Binary neutron star mergers, short gamma-ray bursts, and kilonovae

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

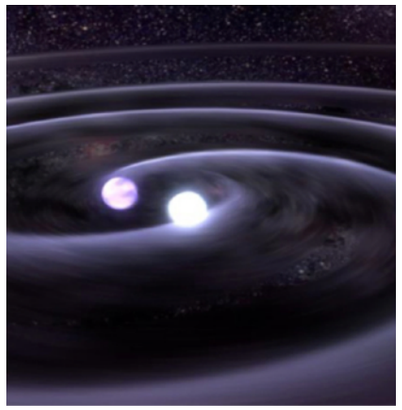
Ciolfi & Kalinani 2020, submitted ArXiv:2004.11298

Lazzati, Ciolfi, Perna 2020, ApJ accepted ArXiv:2004.10210

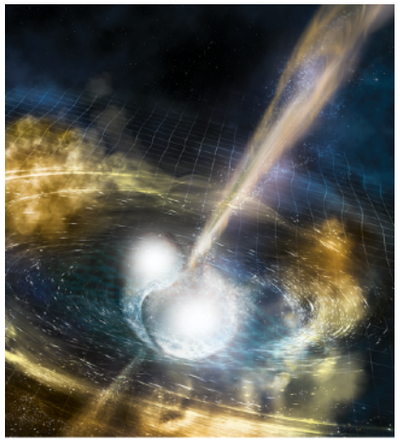
TCAN on Binary Neutron Stars Workshop 2020

10th July 2020

GW170817 detection timeline

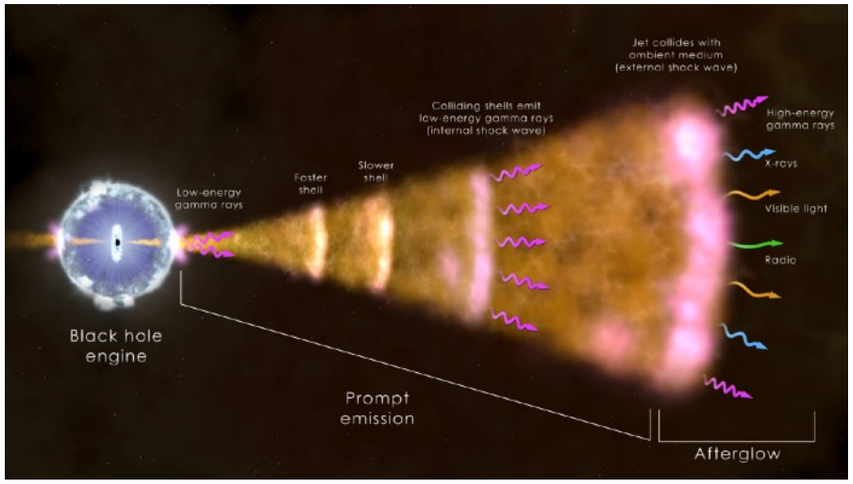


merger



short GRB

GRB170817A



X-ray afterglow

radio afterglow

t0

+1.7 sec

+10.87 hours

+9 days

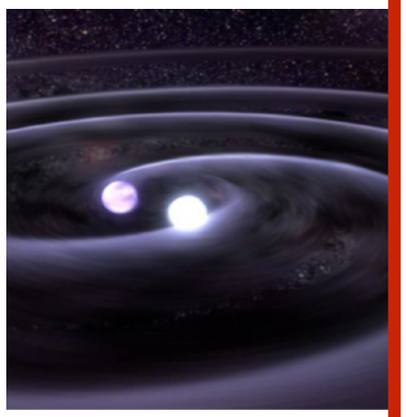
+16 days

optical counterpart

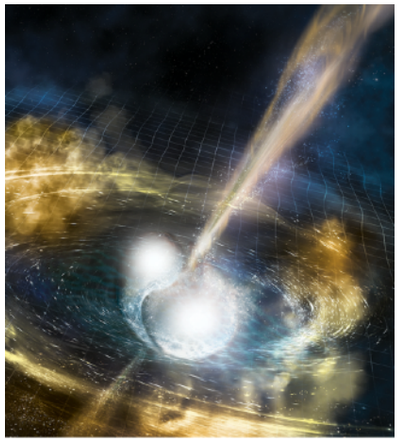
kilonova

AT2017gfo

GW170817 detection timeline

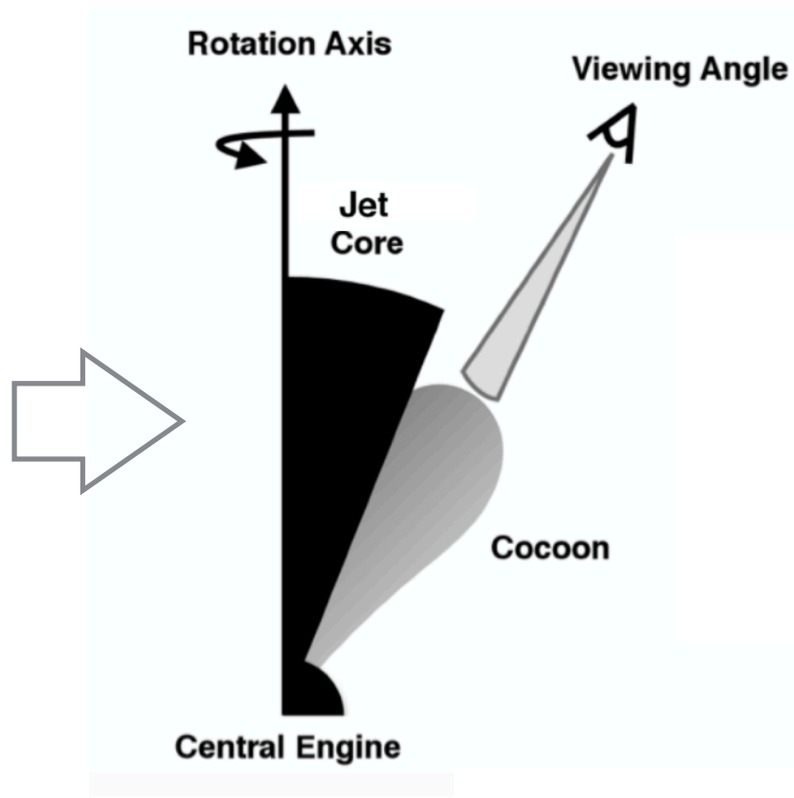


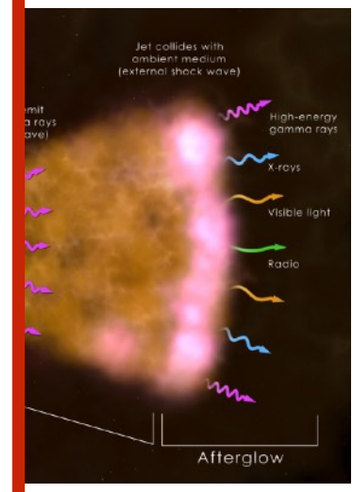
merger



short GRB

GRB170817A





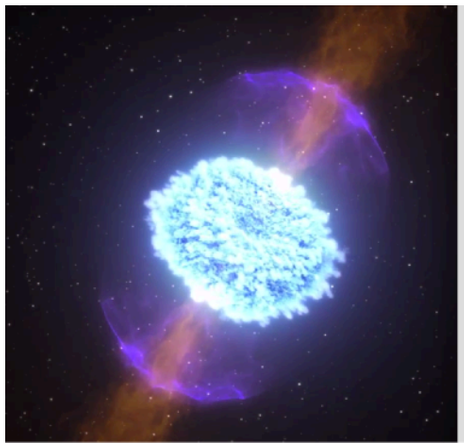
dio afterglow

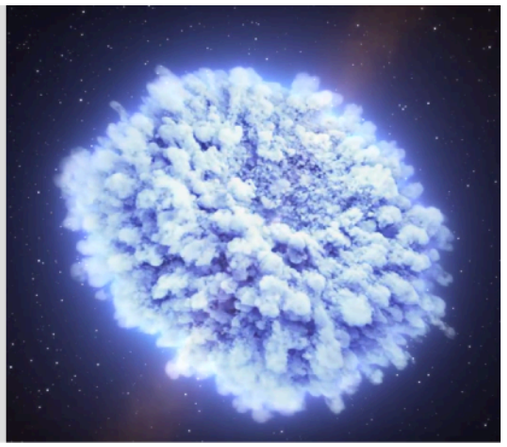
t0 +1.7 sec +10.87 hours +9 days +16 days

optical
counterpart

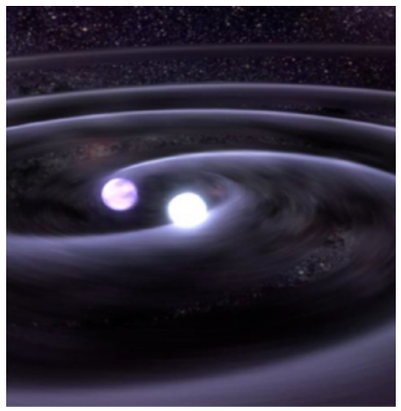
kilonova

AT2017gfo



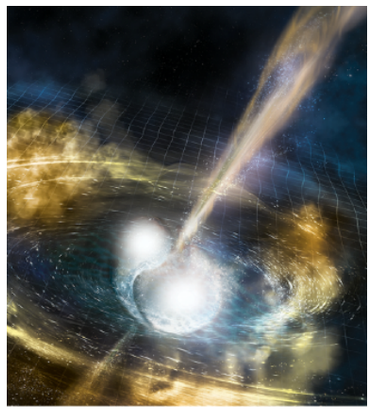


SGRB jets from BNS mergers



GW170817

+



GRB 170817A

??

jet launching mechanism?

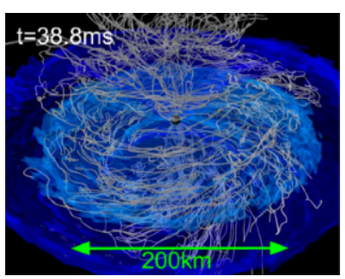
neutrino driven ✗

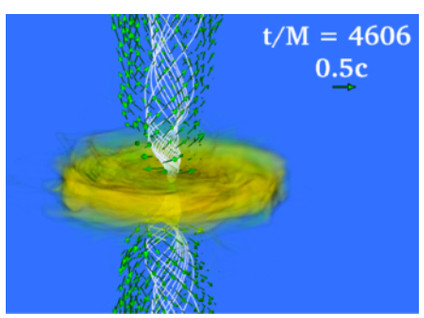
MHD driven ✓

⟶ need GRMHD simulations

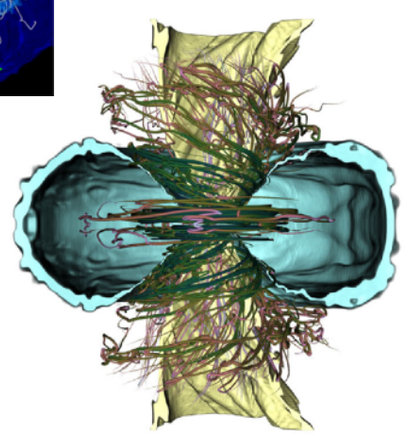
remnant/central engine nature?

Kiuchi+2014





Ruiz+2016



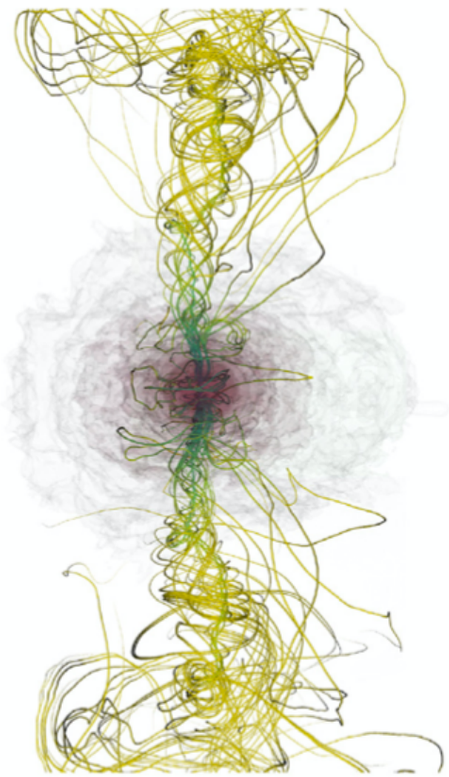
Kawamura+2016

BH + accretion disk

(Blandford-Znajek)

Ciolfi+2017

Ciolfi+2019

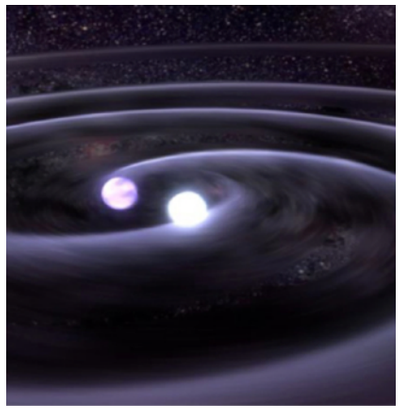


Ciolfi 2020a

massive long-lived NS

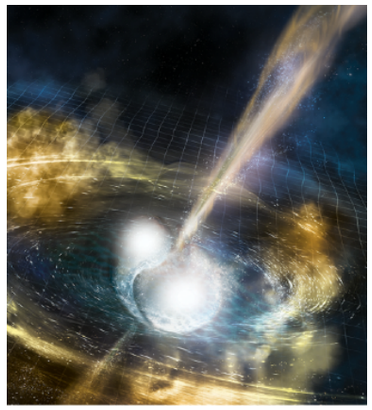
(magnetorotational)

SGRB jets from BNS mergers



GW170817

+



GRB 170817A

??

jet launching mechanism?

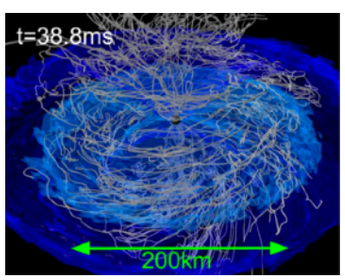
neutrino driven ✗

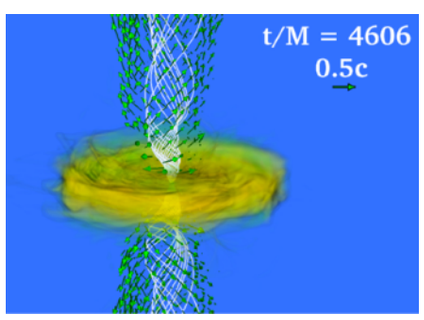
MHD driven ✓

⟶ need GRMHD simulations

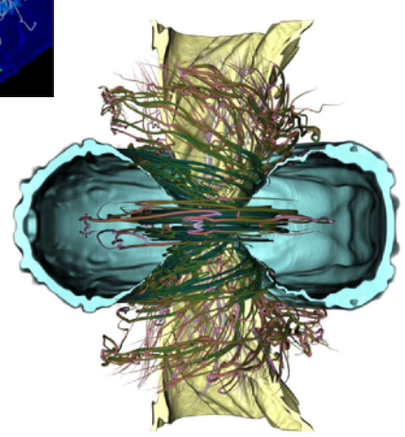
remnant/central engine nature?

