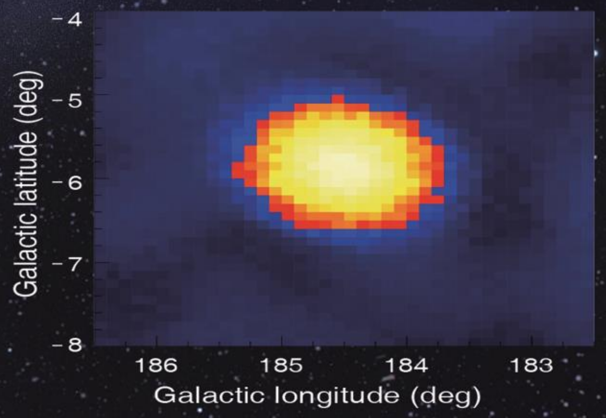
宇宙线的起源

LHAASO的核心科学目标之一



刘四明

西南交通大学

LHAASO合作组

LHAASO
高海拔宇宙线观测站

Large High Altitude Air Shower Observatory

Electromagnetic Detectors (EDs)
Muon Detectors (MDs)
Water Cherenkov Detector Array (WCDA)
Wide Field of view Cherenkov Telescope Arrays (WFCTA)

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.

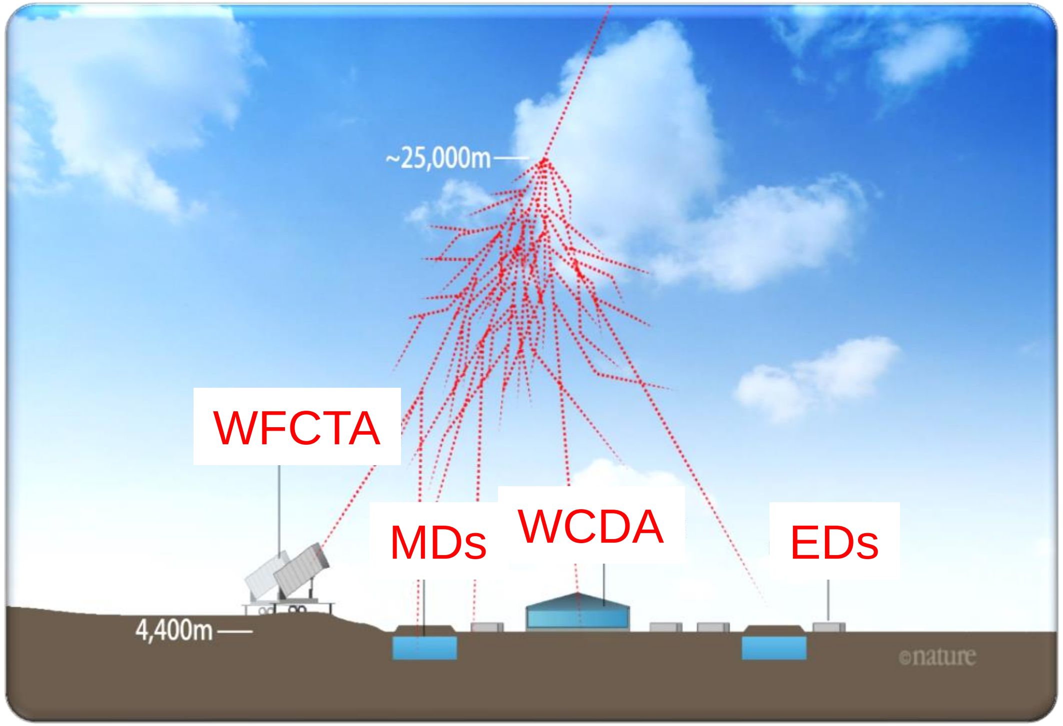
Cosmic Ray Physics

The knees

Compositions : individual species H, He and Fe

Anisotropy: (1 TeV to 10 PeV)

New Physics Front: DM, LIV, etc.



什么是宇宙线？胡红波

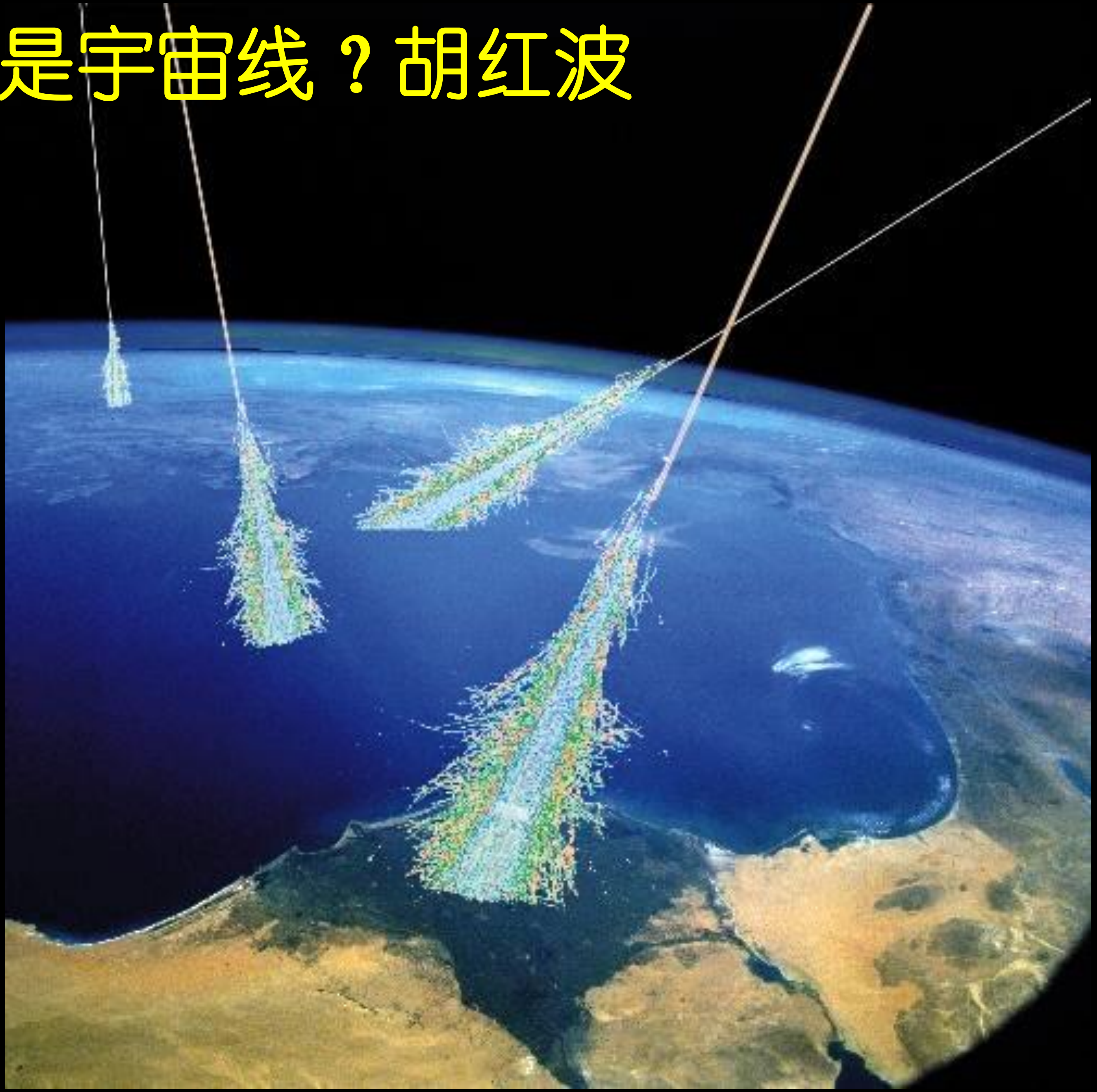
能量：导致空气电离 （必要条件）
进入大气的宇宙线和空气中的原子核很快的反应，产生大量短寿命的粒子并最后都衰变到稳定的粒子。

起源：和核衰变对应产生的高能辐射对应
来自大气层之外

物质粒子：引力波与电磁波对应
宇宙线是来自宇宙空间的高能粒子流,是自动送上门来的宇宙深处的高能物质样品.

宇宙线中大部分是带电粒子，如：质子，α粒子、铁核等等；还有少量的中性粒子如：γ光子、中微子等等。

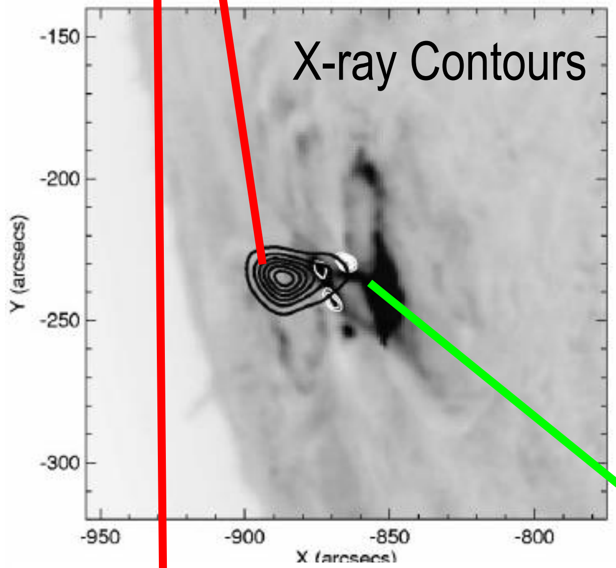
宇宙线无处不在，我们人类浸泡在大量的宇宙线粒子中，例如每秒有数以万亿的中微子穿过我们的身体。暗物质粒子?

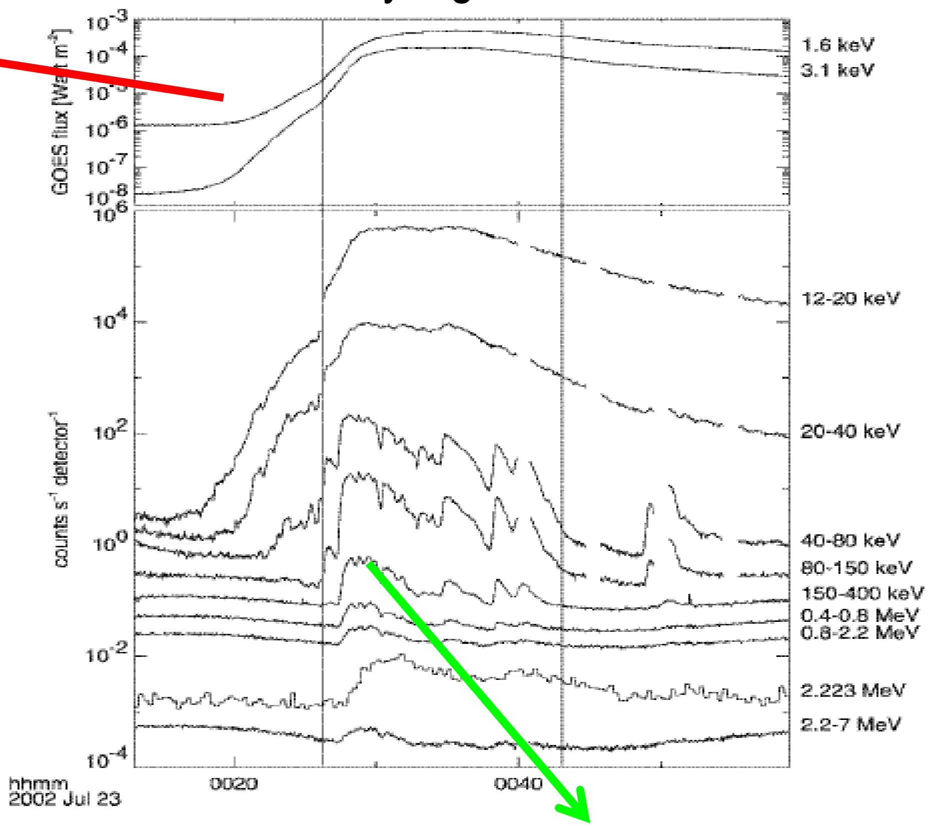


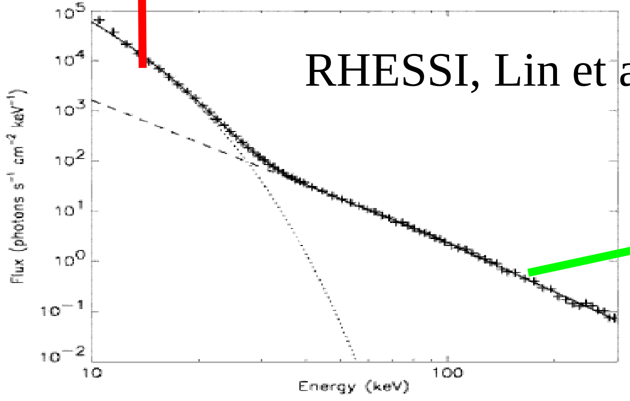
太阳耀斑

Low-energy: Gradual Thermal
Coronal Source

X-ray Light curves







RHESSI, Lin et al (2003)

X-ray Spectrum

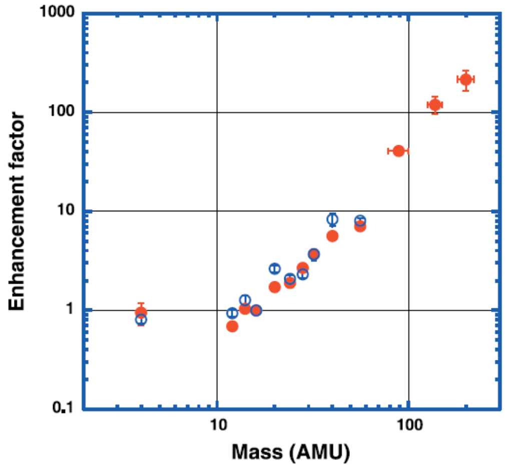
High-energy: Impulsive
Non-thermal
Chromospheric
Footpoints

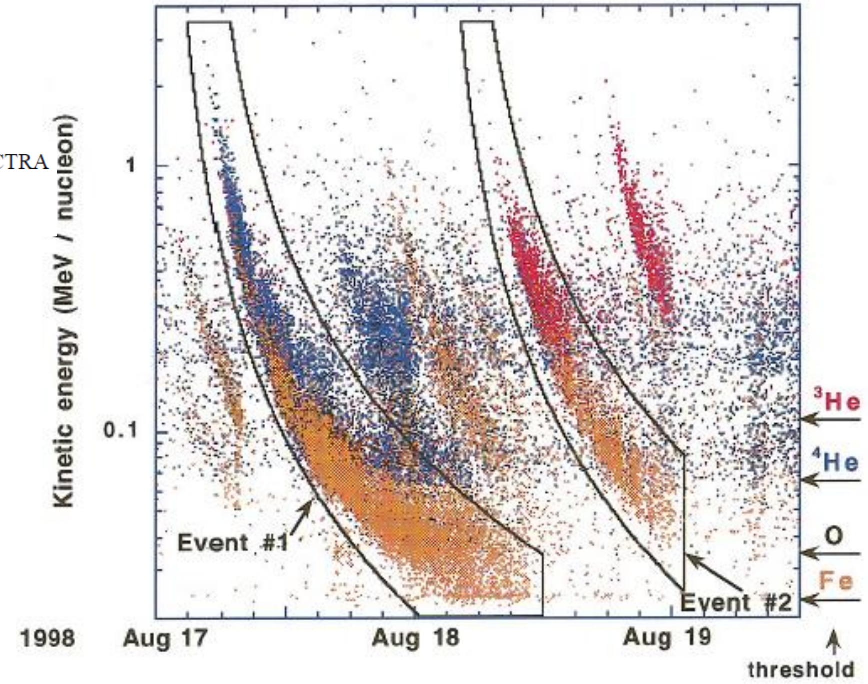
太阳高能粒子

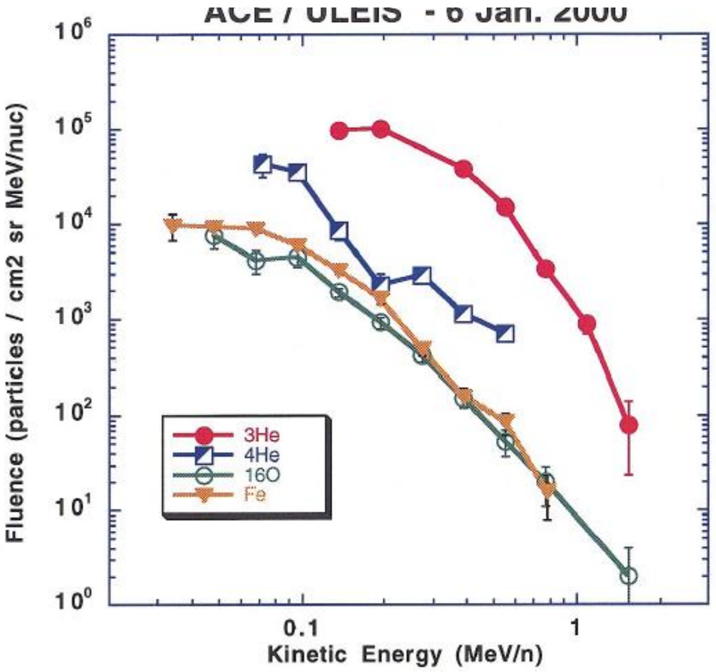
NEW PROPERTIES OF ^{3}He-RICH SOLAR FLARES DEDUCED FROM LOW-ENERGY PARTICLE SPECTRA

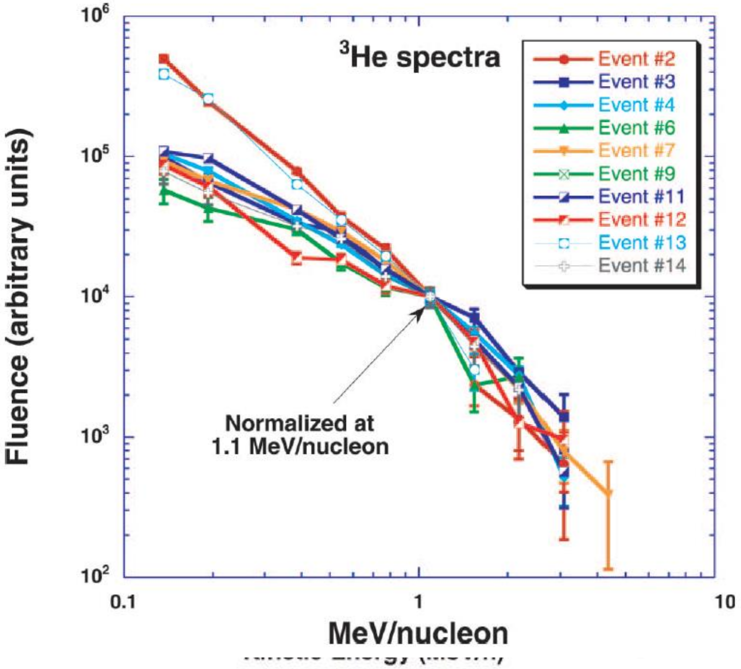
G. M. Mason,[1,2] J. R. Dwyer,[1,3] and J. E. Mazur[4]

Received 2000 August 10; accepted 2000 October 16; published 2000 December 7





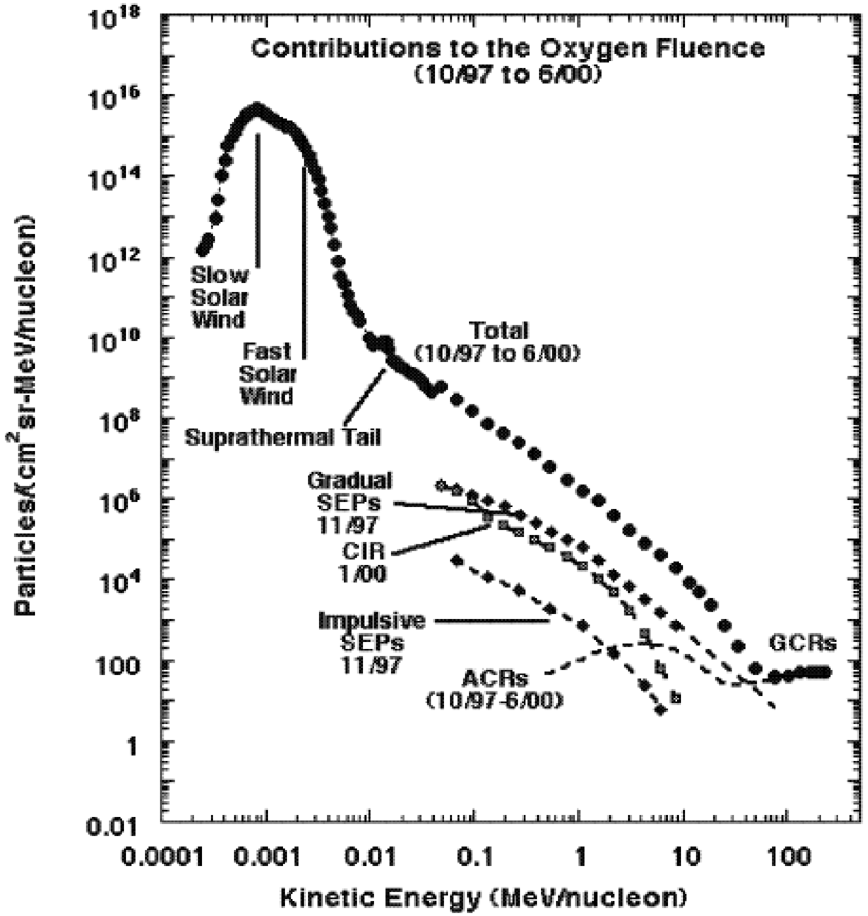


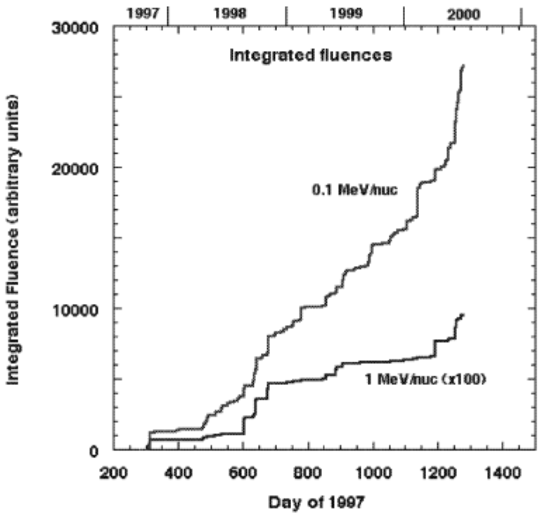


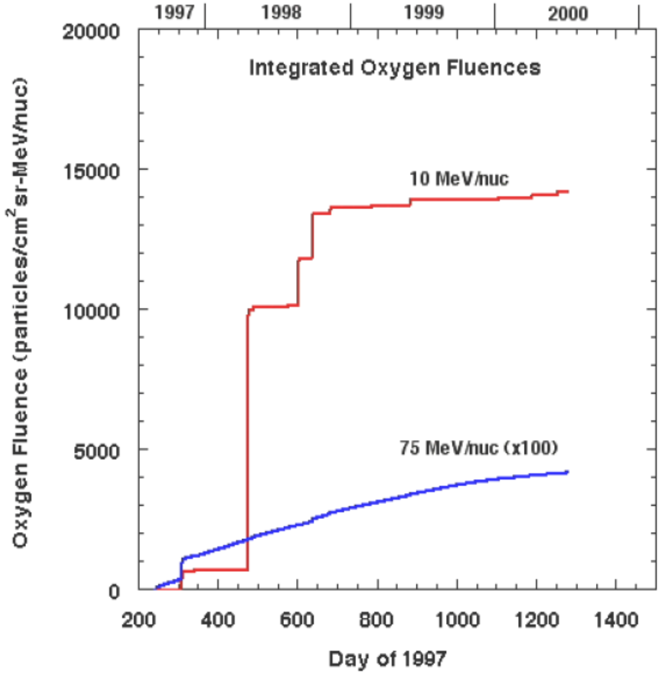
太阳高能粒子

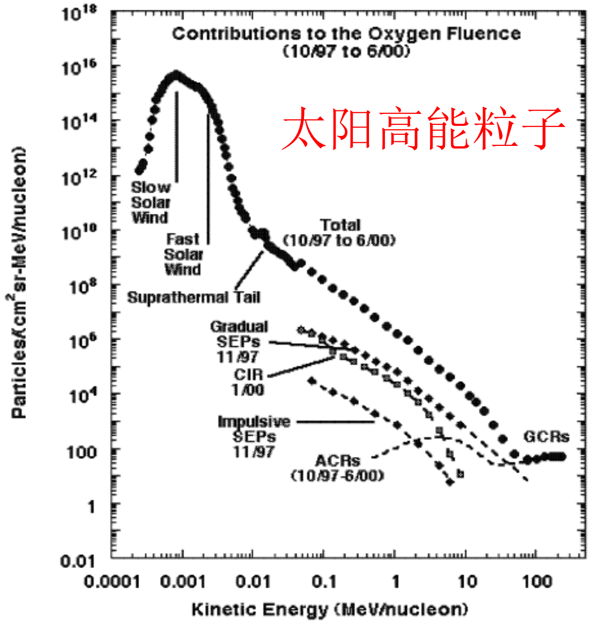
Long-Term Fluences of Solar Energetic Particles from H to Fe

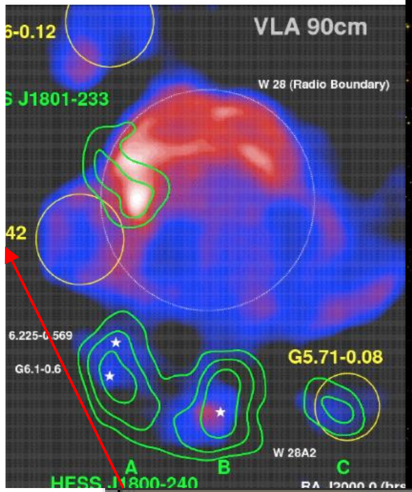
R.A. Mewaldt · C.M.S. Cohen · G.M. Mason ·
D.K. Haggerty · M.I. Desai

