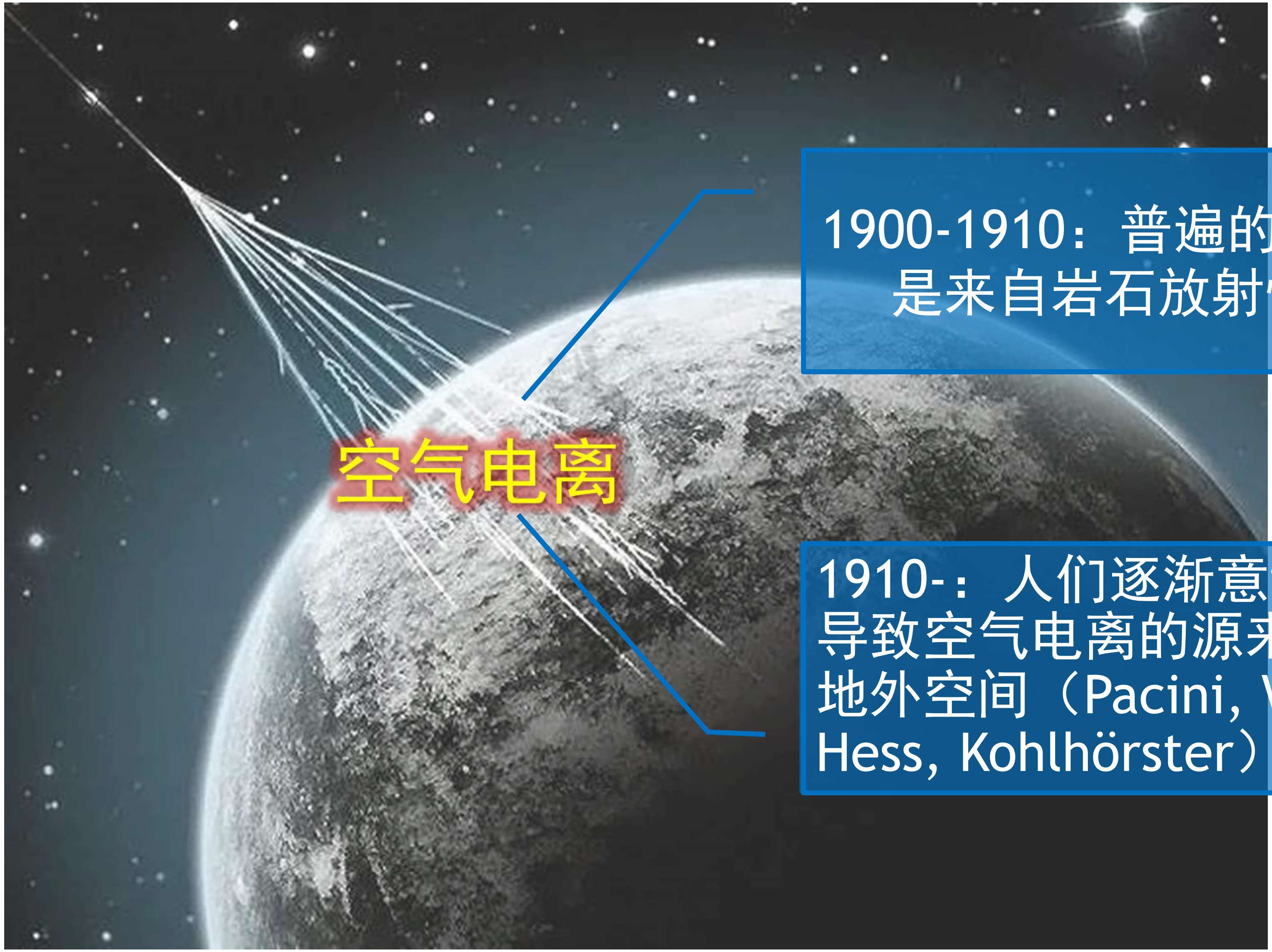
宇宙线起源世纪之谜

袁　强

中国科学院紫金山天文台

中国科学技术大学，见微学术沙龙，2026-04-03

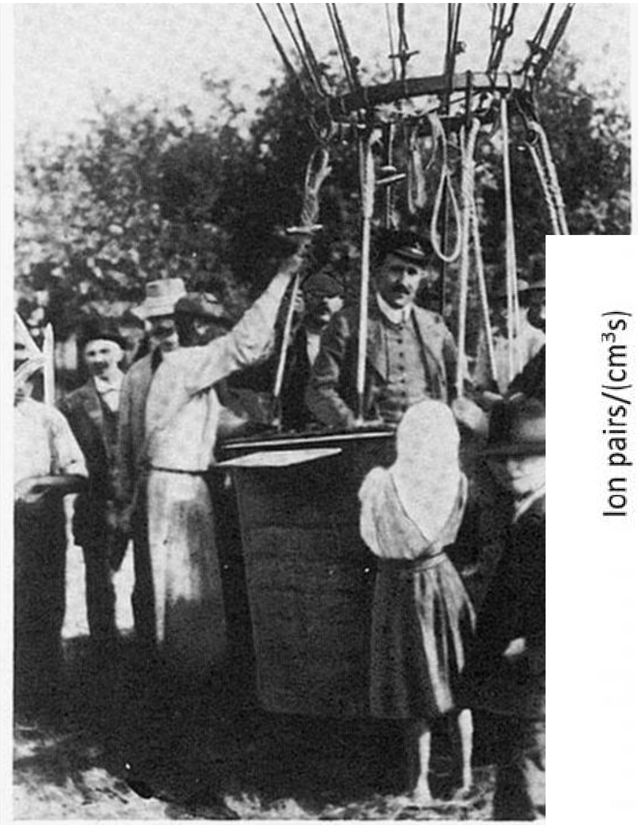
宇宙线发现：1910s



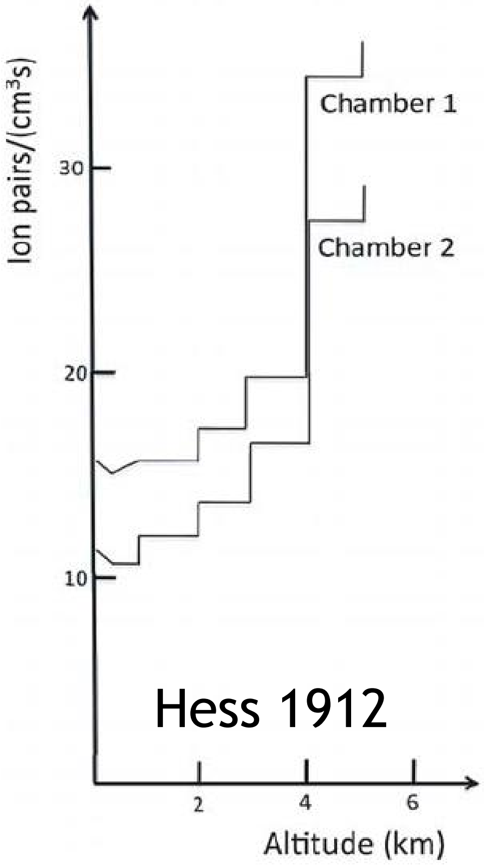
1900-1910：普遍的观点是来自岩石放射性

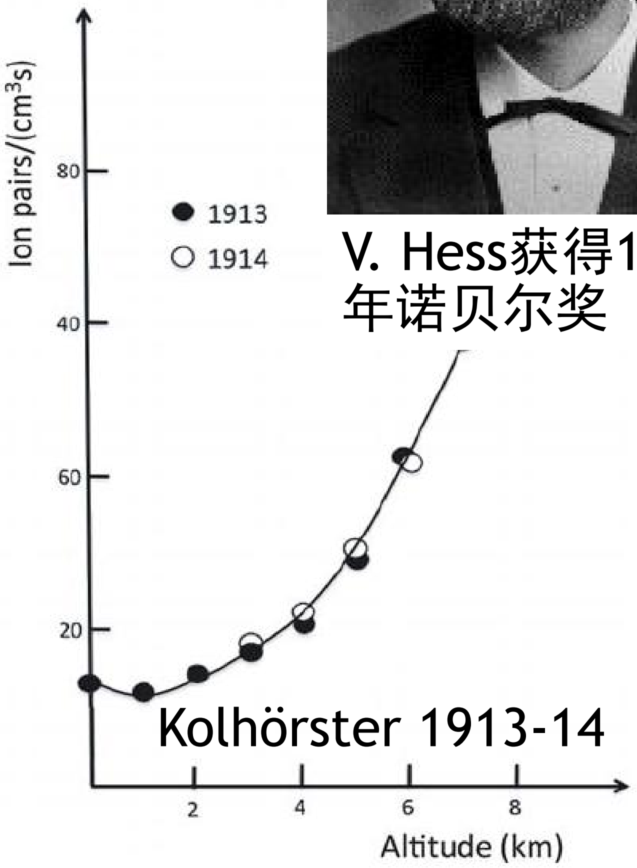
1910-：人们逐渐意识到导致空气电离的源来自地外空间（Pacini, Wulf, Hess, Kohlhörster）

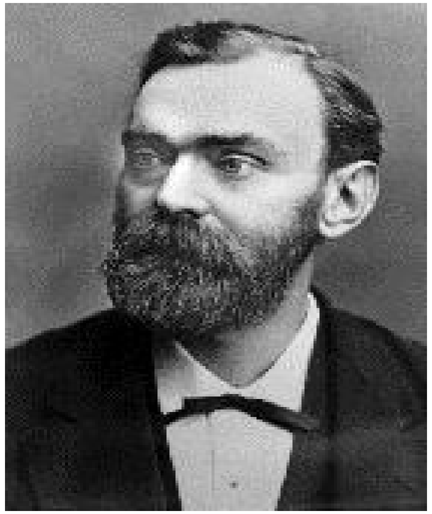
宇宙线发现：1910s



Hess bei Ballonlandung (1912).

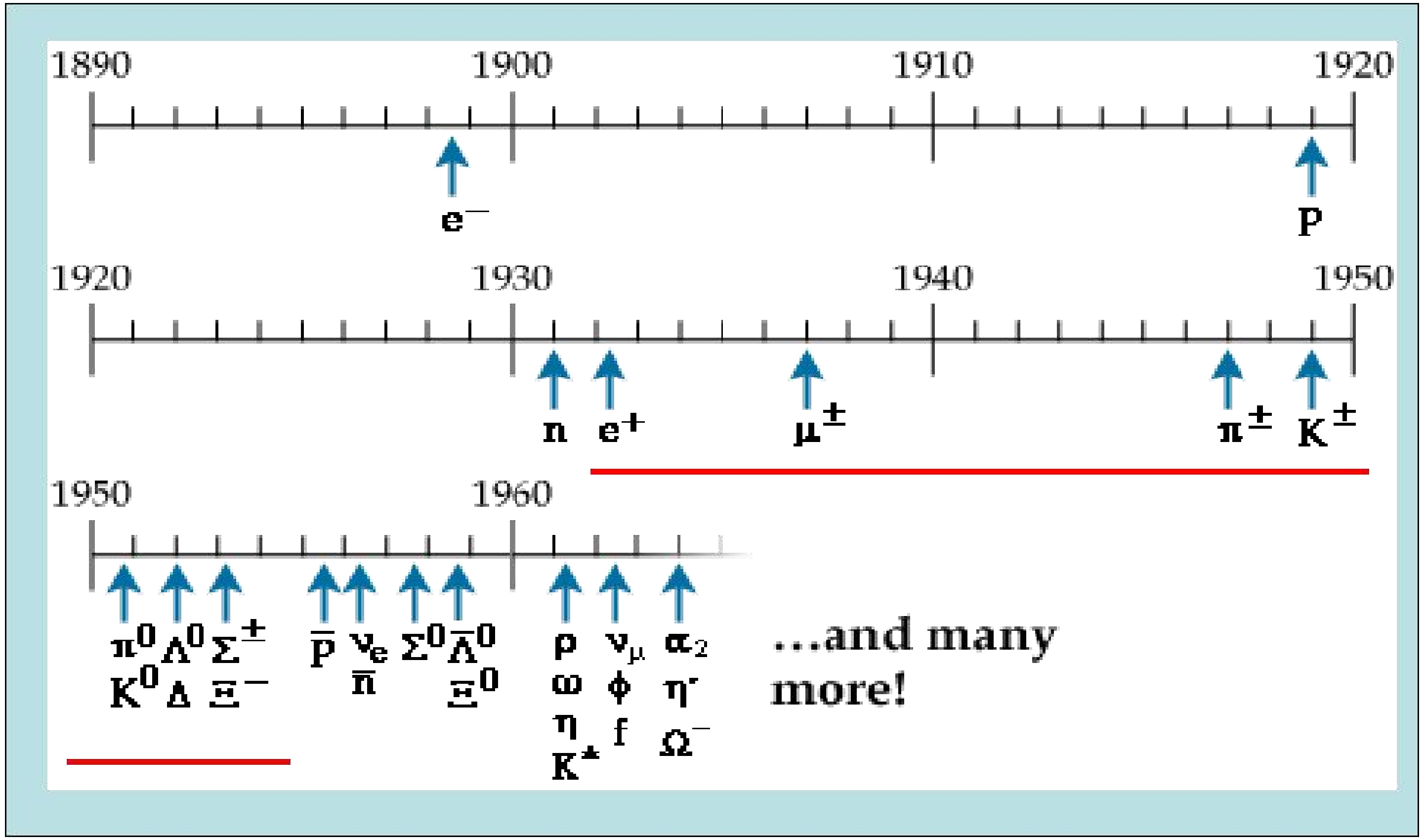






V. Hess获得1936年诺贝尔奖

天然的固定靶实验



宇宙线轰击大气原子核，是研究粒子物理和核物理的天然固定靶实验，为粒子物理标准模型的建立做出了重要贡献

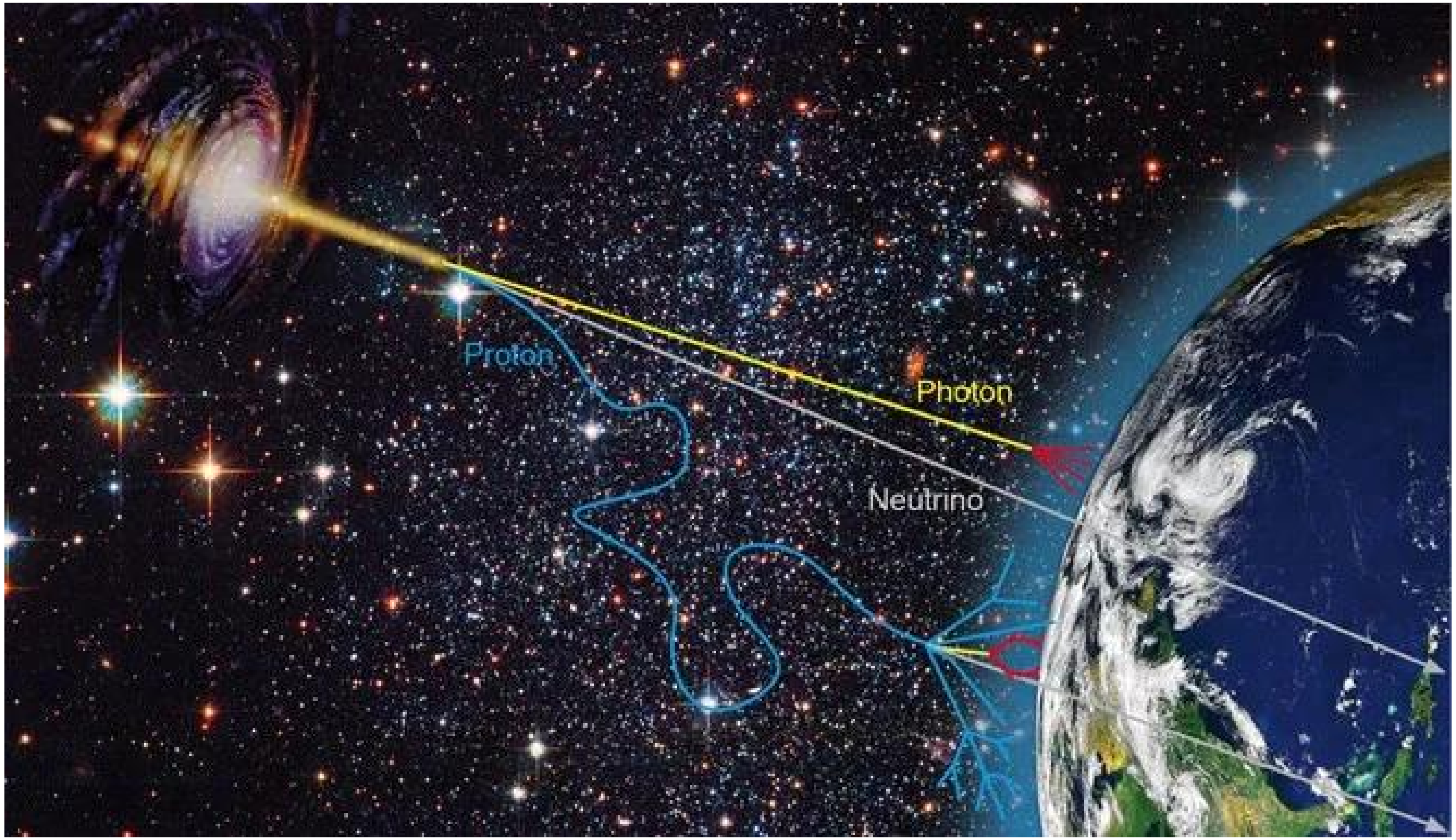
前沿物理和极端天体探针

大型强子对撞机LHC：耗资~100亿美元，能量14 TeV
宇宙线：最高能量~10^{20} eV

宇宙线作为天然加速器 ⇒

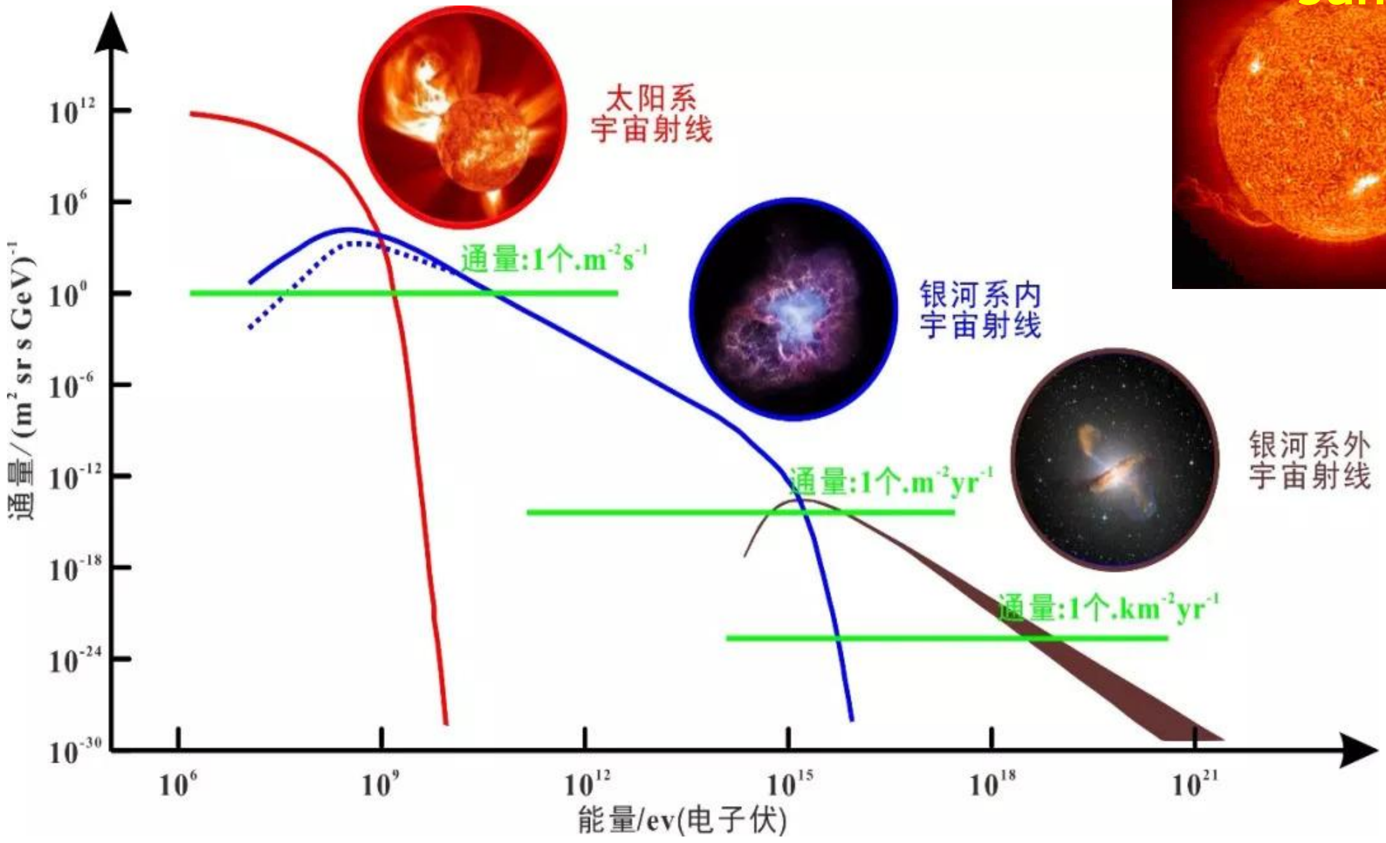
- 前沿物理
  - 暗物质
  - 极高能粒子加速和相互作用
  - 洛伦兹对称性破缺
- 极端天体
  - 多信使天文源
  - 极端条件（密度、能量、磁场）下的天体
  - 星系演化和星际介质

