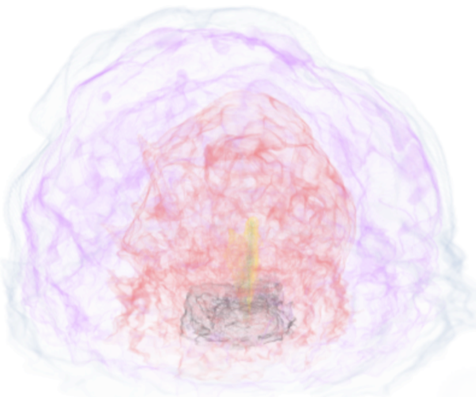
INAF - Osservatorio Astronomico di Padova
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

# From binary neutron star mergers to short gamma-ray burst jets

## towards the first end-to-end numerical modelling



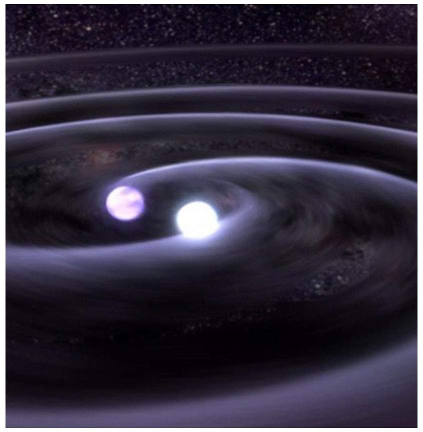
RICCARDO CIOLFI

INAF - Osservatorio Astronomico di Padova
INFN - Sezione di Padova

V CONGRESSO NAZIONALE GRB 2022

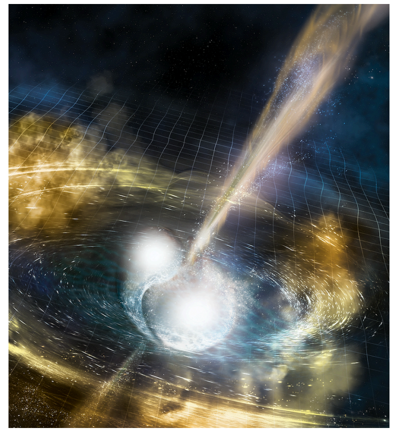
**Trieste, September 13th 2022**

# SGRB jets from BNS mergers



GW170817

+



GRB 170817A

??

jet launching mechanism?

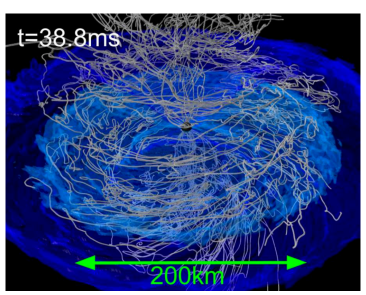
neutrino driven ✗ Just+2016 Perego+2017

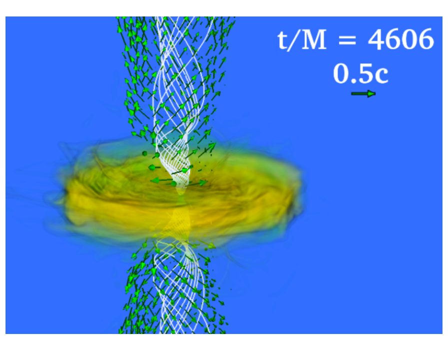
MHD driven ✓

→ need GRMHD simulations

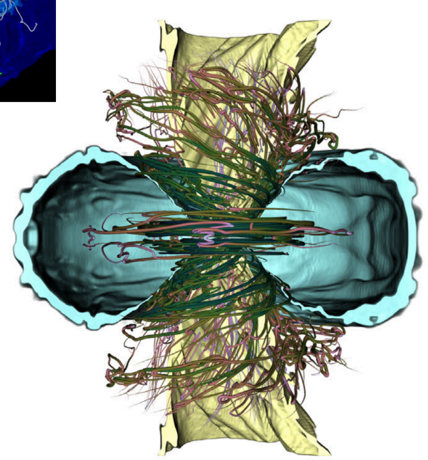
remnant/central engine nature?

Kiuchi+2014




Ruiz+2016



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BH + accretion disk

(Blandford-Znajek)

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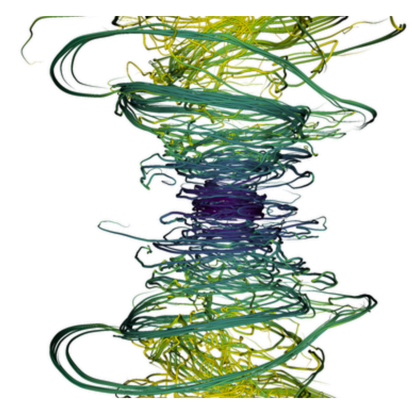

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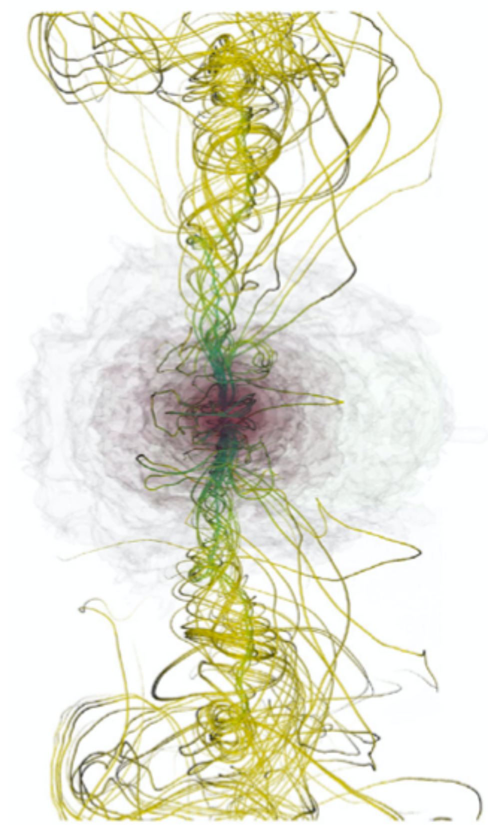

Ciolfi 2020a

massive long-lived NS

(magnetorotational)

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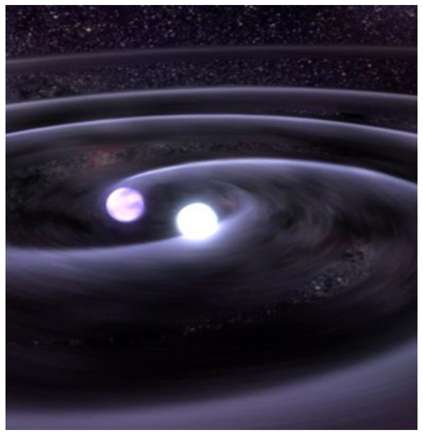

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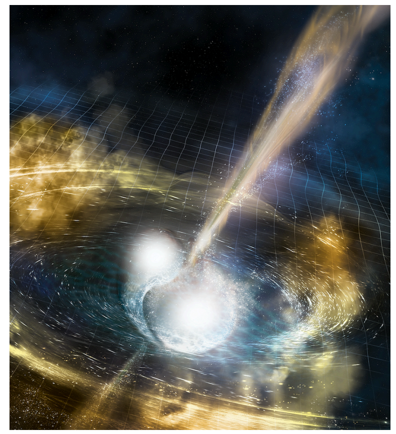

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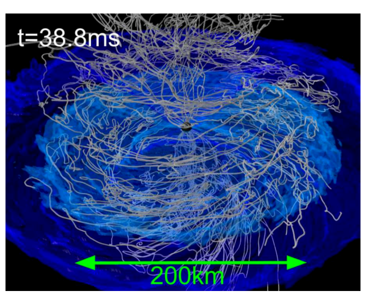


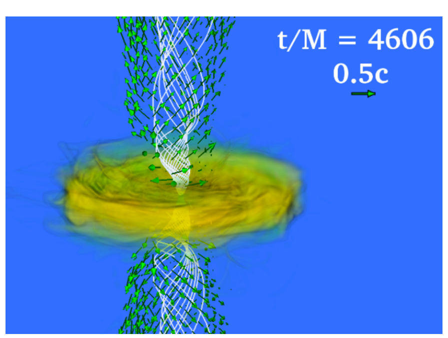


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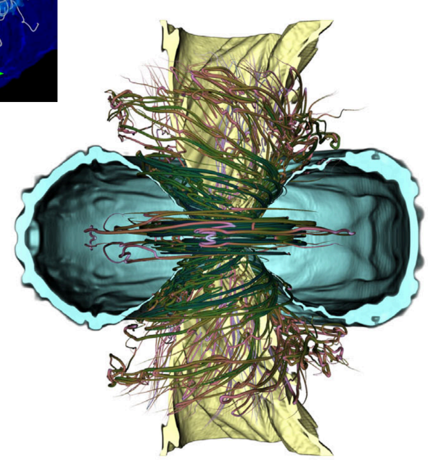

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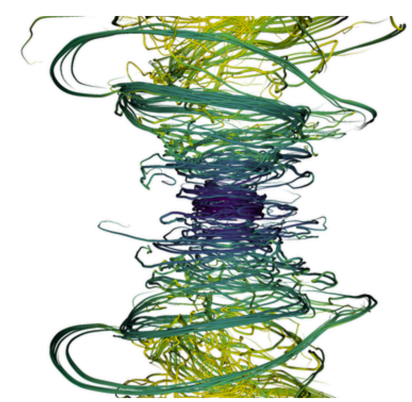

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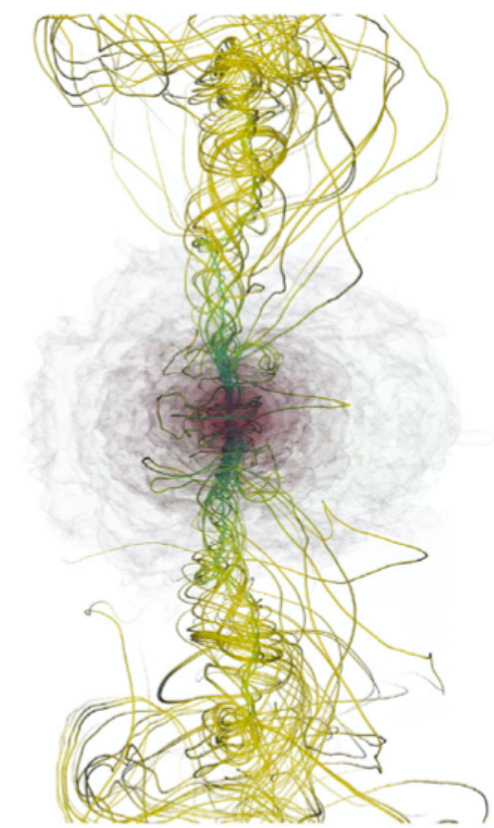
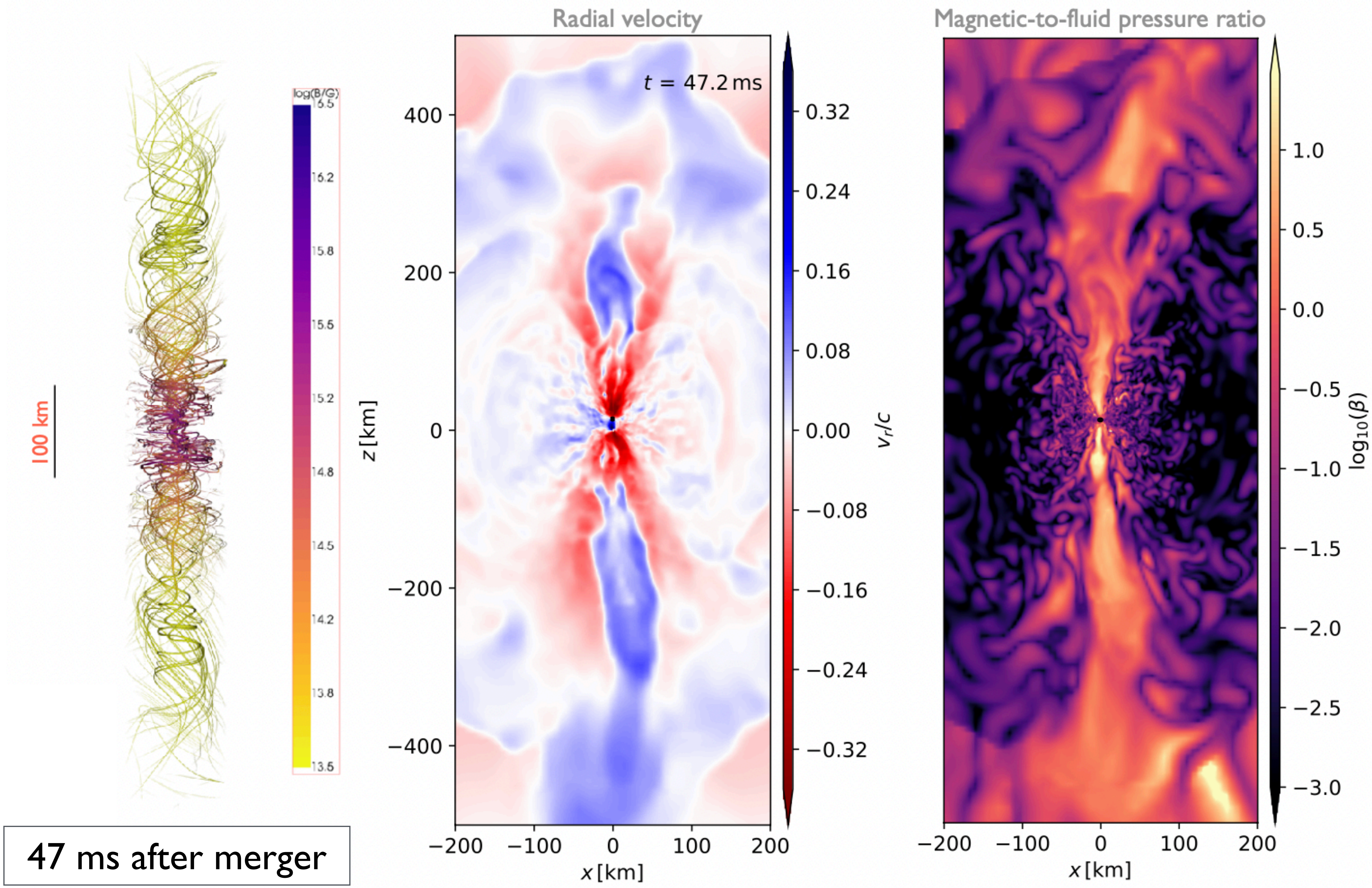


Ciolfi 2020a

# BNS mergers with new GRMHD code *Spritz*

Kalinani+ in prep.




47 ms after merger

29 ms after collapse

simulation by Jay Kalinani

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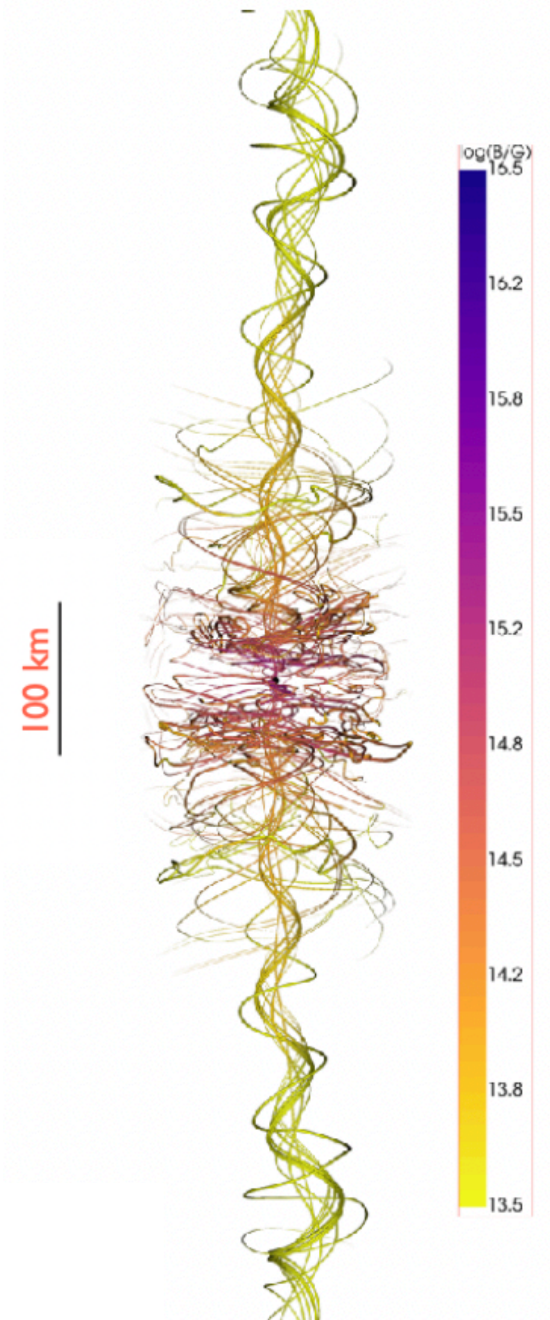


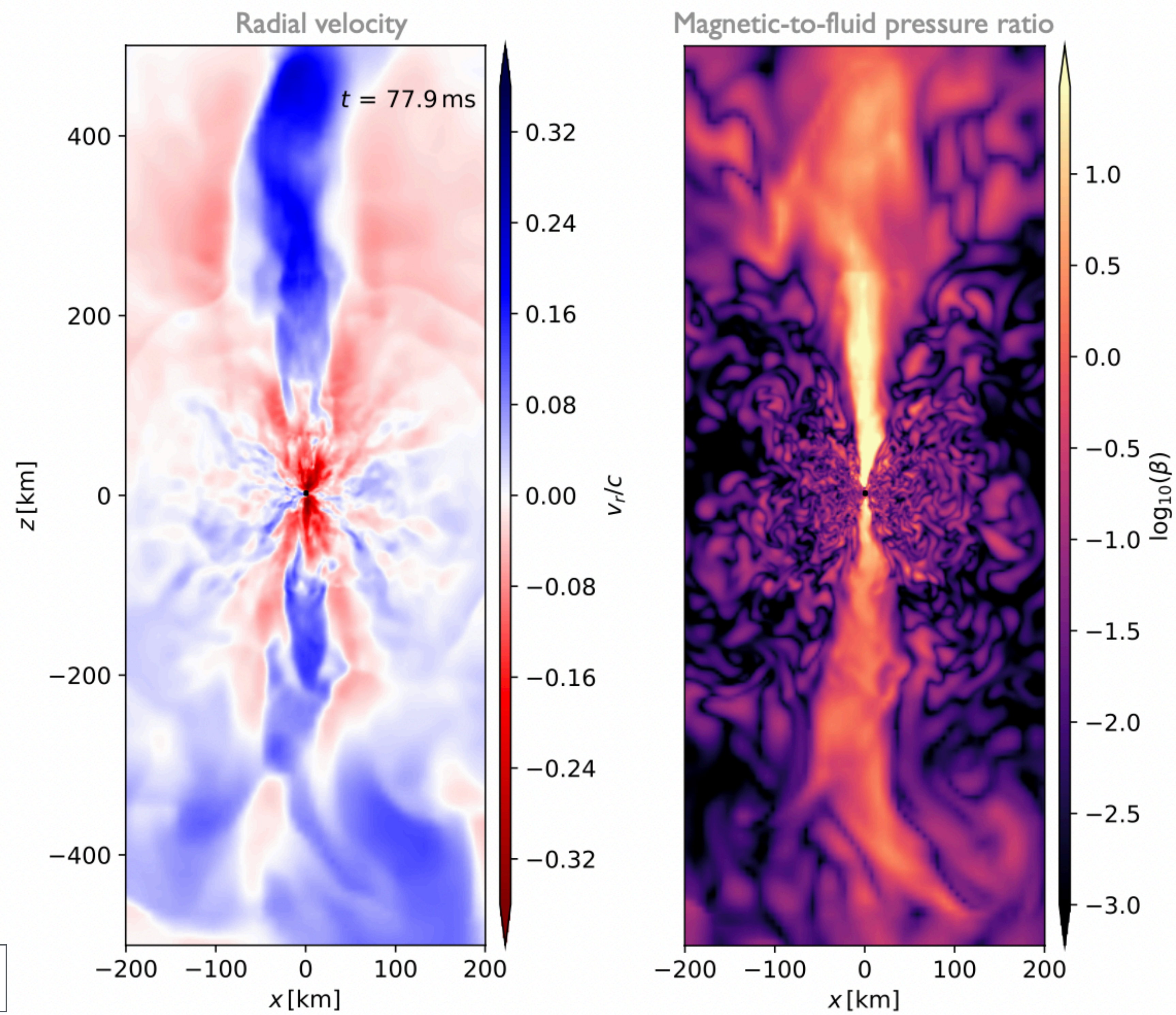


78 ms after merger

60 ms after collapse

simulation by Jay Kalinani

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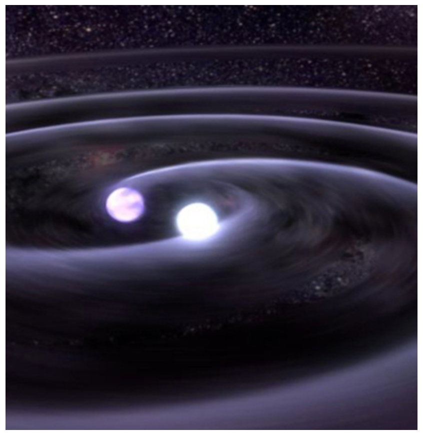

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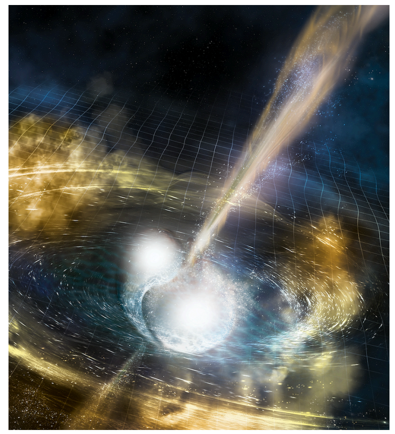

