Re-solving the jet/cocoon riddle of the first gravitational wave with an electromagnetic counterpar

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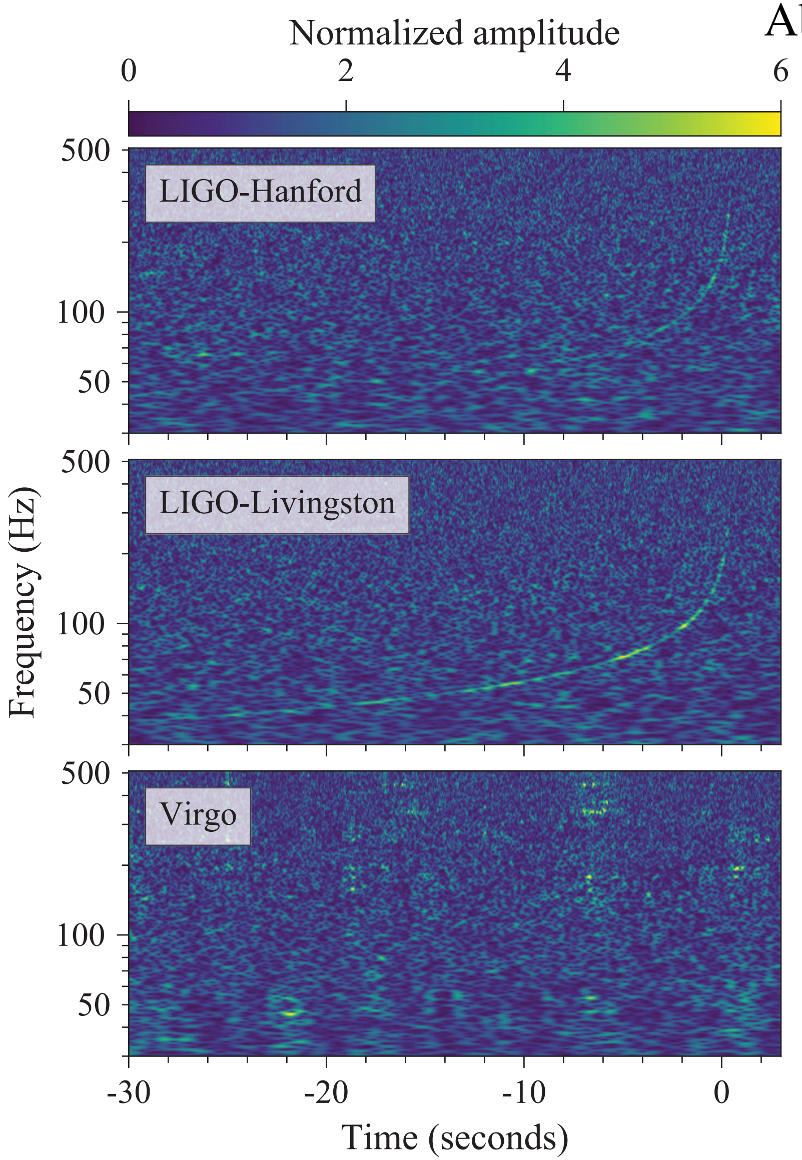
① The "tale" of three discoveries (in ~half a day!)
② Gamma Ray Bursts, jets and related stuff
③ What was GRB(GW)170817?
④ What's next?

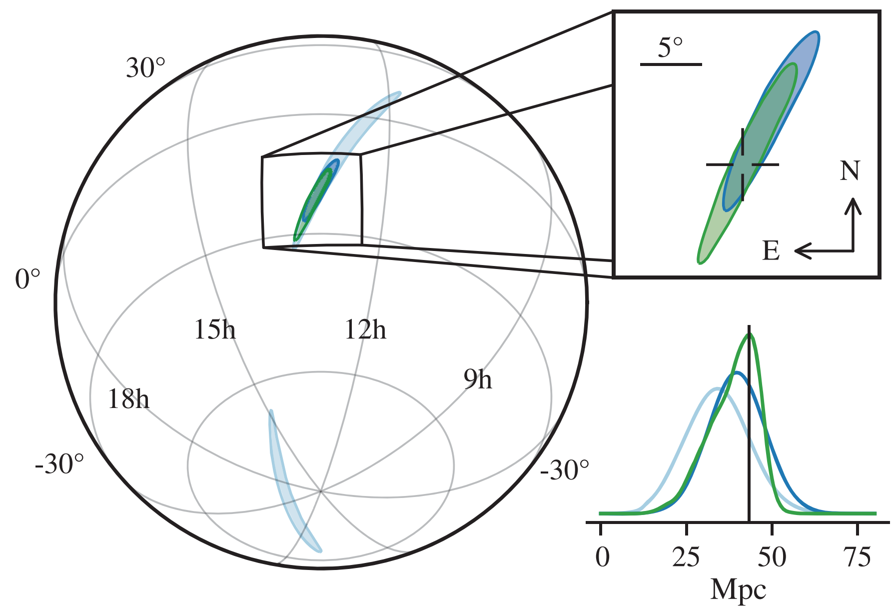
Bologna – 2019/03/21

1 170817 - The "tale" of three discoveries (#1)

Abbott et al. 2017 PRL

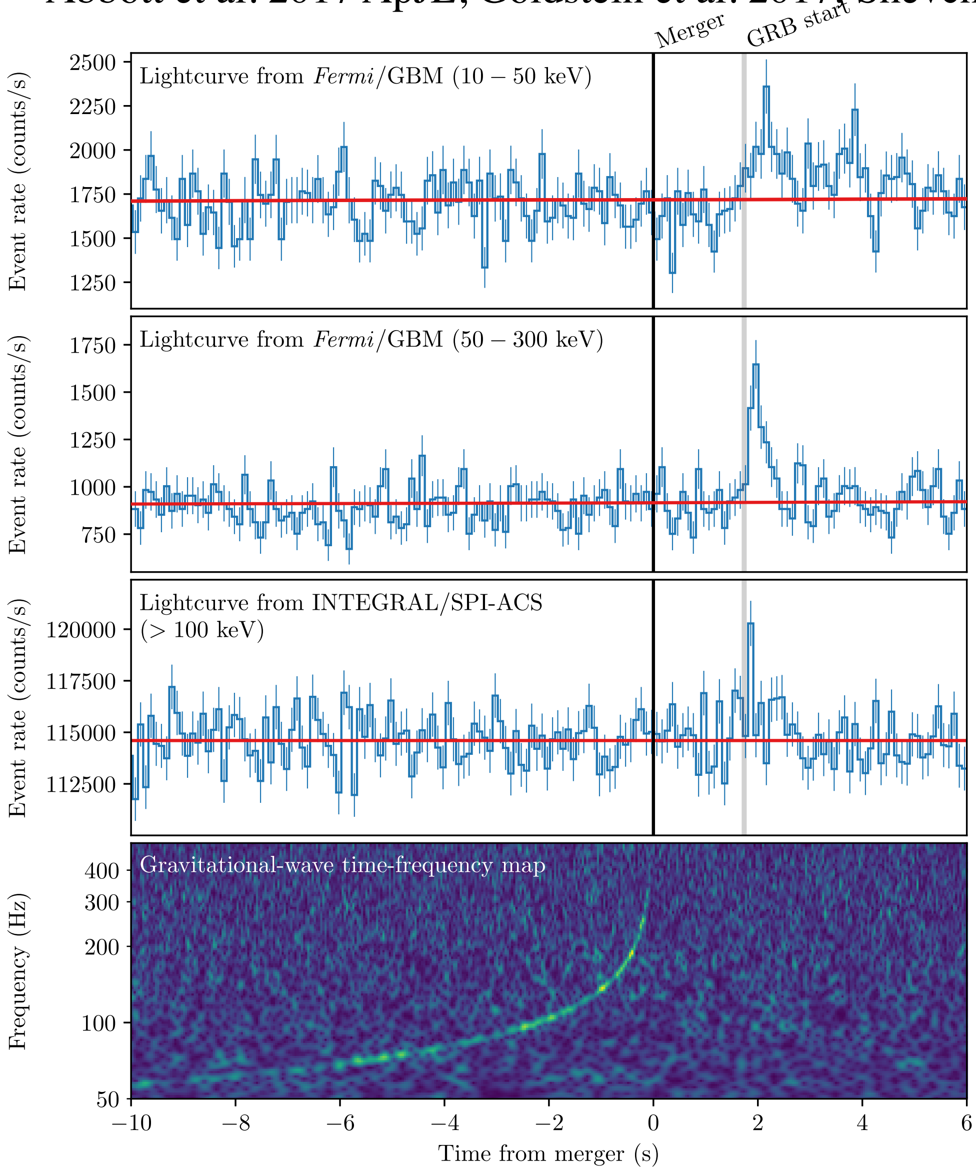


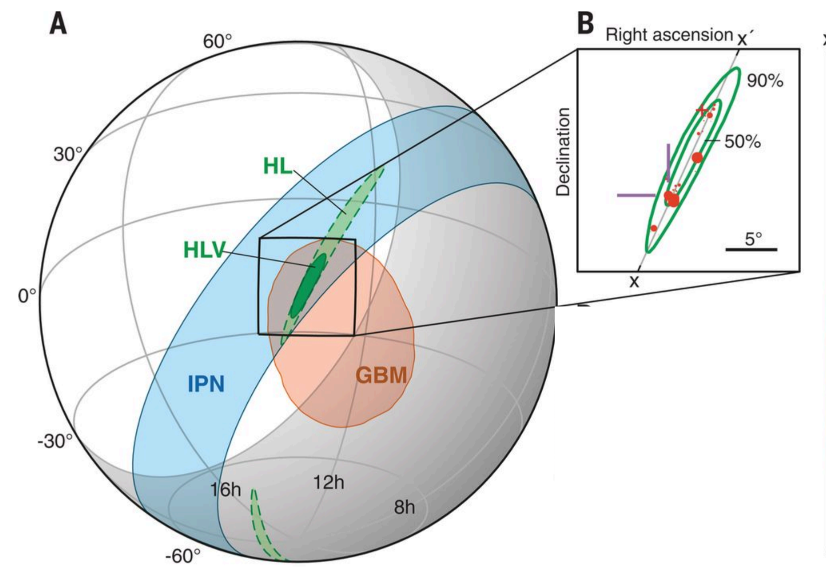
	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800



170817 - The "tale" of three discoveries (#2)

Abbott et al. 2017 ApJL, Goldstein et al. 2017; Shevchenko et al. 2017

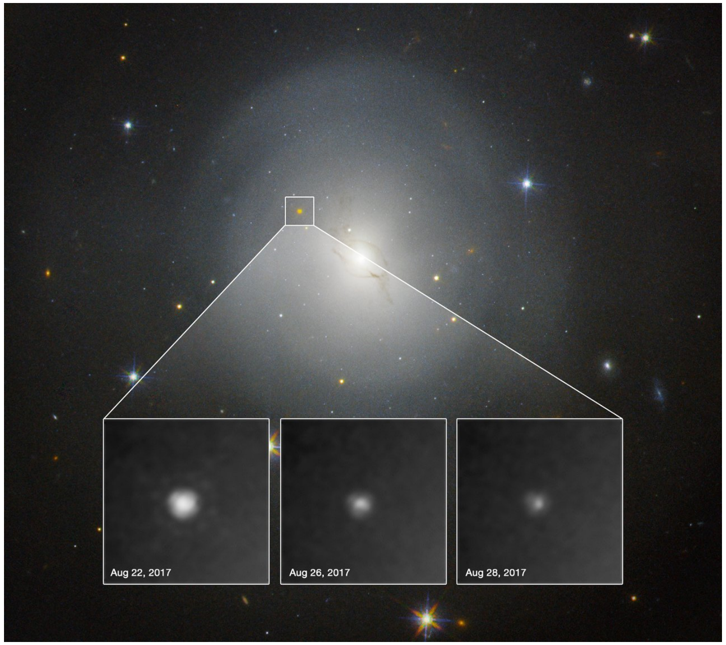




Kasliwal et al. 2017 Sci.

- ❑ ~ 2 sec delay GW-EM
- ❑ ~ 2 sec duration of EM

170817 - The "tale" of three discoveries (#3)

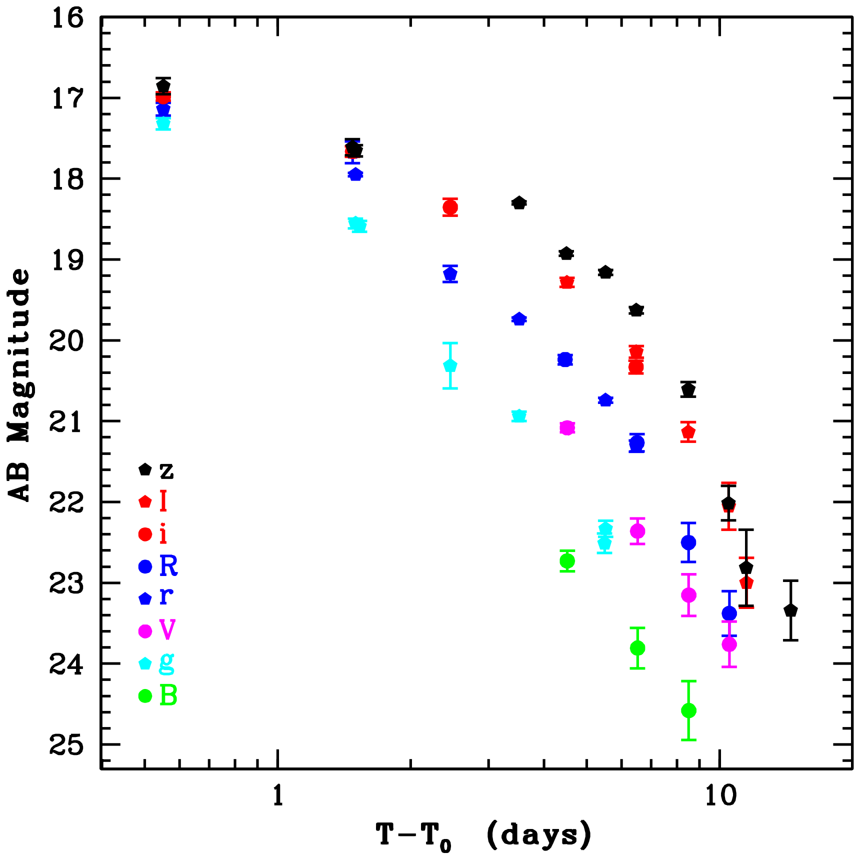


NASA/ESA. HST (credits: Levan et al.)

Coulter et al. 2017 Nat; Andreoni+2017; Cowperthwaite+2017; Diaz+2017; Drout +2017; Pian+2017; Kasliwal+2017; Smartt +2017; Tanvir+2017; Valenti+2017; Covino +2017 … …

Kilonova

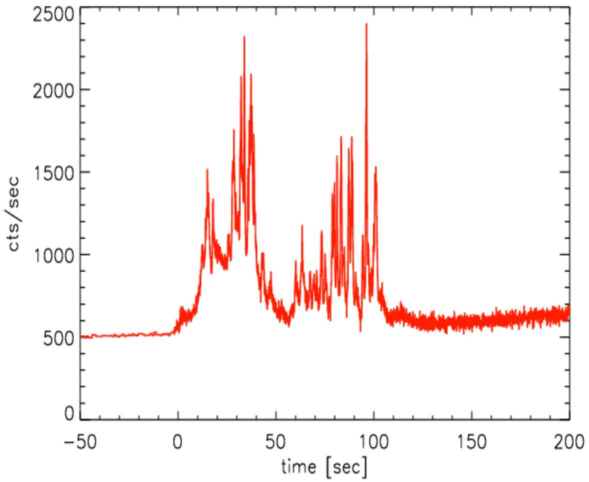
Pian et al. 2017, Nat.



