Acceleration of Galactic Cosmic Rays

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Southwest Jiaotong University

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LHAASO
高海拔宇宙线观测站

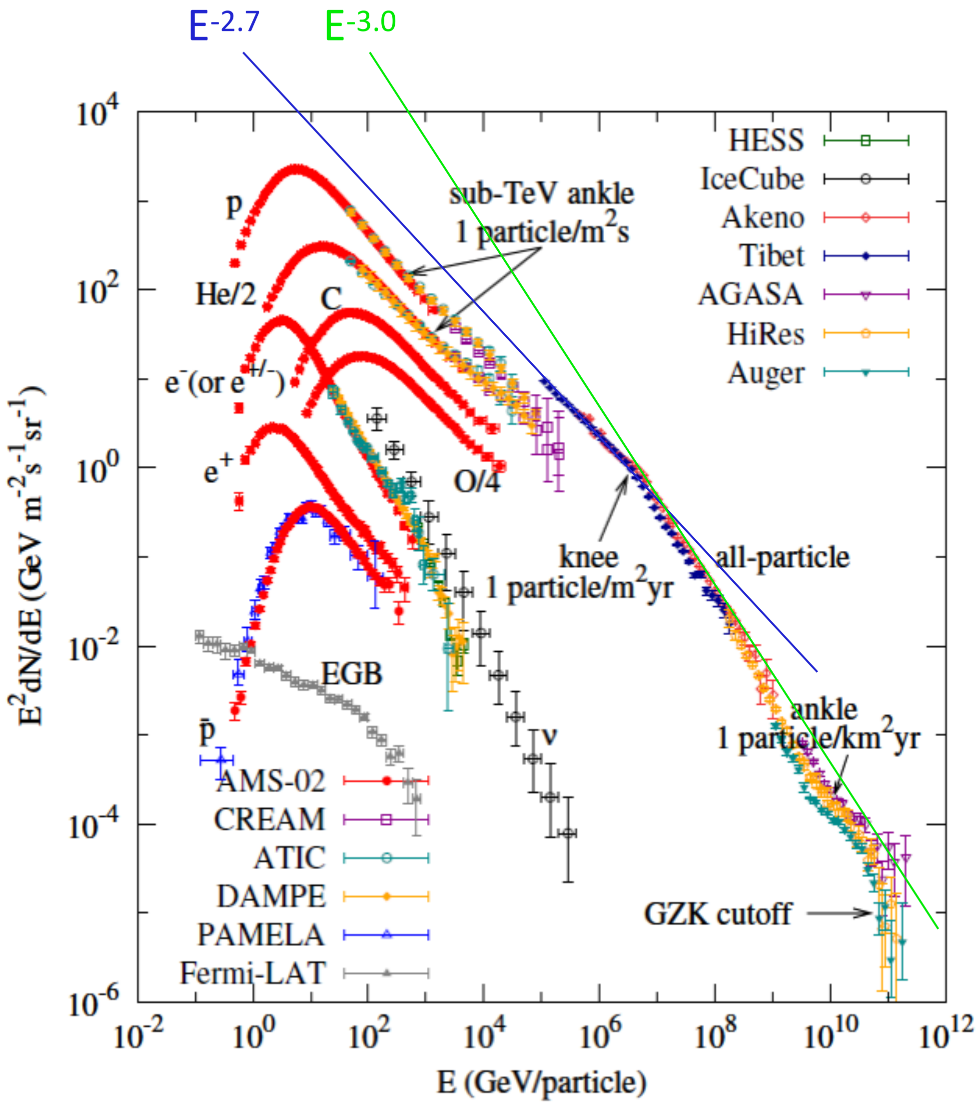
The Second LHAASO Symposium, HK,
March 21-25 2025

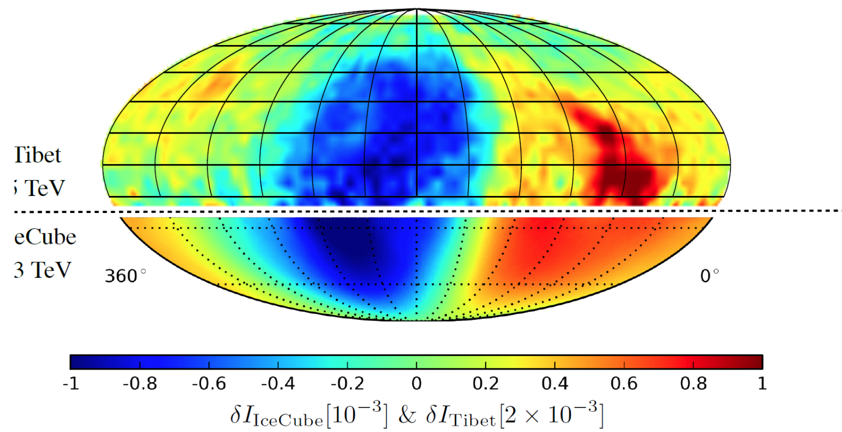
西南交通大學
Southwest Jiaotong University

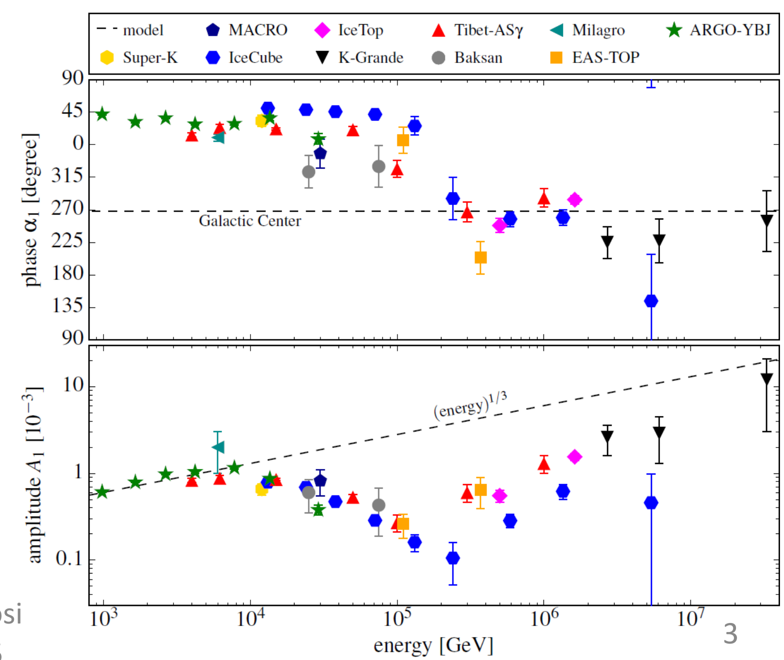
Outline

1. Shocks of Supernova Remnants (SNRs)
2. Some Extreme Acceleration Processes
3. Evidence for Extreme Acceleration of PeV Cosmic Rays (CRs) from LHAASO
4. Conclusions

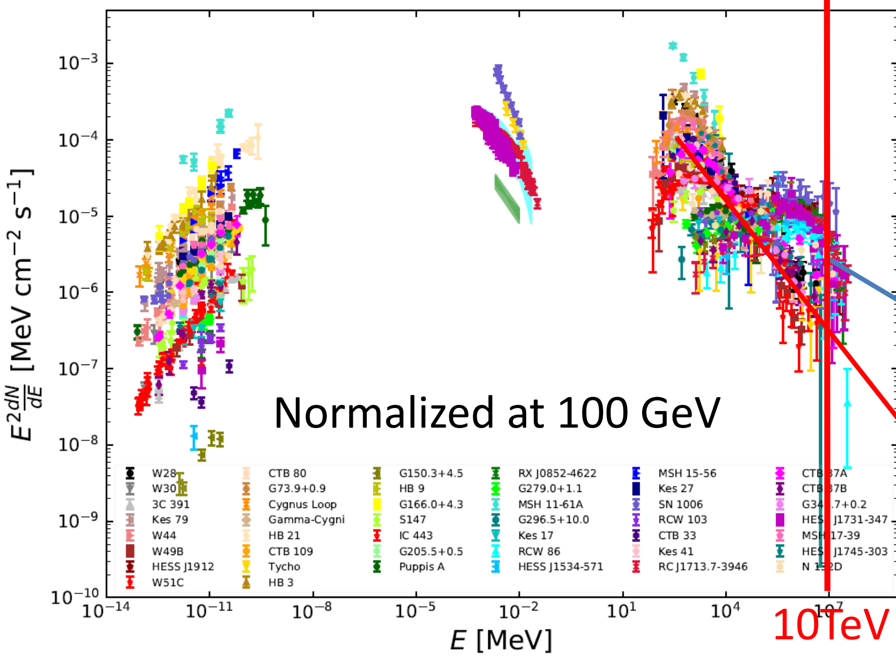
1： Cosmic Ray Spectra and Anisotropy



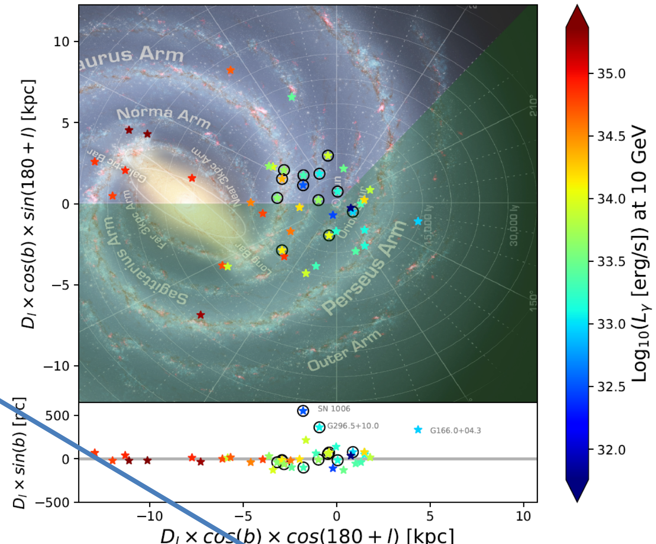


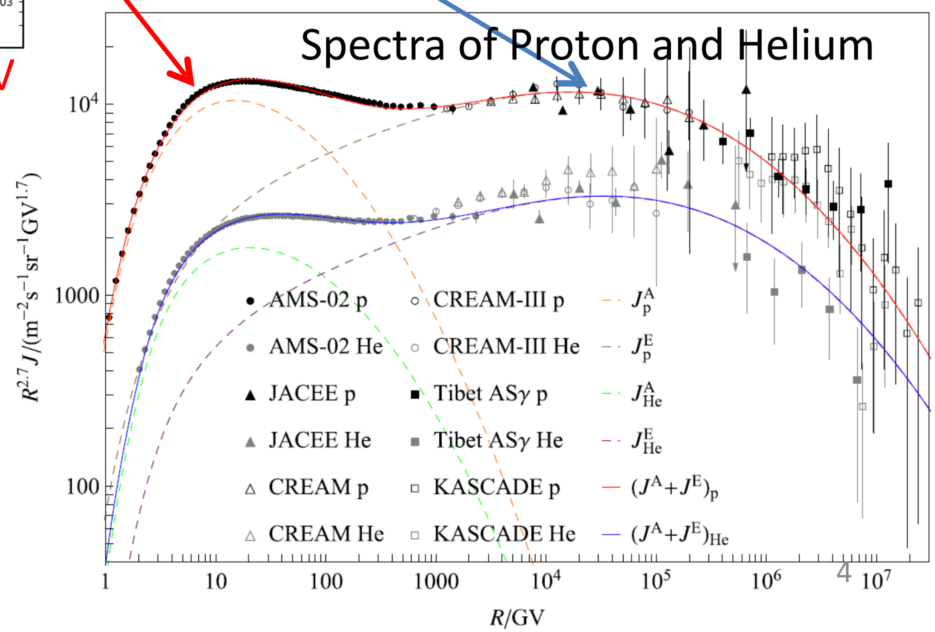


1: Origin of Cosmic Rays



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





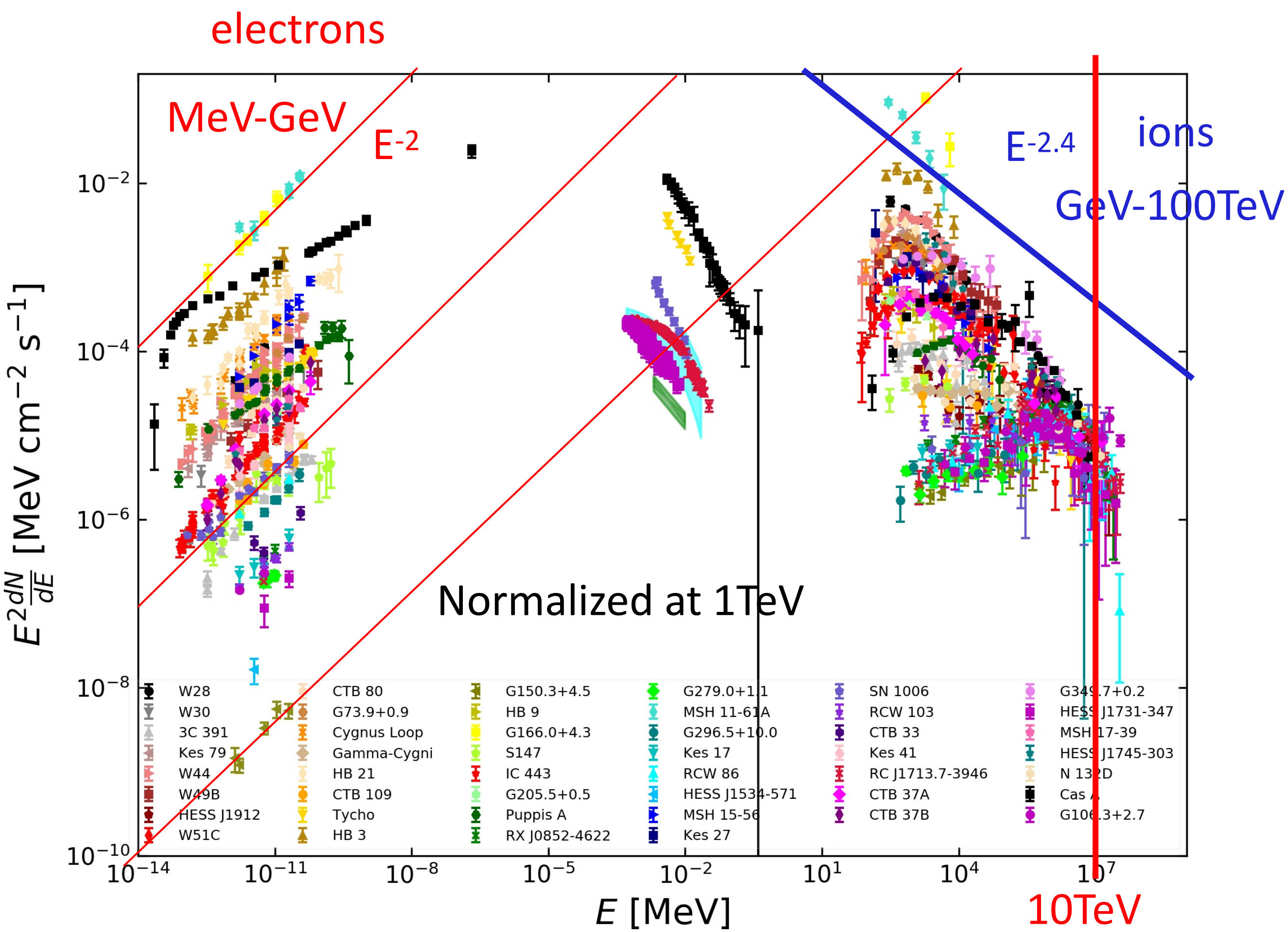
Reviews of Modern Plasma Physics (2022) 6:19
https://doi.org/10.1007/s41614-022-00080-6

REVIEW PAPER

The origin of galactic cosmic rays

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

1：Spectra of 46 SNRs before LHAASO



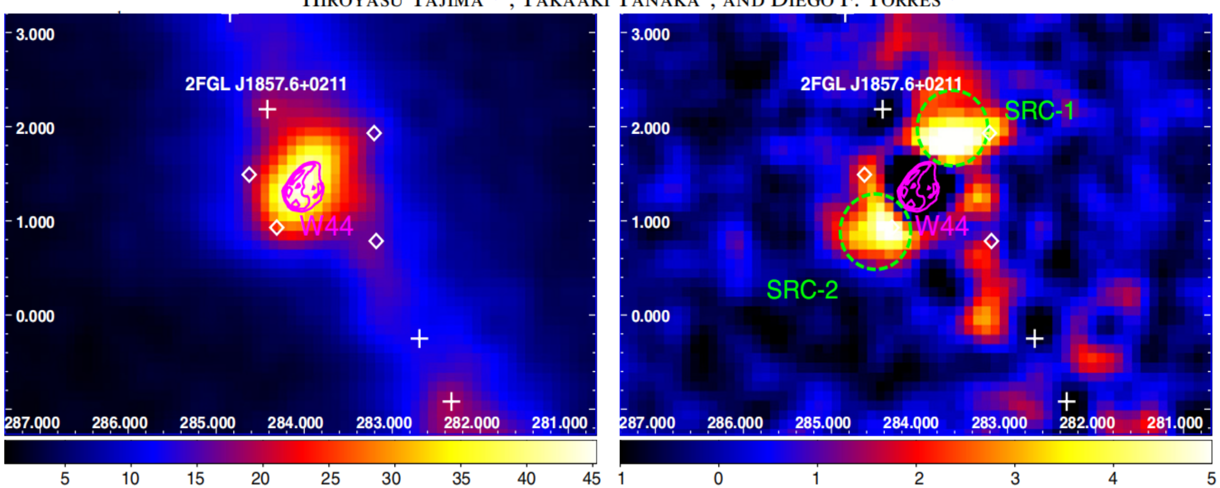
Multiwavelength spectra of 46 SNRs normalized at 1 TeV

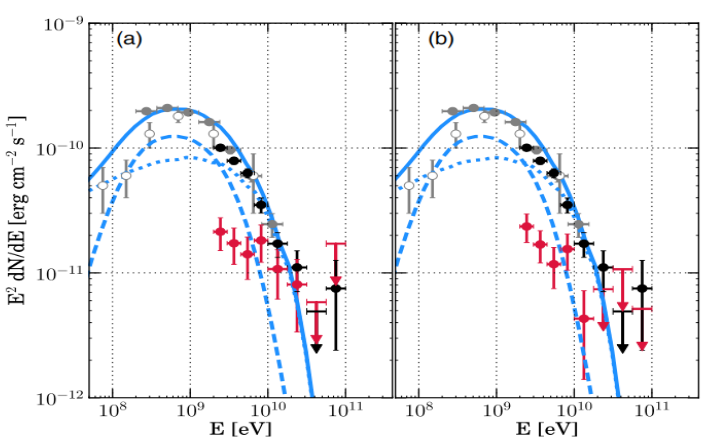
1: Evidence for CRs escaping from SNRs

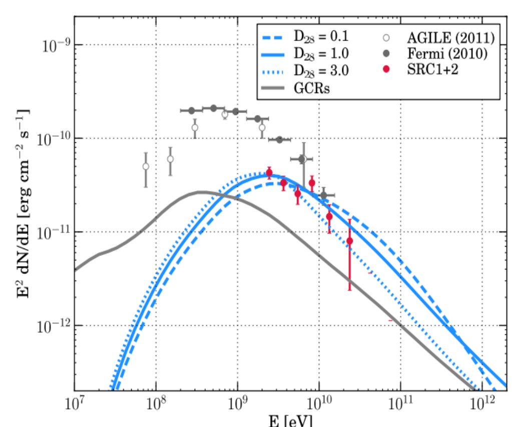
THE ASTROPHYSICAL JOURNAL LETTERS, 749:L35 (5pp), 2012 April 20 doi:10.1088/2041-8205/749/2/L35

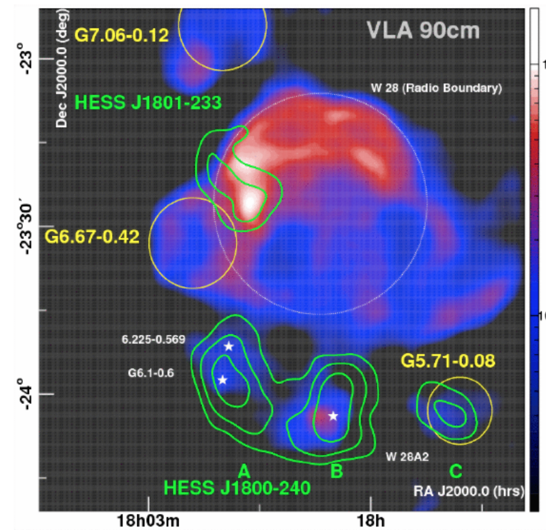
FERMI LARGE AREA TELESCOPE DISCOVERY OF GeV GAMMA-RAY EMISSION FROM THE VICINITY OF SNR W44

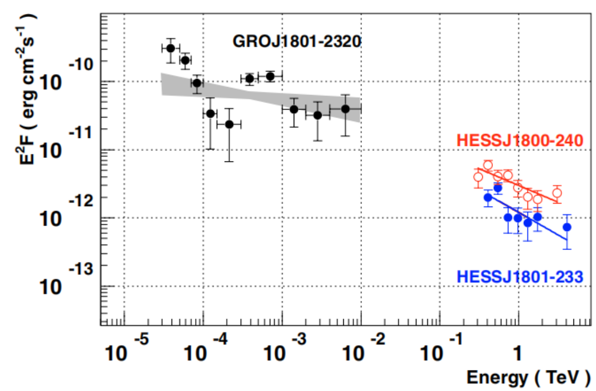
YASUNOBU UCHIYAMA[1,2,8], STEFAN FUNK[1,2], HIDEAKI KATAGIRI[3], JUNICHIRO KATSUTA[1], MARIANNE LEMOINE-GOUMARD[4], HIROYASU TAJIMA[2,5], TAKAAKI TANAKA[2], AND DIEGO F. TORRES[6,7]











A&A 481, 401–410 (2008)
DOI: 10.1051/0004-6361:20077765

Astronomy & Astrophysics

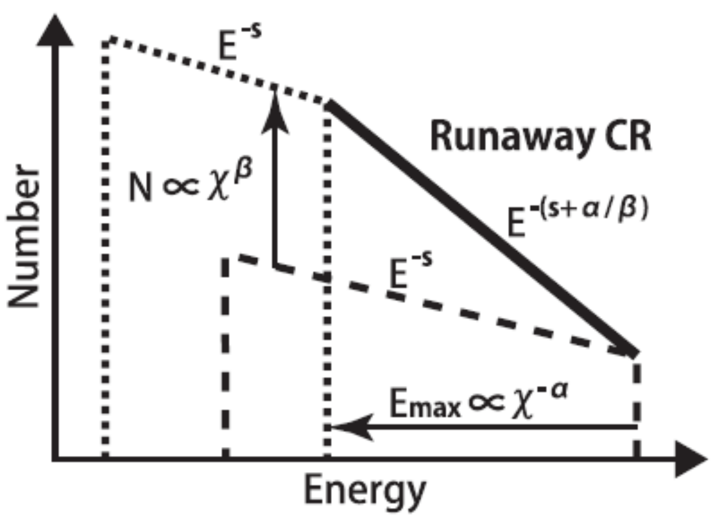
Discovery of very high energy gamma-ray emission coincident with molecular clouds in the W 28 (G6.4–0.1) field★

1： Diffusive Shock Acceleration in SNRs

T: Age
U: shock speed
R: Radius ~ UT
D: Diffusion coefficient ~E^{δ}

Acceleration time： ~D/U^2
Escape time: ~R^2/D

$D/U^2 \leq R^2/D$ then $D \leq UR$ ~T(free expansion)
~$T^{-1/5}$ (Sedov)



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
Mon. Not. R. Astron. Soc. **427,** 91–102 (2012) doi:10.1111/j.1365-2966.2012.21908.x

Escape of cosmic-ray electrons from supernova remnants

Yutaka Ohira,[1★] Ryo Yamazaki,[1] Norita Kawanaka[2] and Kunihito Ioka[3,4]

