NEUTRON STAR MERGERS: GRAVITATIONAL WAVES AND JET STRUCTURE

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Multi-Messenger Astrophysics in the GW era
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Collaborators

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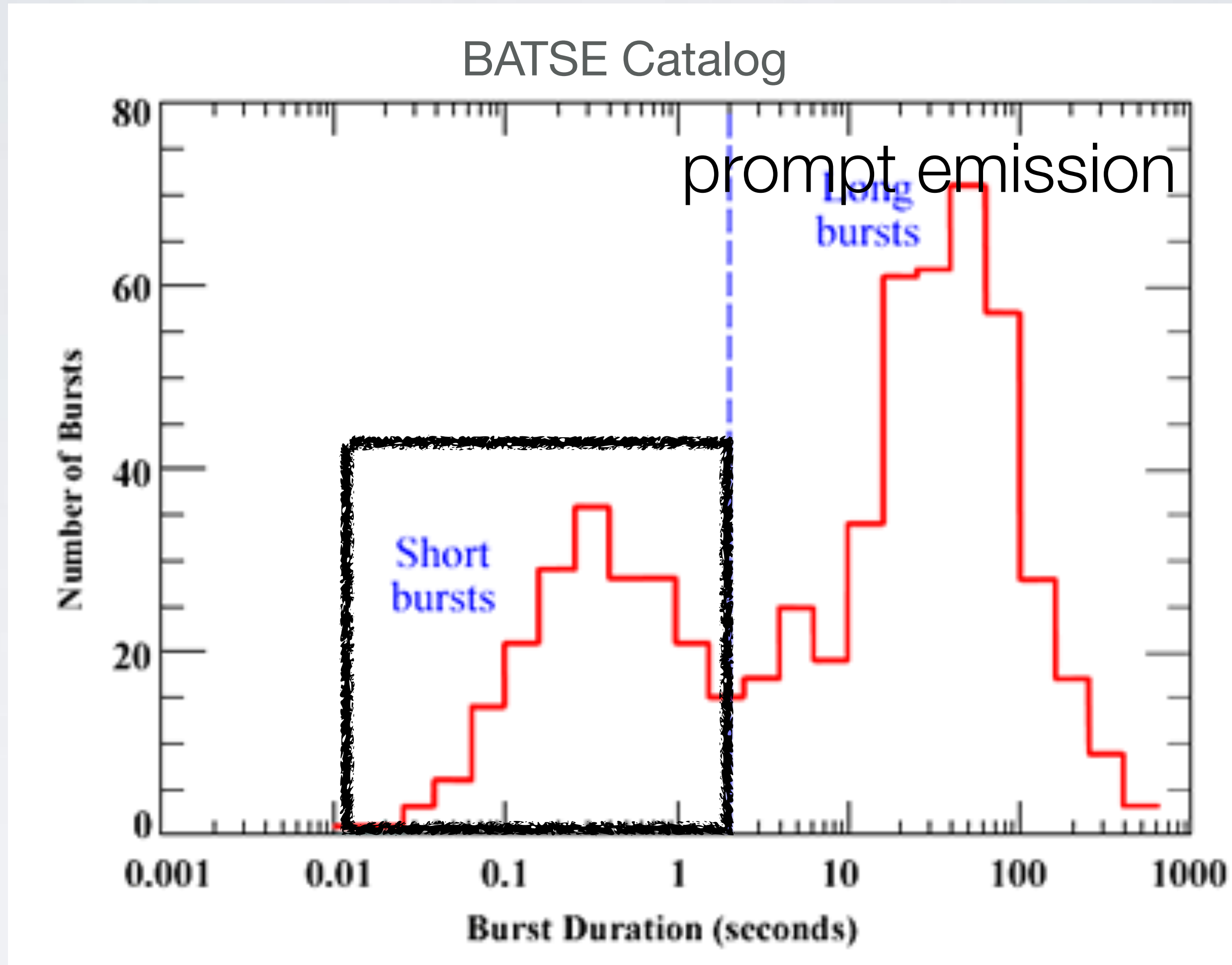
Short Gamma-Ray Bursts

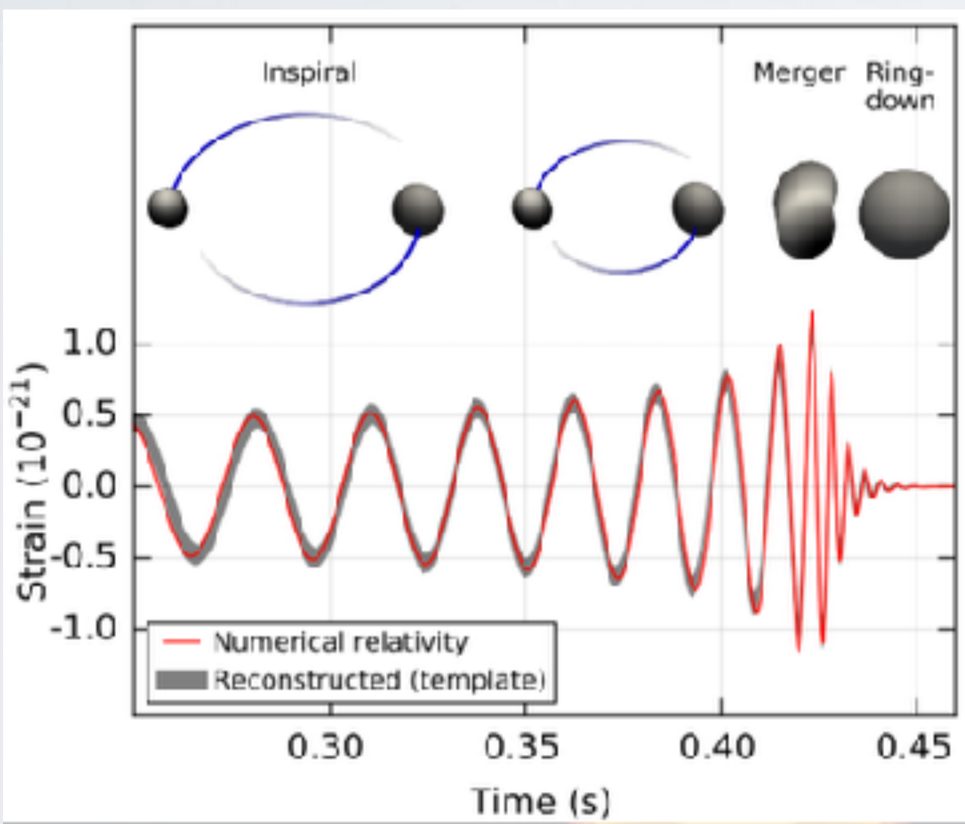


Short GRBs: duration of prompt emission < 2 s
Long GRBs: duration of prompt emission > 2 s (Kouveliotou+1993)

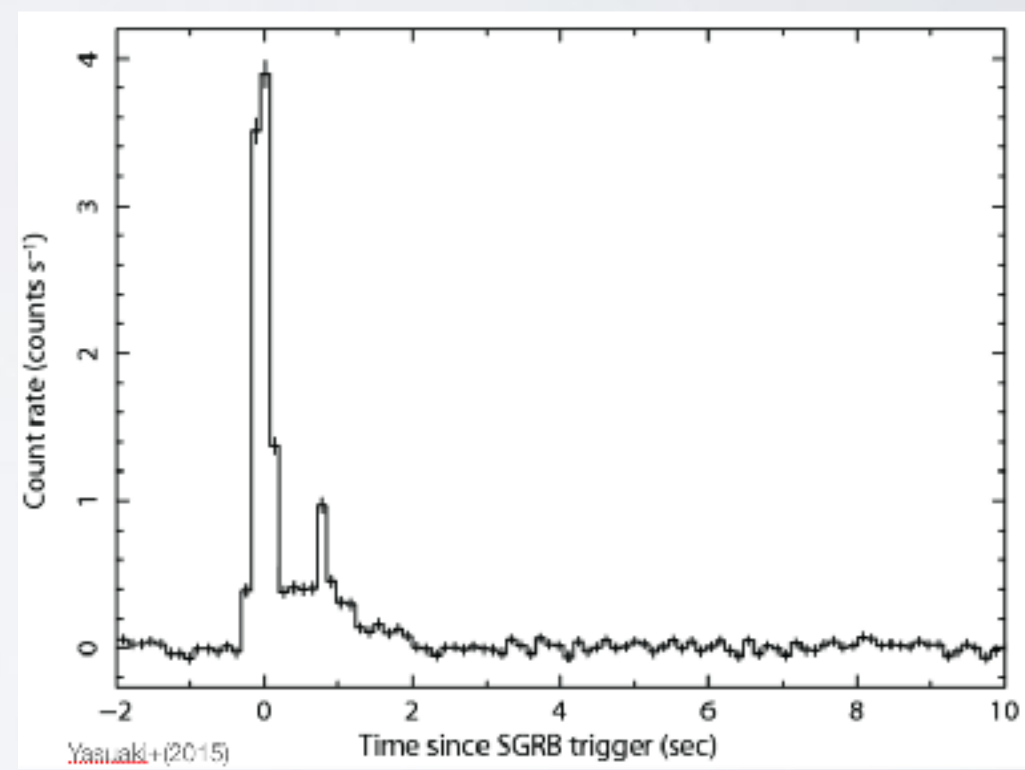
- ~ 30 years ago, it was postulated that GRBs could originate from binary mergers involving NSs (e.g., Eichler+1989, Narayan+1992)

