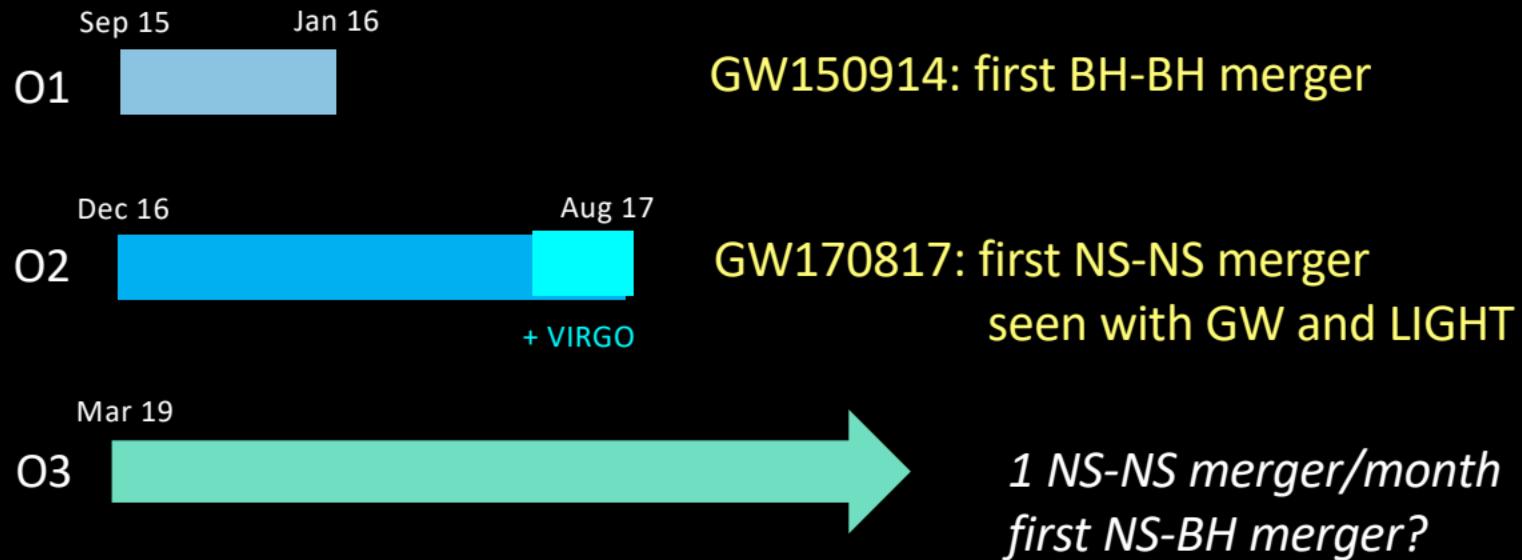


Electromagnetic counterparts of GW sources and Athena

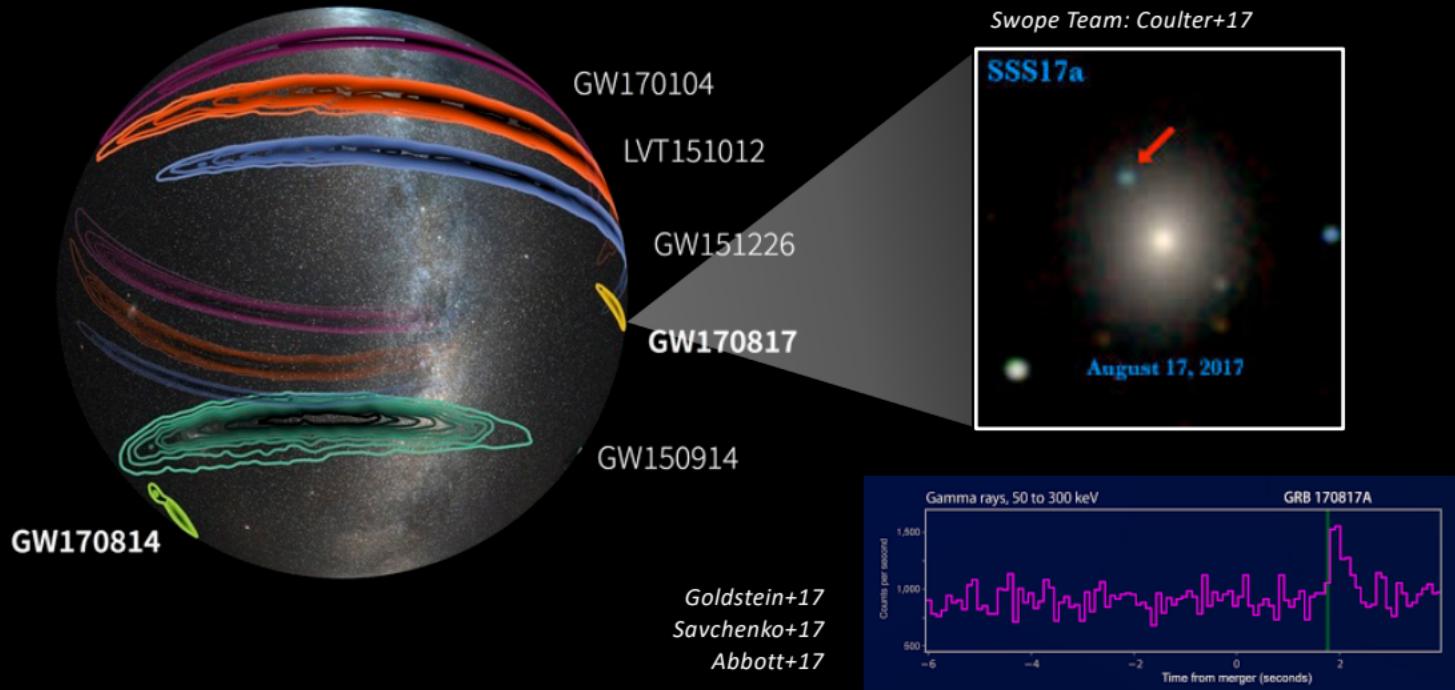
Eleonora Troja (NASA/GSFC & UMD)



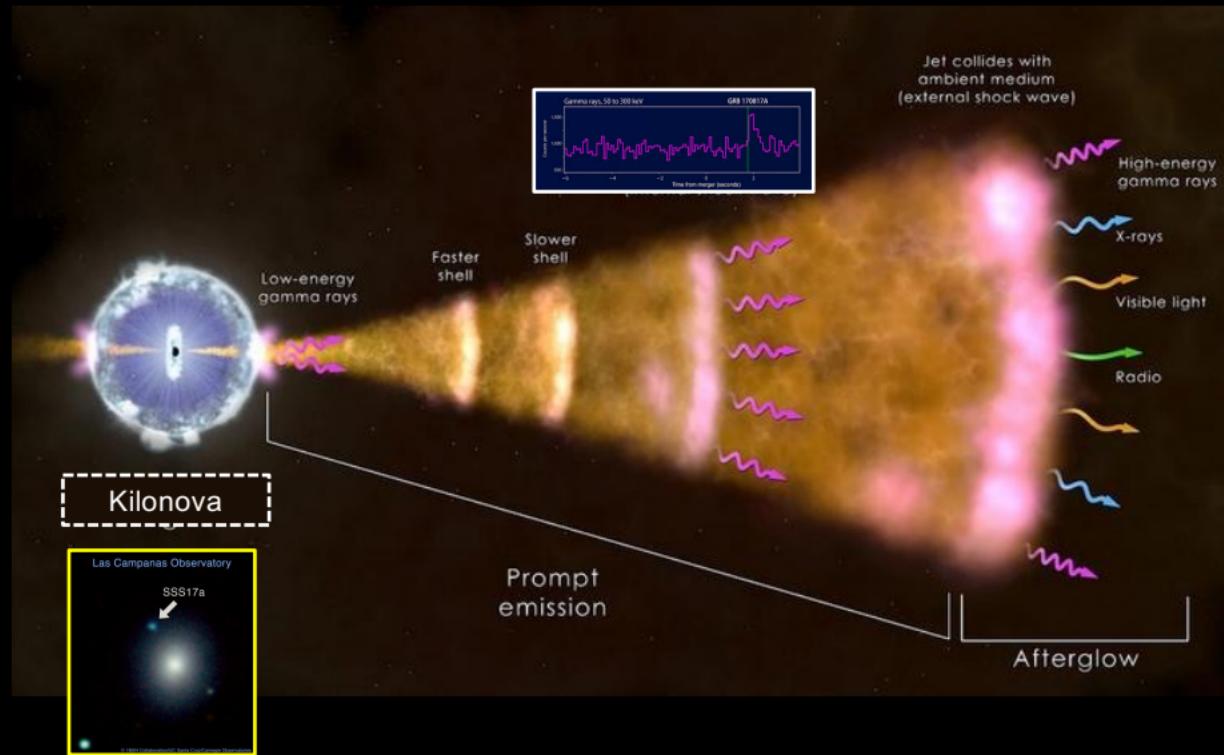
The dawn of GW astronomy



A new era of multi-messenger astrophysics



Standard Framework for short GRBs



Afterglow discovery with *Chandra*

$t=2.2$ d (Margutti et al. 2017)
no X-rays, $f_X < 2 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

