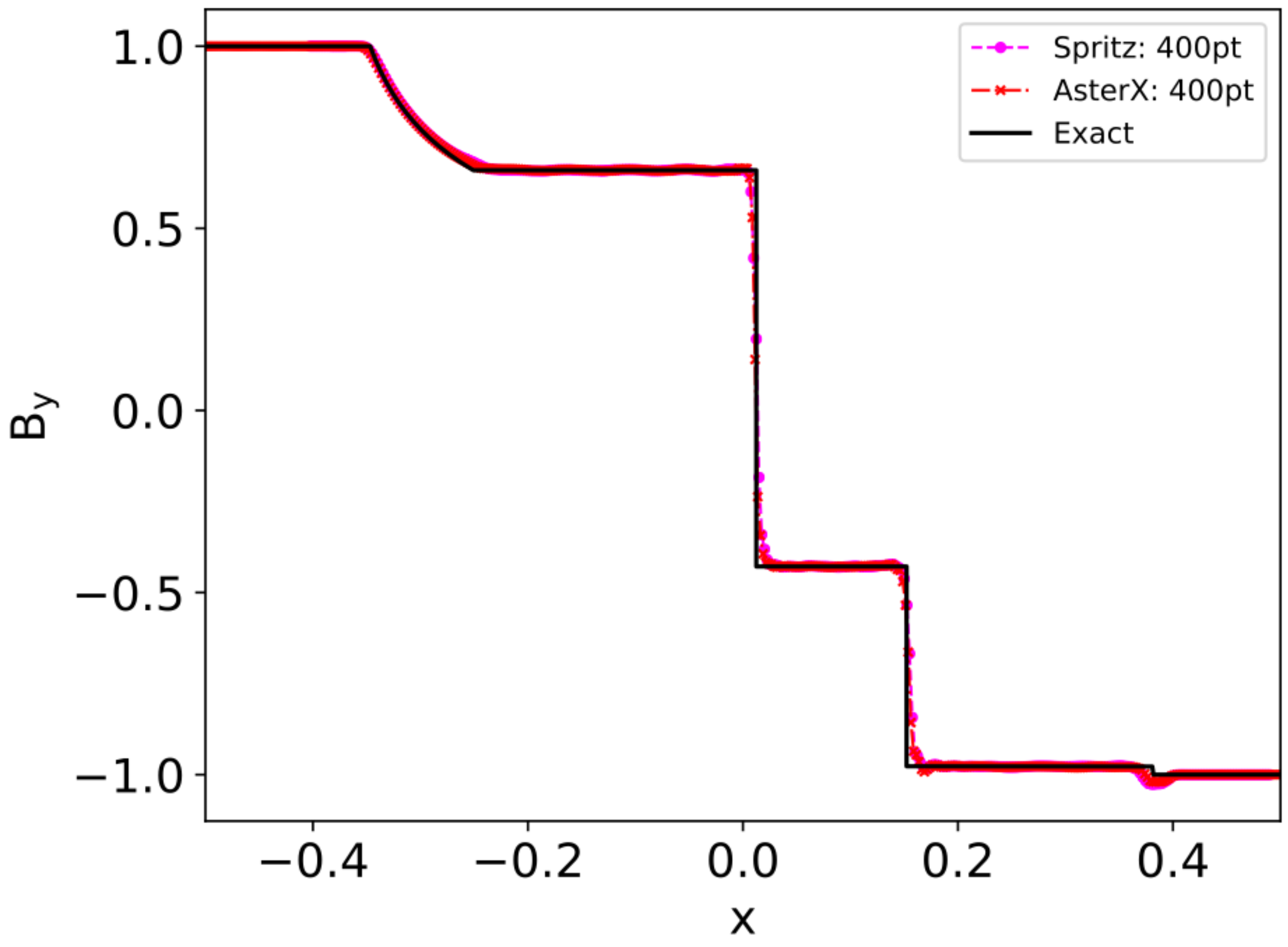
Locations of different grid-functions in a grid-cell

