MWSKY-II *NCRA-TIFR, Pune* *18 Mar 2019*

GMRT view of the first binary NS merger GW170817

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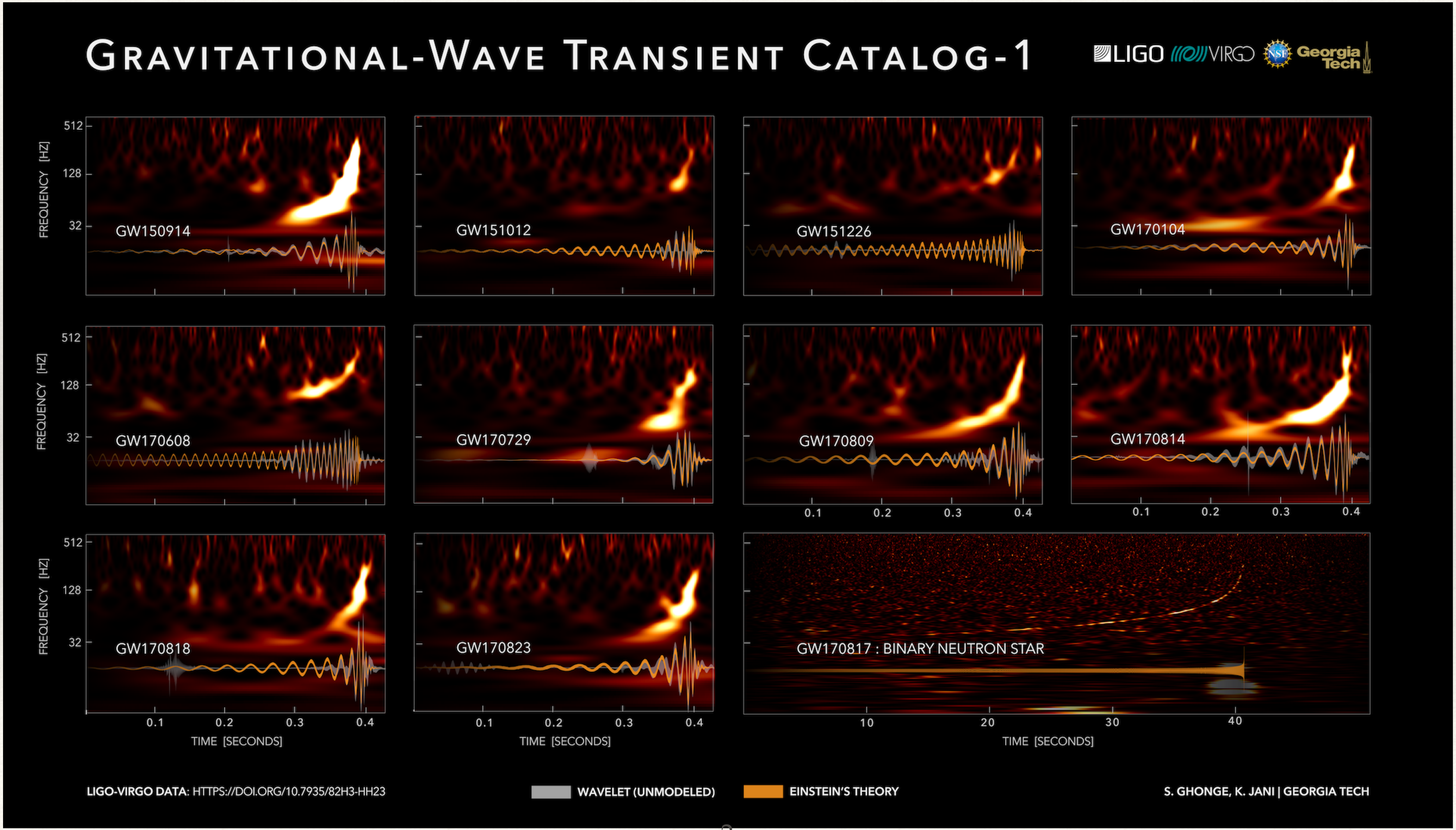
In collaboration with

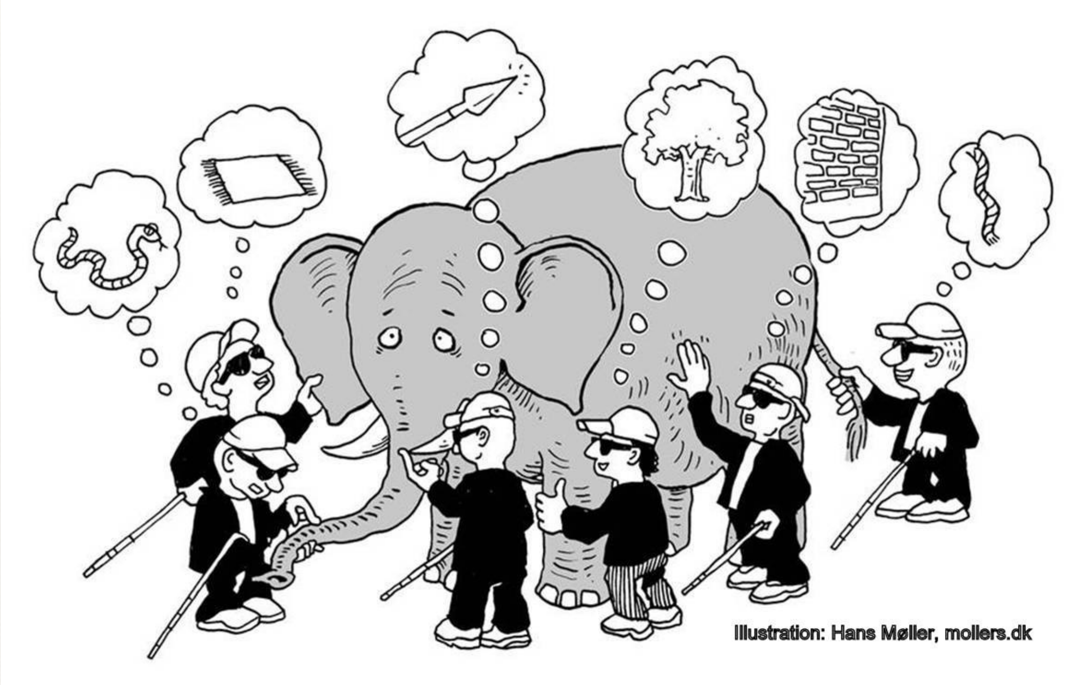
Steve Schulze, C H Ishwara-Chandra, Sam Kim, Kuntal Misra, Johannes Buchner, Nial Tanvir, Paul T O'brien

A new window to the universe



Multi-messenger astronomy

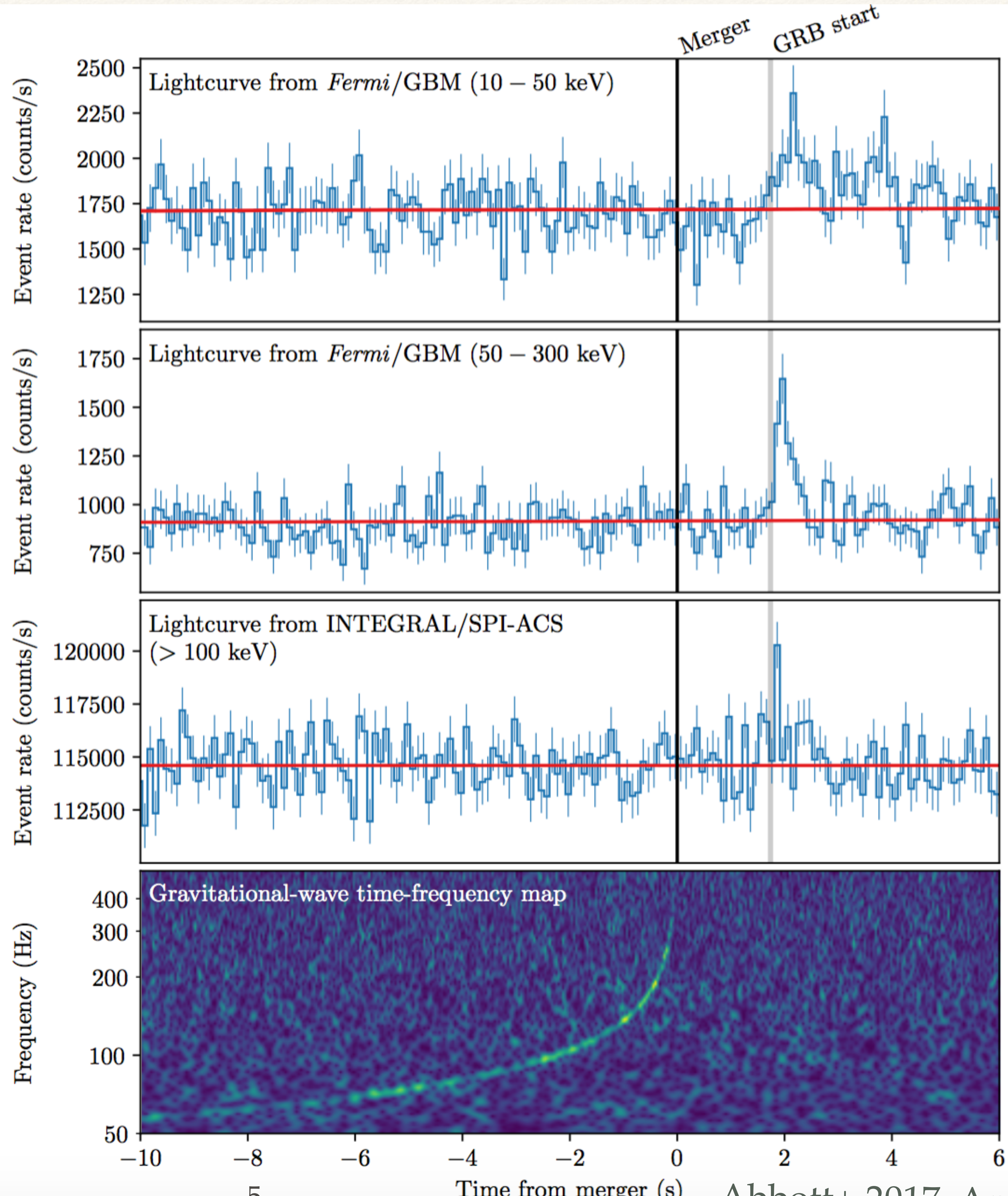
- Physics from a complementary picture.
- New insights on
  - stellar evolution
  - jet physics
  - NS equation of state
  - origin of elements
  - ? …



Outline

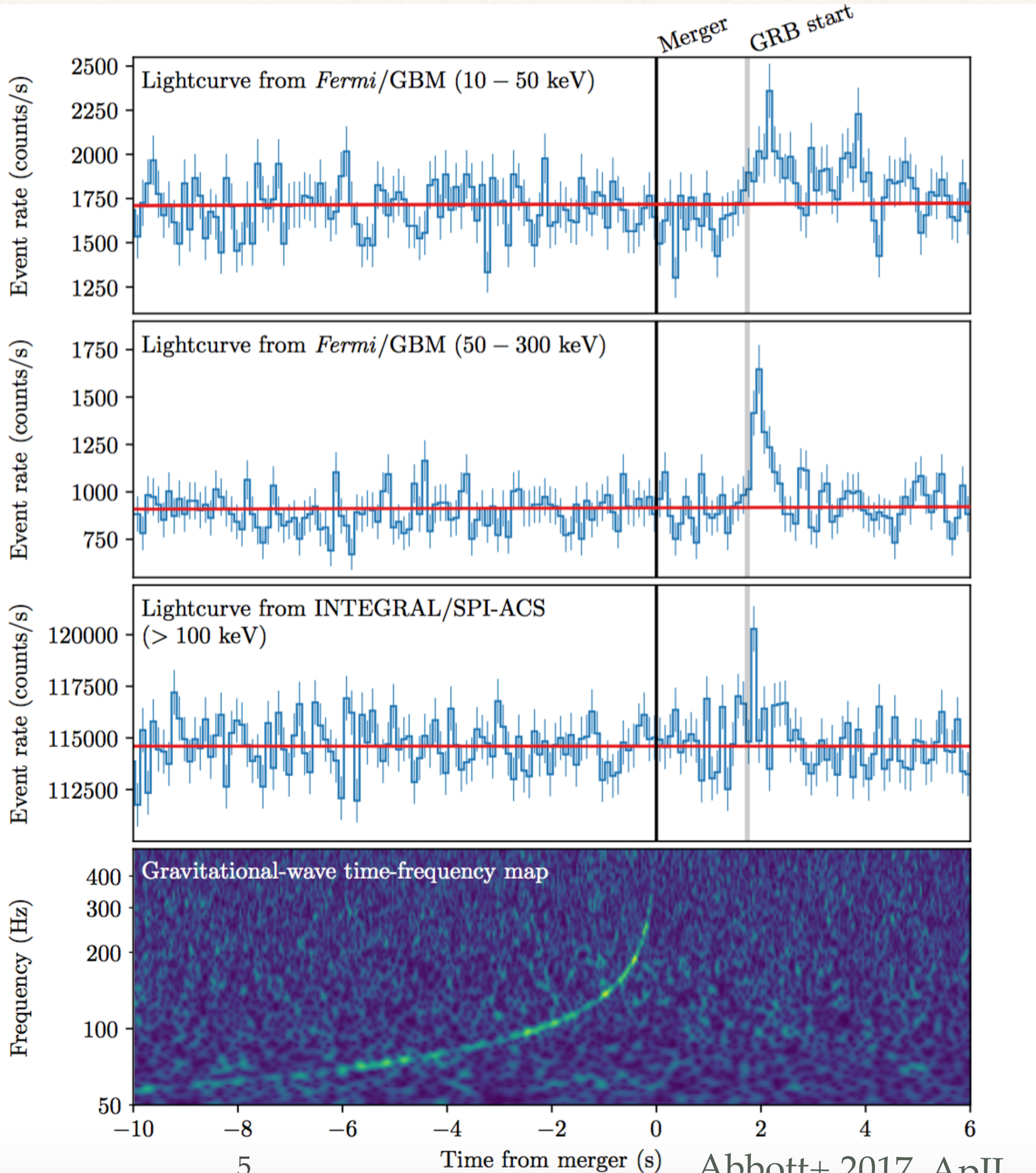
- GW170817 : The first binary NS merger.
- Electromagnetic follow-up, particularly with the uGMRT.
- What do we learn?
- Future of GW-EM multi-messenger astronomy (specifically in radio wavelengths).

