# Supernova Remnant Origin of Galactic Cosmic Rays

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Nanjing University

**The 10th International Workshop on Air Shower Detection at High Altitudes**
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# Outline

1. Standard Paradigm and New Observations

2. Evolution of High-Energy Particle Distribution in SNRs

3. Cosmic Ray Anisotropy, Spectral Anomalies, and PeVatrons

4. Conclusions

# 1: Standard Paradigm

Supernova remnants (SNRs) have been proposed as the dominant contributors to galactic cosmic rays (Baade & Zwicky 1934).

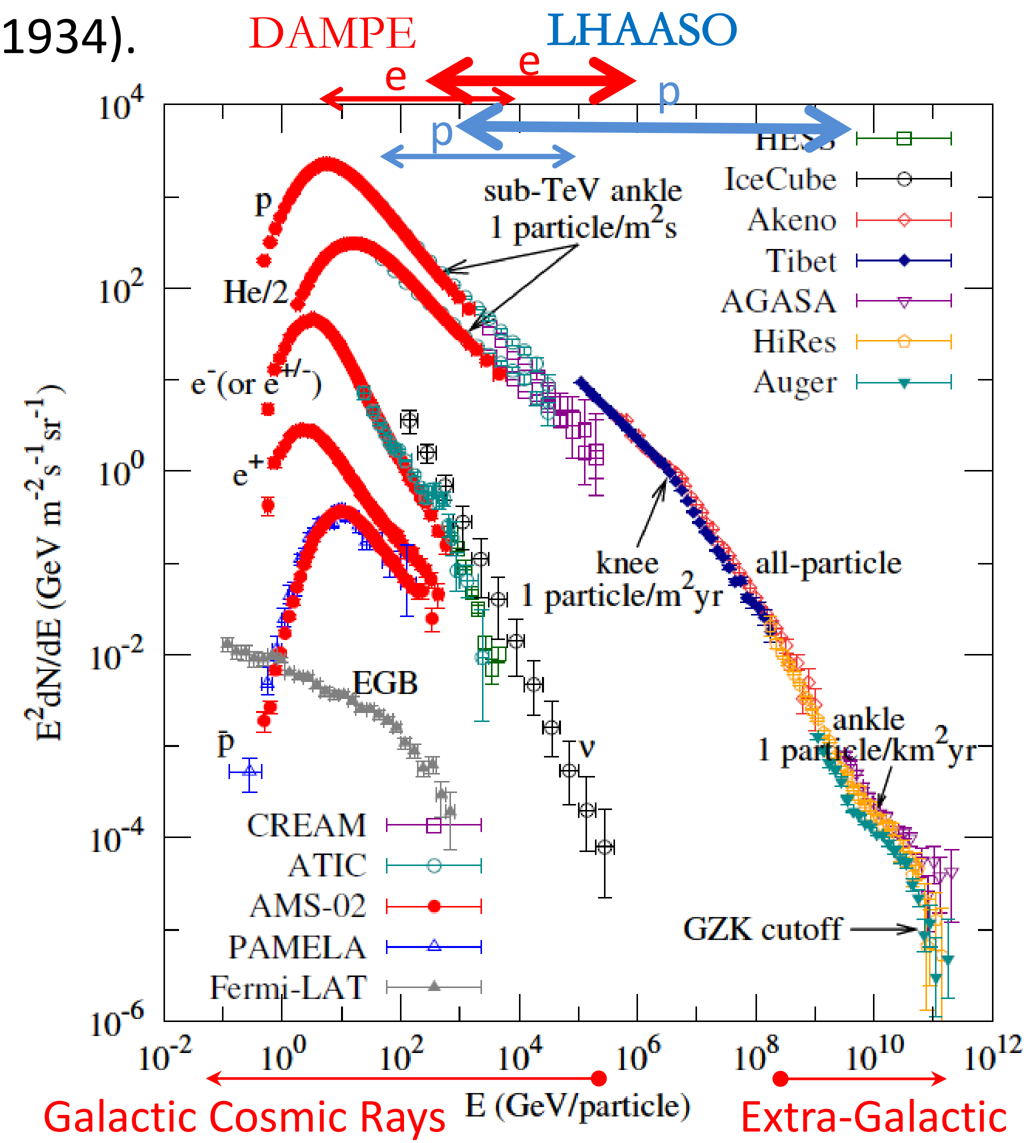
1、SNRs have enough total power ---10%, 3 per century, CR density (1ev/cm3)；

2、 Direct evidence:

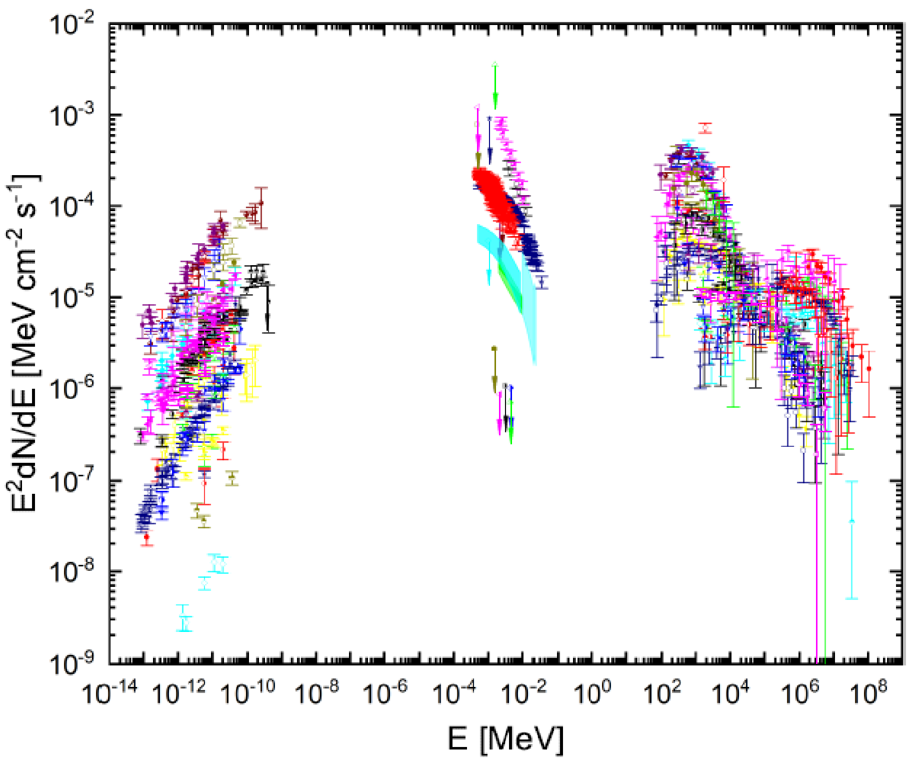
Radio emission (1948) —MeV-GeV electrons

Non-thermal X-ray emission (1995), TeV gamma-rays (2004) — TeV electrons

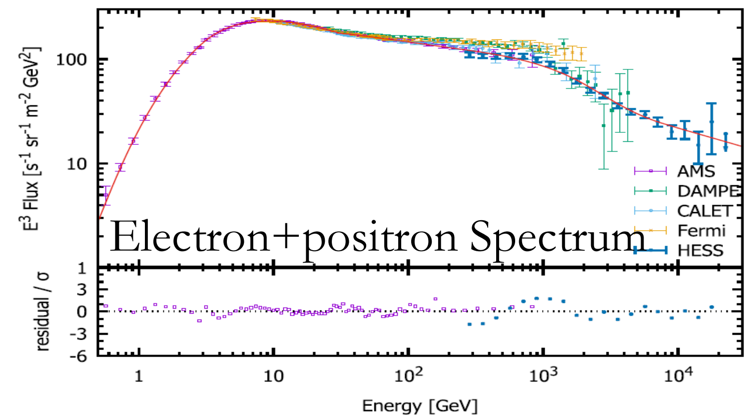
$\pi^0$ bump (2013 )W44,IC443,W51C — GeV protons

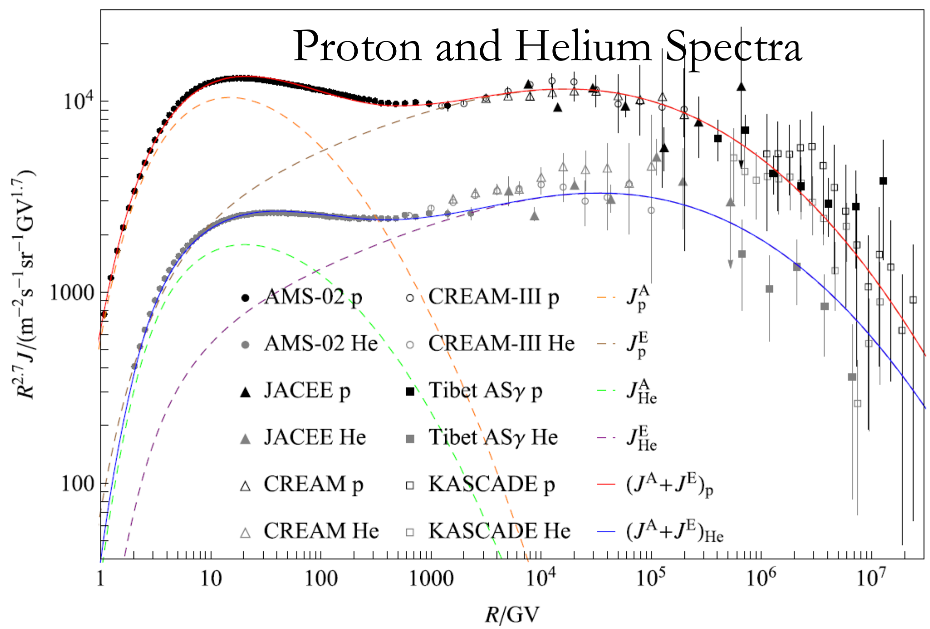


# 1: New Gamma-Ray and CR observations

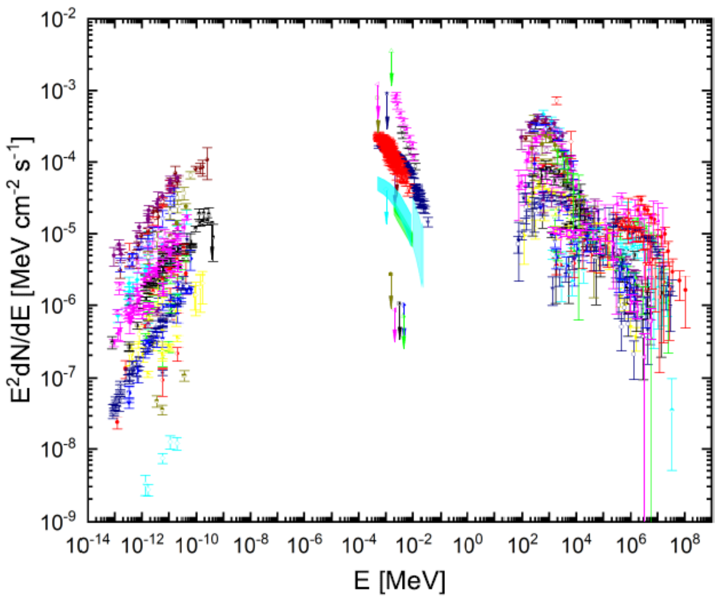



Multi-Wavelength Spectra of 34 SNRs



# 2: Evolution of High-Energy Particle Distribution in SNRs




The Astrophysical Journal, 874:50 (12pp), 2019 March 20 https://doi.org/10.3847/1538-4357/aaf392

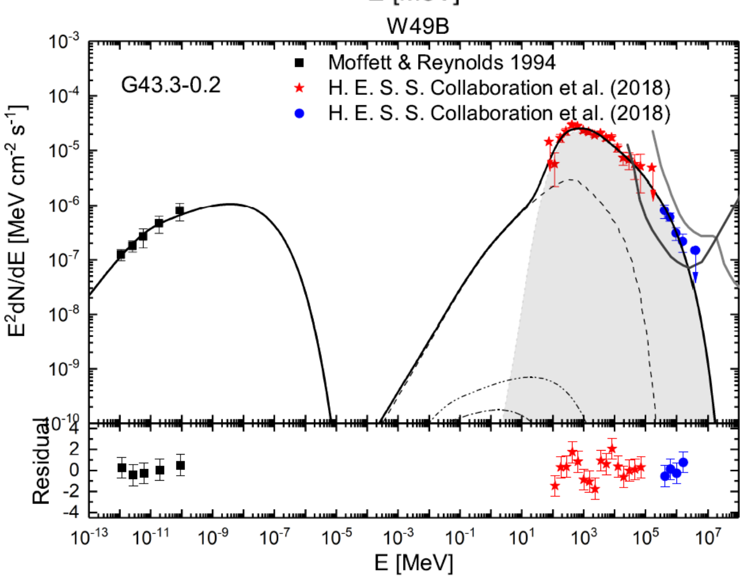

## Evolution of High-energy Particle Distribution in Supernova Remnants

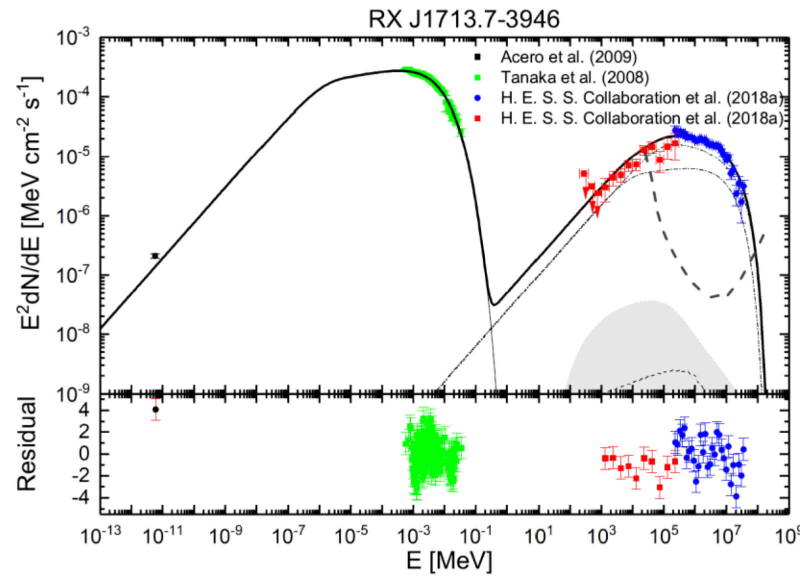
Houdun Zeng, Yuliang Xin, and Siming Liu
Key Laboratory of Dark Matter and Space Astronomy Purple Mountain Observatory, Chinese Academy of Sciences Nanjing 210034, People's Republic of China
zhd@pmo.ac.cn, liusm@pmo.ac.cn

$$N(P_i) = N_{0,i} \exp\left(-\frac{P_i}{P_{i,\mathrm{cut}}}\right) \begin{cases} P_i^{-\alpha} & \text{if} \quad P_i < P_{\mathrm{br}} \\ P_{\mathrm{br}}\, P_i^{-(\alpha+1)} & \text{if} \quad P_i \geqslant P_{\mathrm{br}}, \end{cases}$$

$N_{0,e}/N_{0,p}$ =0.01 $\quad P_{e,\mathrm{cut}} < P_{p,\mathrm{cut}}$

Markov Chain Monte Carlo Algorithm

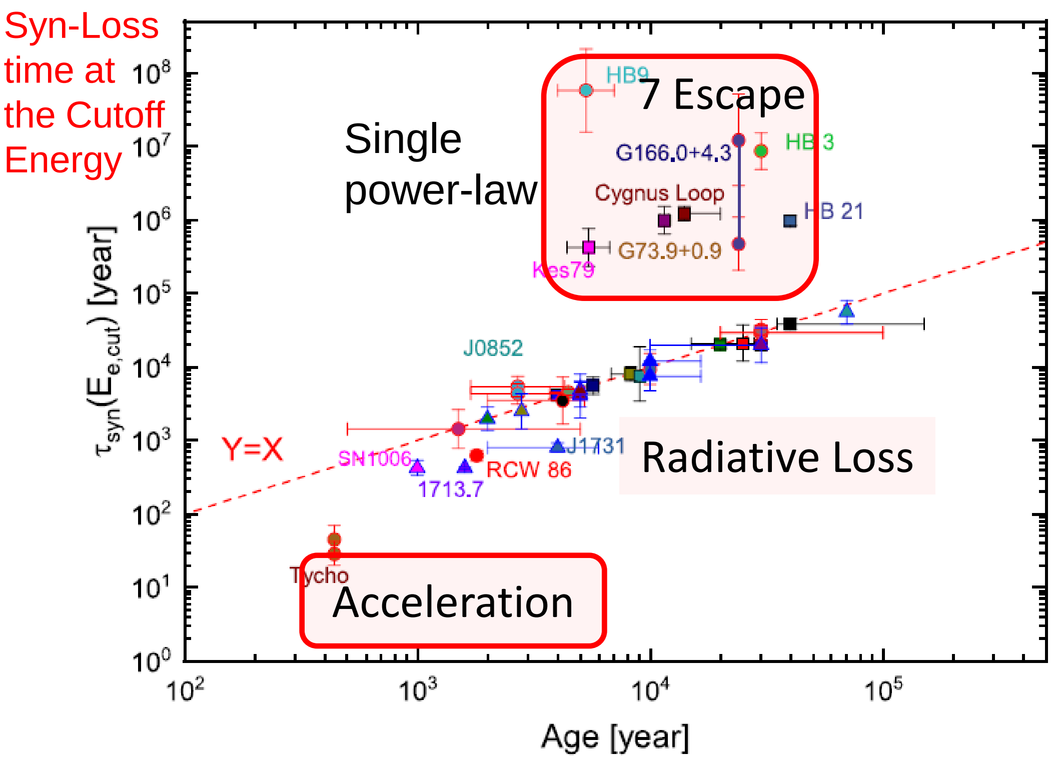


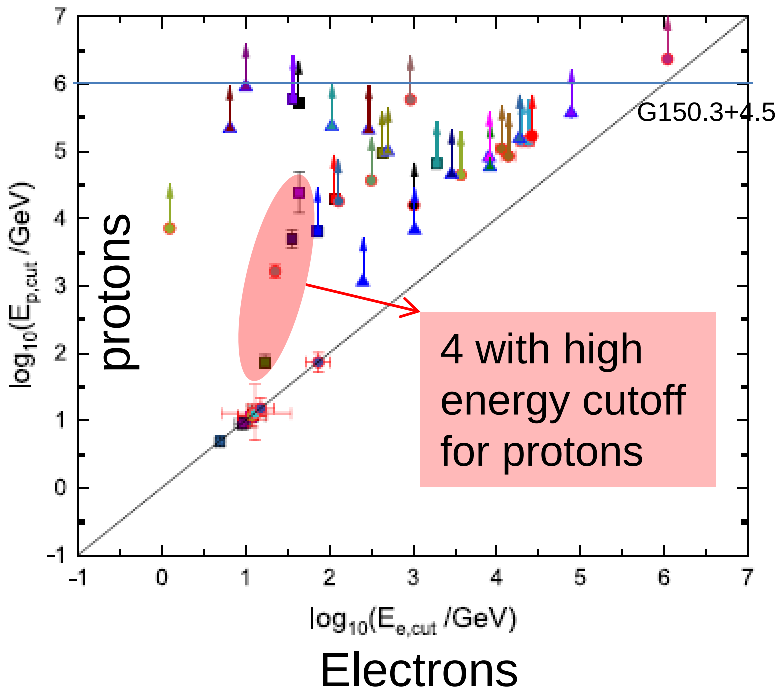
# 2: Evolution of High-Energy Particle Distribution in SNRs

