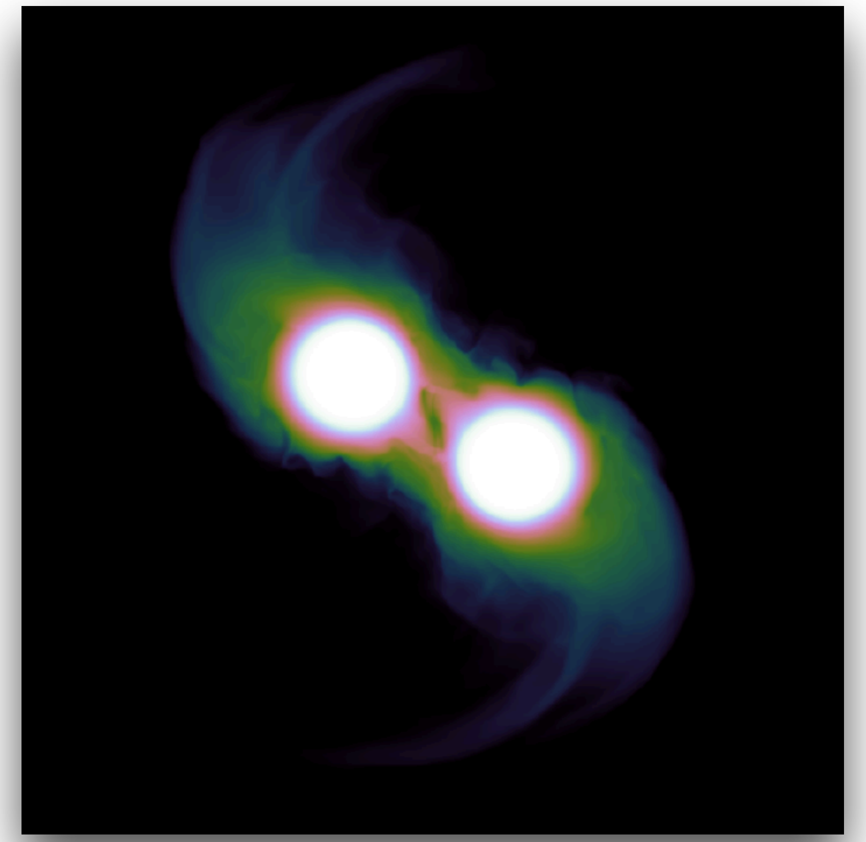
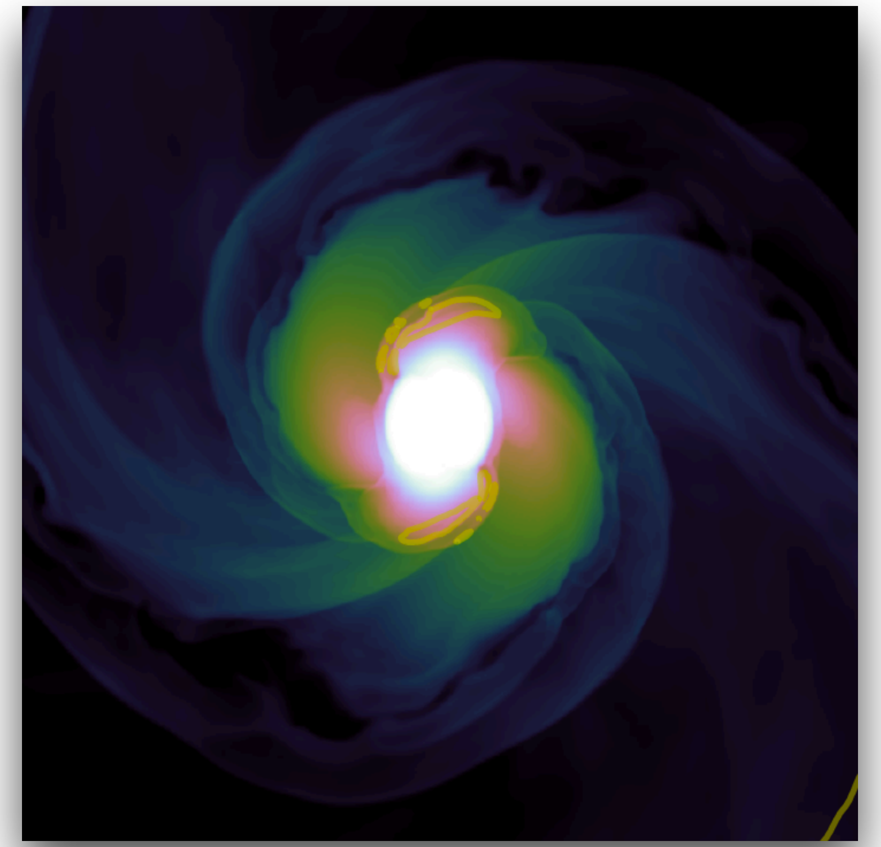
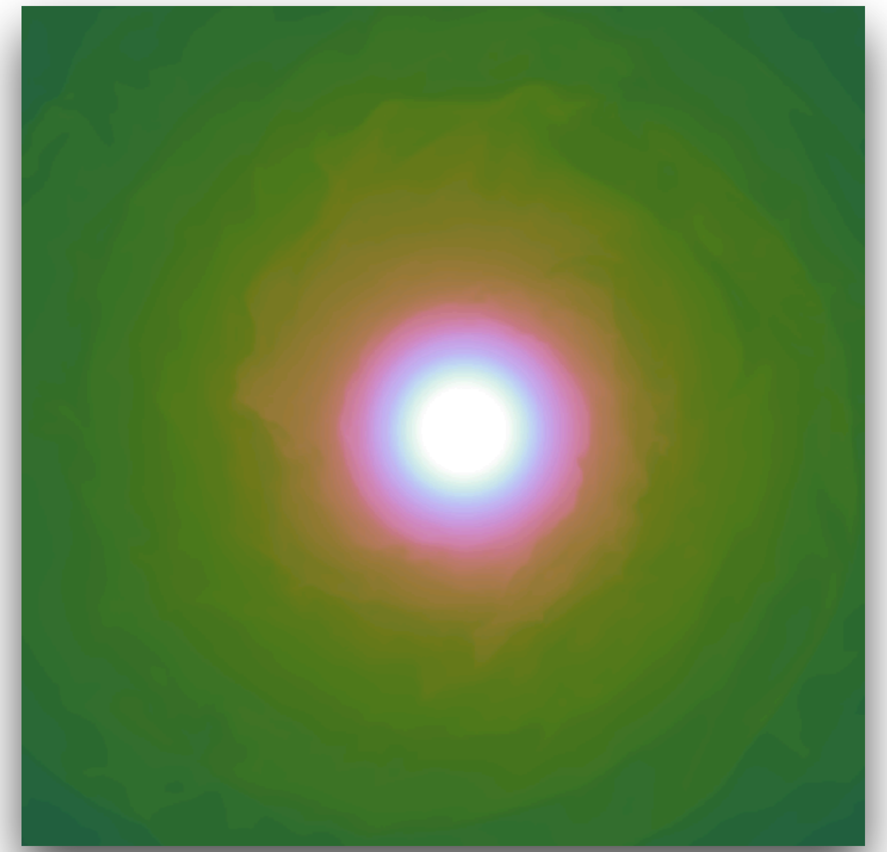
GRMHD Simulations of Binary Neutron Star Mergers

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in collaboration with

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ECT* Workshop: Neutron Stars as Multi-Messenger Laboratories for Dense Matter

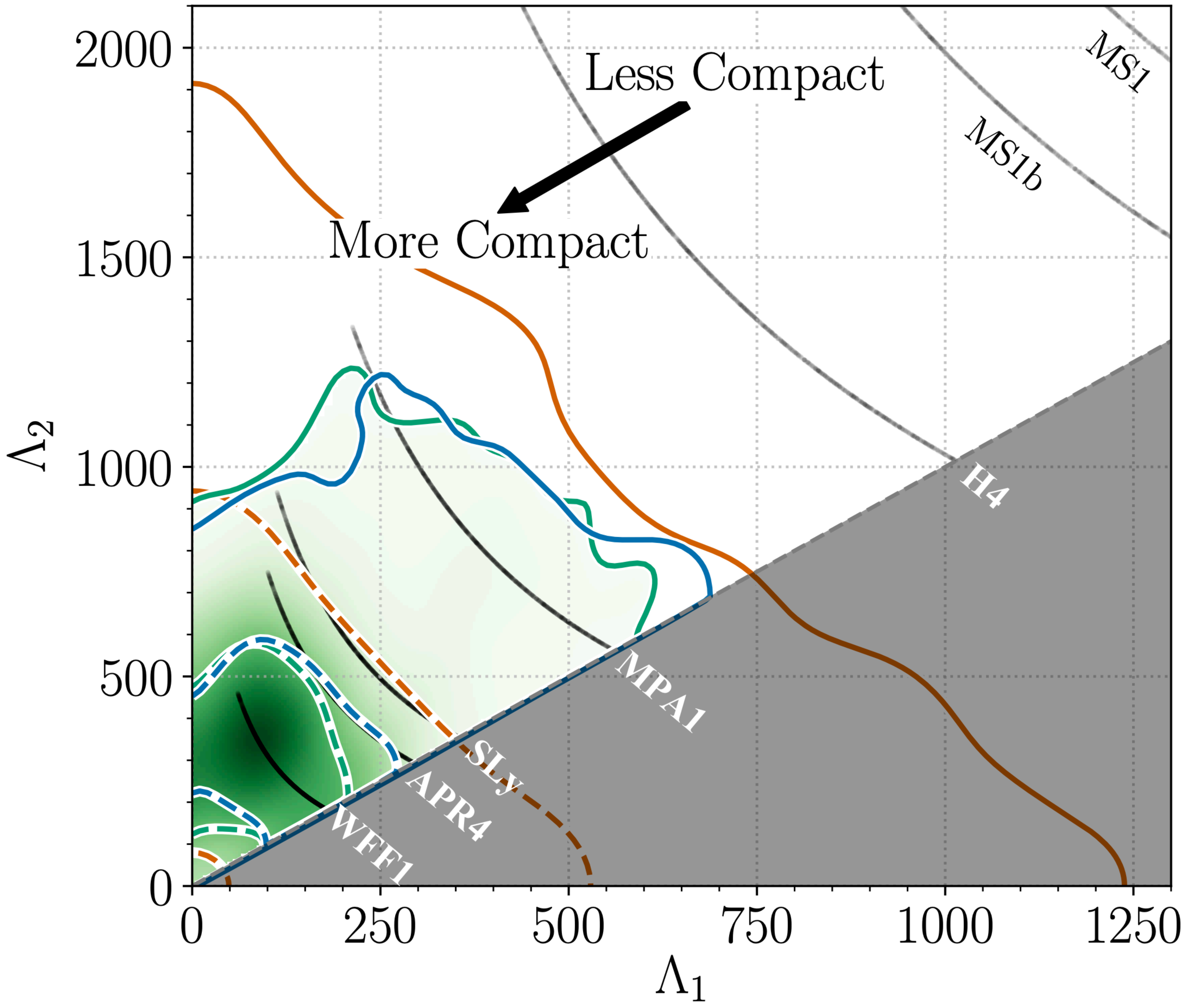
June 14-17, 2021

Binary Neutron Star Mergers

Powerful sources of:

- Gravitational waves
- Short gamma-ray bursts
- Radioactively powered kilonovae

Ideal probes to extract information on NS EOS



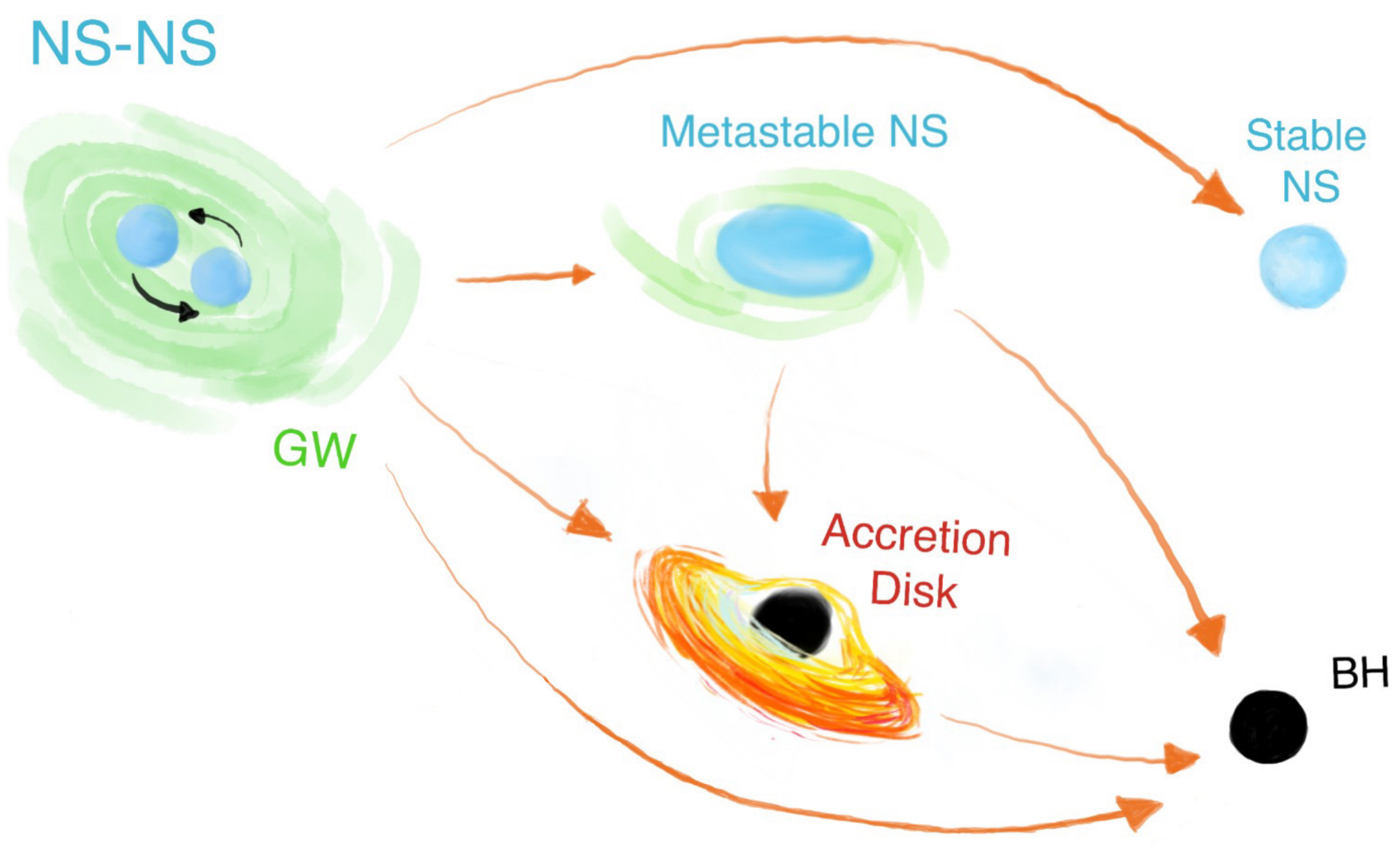
[Abbott+2018]

