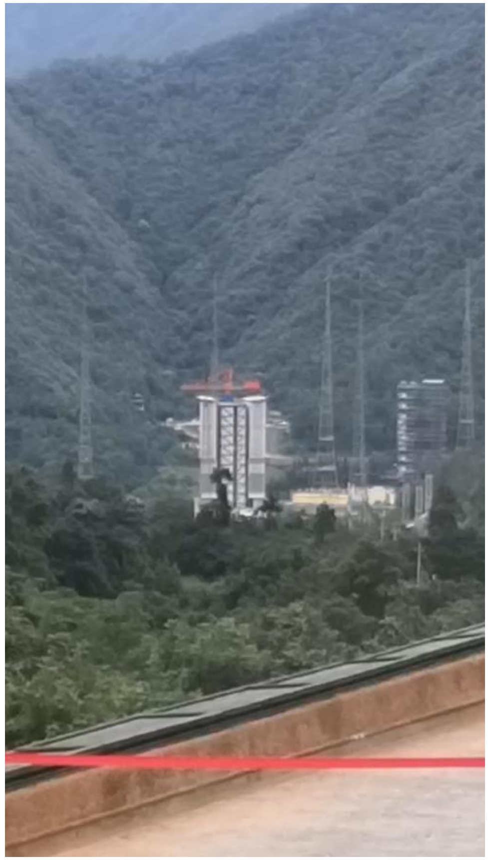
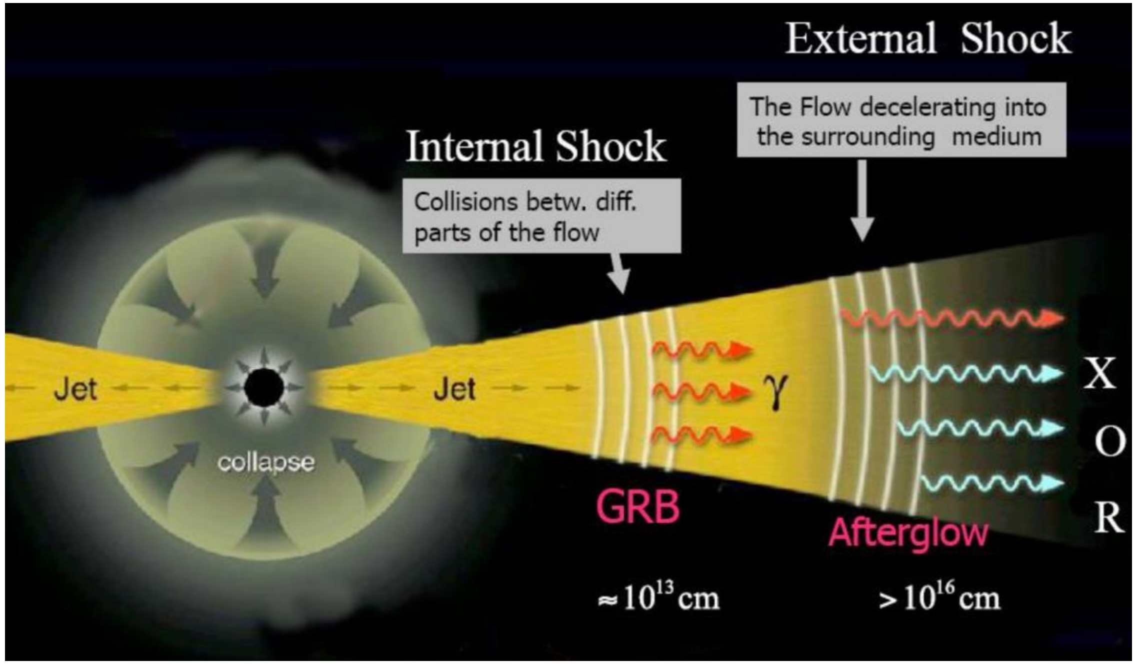
The BOAT GRB & study on very high energy emission

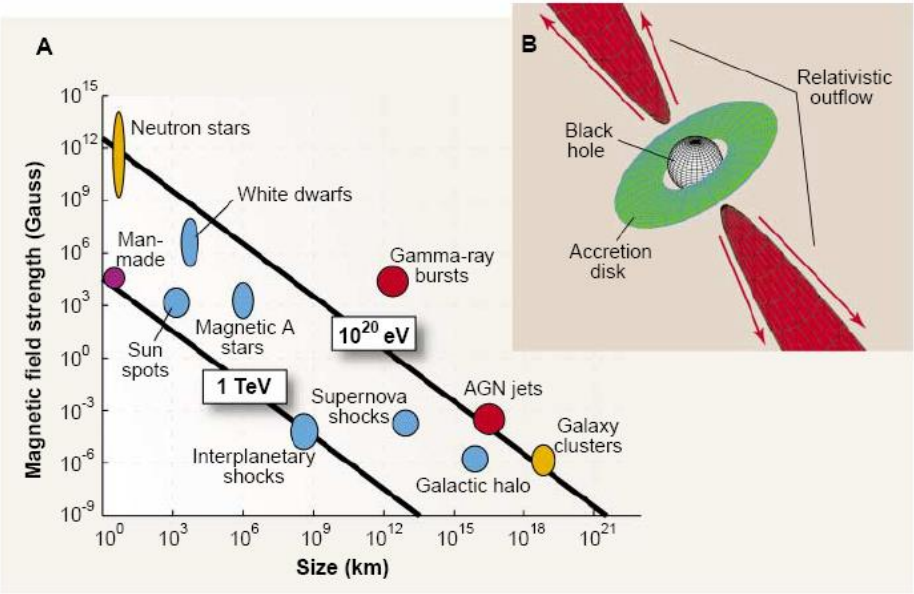


Xiang-Yu Wang
Nanjing University, China

SVOM Scientific Workshop
2024.6.23

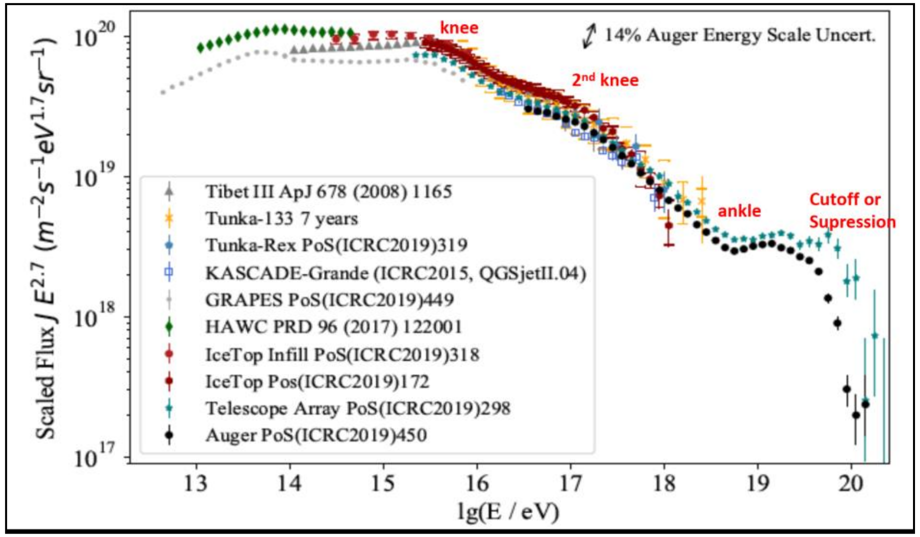
GRB shocks: extreme particle accelerators



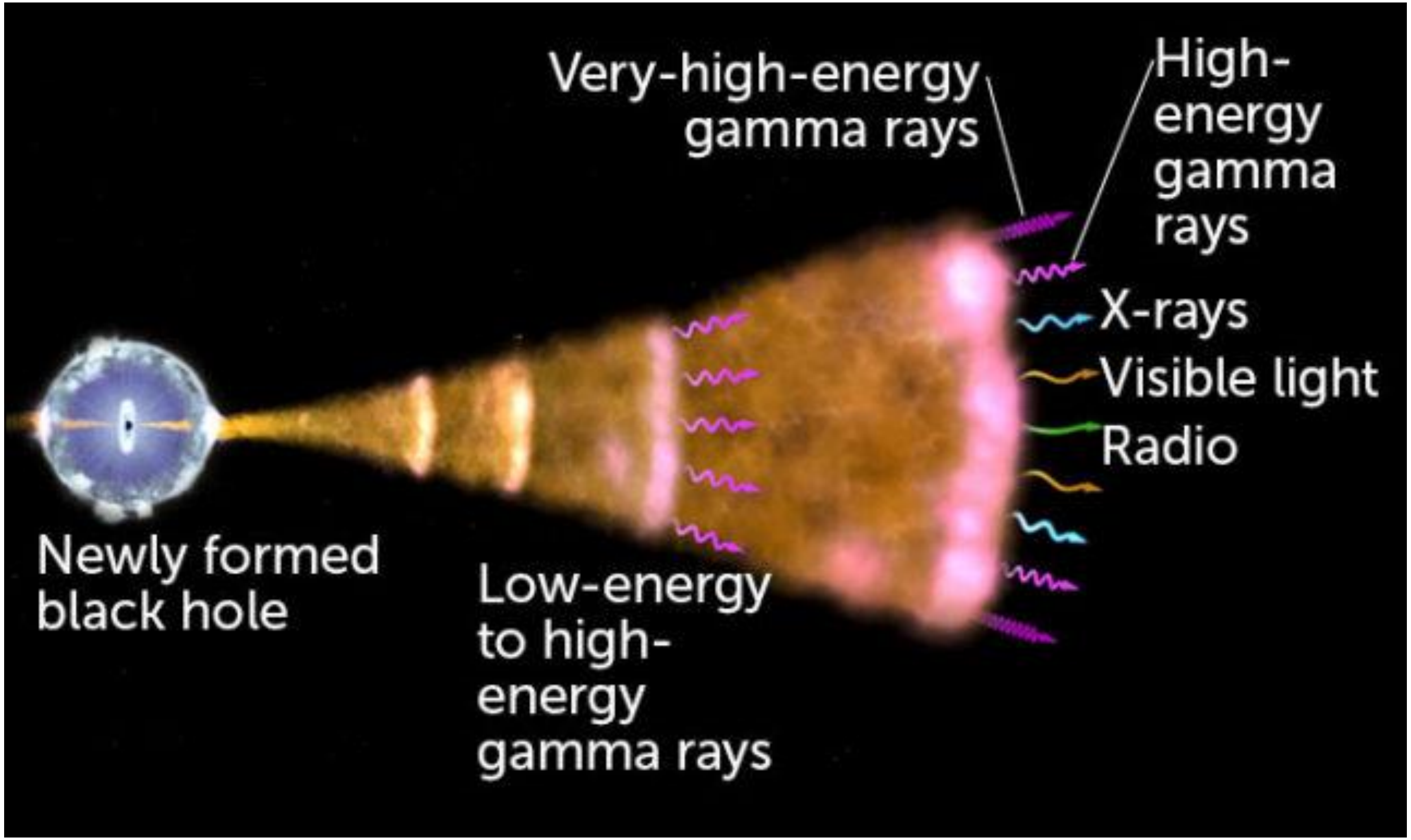


UHE cosmic ray candidate sources

Cosmic ray spectrum



Very high-energy emission (>100GeV)



Outline

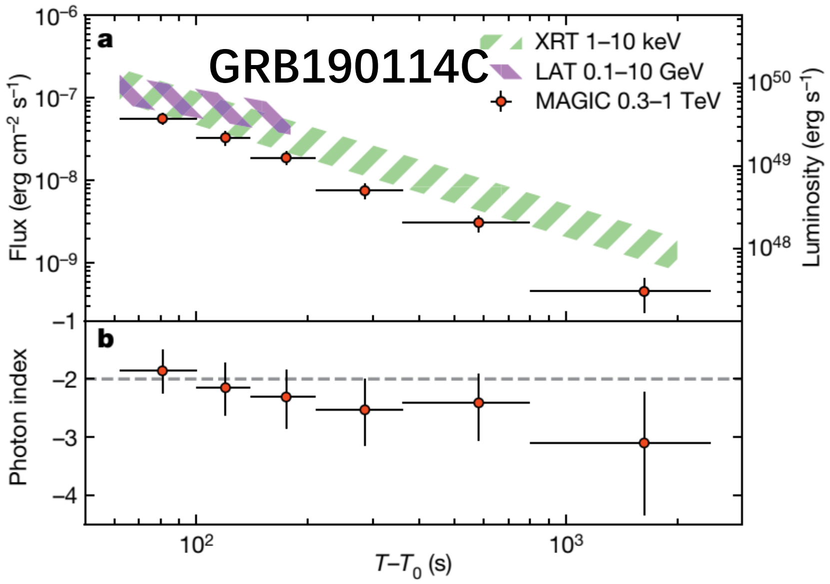
- **TeV afterglows of GRBs: inverse-Compton emission or synchrotron?**