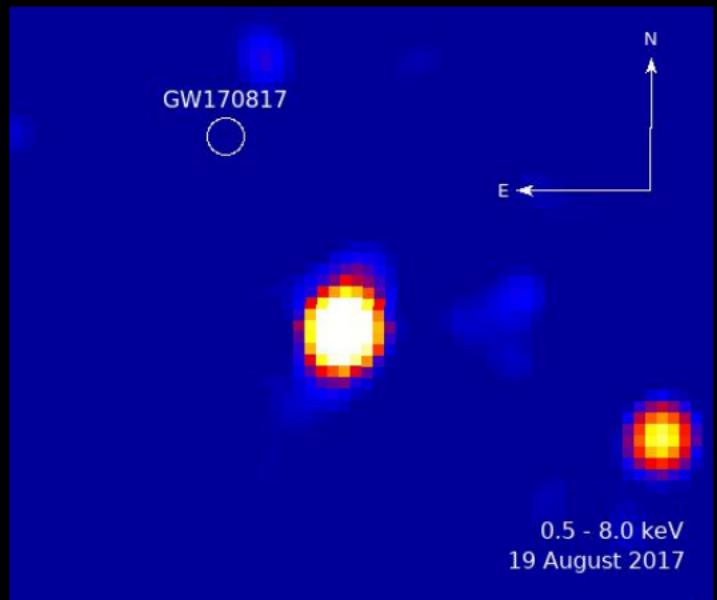
$t=9$ d (PI: Troja)
first X-ray detection, $f_X \sim 4 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

$t=15$ d (PI: Troja)
slowly rising X-rays, $f_X \sim 5 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

$t=16$ d (Haggard et al. 2017)

Basic facts:

- $L_X \sim 10^{39}$ erg s $^{-1}$, $t \sim 9-15$ d
- non-thermal spectrum $\Gamma \sim 1.6$
- Delayed onset



Afterglow discovery with *Chandra*

$t=2.2$ d (Margutti et al. 2017)
no X-rays, $f_X < 2 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

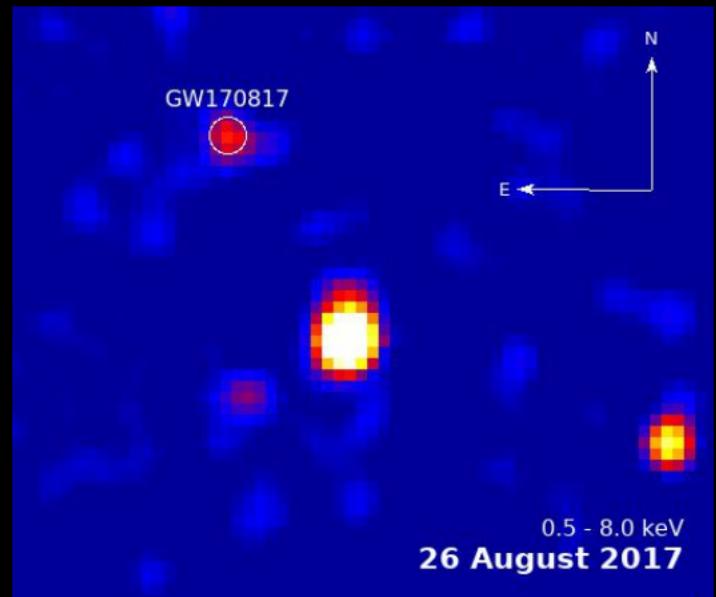
$t=9$ d (PI: Troja)
first X-ray detection, $f_X \sim 4 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

$t=15$ d (PI: Troja)
slowly rising X-rays, $f_X \sim 5 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$

$t=16$ d (Haggard et al. 2017)

Basic facts:

- $L_X \sim 10^{39}$ erg s $^{-1}$, $t \sim 9-15$ d
- non-thermal spectrum $\Gamma \sim 1.6$
- Delayed onset



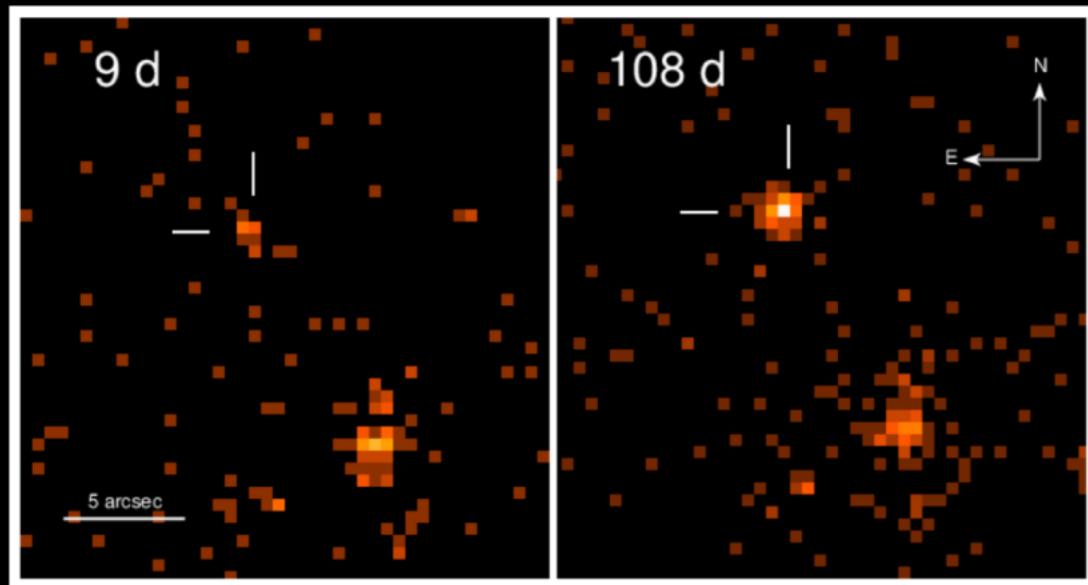
Troja, Piro, et al., *Nature*, 2017

Time evolution: a rising afterglow

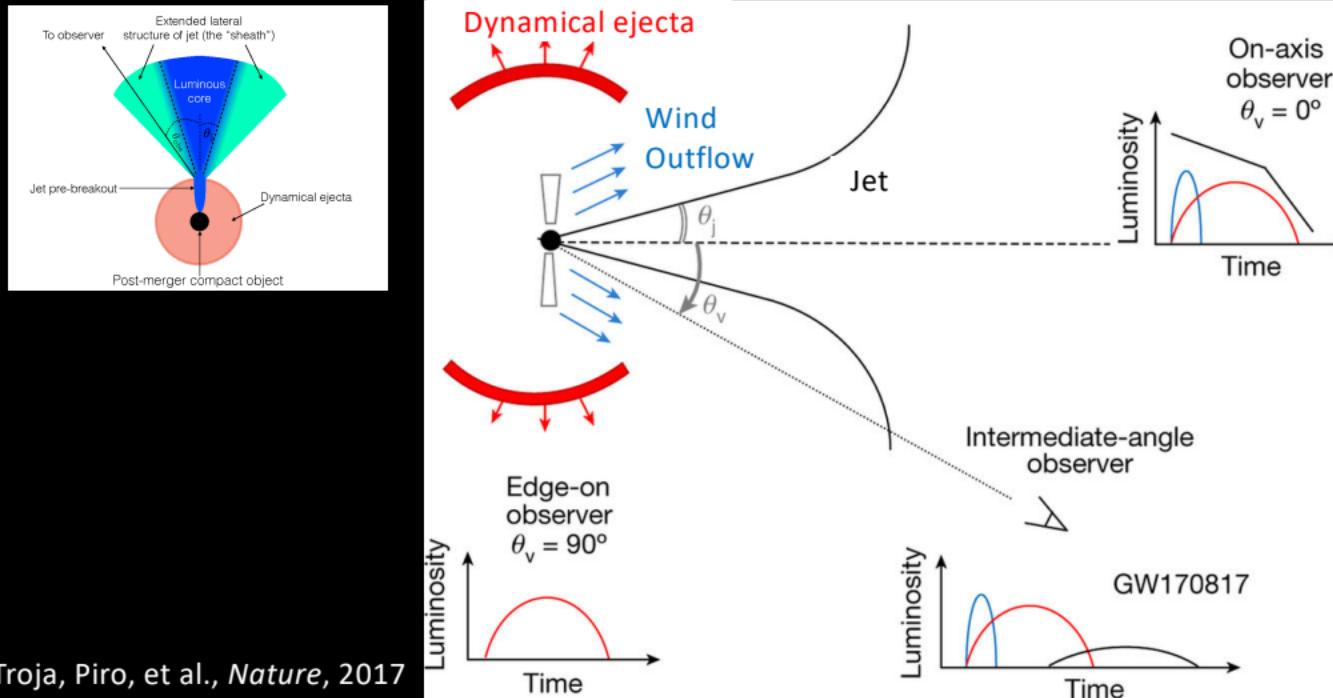
Troja, Piro, et al.,
MNRAS, 2018

Mooley et al. *Nature*, 2018
Ruan et al. *ApJ*, 2018
Margutti et al. *ApJ* 2018
Lyman et al., *Nat Astr*, 2018