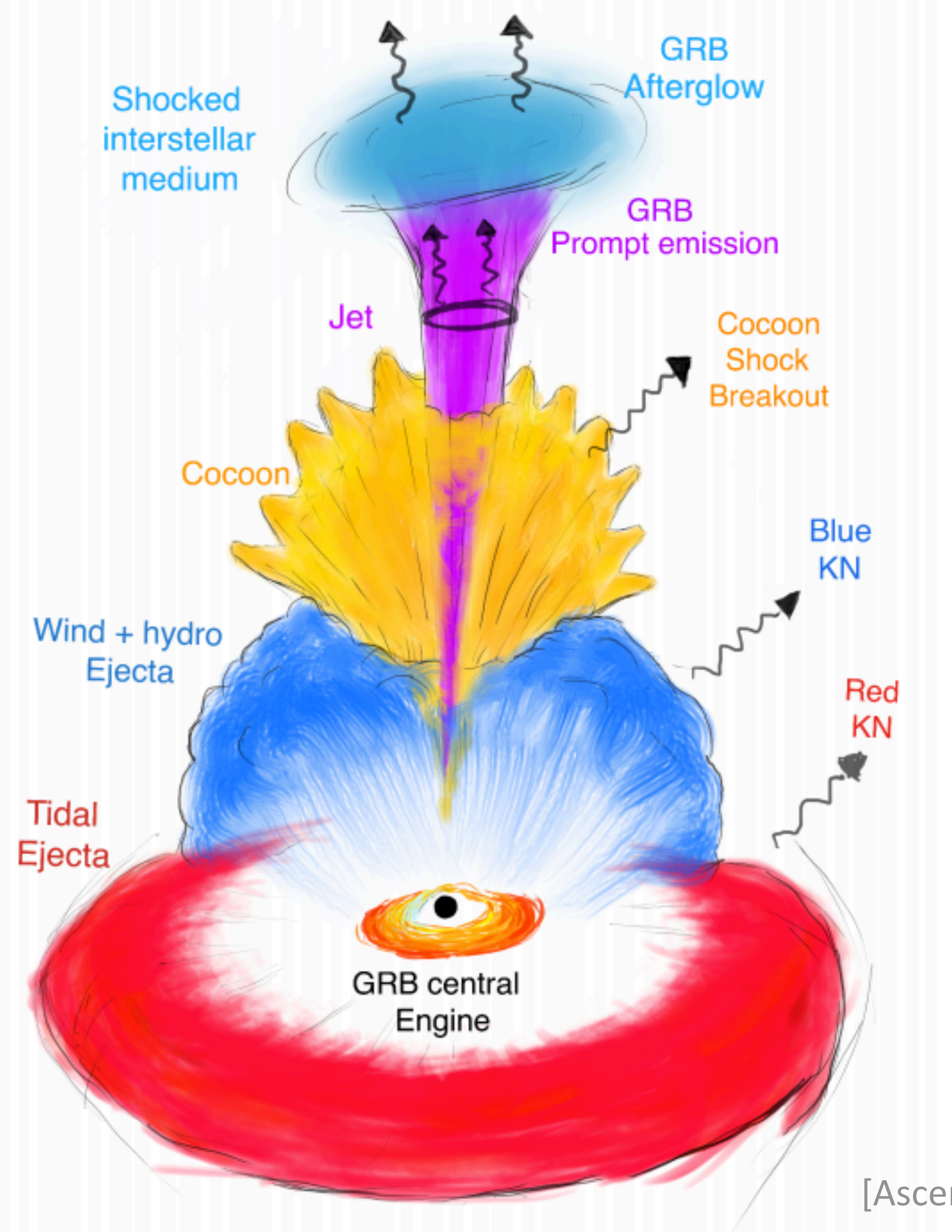
GW170817 | GRB170817A | AT2017gfo

- Smoking gun evidence connecting BNS with SGRBs
- Refined constraints on NS EOS via GWs and EM counterparts (see earlier talk by Prof. Bernuzzi)

A complete description requires finite temperature composition-dependent EOS and neutrino radiation, but also *magnetic fields*

SGRB Central Engines and Kilonova





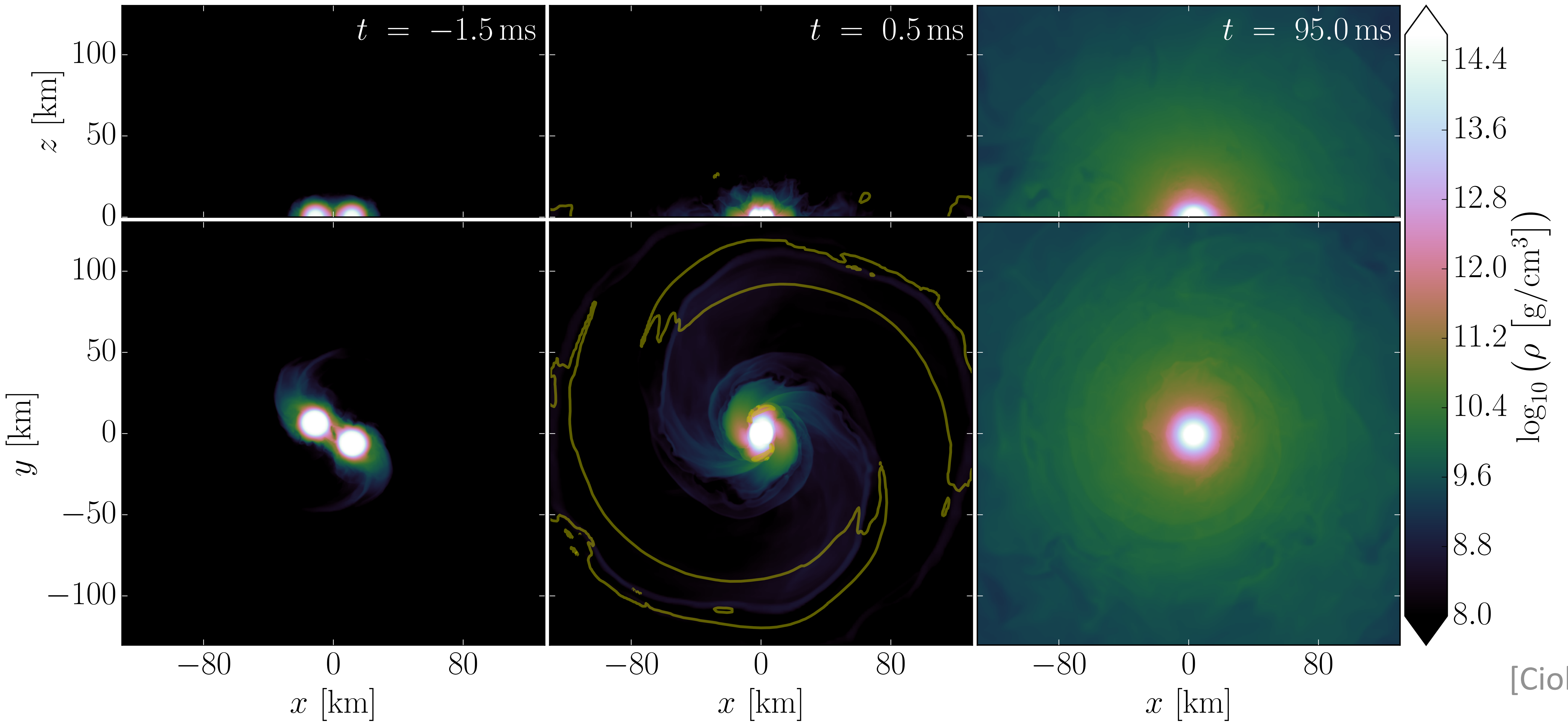
[Ascenzi+2020]

Open Questions:

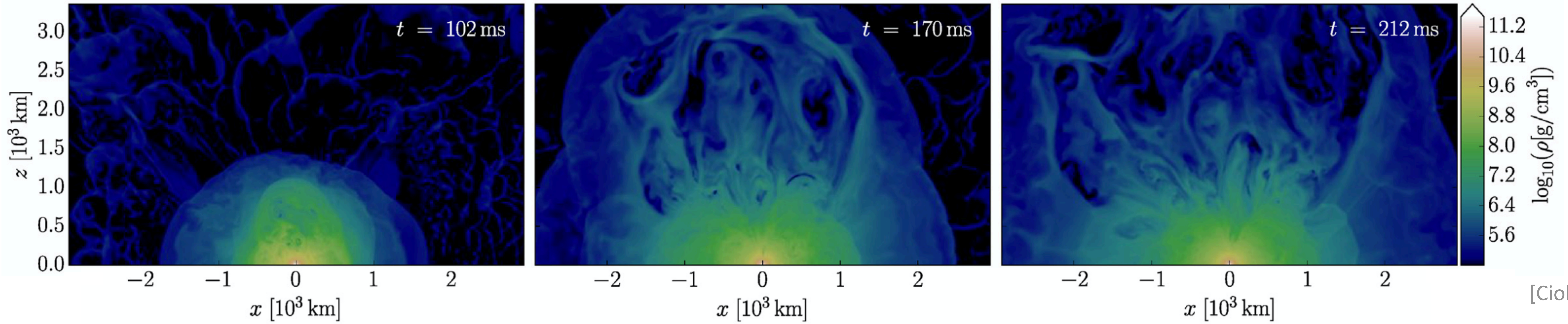
- Can a MNS/magnetar power an SGRB jet?
- What is the structure of an SGRB jet?
- Can the magnetically driven post-merger ejecta from MNS remnant act as a source of *blue* kilonova?

BNS Simulations with Long Post-Merger Evolution

Merger produces a differentially rotating, metastable SMNS



[Ciolfi+2019]

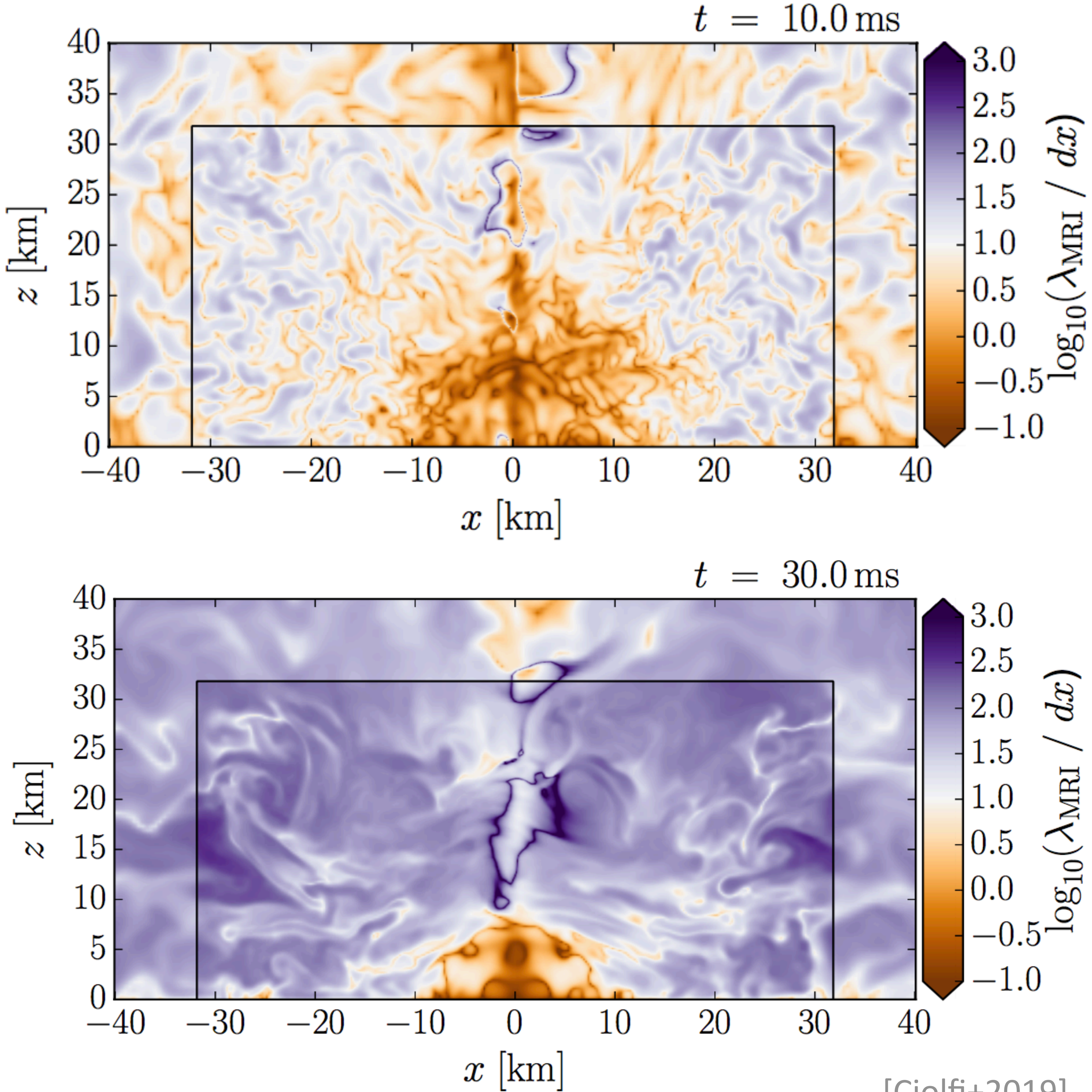


[Ciolfi 2020]

We cover unexplored timescales → Novel insights on how the magnetic field evolves and its effects on the system

