LHAASO Highlight Results on VHE γ-ray sources

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on behalf of the LHAASO collaboration

IHEP,CAS

2024.9.9@11th International Fermi Symposium

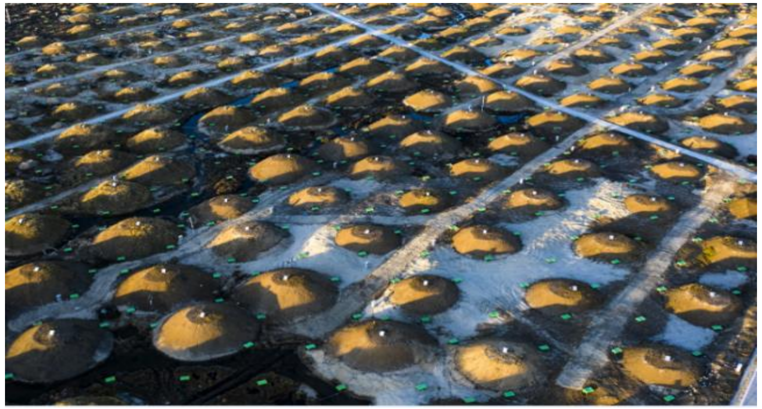
LHAASO 高海拔宇宙线观测站

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Large High Altitude Air Shower Observatory

The partial arrays since 2019
The full arrays since July 2021

WCDA	KM2A	WFCTA+KM2A+WCDA
VHE γ-ray detector	UHE γ-ray detector	Cosmic ray detector
0.1 TeV-20 TeV	10 TeV-10 PeV	10 TeV-100 PeV



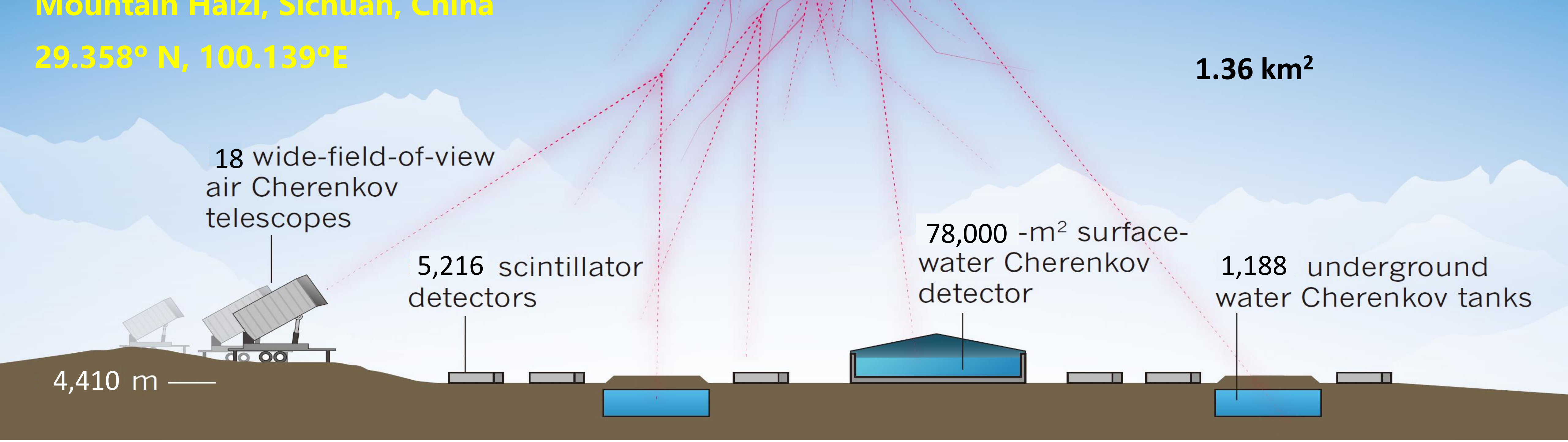
LHAASO detectors

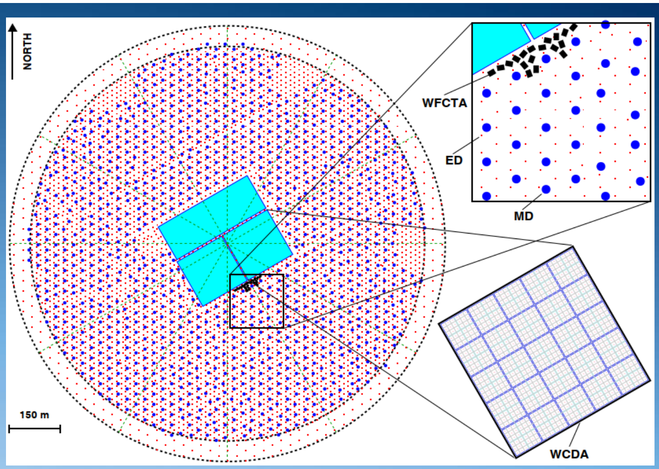
LHAASO Physics Topics

- Gamma-ray Astronomy
- Charged Cosmic rays
- New Physics Frontier

Mountain Haizi, Sichuan, China

29.358° N, 100.139°E

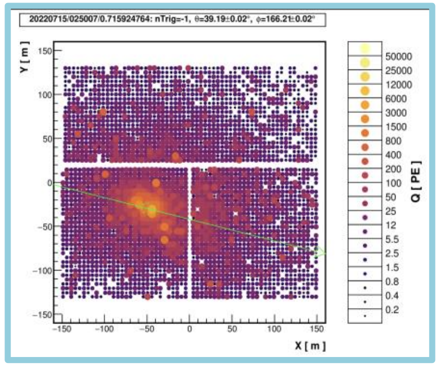




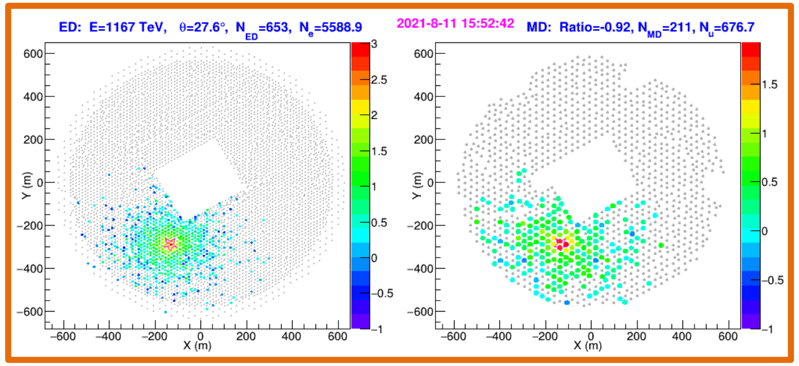
1.36 km²

Status of LHAASO

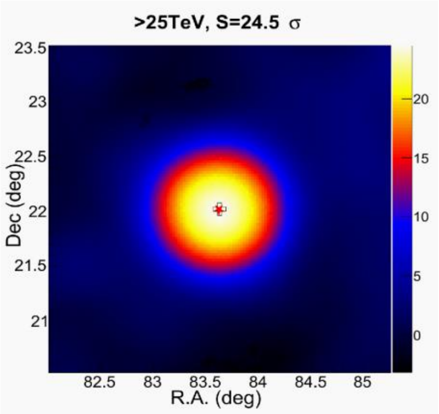
10 TeV event



1.2 PeV event

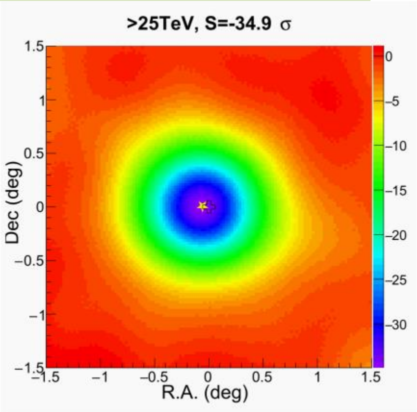


Crab Nebula

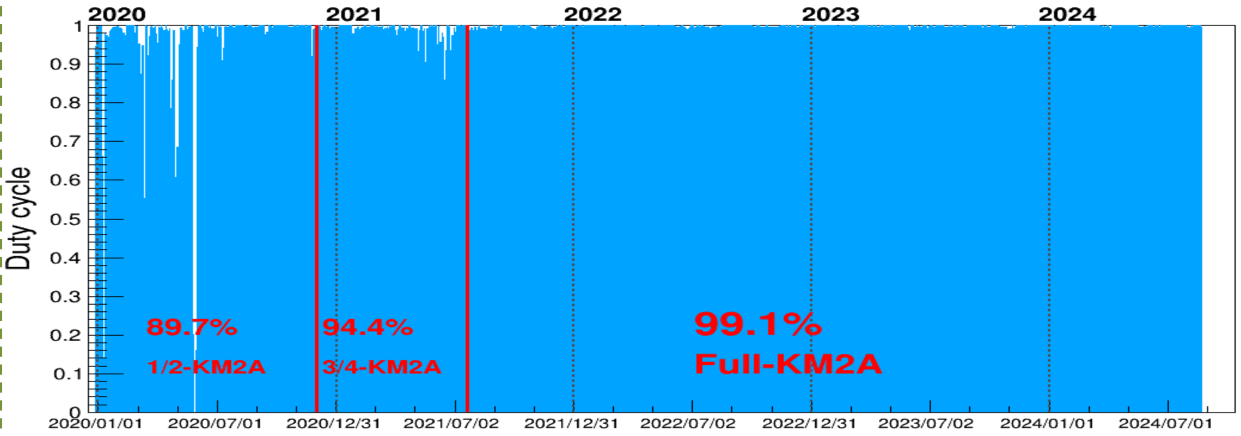


per Month

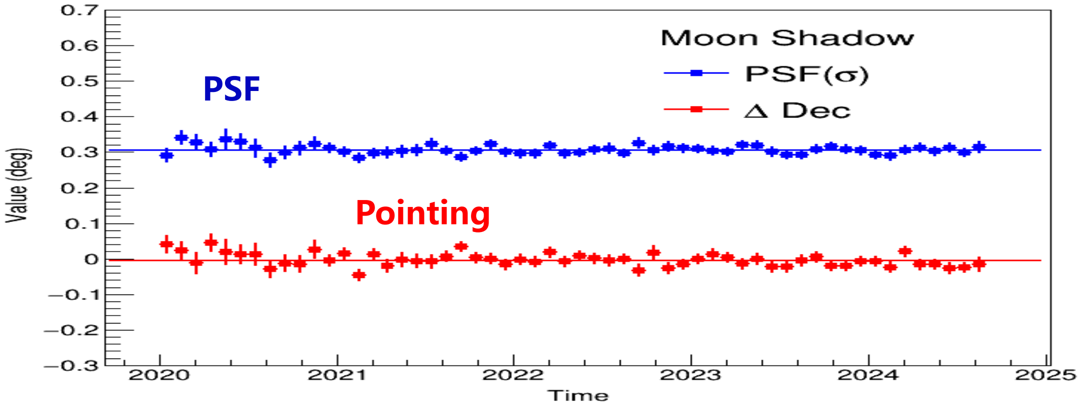
Moon shadow



Duty cycle >99%, 4.5 years data



Stable pointing and angular resolution



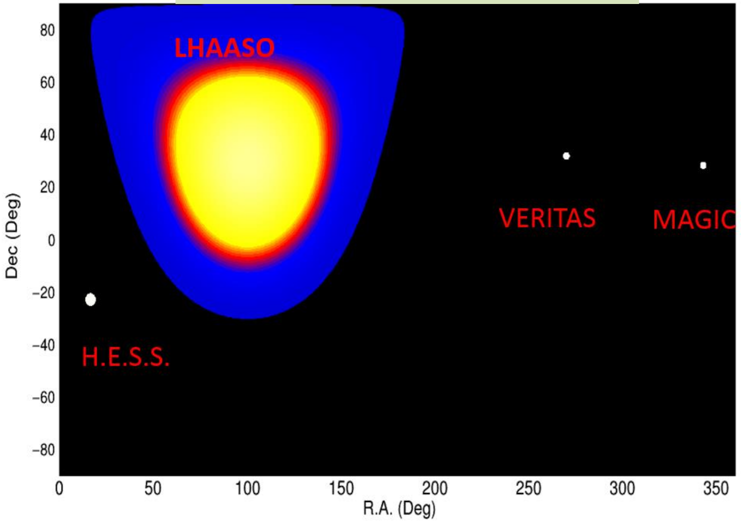
LHAASO for γ-ray astronomy

Good for

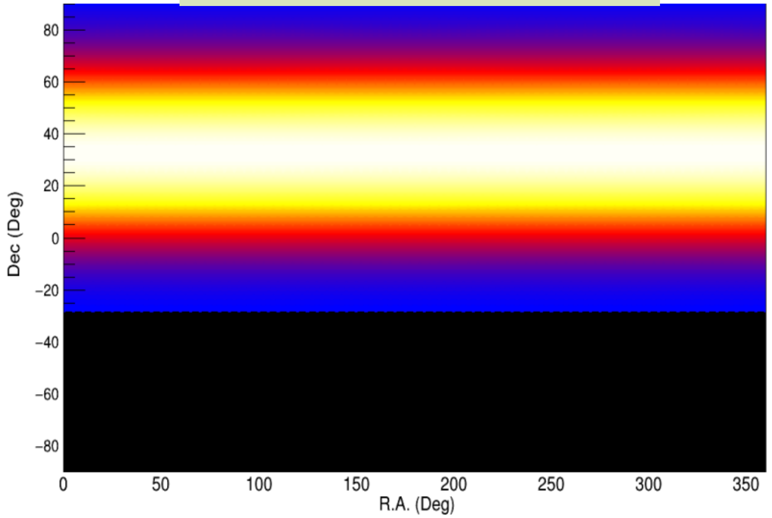
Sky survey, Extended sources, Transient sources

Large FOV

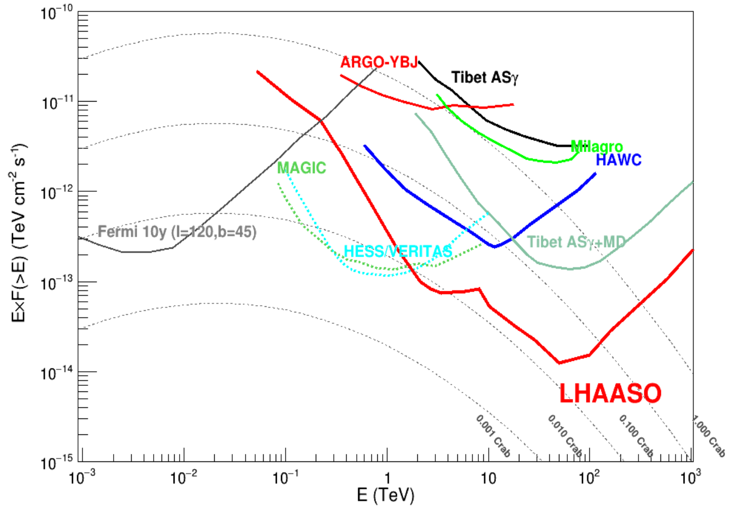
Every moment
(θ<50º,18% sky)



One day
(66% sky)

