The Origin of Cosmic Rays

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Outline

1. Theory of Charged Particle Acceleration and Cosmic Ray (CR) Properties

2. Standard Paradigm and New Observations

3. Evolution of High-Energy Particle Distribution in Supernova Remnants

4. New Paradigm and PeVatrons

5. Conclusions

1: Charged Particles Are Accelerated by Electric Fields

Lorentz Force

$$\dot{\mathbf{p}} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q\left(\mathbf{E} + \frac{\mathbf{w} \times \mathbf{B}}{c}\right),$$

Velocity **w**

Kinetic Energy Change Rate

$$\dot{T} = \frac{\mathrm{d}T}{\mathrm{d}t} = \mathbf{w} \cdot \dot{\mathbf{p}} = q\mathbf{w} \cdot \mathbf{E}(\mathbf{r}, t).$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$ Charge separation

Maxwell equations:

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$ Inductive electric field

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(\frac{\partial \mathbf{E}}{\partial t} + 4\pi \mathbf{j}\right)$$

1: Diffusion-convection equation

First order

$$\frac{\partial f}{dt} = \frac{\partial}{\partial x_i}\left[\frac{w^2\tau}{3}\frac{\partial f}{\partial x_i}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{p}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial p} + \frac{\Gamma}{3p^2}\frac{\partial}{\partial p}\left[\tau p^4\frac{\partial f}{\partial p}\right]$$

$$-\frac{1}{3p^2}\frac{\partial(\tau p^3)}{\partial p}A_i\frac{\partial f}{\partial x_i} - \frac{p}{3}\frac{\partial(\tau A_i)}{\partial x_i}\frac{\partial f}{\partial p} - \frac{2\tau p}{3}A_i\frac{\partial^2 f}{\partial x_i \partial p},$$

Second order

$$= -\frac{\partial}{\partial x_i}\left[\kappa\frac{pA_i}{w^2}\frac{\partial f}{\partial p} - \kappa\frac{\partial f}{\partial x_i} - \frac{U_i}{3}\frac{p\partial f}{\partial p}\right]$$

$$-\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\frac{p}{3}U_i\frac{\partial}{\partial x_i}f - \kappa\frac{p^2\Gamma}{w^2}\frac{\partial f}{\partial p} + \kappa\frac{pA_i}{w^2}\frac{\partial f}{\partial x_i}\right],$$

First order Second order

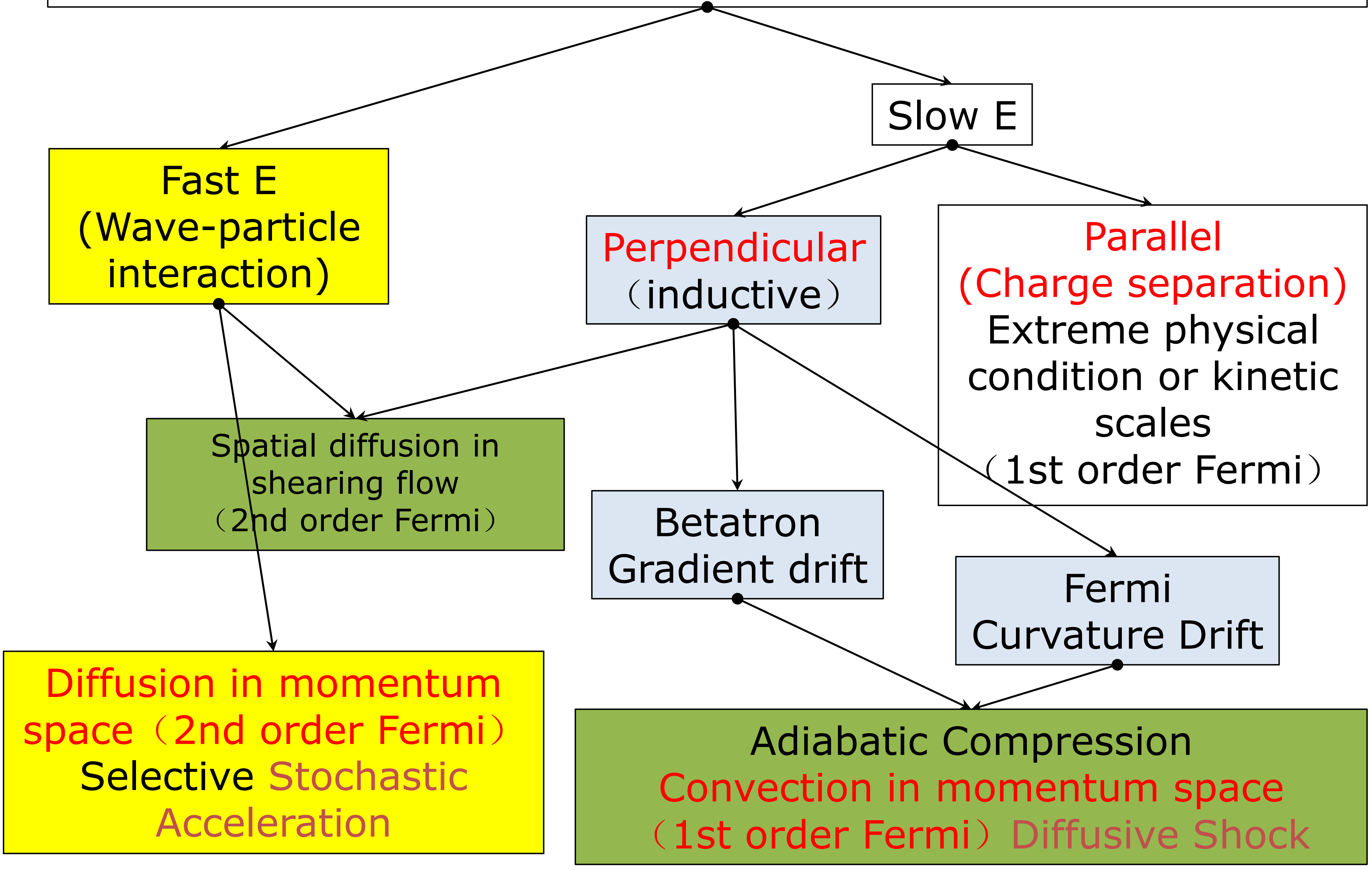
$$\Gamma = \frac{1}{10}\left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right]^2 - \frac{2}{15}\frac{\partial U_i}{\partial x_i}\frac{\partial U_j}{\partial x_j}$$

$\kappa = w^2\tau/3$?

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

Earl, J. A., Jokipii, R. J., & Morfill, G. Cosmic-ray viscosity ApJ, 1988, 331, L91

1: Classification of Acceleration Mechanisms



1: On 1912.8.7 Hess Discovered CRs

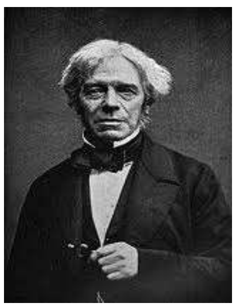
Victor Franz Hess第七次气球飞行线路，最大飞行高度：海拔5350米

（取自**P.Carlson**在**ICRC2011**上的报告）

1: Electrometers

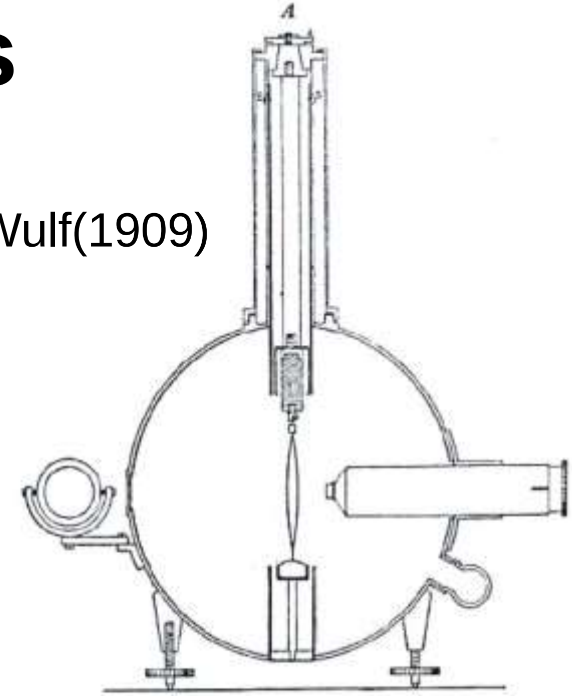
库伦(1785)

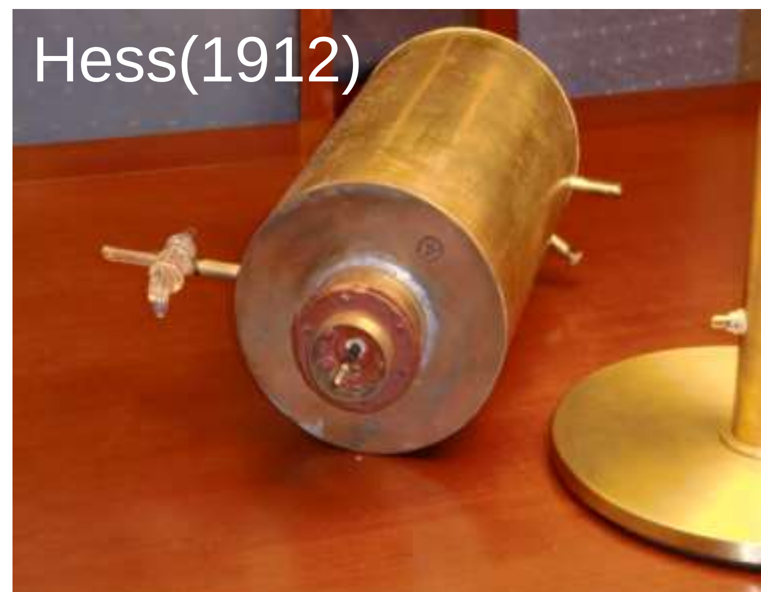
法拉第(1835)



克鲁克斯(1879)

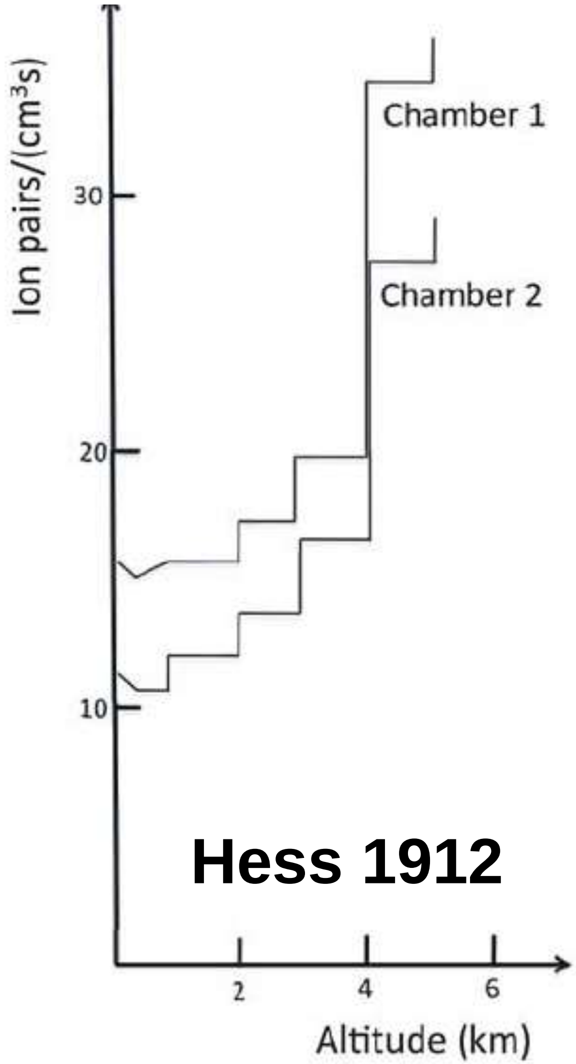
Wulf(1909)

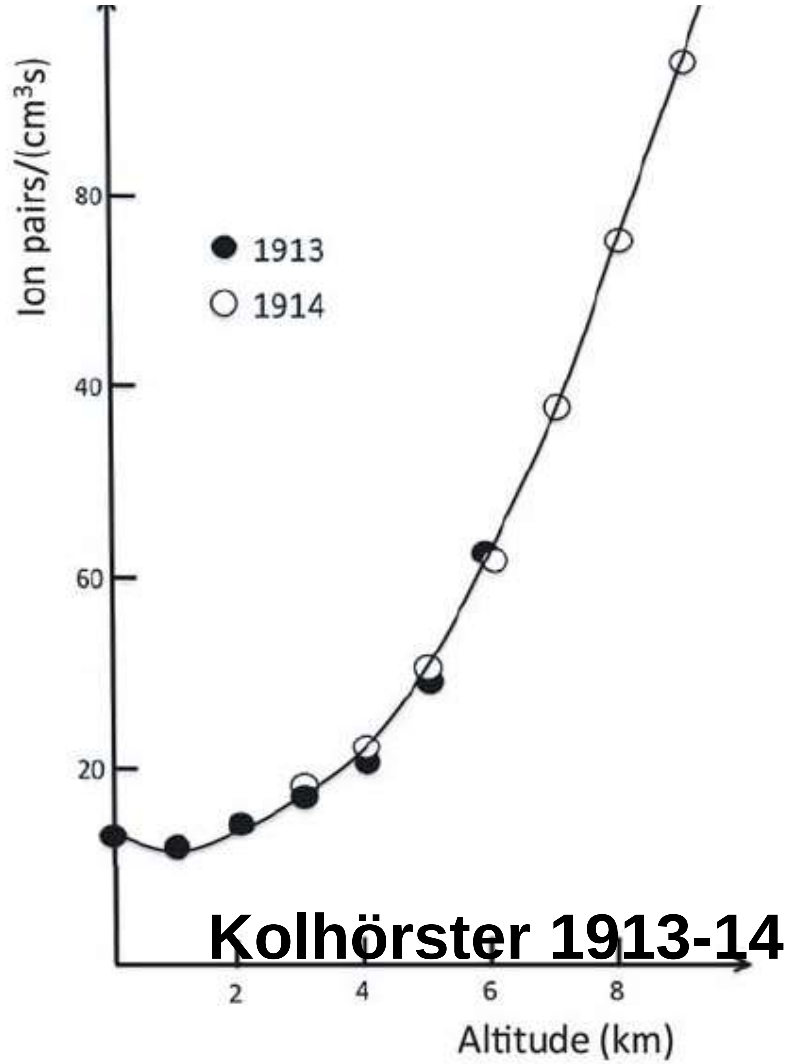




（资料取自**P.Carlson**在**ICRC2011**上的报告）

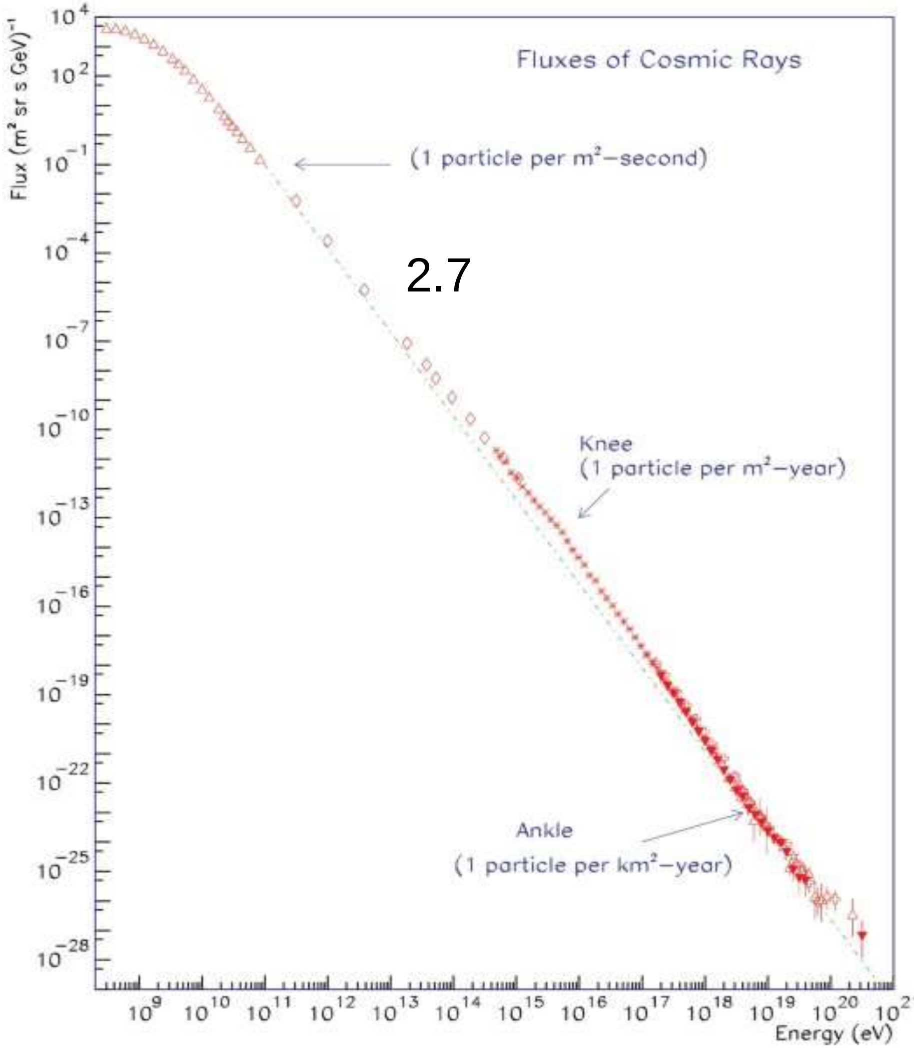
1: Dependence of ionization rate on altitude