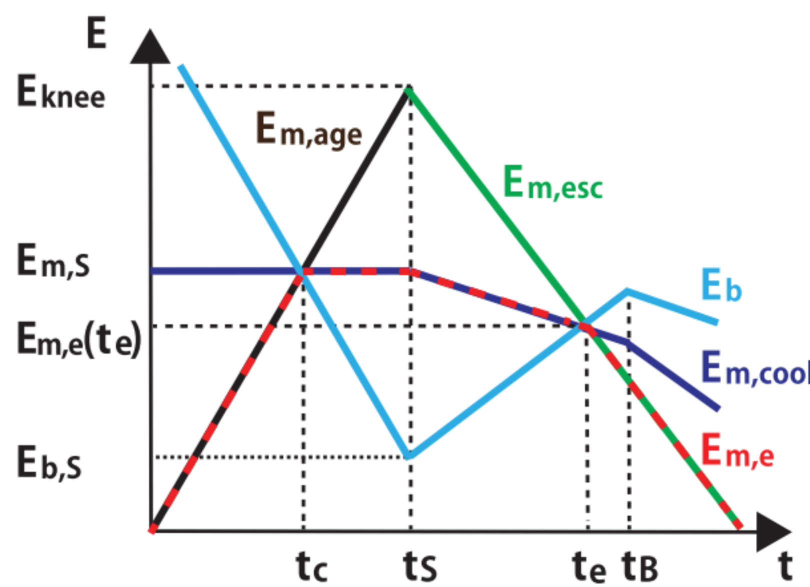
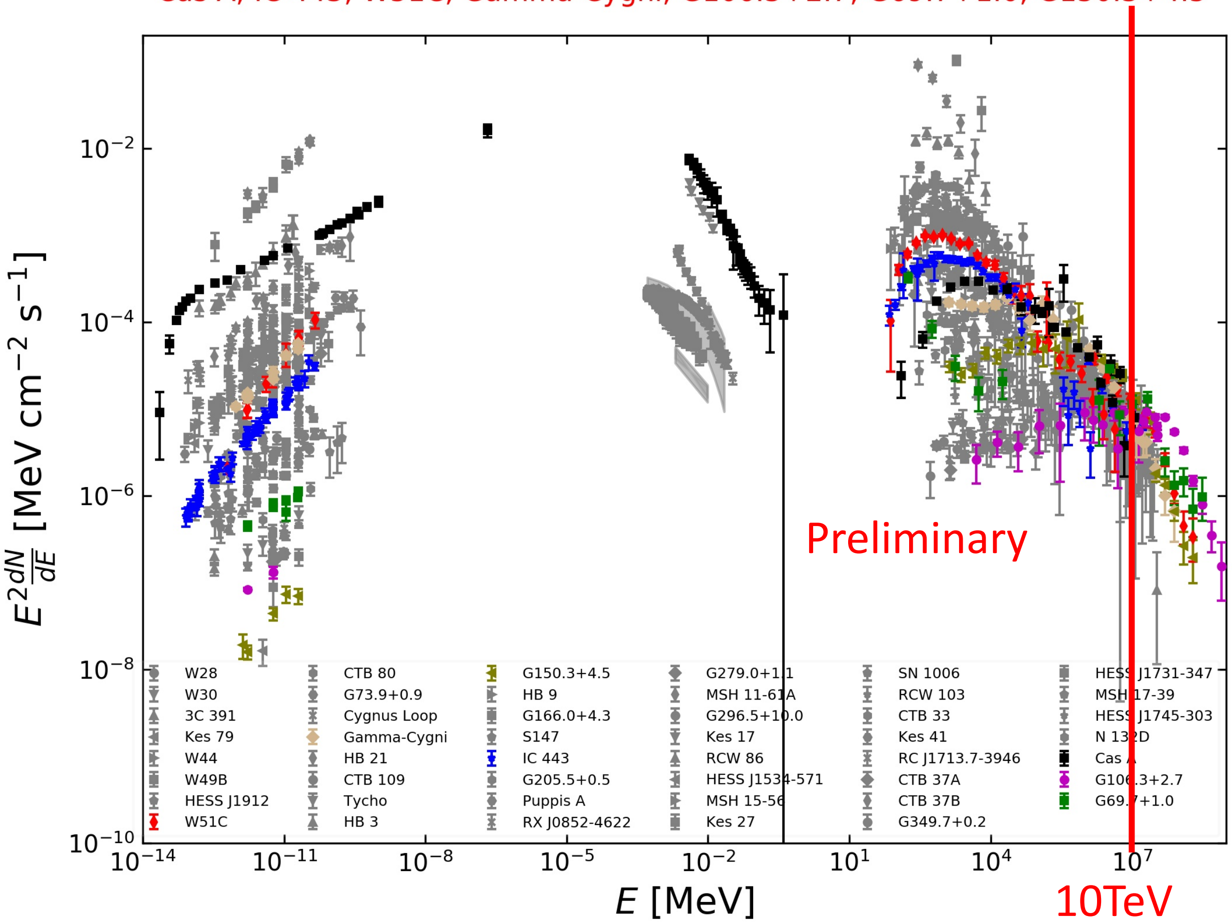


Figure 2. The same as Fig. 1, but for $B^2 \propto u_{sh}^2$ or u_{sh}^3.

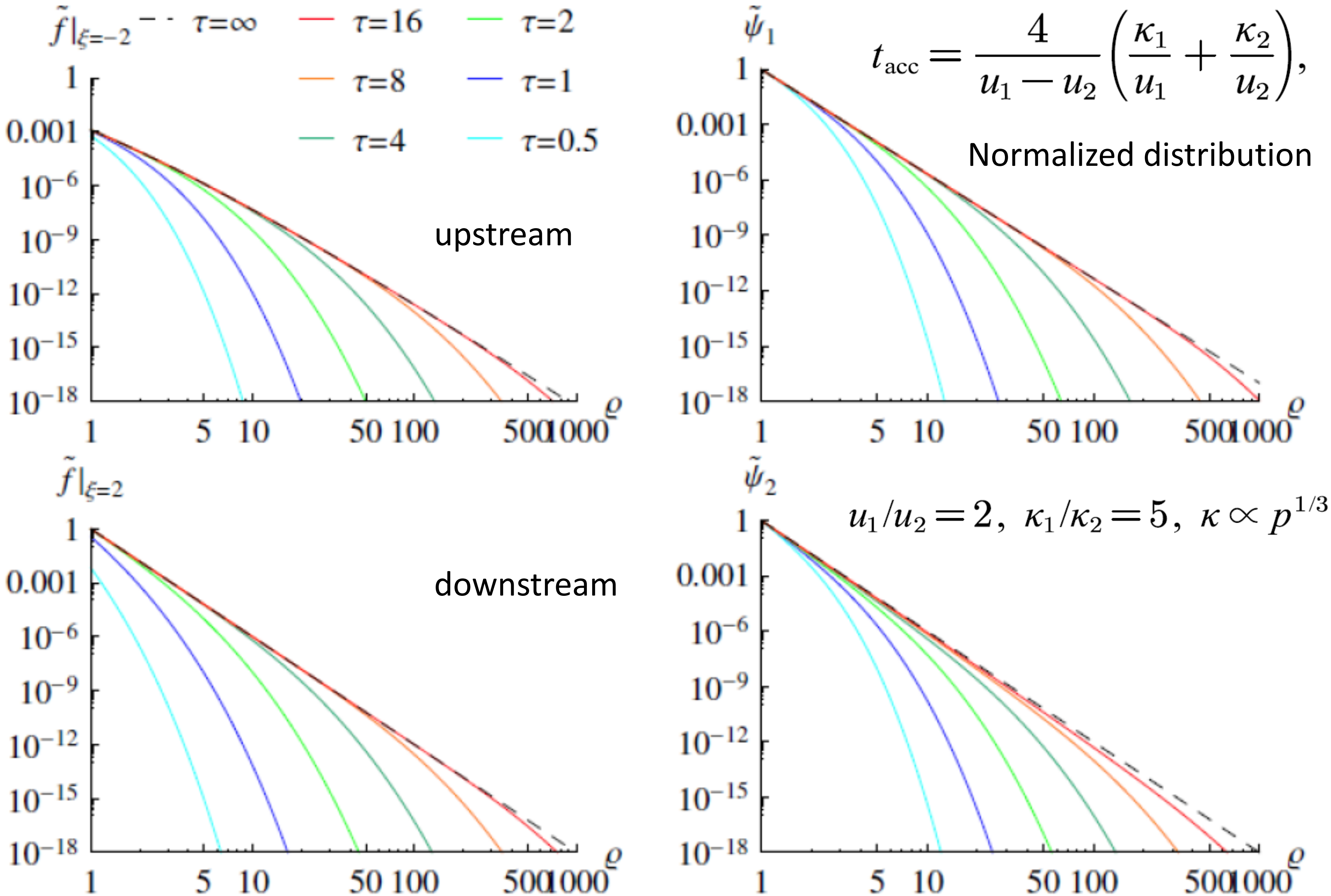
1: 7 SNRs Detected by LHAASO

Cas A; IC 443; W51C; Gamma-Cygni; G106.3+2.7; G69.7+1.0; G150.3+4.5



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

1: An example of time-dependent DSA

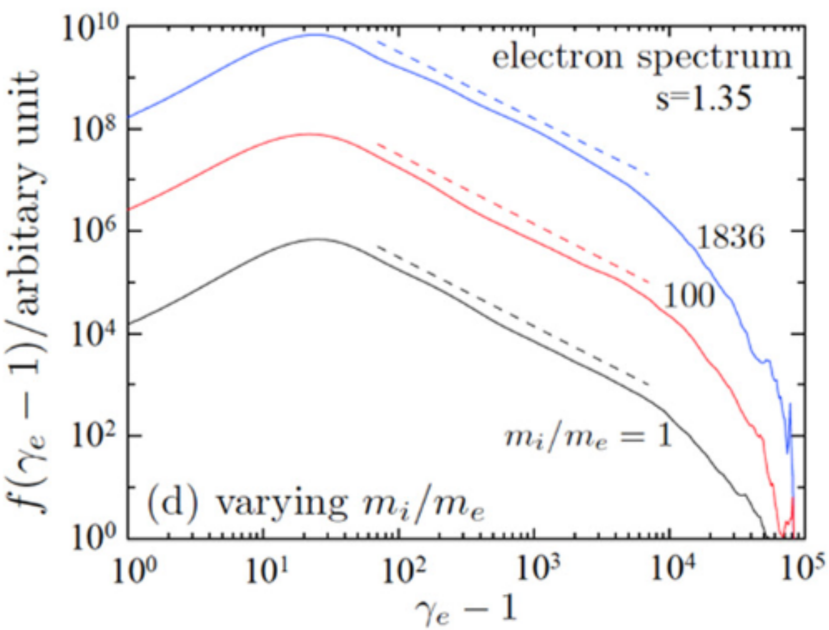


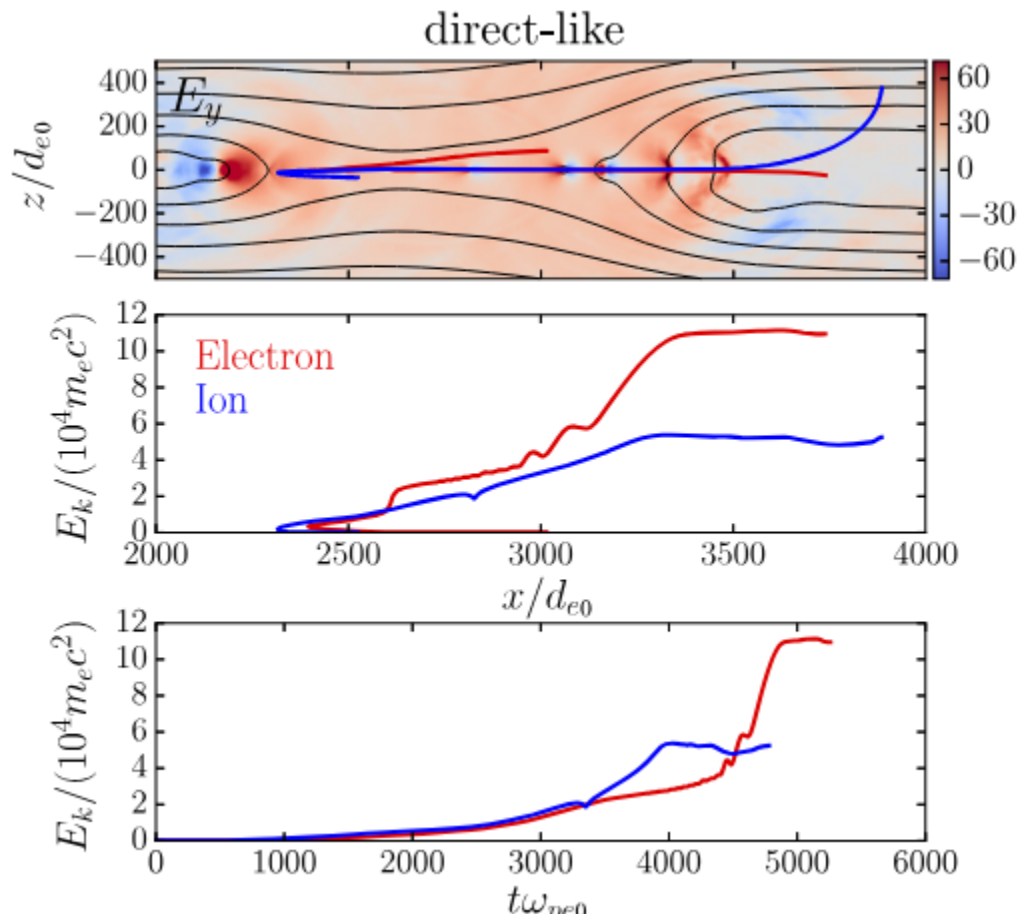
The Astrophysical Journal Letters, 818:L9 (7pp), 2016 February 10
doi:10.3847/2041-8205/818/1/L9

EFFICIENT PRODUCTION OF HIGH-ENERGY NONTHERMAL PARTICLES DURING MAGNETIC RECONNECTION IN A MAGNETICALLY DOMINATED ION-ELECTRON PLASMA

Fan Guo[1], Xiaocan Li[1,2], Hui Li[1], William Daughton[1], Bing Zhang[3], Nicole Lloyd-Ronning[1], Yi-Hsin Liu[4], Haocheng Zhang[1,5], and Wei Deng[1,3]
[1] Los Alamos National Laboratory, Los Alamos, NM 87545, USA; guofan.ustc@gmail.com

2: Acceleration by parallel electric field





2: Shock Drift Acceleration

THE ASTROPHYSICAL JOURNAL, 255:716–720, 1982 April 15

PARTICLE DRIFT, DIFFUSION, AND ACCELERATION AT SHOCKS

J. R. JOKIPII

郝宇飞，陆全明，高新亮等. 等离子体湍动对准垂直激波中粒子加速的影响. 地球物理学报，2013，56(7)： - ，doi:10.6038/cjg20130701.
Hao Y F, Lu Q M, Gao X L, et al. Particle acceleration at shock waves with composite turbulence. *Chinese J. Geophys.* (in Chinese), 2013, 56(7): - , doi:10.6038/cjg20130701.

等离子体湍动对准垂直激波中粒子加速的影响

郝宇飞，陆全明，高新亮，单立灿，王 水

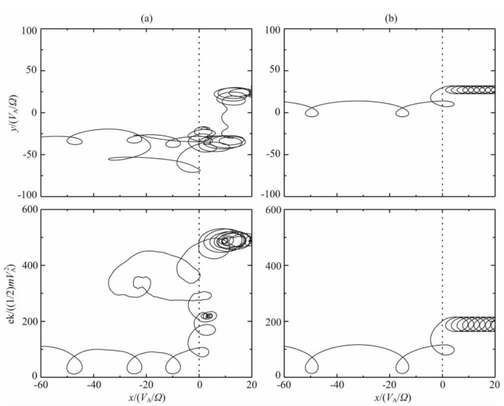
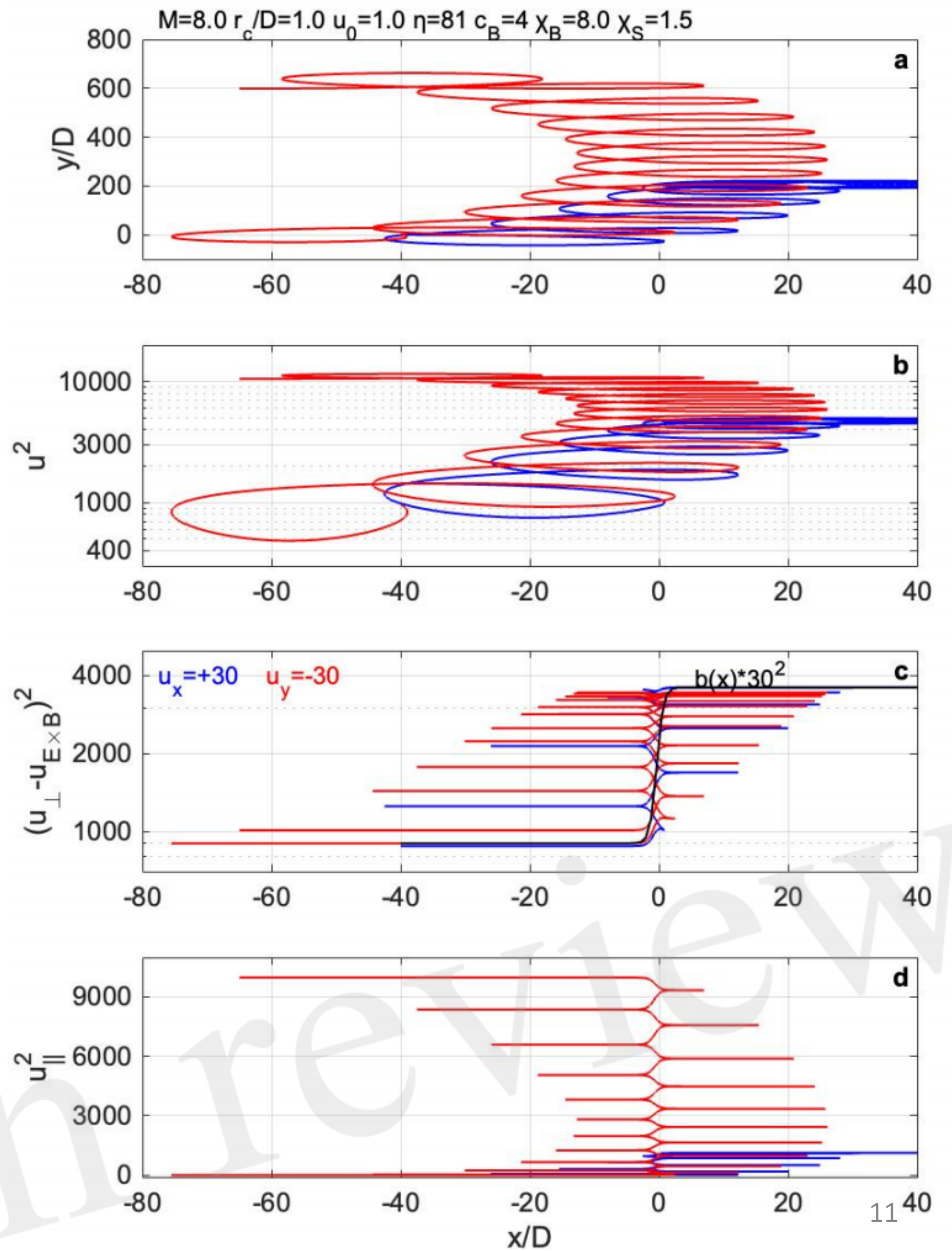


图 1 激波中加湍动与未加湍动的粒子轨迹和能量变化

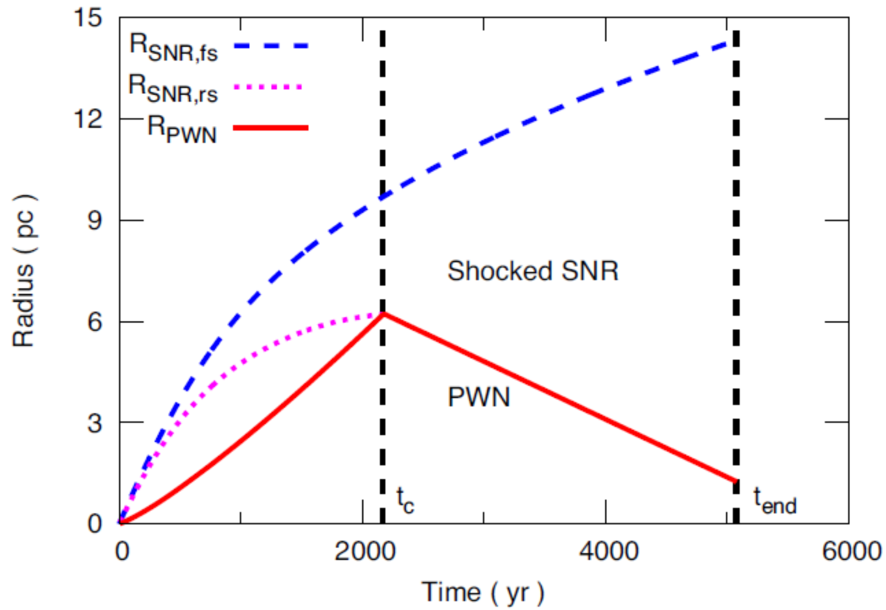


2: PeV Particle Acceleration in PWNS

MNRAS **478**, 926–931 (2018)
Advance Access publication 2018 May 5
doi:10.1093/mnras/sty1159

Pulsar Wind Nebulae inside Supernova Remnants as Cosmic-Ray PeVatrons

Yutaka Ohira,[1,2]★ Shota Kisaka[2] and Ryo Yamazaki[2]



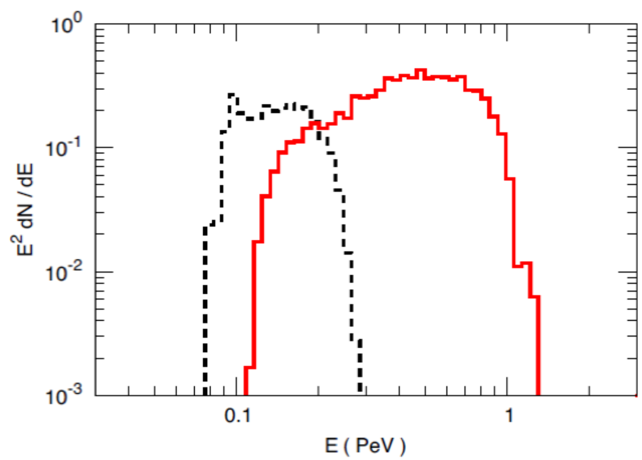
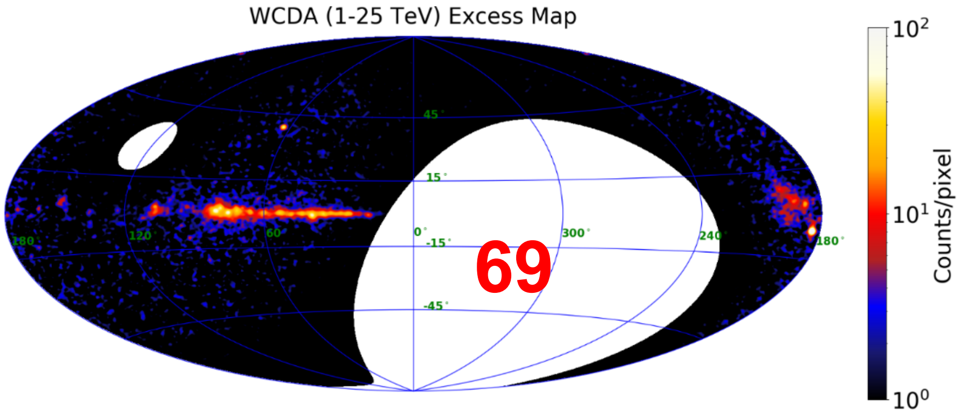
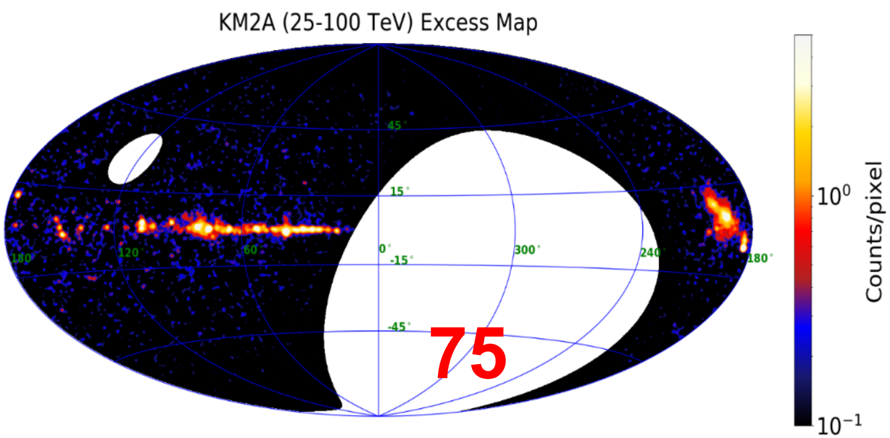


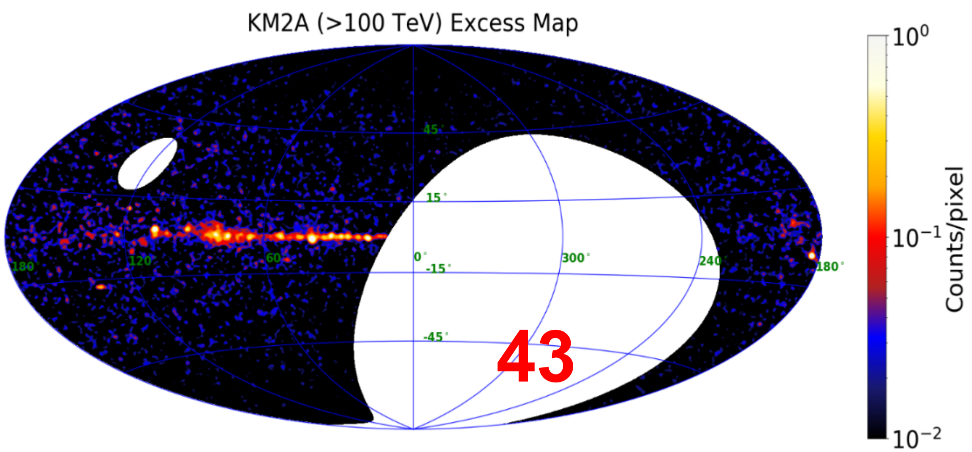
Figure 2. Energy spectra of reaccelerated particles for Model A. The black-dashed and the red solid histograms are energy spectra at $t = t_c$ and t_{end}, respectively. The initial energy is 0.1 PeV.