GW 170817



Abbott+ 2017, ApJL

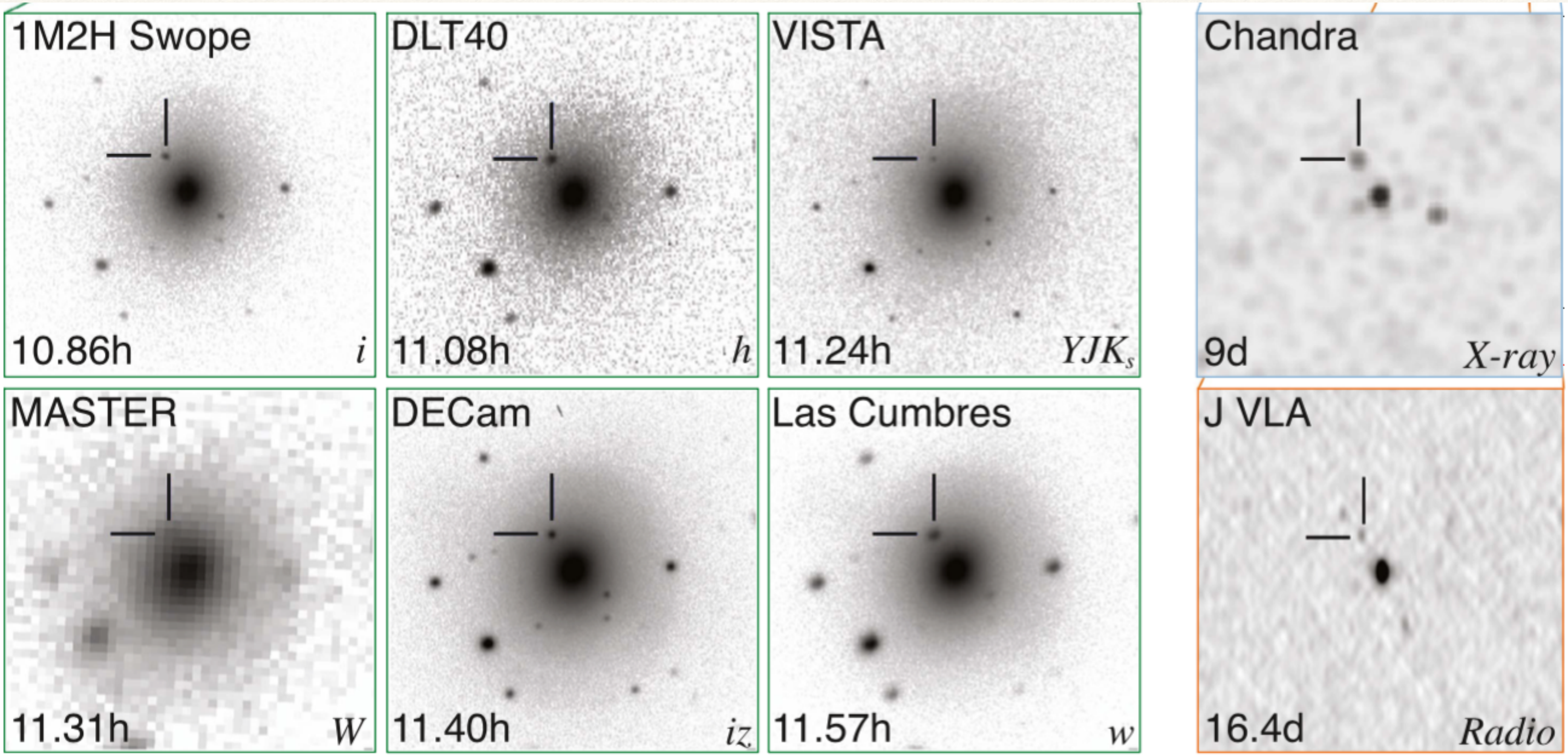
GW 170817



The 1.7s delay can be explained within several models

Abbott+ 2017, ApJL

Multi-wavelength detections



The MMA paper, including **RL**, ApJL, 2017.

Multi-wavelength detections

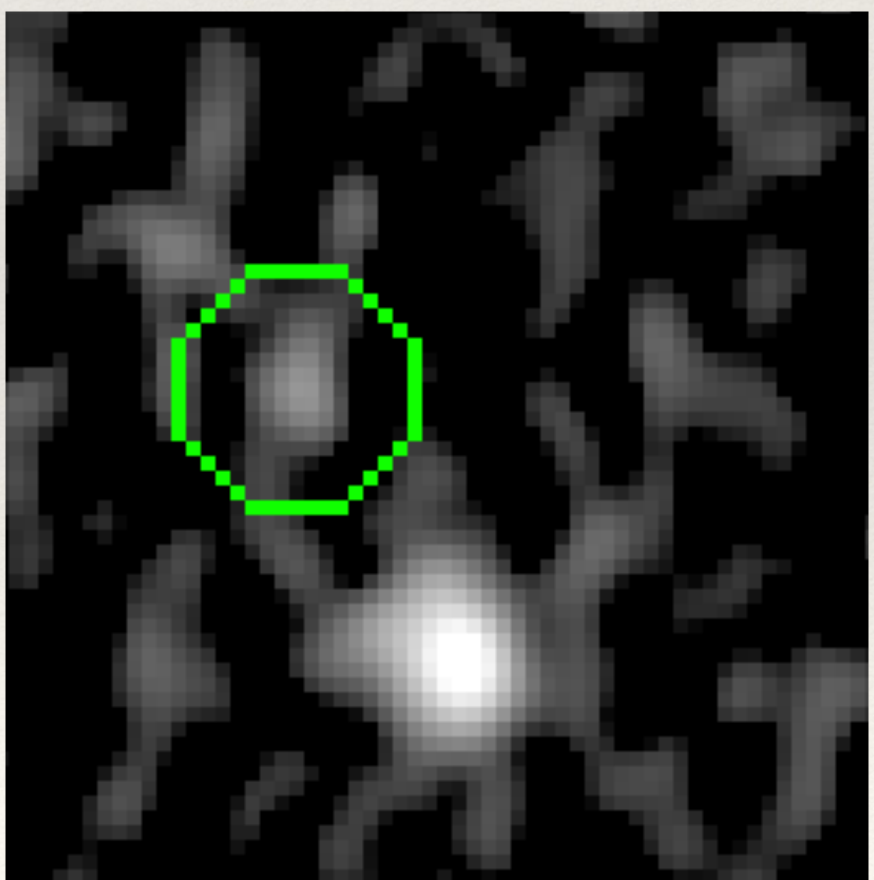
Multi-wavelength detections

Radio band played the most important role in understanding the non-thermal emission, and hence the jet emanated from the merger

Hallinan et al., 2017; Kim, Schulze, **RL** et al., 2017; Margutti et al., 2017; **RL** et al., 2018; Mooley et al., 2018.

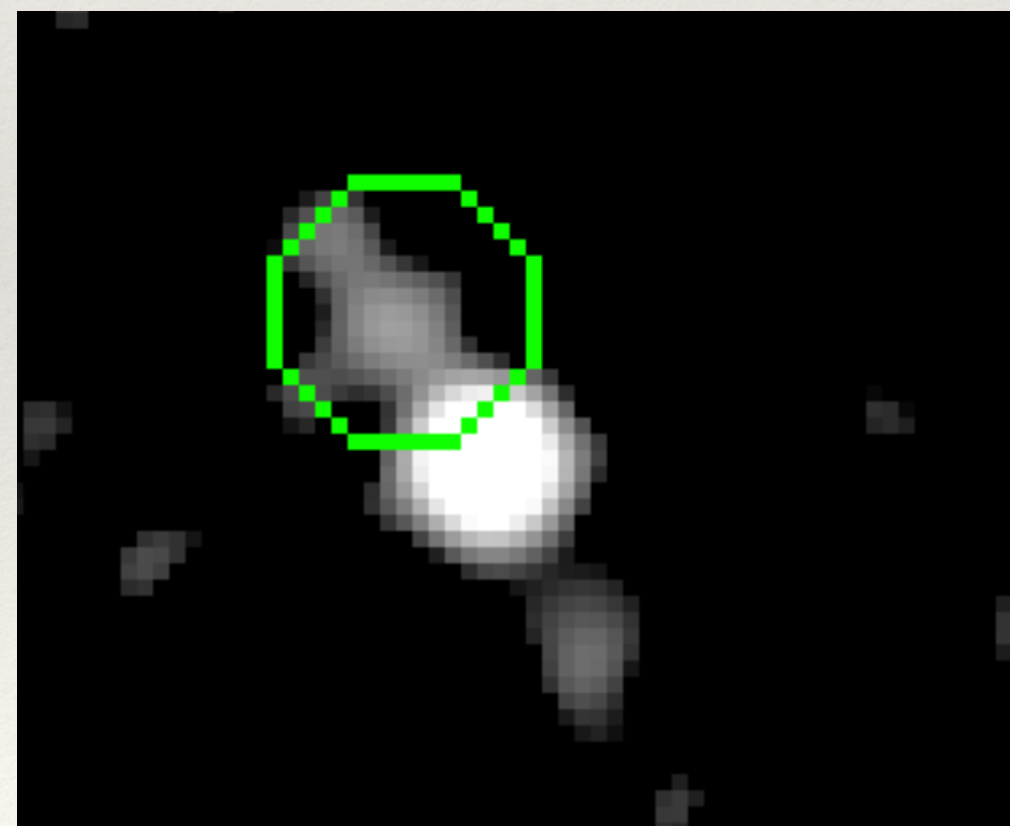
uGMRT detection

- ALMA (undetected) and GMRT campaign from our collaboration
- GMRT observations began ~7 days post the GW event (narrow band correlator). First detection at 60 days with uGMRT.
- Campaign went on for 550 days (February 2019).



[R] 28 Nov
(band-4)

[L] 02 Dec
(band-5)



Kim, Schulze, **RL** et al., ApJL, 2017; **RL** et al., ApJ, 2018.

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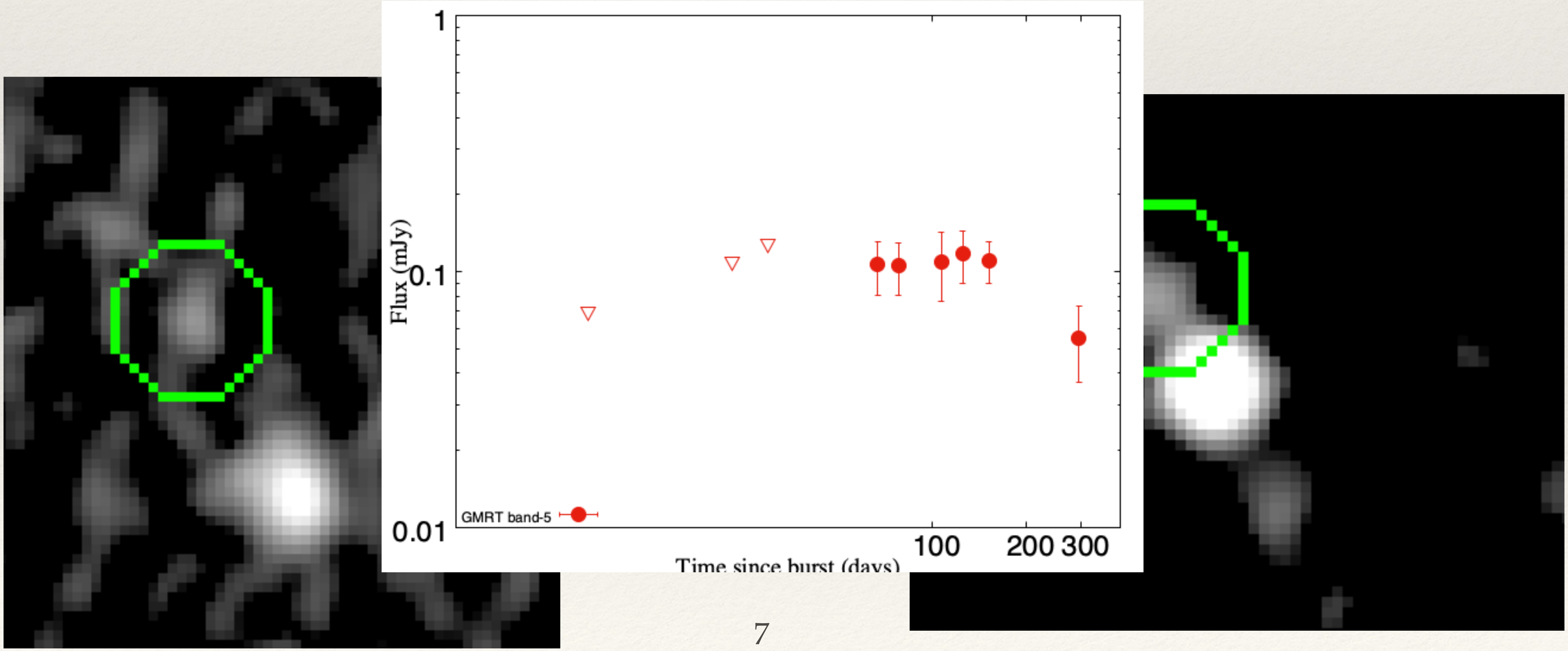

