Tenth International Fermi Symposium
9th-15th October 2022

Studying the viewing geometry of sGRBs and central engine using prompt emission

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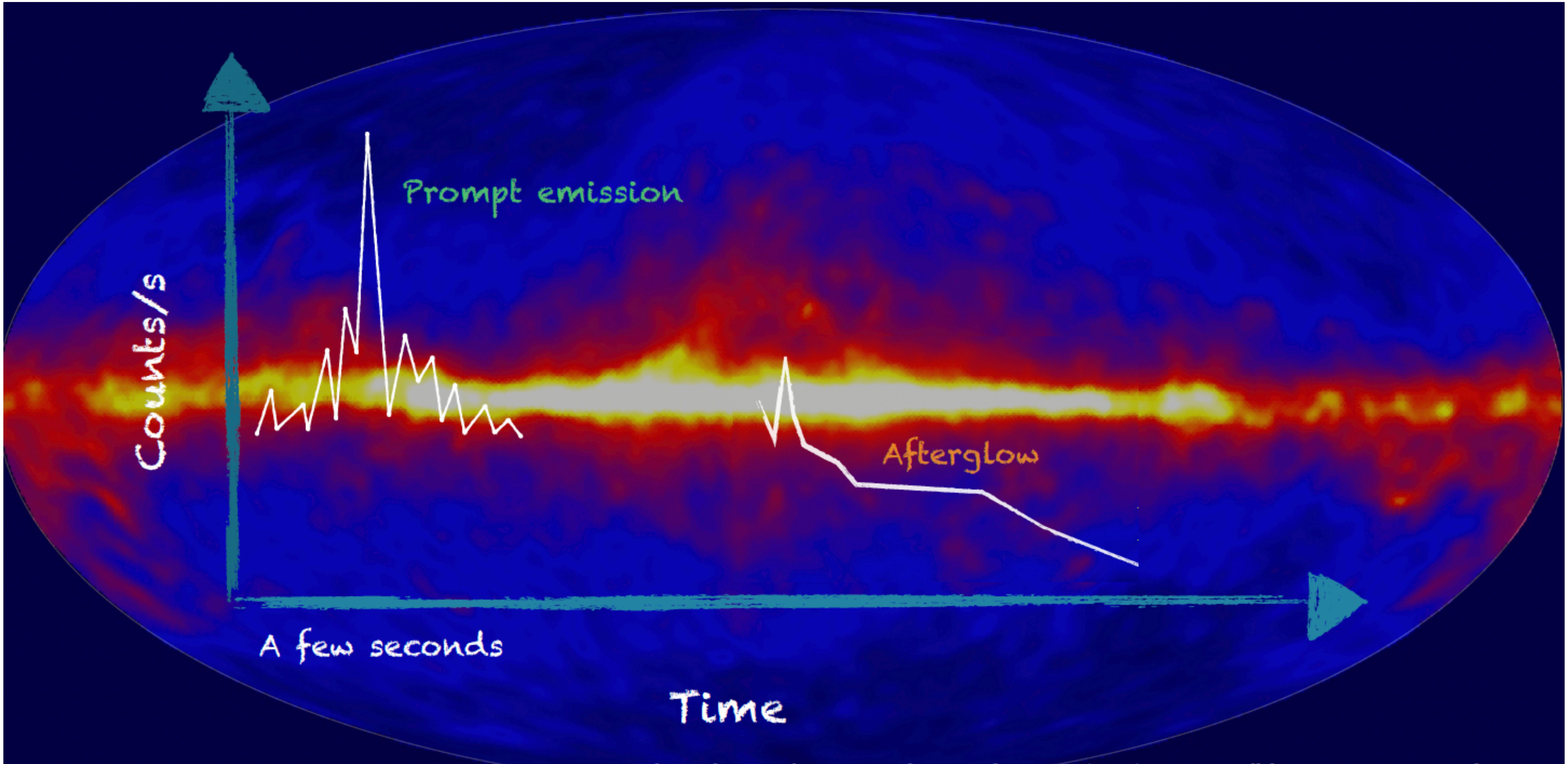
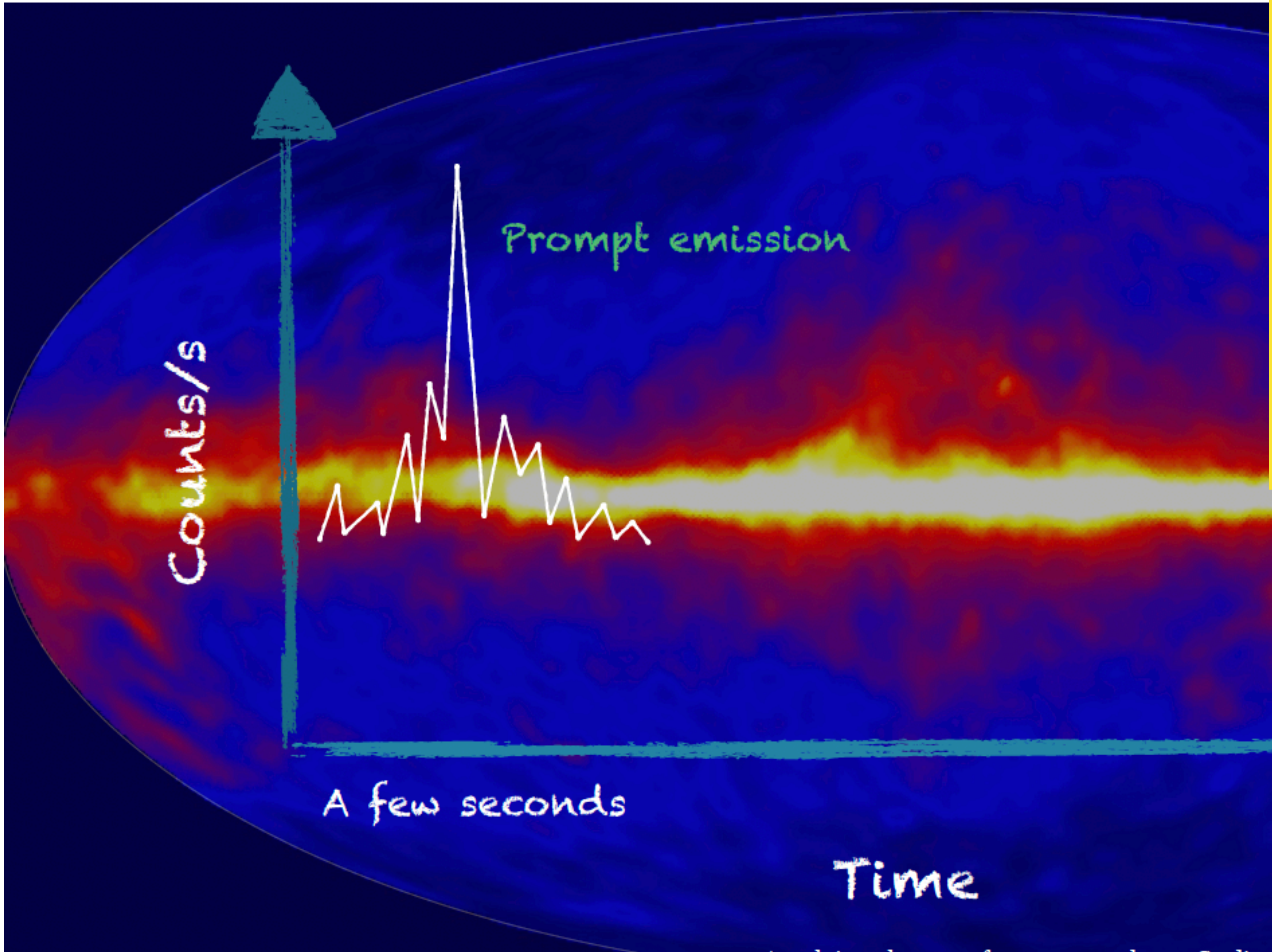
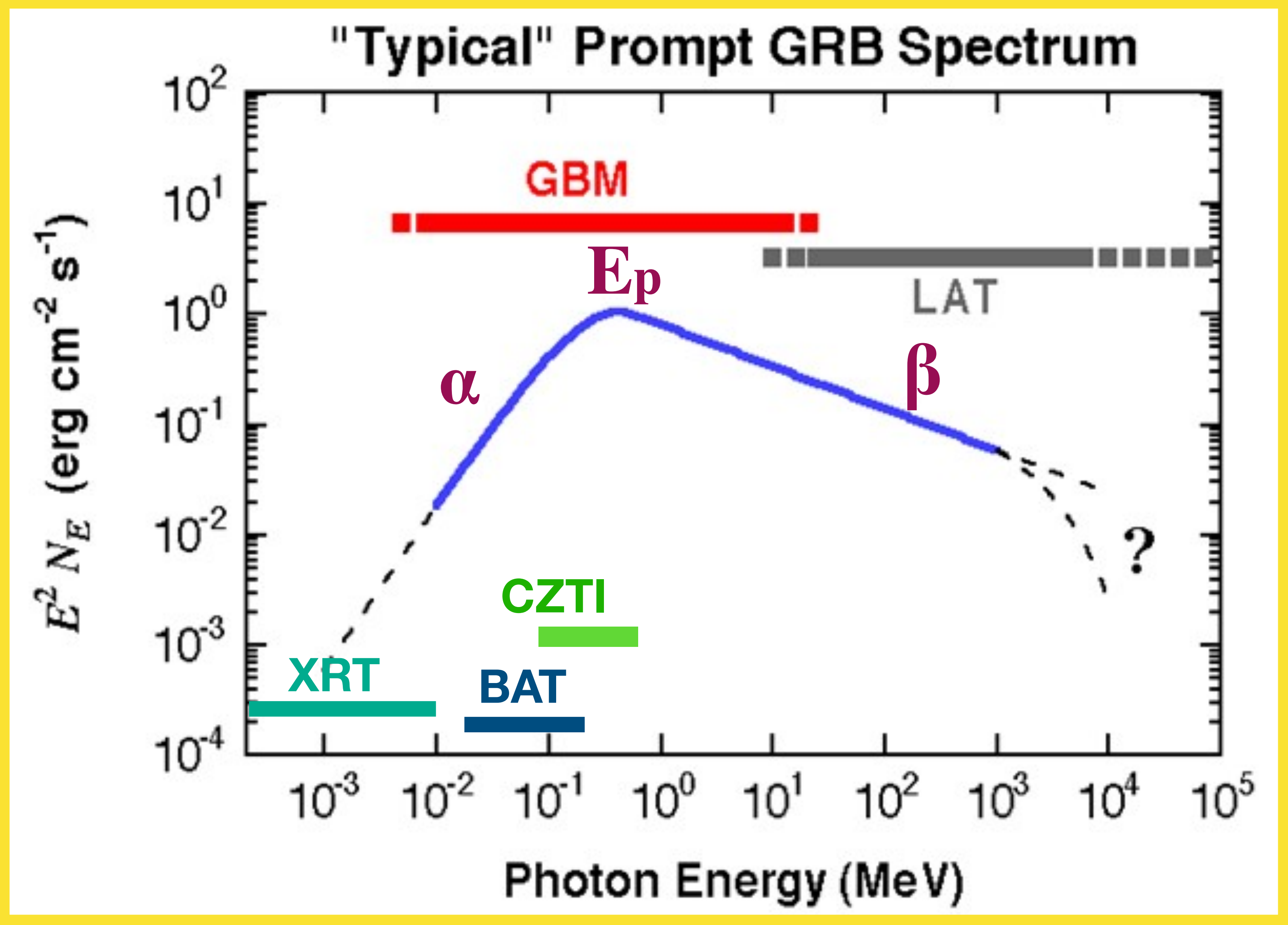
Gamma-ray Bursts



A real time sky-map of a gamma-ray burst: Credits - NASA/DOE/Fermi LAT Collaboration, animation - Andrew Levan

Gamma-ray Bursts





GRB Spectra

e.g. Band Model

(Band et al. 1993)