Kiuchi+2014





Ruiz+2016



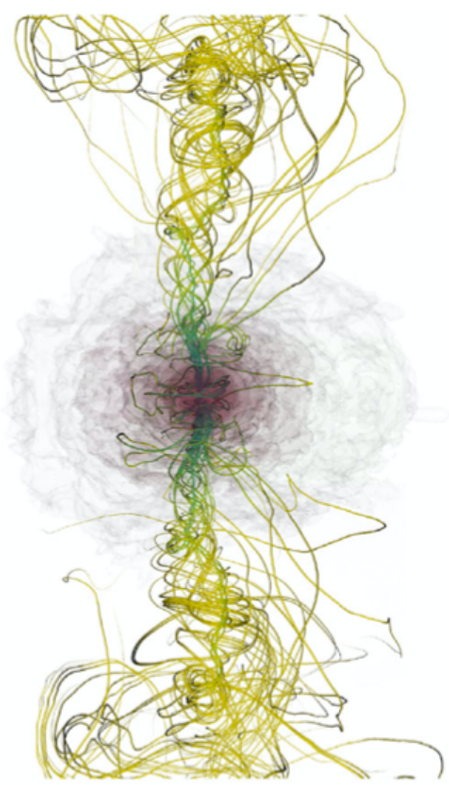
Kawamura+2016

BH + accretion disk

(Blandford-Znajek)

Ciolfi+2017

Ciolfi+2019

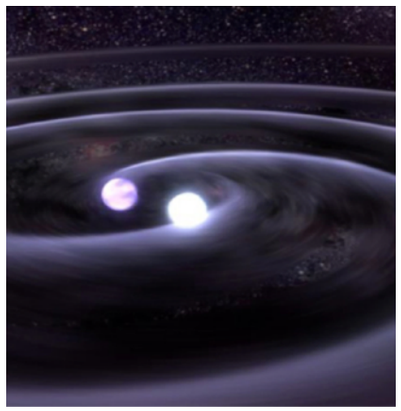


Ciolfi 2020a

massive long-lived NS

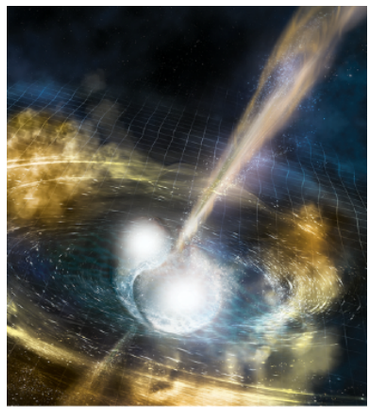
(magnetorotational)

SGRB jets from BNS mergers



GW170817

+



GRB 170817A

??

jet launching mechanism?

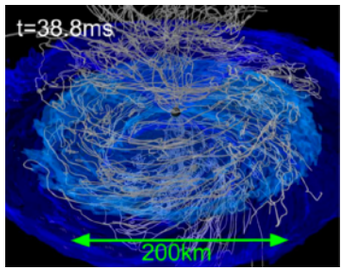
neutrino driven ✗

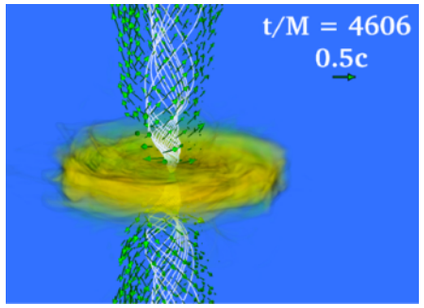
MHD driven ✓

→ need GRMHD simulations

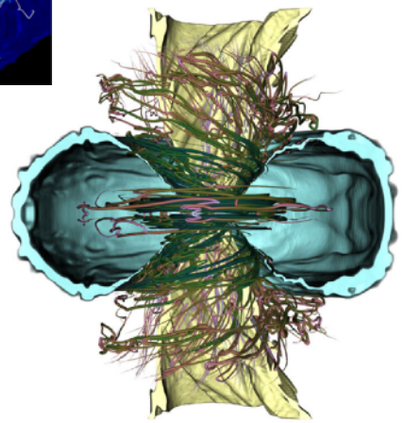
remnant/central engine nature?

Kiuchi+2014





Ruiz+2016



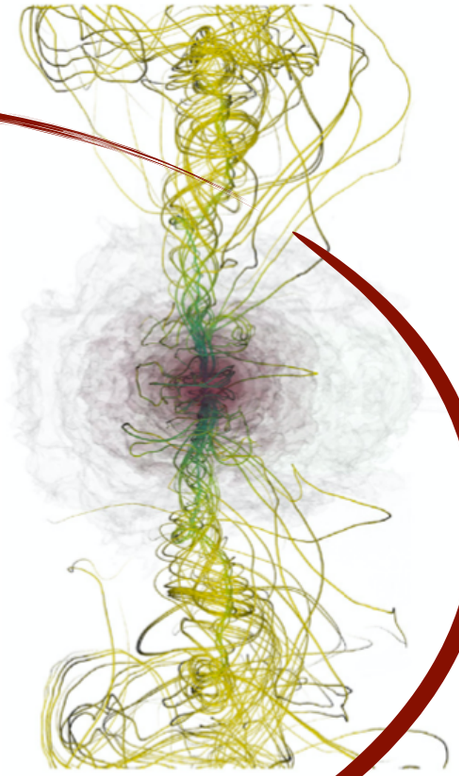
Kawamura+2016

BH + accretion disk

(Blandford-Znajek)

Ciolfi+2017

Ciolfi+2019



Ciolfi 2020a

massive long-lived NS

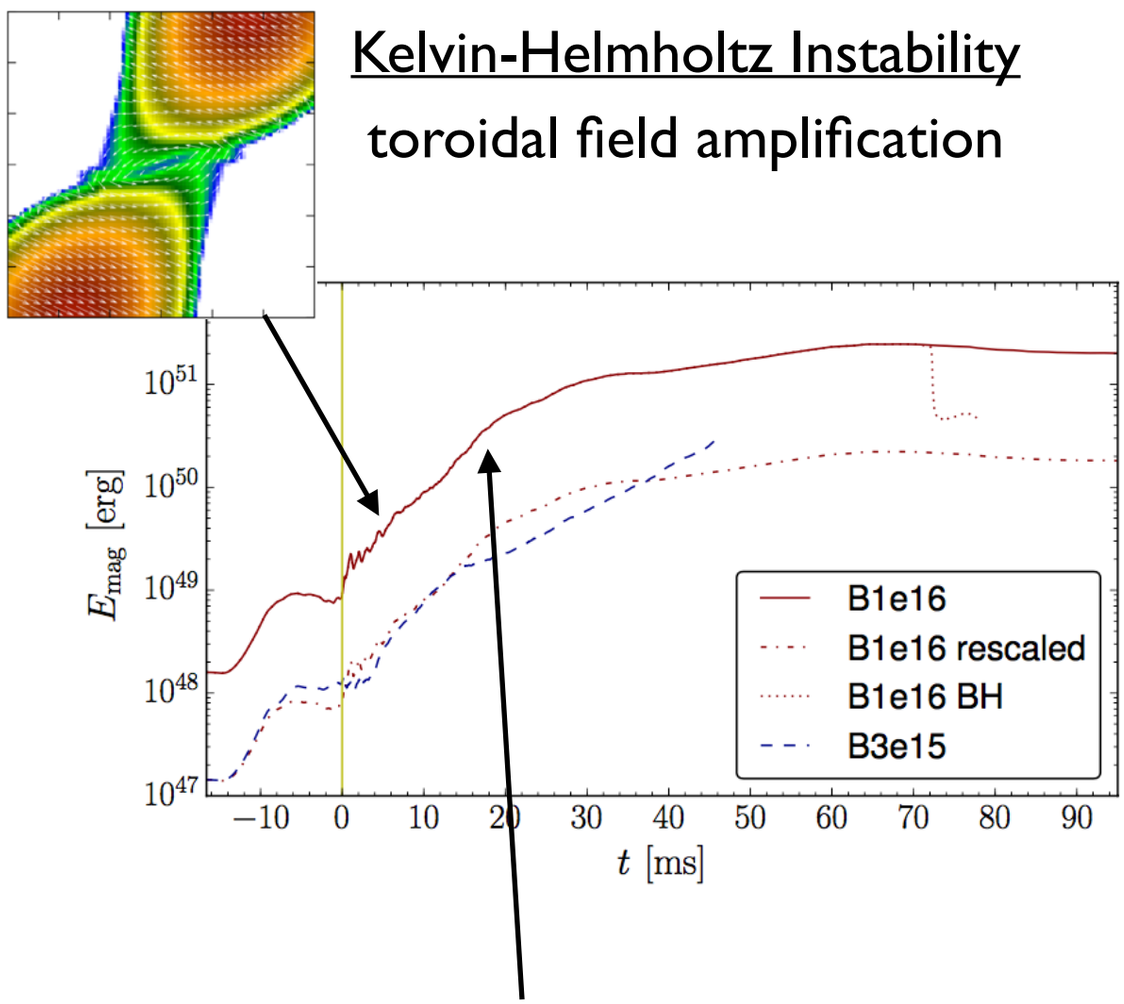
(magnetorotational)

