

# 宇宙线物理基础和实验探测

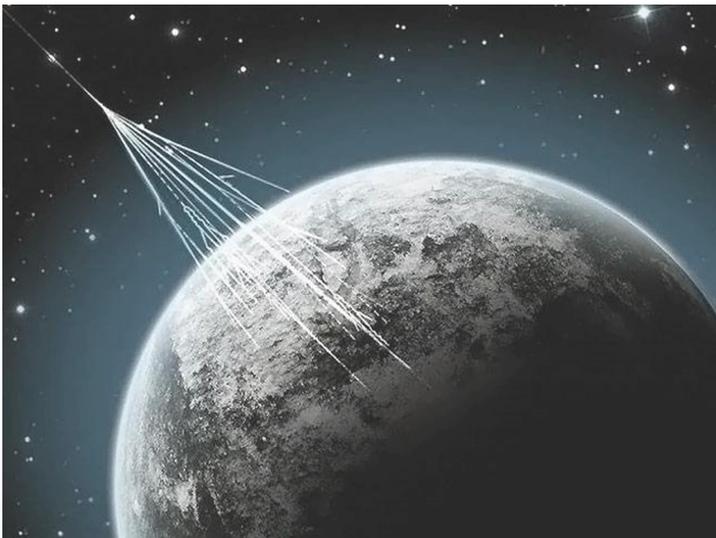
袁 强

中国科学院紫金山天文台

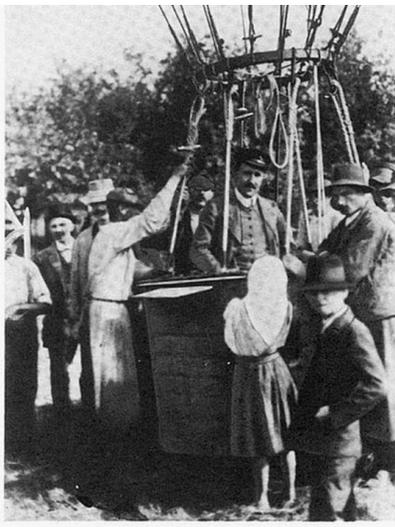
粒子物理标准模型和新物理暑期学校，济南，2023年8月

# 第一部分：宇宙线物理基础

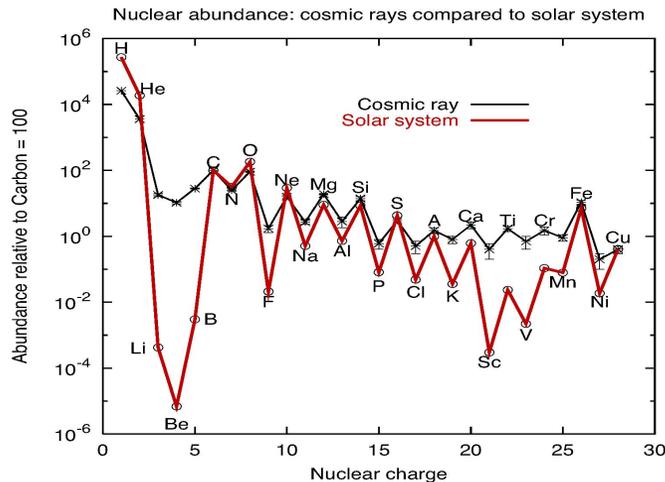
# 宇宙线概述



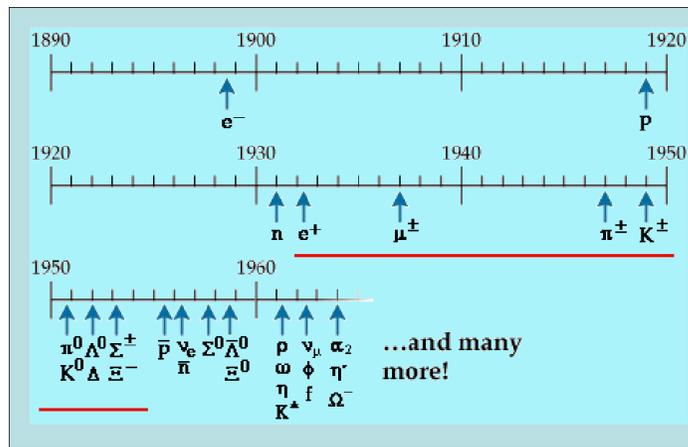
V. Hess 1912  
年发现宇宙线  
(1936年诺奖)



Hess bei Ballonlandung (1912).



宇宙线主要是带电原子核，包括元素周期表中几乎所有核素



宇宙线在粒子物理早期发展中起着奠基性作用(6次获得诺奖)

四大天文观测信使：电磁波、引力波、宇宙线、中微子

新物理

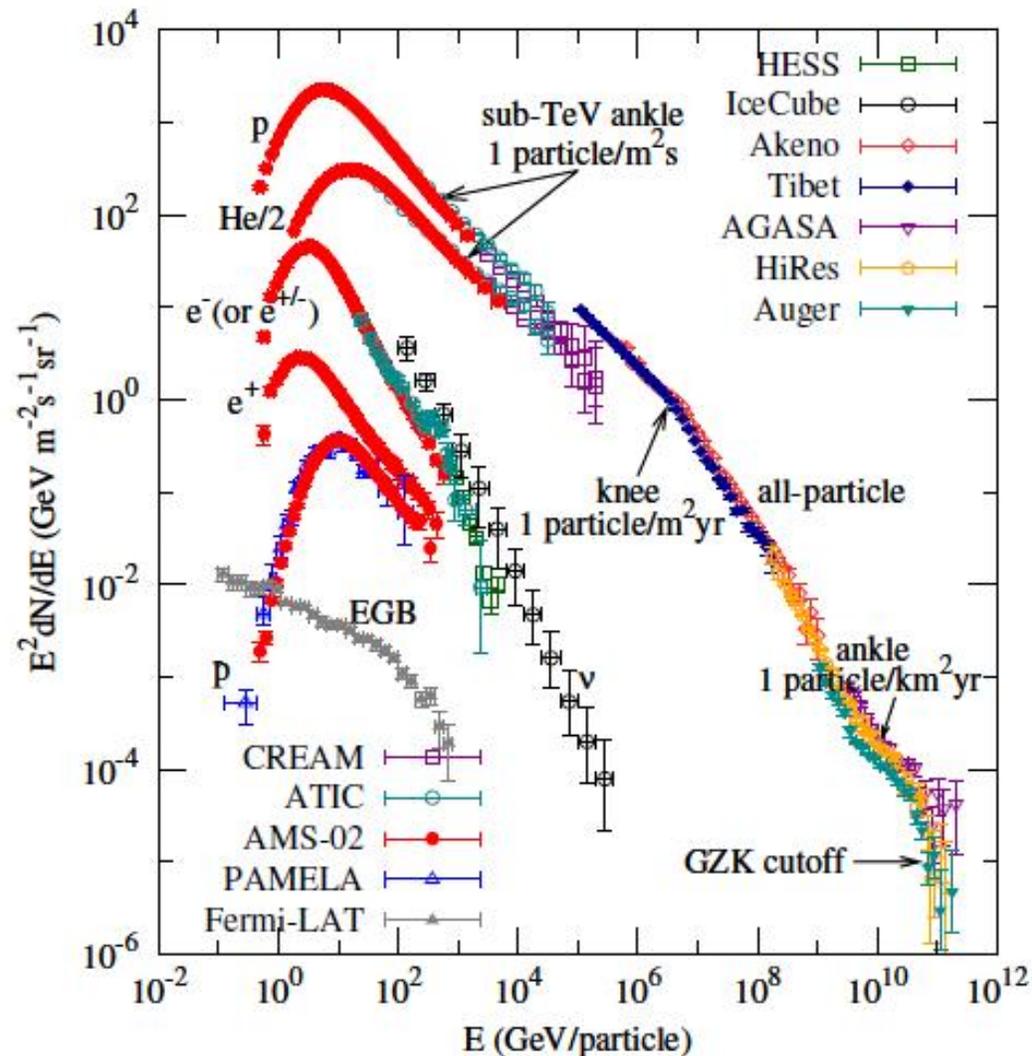
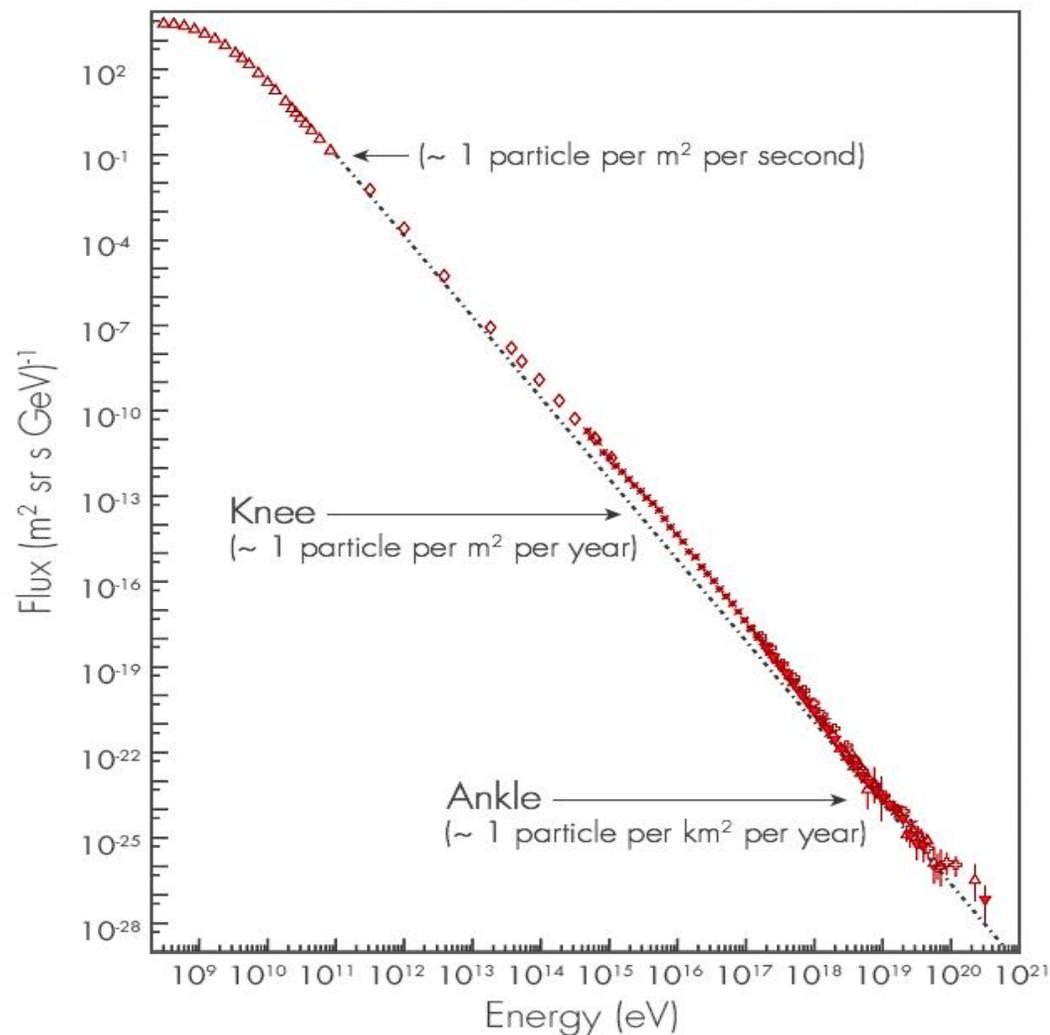
- 暗物质
- 极高能粒子加速和相互作用
- 洛伦兹对称性破缺