3：LHAASO catalog

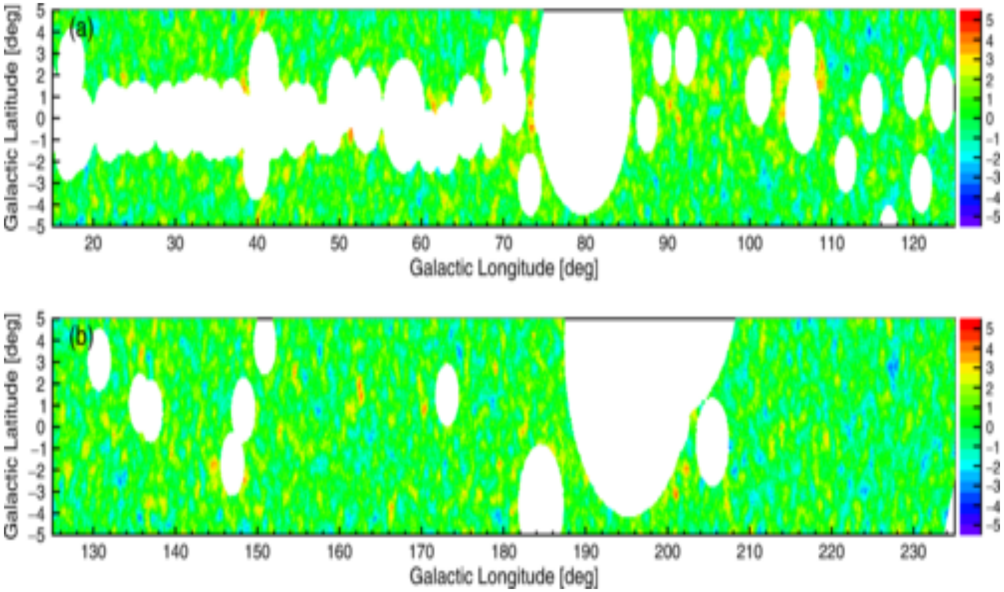
- **90 in 1st LHAASO sources.**
- **32 new discoveries**
- **43 UHE**







3：Diffuse Gamma-ray Emission with KM2A



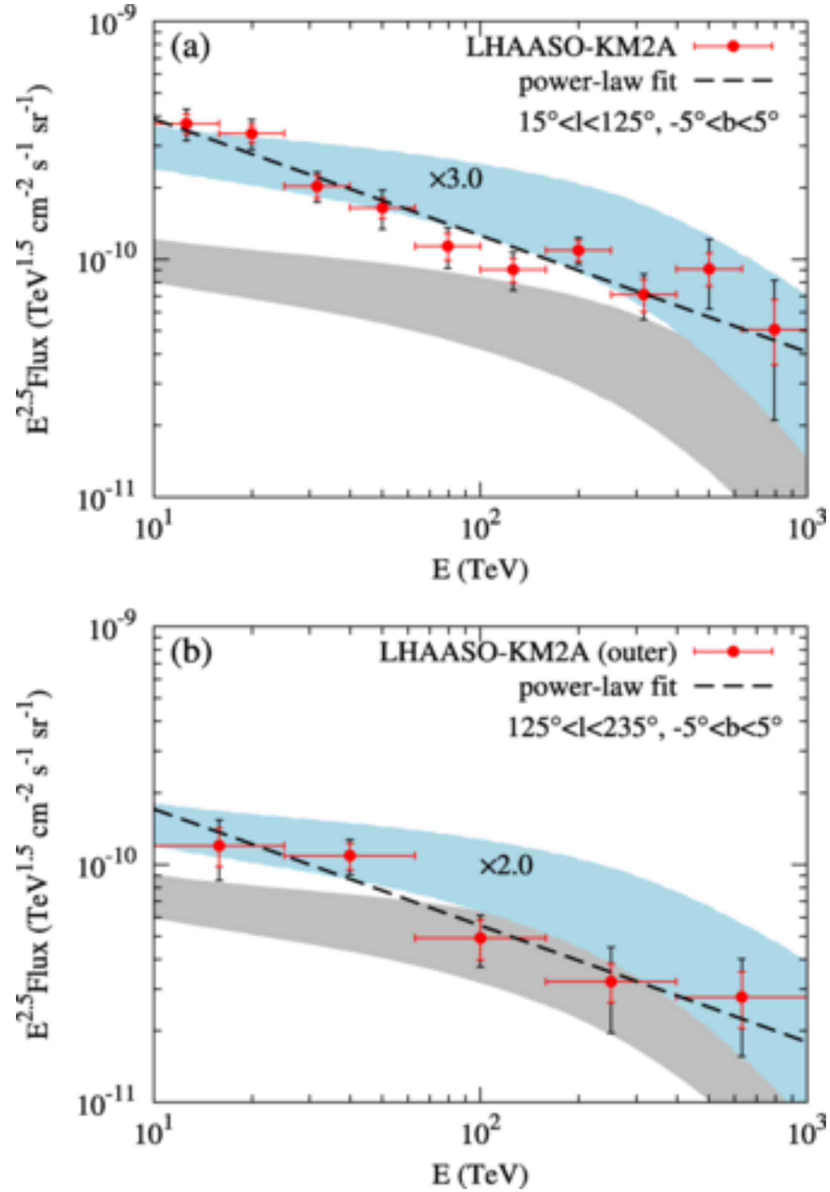


TABLE I. Fitting parameters of the LHAASO-KM2A diffuse spectra.

	ϕ_0 (10^{-14} TeV^{-1} cm^{-2} s^{-1} sr^{-1})	α
Inner Galaxy	$1.00 \pm 0.04_{stat} \pm 0.09_{sys}$	$-2.99 \pm 0.04_{stat} \pm 0.07_{sys}$
Outer Galaxy	$0.44 \pm 0.04_{stat} \pm 0.05_{sys}$	$-2.99 \pm 0.07_{stat} \pm 0.12_{sys}$

3：Diffuse Gamma-ray Emission with WCDA

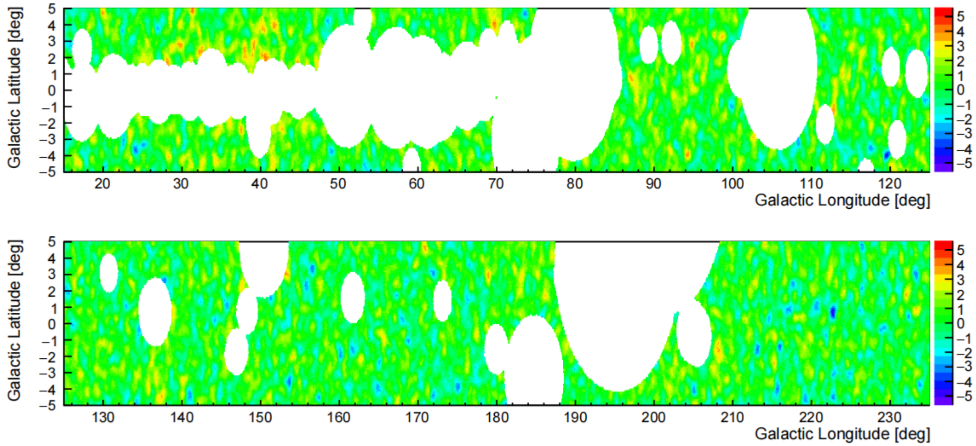
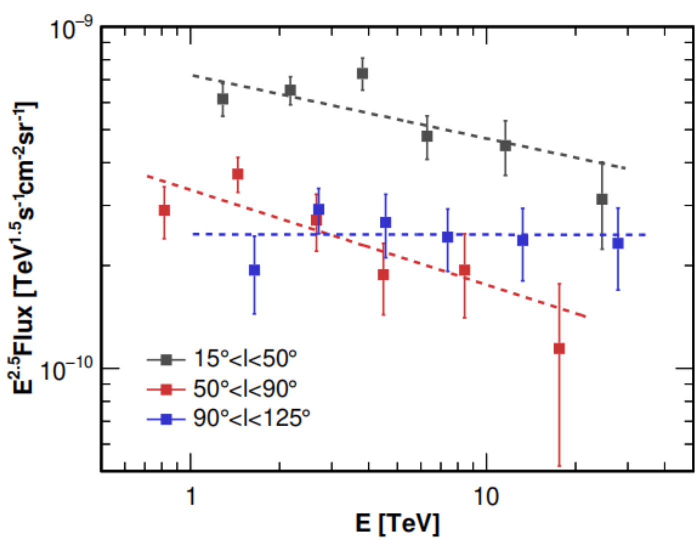
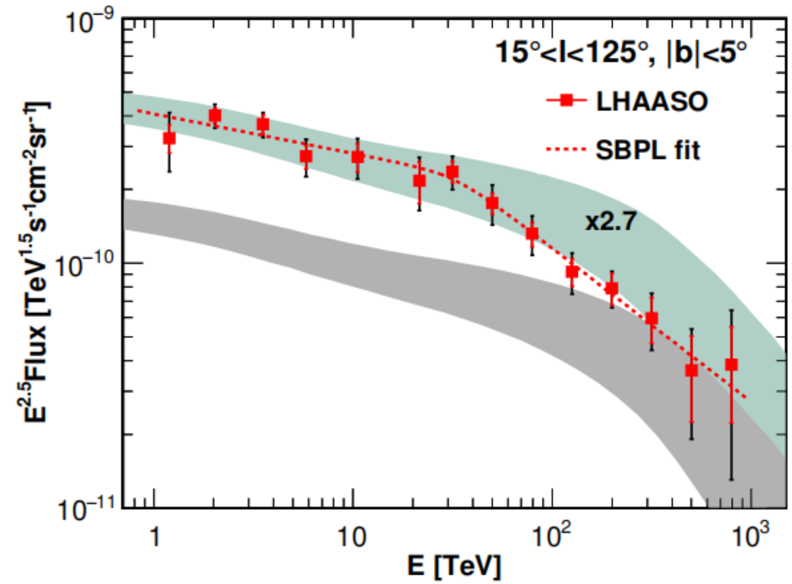
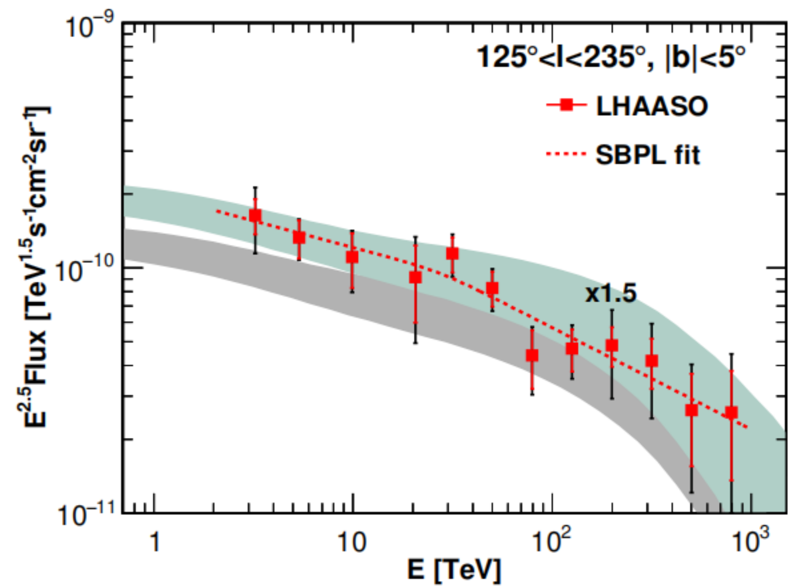


TABLE I. SBPL fitting parameters of the wide-band diffuse emission measured by WCDA and KM2A.

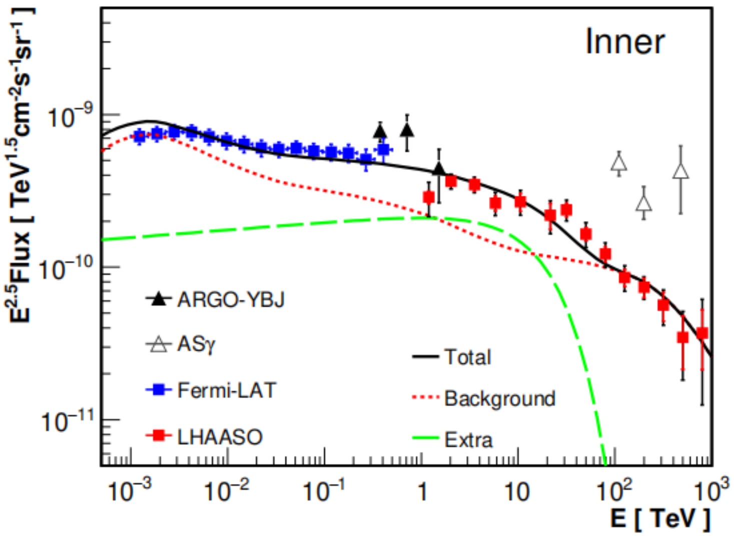
Region	ϕ_0 at 10 TeV (10^{-13} TeV^{-1} cm^{-2} s^{-1} sr^{-1})	α	β	E_{br} (TeV)
$15° < l < 125°$ (inner)	$8.88 \pm 0.53_{stat}$	$-2.66 \pm 0.05_{stat}$	$-3.13 \pm 0.08_{stat}$	$32.84 \pm 11.16_{stat}$
$125° < l < 235°$ (outer)	$3.84 \pm 0.37_{stat}$	$-2.72 \pm 0.10_{stat}$	$-2.92 \pm 0.10_{stat}$	$27.86 \pm 22.49_{stat}$

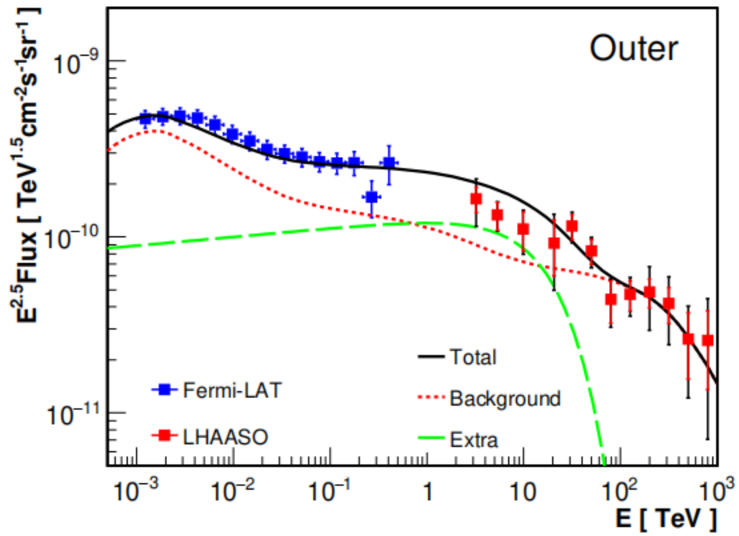






3: Possible explanation of the diffuse emission





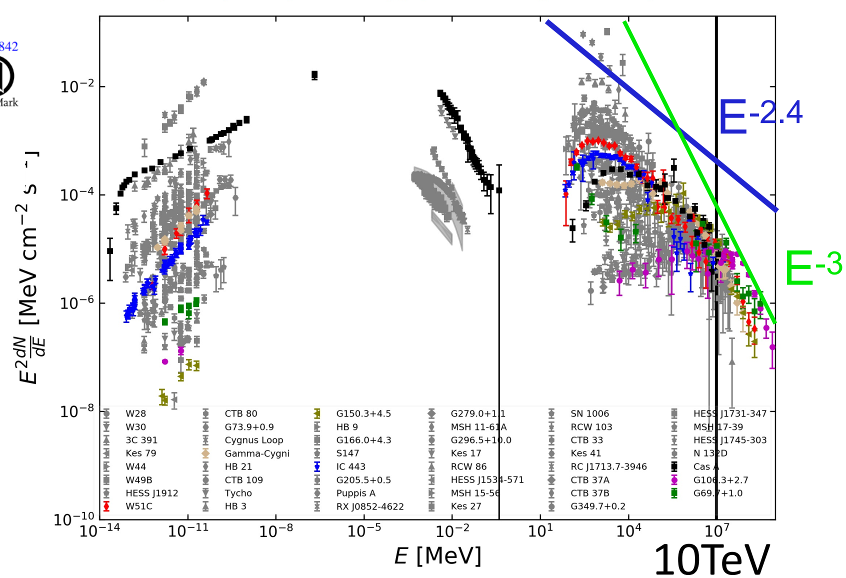
The Astrophysical Journal, 957:43 (10pp), 2023 November 1 https://doi.org/10.3847/1538-4357/acf842

Galactic Diffuse γ-Ray Emission from GeV to PeV Energies in Light of Up-to-date Cosmic-Ray Measurements

Rui Zhang[1,2], Xiaoyuan Huang[1,2], Zhi-Hui Xu[3], Shiping Zhao[1], and Qiang Yuan[1,2]

$$q_{\rm inj} = q_0 R^{-\nu_0} \exp\left(-\frac{R}{R_c}\right) \prod_{i=1}^{n} \left[1 + \left(\frac{R}{R_i}\right)^{\zeta}\right]^{\frac{\nu_{i-1}-\nu_i}{\zeta}}.$$

Cas A; IC 443; W51C; Gamma-Cygni; G106.3+2.7; G69.7+1.0; G150.3+4.5



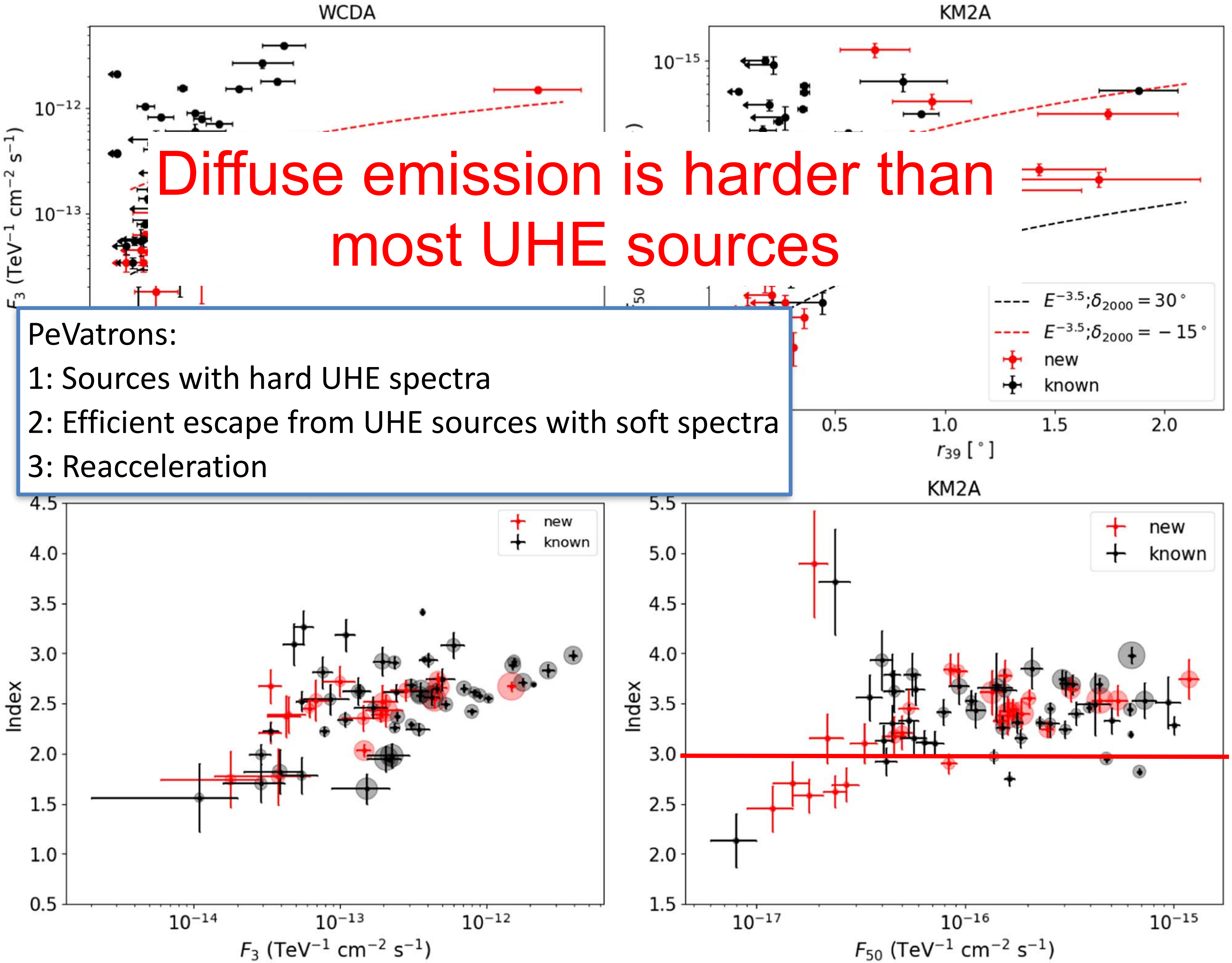
Diffuse emission is harder than most UHE sources

PeVatrons:

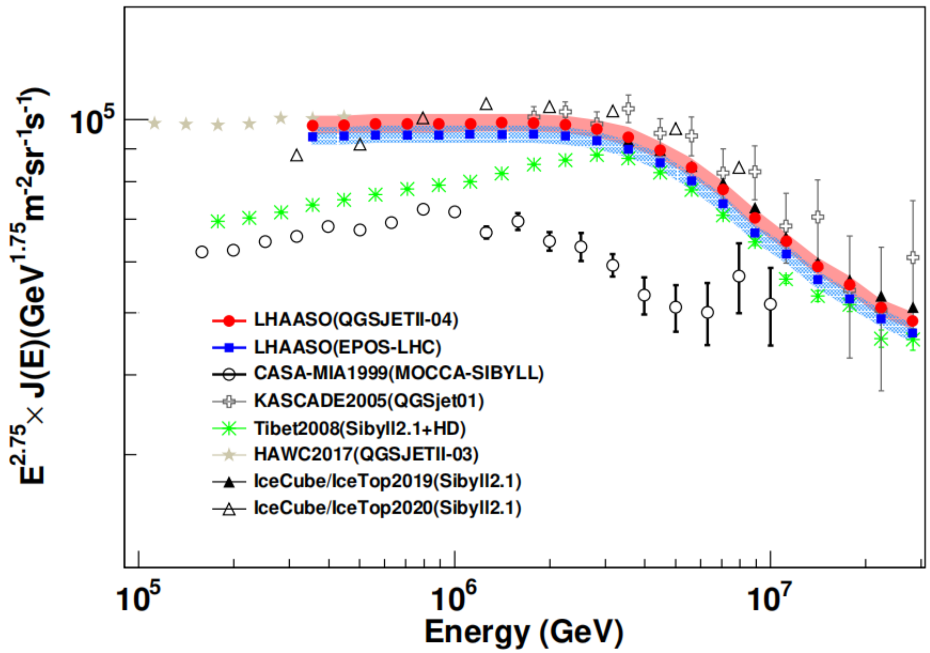
1: Sources with hard UHE spectra

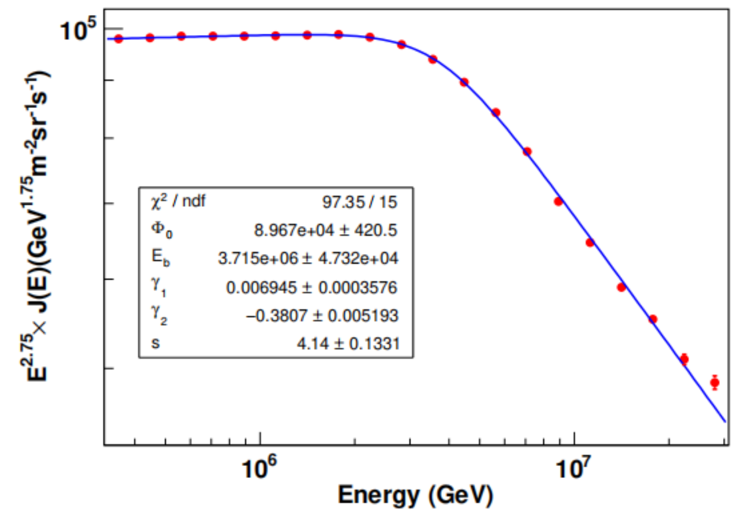
2: Efficient escape from UHE sources with soft spectra