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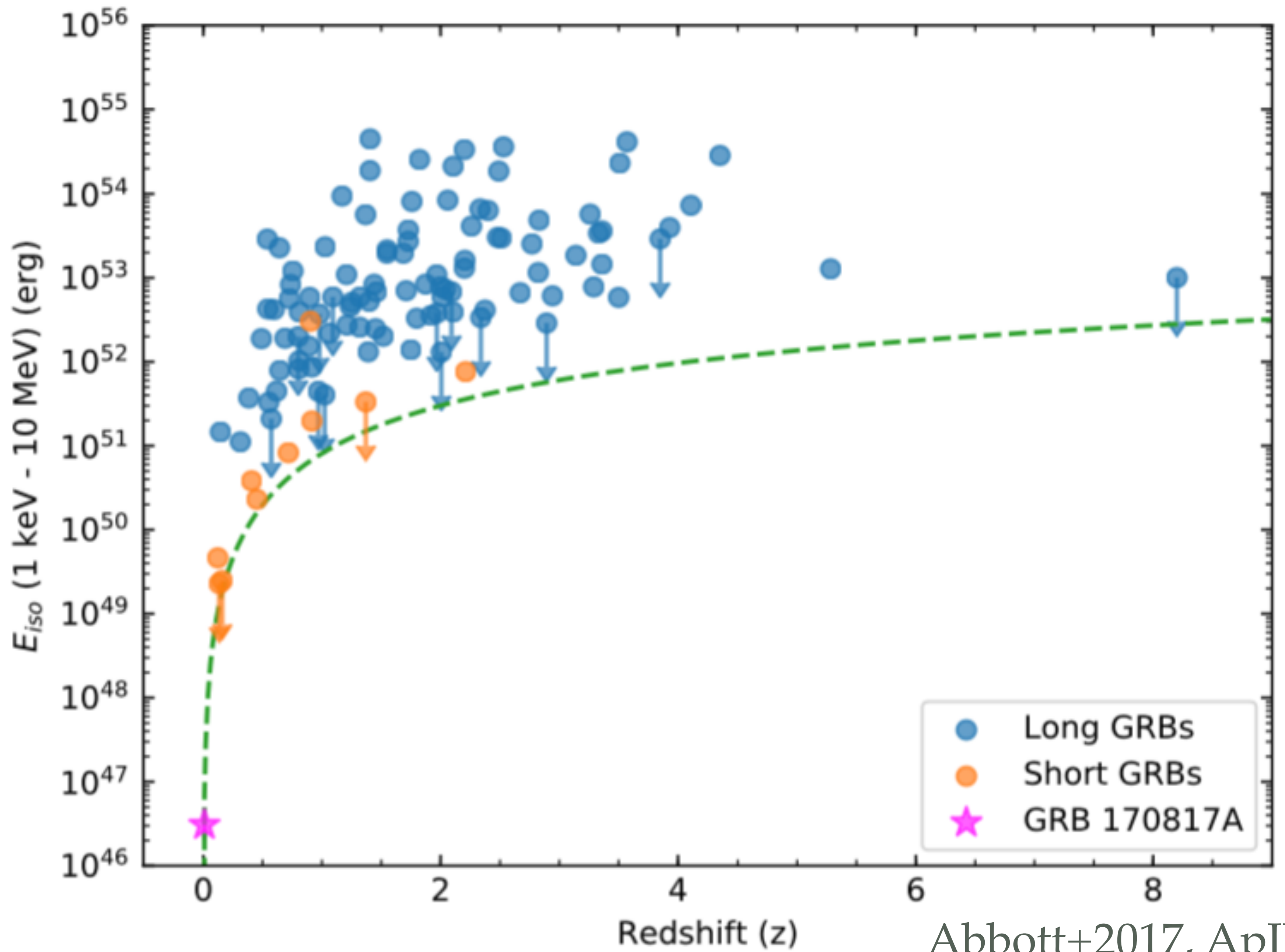
Non-thermal emission: the jigsaw puzzle



Abbott+2017, ApJL

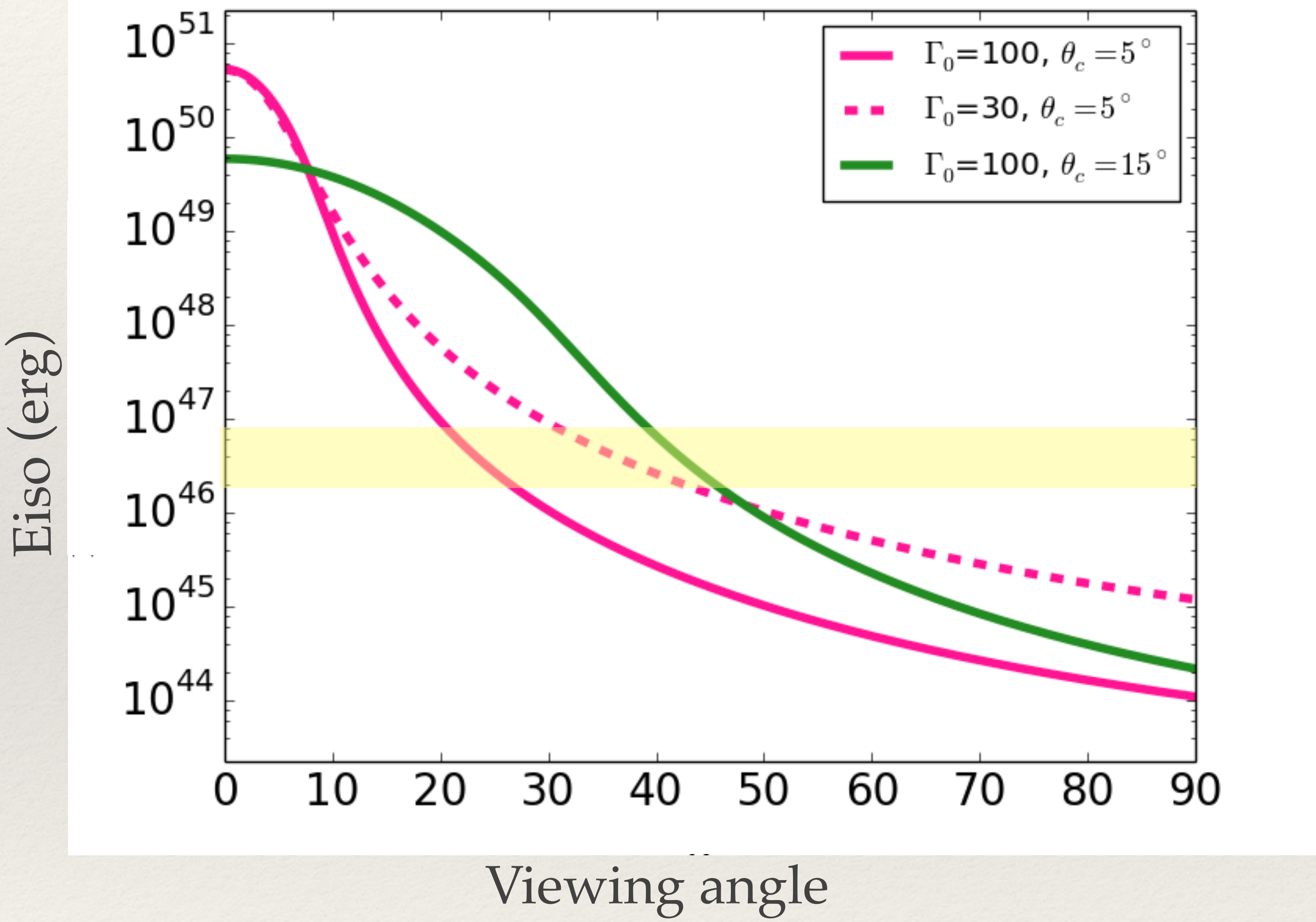
$E_{iso} = 4\,\pi\, d_L^2\;\; F$

time integrated energy flux in γ-rays

GRB 170817A : An under-luminous Gamma Ray-Burst.

Relativity & perceptions : An off-axis GRB

RL et al., ApJ, 2018., Mohan, Saleem, & **RL** 2019, in preparation.



- For a jet of total kinetic energy 10^{48} erg, at the distance of GW170817.
- With an angular distribution of energy and Γ as inferred for GRB170817A from afterglow studies.

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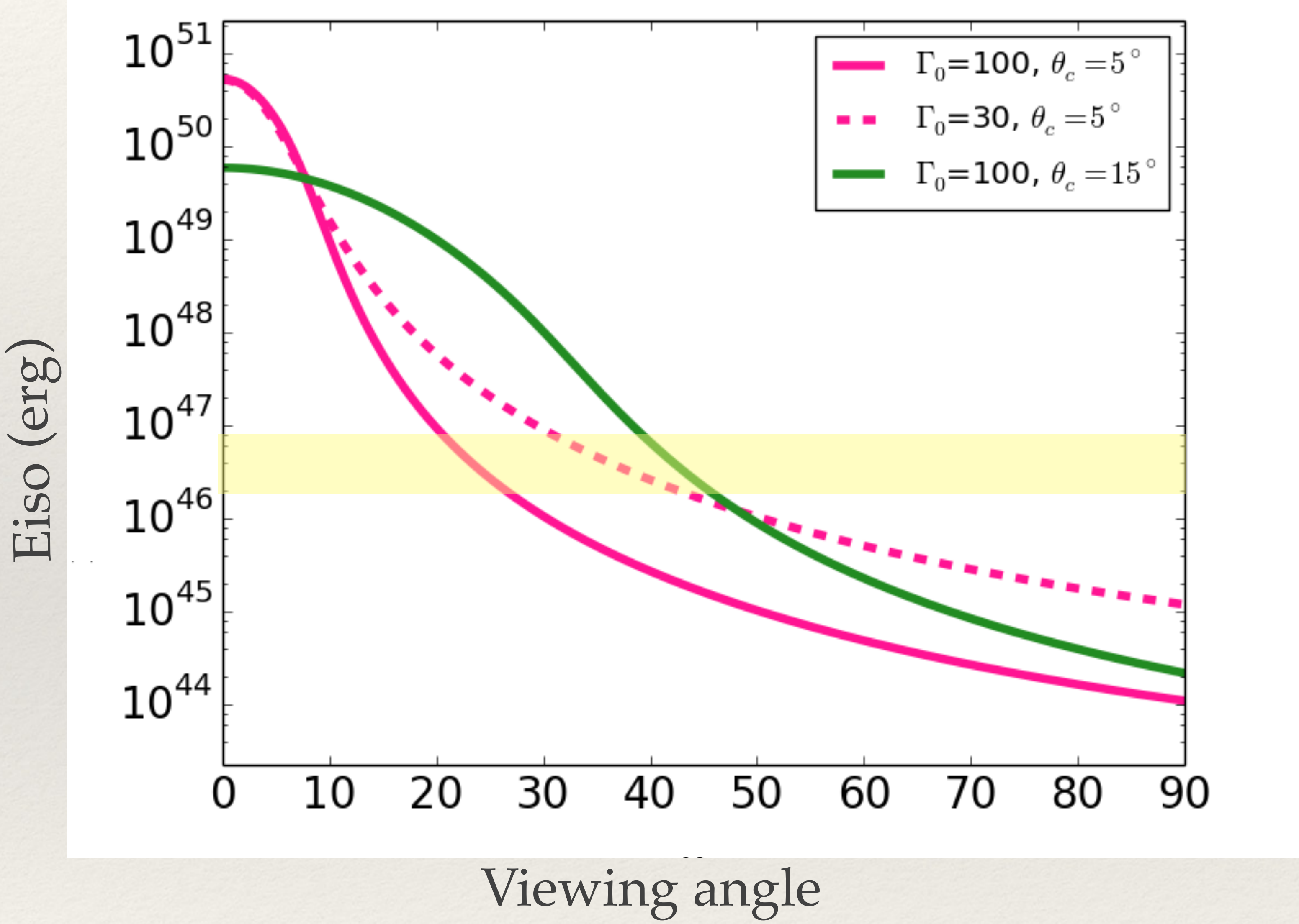
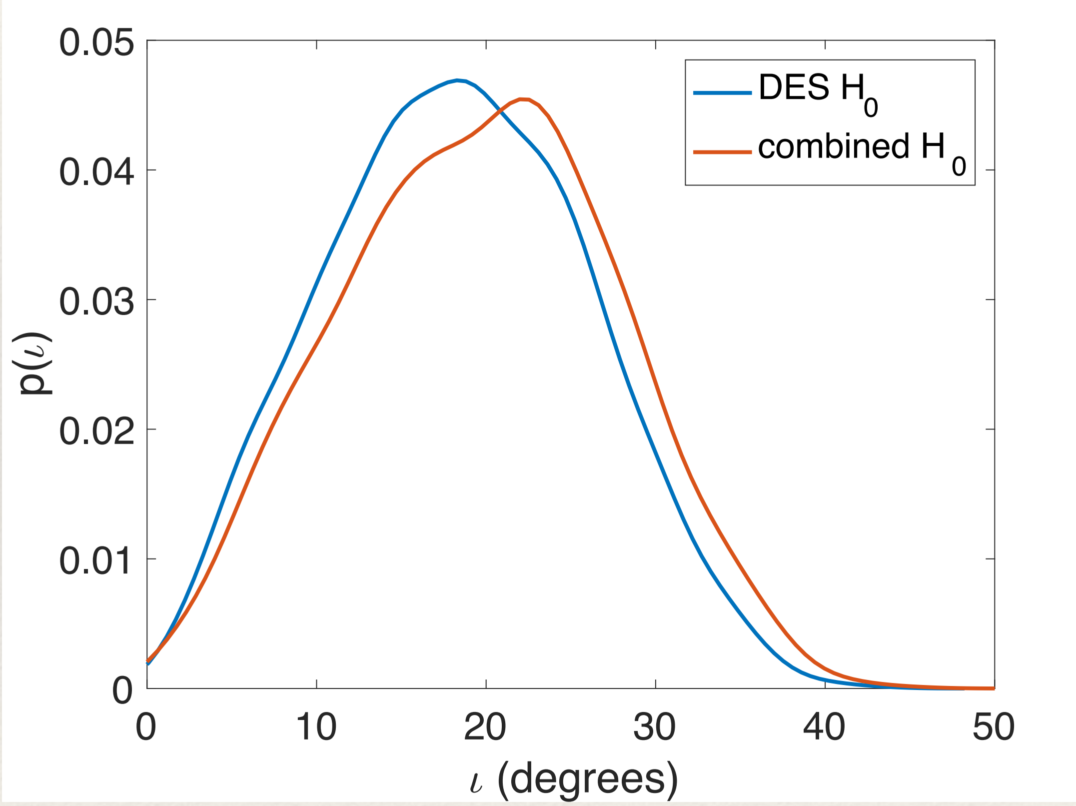


Posterior of viewing angle from GW observations with EM constraints on 3D position.



