LHAASO observation of very high energy gamma-ray emission beyond 10 TeV from GRB 221009A

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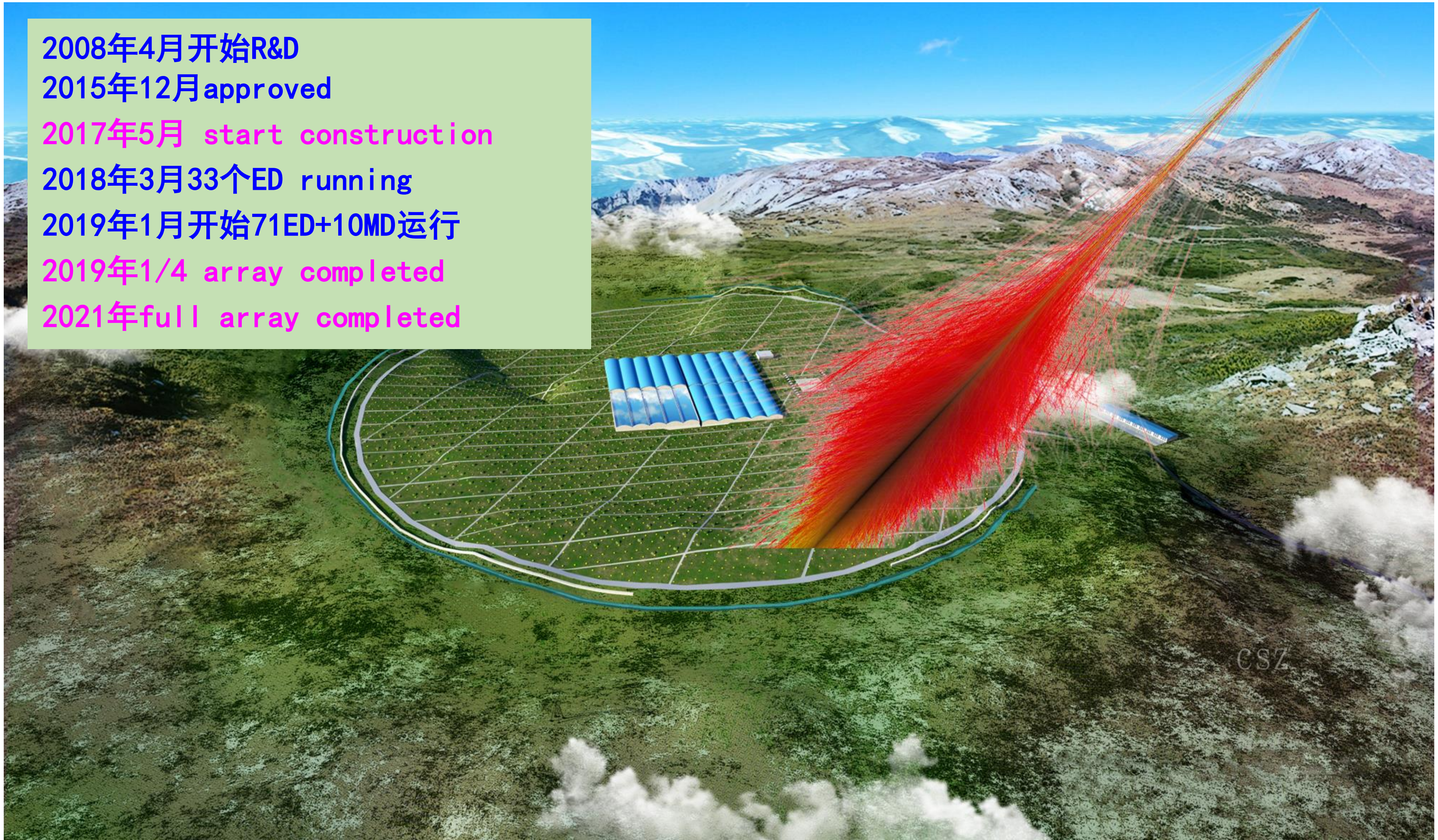
Outline

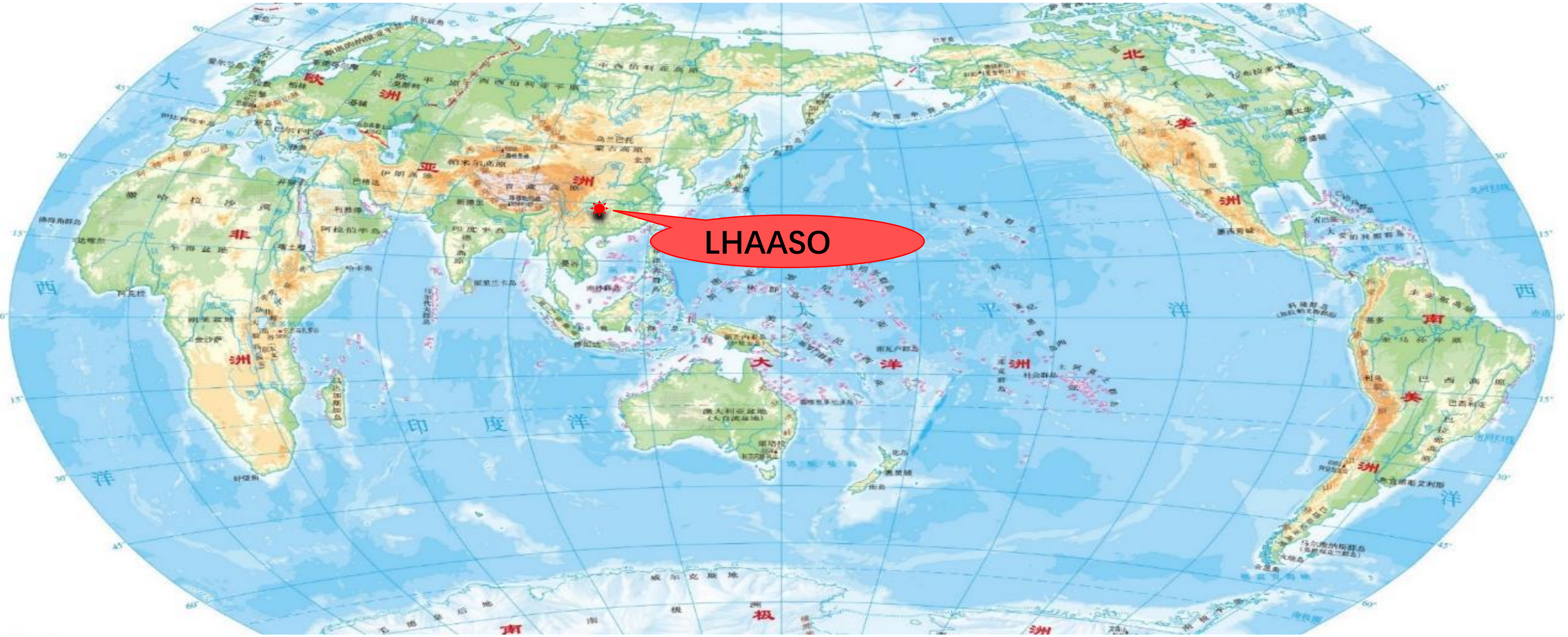
- Brief introduction of LHAASO
- LHAASO observation of GRB 221009A
- Implications of the observation
- Summary

LHAASO: Large High Altitude Air Shower Observatory



Where is LHAASO?

- Haizi Mountain, Sichuan province, China
- Altitude 4410 m a.s.l.
- Location： 29º21’27.6” N, 100º08’19.6” E.



