

Constraining Jet Structure in Low-Luminosity Gamma-Ray Bursts

A Comparative Analysis of Jets in GRB 161219B

G. F Abbey
Postdoctoral Fellow

Collaborators

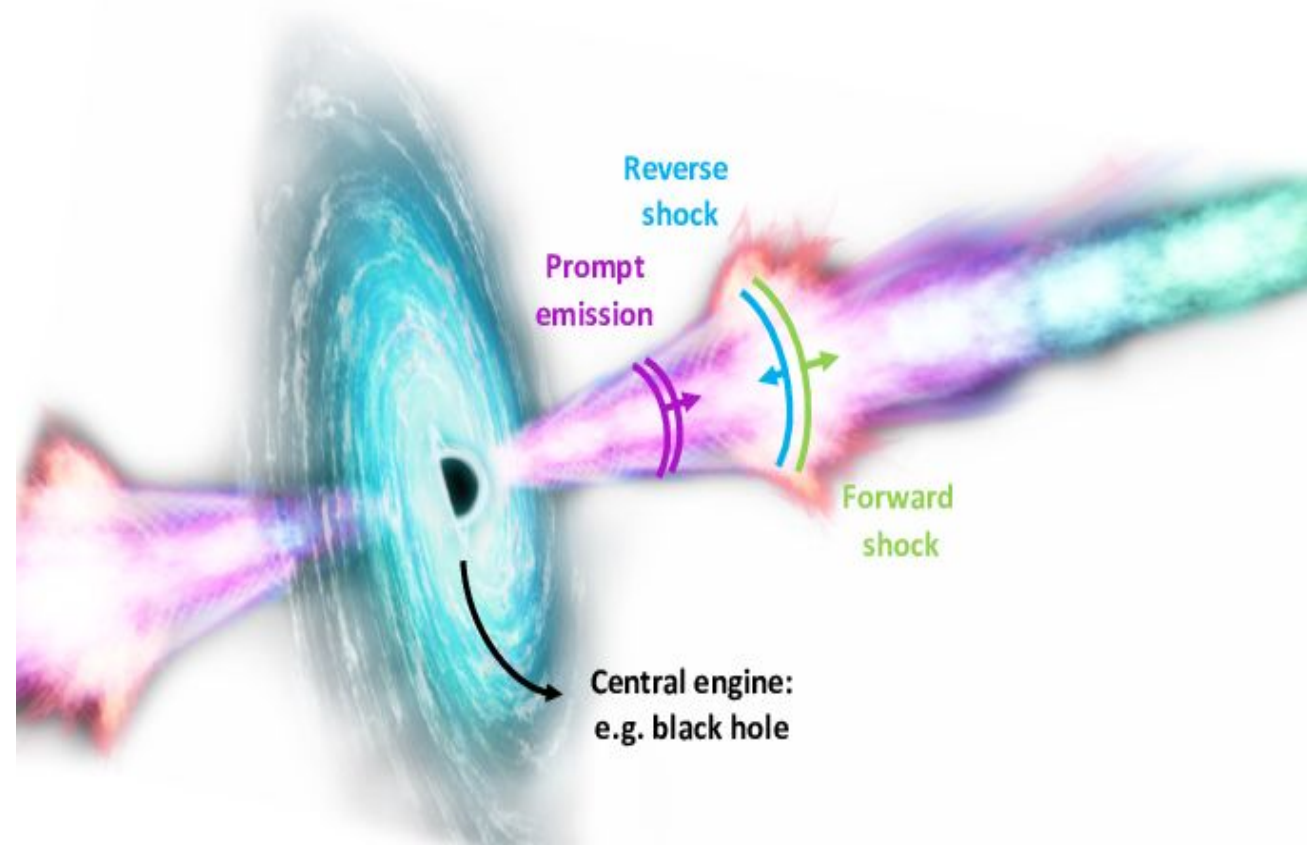
Prof. S. Razzaque: University of Johannesburg, SA (UJ)

Dr. G. Ankur: University of Johannesburg, SA (UJ)

Dr. S. P. Phiri: Copperbelt University, Zambia (CBU)

Astrophysics Research Group: Department of Physics
Copperbelt University Zambia

HEASA 2026 Conference



30th September , 2026

Outline

- Introduction
- Scientific Motivation
- Data
- Modelling
- Results
- Summary
- Future Work

Gamma-ray Bursts (GRBs) and Fireball Model

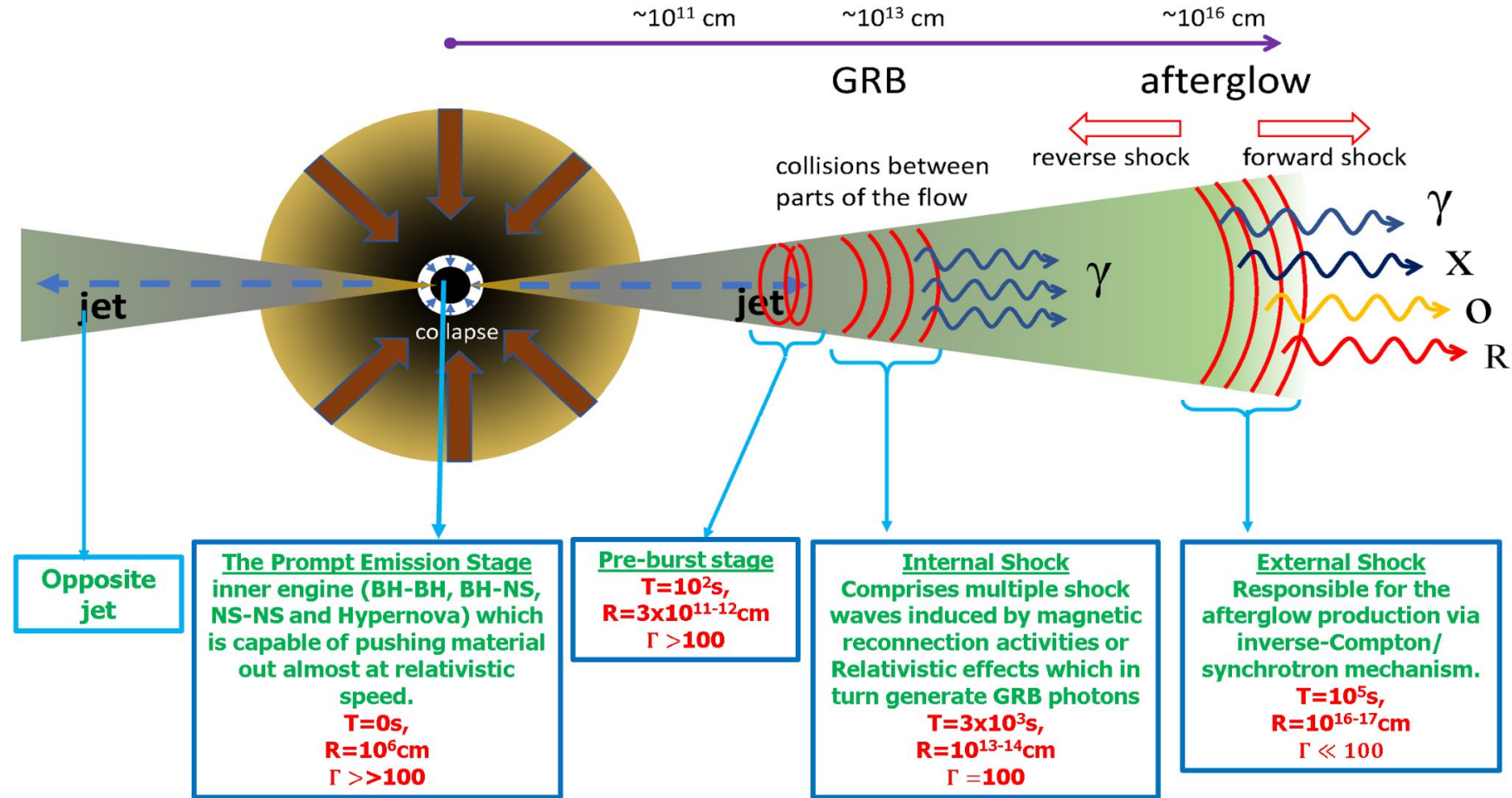
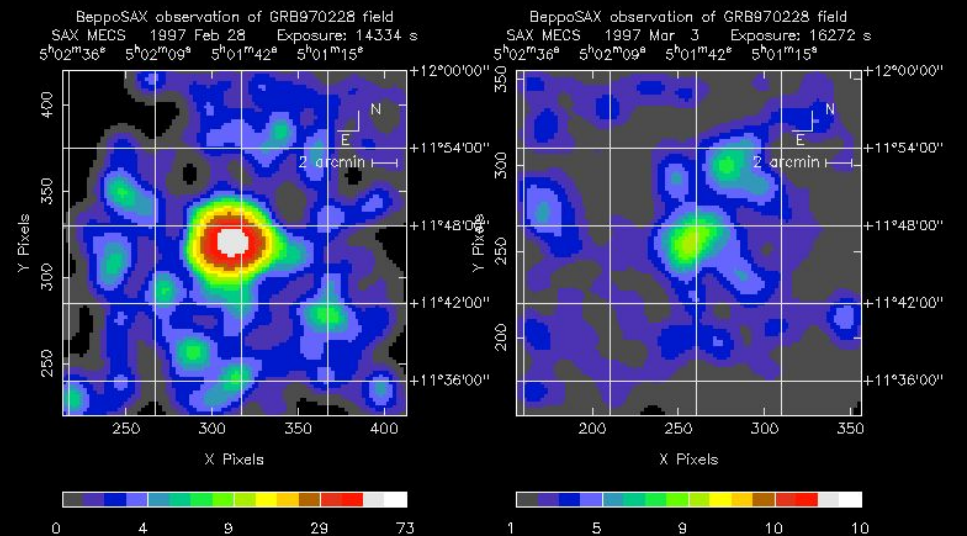
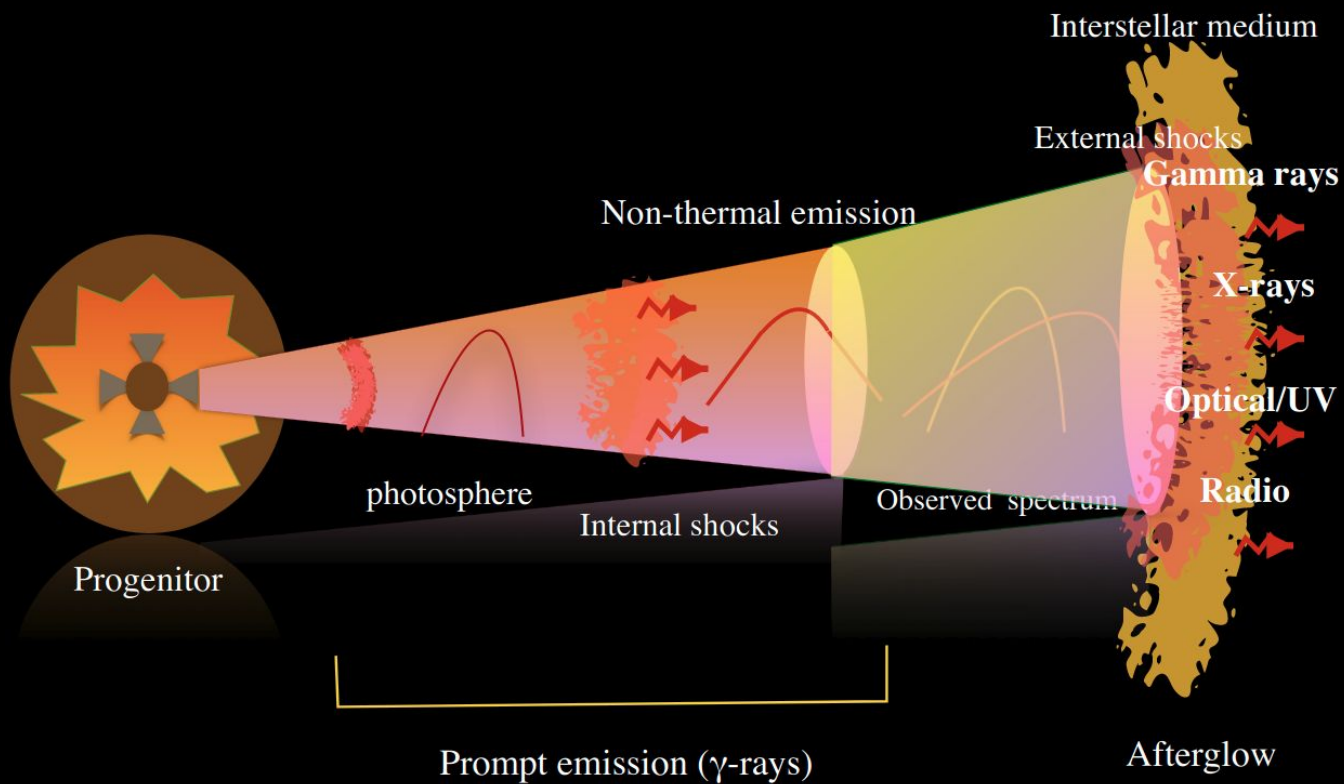