Binary neutron star merger

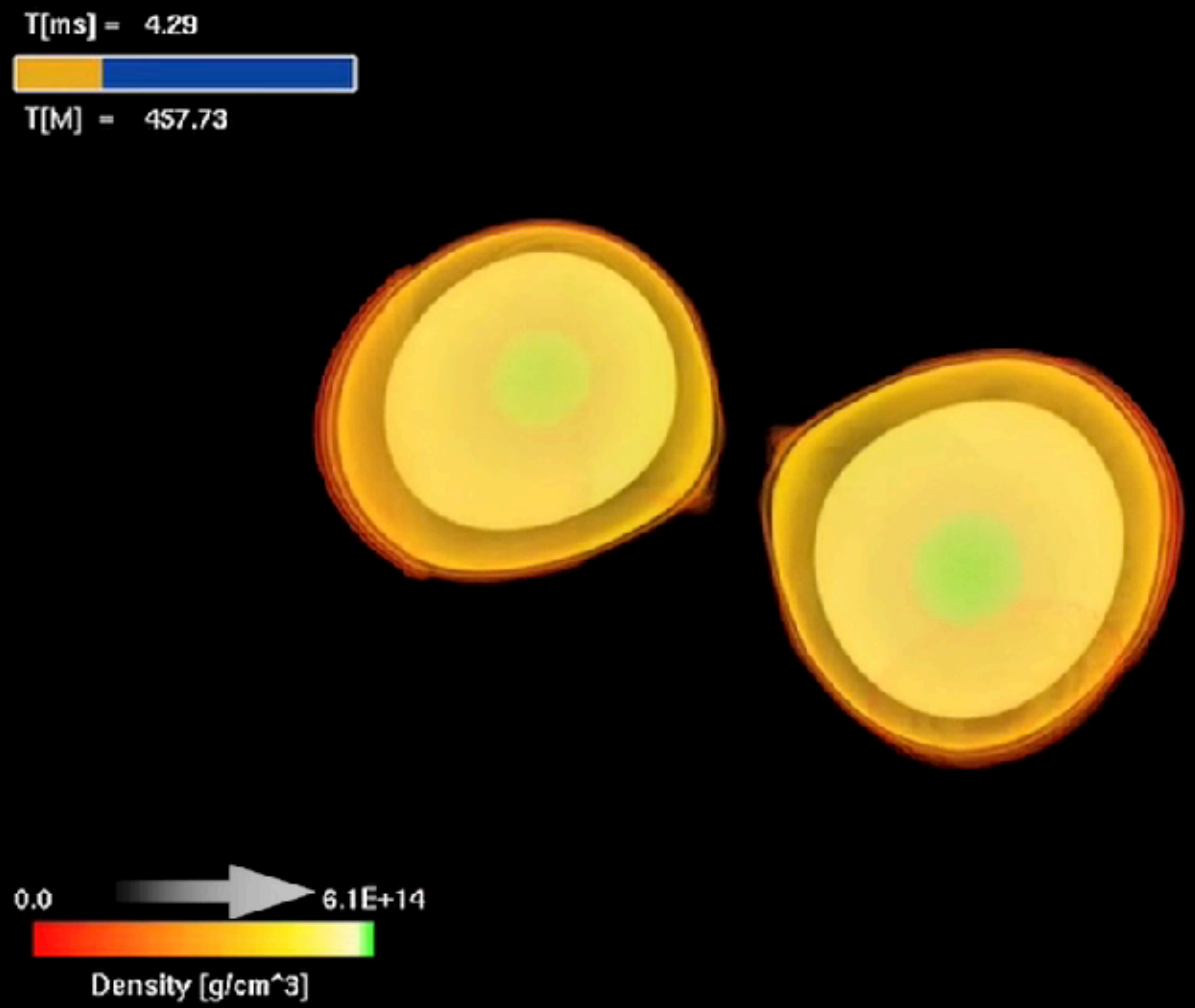
Gravitational waves



Short GRBs

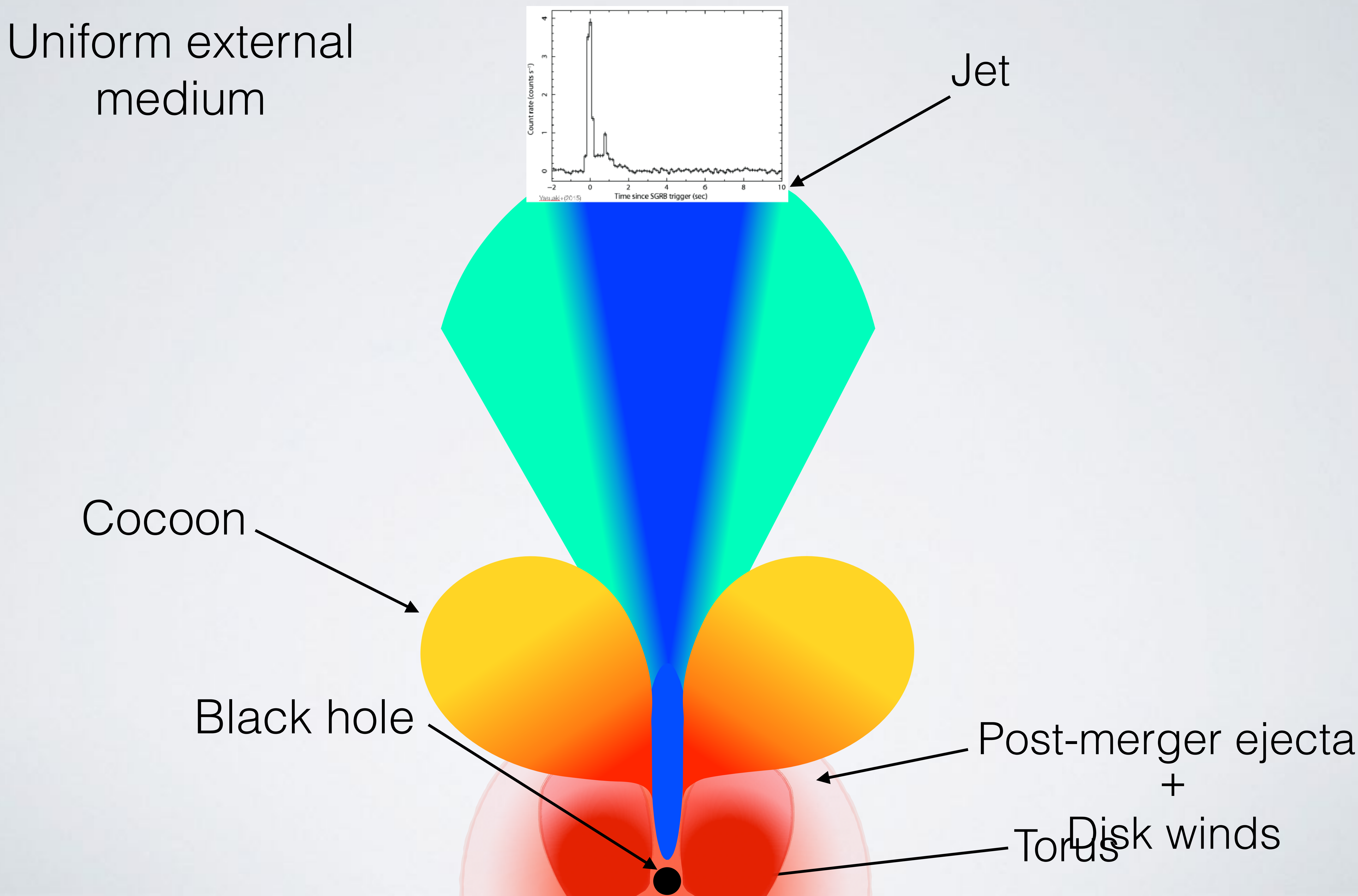


The Progenitor - Binary Neutron Star Merger



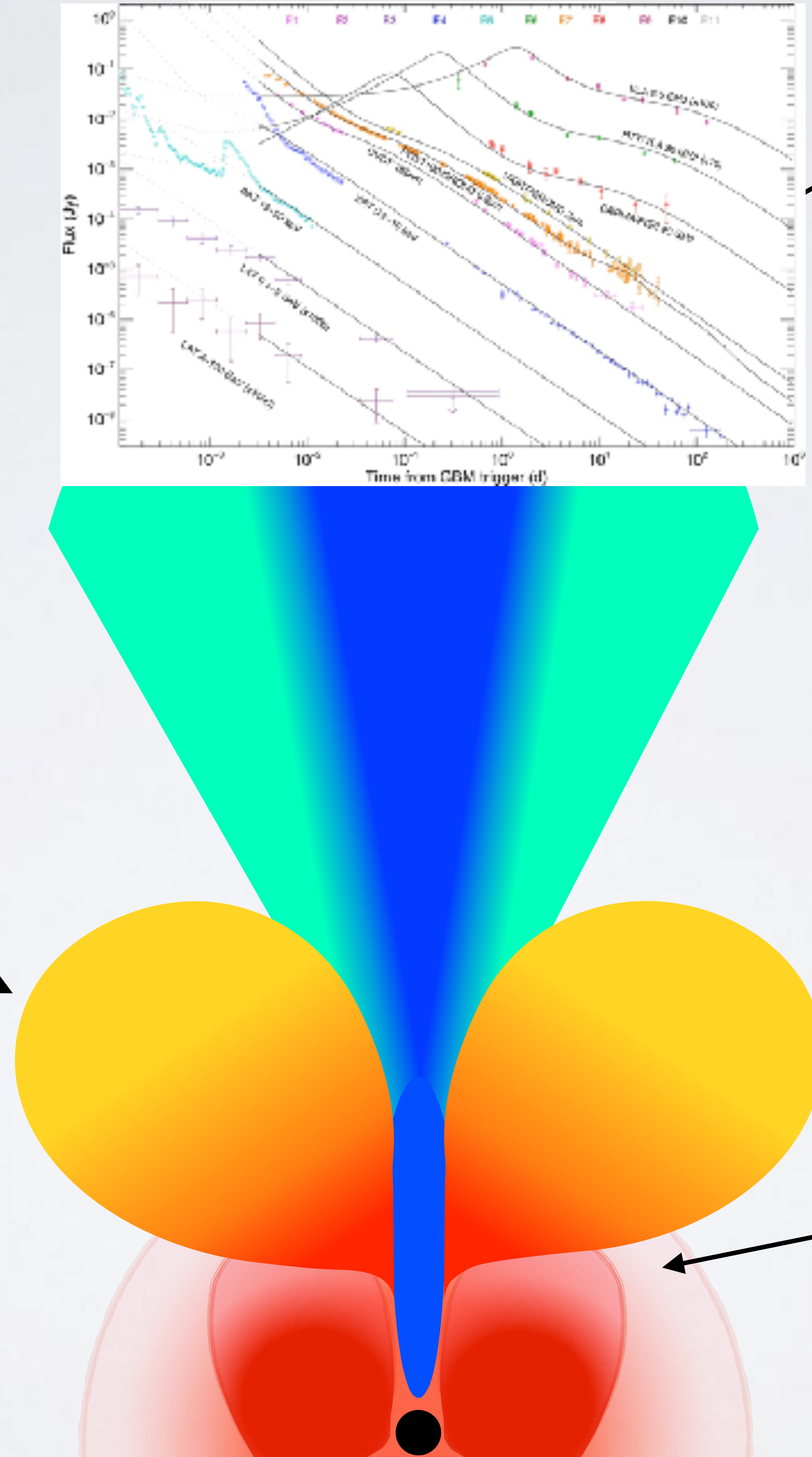
NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