LHAASO aerial image， 2021/12
Area： 1.3km^2
BJ
DC
CD

LHAASO detectors

KM2A

The best UHE gamma-ray detector

4 TeV-20 TeV-10 PeV

WCDA

The best VHE gamma-ray survey detector

0.1 TeV-20 TeV

WFCTA+KM2A+WCDA

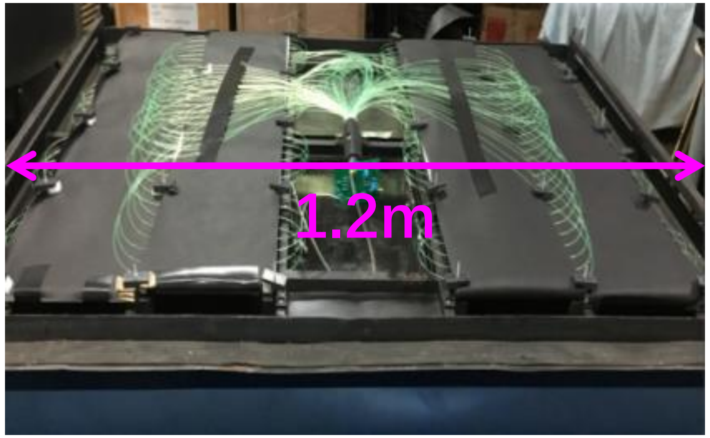
The best cosmic ray detector

10 TeV-100 PeV

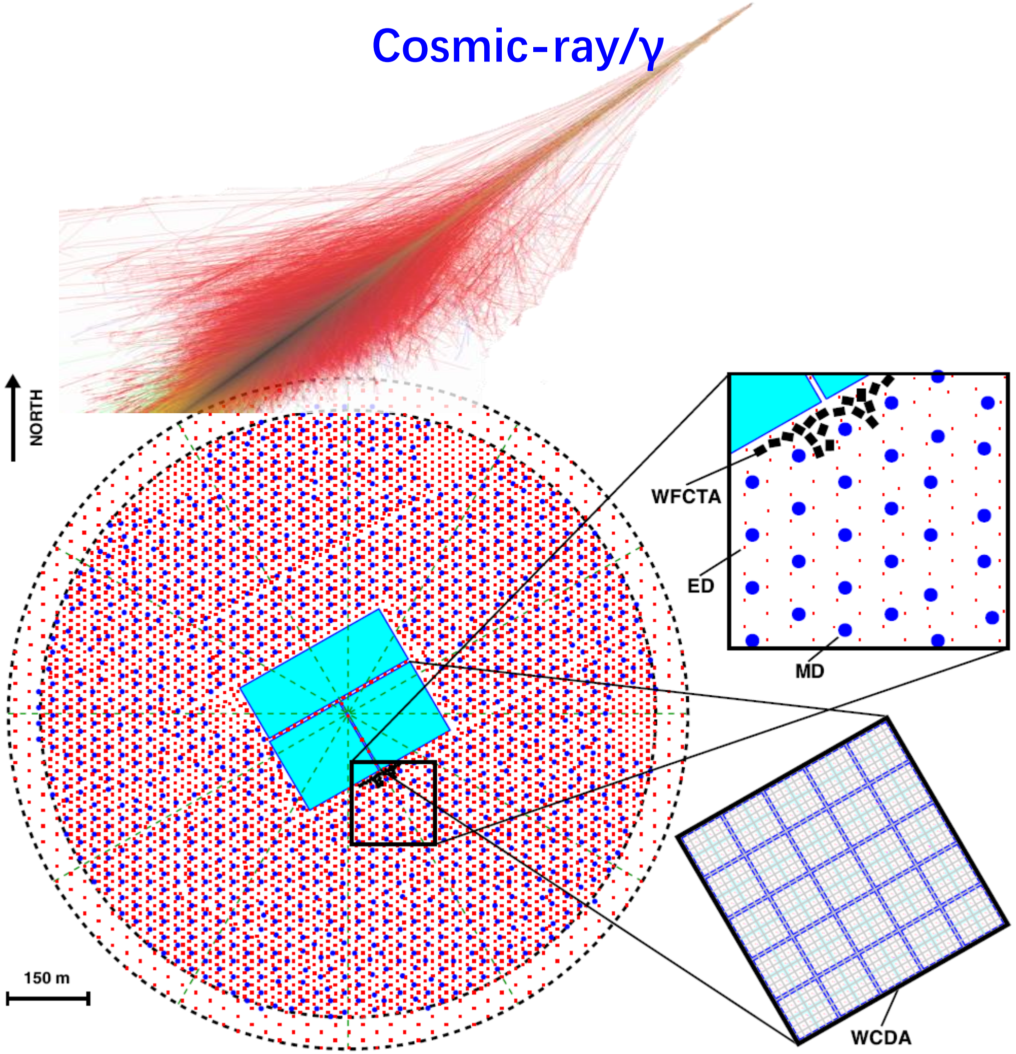
LHAASO detectors

KM2A

MD: 1188x36m^2



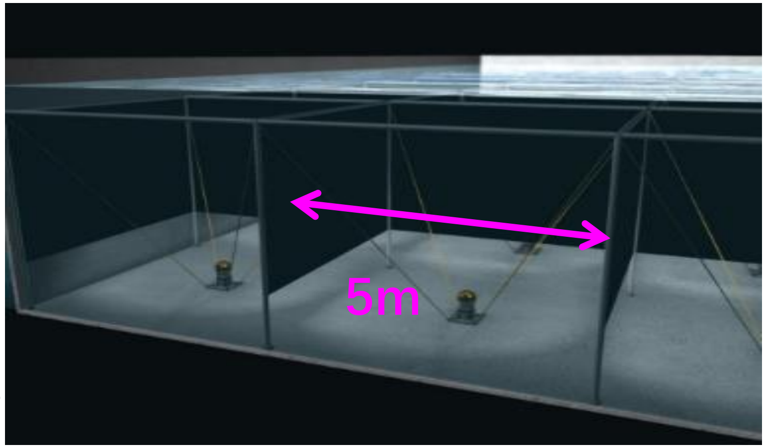
ED: 5216x1m^2



1.3 km^2

WFCTA

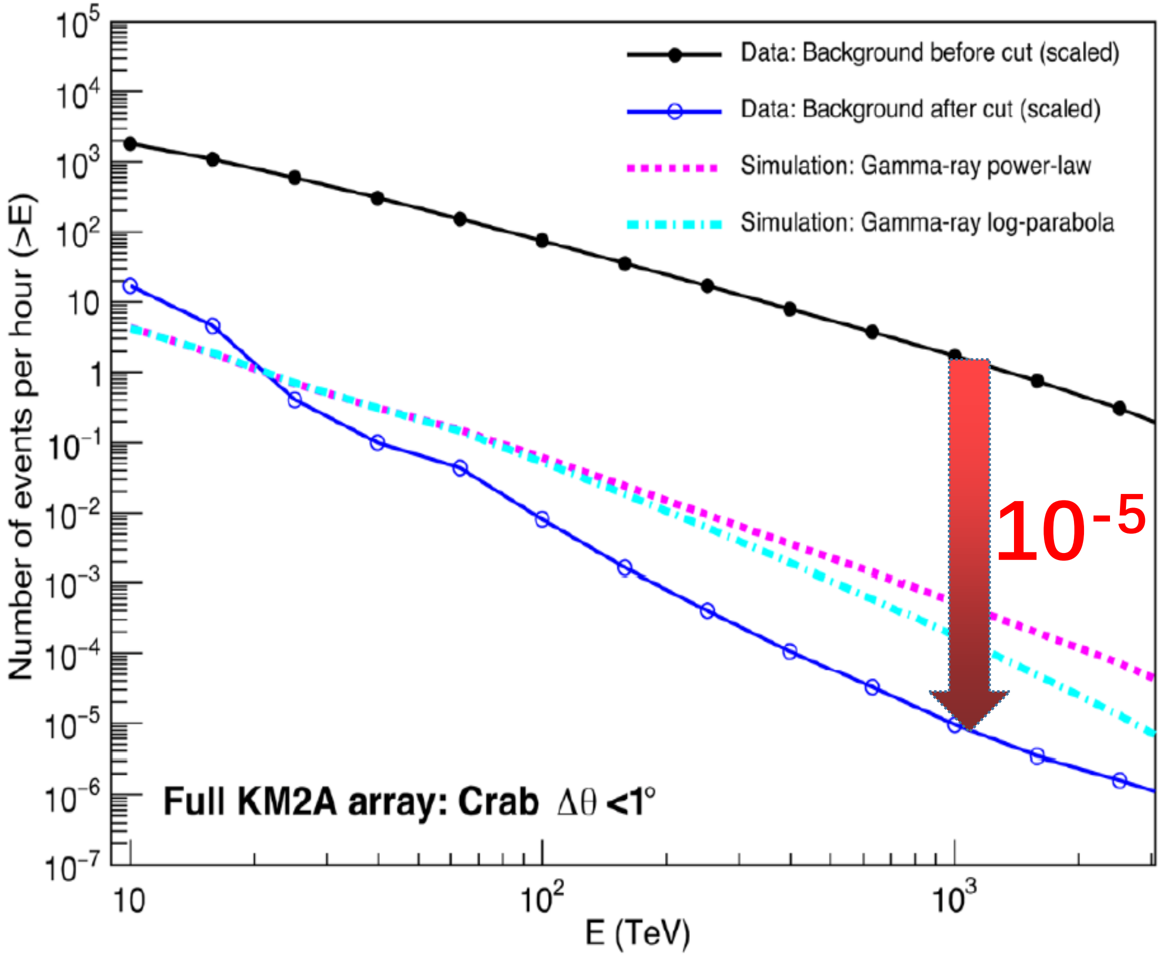
18x4.7m^2



WCDA

3120x25m^2

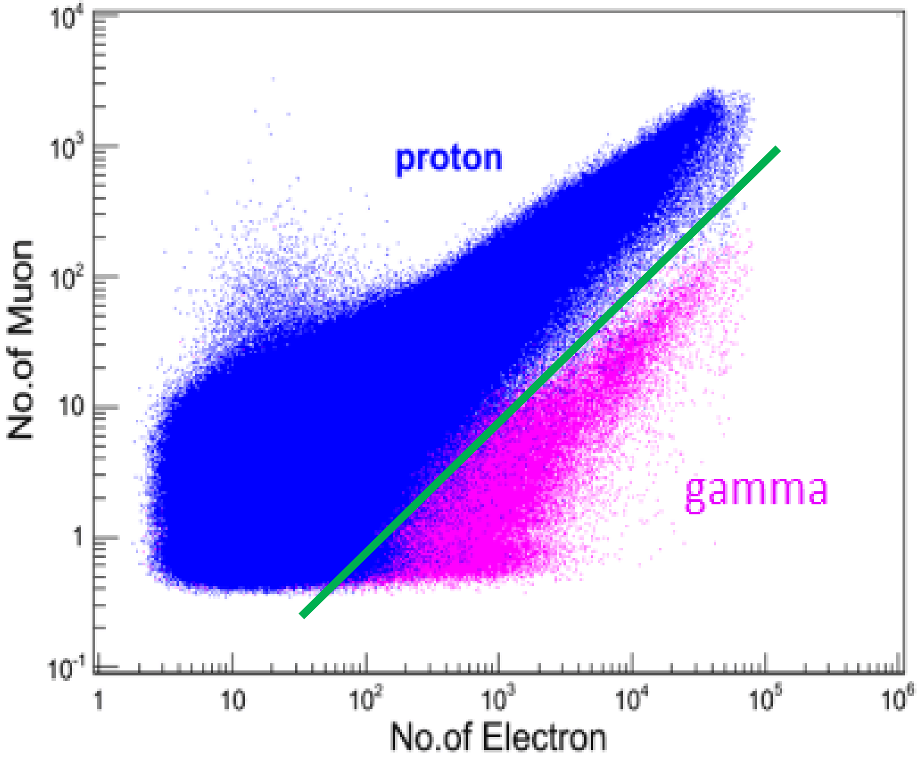
Gamma-ray/cosmic ray discrimination



Before cut: CR rate

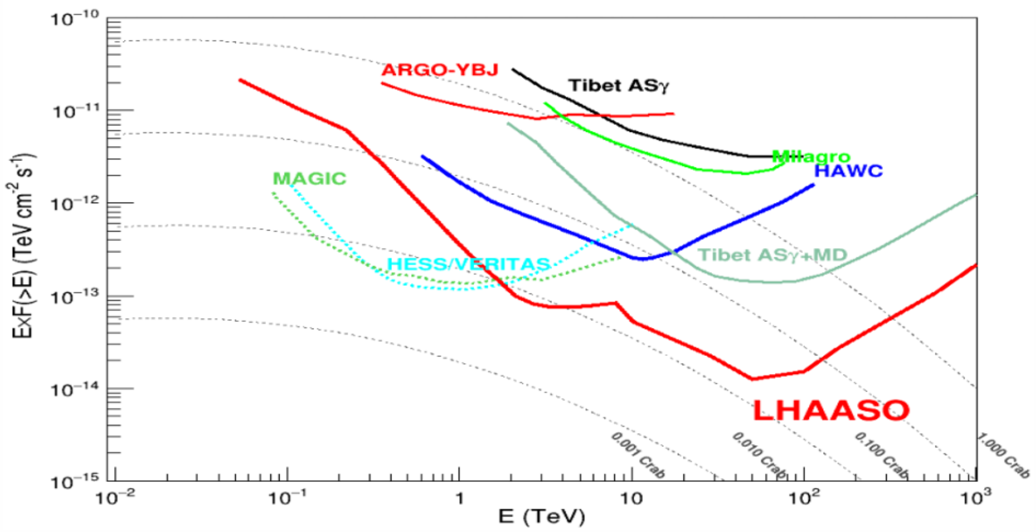
Gamma-ray rate

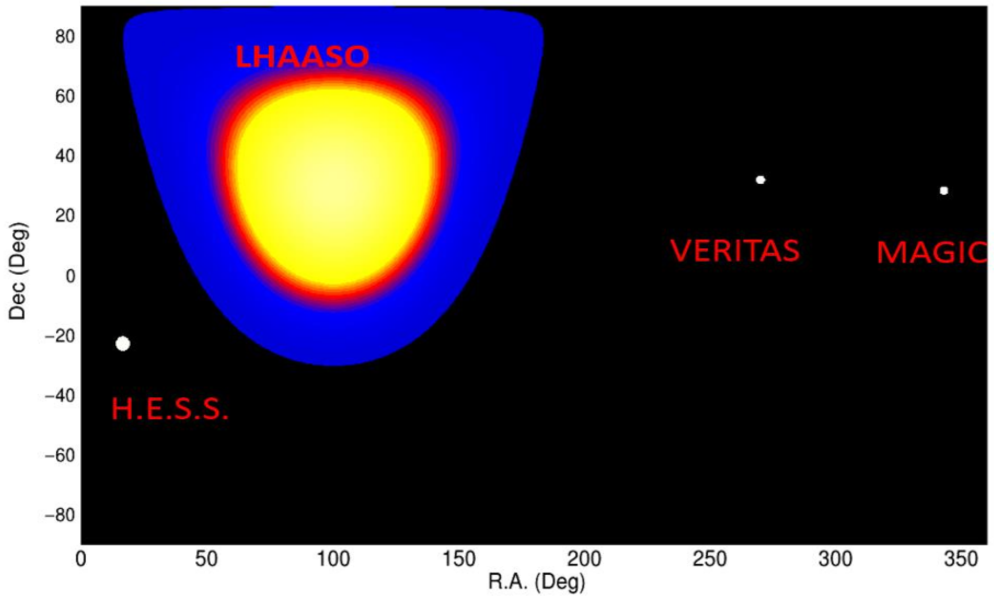
After cut: CR rate

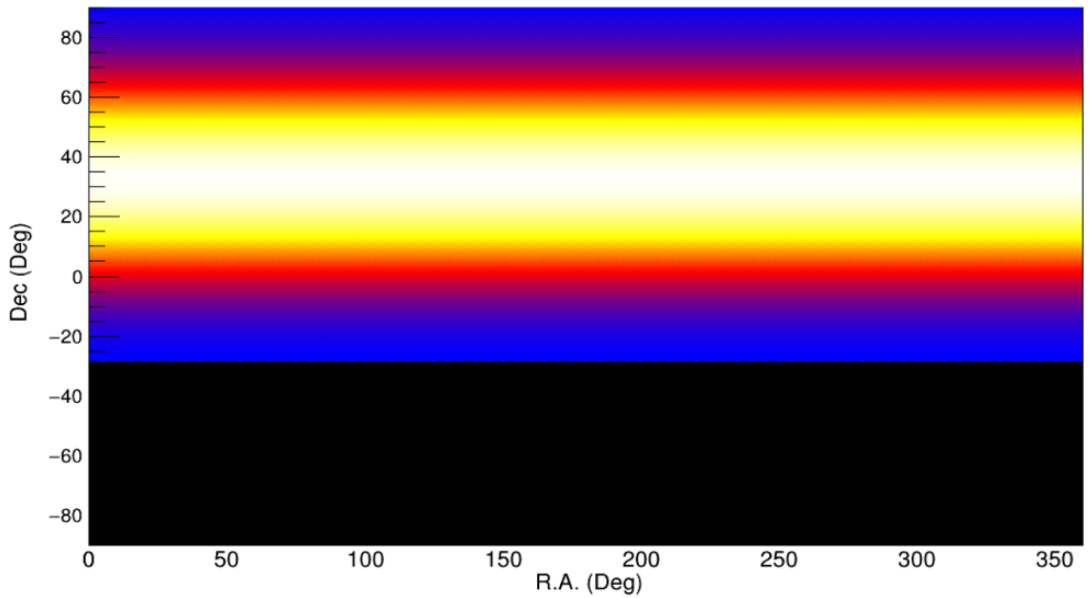


LHAASO for gamma-ray astronomy

- **Features : Large FOV, Full duty cycle, Wide energy, High sensitivity**
- **Important for: sky survey, extended sources, transient sources**







LHAASO important results

2021.02
CPC paper
First paper

2021.05
Nature paper
12 UHE sources
&1.4 PeV photon

2021.06-10
PRL & ApJL
paper
New sources

2021.07
Science paper
PWN Crab

2021

2022.02
PRL paper
LIV limits

2022.12
PRL paper
Decay time of
dark matter

2022

2023.06
Science paper
GRB 221009A

2023.10
PRL paper
Diffuse gamma-
ray

2023.11
Science Adv.
GRB 10 TeV

2023

2024.02
Science Bull.
Super CR sources

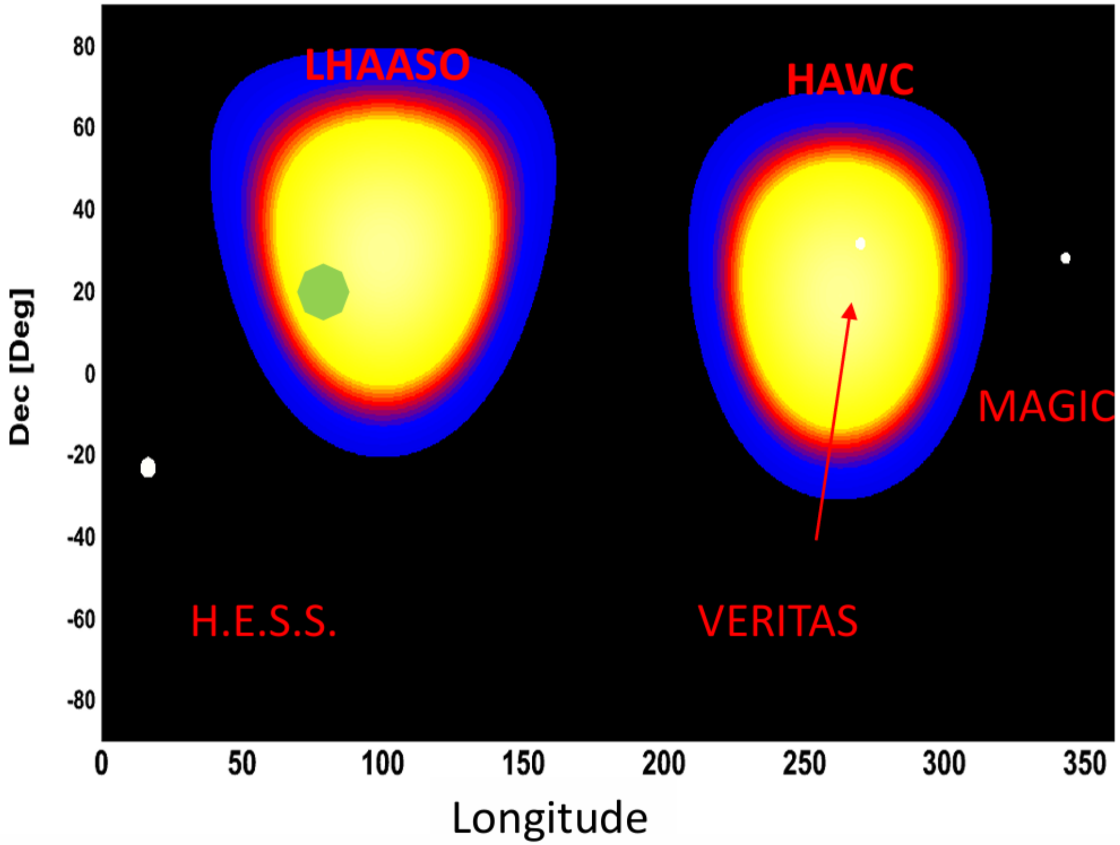
2024.02
ApJS paper
First gamma-
ray catalog