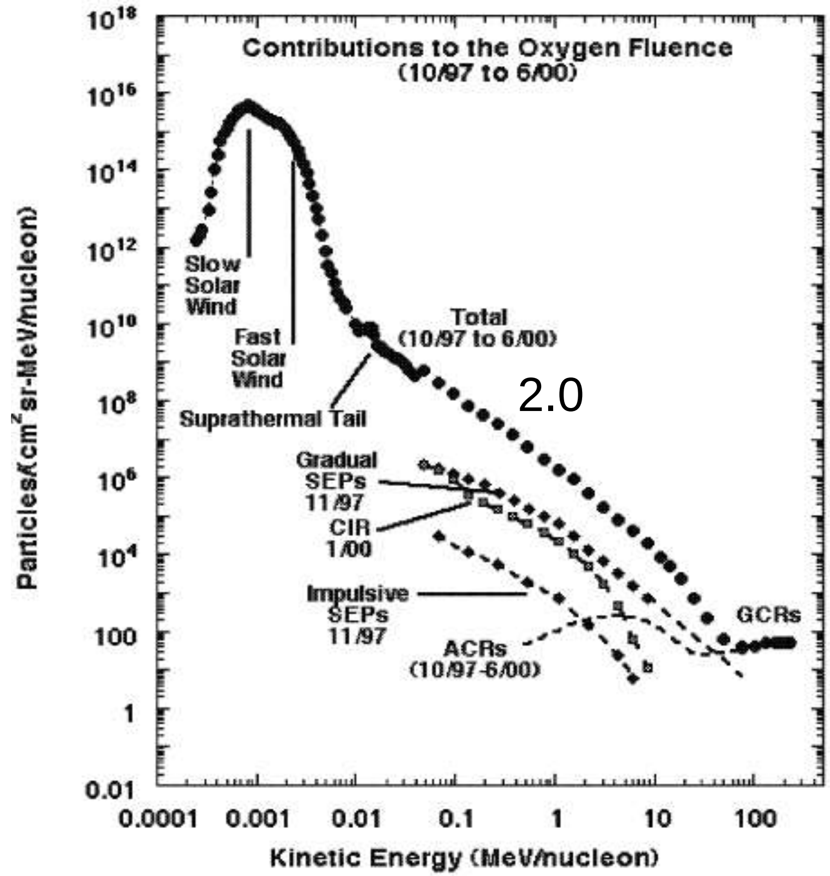




（材料取自P.Carlson在ICRC2011上的报告）

1: Cosmic Ray and Solar Energetic Particle Spectra

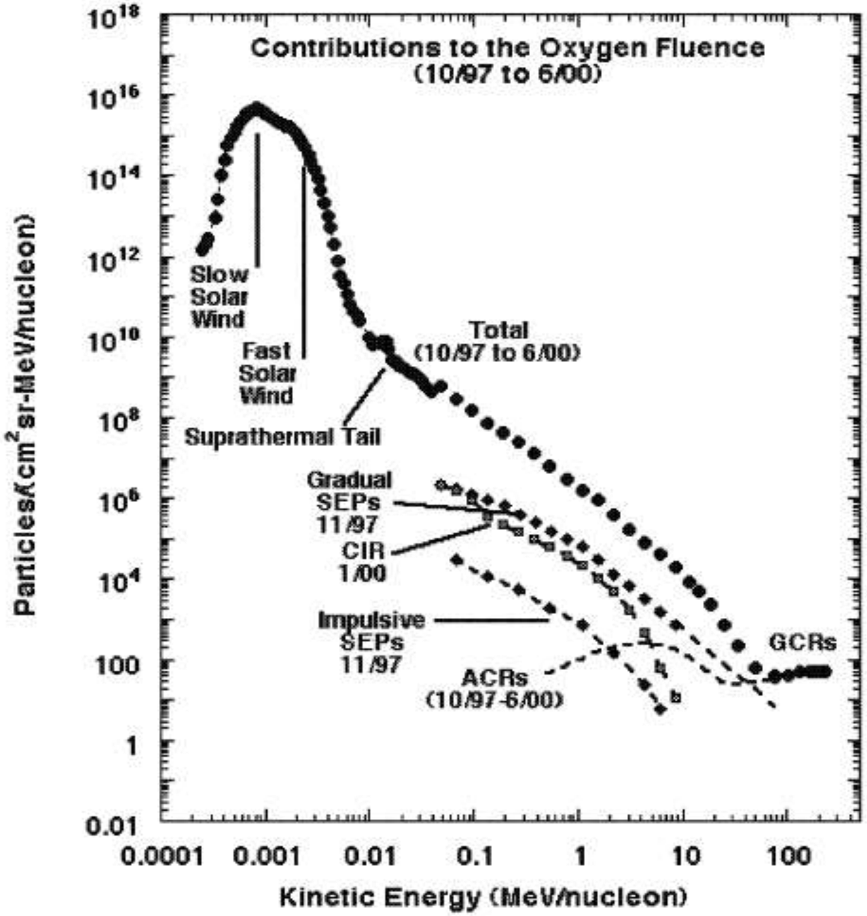


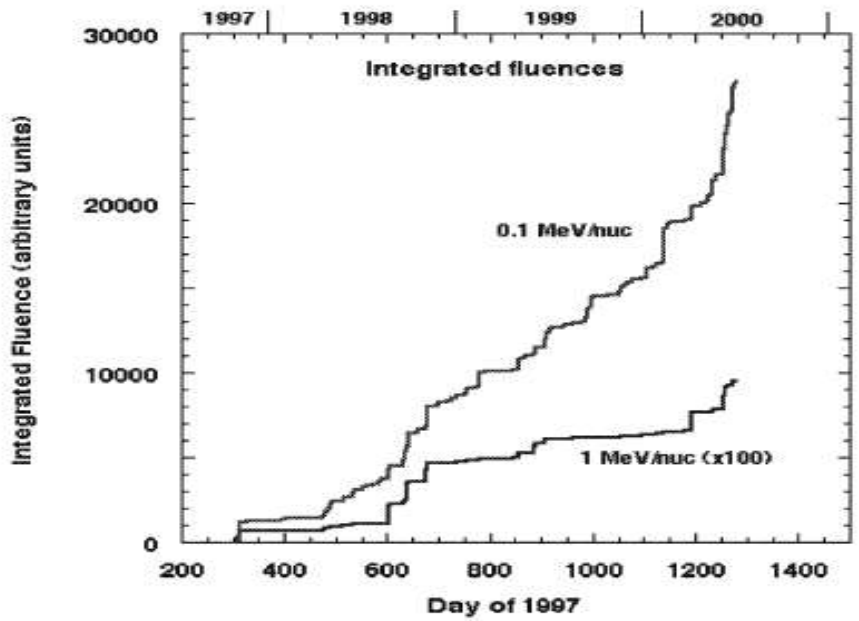


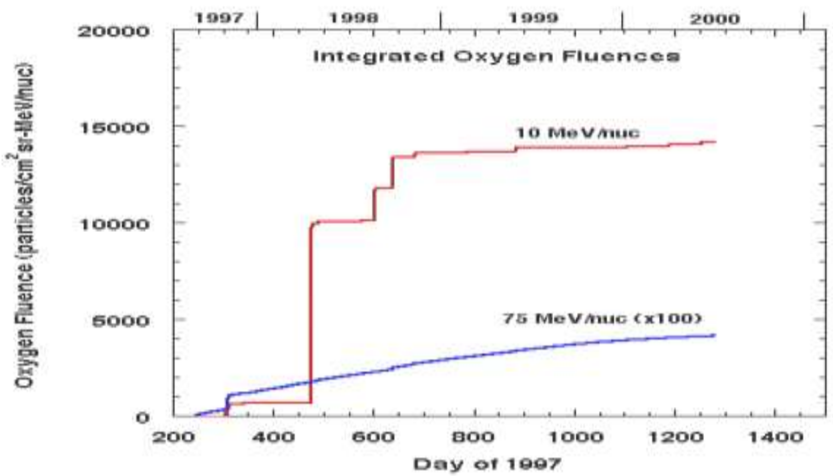
Long-Term Fluences of Solar Energetic Particles from H to Fe

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

1: Heliospheric Energetic Particles







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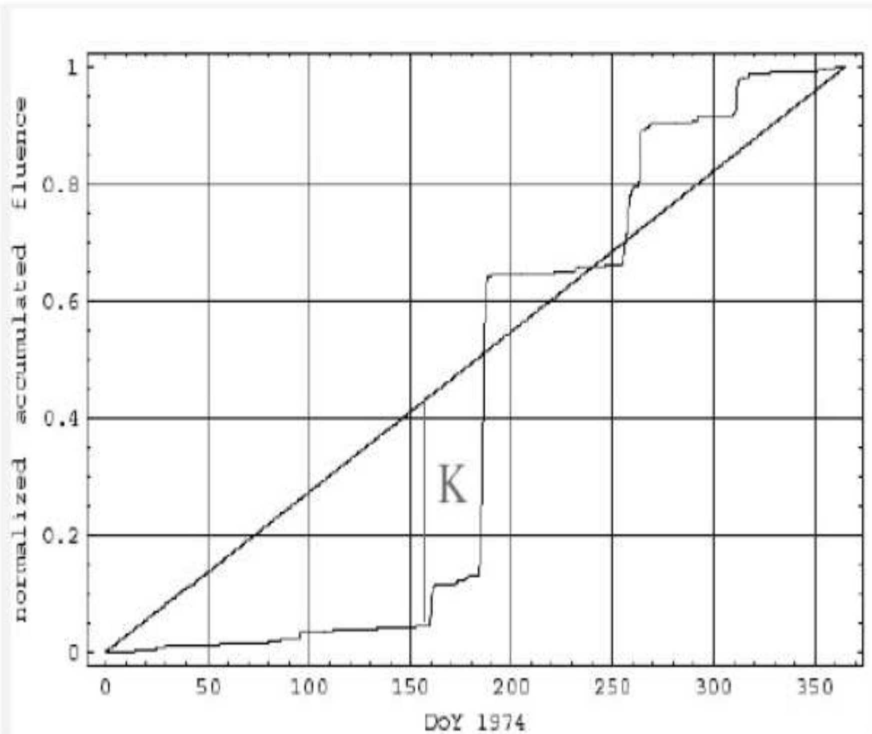


Figure 1: Normalized cumulative fluence plot of 0.29–0.5 MeV ion data of IMP8 CPME, and the

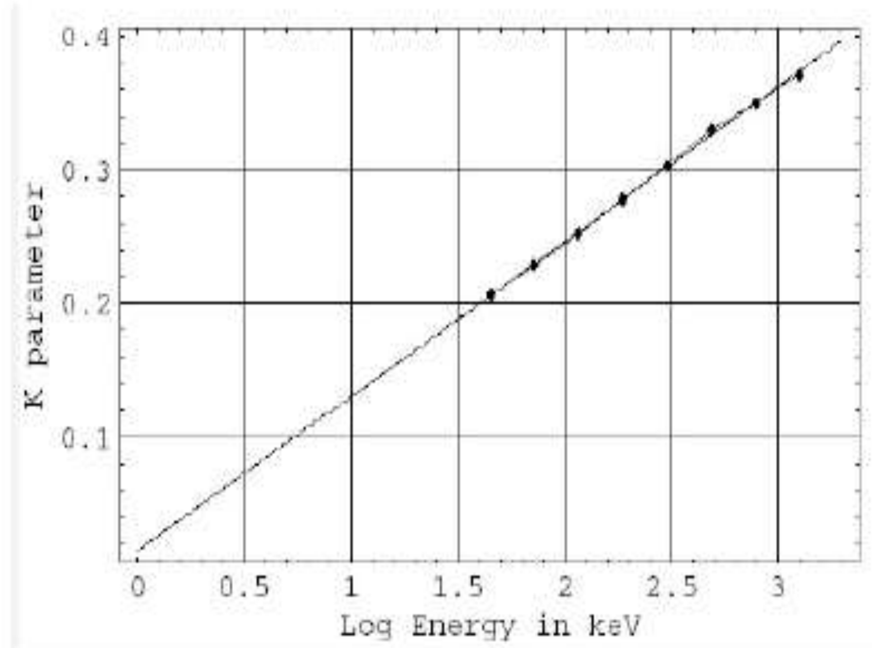
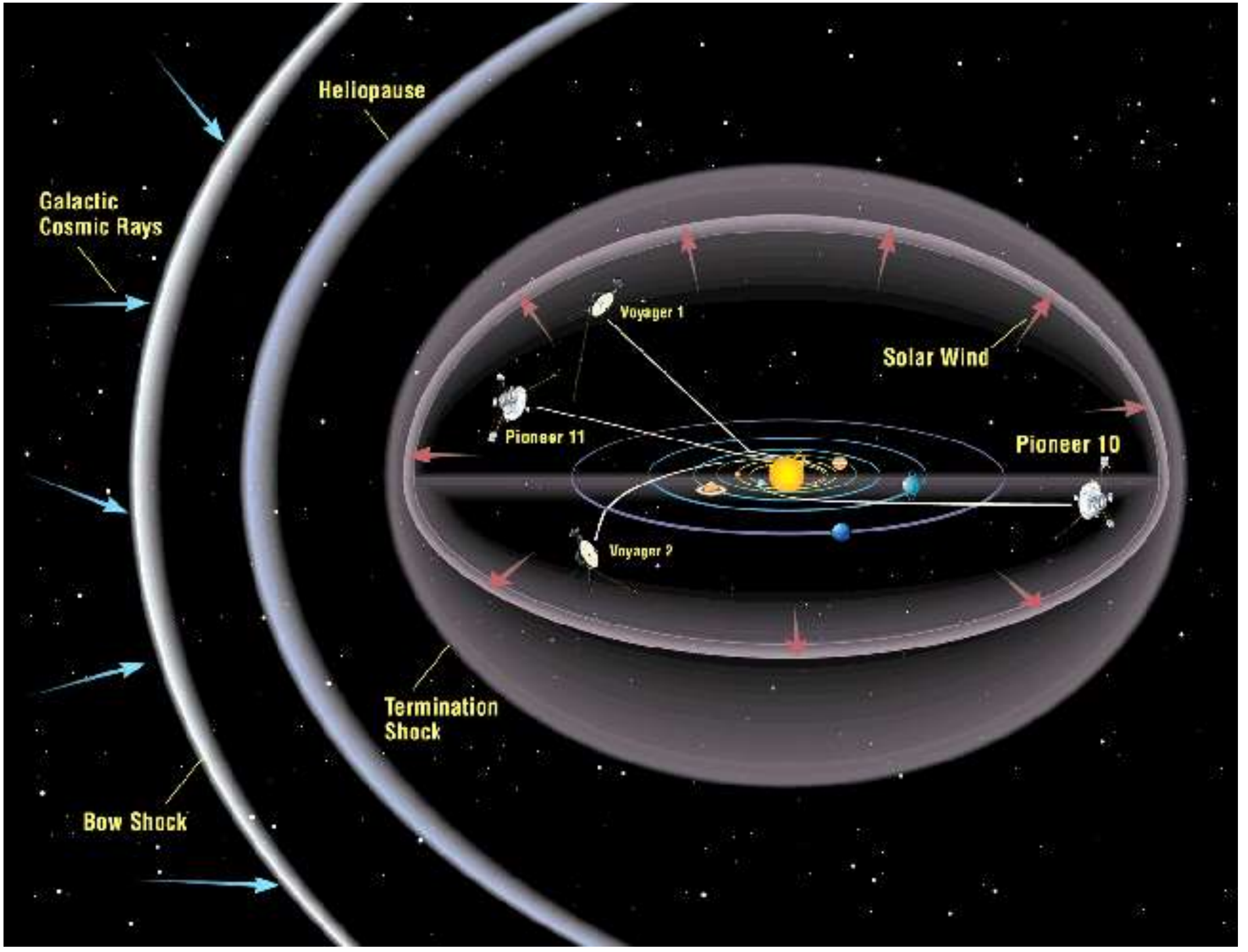


Figure 3: Energy dependence of the mean K parameters for ion fluxes measured by ISEE-3 DFH/EPAS at L1 between 1978 and 1982.