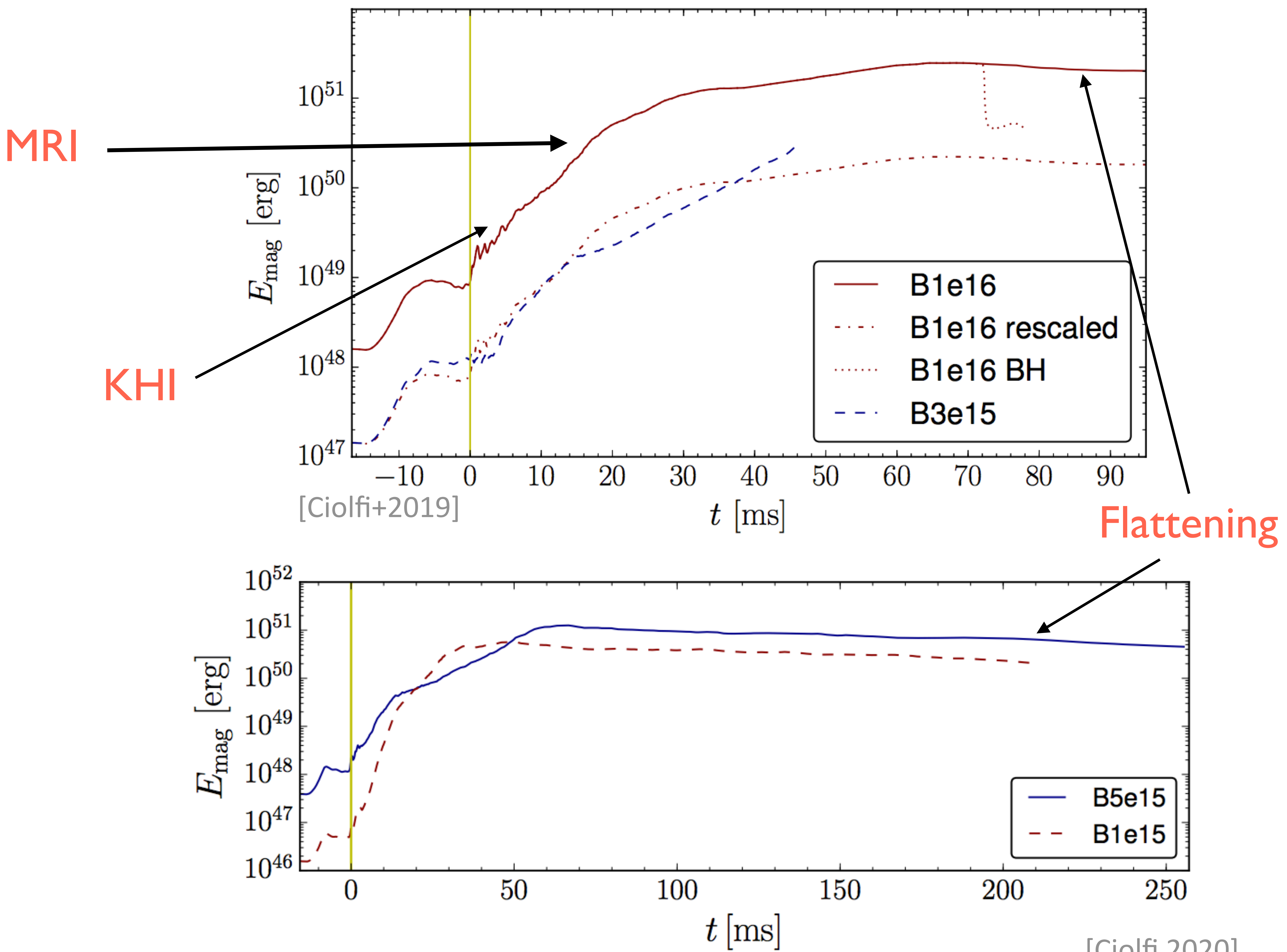
Magnetic Field Amplification

Magneto-Rotational Instability (MRI)



[Ciolfi+2019]

Magnetic Energy Evolution

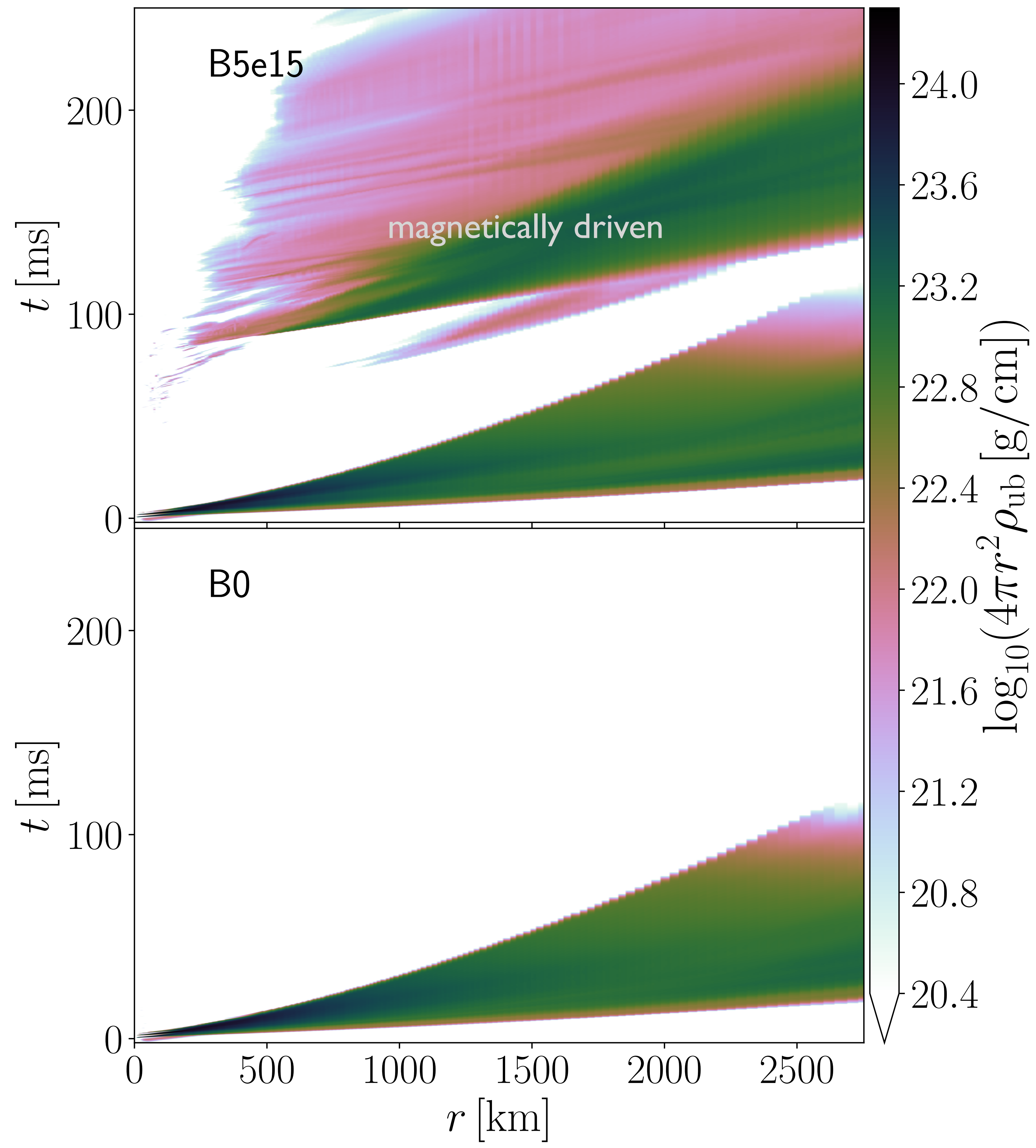


[Ciolfi 2020]

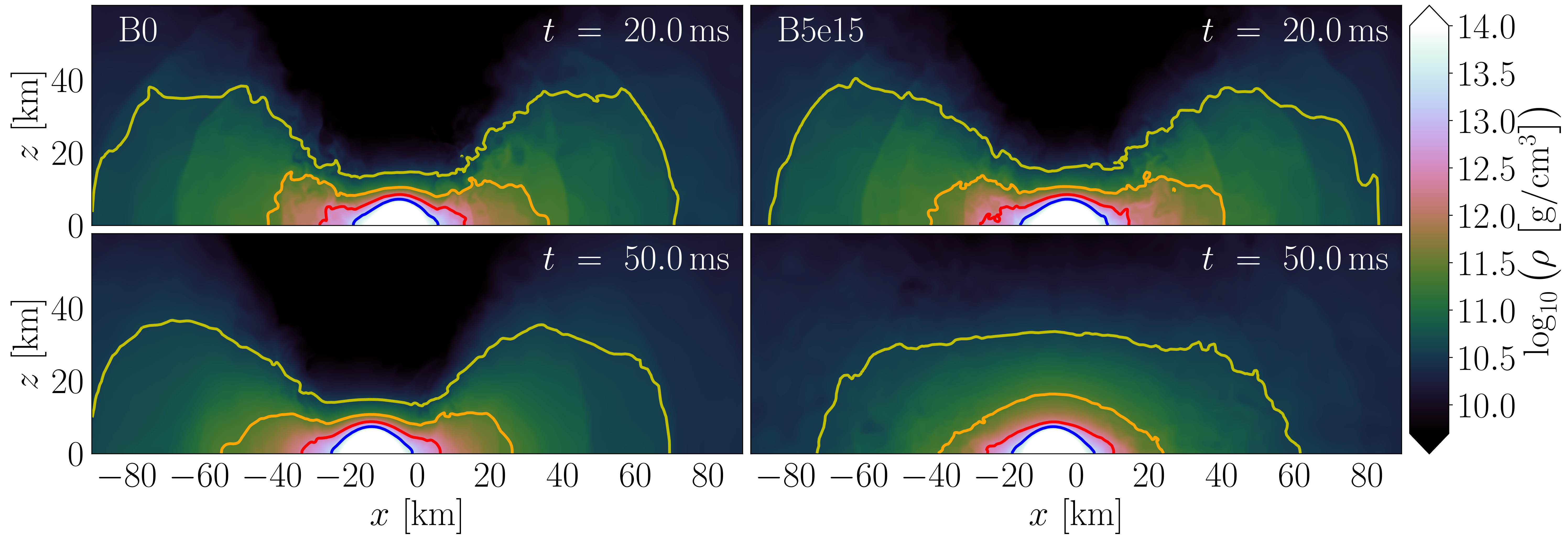
Absolute upper limit for magnetisation of a long-lived NS

Mass Outflows & Remnant Structure

radial distribution of unbound matter



- Magnetically enhanced and isotropic mass outflow

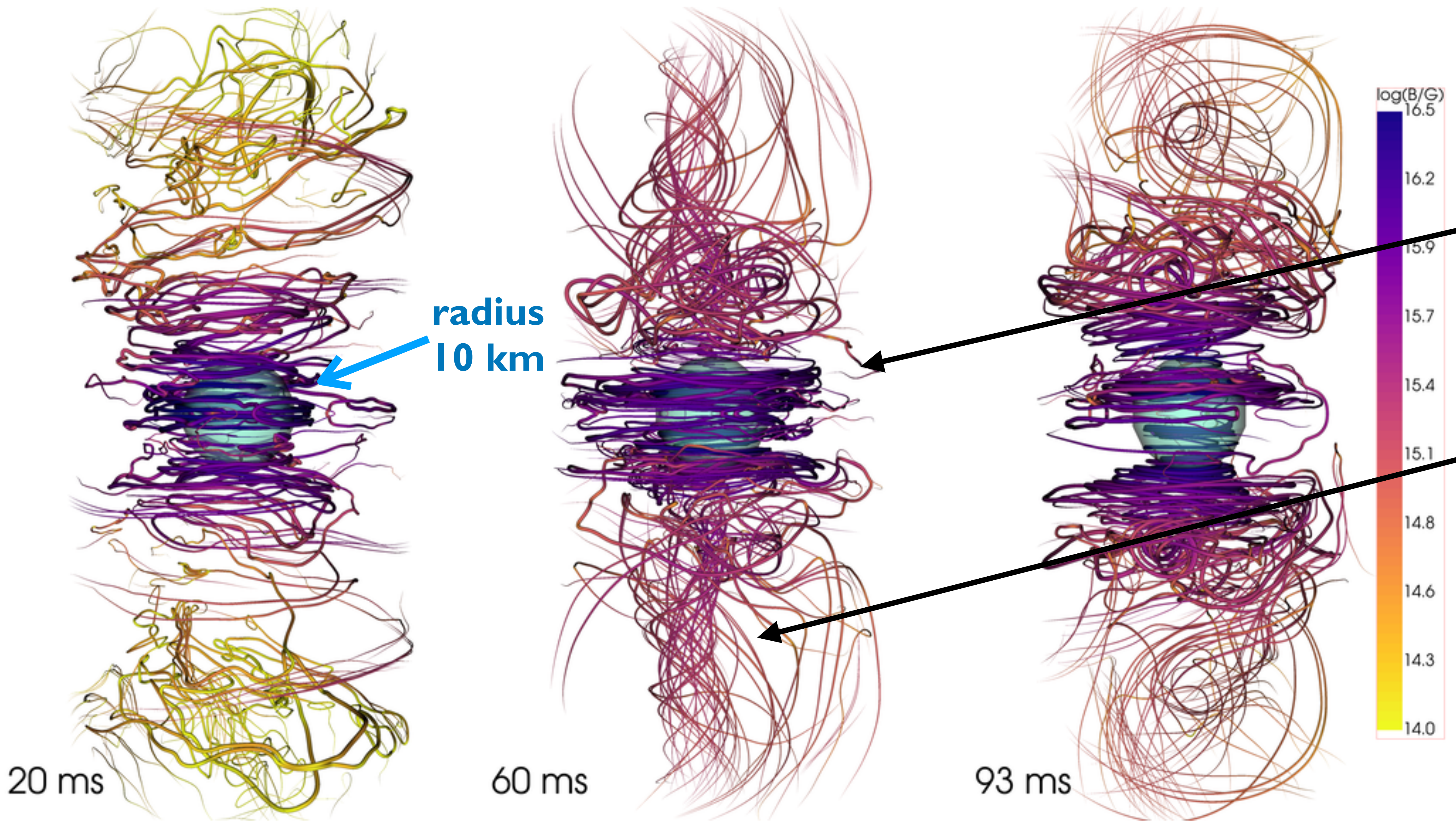


- Around 20ms post-merger: nearly spherical core attached to a torus shaped outer envelope

- At later times: for magnetised case, more isotropic distribution

Baryon pollution problem → Magnetically driven ejecta can act as an obstacle for jet formation