2024.03
PRL paper
CR All particle
Spectrum

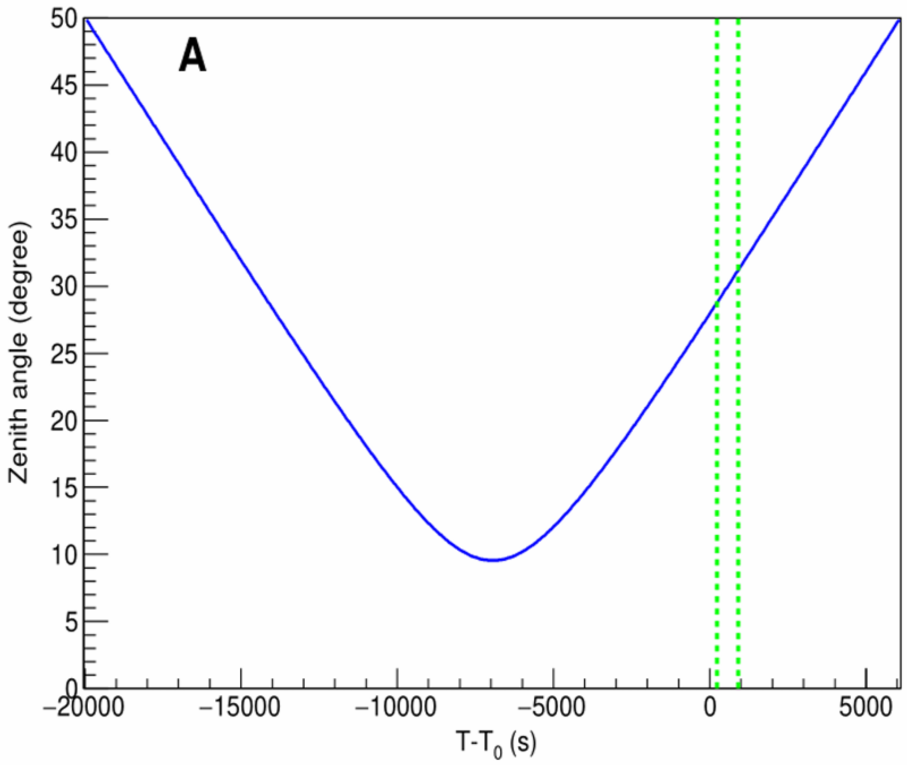
2024

GRB 221009A @FOV of LHAASO

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

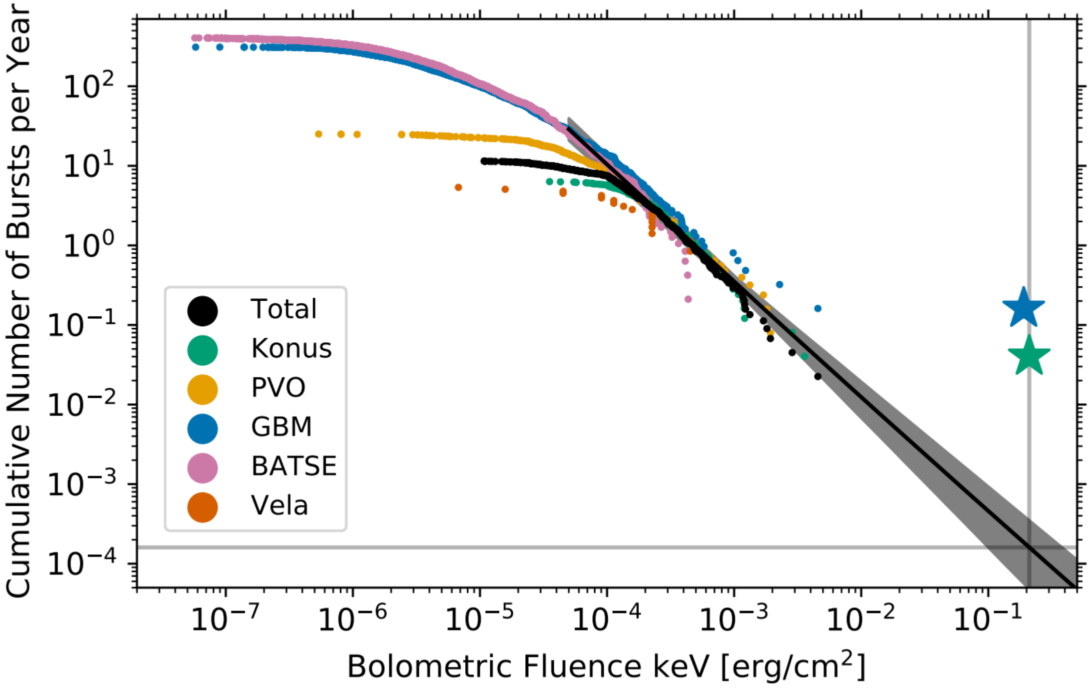


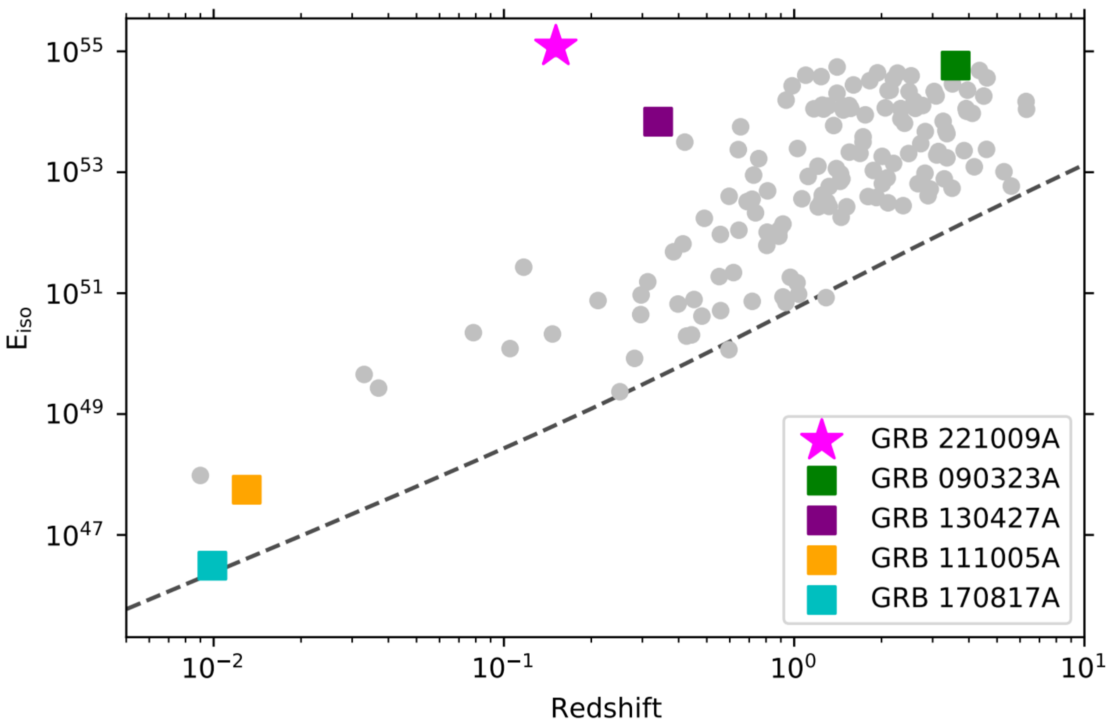
FOV



Zenith angle vs Time

GRB 221009A: A very rare event





Fluence: >5 × 10 $^{-2}$ erg/cm^2

R_GRB≤ 6.1 × 10^{-4} Gpc^{-3} yr^{-1}

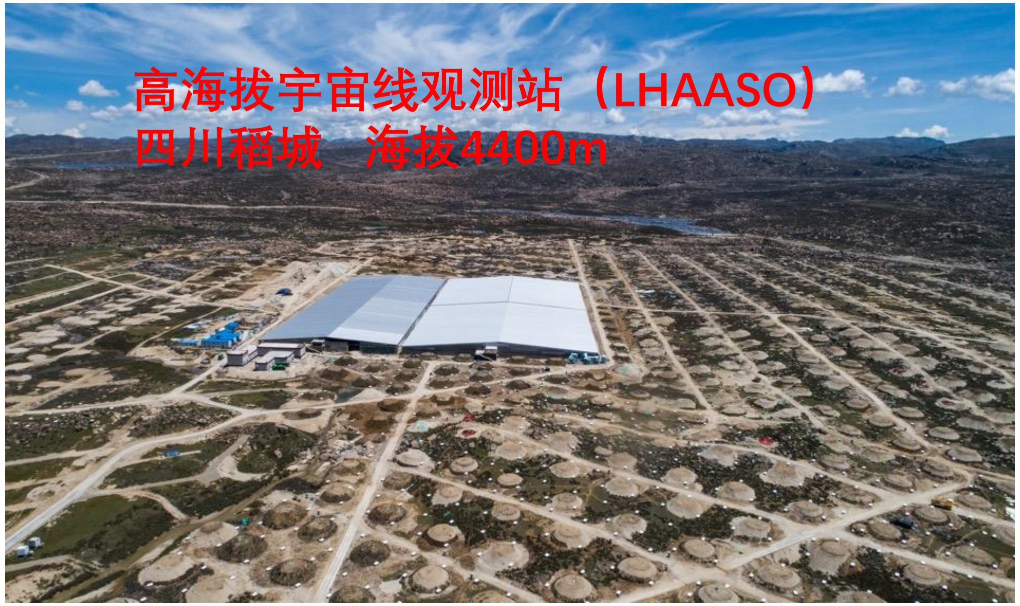
R<10^-3 yr

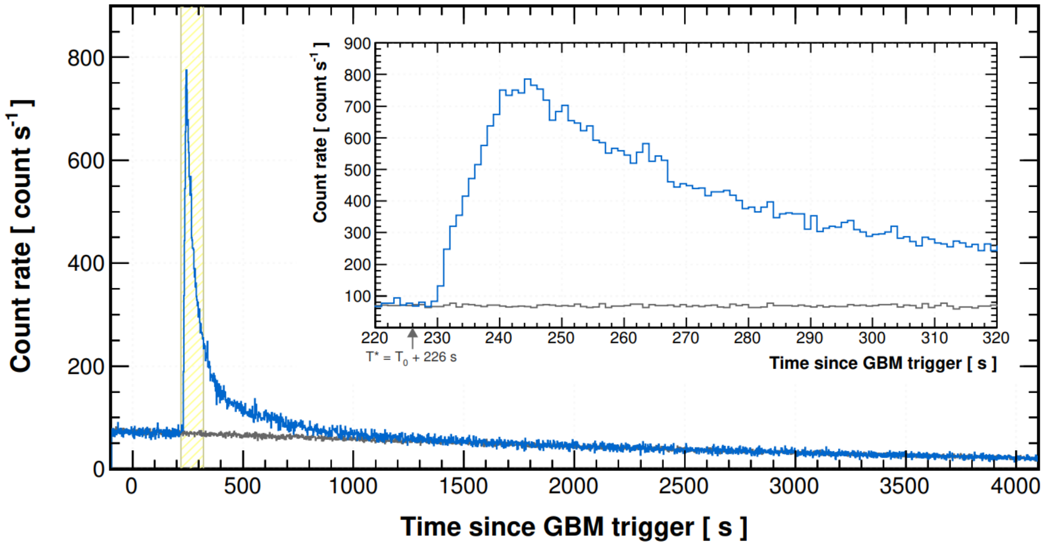
Buns et al. 2023

z=0.151 volume ~ 1 Gpc^3

GRB221009 at LHAASO-WCDA

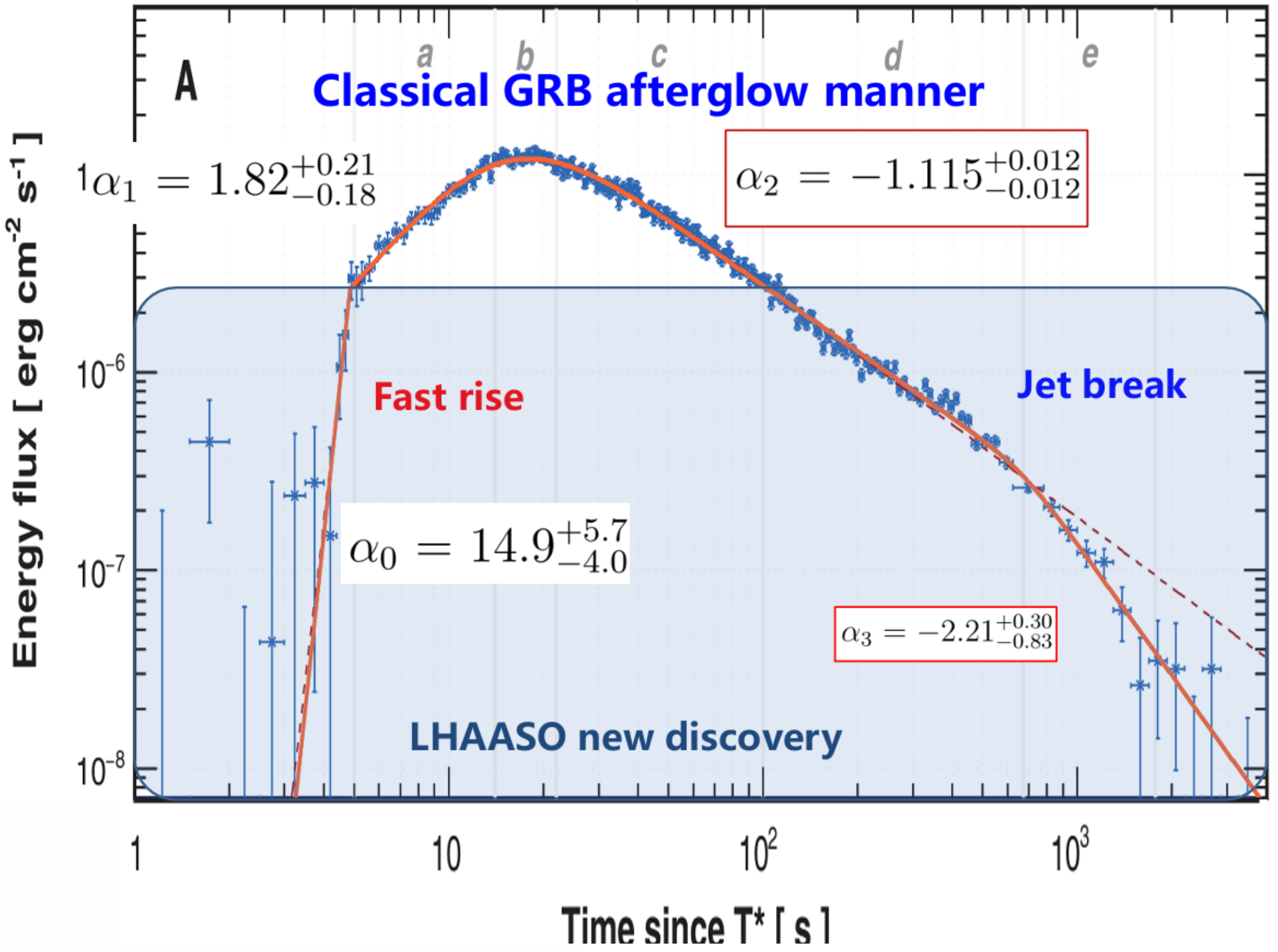
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- The whole process of onset and fade of TeV afterglow is recorded. The onset of TeV afterglow is observed for the first time.
- It is also the first time that a GRB is seen by an extensive air shower detector