Magnetic field amplification and geometry

Ciolfi+2019: 100 ms of post-merger evolution

see talk by Jay Kalinani

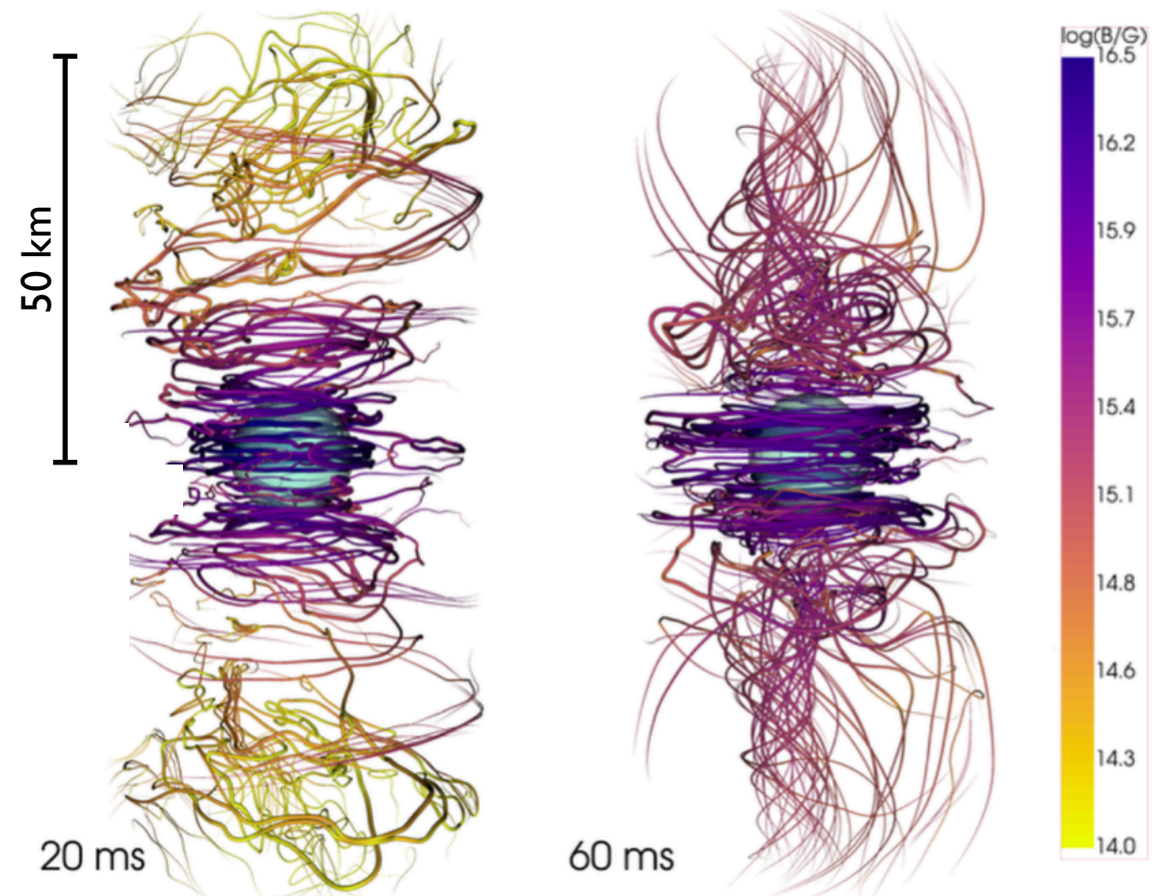
Kiuchi+2015



Kelvin-Helmholtz Instability

toroidal field amplification

MagnetoRotational Instability



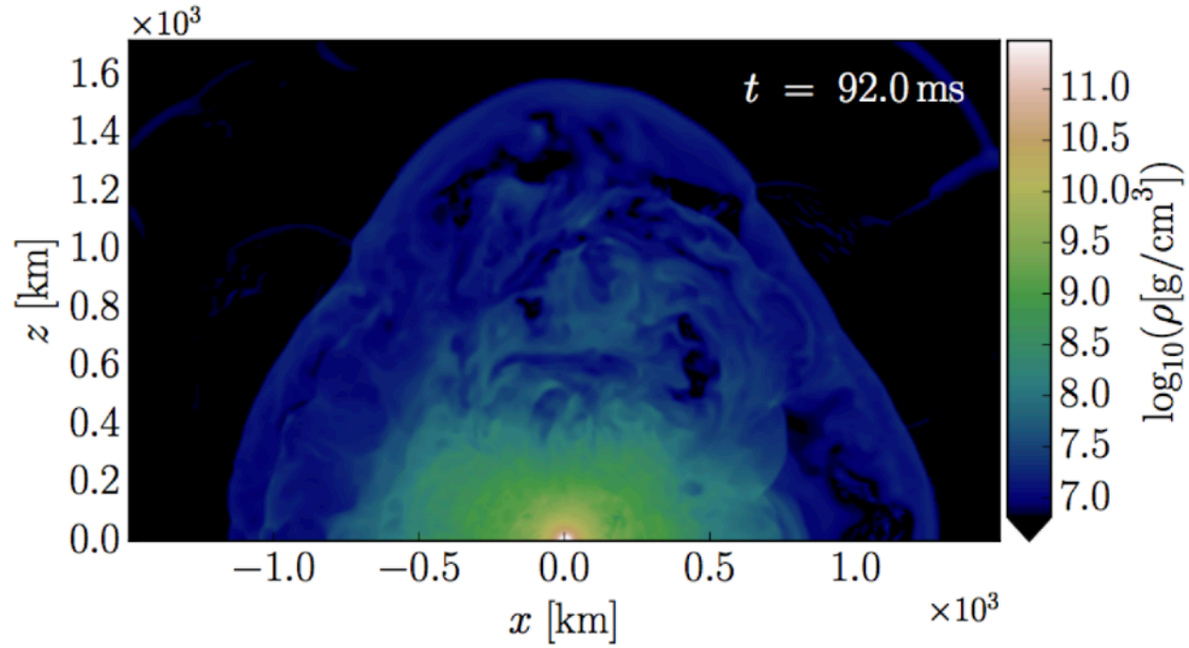
helical structure

Magnetically driven wind

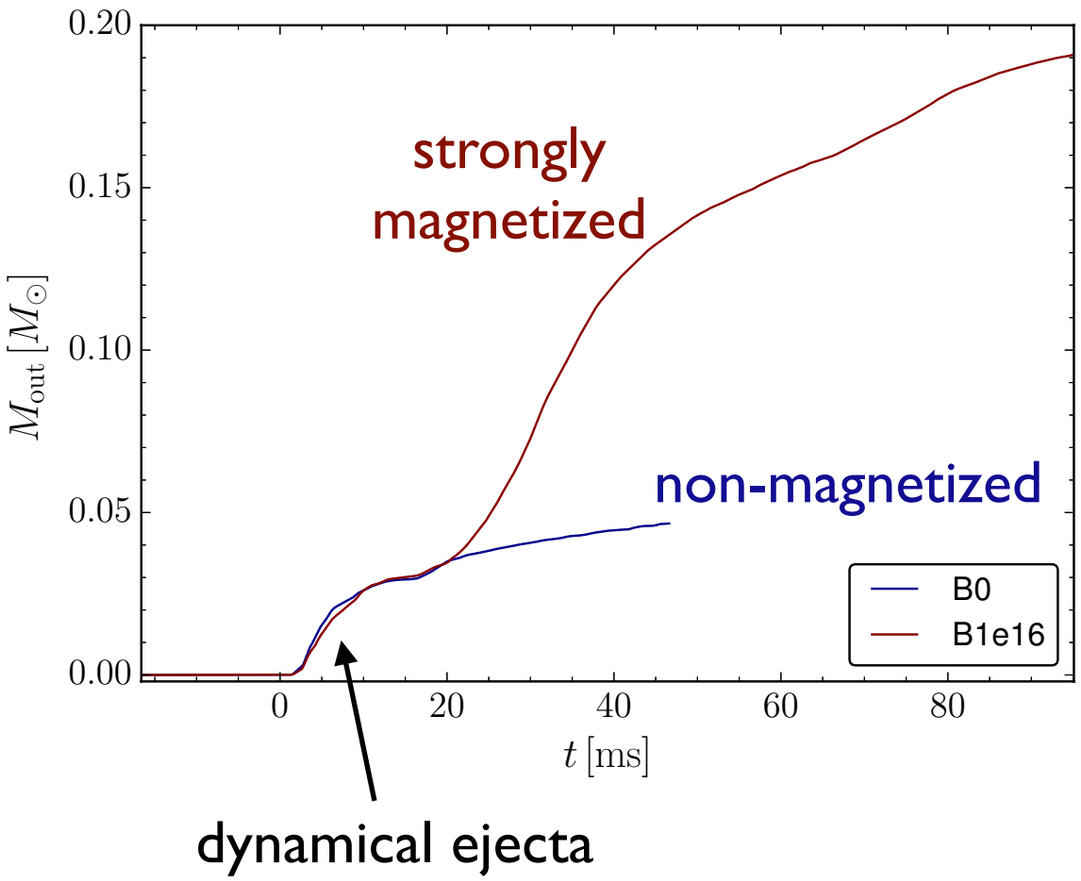
Ciolfi+2019

@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

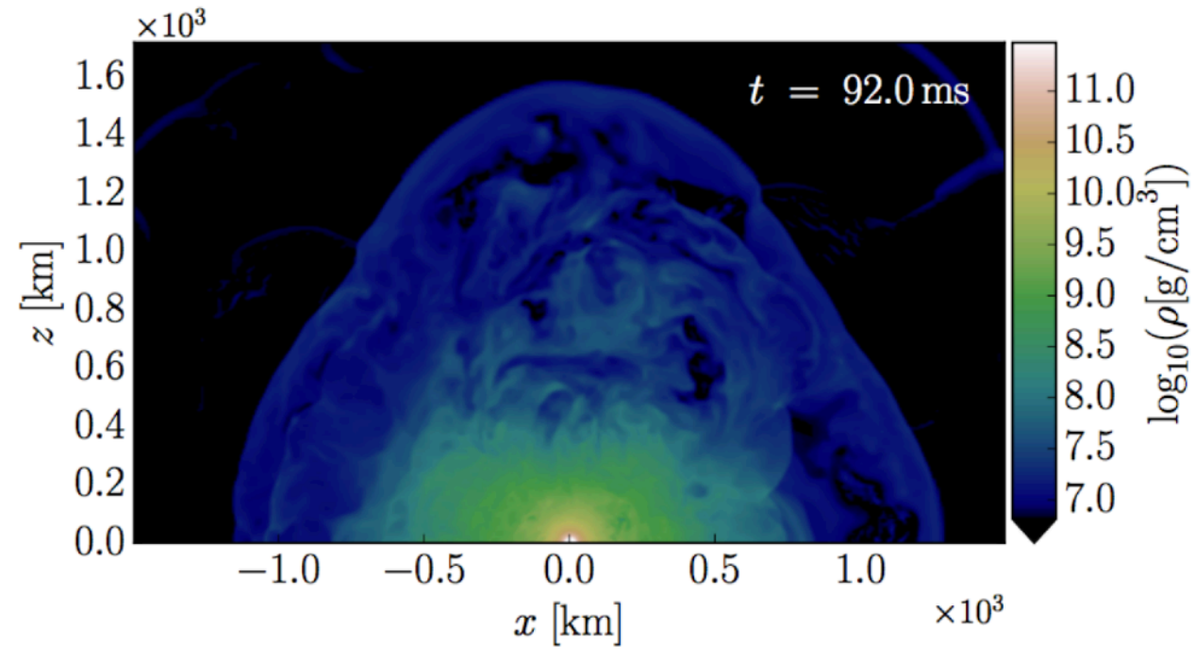
- surrounded by dense isotropic environment
- slow steady outflow maintaining a fixed radial density profile