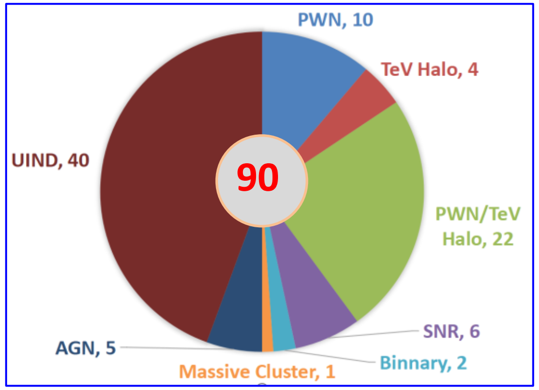


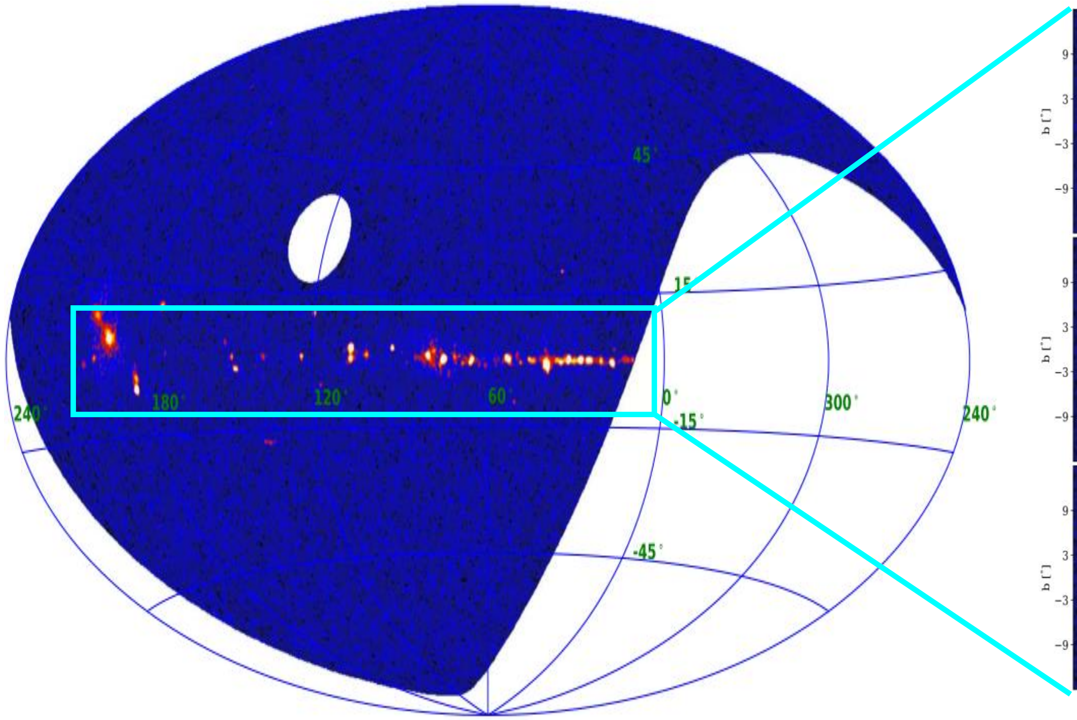
High sensitivity
Wide energy range

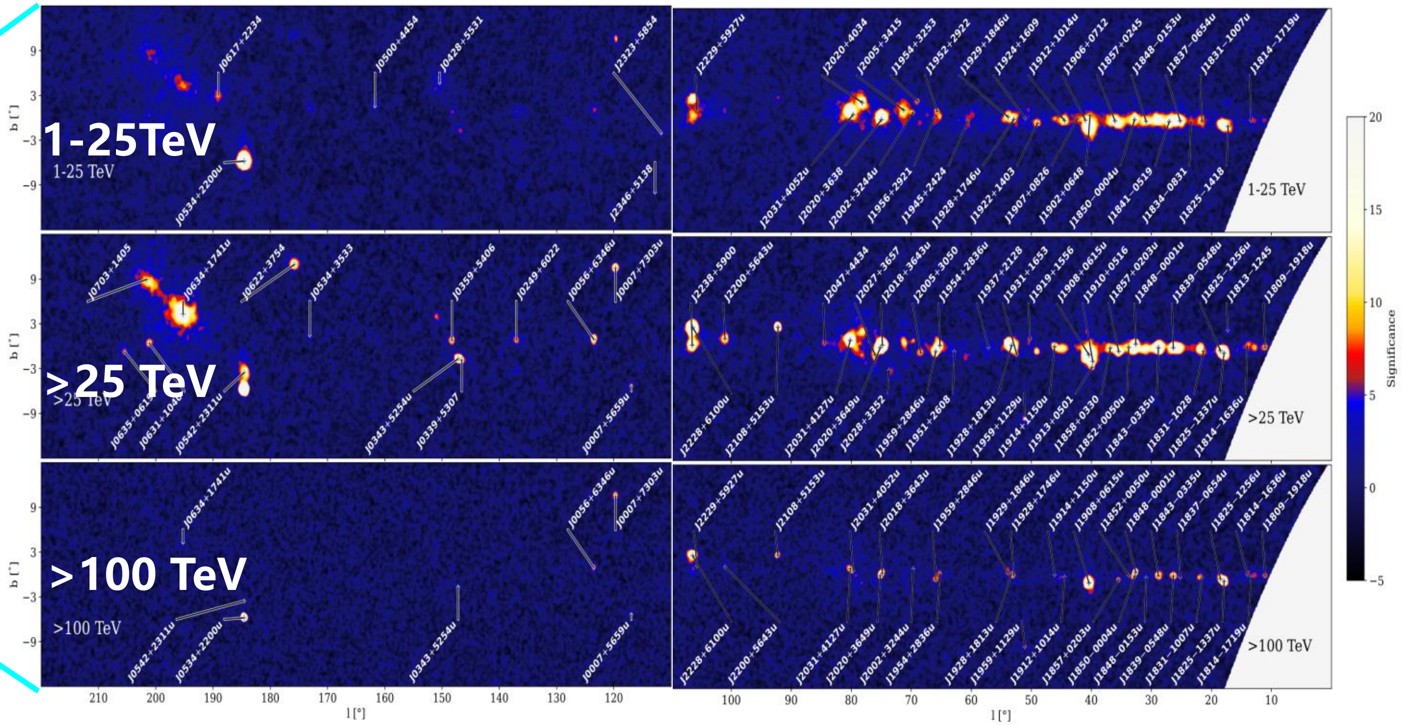


The 1st LHAASO catalog

- **90 VHE sources with 32 new discoveries.**
  - **32 : 7 dark sources, 8 only with Fermi-LAT sources**
- **43 UHE (>100 TeV) sources**







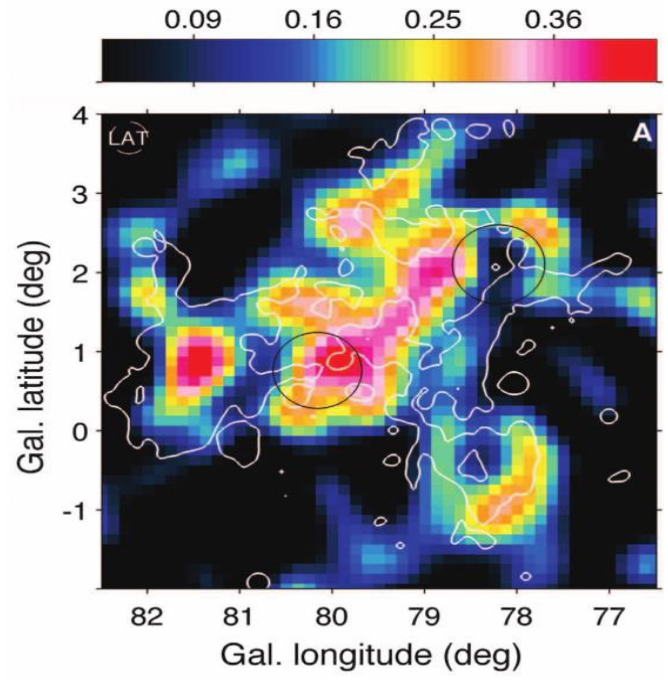
LHAASO coll. ApJS, 271:25 (2024)

LHAASO recent highlight results on Galactic sources

Cygnus Cocoon

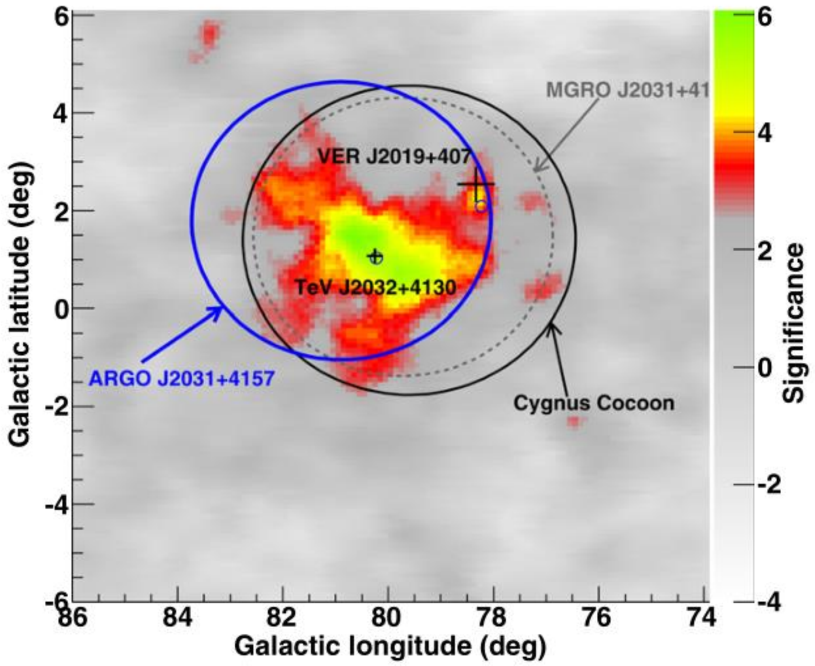
Fermi-LAT firstly revealed a freshly accelerated cosmic rays source!
Extension radius ~2º.

Fermi-LAT: 10~100 GeV



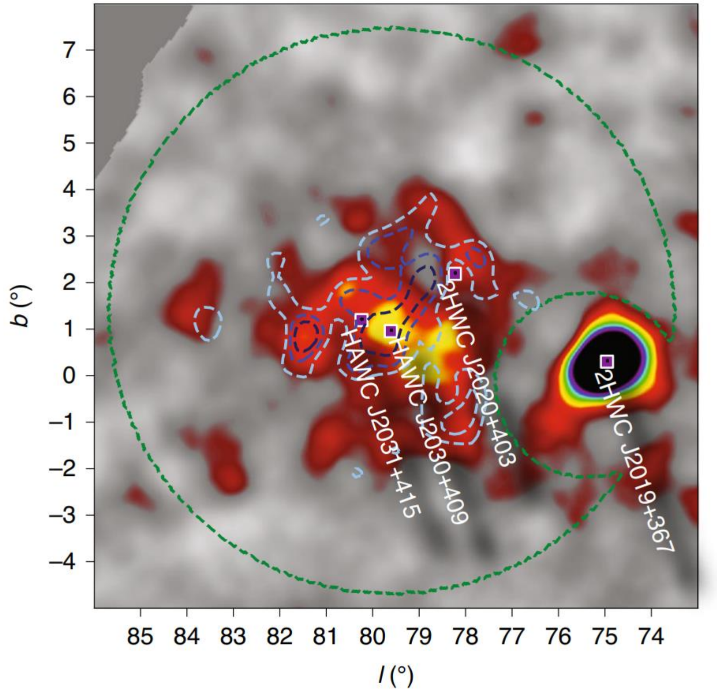
Fermi-LAT coll. 2011

ARGO-YBJ: 0.2-10 TeV



ARGO-YBJ coll. 2014

HAWC: 1-100 TeV



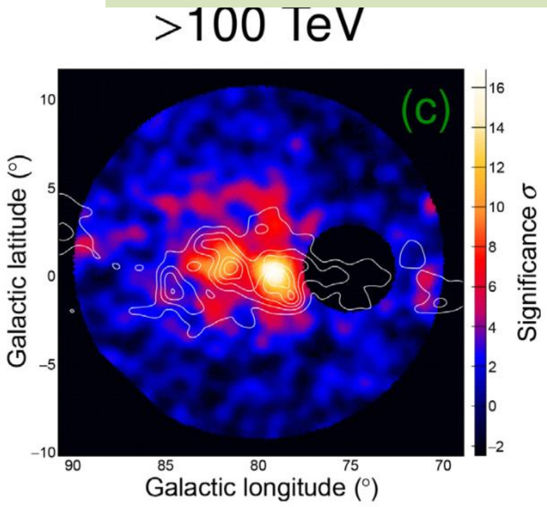
HAWC coll. 2021

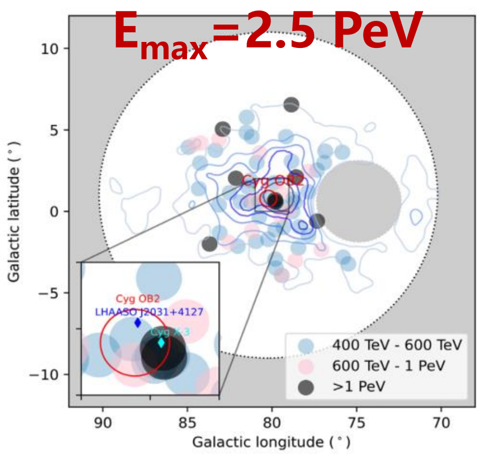
LHAASO identify a super PeVatron

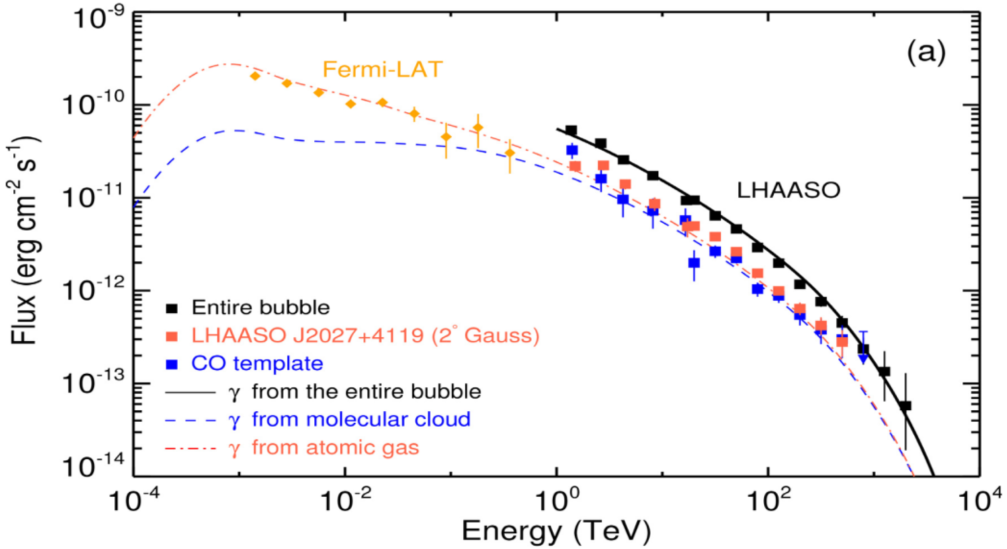
- Large UHE γ-ray bubble with a radius of 6° (~150pc)
  - Larger than the Cygnus Cocoon(2°)
  - SED is connected with Fermi-LAT for core region
- Associated with Molecular Clouds
- 8 photons >1 PeV
- 10 PeV cosmic ray super PeVatron

LHAASO coll. Science Bulletin 69:449–457(2024)

LHAASO: 1-2500 TeV







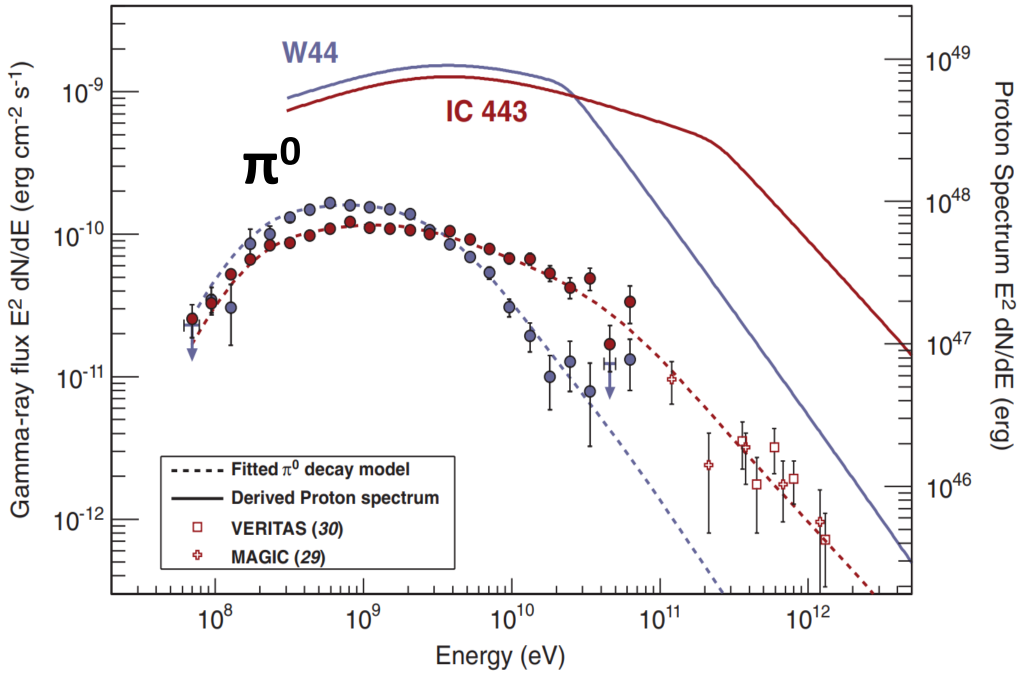
SNR as cosmic ray sources

Fermi-LAT provide the first robust evidence for SNR accelerate CR!

What is the maximum energy that SNR can accelerate?