Gamma Ray Bursts

>1973
Short flashes of keV photons
PROMPT

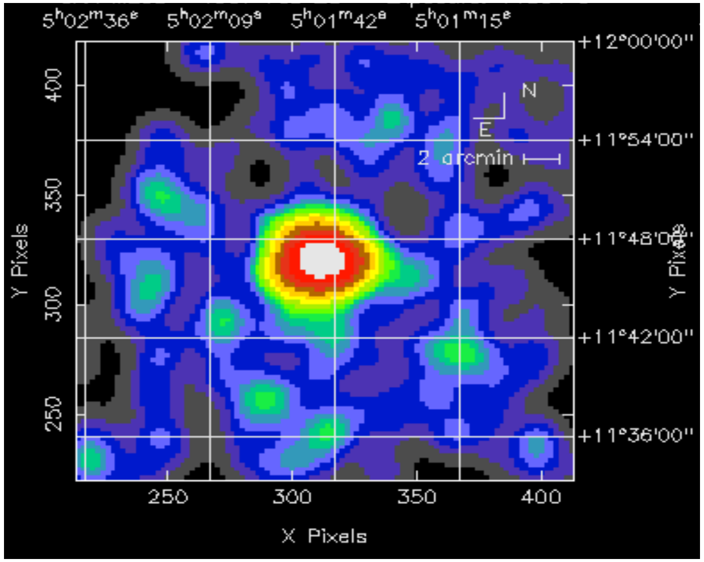
γ-ray



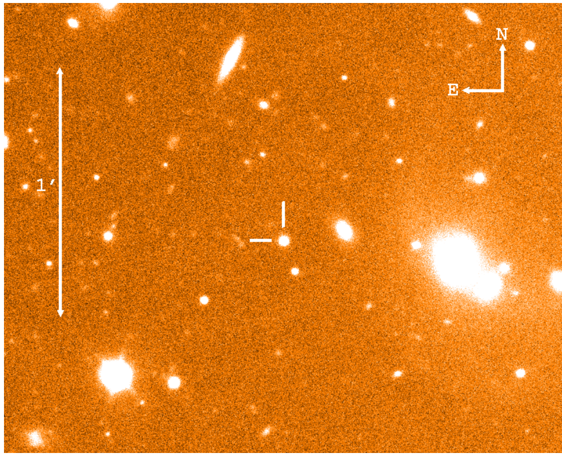
(e.g. Piran 2004, RMP)

>1997
Accompained by emission at lower frequencies
AFTERGLOW

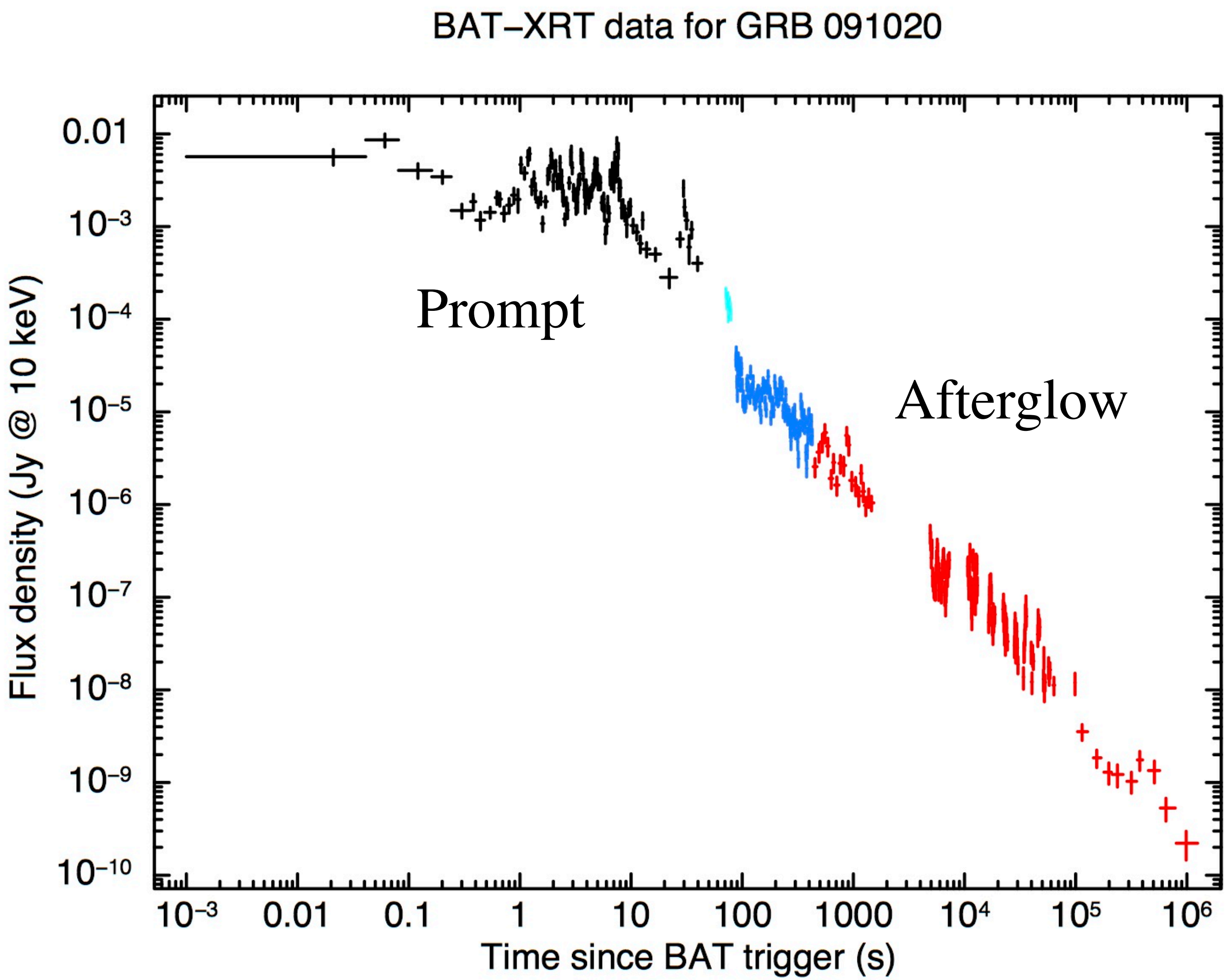
X-ray



Optical

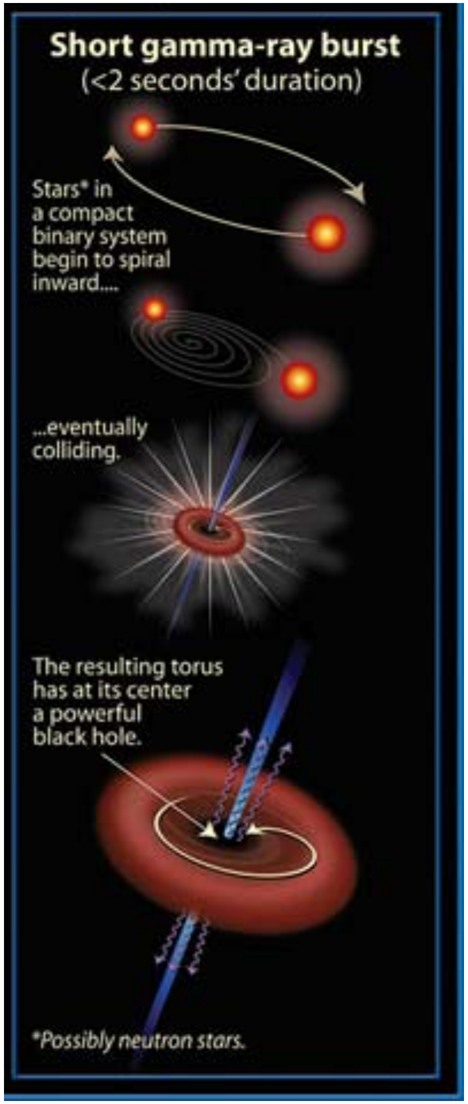


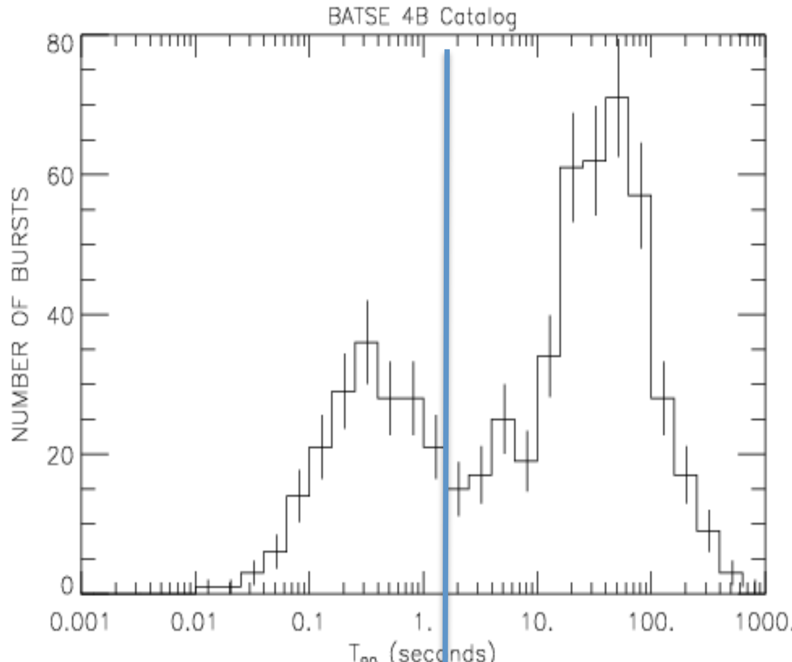
Gamma Ray Bursts

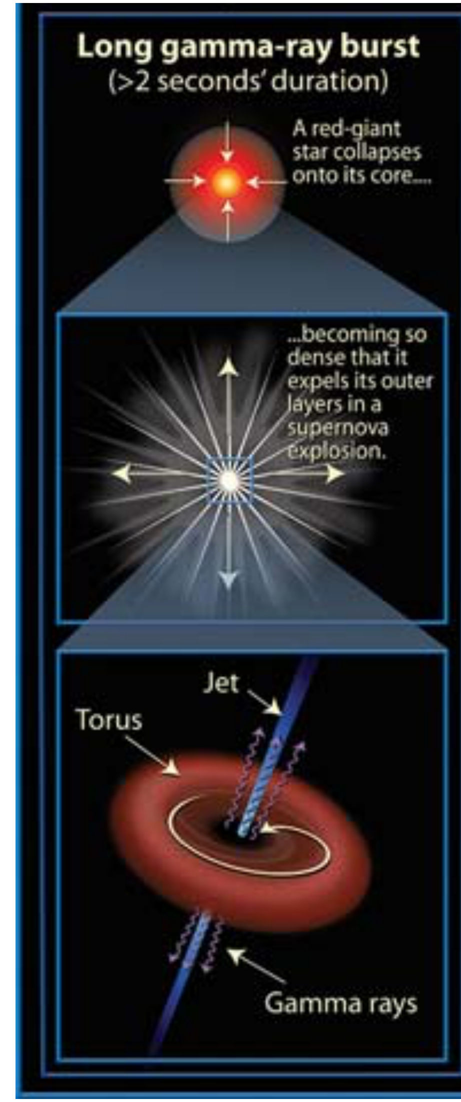


http://www.swift.ac.uk/burst_analyser/

Gamma Ray Bursts





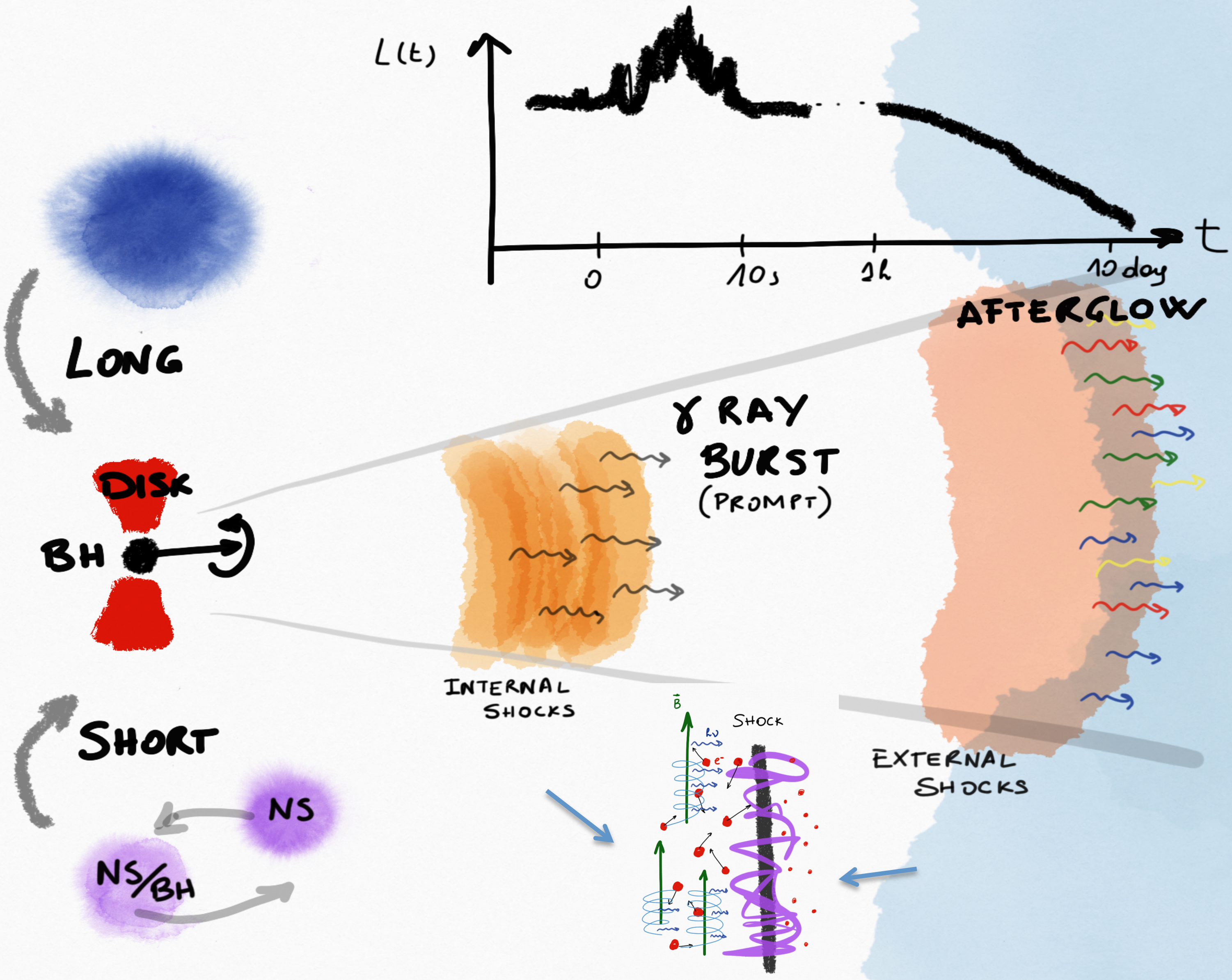


Energy	10^{49-53} erg	10^{48-54} erg
Spectra	Harder	Softer
Afterglow	Fainter	
Hosts	Any	SF
Progenitor	NS-NS (1)	Single M>>