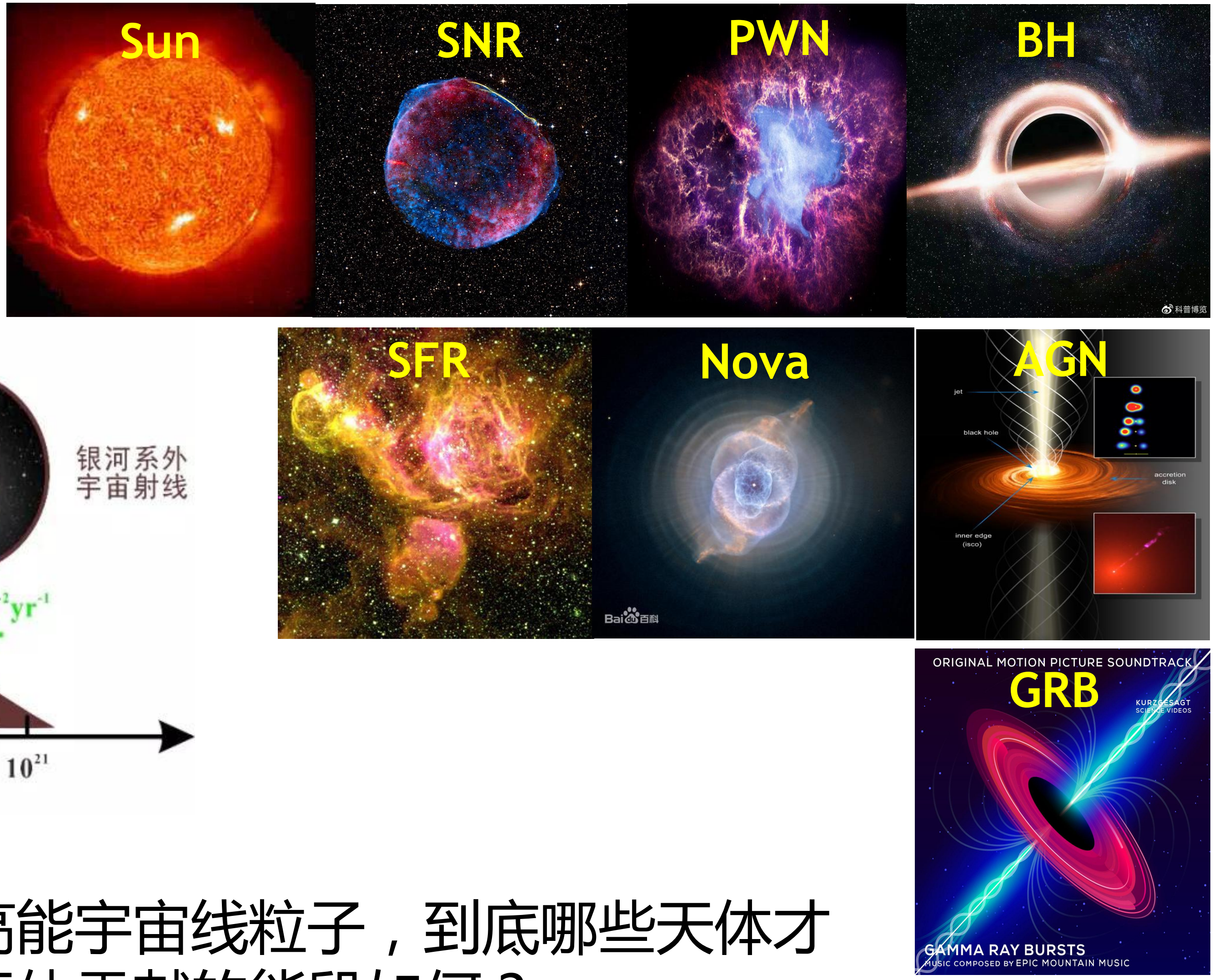
宇宙线的起源、加速和传播



宇宙线物理世纪之谜：宇宙线的起源天体是什么？何种机制将其加速到极端高能量？在宇宙空间中的传播过程如何？

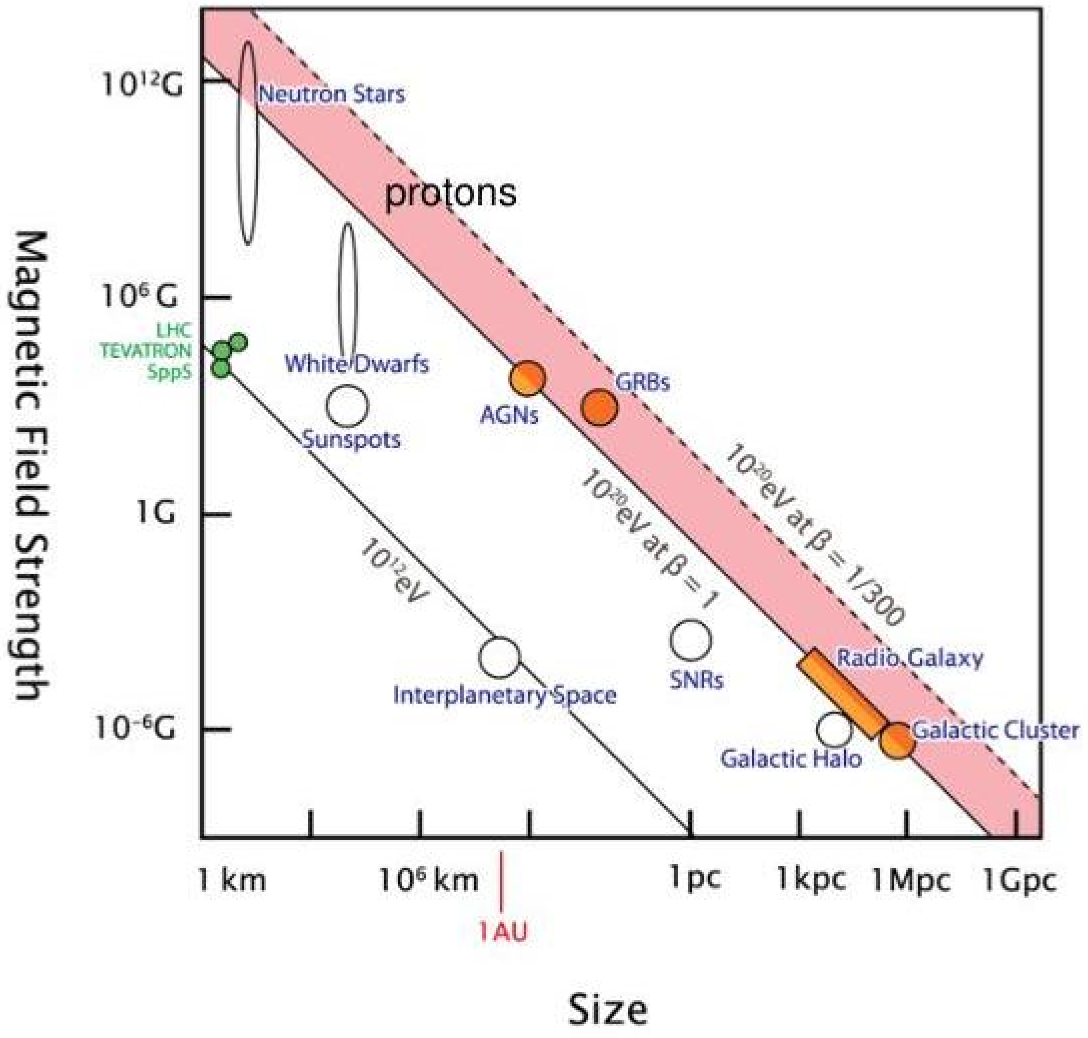
宇宙线的起源天体





伽马射线观测表明很多天体均可以产生高能宇宙线粒子，到底哪些天体才是宇宙线主要的贡献？各类天体贡献的能段如何？

宇宙线的加速极限



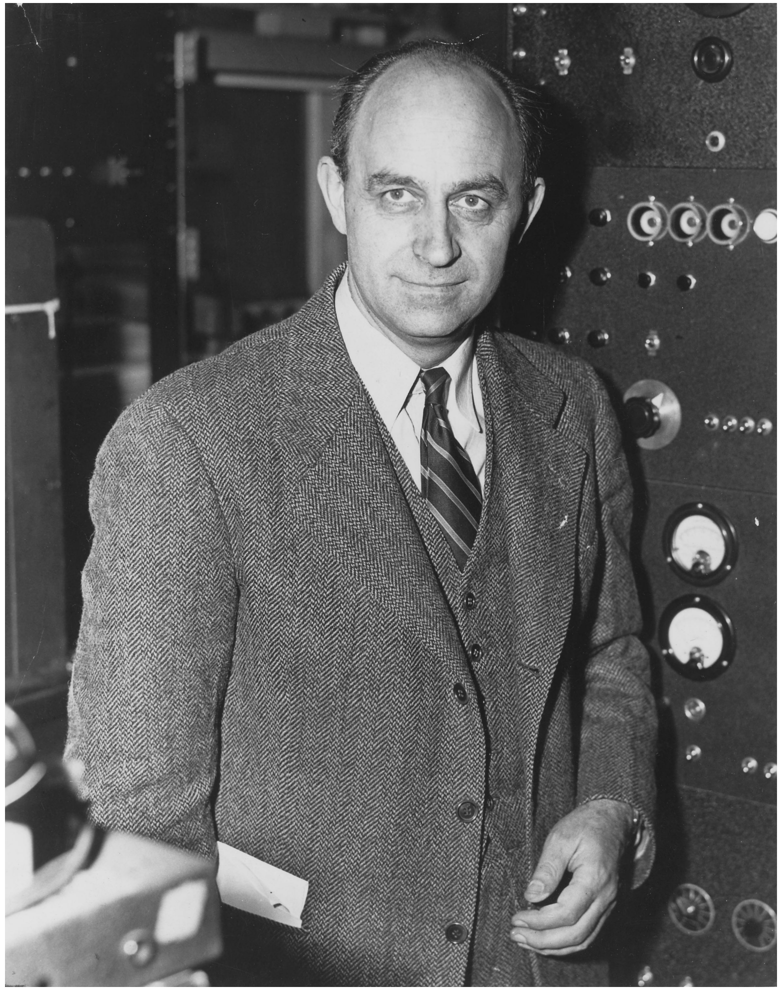
$$\mathbf{E} = -\mathbf{u} \times \mathbf{B}$$

$$E_{max} = uZBL$$

The maximum energy a particle with charge Z can get through moving a distance L in electric field uB

Hillas (1984, ARA&A, 22, 425)

费米统计加速机制



Enrico Fermi

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

Assuming: every “collision” results in energy gain $\Delta E = \xi E$, particle has an escape probability P_{esc}

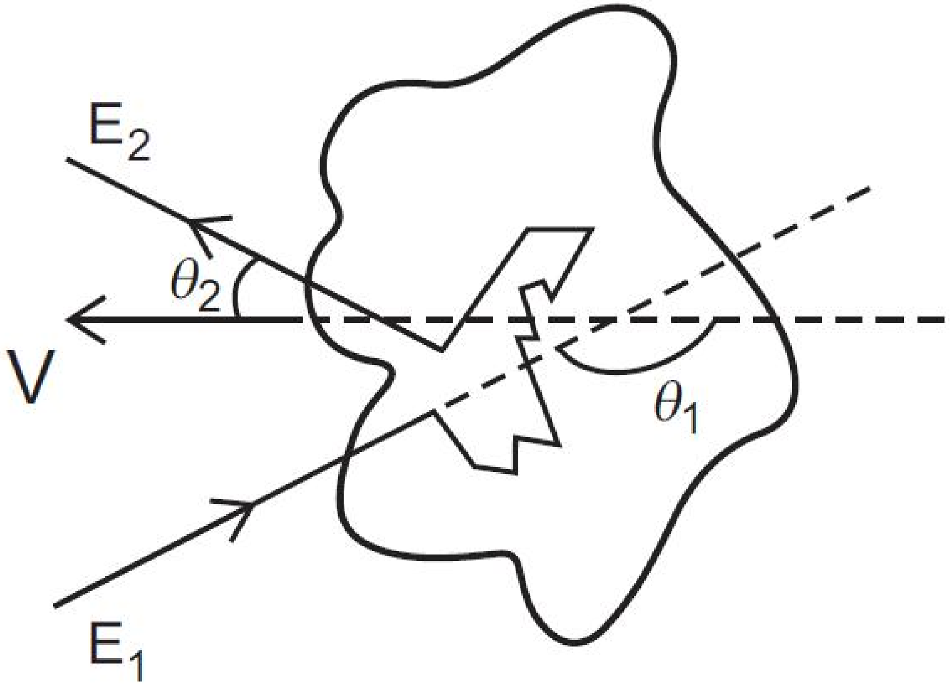
$$N(\geq E) \propto \sum_{m=n}^{\infty} (1 - P_{\rm esc})^m = \frac{(1 - P_{\rm esc})^n}{P_{\rm esc}},$$

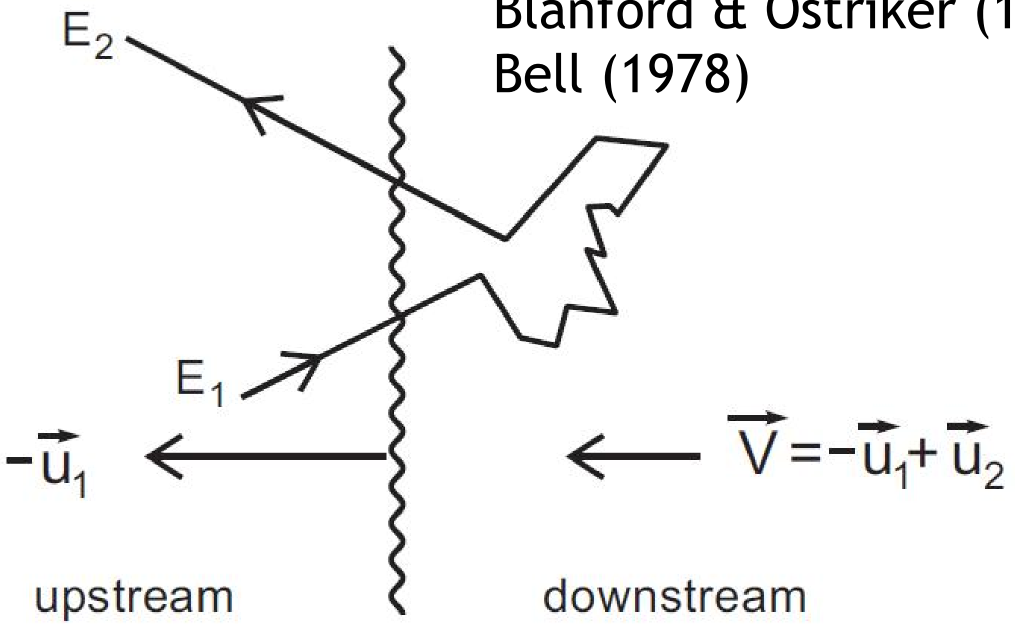
$$= \frac{1}{P_{\rm esc}} \left(\frac{E}{E_0} \right)^{-\gamma}$$

$$\gamma = \ln\left(\frac{1}{1 - P_{\rm esc}}\right) / \ln(1 + \xi) \approx \frac{P_{\rm esc}}{\xi} = \frac{1}{\xi} \times \frac{T_{\rm cycle}}{T_{\rm esc}}$$

二阶和一阶费米加速

Krymskii (1977)
Axford et al. (1978)
Blanford & Ostriker (1978)
Bell (1978)



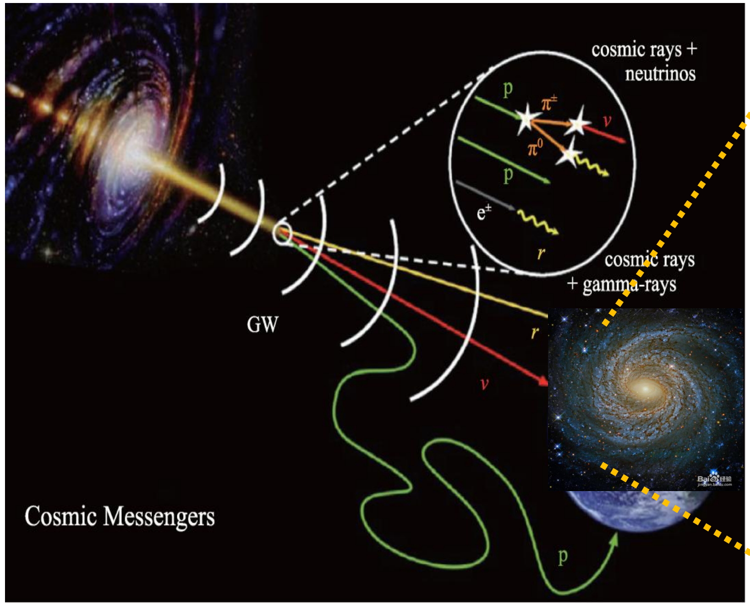


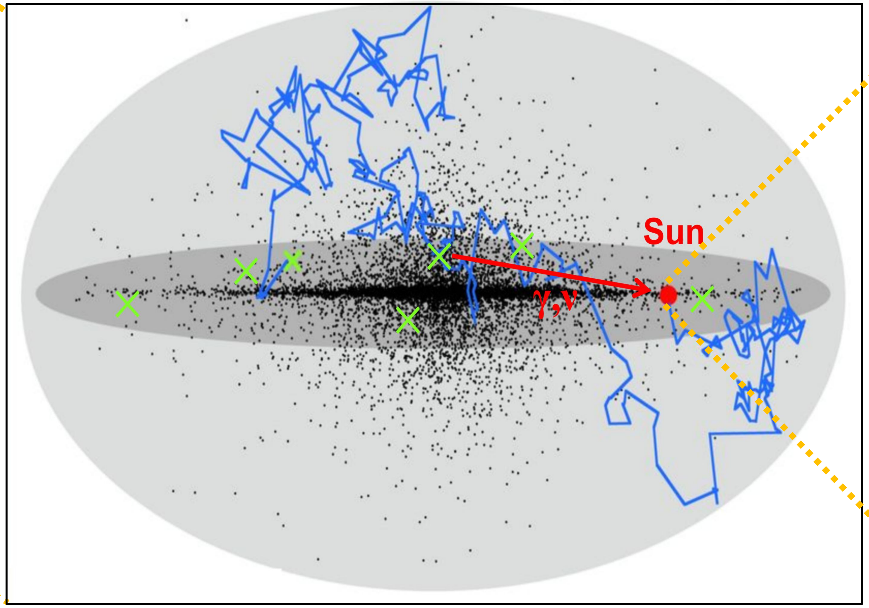
$$\frac{\triangle E}{E_1} = \frac{1+\frac{1}{3}\beta^2}{1-\beta^2} - 1 \sim \frac{4}{3}\beta^2$$

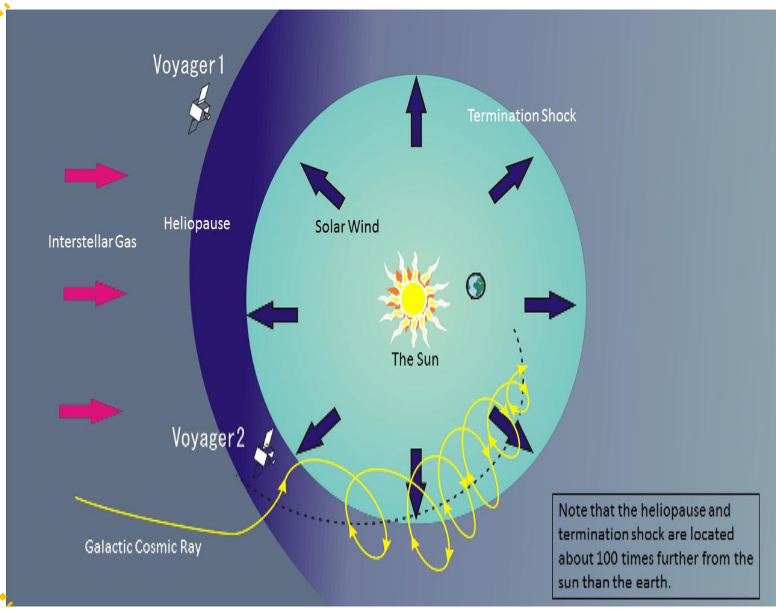
$$\frac{\Delta E}{E_1} = \frac{1+\frac{4}{3}\beta+\frac{4}{9}\beta^2}{1-\beta^2} - 1 \sim \frac{4}{3}\beta$$

Gaisser (1990)

宇宙线传播过程







河外空间

银河系

太阳系

传播方程

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p)$$ sources (SNR, nuclear reactions…)

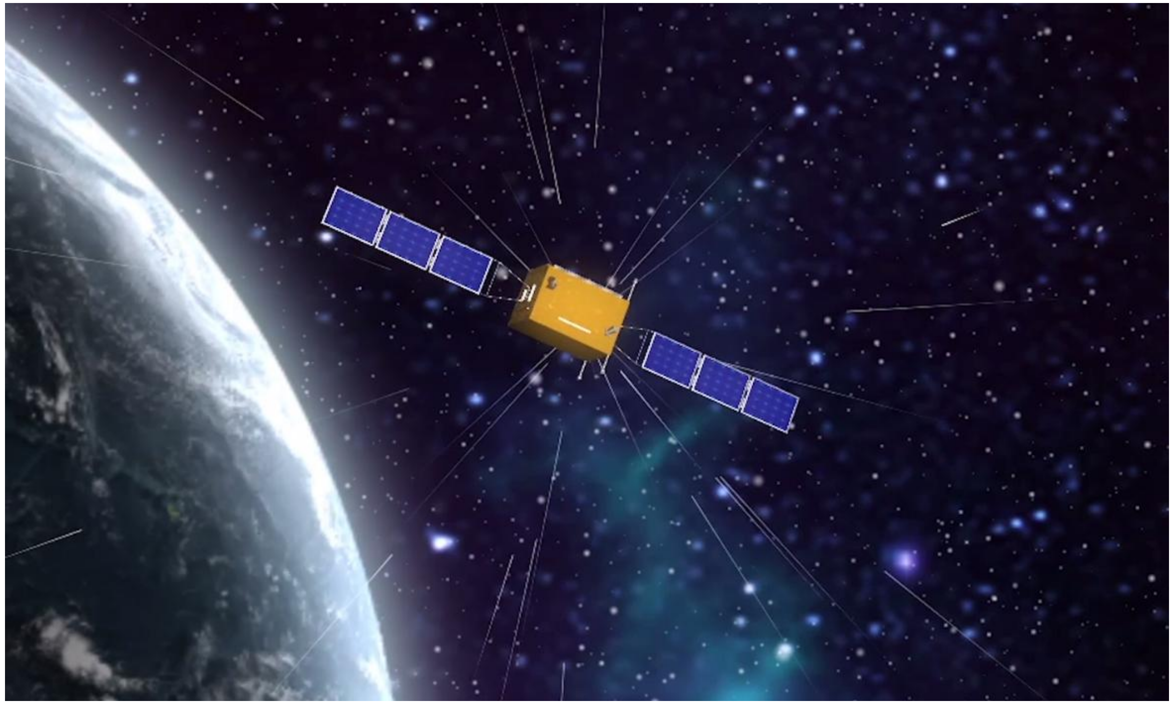
diffusion $$+ \vec{\nabla} \cdot [D_{xx} \vec{\nabla} \psi - \vec{V} \psi]$$ convection

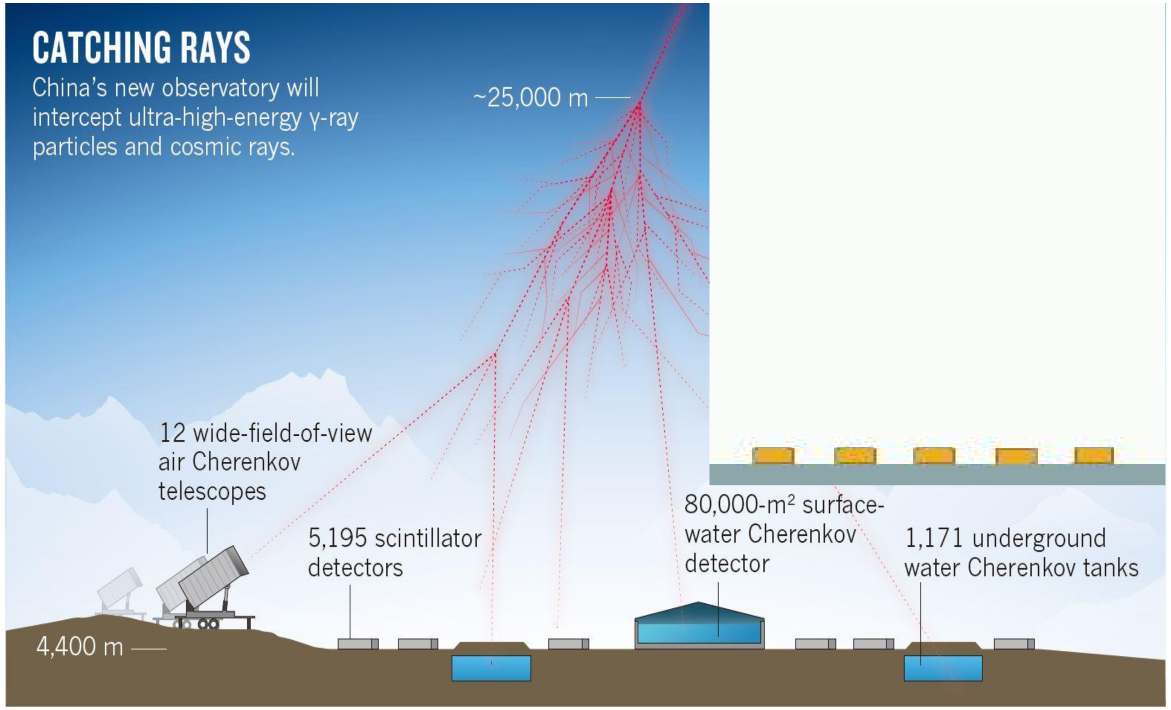
diffusive reacceleration $$+ \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2}\right]$$

energy loss $$- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3} p \vec{\nabla} \cdot \vec{V} \psi\right]$$ adiabatic loss

fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

宇宙线实验探测



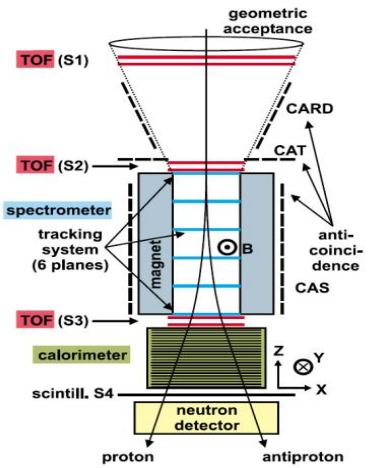


Space direct detection:
- No atmosphere impact, good particle identification
- Small scale, low energy

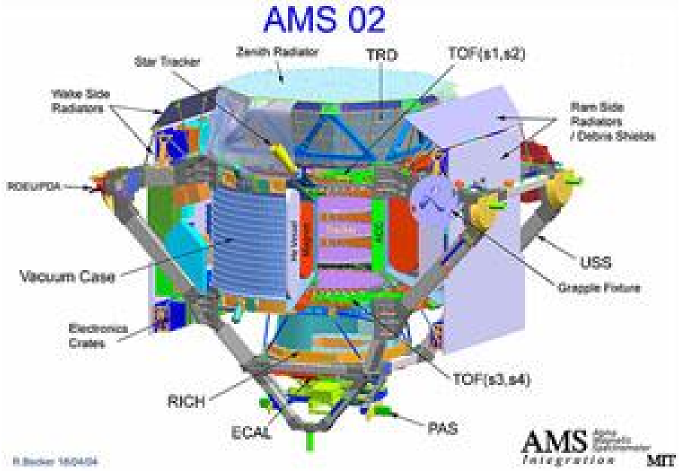
Ground indirect detection:
- Relatively poor particle identification
- Large scale, high energy