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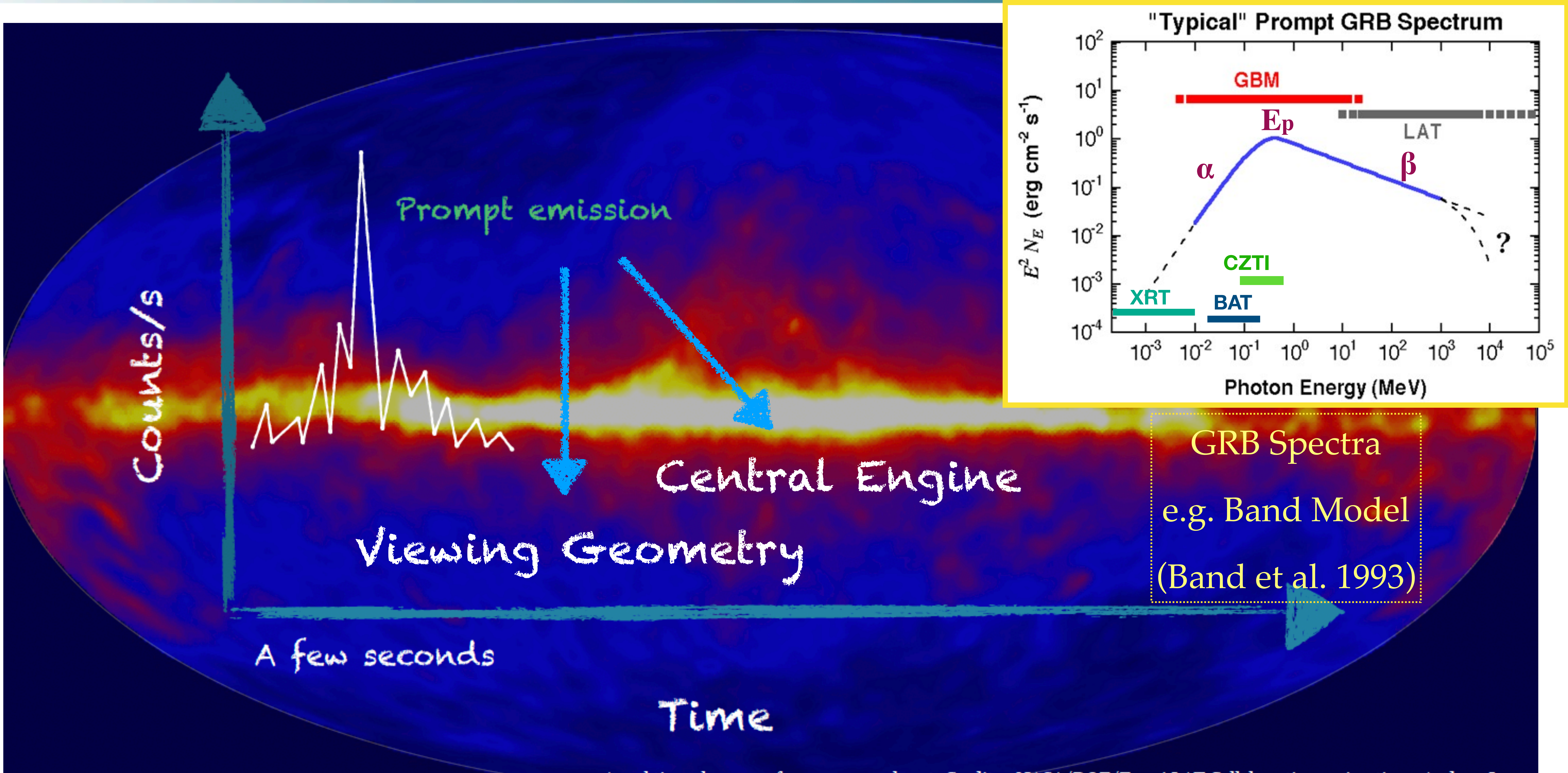
Gamma-ray Bursts



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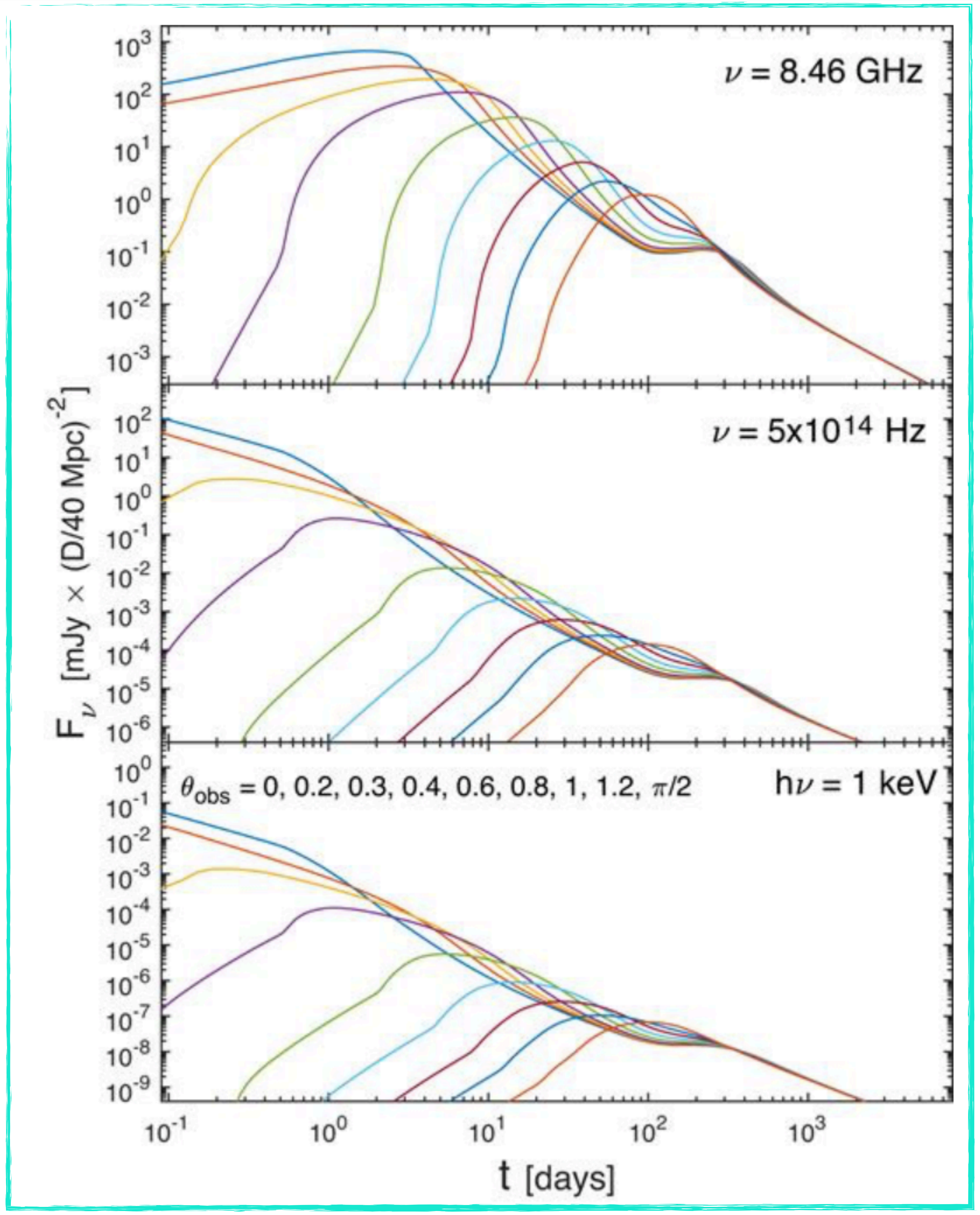
Viewing Geometry