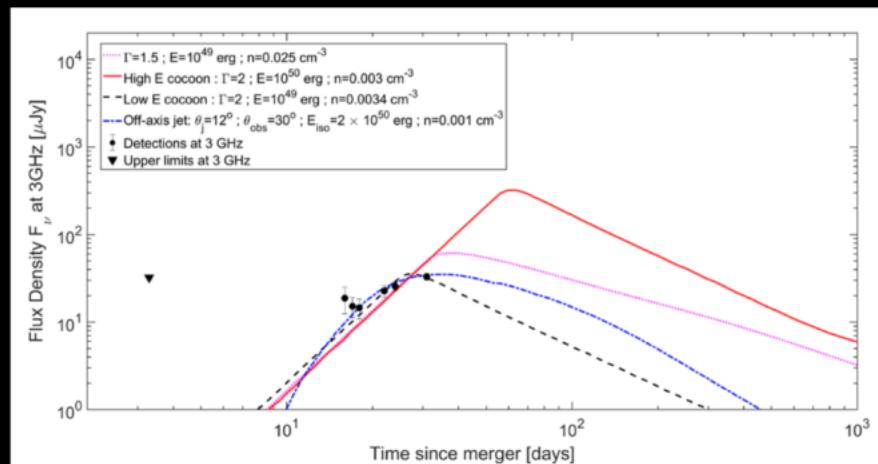
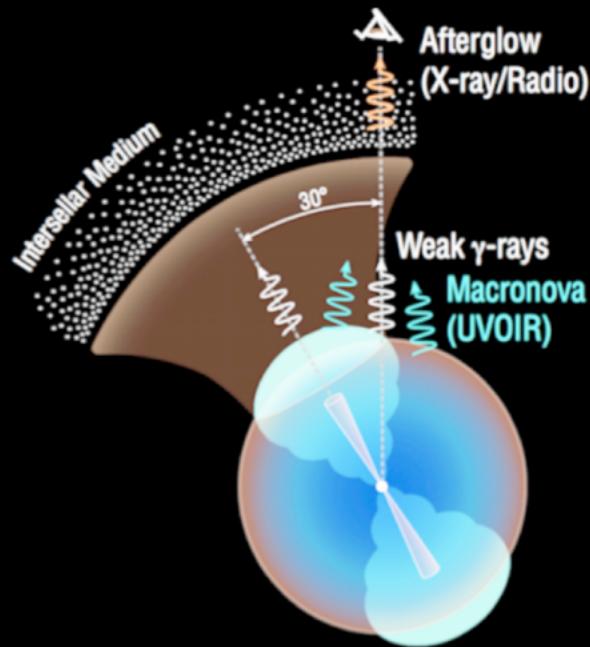
$$F \sim t^{0.9}$$



An off-axis structured jet in GW170817



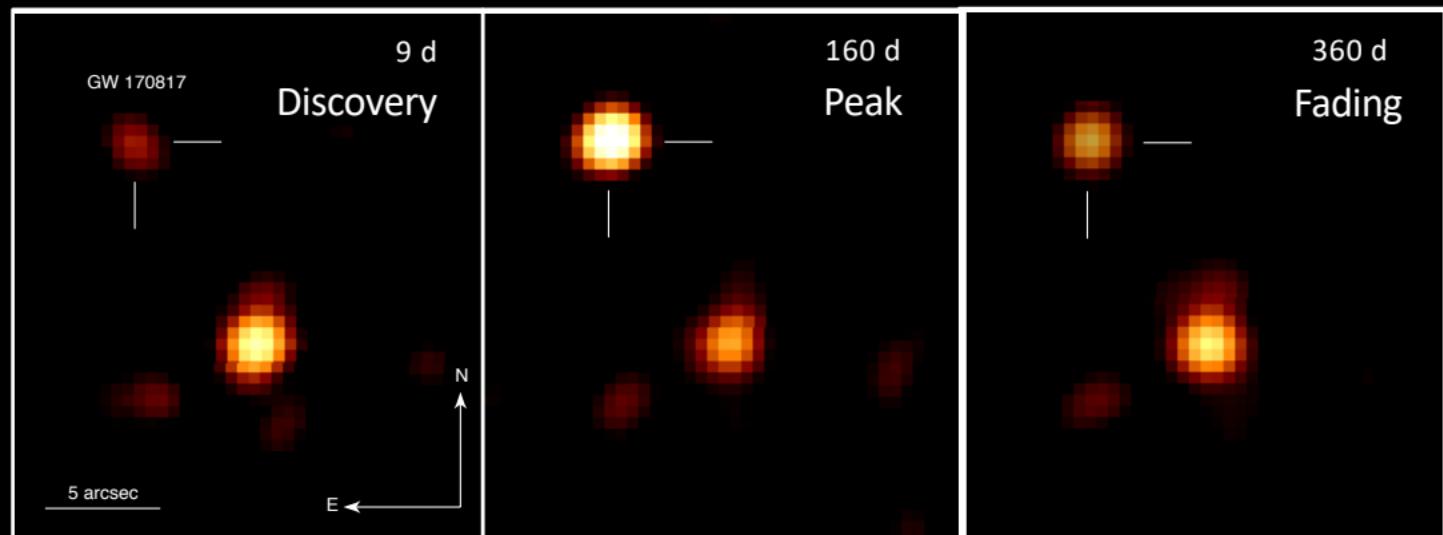
Choked jet: cocoon



Hallinan, Corsi, et al., *Science*, 2017

No strong dependence on the viewing angle

A year in the life of GW170817

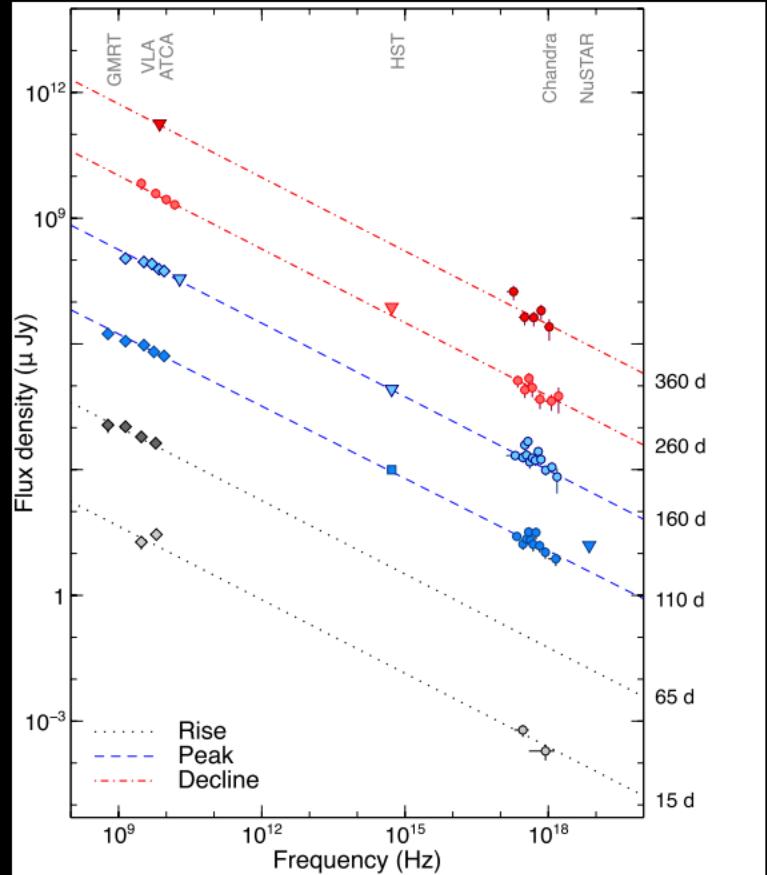
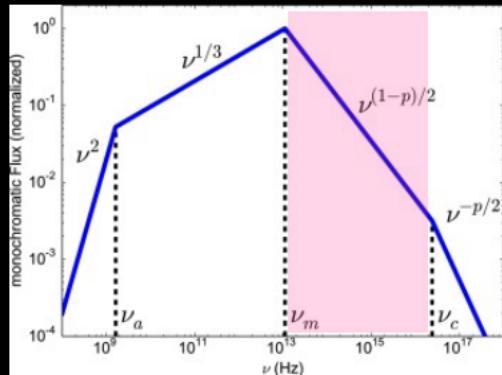


