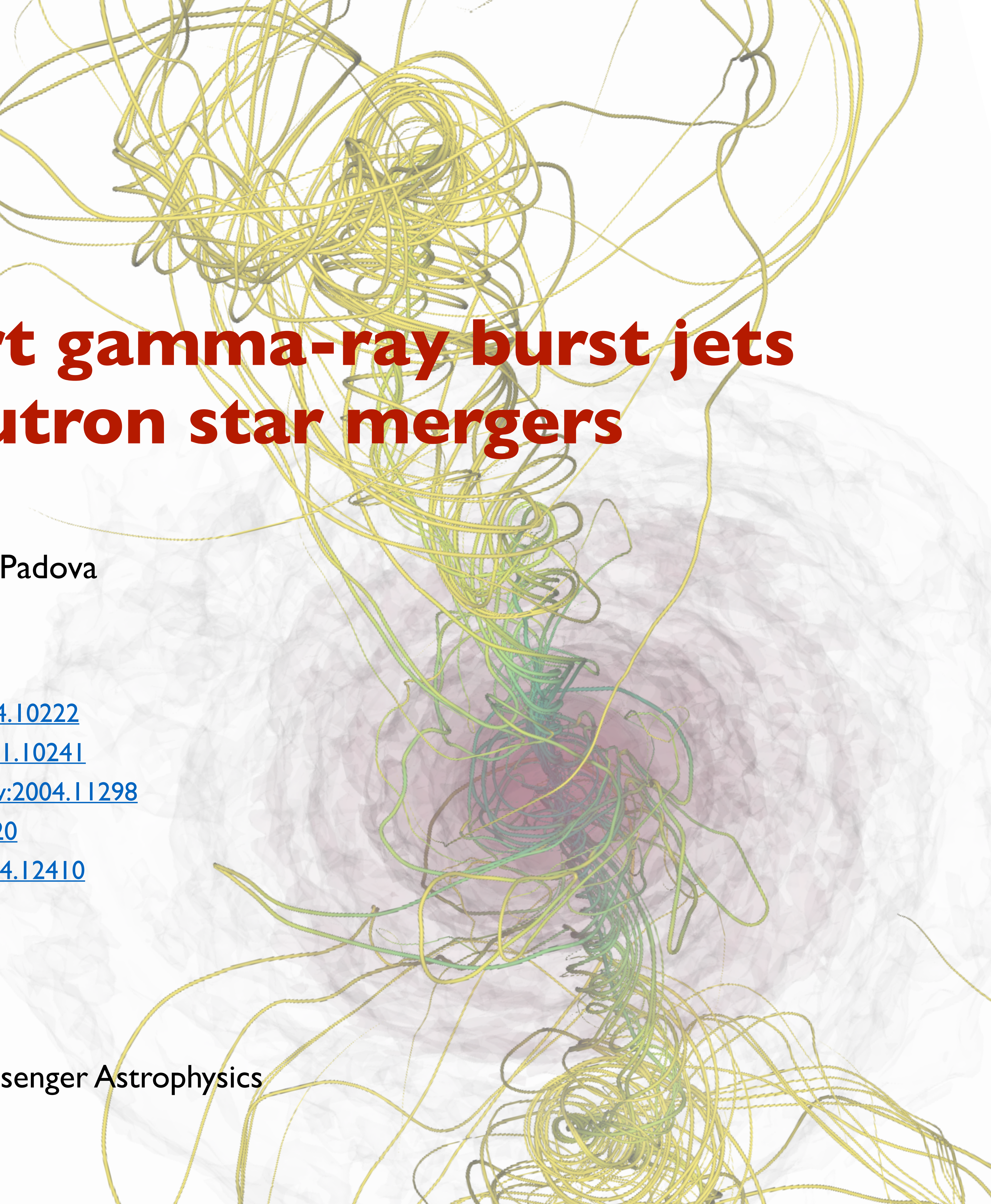


Simulating short gamma-ray burst jets from binary neutron star mergers

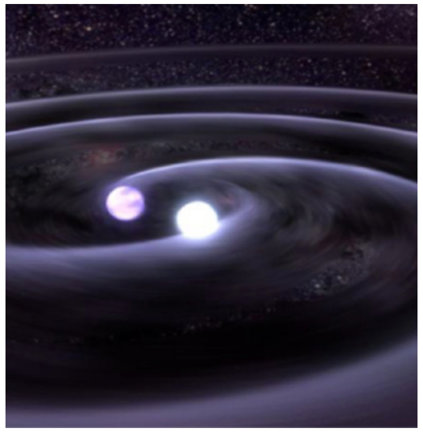
RICCARDO CIOLFI

INAF - Osservatorio Astronomico di Padova
INFN - Sezione di Padova

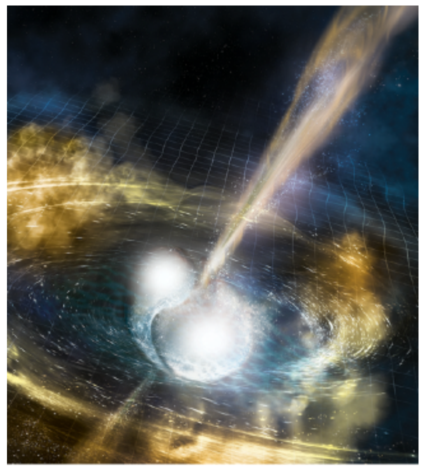
Ciolfi et al. 2019, PRD **100**, 023005 ArXiv:1904.10222
Ciolfi 2020a, MNRAS Lett. **495**, L66 ArXiv:2001.10241
Ciolfi & Kalinani 2020, ApJ Lett. **900**, L35 ArXiv:2004.11298
Kalinani et al. 2021, submitted ArXiv:2107.10620
Pavan et al. 2021, MNRAS **506**, 3483 ArXiv:2104.12410

Computational Challenges in Multi-Messenger Astrophysics
6th October 2020

GW170817 detection timeline

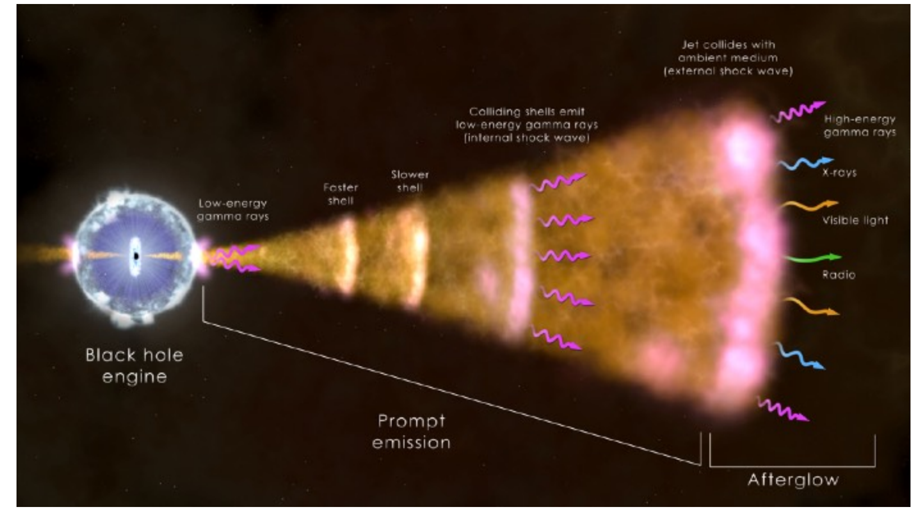


merger



short GRB

GRB 170817A



X-ray afterglow

radio afterglow

t0 +1.7 sec +10.87 hours +9 days +16 days

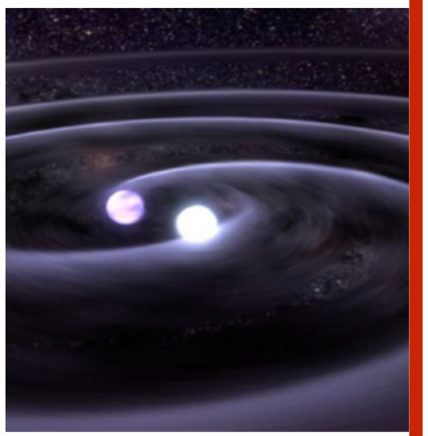
optical counterpart

—

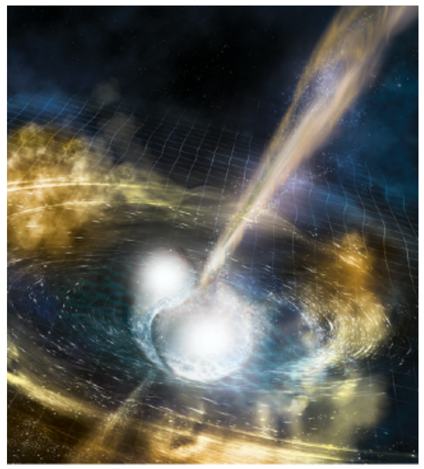
kilonova

AT 2017gfo

GW170817 detection timeline



merger



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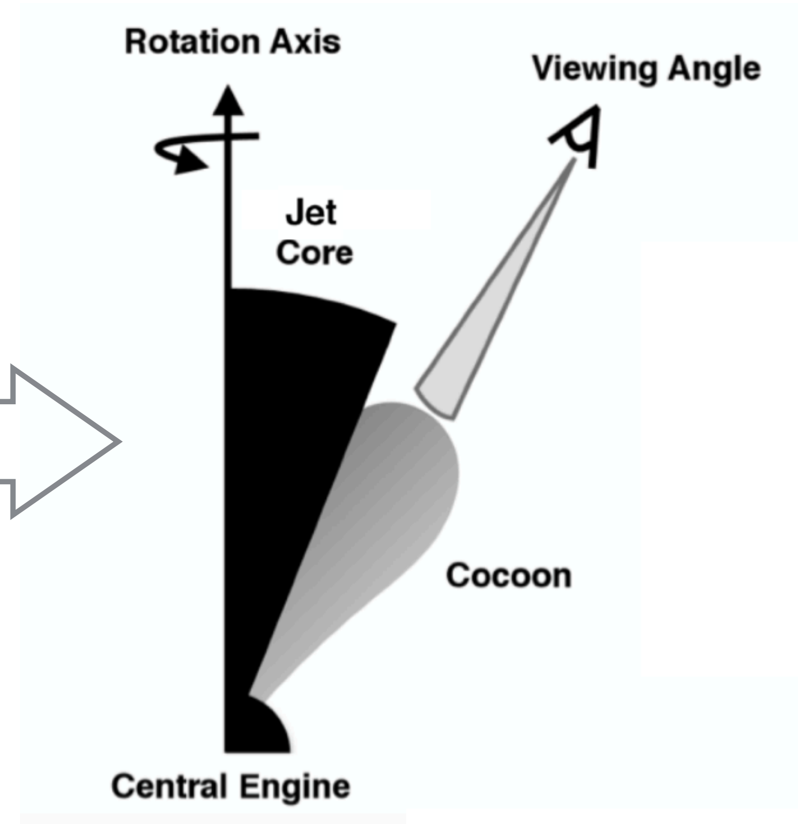
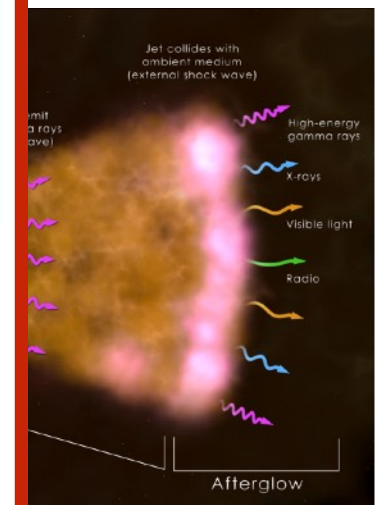
GRB170817A





dio afterglow

t0 +1.7 sec +10.87 hours +9 days +16 days

optical
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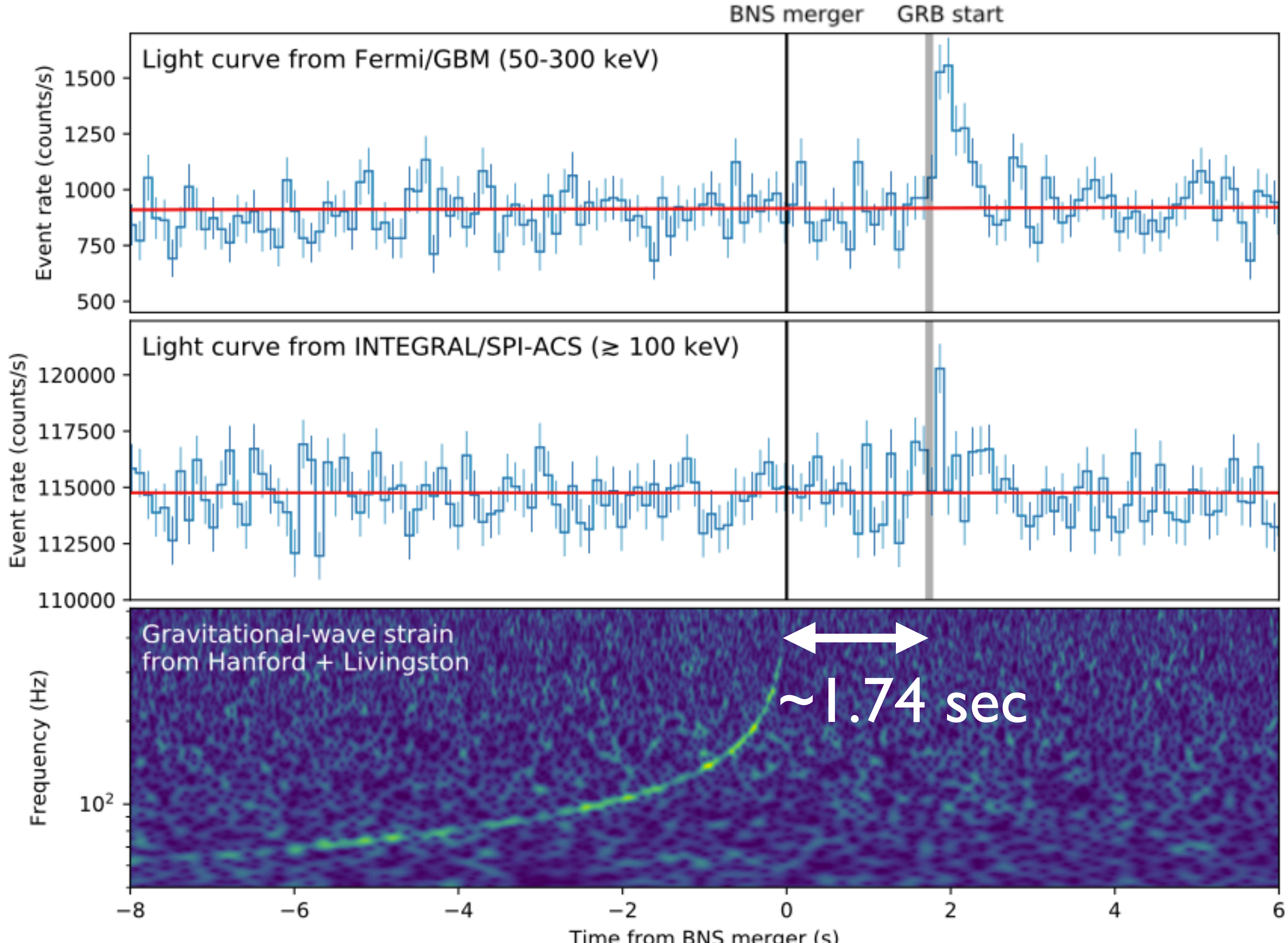
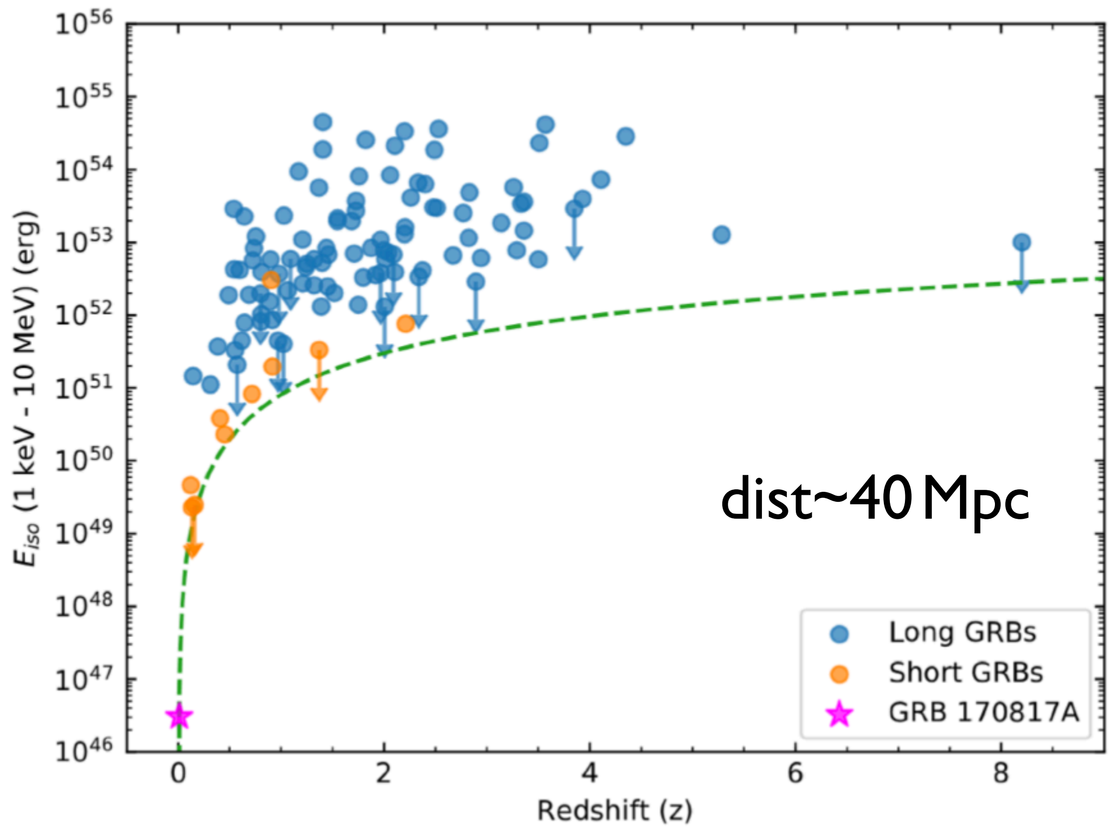
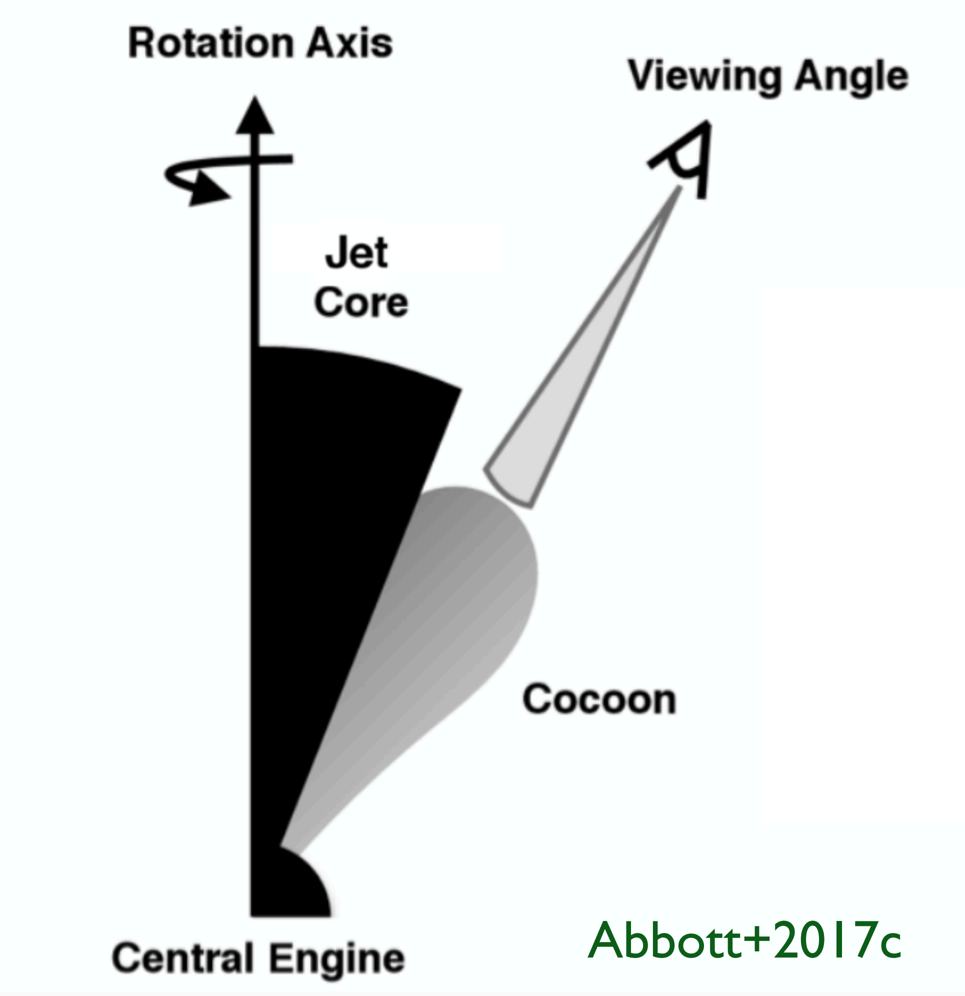
GRB 170817A



Abbott+2017c

GRB 170817A: a peculiar GRB

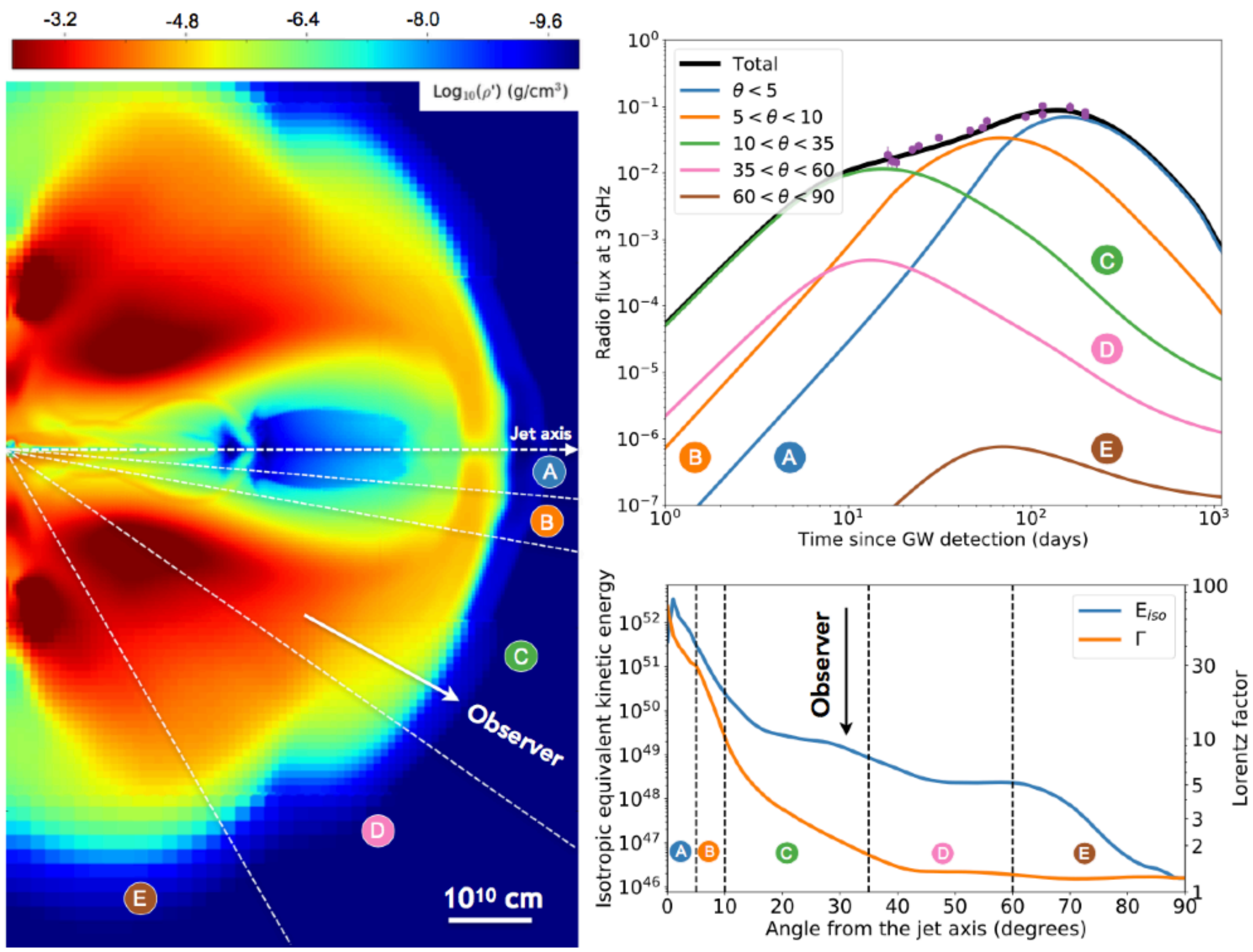




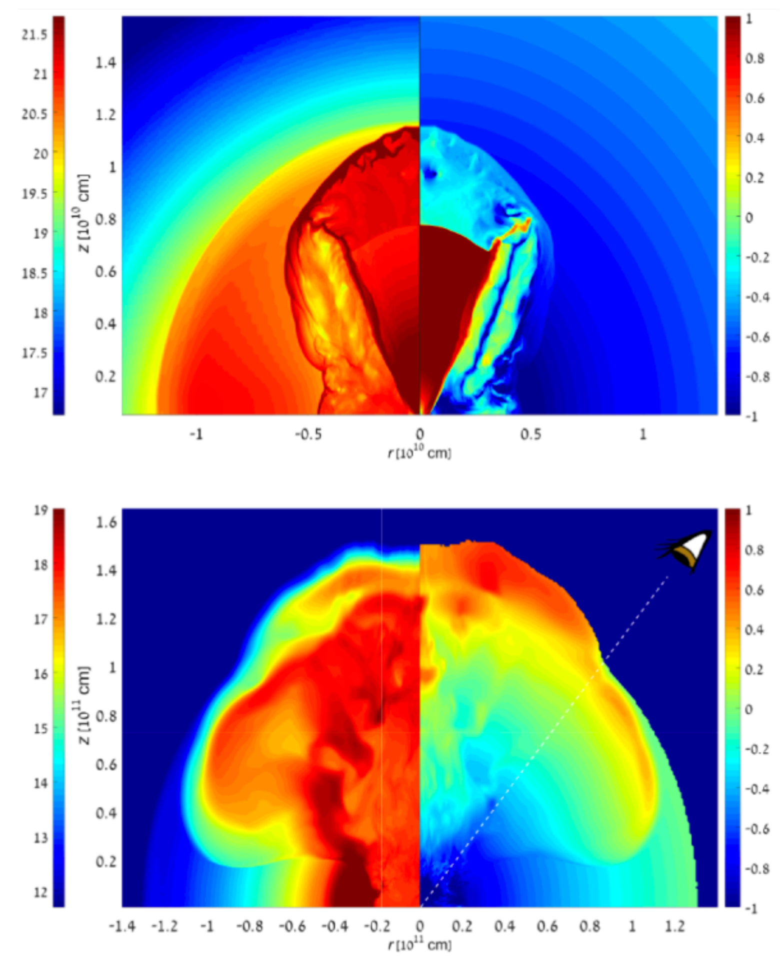
from GRB and multiwavelength afterglow modelling

observed gamma-rays come from mildly relativistic outflow ($\Gamma \sim 2-8$) moving along the line of sight

Canonical SGRB or choked jet?