- **The BOAT GRB 221009A and its TeV emission**

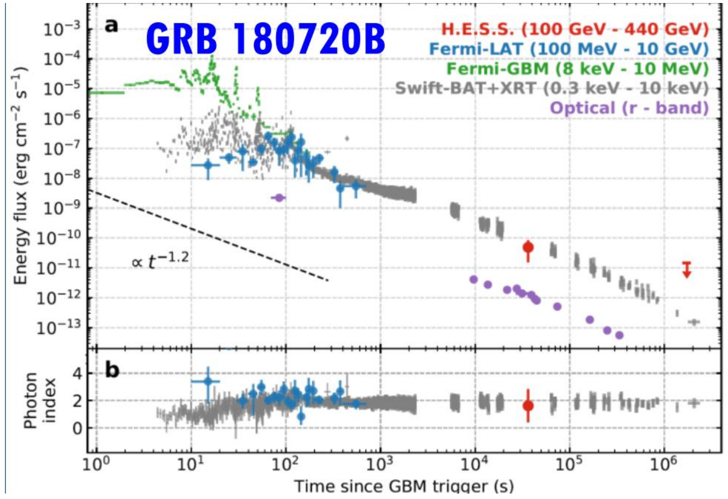
- **Future TeV study of low-luminosity GRBs (observed by SVOM)**

- **Discussions**

TeV observations of GRBs: decaying afterglows

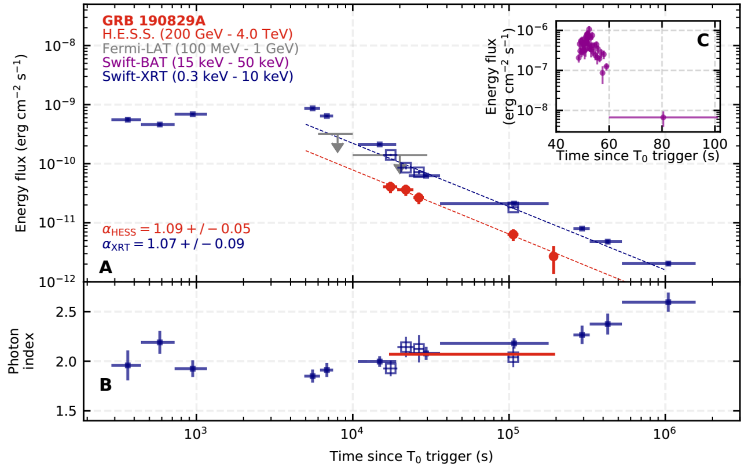


Magic coll. 2019a, Nature



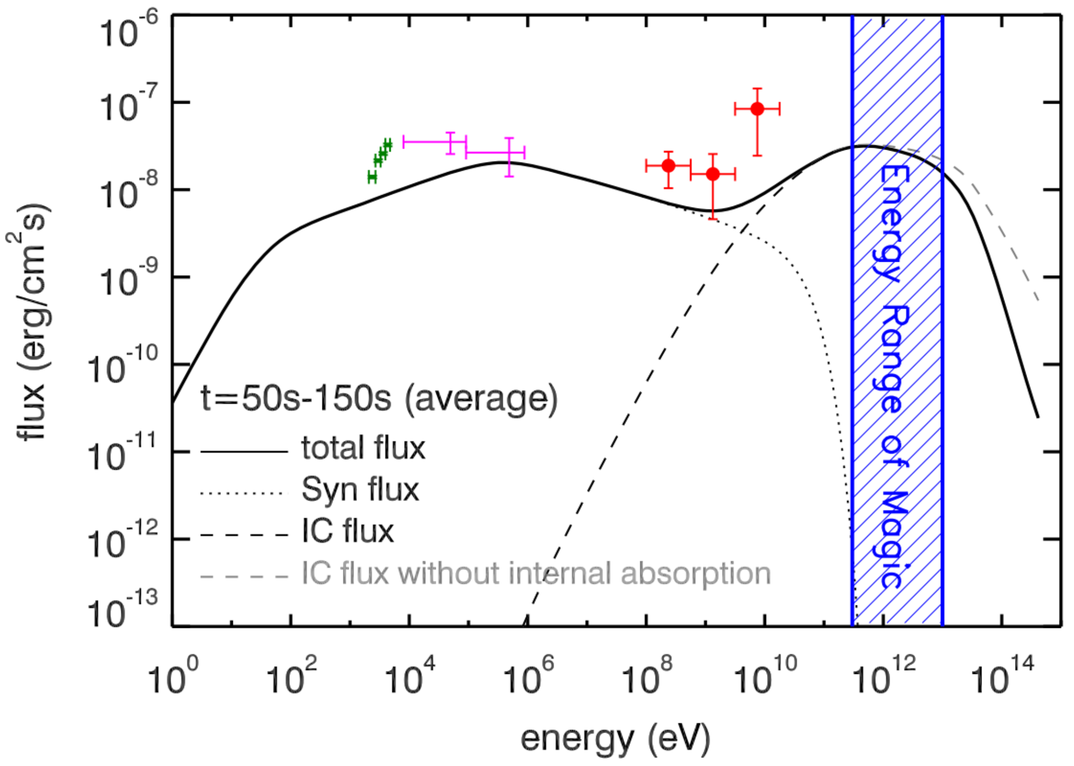
HESS coll. 2019,Nature

GRB190829A

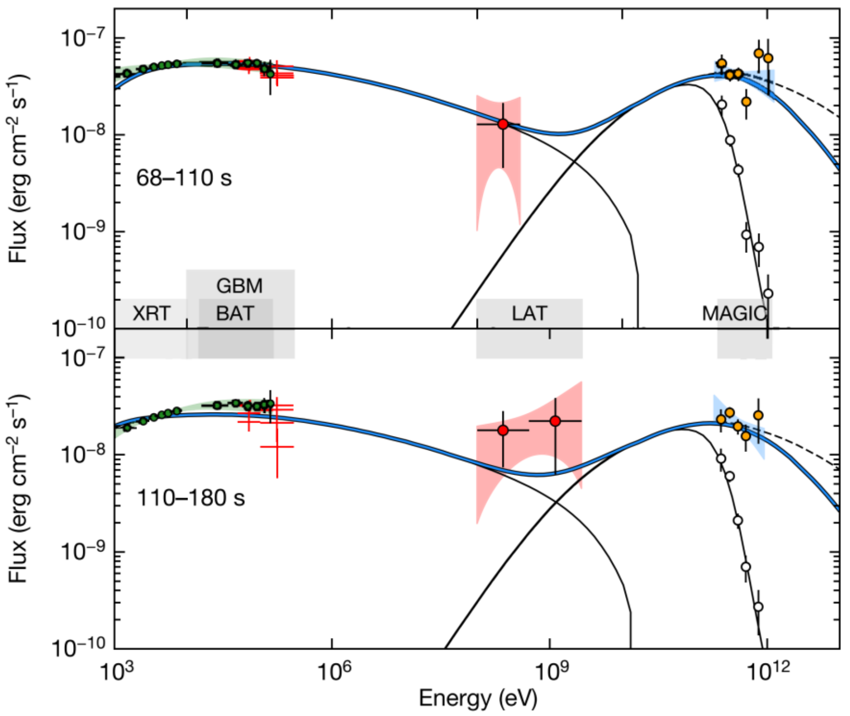


HESS coll. 2021, Science

Two spectral components of GRB 190114C



Wang et al. 2019

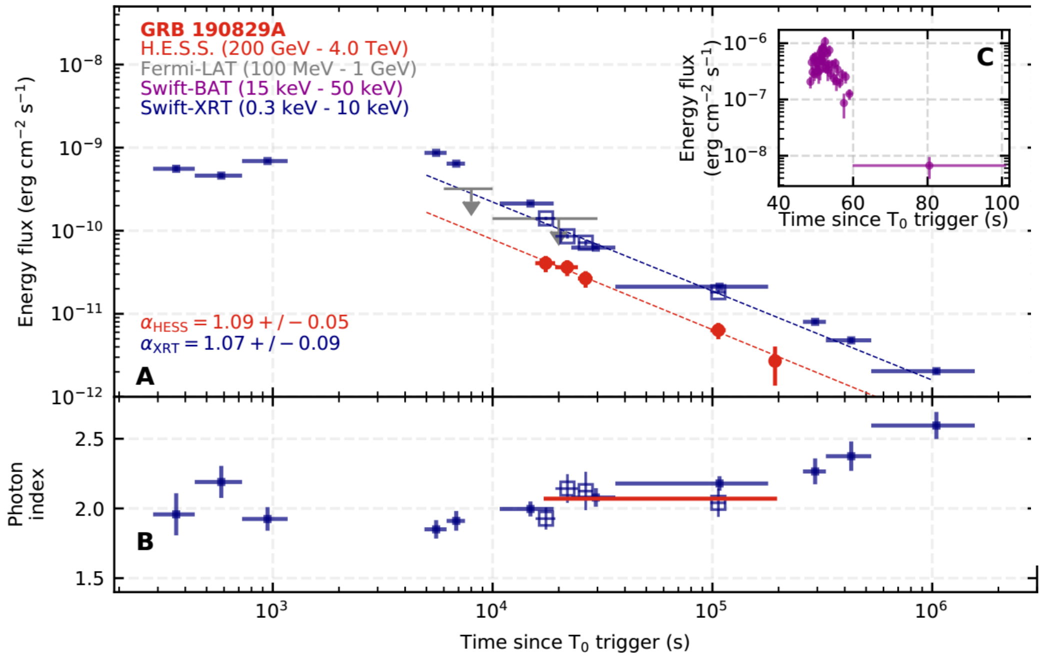


Magic collaboration 2109, Nature

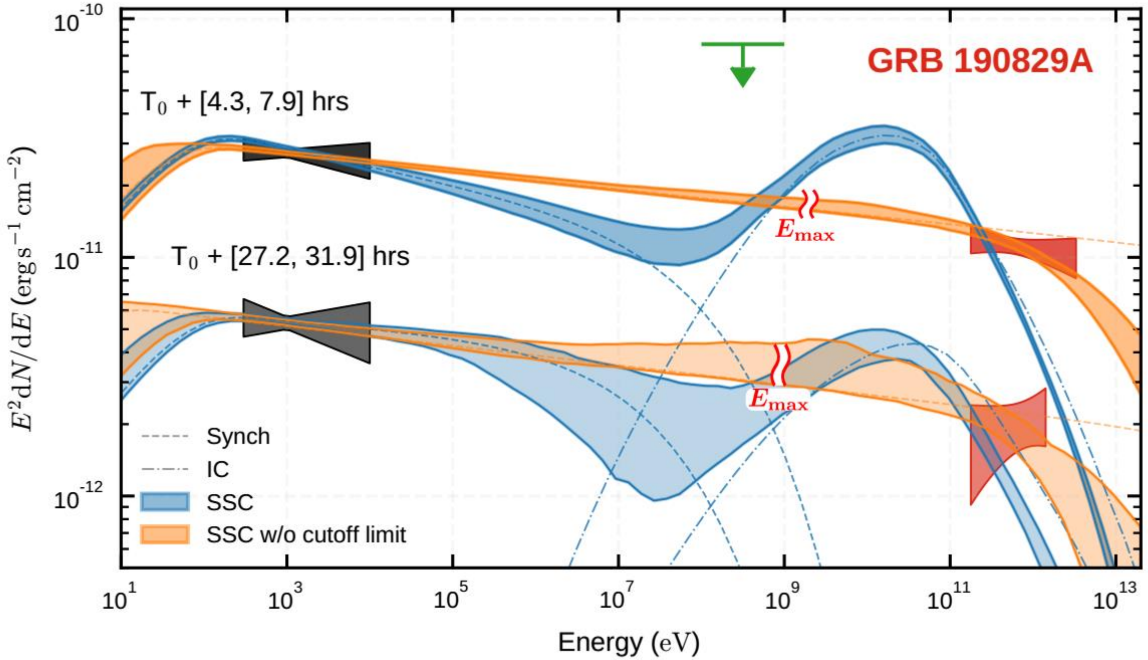
- **Two spectral component: synchrotron + Self-IC (SSC) ?**

But, GRB 190829A: one single spectral component ?

