LHAASO 科学研究进展

毕效军
中国科学院高能物理研究所

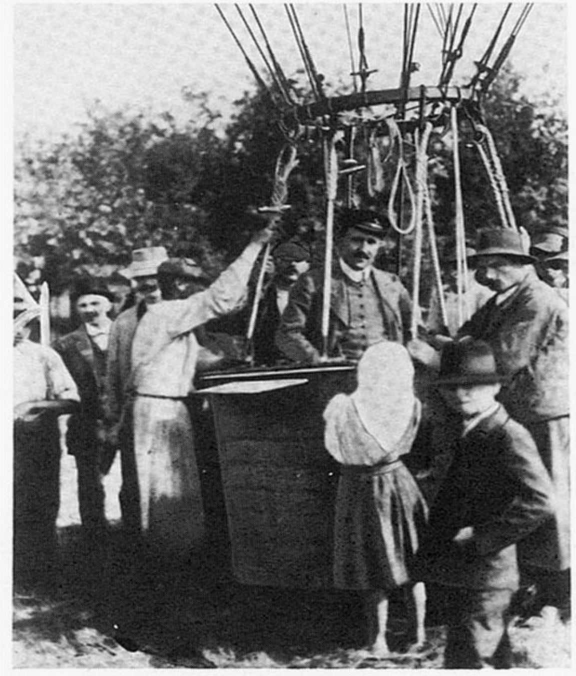
第十六届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会
2023年6月30日-7月4日
天津

Historical review

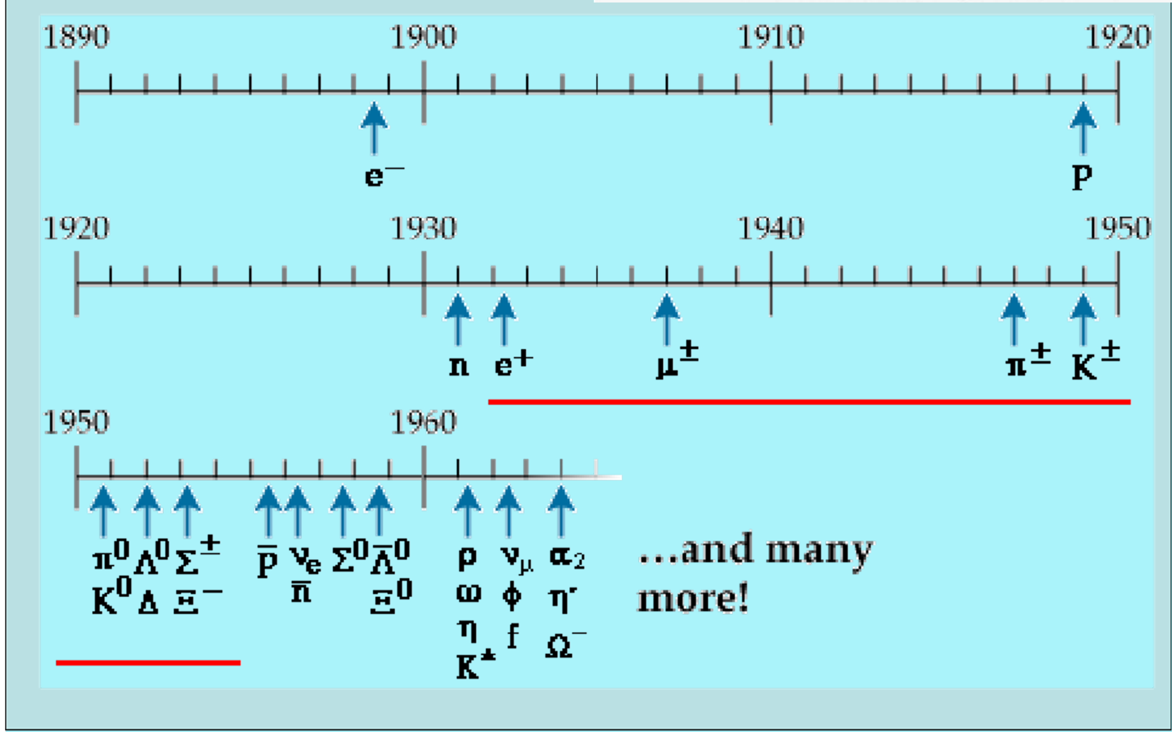
- Cosmic rays were discovered by V. Hess in 1912 by a balloon experiment

- From 1930s to 1950s, cosmic rays observation derives the particle physics development.
- Positron, muon, pion were

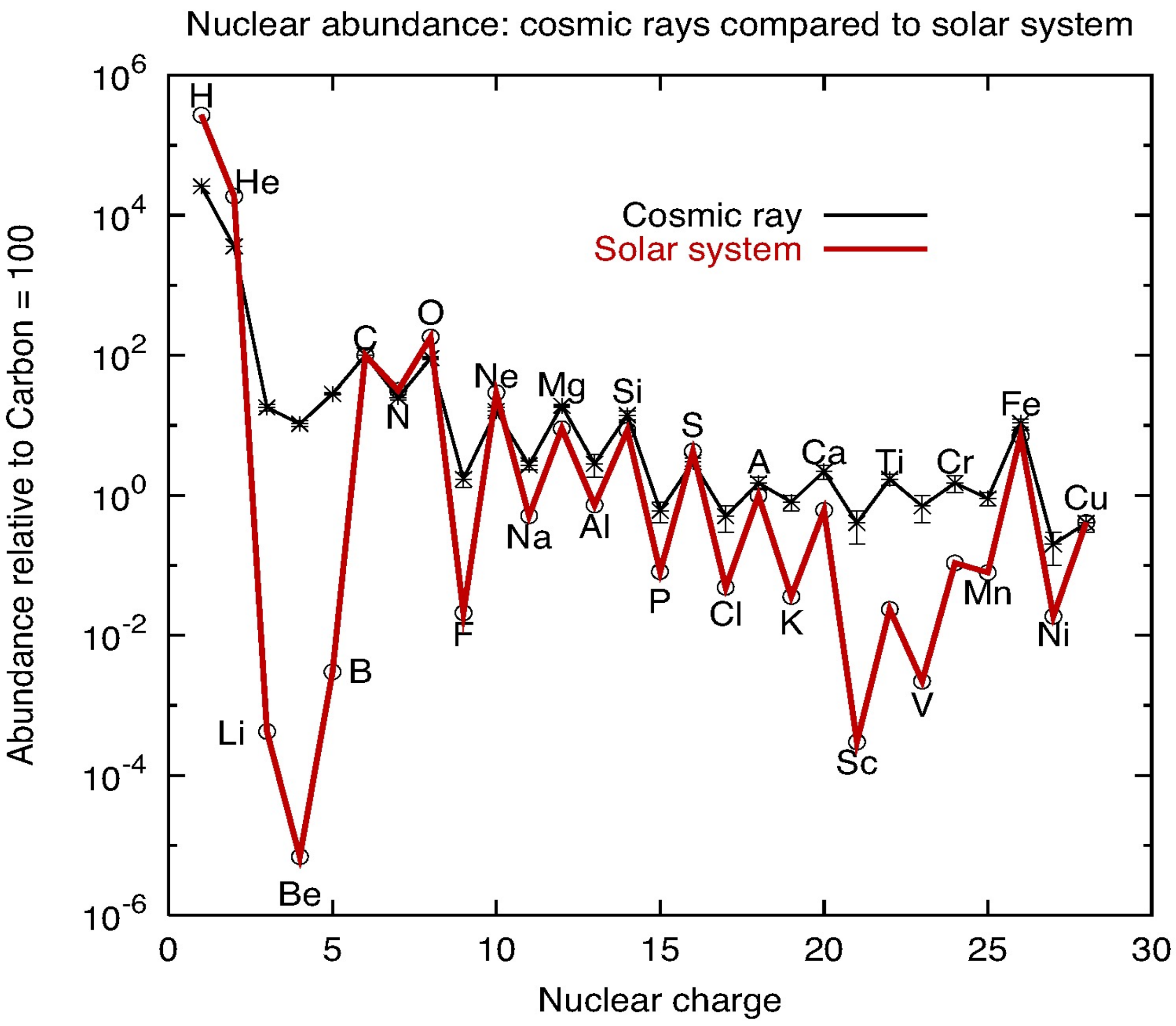
all revolutionary progresses on human being understanding of the world.



Hess bei Ballonlandung (1912).



宇宙线科学



宇宙线中包含地球上发现的几乎所有元素

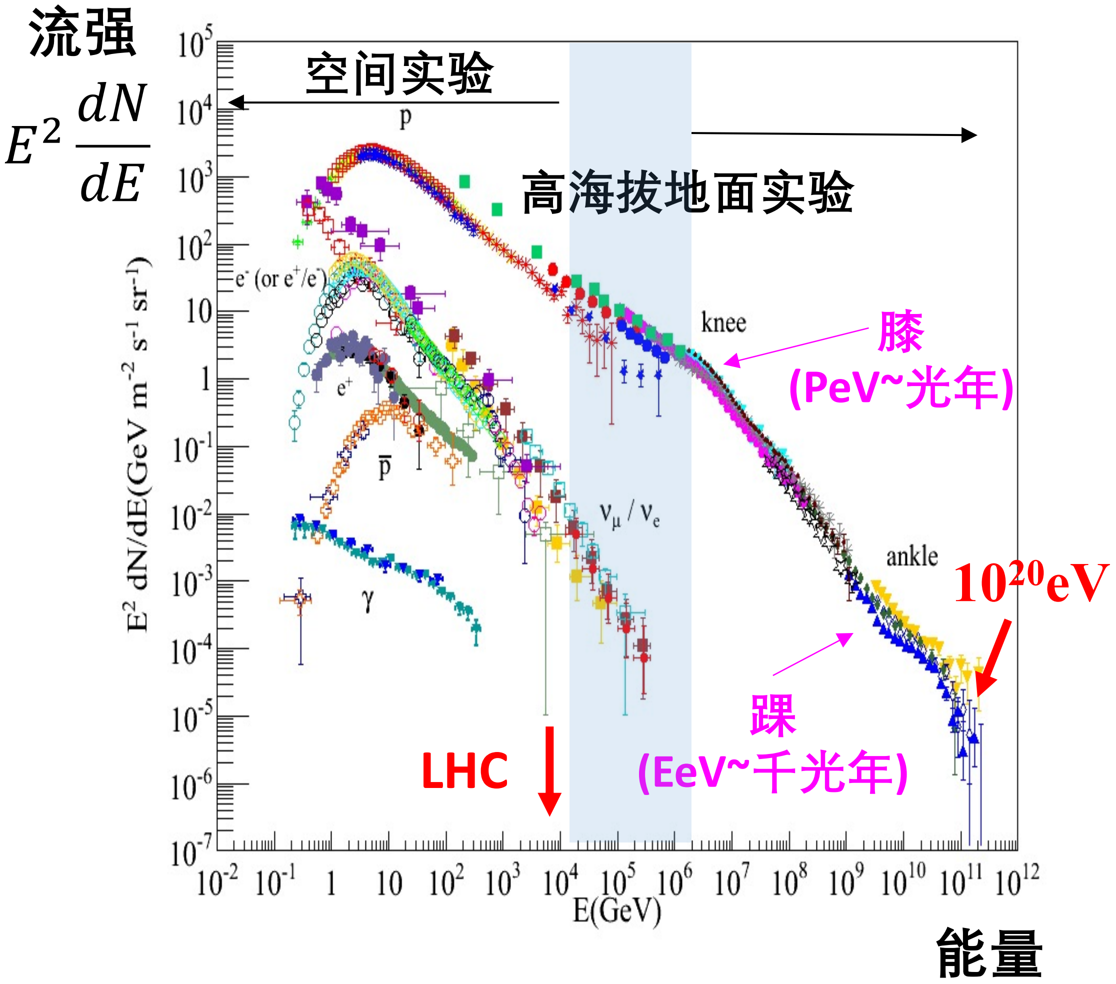
发现新物理
- 寻找暗物质
- 把宇宙线加速到极高能的机制
- 发现洛伦兹破坏等

天文学
- 寻找宇宙线加速源
- 极端条件下物理（极高能、高密、强引力等）

宇宙线实验

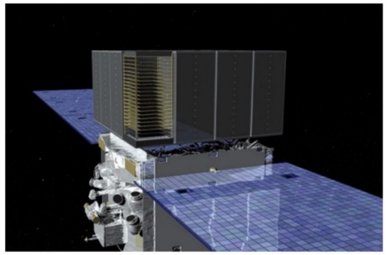
- 宇宙线实验分空间实验和地面实验
  - 空间实验探测能量低（流量高）
  - 能够区分不同粒子种类
  - 磁谱仪可以区分正反粒子

  - 地面实验探测能量高（面积大）
  - 难以区分不同种类的粒子（大气簇射）
- LHAASO面积大、粒子鉴别能力强

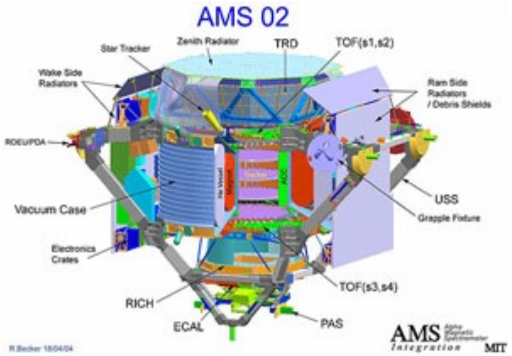


Recent/ongoing experiments

Fermi



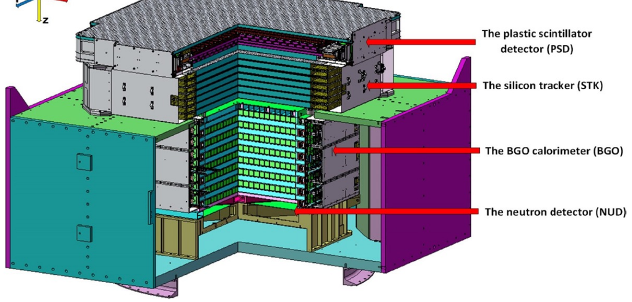
AMS-02



CALET

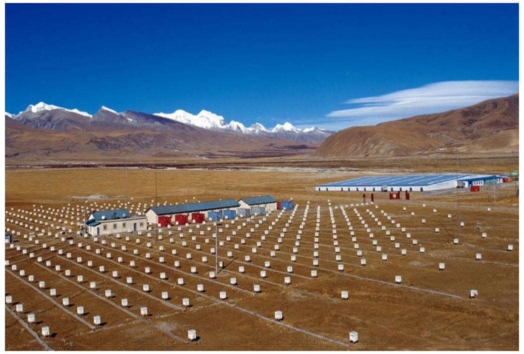
DAMPE

Astropart. Phys., 95, 6 (2017)