Figure 1: GRB Fireball model

(Knust, 2017; Pe’Er, 2015; Piran, 2005; Mészáros, Rees, & Wijers, 1999; Pe’Er, 2015; Piran, 2005).



Intro. Cont...

GRB Statistics

Population

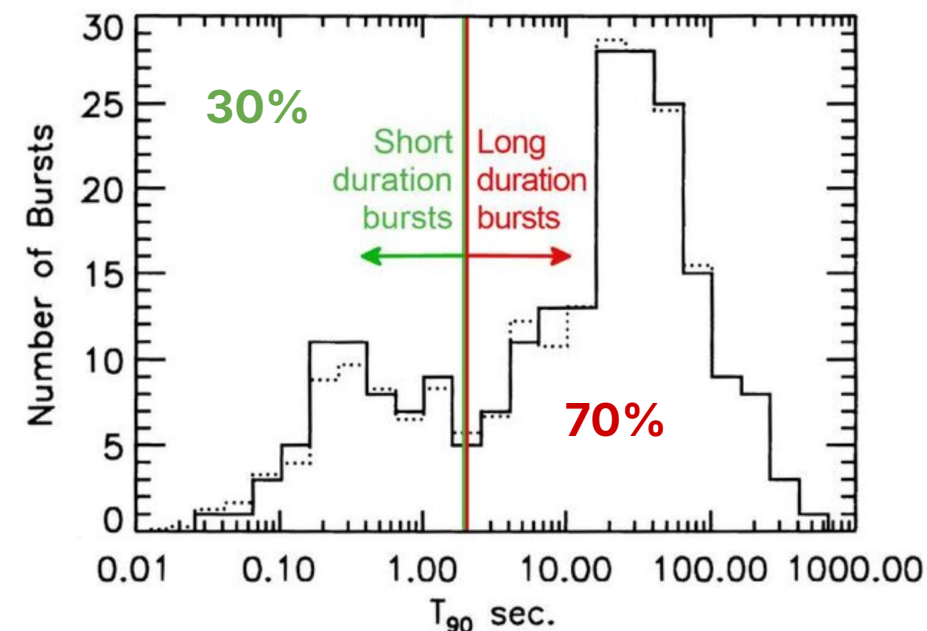
- Swift Observatory (XRT/UVOT): > 2,000 (3/days)
- Fermi Gamma-ray Space Telescope (GBM): > 4,000 (240/year)
- CGRO (BATSE): = 2,704.
- Others **Total~10,000+**

LLGRBs (<0.15%):

Are subclass of LGRBs that release much less gamma-ray energy than typical (classical) long-duration GRBs.

SGRBs

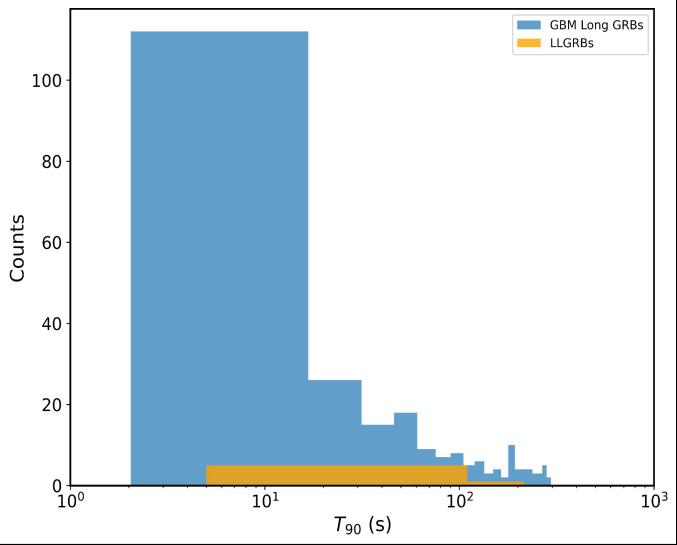
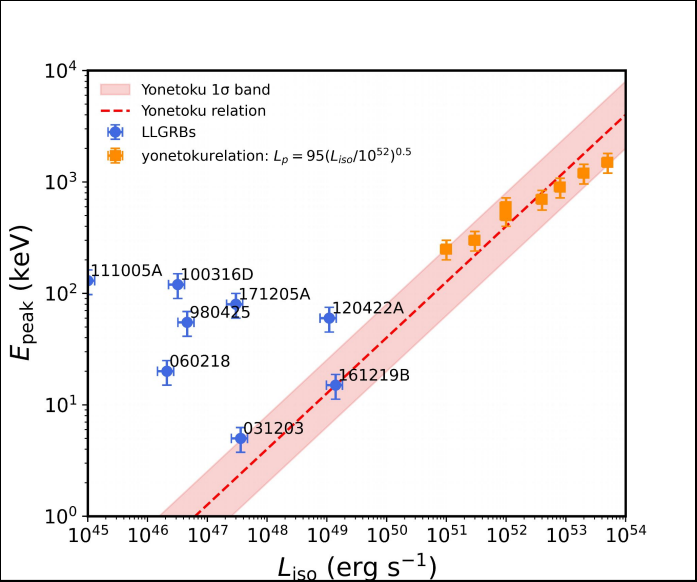
LGRBs



