HEPRO VIII
IAP, 2023.10.23-26

Understanding of the Brightest-of-all-time GRB 221009A

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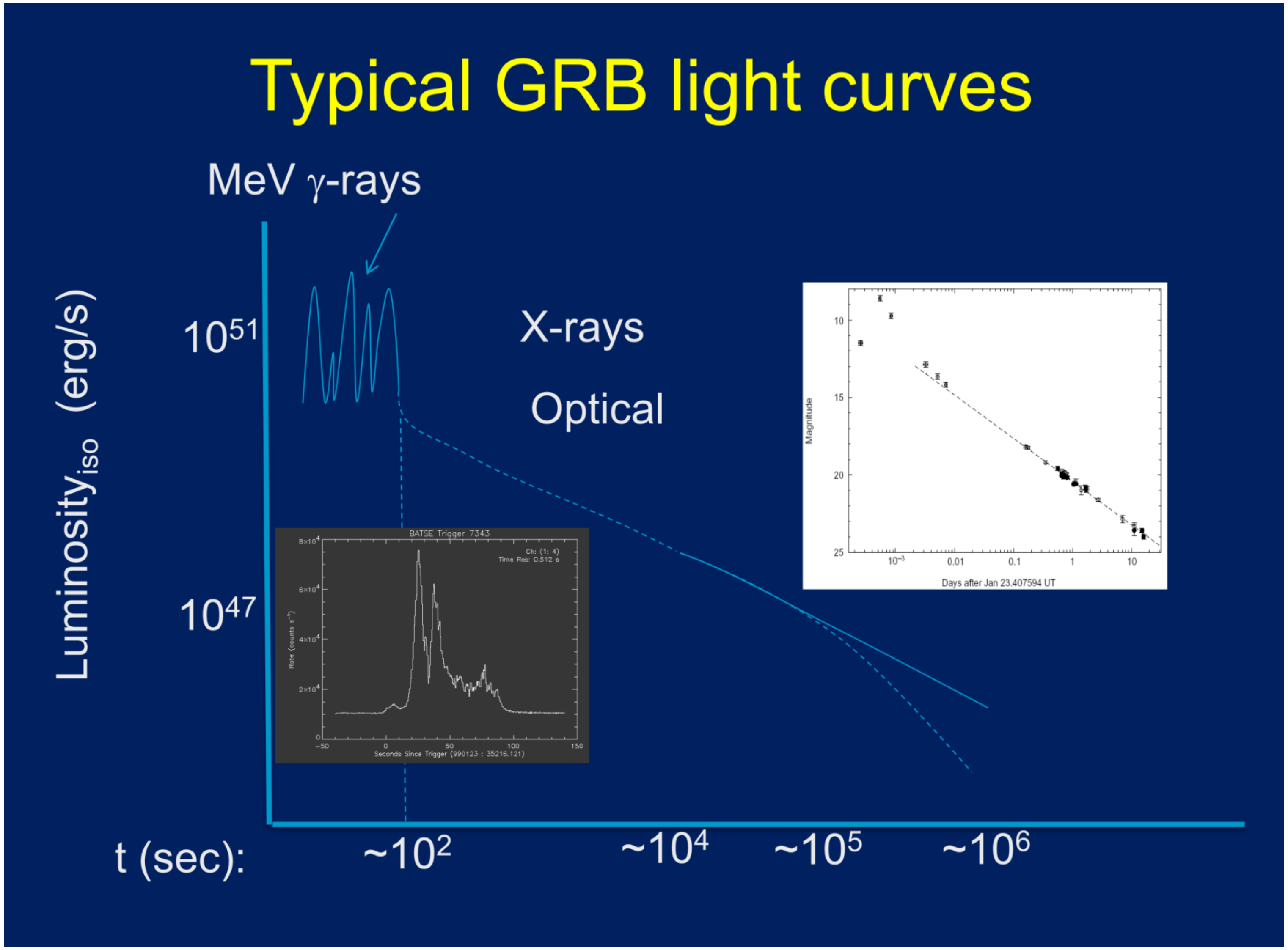
2023.20.23

Outline

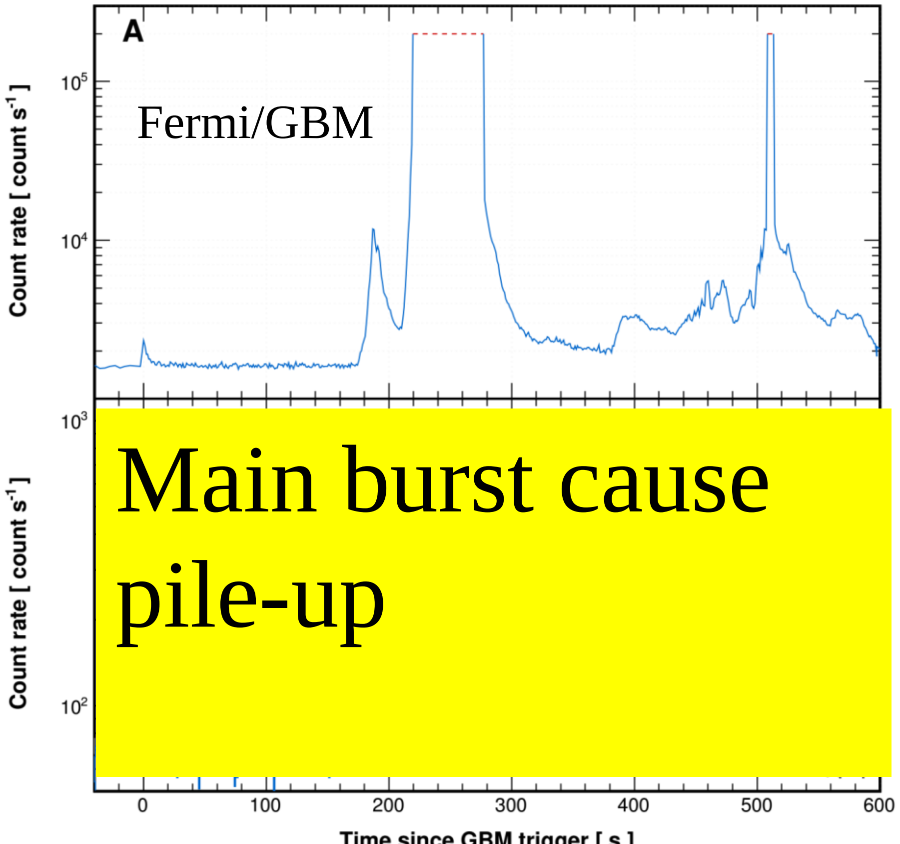
- **Introduction to GRB and GRB 221009A**
- **LHAASO observations of GRB 221009A**
- **A two-component jet model for the multi-wavelength afterglows**
- **Discussions**

GRB emission includes two stages: prompt emission + afterglow

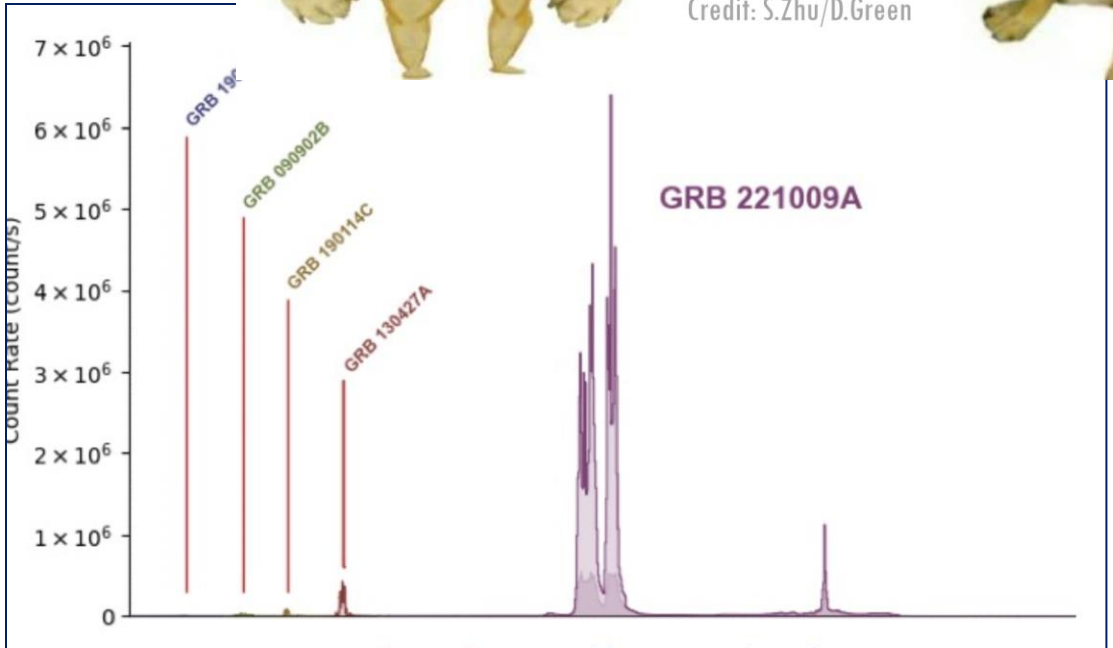


GRB 221009A: brightest-of-all-time (BOAT)

- Triggered on a weak precursor by Fermi
- Fluence: **>0.05 erg/cm^2**,   at low redshift (z=0.151
- Brightest-of-all-time (BOAT GRB)



Main burst cause pile-up

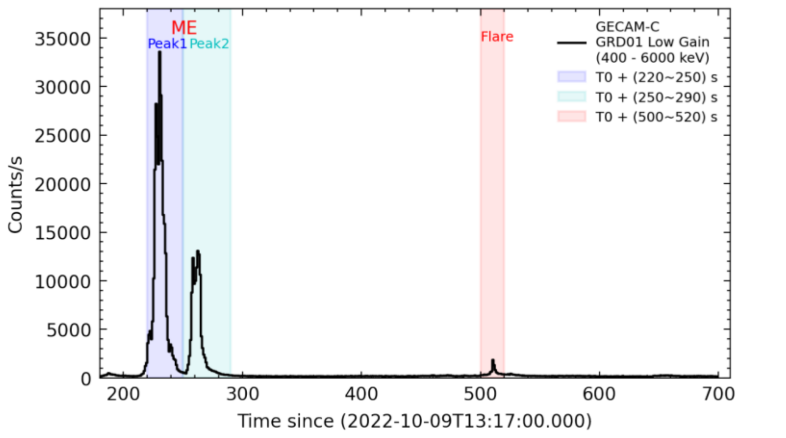


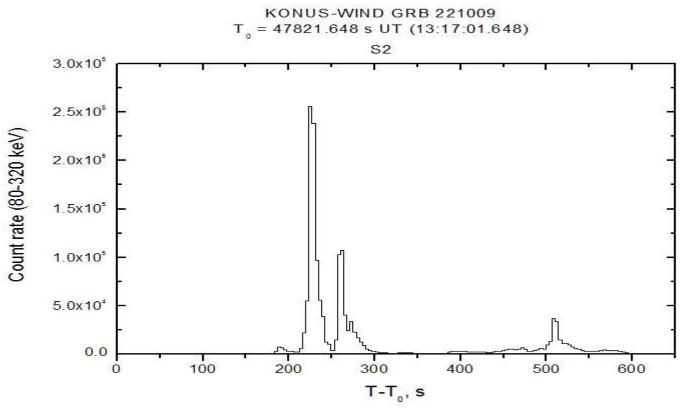
Lesage et al. (2023): https://arxiv.org/abs/2303.14172

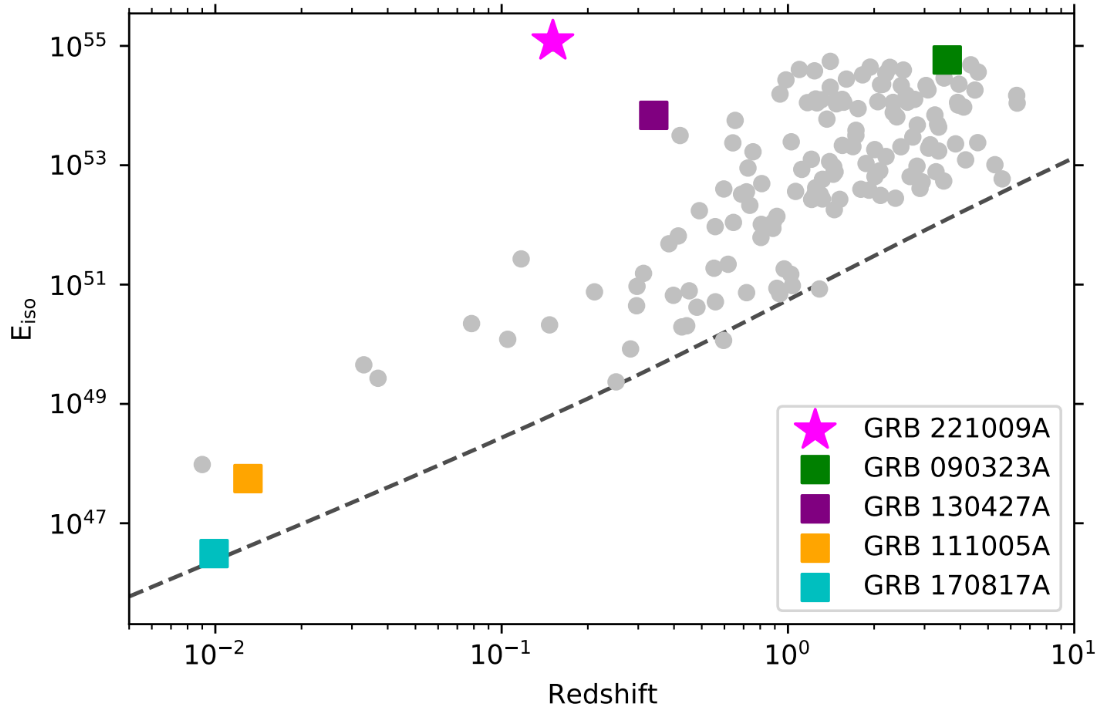
GECAM/Konus-Wind Observations of GRB 221009A