Mandel, ApJL, 2018.

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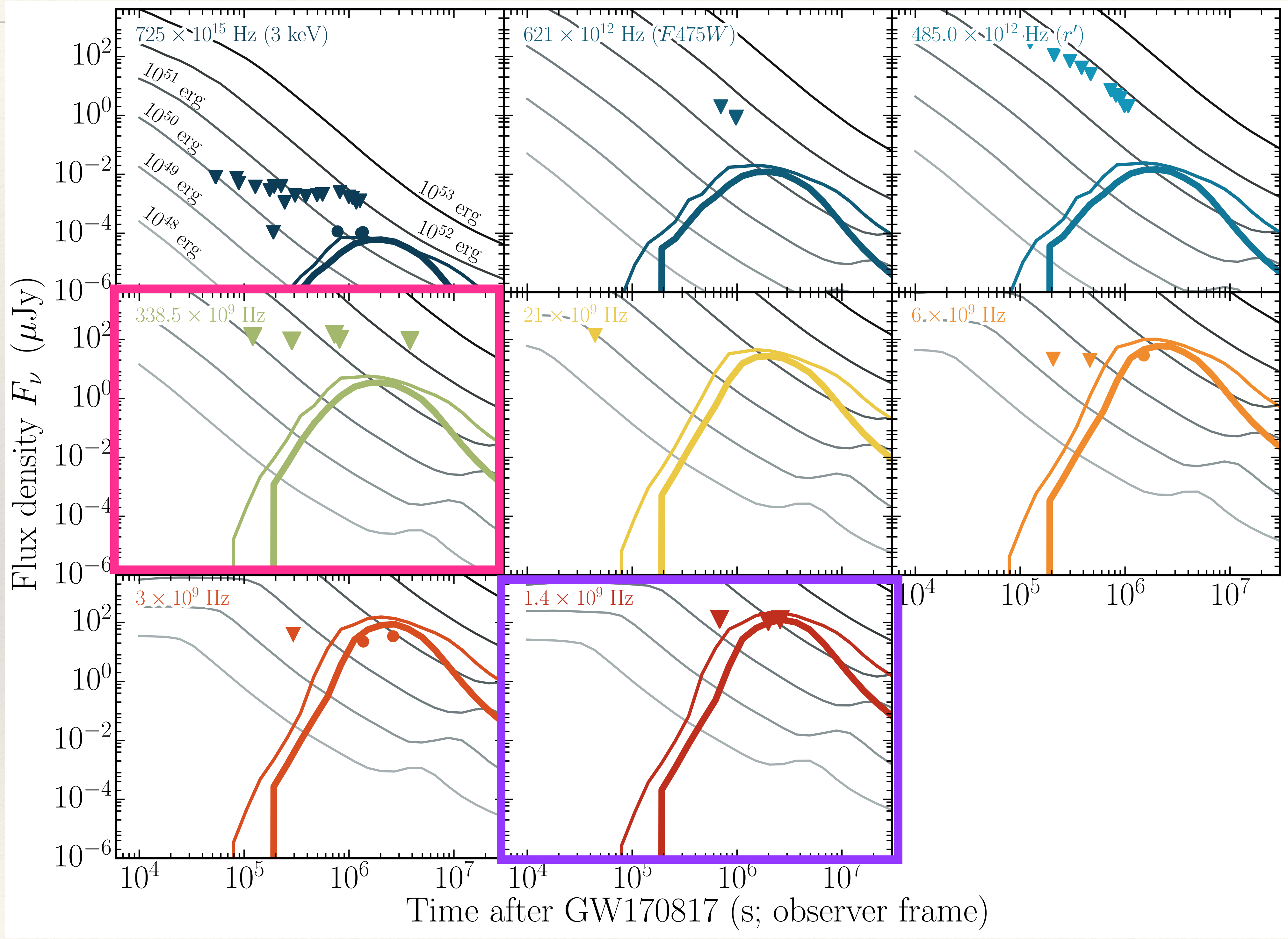
Non-thermal emission: the jigsaw puzzle (contd.)



Kim, Schulze, **RL** et al., ApJL, 2017

An unusual radio/X-ray afterglow

Non-thermal emission: the jigsaw puzzle (contd.)

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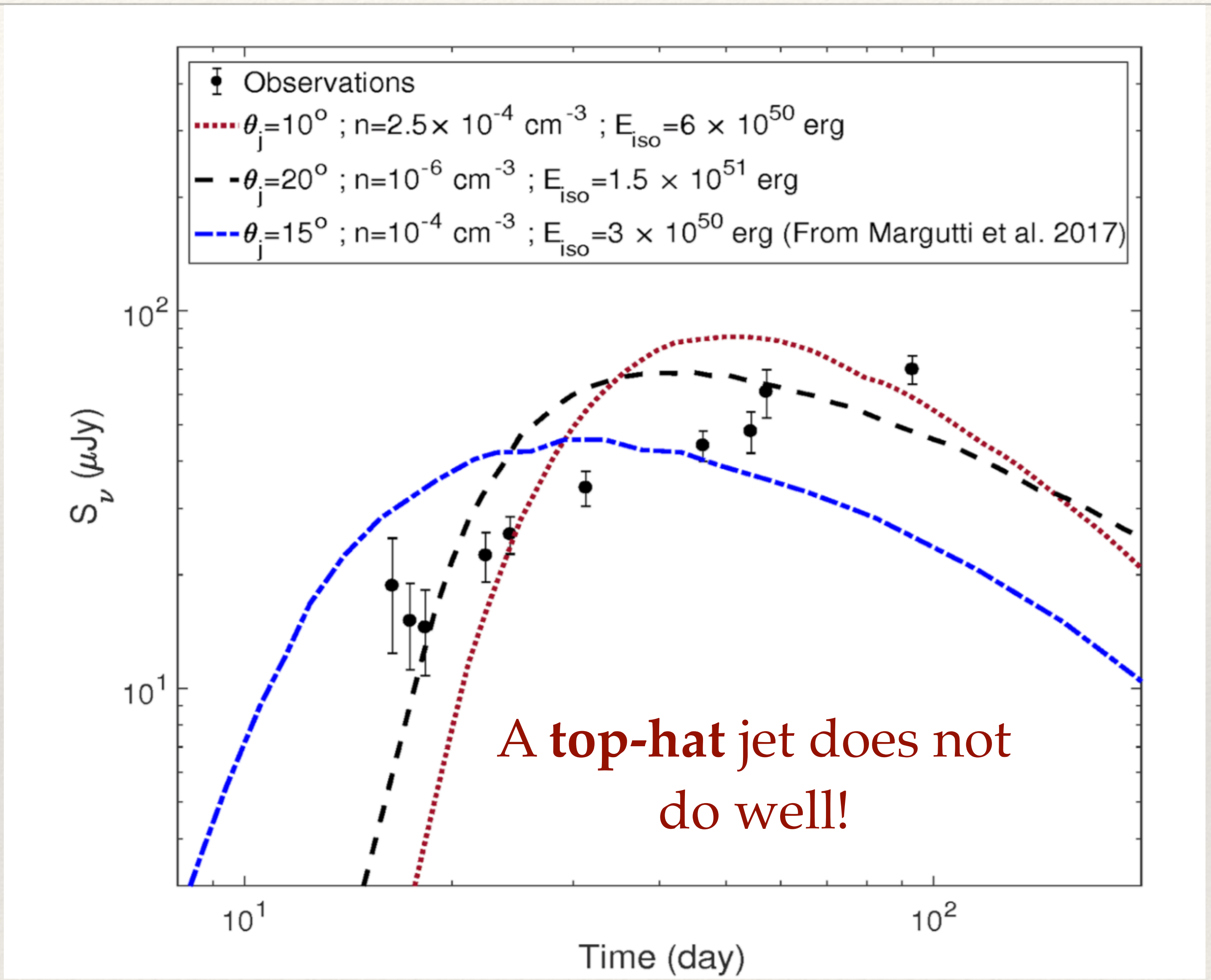


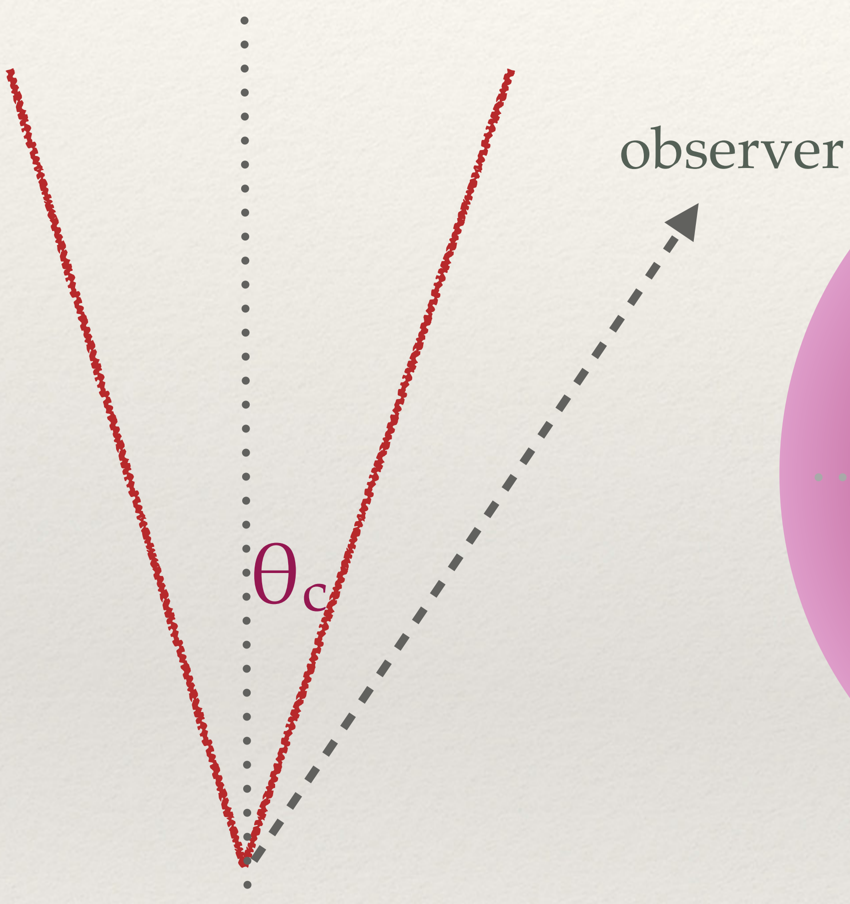
Mooley et al 2017;
Also Margutti+ 2017; Troja+2017

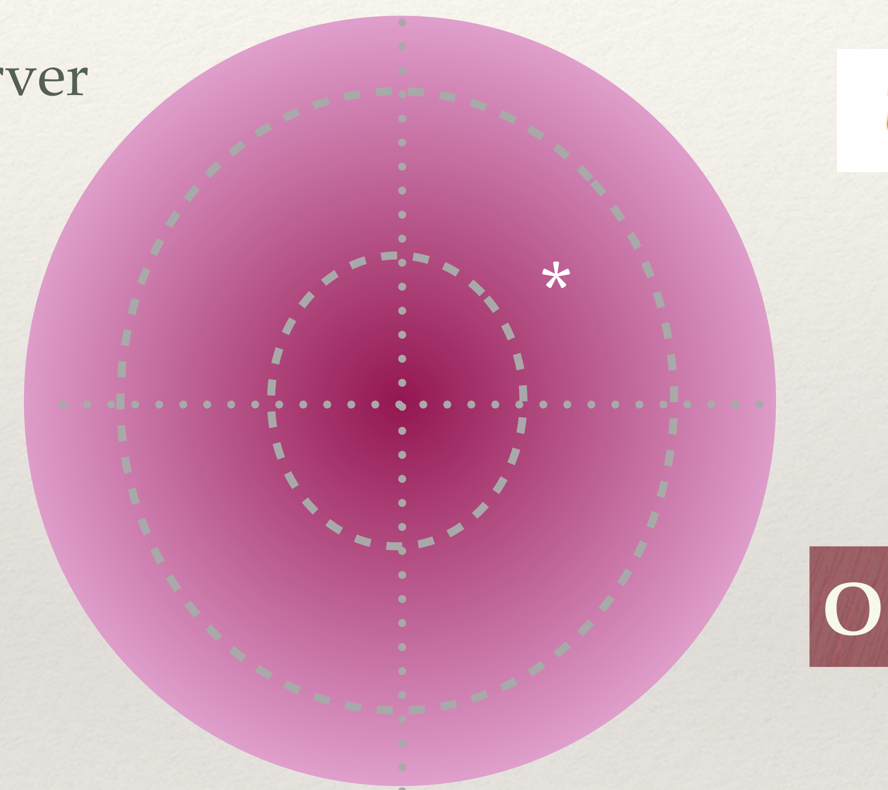
An unusual radio/X-ray afterglow

Laterally structured jet viewed far off its axis

$$E = E_c \exp\left(\frac{-\theta^2}{\theta_c^2}\right),$$

$$\Gamma_0\beta_0 = \Gamma_c\beta_c \exp\left(\frac{-\theta^2}{2\theta_c^2}\right),$$





$$t_{\rm obs} = \frac{r}{\beta(r)c}\left[1 - \beta(r)\cos\alpha_{i,k}\right]$$

$$f_{\rm obs} = a^3 f_{\rm on}(r)$$

$$a = \frac{1-\beta(r)}{1-\beta(r)\cos\alpha_{i,k}}$$

We use the recipe of Lamb & Kobayashi 2017 to estimate the flux

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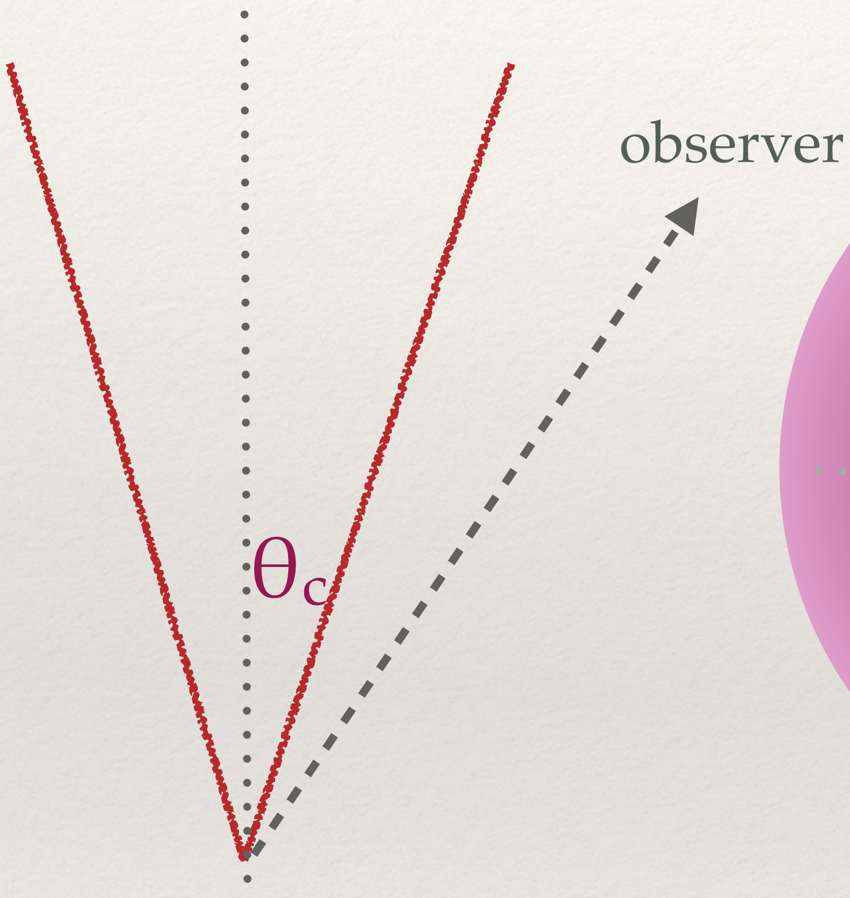