duration ←→ central engine activity

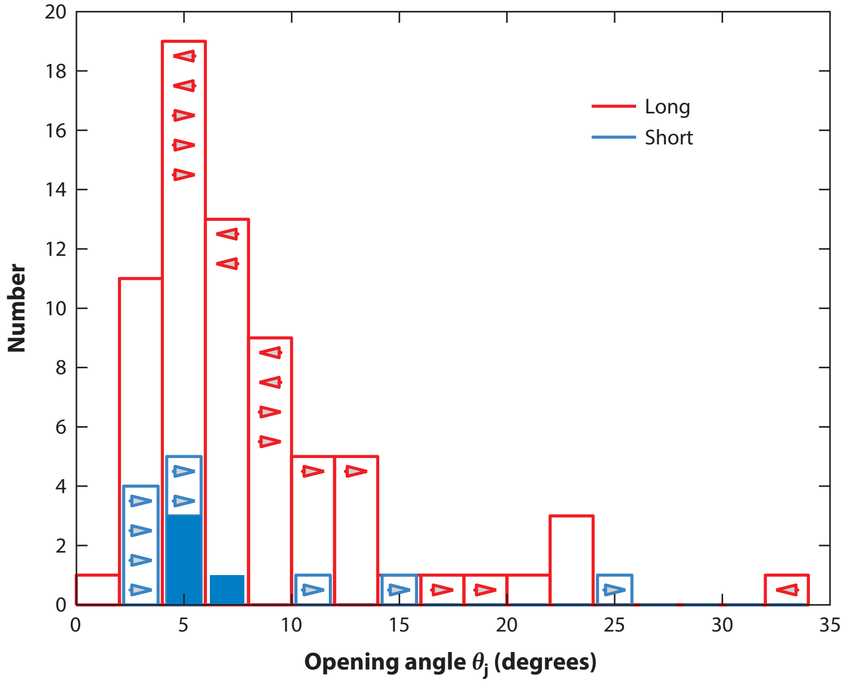
Relativistic jets

Gamma Ray Bursts

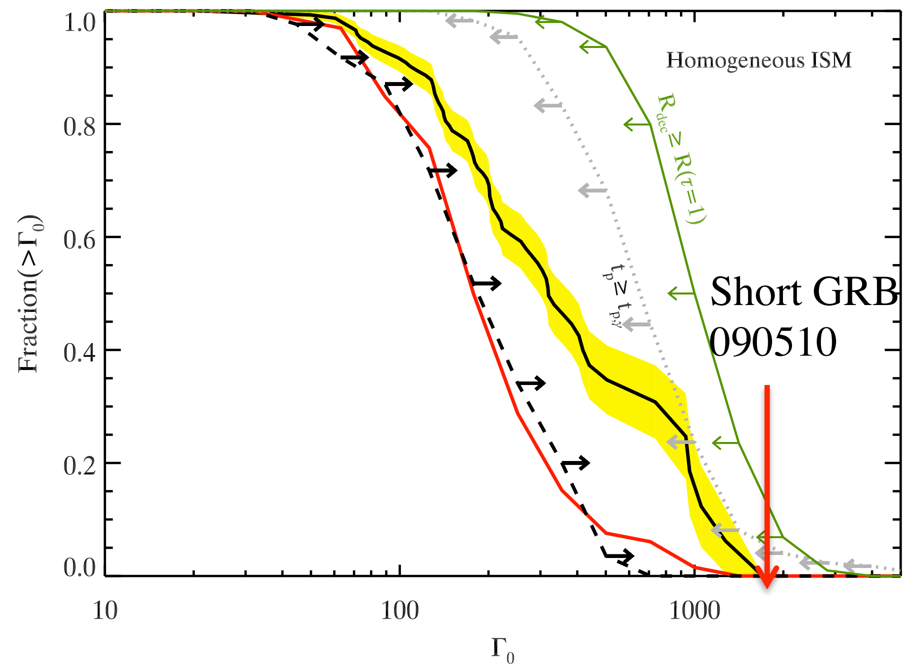


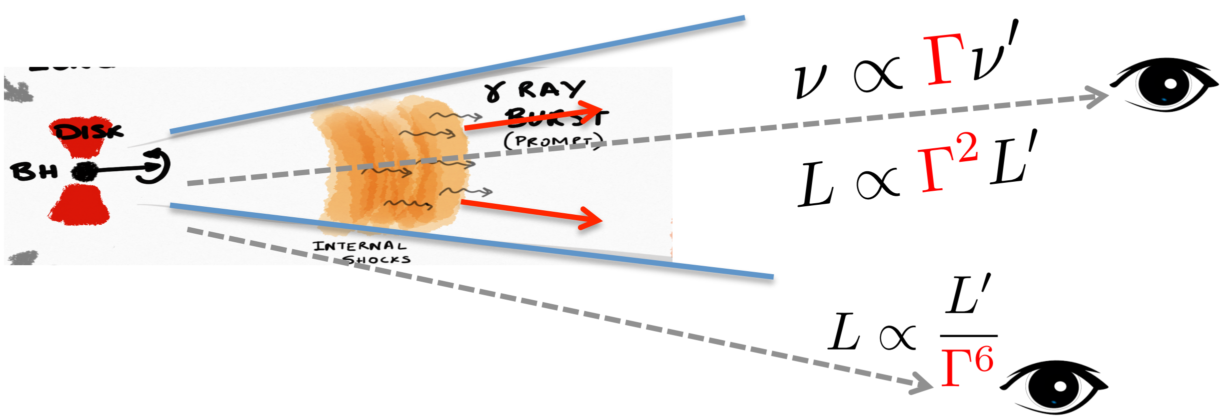
GRBs: collimation and relativistic beaming

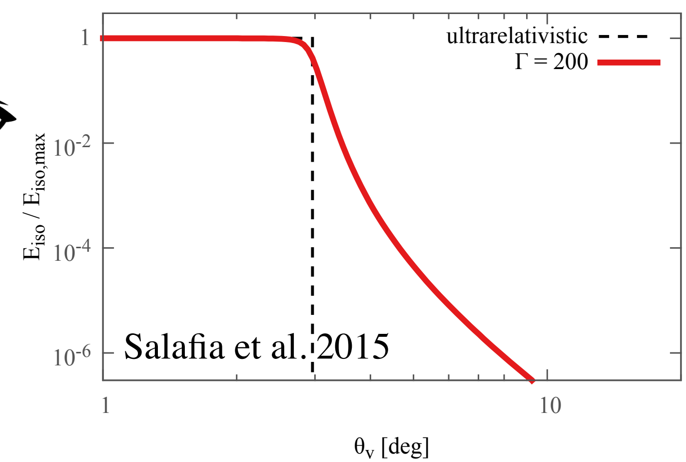
Fong et al. 2016



Ghirlanda et al. 2018



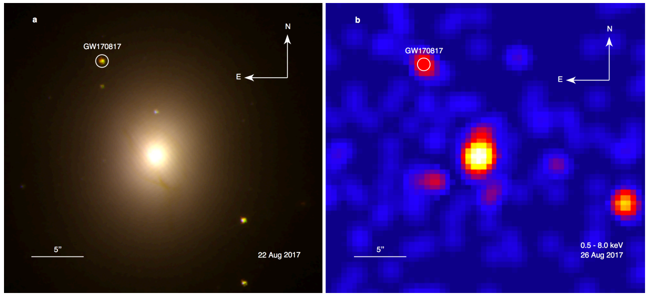




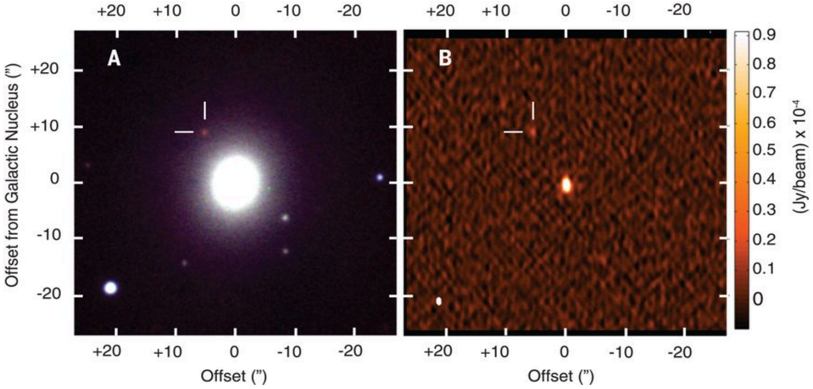
3

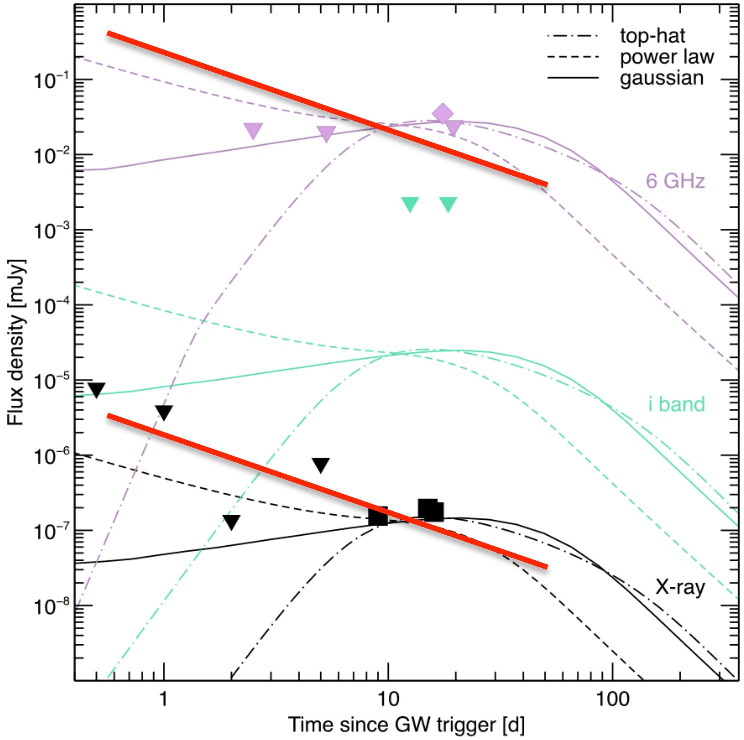
Where is the afterglow of 170817?

Troja et al. 2017, Nat;