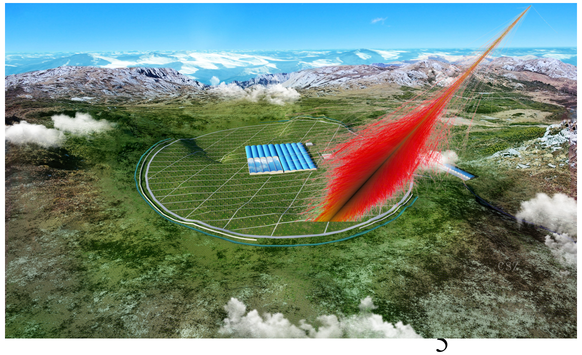
HAWC

羊八井



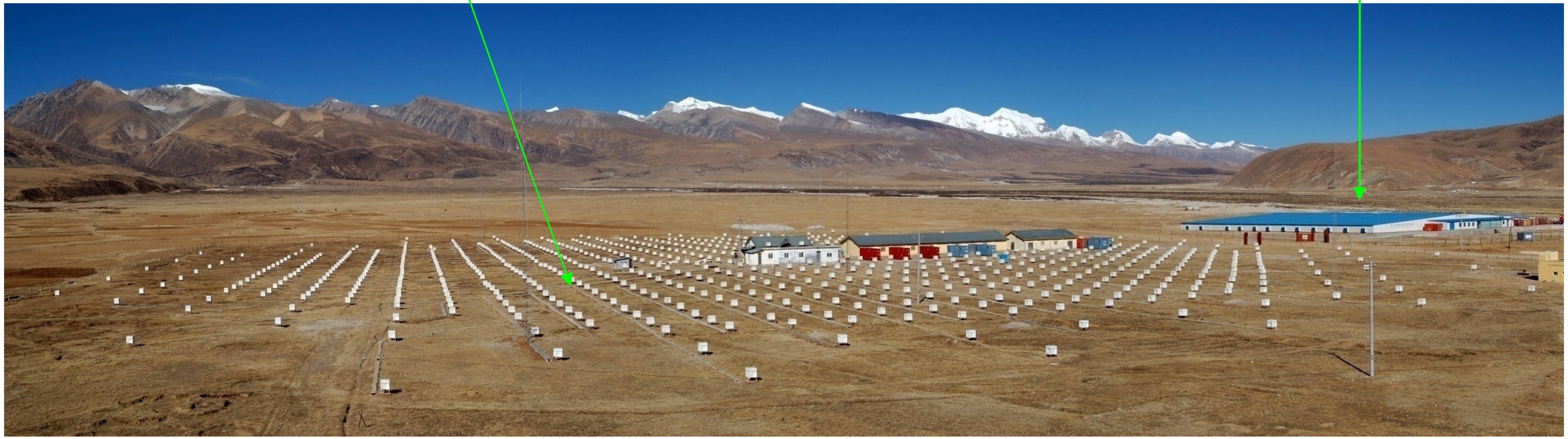
HESS/MAGIC/VERITAS

LHAASO

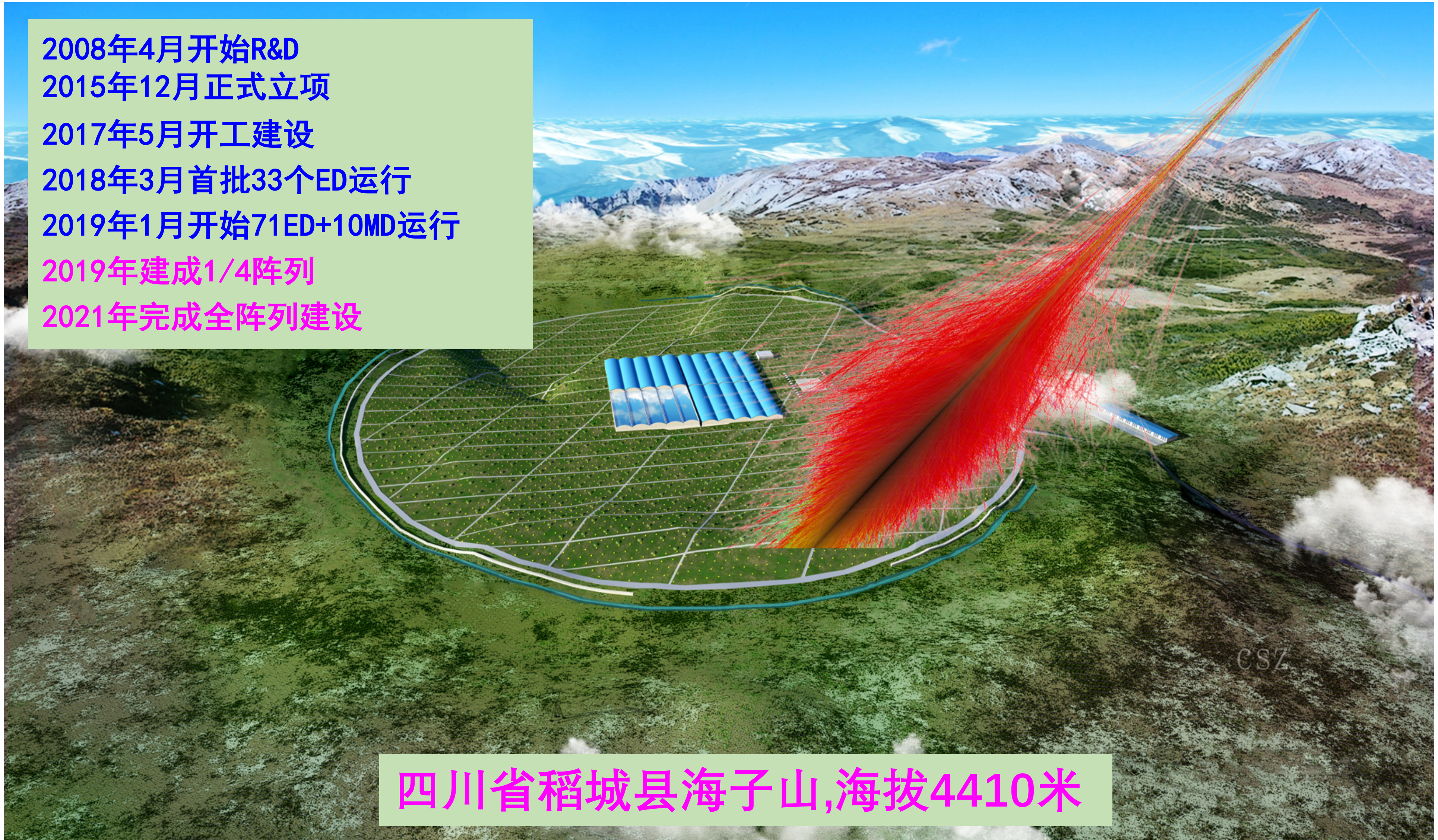


正是广延大气簇射提供给我们另一种探测宇宙线的手段——测量宇宙线和大气相互作用产生的次级粒子，即所谓间接探测。

西藏羊八井宇宙线观测站就是利用广延大气簇射对宇宙线进行探测。

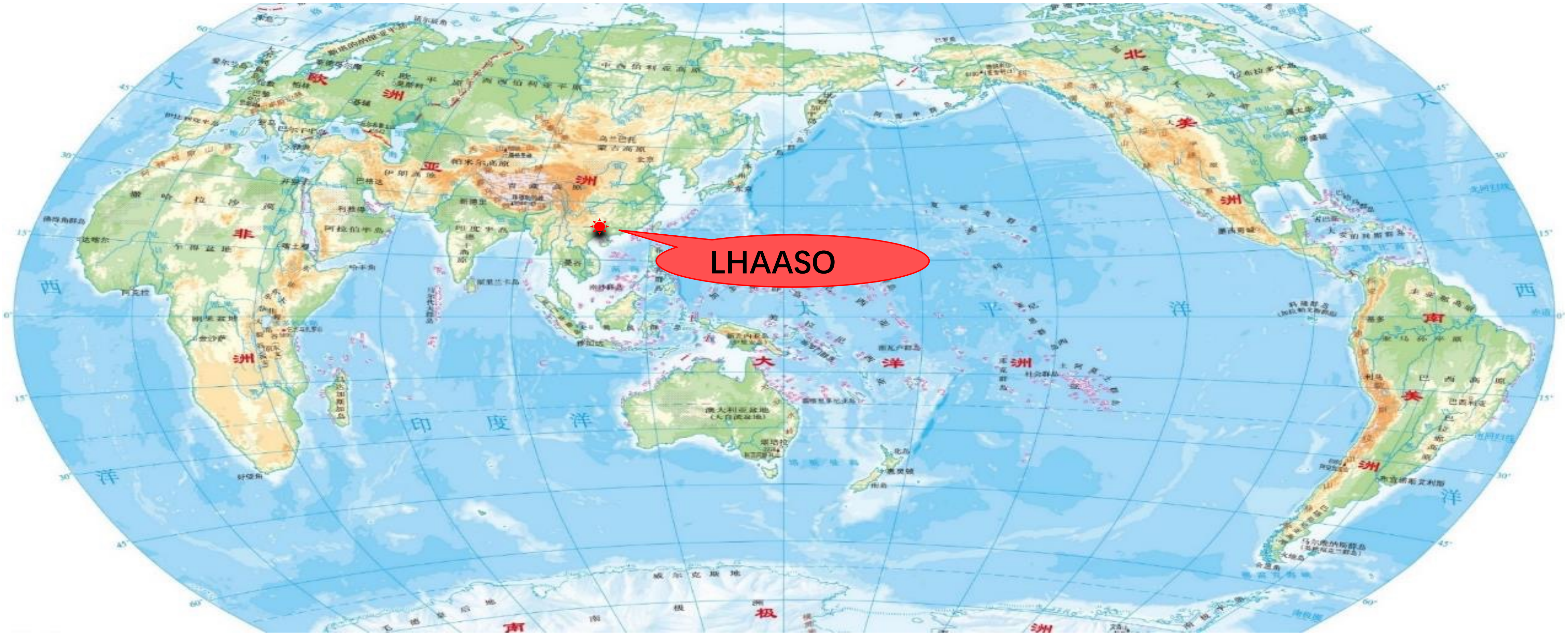


LHAASO: Large High Altitude Air Shower Observatory
高海拔宇宙线观测站



Where is LHAASO?

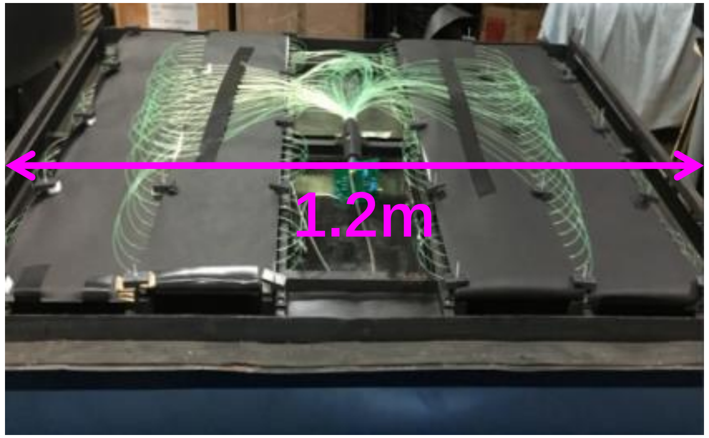
- **Haizi Mountain 4410 m a.s.l. , Sichuan province, China**
- **Location：29°21’ 27.6” N, 100°08’ 19.6” E.**