4-segement Power-law

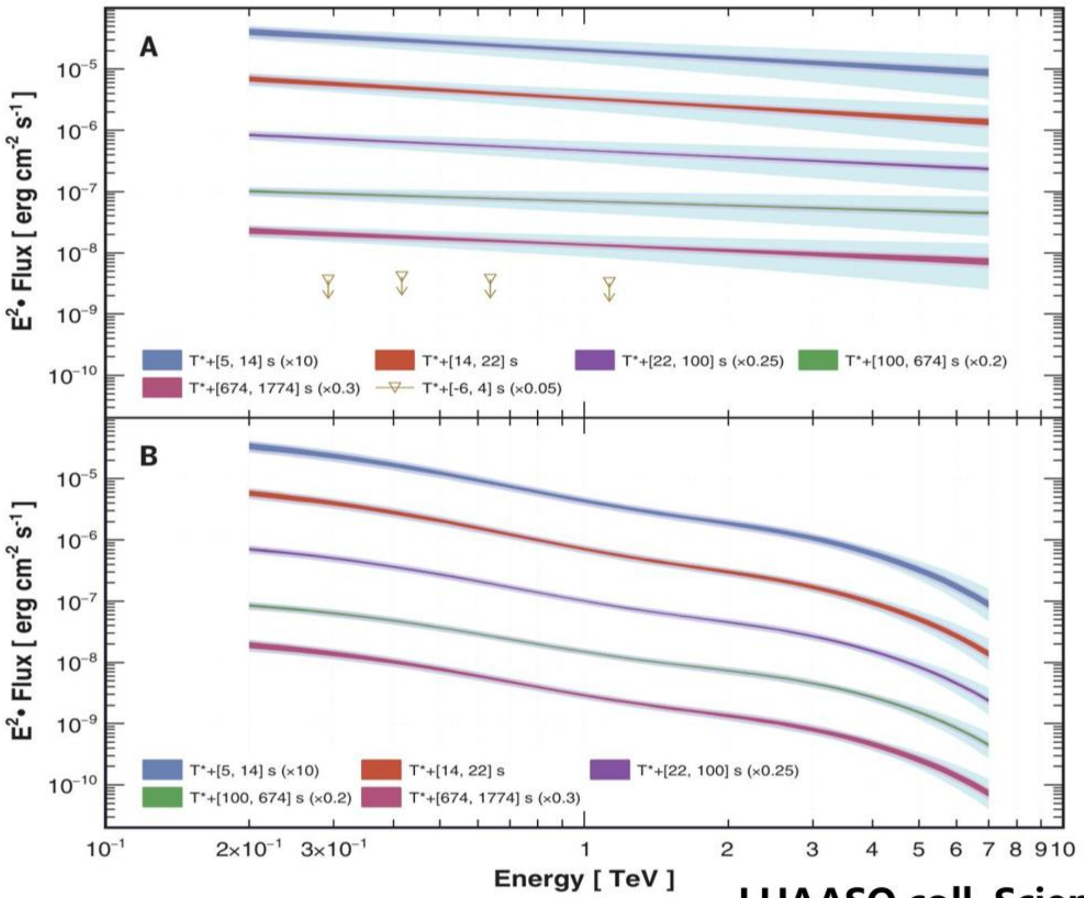
- **Unusual Fast rise:** **energy injection ?**
- **Slow rise:** Favor ISM environment?
- **Peak time:** The bulk Lorentz factor of **440.**
- **Slow decay:** Electron SED index -2.1
- **Fast decay:** A jet break at the earliest time!

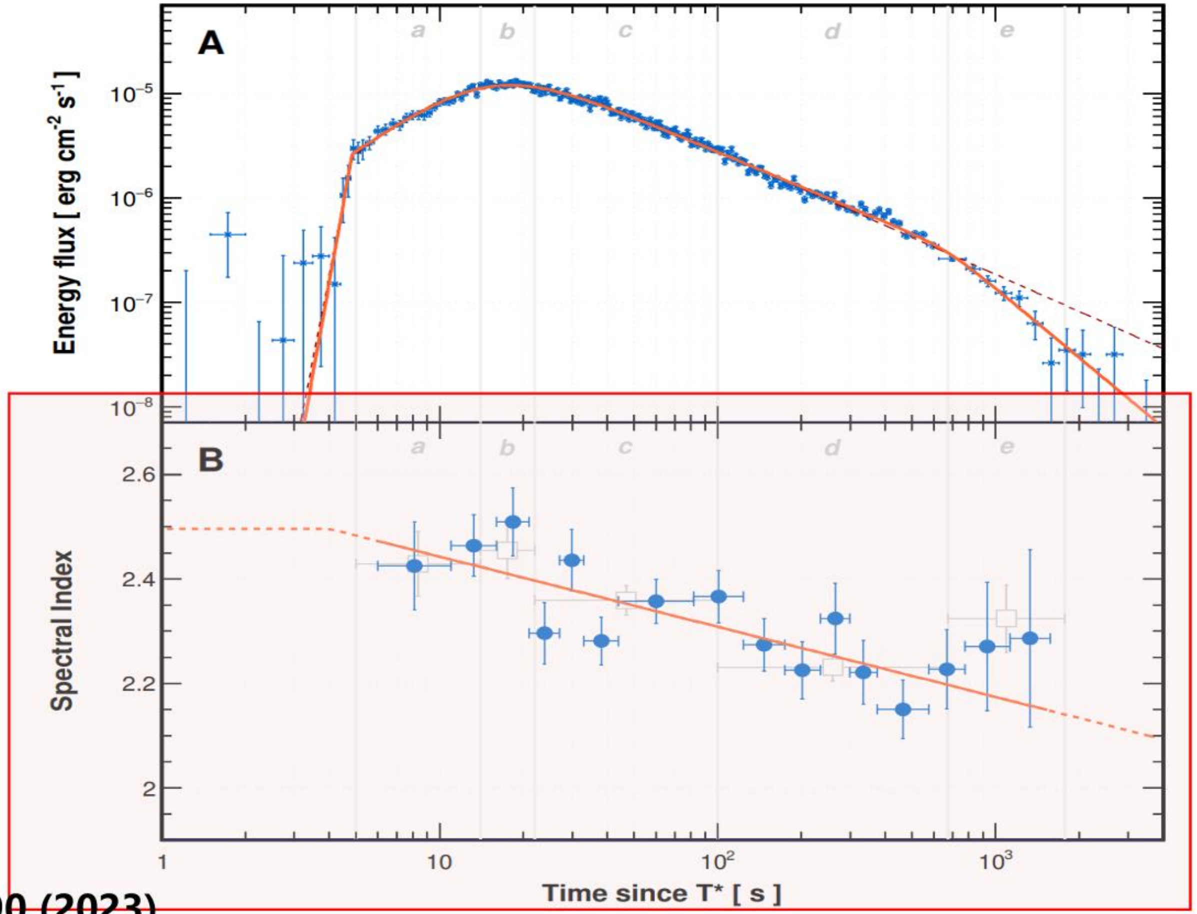


LHAASO coll. Science,380:1390 (2023)

Unexpected SED evolution

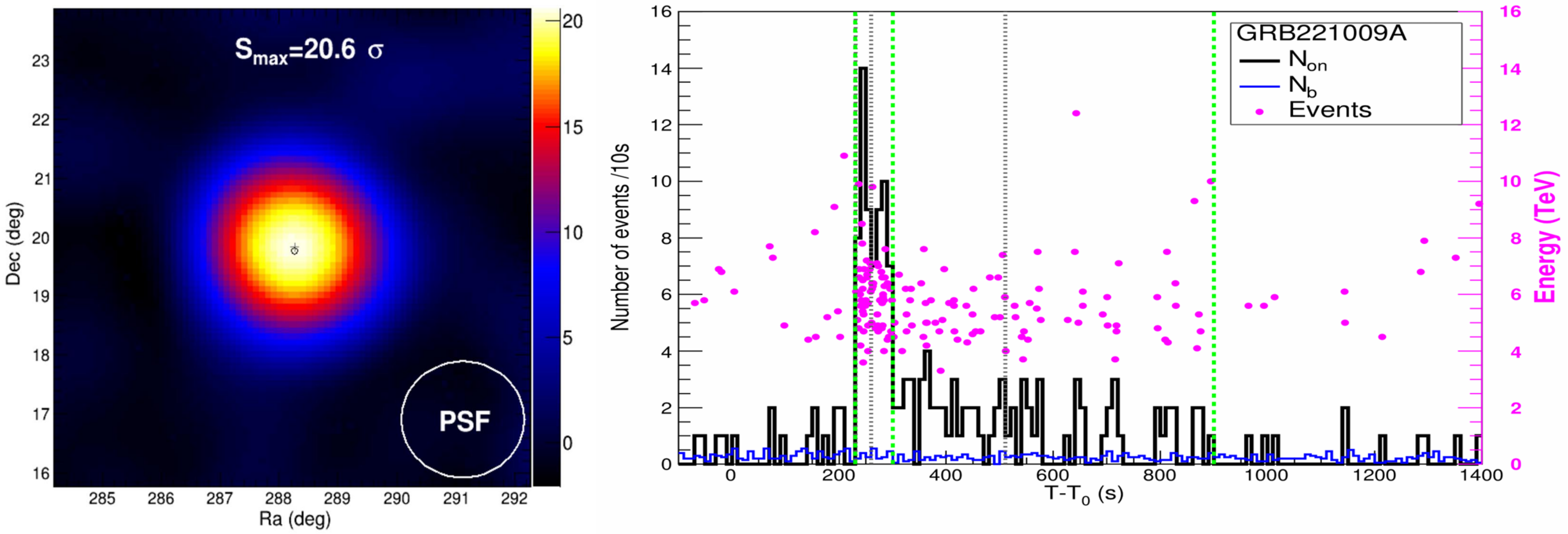
- **The SED become harder as time increasing. This is unexpected from standard afterglow model!**





LHAASO coll. Science,380:1390 (2023)

