INAF Osservatorio Astronomico di Padova

TIFPA Trento Institute for Fundamental Physics and Applications

Short GRB and kilonova: did observations meet our theoretical predictions?

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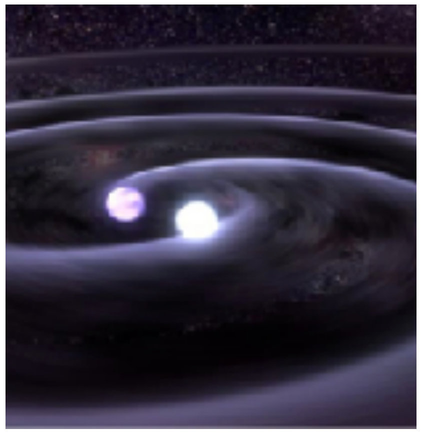
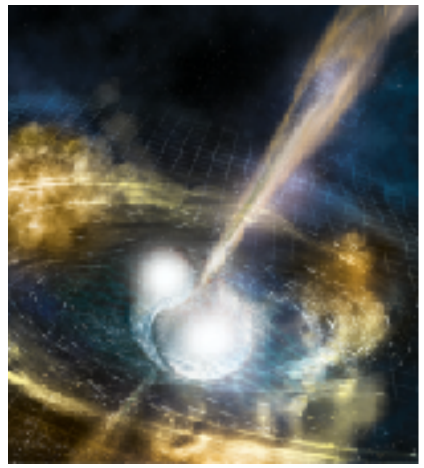
INFN - Trento Institute for Fundamental Physics and Applications

GW170817 Workshop - DFA Padova 25th October 2017

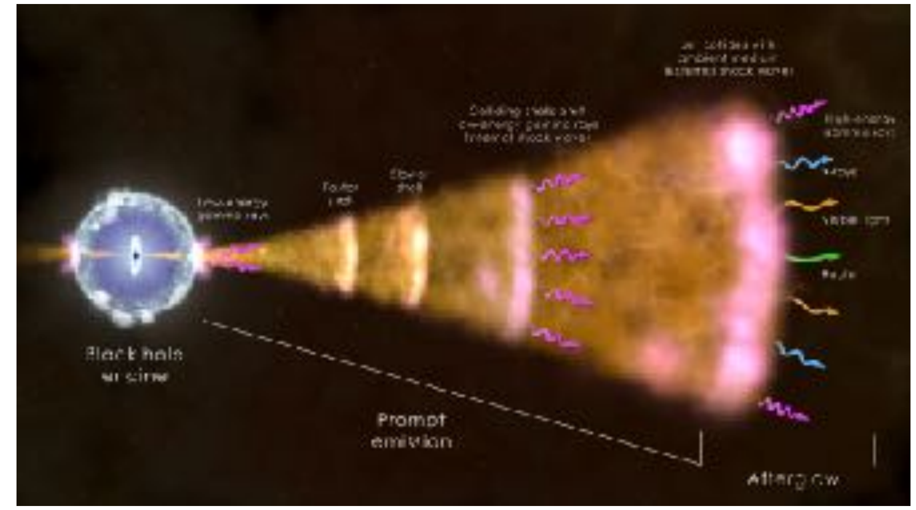
GW170817 detection timeline



merger



short GRB



X-ray afterglow

radio afterglow

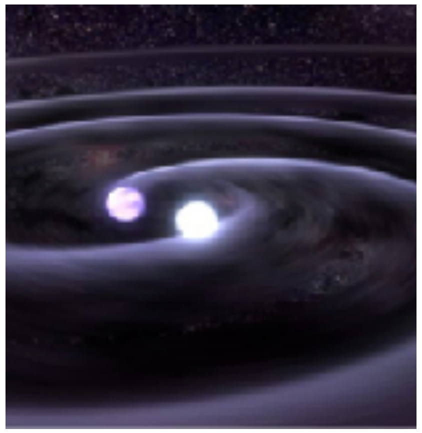
t0 — +1.7 sec — +10.87 hours — +9 days — +16 days

optical counterpart

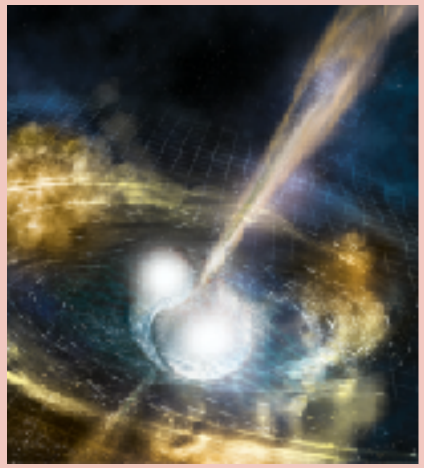
——

kilonova

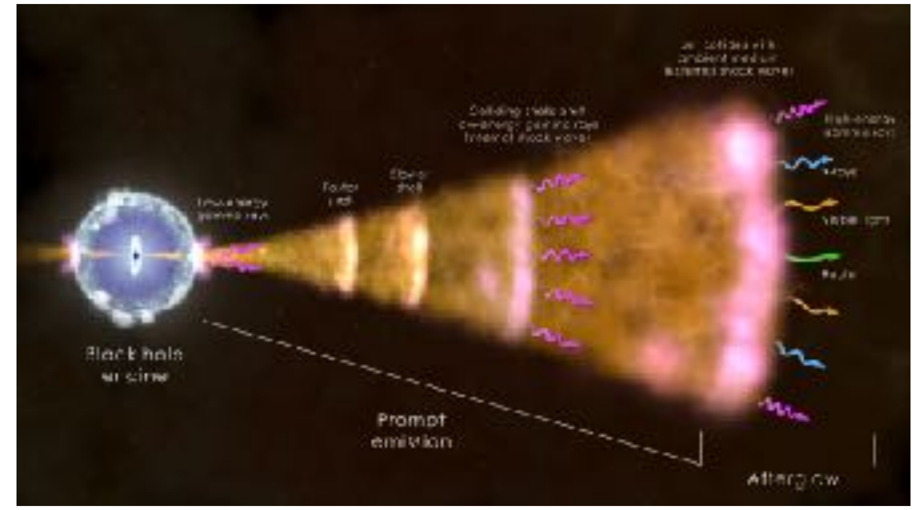
GW170817 detection timeline



merger



short GRB



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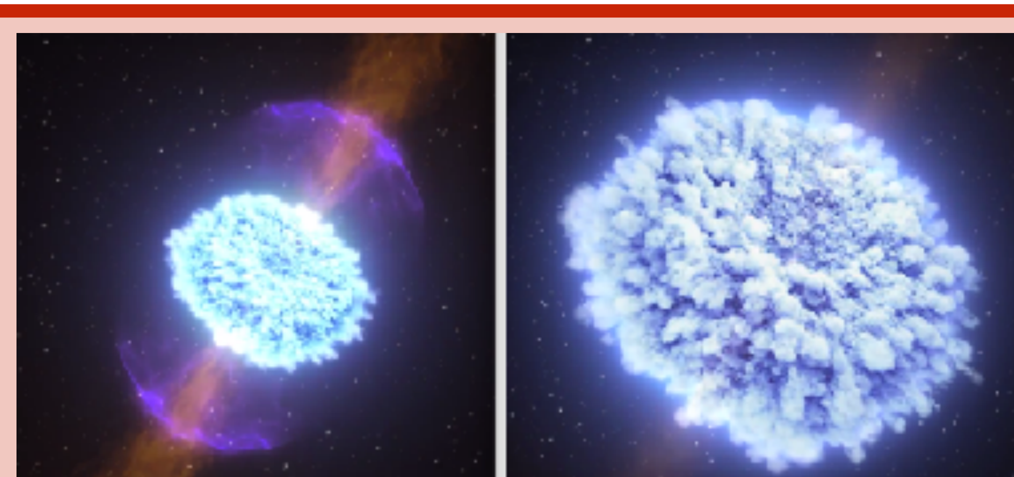
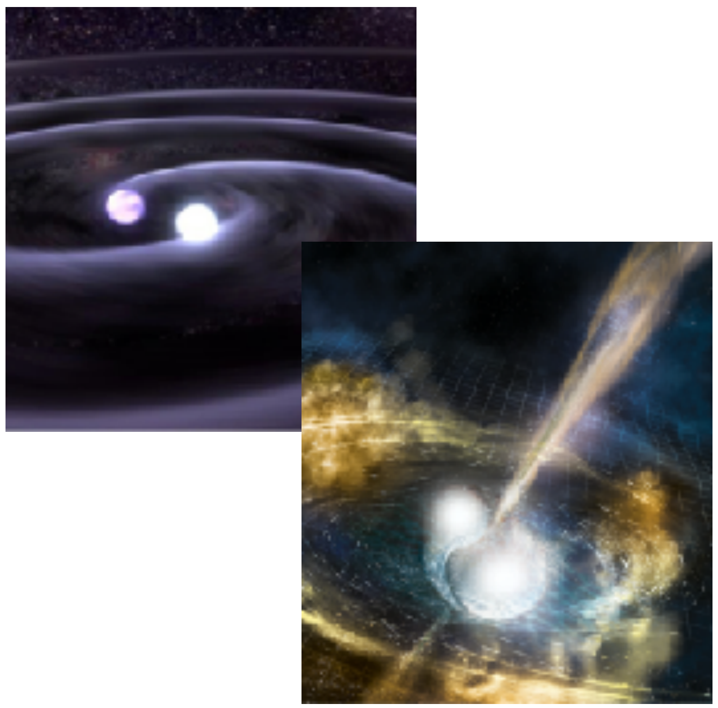
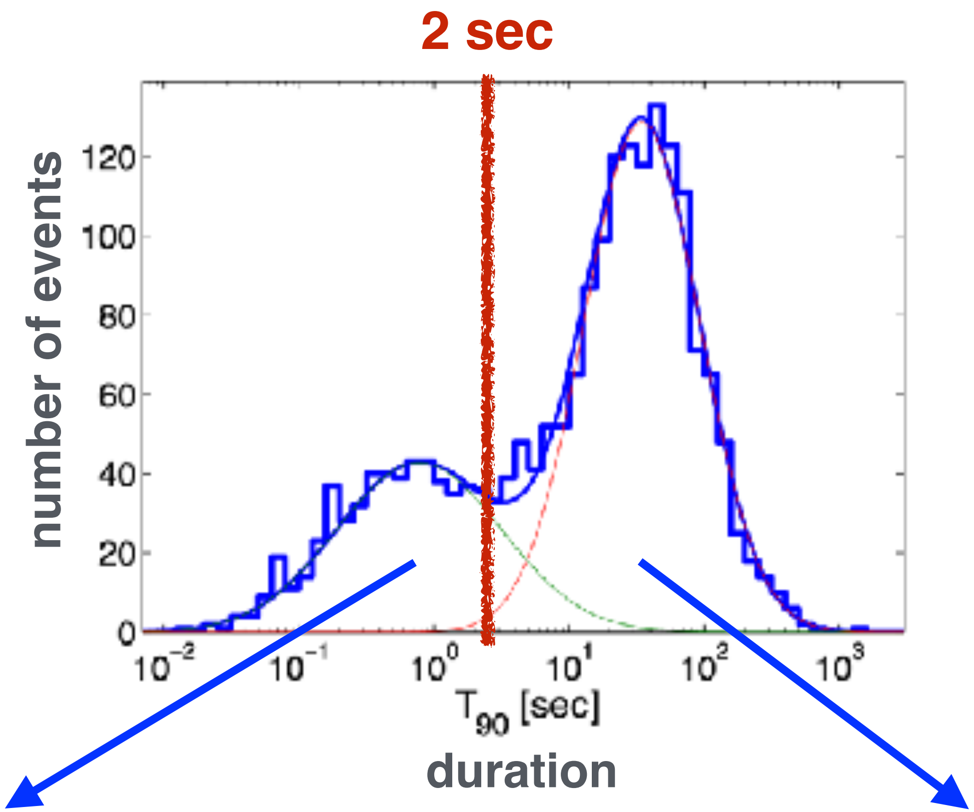
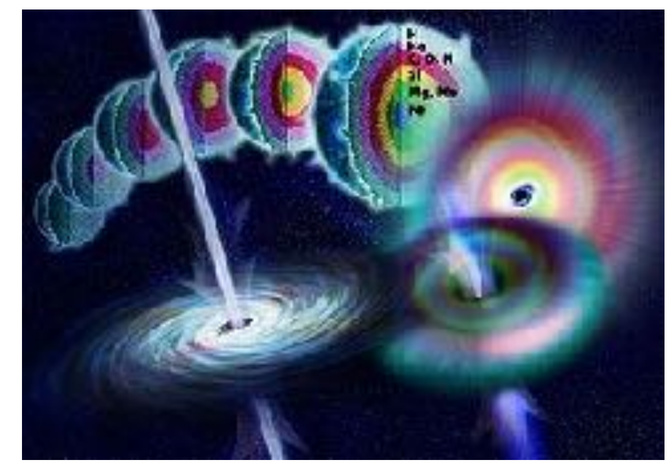