Troja, van Eerten et al., MNRAS, 2018, arXiv:1808.06617

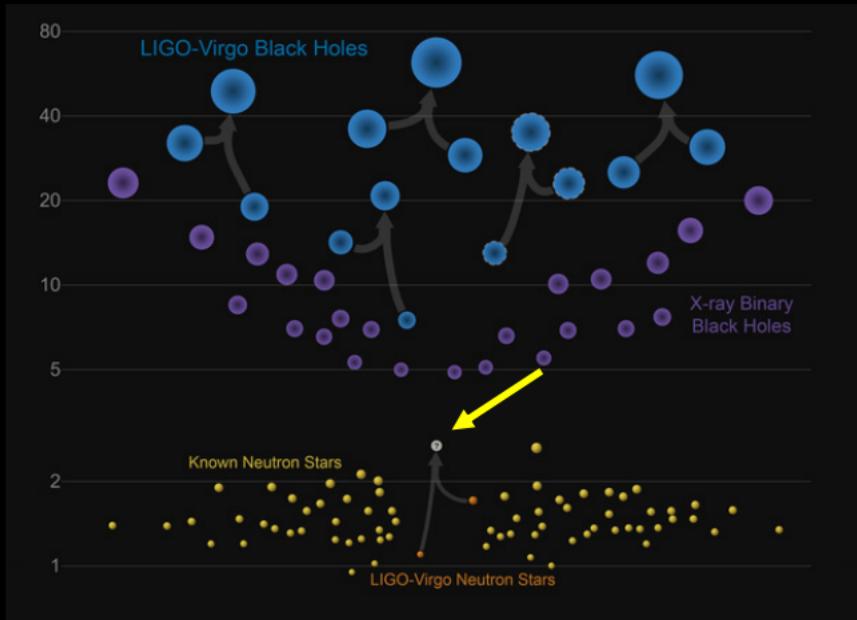
No spectral evolution

Simple power-law spectrum
over 10 decades in energy

Consistent with synchrotron emission
regime $\nu_m < \nu_r < \nu_x < \nu_c$



GW170817 remnant: BH or NS?



X-ray emission very sensitive to NS central engine
either flares or continuous spindown energy injection

$B < 10^{12} \text{ G}$

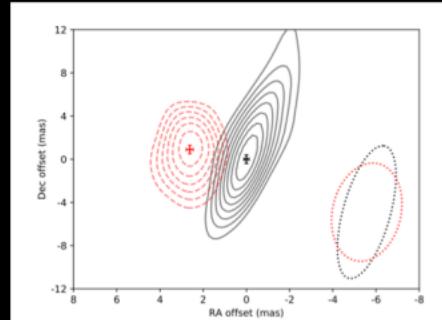
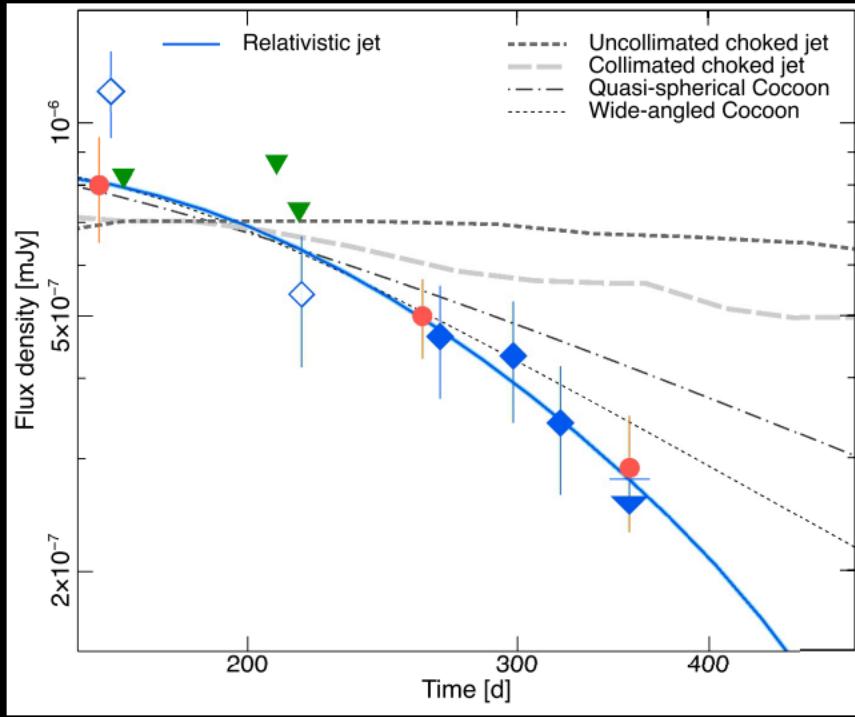
BH

Pooley+18

or stable low-B NS

Piro+18

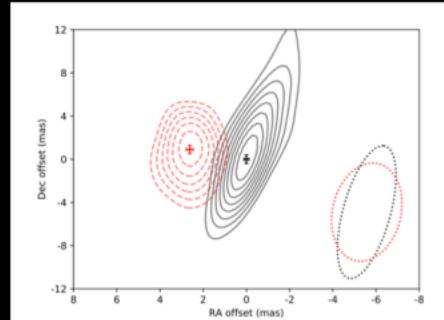
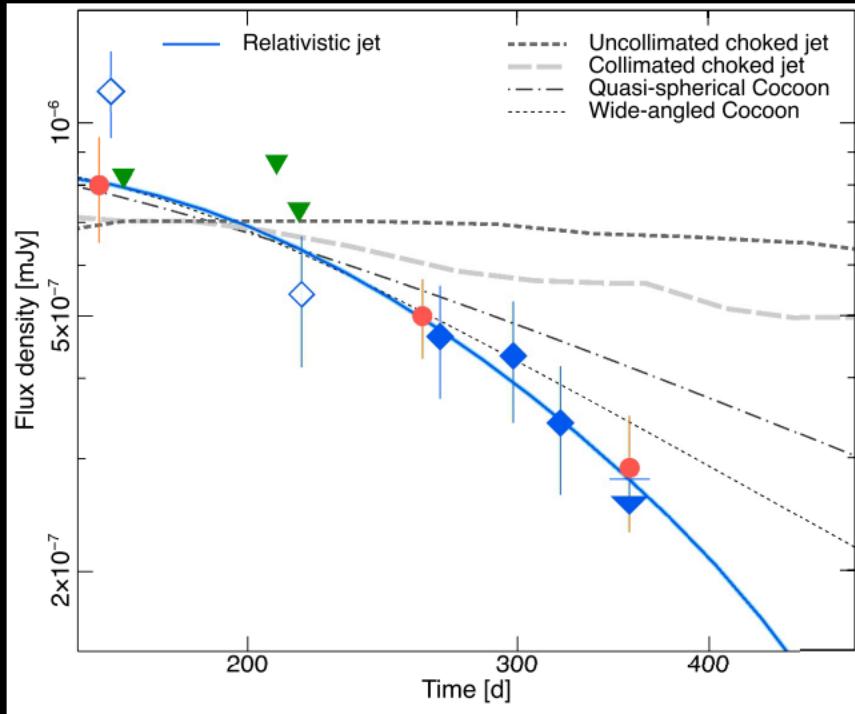
The jet of GW170817: relativistic or choked?



Mooley et al., 2018, Ghirlanda et al., 2018

- Compact unresolved radio source
- Superluminal motion
- Rapid afterglow decline

The jet of GW170817: relativistic or choked?