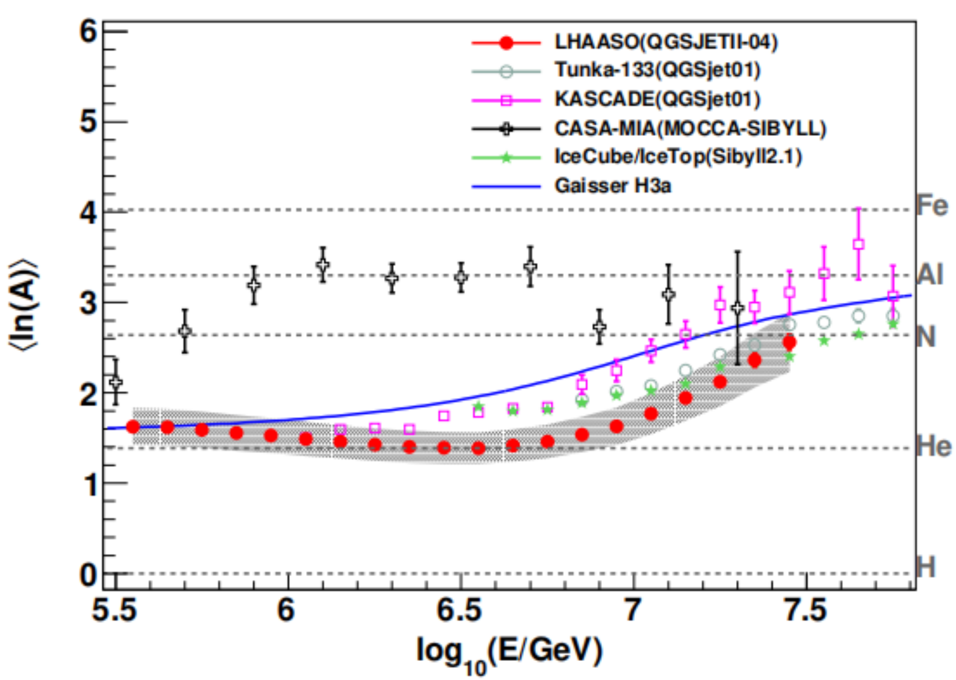
3: Reacceleration

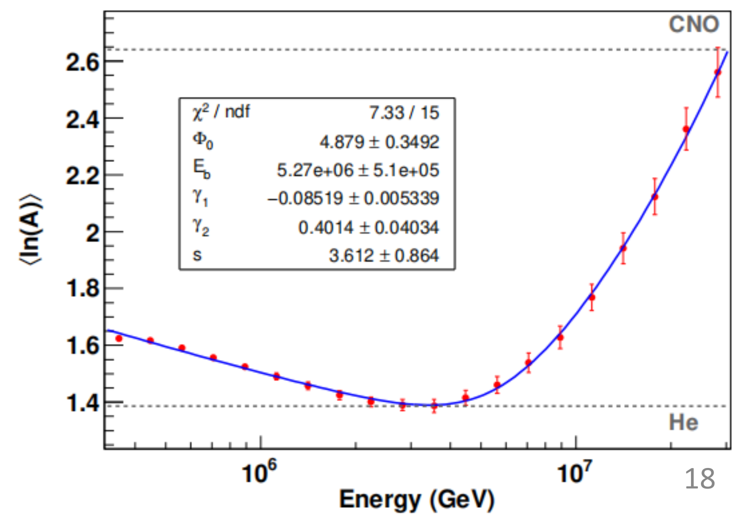


3：Cosmic Ray Spectrum and Mean Logarithmic Mass



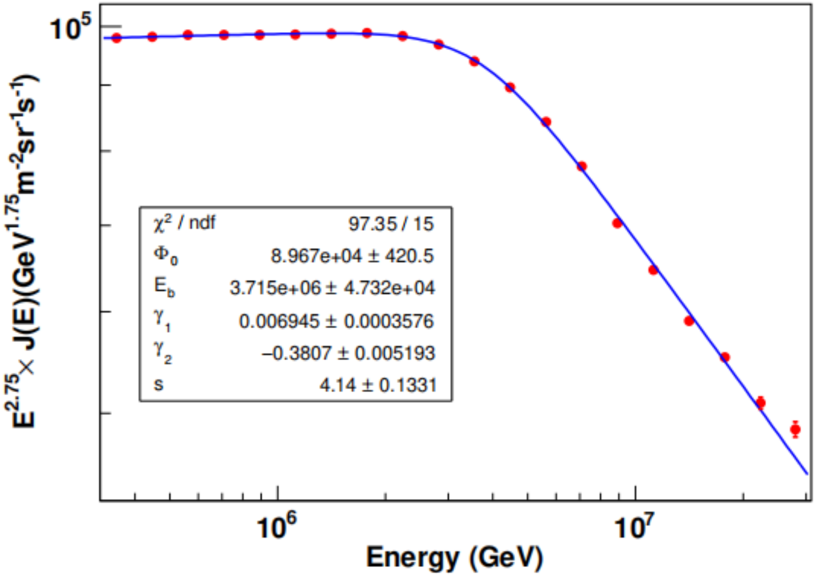


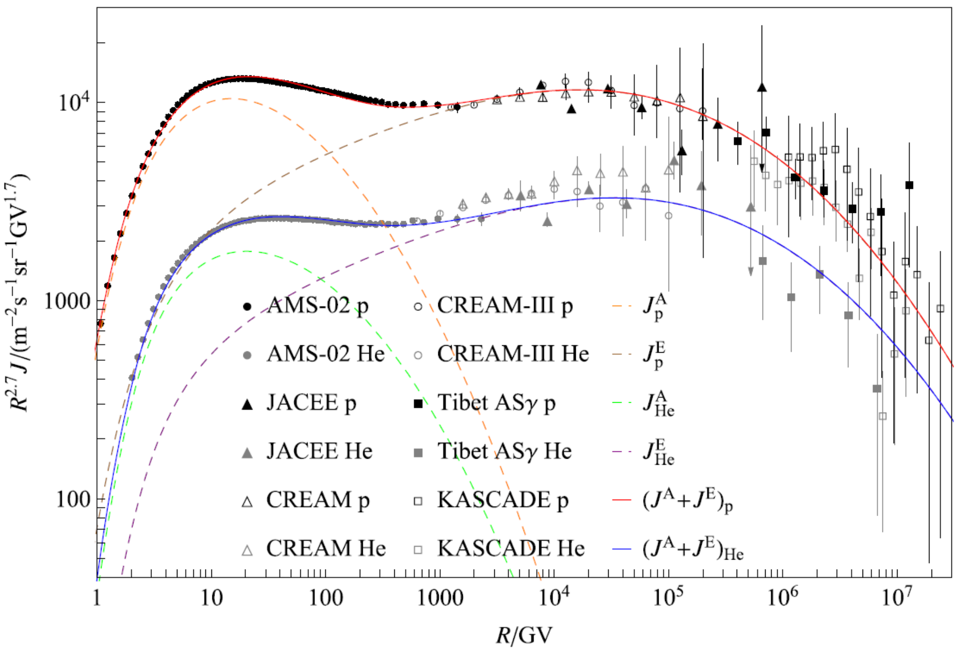


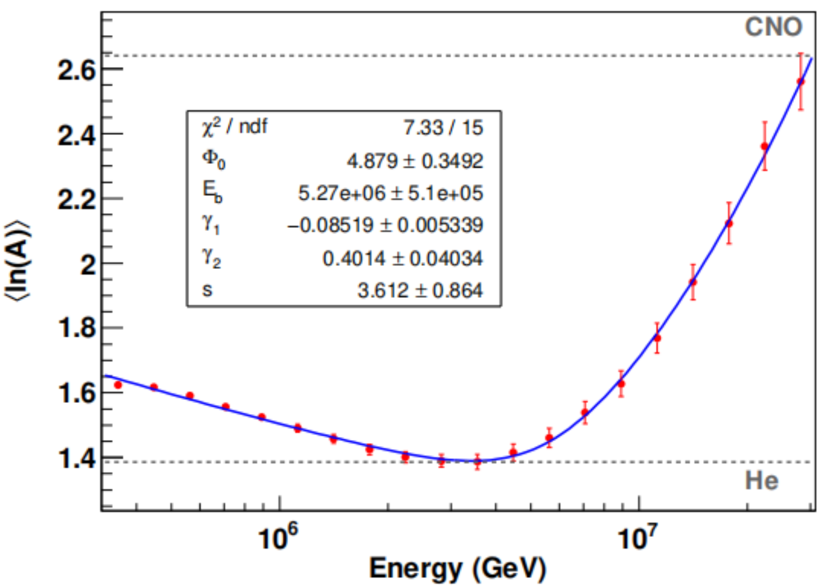


There appears to be three components:
GeV dominated by acceleration of slow shocks
TeV dominated by fast shocks
PeV shock drift acceleration?

PWNs, Young Massive Star Clusters, micro quasars?







Science Bulletin 69 (2024) 449–457

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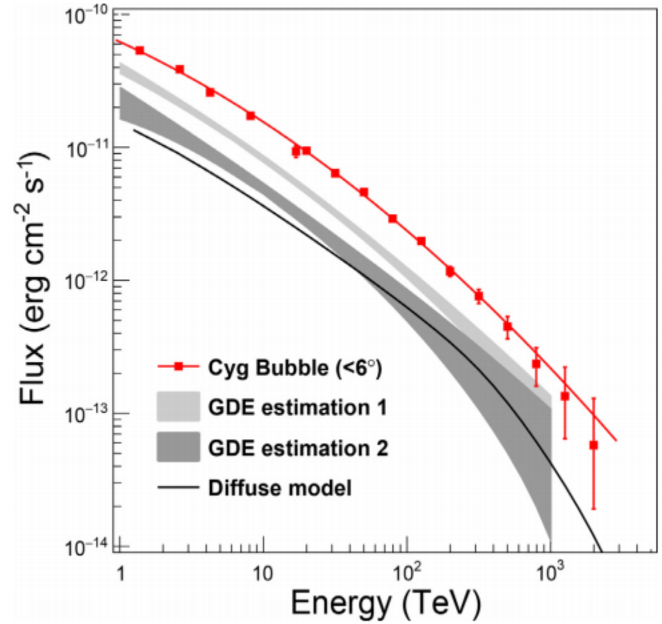
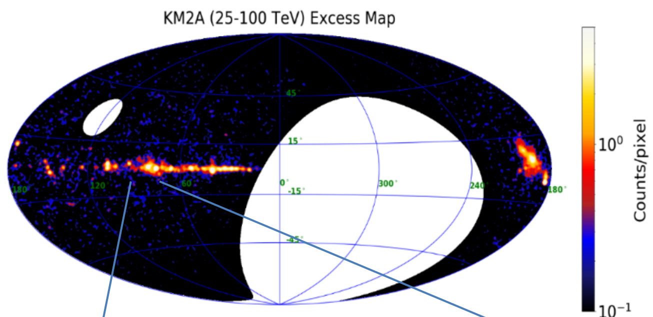
journal homepage: www.elsevier.com/locate/scib

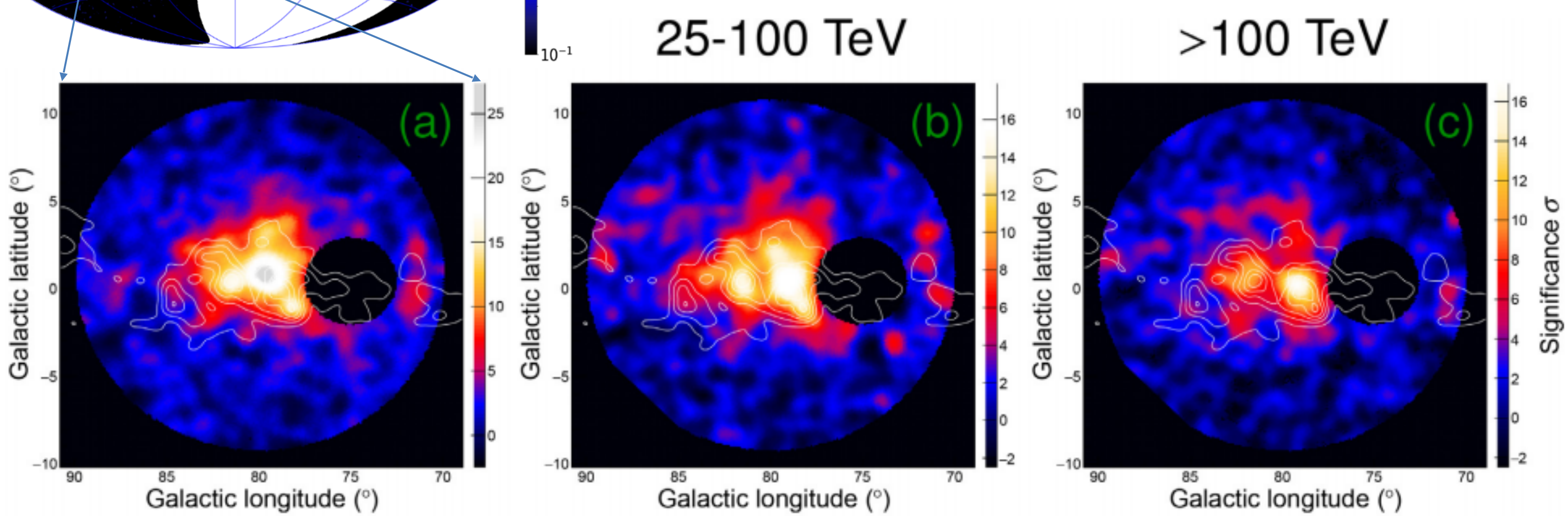
Article

An ultrahigh-energy γ-ray bubble powered by a super PeVatron

LHAASO Collaboration *,1







Conclusions

Extreme acceleration processes dominate the acceleration of the highest energy particles in galactic ultra-high-energy sources

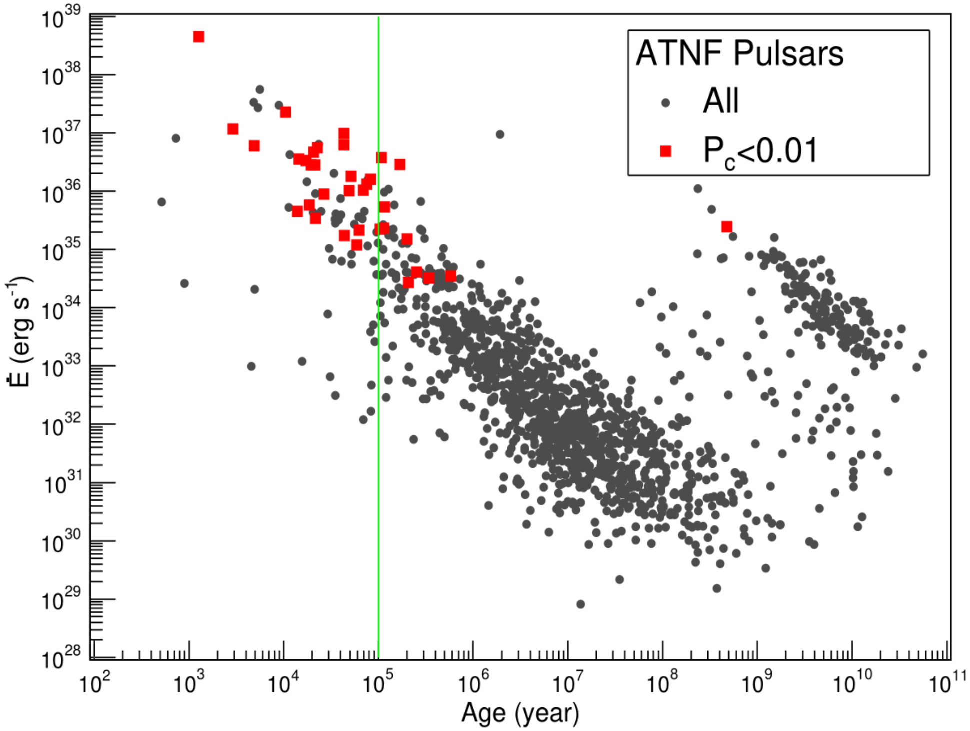
Shock drift acceleration may play an important role in the acceleration of PeV cosmic rays

Parallel electric fields may dominate the PeV particle acceleration in PWNe and Jets

Thanks

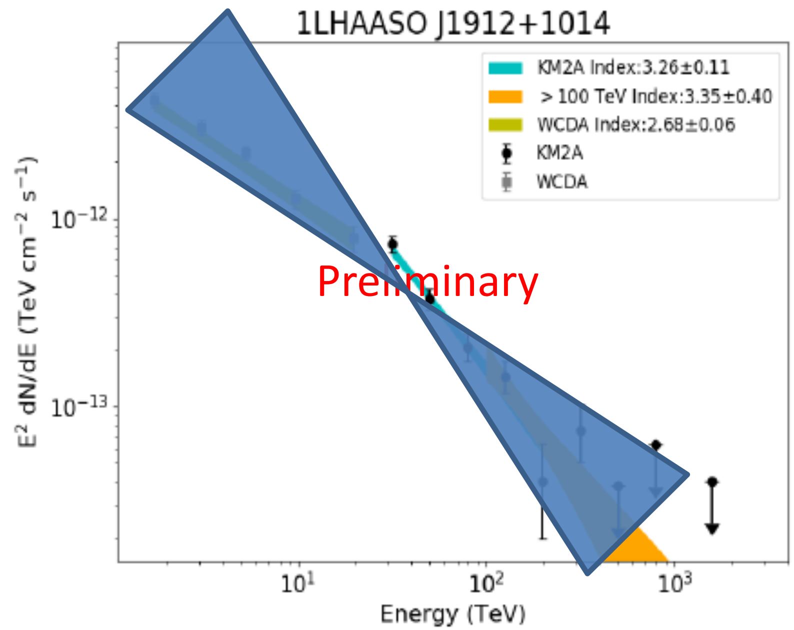
Association with ATNF pulsars

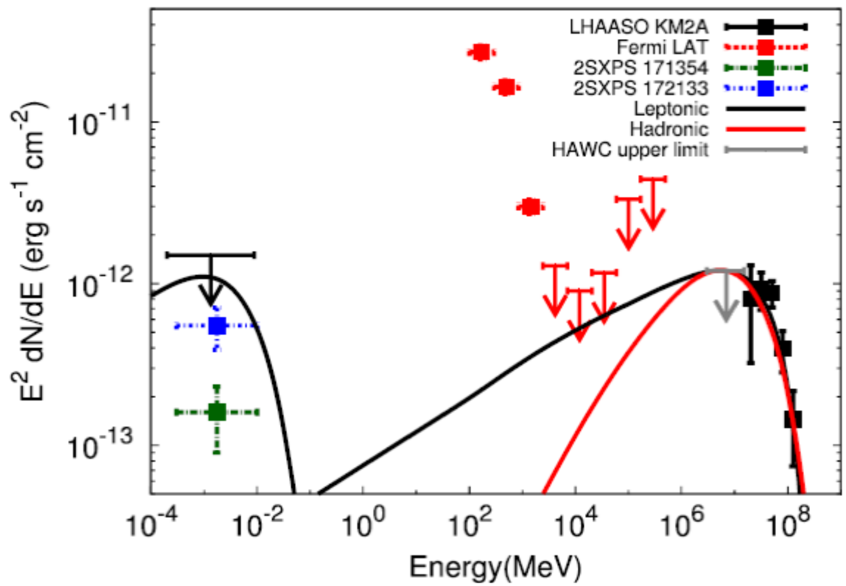
- 65 1LHAASO sources with pulsar nearby <0.5°.
- 35 associations with chance coincide probability <1%. (13 labeled as PWN or Halo in TeVCat)
- 22 new possible PWN/TeV Halo



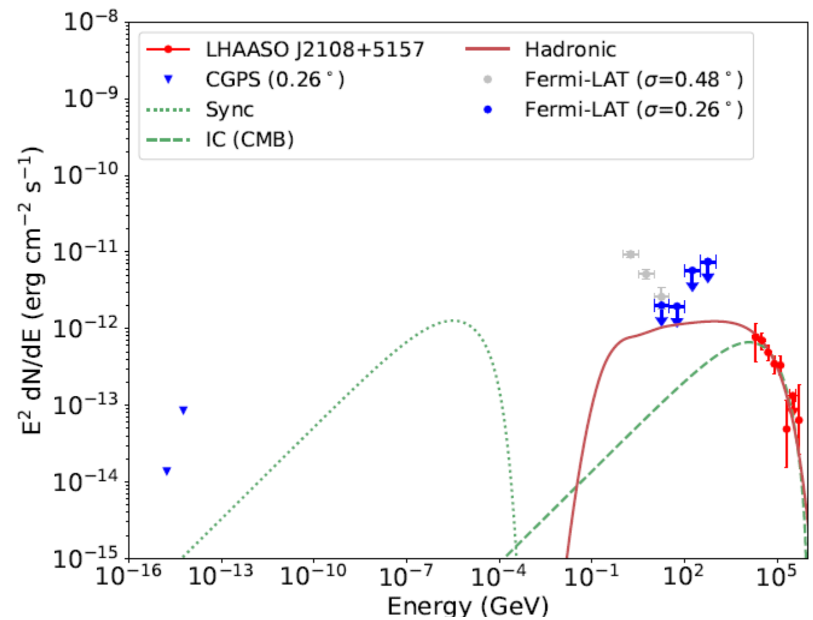
Are Supernova Remnants PeVatrons?

A Few Likely Associated with SNRs





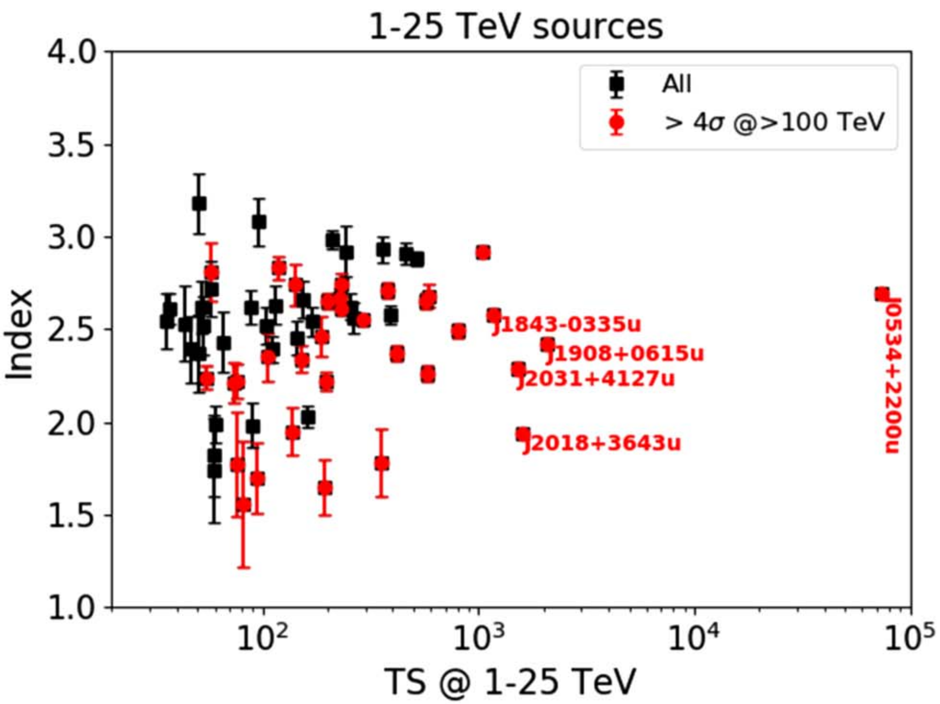
Discovery of a New Gamma-Ray Source, LHAASO J0341+5258, with Emission up to 200 TeV

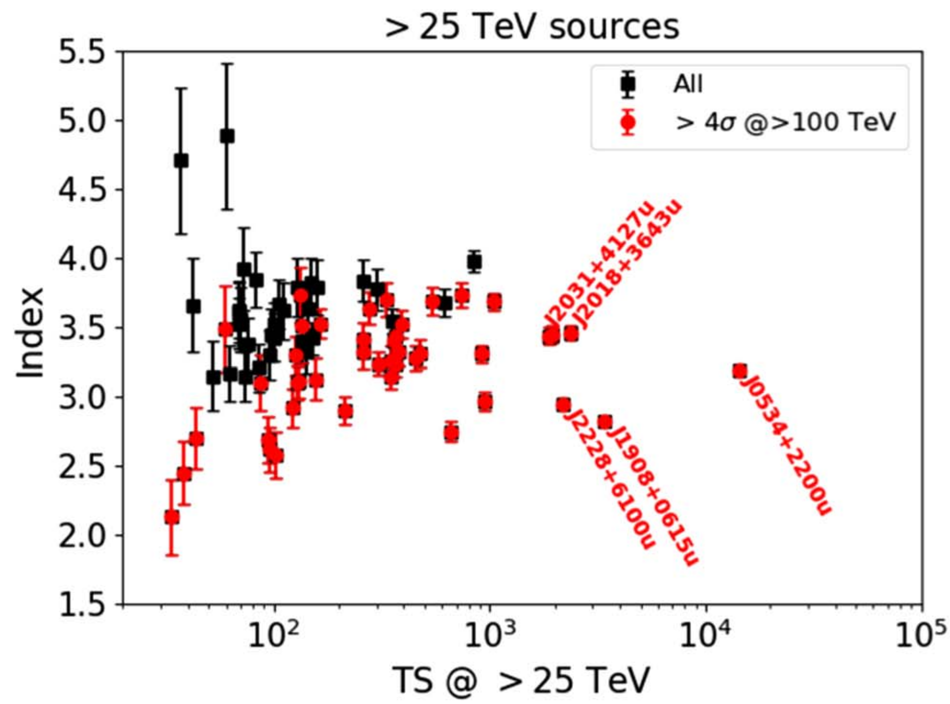


Discovery of the Ultra-high energy gamma-ray source LHAASO J2108+5157

PeVatrons

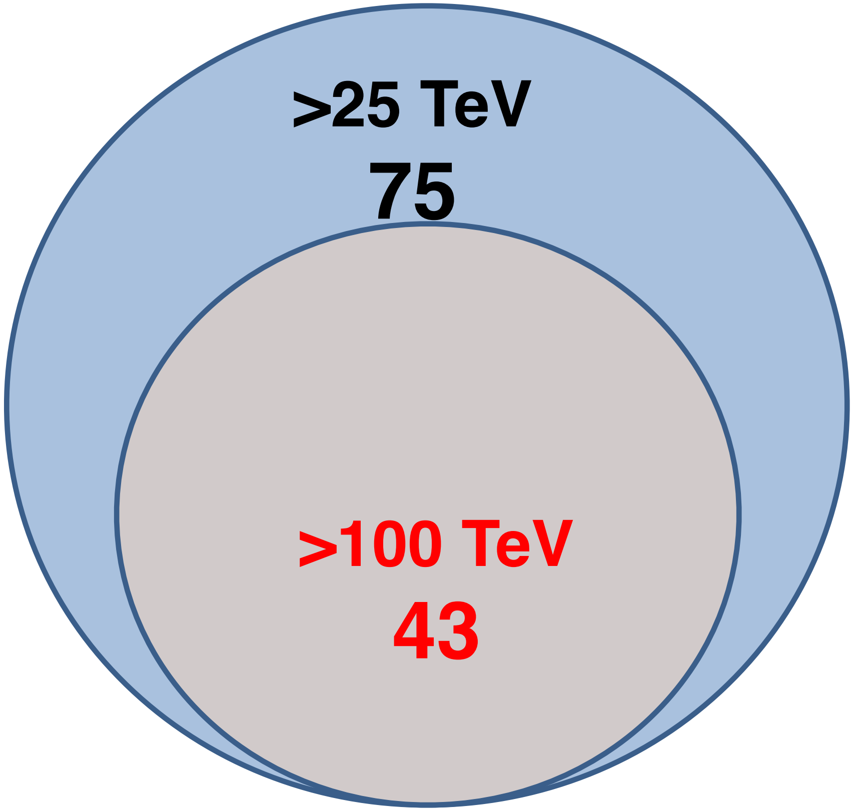
- 51% (35/69) 1-25TeV sources are UHE sources.
- 57% (43/75) >25TeV sources are UHE sources.
- 19% (8/43) UHE sources are not detected at 1-25TeV (new class?).