GRB long/short divide







short GRBs

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

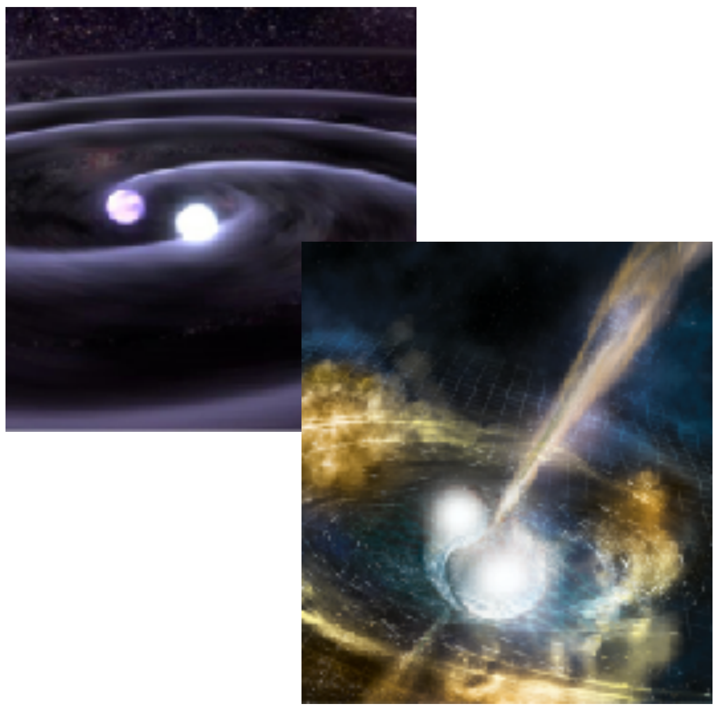
NS-NS (NS-BH) mergers??

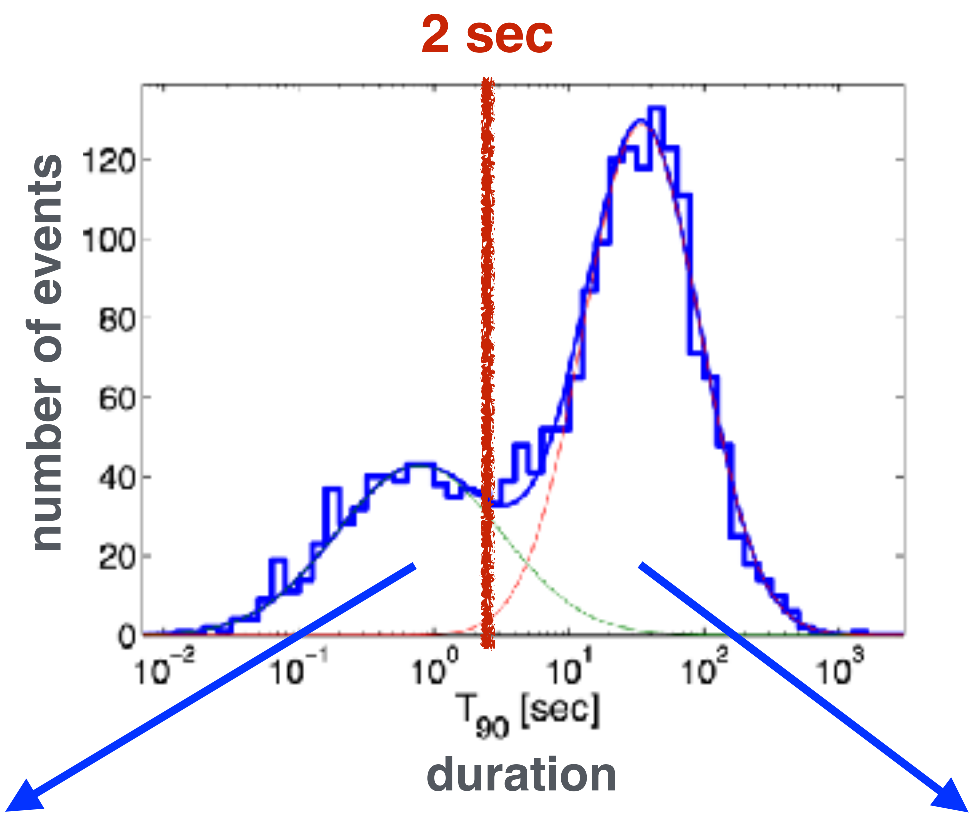
long GRBs

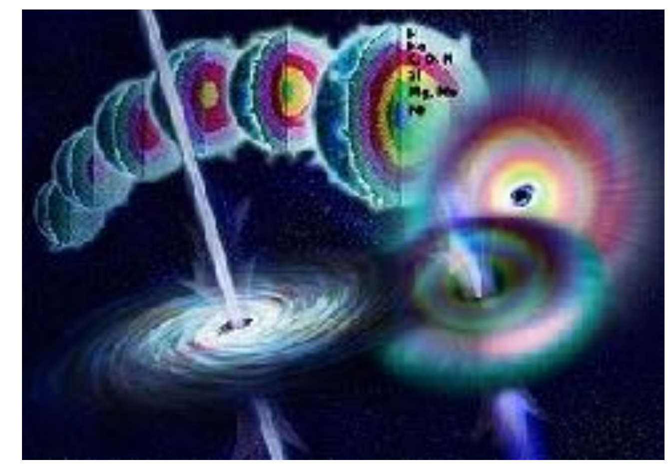
- $T_{90} \gtrsim 2\,\mathrm{s}$
- confirmed supernova associations (Hypernovae $\gtrsim 10^{52}\,\mathrm{erg}$)
- only late-type galaxies with high star formation rates

core-collapse supernovae ✓

GRB 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

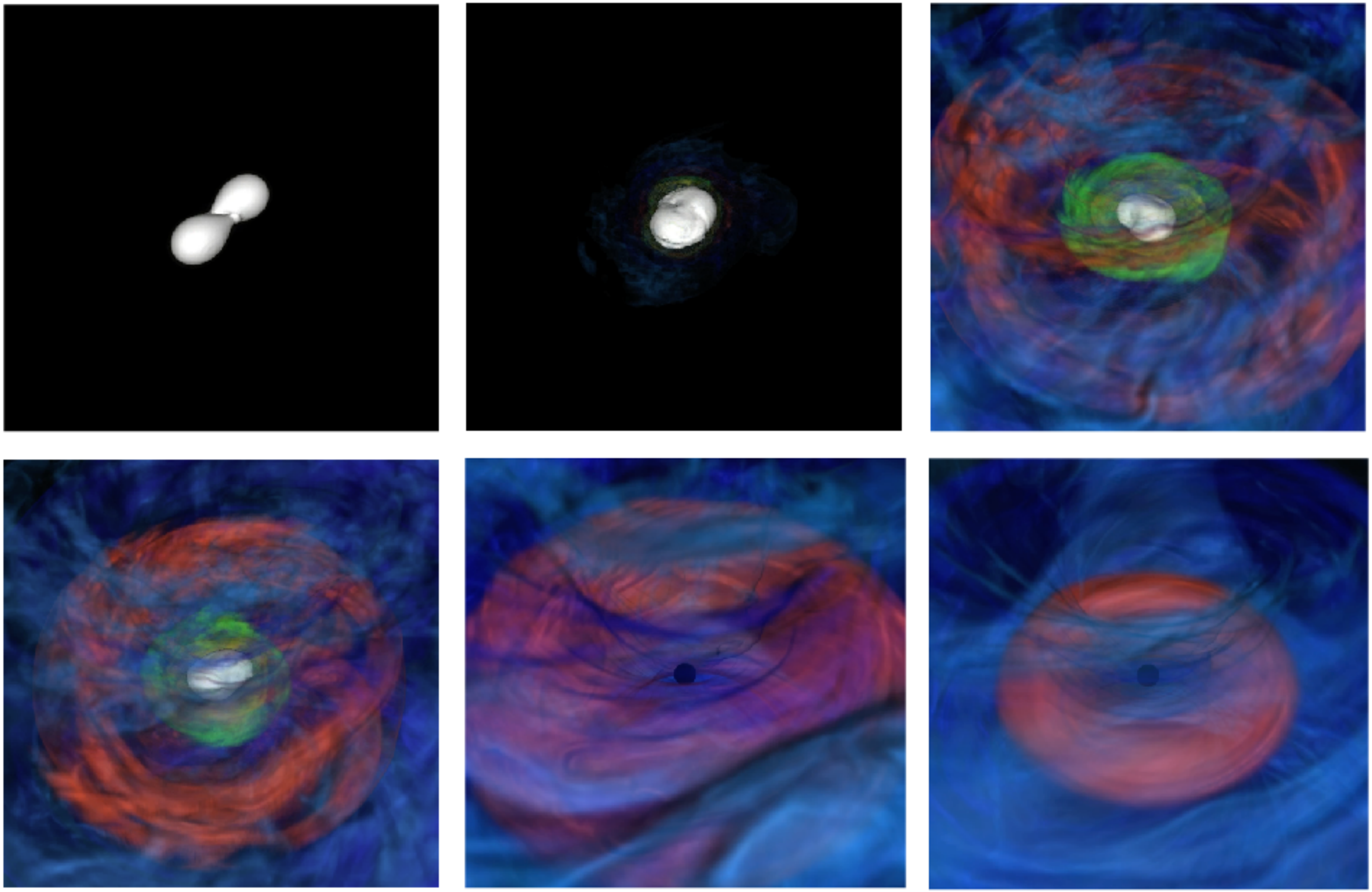
NS-NS (NS-BH) mergers?? **YES!** ✓

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

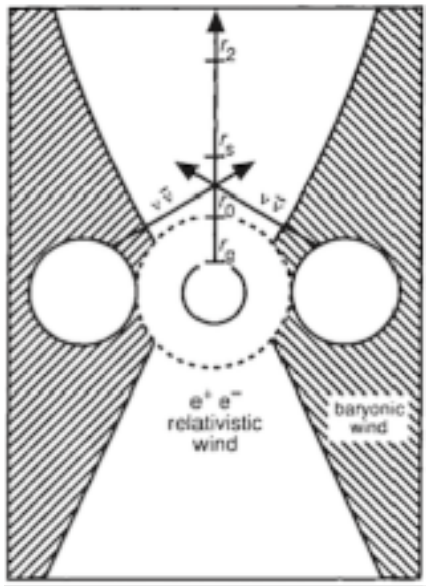
core-collapse supernovae ✓

BH-disk formation in a BNS merger



Jets from BNS mergers?

