Status and Recent Updates of LHAASO

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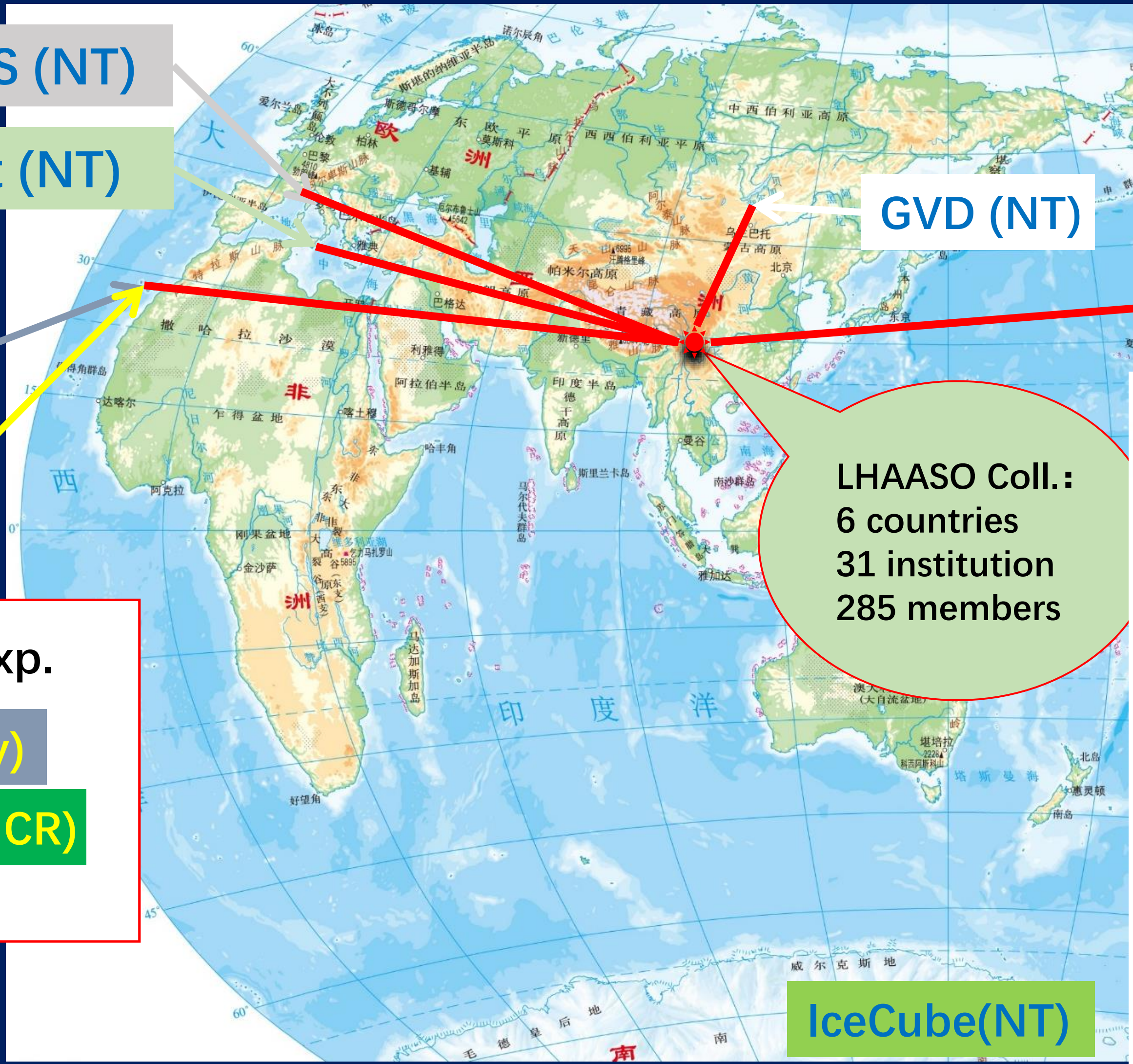
On behalf of LHAASO Collaboration
Institute of High Energy Physics(IHEP),CAS

CTA/LST-Japan Workshop， Kashiwa, 2024.3.

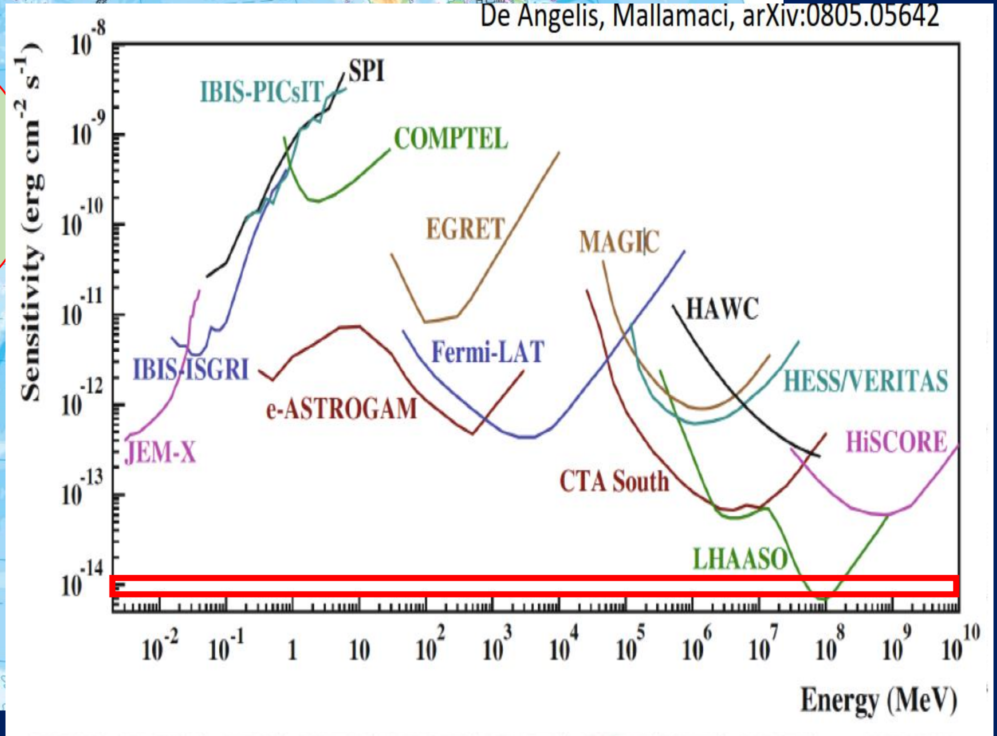
Multi-Messenger Collaboration Network



Space borne Exp.

eROSITA(X-ray)

DAMPE(γ-ray, CR)



The ultimate goal is to identify origins of CRs

Large High Altitude Air Shower Observatory

LHAASO

Scientific Goals

γ-ray astronomy:

Survey for sources (above 500 GeV)

PeVatrons (above 100 TeV)

All kind of sources: SNR, PWN, MYC, binary, pulsar, AGN, GRB etc.

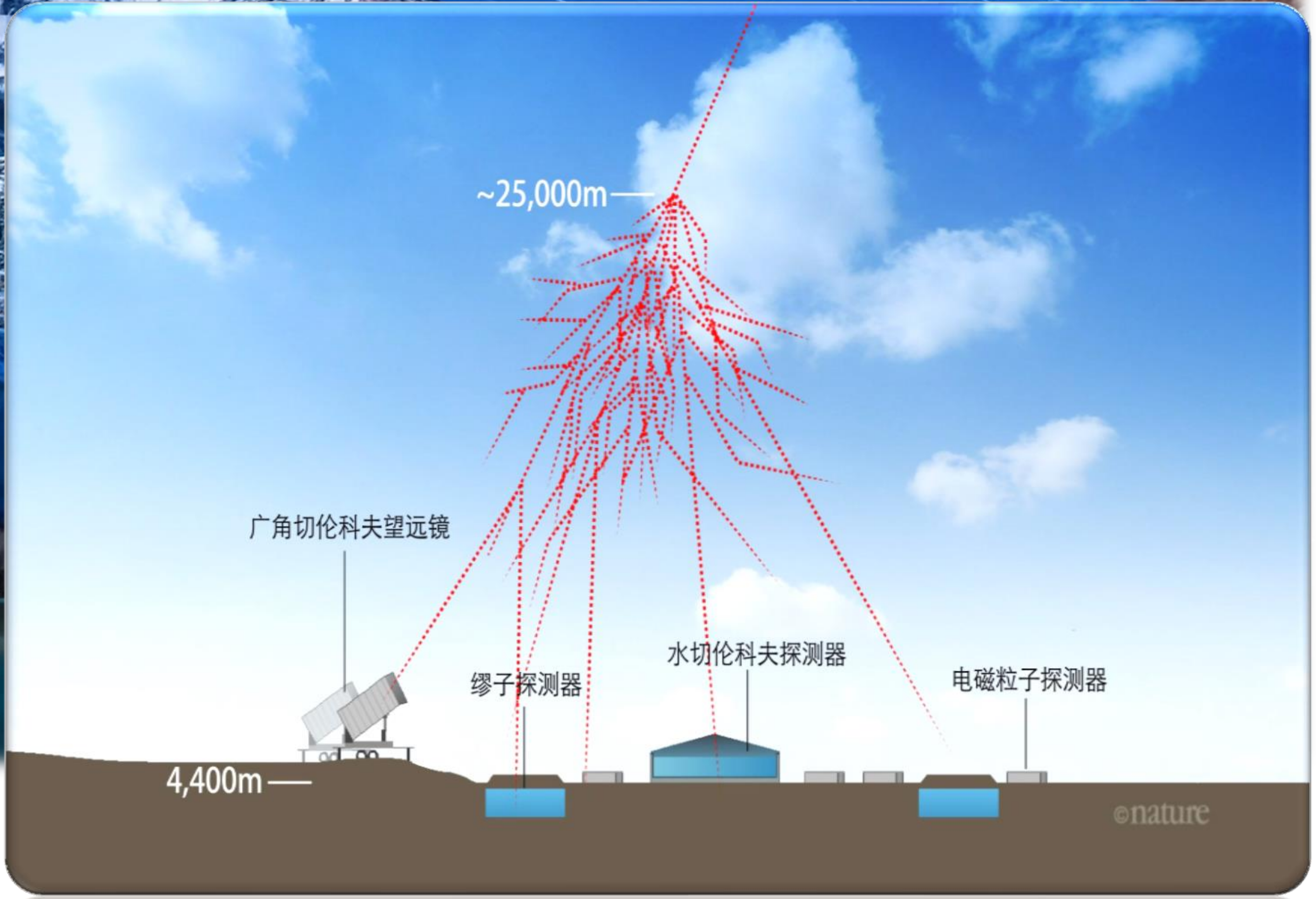
Cosmic Ray Physics:

The knees

Compositions : individual species H, He and Fe

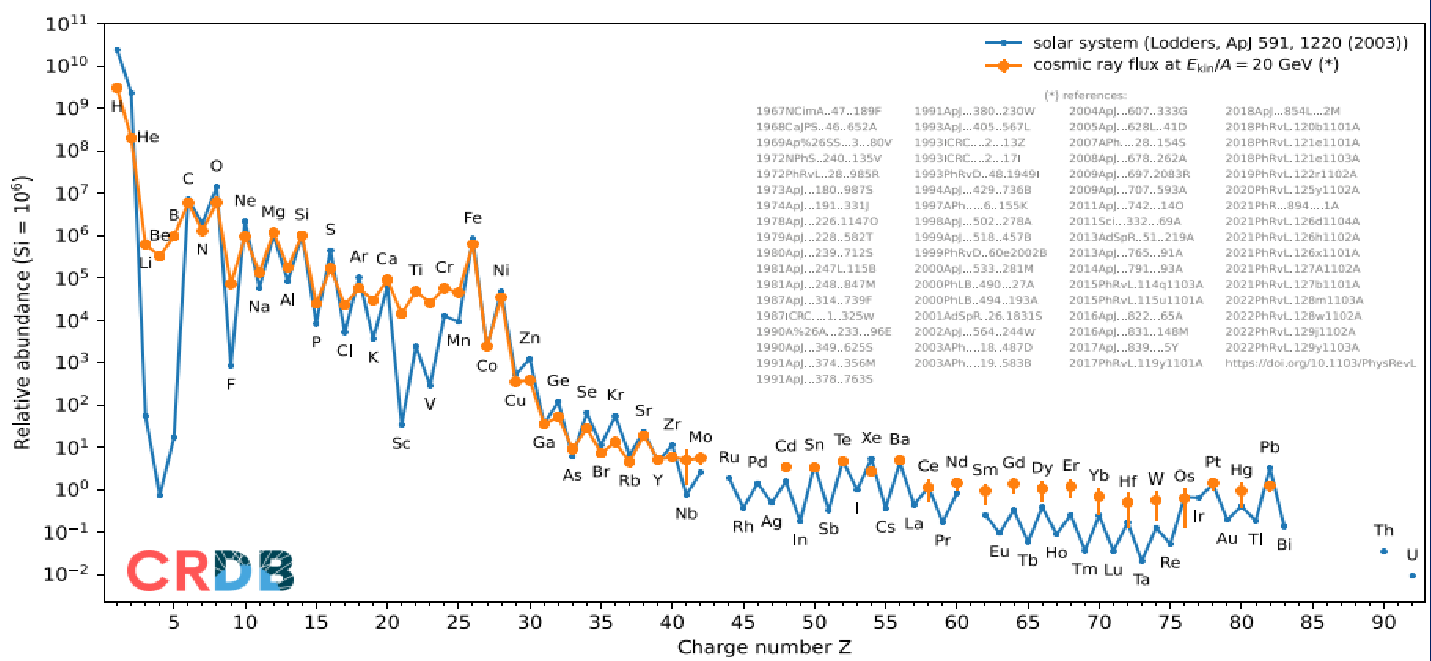
Anisotropy: (1 TeV to 10 PeV)

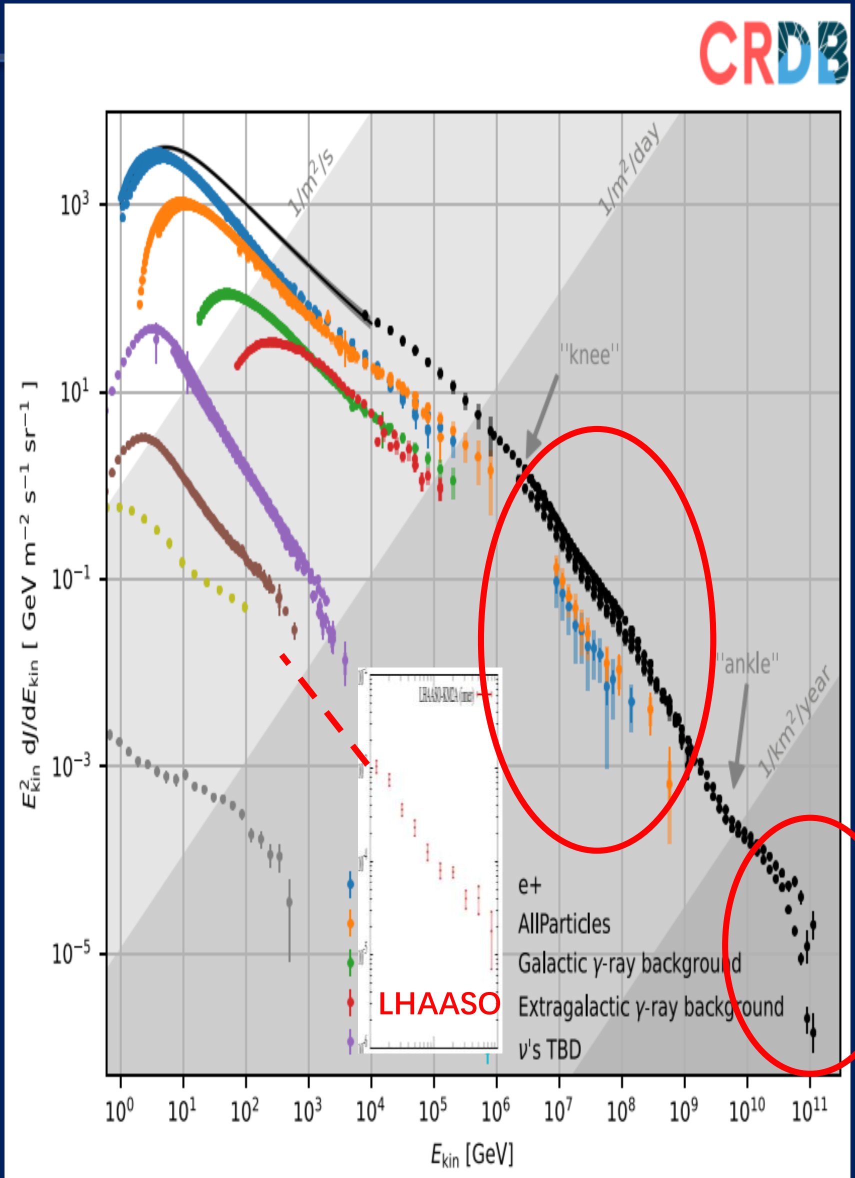
New Physics Front: DM, LIV, etc.



Cosmic Ray Origin

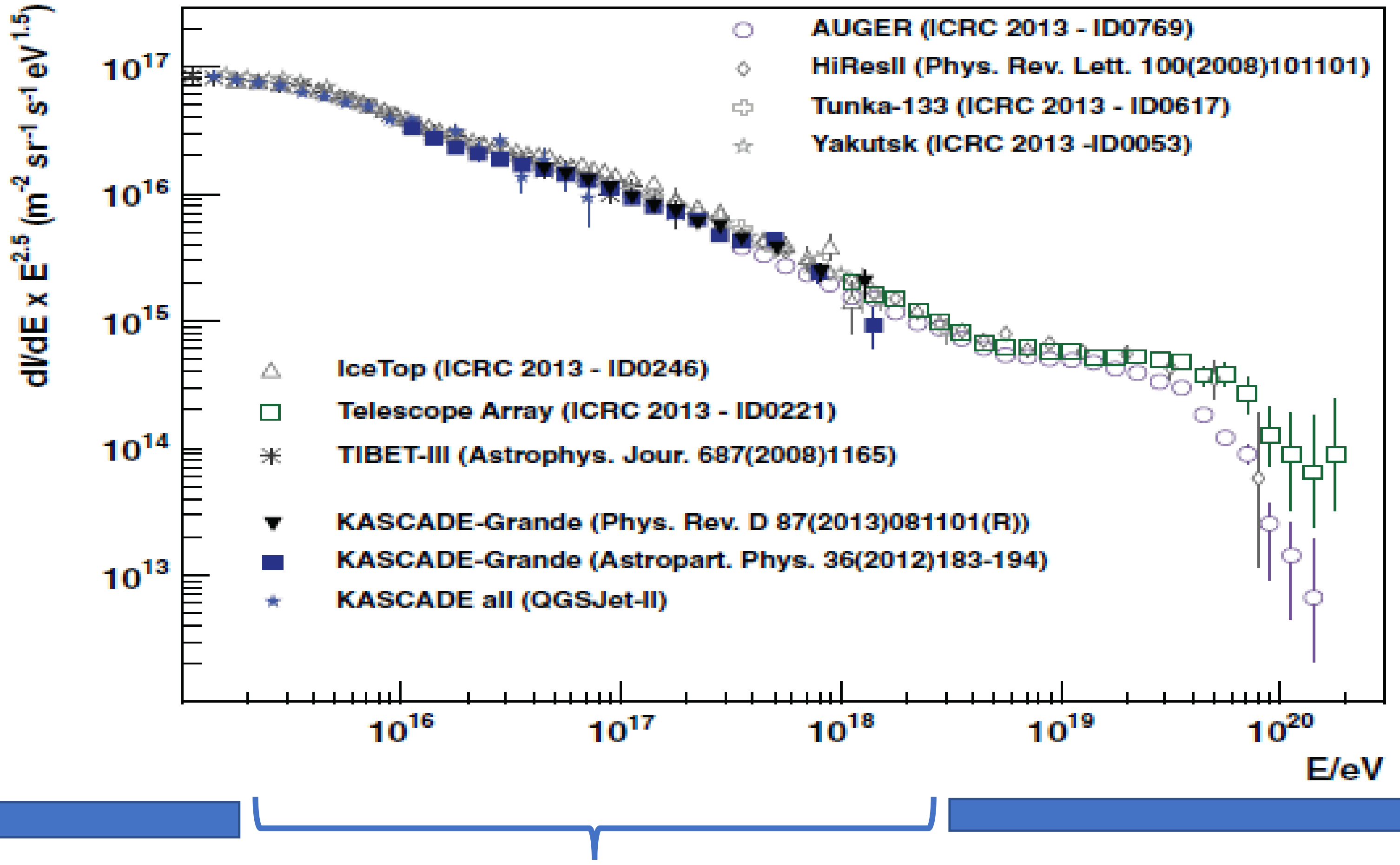
- After 110 years, we have learnt a lot about CRs near the Sun
- Particularly in the era of high precision measurements
- However, their origin is still an open question





There is still no clue about the origins of CRs between the “knee” and the “ankle”

LHAASO
高海拔宇宙线观测站



Galactic sources
mainly SNRs

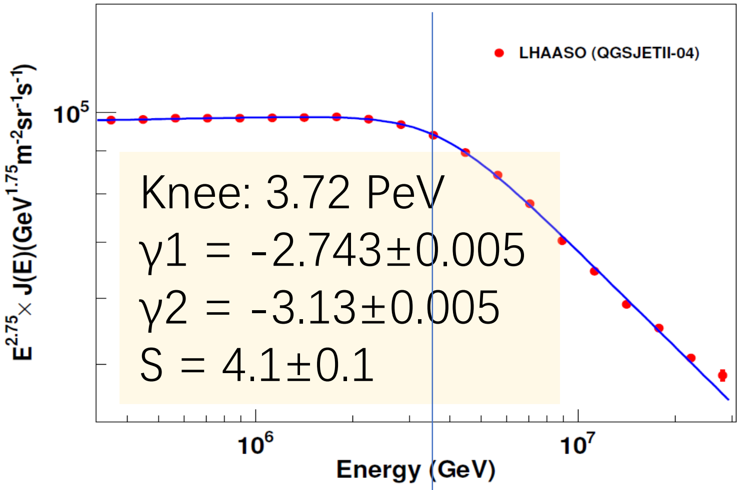
???