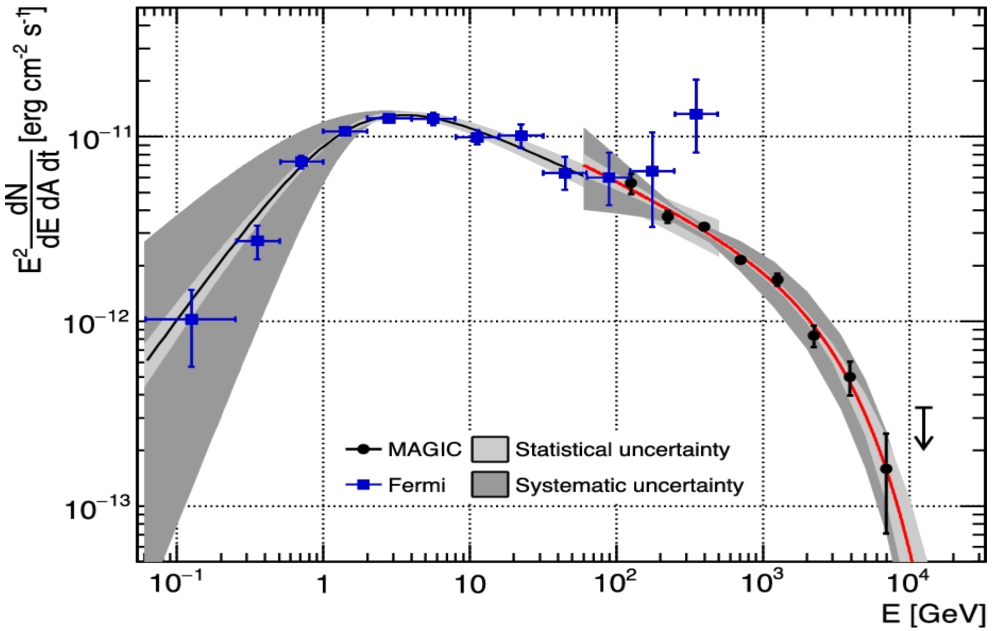
Only up to 10 TeV?

~10k yr



Fermi-LAT coll. 2013

Cas A(330 yr)

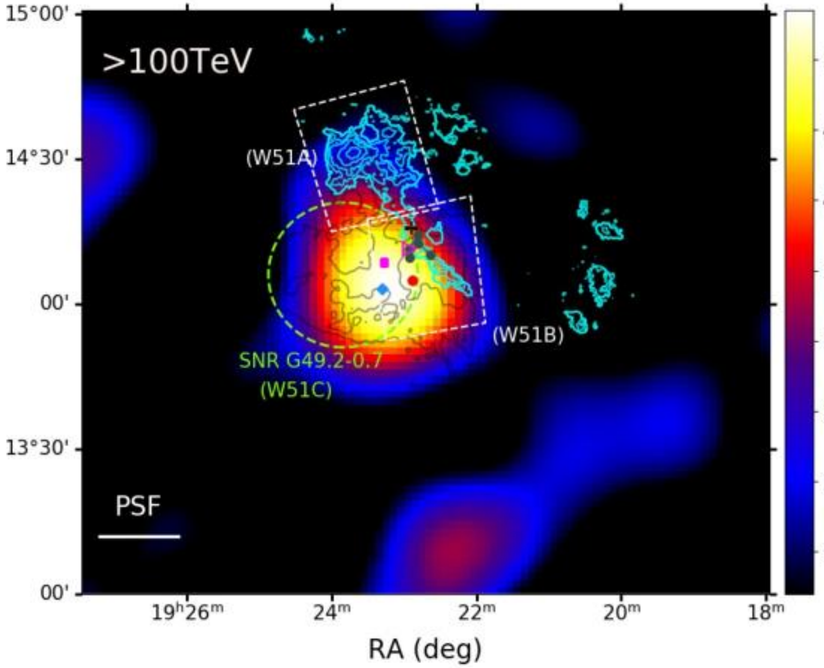


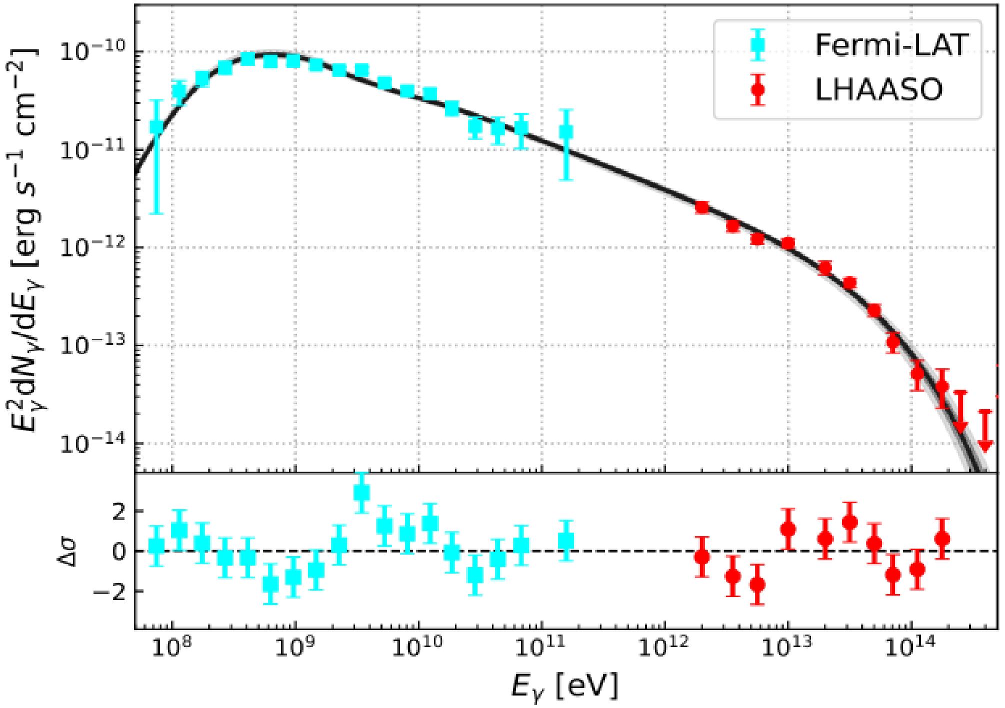
MAGIC coll. 2017

LHAASO reveal SNR approaching PeV

- **SNR W51C**: An interaction region between the cosmic rays and the dense molecular clouds.
- Underline cutoff energy of proton up to $E_{p,\mathrm{cut}} = 385^{+65}_{-55}\ \mathrm{TeV}$

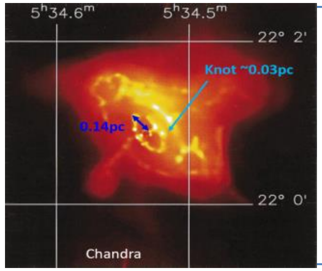
W51C:~30k yr

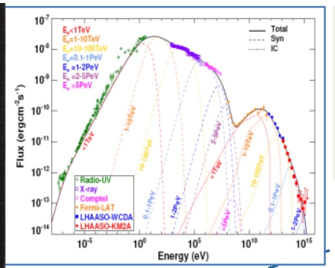




LHAASO coll. Science Bulletin, (2024, https://doi.org/10.1016/j.scib.2024.07.017)

LHAASO reveal new phenomena from PWNs

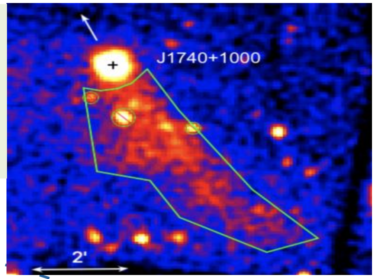


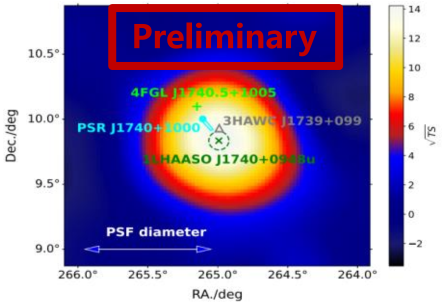


Science,373:425 (2021)

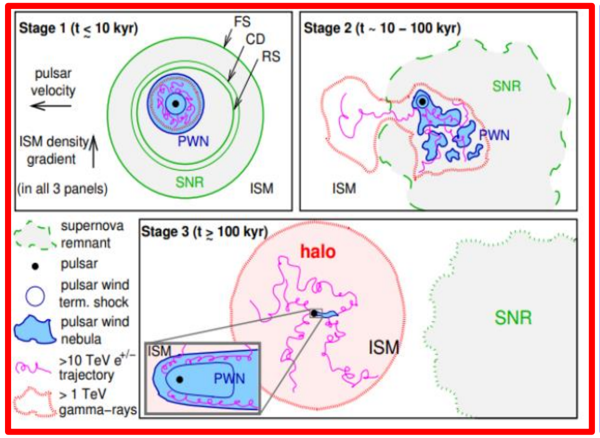
1k yr, 1.1 PeV photon from Crab Nebula

114k yr,UHE from bow show pulsar tail?

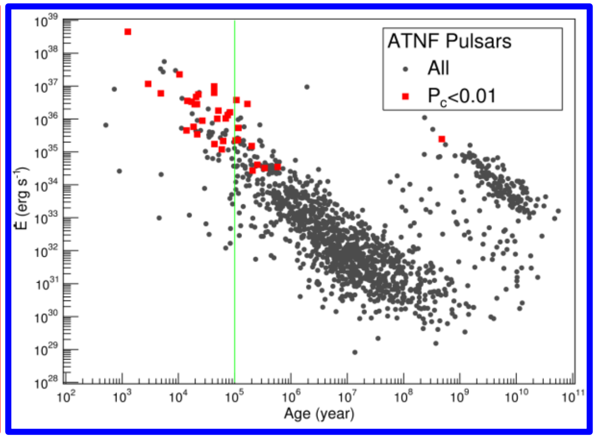




LHAASO sources

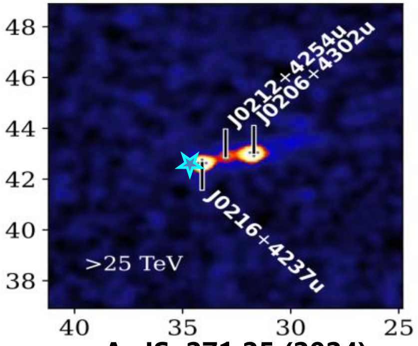


Giacinti et al.(2020)



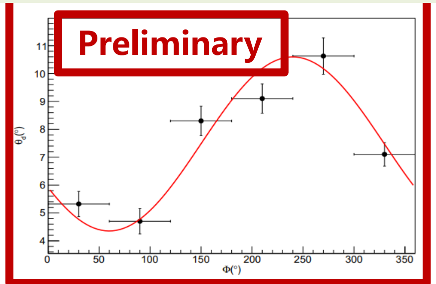
ApJS, 271:25 (2024)

476M yr, UHE MS pulsar wind nebula?

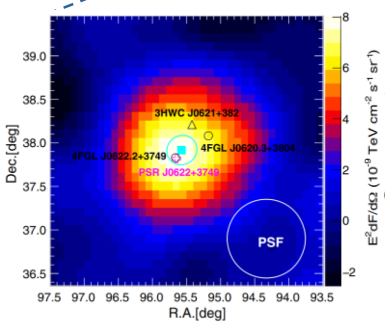


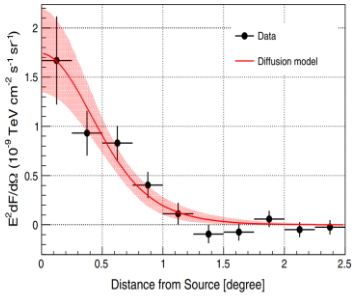
ApJS, 271:25 (2024)

342k yr, Geminga: Asymmetric diffusion



208k yr, New UHE halo





PRL 126, 241103 (2021)

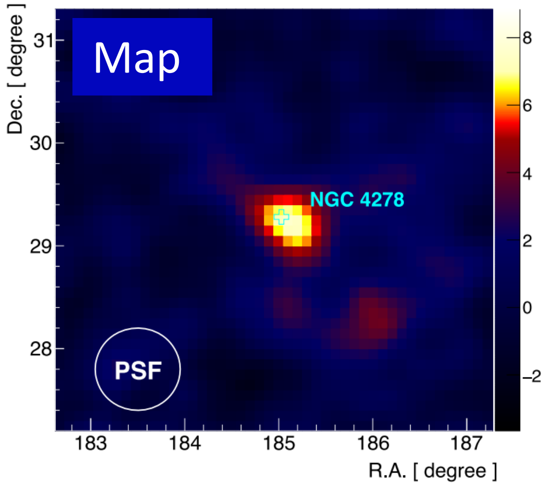
LHAASO recent highlight results on extragalactic sources

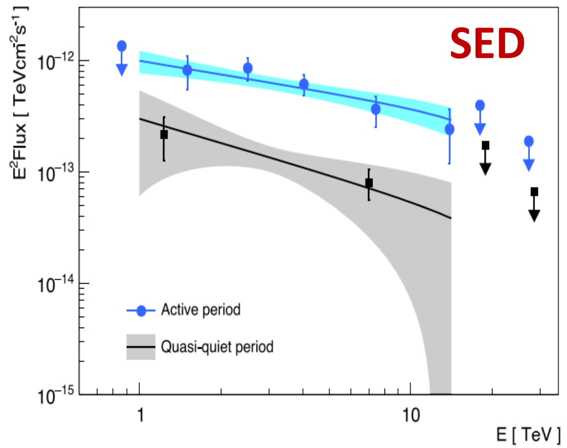
LHAASO extragalactic sources

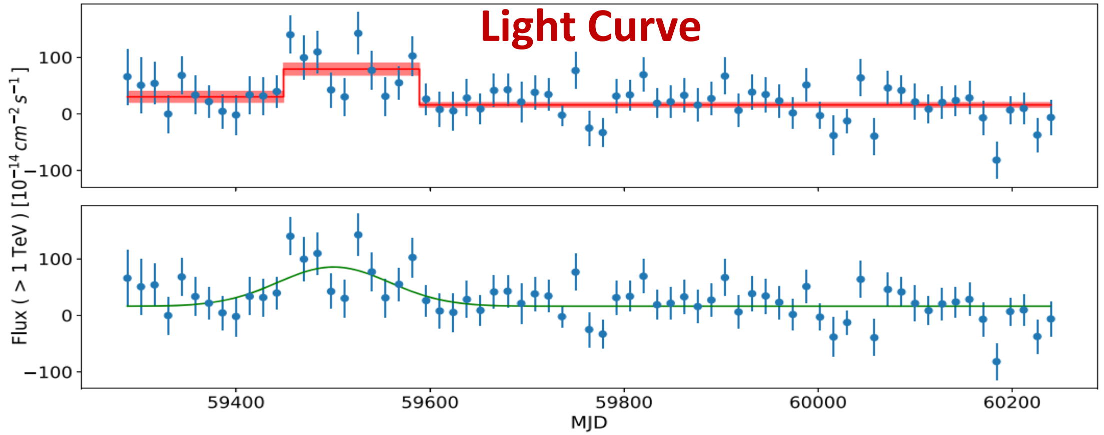
Name	Note	LHAASO Arrays	z	Type
GRB 221009A		WCDA+KM2A	0.151	GRB
Mrk 421	1st catalog	WCDA+KM2A	0.031	Blazar(H)
Mrk 501	1st catalog	WCDA+KM2A	0.034	Blazar(H)
1ES 2344+514	1st catalog	WCDA	0.044	Blazar(H)
1ES 1727+502	1st catalog	WCDA	0.055	Blazar(H)
1ES 1959+650	Atel#16437	WCDA	0.048	Blazar(H)
NGC 1275	flaring	WCDA	0.0176	FRI
M87		WCDA	0.0044	FRI
NGC 4278	1st catalog: New	WCDA	0.002 (16.4Mpc)	Low luminosity AGN
IC 310	Atel#16540	WCDA+KM2A	0.0189	AGN(unknown type)

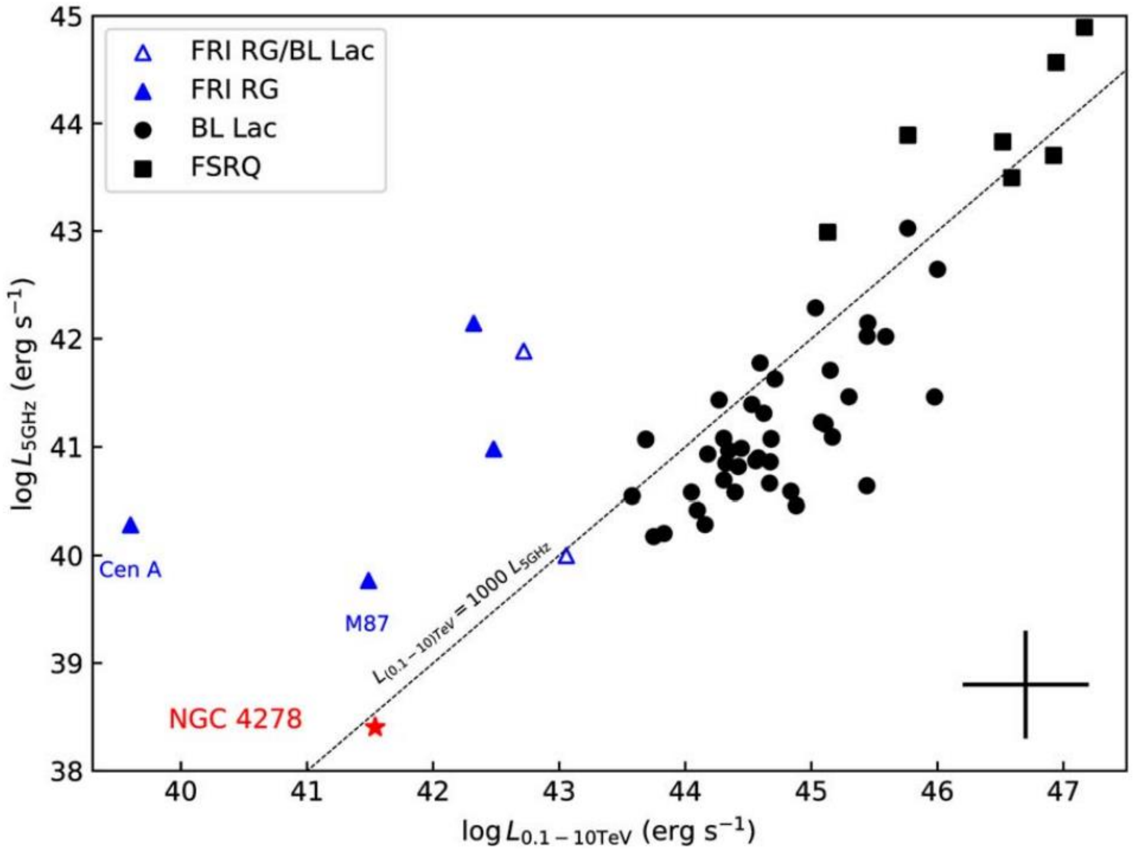
LHAASO observation on NGC 4278

First evidence for the Low-luminosity AGN with VHE γ-ray!