Characteristics of cumulative particle fluences at different heliospheric radii

PÉTER KIRÁLY[1]

1: Heliospheric Energetic Particles



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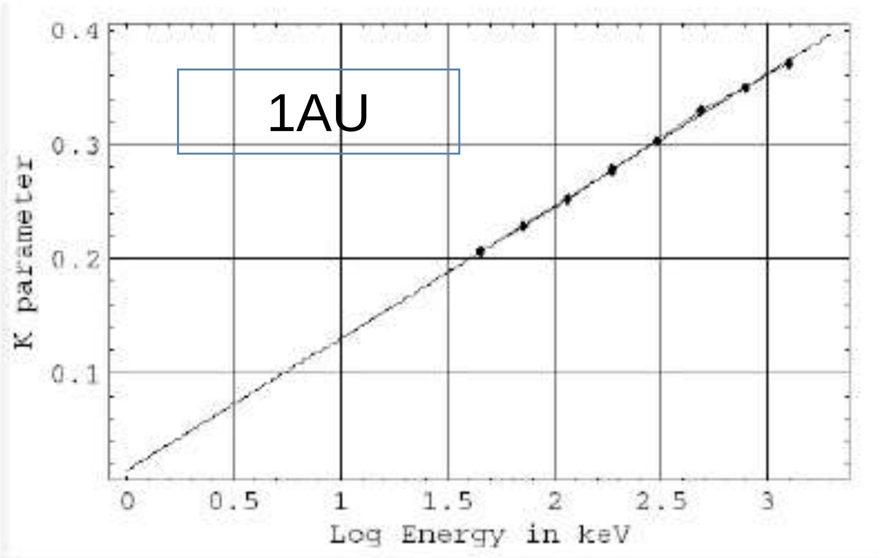


Figure 3: Energy dependence of the mean K parameters for ion fluxes measured by ISEE-3 DFH/EPAS at L1 between 1978 and 1982.

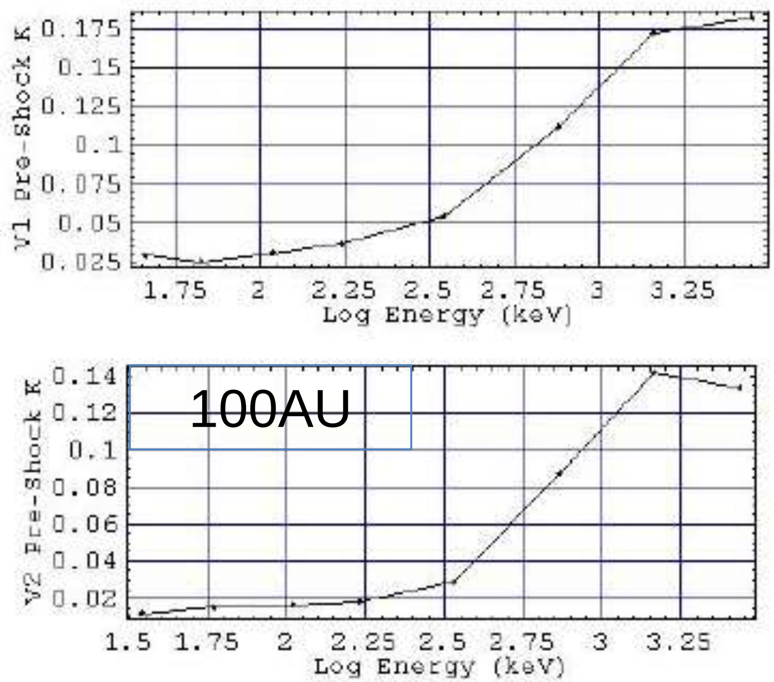
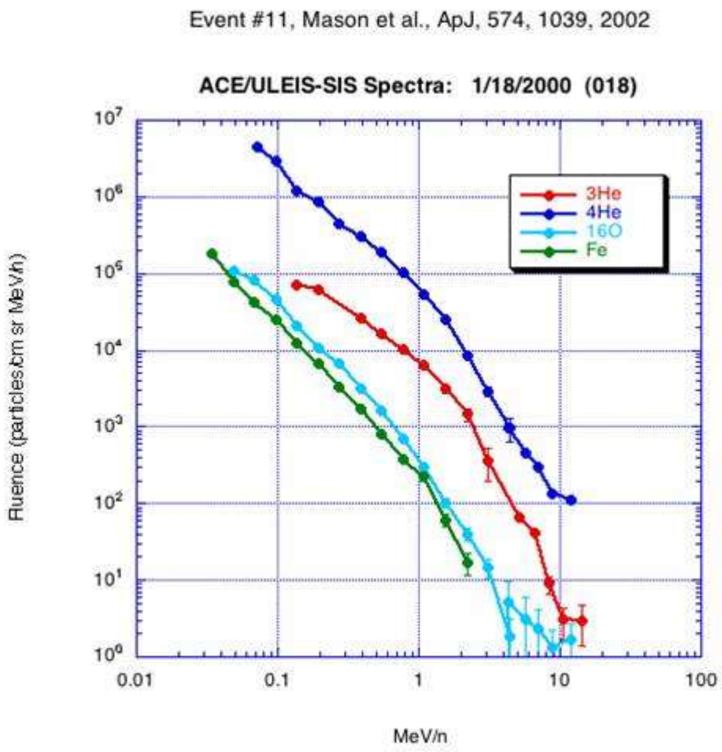


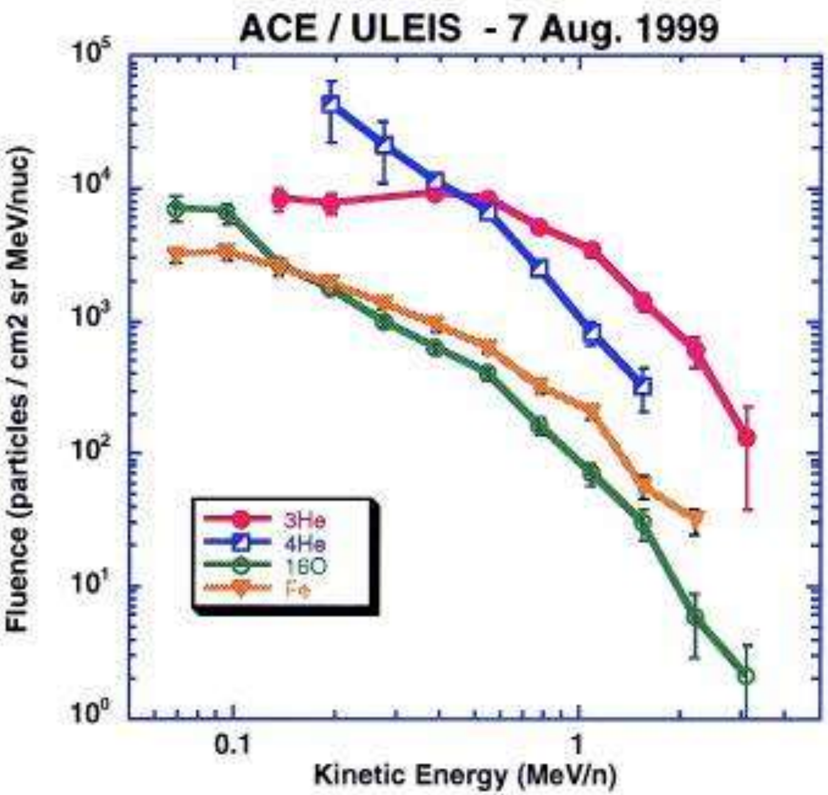
Figure 6: Mean K values for Voyager 1 (top) and Voyager 2 (bottom) as functions of $\log_{10}(E)$. K values were averaged for 2002 to 2004 for V1 and for 2005 to 2007 (up to May 2007) for V2.

Characteristics of cumulative particle fluences at different heliospheric radii

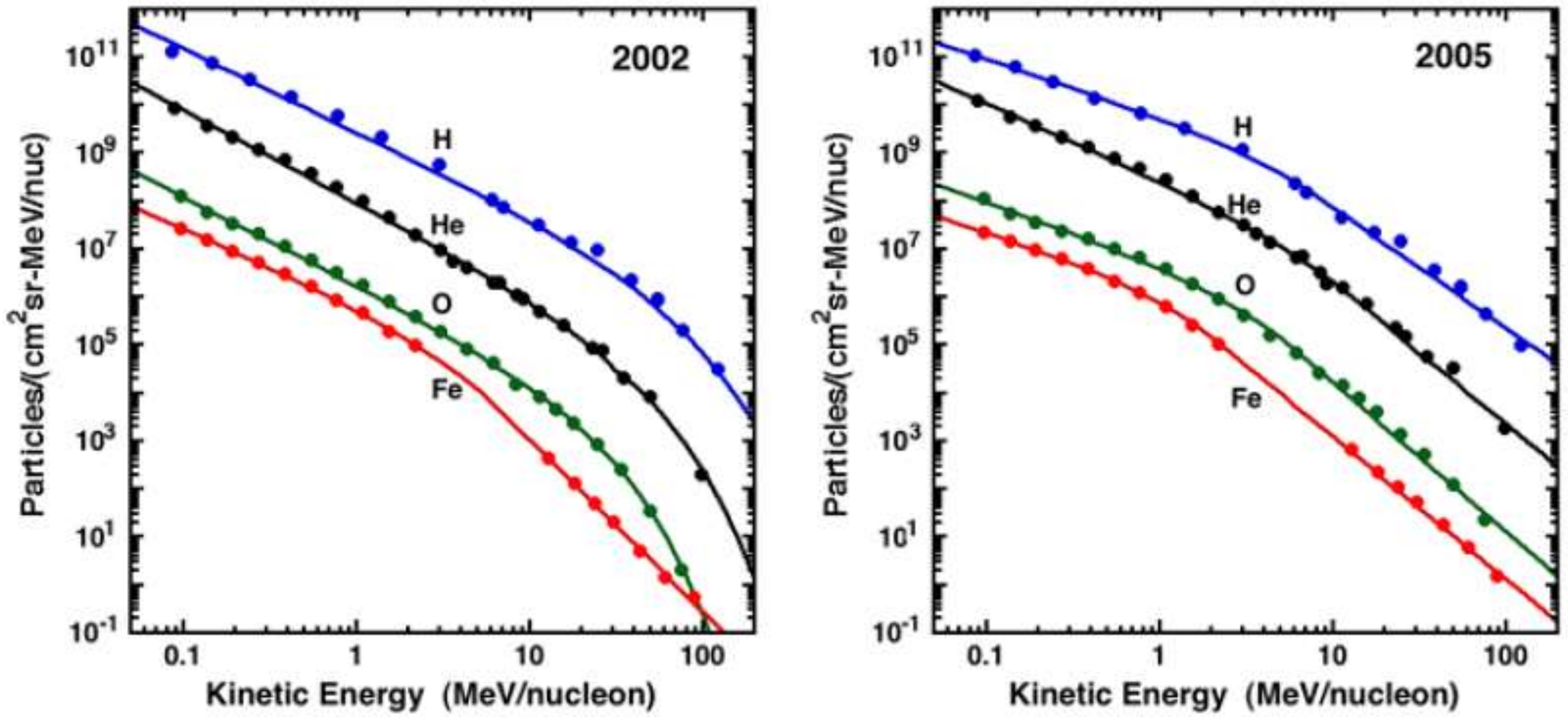
PÉTER KIRÁLY[1]

1: Different Ion Spectra from Two Solar Flares





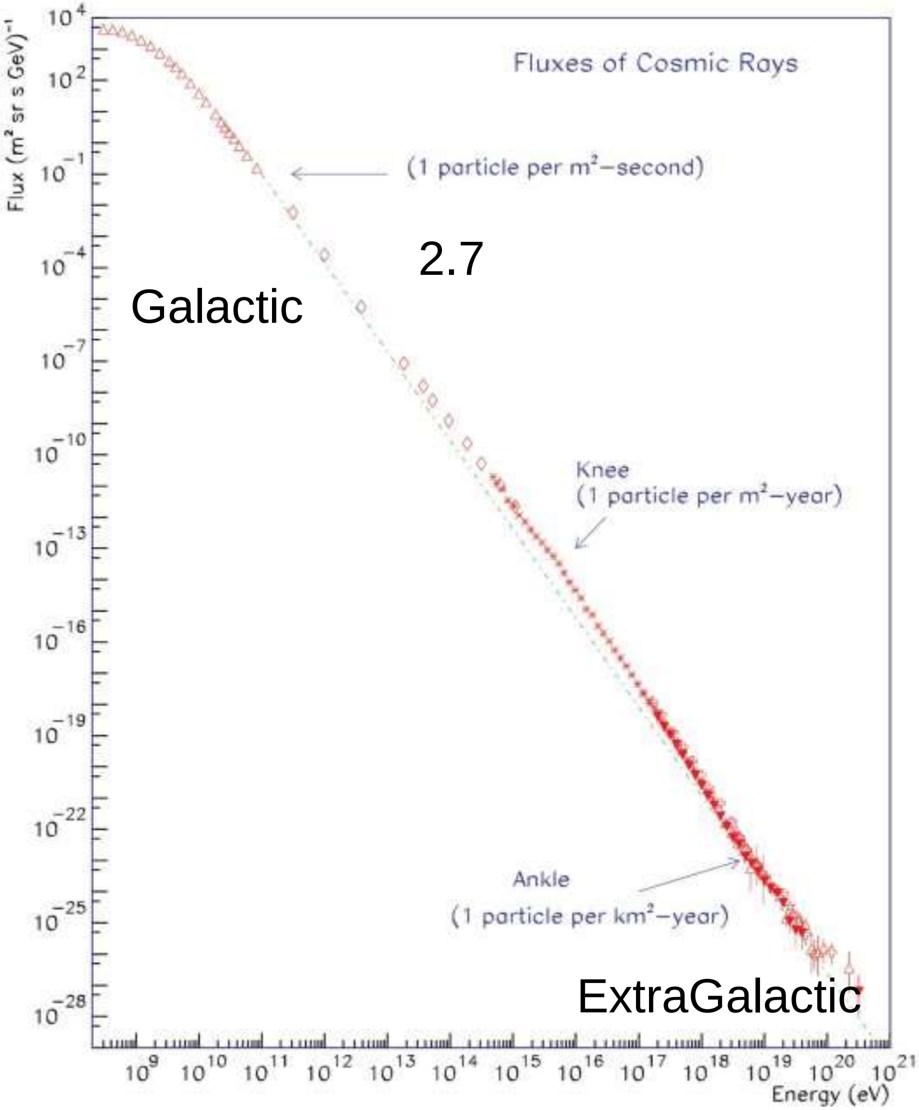
1: Yearly Spectral Variation

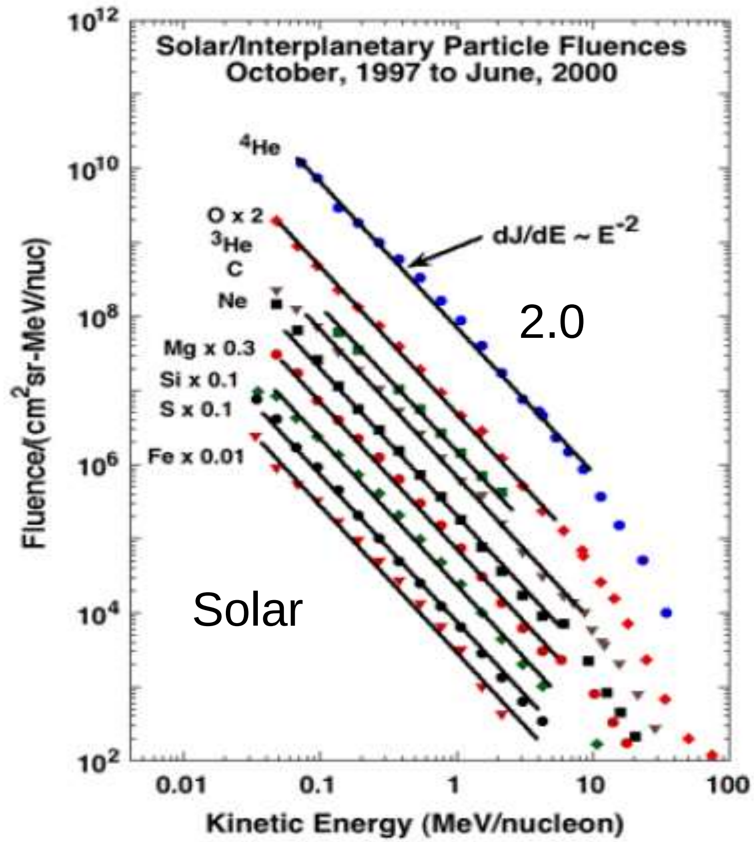


Long-Term Fluences of Solar Energetic Particles from H to Fe

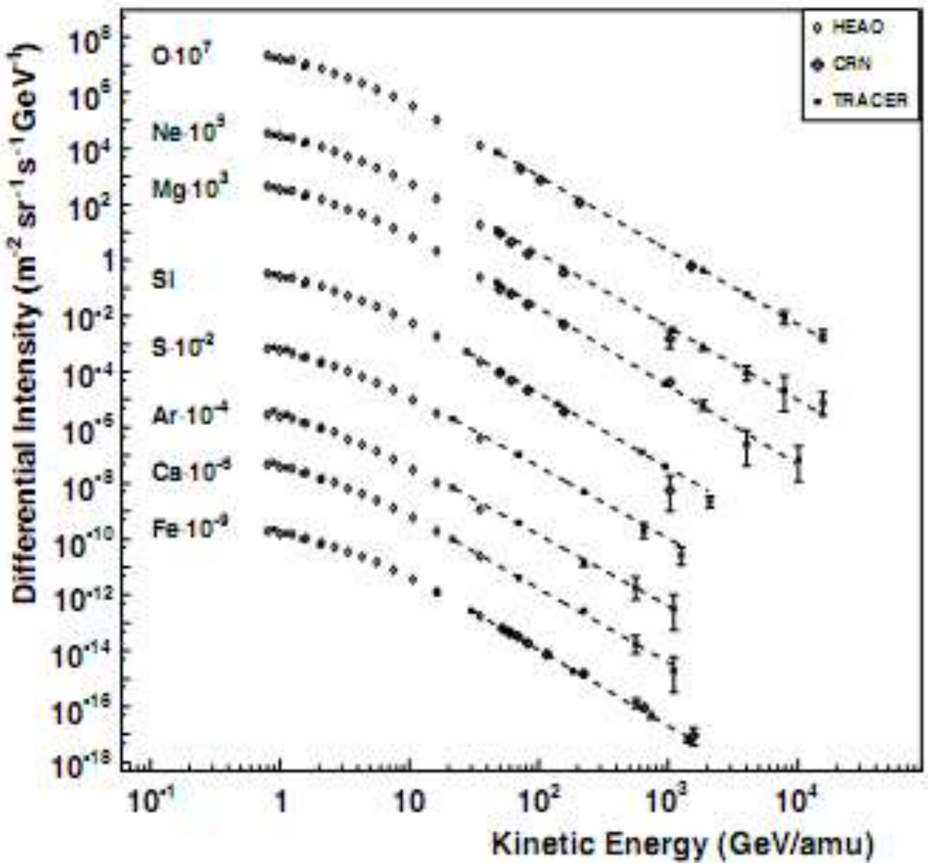
R.A. Mewaldt · C.M.S. Cohen · G.M. Mason · D.K. Haggerty · M.I. Desai