UHE gamma-ray sources

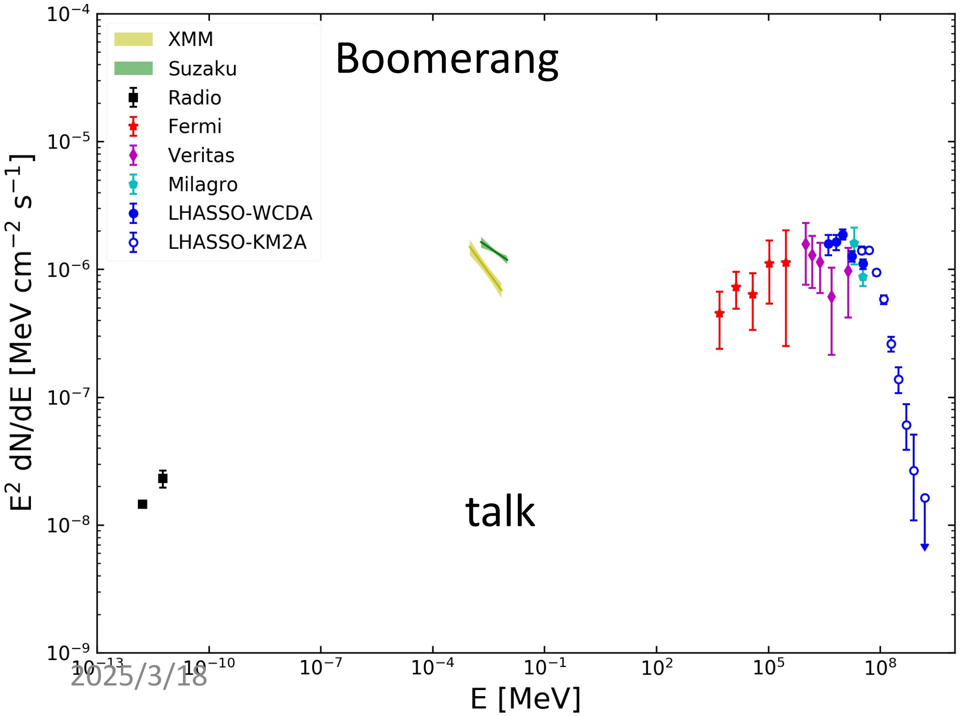
- **The position and extension achieved by KM2A at >25 TeV are used.**
- **Sources with significance >4σ at >100 TeV are labeled as UHE sources**

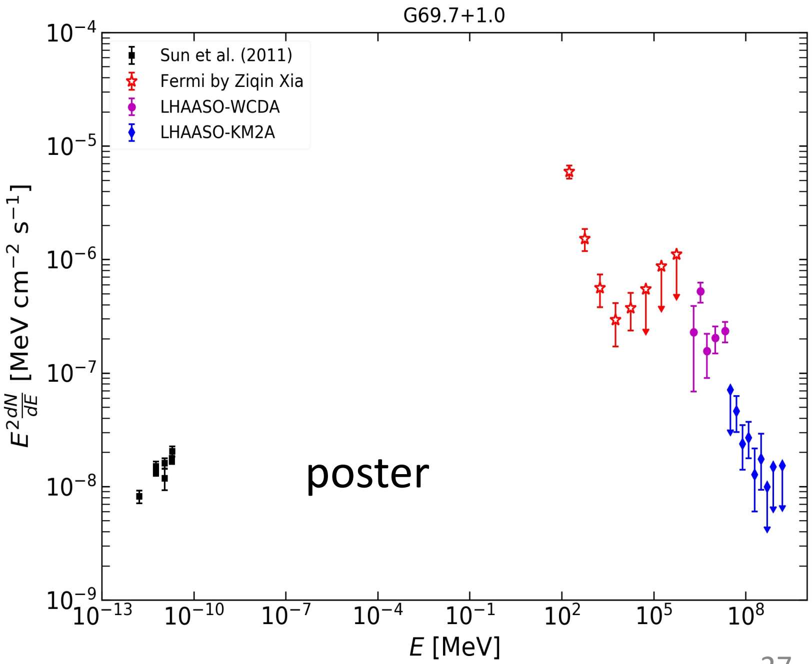


>2 Detected above 100 TeV

Article

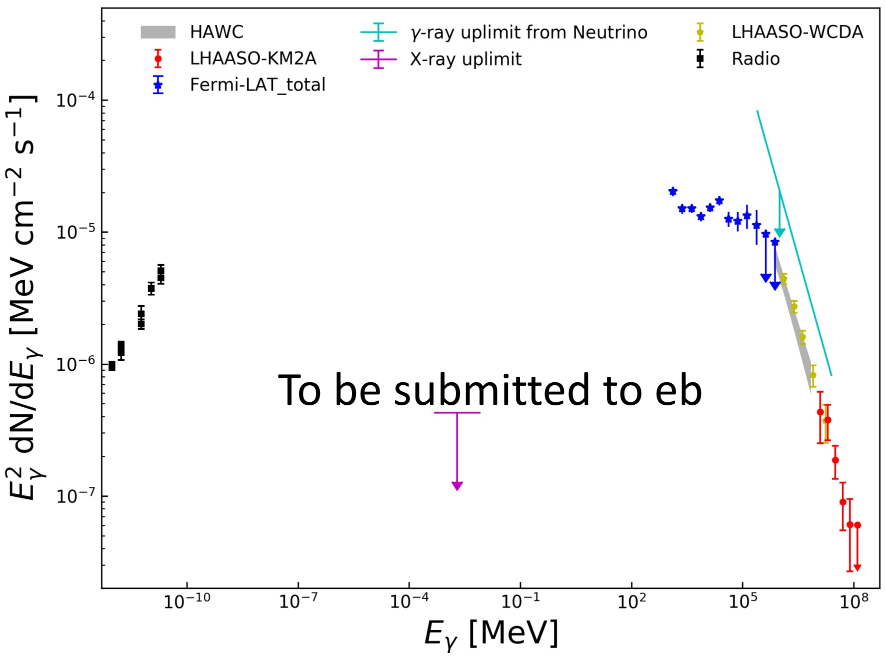
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

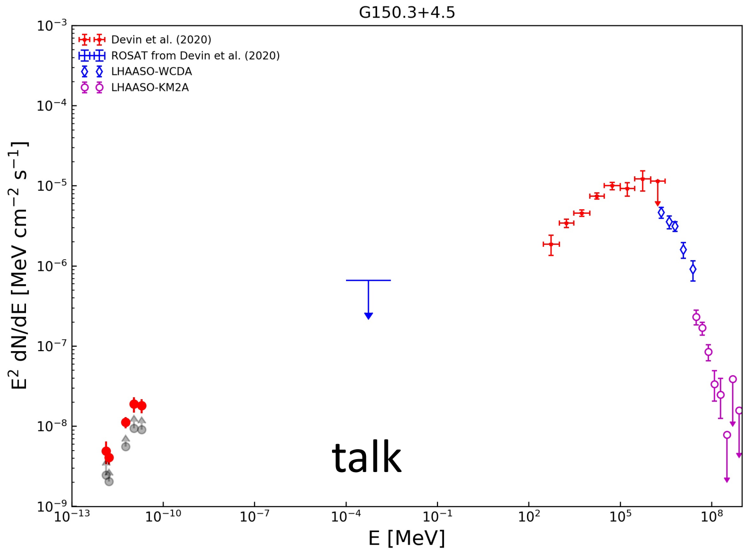


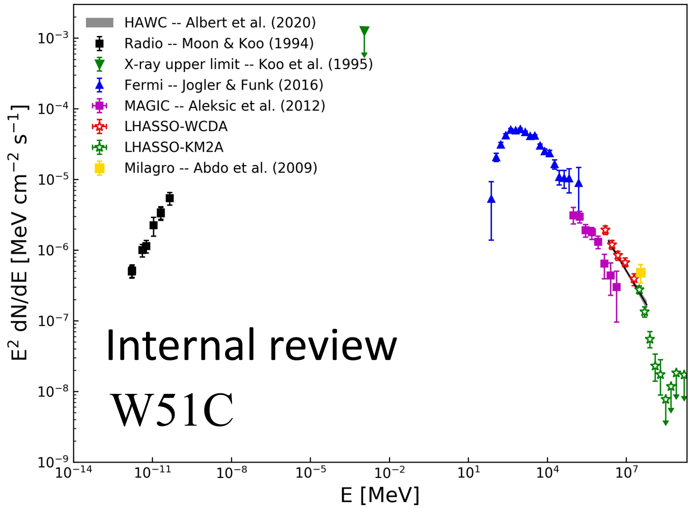


3 Detected up to 100 TeV

Gamma Cygni SNR

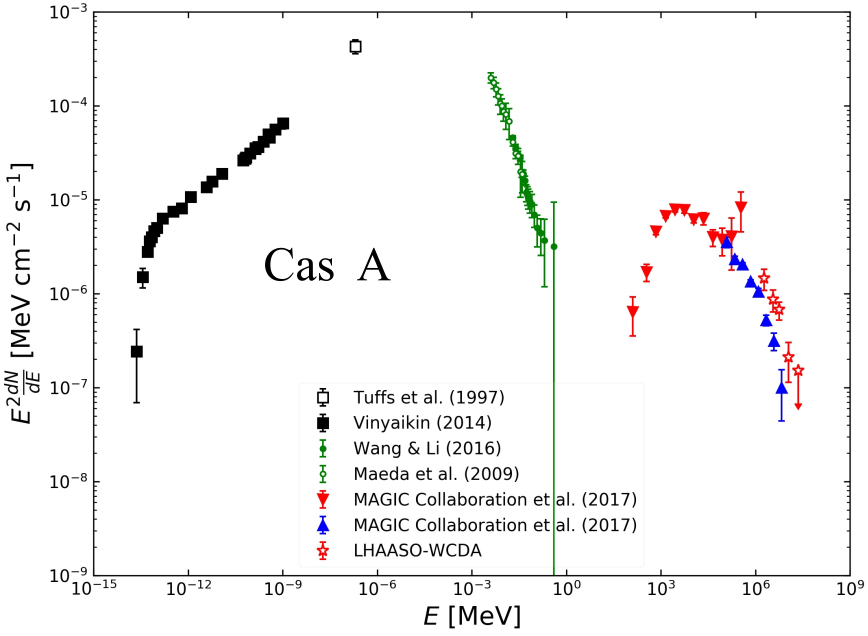


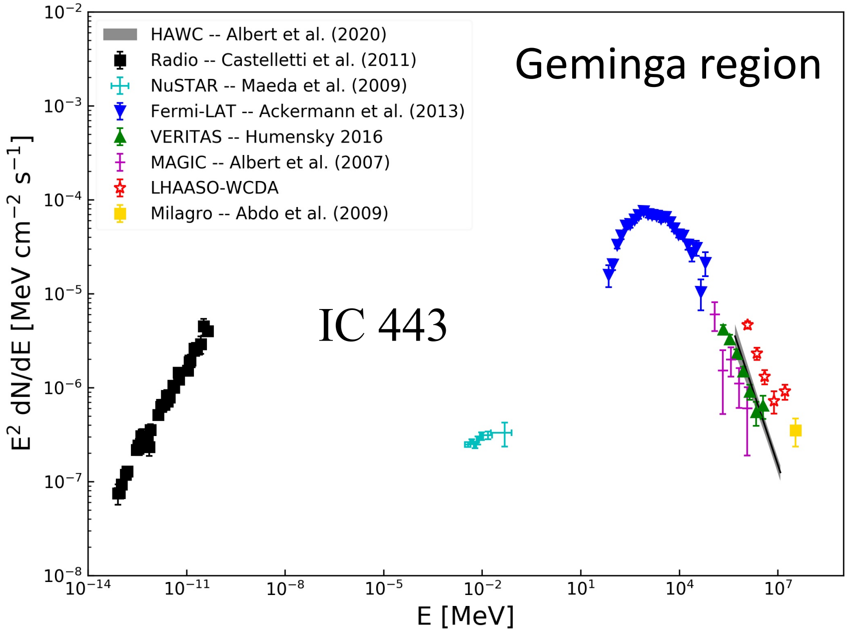




2 Detected up to 10 TeV

published



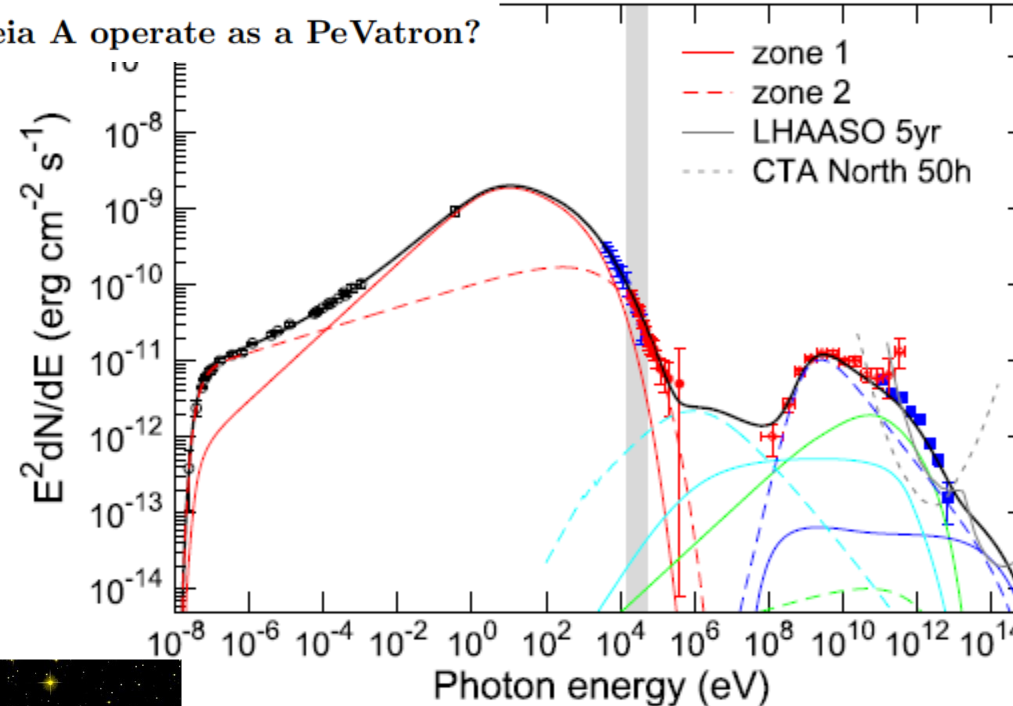


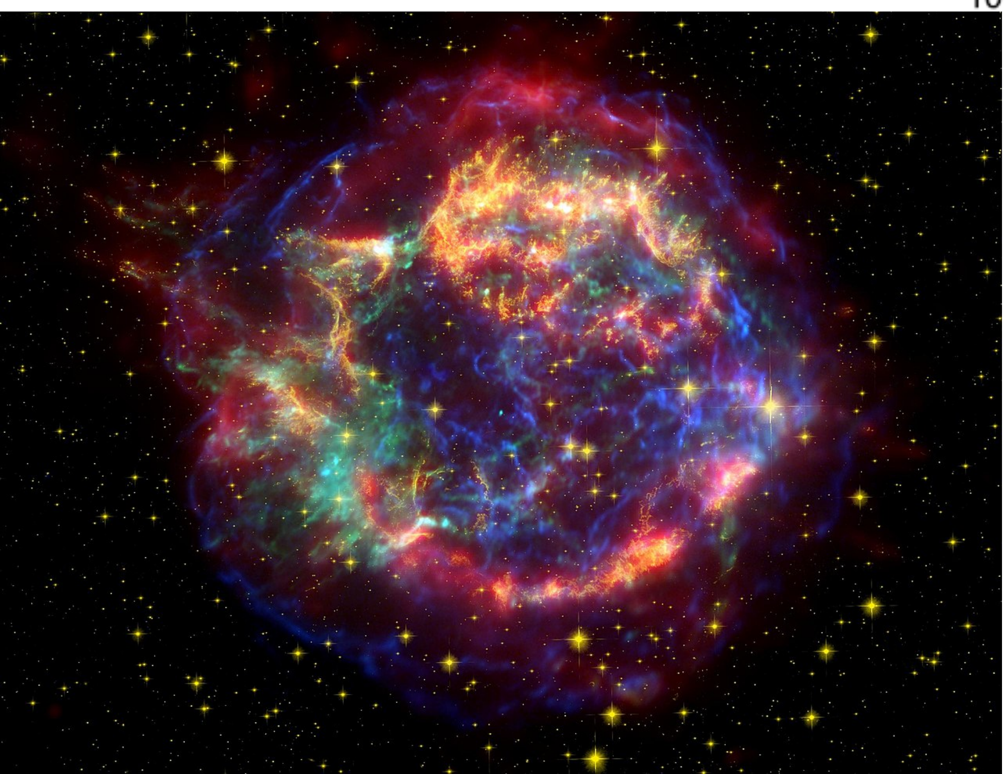
Does or did the supernova remnant Cassiopeia A operate as a PeVatron?

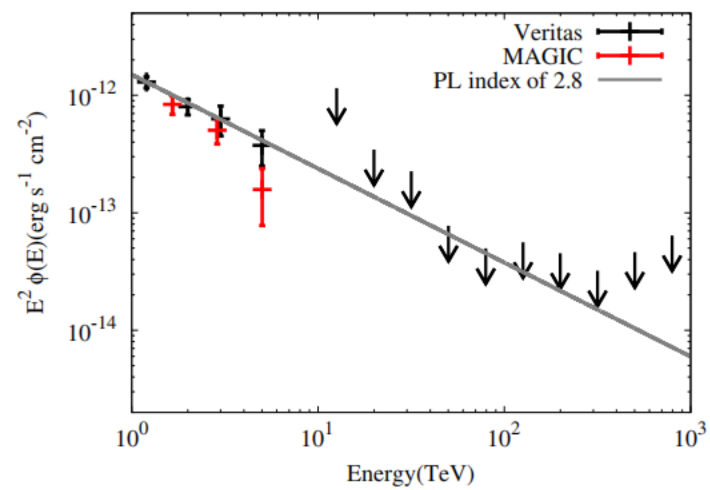
2: Cas A

340years

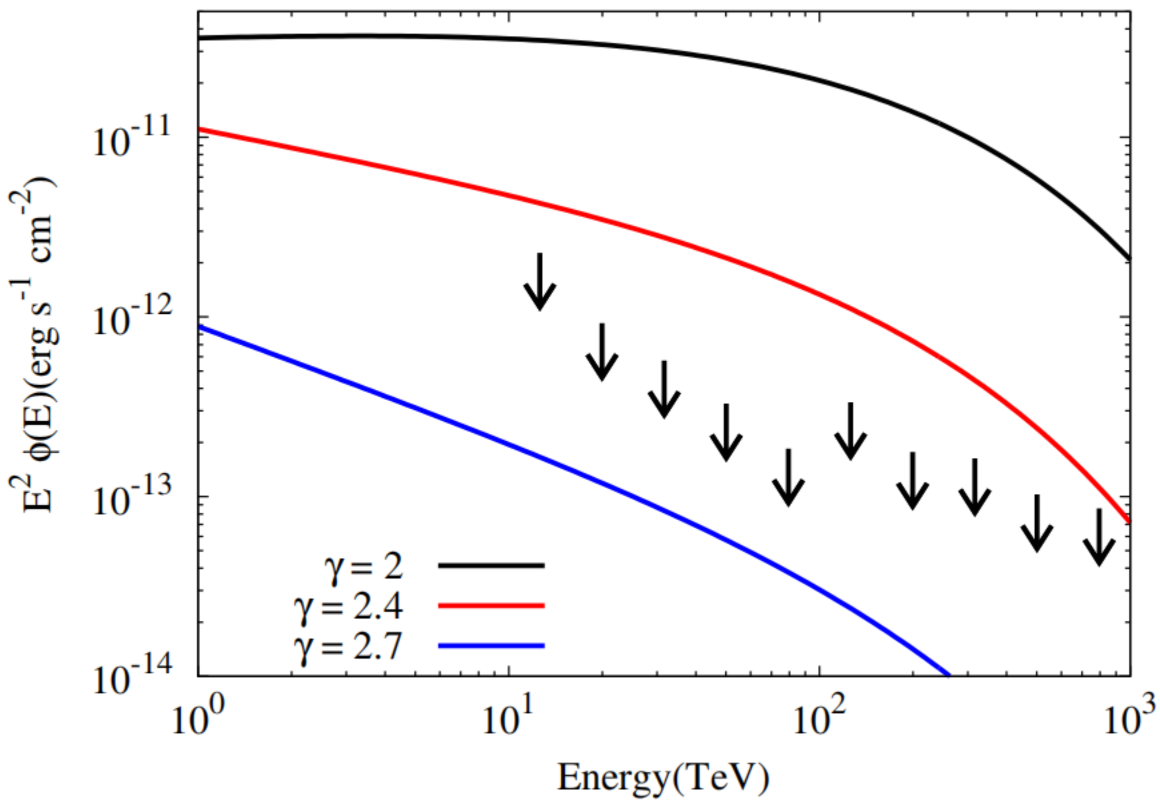
Still in the free expansion phase?