LHAASO coll. ApJL, 971:L45 (2024)

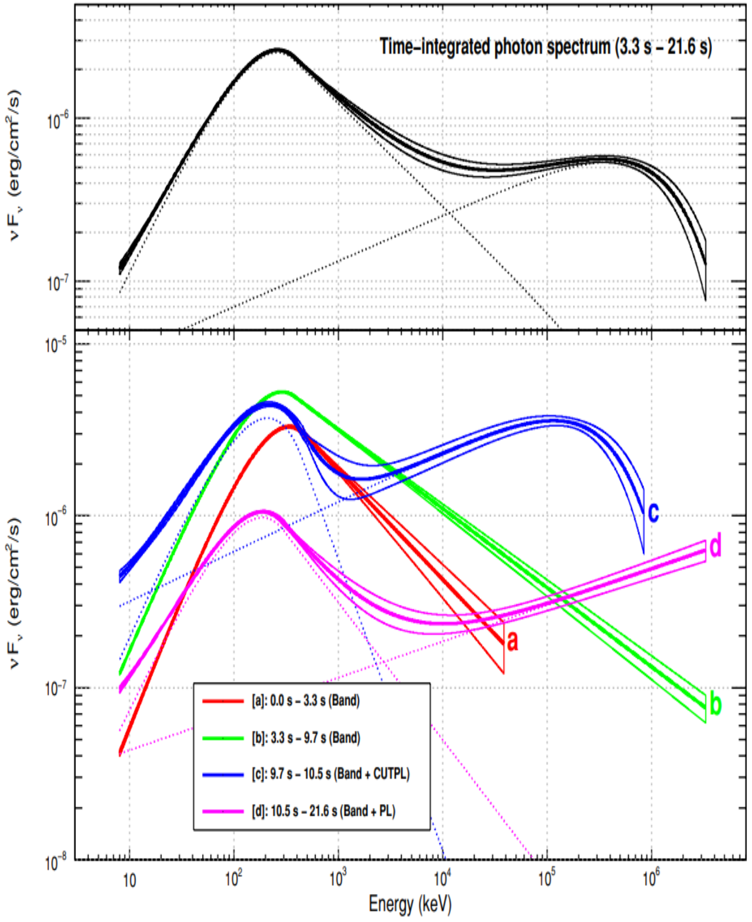
Observation on GRB221009A with LHAASO

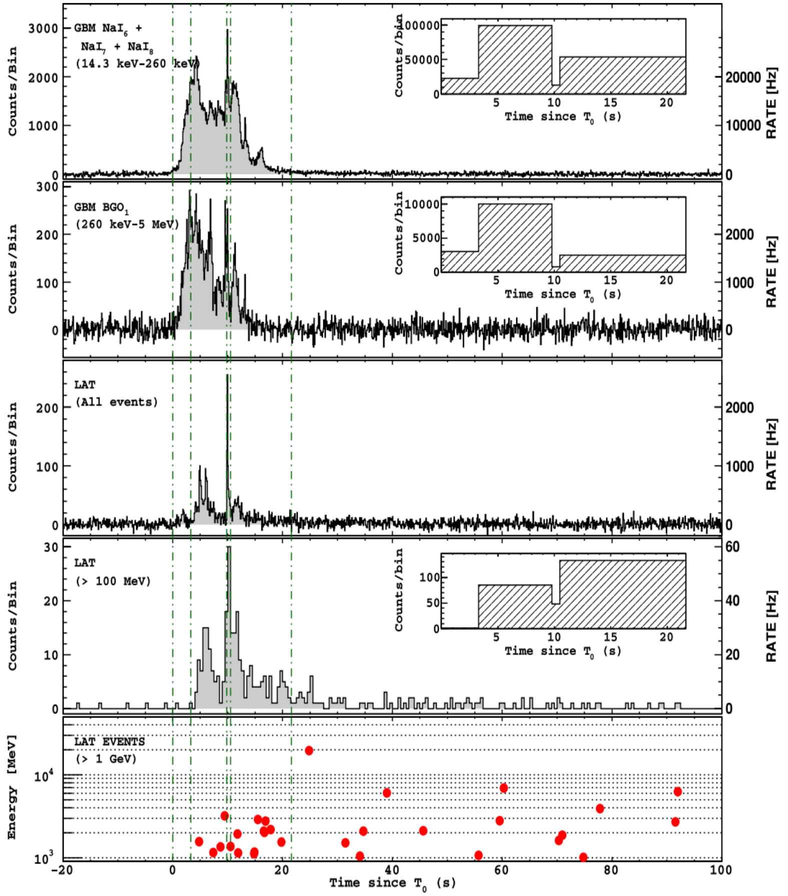
High energy γ-ray from GRB

- Much new knowledges due to Fermi-LAT!
- Light Curve
  - Delayed onset
  - Long last
- SED: Two components

Prompt and afterglow are tangled at GeV!

GRB 090926A

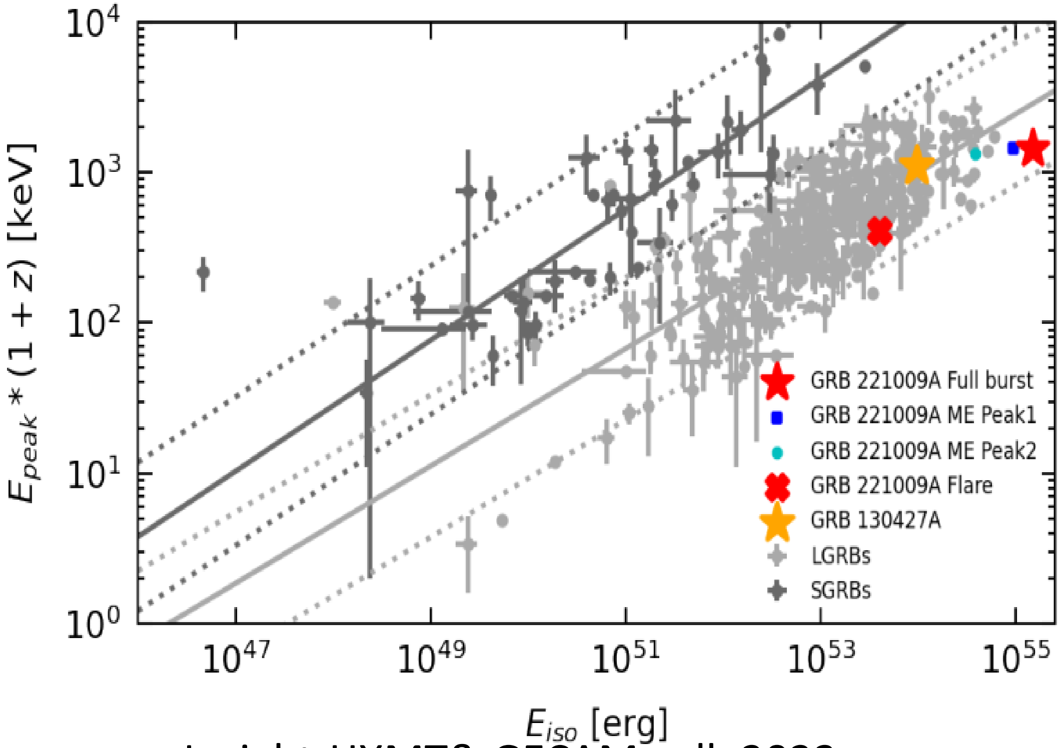




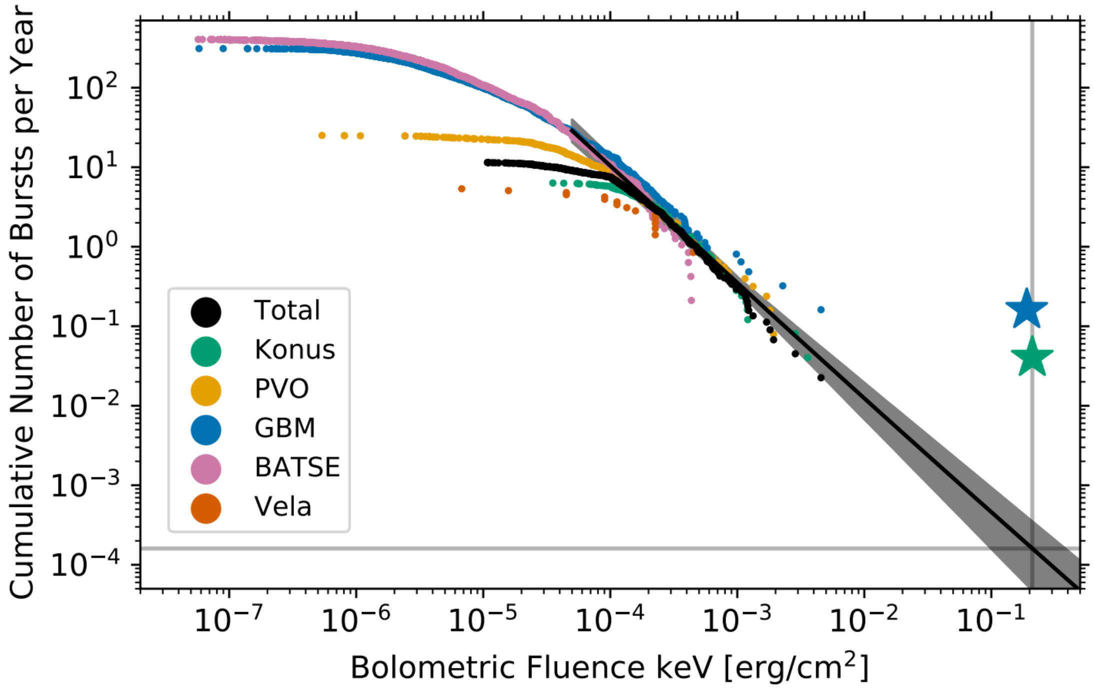
Fermi-LAT coll. et al. 2011

The BOAT GRB 221009A

Detected by Fermi-LAT at 13:16:59.99 UT!



Insight-HXMT& GECAM coll. 2023



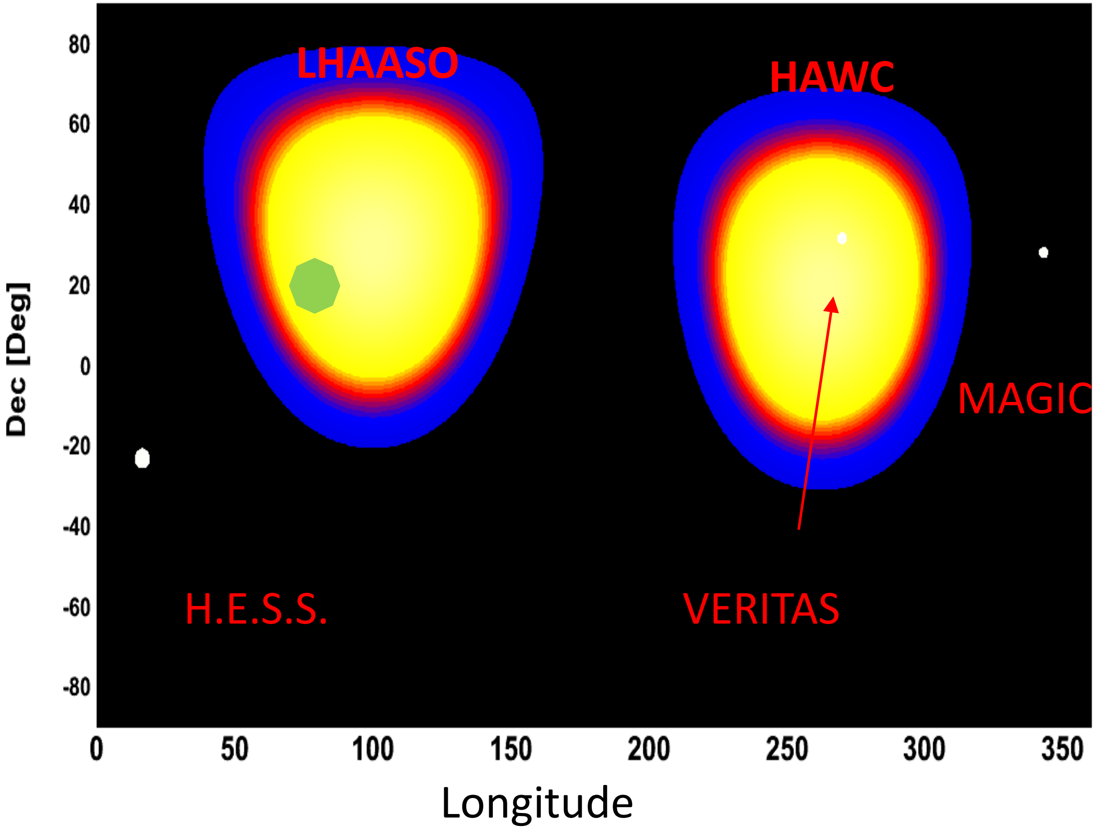
Buns et al. 2023

BOAT（Brightest of all time）！

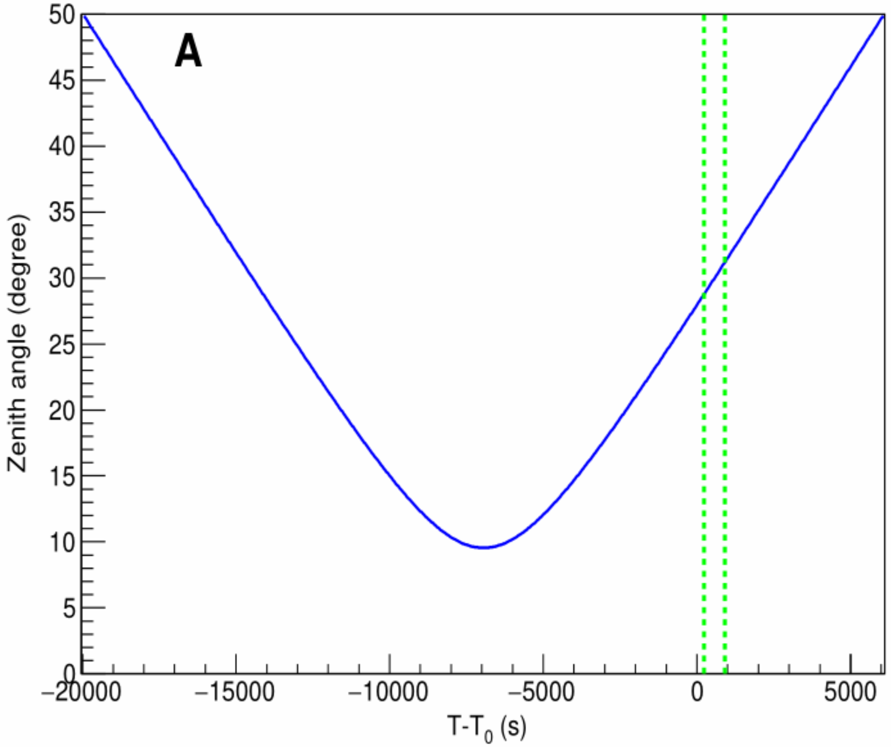
Once every thousands years！

GRB 221009A @FOV of LHAASO

GRB 221009A is well observed by LHAASO at a favorite zenith angle!



