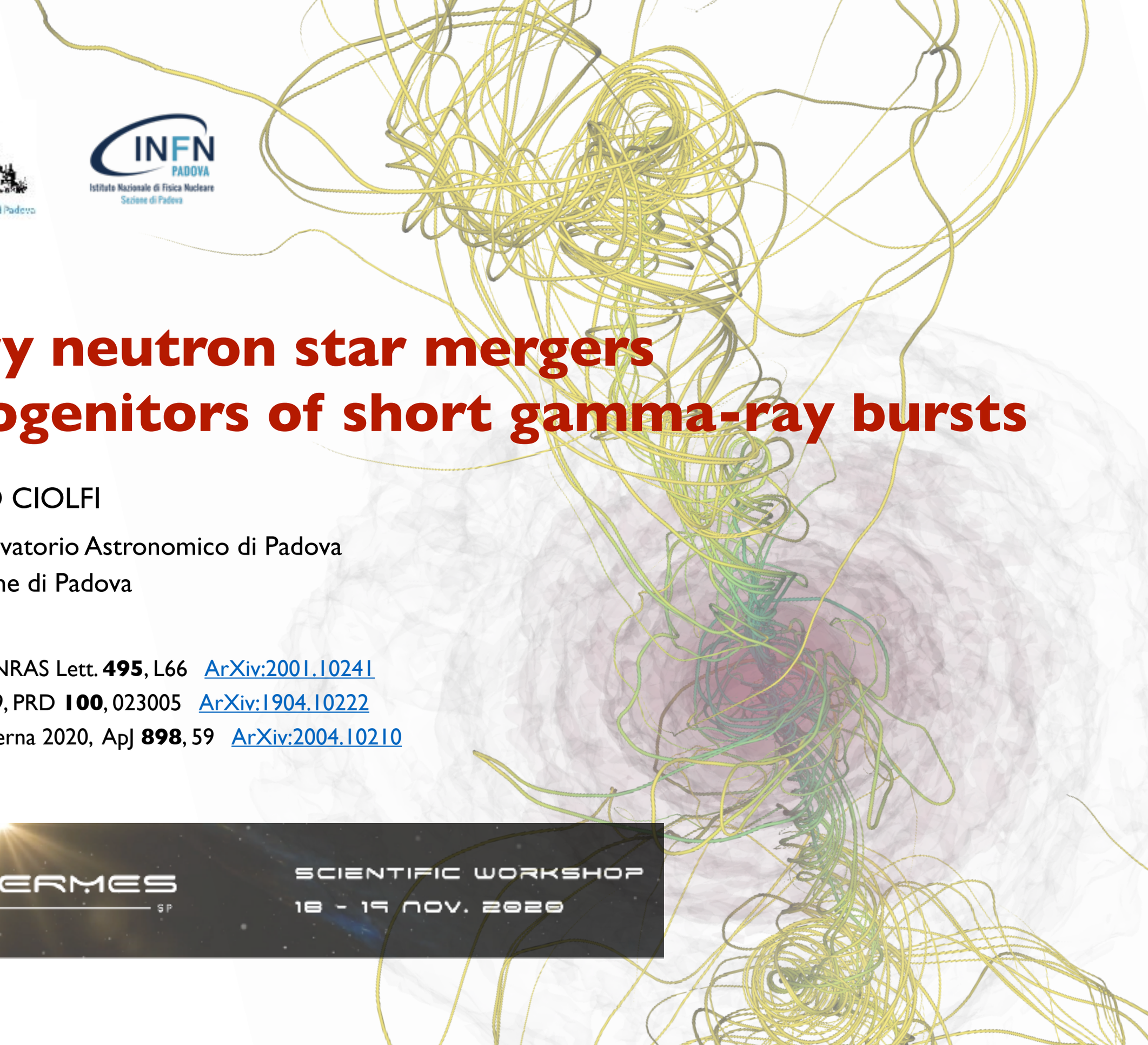


Binary neutron star mergers as progenitors of short gamma-ray bursts

RICCARDO CIOLFI

INAF - Osservatorio Astronomico di Padova

INFN - Sezione di Padova

Ciolfi 2020a, MNRAS Lett. **495**, L66 ArXiv:2001.10241

Ciolfi et al. 2019, PRD **100**, 023005 ArXiv:1904.10222

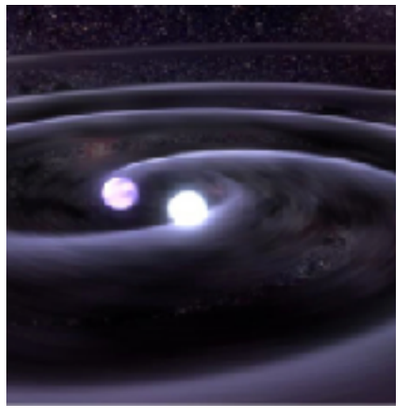
Lazzati, Ciolfi, Perna 2020, ApJ **898**, 59 ArXiv:2004.10210

HERMES SP

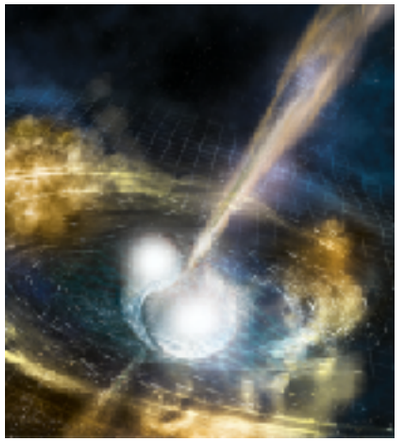
SCIENTIFIC WORKSHOP

18 - 19 NOV. 2020

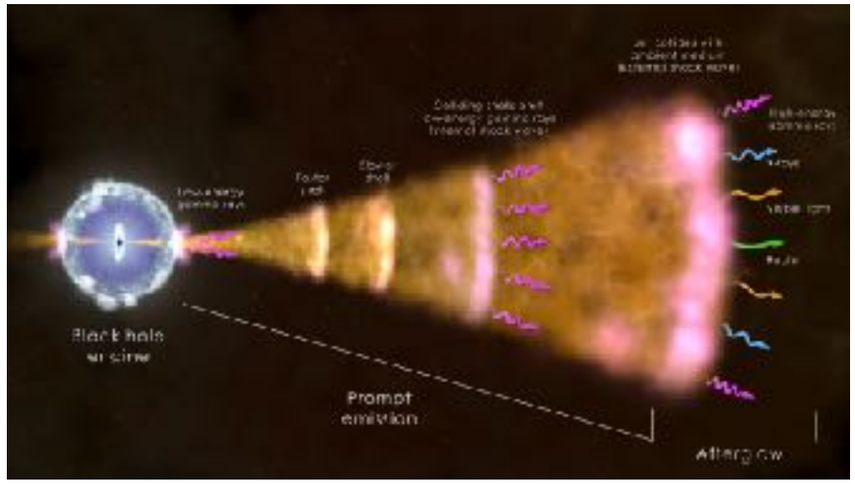
GW170817 detection timeline



merger



short GRB



X-ray afterglow

radio afterglow

t0

+1.7 sec

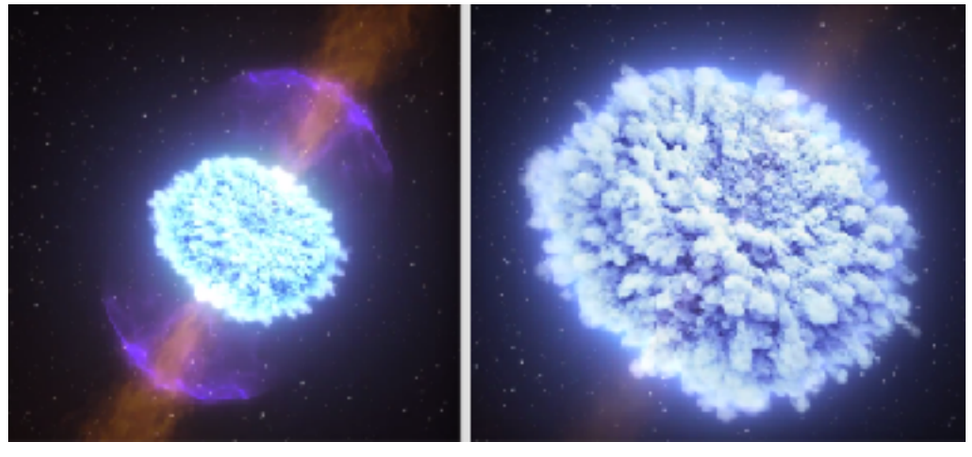
+10.87 hours

+9 days

+16 days

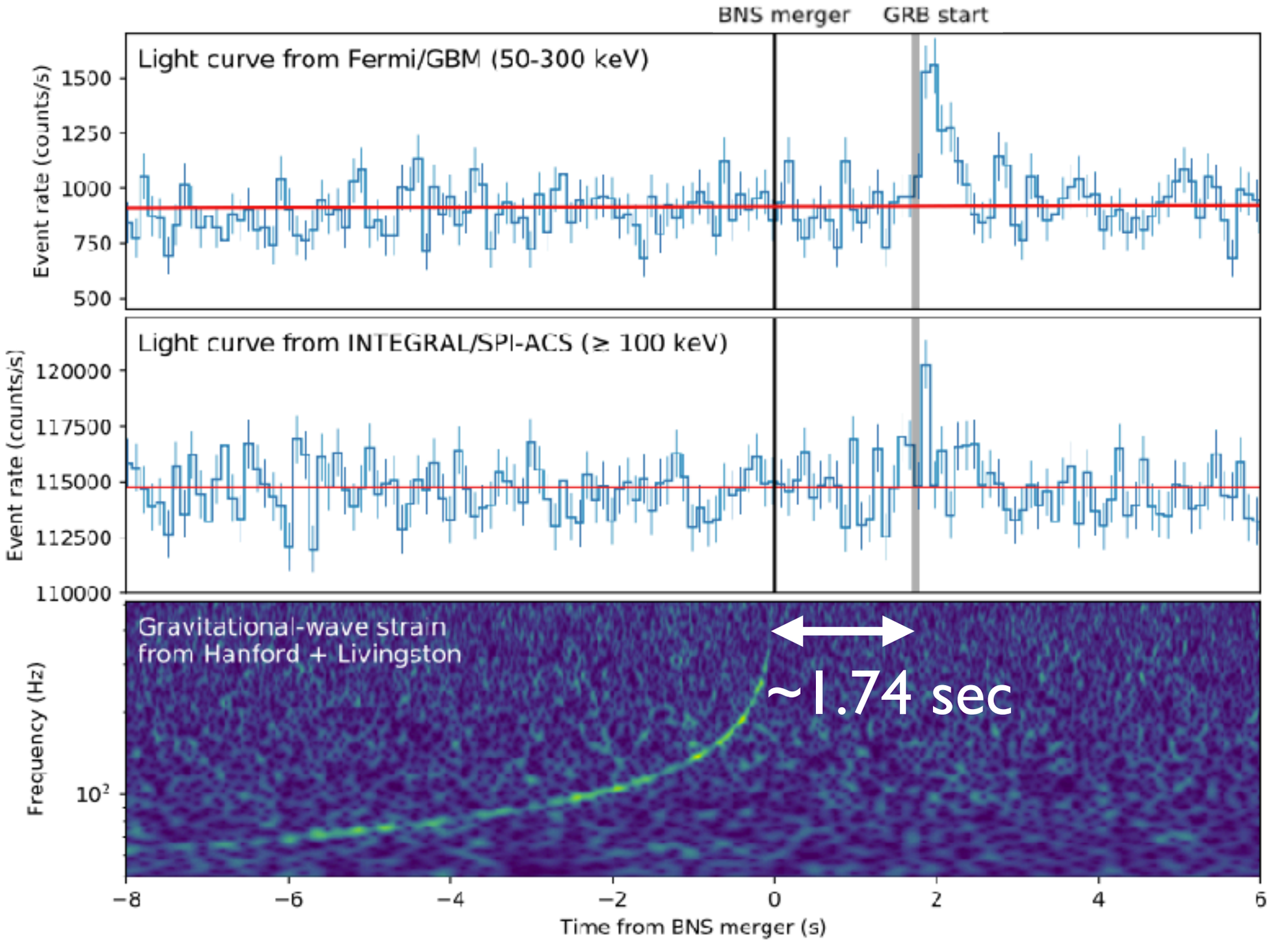
optical
counterpart

kilonova

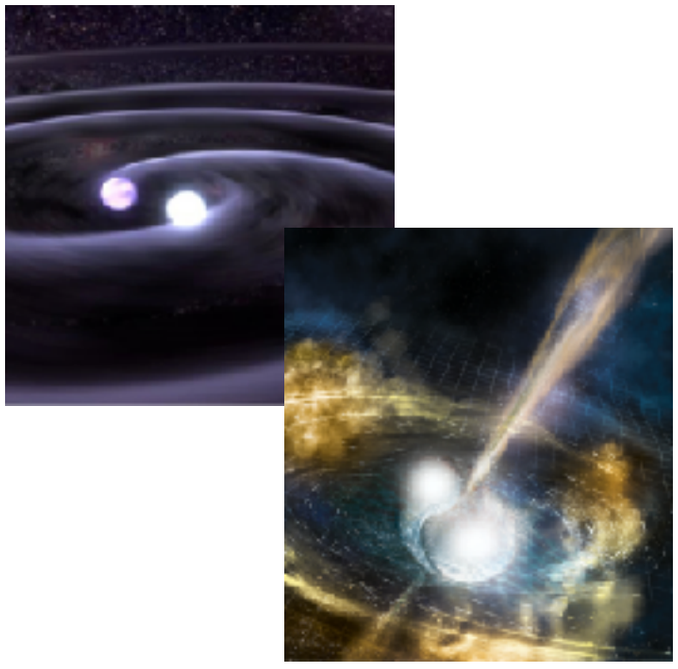


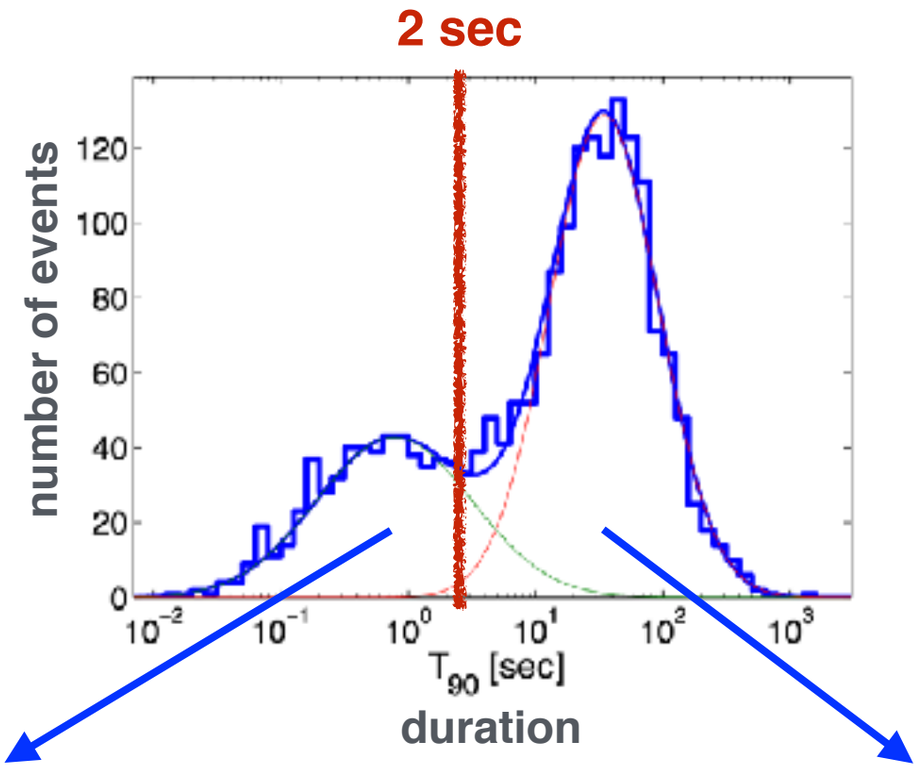
see also talk by
Marica Branchesi

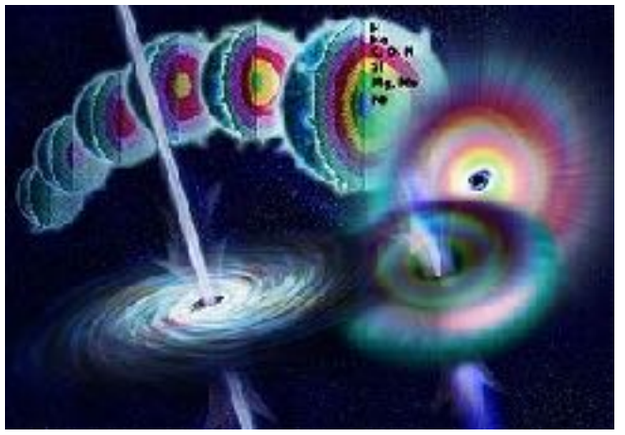
GRB 170817A


BNS merger
GRB start
Light curve from Fermi/GBM (50-300 keV)
Event rate (counts/s)
1500
1250
1000
750
500
Light curve from INTEGRAL/SPI-ACS (≥ 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
110000
Gravitational-wave strain
from Hanford + Livingston
~1.74 sec
Frequency (Hz)
10^2
−8
−6
−4
−2
0
2
4
6
Time from BNS merger (s)

GRB long/short divide







short GRBs

- $T_{90} \lesssim 2\,\mathrm{s}$
- no supernova associations
- both elliptical & late-type galaxies
- larger offsets from host galaxy centres
- candidate kilonova in GRB 130603B