Hallinan et al. 2017, Sci

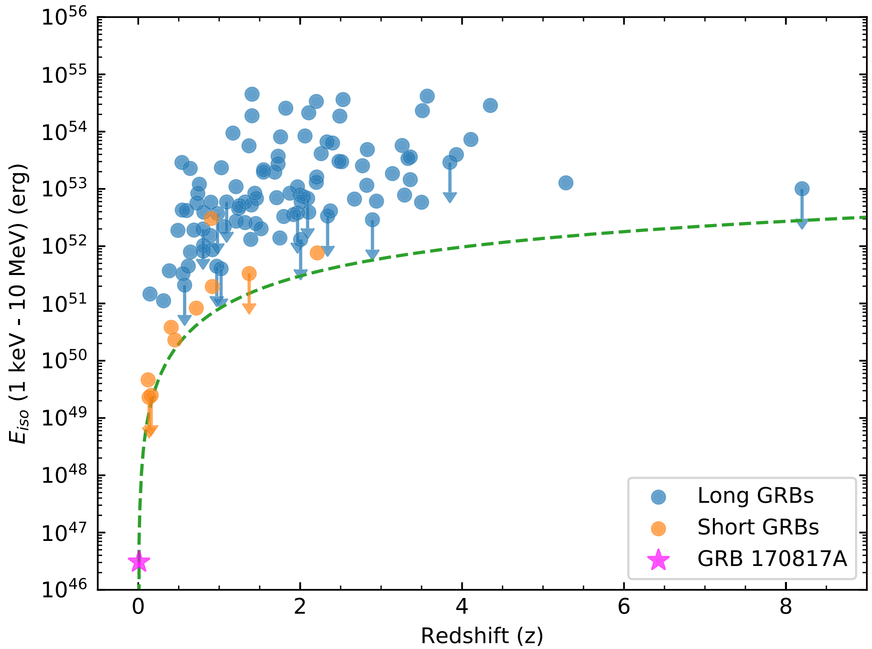




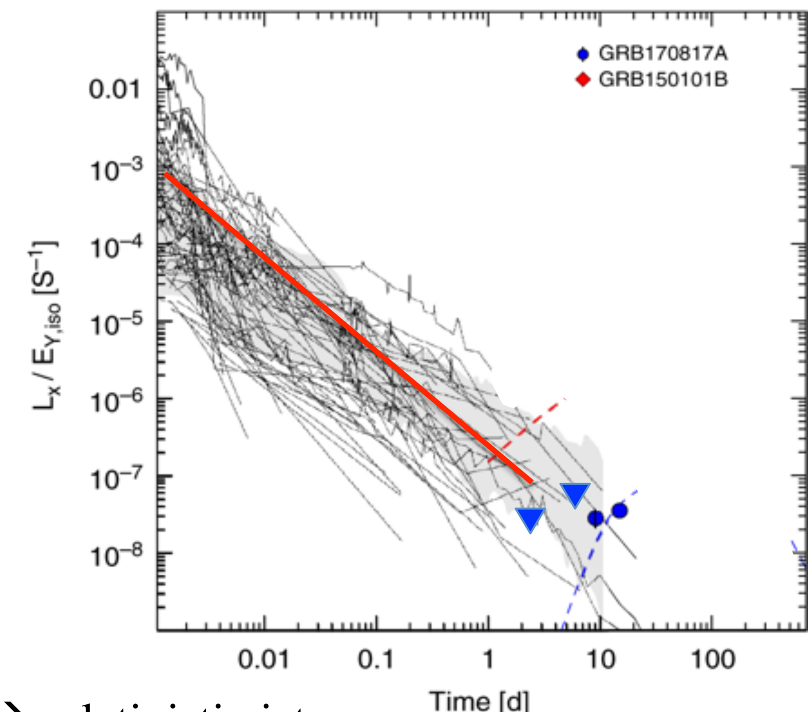
Non standard decay afterglow

3 Short GRBs and 170817

Abbott+2017; Goldstein+2017; Zhang+2018



Troja+2017; Fong+2017



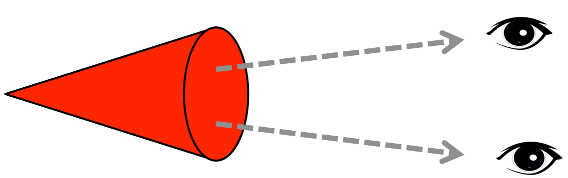
Gamma Ray Bursts → relativistic jets

If 170817 were a standard (Γ>>100; ϑ_{jet}~10°) GRB

L~10^{51} erg/s ✗

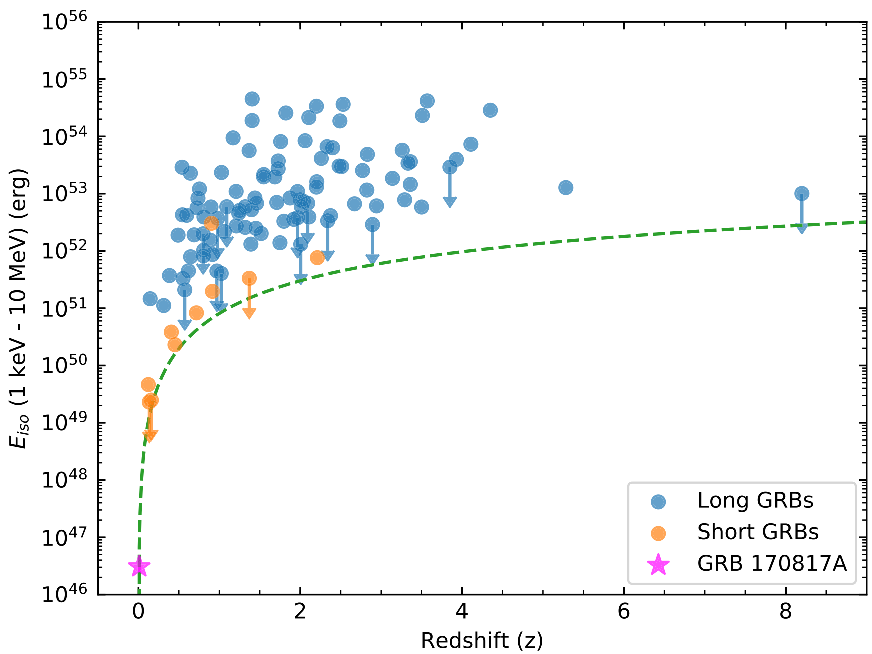
Afterglow t^{-1} ✗

$$P(<\theta_{\rm jet}=10^\circ)=1.5\%$$

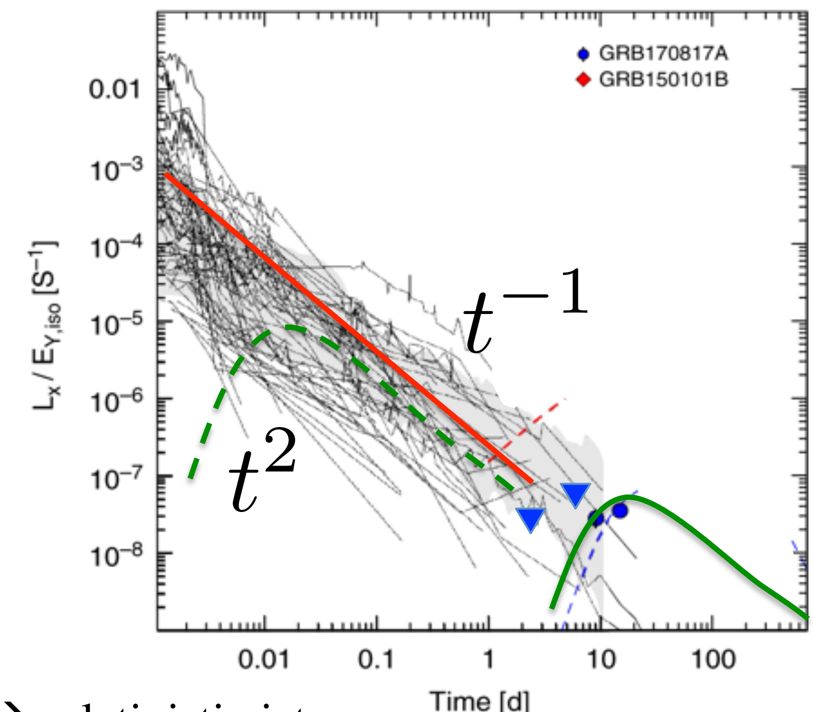


GRB 170817 – Off axis jet

Abbott+2017; Goldstein+2017; Zhang+2018



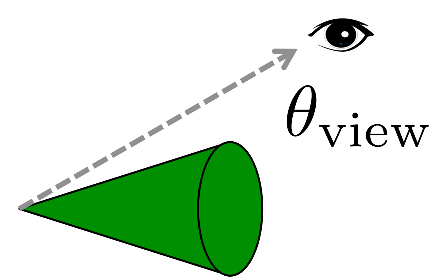
Troja+2017; Fong+2017



Gamma Ray Bursts → relativistic jets

If 170817 were a standard (Γ~100; ϑ_{jet}~10°) GRB **off-axis**

- L~10^{47} erg/s (debeaming)
- Afterglow appears when $\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$

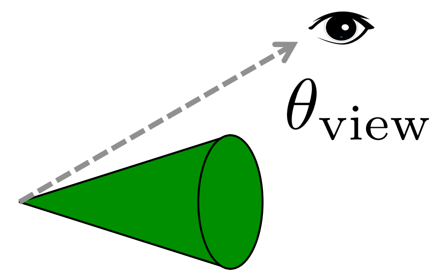


Pian et al. 2017; Margutti et al. 2017; Nakar et al. 2017; Granot et al. 2017 …

GRB 170817 – Off axis jet ??

Gamma Ray Bursts → relativistic jets

If 170817 were a standard ($\Gamma \sim 100$; $\vartheta_{jet} \sim 10°$) GRB **off-axis**

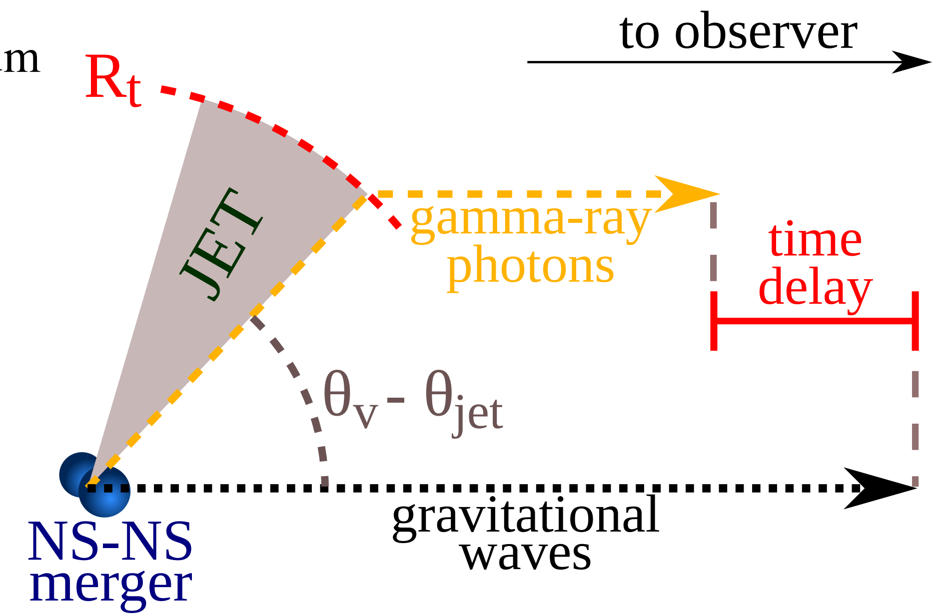


- ✔ L~10^{47} erg/s (δ^{-3})
- ✔ Afterglow appears when

$$\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$$

- ✔ Delay GW-EM

+ GW signal → angular momentum
+ KN color evolution



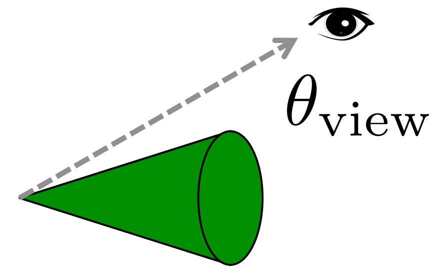
Salafia et al. 2018

But only slightly off axis

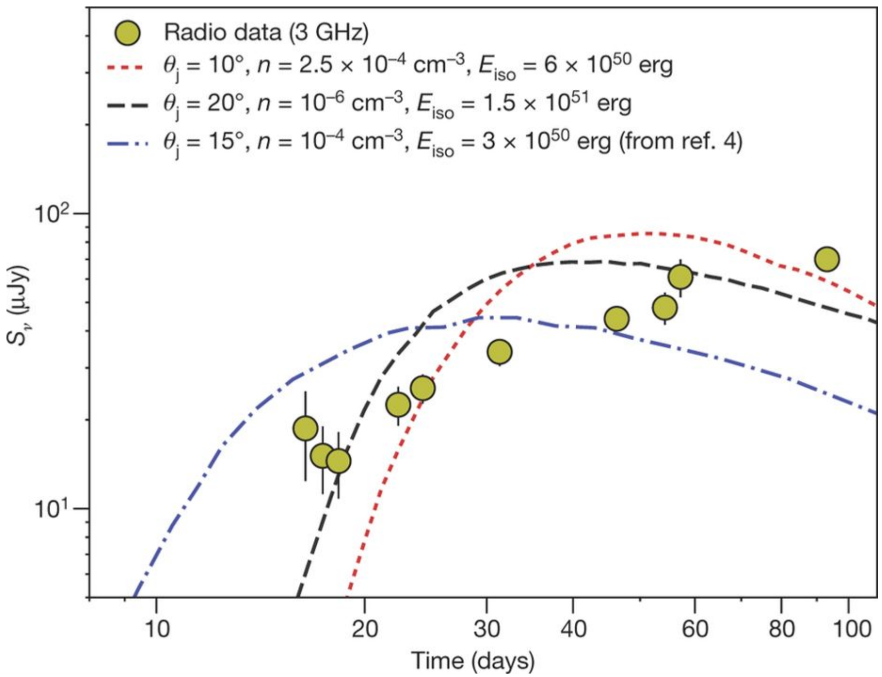
GRB 170817 – Unexpected afterglow

Gamma Ray Bursts → relativistic jets

If 170817 were a standard (Γ~100; ϑ_{jet}~10°) GRB **off-axis**



- ✔ L~10^{47} erg/s (δ^{-3})
- ✔ Afterglow appears when $$\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$$
- ✔ Delay GW-EM
- ✘ Soon after peak the afterglow should decay normally (t^{-1}), instead shallow rise



Mooley et al. 2018; Nat.

Non standard jet seen off-axis

GRB 170817 – Structured jet model

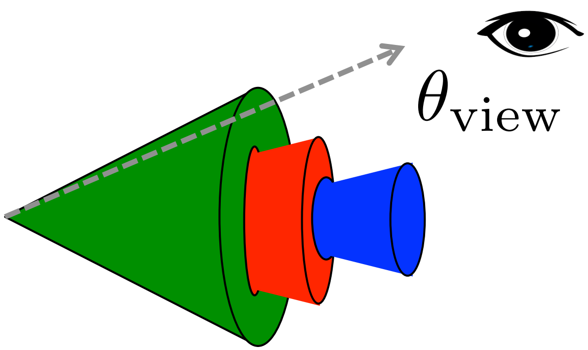
Gamma Ray Bursts → relativistic structured jets

If 170817 were a structured jet

- ✓ L~10^{47} erg/s (δ^{-3})
- ✓ Afterglow appears when

$$\frac{1}{\Gamma(t)} \sim \theta_{\rm view}$$

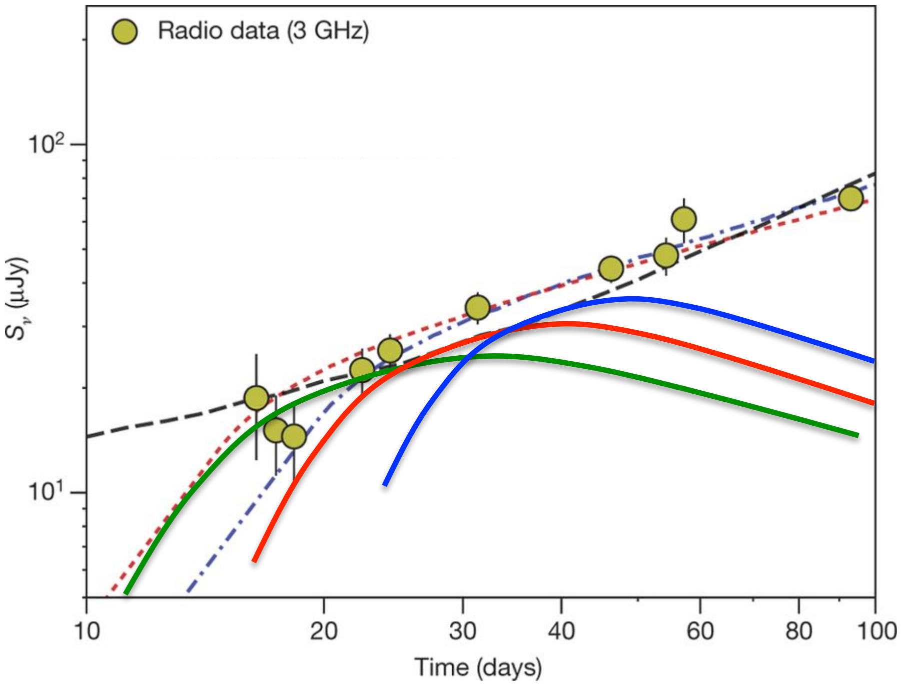
- ✓ Delay GW-EM
- ✓ Shallow rise of the radio light curve



$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$

Discrete→continous structure

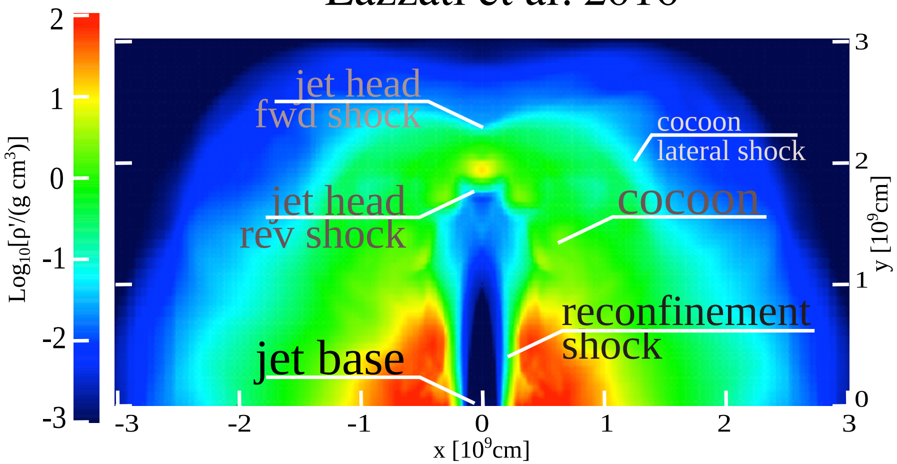


Peak is a combined effect of beming and orientation

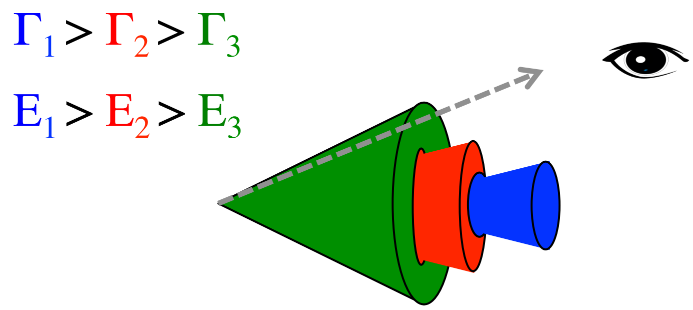
Structured jet in GRBs
Rossi et al. 2002; Zhang et al. 2002;
Granot et al. 2009
… …
Salafia et al. 2015, 2015b, Pescalli et al. 2015