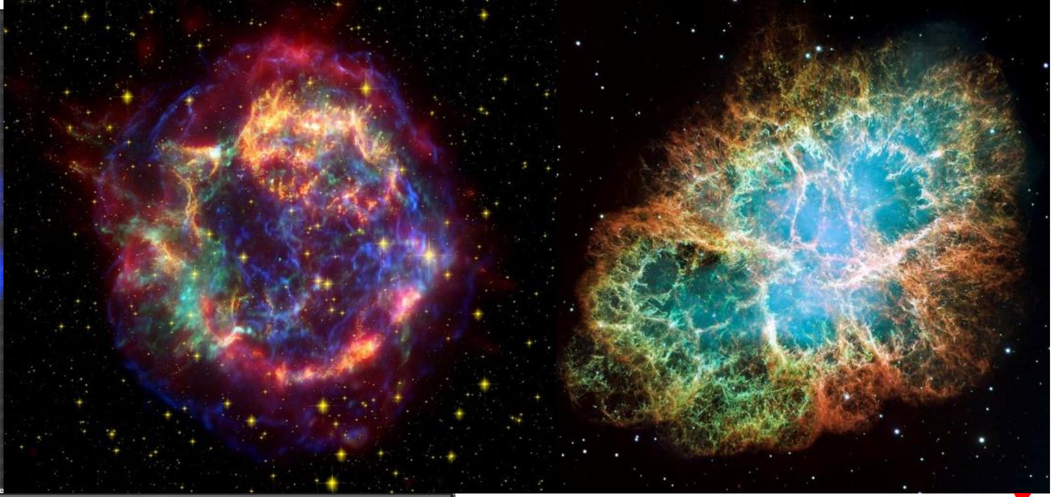


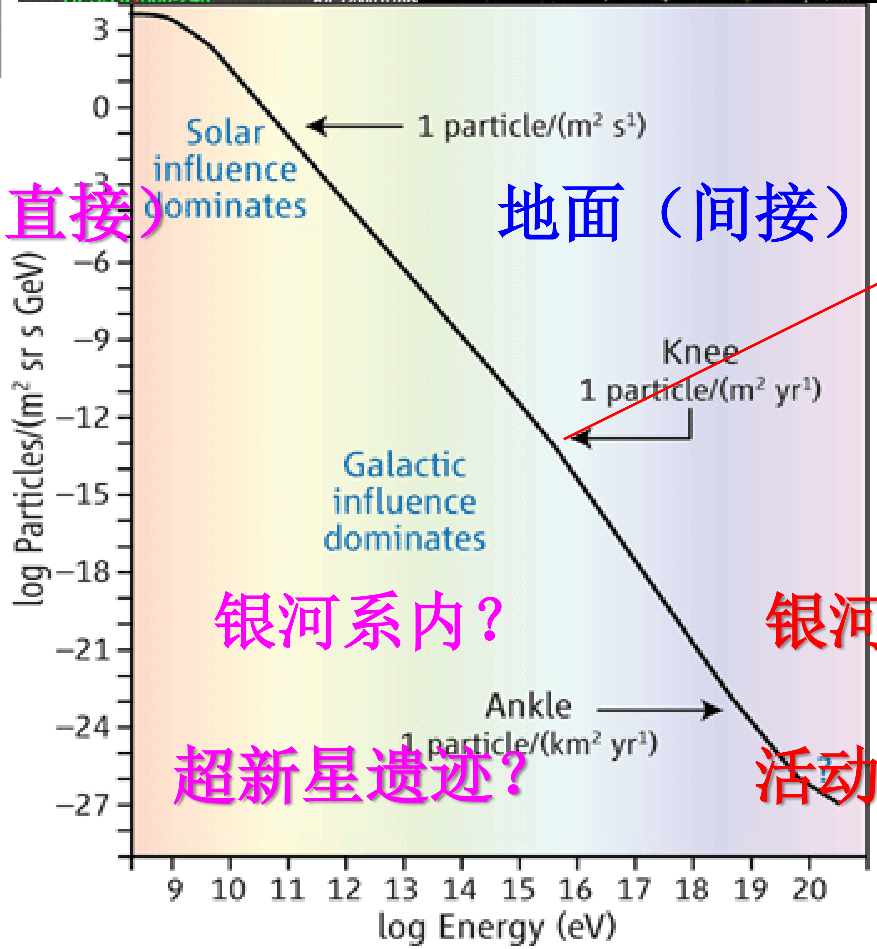






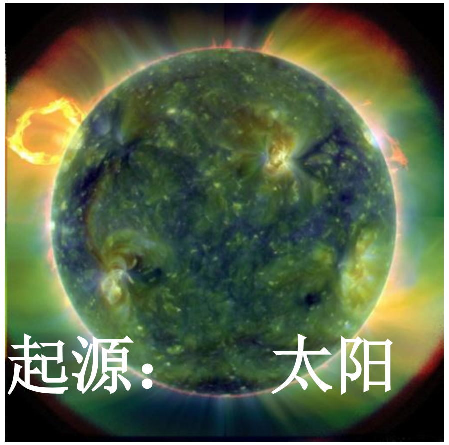






空间（直接）

地面（间接）



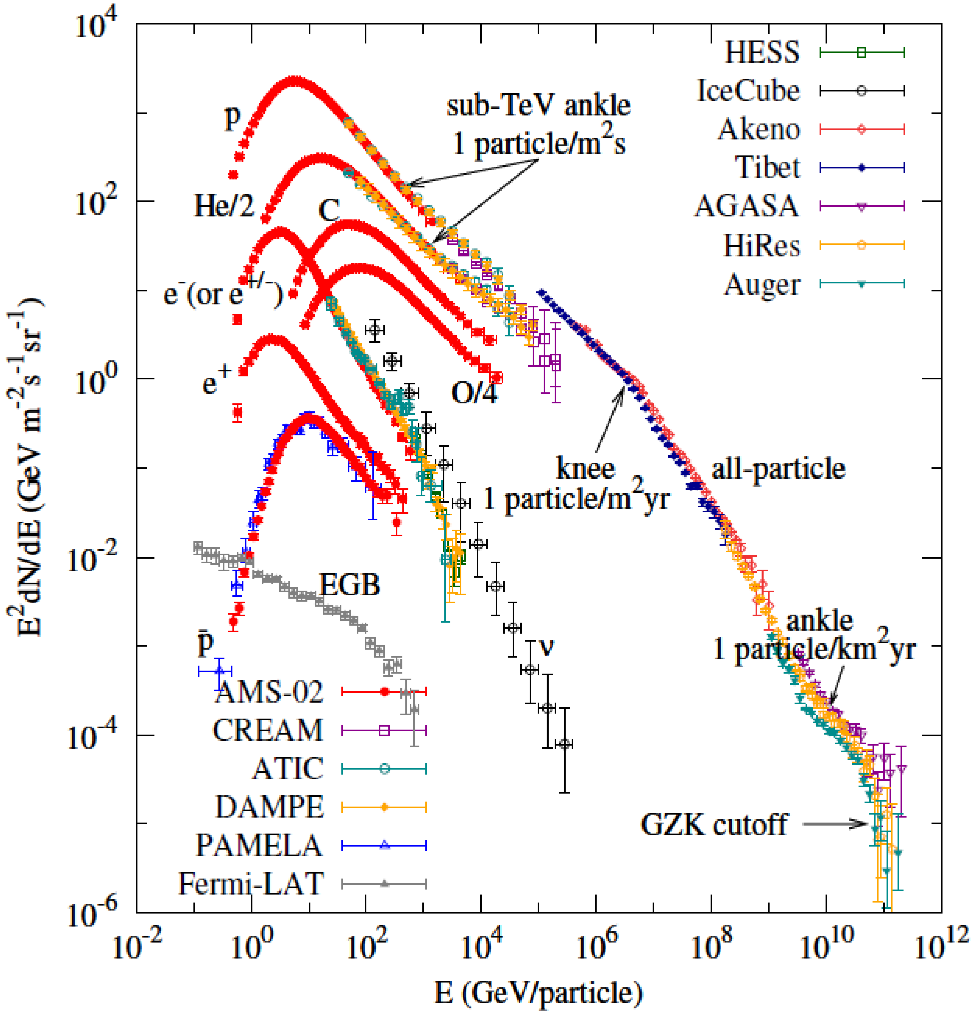
银河系内？

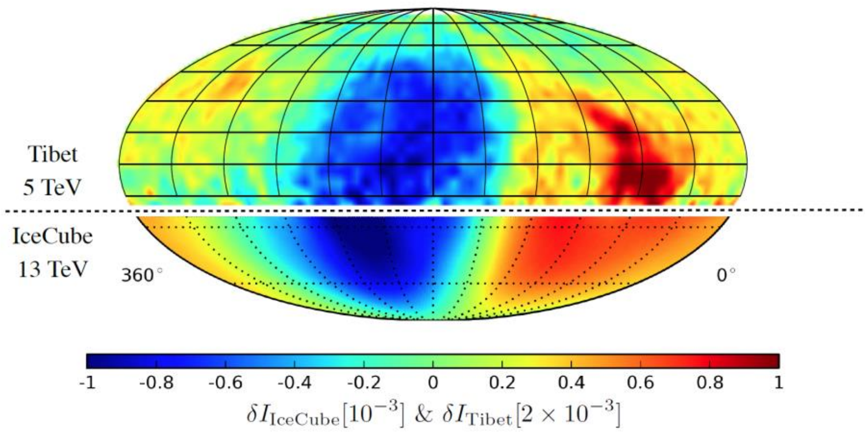
银河系外？

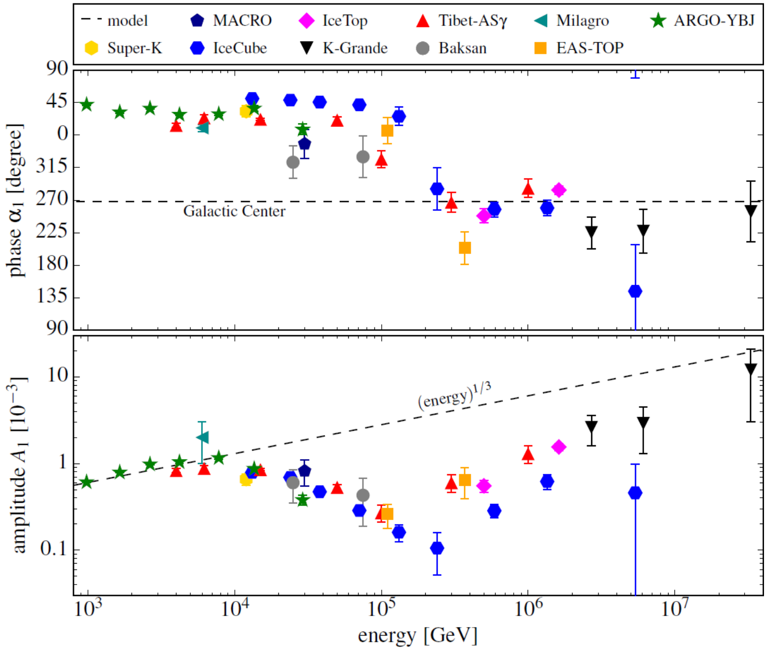
超新星遗迹？

活动星系核？

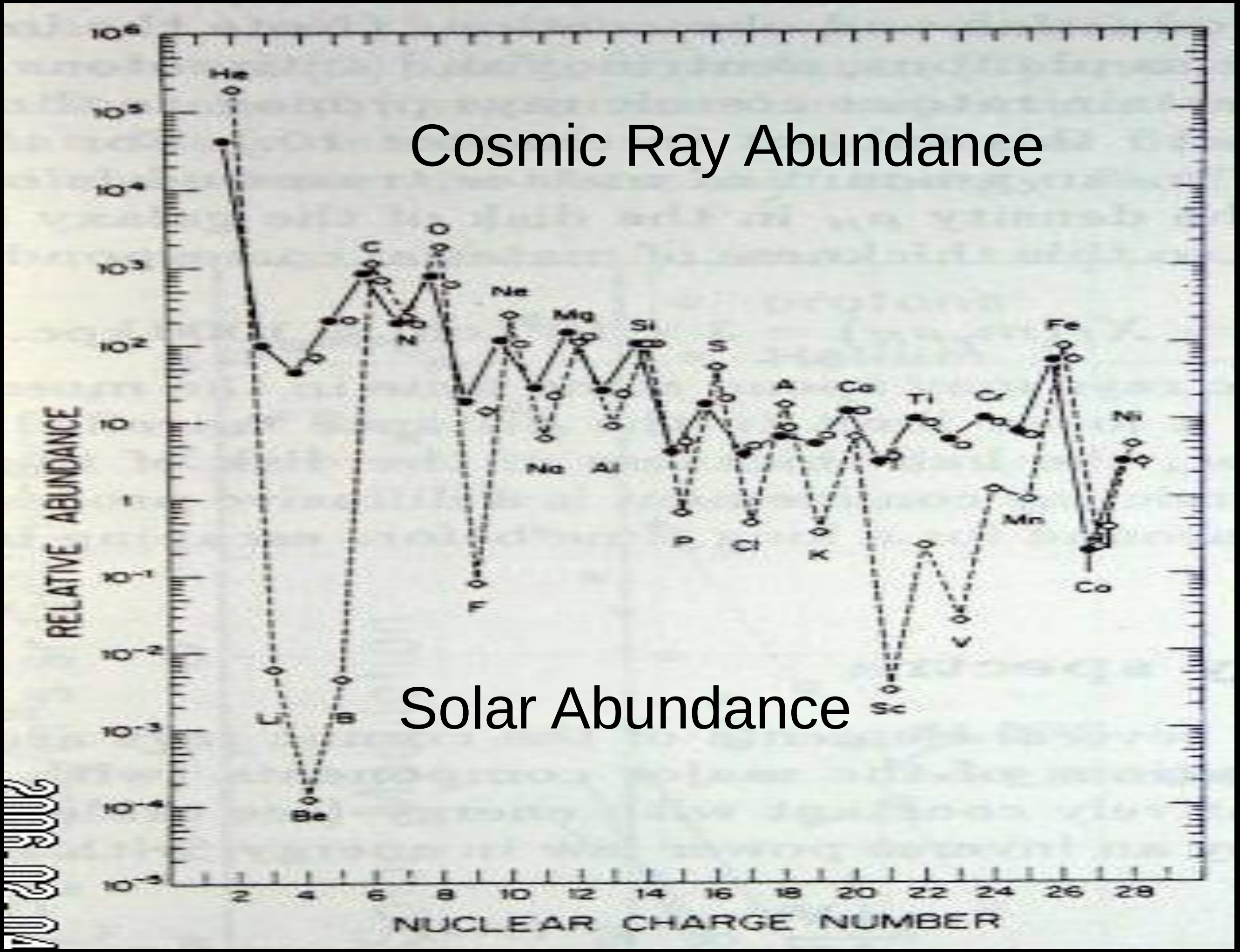
宇宙线的能谱和流量各向异性







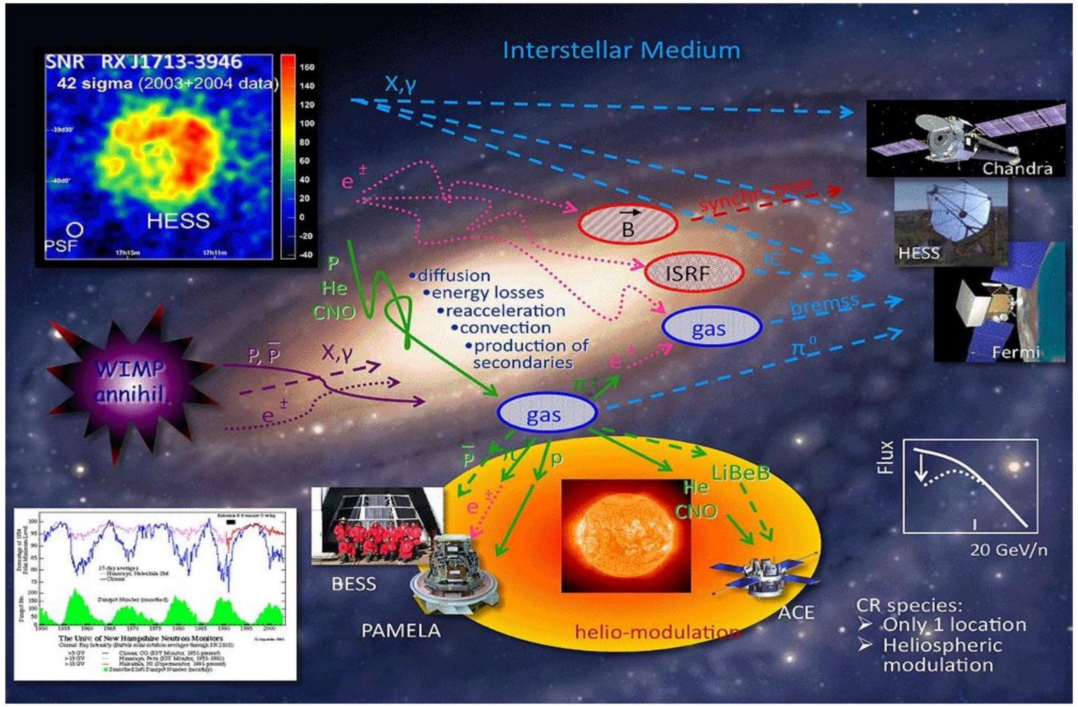
Cosmic Ray Composition



From B/C flux ratio one has a grammage of ~10 g/cm^2.
For an ISM density of 1 per cc, the distance travelled by CR is about 10000kpc, corresponding to an age of ~10 million years.

General picture of Galactic cosmic rays

© *I. V. Moskalenko*



Acceleration at source

↓

Diffusion and Interaction

↓

Helio-sphere propagation

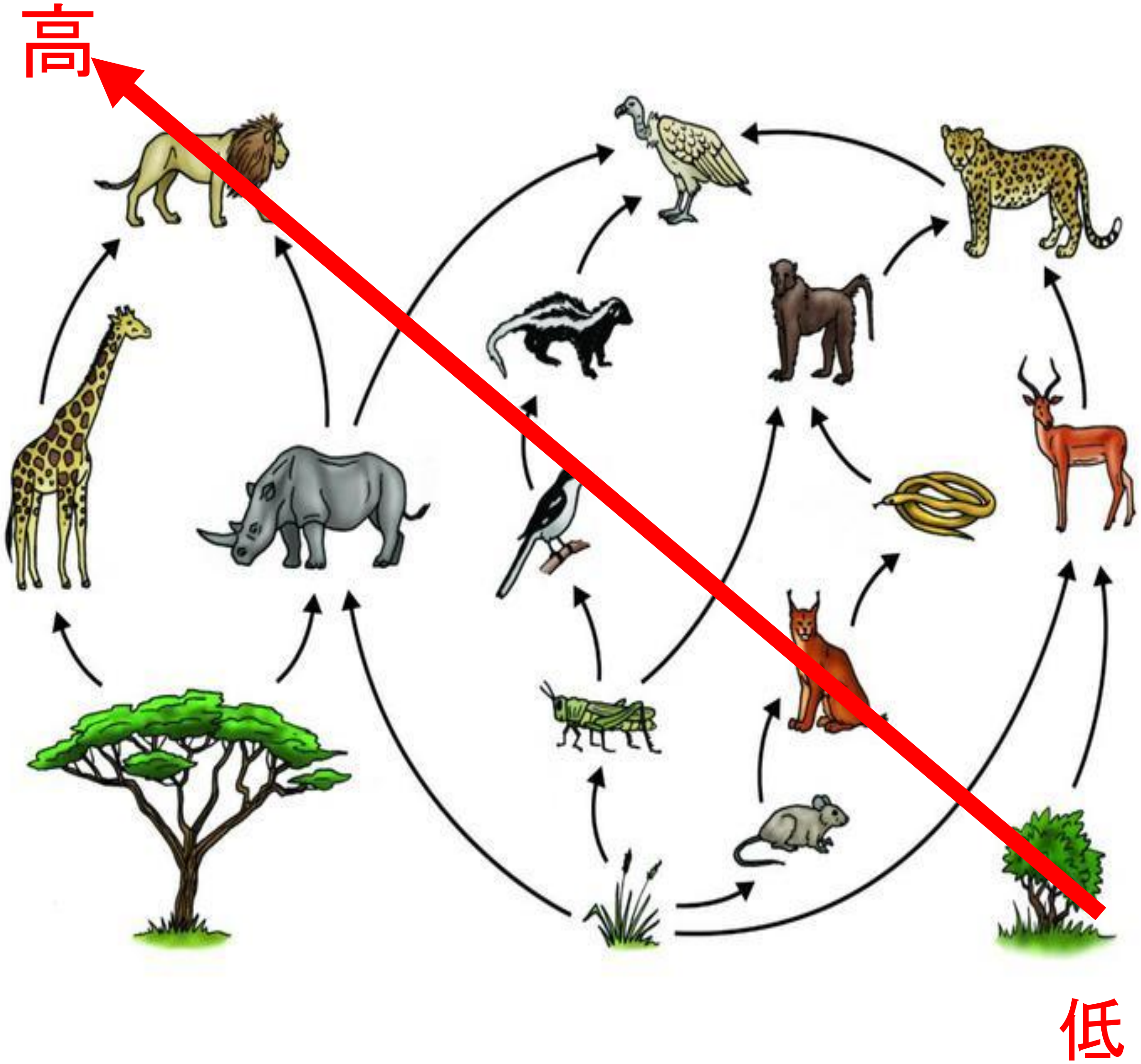
↓

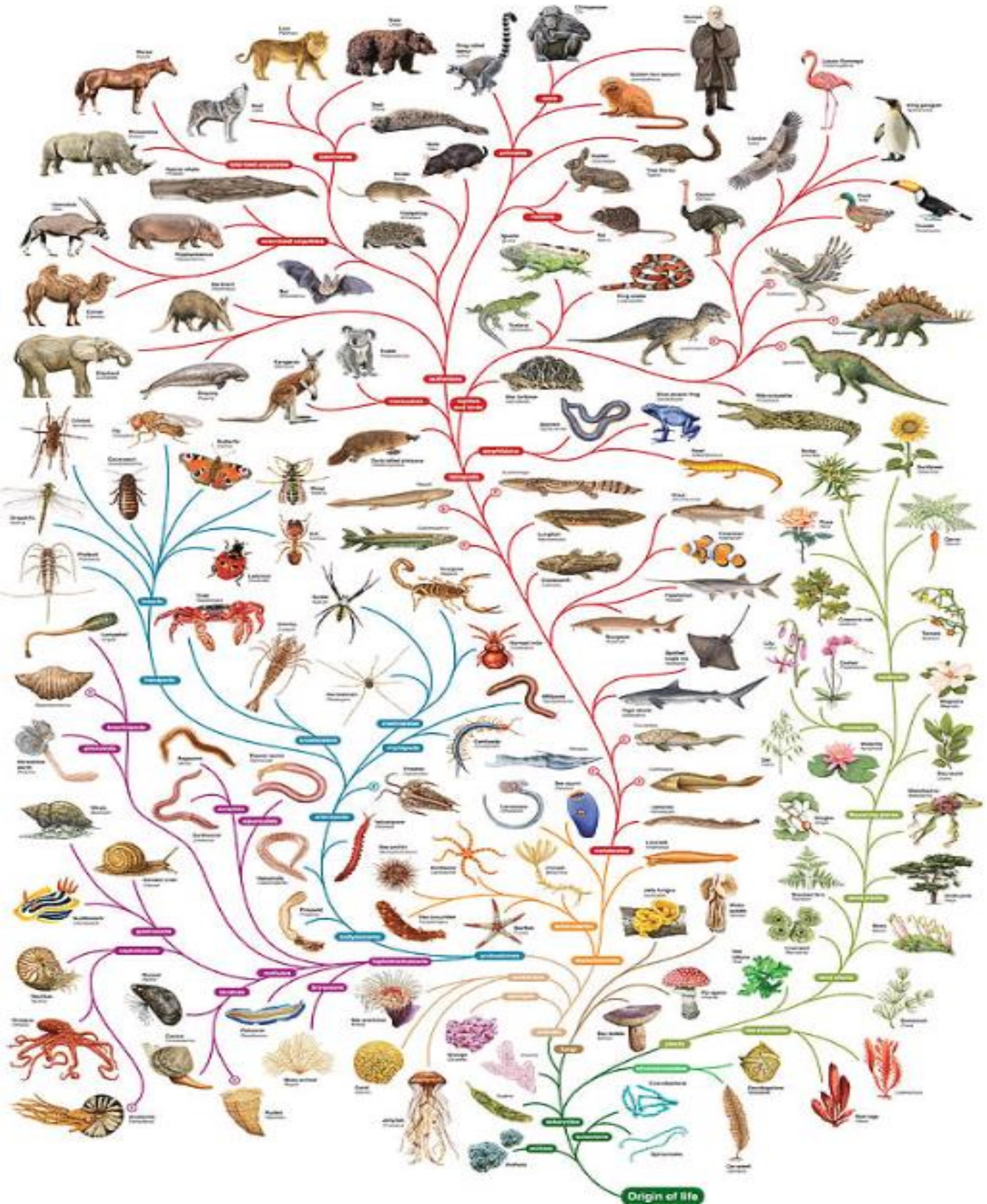
Detection at the Earth

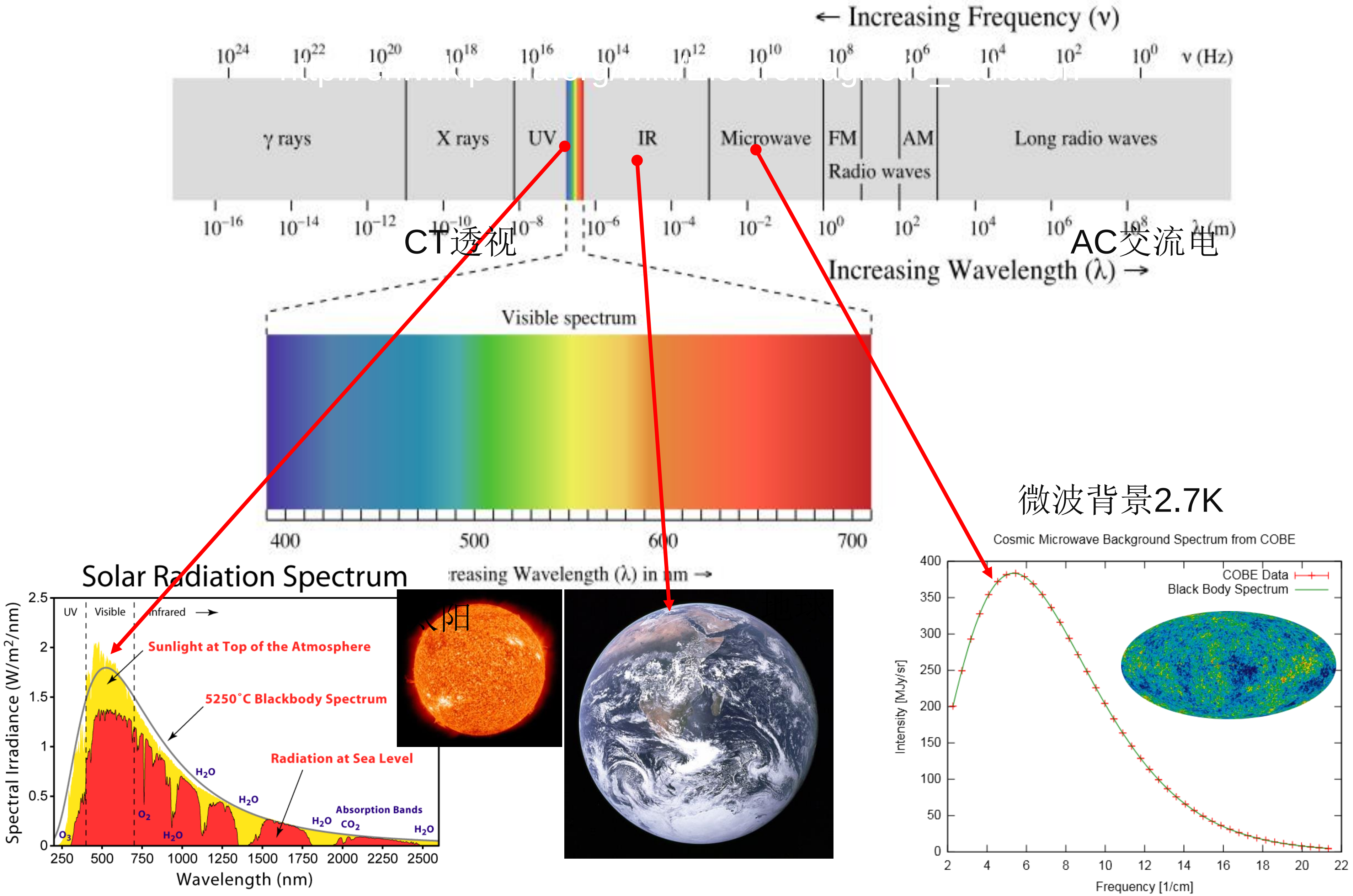
Diffuse γ rays are expected *a priori* to be produced by CR interactions during the propagation, and are thus powerful probe of CR propagation

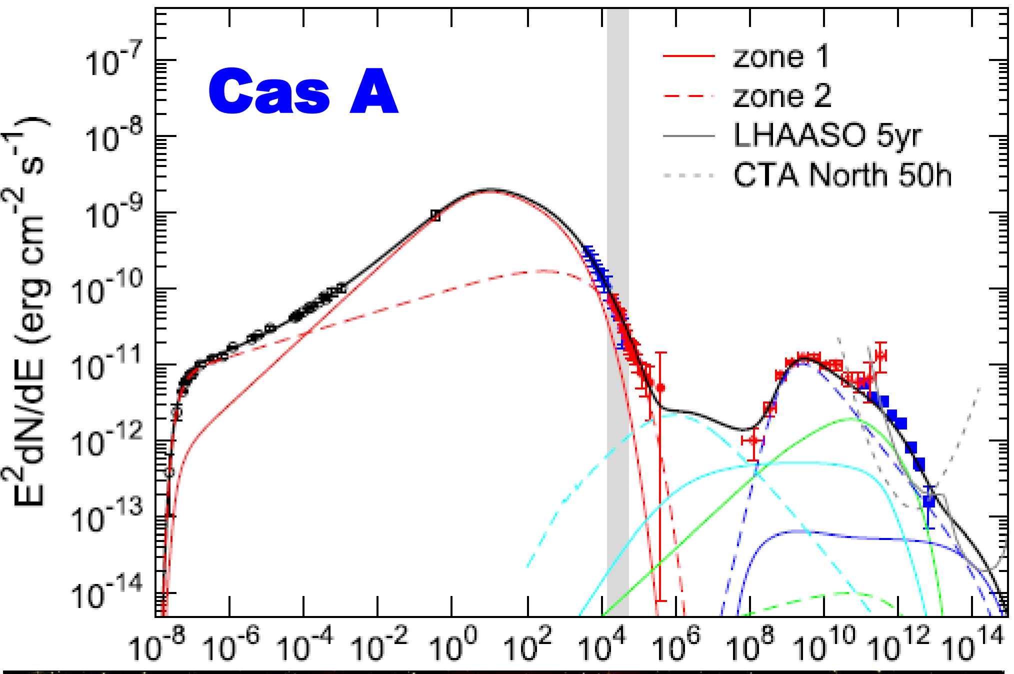
宇宙线的起源

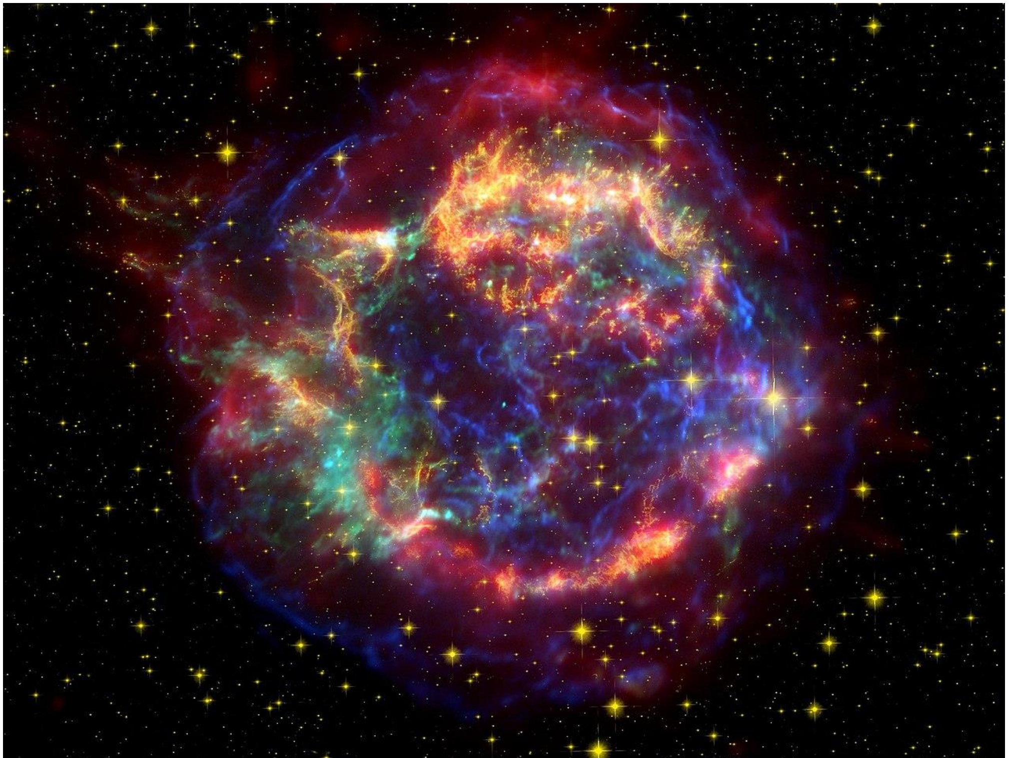
物种起源与食物链

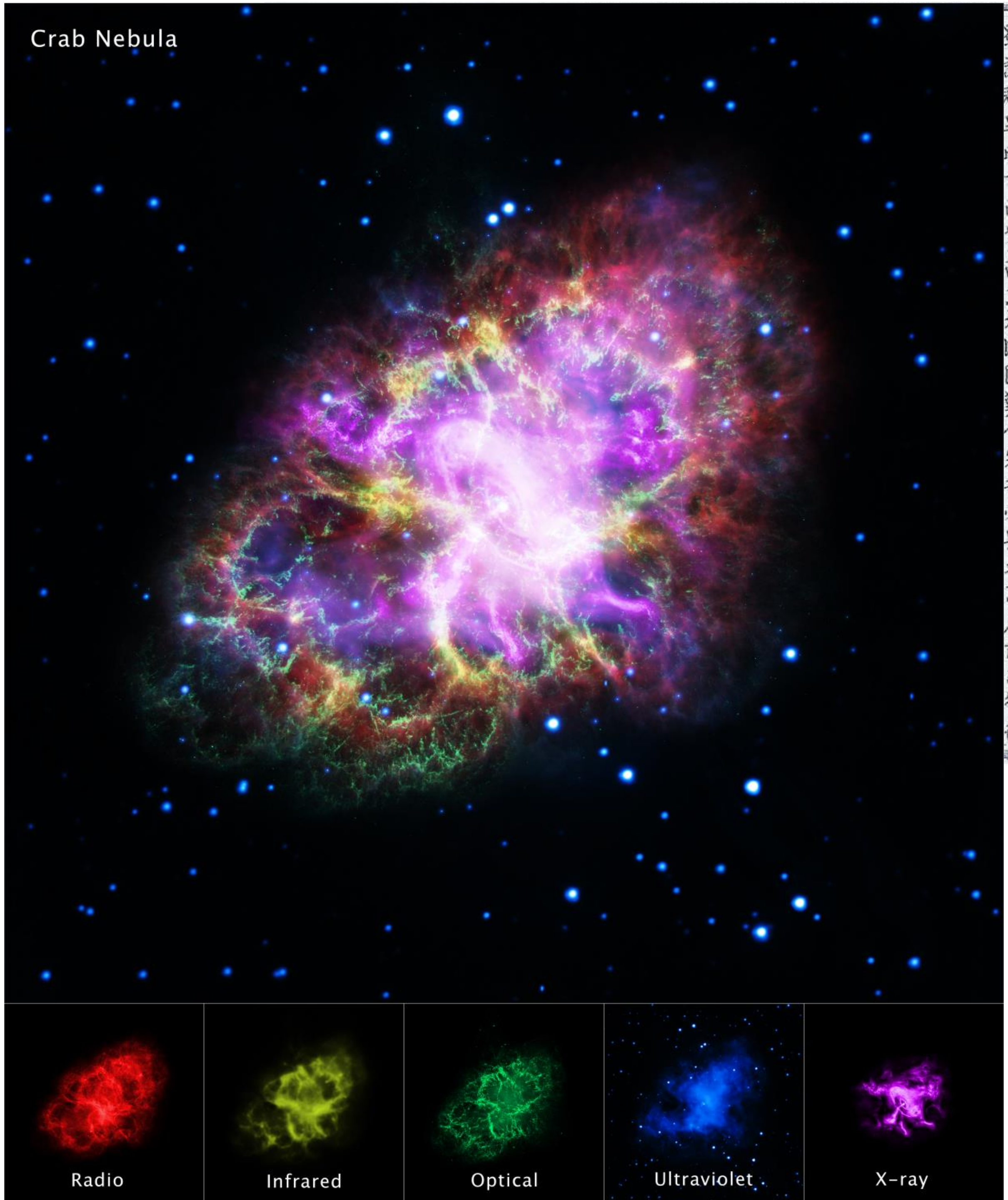


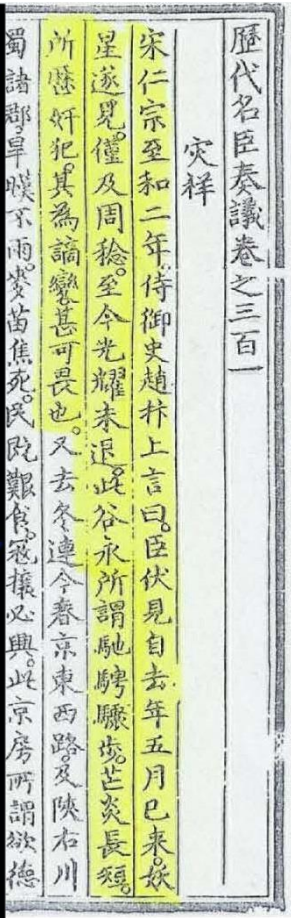



← Increasing Frequency (ν)
ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
λ (m)
CT透视
AC交流电
Increasing Wavelength (λ) →
Visible spectrum
400
500
600
700
Increasing Wavelength (λ) in nm →
Solar Radiation Spectrum
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250°C Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
微波背景2.7K
Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
Frequency [1/cm]