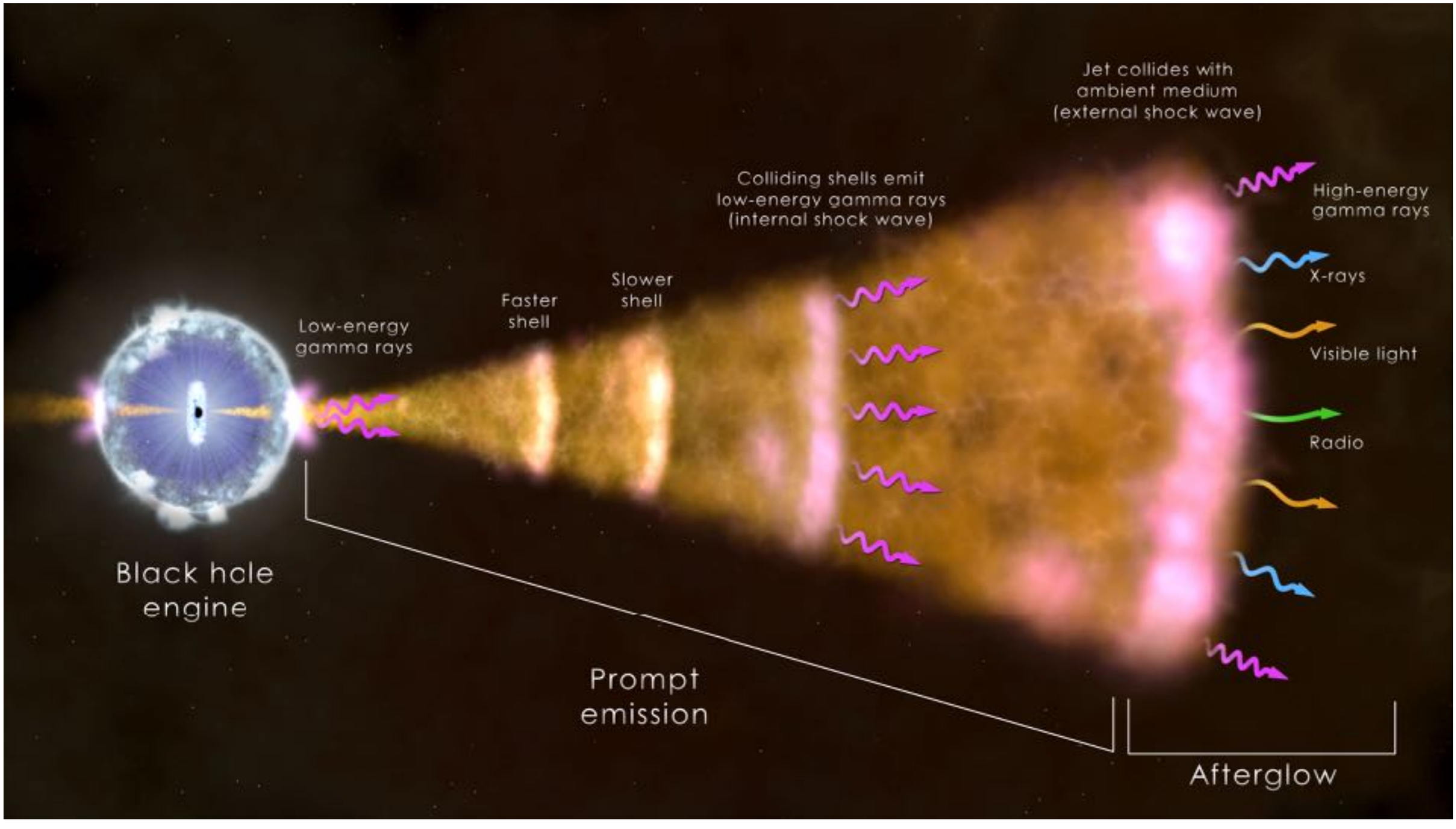
NS-NS (NS-BH) mergers ✓

long GRBs

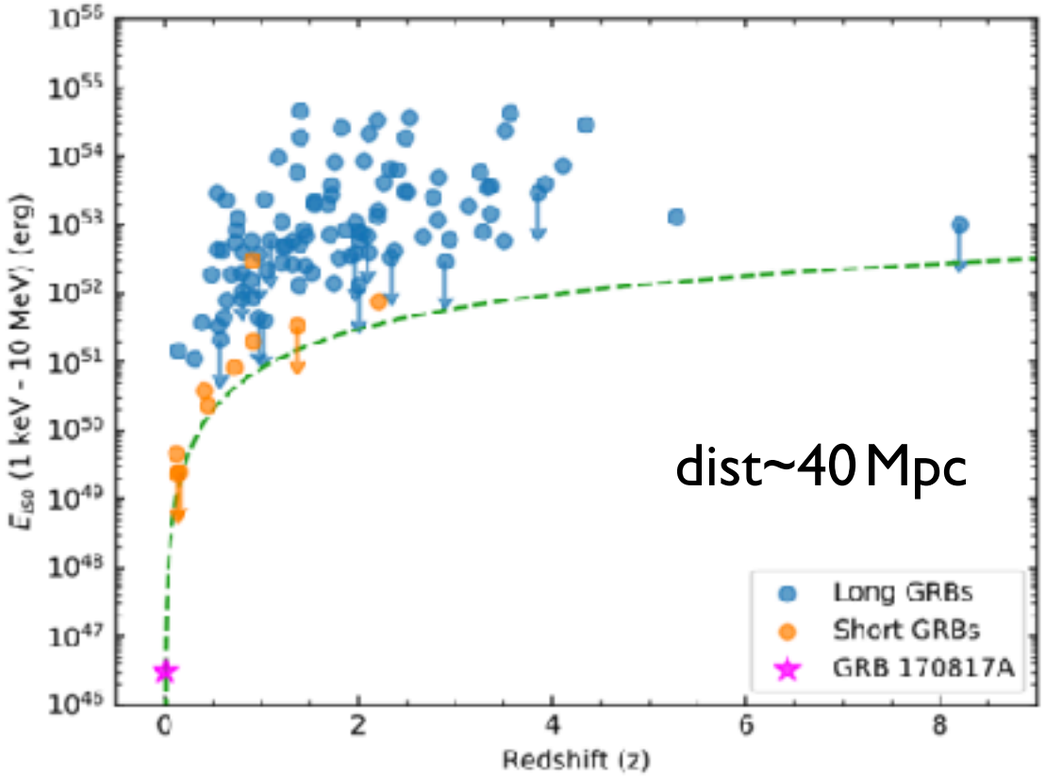
- $T_{90} \gtrsim 2\,\mathrm{s}$
- confirmed supernova associations (Hypernovae $\gtrsim 10^{52}\,\mathrm{erg}$)
- only late-type galaxies with high star formation rates

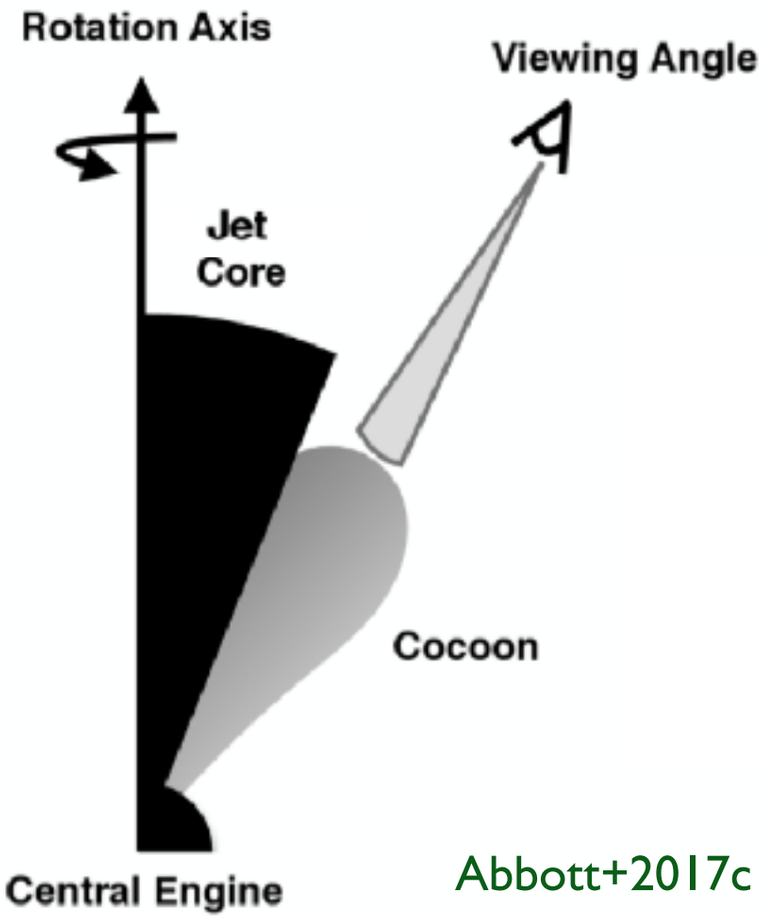
core-collapse supernovae ✓

GRB jet paradigm



GRB 170817A: a peculiar GRB



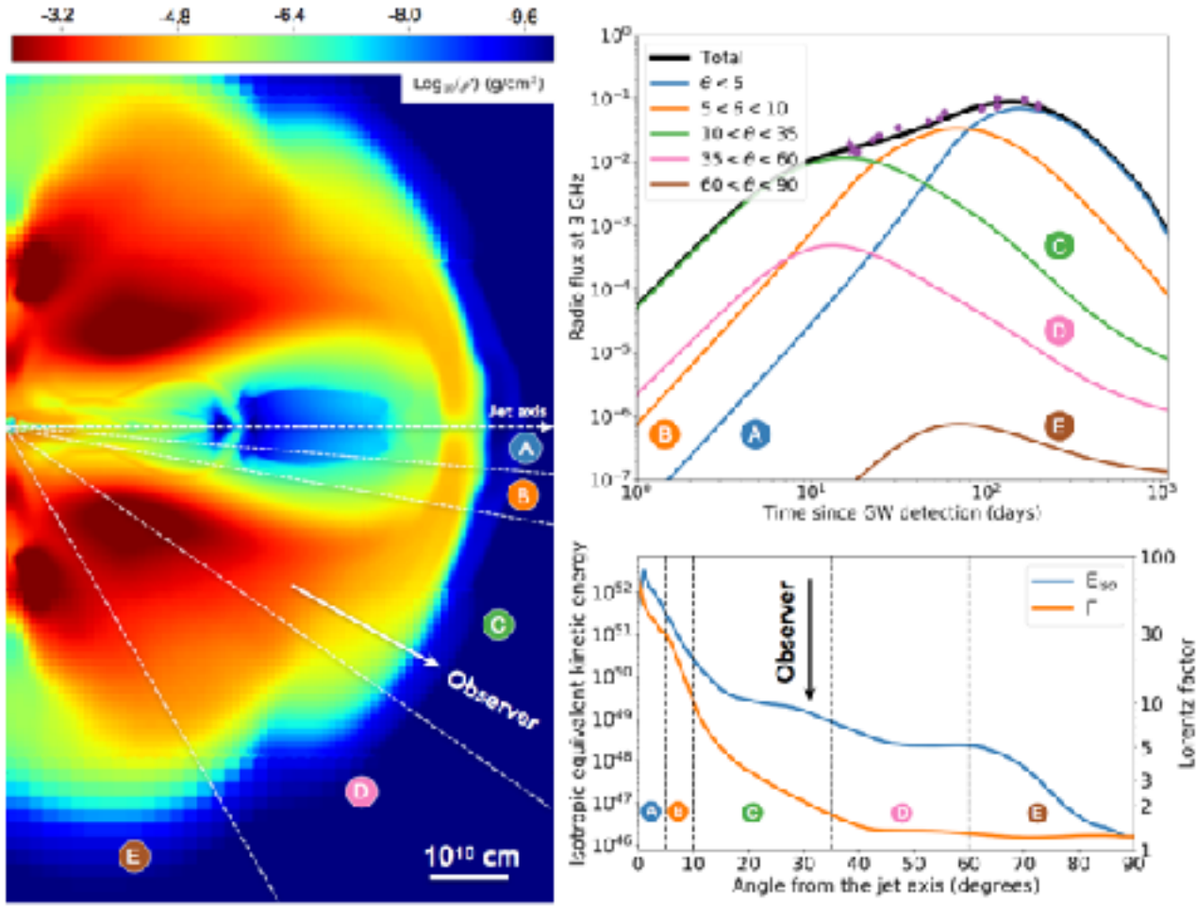


Abbott+2017c

from GRB and multiwavelength afterglow modelling

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

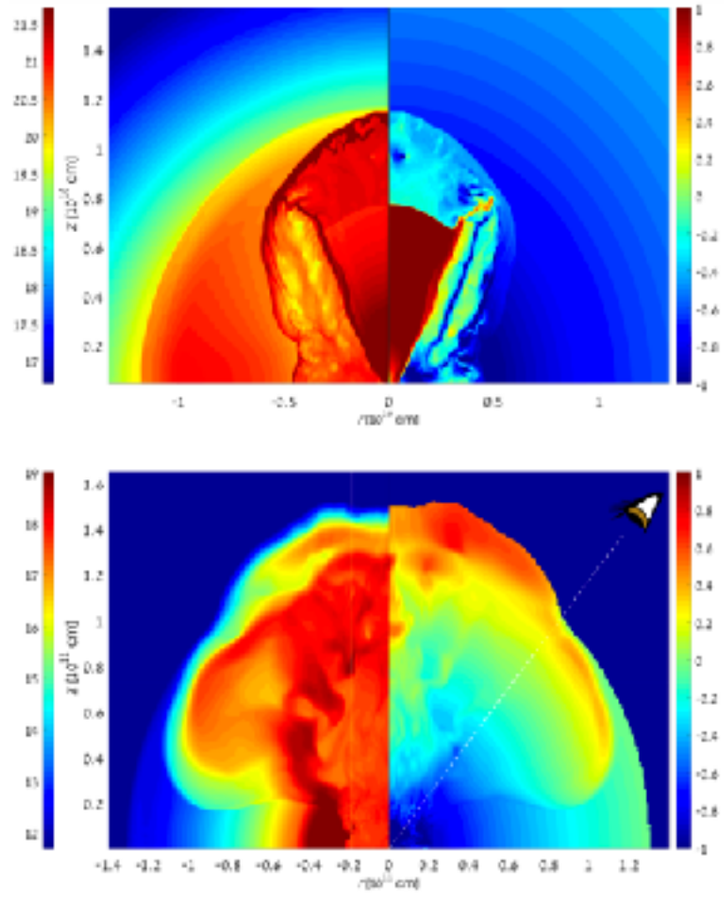
Canonical SGRB or choked jet?



Lazzati+2018

ordinary SGRB event observed off-axis

➡ viable explanation!