An et al. 2023

- Not saturated,   Fleunce~ 0.2 erg /cm^2 , $E_{\gamma,iso}$~$1.5x10^{55}$ erg

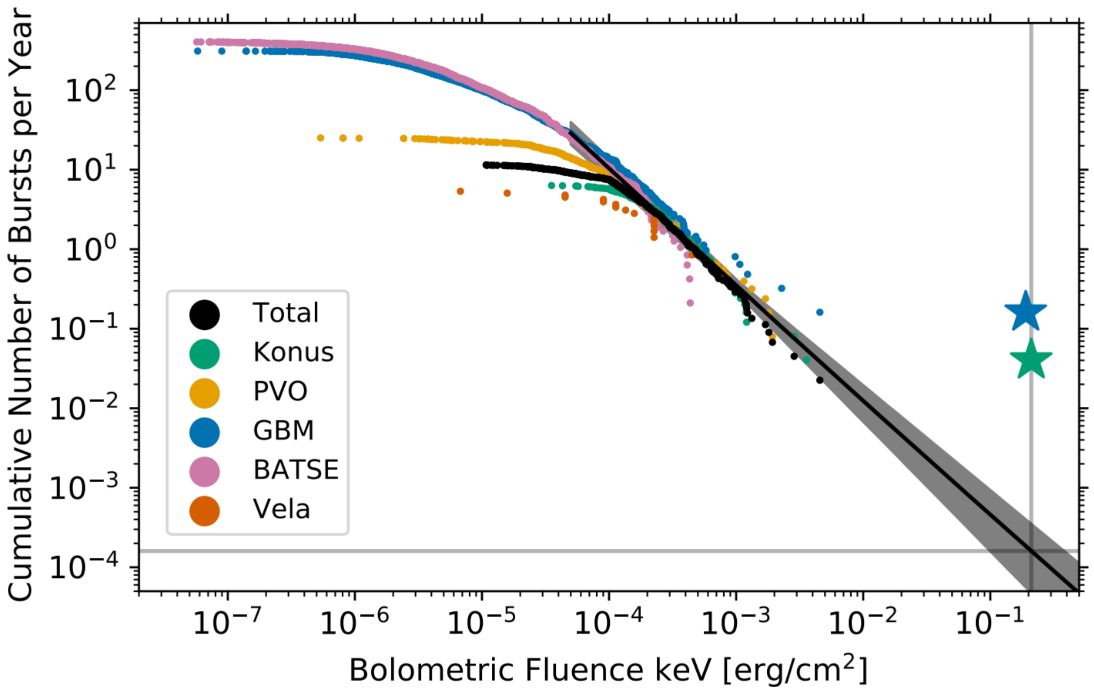






Buns et al. 2023

GRB 221009A: A very rate event



Buns et al. 2023

Fluence: F~ D^{-2}

Event rate: R ~ D^3

→ Event rate R ~ $F^{-3/2}$

Its fleunce is 50 times higher the 2nd brightest GRB

Event rate: R<10^{-3} yr

A Chinese song: “千年等一回”
“waiting a thousand years for once”

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- Discussions

The Electromagnetic Spectrum

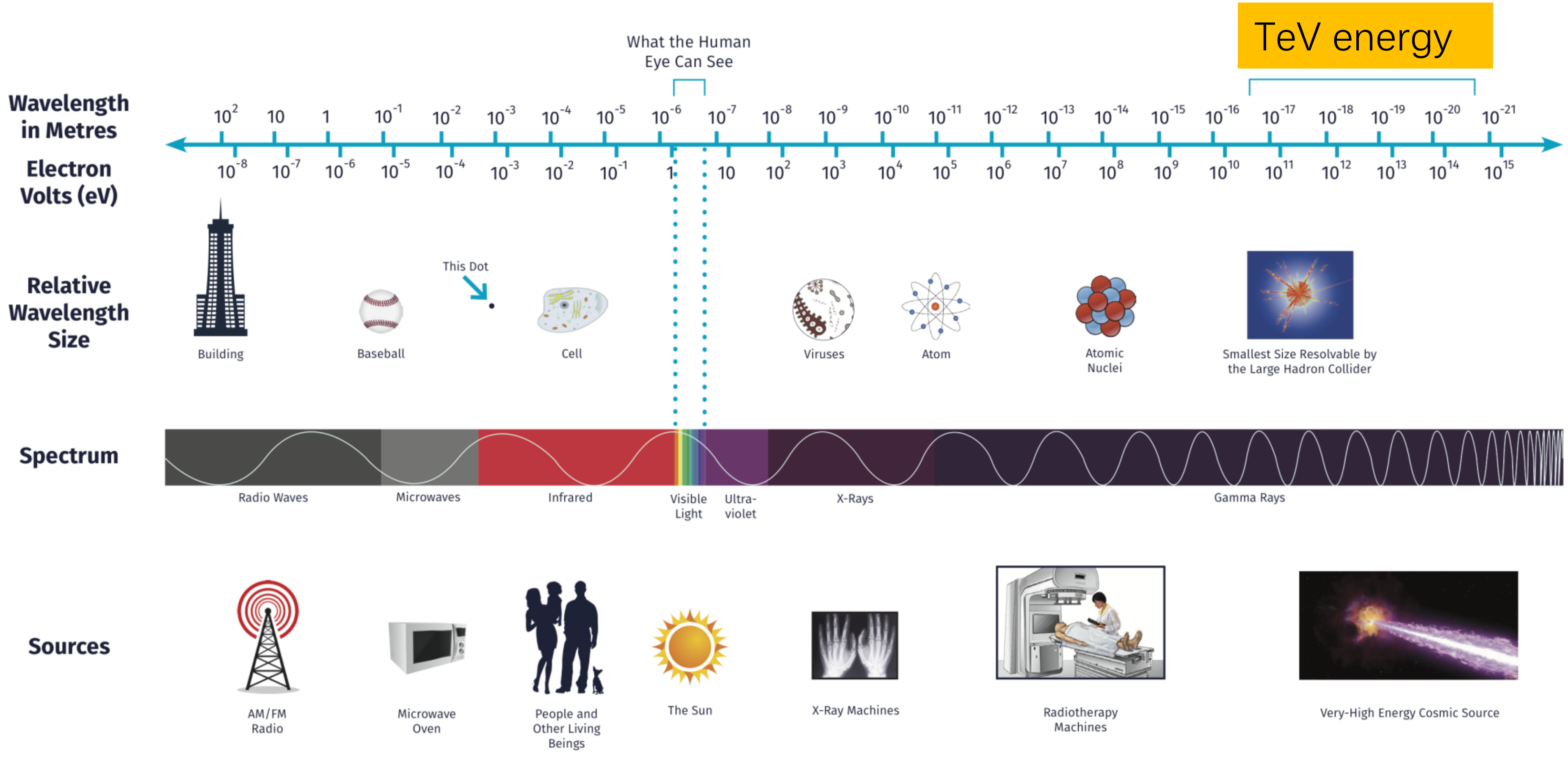
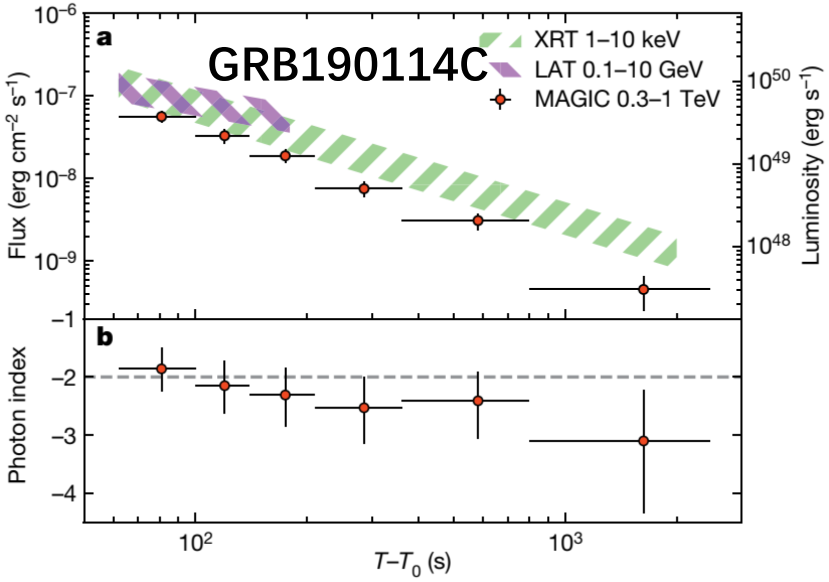
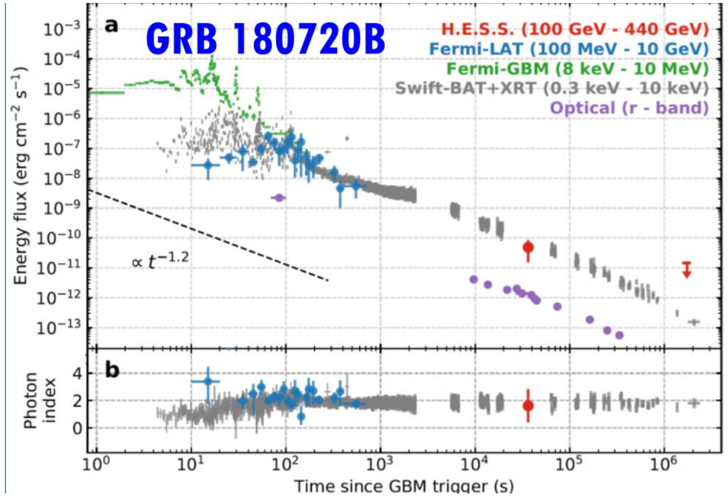


Image credits: Vecteezy.com, Dragonartz.net, NAOJ, NCI, CERN, NASA

TeV observations of GRBs: decaying afterglows

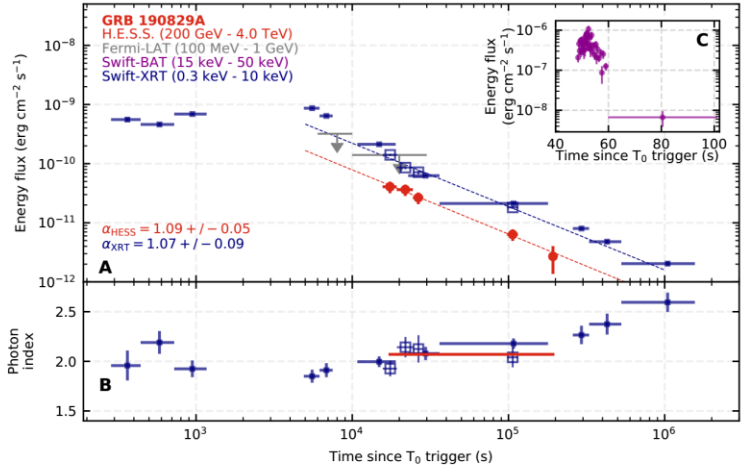


Magic coll. 2019a, Nature



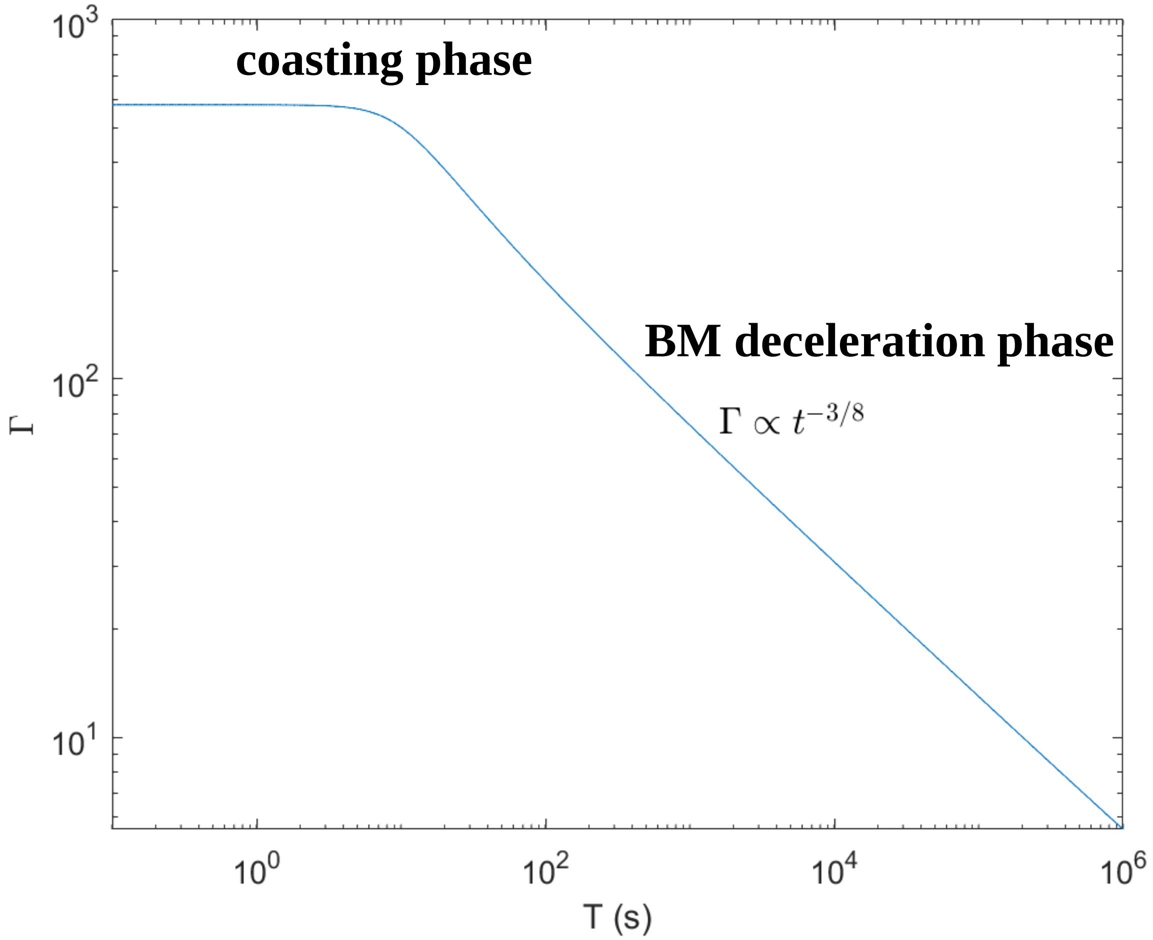
HESS coll. 2019,Nature

GRB190829A



HESS coll. 2021, Science

How about TeV emission before deceleration?