Lazzati+2018



Gottlieb+2017

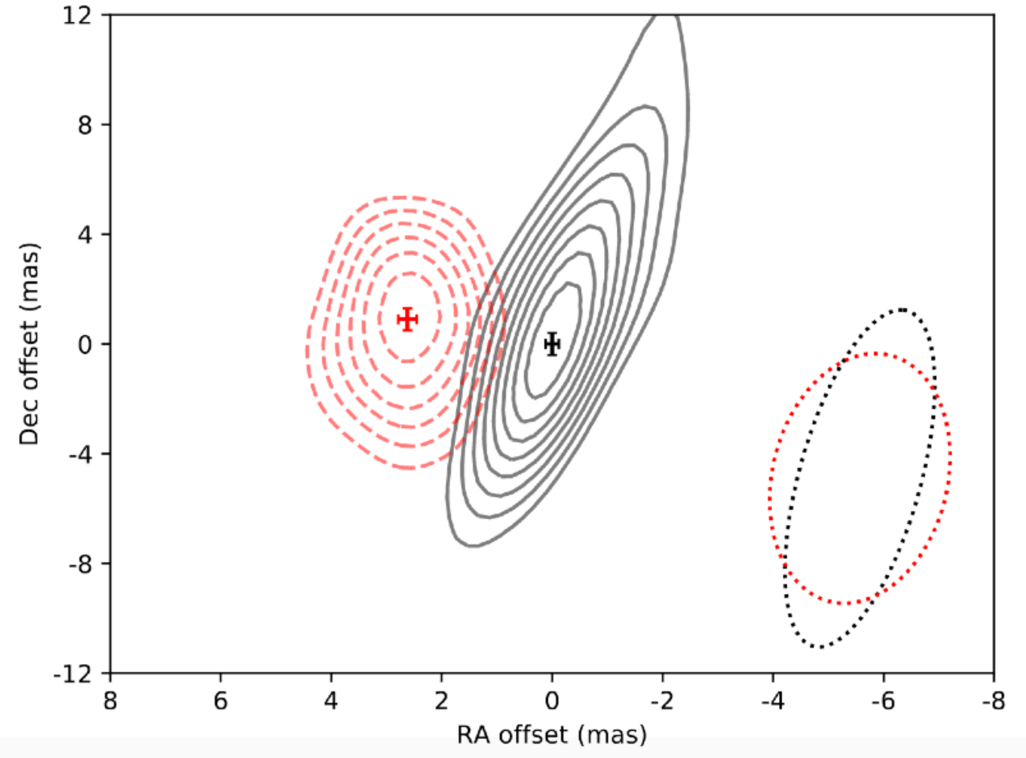
ordinary SGRB event observed off-axis
➡ viable explanation!

unsuccessful jet
no canonical SGRB
➡ also viable

VLBI observations

global network of 32 radio telescopes

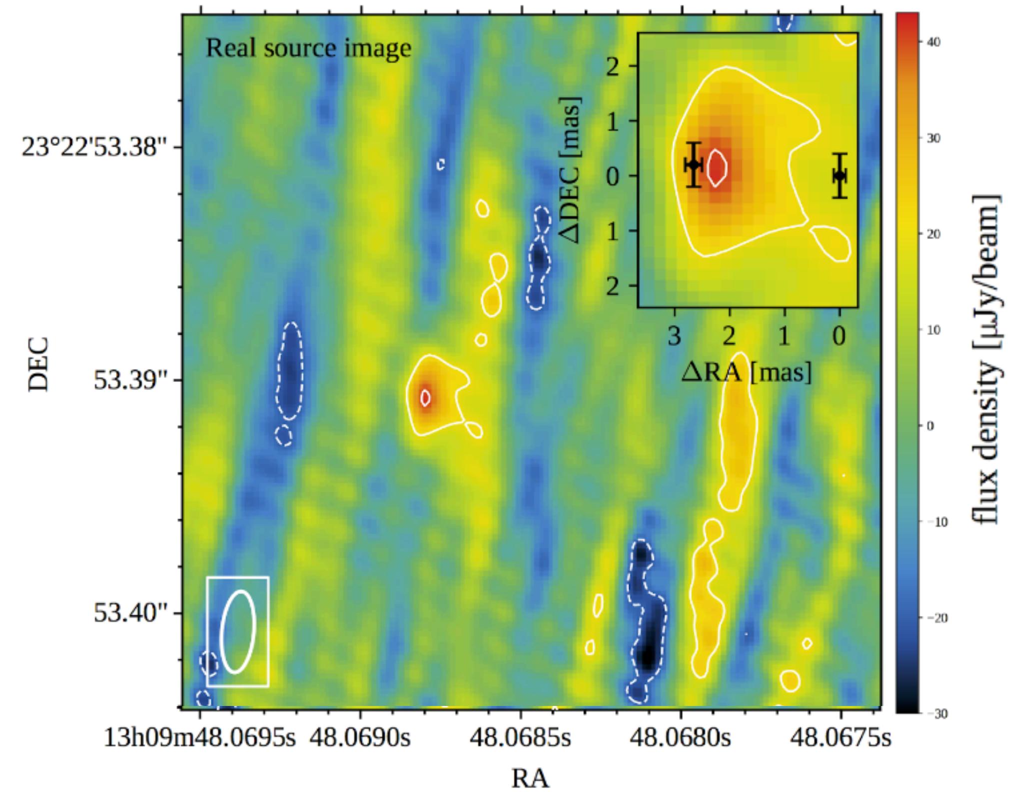
Mooley+2018

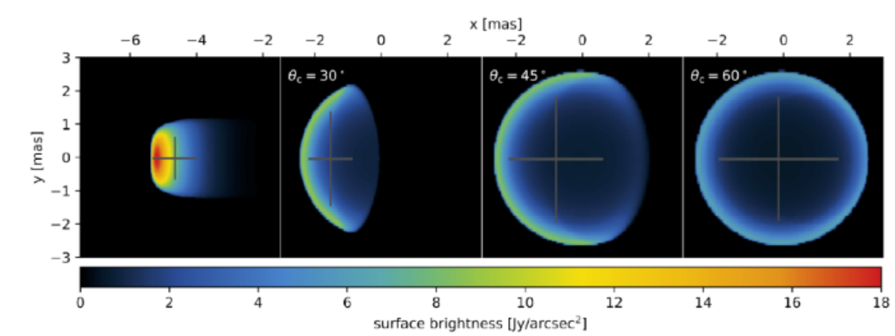


apparent superluminal motion between 75 and 230 days

source is moving relativistically (and getting closer)

Ghirlanda+2018





source size < 2 m arcseconds @ 207 days

source is still rather compact!

VLBI observations

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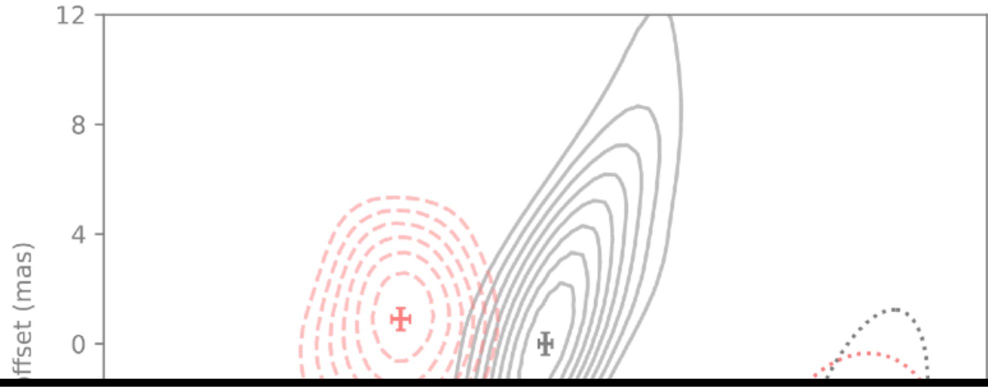

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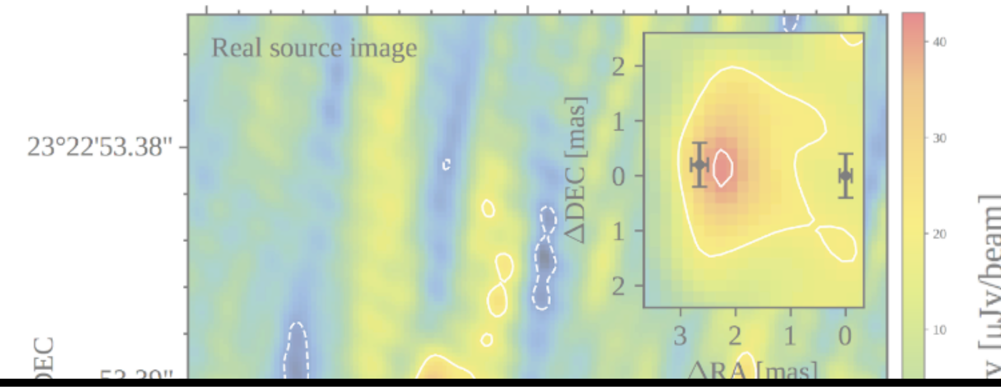
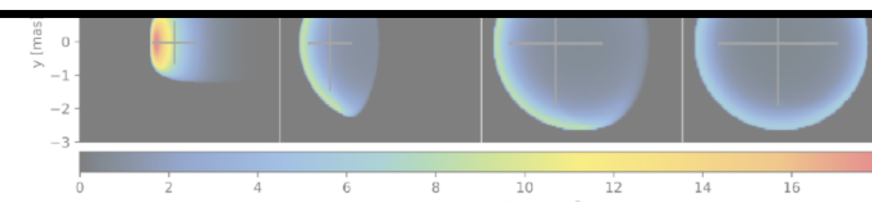


collimated jet (<5 deg), seen ~15-20 deg off-axis

nearly isotropic, mildly relativistic outflow excluded

between 75 and 230 days



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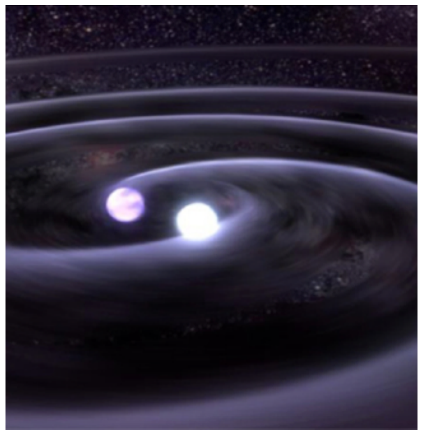
SGRB jets from BNS mergers



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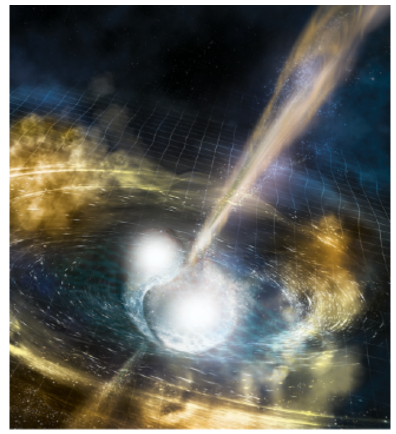

GW170817 GRB 170817A

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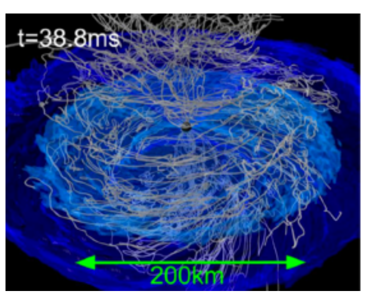
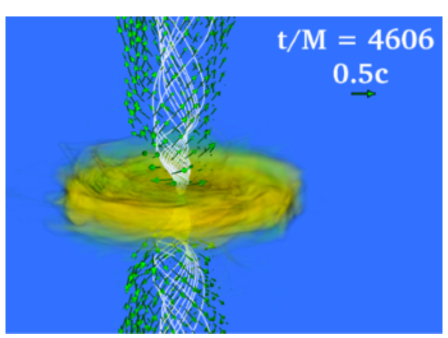
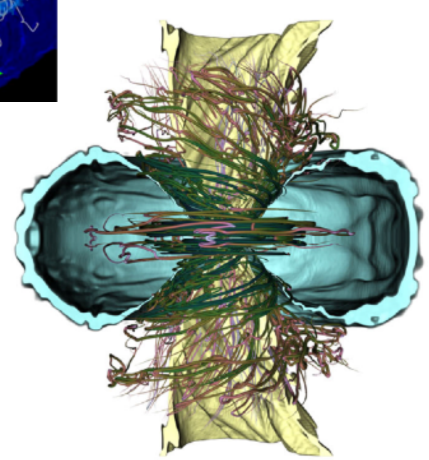
Kiuchi+2014





Ruiz+2016

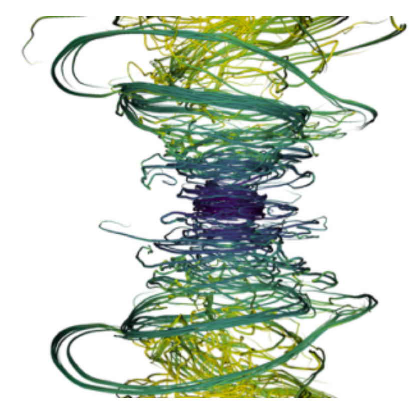


Kawamura+2016

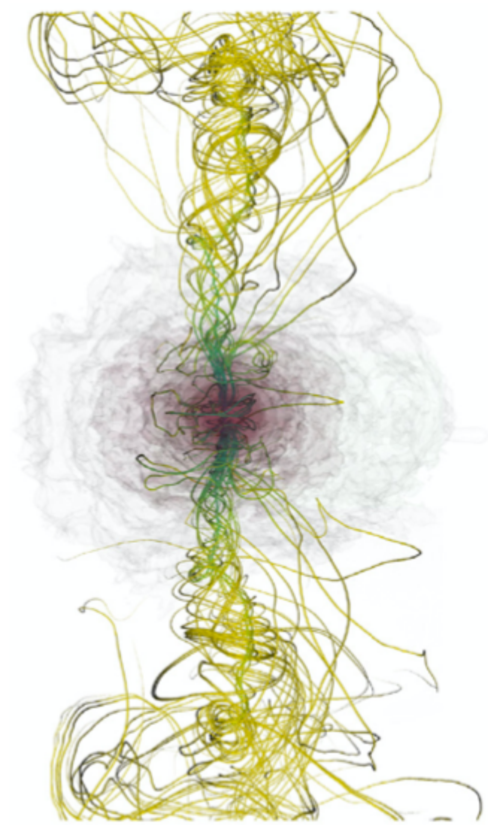
BH + accretion disk

(Blandford-Znajek)

Ciolfi+2017



Ciolfi+2019

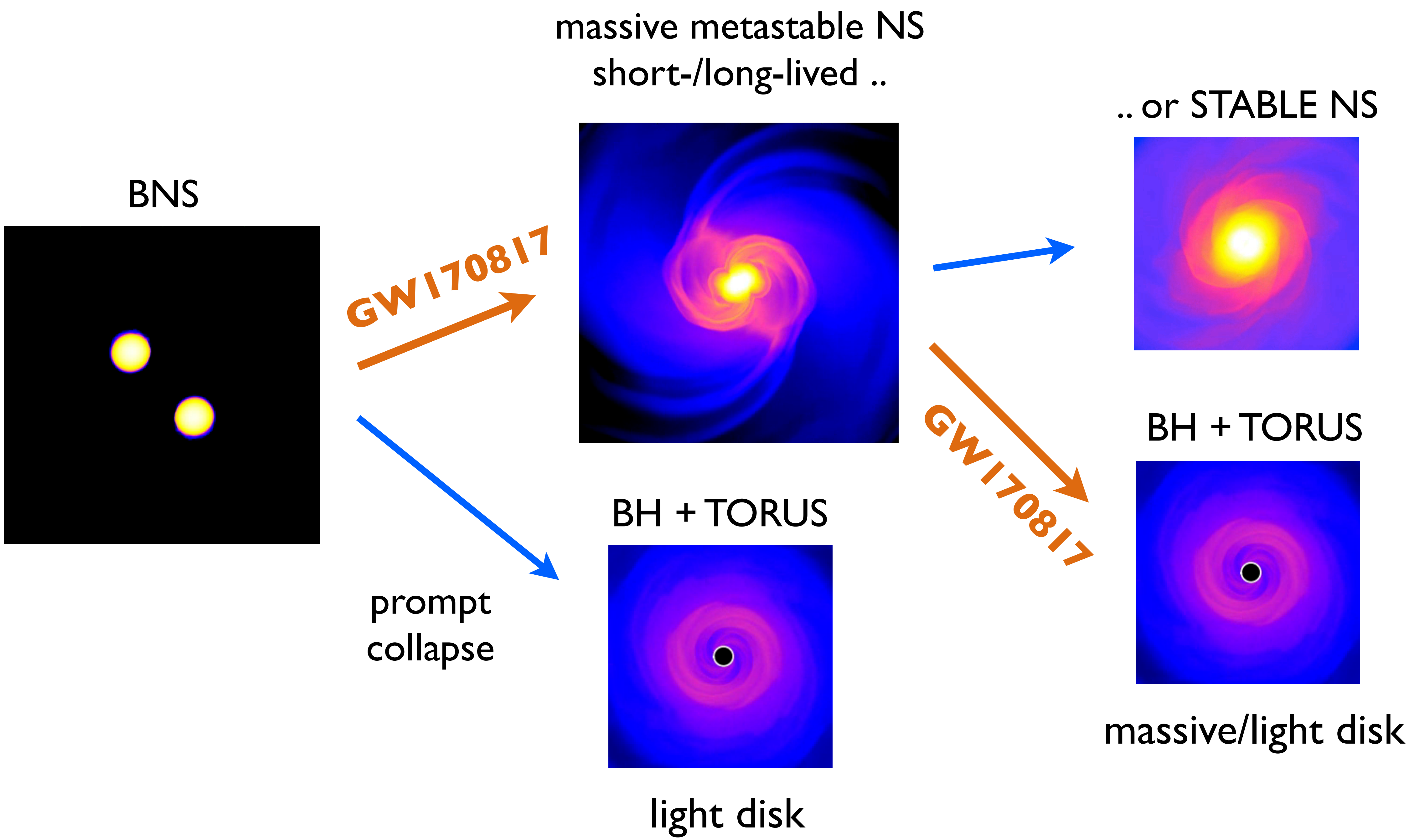


Ciolfi 2020a

massive long-lived NS

(magnetorotational)

Product of BNS mergers



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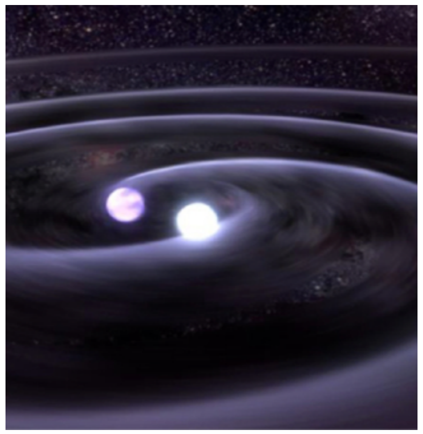
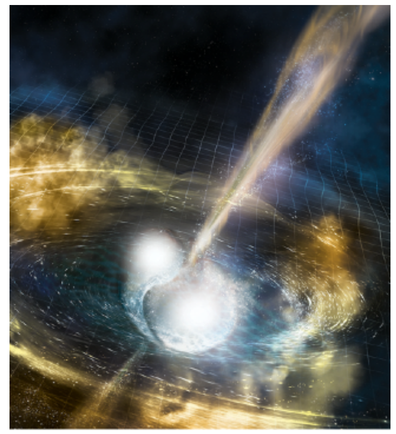


+



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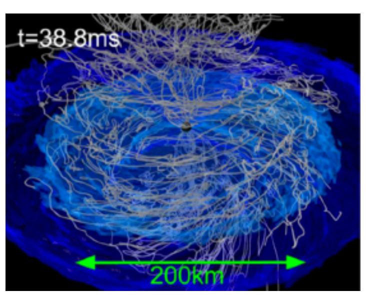
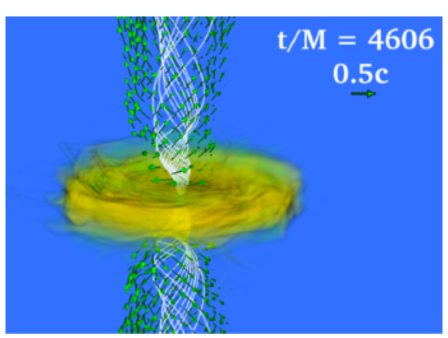
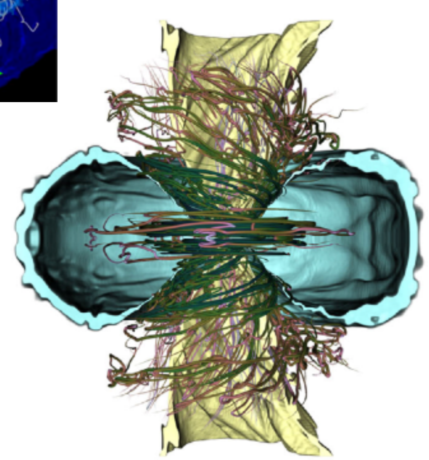




Ruiz+2016



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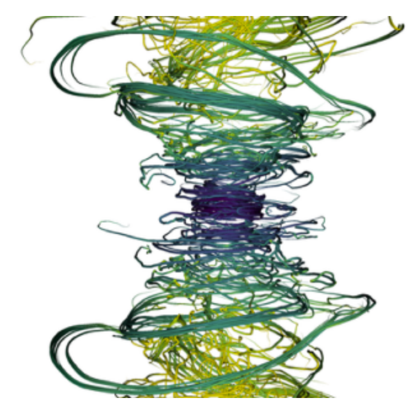

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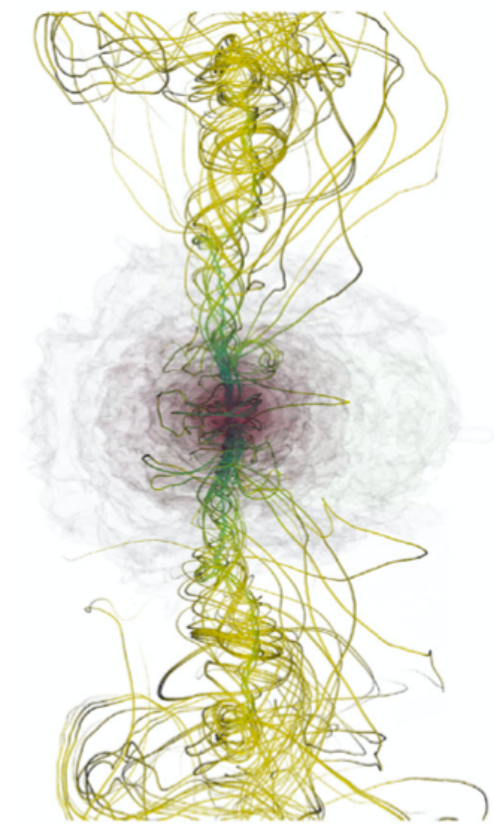

Ciolfi 2020a

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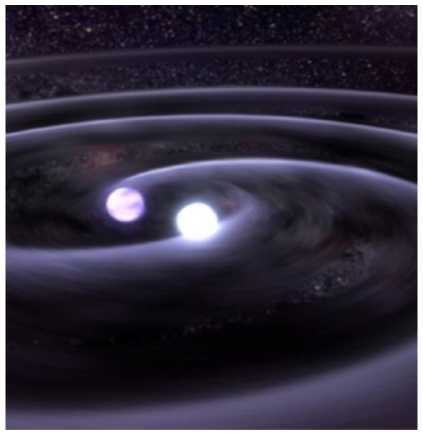