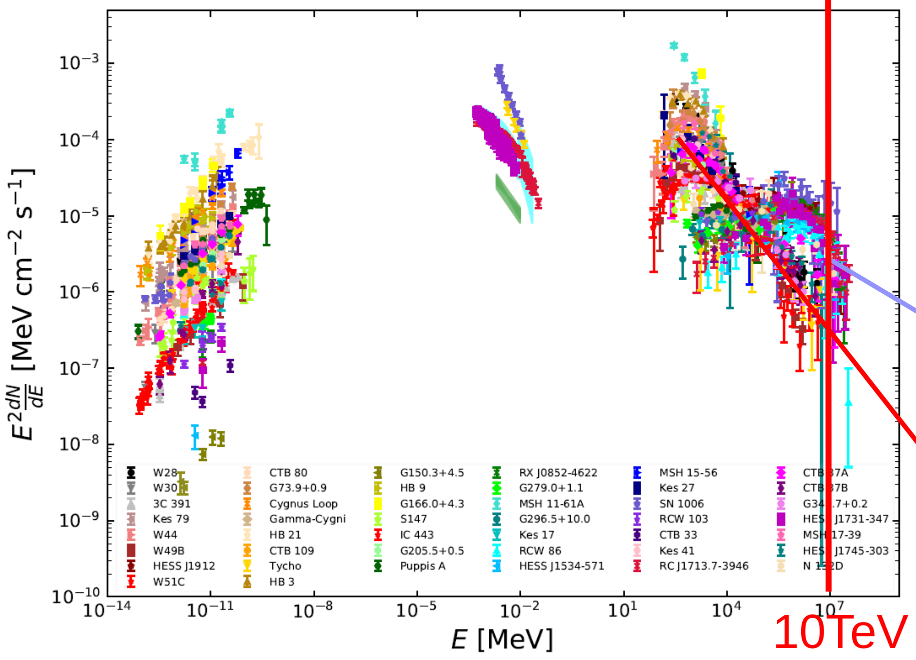

歷代名臣奏議卷之三百一

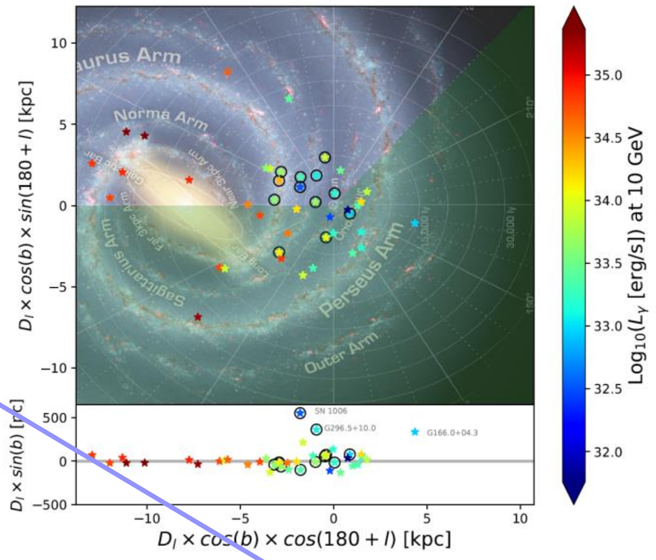
災祥

宋仁宗至和二年。侍御史趙抃上言曰。臣伏見自去年五月已來。妖星遂見。僅及周稔。至今光耀未退。此谷永所謂馳騁驕步。芒炎長䫫。所歷。奸犯其爲譎變甚可畏也。又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨。麥苗焦死。民既艱食。寇攘必興。此京房所謂欲德

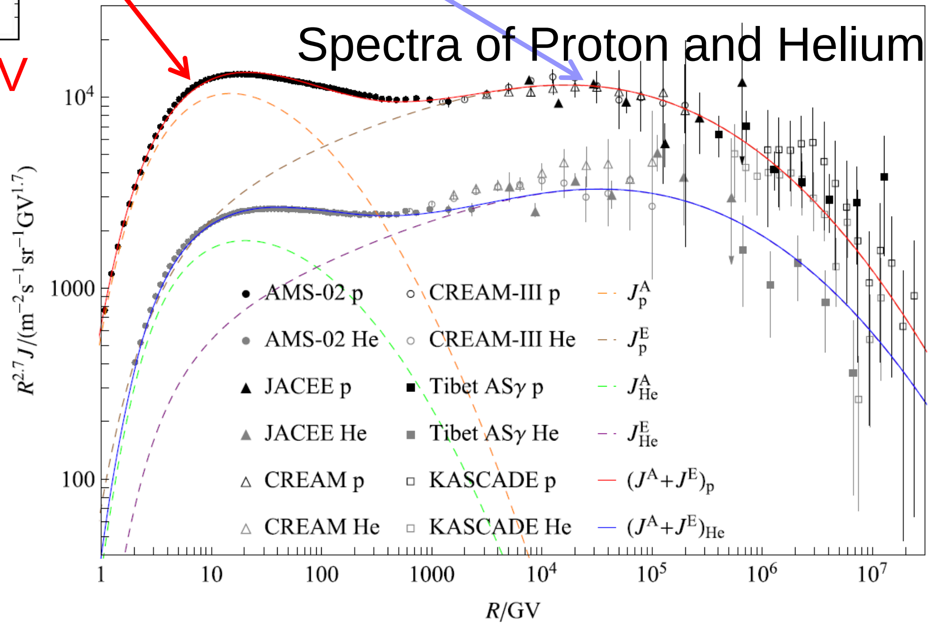
蟹状星云

Origin of Cosmic Rays





Multiwavelength spectra of 44 SNRs normalized at 100 GeV and their distribution in the



Reviews of Modern Plasma Physics (2022) 6:19
https://doi.org/10.1007/s41614-022-00080-6

REVIEW PAPER

The origin of galactic cosmic rays

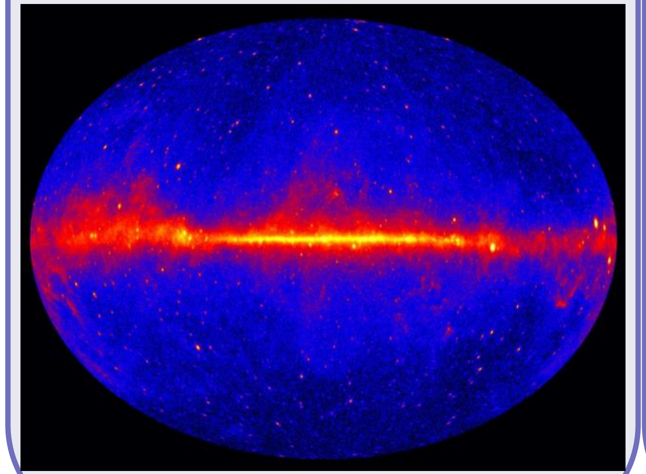
Siming Liu[1] · Houdun Zeng[2,4] · Yuliang Xin[1] · Yiran Zhang[3]

Gamma-ray detectors

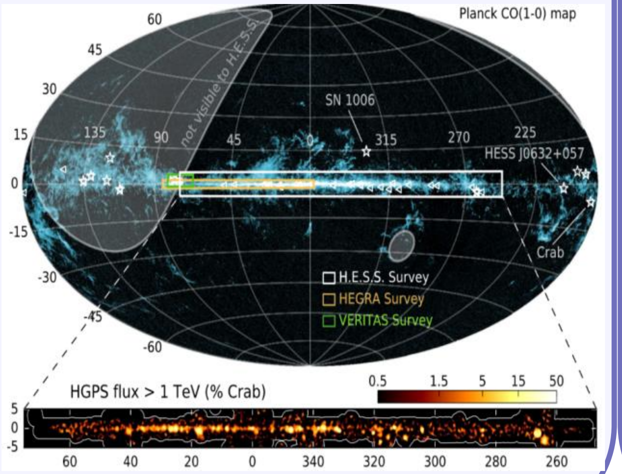
高能	甚高能	超高能
Space-based EGRET, AGILE, Fermi, DAMPE	IACTs: H.E.S.S., MAGIC, VERITAS, CTA	EAS arrays: Milagro, ARGO-YBJ Tibet Asγ, HAWC, LHAASO
		
HE: >0.1 GeV Large FOV 80% duty cycle $0.1^o \sim 5^o$ resolution 1 m^2 area	VHE:>0.1 TeV $3^o \sim 5^o$ FOV 15% duty cycle $0.06^o \sim 0.17^o$ resolution 10^5 m^2 area	VHE: >0.1 TeV UHE: >0.1 PeV Large FOV 100% duty cycle $0.1^o \sim 1^o$ resolution $10^{3\text{-}6}$ m^2 area

Impressive Gamma-ray Source Catalogs

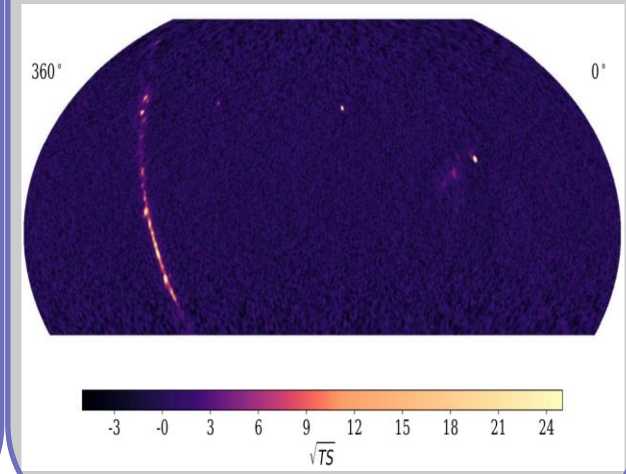
Fermi-LAT
12ys data
6658 sources
50 MeV to 1 TeV



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

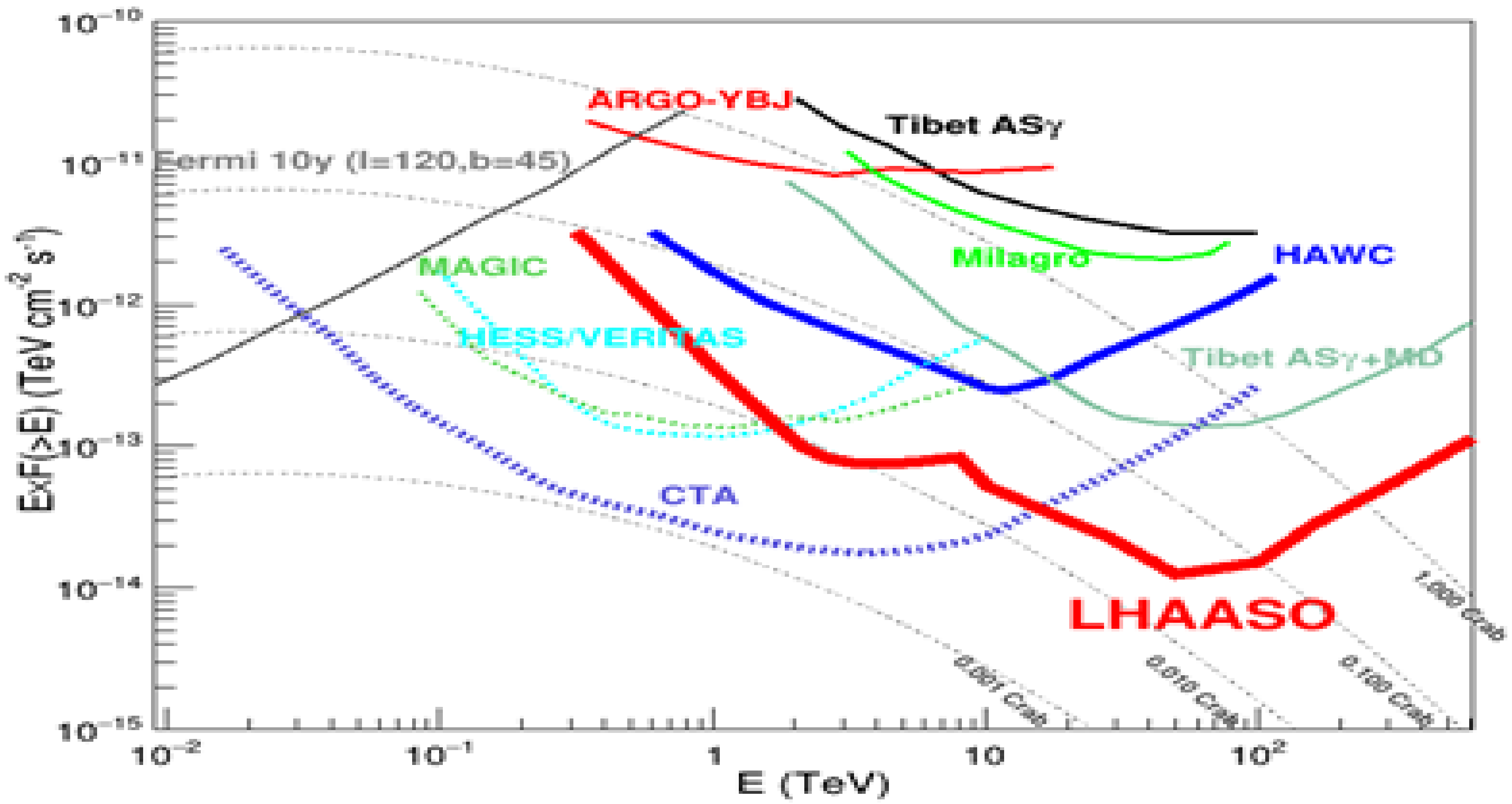


HAWC
5ys data
65 sources
1~100 TeV



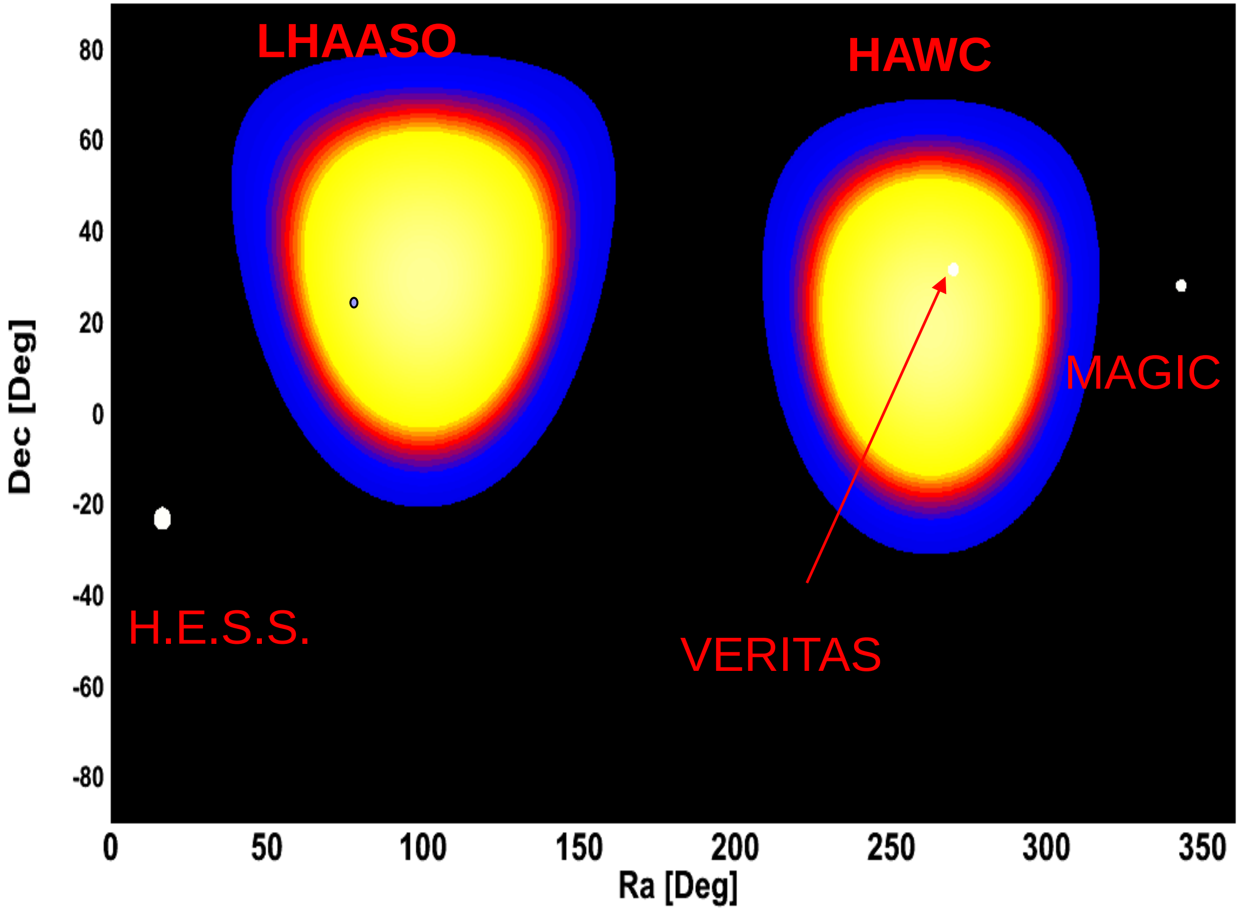
LHAASO sensitivity

With large FOV and high sensitivity, LHAASO is an ideal detector for sky survey to search VHE and UHE sources!



Field of view for GRB/TOO

1/7 of the sky at any time

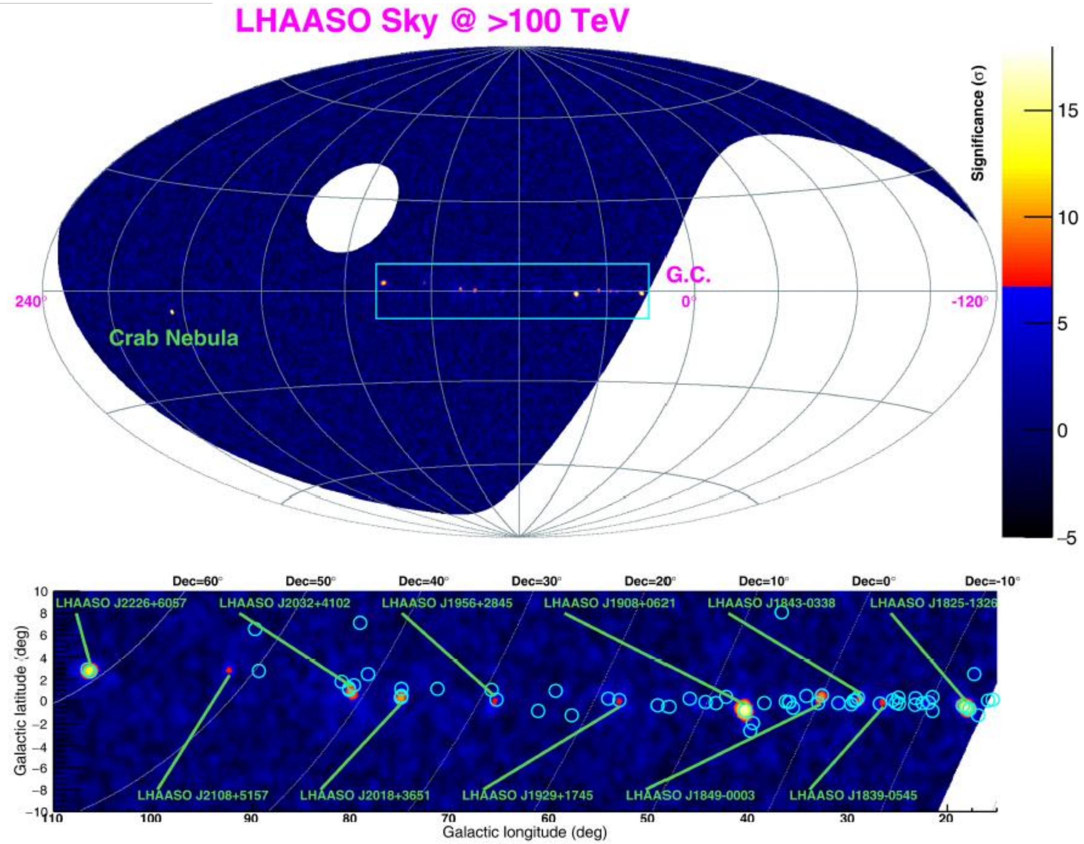


Article

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

https://doi.org/10.1038/s41586-021-03498-z

A list of authors and affiliations appears at the end of the paper.



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

Article

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

https://doi.org/10.1038/s41586-021-03498-z

A list of authors and affiliations appears at the end of the paper.

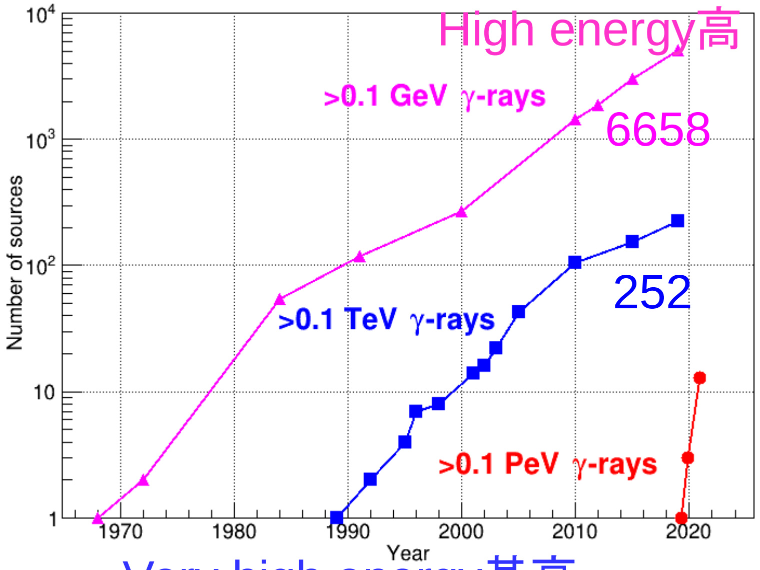
Table 1 | UHE γ-ray sources

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)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

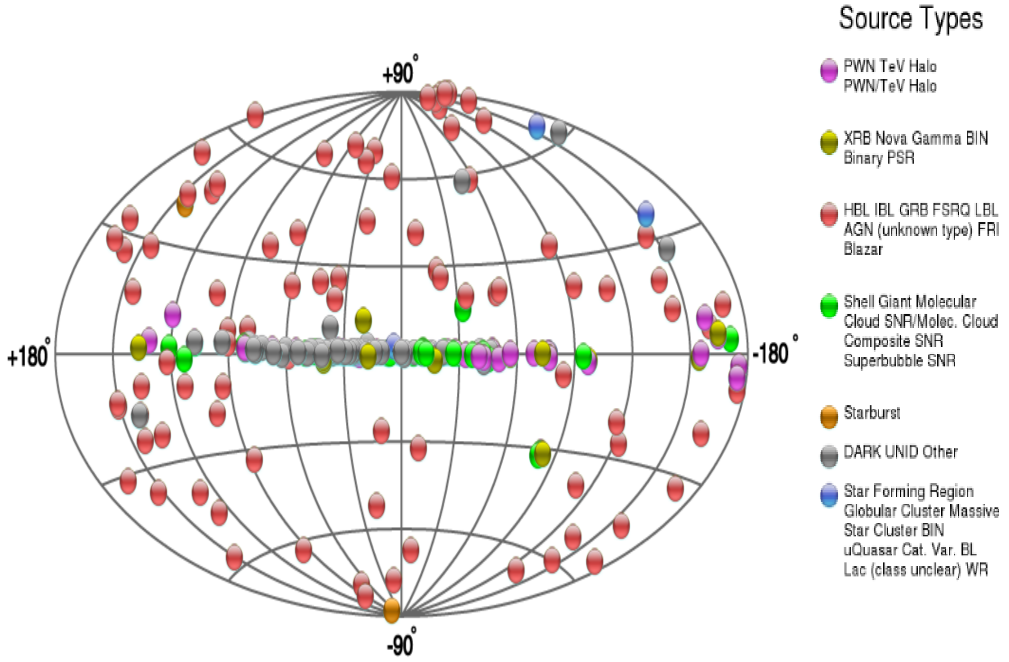
LHAASO开启了超高能伽马射线天文学！

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



Very high energy甚高

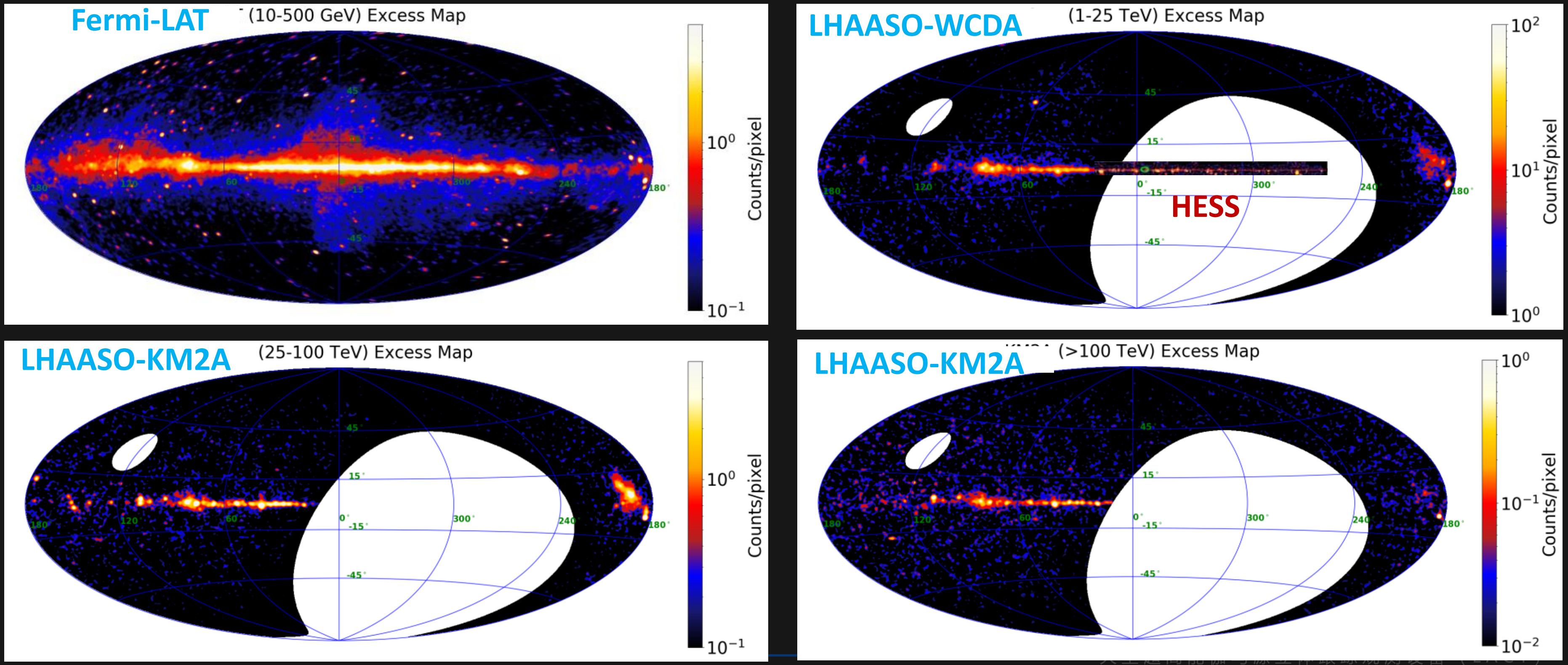
Ultra-high energy超高



Ultra-High-Energy γ-ray Astronomy

arXiv:2305.17030v1

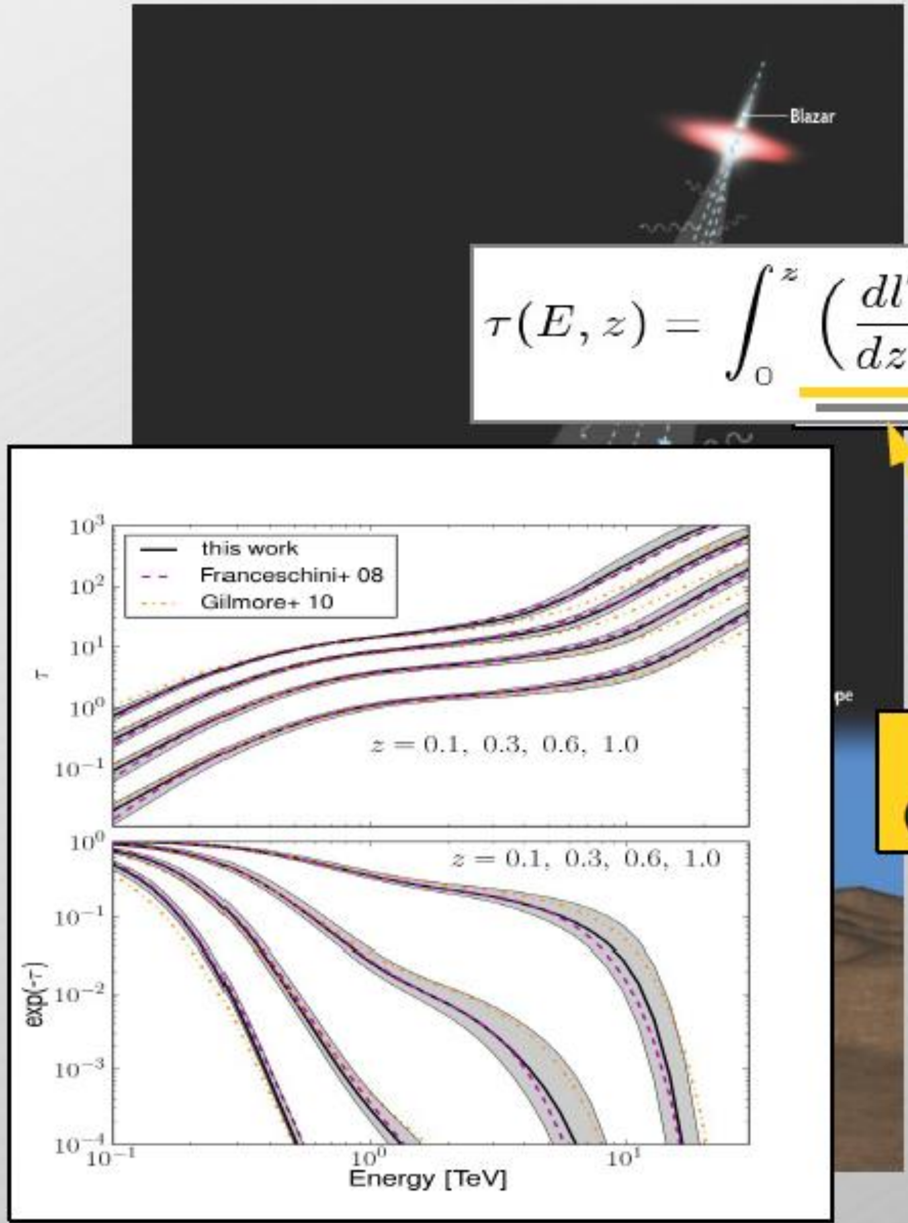
- **Survey discovered 30+ new sources, 40+ PeVatrons and diffuse γ-ray emission**