Gottlieb+2017

unsuccessful jet
no canonical SGRB

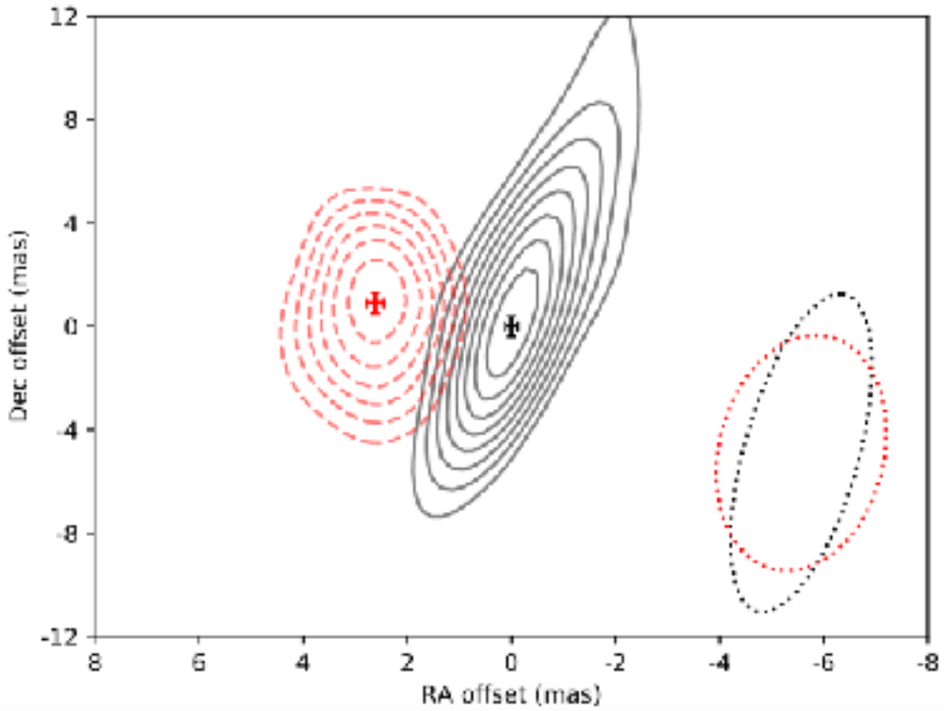
➡ also viable

VLBI observations

global network of 32 radio telescopes

see also talk by Giancarlo Ghirlanda

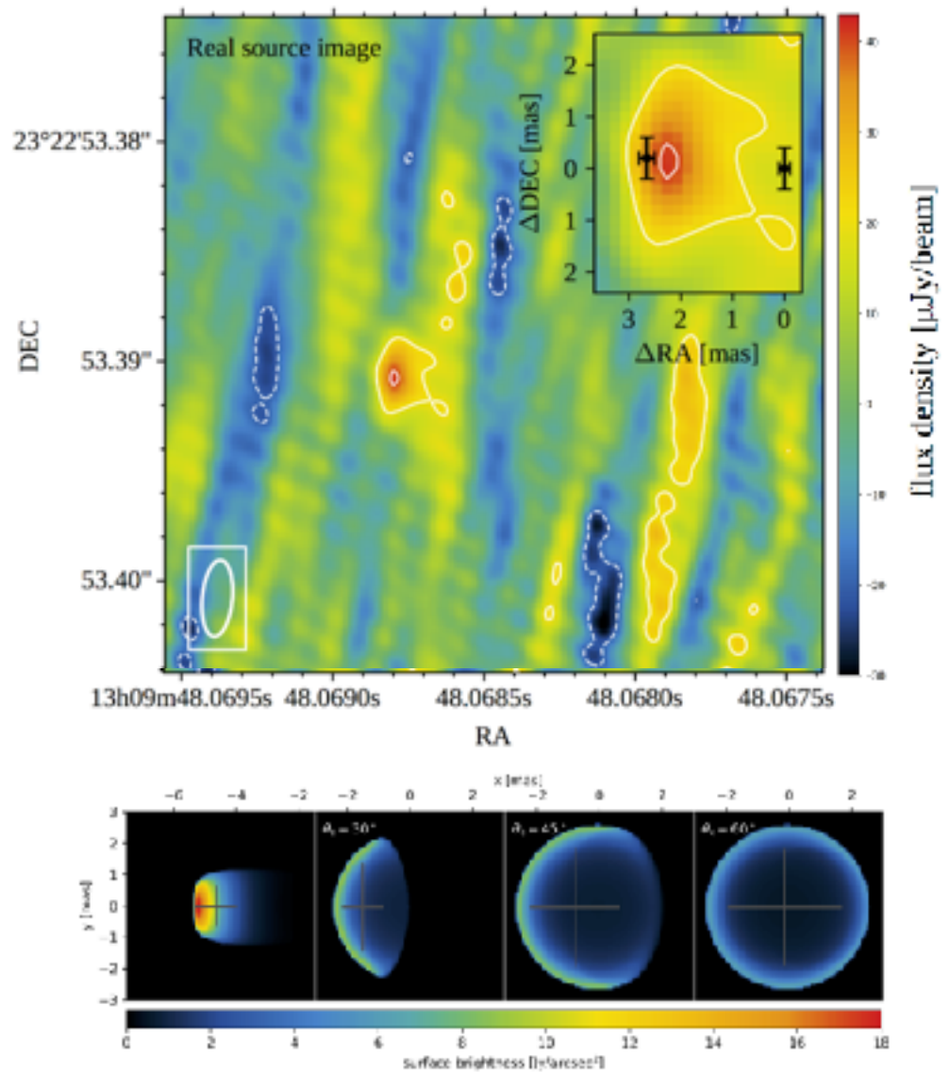
Mooley+2018



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

global network of 32 radio telescopes

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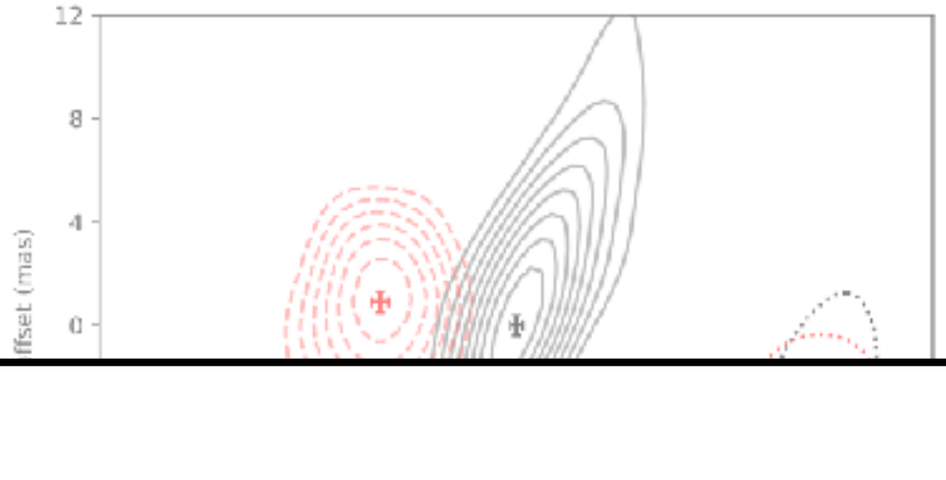
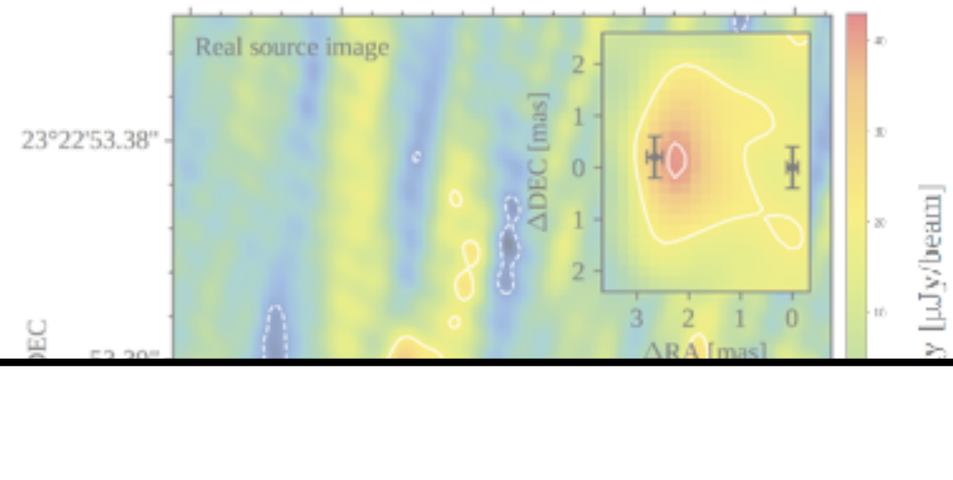
Mooley+2018



Ghirlanda+2018

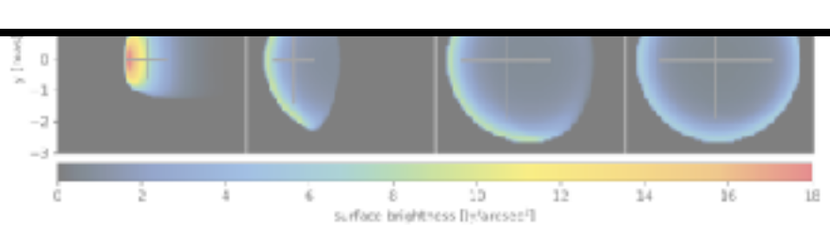


collimated jet (<5 deg), seen ~15-30 deg off-axis

nearly isotropic, mildly relativistic outflow excluded

between 75 and 230 days

source is moving relativistically (and getting closer)



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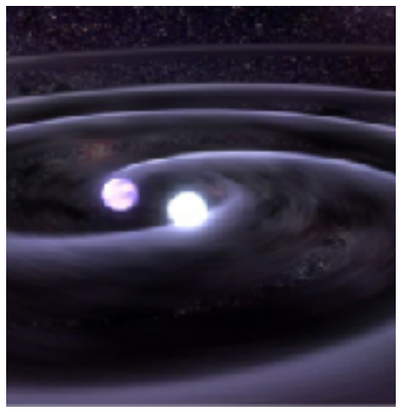
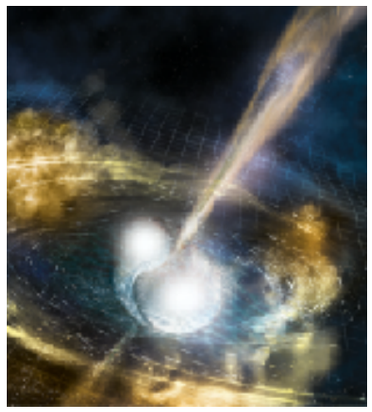
SGRB jets from BNS mergers



GW170817

+



GRB 170817A

??

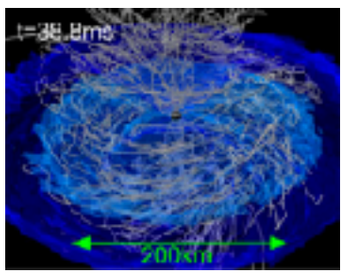
jet launching mechanism?

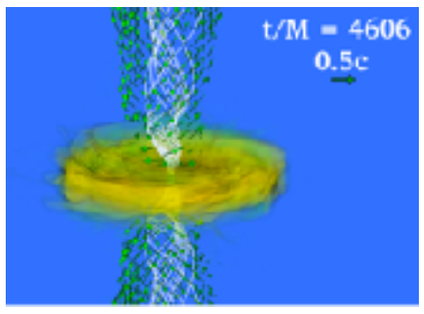
neutrino driven ✗

MHD driven ✓

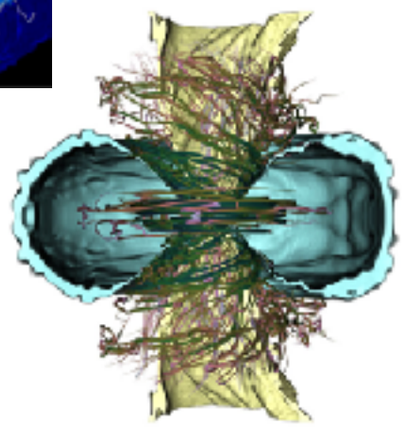
⟶ need GRMHD simulations

Kiuchi+2014





Ruiz+2016



Kawamura+2016

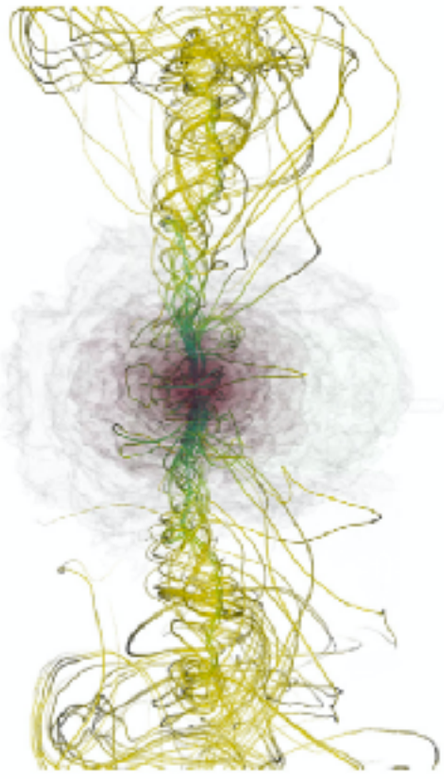
BH + accretion disk

(Blandford-Znajek)

remnant/central engine nature?

Ciolfi+2017

Ciolfi+2019

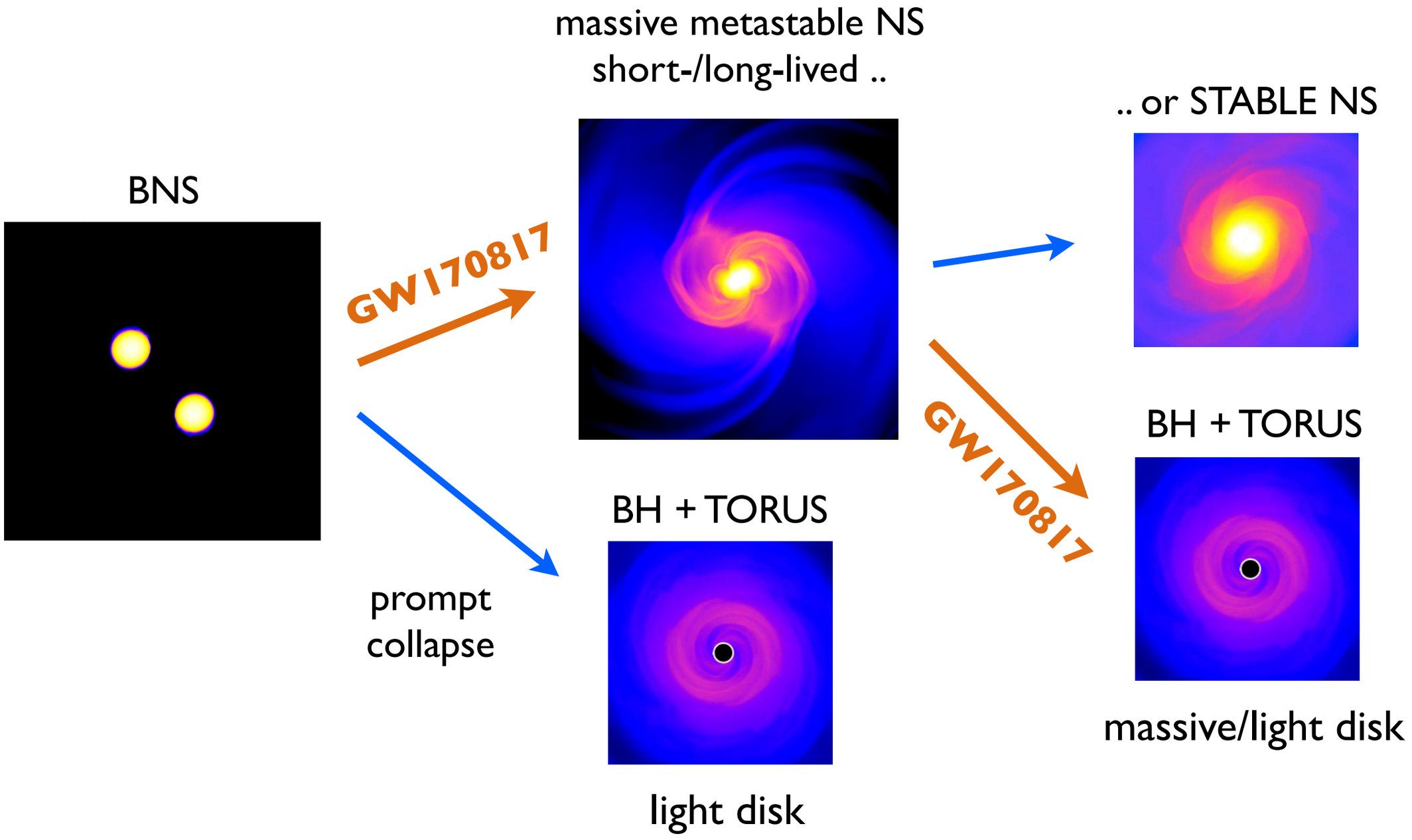


Ciolfi 2020a

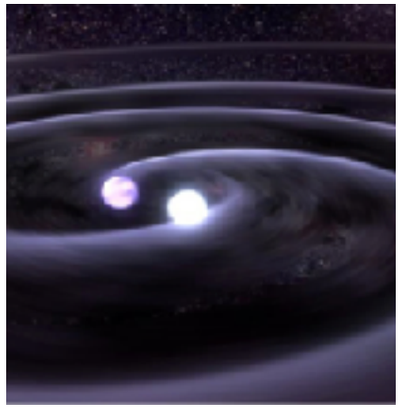
massive long-lived NS

(magnetorotational)

Product of BNS mergers

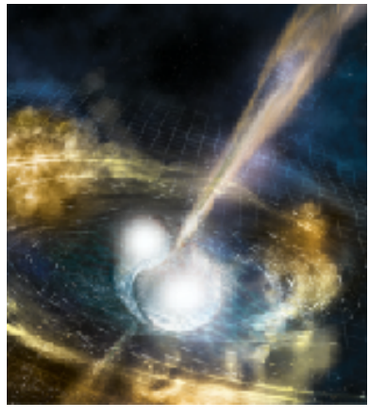


SGRB jets from BNS mergers



GW170817

+



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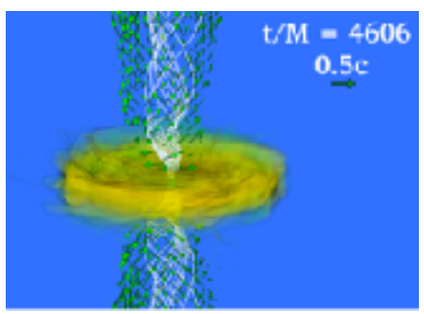

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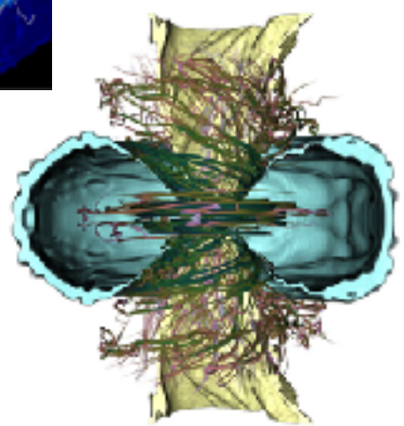

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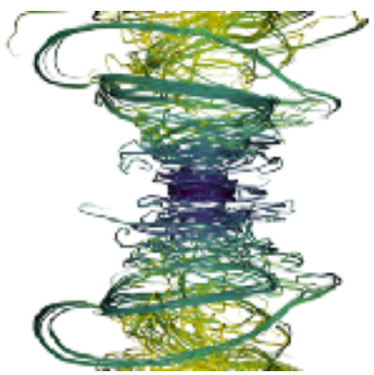
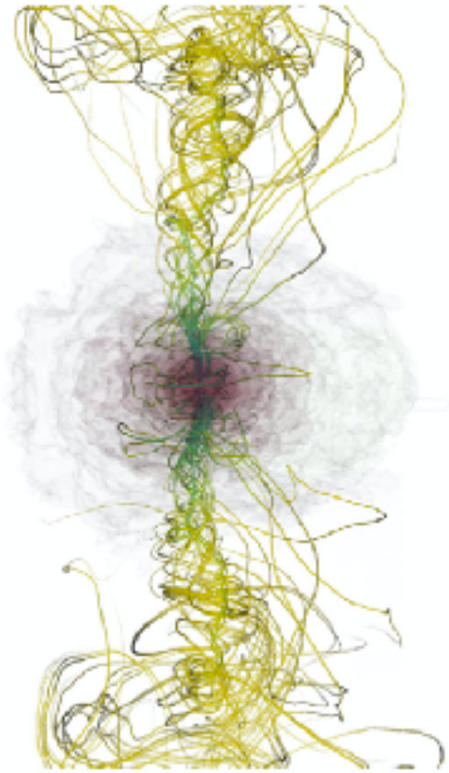


Ciolfi+2019



Ciolfi 2020a

massive long-lived NS

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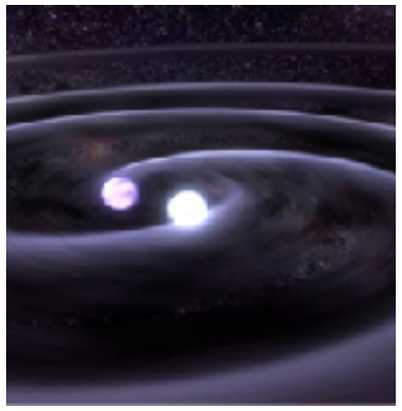
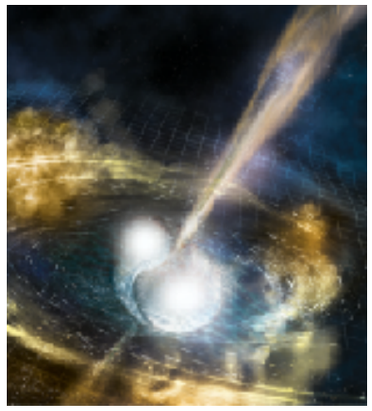


GW170817

+



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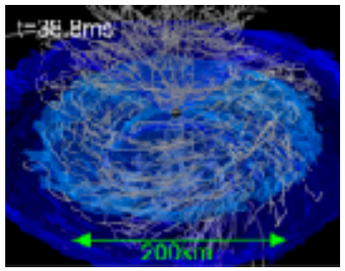

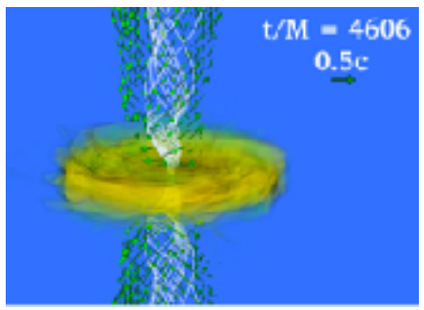

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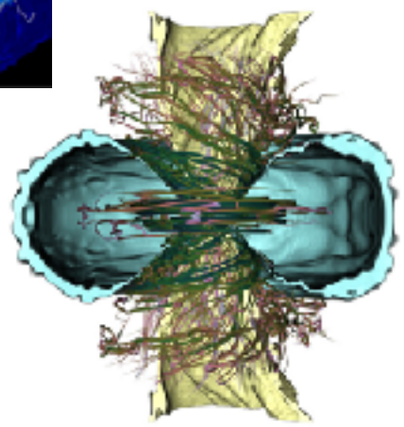