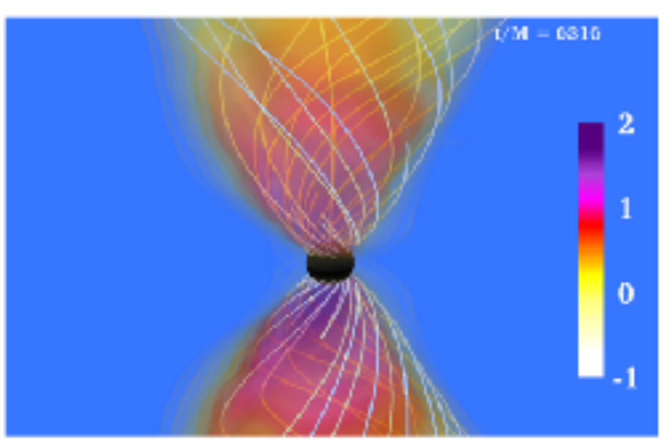
Mochkovitch et al. 1993



neutrino mechanism

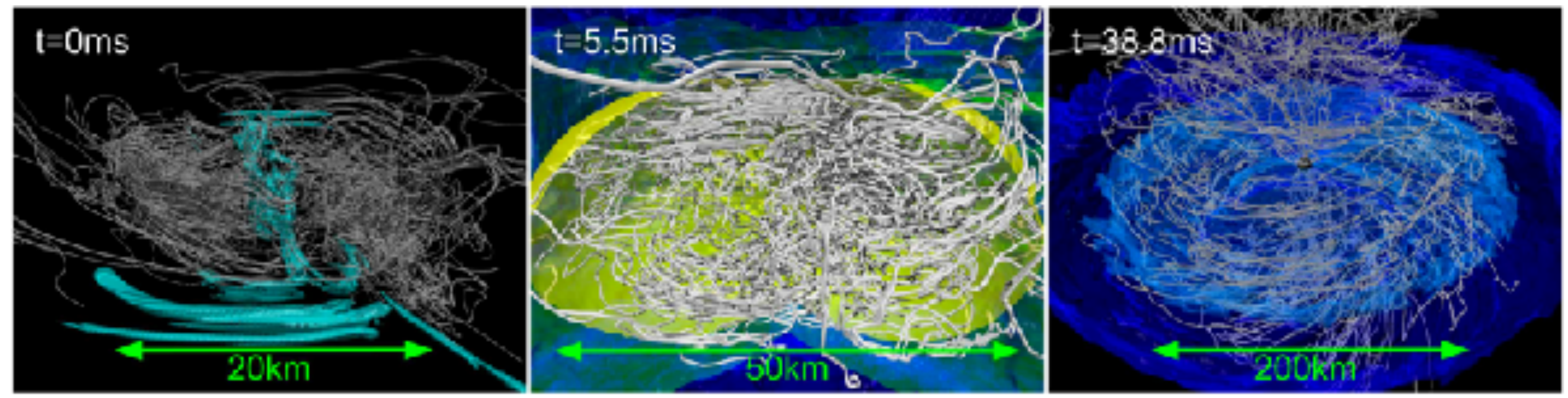
VS

magnetic mechanism
(Blandford-Znajek?)