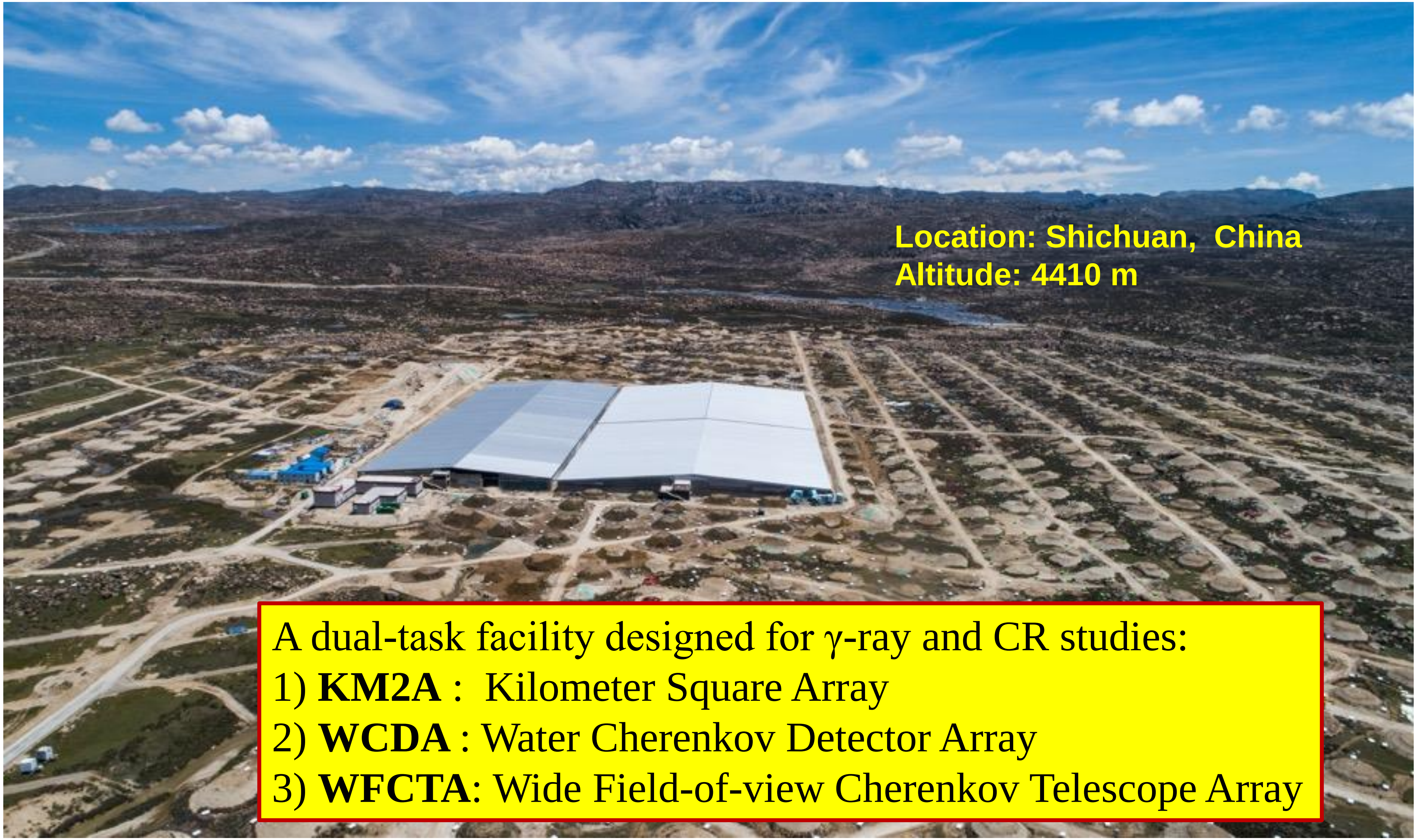


- **TeV emission during the coasting phase ?**
- **Any TeV emission during the prompt emission?**

✓ IACTs are pointed instruments that need time to slew to the GRB

✓ Extensive air shower detectors allow observations during the prompt GRB and the afterglow onset, but no detection yet

LHAASO



A dual-task facility designed for γ-ray and CR studies:

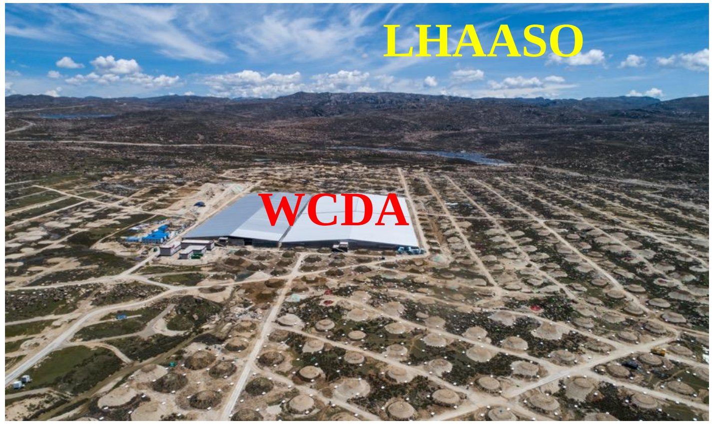
1) **KM2A** : Kilometer Square Array

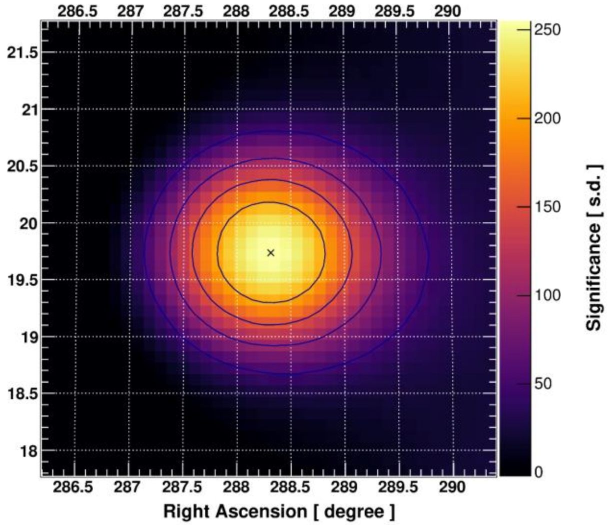
2) **WCDA** : Water Cherenkov Detector Array

3) **WFCTA**: Wide Field-of-view Cherenkov Telescope Array

LHAASO Observations of GRB221009A

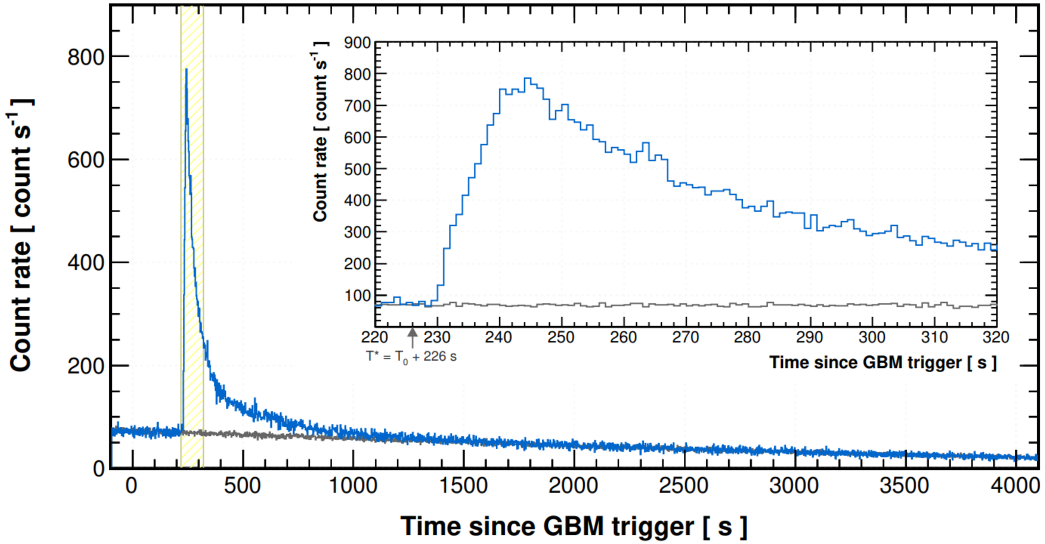
- GRB 221009A occurred within the FOV of LHAASO : first GRB seen by an extensive air shower detector





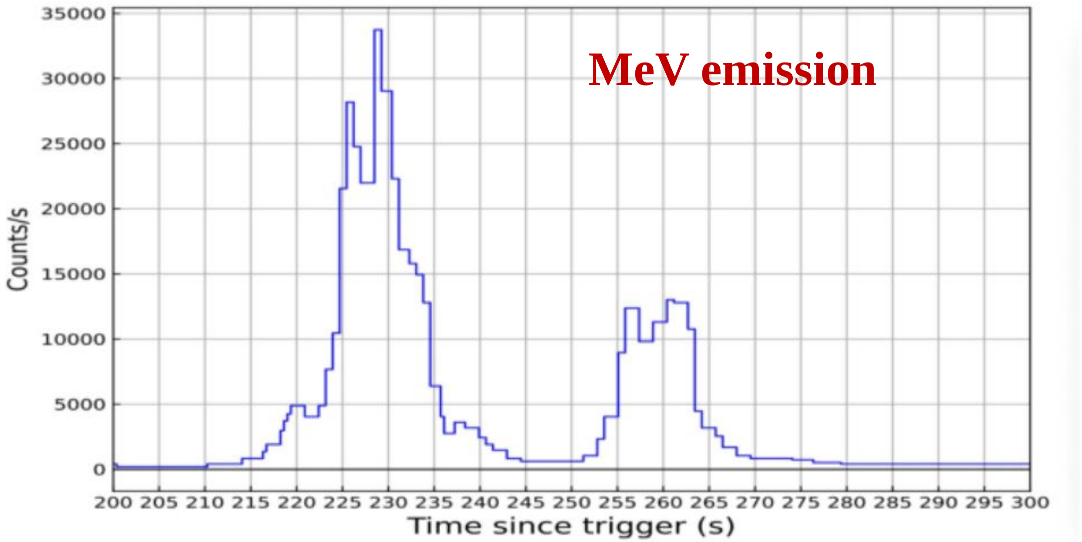
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)

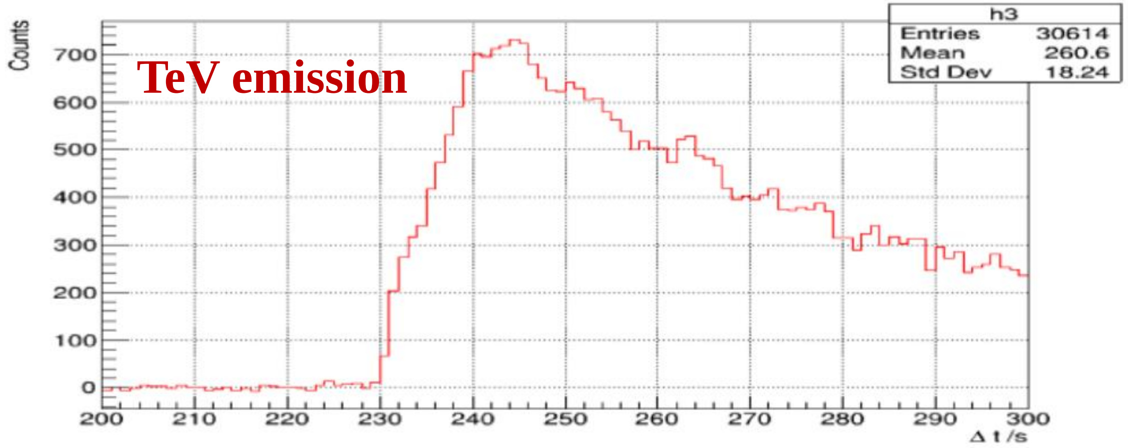
- TeV light curve: a rise to peak after a quiescent phase, then a decay



LHAASO Collaboration, Science 380, 1390 (2023)

MeV vs TeV light curves: external shock origin





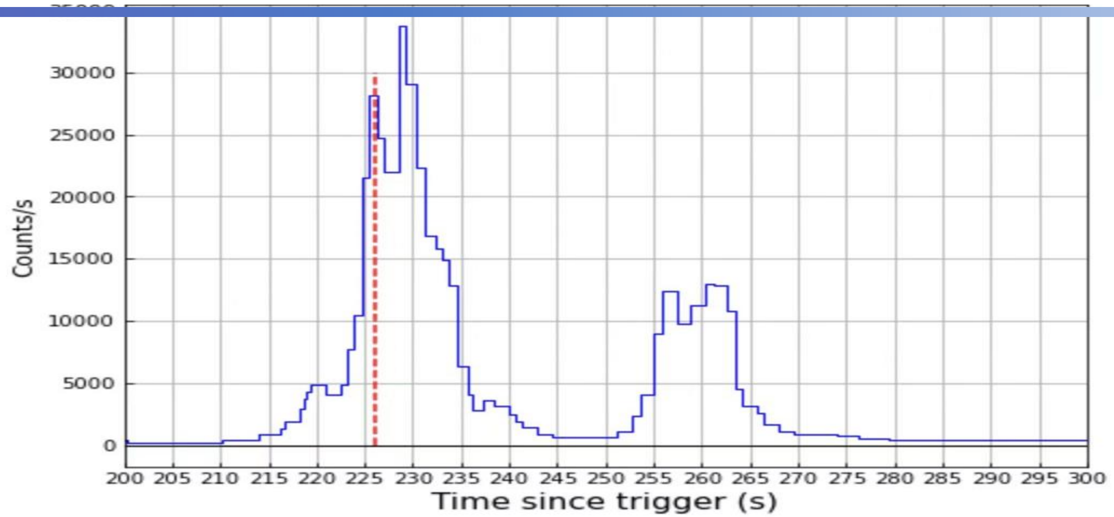
- Smooth temporal profile suggests it is a TeV afterglow
- First time detection of the **onset** of a TeV afterglow!