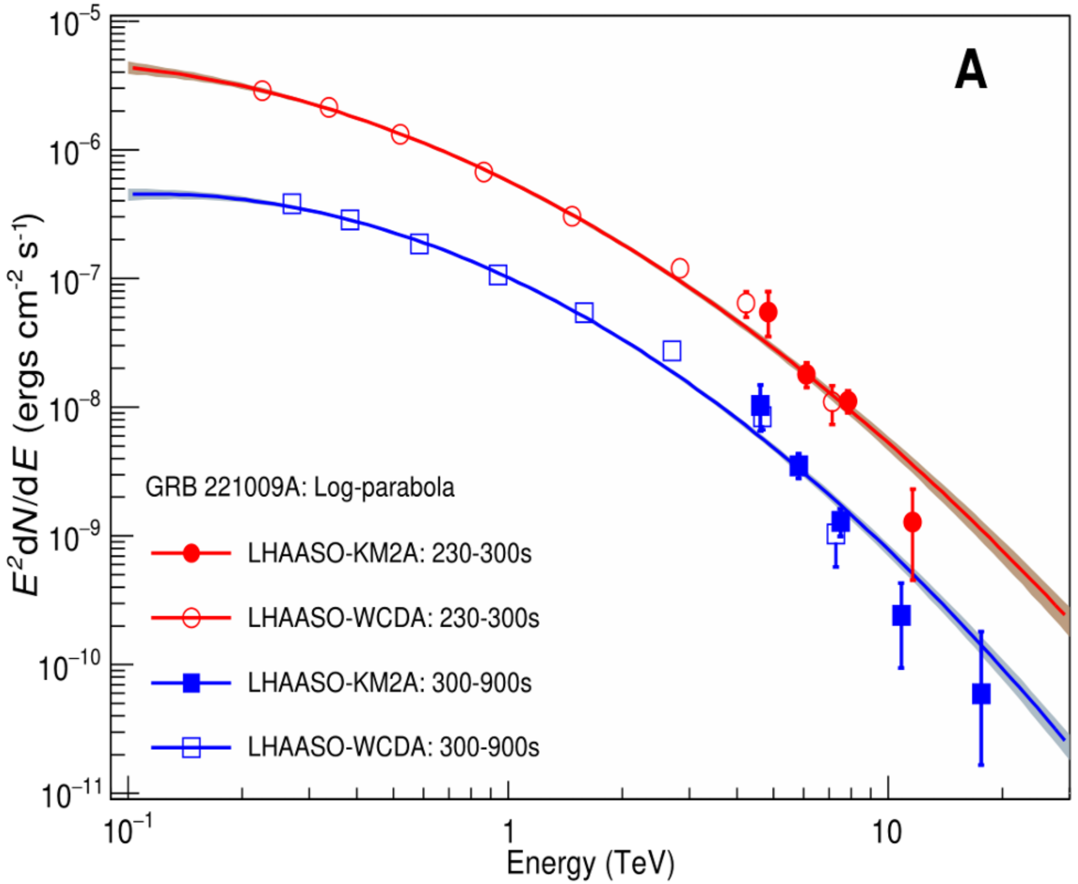
KM2A at higher energies



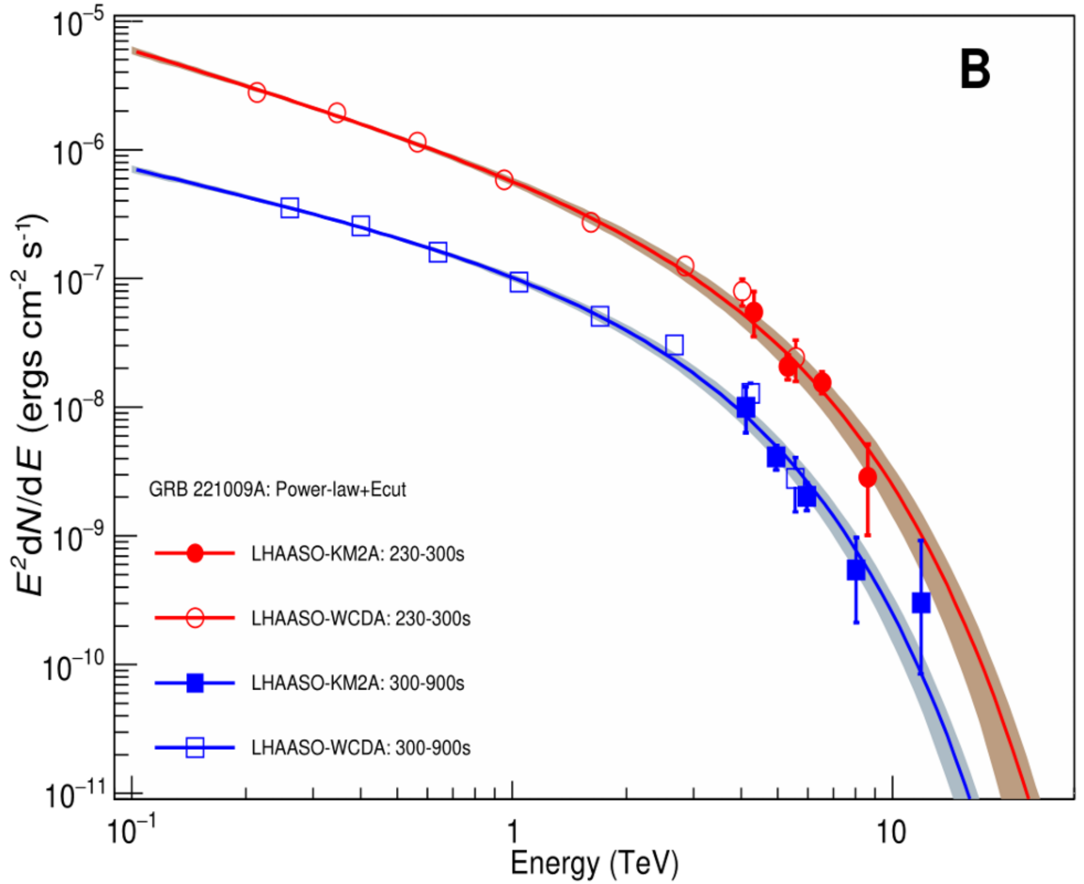
LHAASO coll. Science Advances,9: eadj2778 (2023)

WCDA+KM2A SED (observed)

SED function: log-parabola



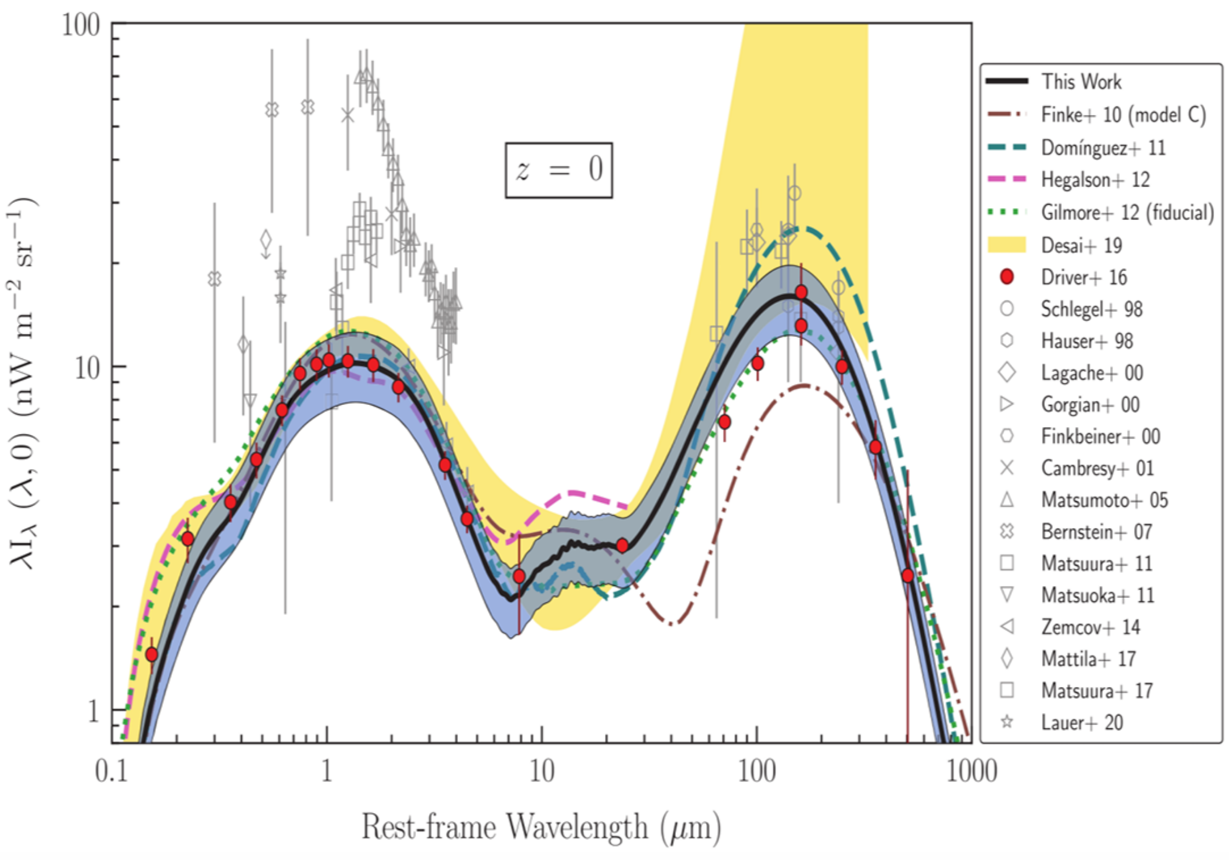
SED function: Power-law+Ecut

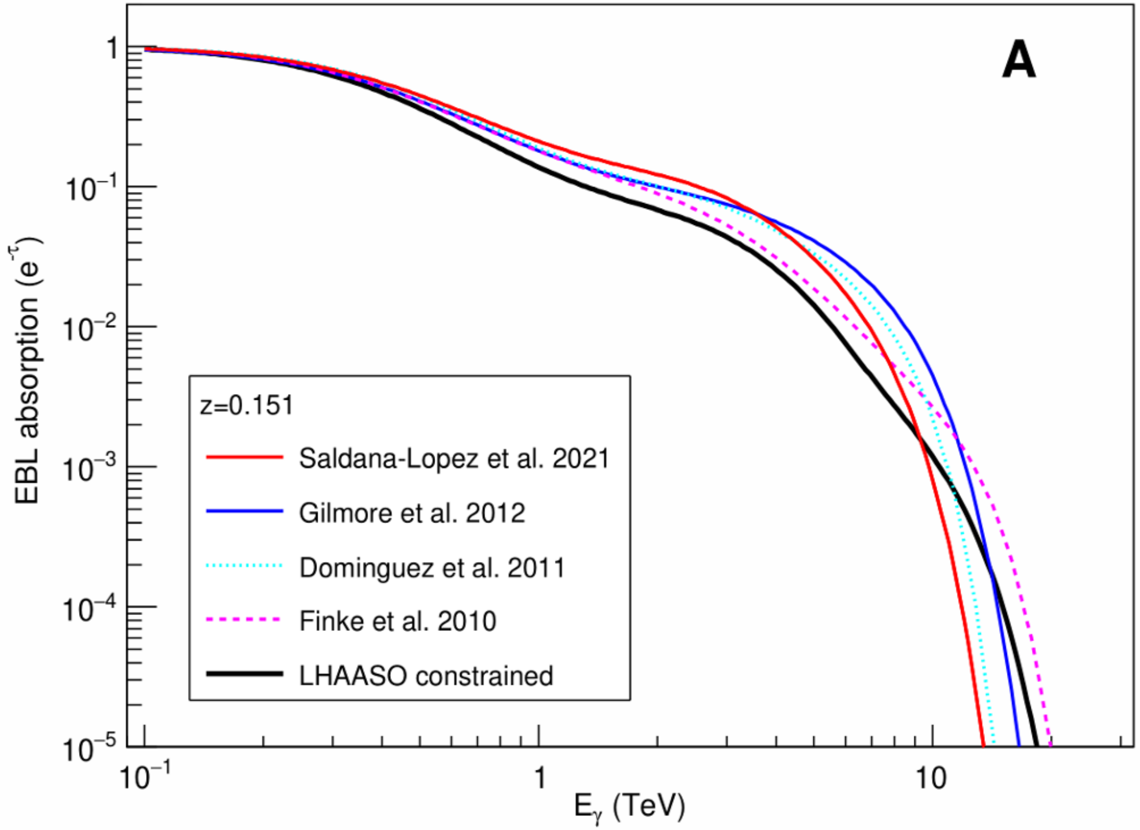


LHAASO coll. Science Advances,9: eadj2778 (2023)

EBL absorption

Alberto Saldana-Lopez[1,2]★ Alberto Domínguez[2]★ Pablo G. Pérez-González[3] Justin Finke[4], Marco Ajello[5] Joel R. Primack[6] Vaidehi S. Paliya[7] and Abhishek Desai[8]

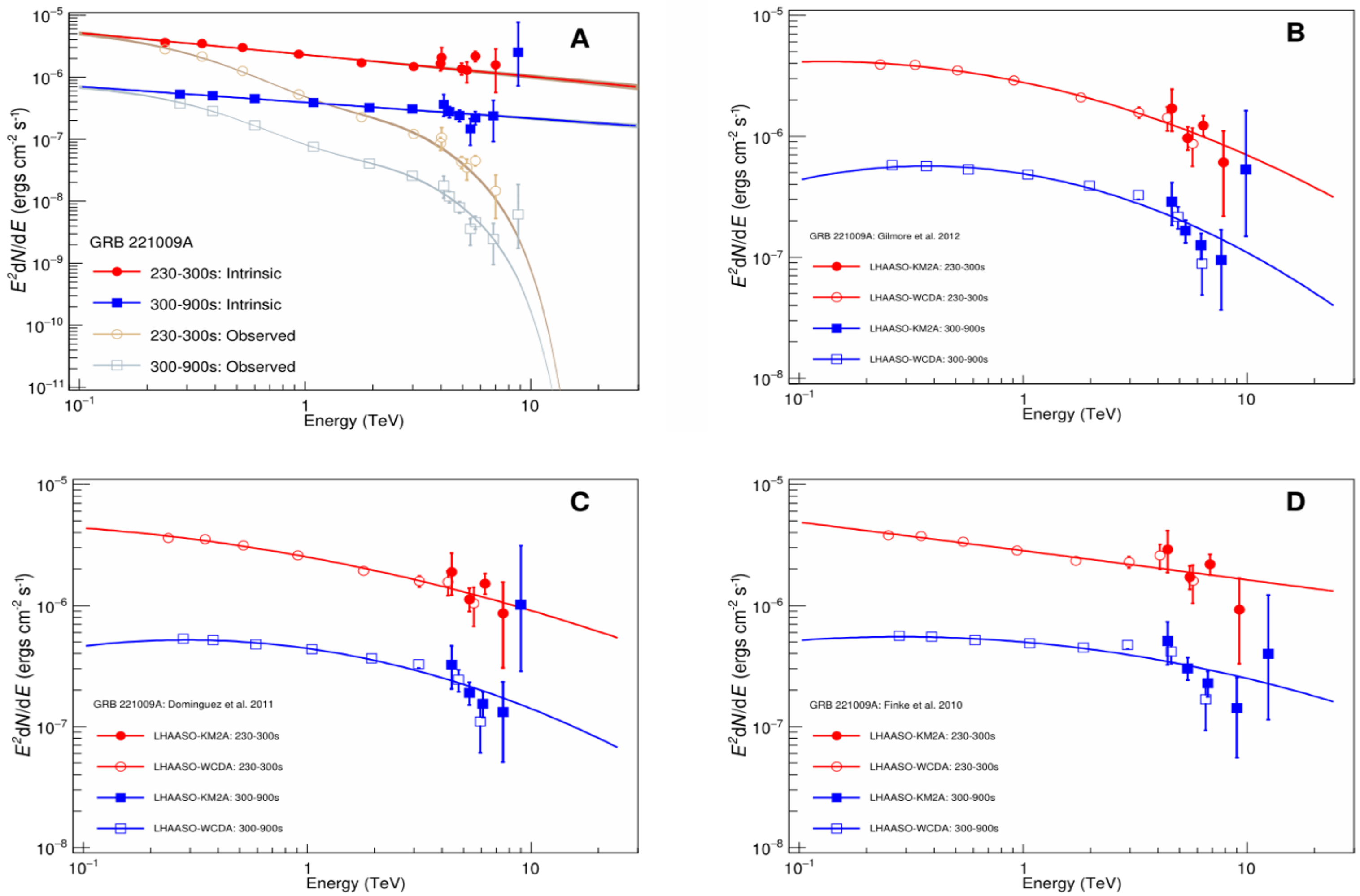




Saldana-Lopez et al. 2021

WCDA+KM2A SED (EBL corrected)

