Multimessenger astrophysics with neutron stars: looking ahead towards the 3G era

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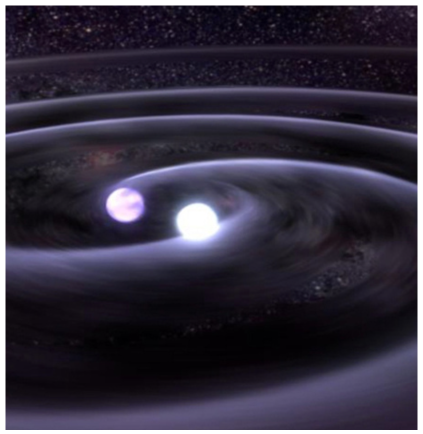
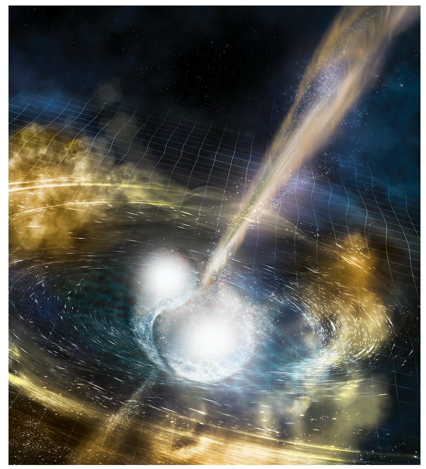
GWADW2019 - Gravitational-Wave Advanced Detector Workshop - From Advanced Interferometers to Third Generation Observatories

La Biodola, Isola d’Elba
20th May 2019

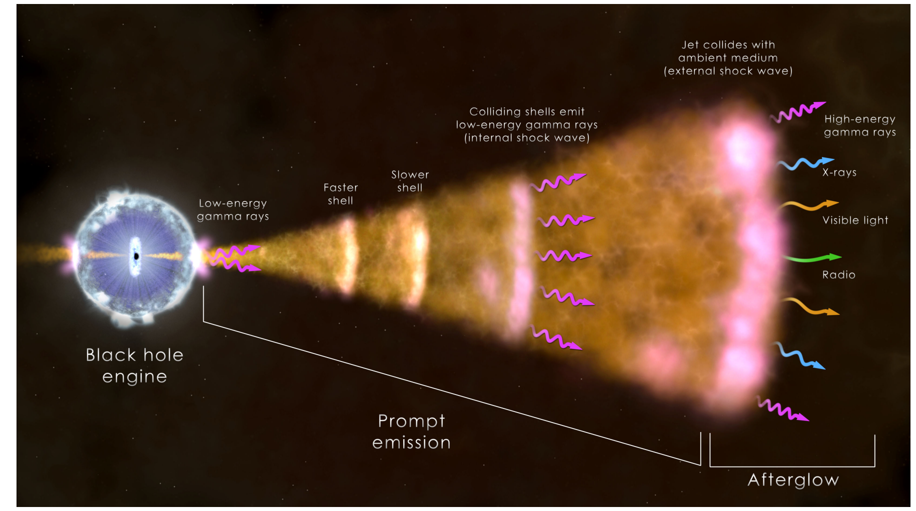
GW170817 detection timeline



merger



short GRB



X-ray afterglow

radio afterglow

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

optical
counterpart

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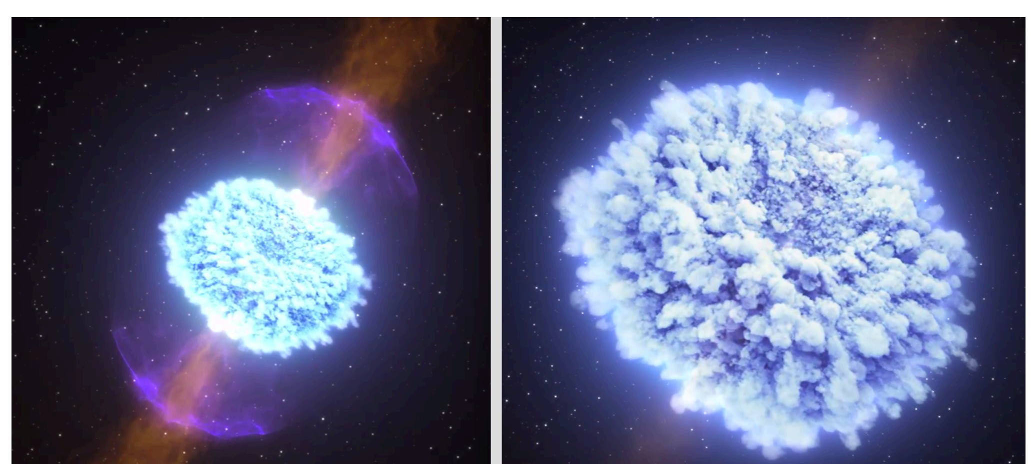
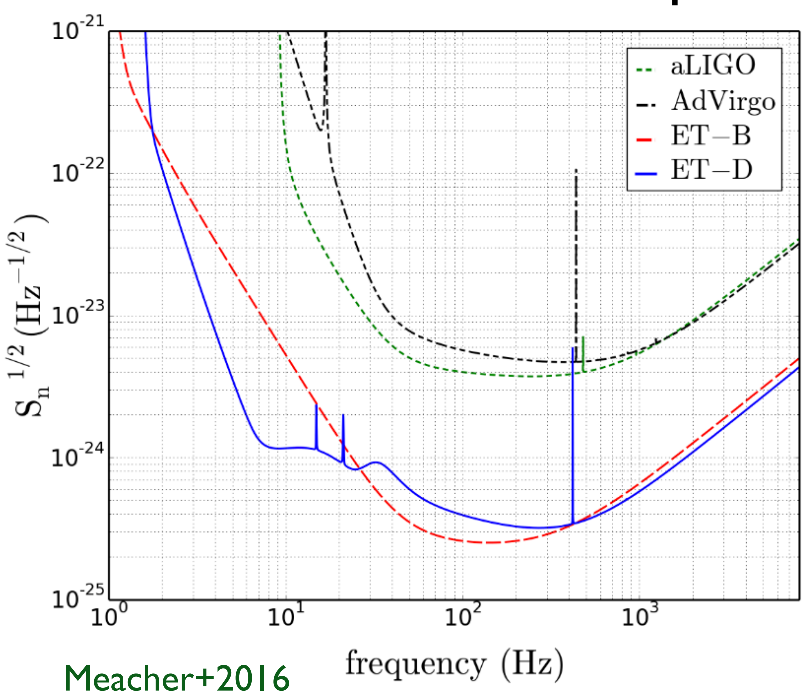
kilonova



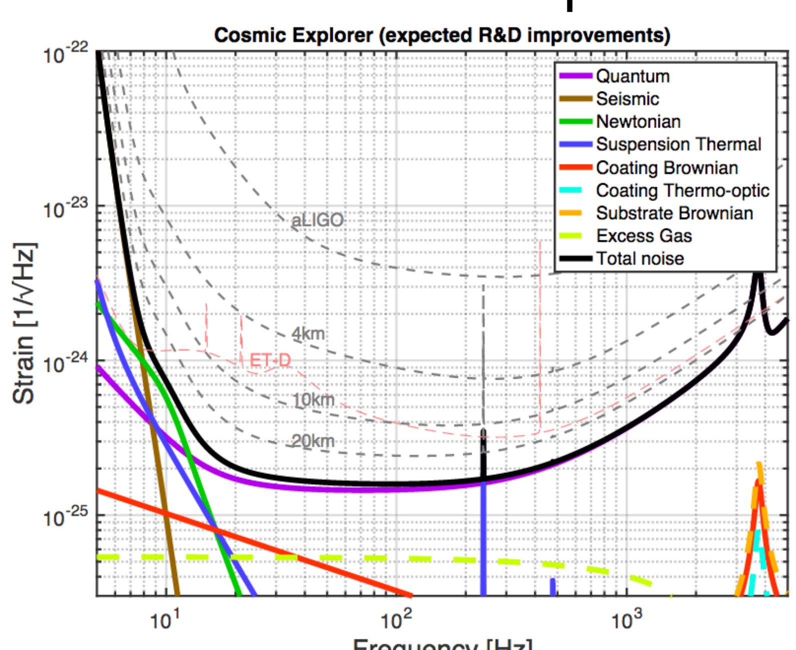
From 2nd to 3rd generation

ET - Einstein Telescope



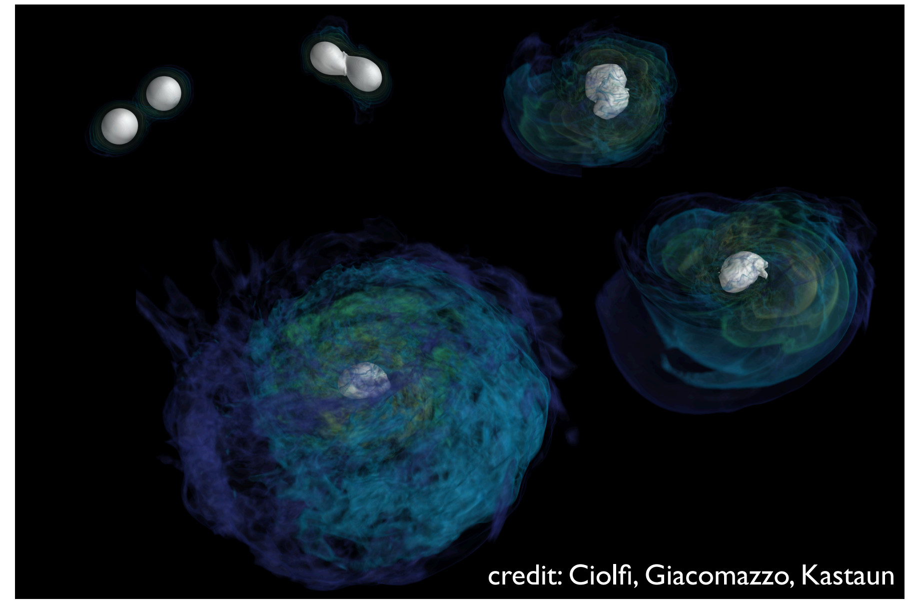
Meacher+2016

CE - Cosmic Explorer



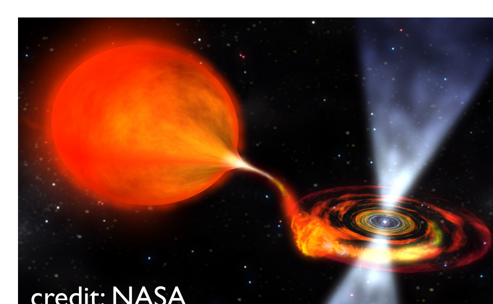
Abbott+2017

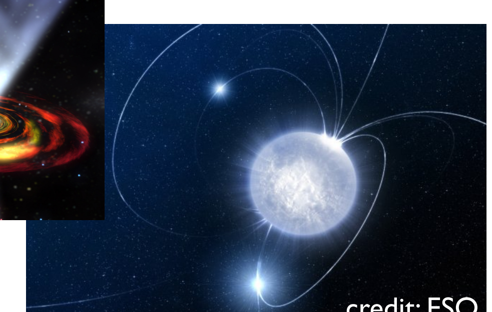
compact binary mergers



supernovae

neutron stars → rotating accreting bursting glitching

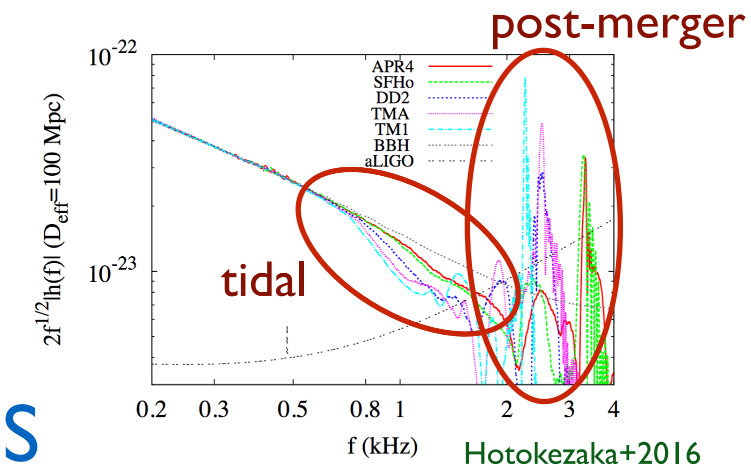


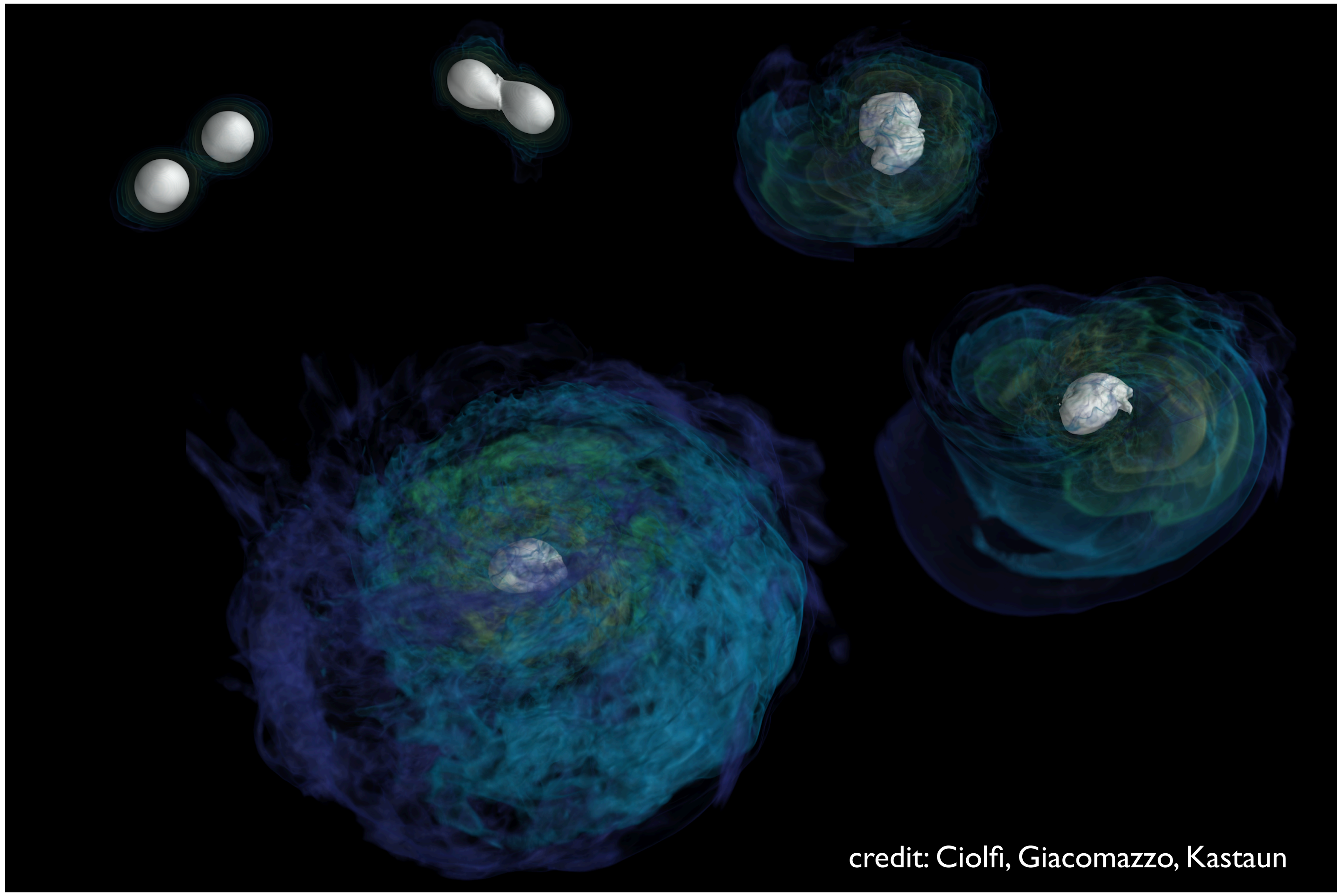


MULTIMESSENGER GW SOURCES

3G: NSNS and NSBH

- huge increase in detection rates
  order ~10^5-10^6 BNS mergers per year!
- much higher SNR for mergers within current range
  NS tidal deformations, post-merger signal ⟶ NS EOS





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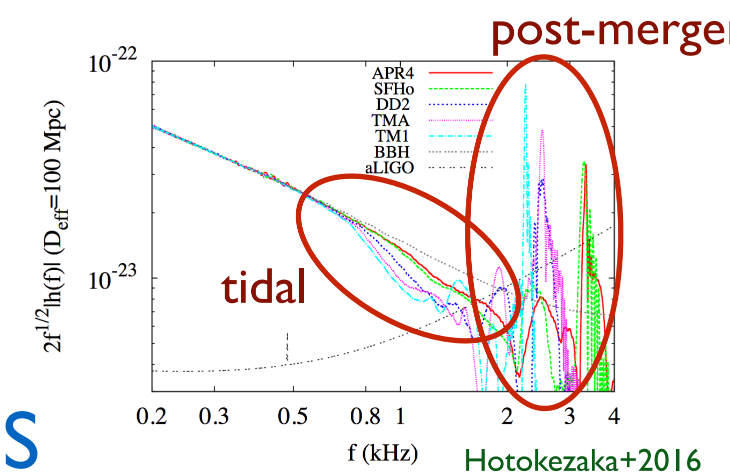


- many mergers (~15k/yr) with ~1 sq. degree localization

~10^3 host galaxy identifications ➡ understanding NSNS, NSBH origin and population

from KN (z<0.5) and sufficiently on-axis SGRB afterglows (z>0.5)

many more SGRB/merger associations ➡ jet structure and properties
link to cosmological SGRBs

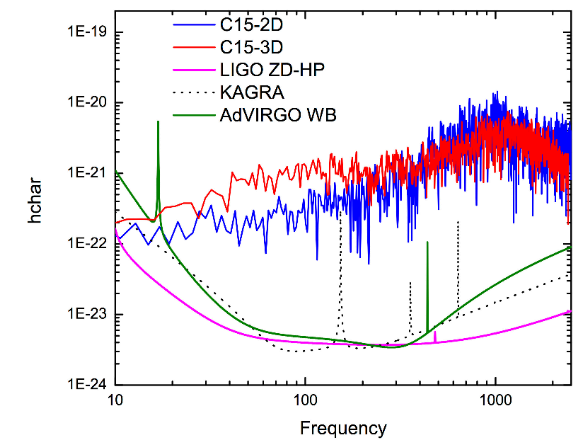
many more kilonova signals ➡ ejecta and nucleosynthesis yields

role of NSNS/NSBH mergers in heavy element production

Supernovae

GW signal currently detectable within galactic distance ~10kpc
limiting factor is the galactic SN rate ~1 in 30-50 yrs

Yakunin+2017

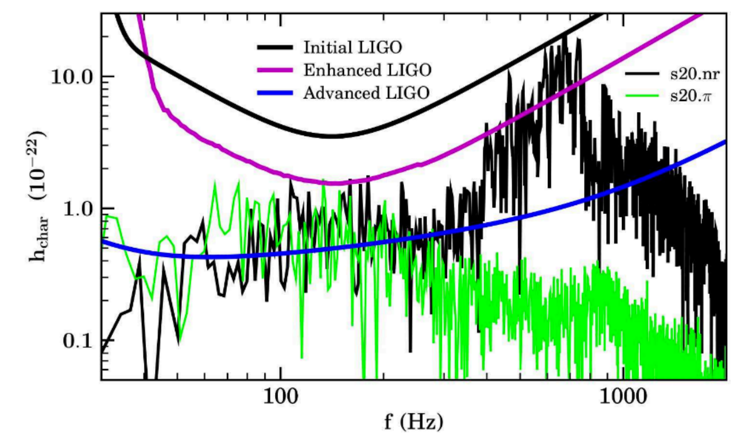


→ GWs are the best probe of the exploding dynamics

<u>different explosion mechanisms</u>:
neutrino-driven, magnetorotational, acoustic, …

<u>different phases/contributions</u>:
collapse-bounce, convection, SASI, proto-NS pulsations, …

Ott+2009

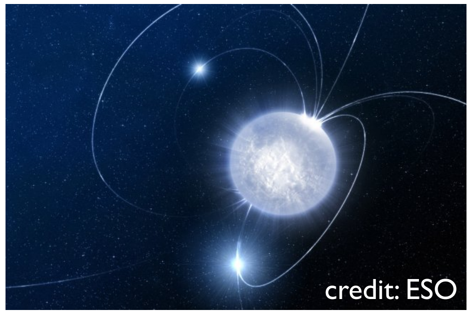


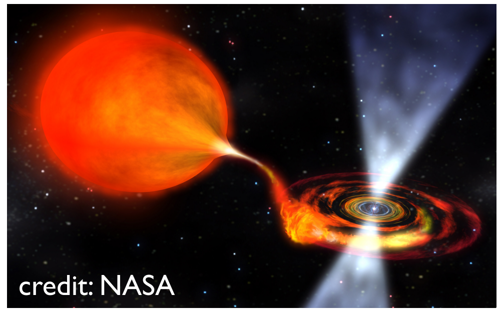
→ multimessenger sources: GW+EM+neutrino signals

3G detectors era:
ability to catch/understand the main signal components for a galactic event

(but not much gain in events rates..)