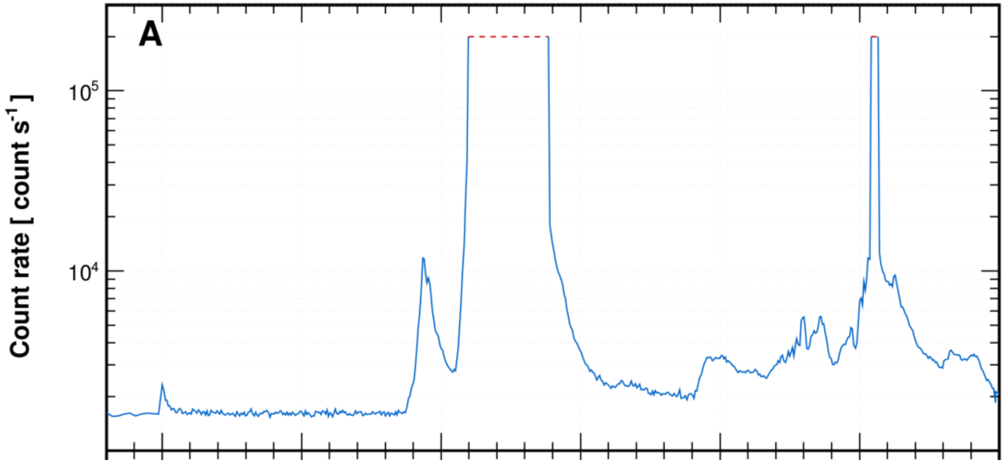
Afterglow starting time: T^*

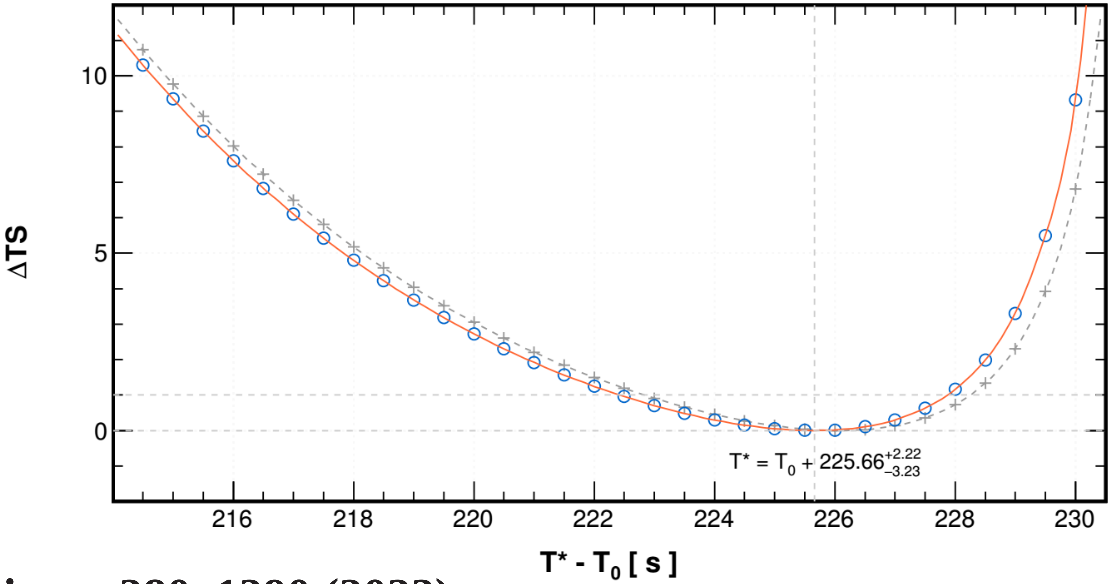
- Triggered on a weak precursor
- measuring times from the beginning of the main burst emission (Kobayashi & Zhang 2007):

$T^* \approx 225–228$ s

- Fitting of LHAASO light curve:







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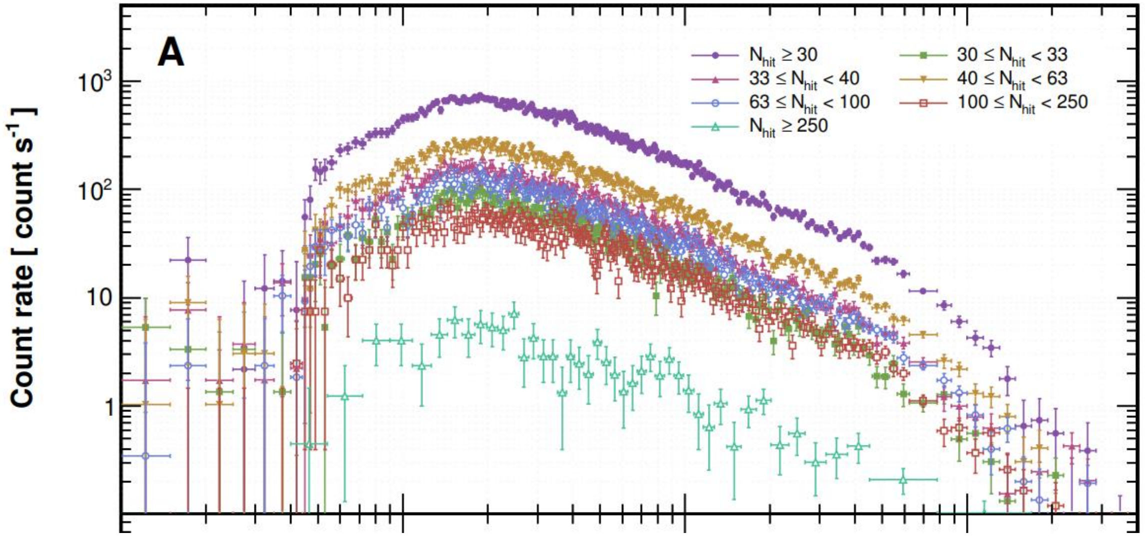
TeV light curves: 4-segement power-law

- Count-rate light curve



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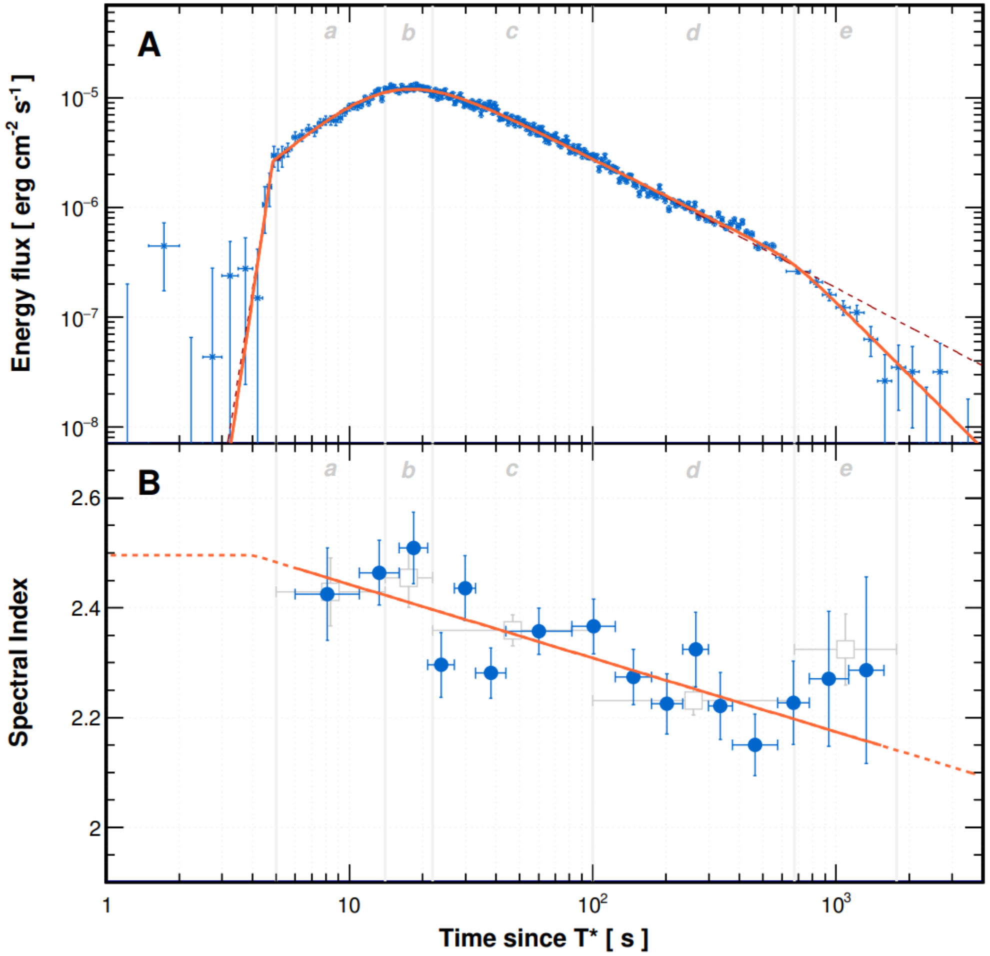
- Energy flux light curve



1. Rising phase

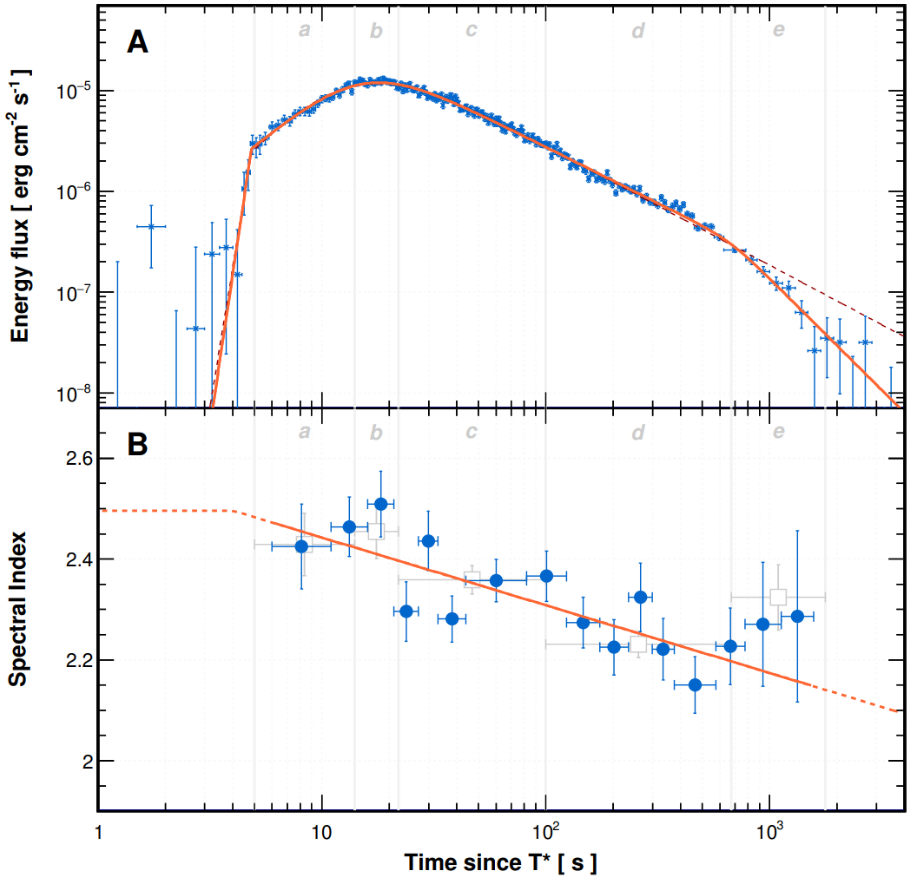
- Fast rise: $\alpha_0 = 14.9^{+5.7}_{-4.0}$
- slow rise, coasting phase

$$\alpha_1 = 1.82^{+0.21}_{-0.18}$$

- Expected light curve: t^2 agrees with k=0 (ISM), inconsistent with k=2 (stellar wind)

$$n \propto R^{-k}$$

- Rapid rise is unusual, possibly due to energy injection



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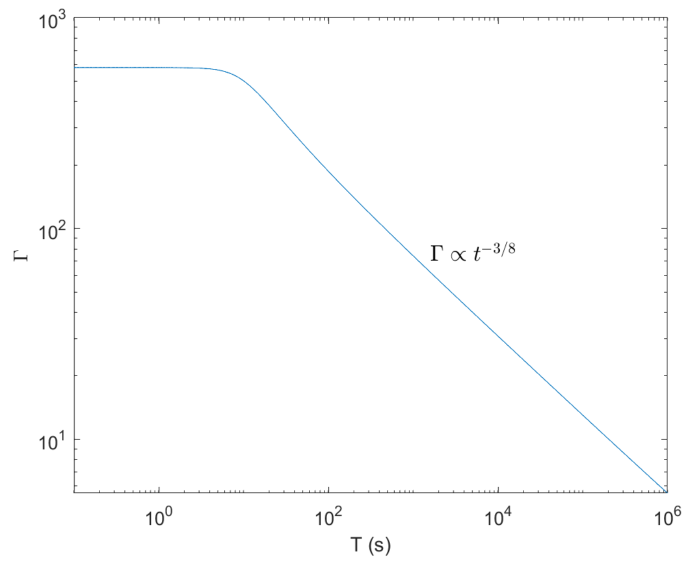
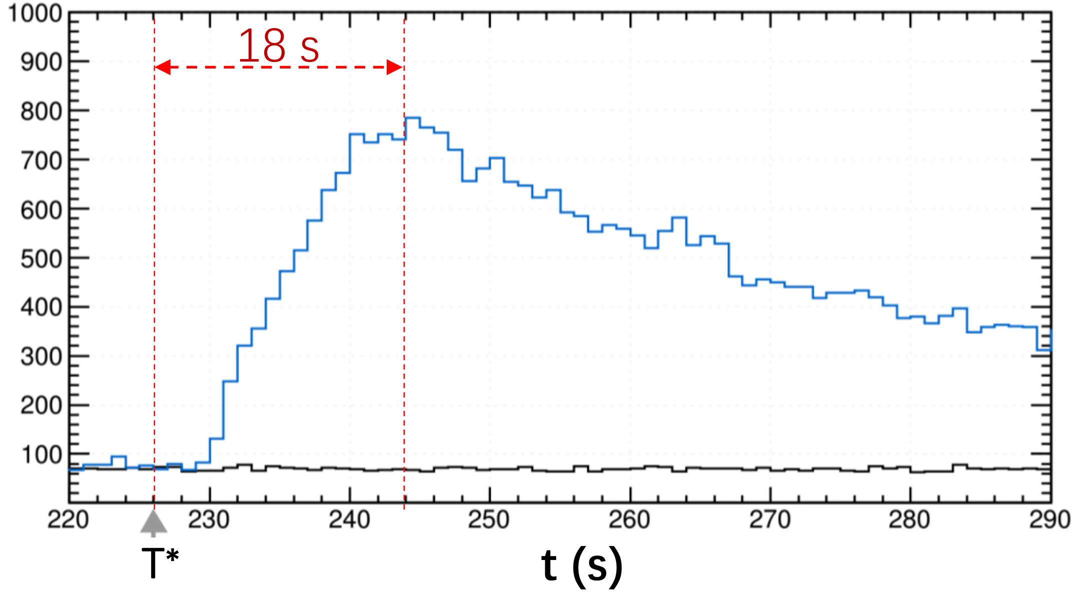
The initial bulk Lorentz factor Γ_0