新天文

- 多信使天文
- 极端条件（密度、能量、磁场）下的天体

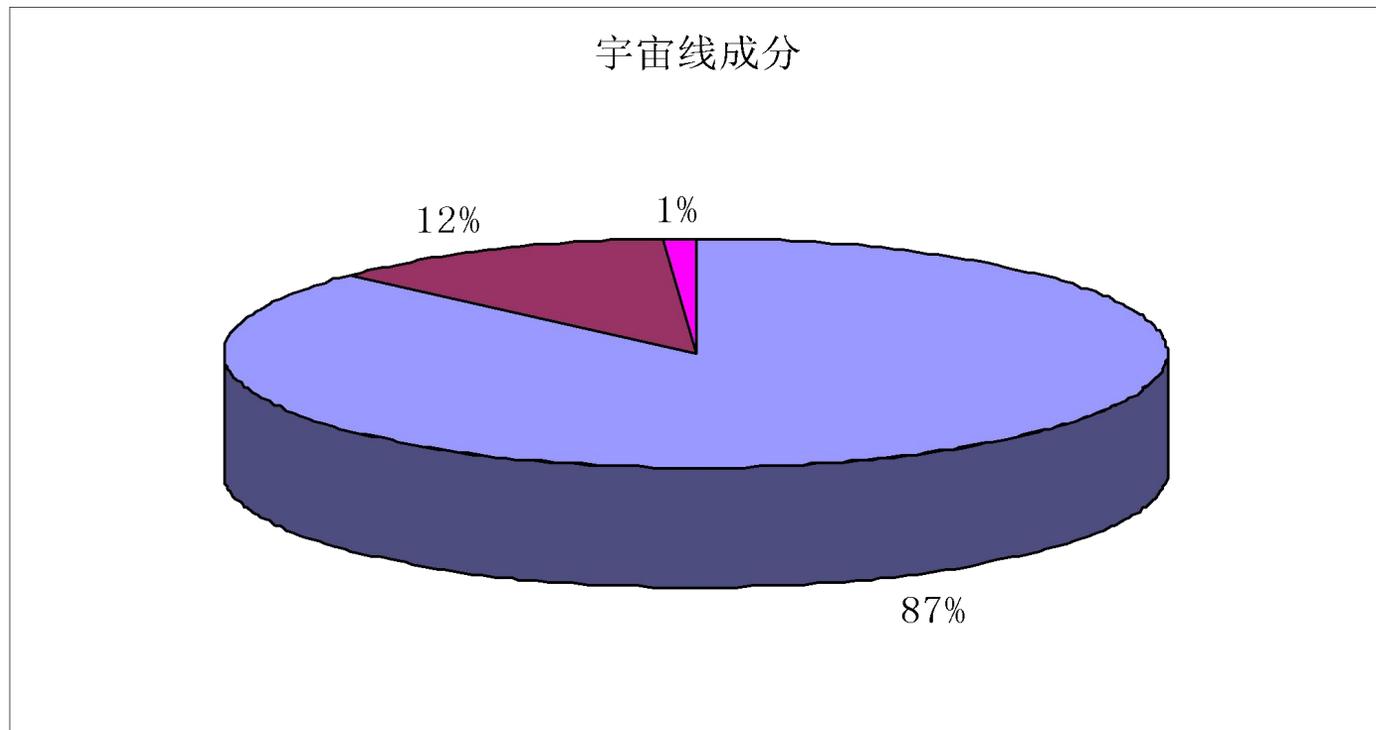
# 宇宙线概述：能谱

FLUXES OF COSMIC RAYS



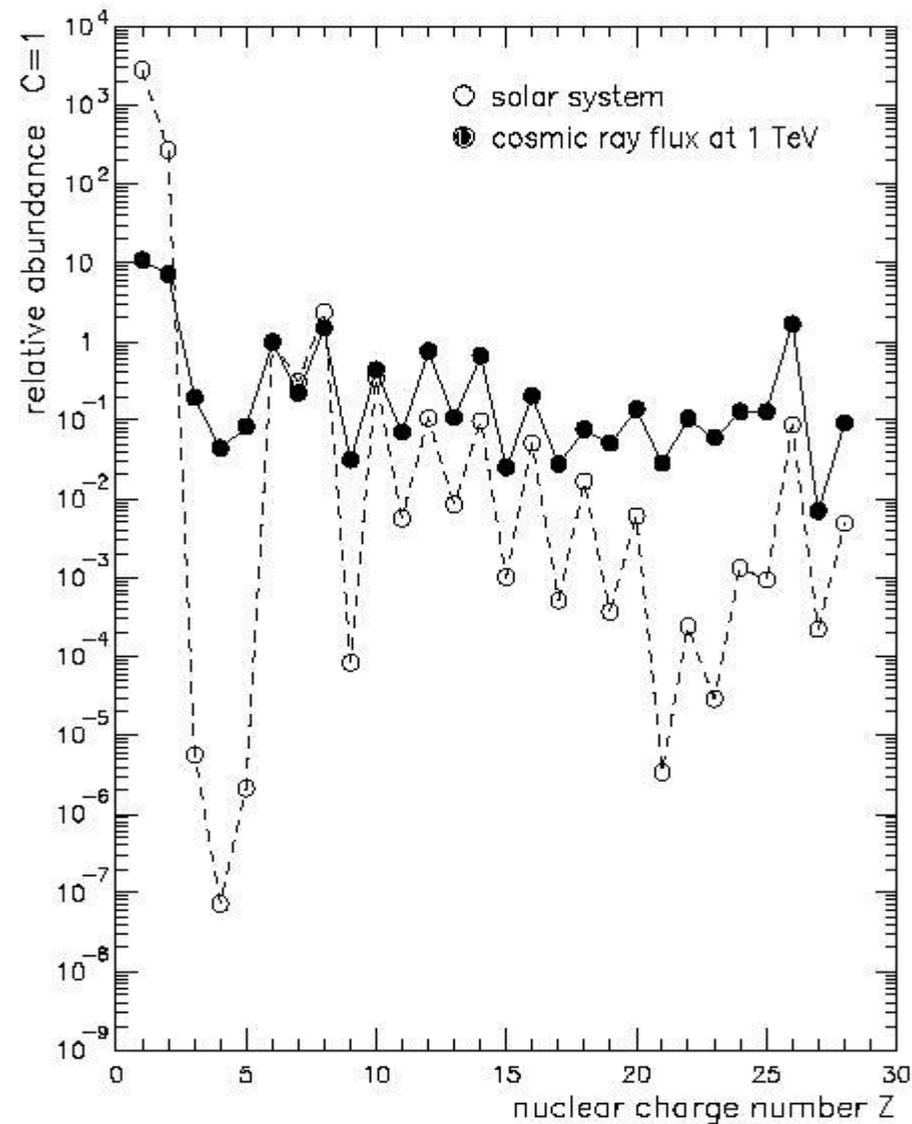
非热幂律谱、多处微小结构

# 宇宙线概述：成分

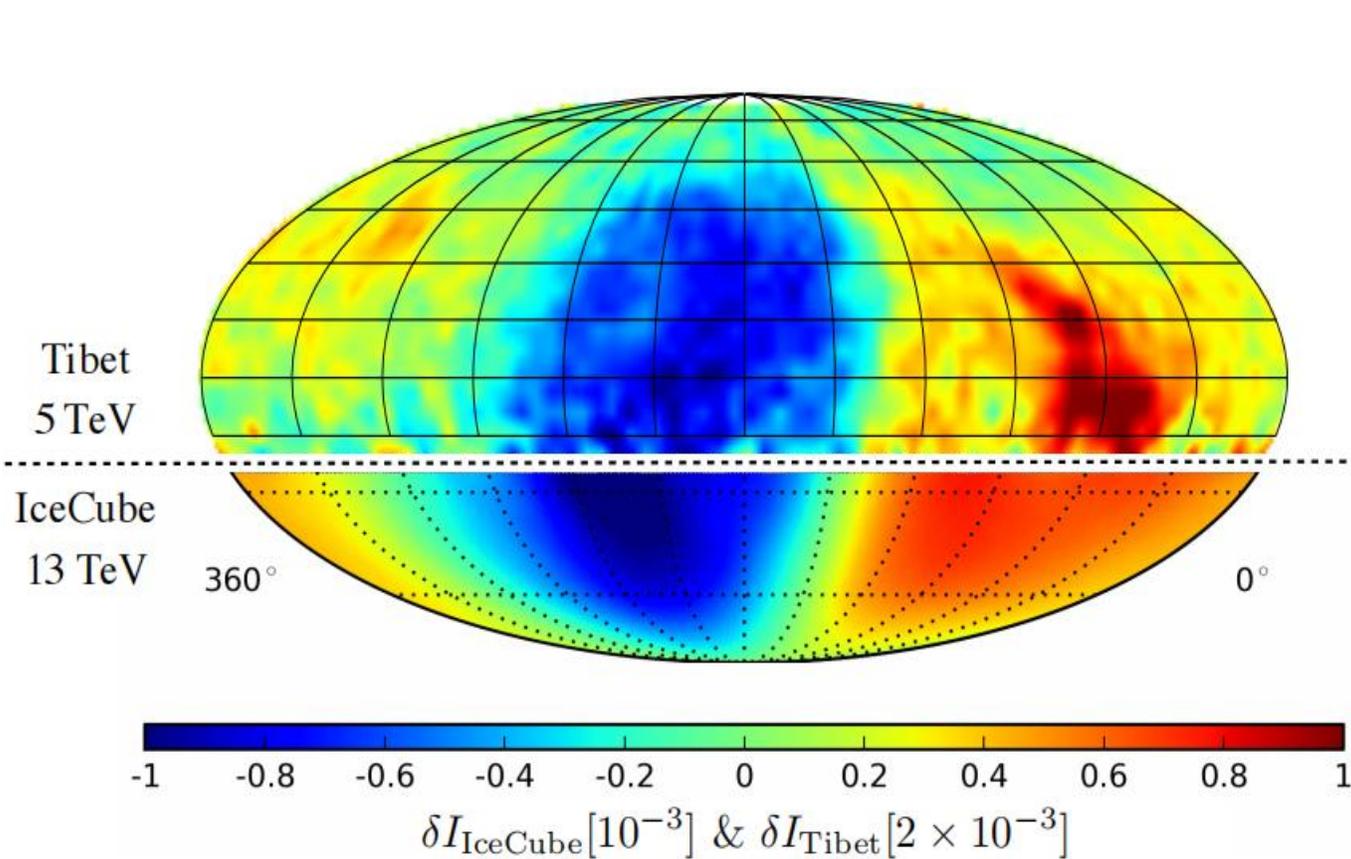


■ 质子    ■  $\alpha$ 粒子    ■ 其它重核

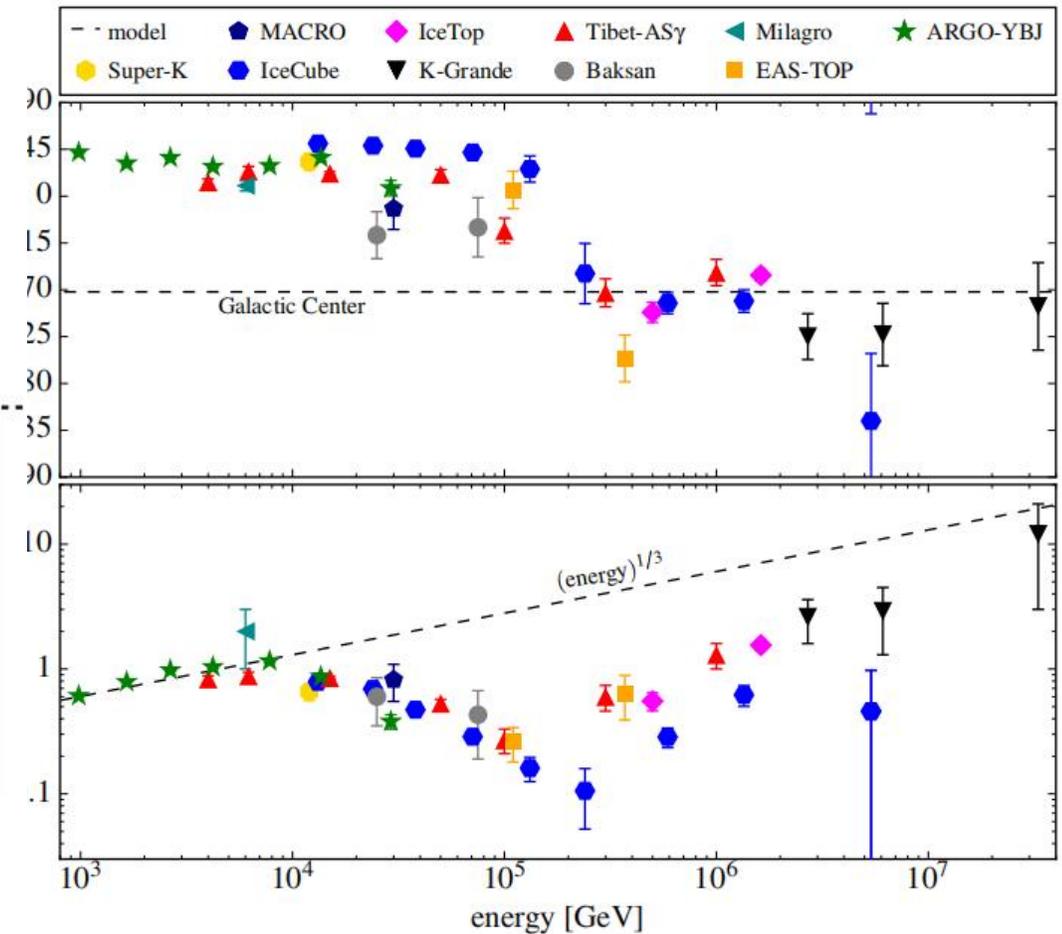
还有少量的电子， $\gamma$ 光子、反粒子等



# 宇宙线概述：方向



Ahlers & Mertsch, 2017, PPNP, 94, 184

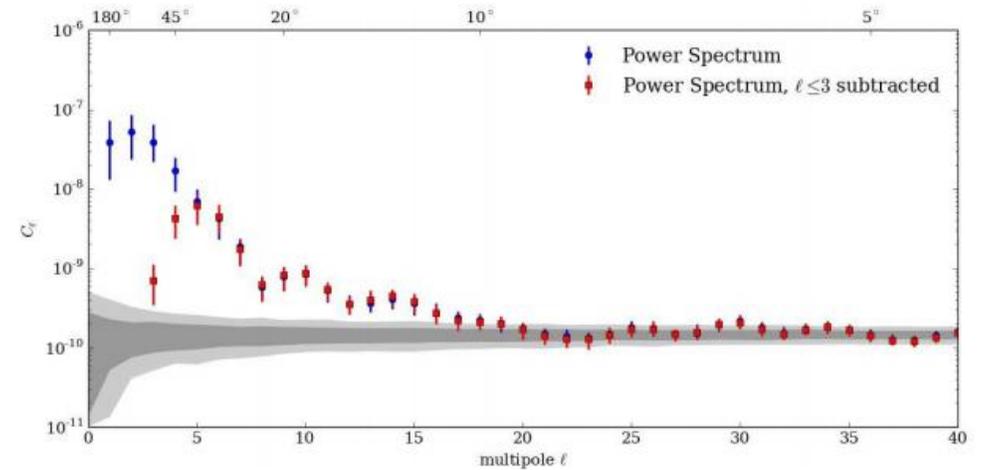
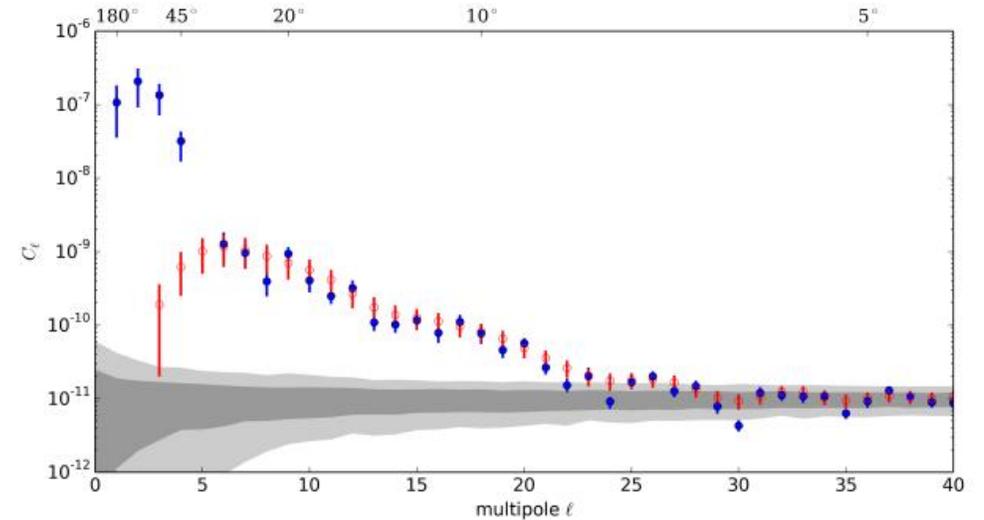
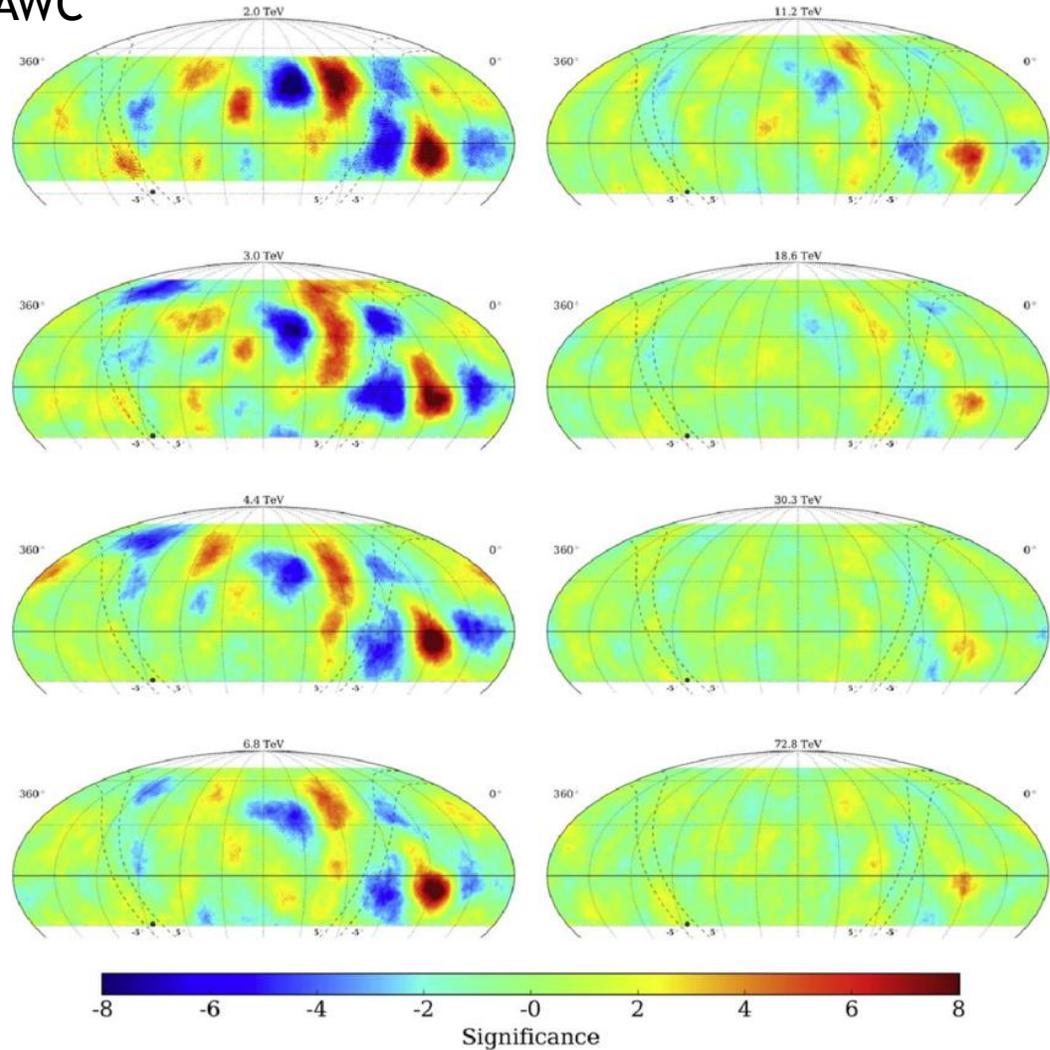


除了太阳宇宙线，宇宙线到达方向高度均匀，各向异性程度在 $10^{-4} \sim 10^{-3}$ ，反映出星际磁场有效抹掉了宇宙线方向

# 宇宙线概述：方向

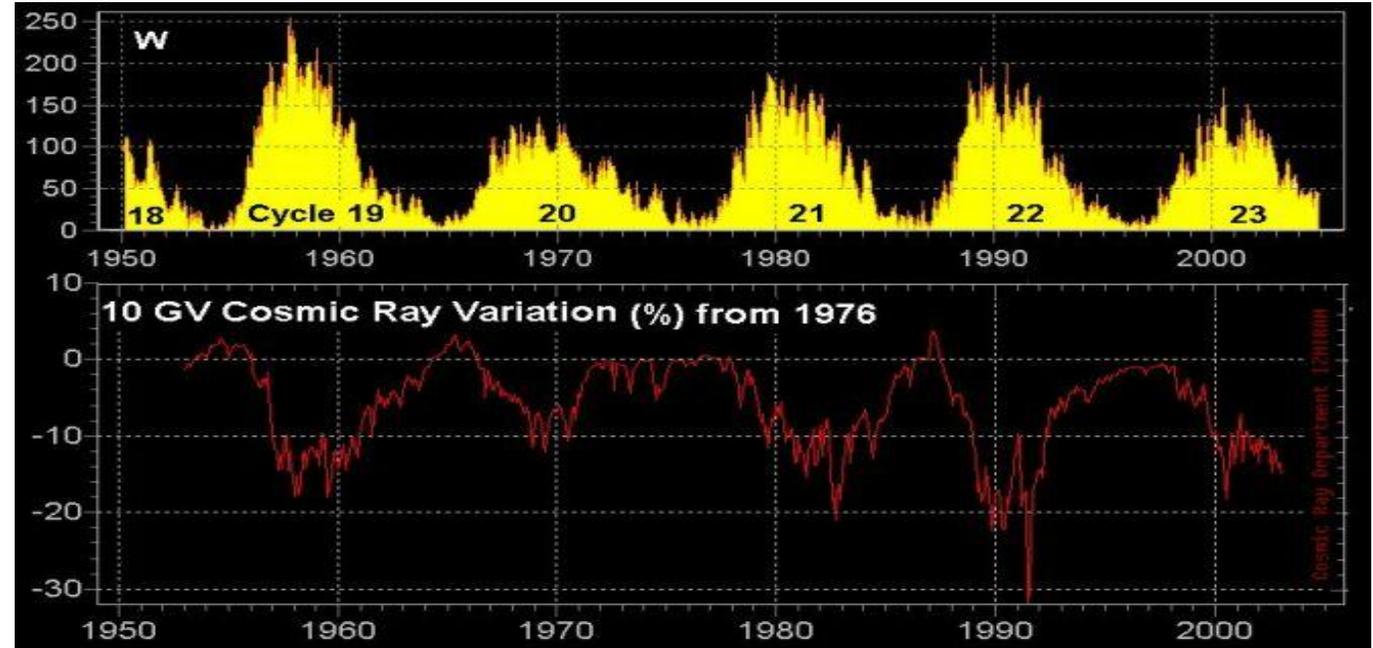
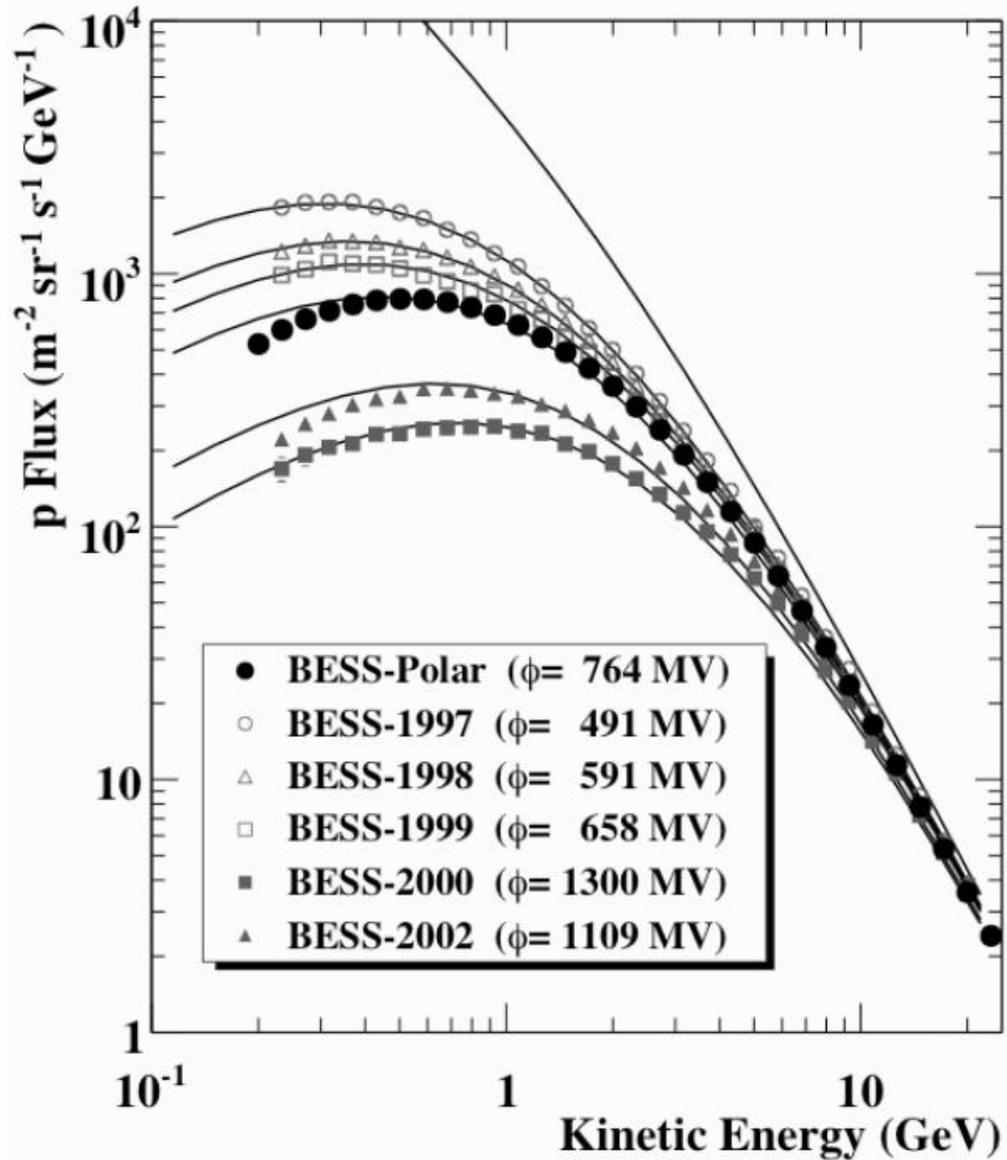
Ahlers & Mertsch, 2017, PPNP, 94, 184