Gamma-Ray Attenuation

$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$



Distance (cosmology)

Interaction angle

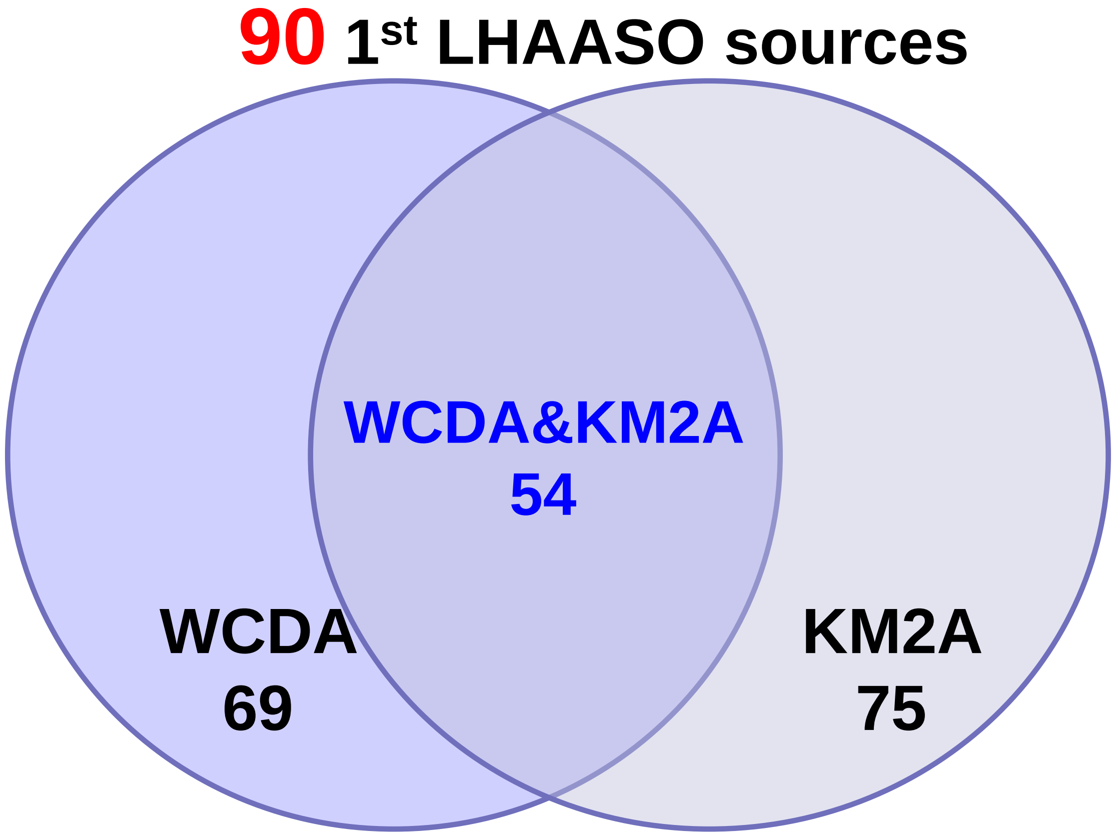
Cross section

EBL photon density evolution (cosmology)

Construction of the 1st LHAASO sources

WCDA&KM2A

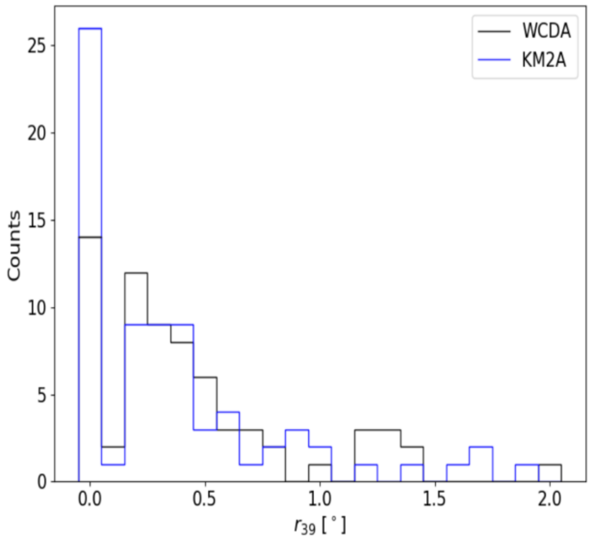
- Separation Angle
- Position error
- Source extension



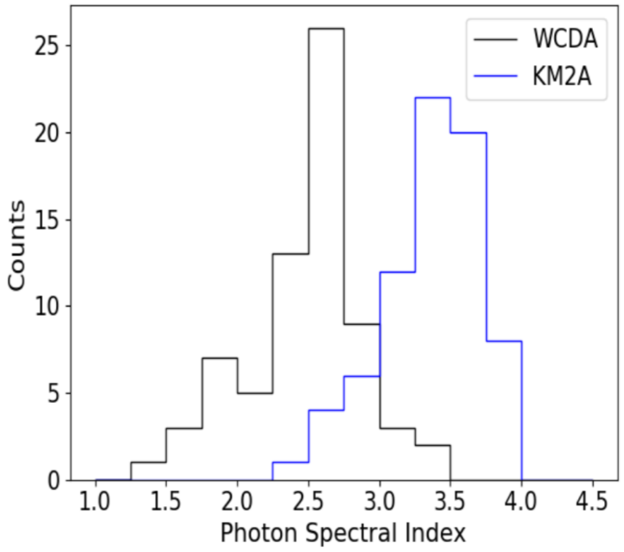
Features of WCDA and KM2A sources

- **WCDA detected 69 sources at >5σ (TS>37) and extension <2º**
- **KM2A detected 75 sources at >5σ (TS>37) and extension <2º**

Source extension

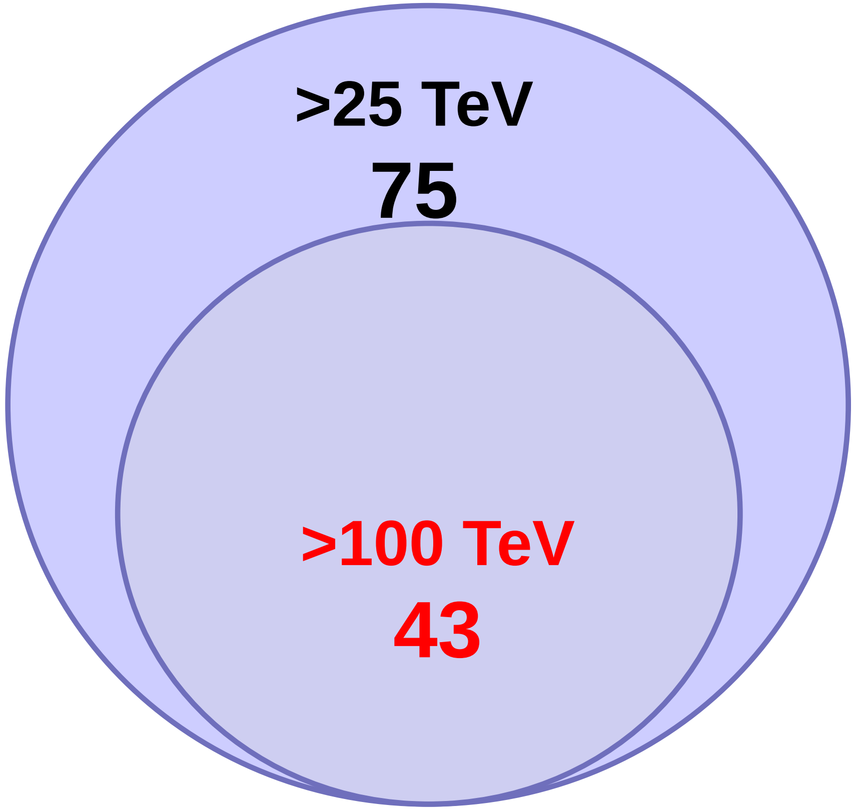


Spectral index

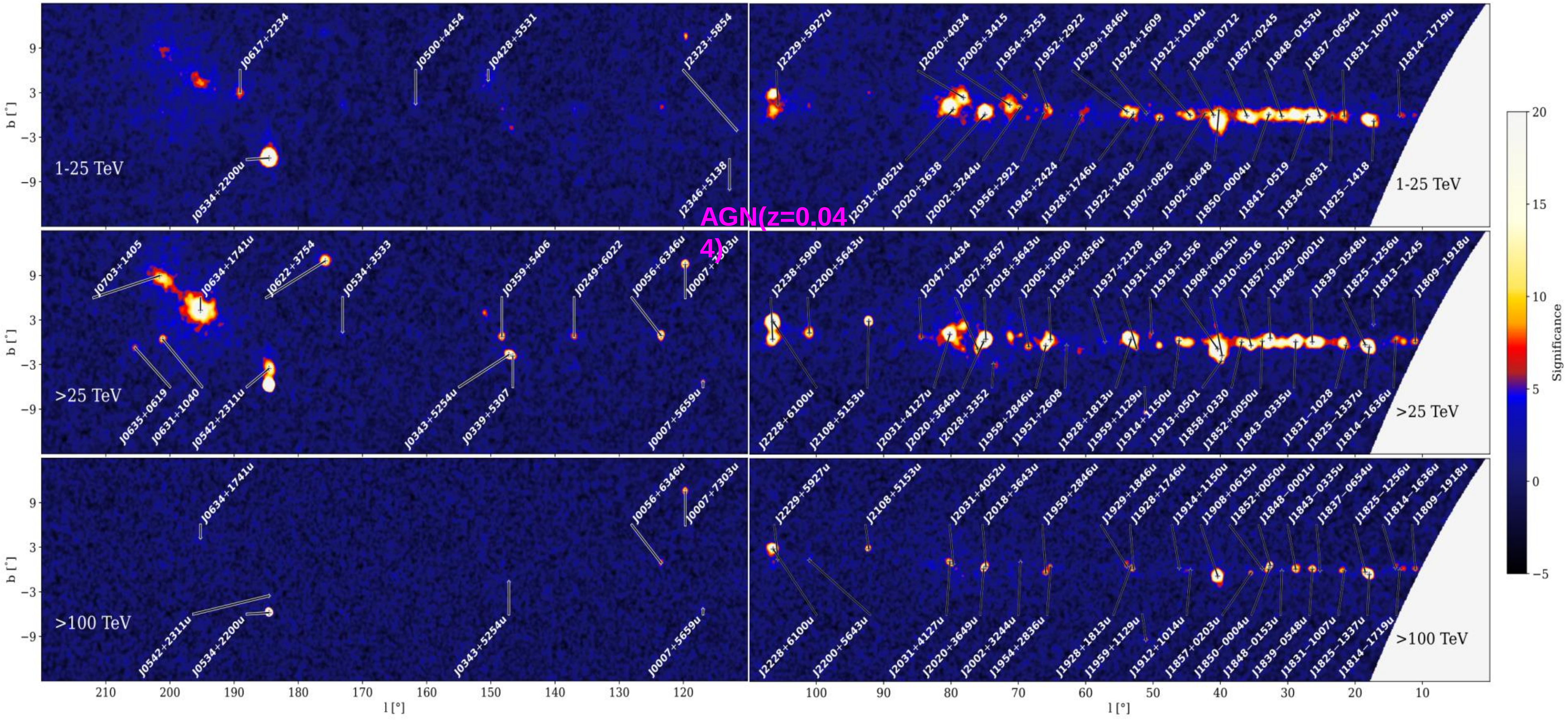


UHE gamma-ray sources

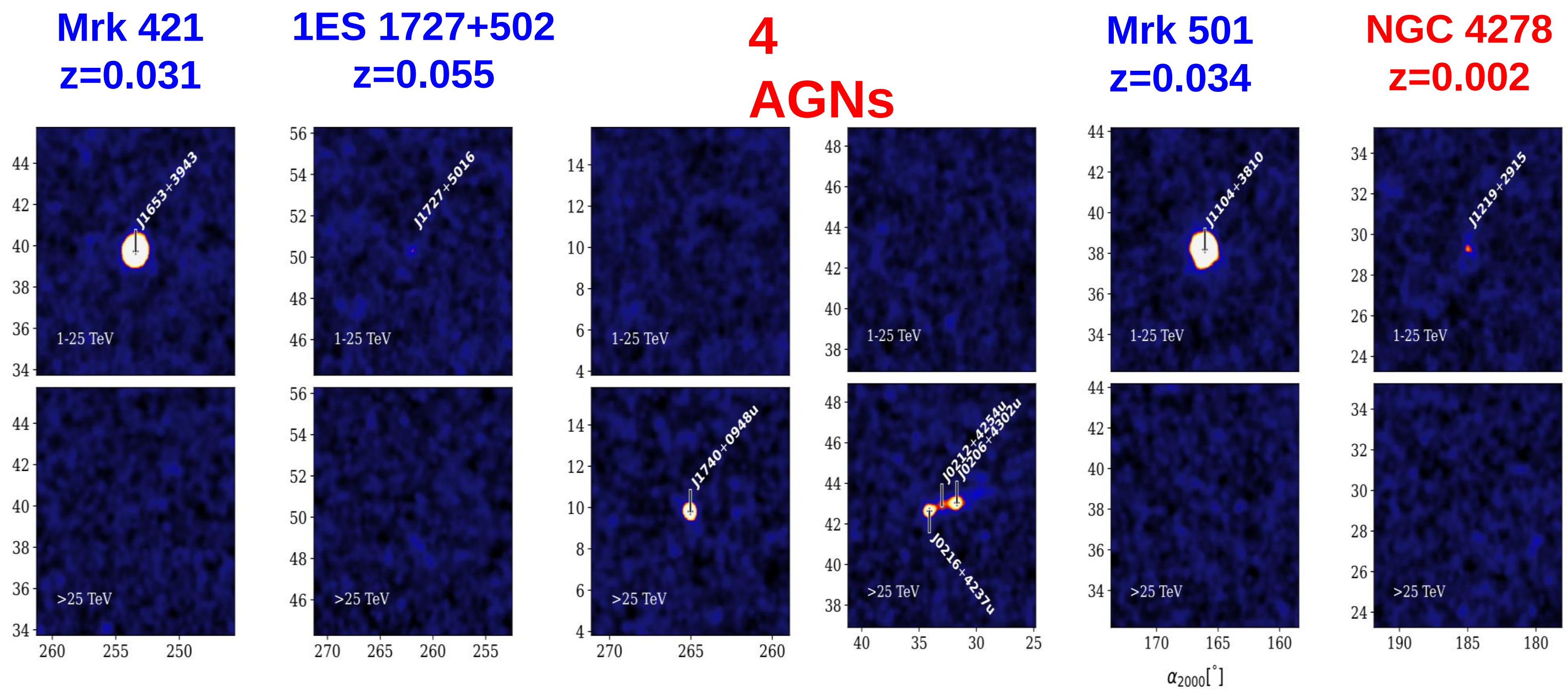
- **The position and extension achieved by KM2A at >25 TeV are used.**
- **Sources with significance >4σ at >100 TeV are labeled as UHE sources**



82 sources with the Galactic latitude |b|<12º

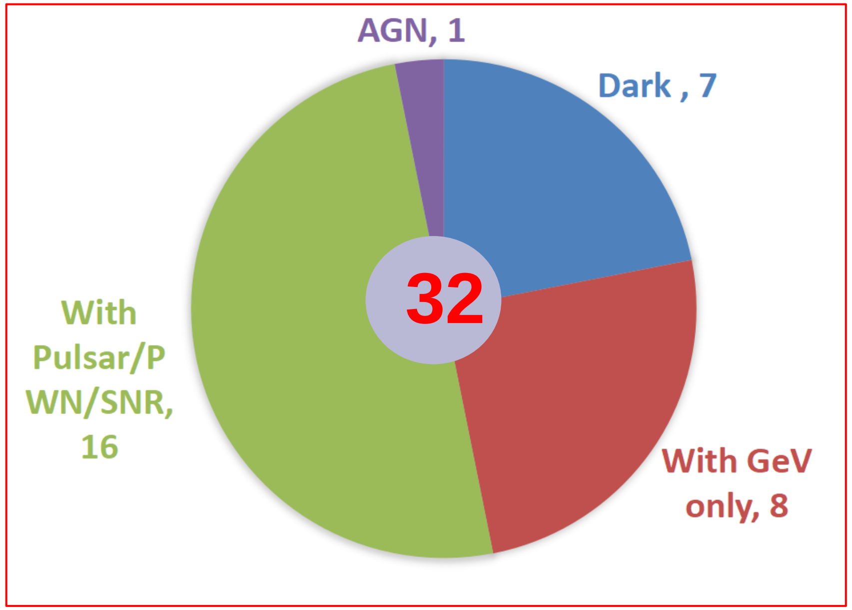


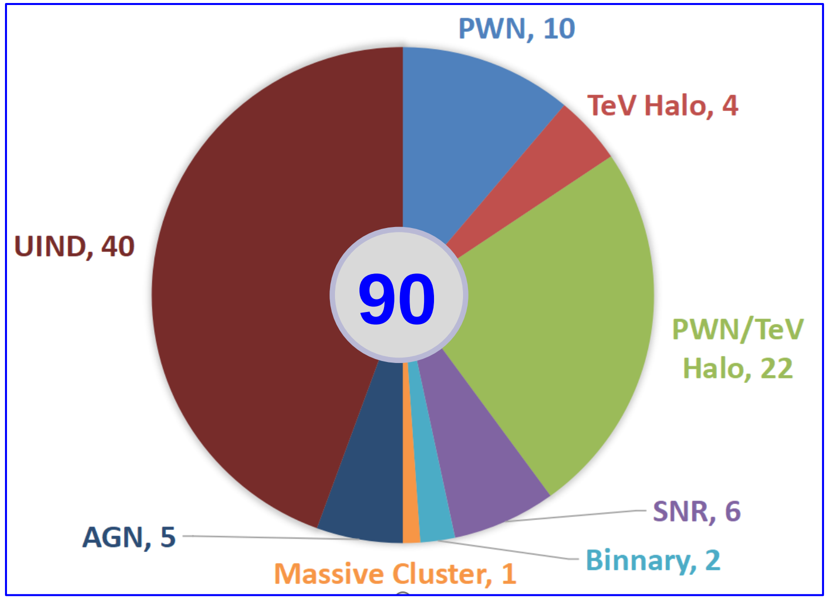
8 sources with the Galactic latitude |b|>12º



Association with known TeV Sources

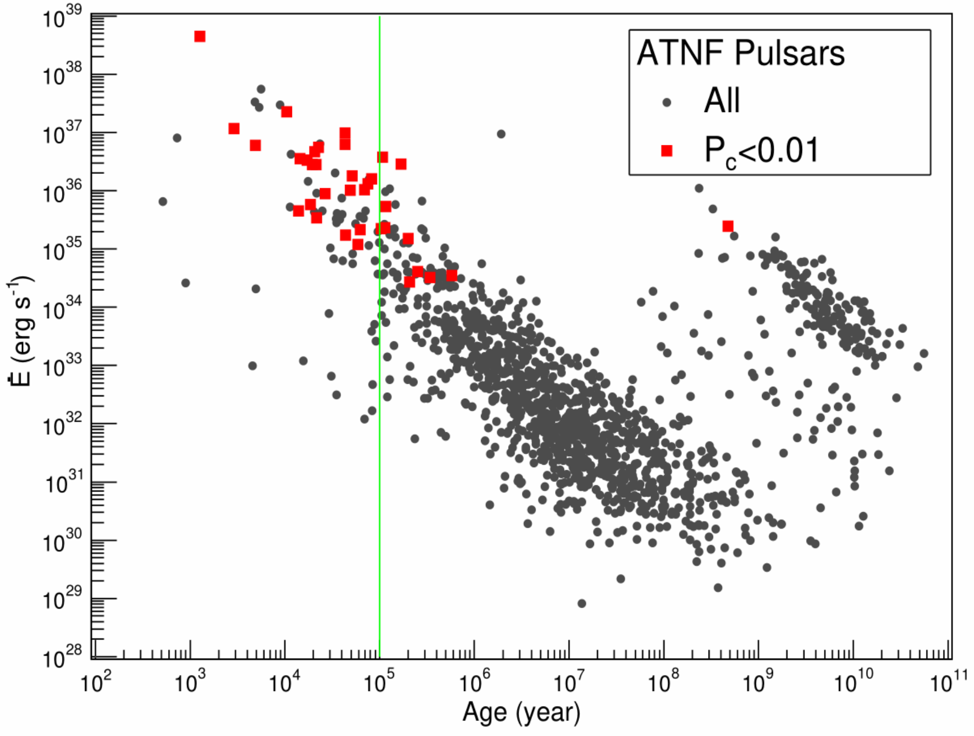
- 58 sources with TeVCat+3HAWC association
- 32 new sources (25+7)

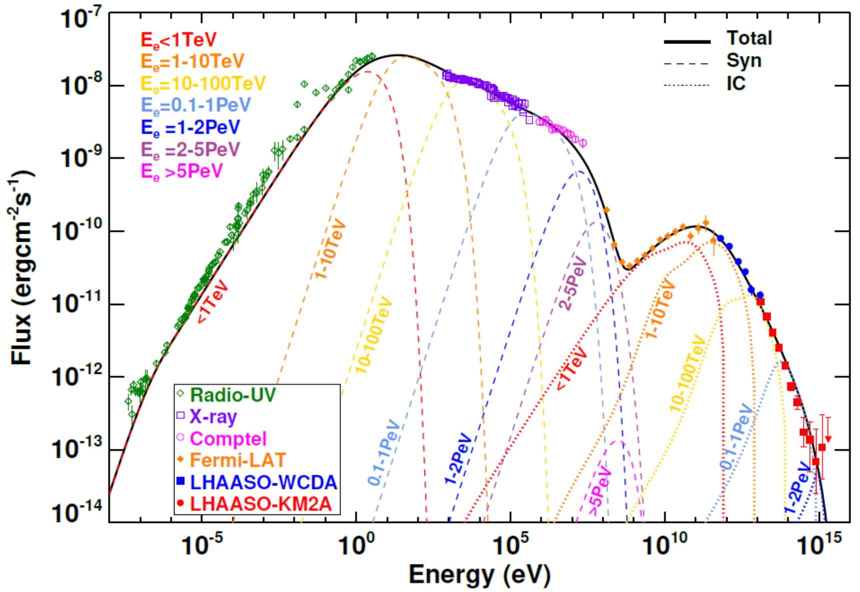




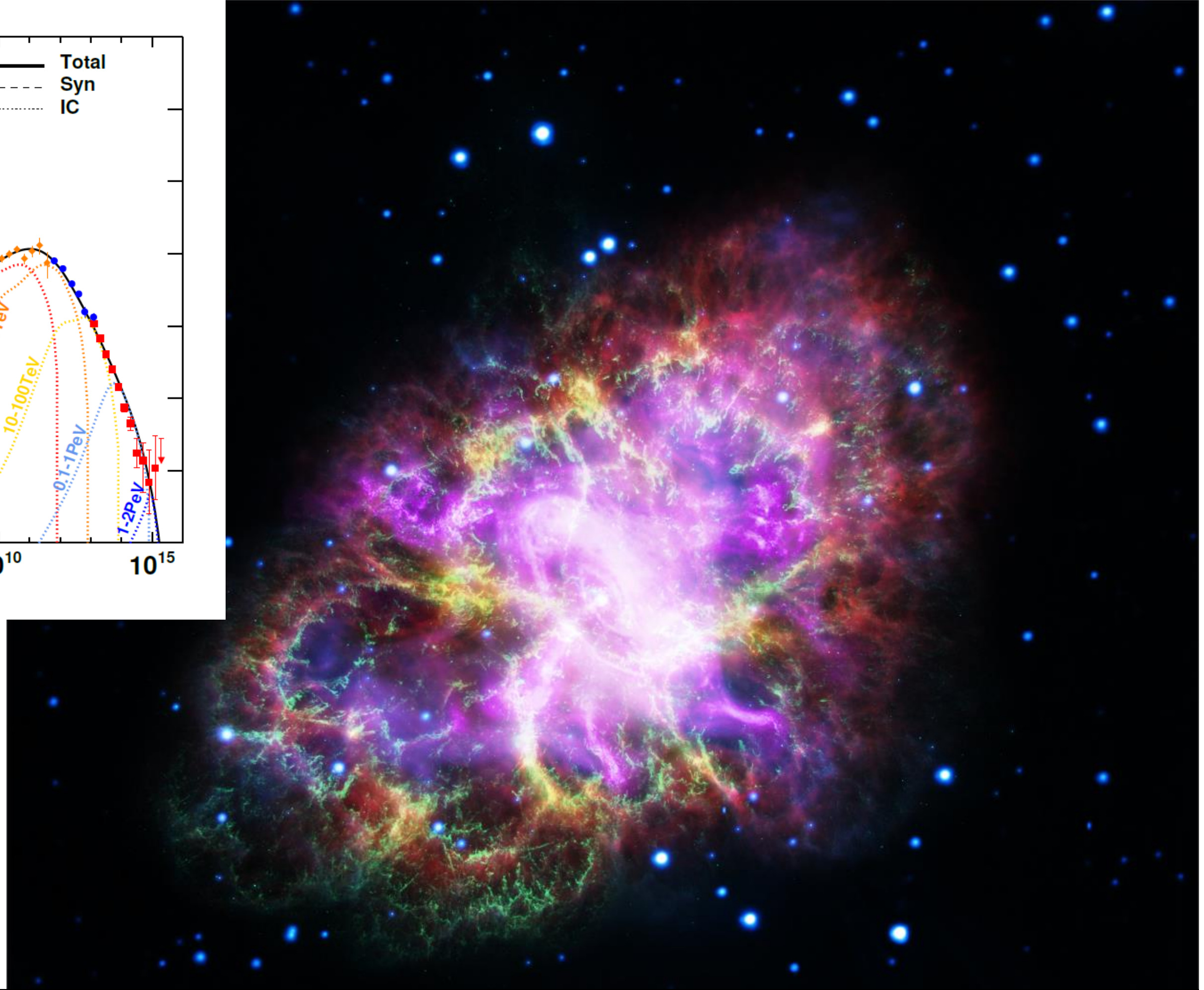
Association with ATNF pulsars

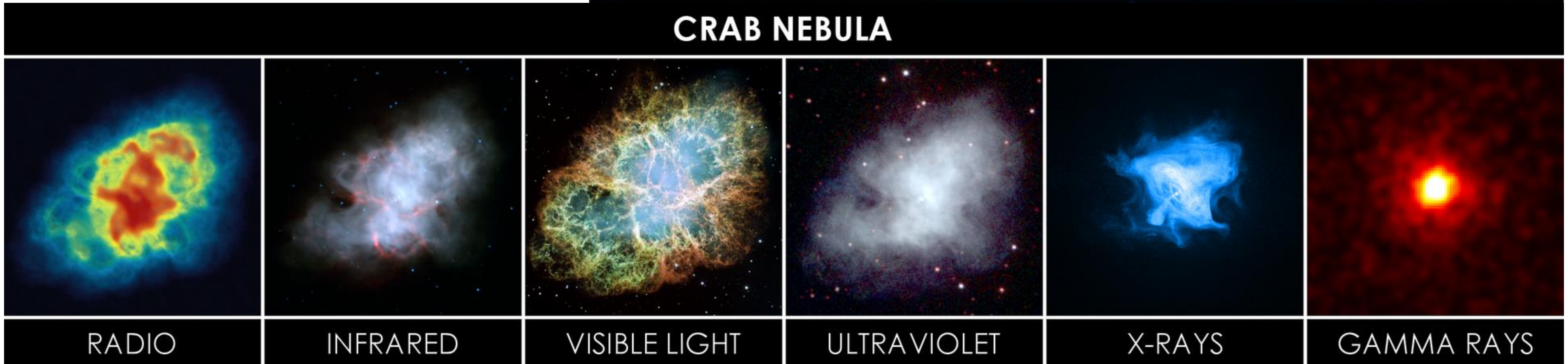
- 65 1LHAASO sources with pulsar nearby <0.5º.
- 35 associations with chance coincide probability <1%. (13 labeled as PWN or Halo in TeVCat)
- 22 new possible PWN/TeV Halo