- From **T*** to the peak, it takes **~18 s**
- The bulk Lorentz factor is estimated as

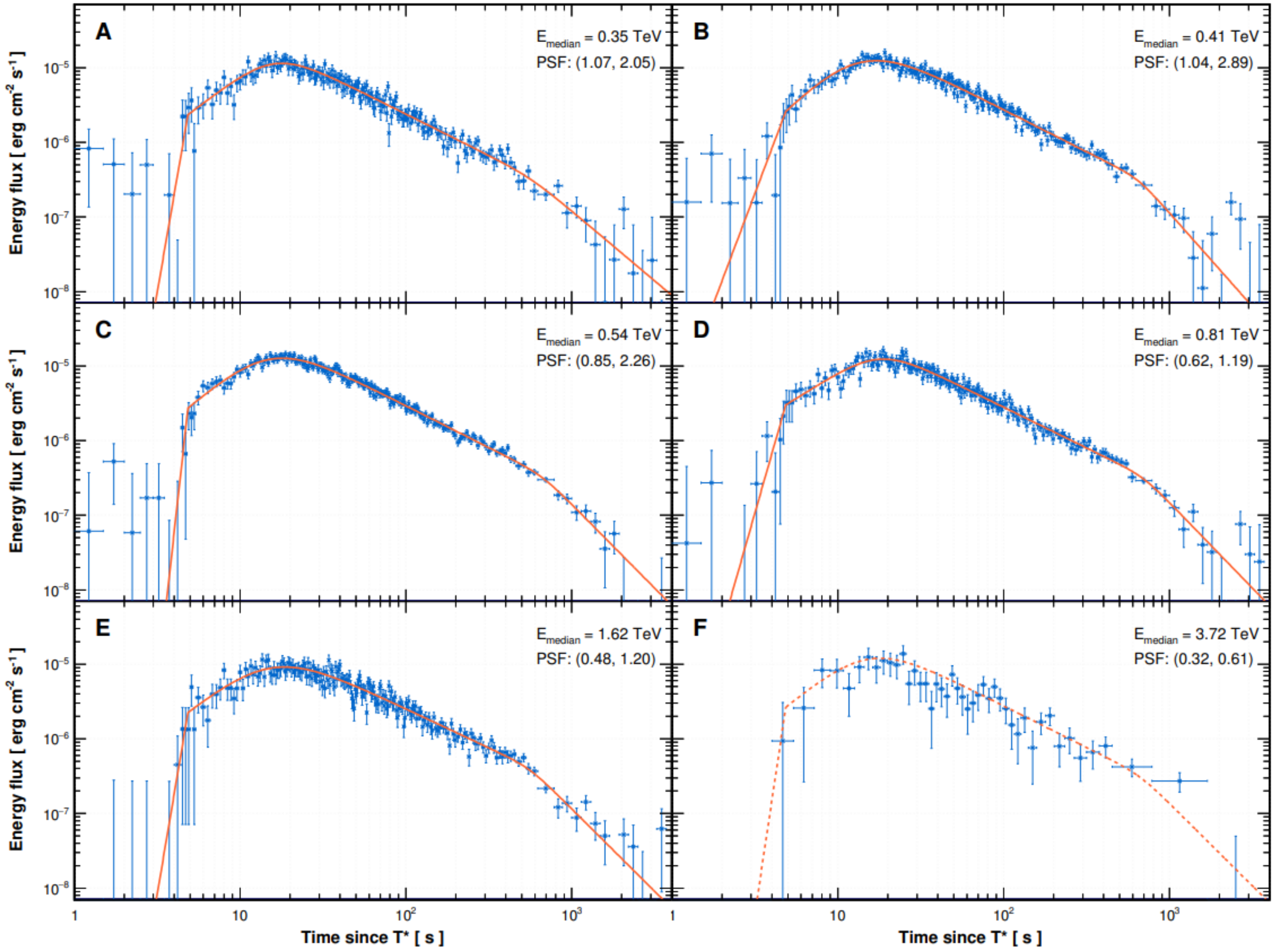
$$\Gamma_0 = \left(\frac{3E_k}{32\pi n m_p c^5 t_{\rm peak}^3}\right)^{1/8} = 440 E_{k,55}^{1/8} n_0^{-1/8} \left(\frac{t_{\rm peak}}{18\,{\rm s}}\right)^{-3/8}$$

it is among the highest values for all GRBs





2. decay phase



$$\alpha_2 = -1.115^{+0.012}_{-0.012}$$

$$\alpha_3 = -2.21^{+0.30}_{-0.83}$$

$$T_{b,2} = T^* + 670^{+230}_{-110}\ \mathrm{s}$$

Revealing a jet break at the earliest time.

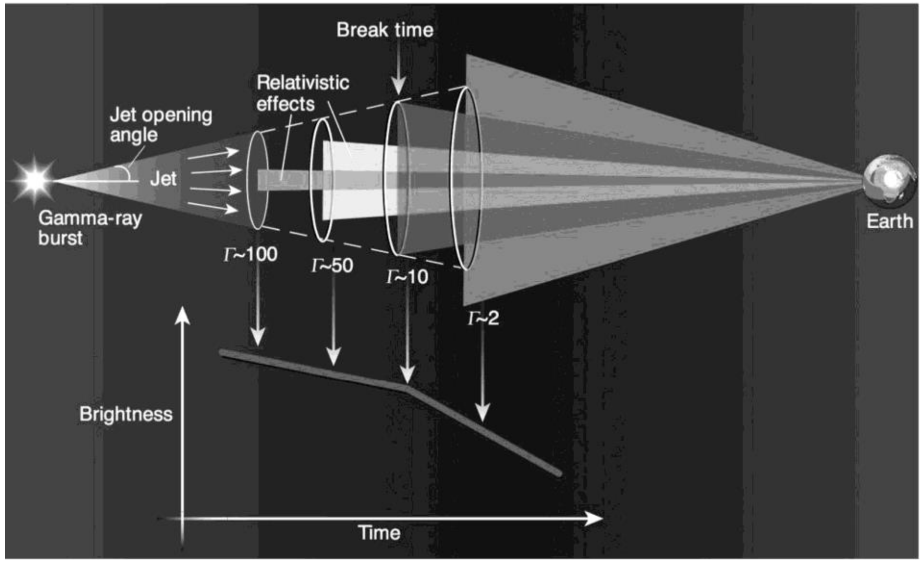
A narrow GRB jet

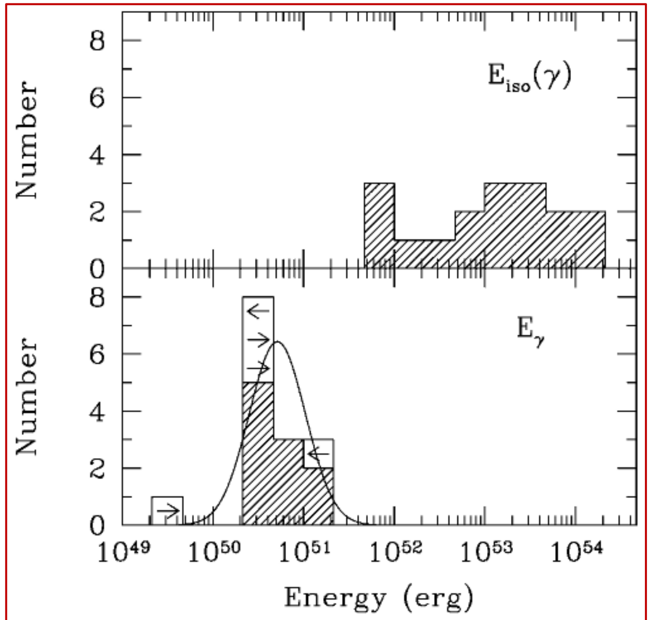
- Light curve steepens when the increasing radiation cone exceeds the jet opening angle
- Jet breaks have been seen in optical/X-ray bands
- An early jet break implies a narrow jet:

$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\rm b,2}}{670\,{\rm s}}\right)^{3/8}$$

- Lead to a normal beaming-correct energy

$$E_{\gamma,j} \;=\; E_{\gamma,\rm iso}\theta_0^2/2 \;\sim\; 7.5\times10^{50}\;\;{\rm erg}E_{\gamma,\rm iso,55}(\theta_0/0.7^\circ)^2$$

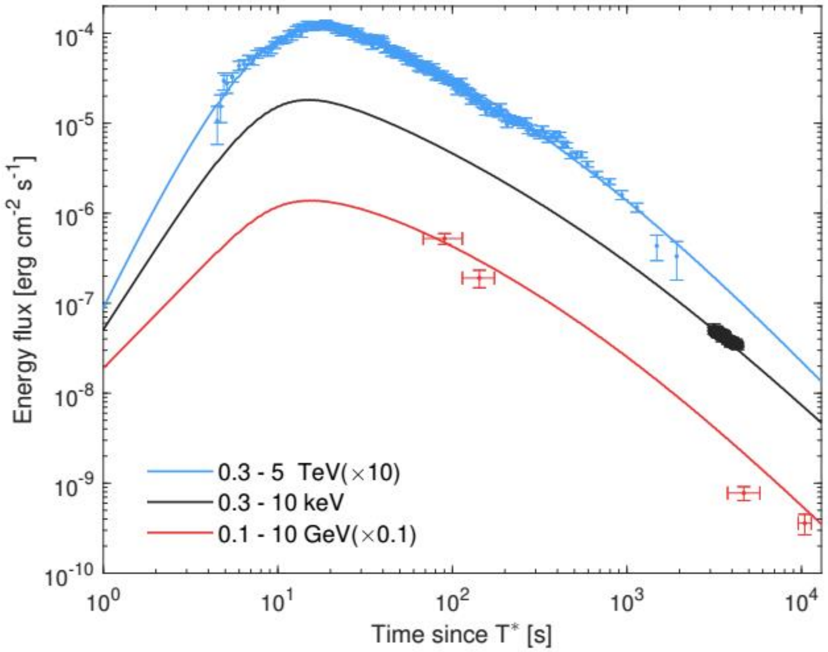


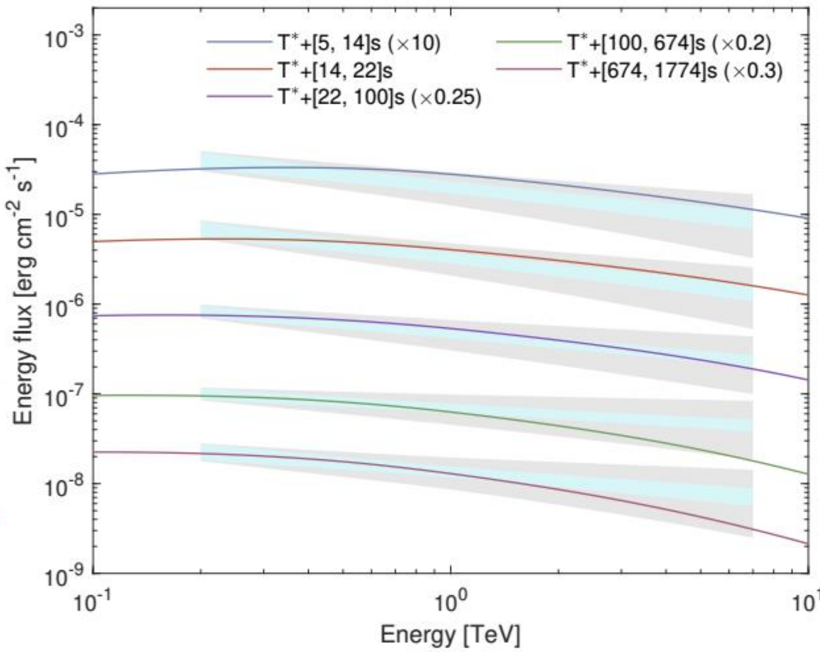


Frail et al. 2001

Multi-wavelength modelling

afterglow synchrotron + SSC (first 10^4 s)



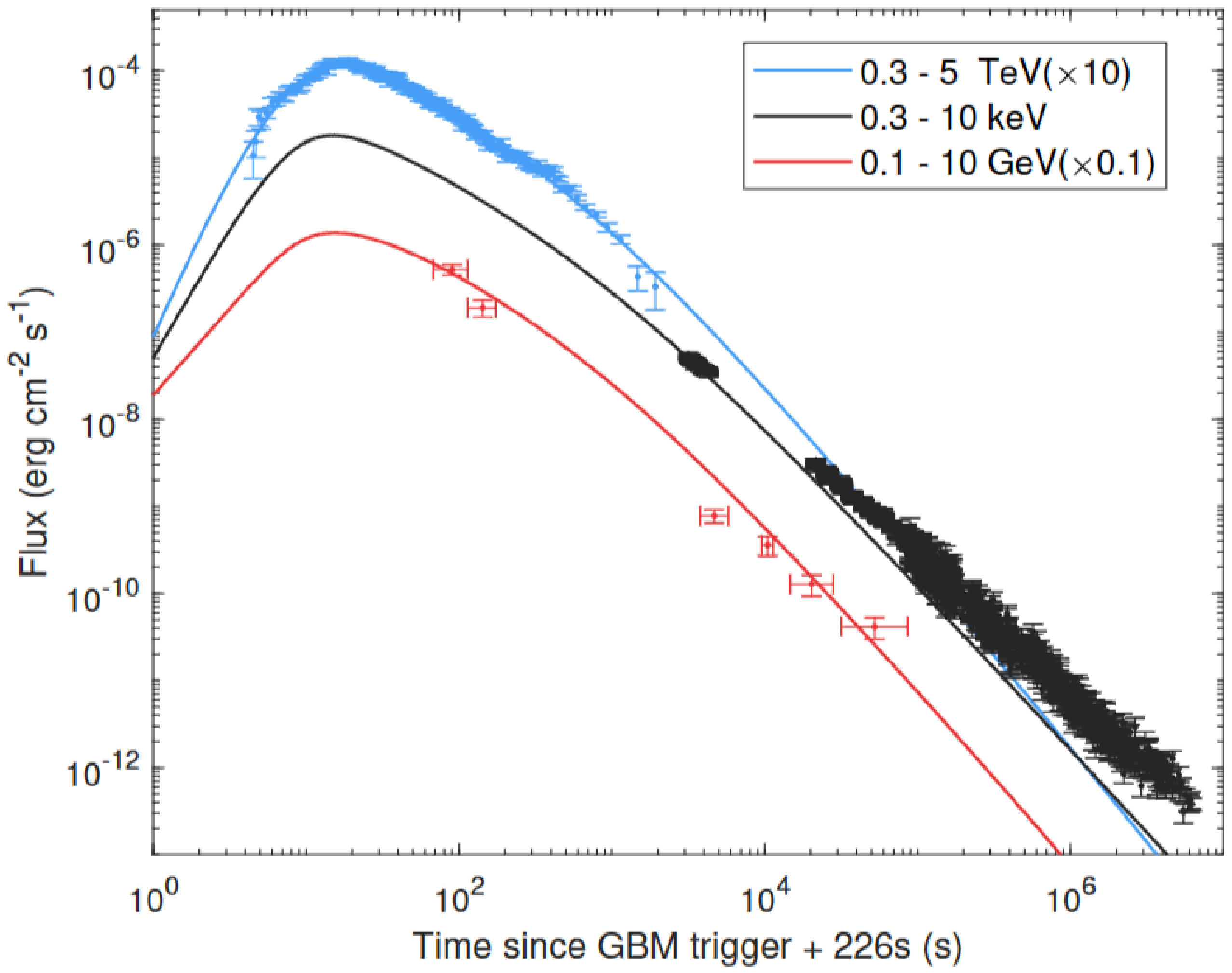


- X-ray: synchrotron
- GeV: synchrotron + SSC
- TeV: SSC

One possible solution: $E_k = 1.5 \times 10^{55}$ erg, $\Gamma_0 = 560$, $\epsilon_e = 0.025$, $\epsilon_B = 6 \times 10^{-4}$, $p = 2.2$, $n = 0.4\,\mathrm{cm}^{-3}$ and $\theta_0 = 0.8°$.