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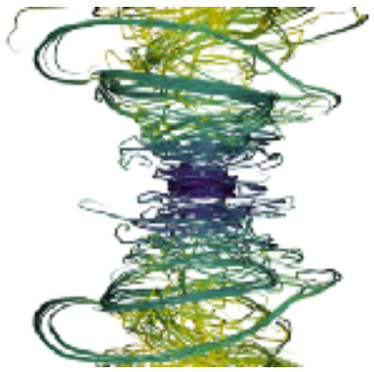
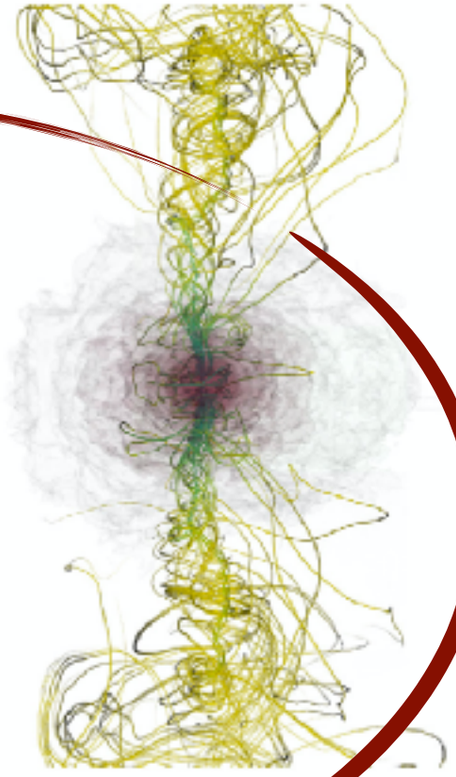


Ciolfi+2019



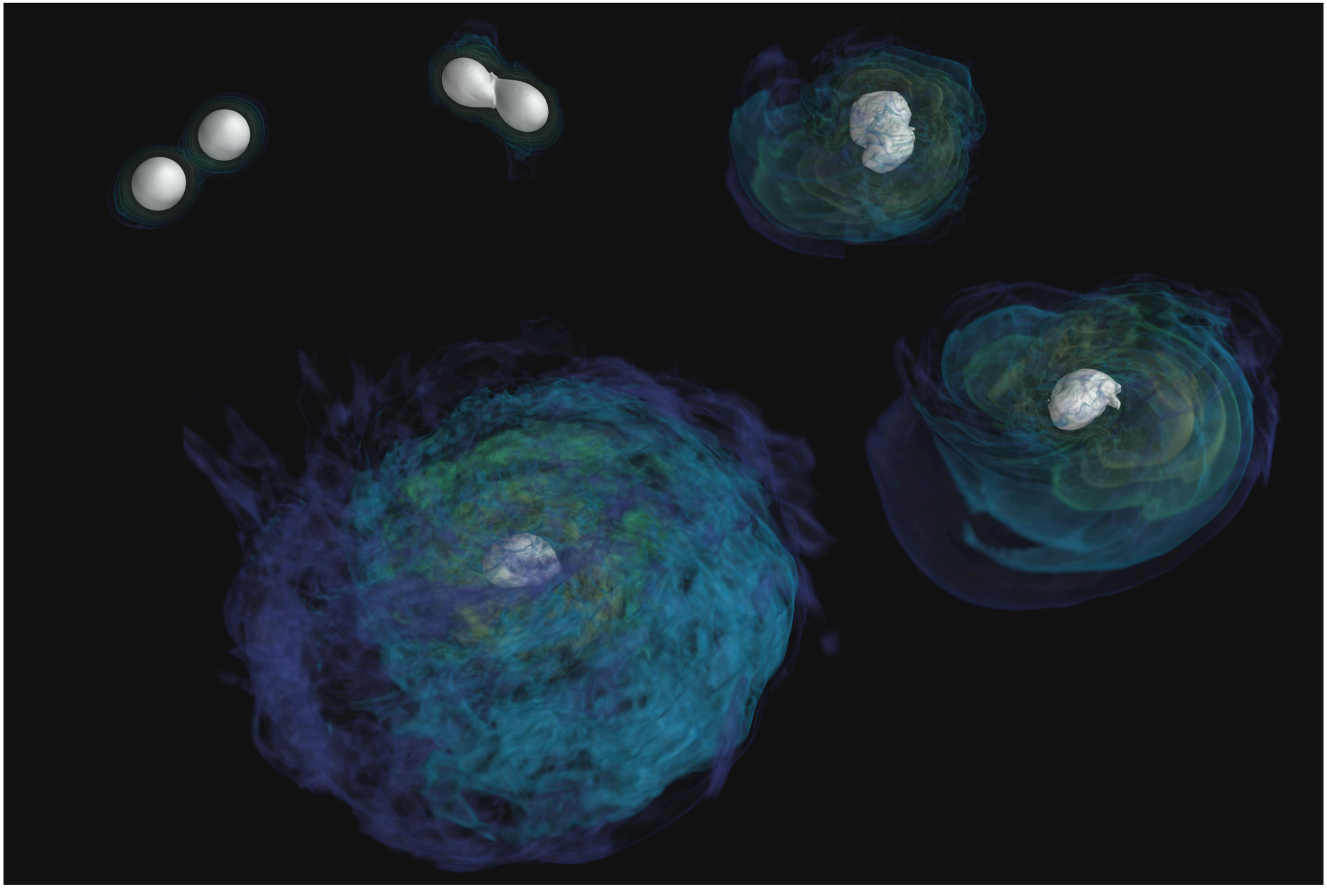
Ciolfi 2020a

massive long-lived NS

(magnetorotational)