GRB	z	D_L (Mpc)	T_{90} (s)	E_{iso} (erg)	L_{iso} (erg s $^{-1}$)	SN	Bands compiled
060218	0.0331	145	~2100–2600	1.66×10^{49}	7.04×10^{45}	2006aj	X-ray(cps), V
100316D	0.0591	265	> 1300	$> 6 \times 10^{49}$	–	2010bh	X-ray, GROND, ATCA
111005A	0.01326	57	27 ± 8	–	–	none (SN-less)	Radio only
120422A	0.283	1452	–	4.5×10^{49}	–	2012bz	X-ray, $r'i'z'YJHK$, mm
161219B	0.1475	700	–	1.6×10^{50}	–	2016jca	X-ray, <i>griz</i> , UVOT, <i>JHK</i> , ALMA, VLA
171205A	0.0368	162	189.4 ± 35.0	2.3×10^{49}	–	2017iuk	X-ray, UVOT, uGMRT
190829A	0.0785	356	–	2×10^{50}	–	2019oyw	X-ray, GTC <i>ugriz</i> , MeerKAT, AMI-LA

Scientific Motivation

Parameter	 LLGRBs (Low-Luminosity GRBs)	 Classical Long GRBs (LGRBs)	Key Difference
 Redshift (z)	0.005 – 0.3	0.5 – 8+	LLGRBs are local; LGRBs are cosmological.
 Duration (T_{90})	10 – 3000 s	2 – 1000 s	LLGRBs often longer and smoother.
 Isotropic Energy (E_{iso})	$10^{47} - 10^{50}$ erg	$10^{51} - 10^{54}$ erg	LLGRBs are 2–4 orders of magnitude lower in isotropic energy.
 Peak Photon Index (Γ)	2.0 – 2.5	1.2 – 2.0	LLGRBs have softer spectra.
 Initial Lorentz Factor (Γ_0)	$\sim 2 - 20$	$\sim 100 - 1000$	LLGRBs are mildly relativistic.
 Viewing Angle (θ_{obs})	$\gtrsim 10^\circ$ (often off-axis)	$\lesssim$ few degrees (on-axis)	LLGRBs possibly structured/ off-axis jets.
 Environment	Low-density ISM / wind	Wind-like (massive star progenitor)	Similar progenitors, different energetics and environments.
 Associated SN	Type Ic-BL (almost always detected)	Type Ic-BL (sometimes detected)	LLGRBs show clearer SN connection.
 Volumetric Rate	$\sim 100 - 1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$	$\sim 1 - 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$	LLGRBs are more common locally.



Intro. Cont...

Synchrotron Forward and Reverse Shock Framework

The general form for the synchrotron flux density at a given time is given by (Sari et al., 1998; Granot & Sari, 2002; Zhang & Mészáros, 2002; Kumar & Zhang, 2015; Gill & Granot, 2020; Zhang, 2023).

$$F_\nu(t) = F_{\nu,\max}(t) \times S(\nu, \nu_m(t), \nu_c(t)),$$

$$F_{\nu,\max}(t) = \frac{N_e}{d_L^2} \frac{e^3 B}{m_e c^2}$$

The Peak Flux

$$\nu_m(t) = \frac{3}{4\pi} \frac{e B \gamma_m^2}{m_e c}$$

The Characteristics Frequency

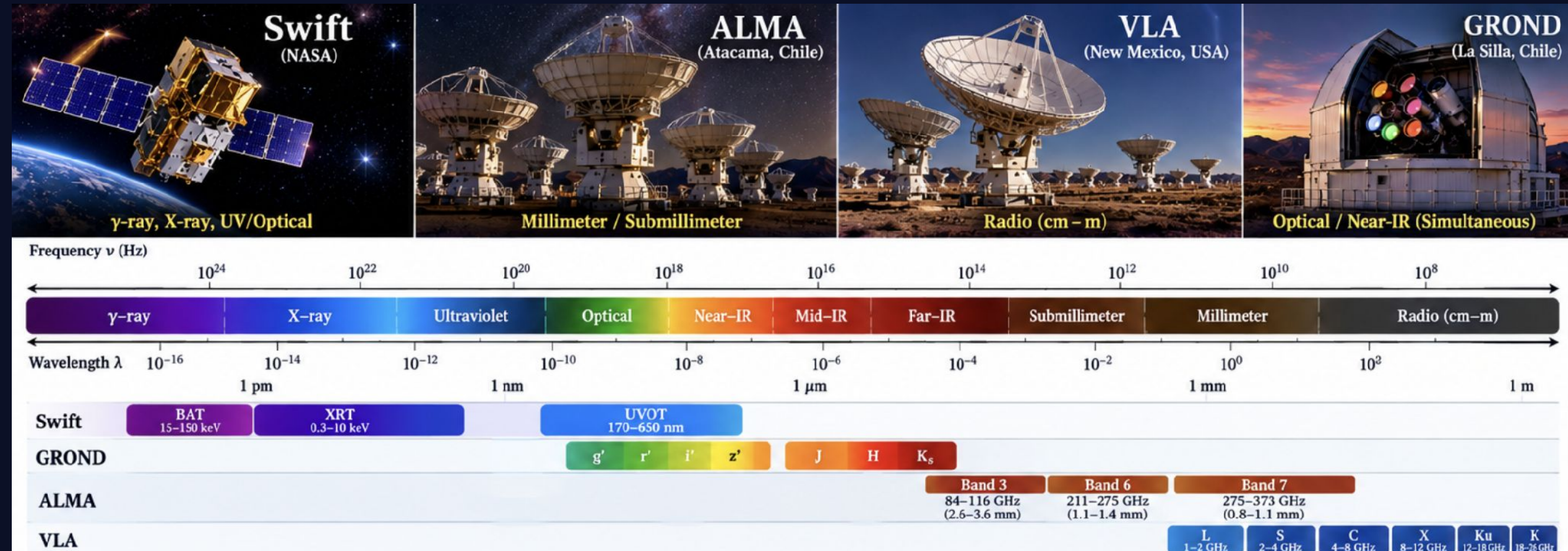
$$\nu_c(t) = \frac{18\pi m_e c}{\sigma_T^2 B^3 t^2}$$

Cooling Frequency

$$S(\nu, \nu_m, \nu_c) = \begin{cases} \left(\frac{\nu}{\nu_m}\right)^{1/3}, & \nu < \nu_m \\ \left(\frac{\nu}{\nu_m}\right)^{-(p-1)/2}, & \nu_m < \nu < \nu_c \\ \left(\frac{\nu_c}{\nu_m}\right)^{-(p-1)/2} \left(\frac{\nu}{\nu_c}\right)^{-p/2}, & \nu > \nu_c \end{cases}$$

The Spectral Shape/Regime

Data: Swift UVOT/XRT, Ashall et al. (2019), Cano et al. (2017), Laskar et al. (2011)