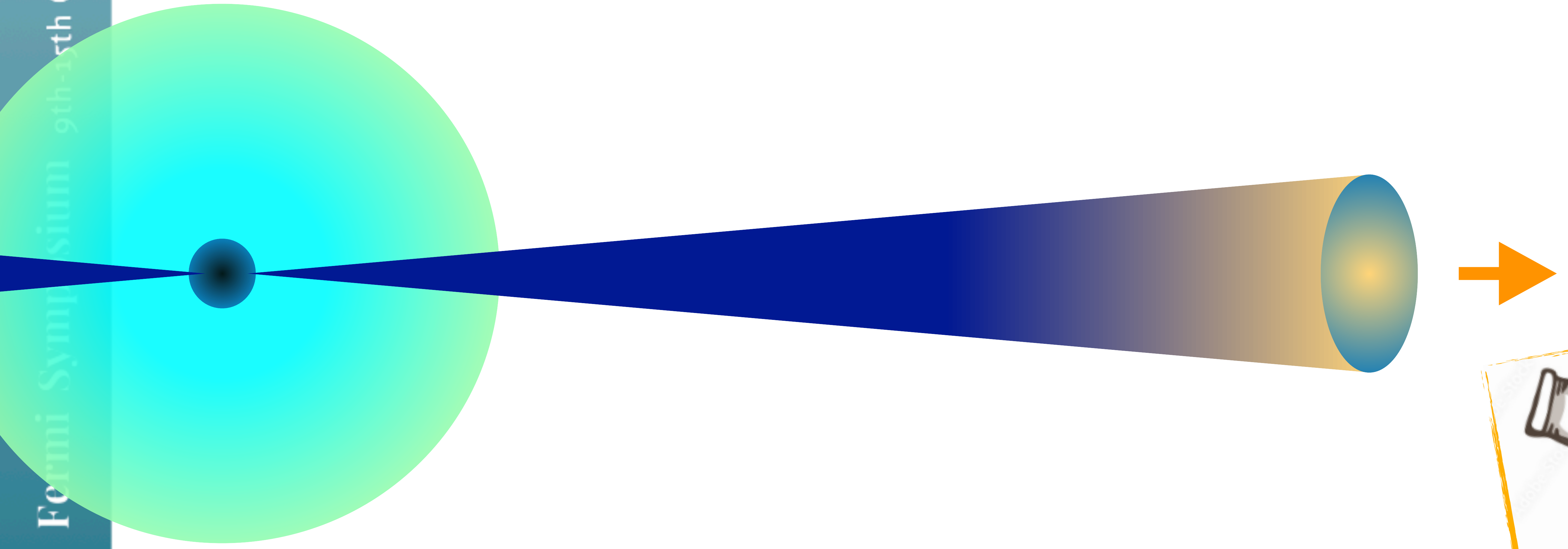
Short GRB 170817A

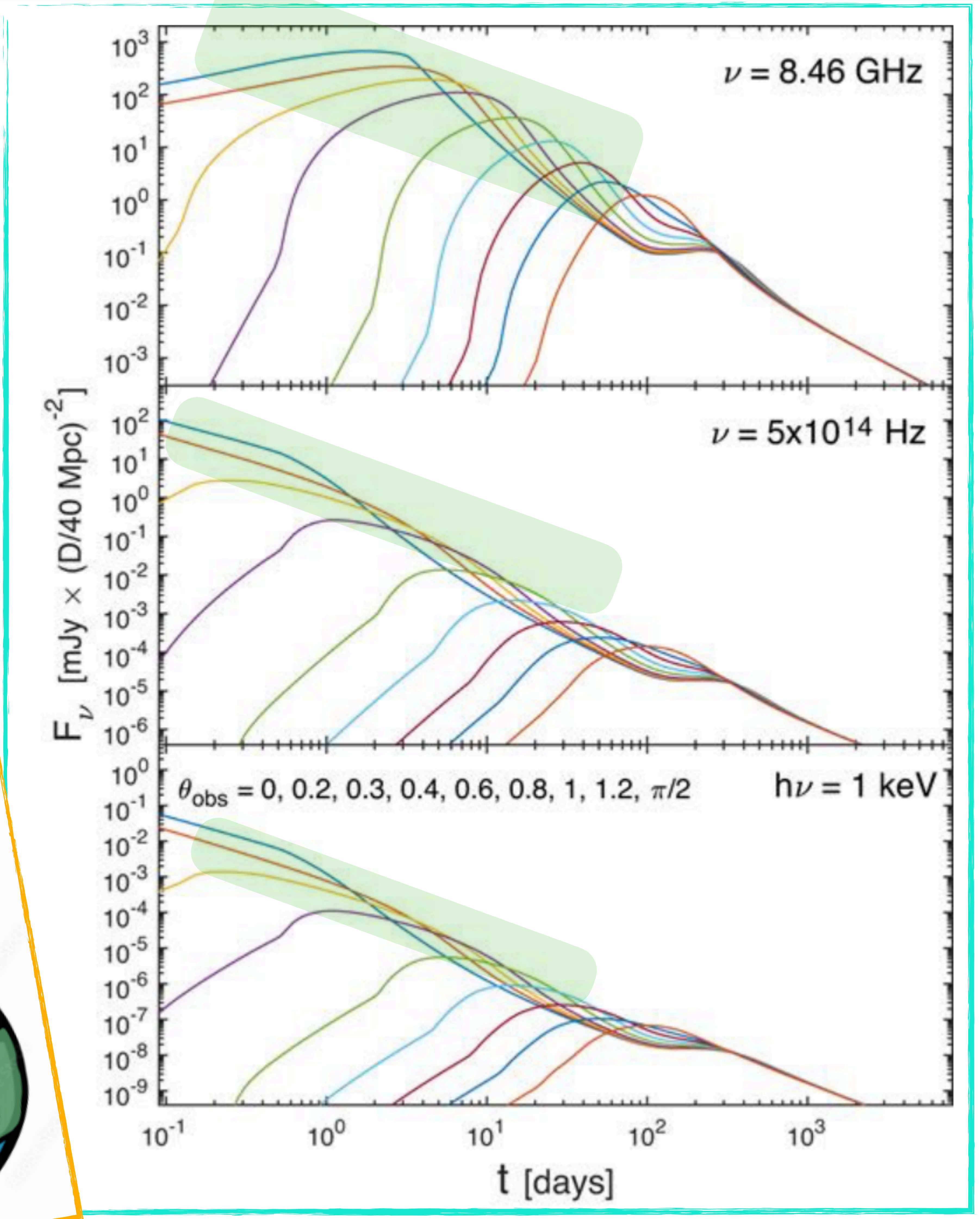
➡ Jet is viewed Off-axis



Granot et al 2018

Jet is viewed On-axis





Granot et al 2018

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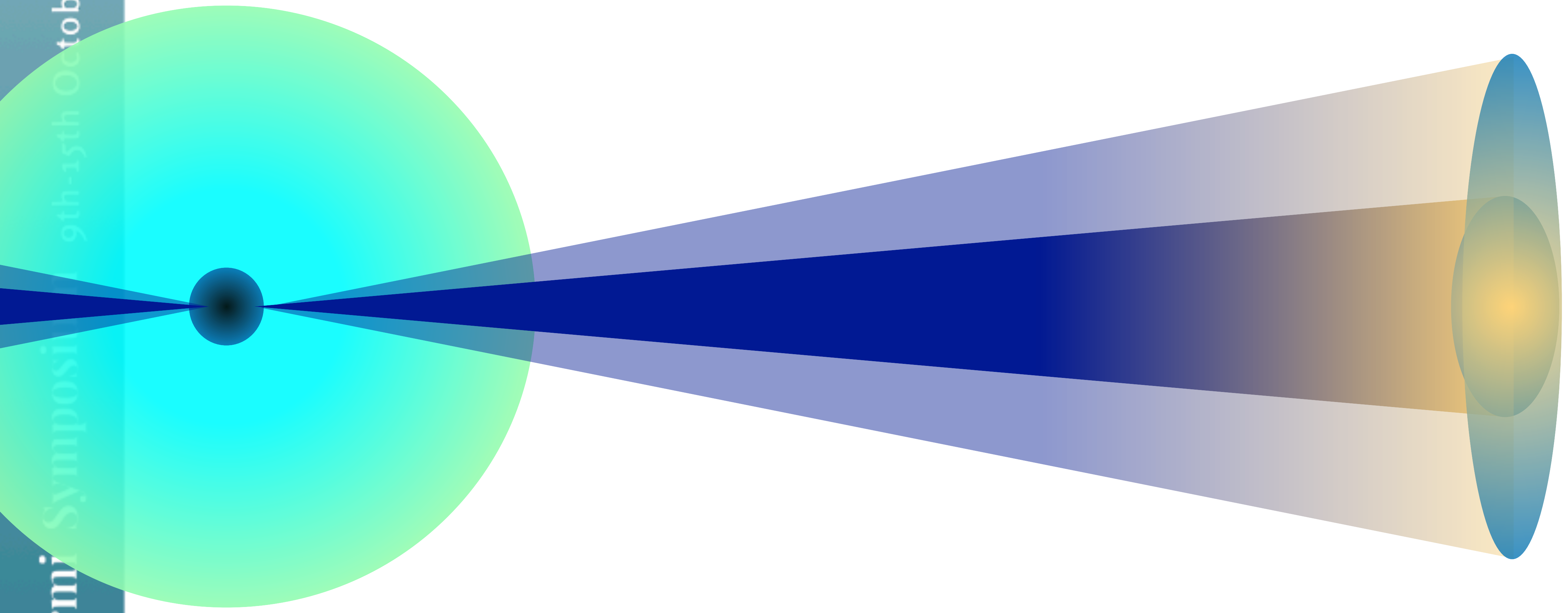

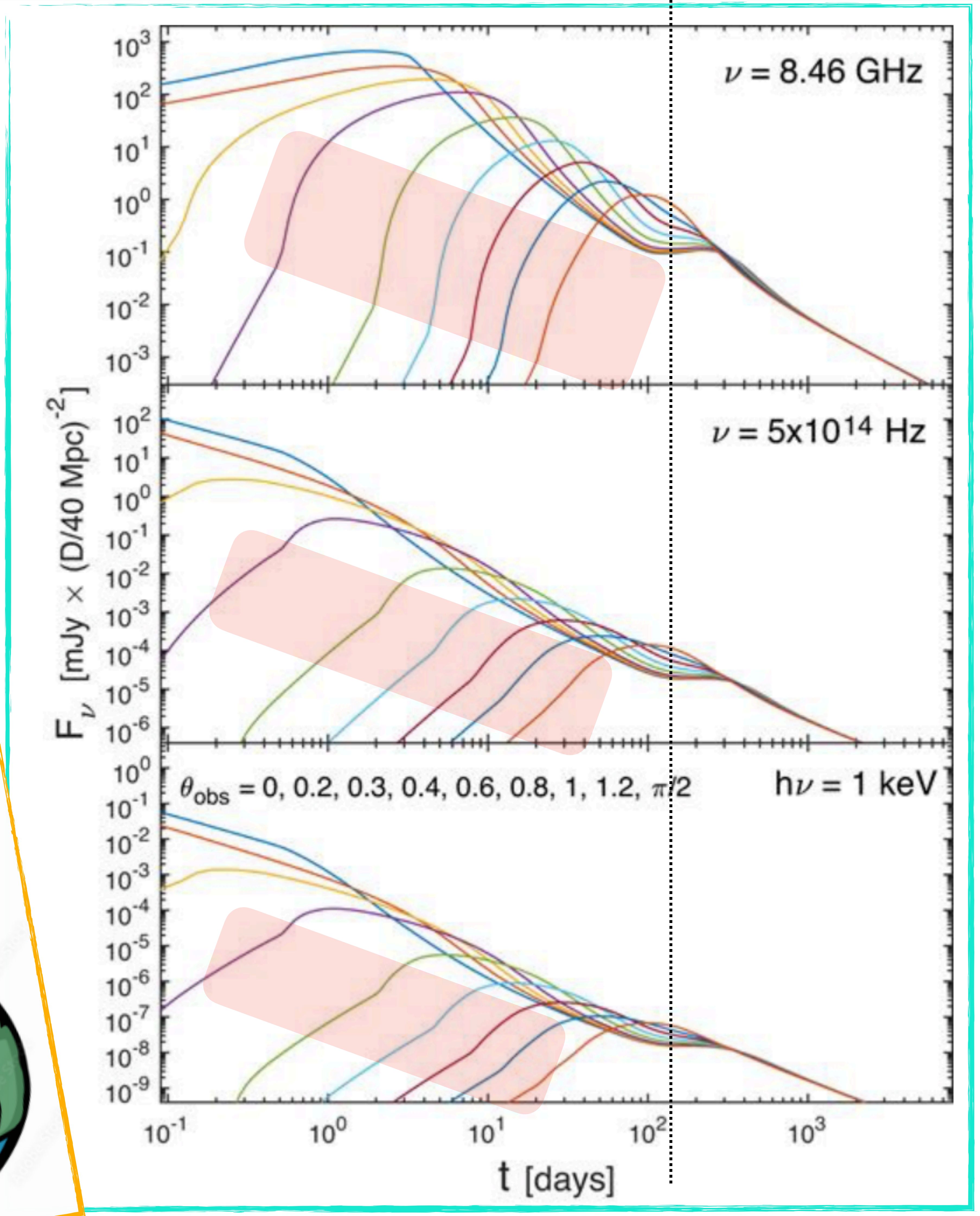

Granot et al 2018

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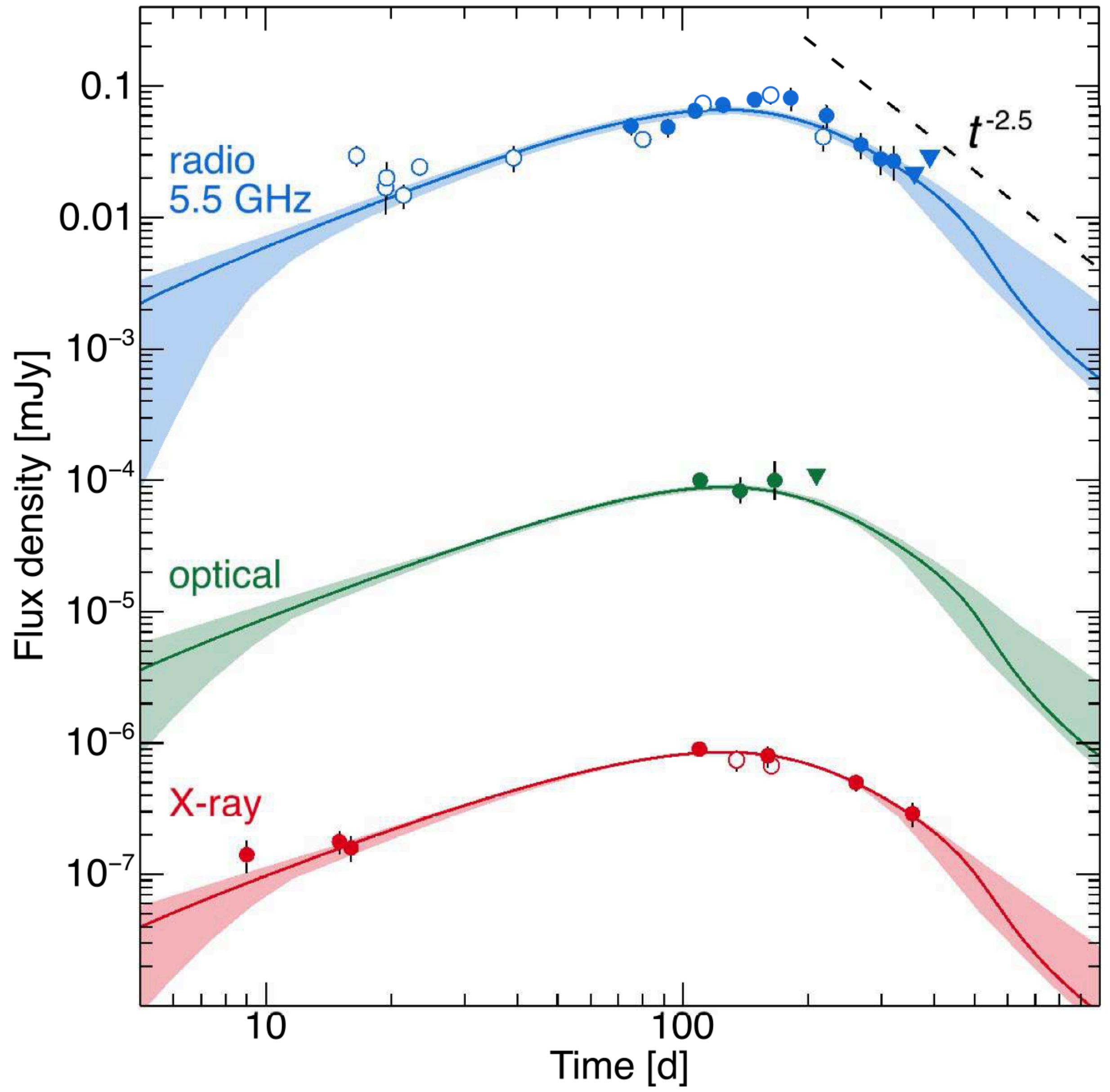
Prompt Emission Study