**Electron Acceleration and Escape**

The cutoff energy of electrons is obtained either via the spectral fit or by the assumption that the energy loss time is equal to the age of the SNR

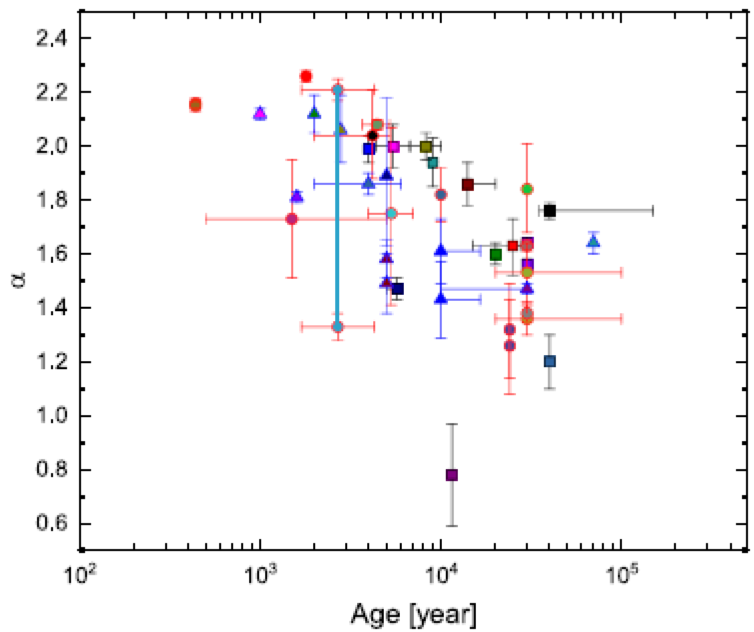



**High Energy Cutoffs**

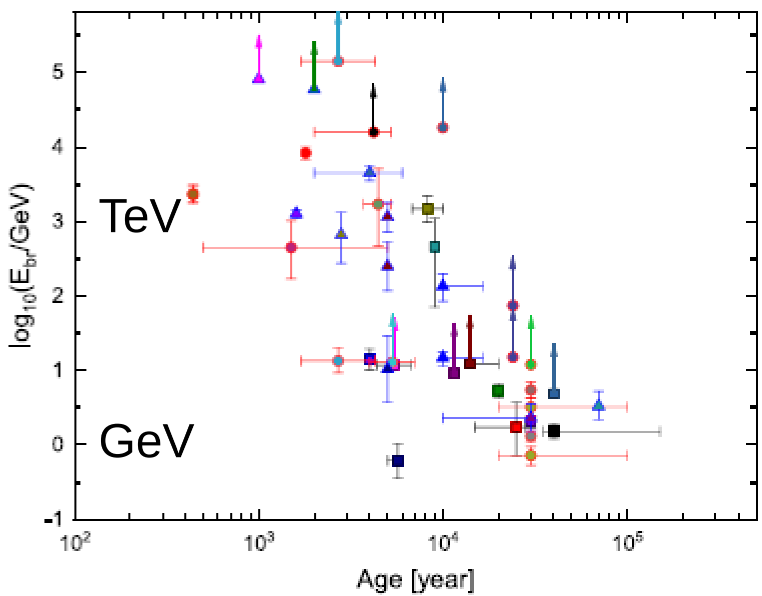


# 2: Evolution of High-Energy Particle Distribution in SNRs

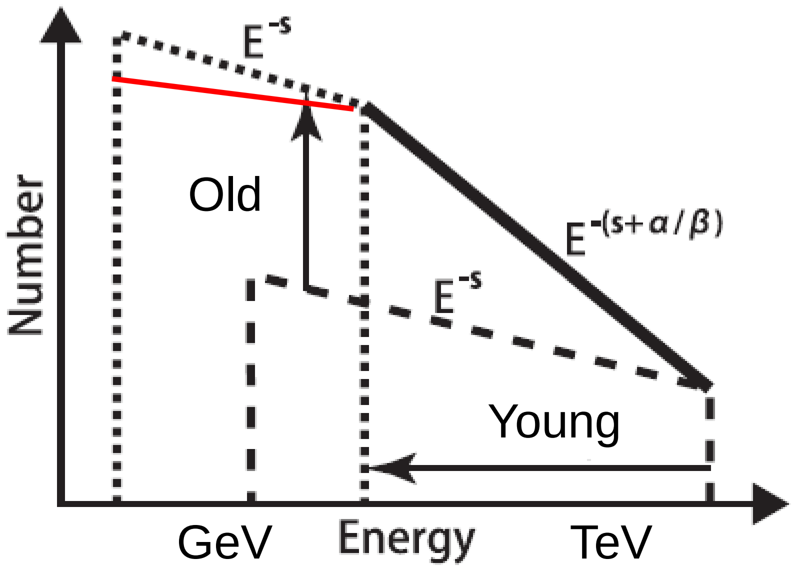
Low Energy Spectral Index

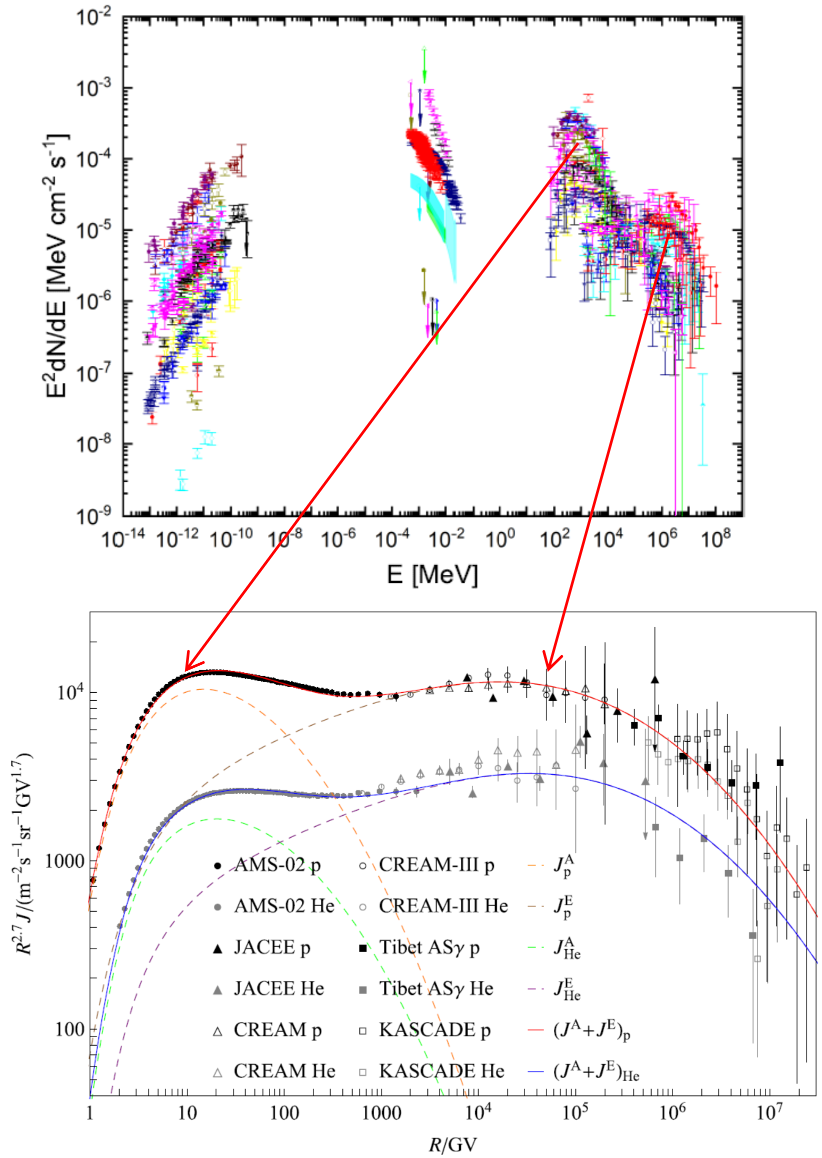



Spectral Break Energy



# 2: Ion Acceleration in SNRs




THE ASTROPHYSICAL JOURNAL LETTERS, 729:L13 (5pp), 2011 March 1 doi:10.1088/2041-8205/729/1/L13


COSMIC-RAY HELIUM HARDENING

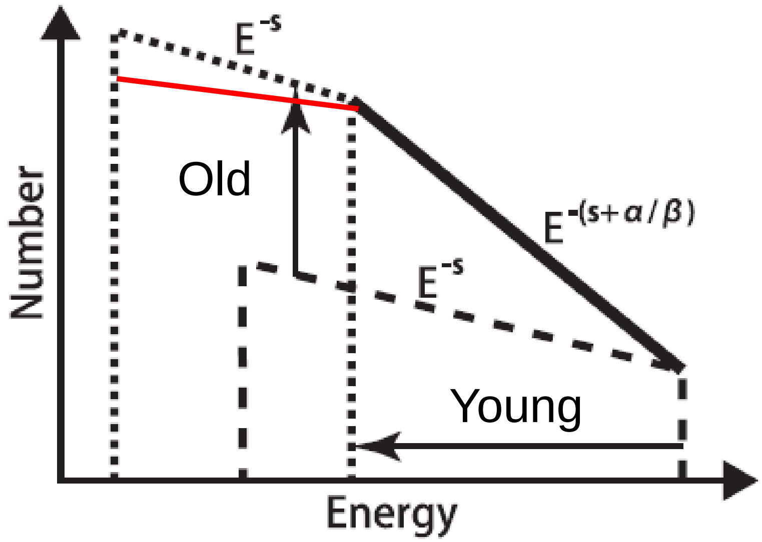
YUTAKA OHIRA AND KUNIHITO IOKA

THE ASTROPHYSICAL JOURNAL LETTERS, 844:L3 (5pp), 2017 July 20 https://doi.org/10.3847/2041-8213/aa7de1


**Anomalous Distributions of Primary Cosmic Rays as Evidence for Time-dependent Particle Acceleration in Supernova Remnants**

Yiran Zhang[1,2], Siming Liu[1,2], and Qiang Yuan[1,2]

# 2: Ion Acceleration in SNRs




THE ASTROPHYSICAL JOURNAL LETTERS, 729:L13 (5pp), 2011 March 1 doi:10.1088/2041-8205/72

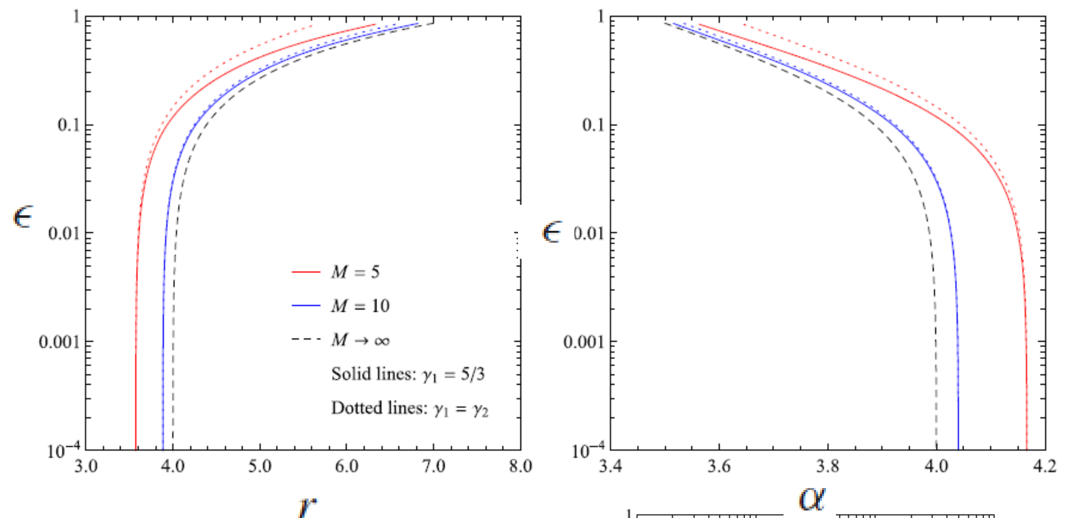

COSMIC-RAY HELIUM HARDENING

YUTAKA OHIRA AND KUNIHITO IOKA

MNRAS 482, 5268–5274 (2019) doi:10.1093/mnras/sty3136
Advance Access publication 2018 November 19

**Global constraints on diffusive particle acceleration by strong non-relativistic shocks**

Yiran Zhang[1,2★] and Siming Liu[1,2★]

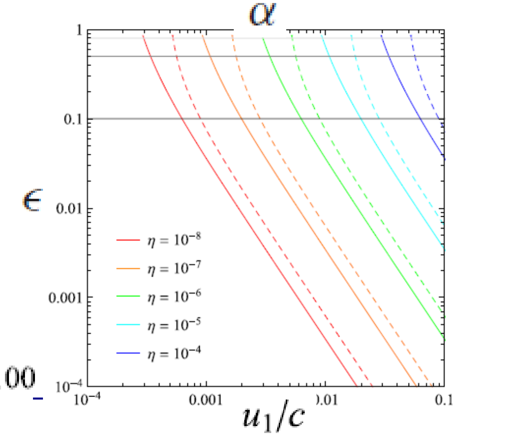



$$\epsilon = \frac{P_{\rm cr}}{P_1 + \rho_1 u_1^2}$$

$$\eta \approx n_{\rm cr}/n$$

$$\xi_{\rm m} = \frac{p_{\rm m}}{mc}.$$

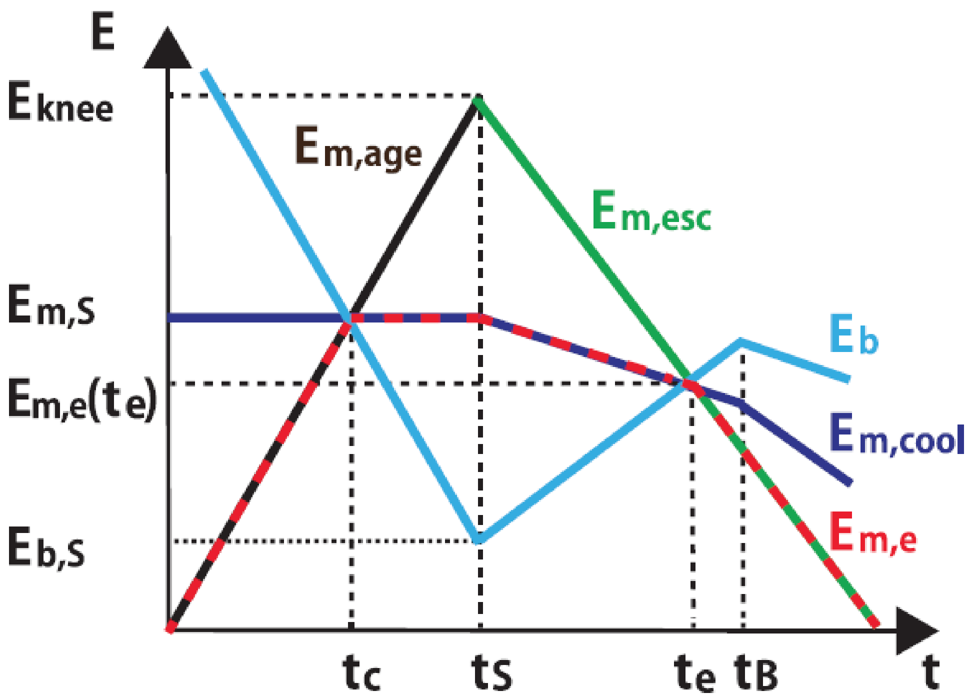
$$r = \frac{\frac{1}{\gamma_1} + M^2 + \sqrt{\left(\frac{1}{\gamma_1} + M^2\right)^2 + \left(\frac{1}{\gamma_2^2} - 1\right)\left(\frac{2}{\gamma_1 - 1} + M^2\right) M^2}}{\left(1 - \frac{1}{\gamma_2}\right)\left(\frac{2}{\gamma_1 - 1} + M^2\right)},$$