The Post-Merger System



The Post-Merger System

Uniform external medium



Jet

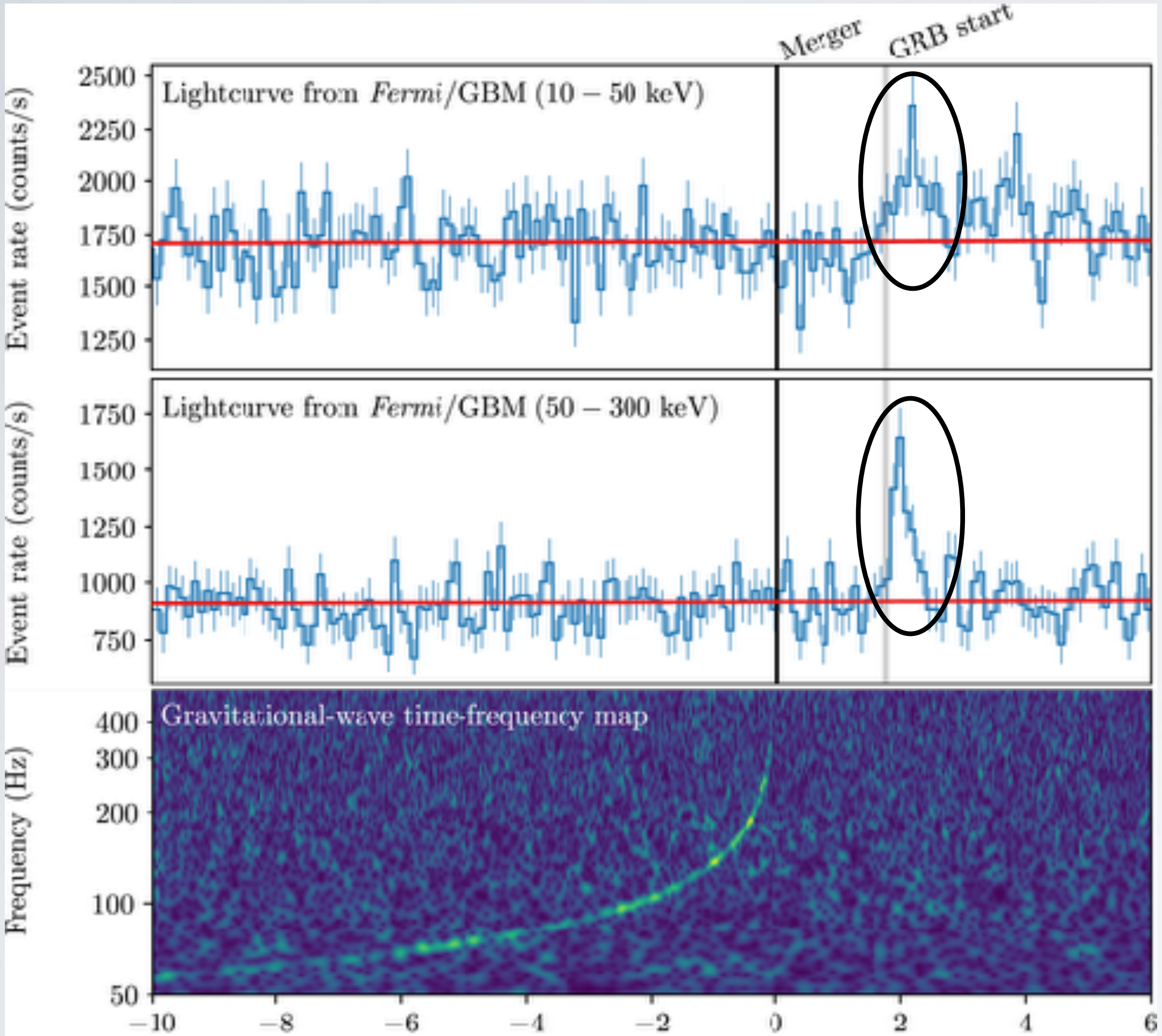
GRB afterglow:
Radio … gamma-rays

Cocoon

Post-merger ejecta
+
Disk winds

The amazing NS merger GW170817

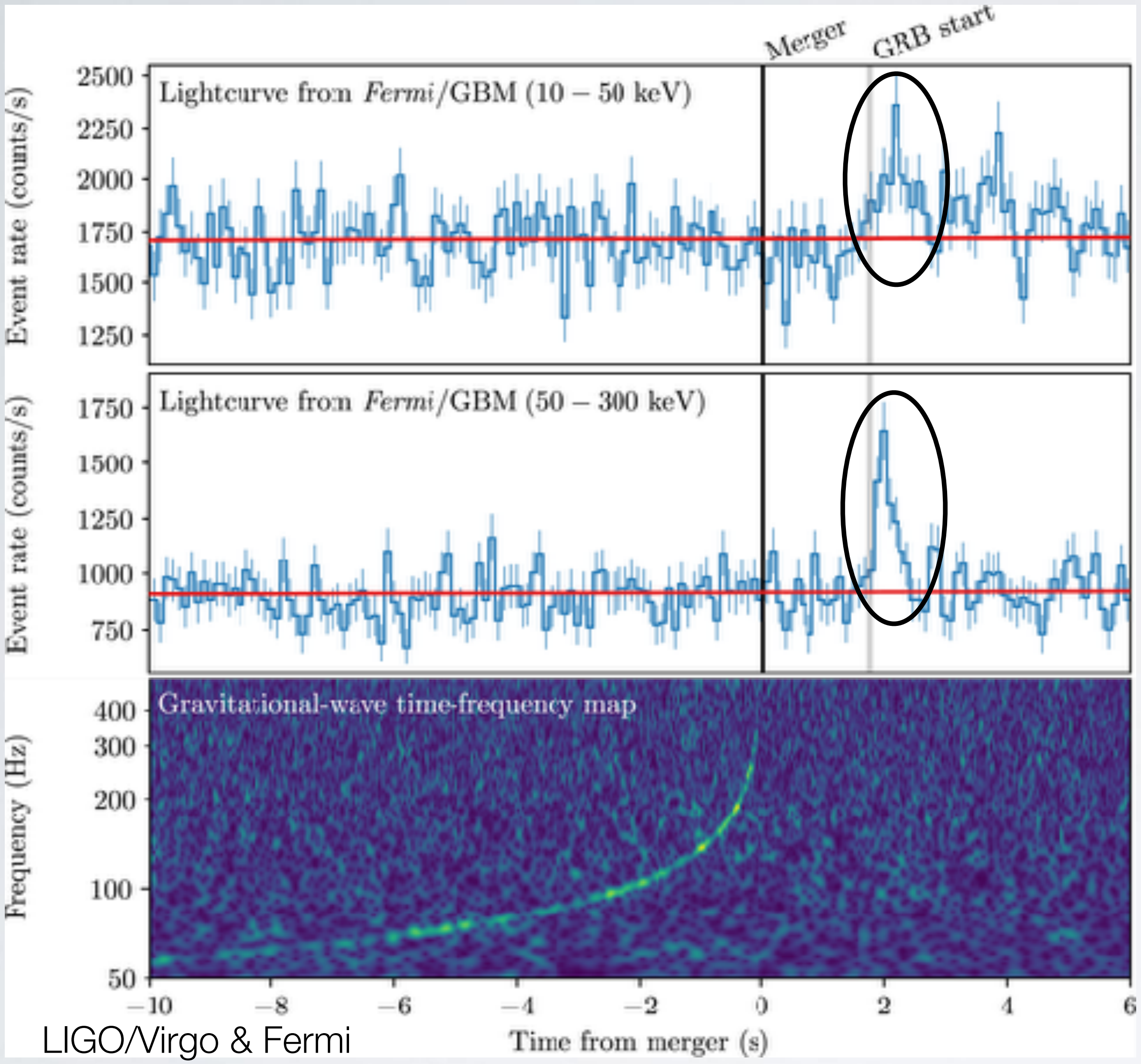
Prompt emission duration of ~1s



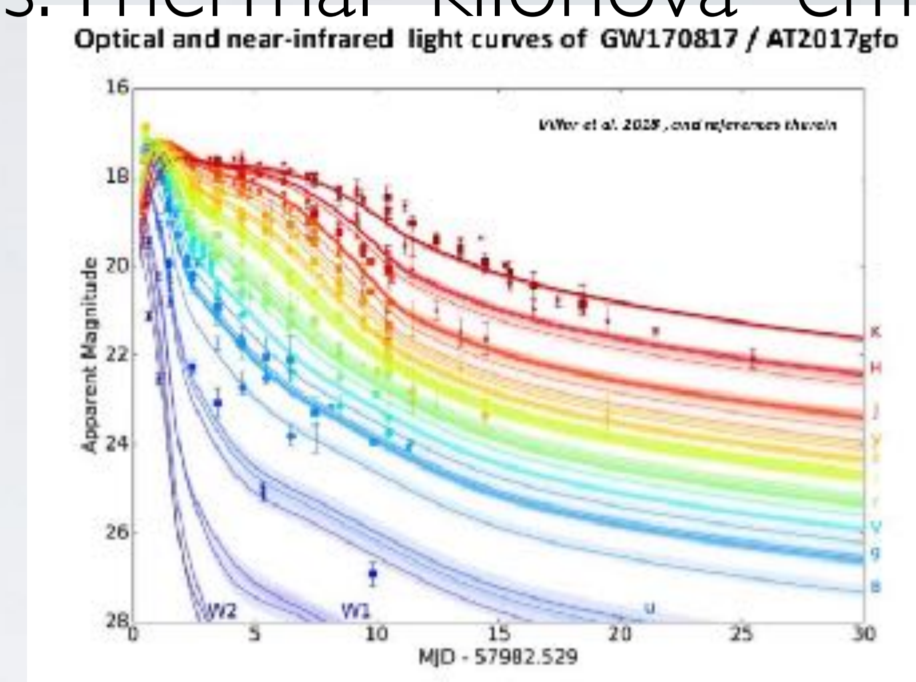
LIGO/Virgo & Fermi

The amazing NS merger GW170817

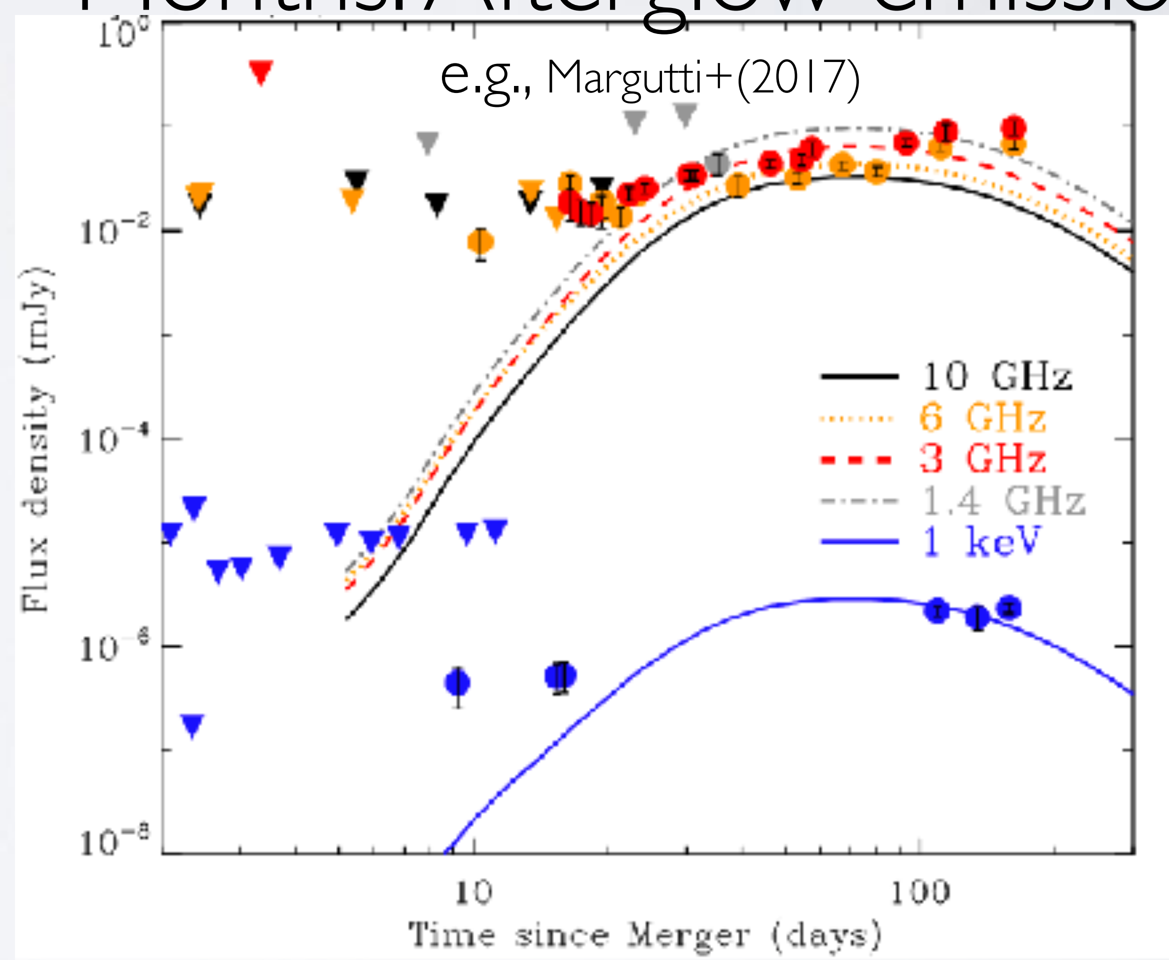
Prompt emission duration of ~1s



Days: Thermal "kilonova" emission



Months: Afterglow emission



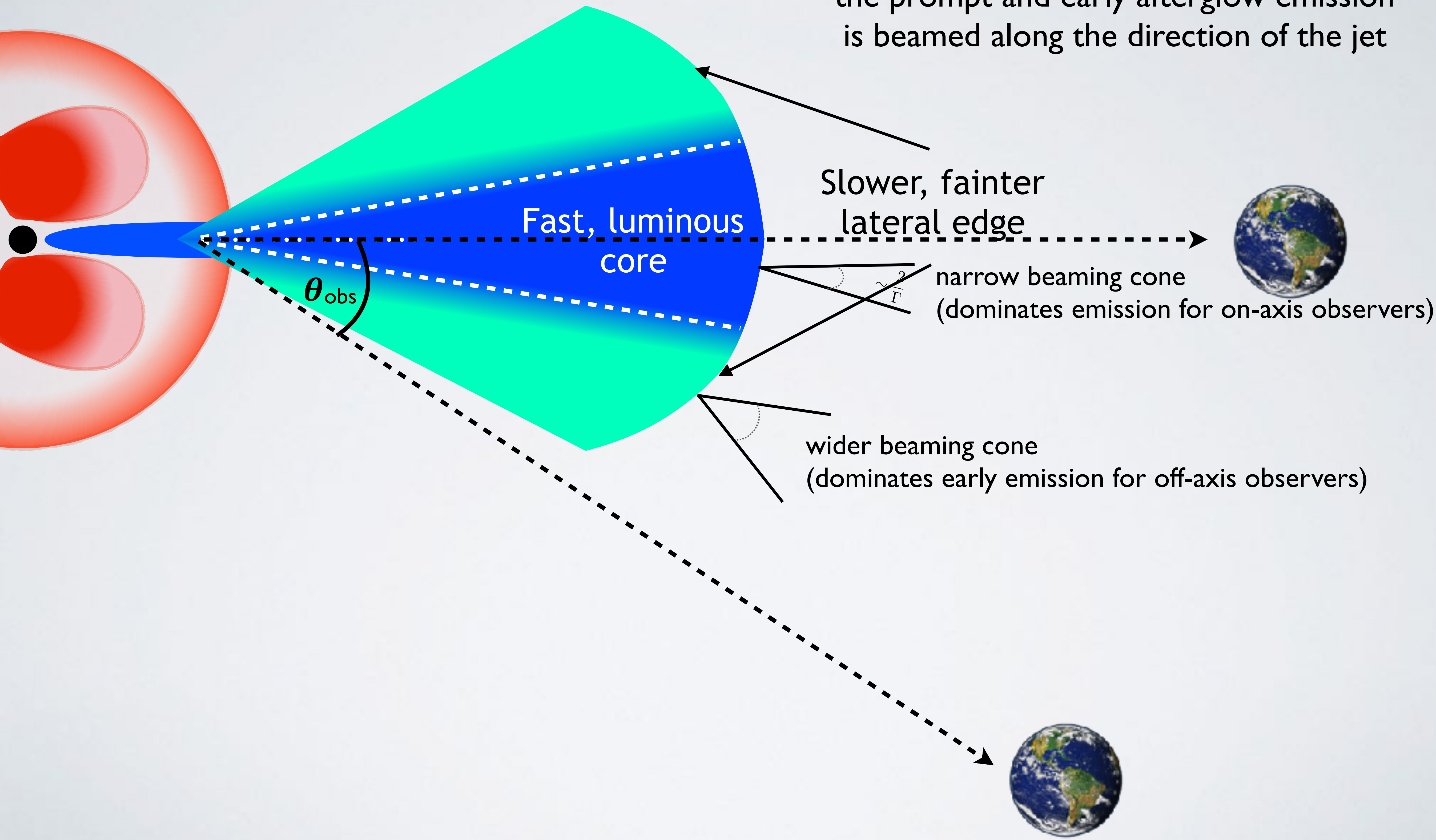
Peculiar Properties of GRB 170817A

- Closest sGRB detected yet (~40 Mpc), but **~10^3 -10^4** times less luminous than typical sGRBs (e.g., Fong +2017, LIGO/Virgo +2017).

- Afterglow emission showed a shallow ($\propto t^{0.8}$) rise for ~150 days.