Magnetically driven wind

Ciolfi+2019

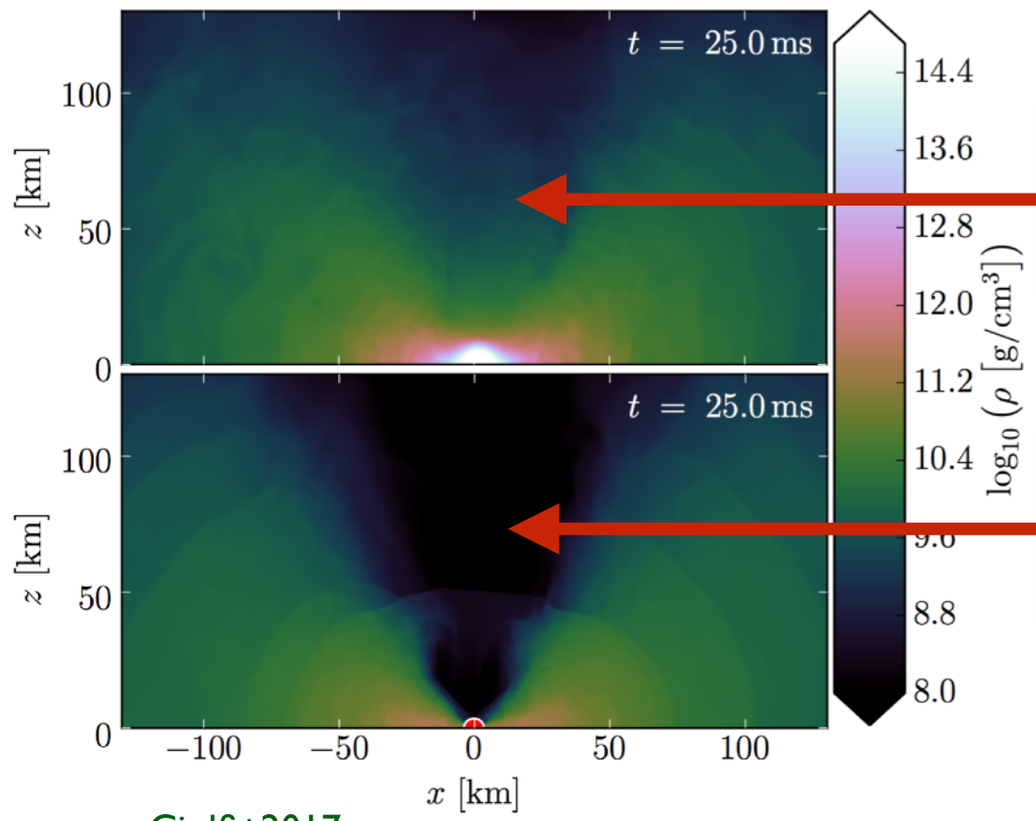
@50-100 ms after merger

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

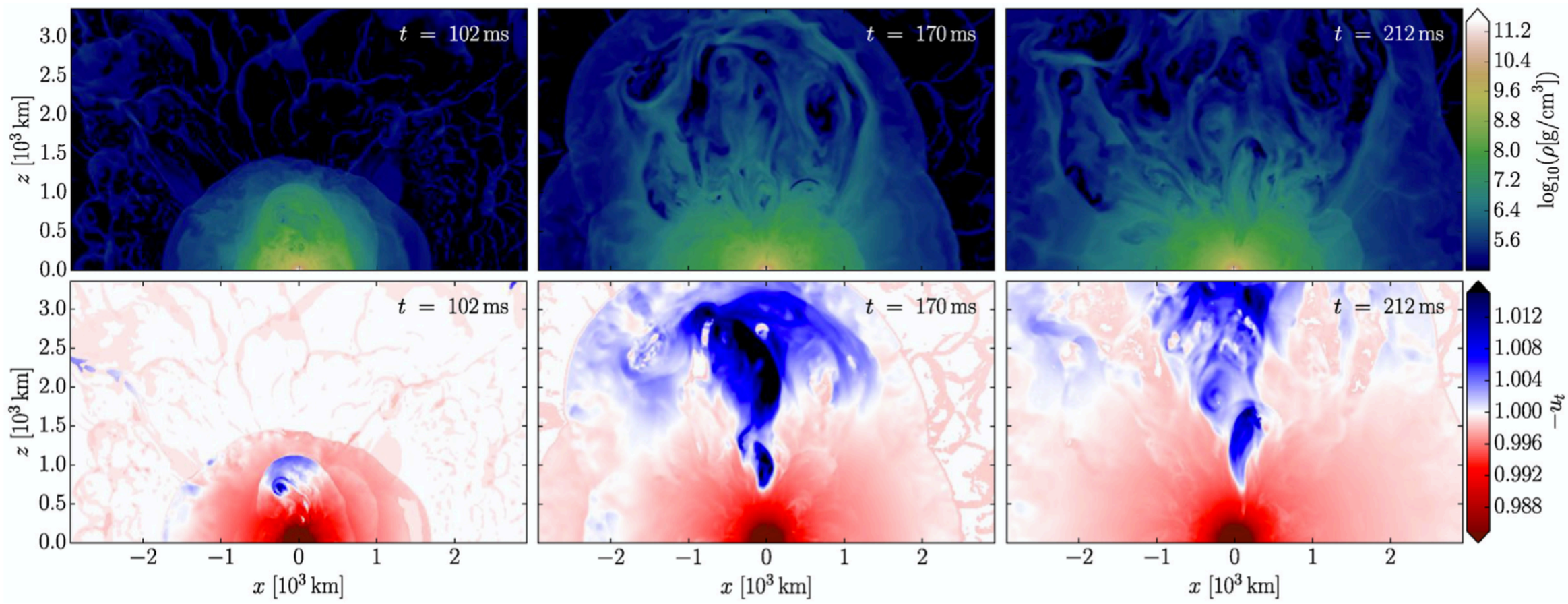
Ciolfi 2020a

- 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

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



massive NS remnant can produce a collimated outflow

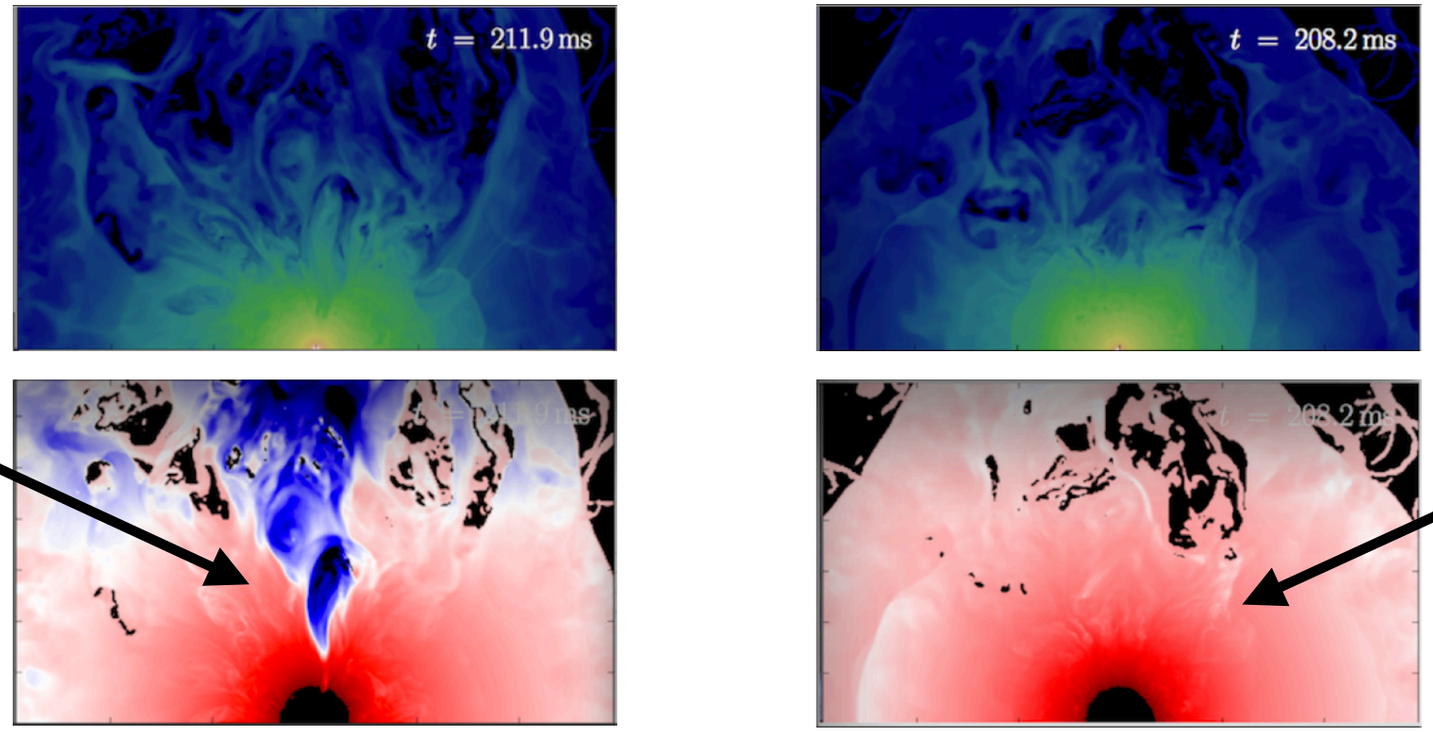
BNS mergers with much longer evolution

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

higher initial magnetization

lower initial magnetization



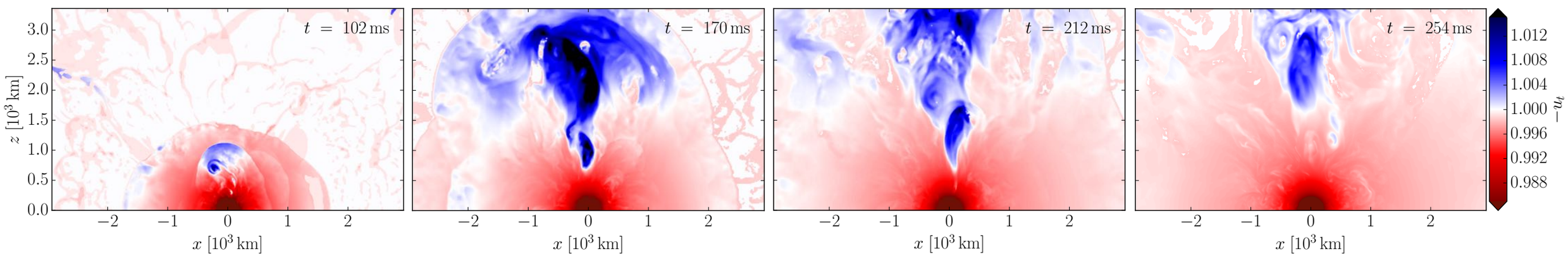
collimated outflow

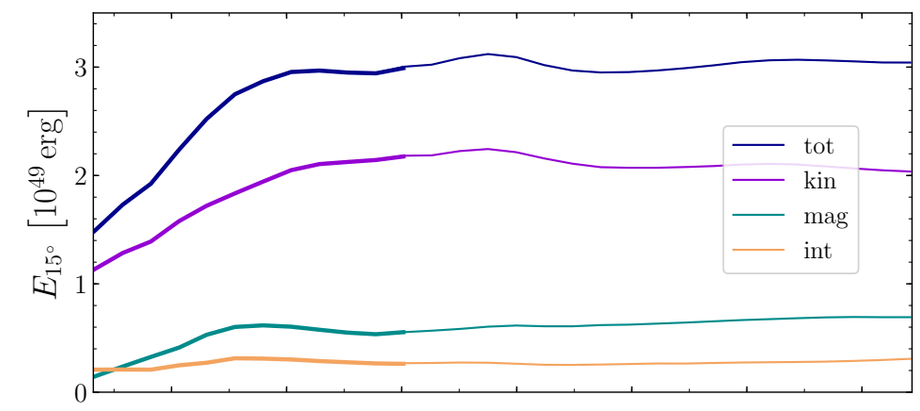
NO collimated outflow

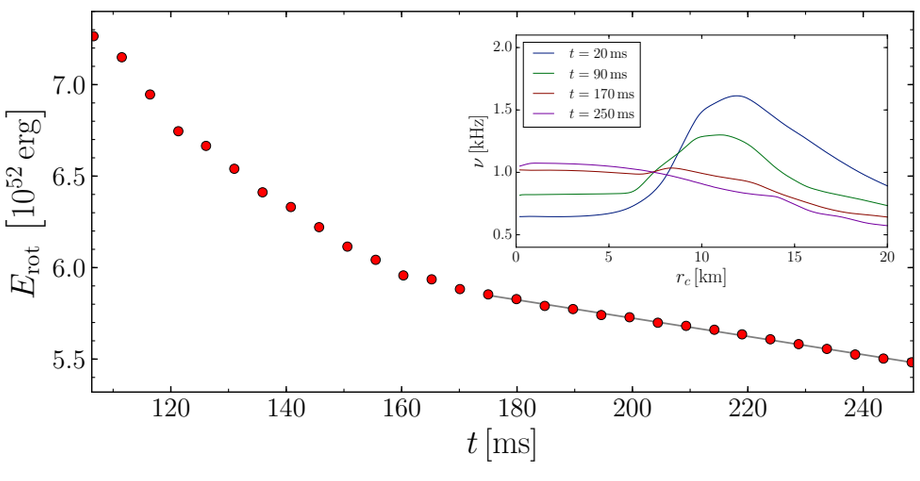
..but not ubiquitous

Origin and properties of the collimated outflow

Ciolfi 2020a







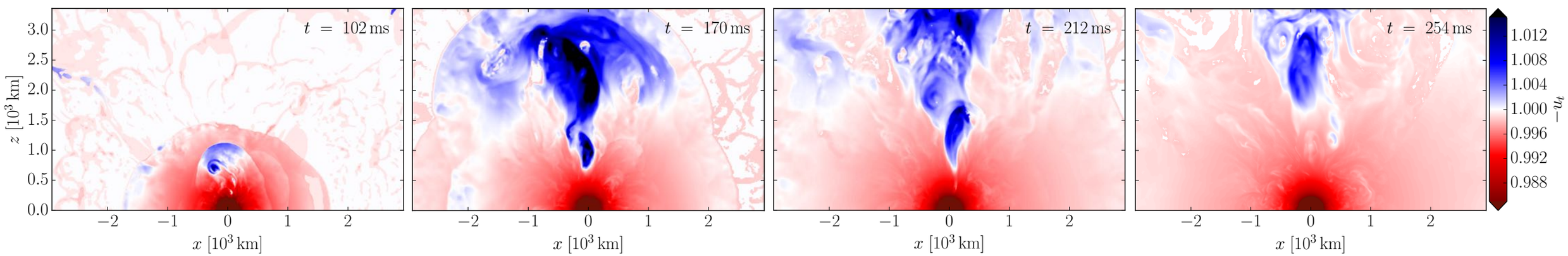
~160 ms after merger

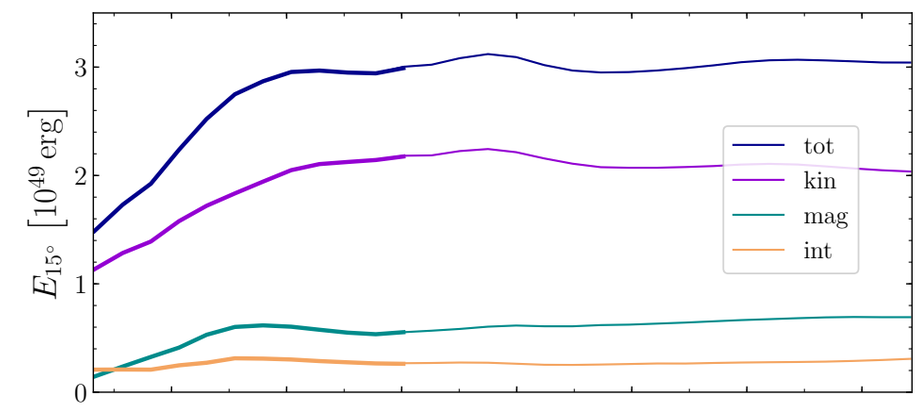
- outflow energy saturation
- change in rotational energy evolution
- differential rotation in the NS core is over

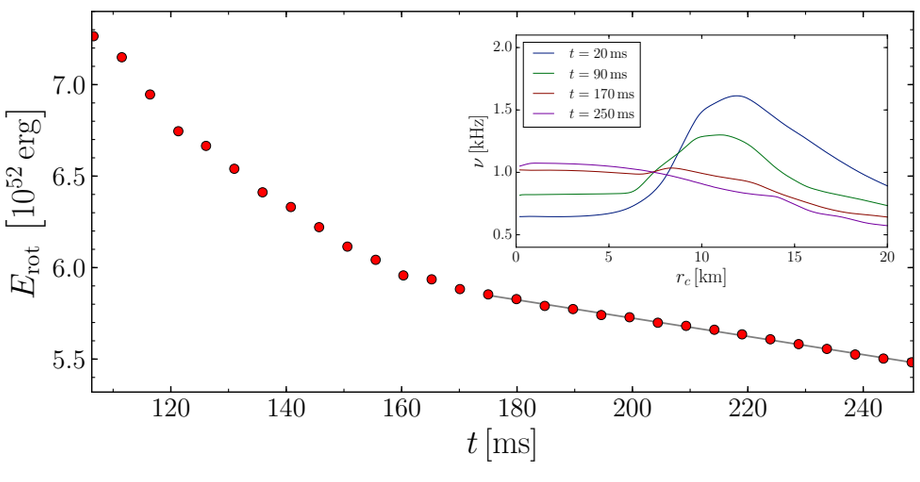
NS differential rotation = energy reservoir

Origin and properties of the collimated outflow

Ciolfi 2020a







magnetorotational launching mechanism

magnetic field amplification

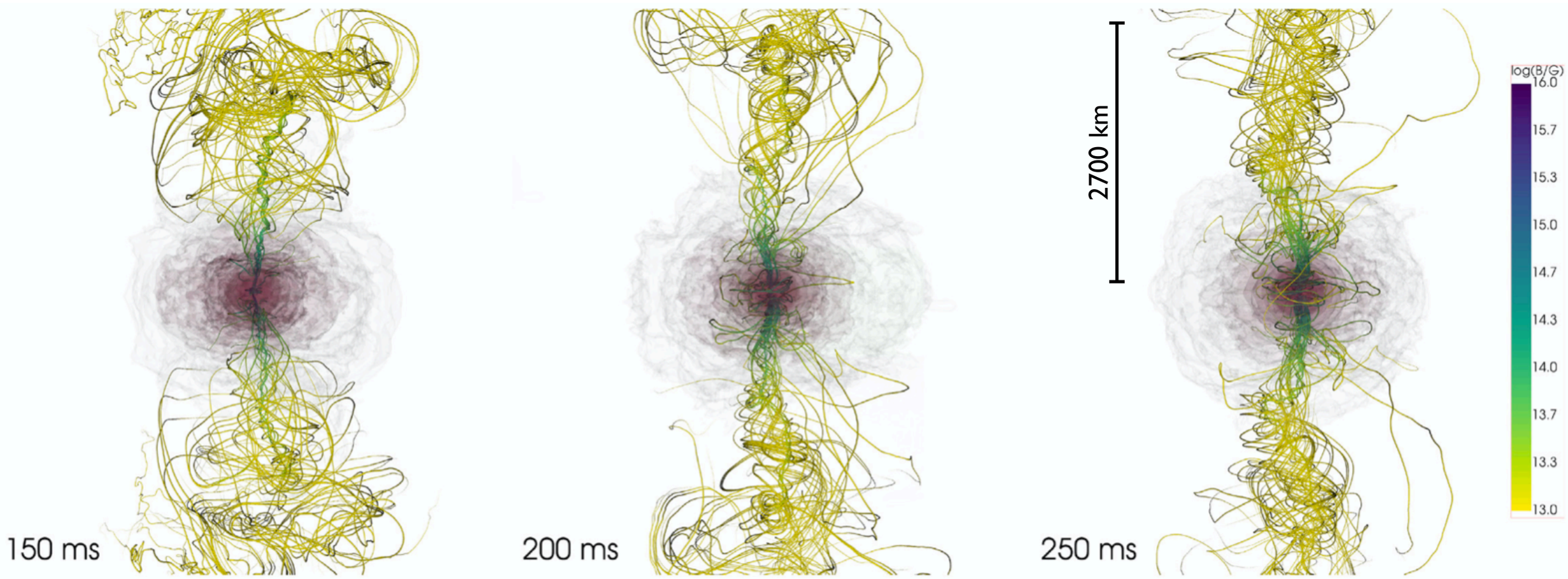
build up of magnetic pressure radial gradient

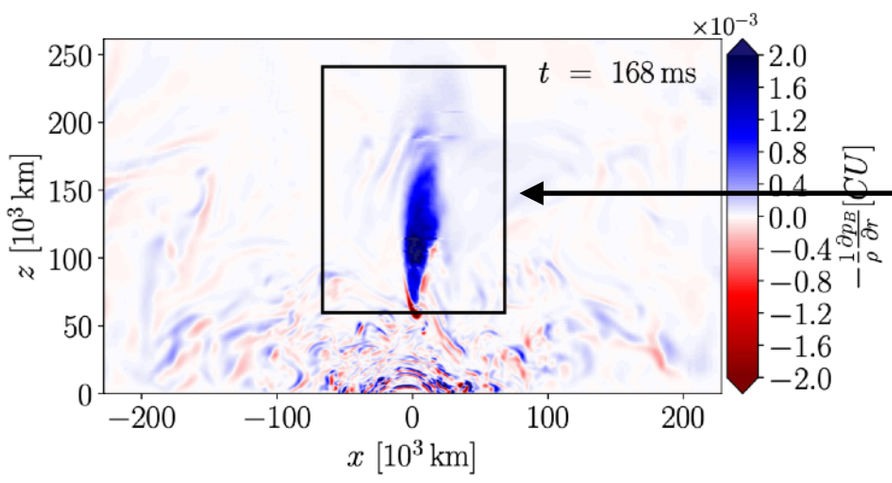
acceleration along the rotation axis

NS differential rotation

Emerging helical magnetic field

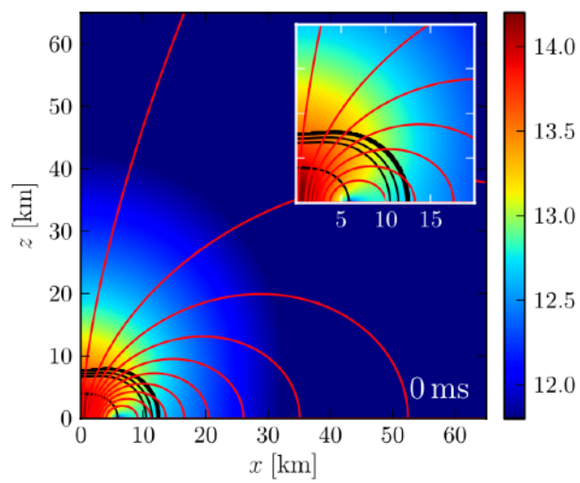
Ciolfi 2020a



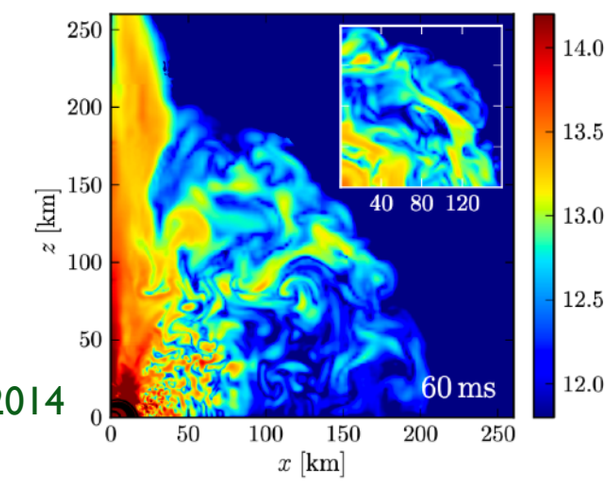


magnetic push
(radial gradient of magnetic pressure)

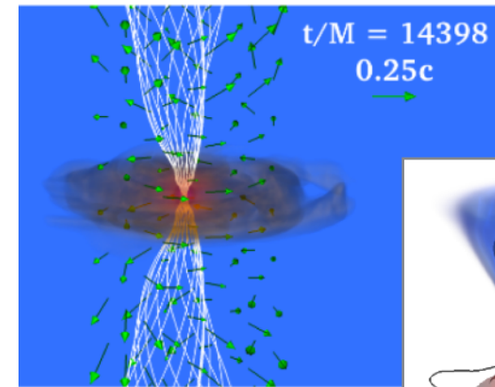
aligned dipolar field imposed on differentially rotating NS



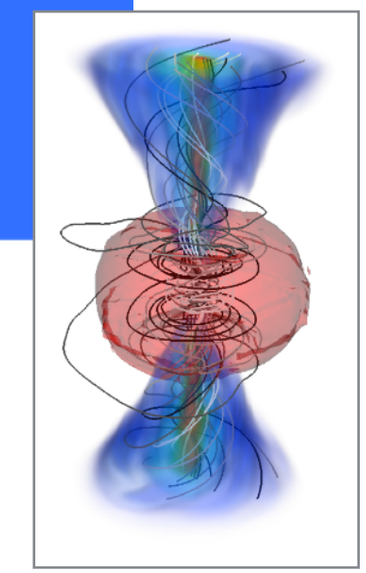
collimated outflow



Siegel+2014

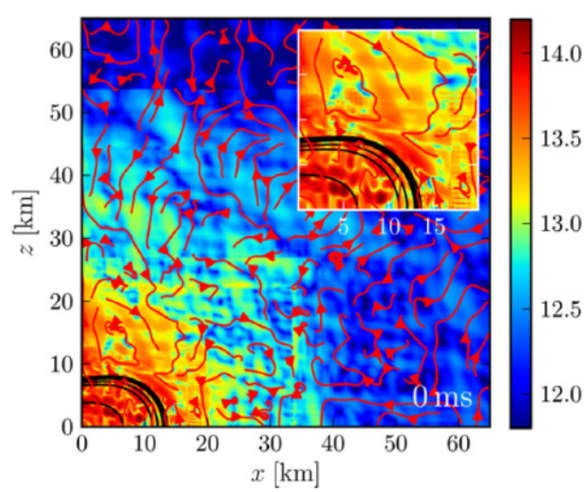


Ruiz+2018

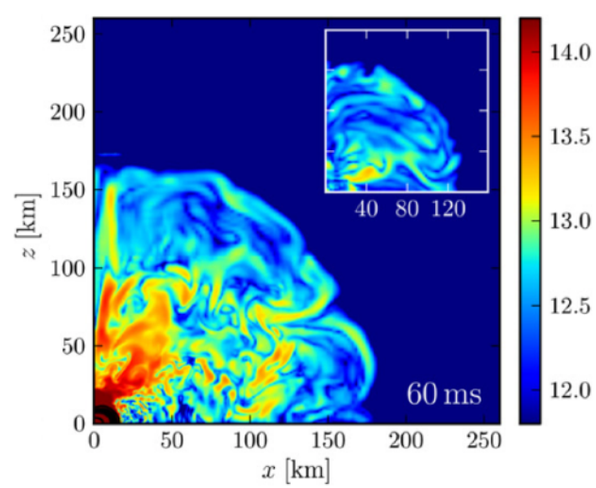


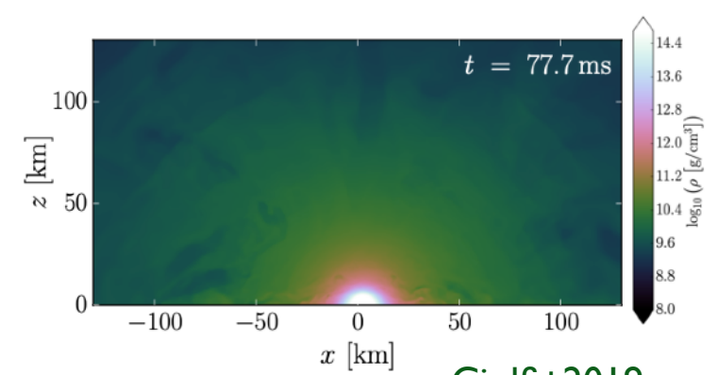
Moesta+2020

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?