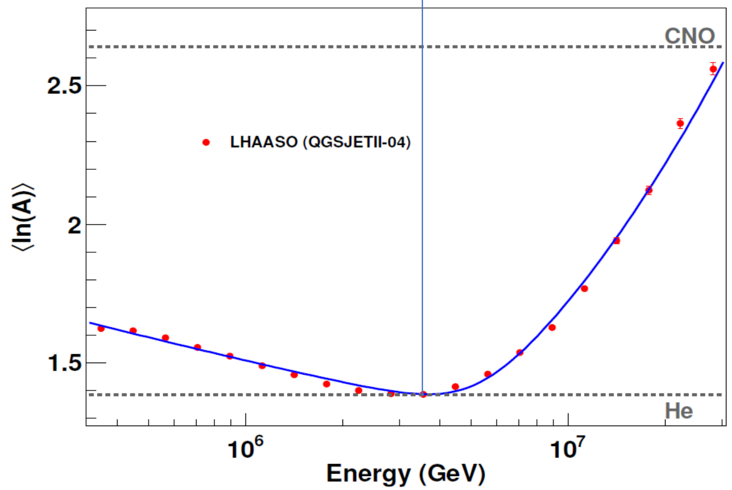
Extragalactic sources

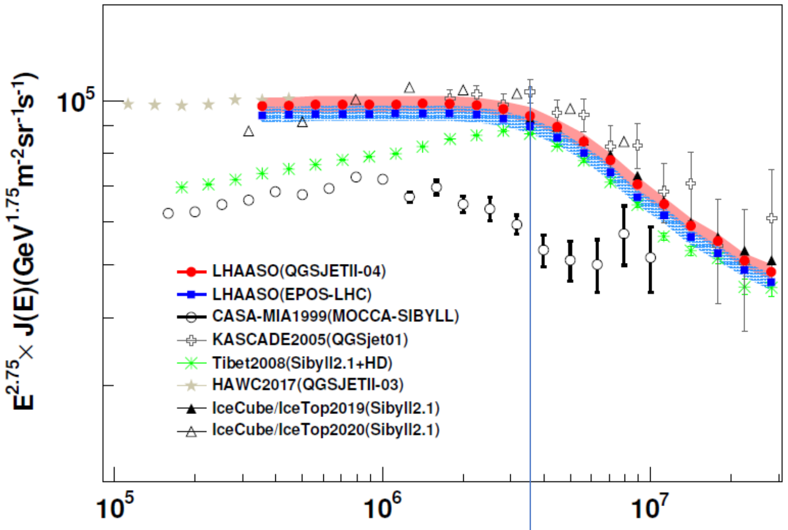
Physics Procedia 61 (2015) 425-434.arXiv:1910.03721v1

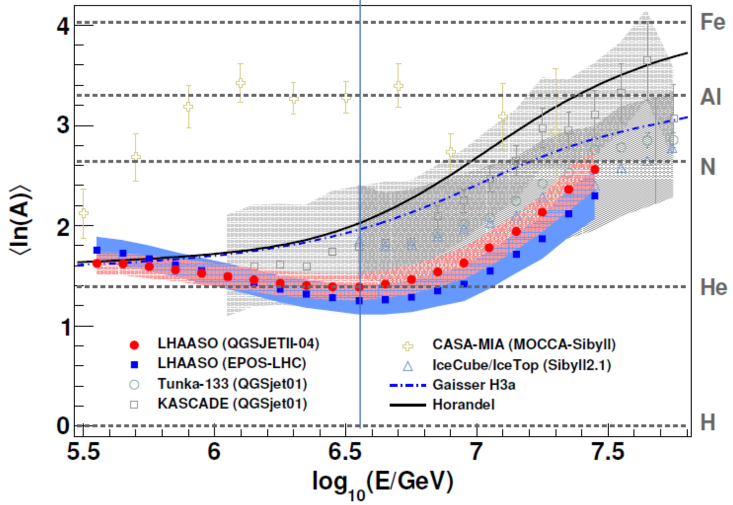
All-particle energy spectrum & composition by LHAASO

(from 0.3 to 30 PeV)





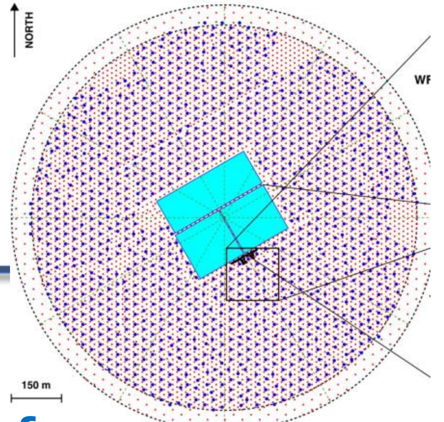




- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

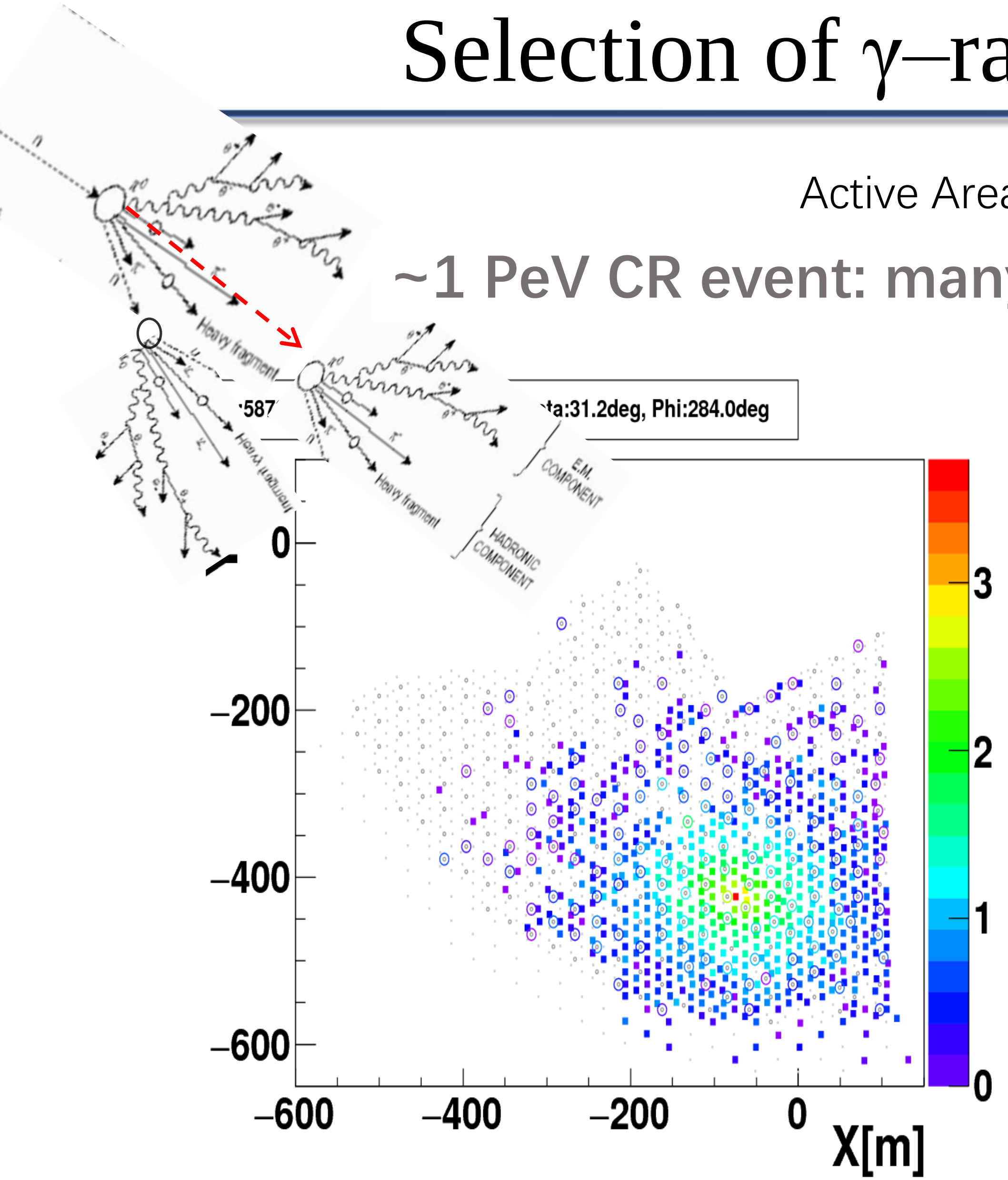
LHAASO-KM2A

Selection of γ–rays out of CR background

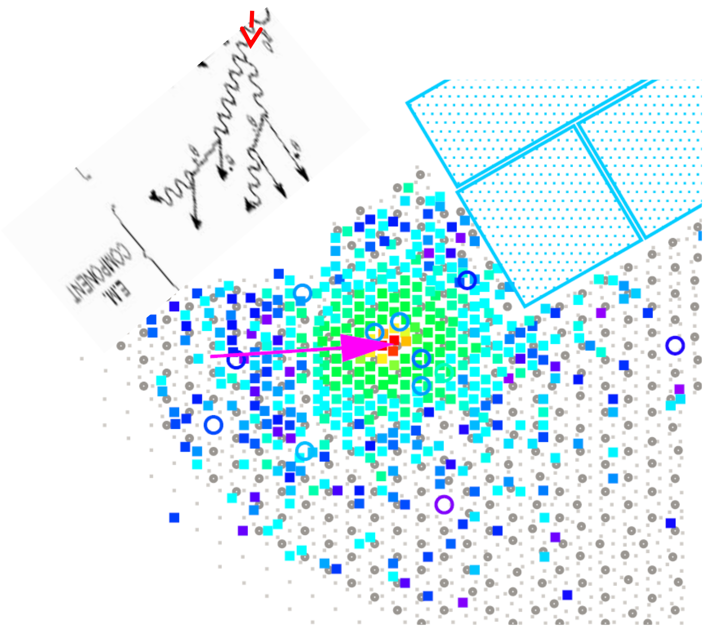


Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons



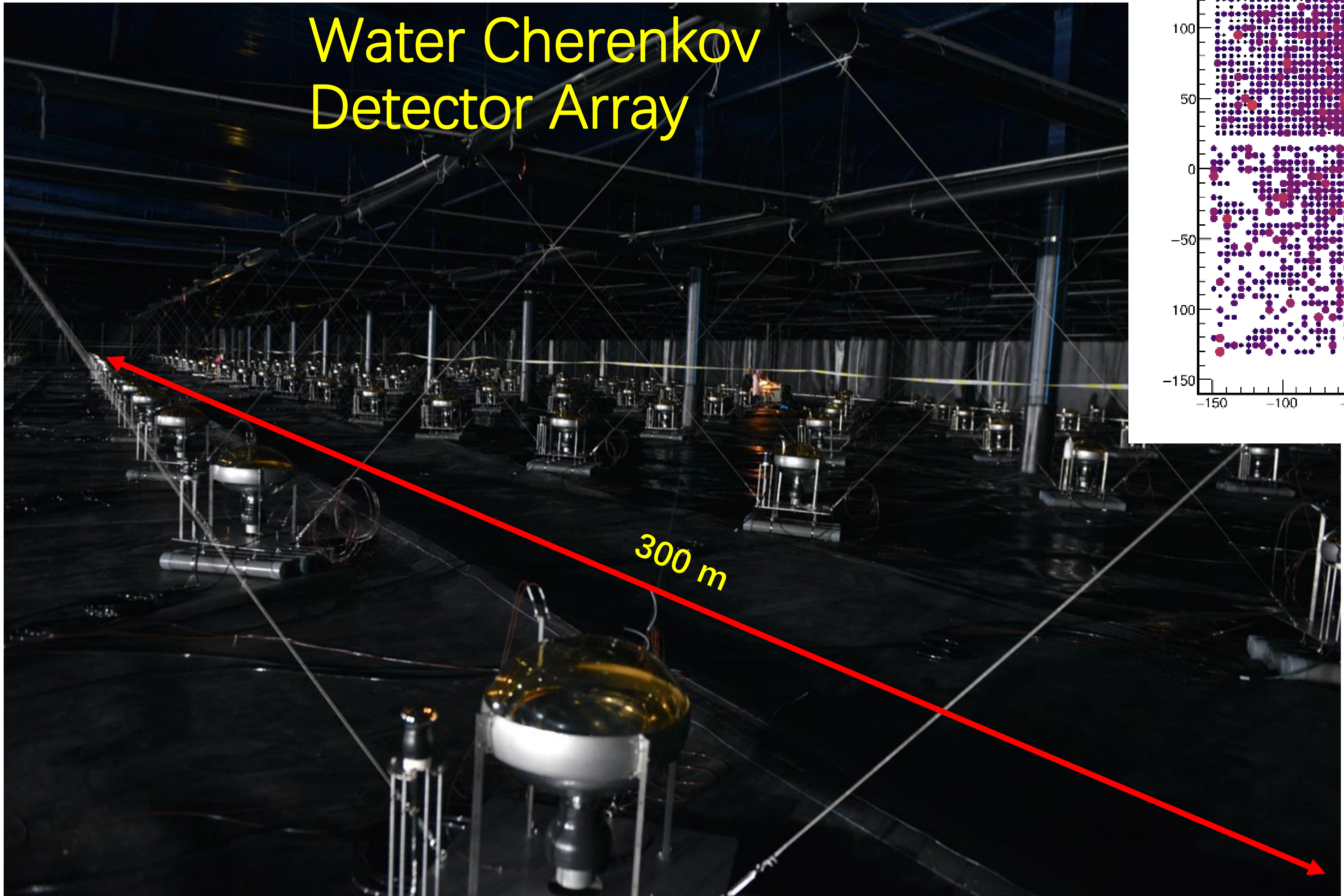
~ 1 PeV γ–ray event： very few muons from the Crab

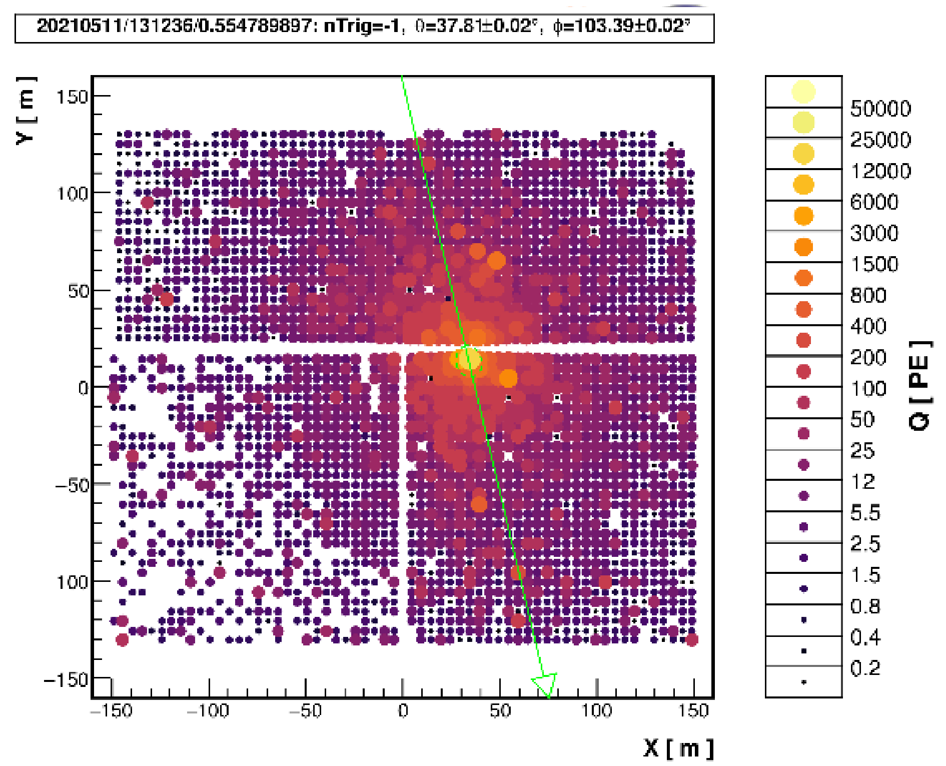


- Area：
  1.3 km^2
- Detectors：
  5216 ED
  1188 MD
- Energy Range：
  0.01-10 PeV

LHAASO-WCDA

Water Cherenkov Detector Array

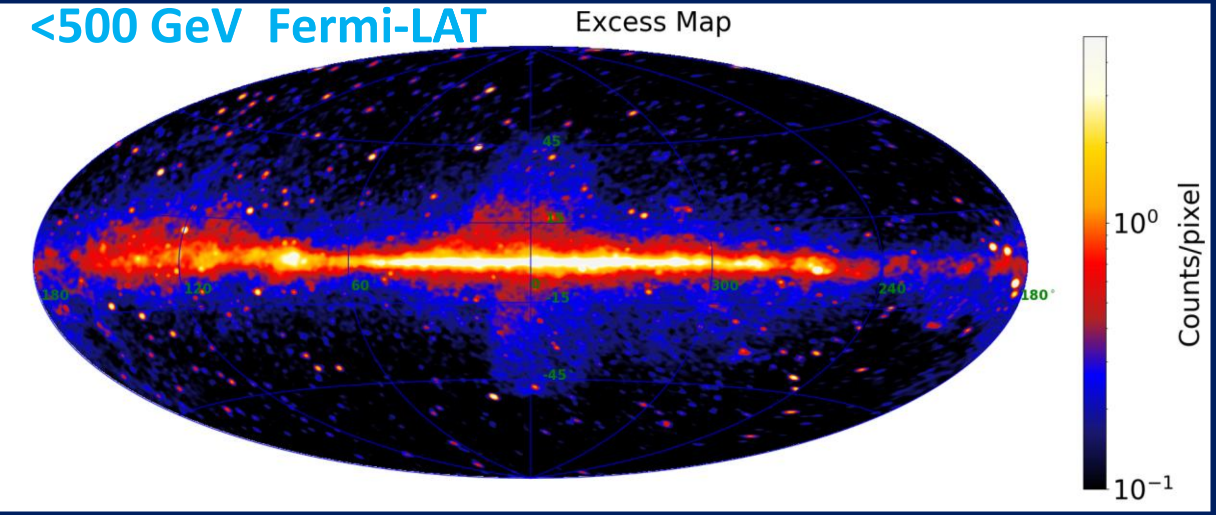


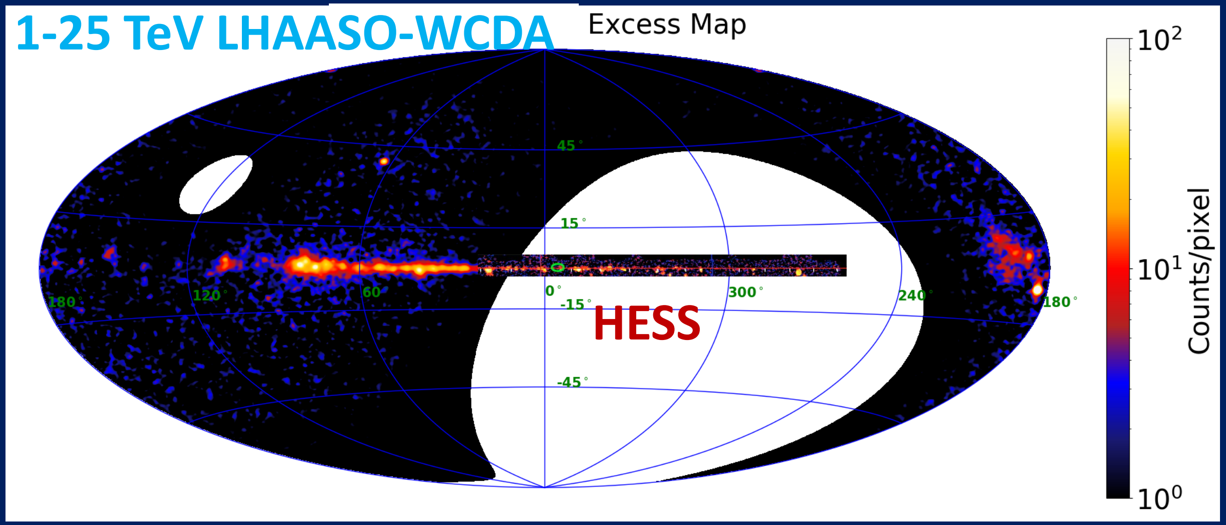


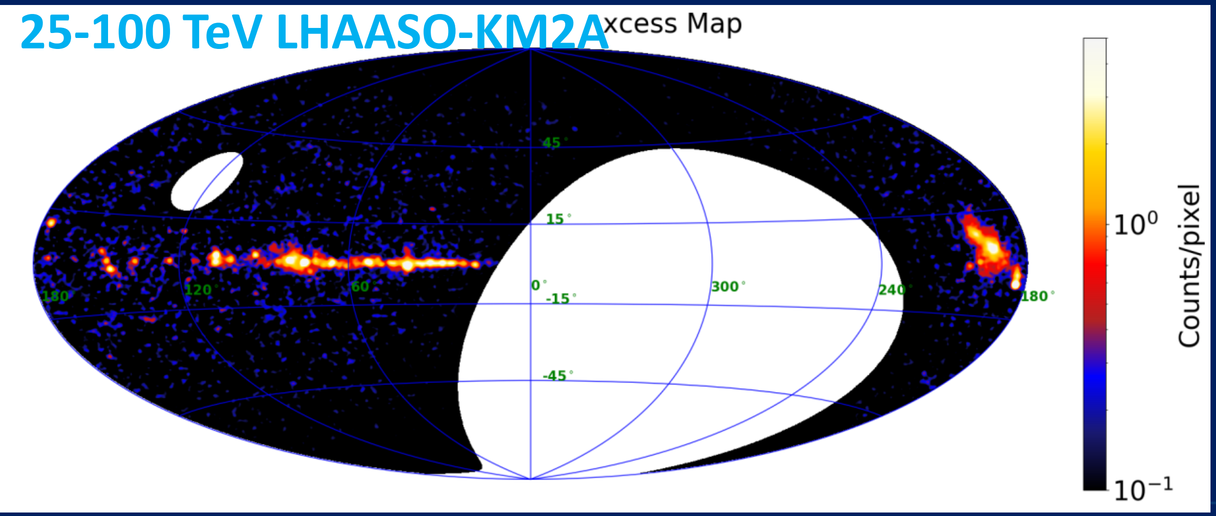
- **Area:**
  78,000 m^2
- **Detector units:**
  3120
- **Energy Range:**
  0.1-10 TeV

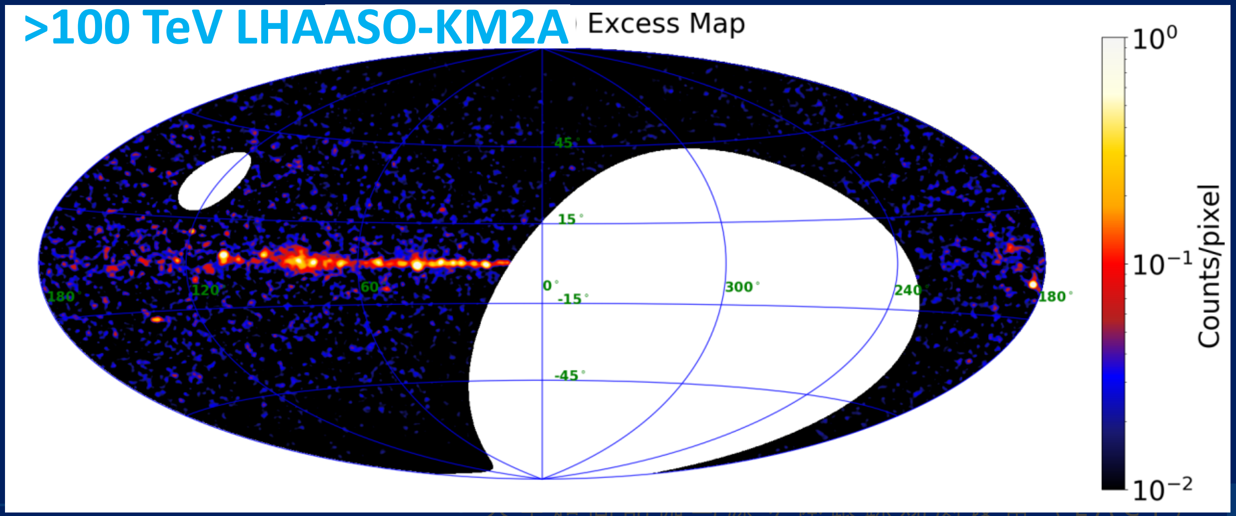
UHE γ-ray Astronomy: sources and diffuse emission

➢ **Survey discovered 30+ new sources, 40+ PeVatrons and diffuse γ-ray emission**