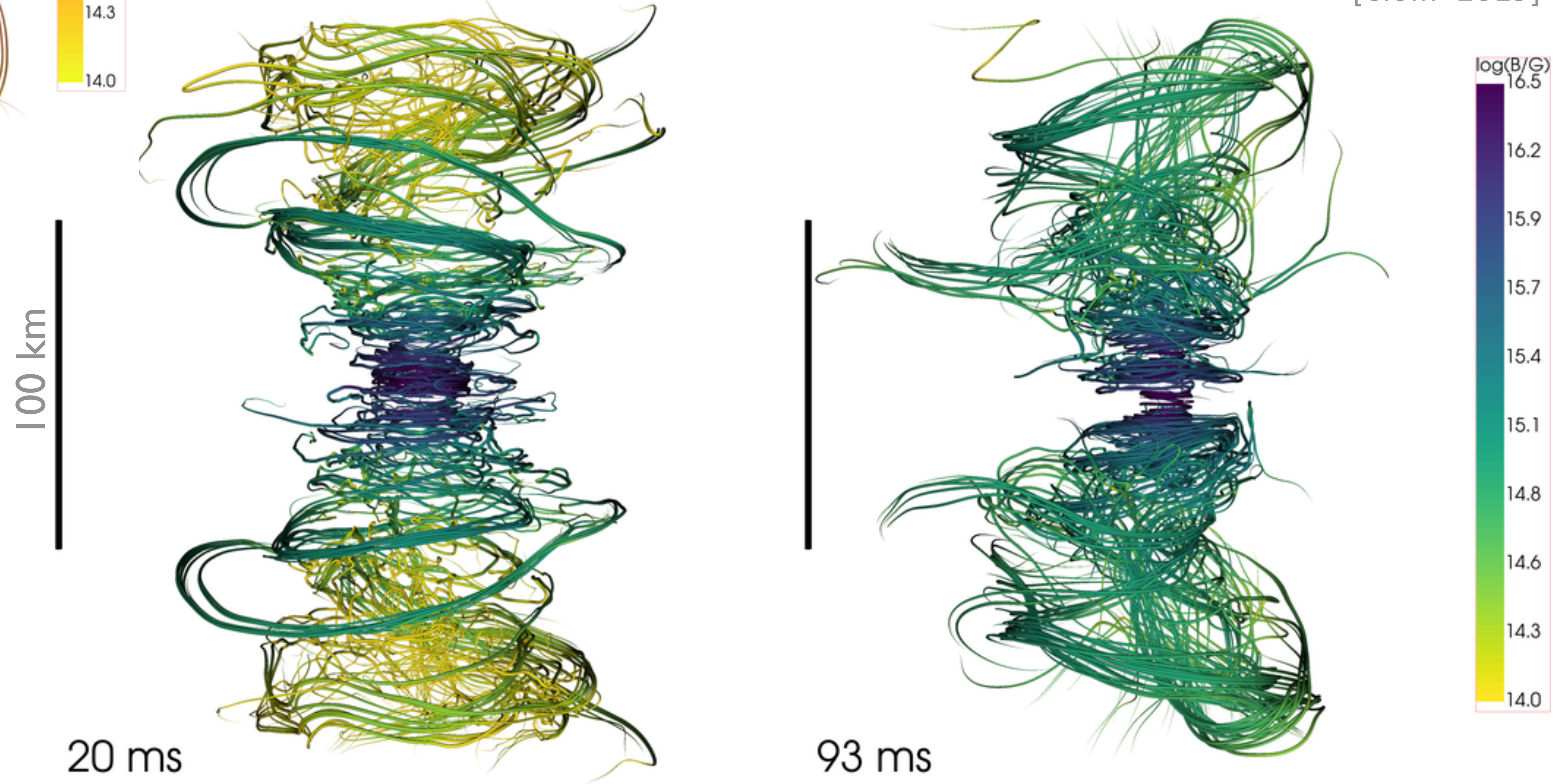
Magnetic Field Geometry



Toroidal field: Strong amplification, mostly equitorial

Poloidal field: Transient helical structures along spin-axis

[Ciolfi+2019]



- Large-scale field lines extending up to more than 100 km

Hints of emerging global magnetic field

BNS Beyond 100 ms

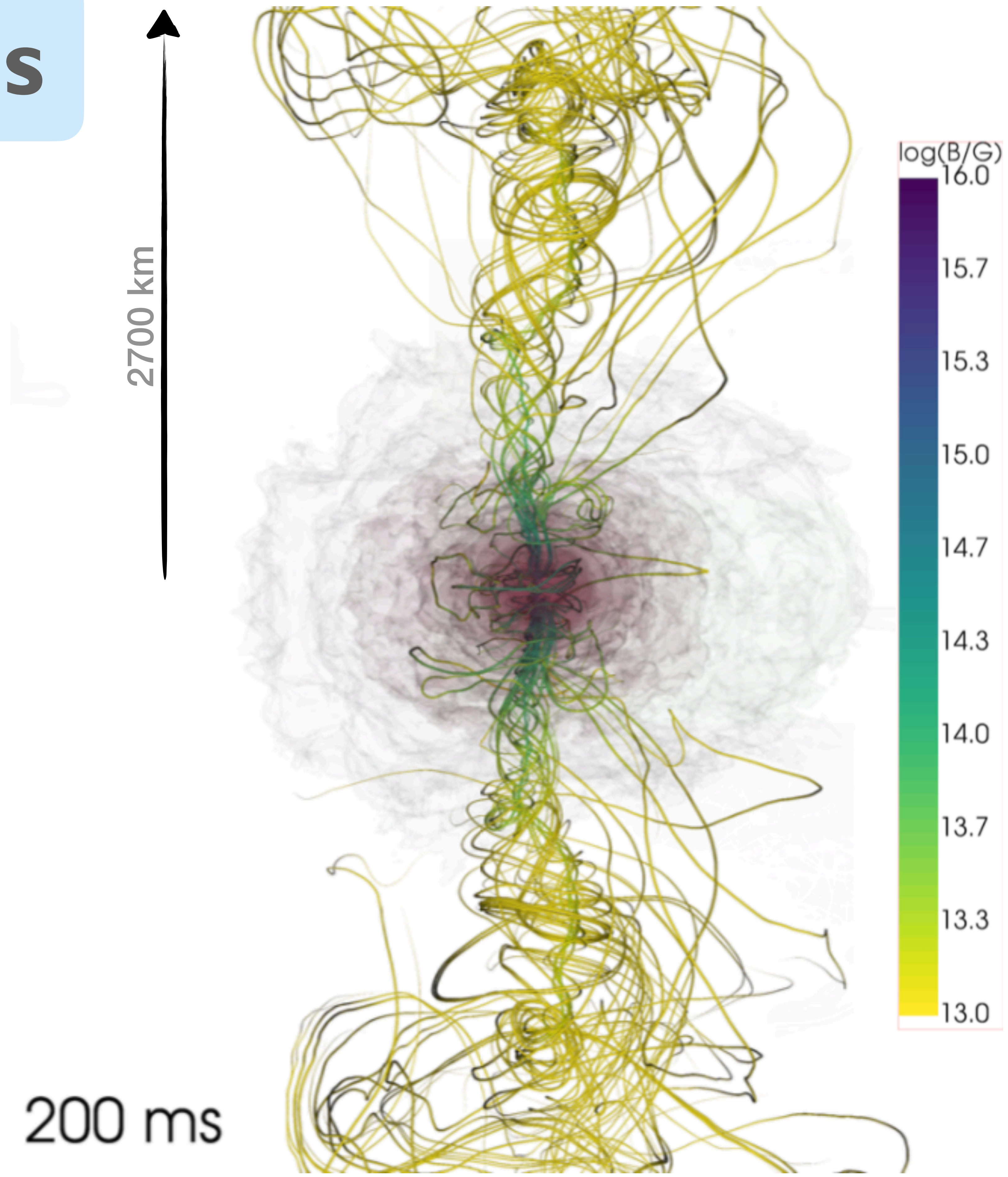
- Jet-like helical structure emerges
- Isotropic matter distribution (no accretion disk)

Collimated outflow

- Breaking out around 170 ms
- Radial velocities reach 0.2-0.3c

Compatibility with GRB 170817A

- Not enough jet core energy
- Outflow too heavy



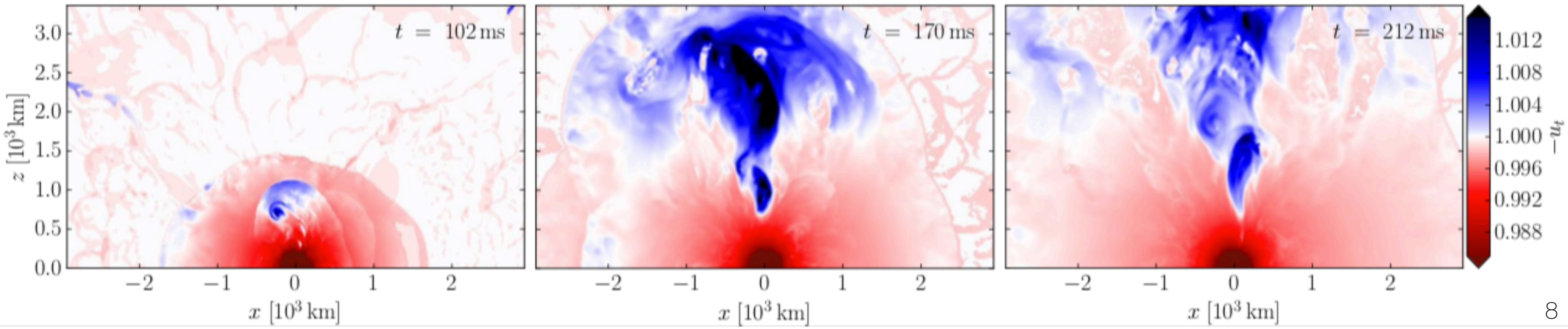
what it has

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

what it needs

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

Matter unbound when $u_t \leq -1$



[Ciolfi 2020]

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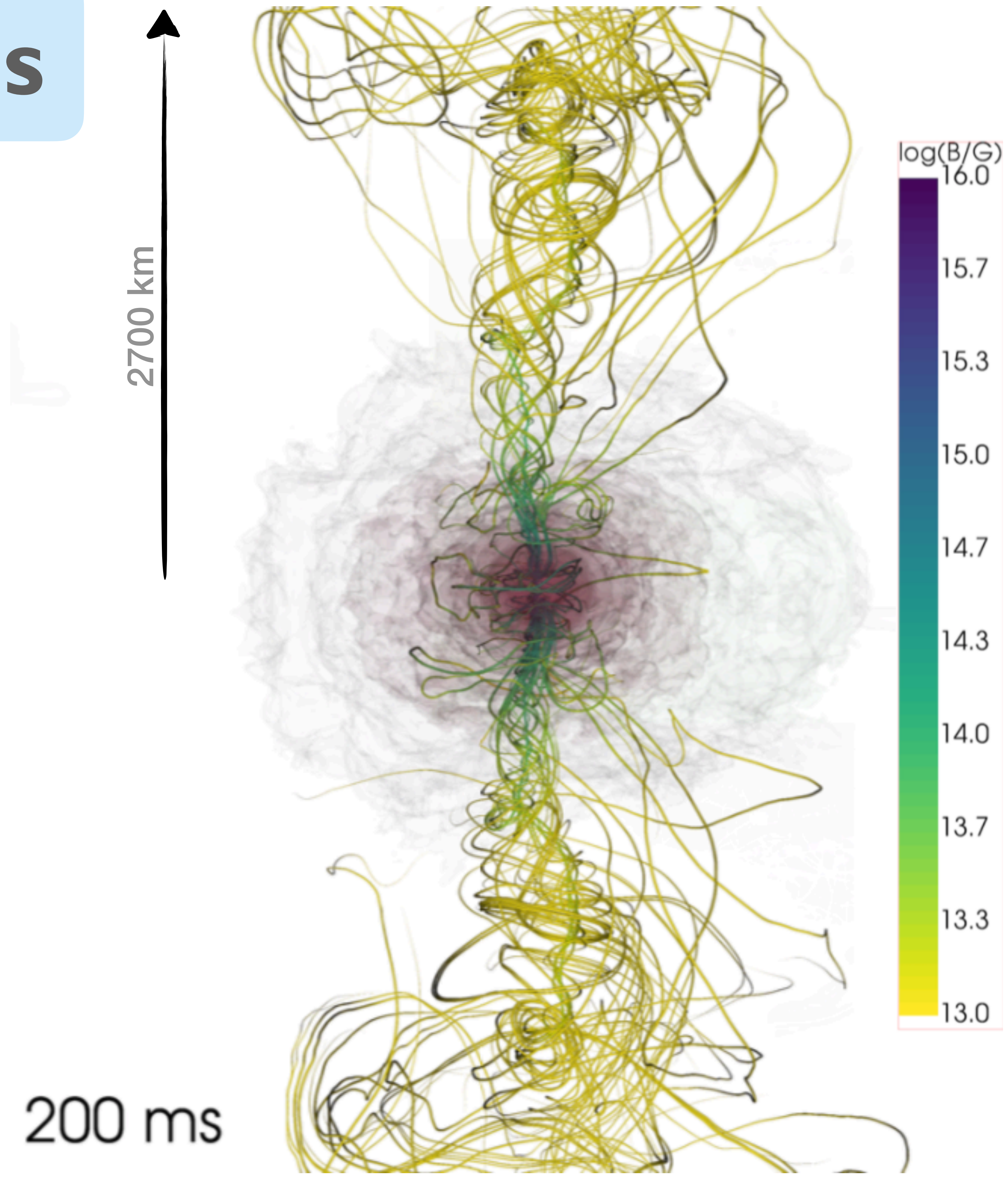

[Ciolfi 2020]

what it has

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what it needs

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

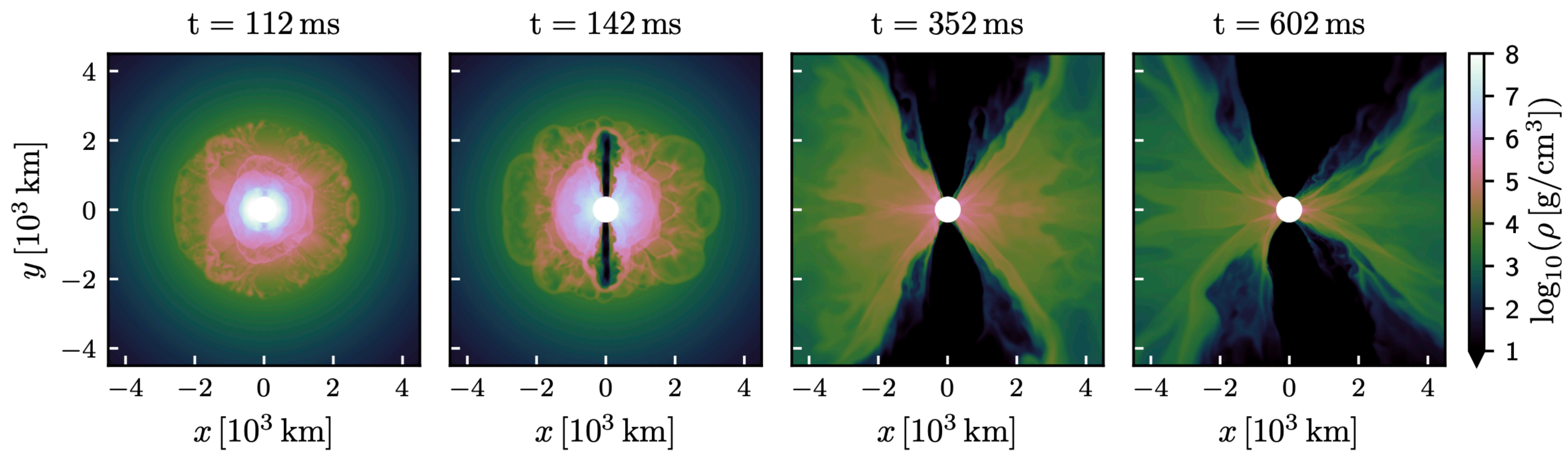
Magnetar scenario disfavoured for producing a SGRB jet