BNS merger simulations

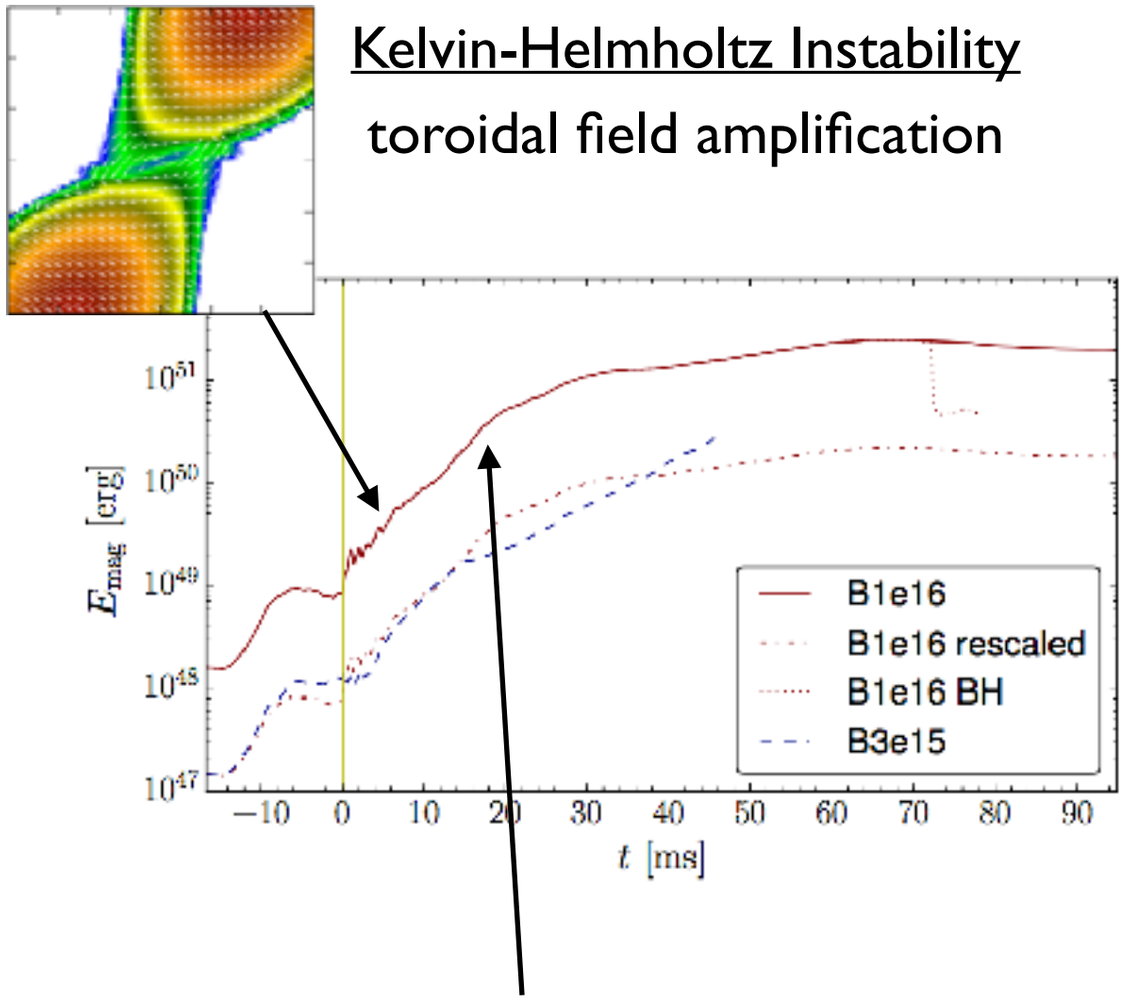
Ciolfi+2017



Magnetic field amplification and geometry

Ciolfi+2019: 100 ms of post-merger evolution

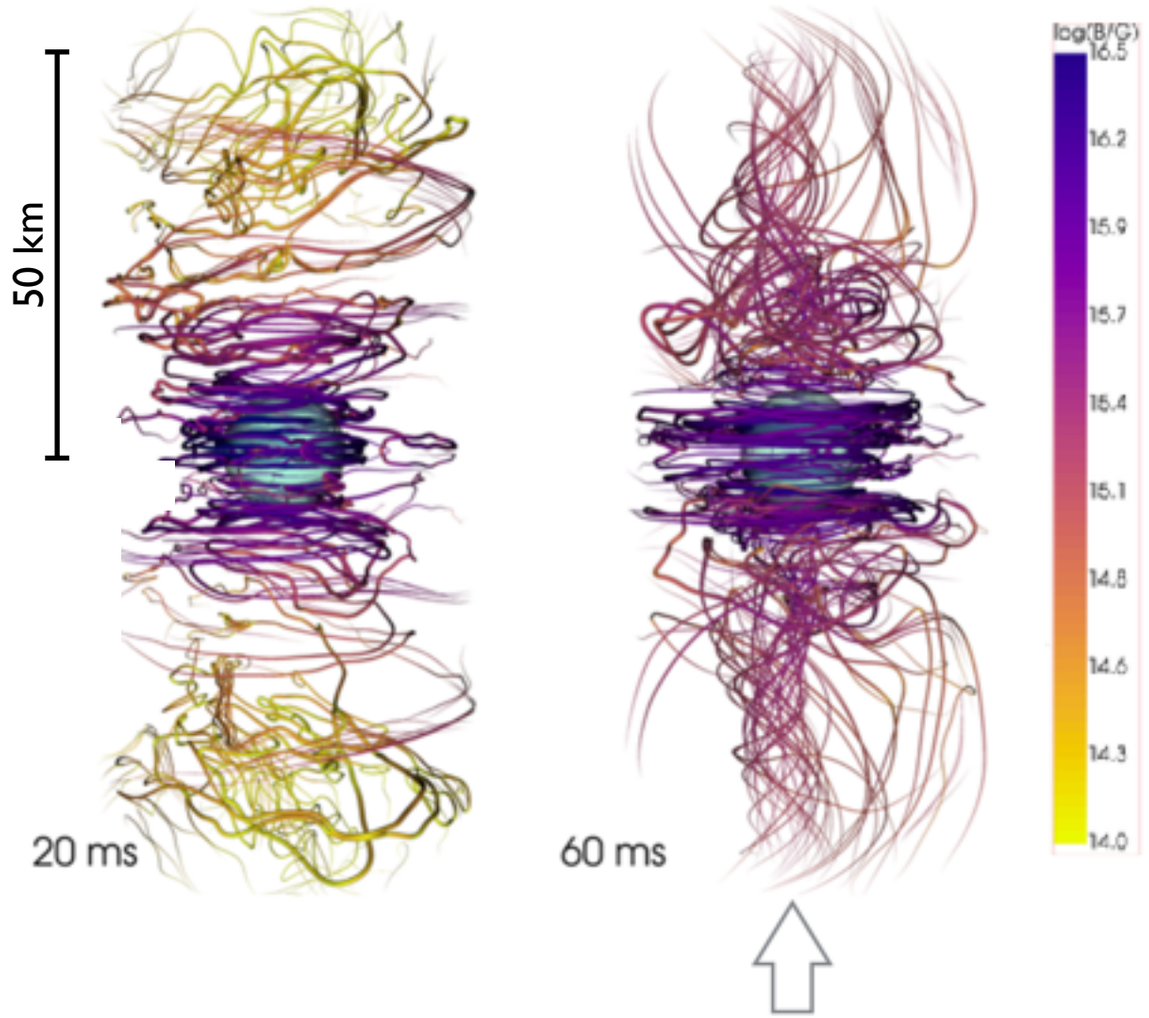
Kiuchi+2015



Kelvin-Helmholtz Instability

toroidal field amplification

MagnetoRotational Instability



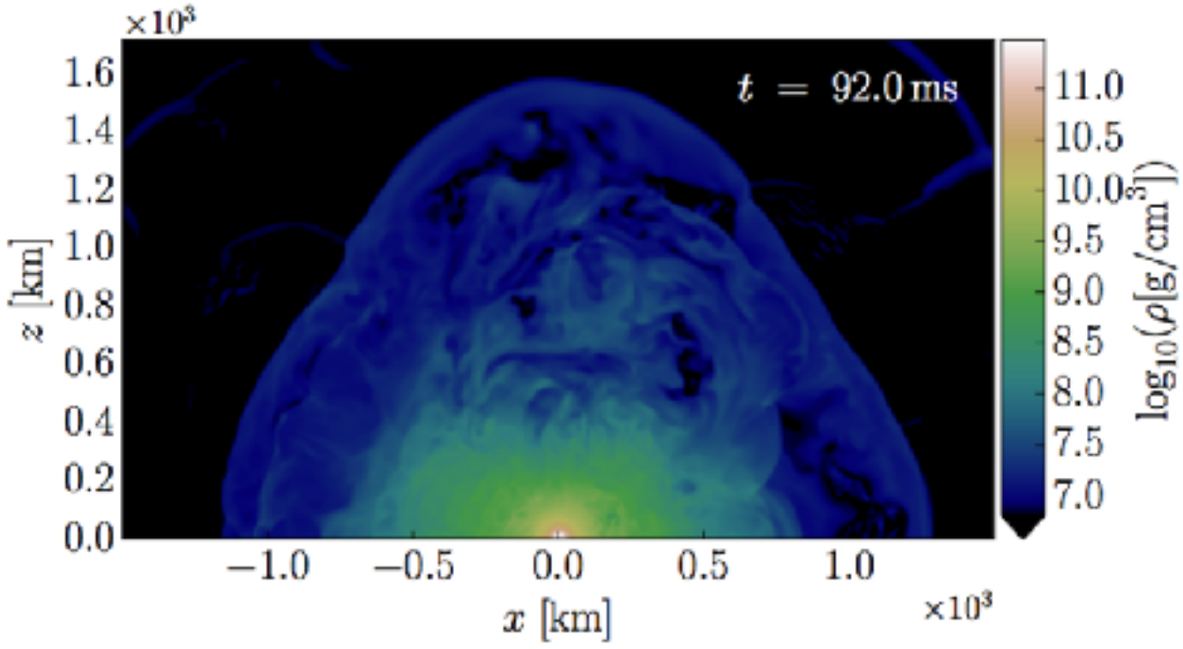
helical structure

Magnetically driven wind

Ciolfi+2019

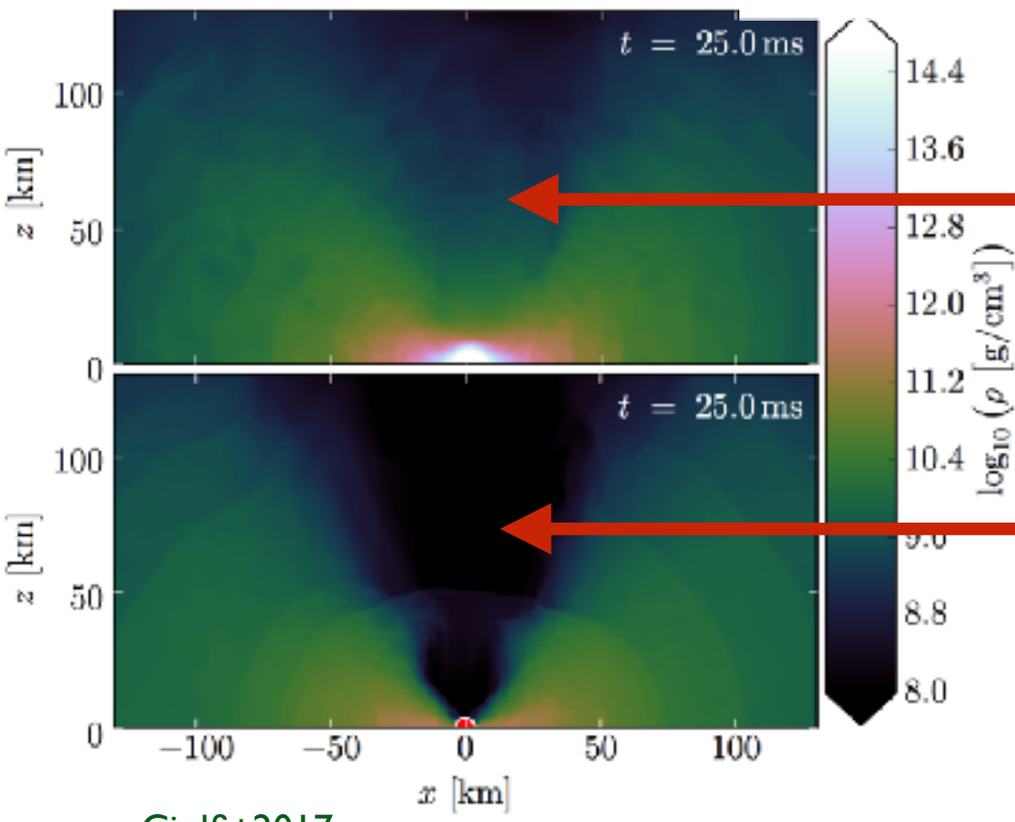
@50-100 ms after merger

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



massive NS remnant

BH remnant



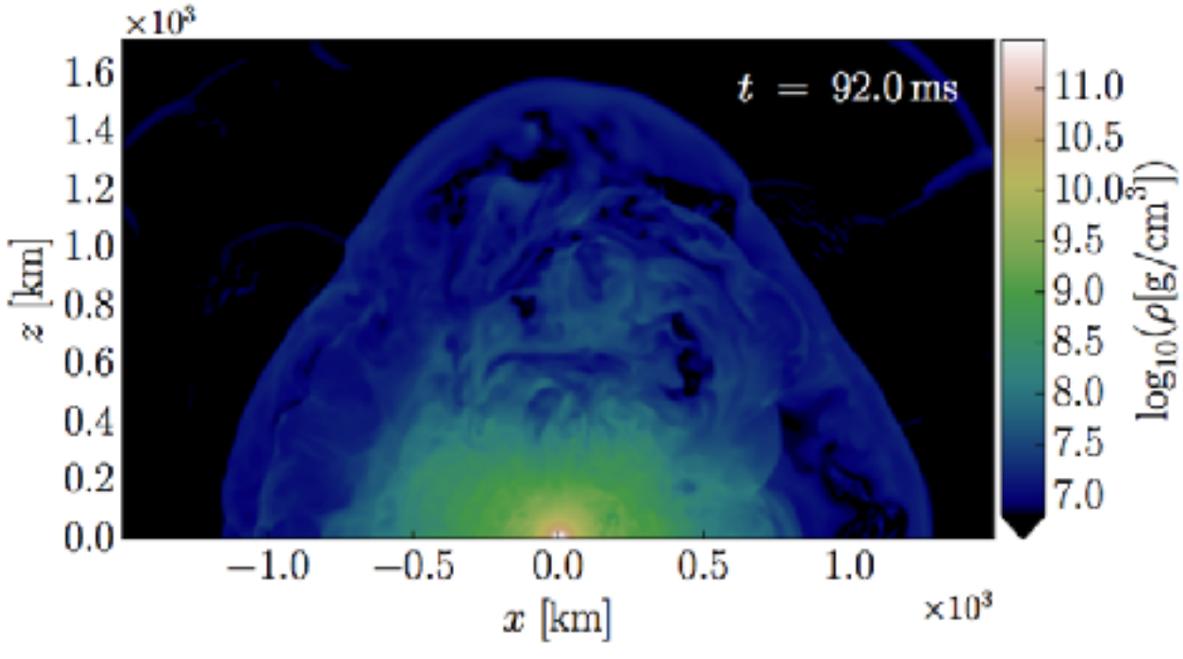
obstacle for jet formation

favourable environment

Ciolfi+2017

Magnetically driven wind

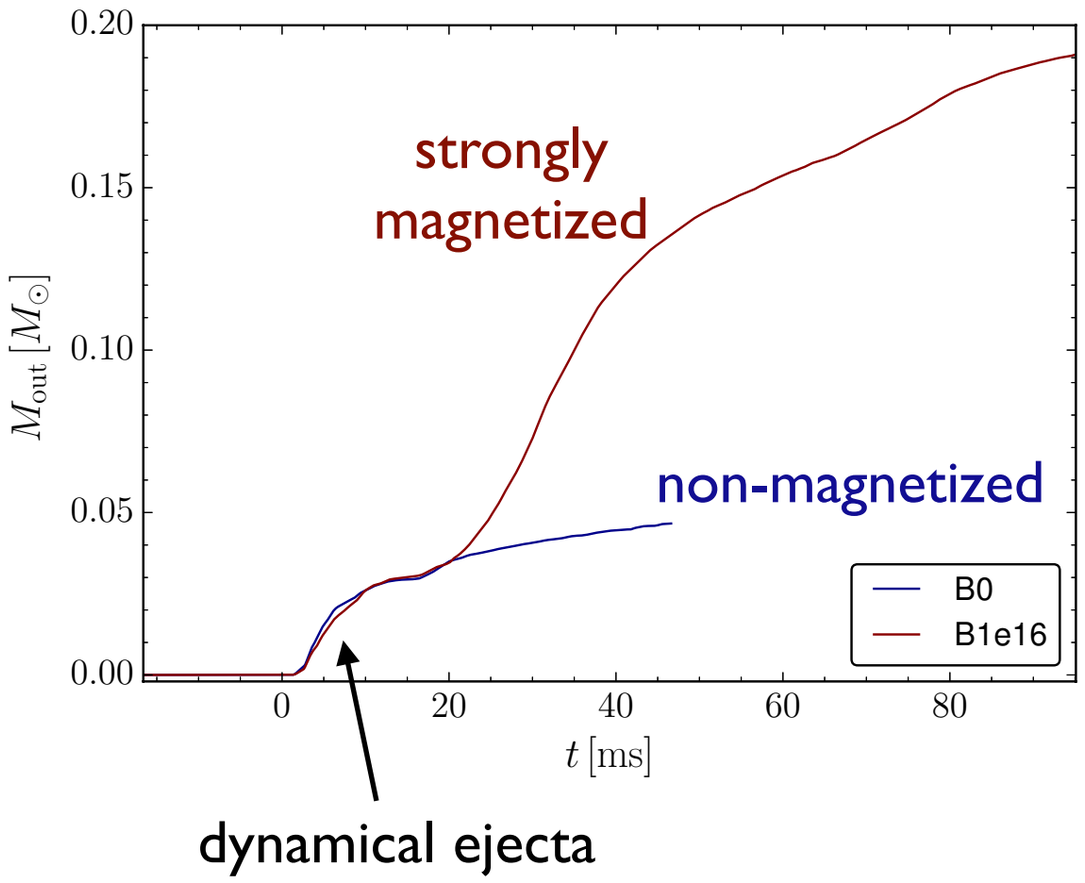
Ciolfi+2019



@50-100 ms after merger

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

cumulative mass flow across 150 km radius



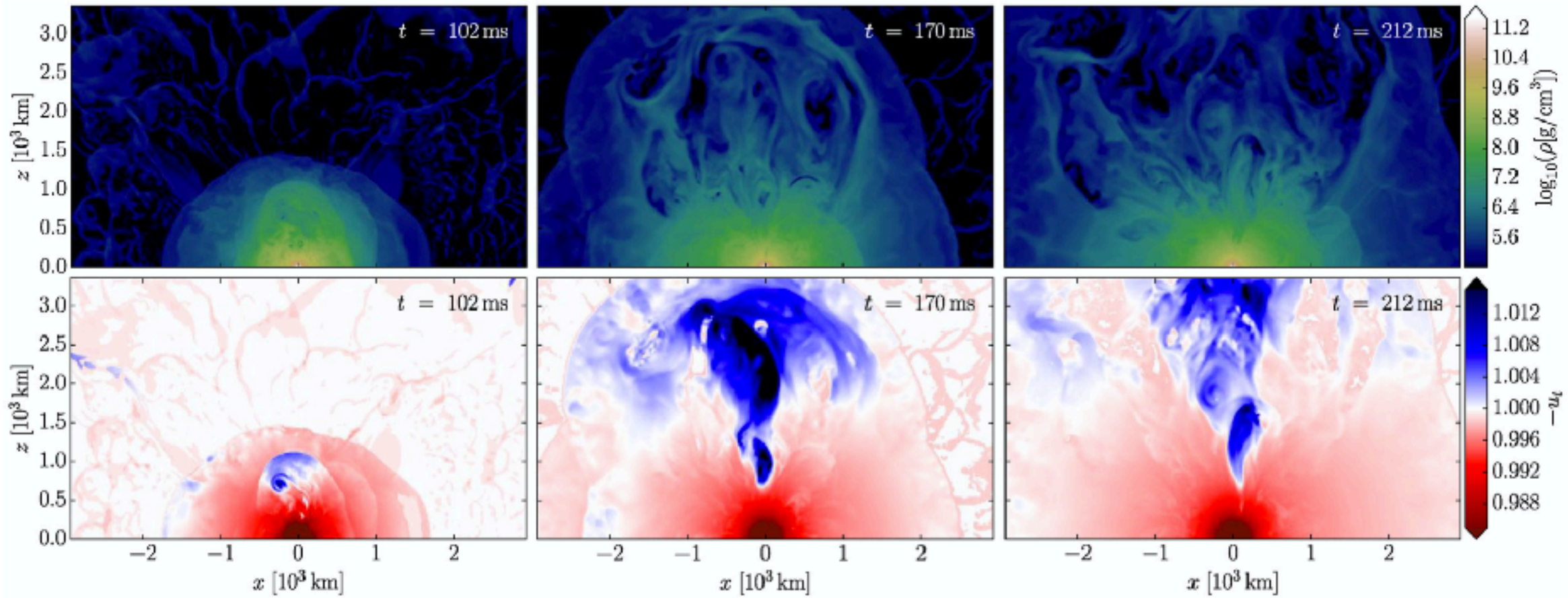
magnetized remnant NS

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

BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with properties (e.g. NS masses) consistent with GW170817
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to ~250 ms after merger



massive NS remnant can produce a collimated outflow!

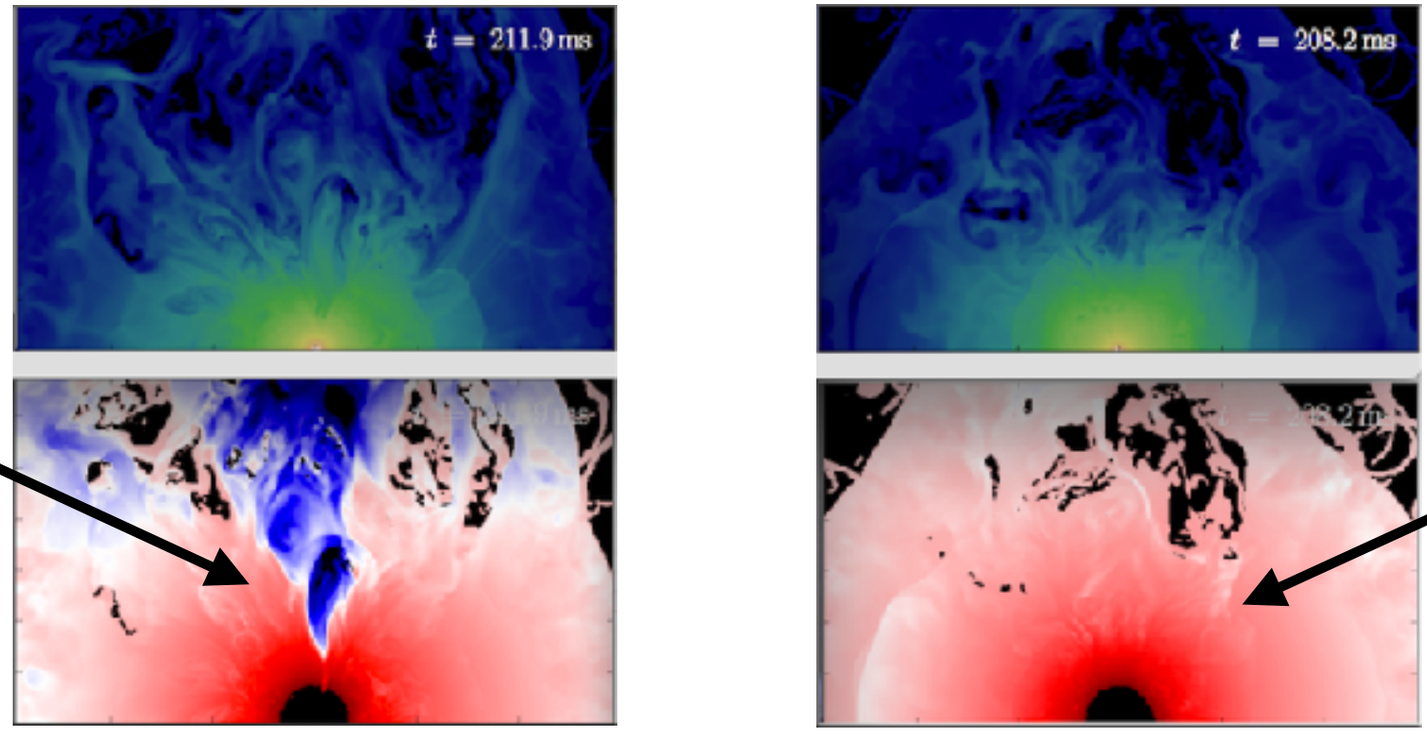
BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with properties (e.g. NS masses) consistent with GW170817
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to ~250 ms after merger

higher initial magnetization

lower initial magnetization



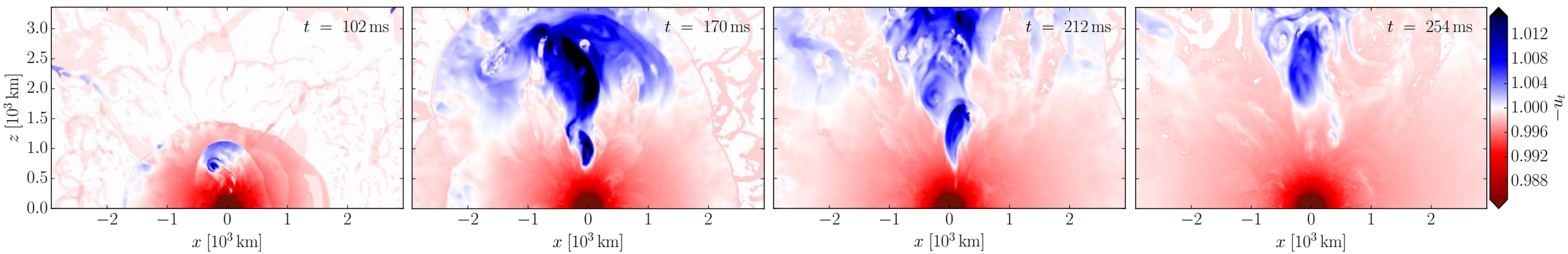
collimated outflow

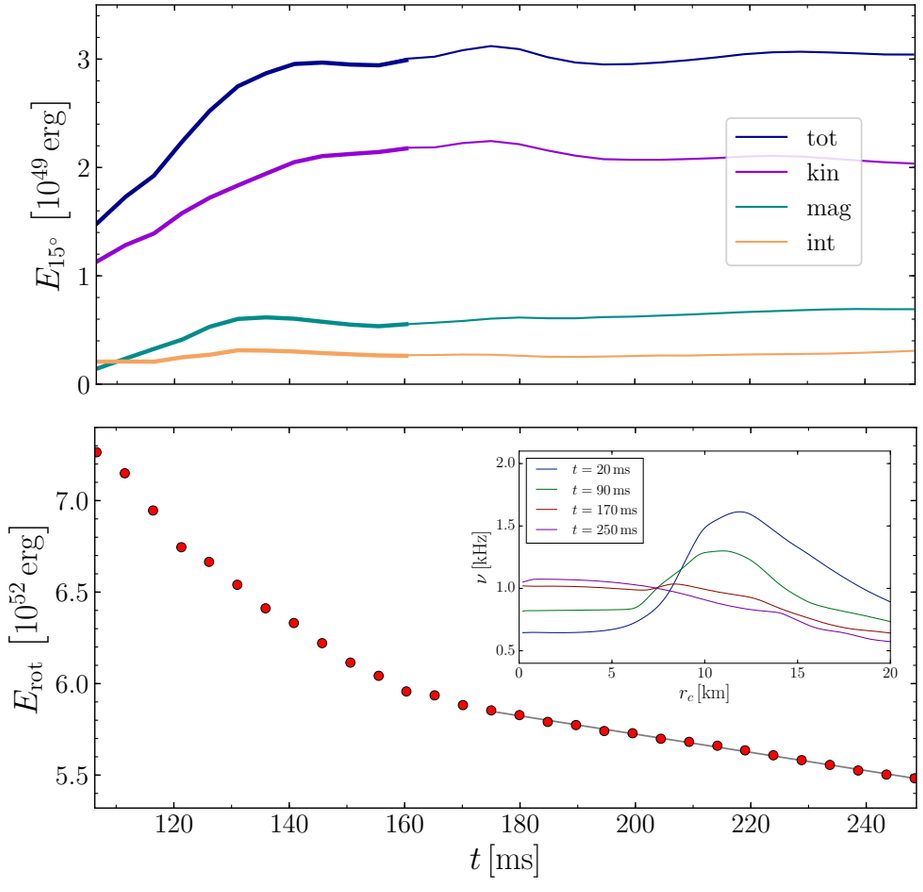
NO collimated outflow

..but not ubiquitous

Origin and properties of the collimated outflow

Ciolfi 2020a





outflow energy saturation

~160 ms after merger

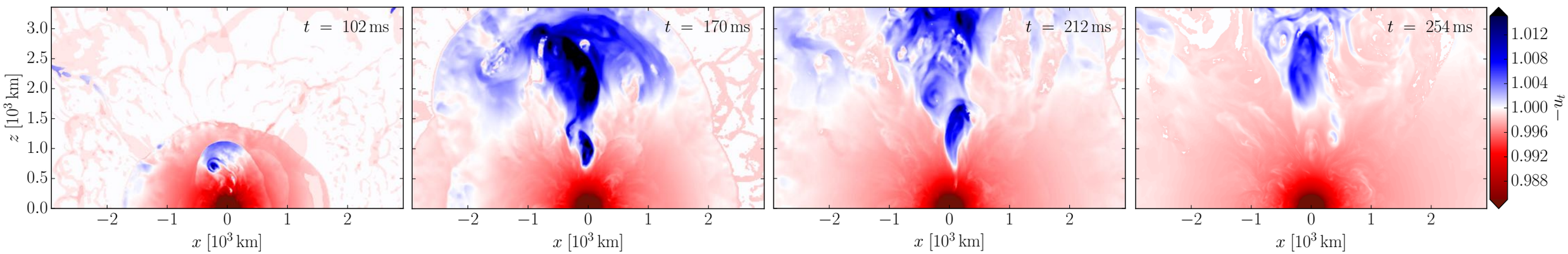
change in rotational energy evolution

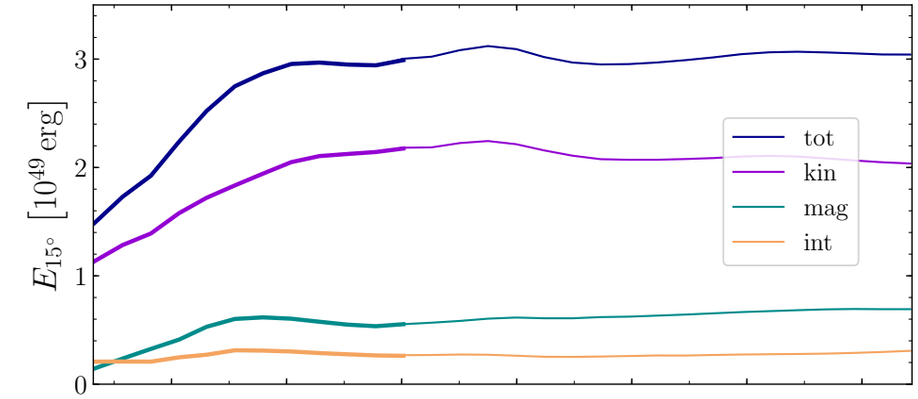
differential rotation in the NS core is over