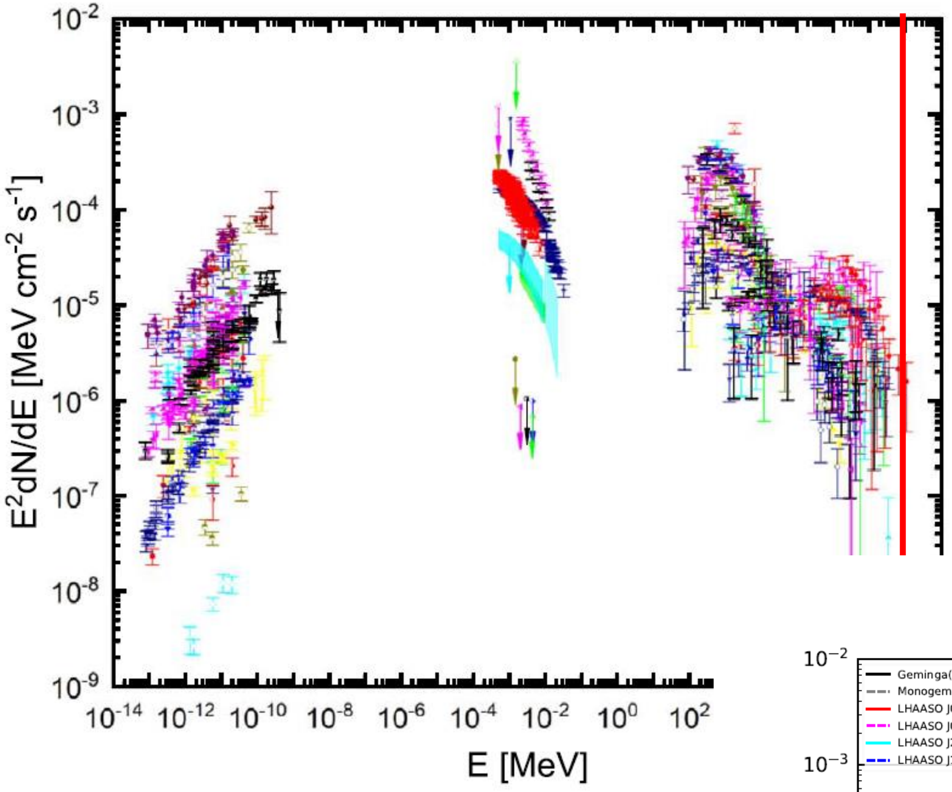


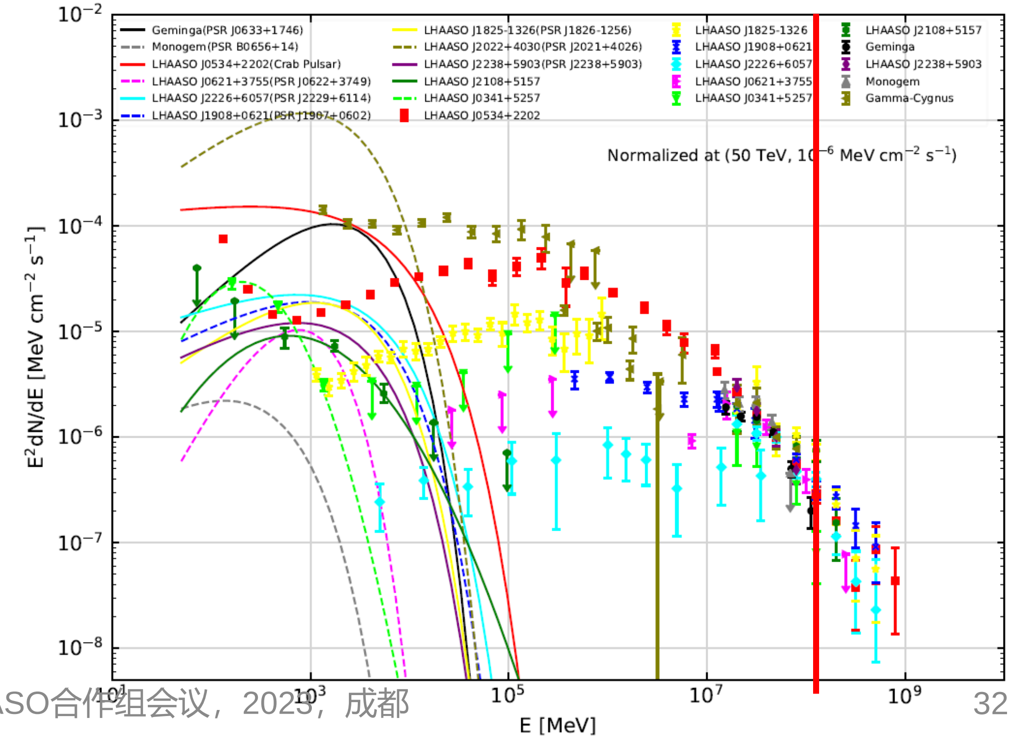

Flux (ergcm^{-2}s^{-1})
Energy (eV)
E_e<1TeV
E_e=1-10TeV
E_e=10-100TeV
E_e=0.1-1PeV
E_e =1-2PeV
E_e =2-5PeV
E_e >5PeV
Total
Syn
IC
Radio-UV
X-ray
Comptel
Fermi-LAT
LHAASO-WCDA
LHAASO-KM2A
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}

蟹状星云

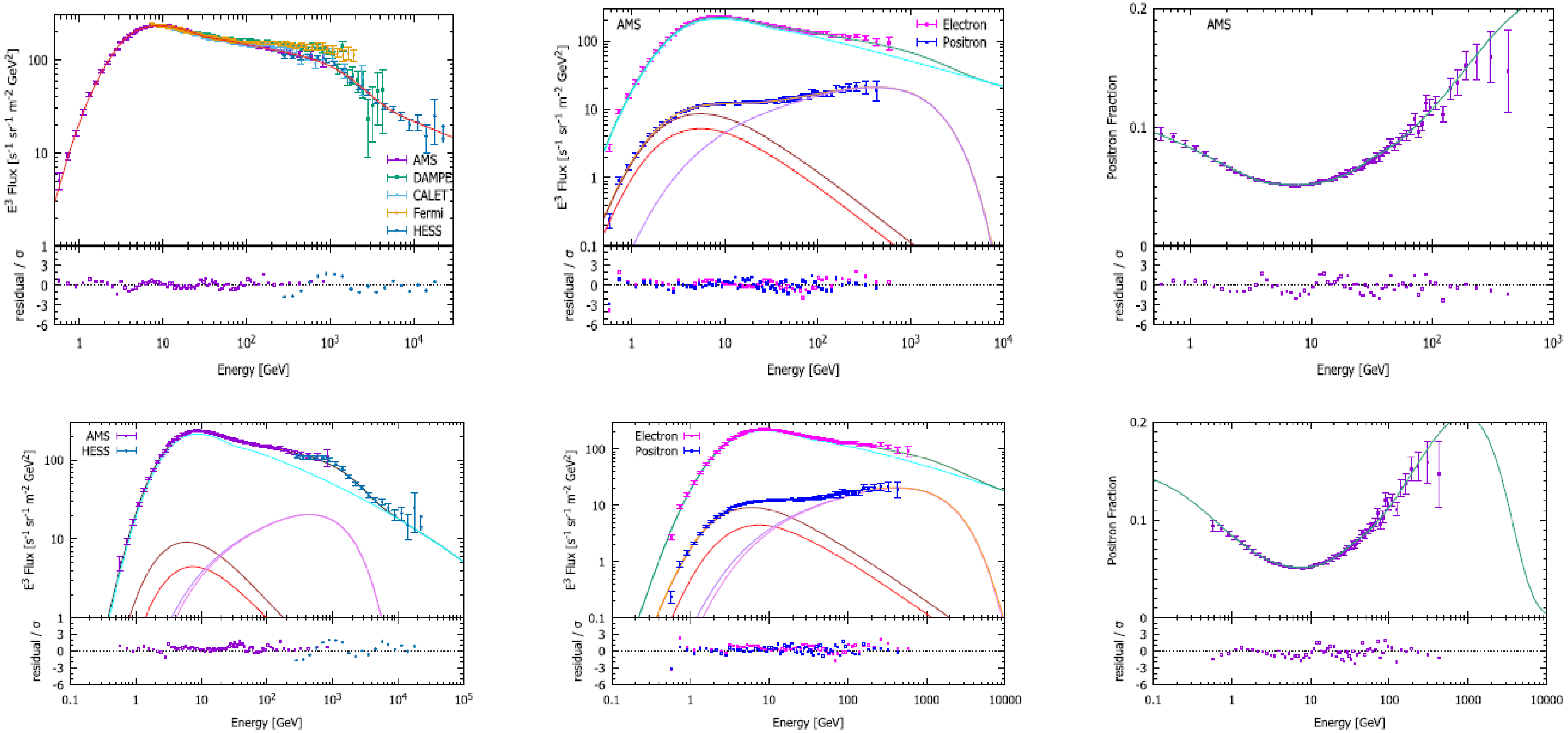



CRAB NEBULA
RADIO
INFRARED
VISIBLE LIGHT
ULTRAVIOLET
X-RAYS
GAMMA RAYS


E²dN/dE [MeV cm⁻² s⁻¹]
E [MeV]


Geminga(PSR J0633+1746)
Monogem(PSR B0656+14)
LHAASO J0534+2202(Crab Pulsar)
LHAASO J0621+3755(PSR J0622+3749)
LHAASO J2226+6057(PSR J2229+6114)
LHAASO J1908+0621(PSR J1907+0602)
LHAASO J1825-1326(PSR J1826-1256)
LHAASO J2022+4030(PSR J2021+4026)
LHAASO J2238+5903(PSR J2238+5903)
LHAASO J2108+5157
LHAASO J0341+5257
LHAASO J0534+2202
LHAASO J1825-1326
LHAASO J1908+0621
LHAASO J2226+6057
LHAASO J0621+3755
LHAASO J0341+5257
LHAASO J2108+5157
Geminga
LHAASO J2238+5903
Monogem
Gamma-Cygnus
Normalized at (50 TeV, 10⁻⁶ MeV cm⁻² s⁻¹)
E²dN/dE [MeV cm⁻² s⁻¹]
E [MeV]

宇宙线正负电子



of the
ROYAL ASTRONOMICAL SOCIETY
MNRAS **485,** 3869–3875 (2019)
Advance Access publication 2019 March 11

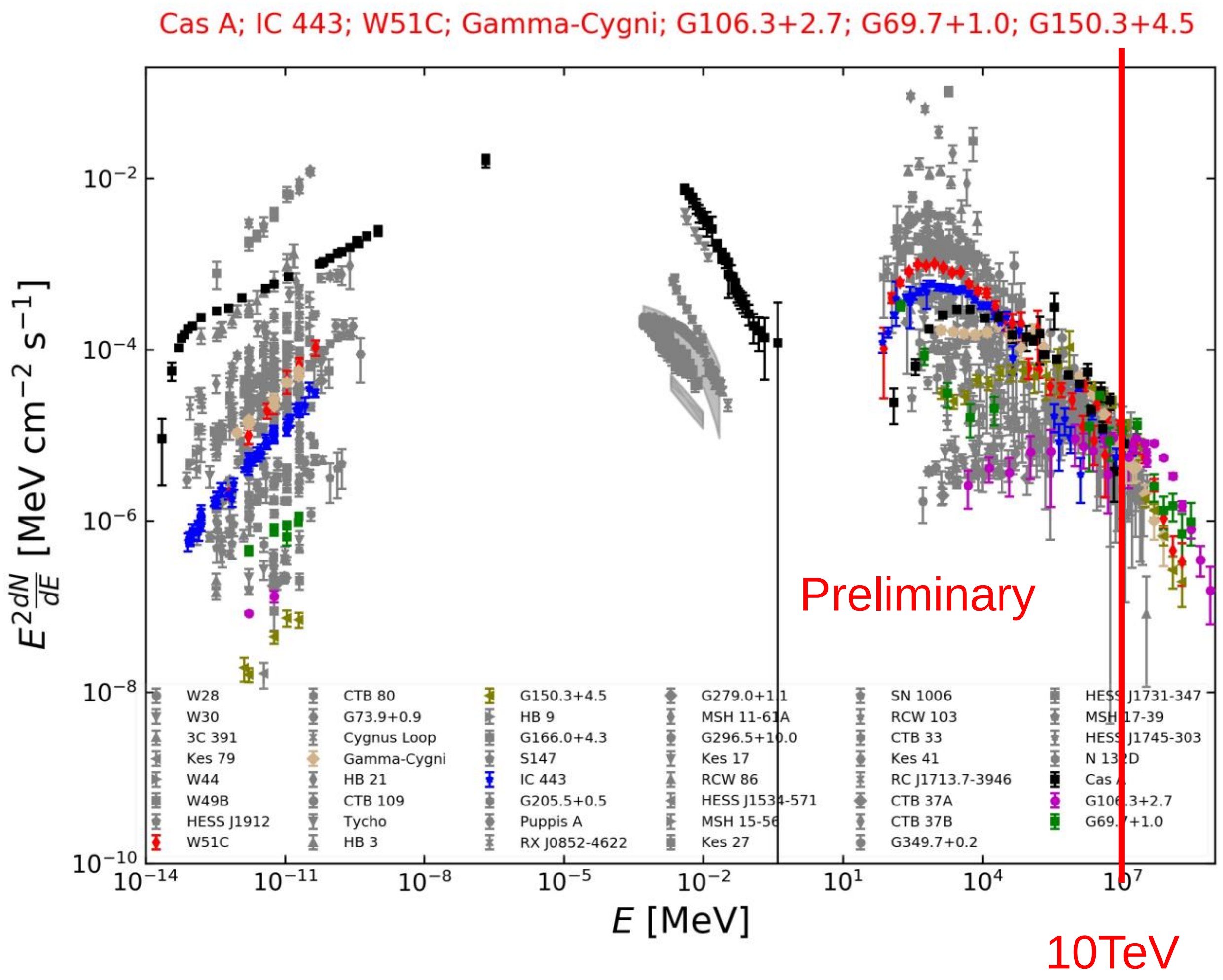
Examining the Secondary Product Origin of Cosmic-Ray Positrons with the Latest AMS-02 Data

Zhi-Qiu Huang[1,2], Ruo-Yu Liu[1,2], Jagdish C. Joshi[1,2], and Xiang-Yu Wang[1,2]

Origin of cosmic ray electrons and positrons

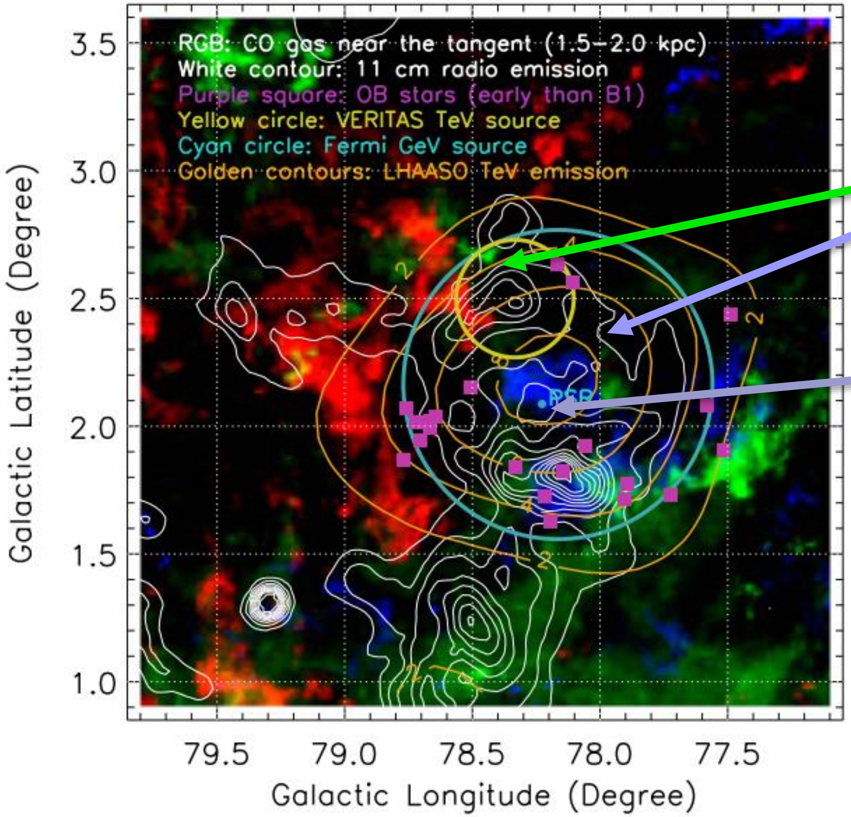
Zhao-Dong Shi[1,2★] and Siming Liu[1,2★]

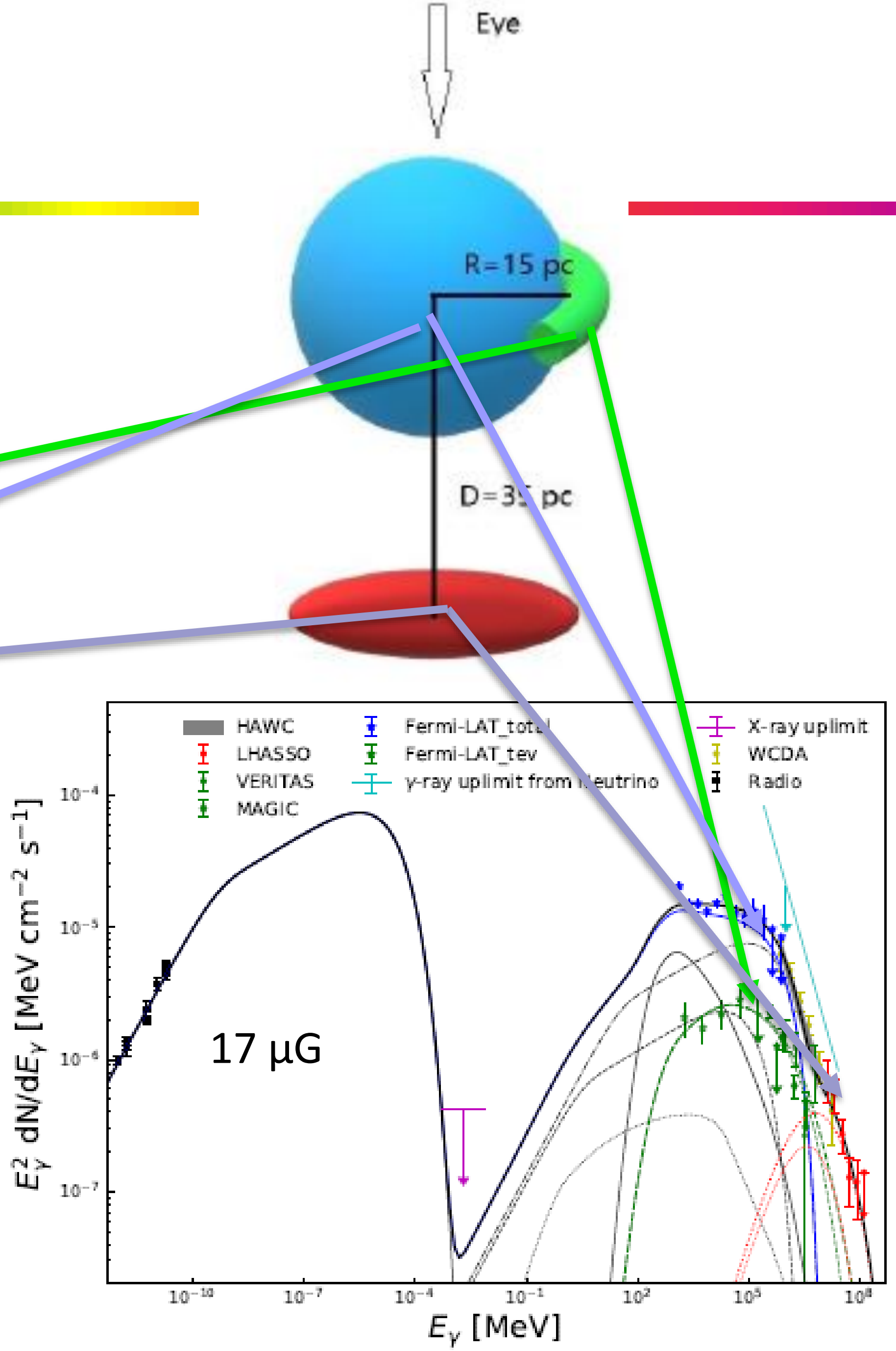
>7 SNRs Detected by LHAASO



The higher energy spectra are softer (but harder than an exponential cutoff)

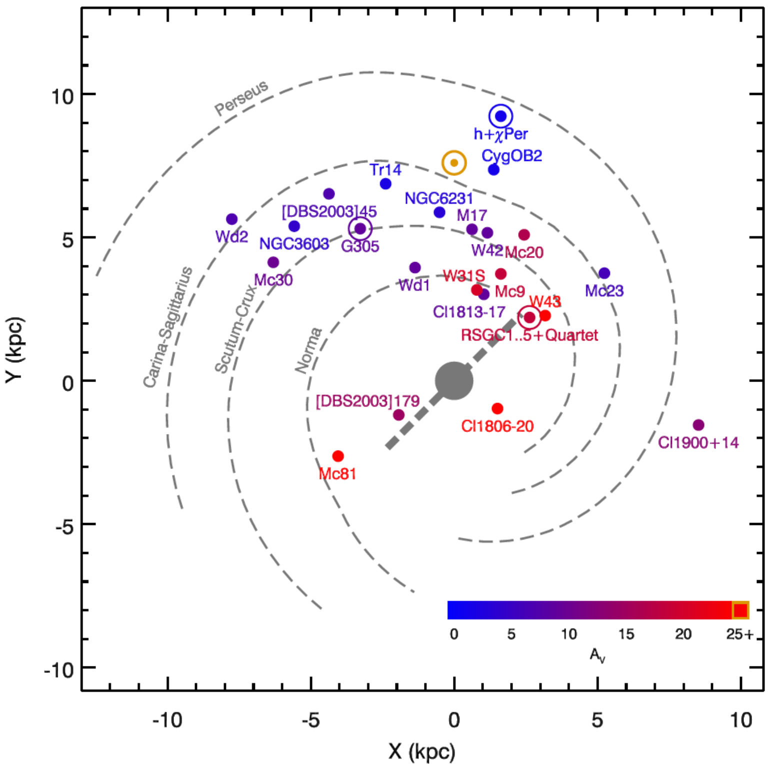
Gamma Cygni





Considering the low density inferred from X-ray observations of 0.2-0.3 cm^{-3} and a high magnetic field

YMSC IN OUR GALAXY



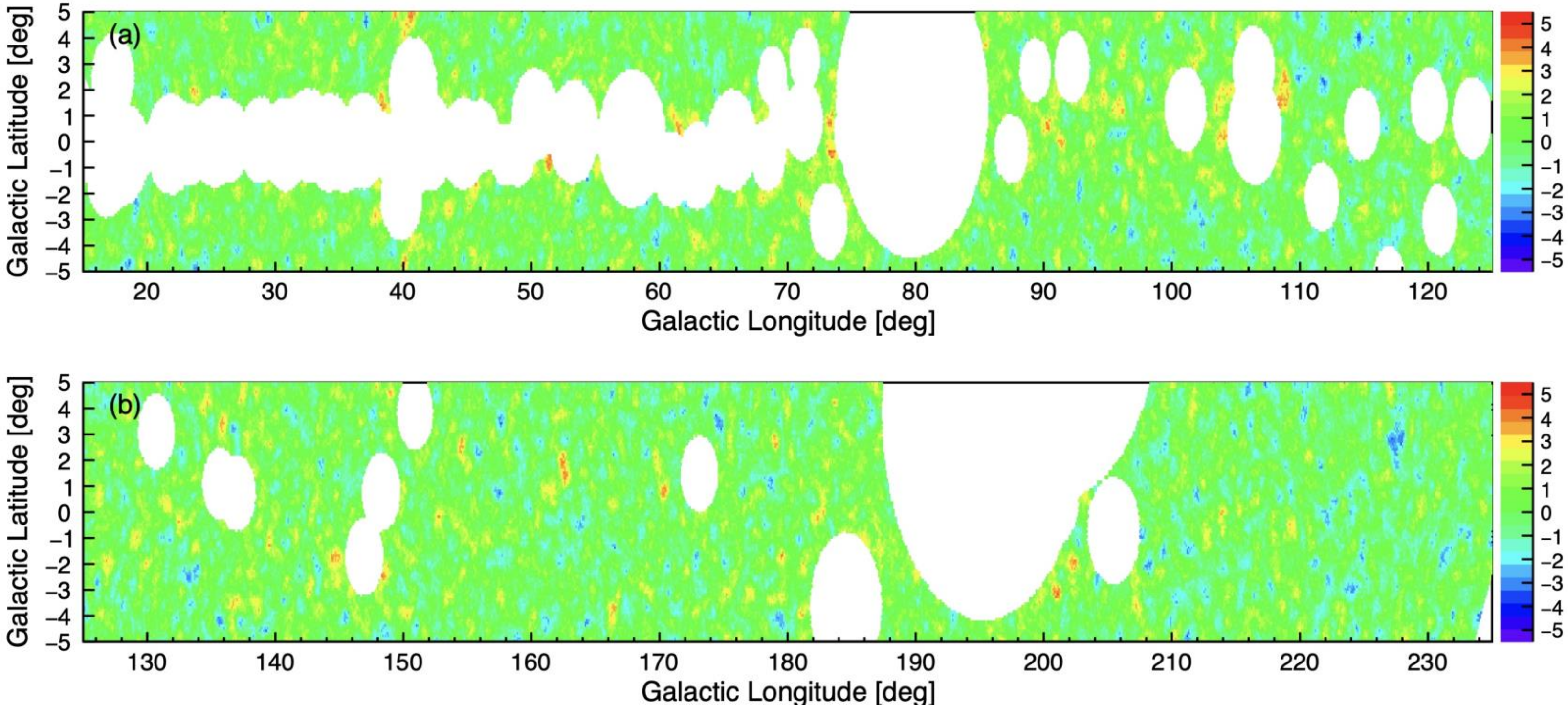
Davies et.al 2011

- ~20 in our Galaxy
- More to be discovered (high extinction in Galactic plane)

Stellar type	log[$\dot{M}$] $M_\odot$ yr^{-1}	V_∞ [km s^{-1}]
WNL	-4.2	1650
WNE	-4.5	1900
WC6-9	-4.4	1800
WC4-5	-4.7	2800
WO	-5.0	3500
O3	-5.2	3190
O4	-5.4	2950
O4.5	-5.5	2900
O5	-5.6	2875

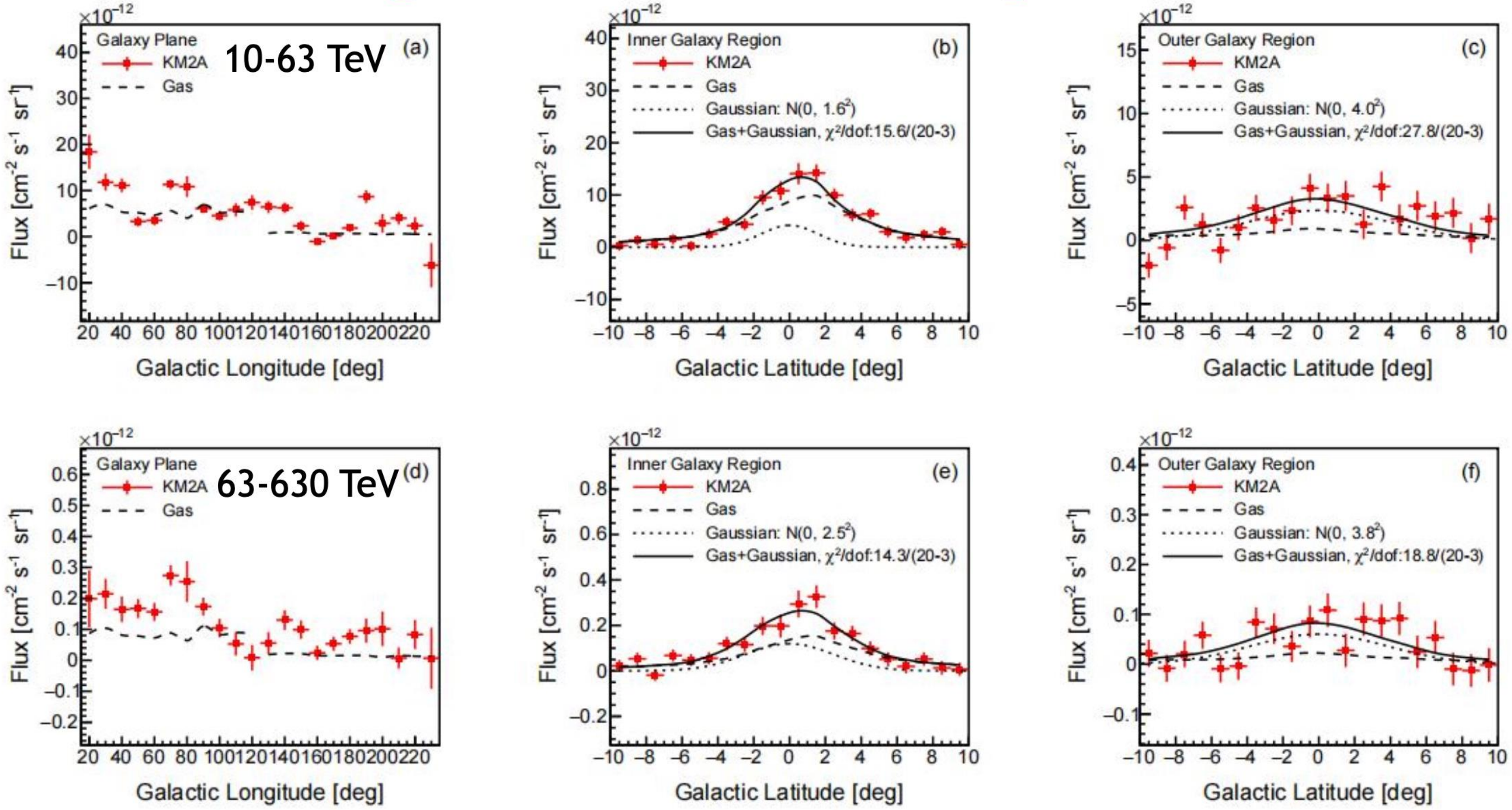
- The wind power of a single young star can be as high as 1e37 erg/s