- a possible low-luminosity GRB (E~10^50 erg) (Chand et al. 2020)
- Very nearby distance ($z = 0.078$)



HESS coll. 2021, Science



See however, Zhang+ 2021 fro proton syn. model

Theoretical aspect: maximum synchrotron energy

- **Expected:** maximum synchrotron energy:
  - ~50 MeV in the shock rest frame (Bohm acceleration approximation)
  - Observer frame： 50MeVxΓ, Γ<100 at 1-10ks

$$\Gamma = 200 E_{54}^{1/8} n_{-2}^{-1/8} (t_2/(1+z))^{-3/8}$$

E_max~5GeV at 1-10ks

- **Observed: >10 GeV photons challenge the synchrotron scenario**

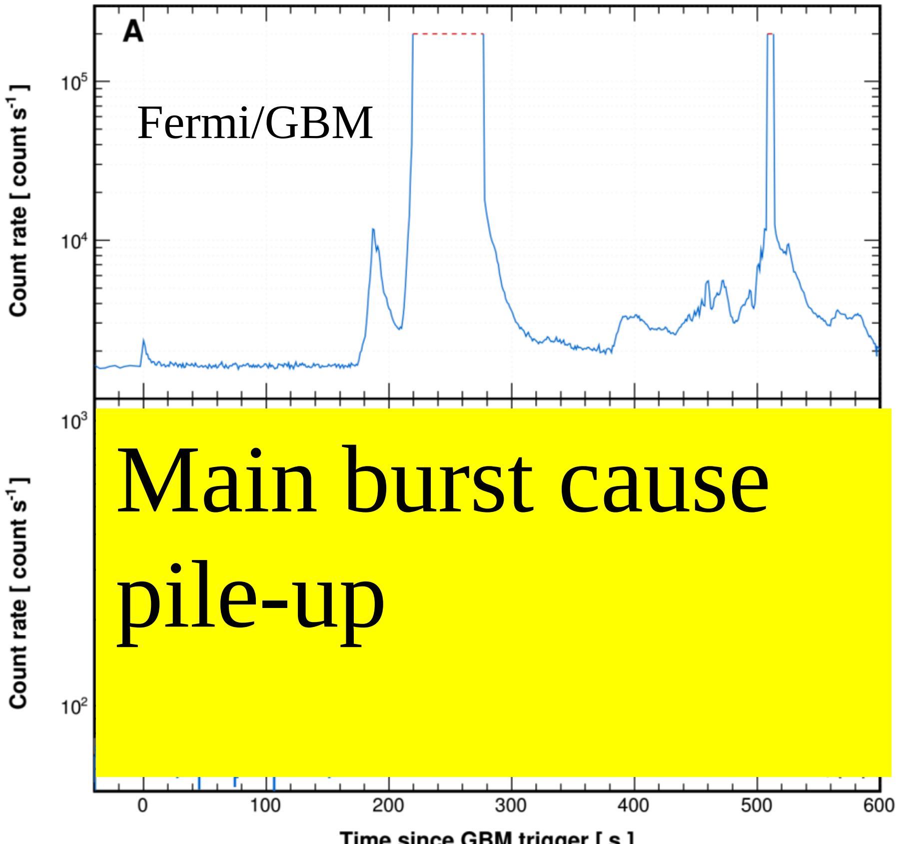
- **But, two zone model: radiation zone different from the acceleration zone …** (see, Kumar 2014)

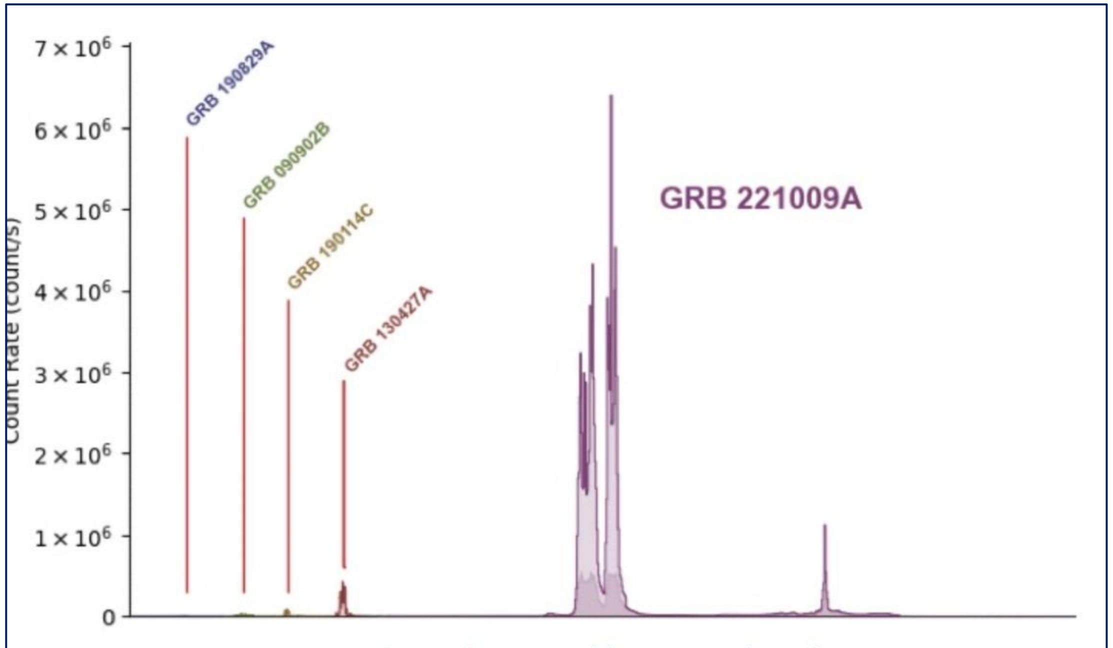
Outline

- TeV afterglows of GRBs: inverse-Compton emission or synchrotron?
- **The BOAT GRB 221009A and its TeV emission**
- Future TeV study of low-luminosity GRBs (observed by SVOM)
- Discussions

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)



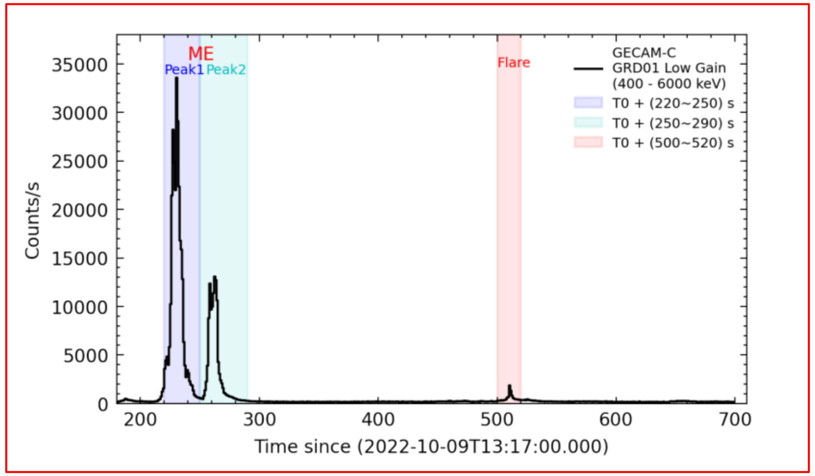


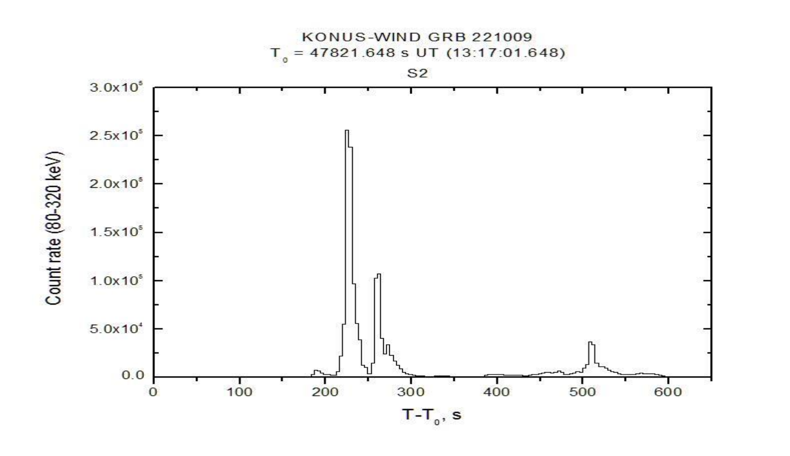
Lesage et al. (2023): https://arxiv.org/abs/2303.14172

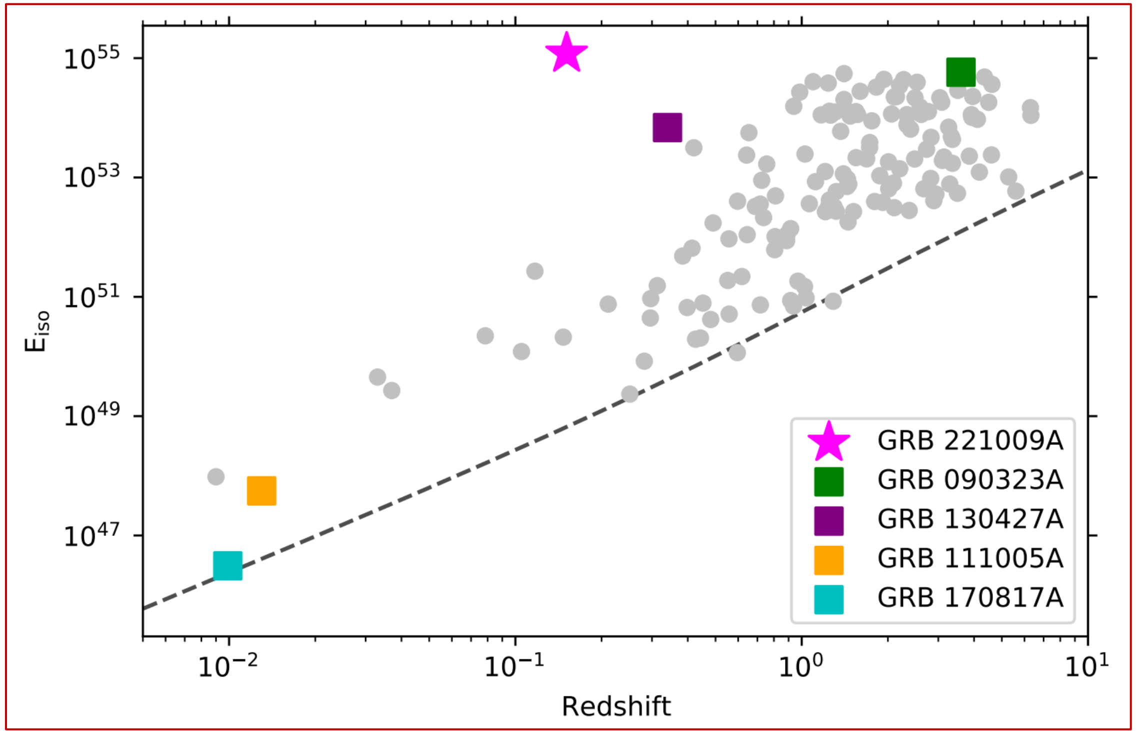
GECAM/Konus-Wind Observations of GRB 221009A