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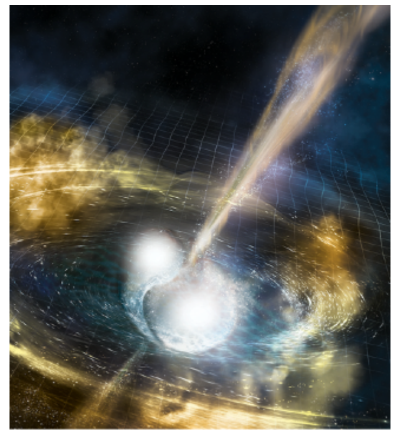

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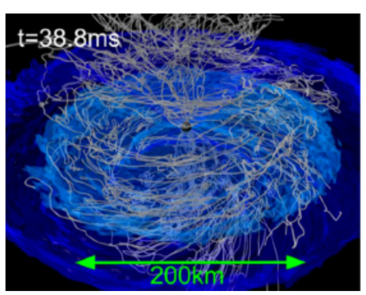

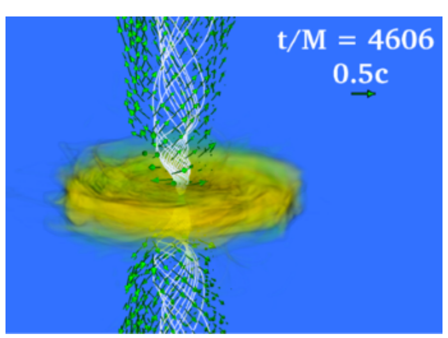

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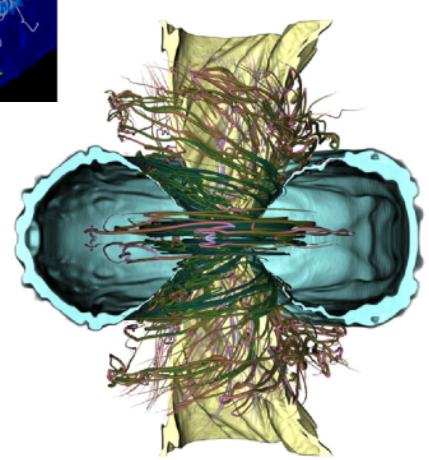

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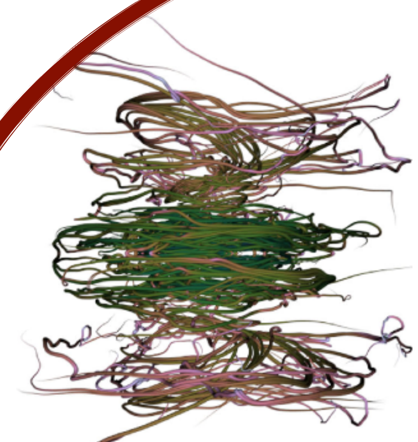

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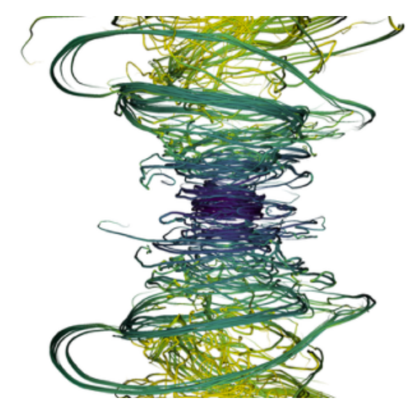
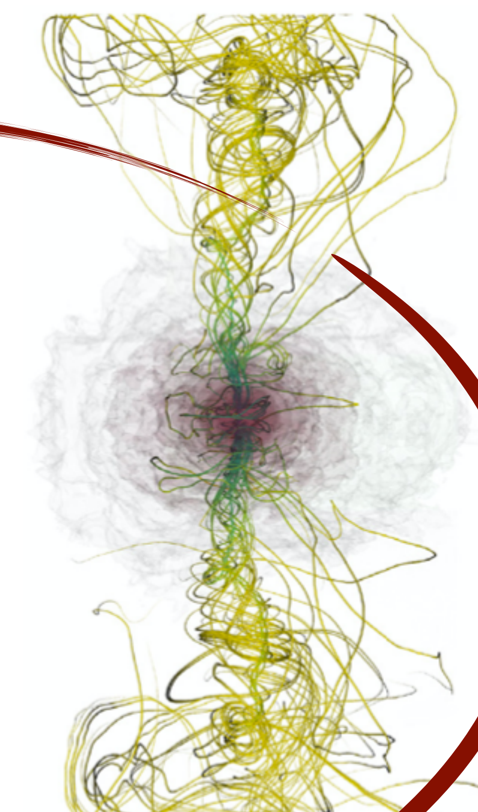


Ciolfi+2019



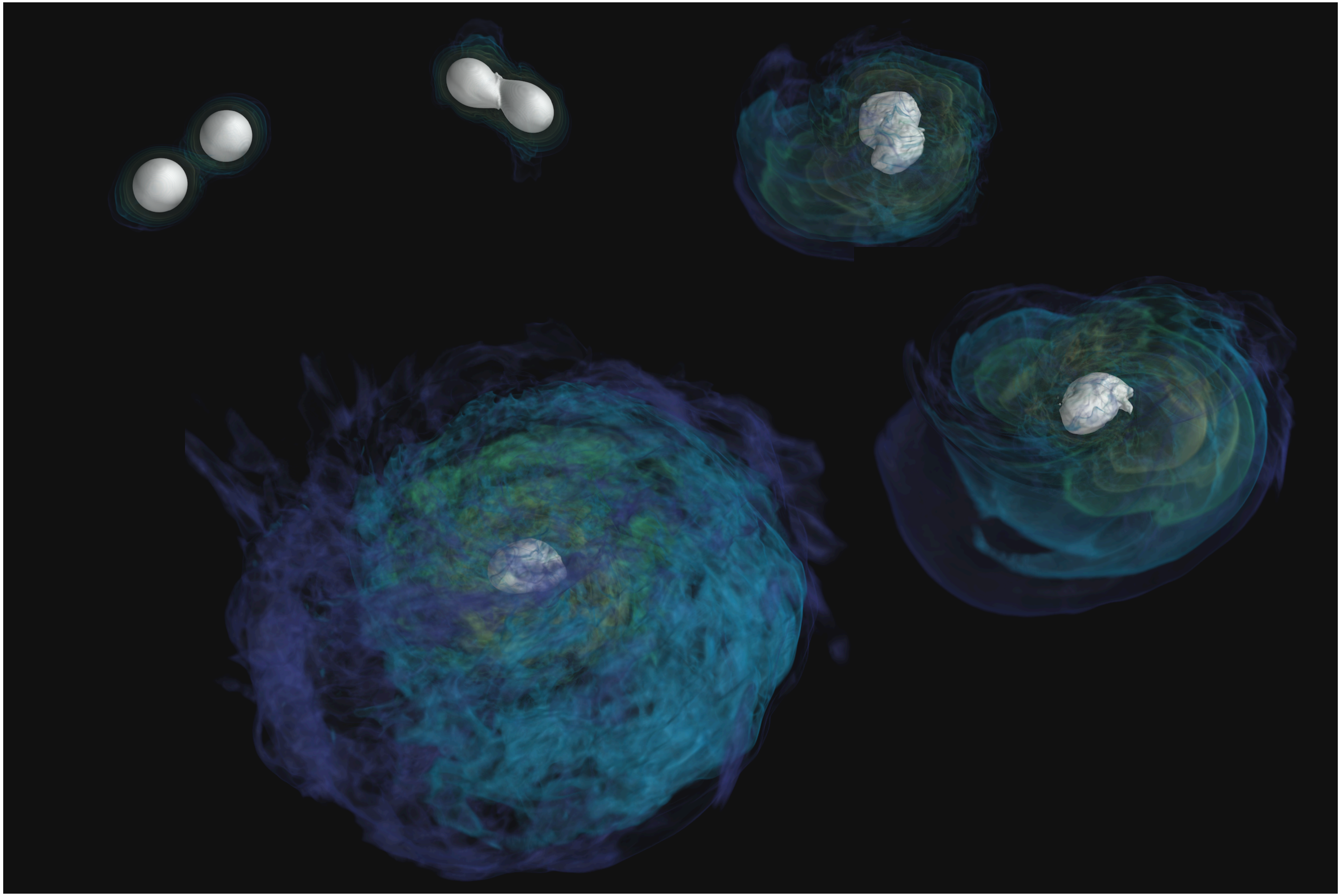
Ciolfi 2020a

massive long-lived NS

(magnetorotational)

BNS mergers with long-lived remnant

Ciolfi+2017

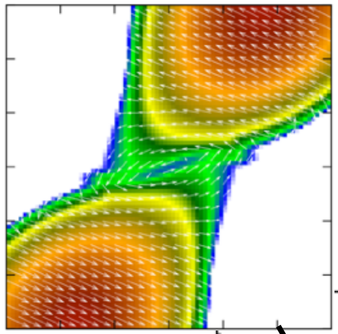


Magnetic field amplification and geometry

Ciolfi+2019: 100 ms of post-merger evolution

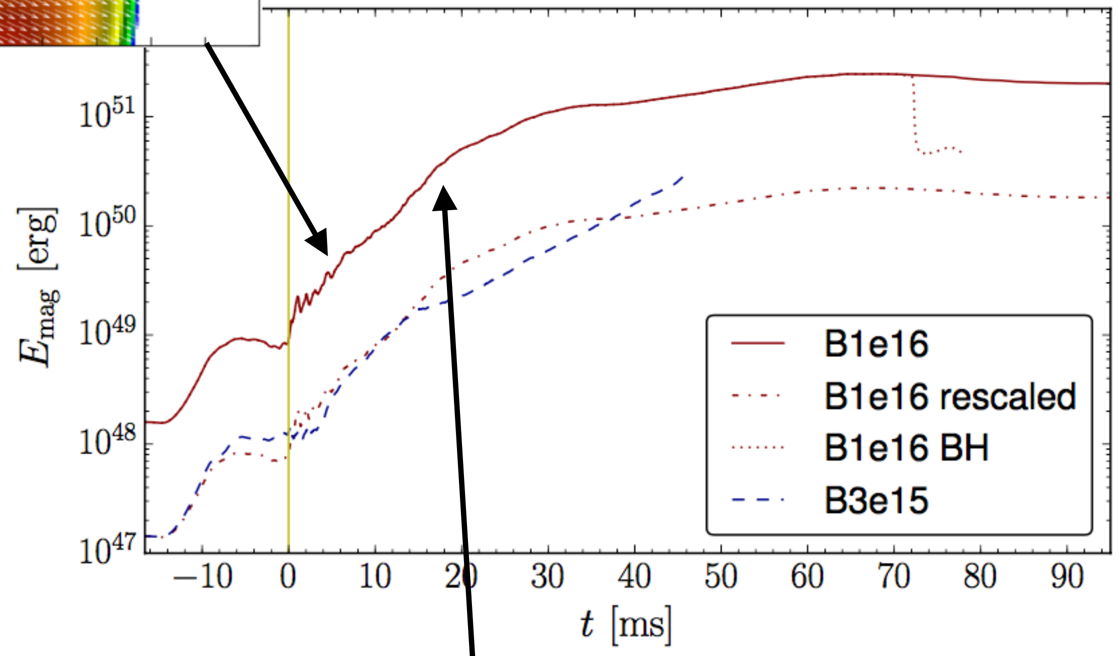
see talk by Carlos Palenzuela

Kiuchi+2015

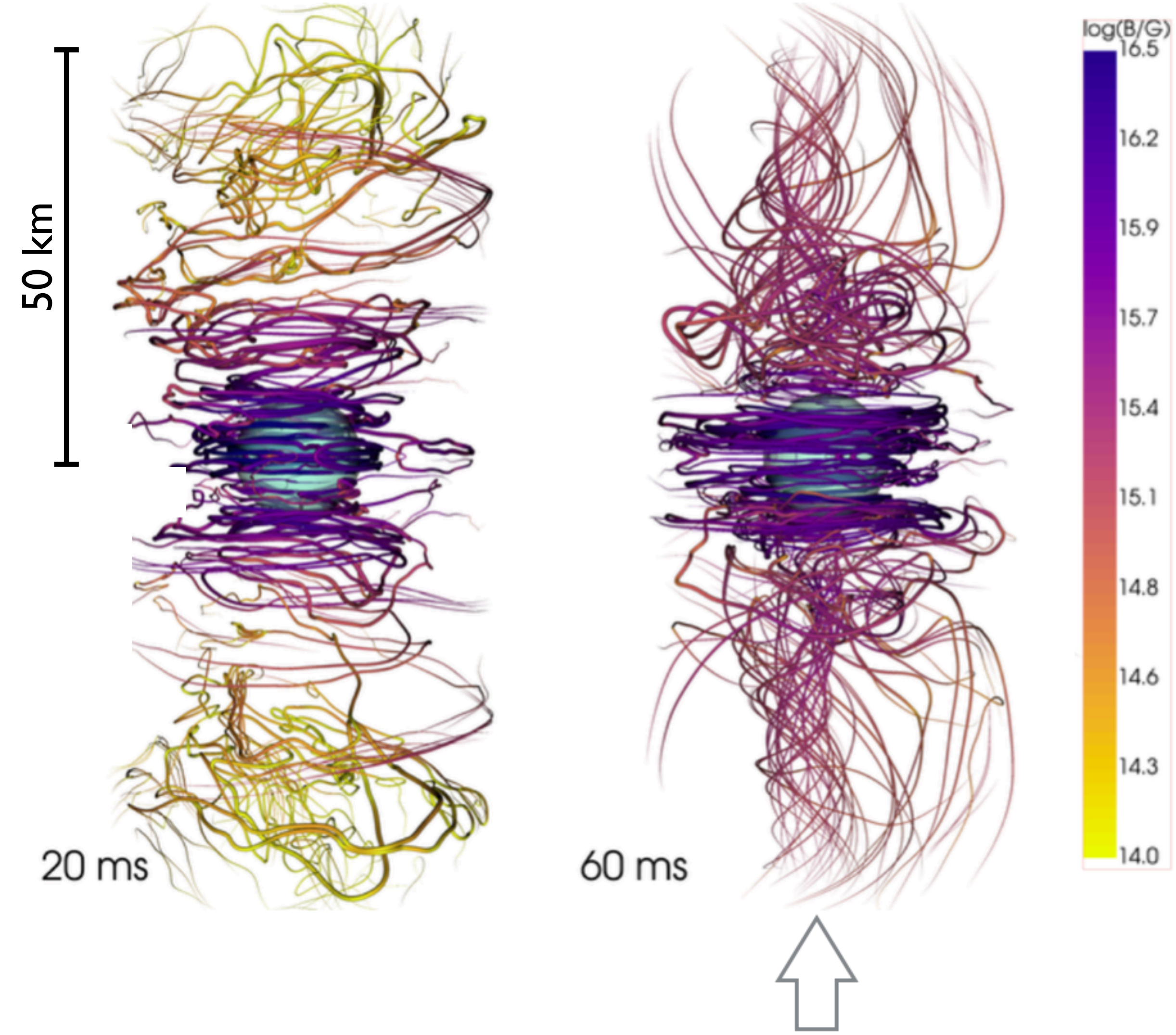


Kelvin-Helmholtz Instability

toroidal field amplification



MagnetoRotational Instability



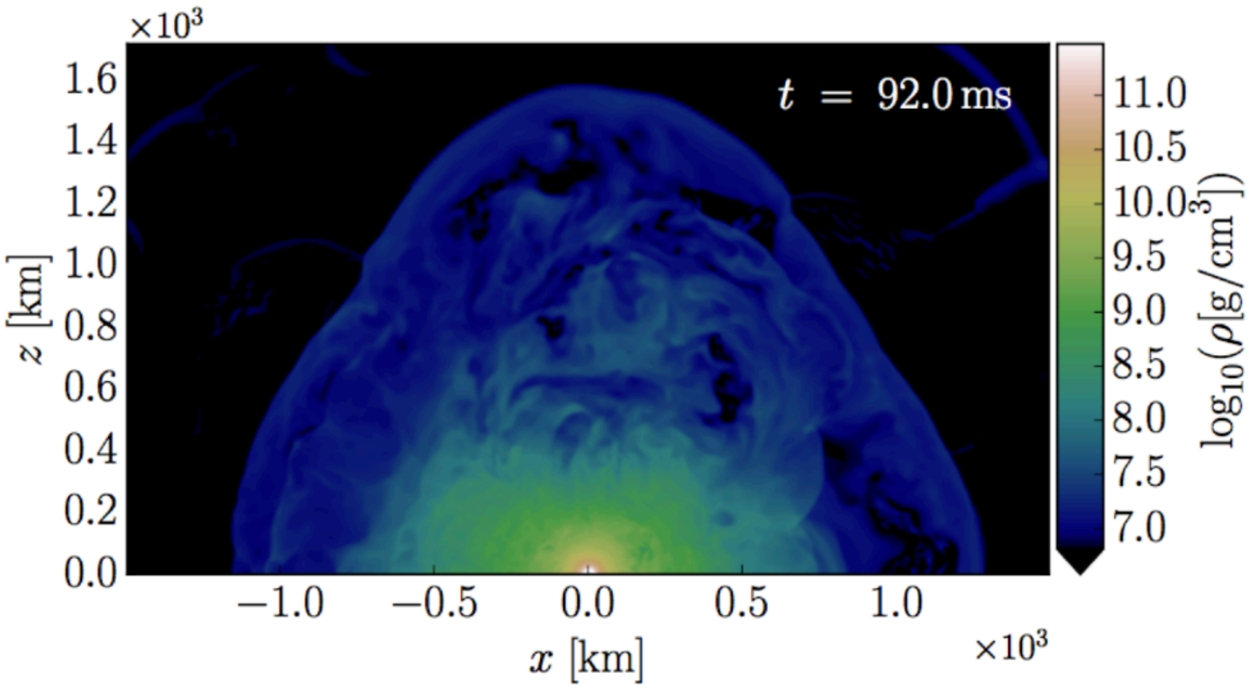
helical structure

Magnetically driven wind

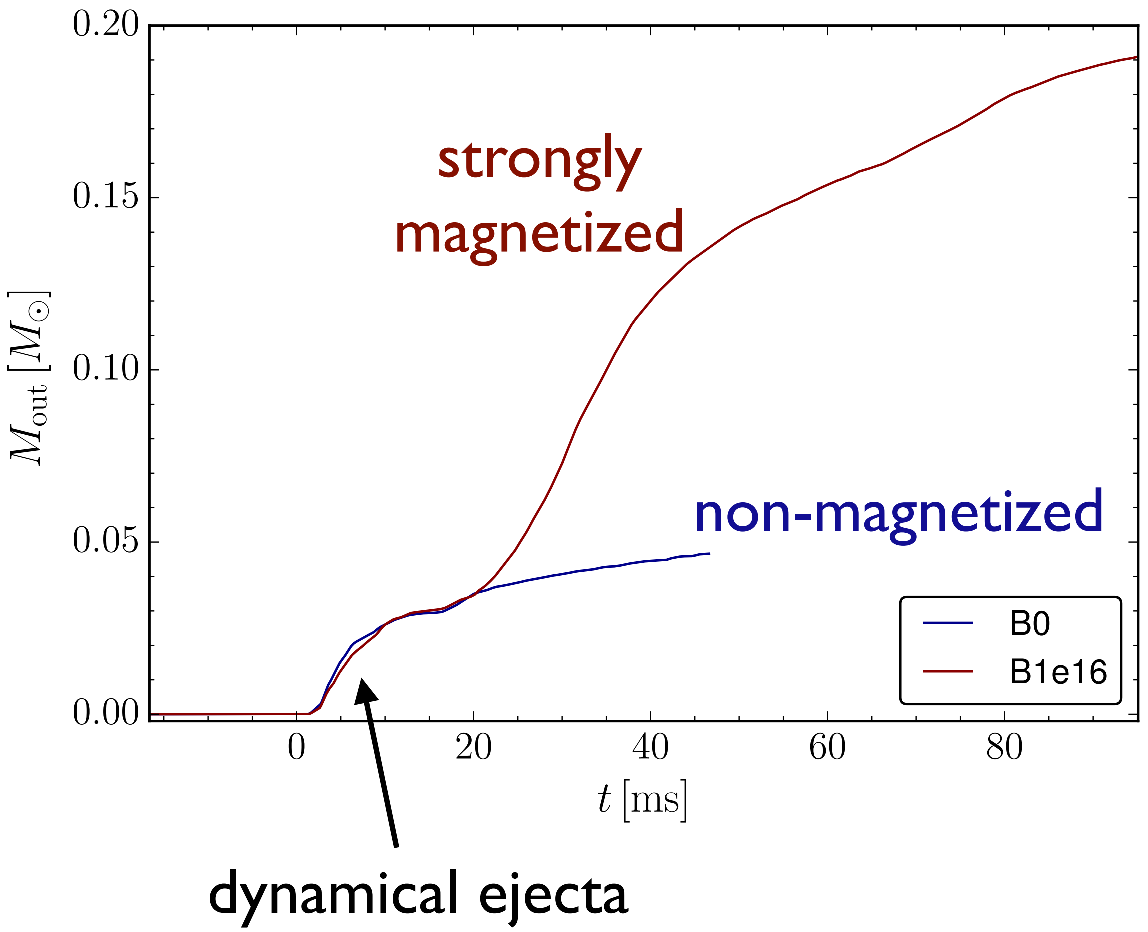
Ciolfi+2019

@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

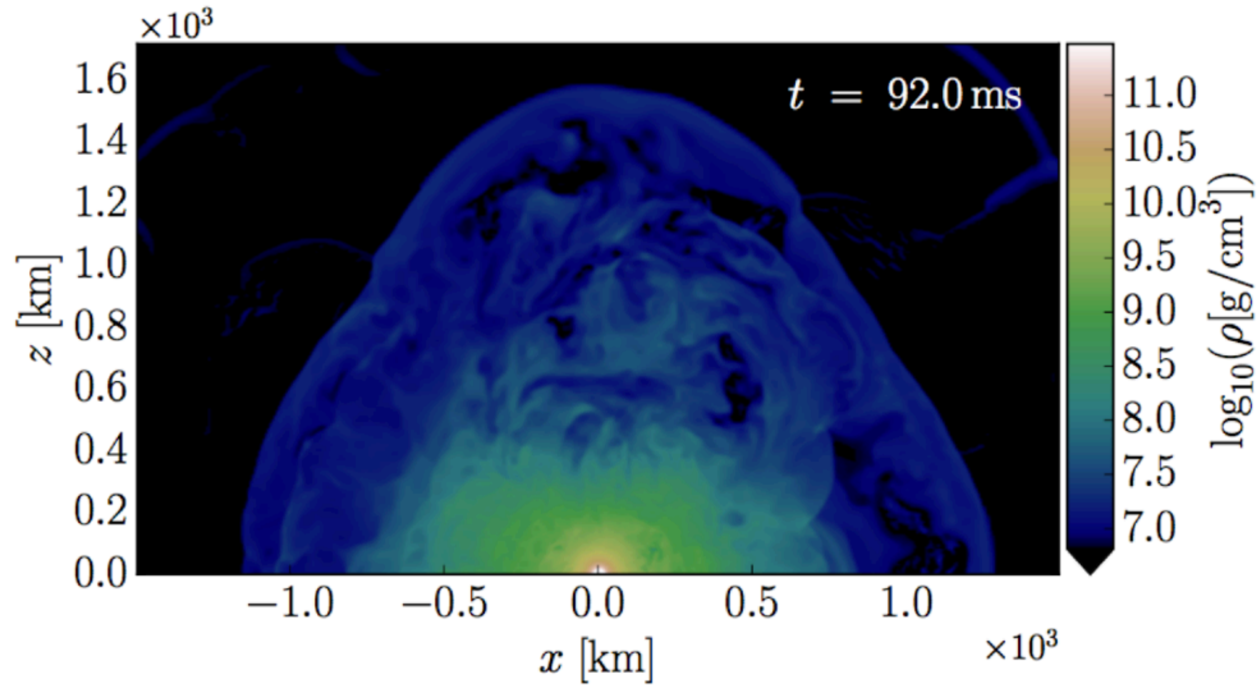
- surrounded by dense isotropic environment
- slow steady outflow maintaining a fixed radial density profile

Magnetically driven wind

Ciolfi+2019

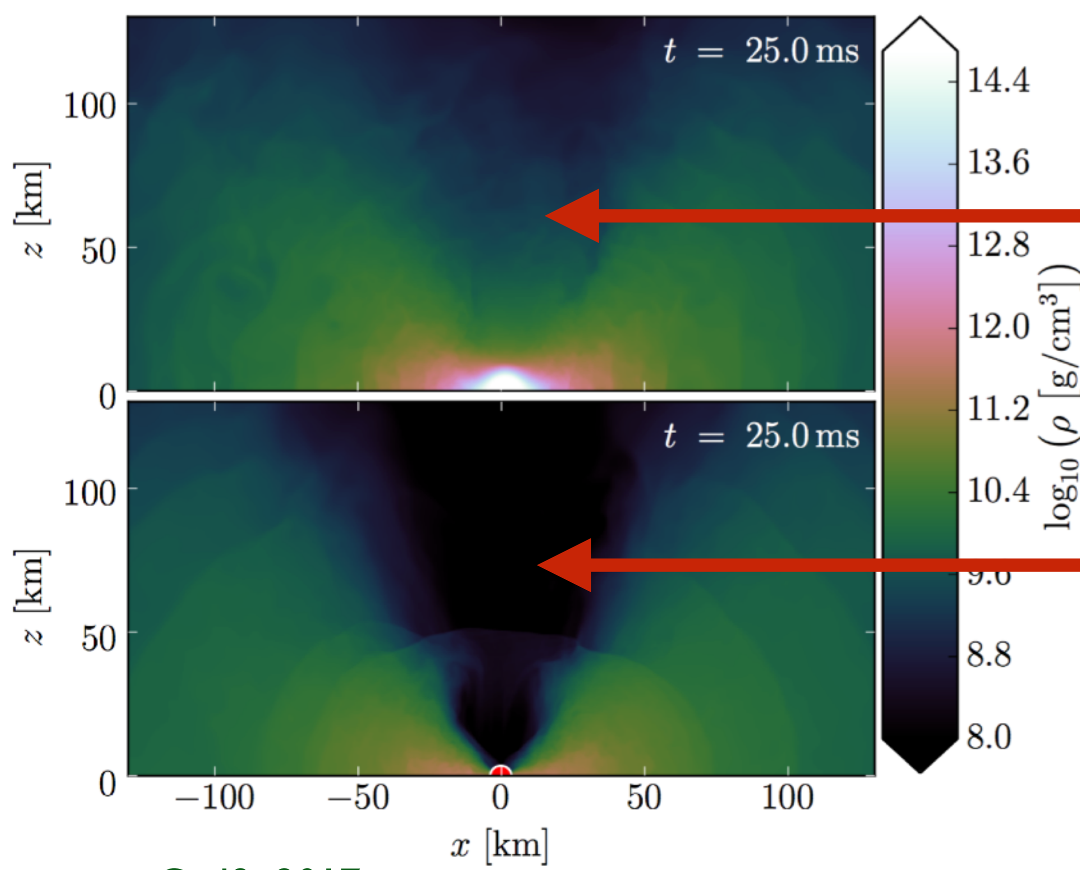
@50-100 ms after merger

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



massive NS remnant

BH remnant



obstacle for jet formation

favourable environment

Ciolfi+2017

BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with chirp mass of GW170817 and q=0.9
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to ~250 ms after merger