FOV

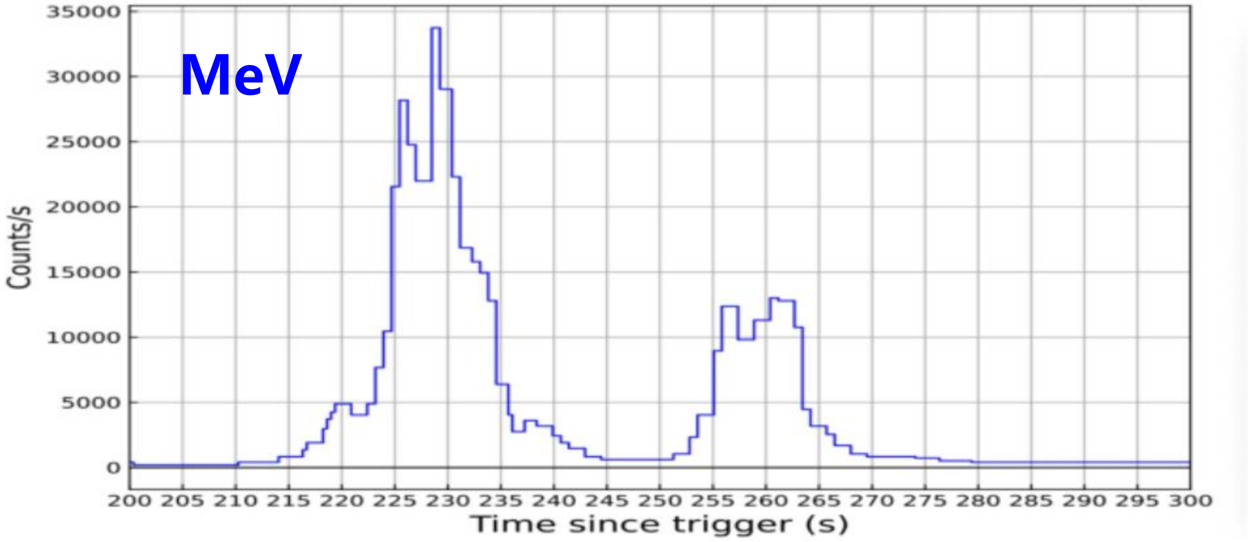


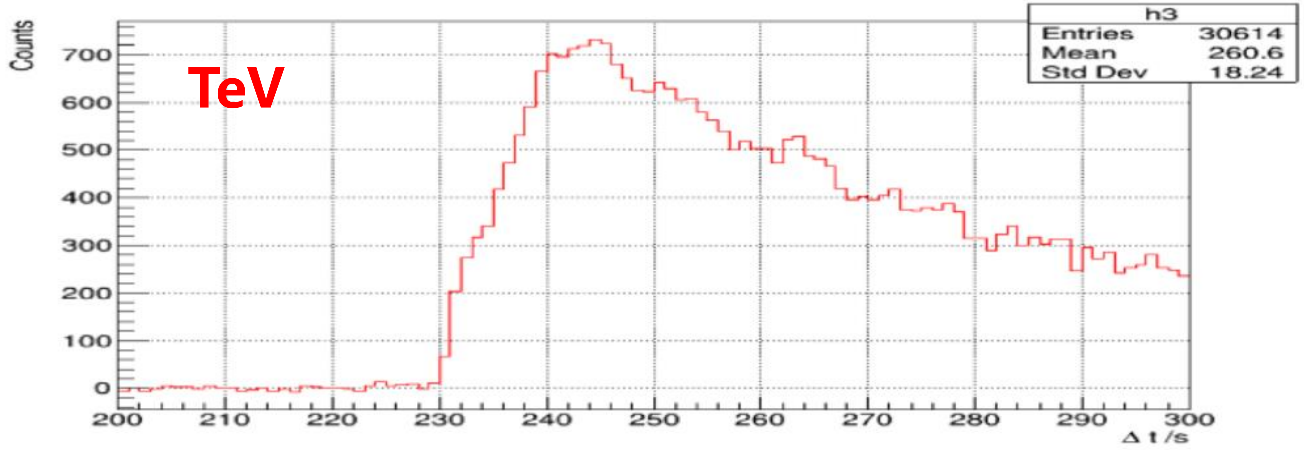
Zenith angle vs Time

WCDA light curve result

- >60,000 photons
- TeV emission is afterglow!
- First time detect onset of the TeV afterglow!
- The most strict limit on the prompt TeV emission: $R = F_{TeV}/F_{MeV} < 2 \times 10^{-5}$

A large $\gamma\gamma$ absorption optical depth ?
OR
A magnetized jet?





Precise Light Curve analysis

The LHAASO TeV light curve provides us with a unique opportunity to study the early afterglow physics!

Slow rise: Favor ISM environment?

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

Peak time : The bulk Lorentz factor of ~**500.**

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

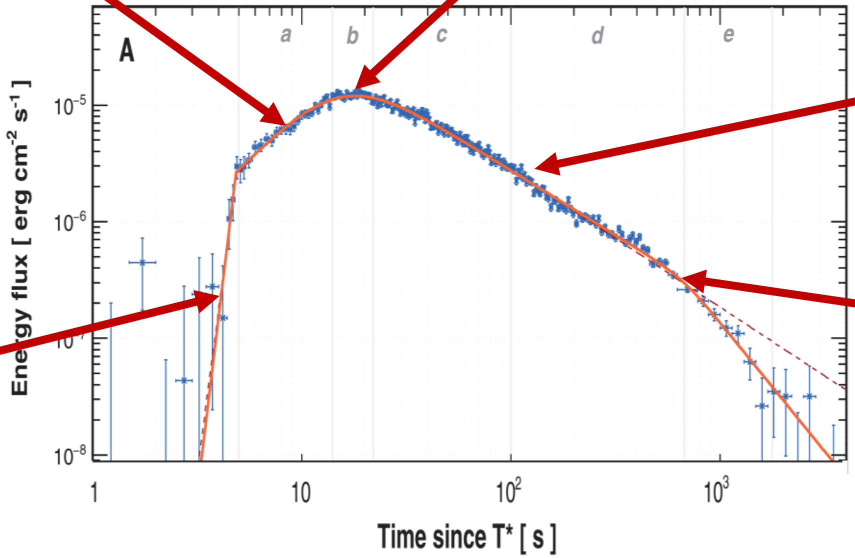
Slow decay: Electron SED index -2.1

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

Unusual Fast rise:

energy injection ?

$\alpha_0 = 14.9^{+5.7}_{-4.0}$



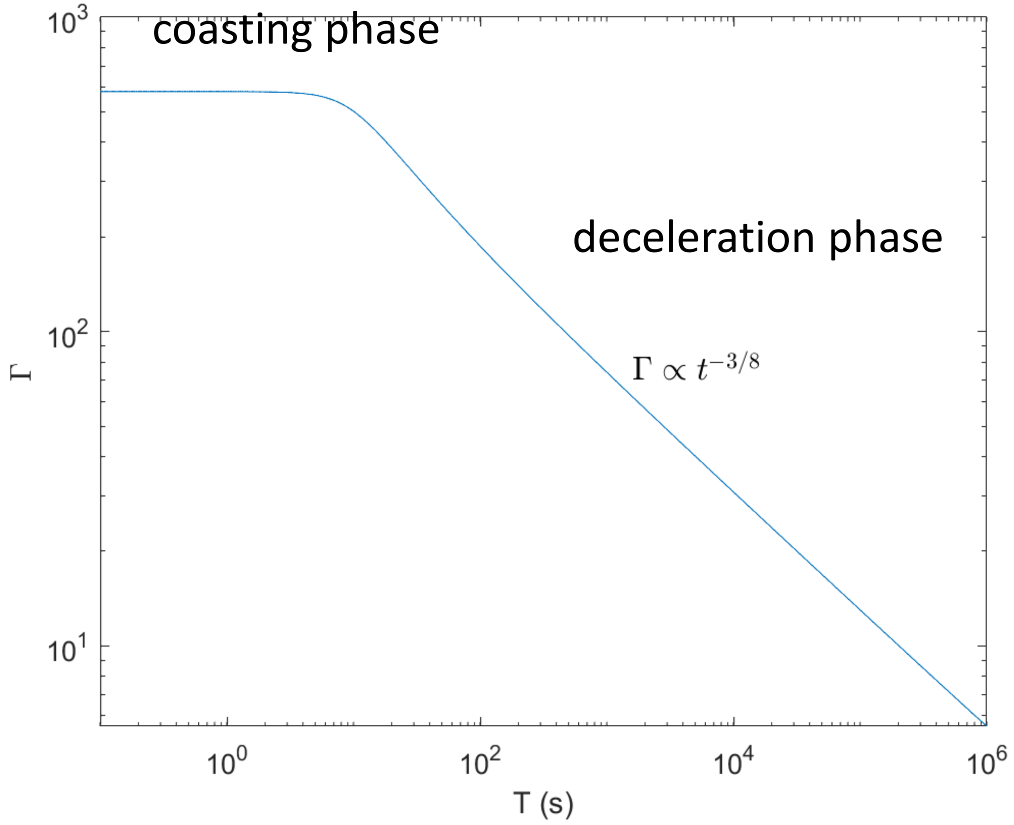
- **Fast decay:** A **jet break** at the earliest time! Jet half opening angle of **0.8º**. $\alpha_3 = -2.21^{+0.30}_{-0.83}$

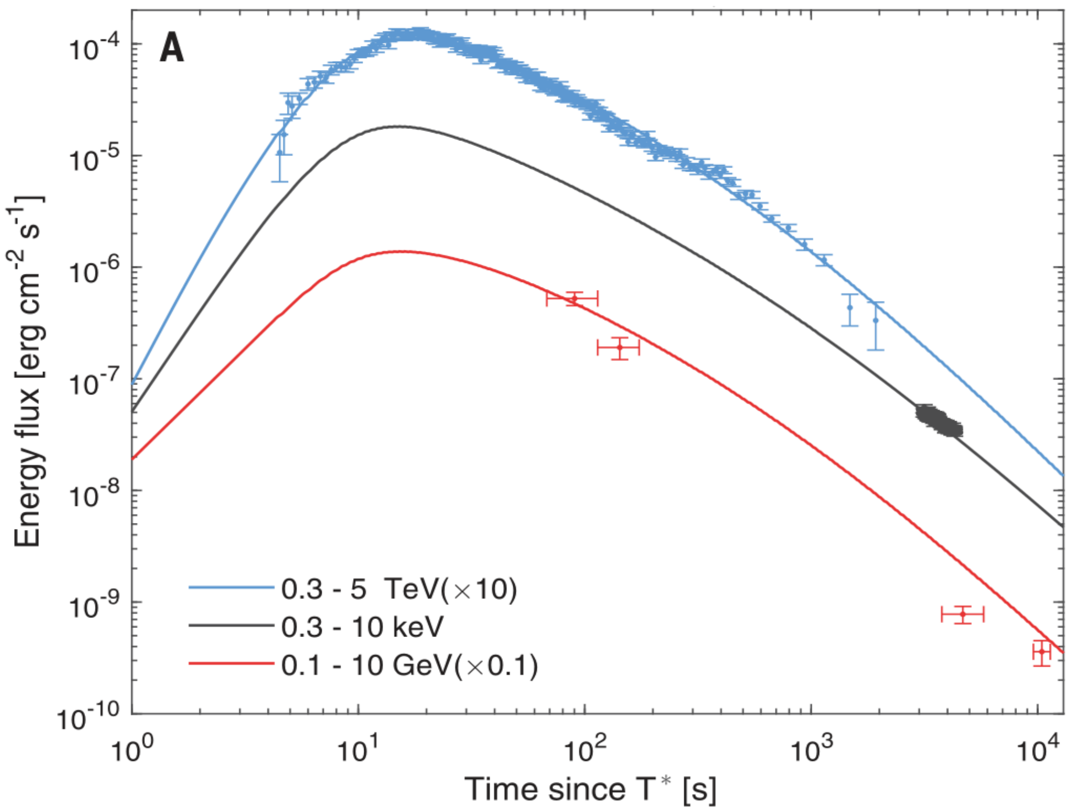
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\rm b,2}}{670\,{\rm s}}\right)^{3/8}$$

LHAASO coll. Science,380:1390 (2023)