Short GRB 170817A

➡ Structure beyond jet core

➡ Jet is viewed Off-axis



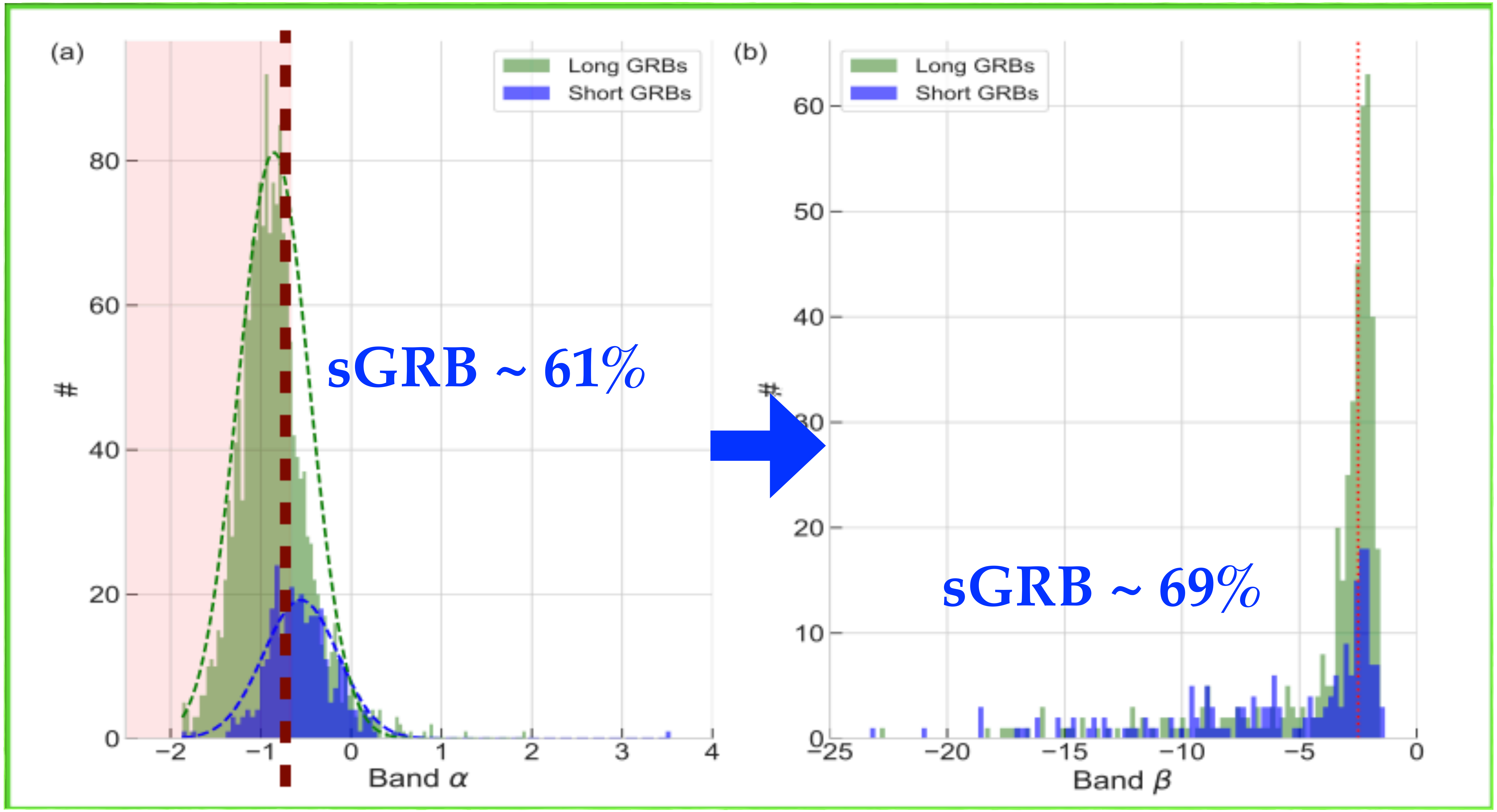
Troja et al 2019

Observed prompt spectra carries imprints of structure jet effects

Jet Off-axis or On-axis; is studied by `AFTERGLOW' light curve !!!

Can `PROMPT SPECTRA' provide a clue about viewing geometry ??

Motivation: Hard & Narrow Spectra



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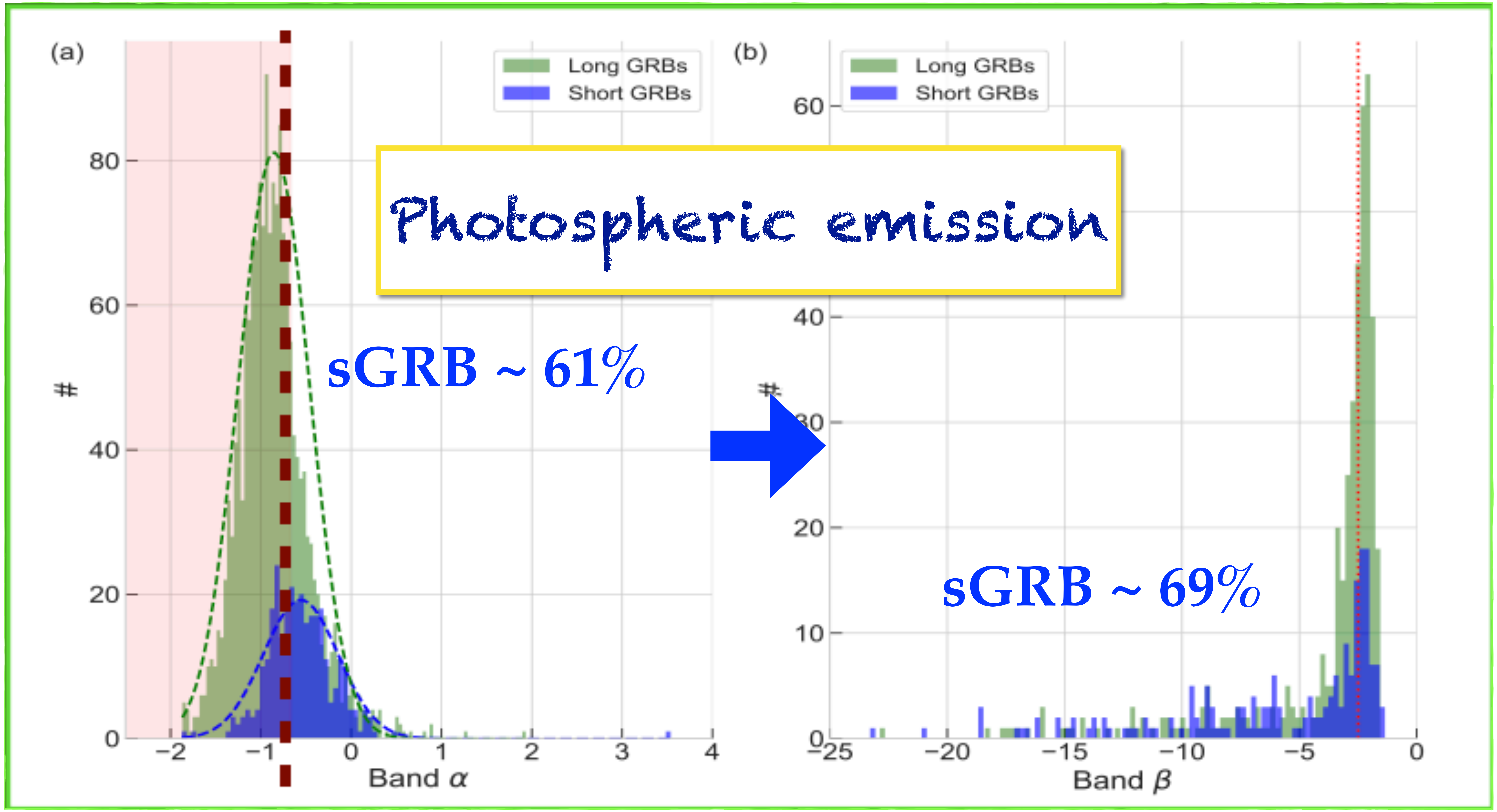
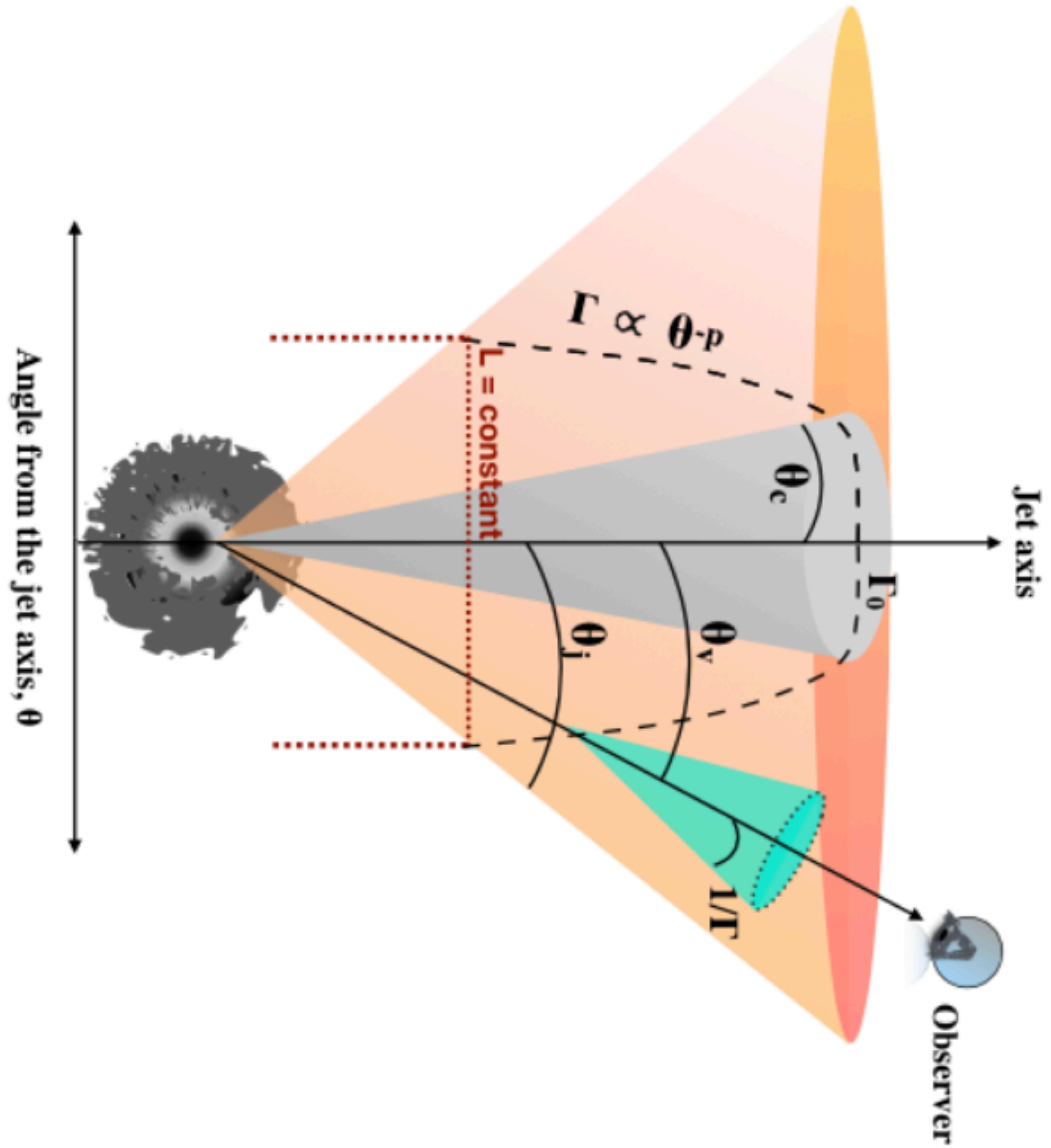