<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 disfavoured

Results from Ciolfi 2020a

- GRMHD BNS merger simulations with up to >250 ms of massive NS remnant evolution
- collimated outflow from 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 indications against the possible production of a SGRB

→ accreting BH scenario is favoured

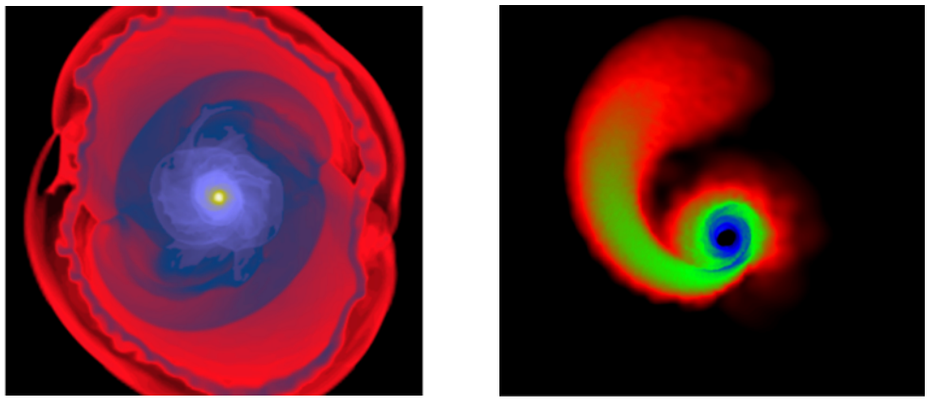
Results from Ciolfi 2020a

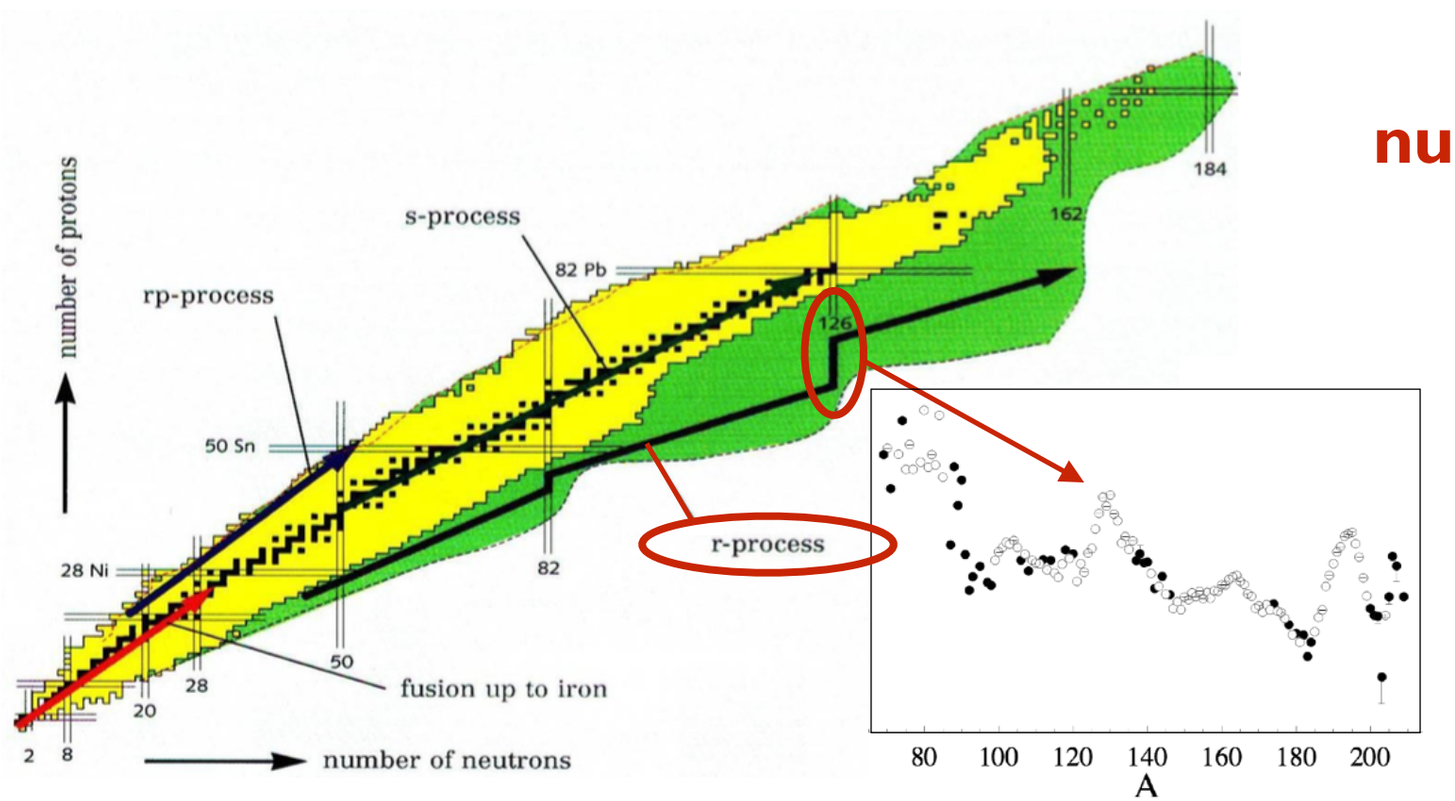
- GRMHD BNS merger simulations with up to >250 ms of massive NS remnant evolution
- collimated outflow from a massive NS obtained for the first time
- massive NS can launch a collimated outflow, but this outcome is not ubiquitous
- followed the full outflow development, studied the associated energetics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

next step: can neutrino radiation alter this conclusion?

A radioactively-powered transient

ejecta in NSNS and NSBH mergers





curtesy of A. Arcones

heavy element abundances

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

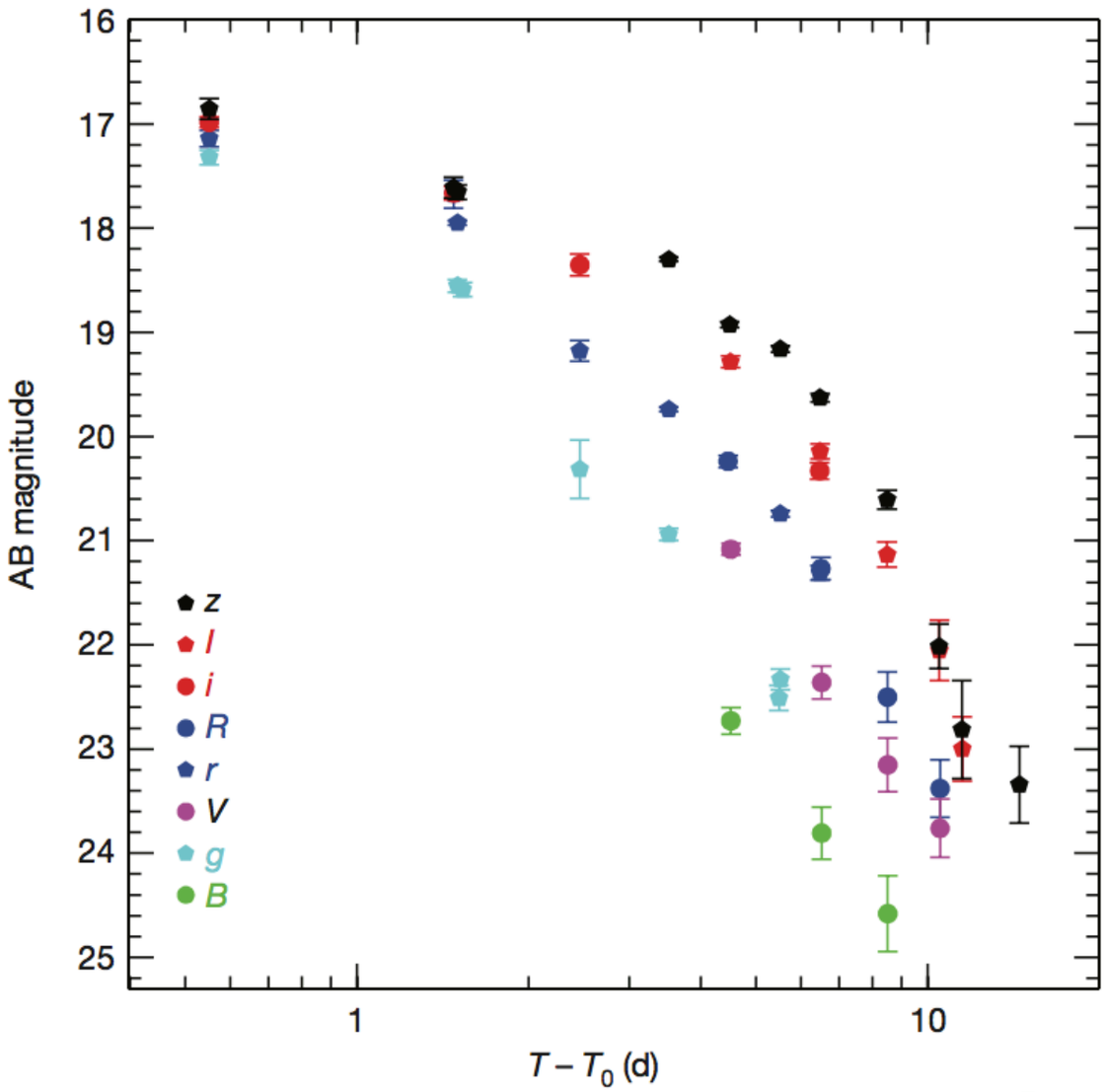
↓

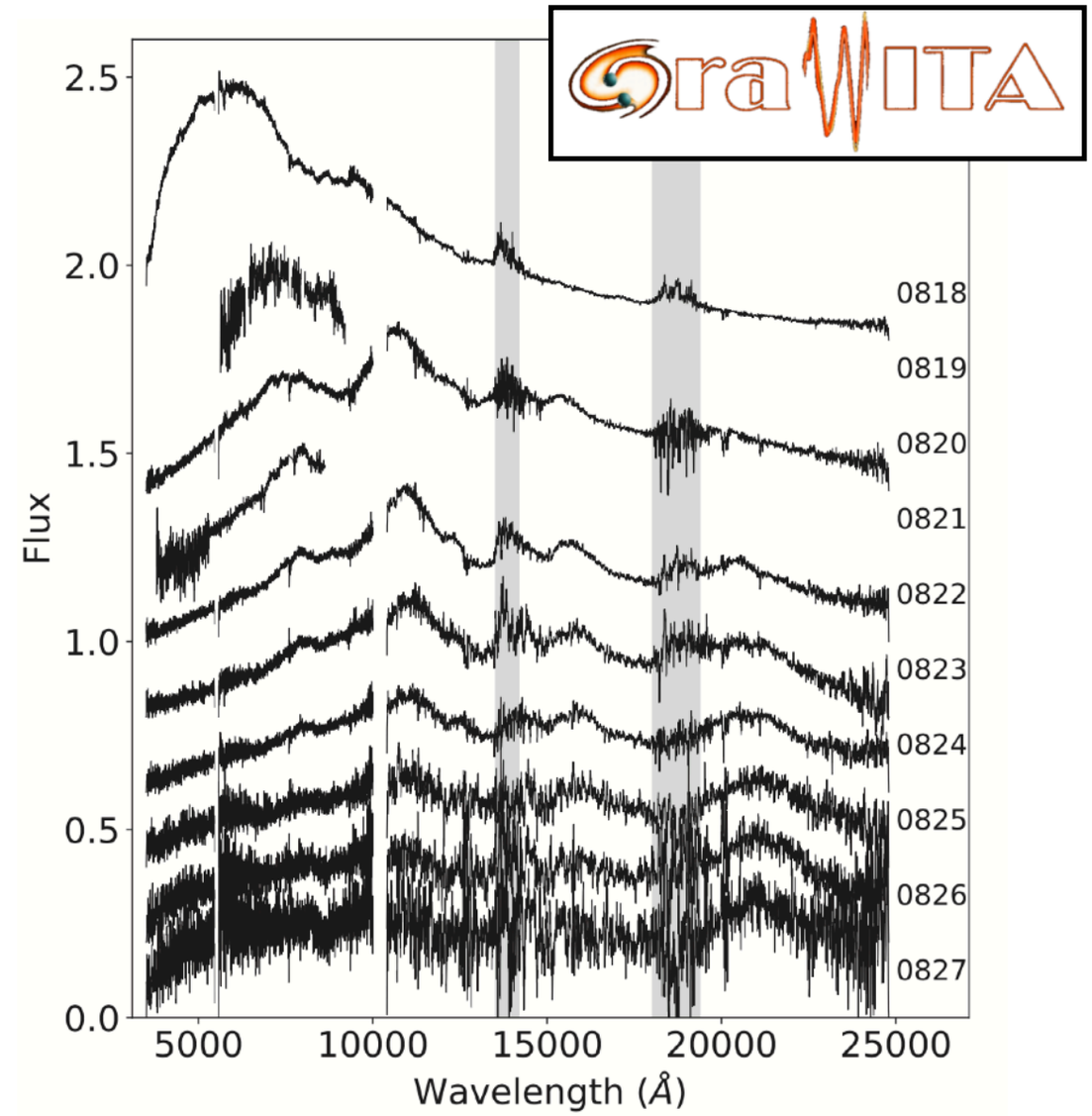
radioactive decay on
timescales of >> sec

↓

optical/IR signal
"kilonova"

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

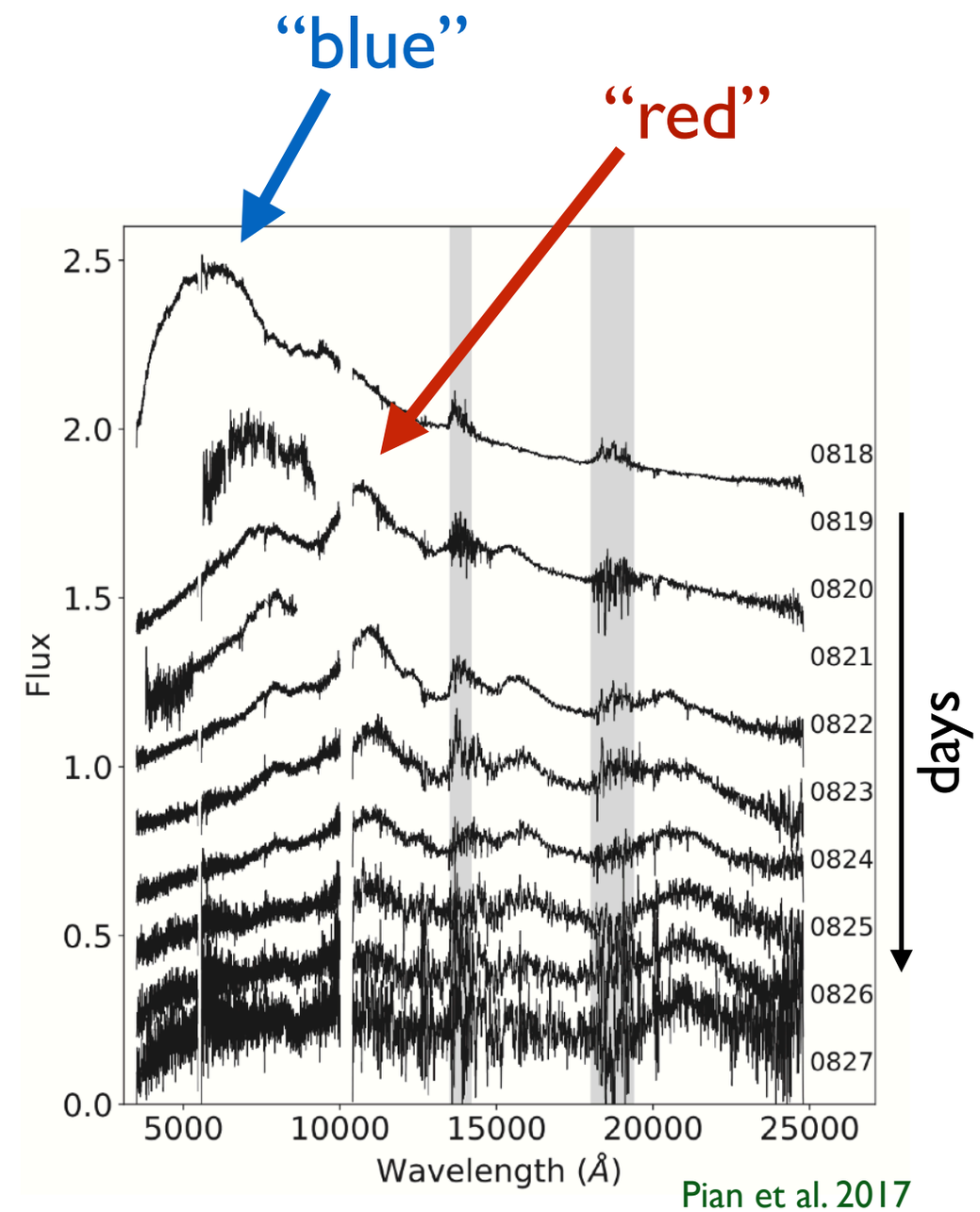
AT2017gfo: blue and red

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)