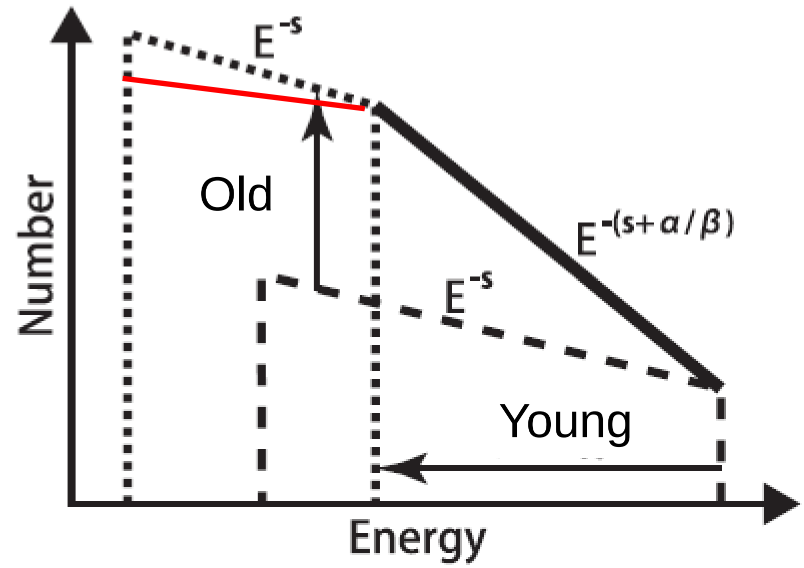



Solid lines: $\xi_{\rm m} = 10$

Dashed lines: $\xi_{\rm m} = 100$

# 2: Electron Acceleration in SNRs




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]

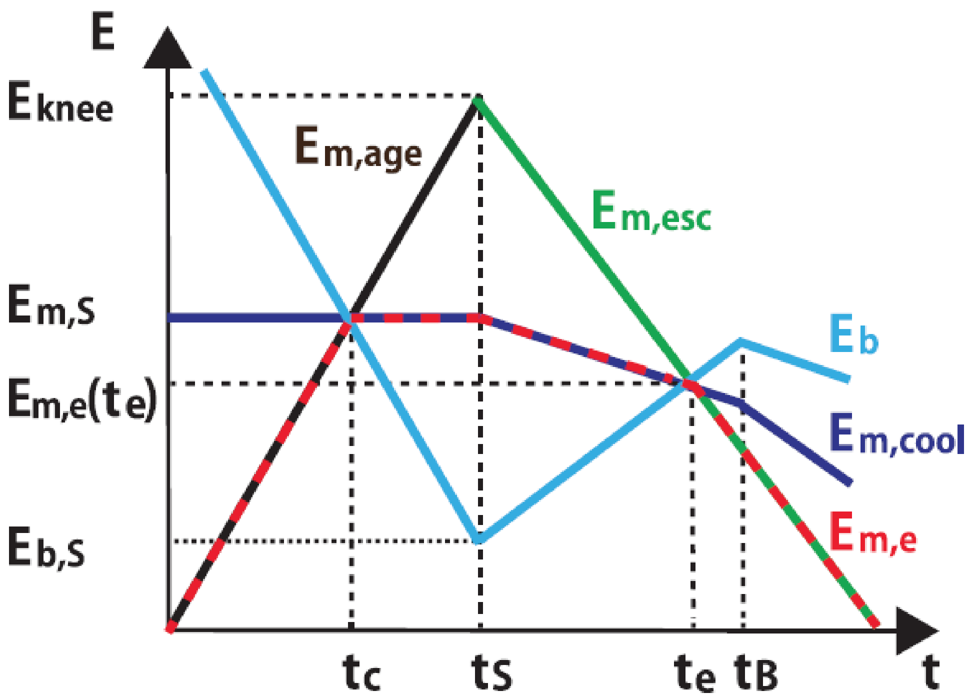
The Astrophysical Journal Letters, 729:L13 (5pp), 2011 March 1 doi:10.1088/2041-8205/729/1/L13


COSMIC-RAY HELIUM HARDENING

Yutaka Ohira and Kunihito Ioka

| | |
|---|---|
| $E_{\mathrm{m,age}}(t)$ | Given by $t_{\mathrm{acc}}(E, t) = t$ |
| $E_{\mathrm{m,esc}}(t)$ | Given by $t_{\mathrm{acc}}(E, t) = t_{\mathrm{esc}}(E, t)$ |
| $E_{\mathrm{m,cool}}(t)$ | Given by $t_{\mathrm{acc}}(E, t) = t_{\mathrm{cool}}(E, t)$ |
| $E_{\mathrm{b}}(t)$ | Given by $t_{\mathrm{cool}}(E, t) = t$ |

# 2: Electron Acceleration in SNRs

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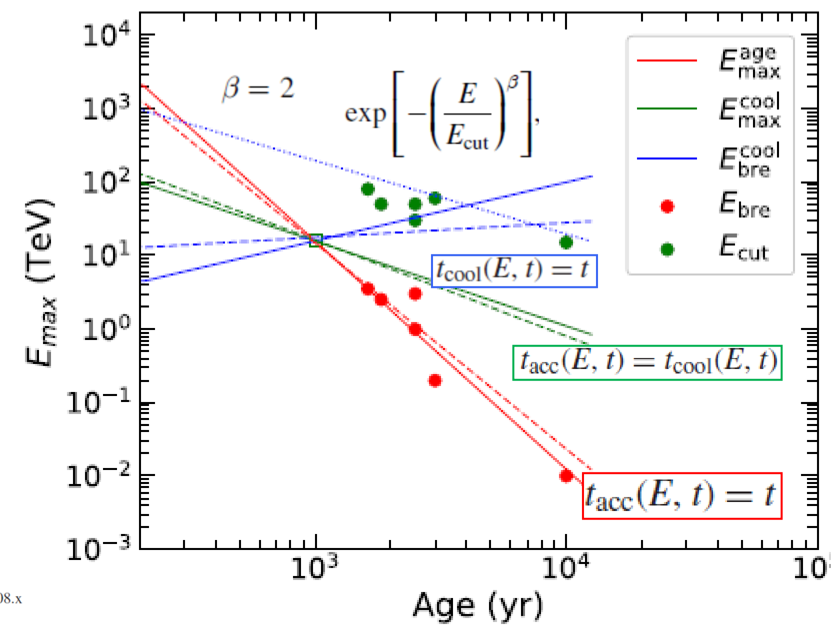
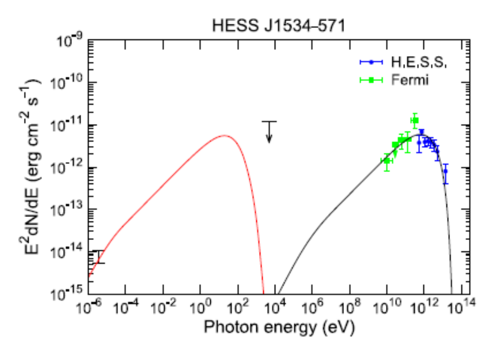
$$\tau_{\rm acc} = \eta_{\rm acc} D(E, t)/u_s^2,$$
$$D(E, t) = \eta_g cE/3eB(t),$$

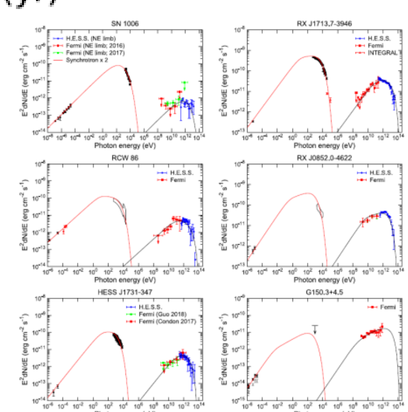
PHYSICAL JOURNAL, 876:24 (8pp), 2019 May 1 https://doi.org/10.3847/1538-4357/ab14df


**Electron Acceleration in Middle-age Shell-type γ-Ray Supernova Remnants**

Xiao Zhang[1,2] and Siming Liu[3]



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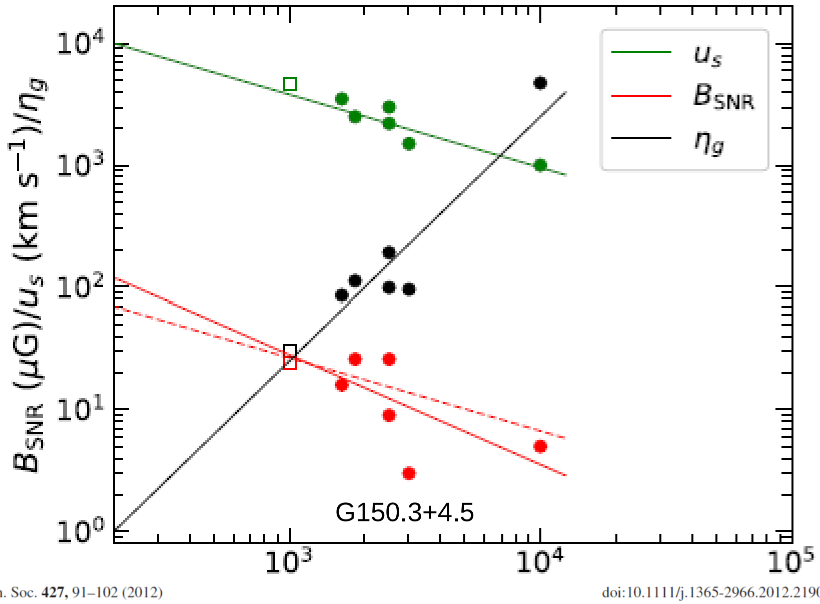


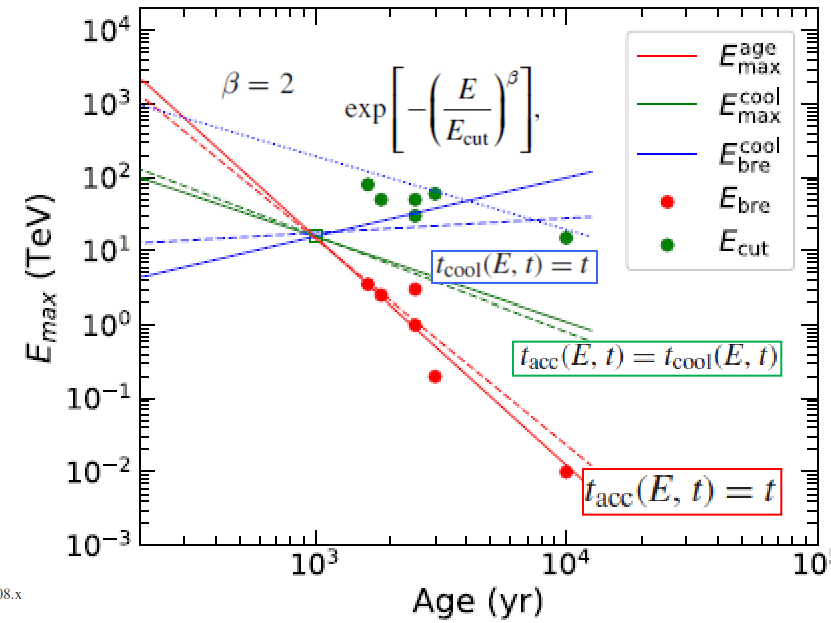


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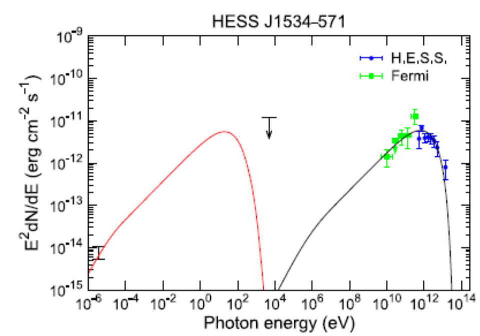
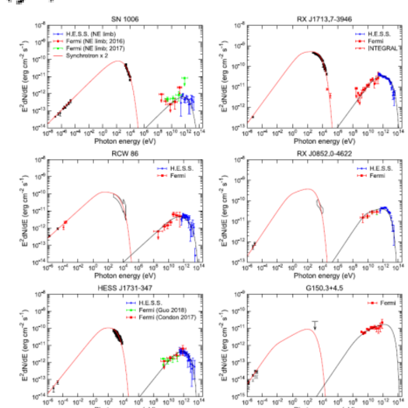
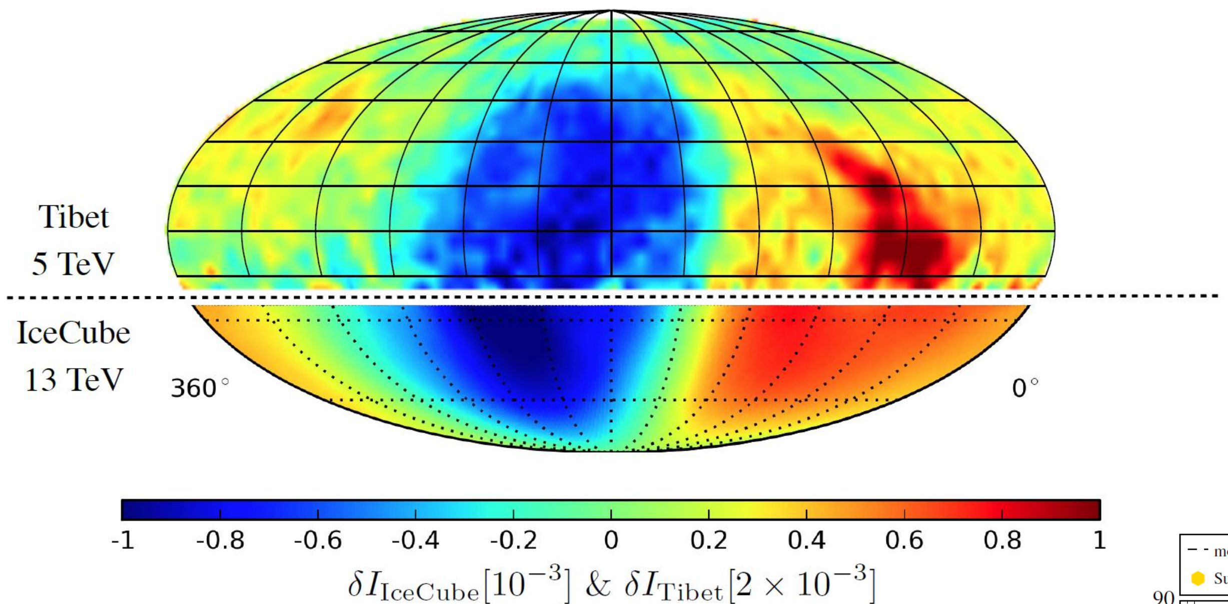
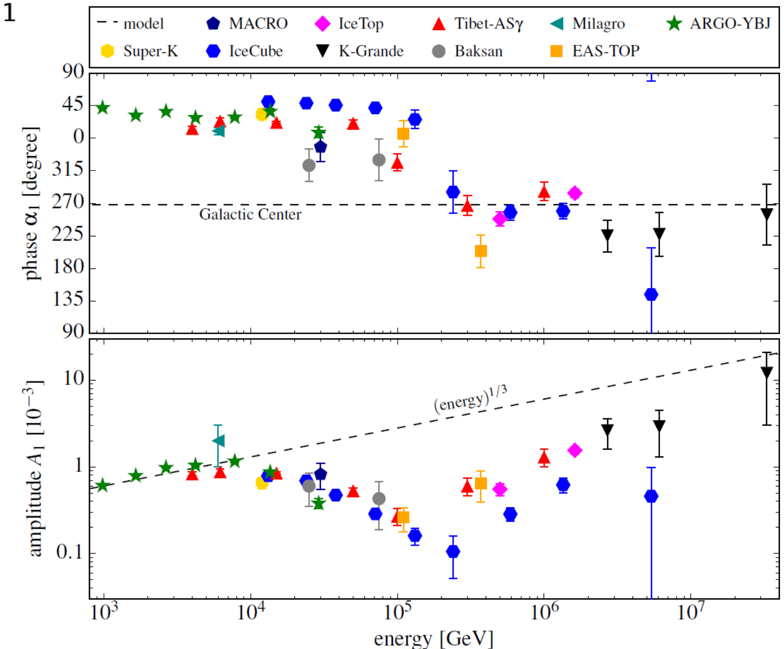


# 3: Cosmic Ray Anisotropy, Spectral Anomalies and PeVatrons




Cosmic ray anisotropy is suppressed in the TeV range!