国际主要实验

PAMELA

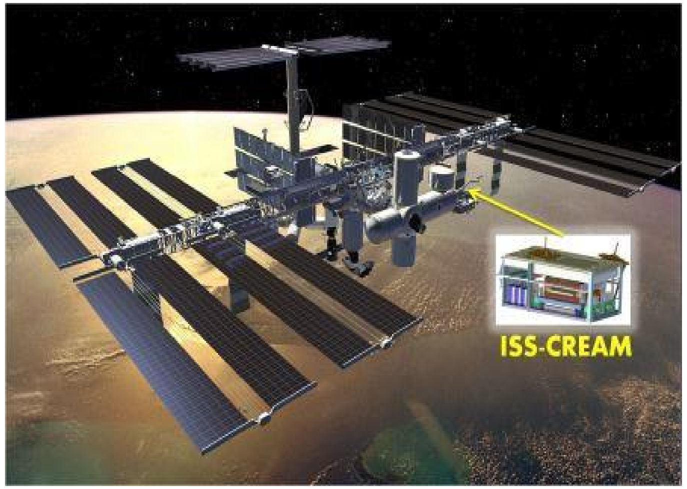


AMS-02



CALET

ISS-CREAM



KSACADE

PAO

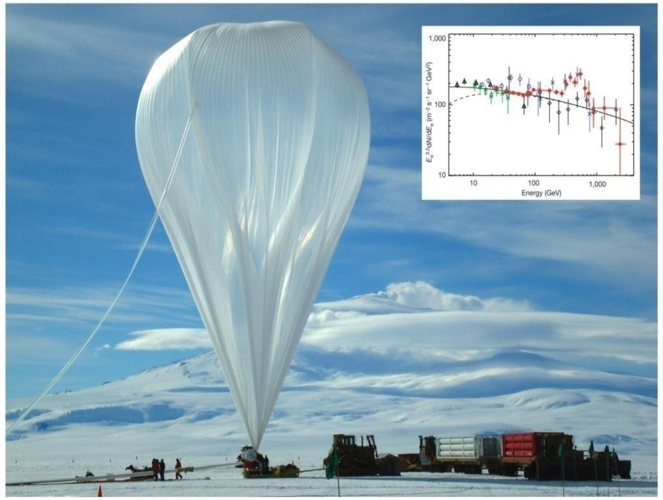
HESS/MAGIC/VERITAS/CTA

HAWC

中国宇宙线研究

Balloon (1970s)

Manned space (1990s)



中美合作南极暗物质粒子气球探测

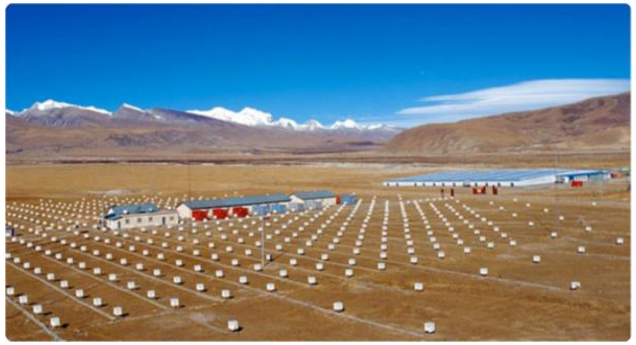
Balloon (2000s)

DAMPE (2010s)

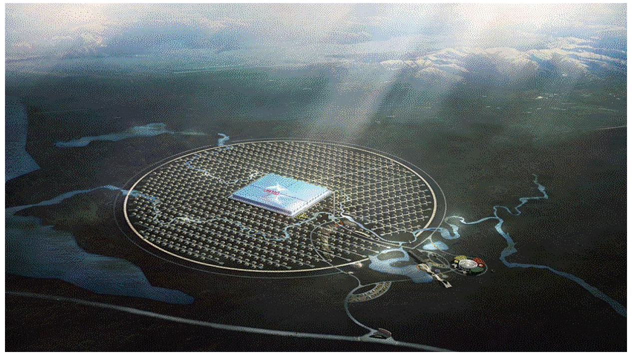
图1　上世纪60—70年代，“头顶青天脚踏云海”的中国科学院原子能研究所云南站

Yunnan (1950s)

Tibet (1970s)



Tibet (1990s)



Sichuan (2010s)

云南站云室

图1 上世纪60—70年代，“头顶青天脚踏云海”的中国科学院原子能研究所云南站

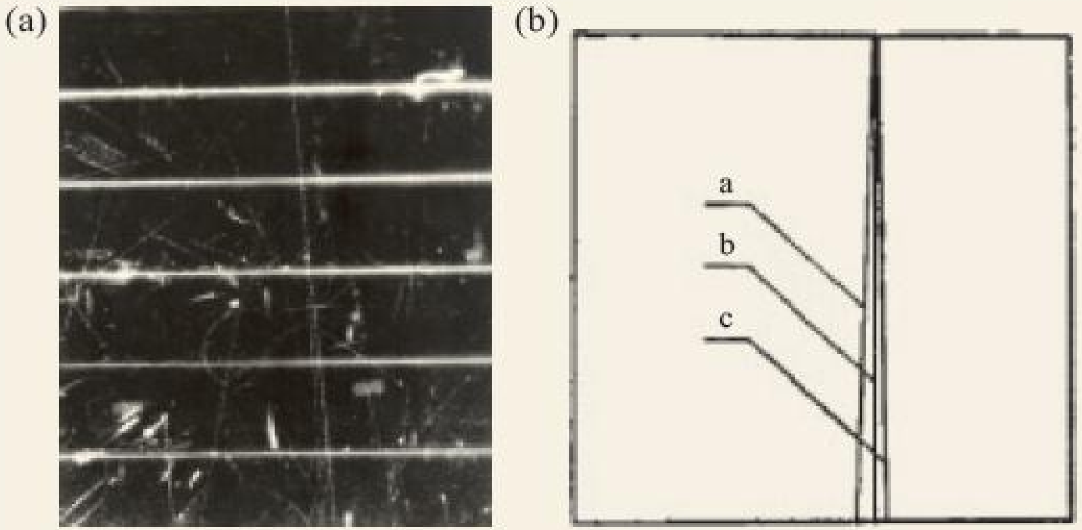
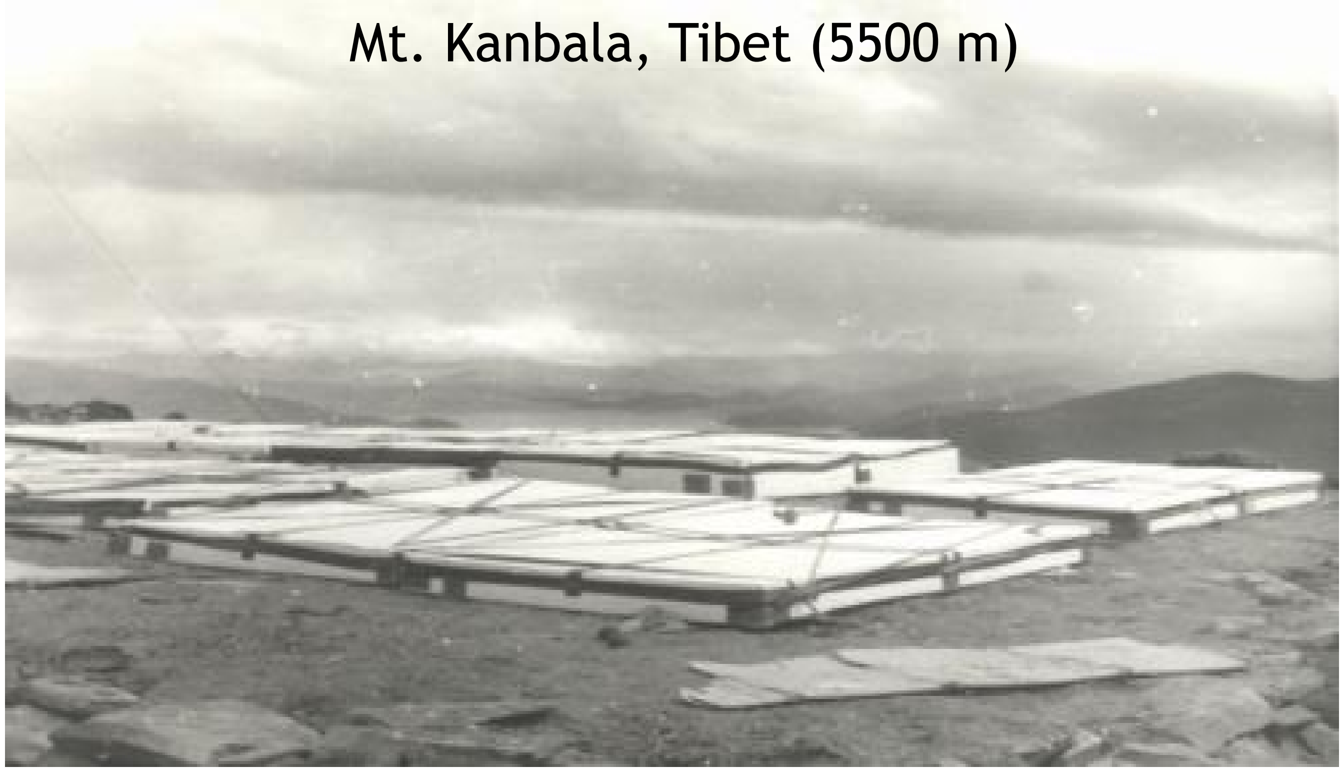


图6 (a)云南事例(16580号)正面全景照片；(b)16580号事例素描

A candidate heavy particle (m>12 GeV) recorded by the cloud chamber

Chen et al. (1997, Phys. Rept., 282, 1)

西藏甘巴拉山乳胶室



Mt. Kanbala, Tibet (5500 m)

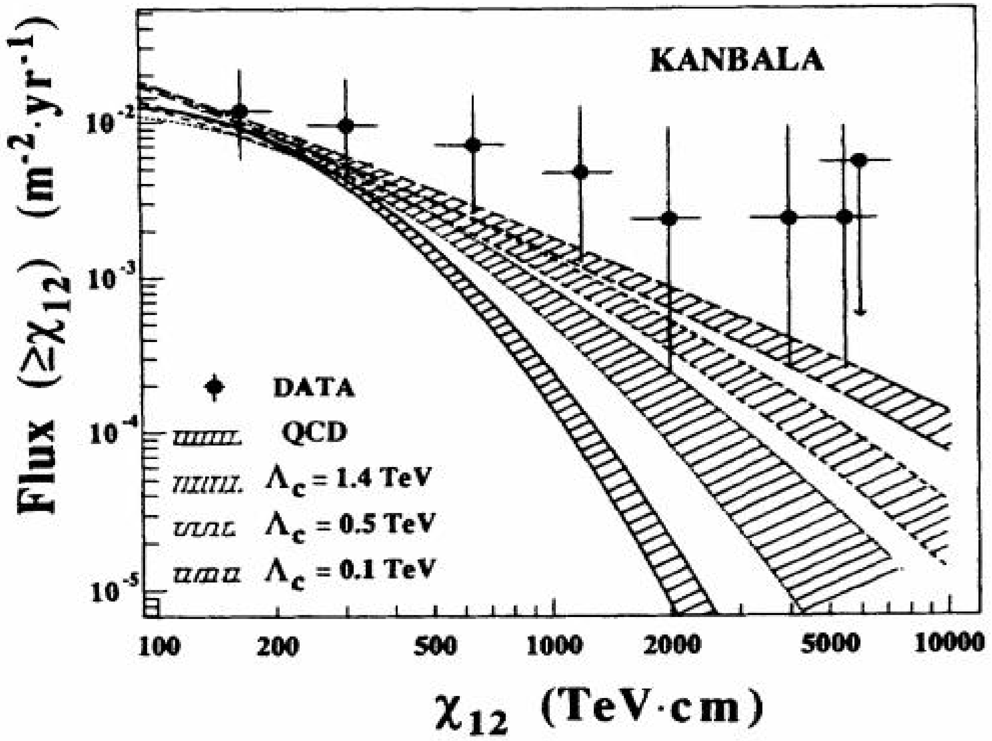
VOLUME 72, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1994

Quark Compositeness, New Physics, and Ultrahigh-Energy Cosmic-Ray Double-Core γ-Family Events

Z. Cao, L. K. Ding, and Q. Q. Zhu
Cosmic Ray Laboratory, Institute of High Energy Physics, Academia Sinica, Beijing 100039, People's Republic of China

Y. D. He
Department of Physics, University of California at Berkeley, Berkeley, California 94720

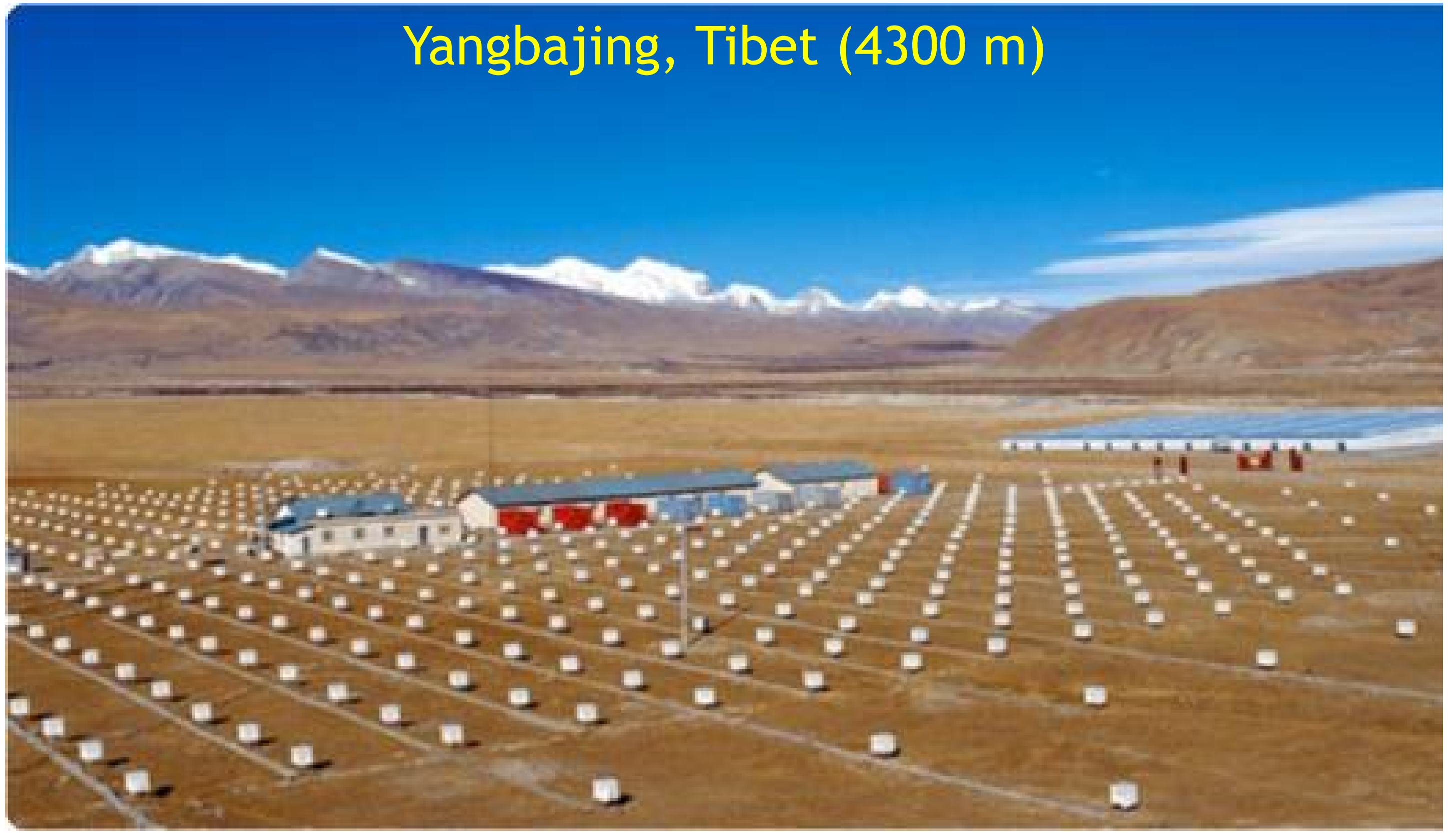
(Received 23 August 1993)

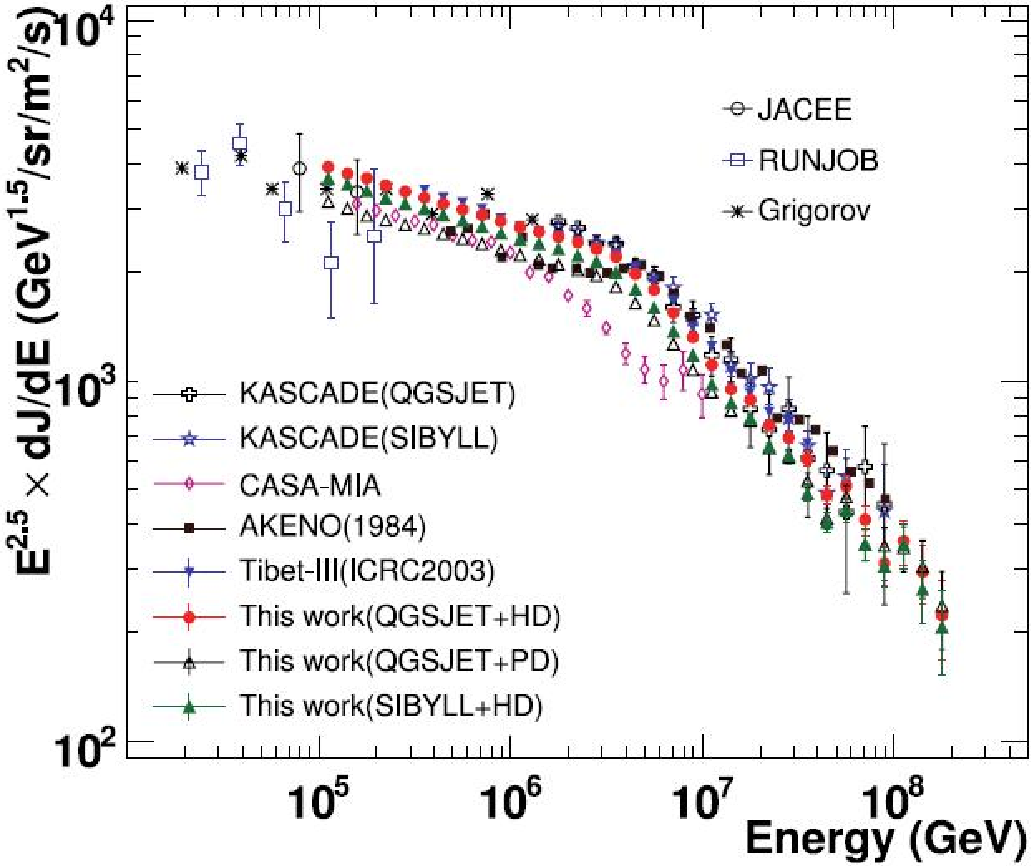


Large pT excesses cannot be accounted for with QCD calculation: indication of onset of new physics!

Cao et al. (1994, PRL, 72, 1794)
Cao et al. (1997, PRD, 56, 7361)

西藏羊八井ASγ

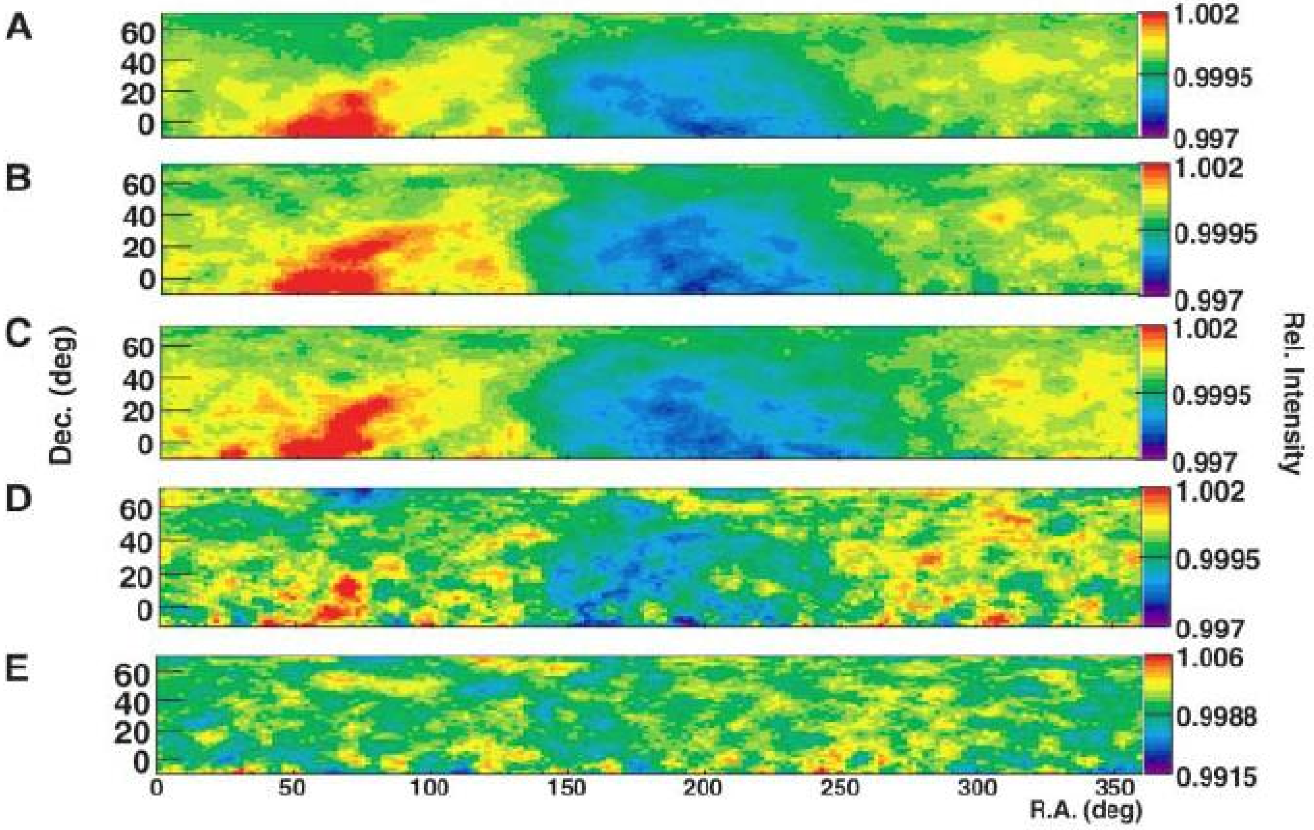


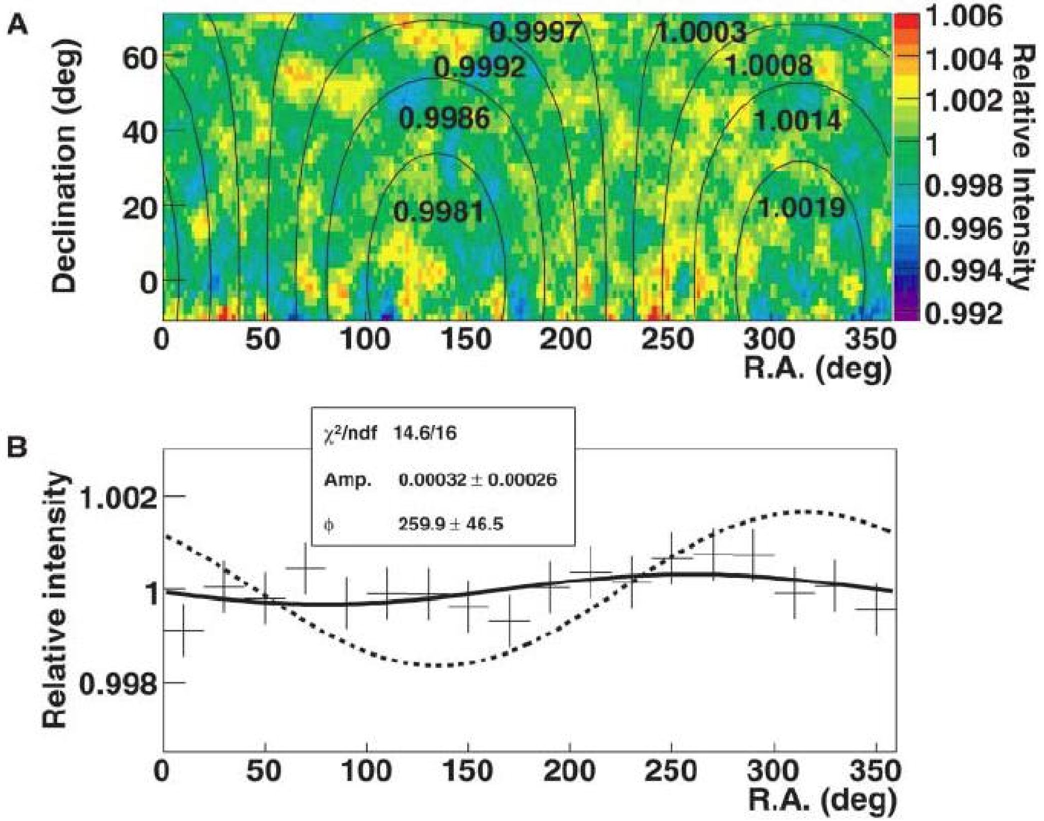


Precise measurements of CR spectra around the "knee" region

Amenomori et al. (2008, ApJ, 678, 1165)

西藏羊八井ASγ





Amenomori et al. (2006, Science, 314, 439)

Two-dimensional anisotropies reveal co-rotation of CRs with the ISM (a milestone of CR studies)

悟空号暗物质粒子探测卫星

立项

2011年12月

电性件

2012年7~9月电性件交付并联调

束流标定

2012.09~10，CERN，电性件验证；2014.11~2015.07鉴定件三次性能标定

初样阶段

2013年4月随整星一起转入初样阶段；2014年1月鉴定件总装完；2014年2~4月通过各项环模试验并交付

正样阶段

2014年下半年整星完成联调及各项环模试验转正样阶段飞行件研制；2015年12月发射，科学卫星系列首发星

悟空号暗物质粒子探测卫星

NEWS IN FOCUS

POLITICS Canada's first science minister brings air of change p.445

STRING THEORY Philosophers join debate over scientific method p.446

2015 IN REVIEW Gene editing, climate change, Pluto and more p.448

PROFILES Ten people who mattered in science this year p.459

2015年12月17日发射

Nature: 暗物质探测器开启
中国空间科学时代

The Monkey King spacecraft, which took to the skies on 17 December, is designed to detect the high-energy particles produced by annihilating dark matter.