Structured jet: a natural expectation

Lazzati et al. 2016



Succesfull jet
Angular structure

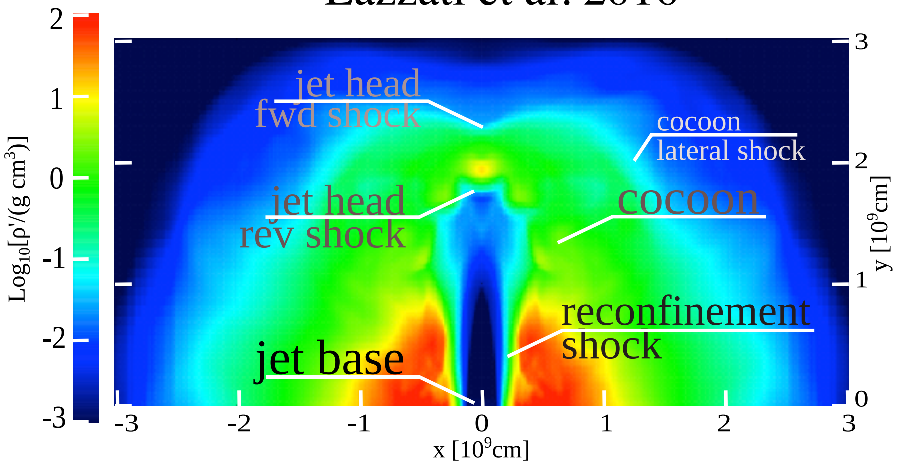


Gottlieb, Nakar et al. 2018

Succesfull jet
or
Structured jet

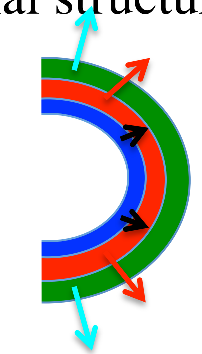
3 Structured jet: a natural expectation … but

Lazzati et al. 2016



Choked jet

Radial structure



$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$

Gottlieb, Nakar et al. 2018

Choked jet

or

Failed jet

or

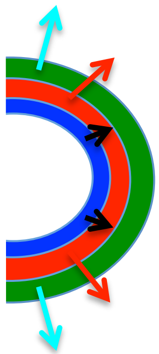
Cocoon

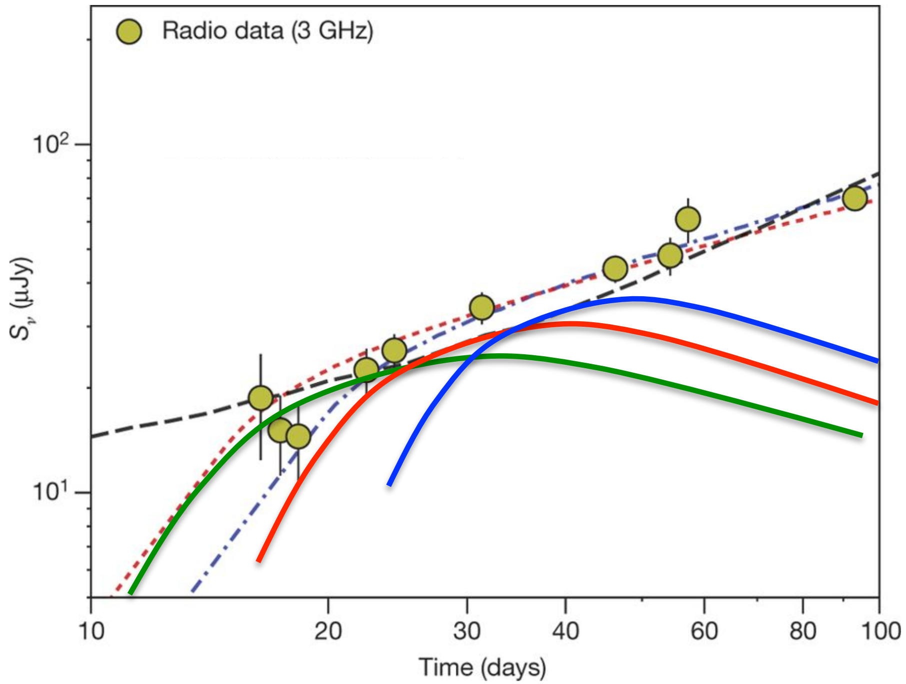
GRB 170817 – choked jet model

Gamma Ray Bursts → relativistic structured jets

If 170817 were a structured jet

- ✔ L~10^{47} erg/s (intrinsically)
- ✔ Afterglow appears → deceleration
- ✔ Delay GW-EM → transparency or dissipation
- ✔ Shallow rise of the radio light curve → energy injection



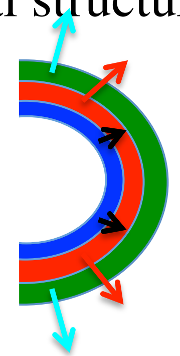


Discrete→continous structure

Peak is a dynamic effect

3 Which structure?

Choked jet
Radial structure



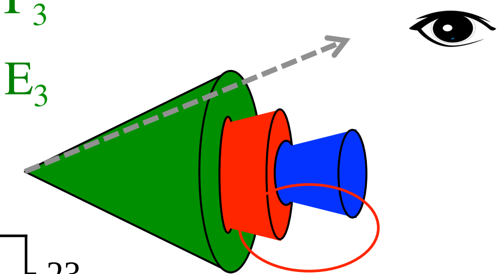
$\Gamma_1 < \Gamma_2 < \Gamma_3$

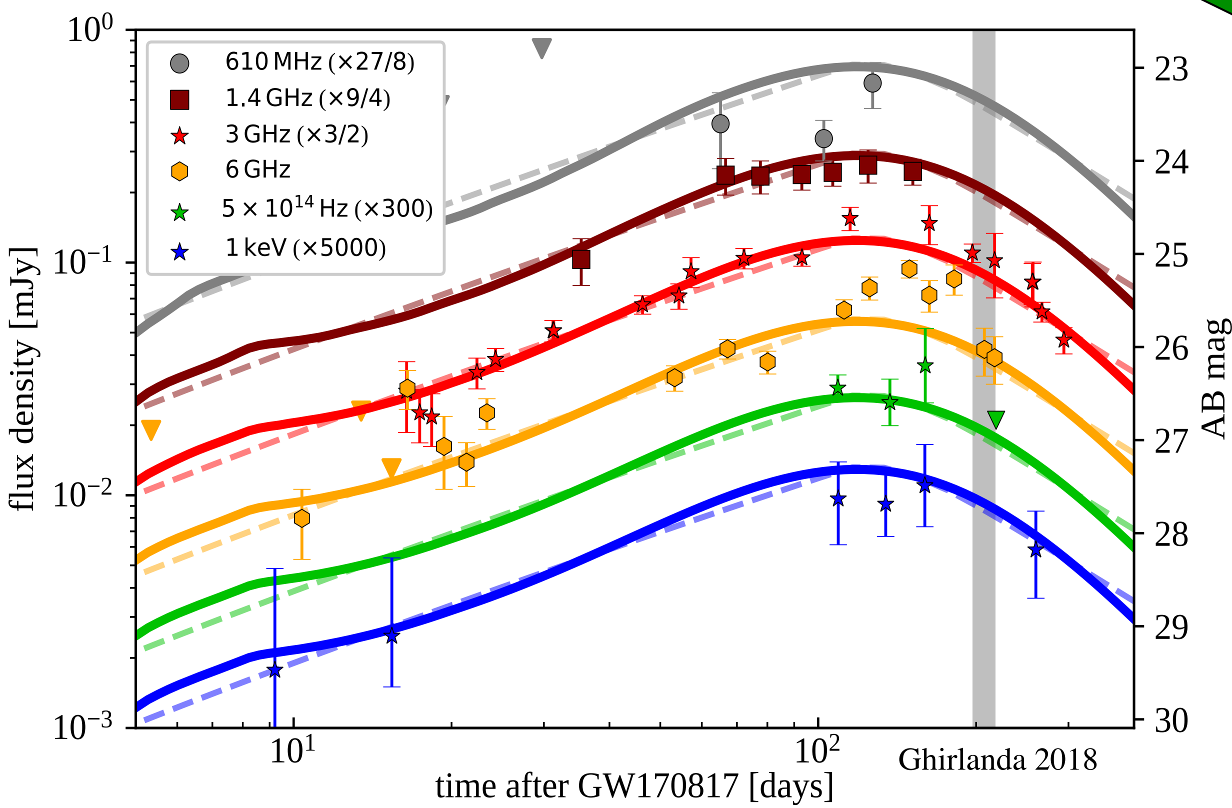
$E_1 > E_2 > E_3$

Succesfull jet
Angular structure

$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$

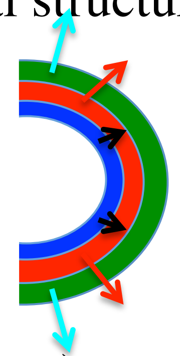




Ghirlanda 2018

Which structure?

Choked jet
Radial structure



$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$

$$E(>\Gamma\beta) = E_0(\Gamma\beta)^{-\alpha}$$

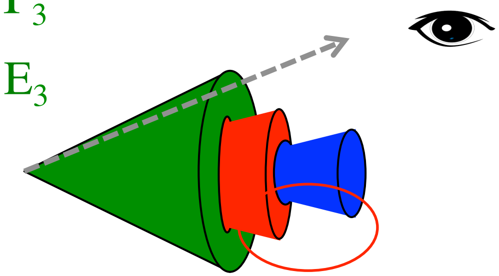
$E_0 = 1.5\text{x}10^{52}$ erg
$\alpha = 6$
$\Gamma_{max} = 6$
$\Theta = 30, 45, 60$ deg

p=2.15; ε_e=0.1; ε_B= 10^{-4}

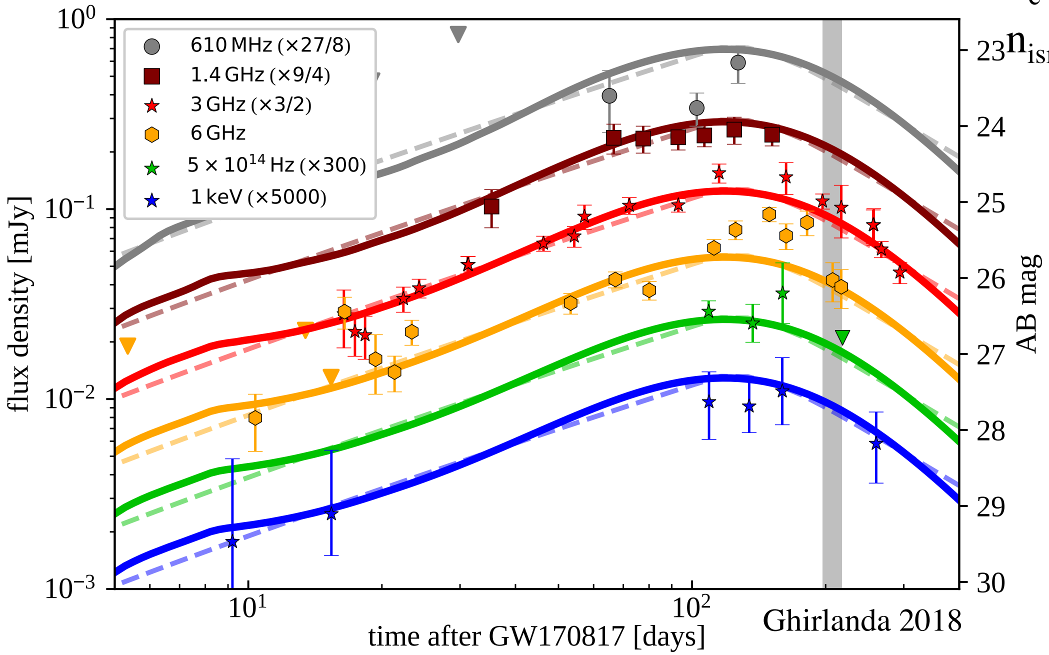
Succesfull jet
Angular structure

$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$



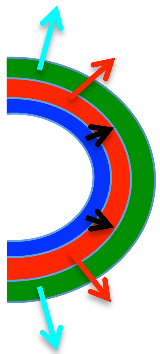
$E_{core}=2.5\text{x}10^{52}$ erg ; s_1=5.5;
Γ_c = 250 ; s_2=3.5; ϑ_{core}=3.4 deg
$n_{ism}=4\text{x}10^{-4}$ cm^{-3} ; ϑ_{view}=15 deg



$$E_{k,iso}(\theta) = \frac{E_{core}}{1-(\theta/\theta_{core})^{s_1}}$$

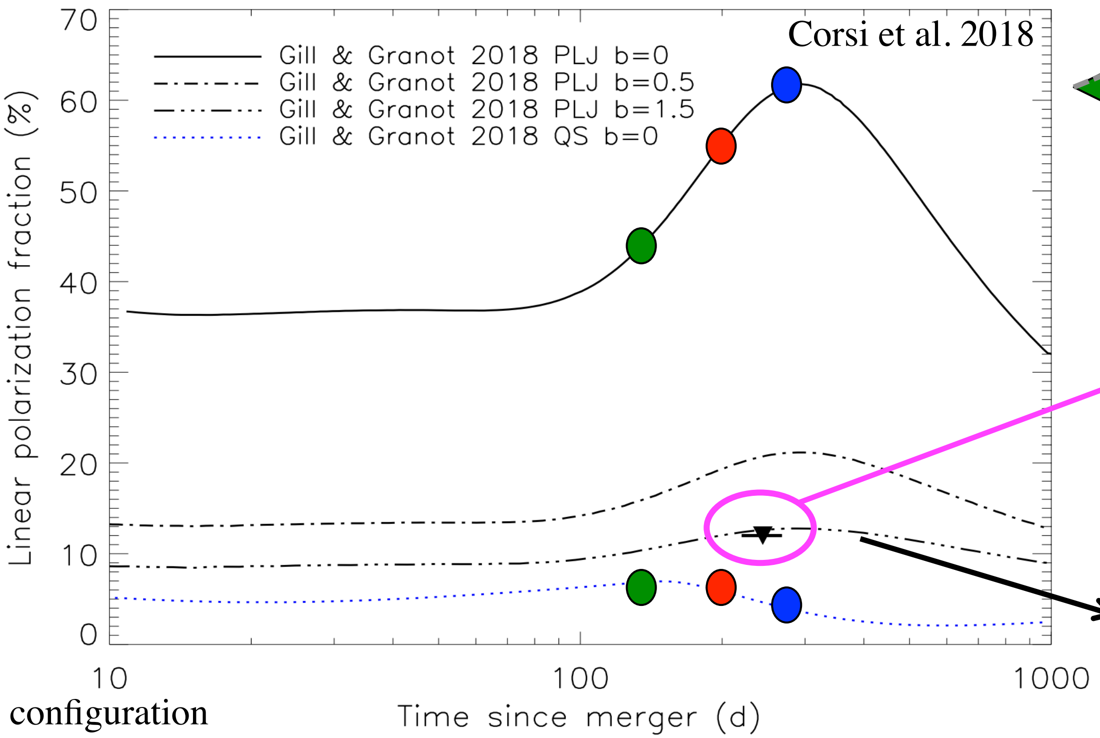
$$\Gamma(\theta) = 1 + \frac{\Gamma_{core}-1}{1+(\theta/\theta_{core})^{s_2}}$$