Mooley et al., 2018, Ghirlanda et al., 2018

- Compact unresolved radio source
- Superluminal motion
- Rapid afterglow decline

An structured jet from a NS merger

Typical of short GRBs

$p \sim 2.17$

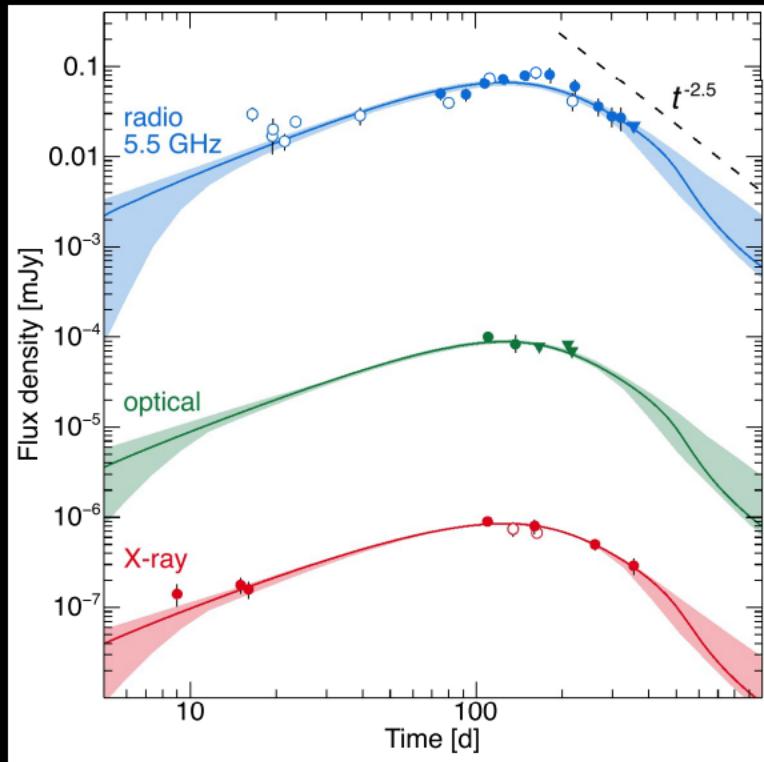
$n < 0.001 \text{ cm}^{-3}$

$E \sim 3 \times 10^{50} \text{ erg}$

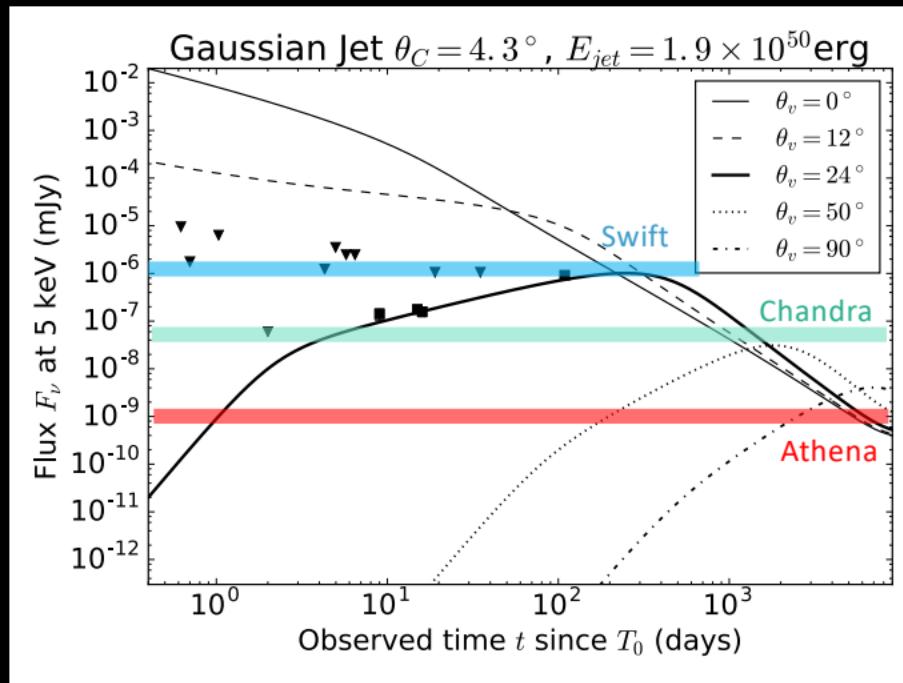
$\theta \sim 4 \text{ deg}$

$\theta_w \sim 22 \text{ deg}$

consistent with
GW inclination



Future prospects



Summary

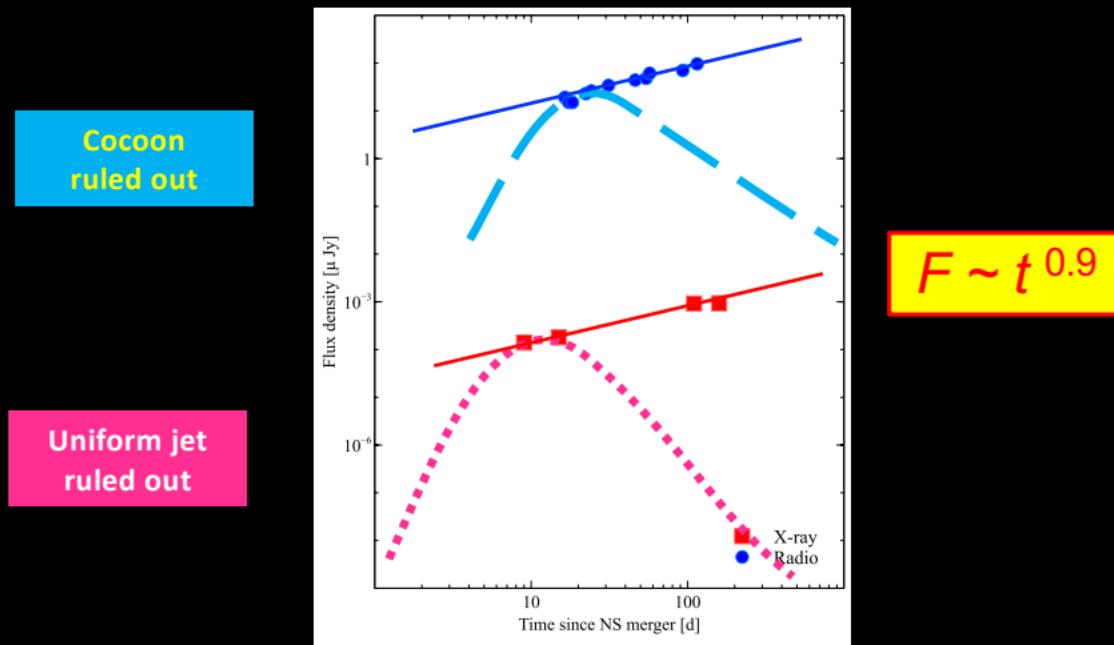
- X-ray observations point to an explosion viewed off-axis ($\theta \sim 20^\circ - 25^\circ$)
- Early afterglow data showed evidence of a mildly relativistic **structured outflow** ejected from the merger remnant
- Late-time monitoring favors a **relativistic jet**:
rapid afterglow decay + high-resolution radio imaging
- *Future observations will probe a variety of viewing angles
population studies, jet structure, cosmology H_0*
- *X-rays could probe emission from newborn NSs and constrain the GW remnant*

Thanks!

BACKUP

Time evolution: simple models ruled out

Troja et al., *MNRAS*, 2018

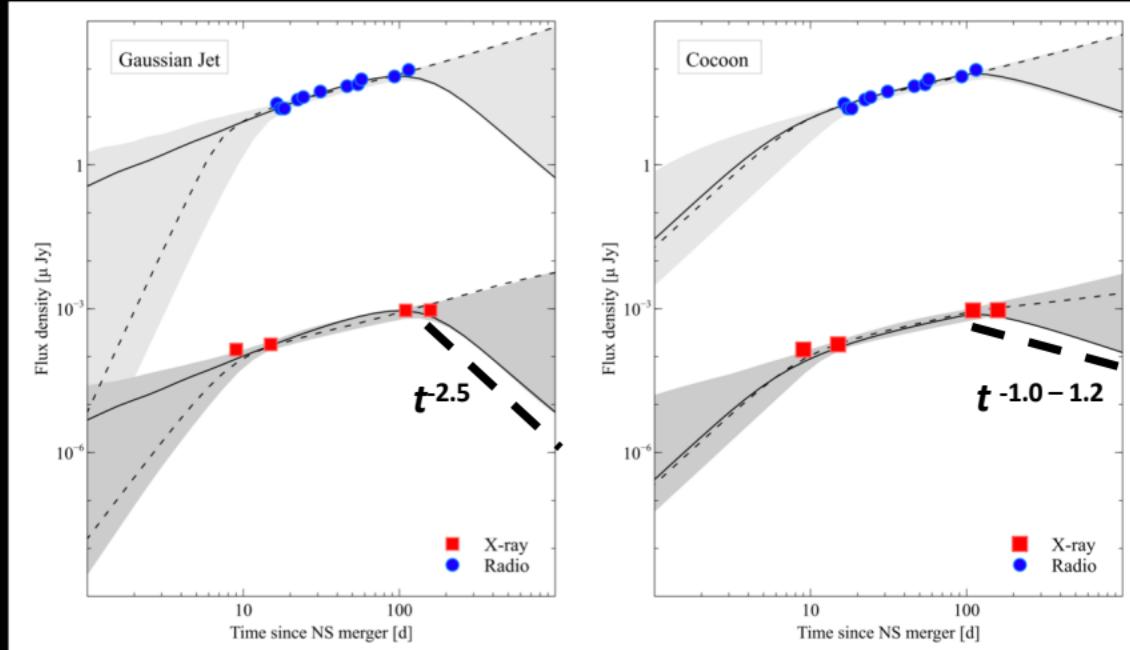
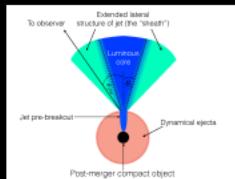