For n=10 cm-3, rule out an injection index <2.5



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **427,** 91–102 (2012)

doi:10.1111/j.1365-2966.2012.21908.x

Escape of cosmic-ray electrons from supernova remnants

Yutaka Ohira,[1★] Ryo Yamazaki,[1] Norita Kawanaka[2] and Kunihito Ioka[3,4]

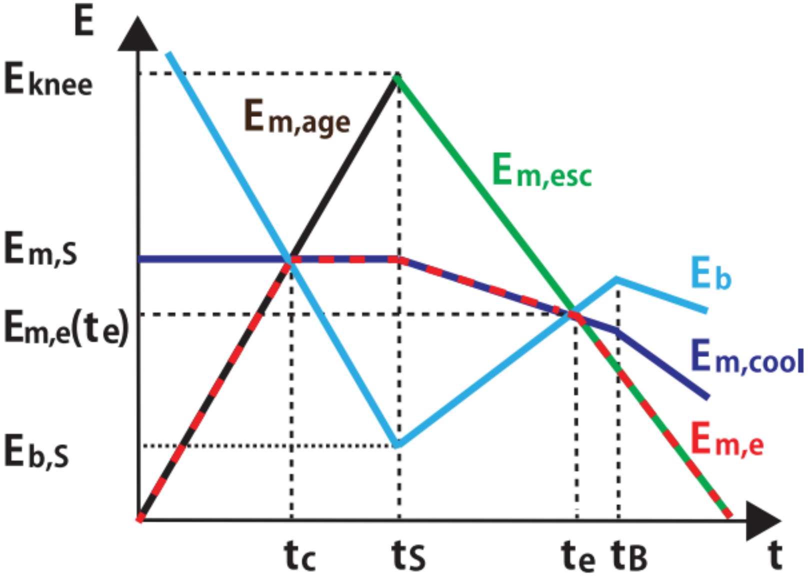
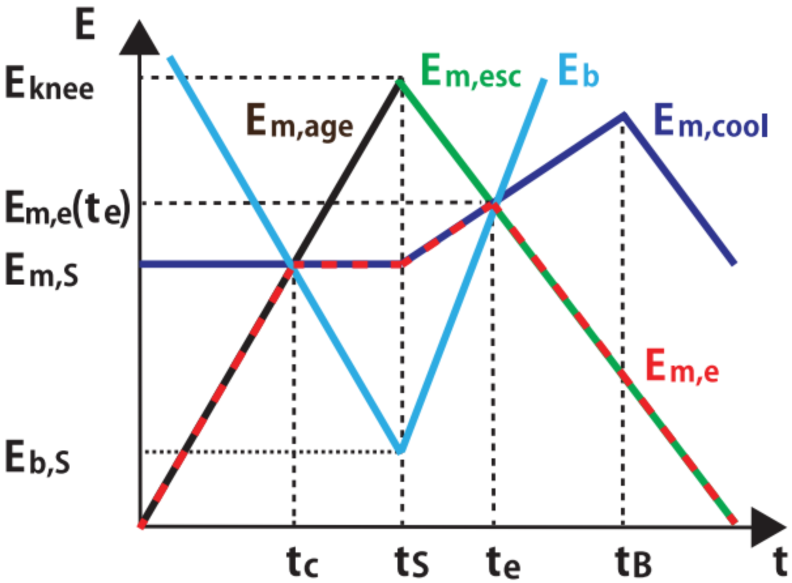
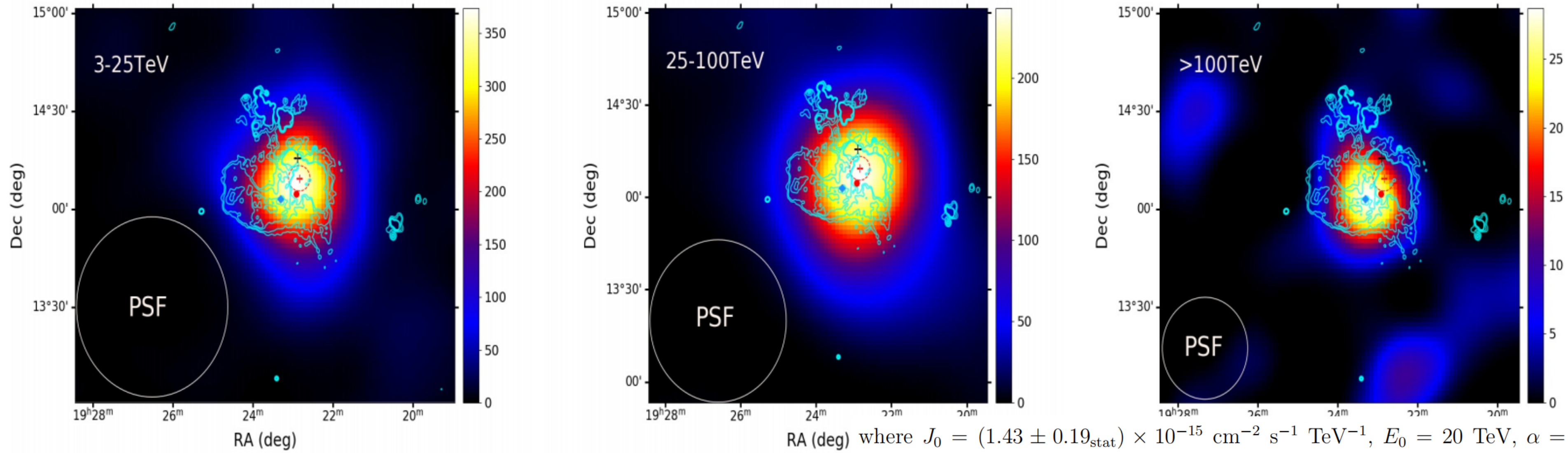


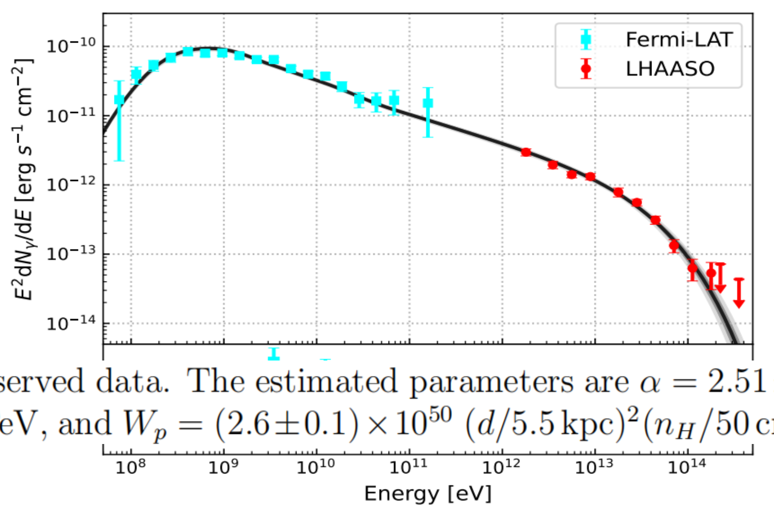
Figure 2. The same as Fig. 1, but for $B^2 \propto u_{sh}^2$ or u_{sh}^3.



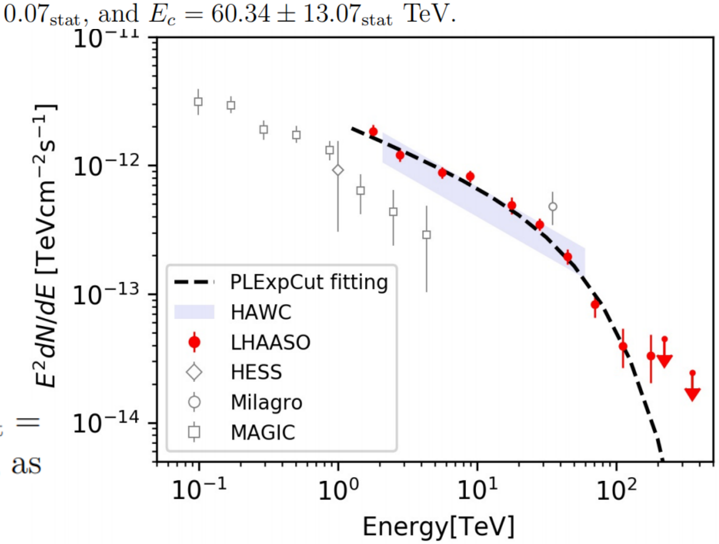
Evidence of Supernova Remnant W51C Accelerating Cosmic Rays to Sub-PeV Energies Unveiled by LHAASO



where $J_0 = (1.43 \pm 0.19_{\rm stat}) \times 10^{-15}$ cm^{-2} s^{-1} TeV^{-1}, $E_0 = 20$ TeV, $\alpha = 2.45 \pm 0.07_{\rm stat}$, and $E_c = 60.34 \pm 13.07_{\rm stat}$ TeV.

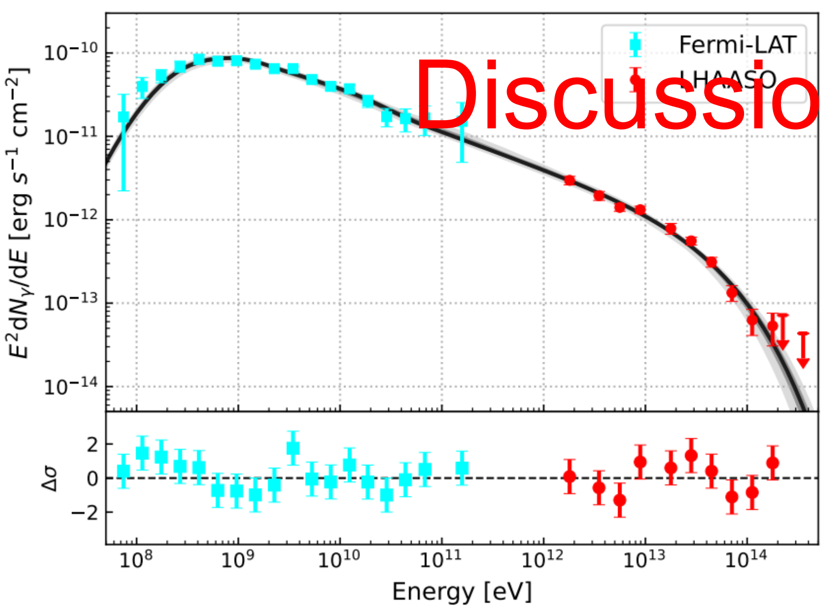


for the observed data. The estimated parameters are $\alpha = 2.51 \pm 0.01$, $E_{\rm cut} = 330 \pm 44$ TeV, and $W_p = (2.6 \pm 0.1) \times 10^{50}$ $(d/5.5\,{\rm kpc})^2 (n_H/50\,{\rm cm}^{-3})^{-1}$ erg, as

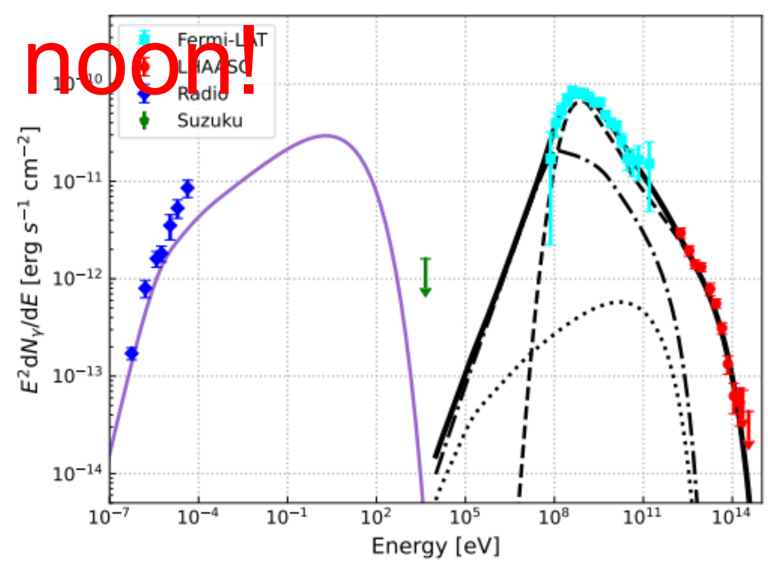


Evidence of Supernova Remnant W51C Accelerating Cosmic Rays to Sub-PeV Energies Unveiled by LHAASO

	α		E_{cut} [TeV]		$\Delta\alpha$		E_{br} [GeV]		BIC
	Best	Mean	Best	Mean	Best	Mean	Best	Mean	
Model 0	2.51	$2.51^{+0.01}_{-0.01}$	332	330^{+47}_{-41}	-	-	-	-	40.53
Model 1	2.53	$2.53^{+0.01}_{-0.01}$	400	400^{+68}_{-56}	-	-	-	-	39.41
Model 2	2.55	$2.56^{+0.04}_{-0.02}$	393	412^{+89}_{-63}	0.15	$0.18^{+0.07}_{-0.06}$	87	104^{+548}_{-74}	37.25
Model 3	2.51	$2.51^{+0.01}_{-0.01}$	413	419^{+85}_{-65}	0.29	$0.45^{+0.27}_{-0.18}$	6.6	$3.8^{+3.0}_{-1.7}$	38.18
Model 4	2.51	$2.52^{+0.01}_{-0.01}$	263	262^{+39}_{-34}	-	-	-	-	43.36



Discussion at noon!



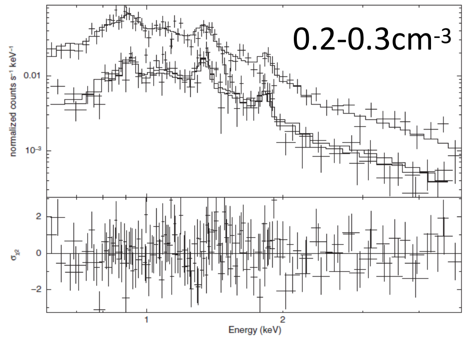
2: Radio/X-ray obs ϒ Cygni SNR

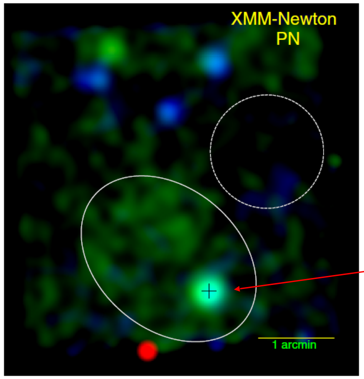
Distance=1.7kpc

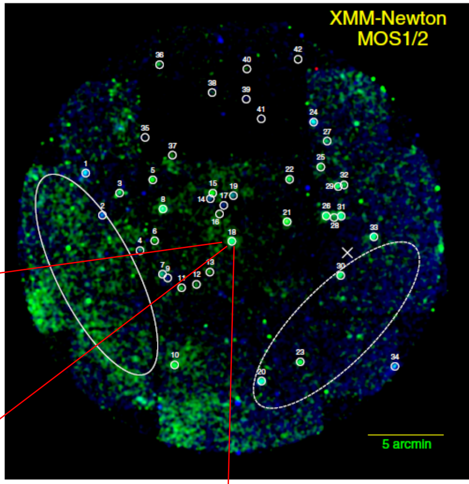
Age =7kyr

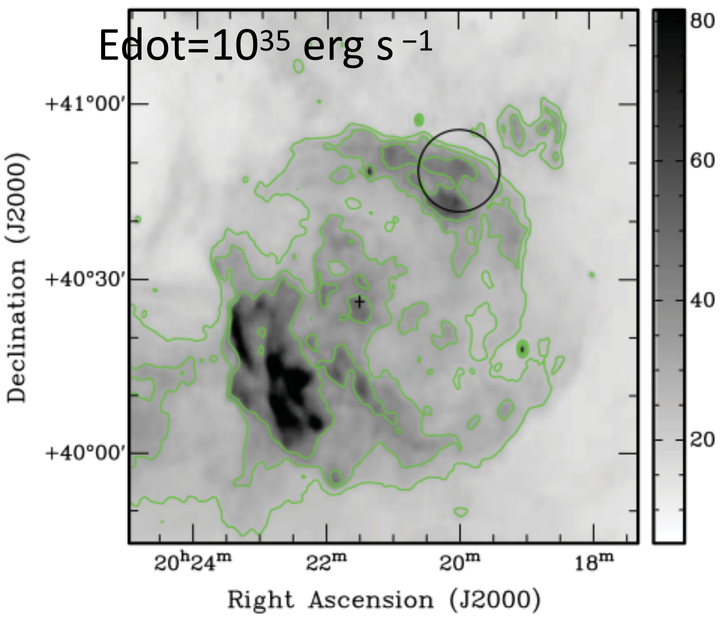
PSR J2021+4026

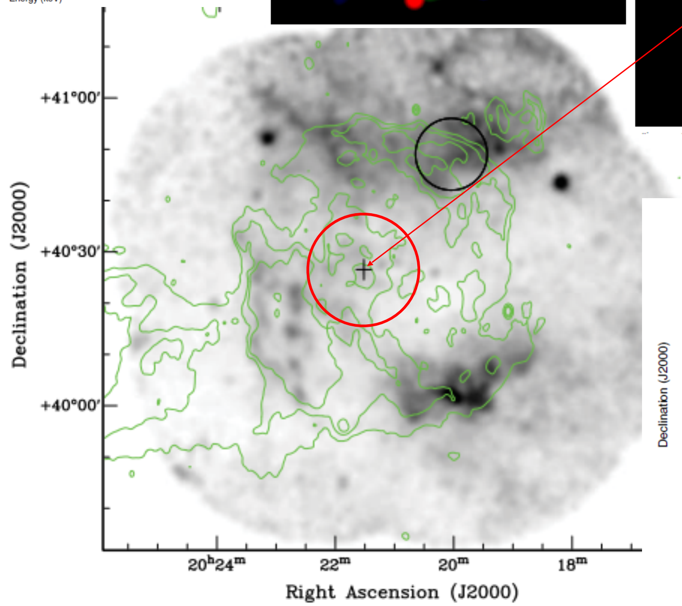
- Distance=2.15kpc
- τ =77kyr(First variable ϒ-ray pulsar)
- Period P=26.5ms
- Edot=10^{35} erg s^{-1}

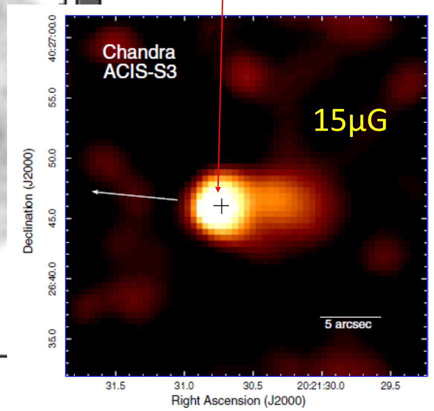










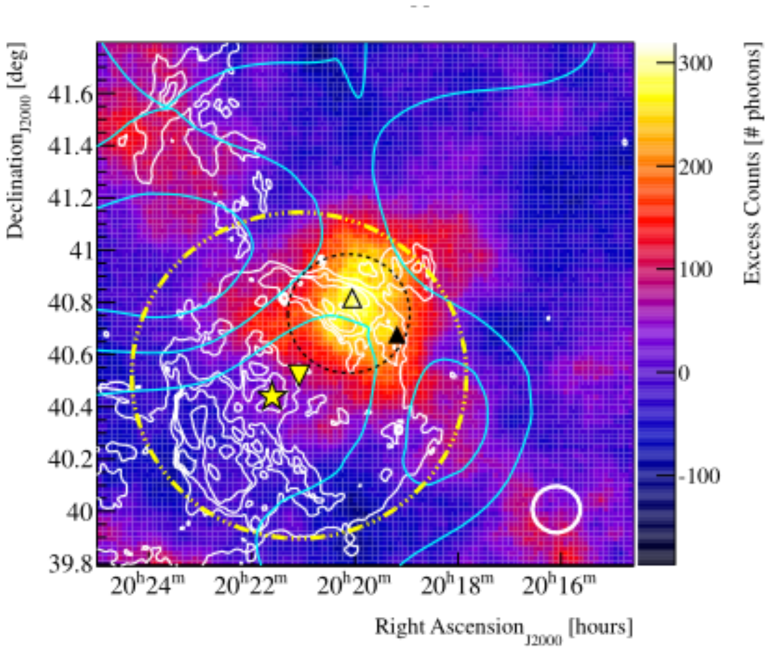


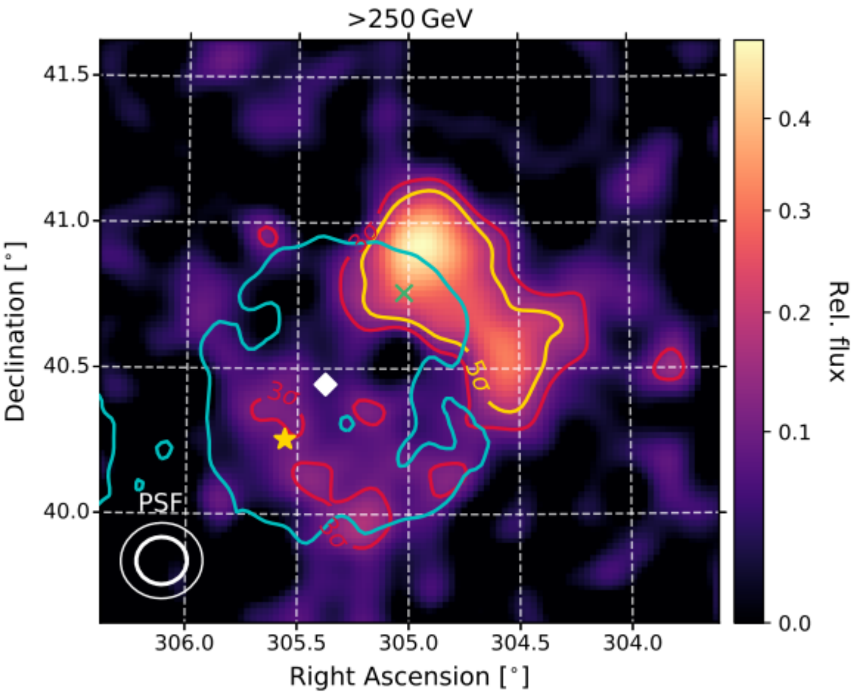
ROSAT PSPC 0.5–2.0keV X-ray image

The 1420-MHz image

MNRAS 436, 968–977 (2013), Hui et al. ApJ, 799, 76, (2015)

2: High Energy Observations





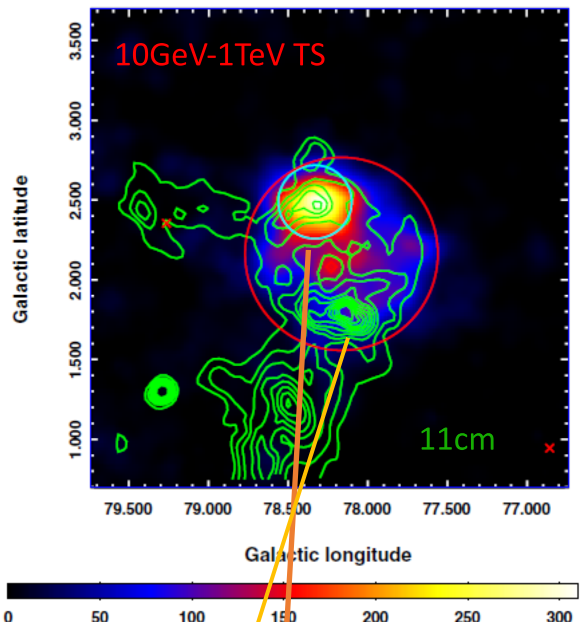
VERITAS >320GeV
Ra=305°.02, Dec= 40° .76;
Extension=0.23°

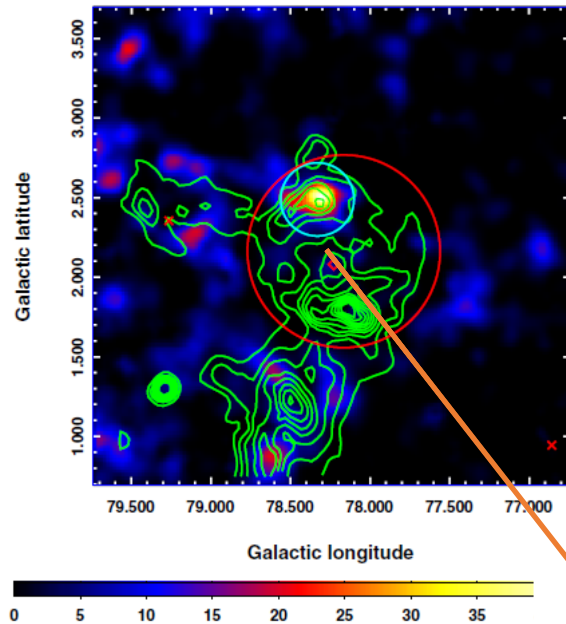
MAGIC >250GeV
Ra=304°.89, Dec= 40° .85;
Extension=0°.16

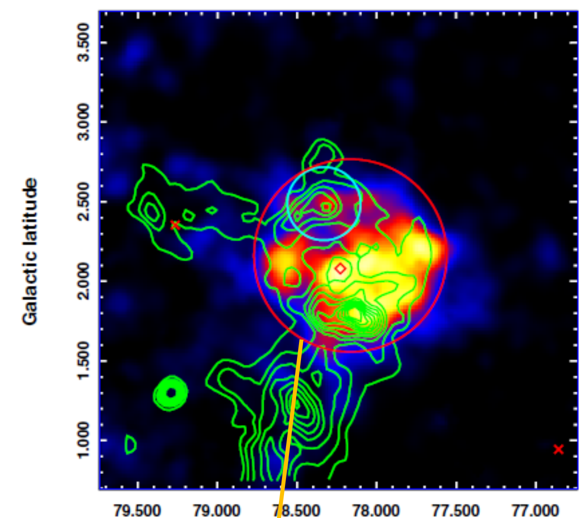
Aliu, E.,et al. 2013, ApJ, 770, 93

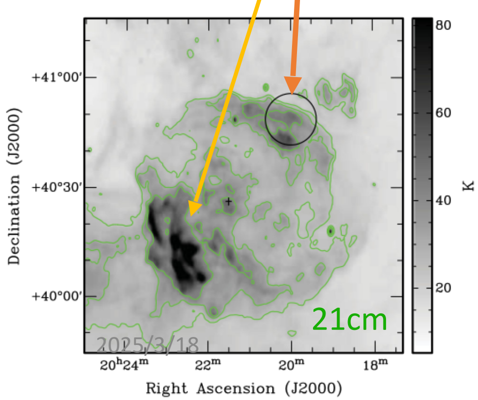
MAGIC, 2023, AA arXiv:2010.15854

2: Fermi Observations







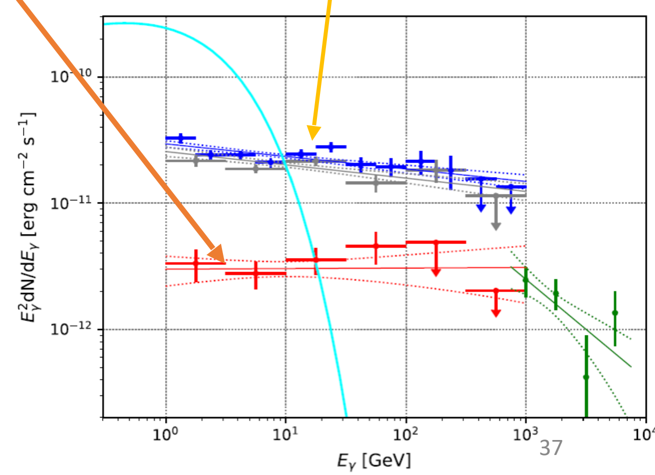


Reviews of Modern Plasma Physics (2022) 6:19
https://doi.org/10.1007/s41614-022-00080-6