COSMOLOGY

Dark-matter probe launches era of Chinese space science

Monkey King is first in a line of Chinese space missions focused on scientific discovery.

BY ELIZABETH GIBNEY, CELESTE BIEVER & DAVIDE CASTELVECCHI

Against a purple morning sky, in a cloud of brown smoke, the Monkey King took off. China's first space-based dark-matter detector — nicknamed Wukong (or Monkey King) after a warrior in a sixteenth-century Chinese novel — rocketed into the air on 17 December, marking the start of a new direction in the country's space strategy.

From Earth's orbit, the craft aims to detect high-energy particles and γ-rays. Physicists think that dark matter — a substance thought to make up 85% of the Universe's matter but so far observed only through its gravitational effects — could reveal itself by producing such cosmic rays as its constituent particles annihilate.

Wukong, officially called the Dark Matter Particle Explorer (DAMPE), is also notable for being the first in a series of five space-science missions to emerge from the Chinese Academy of Sciences' Strategic Priority Program on Space Science, which kicked off in 2011.

China is already one of the world's major space powers, but so far has focused on human and robotic exploration, with little investment in space science. (A notable exception is the Double Star probe launched in collaboration with the European Space Agency in 2003 to study magnetic storms on Earth.)

The DAMPE lift-off from the Jiuquan Satellite Launch Center in northern China will be followed next year by a further two missions: the world's first quantum-communications satellite and an X-ray telescope observing in ▶

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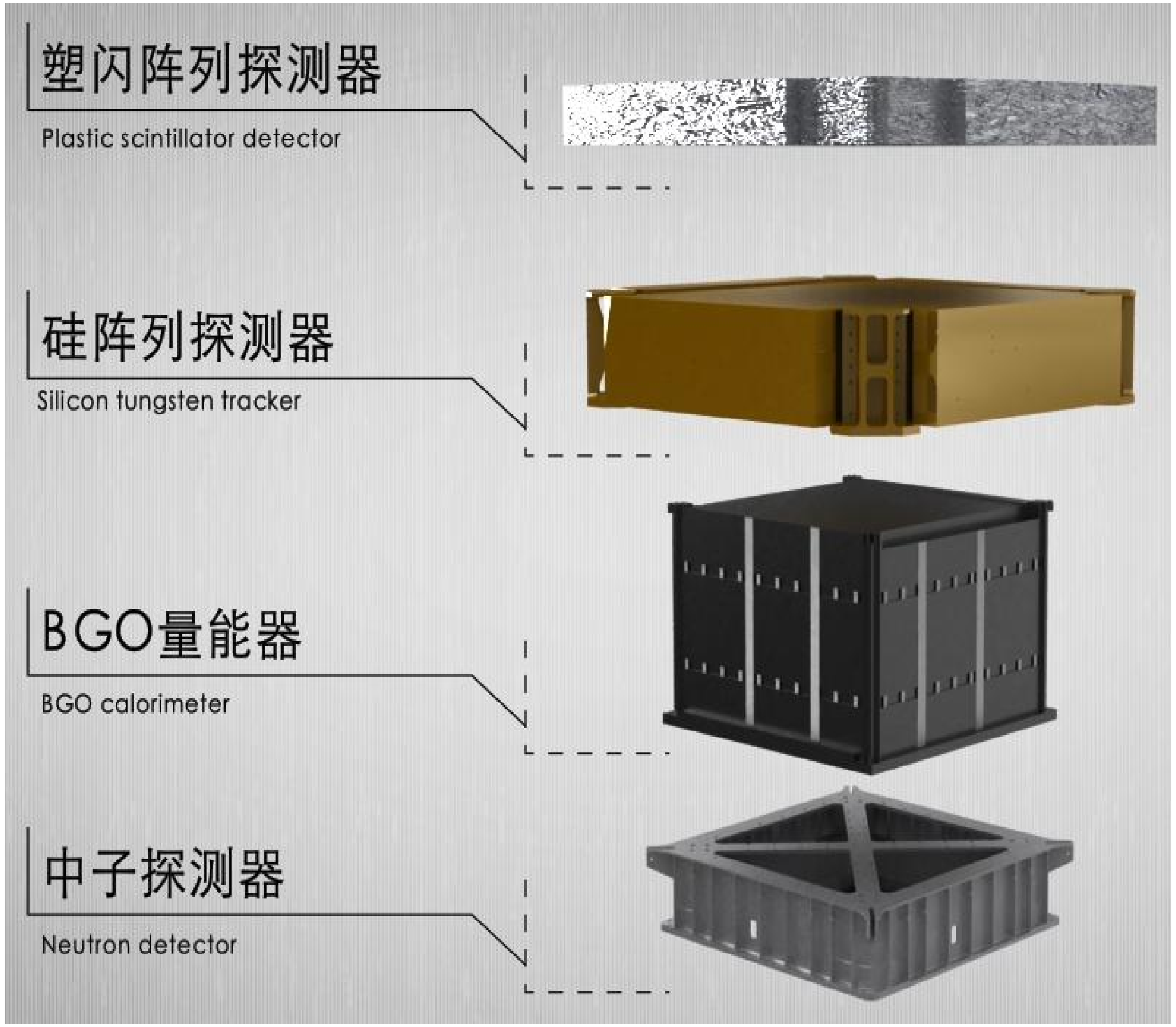
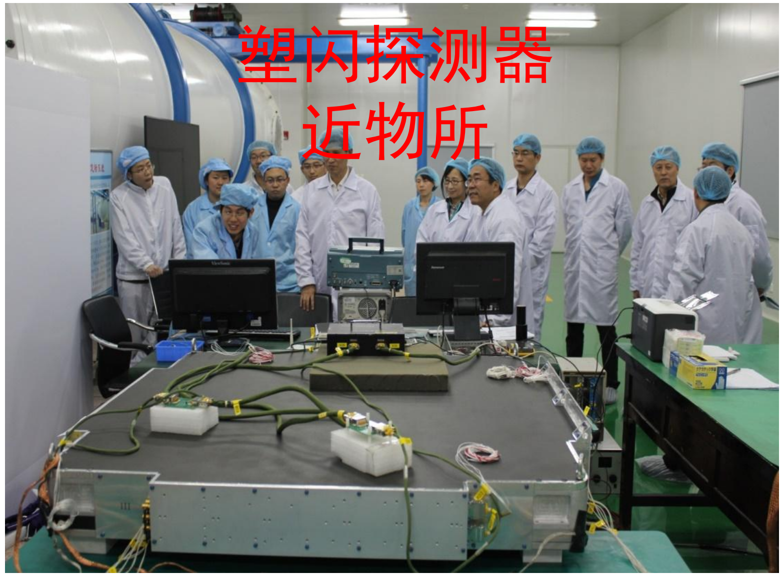
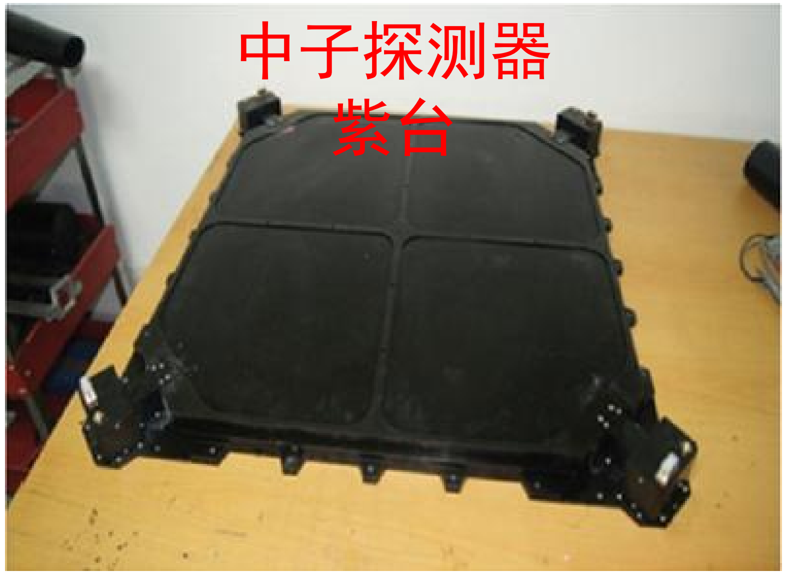
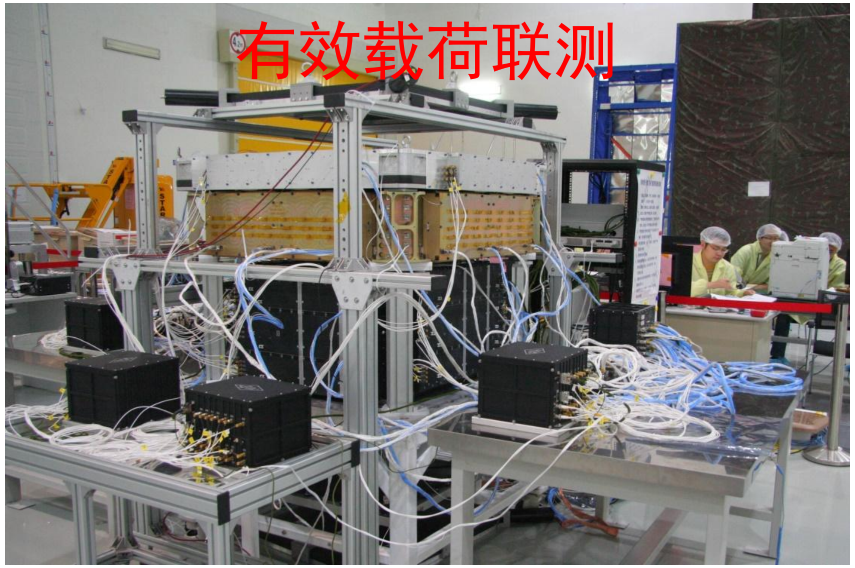


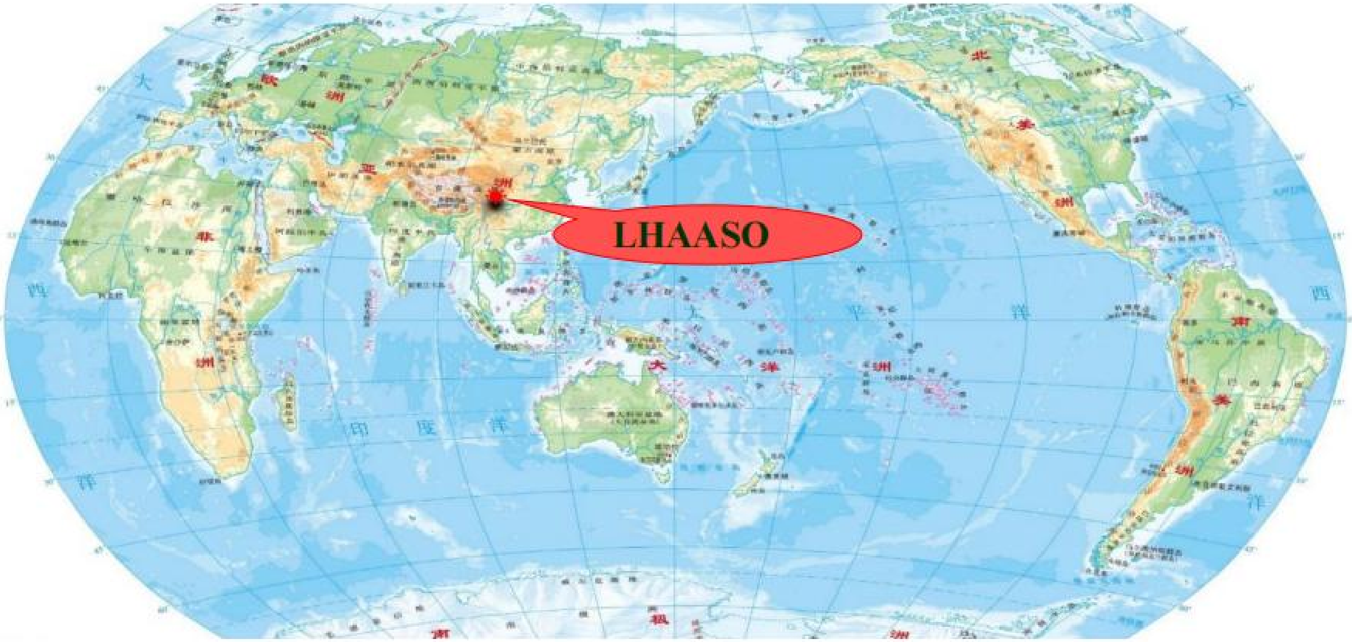
悟空号暗物质粒子探测卫星

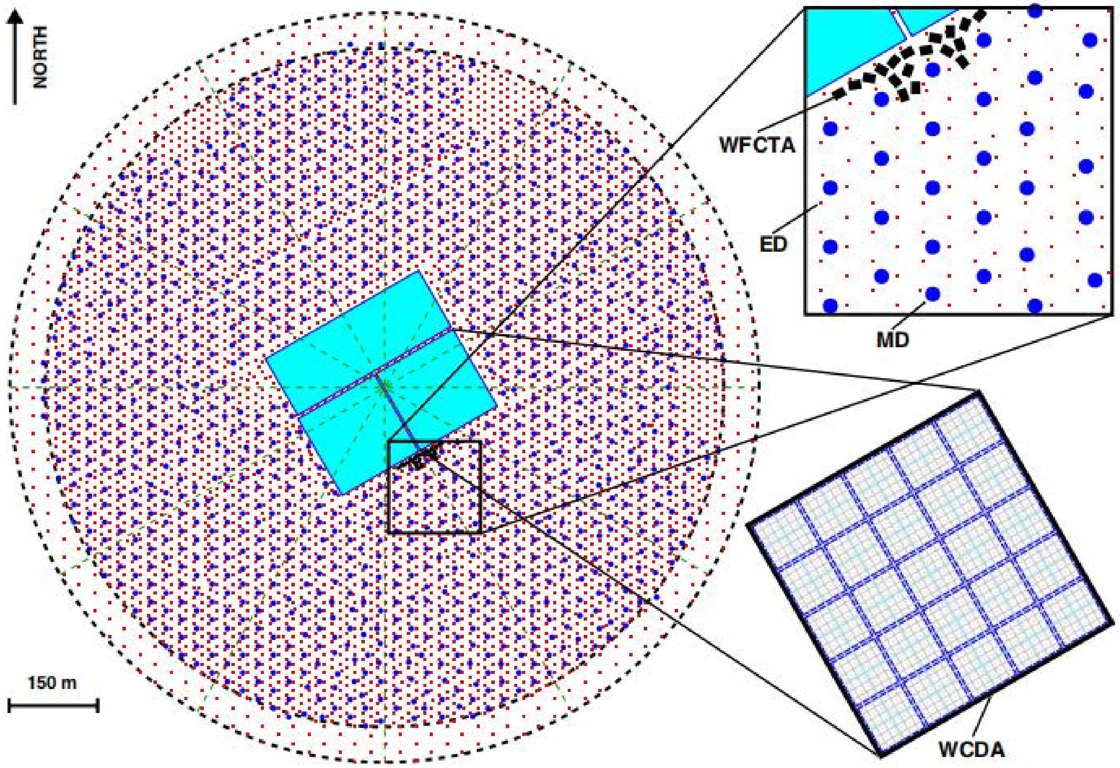






高海拔宇宙线观测站LHAASO

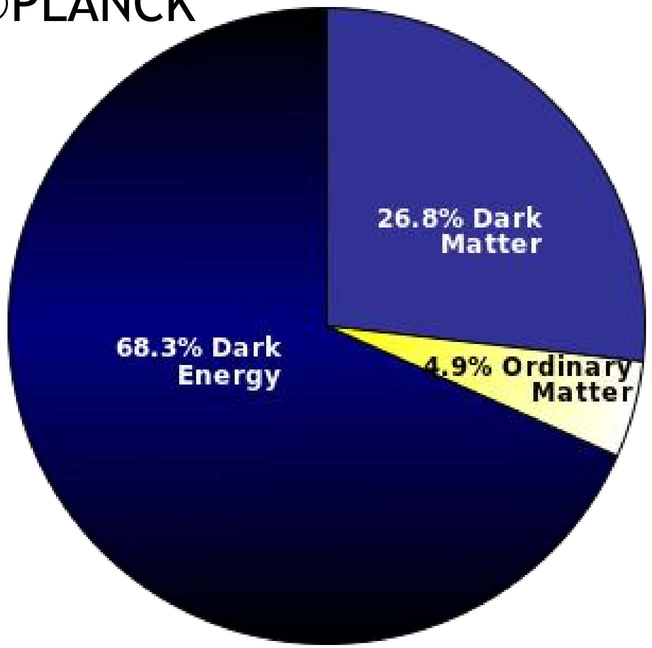


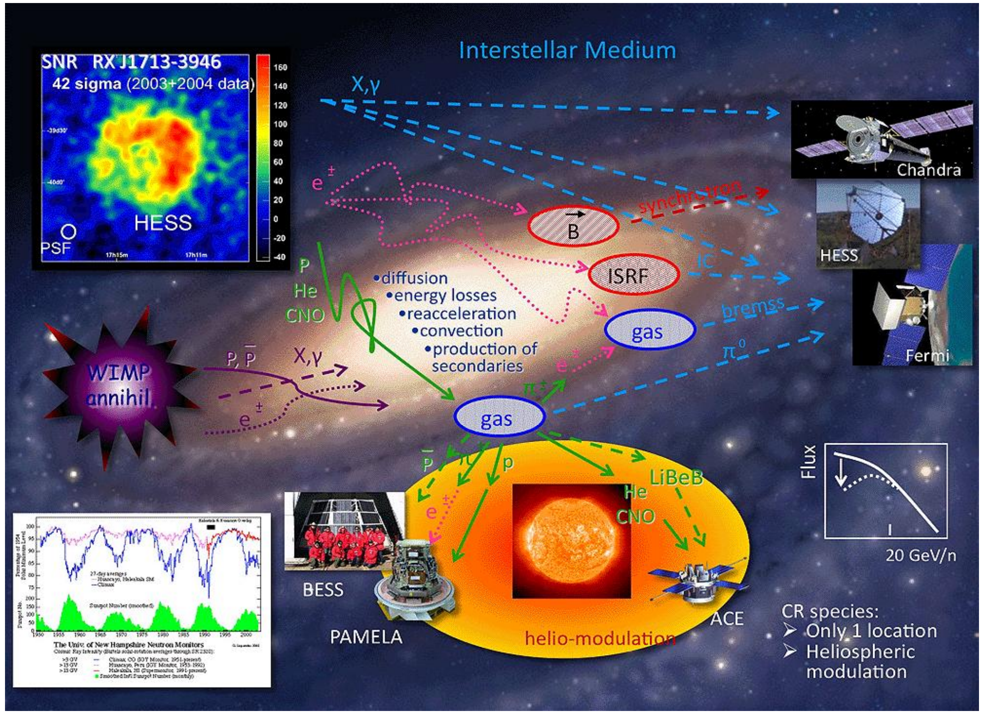


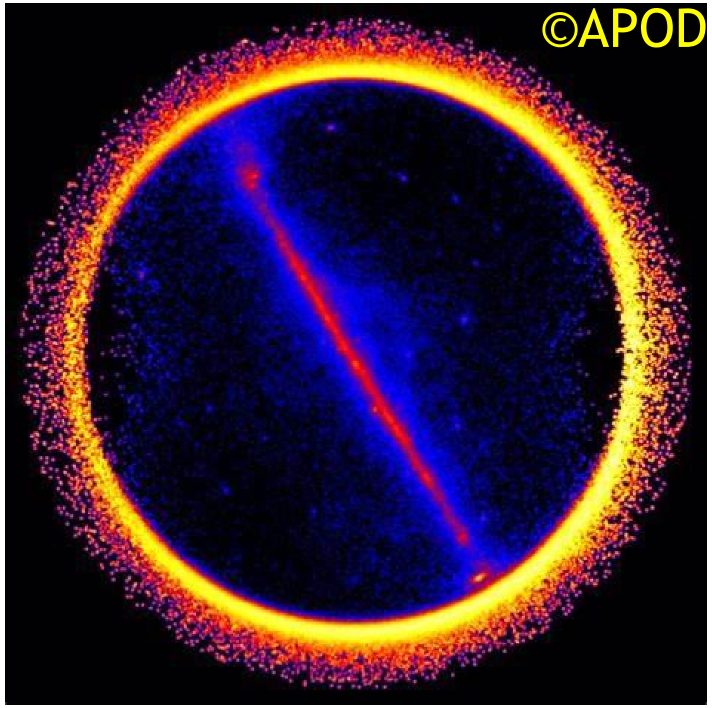
- ➢ Haizi mountain, Sichuan, China, 4410 m above the sea level
- ➢ LHAASO uses hybrid detector arrays: the square kilometer array (KM2A), the water Cherenkov detector array (WCDA), and the wide field-of-view Cherenkov telescope array (WFCTA)
- ➢ Full operation since July 2021