Balsara 1: PPM + HLLE

Rest-mass density

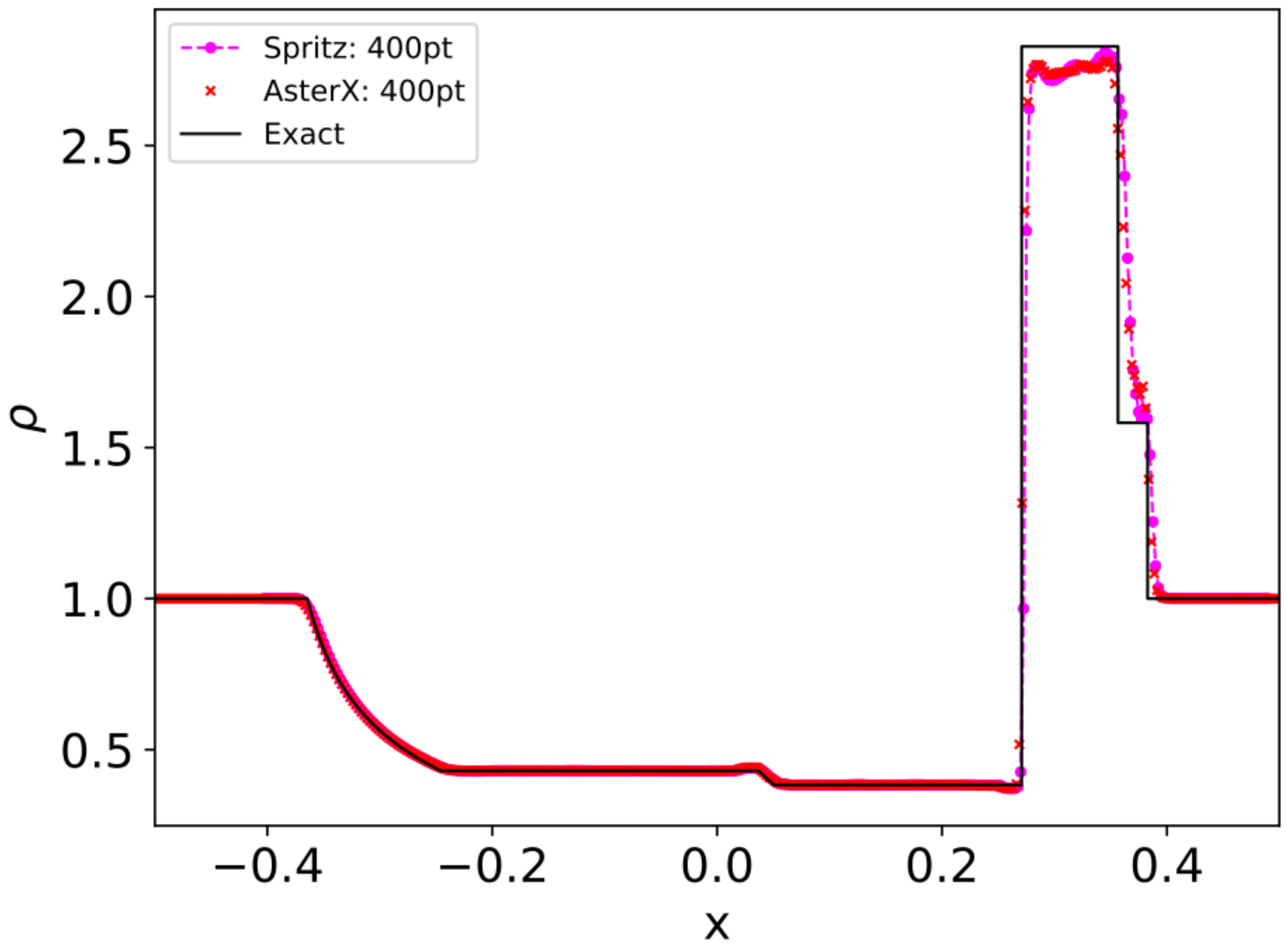


Magnetic field: By

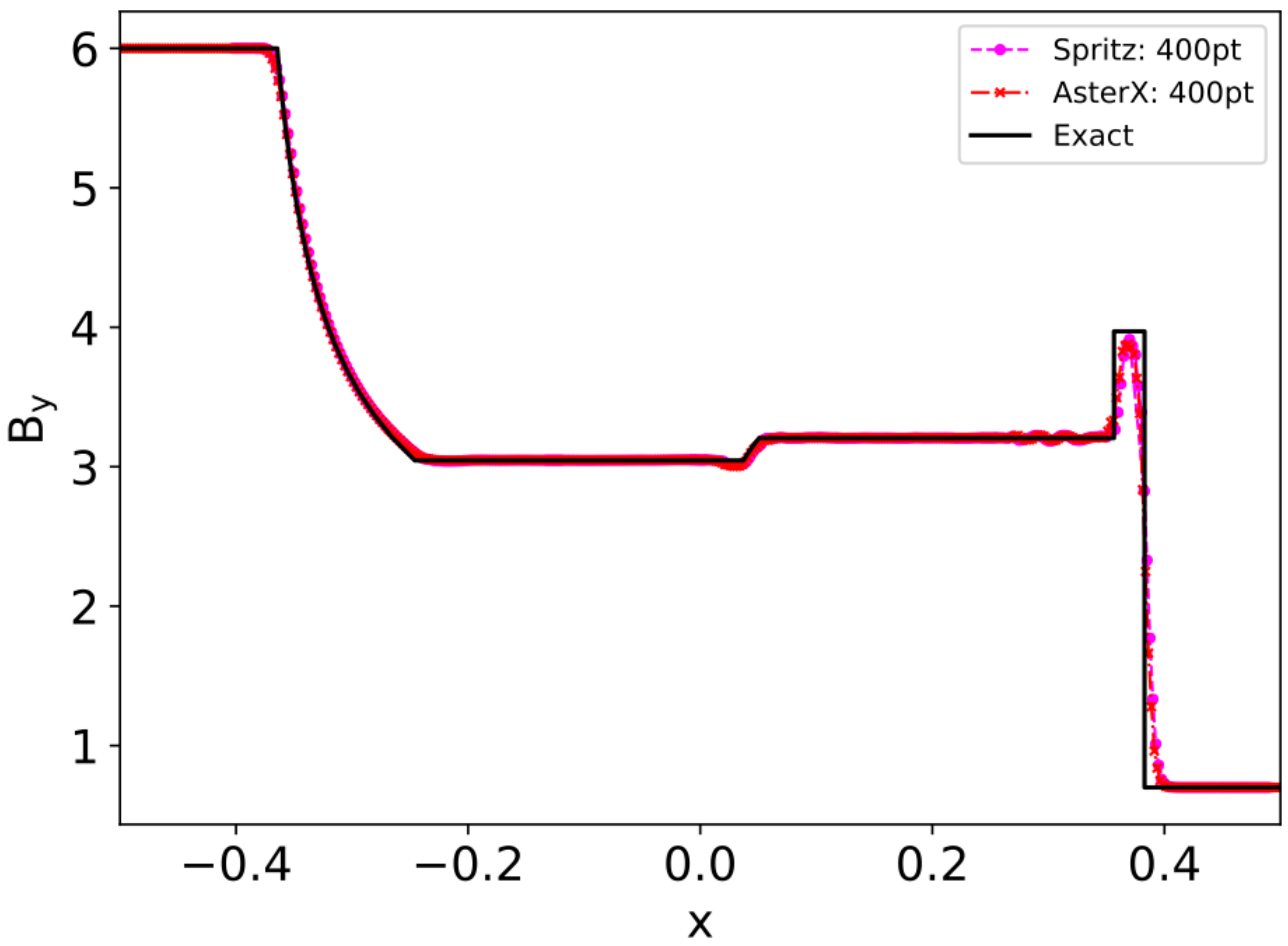


Balsara 2: PPM + HLLE

Rest-mass density

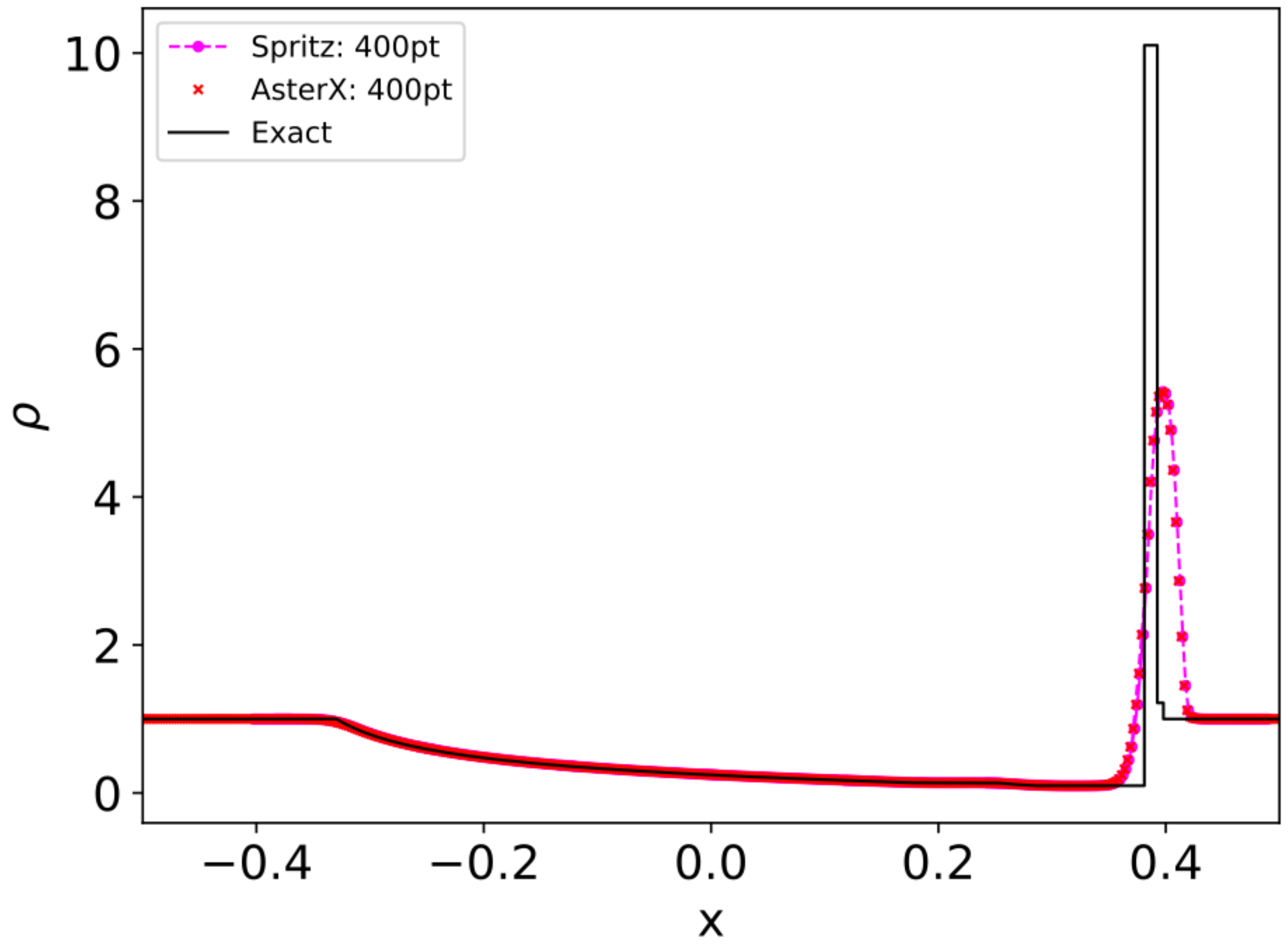


Magnetic field: By