Swift

BAT, XRT 0.3–10 keV, UVOT
UV/optical

GROND

g' r' i' z' J H K_s , simultaneous

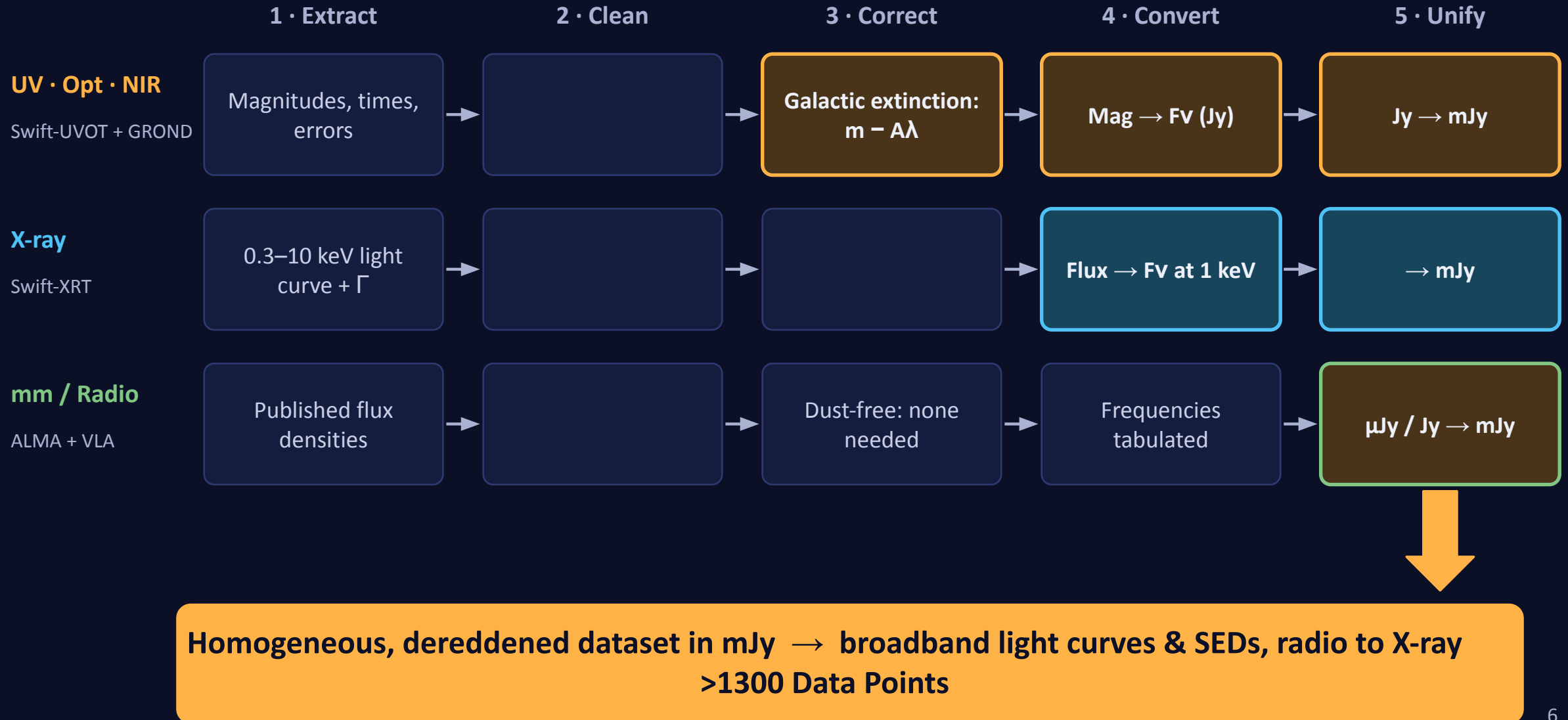
ALMA

Bands 3, 6, 7 (mm/sub-mm)

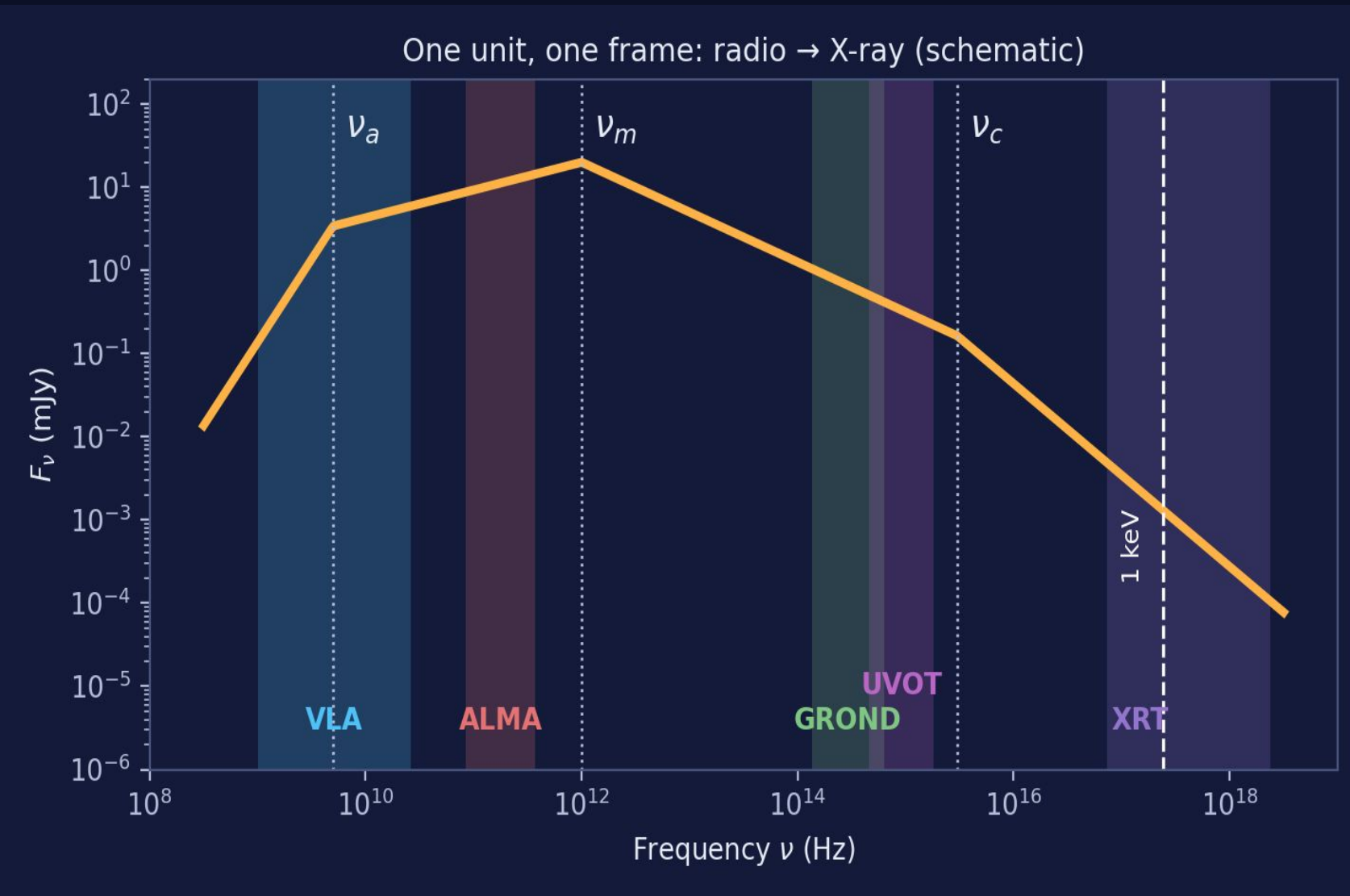
VLA

L to K bands (1–26 GHz)

Our pipeline: from raw archives to one mJy dataset



Our Strongest Point



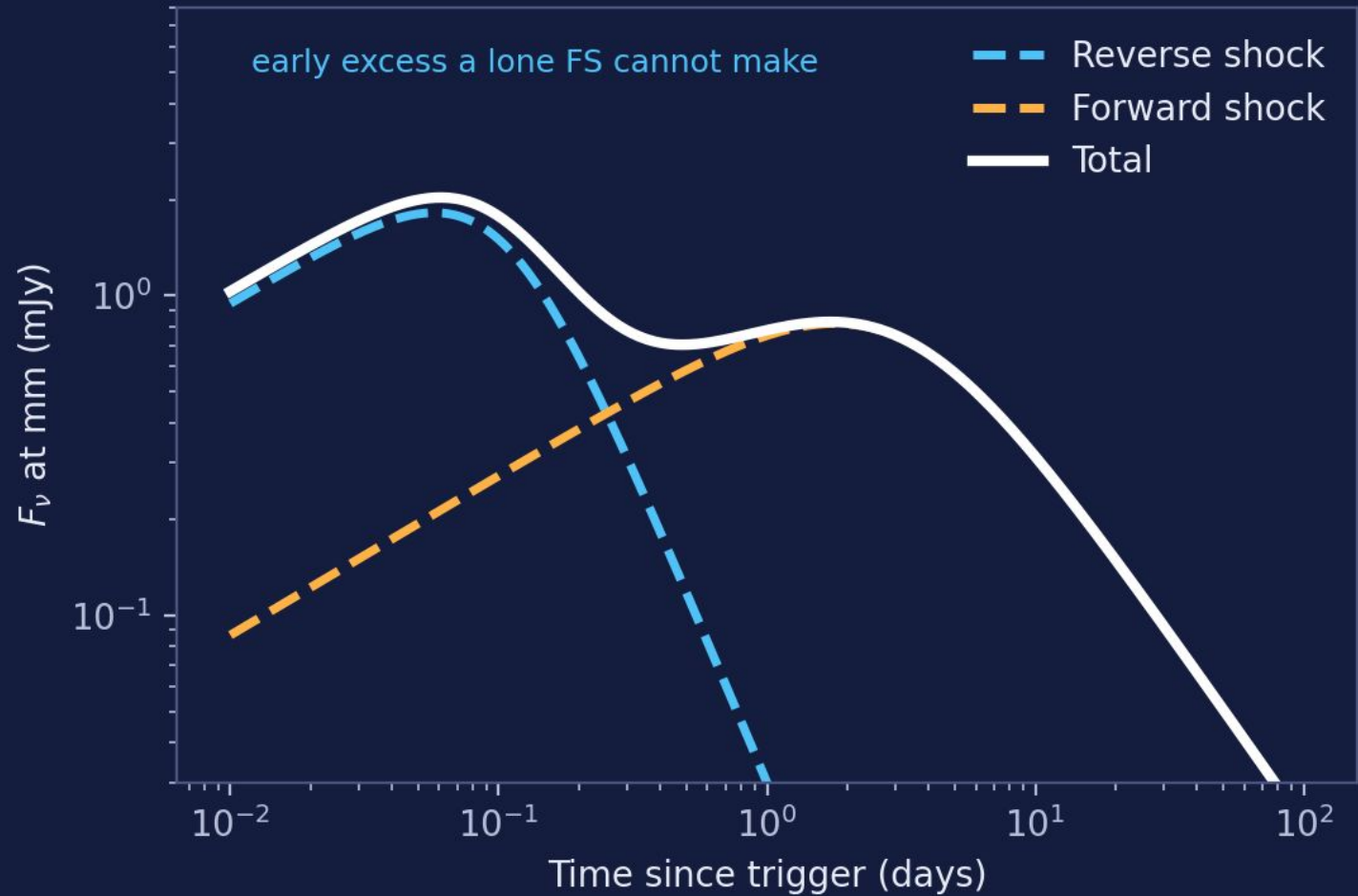
Why mJy?