Continuous GW sources

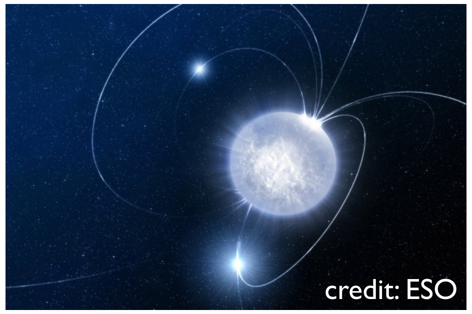


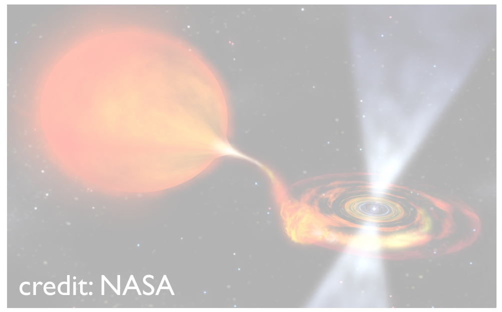


targeted search   EM ⟶ GW

all-sky search   GW ⟶ EM?

Continuous GW sources

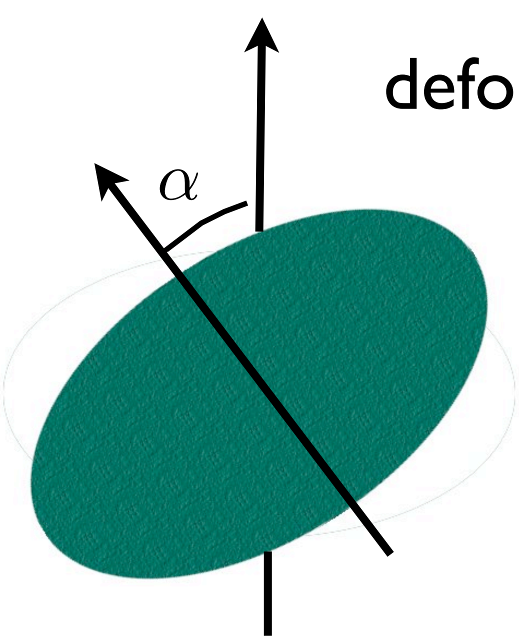




targeted search EM ⟶ GW

all-sky search GW ⟶ EM?

isolated neutron stars

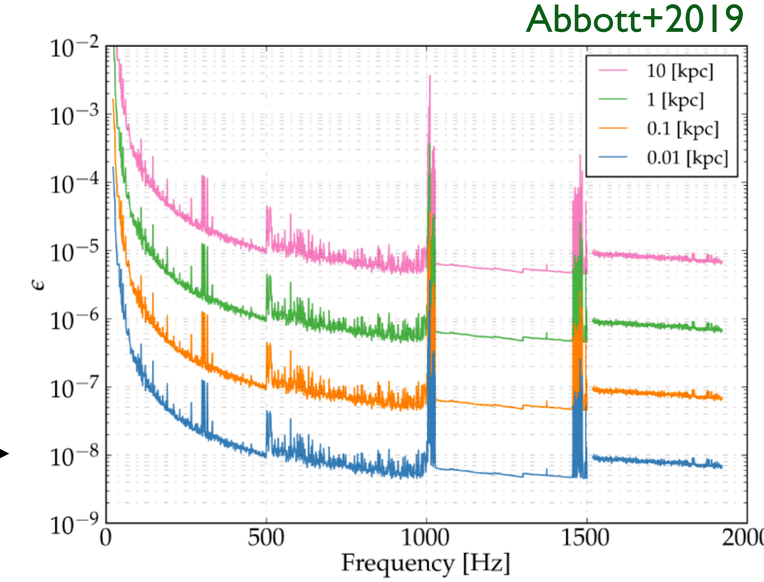


deformation+rotation+misalignment

$$h_0 = \frac{4G}{rc^4}\Omega^2 I|\epsilon_Q|$$

current upper limits ⟶

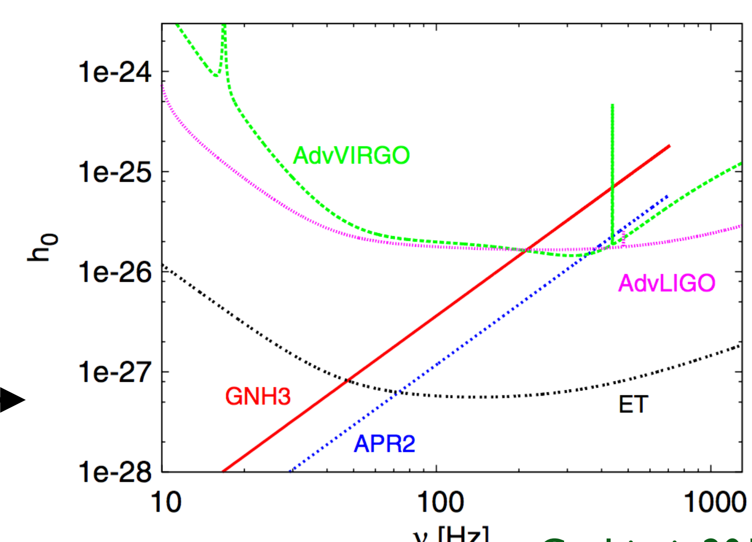
Abbott+2019



magnetic deformations
can be as large as 10^{-5}–10^{-4}

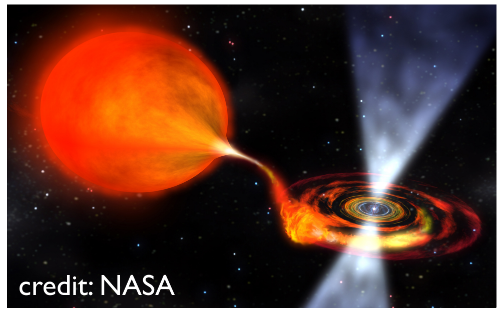
Ciolfi & Rezzolla 2013

newly-born magnetar makes an interesting case! ⟶



Gualtieri+2011

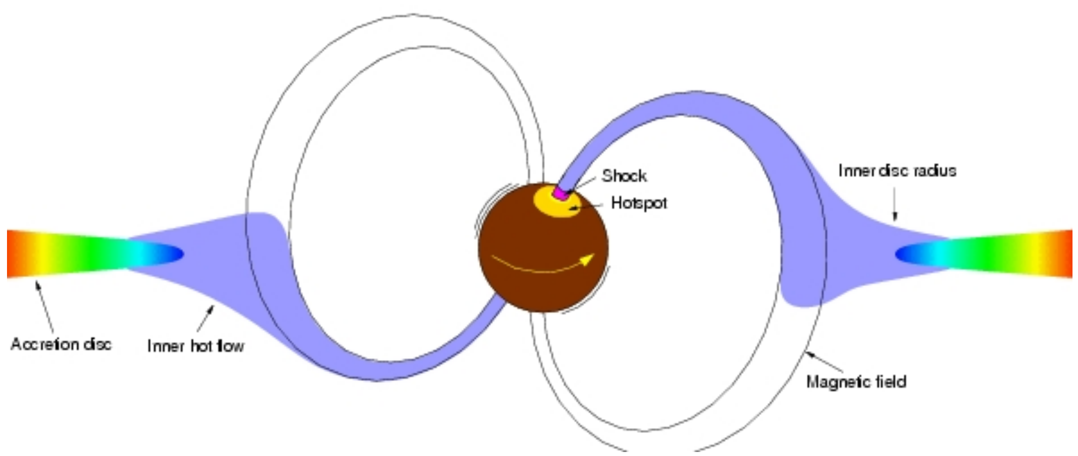
Continuous GW sources



targeted search EM ⟶ GW

all-sky search GW ⟶ EM?

<u>accreting neutron stars</u>

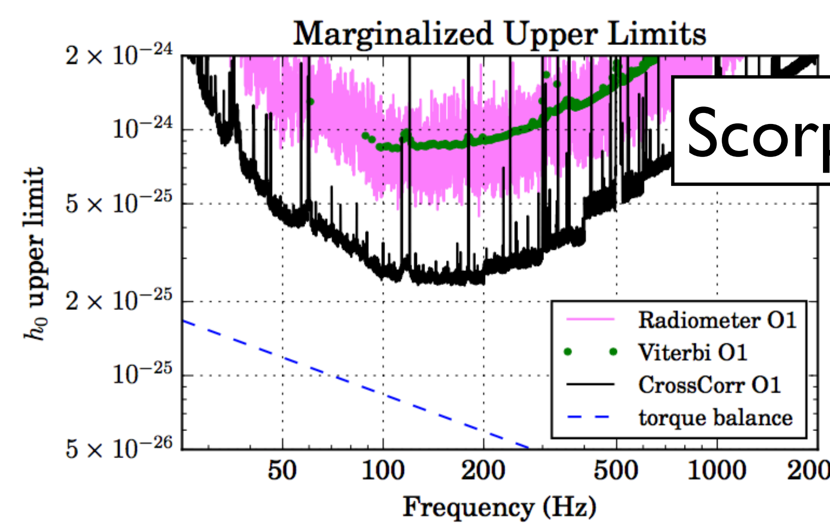


low-mass X-ray binary (LMXB) accretion is responsible for

creation of "mountains" (deformation) & angular momentum transfer (spin-up)

hypothesis of torque balance via GW emission would explain max spin observed ~700Hz

⟶ direct relation of GW and X-ray flux

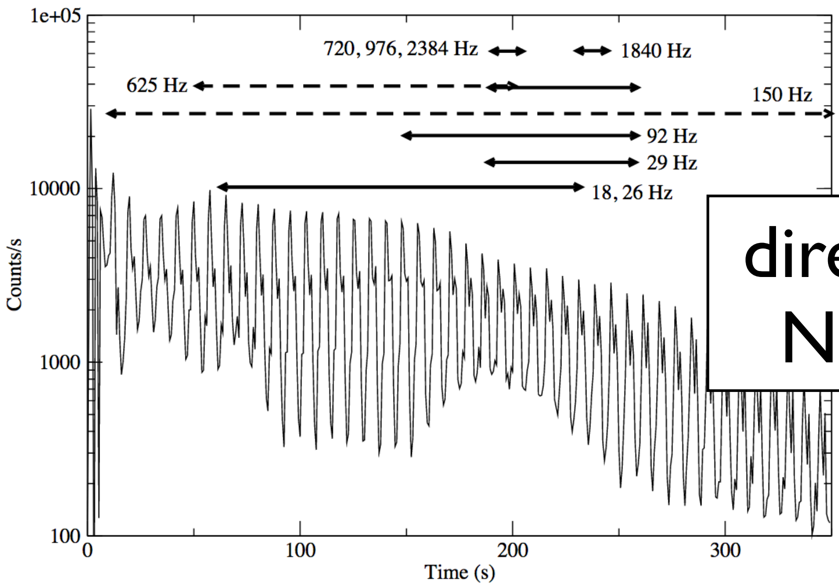


Scorpius X-1

Abbott+2017

Bursting neutron stars

Magnetar (giant) flares



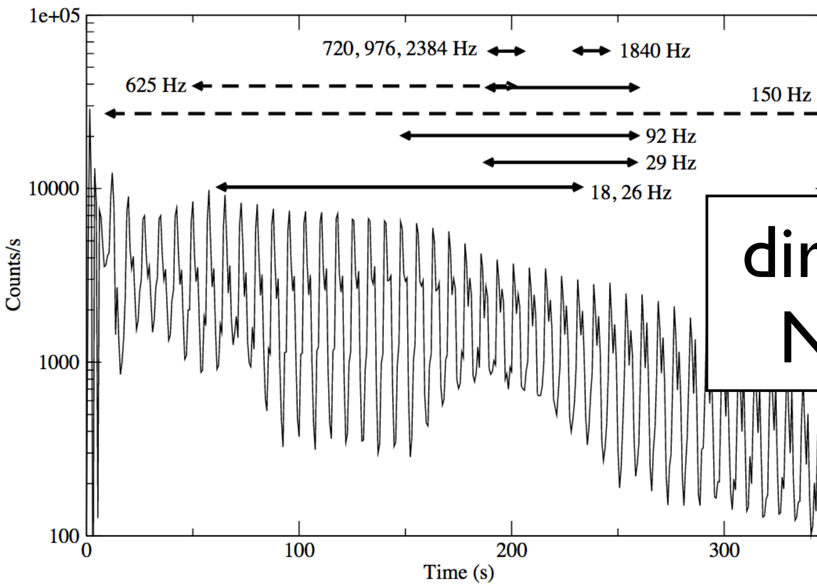
QPOs identified in X-ray transient

direct evidence of NS oscillations!

Strohmayer & Watts 2006

Bursting neutron stars

Magnetar (giant) flares



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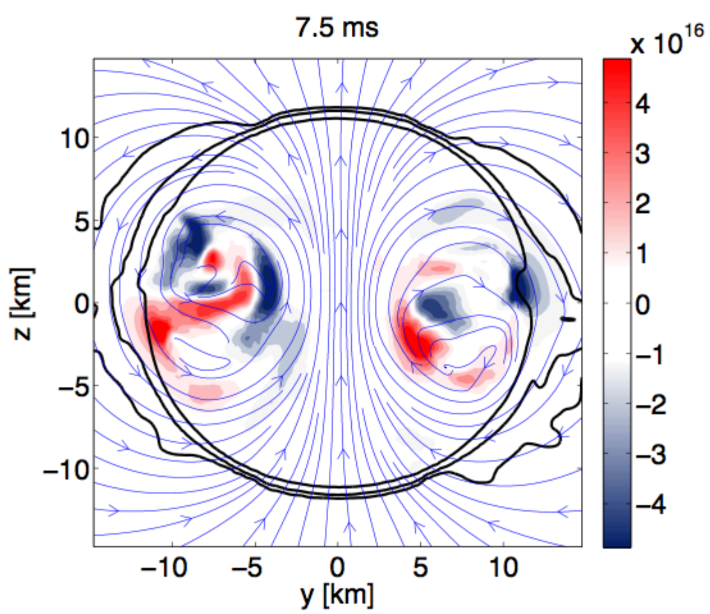
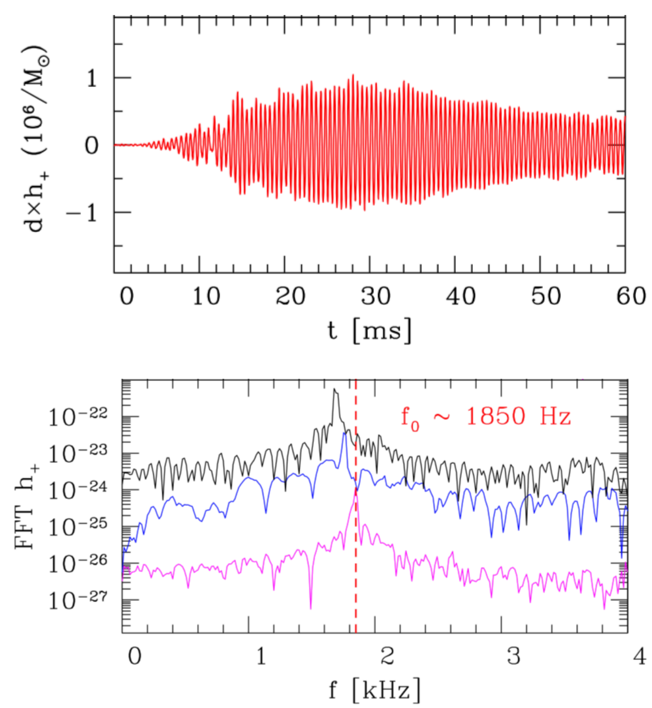
direct evidence of NS oscillations!

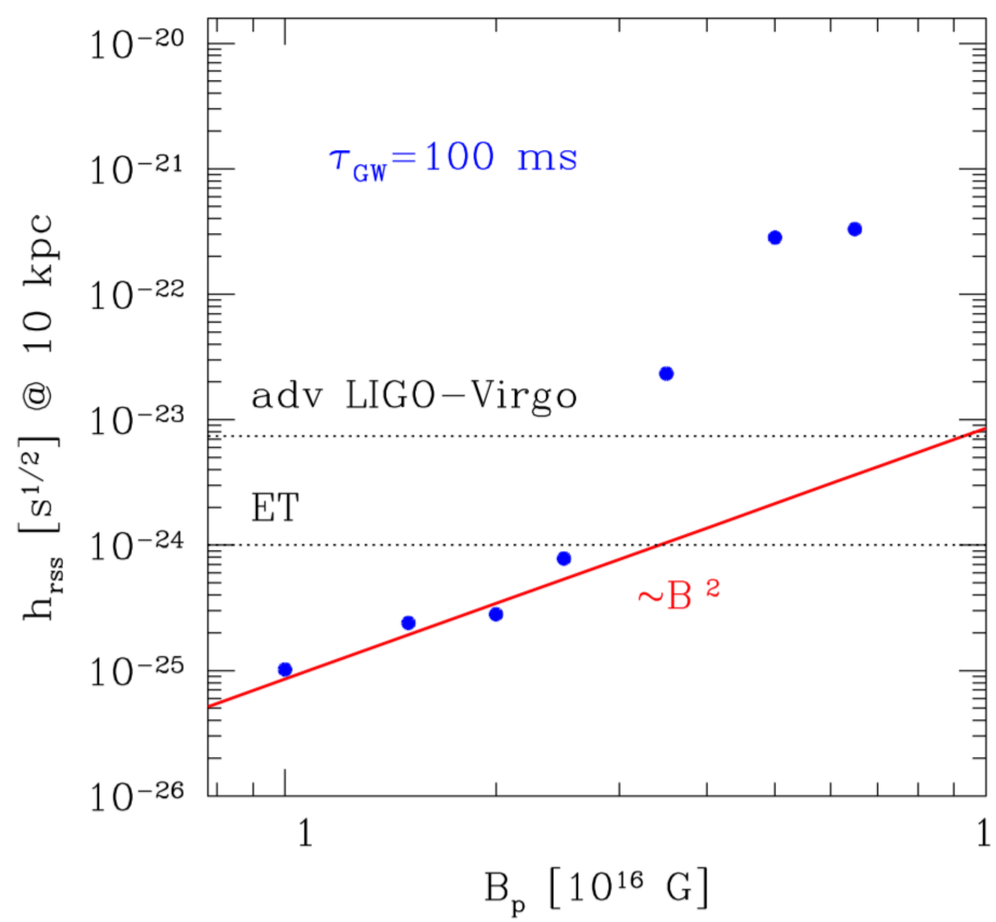
Strohmayer & Watts 2006

hydromagnetic instability ⟶ f-mode oscillations and GW emission



Ciolfi+2011, 2012

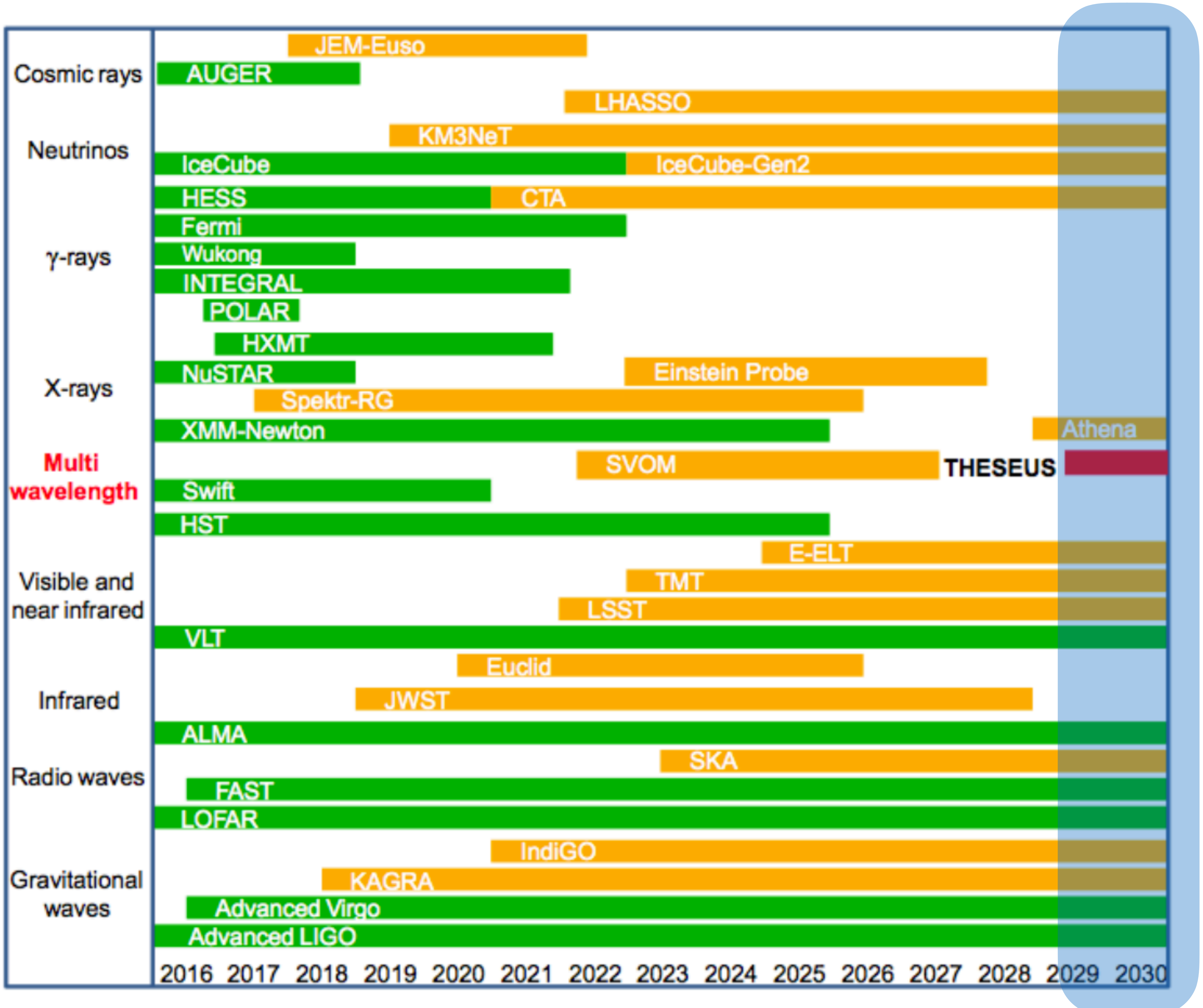




only small fraction of energy pumped into f-mode

Levin & Van Hoven 2011, Ciolfi+2011, 2012, Zink+2011, Lasky+2012

Synergies in 3G era



Stratta+2018

Take-home message

- multimessenger aspects play a key role in the present and future of GW astronomy $\longrightarrow$ should be given full consideration in planning 3G detectors

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3G era - multimessenger perspective

- **NSNS/NSBH** - from single event investigation to large statistical analysis $\longrightarrow$ compact binary population, SGRBs, nucleosynthesis, ..