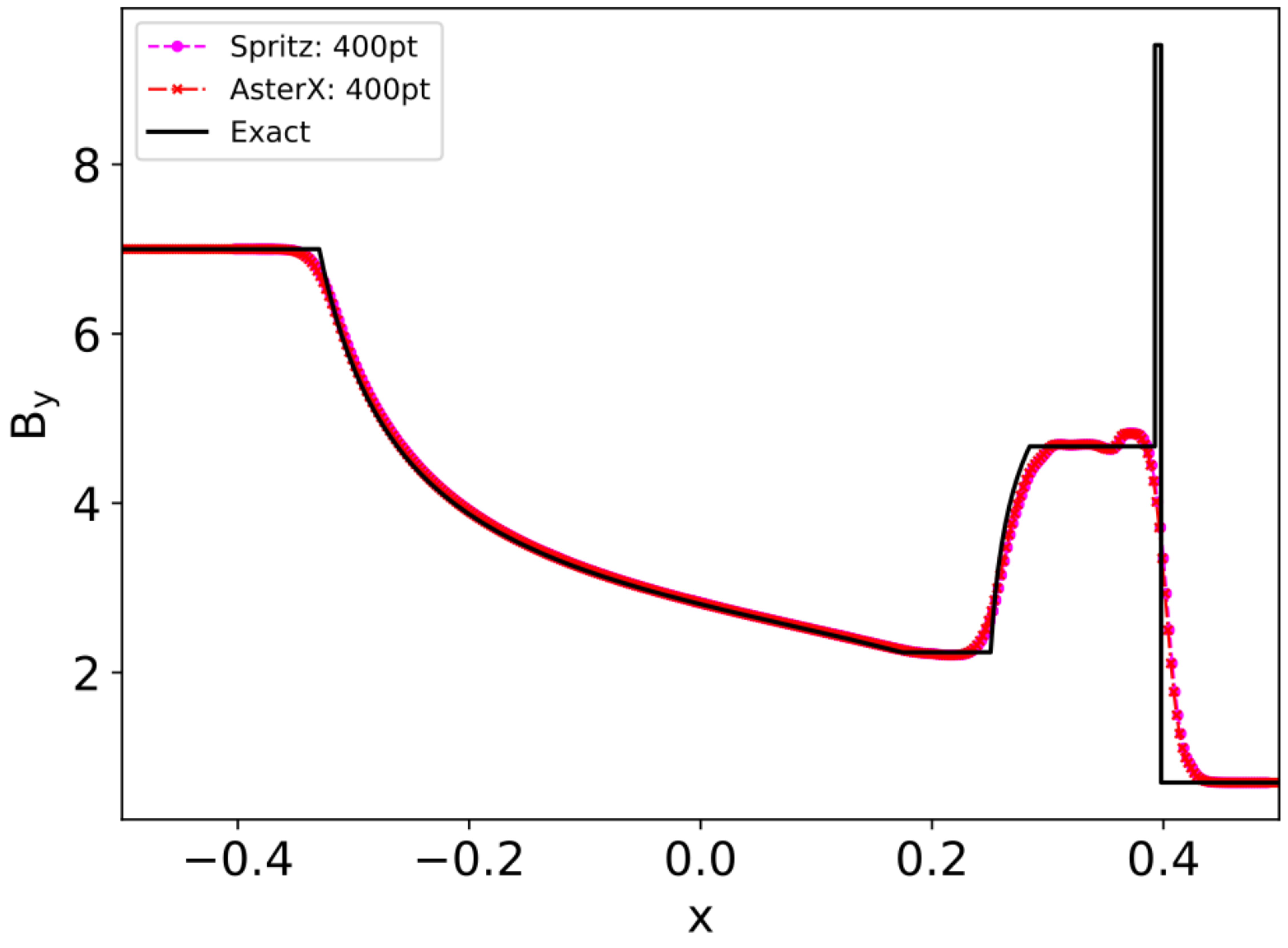


Balsara 3: MinMod + HLLE

Rest-mass density

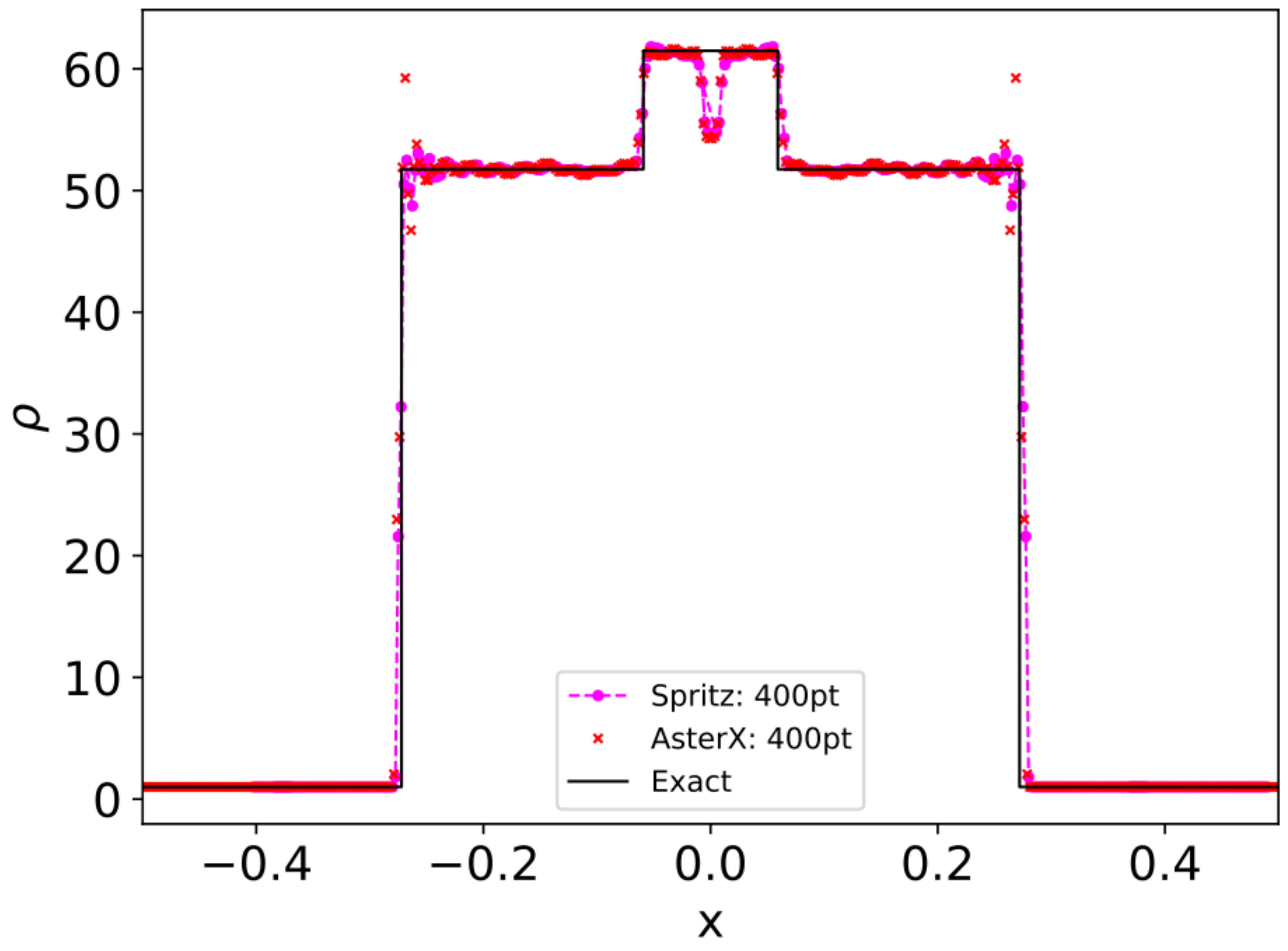


Magnetic field: By

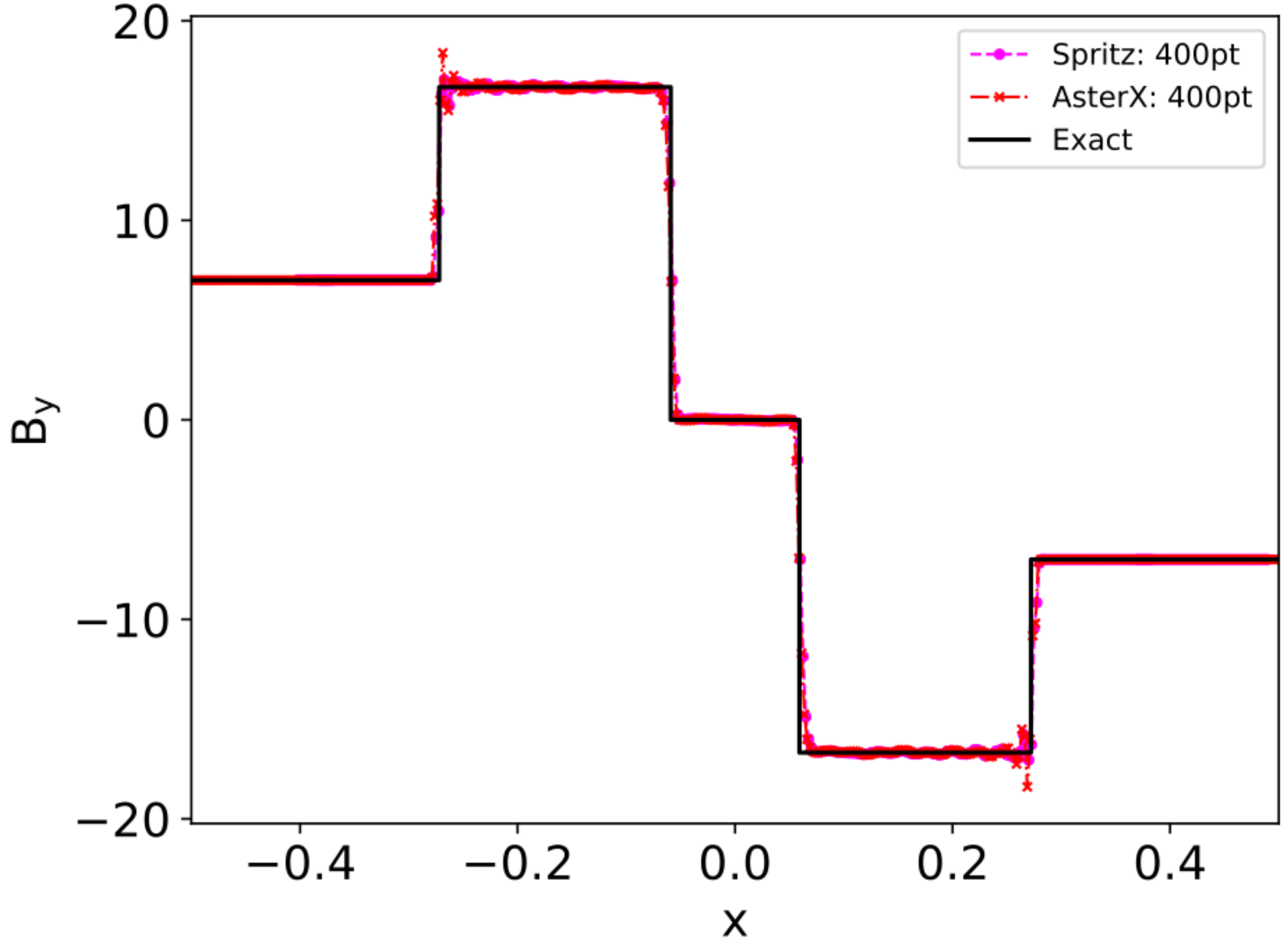


Balsara 4: PPM + HLLE

Rest-mass density

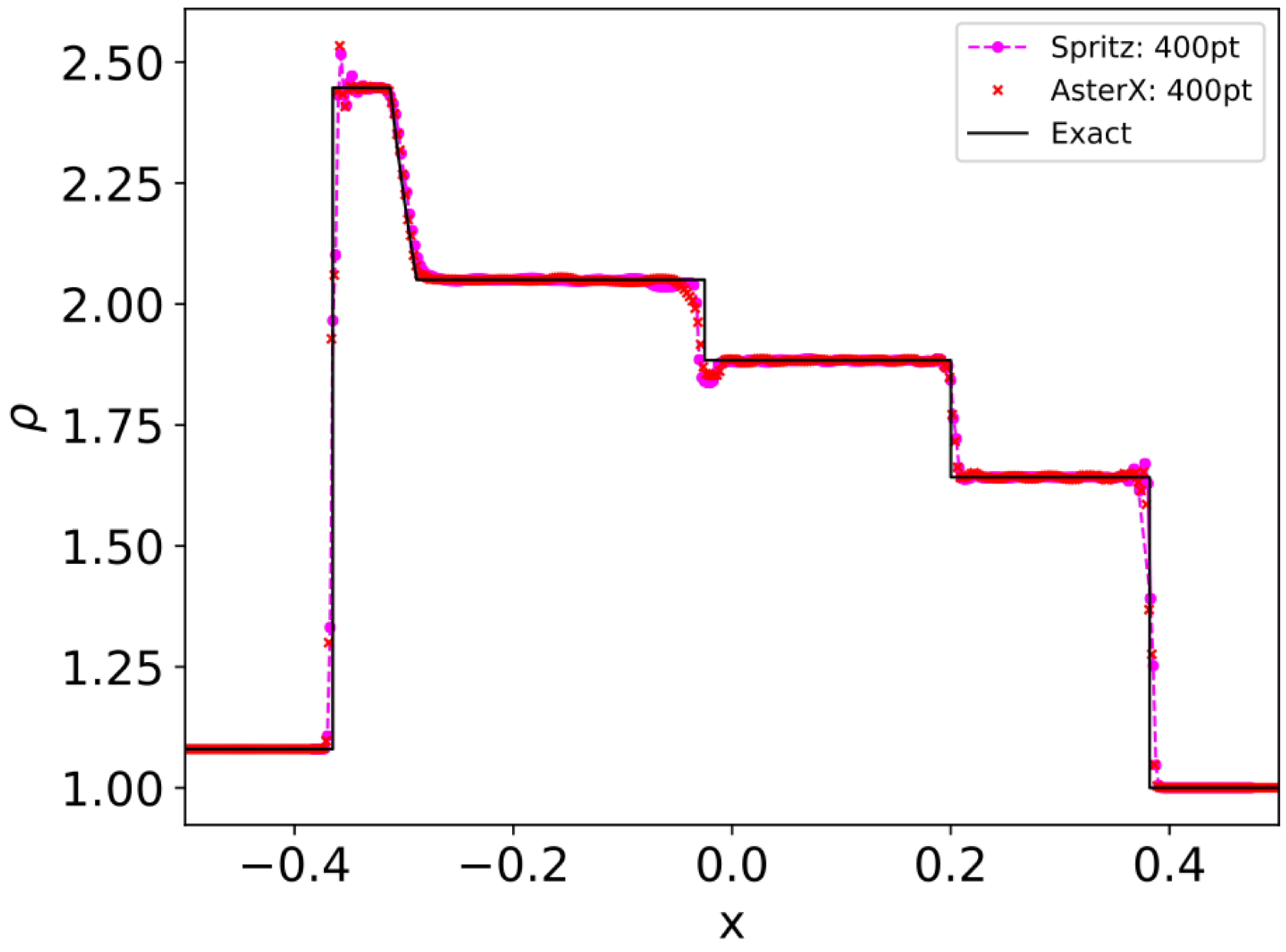