See also Ruan et al. 2018, Mooley et al. 2018

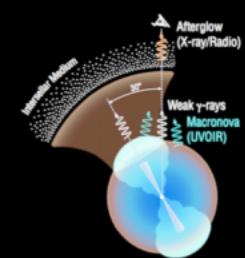
Time evolution: a structured outflow

Troja, Piro et al., *MNRAS*, 2018

Angular structure



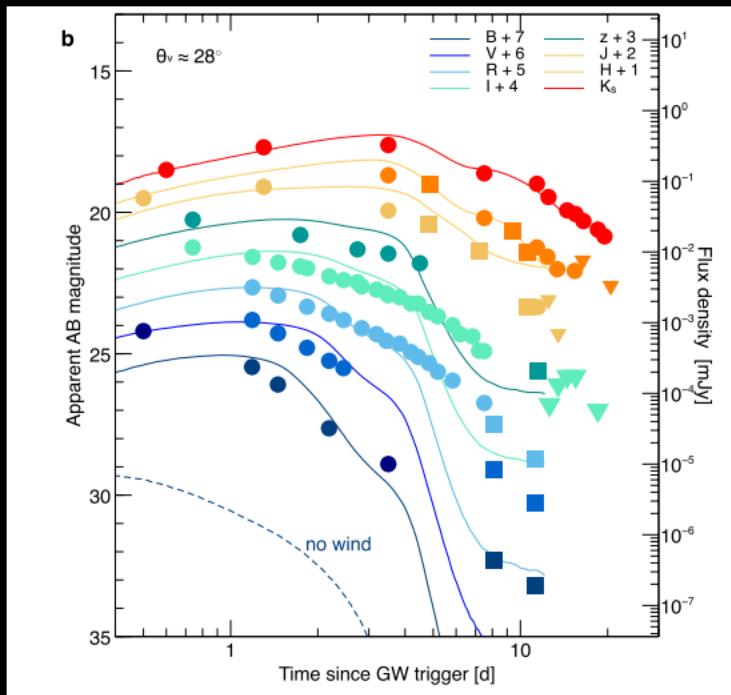
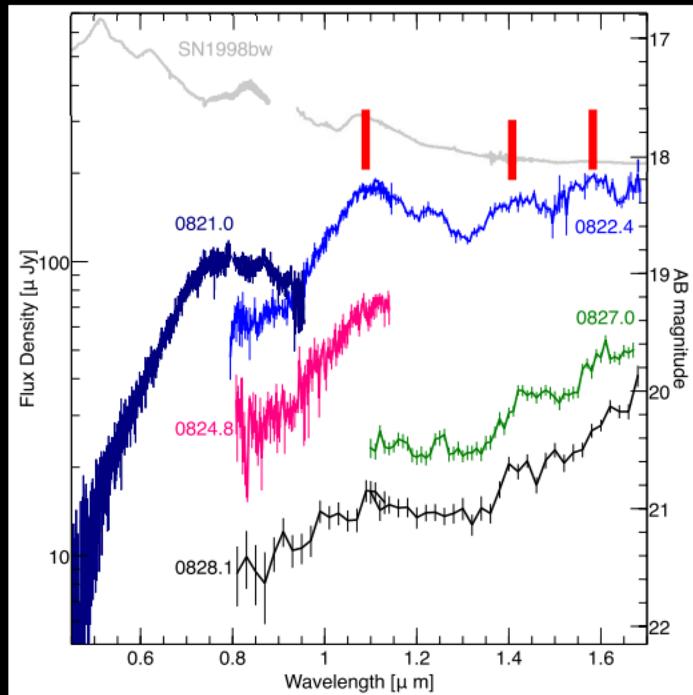
Radial structure



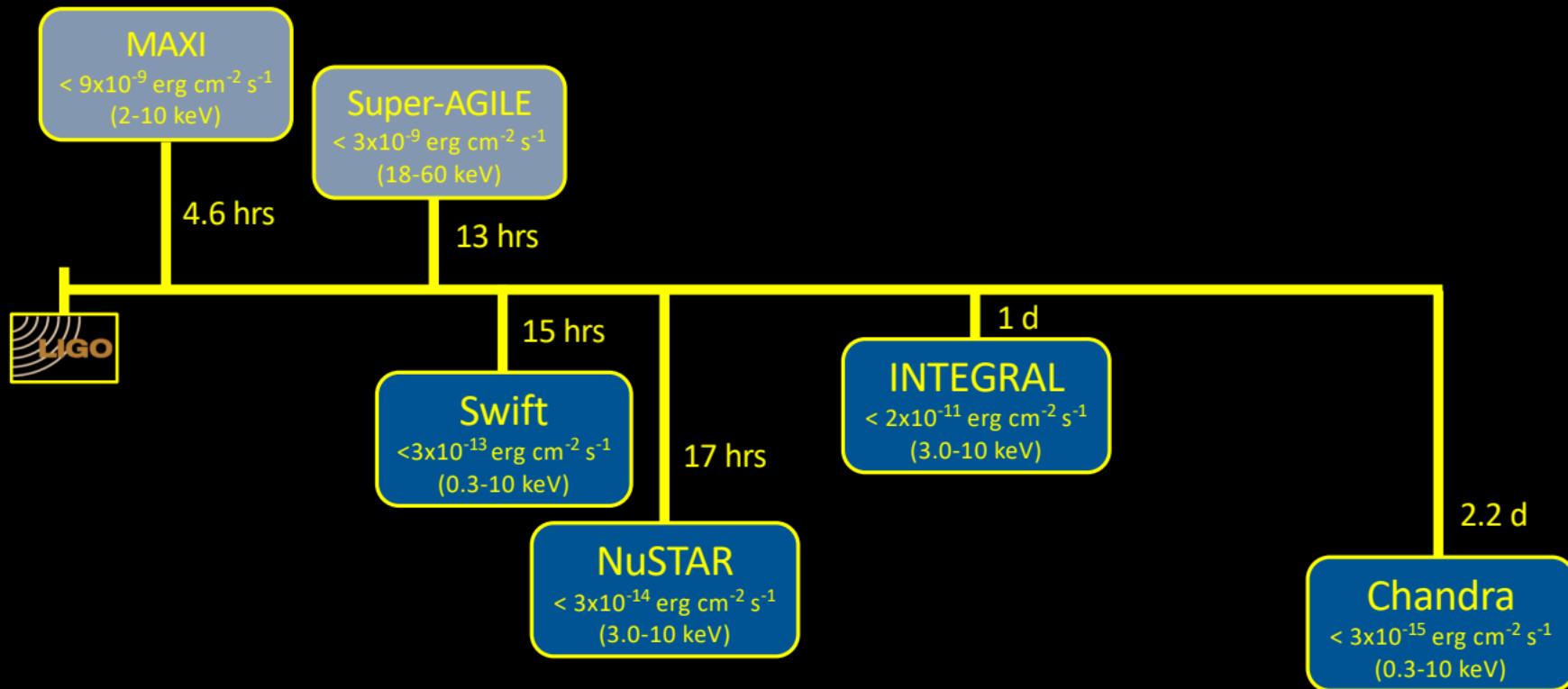
See also Lyman et al. 2018, Lazzati et al. 2018, Margutti et al. 2018