Standard afterglow model fitting

Light curve fitting well in the afterglow model

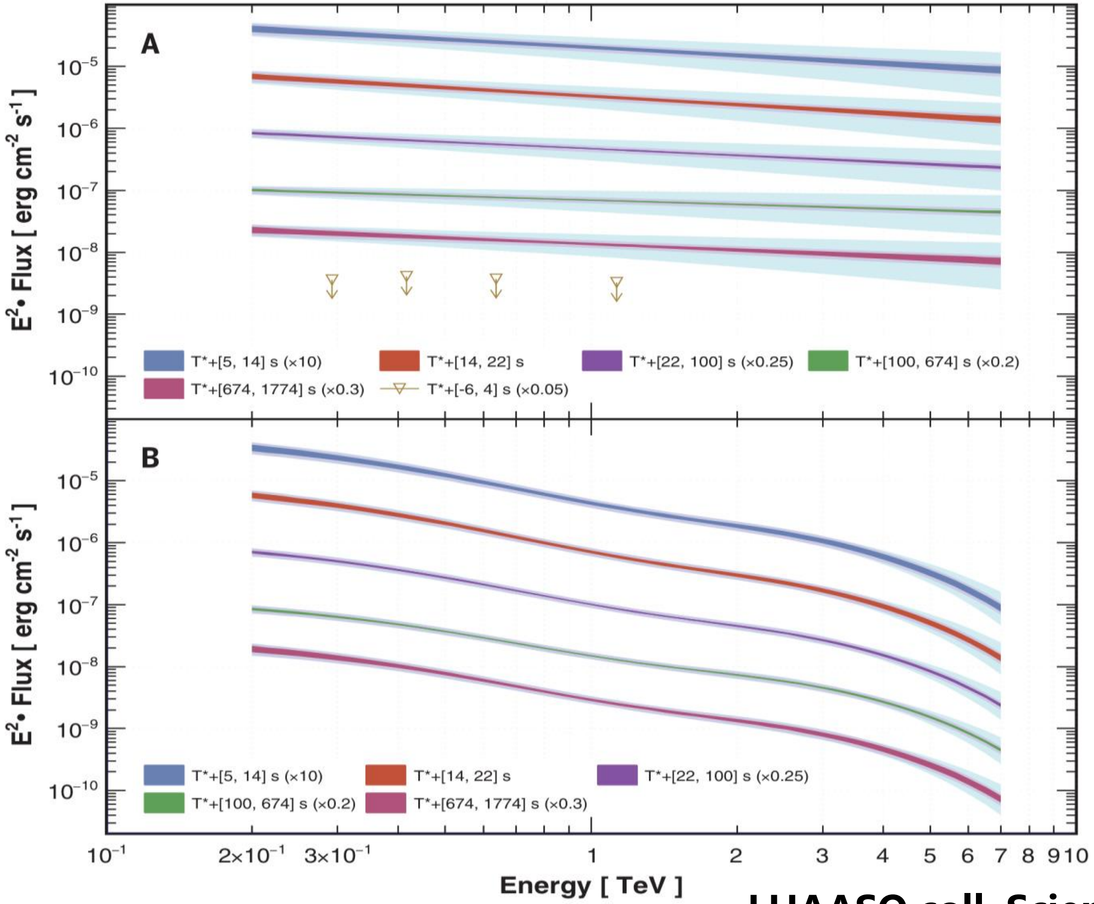


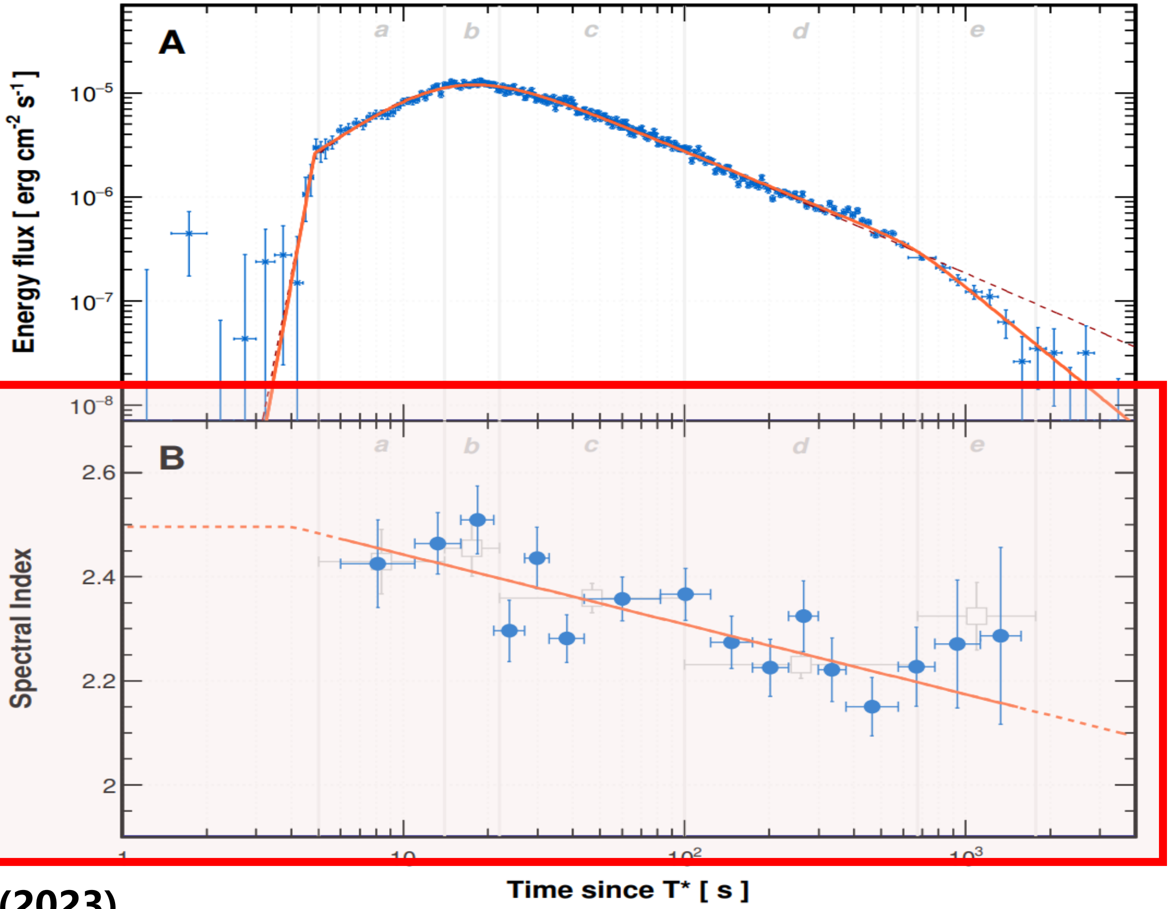


LHAASO coll. Science,380:1390 (2023)

Unexpected SED evolution

- The SED become harder as time increasing. **This is unexpected from afterglow model!**

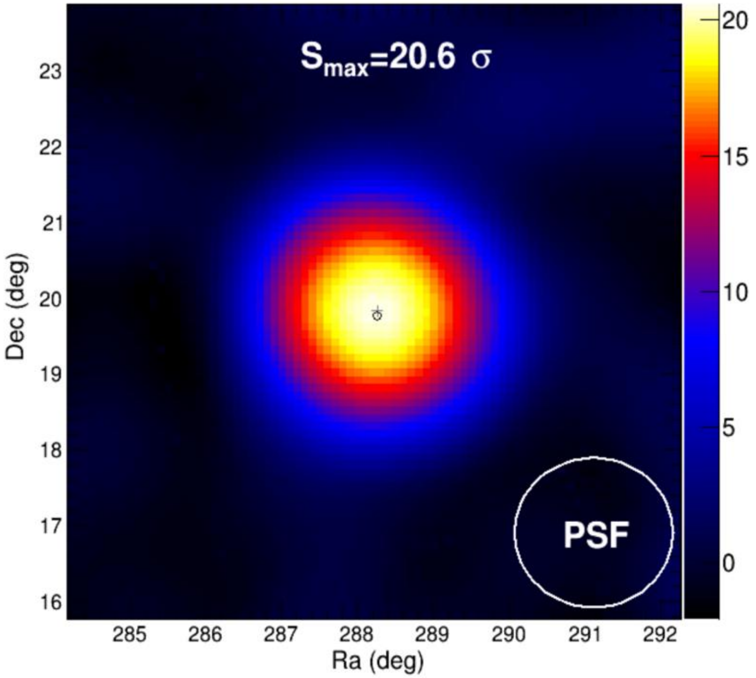


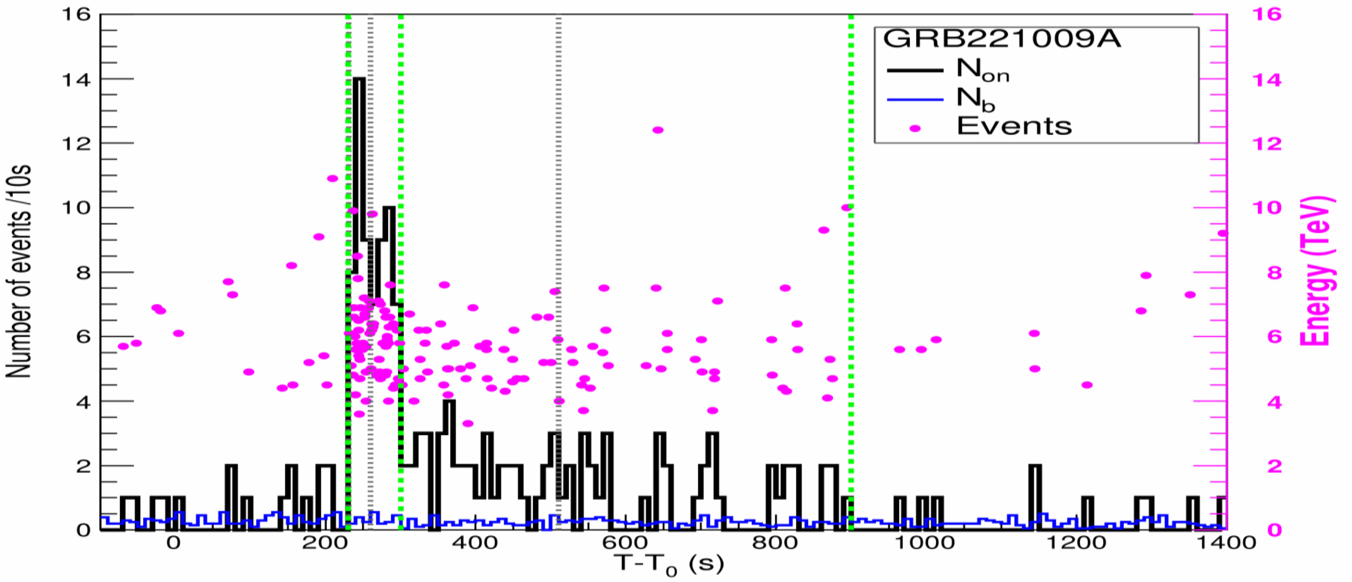


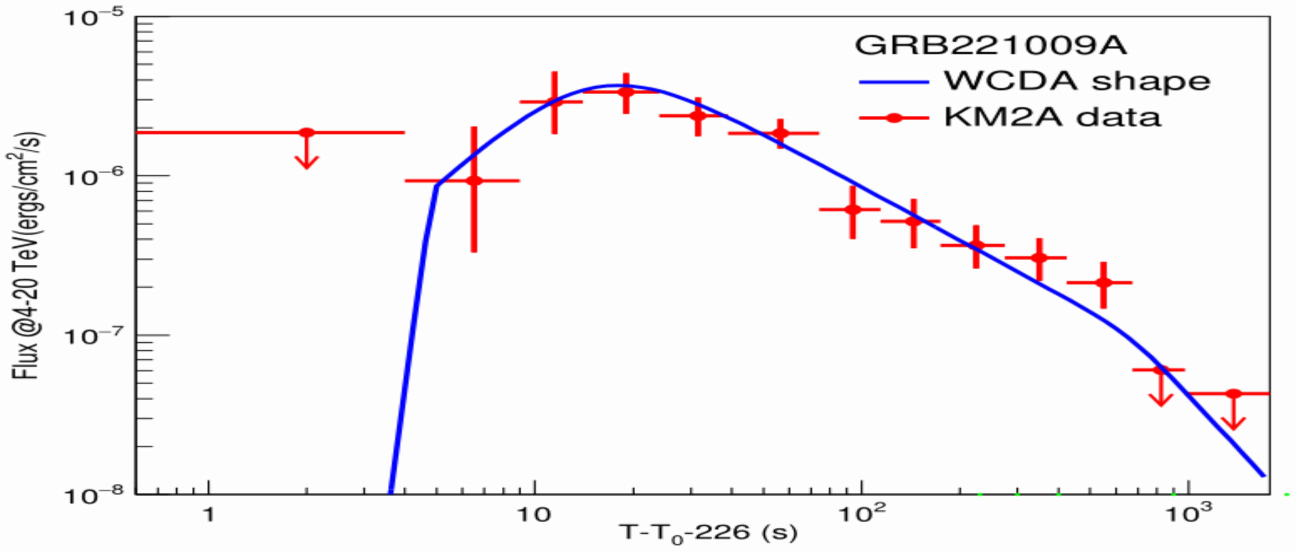
LHAASO coll. Science,380:1390 (2023)

KM2A at higher energies

140 photons with energy >3TeV



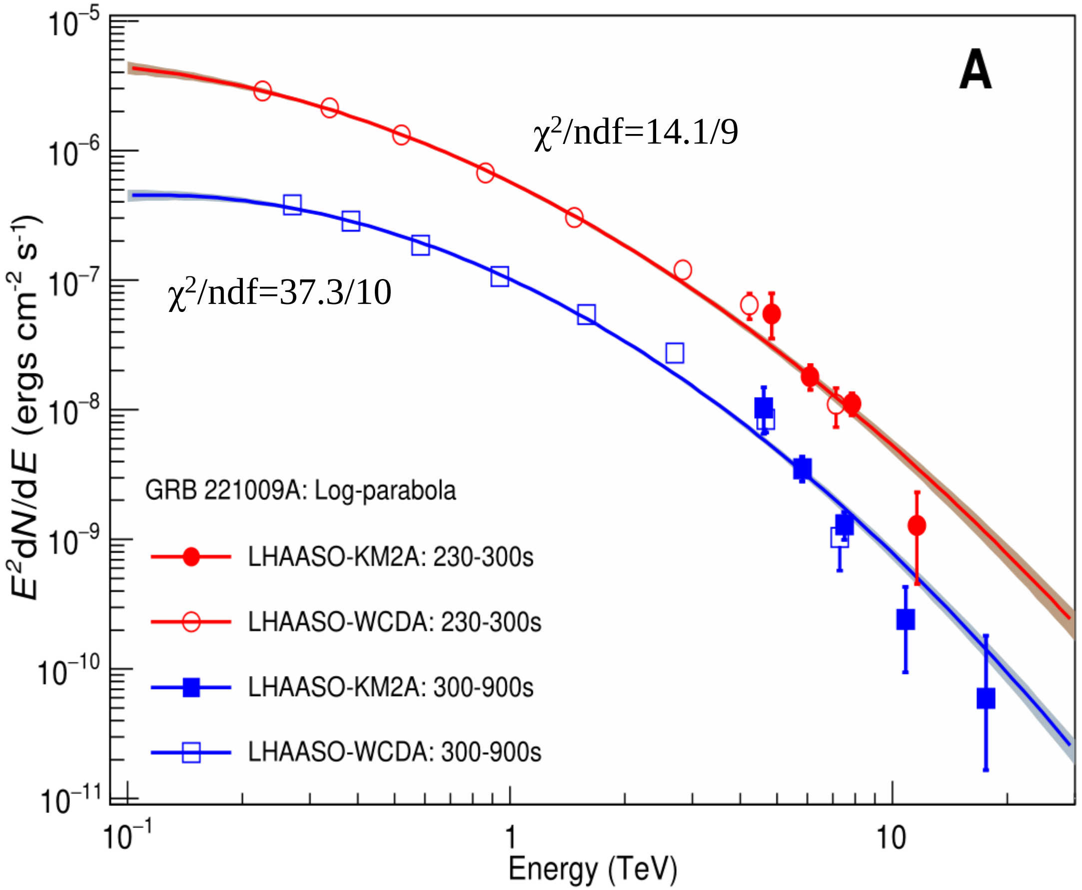




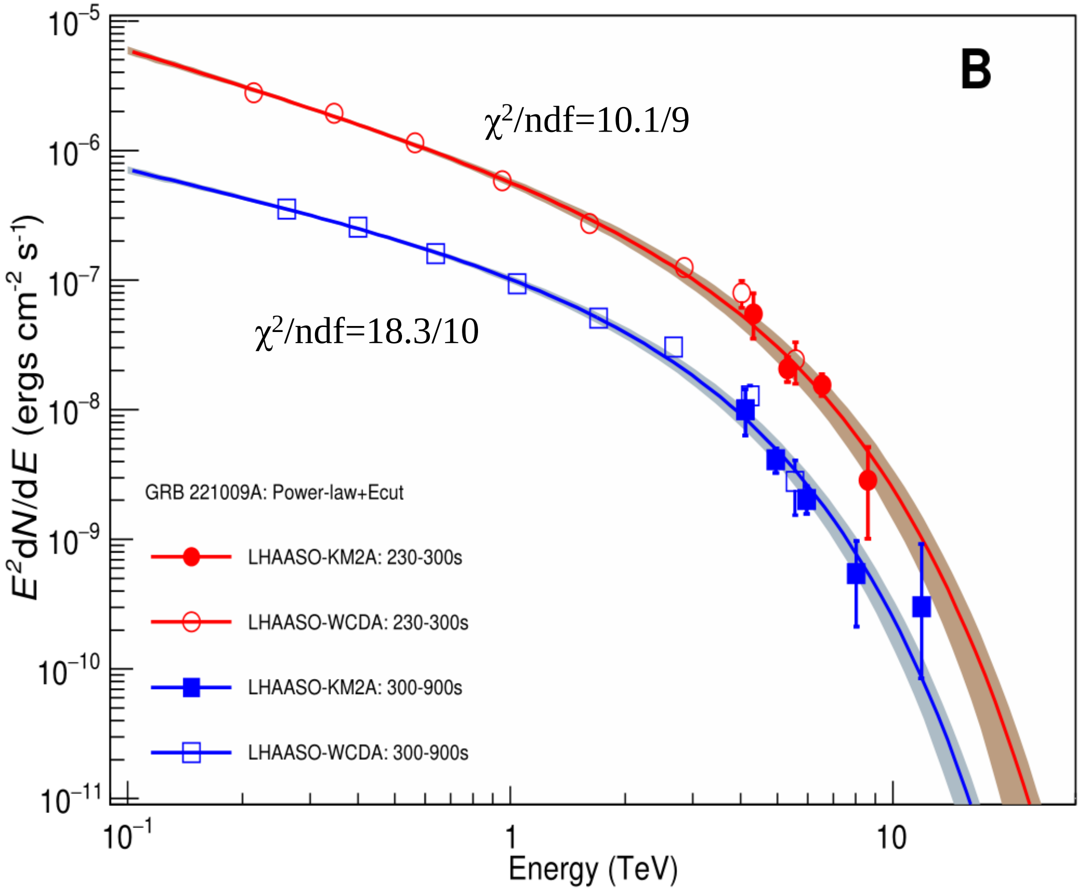
LHAASO coll. Science Advances,9: eadj2778 (2023)

WCDA+KM2A SED (observed)