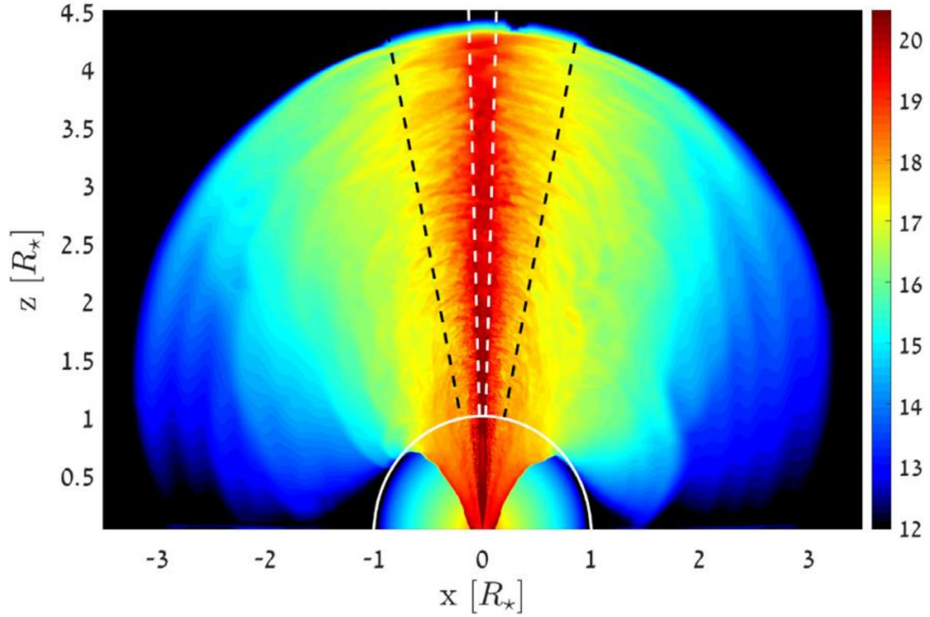
LHAASO Collaboration, Science 380, 1390 (2023)

An inner jet is insufficient



See also O'Connor et al. 23; Gill & Granot 23; Sato et al. 23

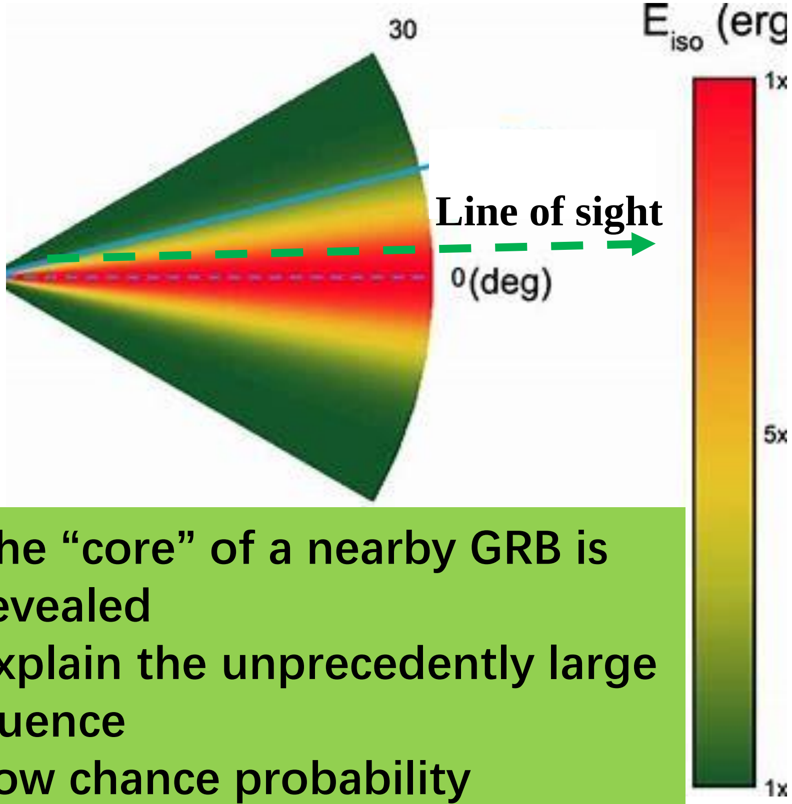
- Late afterglows need outer, wider components
- Implying a structured jet



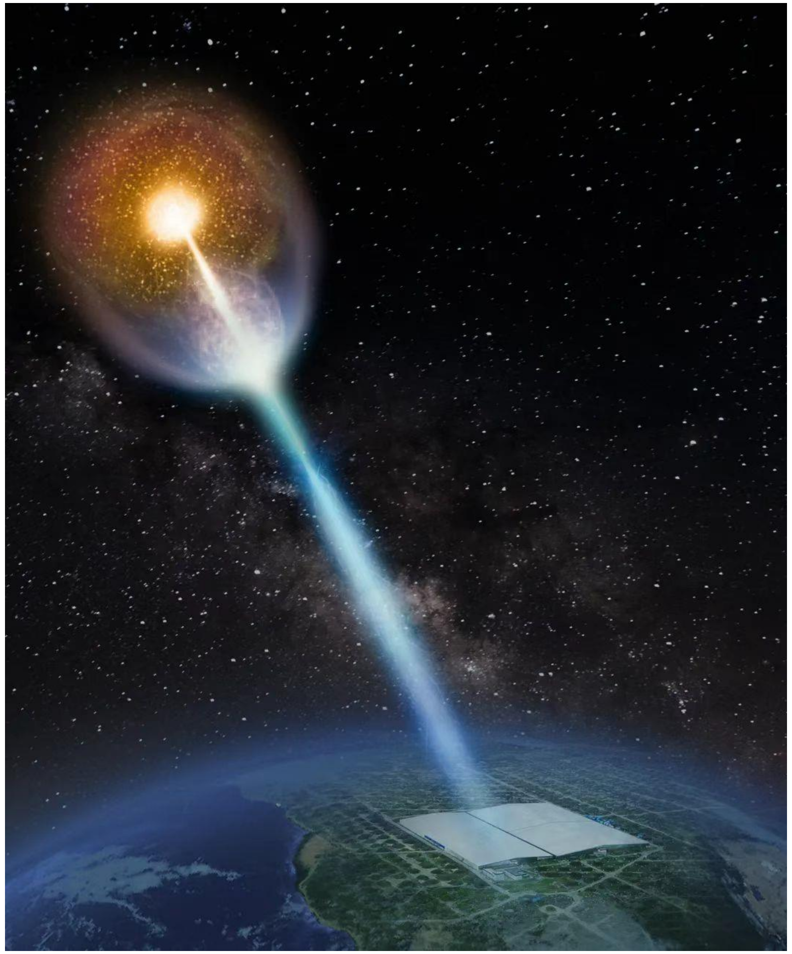
Numerical simulation by Gottlieb et al. 2021

GRB 221009A: seeing the brightest core of a structured jet

- GRB 221009A



- The “core” of a nearby GRB is revealed
- Explain the unprecedently large fluence
- Low chance probability



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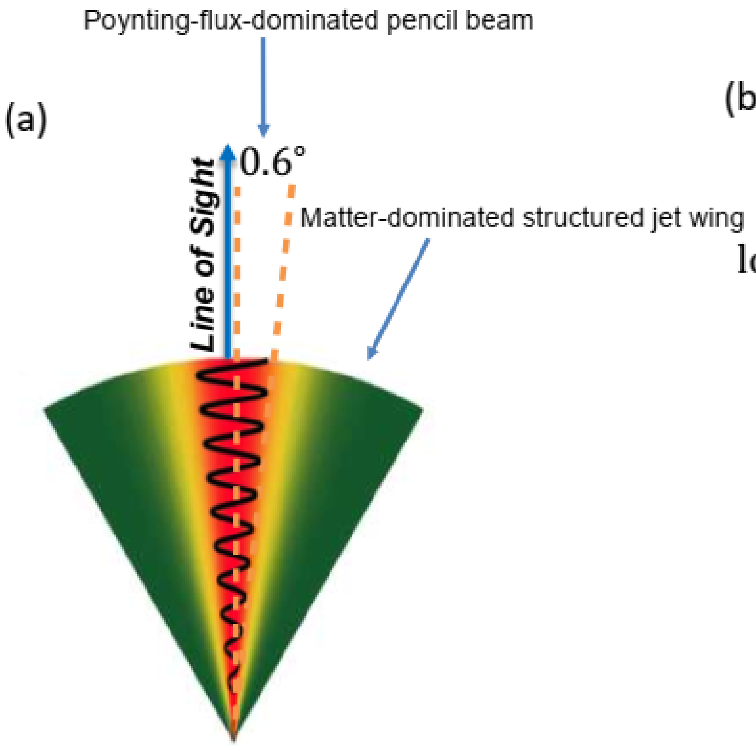
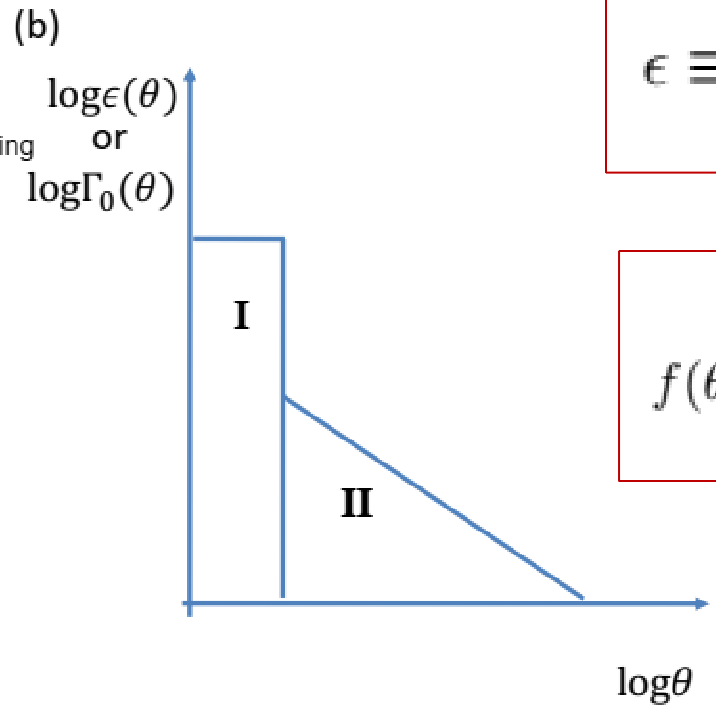
A two-component jet model

- Zhang & Wang (2023), Zheng, Wang, Liu, Zhang (2023)

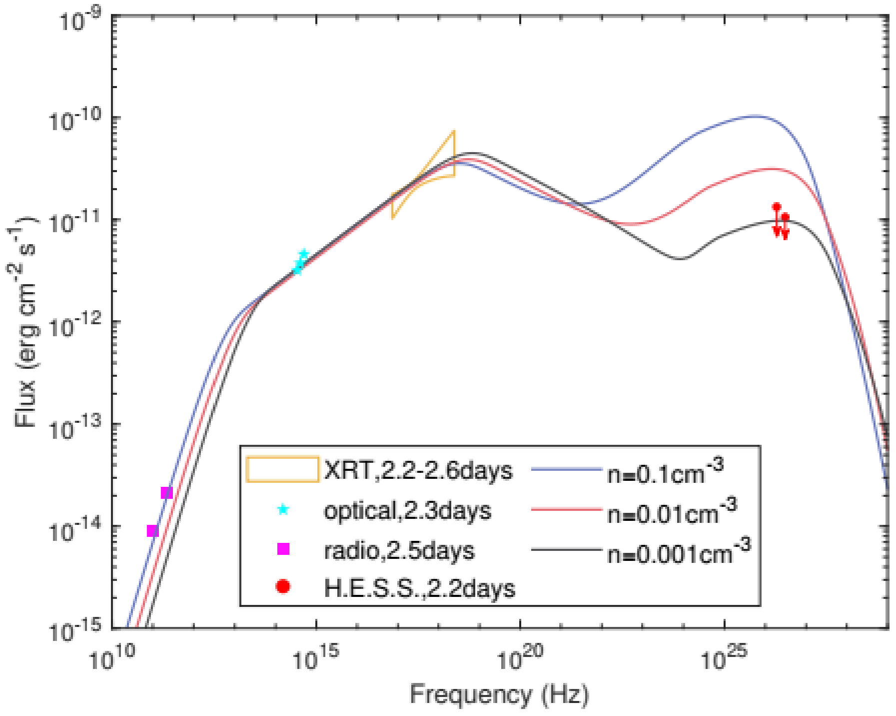




$$\epsilon \equiv \frac{dE}{d\Omega} = \begin{cases} \epsilon_{\rm I}, & \theta < \theta_{\rm j}, \\ \epsilon_{\rm II} f(\theta), & \theta_{\rm j} < \theta < \Theta, \end{cases}$$

$$f(\theta) = \left[\left(\frac{\theta}{\theta_{\rm c,w}} \right)^{2a_1} + \left(\frac{\theta}{\theta_{\rm c,w}} \right)^{2a_2} \right]^{-1/2},$$