See also Nakar & Piran, 2018

The kilonova AT2017gfo

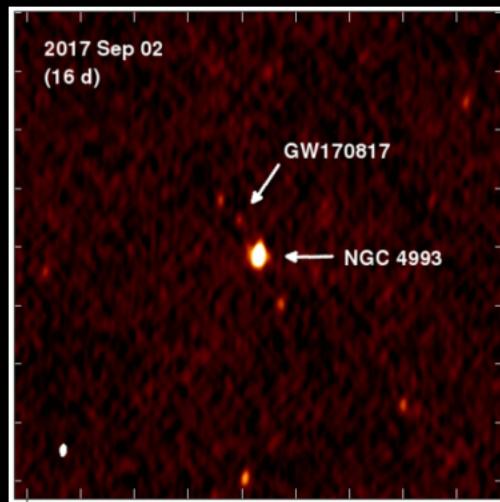


Early X-ray observations of GW 170817

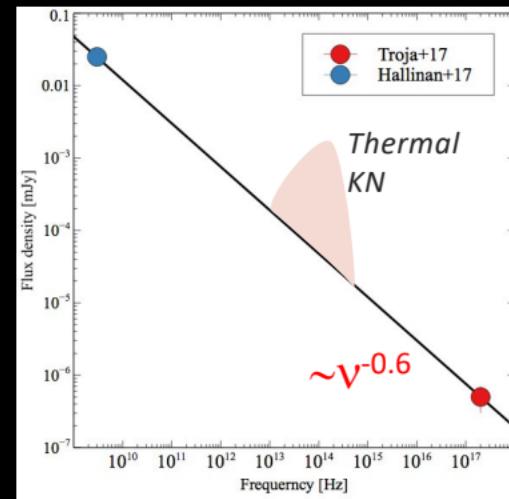


Radio detection with the VLA

Indipendently detected by two groups: Alessandra Corsi (6 GHz), Greg Hallinan (3 GHz)



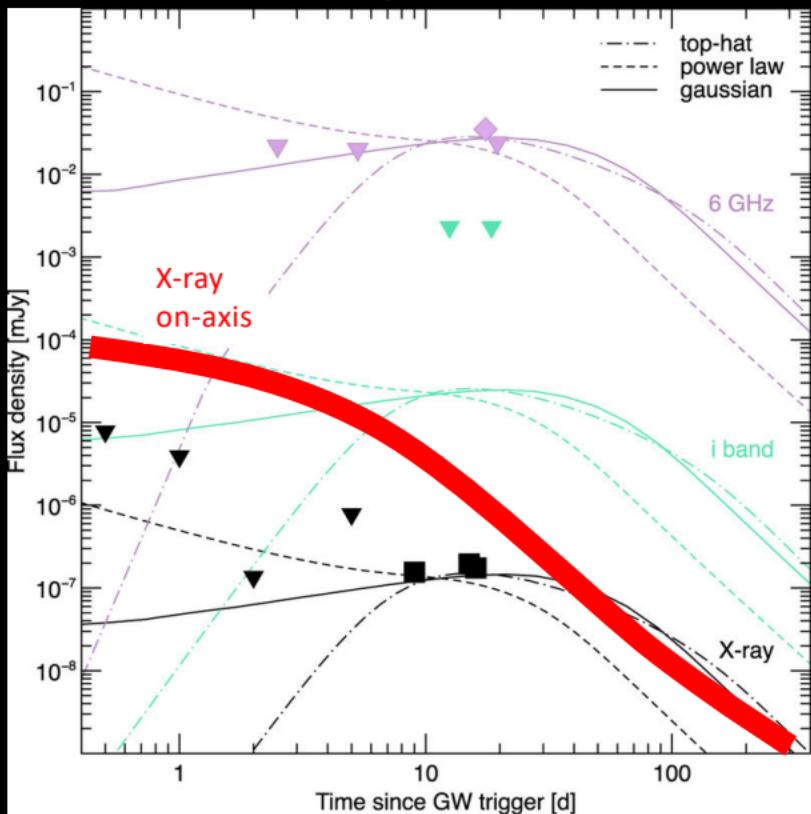
Hallinan, Corsi, et al., *Science*, 2017



Off-axis jet

GRB 170817A is a standard short GRB with ordinary prompt and afterglow emission.

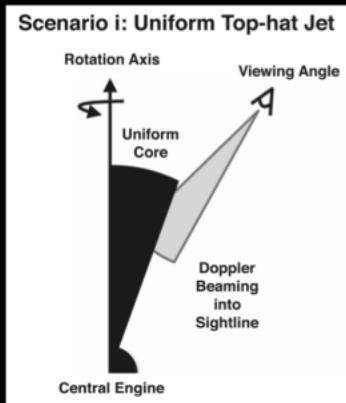
Troja, Piro, et al., *Nature*, 2017



Origin of the X-ray emission

- Magnetar (Zhang & Meszaros 01, Troja+07, Rowlinson+10): unlikely timescales
 - Continued X-ray emission over 2 weeks would require unrealistic magnetic field and spin-period
- Fallback accretion (Rosswog 08, Rossi & Begelman 09): unlikely spectrum
 - The predicted black body spectrum cannot account for the radio emission
- Ejecta-ISM interaction (Nakar&Piran 12): unlikely environment
 - The observed onset at 9 days requires very high densities, not consistent with optical a ray spectra and the galaxy environment
- **Off-axis Afterglow** (Rhoads 97, van Eerten+11, Troja+17)

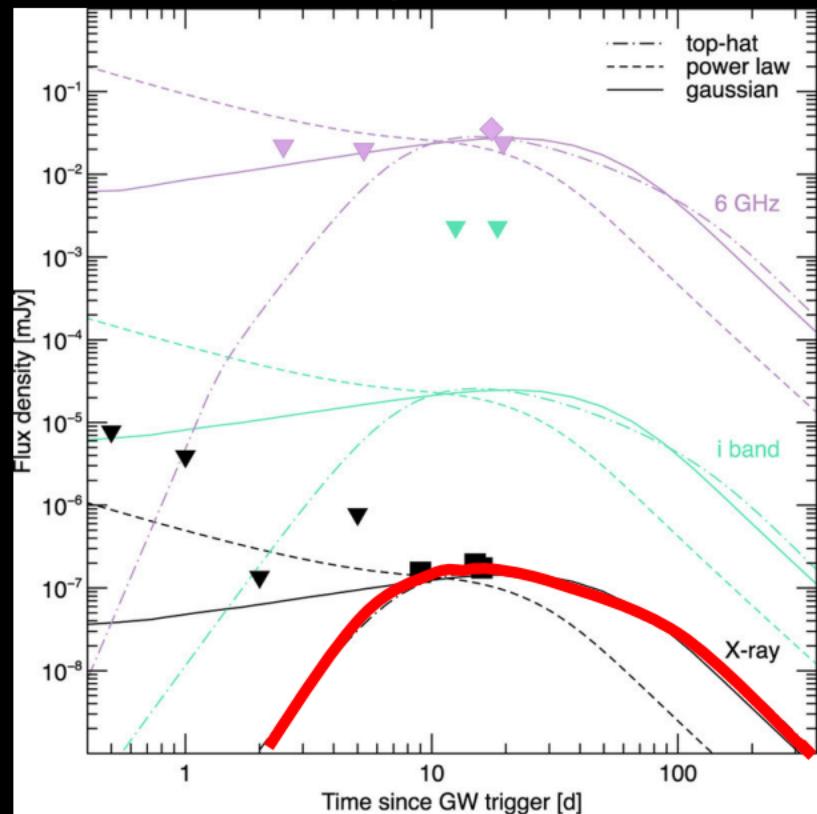
Off-axis jet: uniform



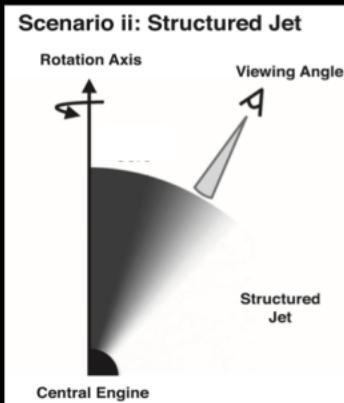
Afterglow: OK at early times

Prompt: unusual properties
either very low Γ or
very hard ($>$ MeV) and energetic
($> 10^{52}$ erg) emission