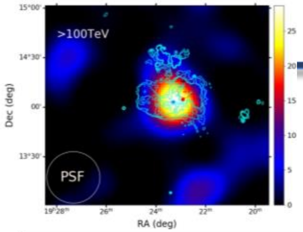








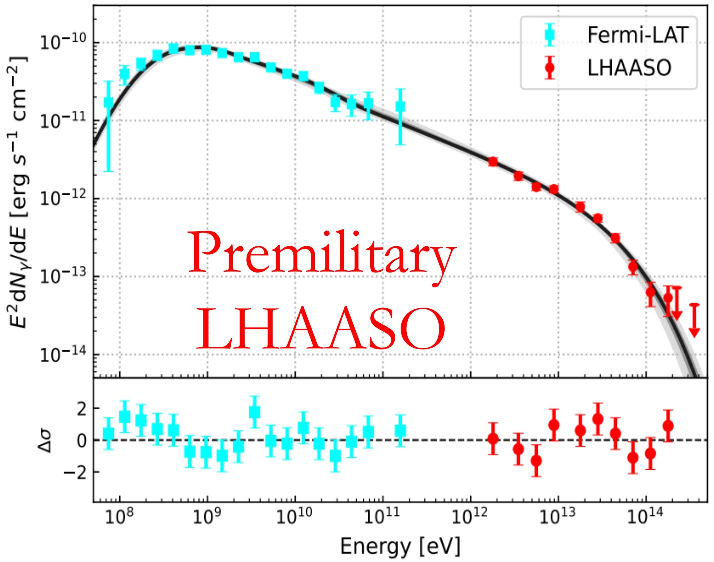
Possible Source Candidates



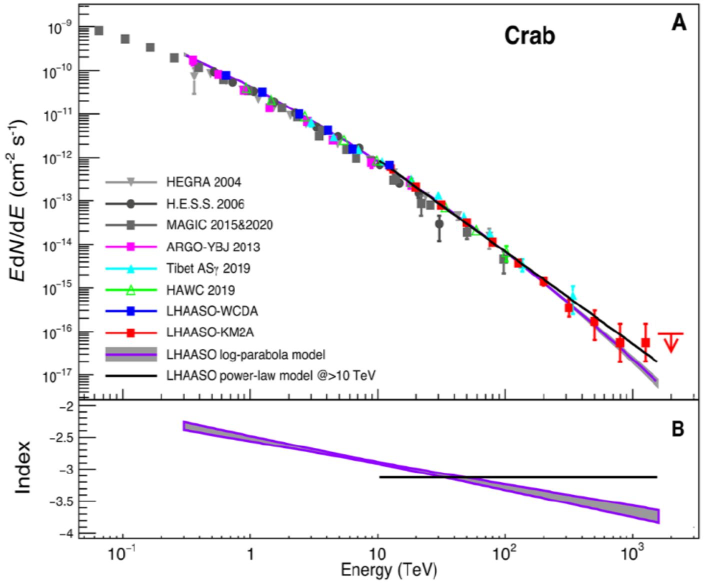
W51C

Crab

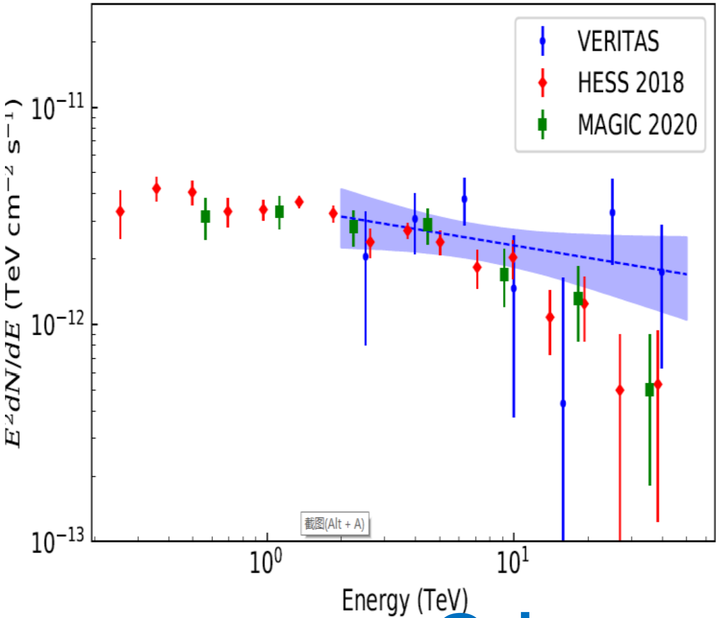
G.C. by IACTs



SNR



PWN



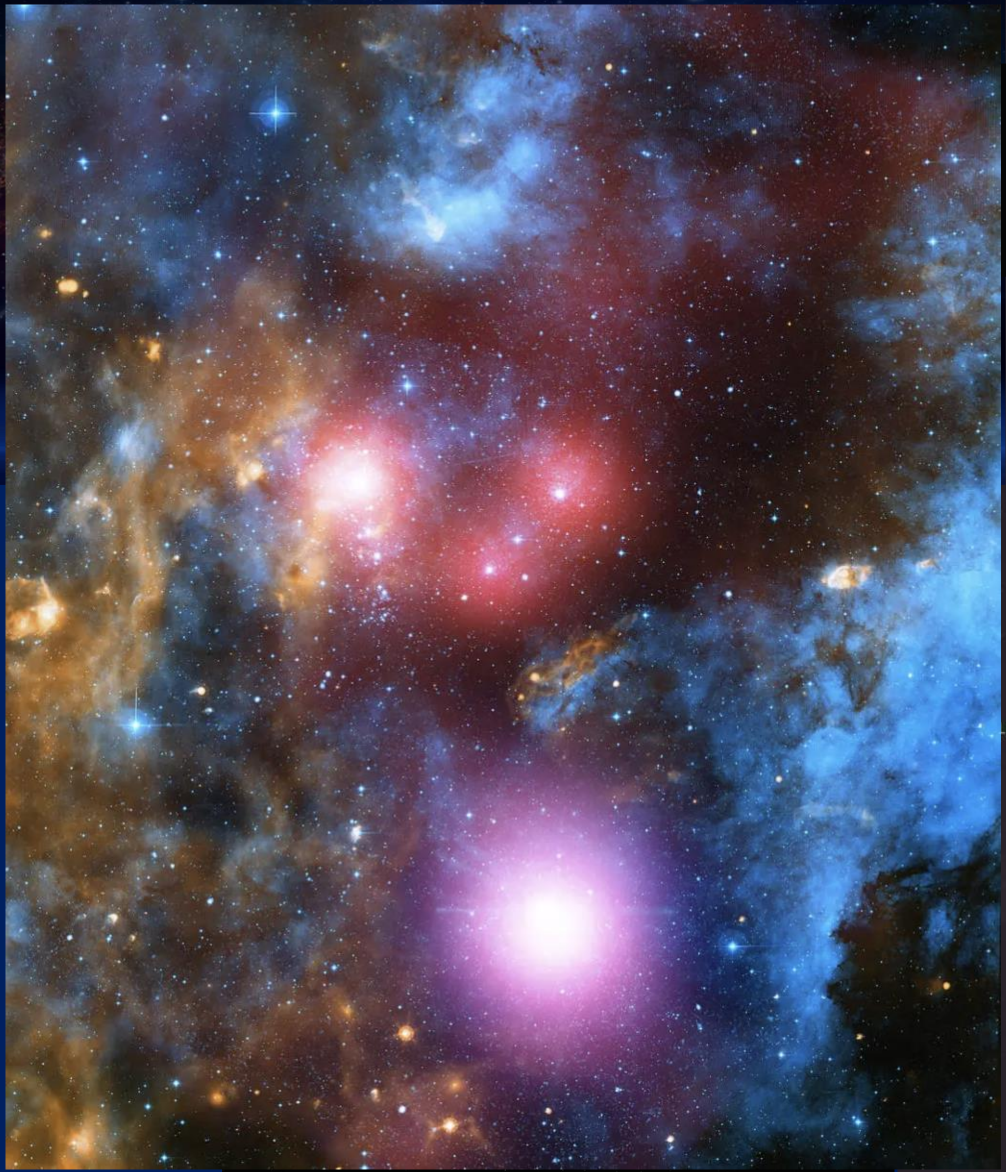
Other sources

...

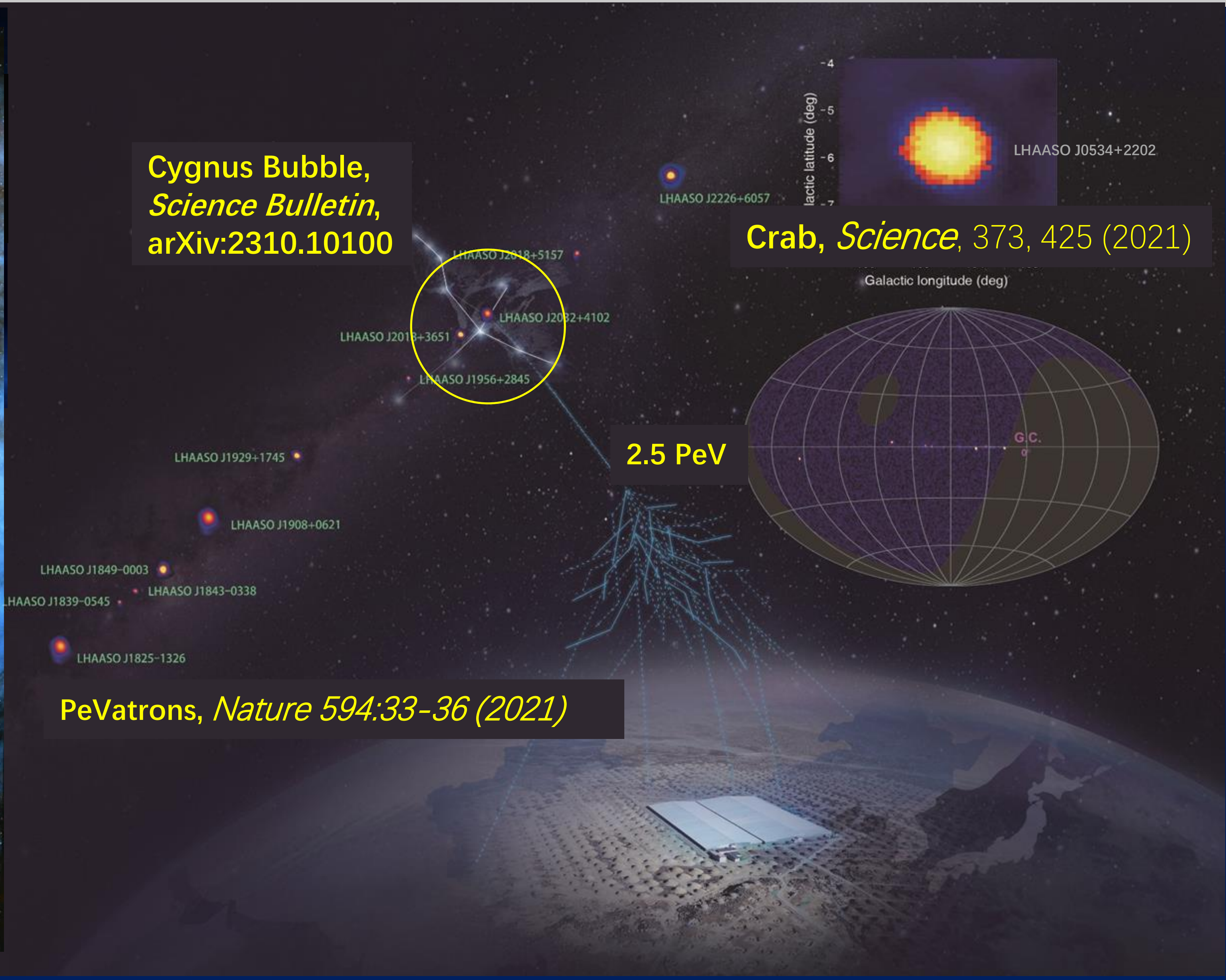
Many types of sources have the potential to accelerate particles to 1 PeV and above

A&A 671, A12 (2023)
Science 10.1126/science.abg5137 (2021).
The Astrophysical Journal, 913:115 (11pp), 2021 June 1

The 1st CR-Source Candidate by LHAASO

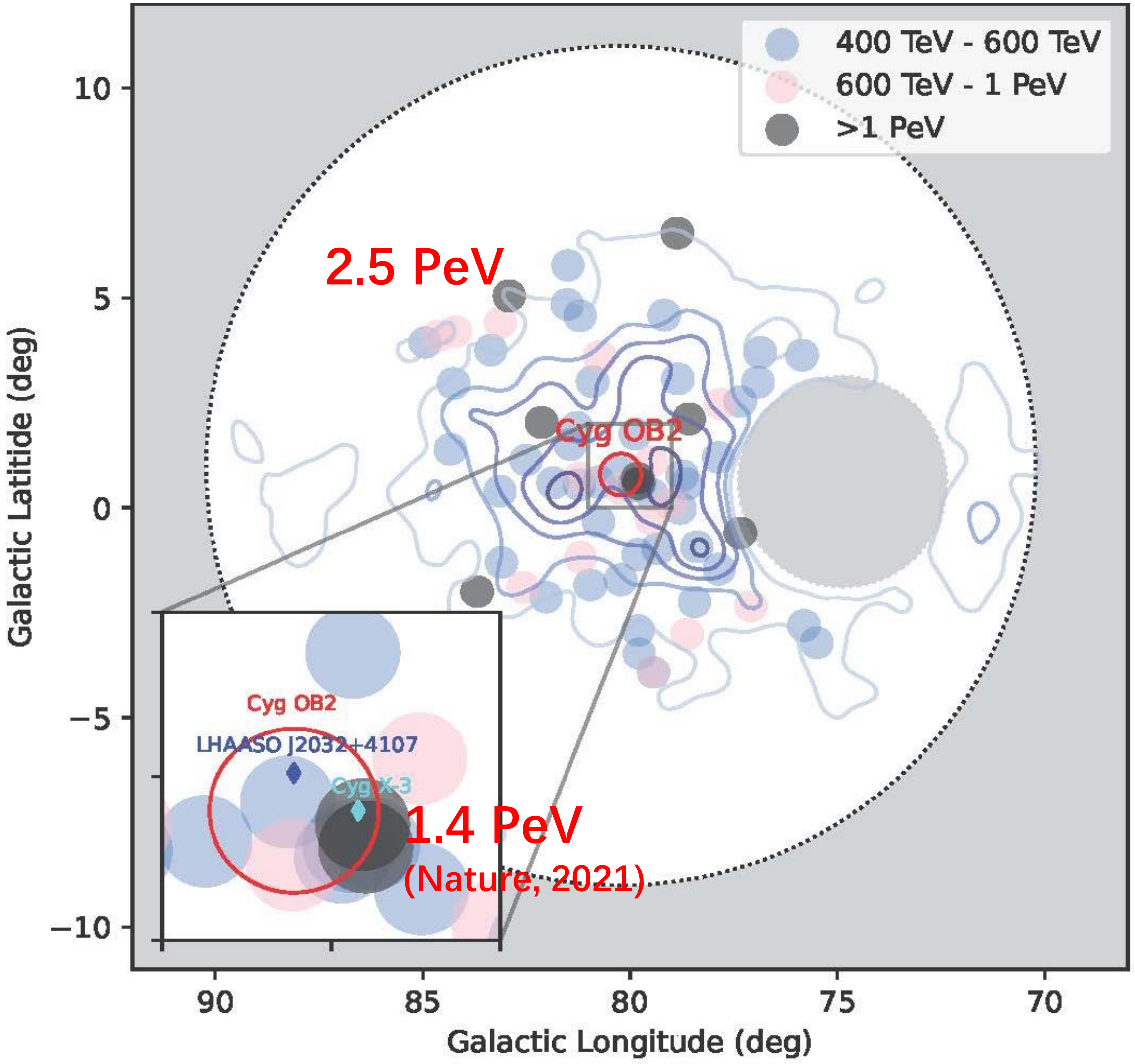


For the first time in the world LHAASO observed



A Bubble of UHE γ's centered at a complex core

Cygnus OB2, binary J2032+4107, MQ X-3



8 γ's above 1 PeV!

Energy (TeV)	Ne	Nu	Theta (deg)	Dr (m)
1087	5904	13	19.4	143
1188	5480	14	34.4	73
1208	6939	13	14.2	131
1350	6938	8	27.1	43
1379	6469	9	17.4	52
1421	6258	7	12.7	57
1784	6665	13	18.0	41
2481	13815	29	33.0	99

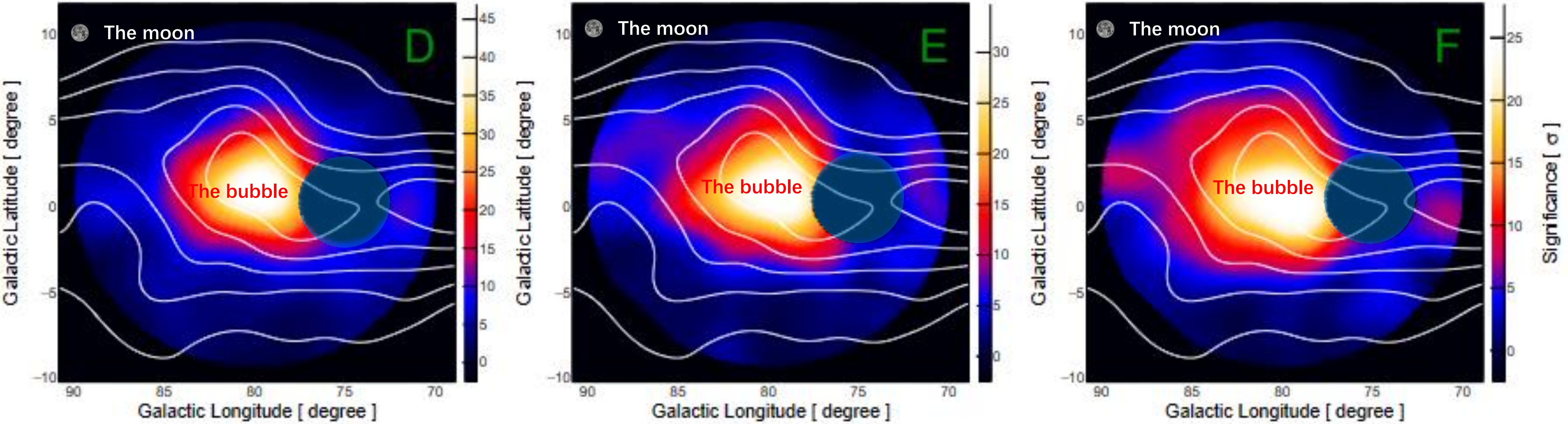
- PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

Association with HI gas distribution over ~200 pc

- The significance map is smoothed with a Gaussian kernel=1.0°
- The contour is from HI4PI 21-cm line survey

◆ Clear correlation with gas distribution indicating a hadronic origin of photons in the Bubble

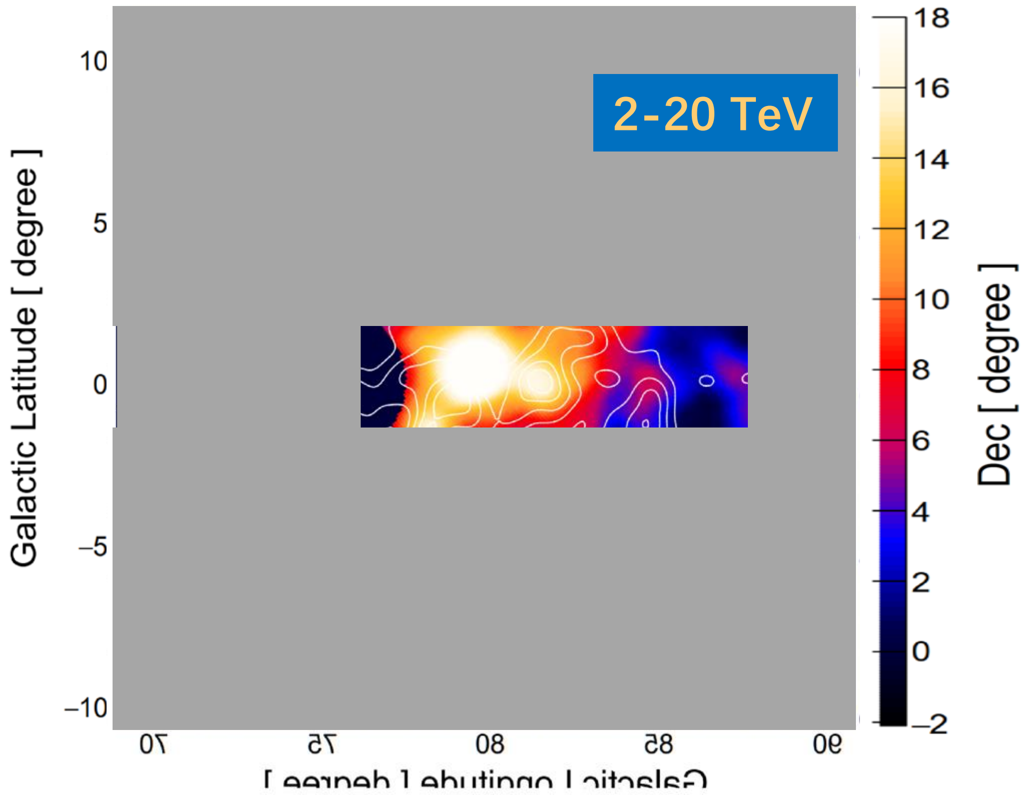
◆ The signal is elongated along the disck and extends to 10°

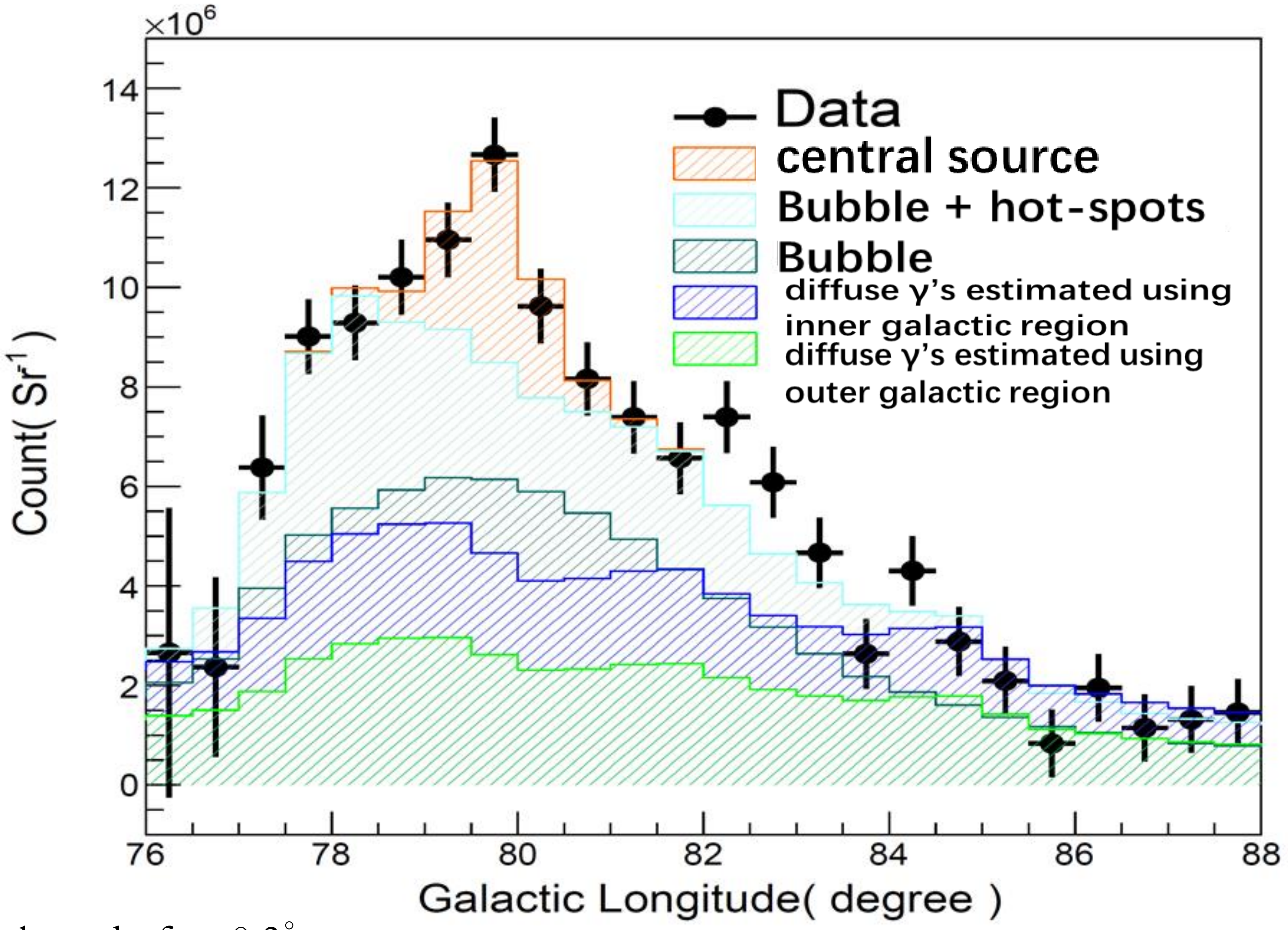


The Bubble at 2-20 TeV by WCDA

1-D Flux in ±2°

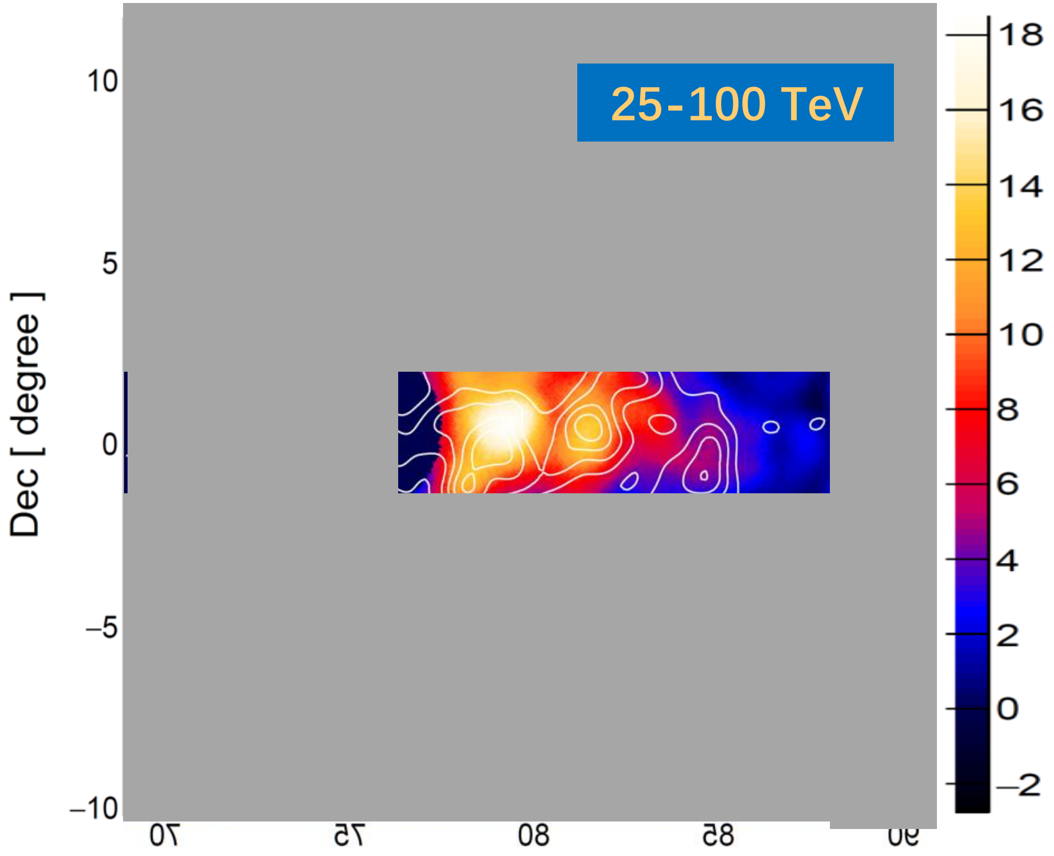
Clampy structure of the Bubble: hot spots