- Intrinsic SED using different EBL models



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

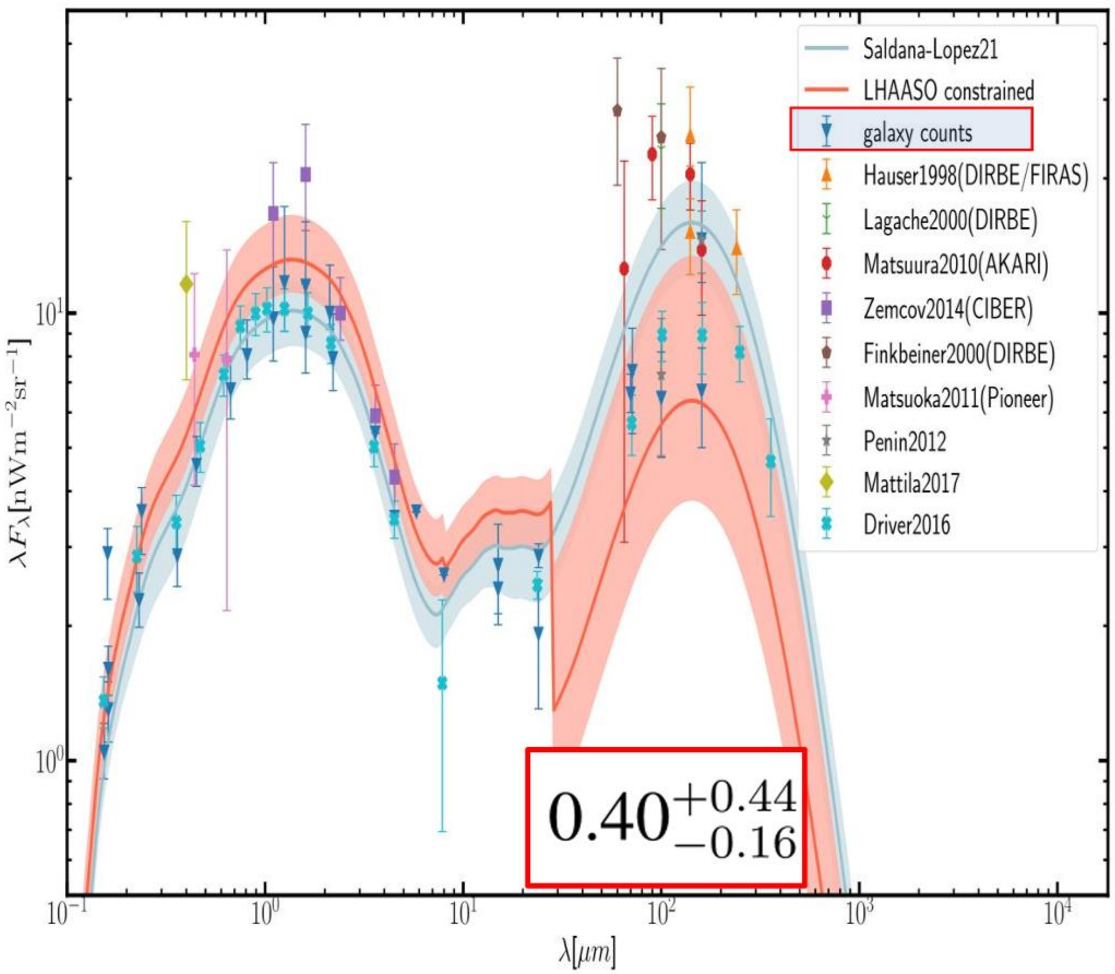
Implications of the LHAASO observation

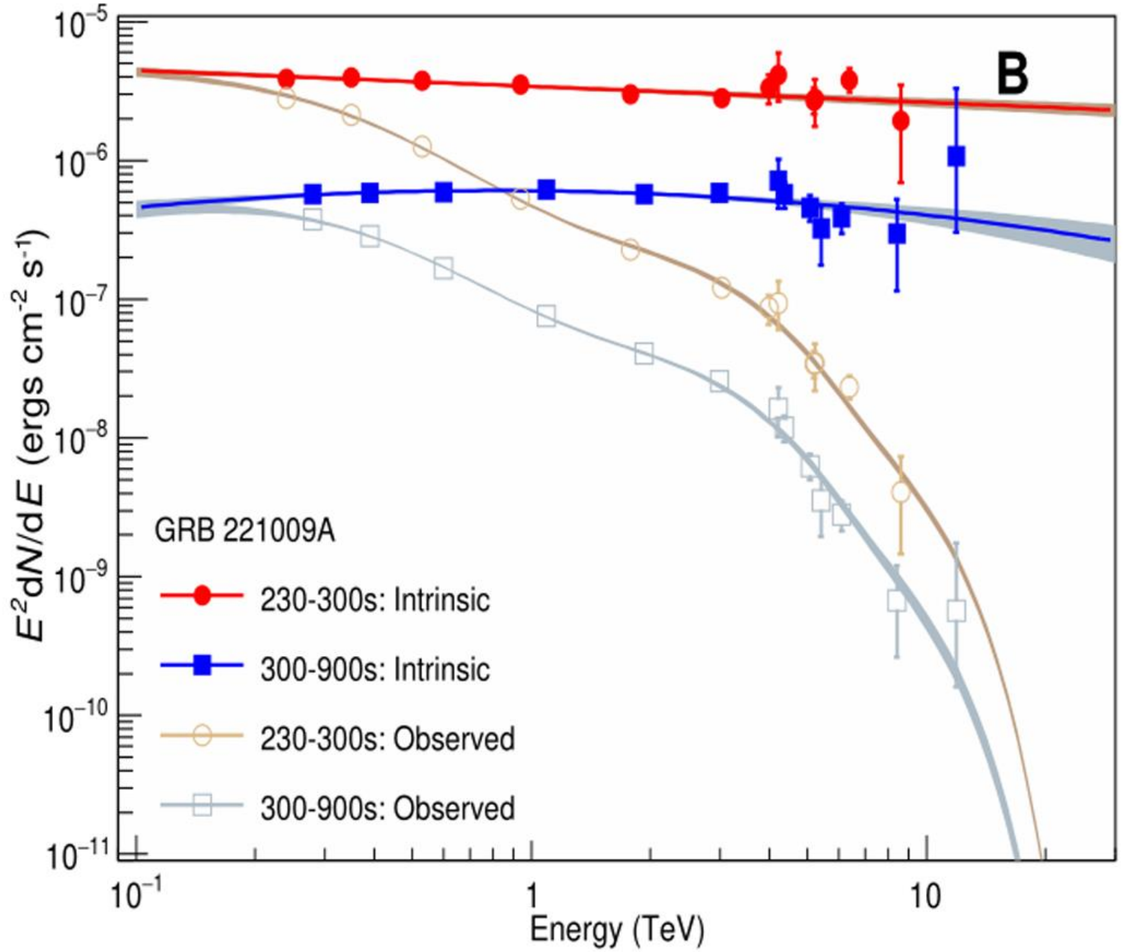
- Constrain the EBL models
- Possible new physics scenarios
    - axion
    - LIV

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

Constraints on EBL distribution

$\lambda < 8\mu m, 8\mu m < \lambda < 28\mu m, \lambda > 28\mu m$

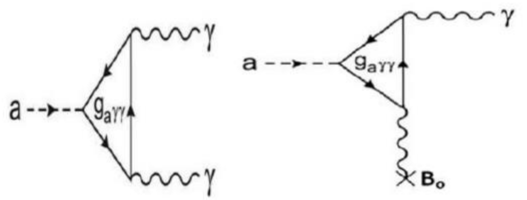




LHAASO coll. Science Advances,9: eadj2778 (2023)

Axion and axion-like particles

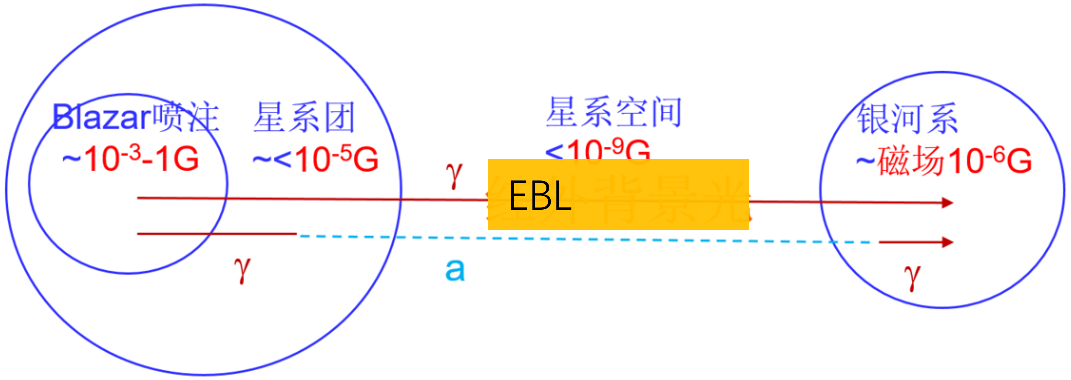
- Axion is introduced to solve the strong CP problems of the SM. It is an ideal cold dark matter candidate
- Axion couples with two photons
- In external magnetic field axion-gamma oscillates into each other



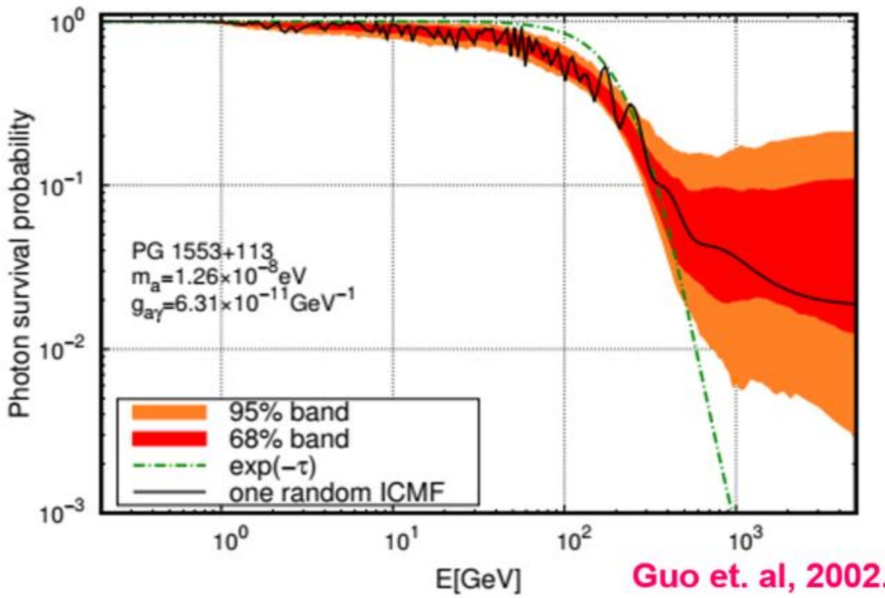
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a \partial^\mu a - m^2 a^2) + \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} ,$$

gamma-axion oscillation

- Oscillation between axion-gamma evade the absorption by EBL



- The gamma ray spectrum is modified



Guo et. al, 2002.07571

Best fit of axion is not significant

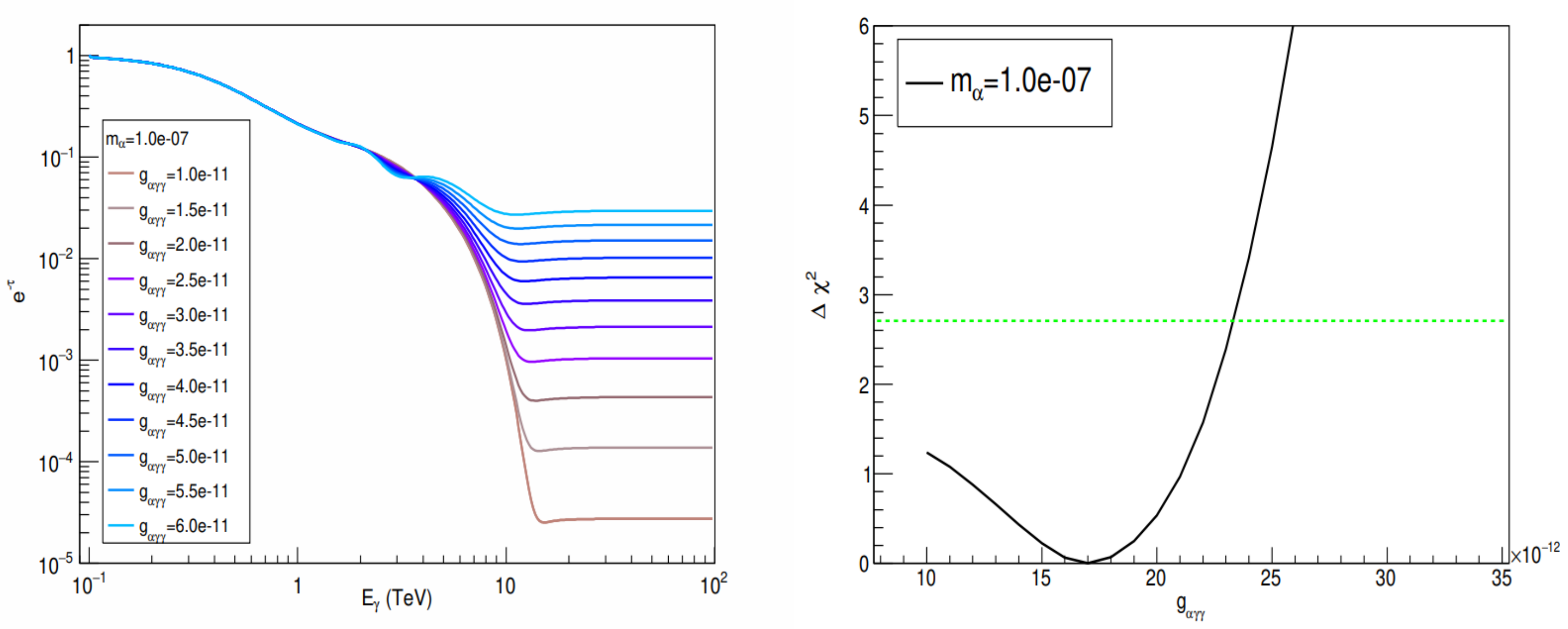
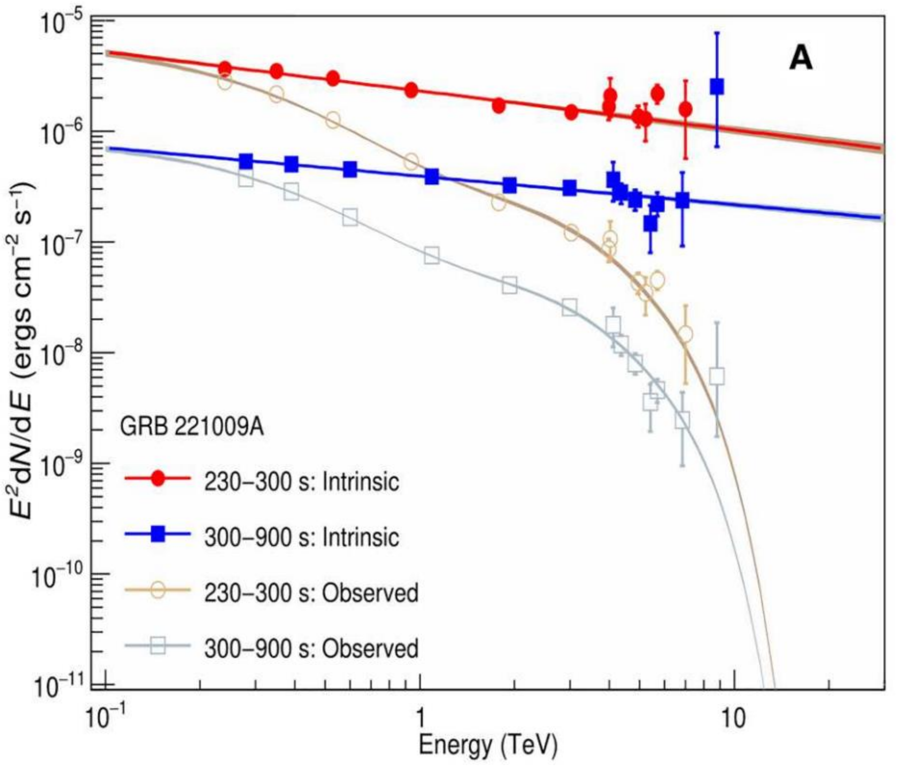