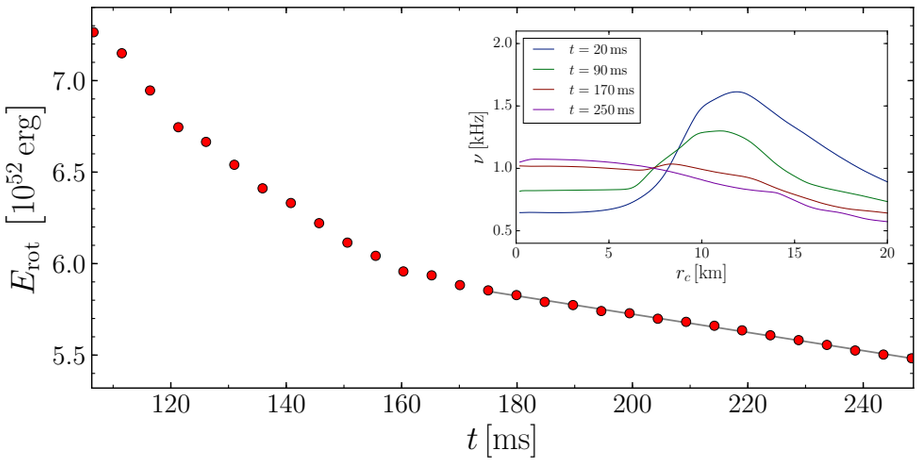
NS differential rotation = energy reservoir

Origin and properties of the collimated outflow

Ciolfi 2020a







magnetorotational launching mechanism

magnetic field amplification

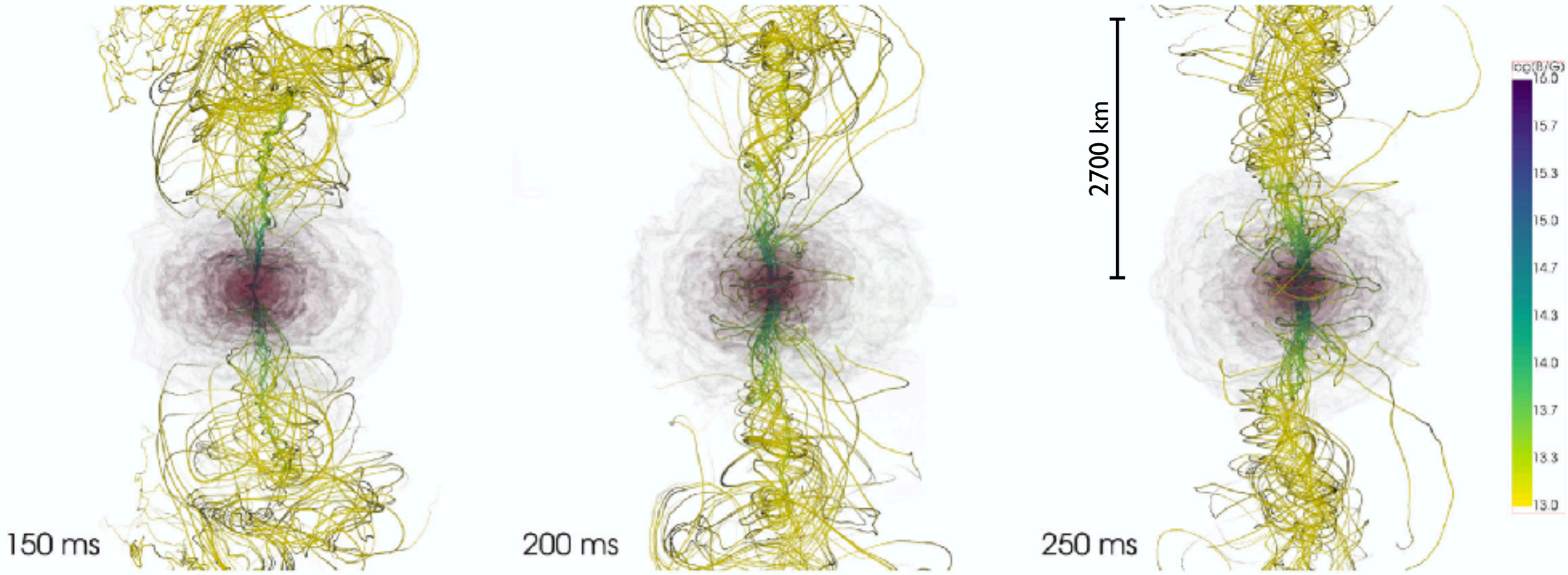
build up of magnetic pressure radial gradient

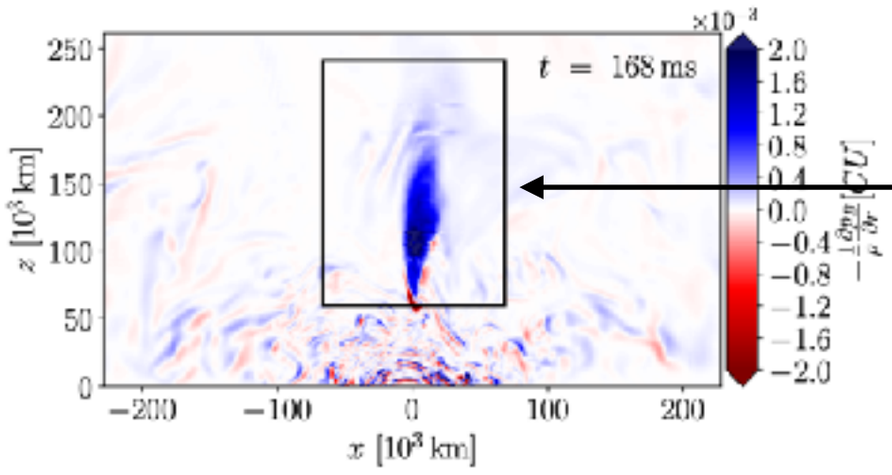
acceleration along the rotation axis

NS differential rotation

Emerging helical magnetic field

Ciolfi 2020a





magnetic push
(radial gradient of magnetic pressure)

Can this collimated outflow evolve into a SGRB jet?

<u>compared to GRB 170817A jet parameters:</u>

- 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 strongly disfavoured

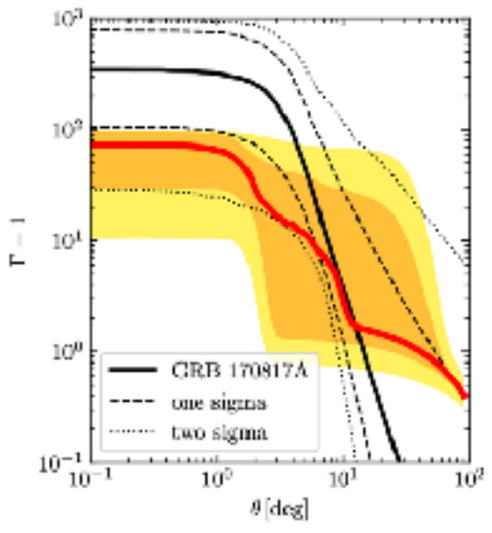
Connecting with EM observations

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

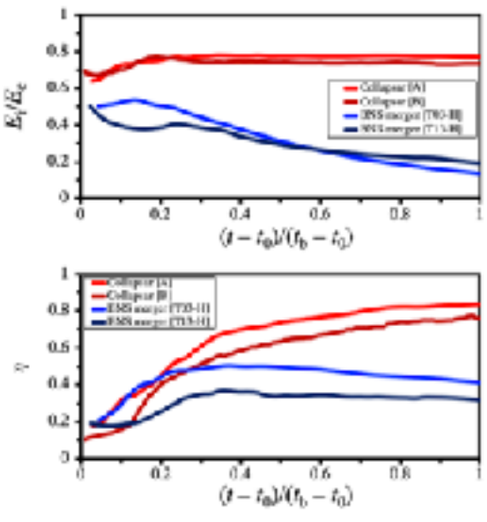
need for models of jet propagation across the environment up to large scales

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

semi-analytical

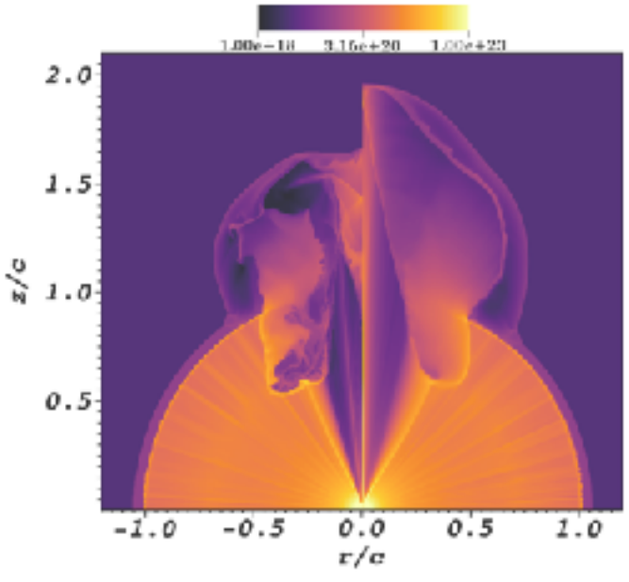


Salafia et al. 2020



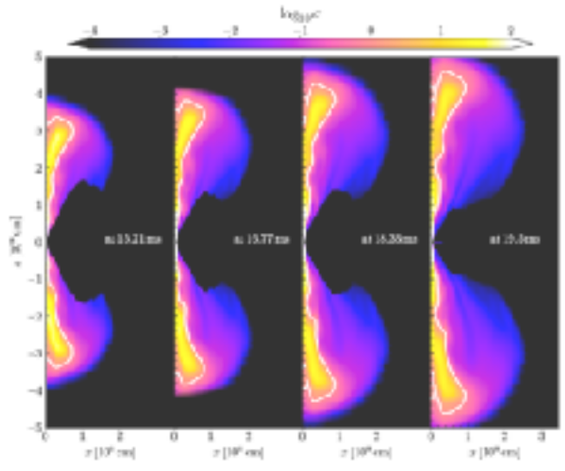
Hamidani & Ioka 2020

2D HD



Urrutia et al. 2020

3D MHD



Nathanail et al. 2020

GRB 170817A: intrinsic jet properties

Lazzati, Ciolfi, Perna 2020

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

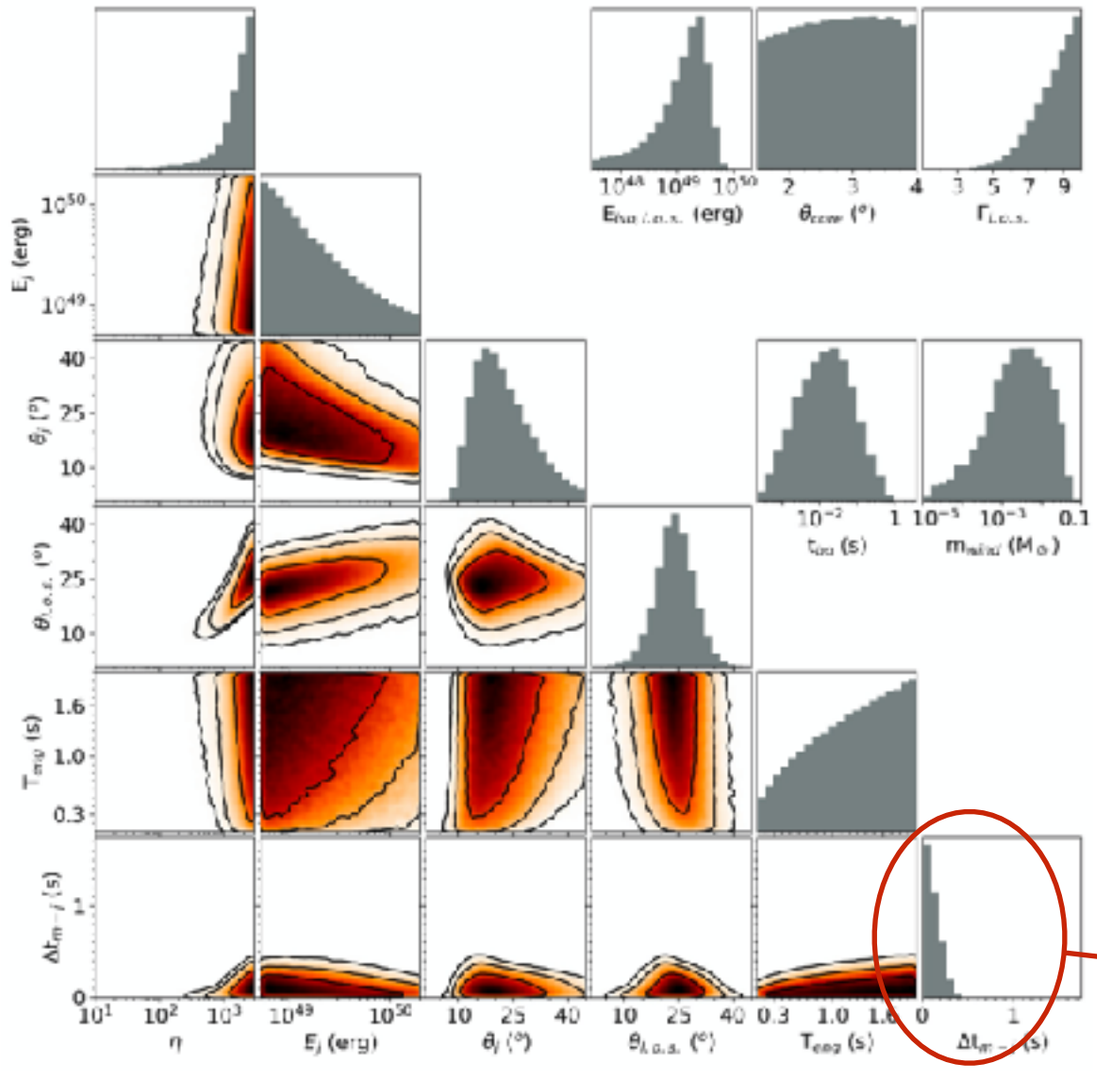
- jet energy and duration
- terminal Lorentz factor
- initial opening angle
- jet launching time

- wind mass

(simulation-inspired environment depending on launching time)

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

(line of sight)



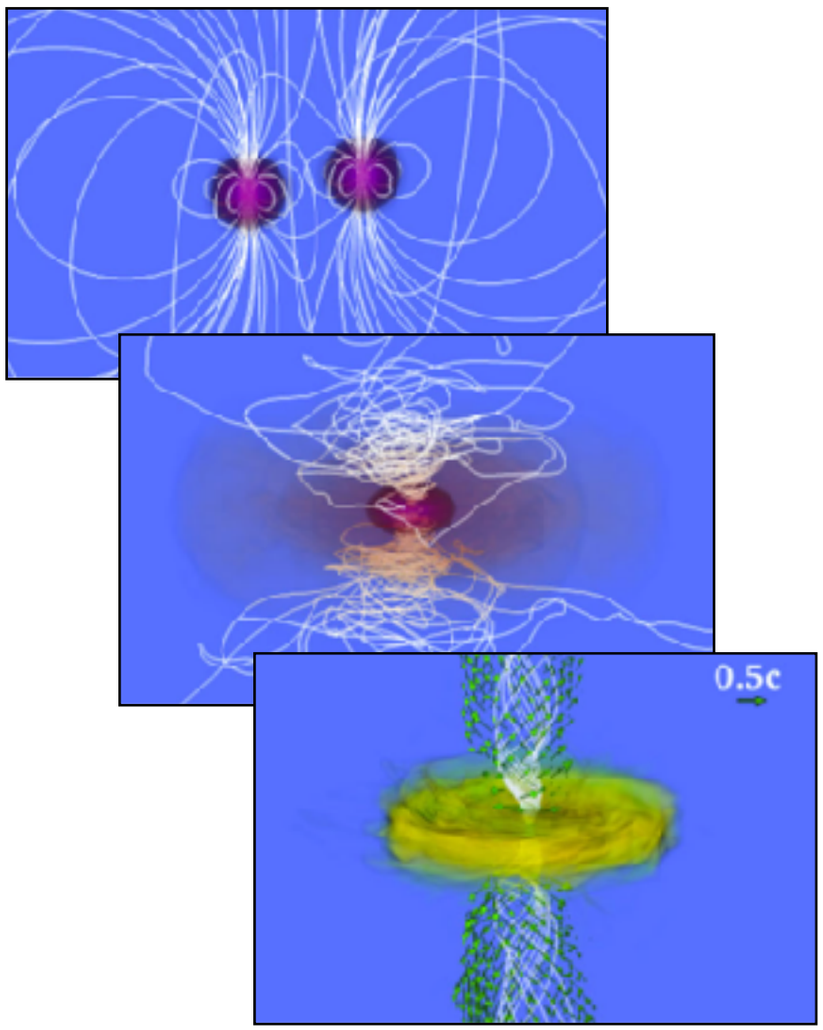
- **input** parameters
- **output** parameters (constrained by observations)

Model	Δt_{m-j} (s)	η_j	$\theta_{l.o.s}$ (°)	θ_j (°)
Simulations; baseline ($Y_e = 0.5$; $\Gamma_{l.o.s.} \leq 10$; m_w unconstrained)	**< 0.36**	**> 240**	$\mathbf{23.5^{+5.5}_{-4.5}}$	$\mathbf{17.9^{+12.6}_{-3.2}}$
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	$23.6^{+4.8}_{-3.5}$	$17.3^{+13.4}_{-2.5}$
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	$22.0^{+9.9}3.3$	$18.1^{+13.4}_{-3.1}$
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**	$\mathbf{30.3^{+8.5}_{-8.0}}$	$\mathbf{10.2^{+8.8}_{-3.0}}$
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	$30.5^{+8.3}_{-8.8}$	$10.8^{+8.6}_{-1.6}$