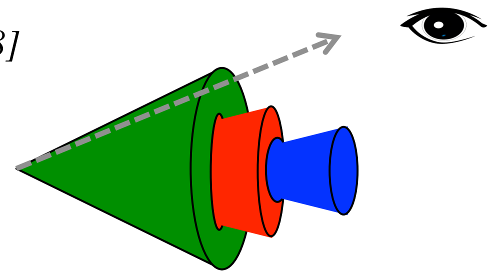
Polarization



$$b = 2\frac{< B_{\perp} >}{< B_{\parallel} >}$$

[Rossi+2004 … Gill & Granot 2018; Nakar+2018; Lazzati+2018]





JVLA @ 244d, 2.8 GHz

Π<12% (90%)

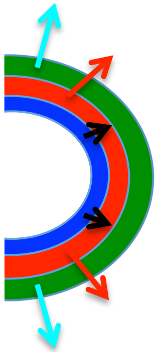
Corsi et al. 2018

Still compatible with a structured jet with B component perp. shock

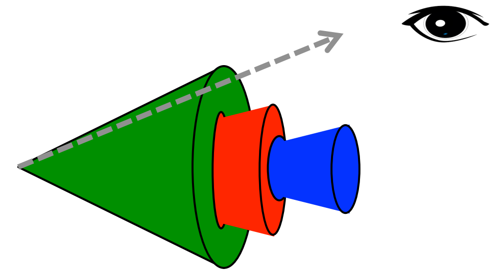
Contribute:

1) Magnetic field configuration (randomness & compression)
2) Γ
3) Geometry (ϑ_{jet} ; ϑ_{view})
4) Emission mechanism

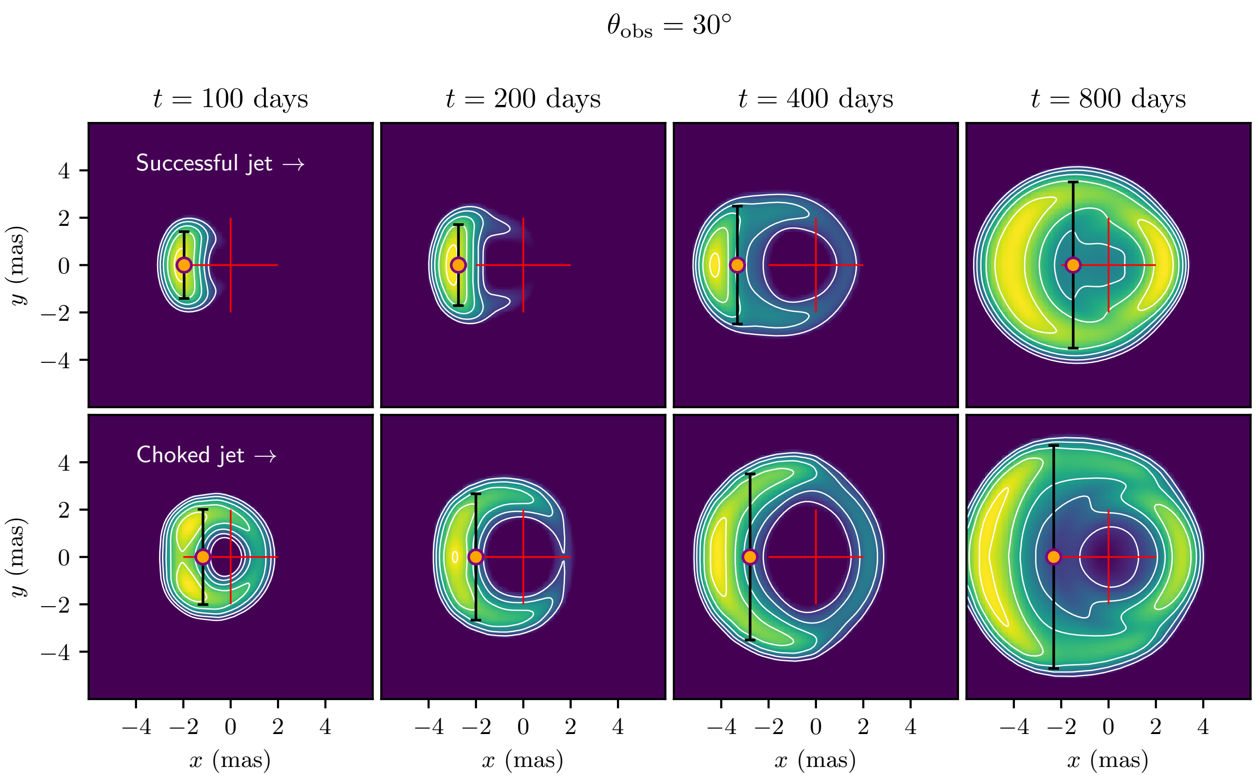
Imaging



1) apperent motion
2) source size



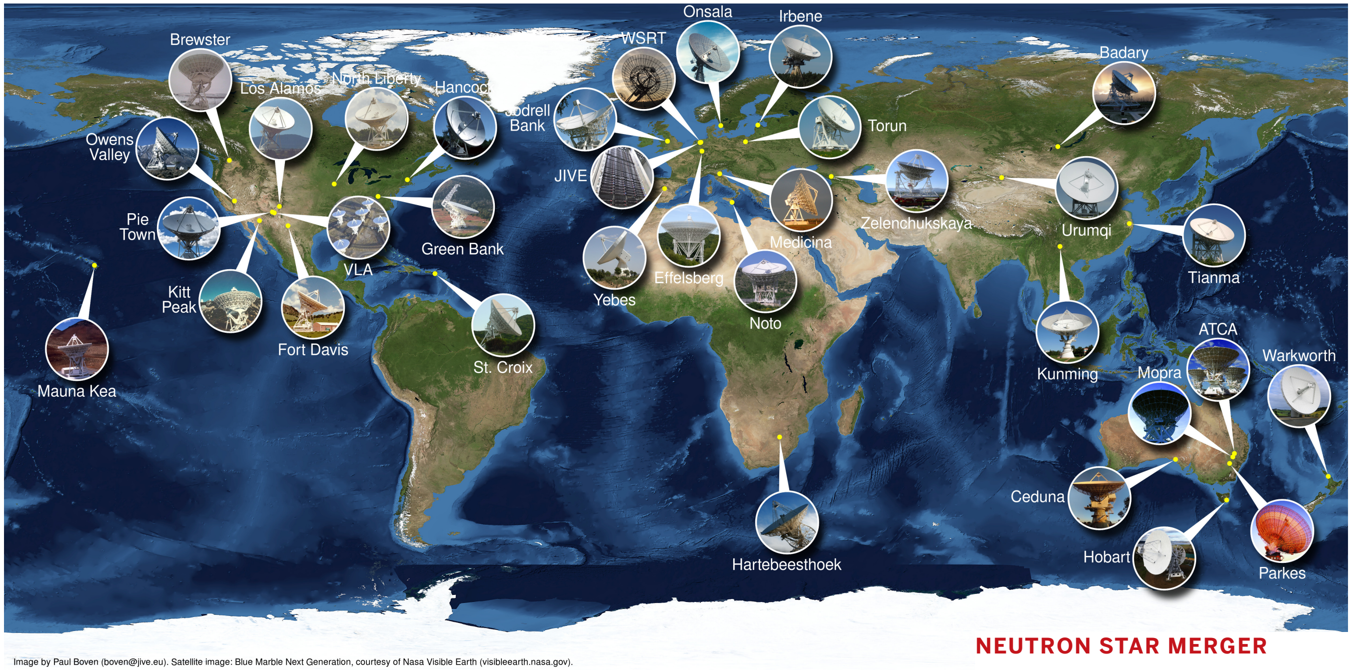
[Gill & Granot 2018; Nakar+2018; Zrake+2018; Mooley+2018; Ghirlanda+2018]



Structured jet has larger displacement and smaller size than cocoon

Imaging

Global-VLBI EVN project (GG084) + eMERLIN (CY6213) {+ EVN (RG009)}



33 telescopes
5 continents
11 Research Institutes

12-13 March 2018 = 204.7 days @ 5 GHz (32 ant. but VLA)

Science

NEUTRON STAR MERGER

Compact radio emission indicates a structured jet was produced by a binary neutron star merger

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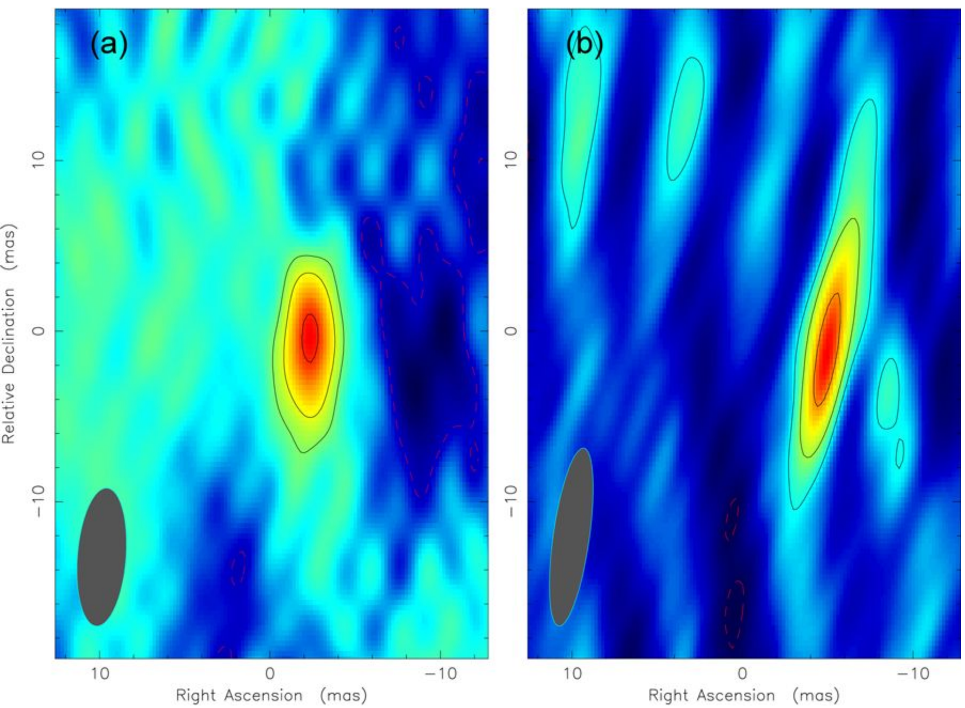
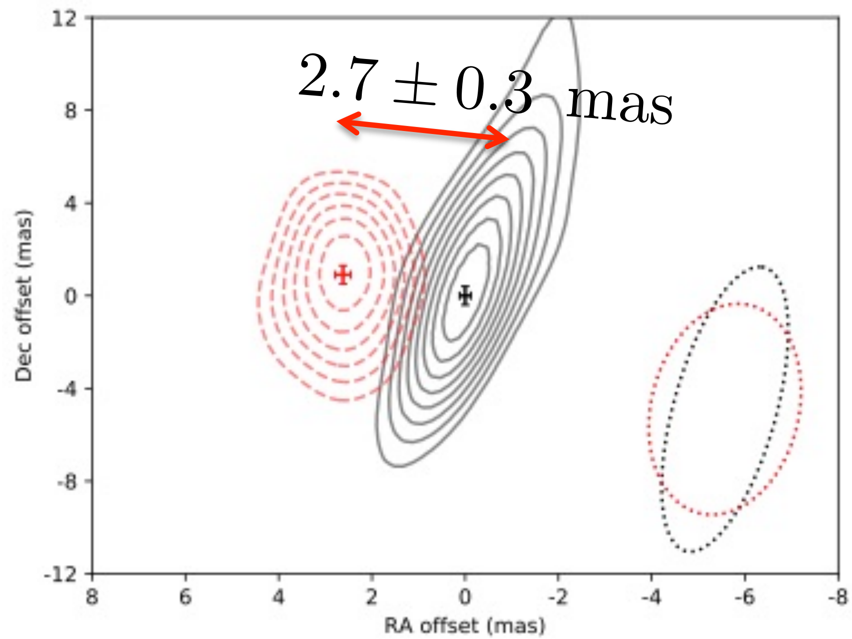
Imaging

Apparent motion *[Mooley+2018, Nat.]*

VLBA + VLA + GBT: 2/4 epochs (Sept 2017 – Apr. 2018, L,S,C,C) @ <75d> and <230d> (4.5 GHz)