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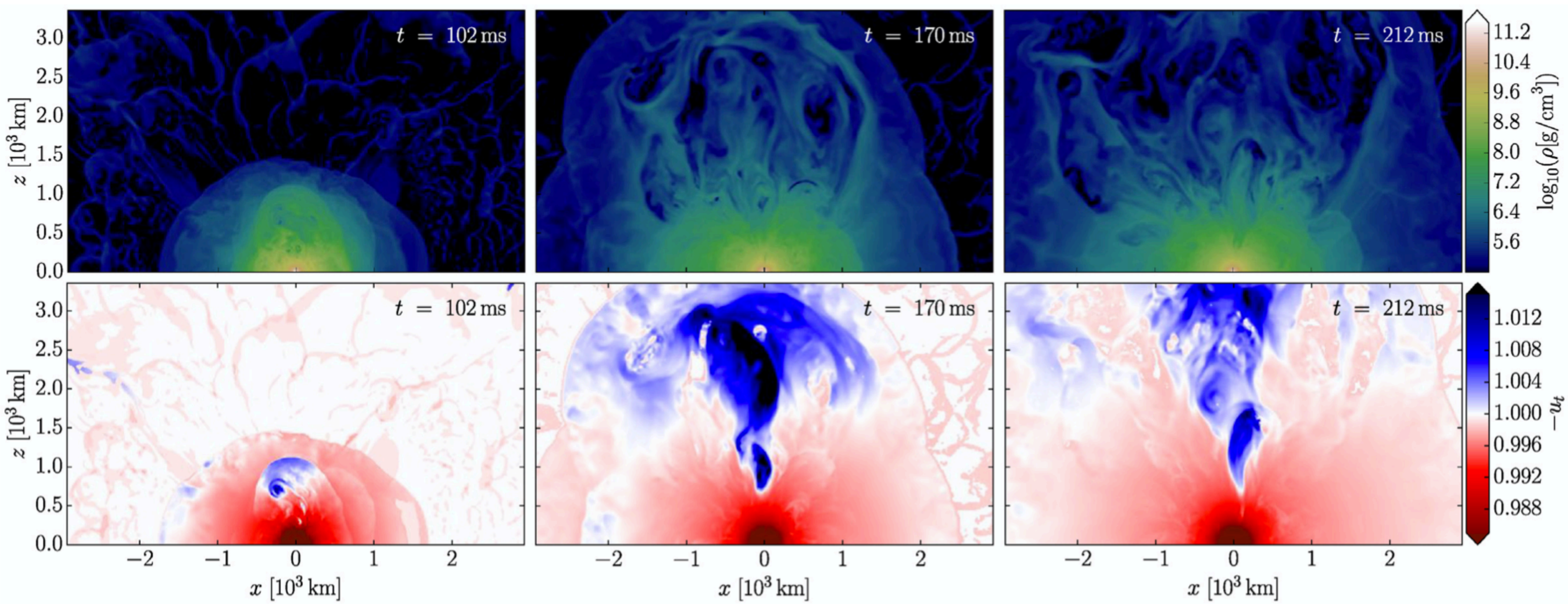

massive NS remnant can produce a collimated outflow

BNS mergers with much longer evolution

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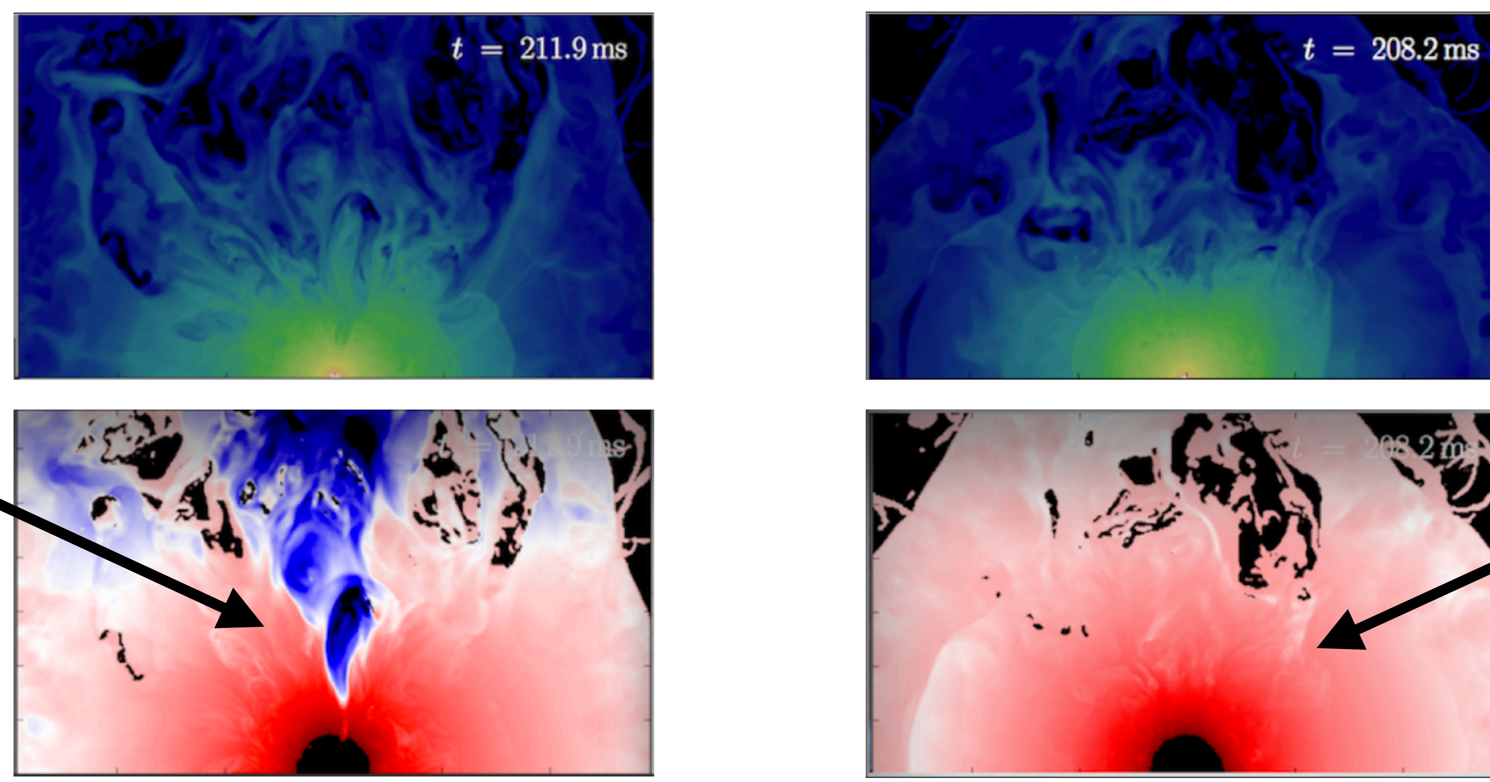
higher initial magnetization | lower initial magnetization



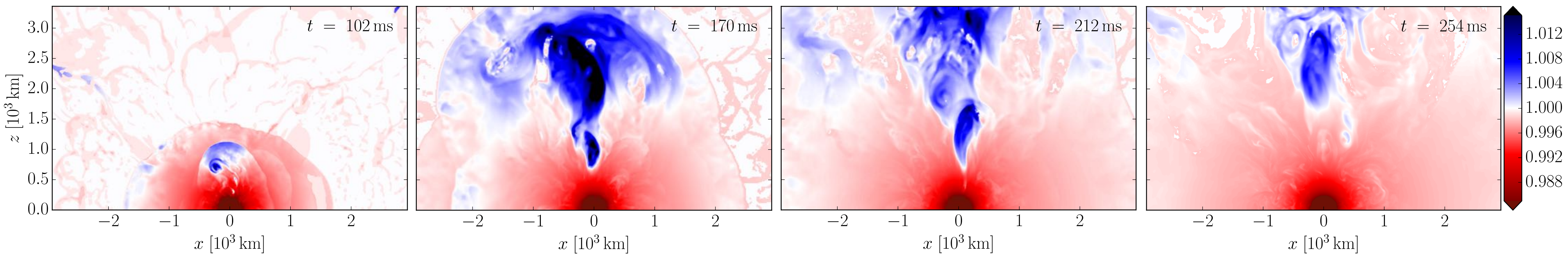
collimated outflow

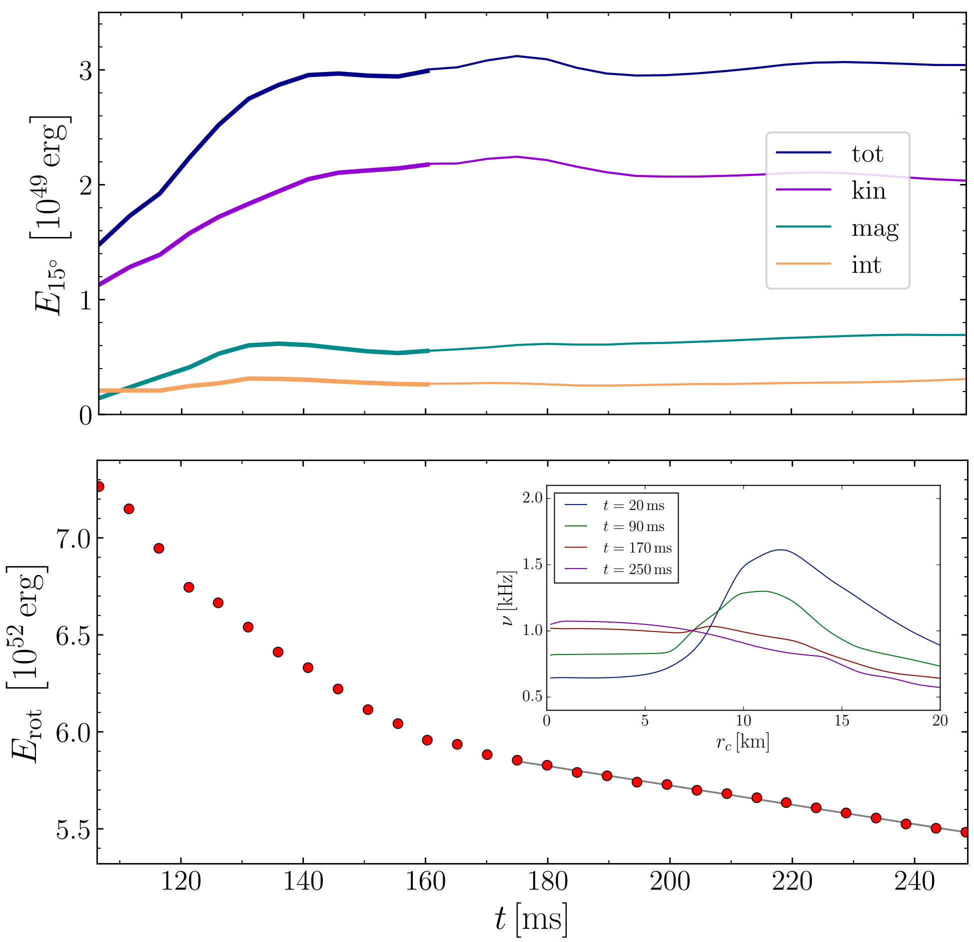
NO collimated outflow

..but not ubiquitous

Origin and properties of the collimated outflow

Ciolfi 2020a





~160 ms after merger → outflow energy saturation

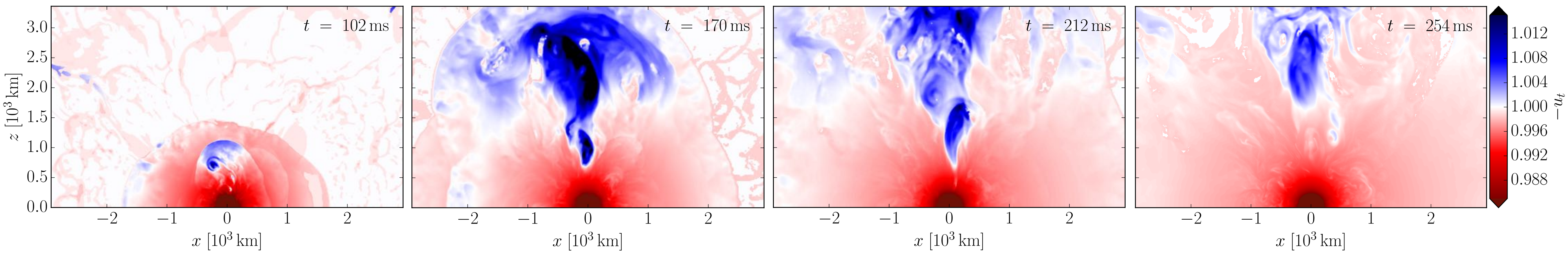
→ change in rotational energy evolution

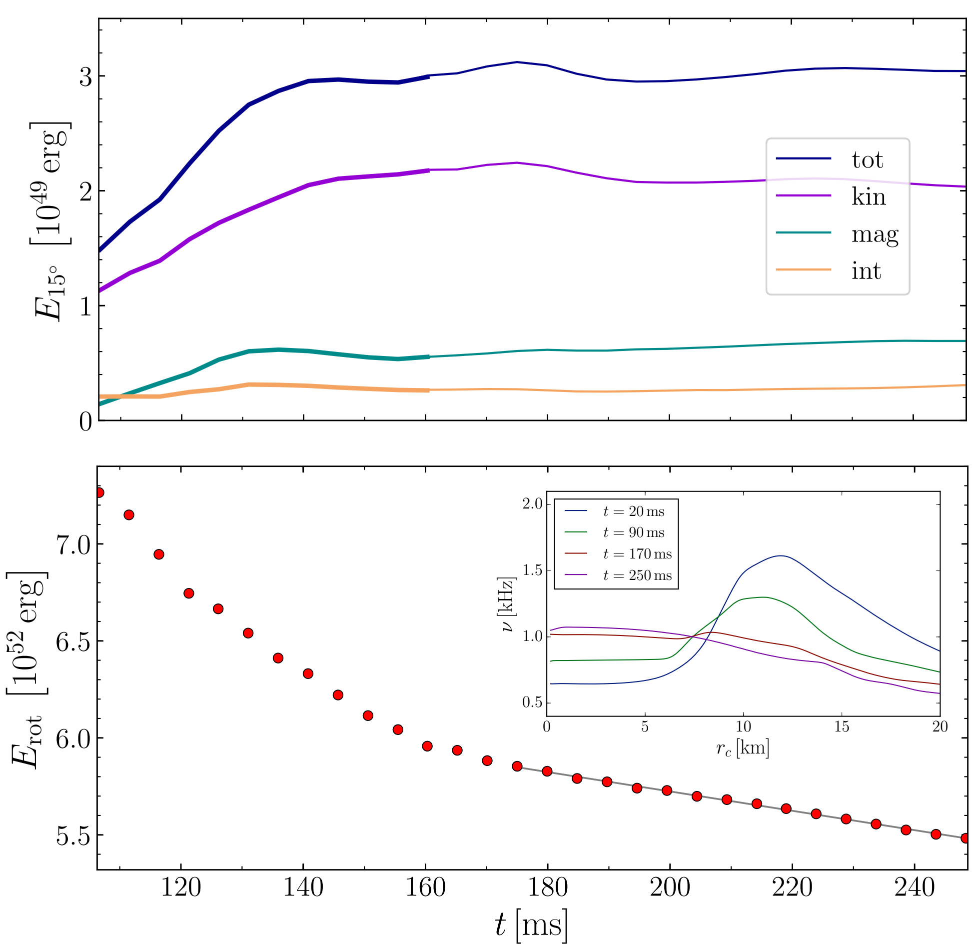
→ differential rotation in the NS core is over

NS differential rotation = energy reservoir

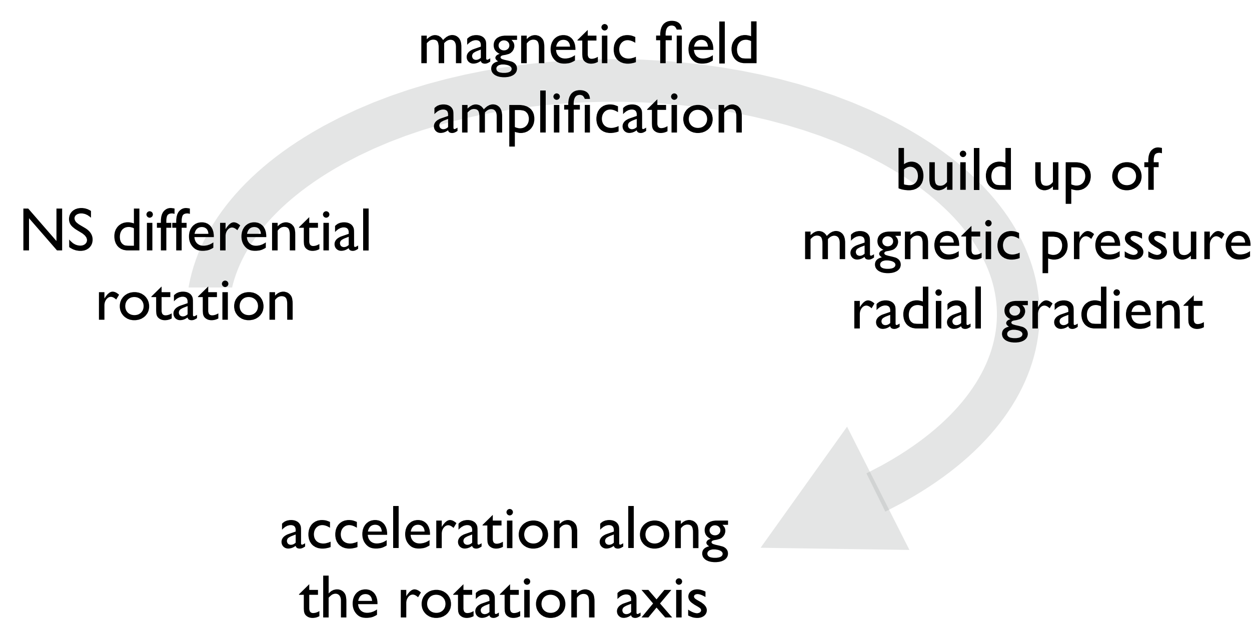
Origin and properties of the collimated outflow

Ciolfi 2020a



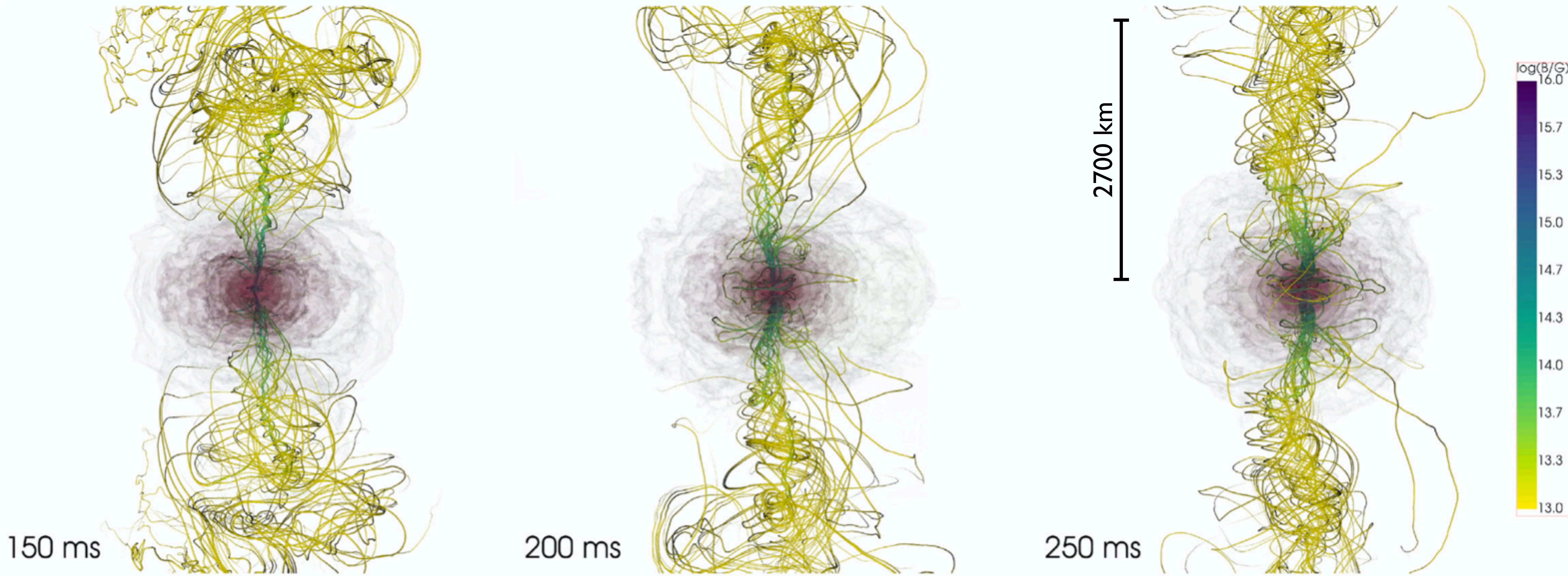


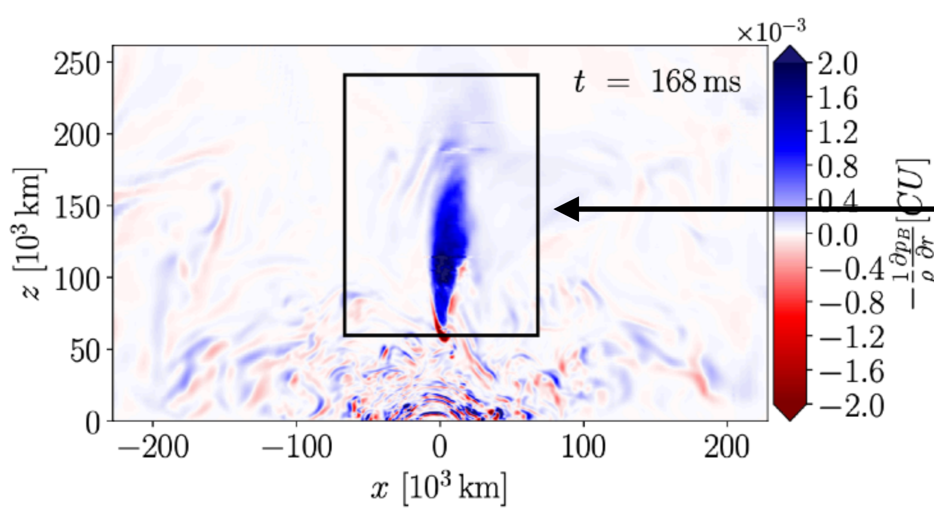
magnetorotational launching mechanism



Emerging helical magnetic field

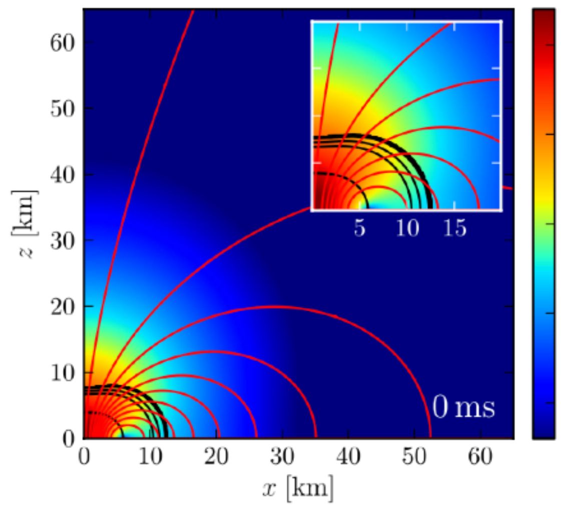
Ciolfi 2020a



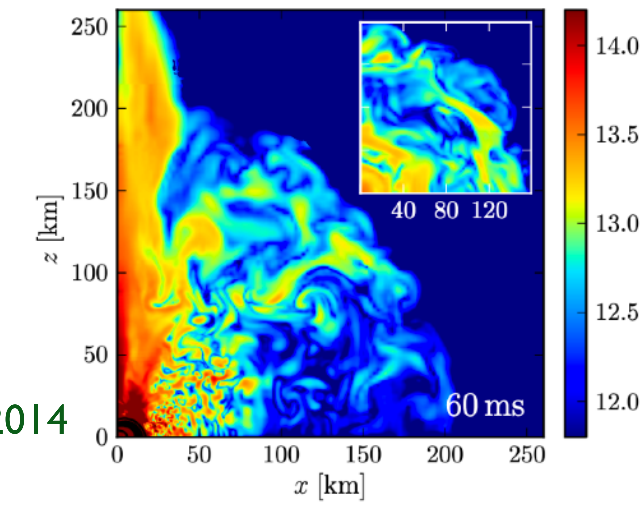


magnetic push
(radial gradient of magnetic pressure)