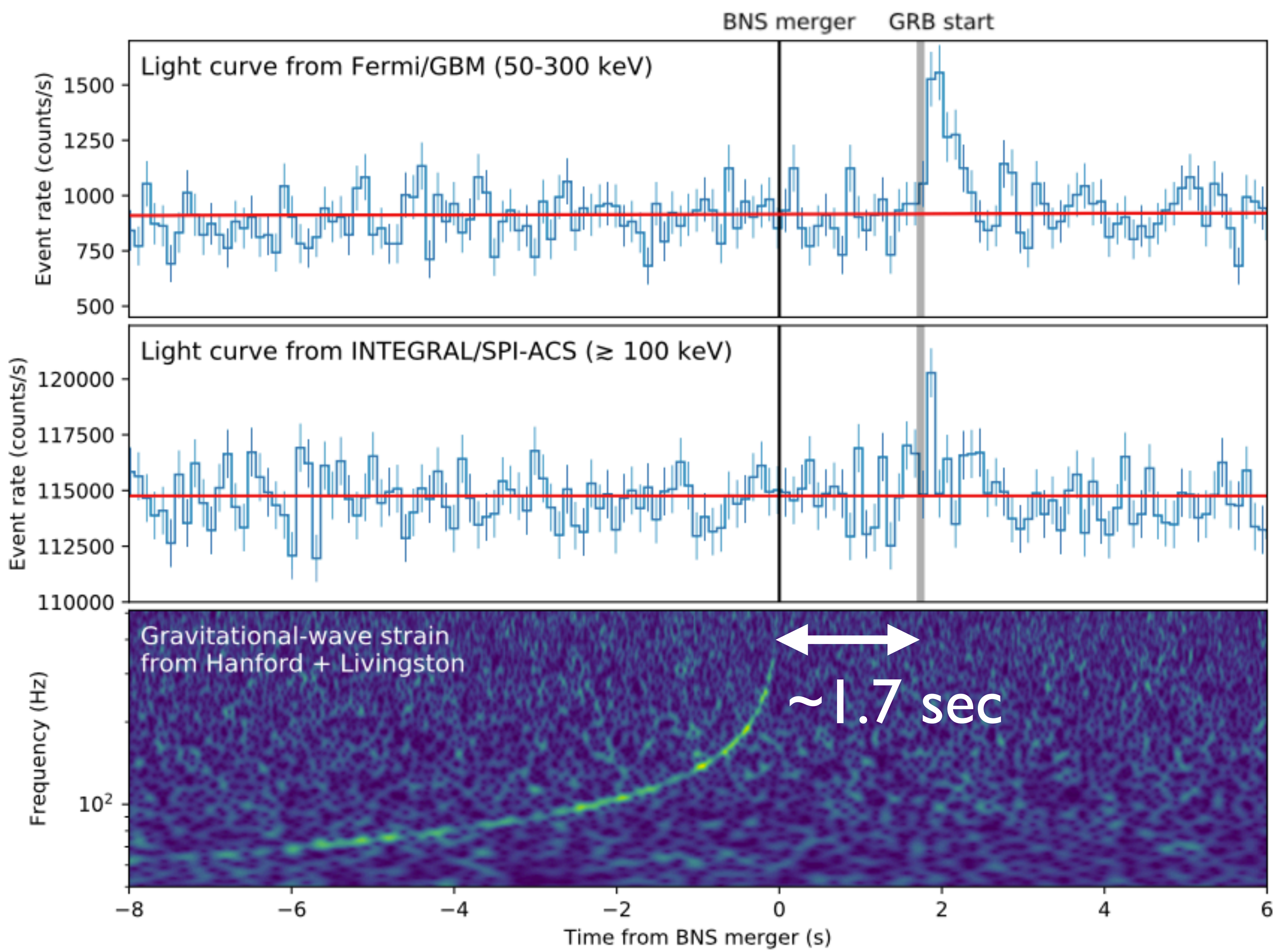
- great opportunities for yet undetected sources

  - increased potential to fully understand GW emission from **galactic SNe** (but not increased event rates)

  - much better prosepects to detect continuous GW signals from **isolated and accreting NSs** and GW transients from **bursting/glitching NSs**

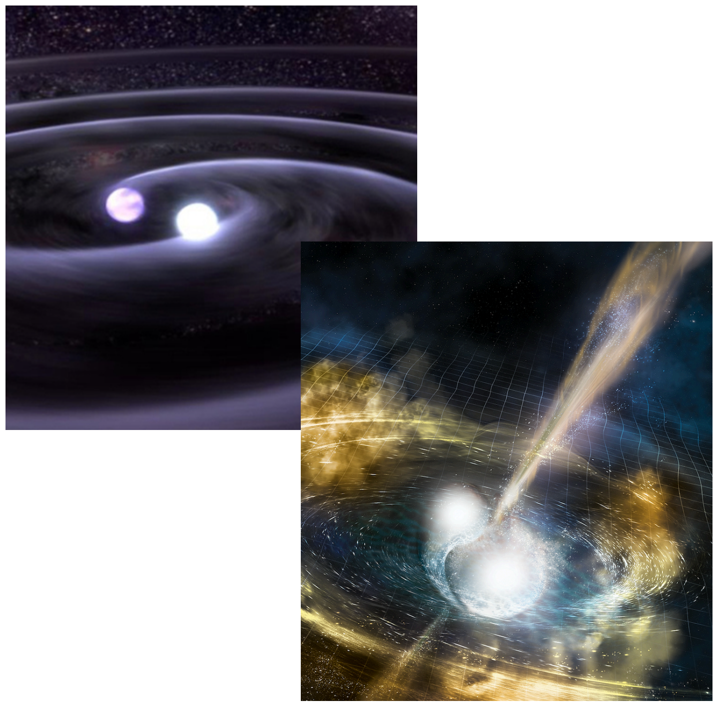
BACKUP SLIDES

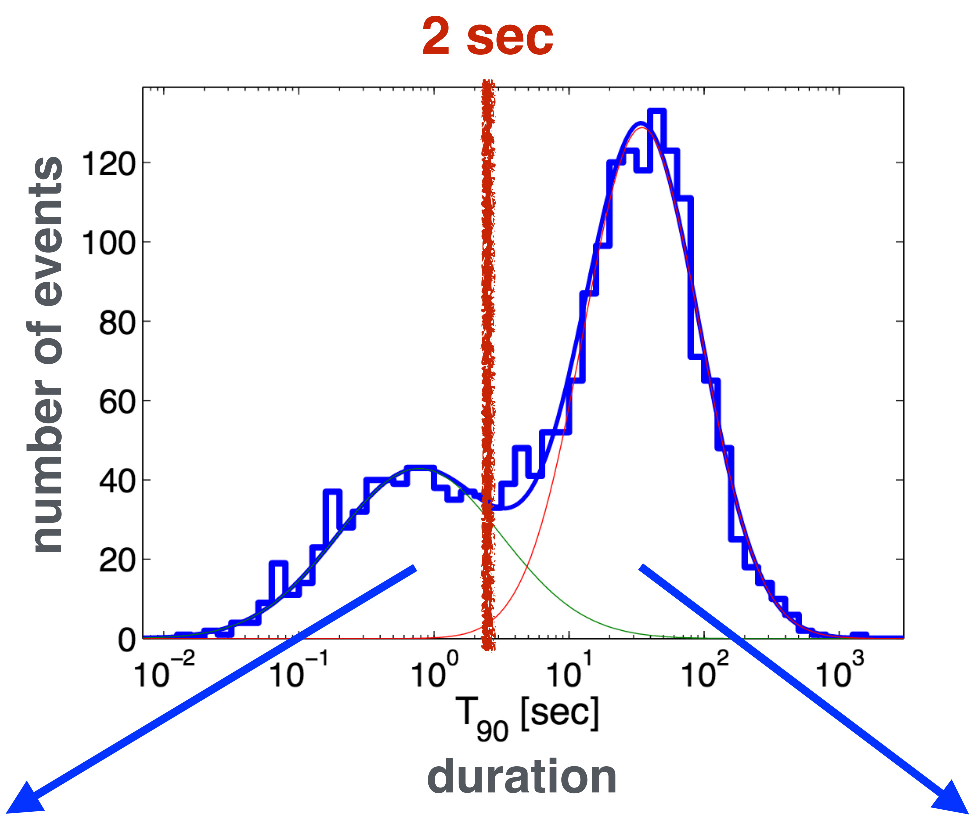
GRB 170817A

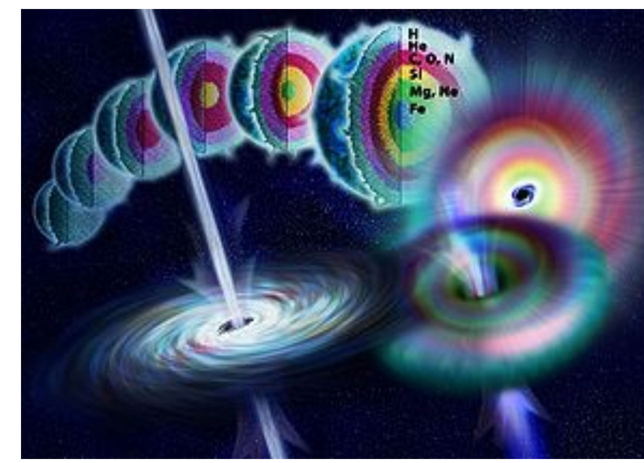


BNS merger
GRB start
Light curve from Fermi/GBM (50-300 keV)
Event rate (counts/s)
1500
1250
1000
750
500
Light curve from INTEGRAL/SPI-ACS (≳ 100 keV)
120000
117500
115000
112500
110000
Gravitational-wave strain
from Hanford + Livingston
~1.7 sec
Frequency (Hz)
10^2
−8
−6
−4
−2
0
2
4
6
Time from BNS 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 GRB130603B

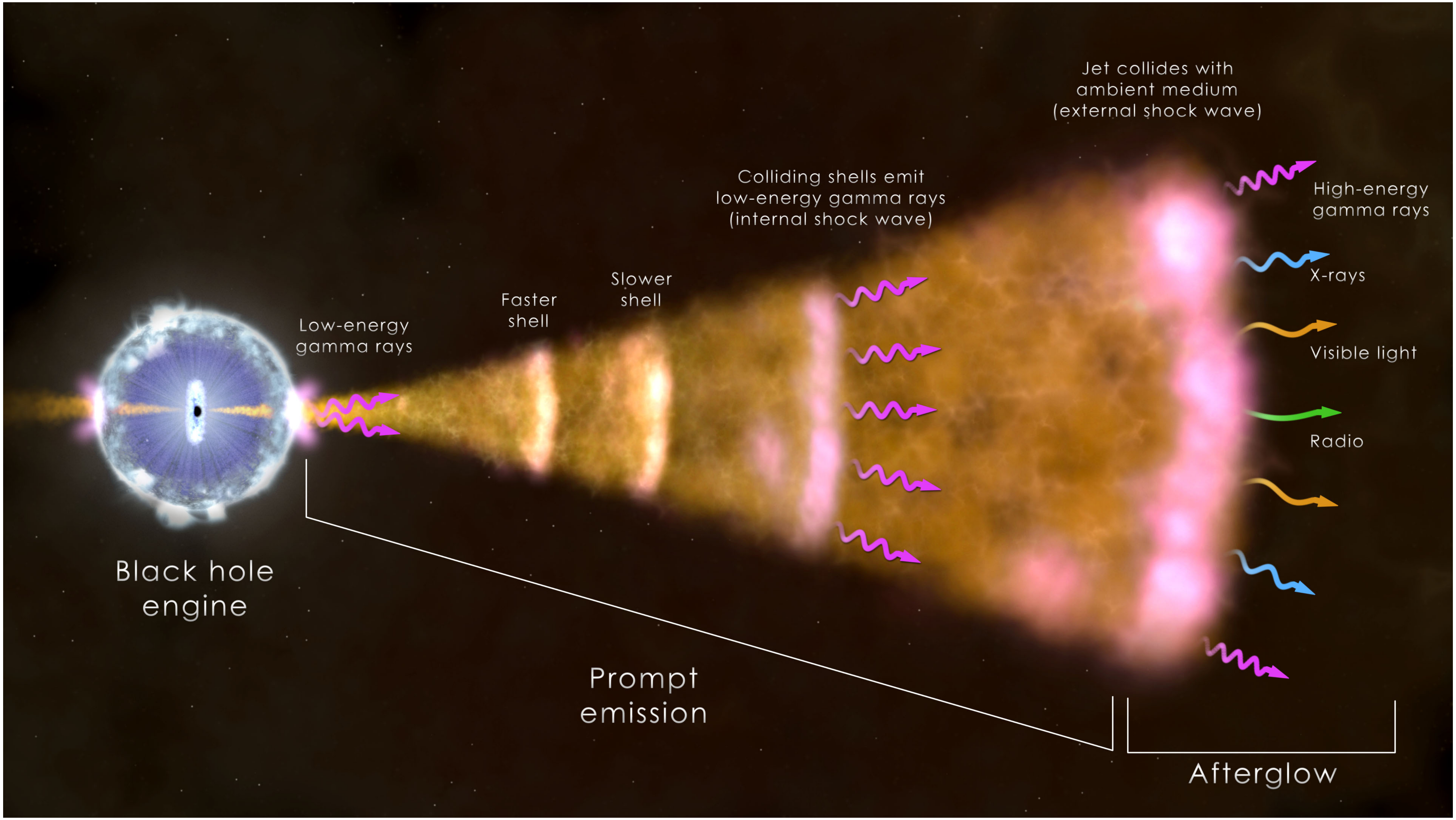
NS-NS (NS-BH) mergers ✓

long GRBs

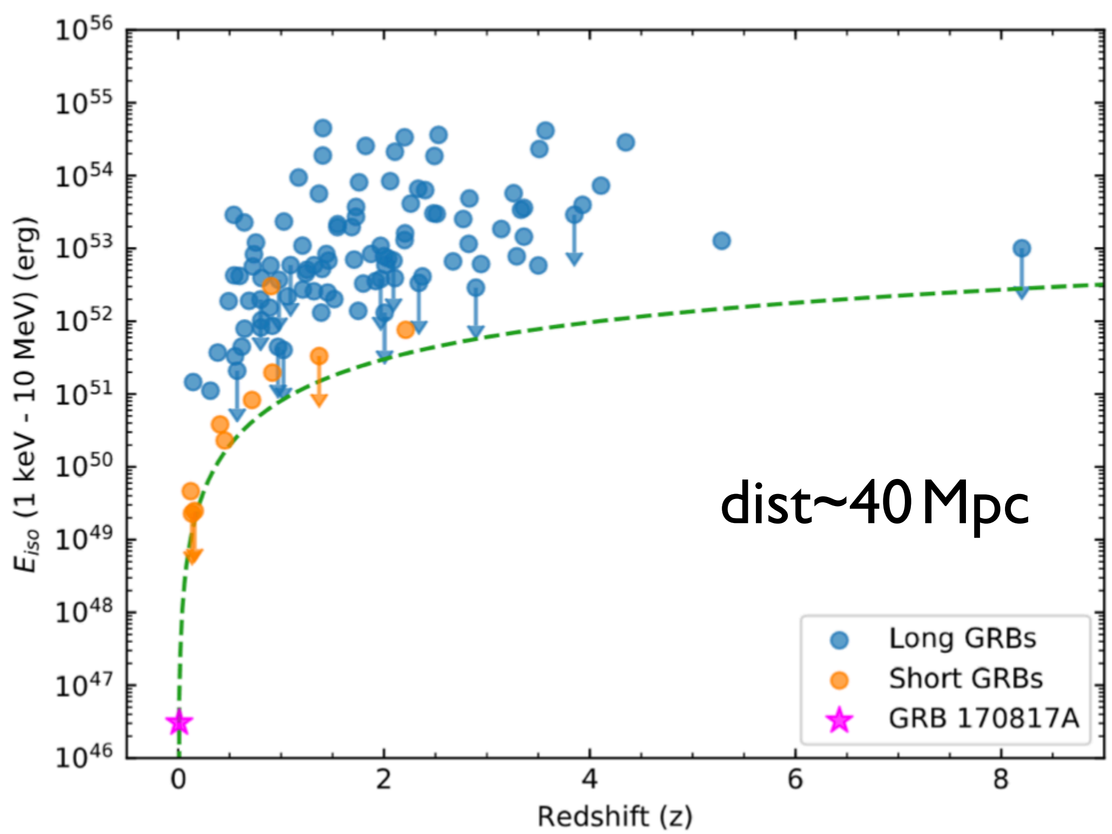
- $T_{90} \gtrsim 2\,\mathrm{s}$
- confirmed supernova associations (Hypernovae $\gtrsim 10^{52}\,\mathrm{erg}$)
- only late-type galaxies with high star formation rates

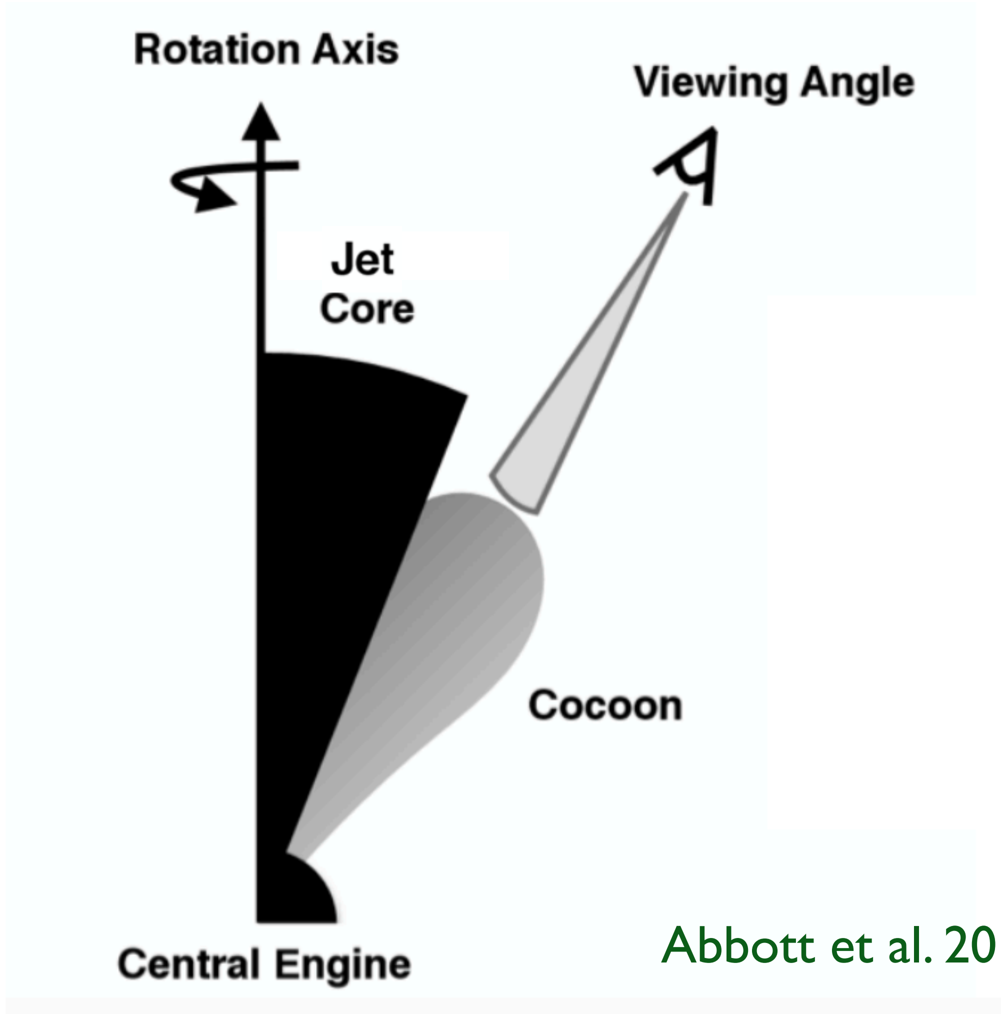
core-collapse supernovae ✓

GRBs from jets



GRB 170817A: off-axis short GRB?