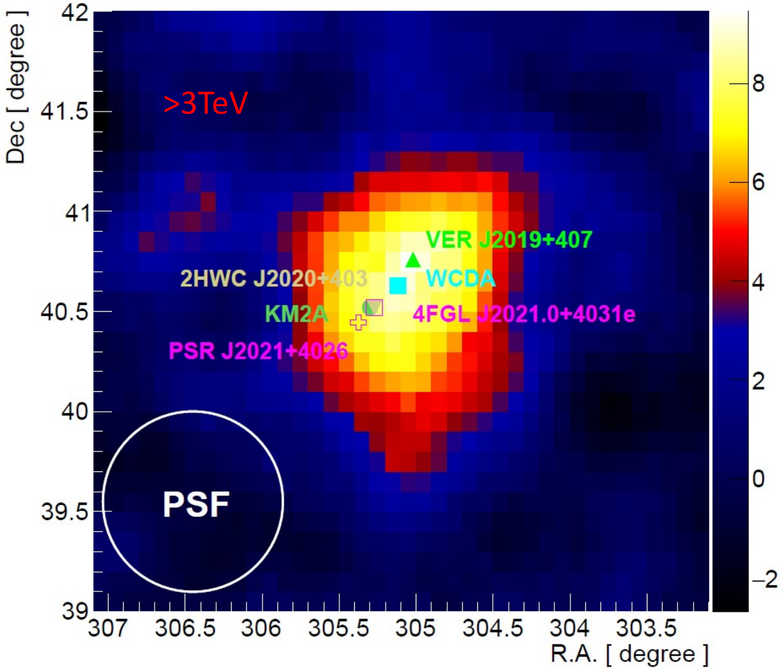
REVIEW PAPER

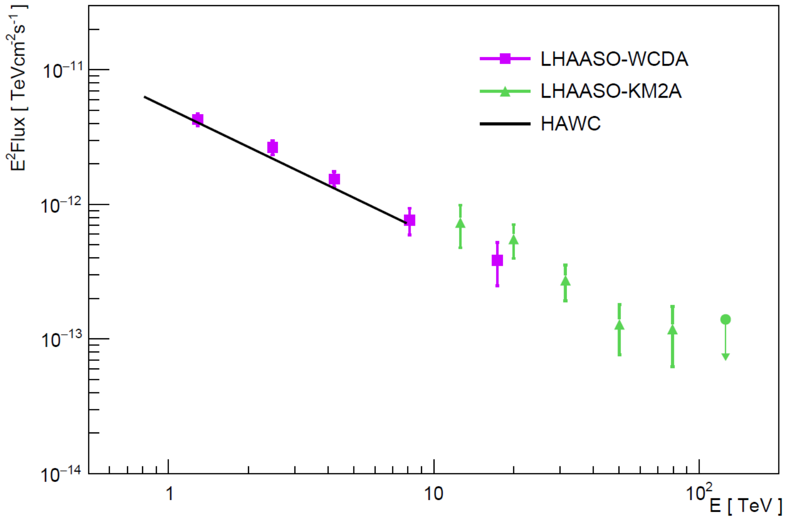
The origin of galactic cosmic rays

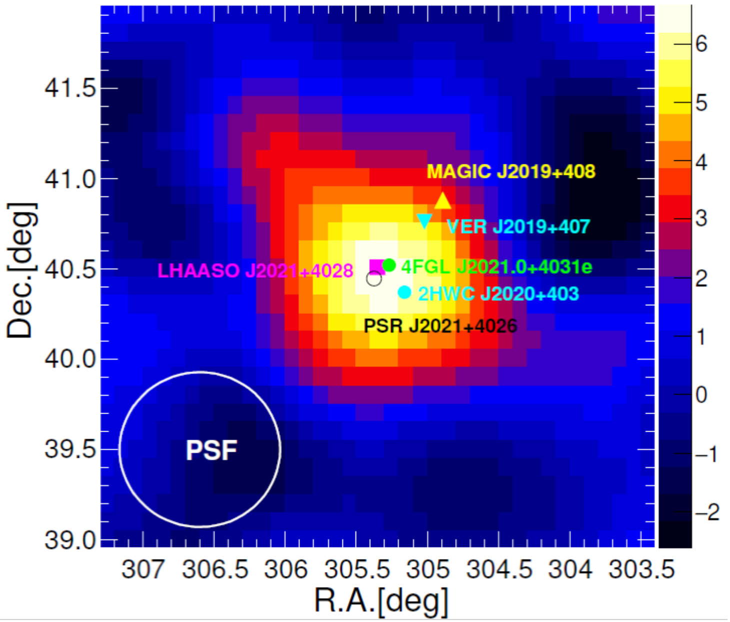
Siming Liu[1] · Houdun Zeng[2,4] · Yuliang Xin[1] · Yiran Zhang[3]



2: LHAASO Results

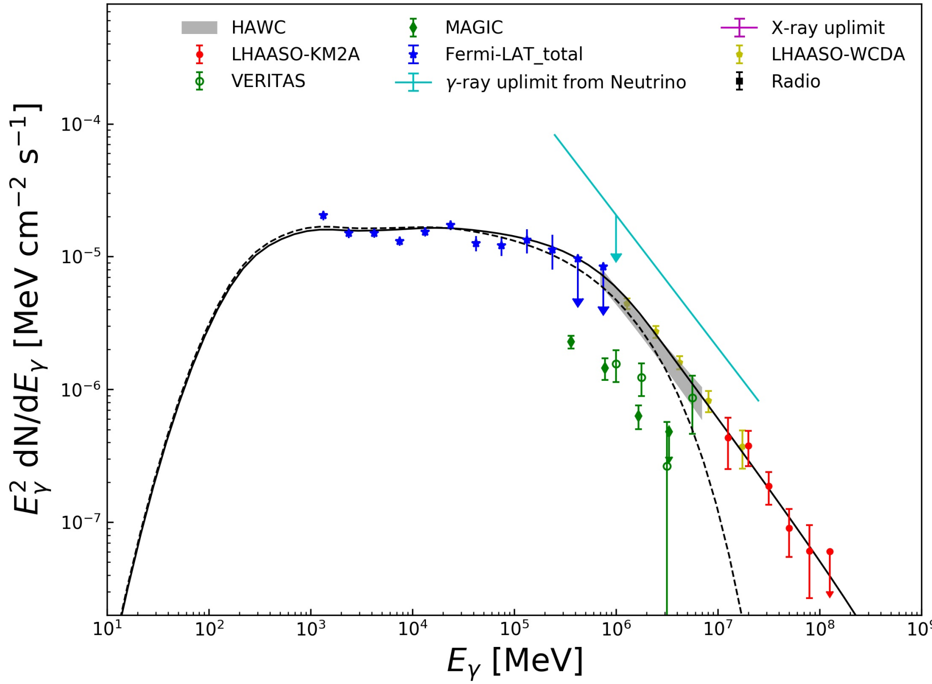


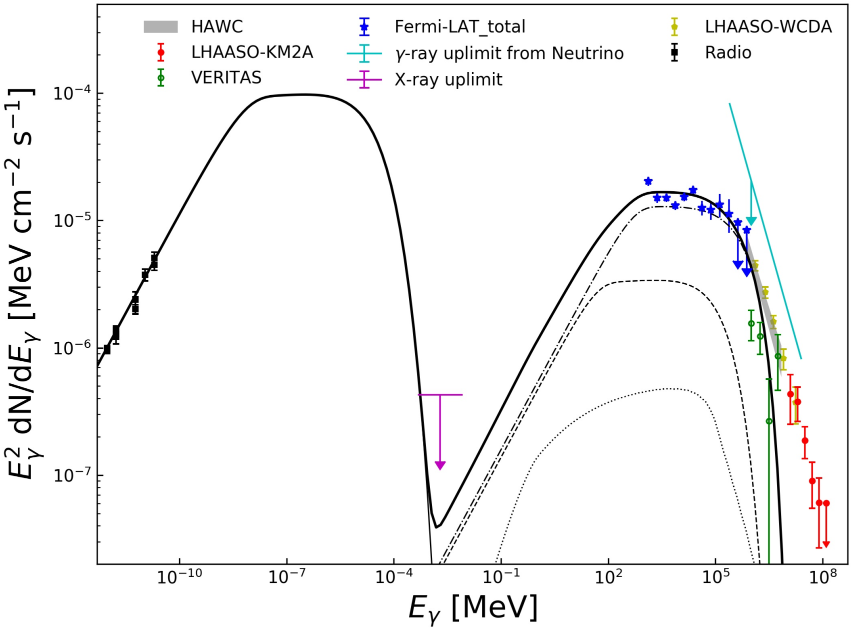




- gaussian： sigma = 0.374 +/- 0.040
- disk： radius = 0.592 +/- 0.056

2: Hadronic vs Leptonic Models





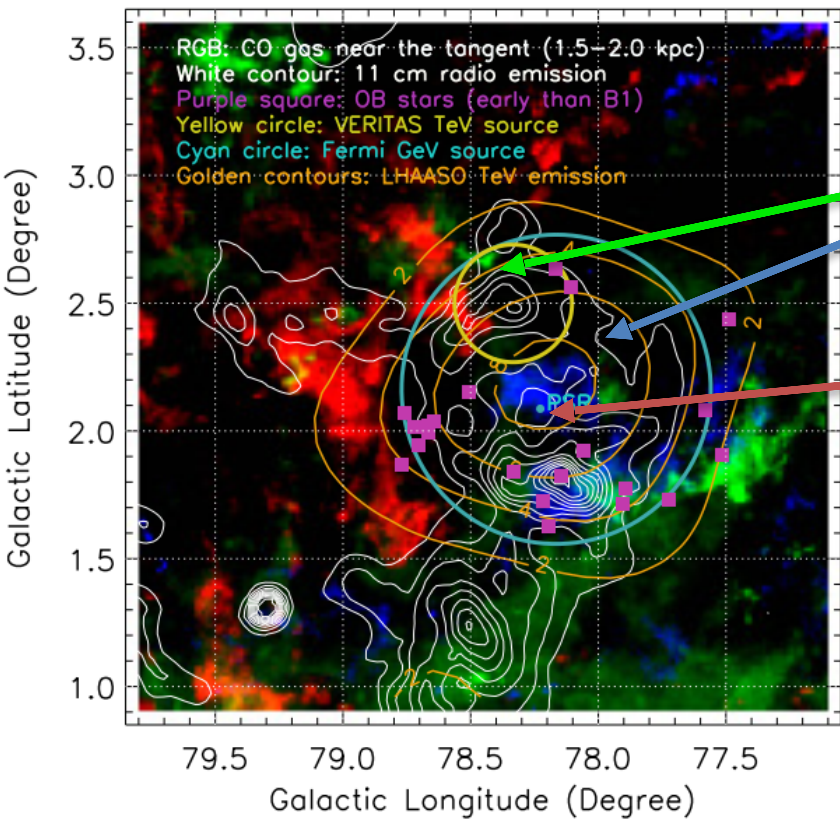
Hadronic with
an exponential cutoff of 10TeV (dotted)
a break at 4TeV (solid)
Index 2.1->3.1

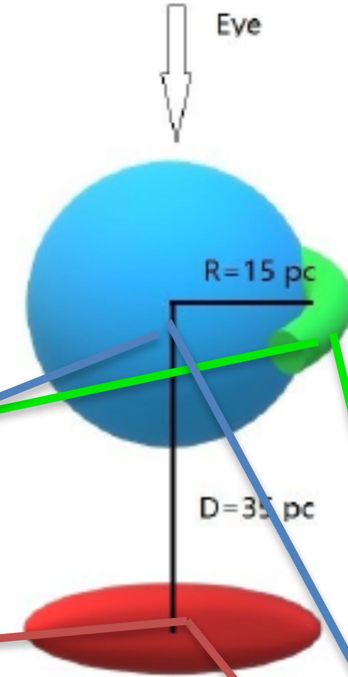
Leptonic with a ~17 μG B

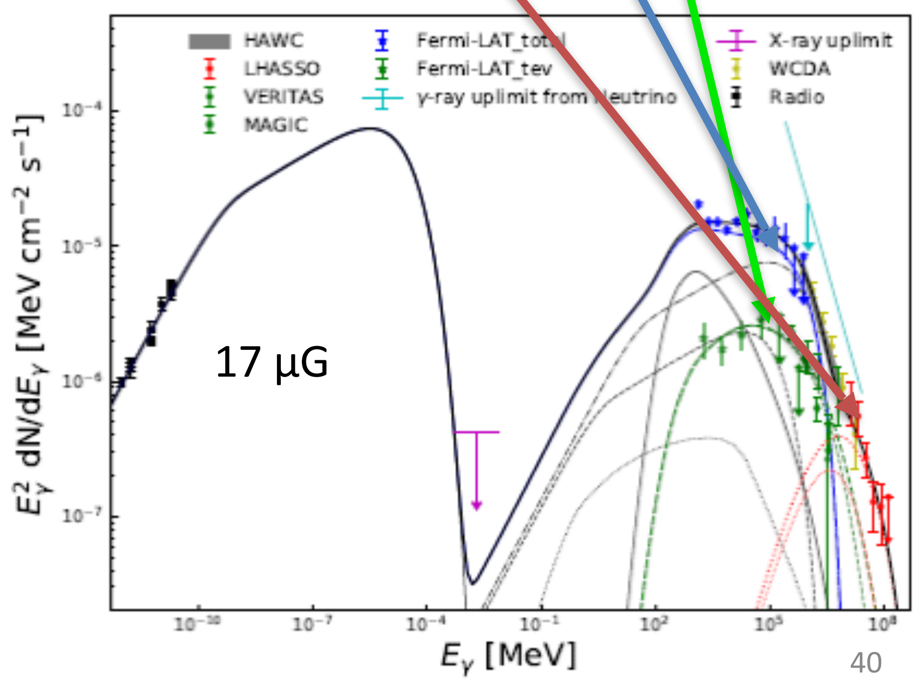
Zeng et al. ApJ, 910, 78, (2021)

Liu et al. RMPP, 6, 19, (2022)

2: A Possible Model

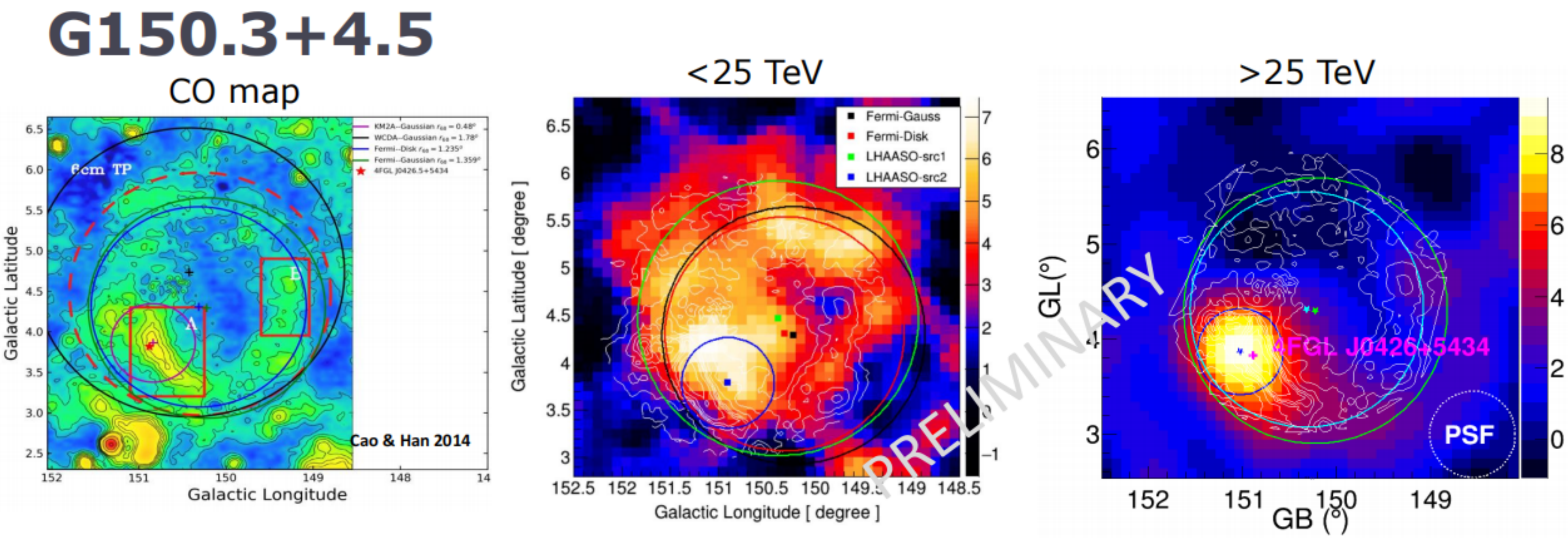






Considering the low density inferred from X-ray observations of 0.2-0.3 cm^{-3} and a high magnetic field

3： SNR G150



Fitted with two Gaussians: One is spatially coincident with the radio and Fermi-LAT observation (G150.3+4.5); another is very closed the unidentified source 4FGL J0426.5+5434.

(150.38, 4.47), extension =1.45; (150.9, 3.79), extension =0.26

The distance of CO emission (MWISP): 0.8 kpc, and a uniform density: ~1.0 cm^{-3}, with an age: ≤1.3×10^4 yr.

3：SNR G150

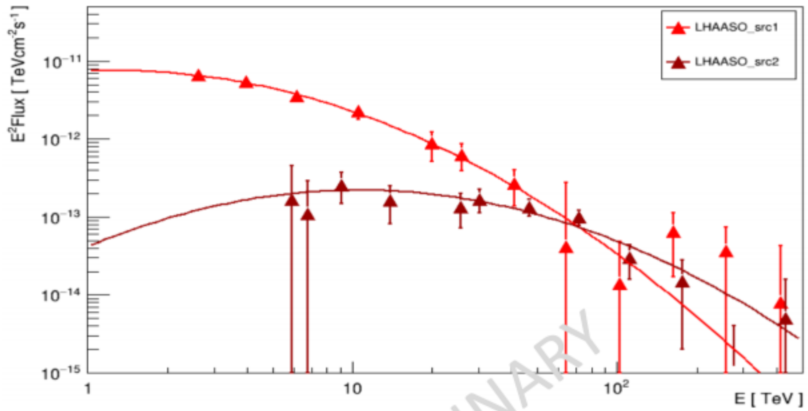
G150.3+4.5

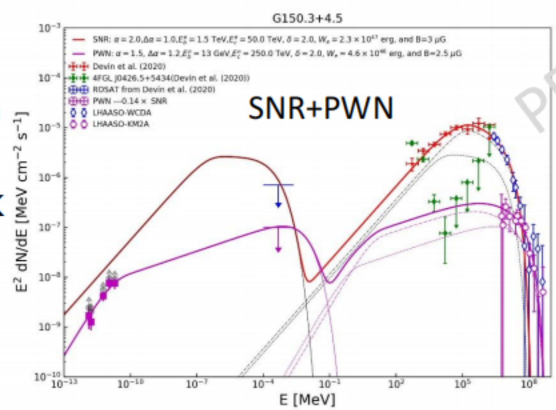
The SEDs at 1—400 TeV can be fitted with log-parabola models.

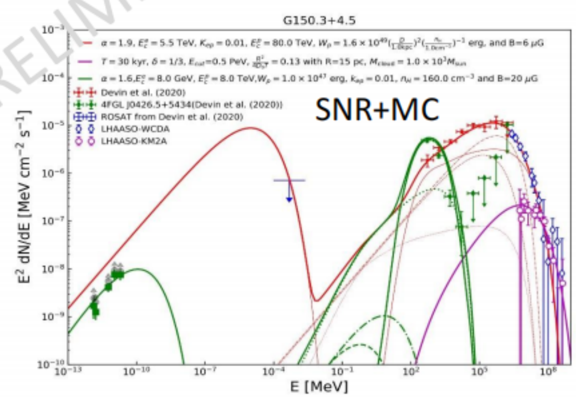
$$dN/dE = J_0\,(E/E_0)^{-\alpha-\beta\log(E/E_0)}$$

Scenario A: sync.+ SSC from SNR G150.3+4.5 and PWN, respectively.

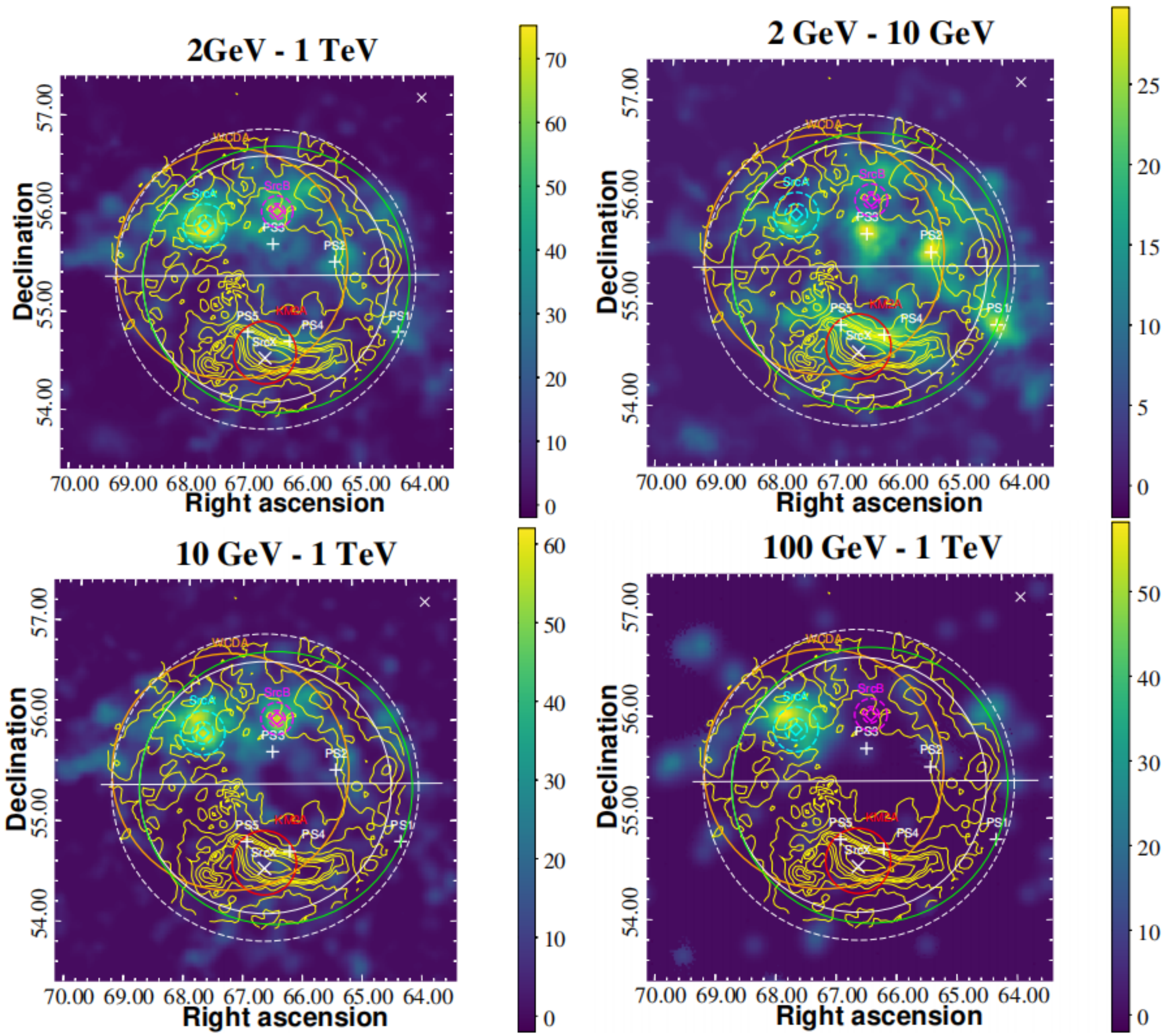
Scenario B: sync. + SSC from SNR G150.3+4.5; Escaped CR interacting with MC, and shock colliding with MC.