2) "red" kilonova

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 et al. 2017

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

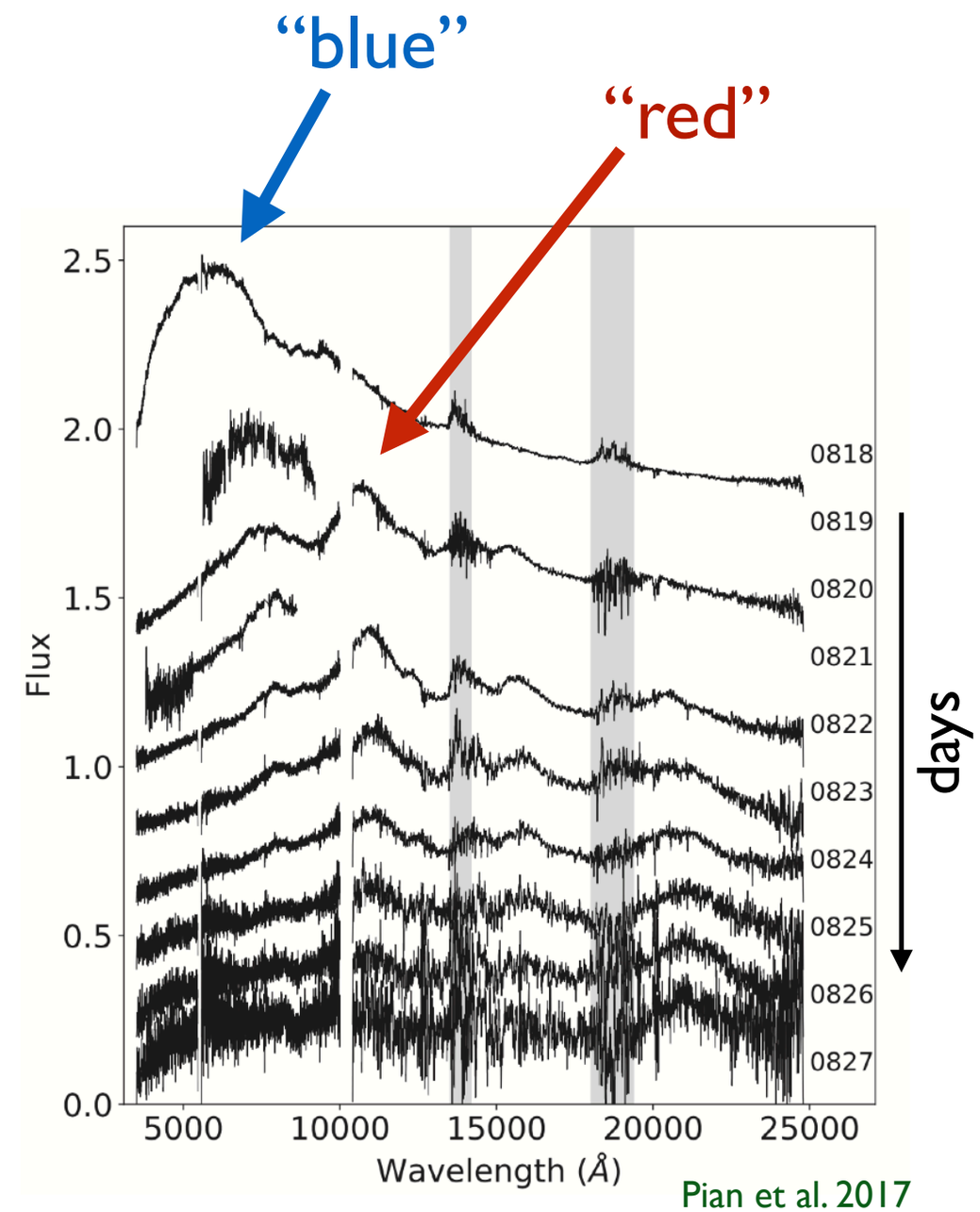
AT2017gfo: blue and red

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)

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 et al. 2017

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

AT2017gfo: blue and red

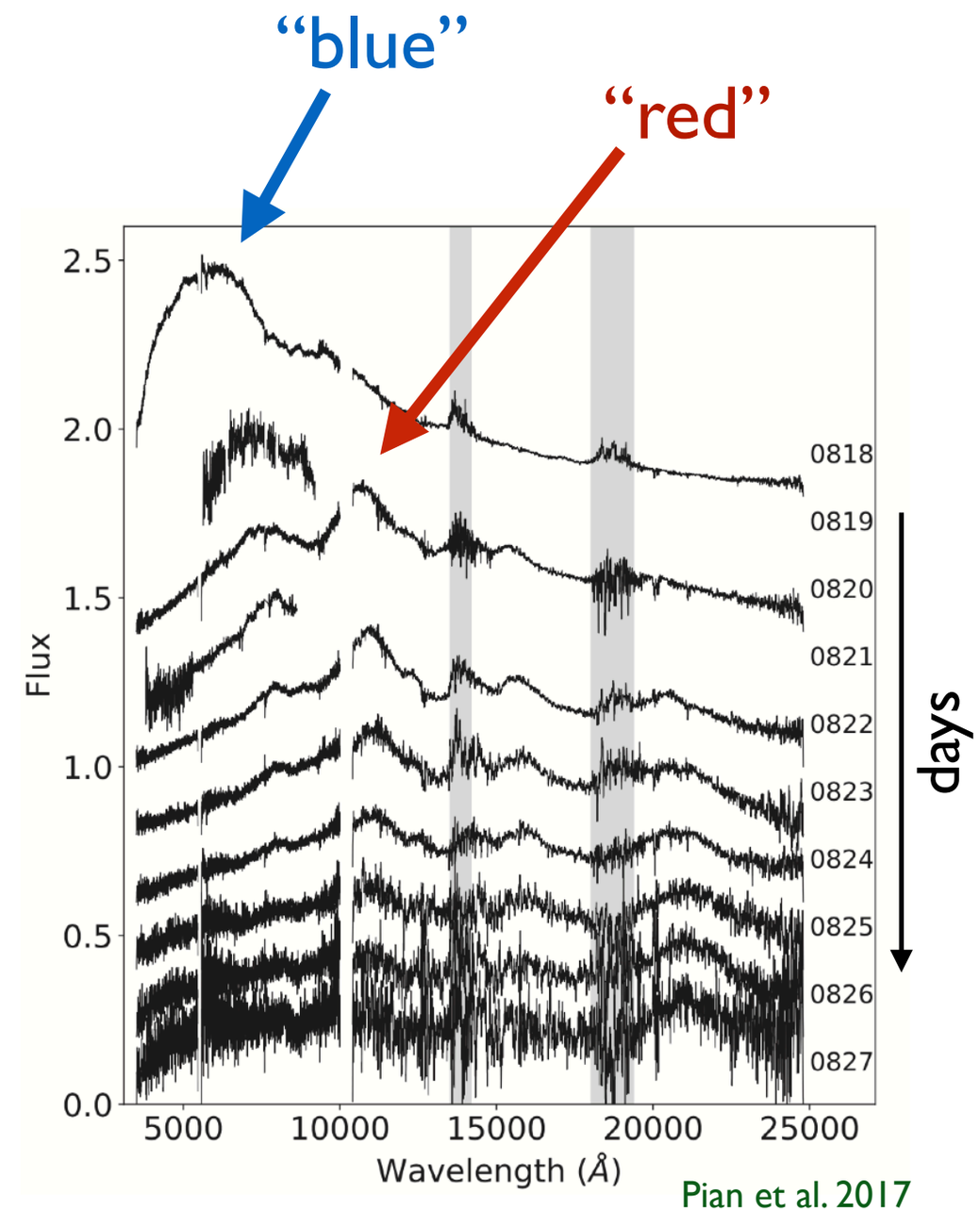
1) "blue" kilonova

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)

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

expected opacity fits the requirement
e.g. Perego et al. 2014

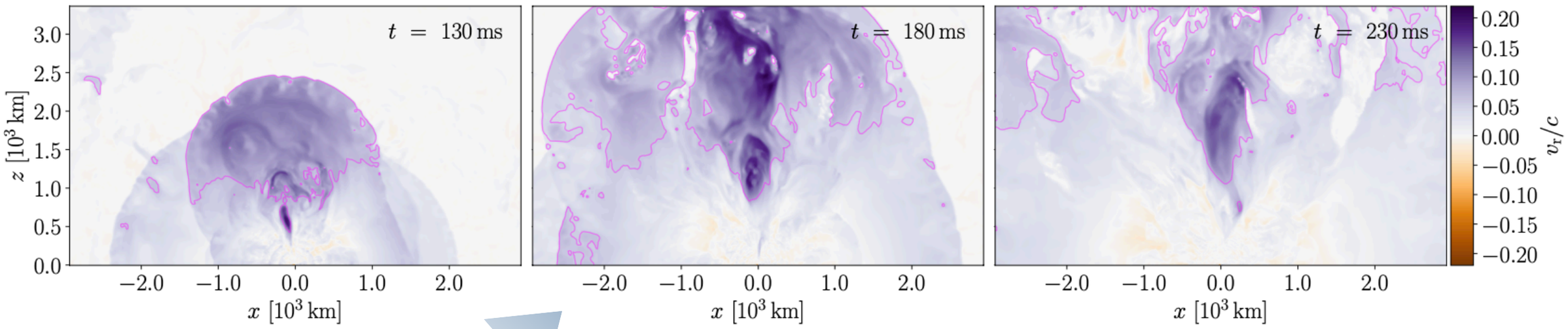
magnetic enhancement of mass outflow and acceleration to sufficiently high velocities → **to be demonstrated!**



Pian et al. 2017

Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

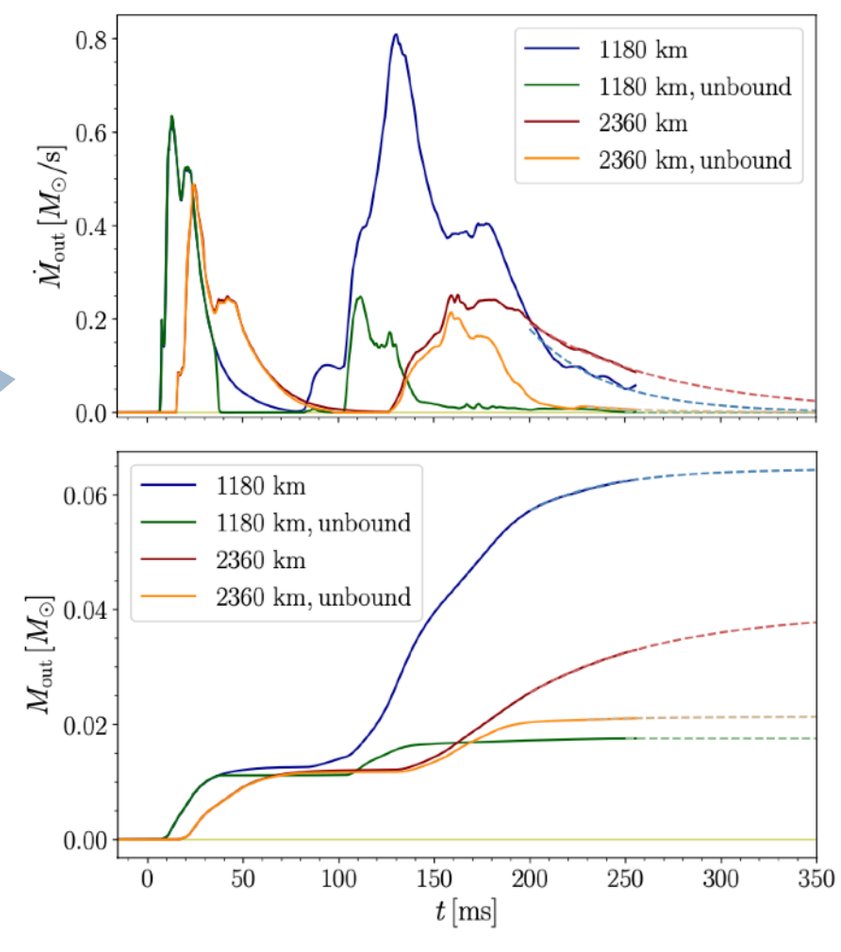


✓ **ejecta velocity**

~0.2 c marginally consistent with blue kilonova

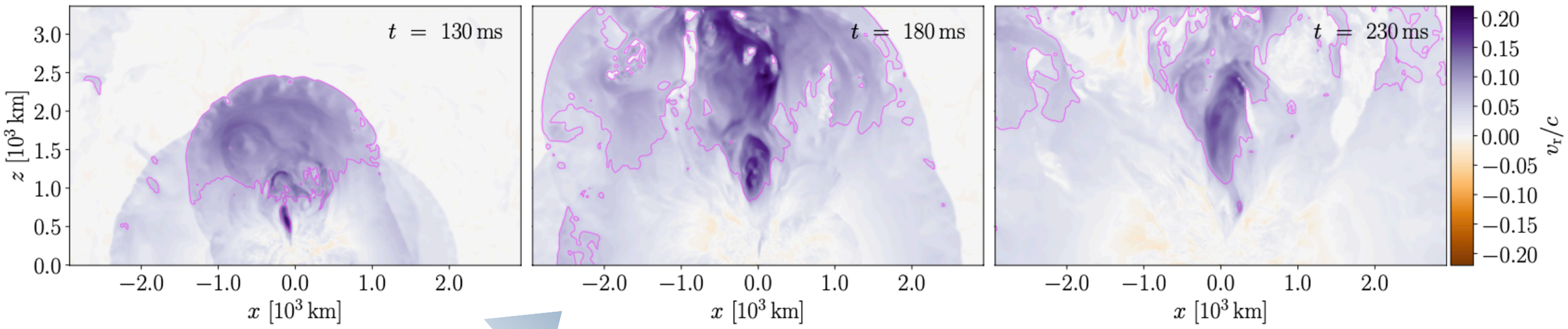
⟶ possible further enhancement

ejecta mass ?



Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

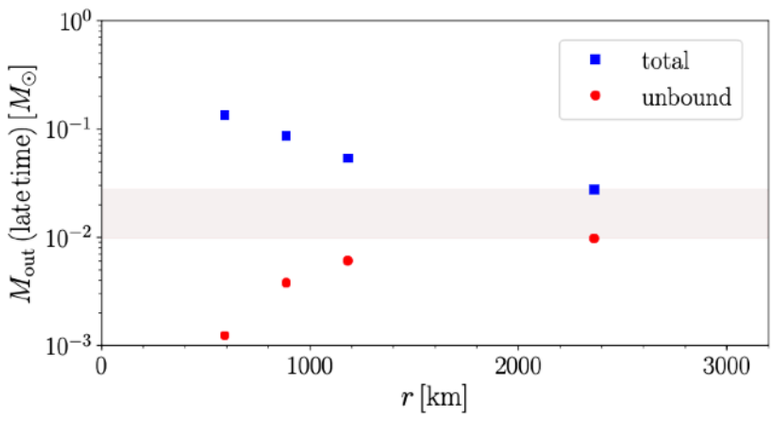


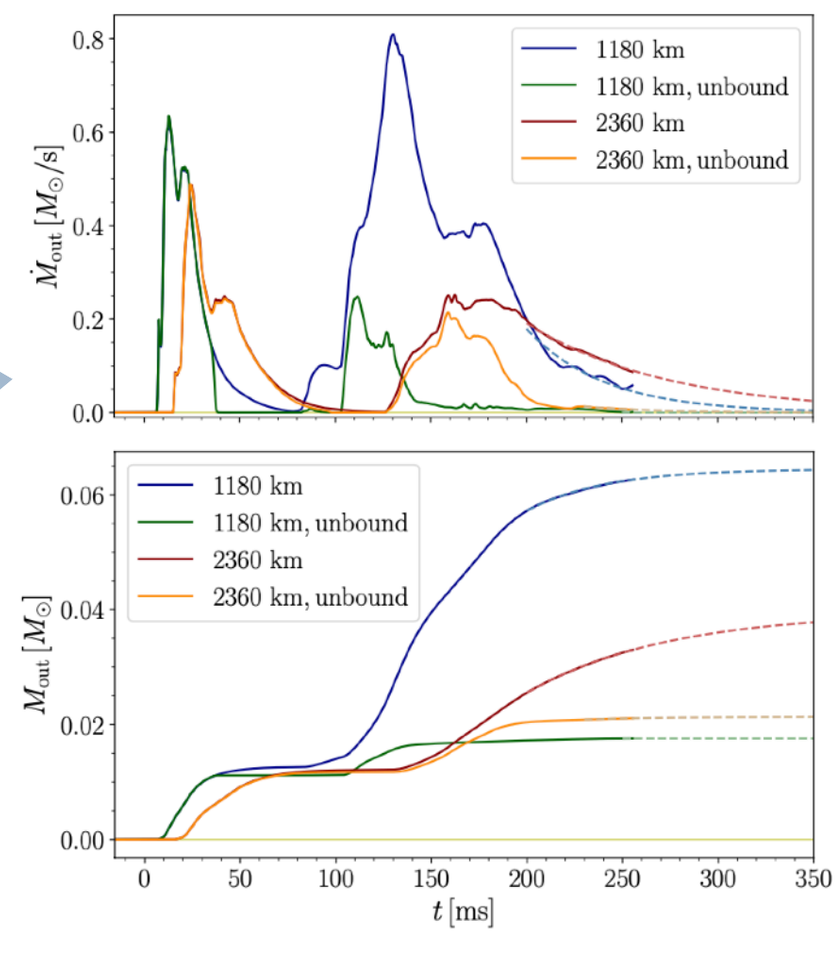
ejecta velocity

~0.2 c marginally consistent with blue kilonova

⟶ possible further enhancement

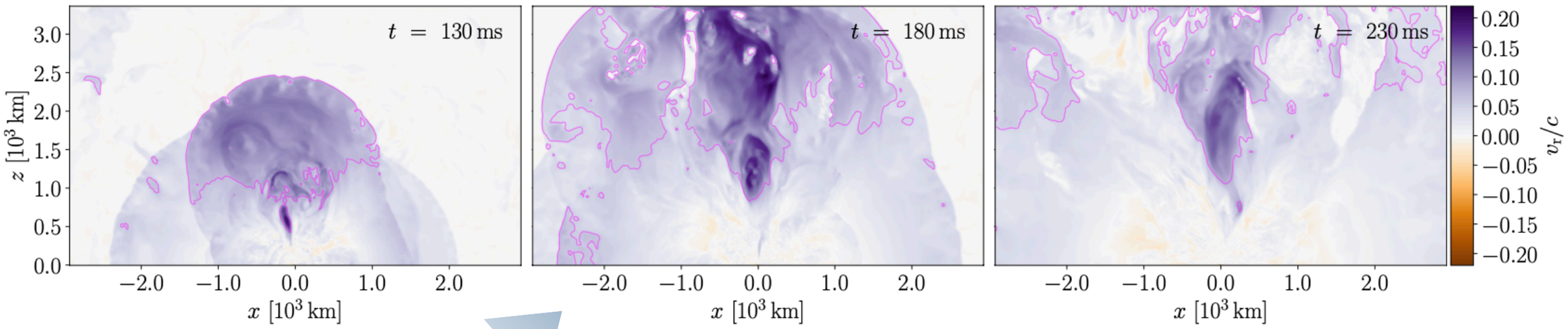
ejecta mass ?





Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

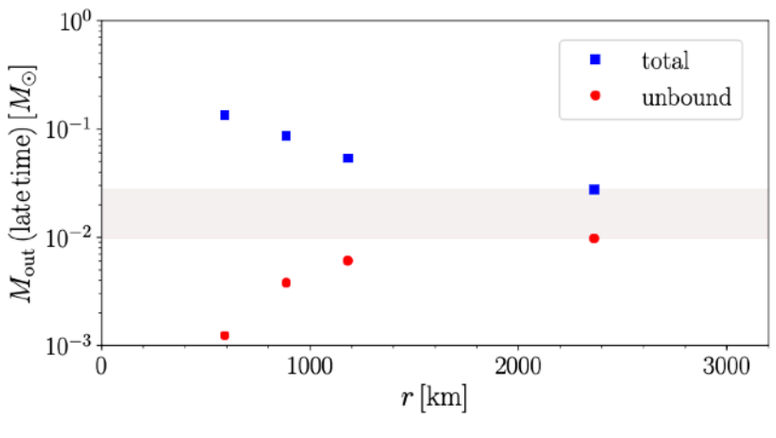


ejecta velocity

~0.2 c marginally consistent with blue kilonova

⟶ possible further enhancement

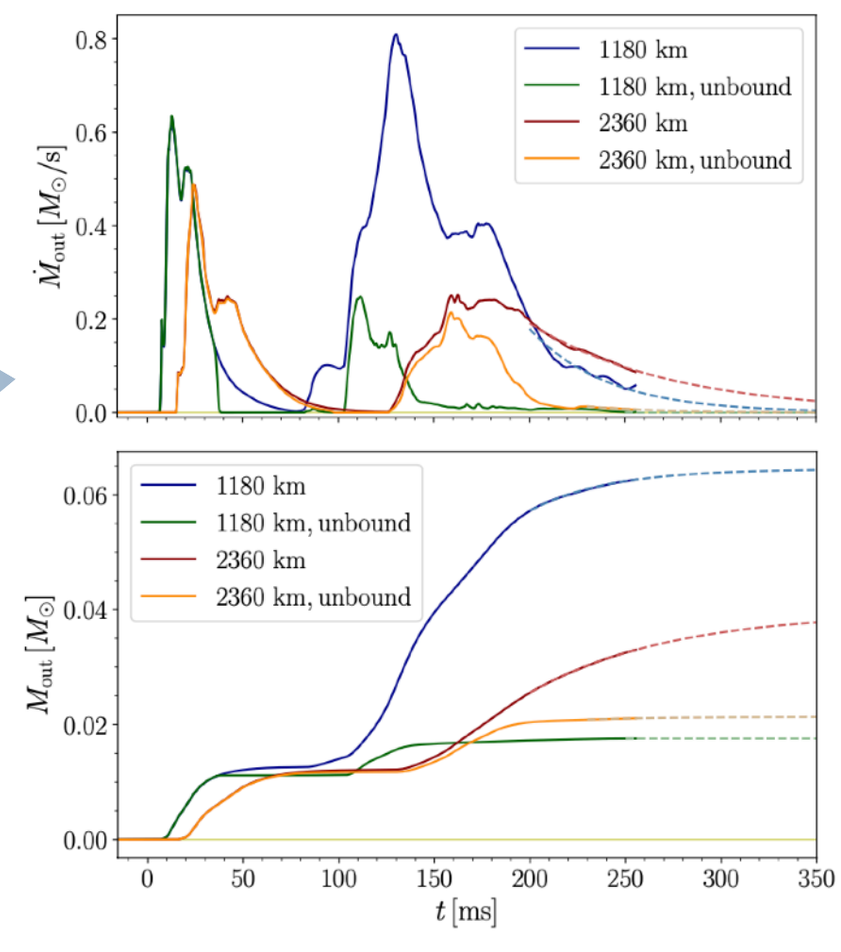
ejecta mass



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

to be compared with

$0.015 - 0.025\, M_\odot$



A scenario for GW170817

I) the merger produced a metastable massive NS, surviving fo a few x 100 ms

- the massive NS did not produce a jet
- its magnetically driven wind provided the main contribution to the **blue kilonova**

II) the collapse led to a BH surrounded by a massive disk (~0.1 Msun)

- the accreting BH launched the **SGRB jet** (possibly via Blandford-Znajek)
- baryon wind form the disk led to the **red kilonova**

Take-home message

- 2017 BNS merger left important question unanswered on the physical origin of the SGRB jet and the kilonova
- GRMHD simulations of the merger process represent the necessary investigating tool
- we found that massive NS remnants can launch collimated outflows and power blue kilonovae, but to produce a SGRB jet we (likely) need an accreting BH

References

- **R. Ciolfi**, J.V. Kalinani (2020), submitted, ArXiv:2004.11298
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

- **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, **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

- 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 REVIEW ARTICLES

- **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

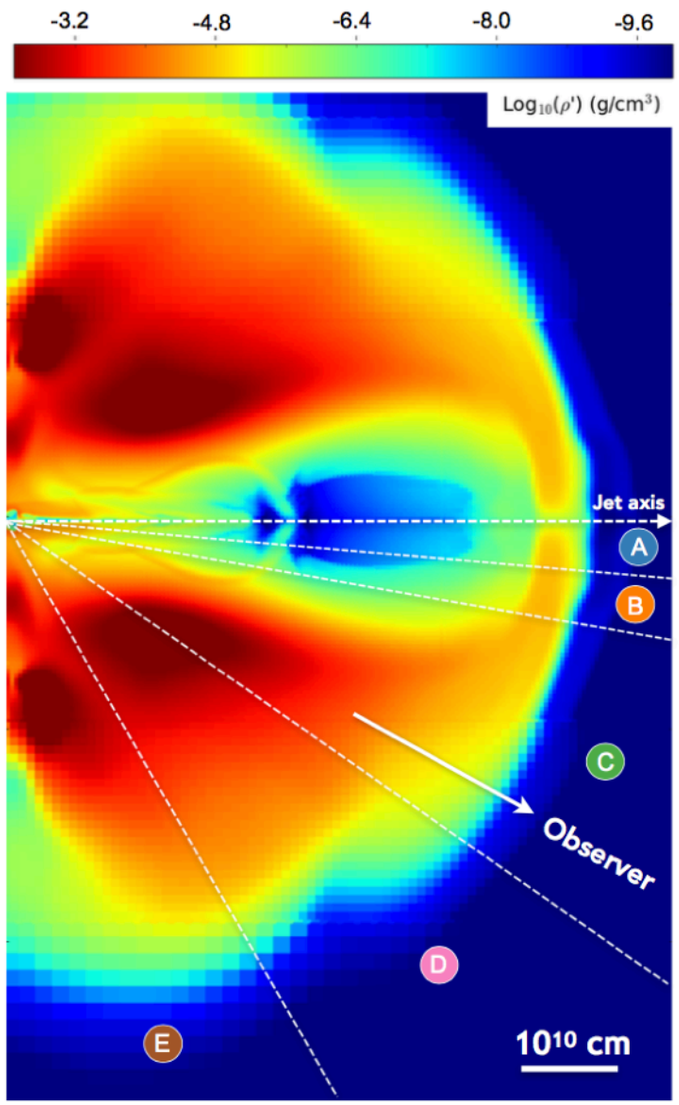
- **R. Ciolfi** (2020b), General Relativity and Gravitation **52**, 59, Invited Review for the Topical Collection on “Binary neutron star mergers” (Guest Editor N. Stergioulas)
The key role of magnetic fields in binary neutron star mergers

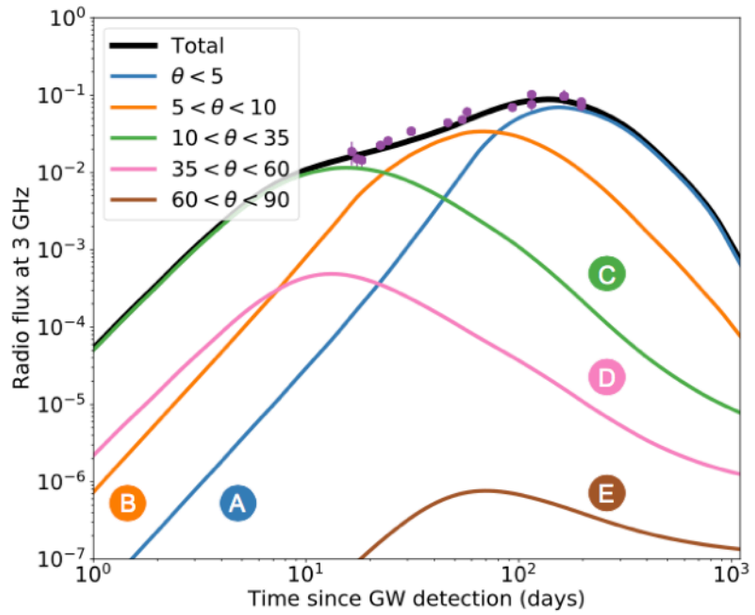
- **R. Ciolfi** (2018), IJMPD **27**, No. 13, 1842004, Invited Review for the Special Issue “Gamma-Ray Bursts in the Multi-Messenger Era” (Guest Editor L. Nava)
Short gamma-ray burst central engines

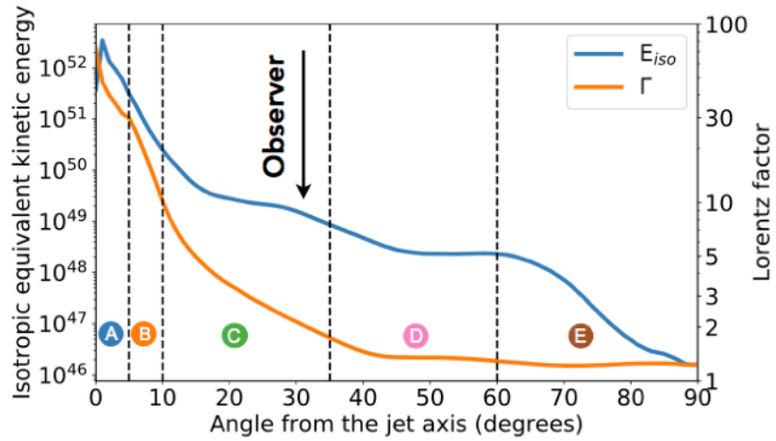
BACKUP SLIDES

GRB 170817A: Canonical SGRB?

Lazzati+2018





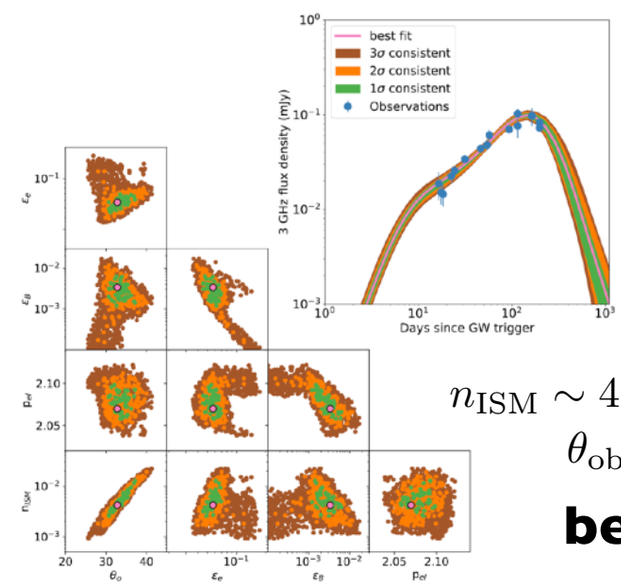


special relativistic jet simulation

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

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

multiwavelength afterglow calculation



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

$\theta_{\rm obs} \sim 33°$

best fit

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

GRB 170817A: intrinsic jet properties

Lazzati, Ciolfi, Perna 2020

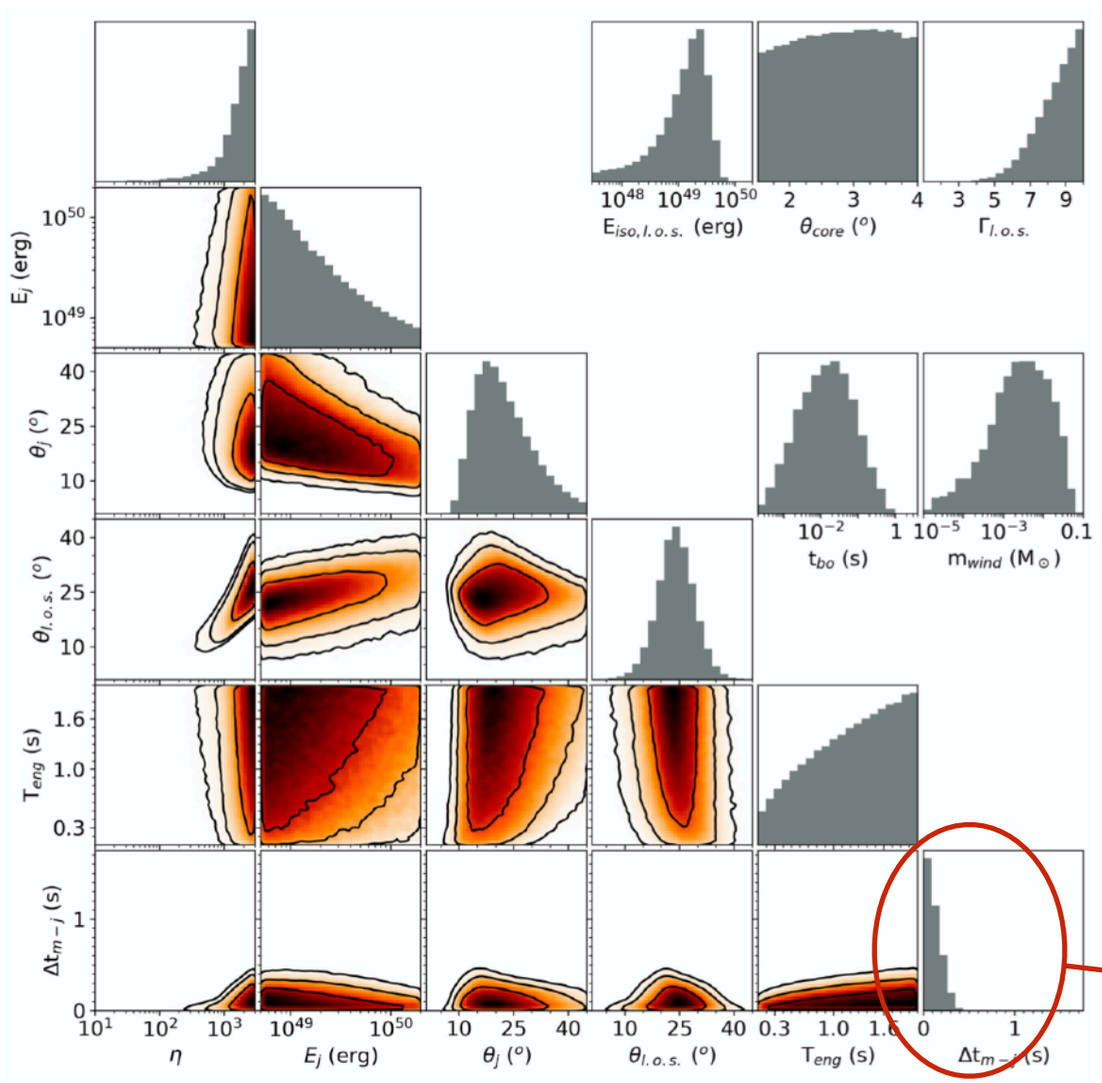
incipient jet → interaction with the baryon wind from the massive NS → final jet properties