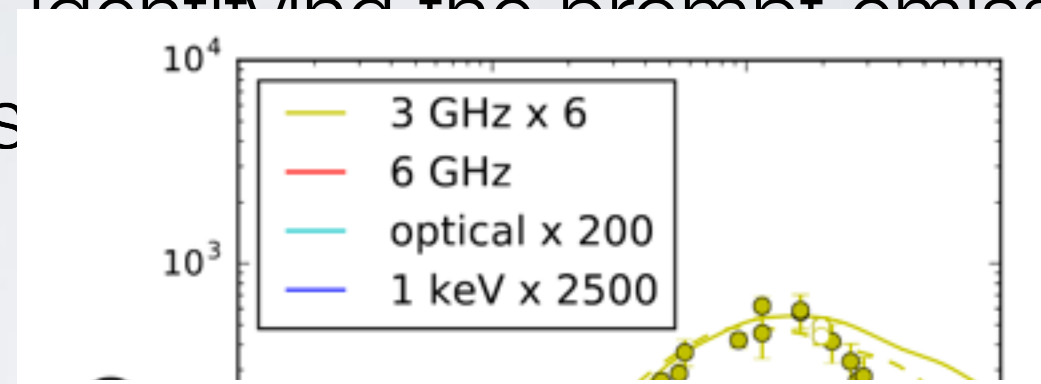
Structured jet:
On-Axis vs. Off-Axis Observers

Since the jet is initially ultra-relativistic, the prompt and early afterglow emission is beamed along the direction of the jet



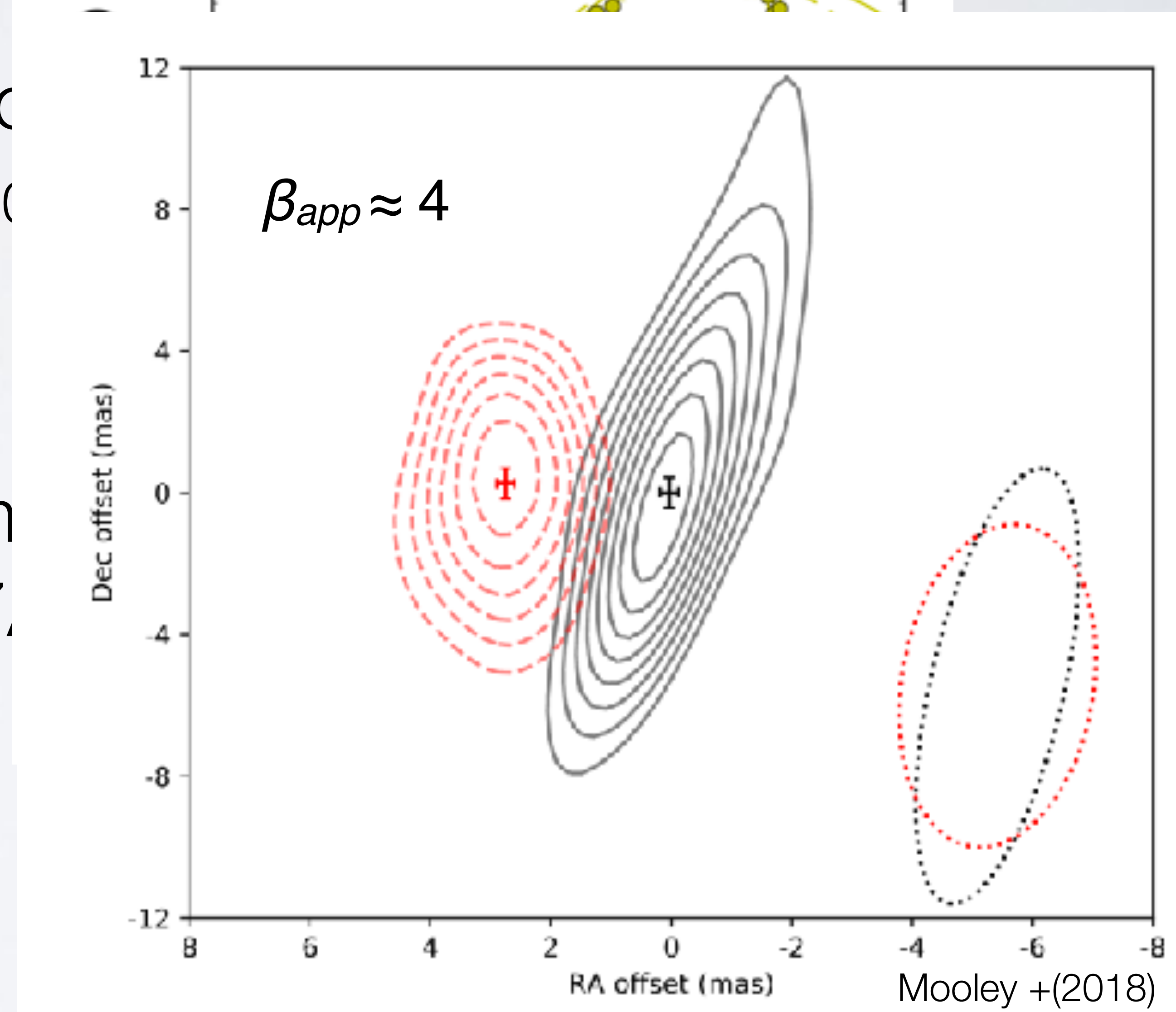
Structured Jet Interpretation of GRB 170817A

- A coincident GW trigger and proximity of a LIGO/Virgo can increase the chances of detecting and identifying the prompt emission of structured jets for off-axis obs Lazzati+2017).



- The shallow rise in the aftergl jet viewed off-axis (e.g., Alexander+20

- Observation of superluminal n a structured jet in GRB 170817

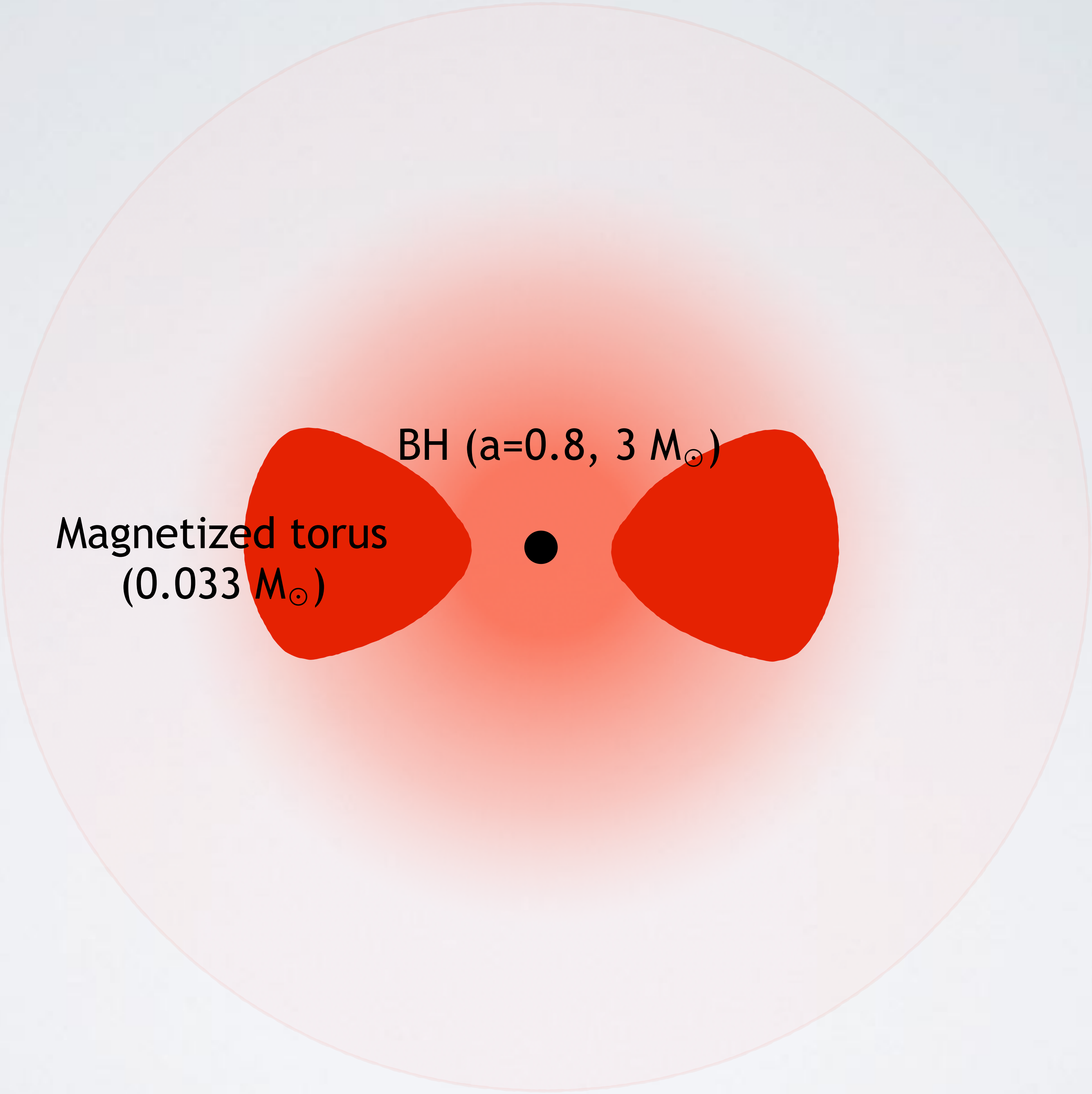


How is the Jet Structure Obtained?

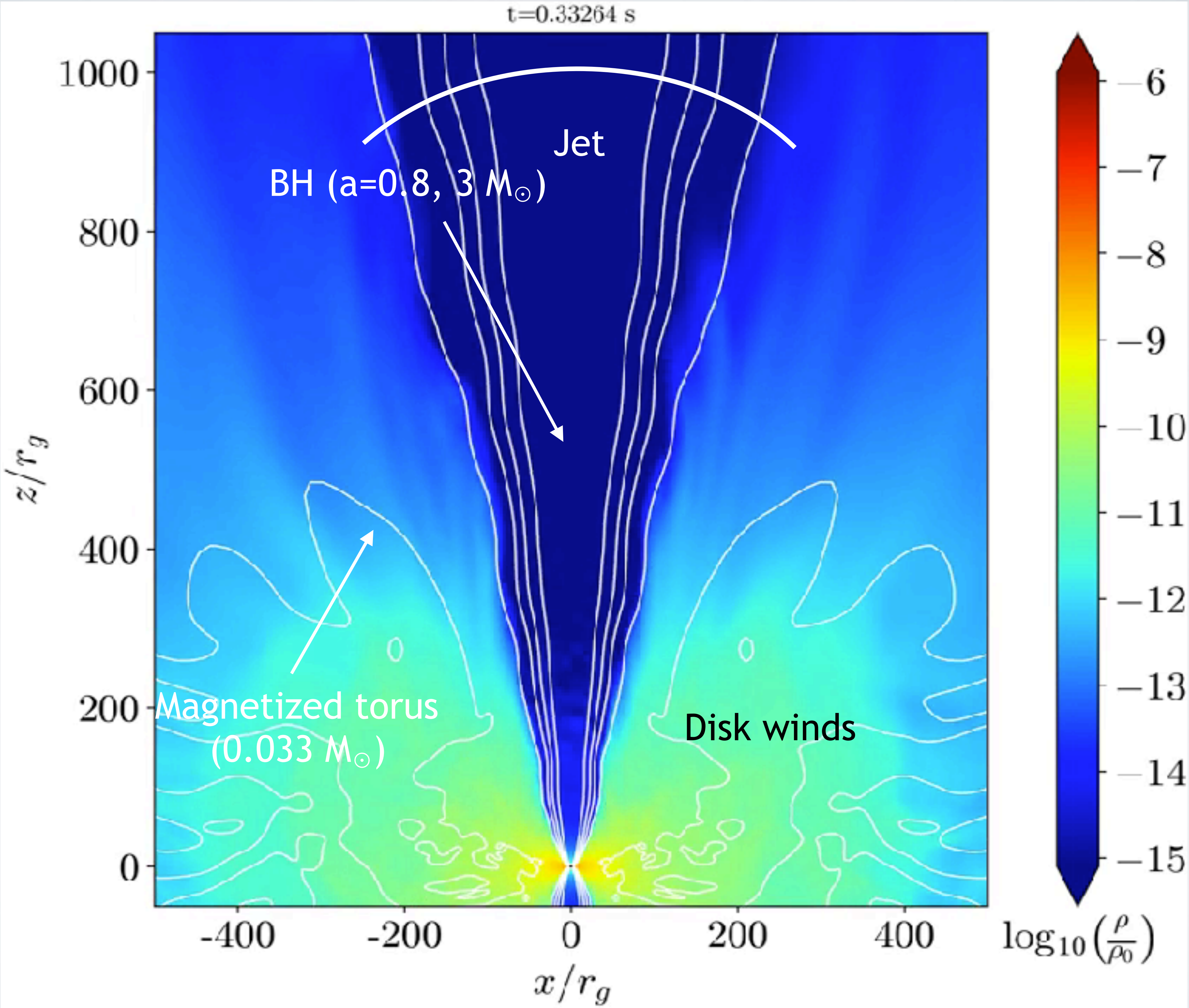
- We want to eliminate initial assumptions made about the jet structure in the modeling.

- Utilize 3D general relativistic magnetohydrodynamic (GRMHD) simulations of a post-merger system, starting at the central engine.