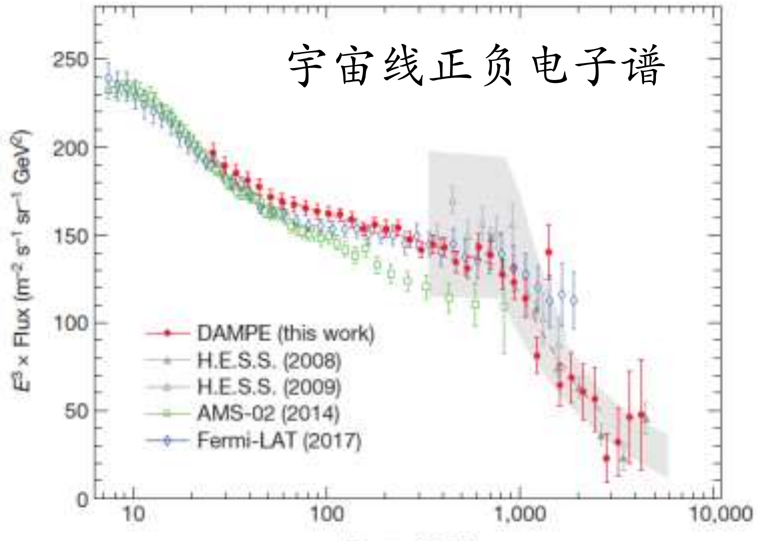
1: What determines the spectral index and breaks?

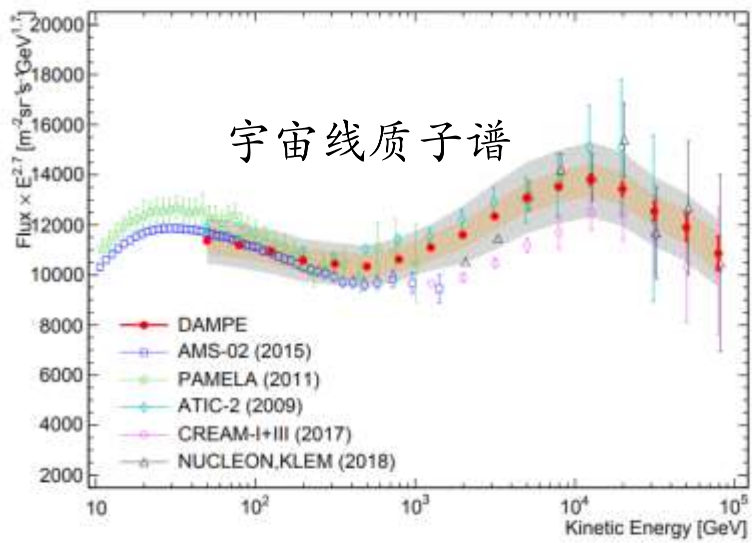




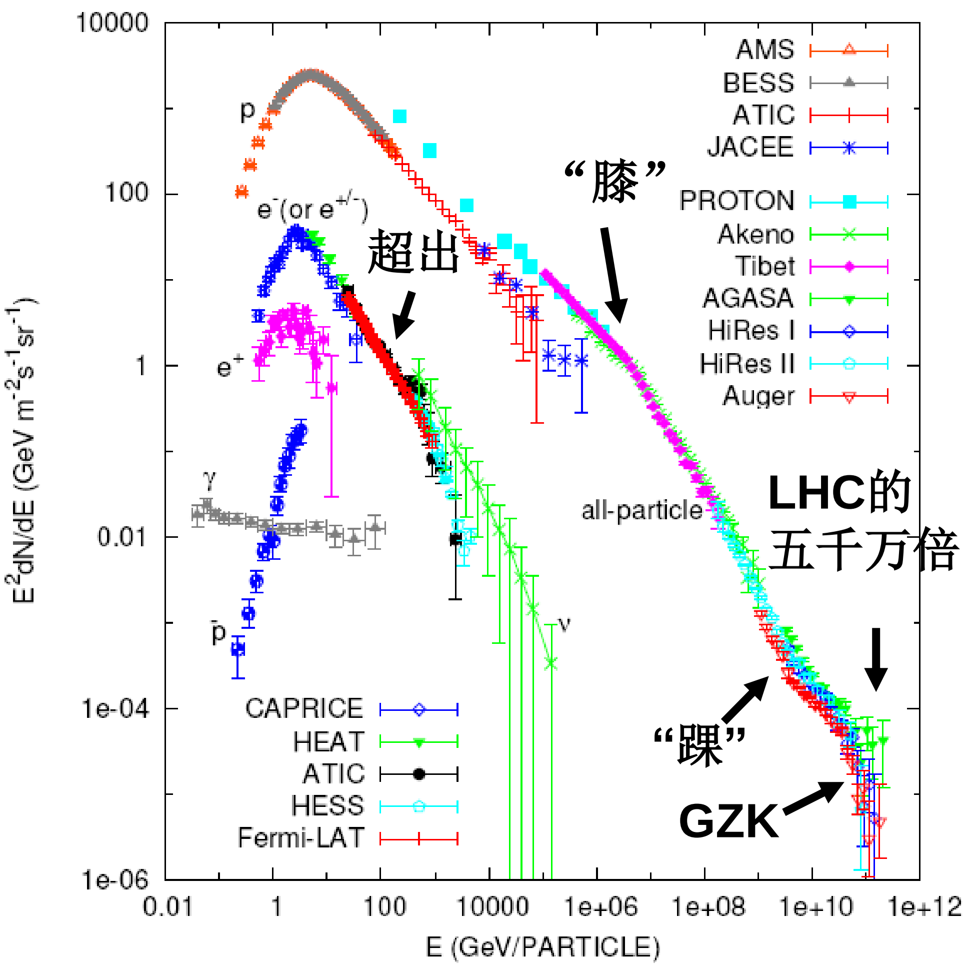
1： CR spectral measurements in Space





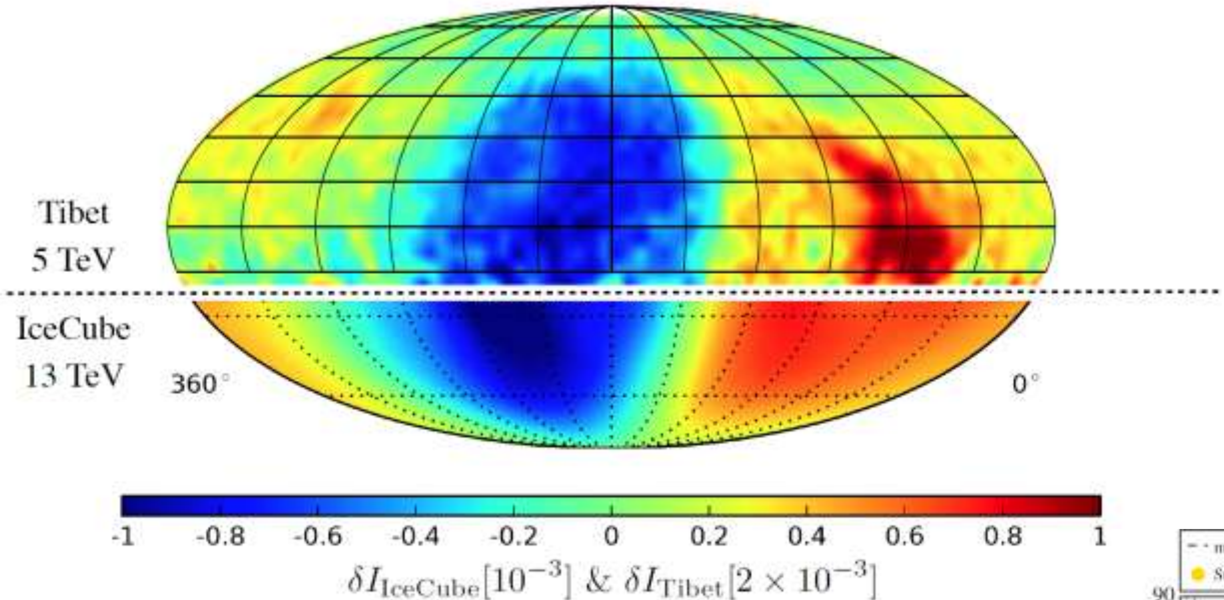


1:宇宙线的成份和能谱

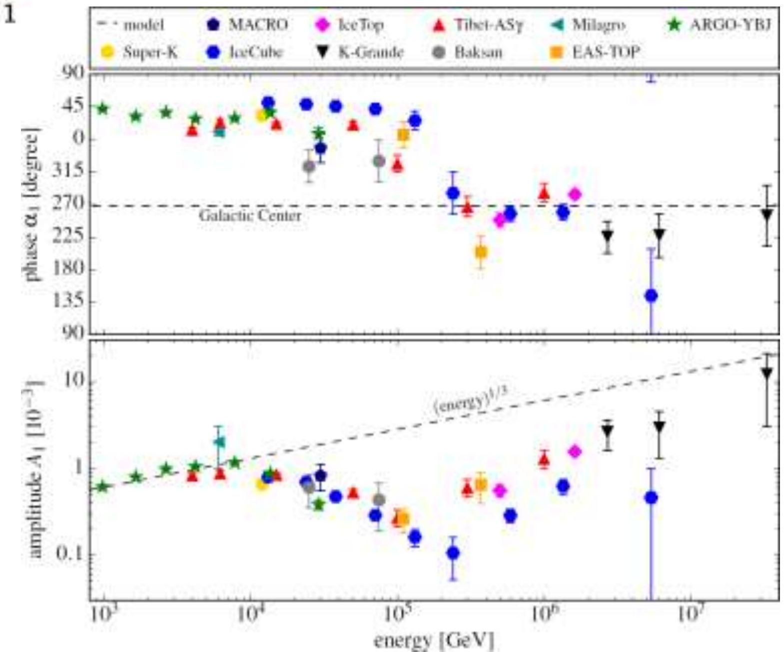


- 宇宙线主要由原子核构成；
- 年龄：10^7年；
- 能量密度：1eV/cm^3；
- 功率：~10^{41}尔格/秒；
- 最高宇宙线粒子的能量达到3×10^{20}eV，约50焦耳。已知物理学基本规律在此能量下是否还成立？
- 宇宙线e$^\pm$对宇宙线起源，加速，对暗物质粒子寻找，对量子引力、天文学和宇宙学研究有重要意义。
- 宇宙线基本上呈幂率谱，~200GeV处谱变硬；4PeV有拐折，被称为“膝”，小于此能量被认为是银河内起源，大于则河外；
- 极高能有“踝”和GZK截断

1: Cosmic Ray Anisotropy



Cosmic ray anisotropy is suppressed in the TeV range!



2: Standard Paradigm

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

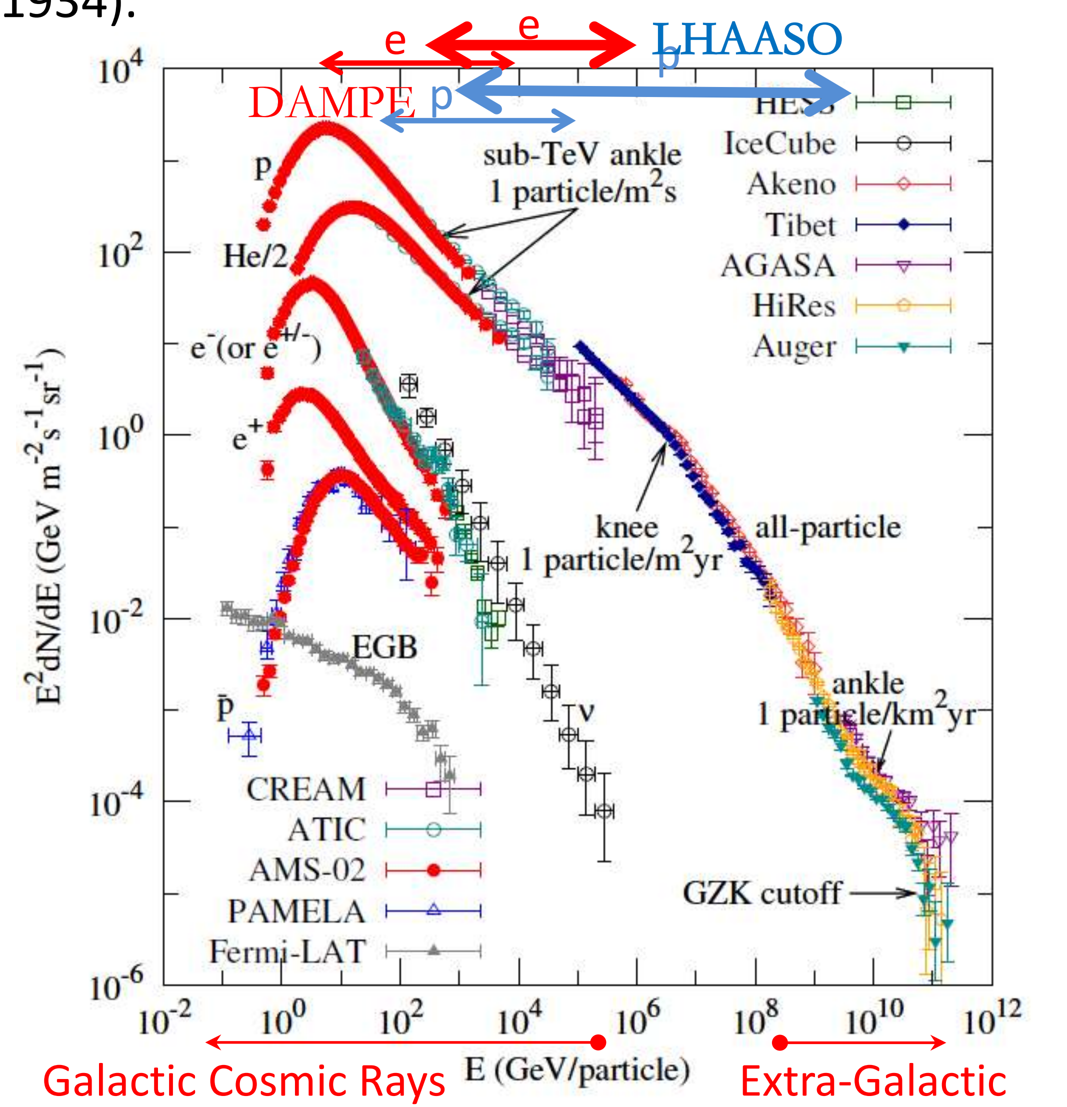
1、SNRs have enough total power ---10%, 3 per century, CR density (1ev/cm3)；

2、 Direct evidence:

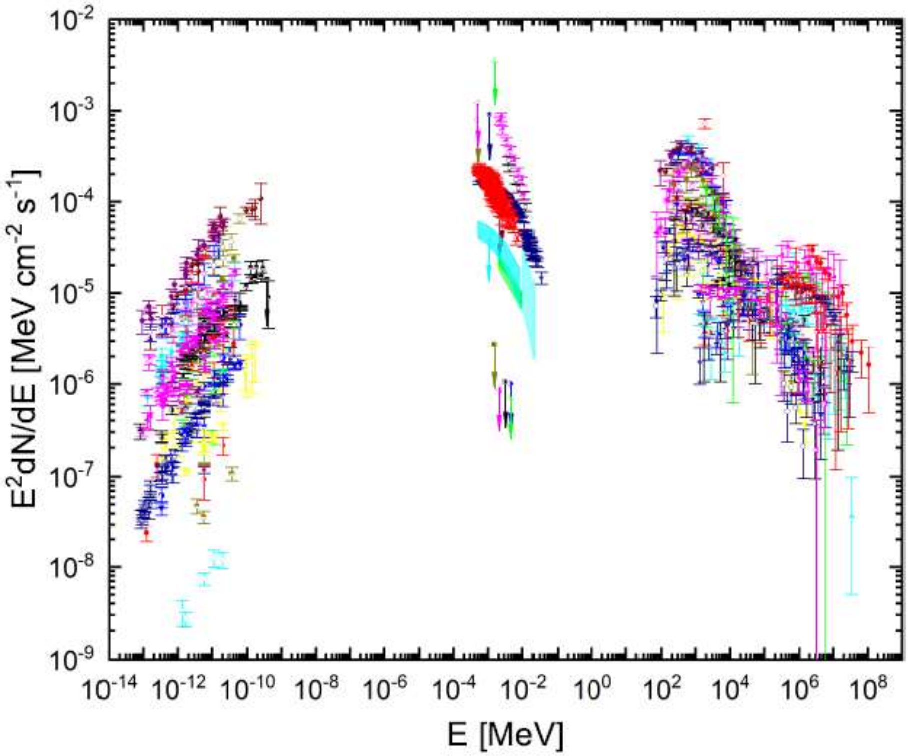
Radio emission (1948) —MeV-GeV electrons

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

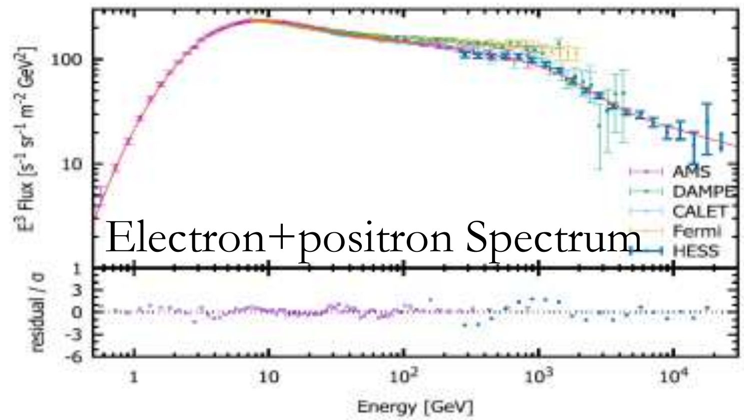
π^0 bump (2013)W44,IC443,W51C — GeV protons

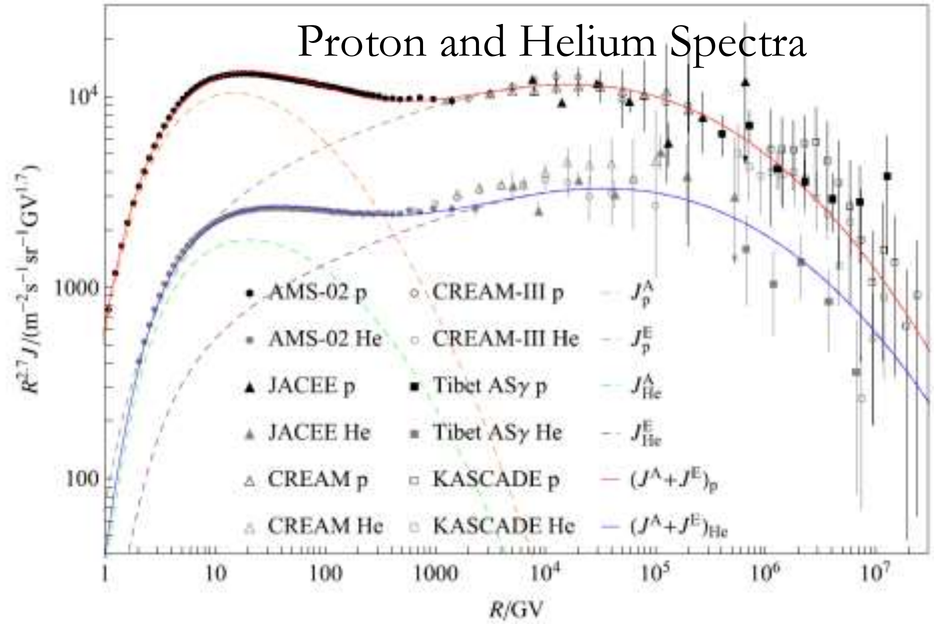


2: New Gamma-Ray and CR observations

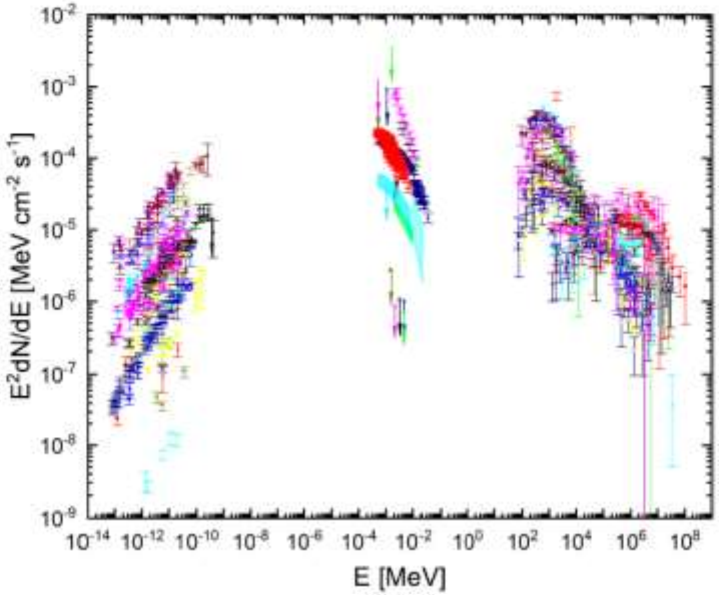


Multi-Wavelength Spectra of 34 SNRs





3: 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
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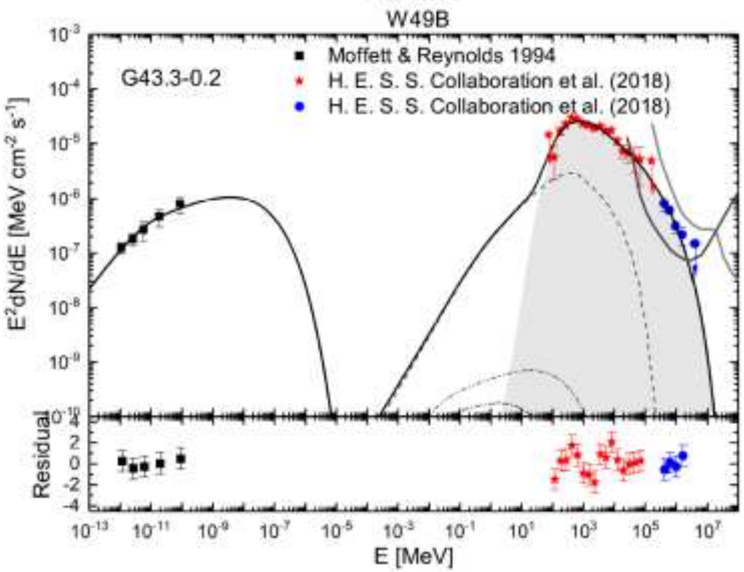
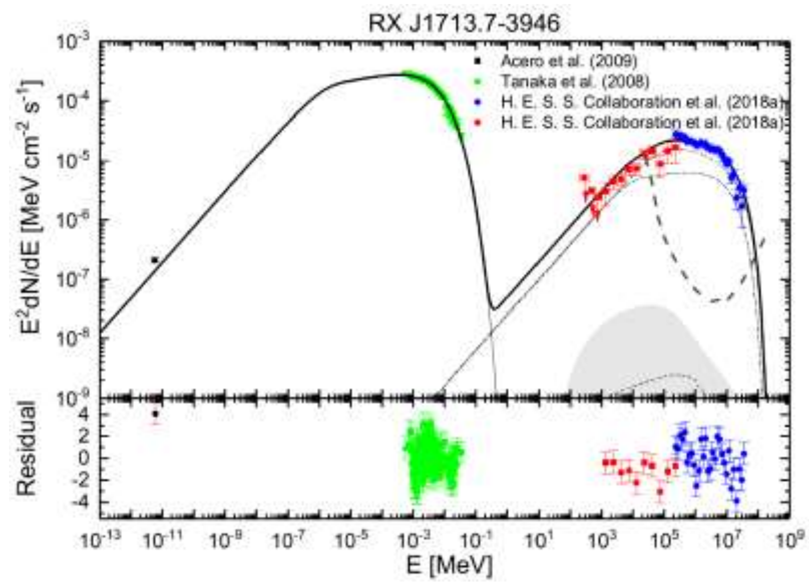
$$N(P_i) = N_{0,i}\exp\left(-\frac{P_i}{P_{i,\mathrm{cut}}}\right)\begin{cases}P_i^{-\alpha} & \text{if } P_i < P_{\mathrm{br}}\\ P_{\mathrm{br}}\,P_i^{-(\alpha+1)} & \text{if } P_i \geqslant P_{\mathrm{br}},\end{cases}$$

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

Markov Chain Monte Carlo Algorithm



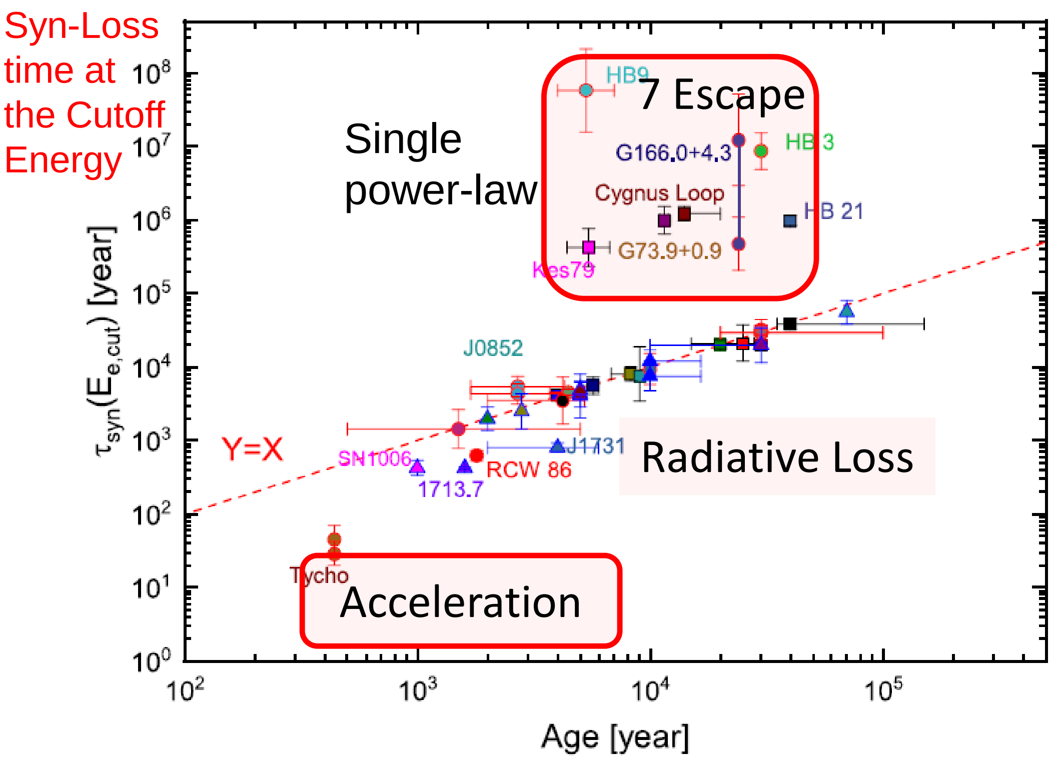


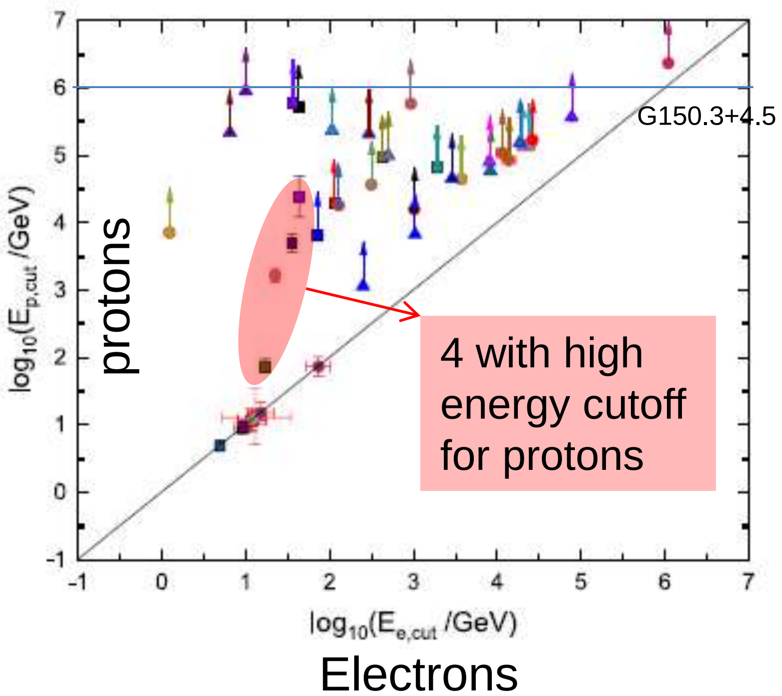
3: Evolution of High-Energy Particle Distribution in SNRs