HAWC



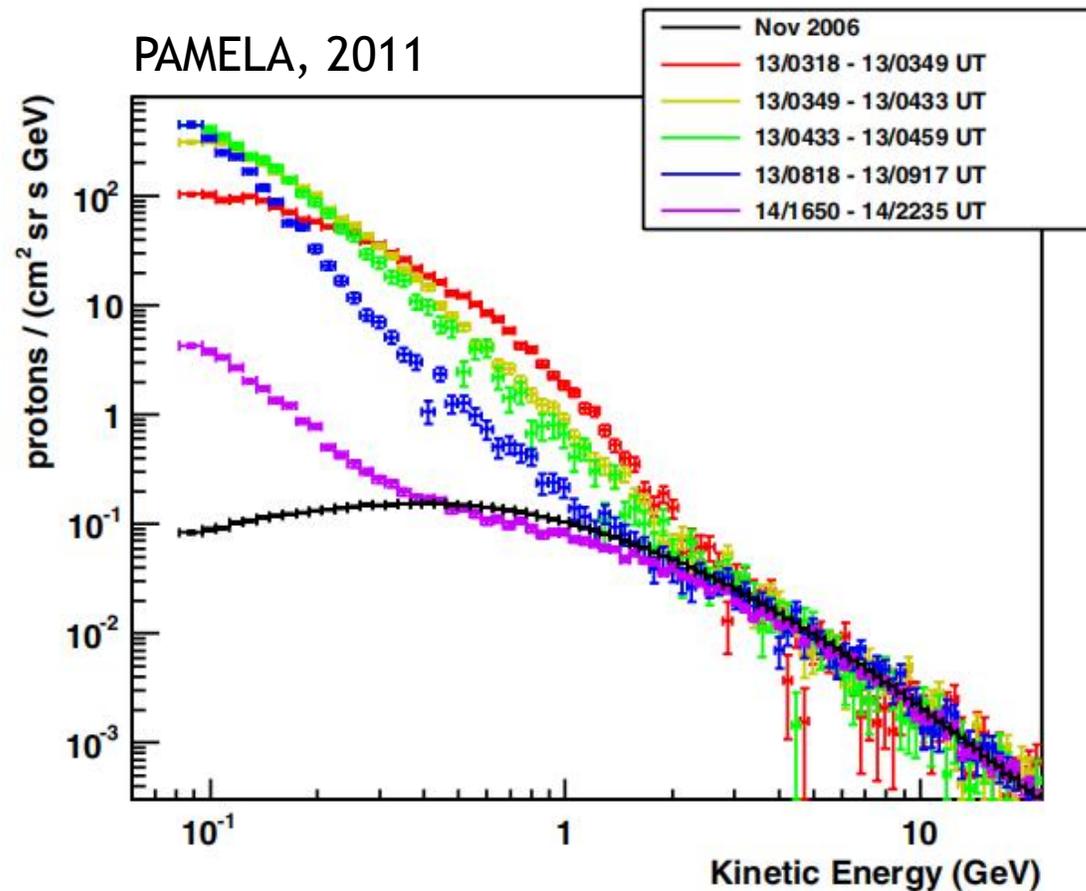
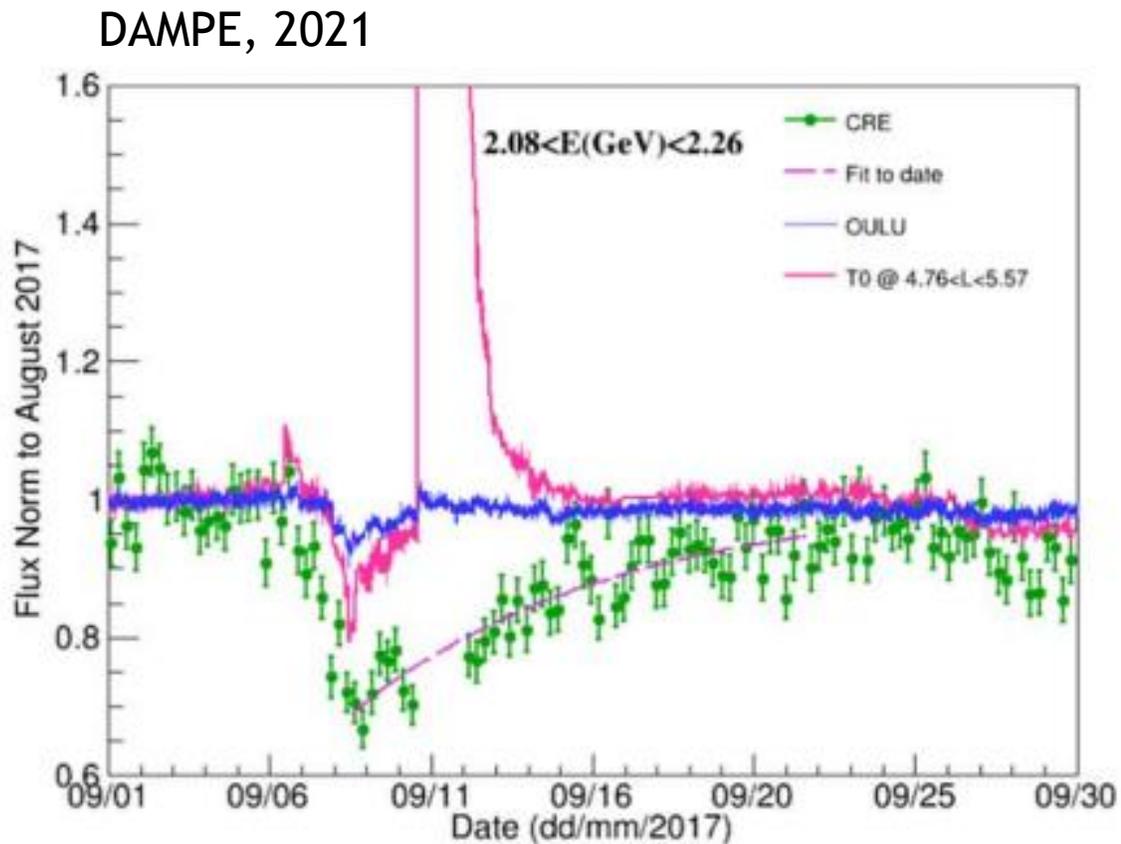
除了大尺度各向异性，宇宙线还存在中小尺度各向异性，可能和星际湍流分布相关

# 宇宙线概述：时变



低能宇宙线流量体现出和太阳活动的显著反相关性，称作太阳调制，反映了宇宙线在太阳系内的传播特性受太阳系环境变化的影响

# 宇宙线概述：时变



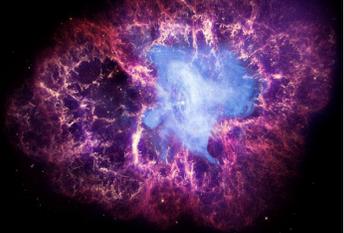
- 当太阳上发生剧烈耀斑活动时，日冕物质抛射对行星际空间环境给出强烈扰动，宇宙线流量会呈现出快速下降行为而后缓慢恢复，称为Forbush下降
- 太阳耀斑活动也会加速带电粒子，称作太阳高能粒子事件

# 宇宙线起源、加速、传播、探测

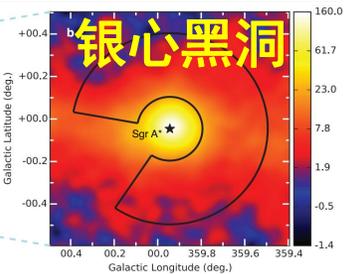
超新星遗迹



脉冲星风云



银心黑洞

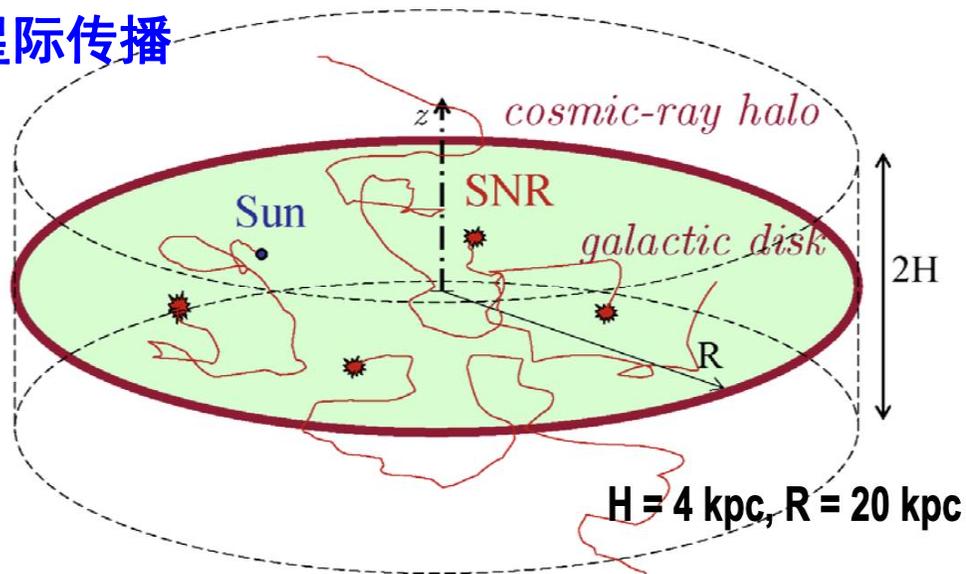


恒星形成区



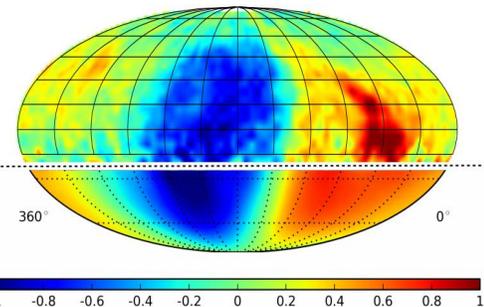
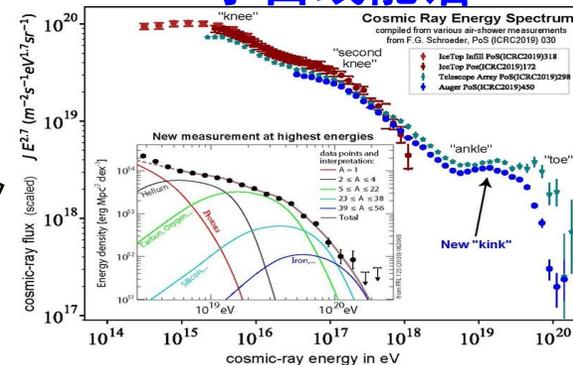
全链条：起源、加速、传播和探测

星际传播

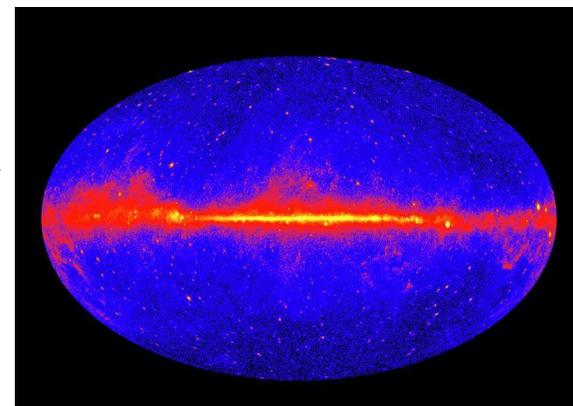


多信使：粒子能谱、各向异性、电磁辐射

宇宙线能谱

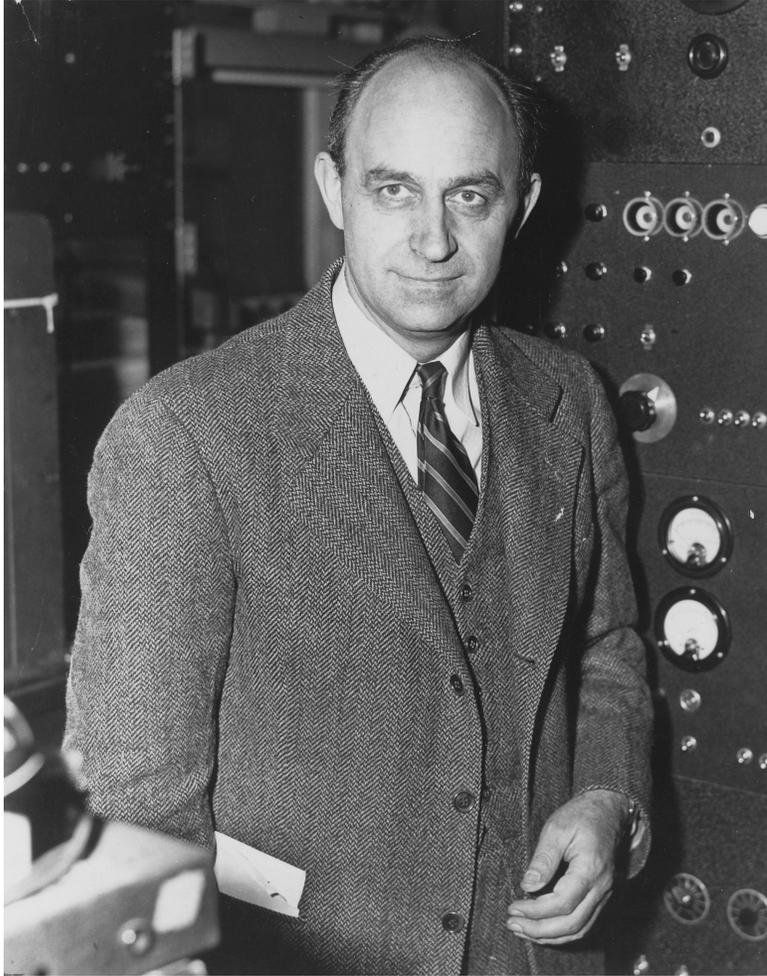


各向异性



多波段辐射

# 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.

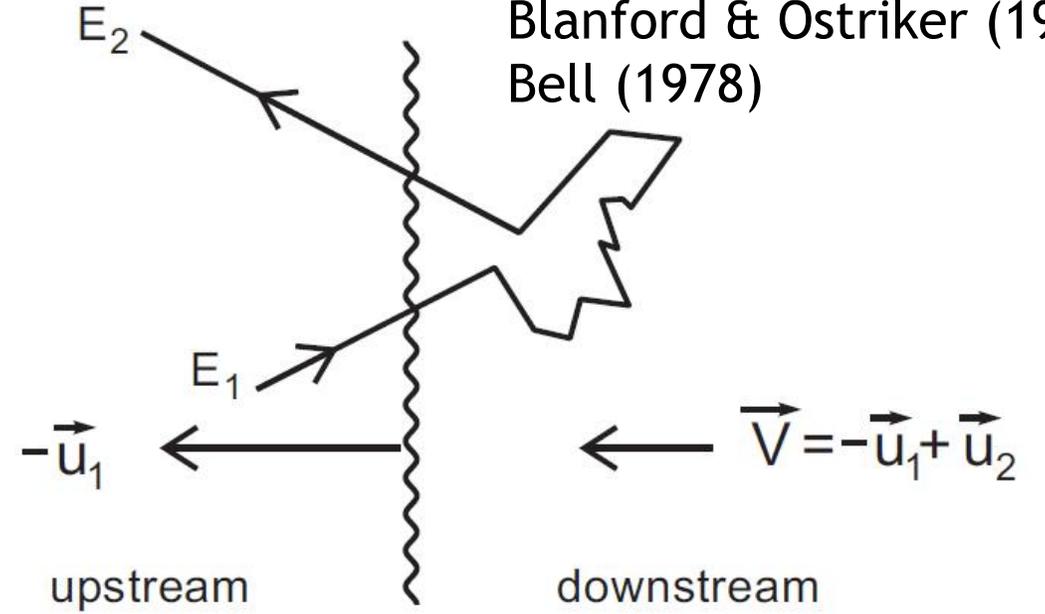
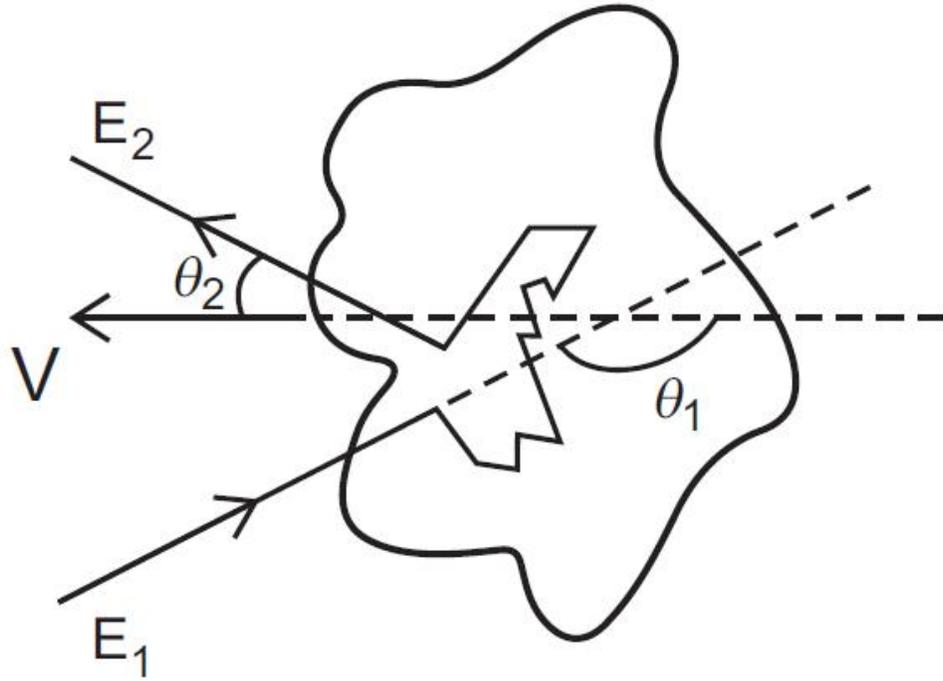
Assuming: every “collision” results in energy gain  $\Delta E = \xi E$ , particle has an escape probability  $P_{esc}$

$$N(\geq E) \propto \sum_{m=n}^{\infty} (1 - P_{esc})^m = \frac{(1 - P_{esc})^n}{P_{esc}},$$
$$= \frac{1}{P_{esc}} \left( \frac{E}{E_0} \right)^{-\gamma}$$