Initial Setup of Post-Merger System



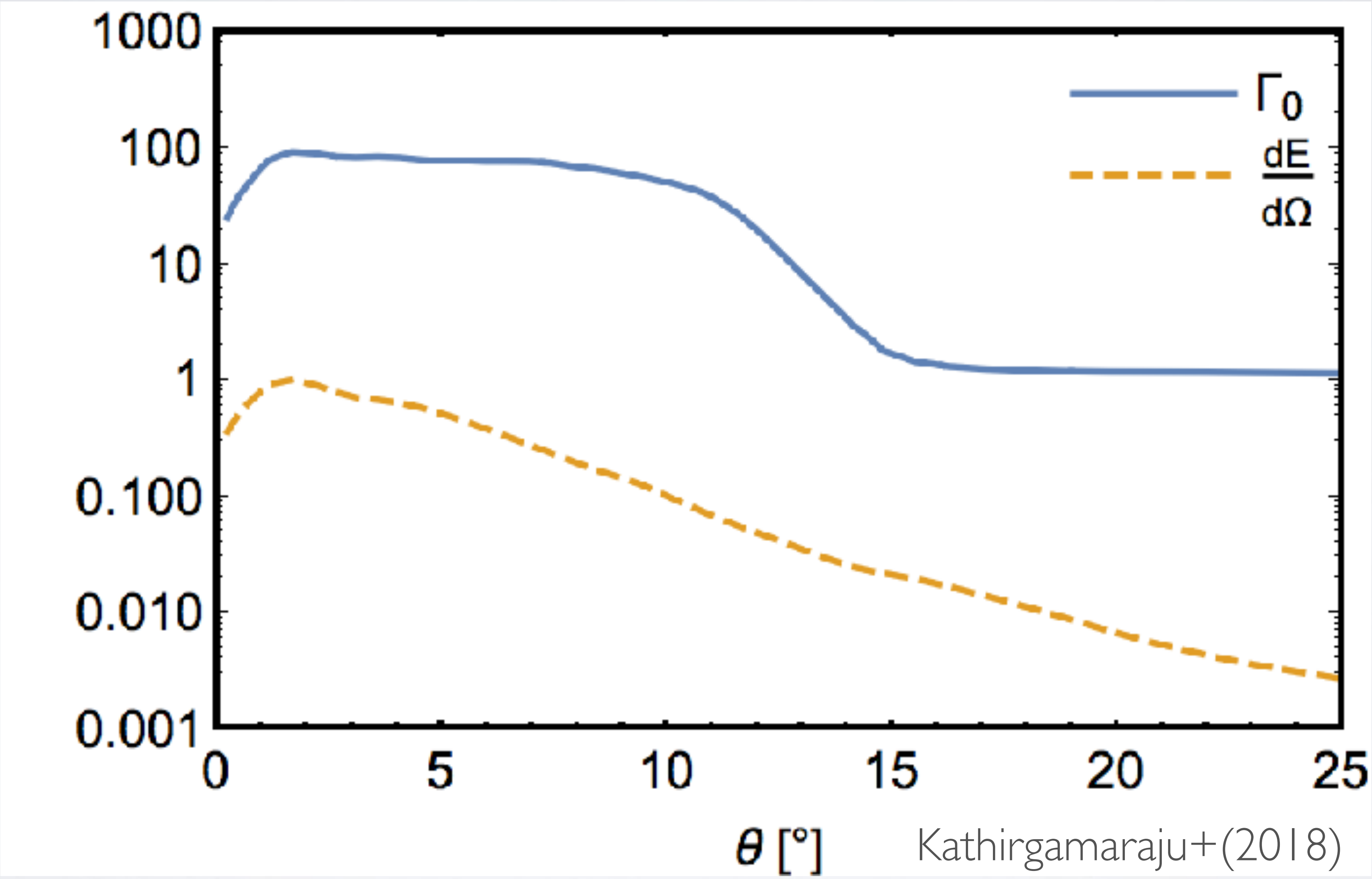
Simulations of the Post-Merger System



Fernández+(2018), Kathirgamaraju+(2018)

Extracting Jet Structure

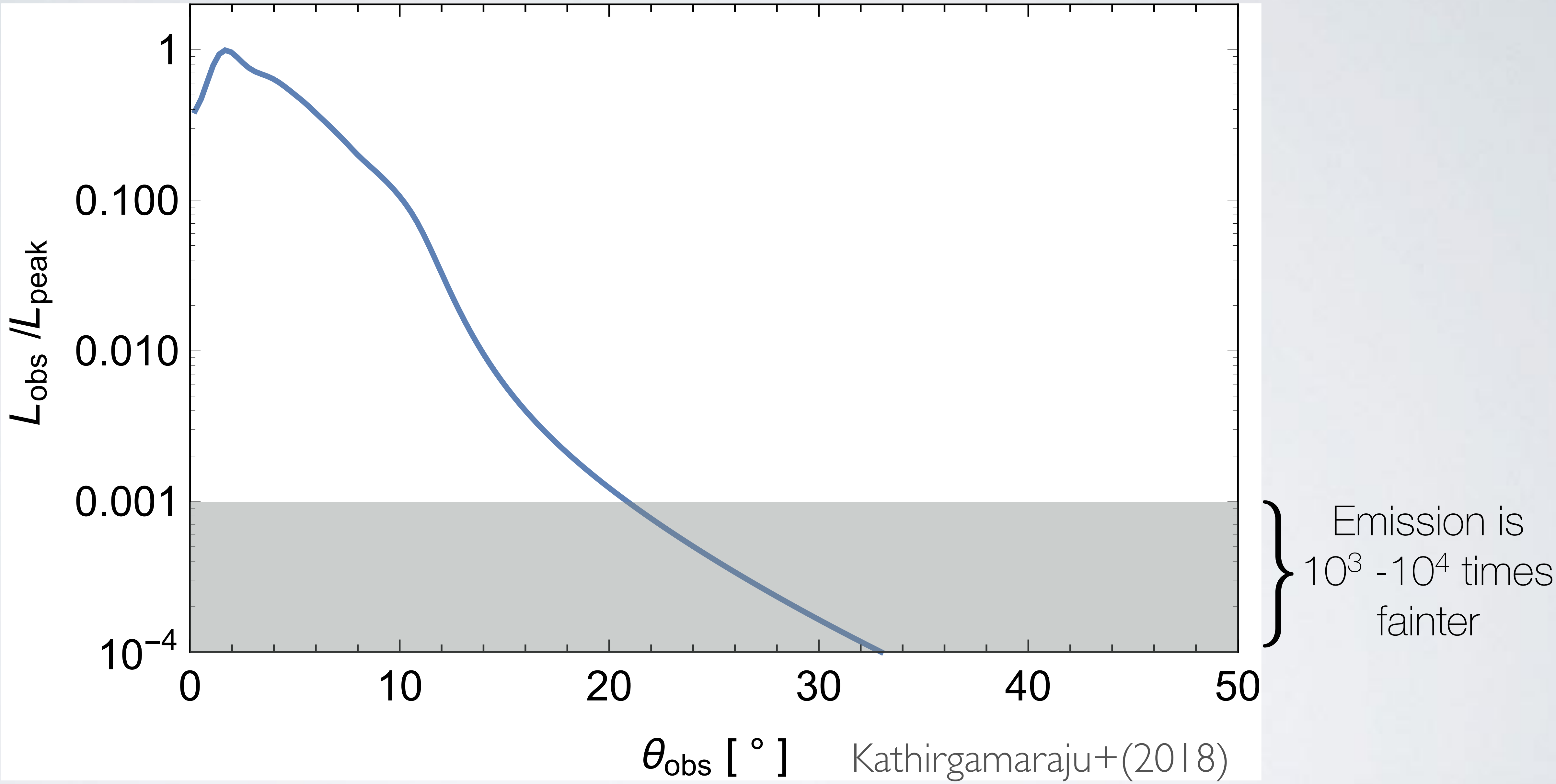
- Measure the average Lorentz factor and energy of the jet (averaged over azimuthal angle) flowing through a surface of fixed radius.



Energy includes the EM, kinetic and thermal components.

Prompt Emission Profile

- Calculate how the total observed luminosity of the prompt emission is distributed vs. observing angle.



- Prompt emission is 10^3 -10^4 times fainter for observers between **~20°- 30°** (compared to on-axis observers).

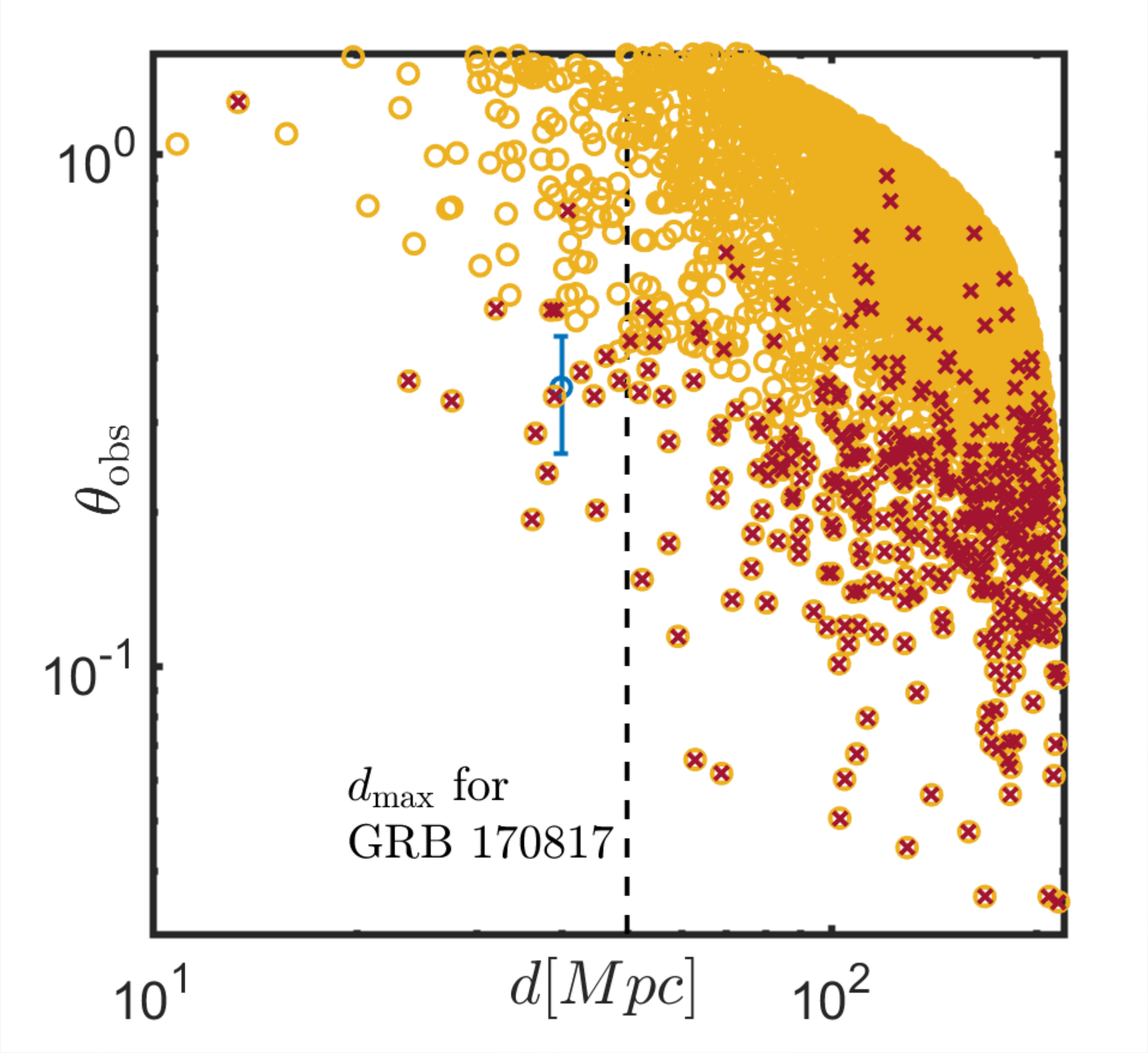
Future detections GW + prompt gamma-rays

The LIGO NS merger rate and the sGRB rates imply that

i) a large fraction of mergers have successful jets

ii) the jet core opening angle is ~**3°- 5°**

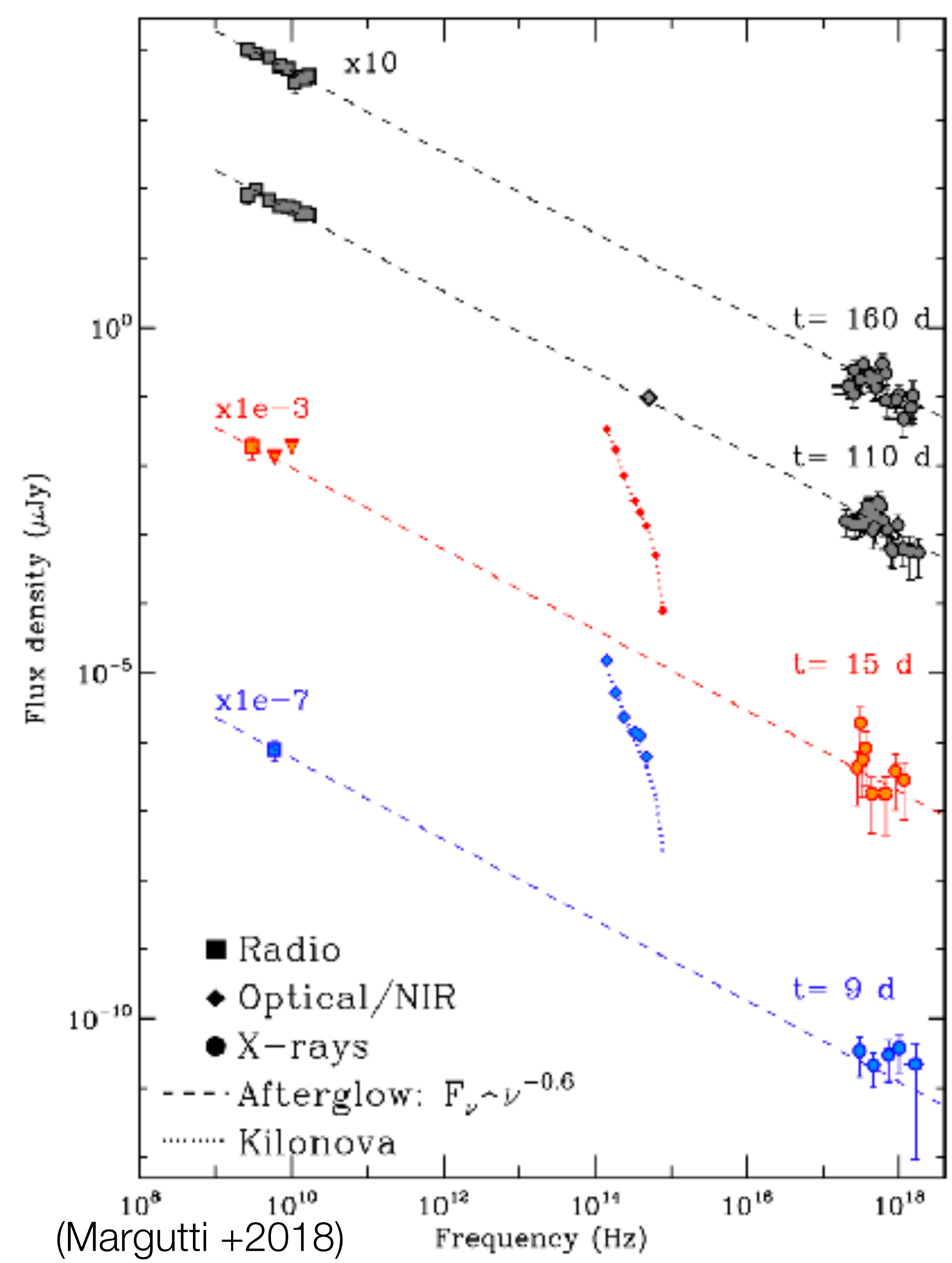
iii) only ~1-10% of the GW NS mergers will have GRB detection