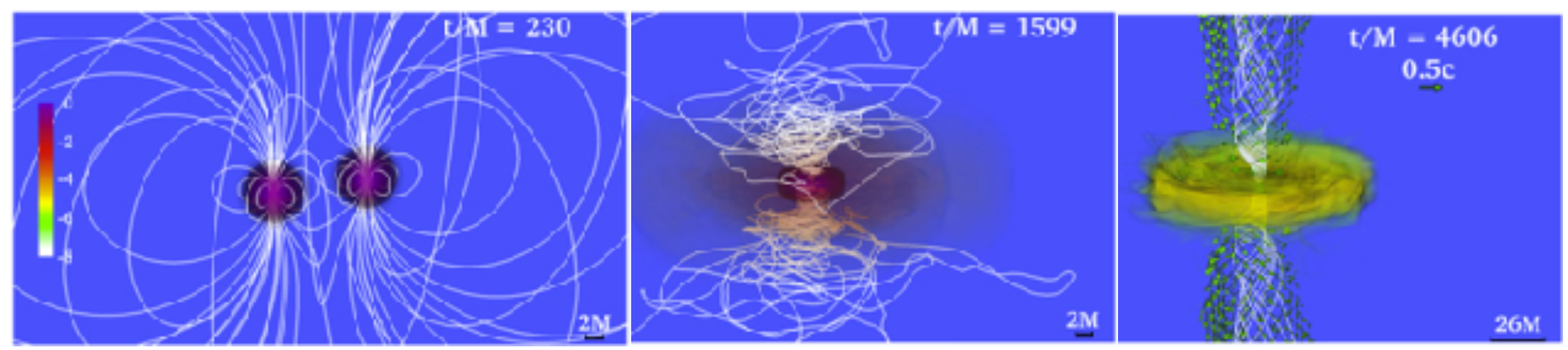


Paschalidis et al. 2015

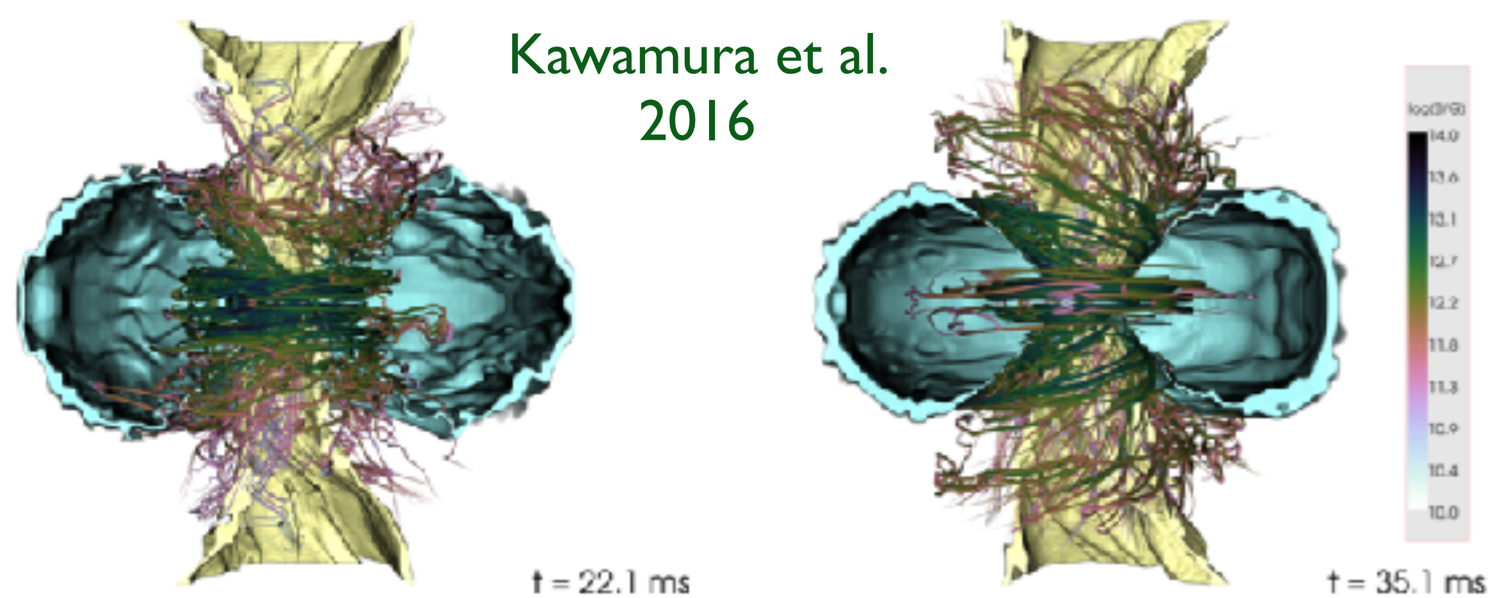
Kiuchi et al. 2014



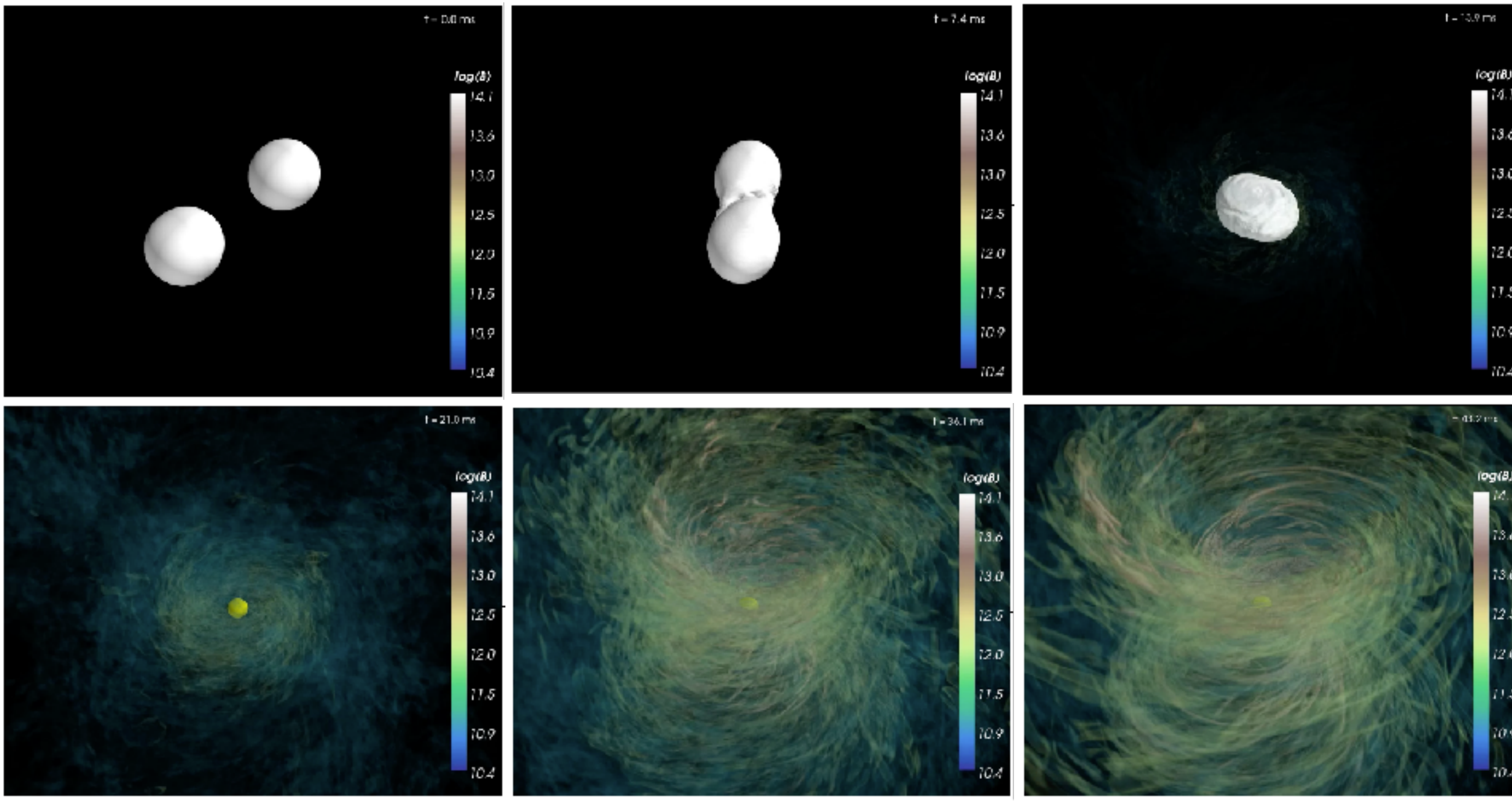
Ruiz et al. 2016



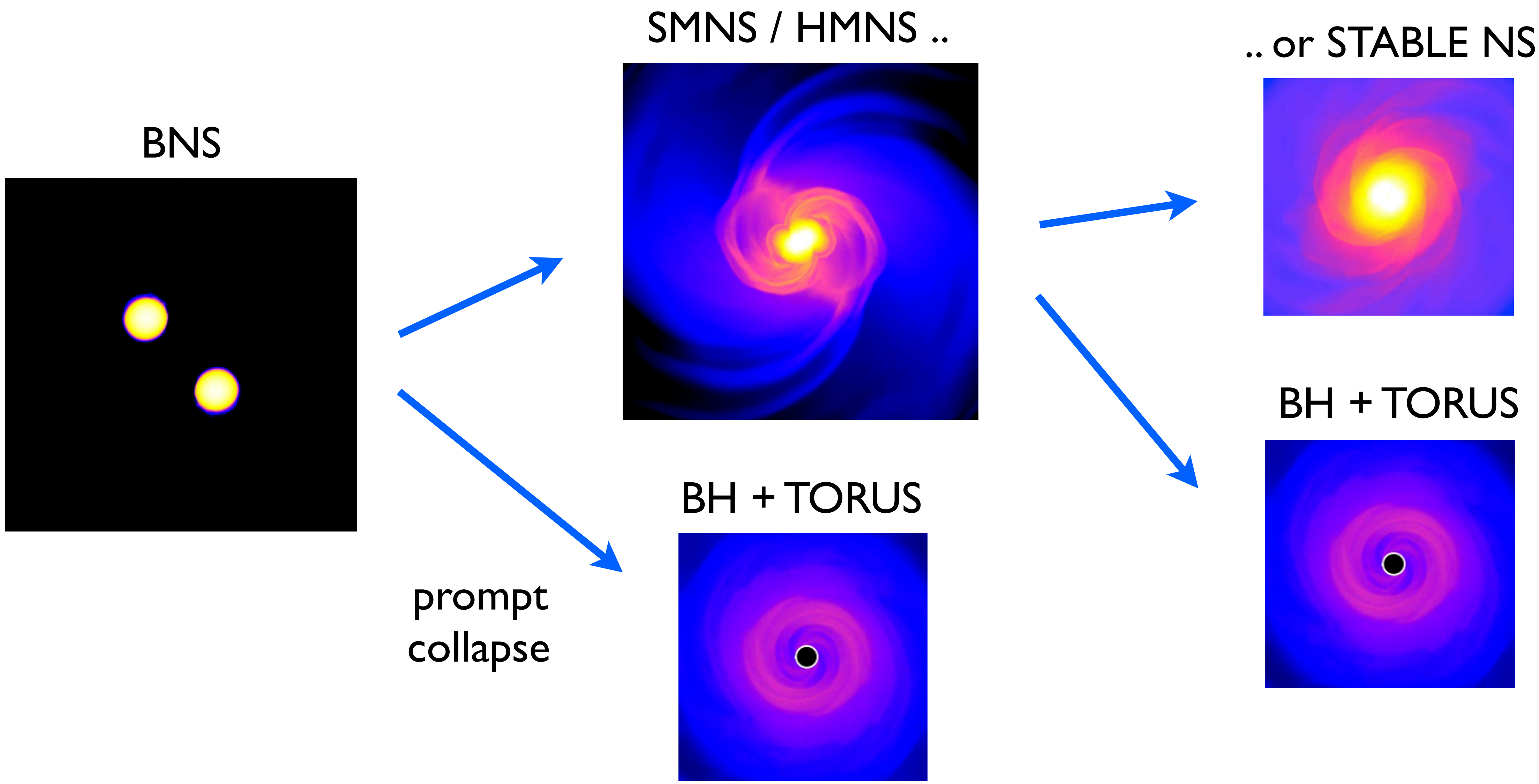
Kawamura et al.
2016



Magnetic field structure

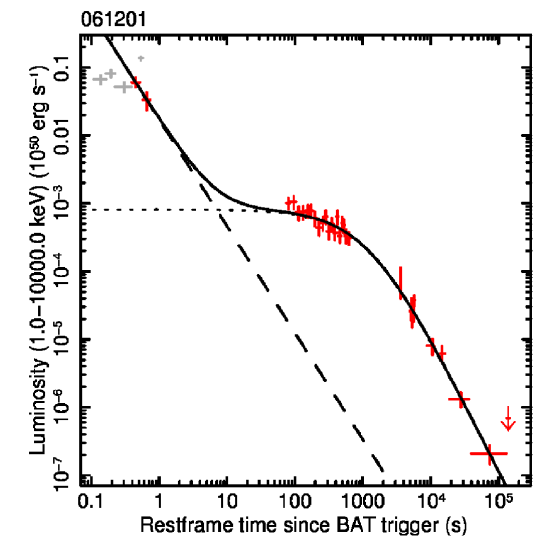


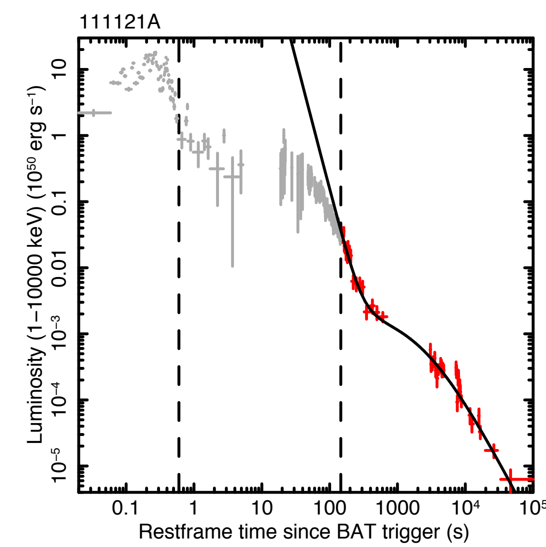
Product of BNS mergers

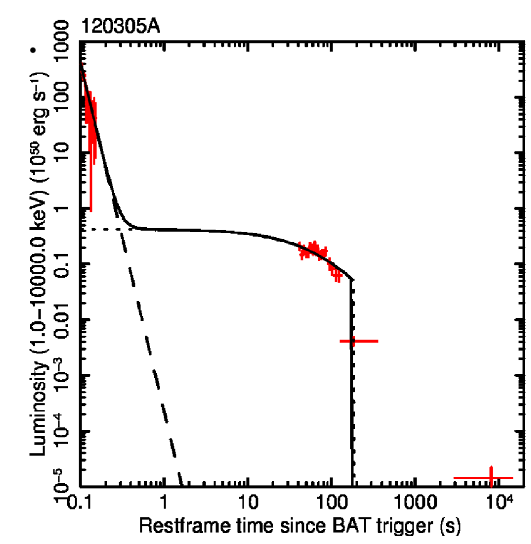


Magnetar SGRB scenario

- Swift revealed that most SGRBs are accompanied by long-duration $(\sim 10^2 - 10^5\ \mathrm{s})$ and high-luminosity $(10^{46} - 10^{51}\ \mathrm{erg/s})$ 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 $\gtrsim 10^{14} - 10^{15}\,\mathrm{G}$

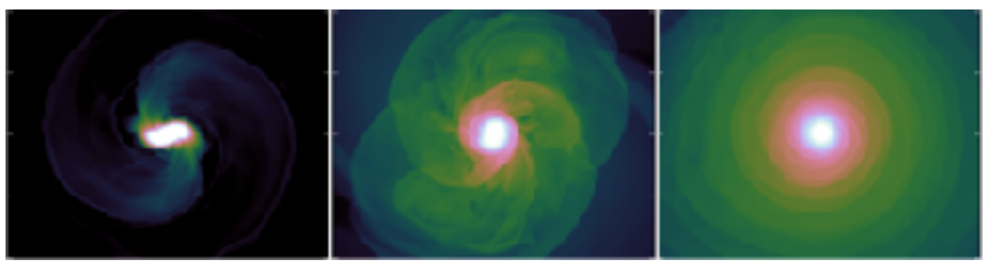
dipole spindown

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

PROBLEM OF THE MAGNETAR MODEL:

strong baryon pollution can choke the formation of a relativistic jet

→ HARD TO EXPLAIN THE SGRB PROMPT EMISSION



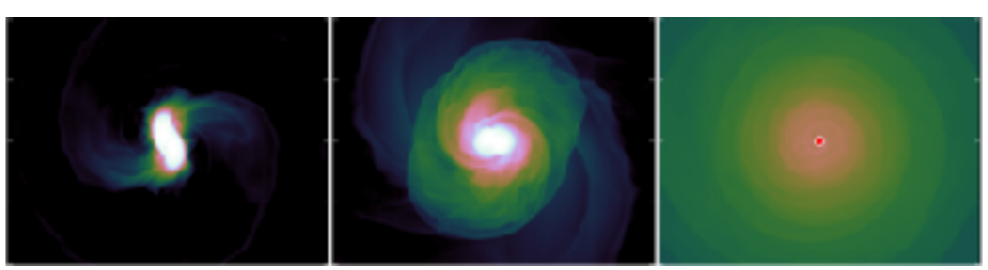
long-lived NS

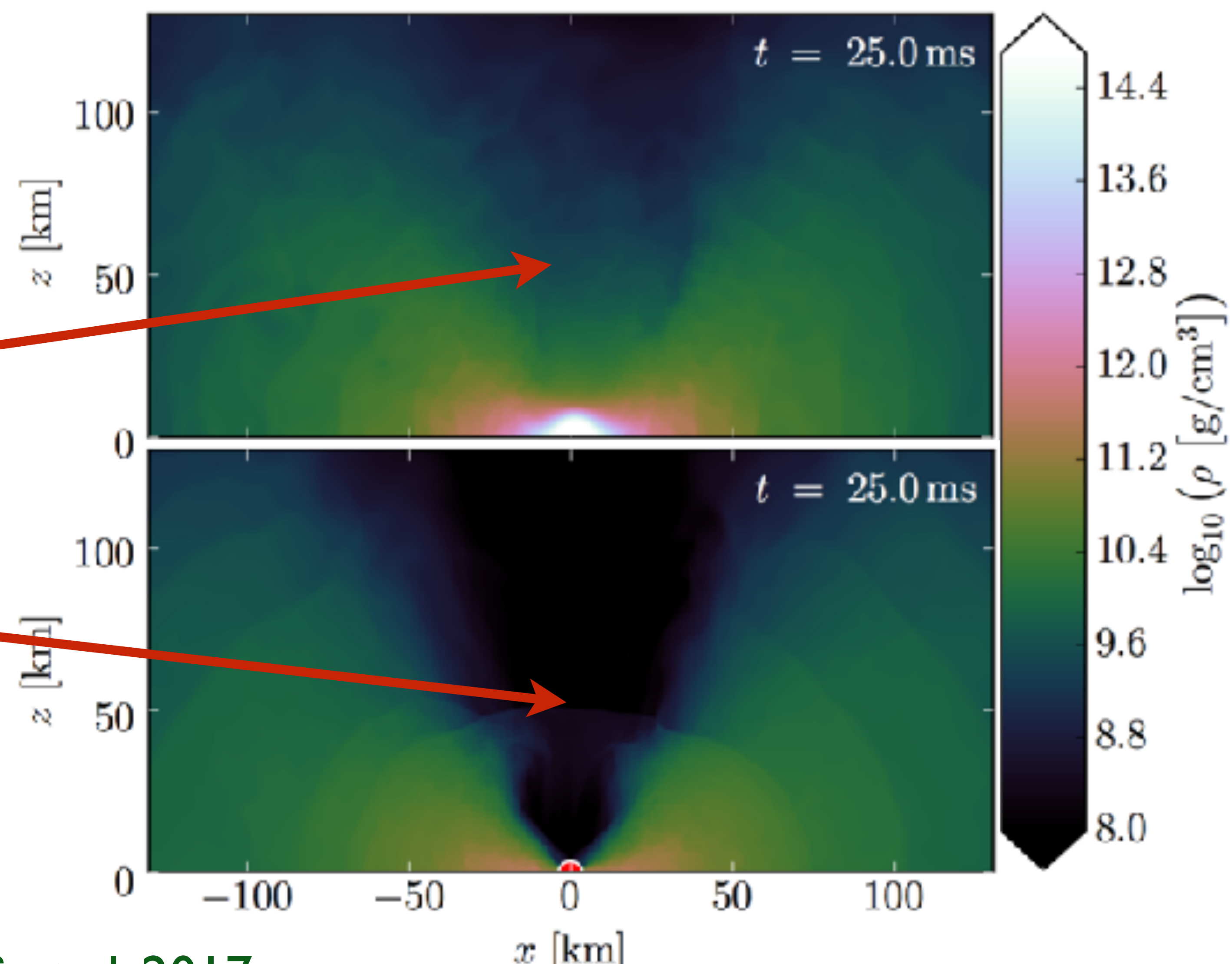
baryon-loaded funnel

vs

BH-disk

baryon-free funnel

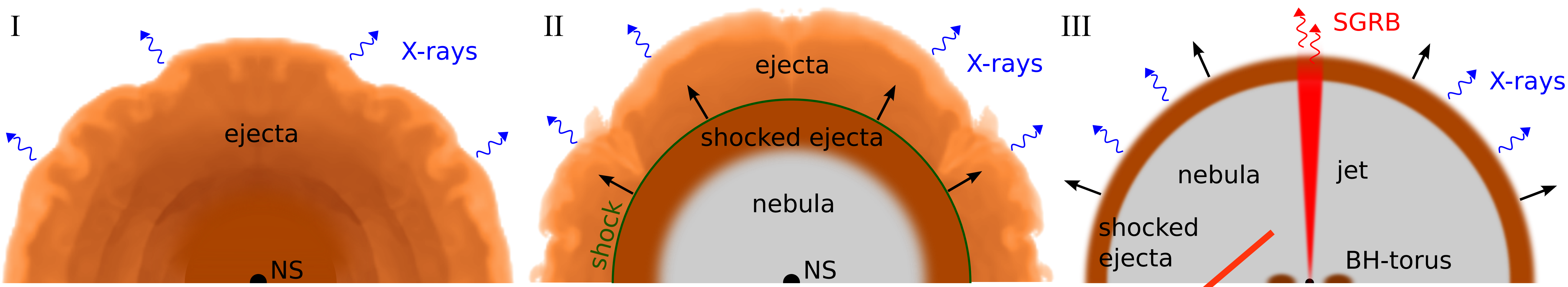


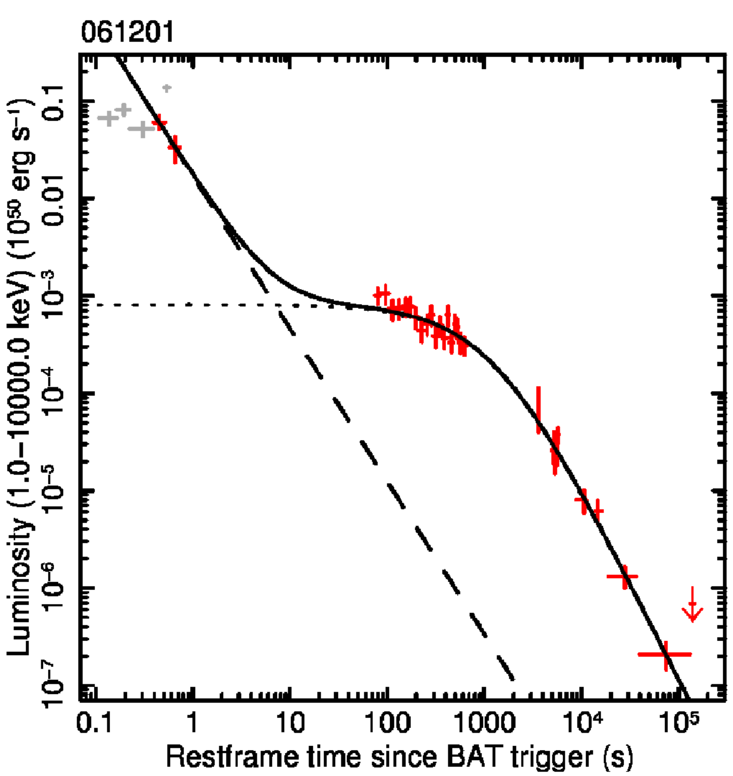


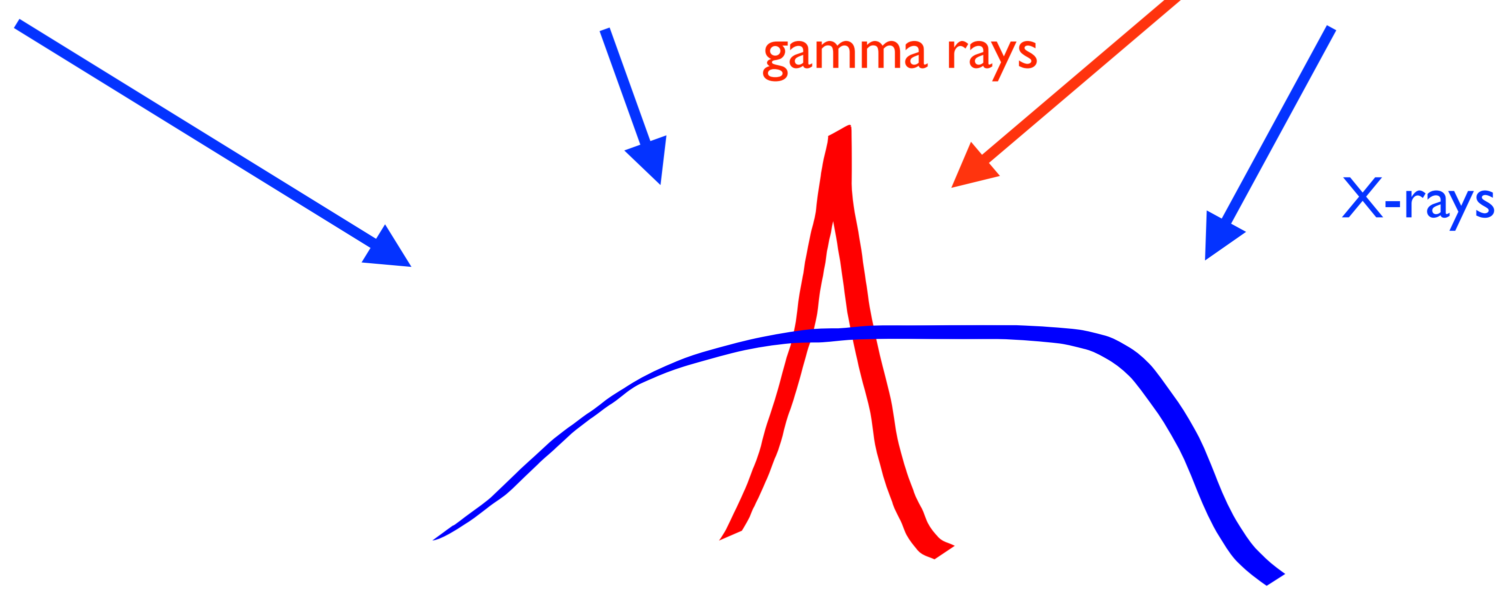
Ciolfi et al. 2017

“Time-reversal” scenario for SGRBs

Ciolfi & Siegel 2015







The spin-down emission is given off before but (in part) observed after the prompt SGRB radiation

Short GRB summary

take-home message:

the first coincident SGRB/BNS merger detection proves a long-standing hypothesis and thus meets the expectations

.. but open questions remain on the central engine:

BH-disk or long-lived massive NS?

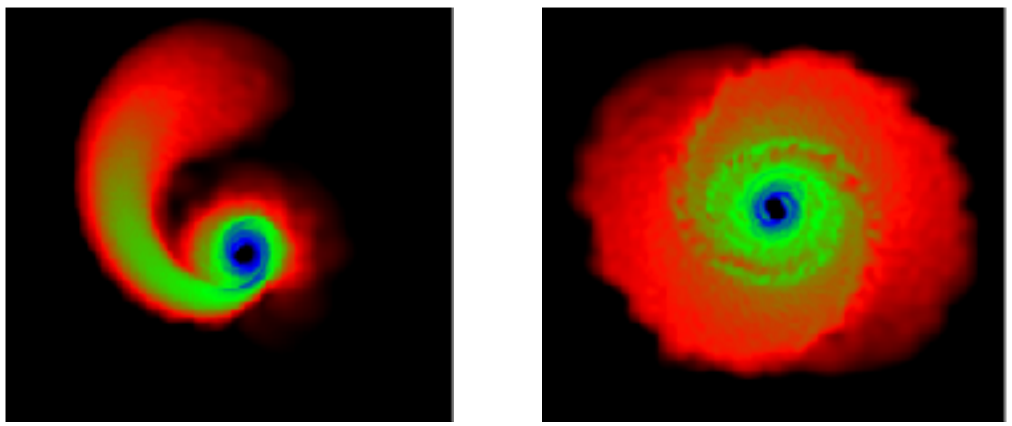
future observations will shed light by assessing the presence/absence of persistent X-ray emission

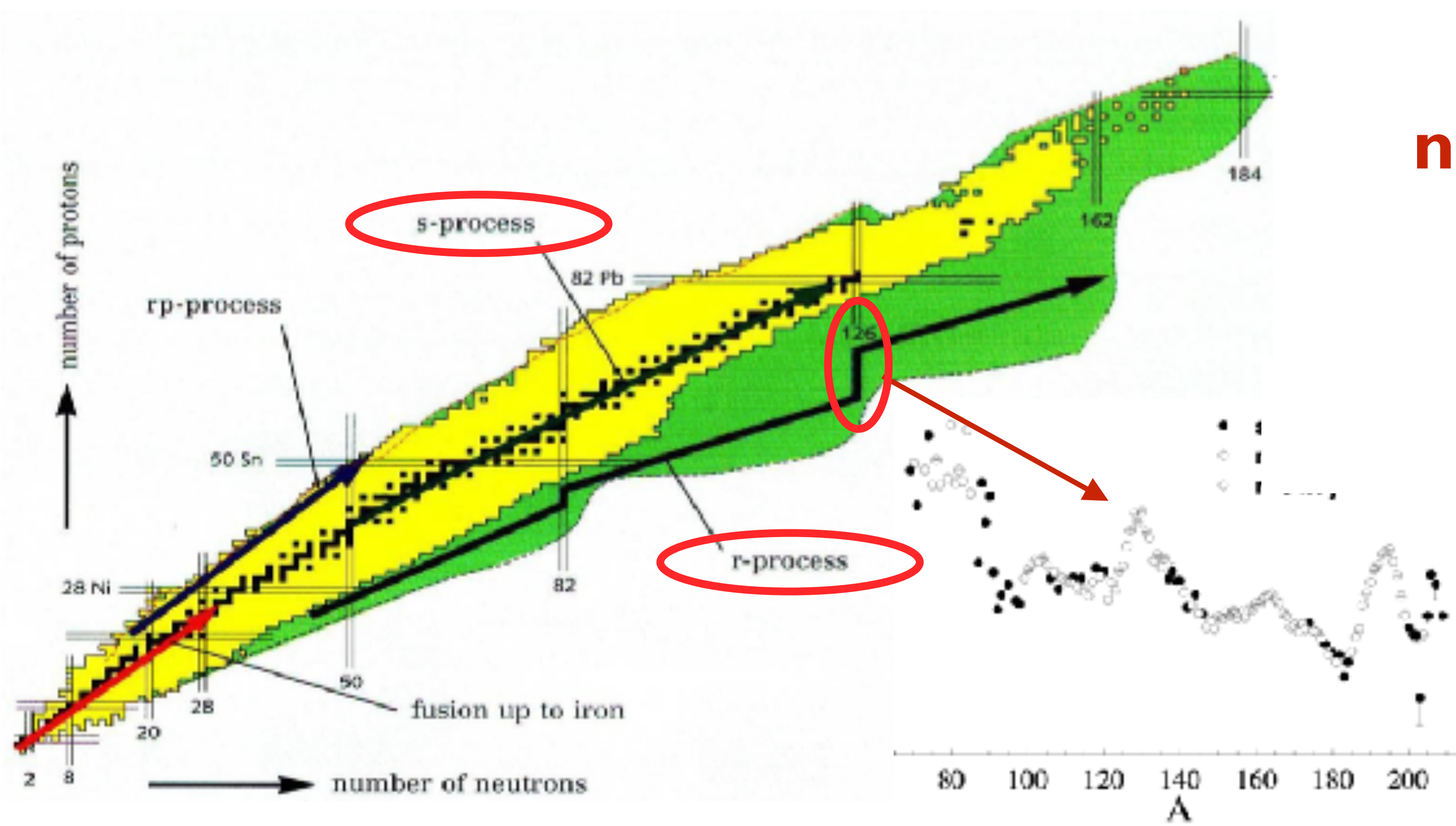
theoretical models will clarify the mechanism to produce a jet

a lot to do in the next years!

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})

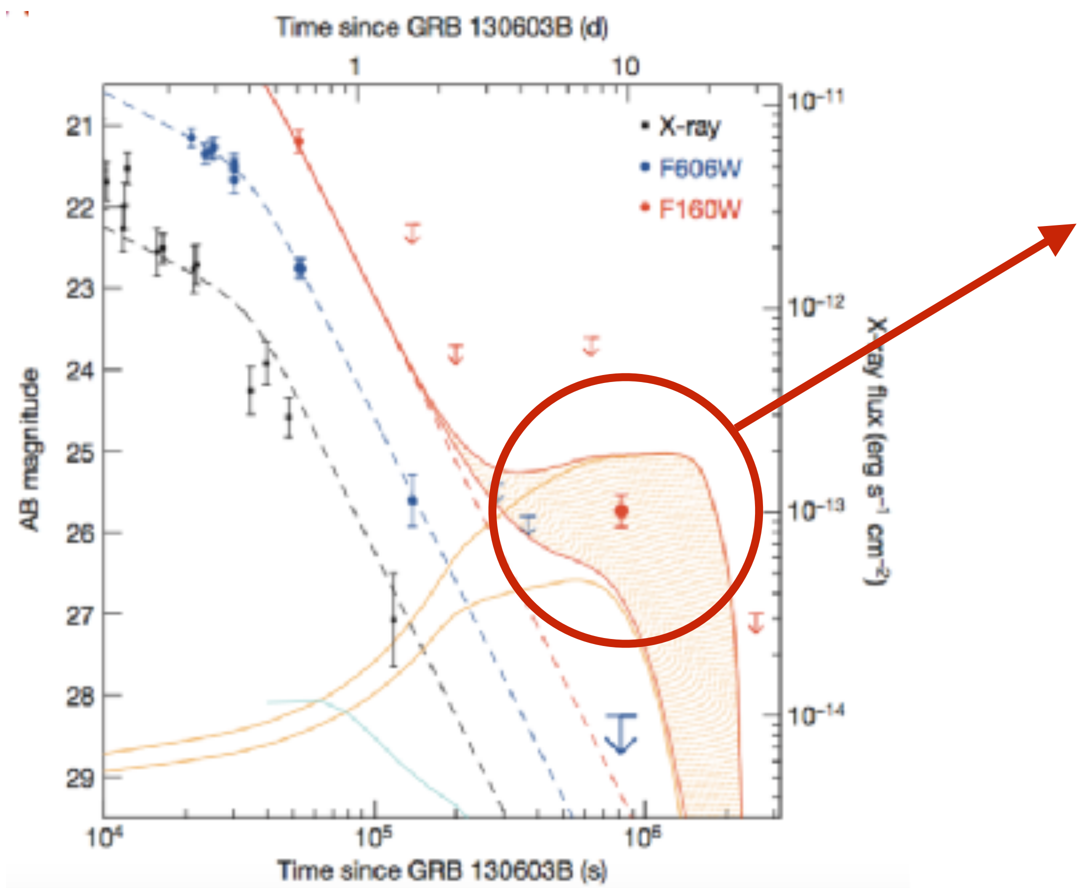
nucleosynthesis of heavy nuclei

initially unstable

radioactive decay on timescales of >days

optical/NIR signal!