Consistent with Acuner & Ryde 2018 and Dereli-Bégué et al 2020

Physical model with structural jet profile



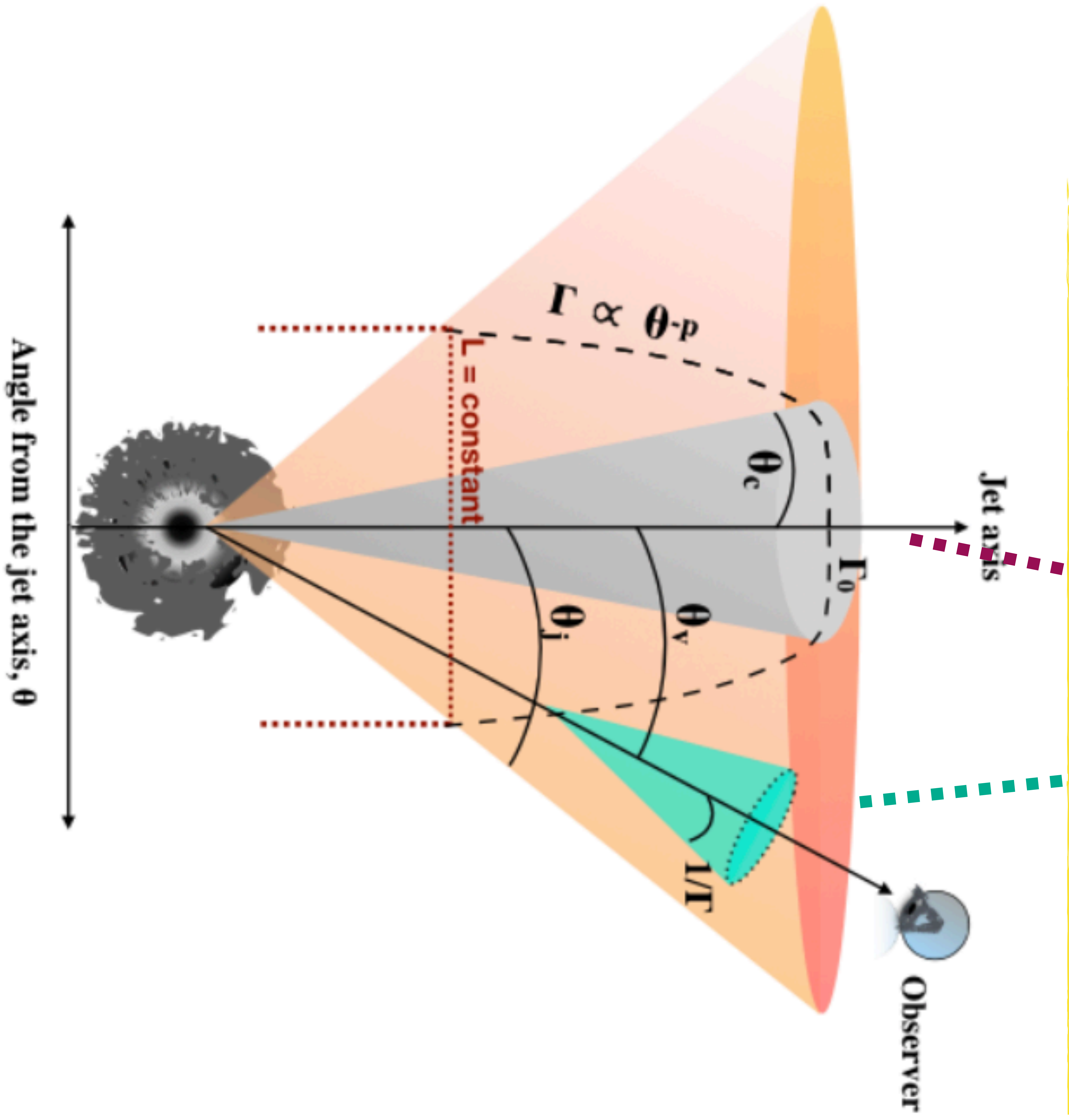
Lundman et al. 2013

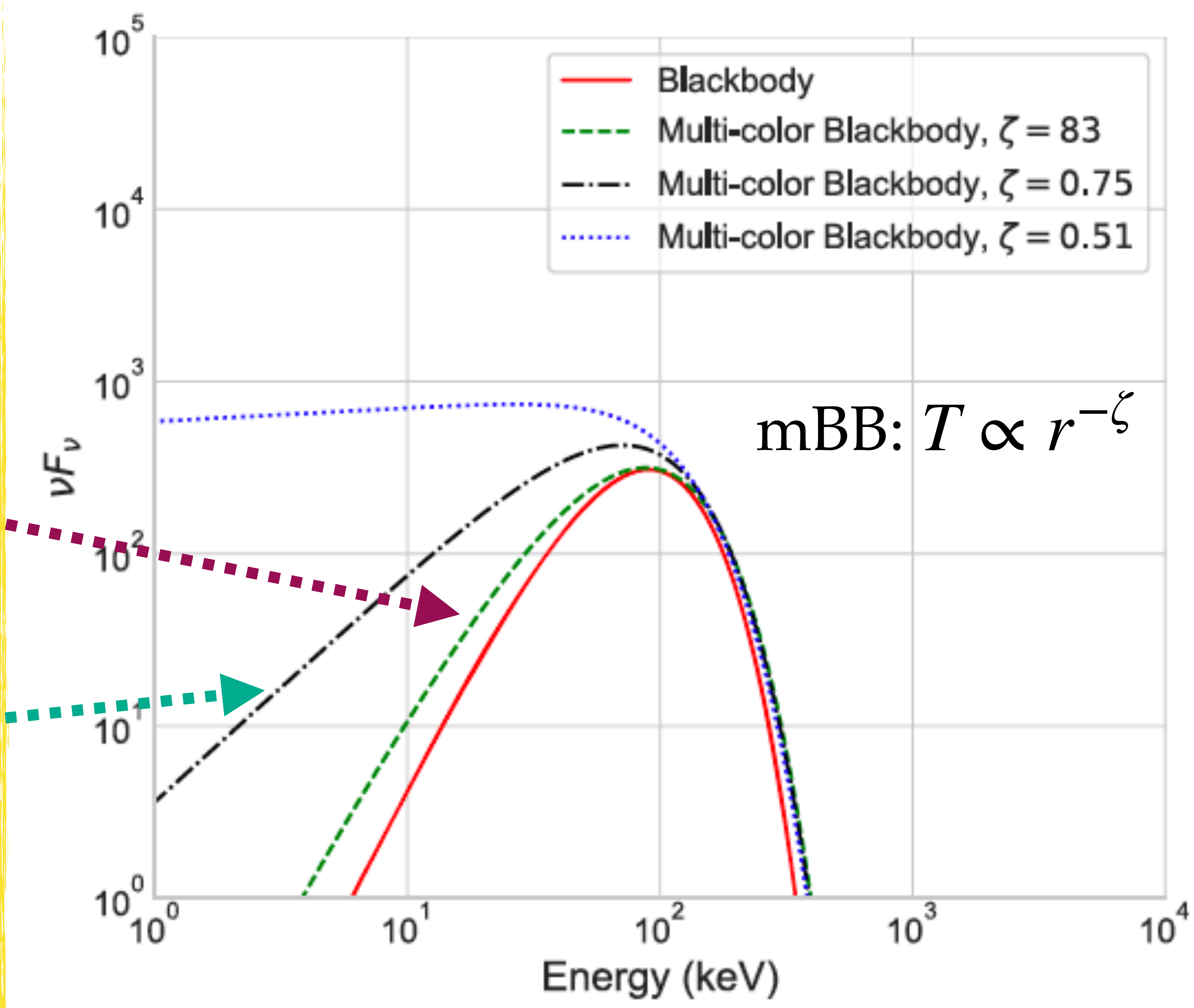
- Monte Carlo Simulation for 3D jet structure
- Non-dissipative photosphere
- Angle-dependent Lorentz Factor Profile,
  $\Gamma \propto \theta^{-p}$

✓ Depending upon viewing angle:
Hard to Soft alpha

✓ Obtained spectrum:
Superposition of many black-bodies

Multi-color blackbody spectra





mBB: $T \propto r^{-\zeta}$

Probing Geometry from prompt spectra

➡ **39 sGRBs:** Fermi & Swift detected + known redshift (2004-2018)

➡ **Spectral** model: Blackbody (BB) or diskpBB (mBB)

✓ **37 GRBs: ~ 69% mBB, ~ 26% BB** —> Studying Structured Jet Model

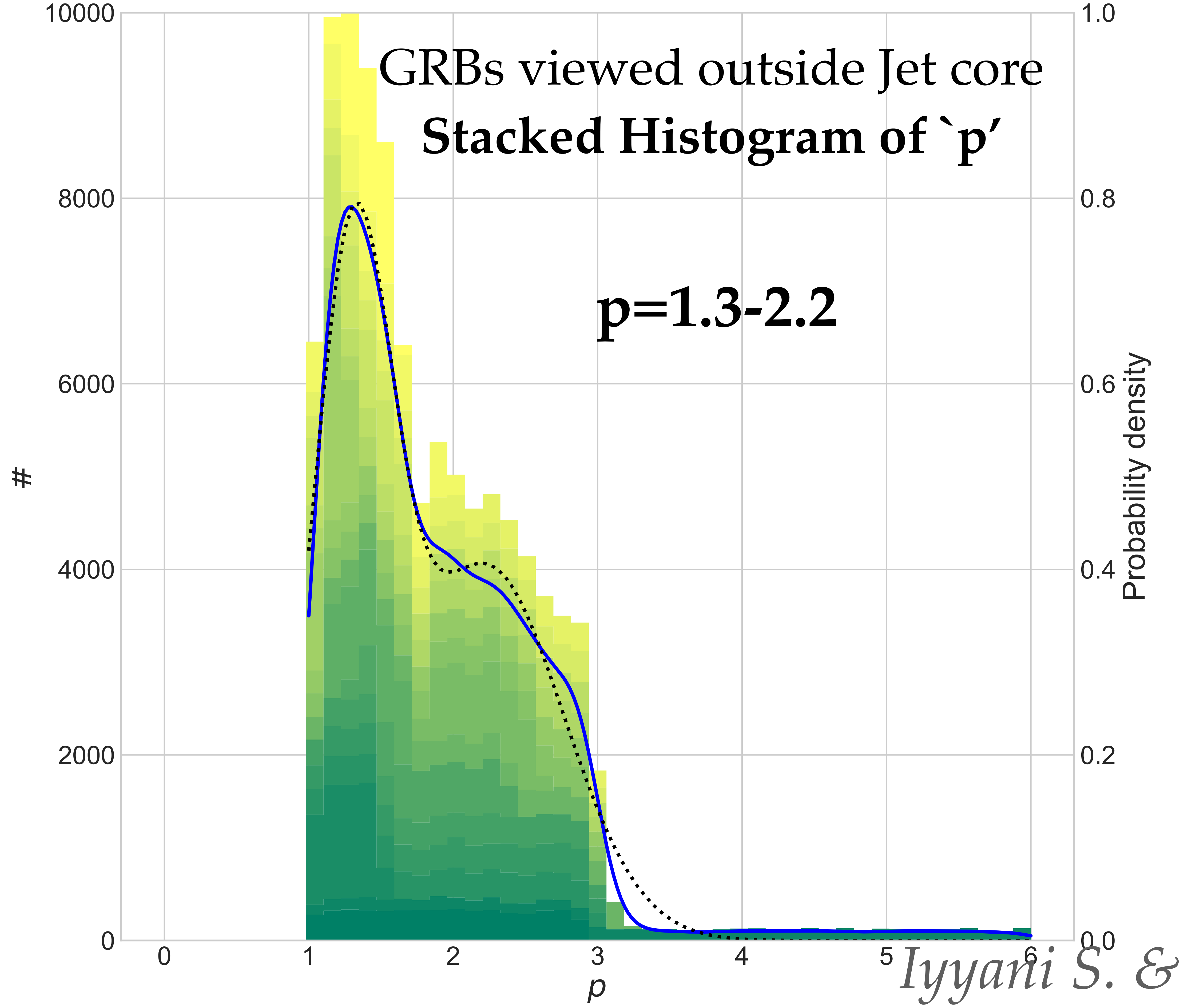
Lundman et al. 2013: predicted `$\alpha$' & `p' ($\Gamma \propto \theta^{-p}$) relation

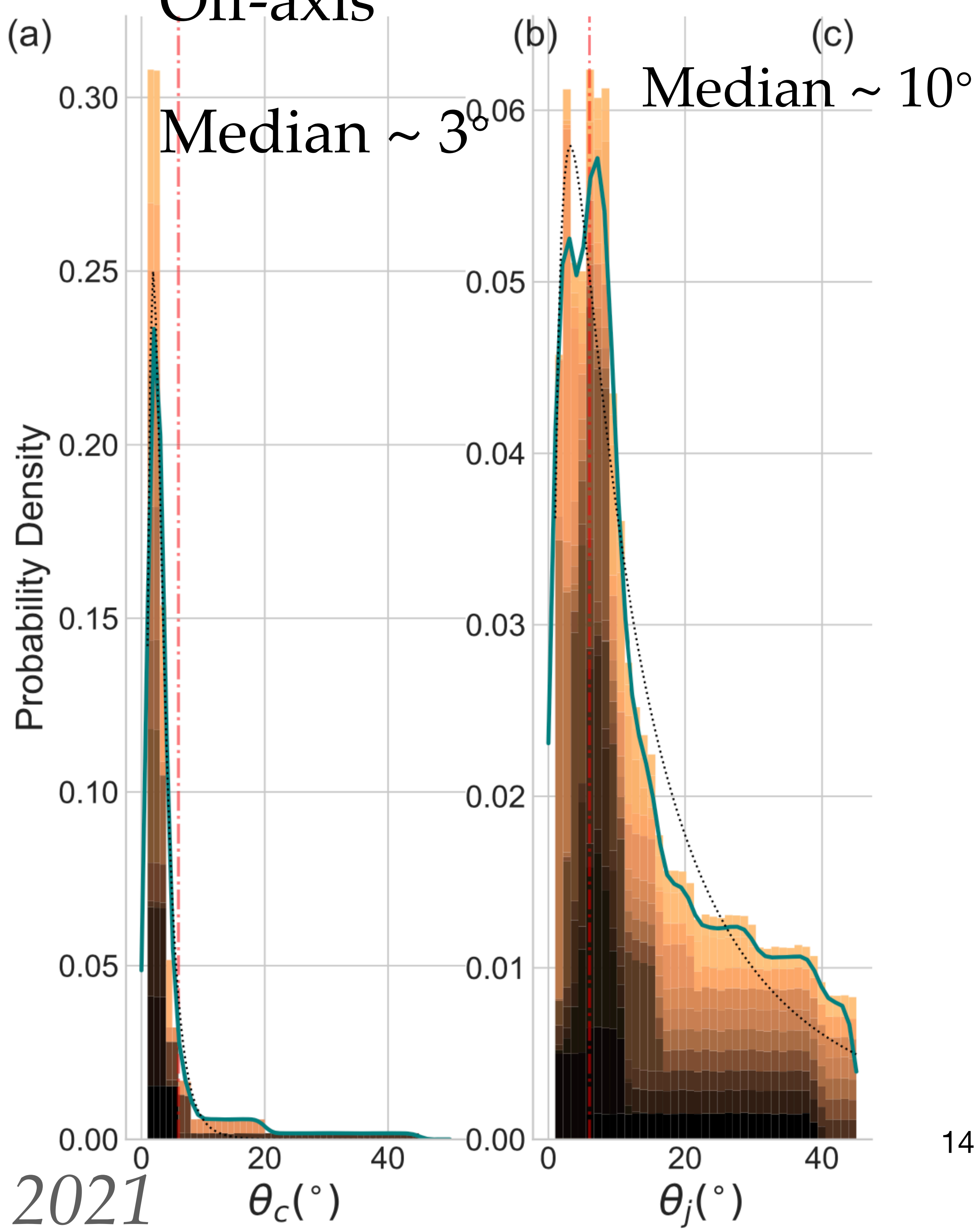
- $-1 < \alpha < -0.5$: Photospheric spectra for off-axis observer
- $\alpha > -0.5$: Viewed on-axis

Structured Jets

Outside Jet Core —> 16/37~43%: $\alpha < -0.5$ and jet opening angle not observed

Within Jet Core —> 57%: $\alpha > -0.5$ Or, Jet break





Iyyani S. & Sharma V., ApJS 2021

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Results

(1) **39 short GRBs:** Fermi & Swift detected + known redshift (2004-2018)

(2) We observe 37/39 ~ 95% are consistent with Photospheric emission model; 69% are consistent with multicolor blackbody & rest 26% with blackbody model.