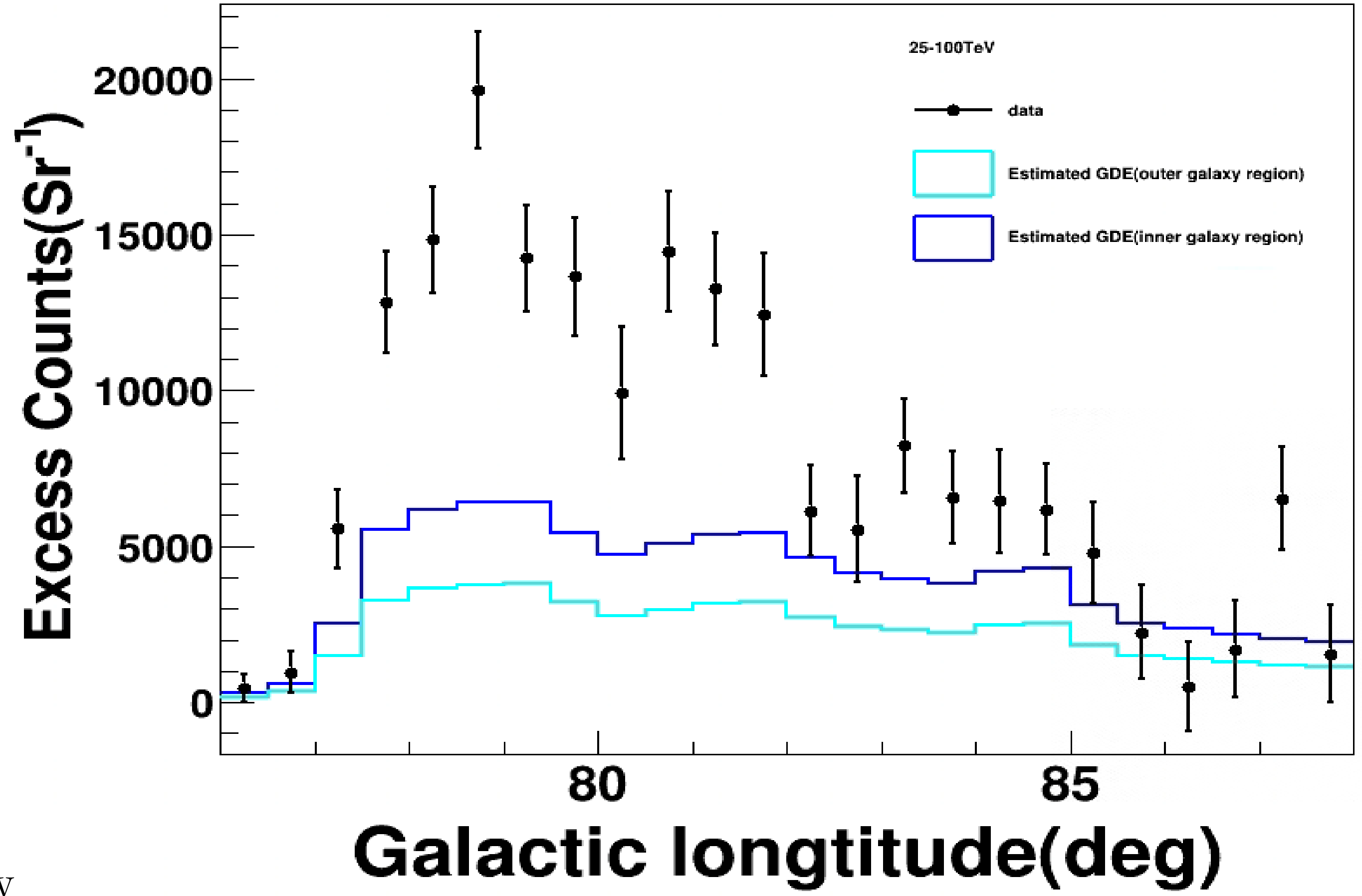




- The contour is from CfA galactic CO survey
- The significance map is smoothed with a Gaussian kernel of σ=0.3°

The Bubble at 25-100 TeV by KM2A 1-D Flux in ±2°





- The contour is from CfA galactic CO survey
- The significance map is smoothed with a Gaussian kernel of σ=0.3°

LHAASO measured the Galactic Diffuse Emission

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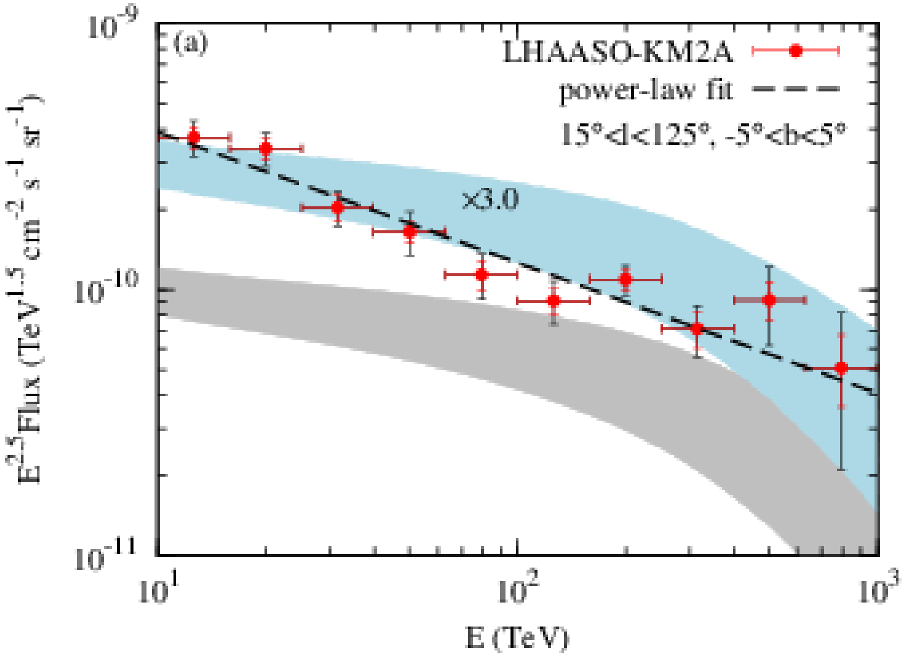
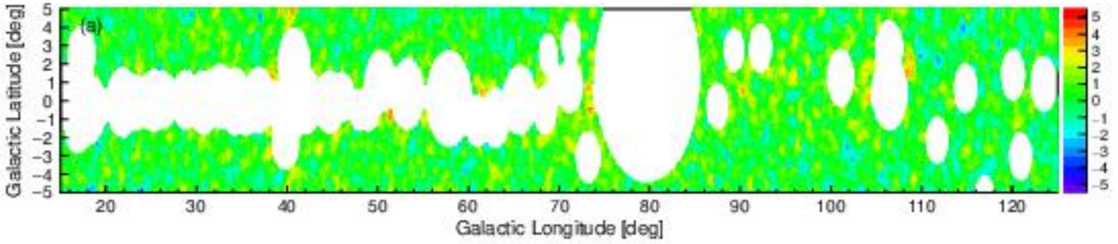
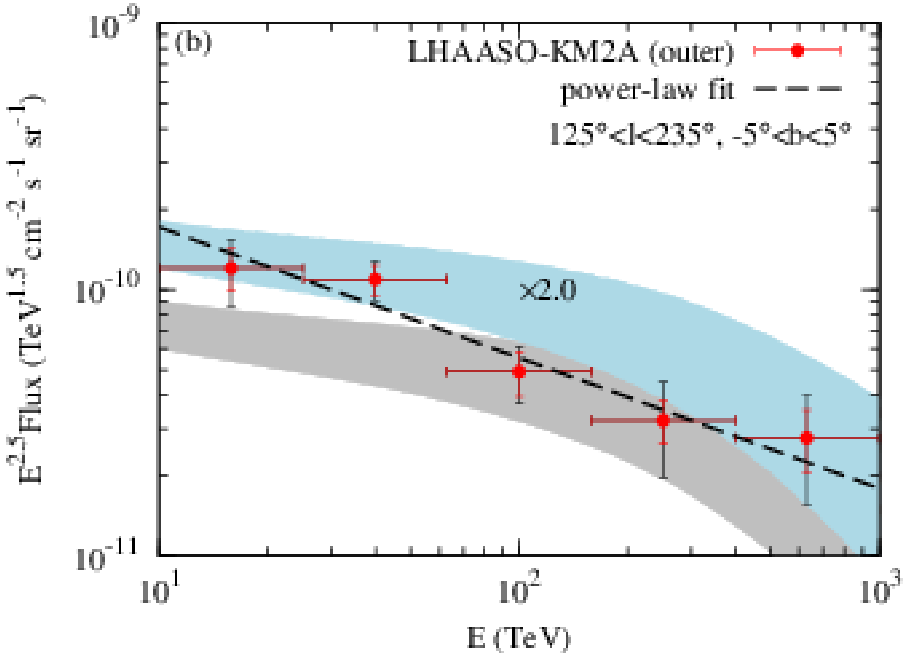
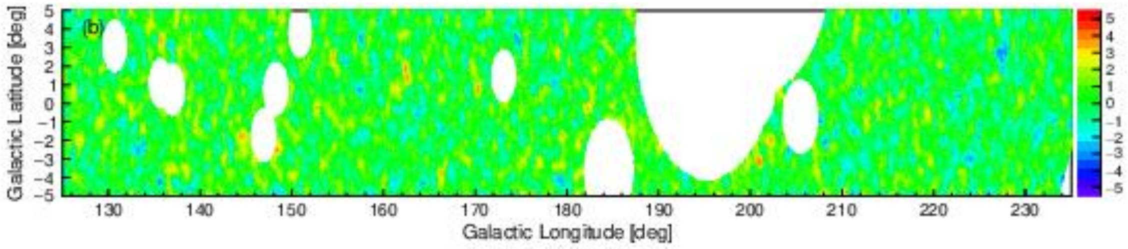
Inner Galactic Region



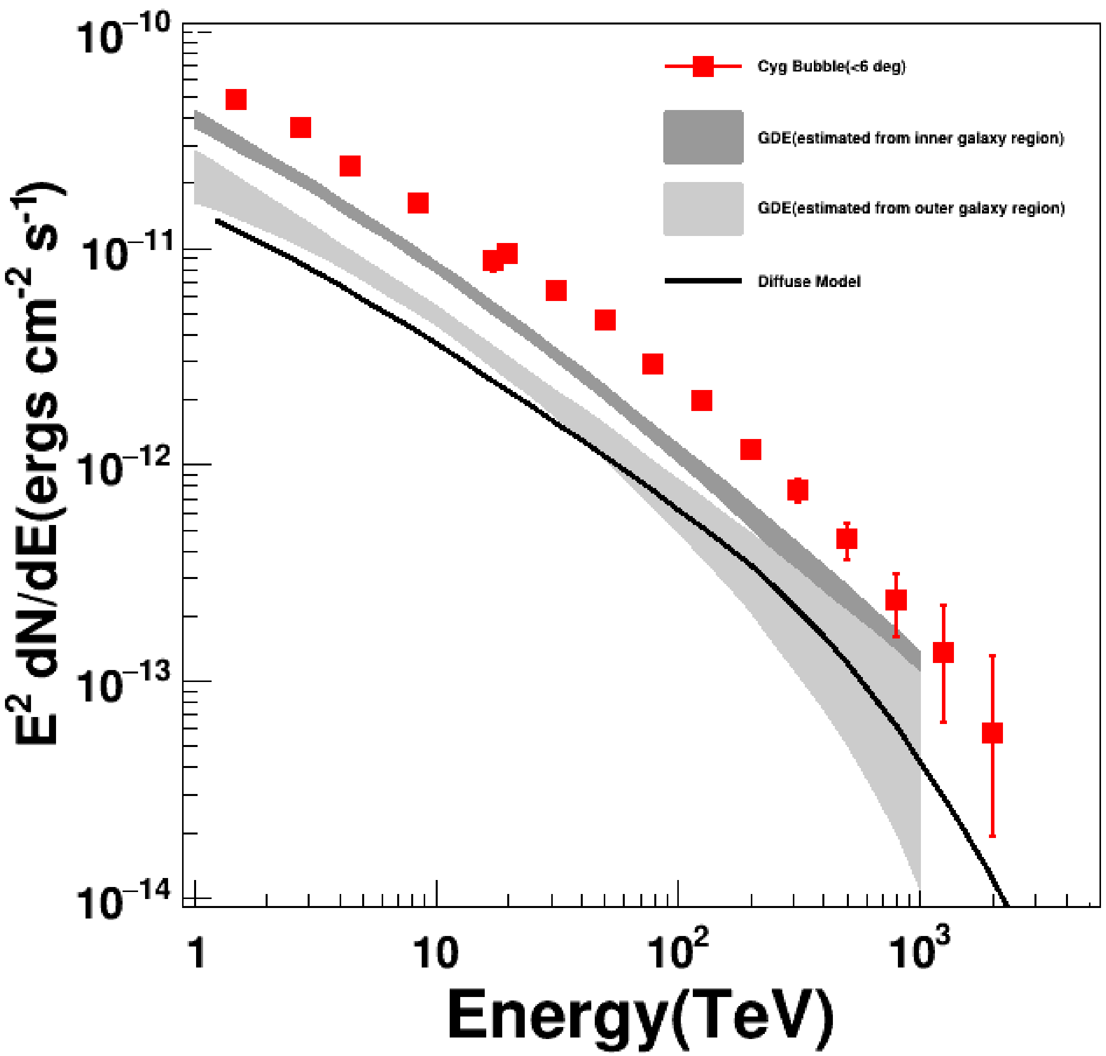


Outer Galactic Region





Spectral Energy Distribution of the Bubble

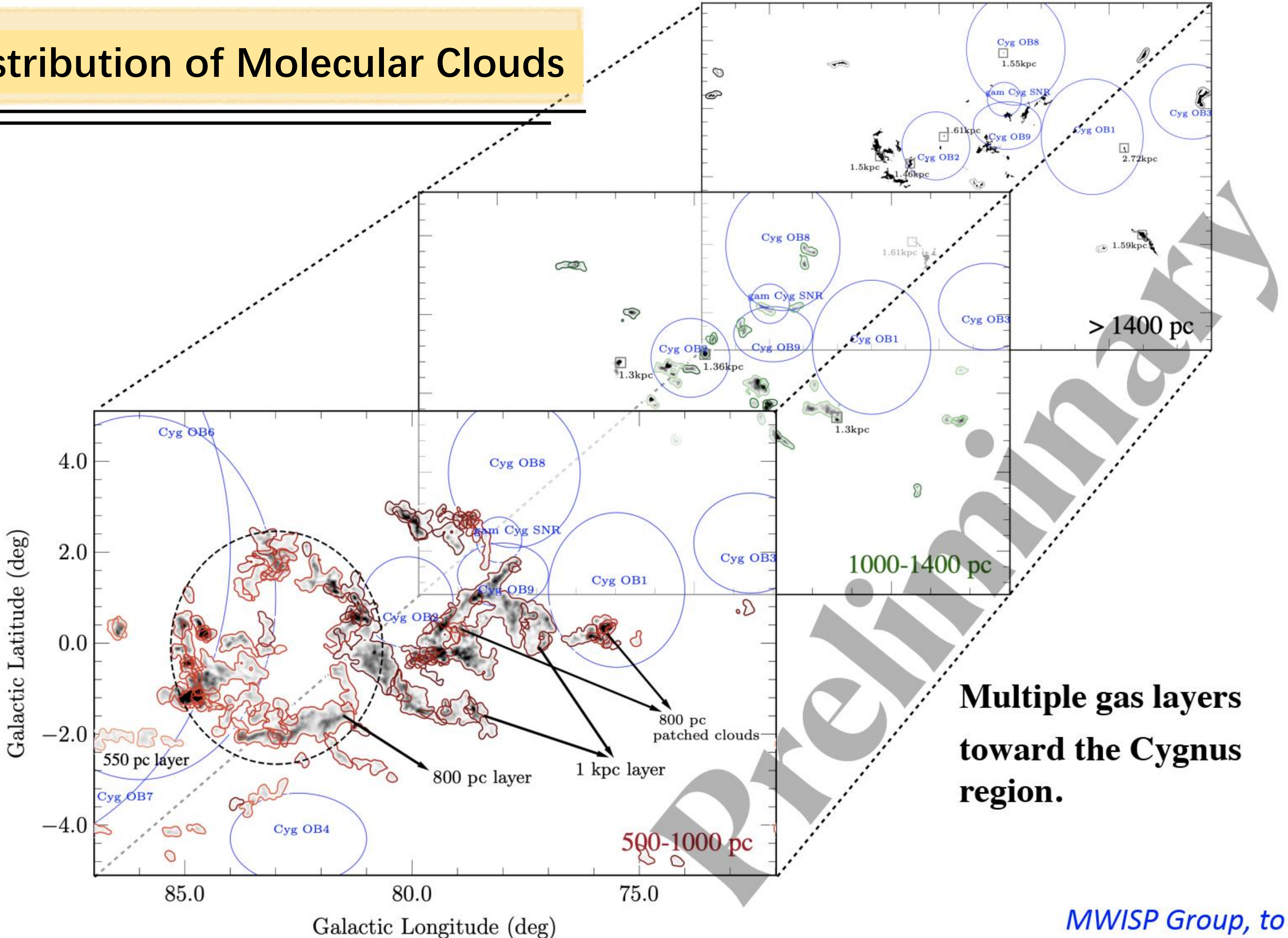


Energy Bin	Non	Nb
400TeV-630TeV	42	6.8
630TeV-1PeV	14	1.9
1PeV-1.6PeV	6	0.6
1.6PeV-2.5PeV	2	0.2

Almost background free

- The spectrum spans 3 decades up to 2 PeV
- Spectral index ~ 2.7
- No indication of cut-off in the spectrum

3-D distribution of Molecular Clouds

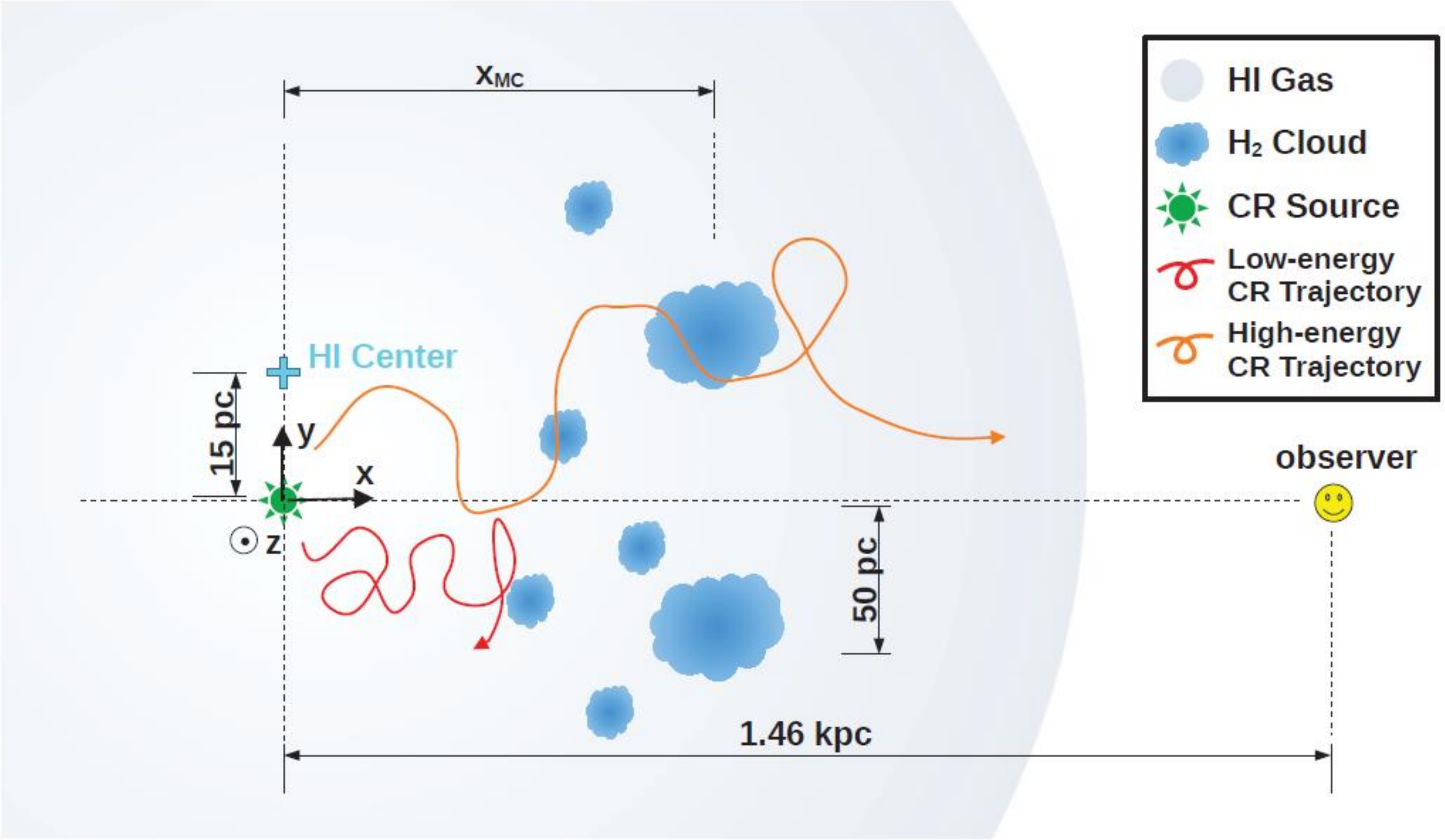


Multiple gas layers toward the Cygnus region.