Kilonova in GRB130603B?

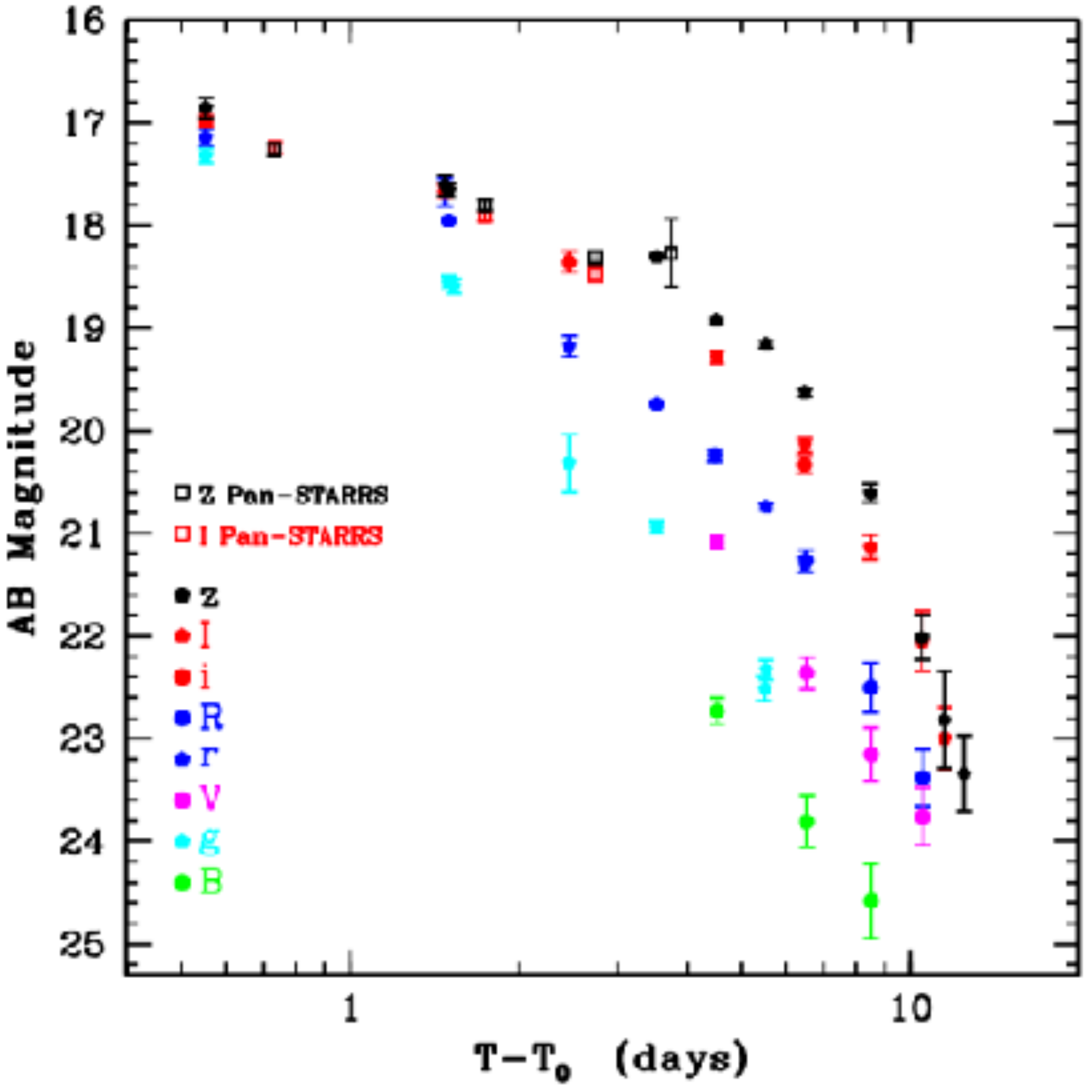


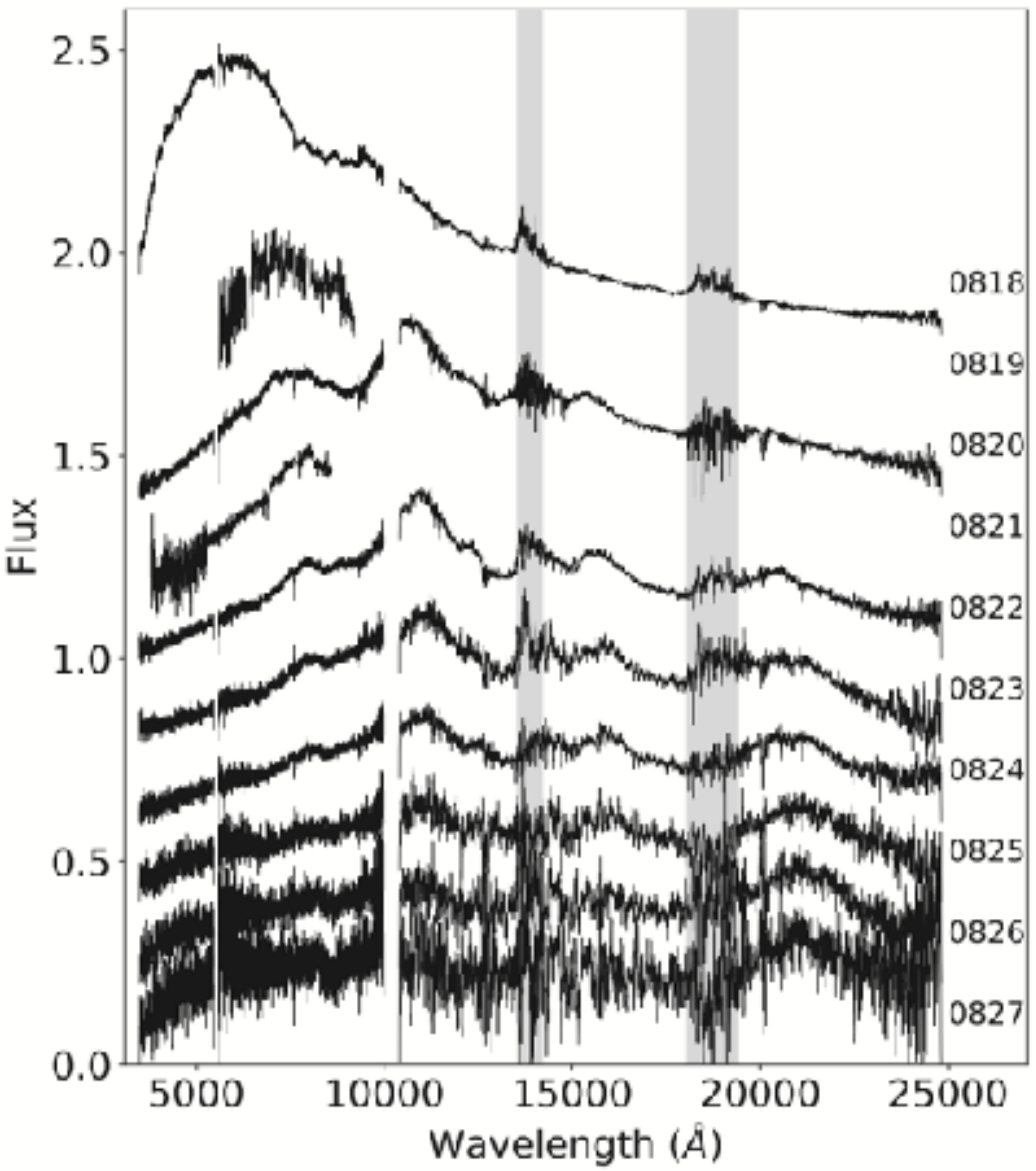
optical rebrightening in GRB 130603B
tentatively interpreted as a kilonova