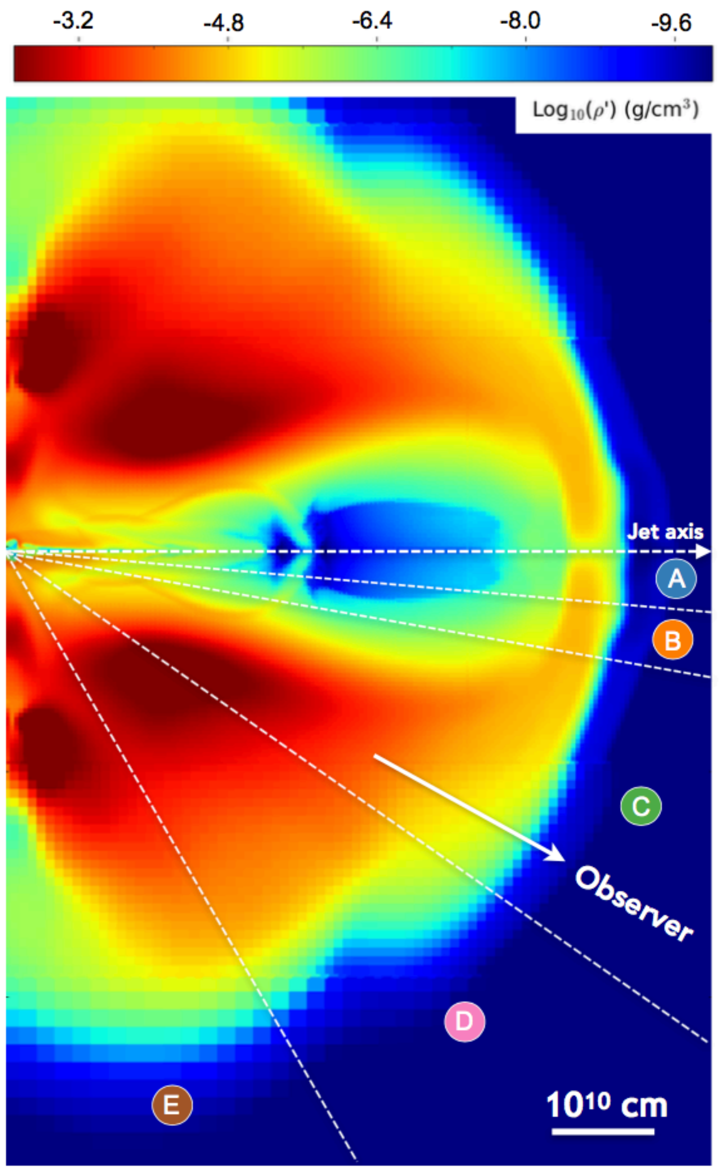
Abbott et al. 2017c

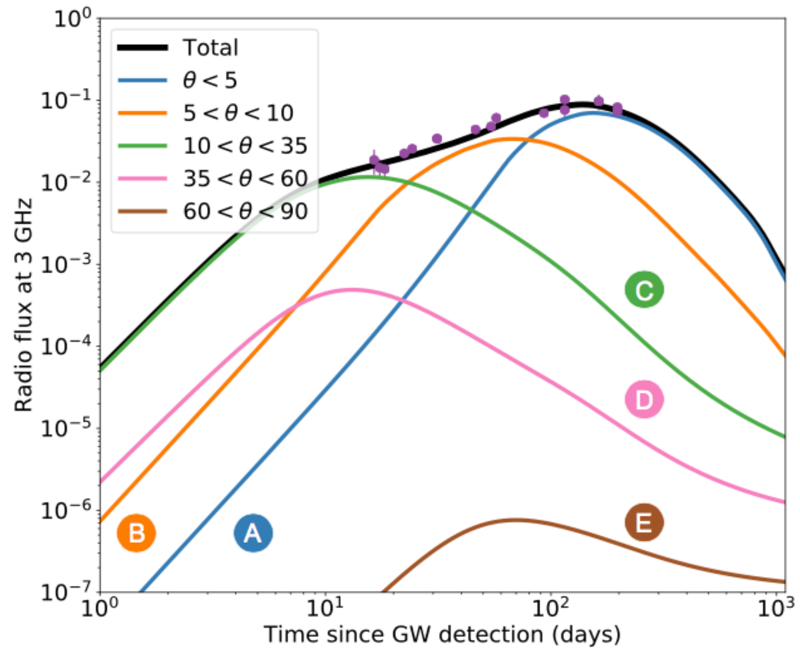
from GRB and multiwavelength afterglow modelling

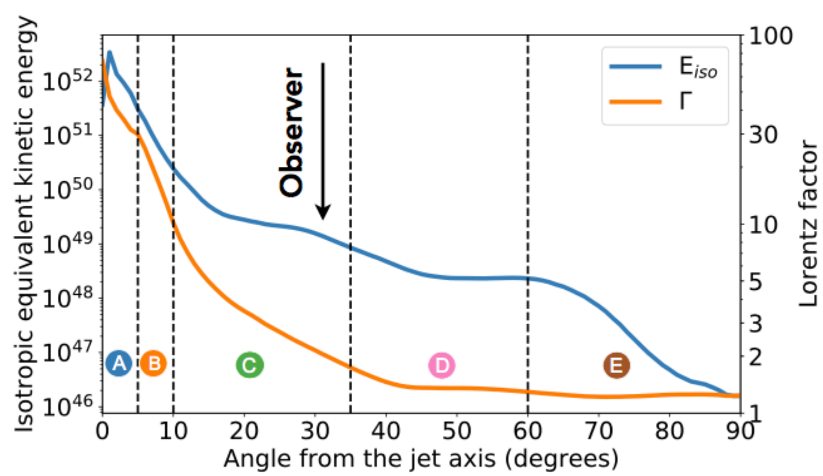
observed gamma-rays come from mildly relativistic outflow ($\Gamma \sim 2-8$) moving along the line of sight

Canonical SGRB

Lazzati et al. 2018





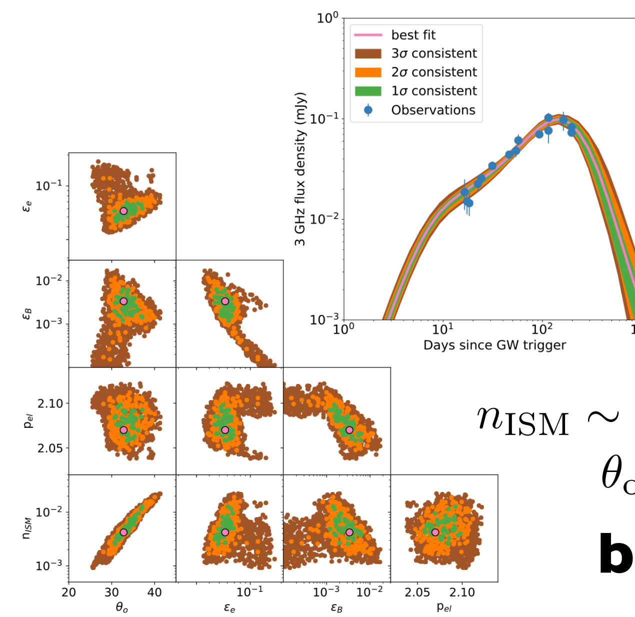


special relativistic jet simulation

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

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

multiwavelength afterglow calculation



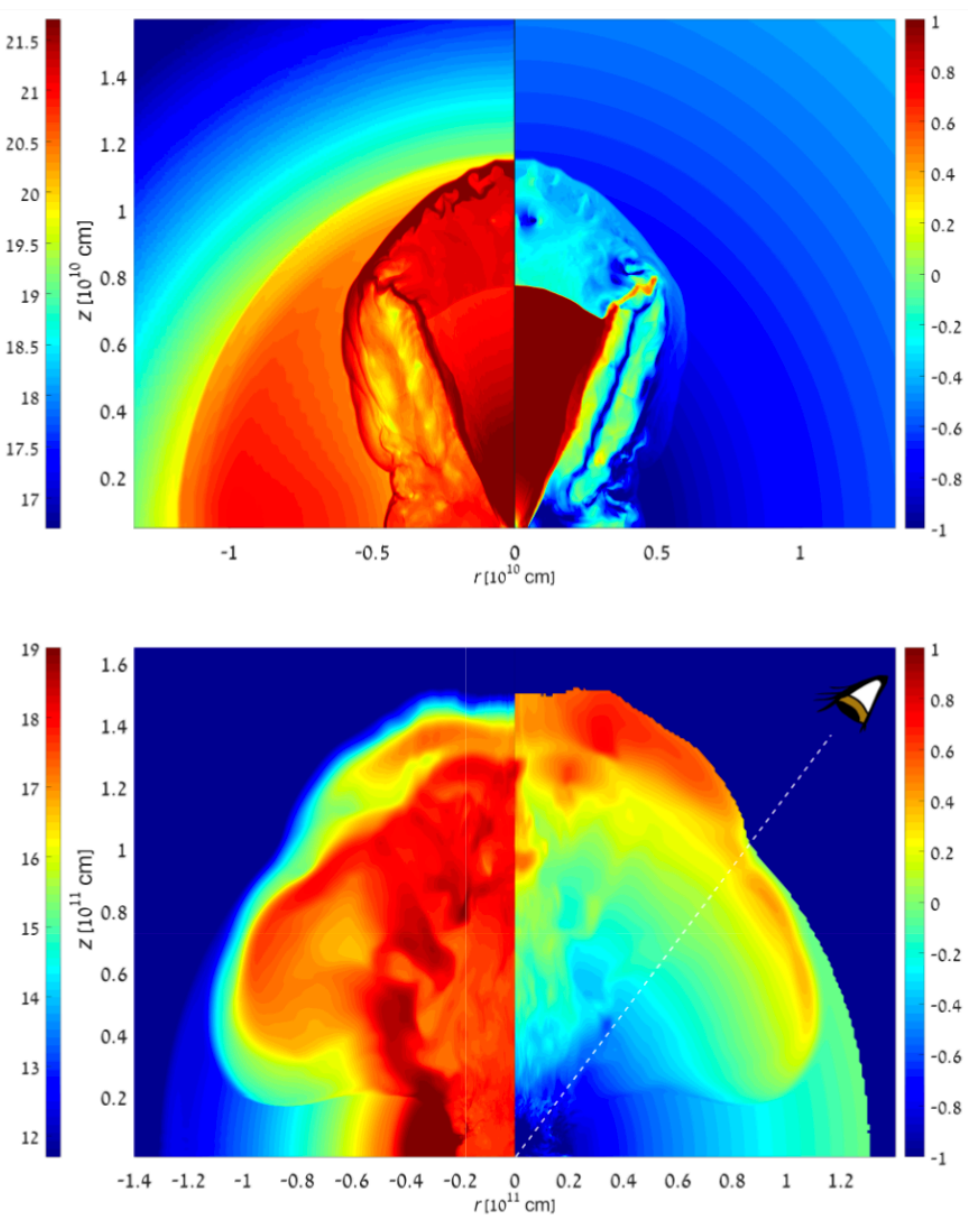
$n_{\rm ISM} \sim 4 \times 10^{-3}\ {\rm cm}^{-3}$

$\theta_{\rm obs} \sim 33°$

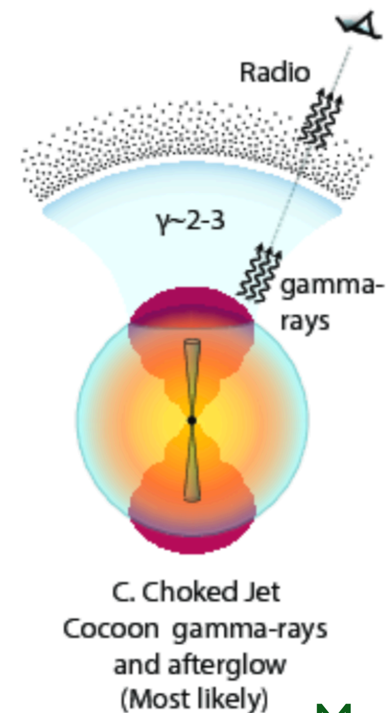
best fit

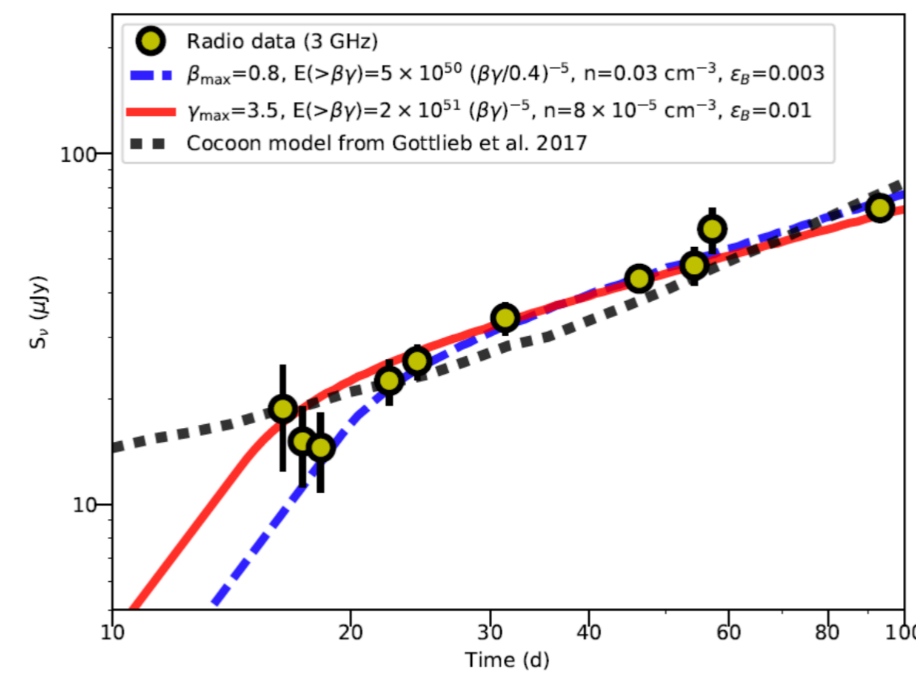
an ordinary SGRB event observed off-axis? ➡ viable explanation!

Choked jet



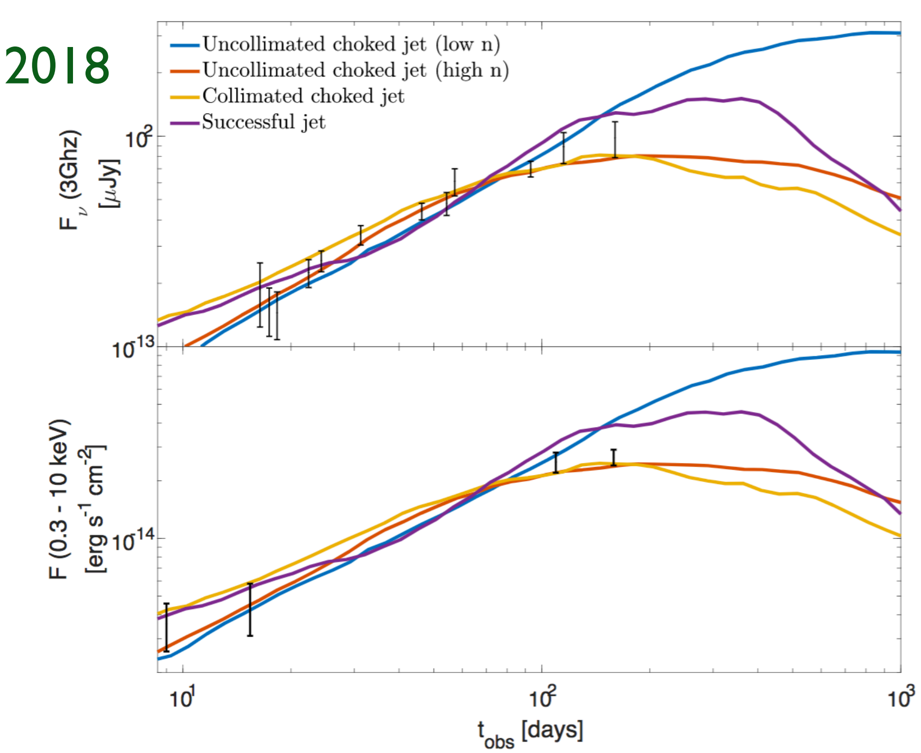
Gottlieb et al. 2017





Mooley et al. 2018

Nakar et al. 2018



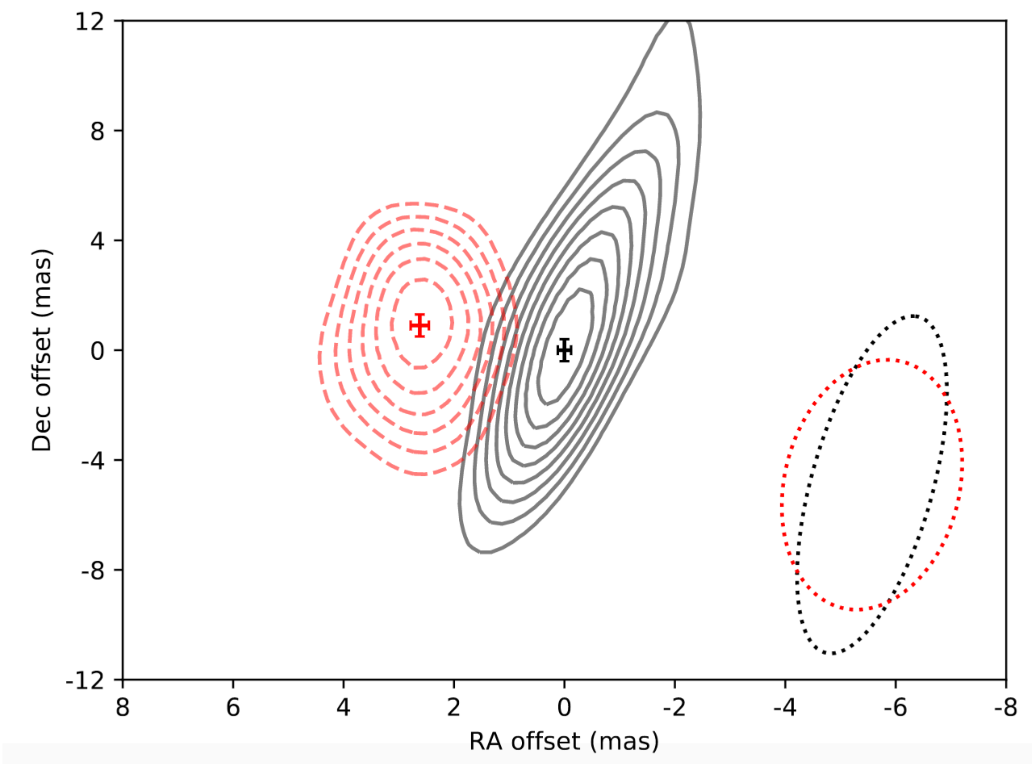
unsuccessful jet, no canonical SGRB

➡ also viable explanation, but..

VLBI observations

global network of 32 radio telescopes

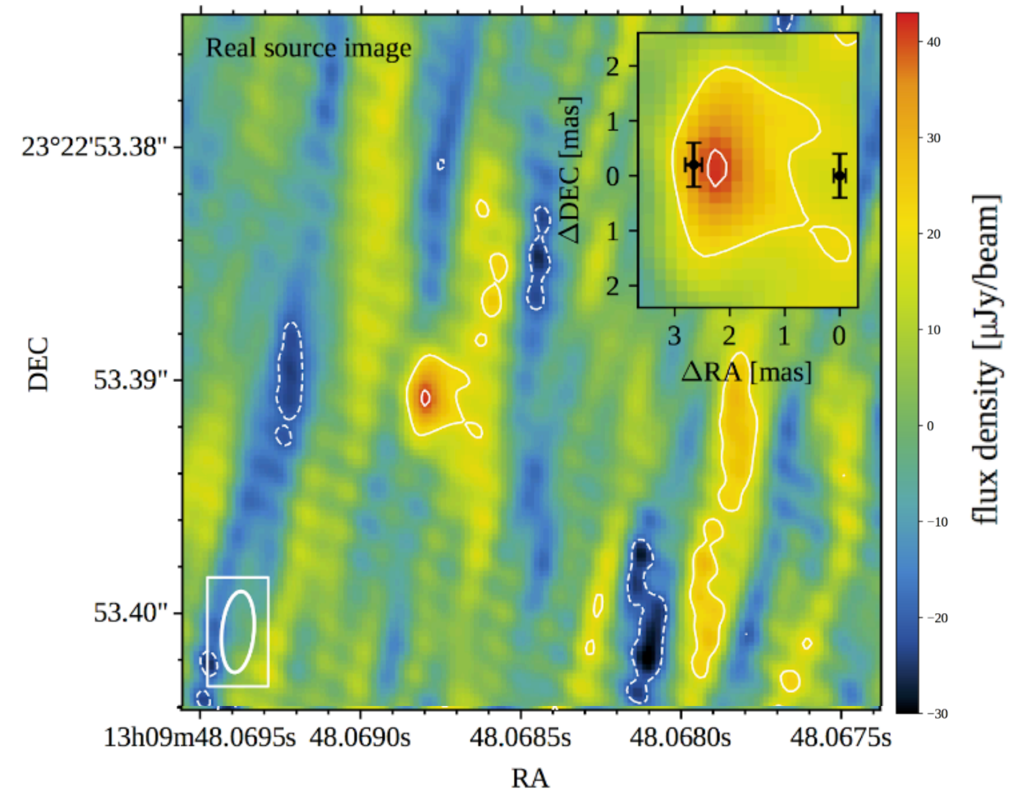
Mooley et al. 2018

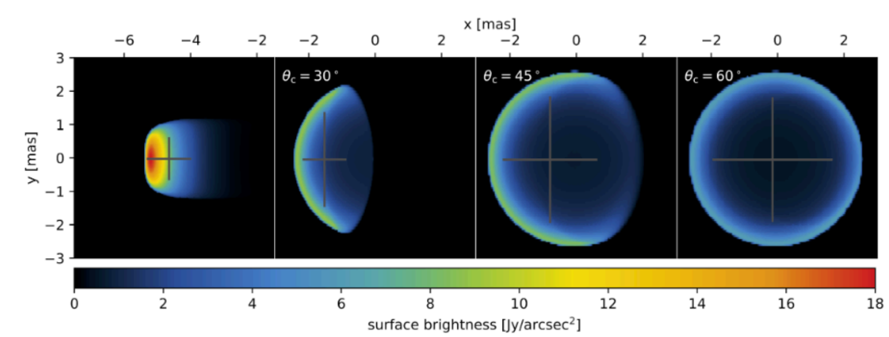


apparent superluminal motion between 75 and 230 days

source is moving relativistically (and getting closer)

Ghirlanda et al. 2018





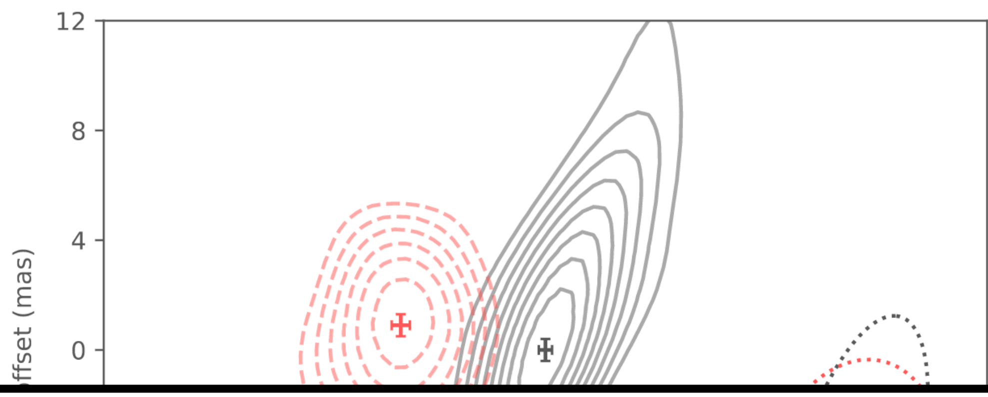
source size < 2 m arcseconds @ 207 days

source is still rather compact!