Beniamini+ 2019

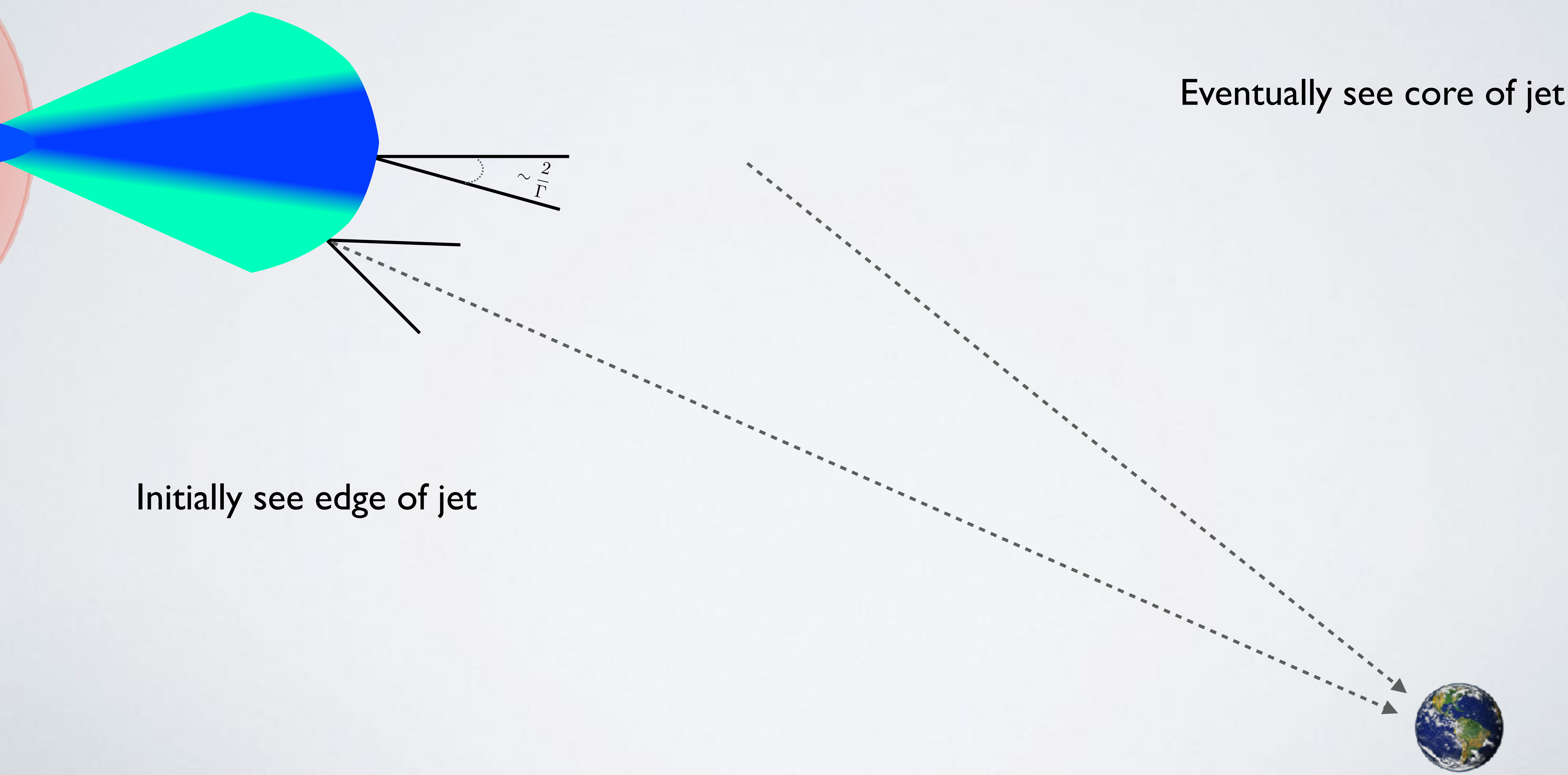
Afterglow of the Structured Jet

- Calculate the synchrotron er
  propagating in an external m i+1999).
- The initial structure of the bla as that
  of the jet.
- Particles in forward shock ac $d\gamma \propto \gamma^{-p}$
- We use p=2.17 as indicated RB
  170817A afterglow (Margutti+2



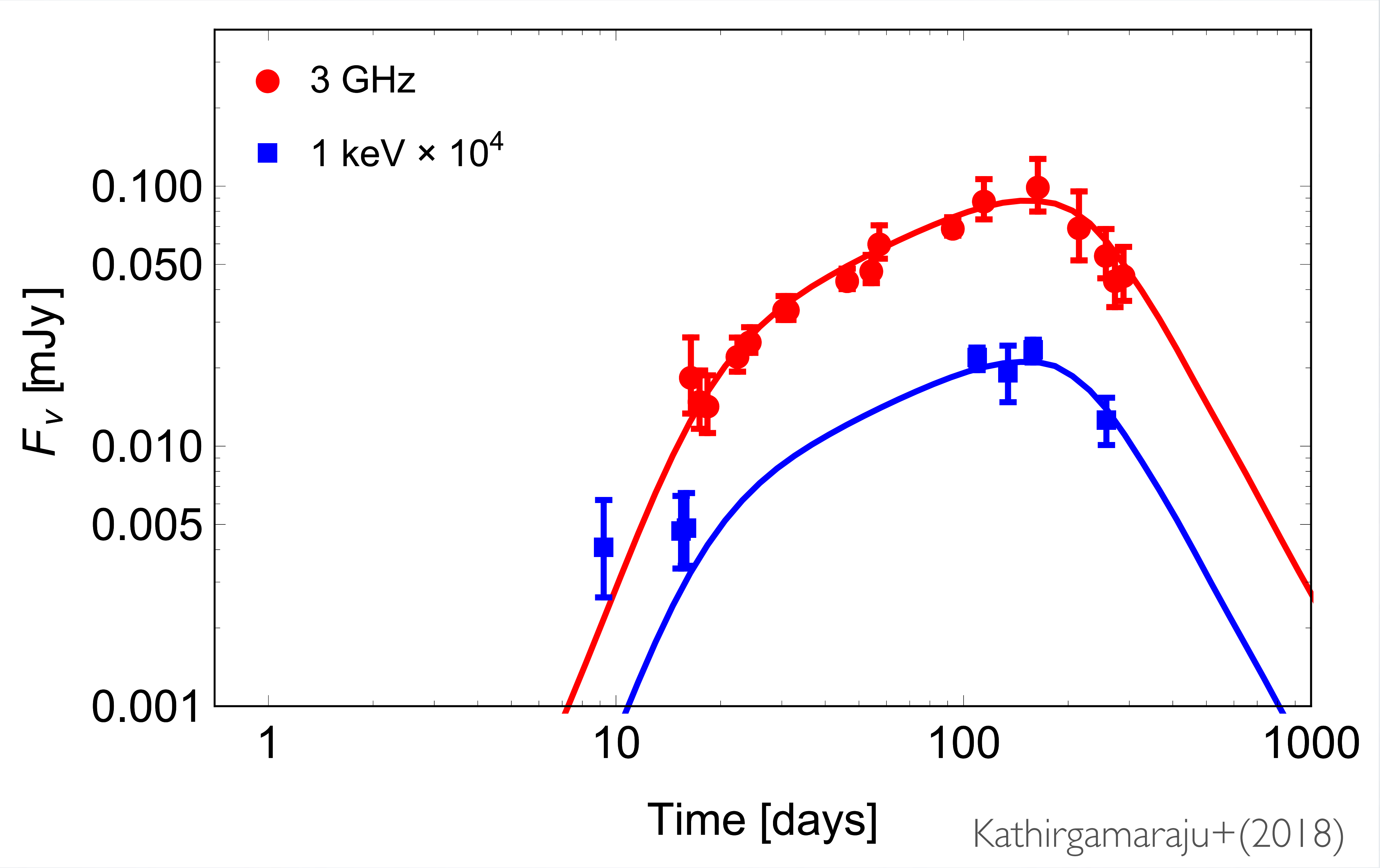
(Margutti +2018)

Structured Jet Afterglow for Off-Axis Observers



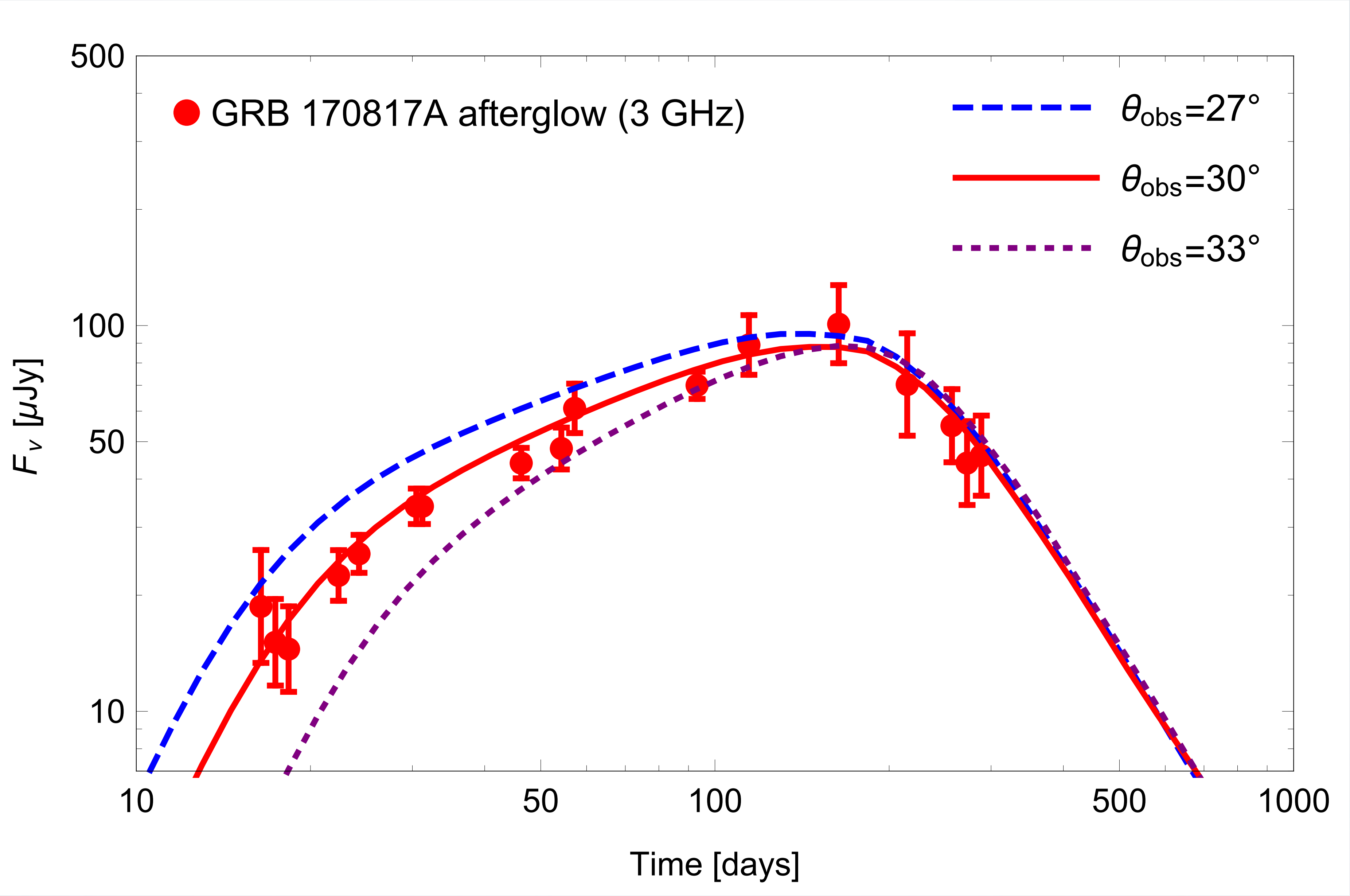
Afterglow of GRB 170817A

Data points from Margutti+(2018), Alexander+(2018)