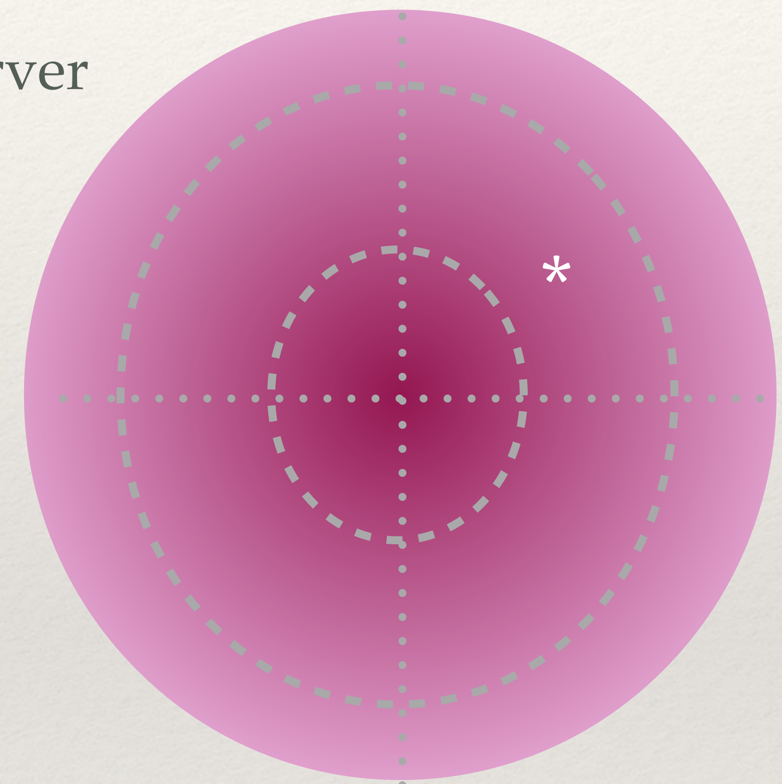

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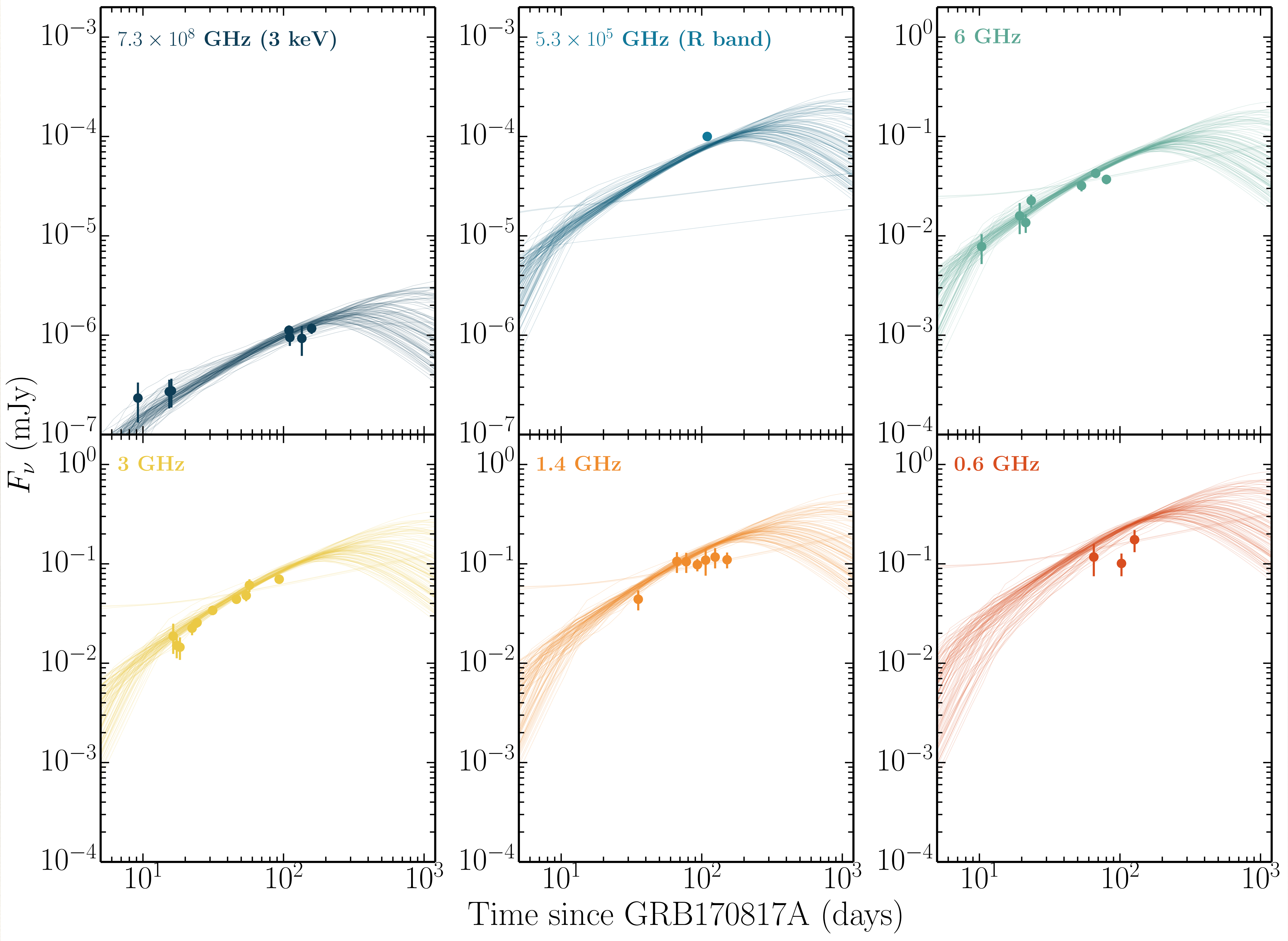
Hydrodynamical simulations show that the jet successfully emerges out of the tidal debri at about 10^{11}cm or so (Xie et al 2018) and develops a structure as it does (Kathirgamaraju et al, 2018). Also Gill+2019.



RL, Schulze, Ishwara-Chandra, Misra et al., ApJ, 2018

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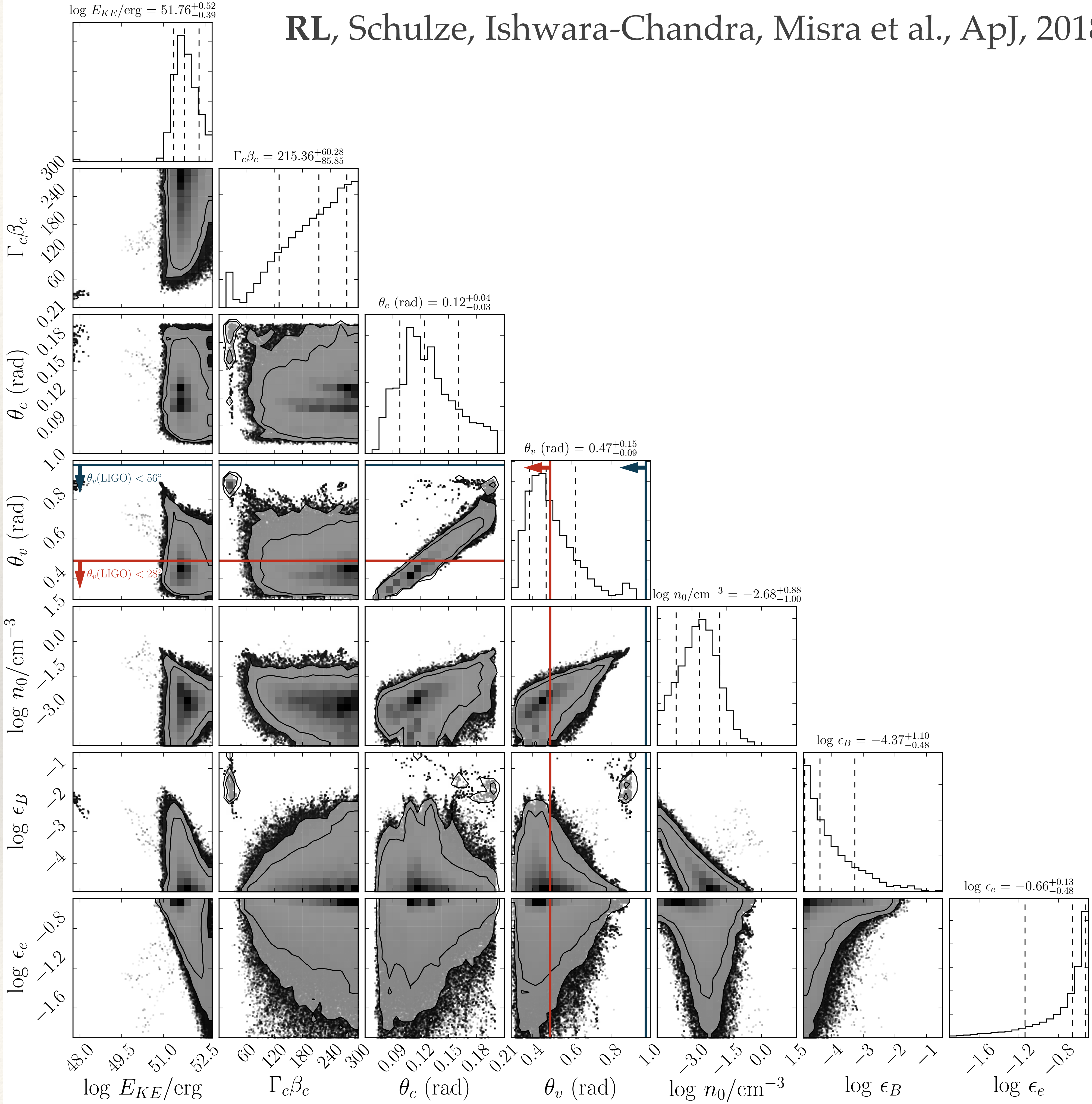
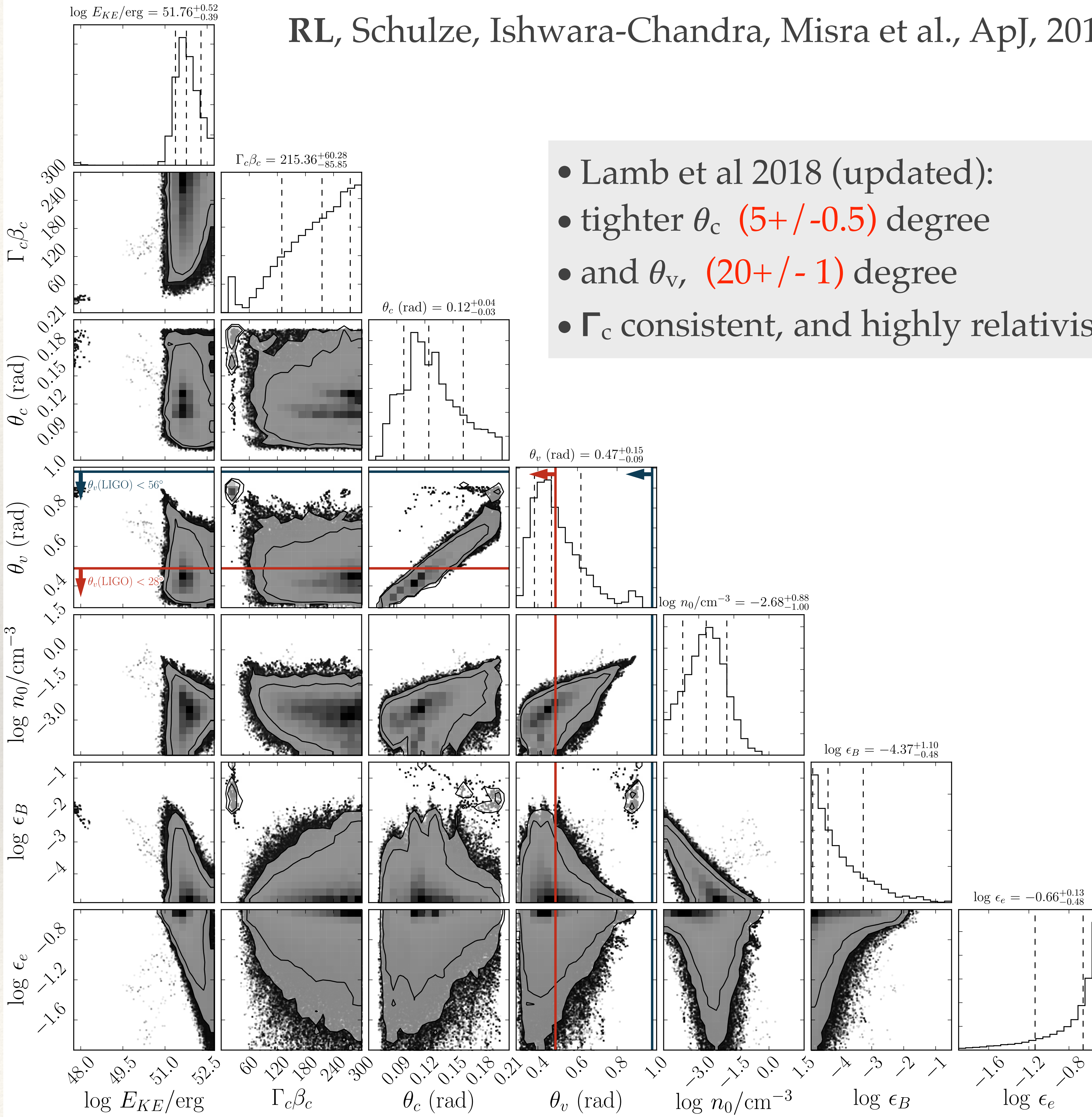
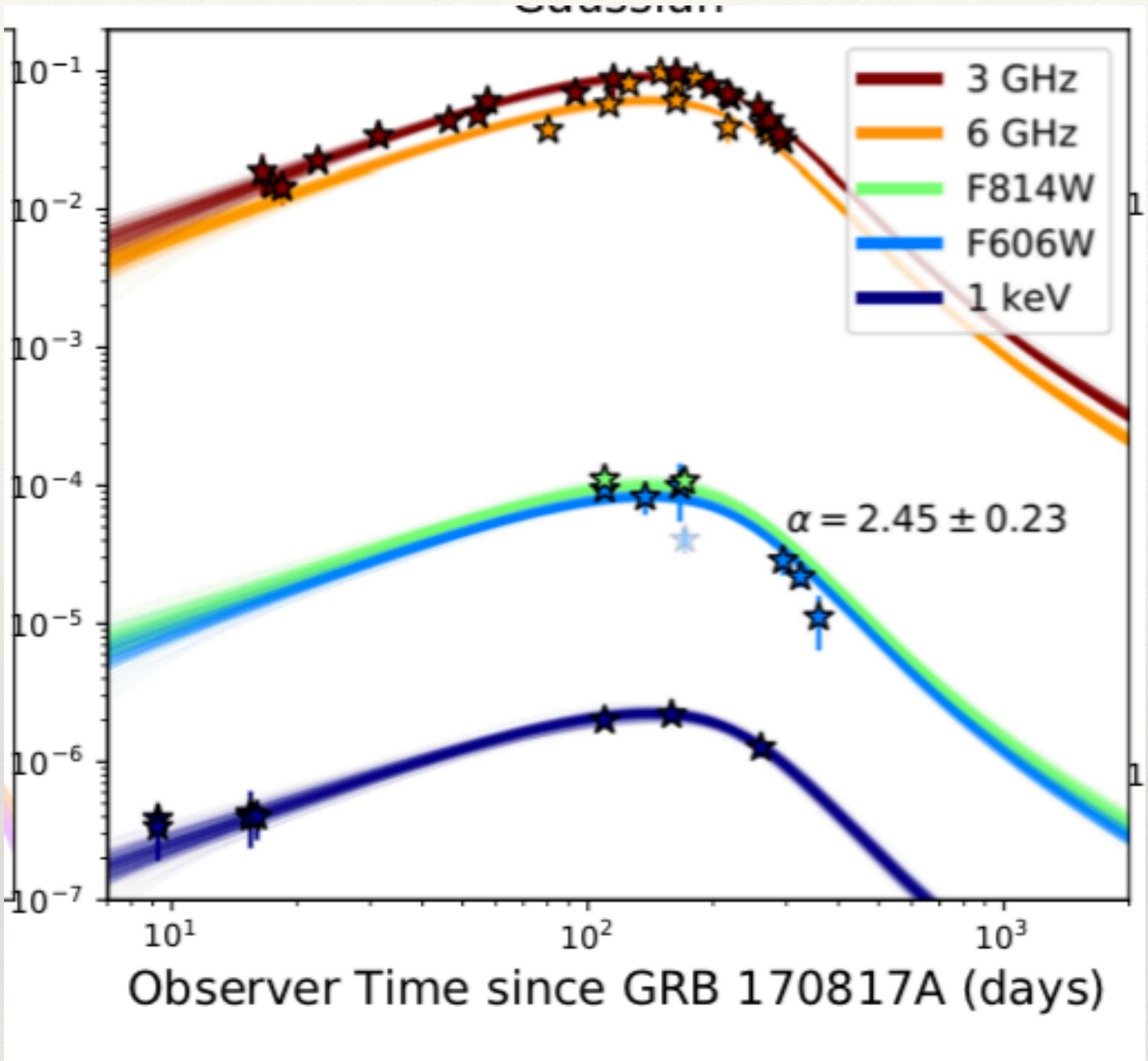