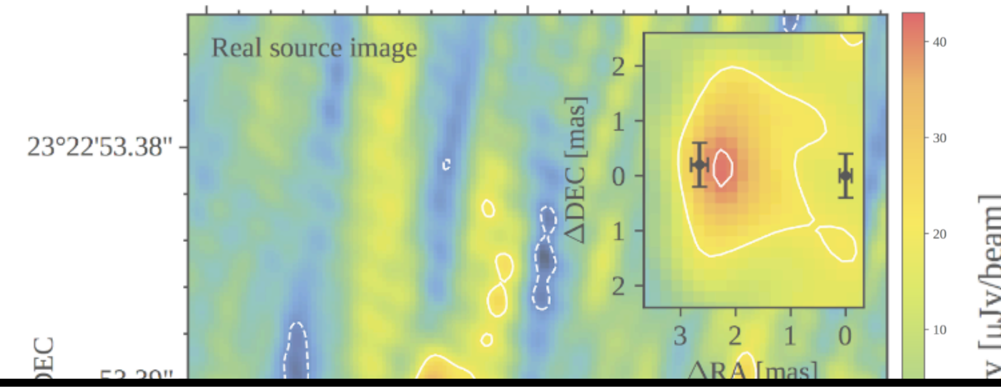
VLBI observations

global network of 32 radio telescopes

Mooley et al. 2018



Ghirlanda et al. 2018

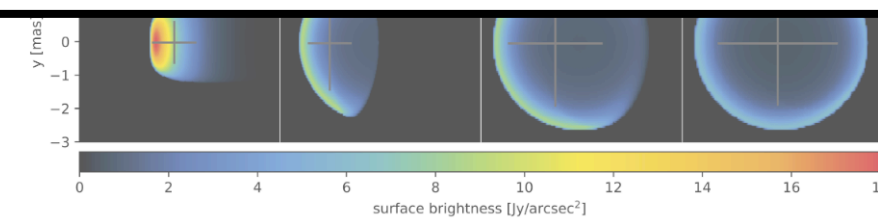


collimated jet (<5 deg), seen ~20 deg off-axis

nearly isotropic, mildly relativistic outflow excluded

between 75 and 230 days

source is moving relativistically (and getting closer)



source size < 2 m arcseconds @ 207 days

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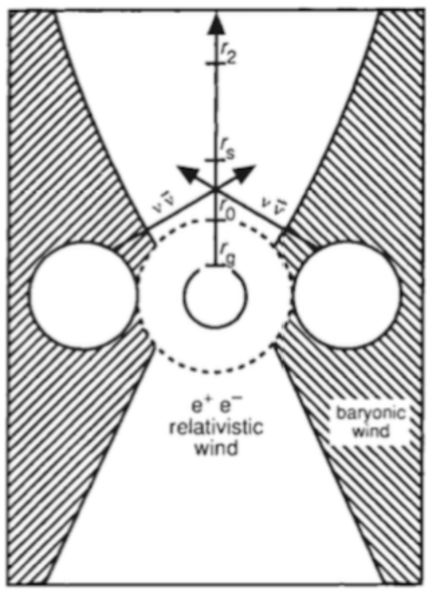
Jets from BNS mergers?

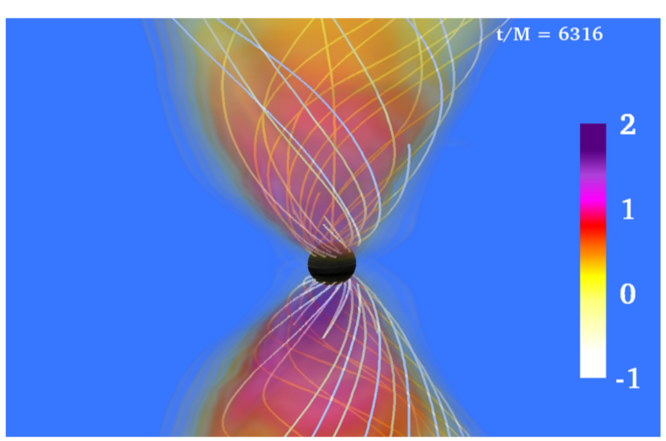
Mochkovitch et al. 1993



neutrino mechanism

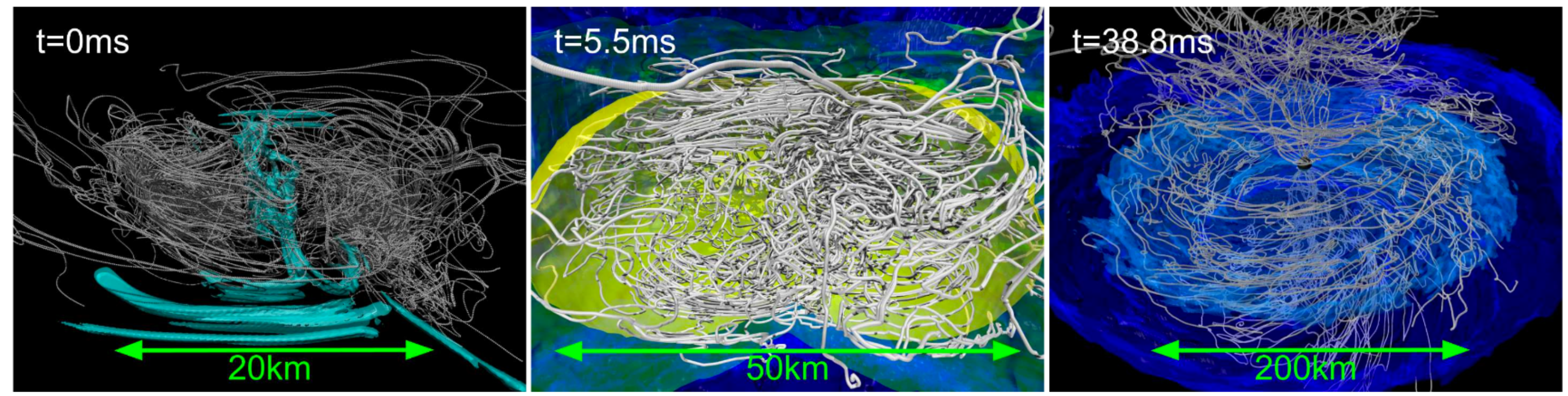
VS

magnetic mechanism
(Blandford-Znajek?)

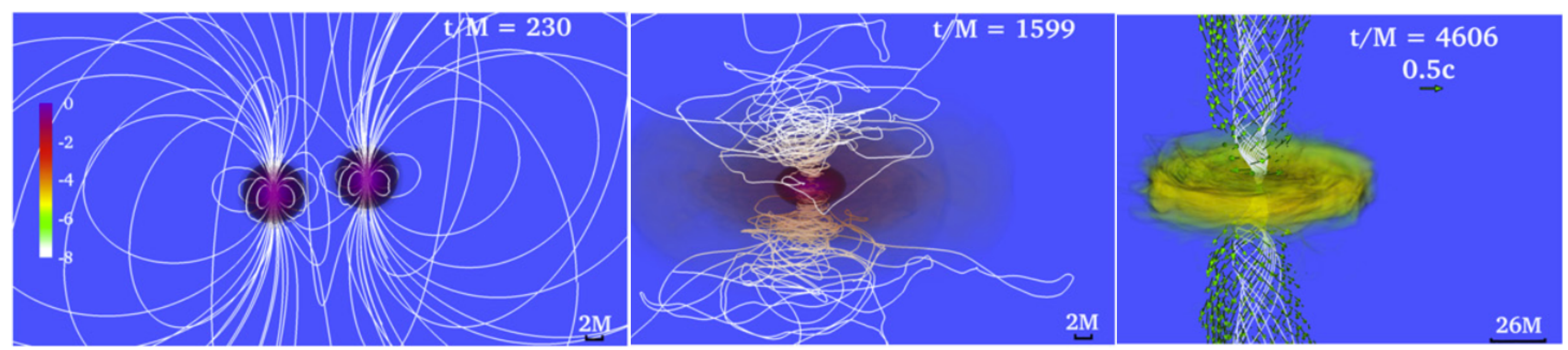


Paschalidis et al. 2015

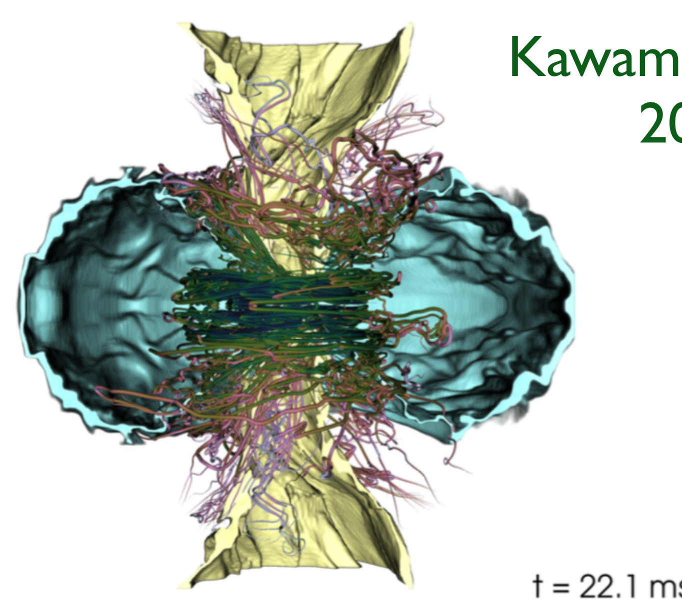
Kiuchi et al. 2014

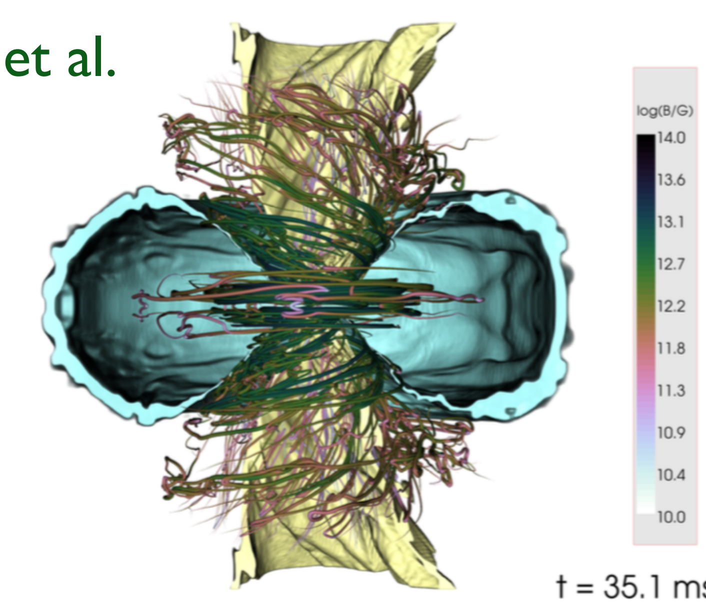


Ruiz et al. 2016



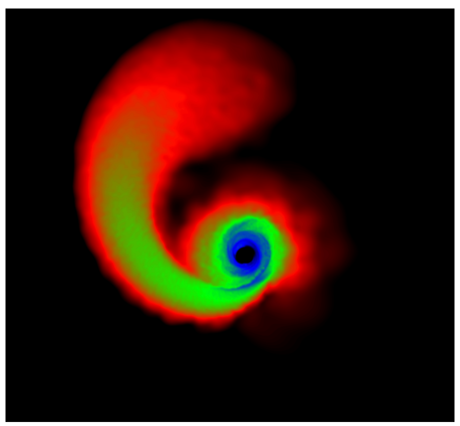
Kawamura et al.
2016

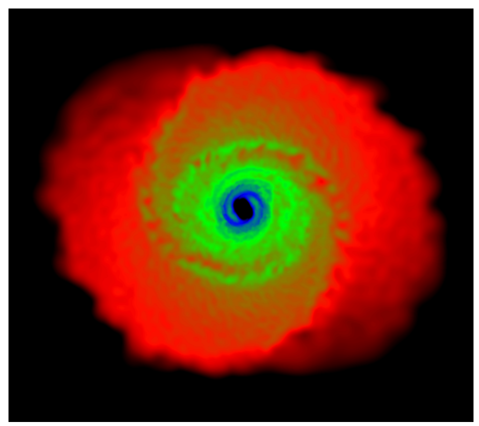


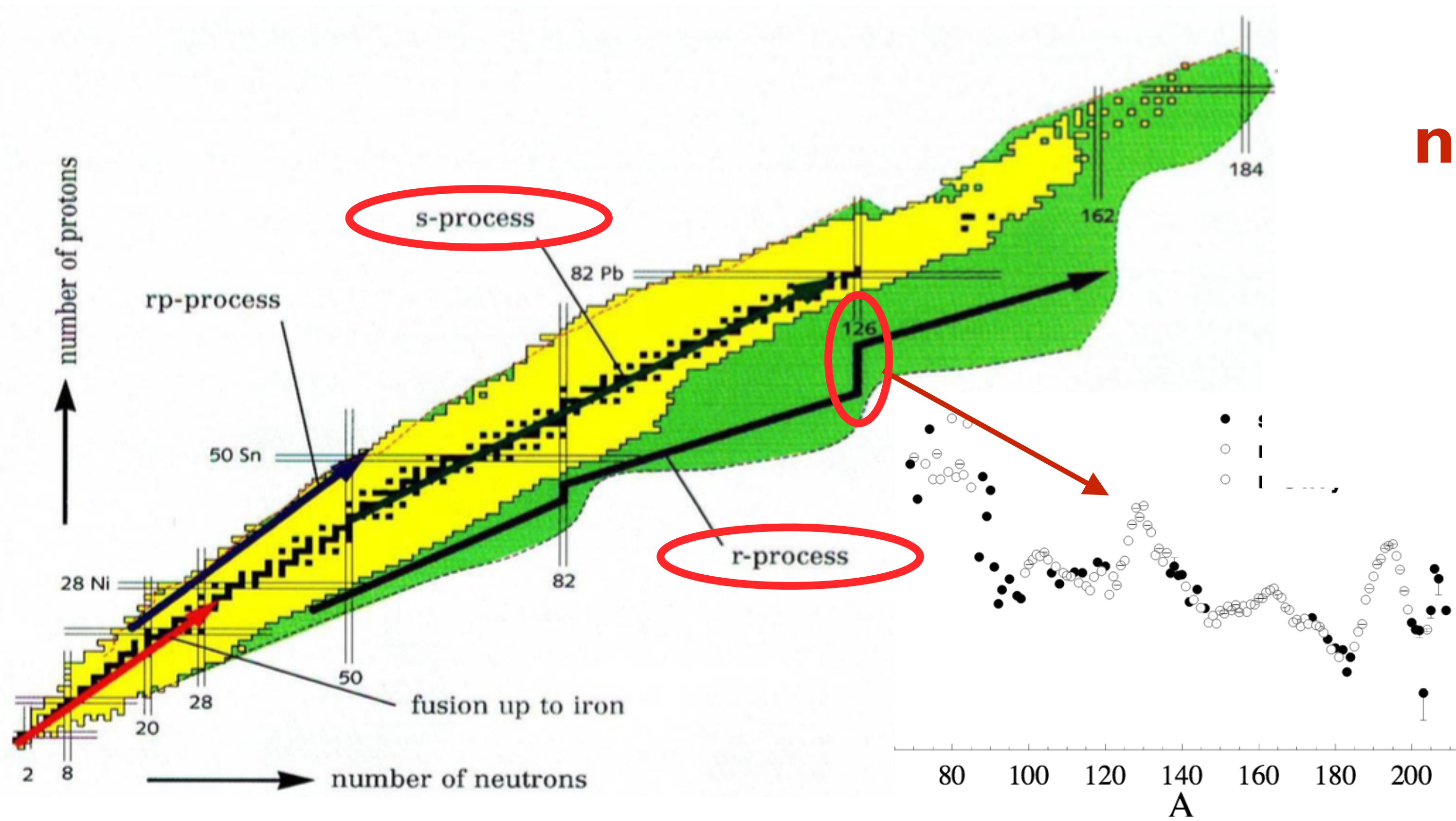


Merger ejecta and r-process nucleosynthesis

ejecta in BNS and NS-BH 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})

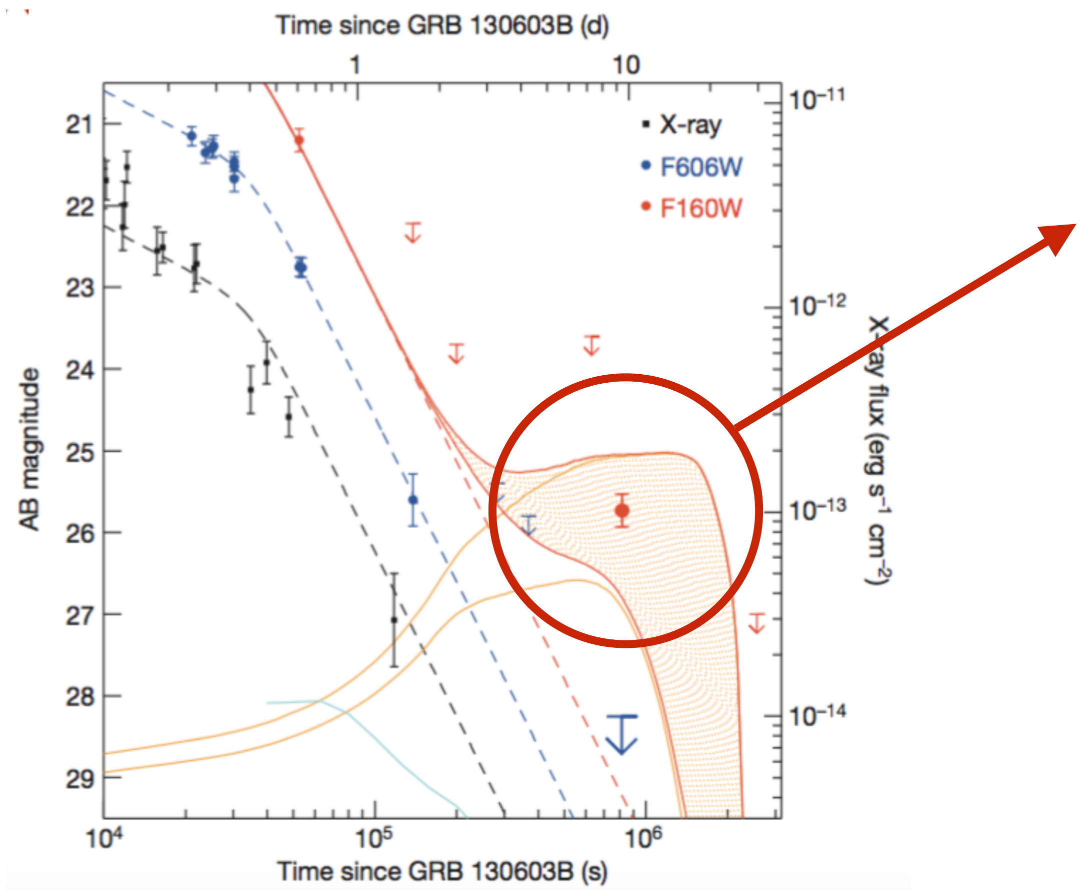
nucleosynthesis of heavy nuclei

initially unstable

radioactive decay on timescales of >days

optical/NIR signal!

Kilonova in GRB130603B?