SED function: log-parabola



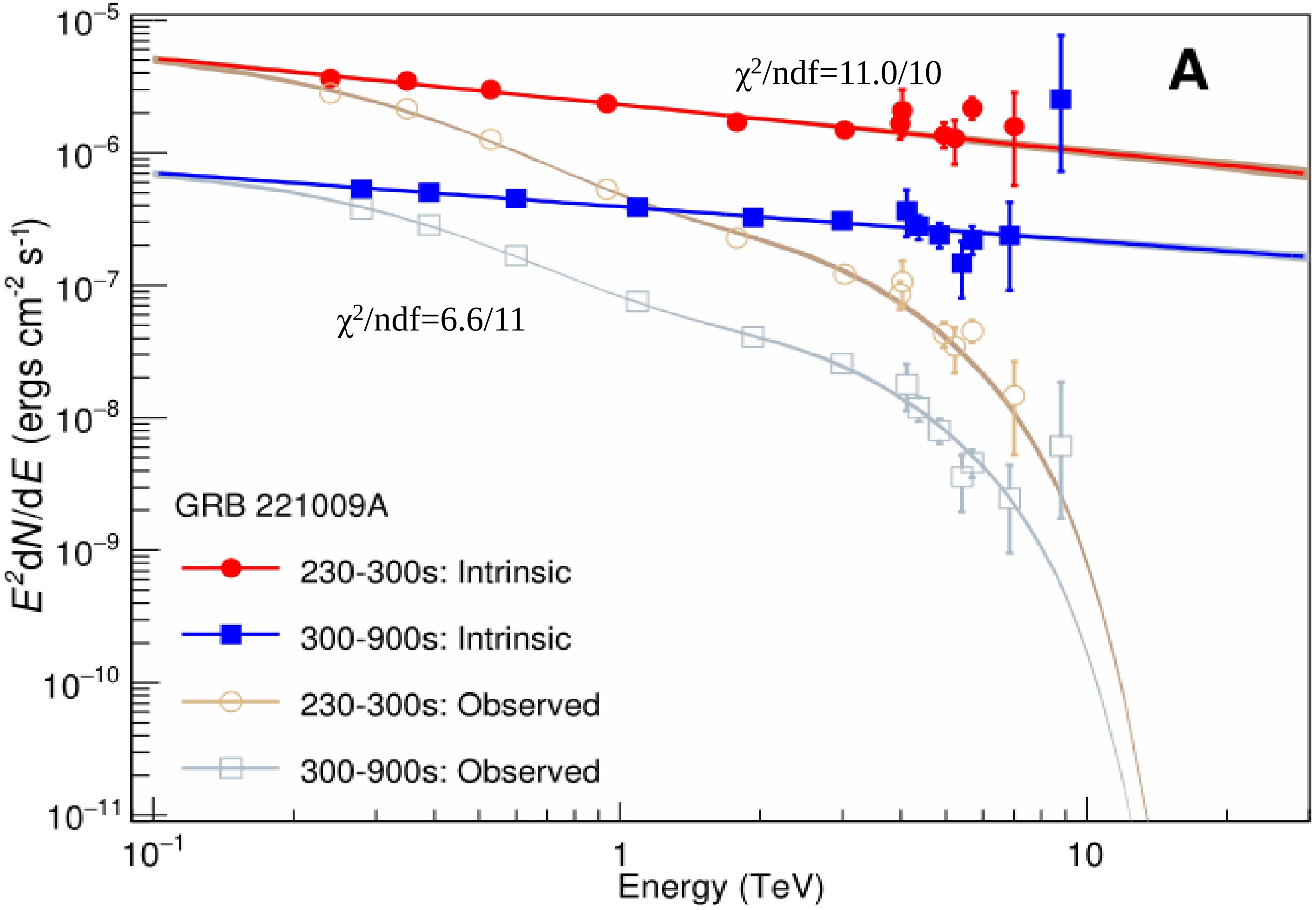
SED function: Power-law+Ecut (favored)



LHAASO coll. Science Advances,9: eadj2778 (2023)

WCDA+KM2A SED (EBL corrected)

EBL model：
Saldana-Lopez et al.2021



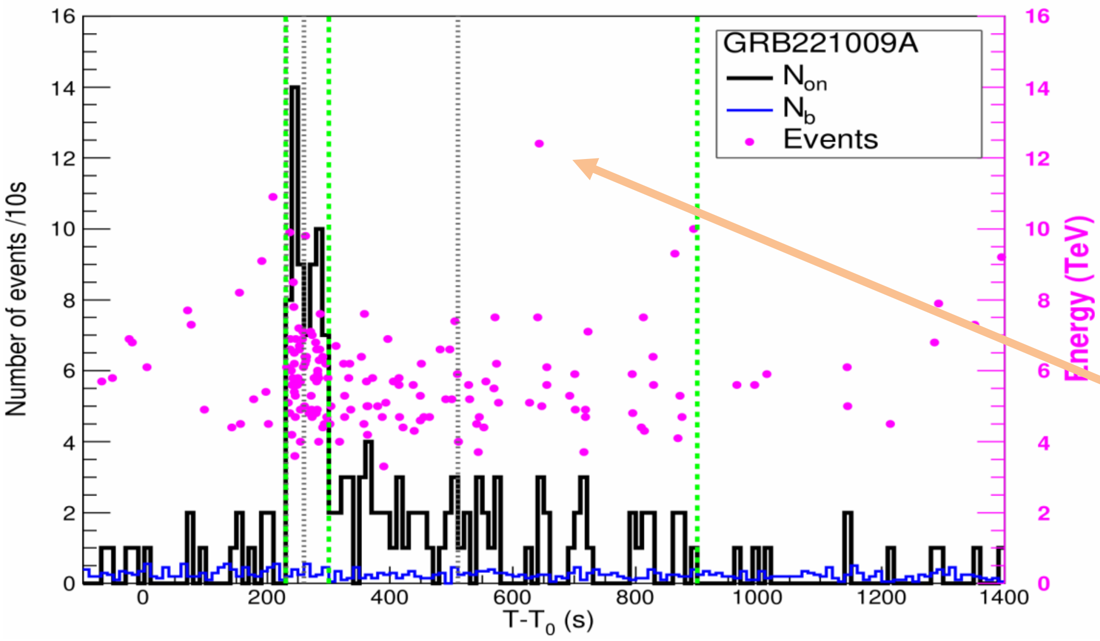
LHAASO coll. Science Advances,9: eadj2778 (2023)

The high energy photons

- **Bayes theorem used for energy estimation**
- **E_{max}:**
  - **17.8TeV for LP SED model**
  - **12.2TeV for PLEC model**
  - **12.5TeV for LP+EBL model**

$$P(E|(E_{rec},\theta)) = \frac{f(E)A_{eff}(E,\theta)P(E_{rec}|(E,\theta))}{\int f(E)A_{eff}(E,\theta)P(E_{rec}|(E,\theta))dE}$$

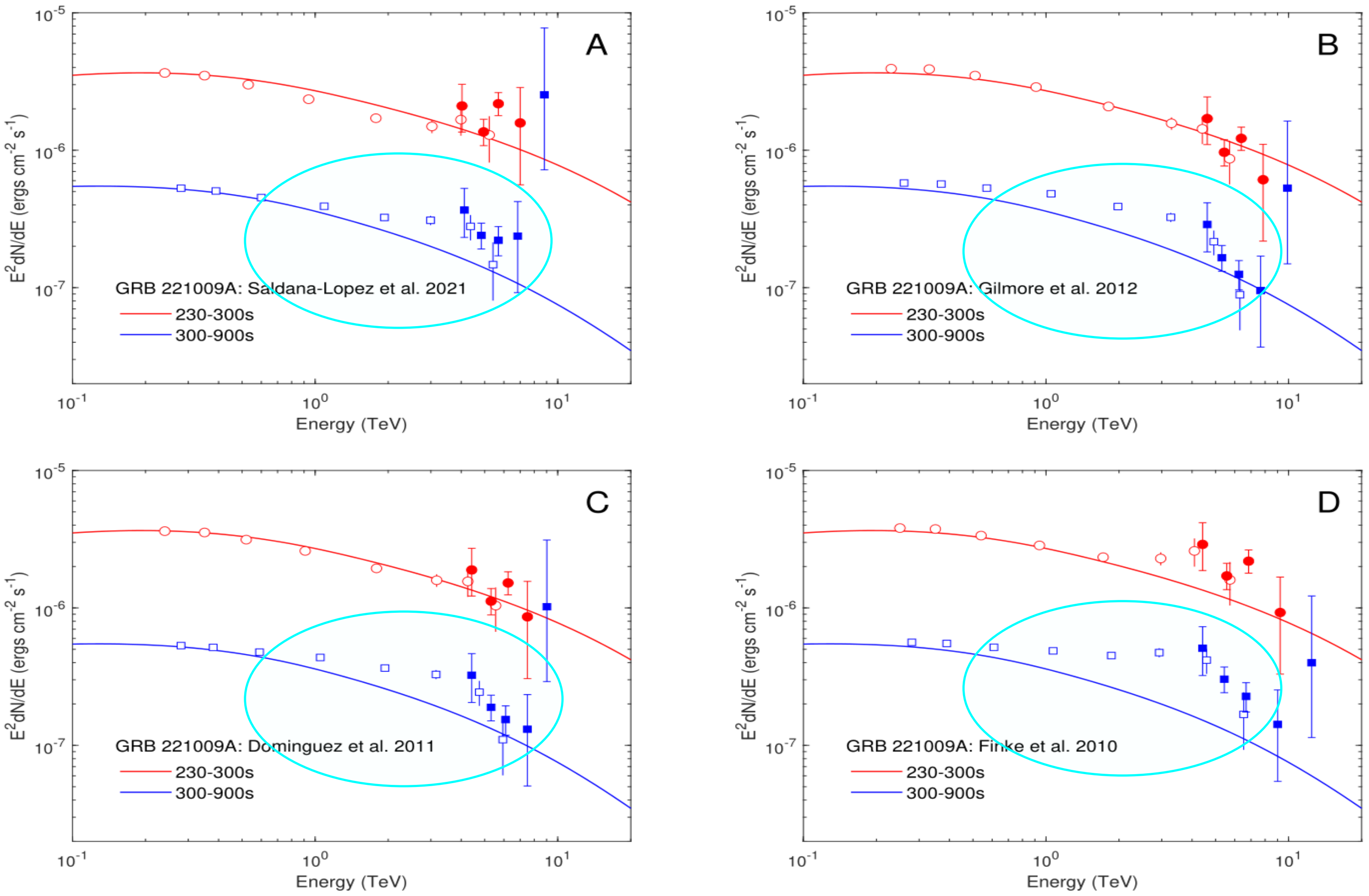
$$\xi = \int_0^{E_\xi} P(E|(E_{rec},\theta))dE$$



T_{event}(s)	E_{LP} (TeV)	E_{PLEC} (TeV)	E_{EBL} (TeV)	N_e	N_μ	θ (°)	$\Delta\psi$ (°)	D_{edge} (m)	P (%)
236.6	$12.7^{+6.2}_{-3.8}$	$9.7^{+3.3}_{-2.1}$	$9.8^{+3.1}_{-2.3}$	60.6	0	28.5	0.46	77	7.0
242.5	$10.5^{+5.0}_{-3.2}$	$8.3^{+3.0}_{-2.1}$	$8.4^{+3.2}_{-2.2}$	57.4	0	28.8	0.45	111	10
262.4	$12.6^{+5.5}_{-3.8}$	$9.5^{+3.4}_{-2.3}$	$9.6^{+3.3}_{-2.4}$	57.3	0	28.6	0.53	180	5.7
358.1	$10.0^{+4.8}_{-3.2}$	$7.4^{+3.1}_{-1.8}$	$7.9^{+3.3}_{-2.2}$	46.0	0	28.7	0.54	119	6.0
571.1	$9.4^{+5.1}_{-3.0}$	$7.4^{+2.6}_{-2.5}$	$7.7^{+3.0}_{-2.5}$	45.7	0	29.5	0.52	99	7.8
643.0	$17.8^{+7.4}_{-5.1}$	$12.2^{+3.5}_{-2.4}$	$12.5^{+3.2}_{-2.4}$	81.8	0.3	29.7	0.62	181	4.5
812.4	$11.1^{+5.9}_{-4.3}$	$7.4^{+3.6}_{-2.8}$	$7.6^{+3.9}_{-3.0}$	68.0	0	30.3	0.66	112	11
863.8	$12.9^{+6.1}_{-3.9}$	$9.2^{+3.0}_{-2.8}$	$9.7^{+3.2}_{-3.1}$	100.2	0.8	30.1	1.07	81	17
894.1	$13.6^{+6.1}_{-4.2}$	$9.7^{+3.4}_{-2.5}$	$10.4^{+3.3}_{-3.0}$	60.5	0	31.8	0.83	214	16

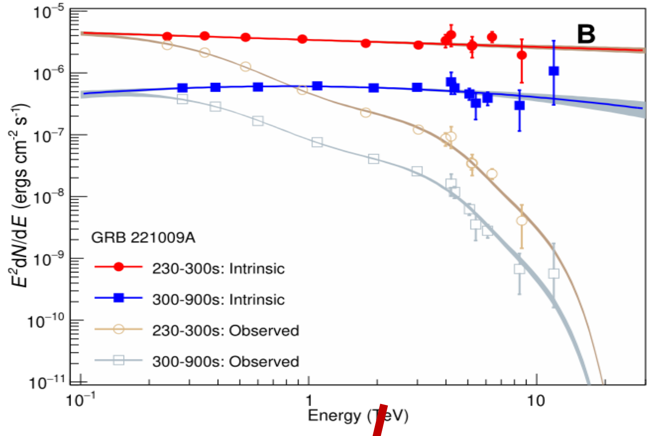
Challenge to GRB afterglow model

- More complicated processes during the early afterglow phase?
- An additional hard spectral component emerges at the highest energy end?

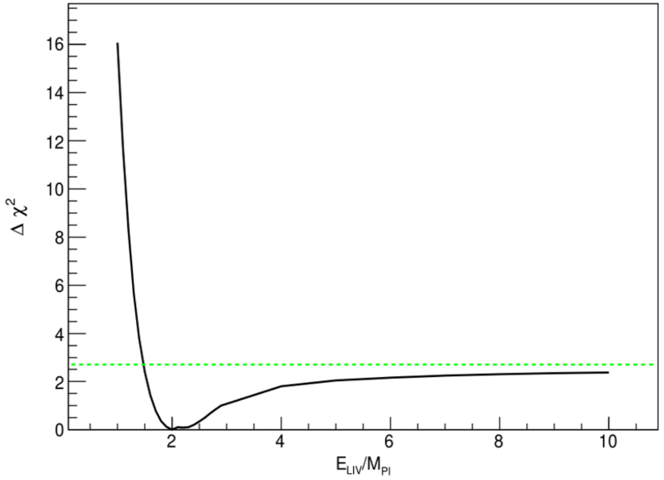


LHAASO coll. Science Advances,9: eadj2778 (2023)