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

# 二阶和一阶费米加速

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



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

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

Gaisser (1990)

# 扩散激波加速

- 扩散激波加速过程可由扩散方程描述

$$\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f - \frac{p}{3} \nabla \cdot \mathbf{u} \frac{\partial f}{\partial p} = \frac{\partial}{\partial x^i} \left( \kappa^{ij} \frac{\partial f}{\partial x^j} \right) + S$$

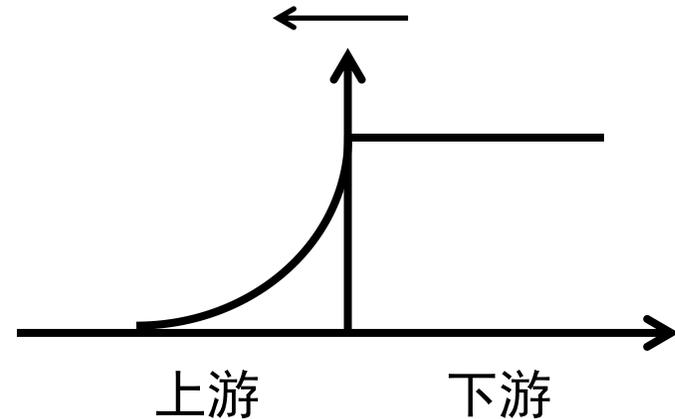
- 考虑稳态、一维情形

$$u \frac{\partial f}{\partial x} - \frac{p}{3} \frac{\partial u}{\partial x} \frac{\partial f}{\partial p} = \frac{\partial}{\partial x} \left( \kappa \frac{\partial f}{\partial x} \right) + S$$

$$u(x) = u_1 + (u_2 - u_1) H(x),$$

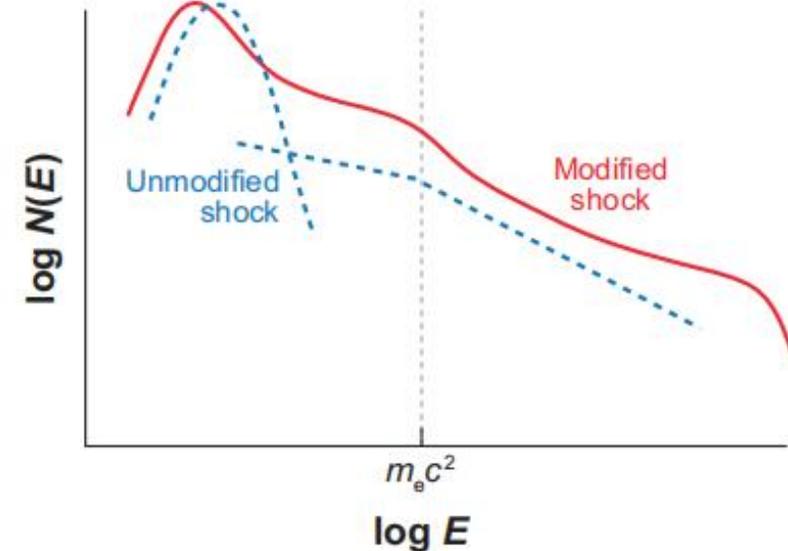
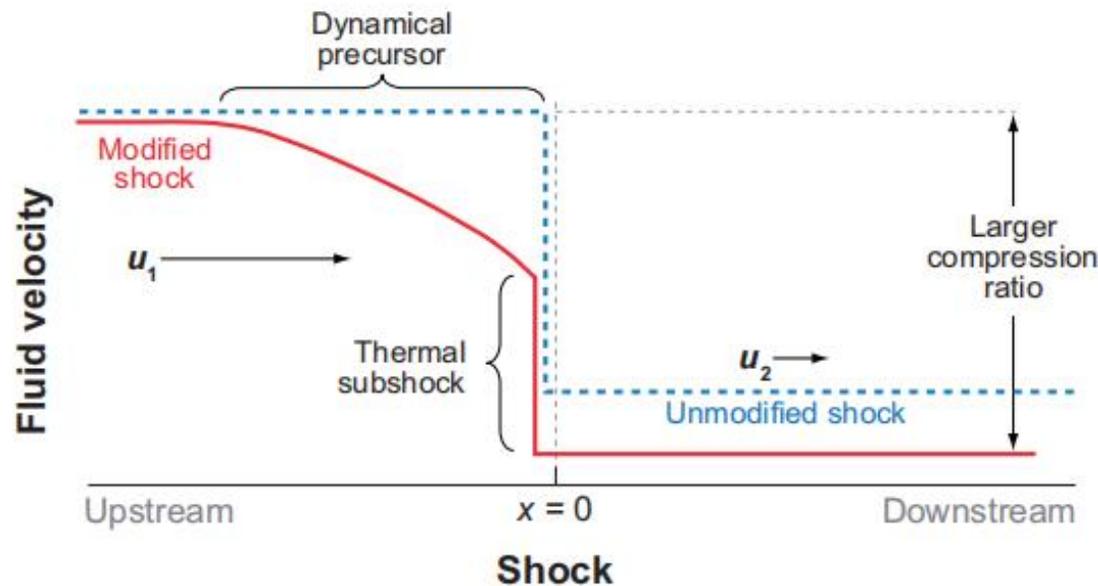
$$\kappa(x, p) = \kappa_1 + (\kappa_2 - \kappa_1) H(x),$$

$$S(x, p) = \frac{Q}{4\pi p_0^2} \delta(x) \delta(p - p_0),$$



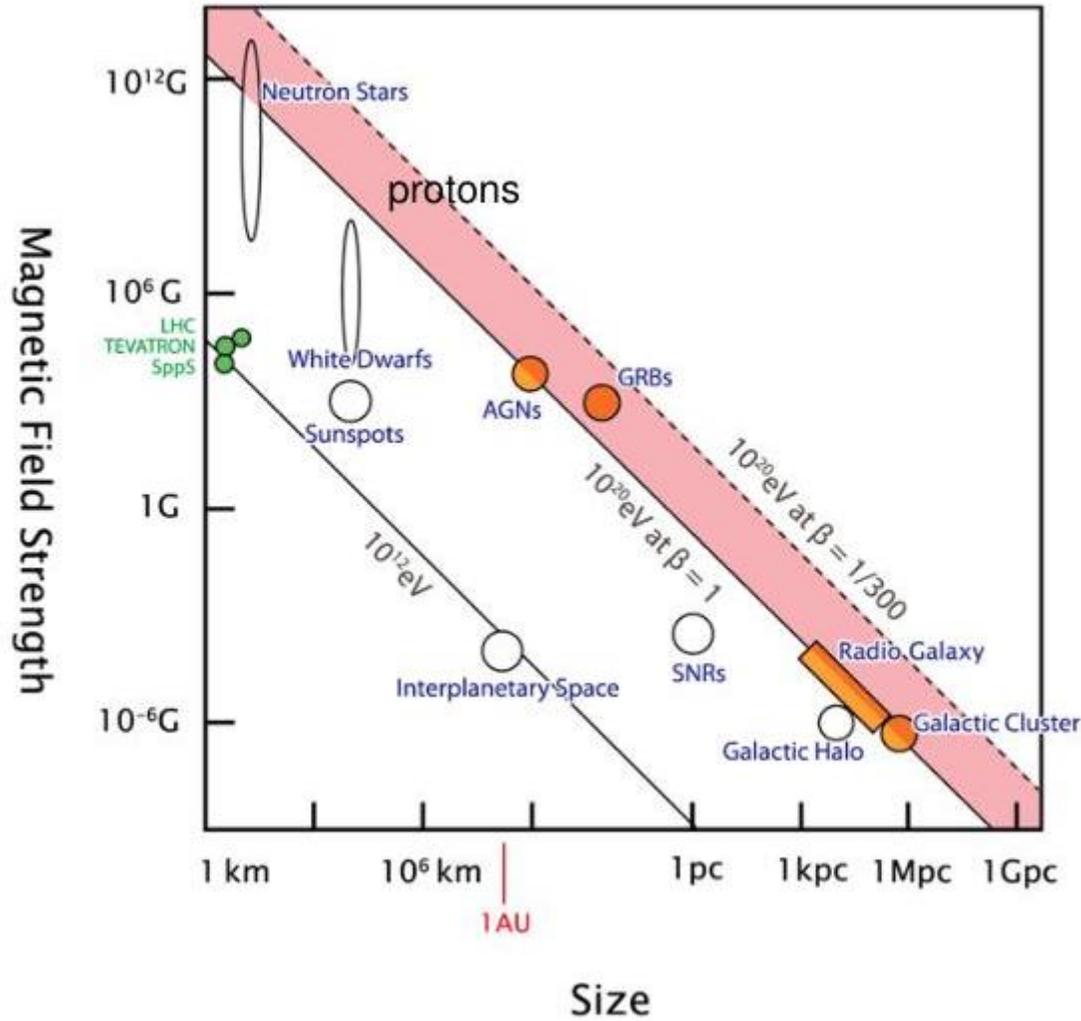
# 非线性扩散激波加速

- 被加速粒子对背景流体可能具有反作用，产生非线性效应。尽管被加速的粒子数目稀少，但每个粒子通常具有很高的能量，它们对背景的影响往往不可忽略，需要将粒子加速方程和磁流体力学方程耦合求解
- 被加速粒子产生的最显著的非线性效应之一即改变激波下游流体的绝热指数，从而改变被加速粒子能谱指数



Reynolds, 2008, ARA&A

# 理论最大加速能量：Hillas判据



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

$$E_{max} = uZBL$$

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

Actually, the maximum energy depends on specific source properties and environments

# 超新星遗迹和宇宙线起源

Badde & Zwicky (1934)

Ginzburg & Syrovatskii (1964)

银河宇宙线总功率

$$L_{\text{CR}} = \frac{V_D \rho_E}{\tau_R} \sim 5 \times 10^{40} \frac{\text{erg}}{\text{sec}},$$

假设超新星率为 3/100 yr, 每次爆发平均释放能量  $10^{51}$  erg, 超新星的总功率为

$$L_{\text{SN}} \sim 10^{42} \text{ erg/s.}$$

只要百分之几的能量转化给宇宙线就足以产生所有宇宙线

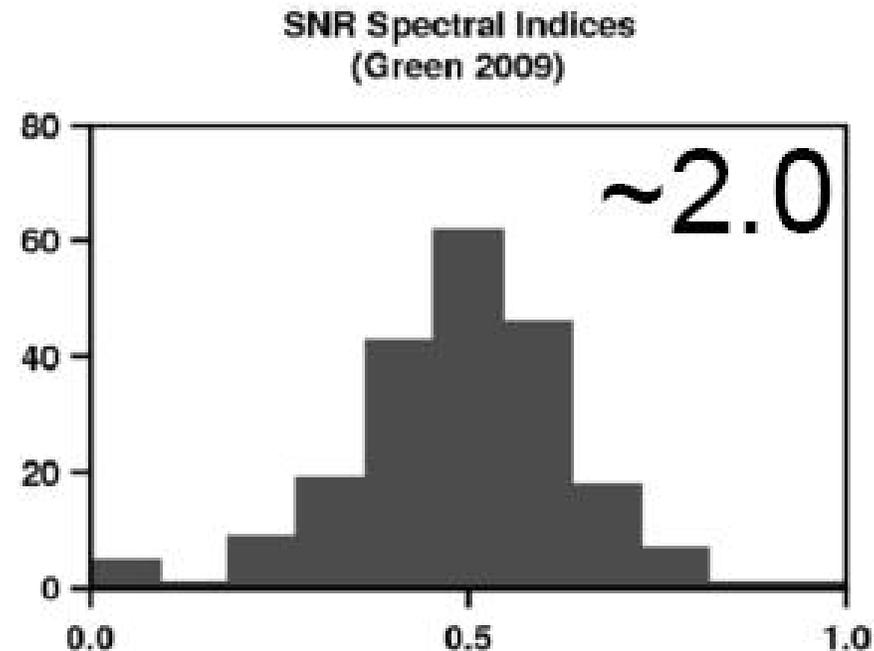
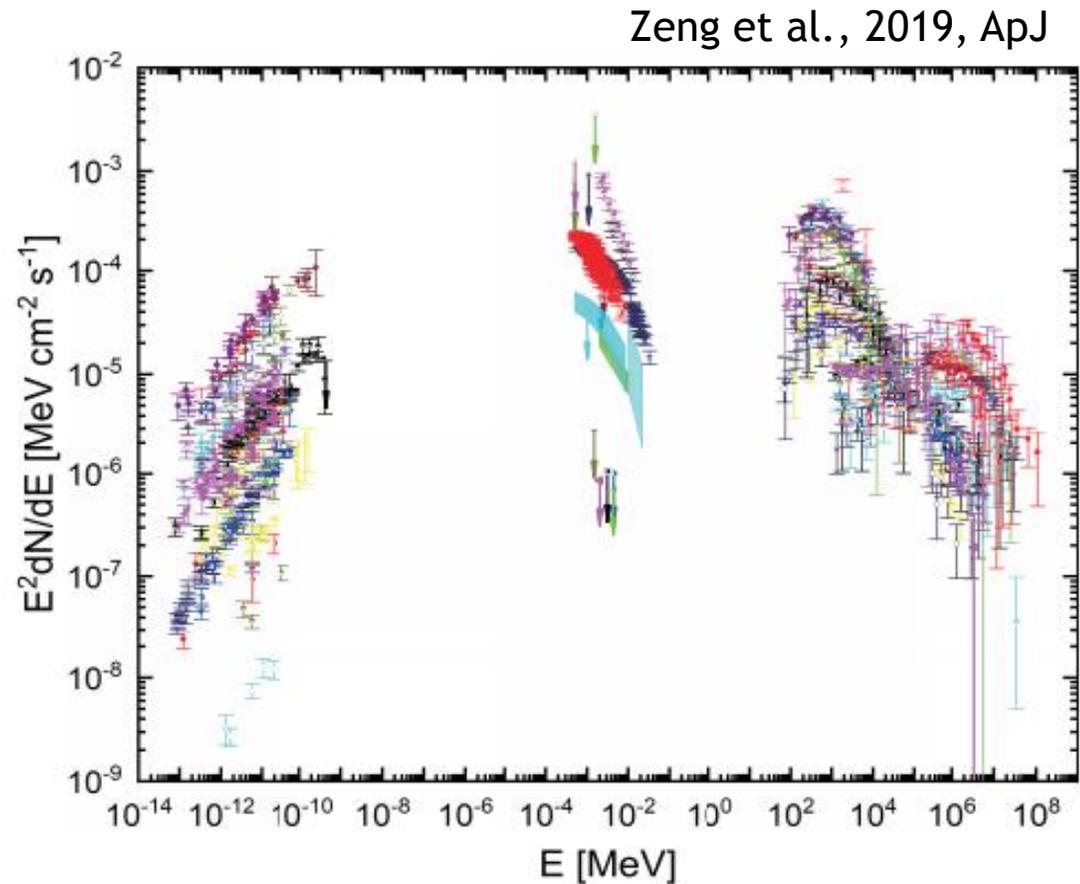
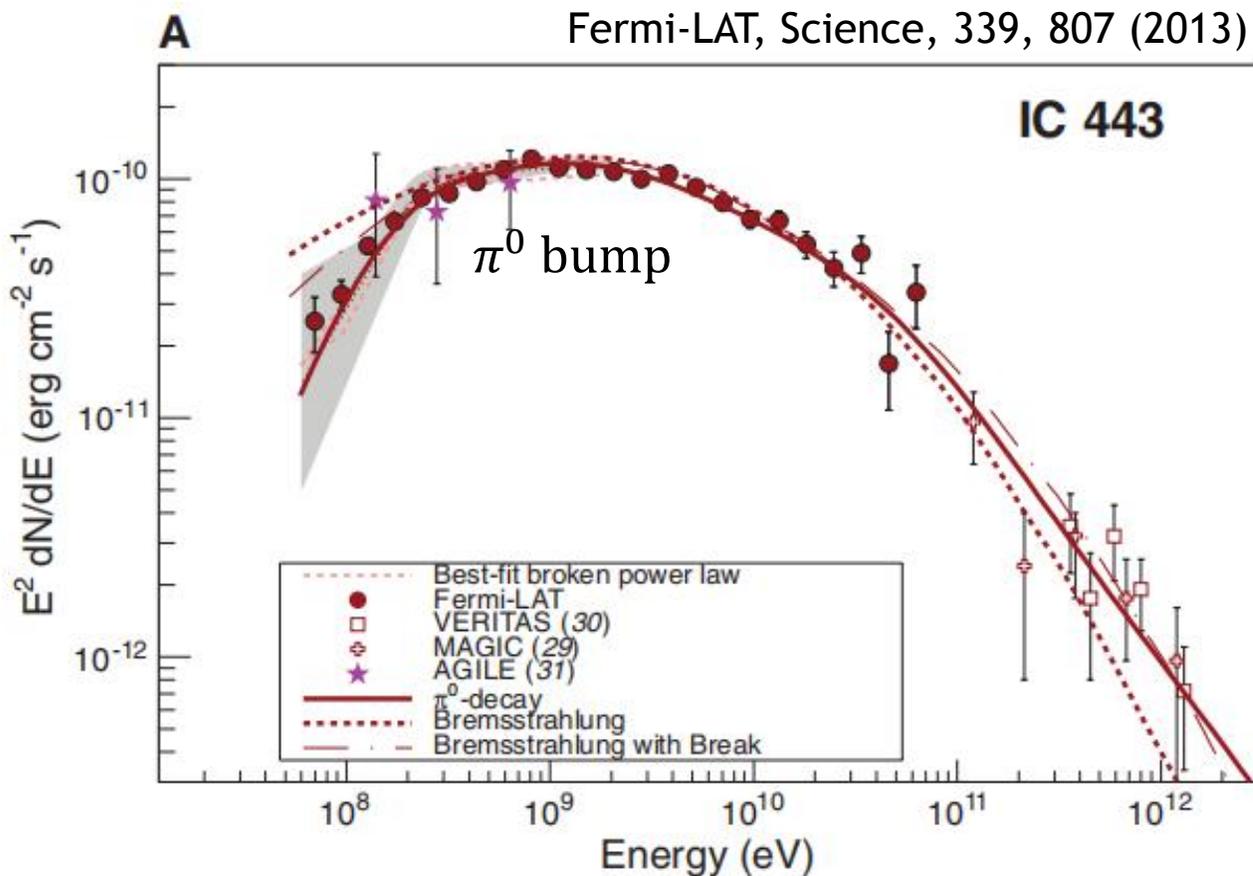


Fig. 1 Histogram of shell SNRs with fairly well-measured radio spectral indices, from Green 2009. PWNe are excluded.