(3) For the First time, **Prompt Emission** is used for **probing the Viewing Angle**.

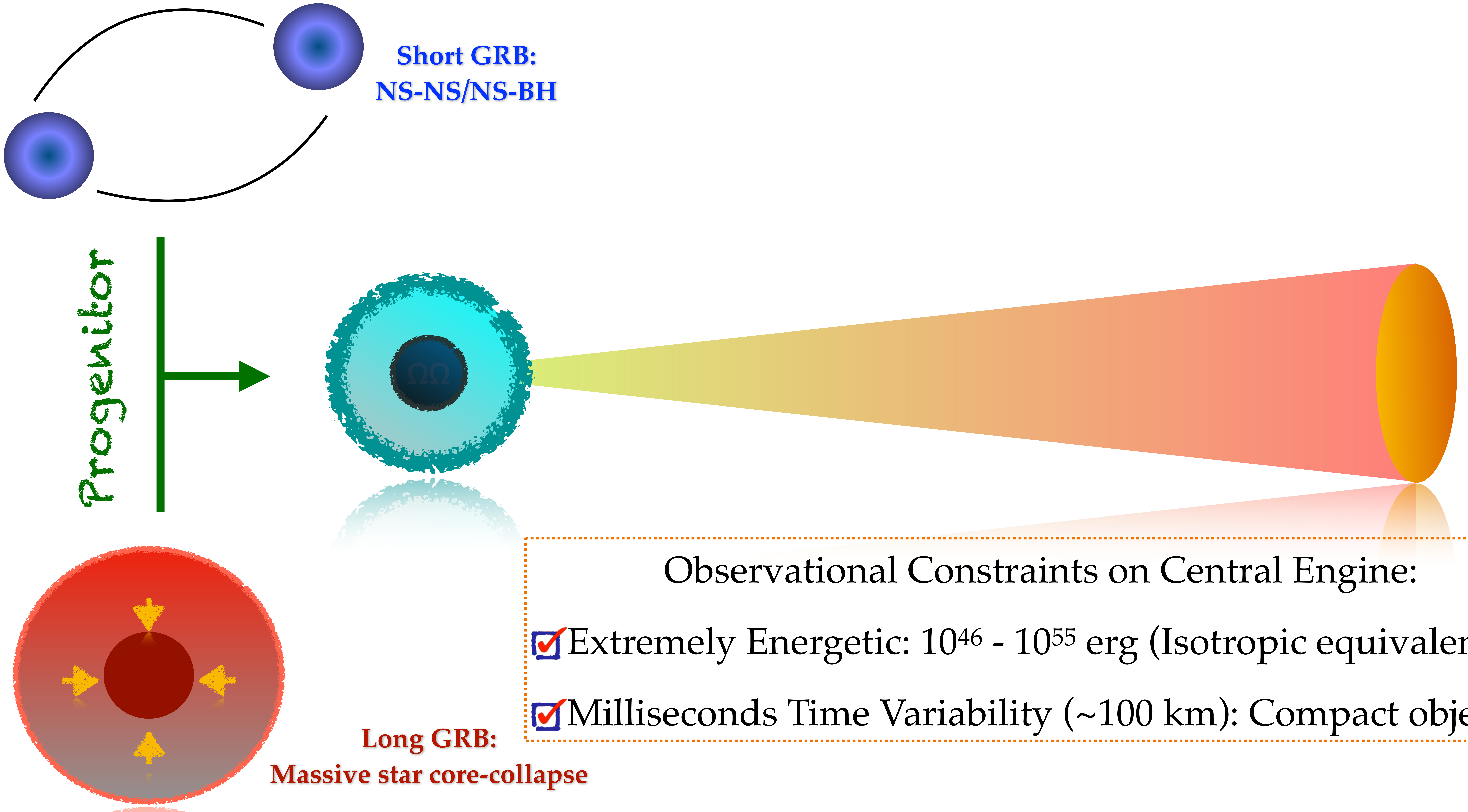
✓ 57%: On-axis ones Intrinsic jet luminosity is found to be, 10^{48} - 10^{53} erg/s.

(4) For the GRBs viewed by off-axis are found to possess narrow jet core, $\theta_c \sim 3°$.

The detection of bright sGRBs with LIGO is inferred as 0.19–2.87 events per year.

Conclusion: Simple non-dissipative photospheric emission model; allows us to access viewing geometry & Lorentz Factor profile of jet!

Nature of central engine



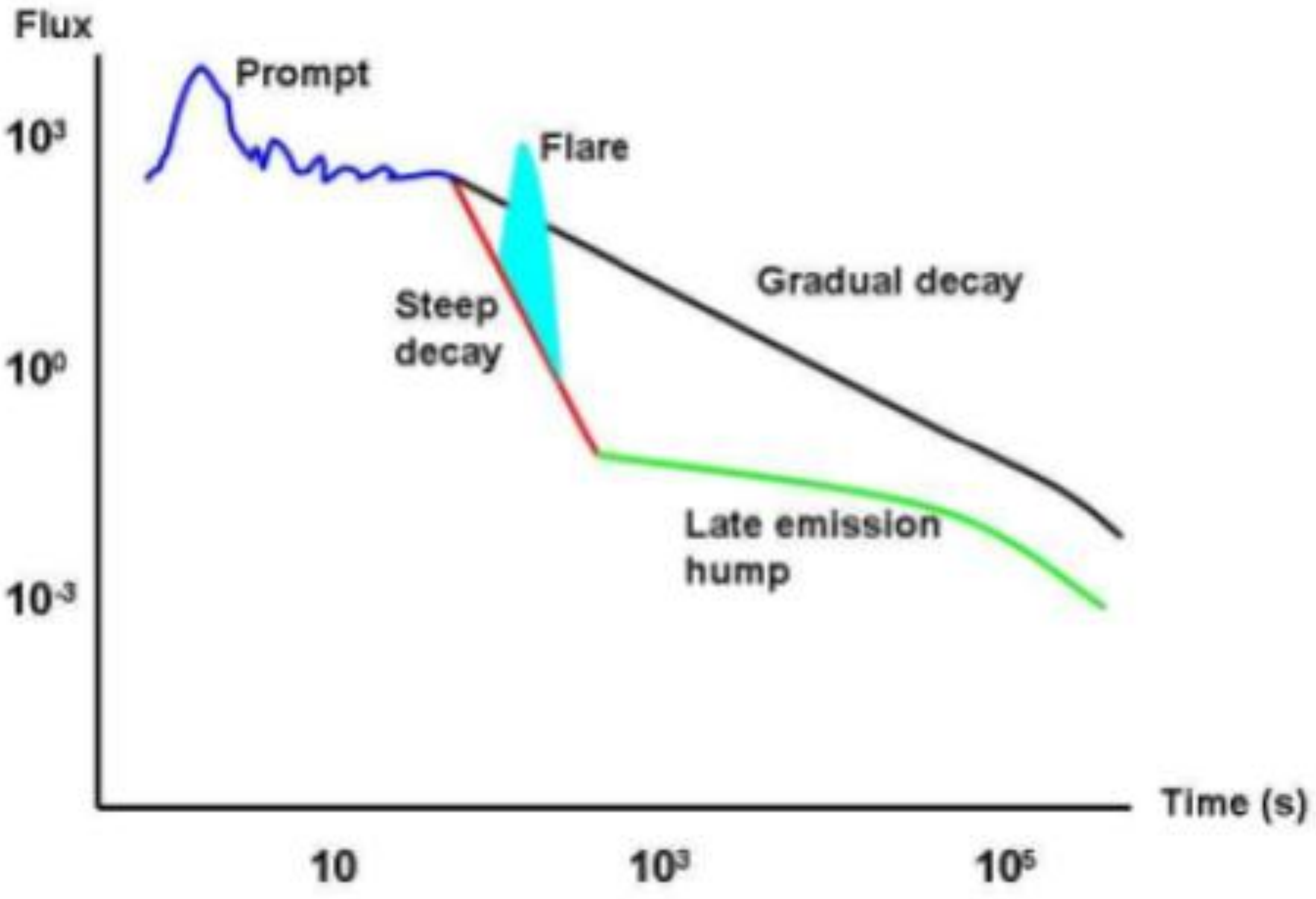
Observational Constraints on Central Engine:

- ☑ Extremely Energetic: 10^{46} - 10^{55} erg (Isotropic equivalent)
- ☑ Milliseconds Time Variability (~100 km): Compact objects

Sources powering the GRBs

Hyper-accreting stellar-mass Black hole or
Rapidly spinning, highly magnetised NS, Magnetar

(a) Afterglow light curve shows late time activity:
Magnetar Or Black hole model,
External shock, Viewing angle effect.



O'Brien et al 2007

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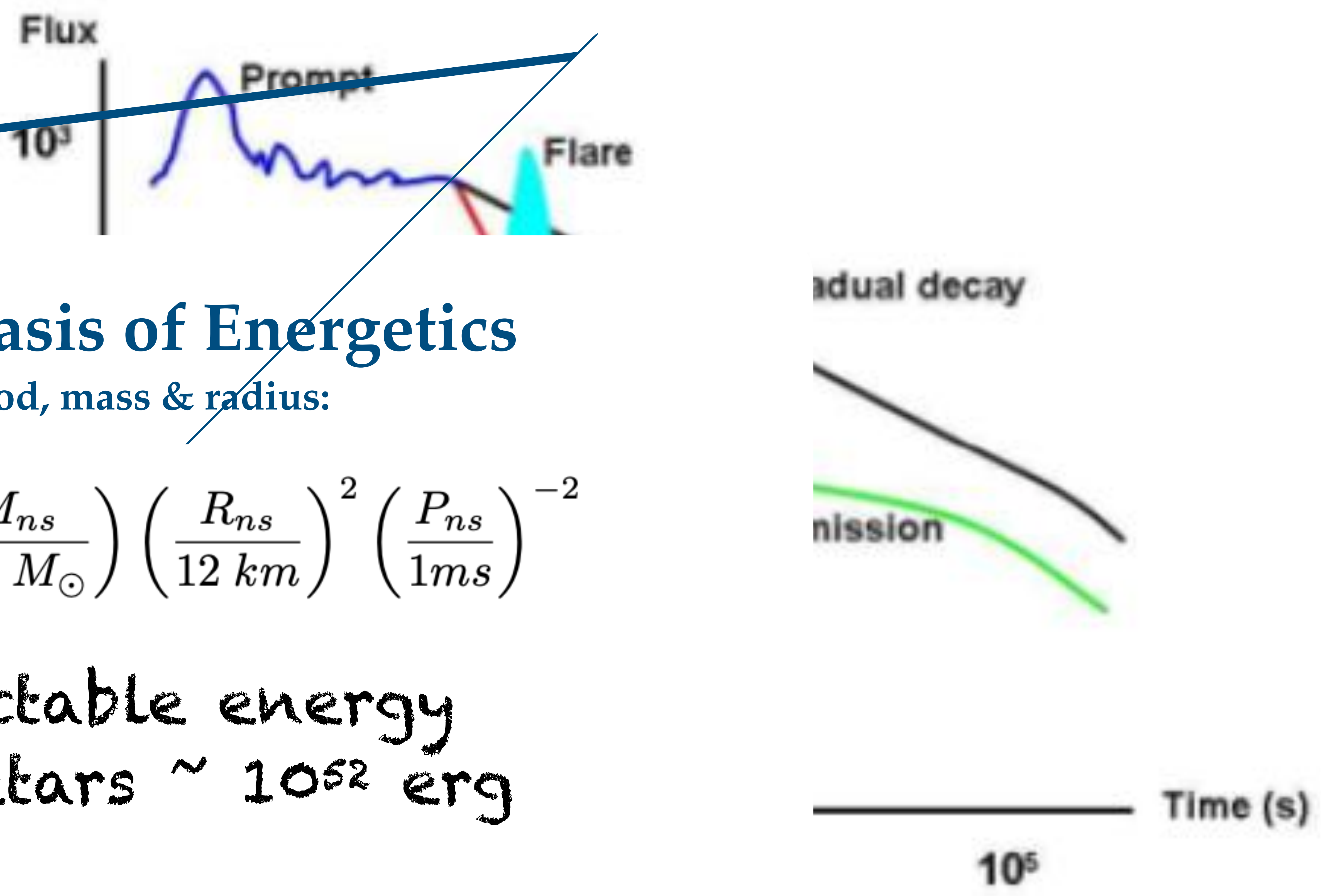