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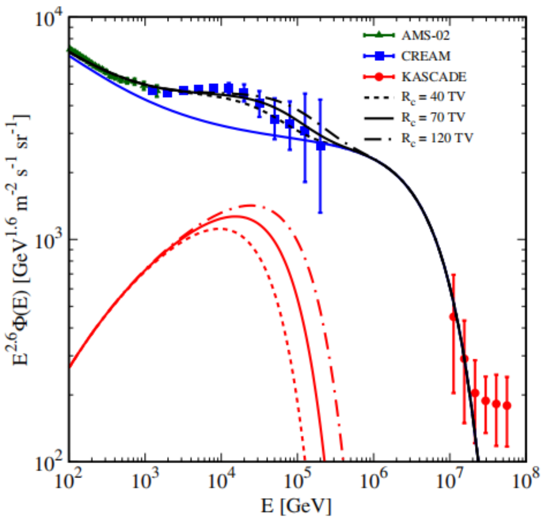
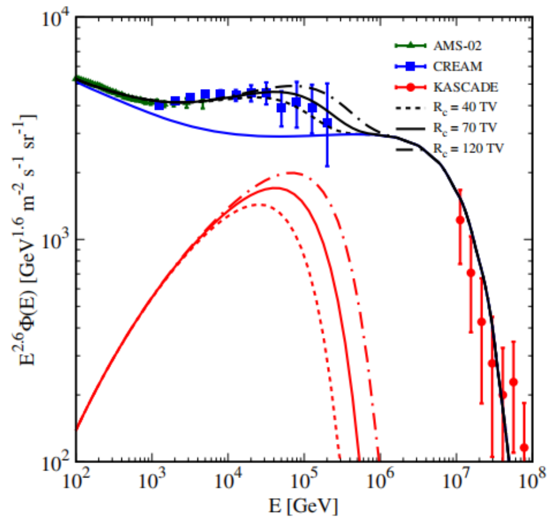


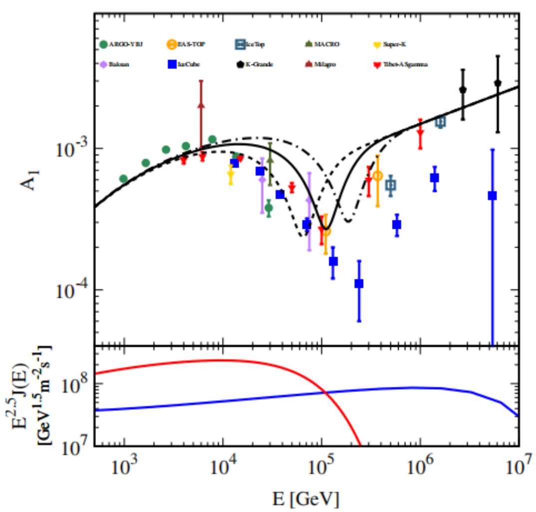

Journal of Cosmology and Astroparticle Physics

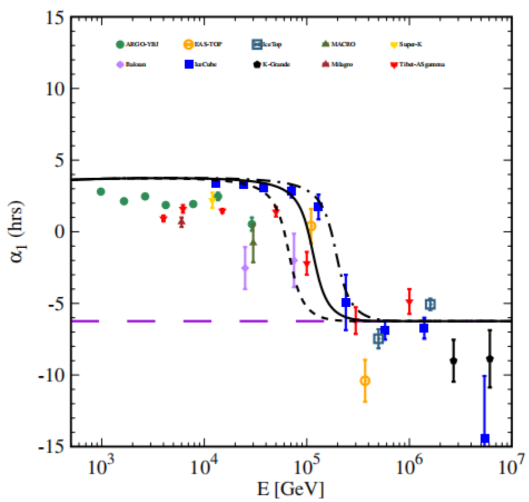
An IOP and SISSA journal

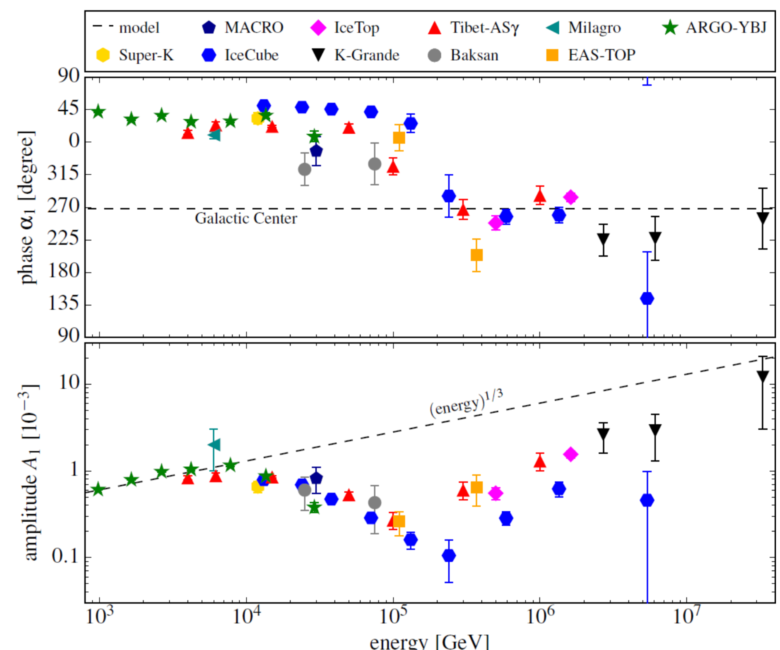
## Anisotropies of different mass compositions of cosmic rays


Bing-Qiang Qiao,[a,b,1] Wei Liu,[c,1] Yi-Qing Guo[c,1] and Qiang Yuan[a,b,d,1]


Rc=28TV



# 3: Cosmic Ray Anisotropy, Spectral Anomalies and PeVatrons

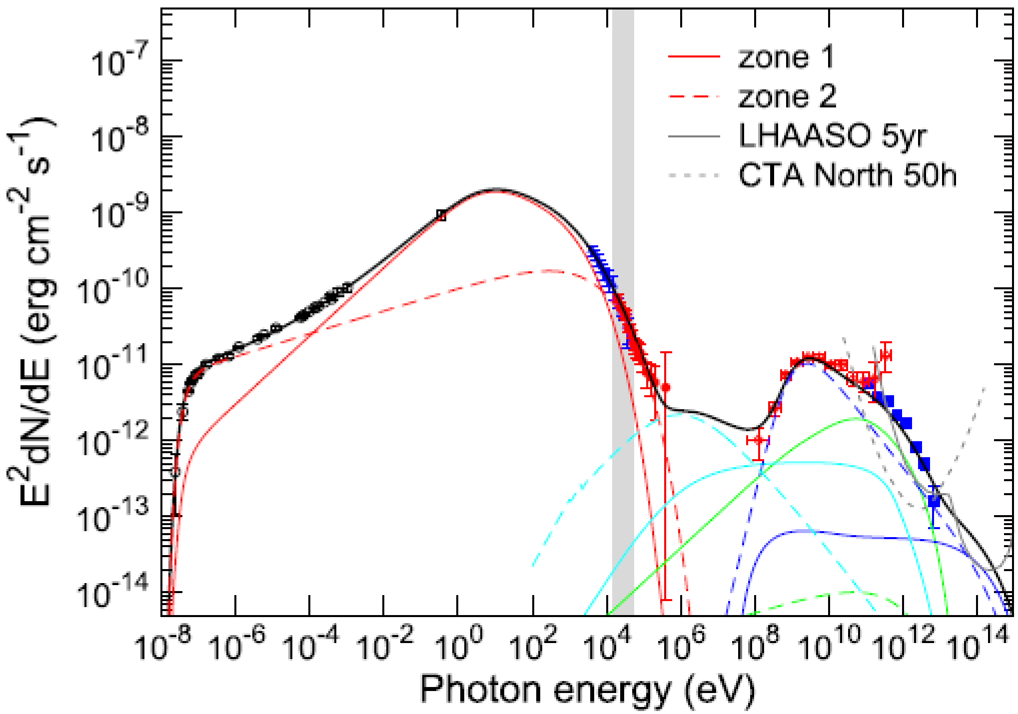
THE ASTROPHYSICAL JOURNAL, 874:98 (6pp), 2019 March 20 https://doi.org/10.3847/1538-4357/ab09fe


CrossMark

## Is Supernova Remnant Cassiopeia A a PeVatron?

Xiao Zhang[1,2] and Siming Liu[3]

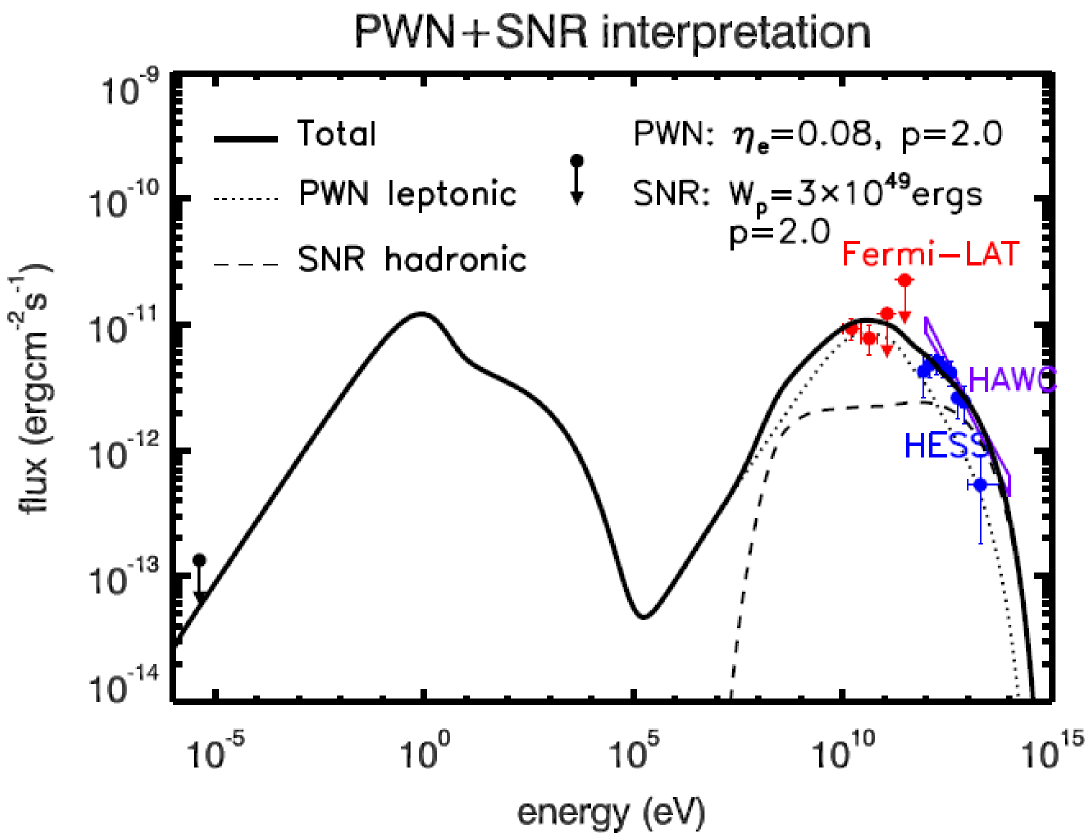
Wp = 1e48ergs

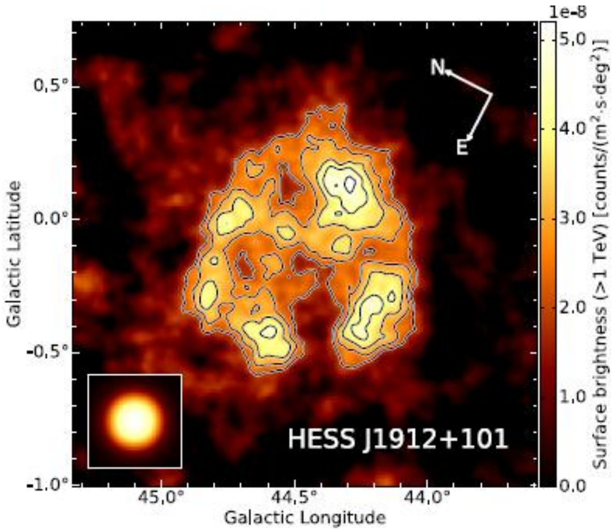


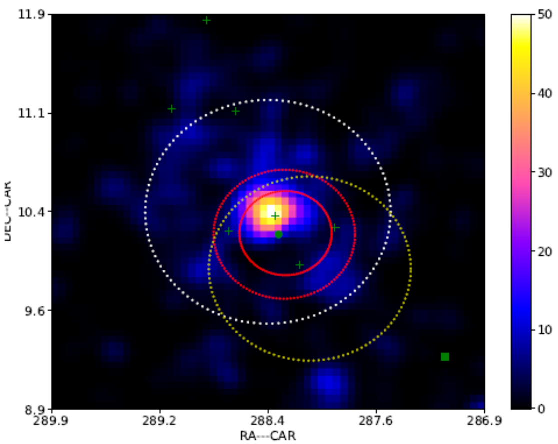
# 3: Cosmic Ray Anisotropy, Spectral Anomalies and PeVatrons

DISCOVERY OF A SPATIALLY EXTENDED GEV SOURCE IN THE VICINITY OF THE TEV HALO CANDIDATE 2HWC J1912+099: A TEV HALO OR SUPERNOVA REMNANT ?

HAI-MING ZHANG[1,4], SHAO-QIANG XI[1,4], RUO-YU LIU[1,2], YU-LIANG XIN[3], SIMING LIU[3], XIANG-YU WANG[1,4]



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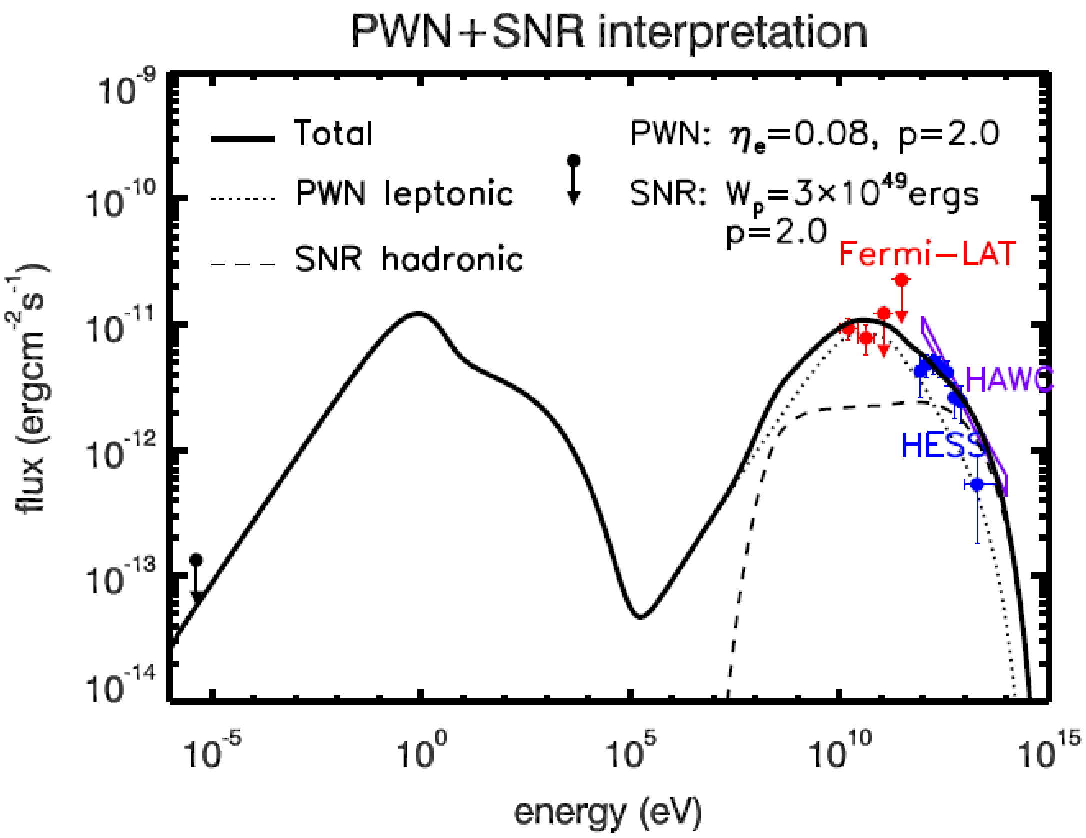
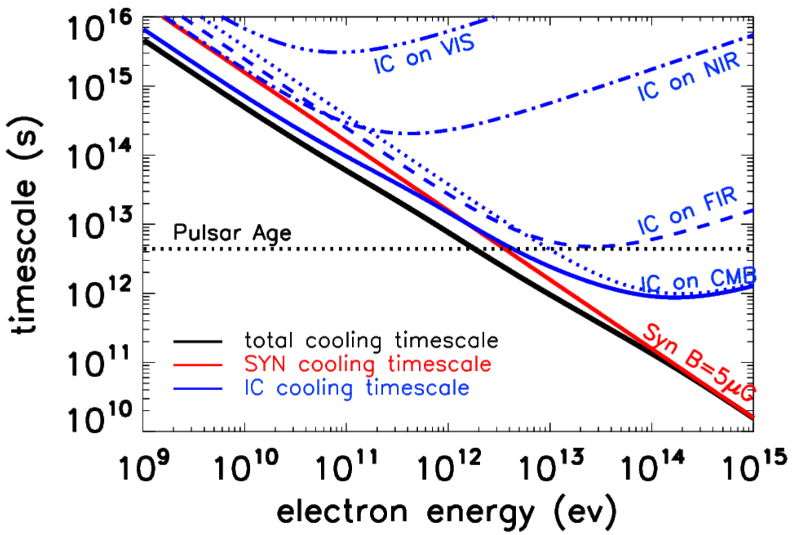



70-200kyr

Ec<300TeV

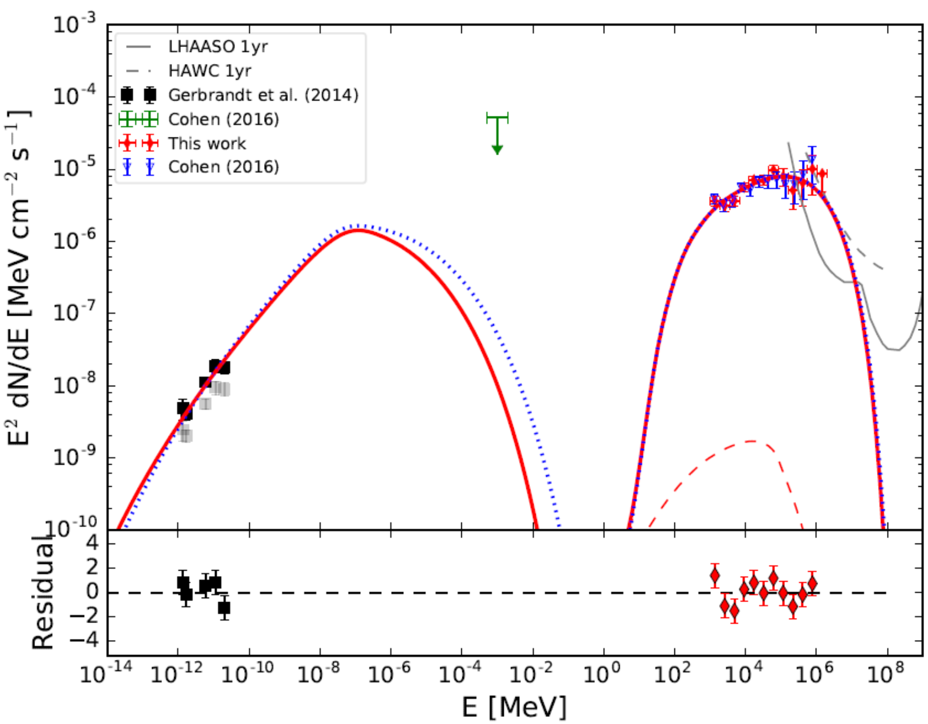
# 3: Cosmic Ray Anisotropy, Spectral Anomalies and PeVatrons