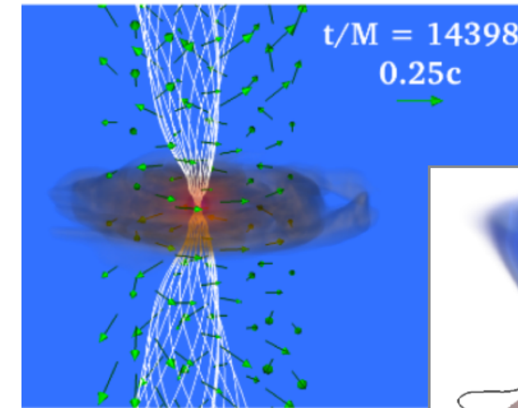
aligned dipolar field imposed on differentially rotating NS



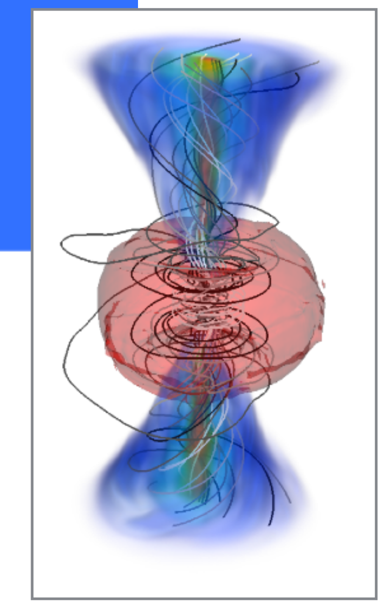
collimated outflow



Siegel+2014

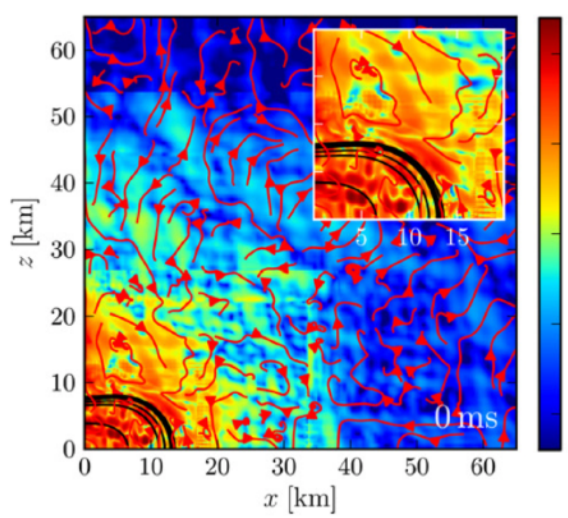


Ruiz+2018

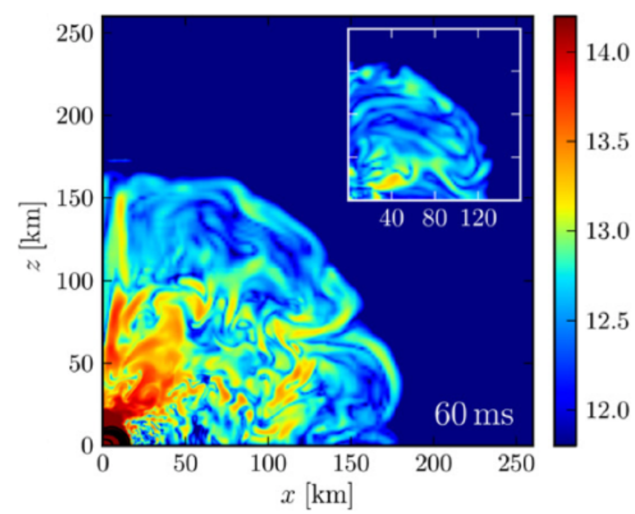


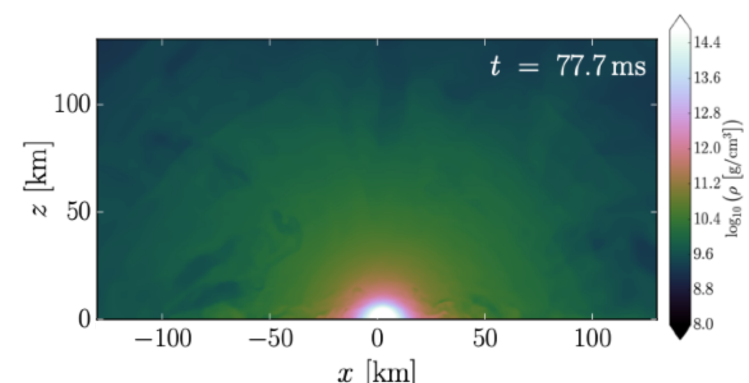
Moesta+2020

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)

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

Results from Ciolfi 2020a

- GRMHD BNS merger simulations with up to >250 ms of massive NS remnant evolution
- massive NS remnant can launch an MHD-driven collimated outflow, but this outcome is not ubiquitous
- followed the full outflow development, studied the associated energetics and properties
- identified the energy reservoir (NS differential rotation)
- identified the launching mechanism (magnetorotational)
- found indications against the possible production of a SGRB

⟶ accreting BH scenario is favoured

Results from Ciolfi 2020a

- GRMHD BNS merger simulations with up to >250 ms of massive NS
  re

- ma ... ow,
  bu

- fo
  en

<u>MAIN CAVEATS</u>

- much higher resolution

see talk by Carlos Palenzuela

- finite temperature EOS and neutrino radiation

(e.g. Moesta+2020)

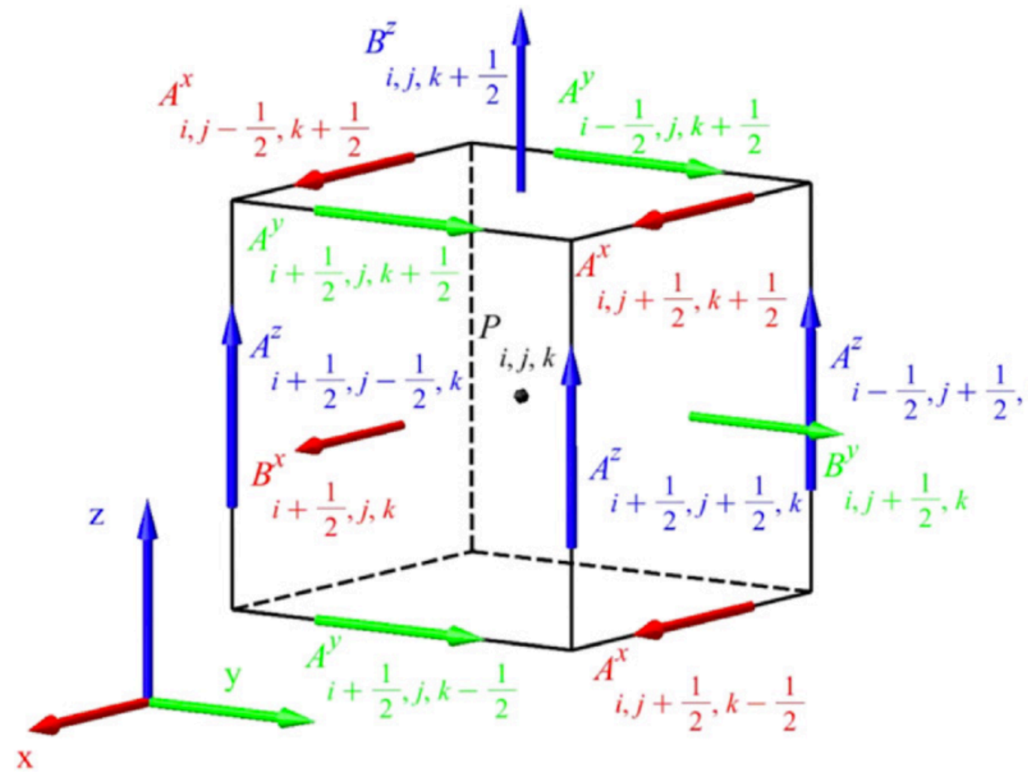
- identified the energy reservoir (NS differential rotation)

- identified the launching mechanism (magnetorotational)

- found indications against the possible production of a SGRB

⟶ accreting BH scenario is favoured

Spritz: a new GRMHD code

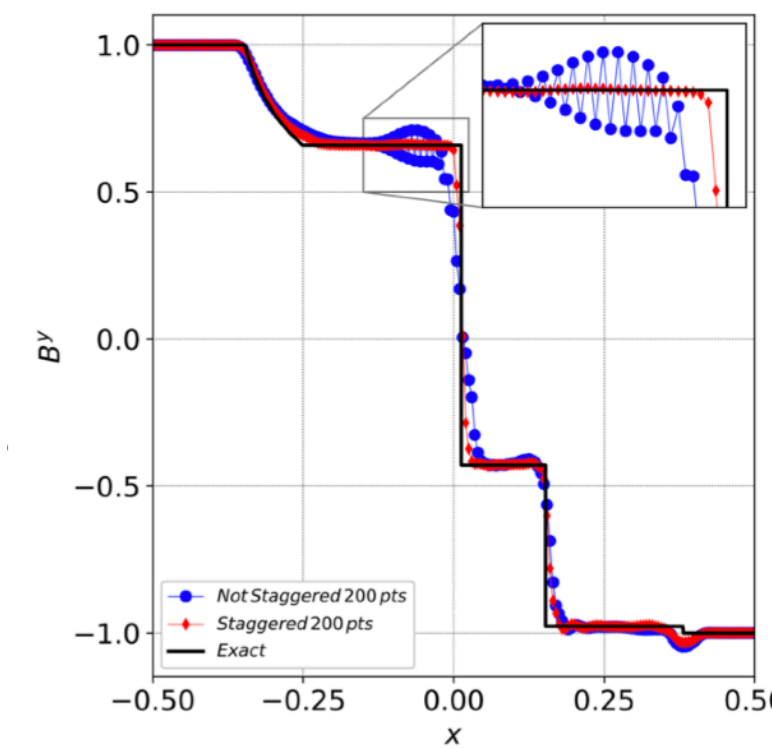


Version 1.0: Cipolletta+2020

- 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*

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+2021

- 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

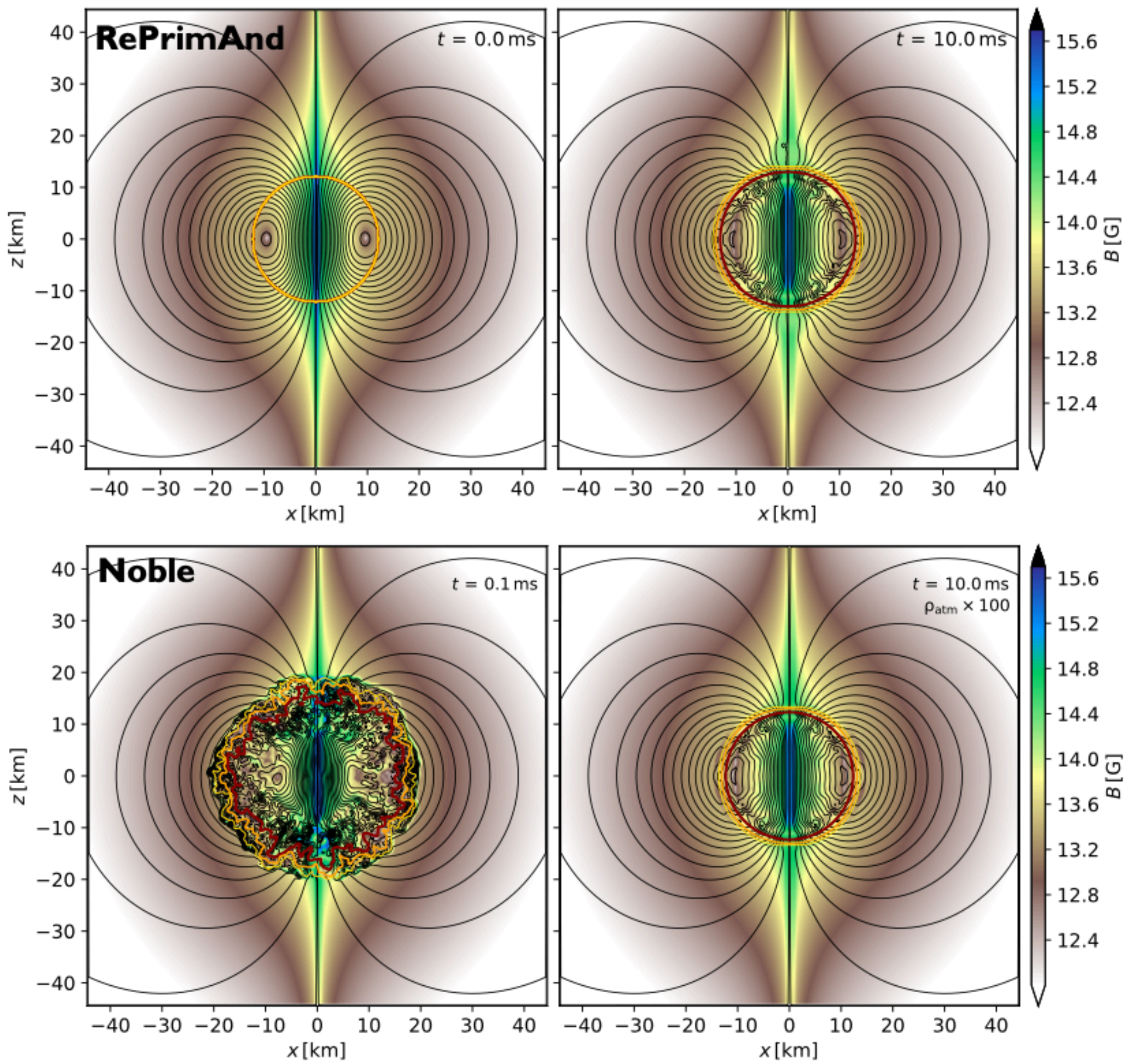
List of 3D tests:

- 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

adapted from slide by Jay Kalinani

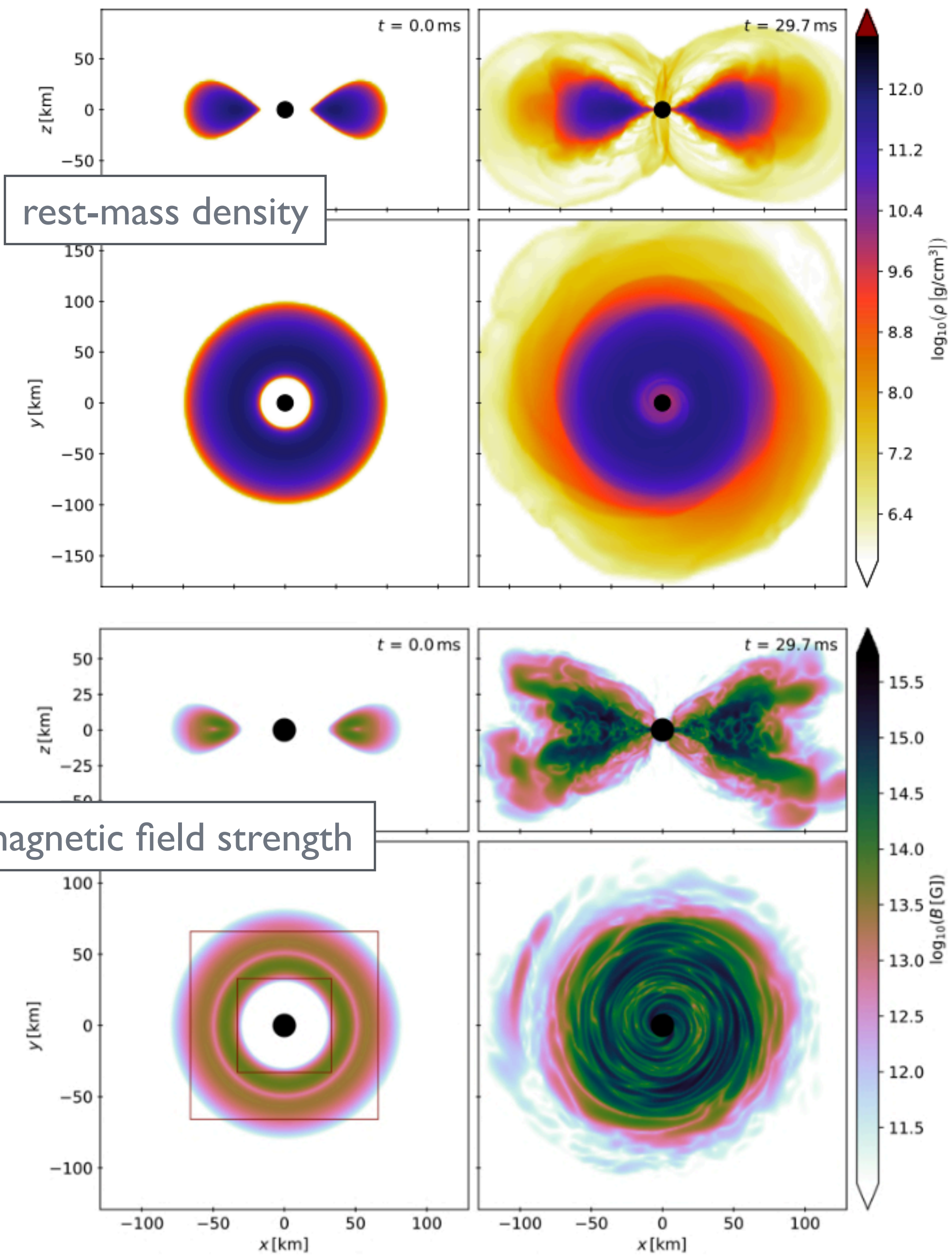
Conservative-to-primitive recovery scheme *RePrimAnd*

NS with extended dipolar field



magnetic field strength + field lines + density contours

Fishbone-Moncrief BH-accretion disk



rest-mass density

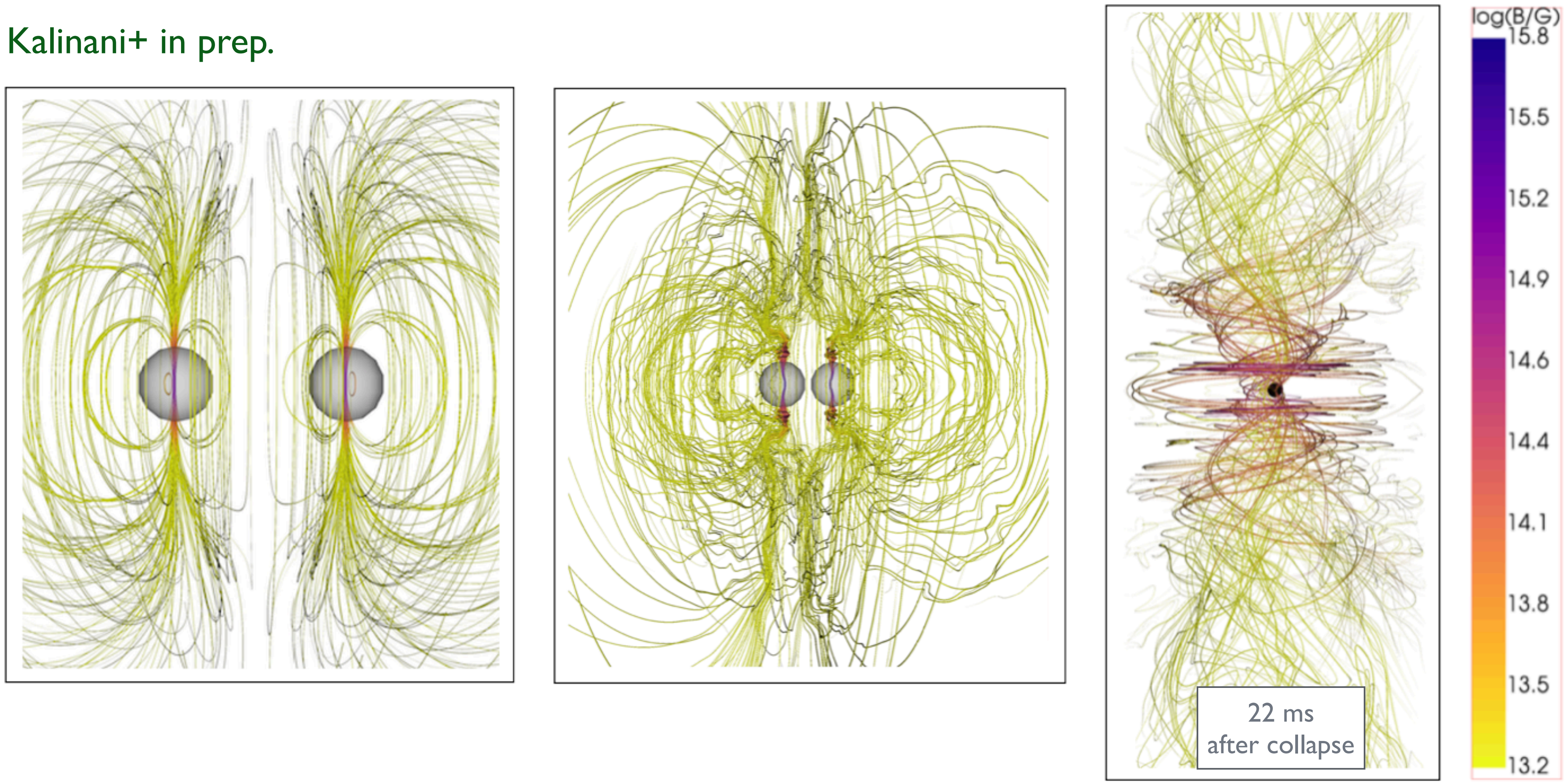
magnetic field strength

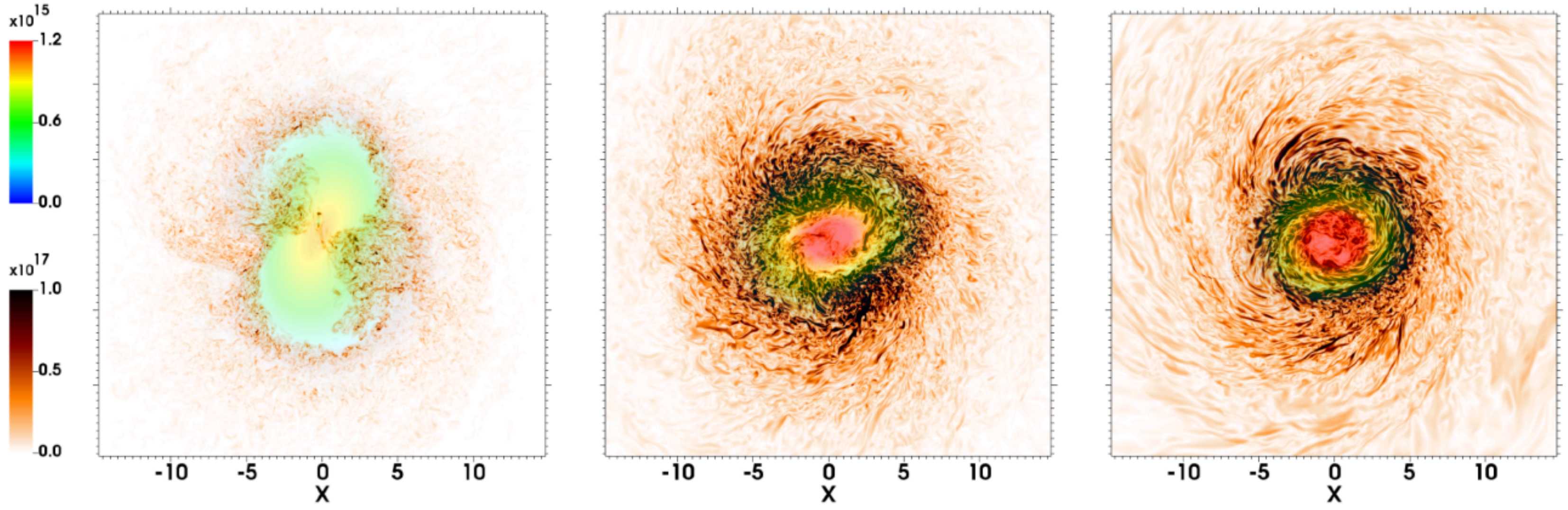
Kalinani+2021

adapted from slide by Jay Kalinani

Using *RePrimAnd* in BNS merger simulations

Kalinani+ in prep.