SGRBs in BNS Merger Environments

[Pavan+2021]

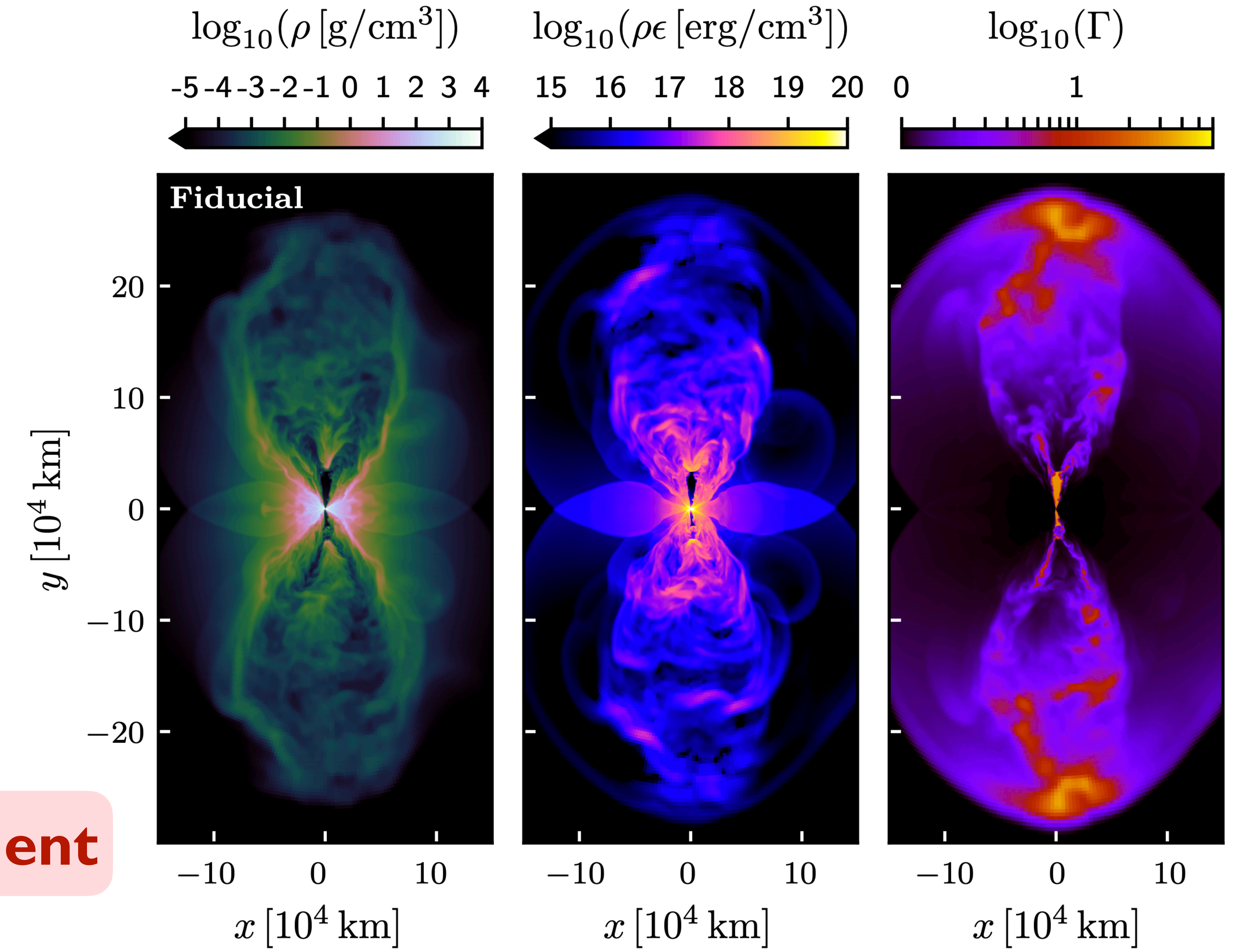
Physical setup:

- RHD jet simulations in PLUTO
- Importing ID from BNS merger simulation
- 'Top hat' jet injection
- Taub EOS for evolution
- Newtonian gravity included



Key results:

- Gravitational pull: important effect
- Realistic BNS merger environment impacts the final jet properties (compared to simpler hand-made environment)
- Dependence on jet launching time



First SGRB jet simulations in a BNS merger environment

Magnetically Driven Baryon Winds and 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)

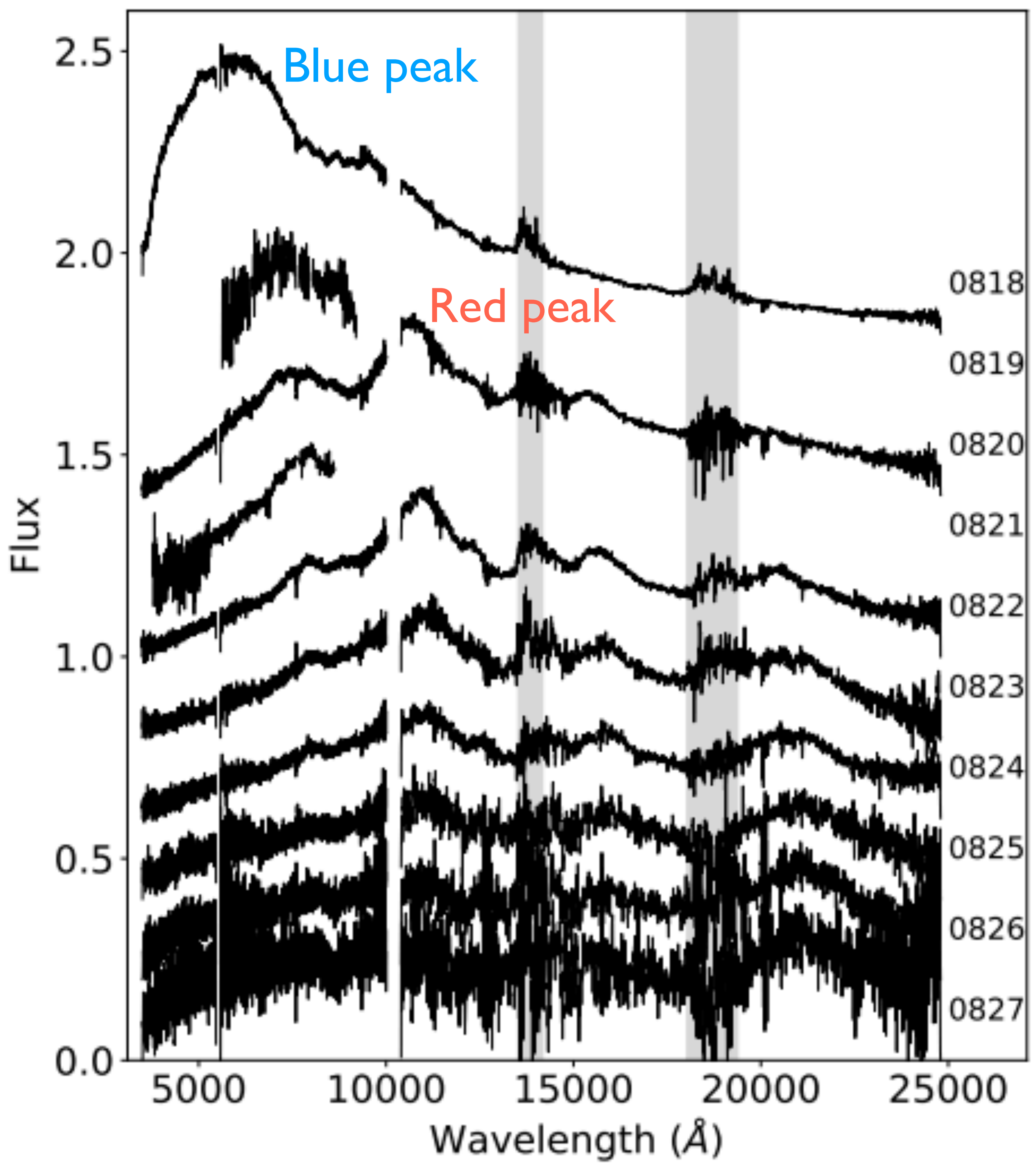
-ejecta velocities: about **0.1c**

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

-source: post-merger disk winds

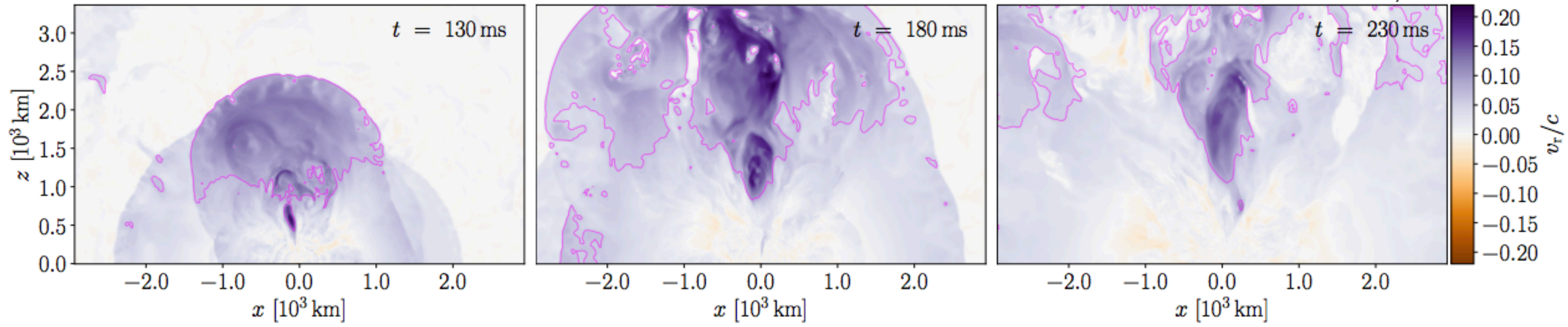
[Perego+2014, Siegel & Metzger 2017a,b,....]

[Pian+2017]