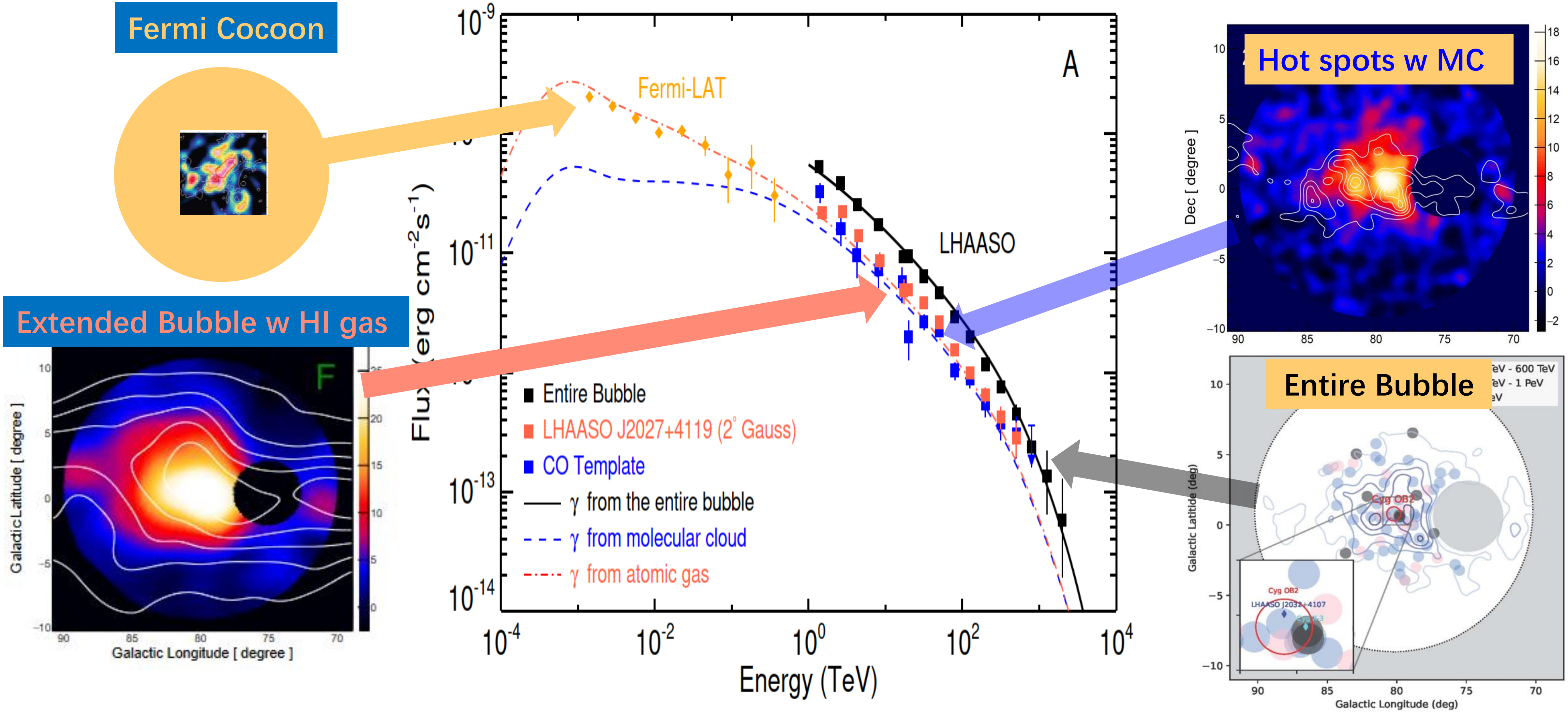
MWISP Group, to be submitted

HE Protons injection from the core region

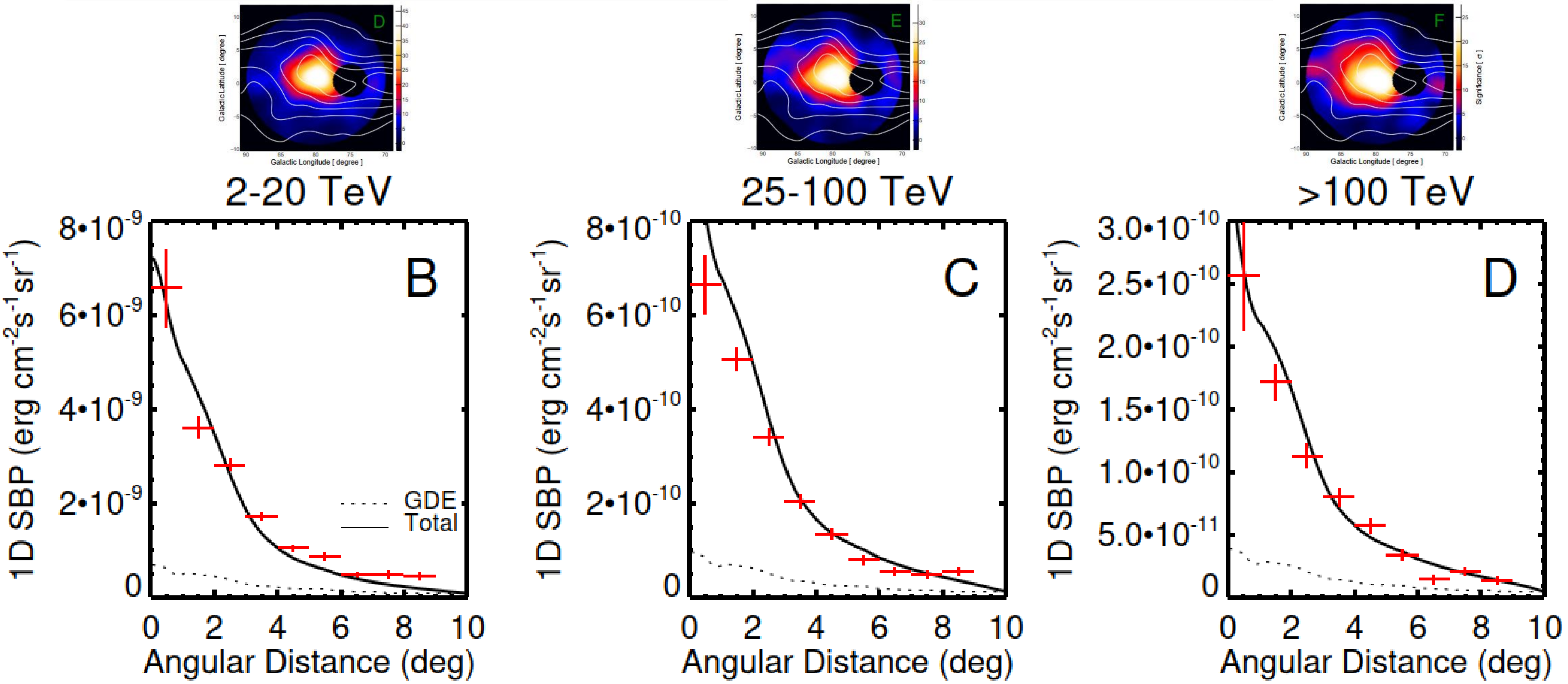
- High energy cosmic rays escape from the accelerator in the core
- Diffusing through the H1 gas and producing γ's in p-p collisions
- Hitting on clampy molecular clouds making hot-spots
- Slow diffusion ~1%DC in ISM



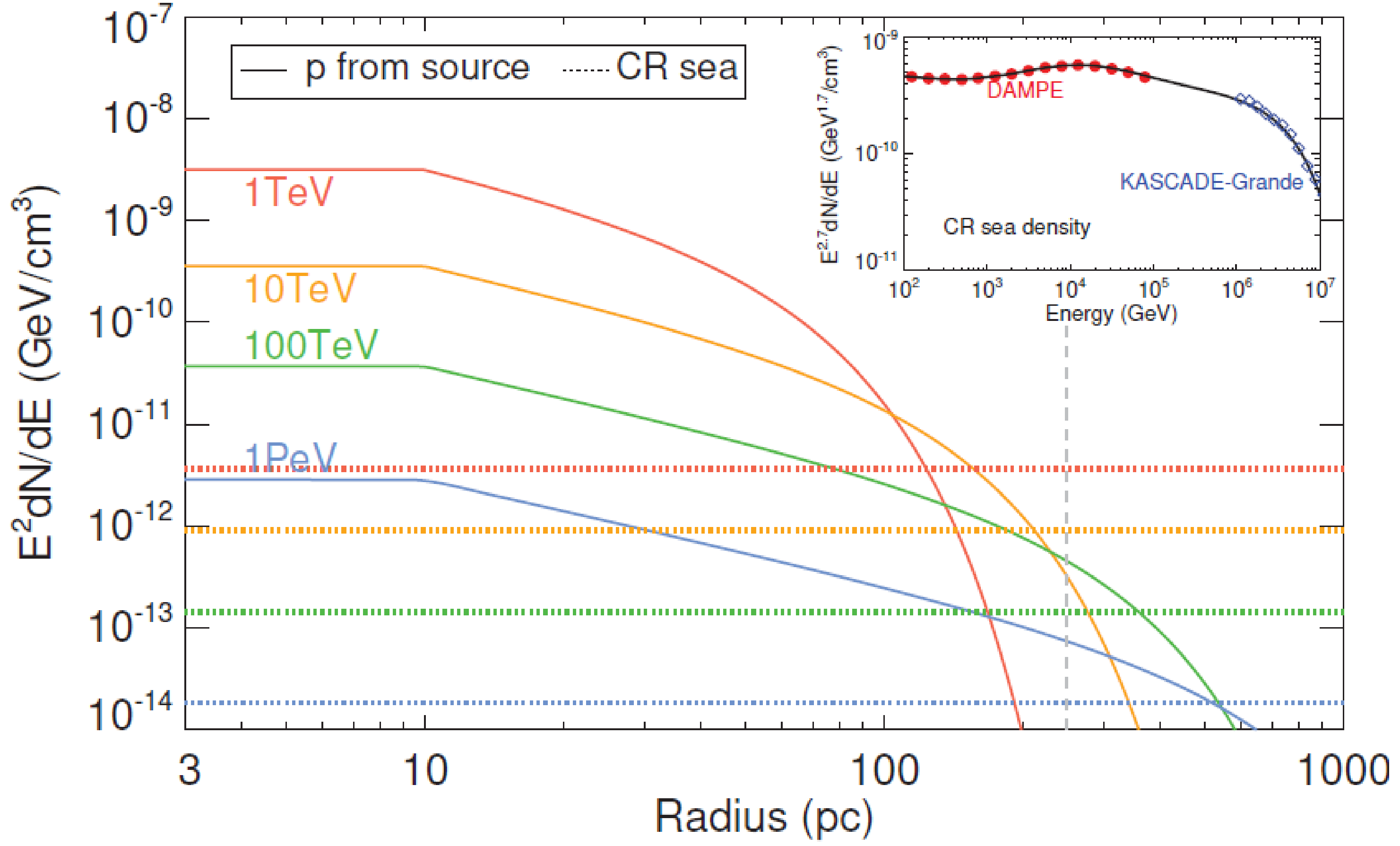
Model w 3 components : SED over 8 decades



Model: Diffuse CR’s generate γ’s Spatial Profile over 10° from the core



Derived Cosmic Ray bubble over ~200 pc

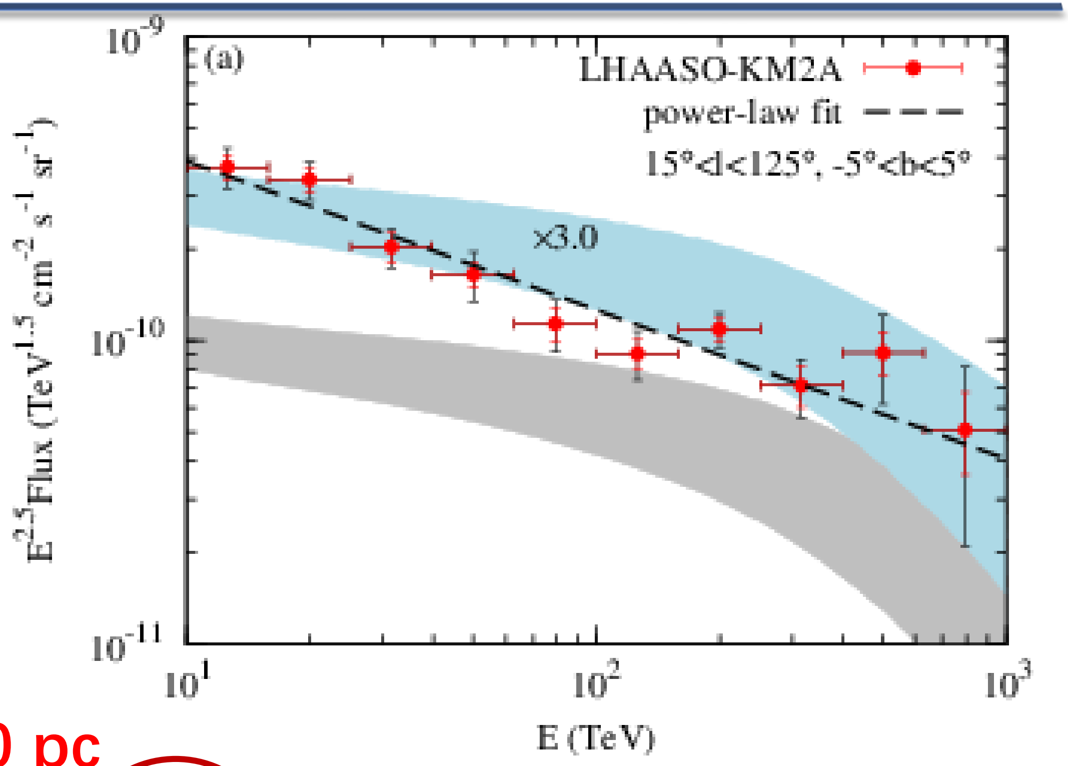


- There is a large cosmic ray bubble
- A rather small propagation ecoefficiency around the source
- The size of the visible bubble depends on the level of diffuse γ-rays

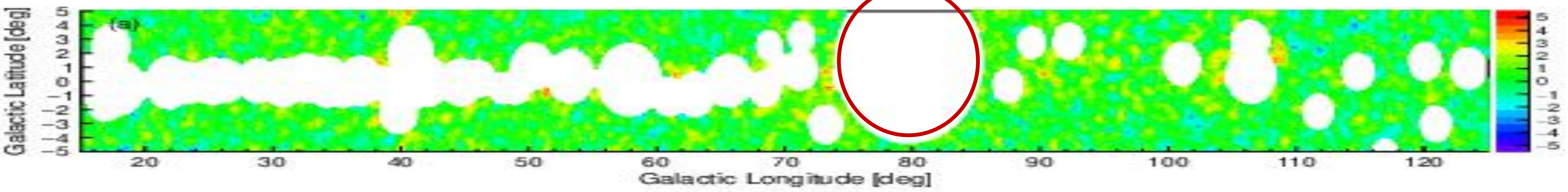
The Galactic Diffuse Emission is X3 higher than the expectation

Inner Galactic Region

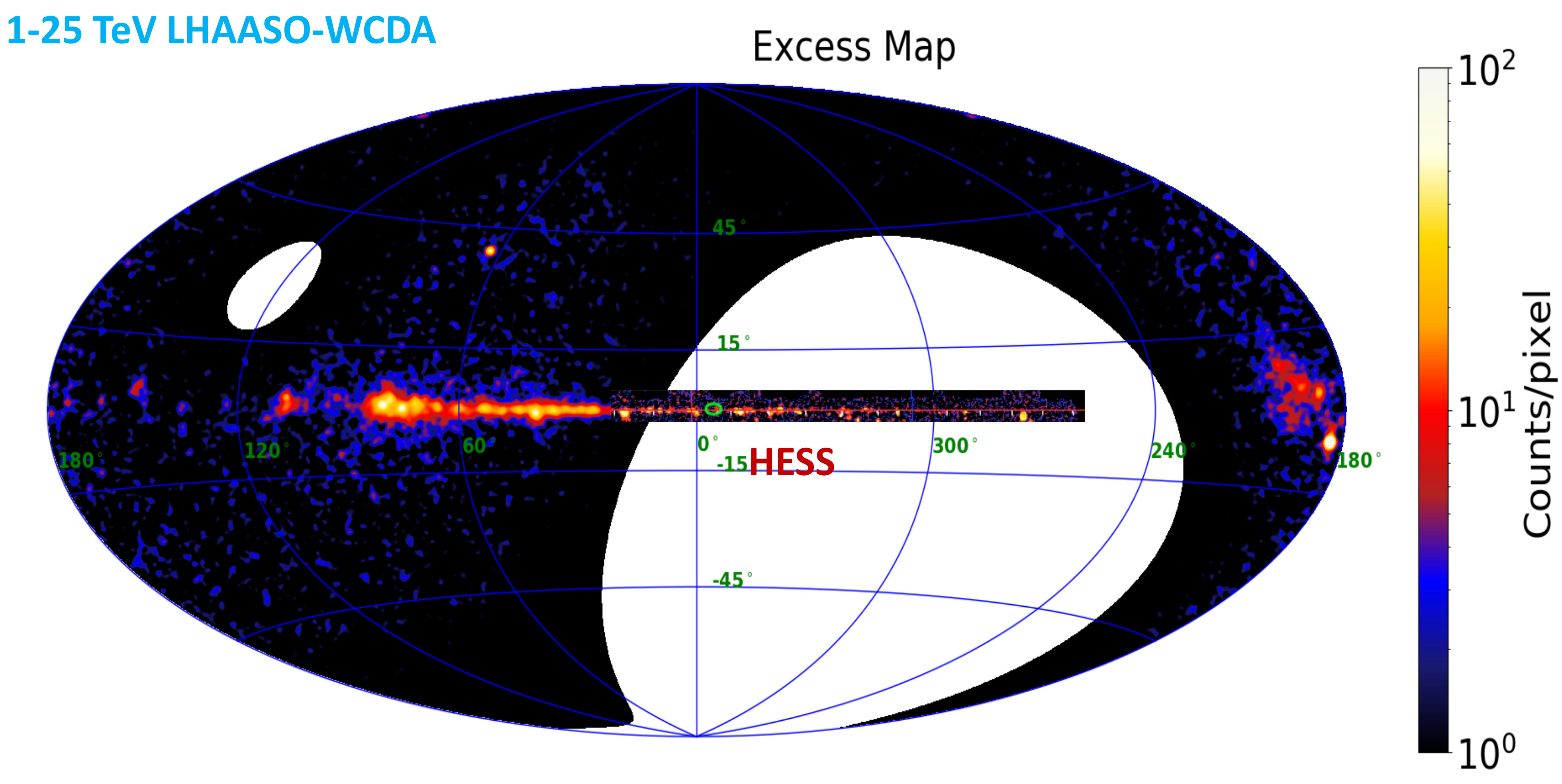
- Likely to be the extension of bubbles
- Cygnus bubble is a good example



150 pc

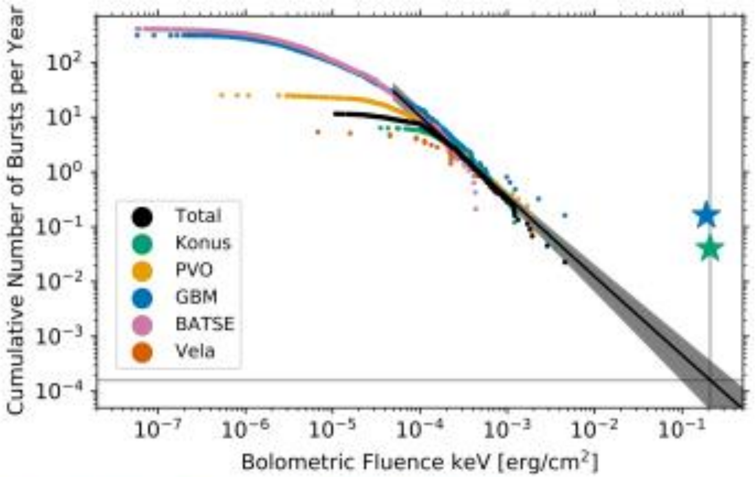


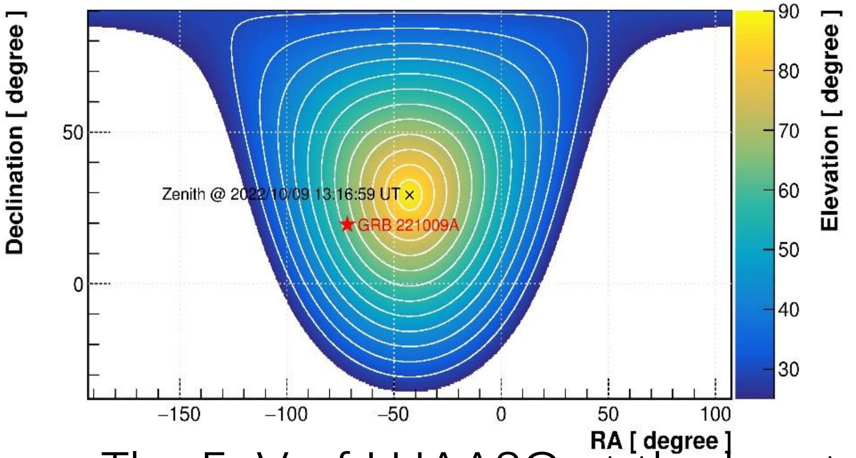
Extra-galactic sources: ~12, AGNs



GRB 221009A:
The brightest of all time

- Highest fluence / peak flux (An et al. 2023)
- Nearby
- Highest energy / peak luminosity (An et al. 2023)
- Once a 1,000/10,000 yr event (Burns et al. 2023)





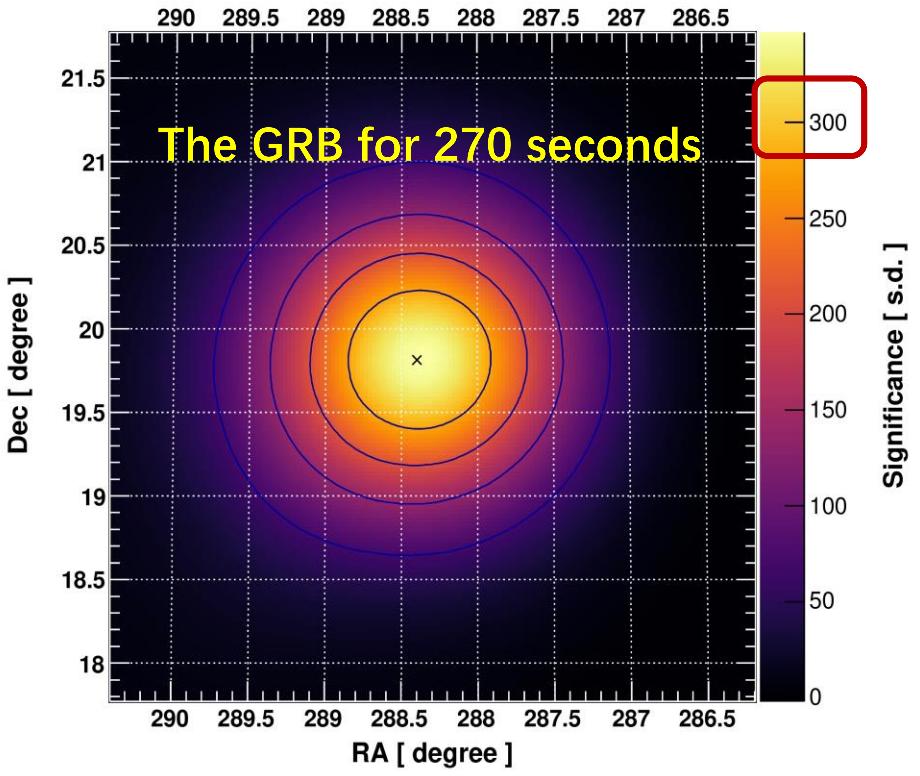
The FoV of LHAASO at the burst

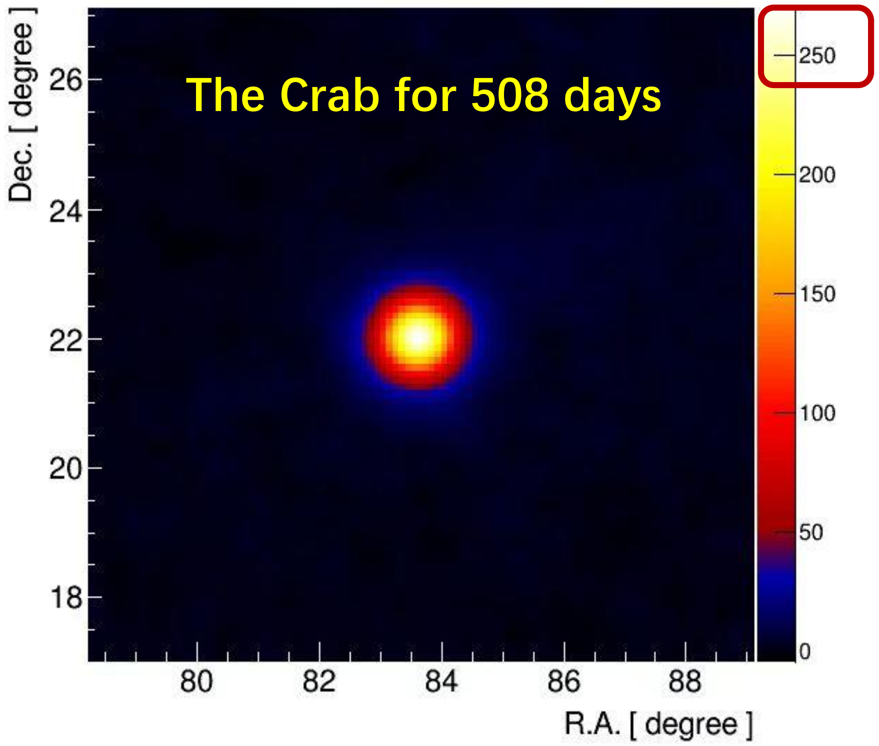
By Bing Zhang

Even much less chance for it in the middle of FoV of LHAASO

- The burst of 64k photons in **270 seconds**

versus the exposure of the Crab for 508 days

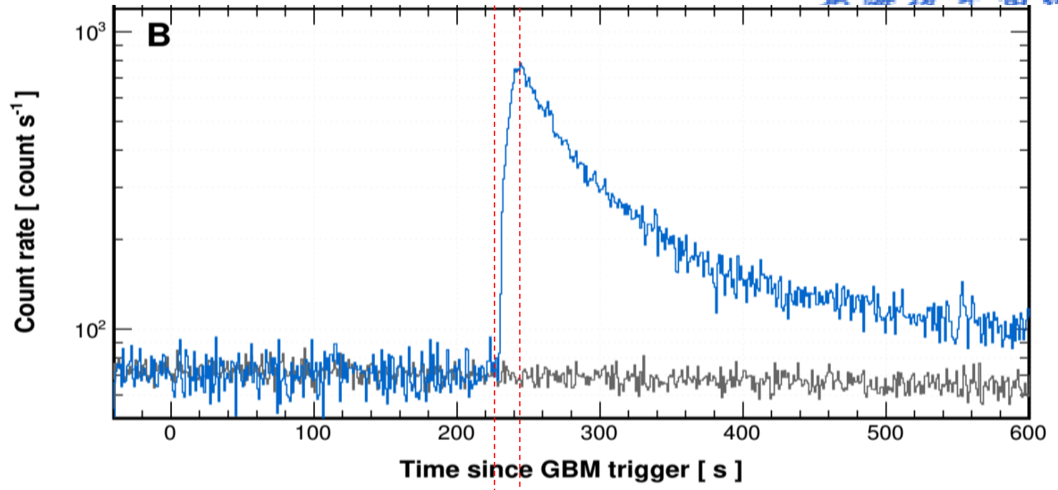


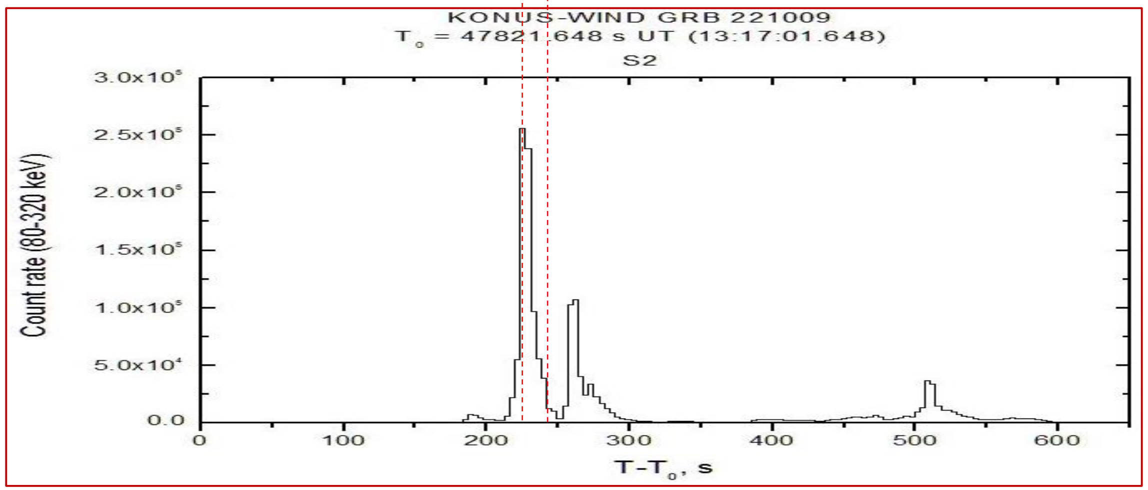


Onset of the afterglow

- LHAASO on GRB 221009A: the 1st GRB seen by EAS detector
- Light curve: complete temporal profile at TeV