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

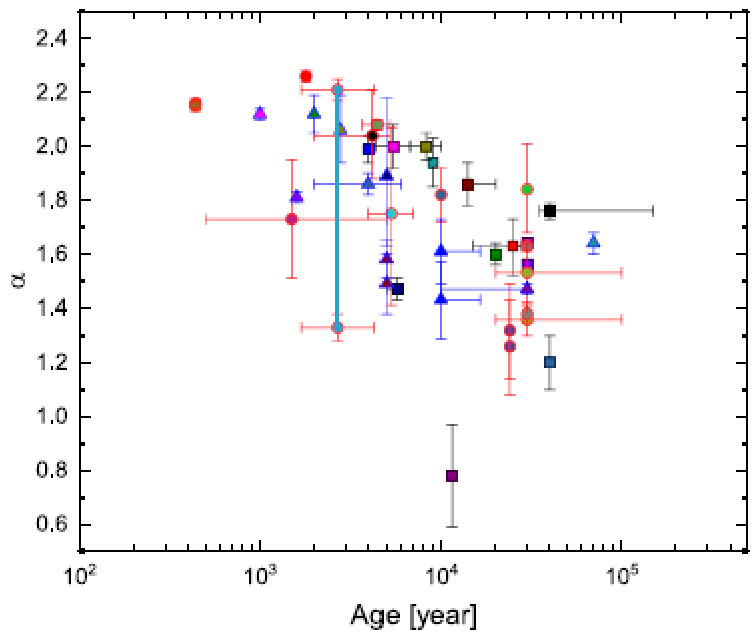
High Energy Cutoffs



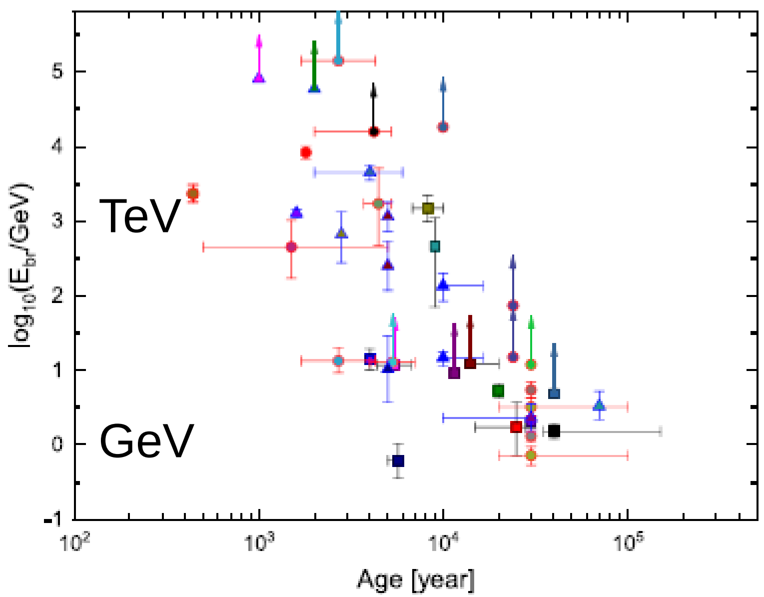


3: Evolution of High-Energy Particle Distribution in SNRs

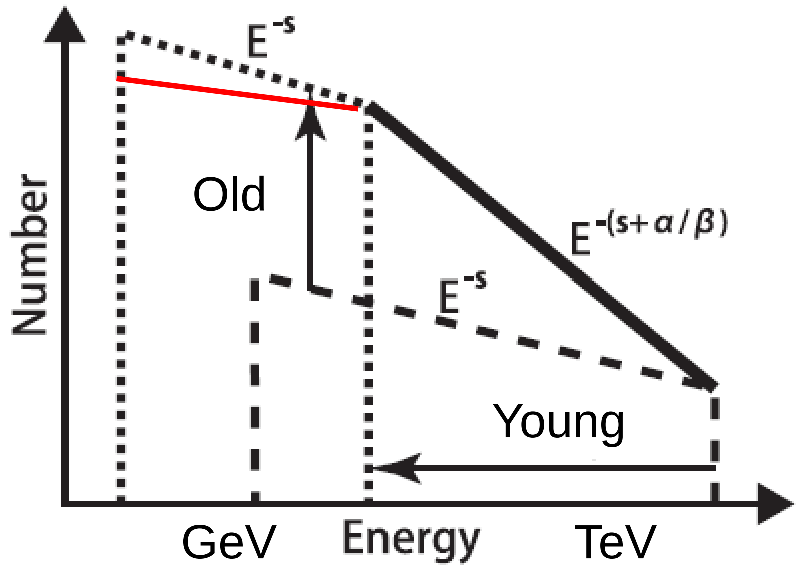
Low Energy Spectral Index



Spectral Break Energy



3: Ion Acceleration in SNRs



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

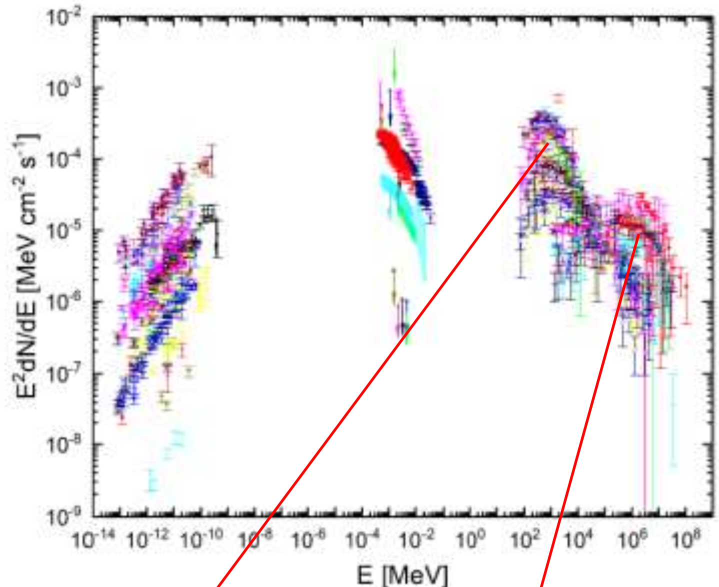
COSMIC-RAY HELIUM HARDENING

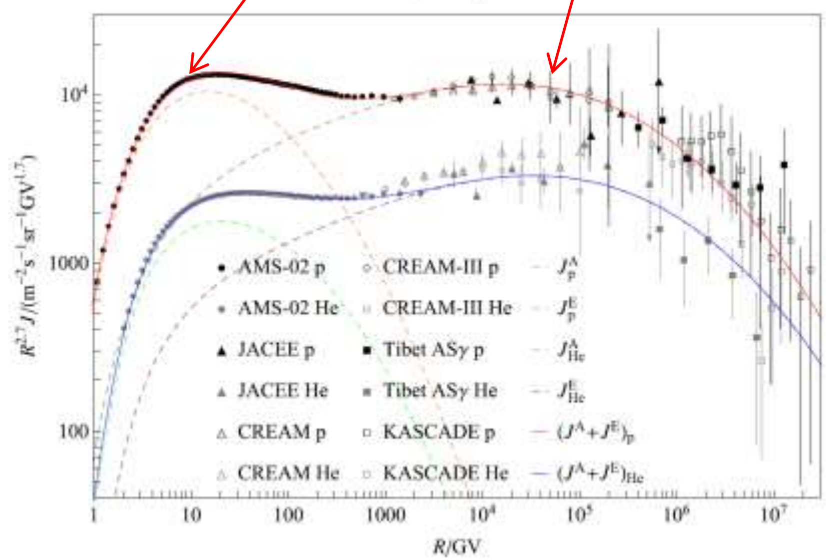
Yutaka Ohira and Kunihito Ioka

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]





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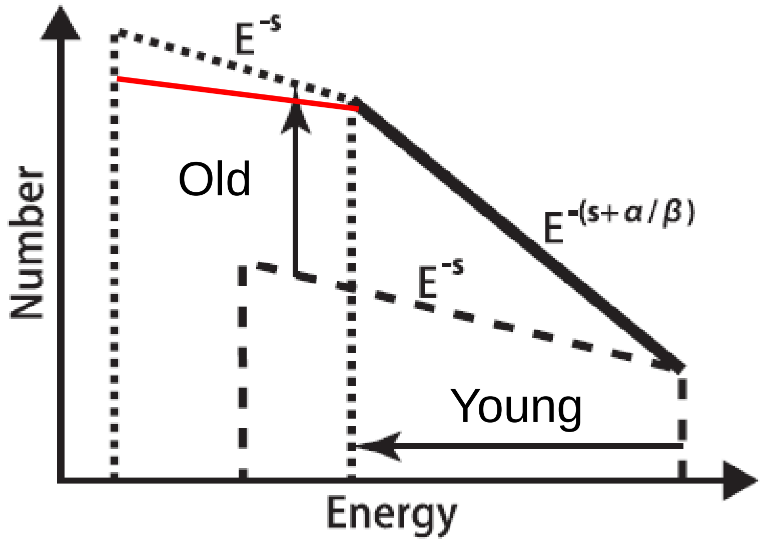
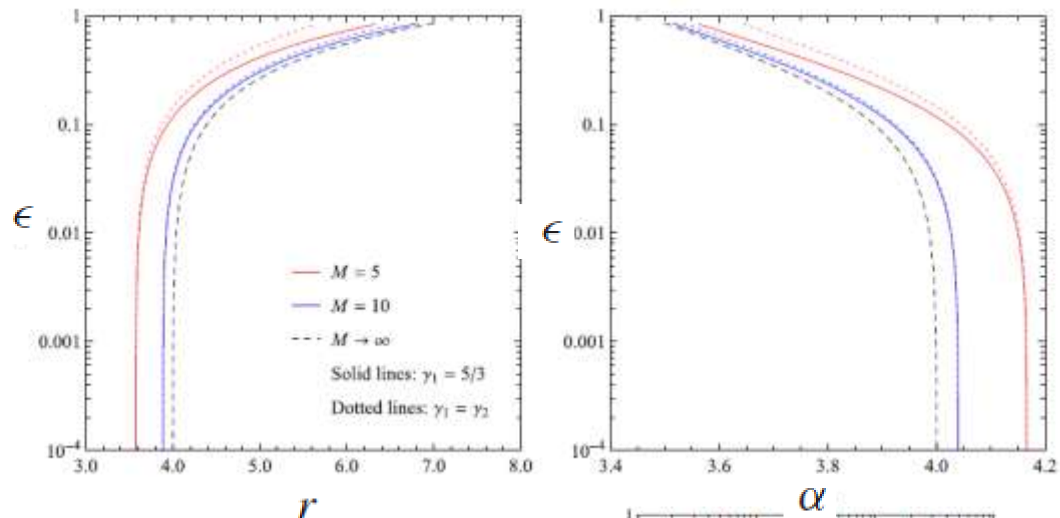


MNRAS 482, 5268–5274 (2019)
Advance Access publication 2018 November 19
doi:10.1093/mnras/sty3136

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

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



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

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

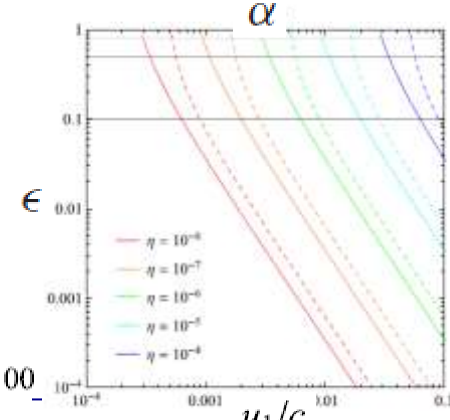
$$\eta \approx n_{\rm cr}/n$$

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

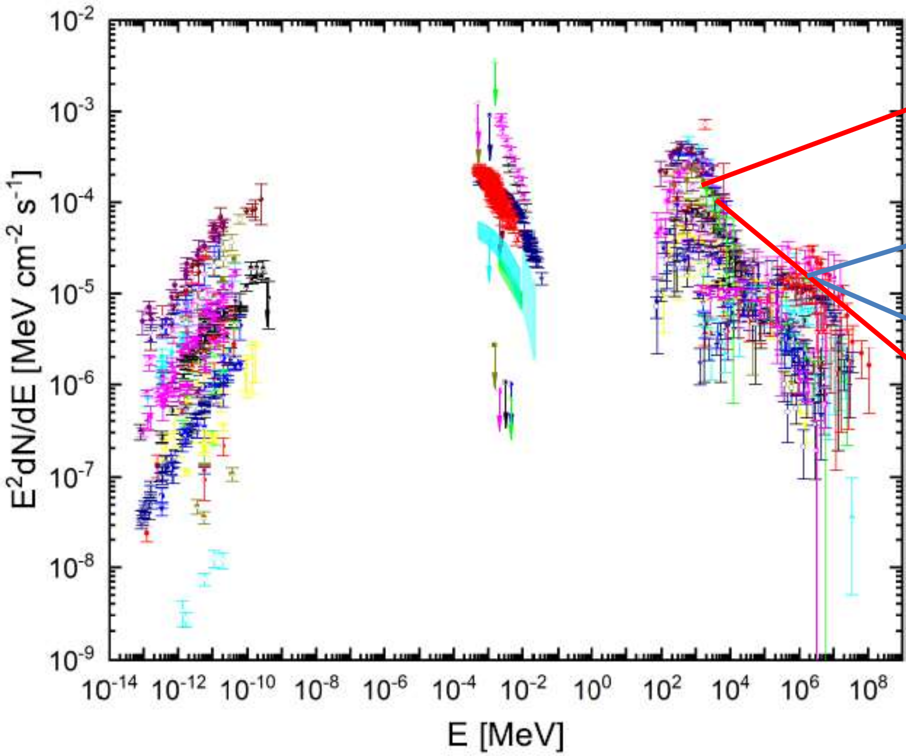
$$r = \frac{\frac{1}{\gamma_1} + M^2 + \sqrt{\left(\frac{1}{\gamma_1} + M^2\right)^2 + \left(\frac{1}{\gamma_2^2} - 1\right)\left(\frac{2}{\gamma_1 - 1} + M^2\right) M^2}}{\left(1 - \frac{1}{\gamma_2}\right)\left(\frac{2}{\gamma_1 - 1} + M^2\right)},$$

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

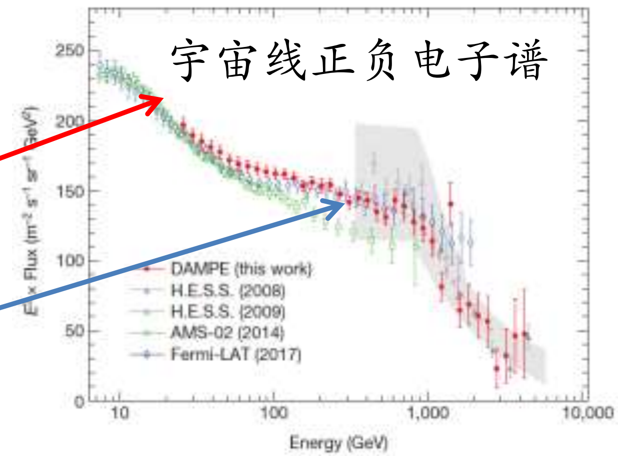
Dashed lines: $\xi_{\rm m} = 100$

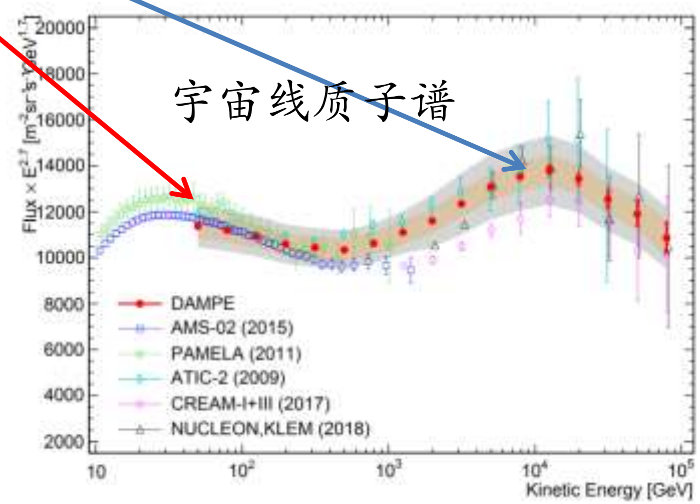


4: New Paradigm and PeVatrons



34个超新星遗迹的能谱





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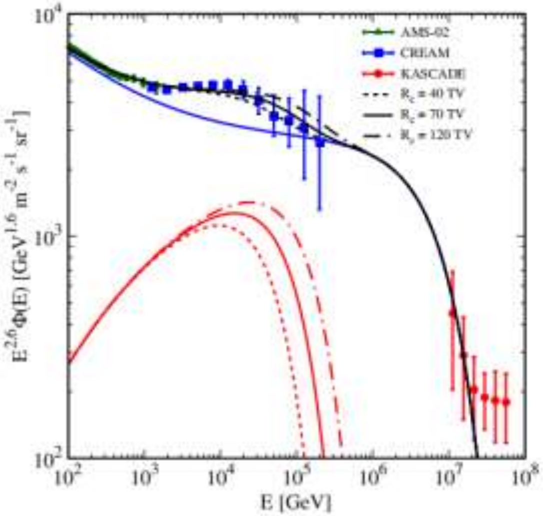
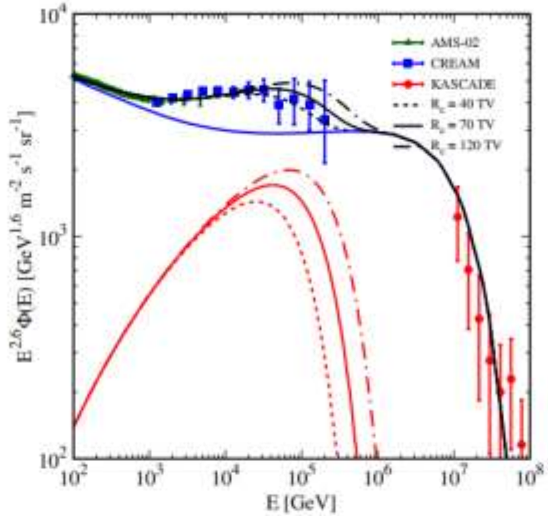


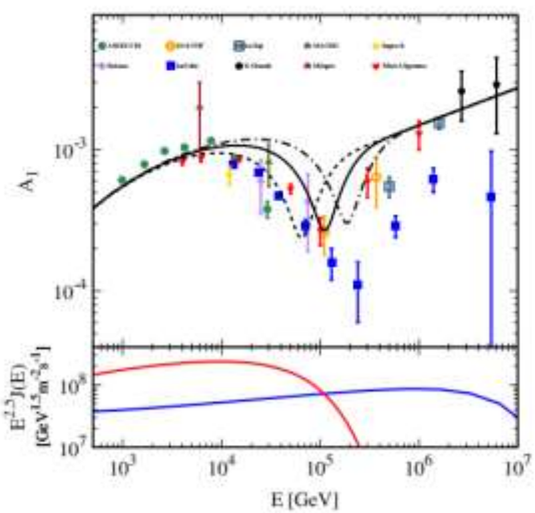


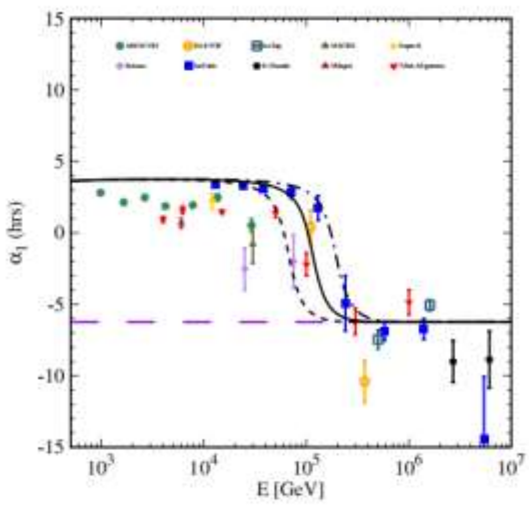
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