3: G150.3+4.5

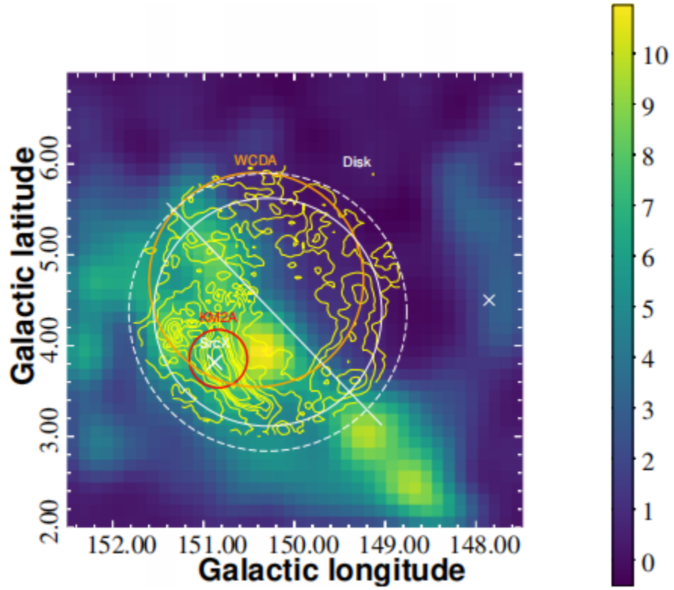


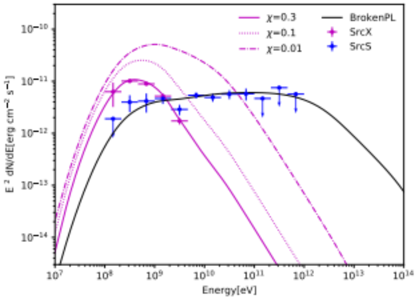
2GeV - 1 TeV
2 GeV - 10 GeV
10 GeV - 1 TeV
100 GeV - 1 TeV
Declination
Right ascension
57.00
56.00
55.00
54.00
70.00 69.00 68.00 67.00 66.00 65.00 64.00
WCDA
SrcA
SrcB
SrcX
PS1
PS2
PS3
PS4
PS5
KM2A
0
10
20
30
40
50
60
70
5
15
25

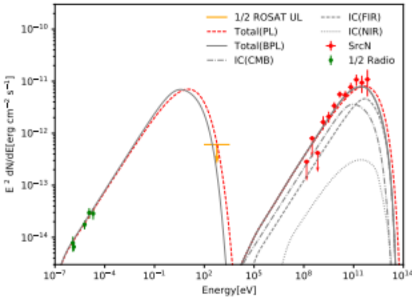
3: G150.3+4.5

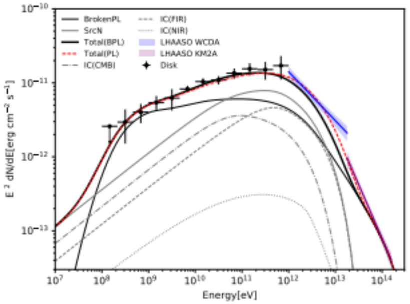
Is SNR G150.3+4.5 a PeVatron?

YUAN LI,[1,2] SIMING LIU,[3] AND GWENAEL GIACINTI[1,2]









3: Boomerang SNR

J2229+6114(G106.3+2.7)

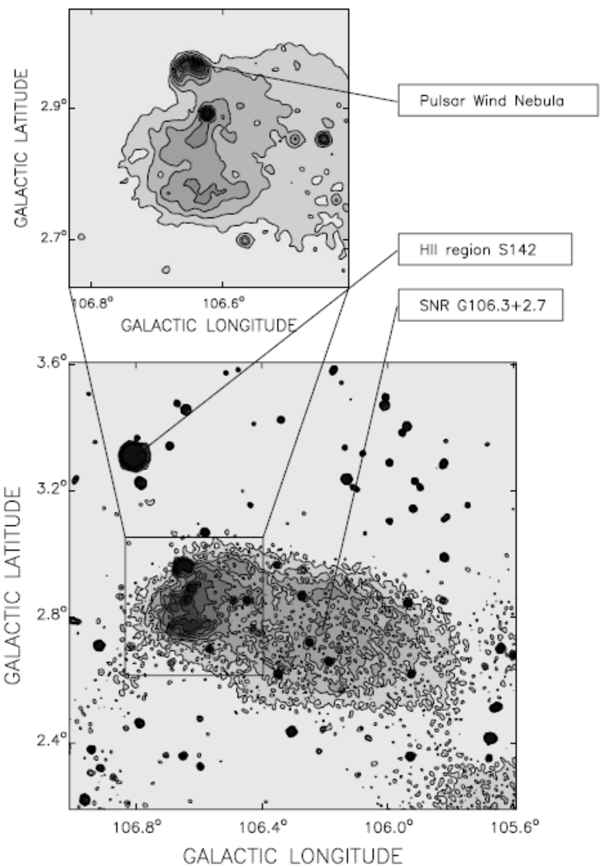
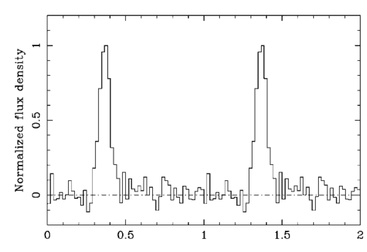


TABLE 1

Parameters of PSR J2229+6114

Parameter	Value
R.A. (J2000)	$22^h29^m05^s.28(7)$
Decl. (J2000)	$+61°14'09''.3(5)$
Galactic longitude (deg)	106.65
Galactic latitude (deg)	2.95
Period (s)	0.05162357393(6)
Period derivative (s s^{-1})	$7.827(2) \times 10^{-14}$
Epoch (MJD)	51980.0
Dispersion measure (cm^{-3} pc)	200(10)
Distance[a] (kpc)	~3
Spin-down luminosity (ergs s^{-1})	2.2×10^{37}
Characteristic age (yr)	10460
Magnetic field (G)	2.0×10^{12}



The Astrophysical Journal, 560:236–243, 2001 October 10

THE SUPERNOVA REMNANT G106.3+2.7 AND ITS PULSAR-WIND NEBULA: RELICS OF TRIGGERED STAR FORMATION IN A COMPLEX ENVIRONMENT

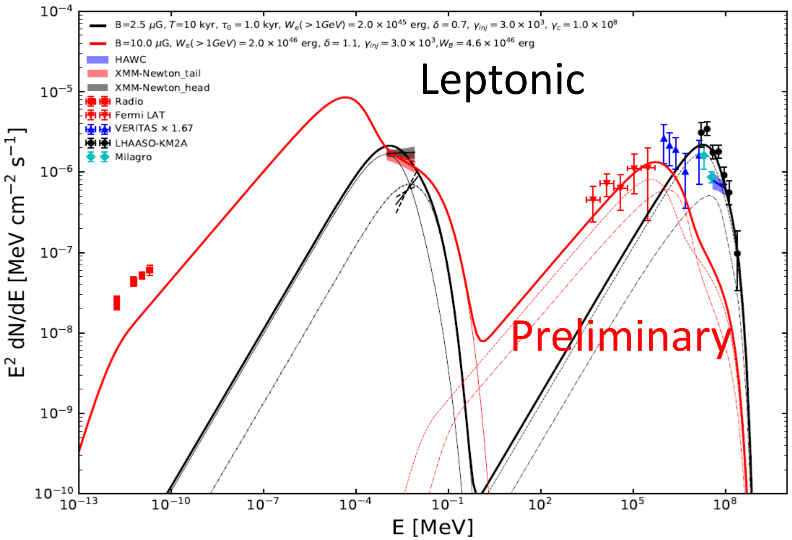
Roland Kothes,[1] Bülent Uyaniker,[1] and Serge Pineault[2]

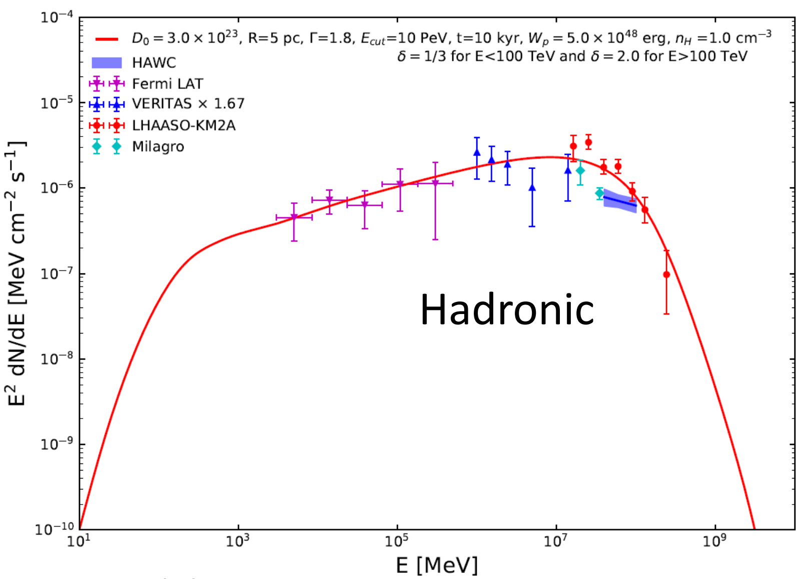
physical Journal, 552:L125–L128, 2001 May 10

PSR J2229+6114: DISCOVERY OF AN ENERGETIC YOUNG PULSAR IN THE ERROR BOX OF THE EGRET SOURCE 3EG J2227+6122

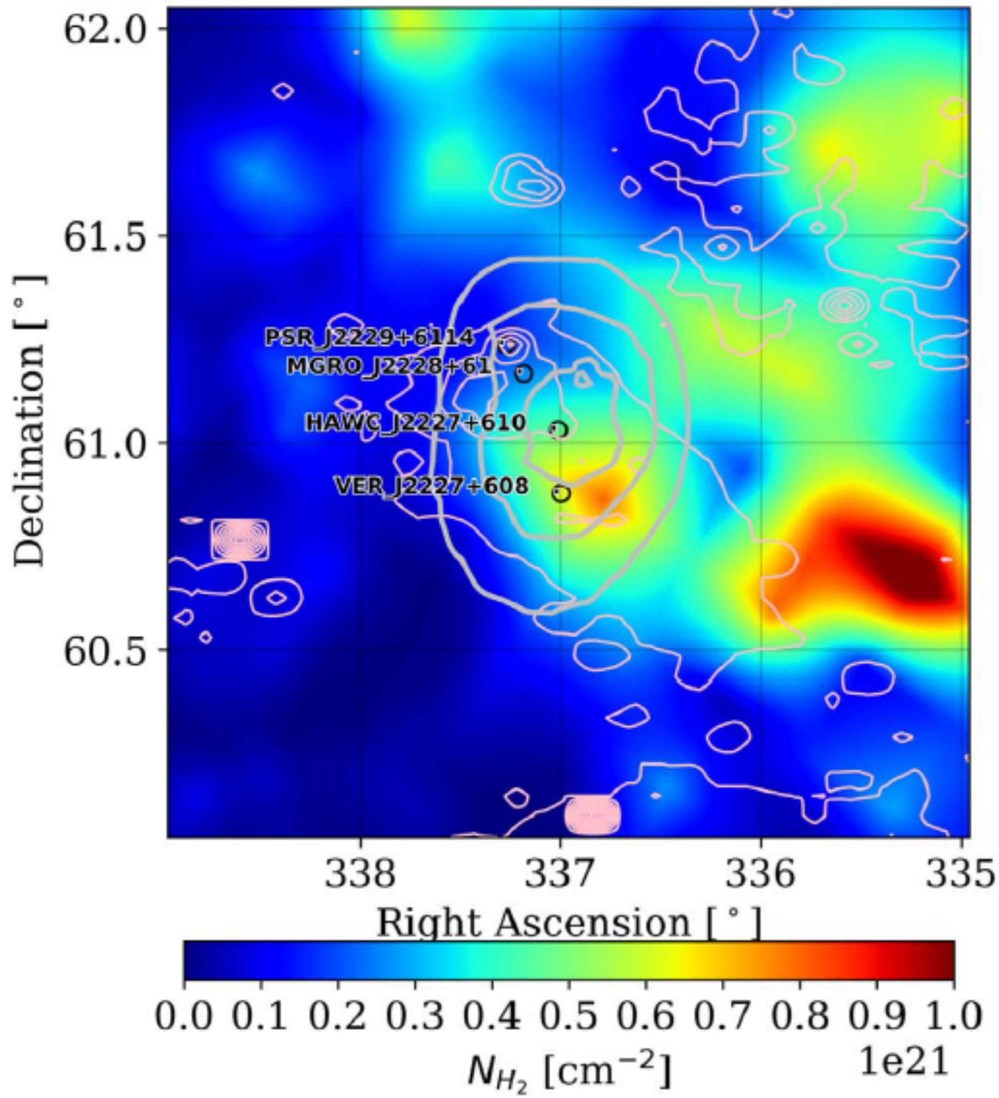
J. P. Halpern, F. Camilo, E. V. Gotthelf, and D. J. Helfand

3: SNR G106.3+2.7, G35.6-0.4





Liu et al. 2020 ApJ, 897, L34

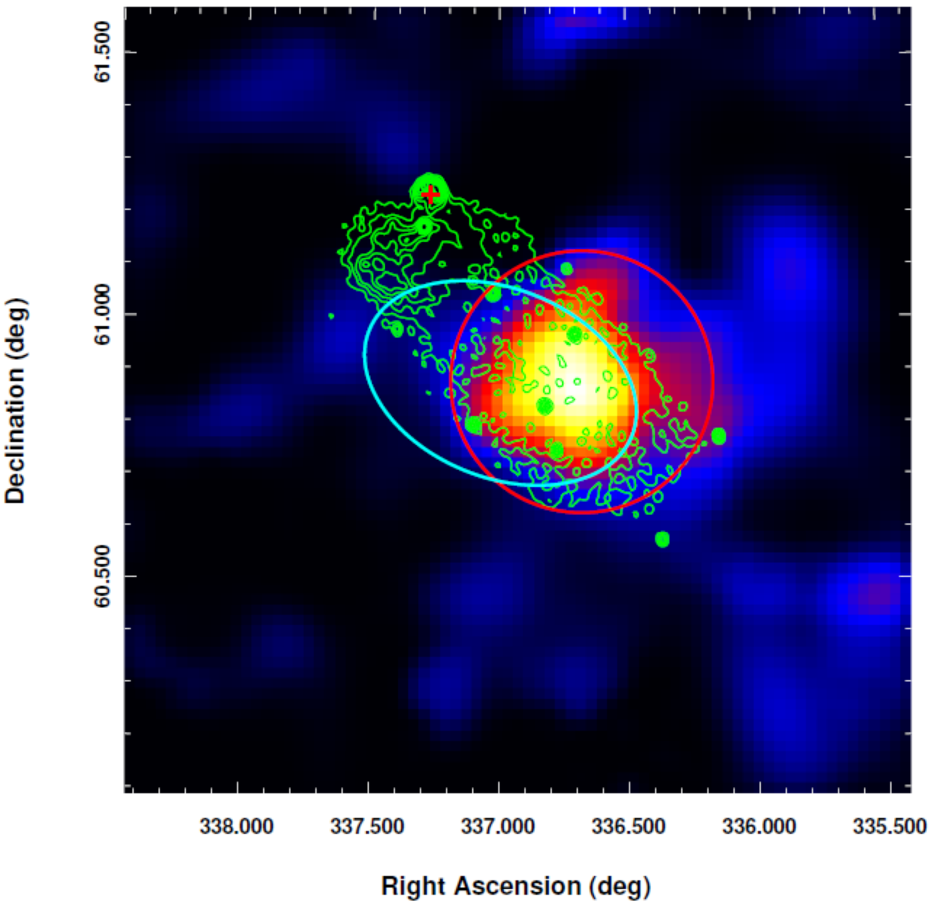


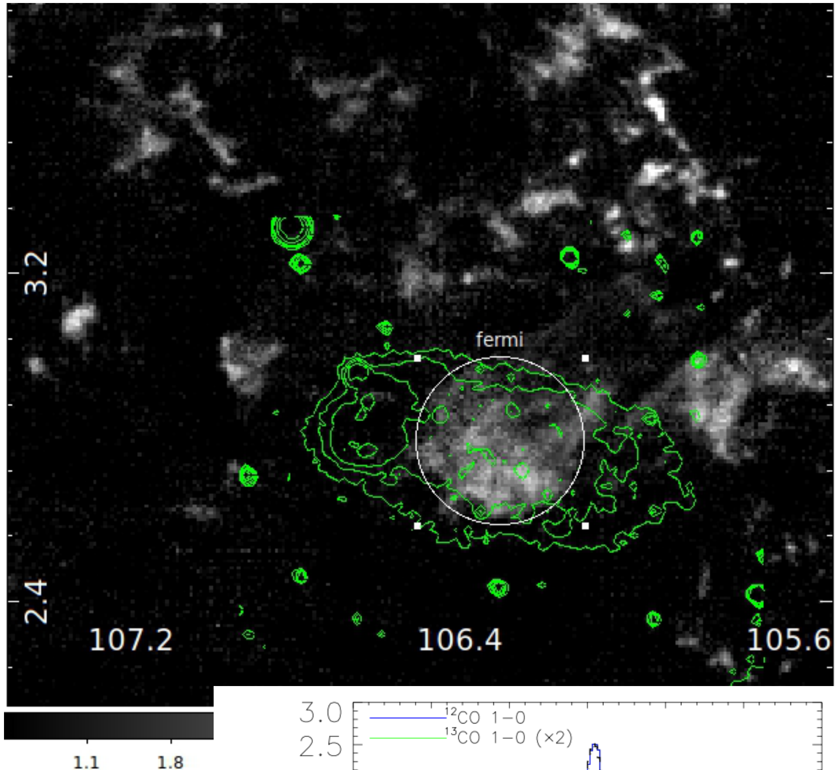
HAWC J2227+610 and Its Association with G106.3+2.7, a New Potential Galactic PeVatron

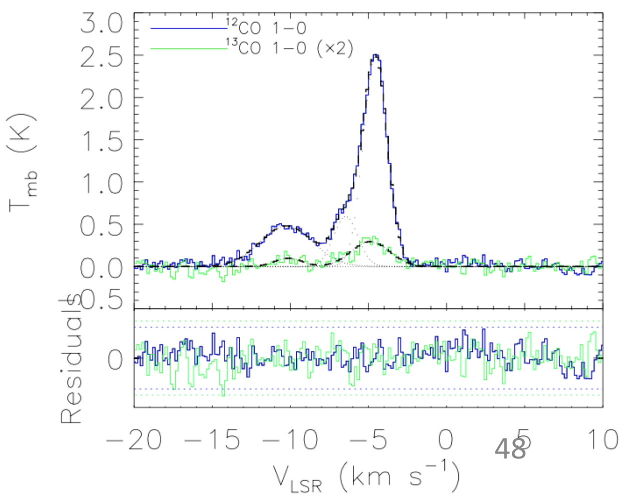
Conclusions

- Observation of Cas A has been published
- Manuscripts on W51C and gamma cygni are to be submitted
- Manuscripts on G150, G106, G35.6 should be submitted by the next collaboration meeting
- G69.7, HESS J1912, LHAASO J2108, J0341, G57.2, G65.1, G205 should also be analyzed

3: Fermi and CO

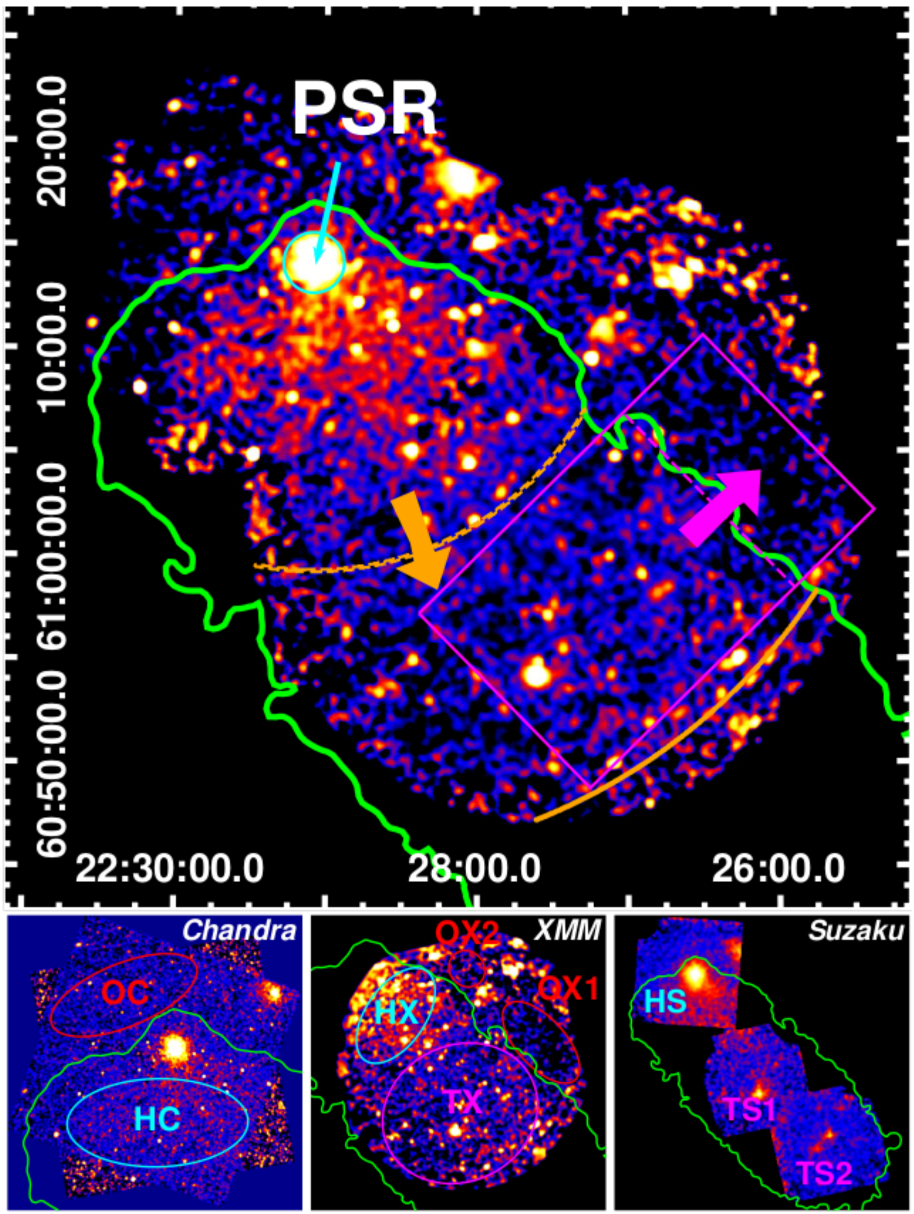


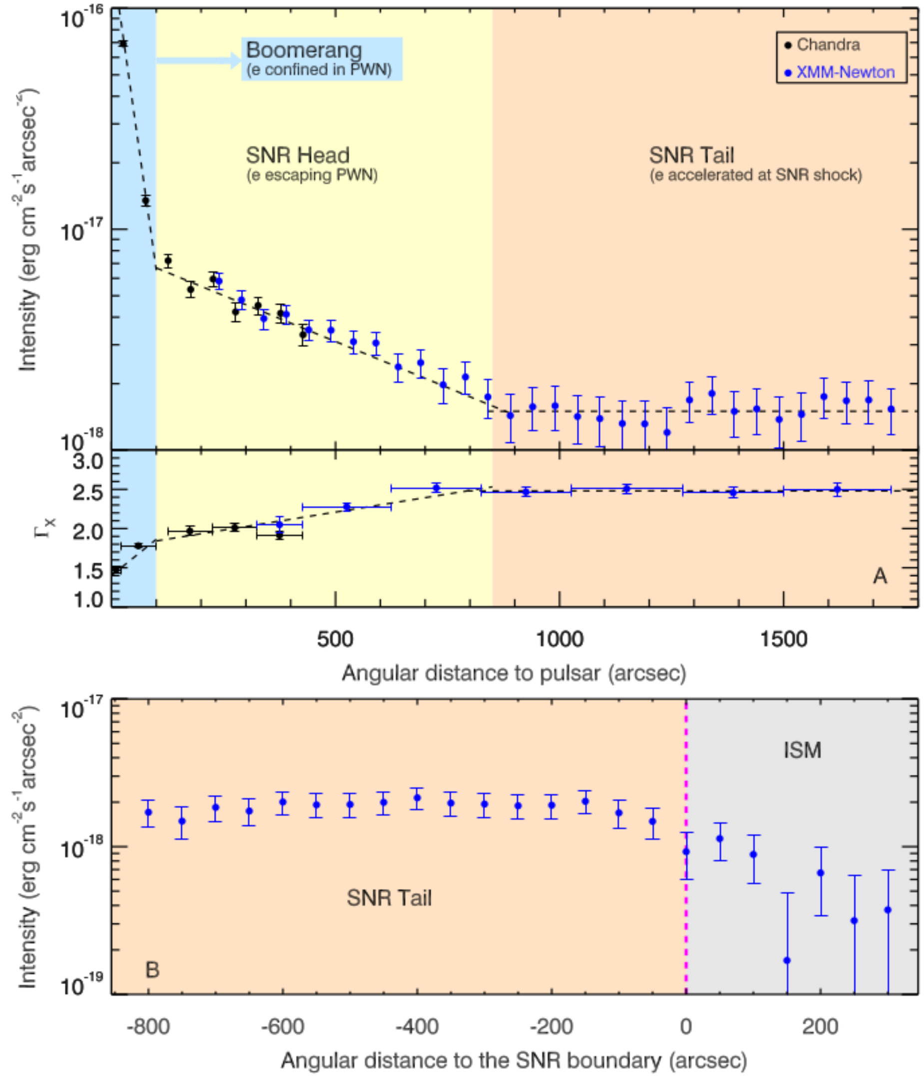




Xin et al. 2019 ApJ, 855, 162

3: X-ray Observations





Nonthernal X-ray emission is detected both from the head close to the PWN and the tail region

Ge, et al. Innovation, 2021, 2, 100118