An et al. 2023

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

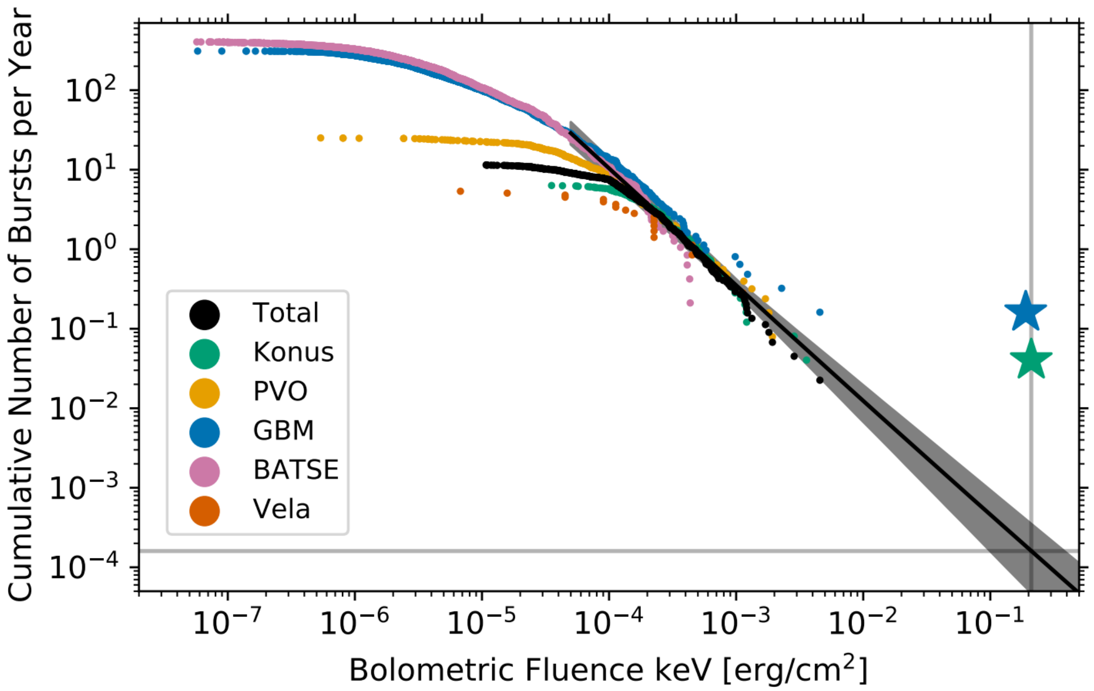






Buns et al. 2023

GRB 221009A: A very rate event



Buns et al. 2023

Fluence: $F \sim D^{-2}$

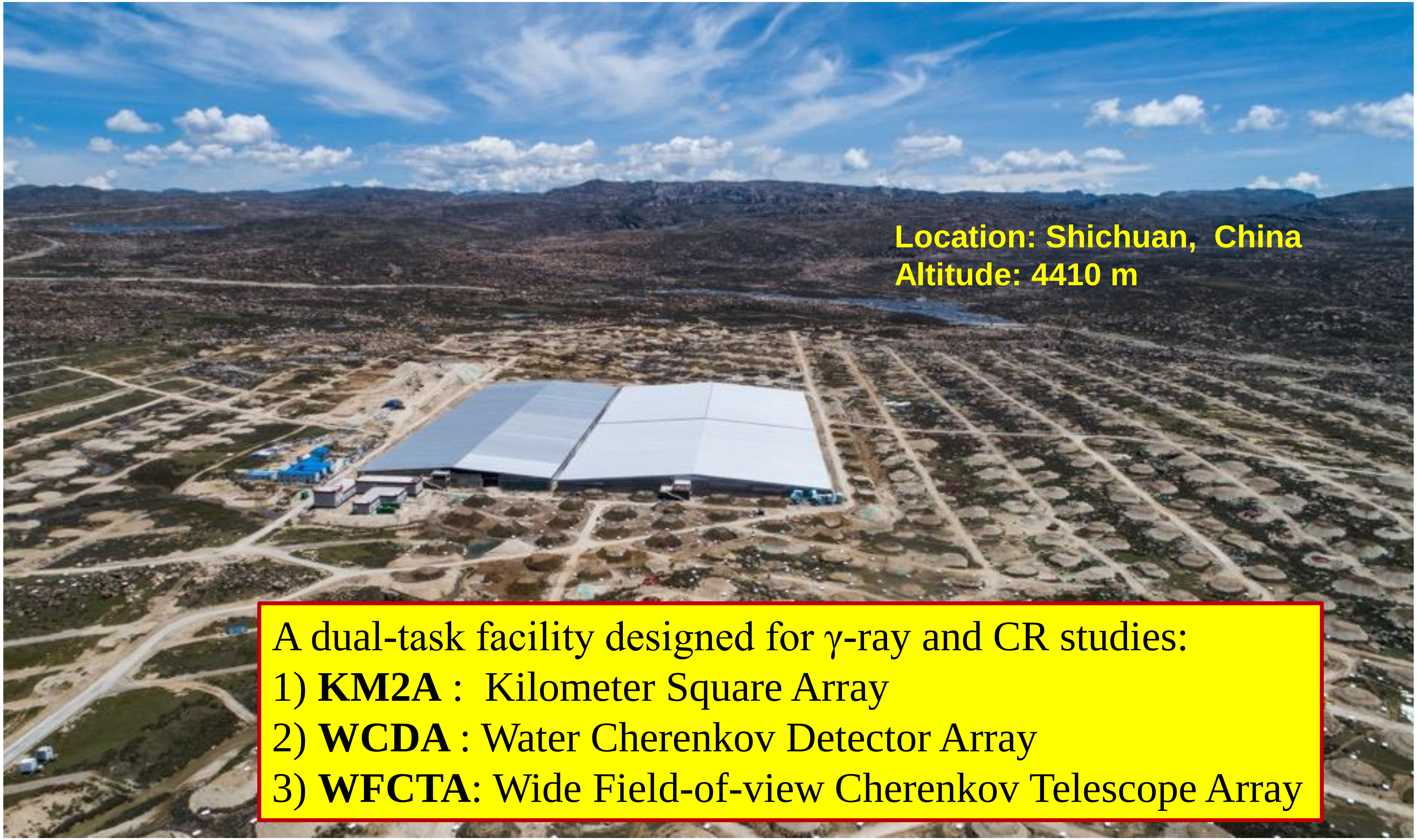
Event rate: $R \sim D^3$

→ Event rate $R \sim F^{-3/2}$

Its fleunce is 50 times higher the 2nd brightest GRB

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

LHAASO



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

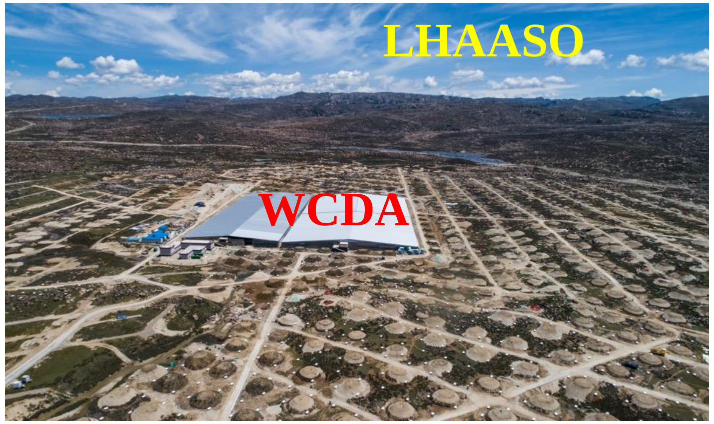
1) **KM2A** : Kilometer Square Array

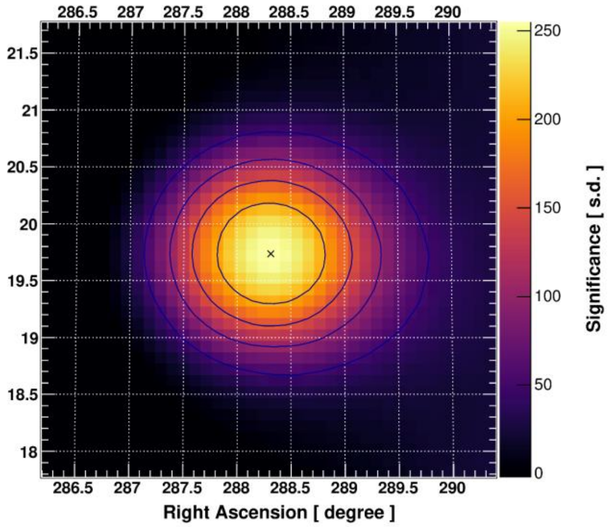
2) **WCDA** : Water Cherenkov Detector Array

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

LHAASO Observations of GRB221009A

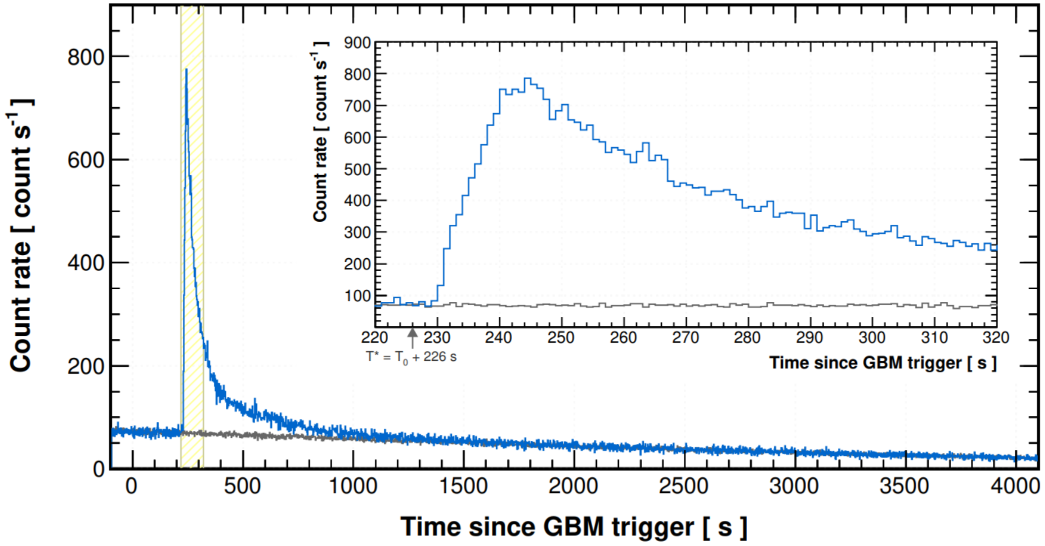
- GRB 221009A occurred within the FOV of LHAASO : first GRB seen by an extensive air shower detector





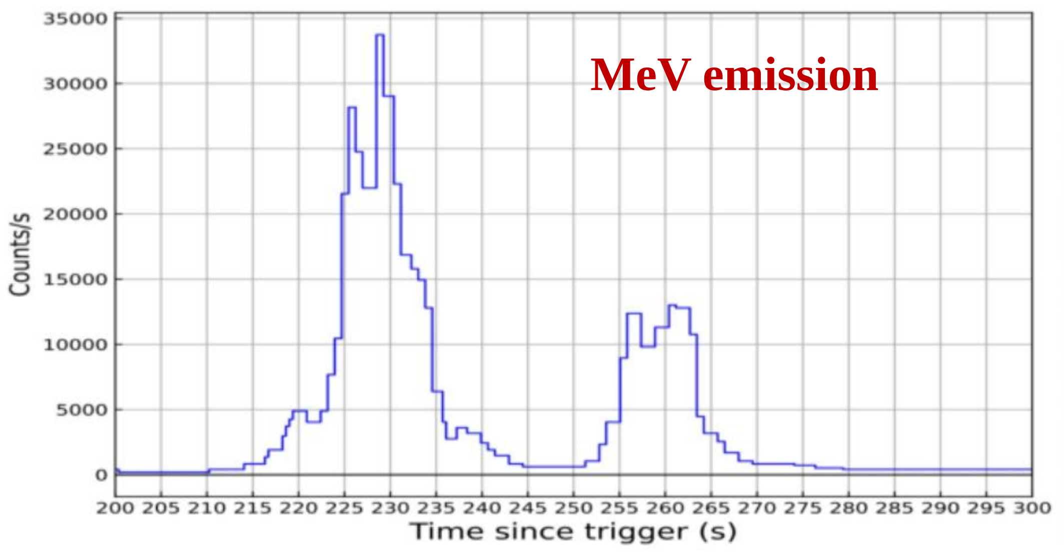
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)

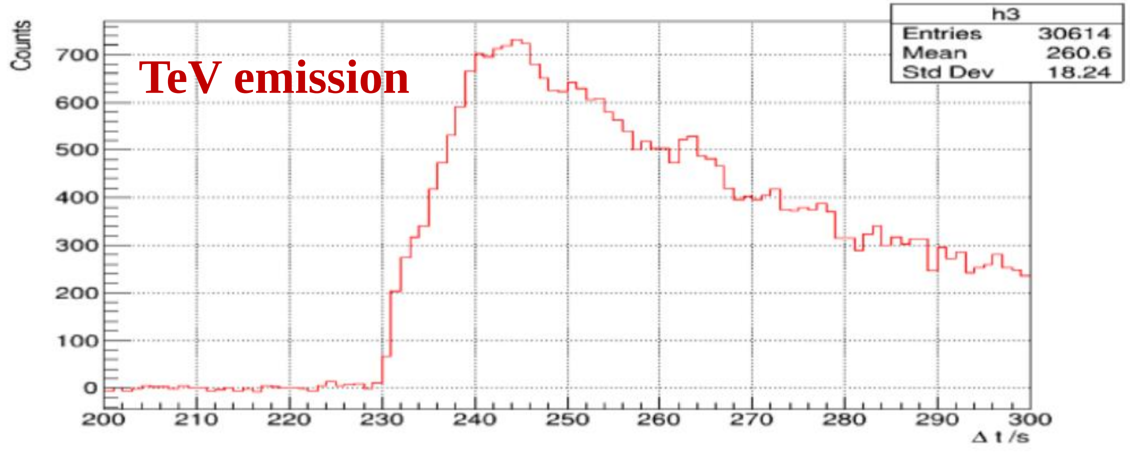
- TeV light curve: a rise to peak after a quiescent phase, then a decay



LHAASO Collaboration, Science 380, 1390 (2023)

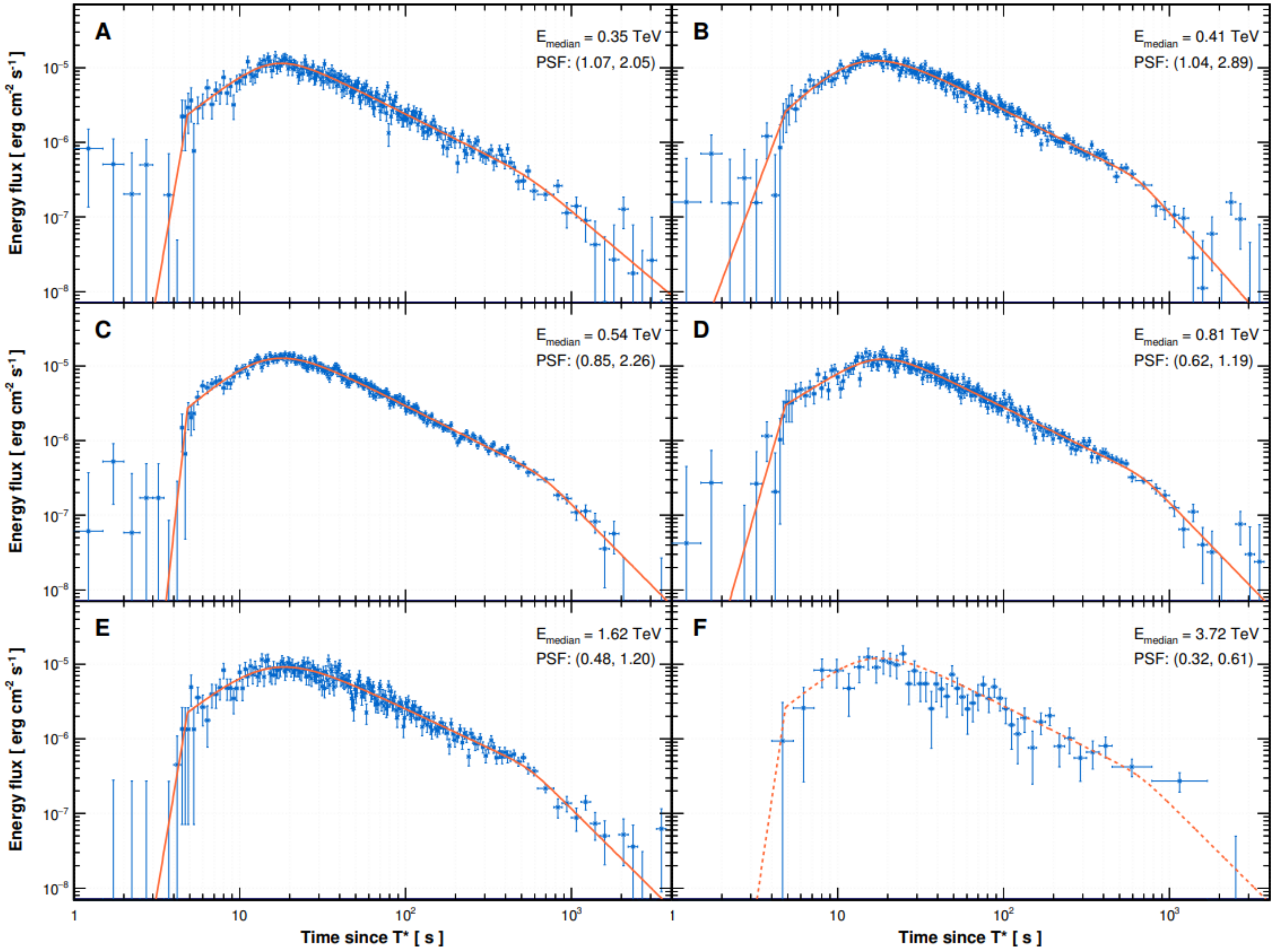
MeV vs TeV light curves: external shock origin