A STRATIFIED DENSITY PROFILE



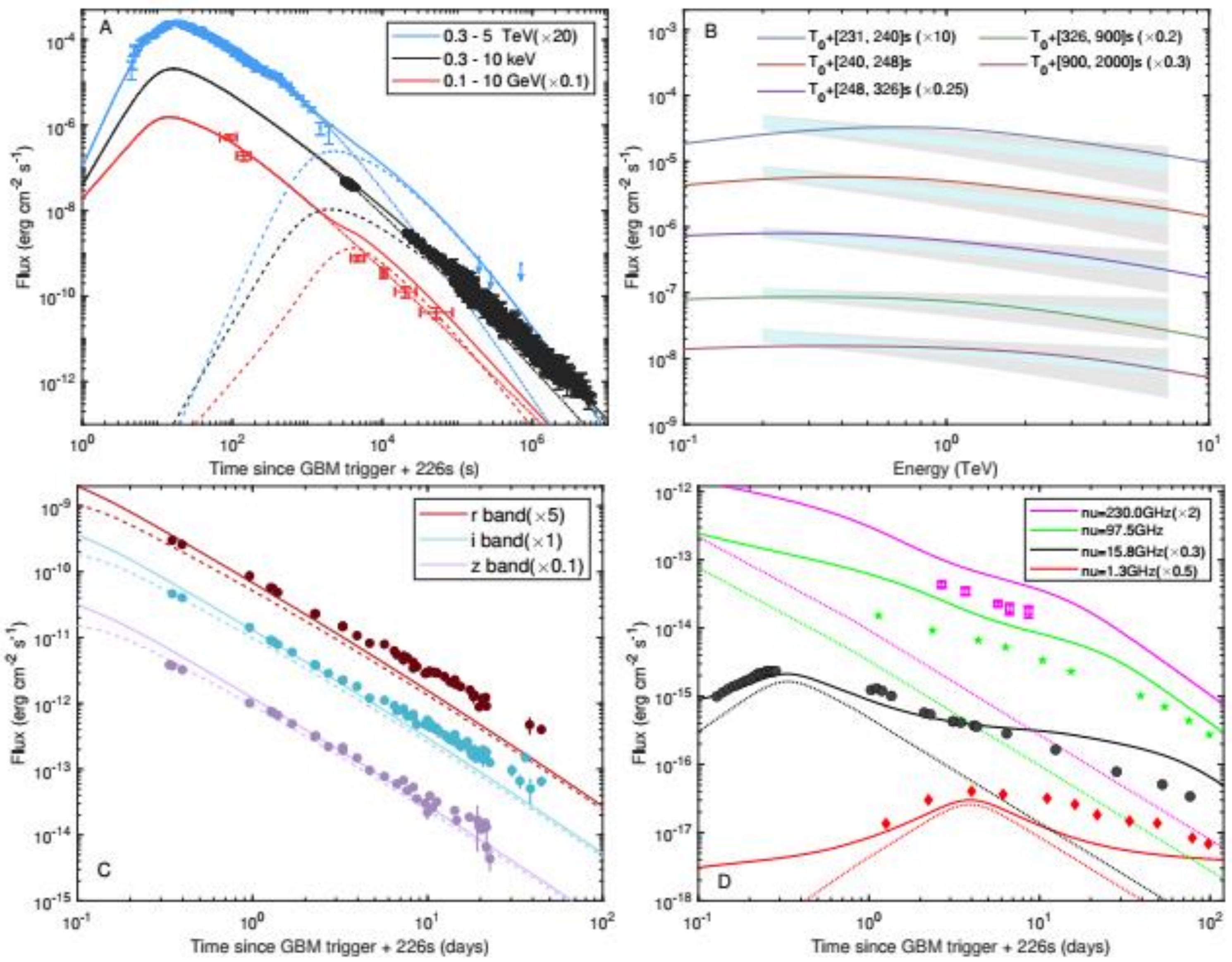
- Transition from constant-density medium to wind-like medium

LHAASO data: $n_0 \geq 0.1\mathrm{cm}^{-3} E_{\mathrm{I,iso},55}^{-\frac{(9-p)}{21-p}} \epsilon_{\mathrm{B},-4}^{-\frac{2(7-p)}{21-p}}.$

$$n_0 \leq 0.007\mathrm{cm}^{-3} E_{\mathrm{II,iso},54}^{-\frac{(3-p)}{7-p}} \epsilon_{\mathrm{B},-4}^{\frac{2(p-1)}{7-p}}.$$

$$n(r) = \begin{cases} n_0, & r < r_c \\ Ar^{-2}. & r \geq r_c \end{cases}$$

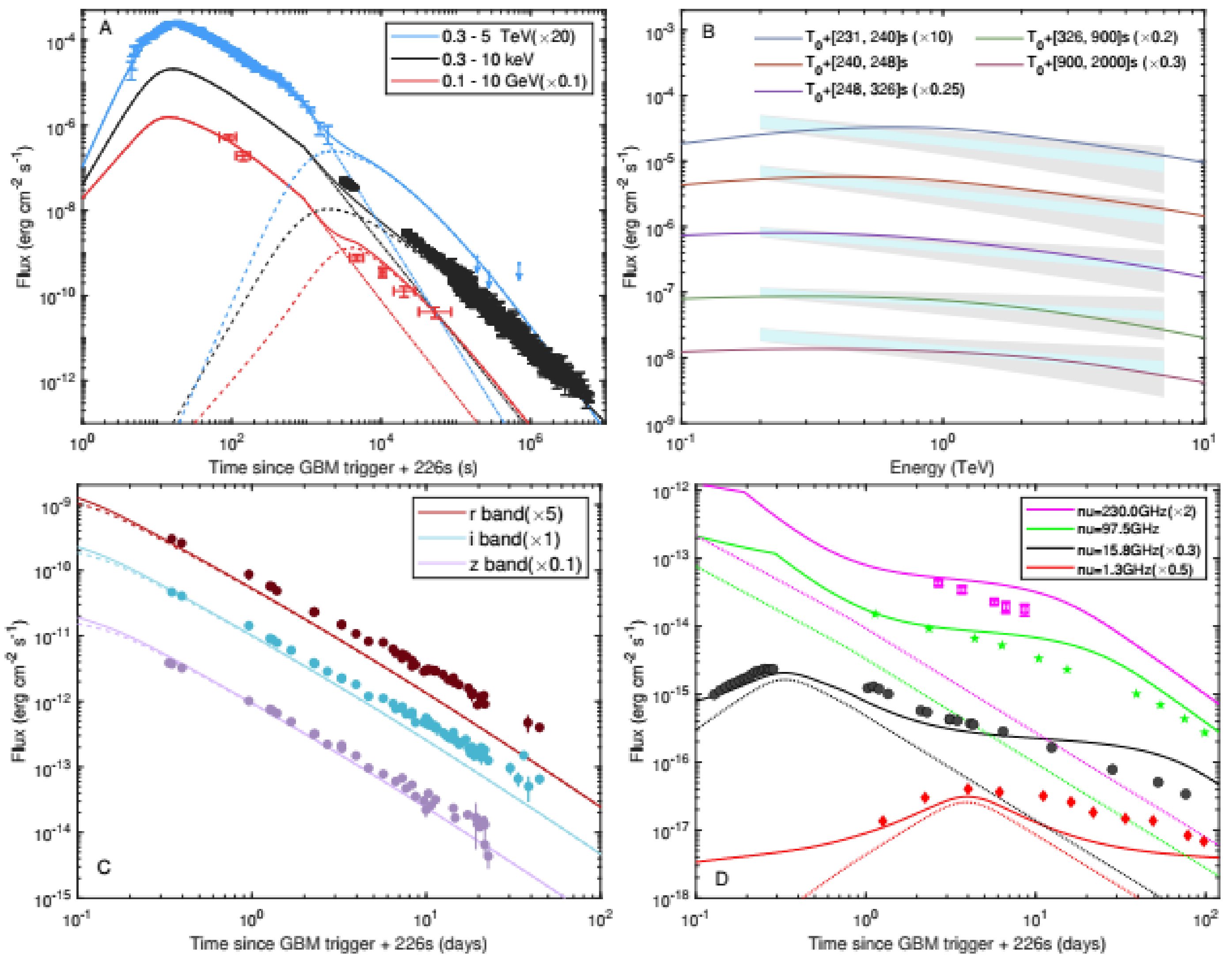
A two-component jet model



	$4\pi\epsilon_{\rm I}$(erg)	$\theta_{\rm j}$	$\Gamma_{\rm I,0}$	$\epsilon_{\rm I,e}$	$\epsilon_{\rm I,B,-3}$	$\xi_{\rm I,e}$	$p_{\rm I}$	$4\pi\epsilon_{\rm II}$(erg)	$\theta_{\rm c,w}$	$\Gamma_{\rm II,0}$	a_1	a_2	$\epsilon_{\rm II,e}$	$\epsilon_{\rm II,B,-3}$	$\xi_{\rm II,e}$	$p_{\rm II}$
FS1	9×10^{54}	0.6°	560	0.04	1	1	2.2	4×10^{53}	3°	60	0	0.8	0.06	2	0.15	2.4
FS2	9×10^{54}	0.6°	560	0.04	1	—	2.2	4×10^{53}	3°	60	0	0.8	0.06	2	—	2.5

A two-component jet model with sideways expansion

- Assuming side expansion for the narrow jet
- Fit to the GeV data is improved
- But the radio flux exceed the data by a factor of ~2



Considering the time-varying microphysical parameter: a decreaing acceleration fraction ?

- Decreasing k_e is required by the data

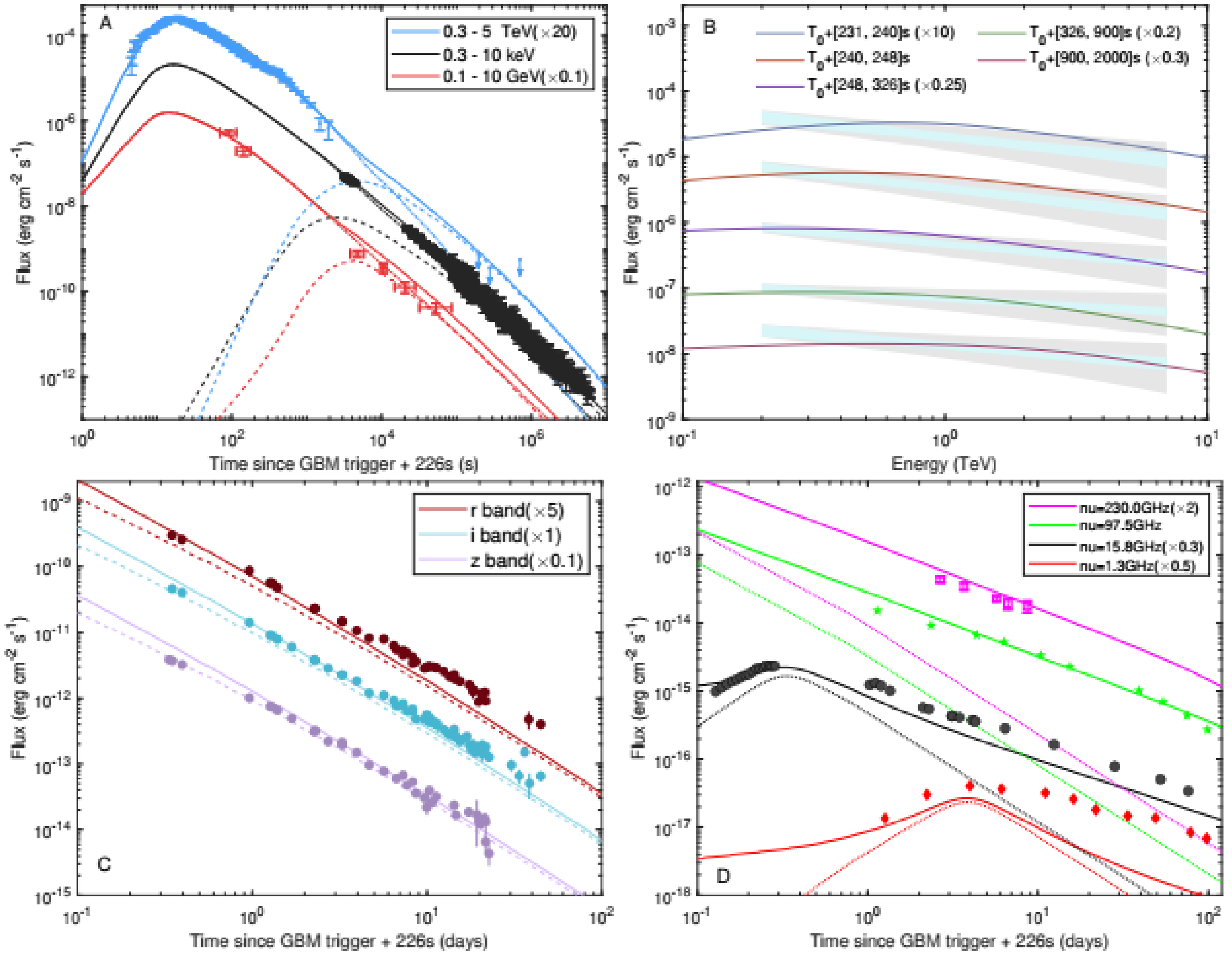
$$k_{\rm e} = \epsilon_{\rm e}/\xi_{\rm e}$$

- Decreasing *Acceleration Fraction* ξ_e

$$\xi_{\rm e} \propto t^{-\alpha_\xi}$$

$$F_\nu \propto \begin{cases} t^{-\frac{a}{3(4-a)}-\frac{5}{3}\alpha_\xi}, & \nu < \nu_m \\ t^{-\frac{2(3p-1)-a(p-1)}{2(4-a)}+\alpha_\xi(p-2)}, & \nu_m < \nu < \nu_c \\ t^{-\frac{2(3p-2)-a(p-2)}{2(4-a)}+\alpha_\xi(p-2)}. & \nu > \nu_c \end{cases}$$

- Or increasing ϵ_e



Decaying Magnetic Field model

- standard afterglow shock model assume a homogeneous magnetic field in the downstream of the shock.