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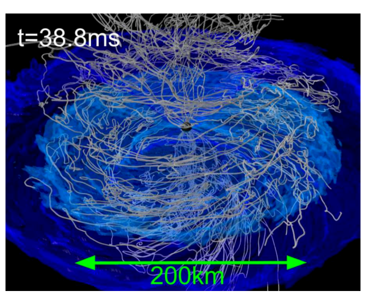


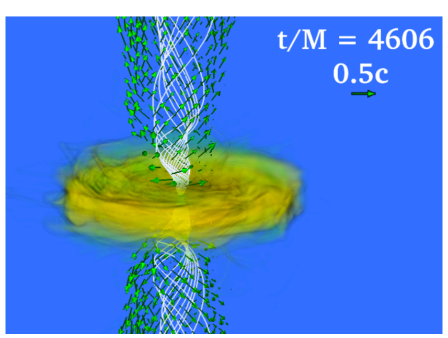


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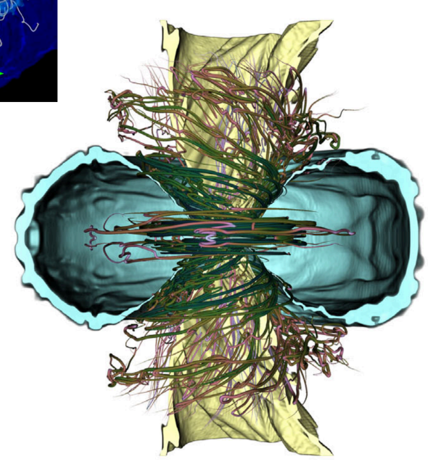

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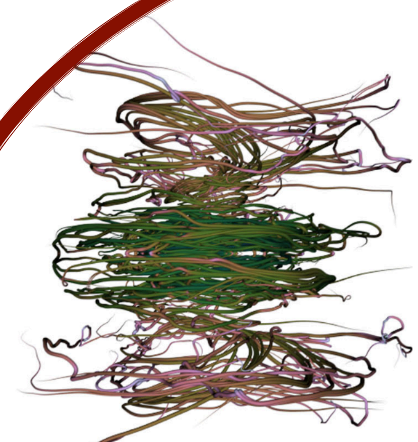
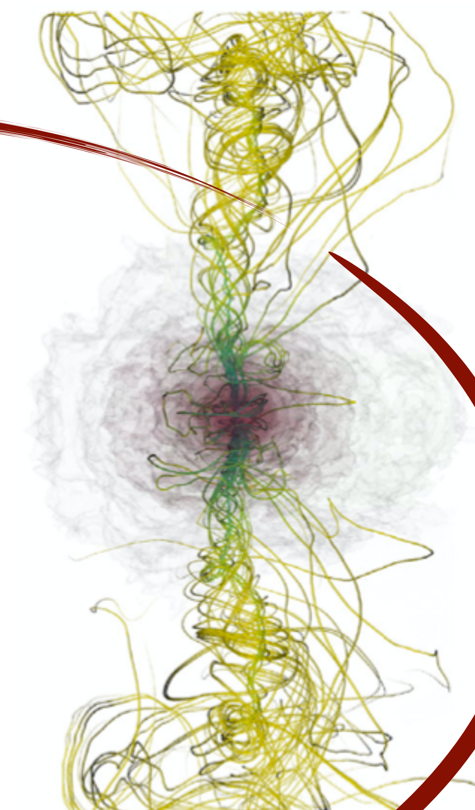


Ciolfi+2017

Ciolfi+2019



Ciolfi 2020a

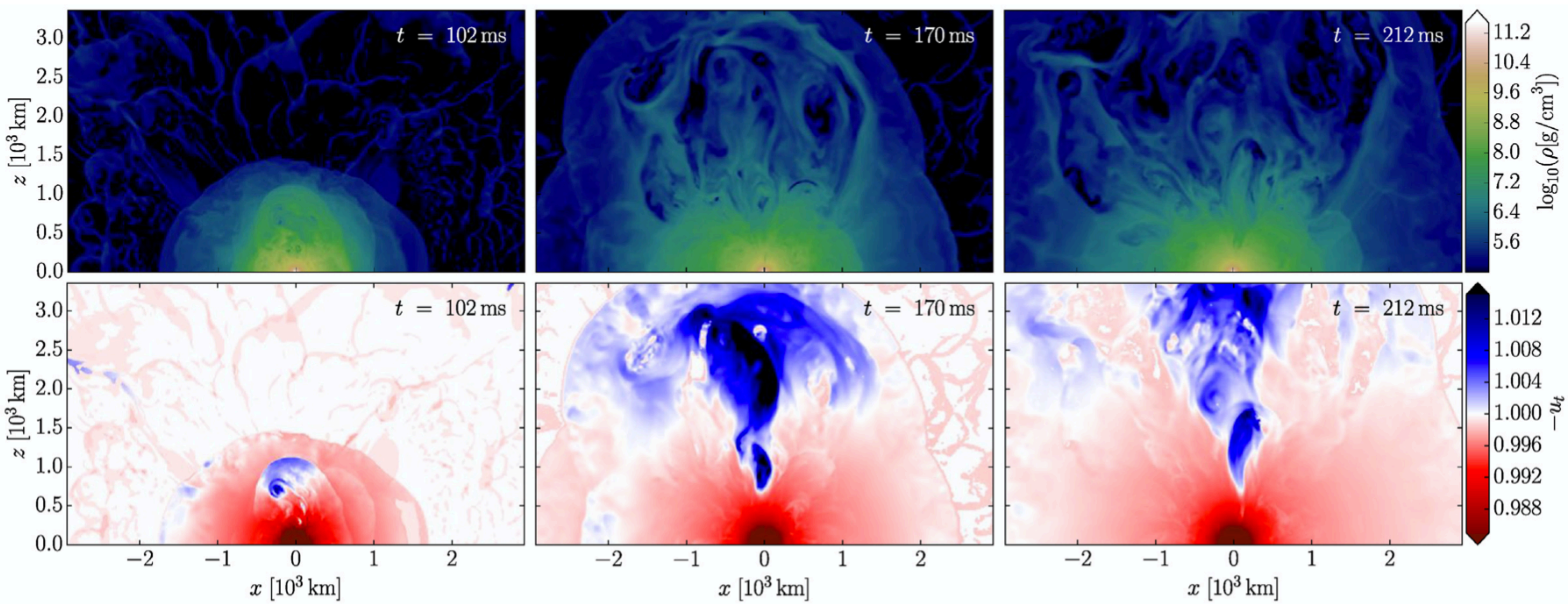
massive long-lived NS

(magnetorotational)

# BNS mergers with much longer evolution

Ciolfi 2020a

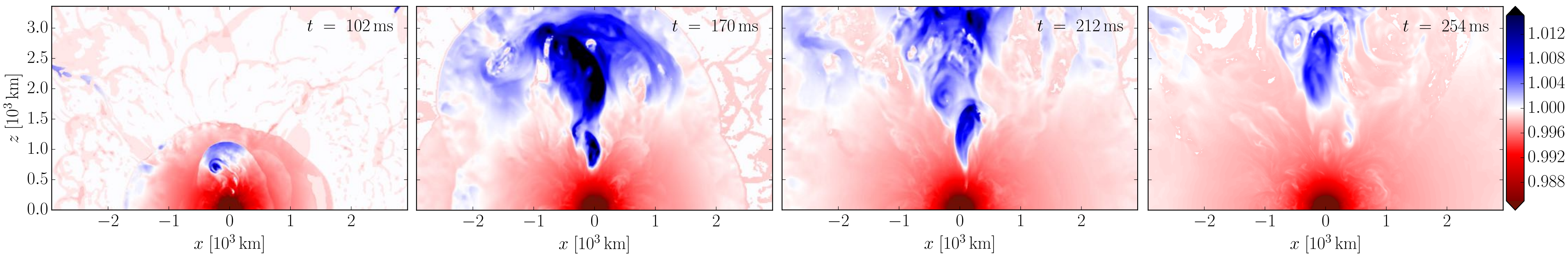
- BNS system with chirp mass of GW170817 and q=0.9
- PP APR4 EOS, initial magnetization 4e47 erg, confined poloidal field
- longest evolution up to ~255 ms after merger

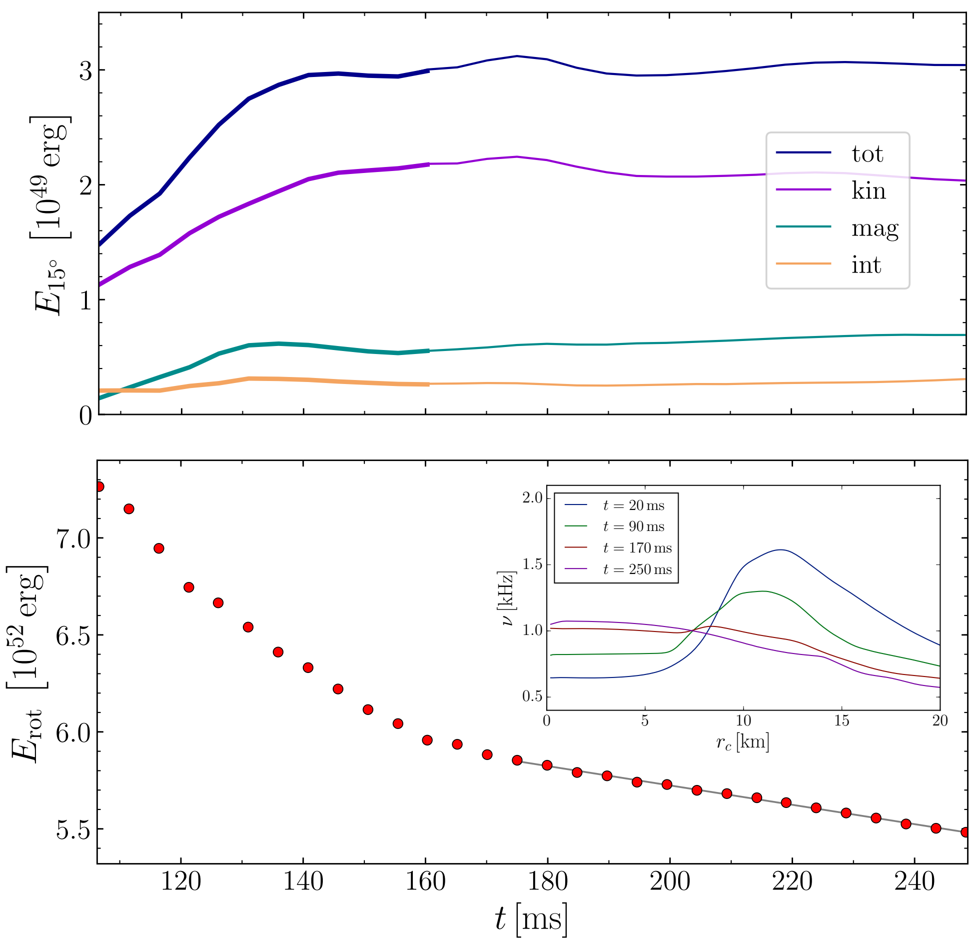



**massive NS remnant can produce a collimated outflow**

# Origin and properties of the collimated outflow

Ciolfi 2020a




~160 ms after merger → outflow energy saturation

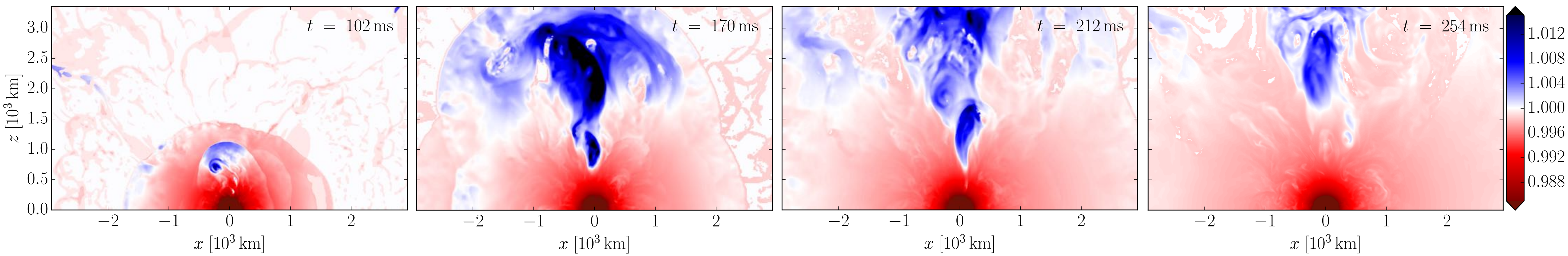
→ change in rotational energy evolution

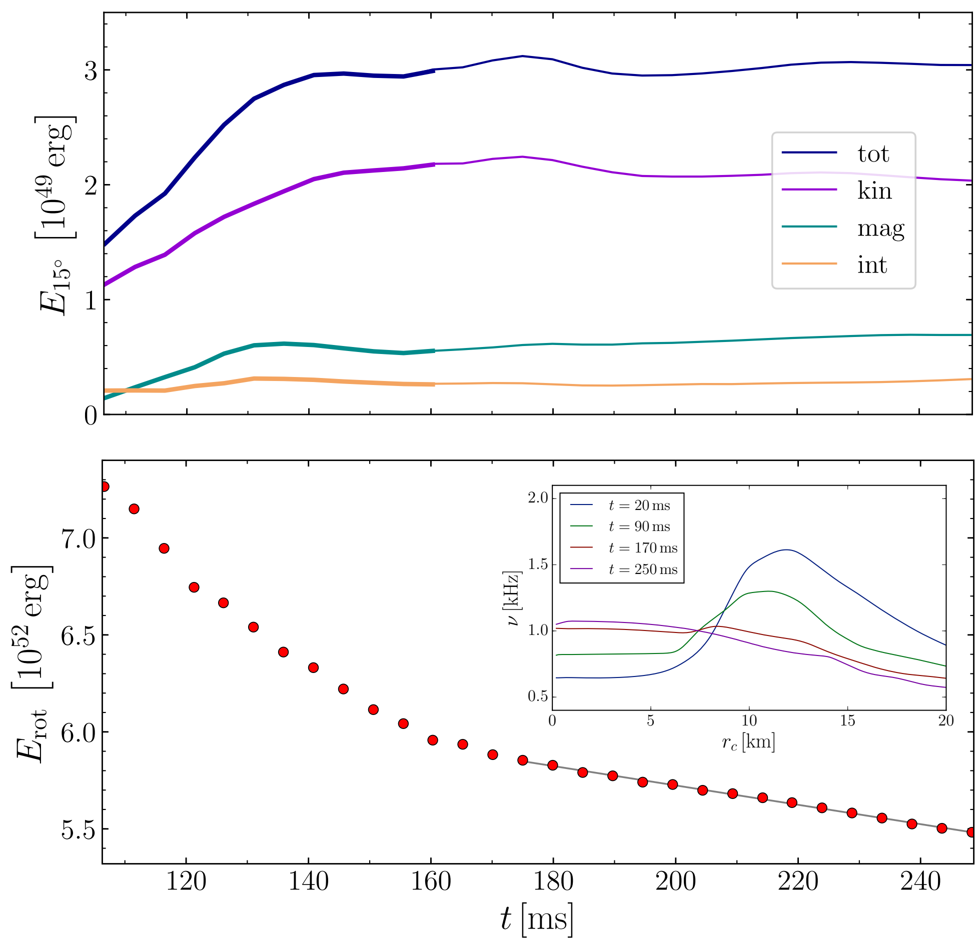
→ differential rotation in the NS core is over

NS differential rotation = energy reservoir

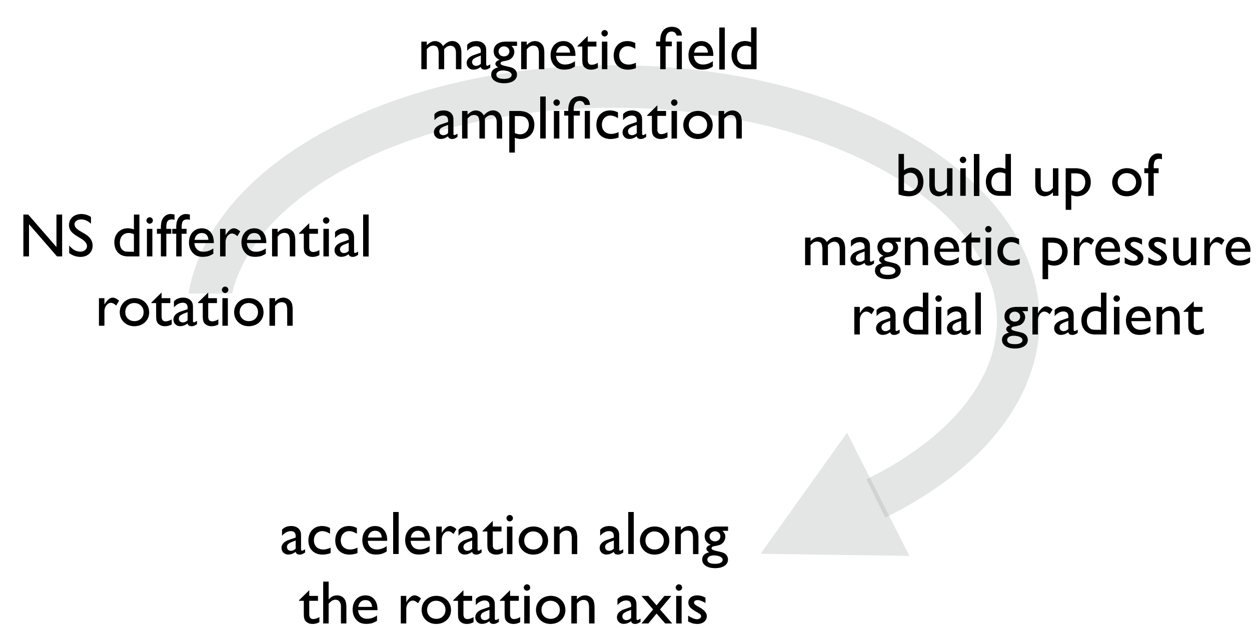
# Origin and properties of the collimated outflow

Ciolfi 2020a



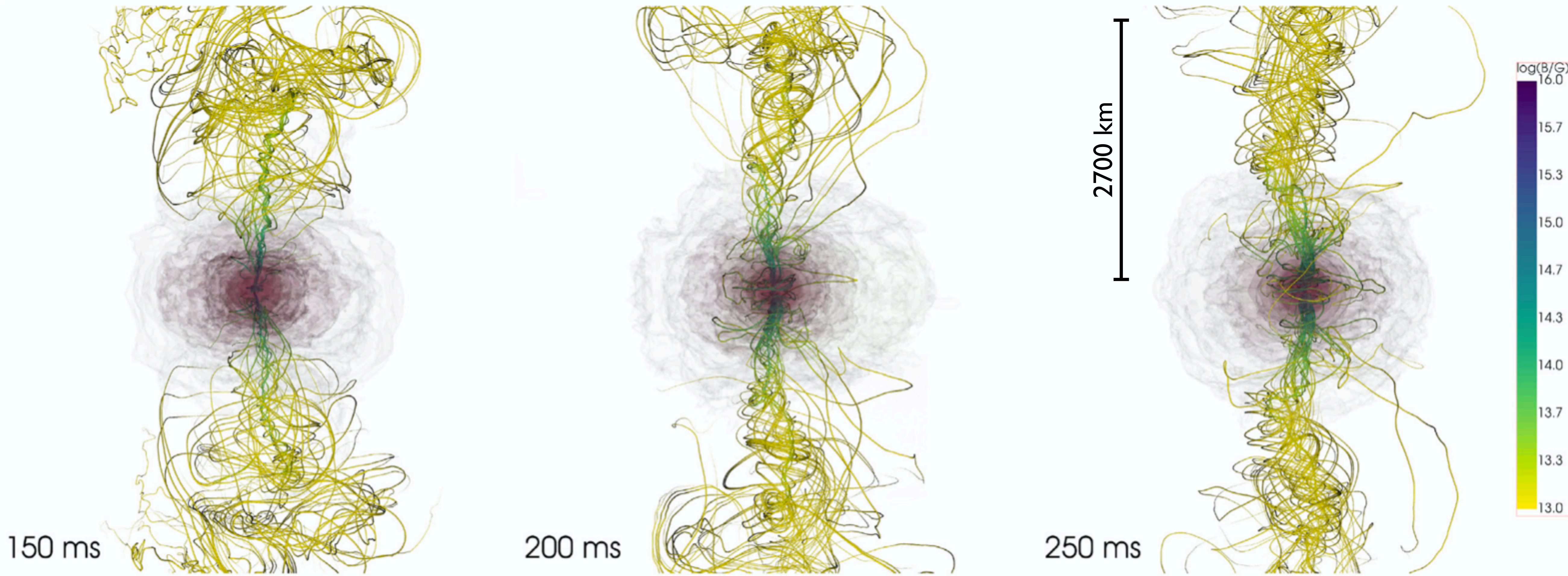



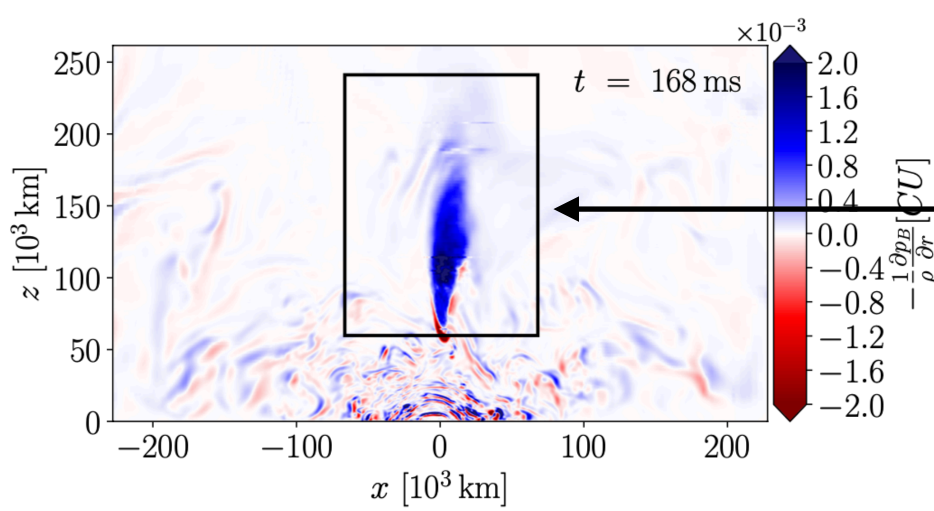

**magnetorotational launching mechanism**



# Emerging helical magnetic field

Ciolfi 2020a




magnetic push
(radial gradient of magnetic pressure)

# Can this collimated outflow evolve into a SGRB jet?

compared to GRB 170817A jet parameters:

- outflow energy is insufficient (or at most marginally consistent)
- outflow collimation is insufficient
- low outflow velocity of ~0.2c and energy-to-mass flux ratio <0.01

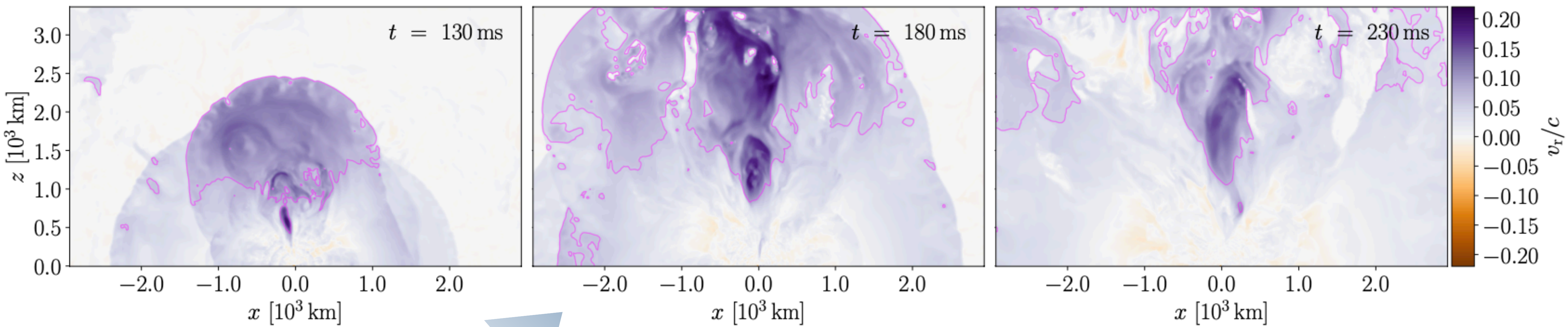
⟶ no way to accelerate up to ~0.995c (Lorentz factor of 10) or more

outflow is at least 3 orders of magnitude too heavy!