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

Jet break



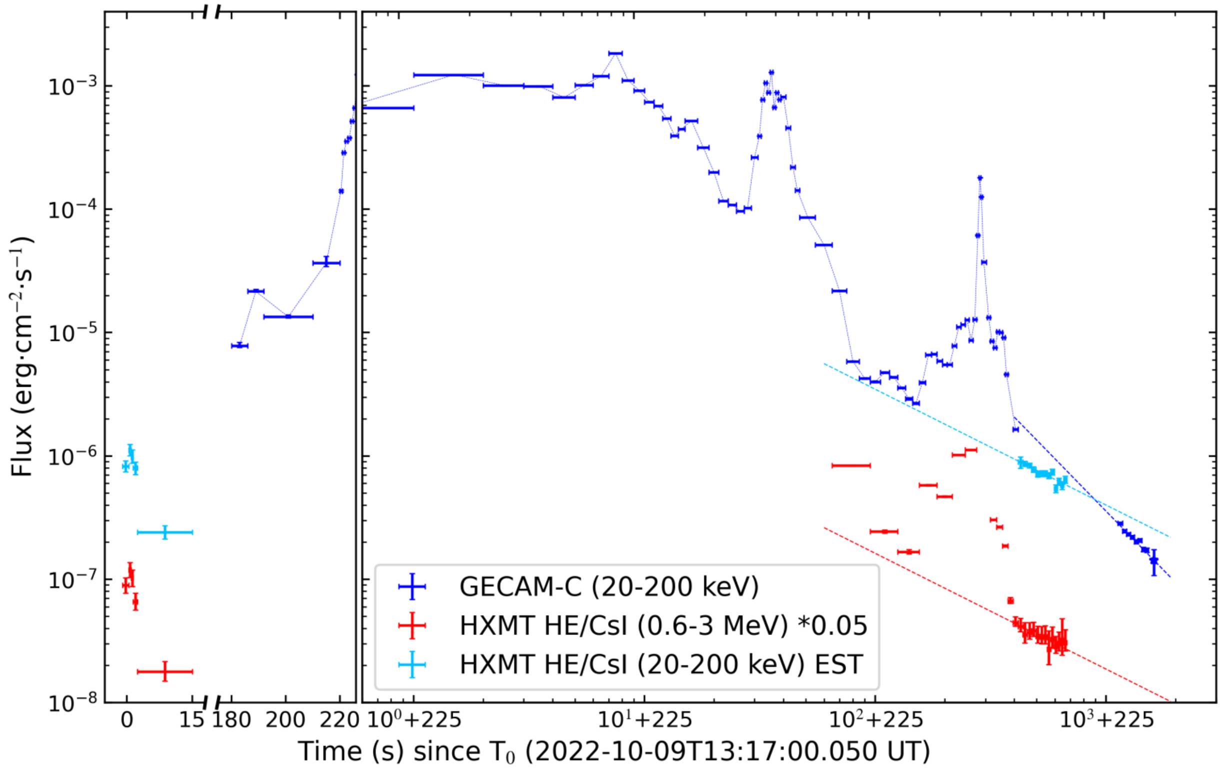
$$\alpha_2 = -1.115^{+0.012}_{-0.012}$$

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

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

Revealing a jet break at the earliest time.

HXMT & GECAM Obs.



arXiv > astro-ph > arXiv:2303.01203

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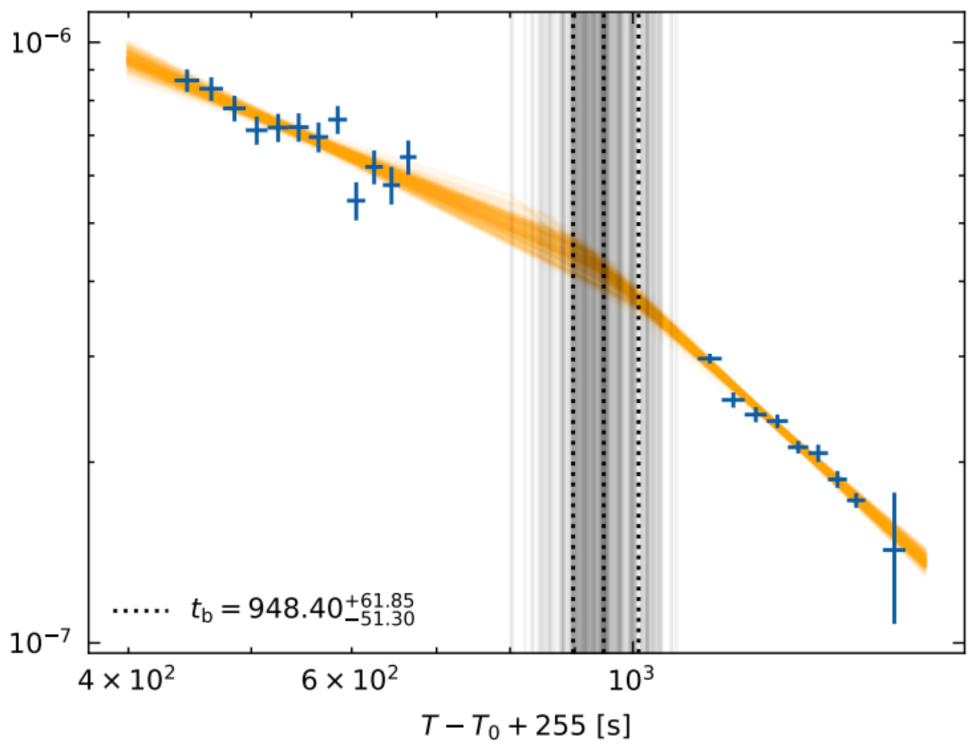
Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 2 Mar 2023 (v1), last revised 3 Mar 2023 (this version, v2)]

Insight-HXMT and GECAM-C observations of the brightest-of-all-time GRB 221009A

Zheng-Hua An, S. Antier, Xing-Zi Bi, Qing-Cui Bu, Ce Cai, Xue-Lei Cao, Anna-Elisa Camisasca, Zhi Chang, Gang Chen, Li Chen, Tian-Xiang Chen, Wen Chen, Yi-Bao Chen, Yong Chen, Yu-Peng Chen, Michael W. Coughlin, Wei-Wei Cui, Zi-Gao Dai, T. Hussenot-Desenonges, Yan-Qi Du, Yuan-Yuan Du, Yun-Fei Du, Cheng-Cheng Fan, Filippo Frontera, He Gao, Min Gao, Ming-Yu Ge, Ke Gong, Yu-Dong Gu, Ju Guan, Dong-Ya Guo, Zhi-Wei Guo, Cristiano Guidorzi, Da-Wei Han, Jian-Jian He, Jun-Wang He, Dong-Jie Hou, Yue Huang, Jia Huo, Zhen Ji, Shu-Mei Jia, Wei-Chun Jiang, David Alexander Kann, A. Klot Ling-Da Kong, Lin Lan, An Li, Bing Li, Chao-Yang Li, Cheng-Kui Li, Gang Li, Mao-Shun Li, Ti-Pei Li, Wei Li, Xiao-Bo Li, Xin Qiao Li, Xu-Fang Li, Yan-Guo Li, Zheng-Wei Li, Jing Liang, Xiao-Hua Liang, Jin-Yuan Liao, Lin Lin, Cong-Zhan Liu, He-Xin Liu, Hong-Wei Liu, Jia-Cong Liu, Xiao-Jing Liu, Ya-Qing Liu, Yu-Rong Liu, Fang-Jun Lu, Hong Lu, Xue-Feng Lu, Qi Luo, Ta Luo, Bin-Yuan Ma, Fu-Li Ma, Rui-Can Ma, Xiang Ma, Romain Maccary, Ji-Rong Mao, Bin Meng, Jian-Yin Nie, Mauro Orlandini, Ge Ou, Jing-Qiang Peng, Wen-Xi Peng, Rui Qiao, Jin-Lu Qu, Xiao-Qin Ren, Jing-Yan Shi, Qi Shi, Li-Ming Song, Xin-Ying Song, Ju Su, Gong-Xing Sun, Liang Sun, Xi-Lei Sun, Wen-Jun Tan, Ying Tan et al. (78 additional authors not shown)



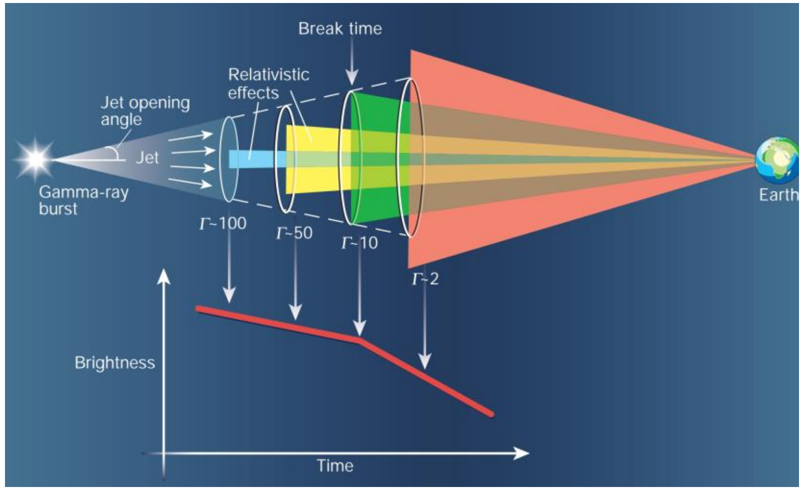
A narrow GRB jet

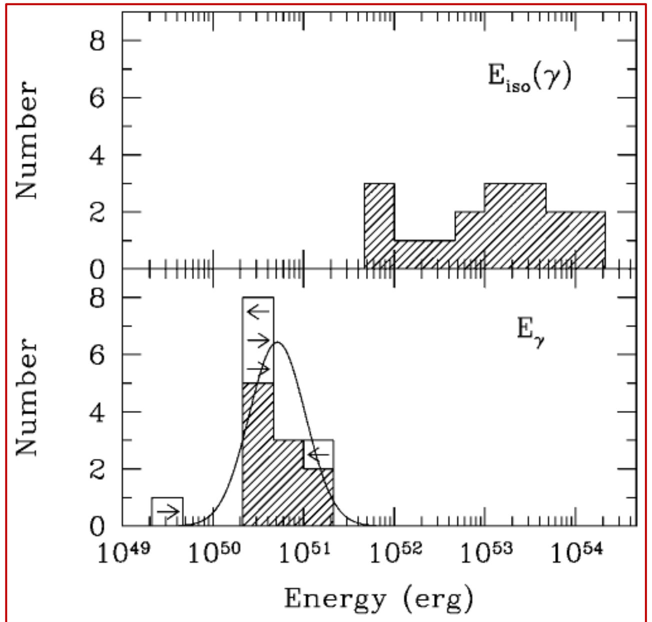
- Light curve steepens when the increasing radiation cone exceeds the jet opening angle
- Jet breaks have been seen in optical/X-ray bands
- An early jet break implies a narrow jet:

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

- Lead to a normal beaming-correct energy

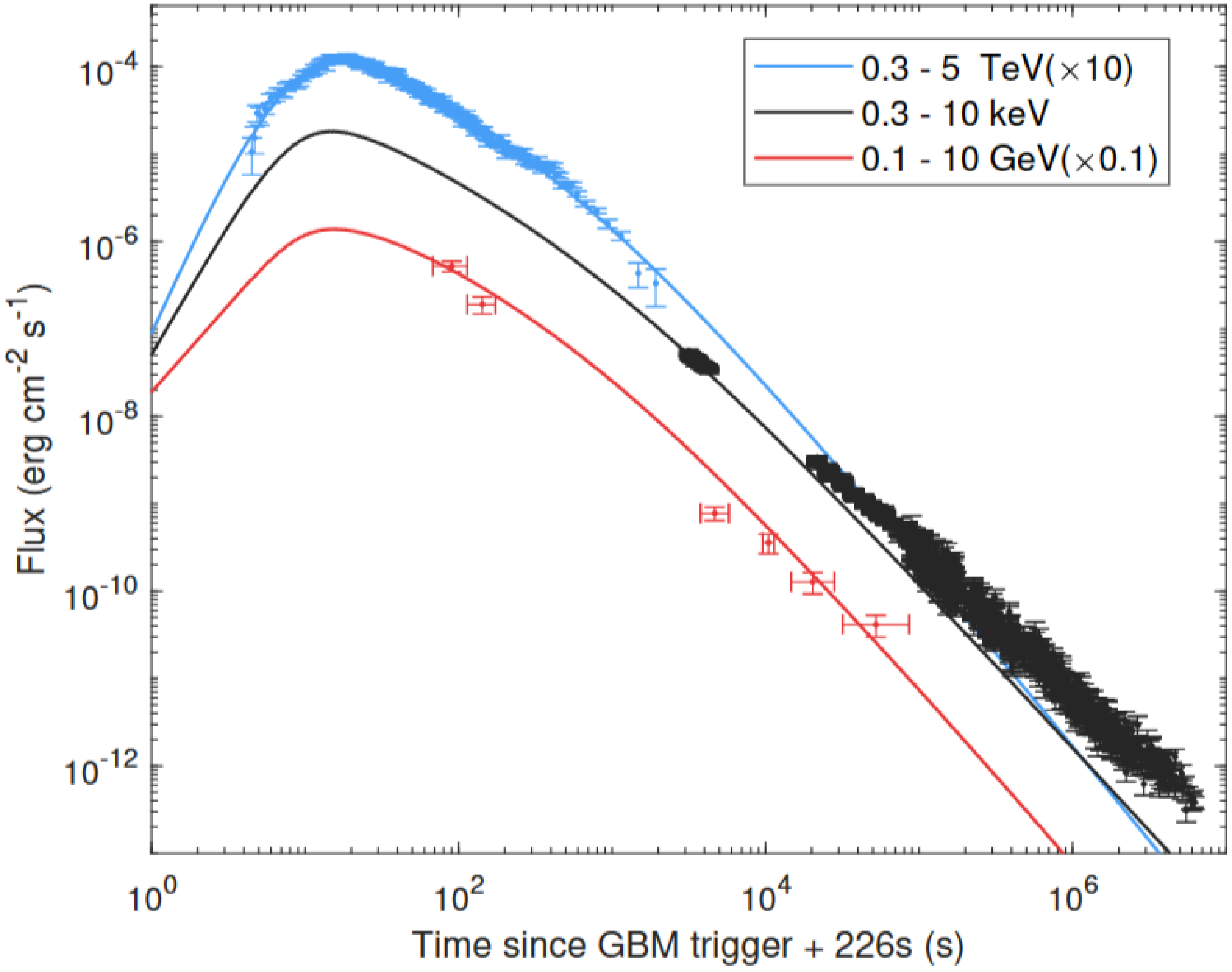
$$E_{\gamma,j} \ = \ E_{\gamma,\mathrm{iso}} \theta_0^2/2 \ \sim \ 7.5 \times 10^{50} \ \ \mathrm{erg} E_{\gamma,\mathrm{iso},55} (\theta_0/0.7^\circ)^2$$





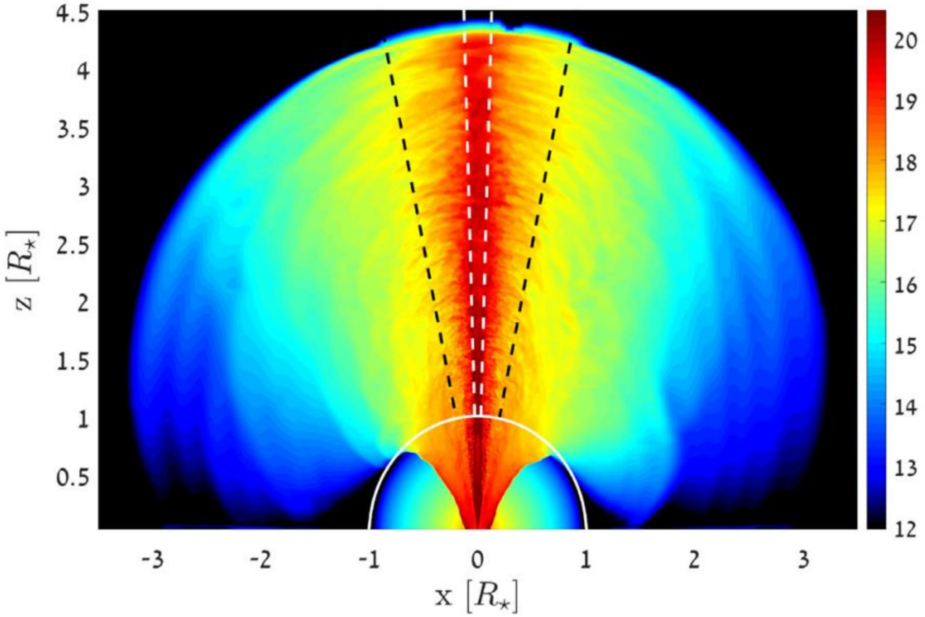
Frail et al. 2001

Late-time data: an inner jet is insufficient



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

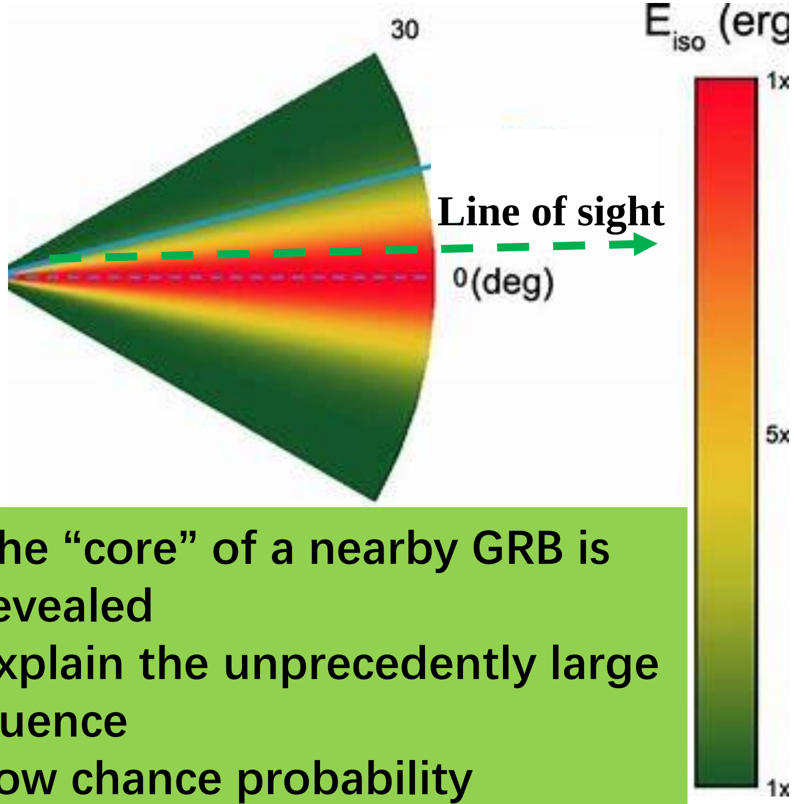
- Late afterglows need outer, wider components
- Implying a structured jet



Numerical simulation by Gottlieb et al. 2021

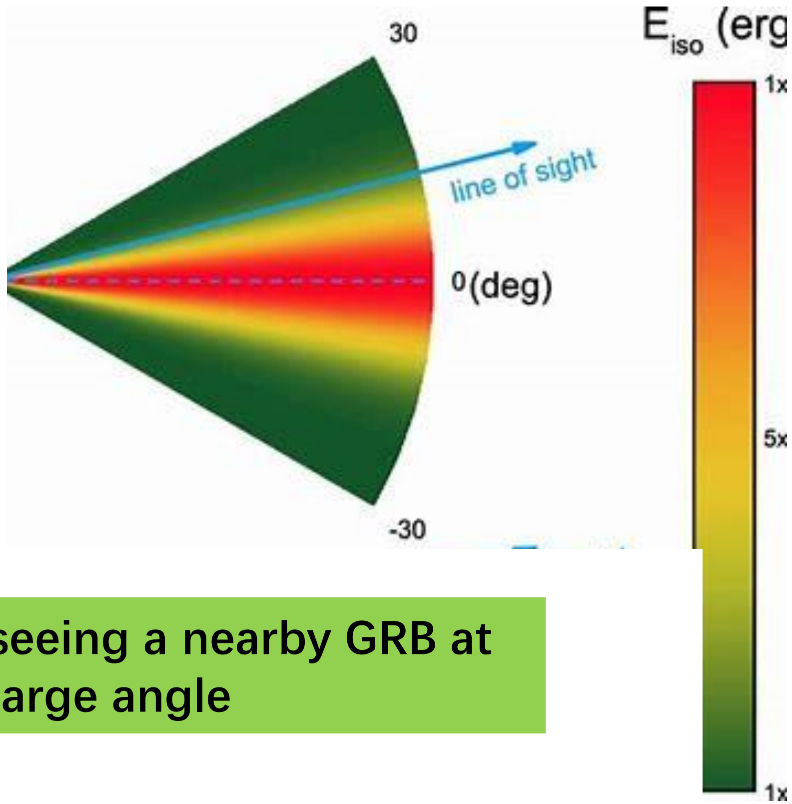
GRB 221009A: seeing the brightest core of a structured jet

- GRB 221009A (on-axis)



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

GRB 170817A (off-axis)