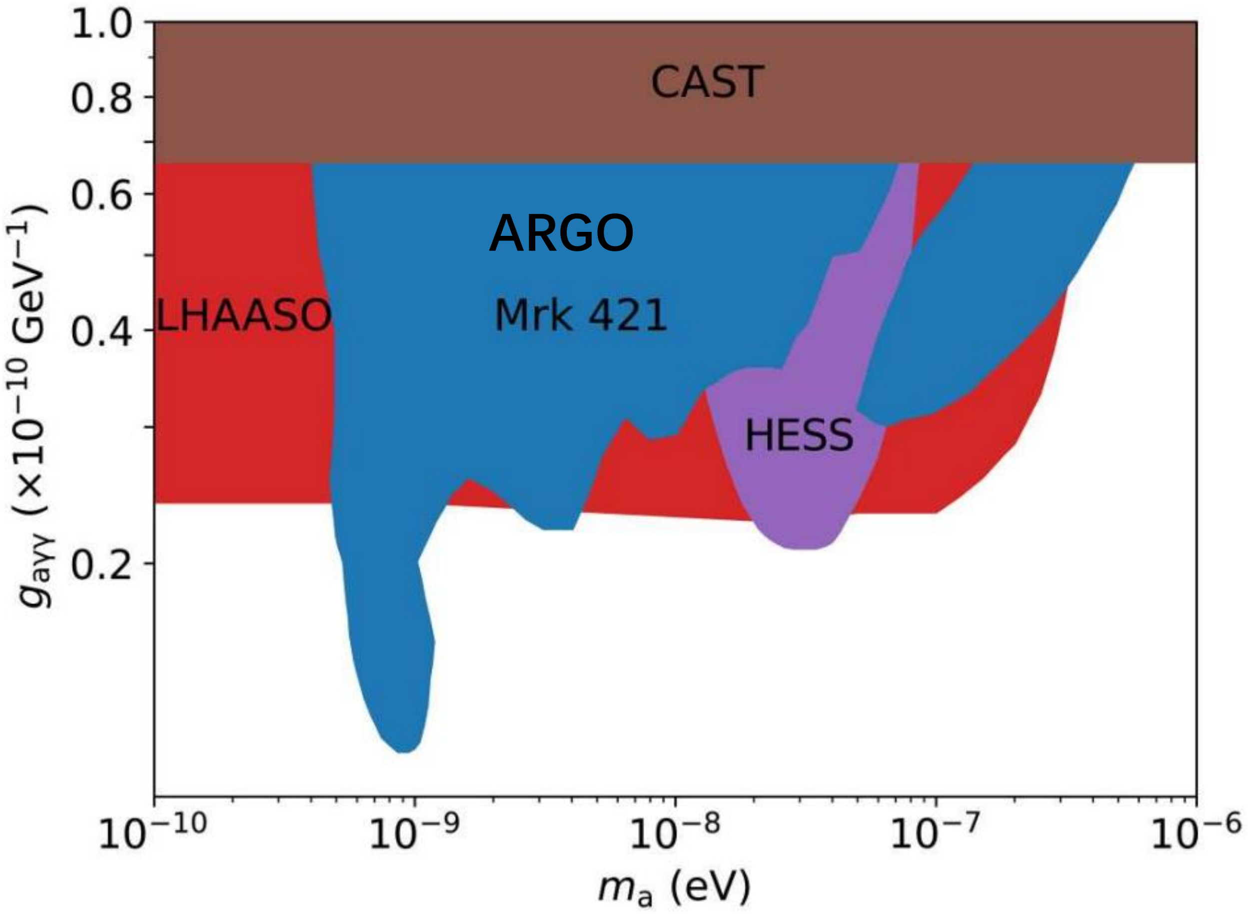
Figure S2: **The EBL absorption and the χ^2 of spectral fitting taking into account the ALP oscillation.** Panel A shows EBL absorption models for very high-energy gamma-rays from a redshift of $z = 0.151$, taking into account the oscillation between gamma-rays and ALPs assuming $m_a = 10^{-7}$ eV and $g_{a\gamma}$=(1 to 6)$\times 10^{-11}$ GeV^{-1}. The EBL model used is Saldana et al. 2021. Panel B shows $\Delta\chi^2$ relative to the minimum that fits the spectral energy distribution data as a function of the ALP $g_{a\gamma}$ for $m_a = 10^{-7}$ eV. The line indicates $\Delta\chi^2 = 2.71$ used to define the upper limit on $g_{a\gamma}$.

A stringent constraint is set on axion coupling

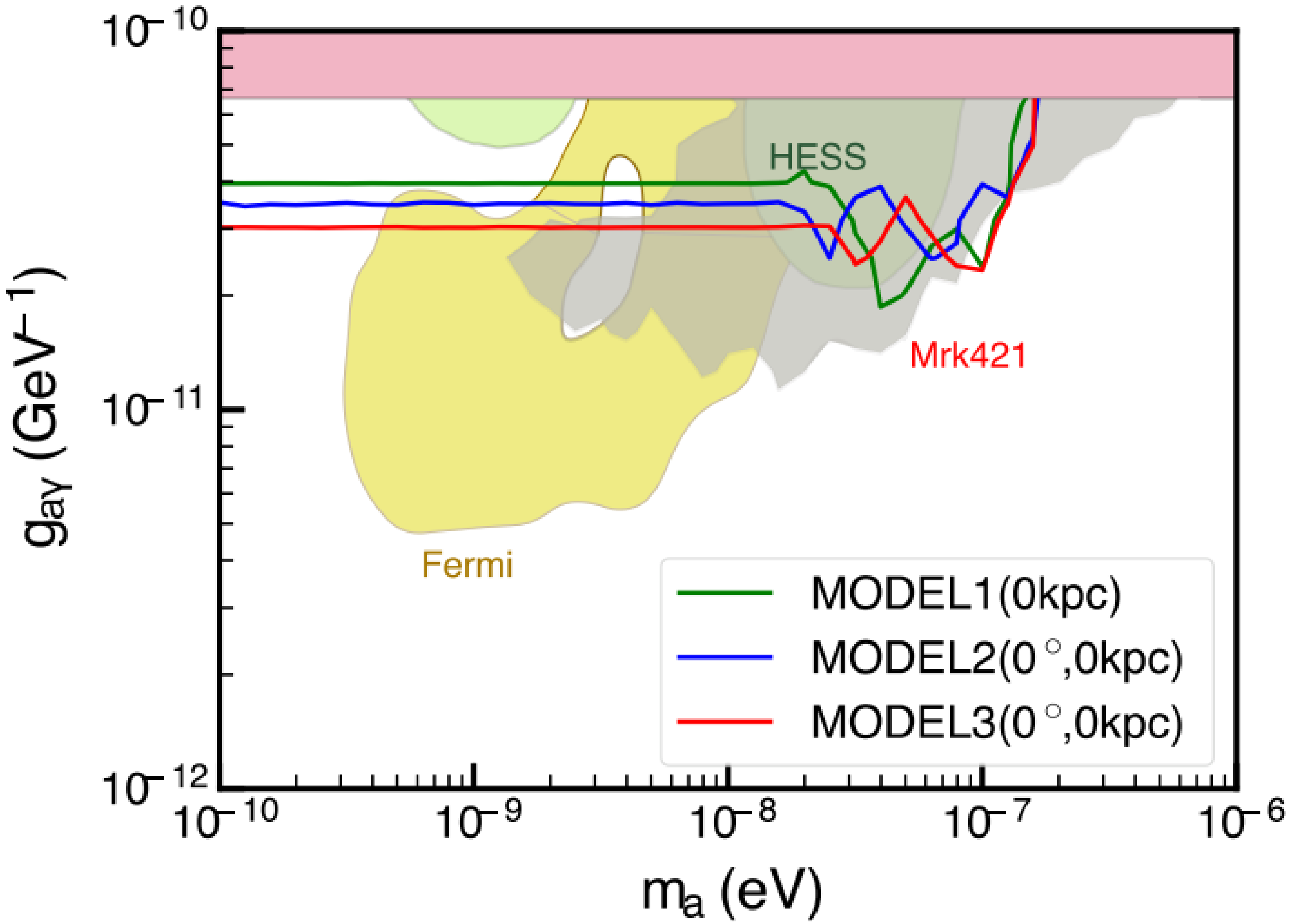
LHAASO coll. 2023 (Science adv. 9, 2778)

- Axion significance < 2sigma, we give constraints on axion coupling





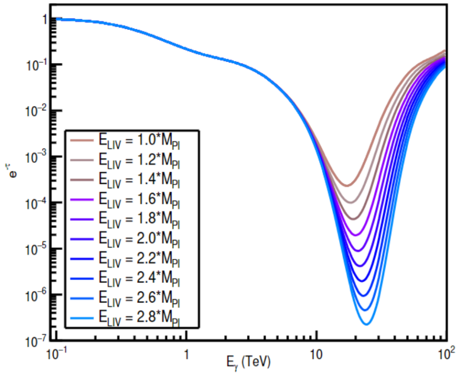
In comparison with other constraints



Gao, BXJ, Yao, Yin,
JCAP01(2024)026

Kinetics with LIV $E^2 = p^2 c^2 *(1 + a1(pc/ M_{pl} c^2) + a2(pc/ M_{pl} c^2)^2 + \cdots)$

- A free photon in vacuum is stable in LI; For LIV, if the effective mass of a photon $E_\gamma^2 - p_\gamma^2 = \frac{p^{n+2}}{E_{LIV}^n} = m_{\gamma,eff}^2$ is greater than a pair of e+e-, the photon decay γ -> e+e- very fast and leads to a sharp cutoff at the SED



- Change the threshold of an interaction. The threshold of

γγ -> e+e- $\epsilon_{\rm thr} = \frac{m_e^2 c^4}{E} + \frac{1}{8}\left(\frac{E}{E_{\rm LIV}}\right) E$ is improved; more transparent for

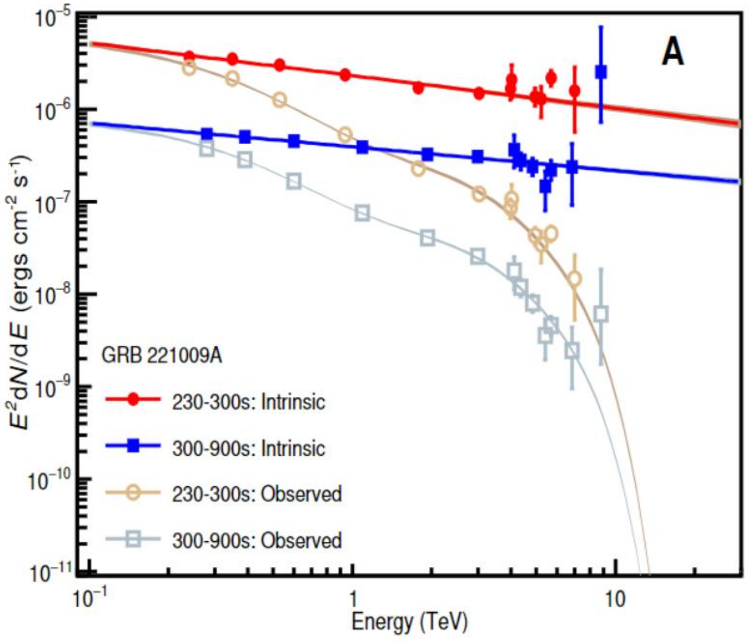
- Energy dependent speed of light at LIV; v(E) = $\partial\omega / \partial k = \partial E / \partial p$ $\approx c\,(1 \pm \frac{1+n}{2}(E/E_{LIV,n})^n])$, it leads to time delay for different E from z,
- ⋯ others

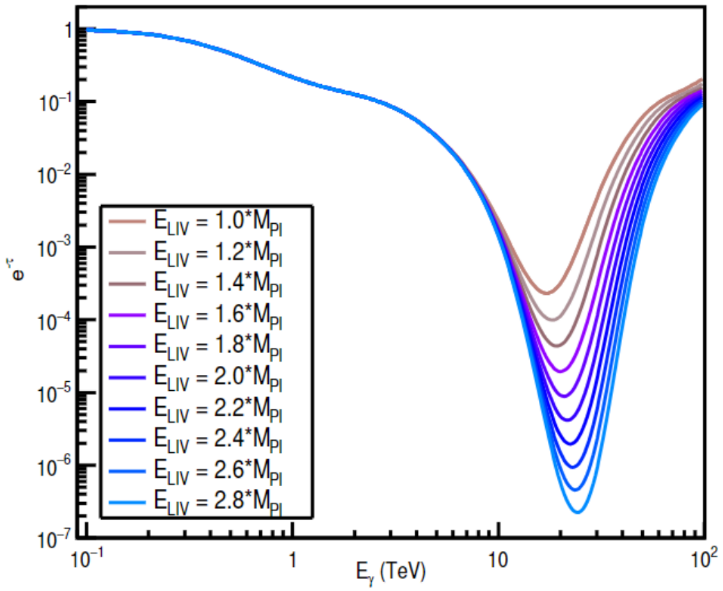
$$\Delta t = \frac{\Delta z}{H_0} = \frac{1+n}{2H_0}\left(\frac{E_0}{\xi E_{pl}}\right)^n \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

LIV by GRB 221009A

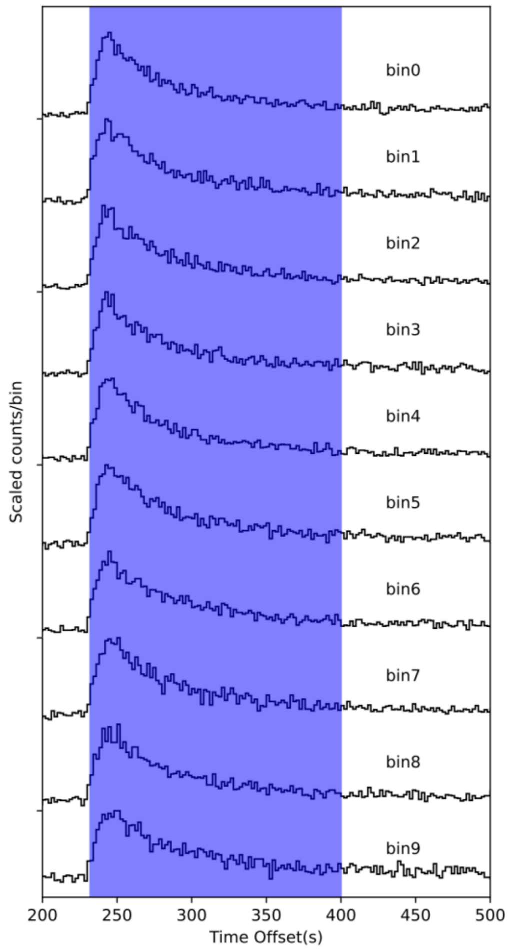
- The intrinsic gamma spectrum shows a bump at the highest energy. It stimulates a lot of interests. LIV is a possible solution which leads to more transparent EBL.