Time-evolution of AT2017gfo spectra

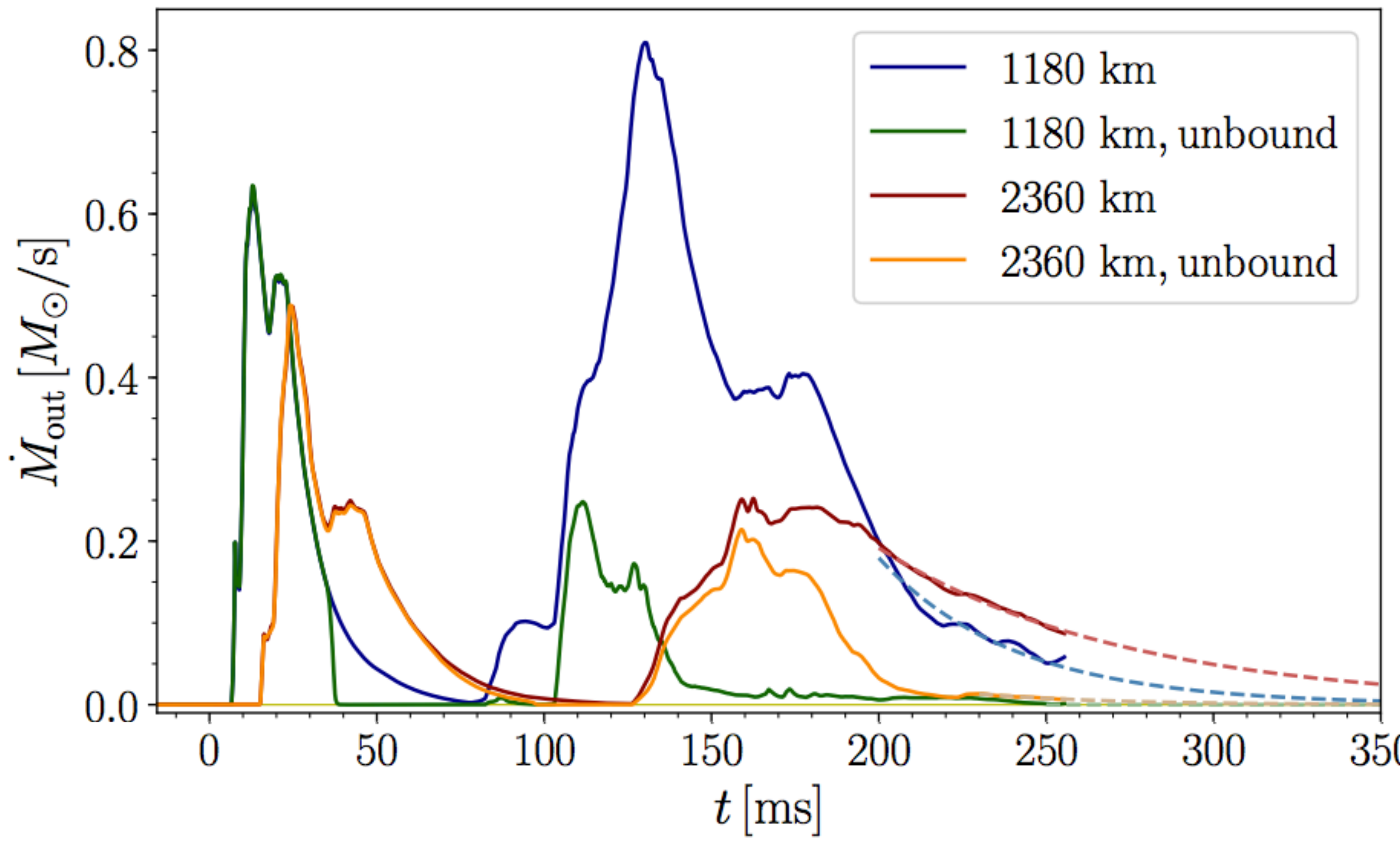
Radial velocity evolution



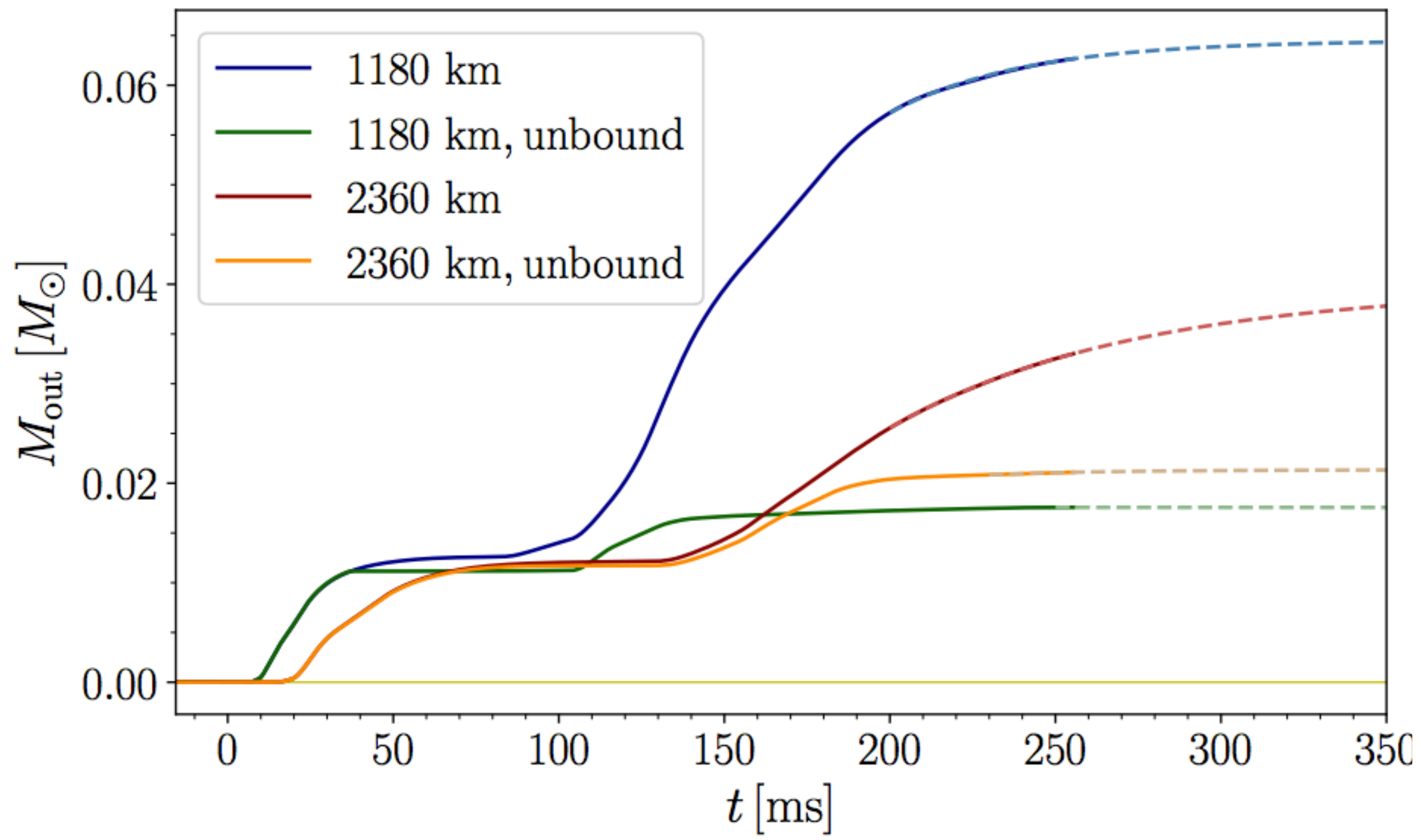
ejecta velocities reach about **0.2-0.22c**

[Ciolfi, Kalinani 2020]

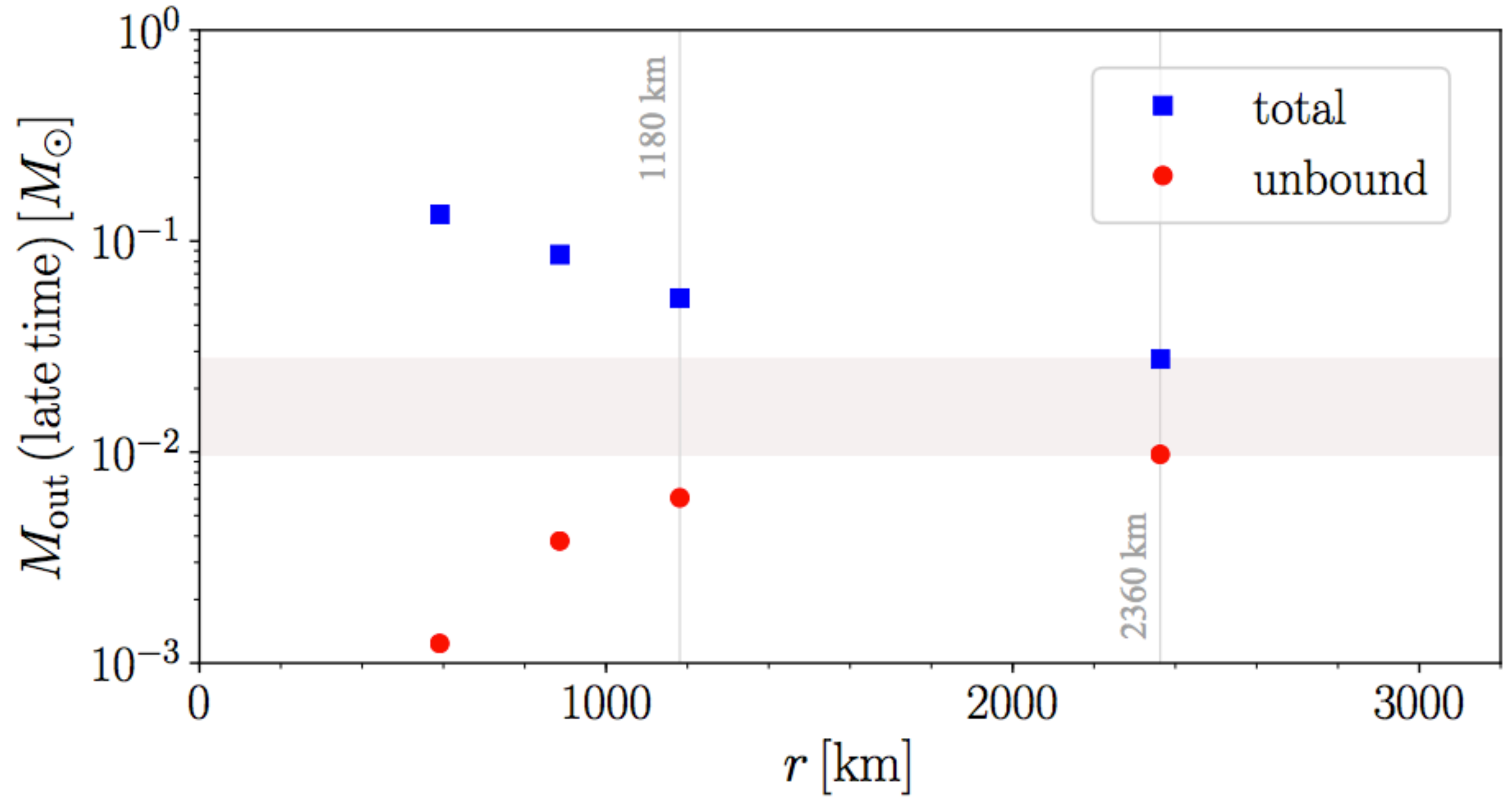
Mass outflow rate evolution



Mass outflow evolution



Radial distribution of mass outflow



total unbound ejecta mass reaches about **0.01-0.028 M_{sun}**

Ejecta velocities and mass consistent with the blue component of the kilonova

The Spritz code: GRMHD with Neutrino Leakage

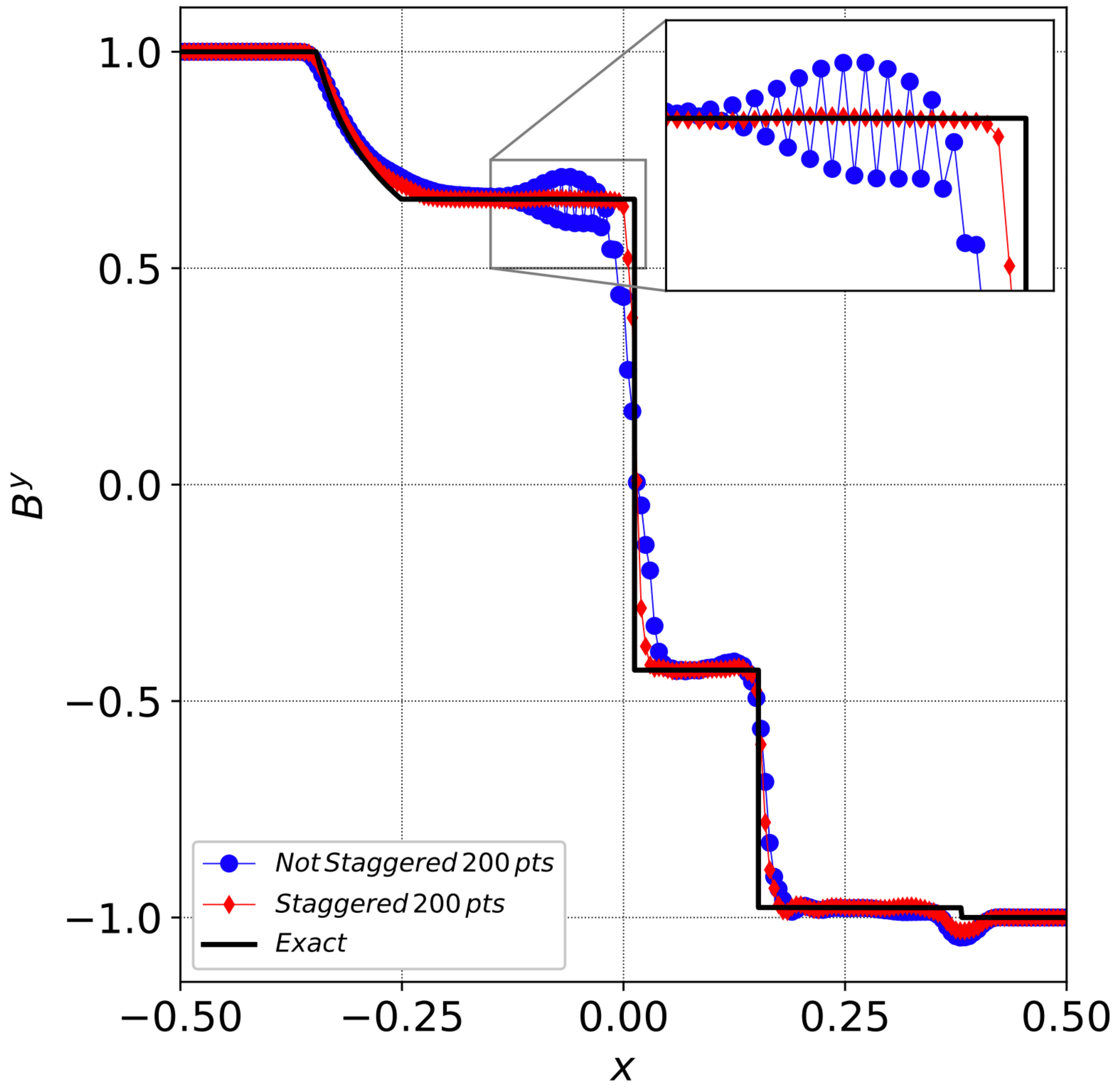
[Cipolletta+2020, Cipolletta+2021]

Version 1.0:

- Vector potential staggered evolution
- Designed to work within Einstein Toolkit framework
- Support for ideal gas and polytropic EOSs via EOS_Omni
- Undergone extensive 1D, 2D and 3D testing

Version 2.0:

- Support for composition-dependent finite temperature EOS
- ZelmaniLeak neutrino leakage scheme [Ott+2012]
- Evolution equation of electron fraction
- 1D Palenzuela C2P scheme
- Higher order schemes: WENOZ with HLLE4 and HLLE6
- Publicly available on Zenodo: 10.5281/zenodo.4350072