**massive NS scenario for SGRBs is disfavoured**

# Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

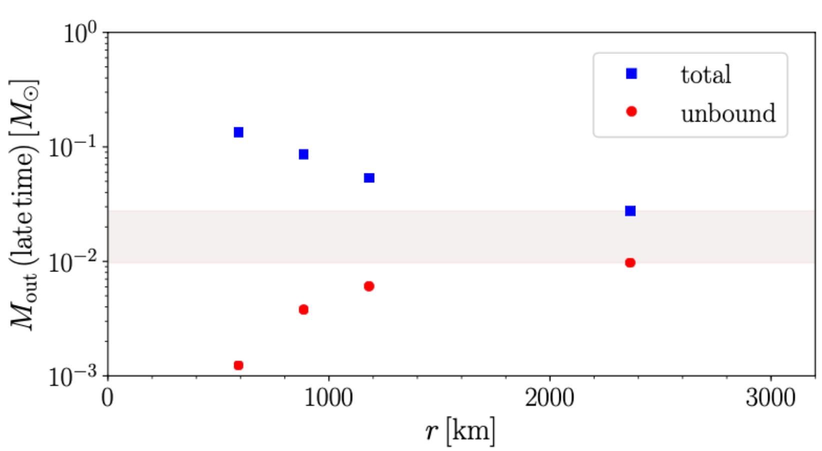



**ejecta velocity**

~0.2 c marginally consistent with blue kilonova

→ possible further enhancement

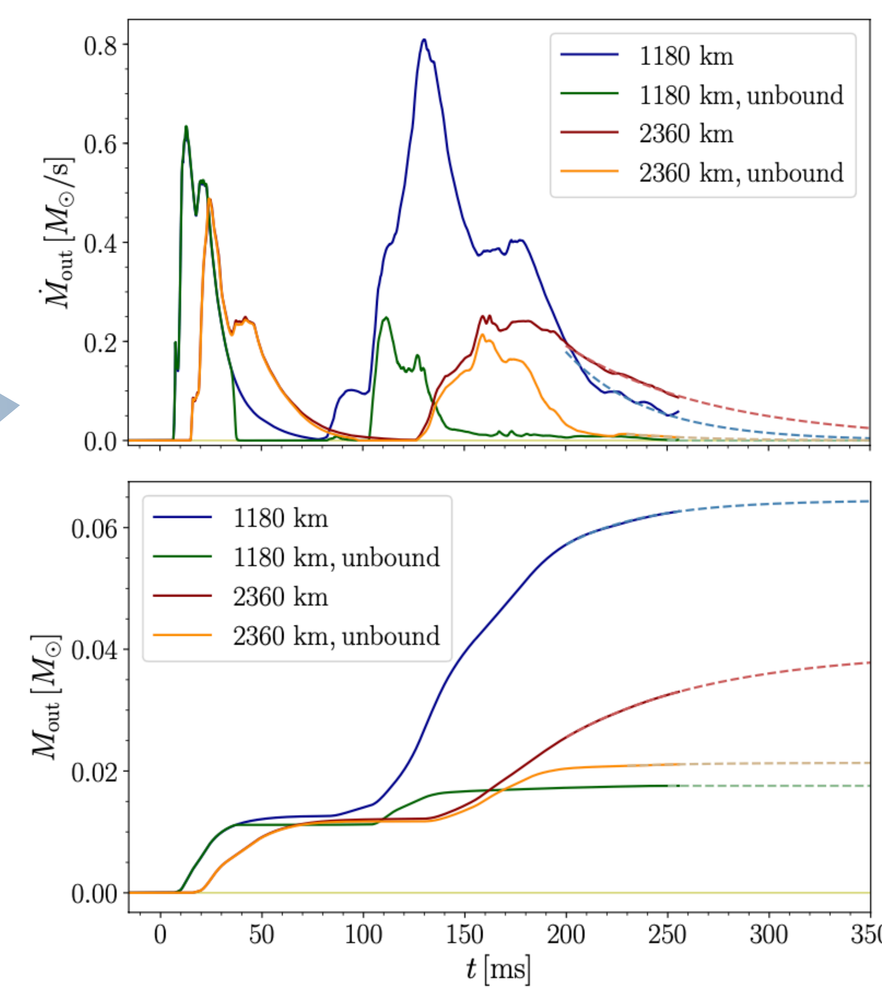
**ejecta mass**



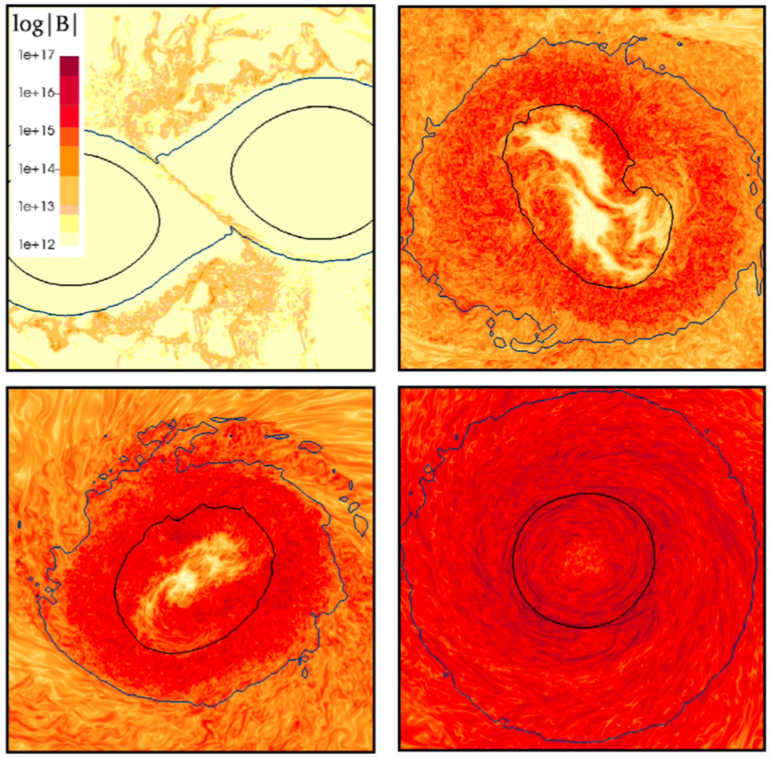

$M_{ej,\,wind} \simeq 0.010–0.028\, M_\odot$

to be compared with

$0.015 - 0.025\, M_\odot$

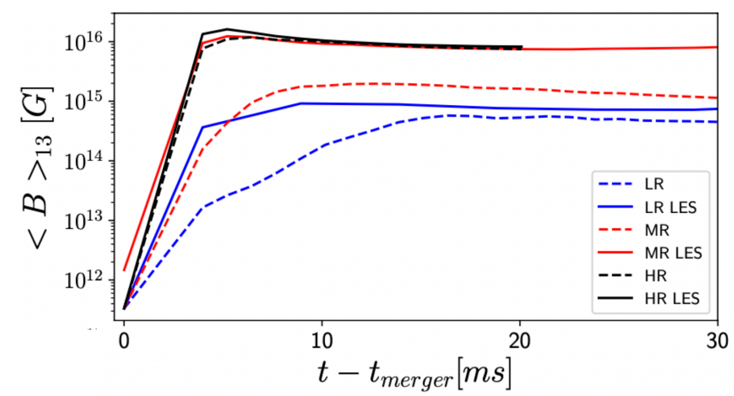


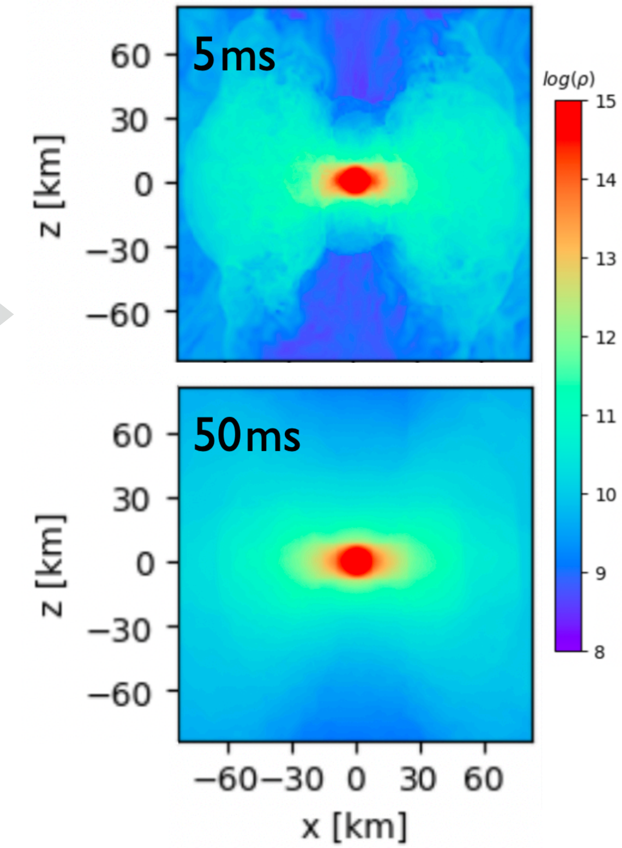
# Caveat 1 - MHD not fully resolved




Palenzuela+2022

first-time convergence
in magnetic field amplification!




subgrid modelling of MHD turbulence
Large-Eddy-Simulation approach

difficulties in producing an incipient jet
without BH are confirmed

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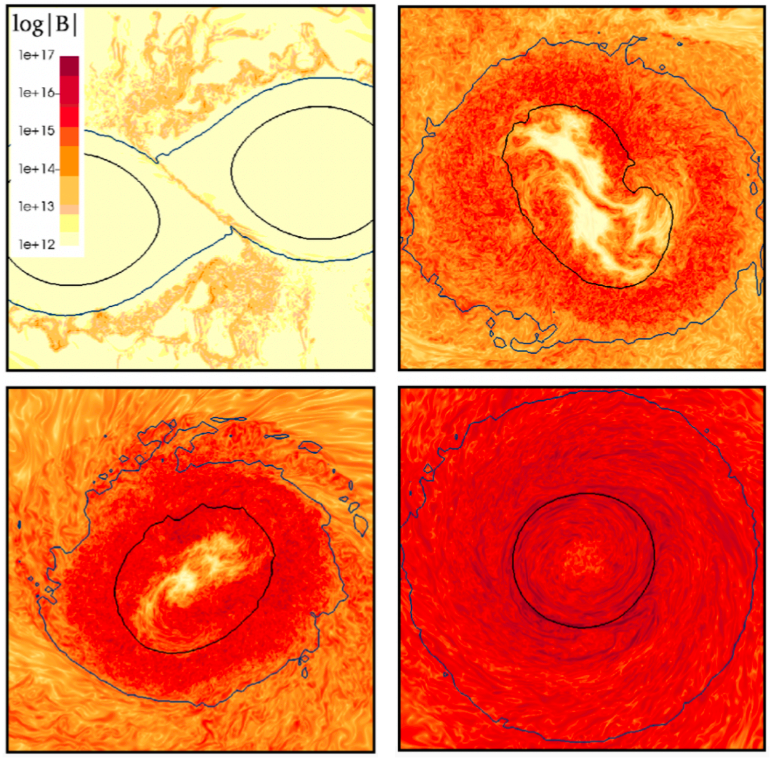


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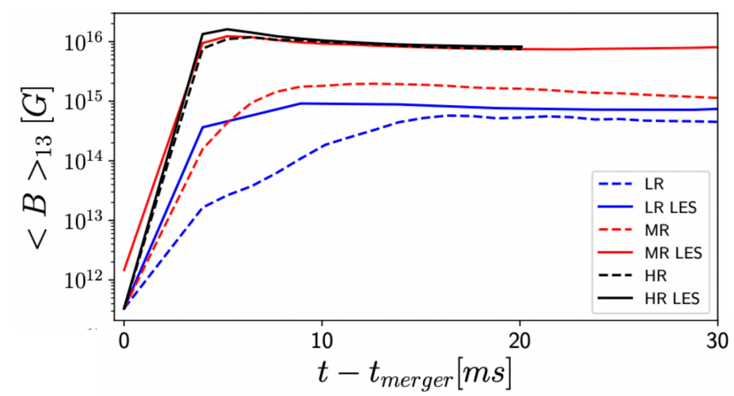


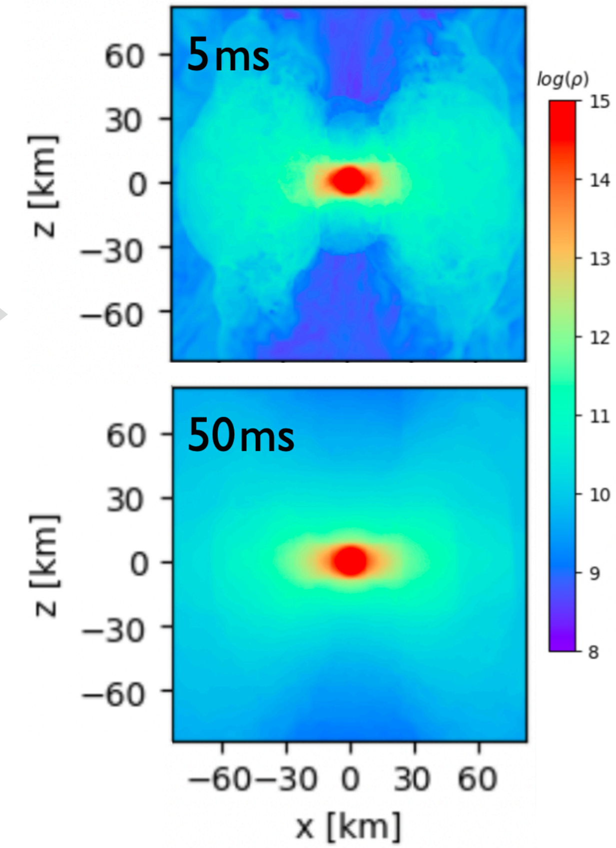


difficulties in producing an incipient jet
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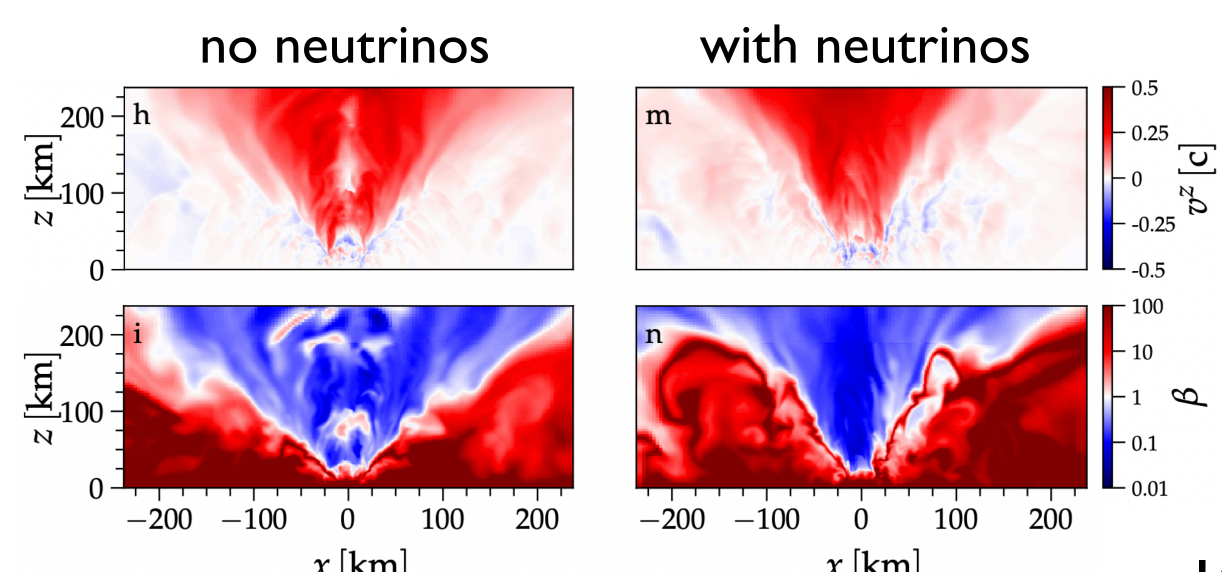
# Caveat 2 - “hot” EOS and neutrinos

may lower baryon pollution along the spin axis

⇩

is this sufficient to fill the 3-4 orders of
magnitude missing in terminal Lorentz factor?