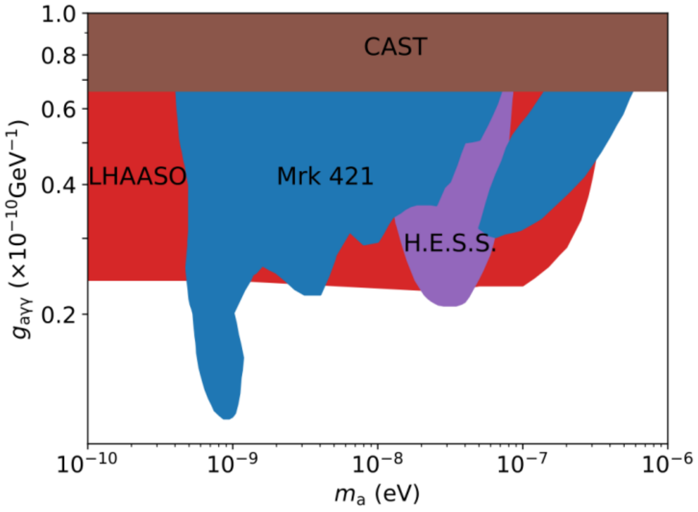
Constraints on related physics



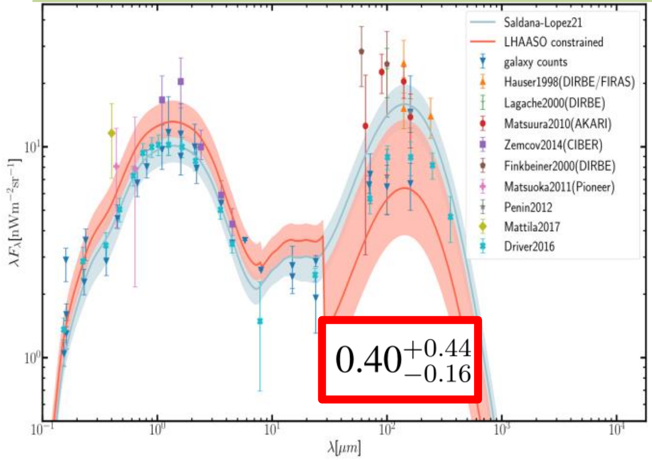
Constraints on LIV
E_{LIV} >1.5 M_{Pl}



Constraints on the axion-γ-ray coupling



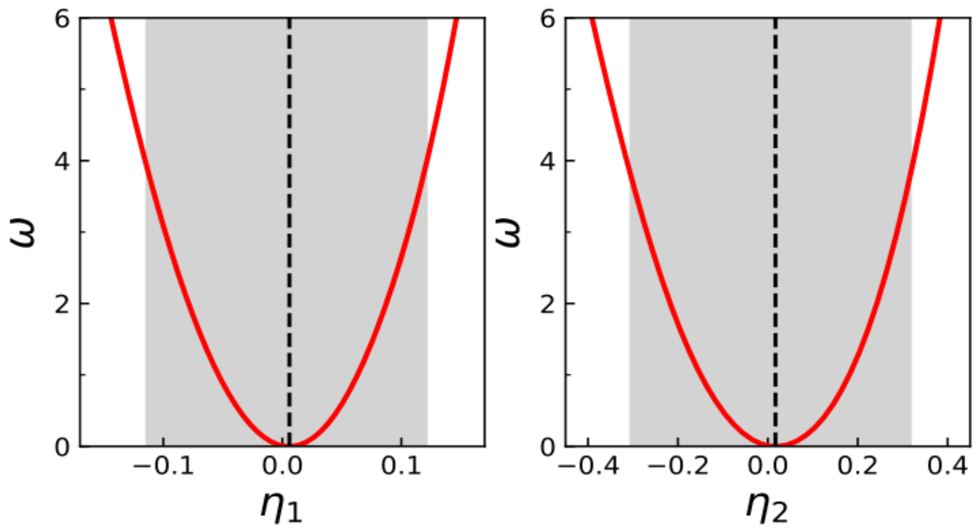
Constraints on EBL distribution

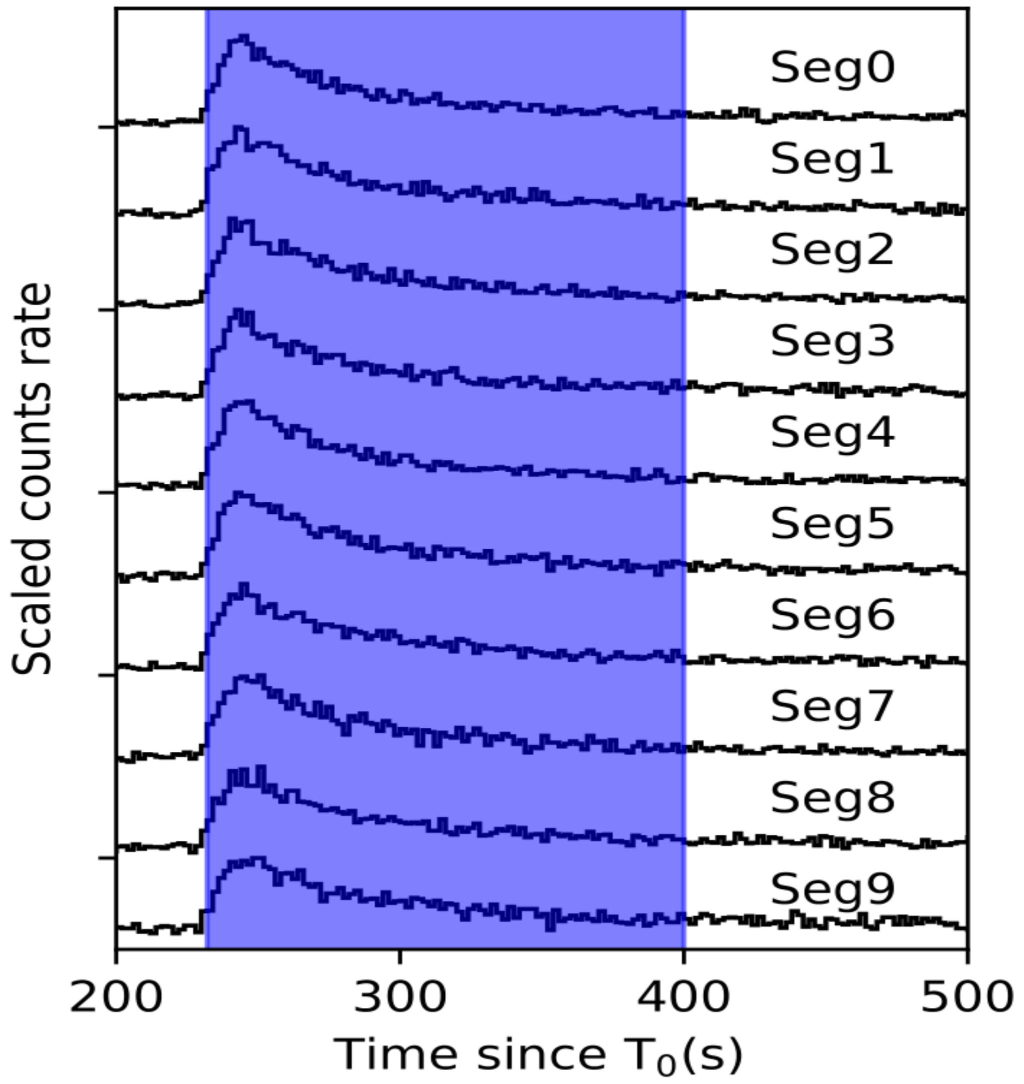


LHAASO coll. Science Advances,9: eadj2778 (2023)

Constraints on LIV using time lag

- **For both the subluminal and superluminal cases**
- $$\Delta t_{\rm LIV} = s\frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{{\rm QG},n}^n}\int_0^z \frac{(1+z')^n}{H(z')}dz'$$
- $E_{\rm QG,1} > 10\, E_{\rm Pl}$ $\quad E_{\rm QG,2} > 6\times 10^{-8} E_{\rm Pl}$



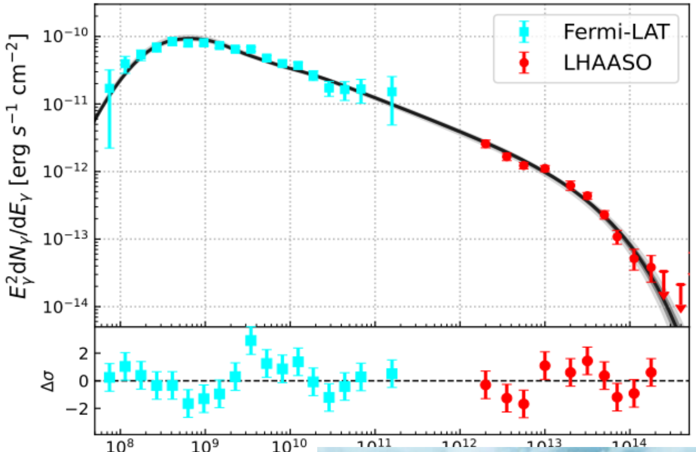


LHAASO coll. PRL 133, 071501(2024)

Summary

- LHAASO, fully operated since July 2021, open-up a new era with many new discoveries about **Massive star, SNR, PWN, AGN, GRB and so on.**
- **There still much more new interesting phenomena ahead!**
- **LHAASO is also very lucky to overlap with the Fermi-LAT era, since GeV-TeV-PeV joint measurement are crucial for many physics.**

Fermi-LAT
0.1GeV-300GeV
(2008-now)



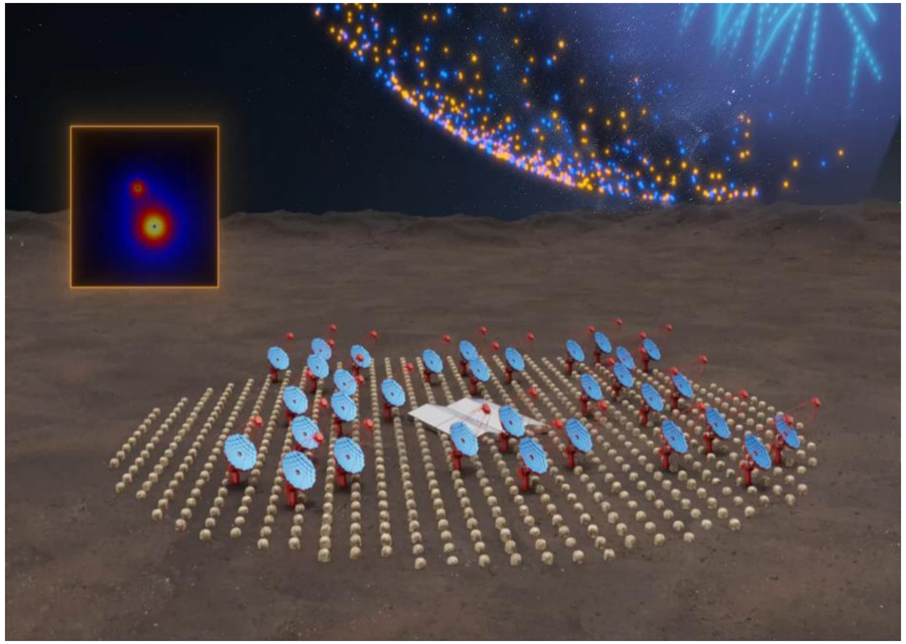
LHAASO
0.3TeV-10000TeV
(2019-2021-now)

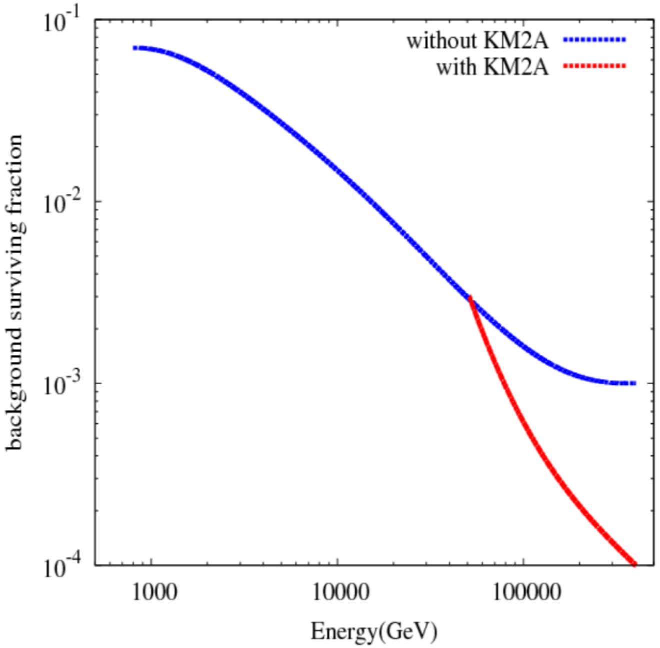
Outlook: LHAASO upgrade plan LACT

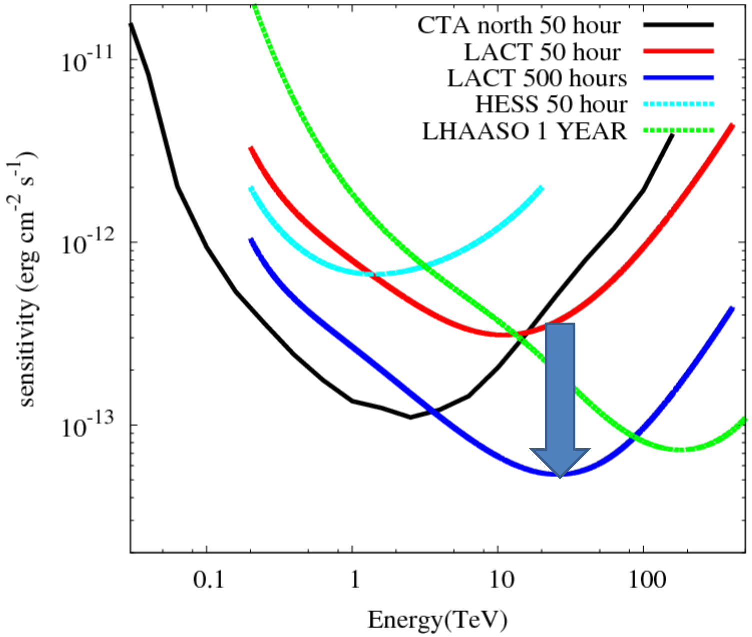
- **LACT improve the angular resolution <0.05°**
- **LACT + KM2A muon detectors**

  → **Better gamma-ray selection**
- **Construction: 2024.10 – 2028.9**

A prototype in LHAASO



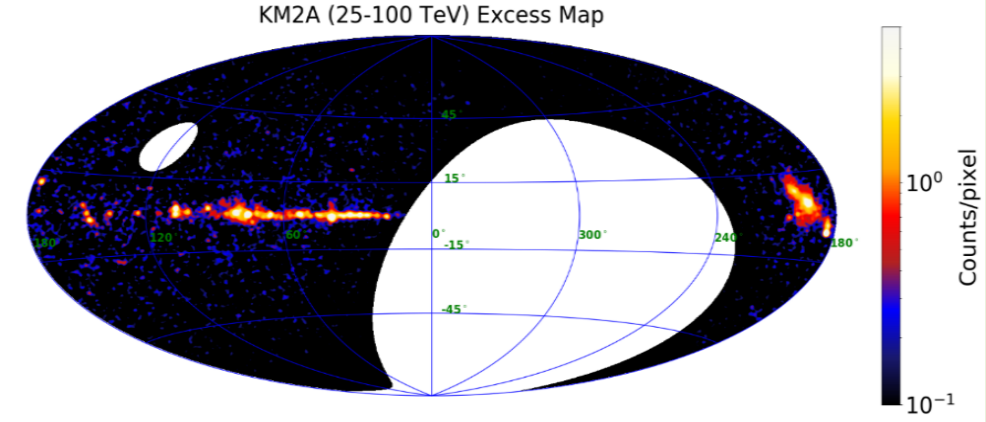


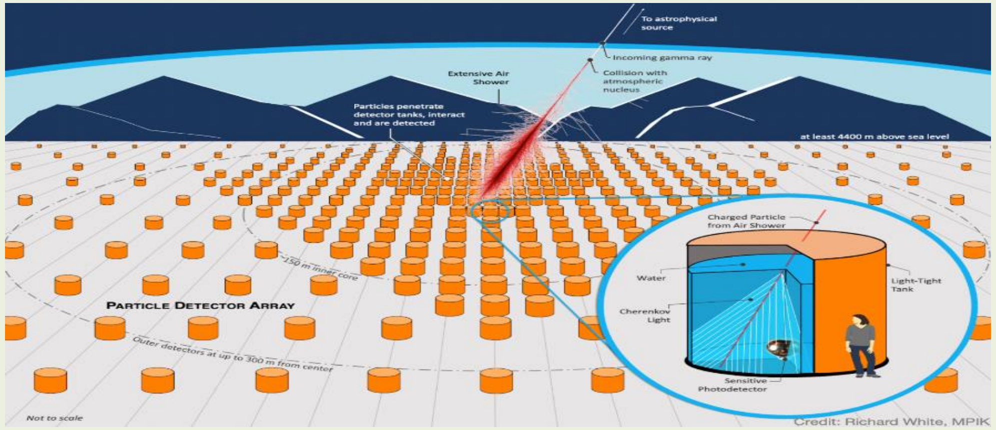


Outlook：Future plans

SWGO

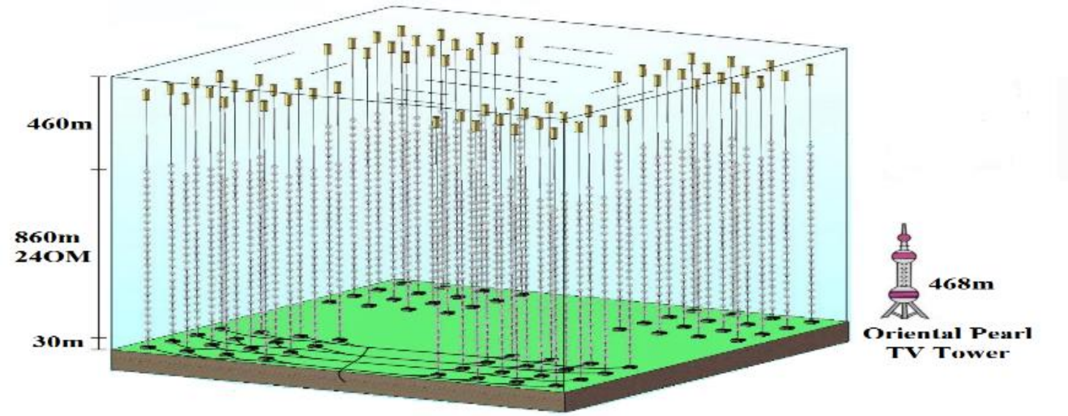
(Southern Wide-field Gamma-ray Observatory)





HUNT

(High-energy Underwater Neutrino Telescope)



More LHAASO results can be found from:
http://english.ihep.cas.cn/lhaaso/

Thank you!