- Nonetheless, the realistic magnetic field may have a spatial distribution behind the shock: decaying with the distance from the shock front (Lemoine et al. 2013)

$$\alpha_t = \frac{\log\left[\epsilon_{B-}/\epsilon_{B+}\right]}{\log\left[t_{\rm dyn}/\tau_{\delta B}\right]}$$

$$-0.5 \lesssim \alpha_t \lesssim -0.4.$$

- Radio-emitting electrons may radiate most of their energy at the back of the blast wave, where the magnetic field has decayed to a low value (Lemoine 2013; Wang et al. 2013).

Discussion: 1) origin of ~10 TeV photons

- Klein-Nishina effect leads to a spectral steepening in SSC emission
- KM2A detected 3-13 TeV photons
- > 3 TeV emission **needs a new component**

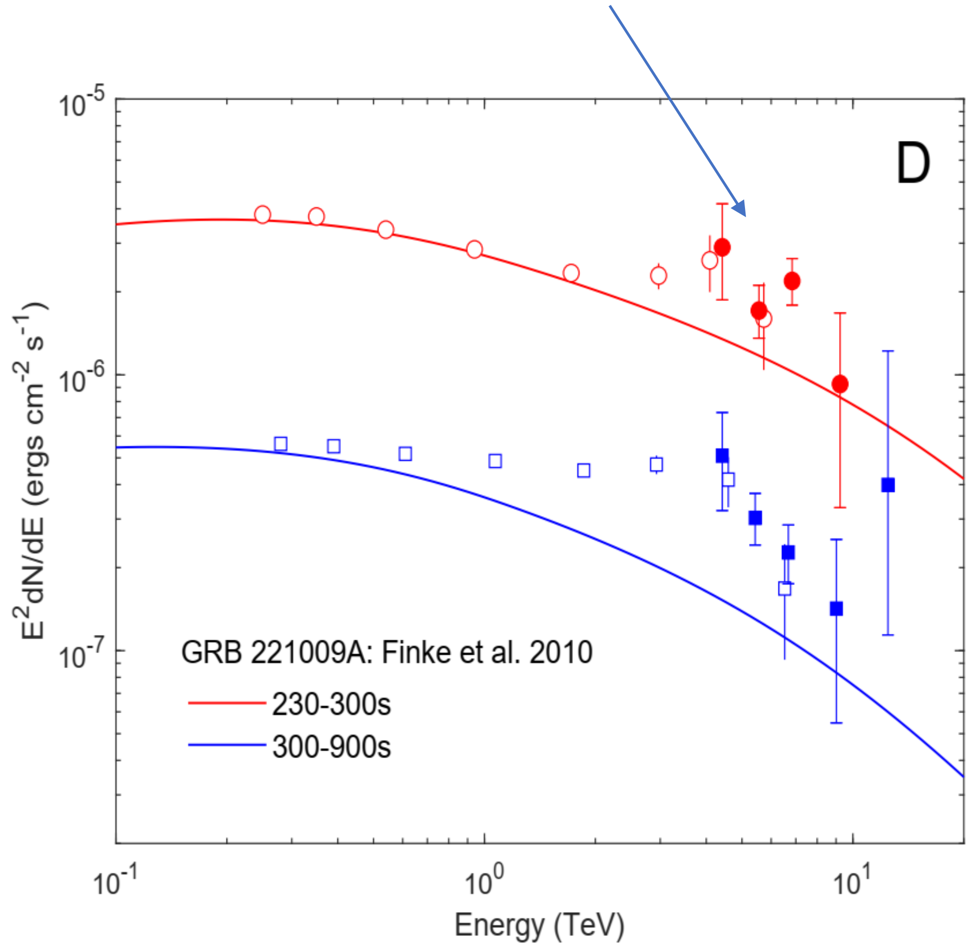
➢ Reverse shock proton synchrotron emission (Zhang et al. 2023)

➢ UHECR propagating in IGM (e.g., Das & Razzaque 2023)

➢ An extra hard electron component

--Can GRB produce UHECRs ?

Solid dots/squars: LHAASO-KM2A data



LHAASO coll., submitted, 2023

Proton synchrotron emission: TeV afterglow emission

Hybrid Emission Modeling of GRB 221009A: Shedding Light on TeV Emission Origins in Long-GRBs

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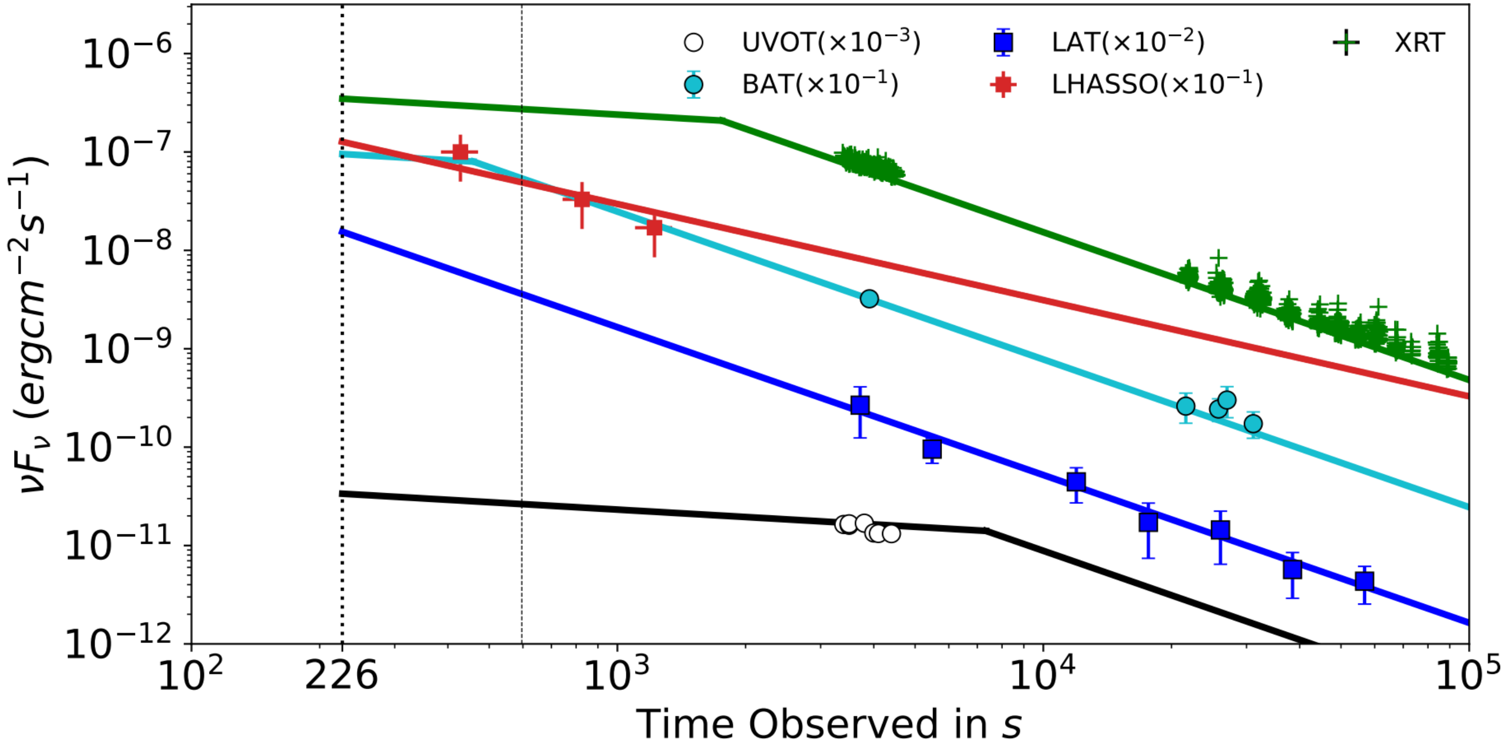


Discussion: 2) prompt TeV emission limit

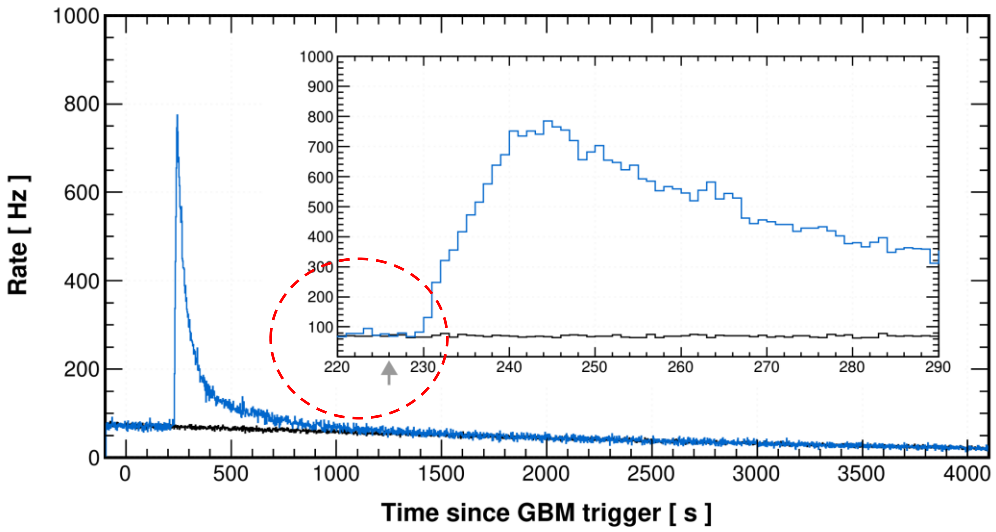
- The most strict limit on the prompt TeV emission

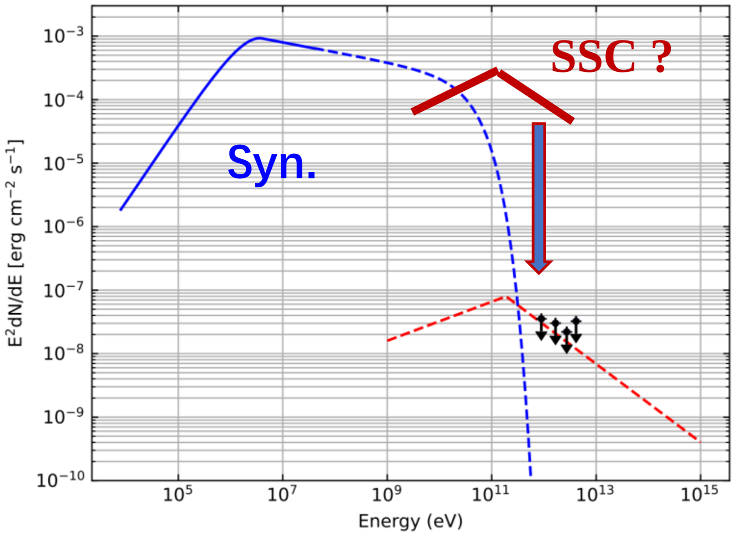
$$\mathbf{R}=F_{\mathrm{TeV}}/F_{\mathrm{MeV}} < 2 \times 10^{-5}$$

- If MeV emission arises from synchrotron emission, **where is the IC emission**?

- internal $\gamma\gamma$ absorption leads to an exponential cutoff ?

$$\gamma\gamma \rightarrow e^{+}e^{-}$$





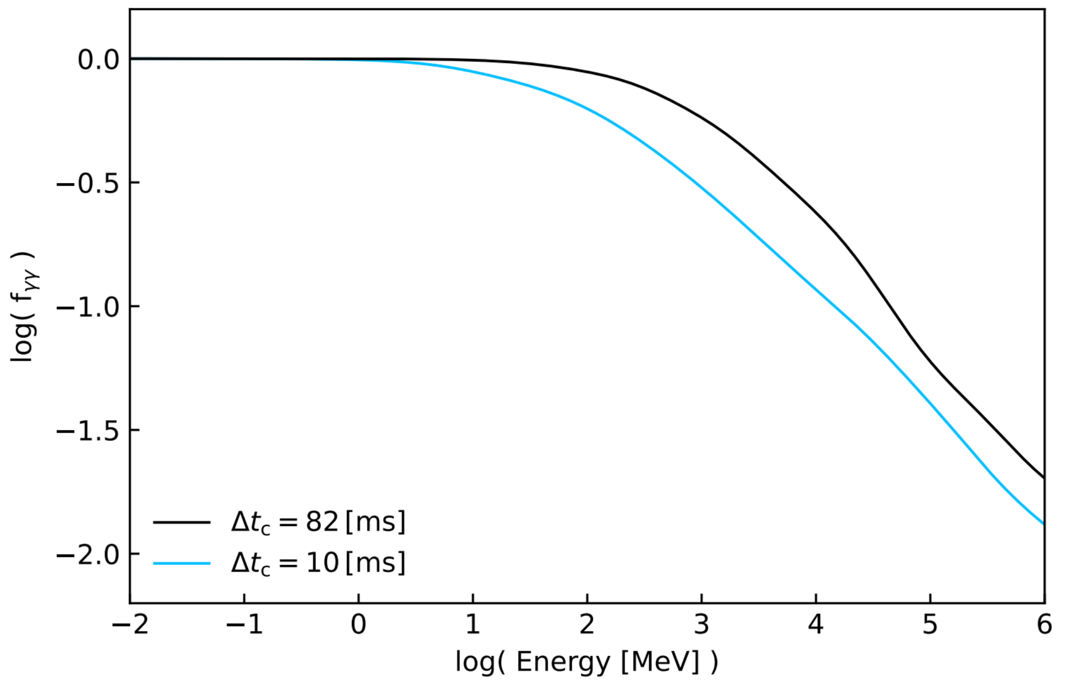
A Poynting-flux-dominated jet?

- **But,** internal shock simulations result in a broken power-law spectrum (Aoi et al. 2010; Dai et al. 2023)

- Then, we need a low ratio between SSC and synchrotron emission outputs.

- Implying the magnetic field energy density is much larger than the electron energy density: $\epsilon_B \gg \epsilon_e$

- A Poynting-flux-dominated jet suppress the SSC emission ?



Dai et al. 2023, arXiv:2307.14113

Conclusions

1. First time observing the onset of a GRB TeV afterglow

   This enables

   ① Estimating the initial bulk Lorentz factor Γ_0 of the jet

   ② Setting the most strict limit on the prompt TeV emission (a Poynting-flux-dominated jet?)

2. Finding a jet break in the TeV light curve in its decay phase

   ① The narrowest jet of 0.8° , revealing the “core” of a structured jet

   ② The unprecedently large fluence may be due to seeing the brightest core of a nearby GRB jet

3. A two-component jet model can explain the multi-wavelength data, and may requires time-varying microphysical parameters.