  — **dominated by the external shock origin**

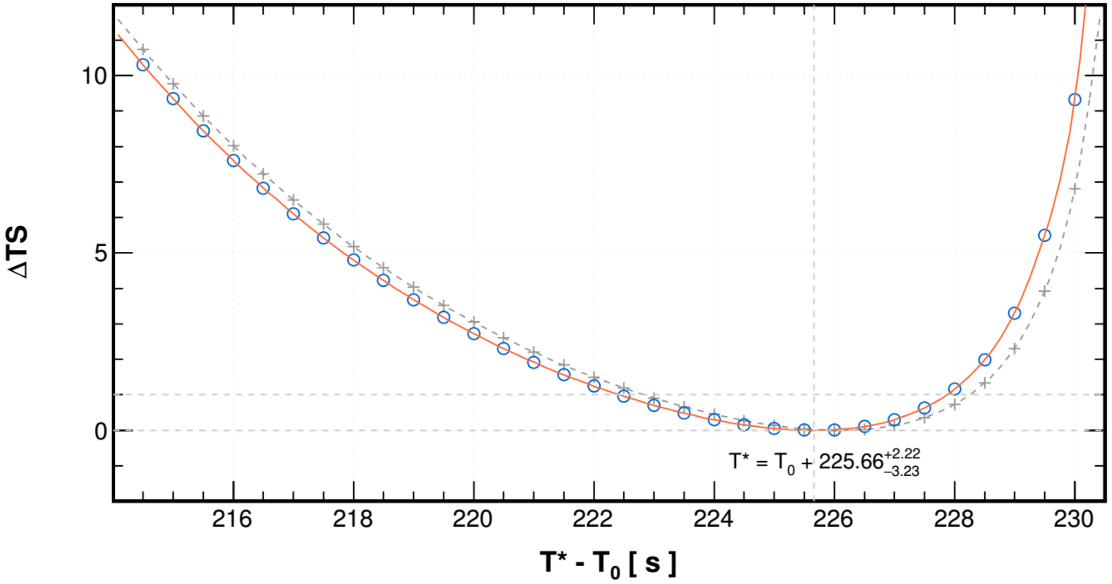


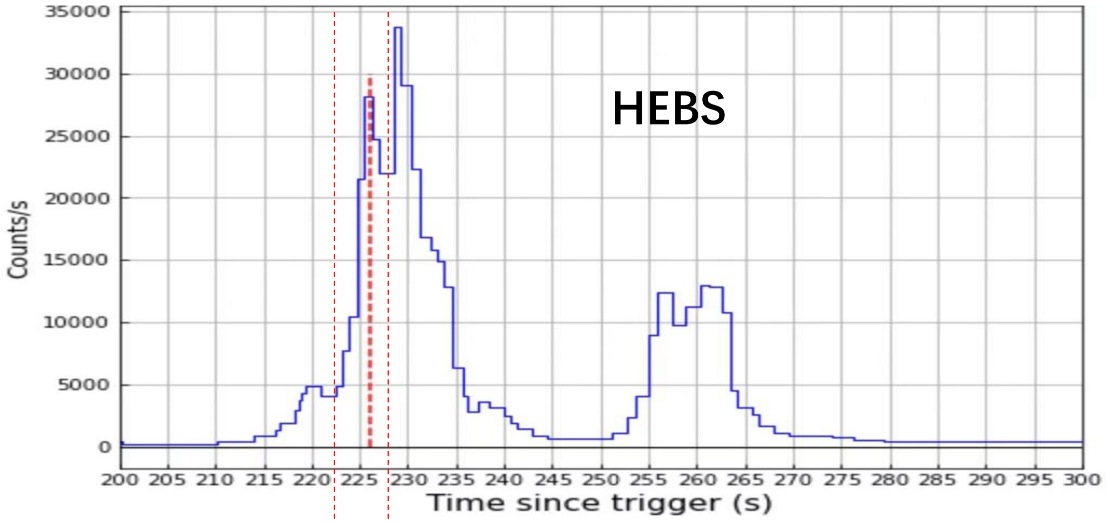


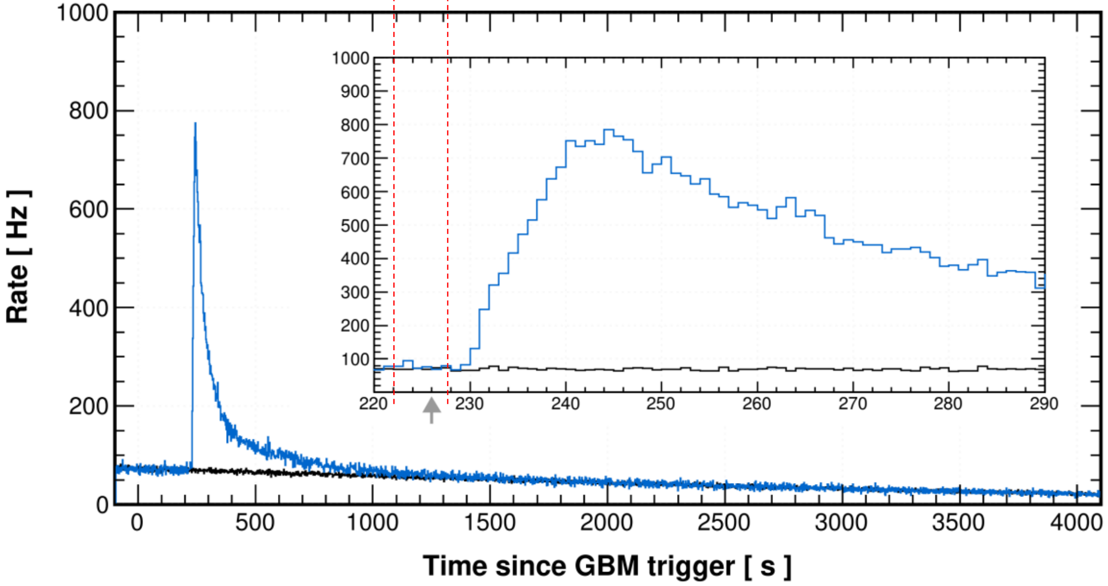
Reference time T*

- The reference time: T* ≈ 225–228 s
- A good approximation of T* is the main burst in prompt phase (Lazzati, Zhang…)
- Fitting of LHAASO light curve:

$$T^{*} \approx 226_{-3}^{+2} \ \ s$$







What we've learnt from the GRB 221009A

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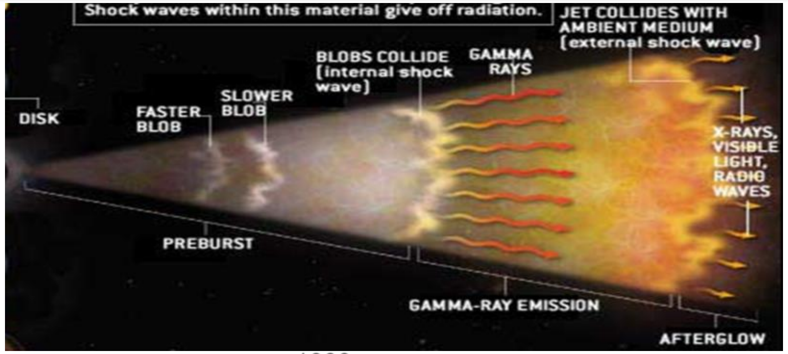
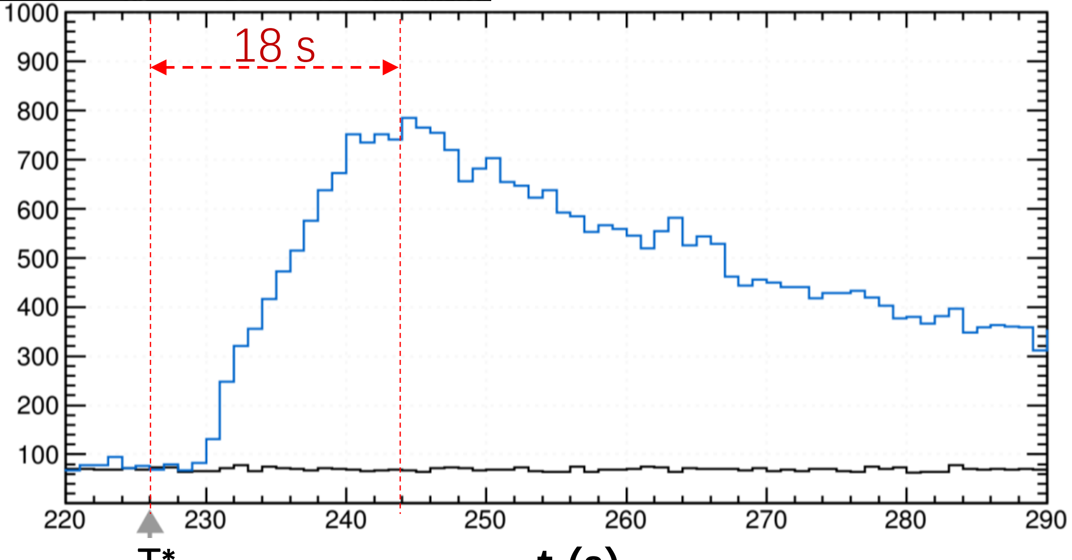
R ~ 10^{15} cm 10^{18} cm

1. The initial bulk Lorentz Factor of the ejecta





- From the time when the main prompt emission reaches the peak flux (~T*) to the moment when the afterglow reaches the peak, it takes

~18 s

- The initial bulk Lorentz factor is estimated as

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

LHAASO
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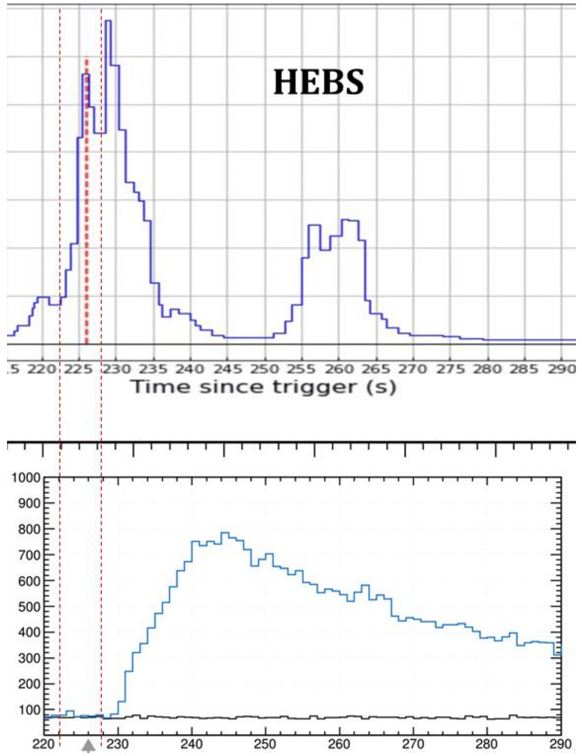
2. Upper limit on emission in TeV band in prompt phase

- The most strict limit on the TeV prompt emission before T*

$$R = F_{TeV} / F_{MeV} < 3 \times 10^{-5}$$

- As a consequence, the jet might be highly magnetized



Implying a low Compton ratio

Assuming the internal dissipation radius ~10^{15} cm,
according to the scale of variability of the prompt emission

$$Y \equiv L_{\rm SSC}/L_{\rm syn} \sim \bar{R}/(f_{\gamma\gamma} f_{\rm spec}) \leq 1.6 \times 10^{-3} R_{\rm in,15}^{-1} f_{\rm spec}^{-1}$$

$$\overline{Y} \approx Y(\gamma_m) \approx \frac{\epsilon_e}{\epsilon_B} \begin{cases} 1 & \frac{\gamma_m}{\widehat{\gamma_m}} < (p-2)^2 \\ (p-2)\left(\frac{\gamma_m}{\widehat{\gamma_m}}\right)^{-1/2} & \frac{\gamma_m}{\widehat{\gamma_m}} > (p-2)^2, \end{cases}$$

→ $f_{\rm KN} \sim 0.1$

$$\epsilon_{\rm B,in} \geq 30 \epsilon_{\rm e,in}$$

magnetic field energy density is much larger than the energy of relativistic electrons

Favors a magnetically dominated jet

3. Rising phase

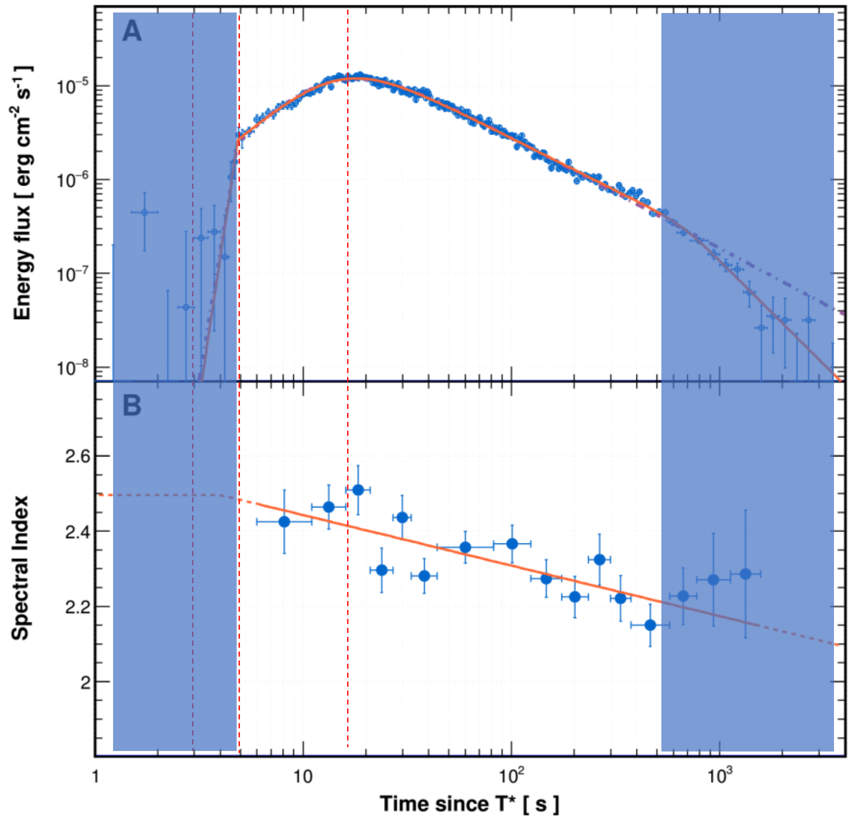
$$\alpha_1 = 1.82^{+0.21}_{-0.18}$$

- **Synchrotron Self-Compton mechanism** is implied by the broken power-law
- Light curve ~t^2 favors k=0 (ISM), and
  disfavors k=2 (stellar wind)

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

$$F_\nu = \begin{cases} F_m^{\rm IC}\left(\frac{\nu}{\nu_m^{\rm IC}}\right)^{-\frac{p-1}{2}} \propto t^{\frac{16-(9+p)k}{4}}\nu^{-\frac{p-1}{2}}, & \nu_m^{\rm IC} < \nu < \nu_c^{\rm IC} \\ F_m^{\rm IC}\left(\frac{\nu}{\nu_c^{\rm IC}}\right)^{-\frac{1}{2}} \propto t^{\frac{8-3k}{4}}\nu^{-1/2}, & \nu_c^{\rm IC} < \nu < \nu_m^{\rm IC} \\ F_m^{\rm IC}(\nu_m^{\rm IC})^{\frac{p-1}{2}}(\nu_c^{\rm IC})^{\frac{1}{2}}\nu^{-\frac{p}{2}} \propto t^{\frac{8-(2+p)k}{4}}\nu^{-\frac{p}{2}}. & \nu > \max(\nu_m^{\rm IC}, \nu_c^{\rm IC}) \end{cases} \quad (12)$$

- **The fast rising**: implying a free expansion with an increase of number of electrons accelerated at the external shocks



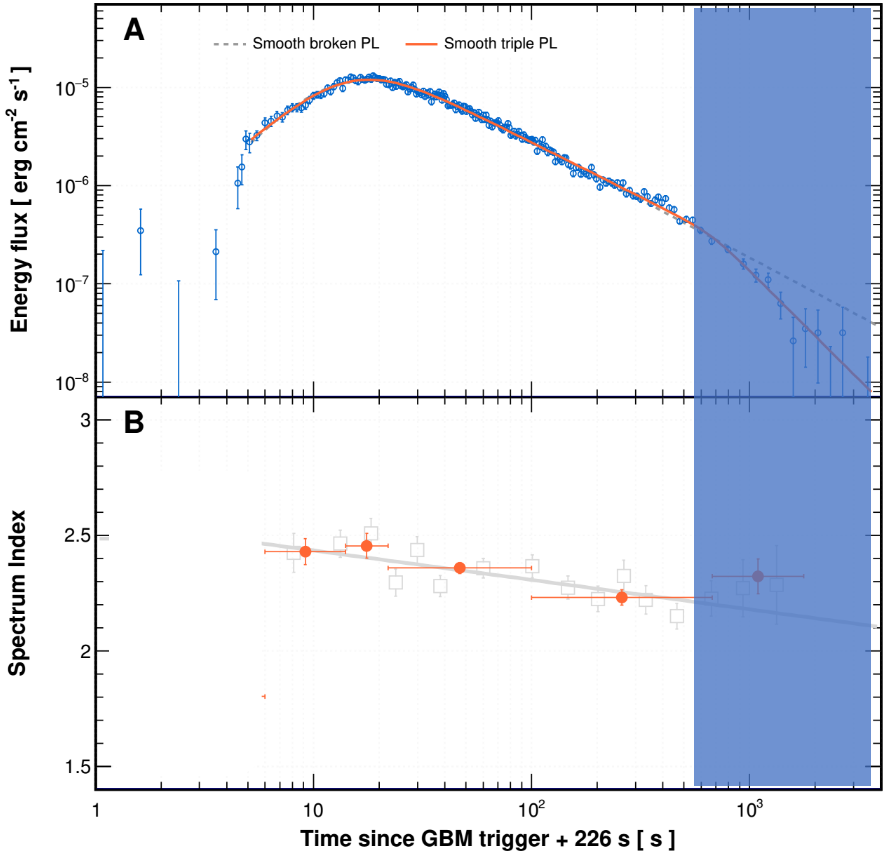
Decay phase: SSC

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

- Standard decaying behavior

$$F_\nu = \begin{cases} F_m^{\rm IC}\left(\frac{\nu}{\nu_m^{\rm IC}}\right)^{-\frac{p-1}{2}} \propto t^{\frac{11-9p}{8}}, & \nu_m^{\rm IC} < \nu < \nu_c^{\rm IC} \\ F_m^{\rm IC}\left(\frac{\nu}{\nu_c^{\rm IC}}\right)^{-\frac{1}{2}} \propto t^{\frac{1}{8}}, & \nu_c^{\rm IC} < \nu < \nu_m^{\rm IC} \\ F_m^{\rm IC}(\nu_m^{\rm IC})^{\frac{p-1}{2}}(\nu_c^{\rm IC})^{\frac{1}{2}}\nu^{-\frac{p}{2}} \propto t^{\frac{10-9p}{8}}, & \nu > \max(\nu_m^{\rm IC}, \nu_c^{\rm IC}) \end{cases} \quad (13)$$

$$dN_e/dE \propto E_e^{-p}, \quad p \sim 2.1$$

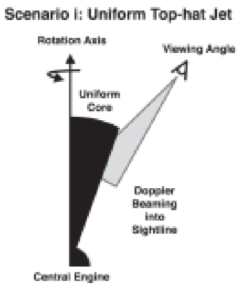


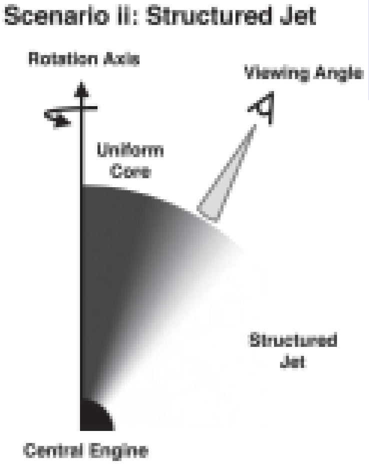
A fast component!