- As the significance is not high. Constraint on LIV is set finally $E_{LIV} > 1.5\ M_{Pl}$.

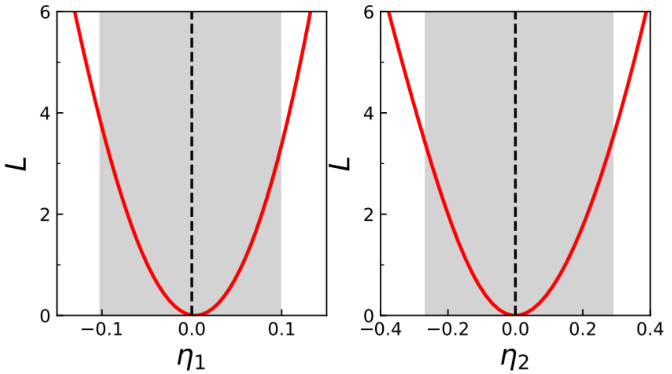




Constraint on LIV by time lag of different energy photons from GRB 221009A



- **Cross correlation function (CCF)**. Light curves of different energy bands are given by the WCDA data. CCF method is adopted to derive the time lags of the different light curves.
- **Maximal likelihood method**. The probability density function (PDF) of a photon at time t and N_{hit} is given. λ(t) is the intrinsic light curve with possible time lag $\Delta t_{LIV}(E)$.



$$P\left(t, N_{\mathrm{hit}}|\eta_n,\ I\right) \propto \int_0^{\infty} \lambda\left[t - \Delta t_{\mathrm{LIV}}\left(E,\ \eta_n\right)\right] \gamma(E) \times F(E) A_{\mathrm{N_{hit}}}(E)\, dE;\ N_{hit} = 0, 1, ..., 9$$

The stringent LIV constraint by time of flight

Cao, Z. et al., PRL 2024

- For the 2nd LIV the LHAASO constraint is the best one with 6-8 times improvement to Fermi-LAT result.

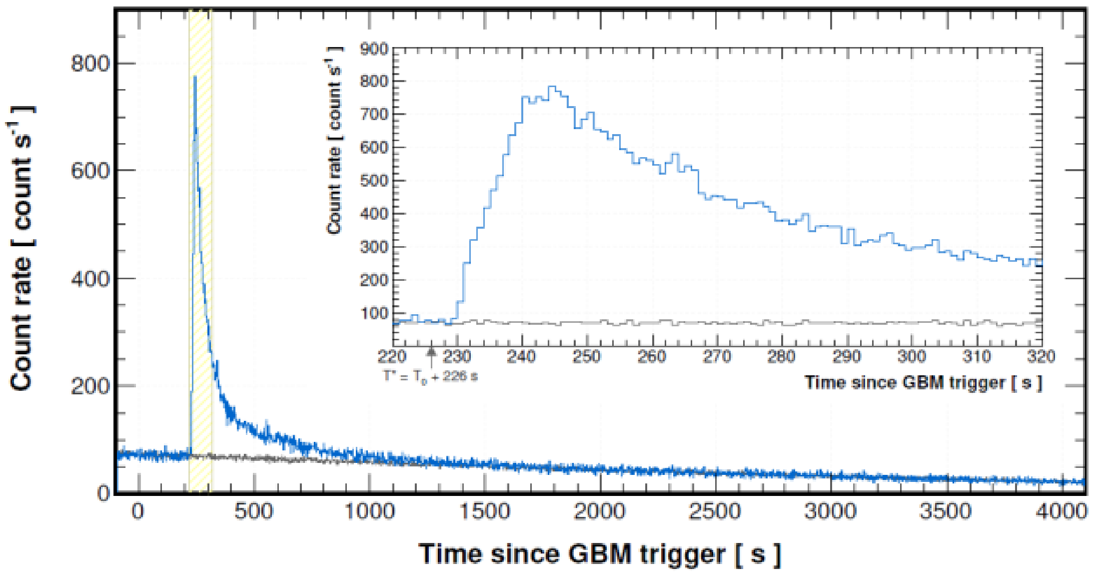
Method	Cross correlation function			Maximum likelihood		
	η^{LL}	η^{BF}	η^{UL}	η^{LL}	η^{BF}	η^{UL}
η_1	−0.25	0.05	0.18	−0.10	0.00	0.10
η_2	−0.60	0.25	0.64	−0.27	0.00	0.29
	superluminal		subluminal	superluminal		subluminal
$E_{QG,1}$ [10^{20} GeV]	0.5		0.7	1.2		1.2
$E_{QG,2}$ [10^{11} GeV]	5.0		4.8	7.5		7.2

GRB 221009A

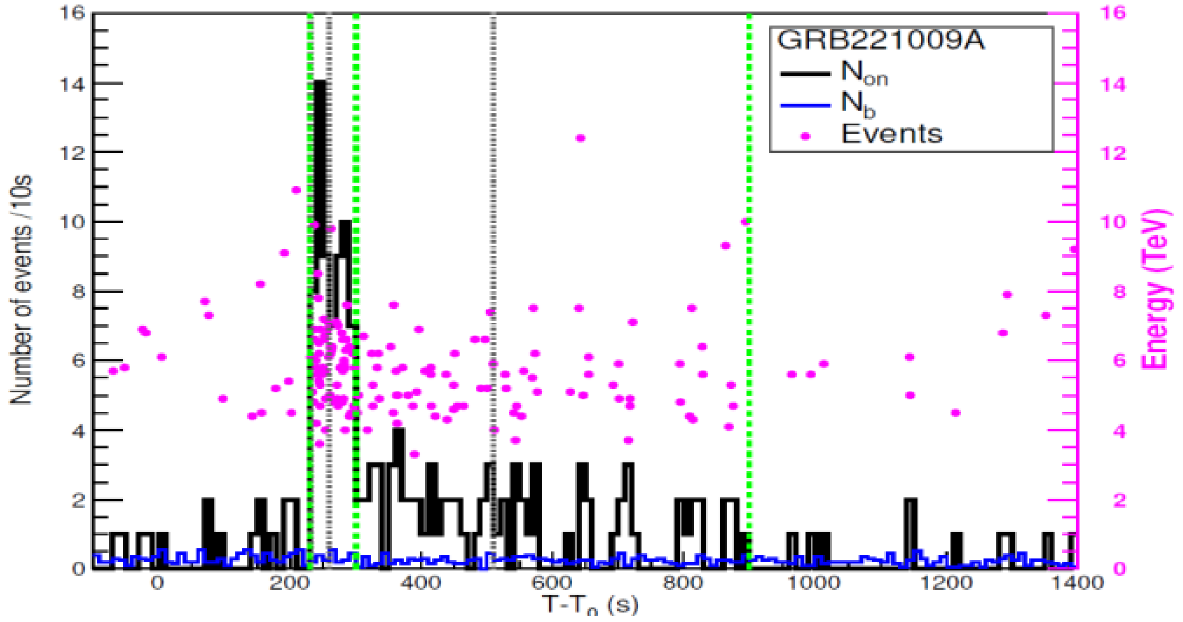
Yang, BXJ, Yin, JCAP 04 (2024) 060

Combining the KM2A and WCDA data to give a strict limit on LIV

WCDA: 在 3000s 内、~0.2-7TeV 范围内探测到了大约 64, 000 个光子（LHAASO Collaboration.Science 380, 1390 (2023)）



KM2A: 在 230-900s 内、~3-13TeV 范围内探测到了 142 个光子（LHAASO Collaboration.Science Advances 9 (46) (2023)）



利用 KM2A 230-900s 的 142 个光子计算 likelihood function：

$$\mathcal{L}\left(\eta_n \,\middle|\, \left\{t^{(i)}, E_{\text{est}}^{(i)}\right\}\right) = \prod_{i=1}^{142} P(t^{(i)}, E_{\text{est}}^{(i)} \,|\eta_n)$$

Yang, BXJ, Yin, JCAP 04 (2024) 060

定义：

$$L(\eta_n) \equiv -2\ln\left(\frac{\mathcal{L}_{\eta_n}}{\mathcal{L}_{\hat{\eta}_n}}\right)$$

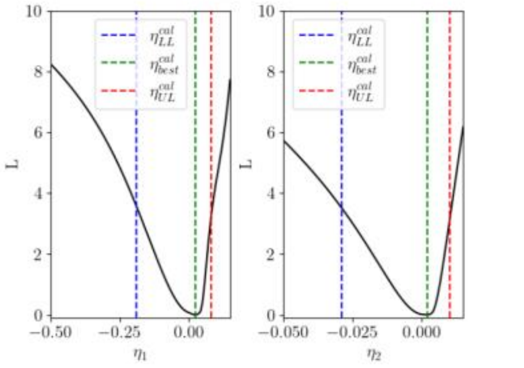


FIG. 3. The $L-\eta_1$ (left) and $L-\eta_2$ (right) curves (black solid lines) of Model-1. The green dashed lines represent the position of $\eta_{\rm best}^{\rm cal}$, while the red dashed lines and blue dashed lines indicate the the lower and upper ranges of the 95% CI

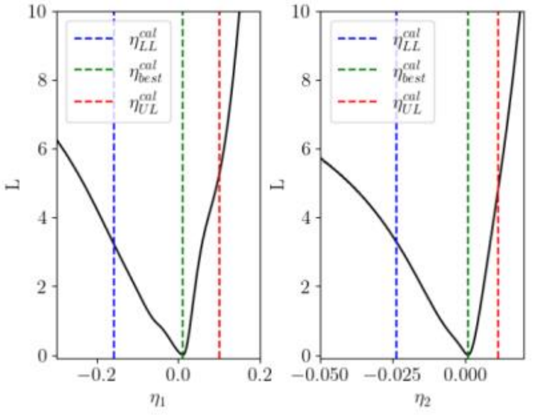


FIG. 4. Same as Fig. 3, but for Model-2.

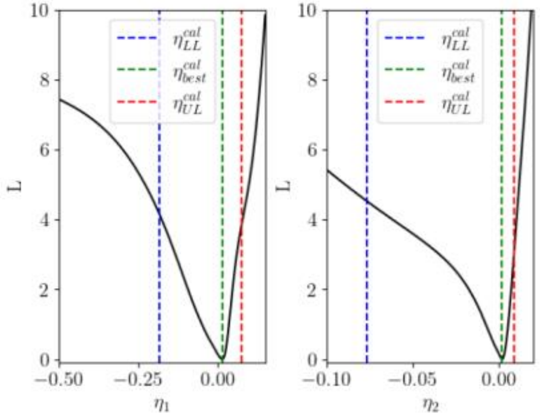


FIG. 5. Same as Fig. 3, but for Model-3.

TABLE II. The calibrated best fits of η_n, the lower and upper bounds of the 95% CIs of η_n, and the corresponding 95% CL lower limits on the $E_{\rm QG}$.

	η_1			η_2			$E_{\rm QG,1}$ [10^{19}GeV]		$E_{\rm QG,2}$ [10^{11}GeV]	
	$\eta_{\rm LL}^{\rm cal}$	$\eta_{\rm best}^{\rm cal}$	$\eta_{\rm UL}^{\rm cal}$	$\eta_{\rm LL}^{\rm cal}$	$\eta_{\rm best}^{\rm cal}$	$\eta_{\rm UL}^{\rm cal}$	$\mathcal{S}=+1$	$\mathcal{S}=-1$	$\mathcal{S}=+1$	$\mathcal{S}=-1$
Model-1	-0.189	0.024	0.083	-0.029	0.002	0.010	14.7	6.5	12.0	7.2
Model-2	-0.159	0.011	0.100	-0.024	0.001	0.011	12.2	7.7	11.5	7.9
Model-3	-0.184	0.015	0.074	-0.077	0.002	0.009	16.4	6.6	13.1	4.4

The photons with the maximum energy

- The energy of each photon depend on the true SED, which is SED model dependent.

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

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

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

TITLE: GCN CIRCULAR
NUMBER: 32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE: 22/10/11 09:21:54 GMT
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

Summary

- LHAASO has large coverage of muon detector. It has large FOV, wide energy range, high sensitivity and achieves impressive success. Dozens of UHE gamma sources have been observed.
- Complete light curve of GRB 221009A for TeV afterglow was observed by LHAASO. The spectrum was measured from ~200GeV – ~10TeV.
- Implications of the measurements on EBL and new physics scenarios are studied. Strong constraints on EBL at large wave length, axion coupling and LIV energy scales are derived.