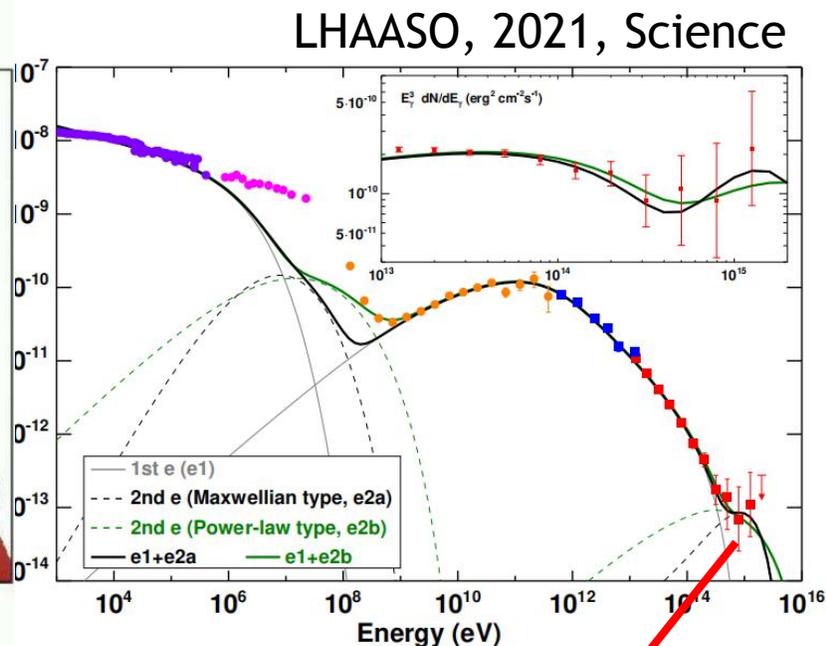
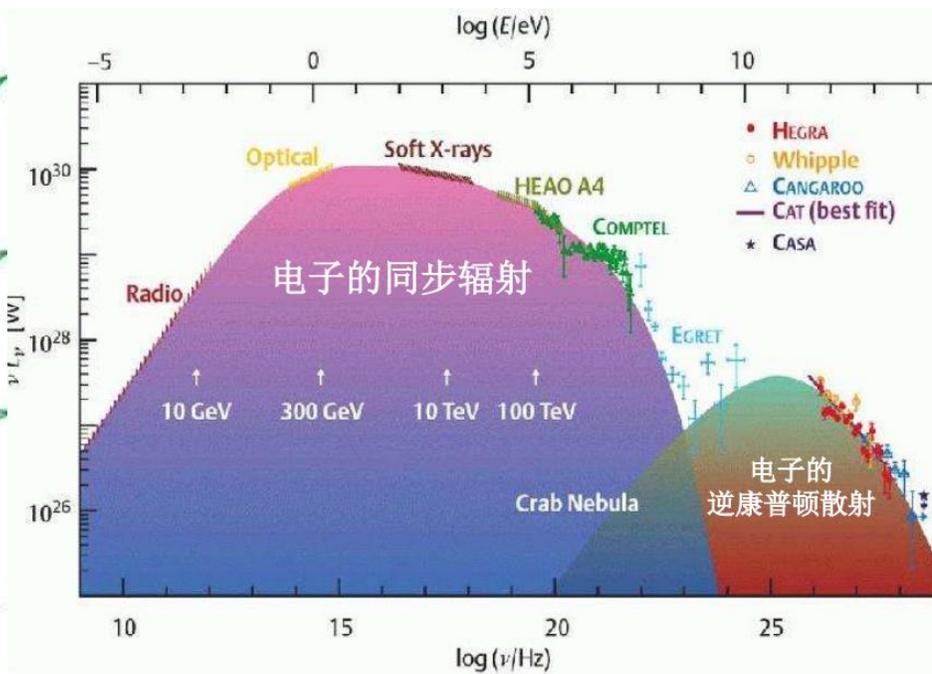
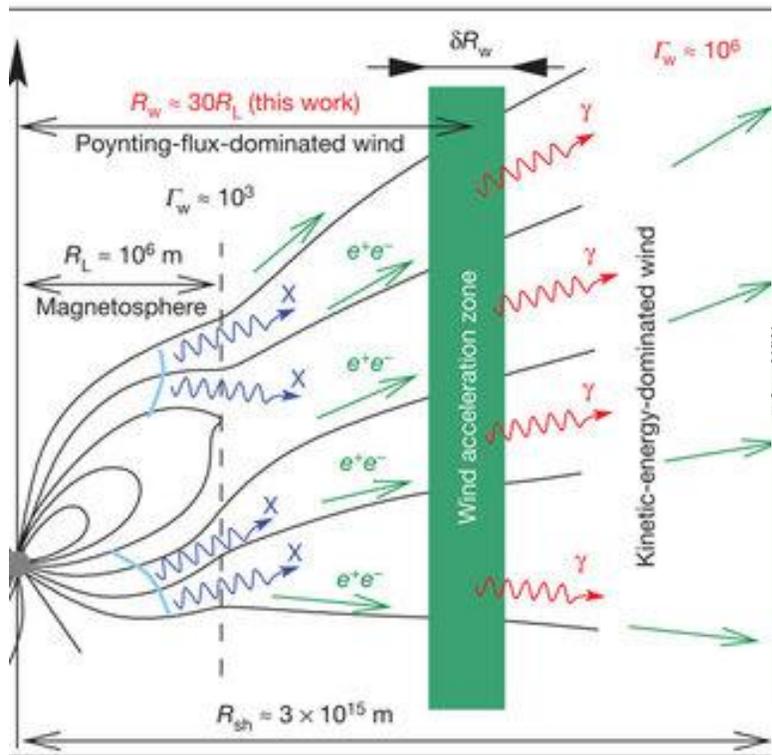
超新星遗迹非热射电谱指数  $\alpha \sim 0.5$ , 加速电子微分能谱指数  $\sim (2\alpha + 1) \sim 2$

# 超新星遗迹和宇宙线起源



- Fermi曾观测到超新星遗迹加速强子宇宙线的证据，入选Science 2013年世界十大科学突破
- 超新星遗迹伽马射线能量目前没有发现超过100 TeV且多数在数十TeV即存在截断，意味着超新星遗迹可能无法加速PeV能量以上的宇宙线

# 脉冲星风云

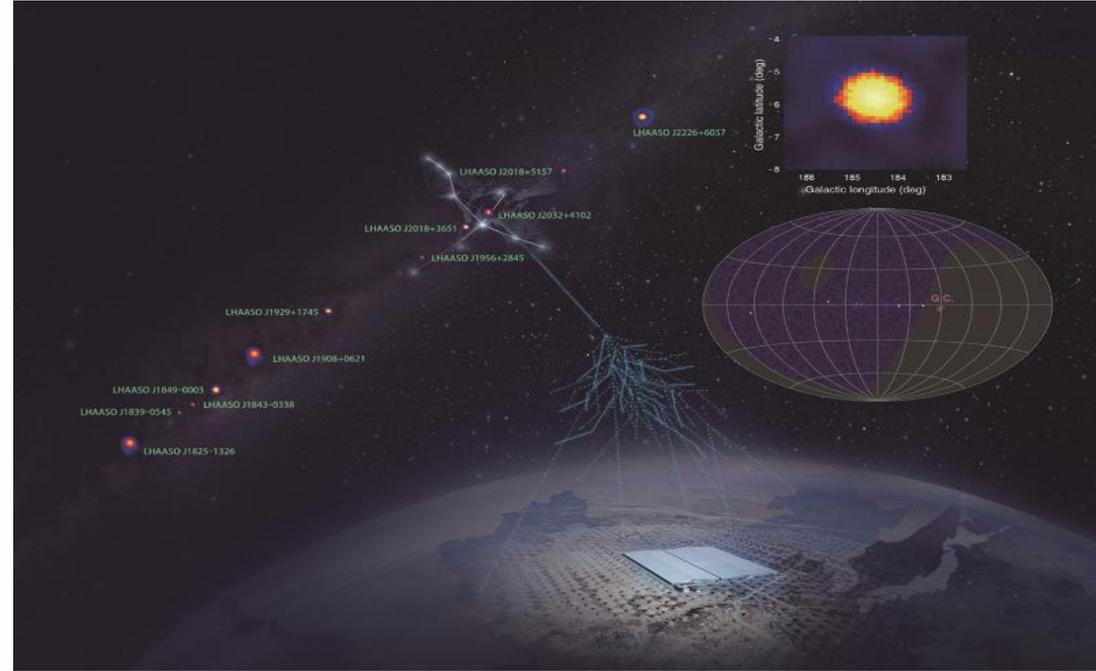
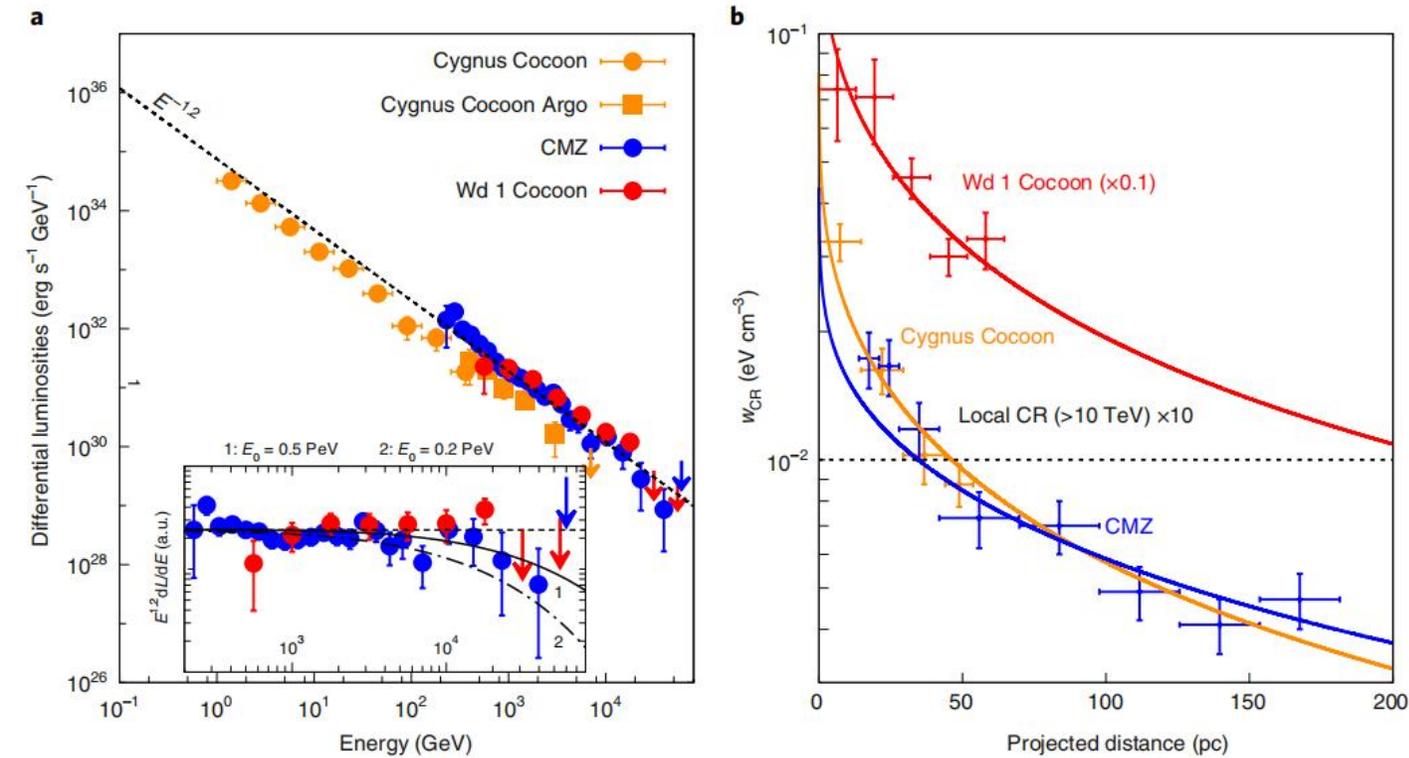


- 脉冲星风云：由脉冲星产生的正负电子风和星际介质碰撞形成的激波加速粒子并产生多波段辐射，一般被认为是高能电子加速源
- 羊八井AS $\gamma$ 实验测到来自Crab的能量高达450 TeV的光子；高海拔宇宙线观测站LHAASO记录到来自Crab超过PeV的光子，最高能量1.1 PeV（截至2021年7月）

# 年轻巨星团

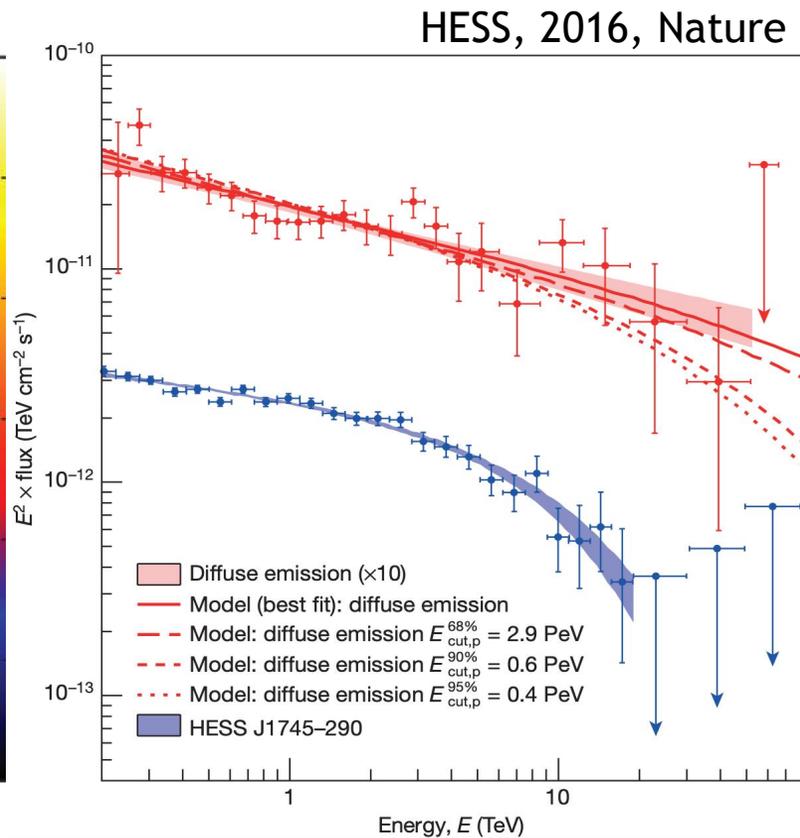
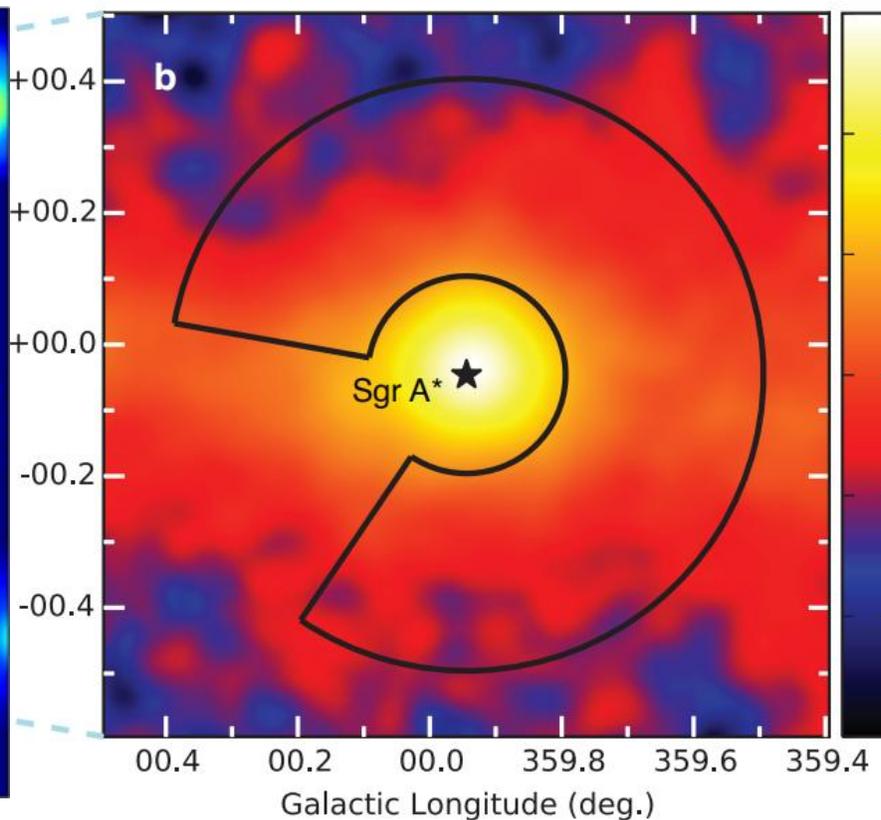
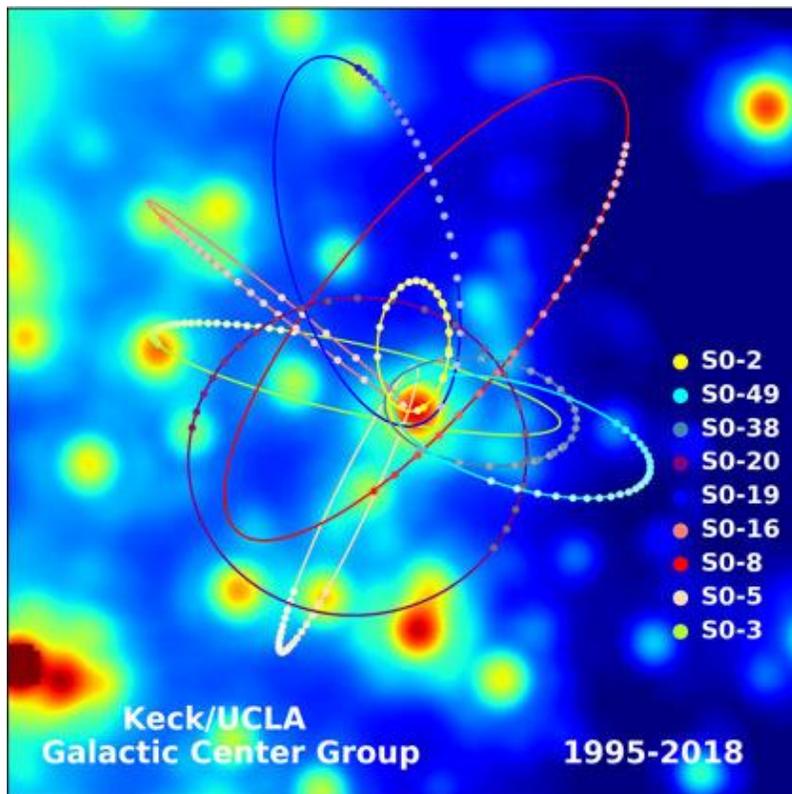
Aharonian et al. 2021, Nat. Astron.