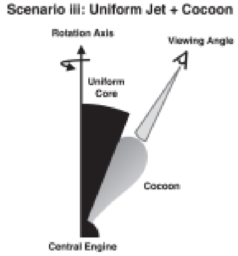
- **Very fine jet structure may be revealed at VHE ?**

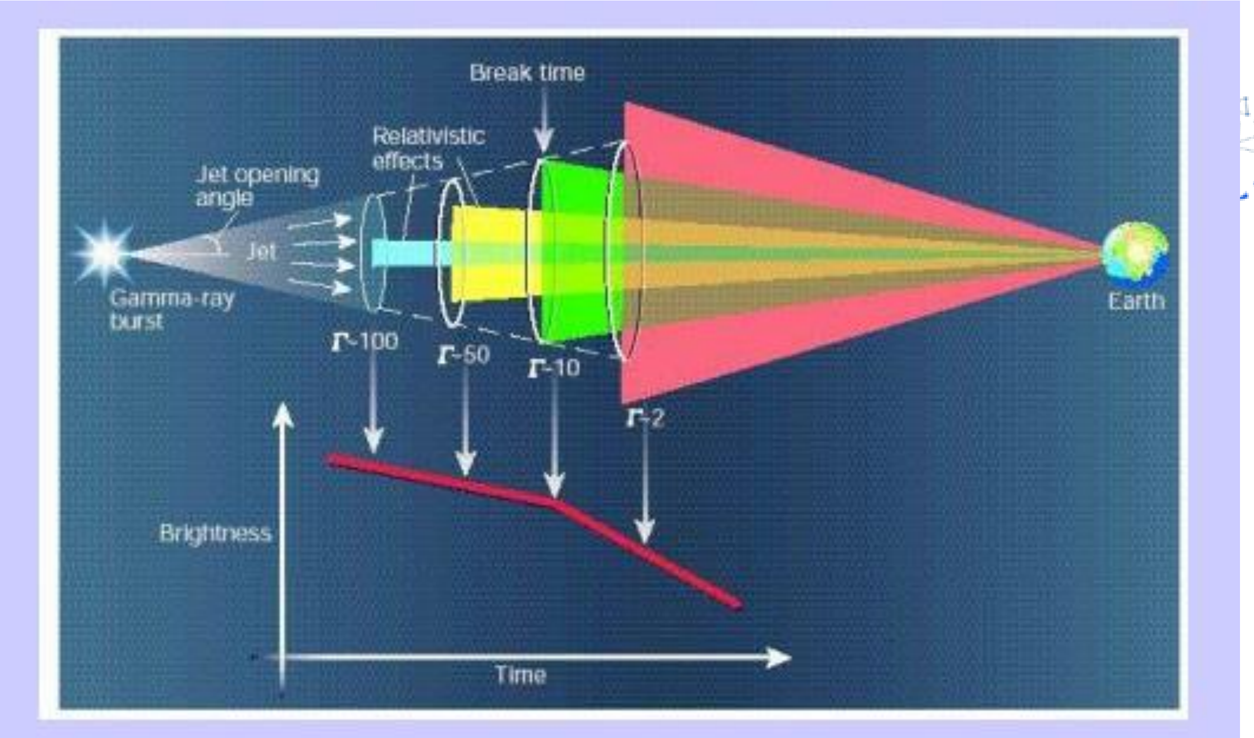
Jet Features

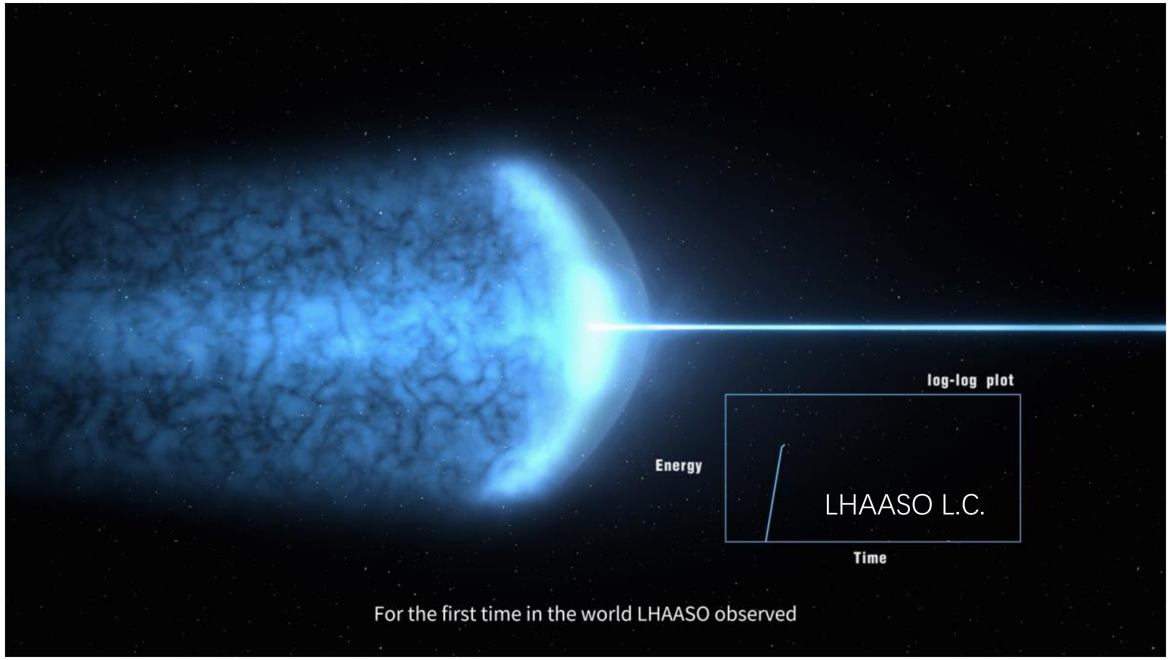
- Jet structure may be revealed at VHE band
- A “jet break” at high energy, indicated by the existence of the fast decay component, could be the evidence of the narrowest beam ~1°
- 1st time to see the HE “core” of the jet





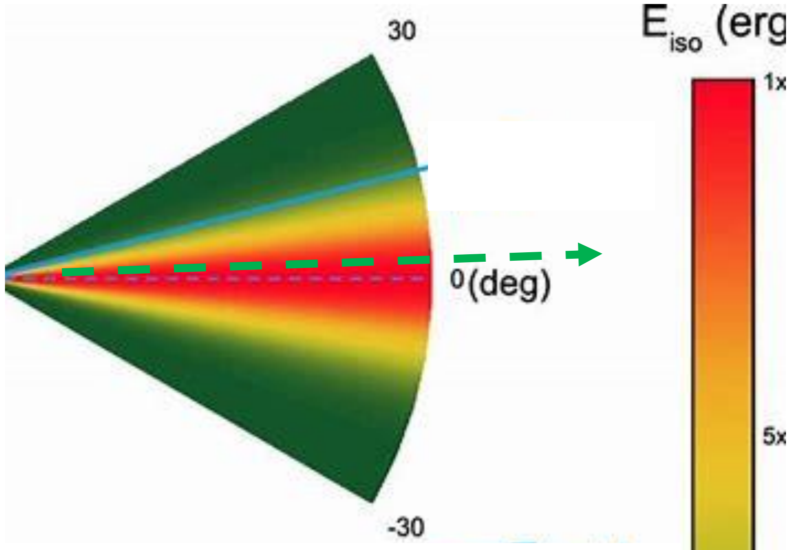






Very lucky! Almost totally alimented wit the jet

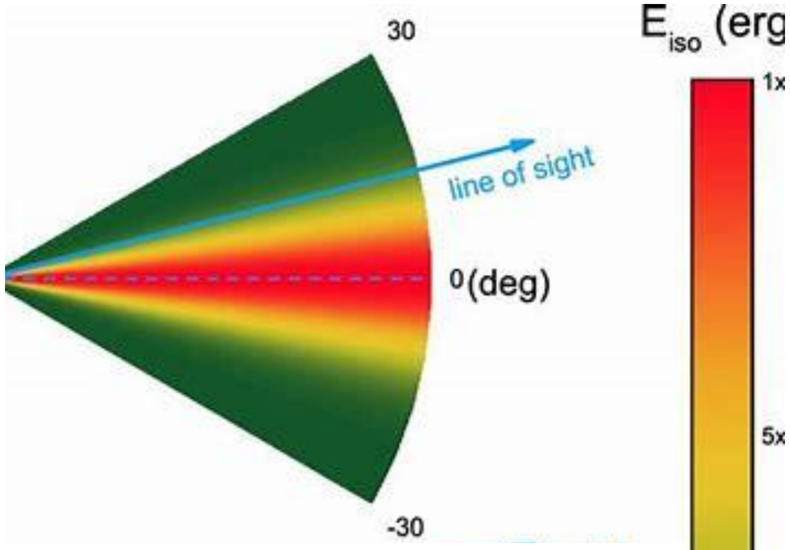
- GRB 221009A



The “core” of a nearby GRB might be revealed:
A good hint for the unprecedently large fluence

Versus

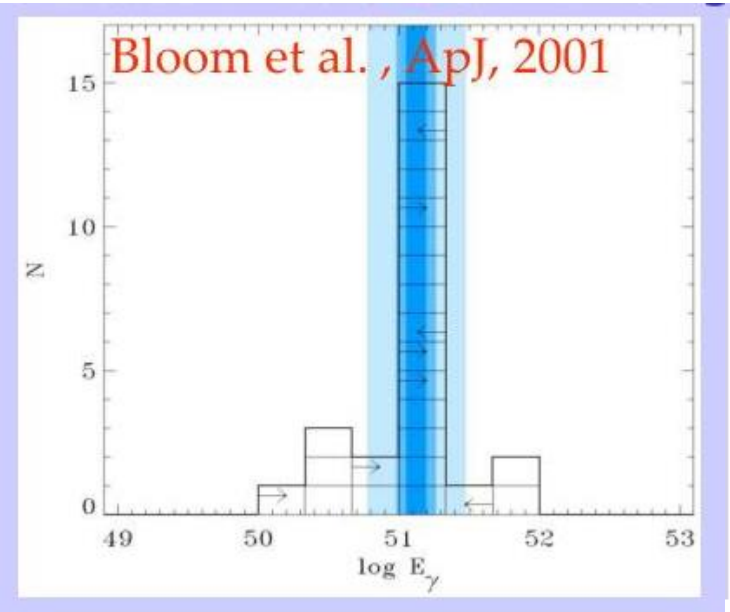
GRB 170817A (off-axis)

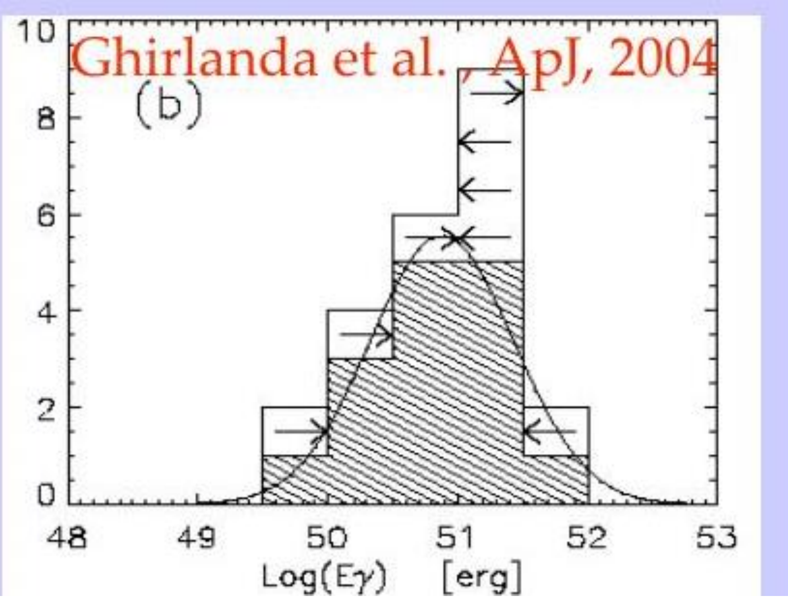


seeing a nearby GRB at large angle

Very narrow jet:
GRB 221009A an ordinary burst

- **First time seeing a jet break at TeV band**
- This helps to understand why it is the BAOT GRB
- The total energy of the GRB is normal



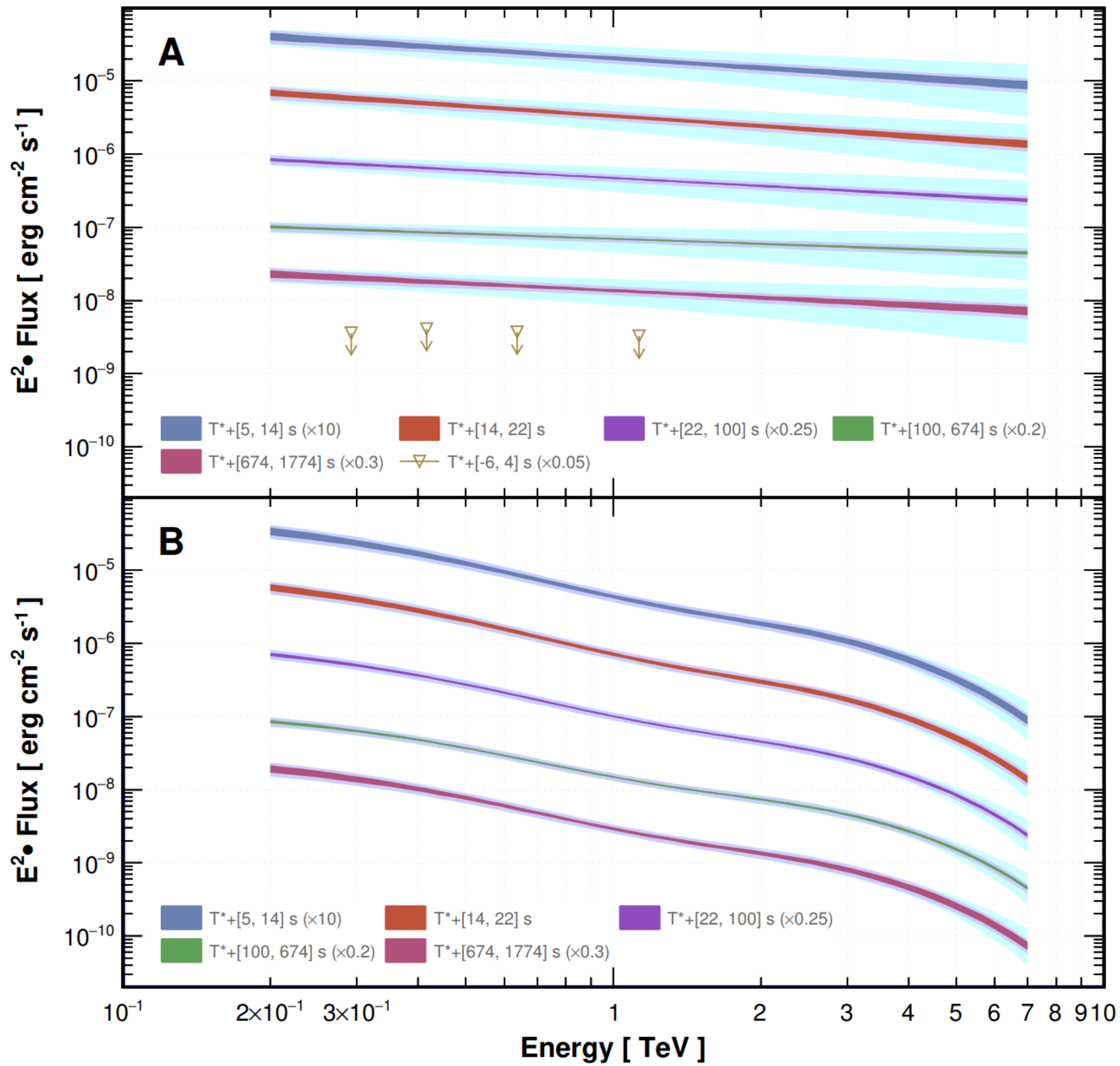


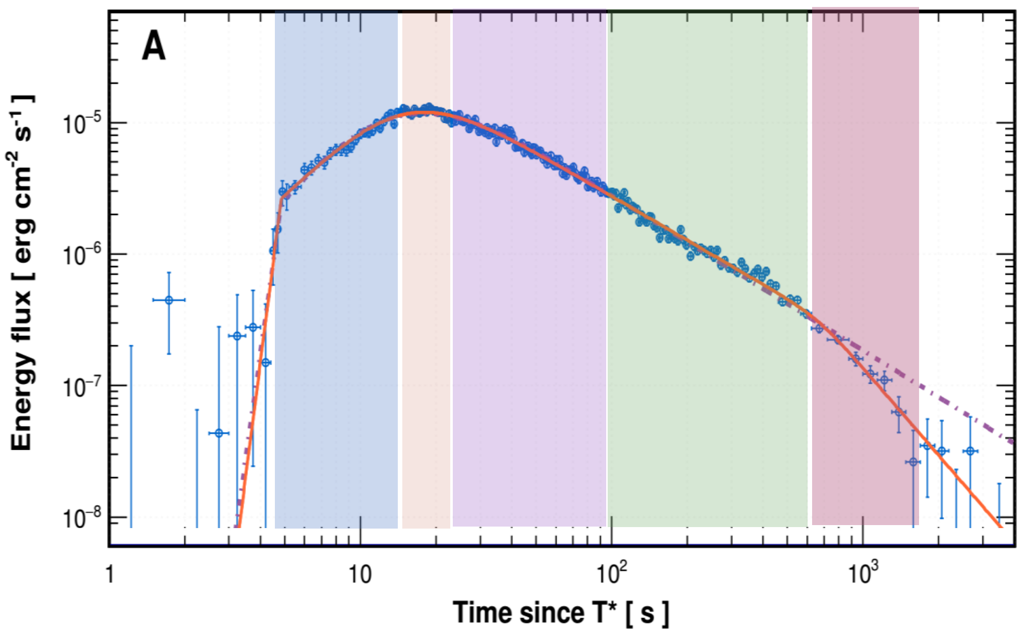
$$\theta_0 \sim 0.7^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\mathrm{b},2}}{670\ \mathrm{s}}\right)^{3/8}$$

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

5. Time-sliding SEDs:

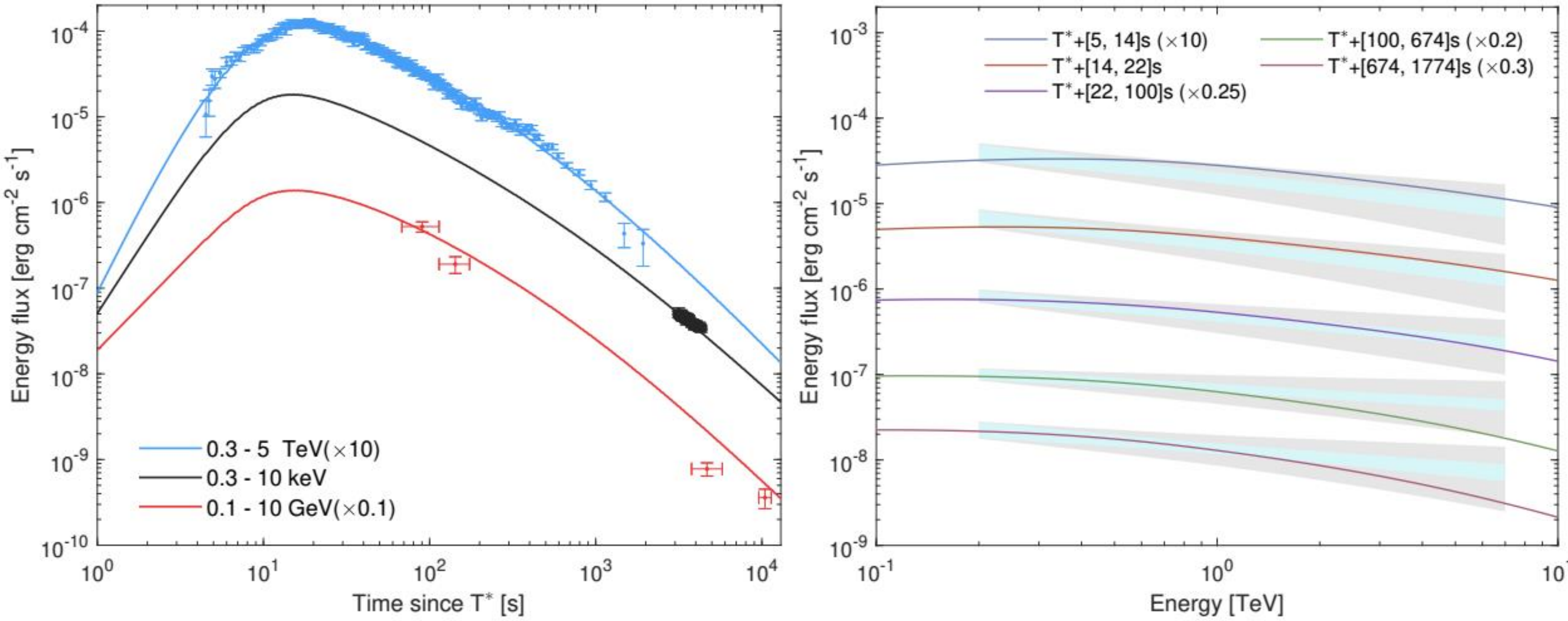
- z ~ 0.152, EBL absorption above 3 TeV
  - EBL model: A. Saldana-Lopez et al., Mon. Not. R. Astron. Soc. 507, 5144-5160 (2021)
- Intrinsic SED:
  - Power law: $\sim E^{-2.3}$
  - No hint about cut-off below 10 TeV
  - Moderate spectral evolution is observed





Multi-wavelength modelling of afterglow synchrotron + SSC:

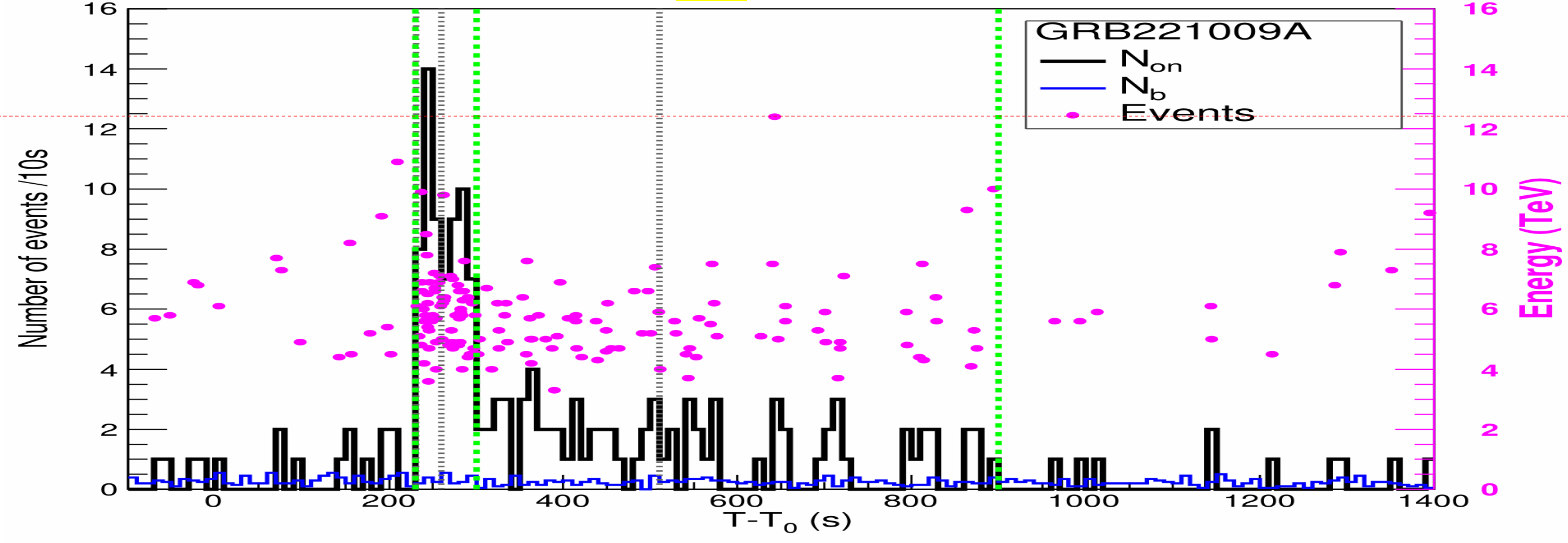
simultaneously fit light-curves in ΔE and time-sliding SEDs