(b) Probing on the basis of Energetics

Based on observed period, mass & radius:

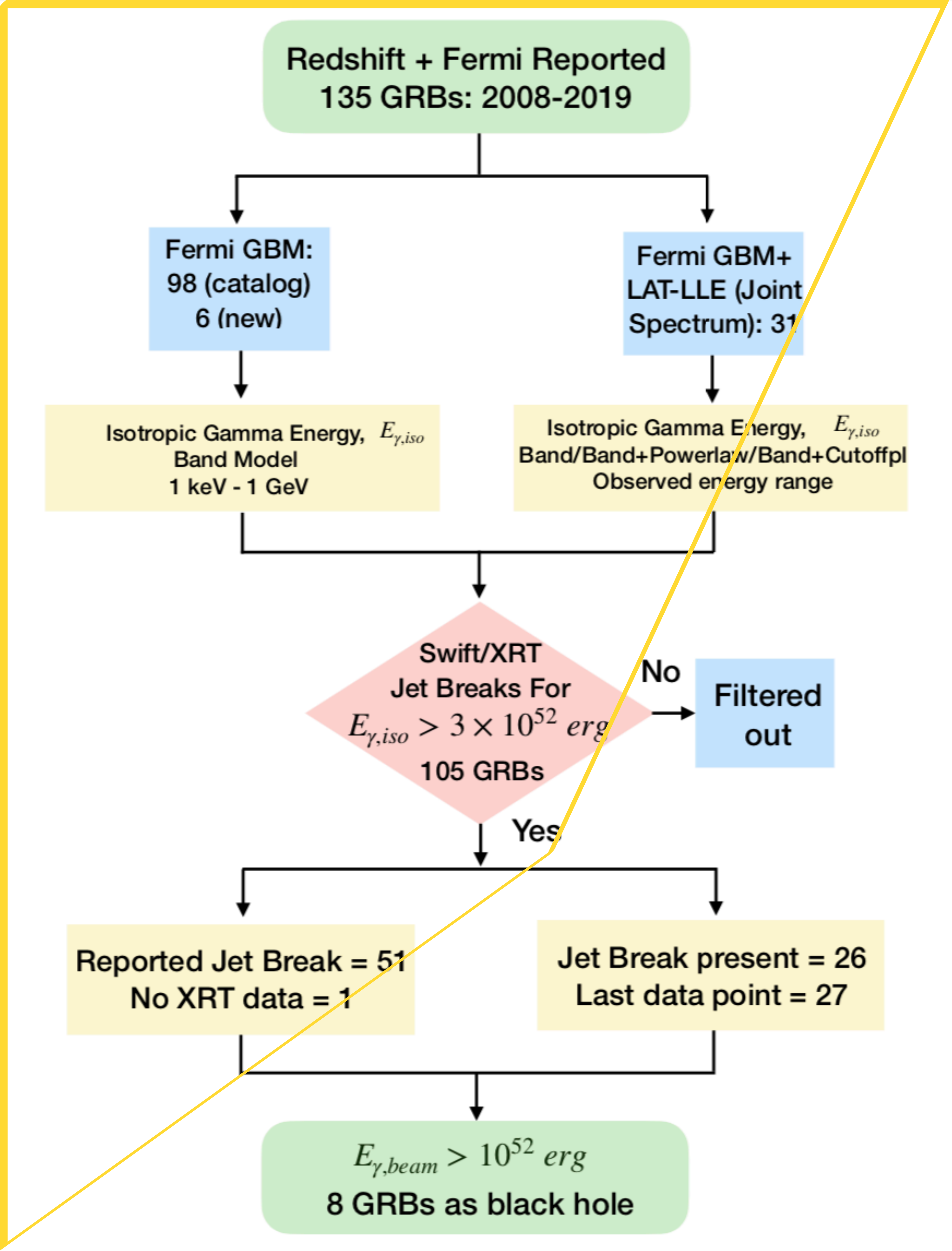
$$E_{\rm rot} \simeq \frac{1}{2} I\,\Omega^2 \approx 3\times 10^{52} erg \left(\frac{M_{ns}}{1.5\ M_\odot}\right)\left(\frac{R_{ns}}{12\ km}\right)^2\left(\frac{P_{ns}}{1ms}\right)^{-2}$$

Maximum extractable energy
in case of magnetars ~ 10^{52} erg

Rotational Energy –> Jet Energy

Energy Estimation

- Redshift
- Prompt emission spectrum



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Energy Estimation

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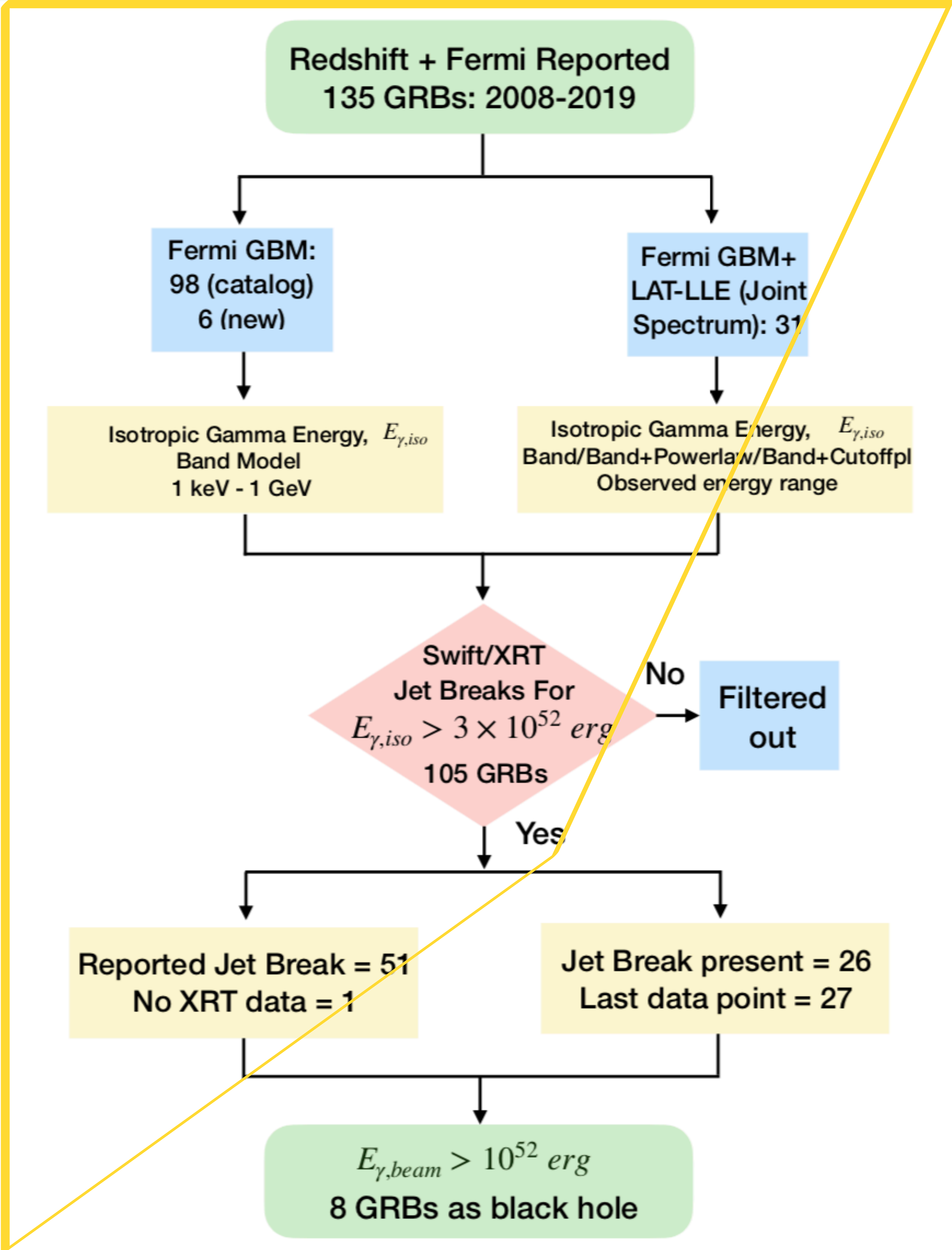
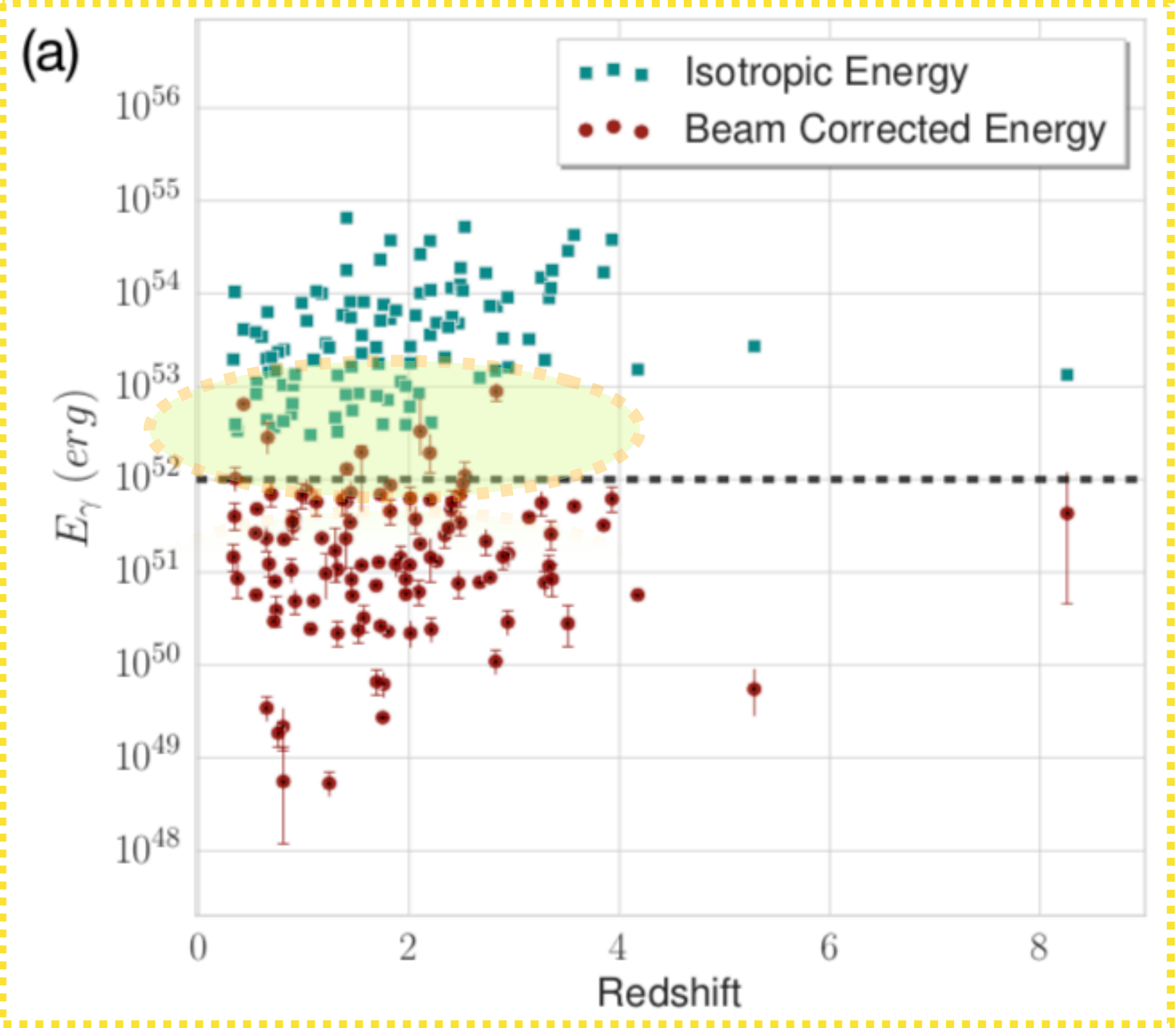
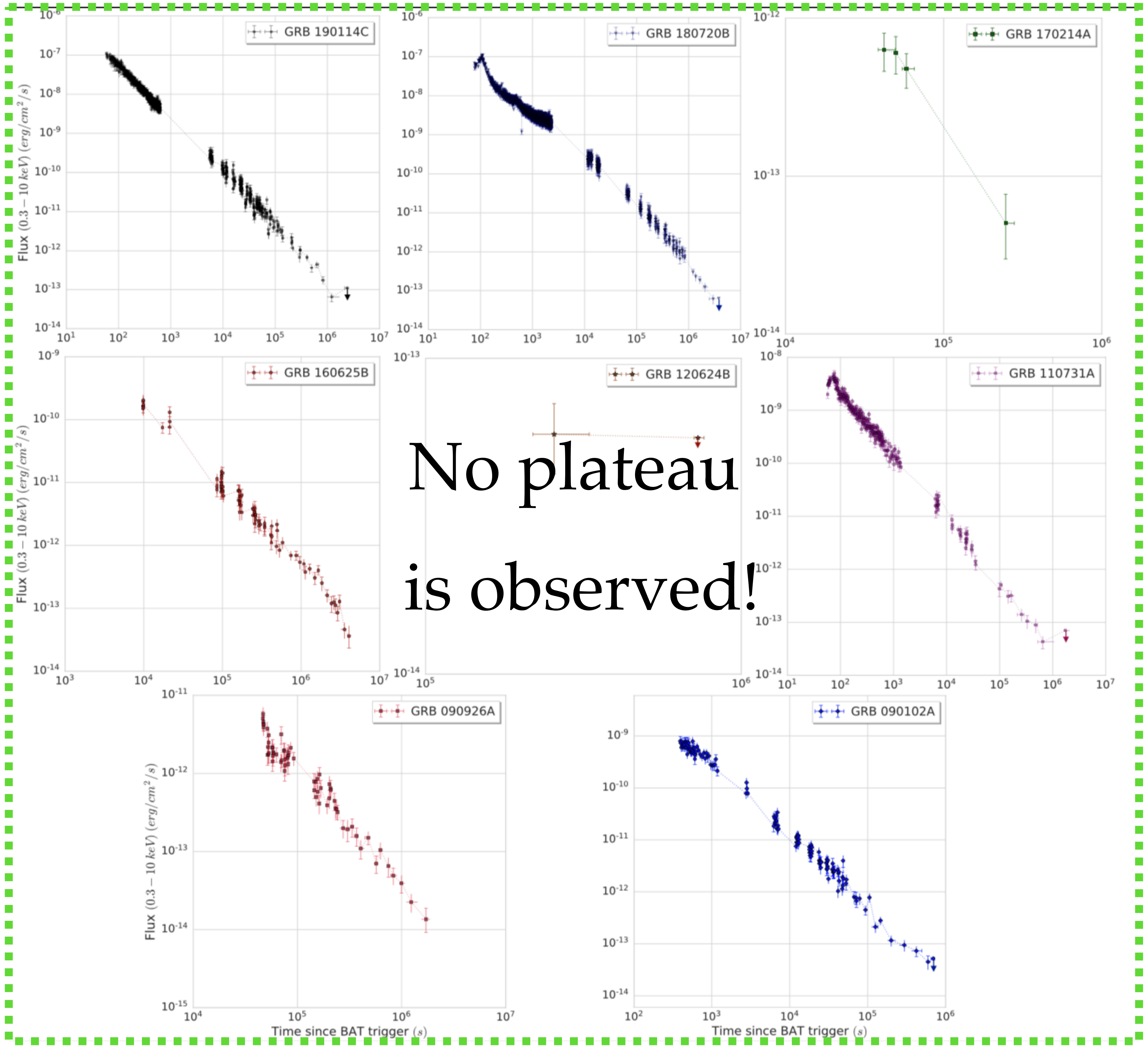