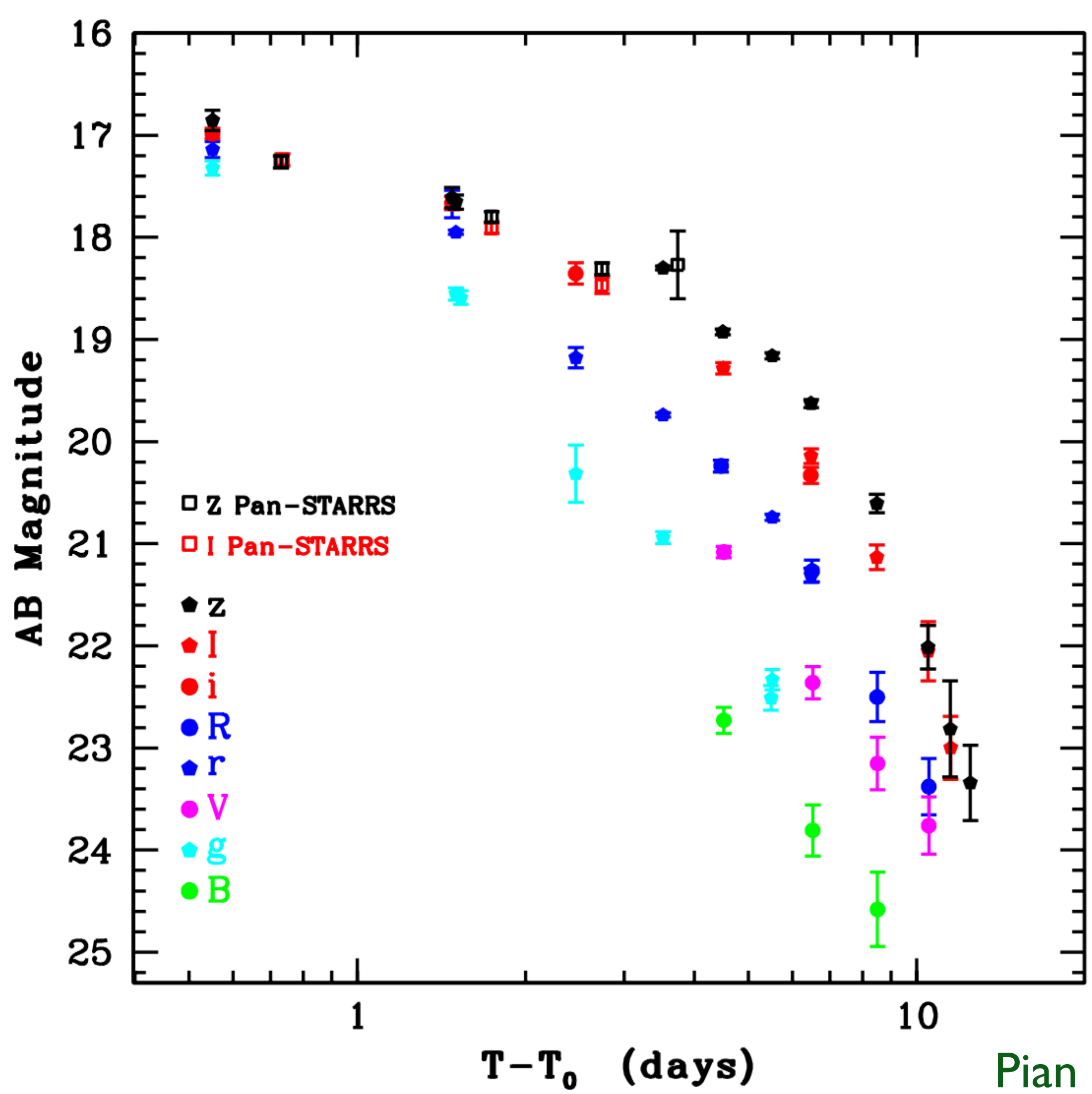
optical rebrightening in GRB 130603B tentatively interpreted as a kilonova

connection

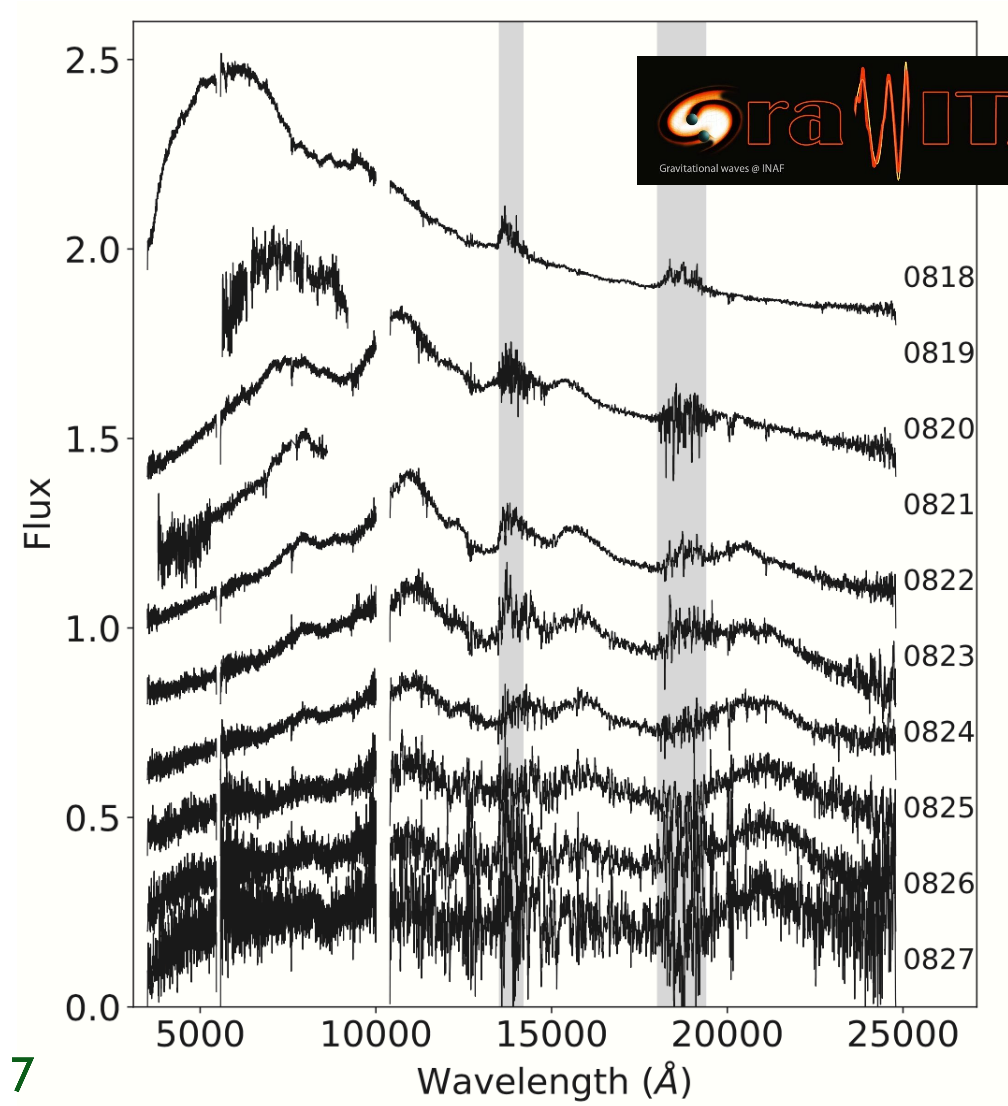
SGRB ⟷ BNS or NS-BH mergers

Tanvir et al. 2013, Berger et al. 2013

GW170817 Kilonova



Pian et al. 2017



light curves and spectra are consistent with a kilonova!

Red and blue kilonovae

neutron-rich ejecta
low electron fraction Ye<0.2

strong r-process
very heavy elements (A>140)
lanthanide-rich

higher opacity

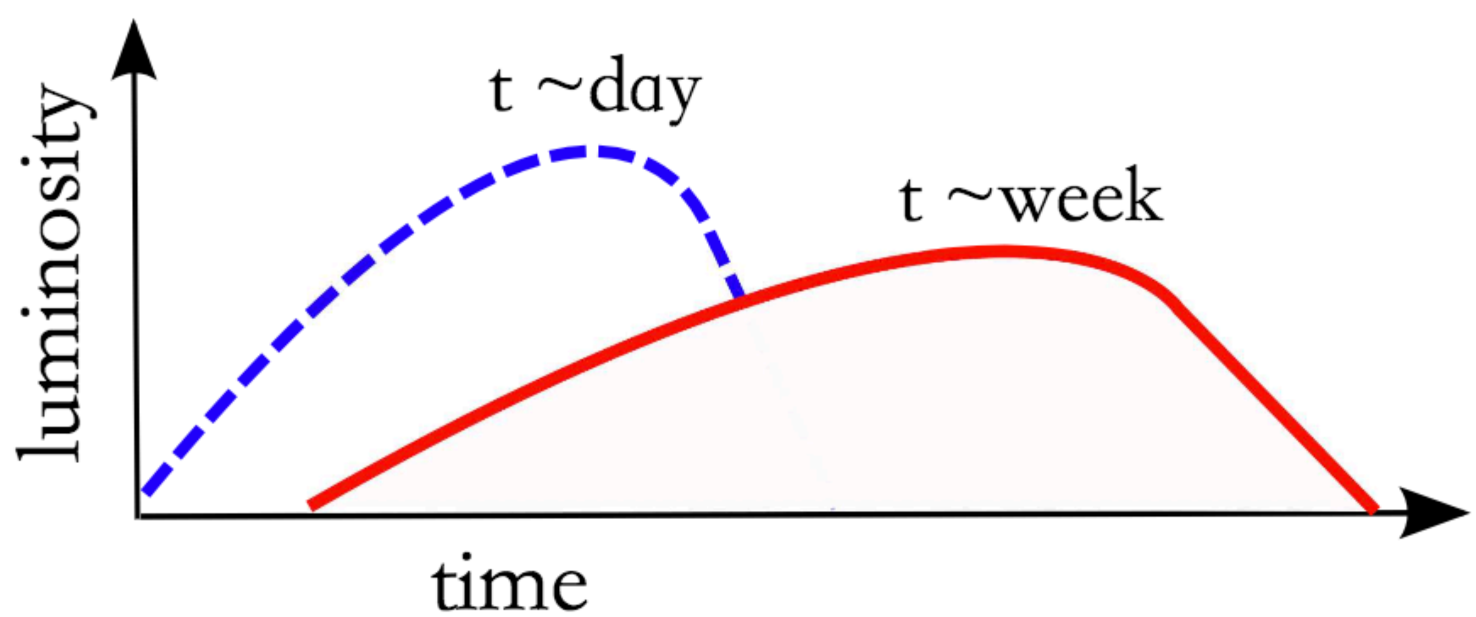
red to infrared, peak time ~1 week

neutron-poor ejecta
high electron fraction Ye>0.2

weak r-process
not very heavy elements (A<140)
lanthanide-poor

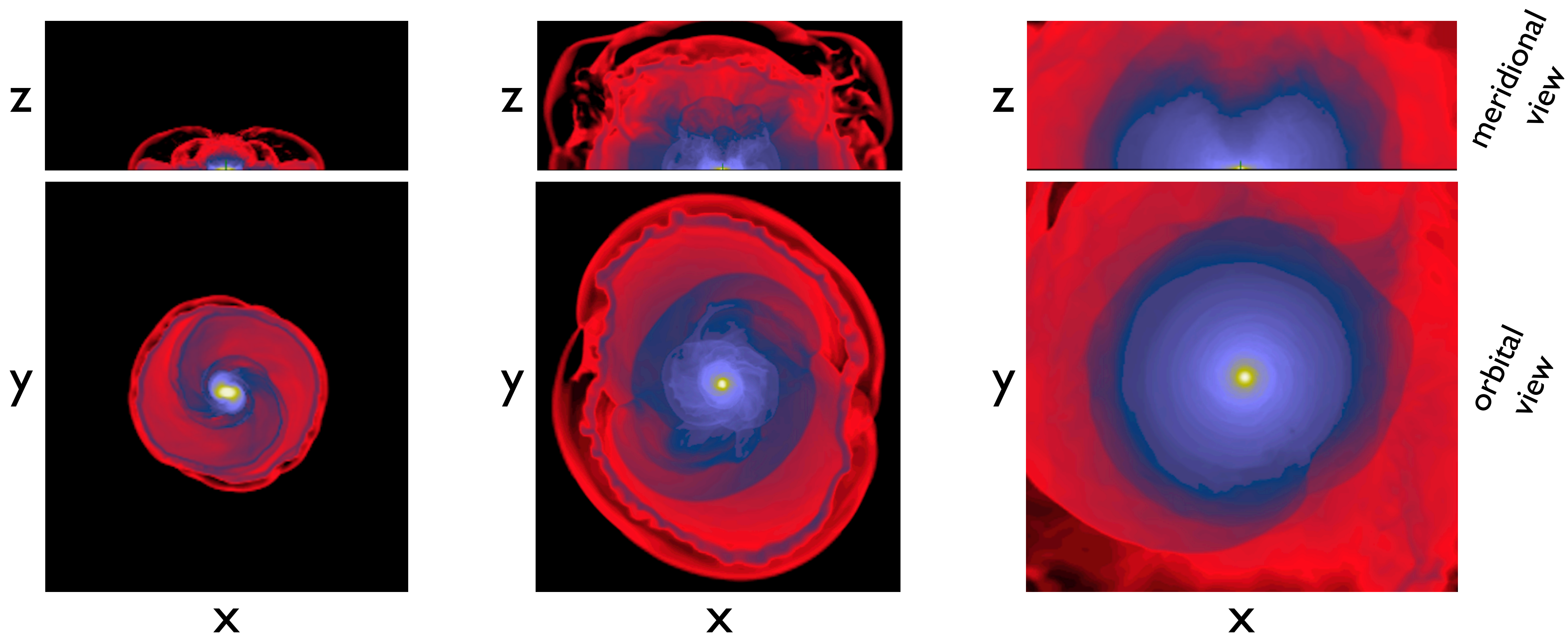
lower opacity

blue, peak time ~1 day



Different ejecta components

tidal ejecta	shock-driven ejecta	post-merger winds
only on orbital plane	mostly polar (along z)	isotropic
cold and neutron-rich	hot and neutron-poor	wide range of Ye (0.1-0.4)
⇩	⇩	⇩
red kilonova	blue kilonova	red and blue kilonova



The GW170817 kilonova in numbers

1) “blue” component

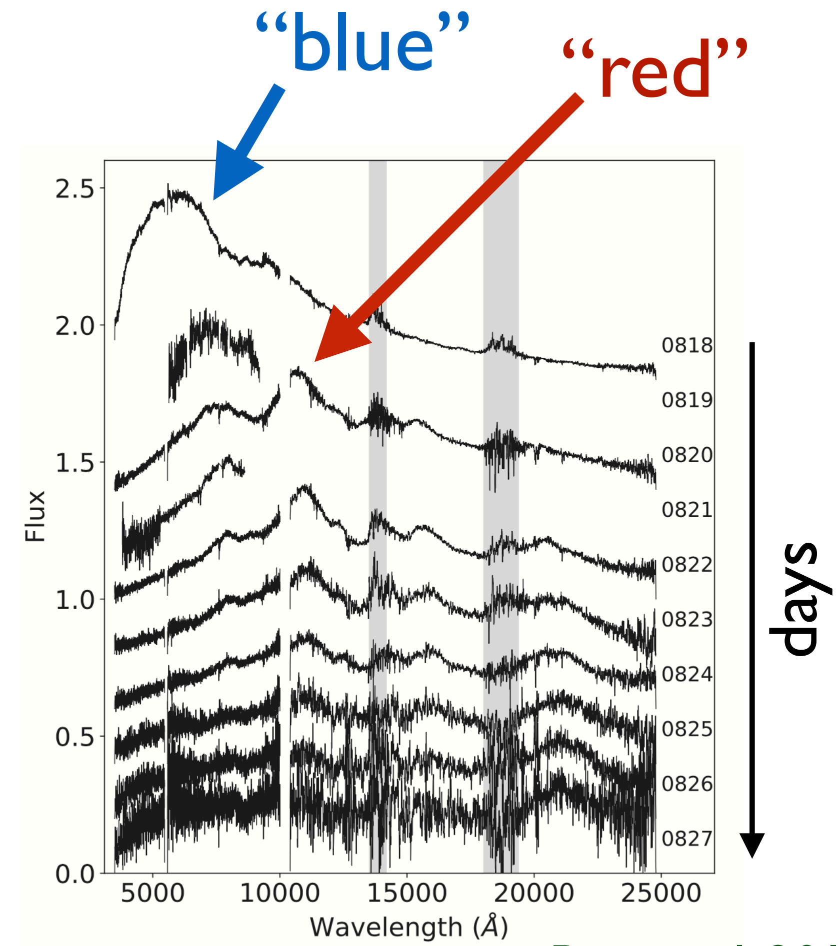
peaking ~1 day after merger between UV and blue

ejecta expansion velocity ~0.2 c

ejecta mass ~10^{-2} M_{sun}

opacity ~0.5 cm^2/g (lanthanide-poor)

- ✗ tidal ejecta (too massive, opacity too low)
- ✓ ✗ ?? shock-driven ejecta (may still be too massive)
- ✗ post-merger winds (too fast)



Pian et al. 2017

2) “red” component

peaking several days after merger, IR wavelengths

ejecta expansion velocity ~0.1 c

ejecta mass ~5x10^{-2} M_{sun}

opacity ~10 cm^2/g (lanthanide-rich)

- ✗ tidal ejecta (too massive, too slow)
- ✗ shock-driven ejecta (too slow, opacity too high)
- ✓ post-merger winds match all properties

abundances

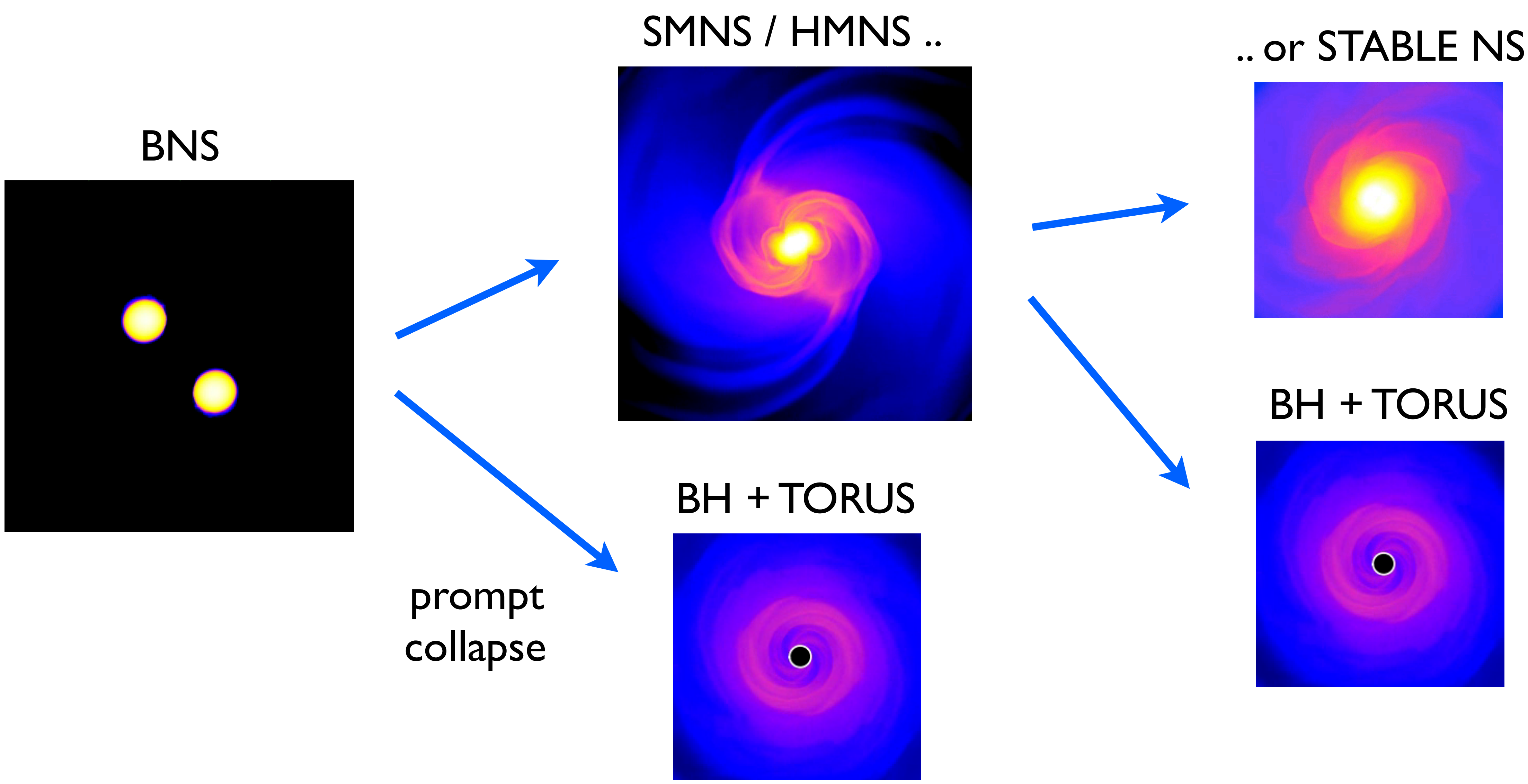
~10^{-2} M_{sun} of heavy r-process yield (A>140)

 gold yield ~100 x 

Summary of a breakthrough

- first GW detection of a BNS merger
- GW-inspired constraints on NS EOS
- independent measure of Hubble constant
- first multimessenger observation of a GW source ⟶ GW+EM signals
- confirmed BNS-SGRB connection
- first close look at the angular structure SGRB jets
- confirmed existence of kilonovae and first detailed characterization
- established key role of BNS mergers in producing very heavy elements (e.g. gold)

Product of BNS mergers



Magnetar SGRB scenario

- Swift revealed that most SGRBs are accompanied by long-duration $(\sim 10^2 - 10^5 \text{ s})$ and high-luminosity $(10^{46} - 10^{51} \text{ erg/s})$ X-ray afterglows
- total energy can be higher than the SGRB itself
- hardly produced by BH-torus system - they suggest ongoing energy injection from a long-lived NS