LHAASO, Nature, 594, 33 (2021)



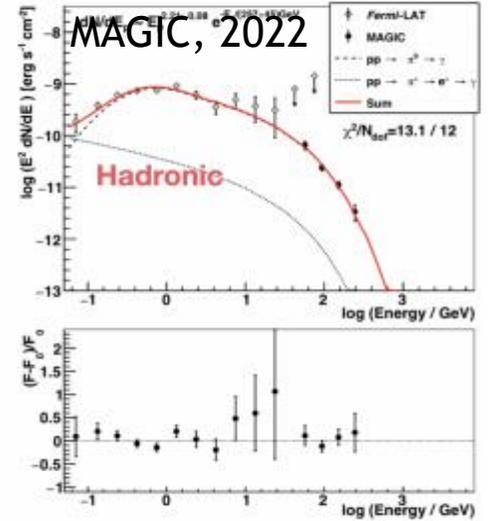
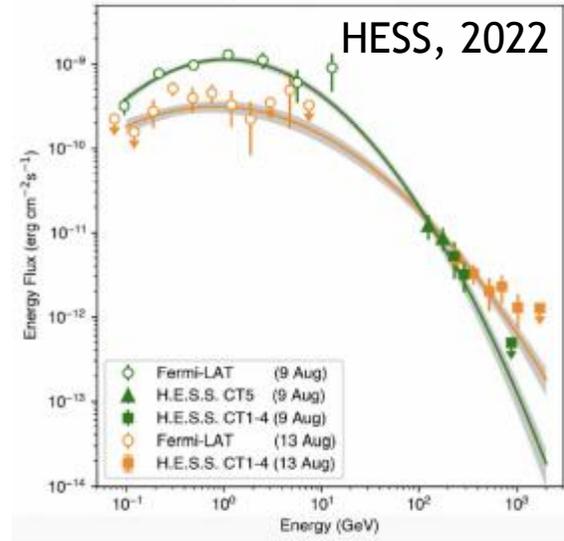
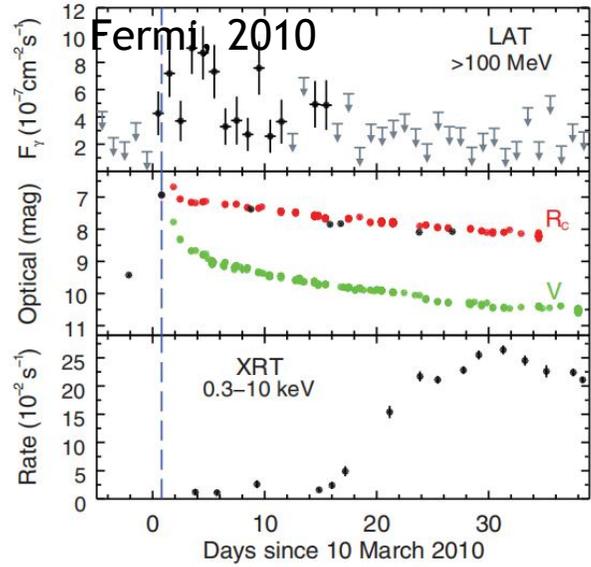
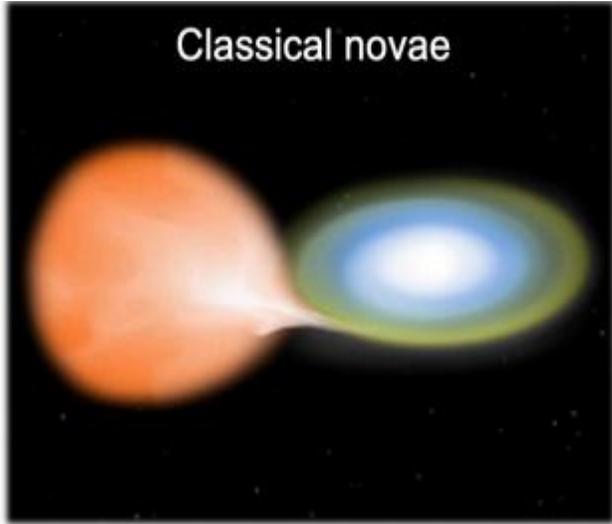
- 年轻巨星团剧烈星风产生的激波可以加速高能宇宙线
- LHAASO观测到来自Cygnus cocoon方向最高达1.4 PeV的光子表明年轻巨星团的加速能力可能远高于PeV

# 银心超大质量黑洞

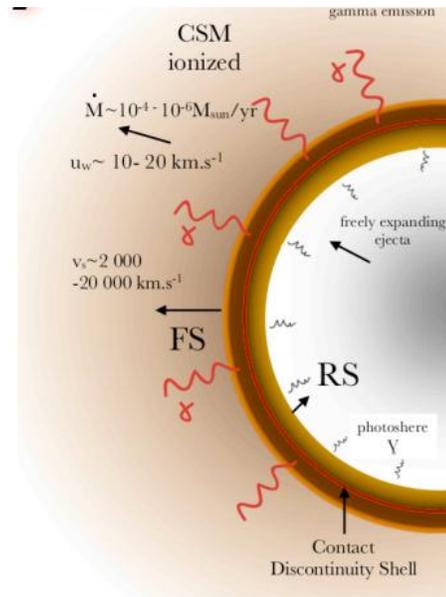
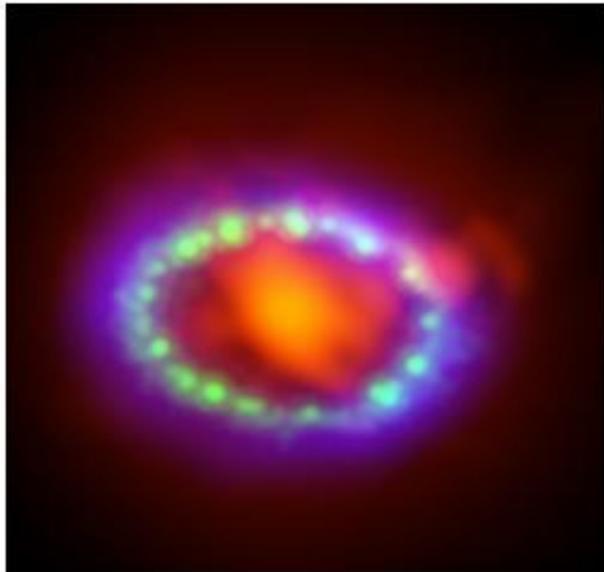


- 银河系中心超大质量黑洞吸积可能产生喷流，加速宇宙线粒子
- HESS观测到银心的伽马射线辐射直至50 TeV能量，意味着银心可以加速宇宙线质子至PeV以上能量

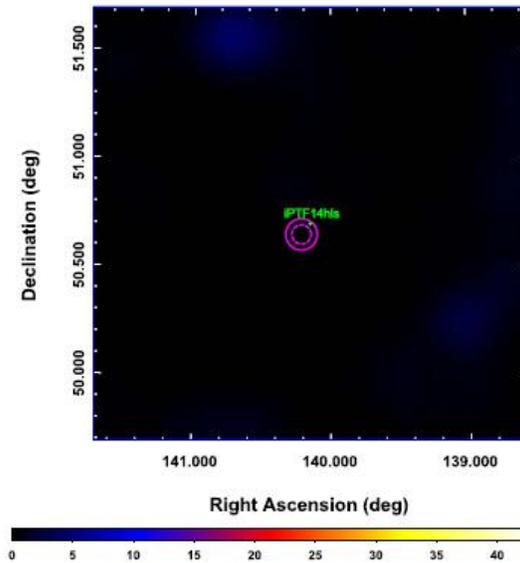
# 新星、超新星



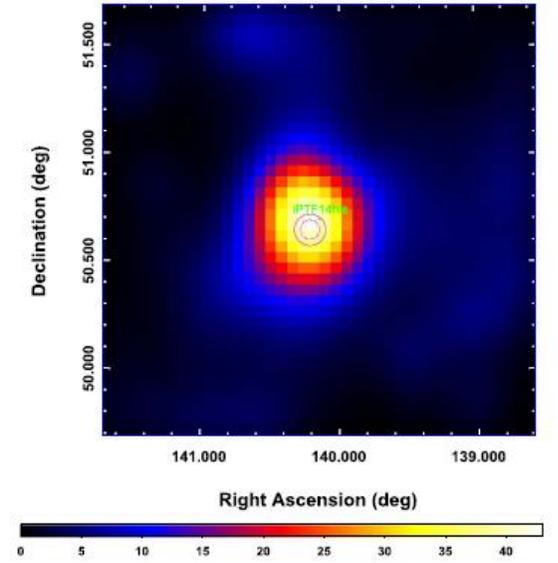
SN 1987A



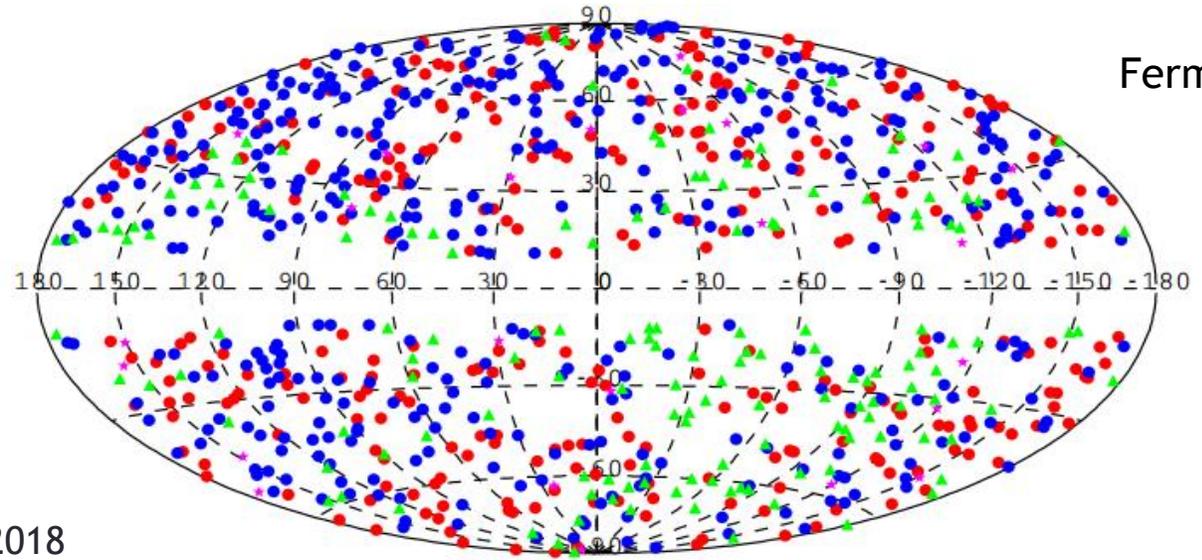
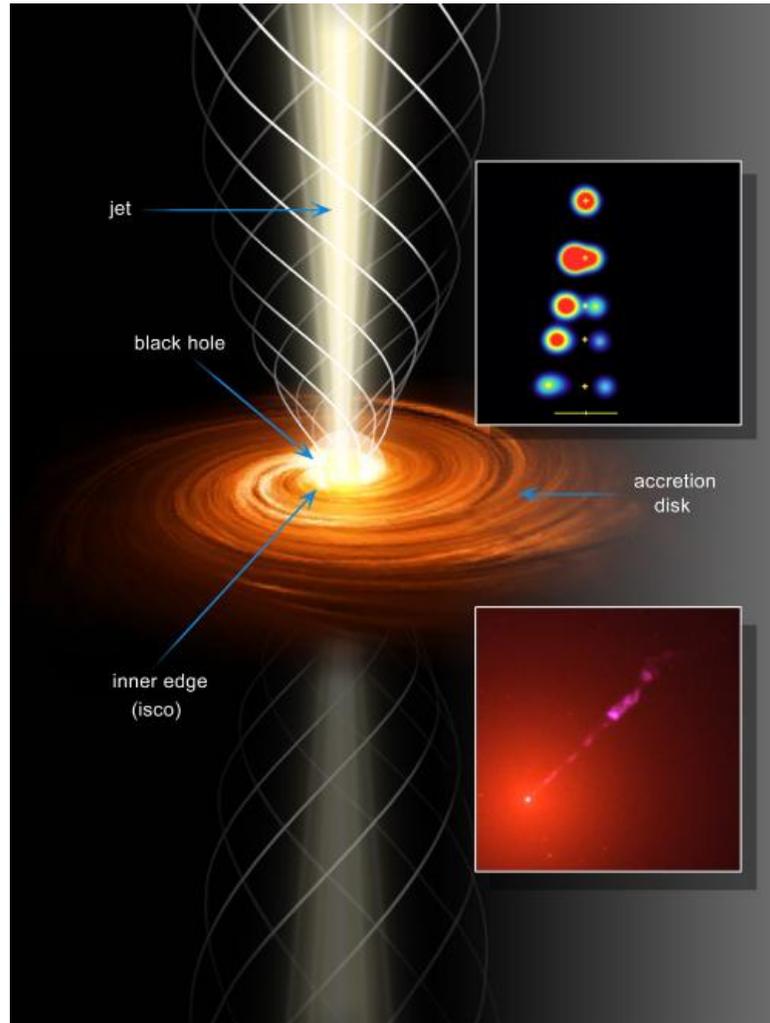
iPTF14hls by Fermi