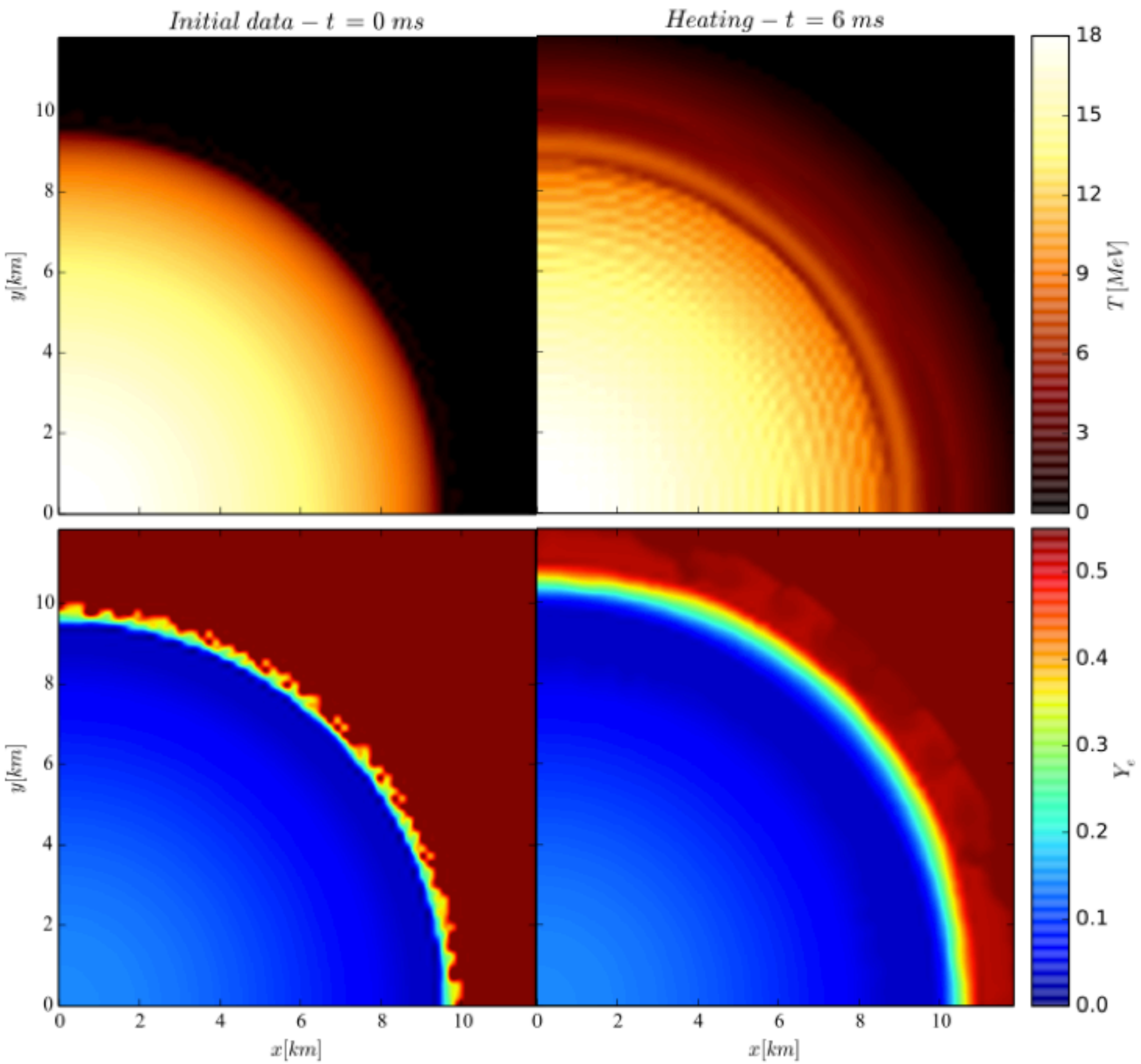


Balsara 1 shocktube test: staggered vs non-staggered vector potential evolution

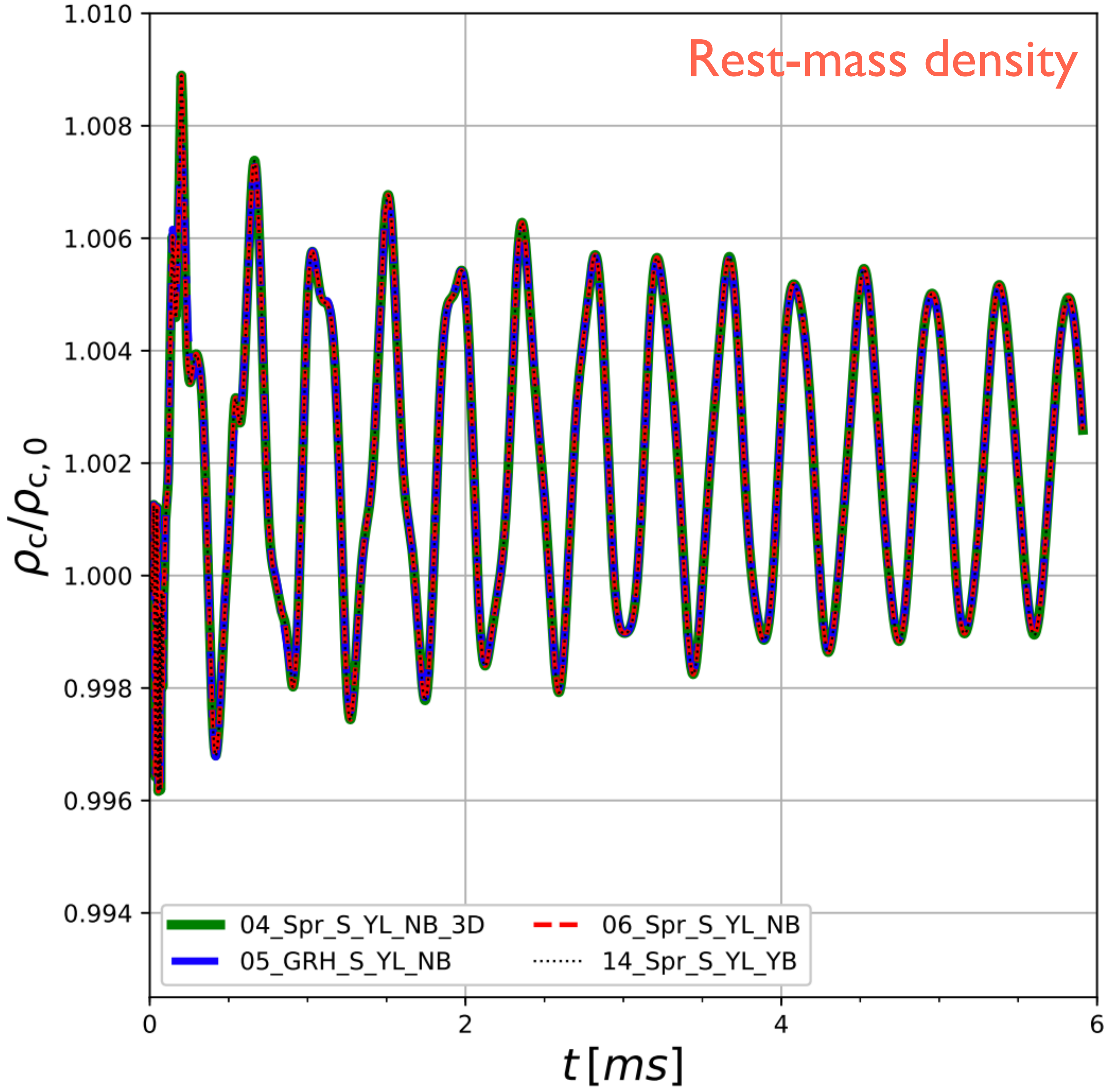
3D TOV tests

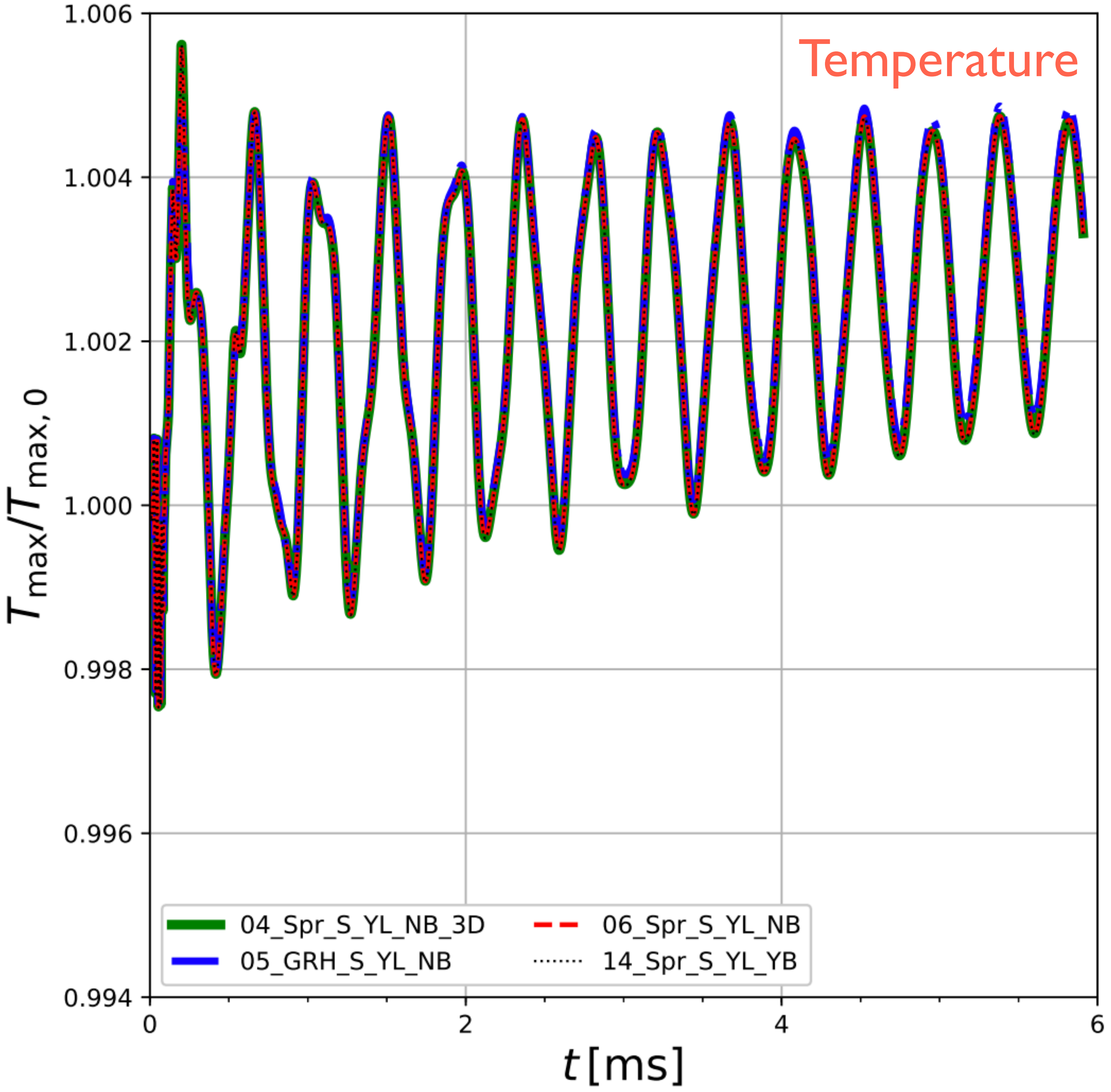
List of TOV simulations with different configurations

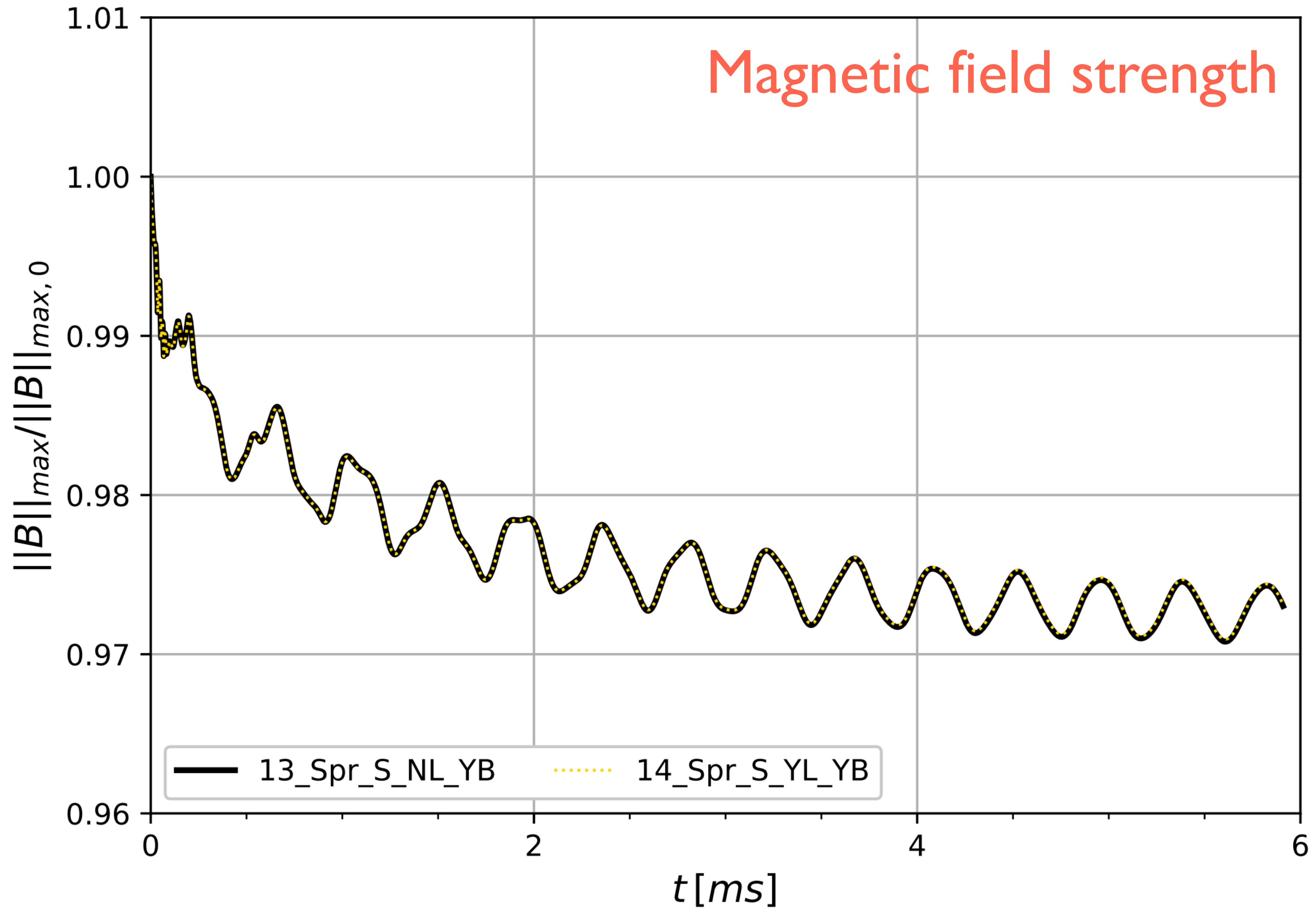
ID	Test Name	β-eq. Initial Data	ν Leakage	T evolution
01	Spr_S_NL_NB_3D	S-slice $1k_b$/bar	Disabled	Yes
02	GRH_S_NL_NB	S-slice $1k_b$/bar	Disabled	Yes
03	Spr_S_NL_NB	S-slice $1k_b$/bar	Disabled	Yes
04	Spr_S_YL_NB_3D	S-slice $1k_b$/bar	Enabled	Yes
05	GRH_S_YL_NB	S-slice $1k_b$/bar	Enabled	Yes
06	Spr_S_YL_NB	S-slice $1k_b$/bar	Enabled	Yes
07	GRH_T_NL_NB	T-slice 0.01 MeV	Disabled	Yes
08	Spr_T_NL_NB	T-slice 0.01 MeV	Disabled	Yes
09	Spr_T1_NL_NB	T-slice 0.01 MeV	Disabled	Yes (t = 2ms)
10	GRH_T_YL_NB	T-slice 0.01 MeV	Enabled	Yes
11	Spr_T_YL_NB	T-slice 0.01 MeV	Enabled	Yes
12	Spr_T1_YL_NB	T-slice 0.01 MeV	Enabled (t = 3ms)	Yes (t = 2ms)
13	Spr_S_NL_YB	S-slice $1k_b$/bar	Disabled	Yes
14	Spr_S_YL_YB	S-slice $1k_b$/bar	Enabled	Yes
15	Spr_T1_NL_YB	T-slice 0.01 MeV	Disabled	Yes (after t = 2ms)
16	Spr_T1_YL_YB	T-slice 0.01 MeV	Enabled (t = 3ms)	Yes (after t = 2ms)