科学目标

©PLANCK





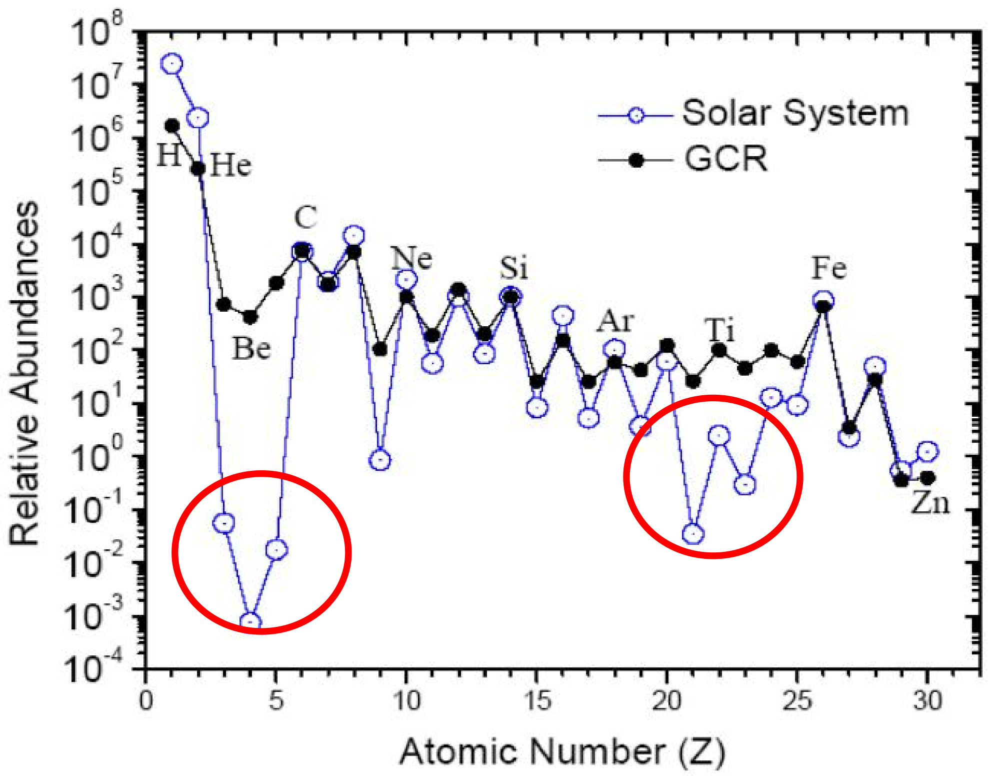


暗物质粒子探测

宇宙线起源和传播

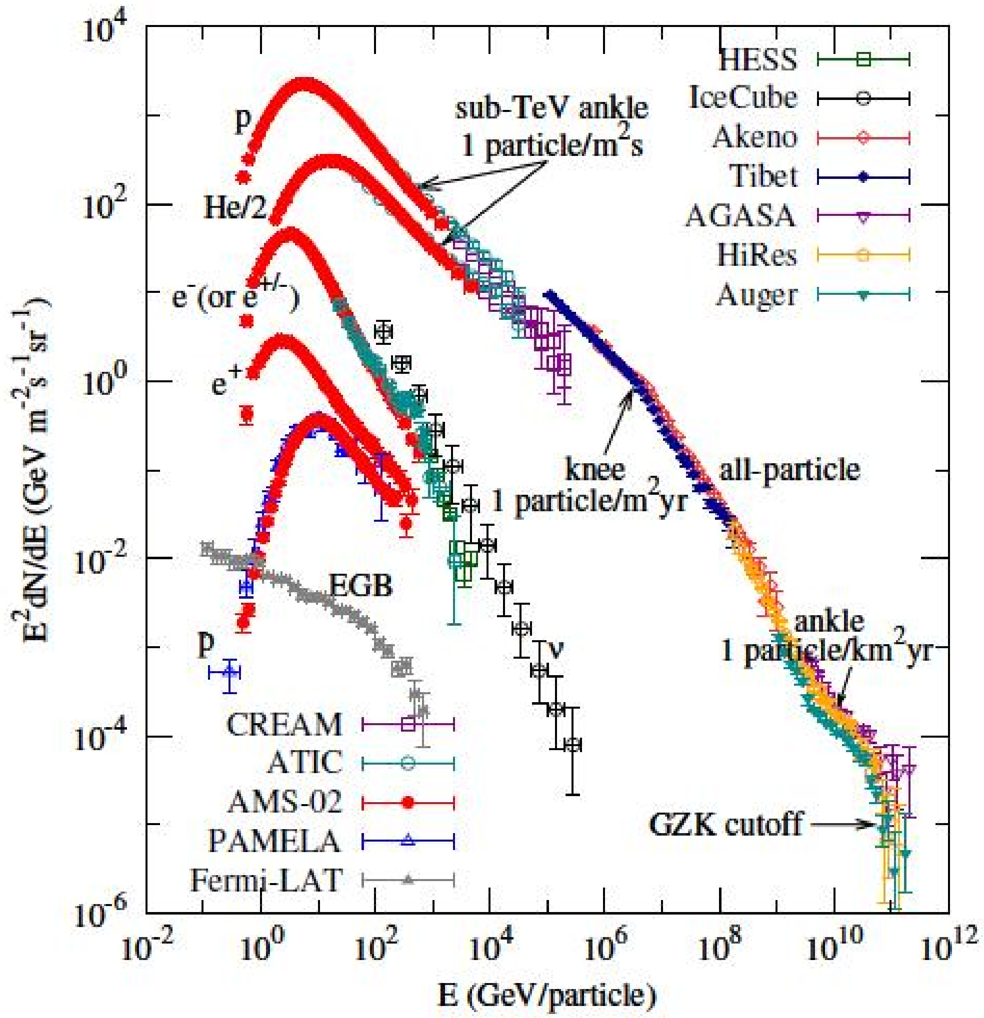
伽马射线天文

宇宙线能谱精确测量

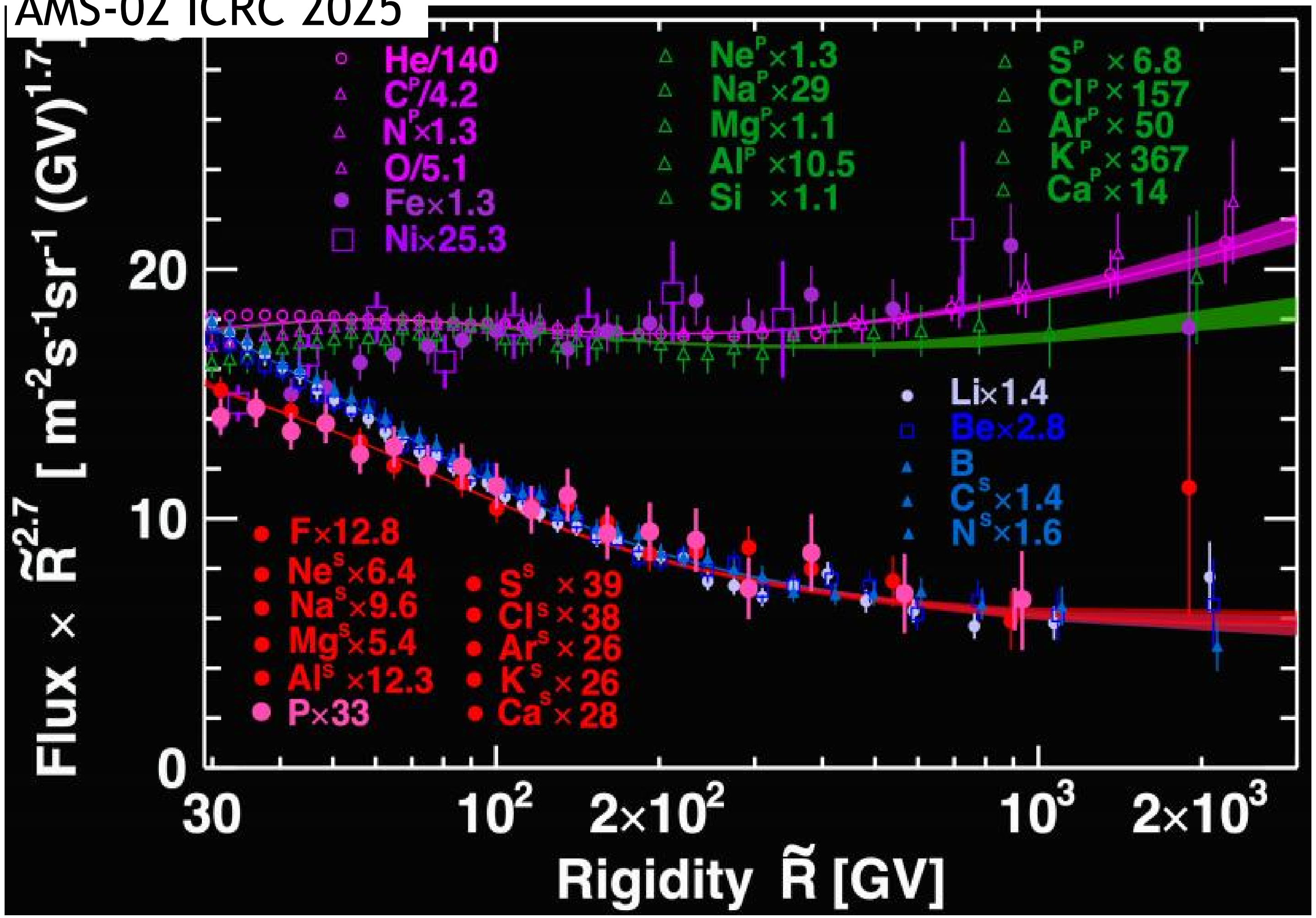


- 初级宇宙线：宇宙线中相对高丰度成分，如质子、氦、碳、氧、氖、镁硅、铁等，反映宇宙线起源和加速特性
- 次级宇宙线：相对低丰度成分，如氘、氦-3、锂、铍、硼、亚铁元素等，反映宇宙线传播和相互作用特性
- 混合宇宙线：氮、钠、铝、氩、钙等具有初级和次级共同起源

宇宙线能谱精确测量

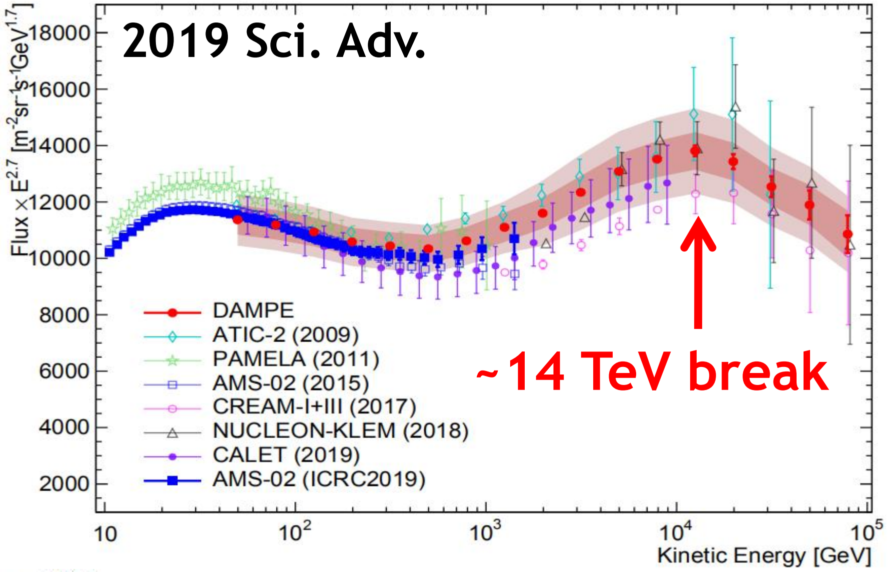


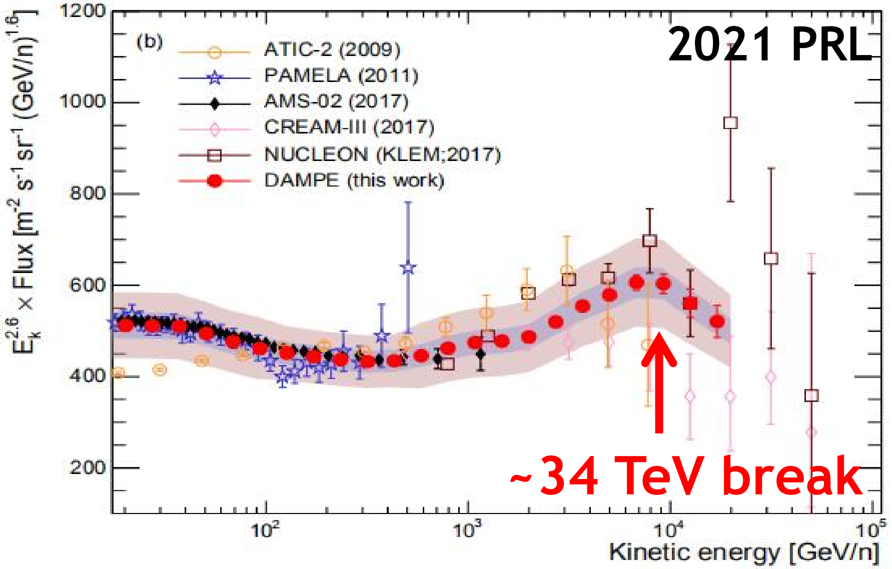
AMS-02 ICRC 2025

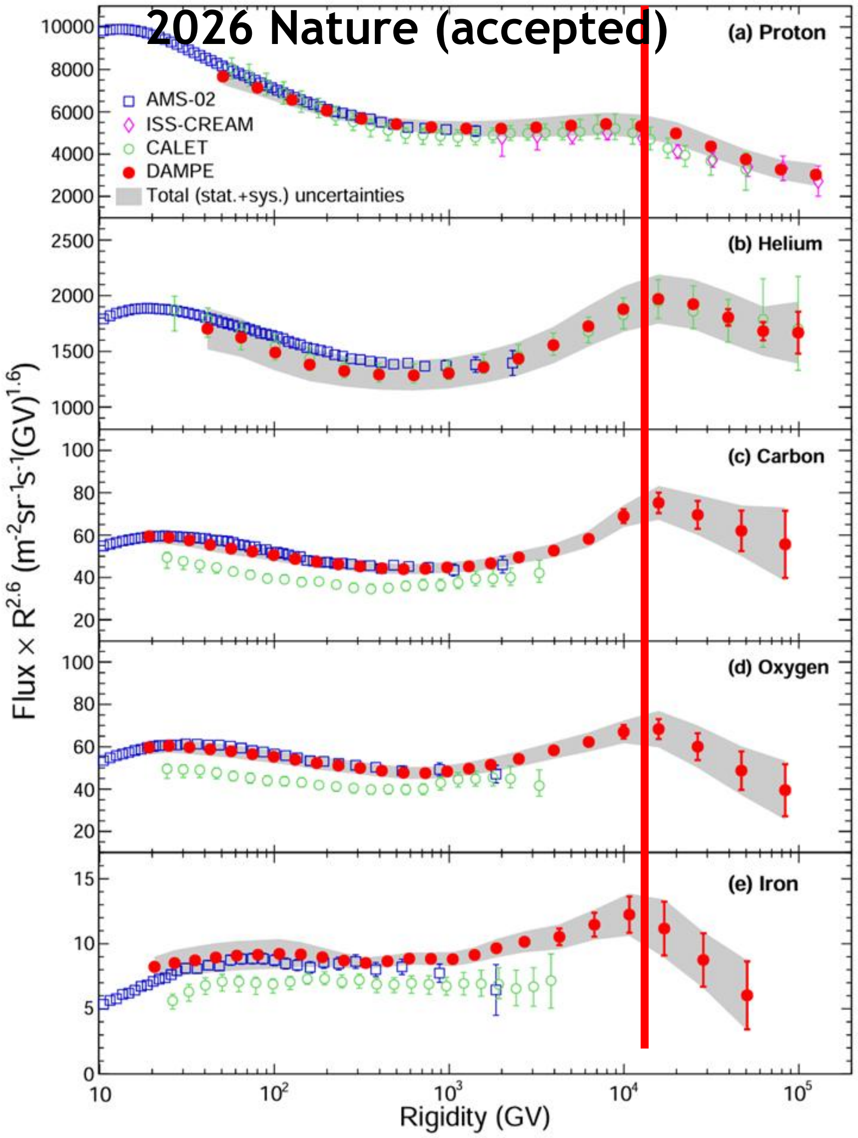


TeV以上能段（特别是空间和地面衔接的能段，~100 TeV）精度有限

悟空号揭示初级宇宙线~15 TV统一拐折

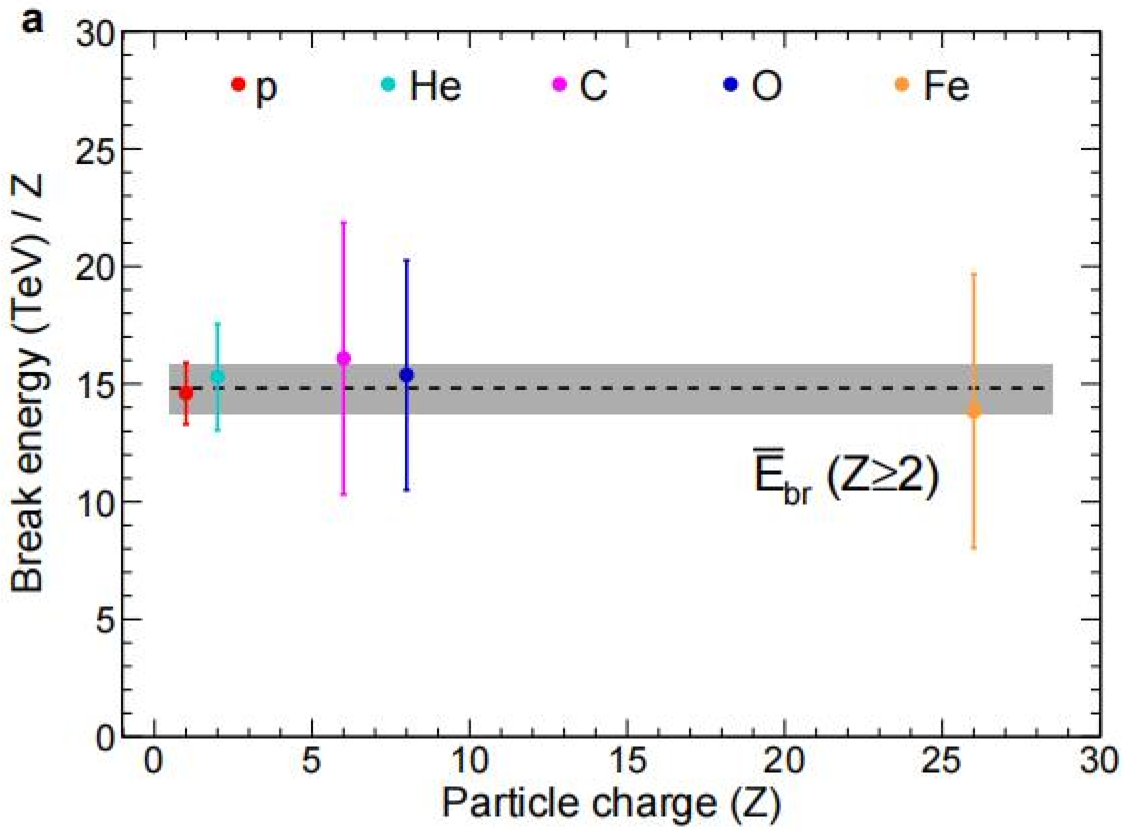


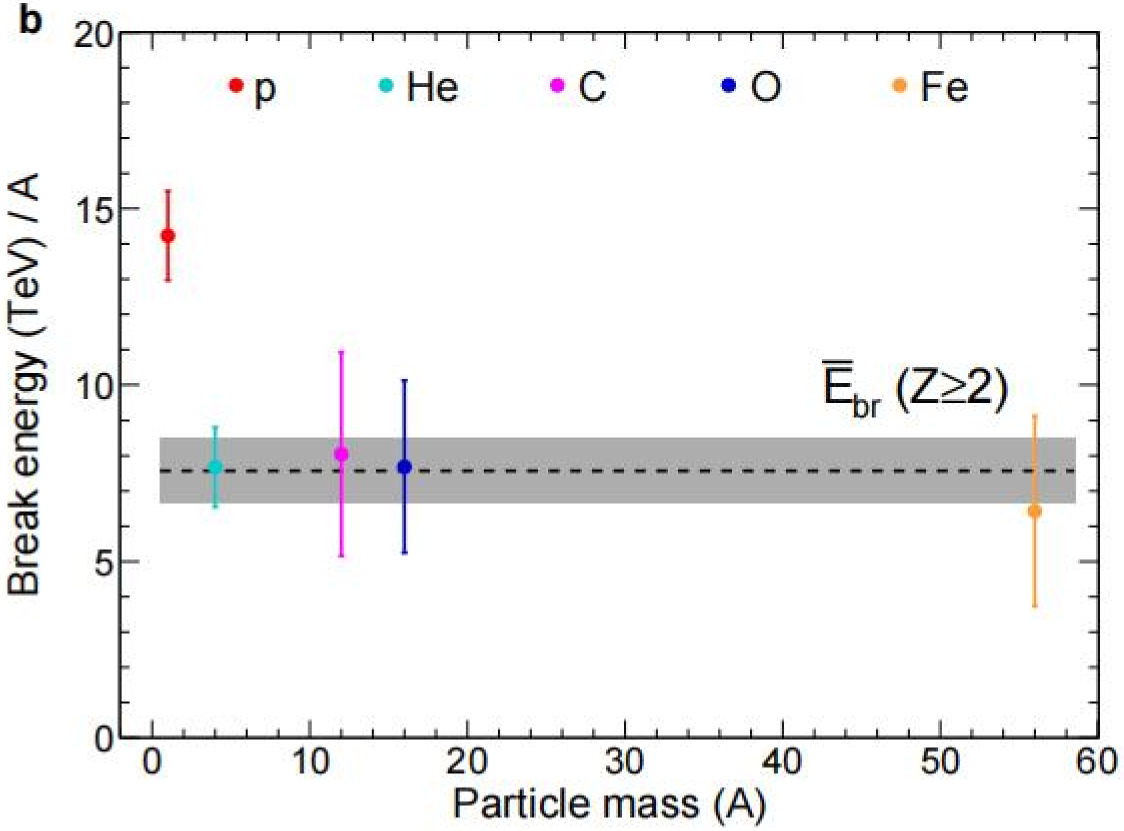




DAMPE精确测量了质子、氦、碳、氧、铁等核素宇宙线的宽能段能谱，发现存在统一的先变硬后变软拐折结构，拐折能量与电荷线性相关

悟空号揭示初级宇宙线~15 TV统一拐折

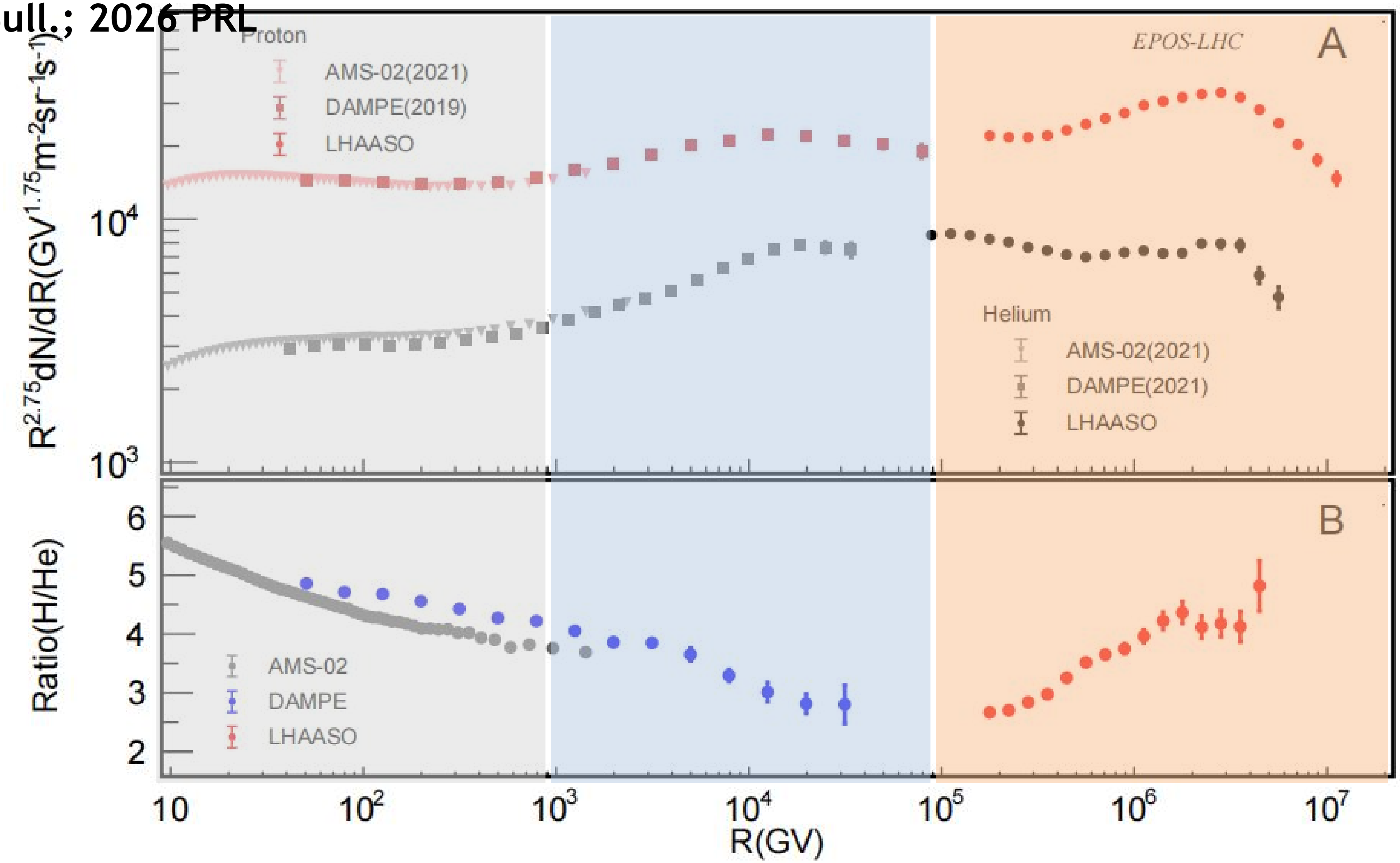




拐折能量正比于粒子电荷Z；质量数A依赖的关系被4.4σ排除

拉索p, He膝区能谱精确测量

2025 Sci. Bull.; 2026 PRL

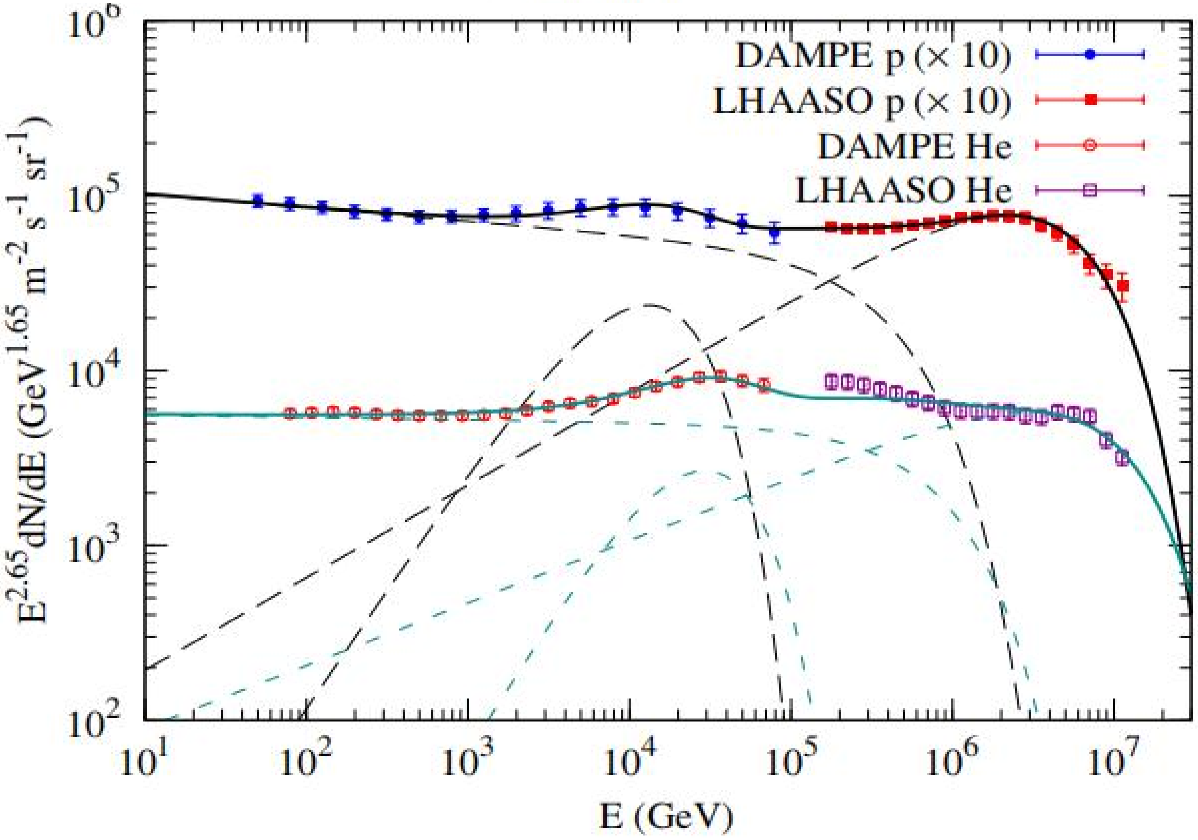


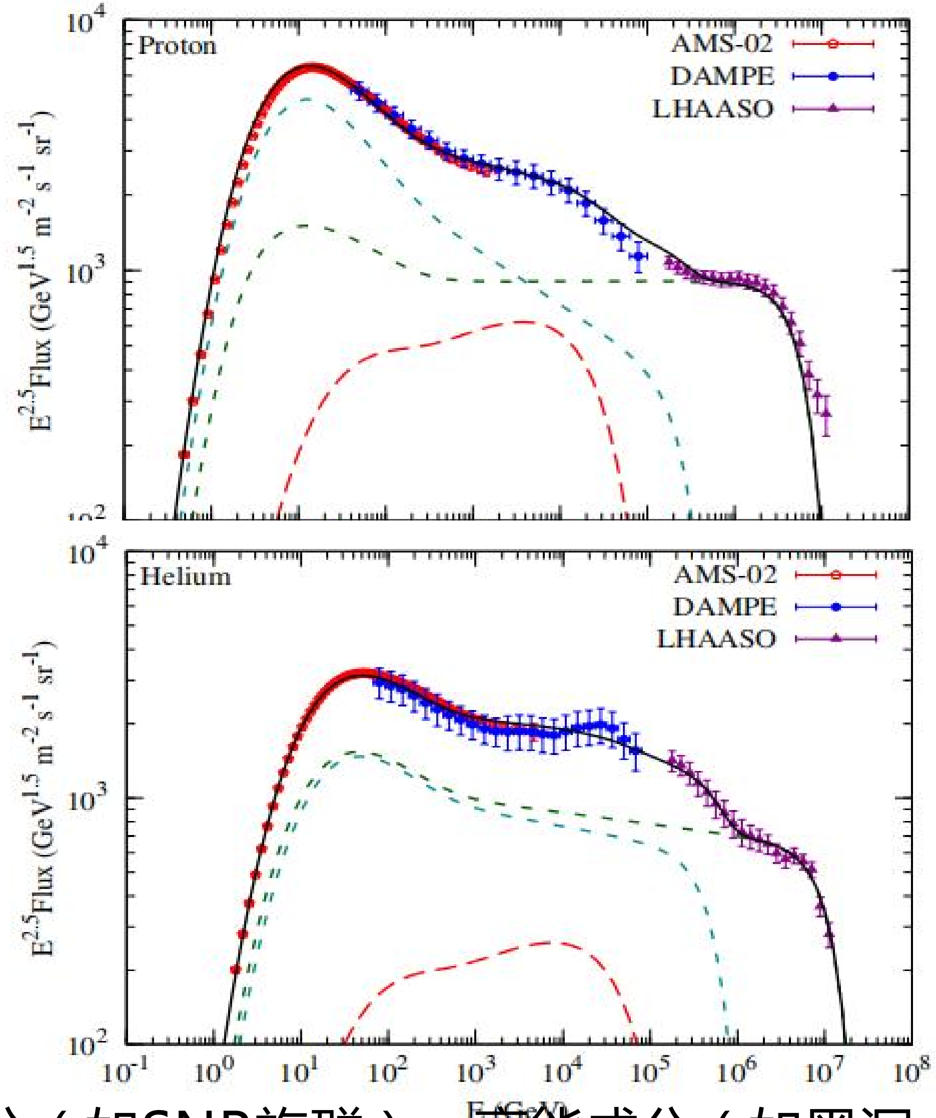
宽能段能谱呈现丰富的超预期结构，意味着宇宙线可能存在多种起源

宇宙线能谱结构的三成分解释

Implication of multiple source populations of Galactic cosmic rays from proton and helium spectra