Magnetic field: By

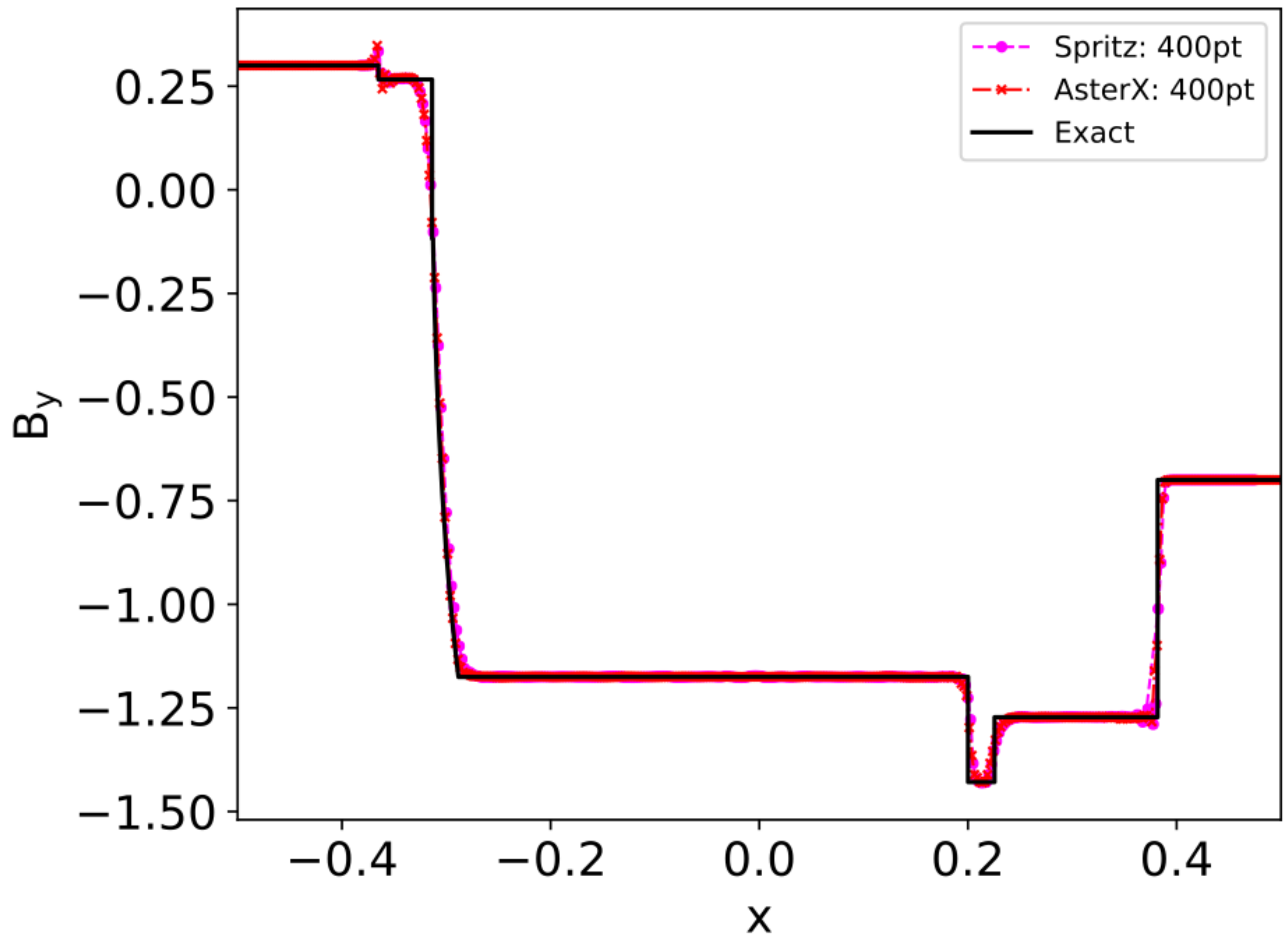


Balsara 5: PPM + HLLE

Rest-mass density

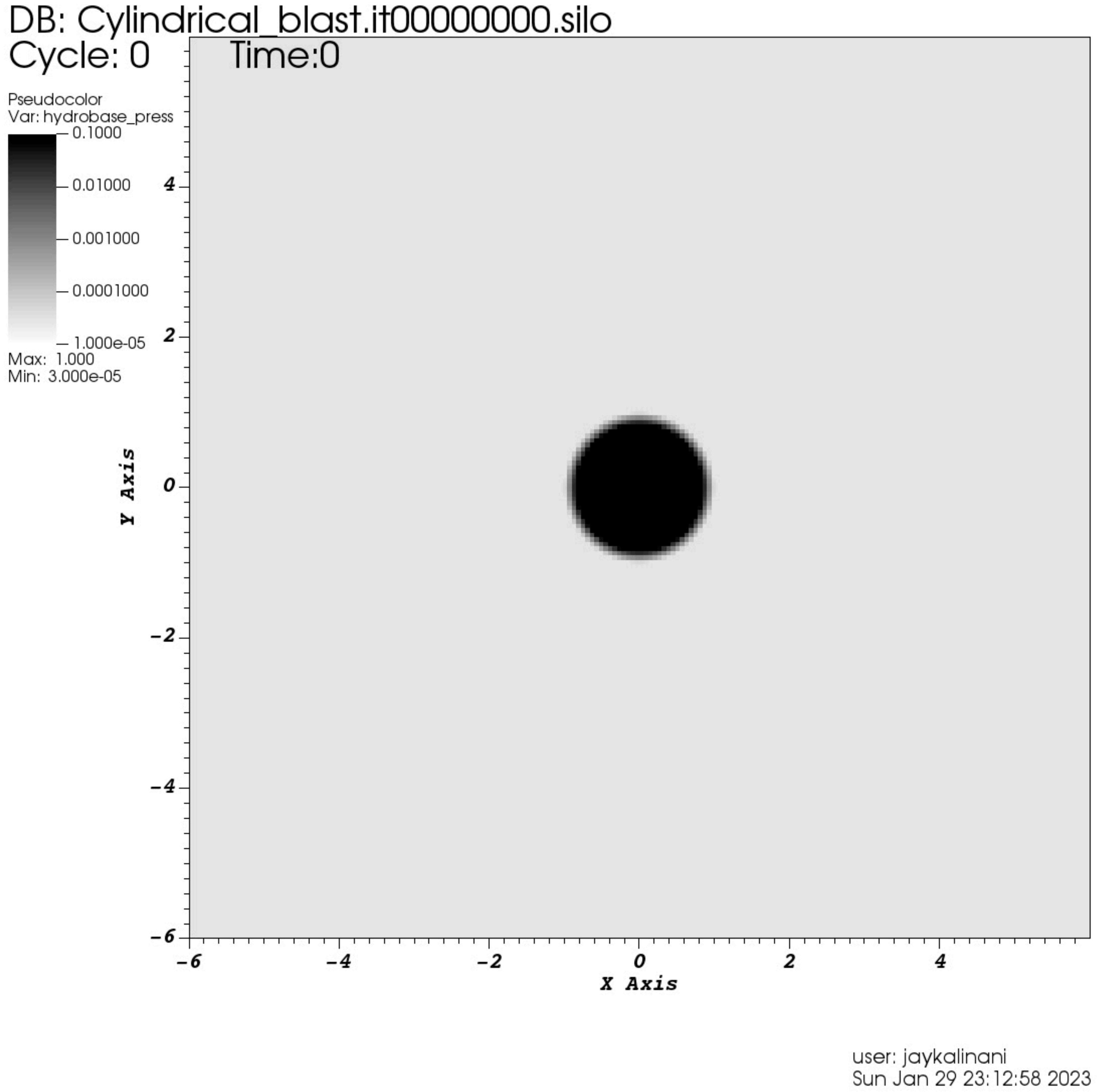


Magnetic field: By

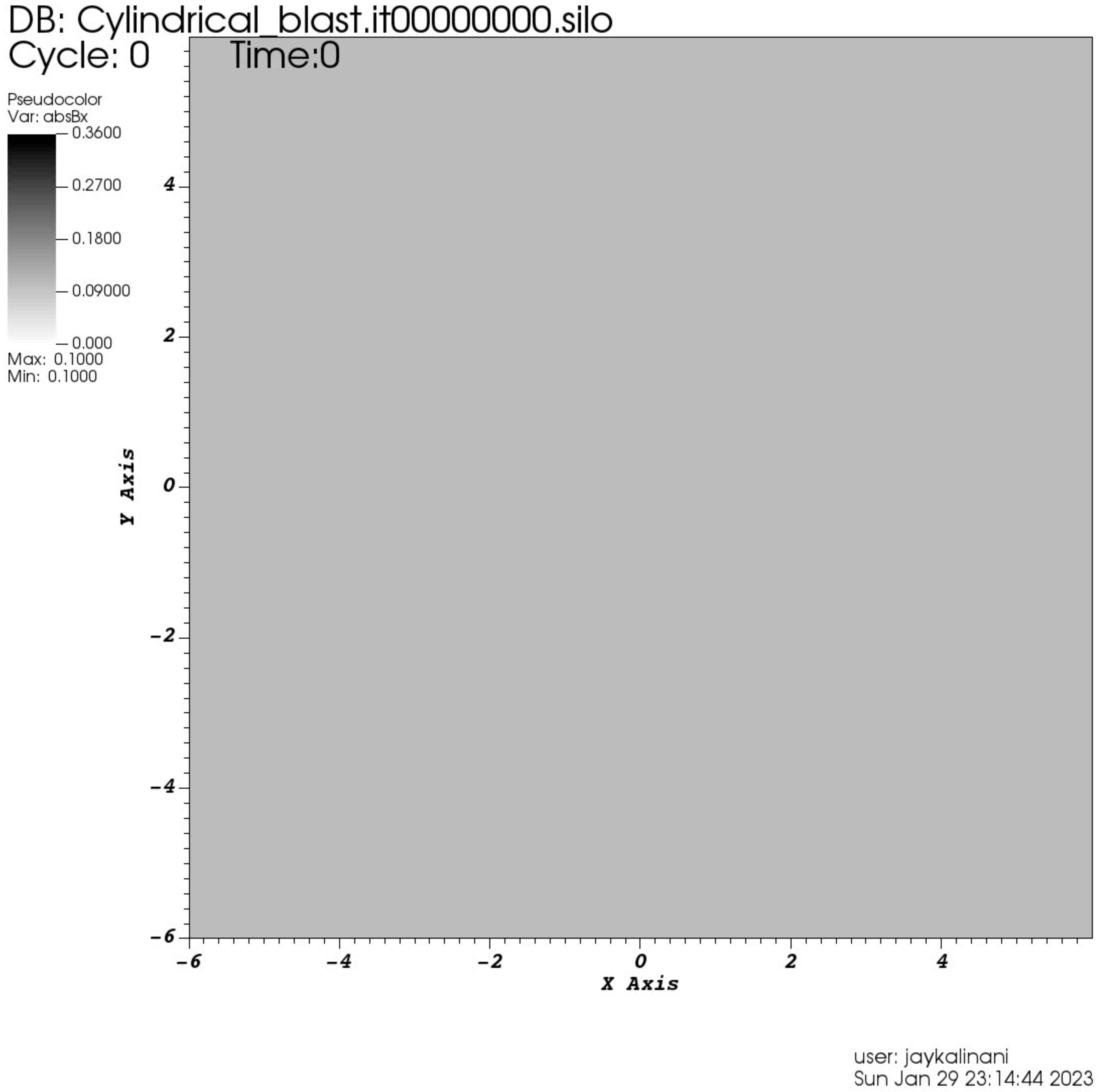


Cylindrical Explosion: MinMod + HLLE