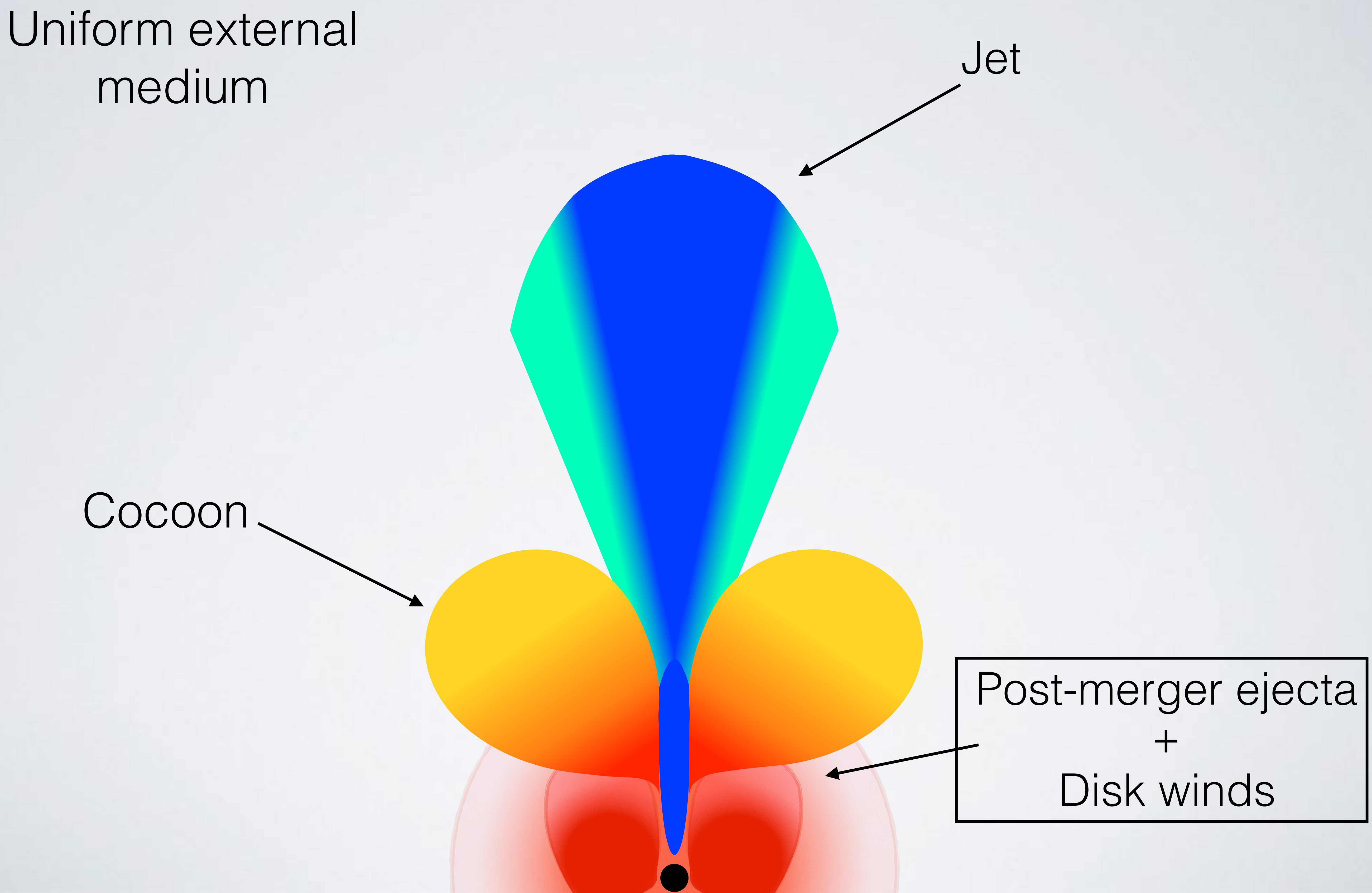
$E_j \approx 5 \times 10^{50}$ erg, $\theta_{obs} = 30°$

Viewing angle of GRB 170817A



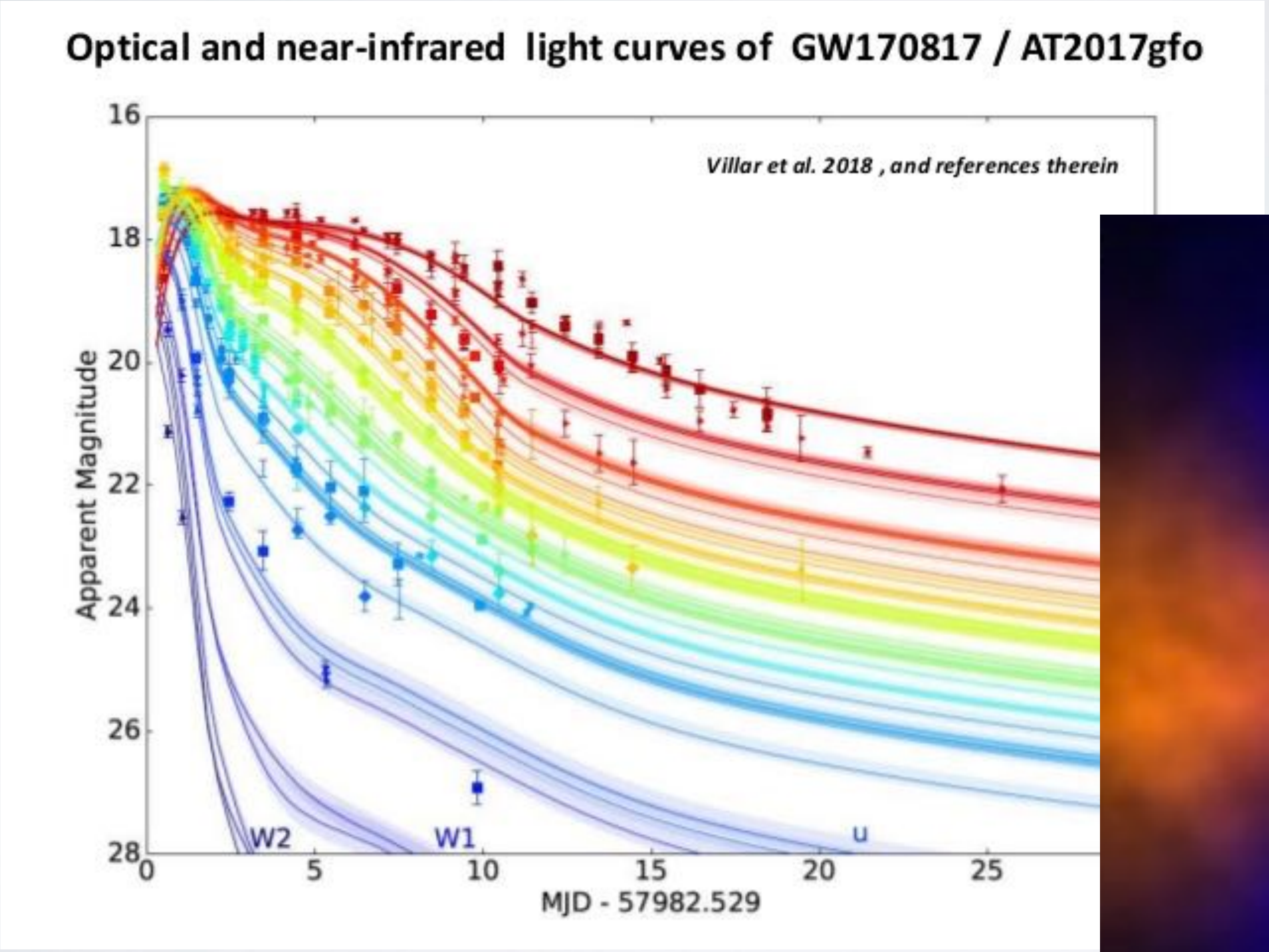
- The larger the viewing angle, the steeper the rise of the afterglow, constraining the observing angle at ~**30°.**

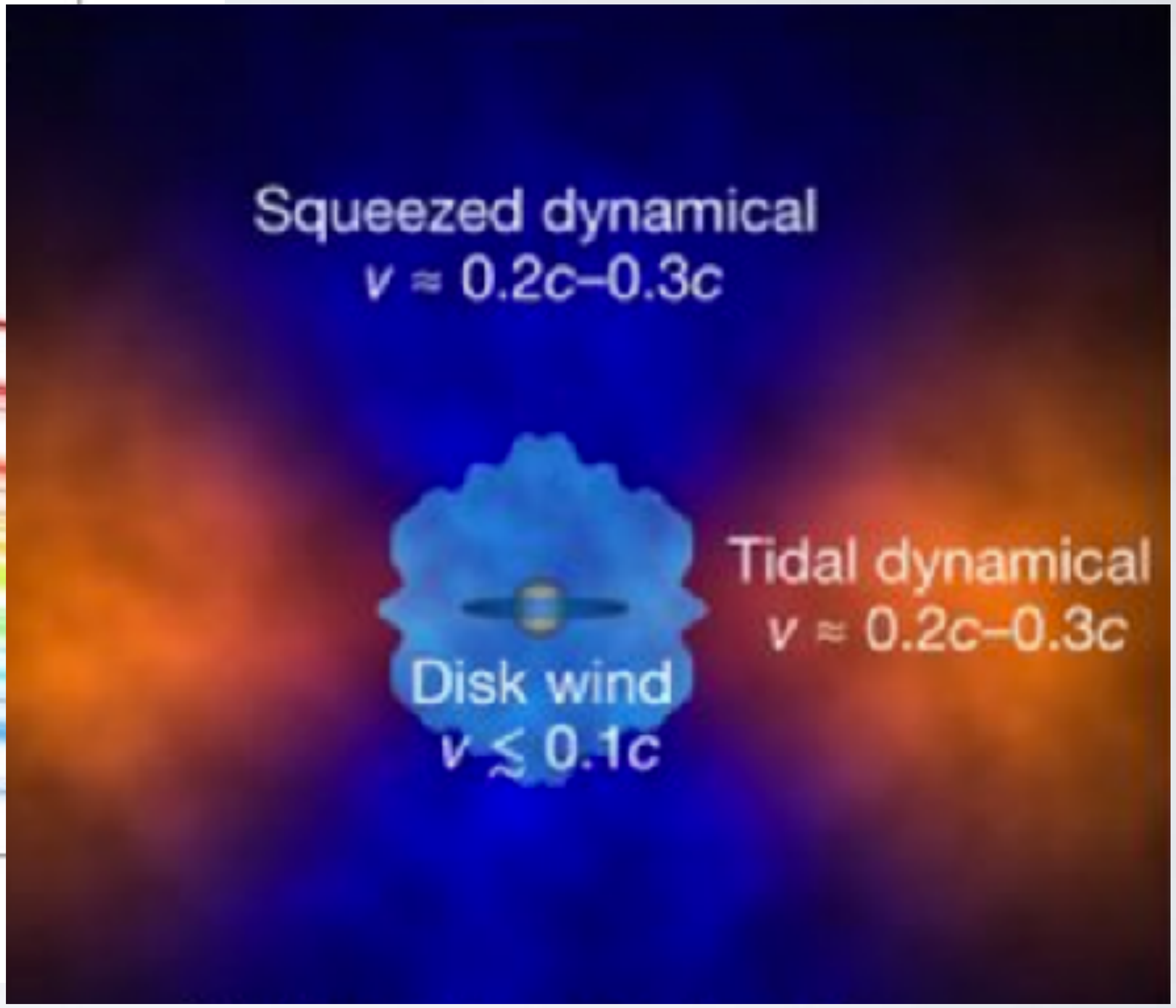
The Post-Merger System



The Kilonova AT2017gfo

Thermal: powered by radioactive decay





Non-thermal: kilonova afterglow?

The kilonova afterglow

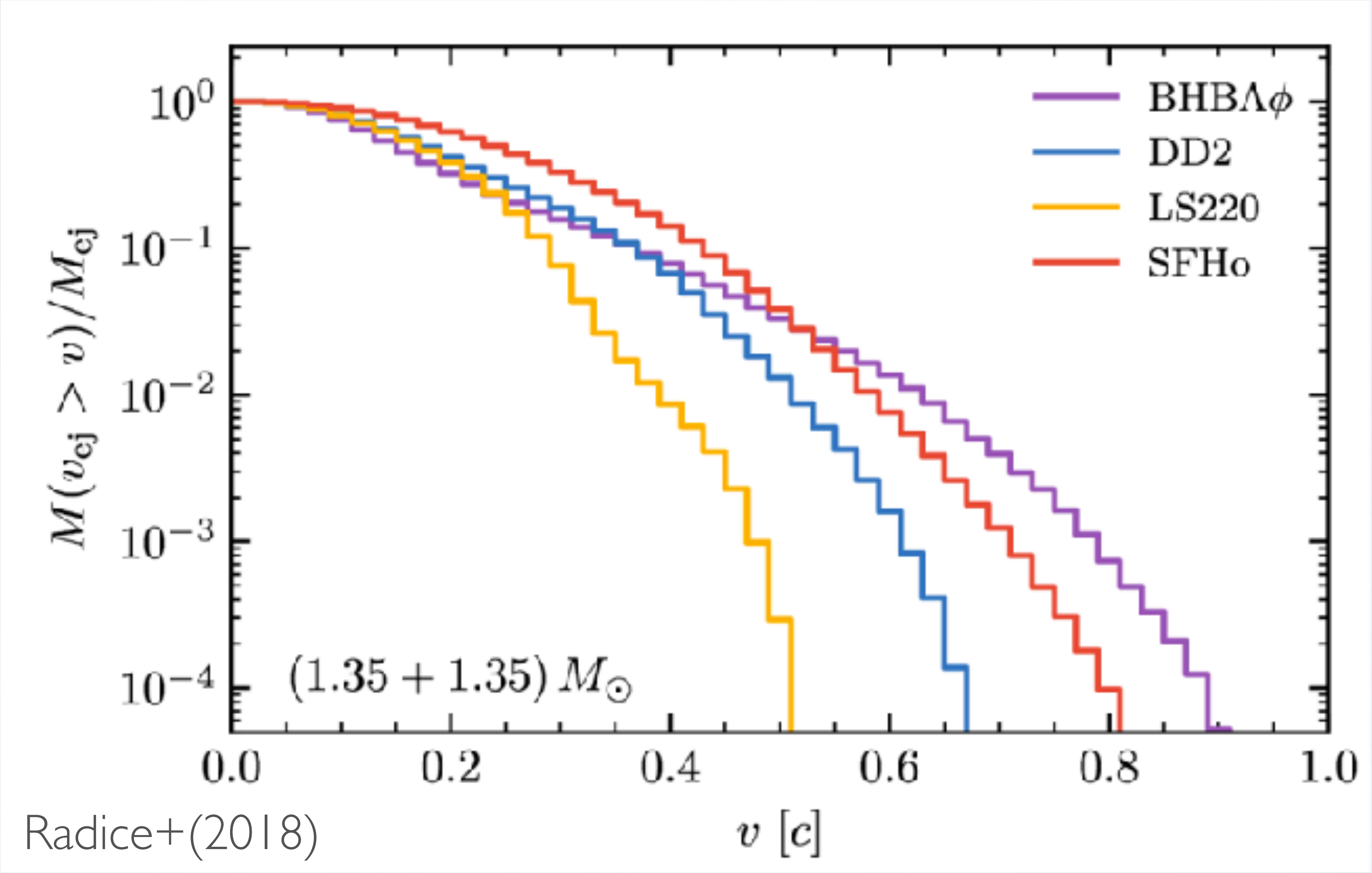
- The KN ejecta drives a shock through the external medium producing an afterglow (e.g., Nakar & Piran 2011)