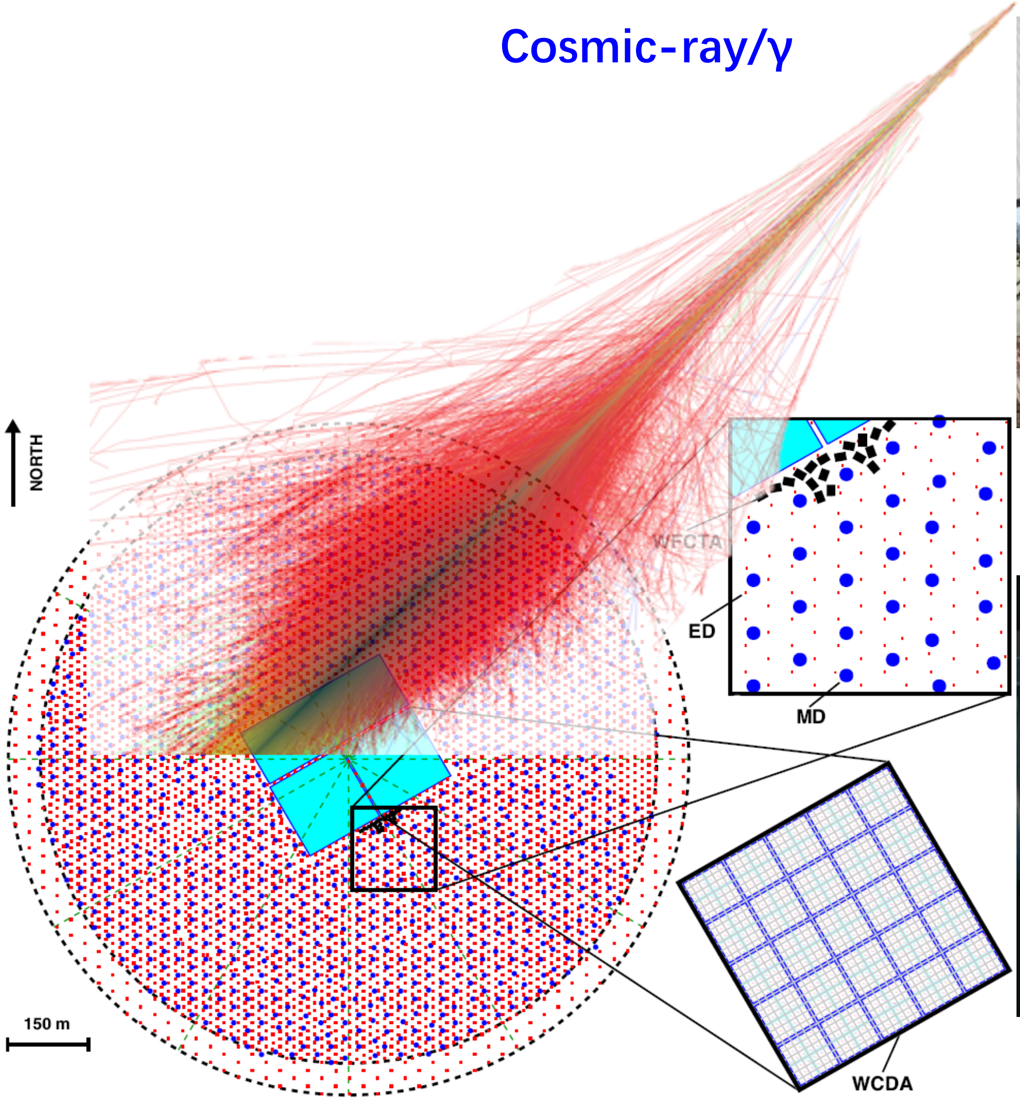
LHAASO detectors

KM2A

MD: 1188x36m^2



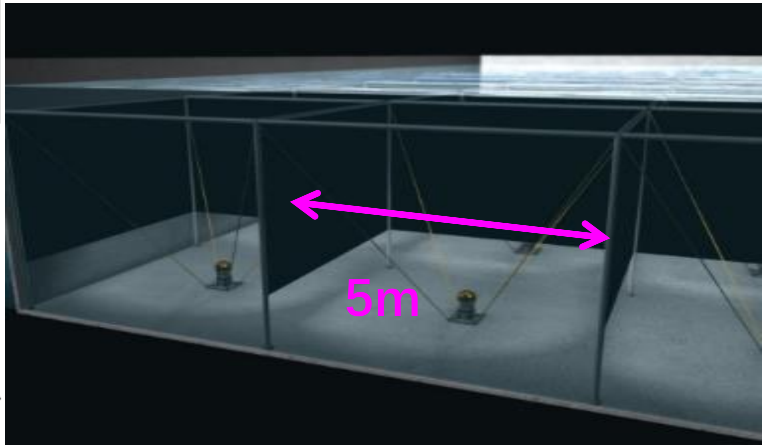
ED: 5216x1m^2



1.3 km^2

WFCTA

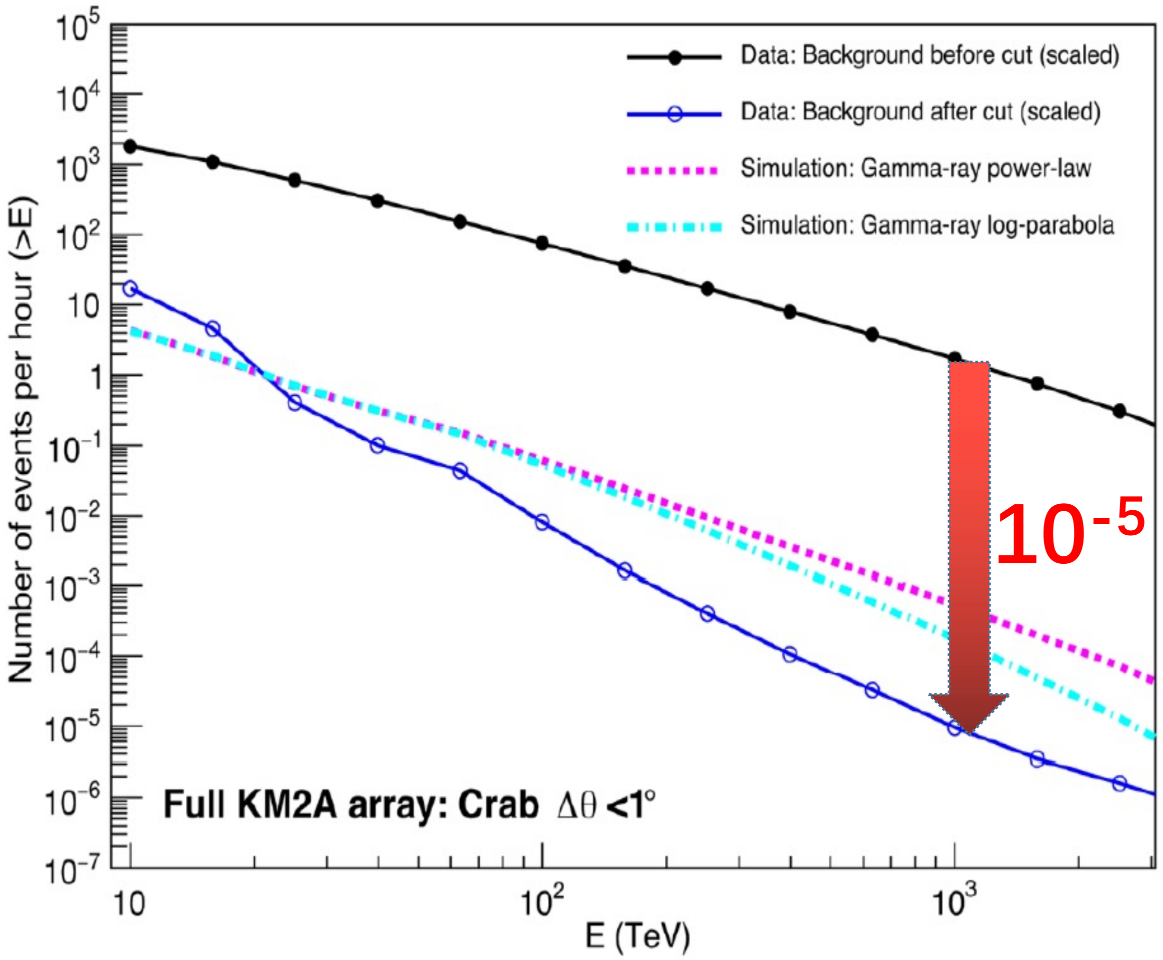
18x4.7m^2

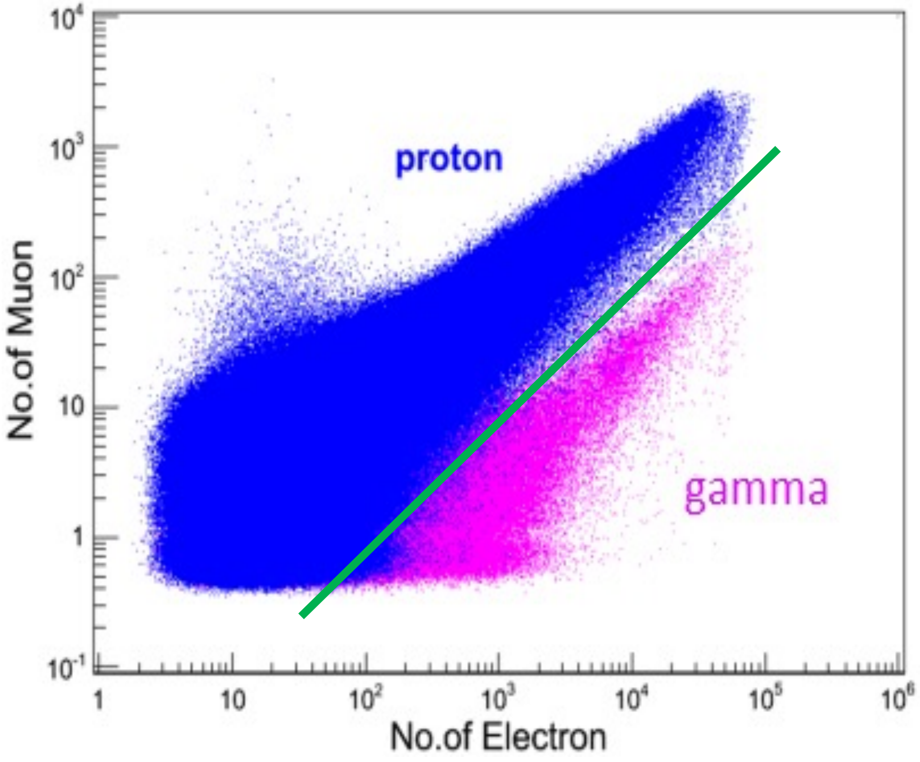


WCDA

3120x25m^2

Gamma-ray/cosmic ray discrimination





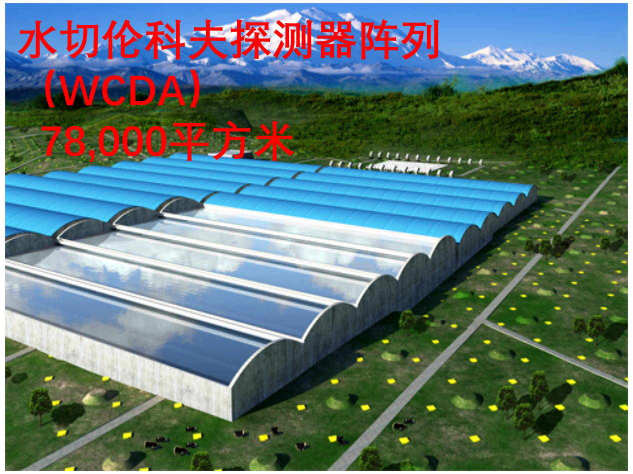
Before cut: CR rate

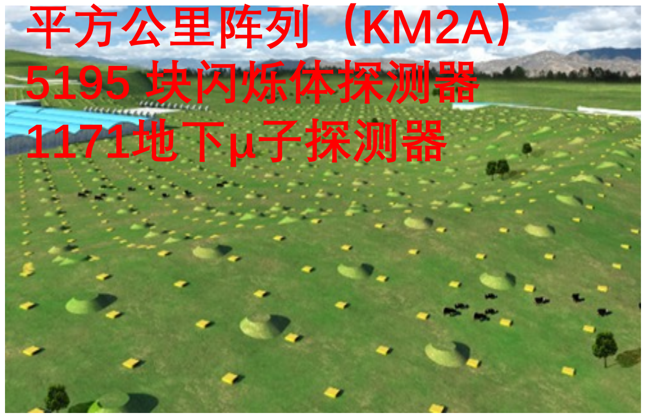
Gamma-ray rate

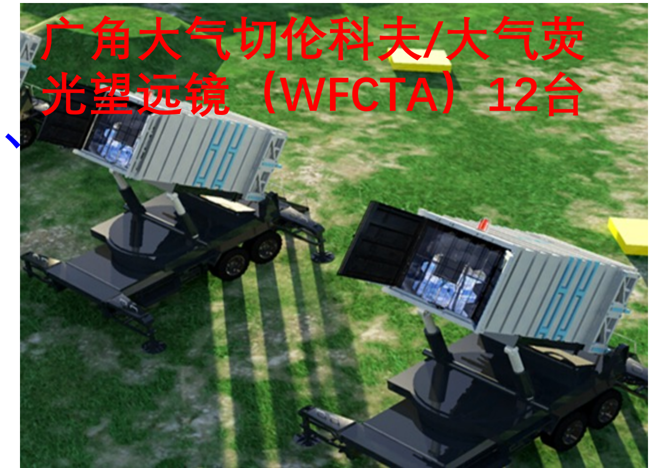
After cut: CR rate

LHAASO主要科学目标

- TeV伽马巡天 → WCDA (100 GeV-30 TeV)
  - 活动星系核、伽玛暴、双星…
- >20 TeV 伽马巡天→KM2A (10TeV-1PeV)
  - 超新星遗迹、脉冲星风云、 …
- 宇宙线能谱→WFCTA (10TeV to EeV)
  - 联合WCDA和KM2A测量宇宙线成分能谱
- 其它方向:
  - 新物理（暗物质、洛伦兹破缺）、太阳物理、粒子物理 …







1 First view of the UHE universe

LHAASO最新成果

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

LHAASO Collaboration • Zhen Cao et al. (May 17, 2021)

Published in: *Nature* 594 (2021) 7861, 33-36

- 打开伽马射线探测新的能量窗口
- 首次测量到拍电子伏的伽马射线

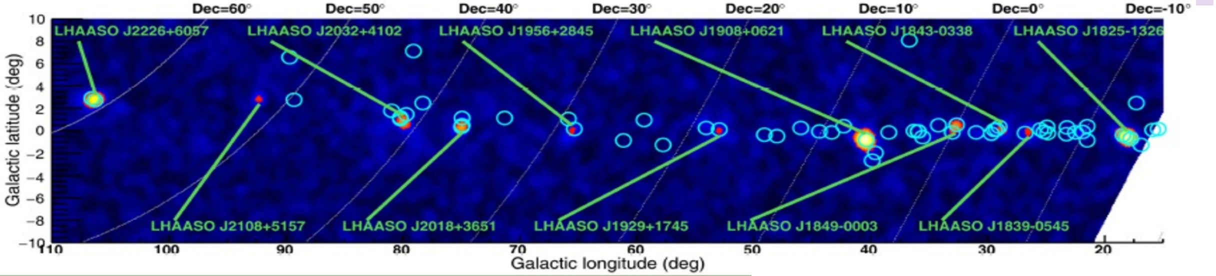


Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

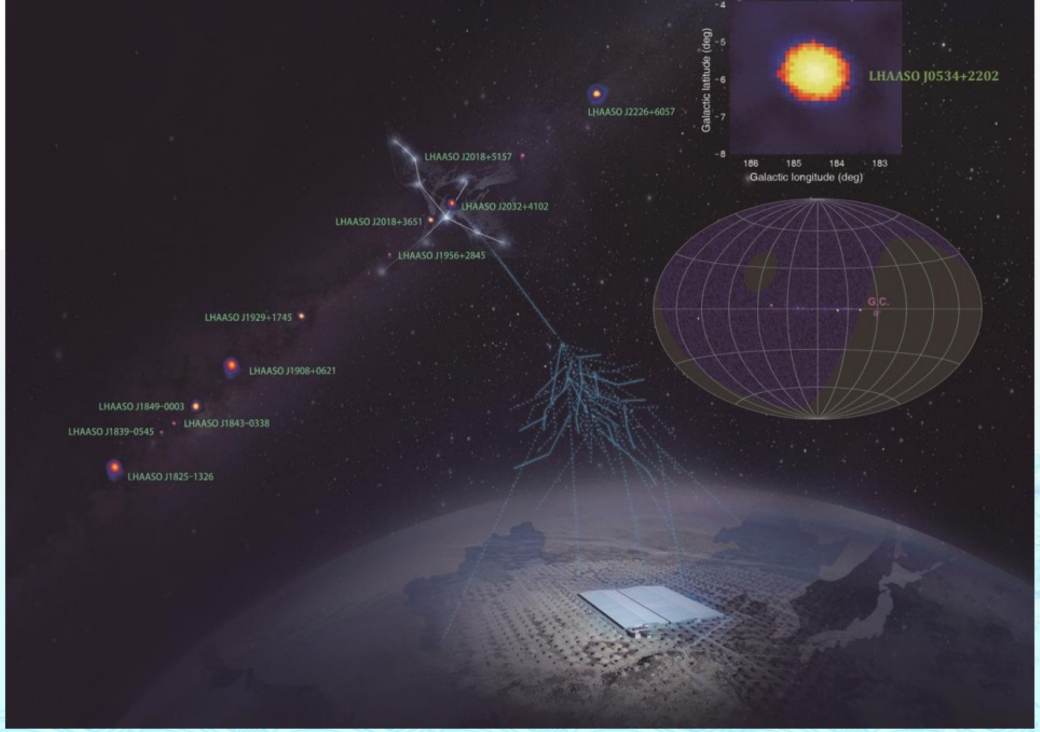
12 PeVatrons are discovered

◆**High Standard： significance >7σ**

◆**BG-free： Cosmic Ray background rejection rate <10^{-4}**

◆**High Statistics： 530 UHE photons many more now**

LHAASO, Nature, 594, p.33-36, 2021



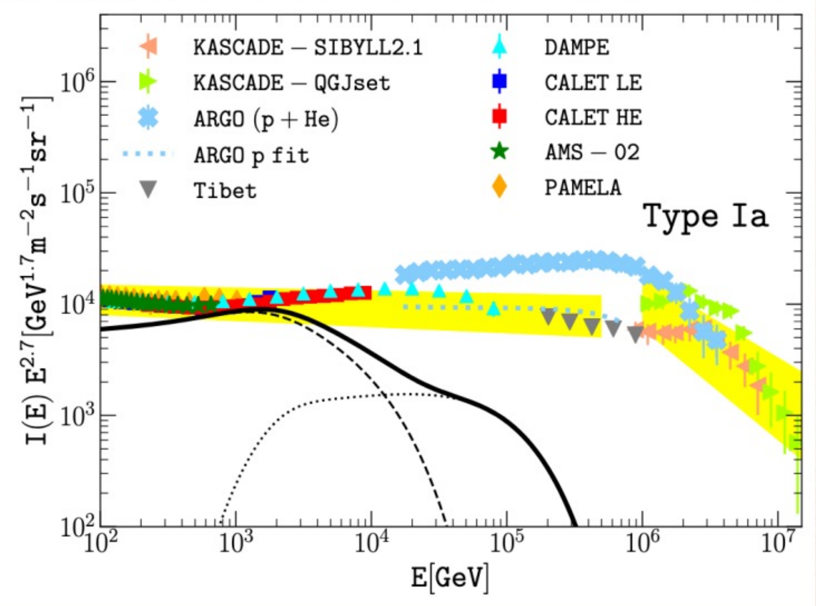
Application of Bell instability to different type of SNRs: comparison with CR spectrum at Earth

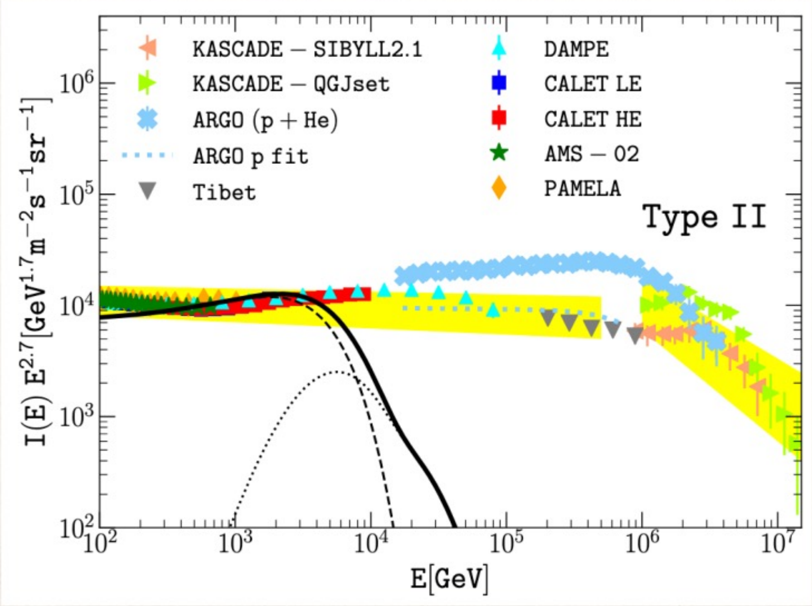
Assumed acceleration efficiency $\xi_{cr} \approx 0.10$

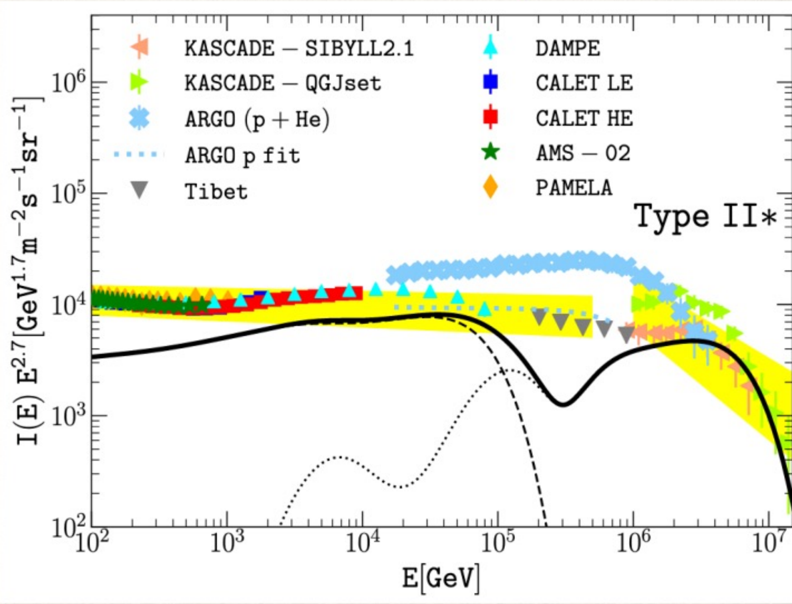
	Type Ia	Type II	Type II*
E_{SN} $[10^{51}$ erg$]$	1	1	$5 \div 10$
$\dot{M}_{wind}$ $[M_\odot/yr]$	$--$	10^{-5}	10^{-4}
M_{ej} $[M_\odot]$	1.4	10	1.0
ν_{SN} $[yr^{-1}]$	10^{-2}	2×10^{-2}	3×10^{-4}

[Cristofari, Blasi, Amato, APh 2020]

Only very rare and powerful events can account for PeV particles



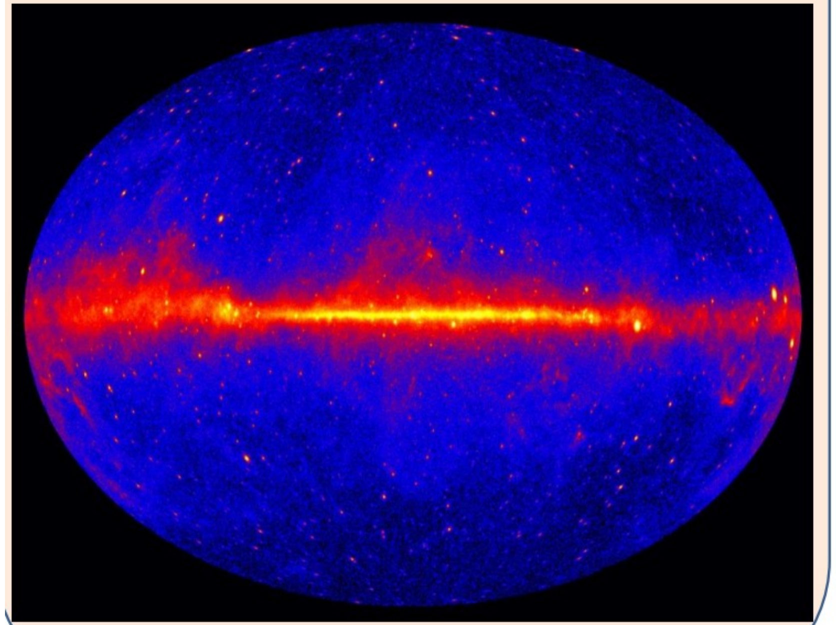




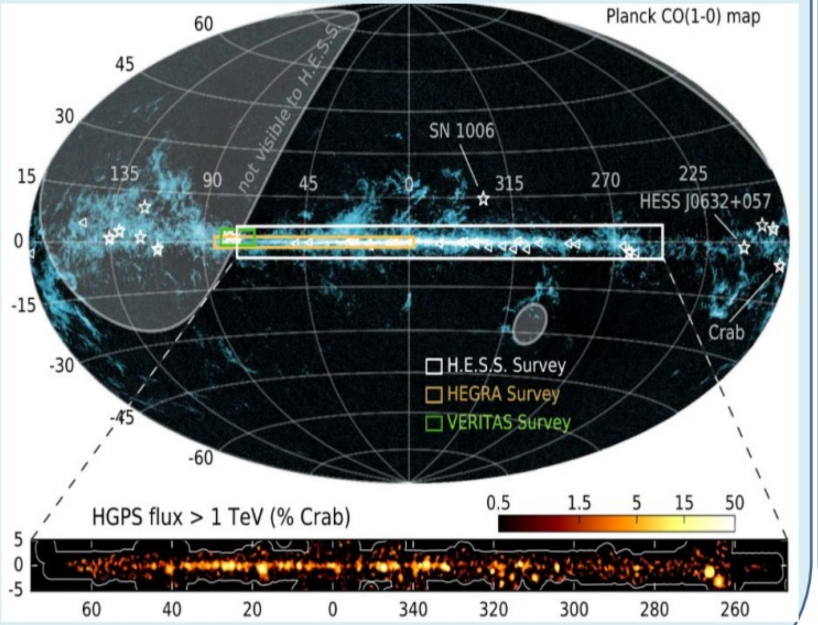
2 LHAASO Catalog of new VHE/UHE sources

Impressive Gamma-ray Source Catalogs

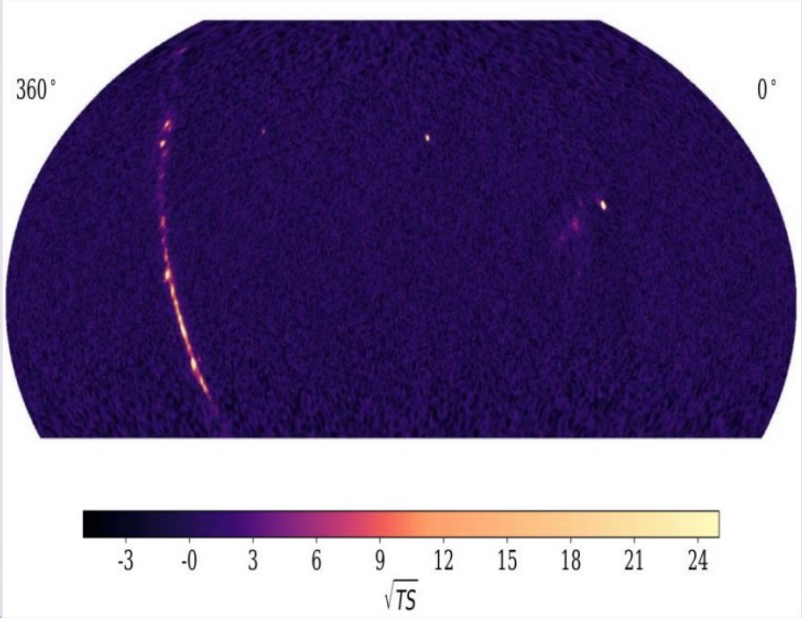
Fermi-LAT
12ys data
6658 sources
50 MeV to 1 TeV