connection
SGRB ⟷ BNS or NS-BH mergers

Tanvir et al. 2013, Berger et al. 2013

GW170817 Kilonova





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

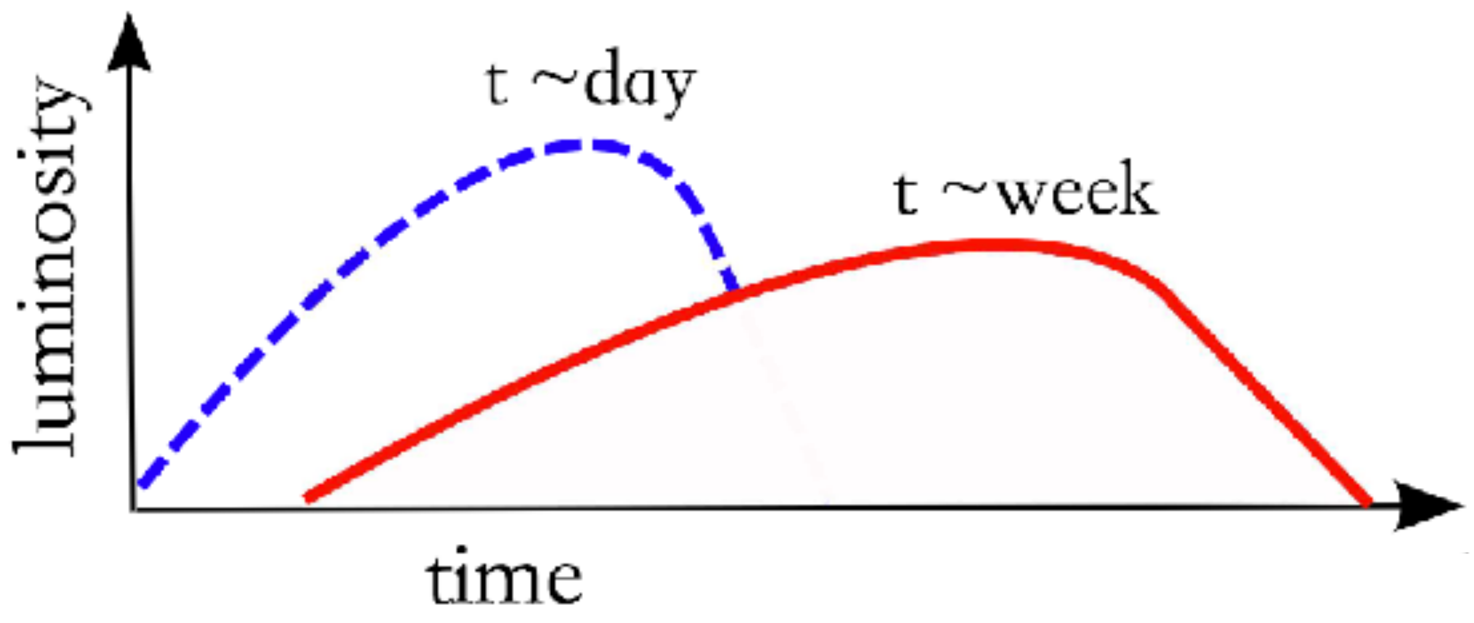
red to infrared, peak time ~1 week

neutron-poor ejecta
high electron fraction Ye>0.2

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

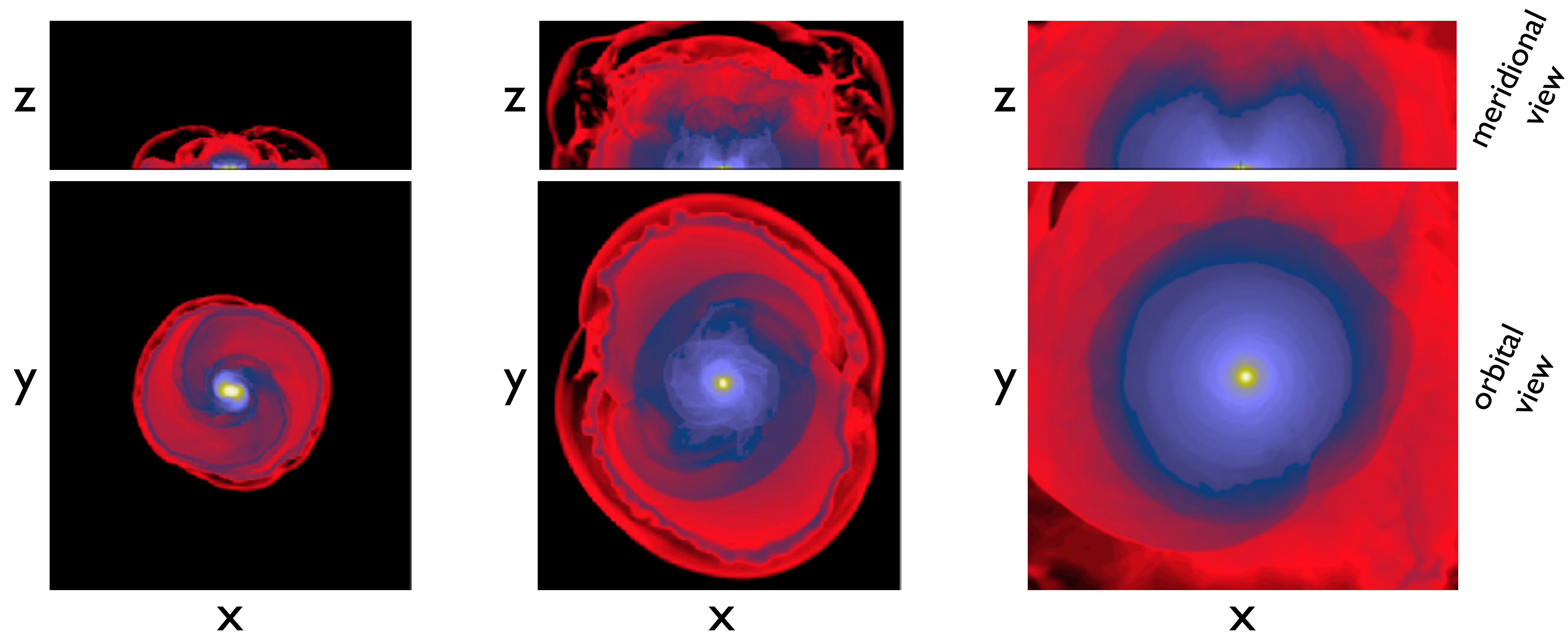
lower opacity

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



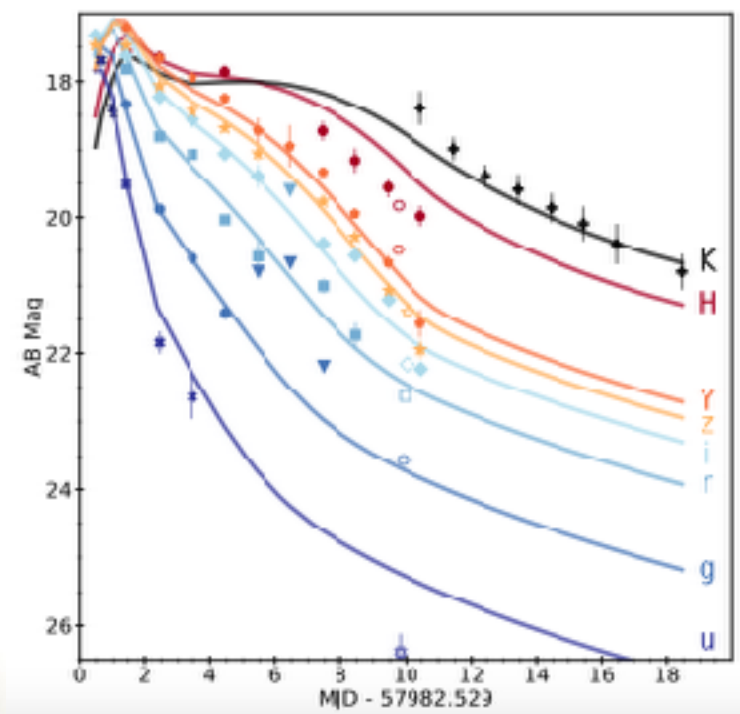
Kilonova summary

the optical/IR signal is fully consistent with being a kilonova
again, a proof of a long-standing hypothesis

ejecta mass estimates from present modelling

Blue KN ejecta ($A_{\rm max} \lesssim 140$)	$\approx 0.01 - 0.02 M_\odot$
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	$\approx 0.04 M_\odot$
Light r-process yield ($A \lesssim 140$)	$\approx 0.05 - 0.06 M_\odot$
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$
Gold yield	$\sim 100 - 200 M_\oplus$
Uranium yield	$\sim 30 - 60 M_\oplus$

(from Metzger 2017)



Cowperthwaite et al. 2017

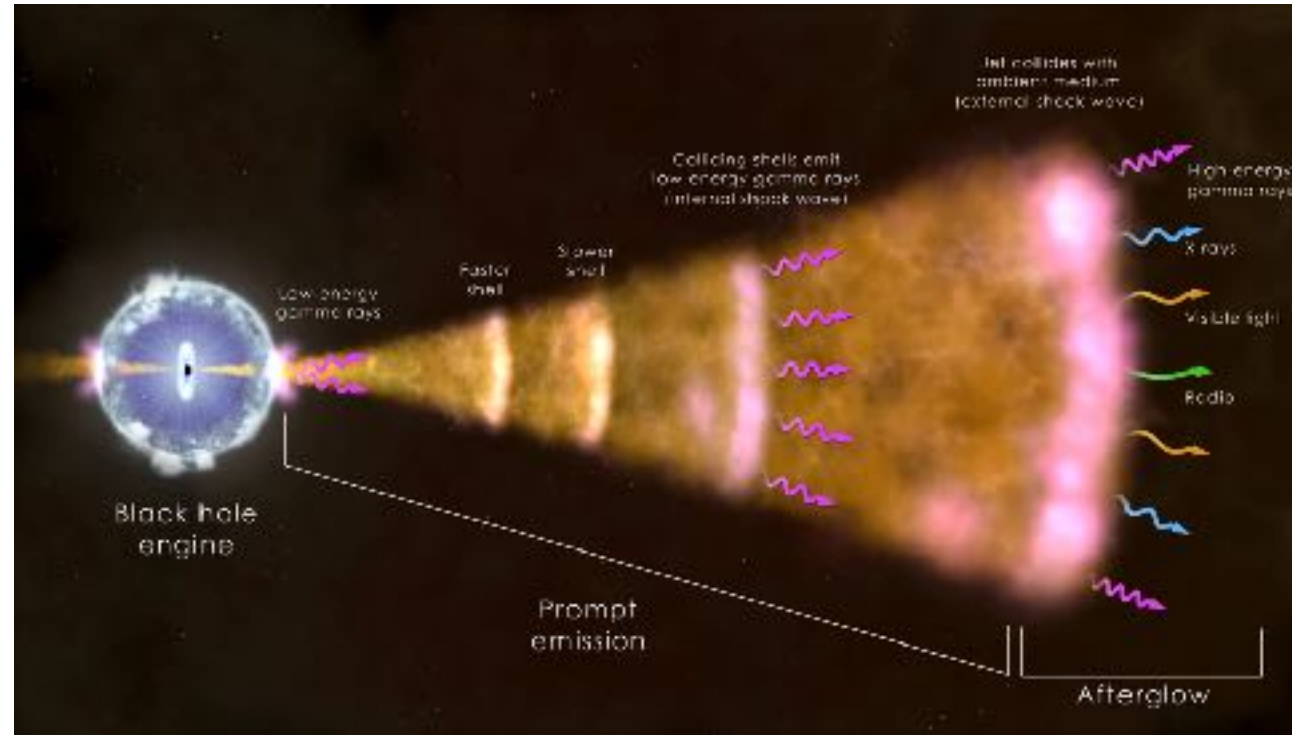
we need more events and better models to
grasp the details of such phenomenon..

BACKUP SLIDES

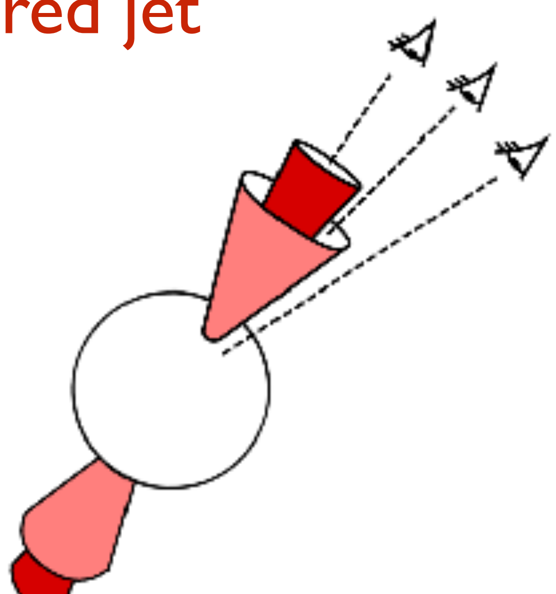
Off-axis SGRB and jet afterglows

- forward shock emission
  (canonical afterglow)