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



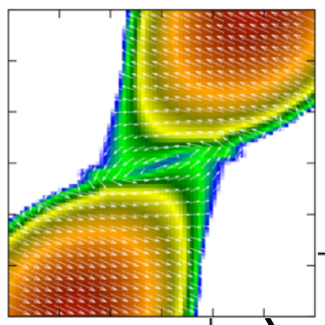
jet launching time < 0.4 s

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	$30.5^{+8.3}_{-8.8}$	$10.8^{+8.6}_{-3.6}$

Magnetic field amplification

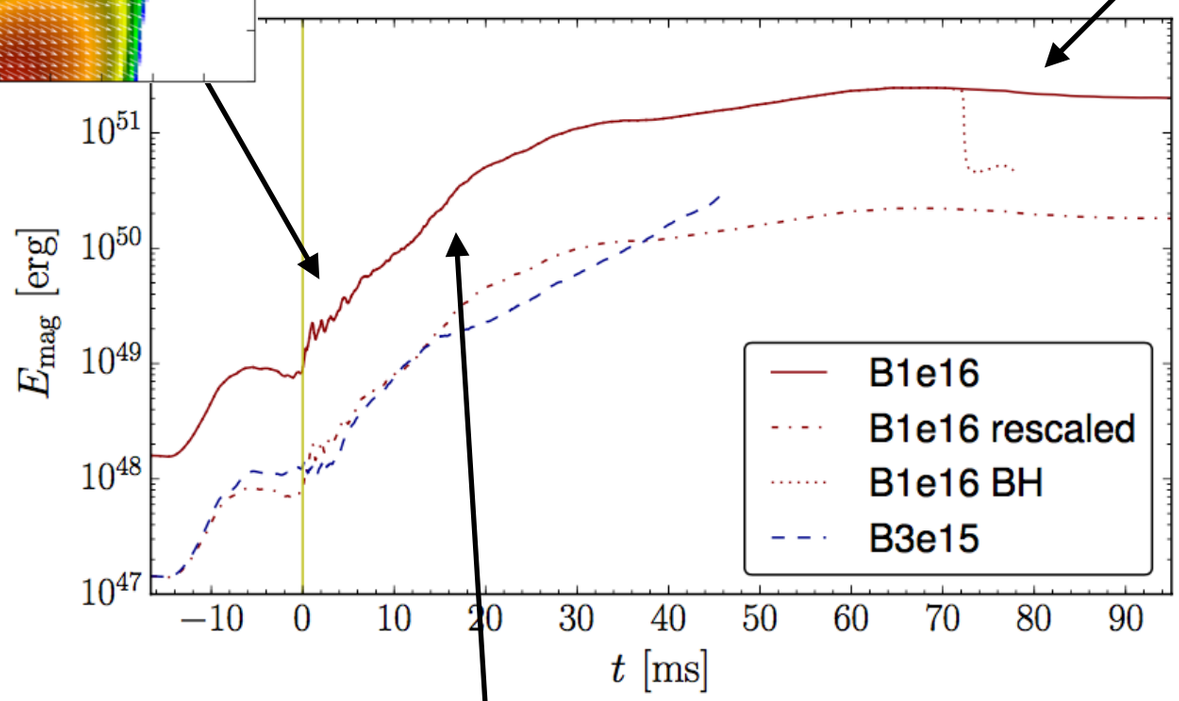
Ciolfi+2019

Kiuchi+2015



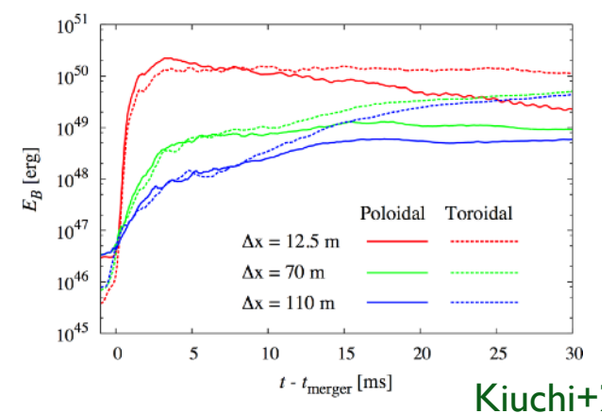
Kelvin-Helmholtz Instability

toroidal field amplification



magnetic energy saturation

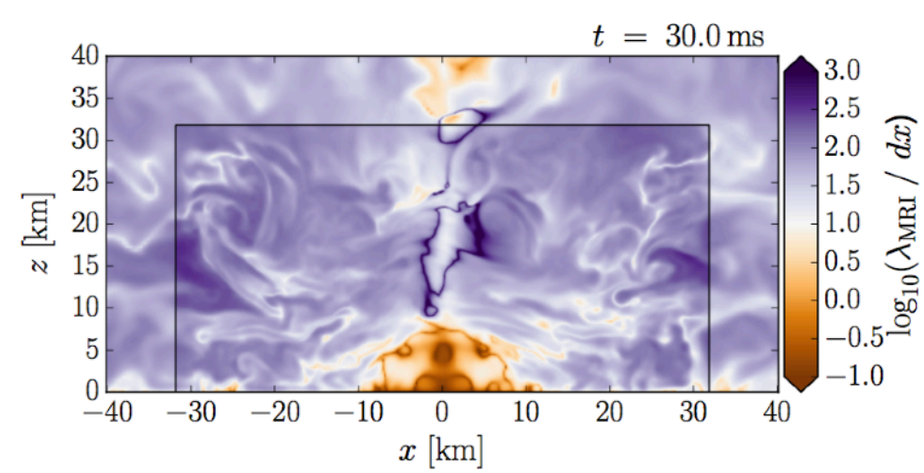
- clear signs of a physical saturation
- indication of maximum magnetic energy achievable in BNS mergers



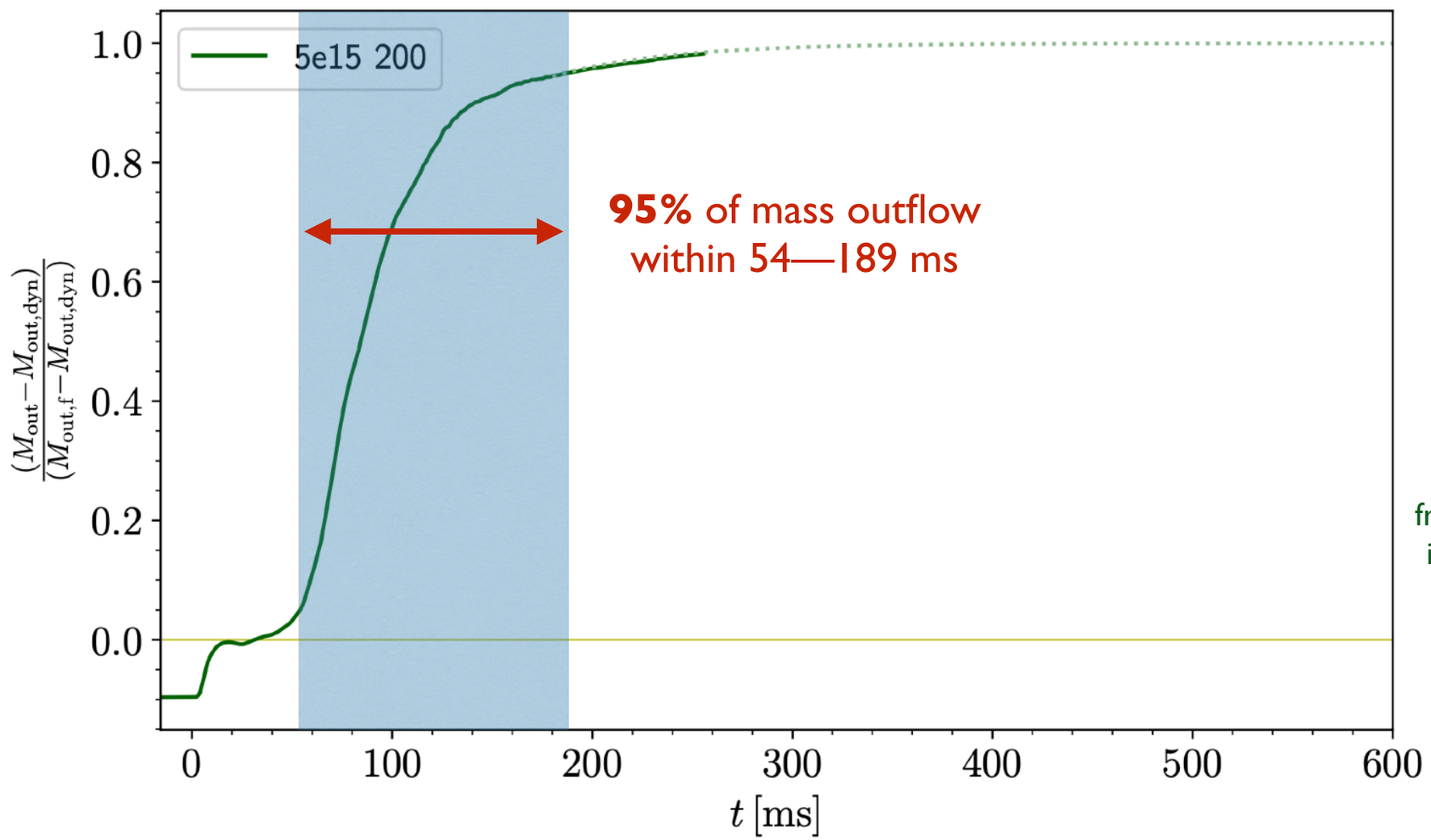
Kiuchi+2018

MagnetoRotational Instability

- well resolved 30 ms after merger
- inactive in the remnant NS core (<10 km from spin axis)



post-merger outflow at 300km



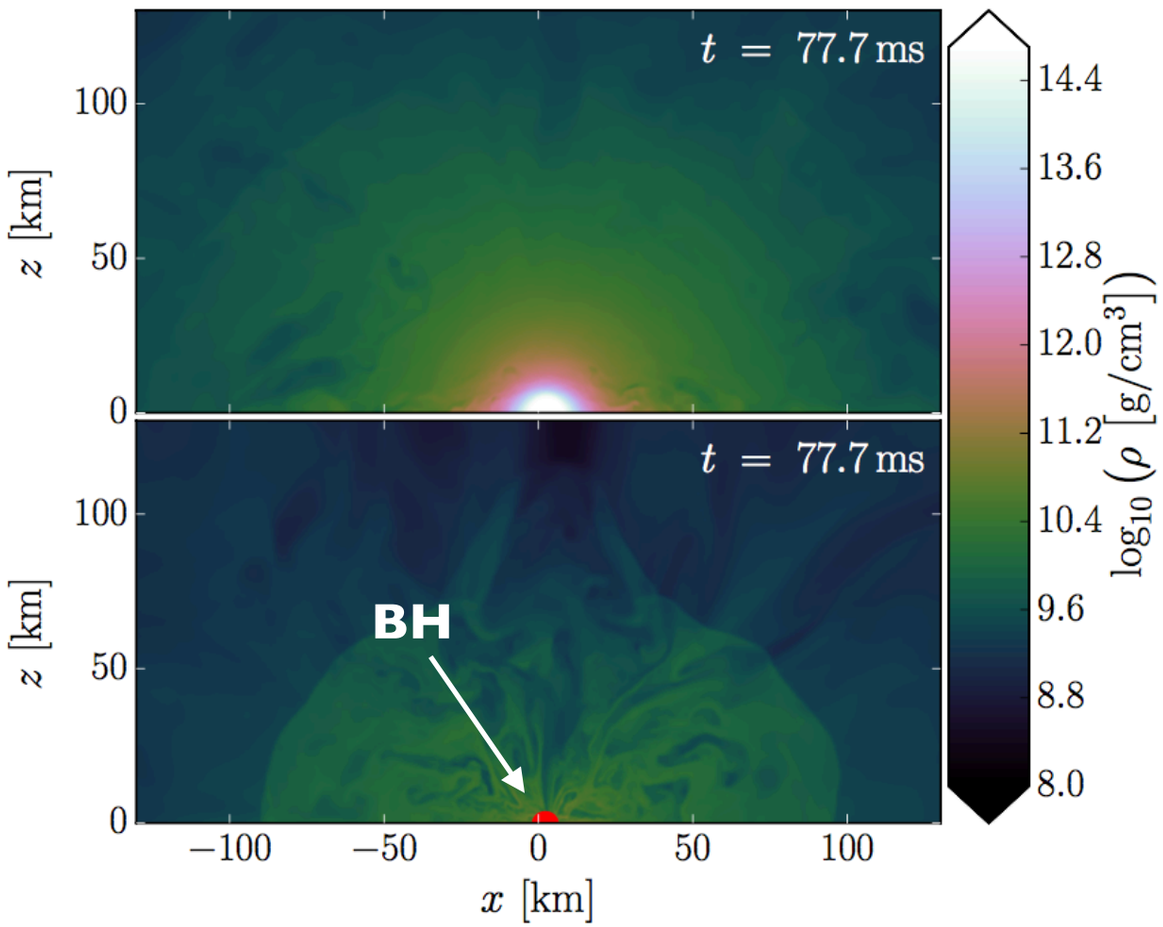
from simulation
in Ciolfi2020a

- 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)

What if the remnant collapses?



induced collapse 72 ms after merger

BH mass	$M_{\rm BH} \simeq 2.5\,M_\odot$
BH spin	$\chi \equiv Jc/GM^2 \simeq 0.5$
disk mass	$M_{\rm disk} \simeq 0.1\,M_\odot$

$$L_{\rm BZ} \sim 10^{52}\left(\frac{\chi}{0.5}\right)^2\left(\frac{M_{\rm BH}}{2.5\,M_\odot}\right)^2\left(\frac{B_{\rm BH}}{10^{16}\,{\rm G}}\right)^2\ {\rm erg/s}$$

BZ jet likely able to drill through heavy ejecta layer

relative difference in density collapsing v.s. non-collapsing

no effect above ~200 km