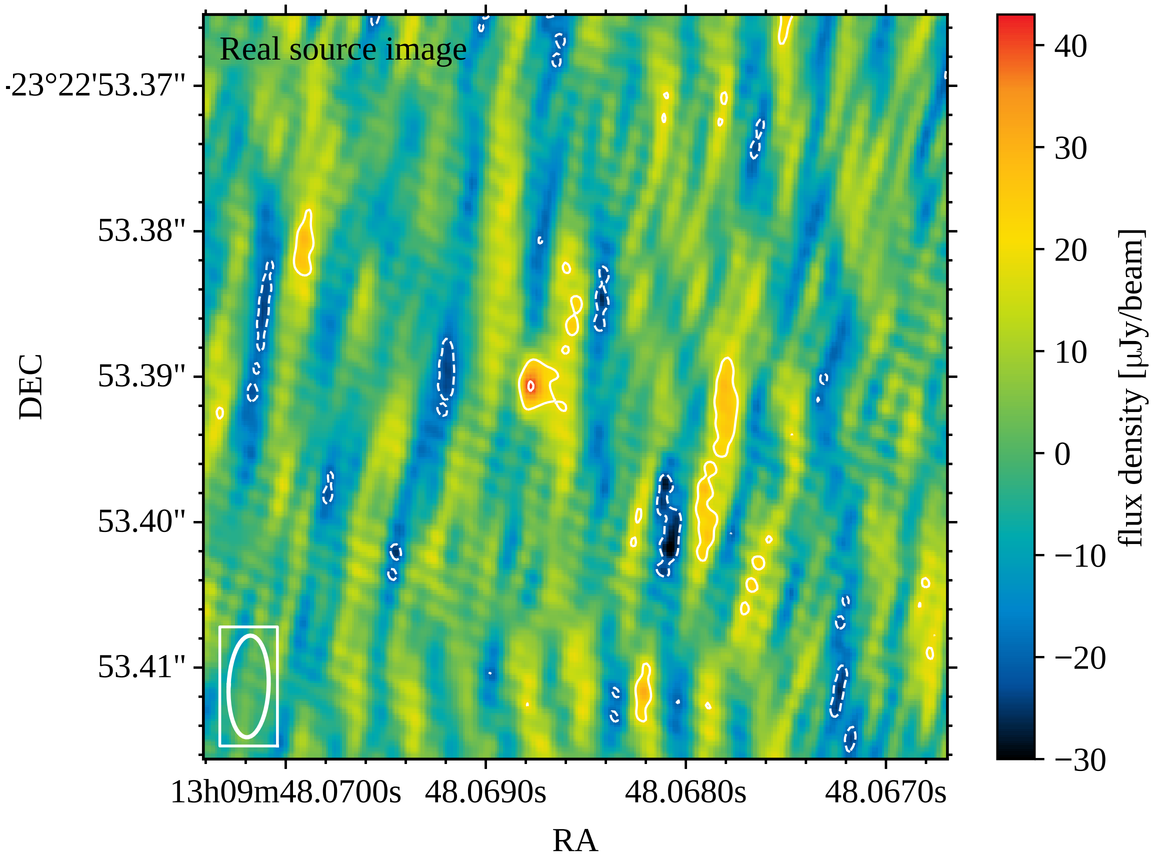
230 days 75 days





Imaging

Size constraints *[Ghirlanda et al. 2019, Sci]*



8 μJy/beam rms

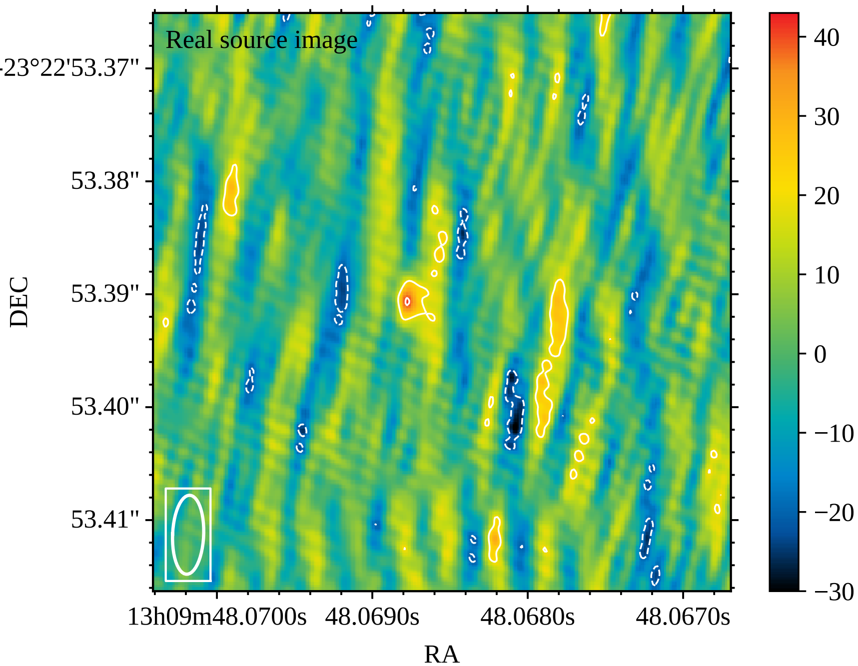
Peak brightness 42 ± 8 μJy/beam
[cnst. interpolating closest JVLA F=47±9 μJy]

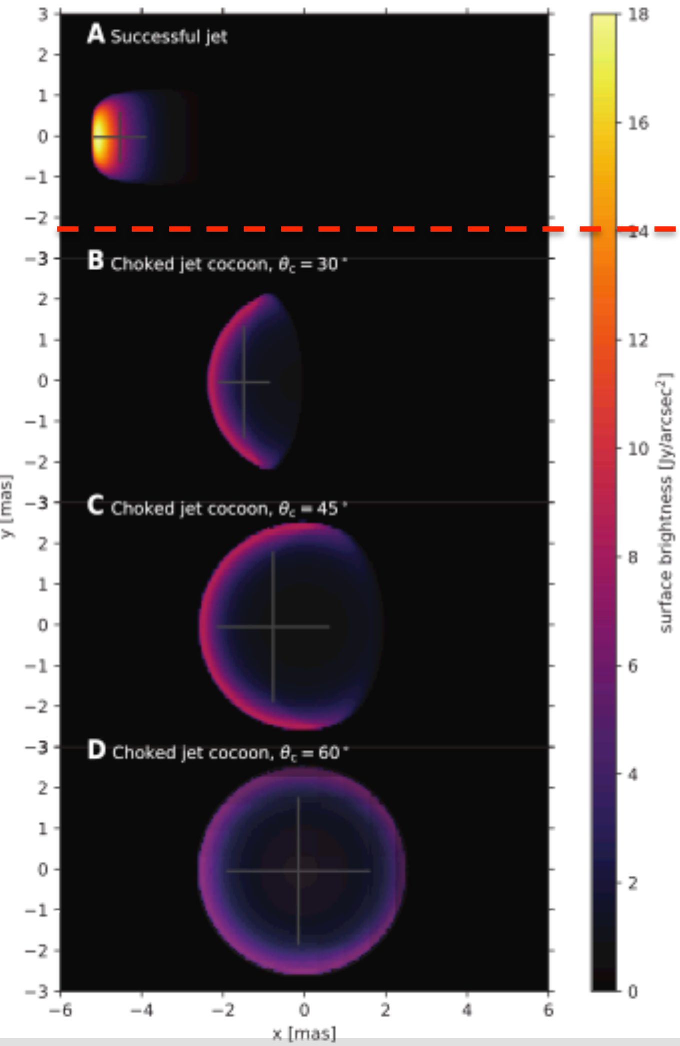
8-22 March (12 runs) eMERLIN
F_p < 60 μJy/beam

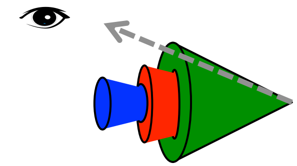
beam = 3.5x1.5 mas; PA=-6 deg
S =2.9 mas (1DGaussian fit but F=93 μJy)
S =1.3±0.6 mas (2DGaussian fit with F=47 μJy)

Imaging

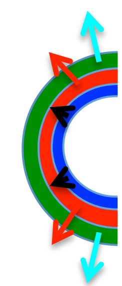
Size constraints *[Ghirlanda et al. 2019, Sci]*







< 2 mas

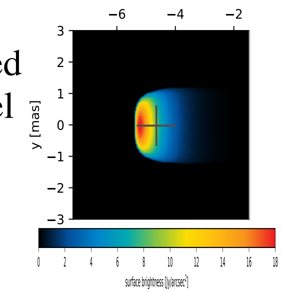


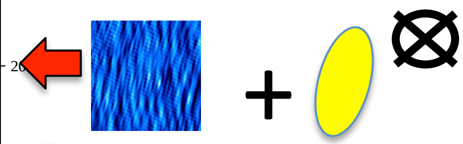
> 3 mas

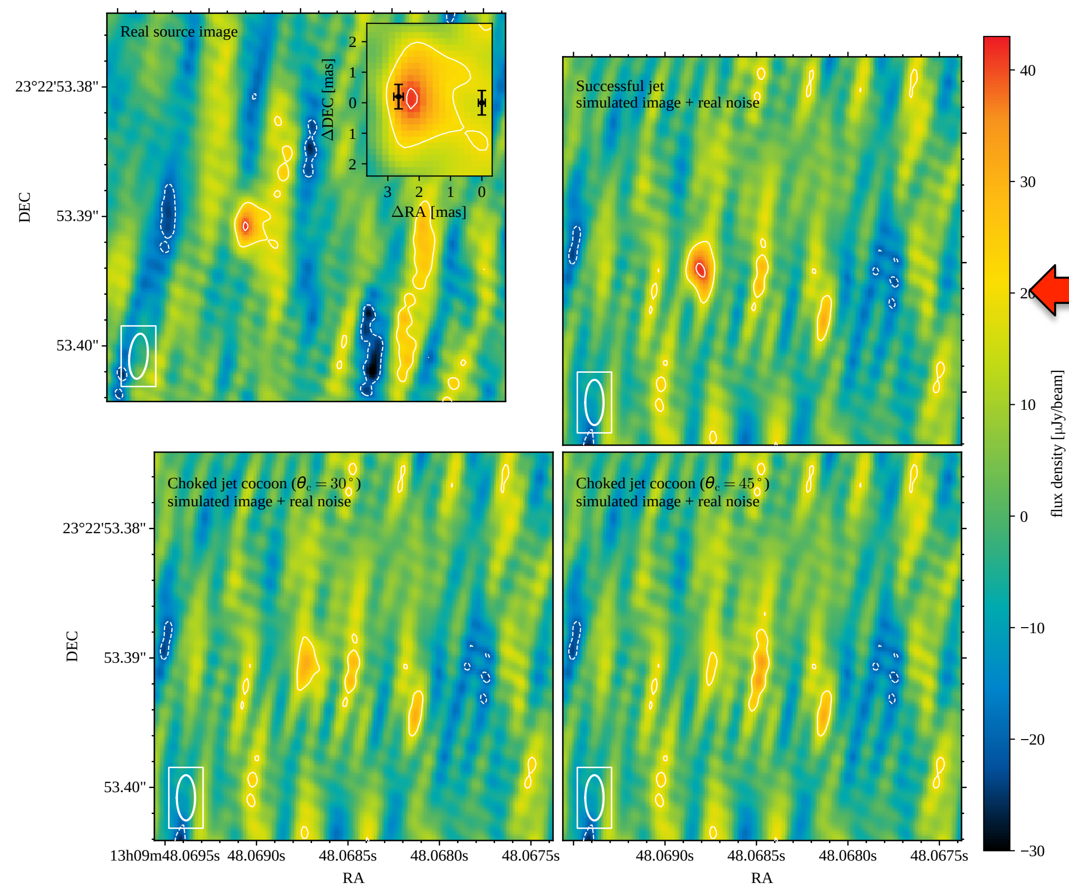
Imaging

Size constraints *[Ghirlanda et al. 2019, Sci]*

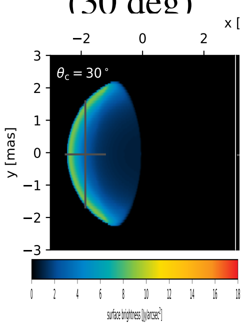
Structured jet model



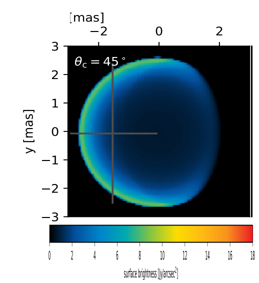




Cocoon (30 deg)



Cocoon (45 deg)



Imaging

Size constraints *[Ghirlanda et al. 2019, Sci]*

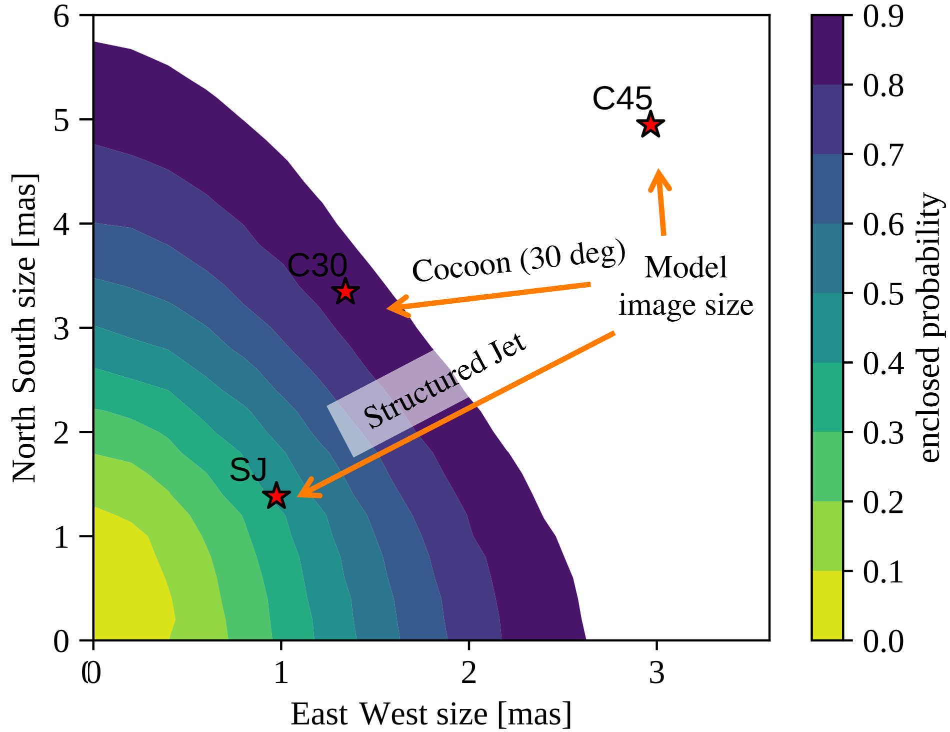
Bayesian approach (MonteCarlo implementation)

Gauss prior (47±9 μJy)

Flat prior

$$P(\sigma_x, \sigma_y, F | F_p) = \frac{P(F_p|\sigma_x, \sigma_y, F)P(F)P(\sigma_x, \sigma_y)}{P(F_p)}$$

$$P(\sigma_x, \sigma_y | F_p) = \int \frac{P(F_p|\sigma_x, \sigma_y, F)P(F)P(\sigma_x, \sigma_y)}{P(F_p)} dF$$



Probability of excluding a size (σ_x σ_y) given that we measure a peak brightness of 42±8 μJy/beam