<https://vegasafterglow.readthedocs.io/en/latest/index.html>

Our Justification

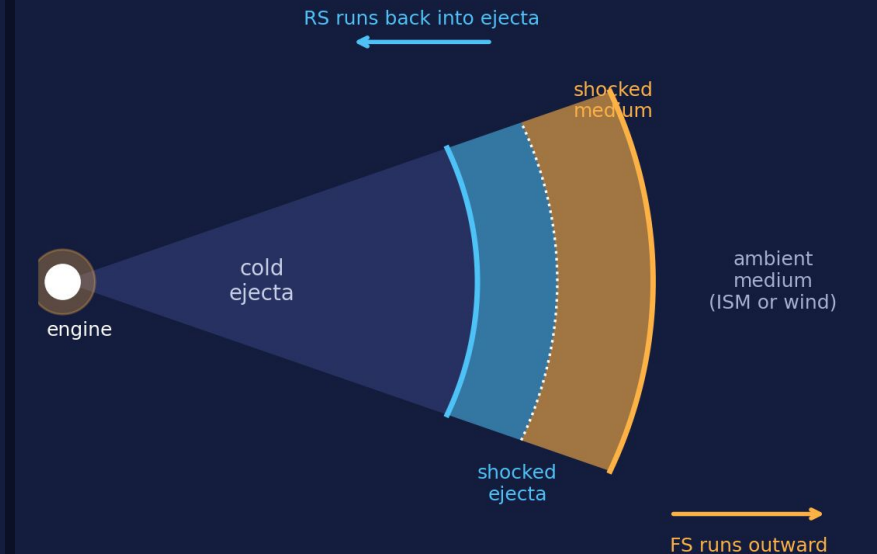
Why both shocks: early mm light curve (schematic)



Our Hope

- Intrinsic or off-axis
- True energy budget
- A fair model choice
- Ejecta magnetisation

Two shocks, two emission sites (schematic)



Why this jet-model combination?

An afterglow fit has to answer two separate questions. We chose models that answer each one, then combine them.

Q1 · Angular structure

How is energy spread across the jet, and where are we looking from?

Top-hat

Gaussian

Power-law

Q2 · Emission sites

Which shock makes the light we see, and when?

Forward shock

Reverse shock

3 jet structures × (forward + reverse shock) = 3 physical models, fitted to the same dataset and compared statistically

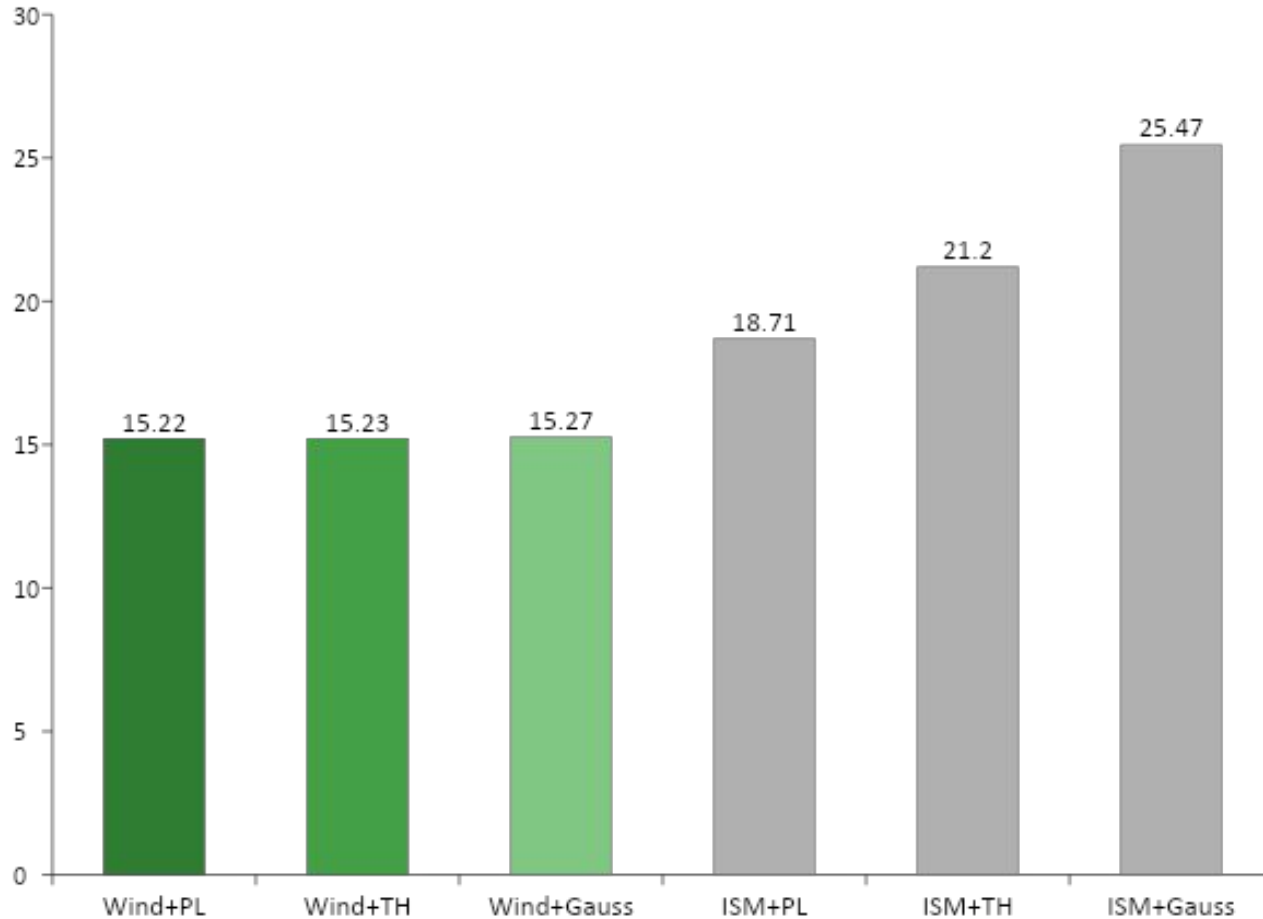
What's New

Previous works vs this work

Aspect	Previous works (Cano; Ashall; Laskar)	This work
Galactic extinction	Magnitudes plotted directly	Every UV/optical/NIR band dereddened with its own A_λ
Photometric quantity	Magnitudes (AB and Vega mixed)	Flux density F_ν (AB- and Vega consistent)
Units	Jy, μJy , mag, $\text{erg cm}^{-2} \text{s}^{-1}$	Everything in mJy
X-ray	Integrated 0.3–10 keV flux	Flux density at 1 keV
Coverage	Regime by regime	One radio-to-X-ray dataset
Jet modelling	Standard jet framework; FS + RS (Laskar)	Top-hat, Gaussian and power-law jets, each with FS + RS

Results

Goodness of fit (lower is better)