Rest-mass density

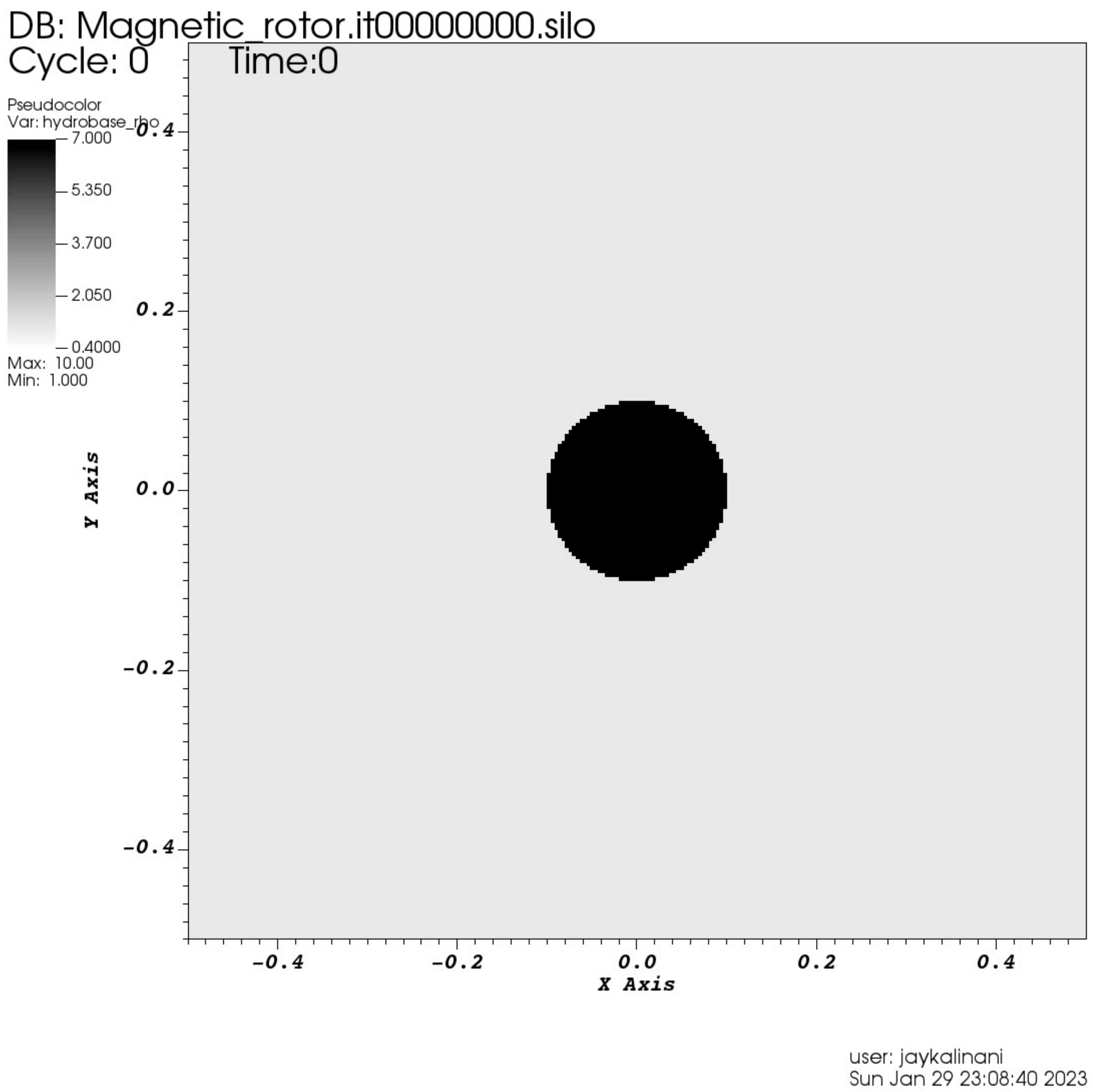


Magnetic field: abs(Bx)

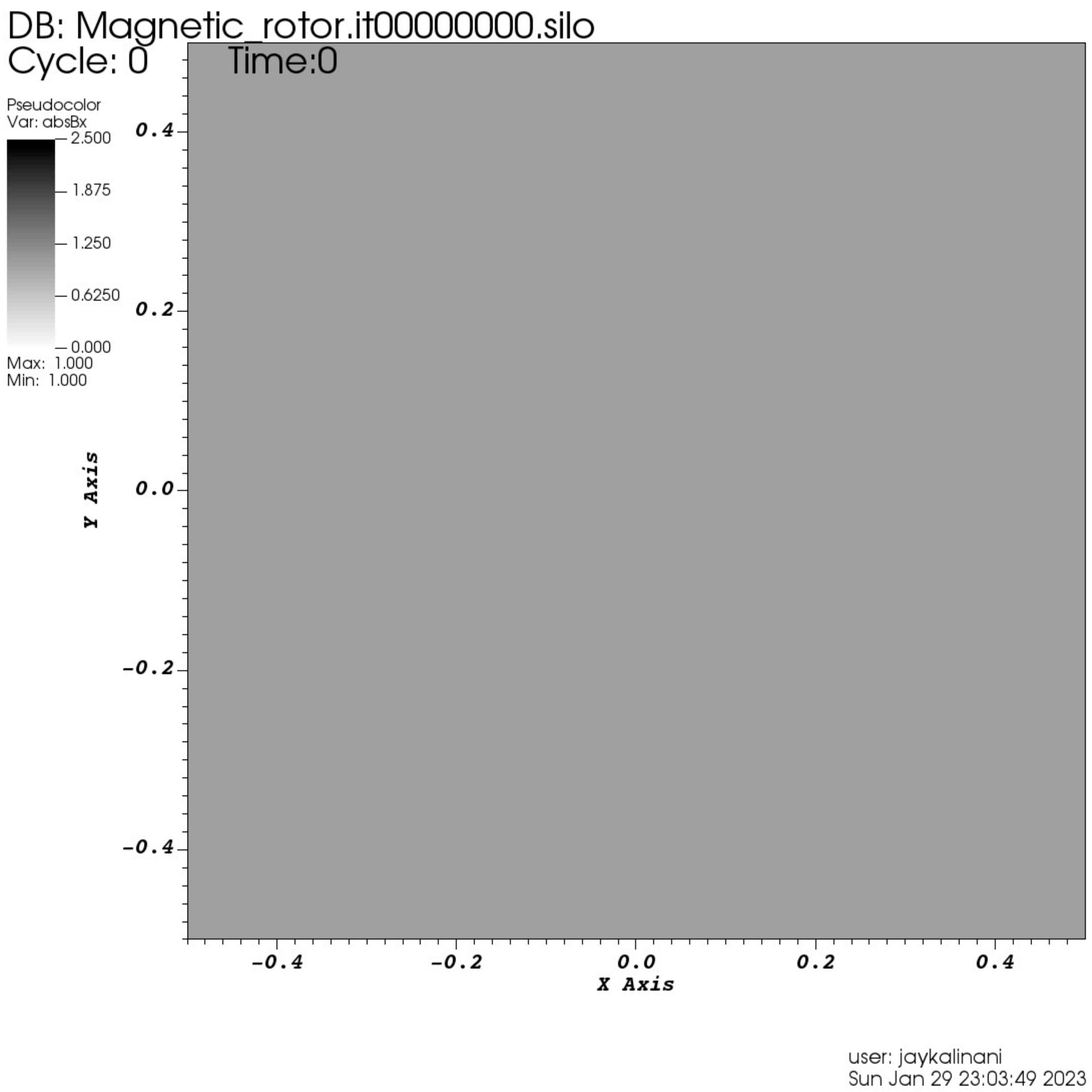


Magnetic Rotor: PPM + HLLE

Rest-mass density

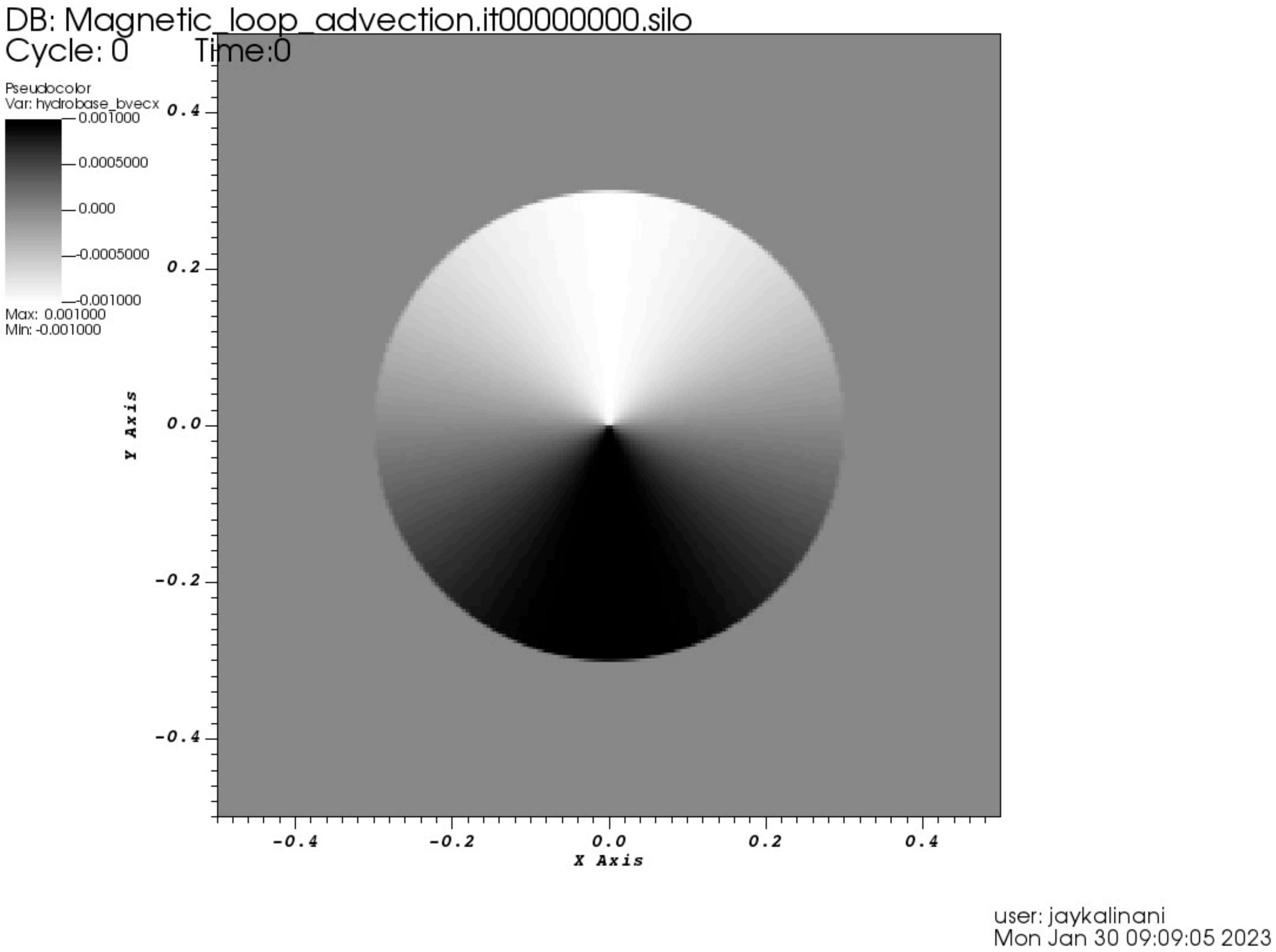


Magnetic field: abs(Bx)