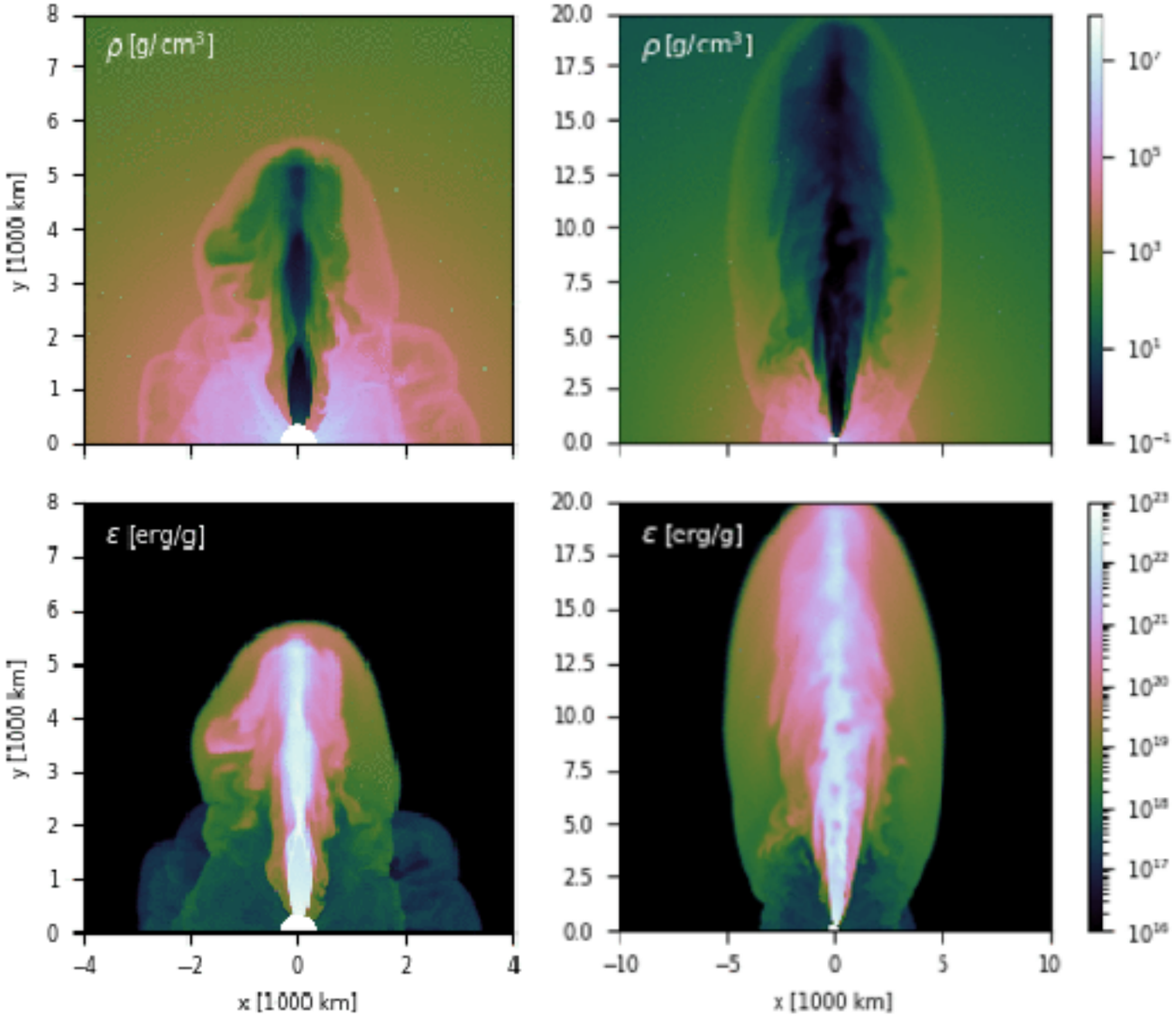
jet launching time < 0.4 s

Towards the full picture..

NEXT CHALLENGE: putting together BNS mergers and jet propagation simulations



Ruiz et al. 2016



Pavan et al., in preparation

..stay tuned!

Take-home message

- BNS merger can produce short GRBs!

- Open questions: How is the jet launched?
  Is the central engine a massive NS or an accreting BH?

- leading investigation tool: GRMHD simulations of the merger process
  → current results favour the BH scenario, but this conclusion is not final

- modelling the propagation of incipient jets across the environment at large scales is necessary to connect with EM observation, but current studies are not directly linked to the merger process

- Next challenge: putting things together

References

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

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

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

- D. Lazzati, R. Perna, B. J. Morsony, D. López-Cámara, M. Cantiello, **R. Ciolfi**, B. Giacomazzo, J. C. Workman (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

Recent Reviews

- **R. Ciolfi** (2020c), Frontiers in Astronomy and Space Sciences **7**, 27, Invited Review for the Article Collection "Gravitational Waves: A New Window to the Universe" (hosted by R. Perna and B. Giacomazzo)
Binary neutron star mergers after GW170817

- **R. Ciolfi** (2020b), General Relativity and Gravitation **52**, 59, Invited Review for the Topical Collection on “Binary neutron star mergers” (Guest Editor N. Stergioulas)
The key role of magnetic fields in binary neutron star mergers

- **R. Ciolfi** (2018), IJMPD **27**, No. 13, 1842004, Invited Review for the Special Issue “Gamma-Ray Bursts in the Multi-Messenger Era” (Guest Editor L. Nava)
Short gamma-ray burst central engines

BACKUP SLIDES

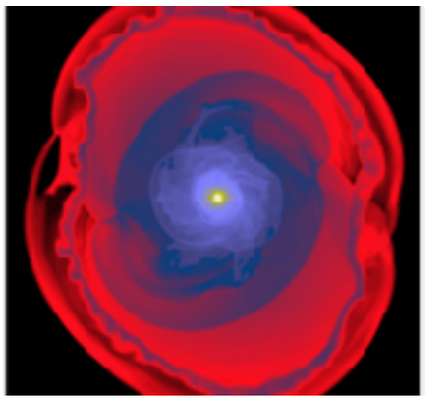
Results from Ciolfi 2020a

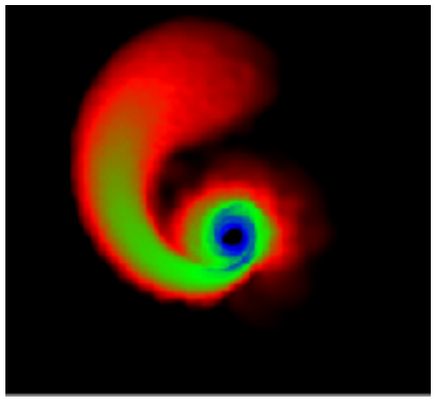
- GRMHD BNS merger simulations with up to >250 ms of massive NS remnant evolution
- collimated outflow form a massive NS obtained for the first time
- massive NS can launch a collimated outflow, but this outcome is not ubiquitous
- followed the full outflow development, studied the associated energetics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

→ accreting BH scenario is favoured

A radioactively-powered transient

ejecta in NSNS and NSBH mergers





r-process

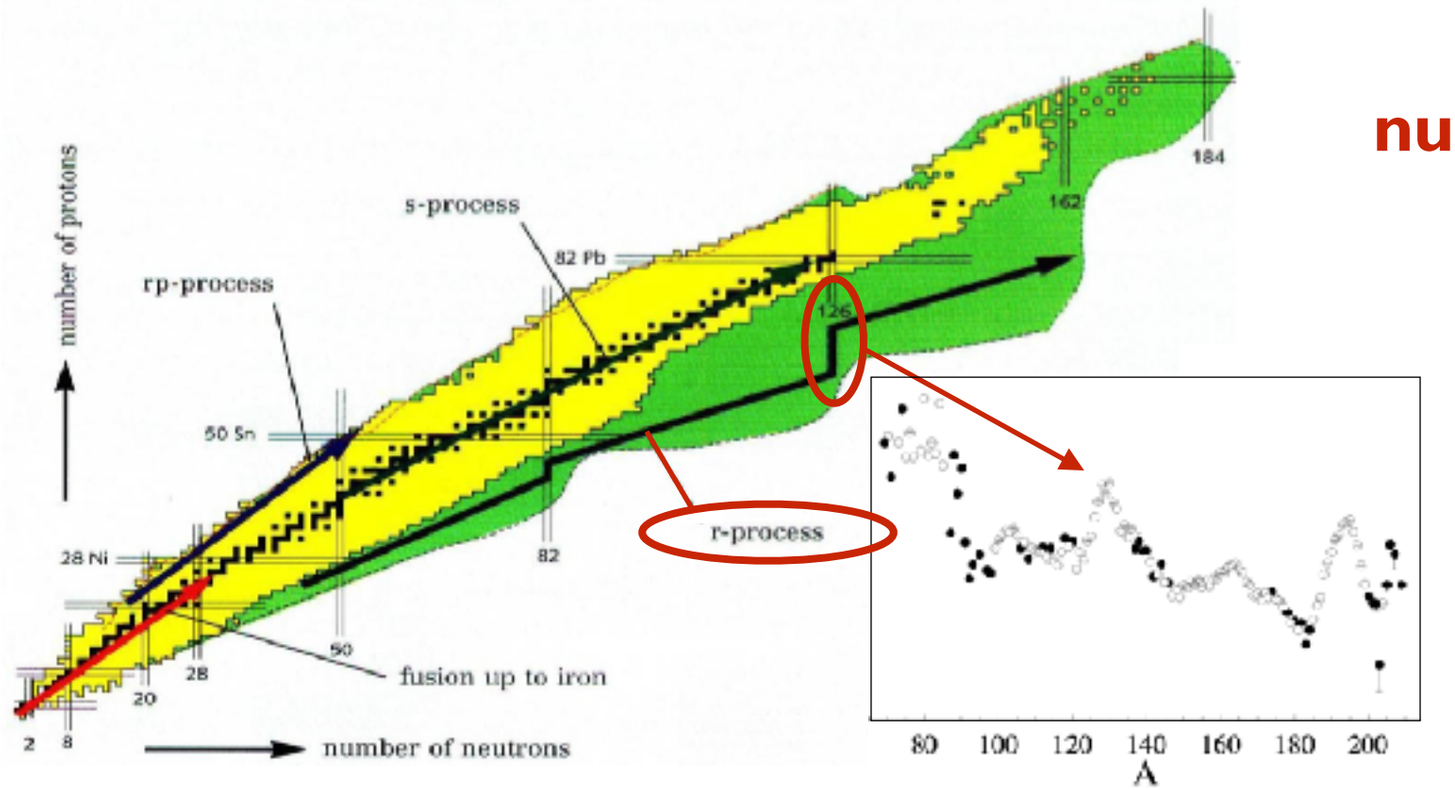
capture rate much faster than decay
more than one neutron capture at a time
requires very special conditions:

- High T ($T > 10^9$ K)
- High neutron density ($n_n > 10^{22}$ cm^{-3})

nucleosynthesis of heavy nuclei

radioactive decay on
timescales of >> sec

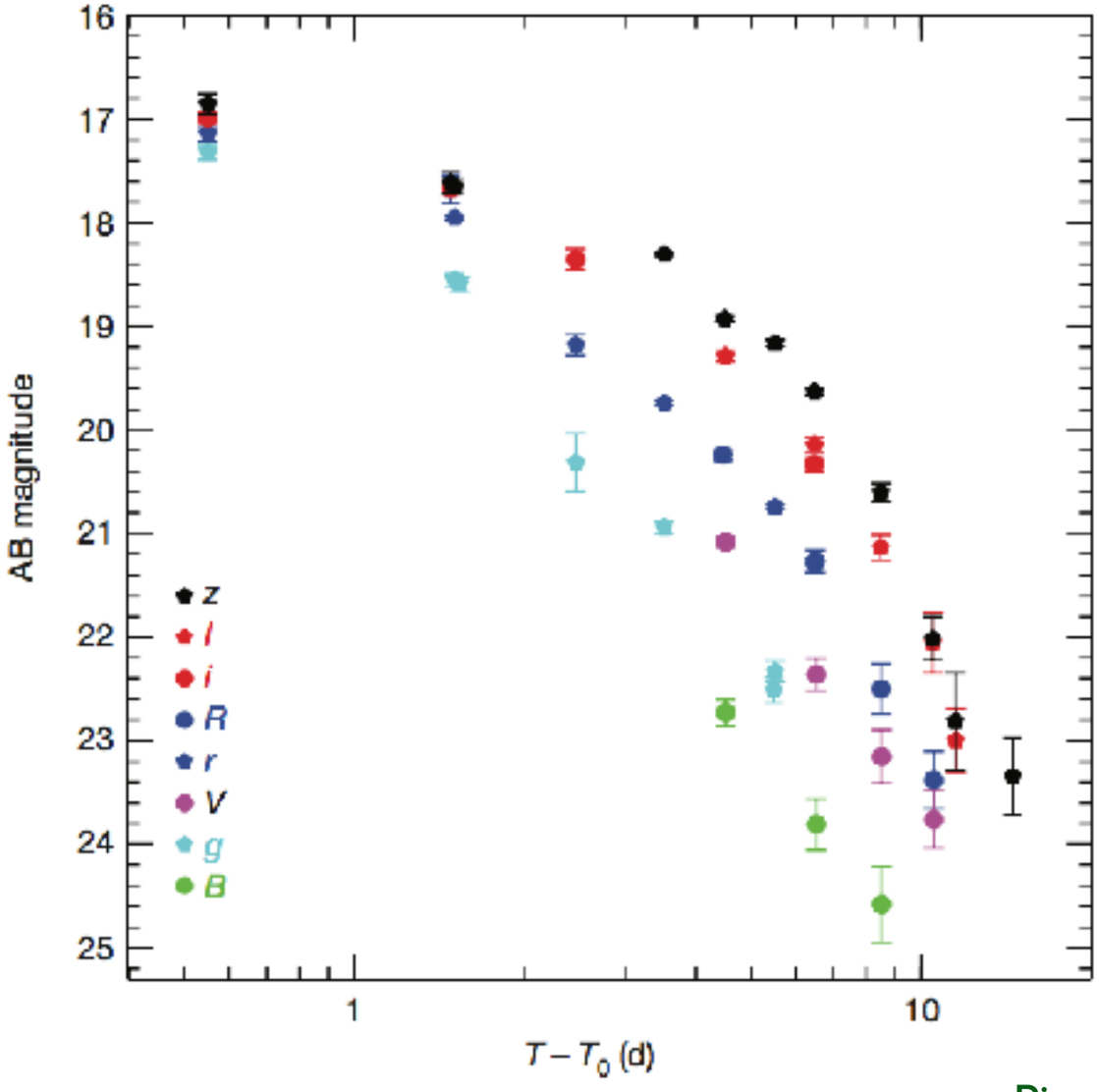
optical/IR signal
"kilonova"

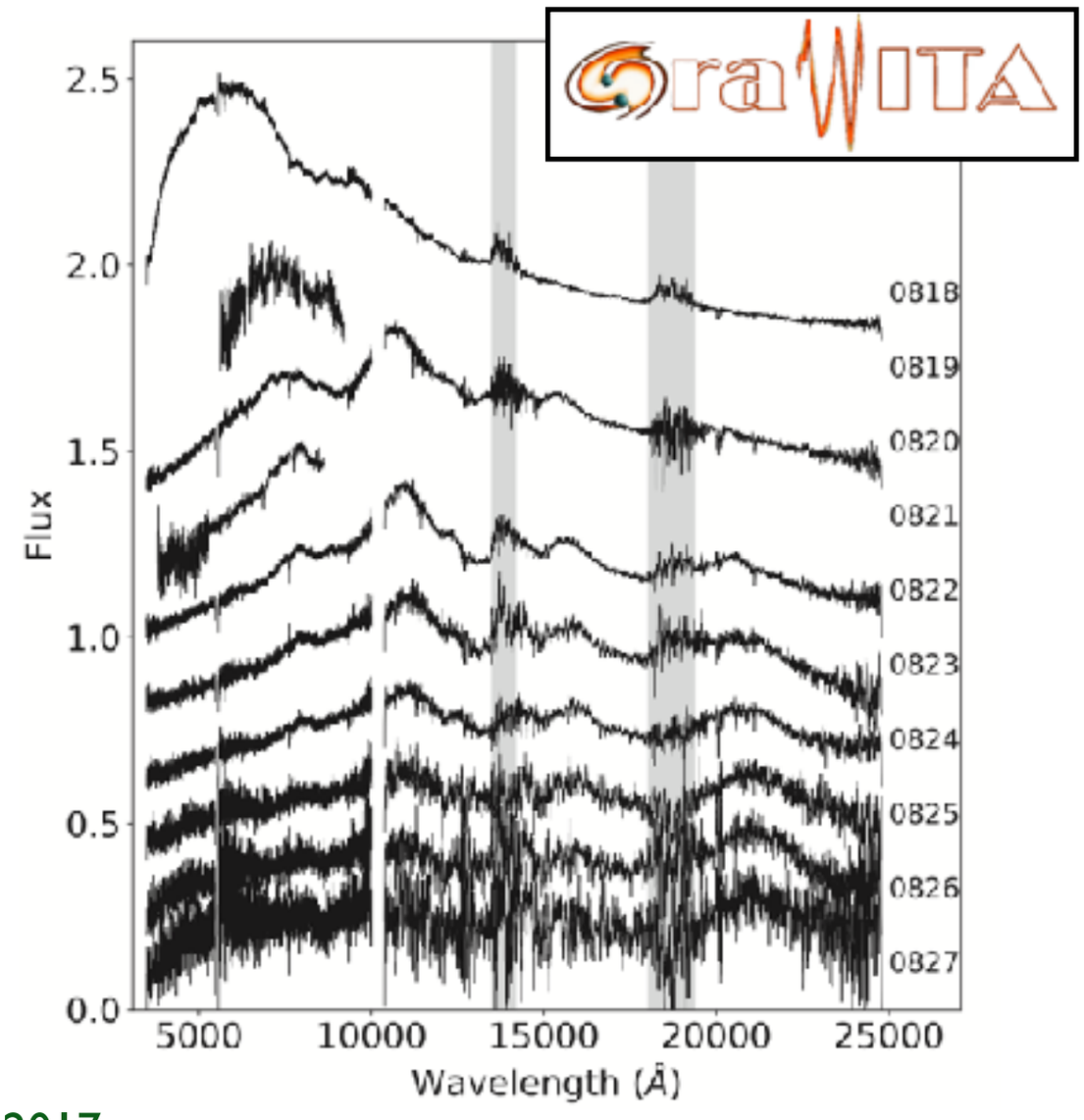


curtesy of A. Arcones

heavy element abundances

August 2017 kilonova (AT2017gfo)