Two best-fit models

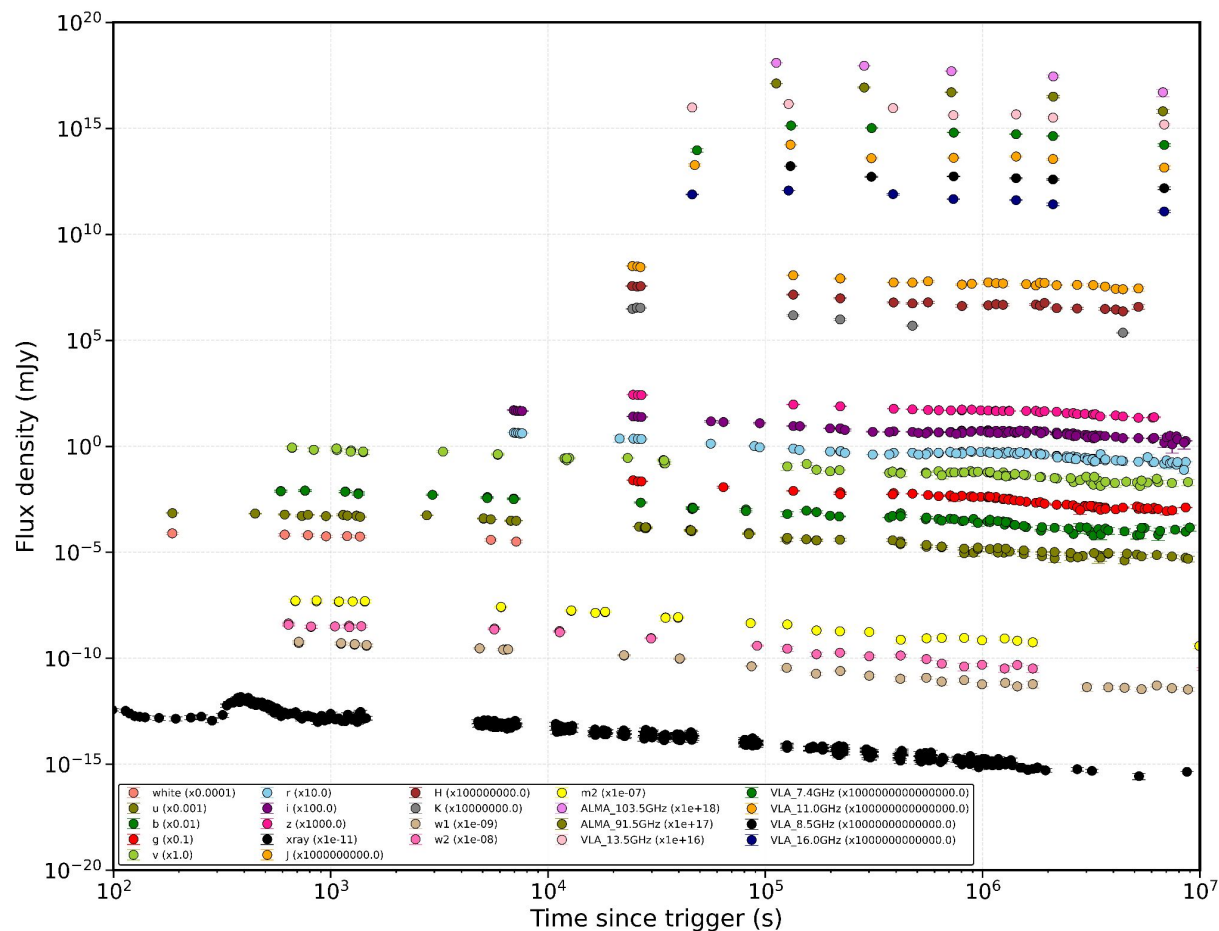
Wind + Power-law jet ($\chi^2_{\text{red}} = 15.22$, best AIC/BIC)

Wind + Top-hat jet ($\chi^2_{\text{red}} = 15.23$, statistically tied)

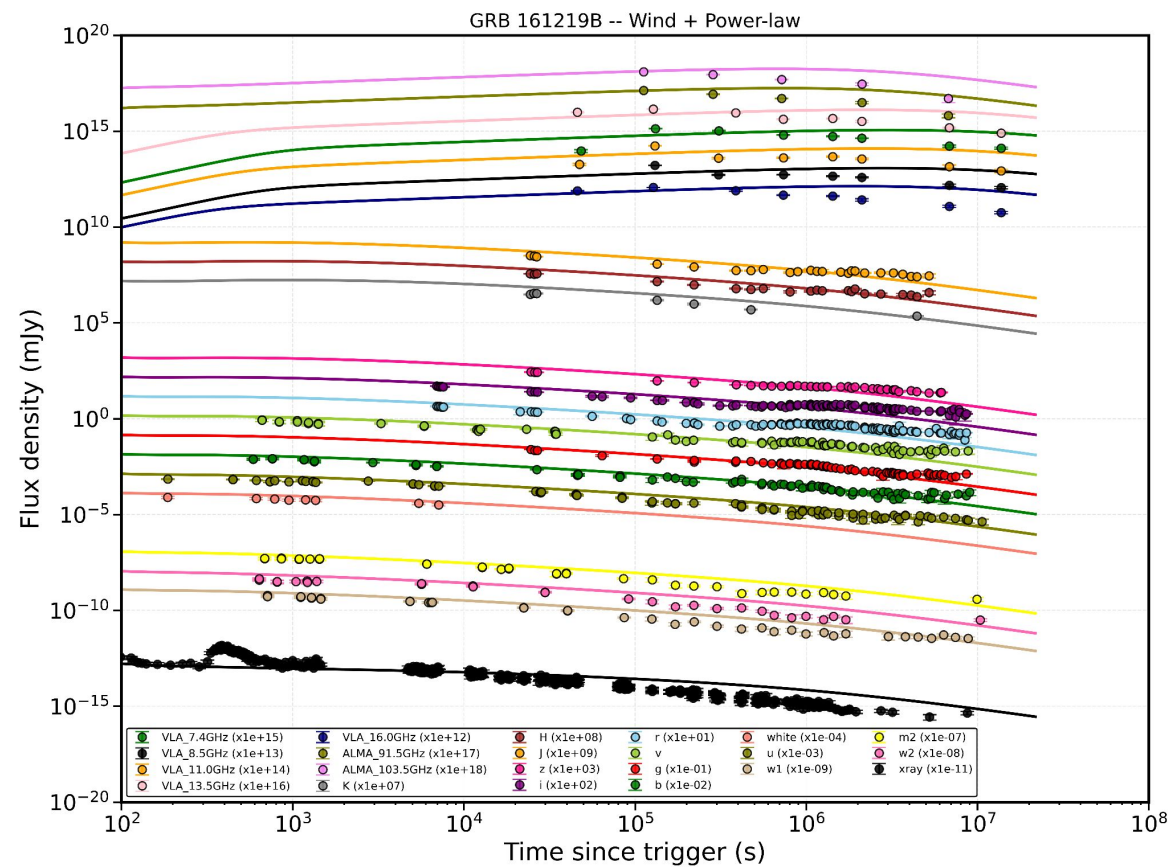
Physical reading

161219B's afterglow strongly prefers a wind-stratified circumburst medium ($n \propto r^{-2}$) -- the signature of a massive, mass-losing progenitor consistent with the associated SN 2016jca.

Results

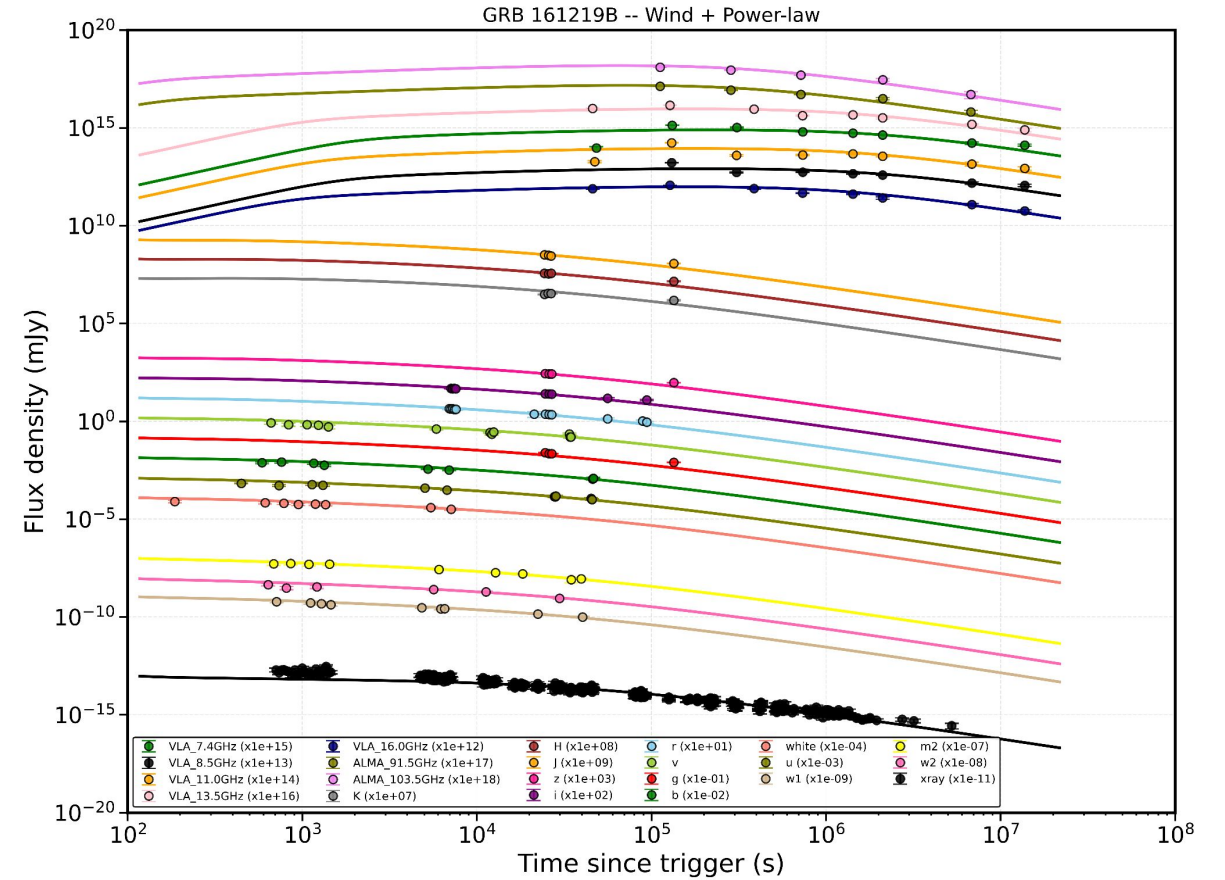
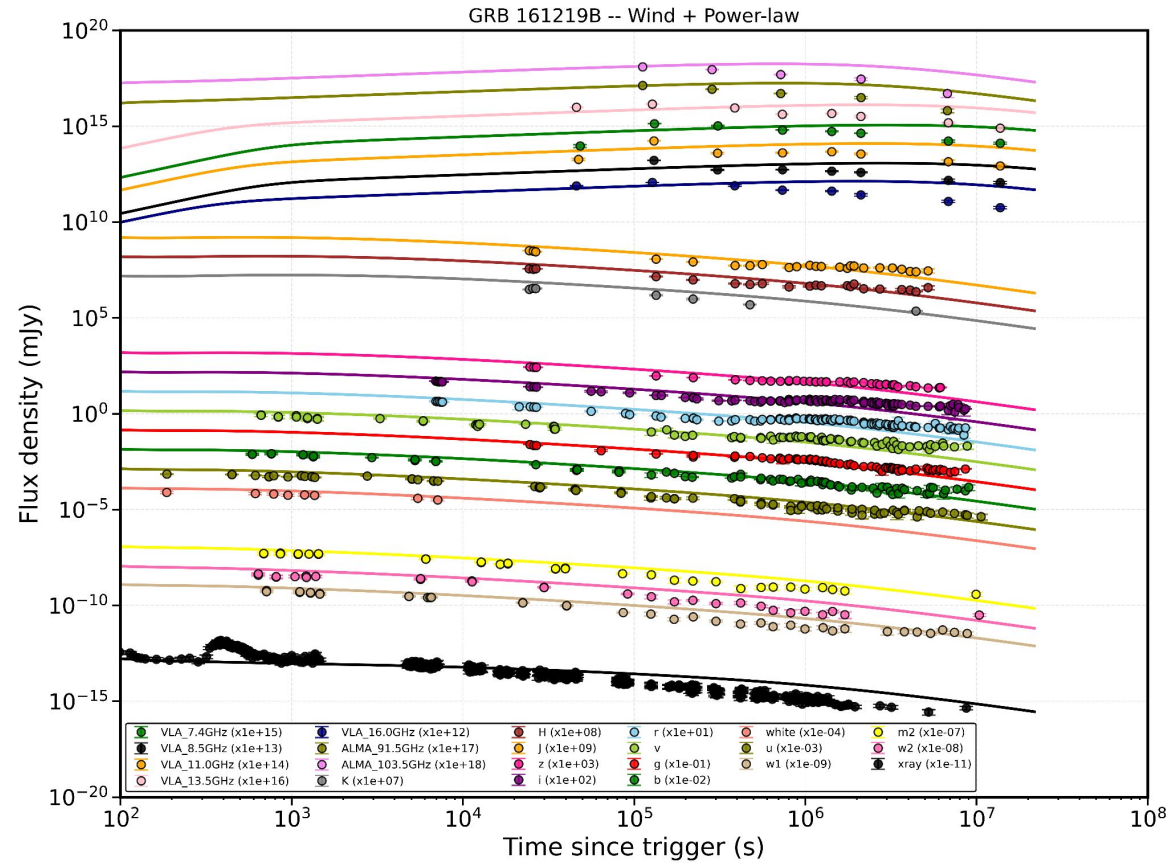