Moesta+2020

# Connecting with SGRB observations

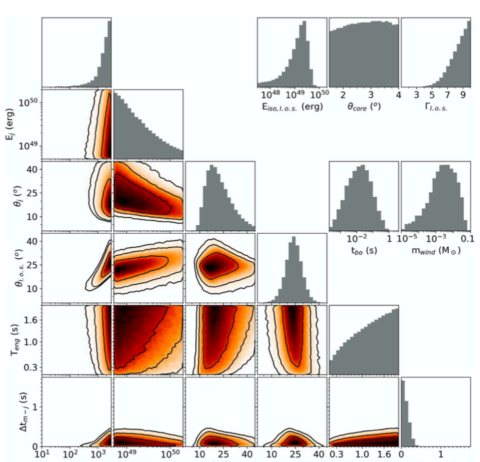
BNS merger simulations limited to scales ~100ms/1000km → disconnected from scales relevant for SGRB EM radiation (prompt & afterglow)

**need for models of jet propagation across the environment up to large scales**

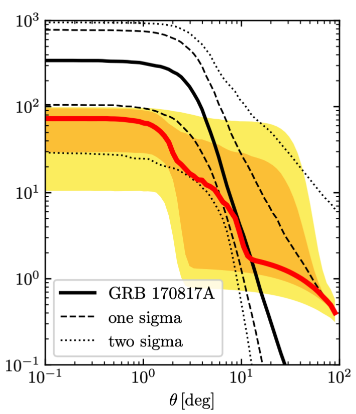
incipient jet + environment → propagation model → final jet structure, prompt & afterglow emission

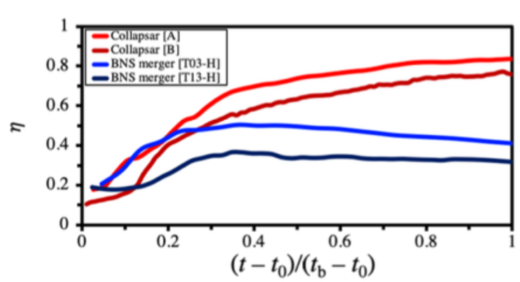
## semi-analytical

Lazzati+2020



Salafia+2020

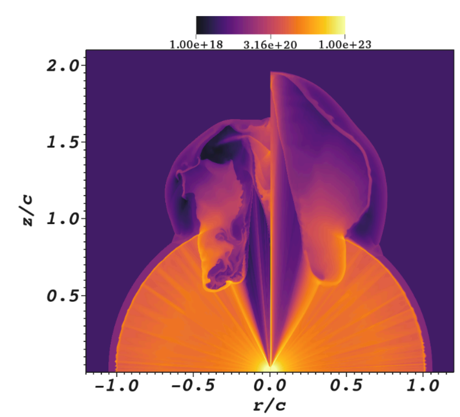


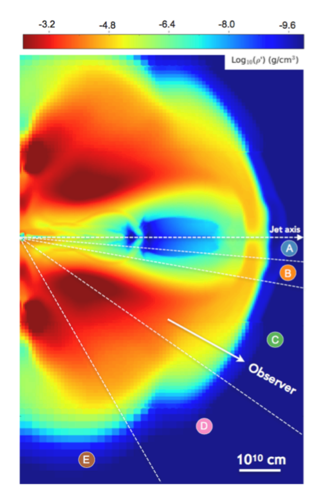

Hamidani & Ioka 2020

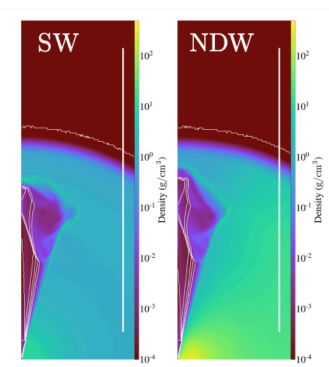
## 2D/3D HD

Urrutia+2020




Lazzati+2018

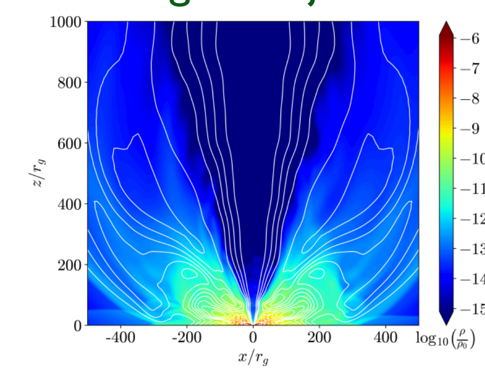


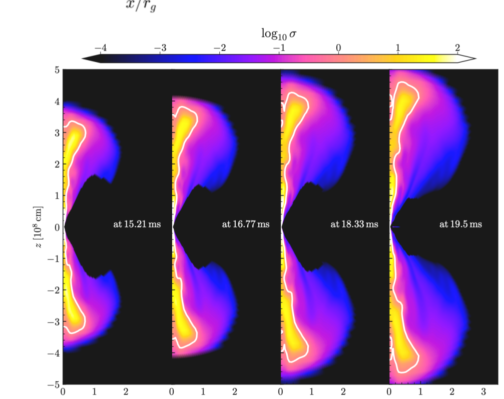




Murguia-Berthier+2021

## 3D GRMHD

Kathirgamaraju+2019





Nathanail+2020, 2021

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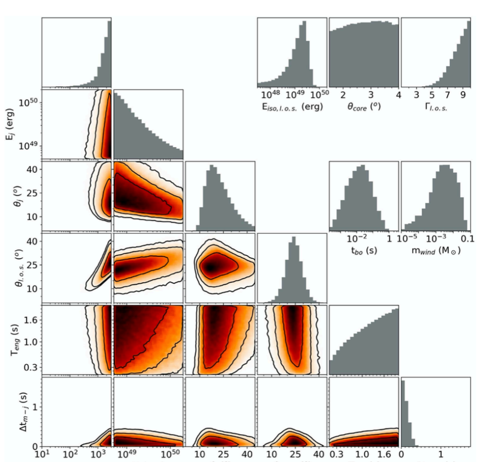

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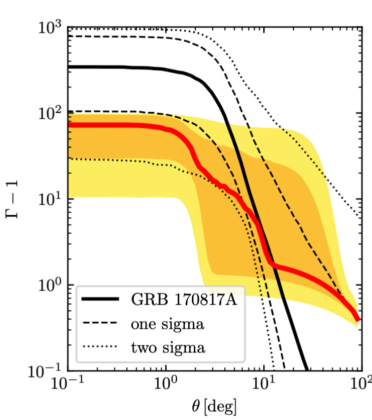


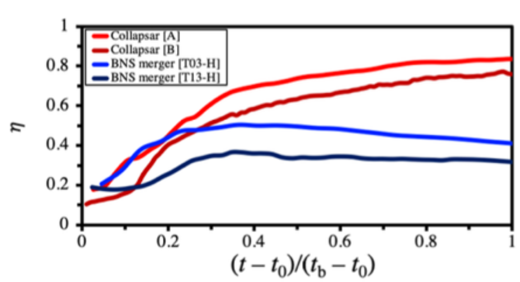


Hamidani & Ioka 2020

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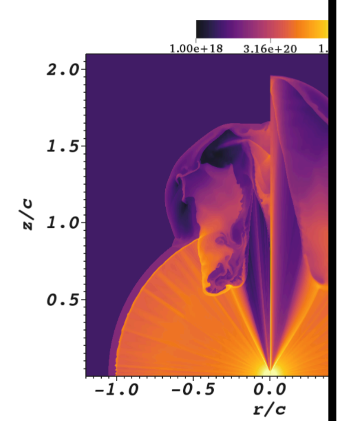
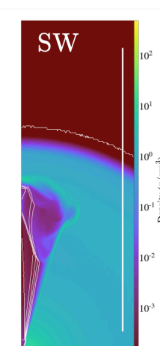
Urrutia+2




Murguia-Berthier+2021

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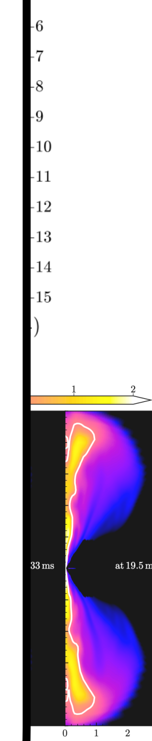

Nathanail+2020, 2021

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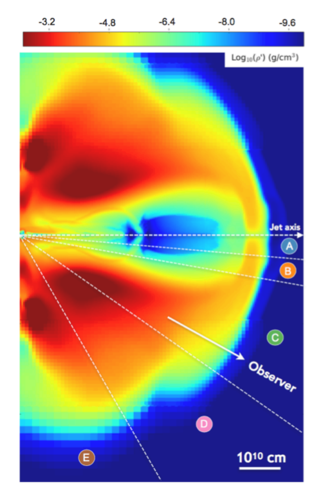
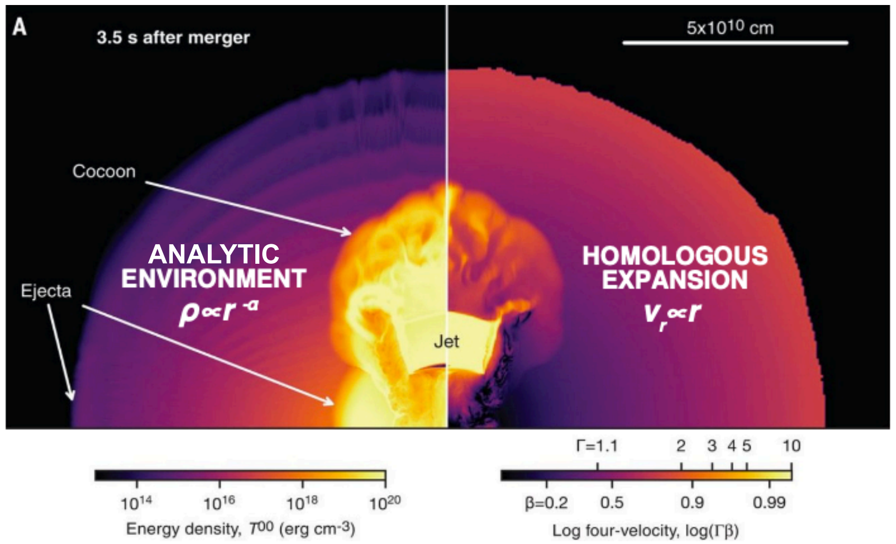



Aspen Institute Italia

Aspen Institute Italia Award 2022!

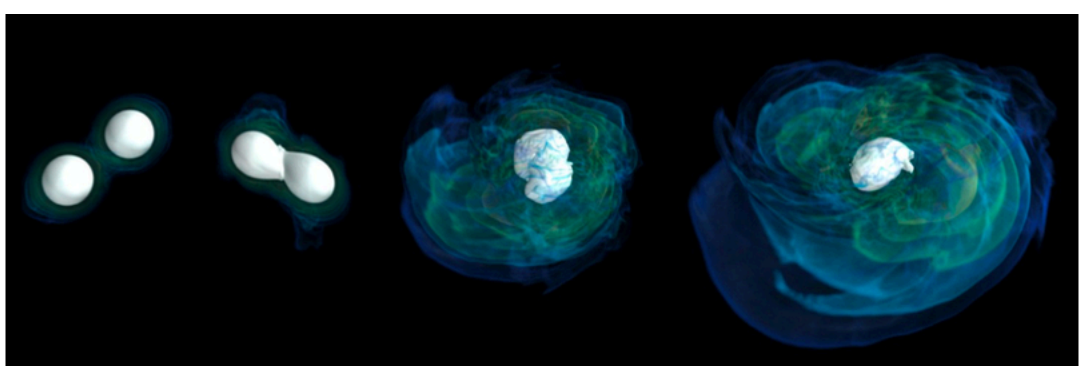
adapted from Kasliwal+2018

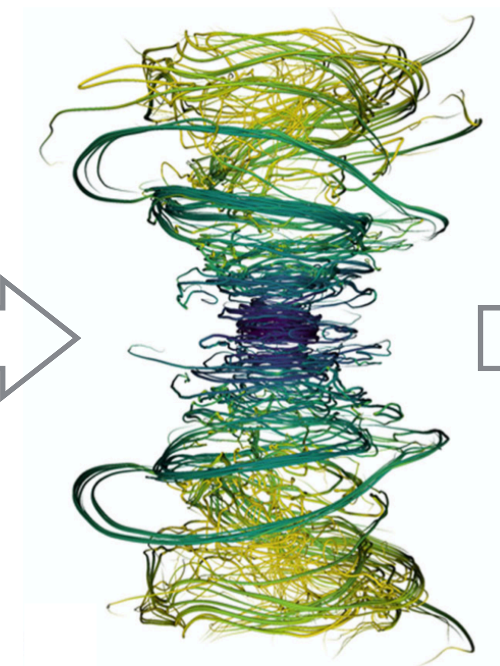


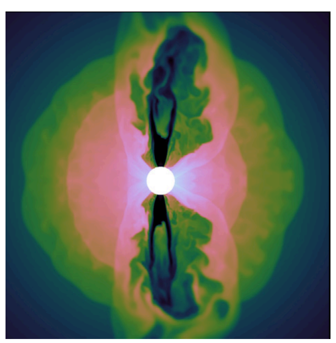

common limitation: incipient jet propagates across hand-made and simplified environment

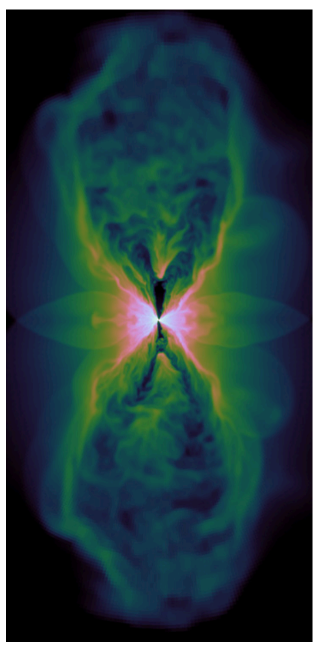
- power-law density profile & homologous expansion or stationary wind
- spherical/axial symmetry

# Towards an end-to-end modelling









consistent description of
BNS merger + jet production + jet propagation across the environment

final goal: constraining properties of the specific merging system via SGRB-related observations

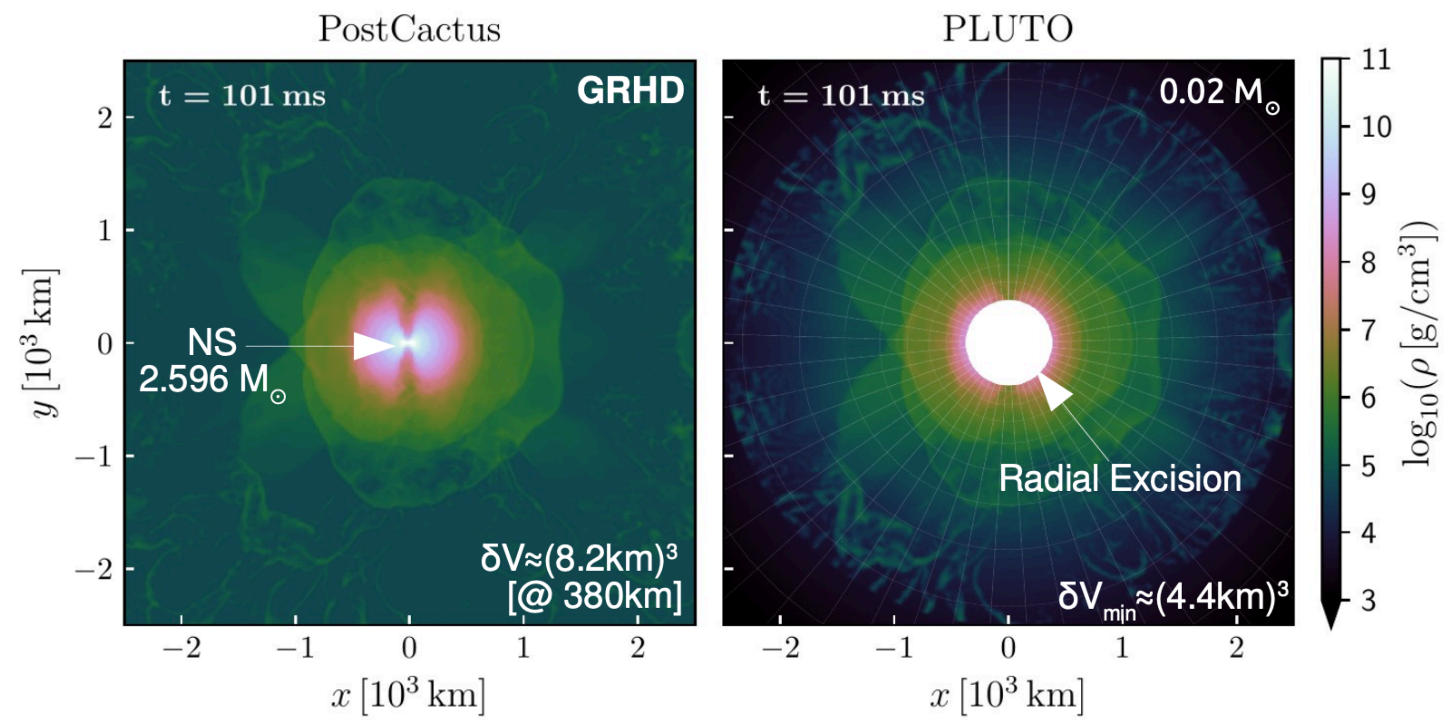
# Jet propagation in BNS merger environment

Pavan+2021

first 3D RHD jet simulations with environment imported from BNS simulation

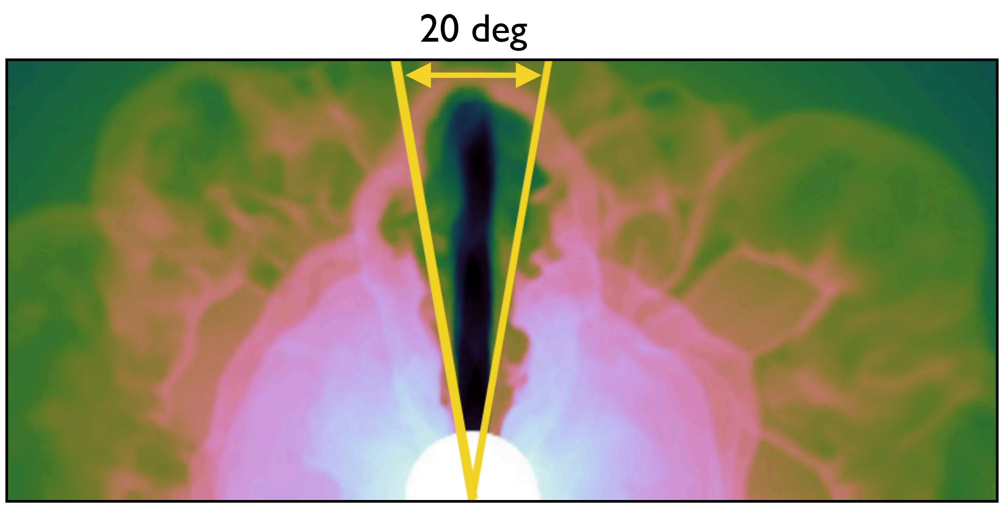
## simulation setup

- PLUTO code   Mignone+2007, 2012
- full 3D spherical grid (log r spacing)
- excised region up to 380km radius
- redefinition of atmospheric floor $\rho_{atm} \propto 1/r^5$
- outer boundary 2.5e6 km
- TAUB EOS   Mignone & McKinney 2005
- Gravitational pull from central object (2.596 Msun)




## jet properties

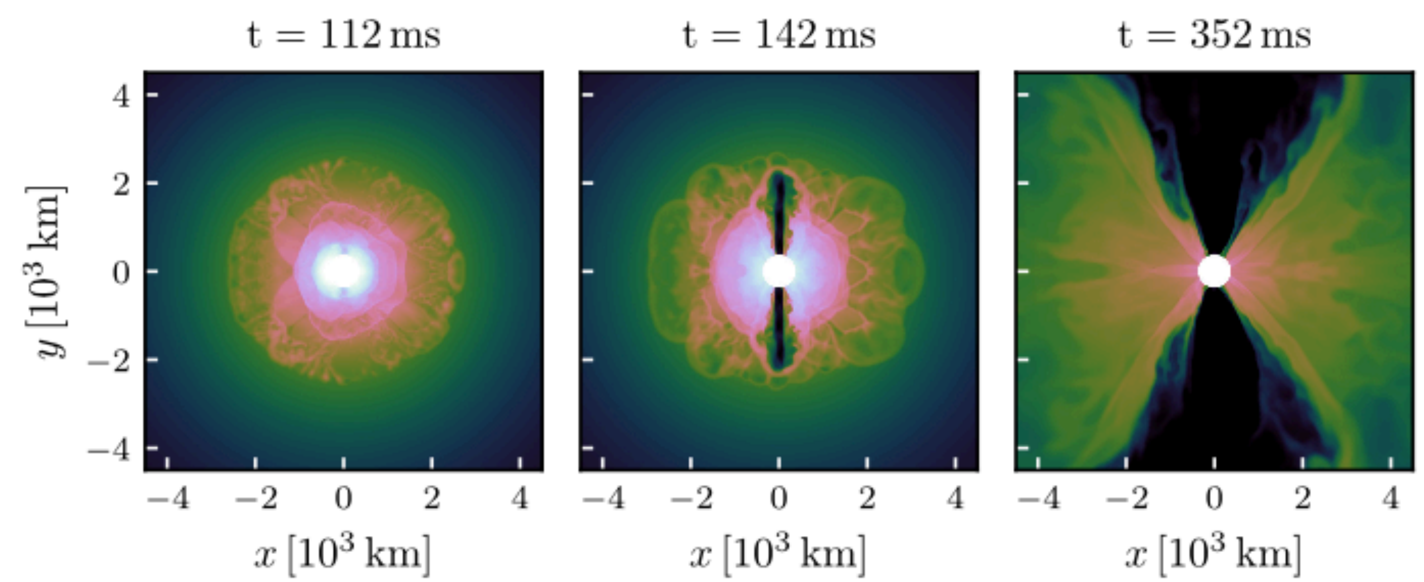
- top-hat, 10 deg half-opening angle, lorentz factor 3
- luminosity 3e50 erg/s, decaying on 0.3 s timescale