Qiang Yuan[a,b*]
[a]*Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, P.R.China*
[b]*School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, P.R.China*
(Dated: November 11, 2025)

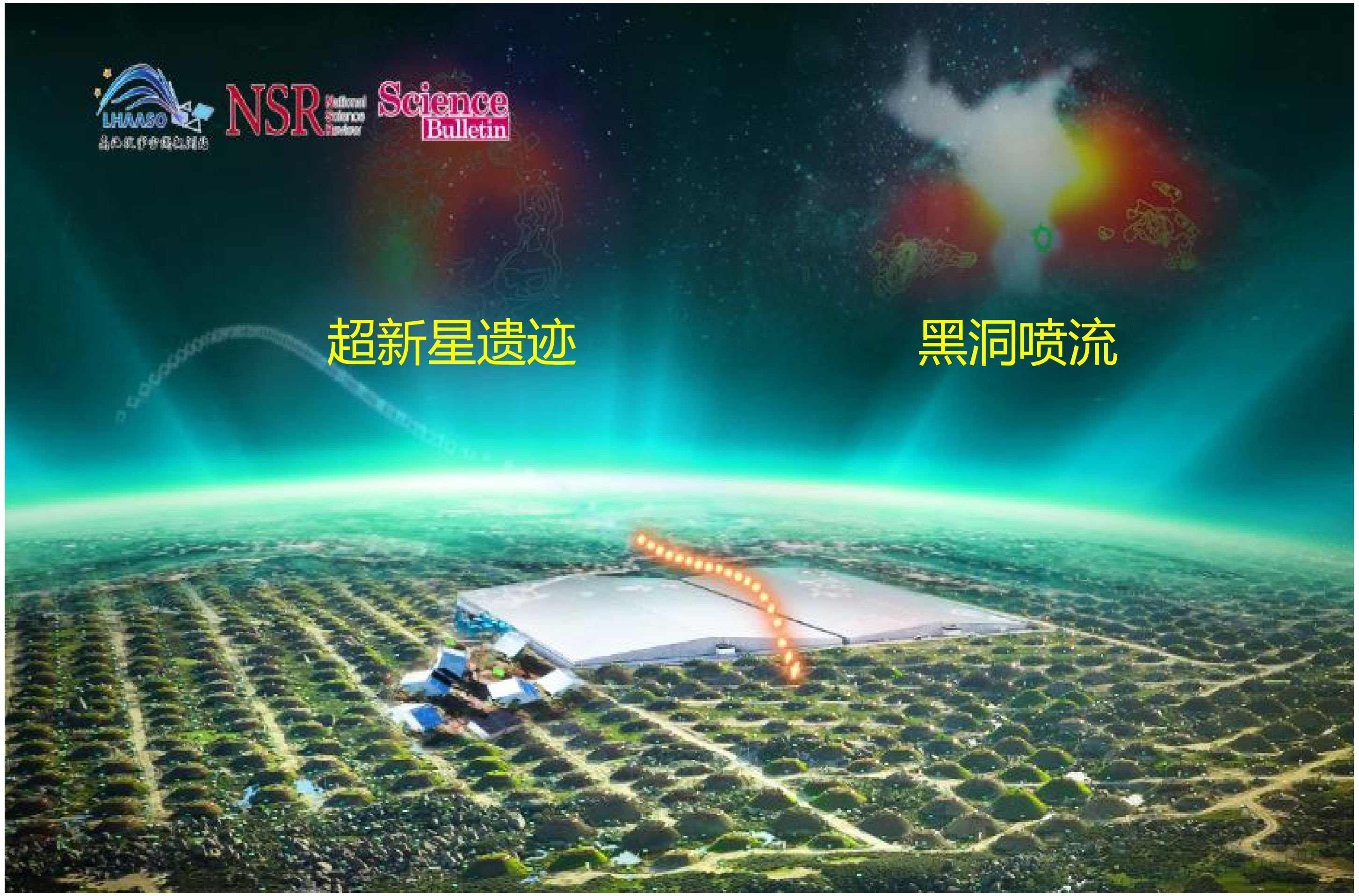


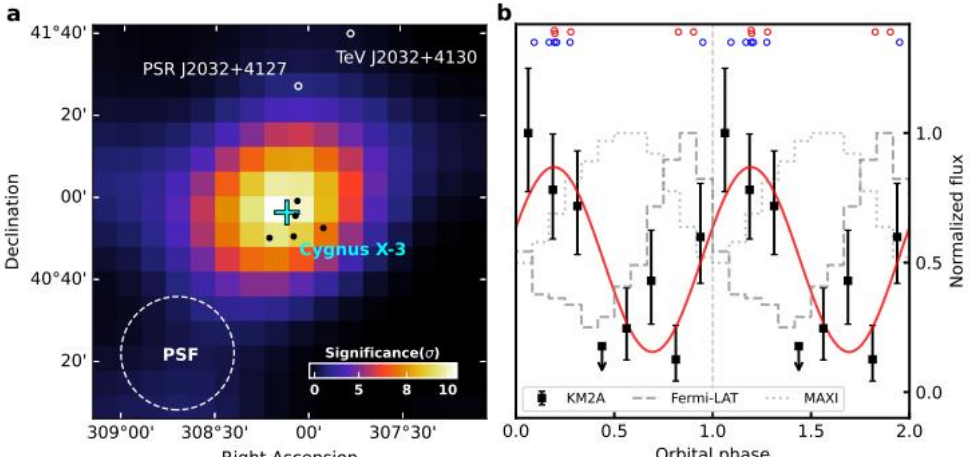


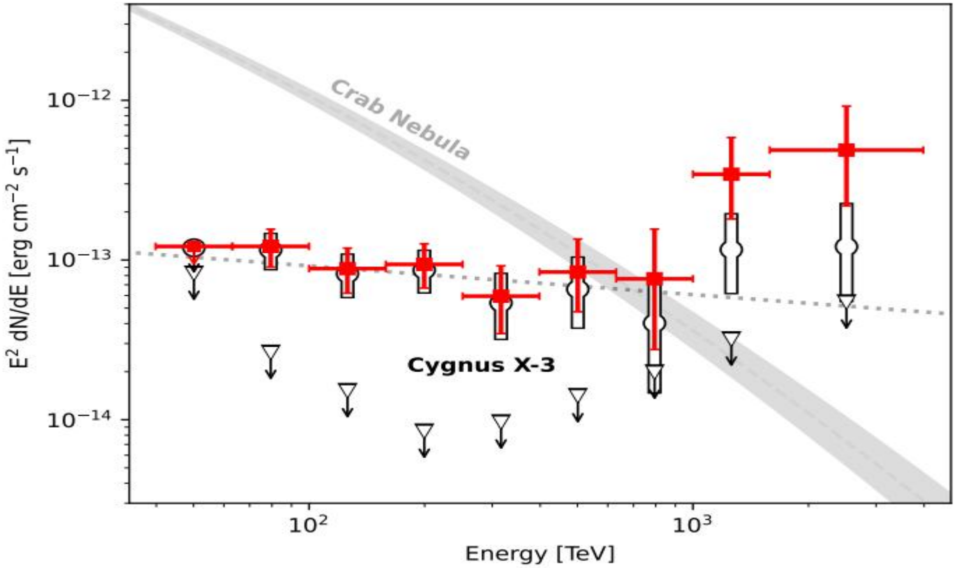
Yuan, arXiv:2511.06733

三成分可能的物理实现：低能成分（如SNR族群）、高能成分（如黑洞喷流）、邻近成分（某单一SNR）

拉索揭示黑洞喷流为超高能宇宙线源



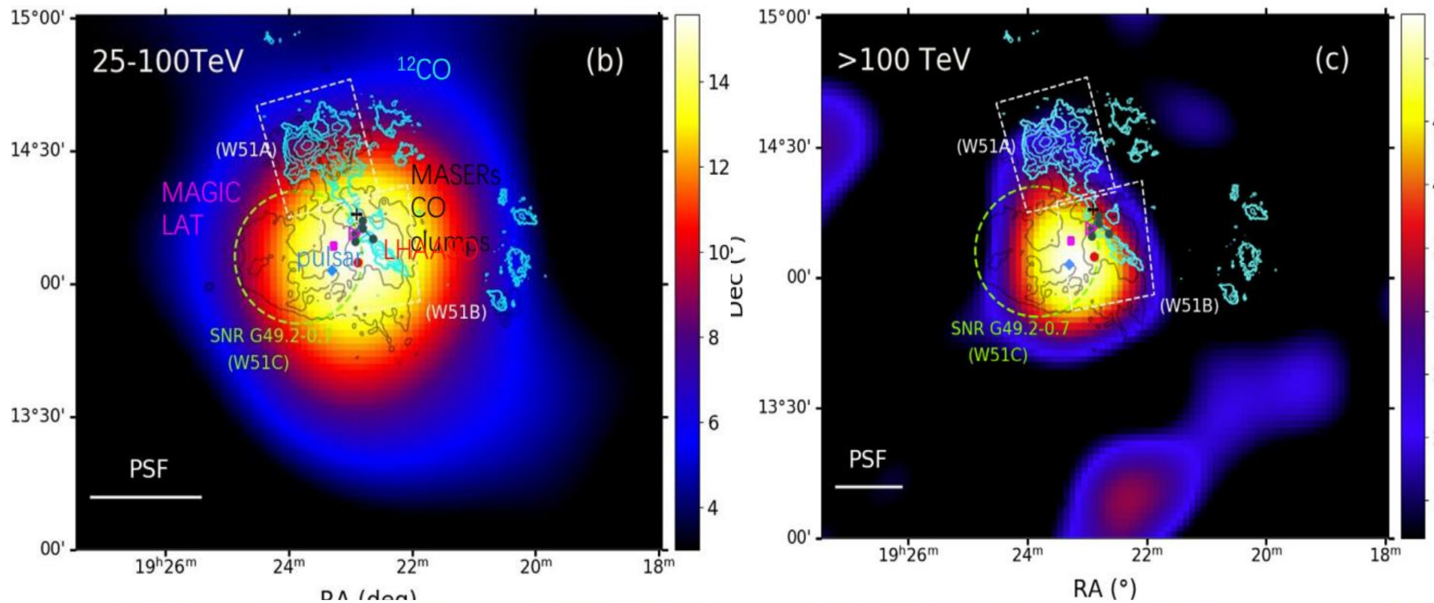


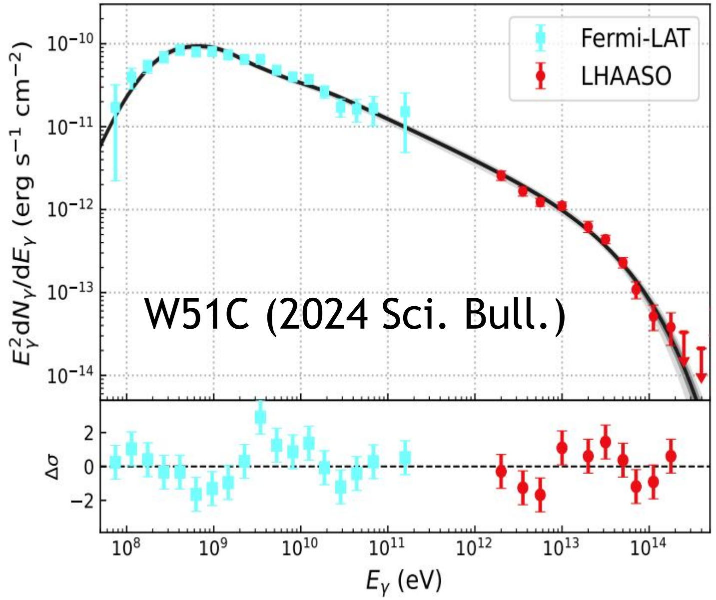


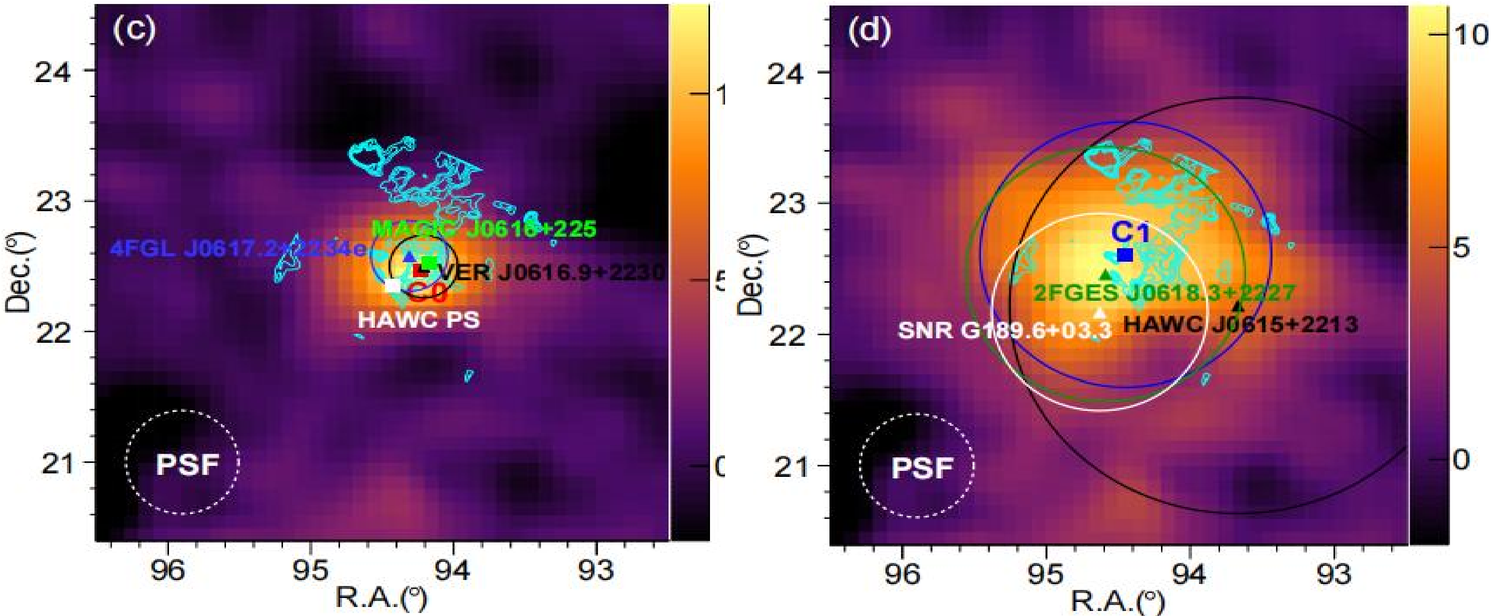
2025 NSR; 2025 arXiv:2512.16638

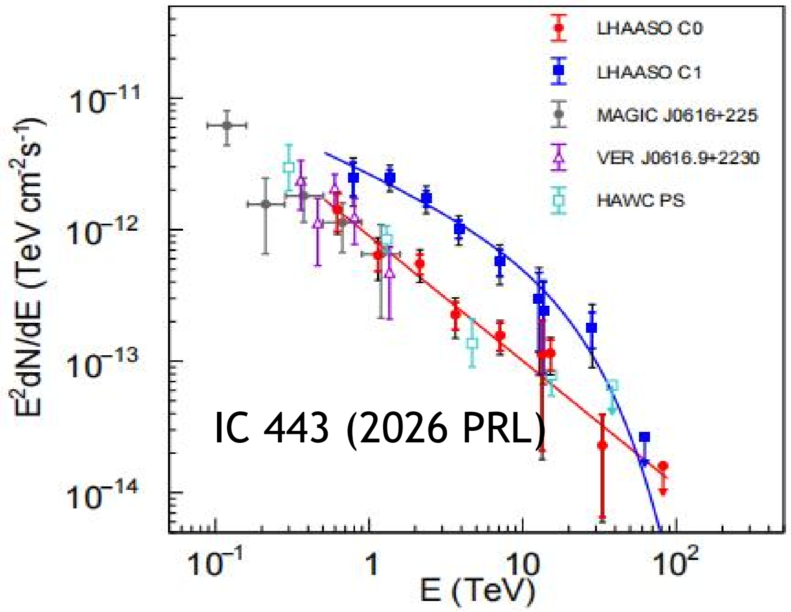
恒星级质量黑洞Cygnus X-3发出迄今为止人类探测到的最高能量光子（3.7 PeV）

超新星遗迹的加速极限(<~PeV)