Aguilera-Miret+2020

Connecting with SGRB observations

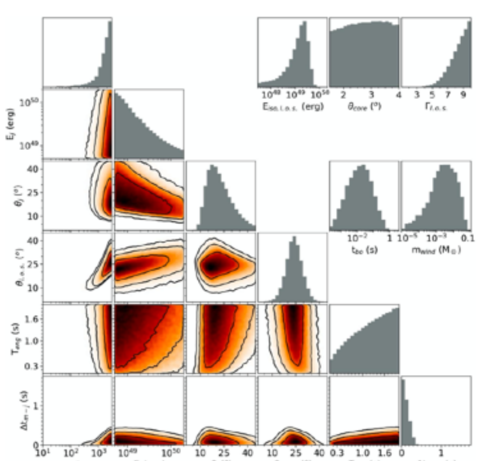
BNS merger simulations limited to scales ~100ms/1000km → disconnected from scales relevant for SGRB EM radiation (prompt & afterglow)

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

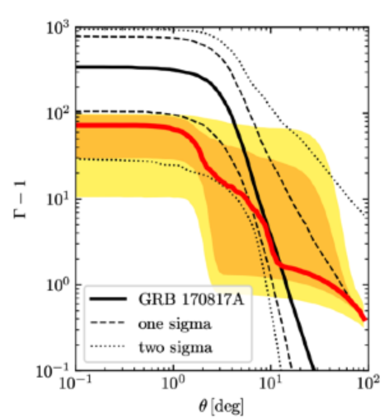
incipient jet + environment → propagation model → final jet structure, prompt & afterglow emission

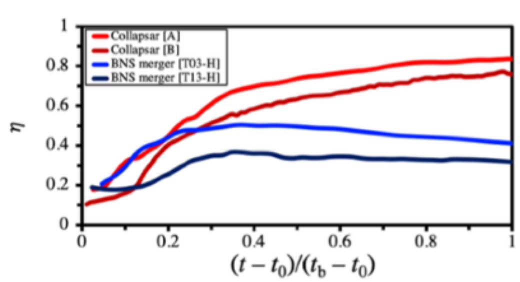
semi-analytical

Lazzati+2020



Salafia+2020

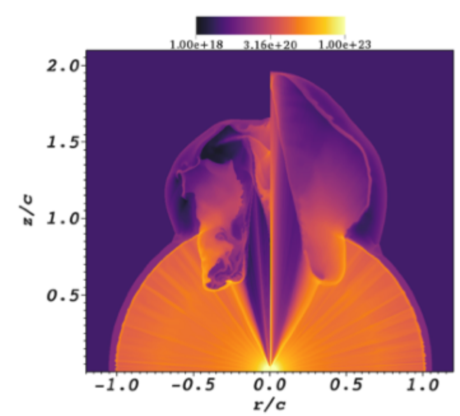




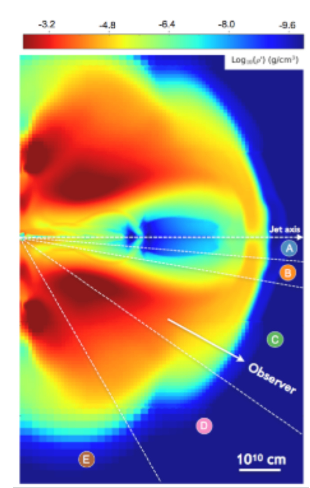
Hamidani & Ioka

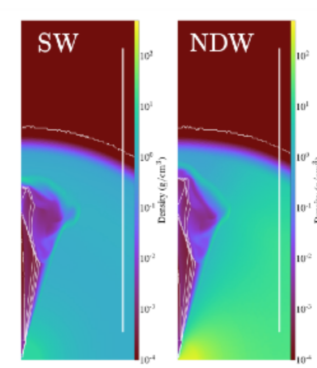
2D/3D HD

Urrutia+2020



Lazzati+2018

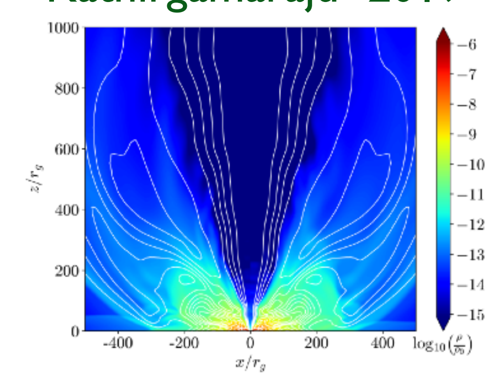


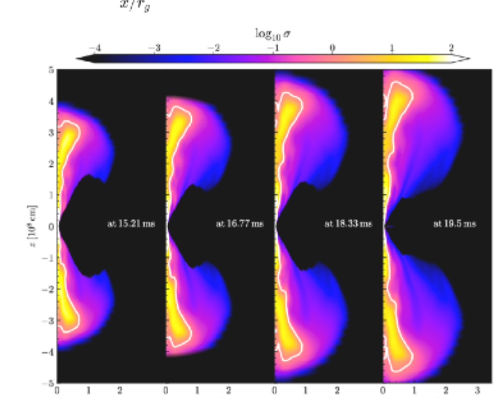


Murguia-Berthier+2021

3D GRMHD

Kathirgamaraju+2019



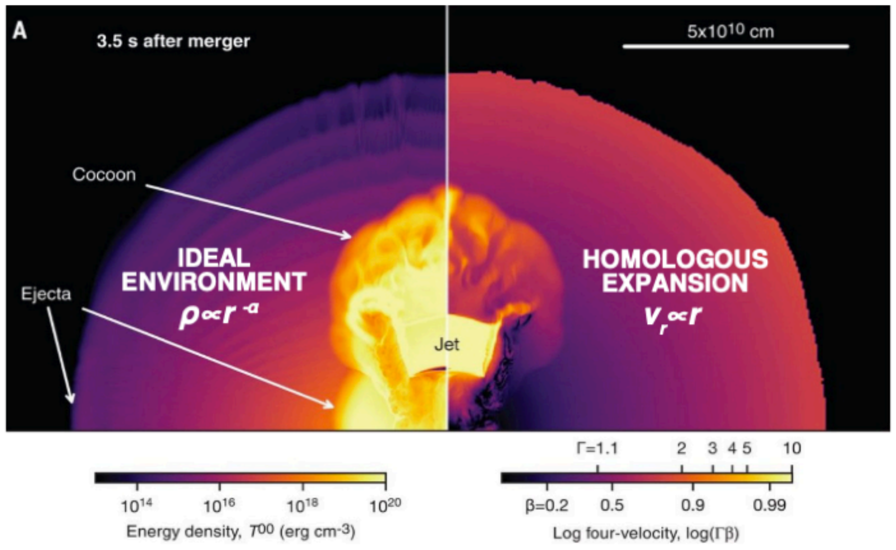


Nathanail+2020, 2021

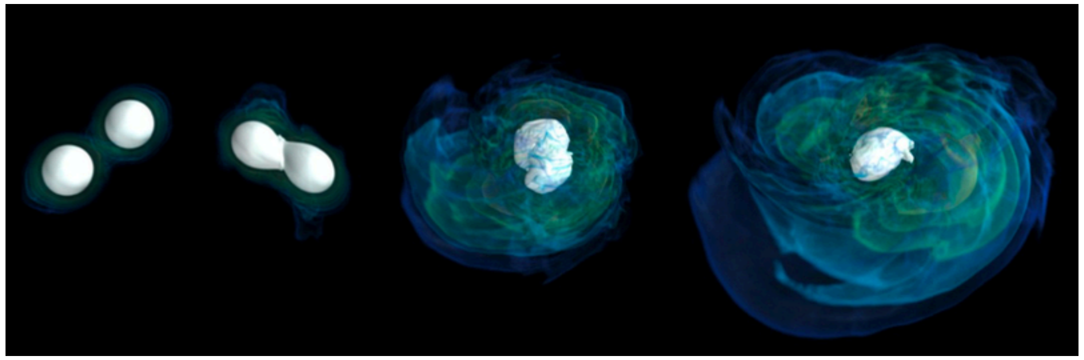
common limitation: incipient jet propagates across hand-made and simplified environment

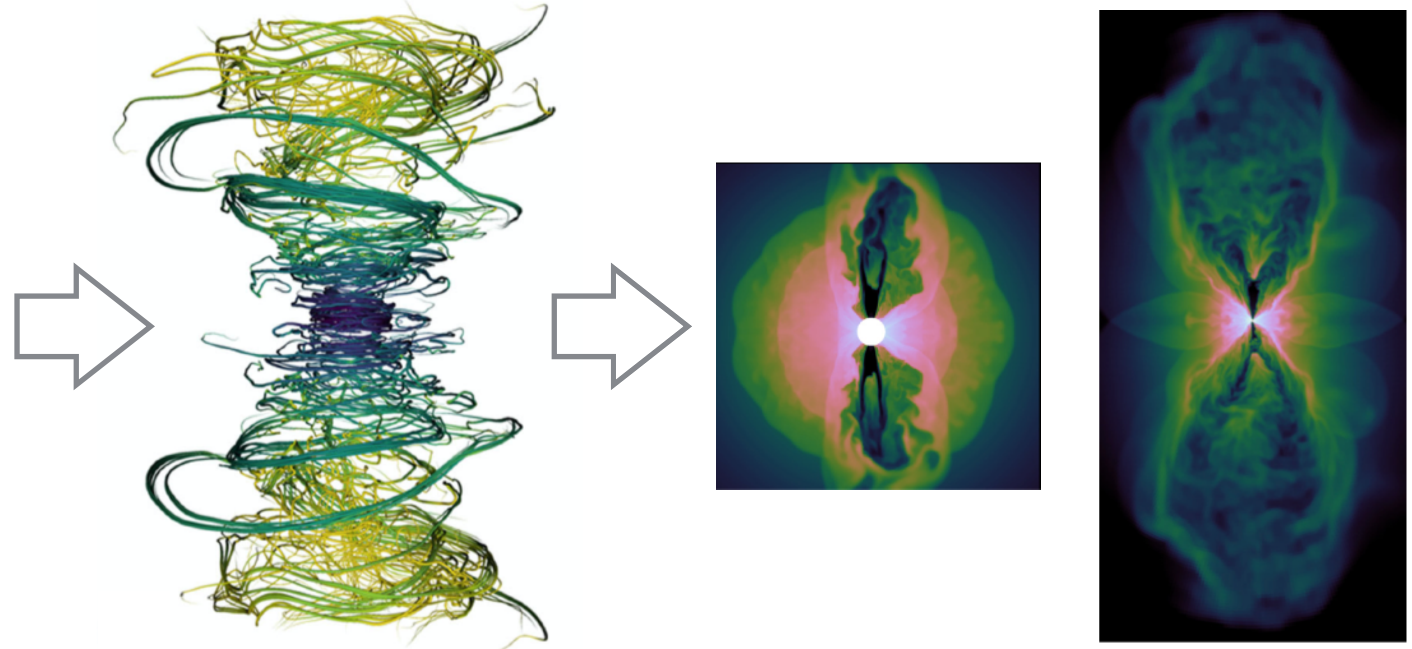
- power-law density profile & homologous expansion or stationary wind
- spherical/axial symmetry

adapted from Kasliwal+2018



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

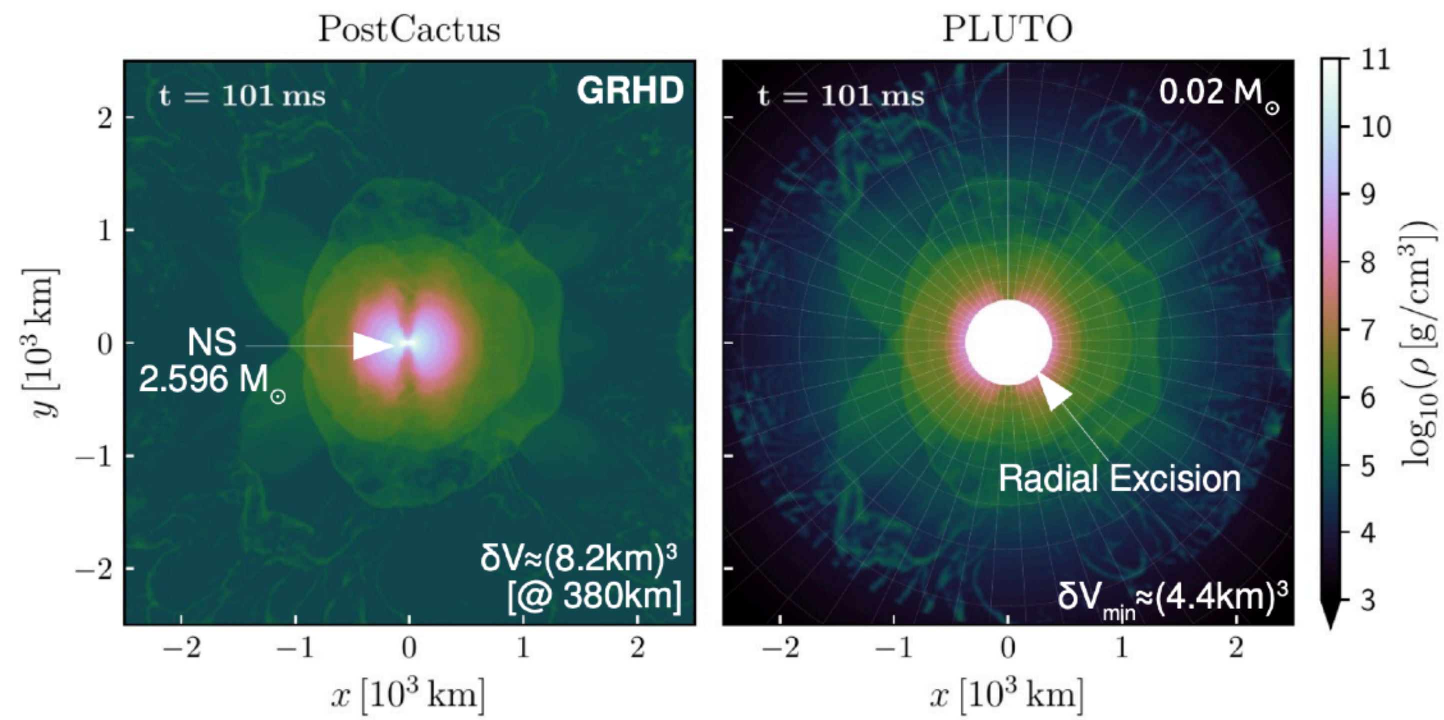
Jet propagation in BNS merger environment

Pavan+2021

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

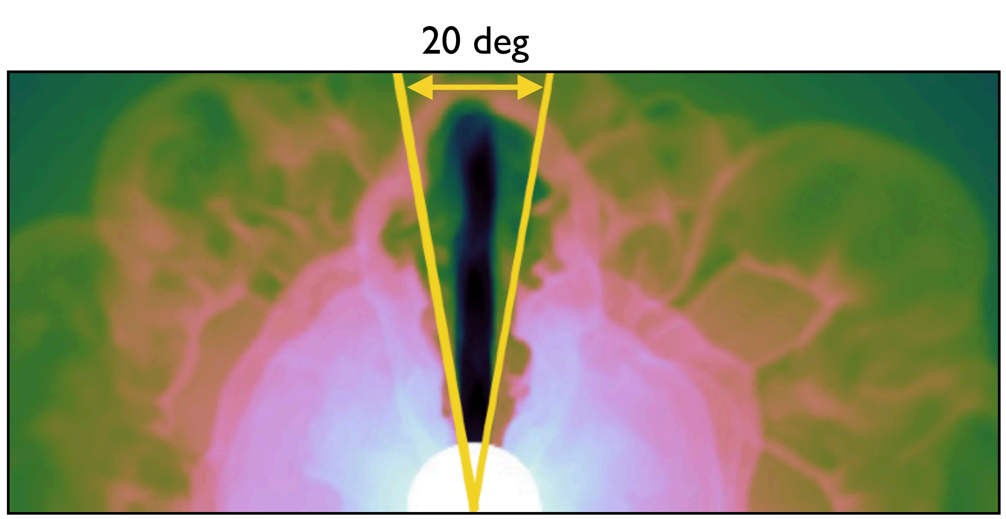
simulation setup

- 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

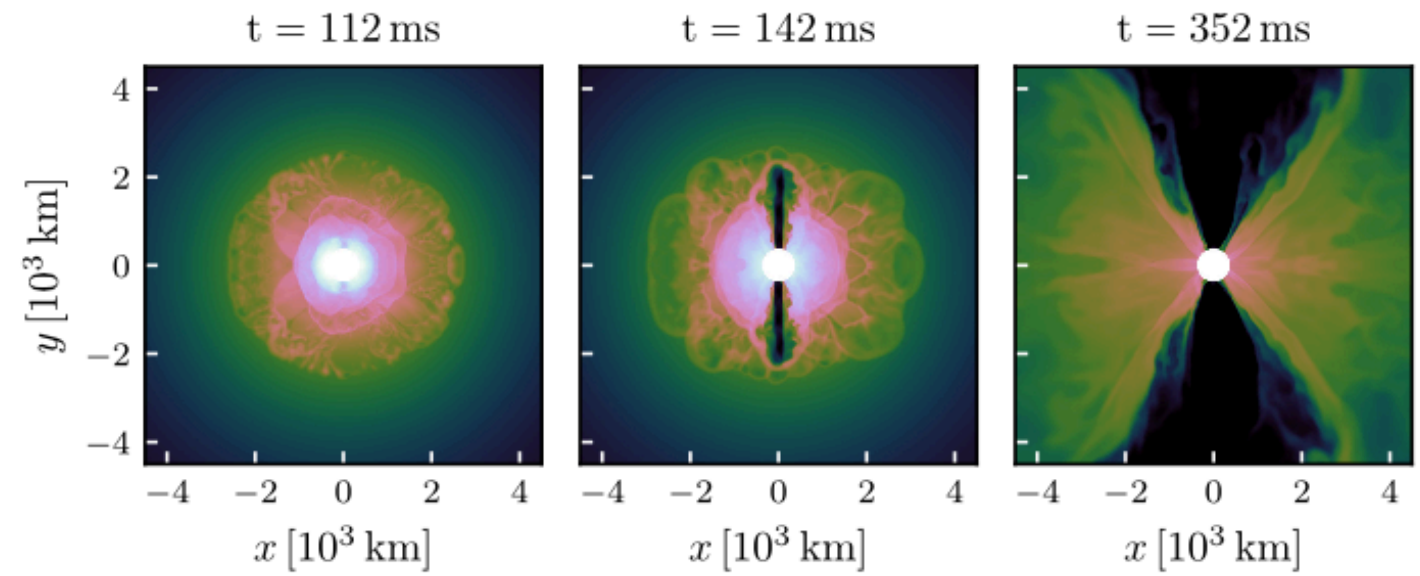
- top-hat, 10 deg half-opening angle, lorentz factor 3
- luminosity 3e50 erg/s, decaying on 0.3 s timescale