H.E.S.S.
10ys data
78 sources
0.2-100 TeV

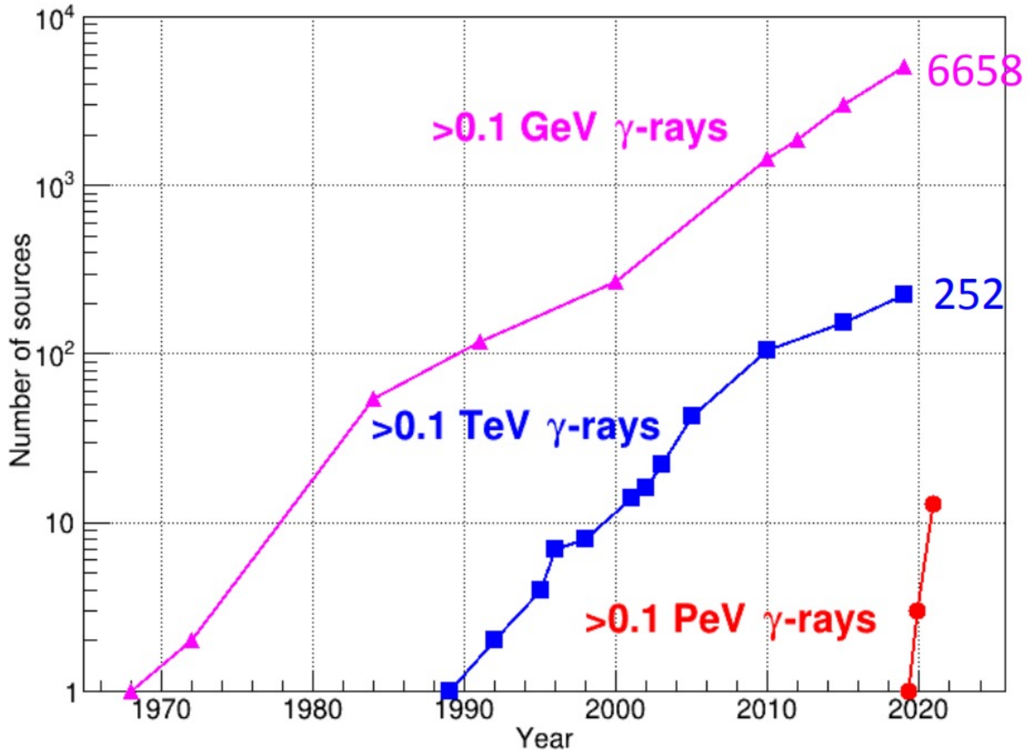


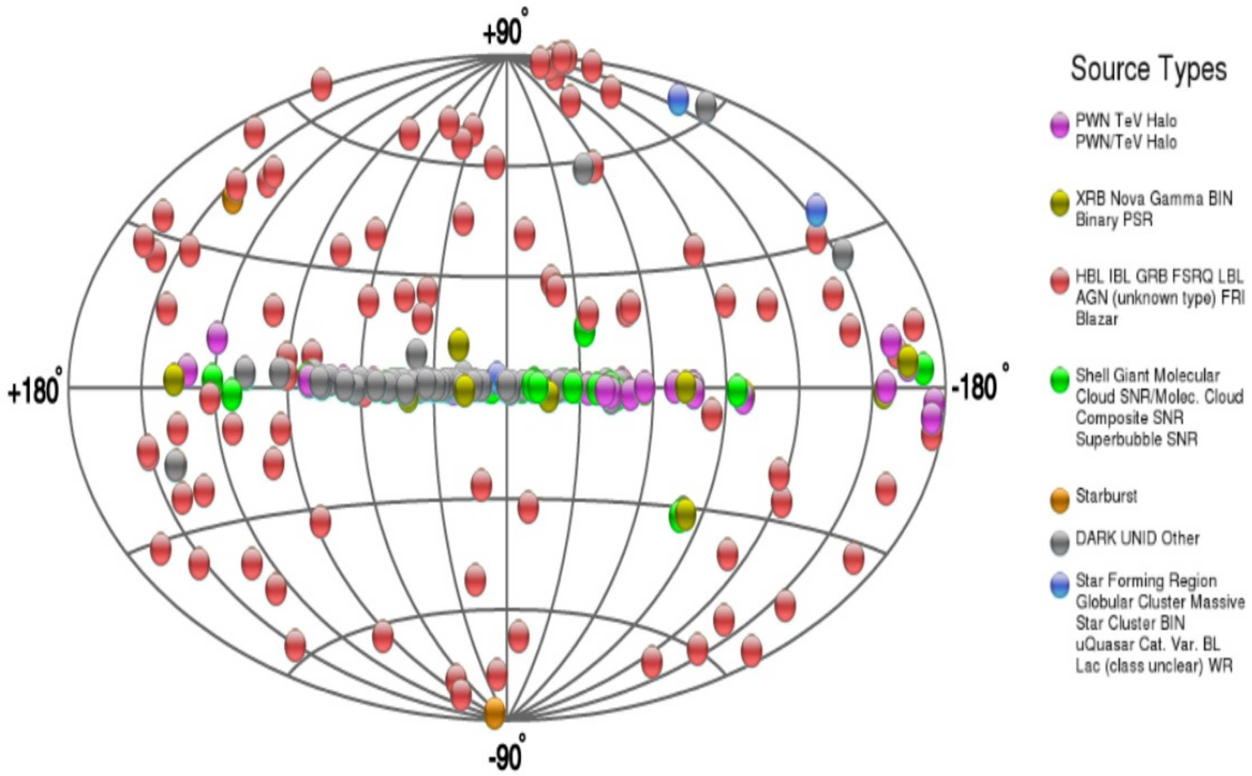
HAWC
5ys data
65 sources
1~100 TeV



Current status of VHE gamma-ray sources

Great progresses are achieved in ground-based VHE gamma-ray astronomy!