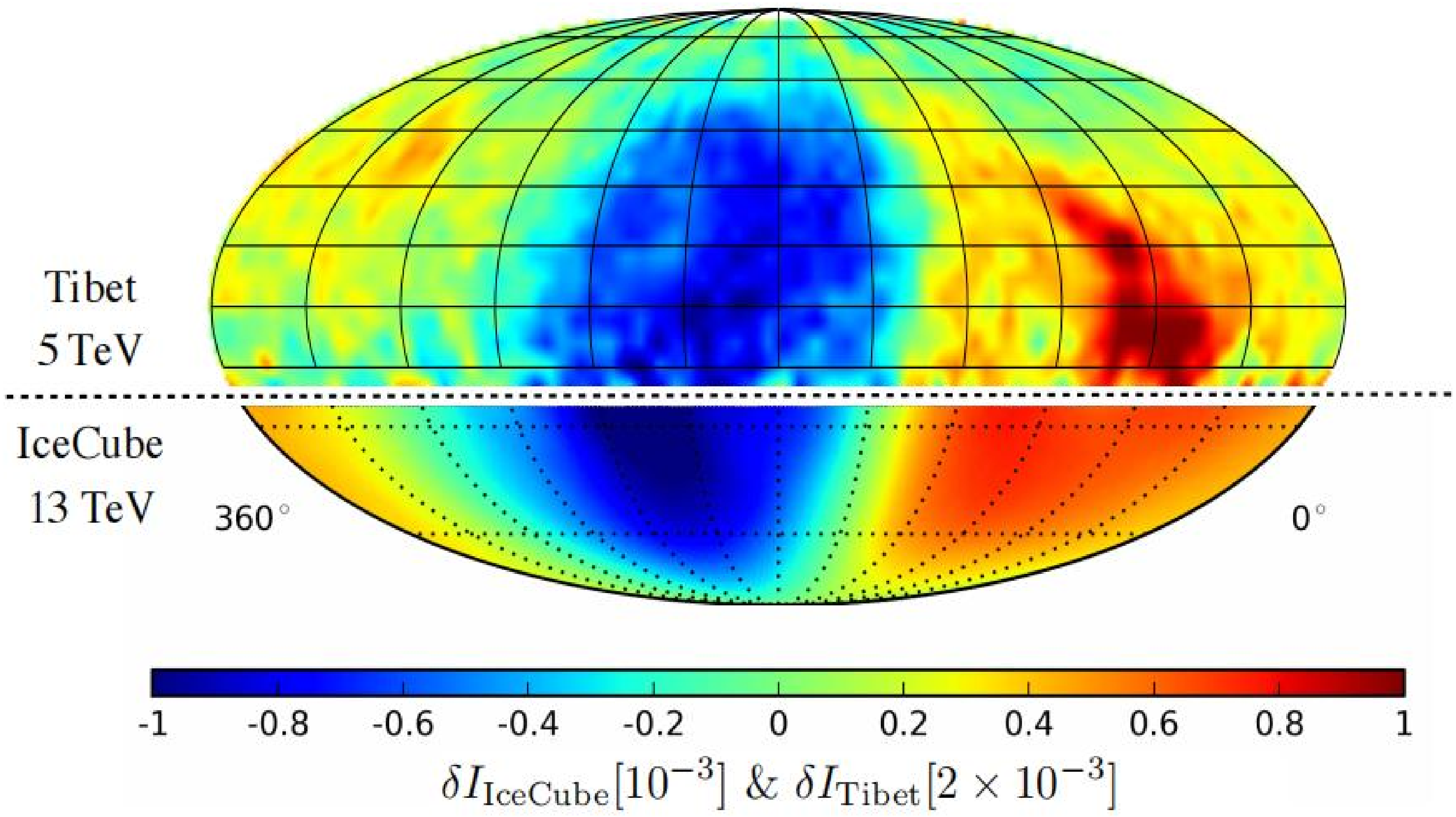






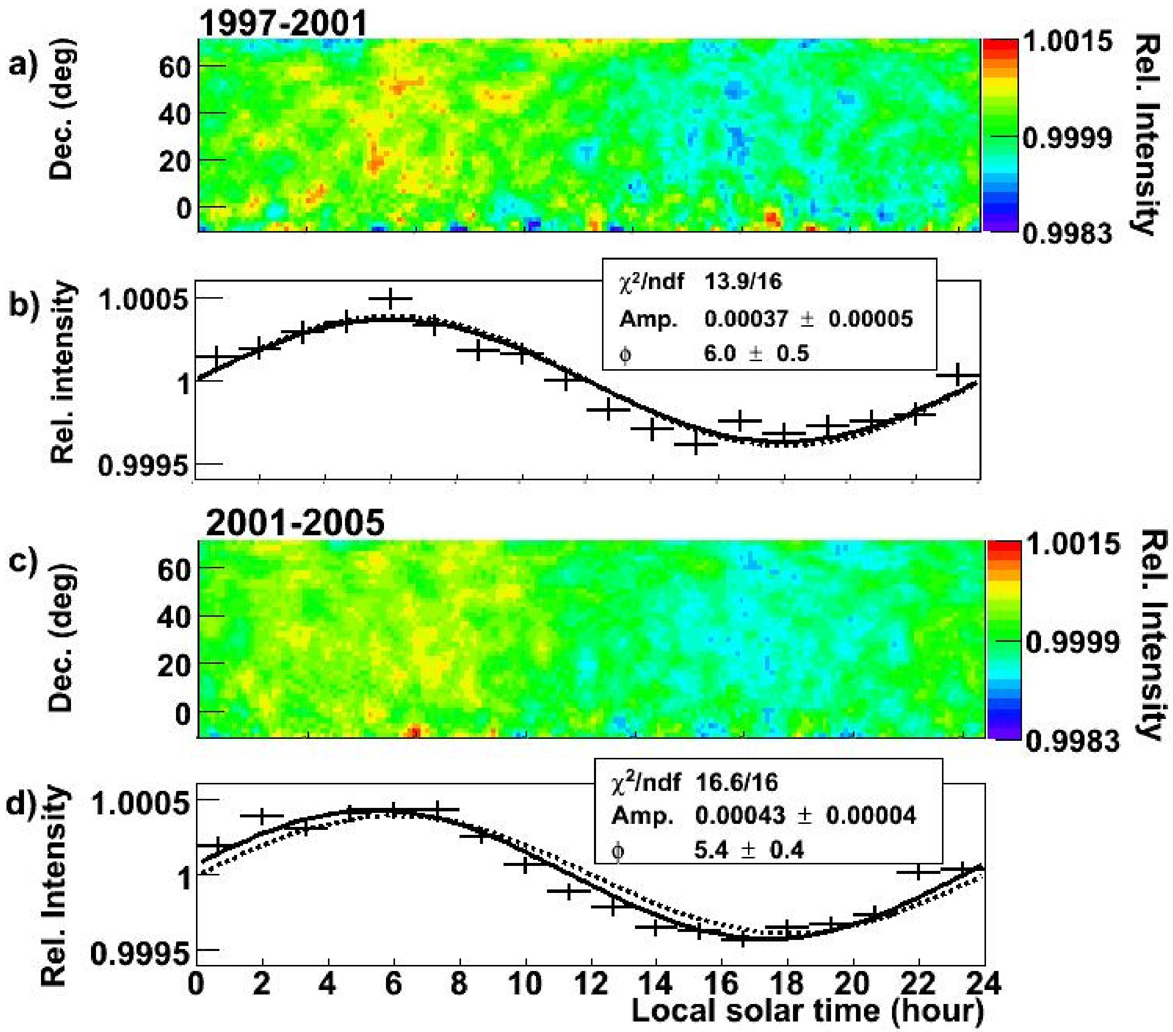


大尺度各向异性



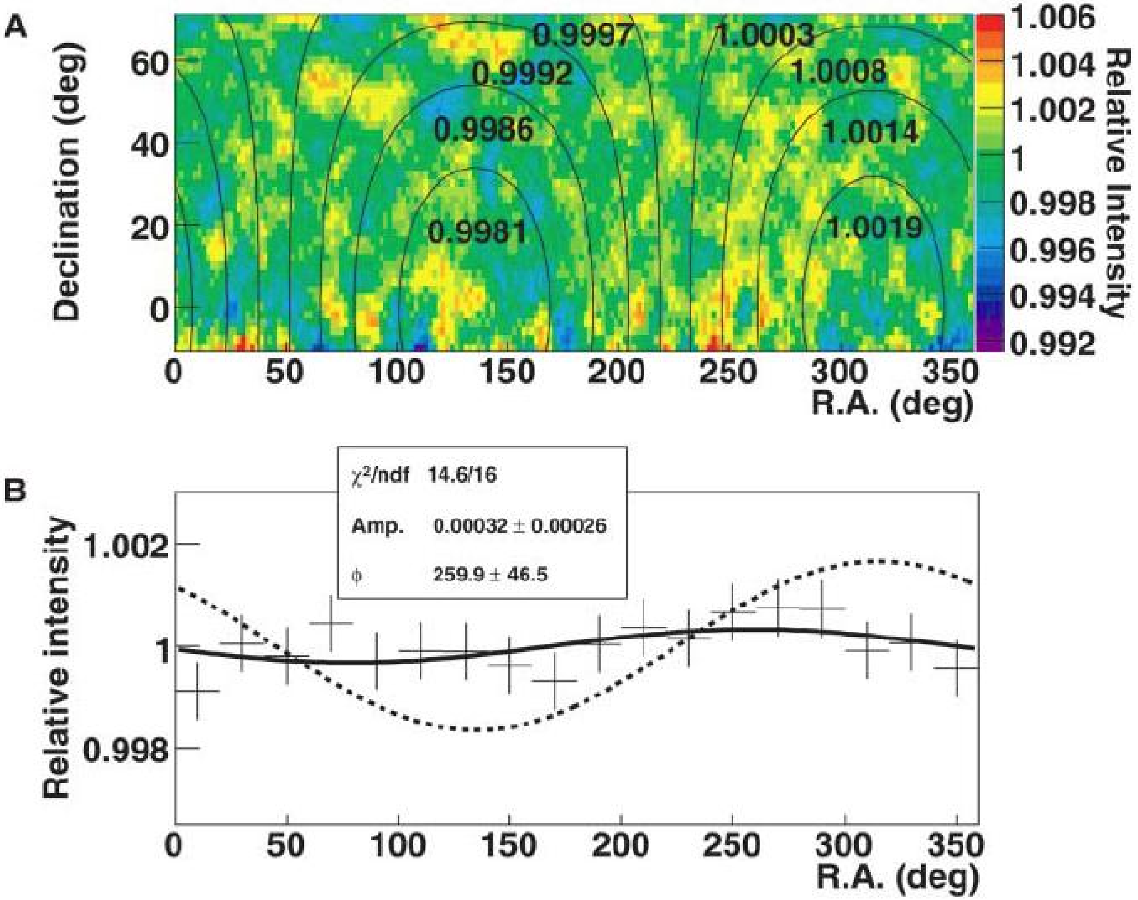
- Compton-Getting effect：观测者运动导致的各向异性
- 宇宙线扩散传播：源分布形成的流量梯度

Compton-Getting effect



太阳时各向异性和地球绕太阳公转预期相符

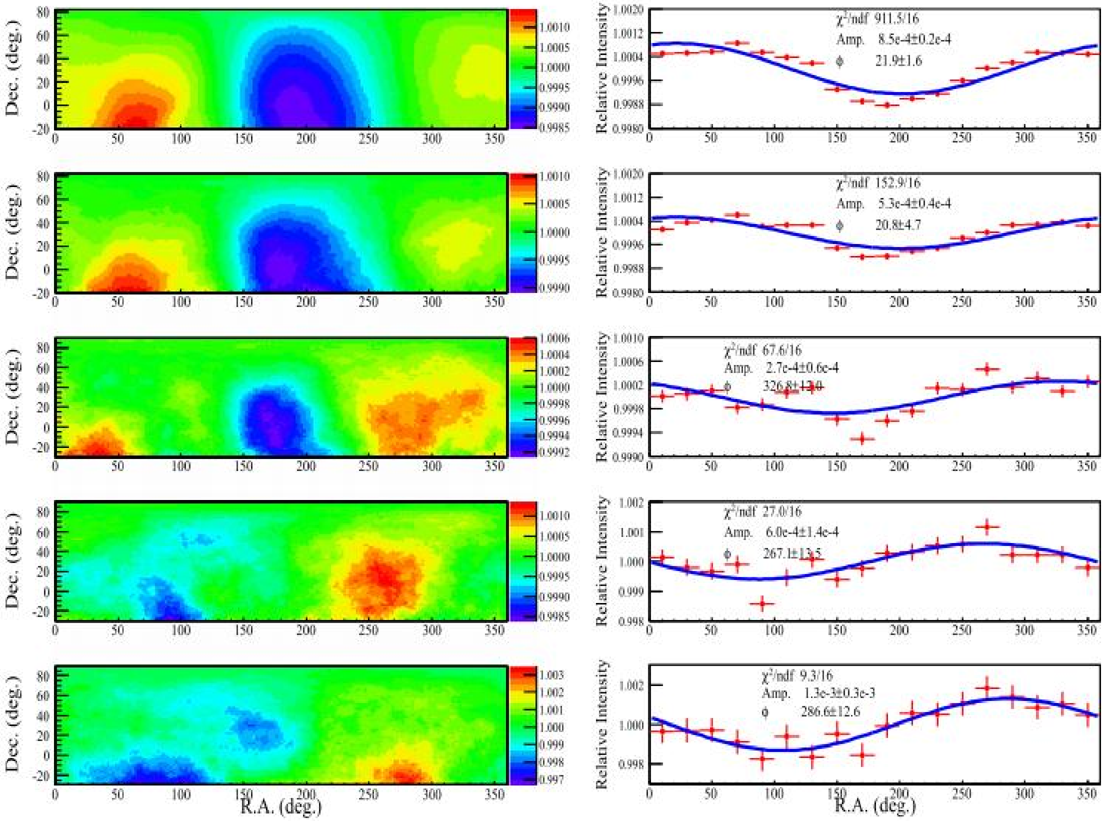
Amenomori et al. (2006, Science, 314, 439)



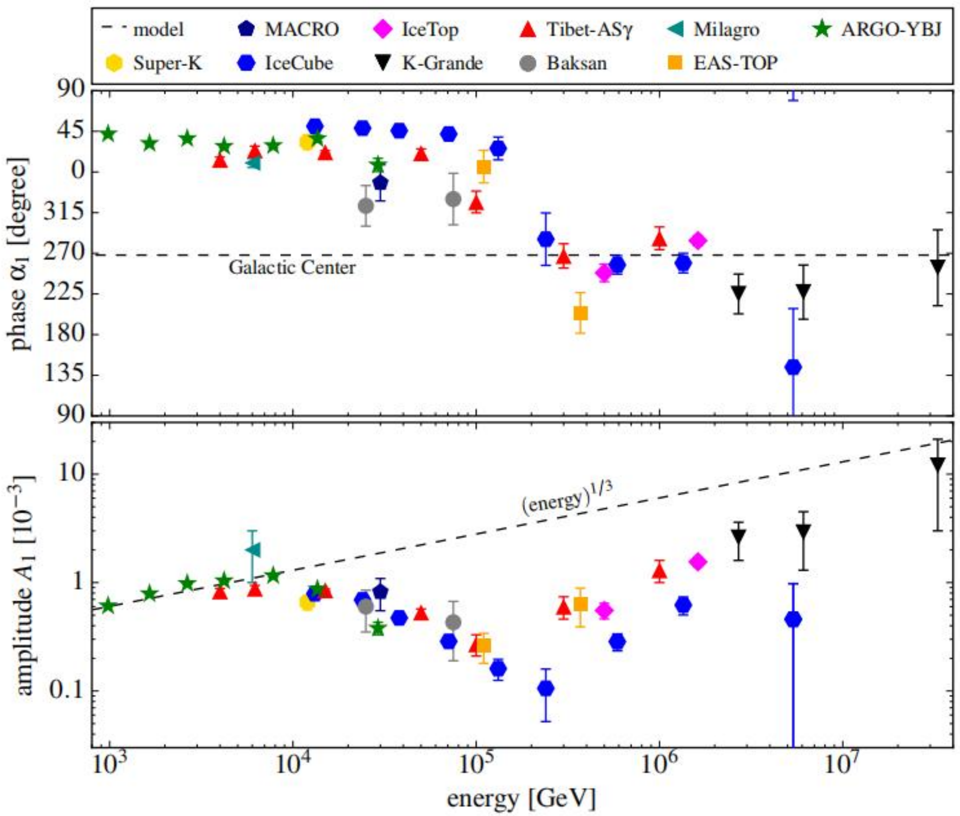
恒星时各向异性未发现和太阳系绕银心公转对应的各向异性，表明宇宙线和太阳系共转

各向异性随能量演化

Tibet-ASγ, ApJ, 836, 153 (2017)

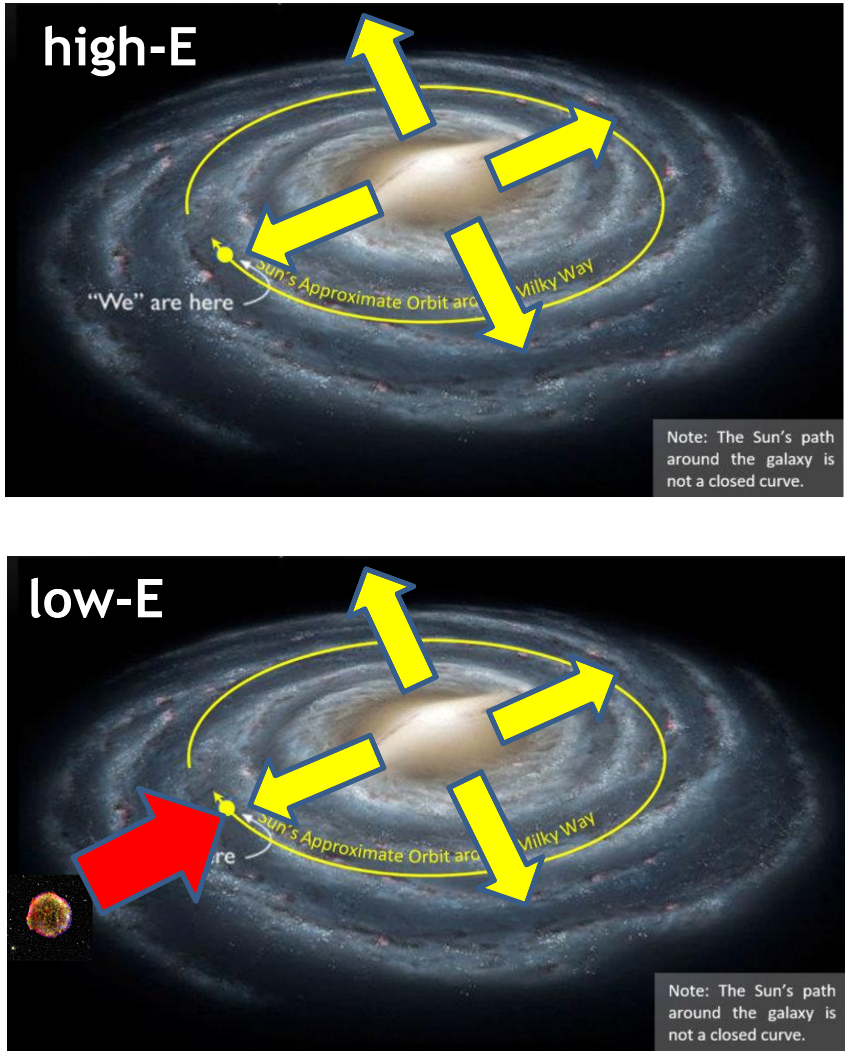


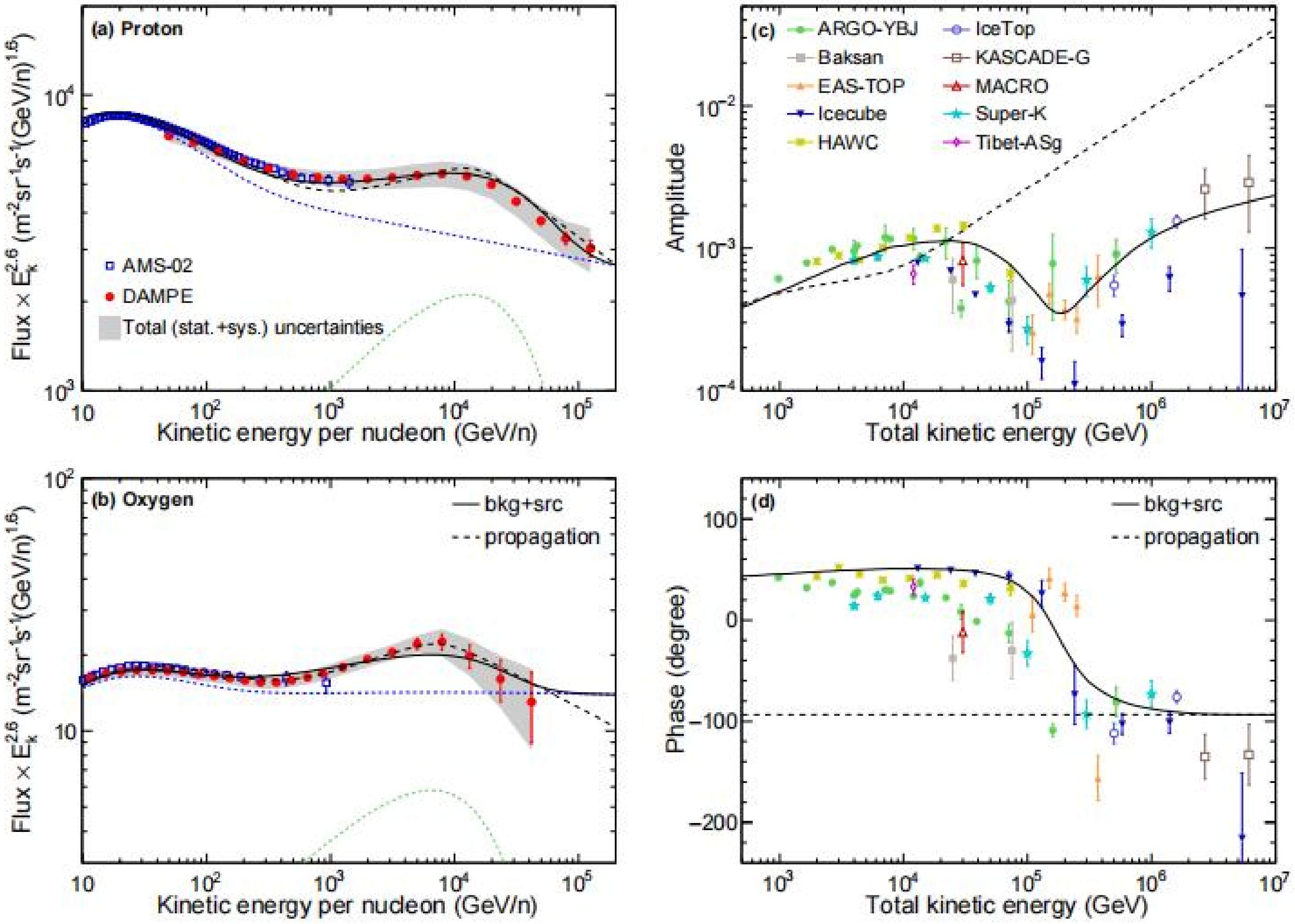
Ahlers & Mertsch, PPNP, 94, 184 (2017)



（恒星时）各向异性并非起源于太阳系运动，而是反映了宇宙线的宏观“流动”；其随能量体现出复杂的演化行为

能谱和各向异性的共同起源





Liu + JCAP (2019); Qiao + ApJ (2023)

能谱：背景+邻近源代数和；各向异性：背景+邻近源矢量和

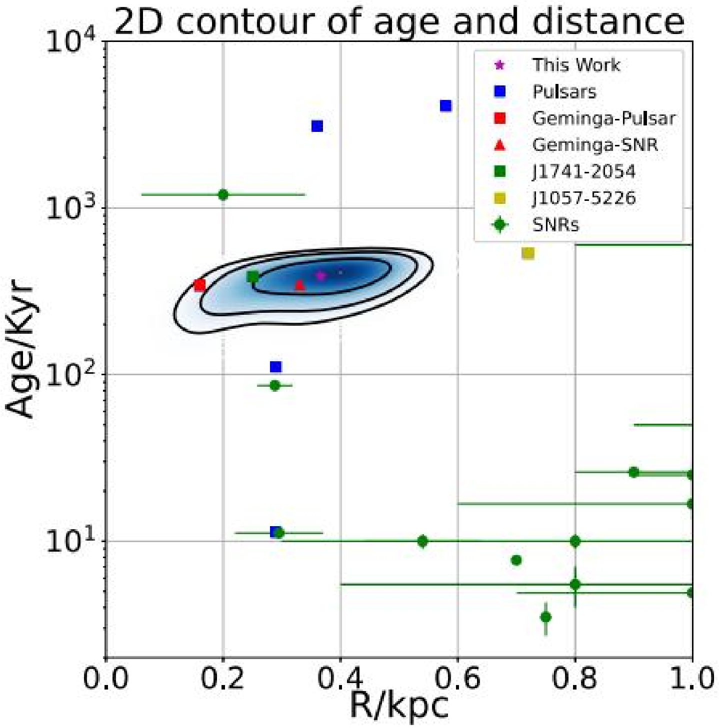
邻近源是Geminga吗？

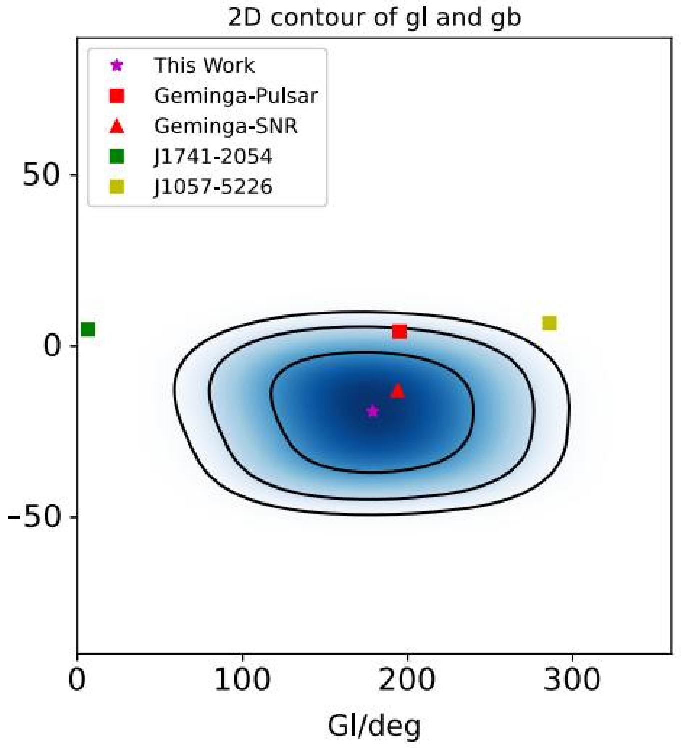
THE ASTROPHYSICAL JOURNAL, 926:41 (8pp), 2022 February 10
https://doi.org/10.3847/1538-4357/ac4416

Geminga SNR: Possible Candidate of the Local Cosmic-Ray Factory

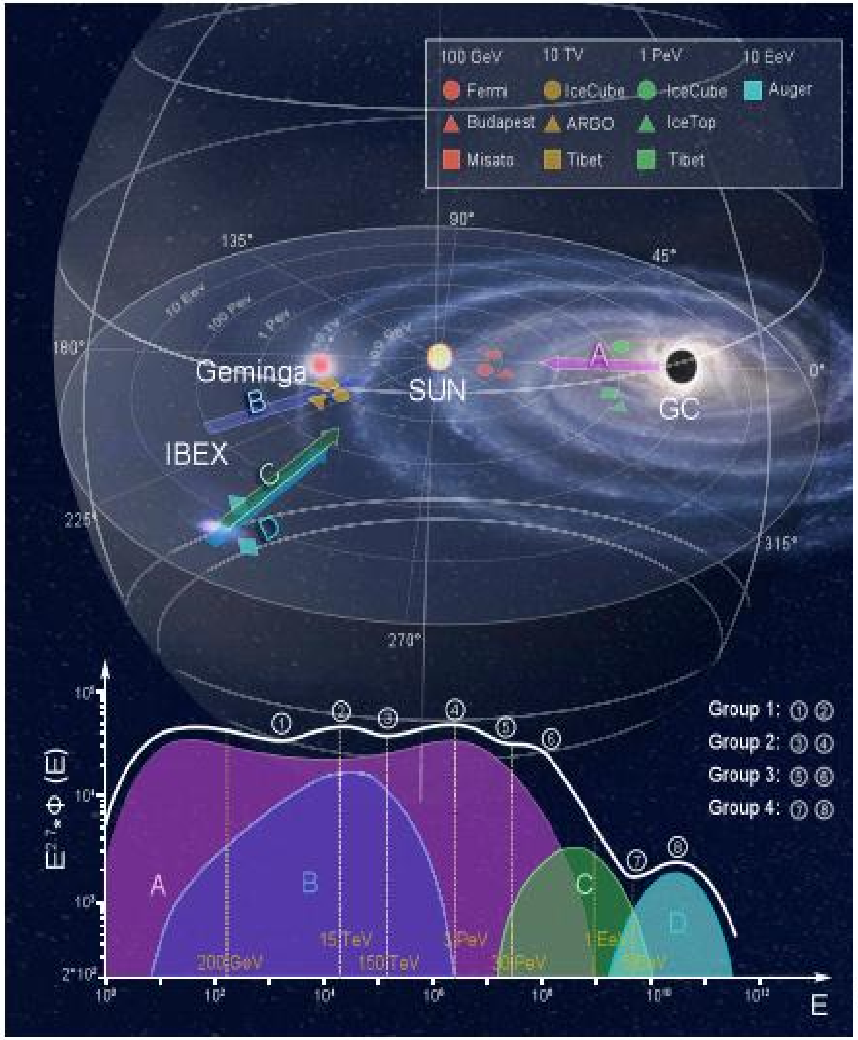
Bing Zhao[1], Wei Liu[2], Qiang Yuan[3,4,5], Hong-Bo Hu[2,6], Xiao-Jun Bi[2,6], Han-Rong Wu[2], Xun-Xiu Zhou[1], and Yi-Qing Guo[2,6]