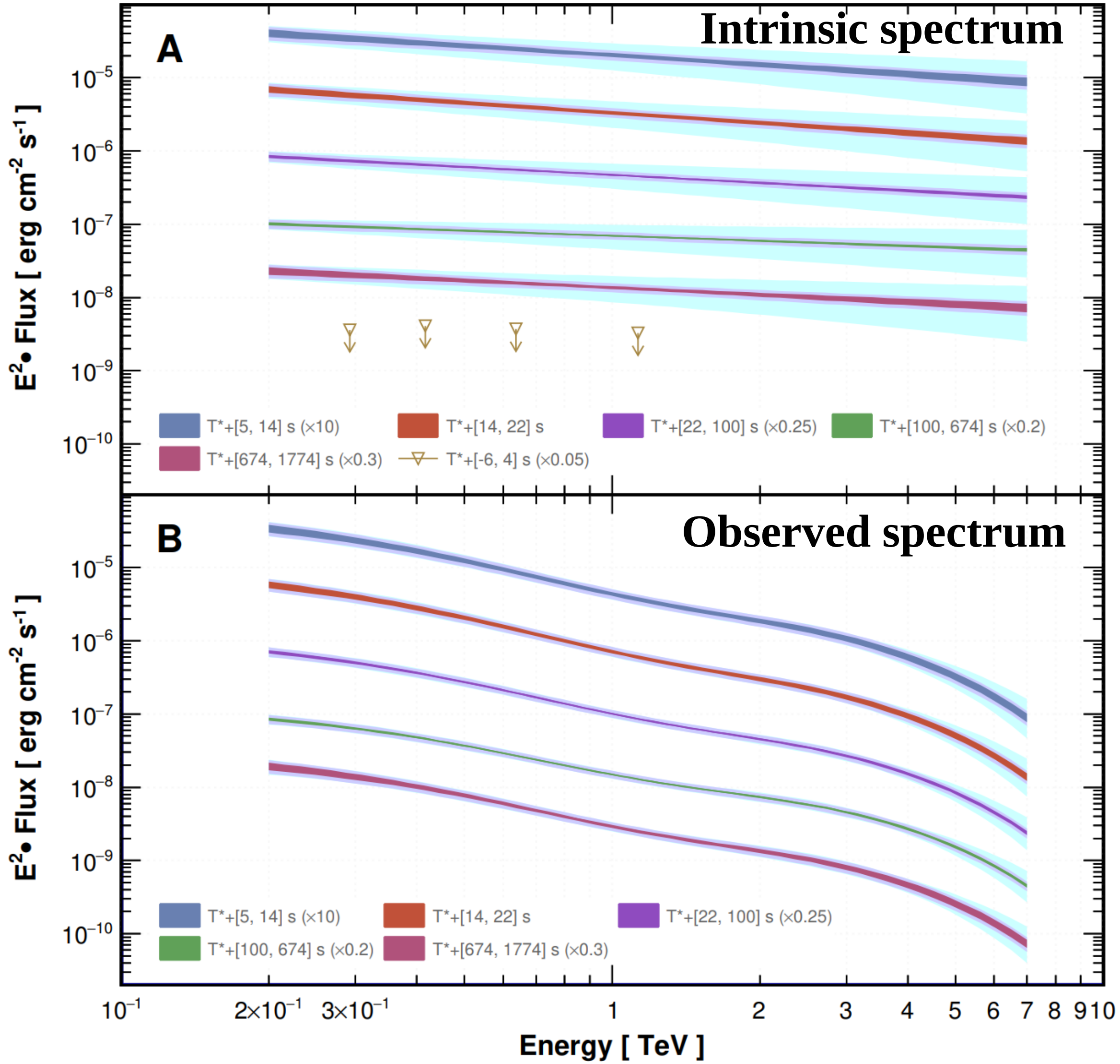


- seeing a nearby GRB at large angle

See Zhang, B., Wang, Zheng, JHEAP

Troja et al. 2018

SED measured by LHAASO-WCDA

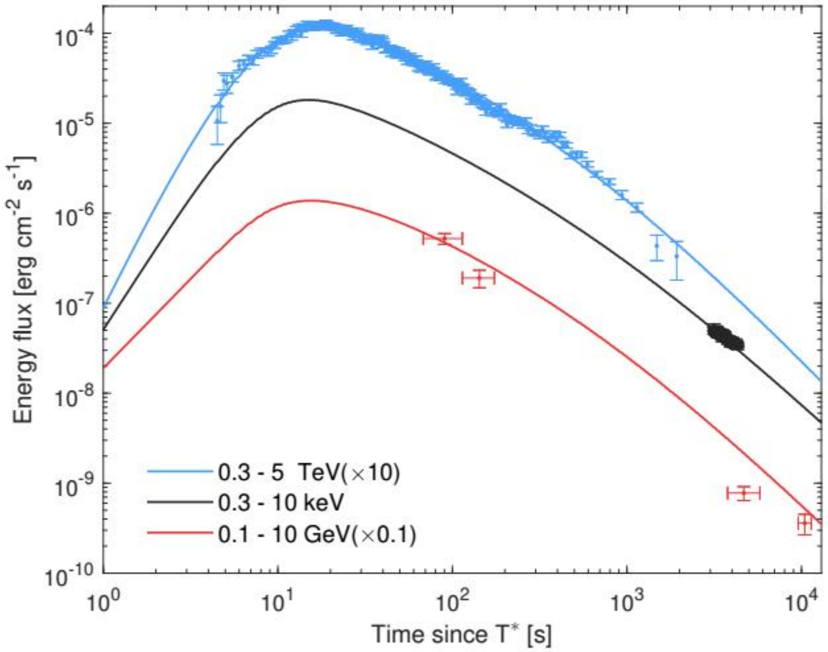


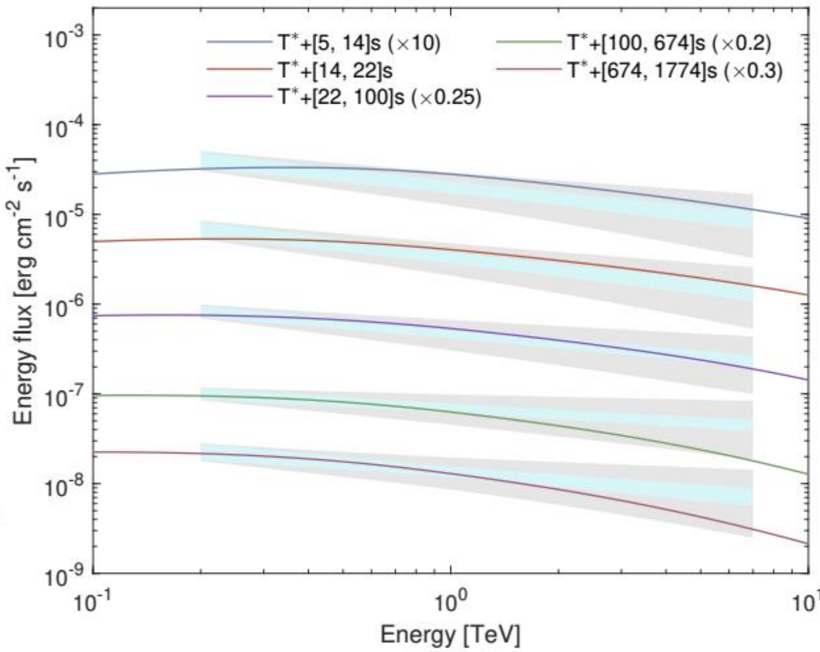
- Intrinsic spectrum: a single PL in 0.2-7 TeV
- Using EBL model: Saldana-Lopez et al. (2021)

Time interval (seconds after T_0)	A (10^{-8} TeV^{-1} cm^{-2} s^{-1})	γ	E_{cut} TeV	χ^2/dof
		Observed spectrum		
231–240	42.9 ± 2.7	2.983 ± 0.061	3.14 (fixed)	4.6/6
240–248	70.1 ± 3.8	3.006 ± 0.052	3.14 (fixed)	8.0/6
248–326	39.9 ± 1.0	2.911 ± 0.028	3.14 (fixed)	14.8/6
326–900	7.35 ± 0.16	2.788 ± 0.026	3.14 (fixed)	8.9/6
900–2000	0.959 ± 0.043	2.880 ± 0.067	3.14 (fixed)	2.9/5
		Intrinsic spectrum, *standard* EBL		
231–240	127.3 ± 7.9	2.429 ± 0.062	\	3.1/6
240–248	208 ± 11	2.455 ± 0.054	\	6.5/6
248–326	117.8 ± 3.0	2.359 ± 0.028	\	8.7/6
326–900	21.77 ± 0.47	2.231 ± 0.026	\	3.4/6
900–2000	2.84 ± 0.13	2.324 ± 0.065	\	2.2/5

Multi-wavelength modelling

afterglow synchrotron + SSC (first 10^4 s)



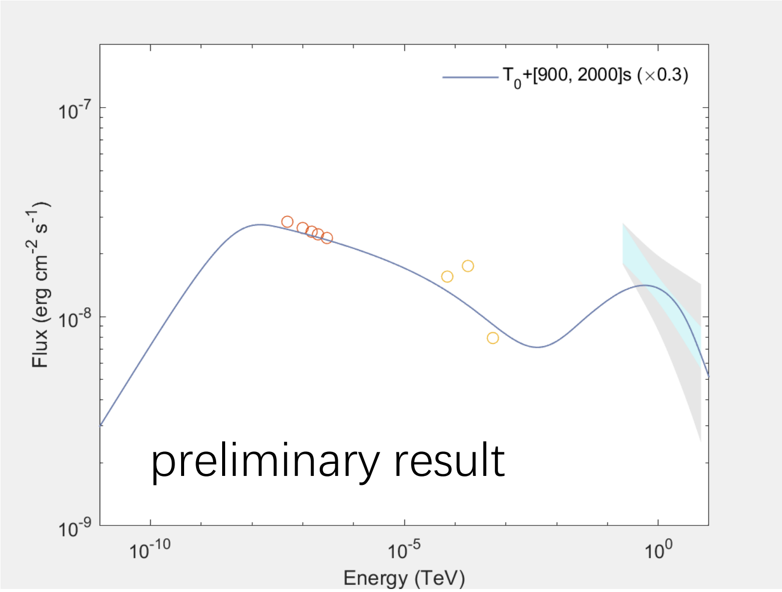


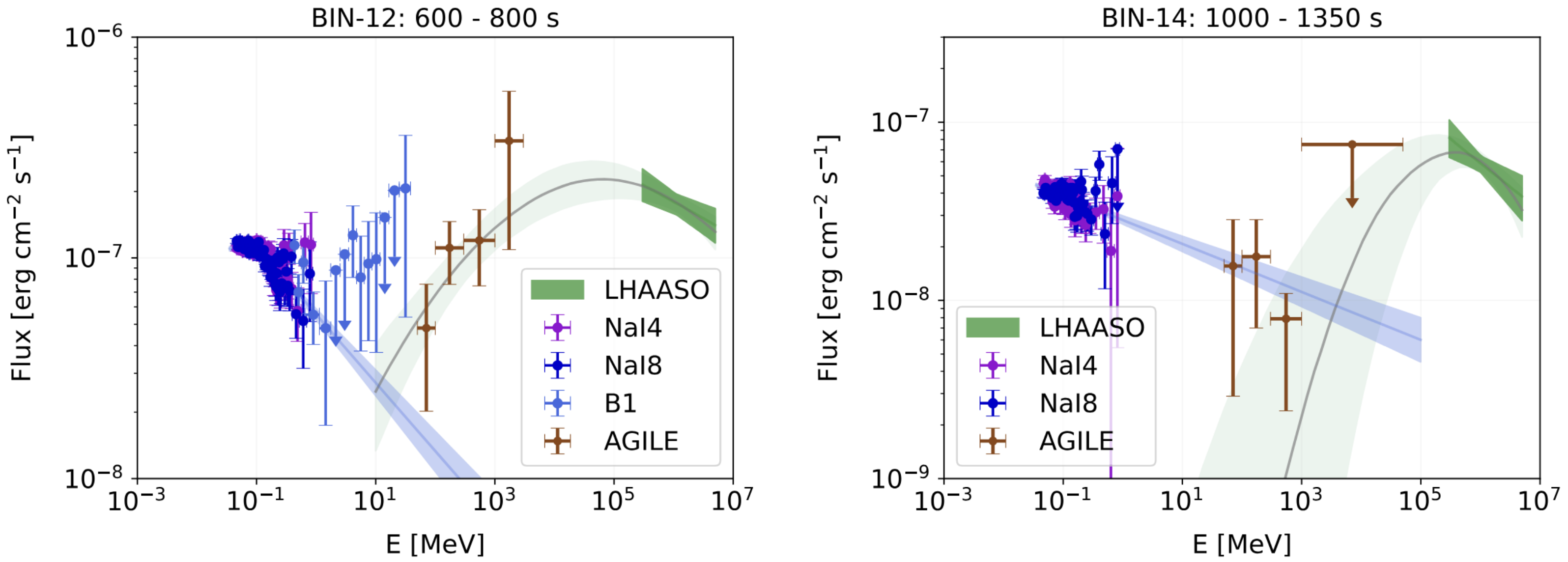
- X-ray: synchrotron
- GeV: synchrotron + SSC
- TeV: SSC

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 $\theta_0 = 0.8^\circ$.

LHAASO Collaboration, Science 380, 1390 (2023)

two spectral components in GRB 221009A?





Banerjee et al. 2024

LHAASO/KM2A observations of GRB 221009A

- The intrinsic spectrum can be described by a power-law after correcting for EBL absorption.
- **Theory**: Klein-Nishina effect leads to a spectral steepening in SSC emission
- > 3 TeV emission may need a new component

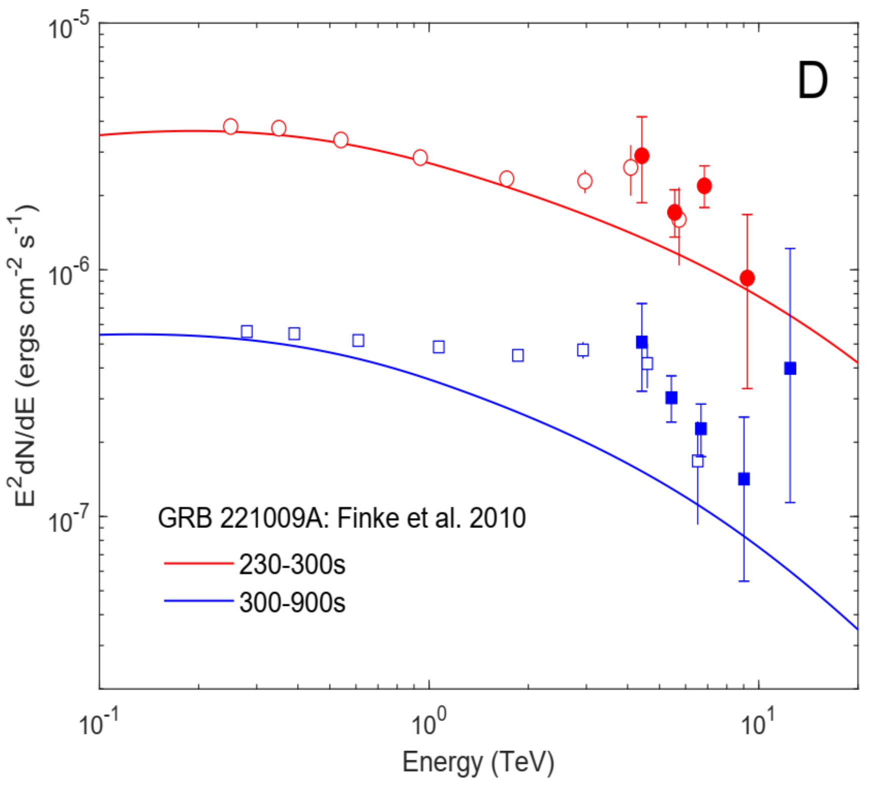
➢ An extra hard electron component

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

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

--Can GRB produce UHECRs ?

Solid dots/squars: LHAASO-KM2A data



LHAASO coll., Science Advance, 2023

Outline

- TeV afterglows of GRBs: inverse-Compton emission or synchrotron?
- The BOAT GRB 221009A and its TeV emission
- **Future TeV study of low-luminosity GRBs (observed by SVOM)**
- Discussions

Discussions

- SSC scenario seems to be ok, but there are exceptions

- GRB190829A is unique or general?