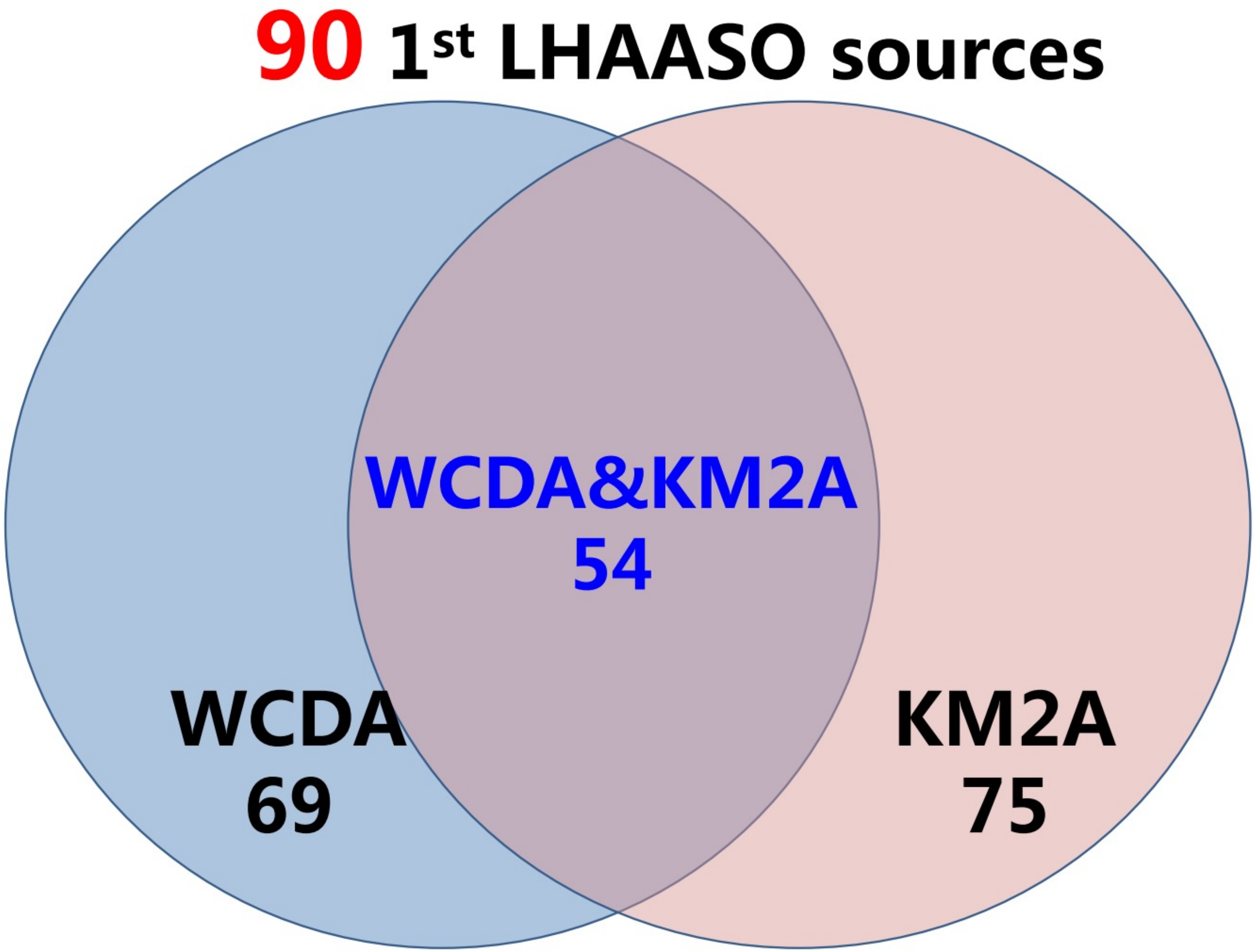




Construction of the 1st LHAASO sources

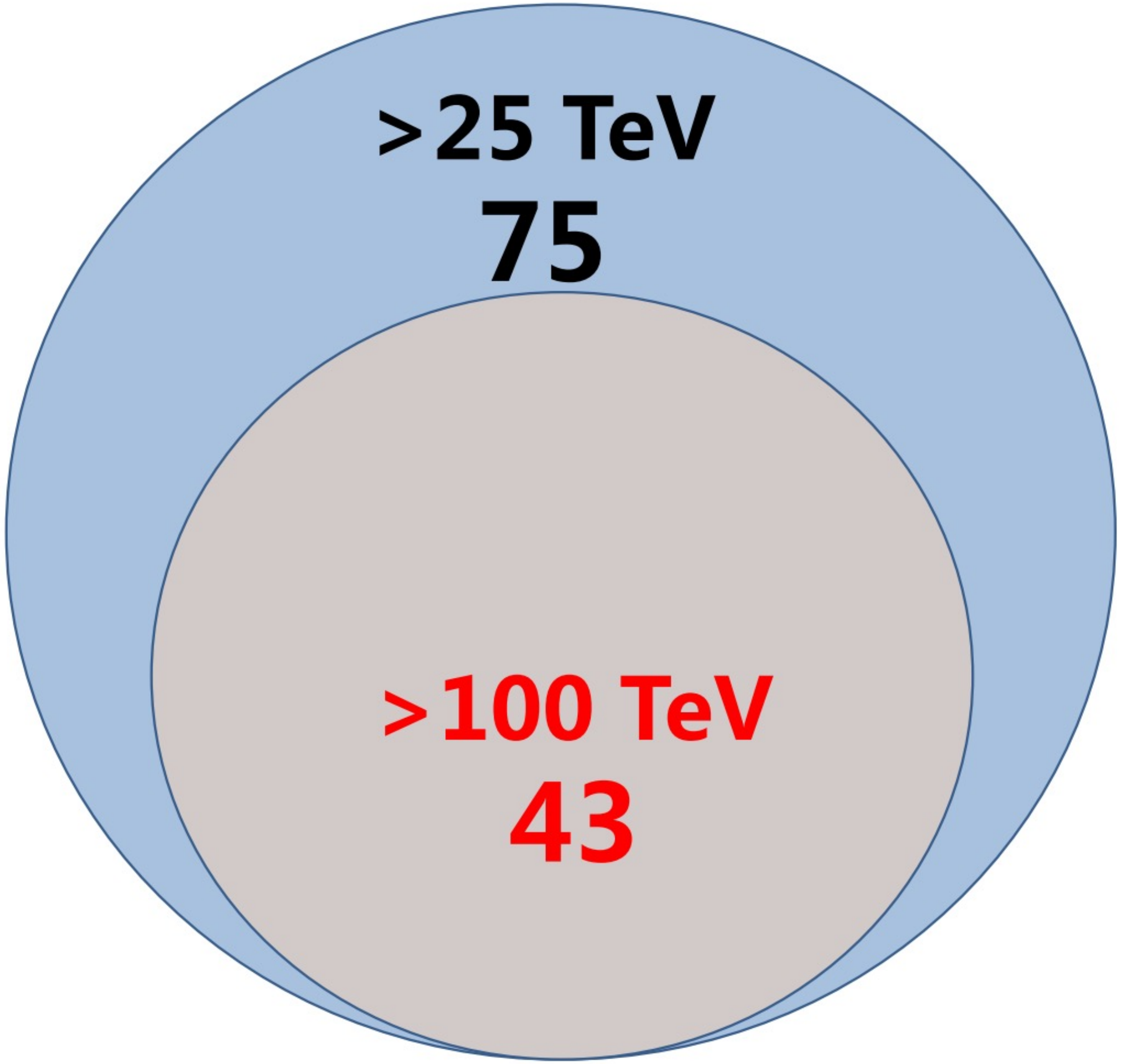
WCDA&KM2A

- Space Angle
- Position error
- Source extension

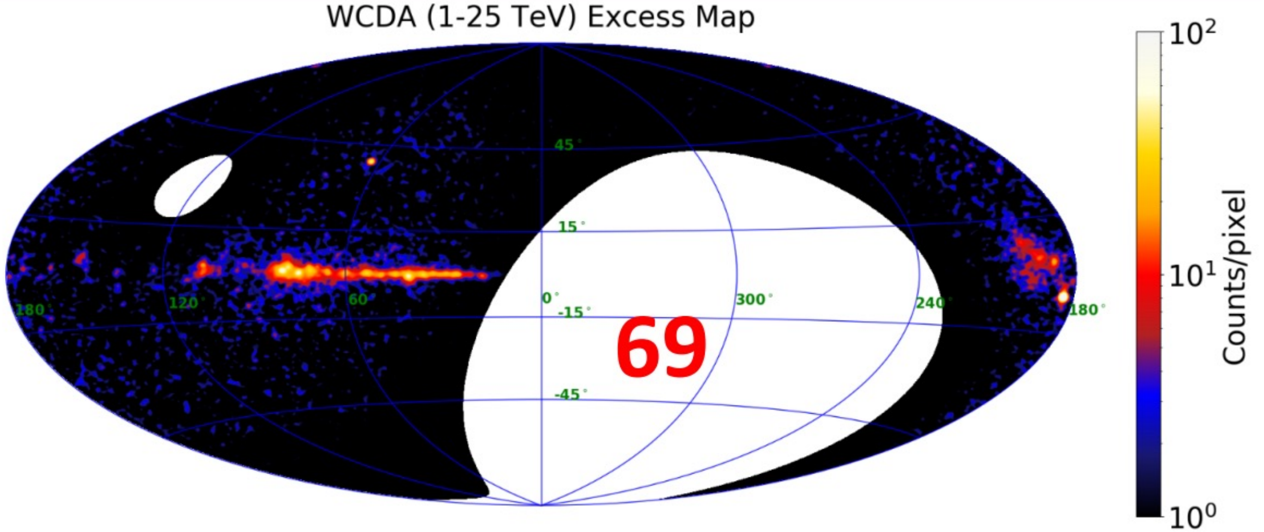


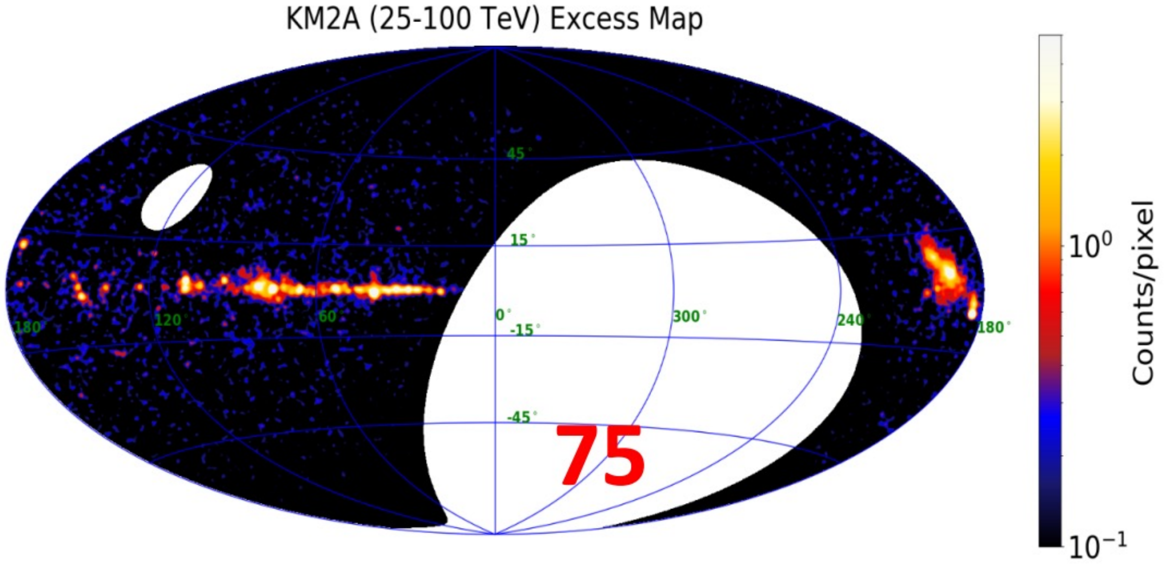
UHE gamma-ray sources

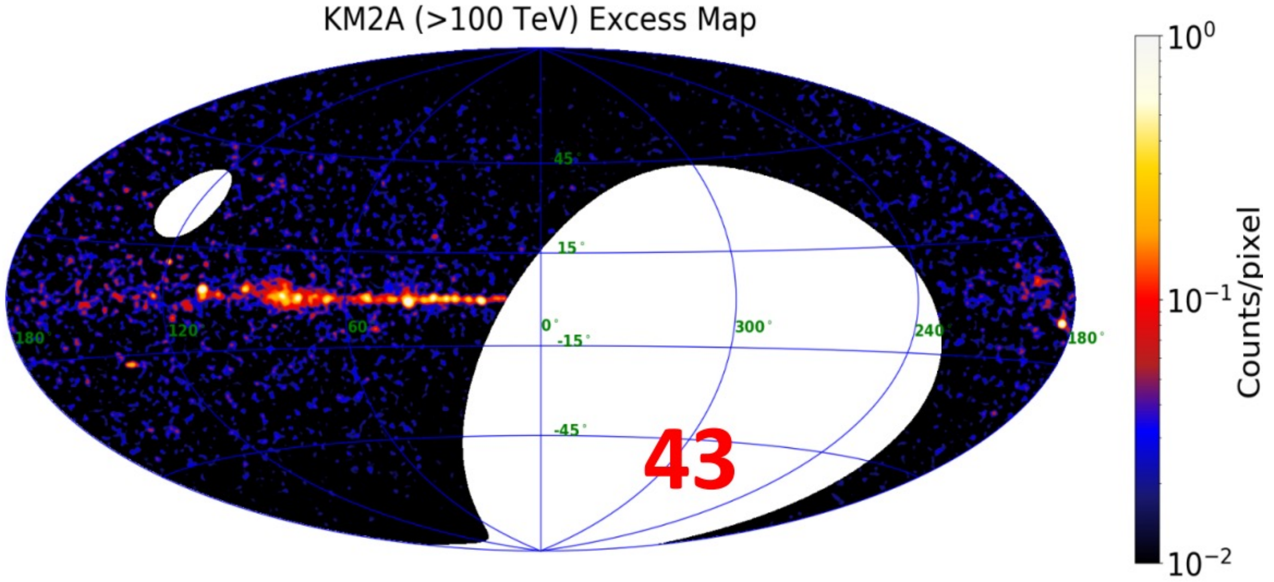
- The position and extension achieved by KM2A at >25 TeV are used.
- Sources with significance >4σ at >100 TeV are labeled as UHE sources



- **90 in 1st LHAASO sources.**
- **32 new discoveries**
- **43 UHE**







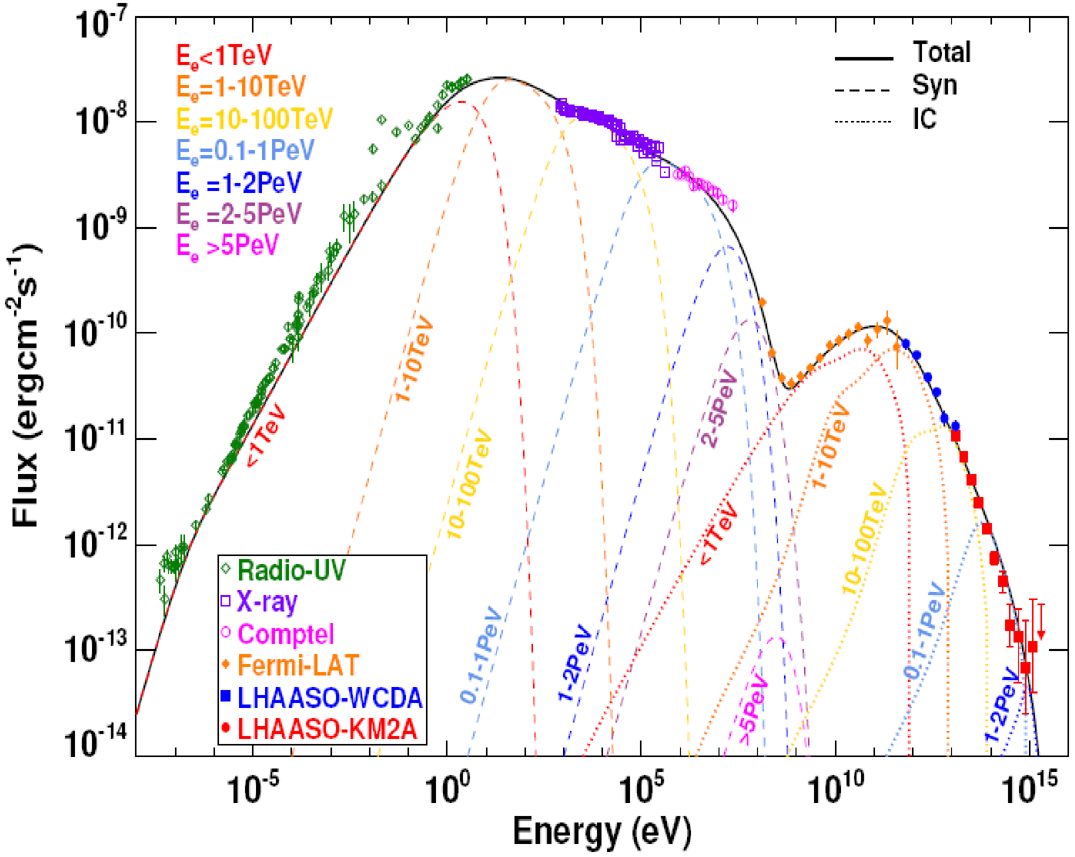
3 Innovative measurement of the standard candle Crab Nebula

Reveal an extreme e-accelerator

$$B \simeq 112^{+15}_{-13}\ \mu\text{G}$$

- 0.3-1.1 PeV measured for the first time.
- Maximum photon energy 1.12±0.09 PeV→ primary electron energy 2.3 PeV

$$E_e \simeq 2.15\left(E_\gamma/1\ \text{PeV}\right)^{0.77}\ \text{PeV}$$



LHAASO coll. 2021 (Science 373:425-430)

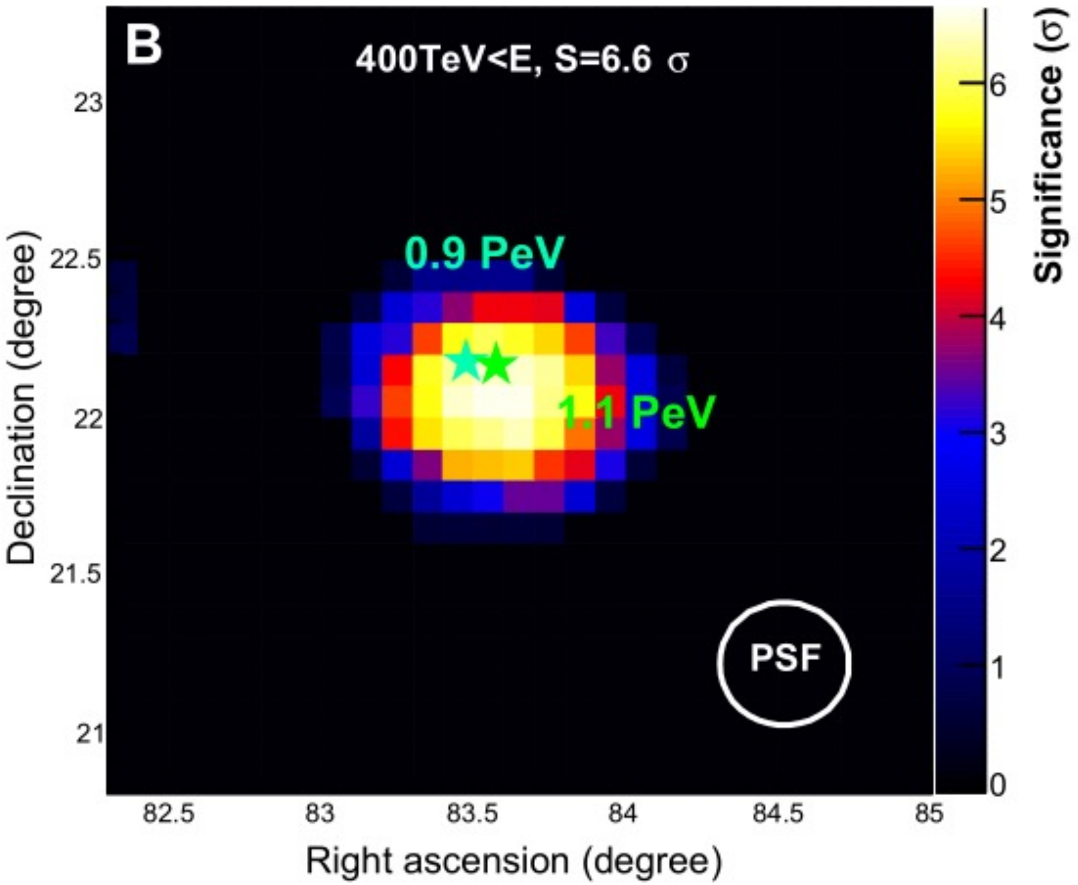
New knowledge of the acceleration rate

- $\eta<1$ according to classical electrodynamics and ideal MHD

- Acceleration rate $\eta\approx0.16$ balancing the synchrotron losses rate for maximum energy.

- 1000×SNR shock acceleration rate

$$\eta = 0.14(B/100\,\mu\text{G})(E_\gamma/1\,\text{PeV})^{1.54}$$

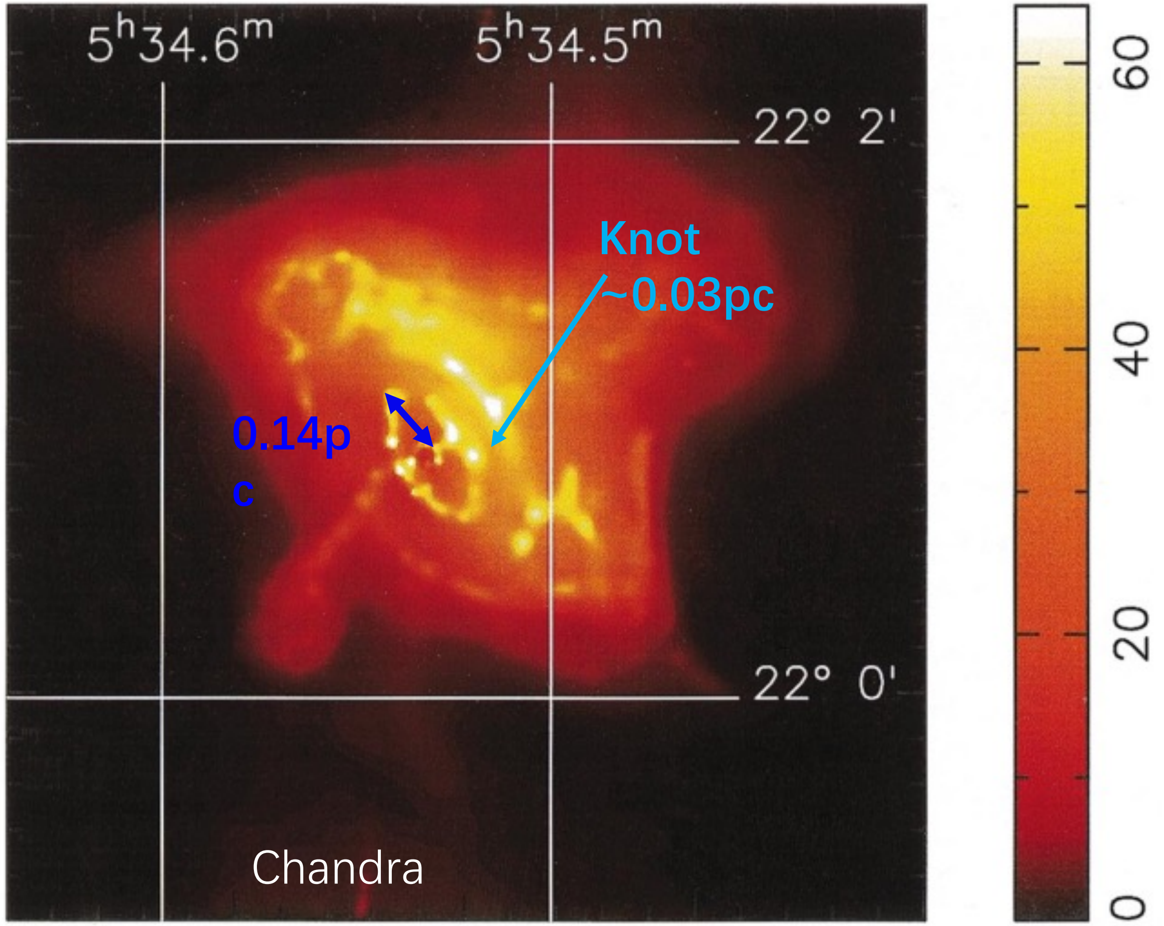


LHAASO coll. 2021 (Science 373:425-430)

New knowledge of the accelerator size

- **Accelerator size l >electron gyro radius R_g=0.025 pc (according to the 1.1 PeV photon)**

$$R_g = E_e / eB$$



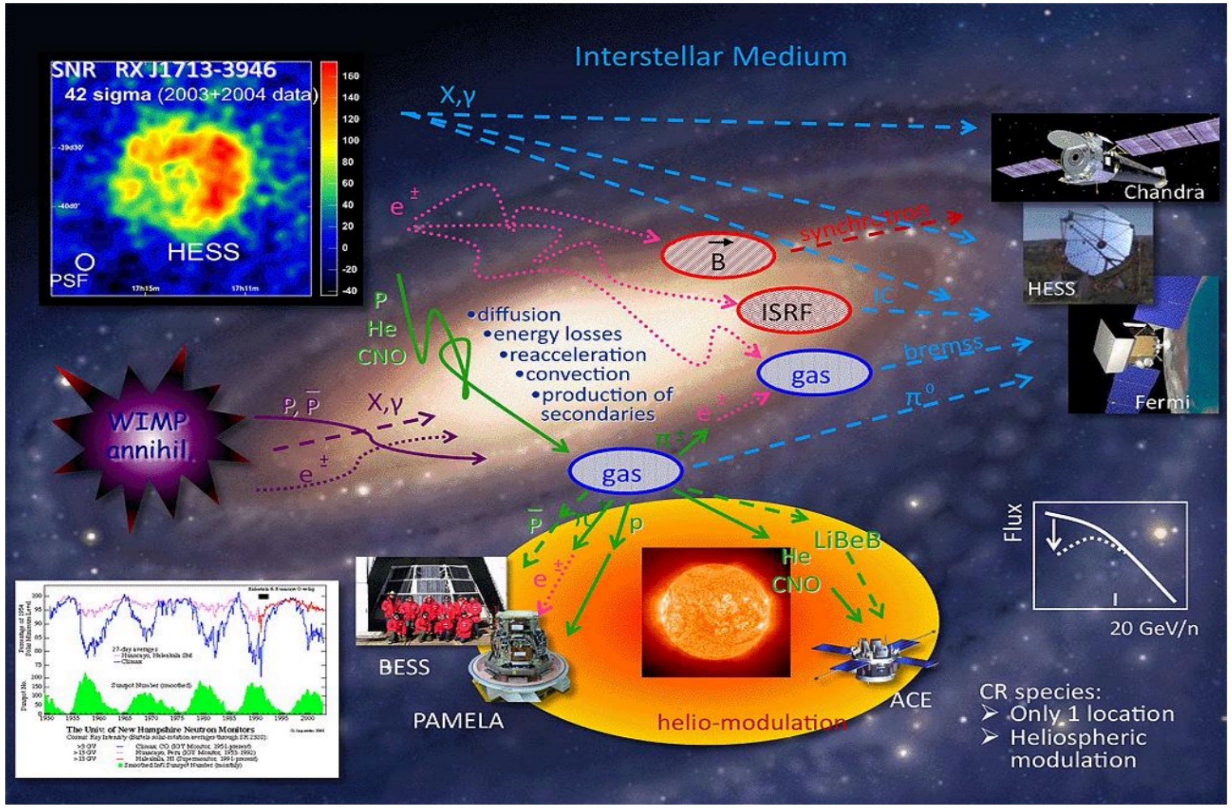
LHAASO coll. 2021 (Science 373:425-430)