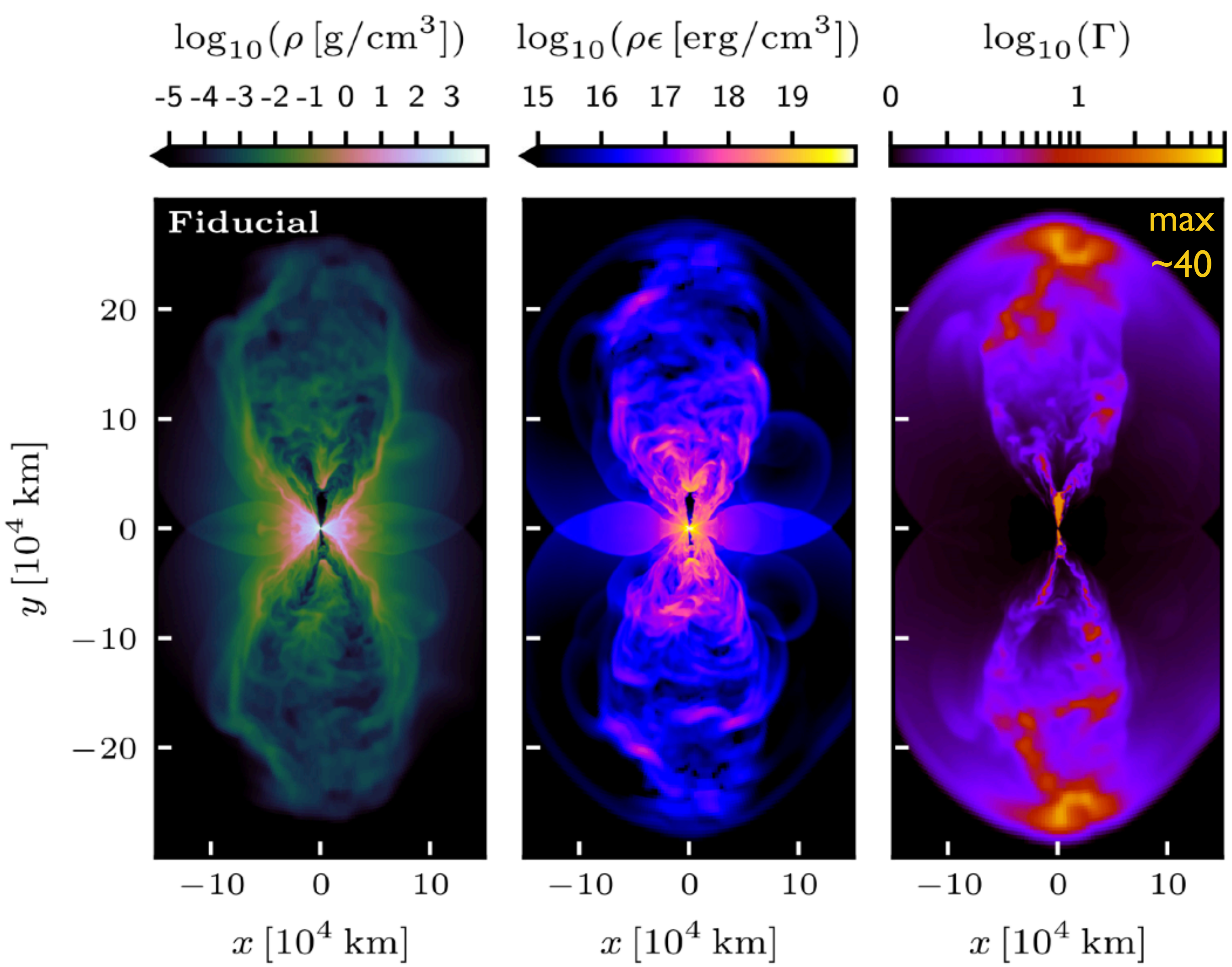
adapted from slides by Andrea Pavan

Fiducial model

early evolution near the engine:
jet breakout and widening

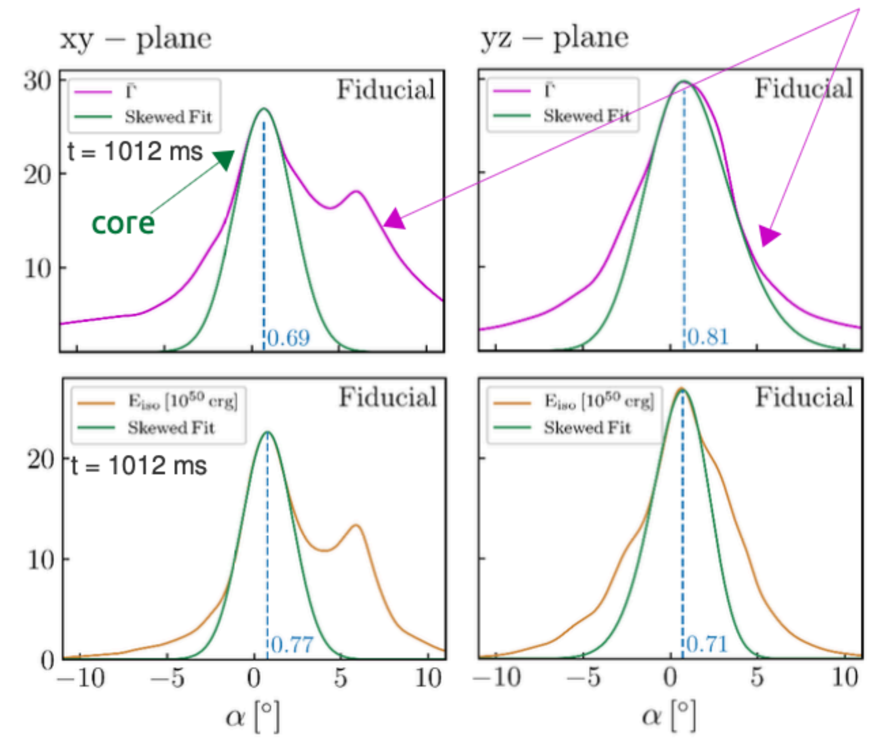


final outflow properties
1012 ms after merger



angular profiles at jet's head

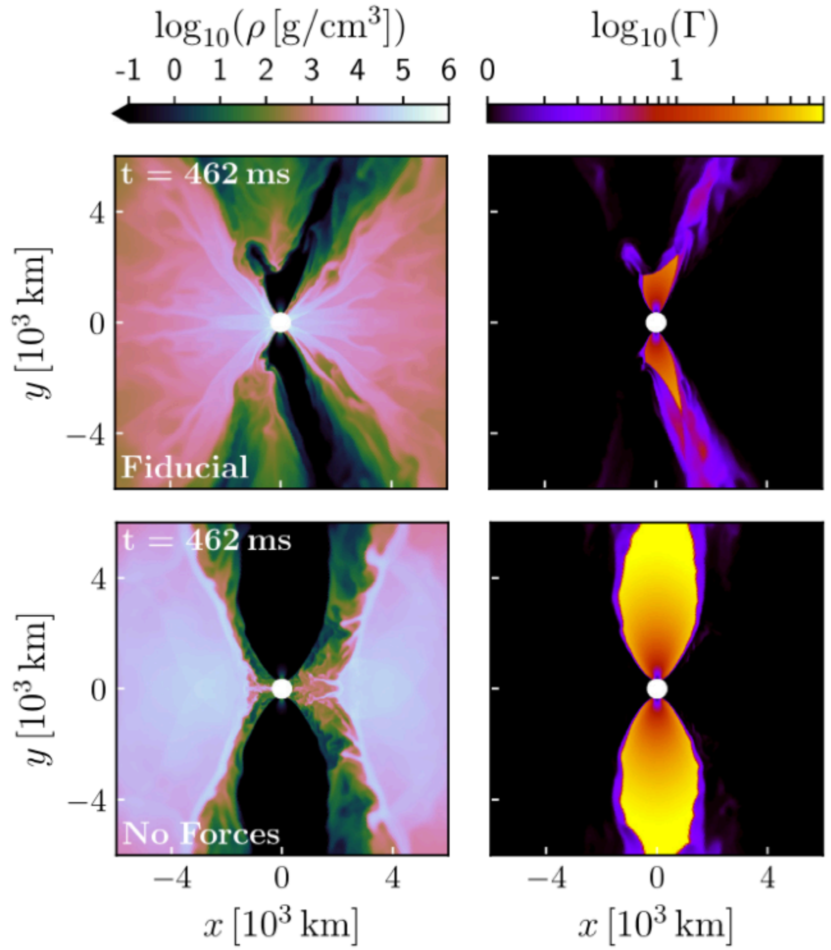
3D asymmetry



asymmetric energy distribution

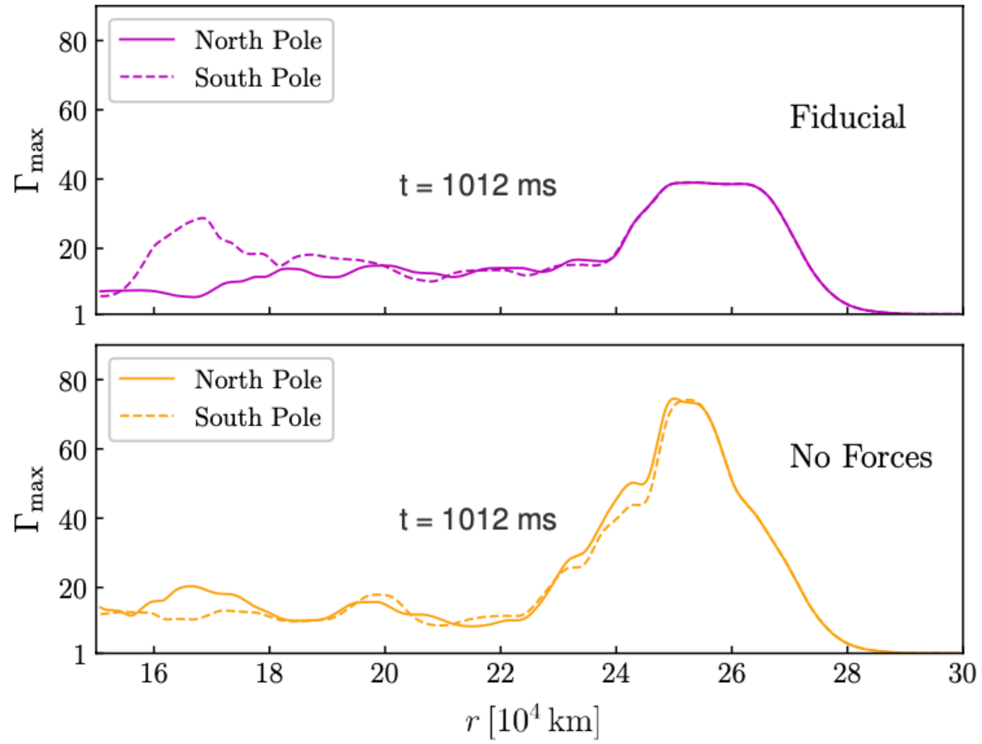
adapted from slides by Andrea Pavan

Impact of gravity



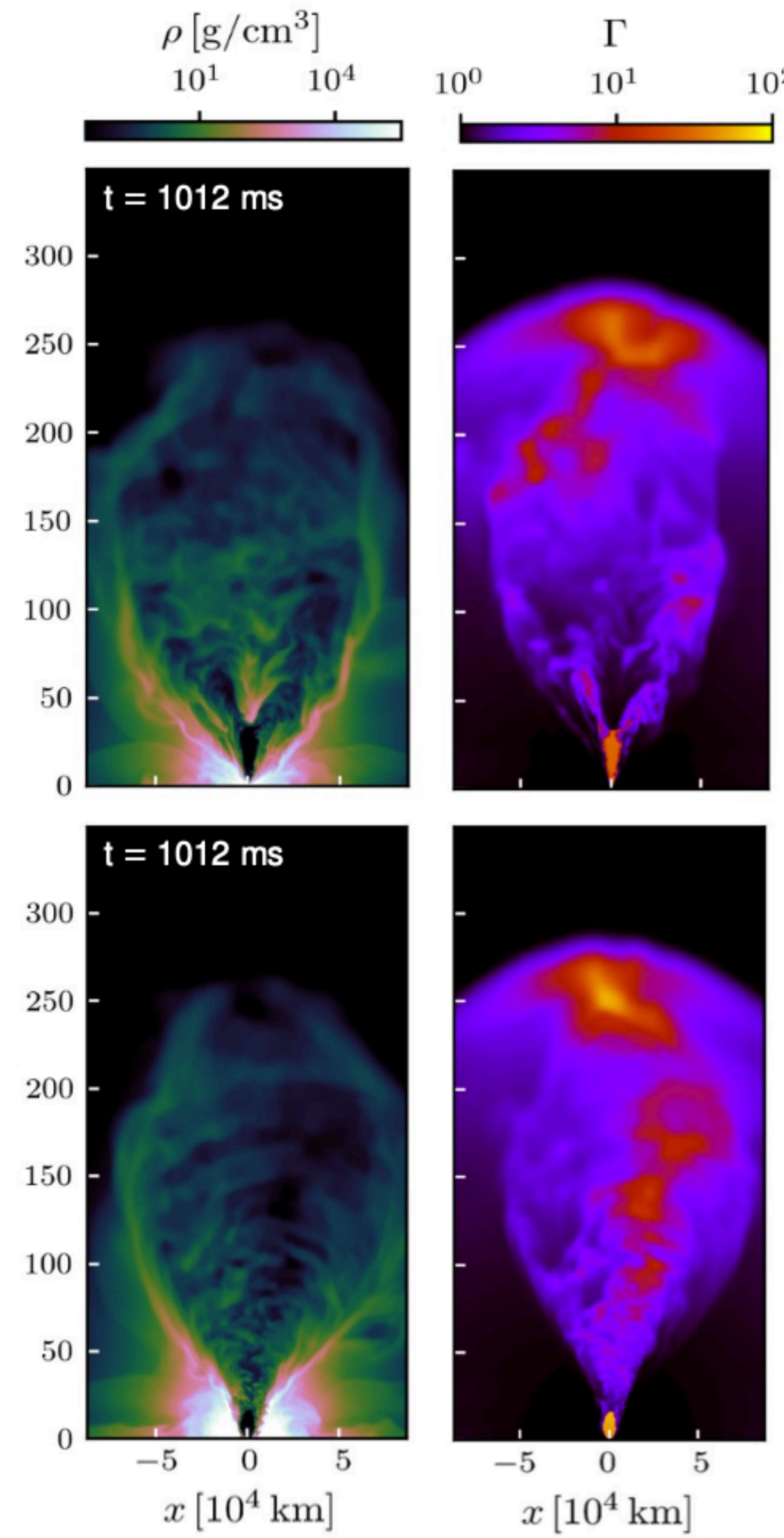
<u>gravity effect</u>:
more turbulence
and baryon loading

<u>no gravity</u>:
unperturbed
collimation shock



<u>no gravity</u>:
more compact
and axisymmetric
jet's head

larger
Lorentz factor



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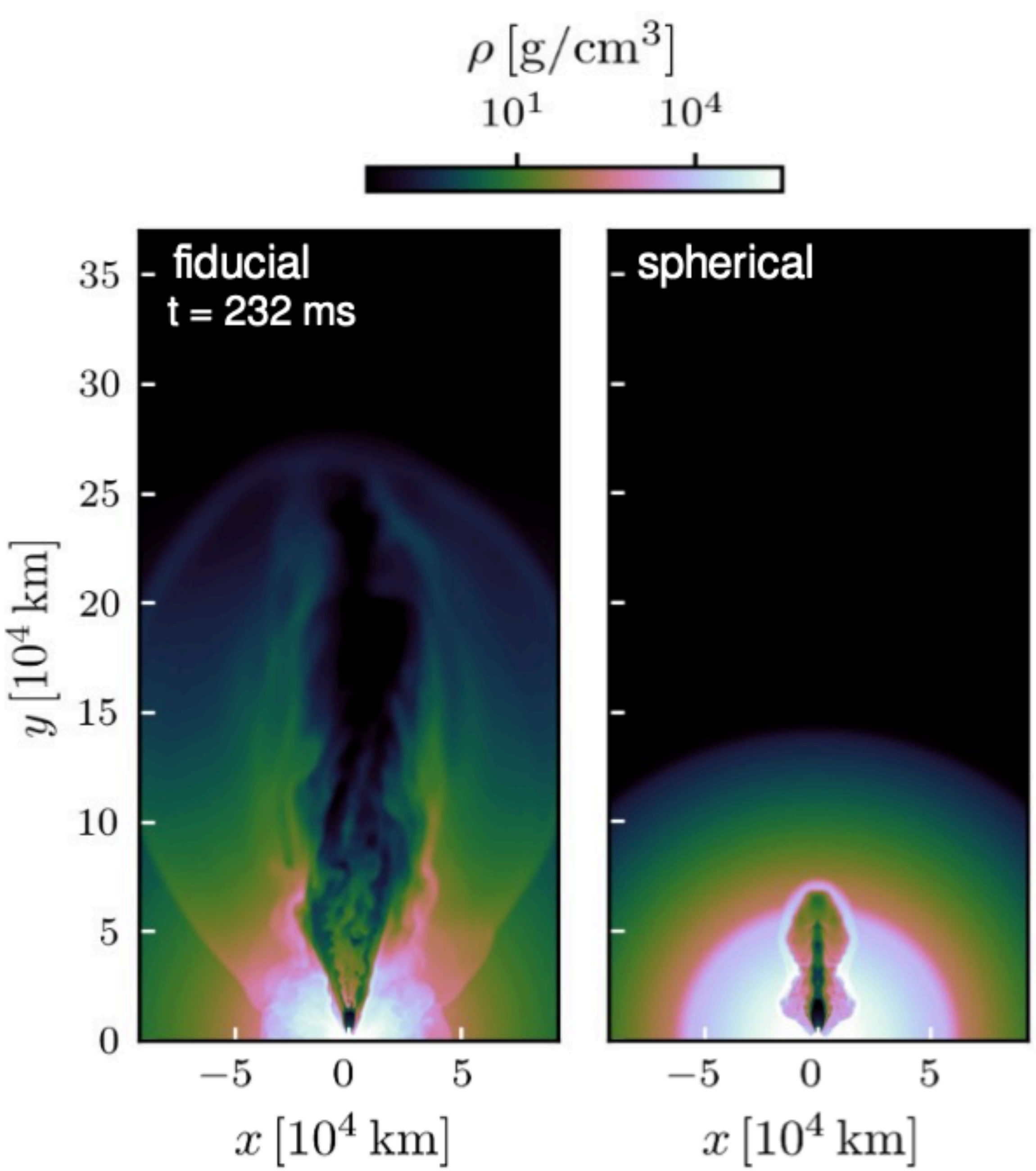
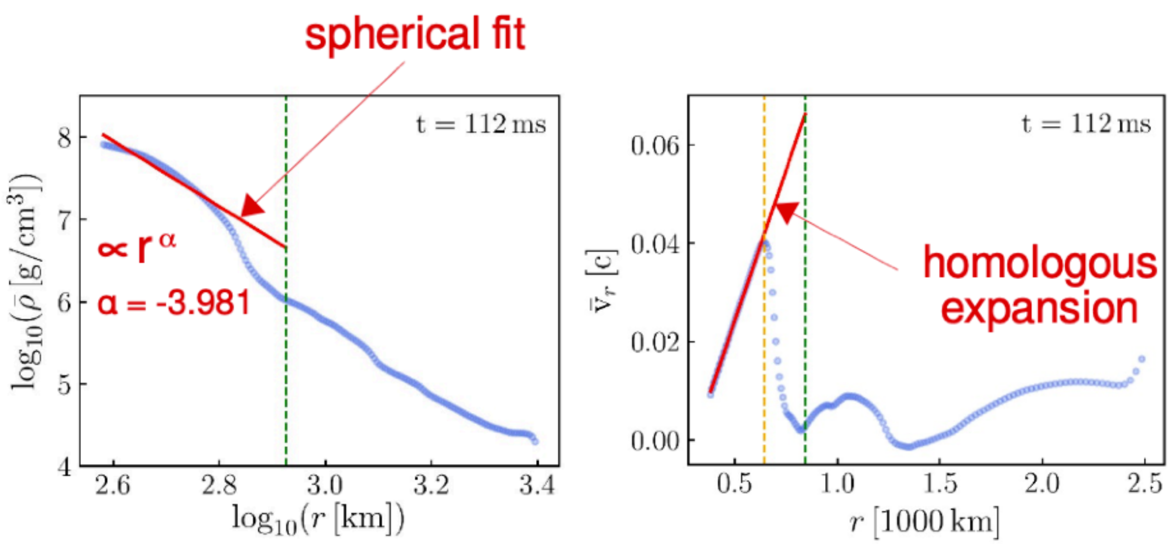
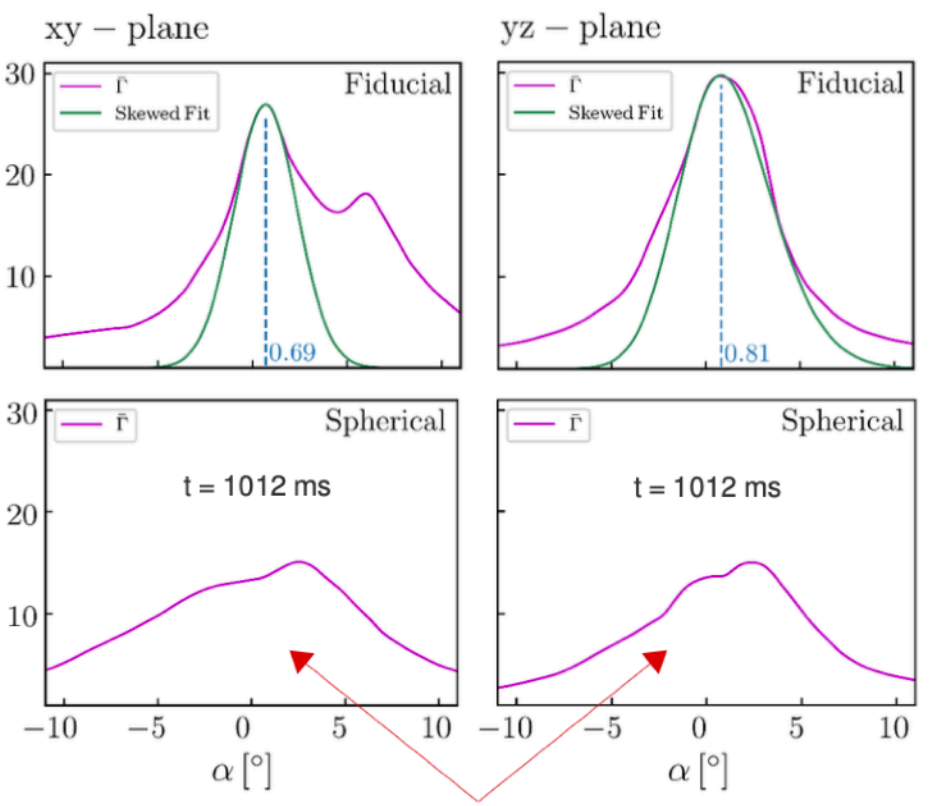
BNS merger vs. hand-made initial conditions



delayed break-out time

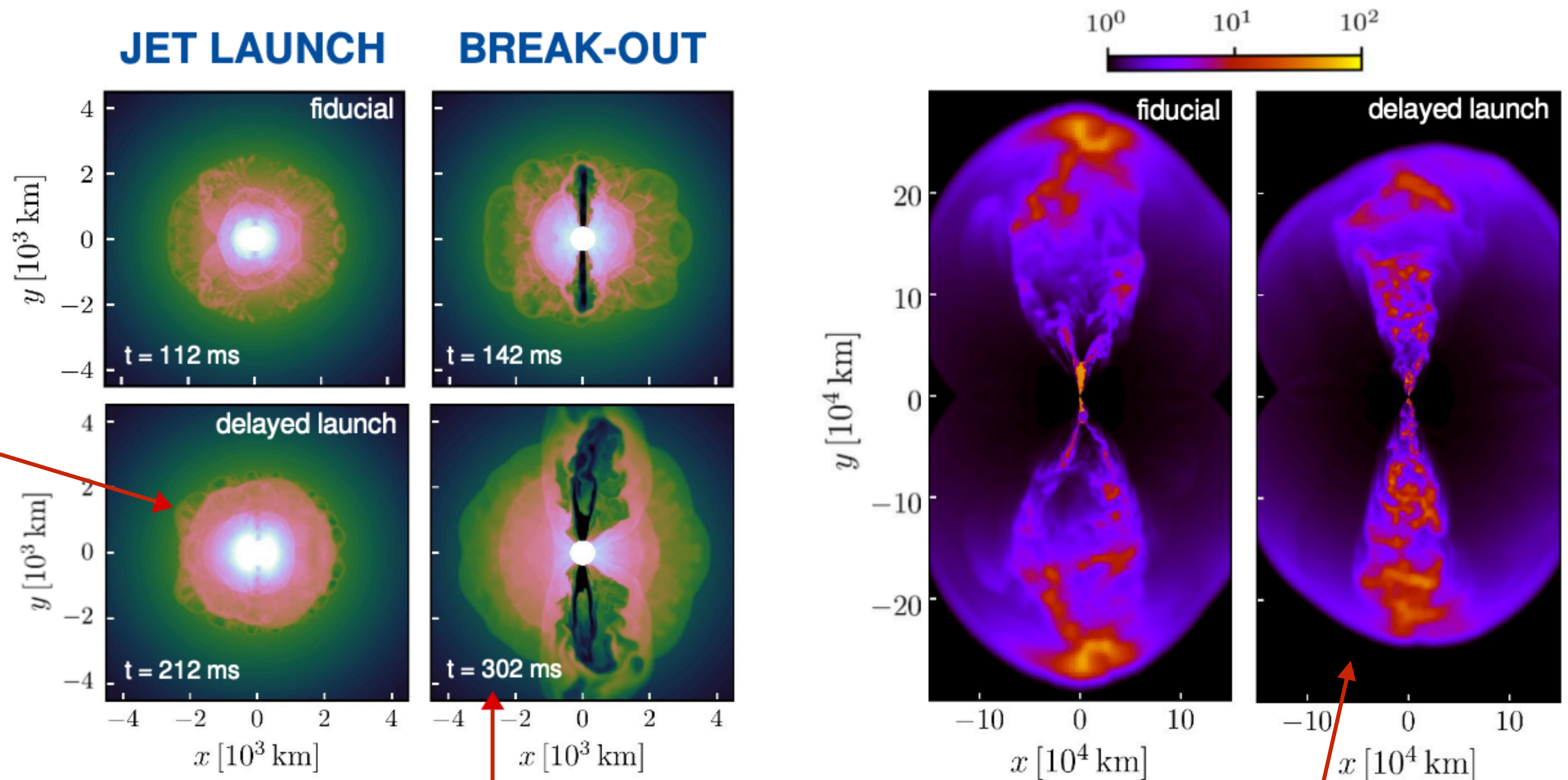




higher 3D symmetry
& lower Lorentz factors

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

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

Work in progress..

short-term

- inclusion of magnetic fields (RMHD)
- adaptive mesh refinement

long-term

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

Take-home message

after GRB 170817A we know that BNS mergers can produce powerful relativistic jets

- GRMHD simulations: necessary tool to investigate launching mechanism and engine nature

- BH engine scenario favoured by current results, but without neutrino emission/absorption/annihilation

MAIN LIMITATION: unresolved MHD instabilities/turbulence

- new GRMHD code *Spritz* + new c2p scheme *RePrimAnd*

  ⟶ now performing the first BNS merger simulations

- jet propagation and connection to prompt/afterglow SGRB observations so far "detached" from merger dynamics

  ⟶ first 3D RHD jet simulations with imported BNS merger environment initial step towards end-to-end consistent description

References

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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), accepted on ApJ, ArXiv:2004.10210
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. (2021), submitted
Implementing a new recovery scheme for primitive variables in…

- 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

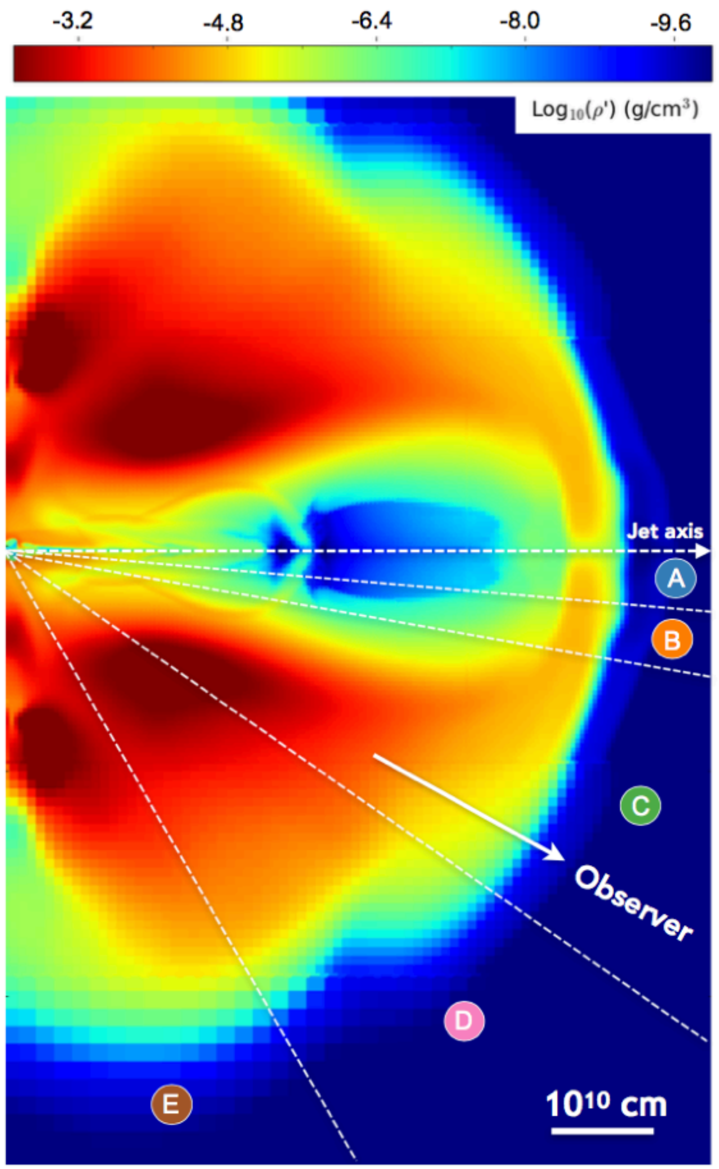
- **R. Ciolfi** (2020b), Gen. Rel. Grav. **52**, 59
The key role of magnetic fields in BNS mergers

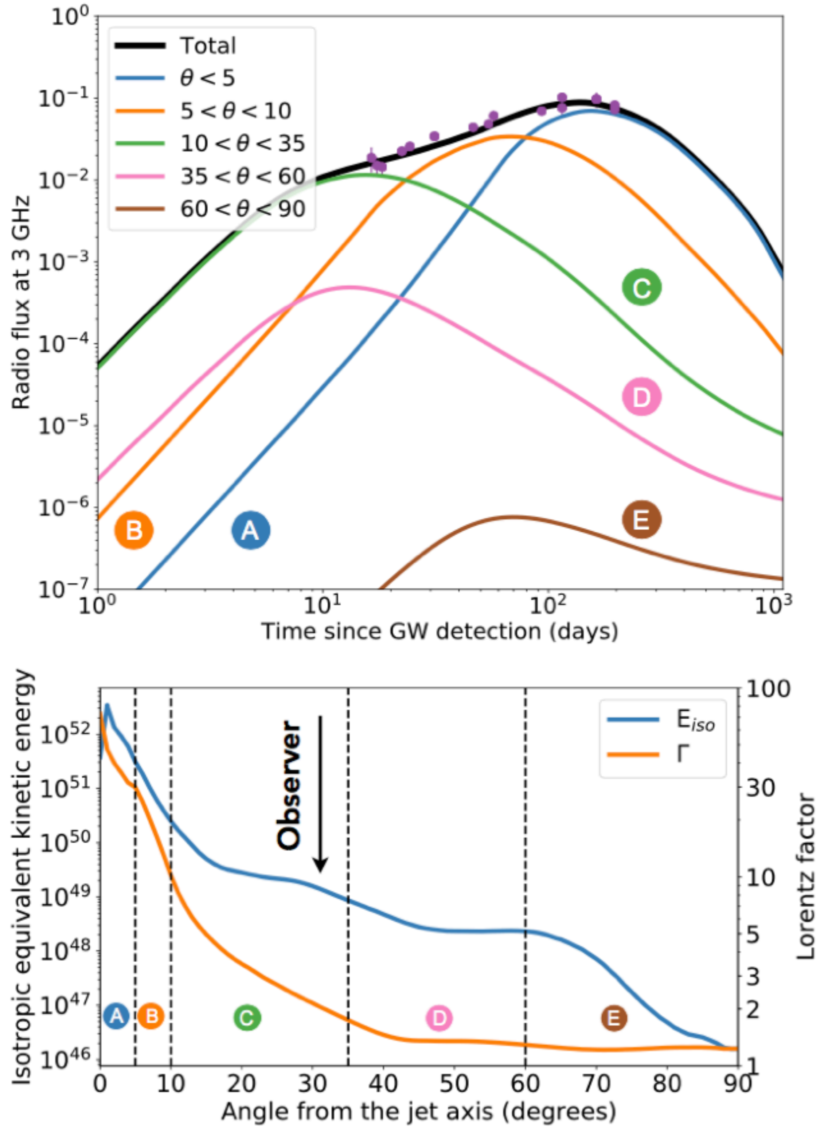
- **R. Ciolfi** (2018), IJMPD **27**, No. 13, 1842004
Short gamma-ray burst central engines

BACKUP SLIDES

GRB 170817A: Canonical SGRB?