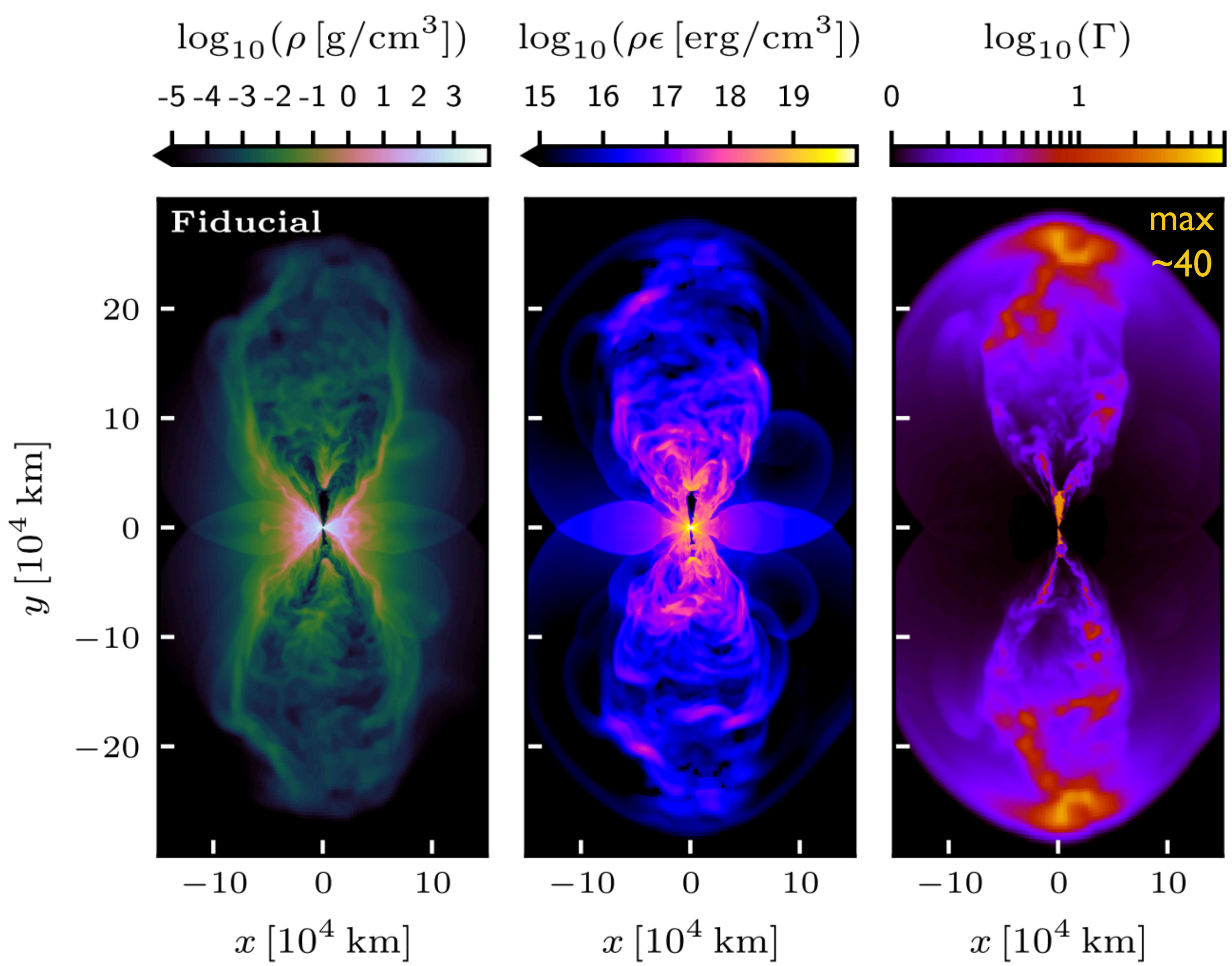

adapted from slides by Andrea Pavan

# Fiducial model

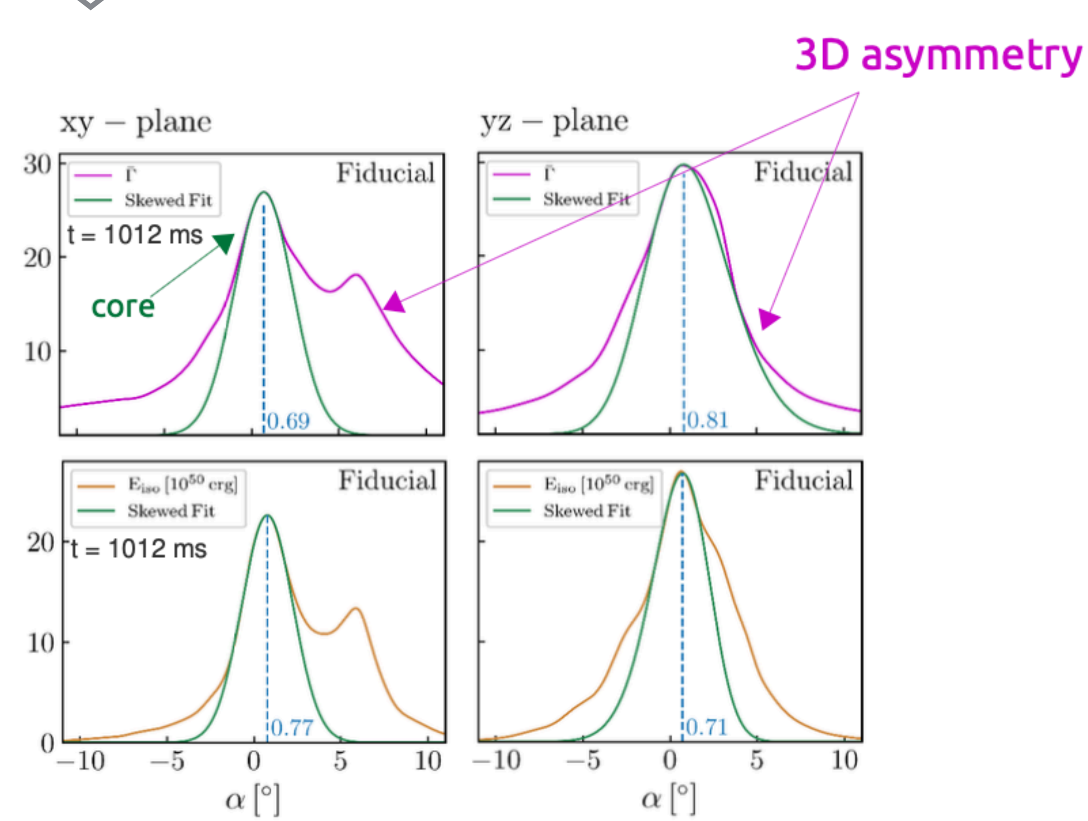
early evolution near the engine:
jet breakout and widening