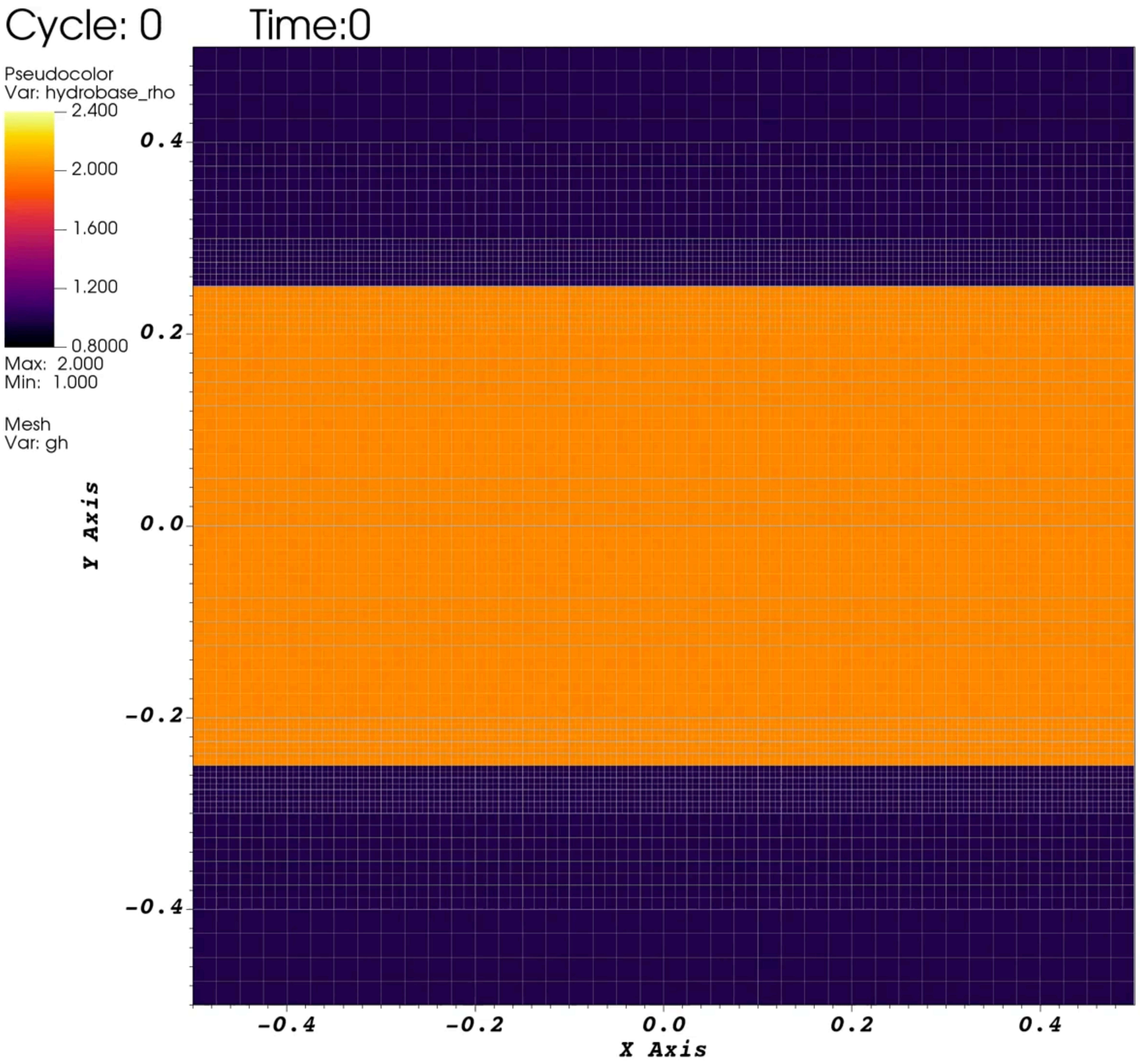
Magnetic Loop Advection: PPM + HLLE

Magnetic field: Bx



Kelvin Helmholtz Instability: PPM + HLLE

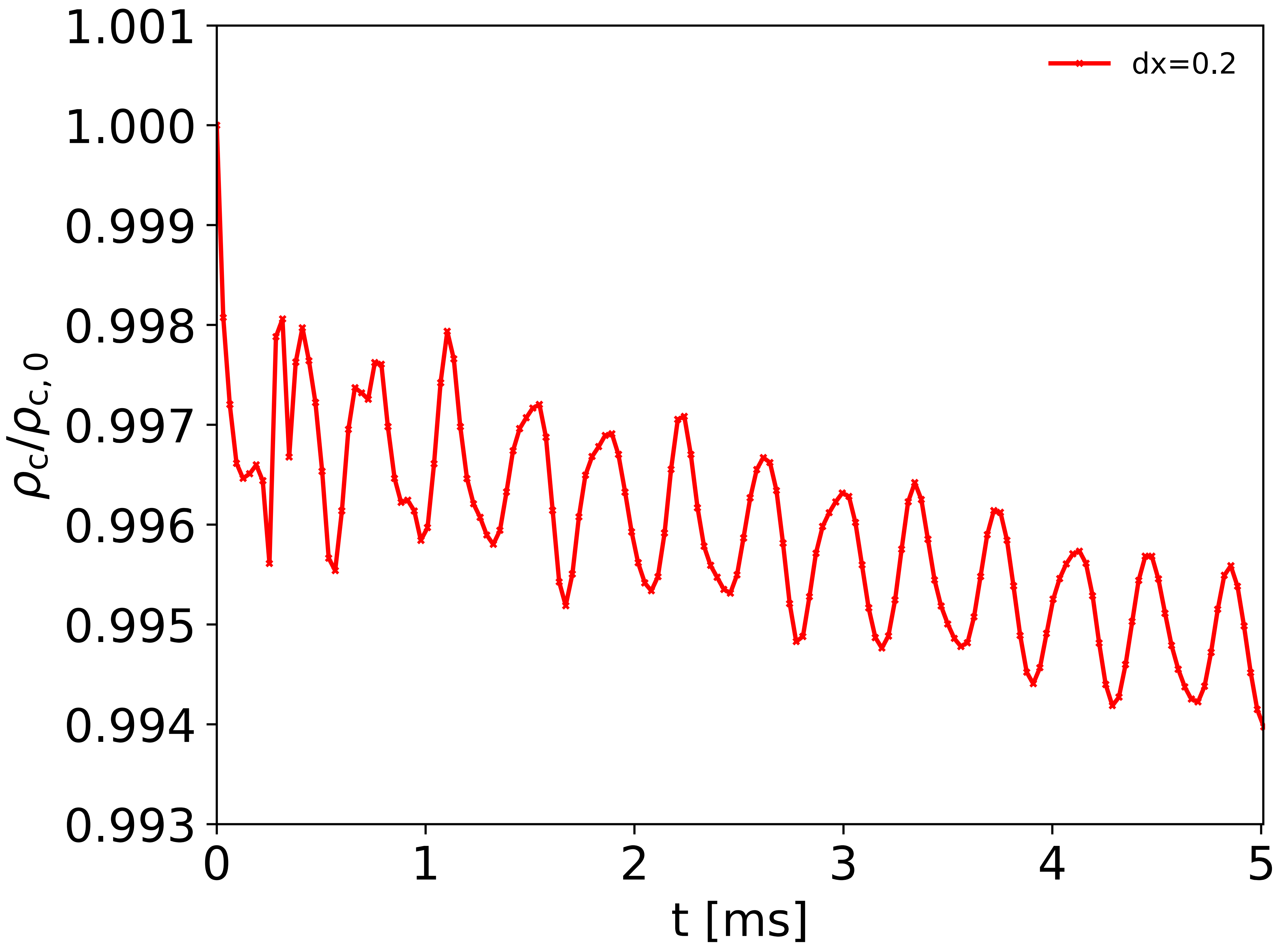
Rest-mass density



Magnetized TOV

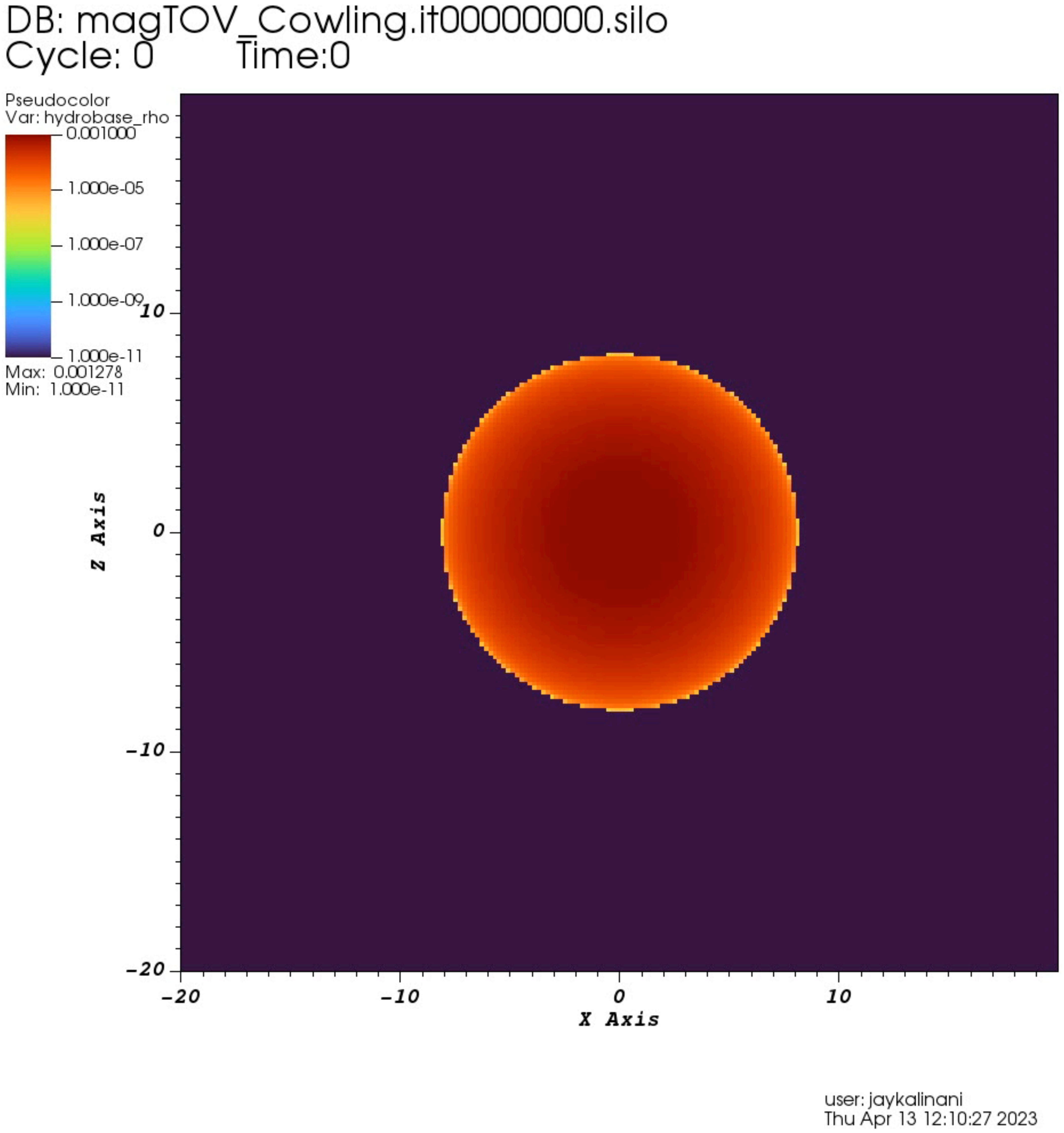
- **Spacetime:** Cowling
- **HRSC:** PPM + HLLE
- **Initial max magnetic field strength**: 5e15 G
- **EOS ID:** Gamma=2, K=100 polytropic
- **EOS evolve:** Gamma=2 ideal gas
- **Resolution:** 295 m
- **Density floor:** 6.67e6 g/cm^3