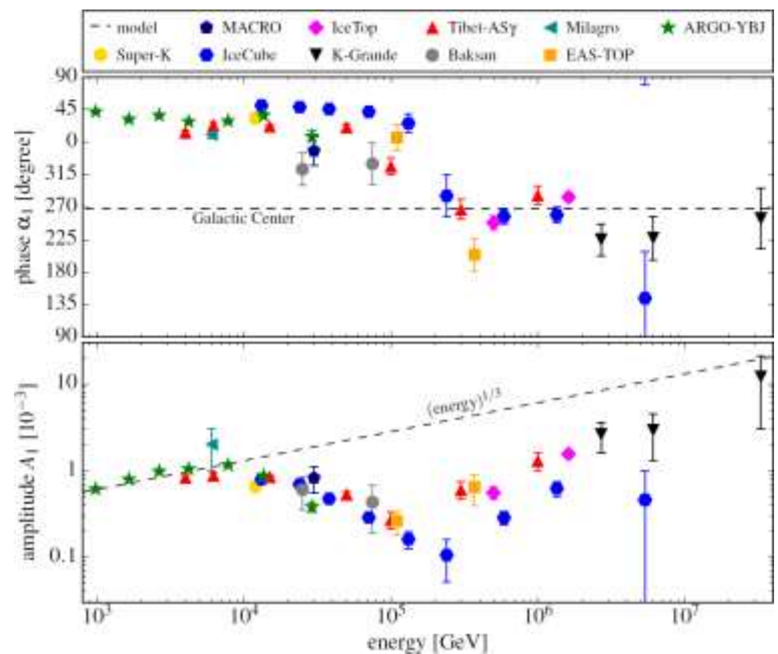
Anisotropies of different mass compositions of cosmic rays

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

Rc=28TV





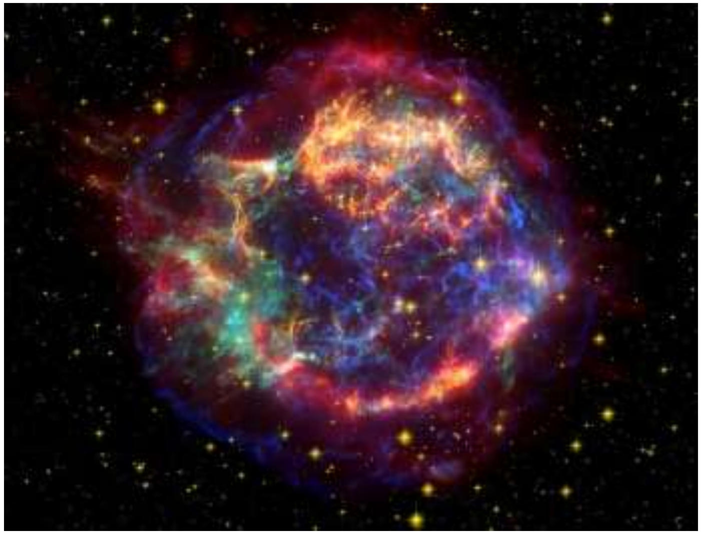


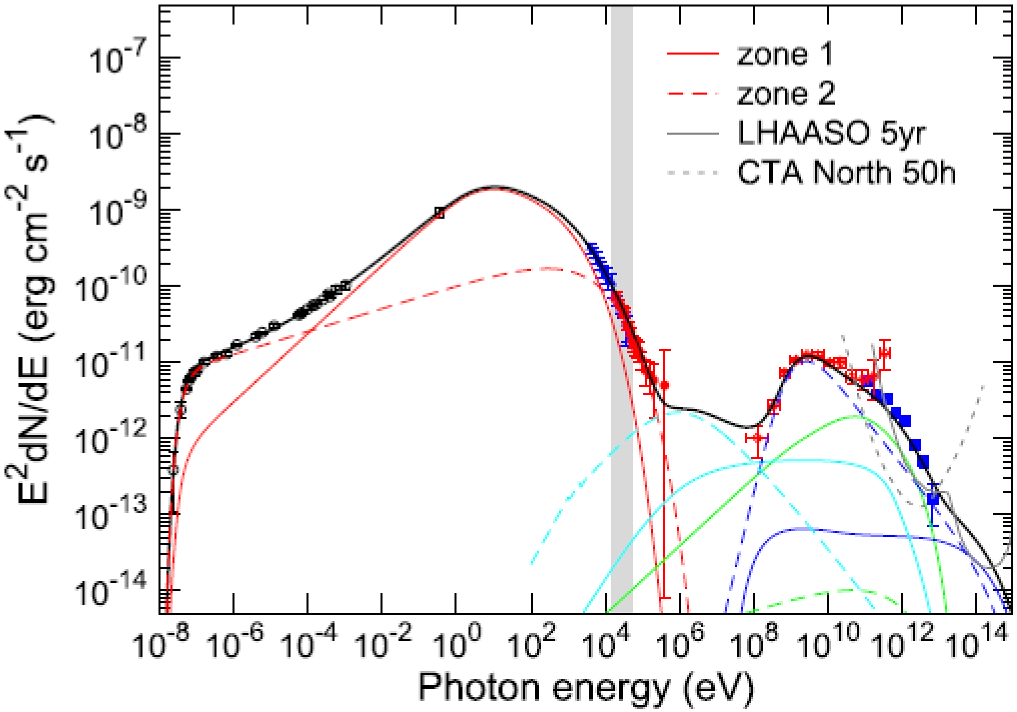
4: New Paradigm and PeVatrons

The Astrophysical Journal, 874:98 (6pp), 2019 March 20
https://doi.org/10.3847/1538-4357/ab09fe

Is Supernova Remnant Cassiopeia A a PeVatron?

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





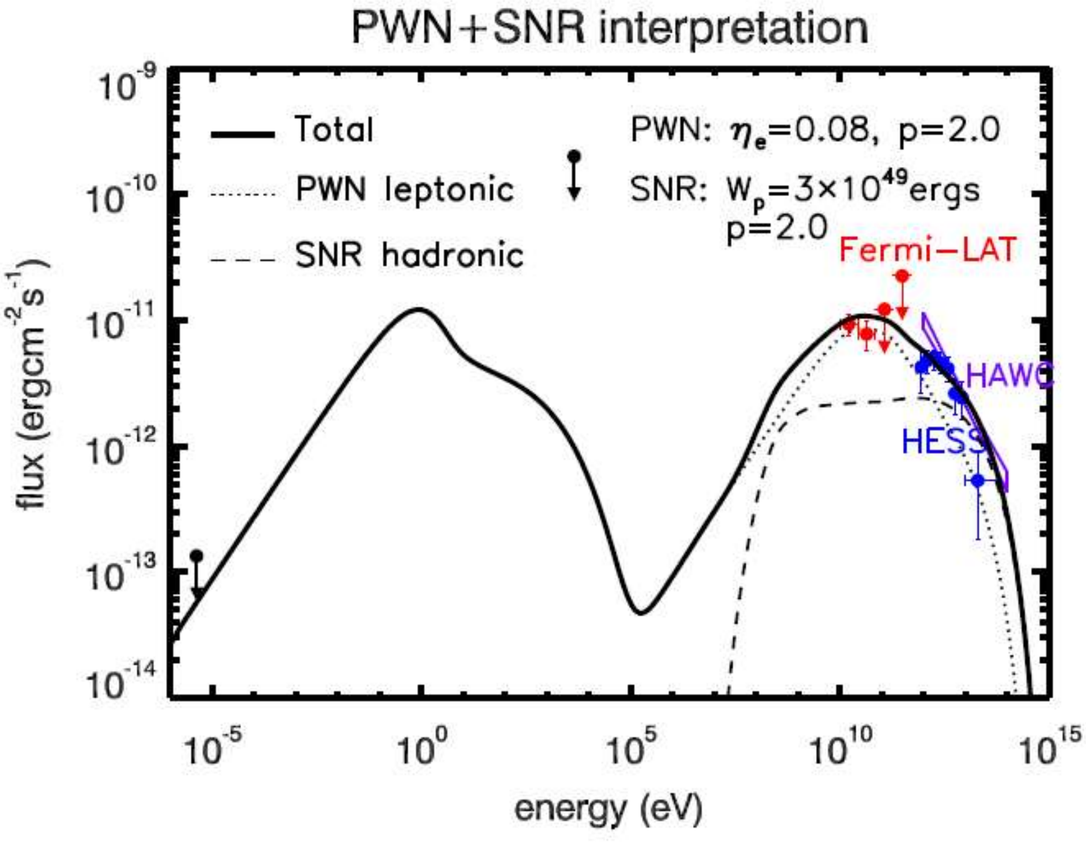
Wp = 1e48ergs

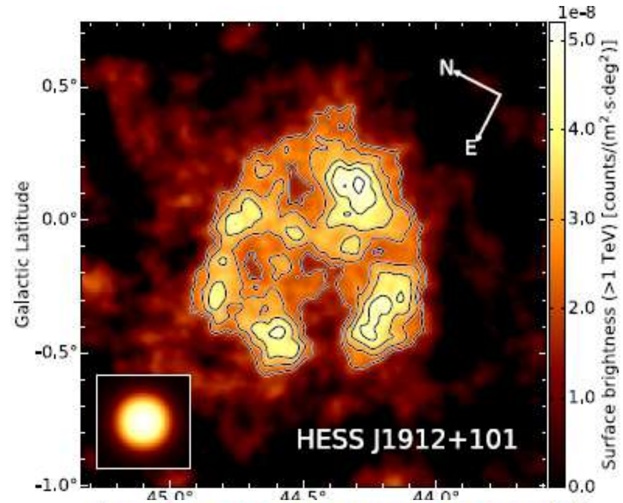
4: New Paradigm and PeVatrons

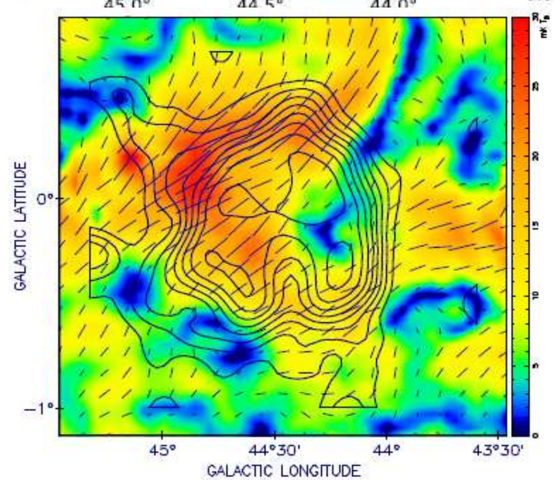
DISCOVERY OF A SPATIALLY EXTENDED GEV SOURCE IN THE VICINITY OF THE TEV HALO CANDIDATE 2HWC J1912+099: A TEV HALO OR SUPERNOVA REMNANT ?

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]

70-200kyr







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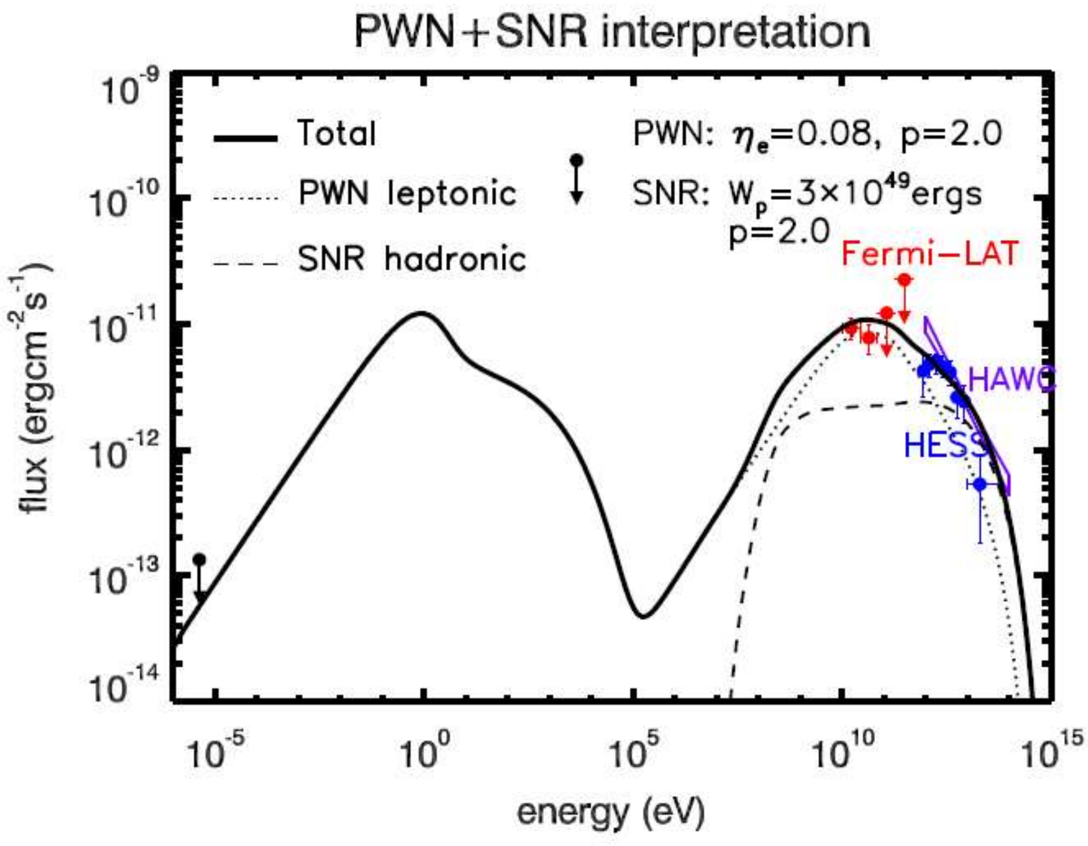
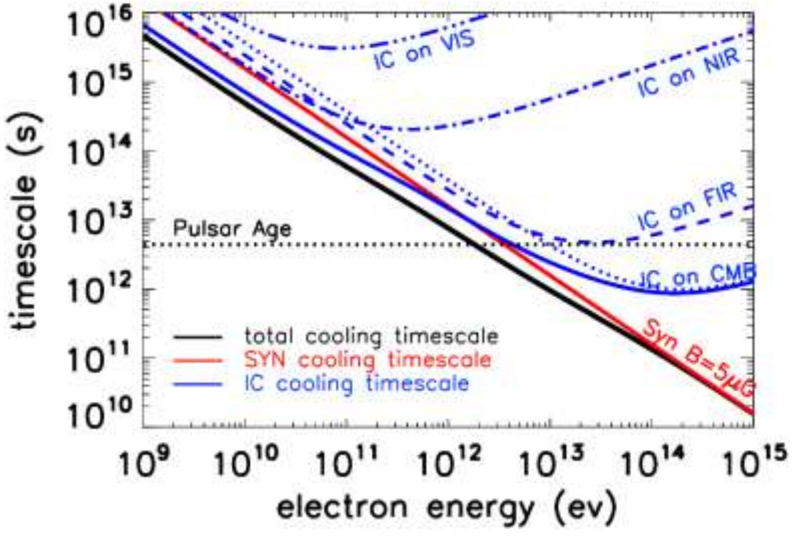




70-200kyr

Ec<300TeV

4: Standard Paradigm

Supernova remnants (SNRs) have bee
galactic cosmic rays (Baade & Zwicky

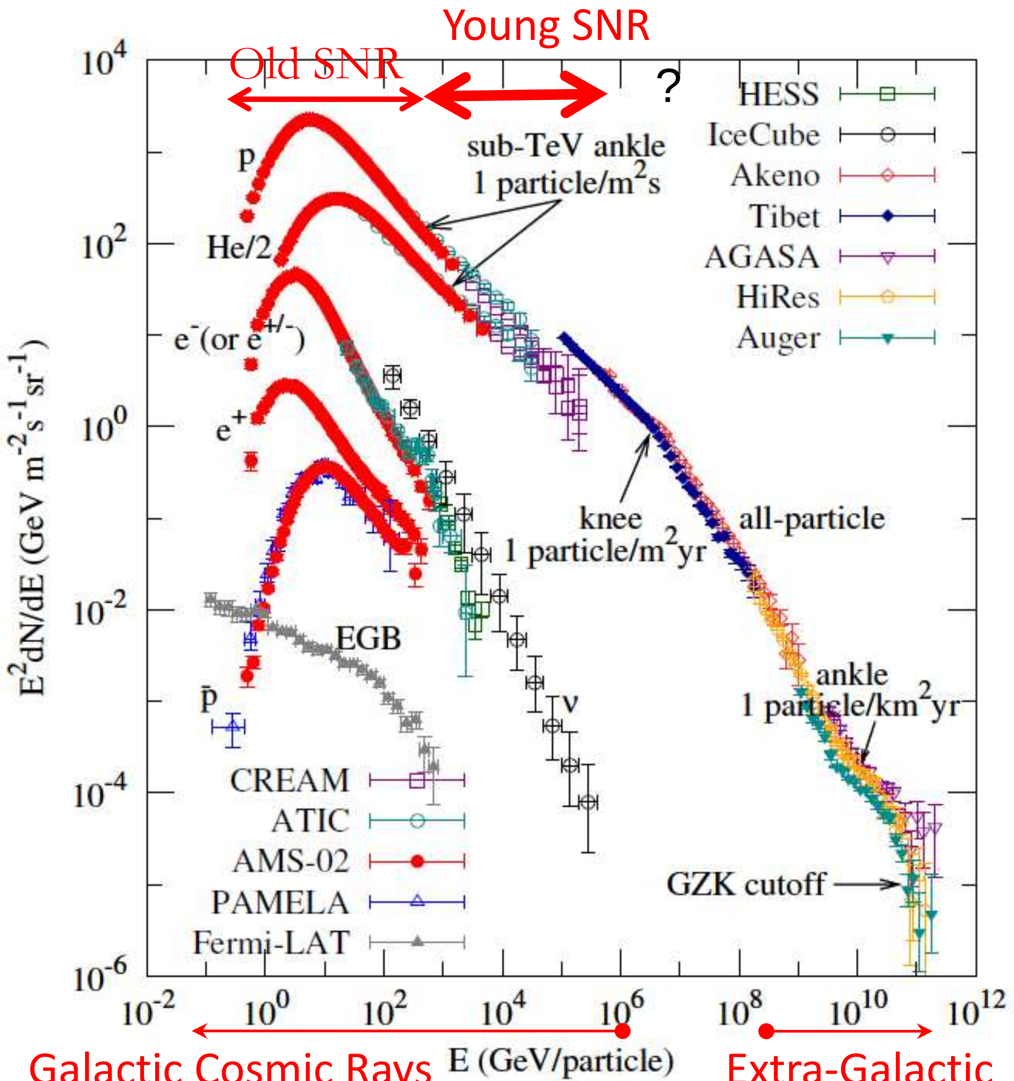
1、 SNRs have enough total power ---10%, 3 per century, CR density (1ev/cm3);