final outflow properties
1012 ms after merger

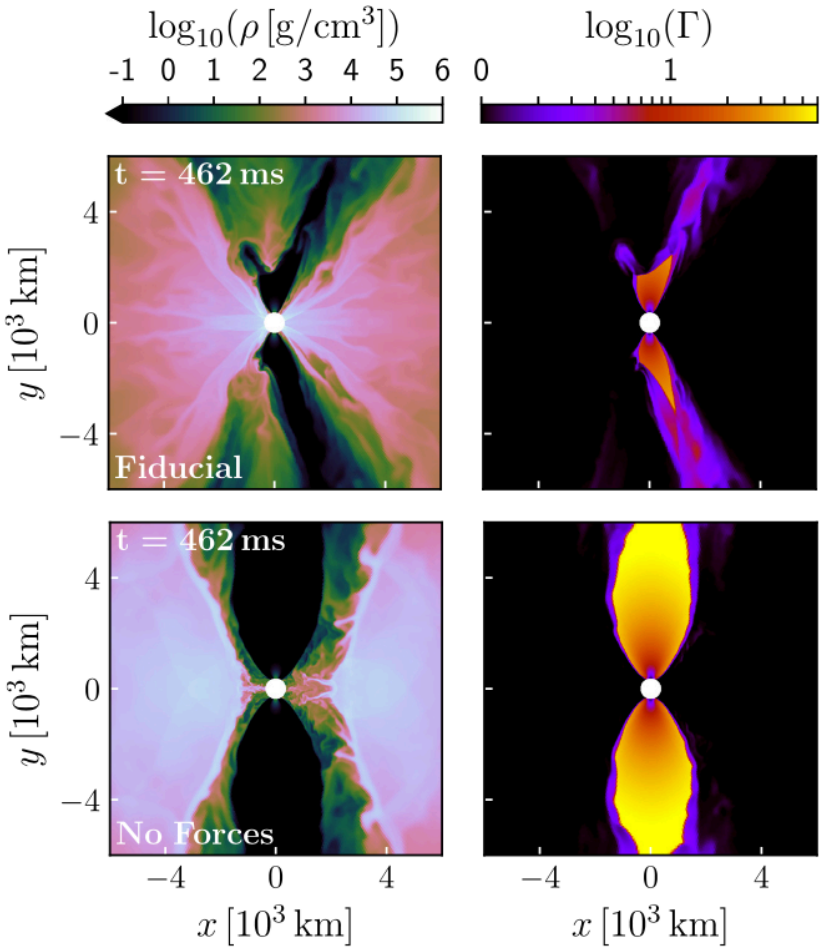



angular profiles at jet's head



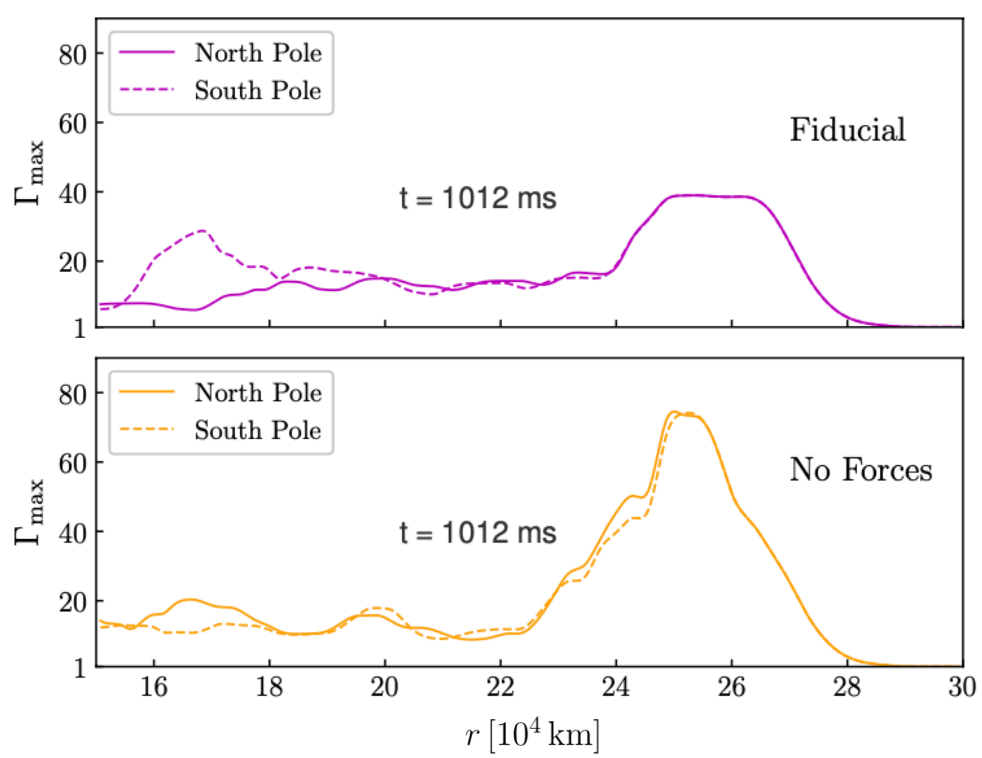

adapted from slides by Andrea Pavan

# Impact of gravity



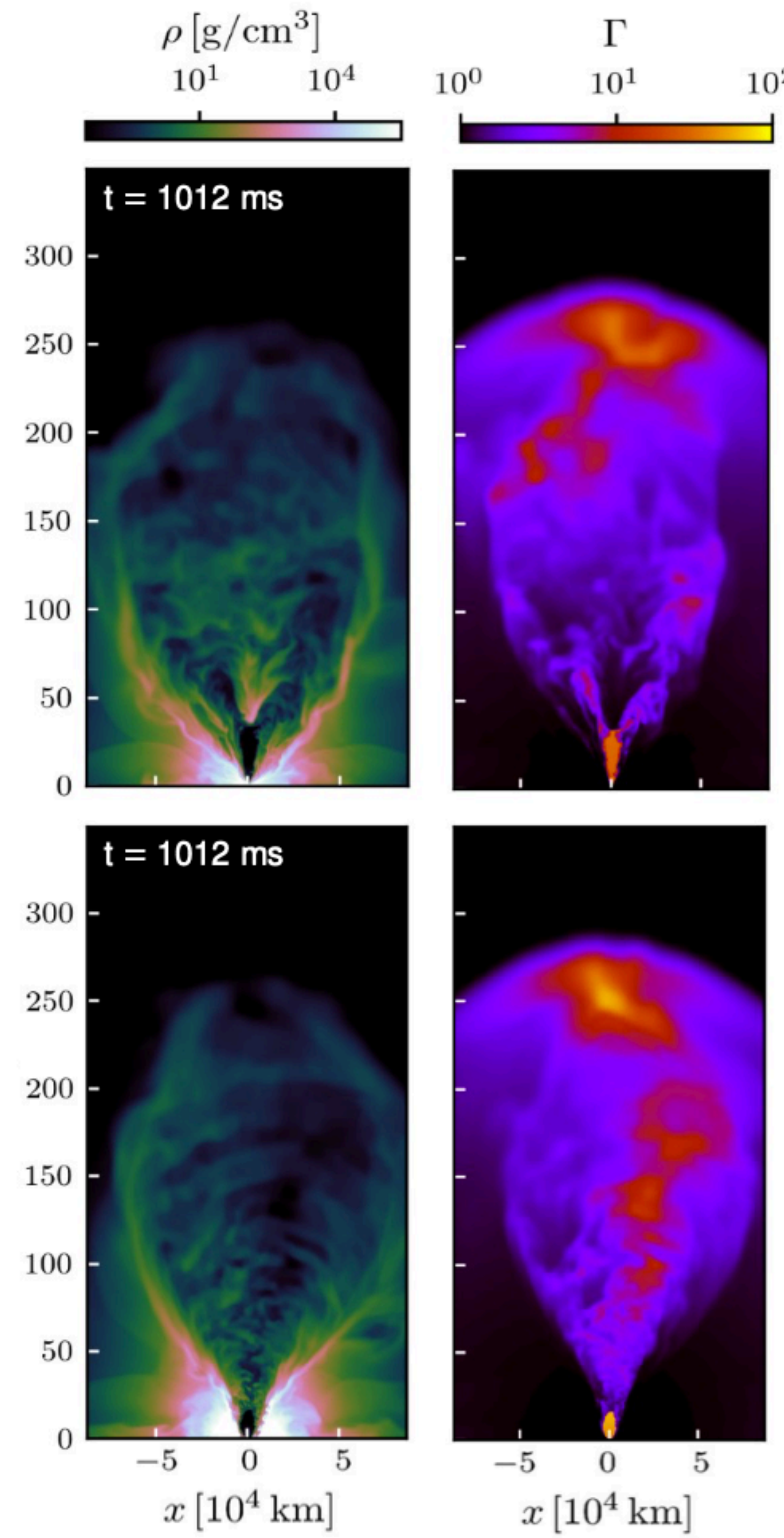

gravity effect:
more turbulence
and baryon loading

no gravity:
unperturbed
collimation shock



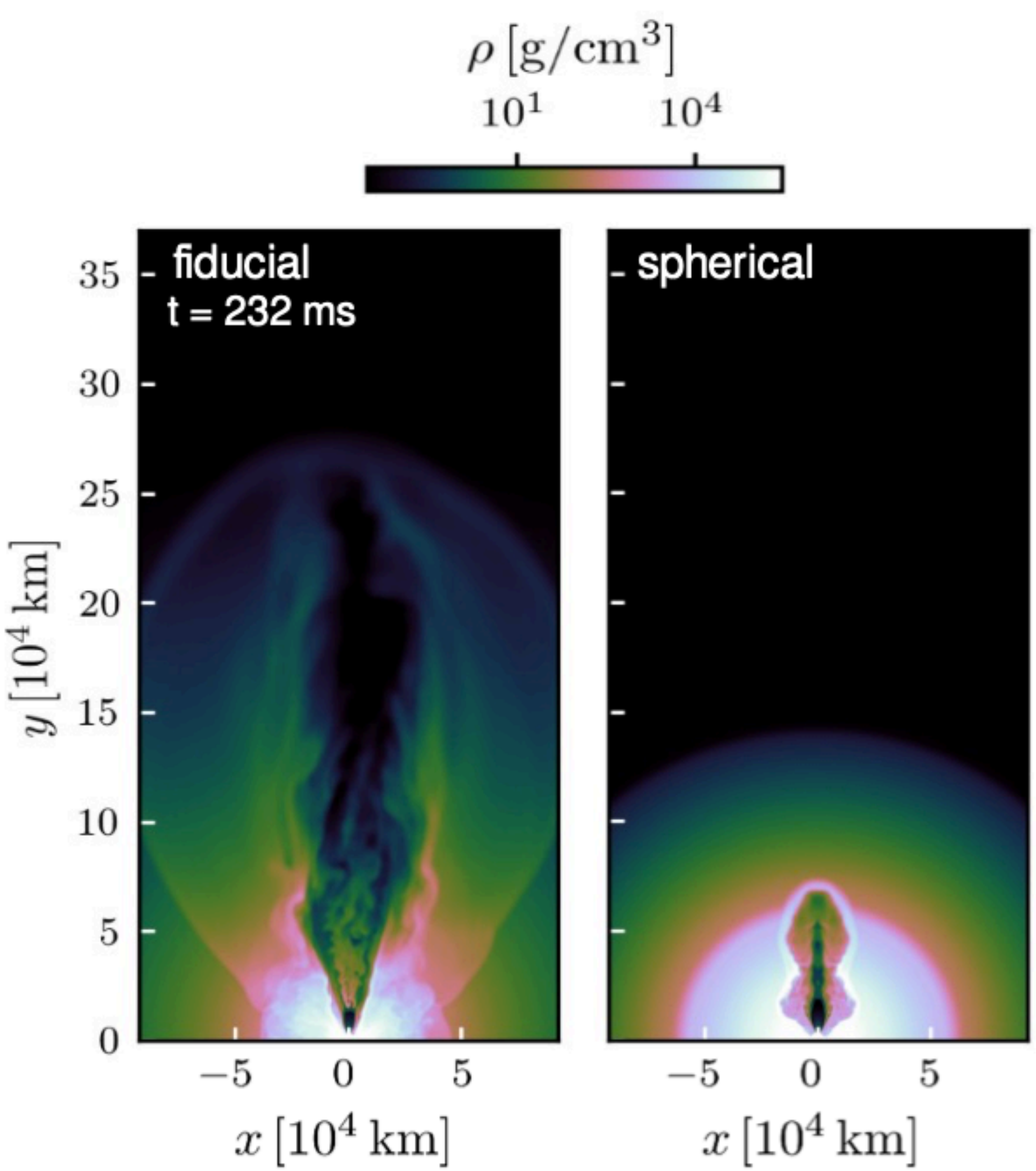

no gravity:
more compact
and axisymmetric
jet's head

larger
Lorentz factor

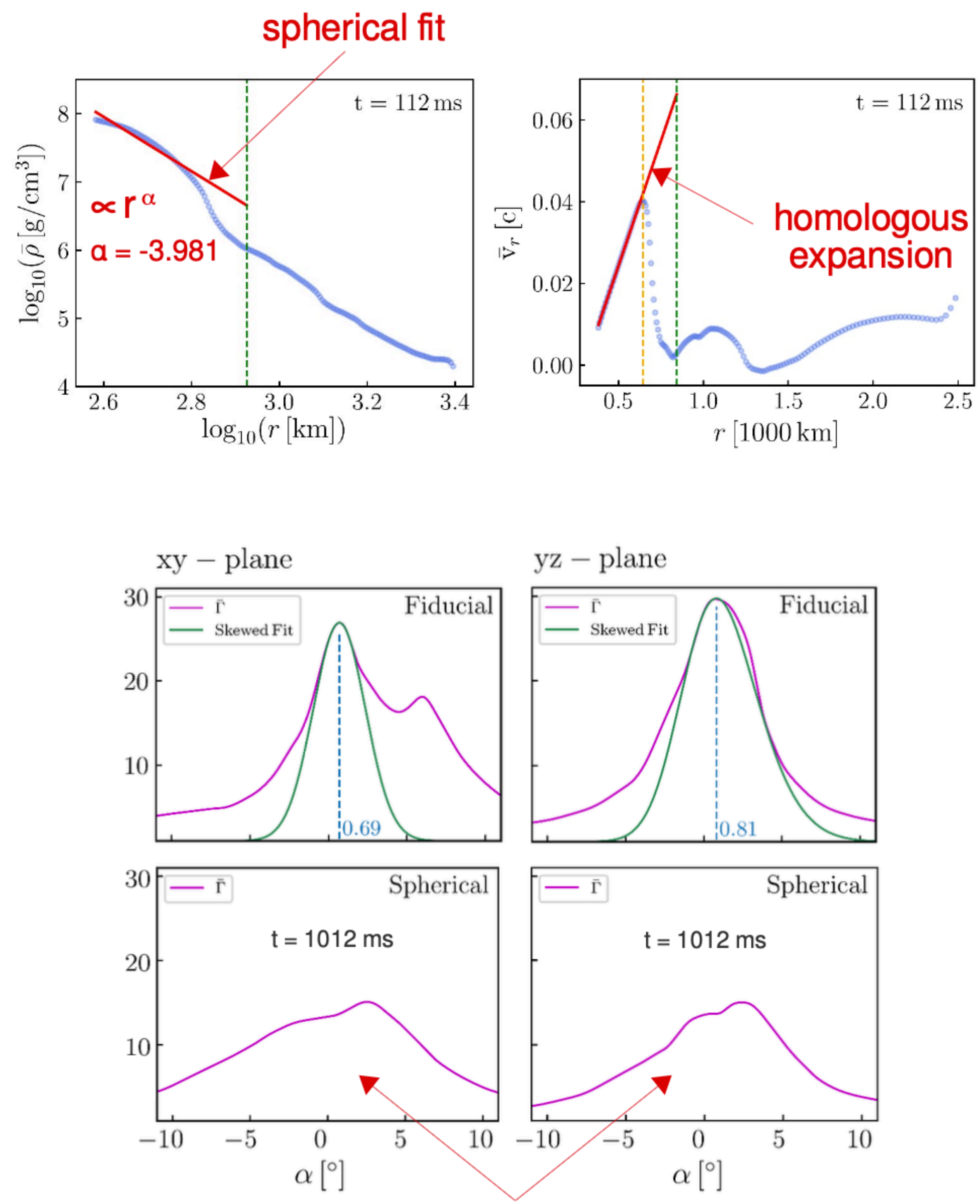



adapted from slides by Andrea Pavan

# BNS merger vs. hand-made initial conditions

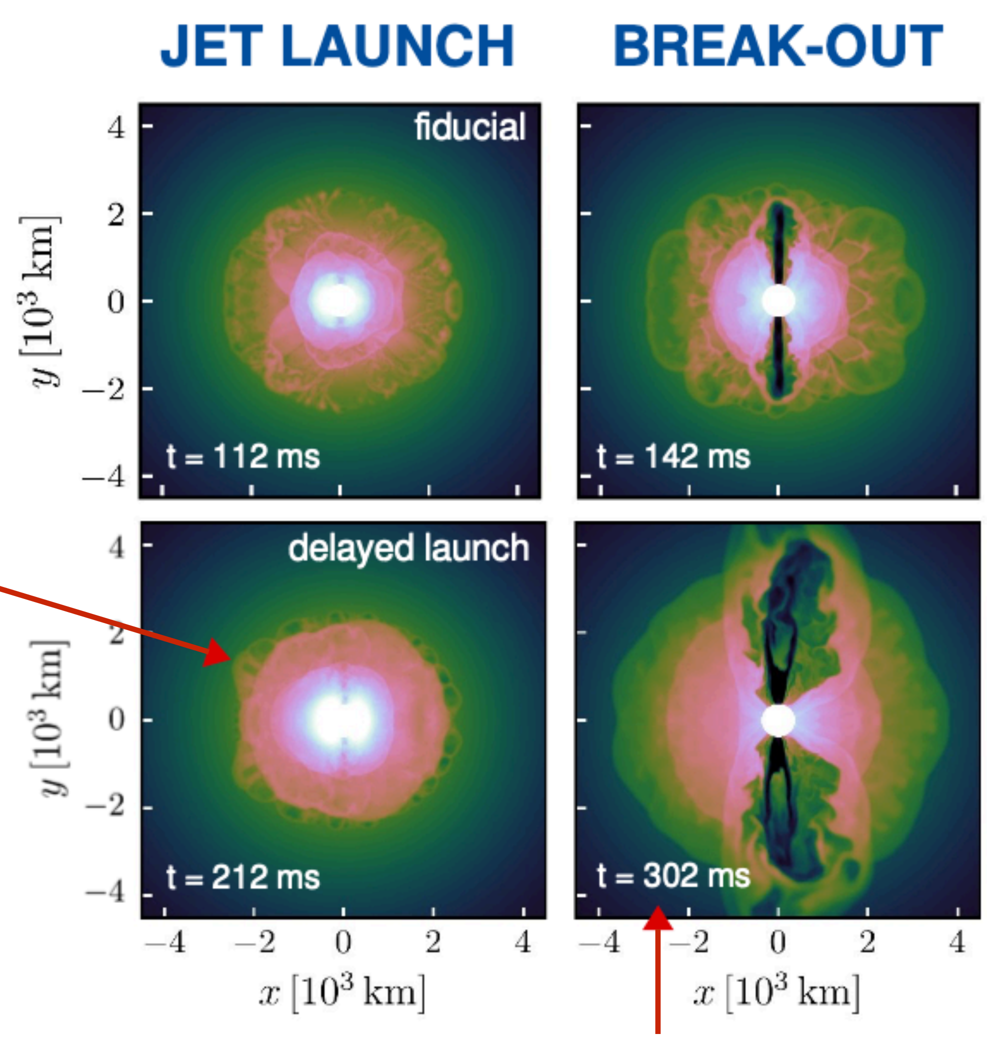


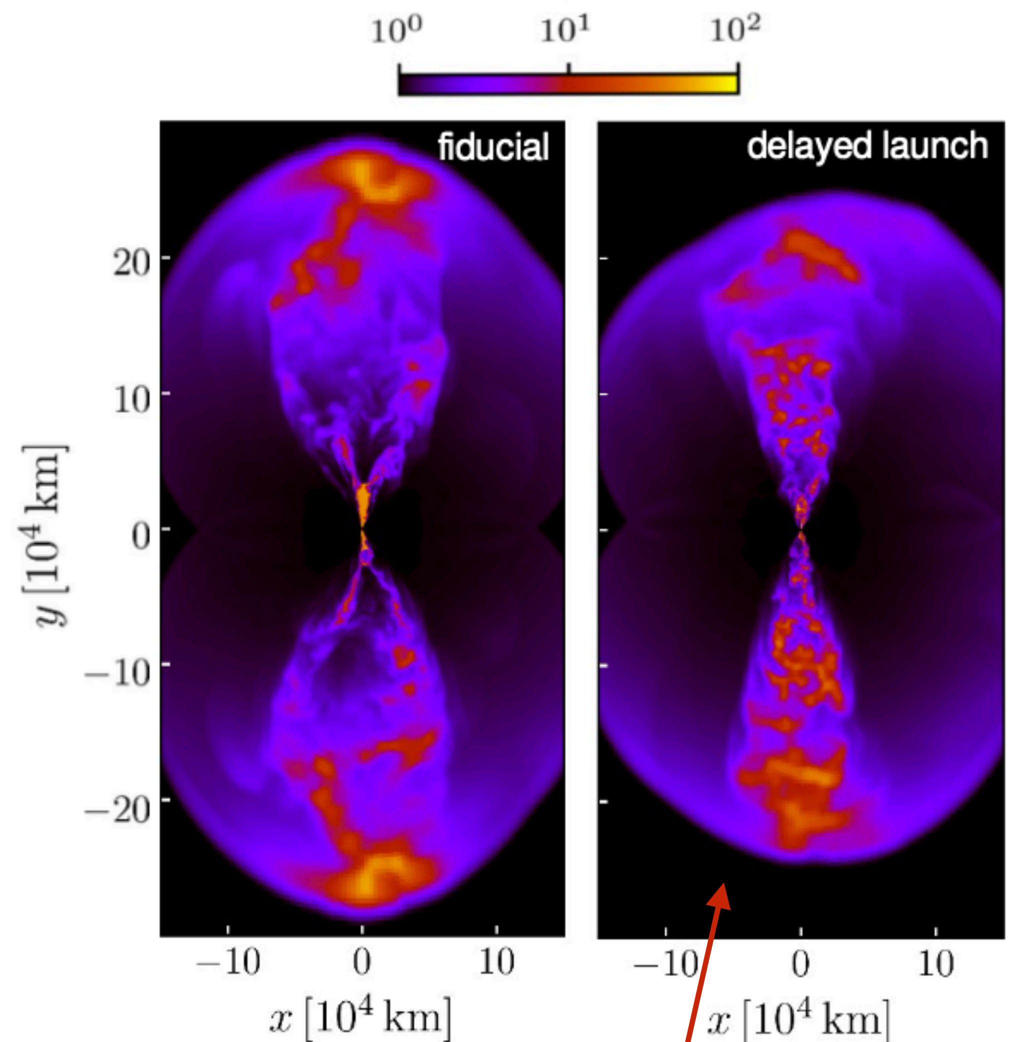

delayed break-out time




adapted from slides by Andrea Pavan

# Dependence on collapse/jet launching time




factor ~3.6
more mass

delayed breakout time (~90 ms)

more collimation and axisymmetry
less expansion, lower Lorentz factor

adapted from slides by Andrea Pavan

# Summary of Pavan+2021

- first 3D RHD jet simulations with environment imported from a BNS merger simulation
- simpler hand-made environments lead to significantly different results
- gravitational pull from central object needs to be included
- outcome may strongly depend on jet launching time

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# Work in progress..

**short-term**

- inclusion of magnetic fields (RMHD)
- combination with afterglow modelling
- adaptive mesh refinement

**long-term**

- jet launched consistently in BNS merger simulation
- radiation transport for thermal and non-thermal photons

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- combination with afterglow modelling
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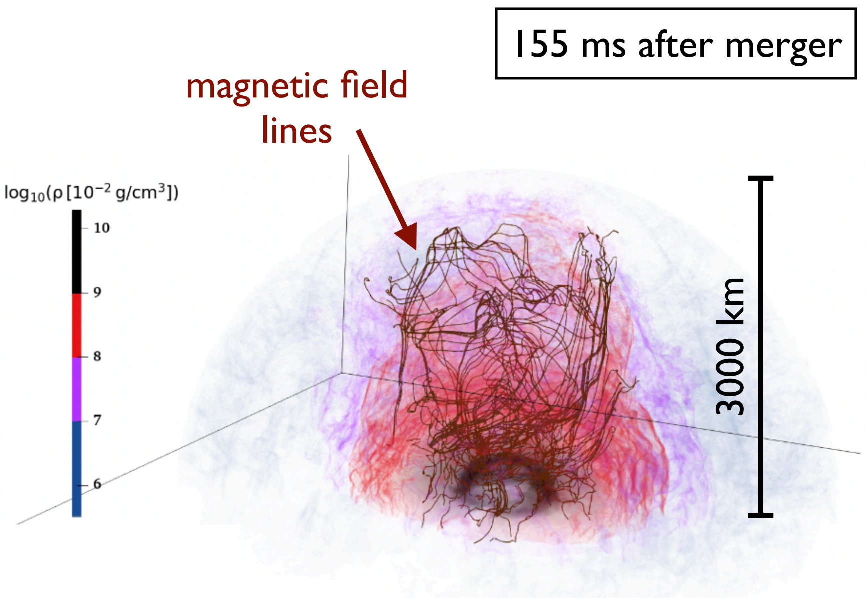
**long-term**

- jet launched consistently in BNS merger simulation
- radiation transport for thermal and non-thermal photons

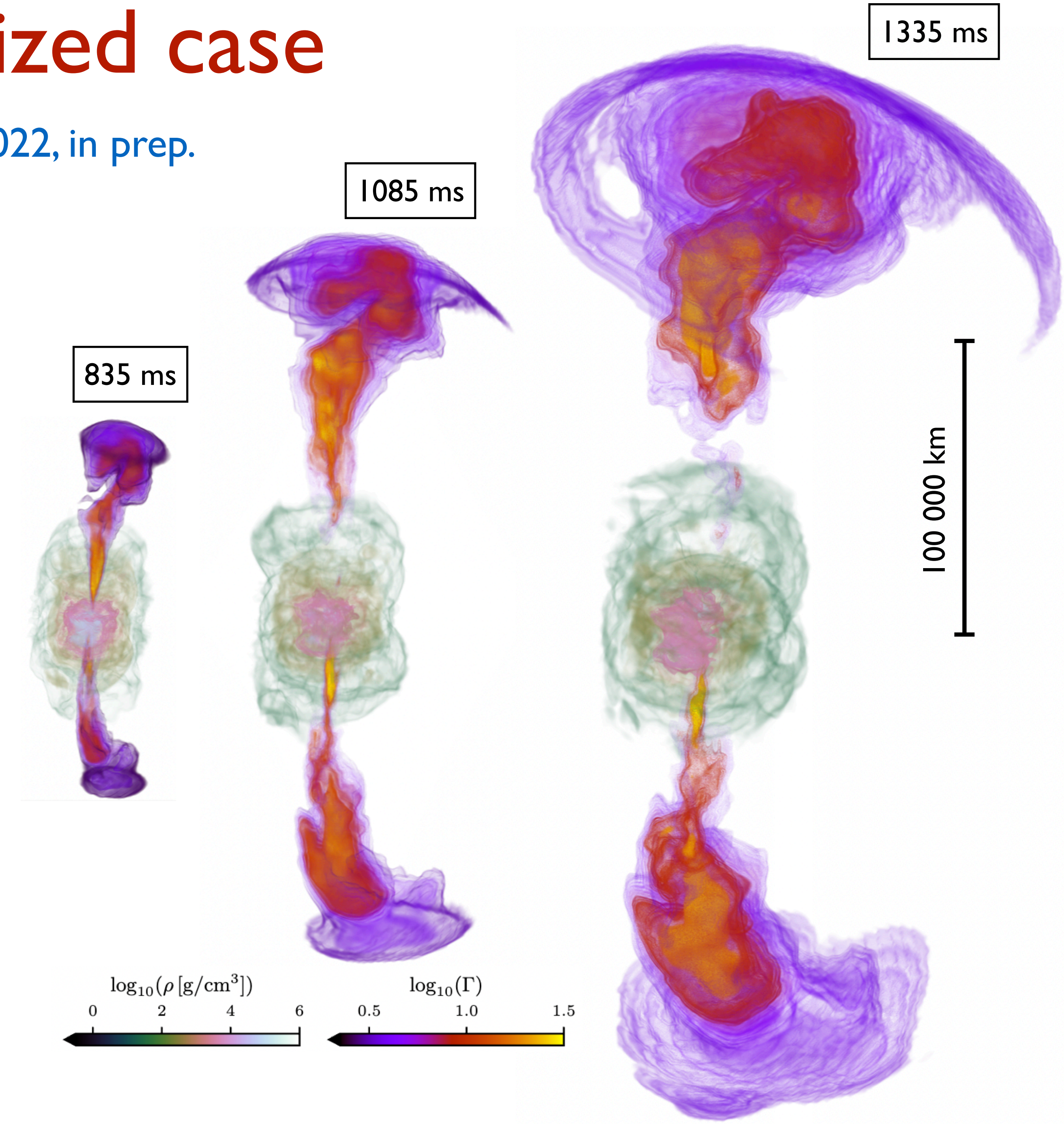
# Jet in realistic BNS merger environments: magnetized case

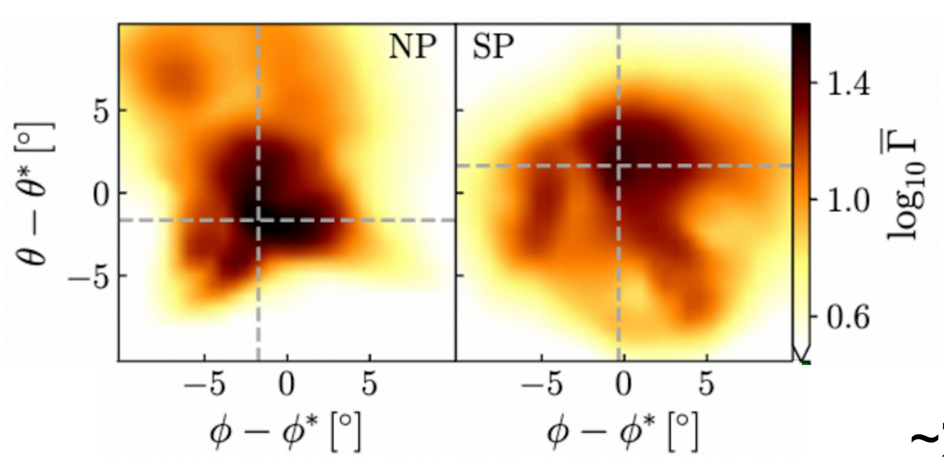
Pavan+2022, in prep.




initial data from magnetized BNS merger simulation of Ciolfi 2020a

injection of magnetized jet




2D angular profiles of Lorentz factor ~2s after jet launching

# Take-home message

- 2017 BNS merger left important questions on the physical origin of the SGRB jet
- GRMHD simulations of the merger process represent the necessary investigating tool
- we found that massive NS remnants can launch collimated outflows, but to produce a SGRB jet we (likely) need an accreting BH
- we also performed the first relativistic simulations of jets propagating through a realistic BNS environment (i.e. imported from the GRMHD simulation)

  ⟶ accomplished key steps toward an end-to-end description

# References


- A. Pavan, R. Ciolfi, J.V. Kalinani, A. Mignone (2021), MNRAS **506**, 3483
*Short gamma-ray burst jet propagation in binary neutron star merger environments*

- R. Ciolfi, J.V. Kalinani (2020), ApJ Letters **900**, L35
*Magnetically driven baryon winds from binary neutron star merger remnants and the blue kilonova of August 2017*

- R. Ciolfi (2020a), MNRAS Letters **495**, L66
*Collimated outflows from long-lived binary neutron star merger remnants*

- D. Lazzati, R. Ciolfi, R. Perna (2020), ApJ **898**, 59
*Intrinsic properties of the engine and jet that powered the short gamma-ray burst associated with GW170817*

- R. Ciolfi, W. Kastaun, J.V. Kalinani, B. Giacomazzo (2019), PRD **100**, 023005
*The first 100 ms of a long-lived magnetized neutron star formed in a binary neutron star merger*

- D. Lazzati, et al. (2018), PRL **120**, 241103
*Late time afterglow observations reveal a collimated relativistic jet in the ejecta of the binary neutron star merger GW170817*

- R. Ciolfi, W. Kastaun, B. Giacomazzo, A. Endrizzi, D. M. Siegel, R. Perna (2017), PRD **95**, 063016
*General relativistic magnetohydrodynamic simulations of binary neutron star mergers forming a long-lived neutron star*


**Spritz and RePrimAnd**


- J.V. Kalinani, R. Ciolfi, W. Kastaun, et al. (2022), PRD **105**, 103031
*Implementing a new recovery scheme for primitive variables in the…*

- W. Kastaun, J.V. Kalinani, R. Ciolfi (2021), PRD **103**, 023018
*Robust Recovery of Primitive Variables in Relativistic Ideal MHD*

- F. Cipolletta, et al. (2021), CQG **38**, 085021
*Spritz: General Relativistic Magnetohydrodynamics with Neutrinos*

- F. Cipolletta, et al. (2020), CQG **37**, 135010
*Spritz: a new fully general-relativistic magnetohydrodynamic code*


**Recent review articles**


- R. Ciolfi (2020c), Front. Astron. Sp. Sci. **7**, 27
*Binary neutron star mergers after GW170817*

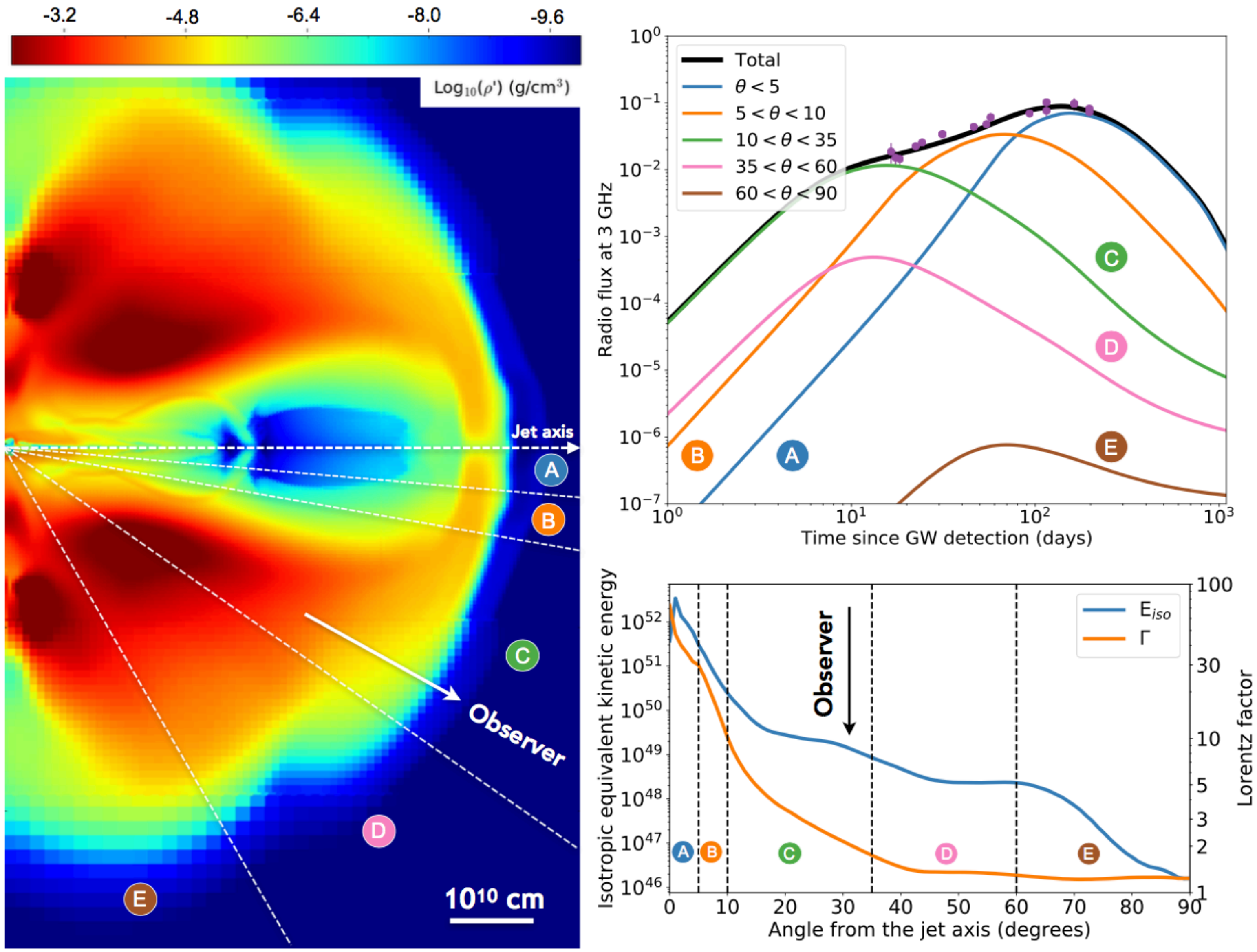
- R. Ciolfi (2020b), Gen. Rel. Grav. **52**, 59
*The key role of magnetic fields in BNS mergers*

- R. Ciolfi (2018), IJMPD **27**, No. 13, 1842004
*Short gamma-ray burst central engines*