THE ASTROPHYSICAL JOURNAL, 843:139 (24pp), 2017 July 10 https://doi.org/10.3847/1538-4357/aa775a

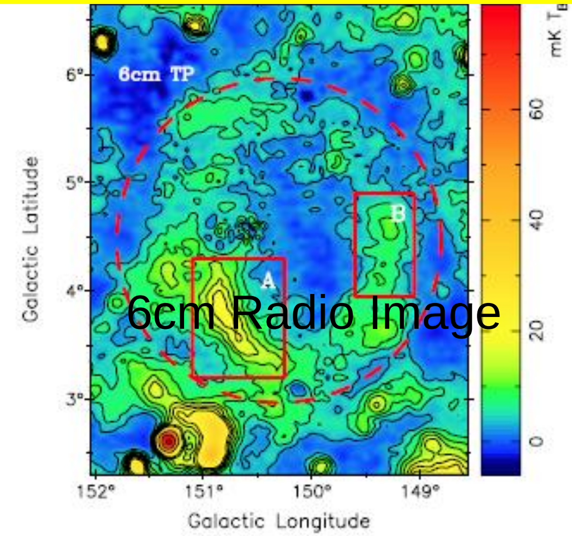

**Search for Extended Sources in the Galactic Plane Using Six Years of *Fermi*-Large Area Telescope Pass 8 Data above 10 GeV**

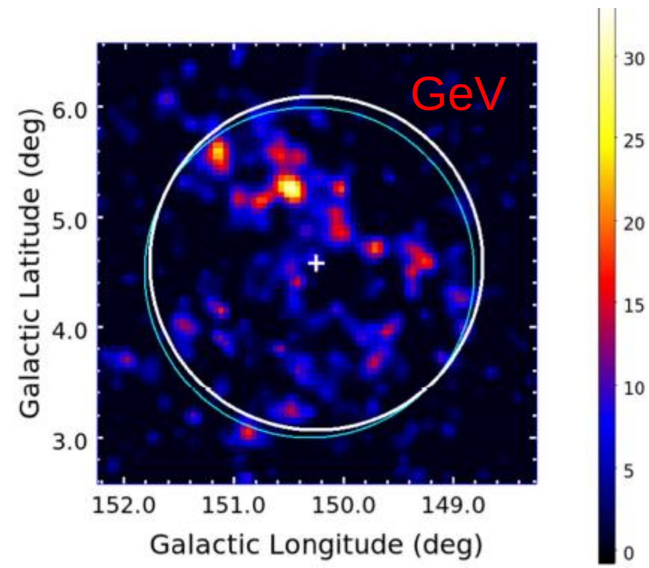
M. Ackermann[1], M. Ajello[2], L. Baldini[3], J. Ballet[4], G. Barbiellini[5,6], D. Bastieri[7,8], R. Bellazzini[9], E. Bissaldi[10], E. D. Bloom[11],

G150.3+4.5 J427.10+5527




Ec=20TeV



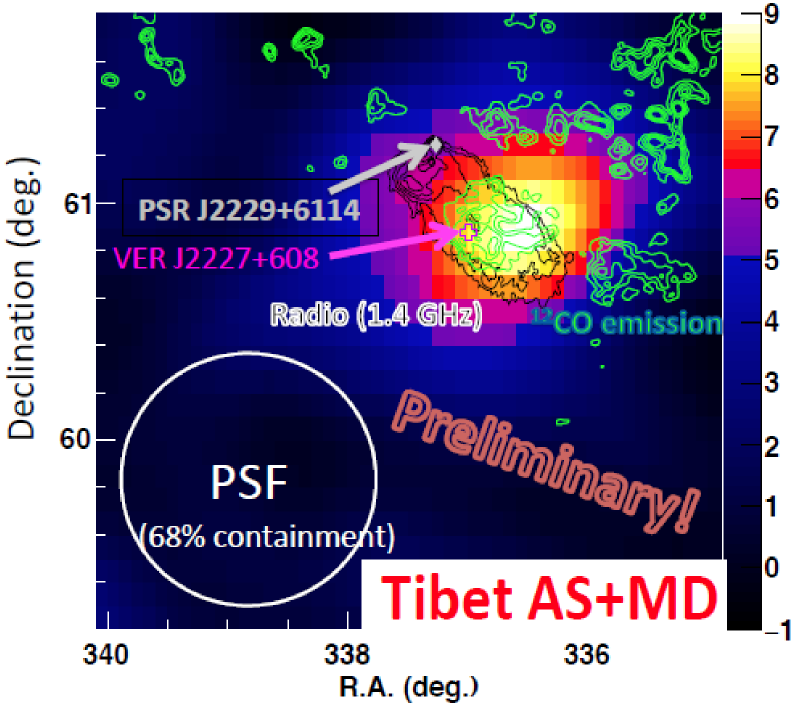
THE ASTROPHYSICAL JOURNAL, 885:162 (6pp), 2019 November 10 https://doi.org/10.3847/1538-4357/ab48ee

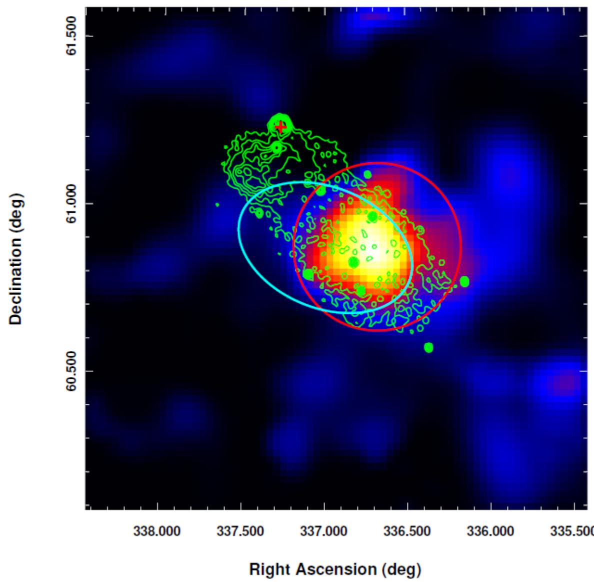

# VER J2227+608: A Hadronic PeVatron Pulsar Wind Nebula?

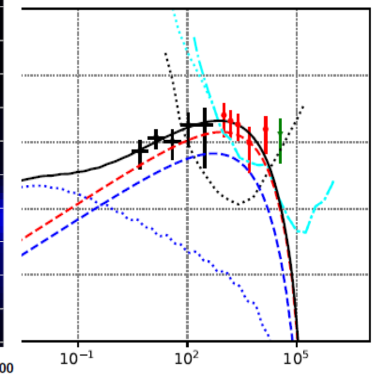
Yuliang Xin[1], Houdun Zeng[1], Siming Liu[1,2], Yizhong Fan[1,2], and Daming Wei[1,2]

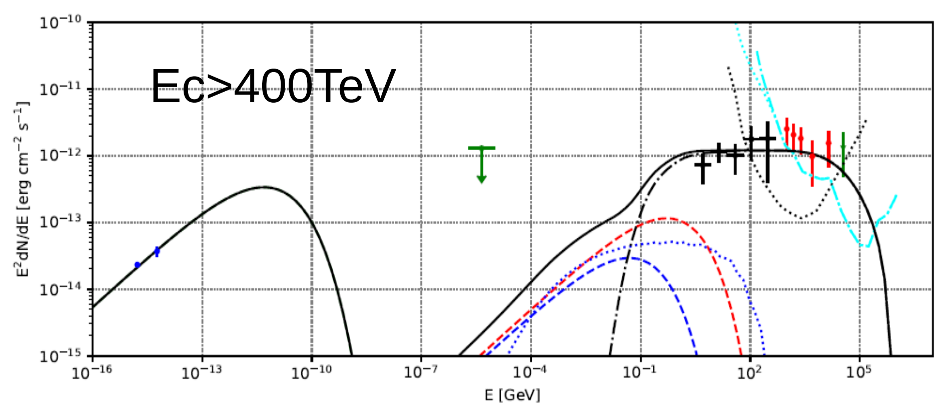
SNR G106.3+2.7

> 10 TeV



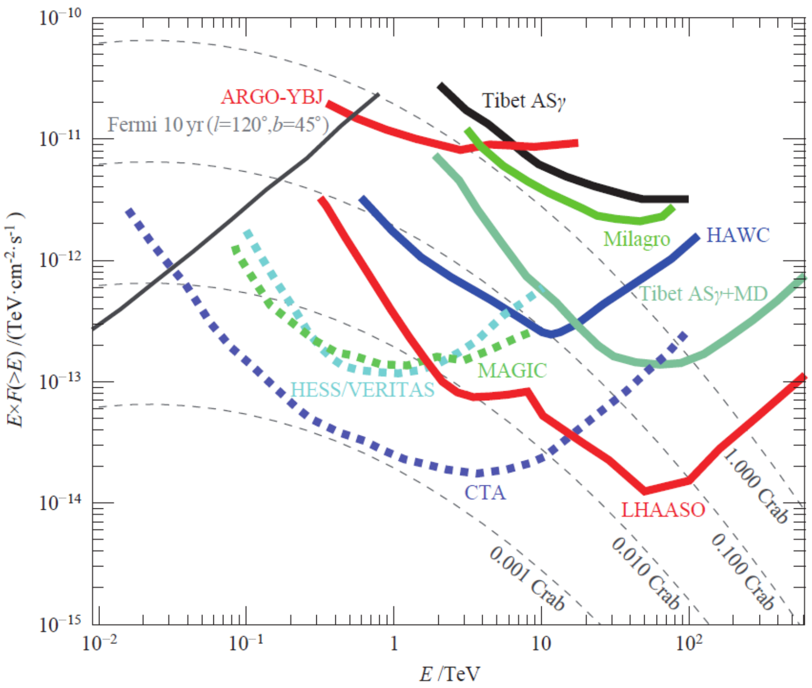


# Conclusions

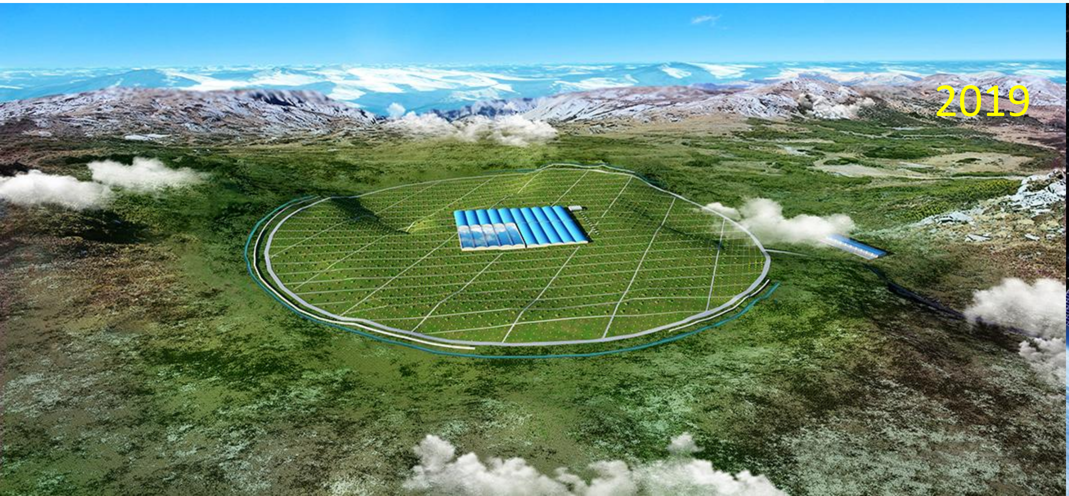
- Multi-wavelength observations suggest that GeV and TeV cosmic rays can be attributed to particle acceleration in old and young SNRs, respectively.
- There is no evidence for PeV particle acceleration in SNRs.
- PWNs may be important PeVatrons

Thanks for your attention!

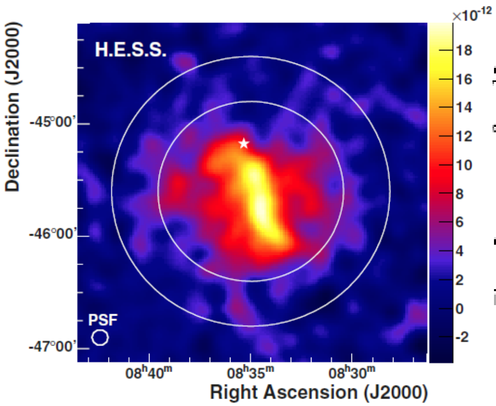
# 立项依据：LHAASO和DAMPE

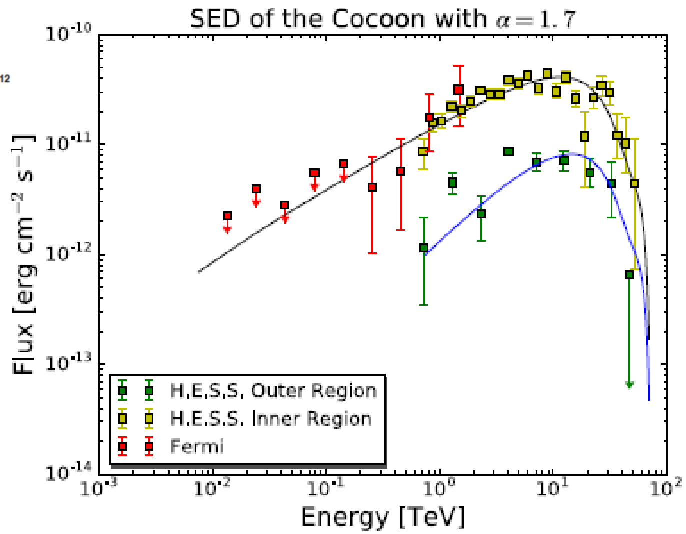


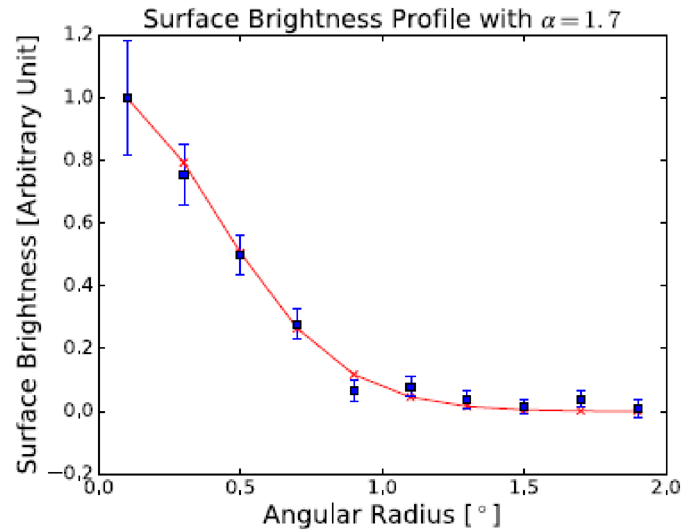

| Parameter | Value |
|---|---|
| Energy range of gamma-rays/electrons | 5 GeV to 10 TeV |
| Energy resolution (electron and gamma) | <1.5% at 800 GeV |
| Energy range of protons/heavy nuclei | 50 GeV to 100 TeV |
| Energy resolution of protons | <40% at 800 GeV |
| Eff. area at normal incidence (gamma) | 1100 $cm^2$ at 100 GeV |
| Geometric factor for electrons | 0.3 $m^2$ sr above 30 GeV |
| Photon angular resolution | <0.2 degree at 100 GeV |
| Field of View | 1.0 sr |