Lazzati+2018



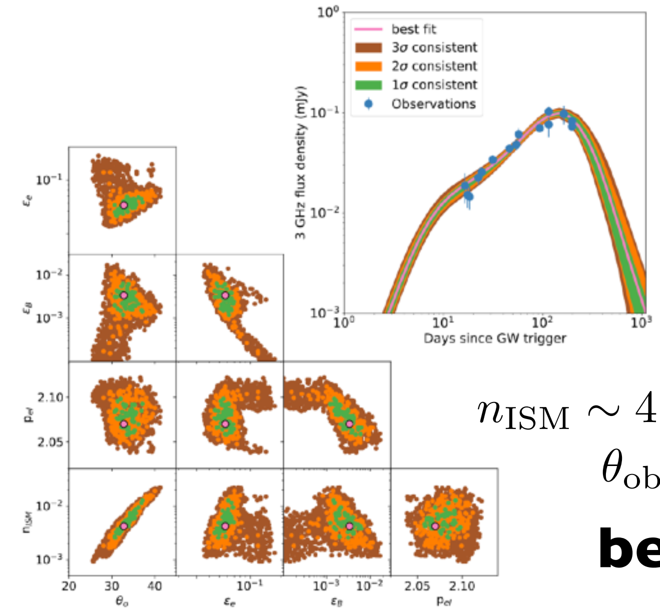


special relativistic jet simulation

$L_j = 10^{50}$ 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!

AT2017gfo: blue and red

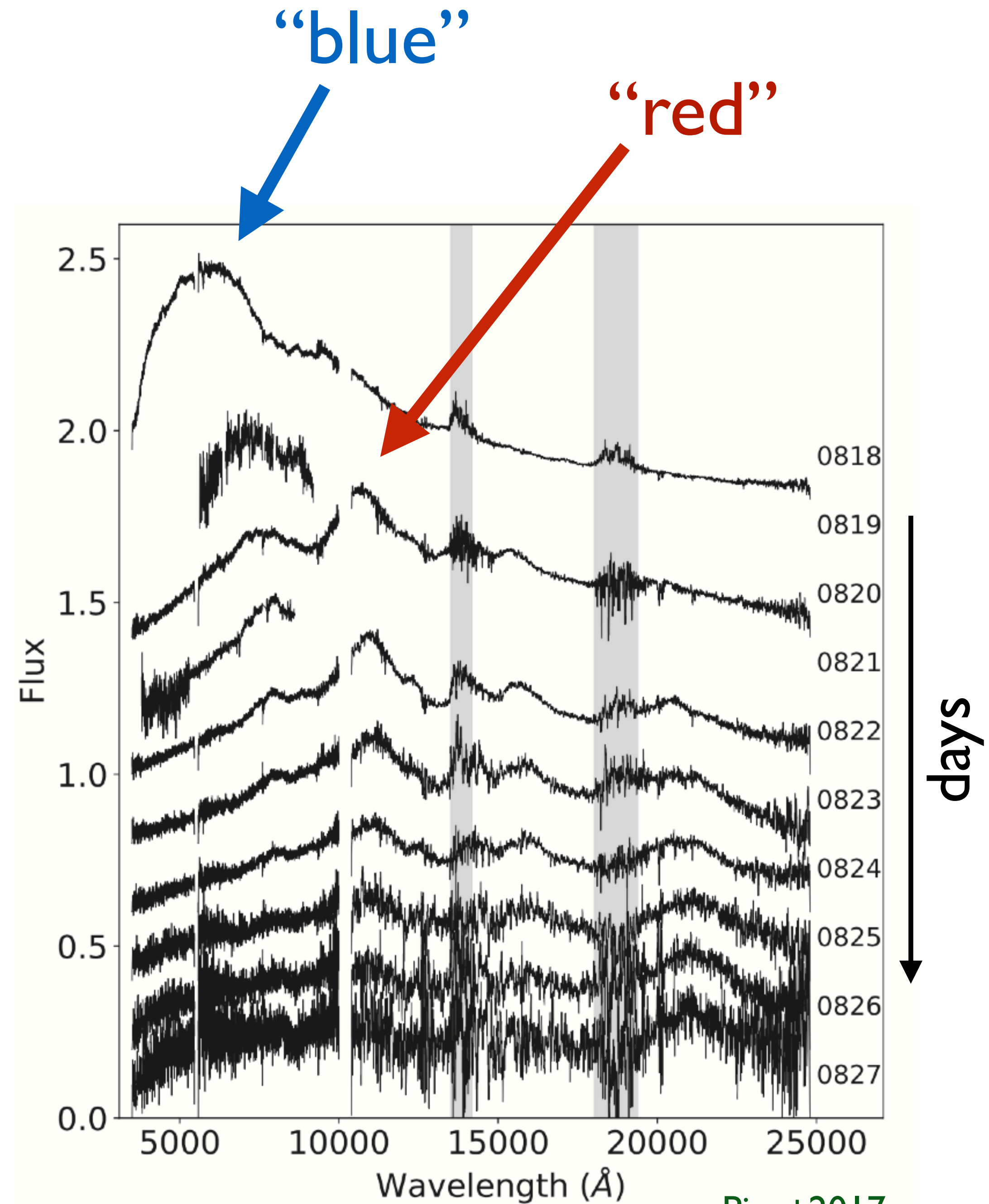
1) "blue" kilonova ➡ ???

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 ➡ likely disk winds

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)



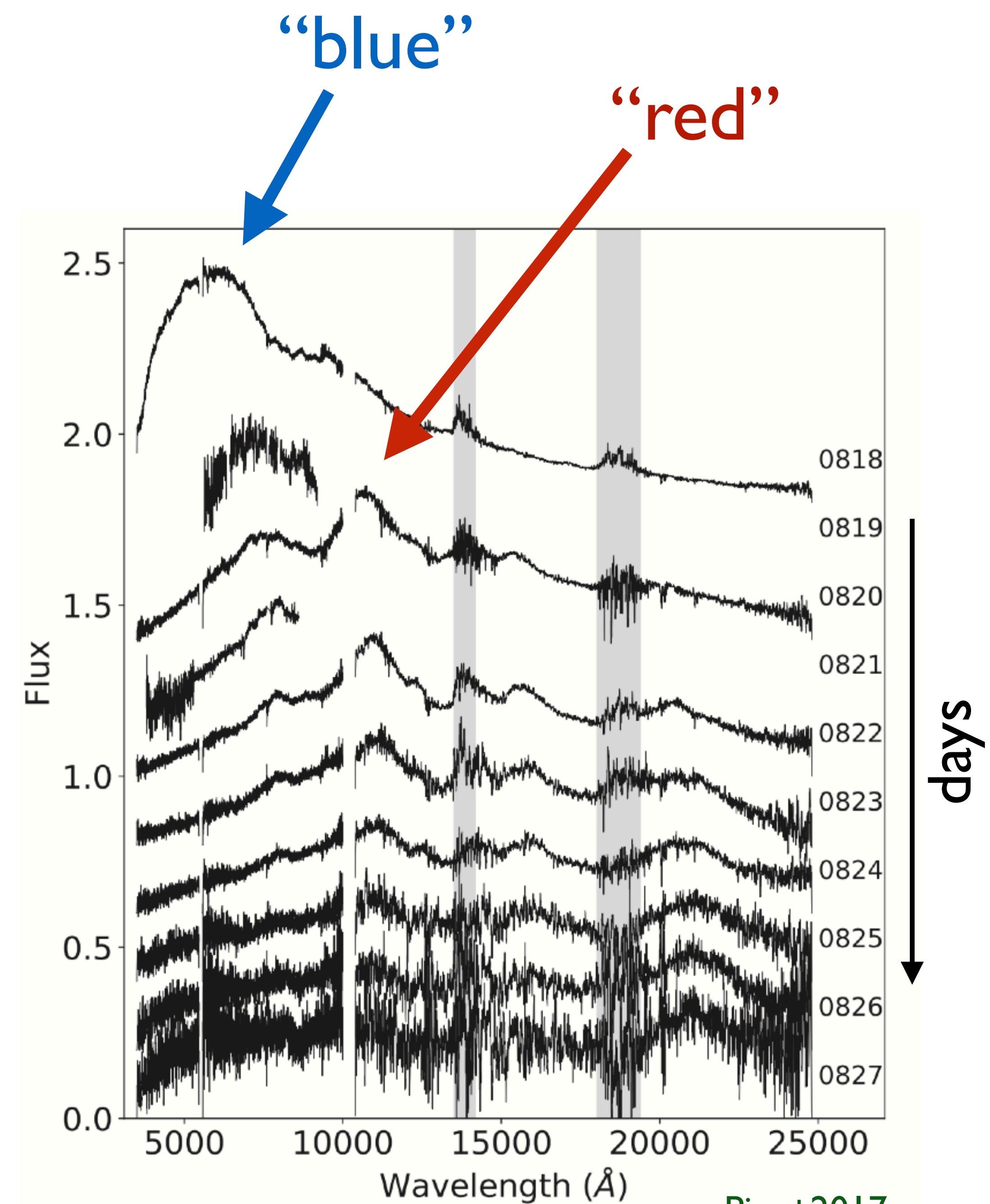
Pian+2017

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

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)



Pian+2017

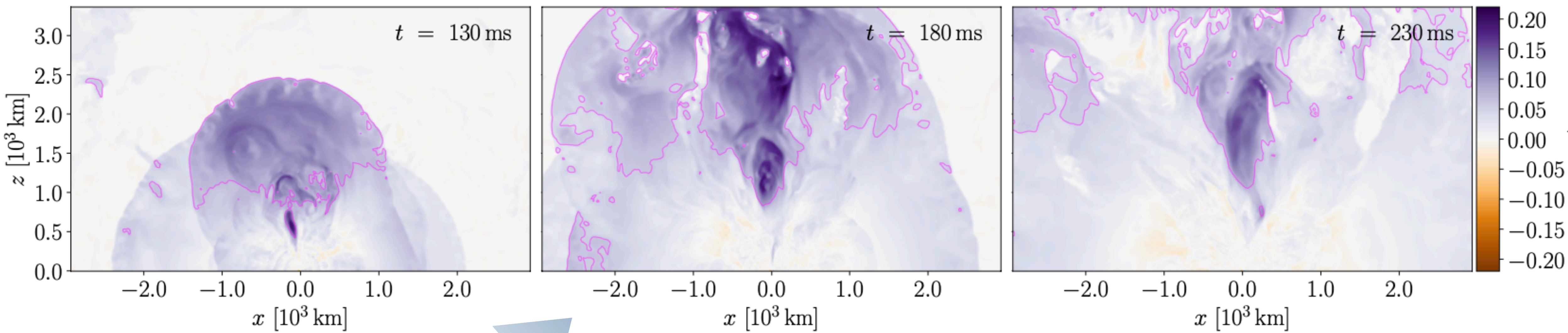
magnetically driven wind from the massive NS ? (before its eventual collapse)

expected opacity fits the requirement
e.g. Perego+2014

magnetic enhancement of mass outflow and acceleration to sufficiently high velocities → **to be demonstrated!**

Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

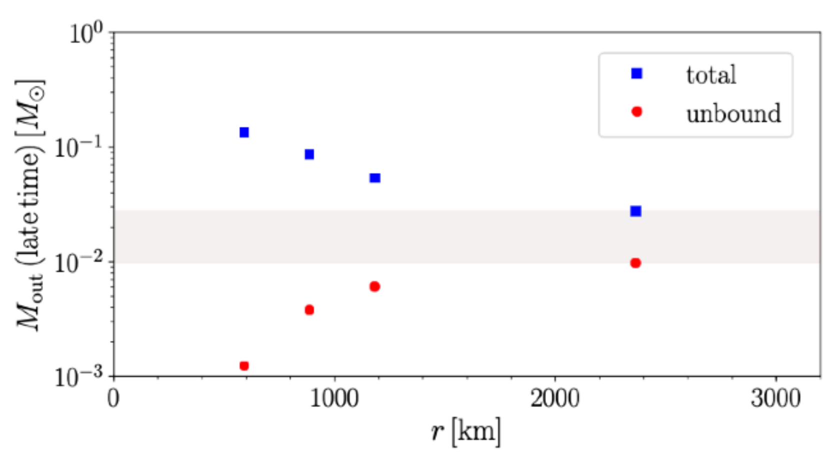


ejecta velocity

~0.2 c marginally consistent with blue kilonova

⟶ possible further enhancement

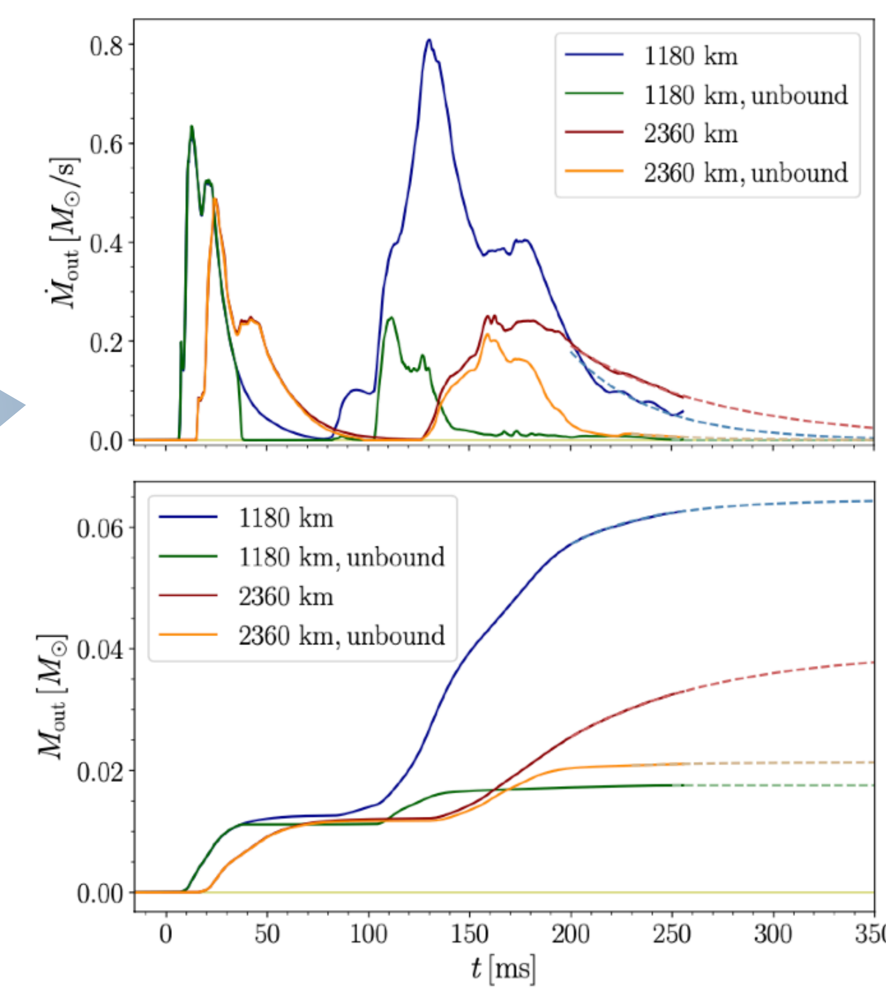
ejecta mass



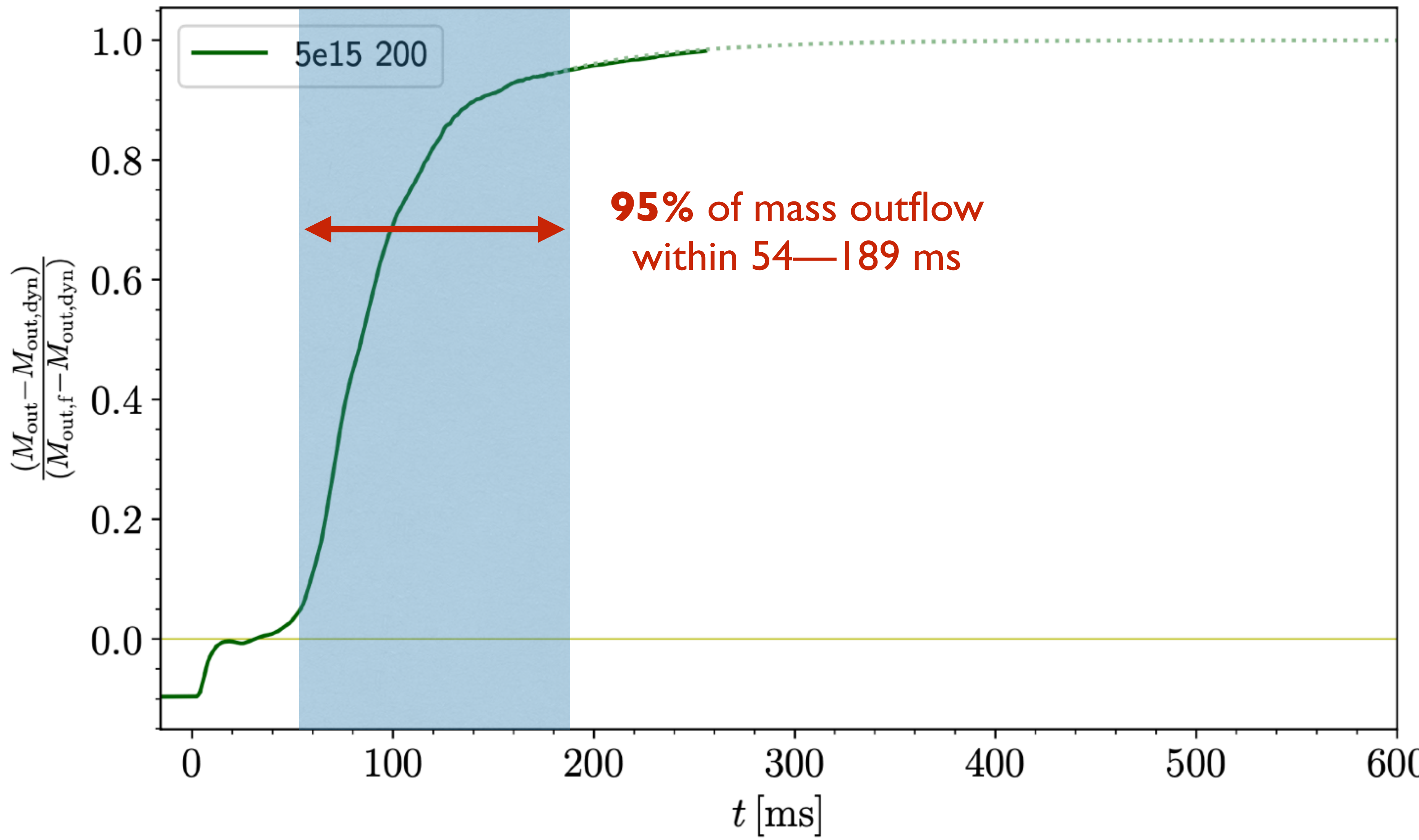
$M_{ej,\,wind} \simeq 0.010–0.028\, M_\odot$

to be compared with

$0.015 - 0.025\, M_\odot$



post-merger outflow at 300km



from simulation
in Ciolfi 2020a

- magnetically driven mass outflow takes time to emerge

  for significant contribution ⟶ NS remnant lifetime > 50ms

- mostly over at 200ms ⟶ slower neutrino driven wind could then take over and persist for longer time (~1sec)

GRB 170817A: intrinsic jet properties

Lazzati, Ciolfi, Perna 2020

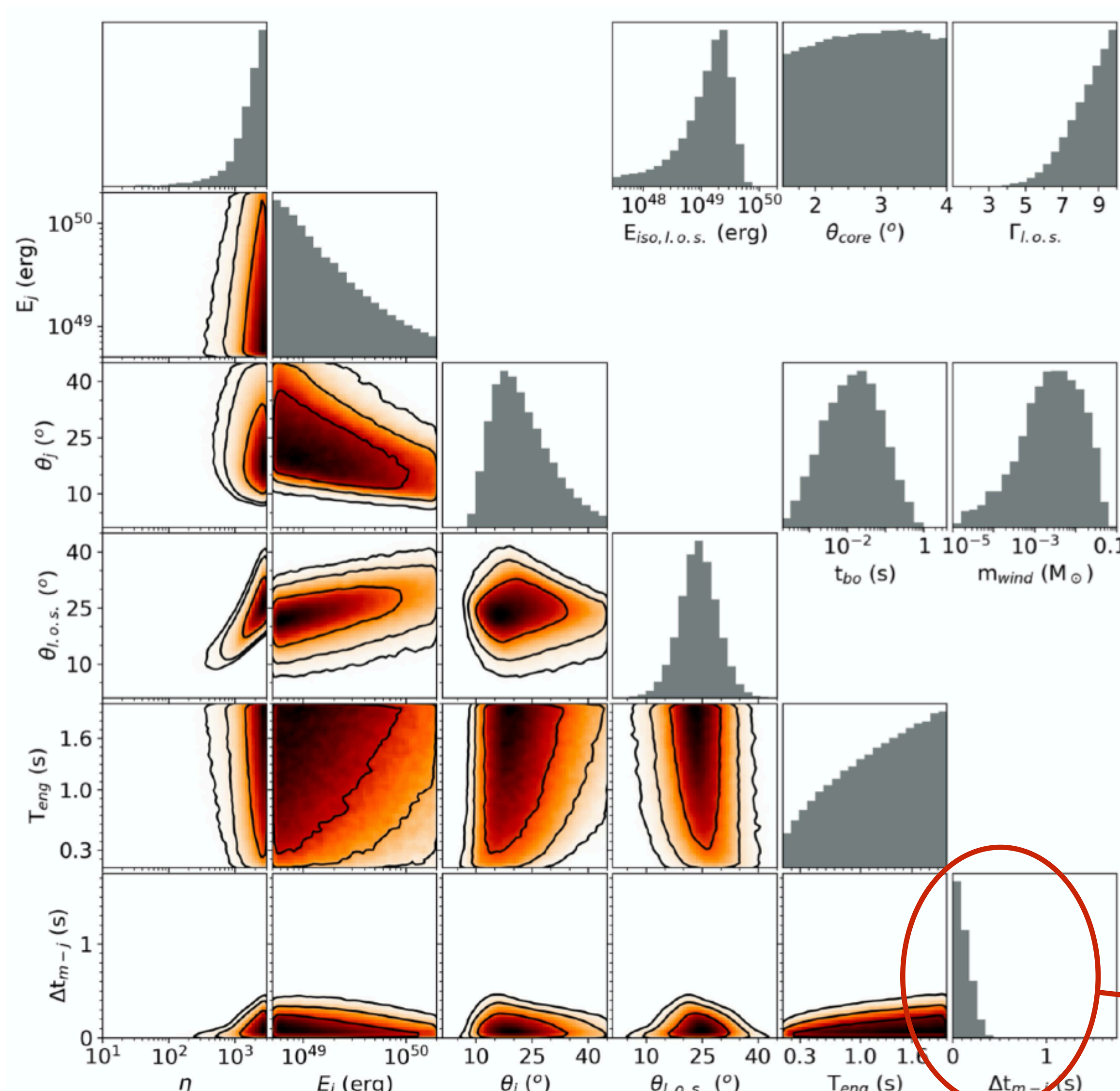
incipient jet → interaction with the baryon wind from the massive NS → final jet properties

incipient jet:
jet energy and duration
terminal Lorentz factor
initial opening angle
jet launching time

interaction with the baryon wind from the massive NS:
wind mass
(simulation-inspired environment depending on launching time)

final jet properties:
viewing angle
jet core opening angle
Eiso
Lorentz factor of gamma-ray emission
delay between merger and GRB

(line of sight)



jet launching time < 0.4 s

■ input parameters
■ output parameters constrained by observations

Model	Δt_{m-j} (s)	η	$\theta_{l.o.s}$ (°)	θ_j (°)
Simulations; baseline ($Y_e = 0.5$; $\Gamma_{l.o.s.} \leq 10$; m_w unconstrained)	**< 0.36**	**> 240**	**$23.5^{+5.5}_{-4.5}$**	**$17.9^{+12.6}_{-3.2}$**
Simulations; $\Gamma_{l.o.s.} \leq 7$	< 0.18	> 240	$24^{+6.9}_{-3.5}$	$18.4^{+12.5}_{-3.1}$
Simulations; $m_w \geq 10^{-2}$	< 0.37	> 390	$23.6^{+4.8}_{-4.5}$	$17.3^{+13.4}_{-2.5}$
Simulations; $\Gamma_{l.o.s.} \leq 7$; $m_w \geq 10^{-2}$	< 0.17	> 250	$24.1^{+6.7}_{-3.6}$	$19.3^{+11.9}_{-3.9}$
Simulations; $Y_e = 1.0$	< 0.27	> 260	$22.0^{+5.9}_{-}3.3$	$18.1^{+13.4}_{-3.1}$
Simulations; $Y_e = 0.2$	< 0.51	> 170	$25.1^{+5.0}_{-6.0}$	$15.8^{+13.2}_{-1.9}$
Parametric; baseline ($Y_e = 0.5$; $\Gamma_{l.o.s.} \leq 10$; m_w unconstrained)	**< 1.1**	**> 150**	**$30.3^{+8.5}_{-8.0}$**	**$10.2^{+8.8}_{-3.0}$**
Parametric; $\Gamma_{l.o.s.} \leq 7$	< 0.87	> 180	$34.4^{+6.4}_{-8.6}$	$9.2^{+9.7}_{-1.8}$
Parametric; $m_w \geq 10^{-2}$	< 0.87	> 420	$27.5^{+6.0}_{-7.1}$	$16.2^{+11.3}_{-3.2}$
Parametric; $\Gamma_{l.o.s.} \leq 7$; $m_w \geq 10^{-2}$	< 0.57	> 800	$30.7^{+6.2}_{-6.8}$	$16.3^{+13.8}_{-1.2}$
Parametric; $Y_e = 1.0$	< 1.0	> 170	$32.3^{+6.4}_{-9.5}$	$9.6^{+9.0}_{-2.5}$
Parametric; $Y_e = 0.2$	< 1.2	> 130	$30.5^{+8.3}_{-8.8}$	$10.8^{+8.6}_{-3.6}$