- Jet opening angle

Jet properties of hyper-energetic GRBs





Masses of Black holes

Assuming, Blandford Znajek mechanism, powering the BH driven jets:

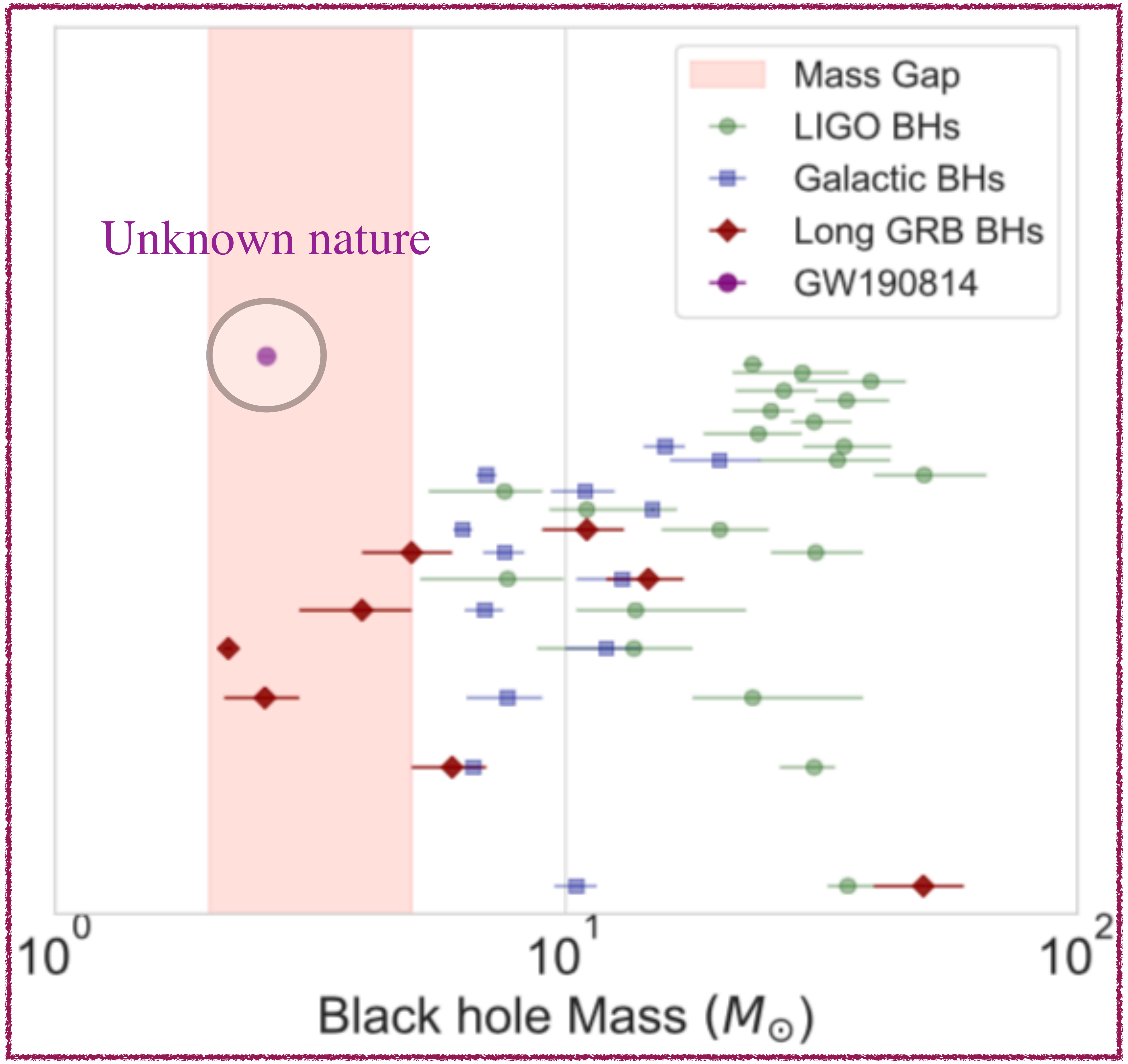
$$\eta \, E_{rot} \approx E_{\gamma,beam}$$

Mass ranges between ~ 2-60 solar masses

BHs formed in these catastrophic events May lie in mass gap region

LIGO: *Abhott et al. 2019*

Galactic BH: *Wiktorowicz et al. 2013*



Sharma V. et al., ApJL, 2021

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Conclusion

Using limits on energetics,
we identify 8 black hole candidates.

- ❖We note, all except one are LAT detected -> subGeV loud.
- ❖ In case of core-collapse of massive stars, mass of BH ranges from a few to tens of solar mass.
- ❖ In XRT light curve, we observe flares and multiple breaks.
- ❖ No plateau is observed for hyper-energetic black holes candidates.

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Thank you for your attention!

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Magnetic Energy

A decade of Gamma-Ray Bursts observed by Fermi-LAT; Ajello et al 2019

netar is one of the two leading hypotheses (the other is a newly-born black hole). The vacuum/force-free electromagnetic spin-down power of a neutron star with surface (equatorial) dipole magnetic field $B_{\rm dip}$ and spin period P is given by (Spitkovsky 2006):

$$\dot{E}_{\rm FF} \approx \frac{4\pi^4 B_{\rm dip}^2 R^6}{P^4 c^3} \sim 10^{49} \left(\frac{B_{\rm dip}}{10^{15}\ {\rm G}}\right)^2 \left(\frac{P}{1\ {\rm ms}}\right)^{-4} \left(\frac{R}{10\ {\rm km}}\right)^6 {\rm erg/s}, \quad (11)$$

GRB name	T_{90} (*Fermi*) (s)	z	Fluence $10^{-4}\ erg/cm^2$	$E_{\gamma,iso}$ $10^{52}\ erg$	θ_j [a] $^\circ$	ϵ [a]	$E_{\gamma,beam}$ $10^{52}\ erg$	Confidence[b] level	$M_*/M_\odot$	*Swift*/ XRT Feature
190114C	116.354	0.425	$8.5^{+0.3}_{-0.3}$	$41.2^{+1.4}_{-1.3}$	> 32.5	0.18	$> 6.5^{+0.2}_{-0.2}$	> 99.99%	40 – 60	3 Breaks
180720B	48.897	0.654	$5.4^{+0.5}_{-0.4}$	$63.3^{+5.7}_{-5.2}$	$> 17.2^{+2.6}_{-2.6}$	–	$> 2.8^{+1.2}_{-0.9}$	99.6%	5 – 7	Flare, 3 Breaks
170214A [c]	122.882	2.53	$3.5^{+0.2}_{-0.1}$	$525.7^{+23.0}_{-21.0}$	$> 3.7^{+0.6}_{-0.6}$	–	$> 1.1^{+0.4}_{-0.3}$	61.5%	2.14 – 3	Straight line
160625B [c,d]	453.385	1.406	$12.4^{+0.4}_{-0.4}$	$657.8^{+22.2}_{-20.6}$	$3.6^{+0.2}_{-0.2}$	0.98	$1.3^{+0.2}_{-0.2}$	98.3%	2.14 – 2.22	1 Break
120624B	271.364	2.197	$3.1^{+0.6}_{-0.5}$	$371.1^{+74.6}_{-57.4}$	$> 5.8^{+0.9}_{-0.9}$	–	$> 1.9^{+1.1}_{-0.7}$	94.6%	3 – 5	A few points
110731A	7.485	2.83	$0.4^{+0.1}_{-0.1}$	$72.9^{+14.5}_{-13.2}$	$28.9^{+0.0}_{-0.7}$	0.86	$8.9^{+1.8}_{-2.0}$	99.9%	12 – 17	Flare, 3 Breaks
090926A [e]	13.76	2.106	$2.4^{+0.03}_{-0.03}$	$267.4^{+33.8}_{-26.2}$	9^{+4}_{-2}	0.98	$3.3^{+4.4}_{-1.5}$	90.8%	4 – 6	Straight line
090102	26.624	1.547	$0.4^{+0.1}_{-0.1}$	$22.8^{+1.6}_{-1.7}$	$23.9^{+1.1}_{-12.1}$	0.25	$2.0^{+0.3}_{-1.5}$	85%	9 – 13	1 Break

Sharma V. et al., ApJL, 2021

Title of this slide

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Prompt emission of short gamma-ray bursts (sGRBs) are analyzed using the model of the multi-color blackbody, which is interpreted as the emission from a non-dissipative photosphere with jet structure and viewing geometry inference. Nearly 69 % and 26 % of the sample is consistent with a multicolor blackbody and a pure blackbody model, respectively. Using this physical interpretation, a narrow jet core with a median of ~ 3 degrees and power-law index of 1.3 - 2.2 as decreasing Lorentz factor profile for the jet structure is deduced. Interestingly, based on the current LIGO sensitivity, the study predicts the rate of coincident detections of bright short GRBs with gravitational waves to be 0.19 - 2.87 events/yr. Another major quest in the field of GRB science is the nature of stellar remnants. Using the magnetar energy limit, 8 GRBs with black hole central engines are identified in 11 years of Fermi GRB sample (long and short both). The estimated masses of these bursts are found to range between 2 - 60 solar masses. A few of them are found to lie in the mass-gap region, suggesting that some of the lighter black holes in the Universe are formed via these catastrophic events.