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

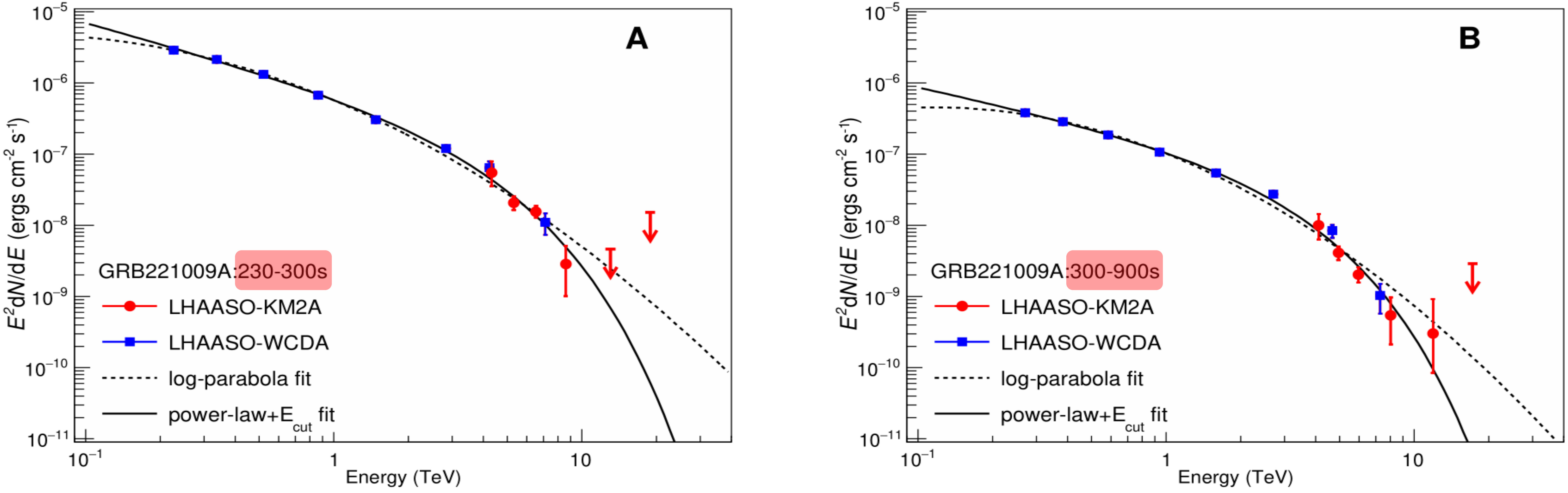
6. The most energetic photons during the burst by LHAASO-KM2A

Light Curve of 130 photons above 4 TeV



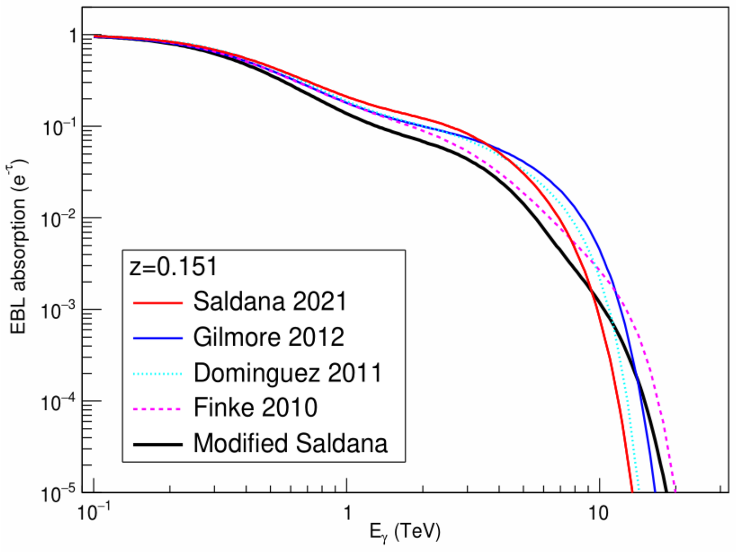
SED in two phases: bright and fading

- The "best fit" among $E^{-\gamma}$, $E^{-\Gamma}$ ($\Gamma=\Gamma_0+k\,log(E/E_0)$) and $E^{-\gamma}\exp\{-E/E_c\}$
  power-law, log-parabola and power law + cut-off
- **The power law + cut-off is favored**



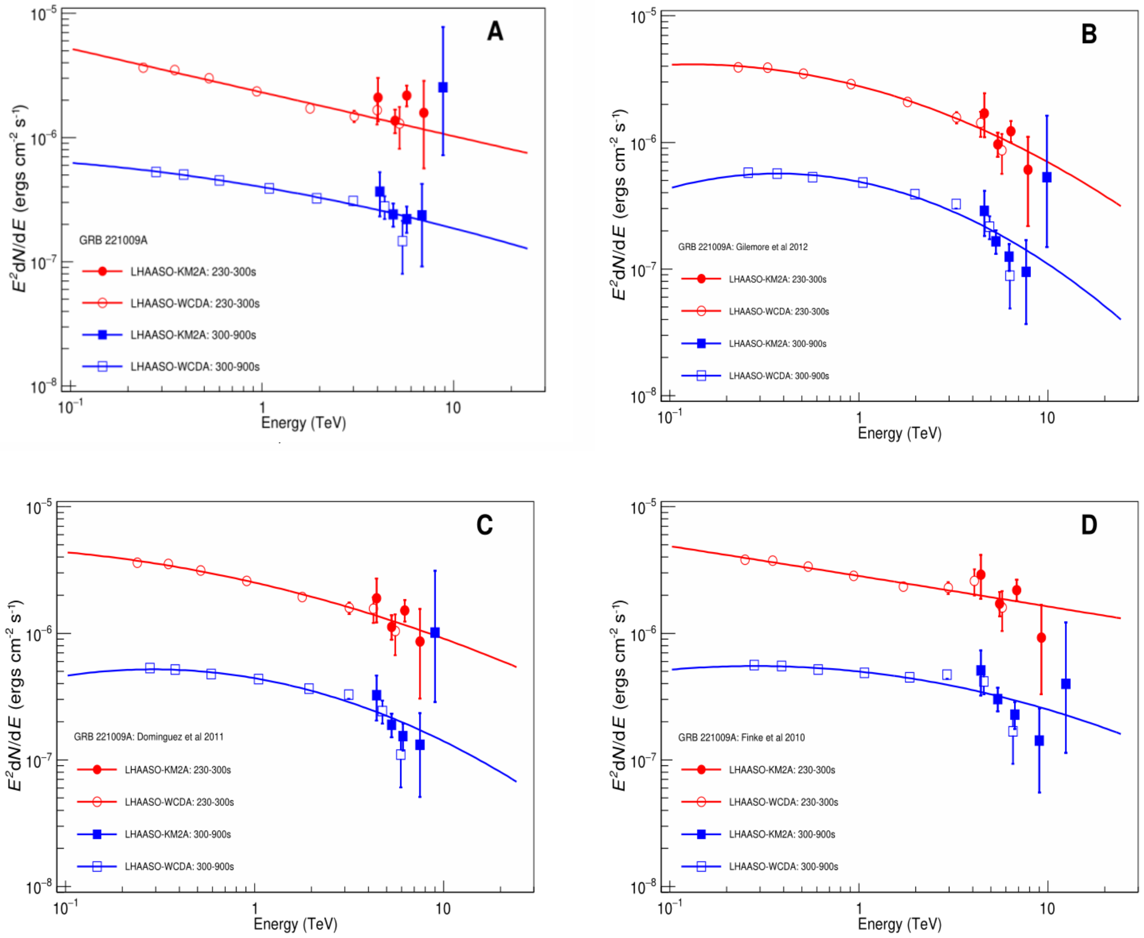
- Assumption 1: those events found at the top of the
- atmosphere are photons directly coming from the GRB at z=0.152

Intrinsic SED using different EBL models



Extended Data Table 3: χ^2/ndf using different EBL models

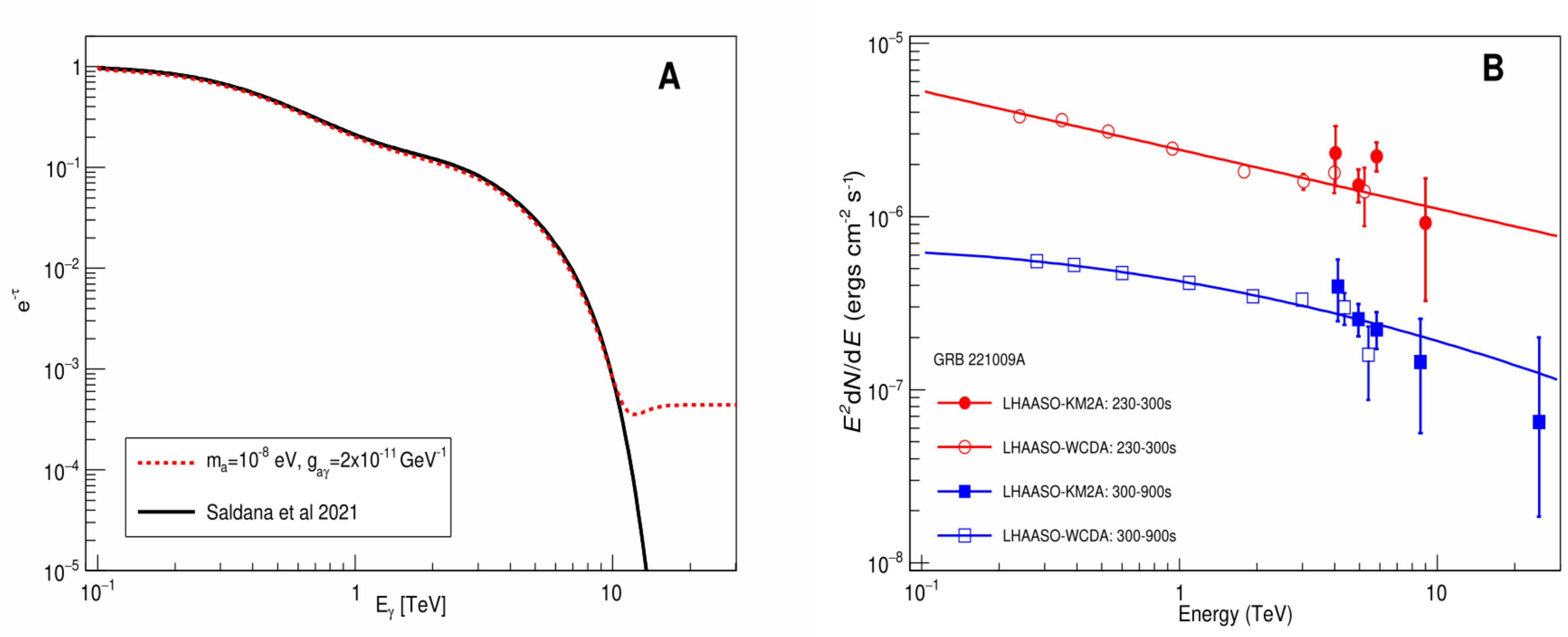
EBL model	230-300s	300-900s	total
Saldana et al 2021	11.02/9	5.44/10	16.46/19
Gilemore et al 2012	3.53/9	15.29/10	18.82/19
Dominguez et al 2011	4.16/9	11.33/10	15.49/19
Finke et al 2010	6.12/9	13.51/10	19.63/19
modified Saldana	5.93/9	5.57/10	11.50/19



Moderate constraints to the EBL models within 1~2σ

- Assumption 2: those γ-like events found at the top of the
- atmosphere may start with something else at the GRB at z=0.152

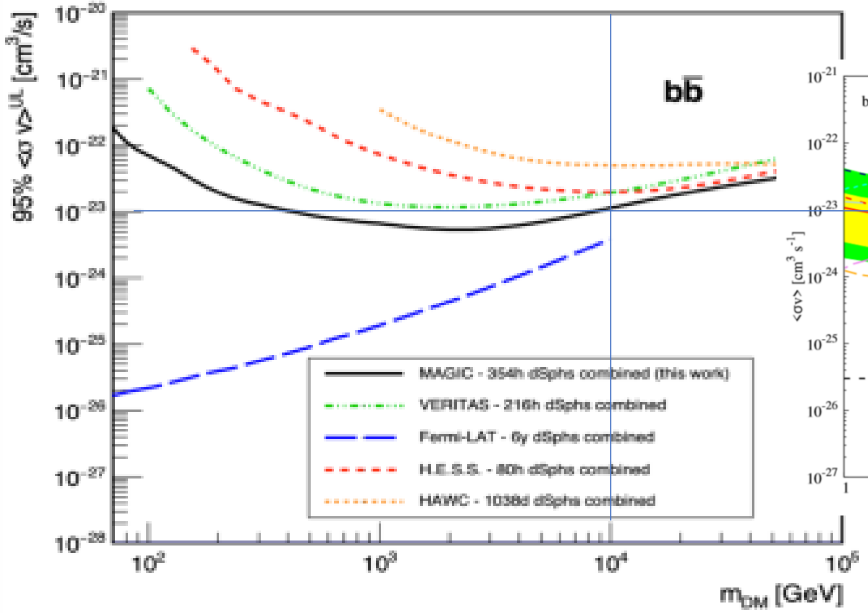
Constraints on Axion and LIV

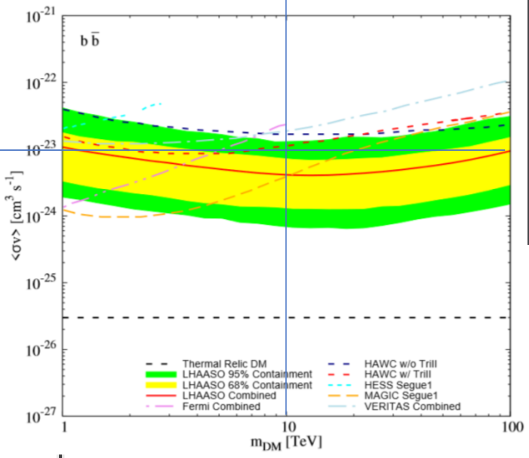


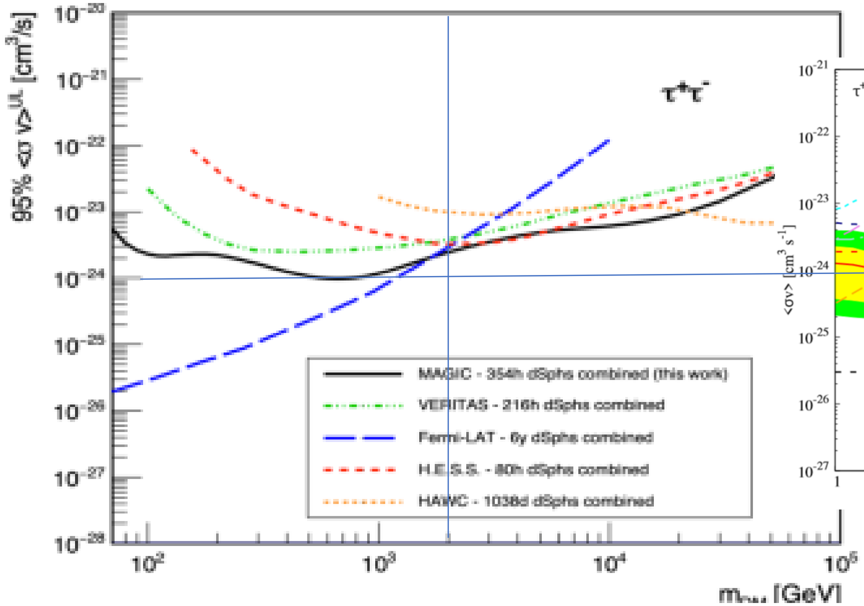
- Analysis is still going on …, but the highest energy could be 25 TeV

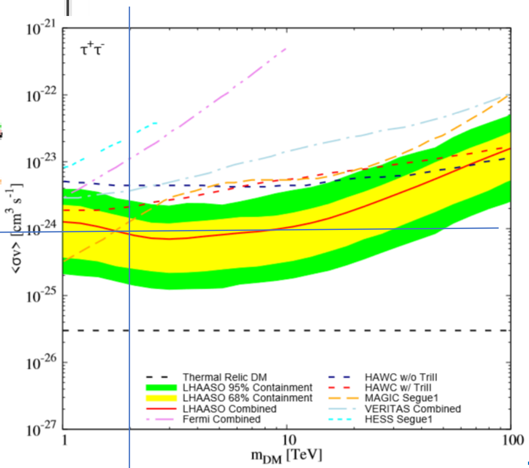
Heavy Dark Mater Search

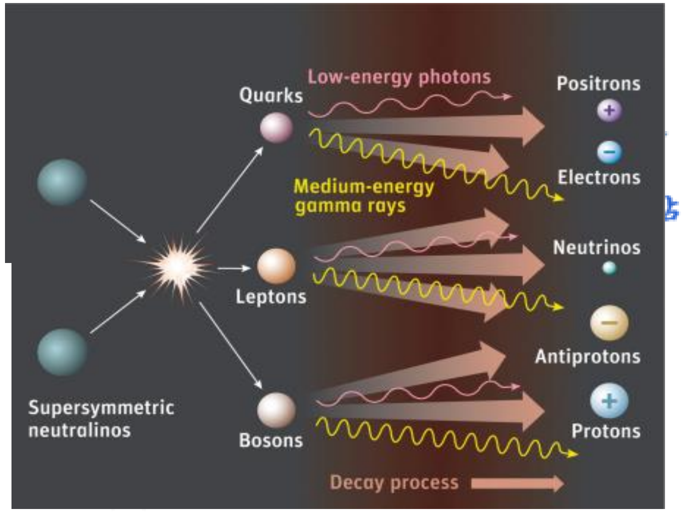
- Signals of annihilation or decay of DM particles
- ~ 20 dwarf galaxies in the FoV of LHAASO
- LHAASO has a good sensitivity to DM in Dwarf Galaxies for m_{DM} > 20 TeV









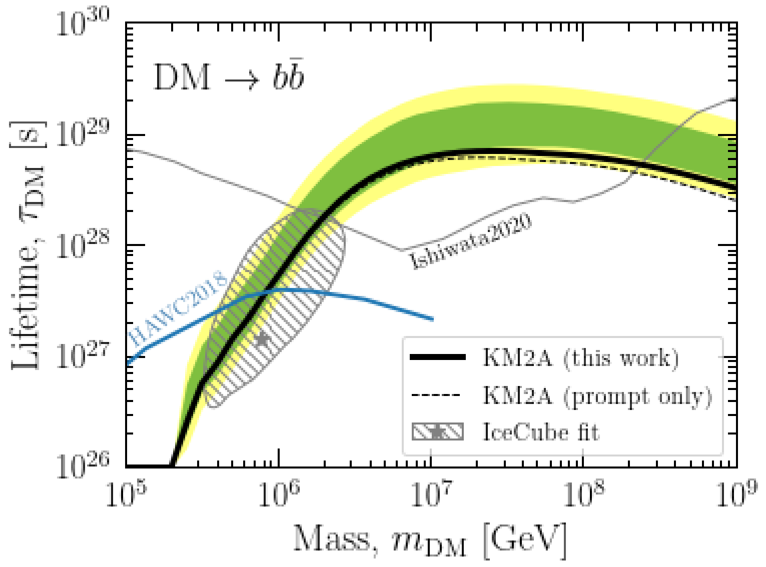


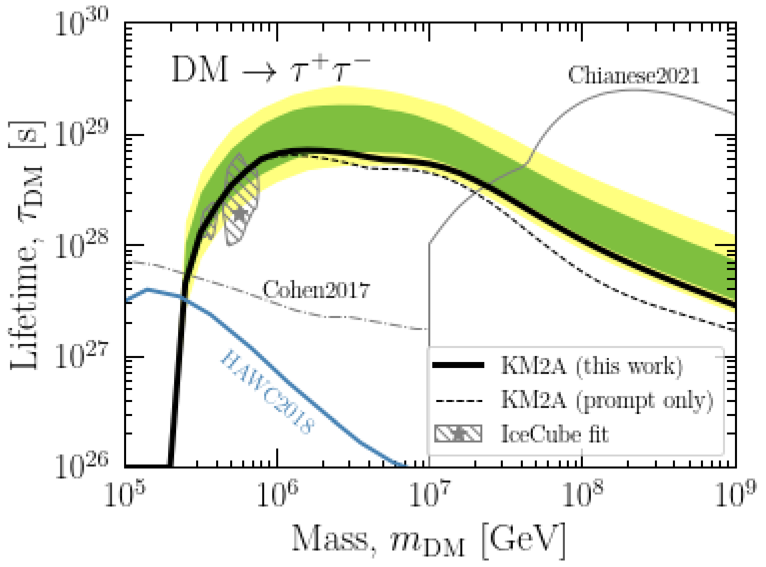
Source	RA. (deg)	DEC. (deg)	θ_{max} (deg)	$\log_{10} J_{obs}$ (GeV^2cm^{-5})
Boötes I	210.02	14.50	0.47	18.2 ± 0.4
Canes Venatici I	202.02	33.56	0.53	17.4 ± 0.3
Canes Venatici II	194.29	34.32	0.13	17.6 ± 0.4
Coma Berenices	186.74	23.90	0.31	19.0 ± 0.4
Draco	260.05	57.92	1.30	18.8 ± 0.1
Draco II*	238.20	64.56	–	18.1 ± 2.8
Hercules	247.76	12.79	0.28	16.9 ± 0.7
Leo I	152.12	12.30	0.45	17.8 ± 0.2
Leo II	168.37	22.15	0.23	18.0 ± 0.2
Leo IV	173.23	−0.54	0.16	16.3 ± 1.4
Leo V	172.79	2.22	0.07	16.4 ± 0.9
Pisces II*	344.63	5.95	–	16.9 ± 1.6
Segue 1	151.77	16.08	0.35	19.4 ± 0.3
Sextans	153.26	−1.61	1.70	17.5 ± 0.2
Triangulum II*	33.32	36.18	–	20.9 ± 1.3
Ursa Major I	158.71	51.92	0.43	17.9 ± 0.5
Ursa Major II	132.87	63.13	0.53	19.4 ± 0.4
Ursa Minor	227.28	67.23	1.37	18.9 ± 0.2
Willman 1*	162.34	51.05	–	19.5 ± 0.9

Dwarf Galaxies in the FoV of LHAASO

Heavy Dark Mater Search

- Signals of annihilation or decay of DM particles
- And good for MD in the galactic halo for m_{DM} > 200 TeV





Accepted by PRL, https://arxiv.org/abs/2210.15989

Exploring for New Physics

- **Lorentz Invariance Violation Testing**

In the superluminal LIV

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

$$\alpha_0 \leq \frac{4m_e^2}{E_\gamma^2 - 4m_e^2},$$

$$E_{LIV}^{(1)} \geq 9.57 \times 10^{23}\mathrm{eV}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^3,$$

$$E_{LIV}^{(2)} \geq 9.78 \times 10^{17}\mathrm{eV}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^2.$$

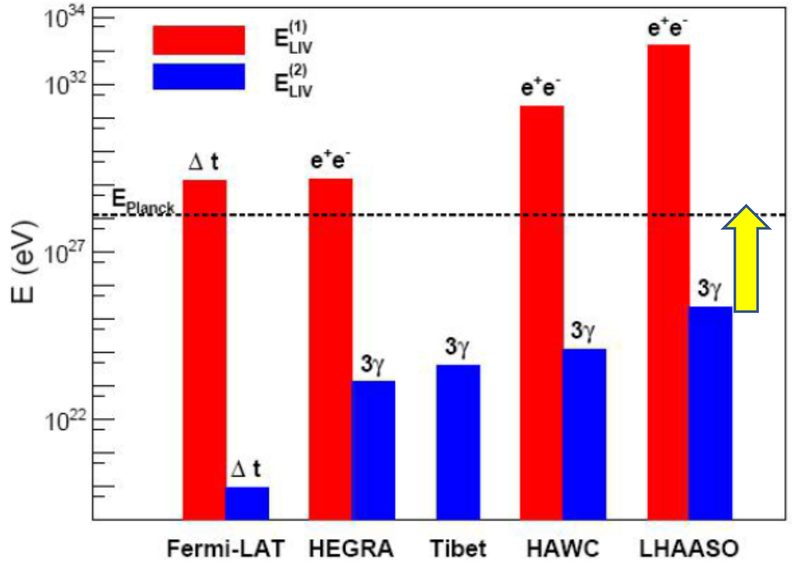
$$\gamma \rightarrow 3\gamma$$

$$\Gamma_{\gamma\rightarrow 3\gamma} = 5 \times 10^{-14} \frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

$$E_{LIV}^{(2)} > 3.33 \times 10^{19}\mathrm{eV}\left(\frac{L}{\mathrm{kpc}}\right)^{0.1}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{1.9}.$$

New CLs method

Source	L (kpc)	E_{max} (PeV)	$E_{cut}^{95\%}$ (PeV)
J0534+2202	2.0	0.88	$0.75^{+0.043}_{-0.043}$
J2032+4102	1.4	1.42	$1.14^{+0.06}_{-0.06}$



3 orders of magnitudes below the Planck-scale

LHAASO Coll. PRL, 128.051102 (2022)

Summary

- LHAASO has been stably operating since 2021
- Diffuse photon flux is found a factor 2 or 3 higher than expectation
- 43 above 100 TeV are detected and published in catalogs w/~40% of them unidentified
- The first CR source as a super-PeVatron is found
- The BOAT GRB brings us many new views of GRB afterglow, the highest energy photon from the GRB opens opportunities exploring for new physics
- Fundamental issues, LIV and DM, are tested w/ limits renewed constantly