弥散伽马射线



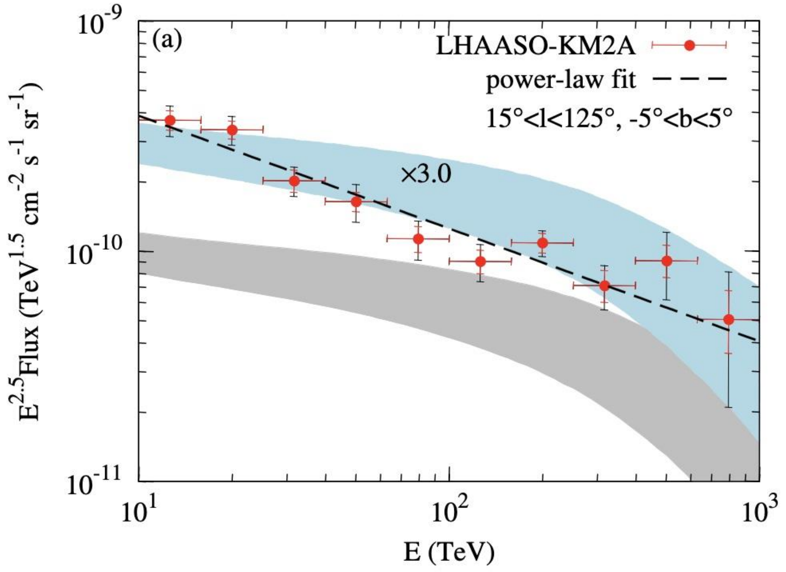
LHAASO collaboration arXiv: 2305.05372

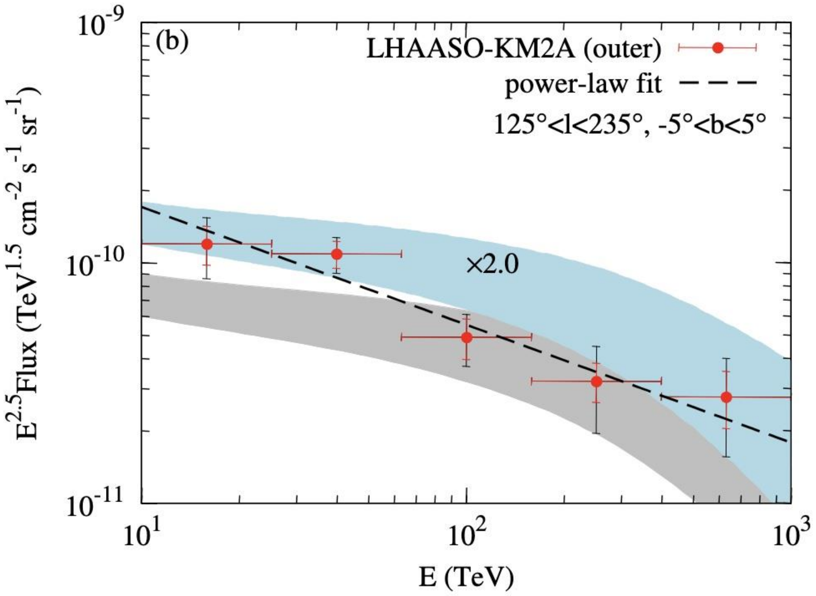
Longitude and latitude profiles



Adding a Gaussian latitude template does not improve the fittings significantly

LHAASO diffuse



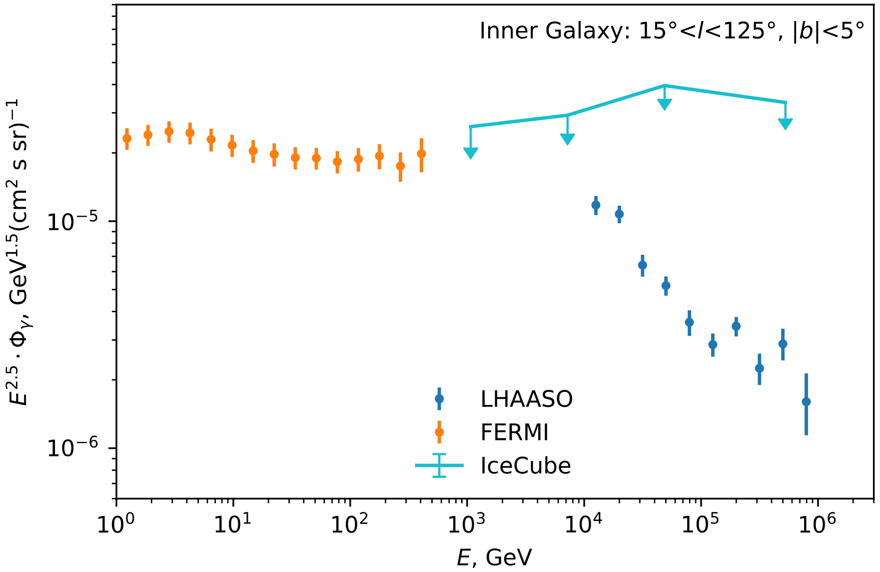


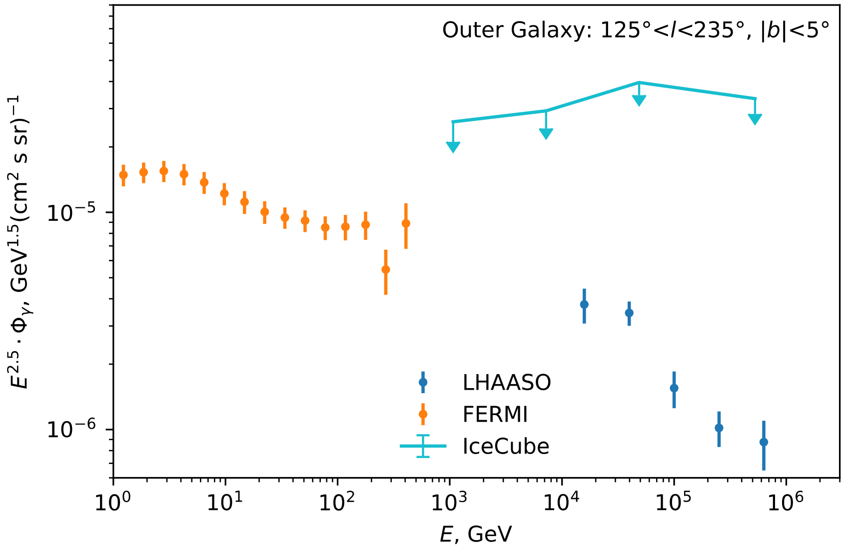
$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\mathrm{gas}}^{A'}(\boldsymbol{x}) I_{\mathrm{CR}}^{A}(E,\boldsymbol{x})$$

$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

arXiv: 2305.05372

Gamma-ray flux in inner and outer Galaxy





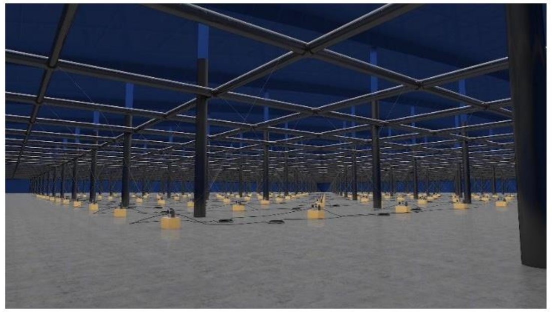
LHAASO data from LHAASO collaboration, 2305.05372

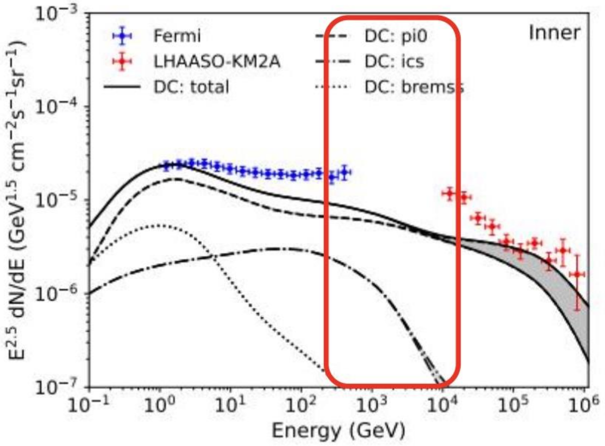
Fermi from R. Zhang et al, 2305.06948

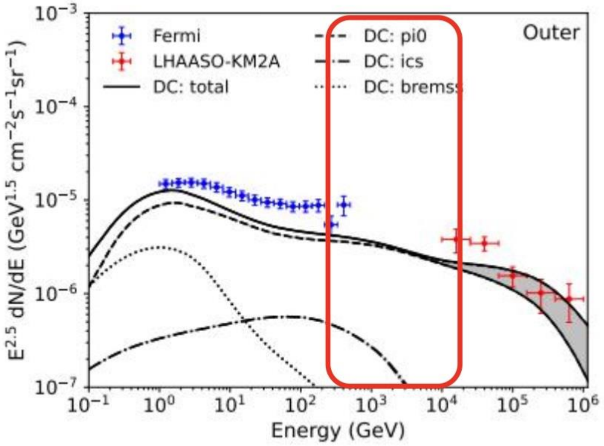
IceCube data from IceCube 7 years limit on Kra-gamma model approximated to |b|<5

Gamma-ray flux in LHAASO is same 1/E^3,
but combination with Fermi looks different.

Energy coverage from sub-TeV to 10 TeV by WCDA







WCDA is expected to cover the energy range from sub-TeV to 10 TeV, and will perfectly bridge Fermi and KM2A.

结论

- 宇宙线起源问题是粒子天体物理的核心科学问题之一，也是LHAASO的主要科学目标之一

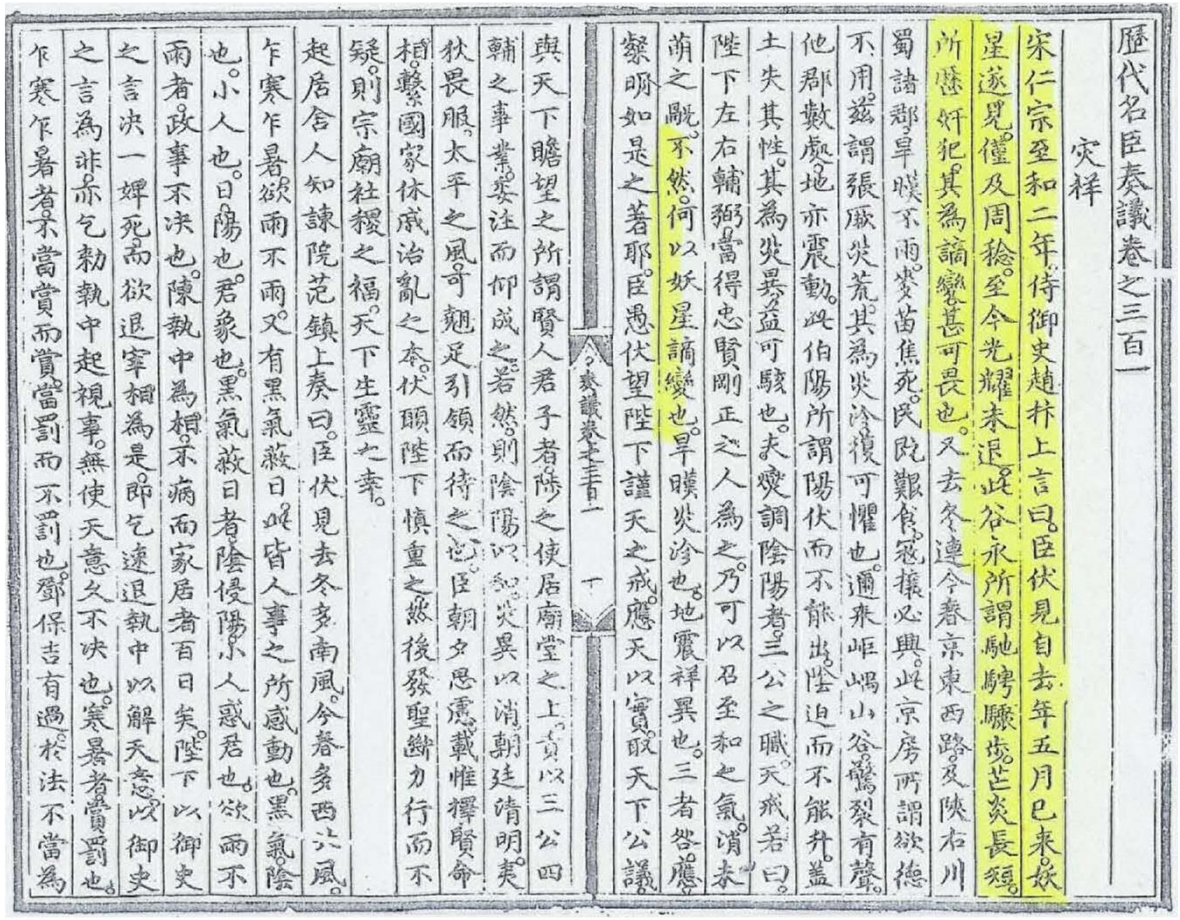
- 过去几十年从射电到甚高能伽马射线的天文多波段研究表明GeV宇宙线主要来自于高密度环境中的超新星遗迹激波加速而TeV宇宙线主要来自于低密度环境中的高速激波粒子加速

- LHAASO观测有望澄清PeV宇宙线的起源问题

Summary

- Construction of LHAASO finished in September 2021. LHAASO operates with almost 100% duty cicle. It’s one year sensitivity is better compared to 50 hours for present Cherenkov telescopes above few TeV. Above 20 TeV it is better compared to future CTA.
- LHAASO presented first catalog of 90 sources from about 2 first years of observation. 32 are new sources. Number of UHE gamma-ray sources above 100 TeV increased from 4 to 43 by LHAASO observations
  - 35 sources are PWN. Crab, Geminga, milisecond pulsar
  - 7 SNR, gamma-Cygni can not be explained by leptons
  - Star clusters Cygnus, w43
- Diffuse emission from Galaxy: new models requered
- GRB 221009A: detailed properties of GRB afterglow from 60000 photons in LHAASO WCDA

1054年的客星



歷代名臣奏議卷之三百一

災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長短
所歷奸犯其為讁變甚可畏也又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民飢艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴復可懼也通來岠嵎山谷驚裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之亂不然何以妖星讁變也旱暵災沴也地震祥異也三者咎應
粲明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

奏議卷之三百一　十

與天下瞻望之所謂賢人君子者陟之使居廟堂之上責以三公四
輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣
狄畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命
相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不
疑則宗廟社稷之福天下生靈之幸
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風
乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰
也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史
之言決一婢死而欲退宰相為是邪乞速退執中以解天意以御史
之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也
乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

Science

RESEARCH ARTICLES

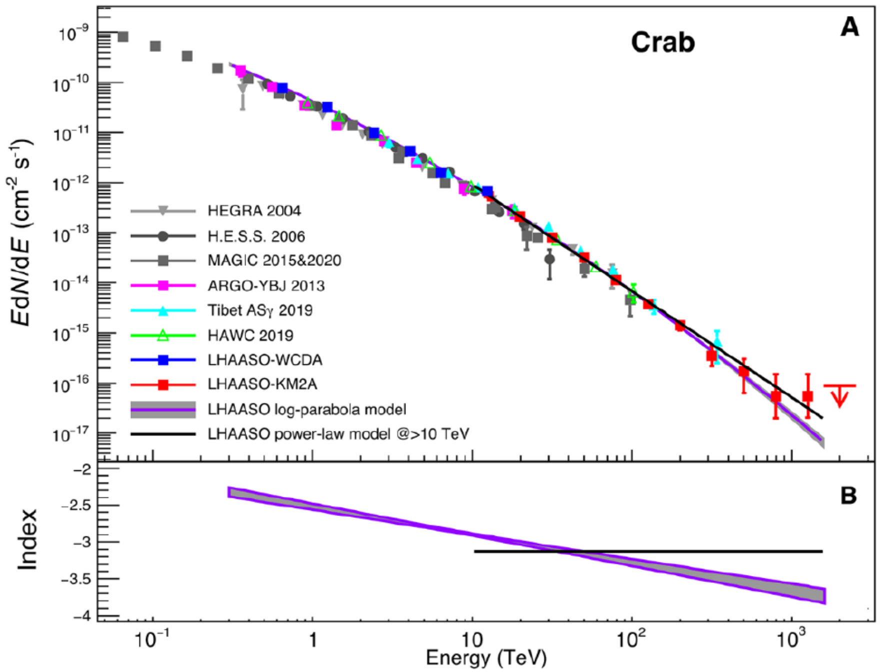
Cite as: The LHAASO Collaboration, *Science* 10.1126/science.abg5137 (2021).

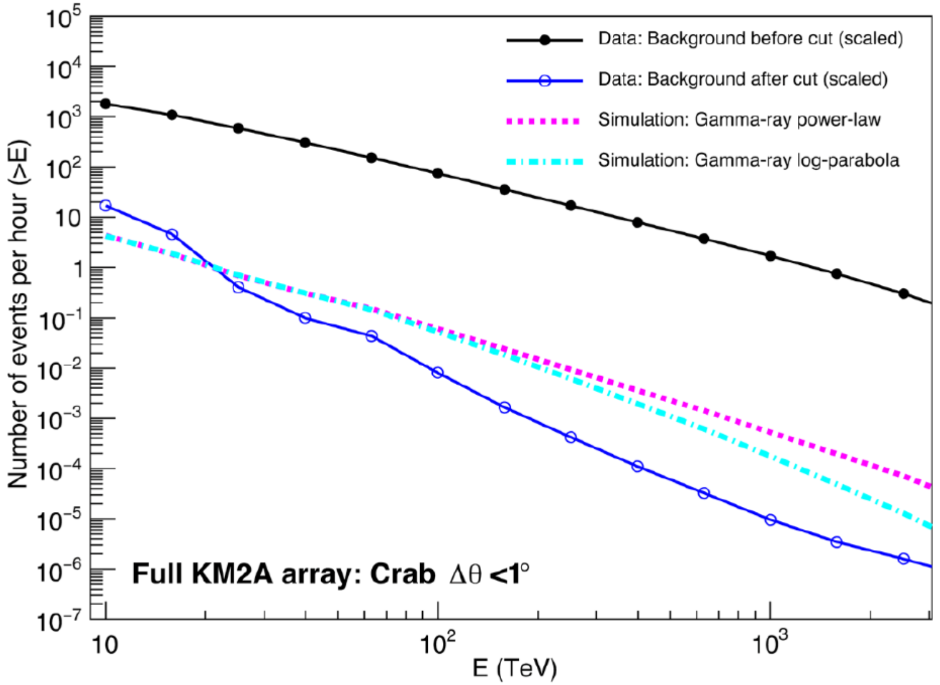
PeV gamma-ray emission from the Crab Nebula

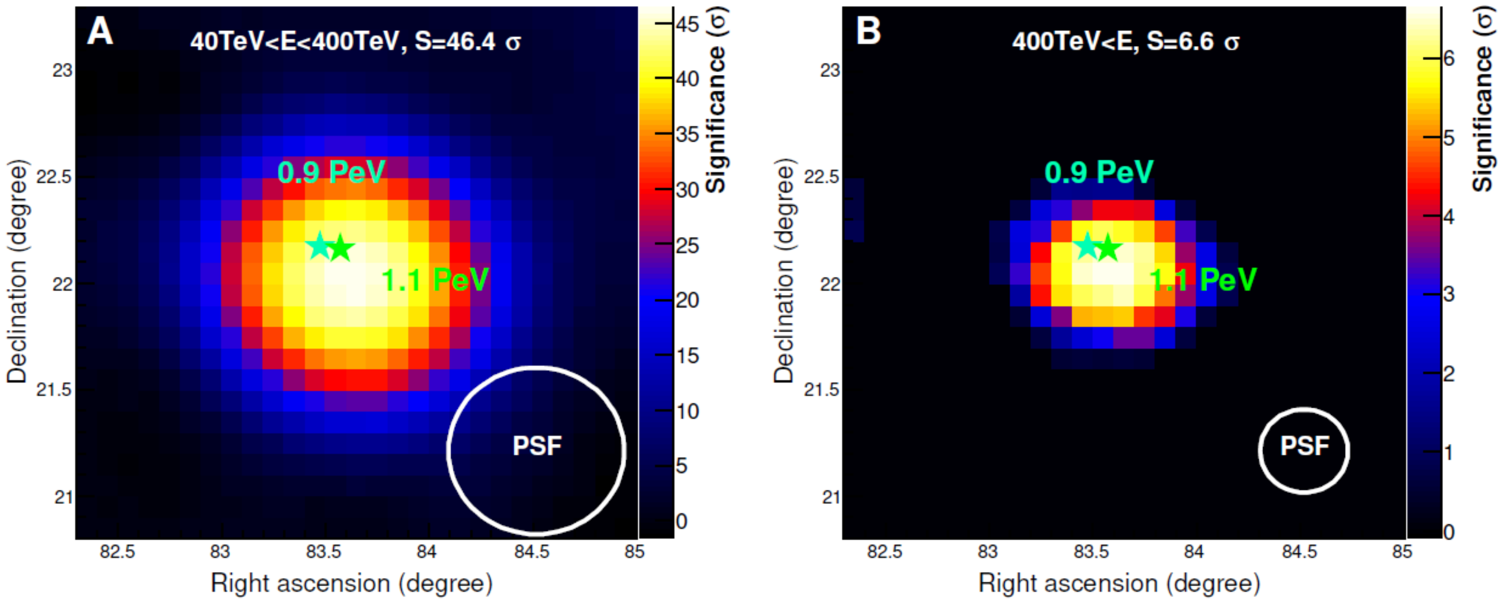
The LHAASO Collaboration*†

*Corresponding authors: Zhen Cao (caozh@ihep.ac.cn); S. Z. Chen (chensz@ihep.ac.cn); S. J. Lin (linsj6@mail.sysu.edu.cn); S. S. Zhang (zhangss@ihep.ac.cn); M. Zha (zham@ihep.ac.cn); Cong Li (licong@ihep.ac.cn); L. Y. Wang (wangly@ihep.ac.cn); L. Q. Yin (yinlq@ihep.ac.cn); F. Aharonian (felix.aharonian@mpi-hd.mpg.de); R. Y. Liu (ryliu@nju.edu.cn)

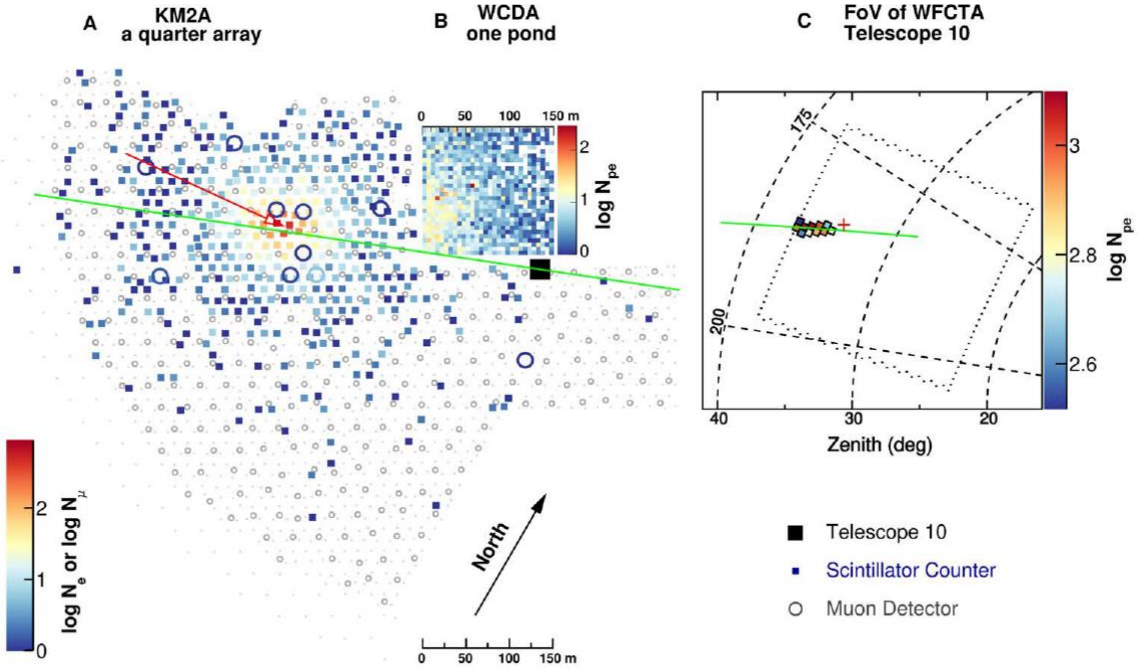
†The LHAASO Collaboration authors and affiliations are listed in the supplementary materials.






A
40TeV<E<400TeV, S=46.4 σ
0.9 PeV
1.1 PeV
PSF
Significance (σ)
Declination (degree)
Right ascension (degree)
B
400TeV<E, S=6.6 σ
0.9 PeV
1.1 PeV
PSF
Significance (σ)
Declination (degree)
Right ascension (degree)

0.88PeV

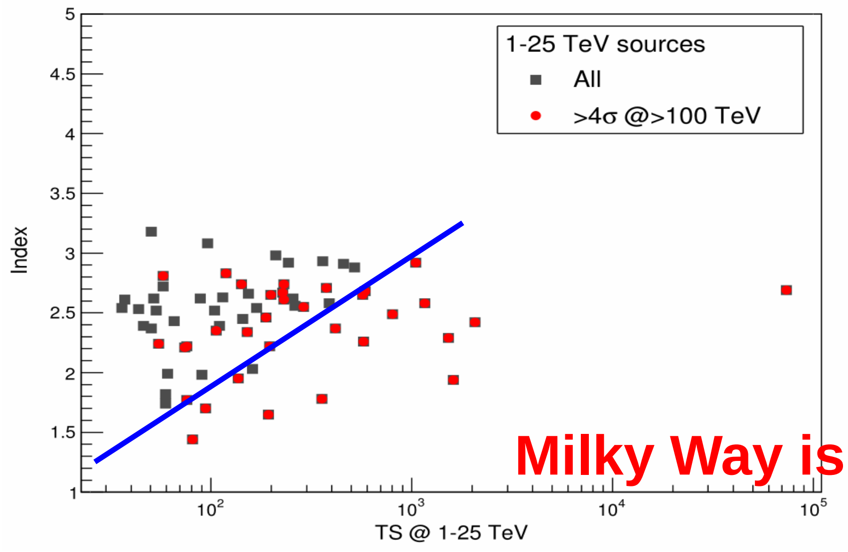

A KM2A
a quarter array
B WCDA
one pond
C FoV of WFCTA
Telescope 10
log N_pe
log N_e or log N_μ
North
0 50 100 150 m
Zenith (deg)
Telescope 10
Scintillator Counter
Muon Detector

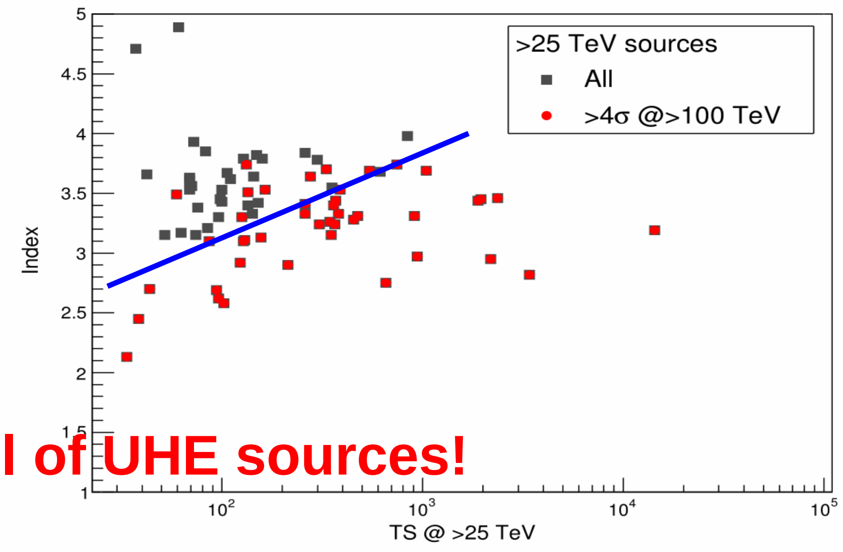
1st LHAASO source catalog

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
1LHAASO J0007+5659u	KM2A	1.86	57.00	0.12	<0.18	86.5	0.33±0.05	3.10±0.20	43.6	
	WCDA						<0.27			
1LHAASO J0007+7303u	KM2A	1.91	73.07	0.07	0.17±0.03	361.0	3.41±0.27	3.40±0.12	171.6	CTA 1 (0.12)
	WCDA	1.48	73.15	0.10	<0.22	141.6	5.01±1.11	2.74±0.11		
1LHAASO J0056+6346u	KM2A	14.10	63.77	0.08	0.24±0.03	380.2	1.47±0.10	3.33±0.10	94.1	
	WCDA	13.78	63.96	0.15	0.33±0.07	106.1	1.45±0.41	2.35±0.13		
1LHAASO J0206+4302u	KM2A	31.70	43.05	0.13	<0.27	96.0	0.24±0.03	2.62±0.16	82.8	
	WCDA						<0.09			
1LHAASO J0212+4254u	KM2A	33.01	42.91	0.20	<0.31	38.4	0.12±0.03	2.45±0.23	30.2	
	WCDA						<0.07			
1LHAASO J0216+4237u	KM2A	34.10	42.63	0.10	<0.13	102.0	0.18±0.03	2.58±0.17	65.6	
	WCDA						<0.20			
1LHAASO J0249+6022	KM2A	42.39	60.37	0.16	0.38±0.08	148.8	0.93±0.09	3.82±0.18		
	WCDA	41.52	60.49	0.40	0.71±0.10	53.3	1.96±0.51	2.52±0.16		
1LHAASO J0339+5307	KM2A	54.79	53.13	0.11	<0.22	144.0	0.58±0.06	3.64±0.16		LHAASO J0341+5258 (0.37)
	WCDA						<0.21			
1LHAASO J0343+5254u*	KM2A	55.79	52.91	0.08	0.20±0.02	388.1	1.07±0.07	3.53±0.10	20.2	LHAASO J0341+5258 (0.28)
	WCDA	55.34	53.05	0.18	0.33±0.05	94.1	0.29±0.13	1.70±0.19		

PeVatrons

- 51% (35/69) 1-25TeV sources are UHE sources.
- 57% (43/75) >25TeV sources are UHE sources.
- 19% (8/43) UHE sources are not detected at 1-25TeV (new class?).