# BACKUP SLIDES

# GRB 170817A: Canonical SGRB?

Lazzati+2018

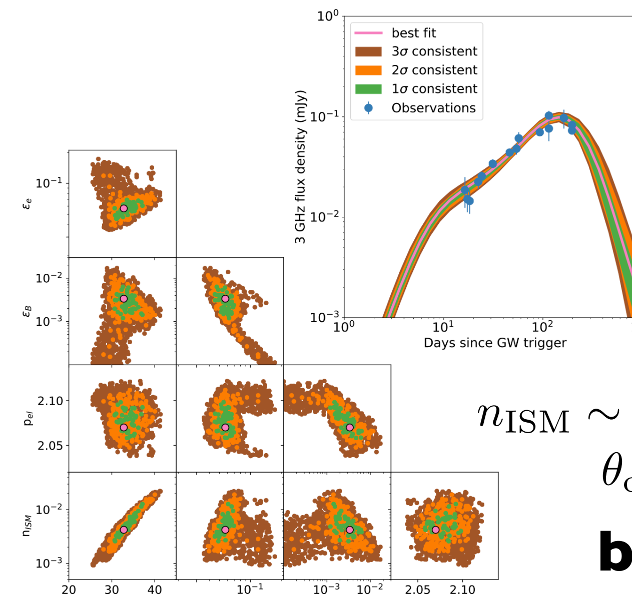



special relativistic jet simulation

$L_j = 10^{50}$ erg/s, $\theta_j = 16°$, $t_{eng} = 1$ s

$M_{ej} = 0.6 \times 10^{-2}\ M_\odot$

multiwavelength afterglow calculation




$n_{ISM} \sim 4 \times 10^{-3}\ \mathrm{cm}^{-3}$

$\theta_{obs} \sim 33°$

**best fit**

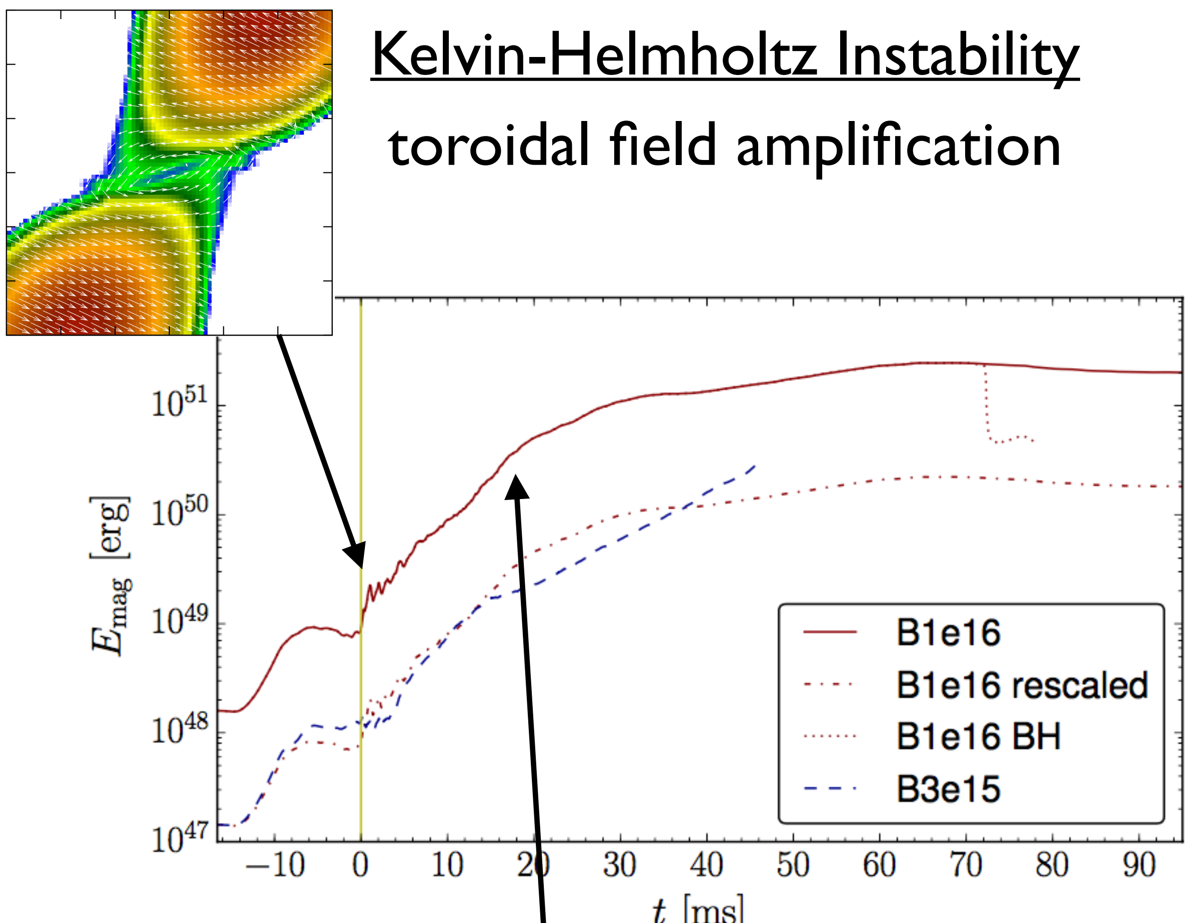
an ordinary SGRB event observed off-axis? ➡ viable explanation!

Aspen Institute Italia Award 2022!

# Magnetic field amplification and geometry

Ciolfi+2019: 100 ms of post-merger evolution

Kiuchi+2015

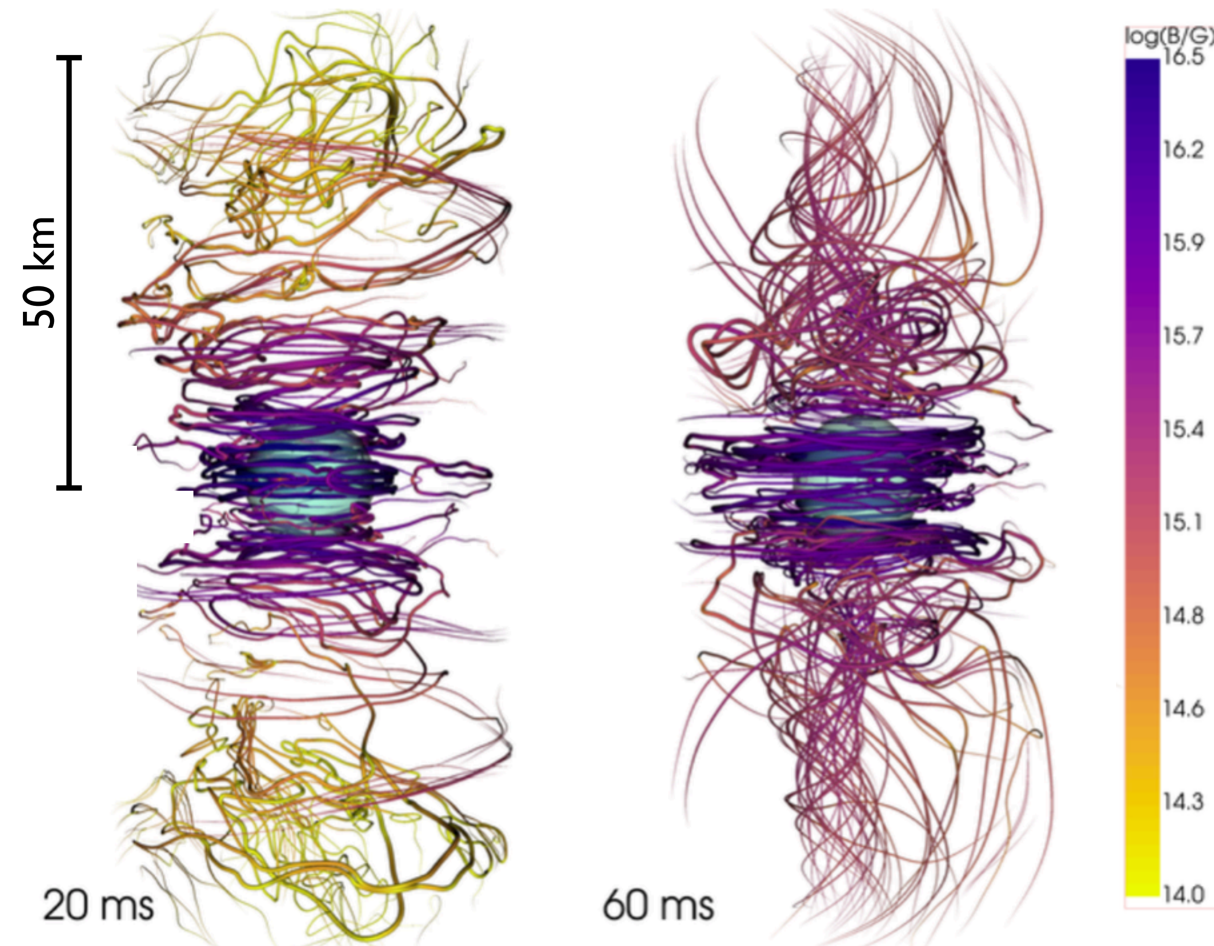



Kelvin-Helmholtz Instability

toroidal field amplification

MagnetoRotational Instability

Magnetic winding



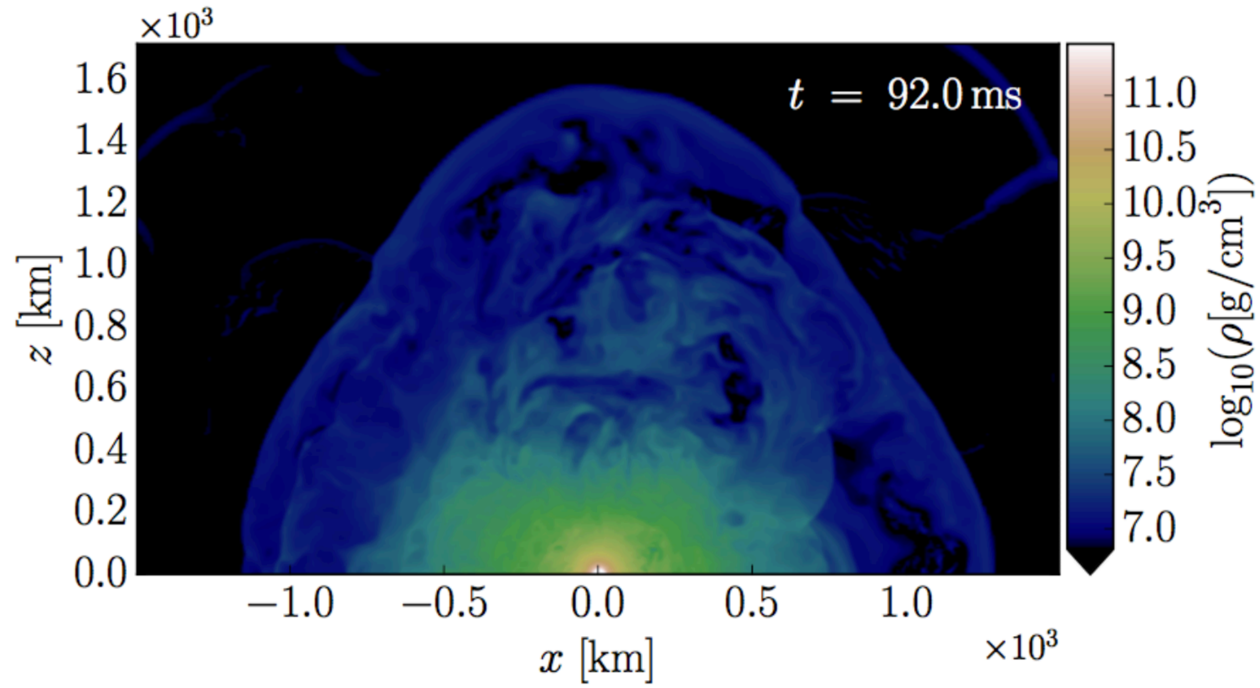

helical structure

# Magnetically driven wind

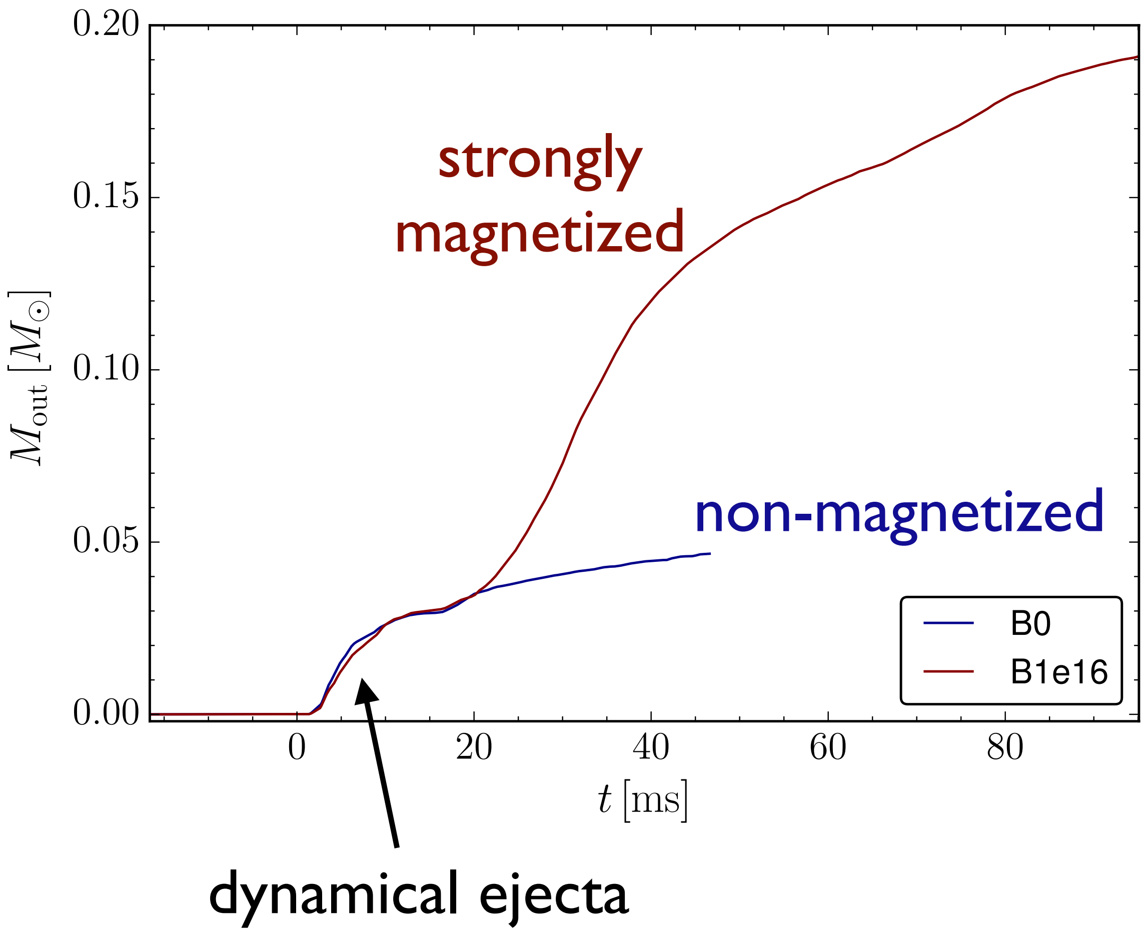
Ciolfi+2019

@50-100 ms after merger

nearly **isotropic** and **constant** density distribution from ~50 km to ~400 km




cumulative mass flow across 150 km radius




## magnetized remnant NS

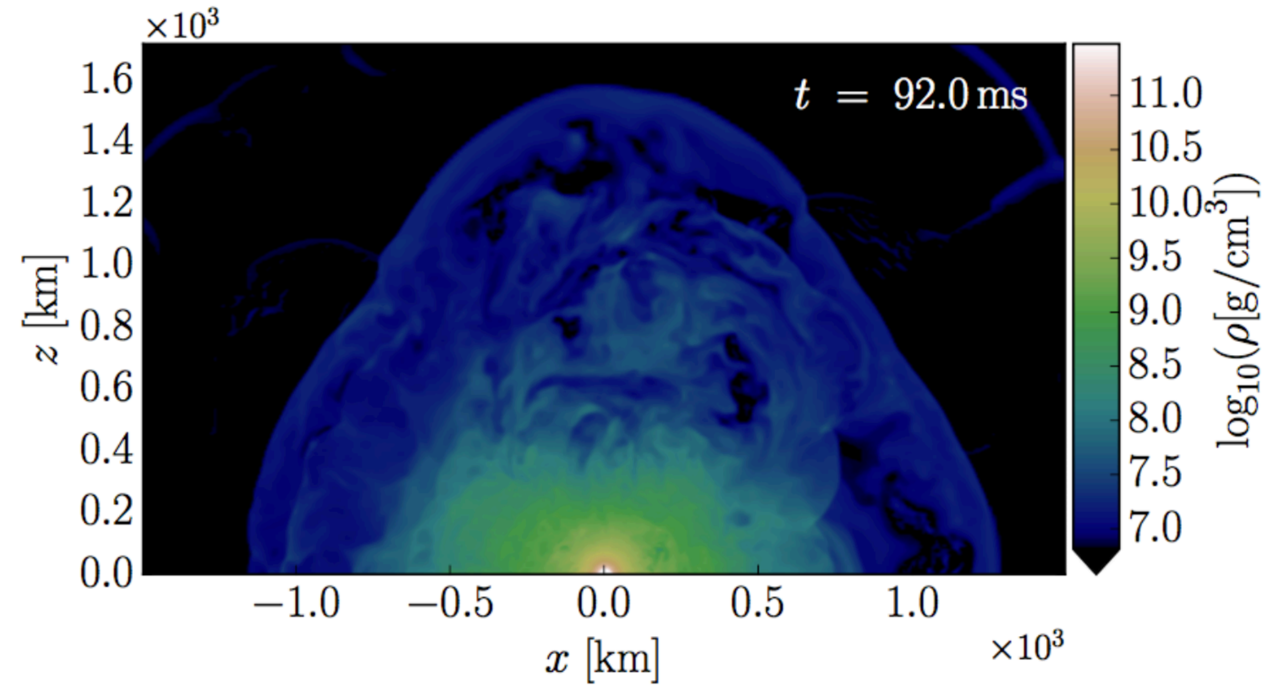
- surrounded by dense isotropic environment
- slow steady outflow maintaining a fixed radial density profile

# Magnetically driven wind

Ciolfi+2019

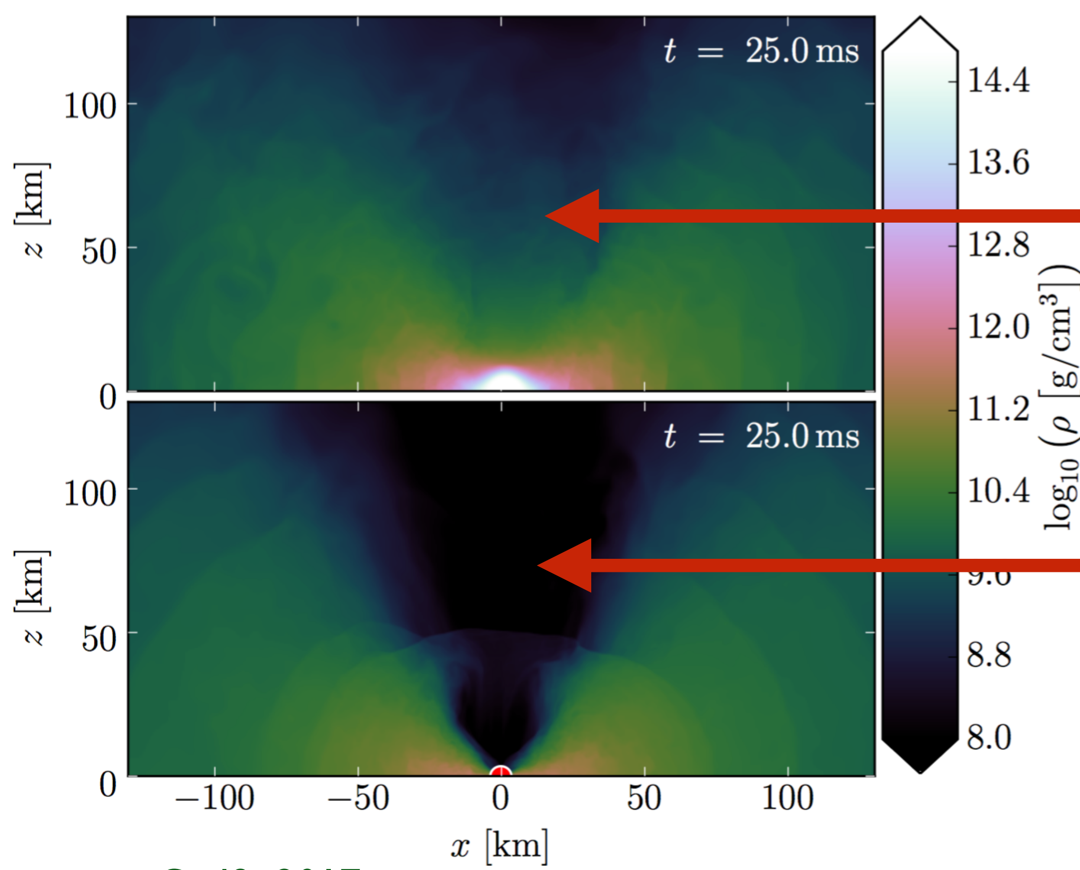
@50-100 ms after merger

nearly **isotropic** and **constant** density distribution from ~50 km to ~400 km




massive NS remnant

BH remnant

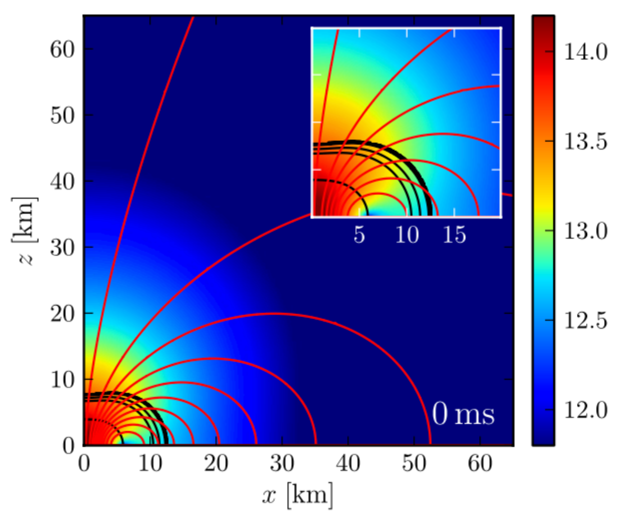



Ciolfi+2017

obstacle for jet formation

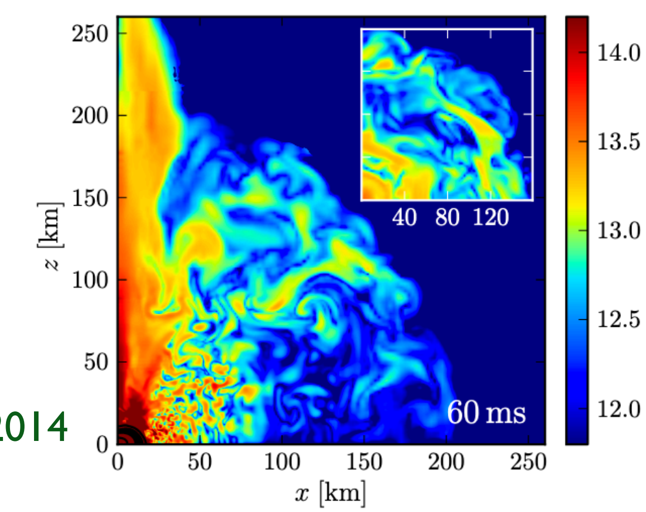
favourable environment

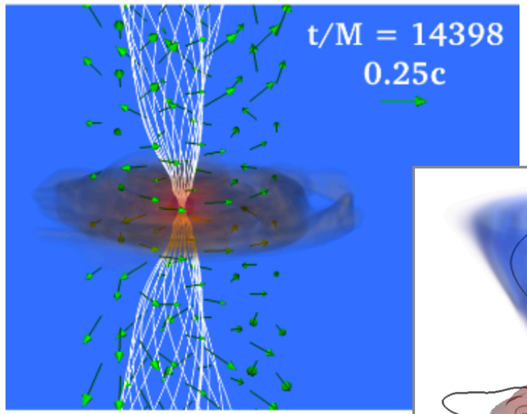
aligned dipolar field imposed on differentially rotating NS