Max. rest-mass density evolution

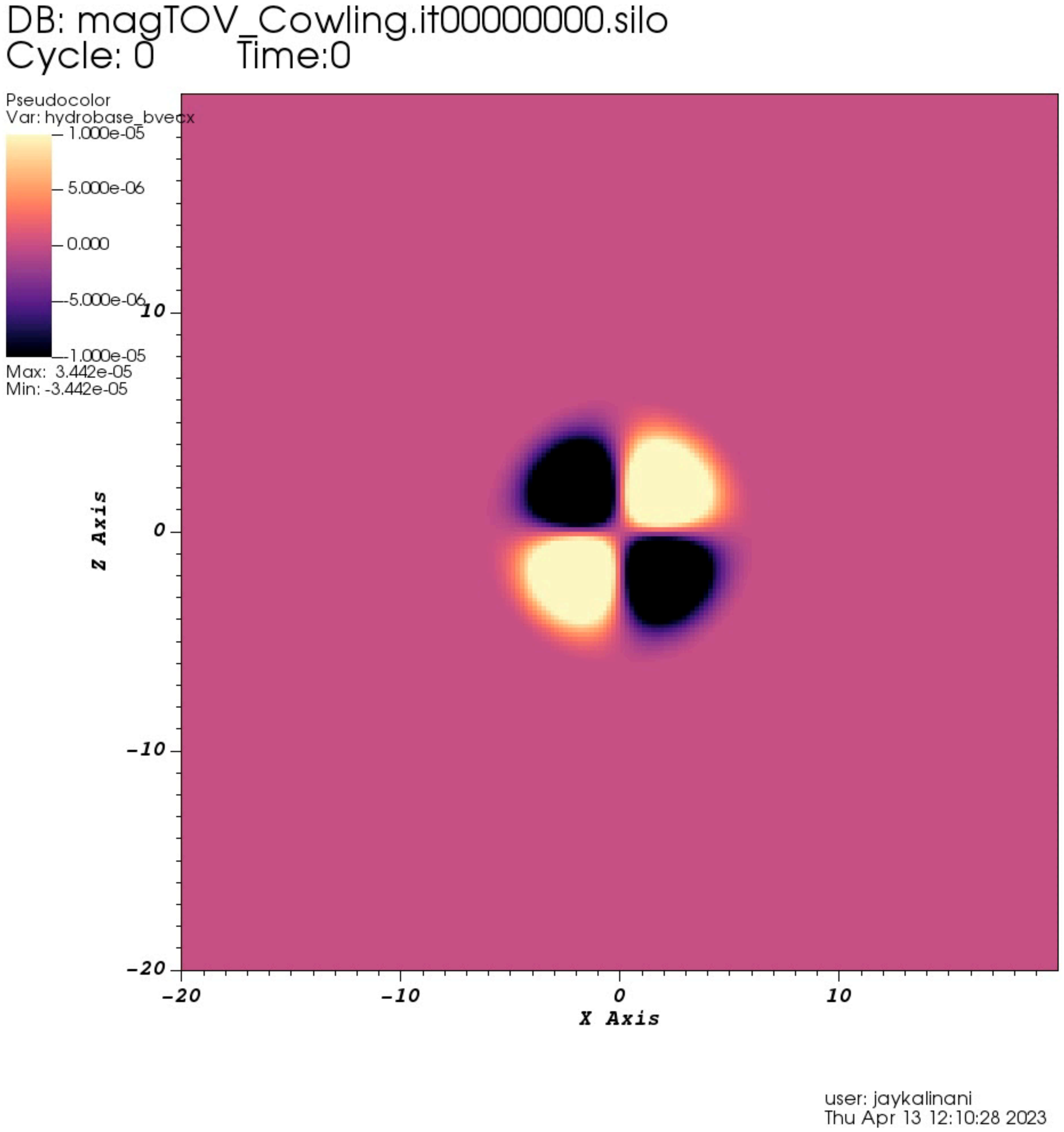


Magnetized TOV

Rest-mass density

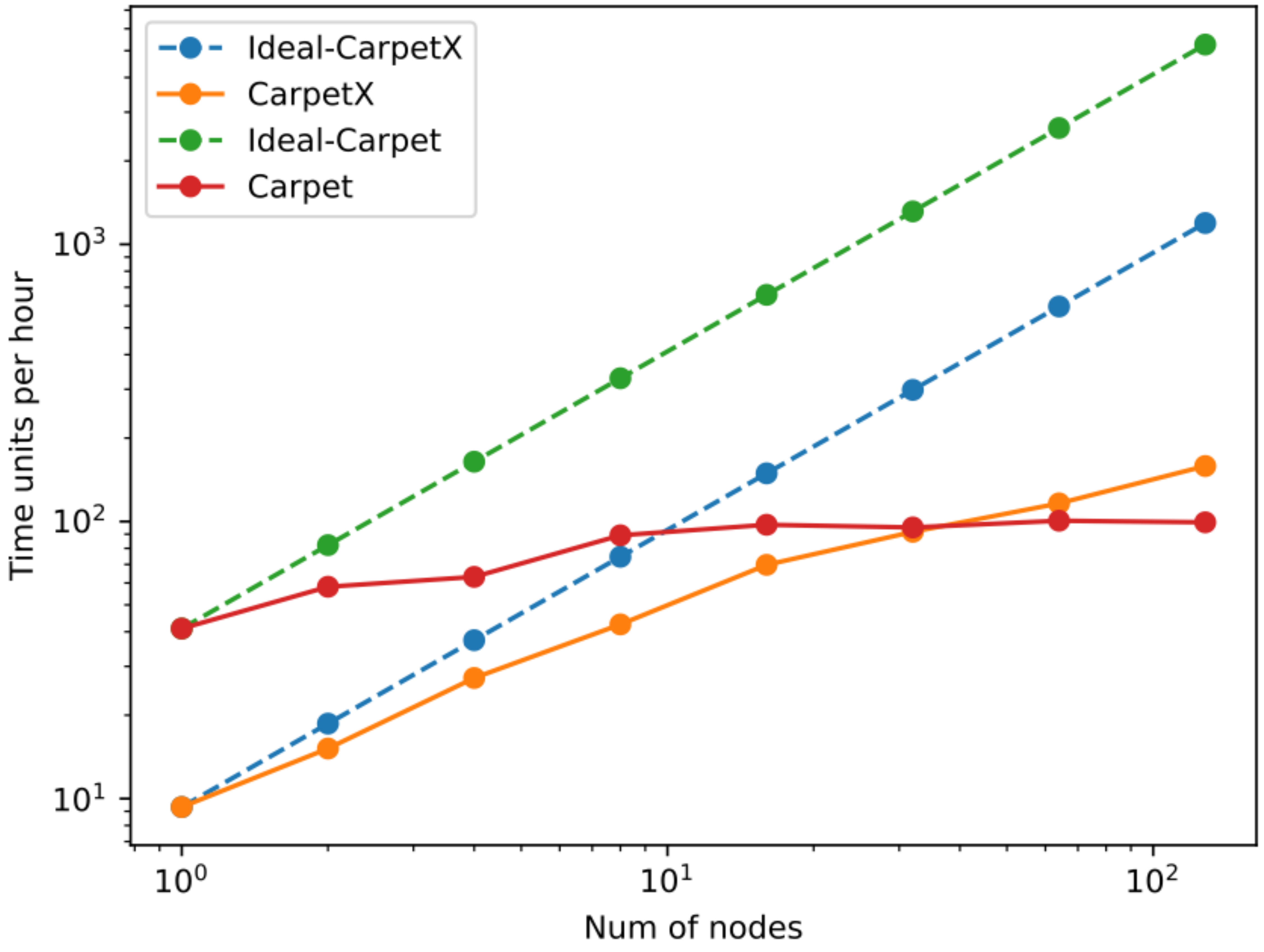


Magnetic field: Bx

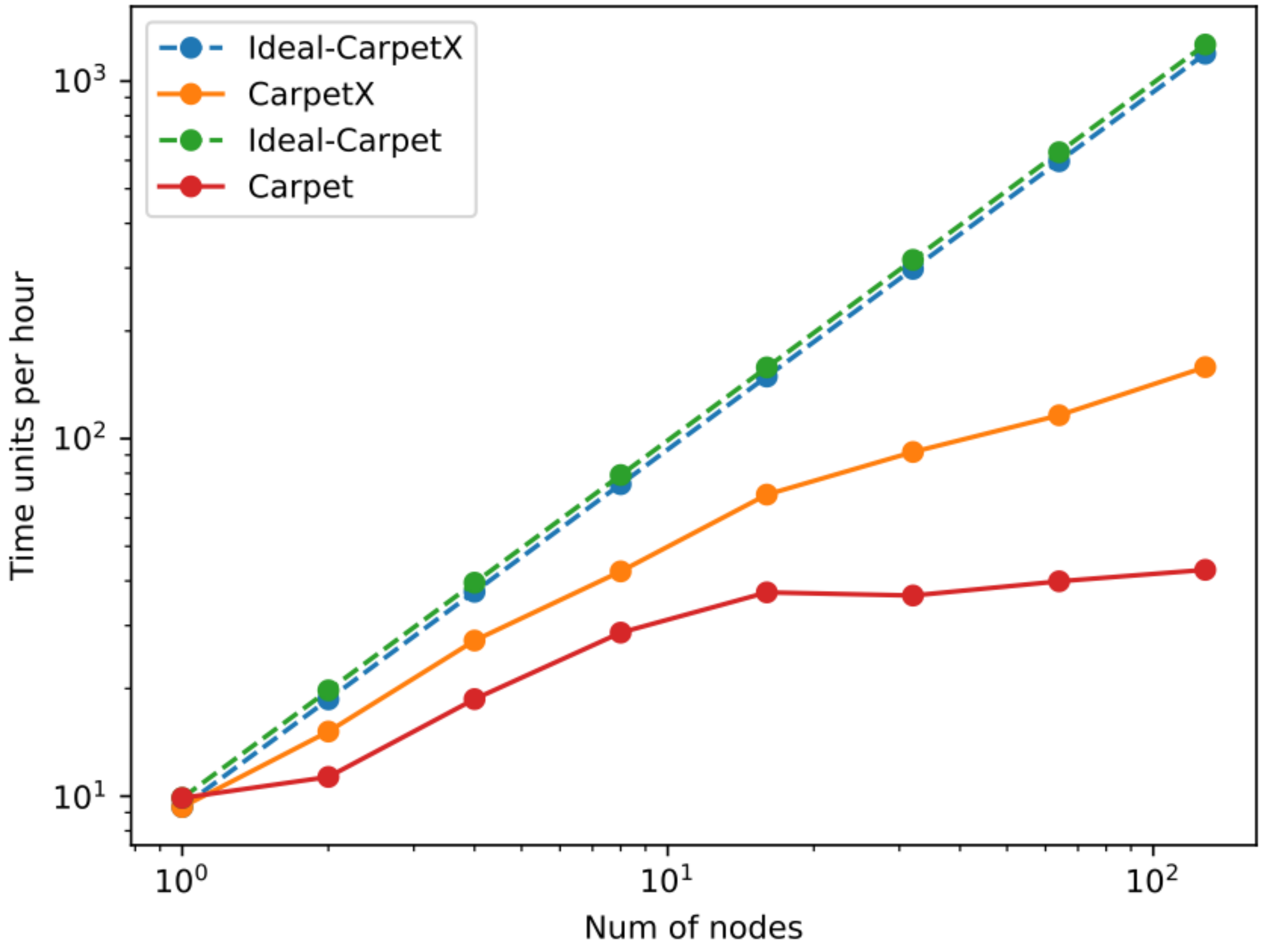


CPU Scaling Tests: CarpetX vs Carpet

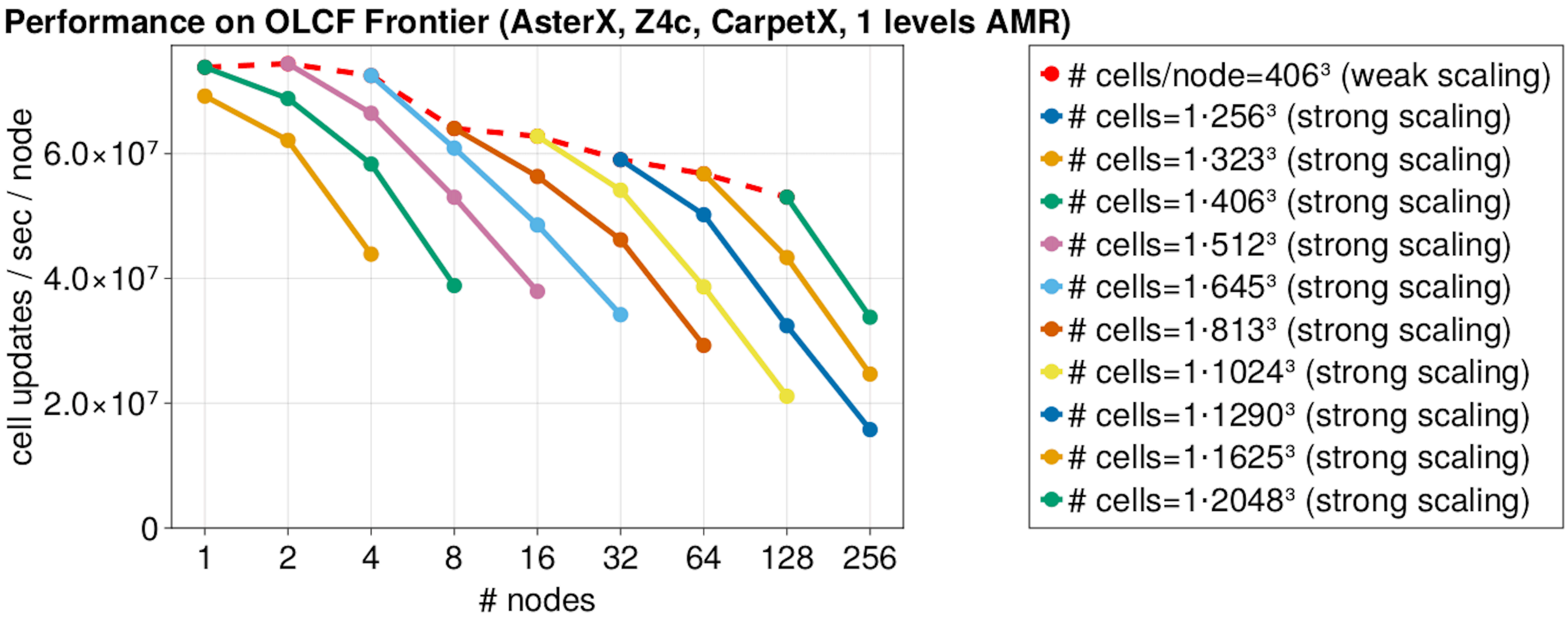
Carpet with sub-cycling in time



Carpet without sub-cycling in time



GPU Scaling Tests: AsterX



Profiling: Nvidia Nsight Systems

CPU workload

GPU workload

Memory transference

Timestep

Profiling: HPCToolkit

Profile: cactus_asterx_amr | Trace: cactus_asterx_amr

schedule.cxx | source.cxx | fluxes.cxx | driver.cxx | ScheduleTraverse.c | rhs.cxx

```
      Fbetay(p.I) = betas(1) * Psi(p.I);
      Fbetaz(p.I) = betas(2) * Psi(p.I);
      G(p.I) = alp(p.I) * Psi(p.I) / sqrtg - calc_contraction(betas, A_vert);
    });
}

extern "C" void AsterX_Fluxes(CCTK_ARGUMENTS) {
  DECLARE_CCTK_ARGUMENTS_AsterX_Fluxes;
  DECLARE_CCTK_PARAMETERS;

  eos_t eostype;
  eos::range rgeps(eps_min, eps_max), rgrho(rho_min, rho_max),
      rgye(ye_min, ye_max);

  if (CCTK_EQUALS(evolution_eos, "IdealGas")) {
    eostype = eos_t::IdealGas;
  } else if (CCTK_EQUALS(evolution_eos, "Hybrid")) {
    eostype = eos_t::Hybrid;
  } else if (CCTK_EQUALS(evolution_eos, "Tabulated")) {
    eostype = eos_t::Tabulated;
  } else {
    CCTK_ERROR("Unknown value for parameter \"evolution_eos\"");
```

Computation of fluxes: most expensive

Top-down view | Bottom-up view | Flat view

Scope	CPUTIME (sec): Sum (I)	CPUTIME (sec): Sum (E)	GPUOP (sec): Sum (I)	GPUOP (sec): Sum (E)	GKER (sec): Sum (I)	GKER (sec): Su
845 » [I] amrex::Gpu::synchronize()	[illegible]					
847 » amrex::Gpu::ErrorCheck(char const*, int)	7.96e-03 0.0%					
1958 » CarpetX::loop_over_blocks(CarpetX::active_levels_t con...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
832 » [I] CarpetX::active_levels_t::loop<CarpetX::loop_over_bl...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
loop at schedule.hxx: 80	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