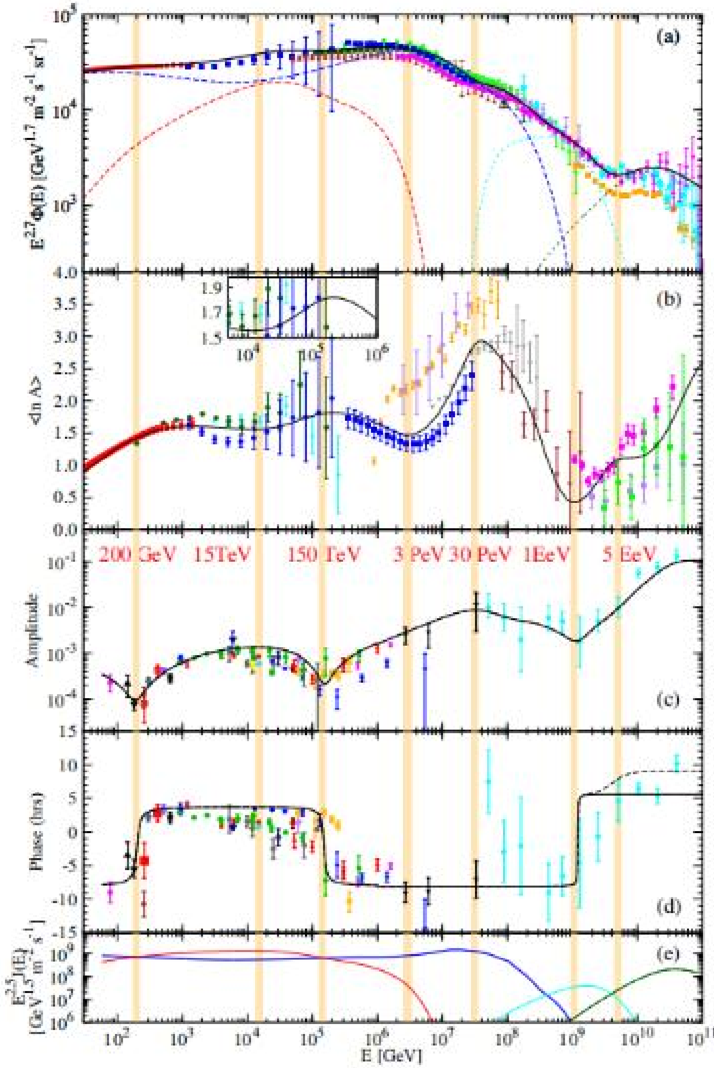
- Geminga SNR/PWN
- d~330 pc, t~34,000 yr
- 10 TeV bump of CR is due to particles accelerated by the SNR
- Electrons/positrons continuously injected by the PWN give e+e- excesses
- Its direction is consistent with the dipole anisotropy phase





全能段能谱、成分、各向异性共同演化





Co-evolution of cosmic ray energy spectra, composition, and anisotropies

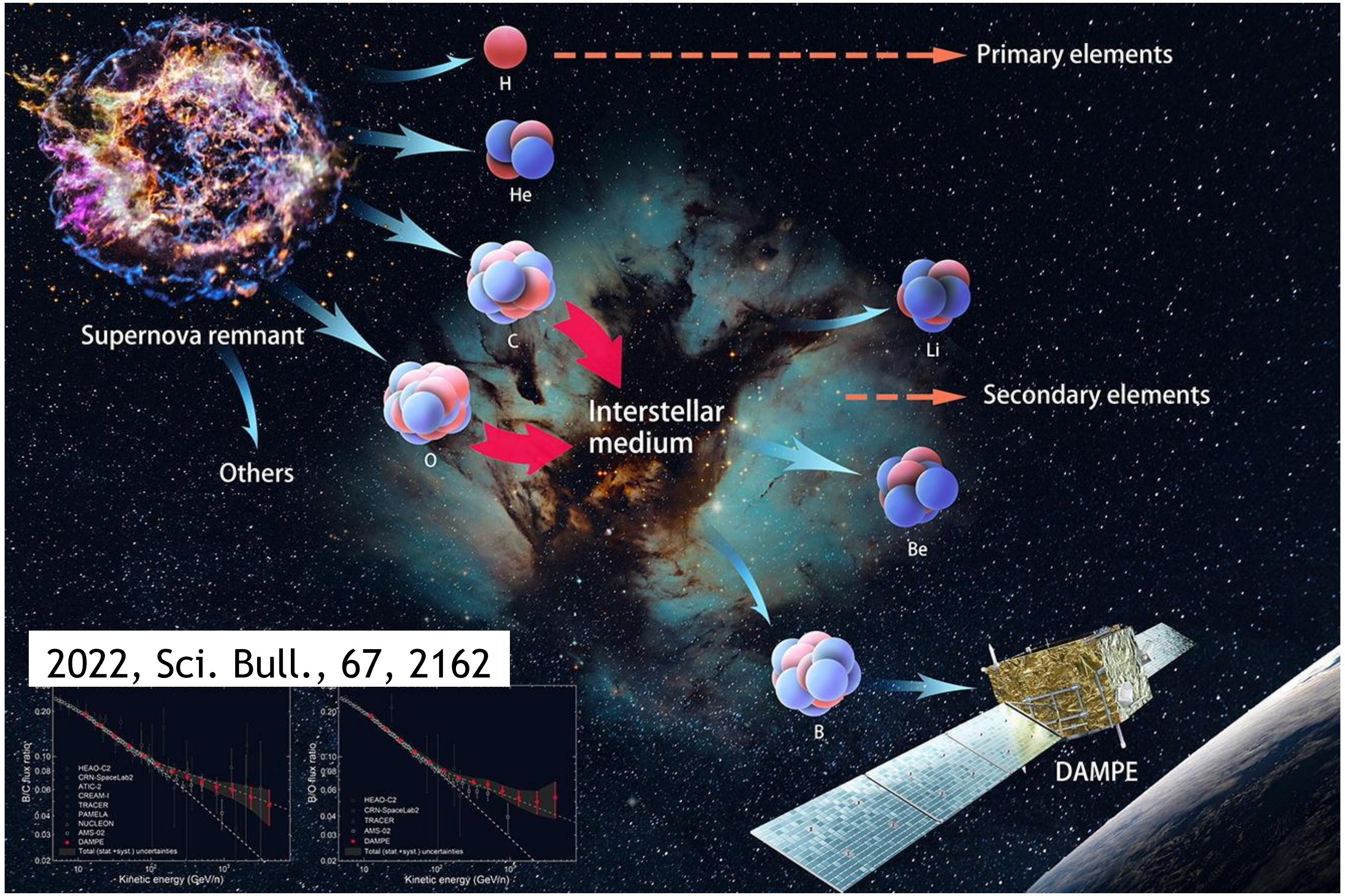
Bing-Qiang Qiao,[1,2] Qiang Yuan,[3,4,*] and Yi-Qing Guo[5,6,7,†]

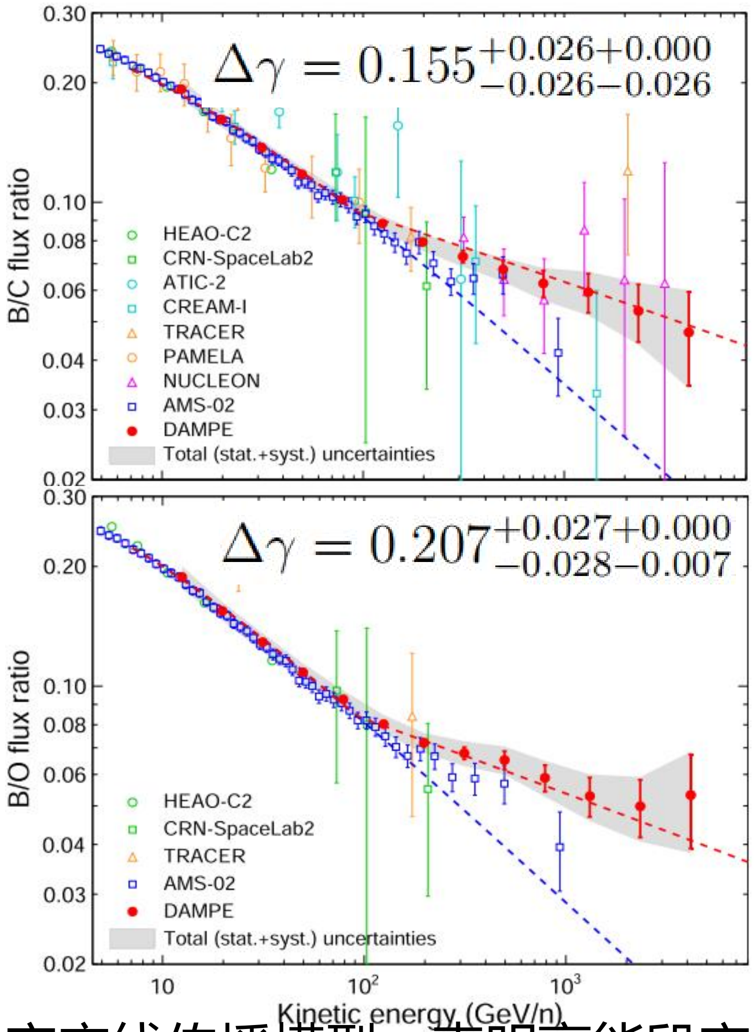
[1]*Deutsches Elektronen Synchrotron DESY, Platanenallee 6, D-15738, Zeuthen, Germany*
[2]*Institut für Physik und Astronomie, Universität Potsdam, D-14476, Potsdam, Germany*
[3]*Division of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China*

在更宽的能段来看，能谱、质量组分和各向异性之间也存在共同演化的特征，可用4-组分模型解释全能段观测结果

Qiao et al. (arXiv:2506.18118)

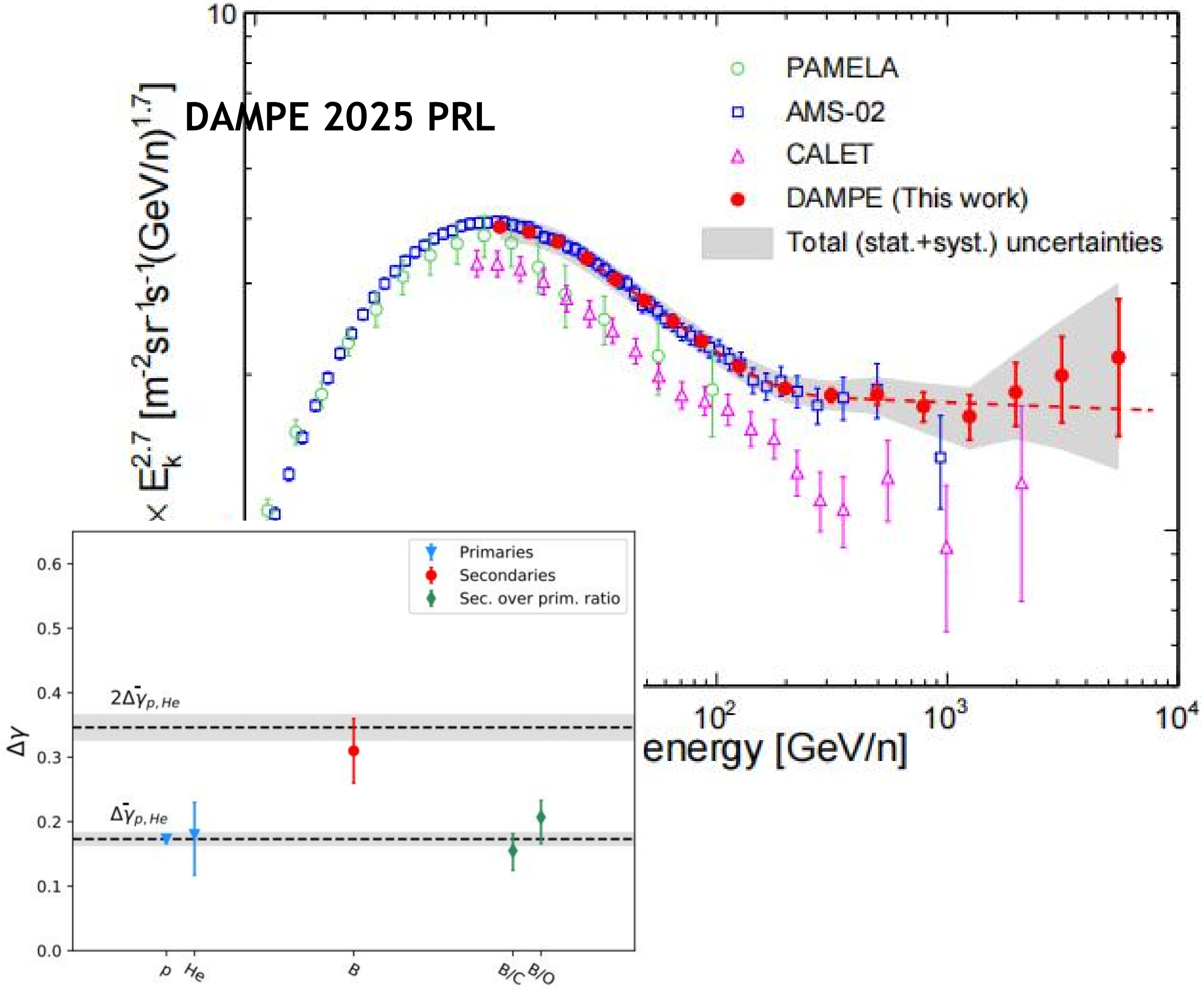
次级/初级粒子比例



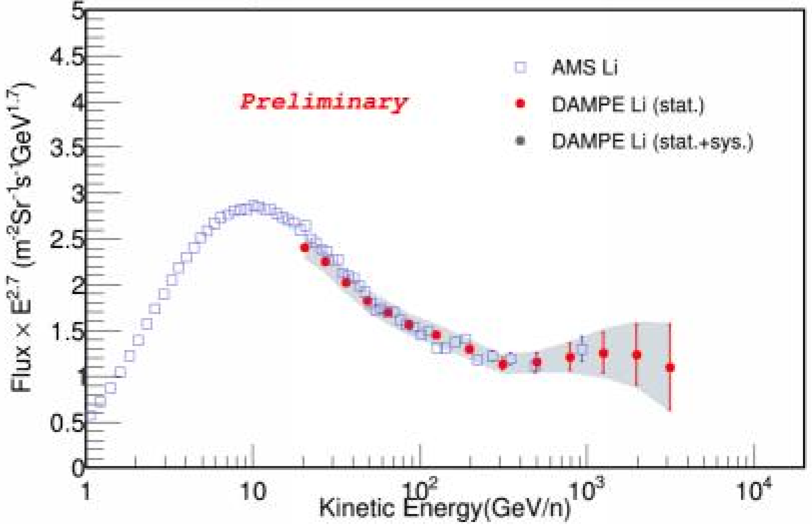


- DAMPE发现次级/原初宇宙线存在明显拐折结构，挑战了经典宇宙线传播模型，表明高能段宇宙线传播比传统模型预期更慢
- 改变反物质天文本底，进而影响暗物质间接探测背景估计

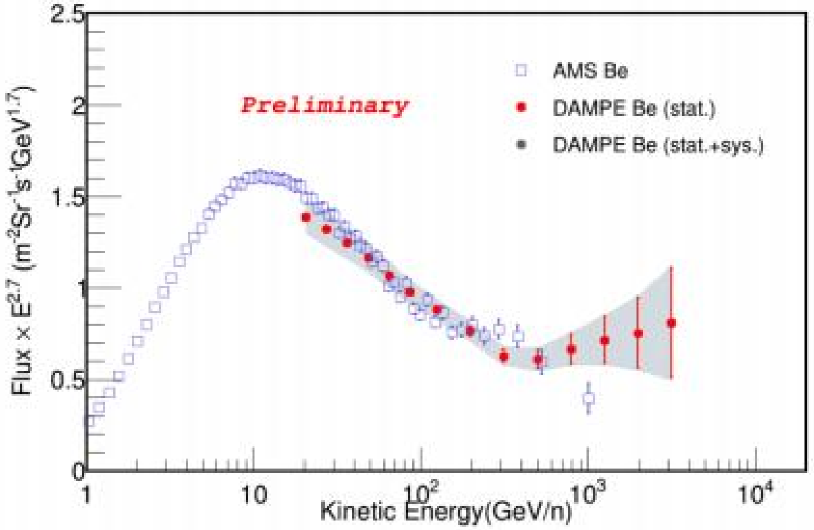
次级粒子能谱



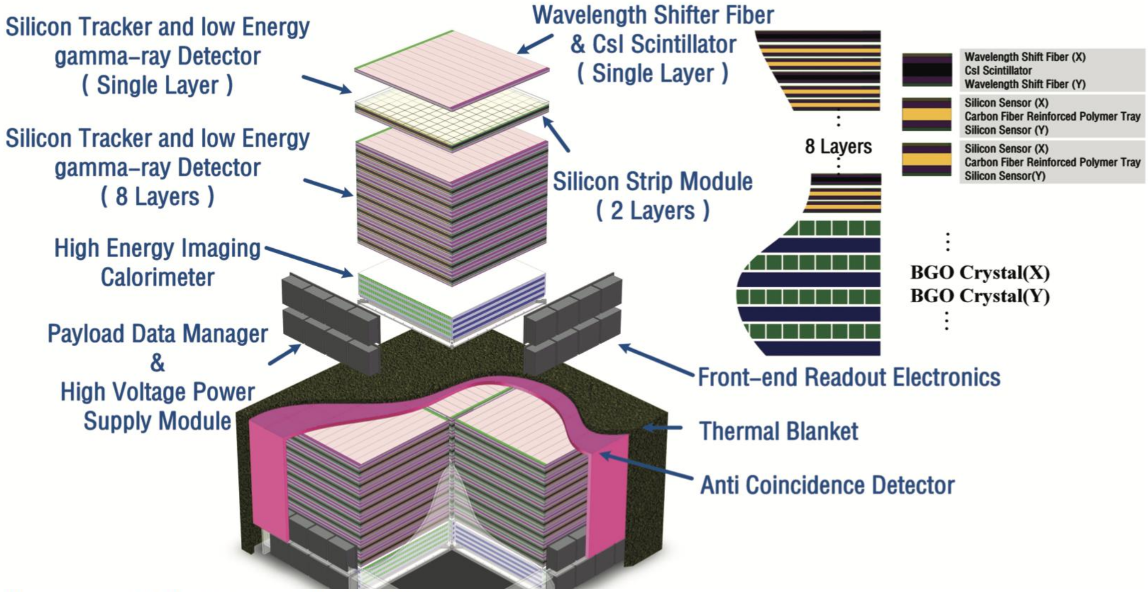
Lithium spectrum



Beryllium spectrum



未来实验

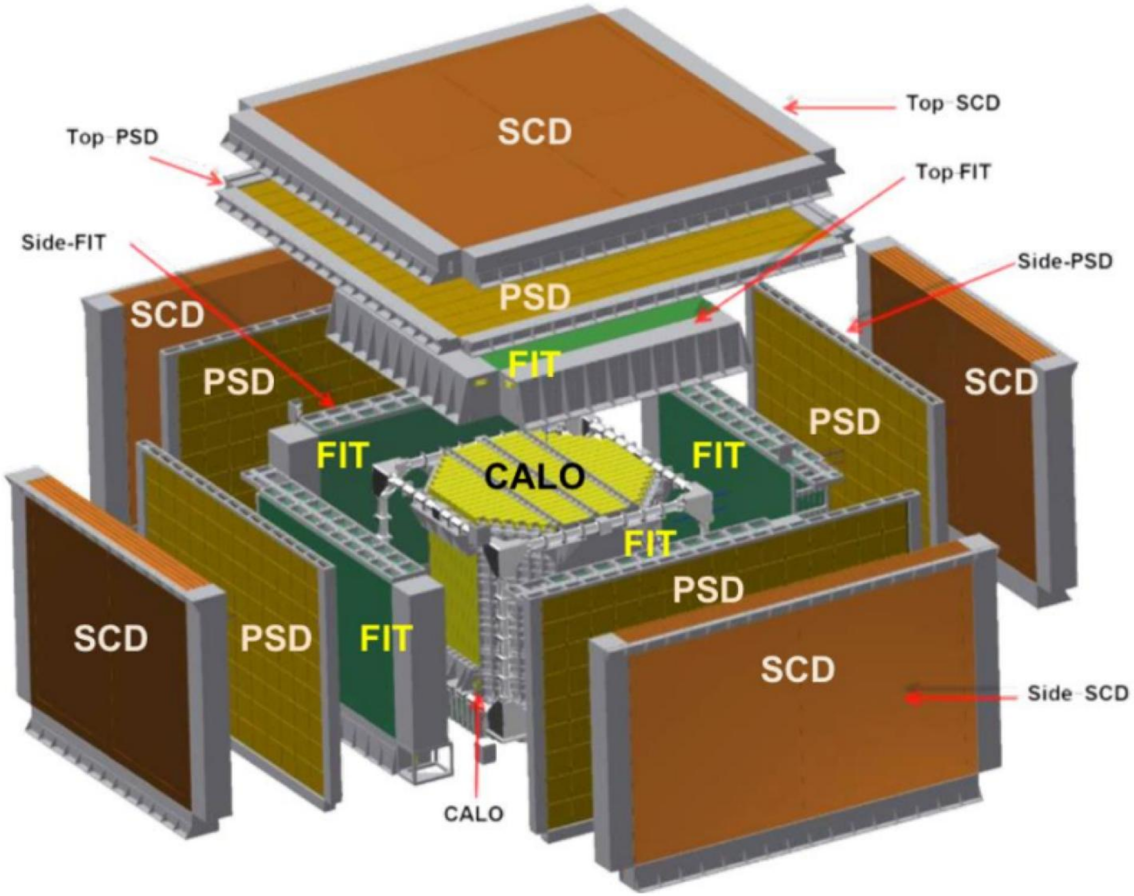


Nuclear Science and Techniques (2024) 35:149
https://doi.org/10.1007/s41365-024-01499-x

Check for updates

Simulation study of the performance of the Very Large Area gamma-ray Space Telescope

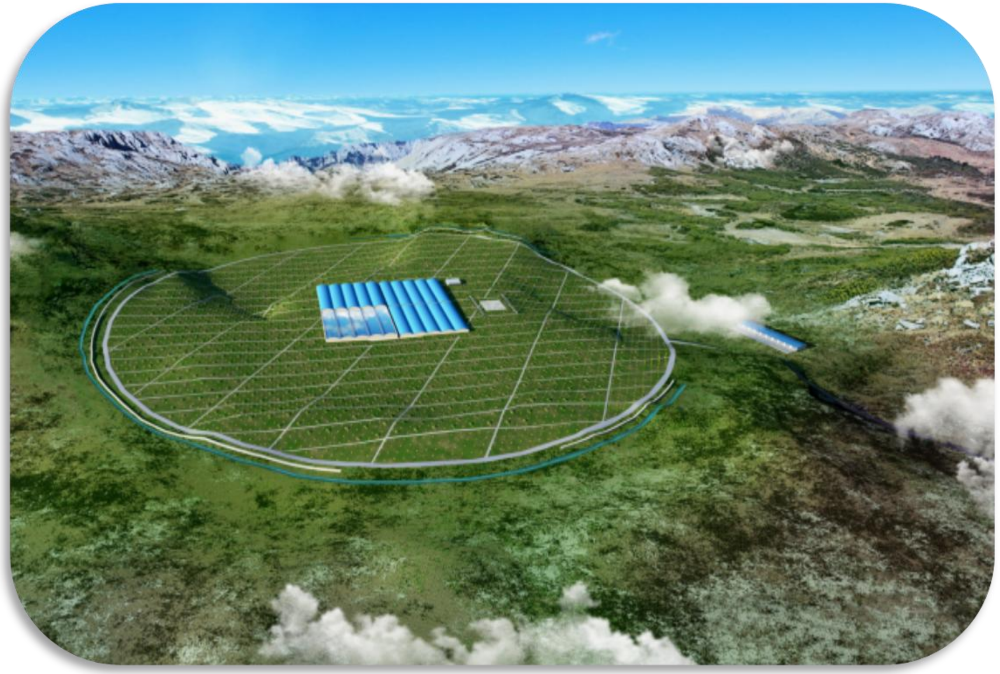
Xu Pan[1,2] · Wei Jiang[1] · Chuan Yue[1] · Shi-Jun Lei[1] · Yu-Xin Cui[1,2] · Qiang Yuan[1,2]



- ➢ VLAST：DAMPE/Fermi下一代旗舰伽马天文台
- ➢ VLAST探路者将于2026年发射！

中国空间站高能辐射探测设施HERD

未来实验



LHAASO（四川稻城）
高海拔宇宙线观测站（1.3 km²）

MPA
PeV伽马射线阵列（~100 km²）

总结

- 宇宙线的起源和传播是重大的前沿科学问题，DAMPE卫星和LHAASO实验是我国领衔研制的大型实验装置，其部分指标国际领先，为深入理解宇宙线相关问题带来了重要的机遇
- DAMPE发现原初宇宙线（p, He, C, O, Fe）在磁刚度~15 TV处存在统一的拐折现象，很可能是邻近加速源留下的印记，验证了宇宙线加速上限$\propto$ Z的理论
- 结合LHAASO测量的高能段质子、氦核能谱和AMS低能测量结果，从亚GeV到10 PeV的超宽能段能谱意味着银河宇宙线存在3个成分
- 结合LHAASO伽马射线观测，PeV以下宇宙线可能来自超新星遗迹，PeV以上能段可能来自黑洞喷流
- 宇宙线次级/初级粒子比例在高能段存在明显拐折，意味着高能段宇宙线比预期传播得更慢

谢谢！