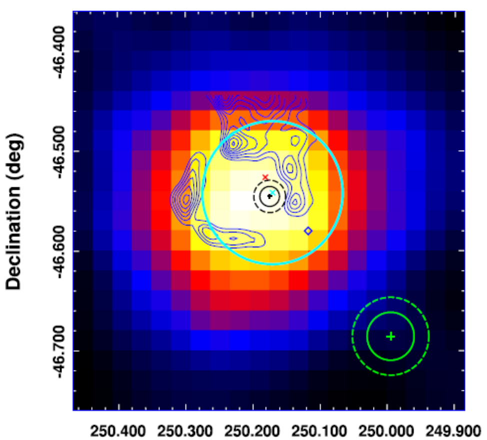


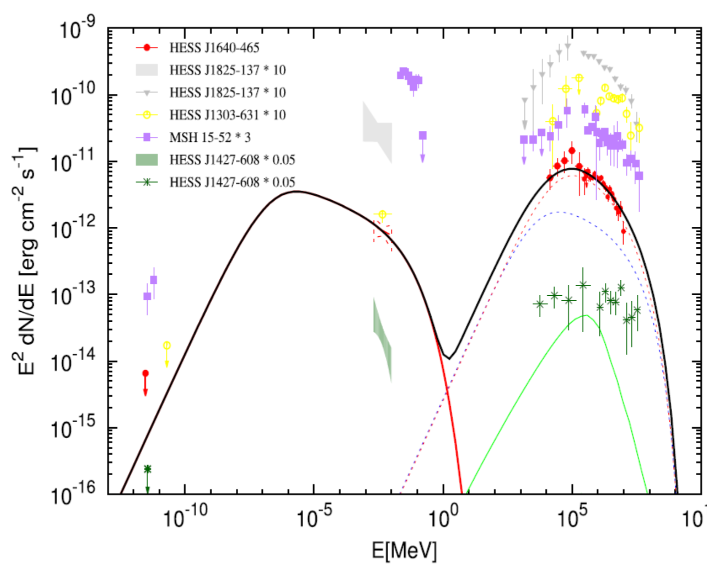

# 2脉冲星风云的能谱演化

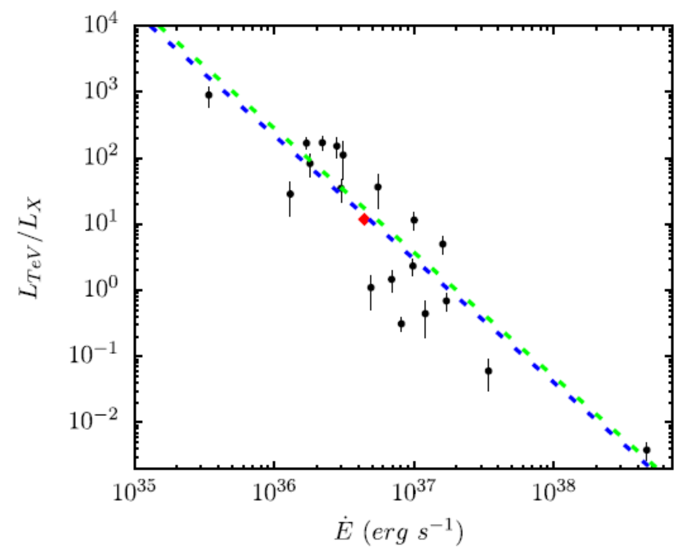


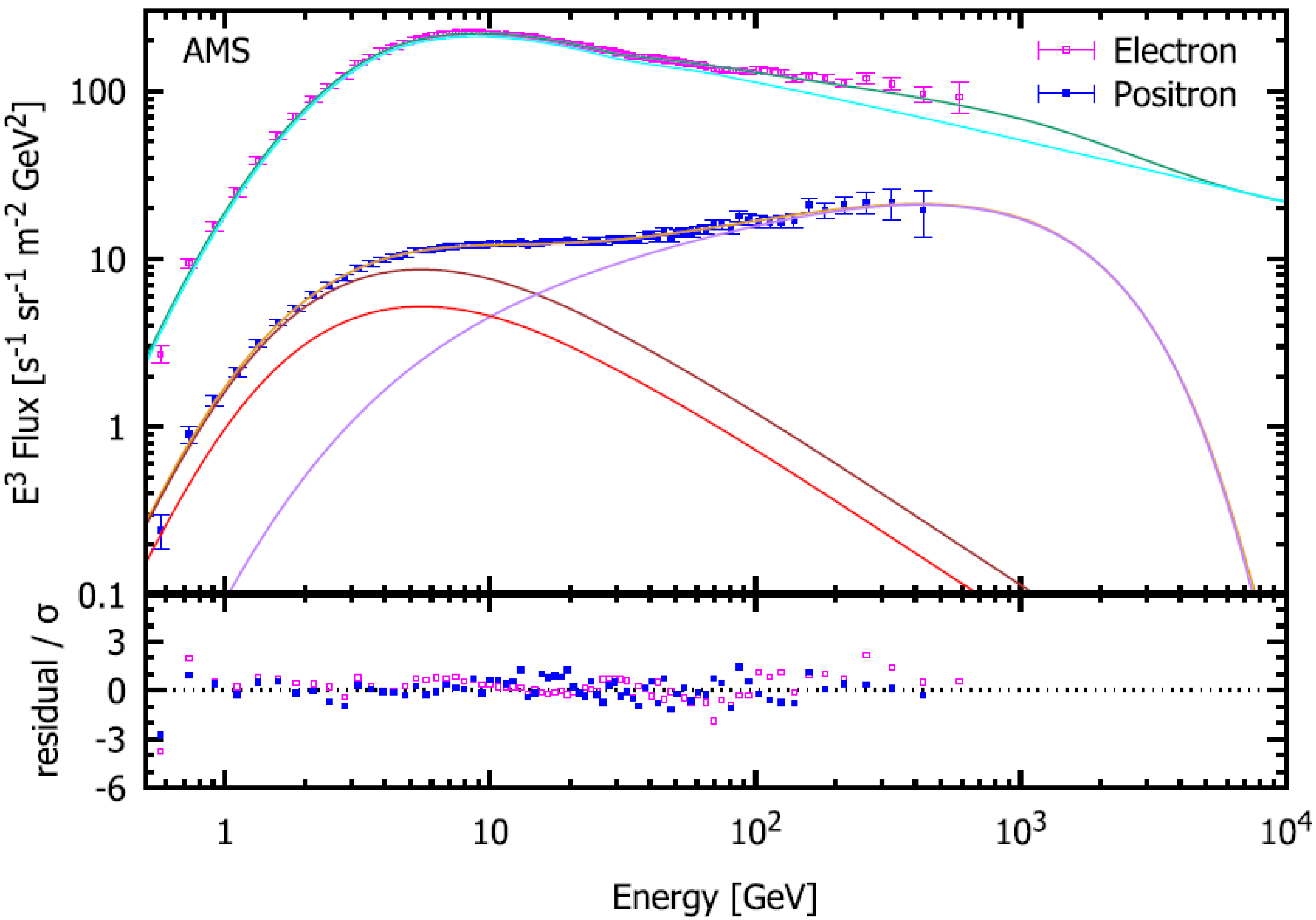



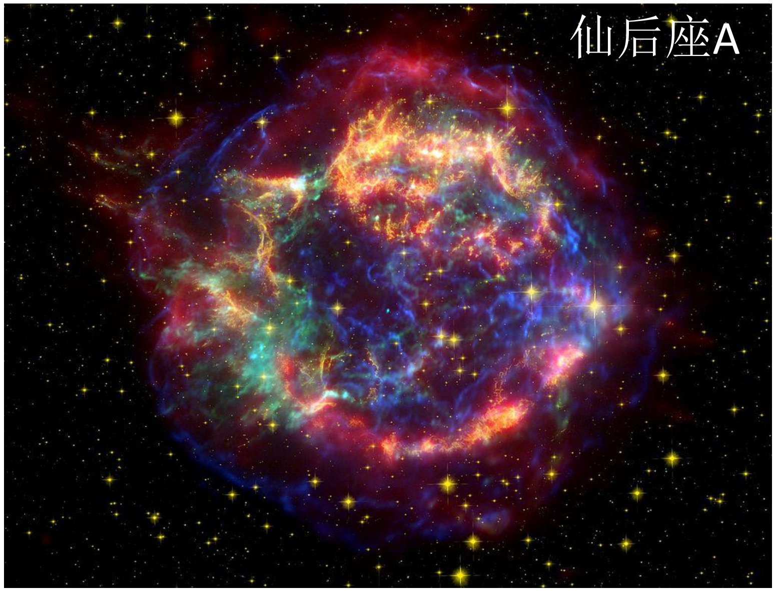



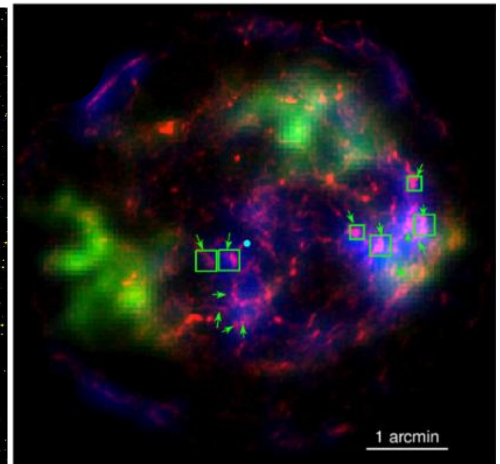



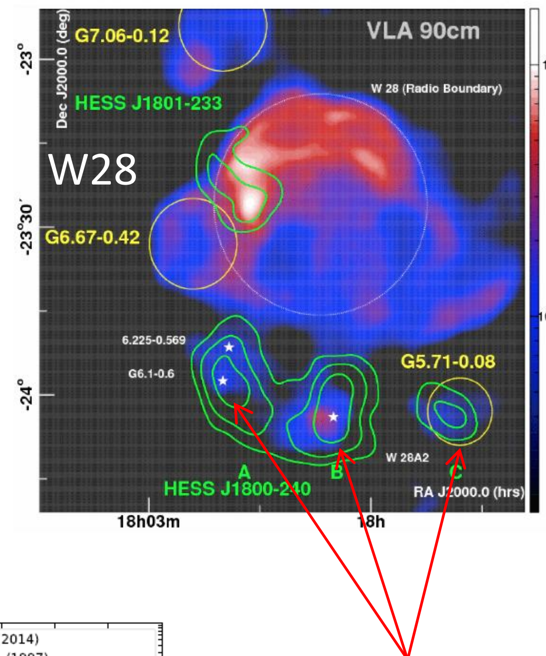
# 脉冲星风云对宇宙线正负电子的贡献



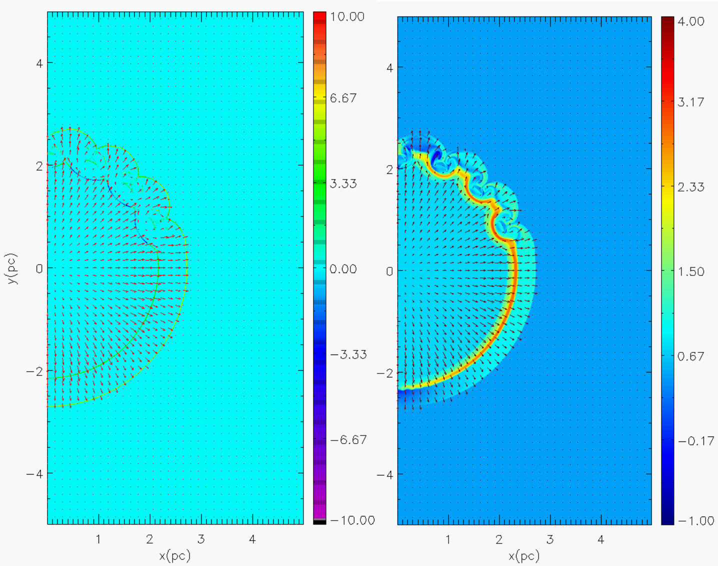
# 3超新星遗迹的结构和高能粒子的逃逸

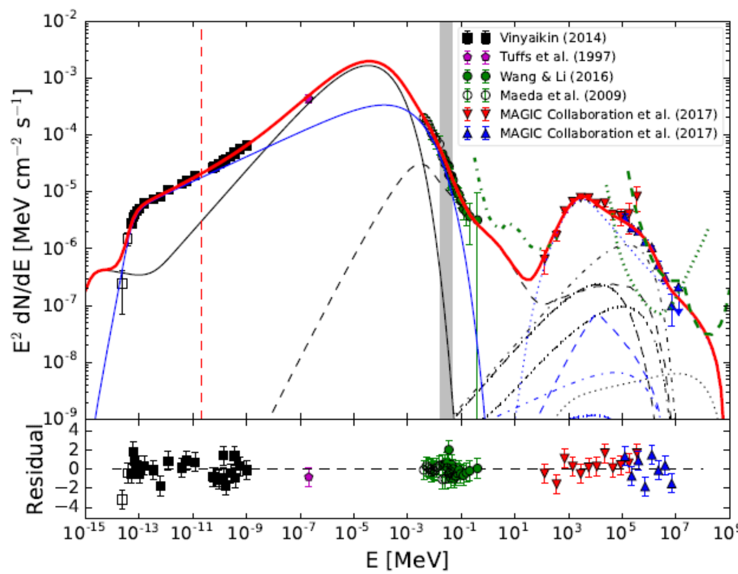


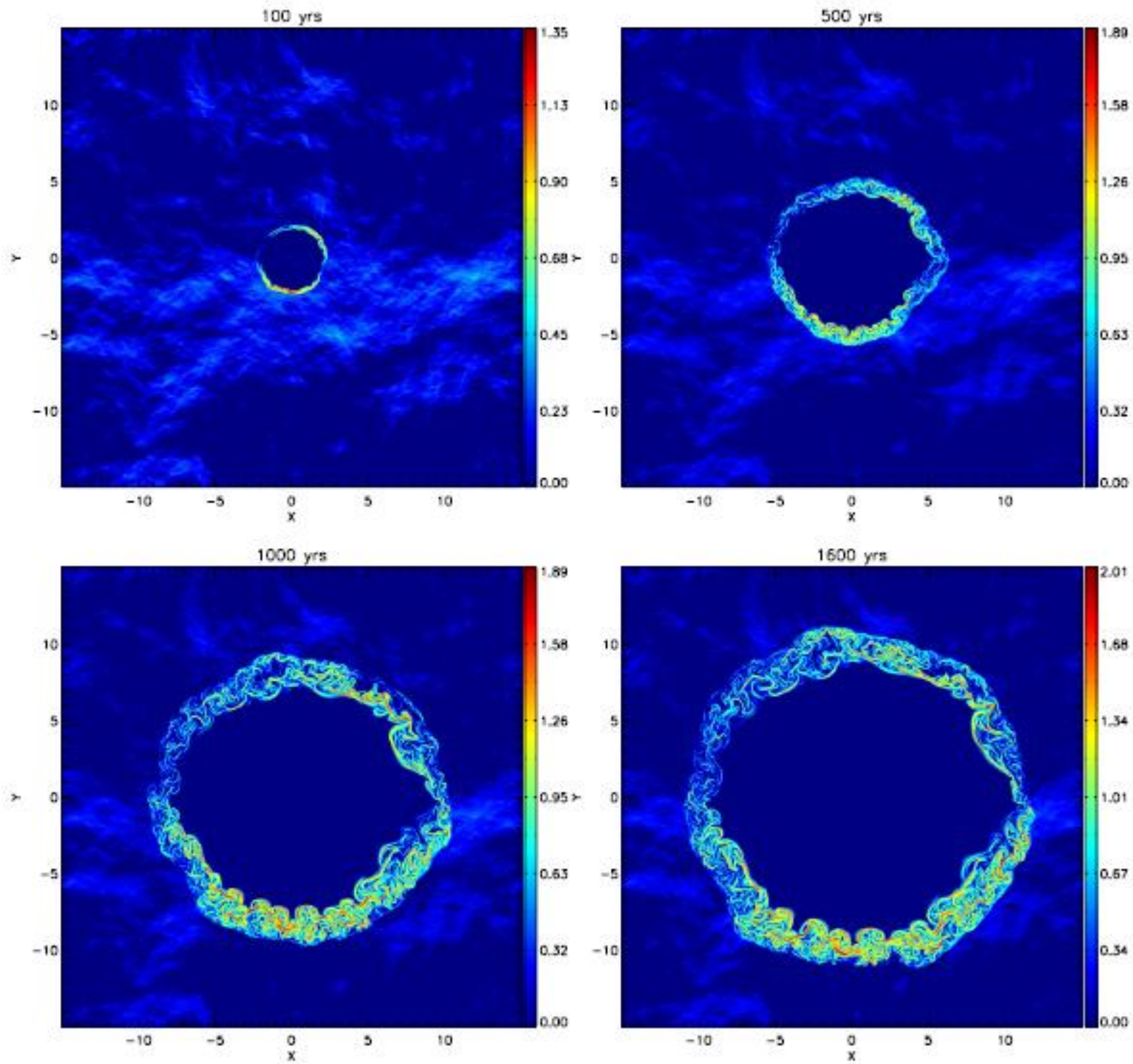




被宇宙线照亮的分子云



# 研究目标A：粒子的加速和逃逸规律




$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] \quad \text{(diffusion)}$$

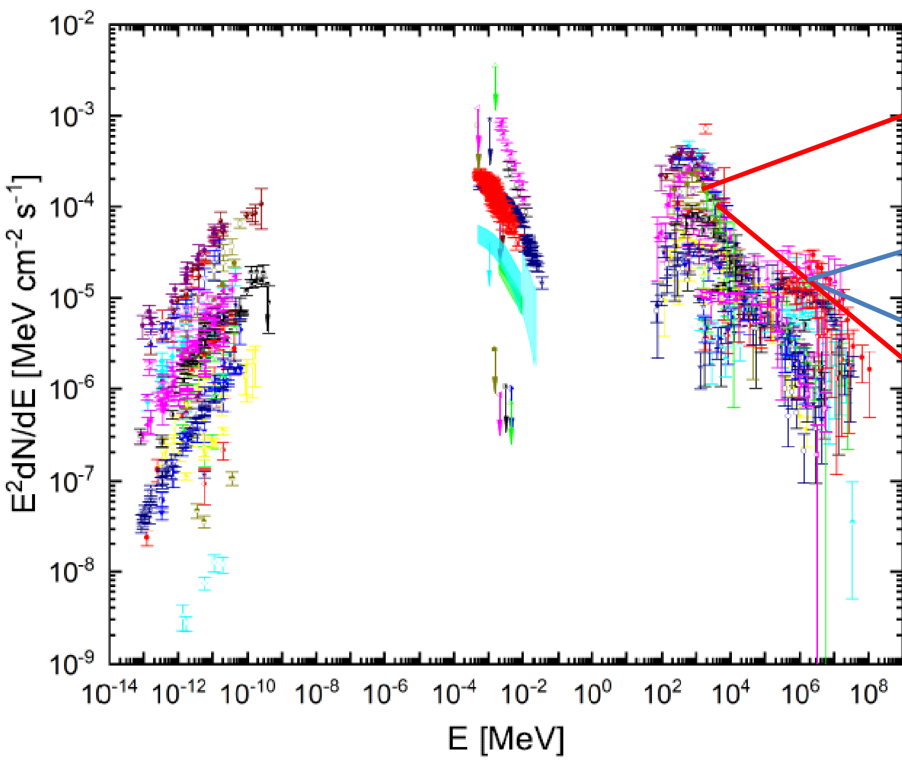
$$- U_i \frac{\partial f}{\partial x_i} \quad \text{(convection)}$$

$$+ \frac{1}{3}\frac{\partial U_i}{\partial x_i}\left[\frac{p \partial f}{\partial p}\right] \quad \text{(energy change)}$$