loop at schedule.hxx: 81	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
84 » [I] operator()<CarpetX::GHExt::PatchData::LevelData>	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
833 » CarpetX::loop_over_blocks(amrex::FabArrayBase&...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
loop at schedule.cxx: 807	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
809 » [I] std::function<void (int, int)>::operator()(int, i...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
706 » std::_Function_handler<void (int, int), Carpet...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
316 » [I] operator()	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
836 » [I] std::function<void (int, int, int, int, _cGH...	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
706 » CCTK_CallFunction	3.91e-02 0.0%		1.03e+01 10.3%		1.03e+01 10.5%	
320 » AsterX_RHS	1.77e-02 0.0%		8.91e-01 0.9%		8.91e-01 0.9%	
320 » AsterX_Fluxes	1.40e-02 0.0%		7.78e+00 7.8%		7.78e+00 8.0%	
320 » AsterX_SourceTerms	7.46e-03 0.0%		1.59e+00 1.6%		1.59e+00 1.6%	
973 » CarpetX_CallScheduleGroup	9.26e+00 4.6%		1.19e+01 12.0%		1.18e+01 12.1%	
953 » CarpetX_CallScheduleGroup	9.25e+00 4.6%		1.19e+01 11.9%		1.18e+01 12.0%	
914 » CarpetX_CallScheduleGroup	9.23e+00 4.6%		1.19e+01 12.0%		1.18e+01 12.1%	
949 » CarpetX_CallScheduleGroup	8.89e+00 4.4%		5.29e+00 5.3%		5.08e+00 5.2%	
1289 » CarpetX_CallScheduleGroup	8.87e+00 4.4%		5.29e+00 5.3%		5.09e+00 5.2%	
969 » CarpetX_CallScheduleGroup	8.80e+00 4.4%		5.29e+00 5.3%		5.09e+00 5.2%	
929 » CarpetX_CallScheduleGroup	8.76e+00 4.3%		5.29e+00 5.3%		5.09e+00 5.2%	
908 » ODESolvers::statecomp_t::copy(CarpetX::valid_t) const	2.87e-01 0.1%		3.34e-01 0.3%		3.34e-01 0.3%	
979 » ODESolvers::statecomp_t::lincomb<3ul>(ODESolvers::statecomp_t con...	2.36e-01 0.1%		7.06e-01 0.7%		7.06e-01 0.7%	

Identifying Bottlenecks

Work in Progress

- Extend EOSX and Con2PrimFactory
- Extend weak and strong scaling tests on GPUs
- Explore error estimator criteria for AMR
- BNS & SMBBH merger simulations!

Thank you for your attention!