- Modeling KN emission indicates ejecta with E ≈10^{51} erg, β ≈ 0.1-0.3 (e.g., Cowperthwaite+ 2018), leading to peak in the afterglow at ~10 yrs (e.g., Alexander+ 2018)

- Assume energy of KN ejecta has a power law dependance on 3-velocity $E(>\beta\Gamma) \propto (\beta\Gamma)^{-\alpha}$ (e.g., Hotokezaka+ 2018, Radice+ 2018)

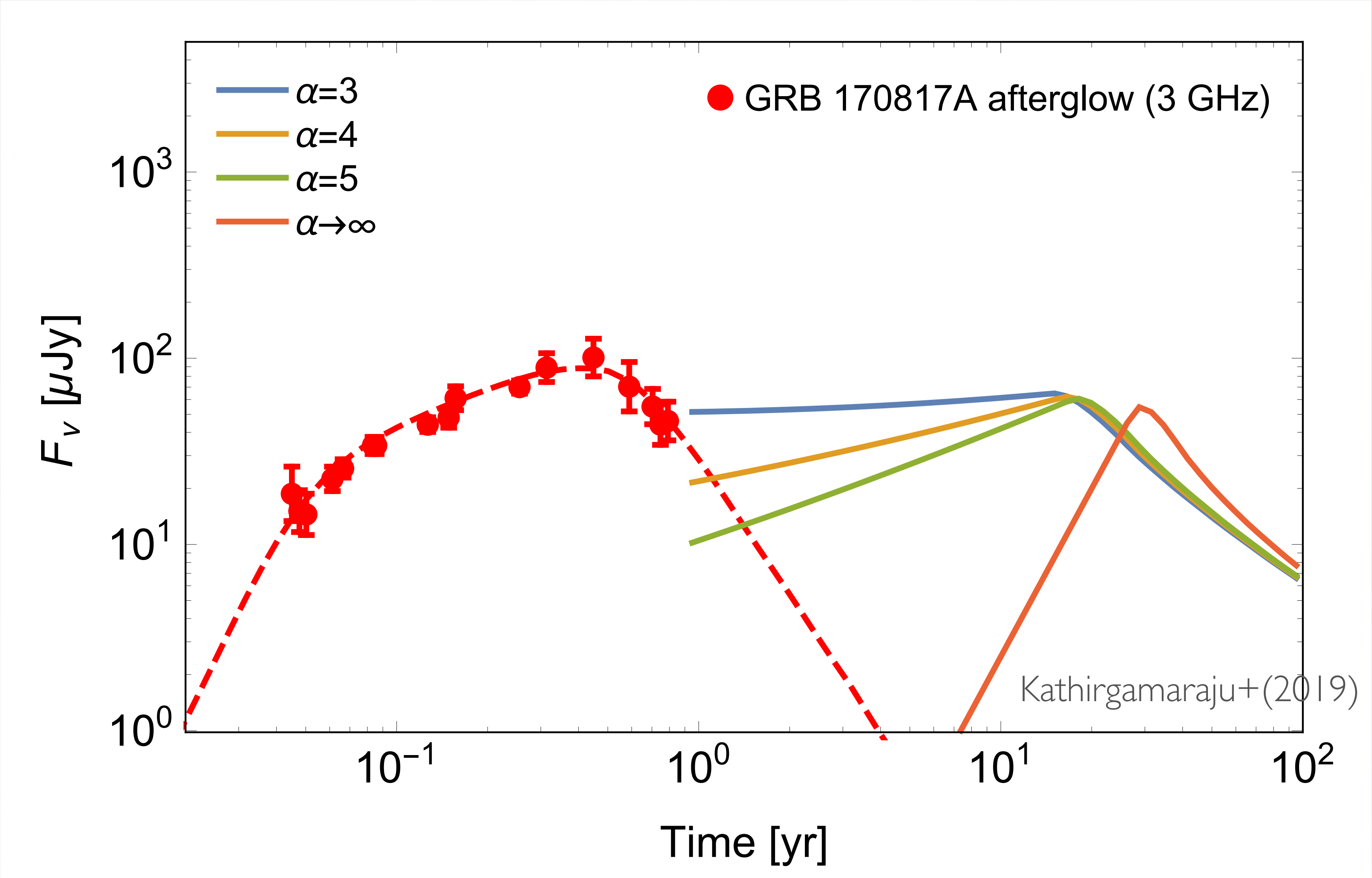
Modeling the kilonova ejecta

- Assume energy of KN ejecta has a power law dependance on 3-velocity $E(>\beta\Gamma) \propto (\beta\Gamma)^{-\alpha}$ (e.g., Hotokezaka+ 2018, Radice+ 2018)



Radice+(2018)

Inferences from the KN afterglow



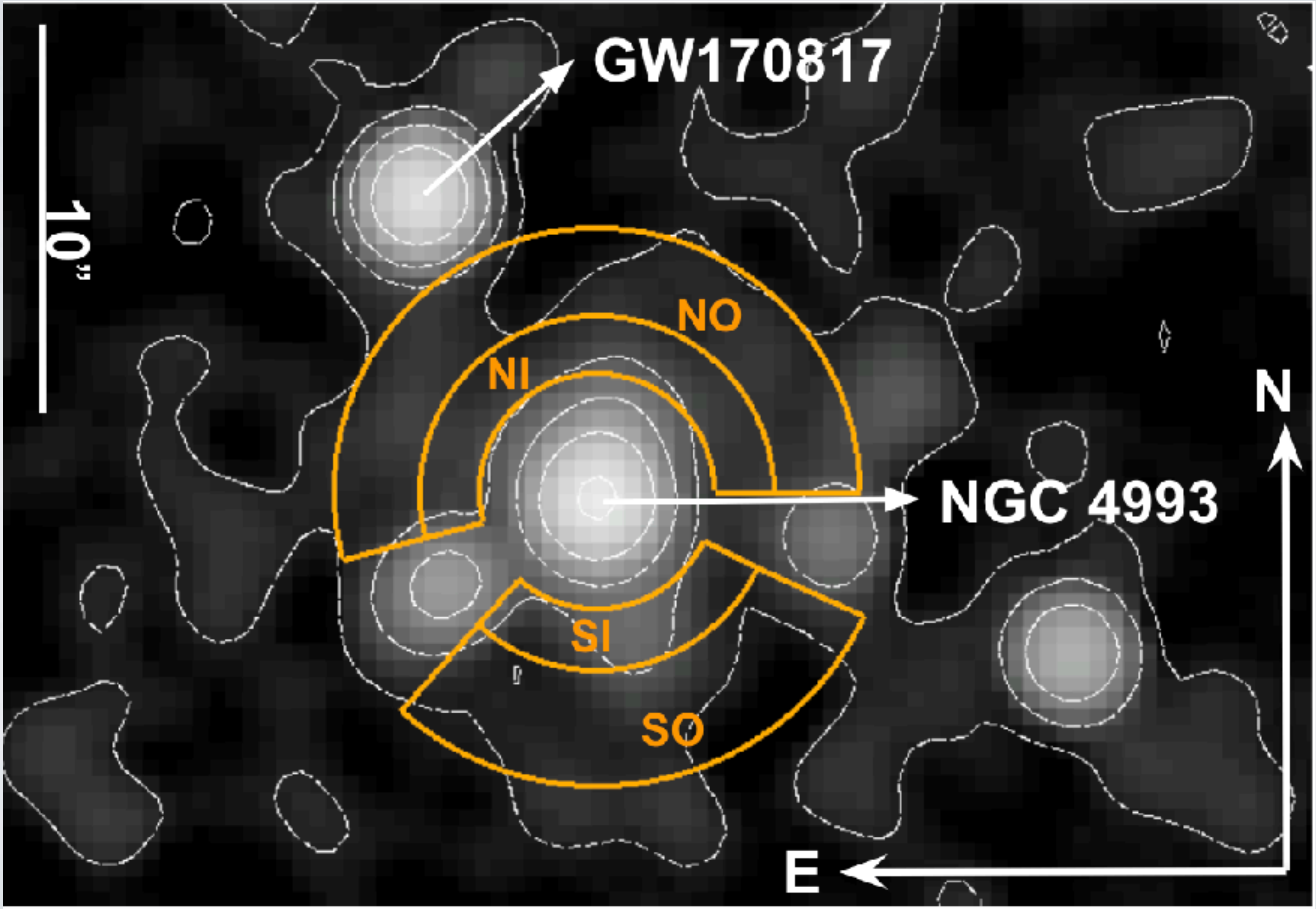
- Peak flux and time can constrain the external density bulk velocity and energy of the outflow

- Slope of light curve can constrain α (larger α leads to a steeper rise)

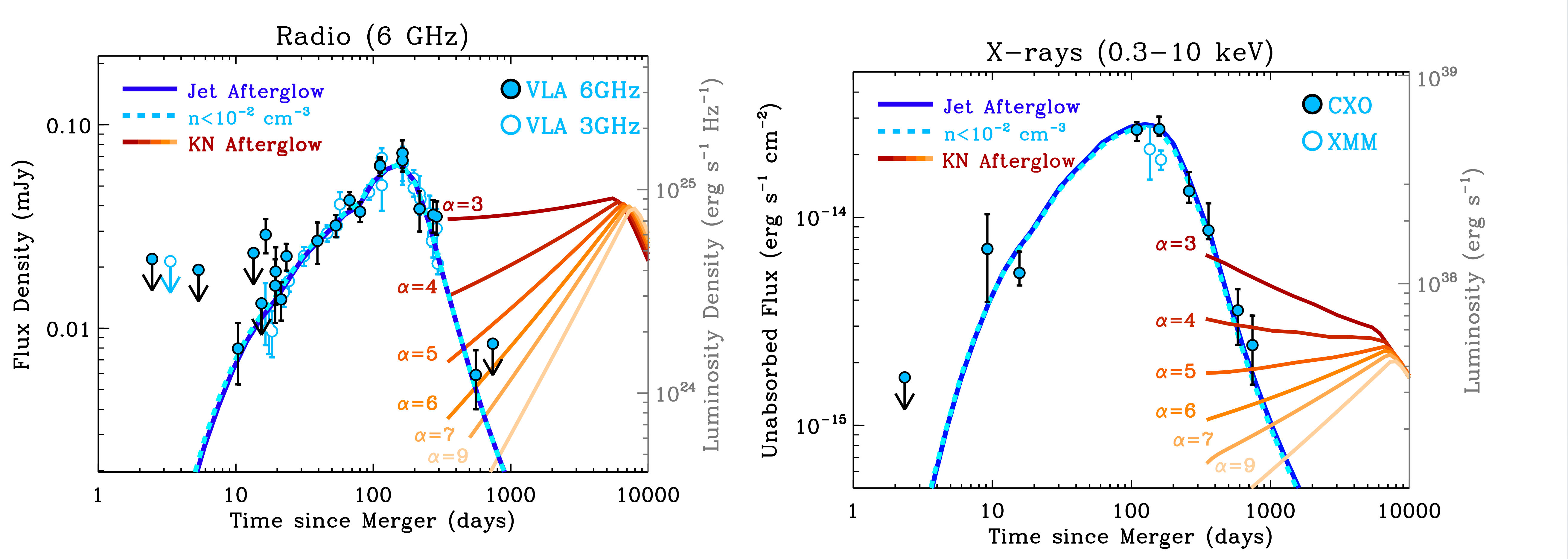
$$E(>\beta\Gamma) \propto (\beta\Gamma)^{-\alpha}$$

X-ray view of the host galaxy Hajela+ 2019

Constraints on ISM density n < 0.01/cc



The latest afterglow data and constraints Hajela+ 2019



Summary

- GW detections of NS mergers allow for unique probes of the structure of the outflowing gas

- Using 3D GRMHD simulations, we studied the emission from the jet of a post-merger system, without making any assumptions on the initial jet structure

- The result is a structured jet, which can explain the properties of both the prompt and afterglow emission of GRB 170817A

- Follow up observations of GW170817 may catch the emergence of the KN afterglow

Breakdown of afterglow from structured jet