1. Possible TeV study in synergy with SVOM

- **GRB190829A-like low-luminosity GRBs**
- Low-luminosity GRB are usually softer and nearby

  GRB060218 (E_peak=5 KeV)
- SVOM may be more efficient in the detection of such GRB populations thanks to the ECLAIRs low threshold energy of 4 keV

Discussions: 1) prompt TeV emission limit

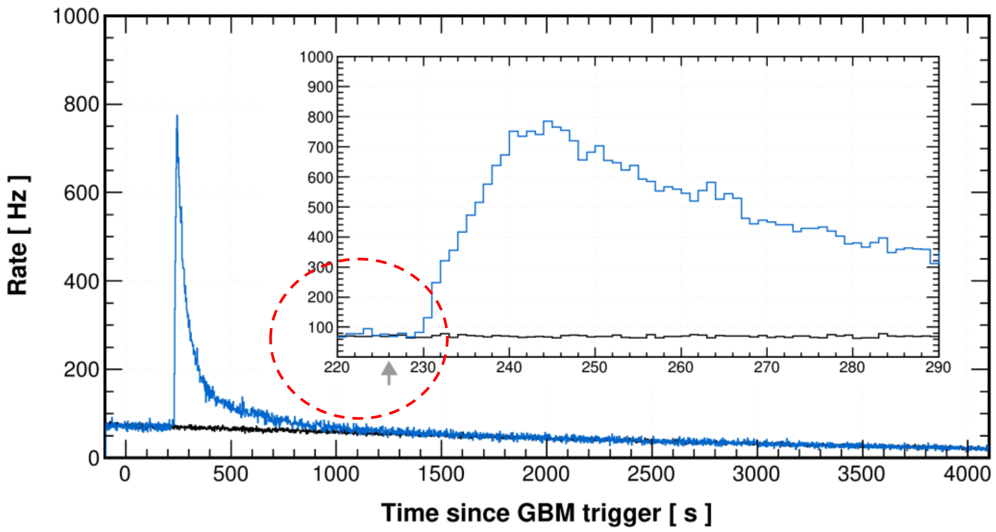
- The most strict limit on the prompt TeV emission

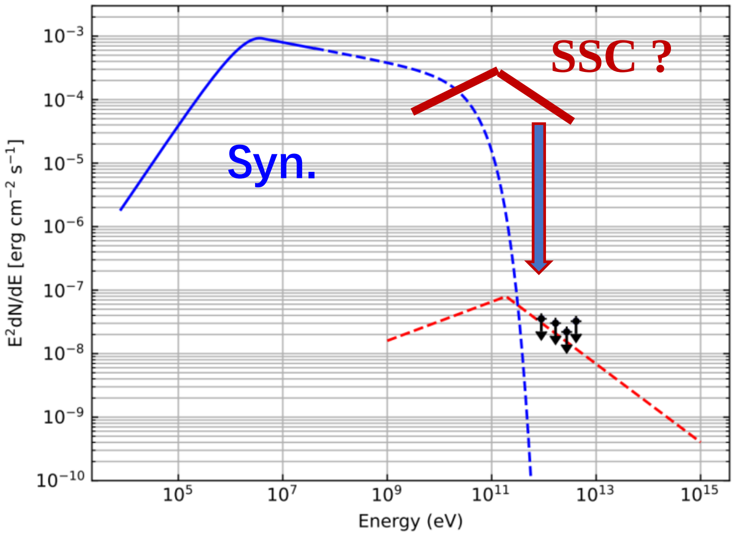
$$\mathbf{R}=F_{\mathrm{TeV}}/F_{\mathrm{MeV}} < 2 \times 10^{-5}$$

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

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

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





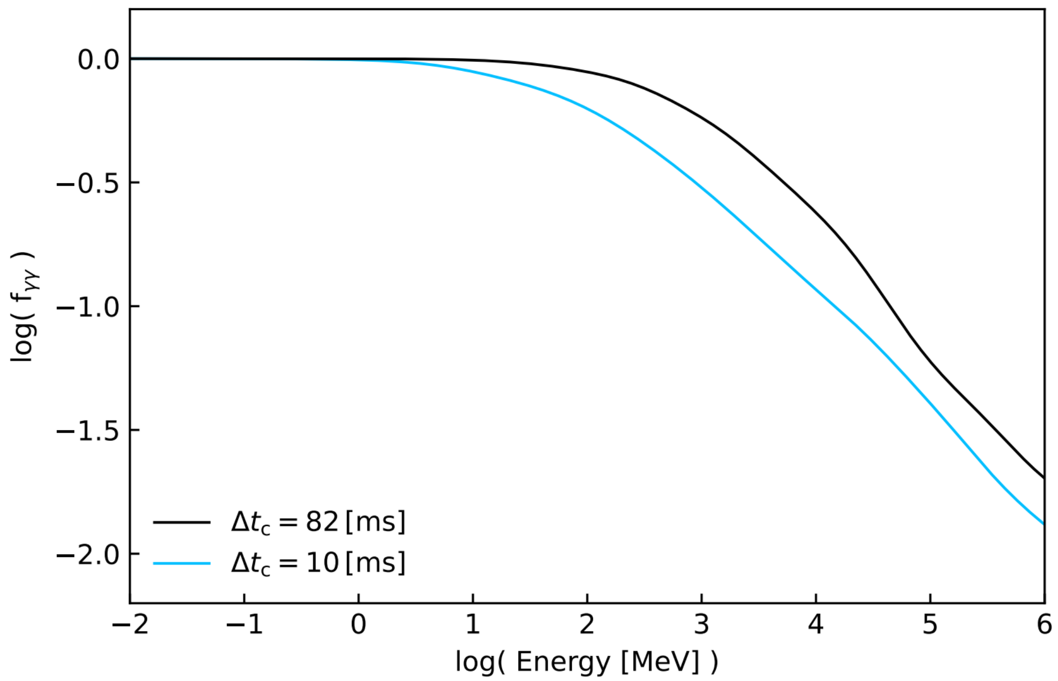
A Poynting-flux-dominated jet?

- **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 ?

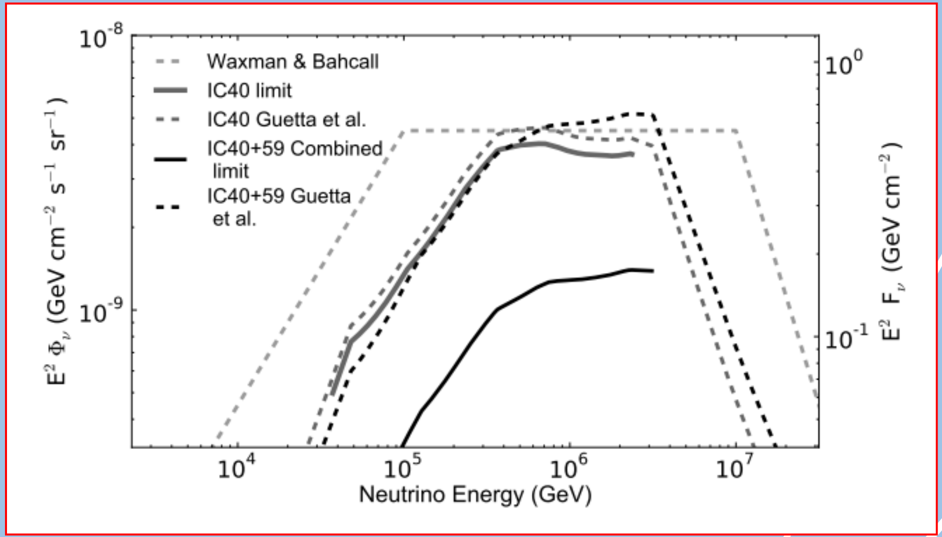


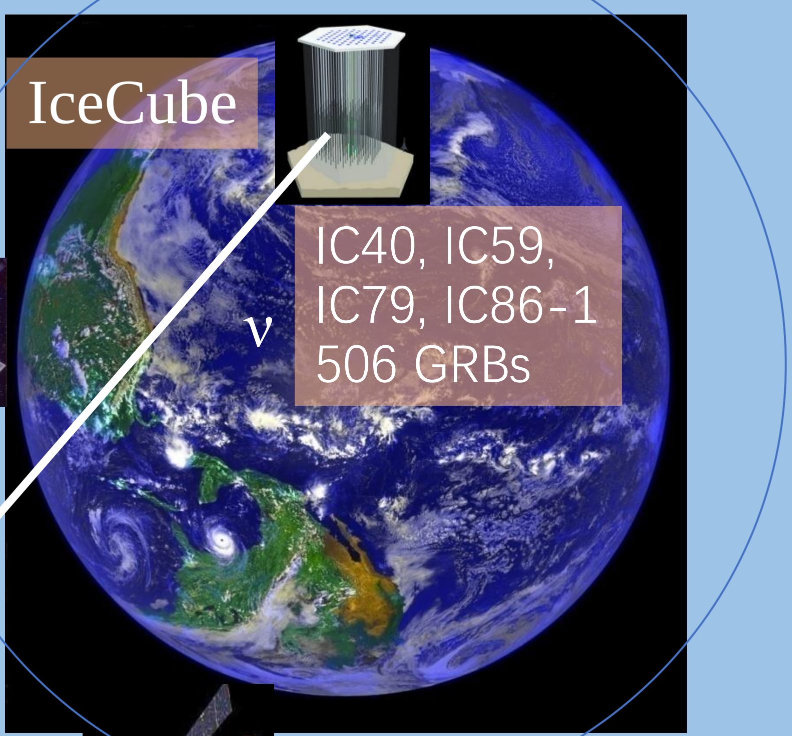
Dai et al. 2023, arXiv:2307.14113

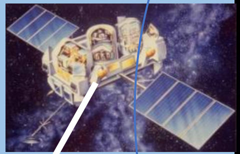
Test it with SVOM GRBs

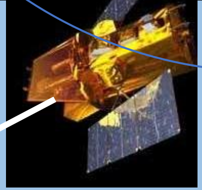
Discussions 2: neutrinos from low-luminosity GRBs

Neutrinos in coincidence with gamma-ray bursts?



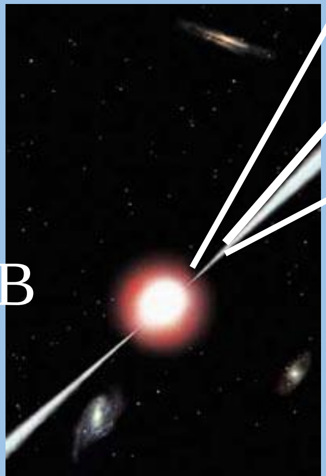






Gamma-ray satellites

γ, ν



distant GRB

This non-detection suggests that the standard GRB population is not the major contributor to the diffuse neutrino flux (IceCube Collaboration et al., 2016).

Neutrinos from low-luminosity GRBs

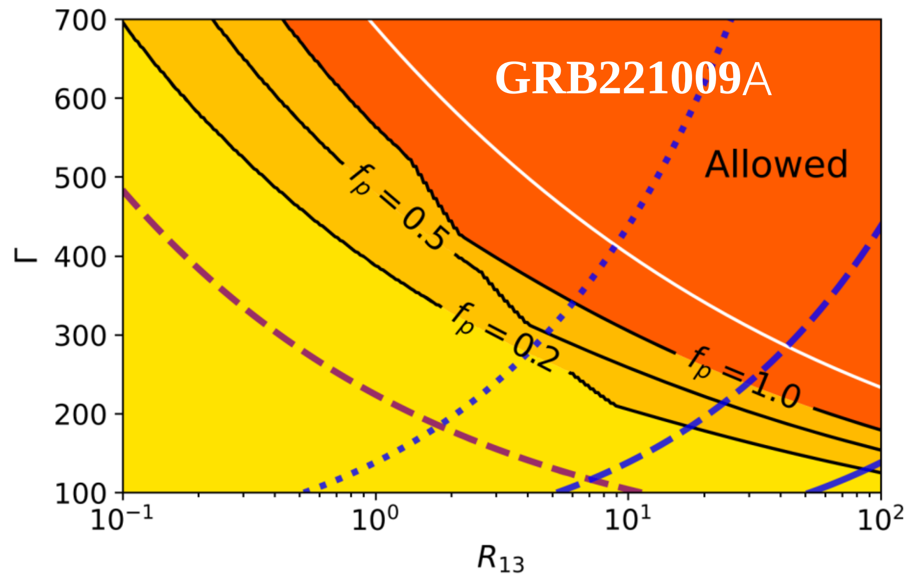
- Normal-luminosity GRBs contribute to <1% neutrino background: constraining the dissipation radius (He et al. 2012)

- No neutrinos from the BOAT GRB 221009A: put useful constraints on the dissipation model

  (Ai & Gao 2023; Liu et al. 2023)

- Low-luminosity GRBs are still possible neutrino sources: high event rate (e.g., Liu et al. 2013; Xiao & Dai 2015)

- **SVOM (and EP) may provide a new sample (LL-GRBs) to search for a correlated neutrino emission.**



Ai & Gao 2023

Summary

- TeV emission origin is still under debate: SSV vs. synchrotron
- >10TeV photons from GRB 221009A pose challenge for SSC, possibly hadronic origin?
- More cases of GRBs (particular nearby low-luminosity GRBs) detected by SVOM are important

- Goal: will LL-GRBs be sources of UHECRs and neutrinos ?