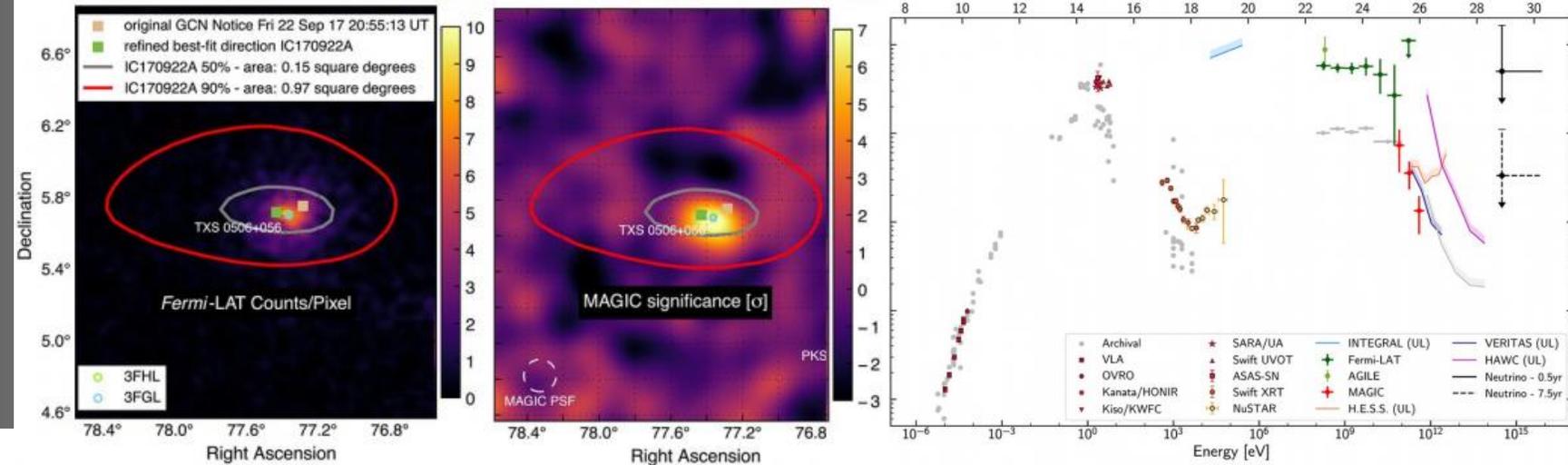
Yuan et al., 2018, ApJL



# 活动星系核



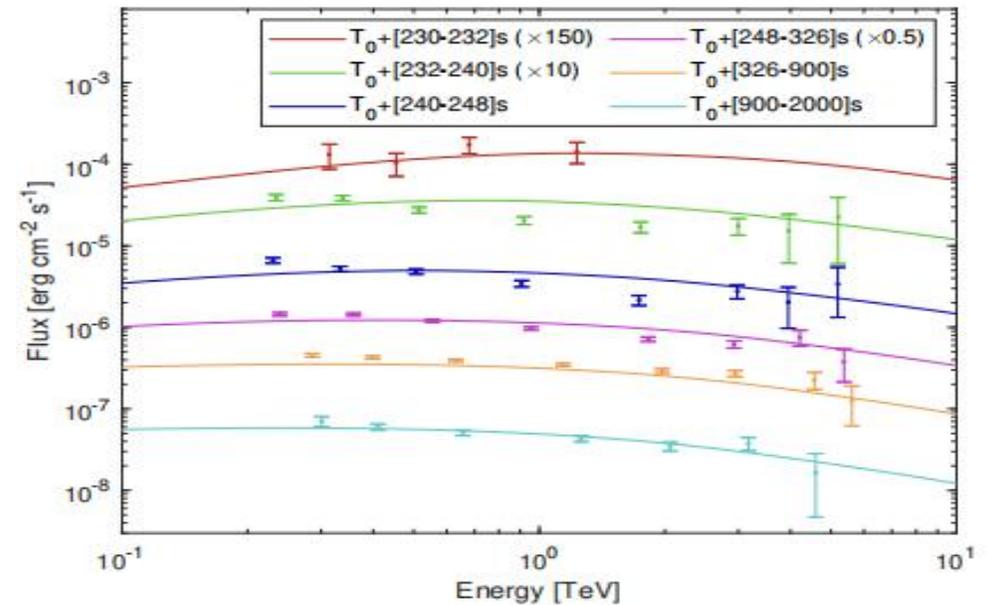
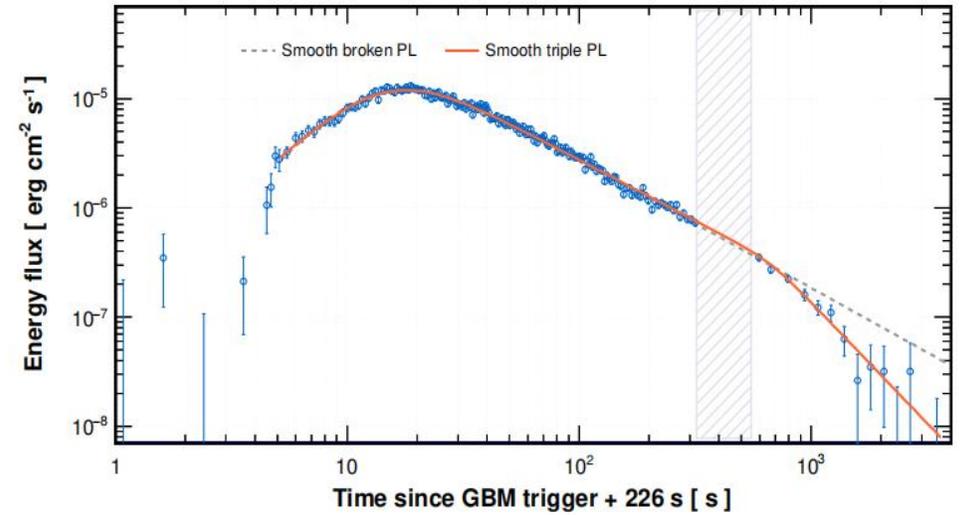
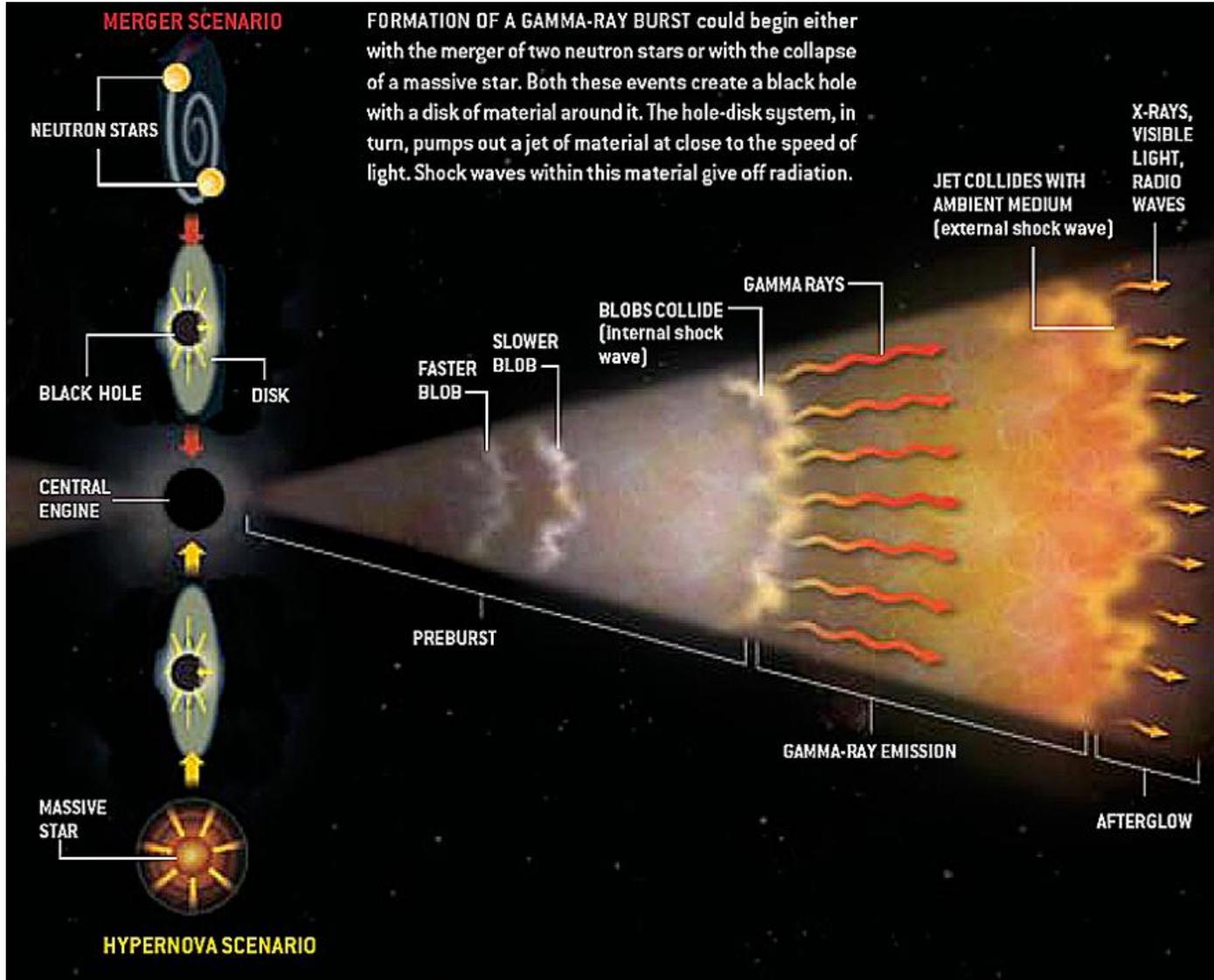
IceCube, 2018



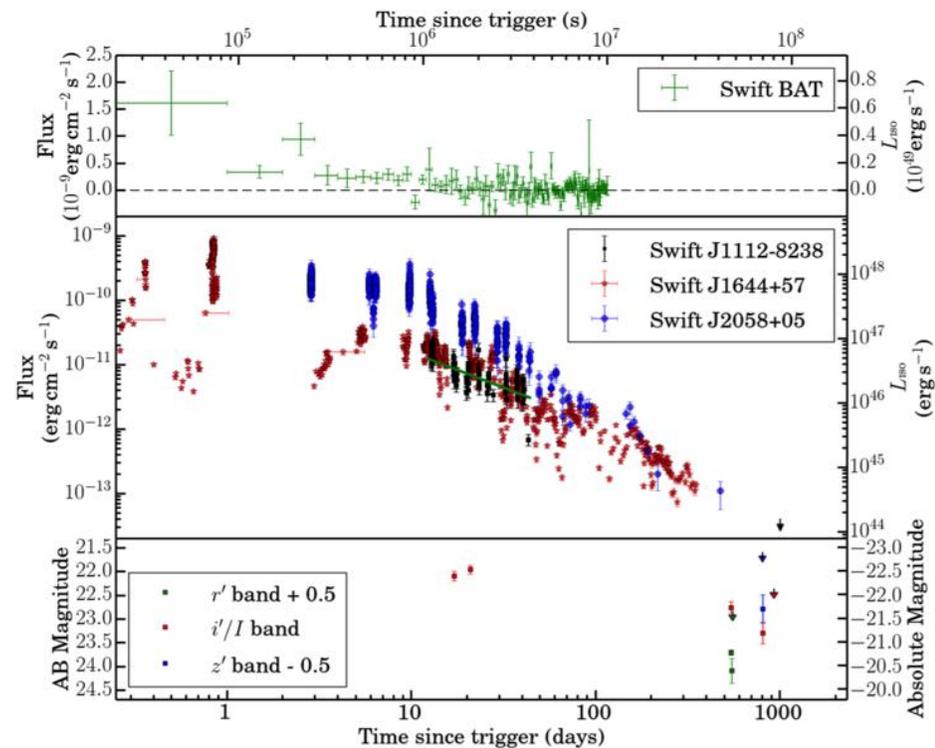
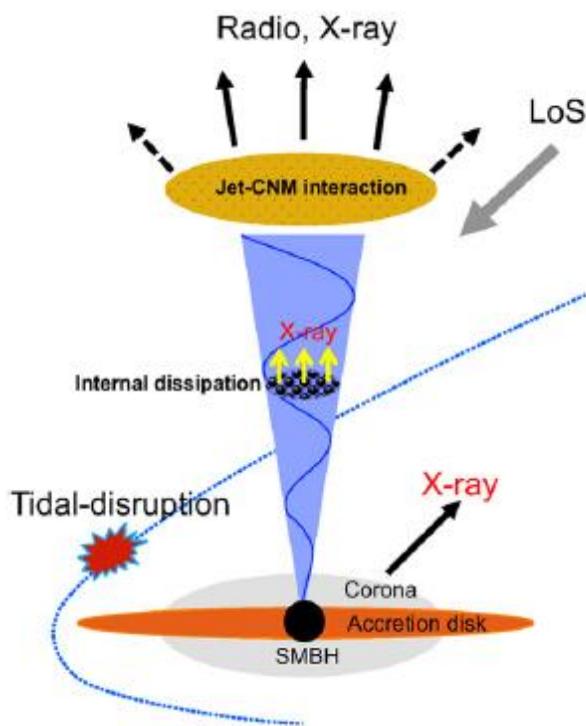
活动星系核长久以来被认为是最主要的一类宇宙线加速源，得到多波段电磁辐射和超高能中微子辐射观测的确证

# 伽马射线暴

LHAASO 2023

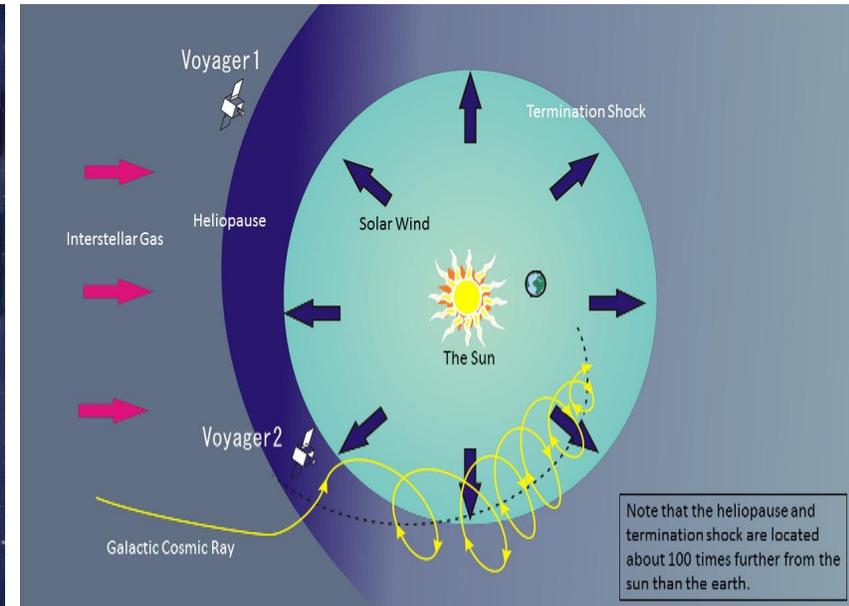
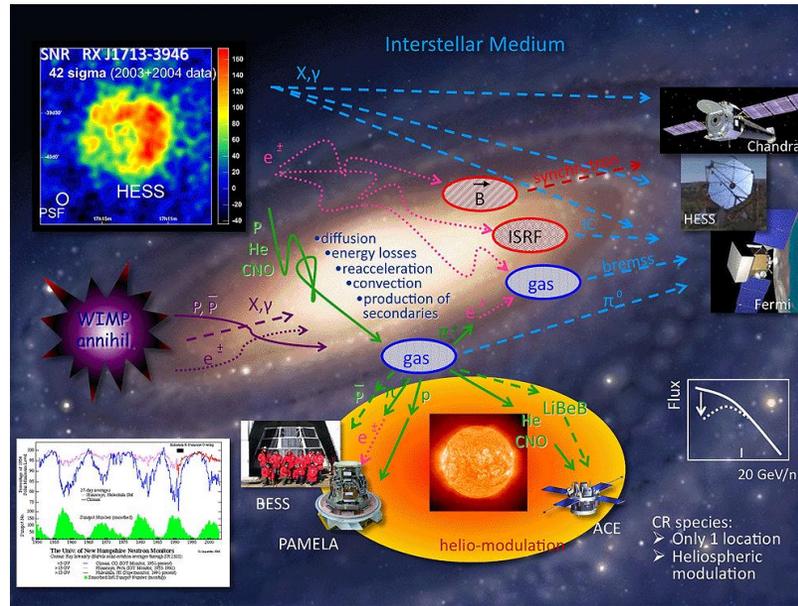
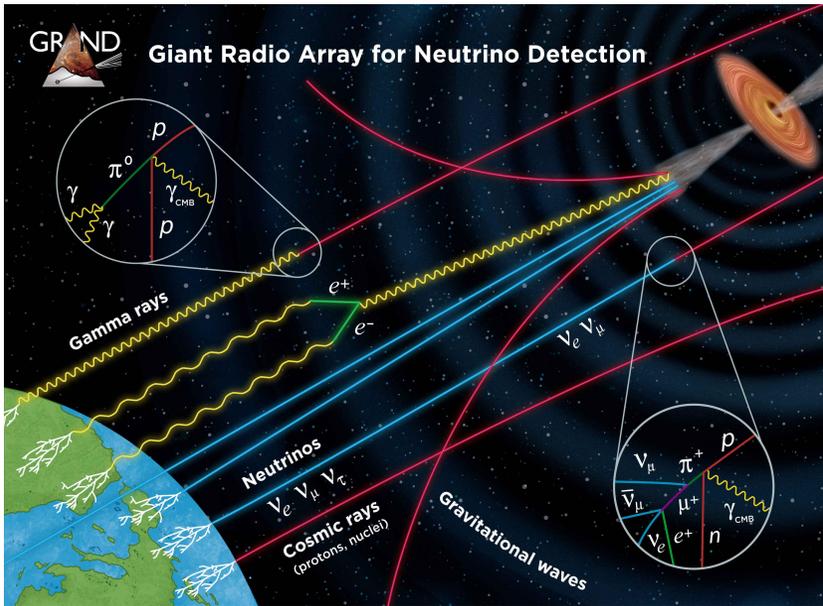


# 黑洞潮汐瓦解事件



- 恒星可能会被超大质量黑洞俘获并瓦解，瓦解的恒星物质形成吸积盘，部分事件可能产生相对论性喷流
- 潮汐瓦解恒星事件产生的非热射电和X射线辐射已被观测到

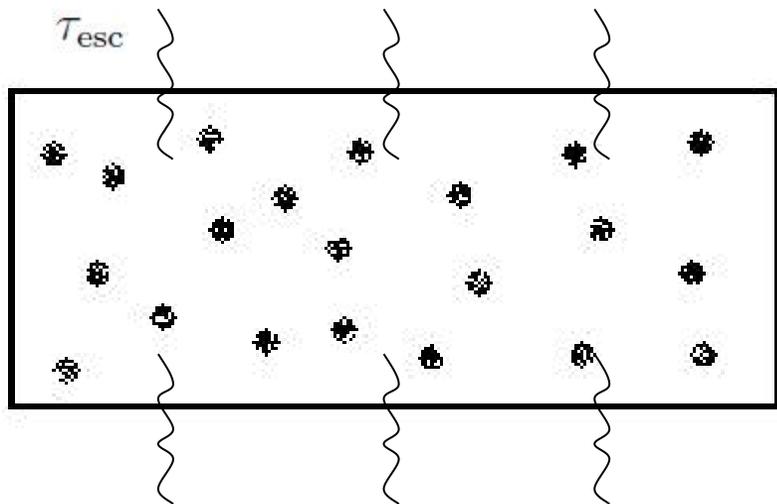
# 宇宙线传播



- 宇宙线在河外空间、银河系内、太阳系内经历复杂的传播过程，包括在磁场中的回旋、和物质/辐射的相互作用等

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

# 银河宇宙线传播：漏箱模型



次级粒子/原初粒子：  
反映传播及相互作用过程

$$\frac{\partial N(E, t)}{\partial t} = Q(E, t) - \frac{N(E, t)}{\tau_{\text{esc}}(E)} - \frac{N(E, t)}{\tau_i(E)} - \frac{N(E, t)}{\gamma\tau_d},$$

稳态解

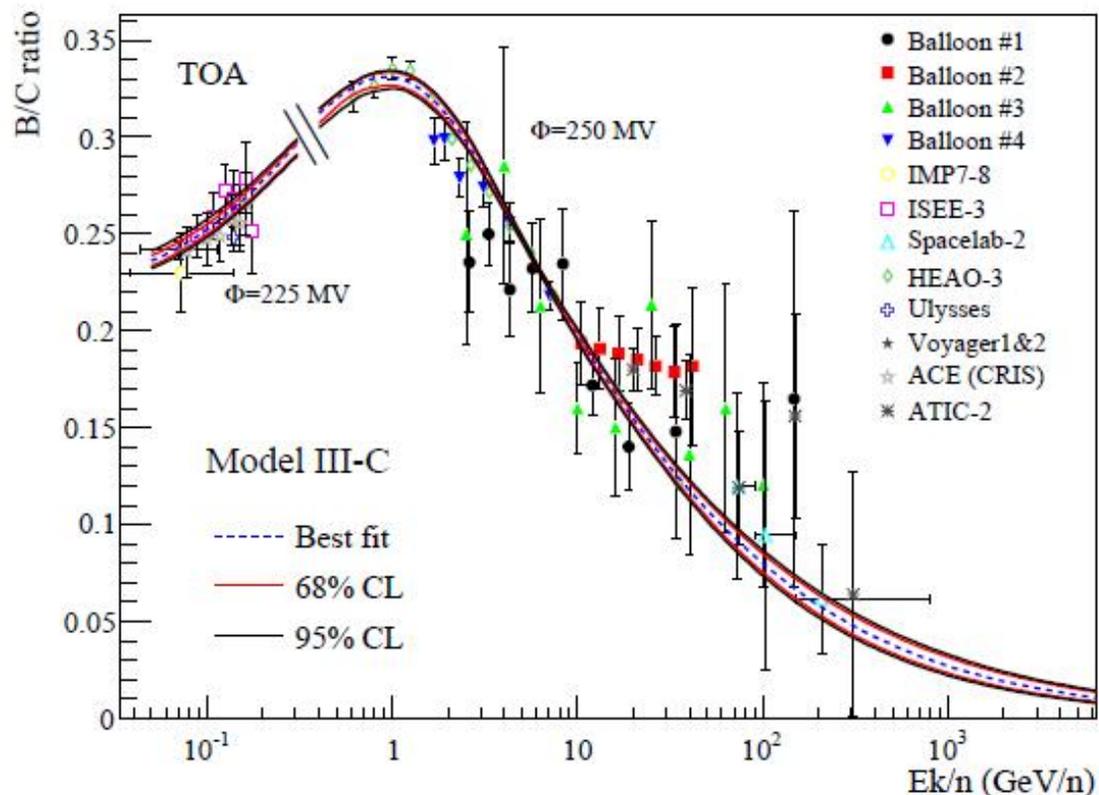
$$N(E) = Q(E) \times \left( \frac{1}{\tau_{\text{esc}}(E)} + \frac{1}{\tau_i(E)} + \frac{1}{\gamma\tau_d} \right)^{-1}$$

$$\frac{N_S}{N_P} = \frac{\tau_{\text{tot}}}{\tau_{P \rightarrow S}}, \quad \tau_{P \rightarrow S} = \frac{1}{n\sigma v}$$

$$\tau_{\text{tot}} = \left( \frac{1}{\tau_{\text{esc}}} + \frac{1}{\tau_i} + \frac{1}{\gamma\tau_d} \right)^{-1}$$