Multiwavelength Light curve of 161219B:



Light Curve Fittings of 161219B:

Multiwavelength Fittings:

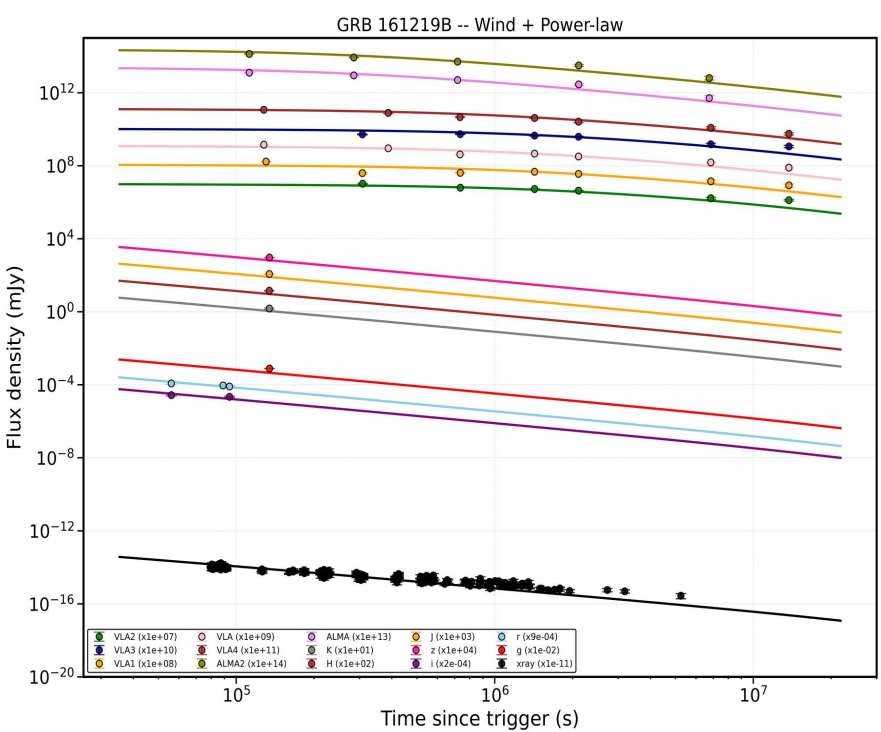
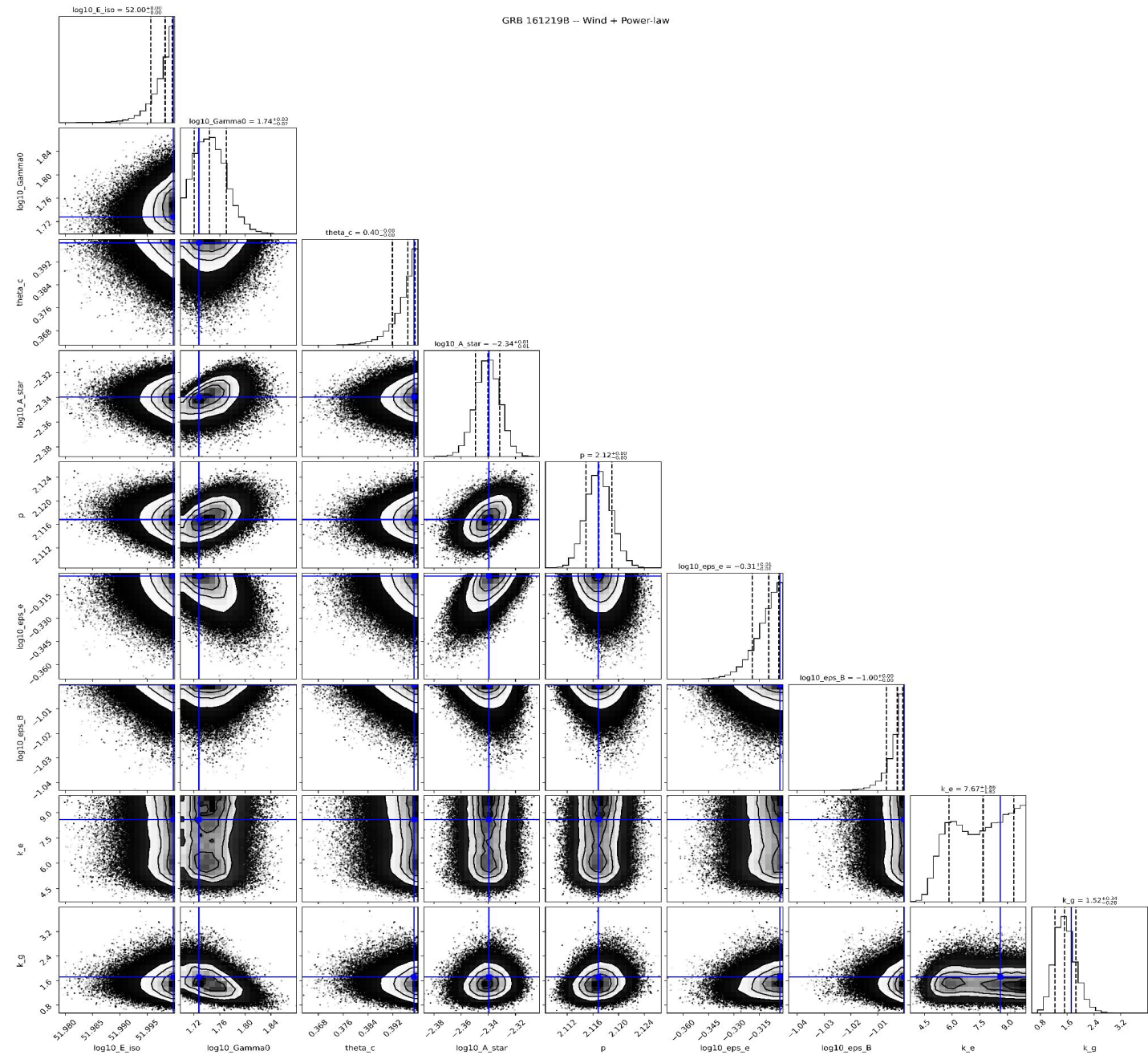


Multiwavelength Fits with SN Data161219B:

1. **t < 0.6 days (51,840 s):** (Ashall et al.) -- forward-shock-only physics doesn't include this.
2. **Optical/NIR, t > 5 days (432,000 s):** SN 2016jca emerges here (spectroscopically confirmed by 3.73d)
3. **Radio below 10 GHz, around t = 1.49 days:** Laskar et al.