2、 Direct evidence:

Radio emission (1948) —MeV-GeV electrons

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

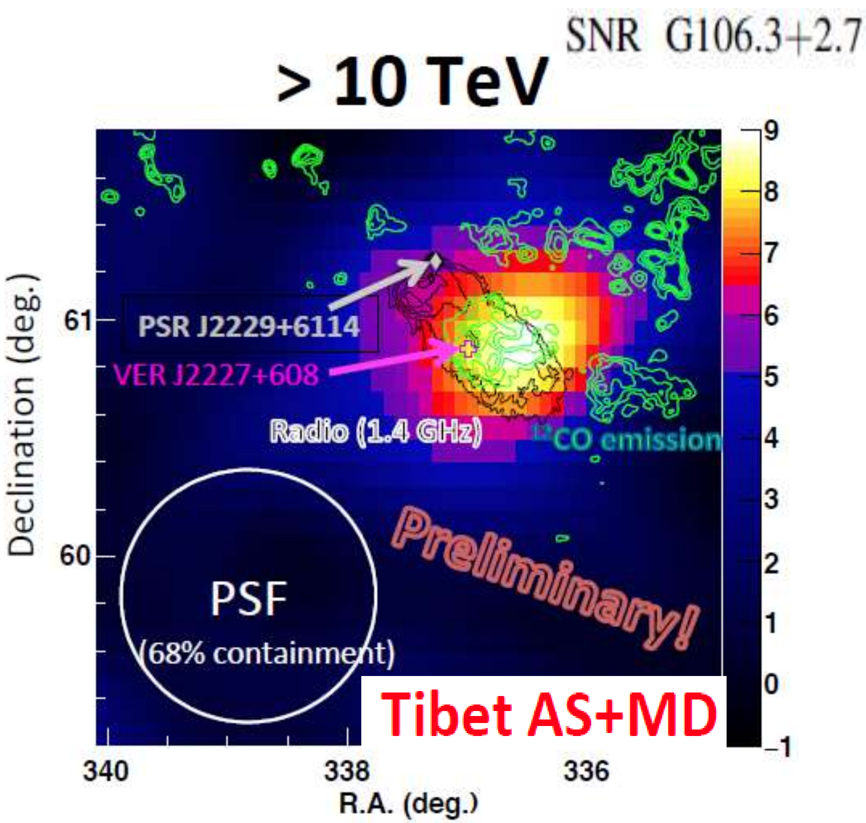
π^0 bump (2013)W44,IC443,W51C

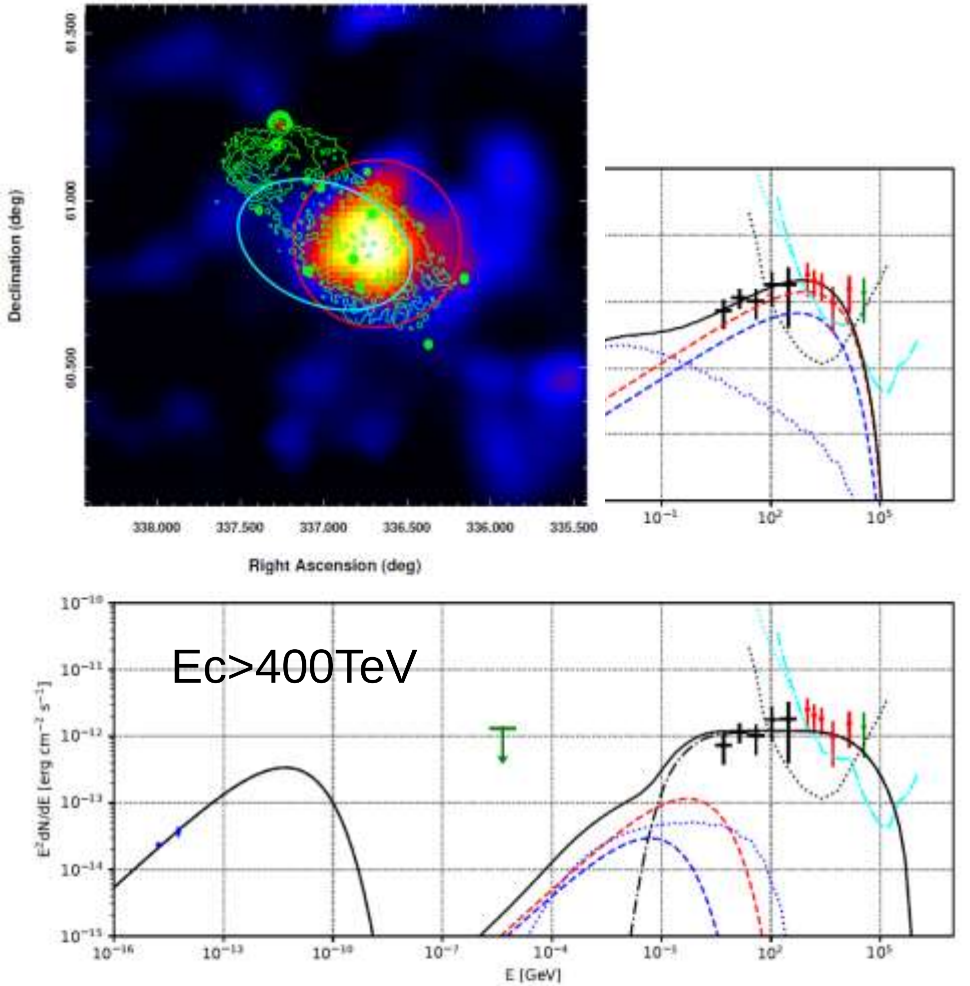


THE ASTROPHYSICAL JOURNAL, 885:162 (6pp), 2019 November 10 https://doi.org/10.3847/1538-4357/ab48ee

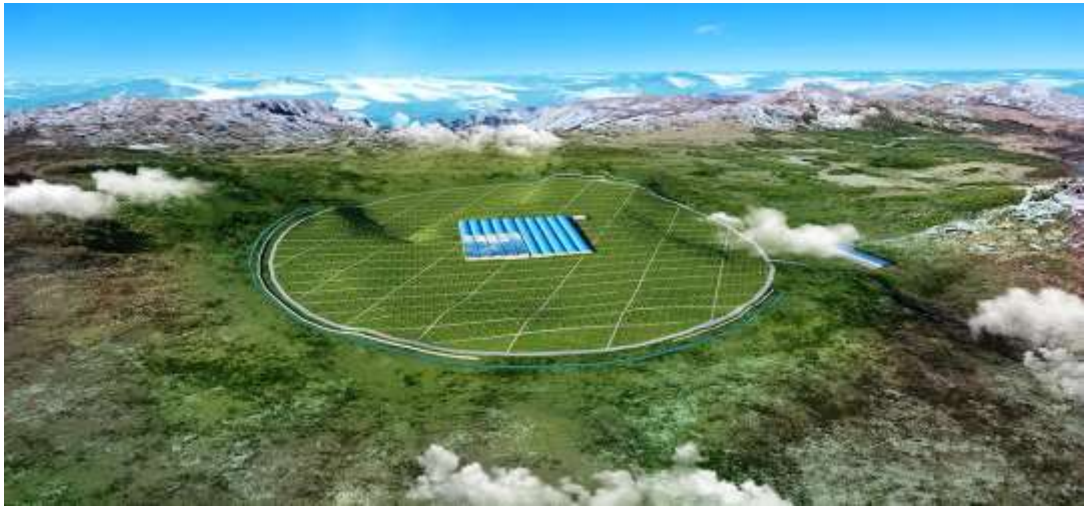
VER J2227+608: A Hadronic PeVatron Pulsar Wind Nebula?

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

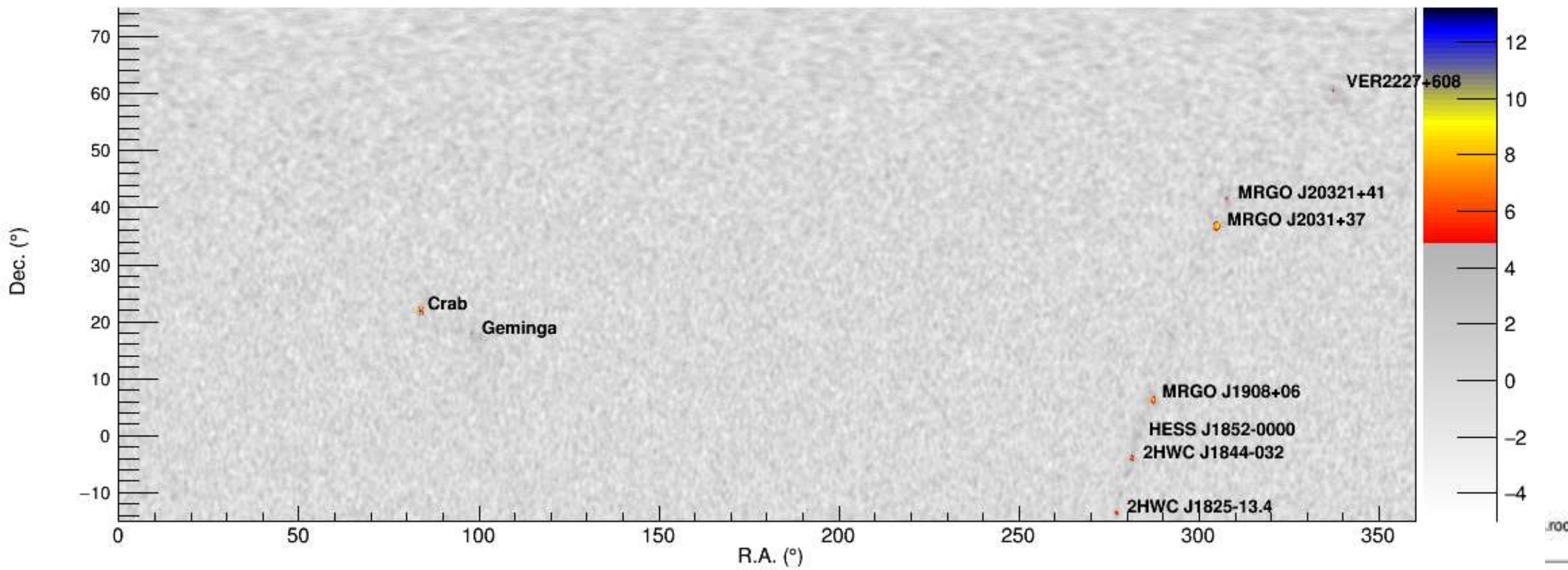


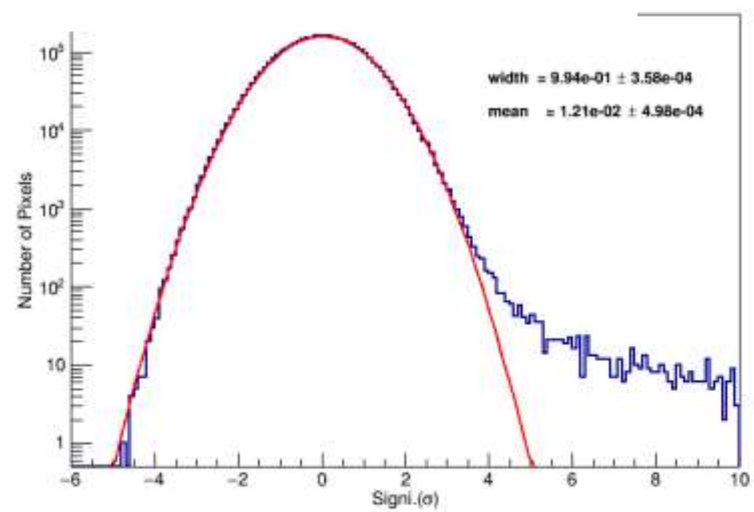


Large High Altitude Air-shower Obervatory (LHAASO)



50TeV





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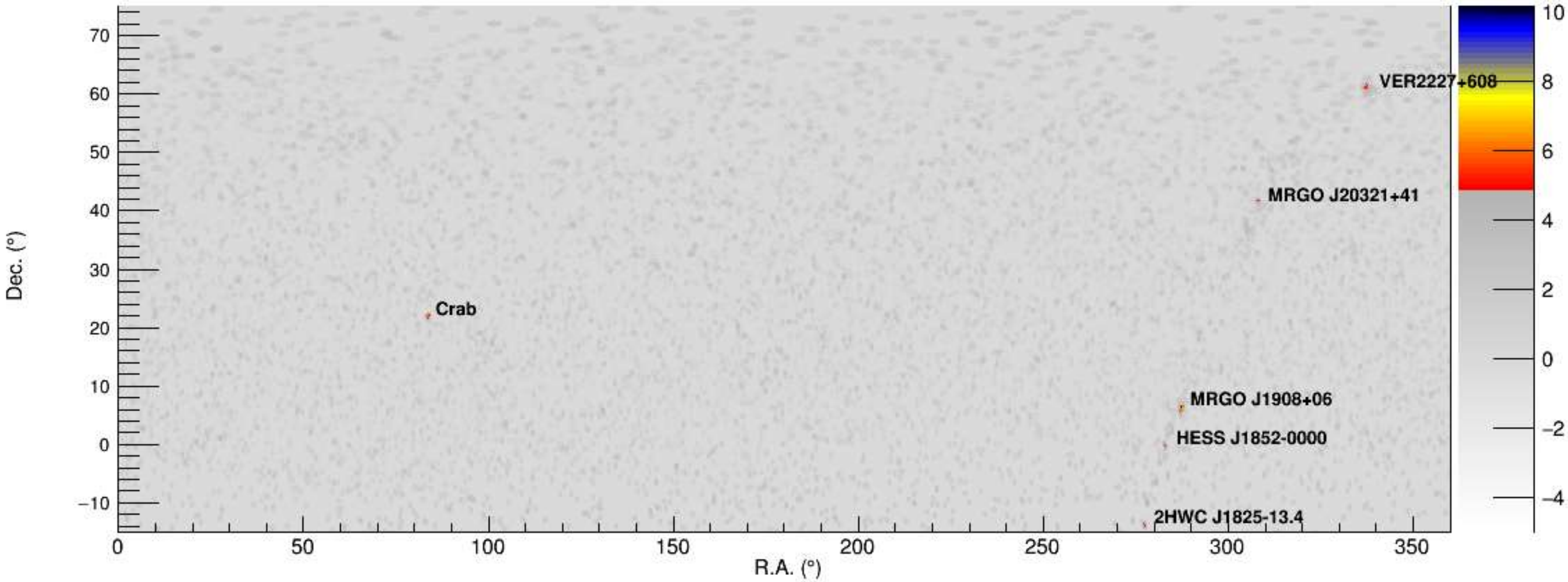
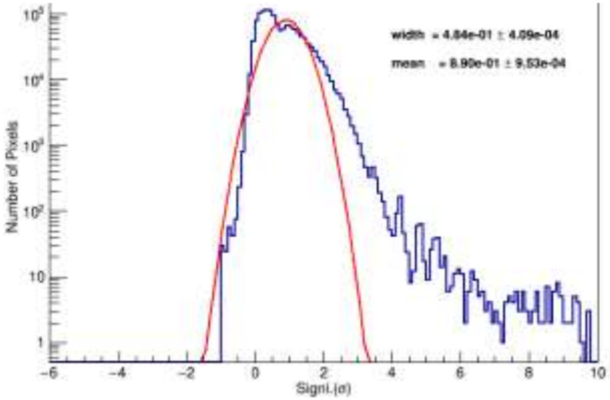
全天（60deg）:统计量90W(905389)

100TeV



Smooth=0.6
全天统计量： 1.3W(13092)个events
时间： 20190911-2020/02/10
0110~0210的数据全部用了



5: 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!