Martin et al. 2000

4 Diffuse gamma rays of the Milky Way

General picture of Galactic cosmic rays

© *I. V. Moskalenko*



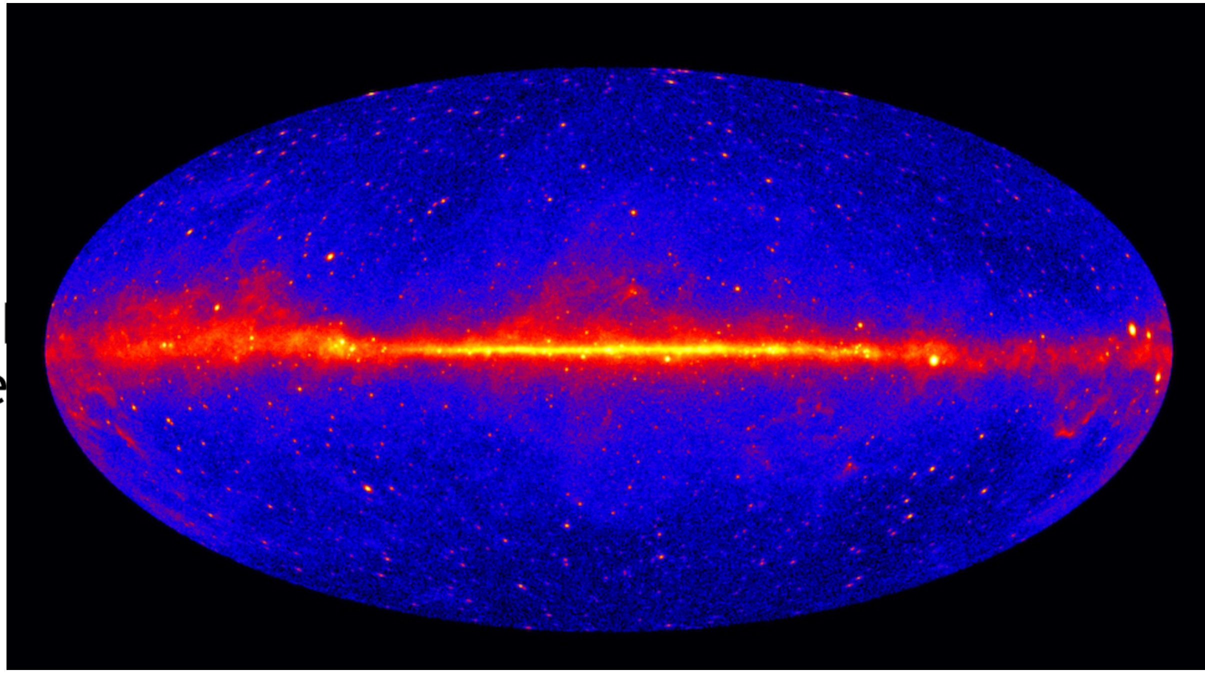
Acceleration at source

↓

Diffusion and Interaction

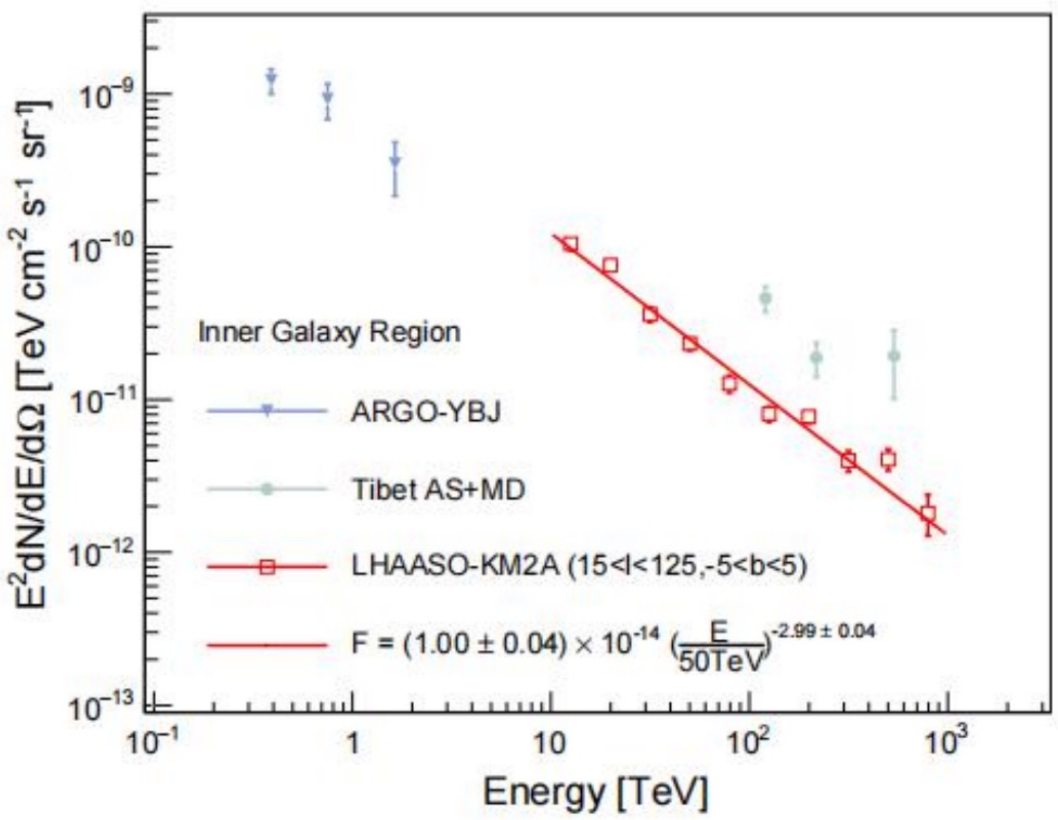
↓

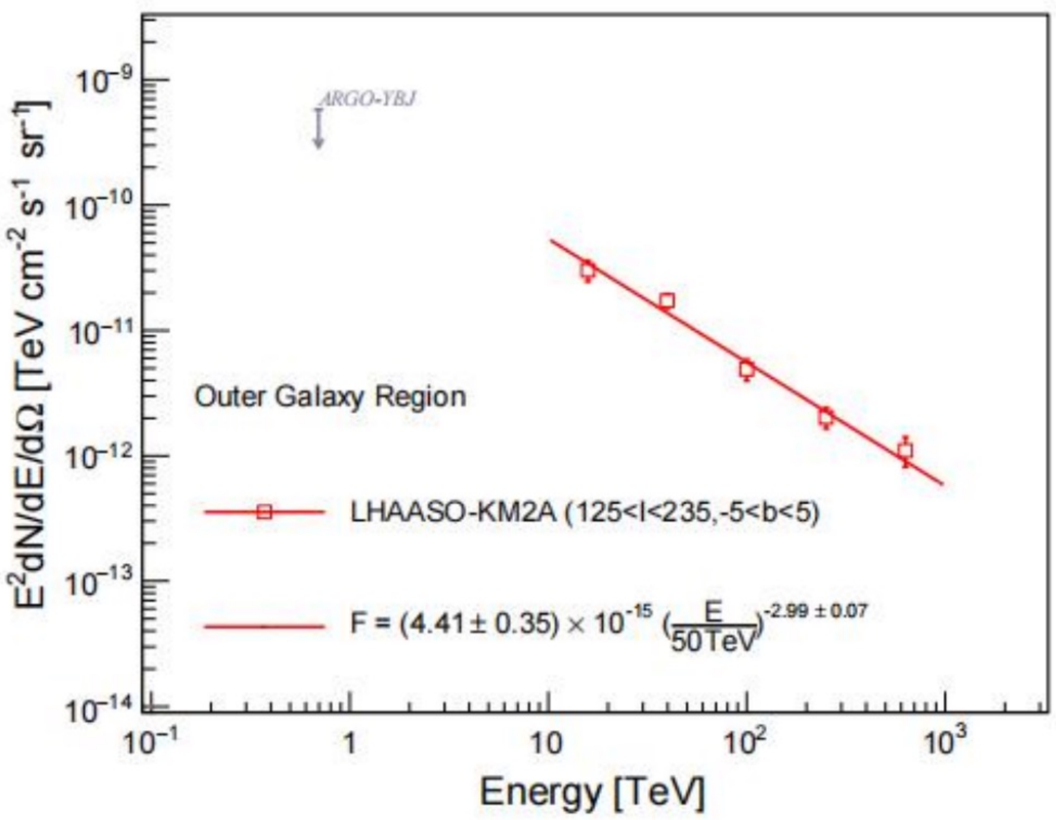
Helio-sphere propagation



Diffuse γ rays are expected *a priori* to be produced
propagation, and are thus powerful probe

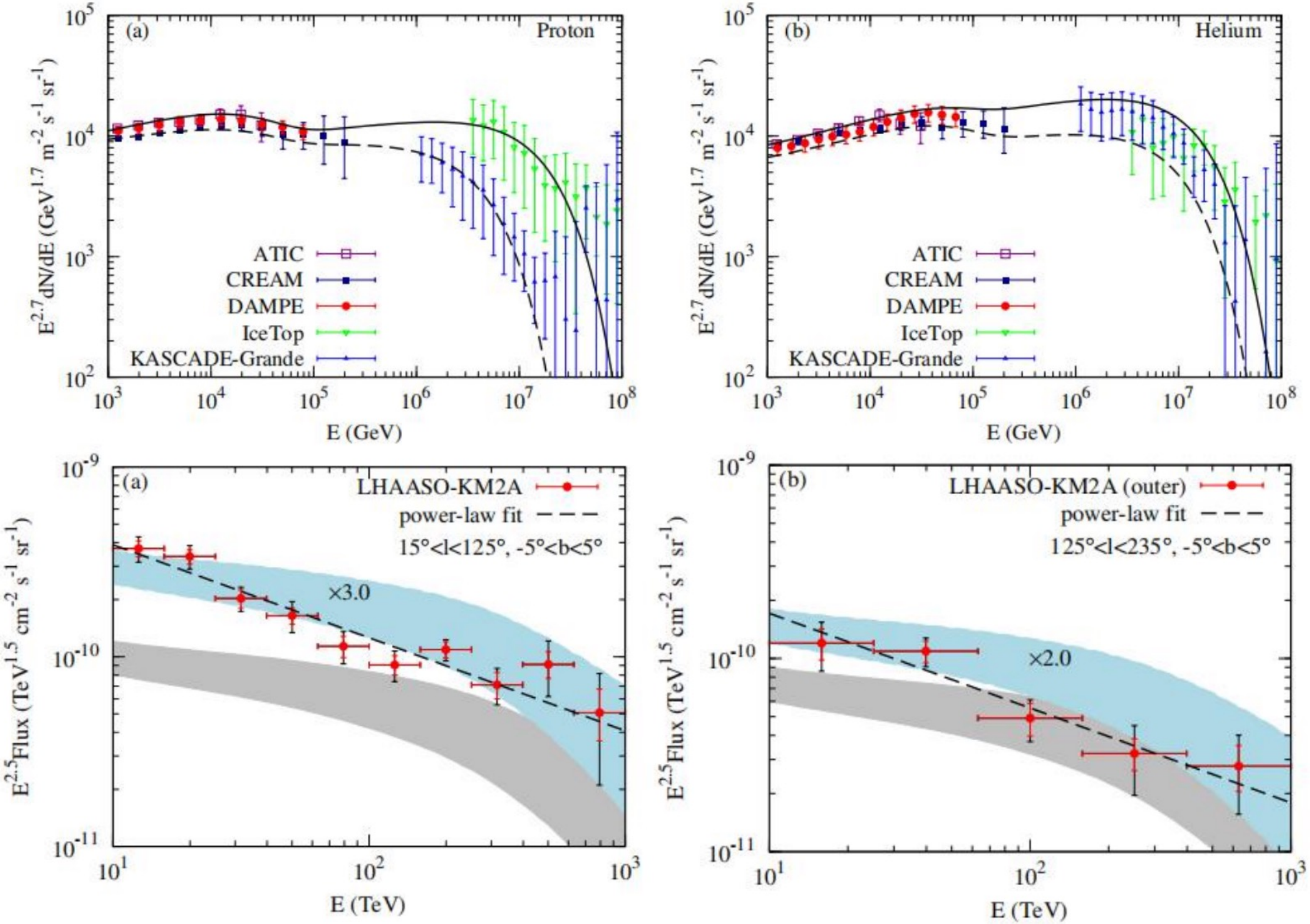
LHAASO diffuse results





- First detection of VHE diffuse emission from outer Galactic plane
- Spectra follow power-law forms with an index of ~3

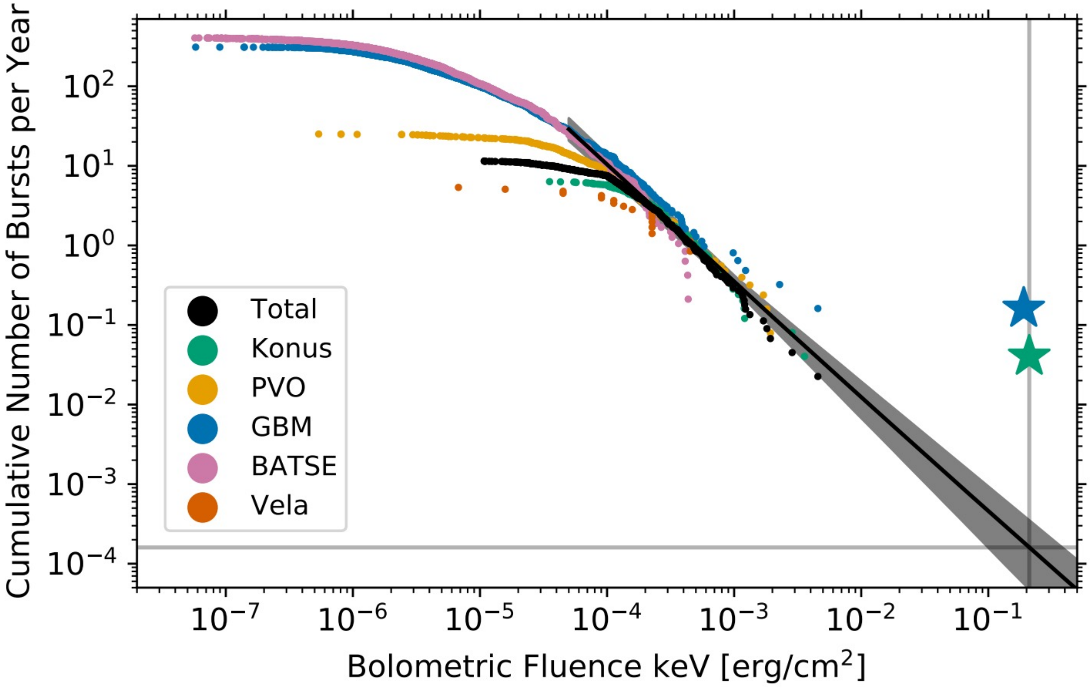
Confront LHAASO fluxes with a toy model

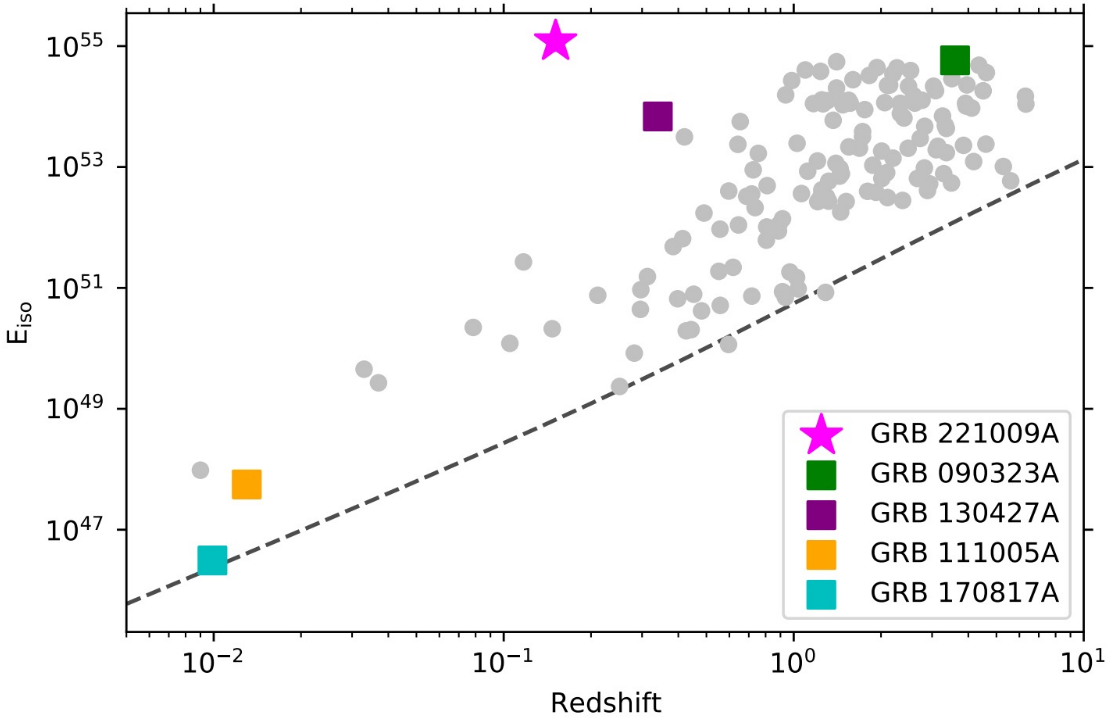


- Toy model prediction: local CR × gas column (PLANCK dust opacity)
- Measured fluxes are higher by a factor of 2~3 than predictions: unresolved sources or propagation effect?