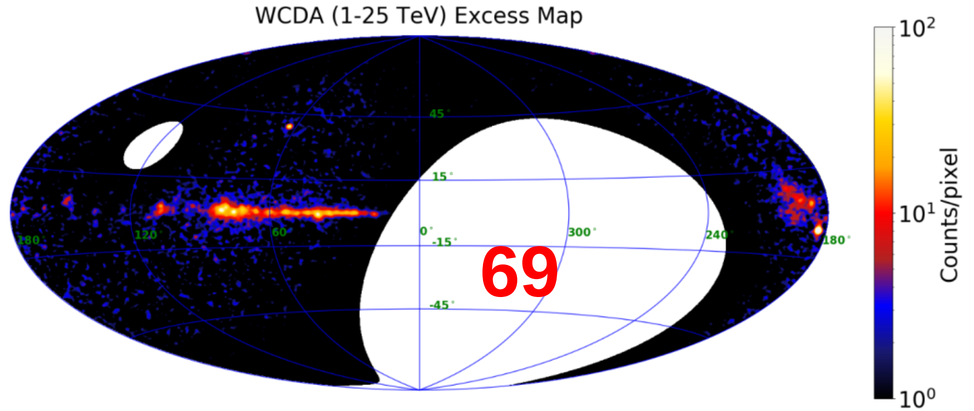


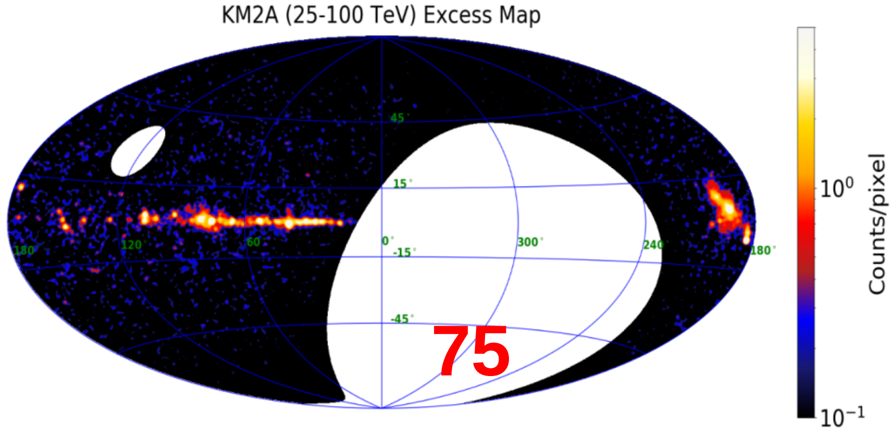


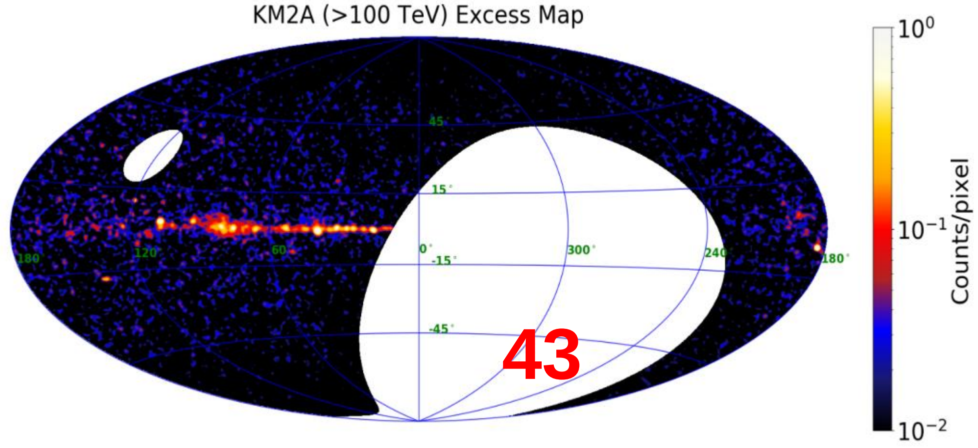
Milky Way is full of UHE sources!

LHAASO catalog

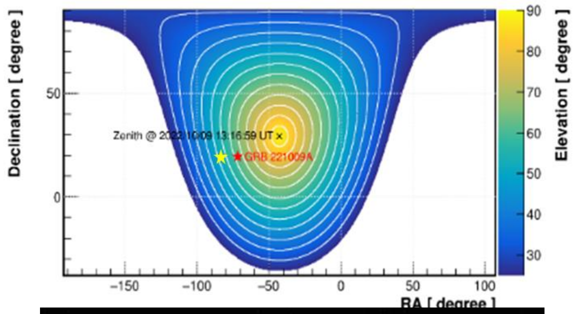
- 90 in 1st LHAASO sources.
- 32 new discoveries
- 43 UHE

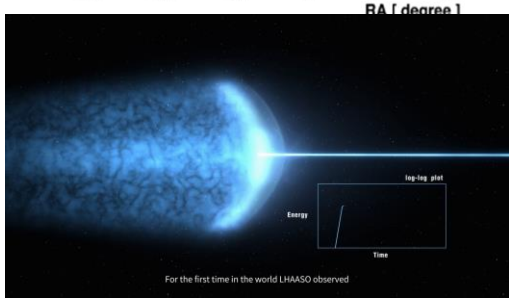


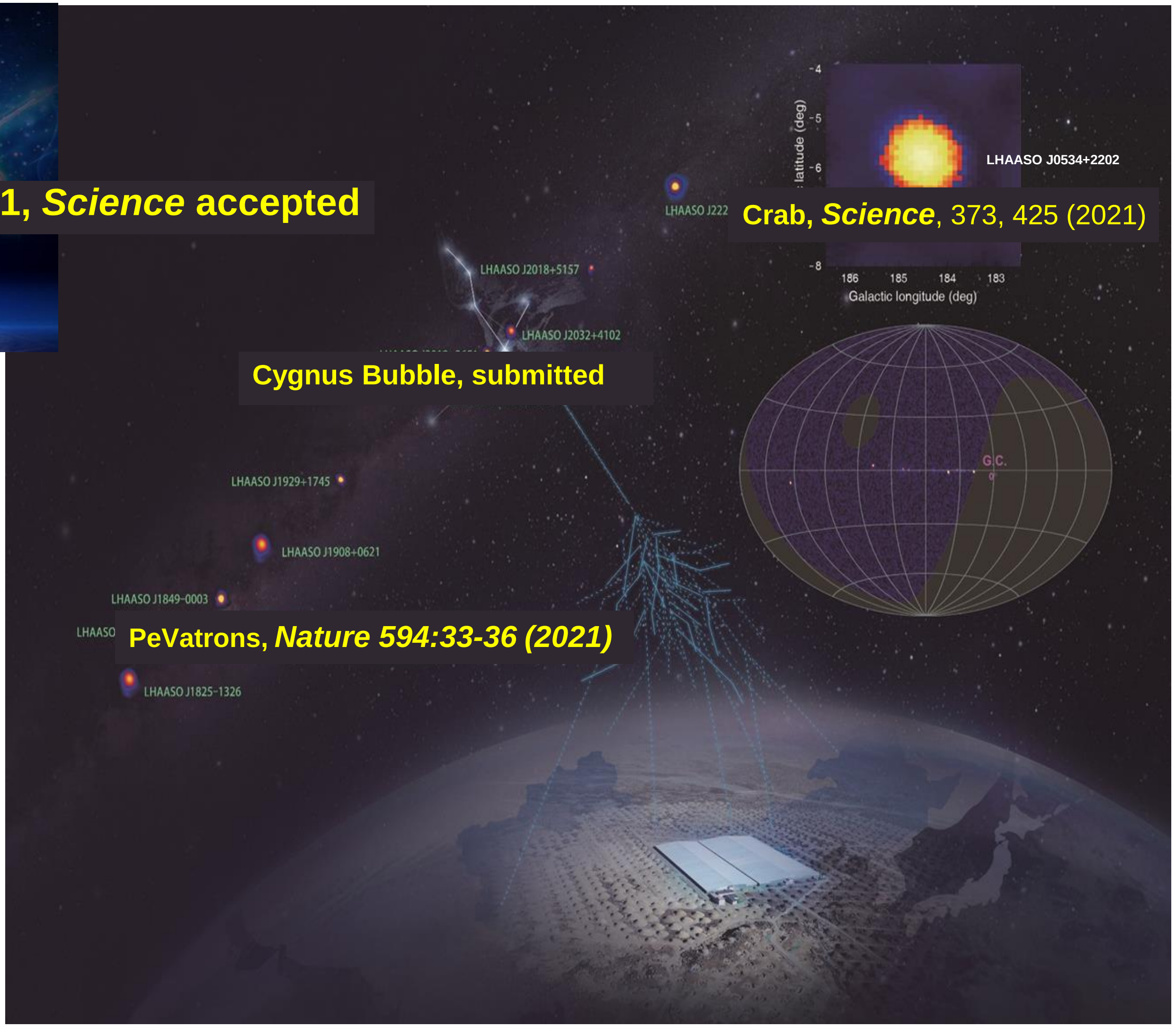




Discovery Highlights

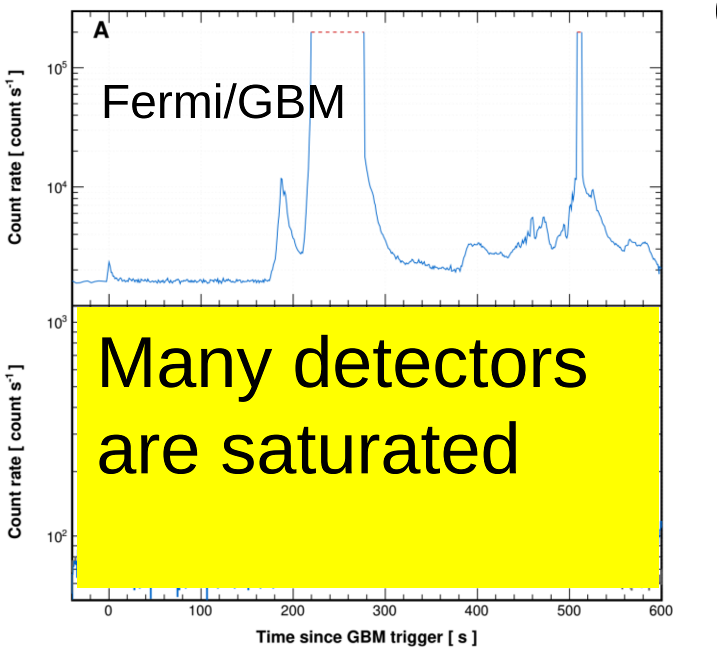


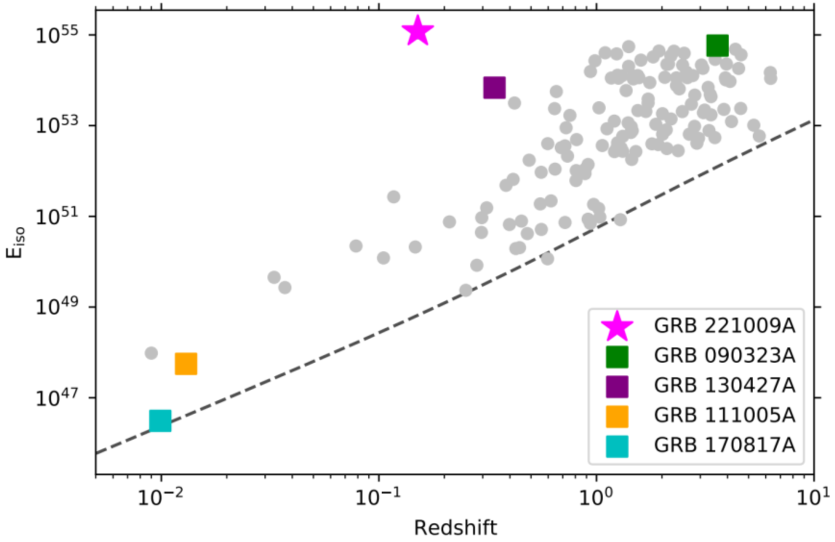




GRB 221009A: brightest-of-all-time (BOAT**)** GRB

- Triggered on a weak precursor
- Fluence: >5e-2 erg/cm^2， low redshift (z=0.151)
- deriving an enormous energy $E_{\gamma,iso}$~**10^{55}** erg



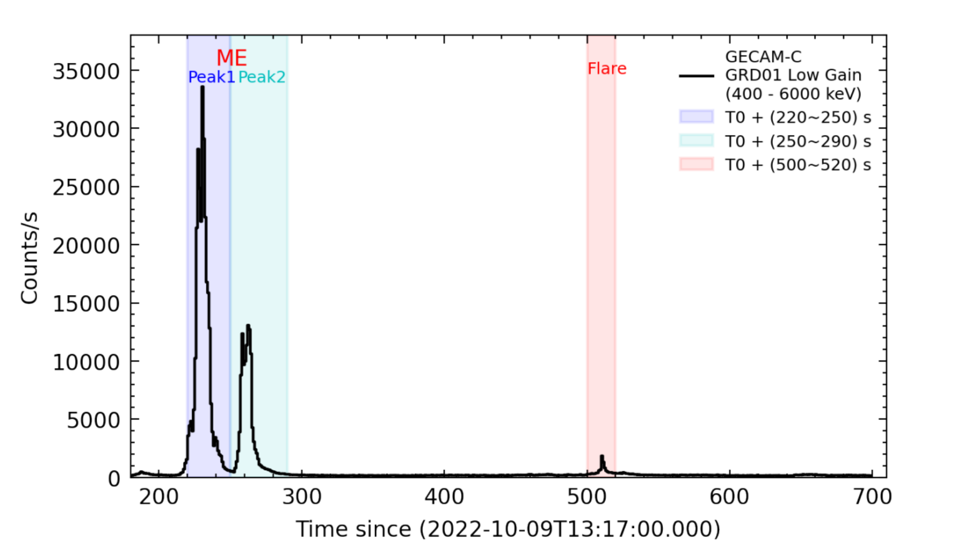


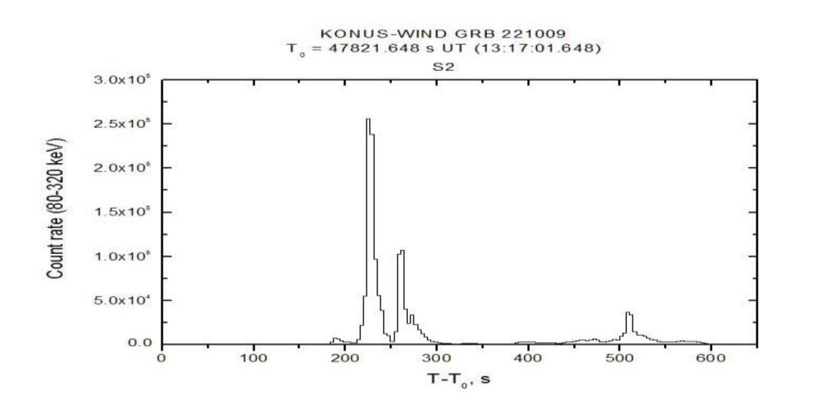
R<10^{-3} yr

R_GRB≤ 6.1 × 10^{-4} Gpc^{-3} yr^{-1}

z=0.151 volume ~ 1 Gpc^3

GECAM/Konus-Wind Observations of GRB 221009A





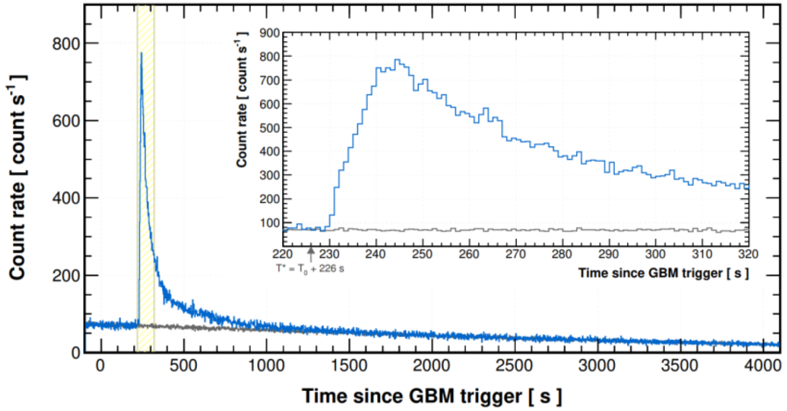
E_iso~ 1.5 × 10^55 erg

Main peak 1 lasts ~10 s

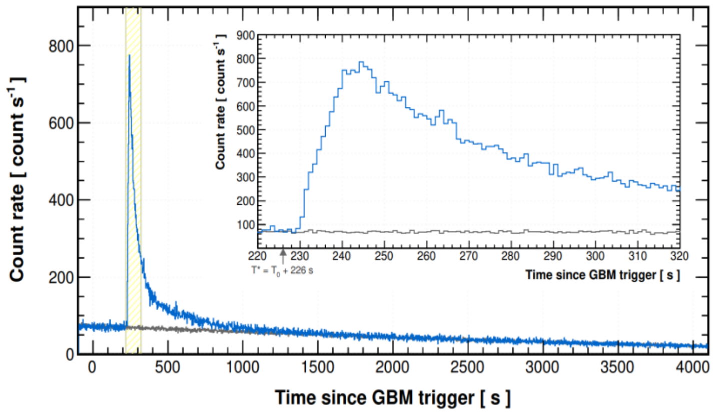
LHAASO GRB221009A

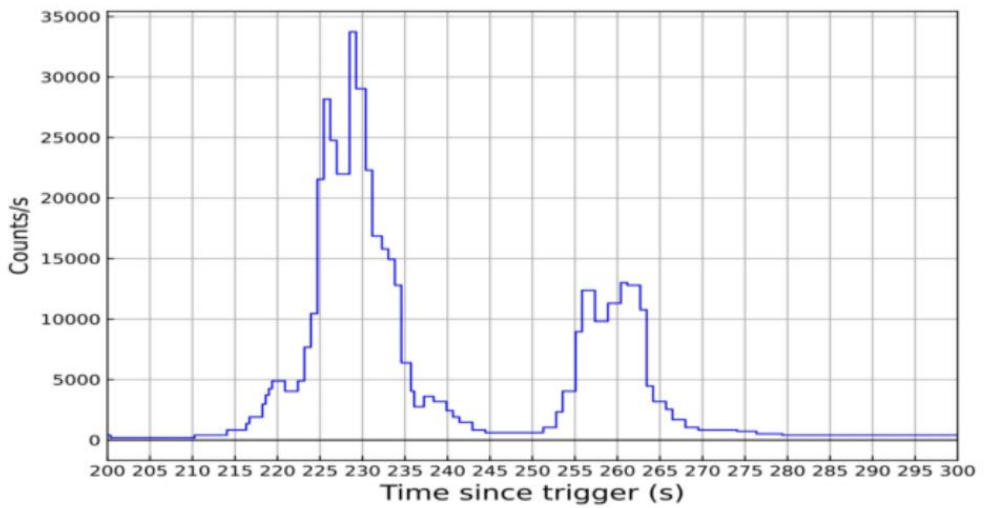
- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- TeV count rate light curve: Smooth temporal profile – **external shock origin**

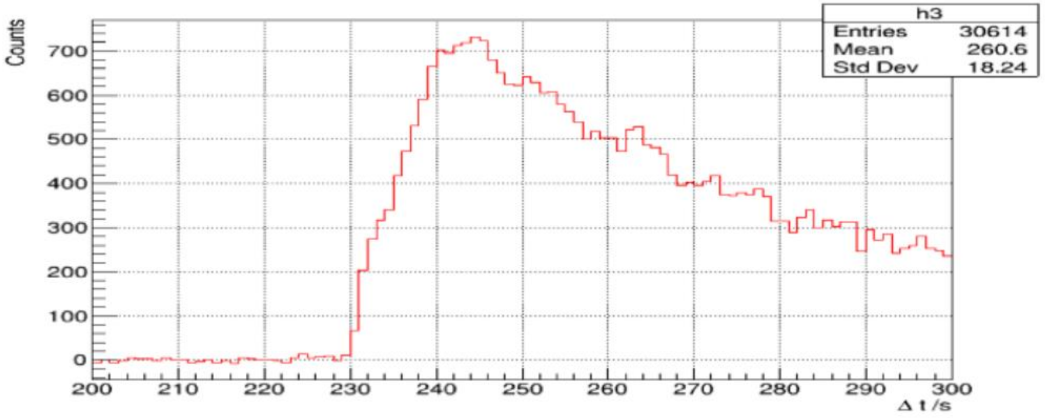
First time detection of the TeV afterglow onset !



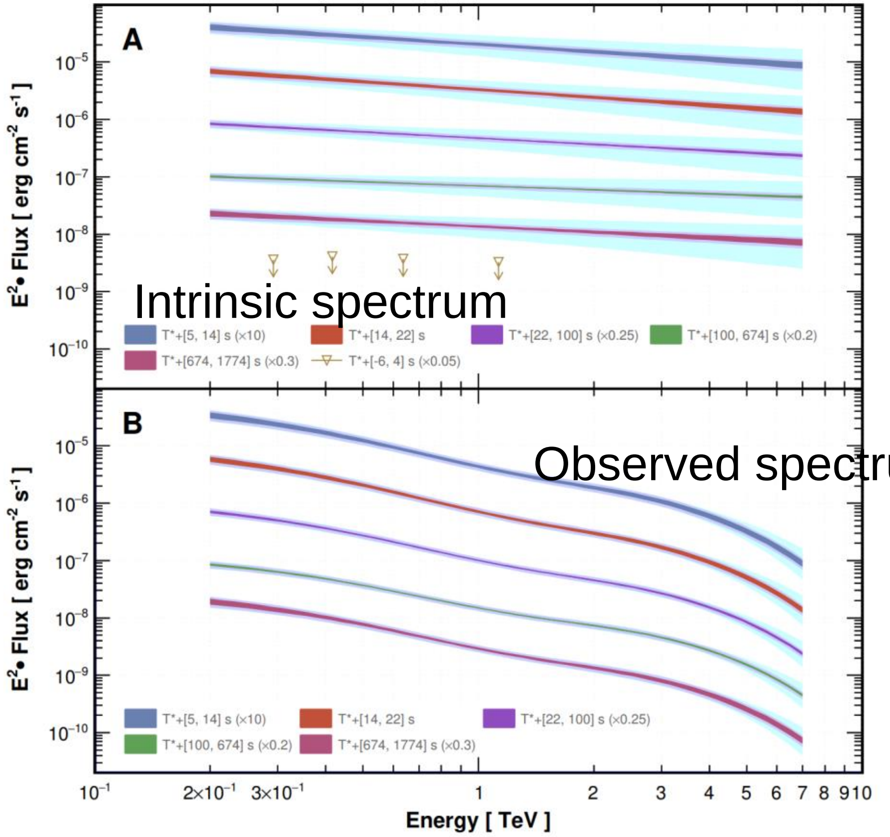
MeV vs TeV light curves: external shock origin







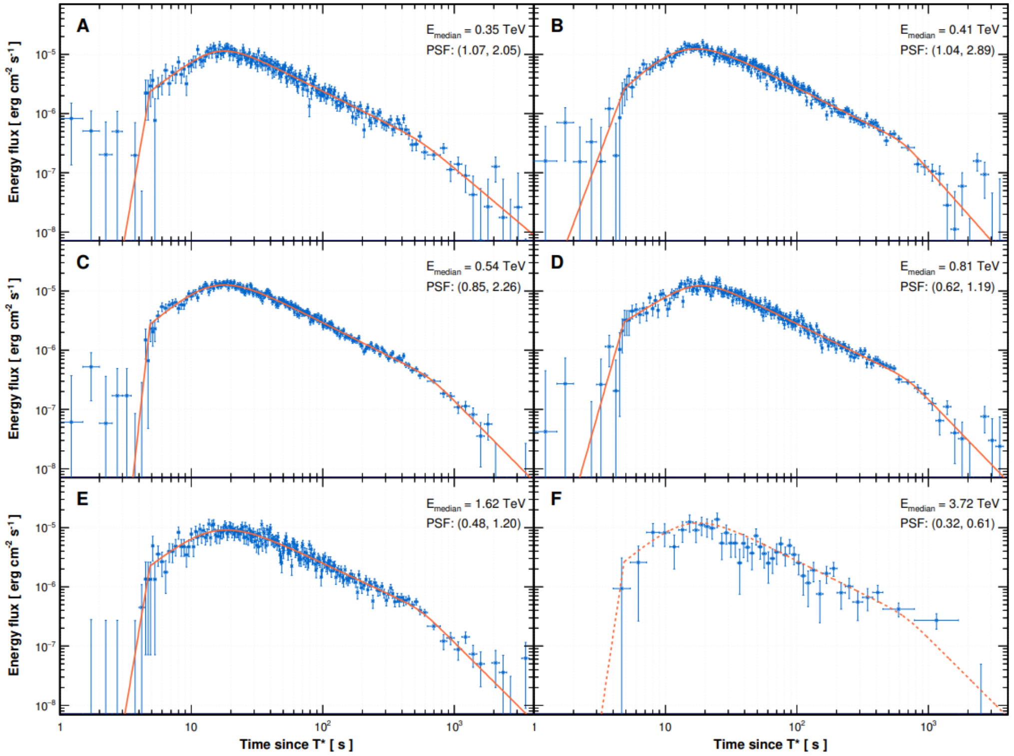
SED measured by LHAASO-WCDA



- 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

Fast decay phase



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

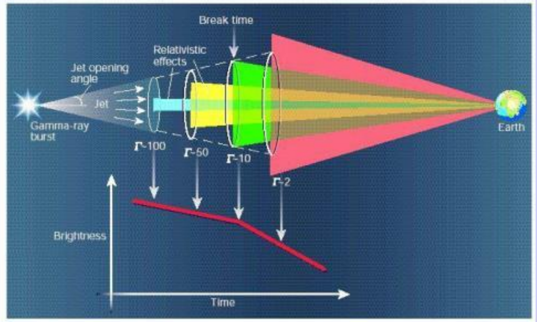
$$T_{\mathrm{b},2} = T^* + 670^{+230}_{-110}\,\mathrm{s}$$

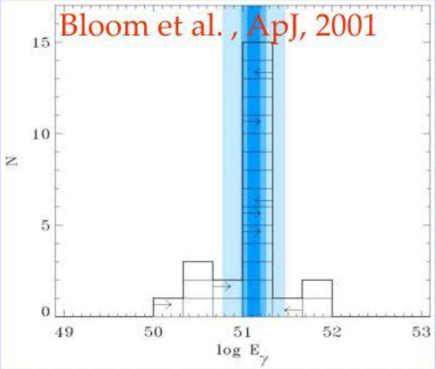
Revealing a jet break at the earliest time.

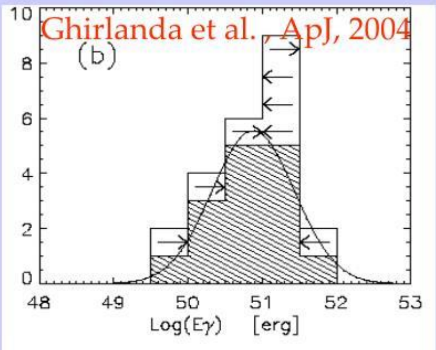
A narrow GRB jet

- 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

- 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.





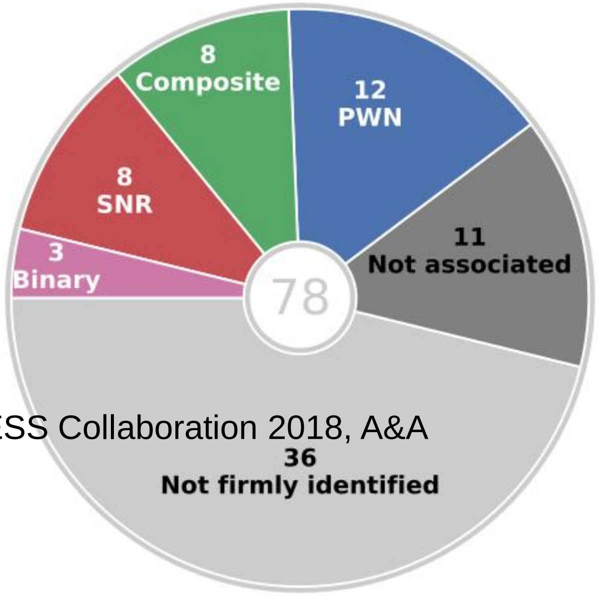


$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{b,2}}{670\,\mathrm{s}}\right)^{3/8}$$

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

Pulsars as Counterparts of VHE gamma-ray sources

Pulsars – the most commonly potential counterparts of detected VHE gamma-ray emitter



HESS Collaboration 2018, A&A

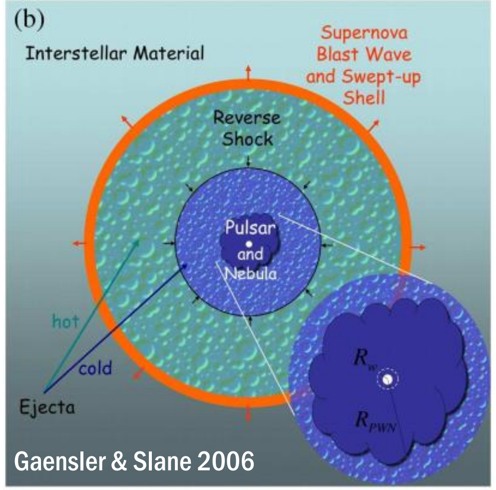
14 firmly identified PWN by HESS

HGPS name	ATNF name	Canonical name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	R_{PWN} (pc)	$L_{1-10\,TeV}$ (10^{33} erg s^{-1})
J1813−178[1]	J1813−1749		37.75	5.60	4.70	<2	2.07 ± 0.05	4.0 ± 0.3	19.0 ± 1.5
J1833−105	J1833−1034	G21.5−0.9[2]	37.53	4.85	4.10	<2	2.42 ± 0.19	<4	2.6 ± 0.5
J1514−591	B1509−58	MSH 15−52[3]	37.23	1.56	4.40	<4	2.26 ± 0.03	11.1 ± 2.0	52.1 ± 1.8
J1930+188	J1930+1852	G54.1+0.3[4]	37.08	2.89	7.00	<10	2.6 ± 0.3	<9	5.5 ± 1.8
J1420−607	J1420−6048	Kookaburra (K2)[5]	37.00	13.0	5.61	5.1 ± 1.2	2.20 ± 0.05	7.9 ± 0.6	44 ± 3
J1849−000	J1849−0001	IGR J18490−0000[6]	36.99	42.9	7.00	<10	1.97 ± 0.09	11.0 ± 1.9	12 ± 2
J1846−029	J1846−0258	Kes 75[2]	36.91	0.728	5.80	<2	2.41 ± 0.09	<3	6.0 ± 0.7
J0835−455	B0833−45	Vela X[7]	36.84	11.3	0.280	2.37 ± 0.18	1.89 ± 0.03	2.9 ± 0.3	0.83 ± 0.11*
J1837−069[8]	J1838−0655		36.74	22.7	6.60	17 ± 3	2.54 ± 0.04	41 ± 4	204 ± 8
J1418−609	J1418−6058	Kookaburra (Rabbit)[5]	36.69	10.3	5.00	7.3 ± 1.5	2.26 ± 0.05	9.4 ± 0.9	31 ± 3
J1356−645[9]	J1357−6429		36.49	7.31	2.50	5.5 ± 1.4	2.20 ± 0.08	10.1 ± 0.9	14.7 ± 1.4
J1825−137[10]	B1823−13		36.45	21.4	3.93	33 ± 6	2.38 ± 0.03	32 ± 2	116 ± 4
J1119−614	J1119−6127	G292.2−0.5[11]	36.36	1.61	8.40	<11	2.64 ± 0.12	14 ± 2	23 ± 4
J1303−631[12]	J1301−6305		36.23	11.0	6.65	20.5 ± 1.8	2.33 ± 0.02	20.6 ± 1.7	96 ± 5

Among the 47 sources not yet identified, most of them (**36**) have possible associations with cataloged objects, notably PWNe and energetic pulsars that could power VHE PWN. —— HGPS

We have presented the third catalog of steady gamma-ray emitters detected by HAWC using 1523 days of data. The catalog consists of 65 sources, including two blazars. The most abundant source class among the potential counterpart of HAWC sources in the Galactic plane is pulsars (56). —— 3HWC (HAWC Collaboration 2020, ApJ)