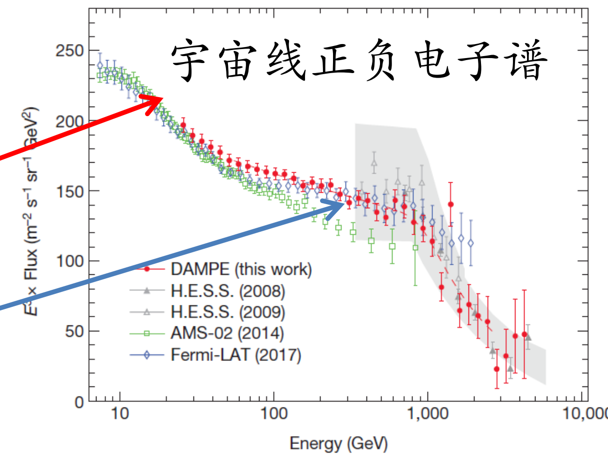
$$+ Q(x_i, t, p) \quad \text{(source)}$$

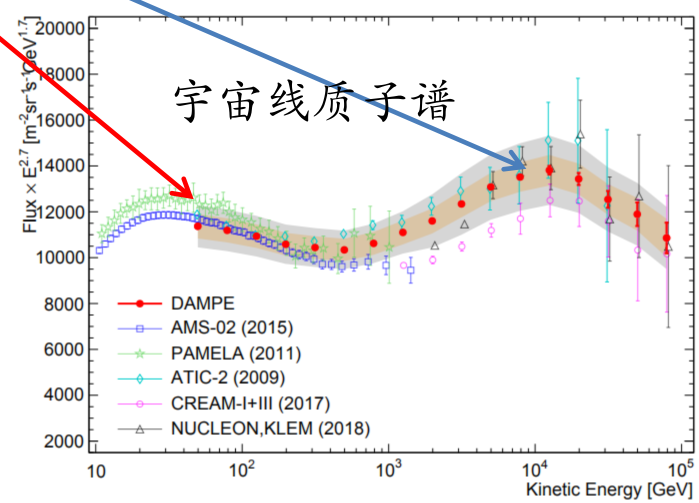
把磁流体数值模拟和扩散激波粒子加速理论相结合发展非线性激波粒子加速理论，总结超新星遗迹中粒子的加速和逃逸规律。

# B：银河宇宙线的超新星遗迹起源学说




34个超新星遗迹的能谱



# 关键问题：粒子的加速和输运

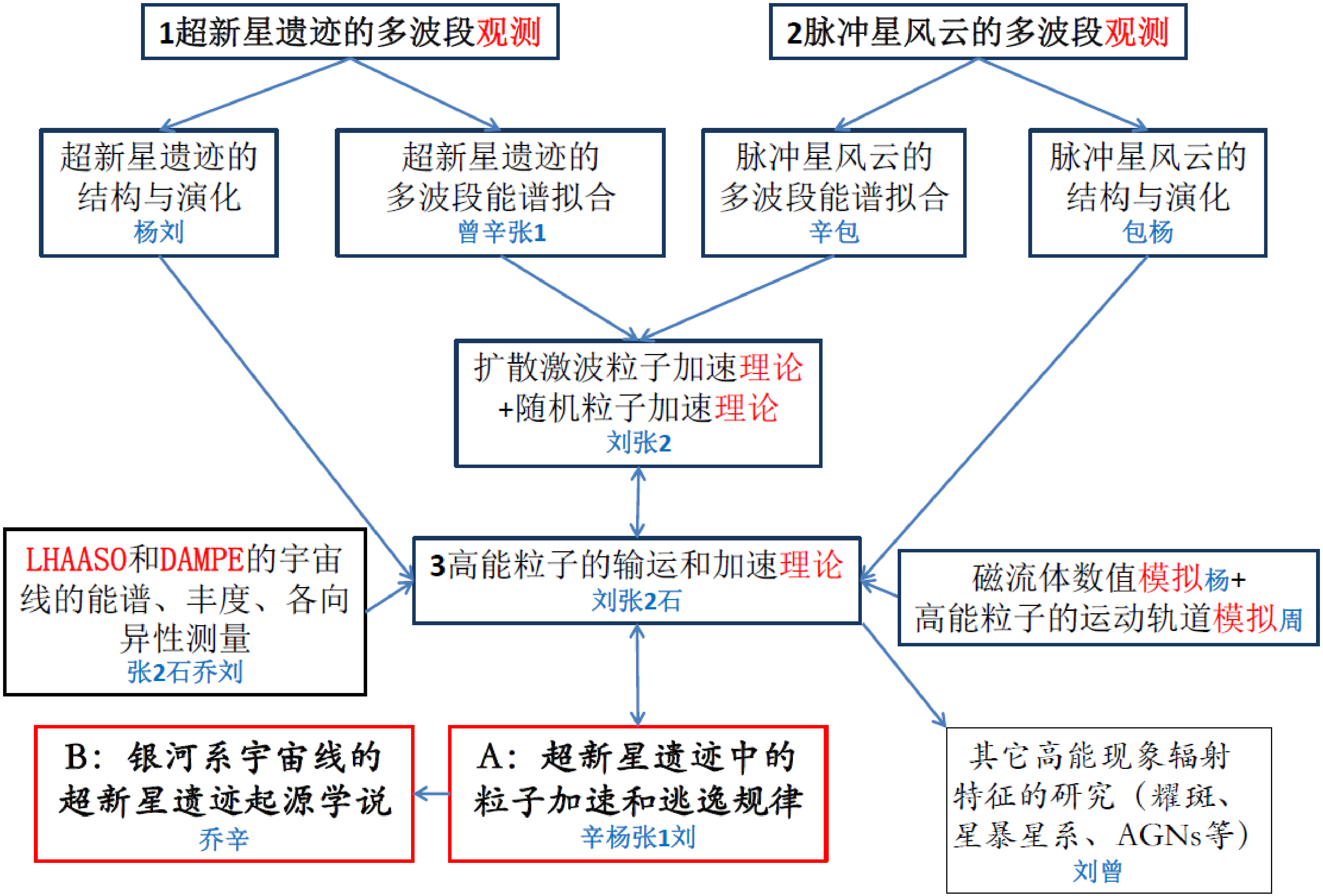
$$\frac{\partial f}{dt} = \frac{\partial}{\partial x_i}\left[\frac{w^2\tau}{3}\frac{\partial f}{\partial x_i}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{p}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial p} + \frac{\Gamma}{3p^2}\frac{\partial}{\partial p}\left[\tau p^4\frac{\partial f}{\partial p}\right]$$
$$-\frac{1}{3p^2}\frac{\partial(\tau p^3)}{\partial p}A_i\frac{\partial f}{\partial x_i} - \frac{p}{3}\frac{\partial(\tau A_i)}{\partial x_i}\frac{\partial f}{\partial p} - \frac{2\tau p}{3}A_i\frac{\partial^2 f}{\partial x_i\partial p} + Q(x_i, t, p),$$

$$\Gamma = \frac{1}{10}\left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right]^2 - \frac{2}{15}\frac{\partial U_i}{\partial x_i}\frac{\partial U_j}{\partial x_j}$$

$$A_i = \frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j}$$

$f$：高能粒子动量分布函数；$w$：粒子速度；$U$：流体速度；
$Q$：源；$\tau$：散射时标。

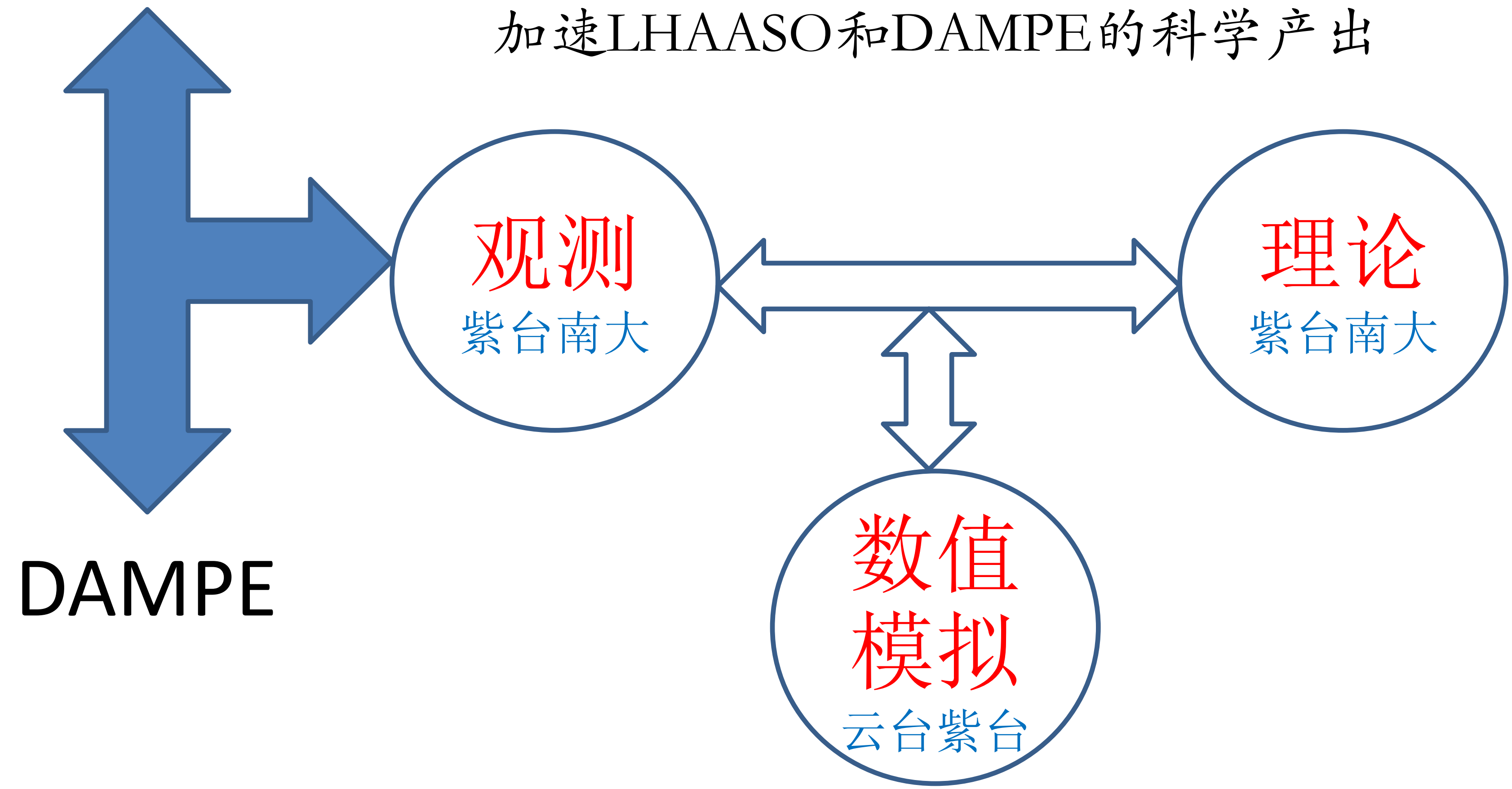
# 研究方案和可行性


1超新星遗迹的多波段观测
2脉冲星风云的多波段观测
超新星遗迹的结构与演化
杨刘
超新星遗迹的多波段能谱拟合
曾辛张1
脉冲星风云的多波段能谱拟合
辛包
脉冲星风云的结构与演化
包杨
扩散激波粒子加速理论+随机粒子加速理论
刘张2
LHAASO和DAMPE的宇宙线的能谱、丰度、各向异性测量
张2石乔刘
3高能粒子的输运和加速理论
刘张2石
磁流体数值模拟杨+高能粒子的运动轨道模拟周
B：银河系宇宙线的超新星遗迹起源学说
乔辛
A：超新星遗迹中的粒子加速和逃逸规律
辛杨张1刘
其它高能现象辐射特征的研究（耀斑、星暴星系、AGNs等）
刘曾

# 特色和创新之处

综合三个单位在超新星遗迹研究方面的优势
将理论研究、数值模拟与观测相结合
加速LHAASO和DAMPE的科学产出

LHAASO



# 基础和条件：近5年代表性文章

1. **Zeng, Houdun; Xin, Yuliang**; **Liu, Siming**; Evolution of high-energy particle distribution in supernova remnants. ApJ, 874, 50 (2019)
2. **Zhang, Xiao; Liu, Siming;** Is Supernova Remnant Cassiopia A a PeVtron? ApJ, 874, 98 (2019)
3. **Shi, Zhaogong**; **Liu, Siming;** Origin of cosmic ray electrons and positrons. MNRAS, 485, 3869 (2019)
4. **Bao, Yiwei; Liu, Siming;** Chen, Yang; On the gamma-ray nebula of Vela pulsar-I. constraining diffusion coefficient within the TeV nebula. ApJ, 877, 54 (2019)
5. **Zhang, Xiao; Liu, Siming;** Electron acceleration in middle age shell-type gamma-ray supernova remnants. ApJ, 876, 24 (2019)
6. **Zhang, Yiran**; **Liu, Siming;** Global constraints on diffusive particle acceleration by strong non-relativistic shocks. MNRAS,482,5268 (2019)
7. **Xin, Yuliang;** Liao, Nenghui; Guo, Xiaolei; Yuan, Qiang; **Liu, Siming;** Fan, Yizhong; Wei, Daming. HESS J1640-465: a gamma-ray emitting pulsar wind nebula? ApJ, 867, 55 (2018)
8. **Xin, Yuliang;** Guo, Xiaolei; Liao, Nenghui; Yuan, Qiang; **Liu, Siming;** Wei, Daming. Revisiting SNR Puppis A with seven years of Fermi LAT observations. ApJ, 843, 90 (2017)
9. **Zhang, Yiran**; **Liu, Siming;** Yuan, Qiang. Anomalous distributions of primary cosmic rays as evidence for time-dependent particle acceleration in Supernova Remnants. ApJ, 844:L3 (2017)
10. **Zeng, Houdun; Xin, Yuliang**; **Liu, Siming**; Jokipii, J. R.; Zhang, Li; Zhang, Shuinai. Evolution of High-energy Particle Distribution in Mature Shell-type Supernova Remnants， ApJ, 834, 153, 9 pp. (2017)
11. Guo, Xiao-Lei; **Xin, Yu-Liang**; Liao, Neng-Hui; Yuan, Qiang; Gao, Wei-Hong; He, Hao-Ning; Fan, Yi-Zhong; **Liu, Siming.** HESS J1427-608: An Unusual Hard, Unbroken Gamma-Ray Spectrum in a Very Wide Energy Range， ApJ, 835, 42 (2017)
12. **Xin, Yu-Liang**; Liang, Yun-Feng; Li, Xiang; Yuan, Qiang; **Liu, Siming**; Wei, Daming. A GeV Source in the Direction of Supernova Remnant CTB 37B， ApJ, 817, 64 (2016)
13. **Zhou, Xiaowei.**; Büchner, J.; Bárta, M.; Gan, W.; **Liu, Siming.** Electron Acceleration by Cascading Reconnection in the Solar Corona. II. Resistive Electric Field Effects. ApJ, 827, 94 (2016)
14. **Zhou, Xiaowei.**; Büchner, J.; Bárta, M.; Gan, W.; **Liu, Siming.** Electron Acceleration by Cascading Reconnection in the Solar Corona. I. Magnetic Gradient and Curvature Drift Effects. ApJ, 815, 6 (2015)
15. **Yang, Chuyuan; Liu, Siming**; Fang, Jun; Li, Hui. The structure of TeV-bright shell-type supernova remnants， AA, 573, 37 (2015)
16. **Yang, ChuYuan**; Zhang, Li; Wang,Jiancheng; On the escape and propagation of high energy protons near young supernova remnants, MNRAS, 448, 3423 (2015)
17. Tang, Yunyong; **Yang, Chuyuan;** Zhang,Li; Wang, Jiancheng; A self-consistent explanation of TeV emissions from HESS J1640-465 and J1641-463. ApJ, 812, 32 (2015)
18. Li, Xiang; Shen, Zhao-Qiang; Lu, Bo-Qiang; Dong, Tie-Kuang; Fan, Yi-Zhong; Feng, Lei; **Liu, Siming**; Chang, Jin. 'Excess' of primary cosmic ray electrons, Physics Letters B, Volume 749, p. 267-271. (2015)
19. Yang, Ruizhi; **Zhang, Xiao**; Yuan, Qiang; **Liu, Siming.** Fermi Large Area Telescope observations of the supernova remnant HESS J1731-347, AA, 567, 23 (2014)
20. Yuan, Qiang; Huang, Xiaoyuan; **Liu, Siming**; Zhang, Bing. Fermi Large Area Telescope Detection of Supernova Remnant RCW 86, ApJ, 785, L22 (2014)

# 基础和条件：LHAASO合作组成员


2019年4月15日紫金山天文台正式加入LHAASO国际合作组

# 结论

利用LHAASO和多波段观测数据，围绕超新星遗迹和脉冲星风云中的粒子加速问题，将理论研究与数值模拟相结合（3个任务），我们将总结超新星遗迹中高能粒子加速和逃逸规律，完善银河系宇宙线的超新星遗迹起源学说（2个目标）。