5 Brightest GRB

GRB 221009A: A very rate event





Fluence: >5 × 10 $^{-2}$ erg/cm^2

R_GRB≤ 6.1 × 10^{-4} Gpc^{-3} yr^{-1}

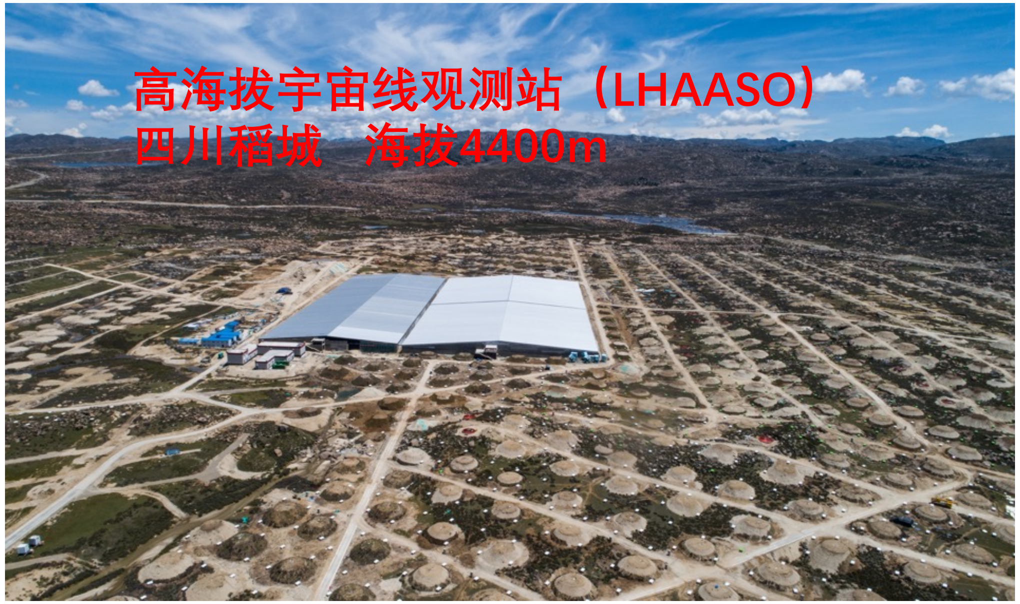
z=0.151 volume ~ 1 Gpc^3

R<10^-3 yr

Buns et al. 2023

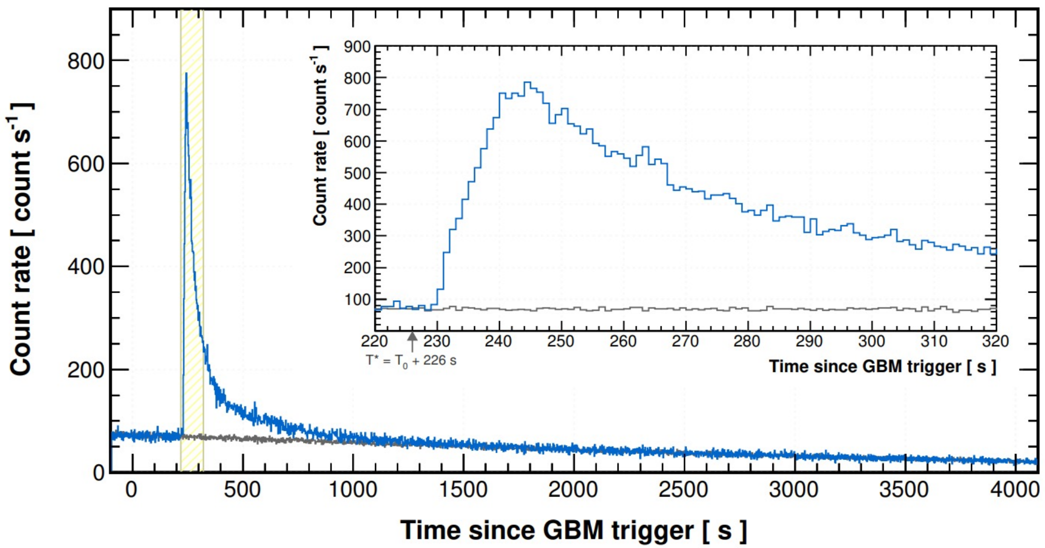
LHAASO对GRB221009A的探测

- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector



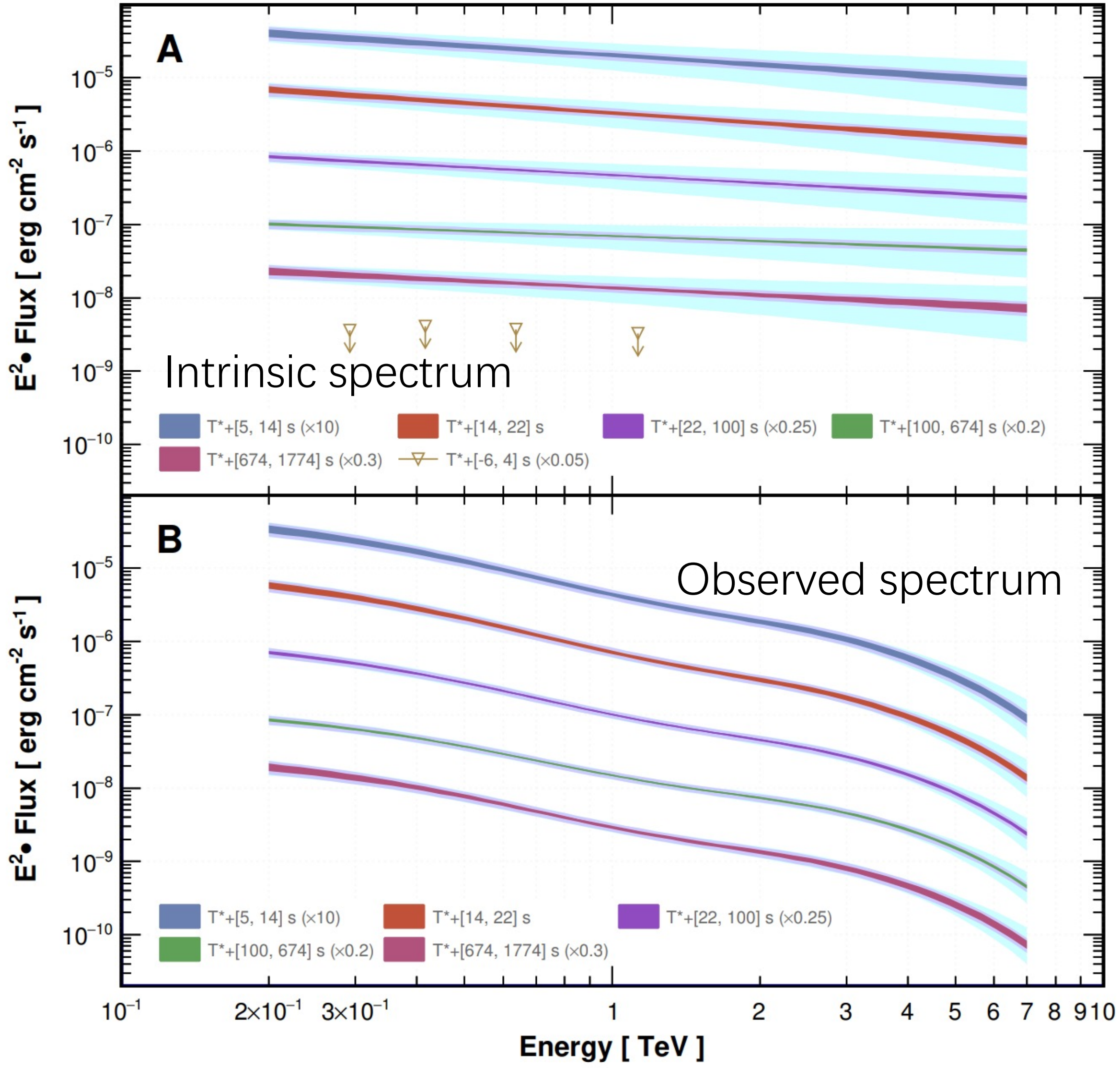
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)

- TeV count rate light curve: Smooth temporal profile – **external shock origin**



First time detection of the TeV afterglow onset !

SED measured by LHAASO-WCDA



- .EBL model: A. Saldana-Lopez et al. (2021)

Time interval (seconds after T_0)	A (10^{-8} TeV^{-1} cm^{-2} s^{-1})	γ	$E_{\rm cut}$ 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

A narrow GRB jet

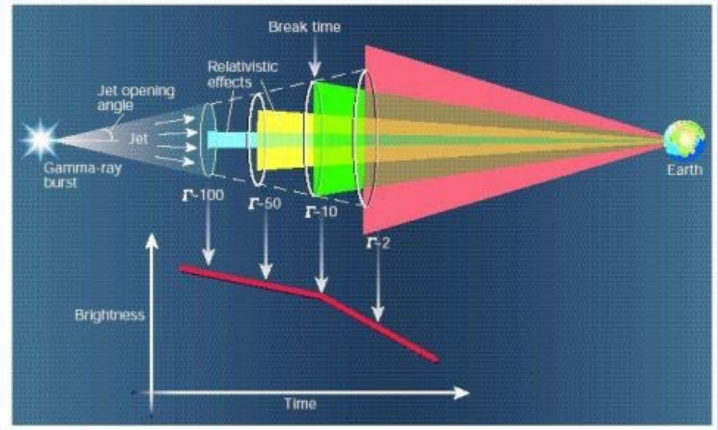
LHAASO coll. 2023 (Science accepted)

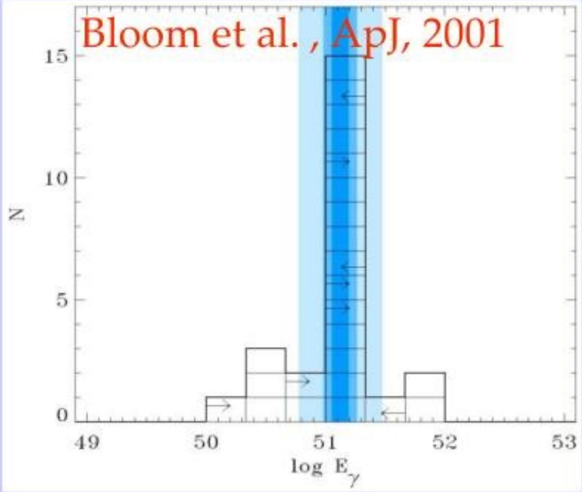
- Jet breaks have been seen in optical/X-ray bands
- First time seeing a jet break at TeV band
- Helps to understand the total energy of the GRB

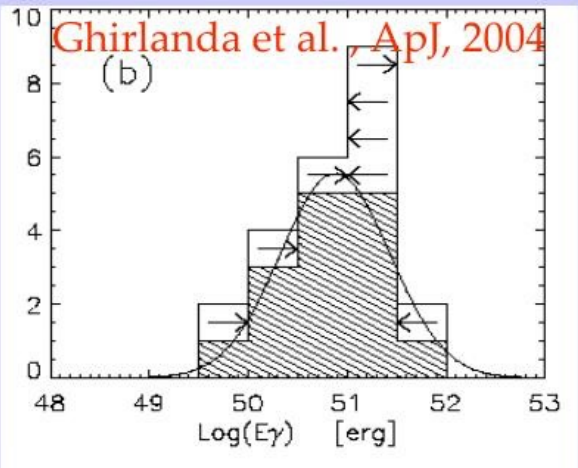
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\rm b,2}}{670\,{\rm s}}\right)^{3/8}$$

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

➢ assuming jet angles derived from the break time of the optical afterglow light curve, the collimation-corrected radiated energy is clustered around ~10^{51} erg.







6 Constraints on Lorentz Invariance violation

Lorentz invariance violation （LIV）

- For the case of Lorentz invariance a free particle satisfies the dispersion relation: $E^2 = m^2 c^4 + p^2 c^2$
- For some quantum gravity theories, Lorentz invariance may be violated at Planck scale, which leads to modification of the dispersion relation at low energies.
- The dispersion relation at low energies, $E^2 = m^2 c^4 + p^2 c^2 * (1 + a1(pc/M_{pl} c^2) + a2(pc/M_{pl} c^2)^2 + \cdots)$
- a1, a2 ⋯ are model parameters of LIV
- LIV effect is suppressed at low energy by $M_{pl} c^2$
- Many exotic phenomena may take place in the LIV scenario which are forbidden in LI

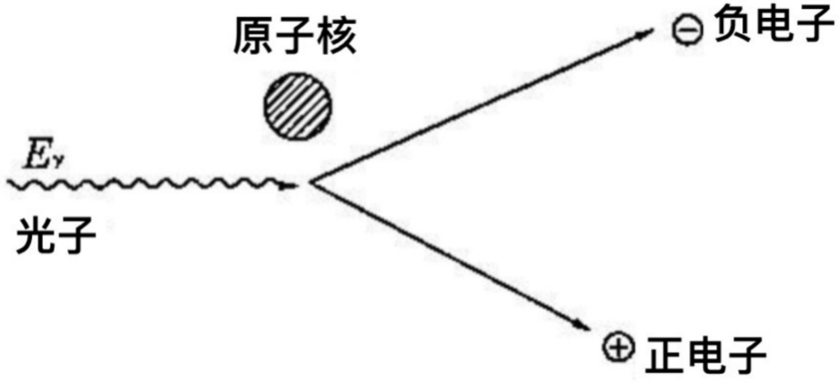
Energy dependent speed of light at LIV

- From the LIV DR, $E^2 = p^2 c^2 *(1 + a1(pc/ M_{pl} c^2) + a2(pc/ M_{pl} c^2)^2 + \cdots)$
- Group velocity $v(E) = \partial\omega / \partial k = \partial E / \partial p$

$$\approx c[1 + \frac{1+n}{2} a_n (pc / M_{pl} c^2)^n] \approx c[1 \pm \frac{1+n}{2} (E/E_{LIV,n})^n]$$

- v(E) is not a constant and can be superluminal or subluminal depending on the sign of a_n, for n=1,2 the first and second order of LIV
- As $(E/E_{LIV,n})$ is highly suppressed for $E \ll E_{LIV,n}$, it is generally very hard to observe the effect
- It is the great advantages for astrophysical probe: the highest energy possibly achieved in the universe; or long distance propagation from the source may accumulated the tiny effect to be observable.
- Constraints on LIV by time decay of photons from GRBs have been set

Decay of a free photon



- A free photon in vacuum is stable in LI
- For LIV, $E_\gamma^2 - p_\gamma^2 = \frac{p^{n+2}}{E_{LIV}^n} = m_{\gamma,eff}^2$
- When the effective mass > a pair of e+e-, the photon decay into e+e- very fast and leads to a sharp cutoff at the SED
- If no such decay the LIV energy scale is constrained as $E_{\rm LIV}^{(n)} > \left(\frac{E_\gamma^n(E_\gamma^2-4m_e^2)}{4m_e^2}\right)^{1/n}$
- For n=1,2, we have

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

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

- The constraints are very sensitive to the highest energy of gamma

Photon splitting

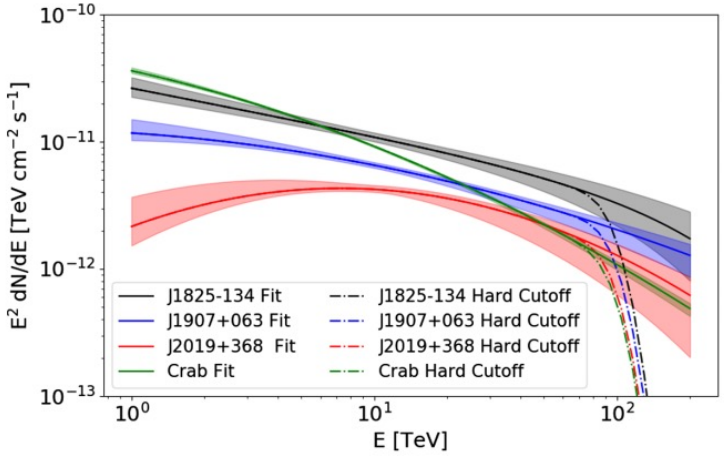
- LIV also leads to a photon splitting to 3 photons