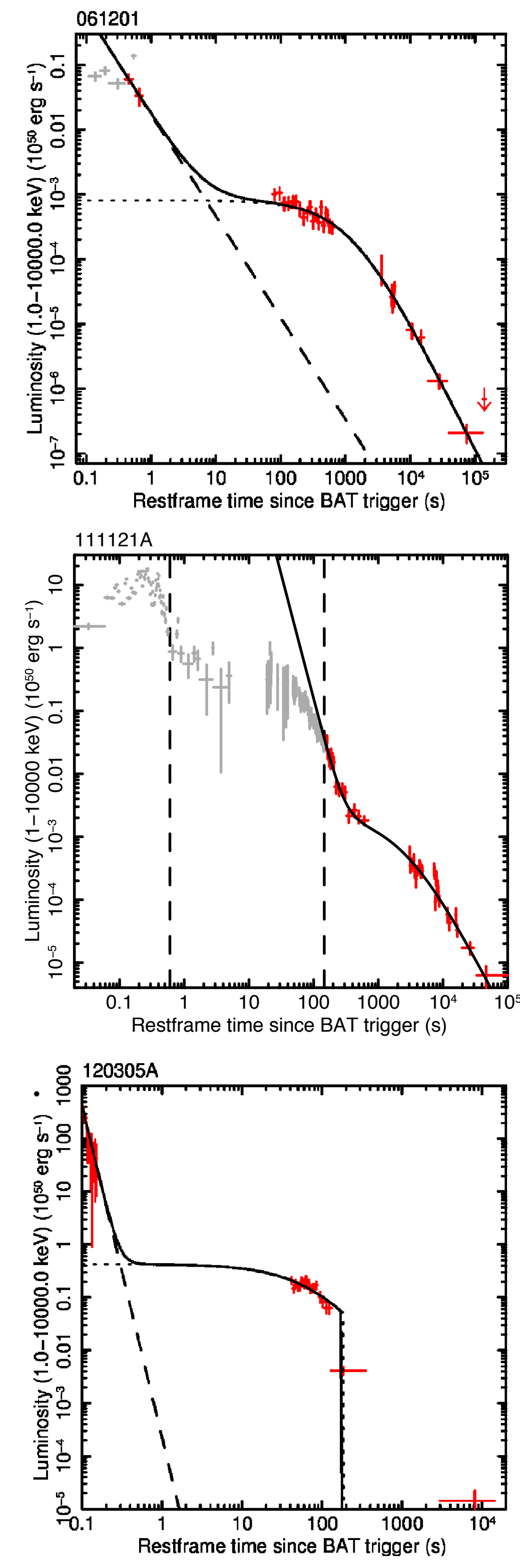
MAGNETAR SCENARIO

Zhang & Meszaros 2001
Metzger et al. 2008

X-ray emission $\longrightarrow$ spindown of a uniformly rotating NS with a strong surface magnetic field $\gtrsim 10^{14} - 10^{15}$ G

dipole spindown

$$L_{\rm sd}(t) \sim B^2 R^6 \Omega_0^4 \left(1 + \frac{t}{t_{\rm sd}}\right)^{-2}$$



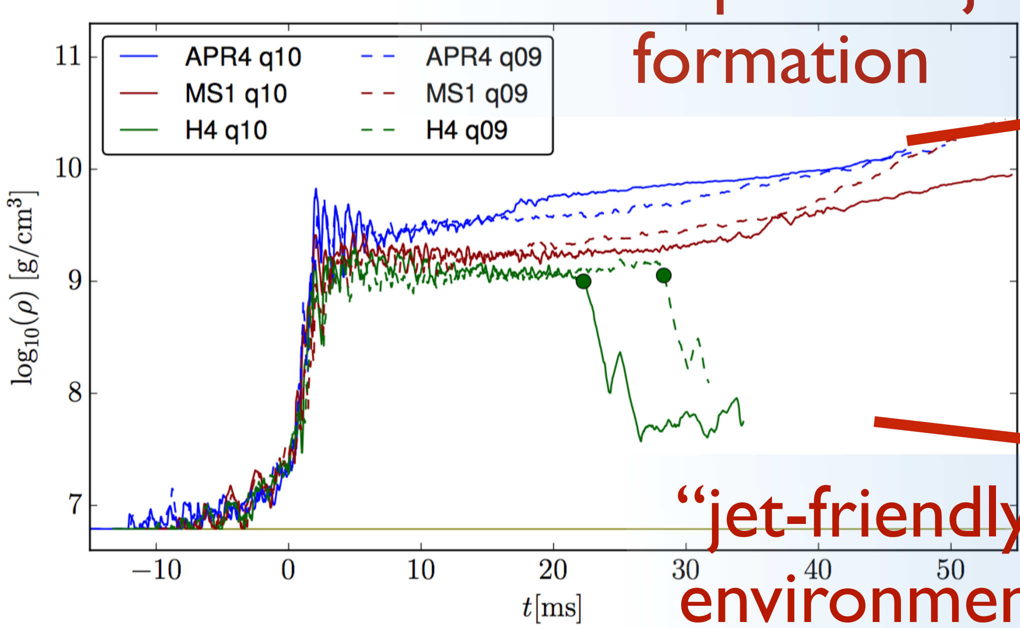
Gompertz et al. 2013
Rowlinson et al. 2013

Problem of the magnetar scenario

strong baryon pollution can choke the formation of a relativistic jet

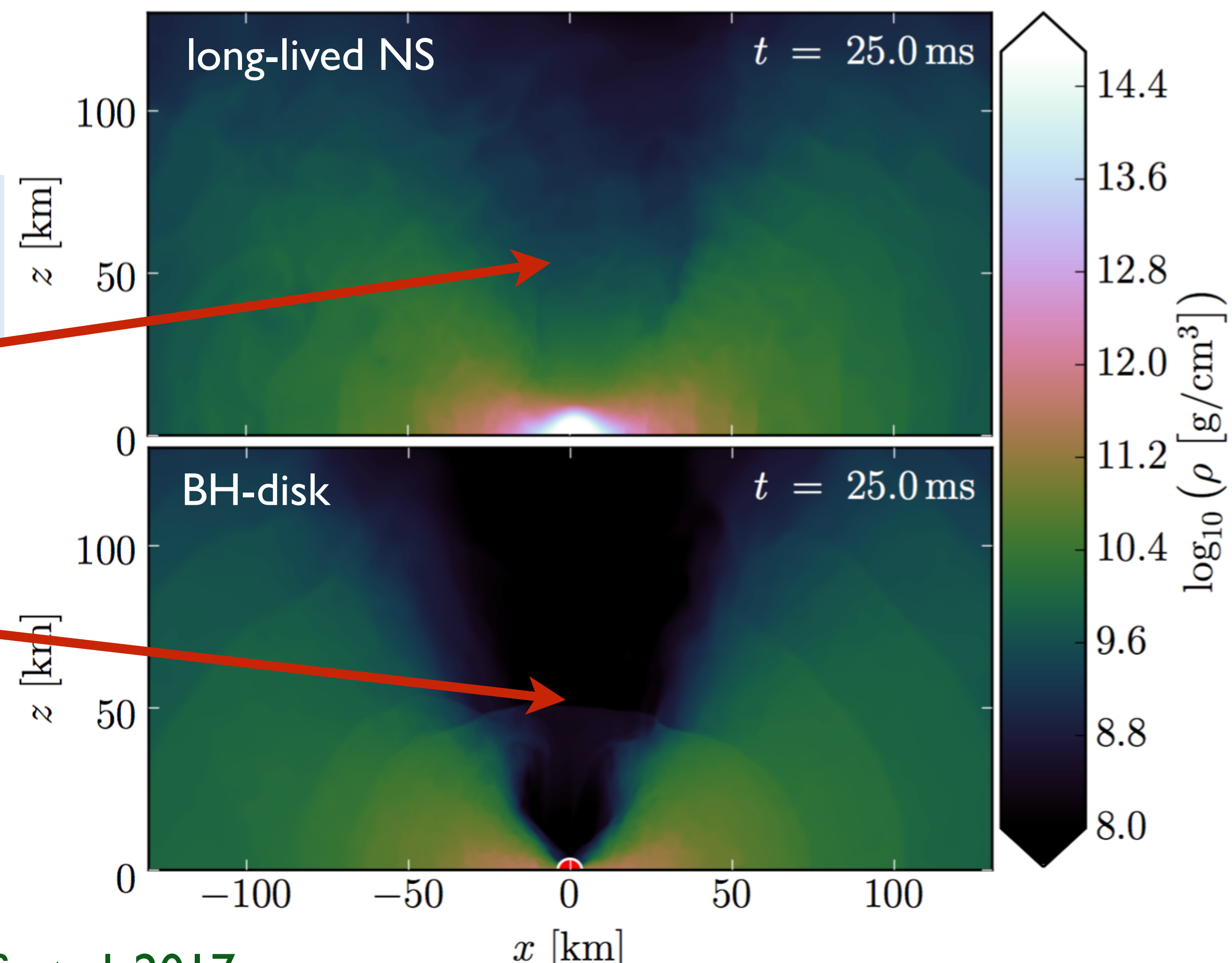
→ HARD TO EXPLAIN THE SGRB PROMPT EMISSION

e.g., Dessart et al. 2009, Hotokezaka et al. 2013, Siegel et al. 2014, Nagakura et al. 2014, Murguia-Berthier et al. 2016



could prevent jet formation

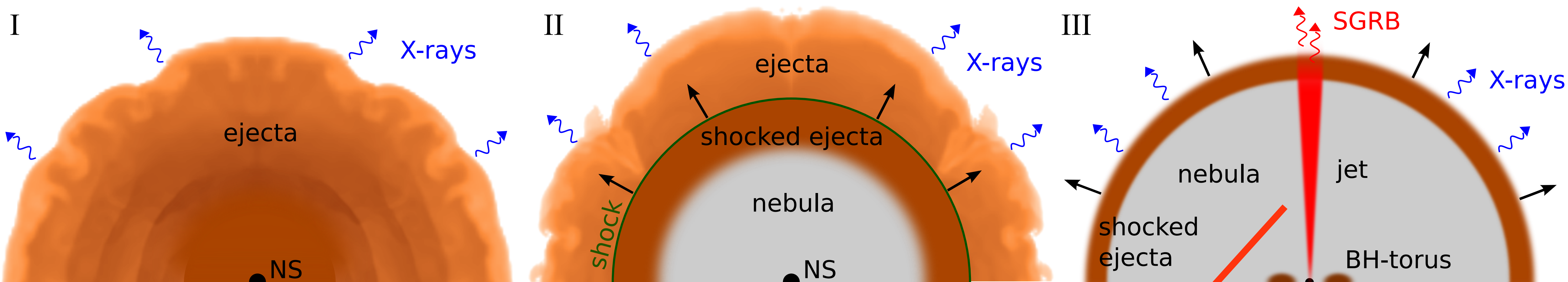
"jet-friendly" environment

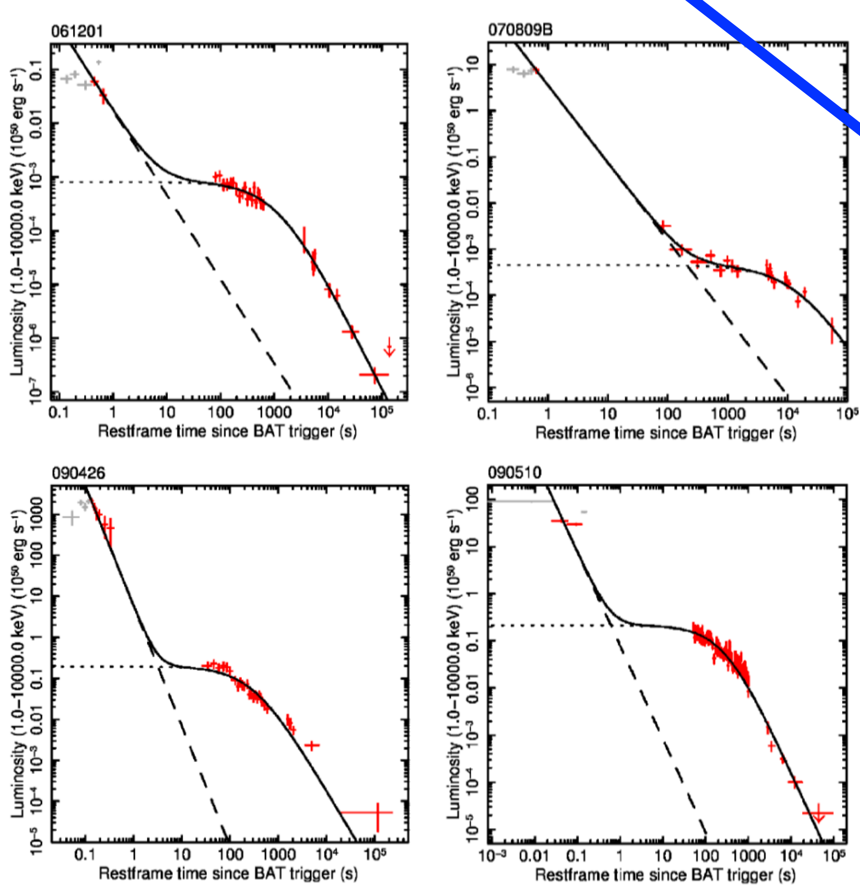


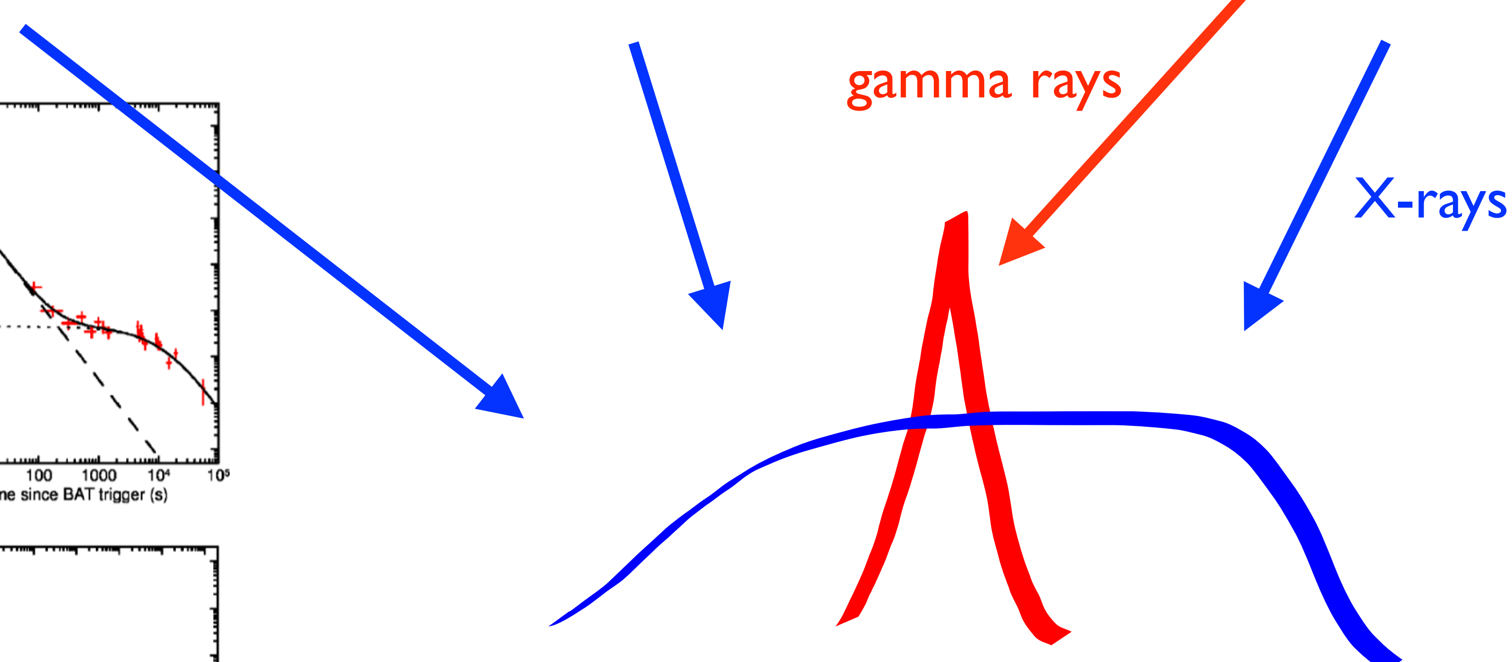
Ciolfi et al. 2017

Time-reversal scenario

Ciolfi & Siegel 2015
Ciolfi 2018







the spindown energy is given off **before** but
(in part) observed **after** the prompt SGRB radiation

GRB 170817A and central engine scenarios

Ciolfi 2018

- **BH-disk** broadly consistent

  remnant lifetime of ~10-100 ms not in tension with 1.7 s delay

- **Time-reversal** reduces to BH-disk

  no significant spindown phase before collapse $\longrightarrow$ no X-ray plateau expected

- **Magnetar** disfavoured

  very high baryon pollution in this event

GRB 170817A and central engine scenarios

Ciolfi 2018

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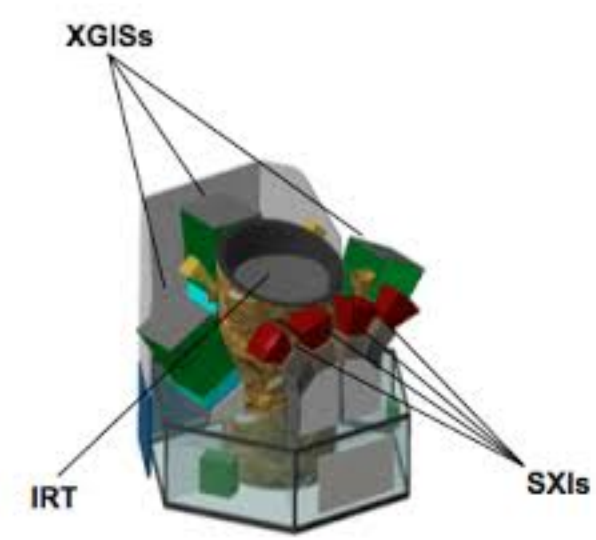
  no significant spindown phase before collapse ⟶ no X-ray plateau expected

?- **Magnetar** disfavoured

  very high baryon pollution in this event

⟶ early soft X-ray observations would have been very helpful

THESEUS will be ideal for this!



theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

GRB 170817A and beyond

- **SGRB-BNS association** now supported by smoking-gun evidence

  the close by and off-axis GRB 170817A disclosed novel aspects of jet properties and propagation

- **jet production in BNS mergers** remains an open question

  mechanisms: neutrino, magnetic (BZ)

  scenarios: BH-disk, magnetar, time-reversal

  theory challenge
  needs numerical relativity

- **was GRB 170817A produced by a BH or by a magnetar?**

  BH favoured by GRB-related information, but..

- **spindown-powered soft X-ray plateaus**

  crucial for future events

  theory and observational challenge

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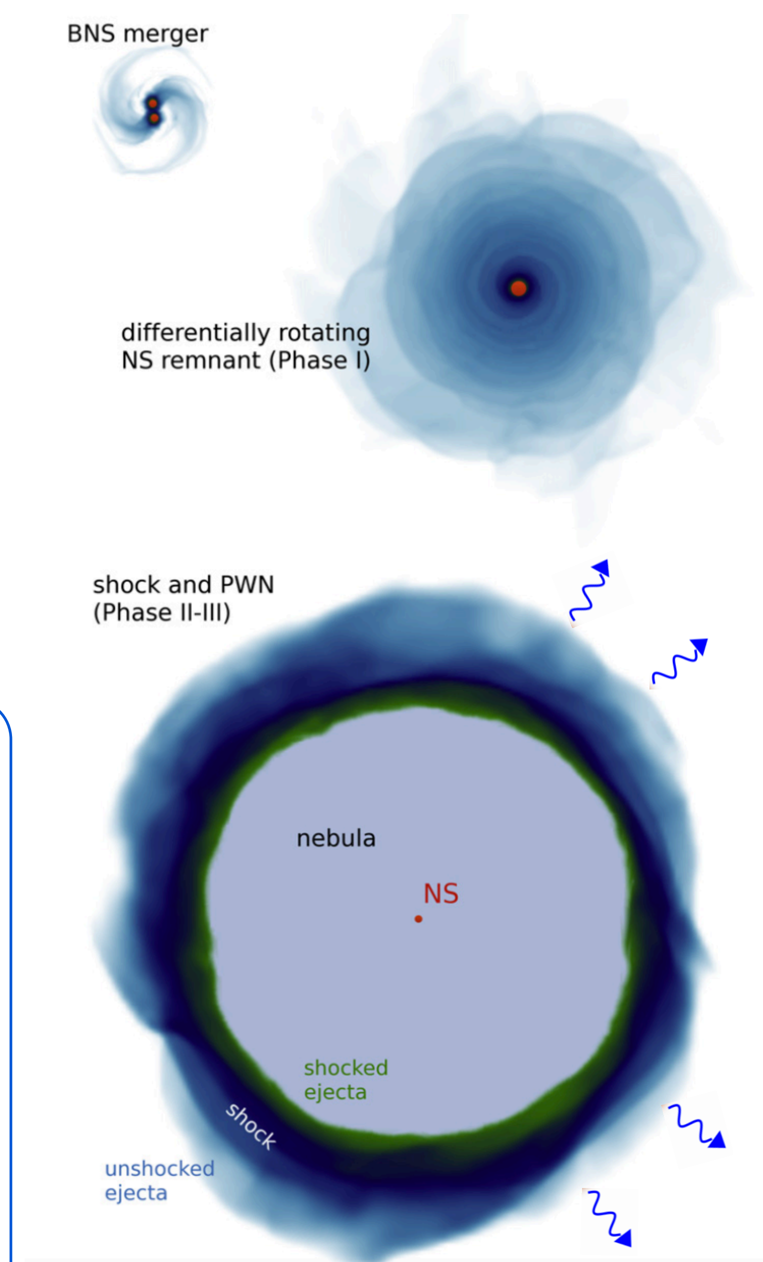

Siegel & Ciolfi 2016a,b

Ascenzi & Ciolfi, in prep.