Multiwavelength Fits without SN Data161219B:

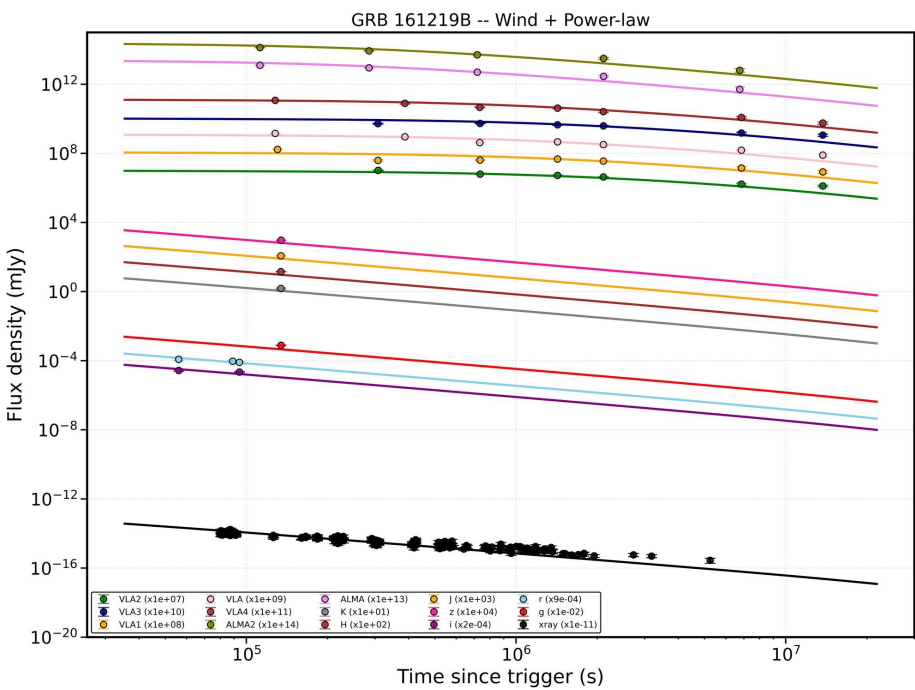
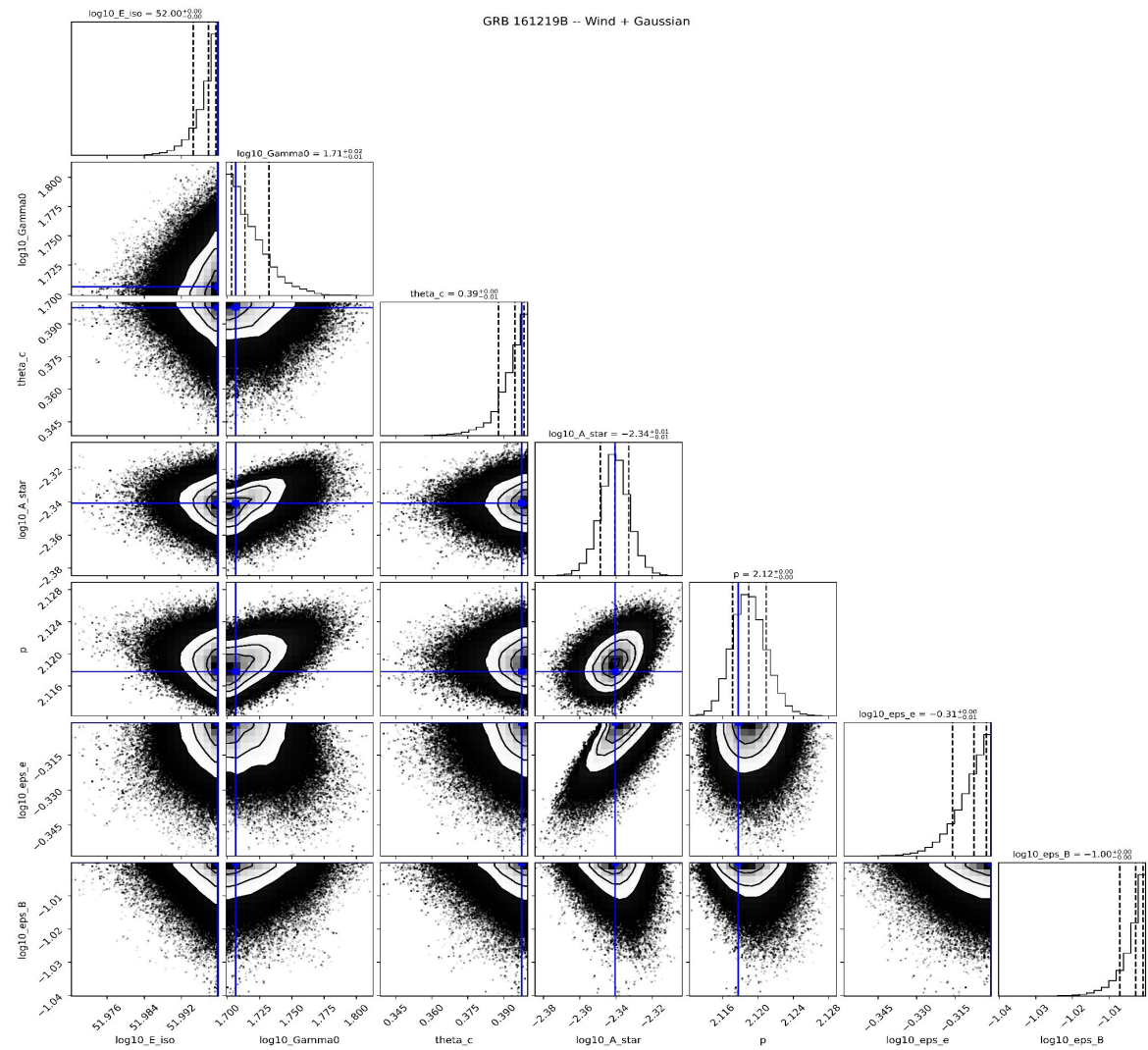
GRB 161219B — Best Fit #1: Wind + Power-law Jet



Parameter	Value
log E_iso [erg]	51.998 (prior-bounded)
Gamma_0	55.5 (+3.4/-3.0)
theta_c [deg]	22.7 (prior-bounded)
log A_star	-2.34 +/- 0.01
p	2.117 +/- 0.002
eps_e	0.49 +/- 0.01
eps_B	0.0993 (prior-bounded)

chi2_red = 15.22 | AIC = 3290.5

GRB 161219B — Best Fit #2: Wind + Top-hat Jet



Parameter	Value
log E_iso [erg]	51.998 (prior-bounded)
Gamma_0	51.3 (+3.0/-2.8)
theta_c [deg]	22.7 (prior-bounded)
log A_star	-2.34 +/- 0.01
p	2.118 +/- 0.002
eps_e	0.49 +/- 0.01
eps_B	0.0993 (prior-bounded)

chi2_red = 15.23 | AIC = 3319.4

Summary of Results

- **161219B's** afterglow strongly prefers a wind-stratified circumburst medium -- the signature of a massive, mass-losing progenitor consistent with the associated SN 2016jca.
- Sharp-edged (top-hat) jet gives essentially the same physical parameters as the power-law jet -- p , ϵ_e , A_{star} and Γ_0 all agree within established standard for LLGRBs 161219B ([Ashall et al. \(2019\)](#), [Cano et al. \(2017\)](#), [Laskar et al. \(2018\)](#)).
- Together, Fits 1 and 2 show the robust result is: **wind medium, mildly relativistic outflow** (50-55), $\theta_c \sim 23$ deg and $\theta_v \sim 10$ degree
- Spectral Indices ($p = 2.12$): matches standard relativistic shock acceleration theory
- $\epsilon_e \sim 0.49$: is close to equipartition energy -- electrons carry nearly as much energy as the magnetic field and protons combined.
- Goodness of Fits (AIC/BIC) between the two best models is not large enough to prefer one jet edge-profile over the other from this dataset alone.
-

Future improvements

What we hope to improve next

Complete the model fits

Run the three jet structures with FS + RS+SN on the full corrected dataset and rank them.

Host-galaxy extinction

Constrain host dust from the corrected SED shape.

LLGRBs sample

Apply the same pipeline to other nearby LLGRBs–SN events for a consistent comparison.

Open dataset

Release the homogenised mJy tables

So others can build on them.

THANK YOU FOR LISTENING