项目的顺利实施将解决LHAASO的关键科学目标之一：宇宙线的起源问题。

# 超新星遗迹粒子加速的两个阶段

The Astrophysical Journal Letters, 844:L3 (5pp), 2017 July 20
https://doi.org/10.3847/2041-8213/aa7de1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## Anomalous Distributions of Primary Cosmic Rays as Evidence for Time-dependent Particle Acceleration in Supernova Remnants

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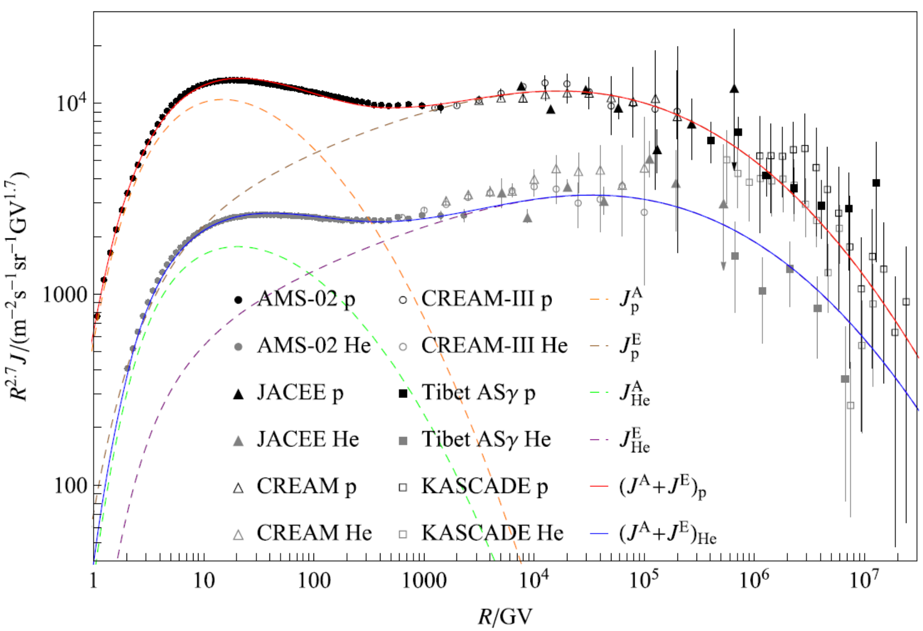
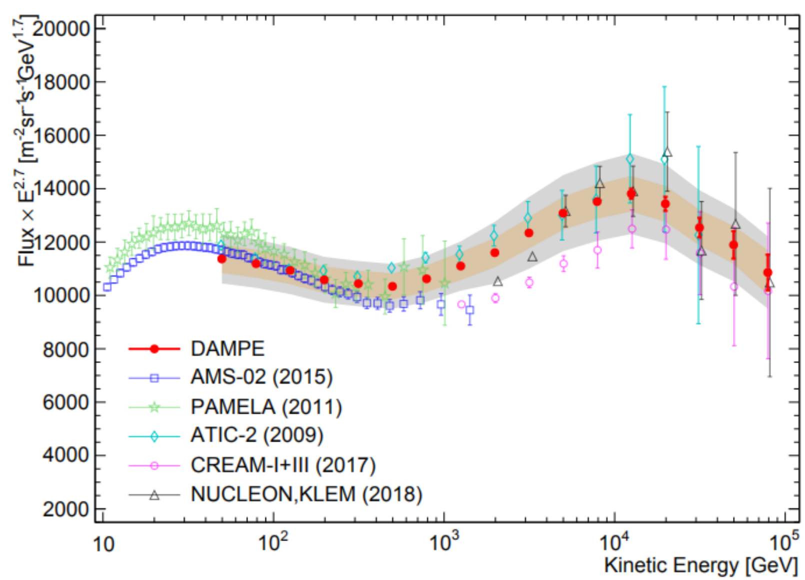
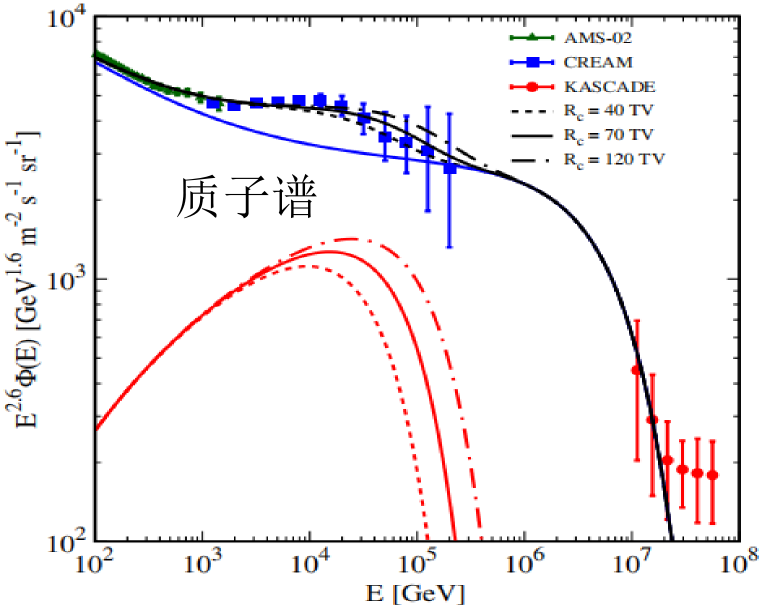
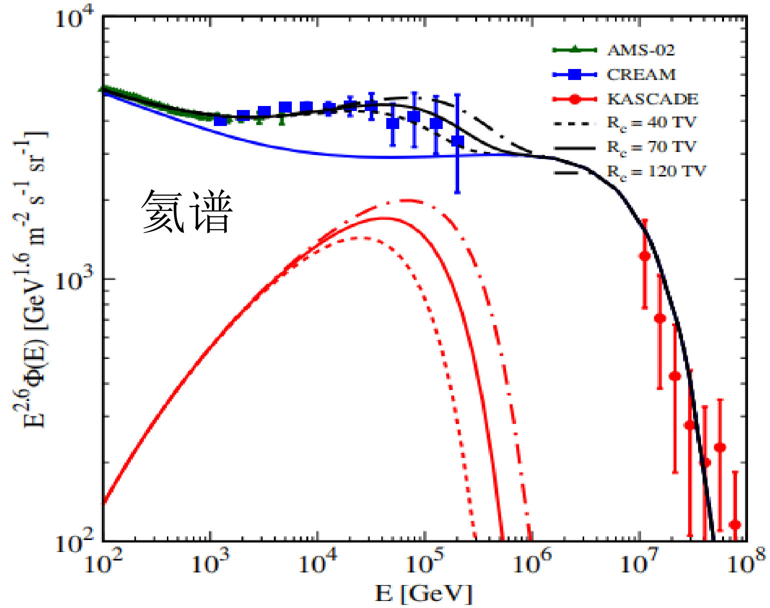
liusm@pmo.ac.cn (SL)
[2] School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, Anhui, China
Received 2017 June 9; revised 2017 June 28; accepted 2017 July 2; published 2017 July 17



# 邻近源的贡献


质子谱
AMS-02
CREAM
KASCADE
R_c = 40 TV
R_c = 70 TV
R_c = 120 TV
E^{2.6}Φ(E) [GeV^{1.6} m^{-2} s^{-1} sr^{-1}]
E [GeV]


氦谱
AMS-02
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R_c = 40 TV
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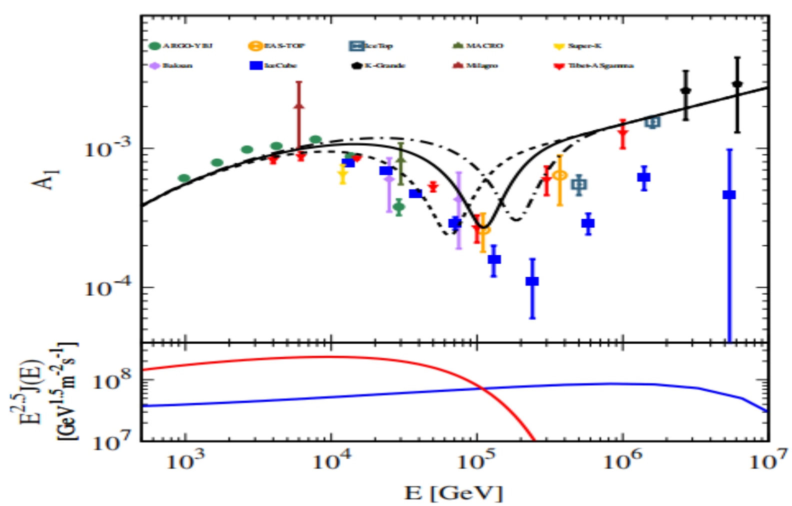
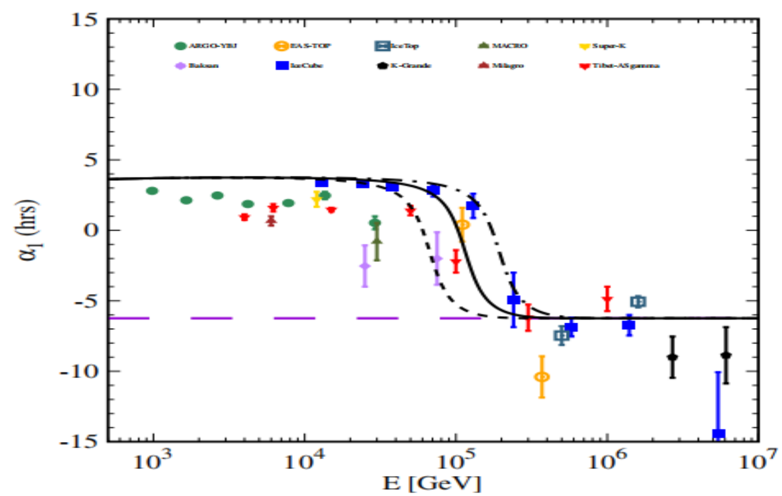
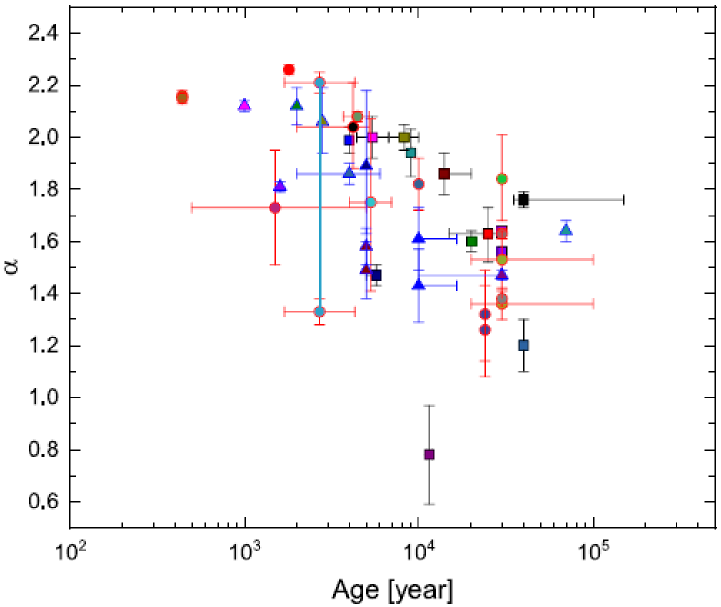
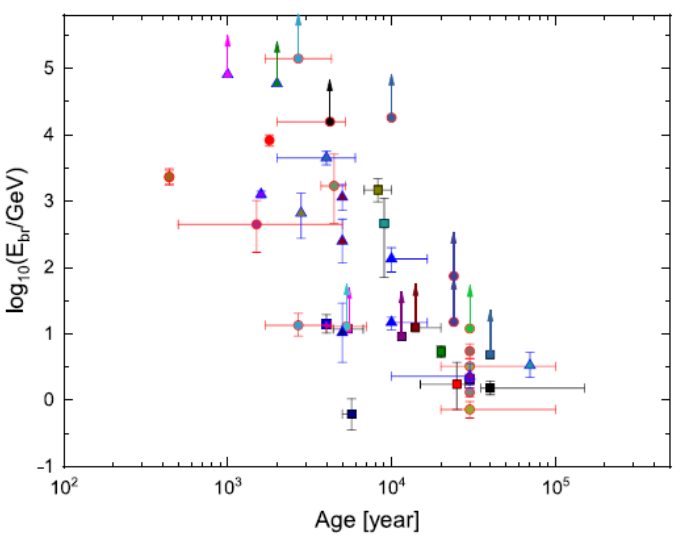
R_c = 120 TV
E^{2.6}Φ(E) [GeV^{1.6} m^{-2} s^{-1} sr^{-1}]
E [GeV]


A_1
E^{2.5}J(E) [GeV^{1.5} m^{-2} s^{-1}]
E [GeV]


α_1 (hrs)
E [GeV]

# 研究内容：1超新星遗迹的能谱演化




THE ASTROPHYSICAL JOURNAL, 874:50 (12pp), 2019 March 20
https://doi.org/10.3847/1538-4357/aaf392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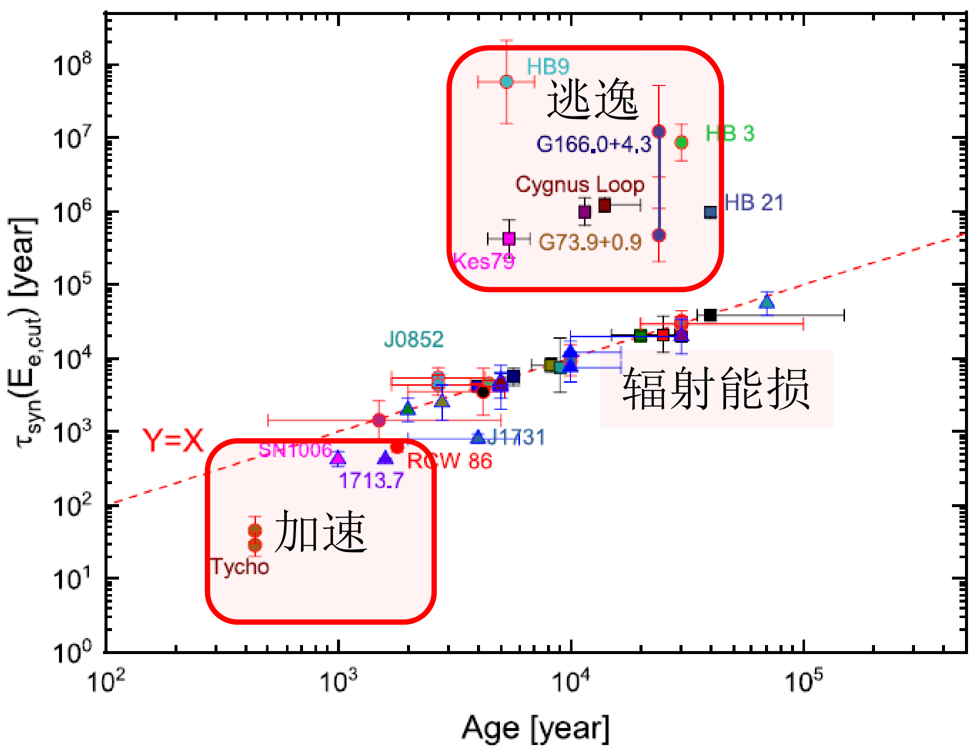
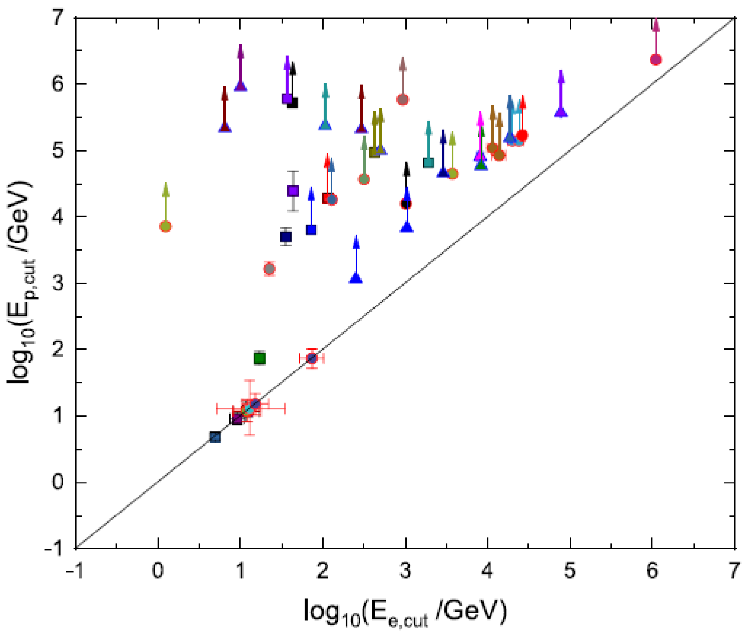
**Evolution of High-energy Particle Distribution in Supernova Remnants**

Ke … f China

$$N(P_i) = N_{0,i}\exp\left(-\frac{P_i}{P_{i,\mathrm{cut}}}\right)\begin{cases} P_i^{-\alpha} & \text{if} \quad P_i < P_{\mathrm{br}} \\ P_{i,\mathrm{br}}P_i^{-(\alpha+1)} & \text{if} \quad P_i \geqslant P_{\mathrm{br}}, \end{cases}$$



# 研究内容：1超新星遗迹的能谱演化




THE ASTROPHYSICAL JOURNAL, 874:50 (12pp), 2019 March 20
https://doi.org/10.3847/1538-4357/aaf392


**Evolution of High-energy Particle Distribution in Supernova Remnants**

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