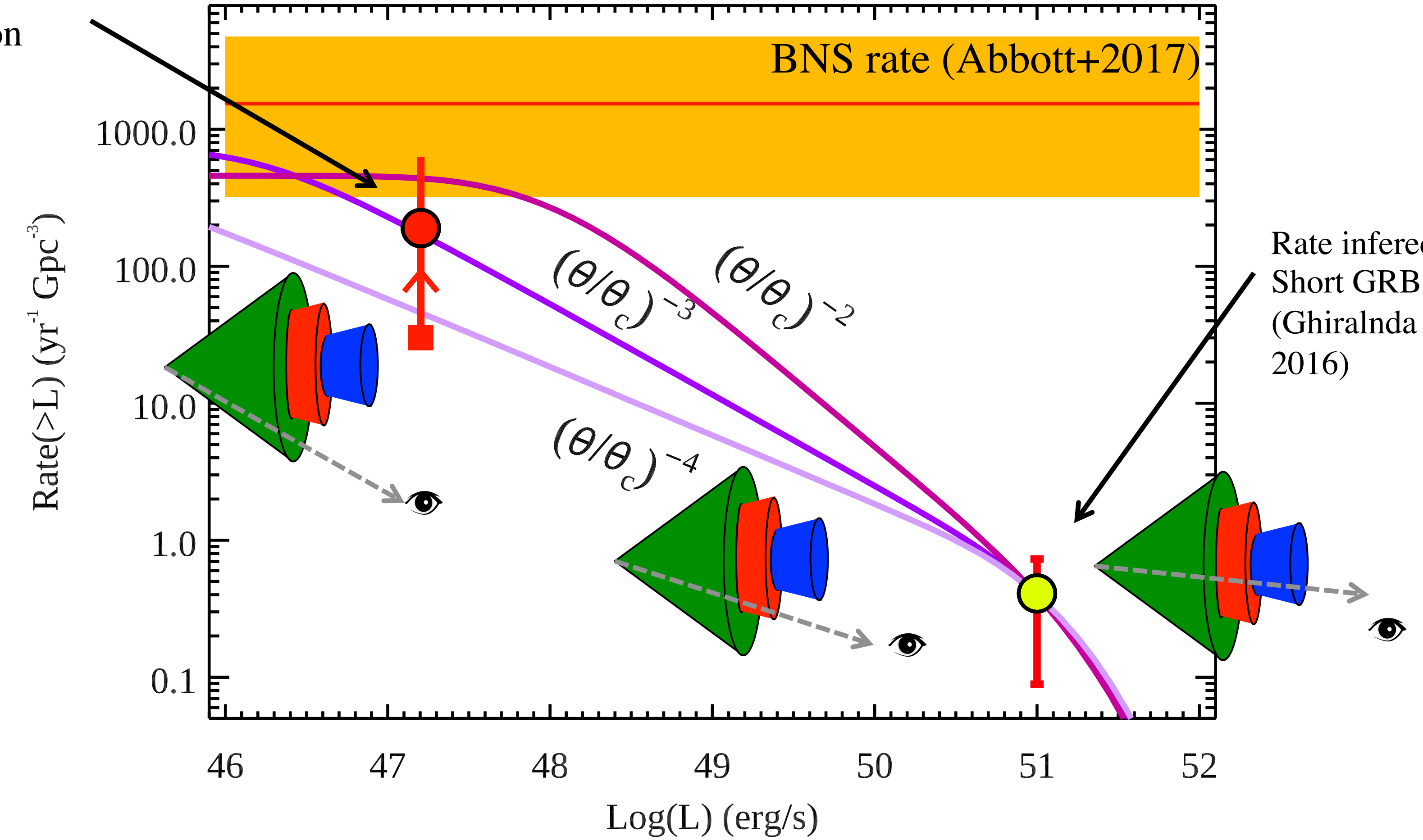
Size (Bayesian) test → Structured Jet P=70%

Structured jet and rates

Structured jet model (universal structure) → Luminosity function (Pescalli et al. 2015; Salafia et al. 2015; Ghirlanda et al. 2016)

At least 10% of BNS launch a jet that succesfully breaks out of the merger ejecta

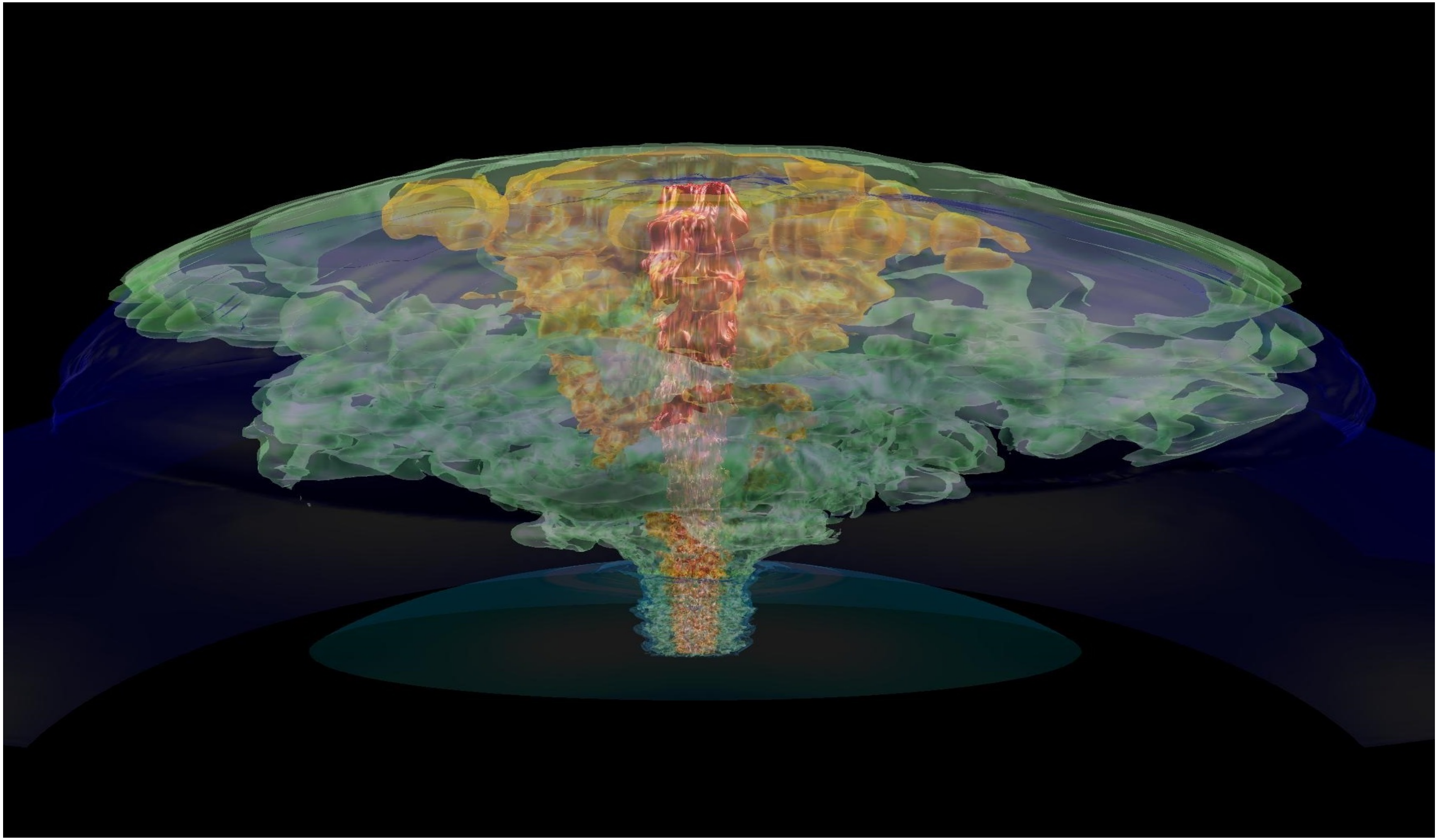
Rate infered from Fermi detection



Rate infered from Short GRBs (Ghiralnda et al. 2016)

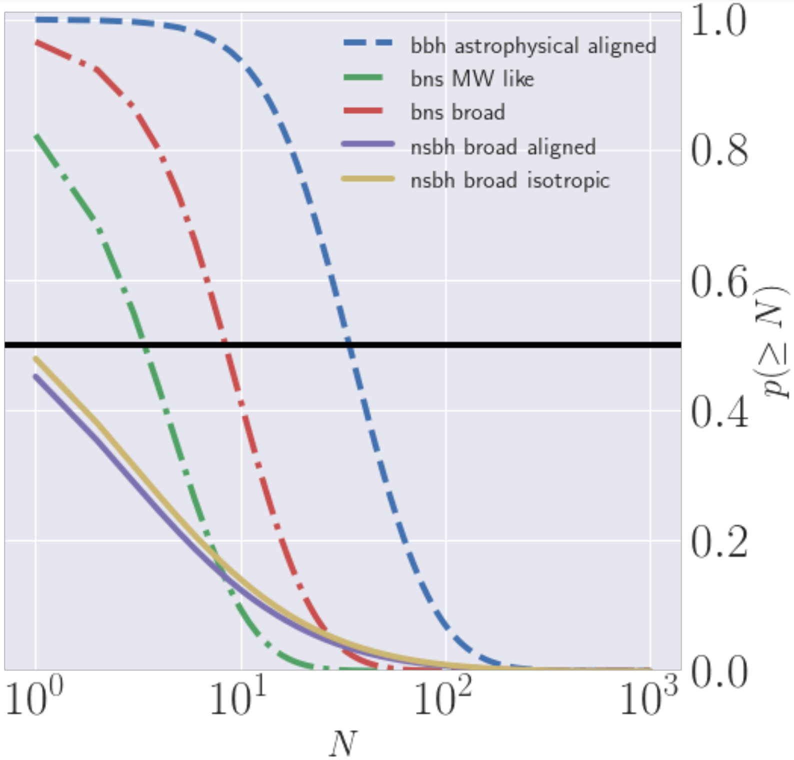
The current interpretation

Video by Gottlieb, Nakar, Harrison



Ready for O3?

DCC: LIGO-G1800370

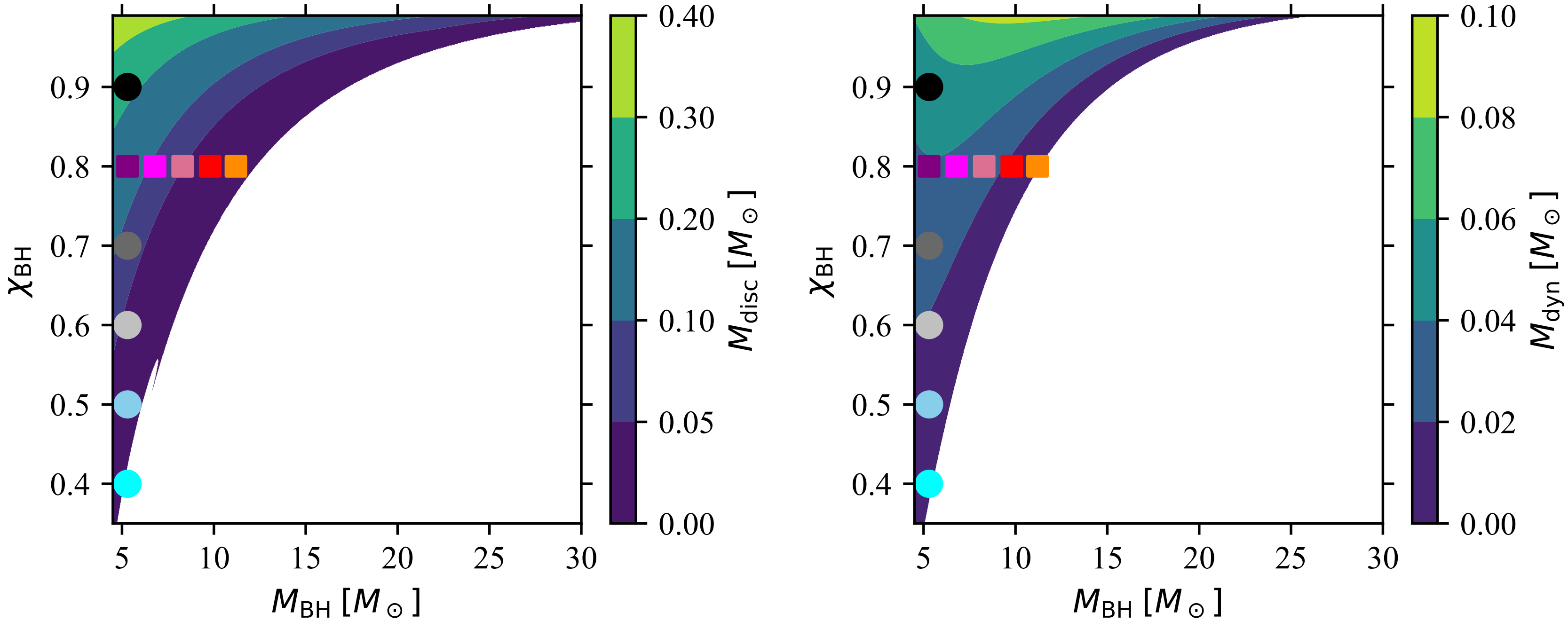


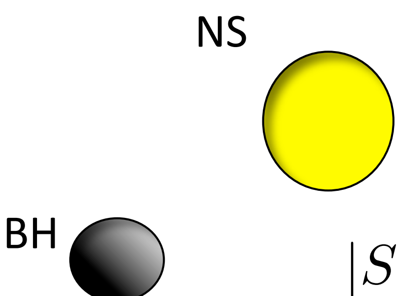
source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	35^{+78}_{-26}
BNS / bns_mw_like	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	4.9×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

The unexplored

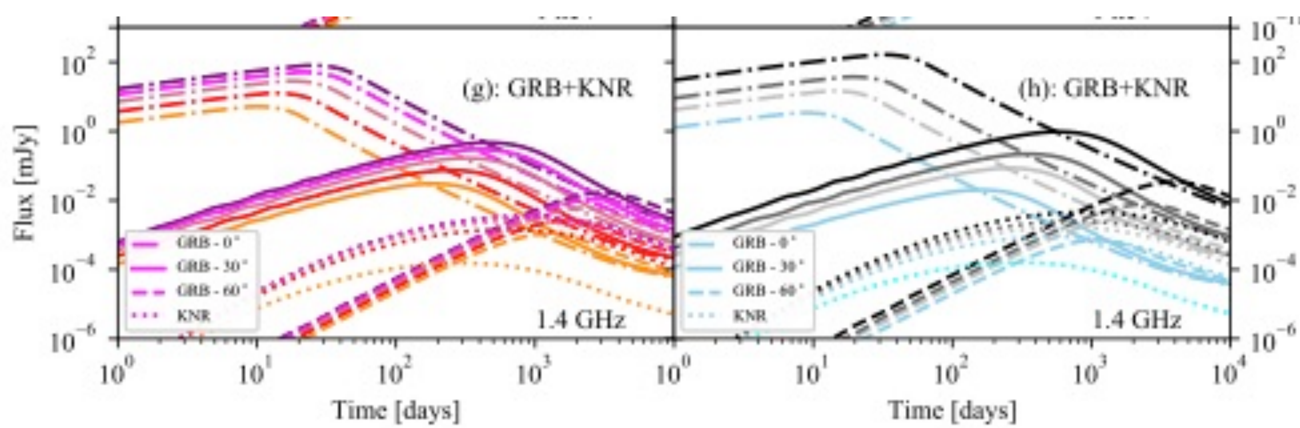
Barbieri C., et al., 2019, arxiV:1903.04543

http://tullio.to.infn.it/~prometeo/#main





$$\chi = \frac{|S|c}{GM^2}$$



Conclusions: the "tale" of three discoveries

- BNS merger are progenitors of short GRBs.

- GW+EM powerful to unveil progenitors and outflow structure, fundamental physics tests, cosmological inference etc.

- GW/GRB170817: did a relativistic narrow jet or a cocoon produce the (non-thermal) long lived afterglow emission?
  - Multi-wavelength modeling of L(t) (10-240 days) cannot tell apart the two scenarios.
  - High resolution radio observations:
    - [Polarization (<12% but geometry or B?)]
    - Imaging:
      - Size < 2.5 mas (95%) @ 204.7 days (EVN global VLBI)
      - Proper motion 2.7 mas @ 75-230 days (HAS)

⇒ Relativistic structured jet

- At least 10% of BNS might produce a jet that breaks out of the polar ejecta.
- Jet structure due to interaction with merger ejecta.
- Structured jets = universal properties (differences mostly due to viewing angle + relativistic dependent effects)