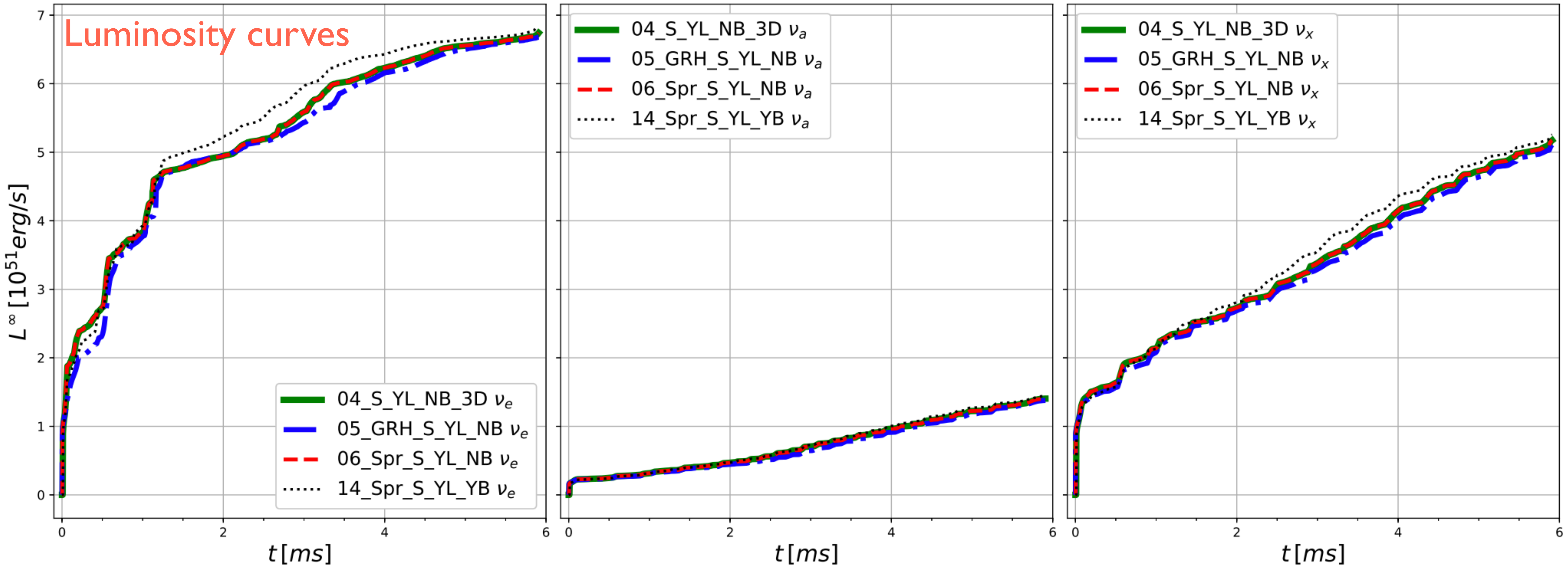


Results of simulation 06. Image courtesy: E. Giangrandi









[Cipolletta+2021]

Preliminary BNS tests with SLy4 EOS

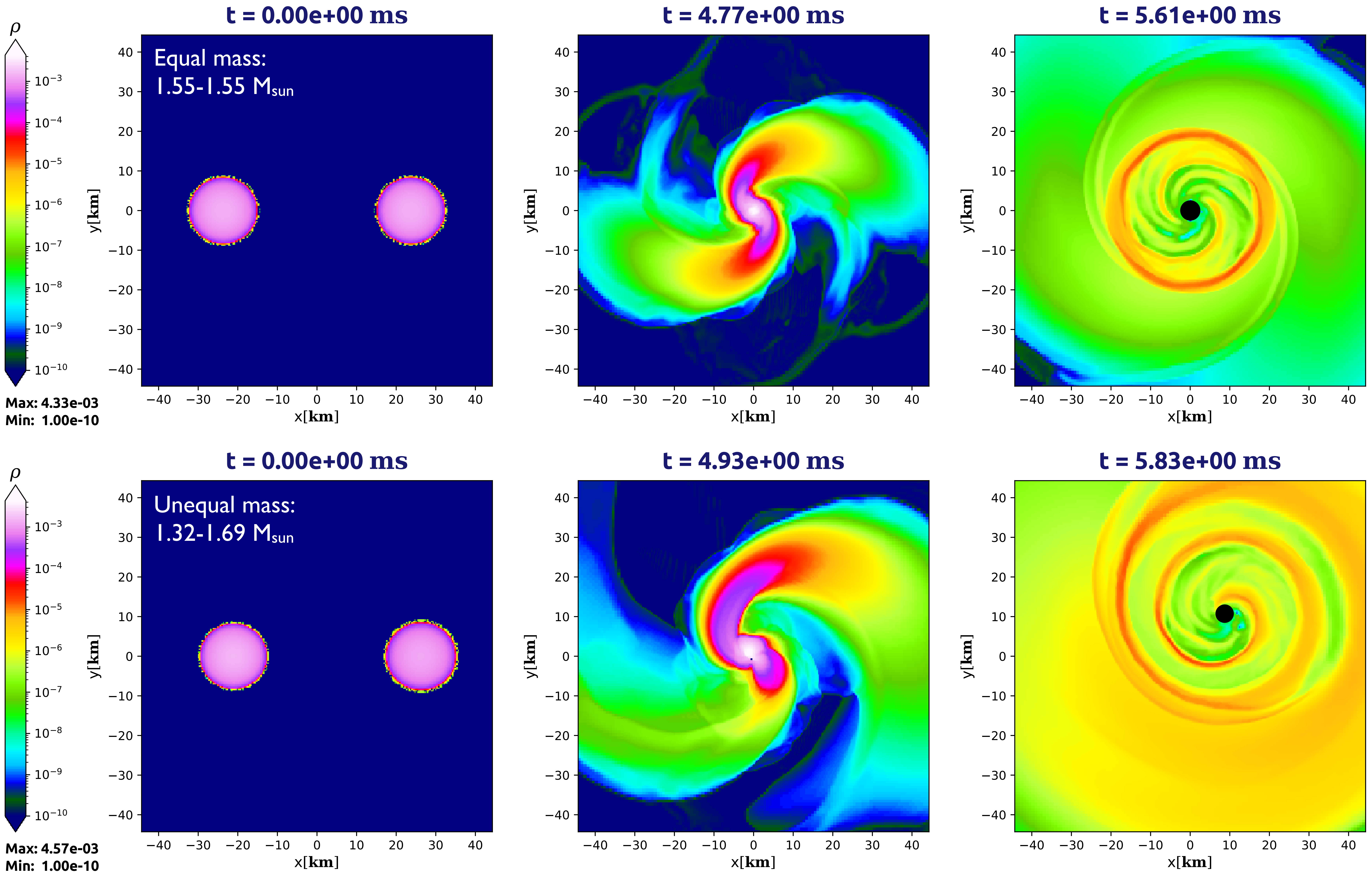


Image courtesy: L. Ennoggi

RePrimAnd C2P scheme in Spritz

Scheme features: [Kastaun+2021]

- Uses root-bracketing scheme
- Alway converges to a unique solution (mathematical proof)
- Strong error policy: guarantees to find invalid evolved variables and applies harmless corrections, if necessary
- EOS-agnostic
- Publicly available code along with an EOS-framework on Zenodo: wokast/RePrimAnd

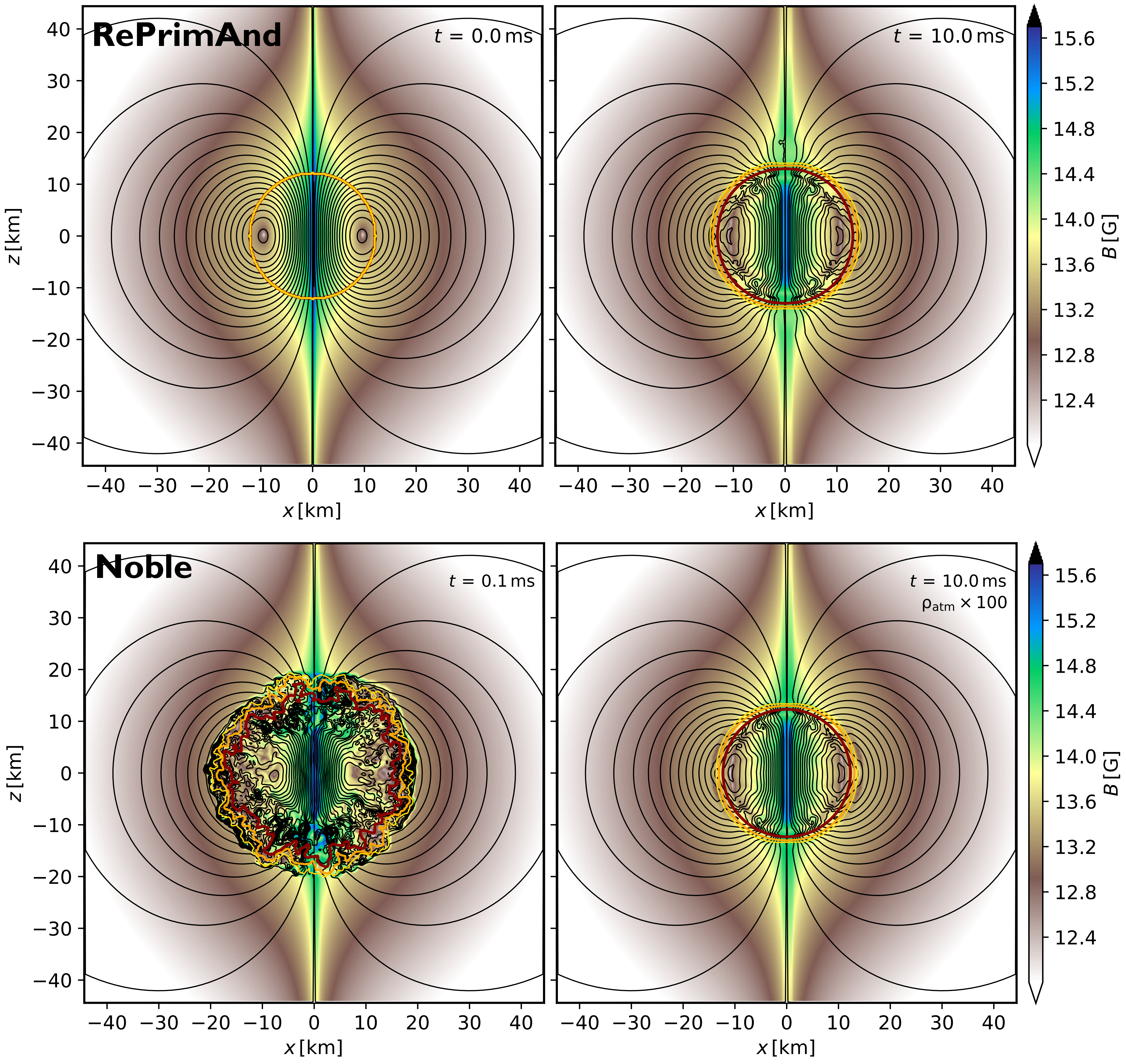
Implementation in Spritz: [Kalinani+ in prep]

- Integrated RePrimAnd library into Einstein Toolkit
- Added option in Spritz to use C2P from RePrimAnd
- Defines and enforces validity range for EOS
- Option to use different error policy within BHs
- Support for fully tabulated EOS underway

List of 3D tests:

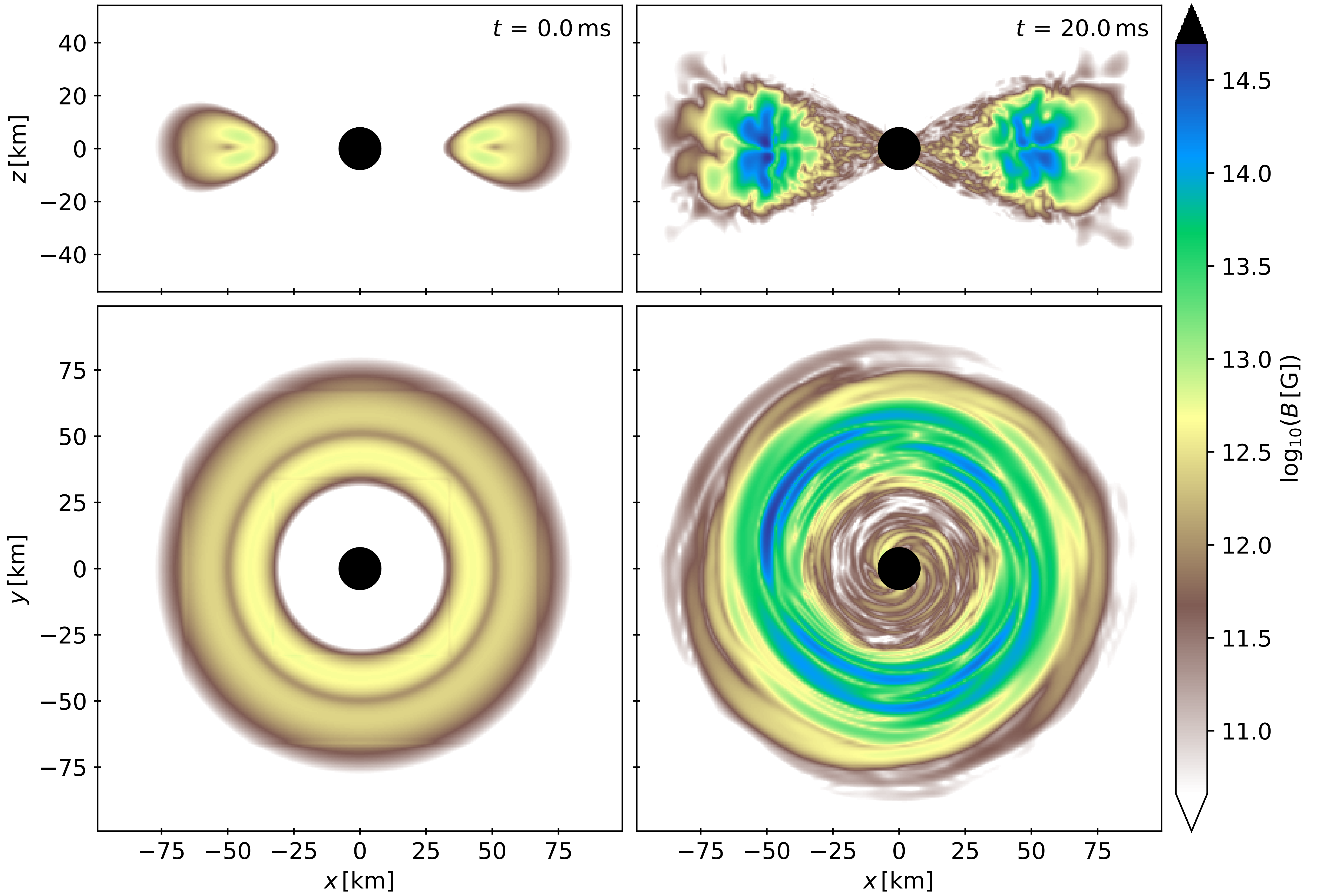
- TOV star with internal magnetic field
- NS with external dipolar magnetic field
- Rotating magnetised NS
- Rotating magnetised NS collapse to BH
- Fishbone-Moncrief BH-accretion disk

NS with extended dipolar field



Magnetic field strength

Fishbone-Moncrief BH-accretion disk



- **RePrimAnd outperforms Noble scheme when handling highly magnetised, low density regimes**
- **RePrimAnd able to handle highly magnetised BH environments**

Summary

Take-home message:

- GRMHD simulations of BNS mergers represent a necessary tool to study the physical properties and mechanisms of NSs, SGRBs and kilonovae
- Magnetar scenario disfavoured as SGRB jet central engine
- Magnetically driven outflows: potential driver behind the blue component of the kilonova
- The Spritz code: a necessary step forward to perform GRMHD simulations with neutrinos
- RePrimAnd C2P: a promising robust, accurate and efficient C2P scheme

Future exploration:

- Temperature and composition dependent EOSs
- Neutrino radiation
- Initial B-fields extending to the exterior (force-free implementation)
- NS spins

Thank you for your attention!