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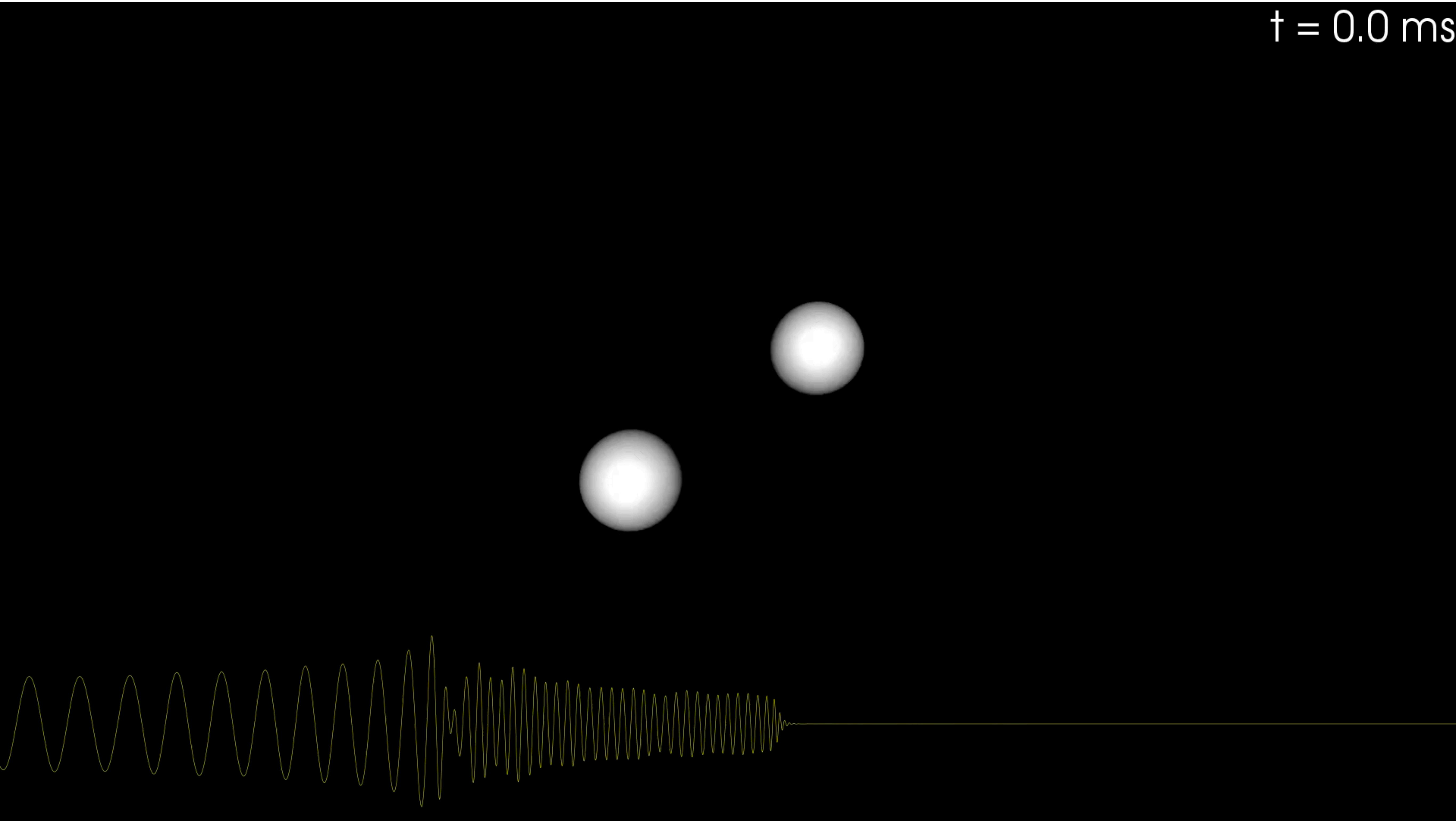
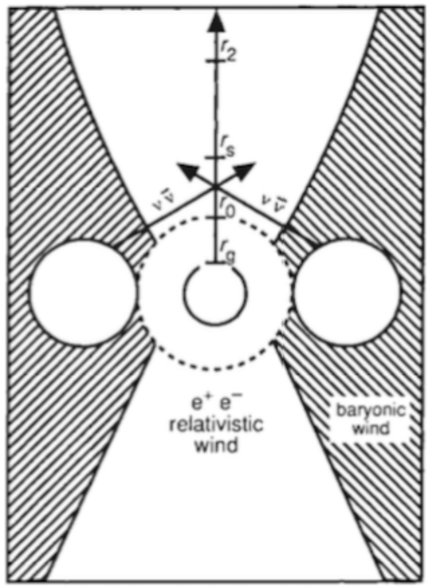
BH-disk formation in a BNS merger



Kawamura et al. 2016

Jets from BNS mergers?

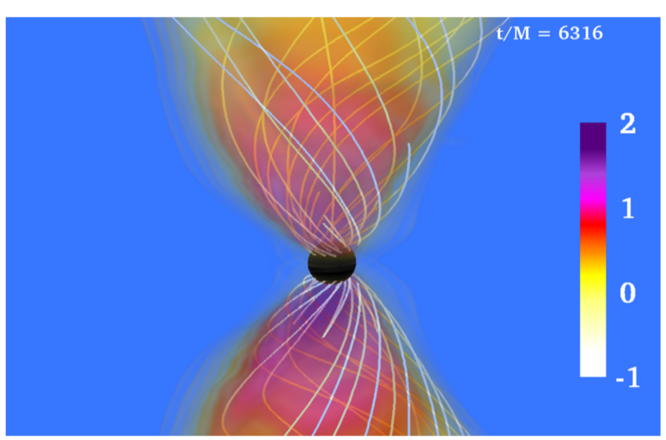
Mochkovitch et al. 1993



neutrino mechanism

VS

magnetic mechanism (Blandford-Znajek?)



Paschalidis et al. 2015

I neutrino annihilation

- too much baryon pollution along orbital axis in NS-NS case

Just et al. 2016

- not enough energy to explain SGRB jets

(even with neutrino radiation from a long-lived remnant)

Perego et al. 2017

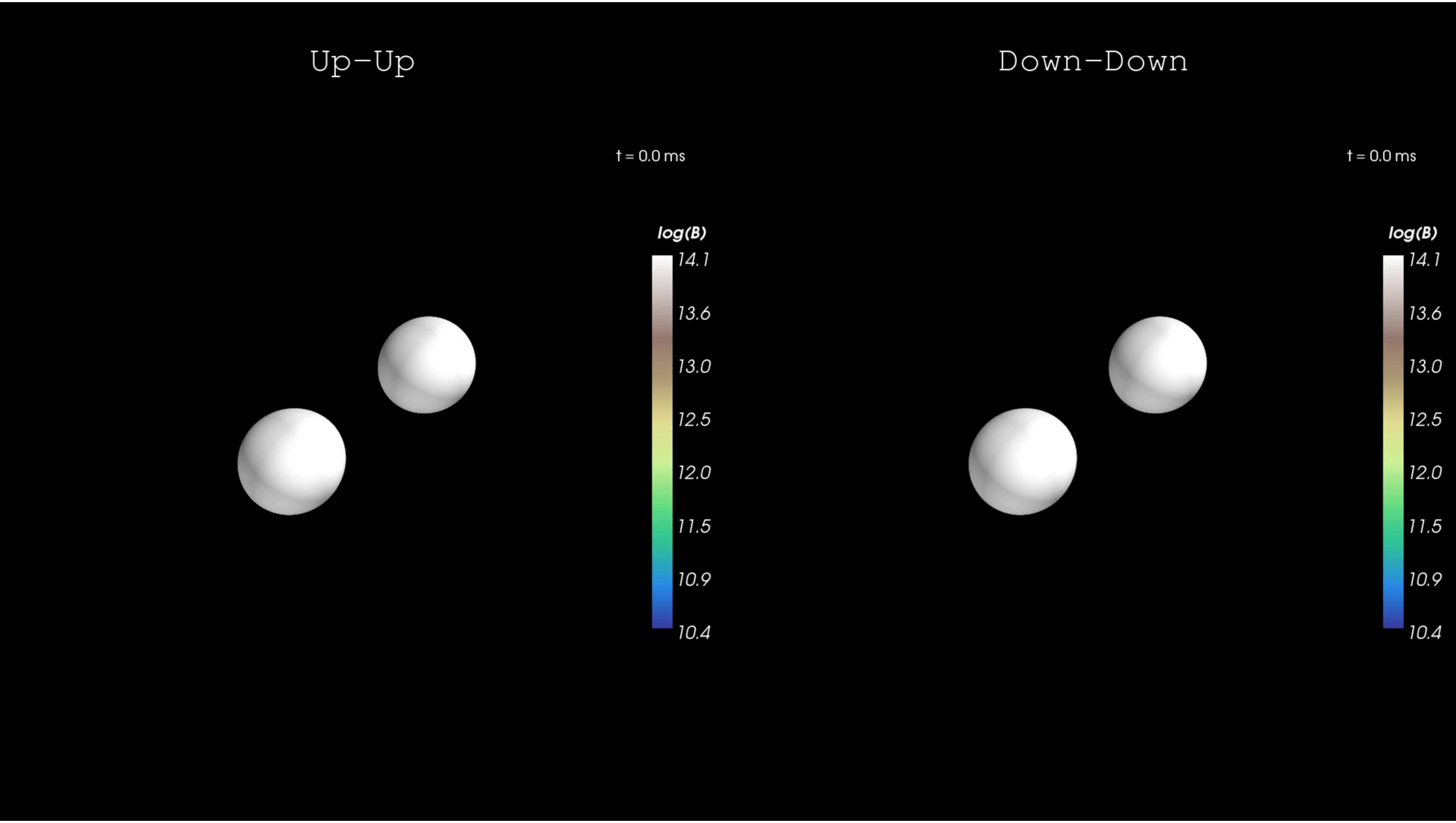
II magnetic fields

- mildly relativistic "incipient" jet emerging inside magnetically dominated funnel

- caveat: obtained with unrealistically high initial magnetic fields ($>10^{16}$ G)

Ruiz et al. 2016

Magnetic field structure

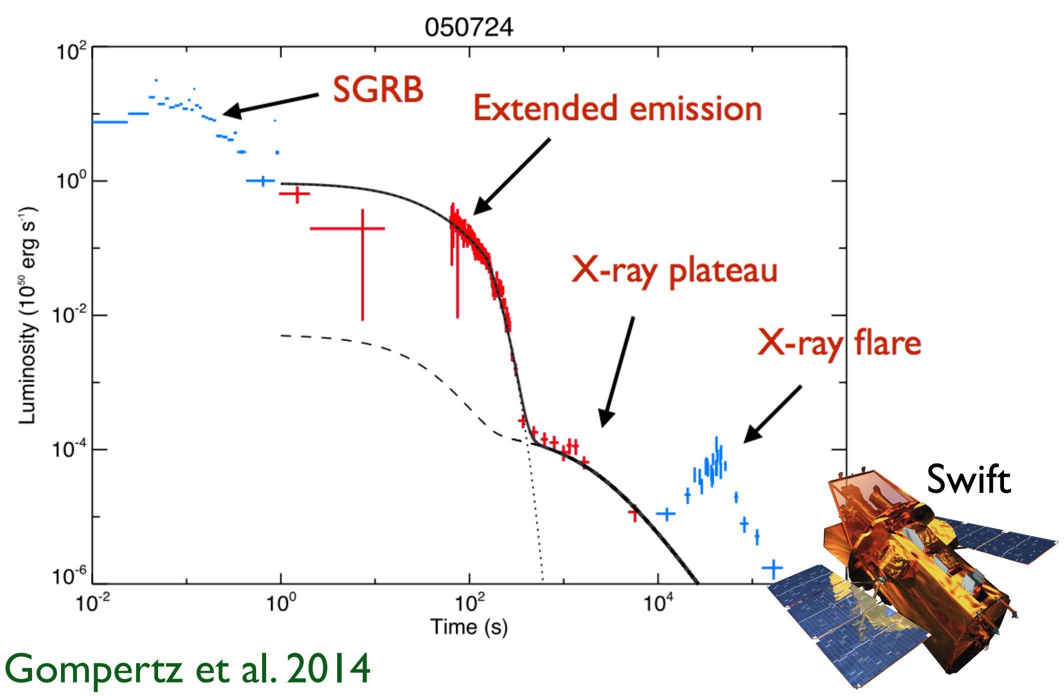


Kawamura et al. 2016

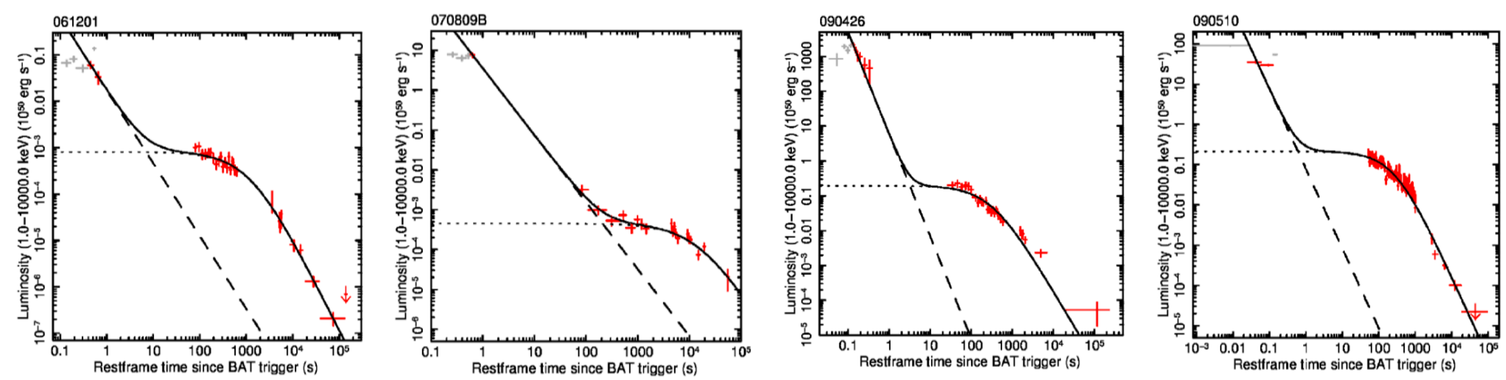
Magnetar scenario

BNS merger → SGRB central engine: rapidly spinning, highly magnetized NS (i.e. millisecond magnetar) → following EM spindown emission (timescale ~minutes/hours)

Favourable indications in the soft X-ray band ⟶ X-ray plateaus (in ~50% of Swift SGRBs)



Gompertz et al. 2014



Rowlinson et al. 2013

a challenge for the BH-disk scenario!

$$\tau_{\rm plateau} \sim 100 - 10^5\,{\rm s} \gg \tau_{\rm accr} \sim 0.1 - 1\,{\rm s}$$

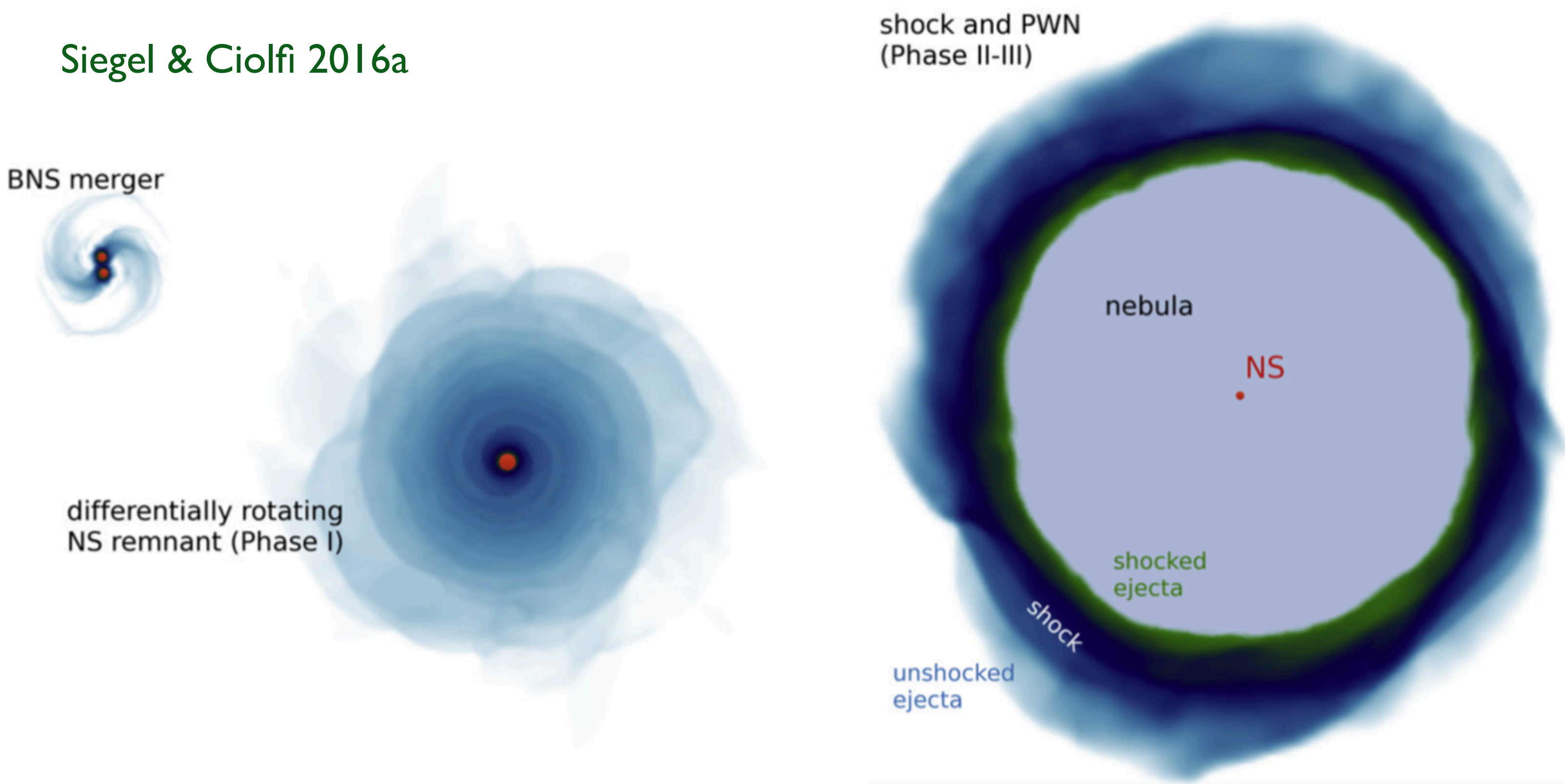
natural explanation via magnetar spindown?

simplest approach: dipole spindown formula $L_{\rm X} = L_0(1+t/t_{\rm sd})^{-2}$

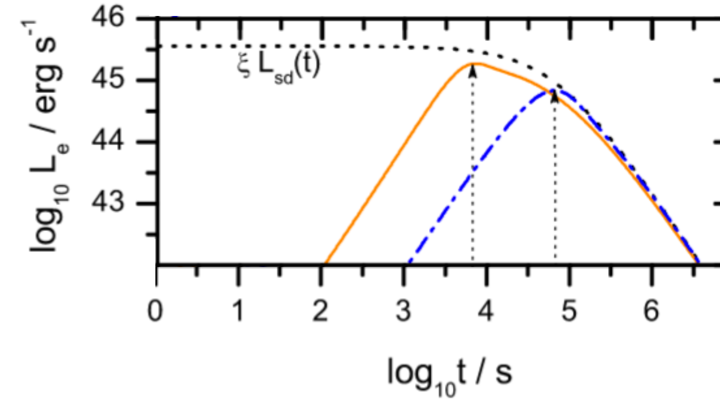
$$L_0 \sim 10^{49}(B_{\rm pole}/10^{15}\,{\rm G})^2(P/\,{\rm ms})^{-4}\ {\rm erg/s}\ ;\quad t_{\rm sd} \sim 3\times10^3(B_{\rm pole}/10^{15}\,{\rm G})^{-2}(P/\,{\rm ms})^2\ {\rm s}$$

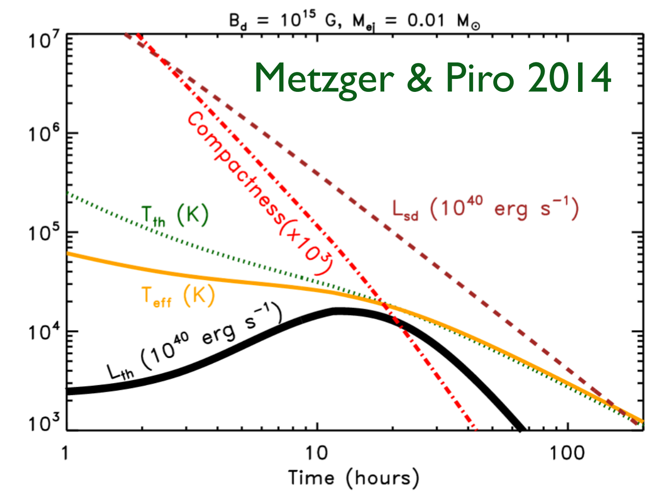
Spindown-powered emission models

Siegel & Ciolfi 2016a



Yu et al. 2013





signal peaks in the soft X-ray to optical band (depending on parameters)

- peak time 10^2-10^4 s after merger (similar range for duration)
- luminosity 10^{46}-10^{48} erg/s

viable explanation for SGRB X-ray plateaus

- peak time 10^4-10^5 s
- luminosity 10^{44}-10^{46} erg/s

luminous and isotropic:
promising EM counterpart!

Stratta et al. 2018

Siegel & Ciolfi 2016b