  - well studied for long GRBs
  - X-rays, but also optical and radio

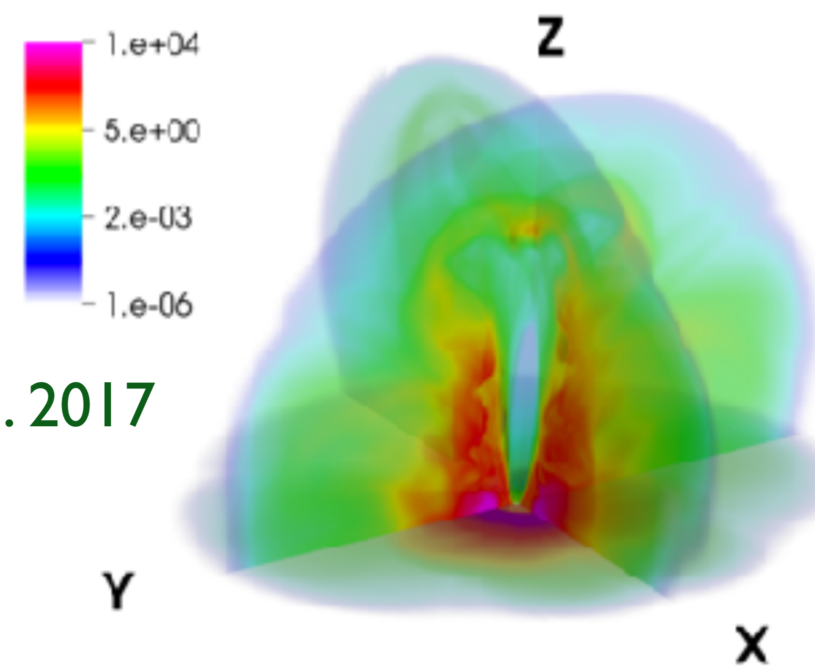


- off-axis emission: structured jet



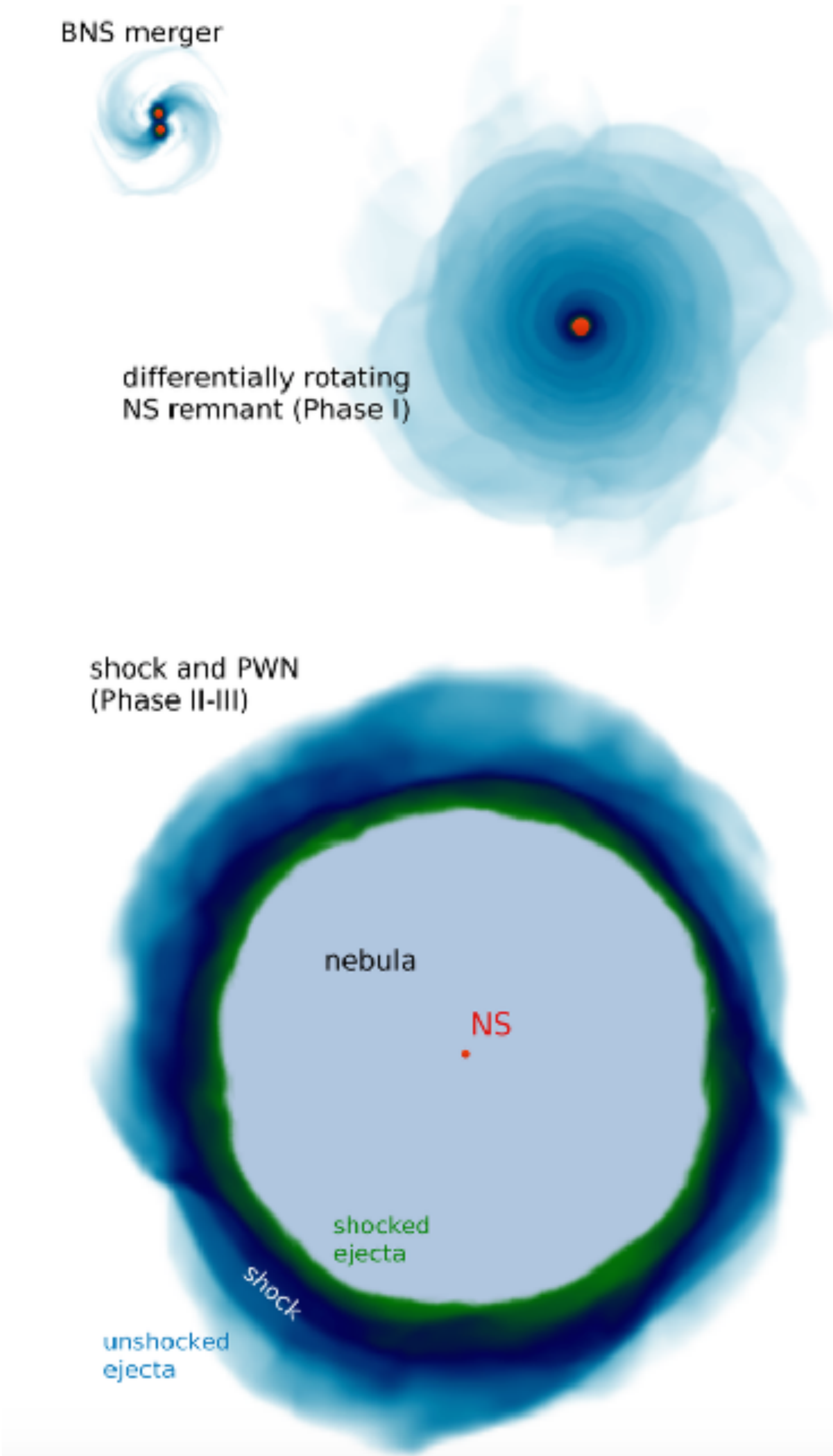
Salafia et al. 2015

- off-axis emission: cocoon emission



Lazzati et al. 2017

EM emission from the long-lived NS remnant



- spindown-powered transients studied only recently

  e.g. Yu et al. 2013
  Metzger & Piro 2014
  Siegel & Ciolfi 2016a,b

- differentially rotating NS remnant
  matter ejection as baryon-loaded wind (neutrino- and/or magnetically-induced)

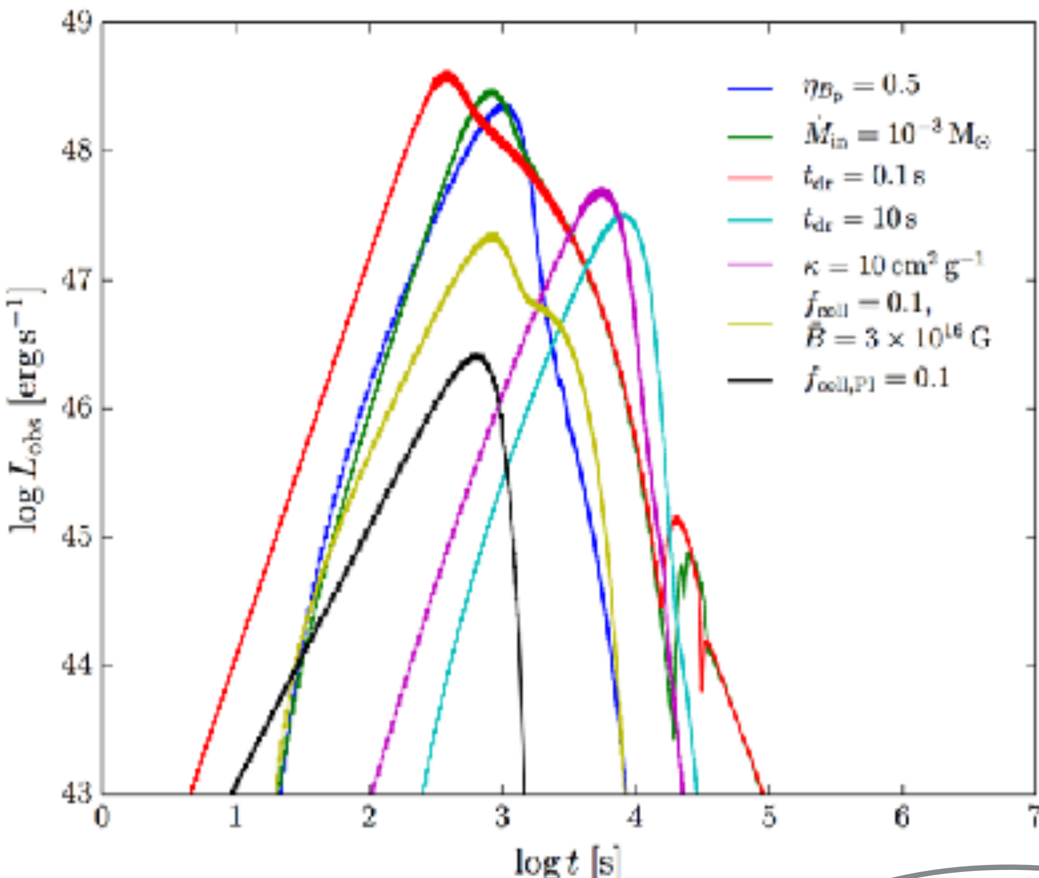
- uniformly rotating NS
  dipole spindown radiation inflates a photon-pair plasma nebula inside ejecta cavity

- radiation reprocessed by the ejecta, finally escaping

- along the evolution, NS can collapse to BH (if supramassive)

EM emission from the long-lived NS remnant

Siegel & Ciolfi 2016a,b

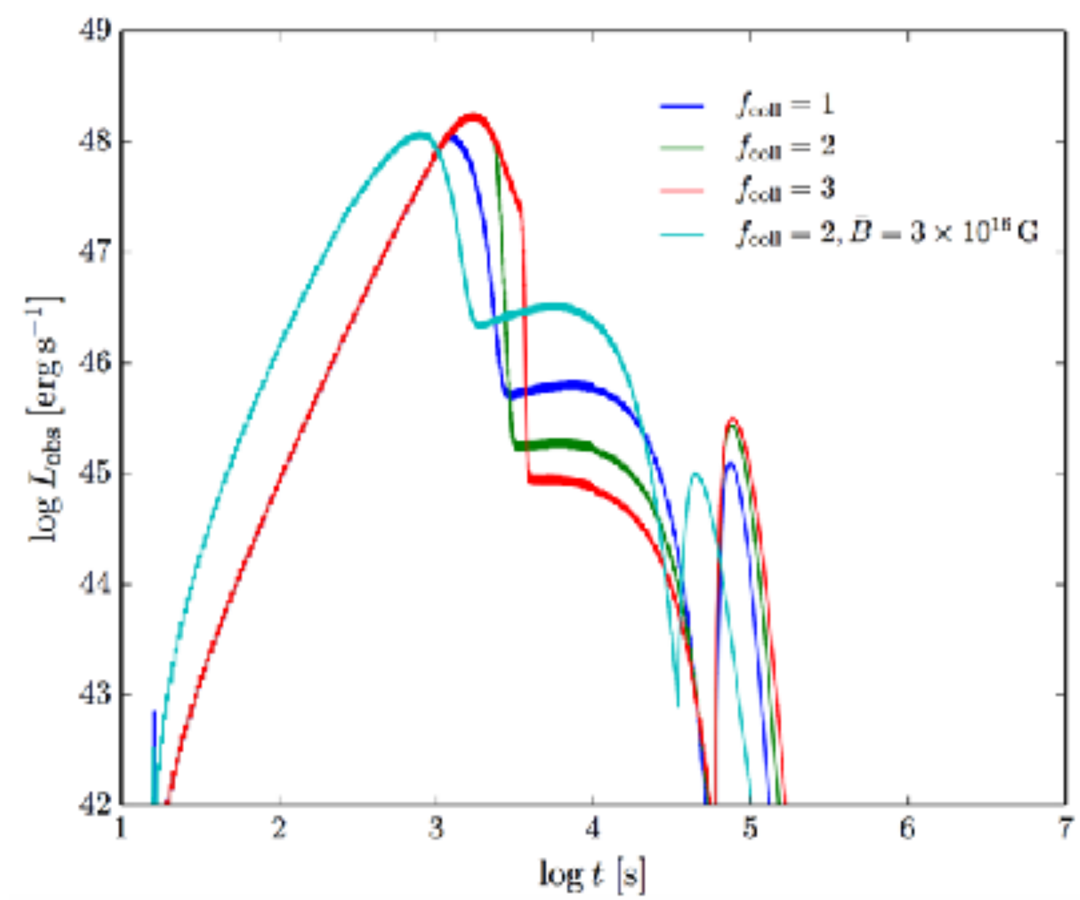


- signal peaks at 10^2-10^4 s (similar range for duration), with ~10-100 s delayed onset
- luminosities 10^{46}-10^{48} erg/s
- mostly in the soft X-rays

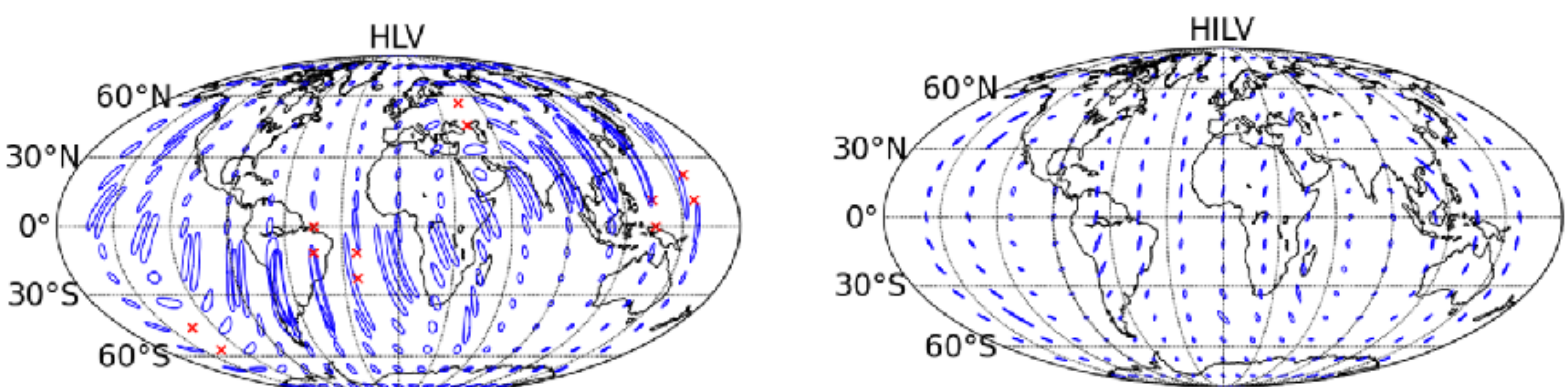
non-collapsing models

Luminosity in soft X-ray band (0.3-10 KeV)

collapsing models



GW detector network



3 detectors **4 detectors**

sky localization (90% confidence level)