RL, Schulze, Ishwara-Chandra, Misra et al., ApJ, 2018

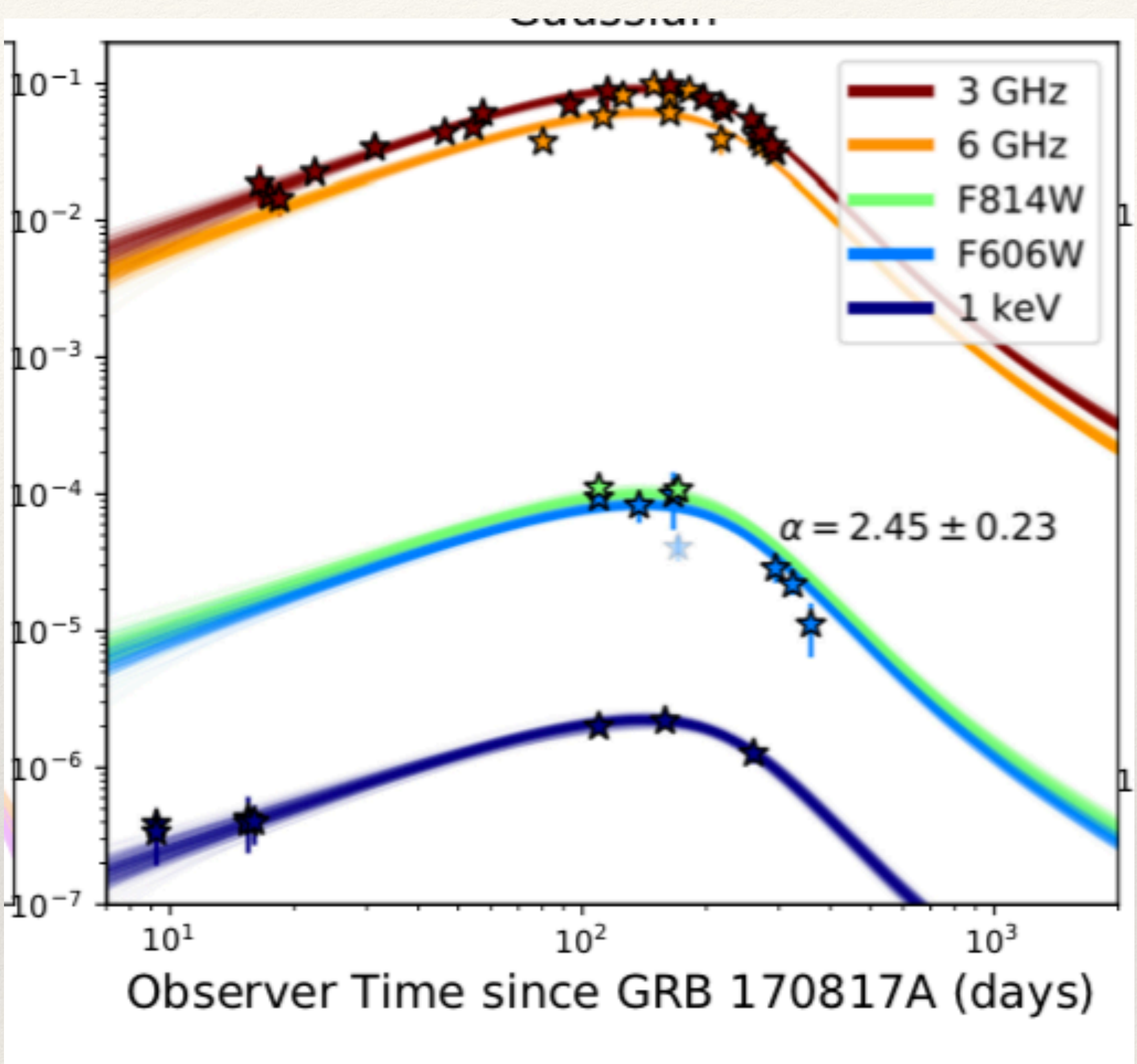
- Lamb et al 2018 (updated):
- tighter θ_c (5+/-0.5) degree
- and θ_v, (20+/- 1) degree
- Γ_c consistent, and highly relativistic





Lamb+ ApJL, 2018

- Lamb et al 2018, after including most recent data (upto 1 yr since merger) with a laterally expanding jet model.



Lamb+ ApJL 2018

They find that a two component (jet + non-relativistic envelope) does not give as good a fit as a structured laterally expanding jet

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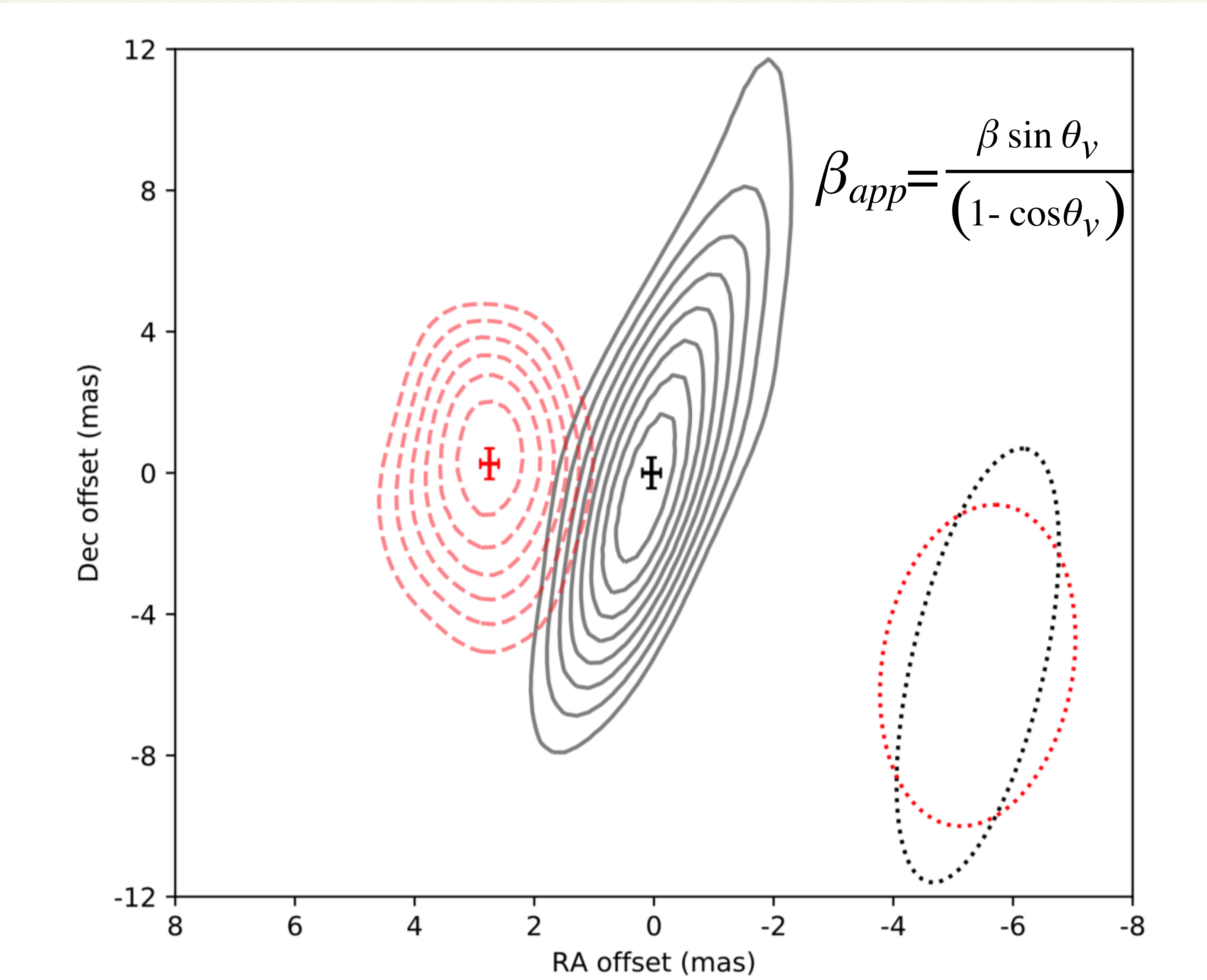
See PCA talk for details

Superluminal motion in GRB170817A



- VLBI measurement of flux centroid of radio AG
- Between 75 (black) and 230 (red) days.
- Proper motion ⇒ apparent velocity in the plane of the sky = (4.1 +/-0.5) c.
- Γ ~ 4 at this epoch.
- Unresolved source ⇒ jet size at peak $< 5°$

Mooley et al, Nautre, 2018
Also Ghirlanda et al, 2018.

pre-Conclusion : GW170817

- A typical short GRB jet, relativistic, viewed off-axis can explain all observations of the non-thermal (γ-ray, X-ray, radio, late-HST, & VLBI) observations of the EM counterpart.
- For the first time with certainty can we say that the jet is viewed off-axis.
- This has brought in the jet wings into view. Lateral structure is being explored.
- An assurance to the most predominant hypothesis of short-GRB origin in compact object mergers.
- A step forward in understanding jets.
- However, fresh surprises should arrive with LIGO-O3 (April 2019 onwards)

What is in store for future?