Troja, Piro, et al., *Nature*, 2017



Off-axis jet: structured



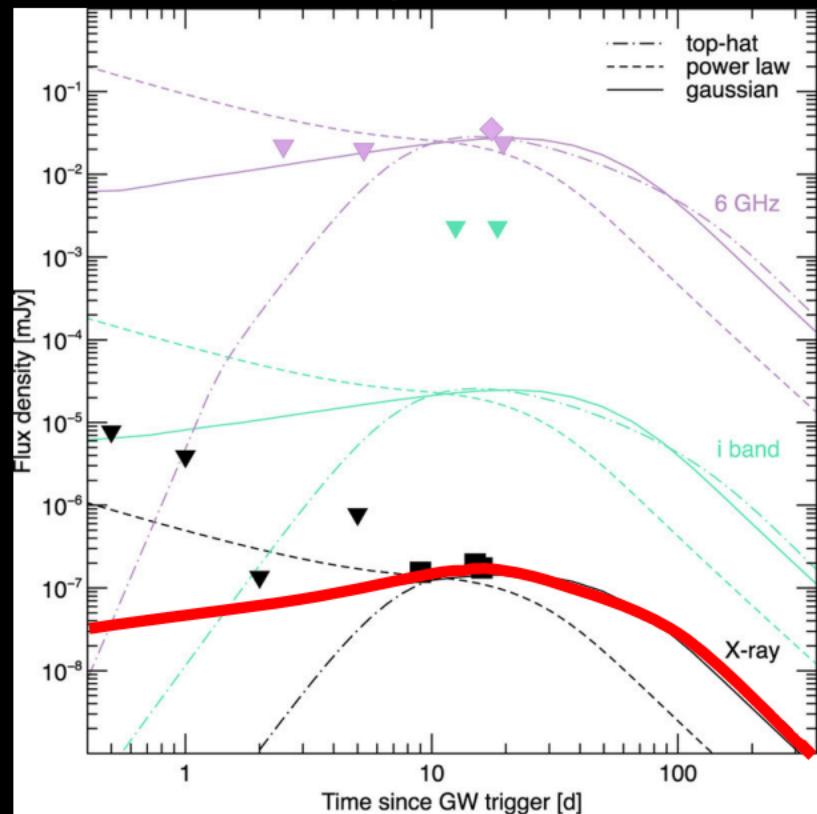
Power-law:
 $E \sim (\theta_{\text{view}}/\theta_{\text{core}})^{-2}$

Gaussian:
 $E \sim \exp(-\theta_{\text{view}}/2\theta_{\text{core}})^2$

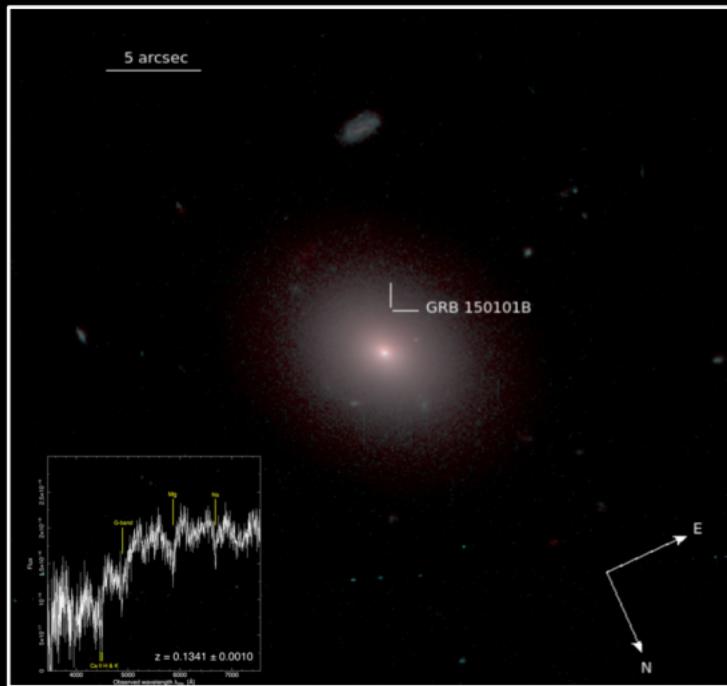
Rossi,Lazzati & Rees 2002
 Aloy+05
 Lamb & Kobayashi+17
 Kathirgamaraju+18

Afterglow: OK

Prompt: OK for a gaussian jet with $\theta_{\text{view}} \sim 4 \theta_{\text{core}}$

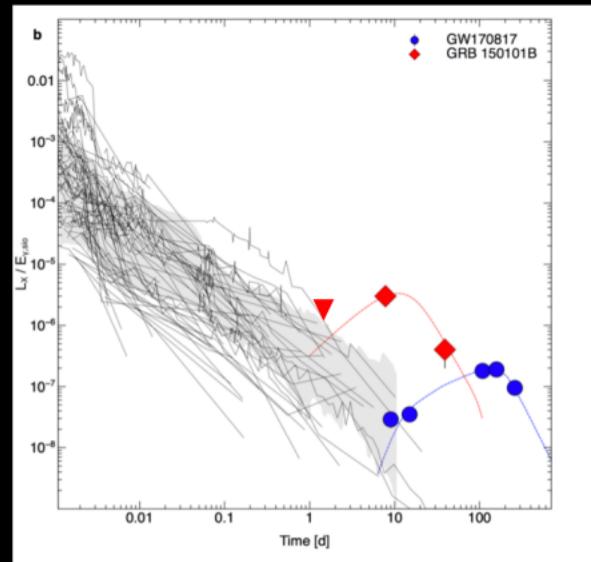


Past observations: the case of GRB150101B

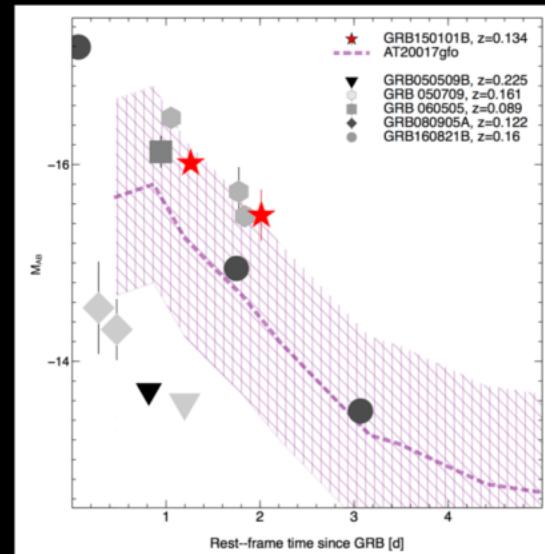


Troja, Ryan et al., 2018
arxiv:1806.10624

A cosmological analogue of GW170817



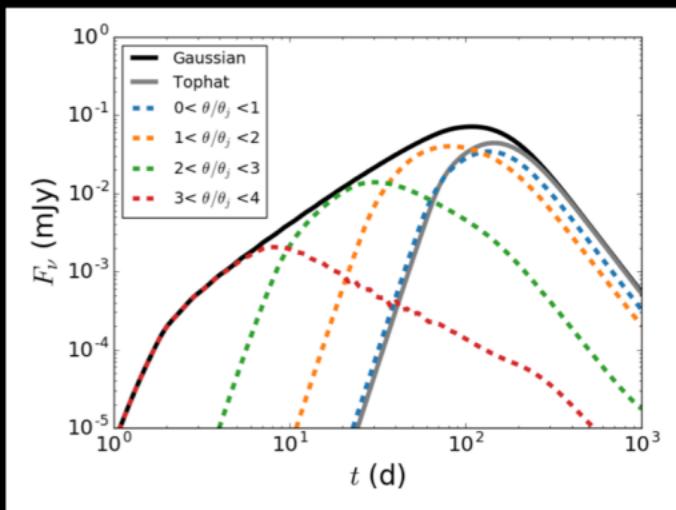
Off-axis explosion (~ 13 deg)



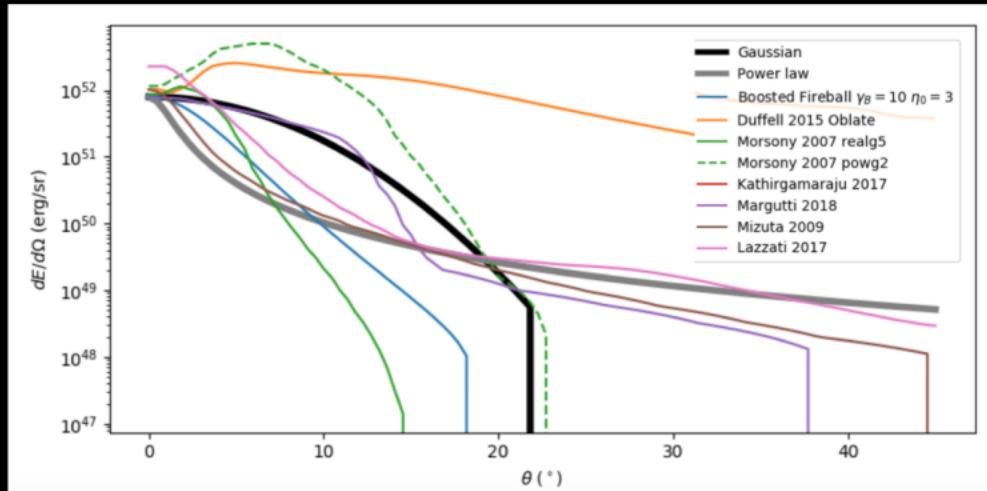
Luminous blue kilonova

Troja, Ryan et al., 2018
arxiv:1806.10624

A semi-analytic approach



Van Eerten, Zhang & MacFadyen (2010),
Troja, E. et al. 2018



Ryan, G. et al. in preparation