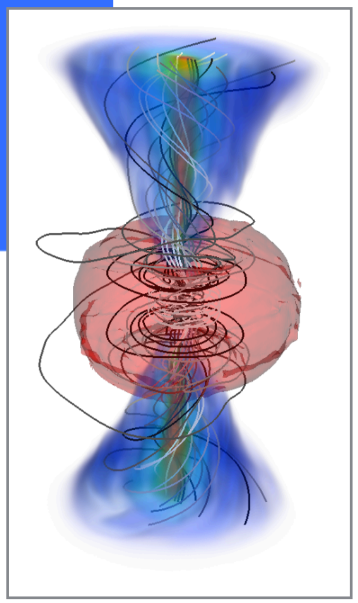

**collimated outflow**

Siegel+2014



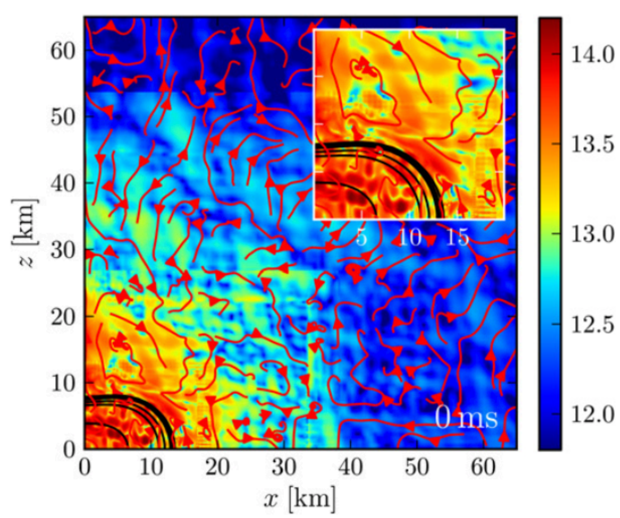




Ruiz+2018

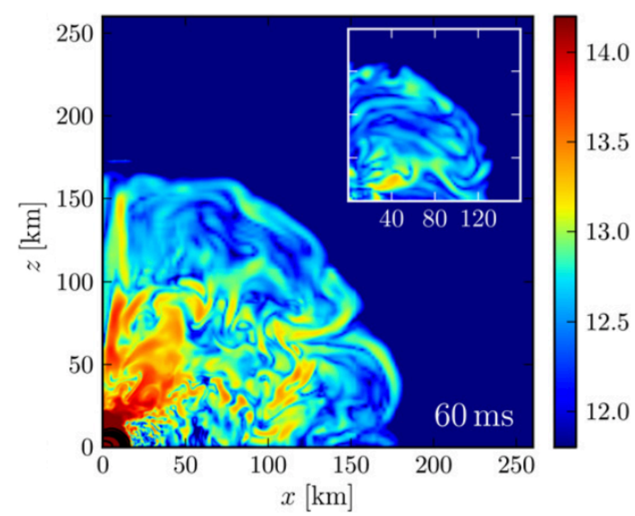


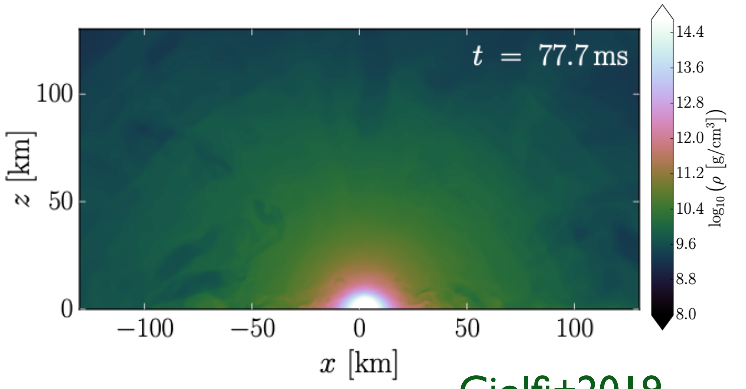
Moesta+2020

disordered magnetic field




**isotropic outflow**




Ciolfi+2019

earlier disordered field creates obstacle for collimated outflow coming later

**helical structure takes time to emerge (and not always does)**

# AT2017gfo: blue and red

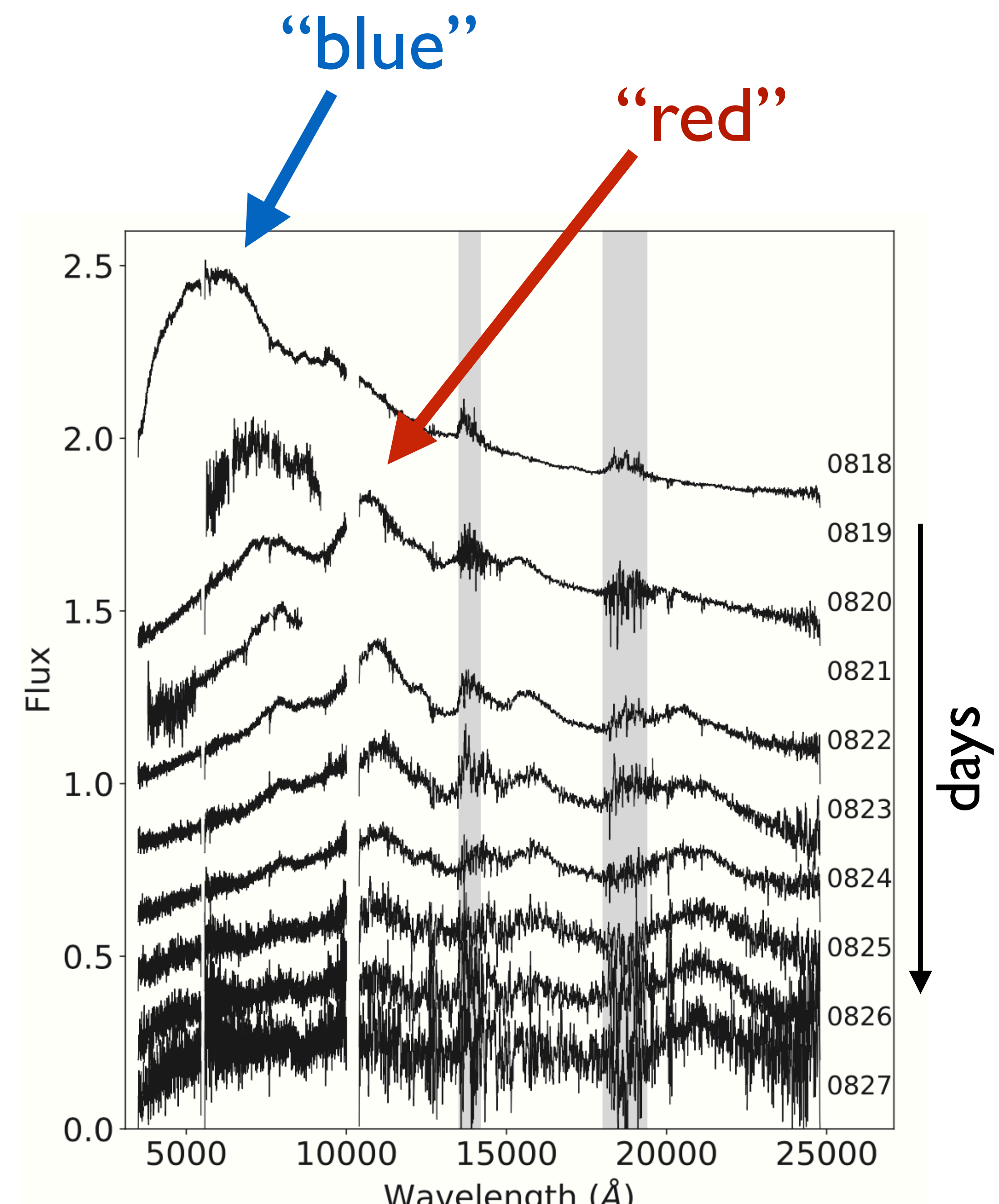
### 1) “blue” kilonova ➡ ???

peaking ~1 day after merger between UV and blue
ejecta expansion velocity ~0.2 - 0.3 c
ejecta mass ~0.015 - 0.025 $M_{sun}$
opacity ~0.5 $cm^2/g$ (lanthanide-poor)

(e.g. Siegel & Metzger 2018)

### 2) “red” kilonova ➡ <u>likely disk winds</u>

peaking several days after merger, IR wavelengths
ejecta expansion velocity ~0.1 c
ejecta mass ~0.05 $M_{sun}$
opacity ~10 $cm^2/g$ (lanthanide-rich)



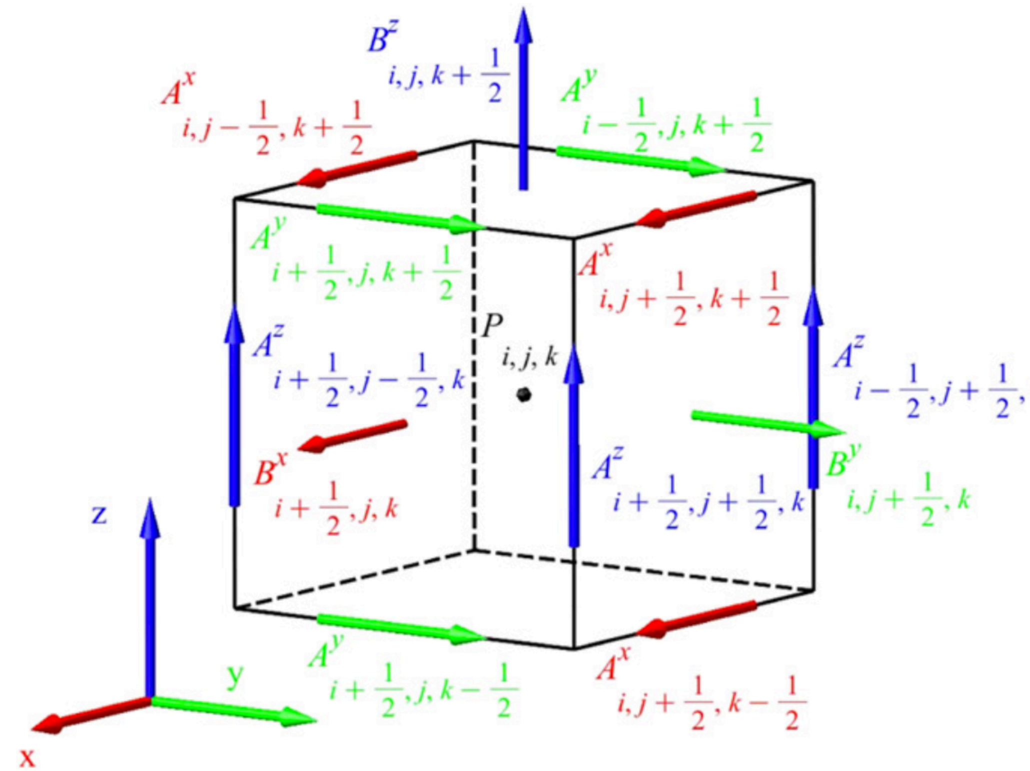

Pian+2017

which type of merger ejecta can explain the blue/red kilonova?

# *Spritz*: a new GRMHD code

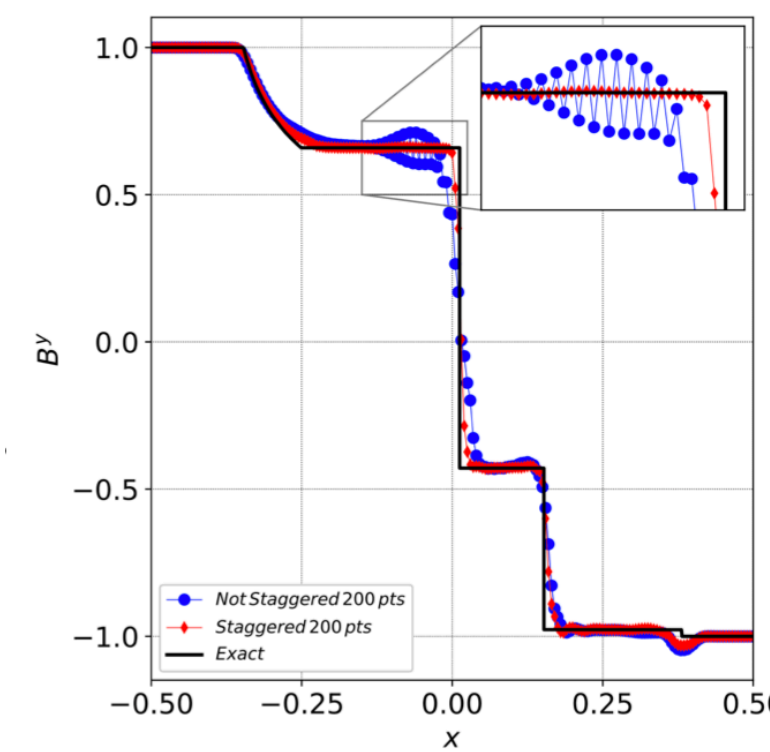
## Version 1.0: Cipolletta+2020

- 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: Cipolletta+2021

- 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

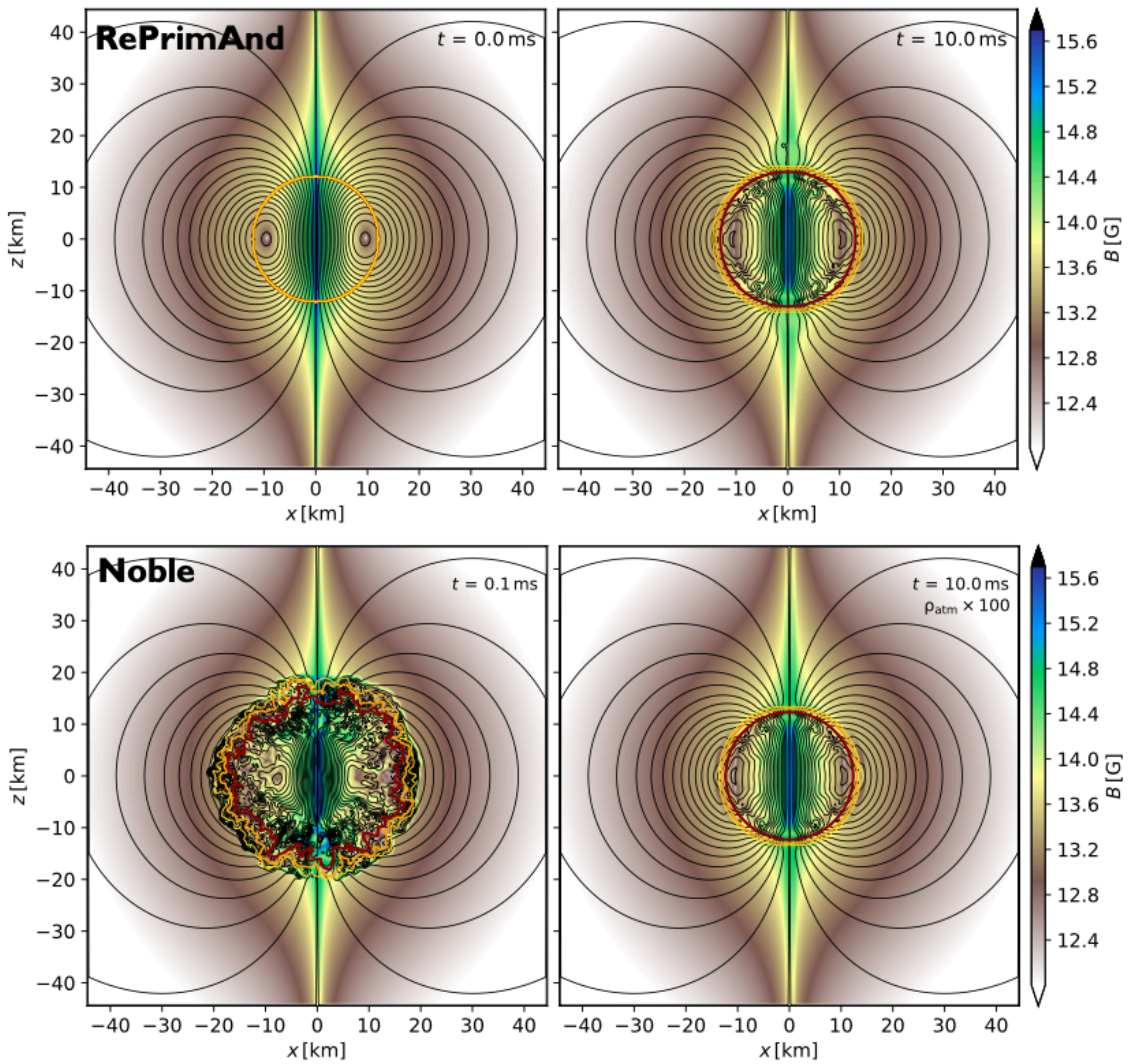



Balsara 1 shocktube test: staggered vs non-staggered vector potential evolution

adapted from slide by Jay Kalinani

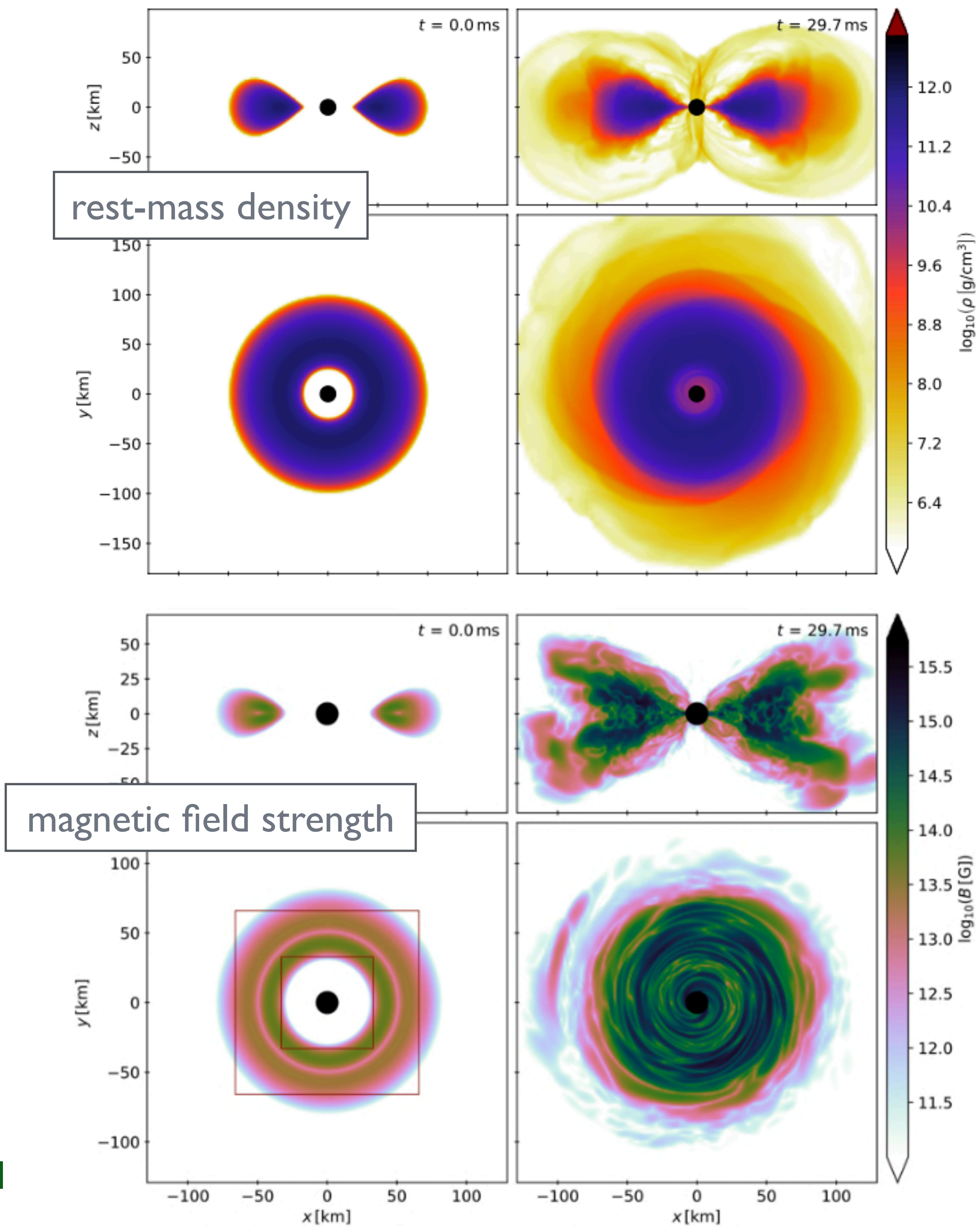
# Conservative-to-primitive recovery scheme *RePrimAnd*

## NS with extended dipolar field




magnetic field strength + field lines + density contours

## Fishbone-Moncrief BH-accretion disk




Kalinani+2021

adapted from slide by Jay Kalinani