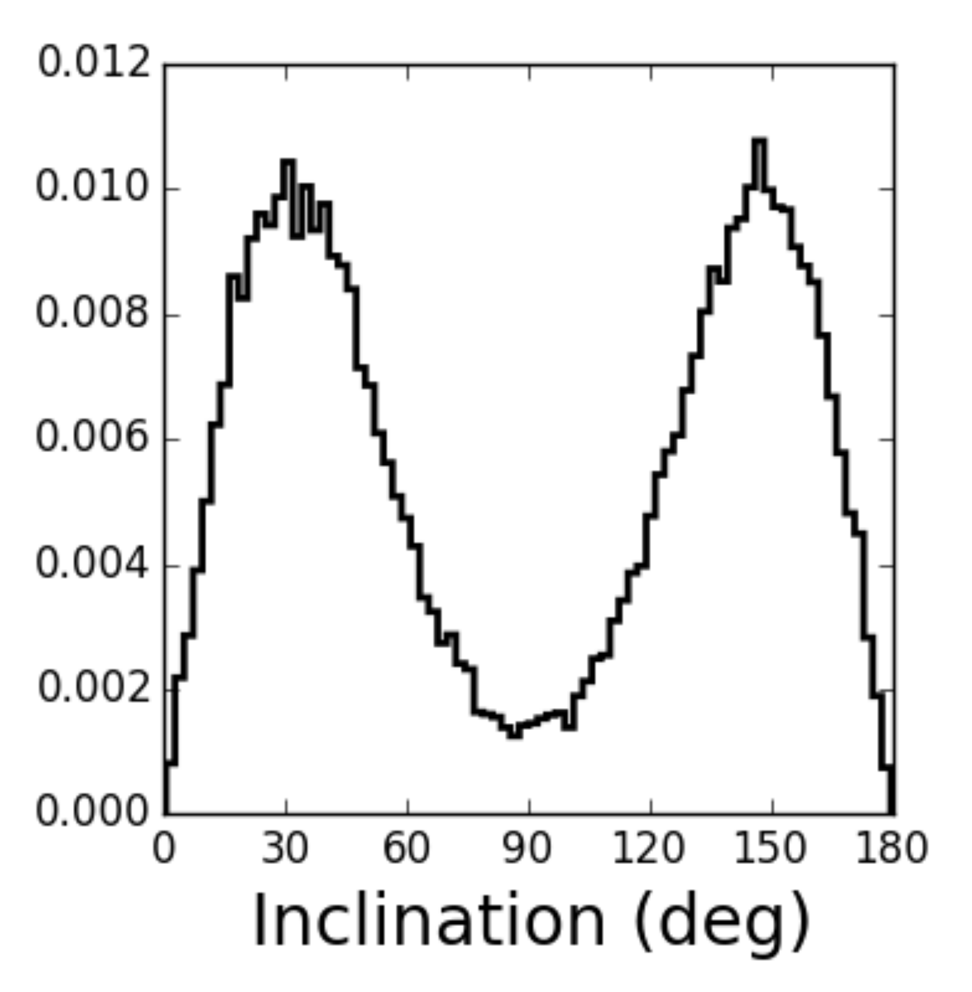
- LIGO to begin O3, longest and most sensitive, in Apr 2019.

Detector	BNS Range (Mpc)
LIGO	120–170
Virgo	65–85
Kagra	8–25

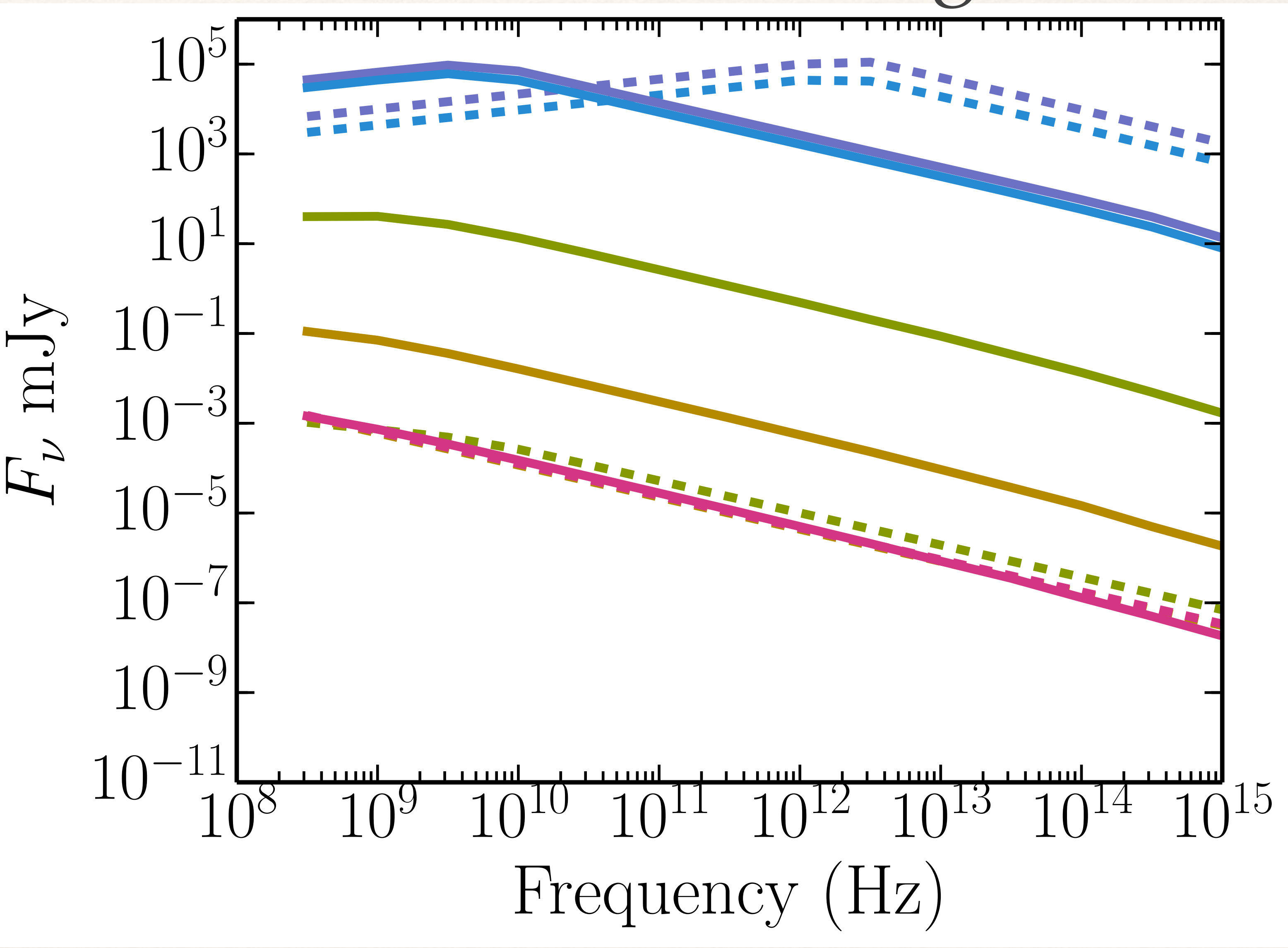
- Radio band will be particularly important to catch non-thermal emission from off-axis jets.
- VLBI observations of nearby BNS (and NS-BH?) mergers

What is in store for future?

θv : 5, 3, 20, 30, 40 degrees



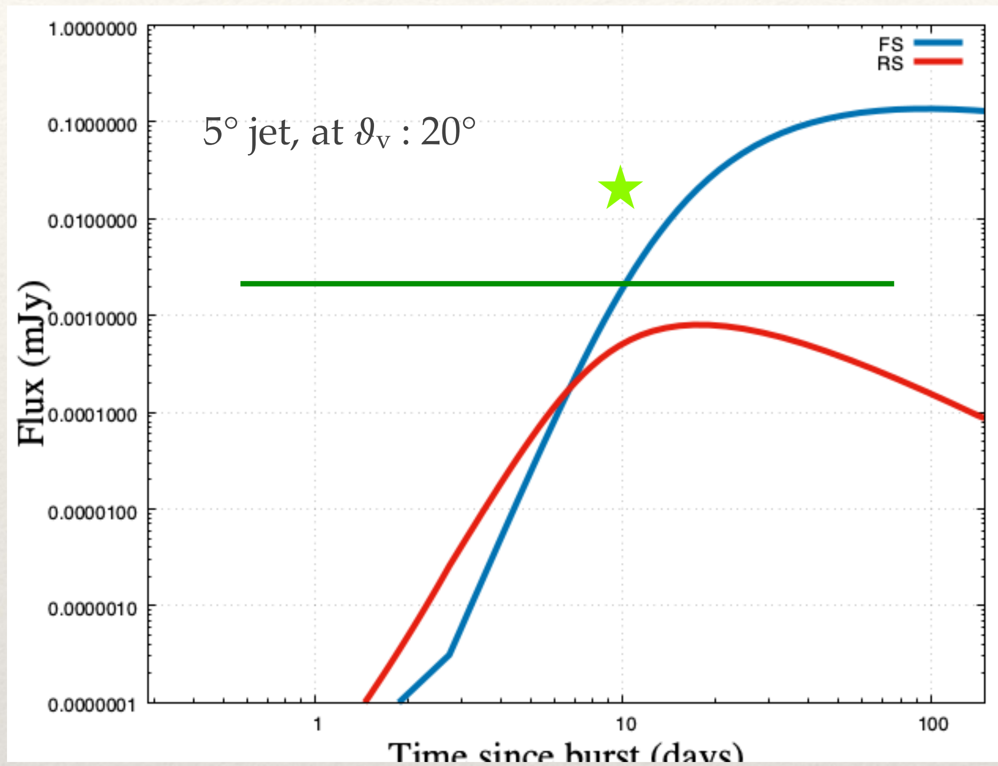
Saleem, **RL**, Misra, Pai, & Arun
MNRAS, 2018, 474, 5340.

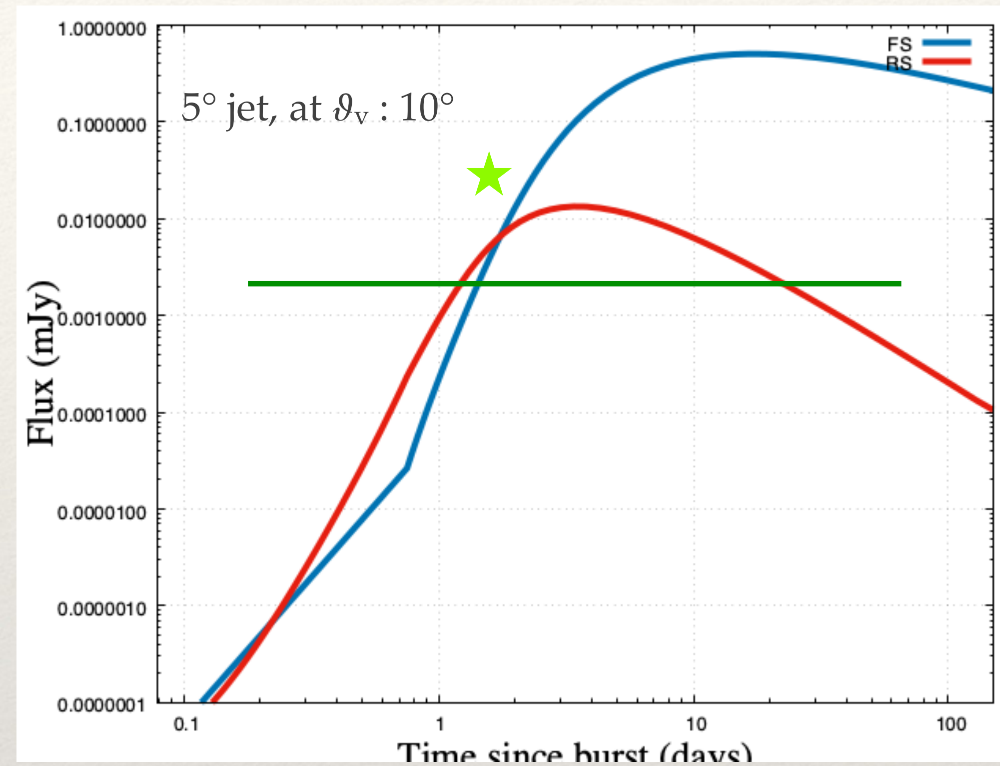


Off-axis synchrotron emission is DEFINITELY more prominent in lower frequencies.