分裂过程: γ→ 3γ

$$\Gamma_{\gamma\to3\gamma} = 5\times10^{-14}\frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

$$E_{LIV}^{(2)} > 3.33\times10^{19}\mathrm{eV}\left(\frac{L}{\mathrm{kpc}}\right)^{0.1}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{1.9}.$$

- LIV decay or splitting leads to s sharp cutoff the high energy end of the spectrum
- We analyze the LHAASO data of gamma ray SED to look for the LIV cutoff



LHAASO发现的大于100 TeV的源

Z. Cao, et al., Nature 594, 33 (2021)

source name	R.A. (°)	dec (°)	Significance (σ) above 100 TeV	E_{Max} (PeV)	Flux (± error) (CU) at 100 TeV
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ±0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ±0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ±0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ±0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ±0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ±0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ±0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ±0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ±0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ±0.19	1.05(0.16)

The result

Phys.Rev.Lett. 128 (2022) 5, 051102

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

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

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

Process: $\gamma \rightarrow 3\gamma$

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

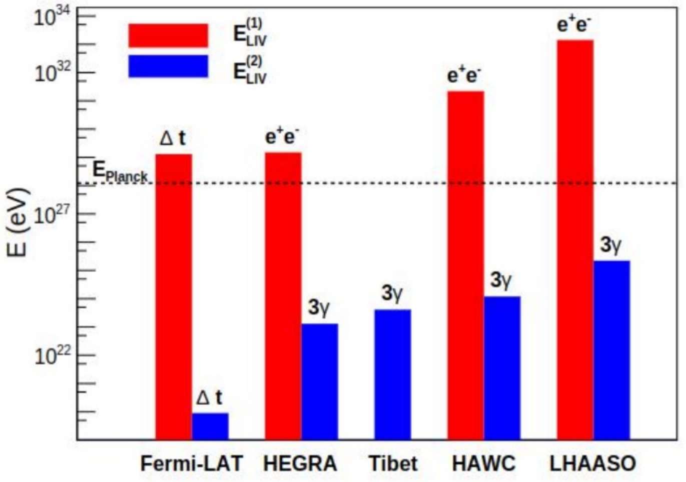
$$E_{LIV}^{(2)} > 3.33 \times 10^{19} {\rm eV} \left(\frac{L}{\rm kpc}\right)^{0.1} \left(\frac{E_\gamma}{\rm TeV}\right)^{1.9}.$$

Source	L (kpc)	$E_{\rm max}$ (PeV)	$E_{\rm cut}^{95\%}$ (PeV)	$E_{\rm LIV}^{(1)}$ (eV) $\times 10^{32}$	$E_{\rm LIV}^{(2)}$ (eV) $\times 10^{23}$	$E_{\rm LIV}^{(2)}$ (3γ) (eV) $\times 10^{25}$
Crab Nebula	2.0	0.88 ± 0.11	$0.75^{+0.04}_{-0.04}$	$4.04^{+0.69}_{-0.62}$	$5.5^{+0.61}_{-0.58}$	$1.04^{+0.11}_{-0.10}$
J2032+4102	1.4	1.42 ± 0.13	$1.14^{+0.06}_{-0.06}$	$14.2^{+2.42}_{-2.18}$	$12.7^{+1.41}_{-1.34}$	$2.21^{+0.23}_{-0.22}$

$E_{\rm planck} = 1.22*10^{19}$ GeV

$10^5\ E_{\rm planck}$

$0.1\%\ E_{\rm planck}$

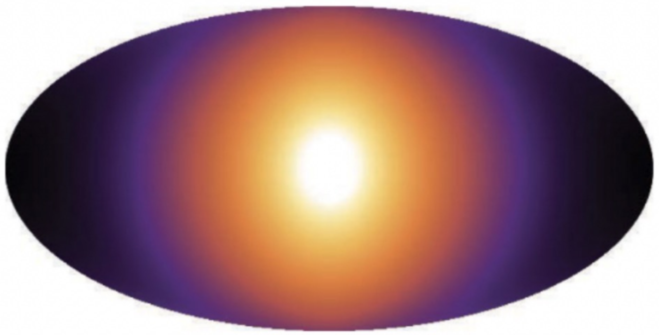


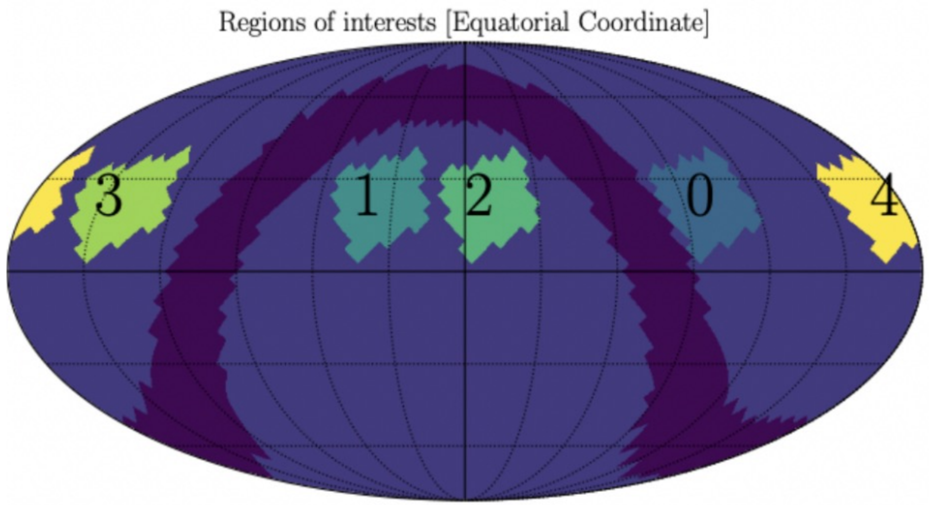
$E_{LIV}^{(1)}$和$E_{LIV}^{(2)}$限制提高了一个量级

7 Dark matter searches

Carefully selected regions for DM decay

- The signal region is chosen ROI_0, around $15^\circ \leq b \leq 45^\circ$ and $30^\circ \leq \ell \leq 60^\circ$
  - Away from Galactic plane and Fermi bubble
  - Close to the GC as possible
- 4 control regions $\mathrm{ROI}_1 - \mathrm{ROI}_4$ by shifting ROI_0 along the RA direction by 90°, 135°, 240°, 285° respectively
  - Same declination and same detector performance
  - For accurate estimate the bkg and eliminate systematics





Likelihood analysis

- For each ROI
- $$\ln L_k(\tau_{DM}, b) = \sum_i N_k^i \ln n_k^i - n_k^i$$
- Combined likelihood
- $$\ln L = \sum_{k=0}^{4} \ln L_k$$

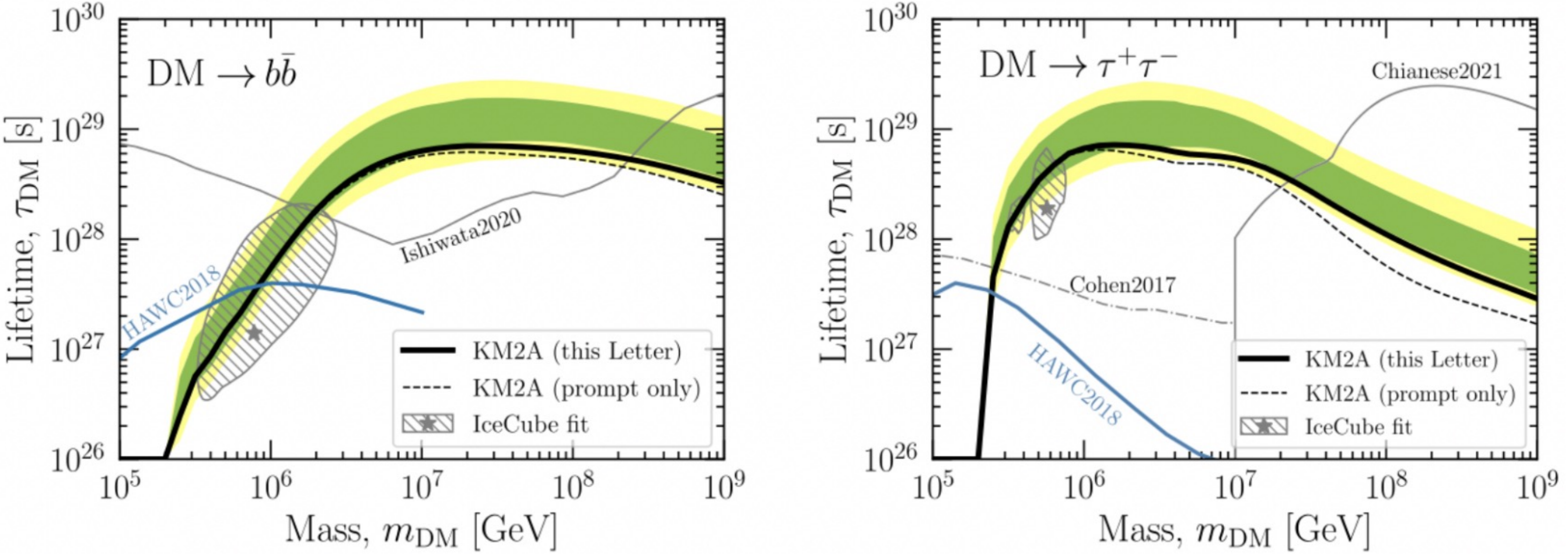
- Important features of this analysis

$$n_k^i(\tau_{\rm DM}, b) = (b^i + s_k^i(\tau_{\rm DM}))\mathcal{E}_k^i \Delta\Omega,$$

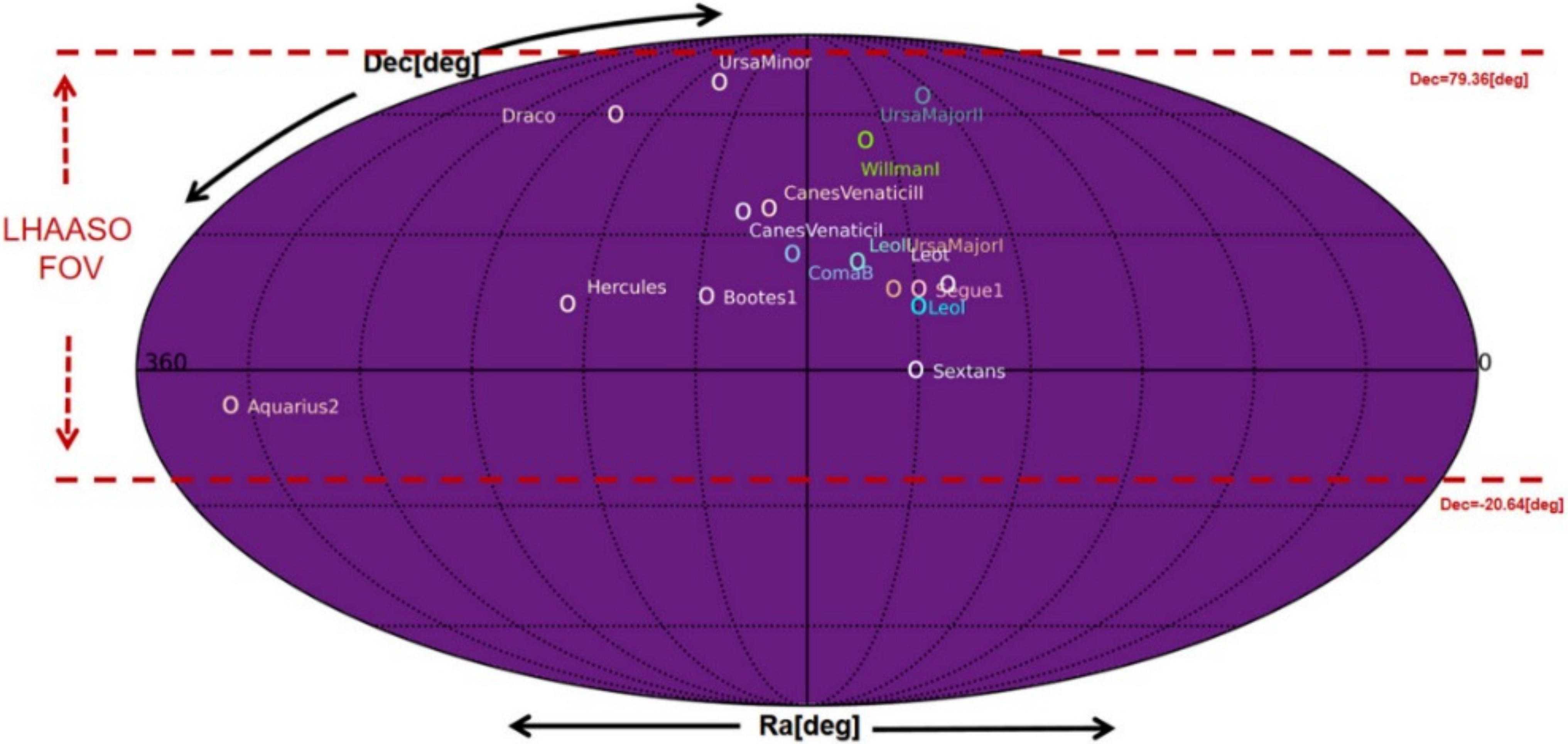
- The background model b^i, is independent of ROI
- Signal s_k^i , is different for each ROI, due to difference in D-factor
- We assume that we don't know b^i
  - allow it to be a free parameter (6 degrees of freedom)

Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations

Phys.Rev.Lett. 129 (2022) 26, 261103

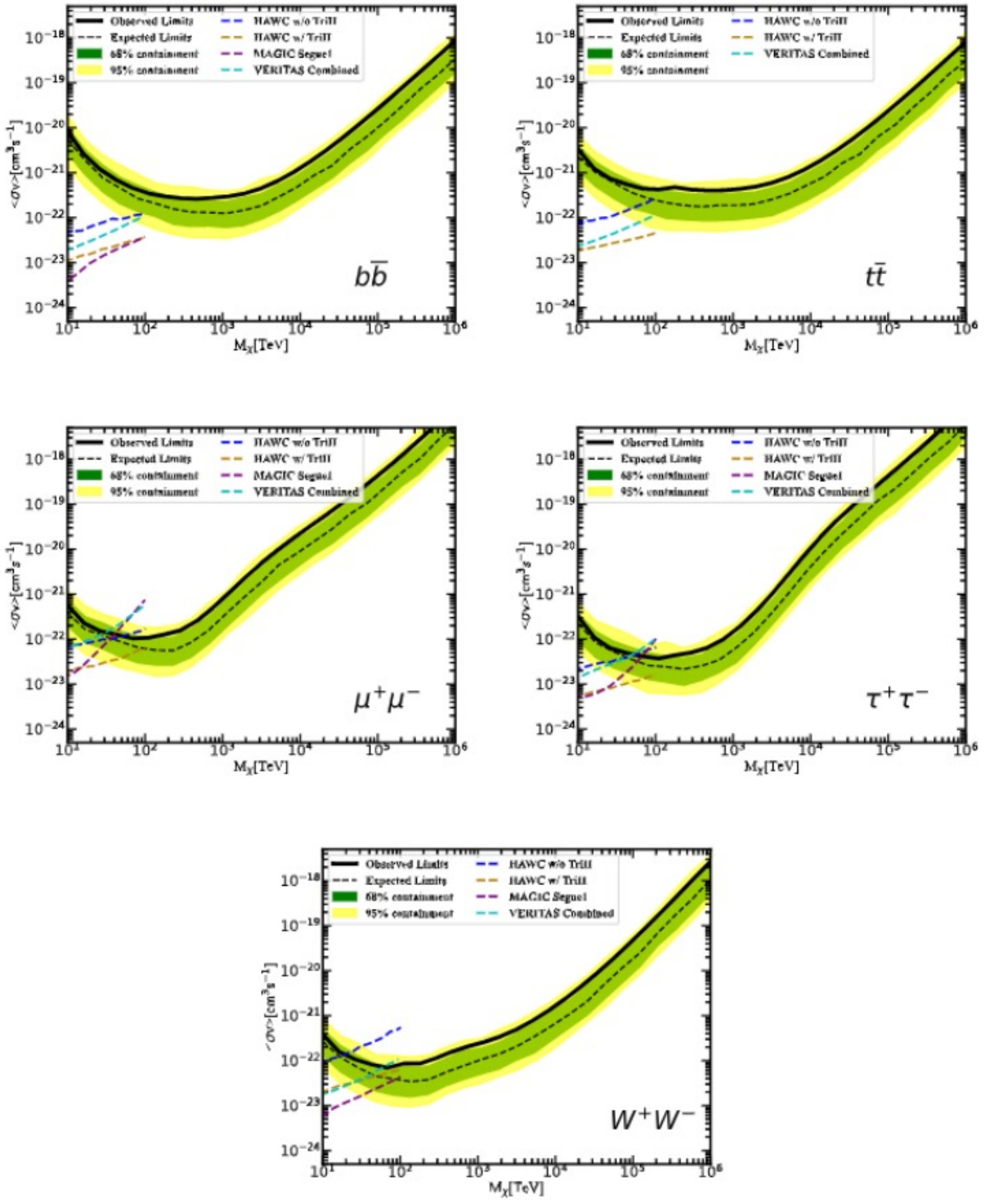


Dark matter annihilation signals from the dwarf galaxies



Constraints on DM anni

- First constraint on PeV DM annihilation



总结

- 由于LHAASO大阵列、高鉴别能力的优势，取得了一些重要的观测进展。
- 目前仍然有大量工作的紧张进行中。

- LHAASO在积极布局下一步的计划，开展高海拔切伦科夫望远镜和贝加尔湖中微子实验项目，争取解决宇宙线起源问题。