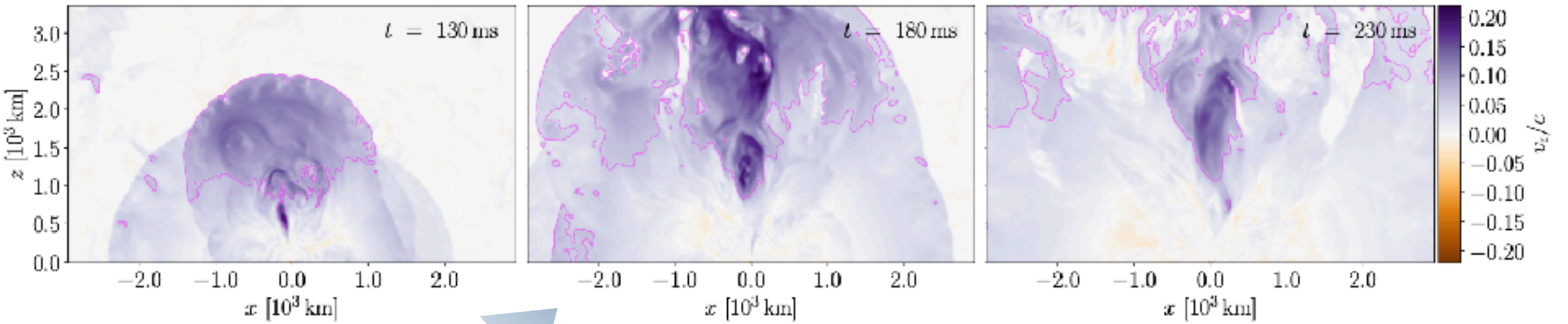


Pian et al. 2017

lightcurves and spectra consistent with a kilonova! ⇨ BNS mergers are confirmed as ideal site for r-process nucleosynthesis

Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

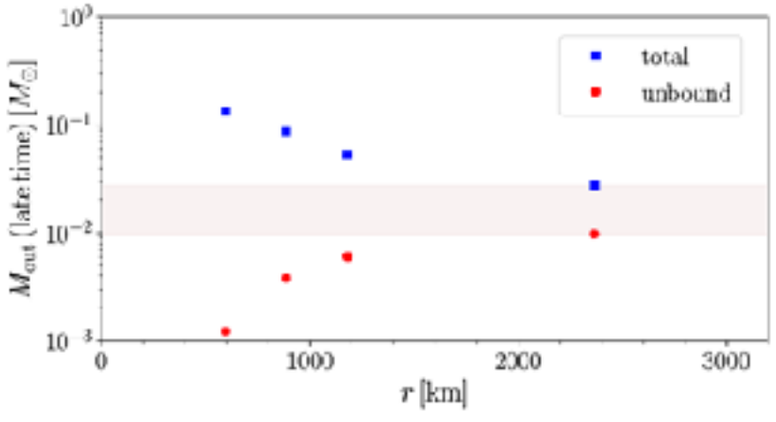


ejecta velocity

~0.2 c marginally consistent with blue kilonova

⟶ possible further enhancement

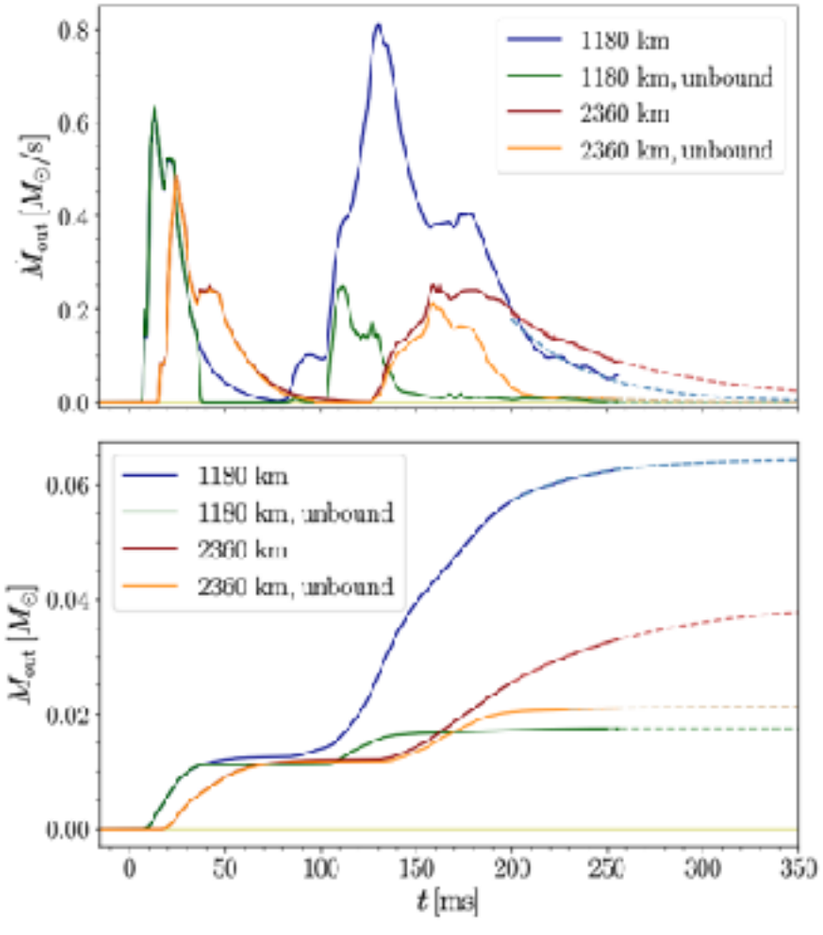
ejecta mass



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

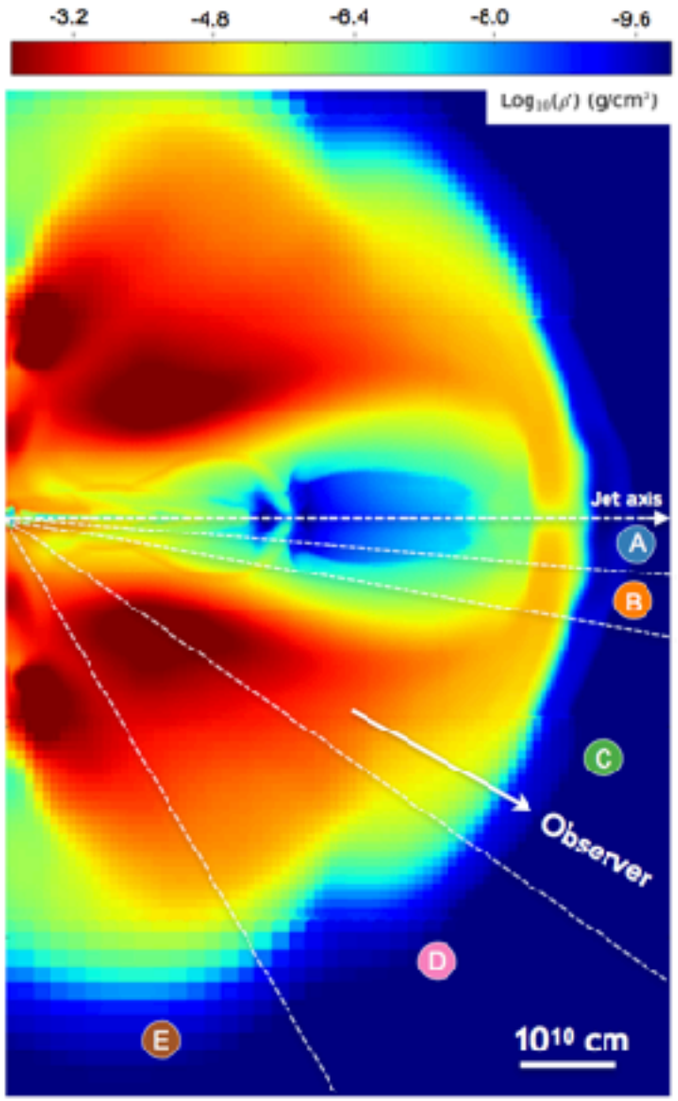
to be compared with

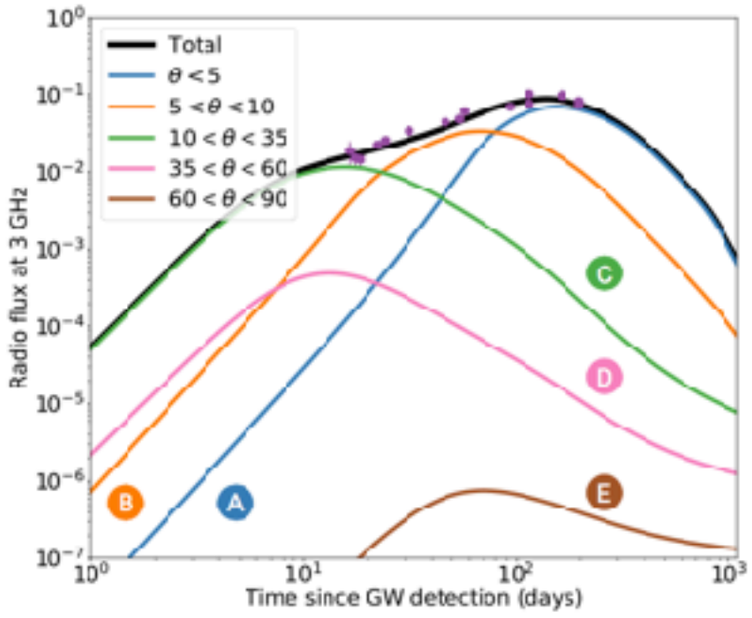
$0.015 - 0.025\ M_\odot$

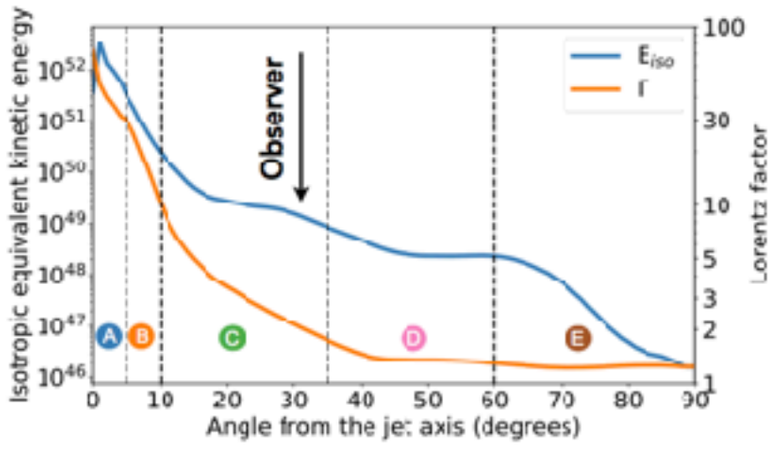


GRB 170817A as a canonical SGRB

Lazzati+2018





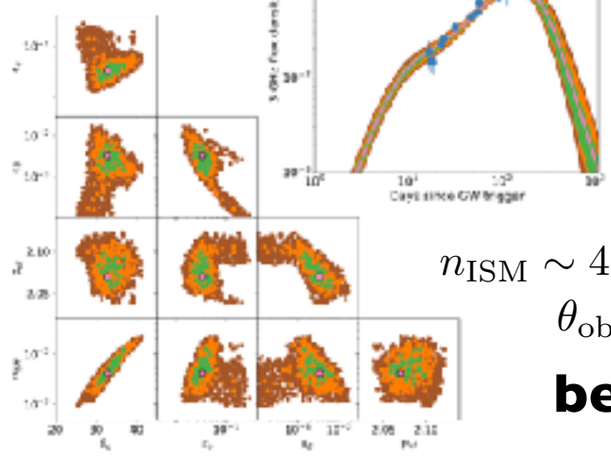


special relativistic jet simulation

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

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

multiwavelength afterglow calculation



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

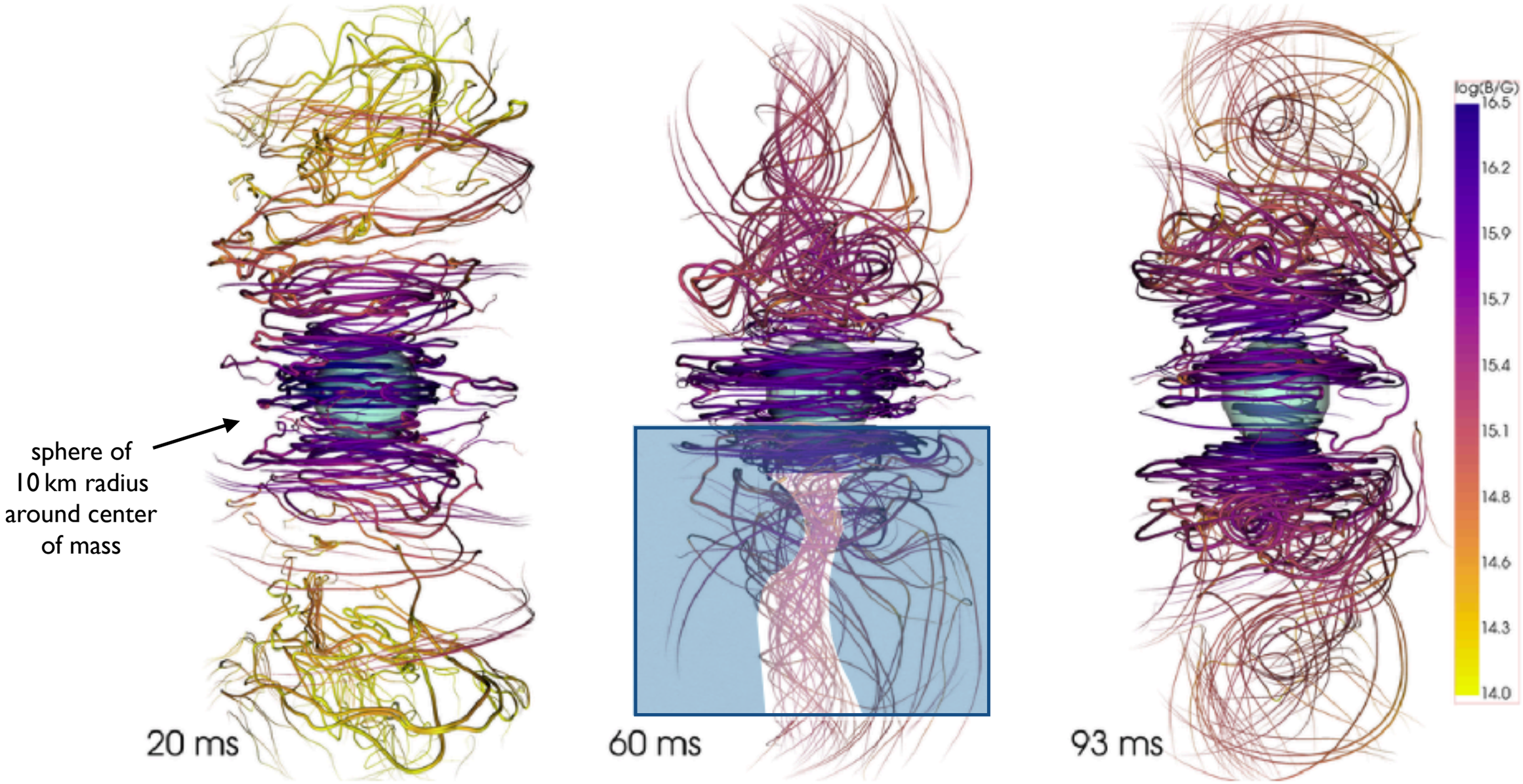
$$\theta_{\mathrm{obs}} \sim 33^\circ$$

best fit

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

Magnetic field configuration

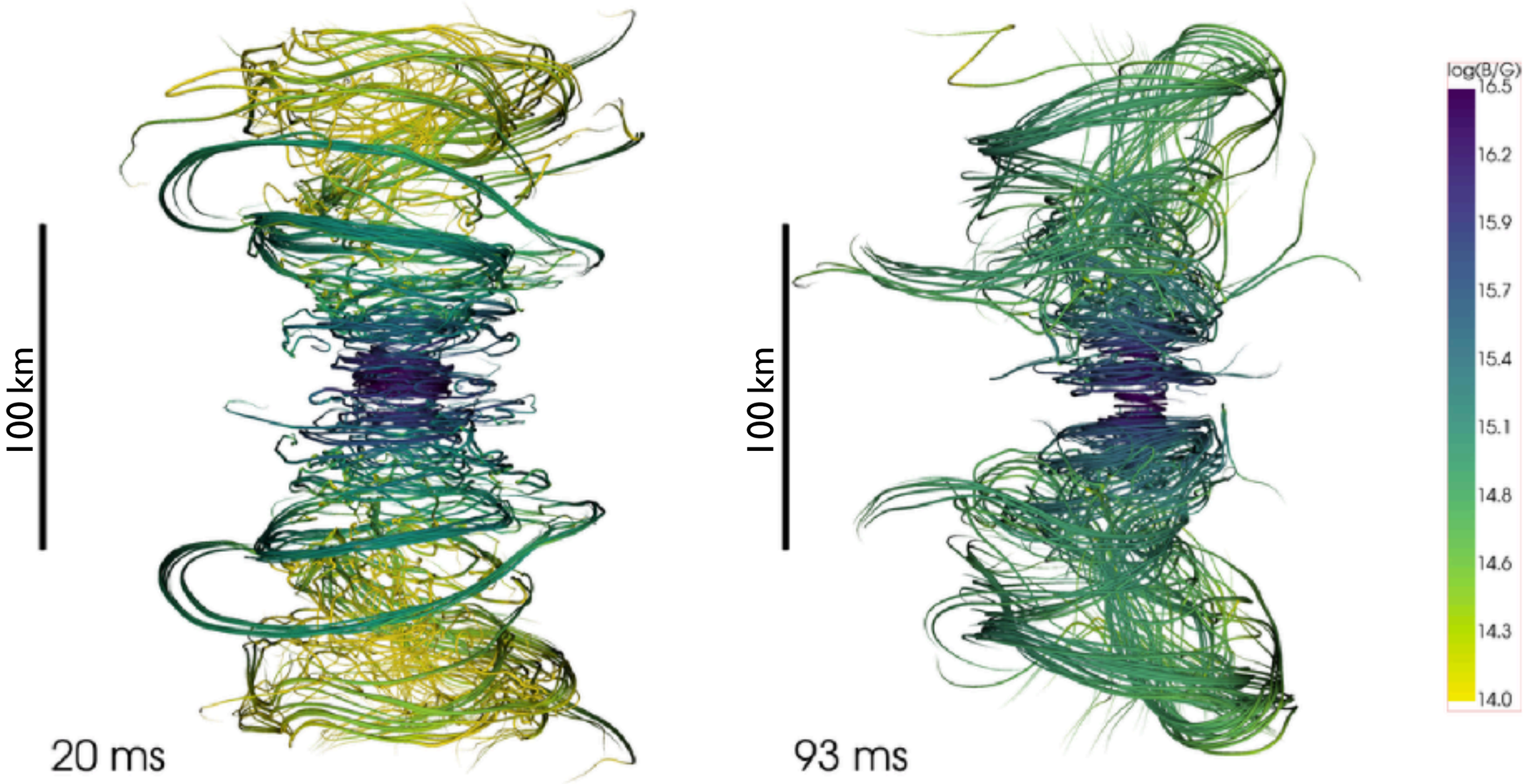
Ciolfi+2019



helical structure

Magnetic field configuration

Ciolfi+2019



hints of an emerging global field structure
with magnetar-like dipolar field