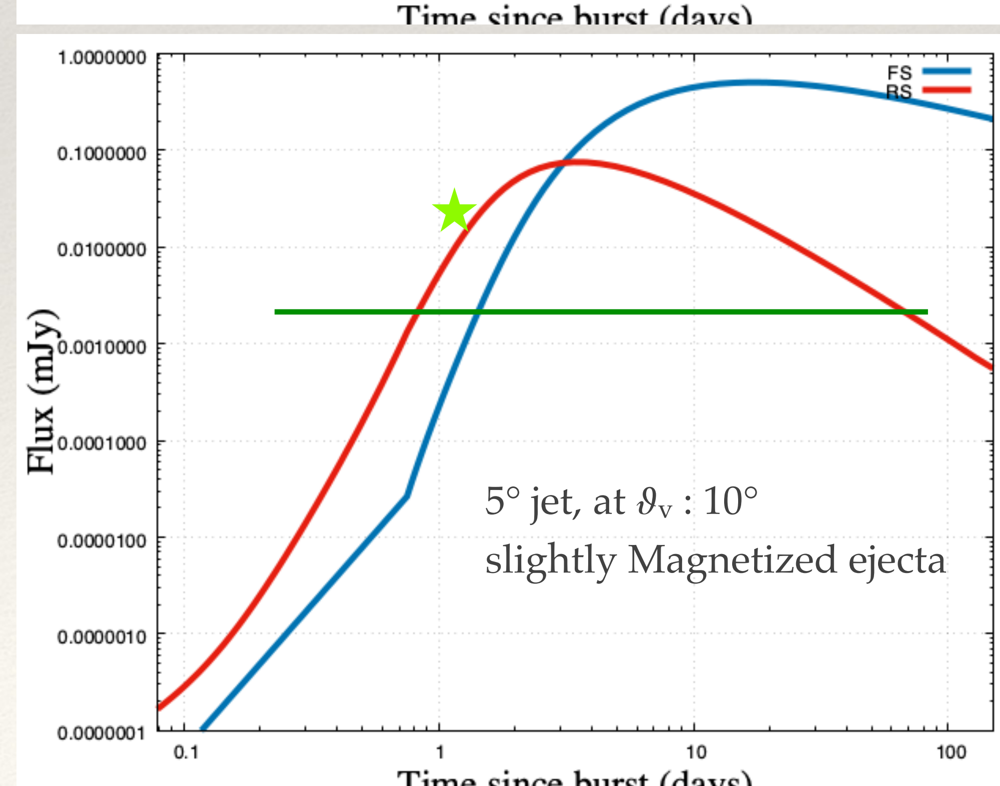
Potential radio counterparts I

Based on RL & Zhang, 2016.



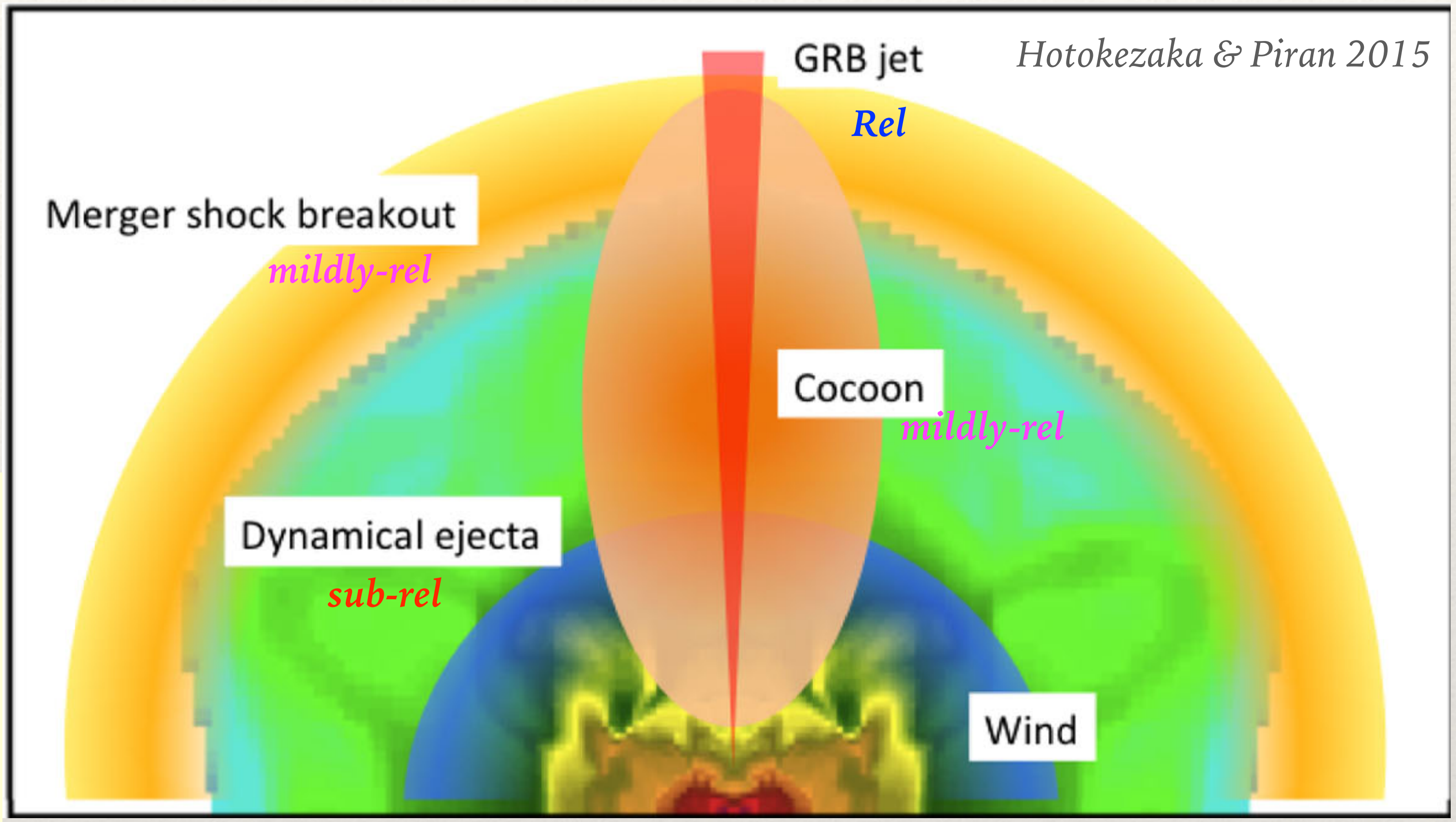


- Detectability of reverse shock emission in radio?



Potential radio counterparts II

$$t_{dec} = \left(\frac{3\,E}{4\,\pi\, m_p\, c^5\, n\, \Gamma(\Gamma\text{-}1)\beta^3} \right)^{\frac{1}{3}}$$



- For n = 0.1;

  - Jet (10^{49}, 30) → t_{dec} = 10.3 days

  - Dyn.Ejecta(10^{49}, 0.2) → t_{dec} = 1781.5 days

Several authors (Metzger & Bower, 2014, Horesh et al 2016, Fong et al 2016) have looked for this emission in VLA/ATCA. Limits of a few mJy.
We are currently studying the same with uGMRT.
SKA era: many such transients will be detected.

Thanks

to the two interferometers of the story!

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Additional slides

What causes the structure?

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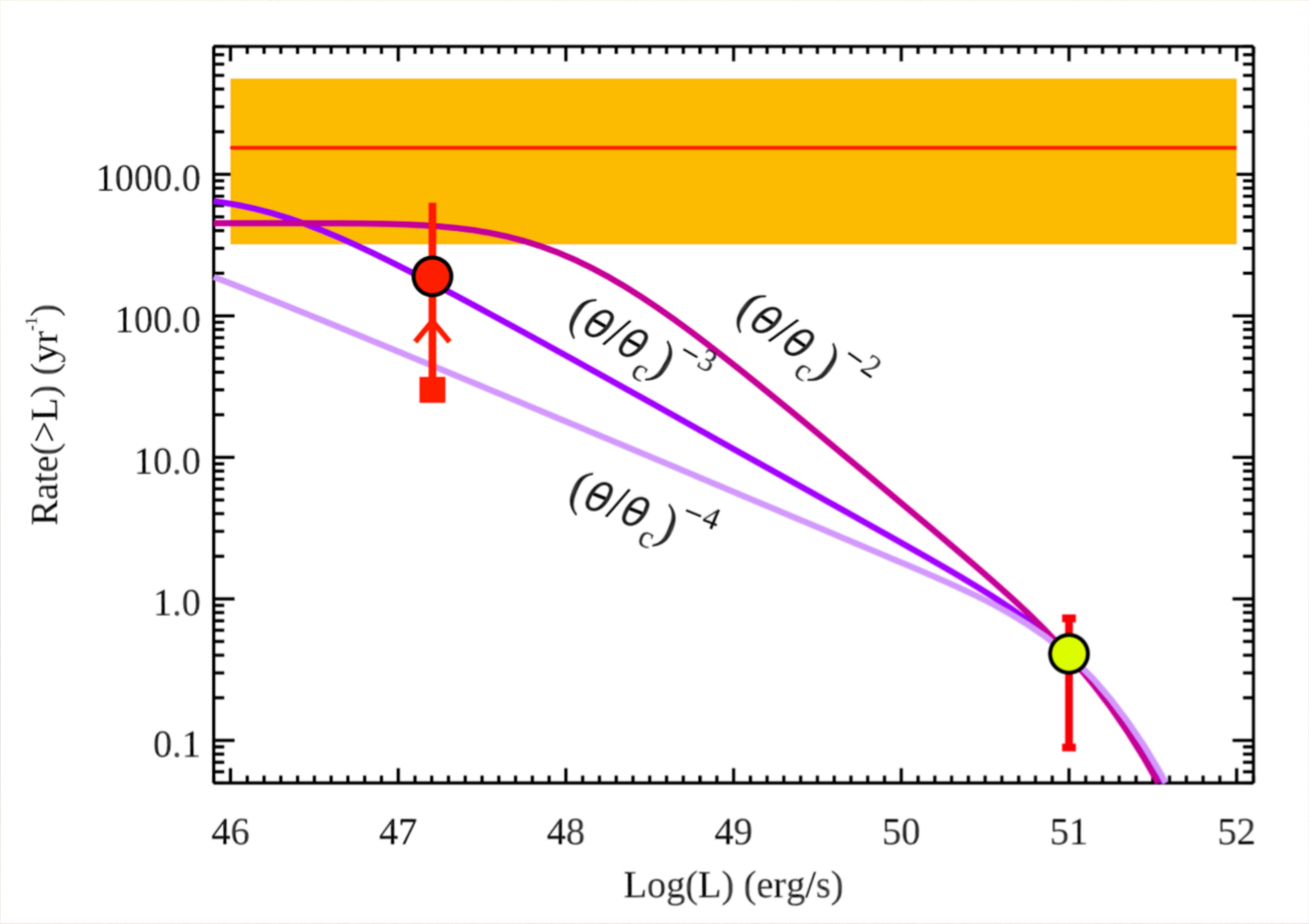
- Kathirgamaraju et al 2018 begins with the BH-accretion disk system, jet launched self-consistently, with an angular structure resulting from the passage through the merger ejecta.



Ghirlanda+2018

What kind of a jet that is?

- Laterally structured relativistic jet
- EM triggered GRB / AG observations of the past hadn't given enough evidence to confidently infer the presence of one such.

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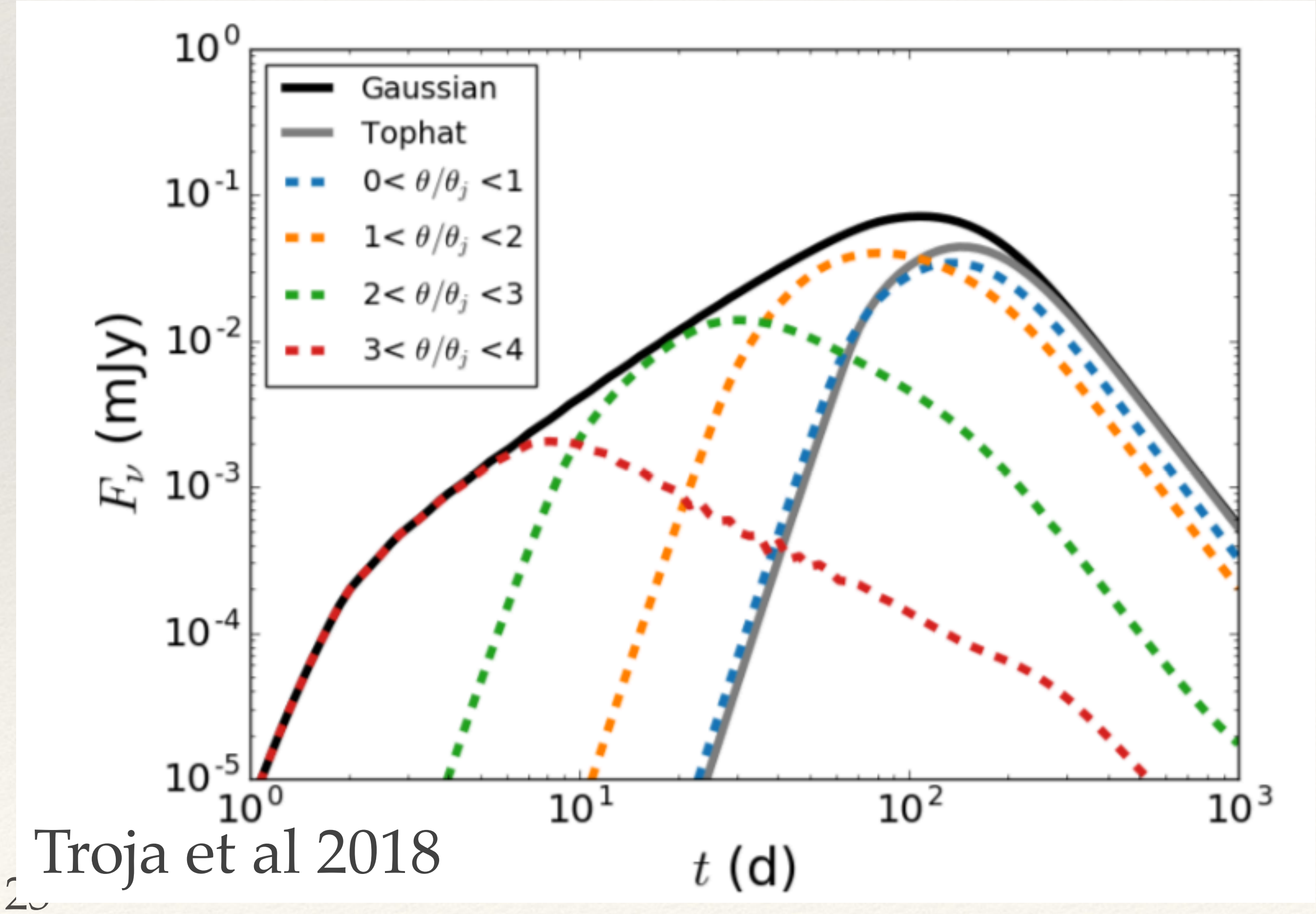

Troja et al 2018