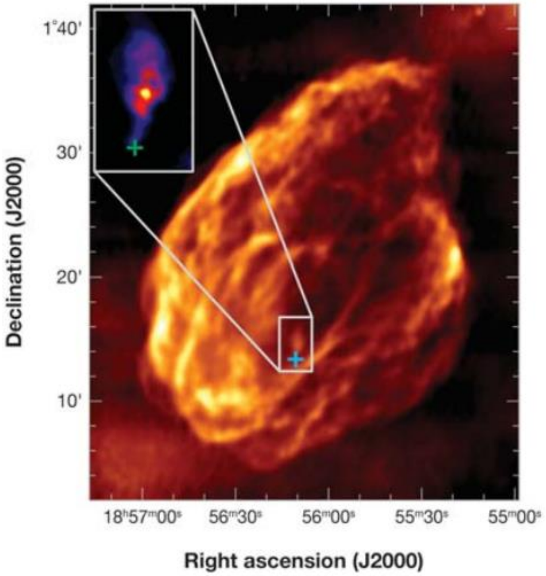
From PWN to Pulsar Halos



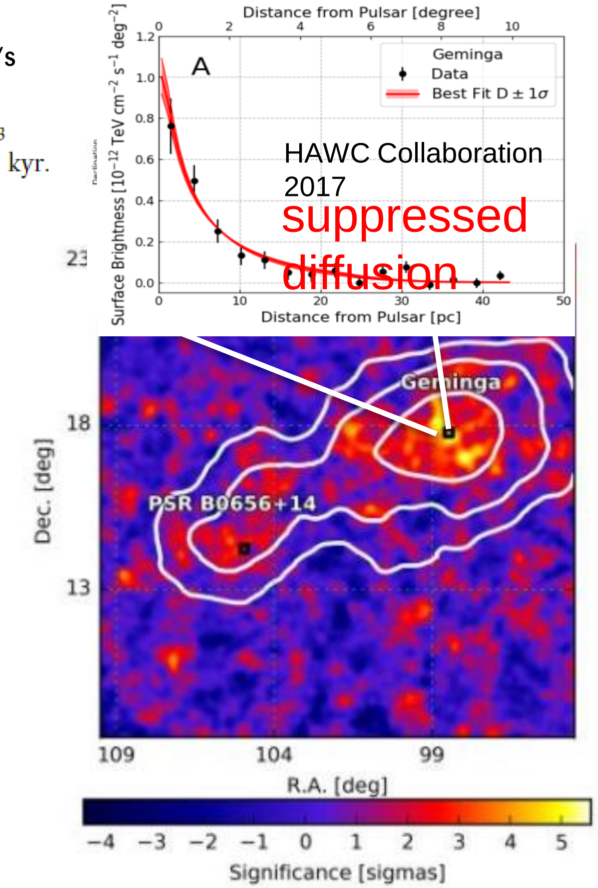
Gaensler & Slane 2006

Conservation of Momentum: Natal kick velocity: 400-500 km/s

$$t_{cross} = 44\left(\frac{E_{SN}}{10^{51}\mathrm{ergs}}\right)^{1/3}\left(\frac{n_0}{1\ \mathrm{cm}^{-3}}\right)^{-1/3}\left(\frac{V_{\mathrm{PSR}}}{500\ \mathrm{km\ s}^{-1}}\right)^{-5/3}\mathrm{kyr.}$$



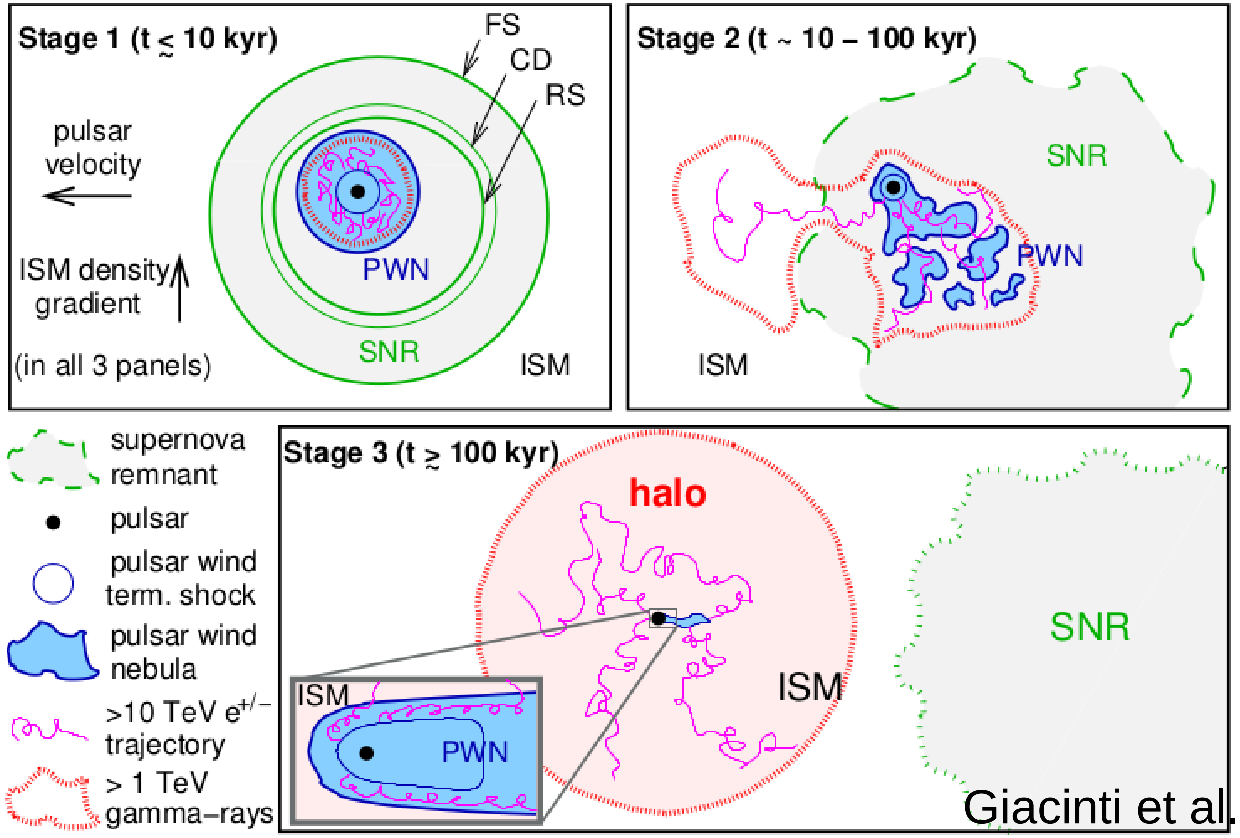
Giacani et al. 1997 Frail et al. 1996



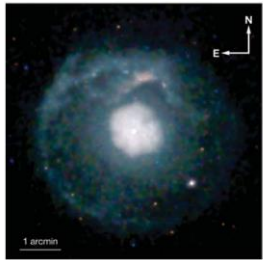
HAWC Collaboration 2017

suppressed diffusion

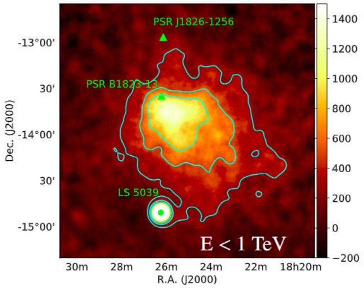
Three Evolution Stages



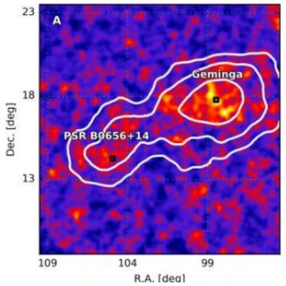
Giacinti et al. 2020



SNR G21.5-0.9
PSR J1833-1034

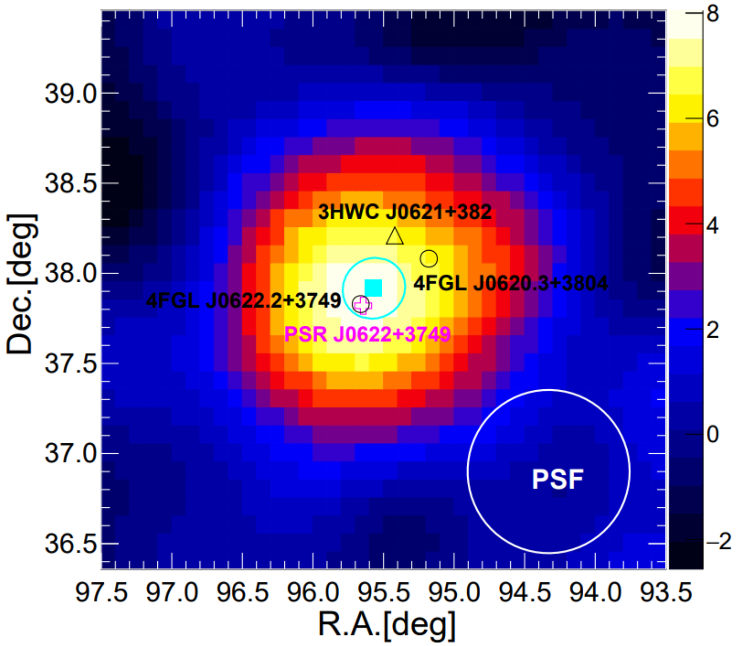


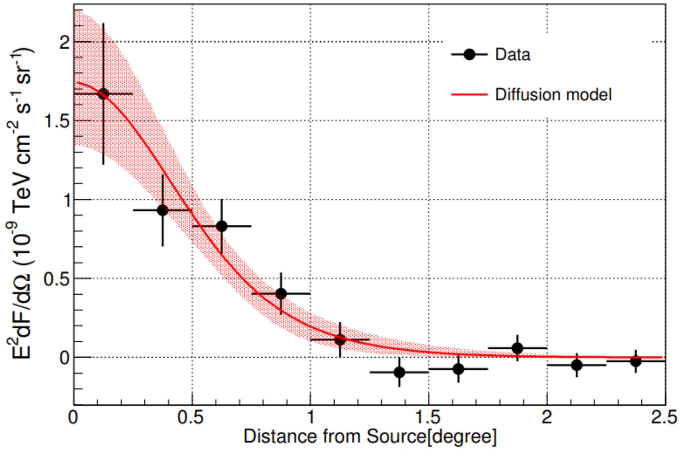
HESS J1825-137
PSR J1826-1334

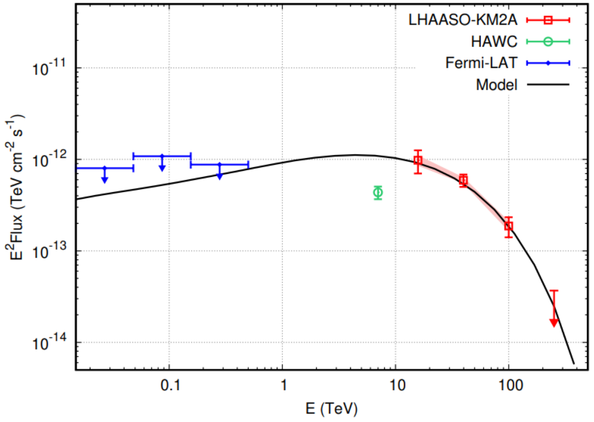


Geminga
Monogem

LHAASO J0621+3755







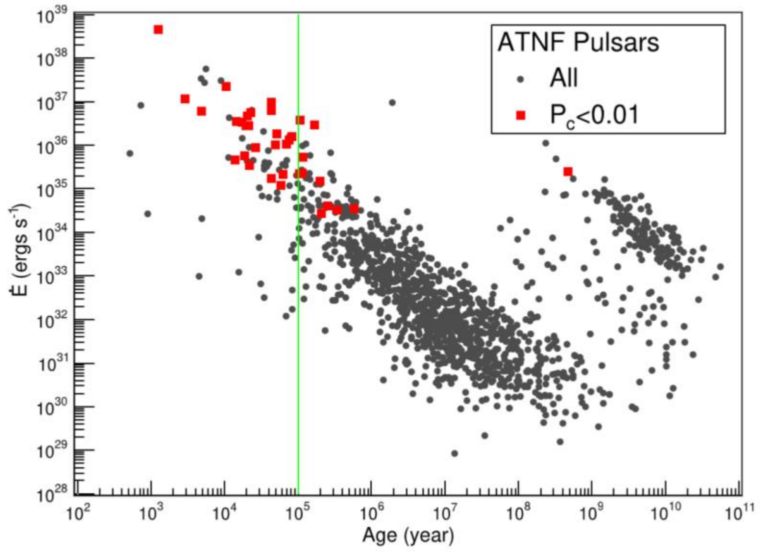
$D \approx (8.9\ ^{+4.5}\ _{-3.9})\ \mathrm{x}10^{27}(d/1.6\ \mathrm{kpc})^2\ \mathrm{cm}^2\mathrm{s}^{-1}$ for $E_e \sim 160$ TeV

LHAASO Collaboration 2021, PRL

1LHAASO Catalogue

35 sources associated with pulsars with $\dot{E} > 10^{34} \mathrm{erg}/s$ at a chance probablity <1% (65 have ≥1 pulsar within 0.5 deg)

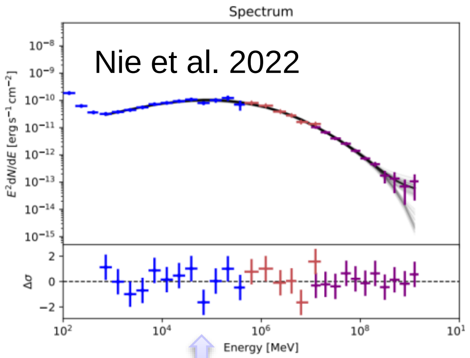
Source name	PSR name	dist.(°)	Distance (kpc)	τ_c (kyr)	$\dot{E}$ (ergs/s)	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Haloa
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	-	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

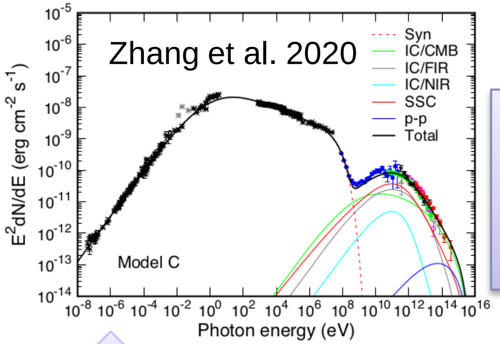


$P_c = 1 - e^{r^2/r_0^2}$ $r_0 = [\pi\rho(\dot{E})]^{-1/2}$

$|b - b_c| < 2.5^\circ$ & $|l - l_c| < 10^\circ$

Crab: PWN as a Super-PeVatron of protons?



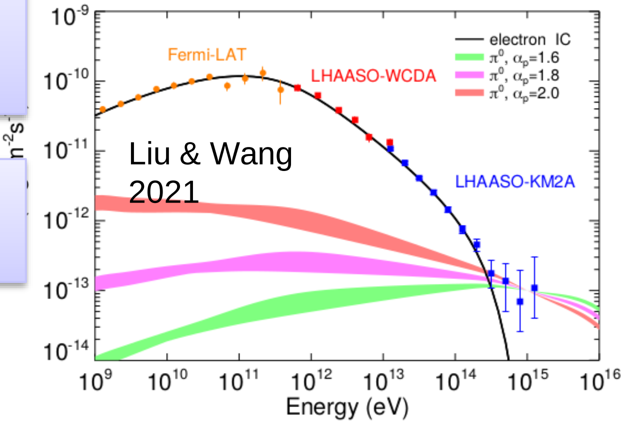


Lepto-Hadronic fitting

W_p~1% W_{rot} inside the nebula

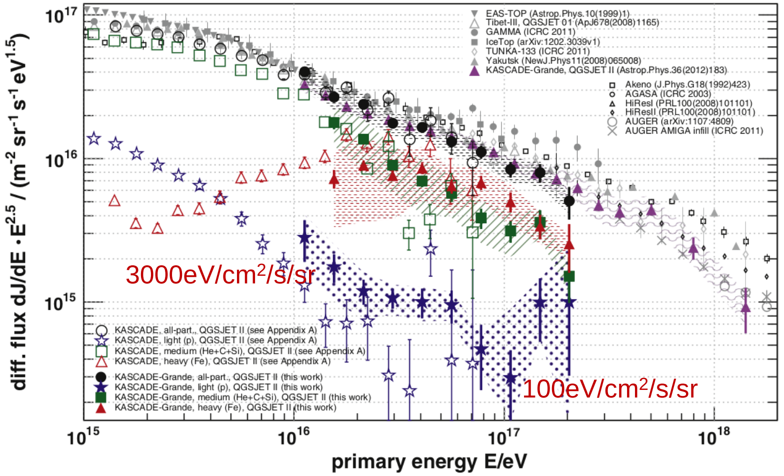
Considering escape W_p~(10-50)%

may account for 10-100PeV protons if each pulsars can accelerate protons >10PeV when they were young



Estimation with a leaky box model

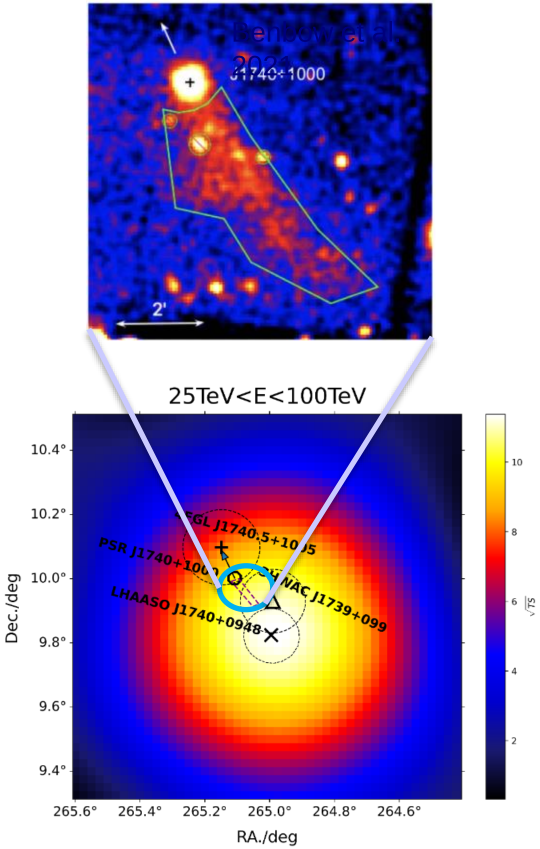
$$F(E_p) = \frac{c}{4\pi}\frac{\eta_p L_{\rm s,tot} t_{\rm esc}}{2\pi R_{\rm Gal}^2 H_{\rm CR} \ln(E_{p,\rm max}/E_{p,\rm min})}$$
$$\approx 2\times 10^3 \left(\frac{f_{\rm pul}\eta_p L_{\rm s,tot}}{10^{39}\ {\rm erg\ s^{-1}}}\right)\left(\frac{E_p}{10\,{\rm PeV}}\right)^{-1/3}$$
$$\times \left(\frac{H_{\rm CR}}{4\,{\rm kpc}}\right)\left(\frac{R_{\rm Gal}}{15\,{\rm kpc}}\right)^{-2}\ {\rm eV\ cm^{-2}s^{-1}sr^{-1}}$$



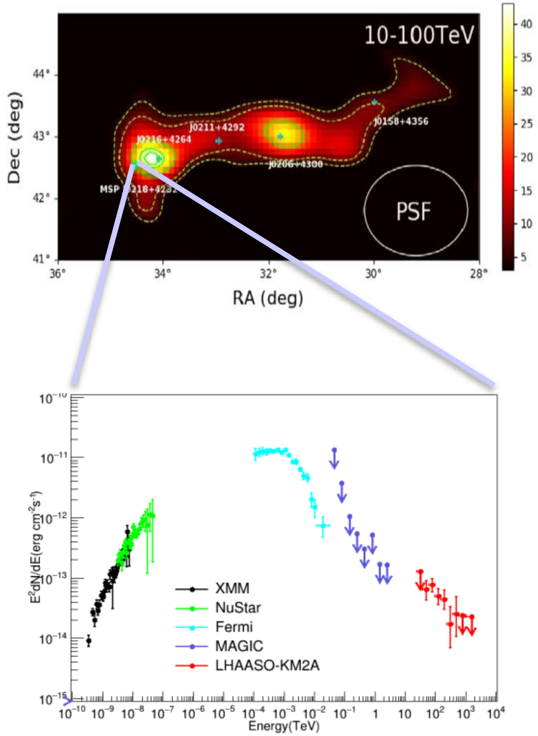
KASCADE-Grande Collaboration 2014

Highlight Talks in PWN/Pulsar Halos by LHAASO

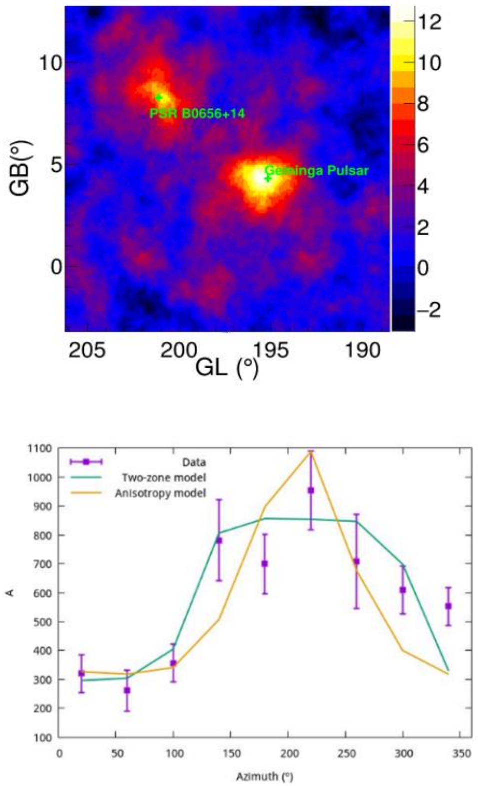
Renfeng Xu's talk



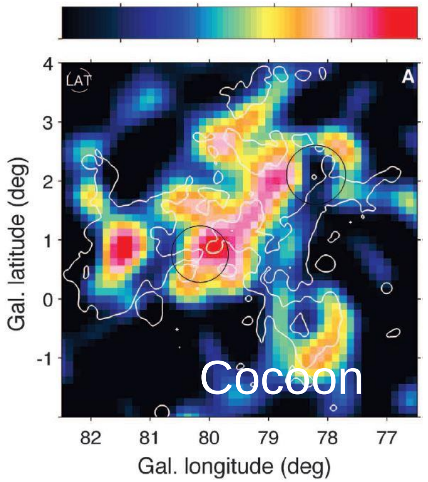
Dr. Zhe Li's talk

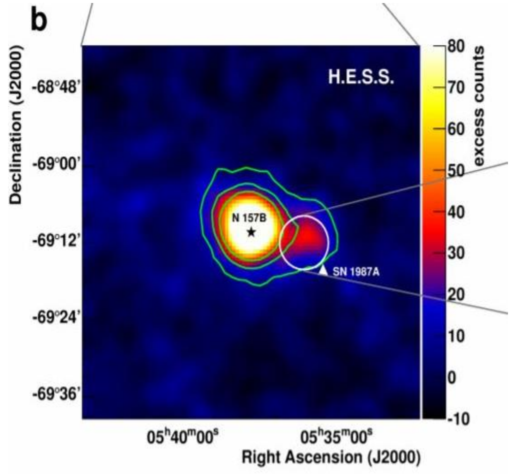


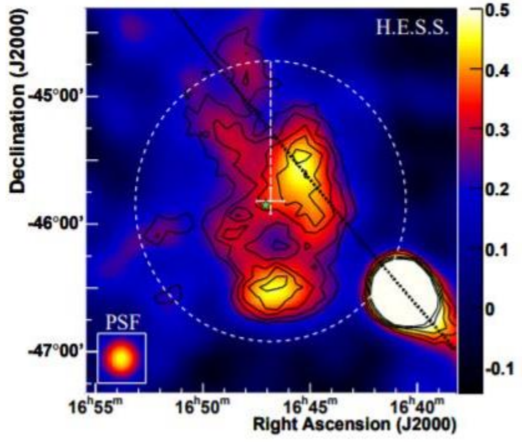
Dr. Yingying Guo's talk



Gamma-ray emitting YMSC





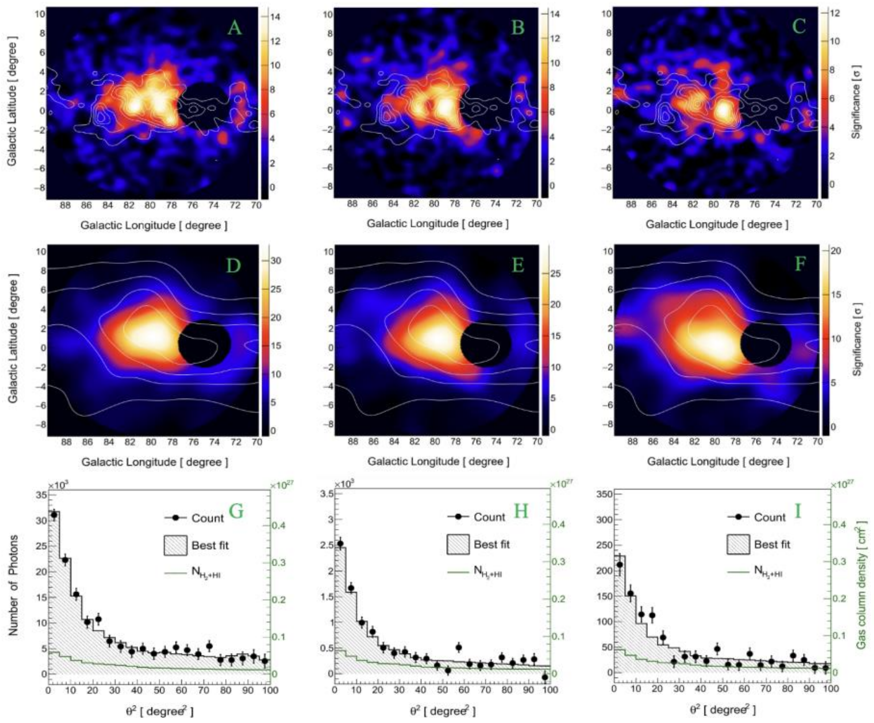


New GAMMA-RAY Source population:

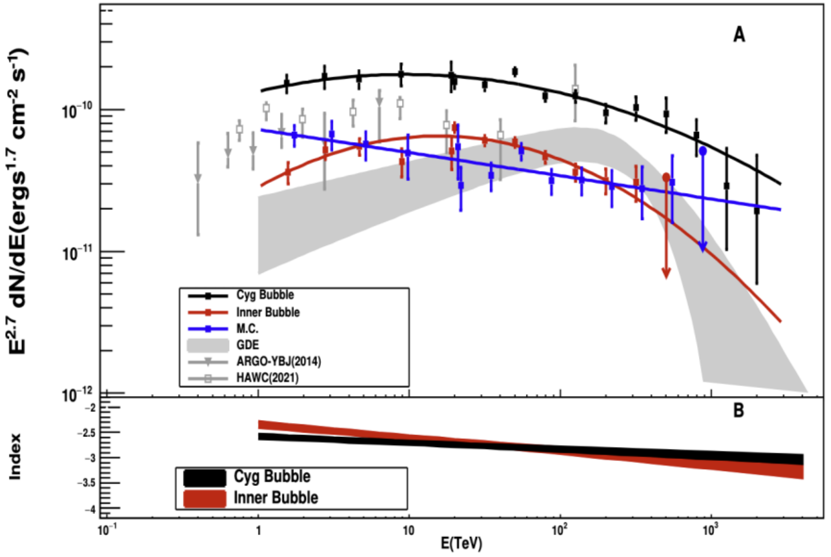
Cygnus Cocoon(GeV-TeV)[Fermi 2012, HAWC2022]

Westerlund 1 (TeV) [HESS collaboration

LHAASO VIEW ON CYGNUS

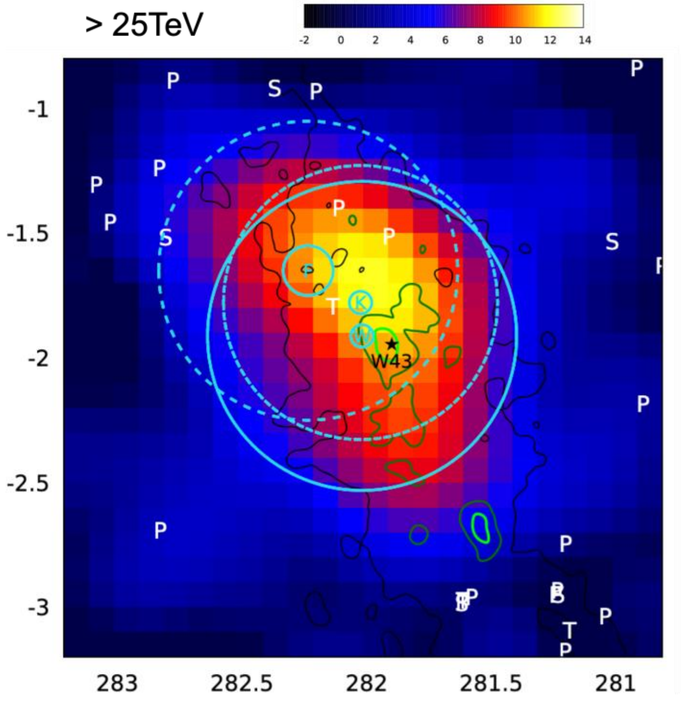


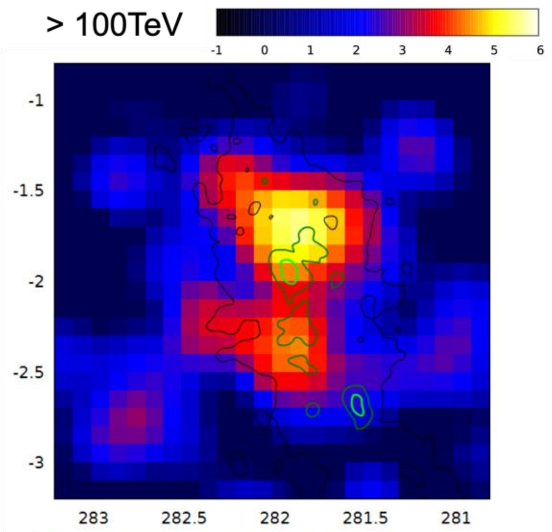
Huge bubble beyond ~10 degrees (200 pc)

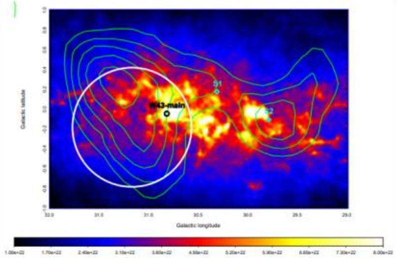


Curved and uniform spectral shape
inner bubble: r~3 degrees, similar to "cocoon"
cygnus bubble: r~10 degrees

LHAASO view on w43







- UHE gamma-ray emission reveal good correlation with dense gas
- Spectrum up to PeV