# 银河宇宙线传播：漏箱模型

Putze et al. (2009)



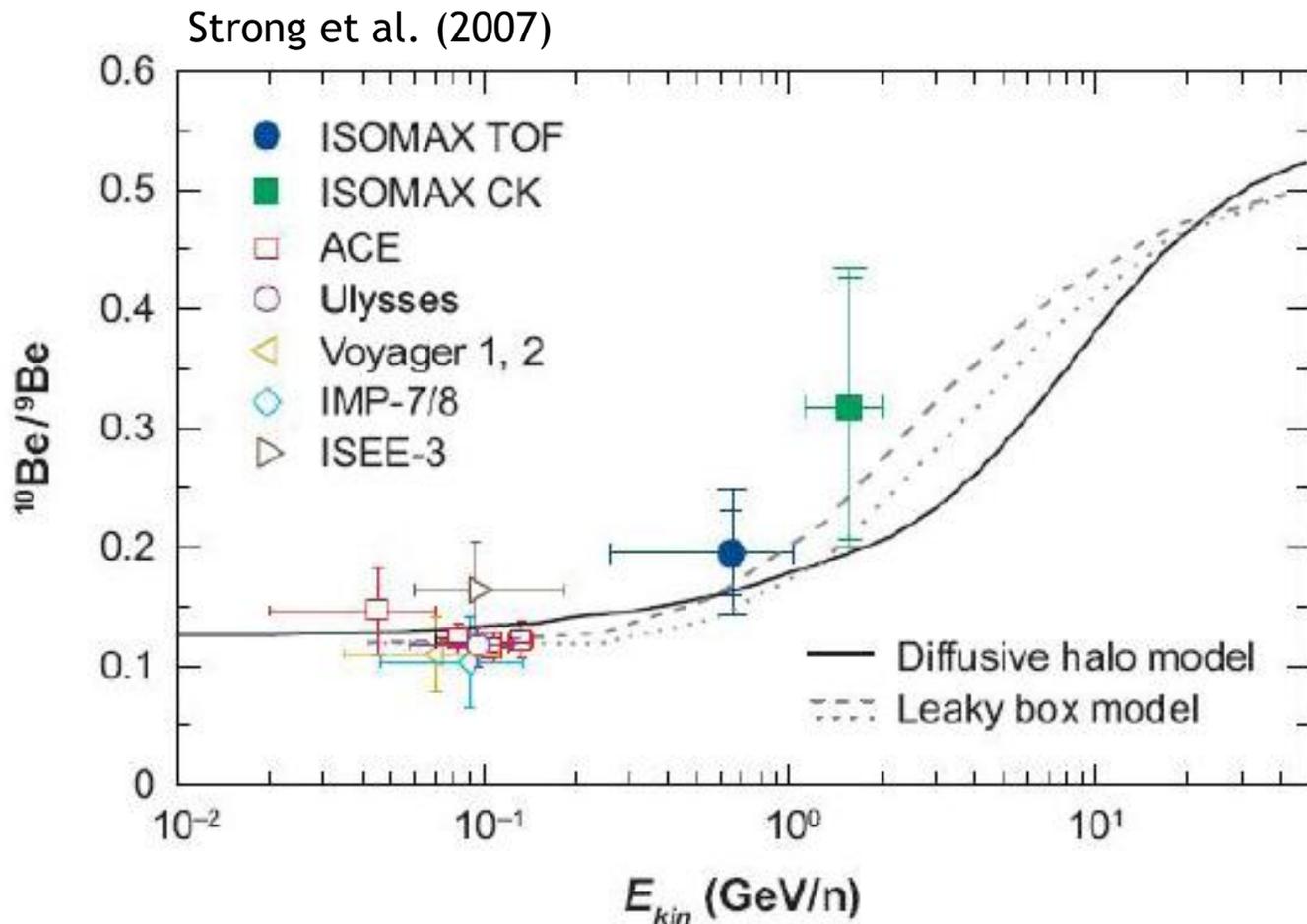
➤  $\lambda$ 为相互作用长度，反映粒子穿过的物质质量多少

➤ 观测宇宙线能谱指数-2.7 → 原初能谱指数-2.2

➤ 简单超新星激波加速预期为-2.1，和上述数值接近！

$$\lambda_{\text{esc}} \equiv \rho\beta c\tau_{\text{esc}} = \begin{cases} 16.3 \times \beta \text{ g cm}^{-2}, & R \leq 2.6\text{GV} \\ 27 \times \beta \left(\frac{R}{\text{GV}}\right)^{-0.53} \text{ g cm}^{-2}, & R > 2.6\text{GV} \end{cases}$$

# 银河宇宙线传播：漏箱模型



- 宇宙线时钟：不稳定次级粒子如  $^{10}\text{Be}$ 和 $^{26}\text{Al}$

$$\tau_{\text{esc}} \sim 2 \times 10^7 \text{ yr}$$

- 根据B/C得到的逃逸长度，可以推断宇宙线粒子平均穿越的介质密度为 $0.3 \text{ cm}^{-3}$ ，远低于银盘的物质密度，意味着宇宙线在扩展晕中传播
- 银河系的厚度 $\sim 1 \text{ kpc}$ ，宇宙线的逃逸时间上千万年，这也表明宇宙线并非走直线，而是经历着随机散射

# 扩散模型（球对称）

- 扩散方程  $\dot{N} = \nabla \cdot (D\nabla N) + Q$
- 格林函数  $G(r, t) = \frac{1}{8(\pi Dt)^{3/2}} \exp[-r^2/(4Dt)]$
- 特征传播距离  $H \sim \sqrt{Dt}$
- 特征时间  $\tau \sim H^2/D$
- 传播速度  $v_{diff} \sim H/\tau \sim D/H$
- 和漏箱模型对照有  $\lambda_{esc} = \rho_g \beta c h H/D$ , 根据  $\lambda_{esc} \sim 10 \text{ g/cm}^2$  有  $D/H \sim 1.5 \times 10^6 \text{ cm/s}$
- 宇宙线各向异性  $\sim v_{diff}/c \sim 10^{-4}$

# 电子扩散（球对称）

➤ 扩散—能损方程

$$\frac{\partial \psi}{\partial t} = \nabla \cdot (D \nabla \psi) + \frac{\partial}{\partial E} (b \psi) + q_e$$

➤ 对r和t的格林函数  
(无穷远边界条件)

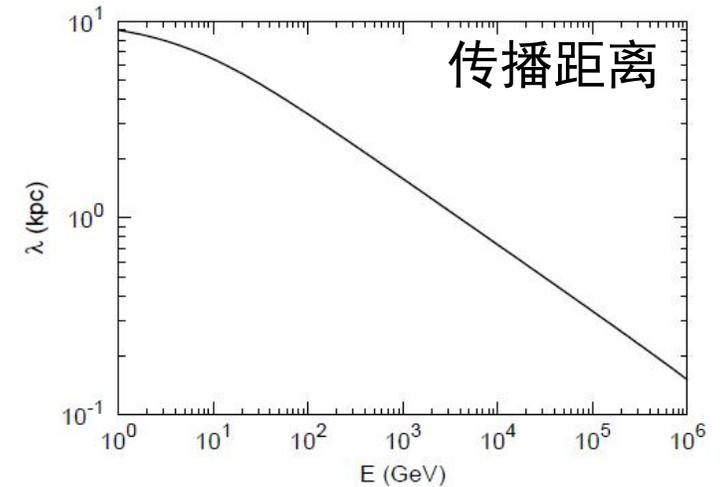
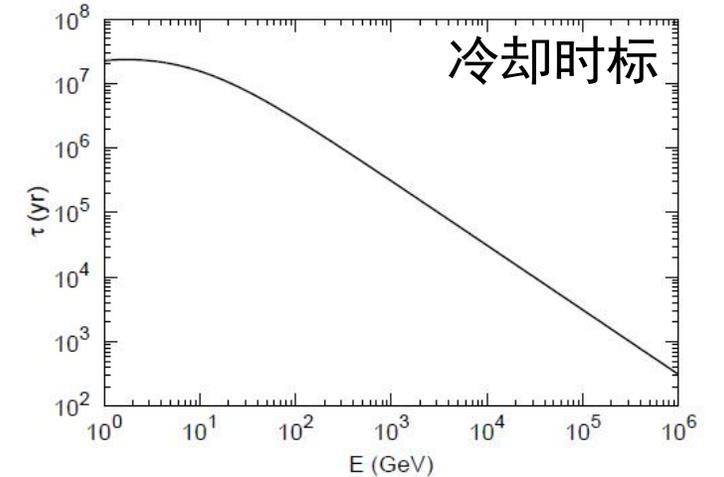
$$G(r, E, t) = \frac{N_{inj}(E_i) b(E_i)}{\pi^{3/2} b(E) \lambda^3} \exp\left(-\frac{r^2}{\lambda^2}\right)$$

➤ 能损率

$$b(E) = b_0 + b_1 E_{\text{GeV}} + b_2 E_{\text{GeV}}^2$$

➤ 扩散半径

$$\lambda(E) = 2 \sqrt{\Delta u} = 2 \left( \int_E^\infty \frac{D(E')}{b(E')} dE' \right)^{1/2}$$



Atoyan et al. (1995)

# 宇宙线传播效应

初级原子核

$$E^{-\alpha}$$

扩散



$$E^{-(\alpha+\delta)}$$

次级原子核

$$E^{-(\alpha+\delta)}$$

扩散



$$E^{-(\alpha+2\delta)}$$

初级正负电子

$$E^{-\alpha}$$

冷却



$$E^{-(\alpha+1)}$$

次级正负电子

$$E^{-(\alpha+\delta)}$$

冷却

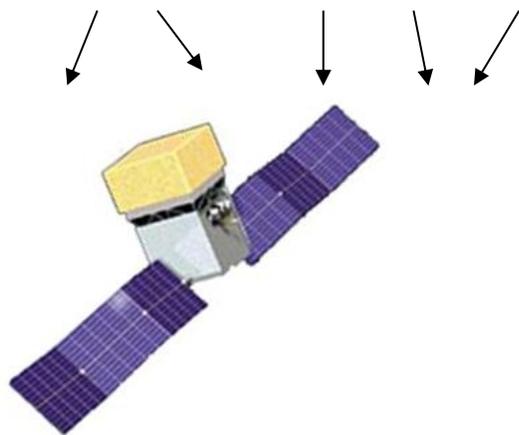


$$E^{-(\alpha+\delta+1)}$$

## 第二部分：宇宙线实验探测

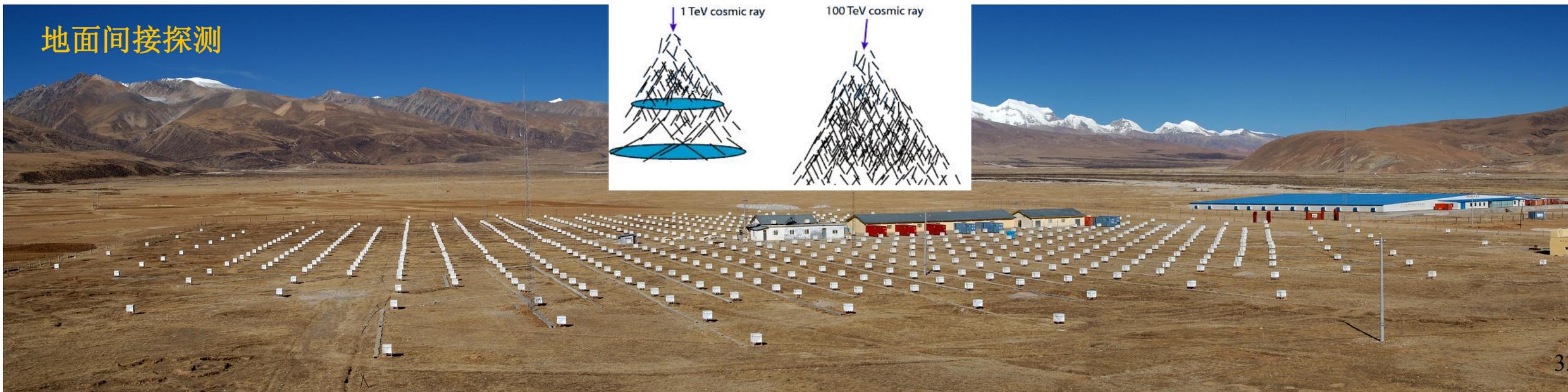
# 宇宙线实验探测

空间直接探测



- 宇宙线的大动态范围对实验探测有特殊的要求
- 低能宇宙线受大气层阻挡，需要在高空(气球、火箭)或空间(卫星)进行**直接探测**：探测成本较高、规模受限
- 高能宇宙线流量太低无法在空间探测。不过高能粒子在空气中会引发级联簇射，从而可以在地面利用大型粒子探测阵列**间接探测**

地面间接探测



# 直接探测

Transition Radiation Detector (TRD)  
Identify  $e^+$ ,  $e^-$



Time of Flight (TOF)  
 $Z$ ,  $E$



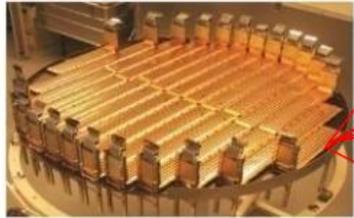
Magnet  
 $\pm Z$



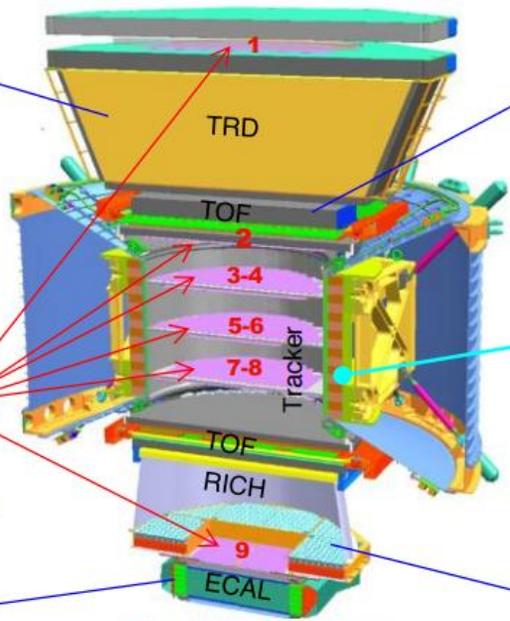
Ring Imaging Cherenkov (RICH)  
 $Z$ ,  $E$



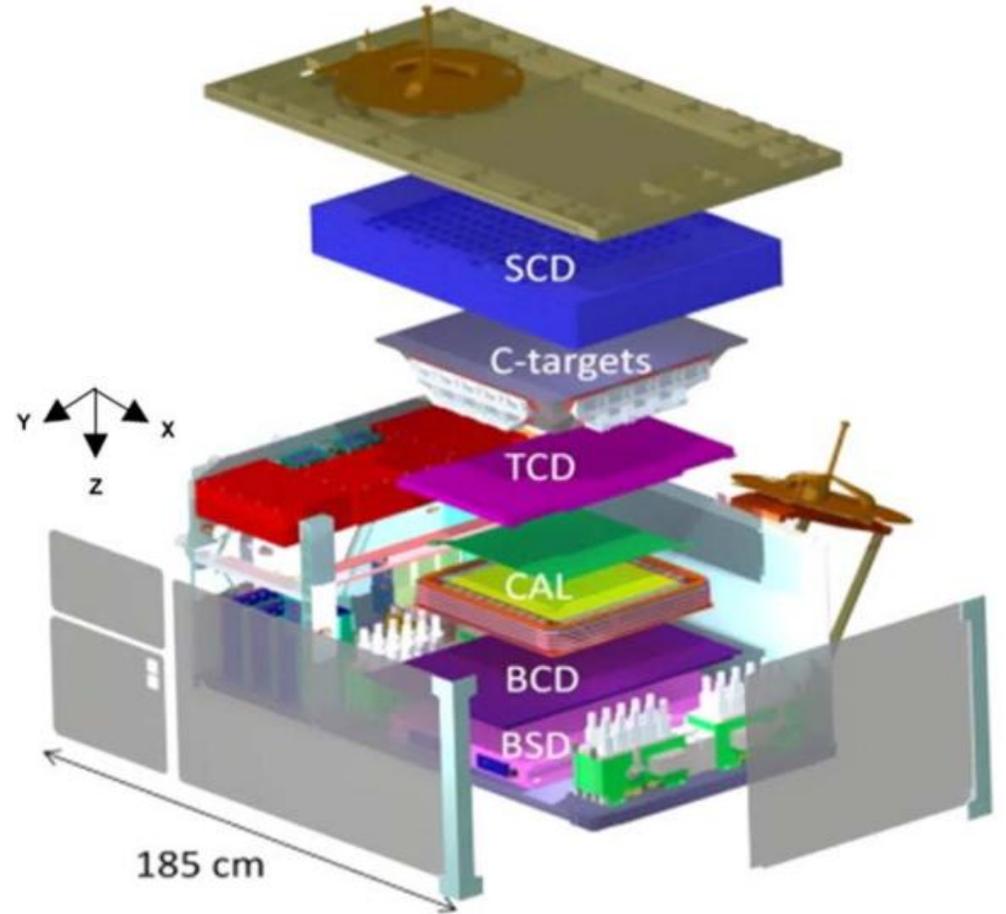
Silicon Tracker  
 $Z$ ,  $P$  or  $R=P/Z$



Electromagnetic Calorimeter (ECAL)  
 $E$  of  $e^+$ ,  $e^-$



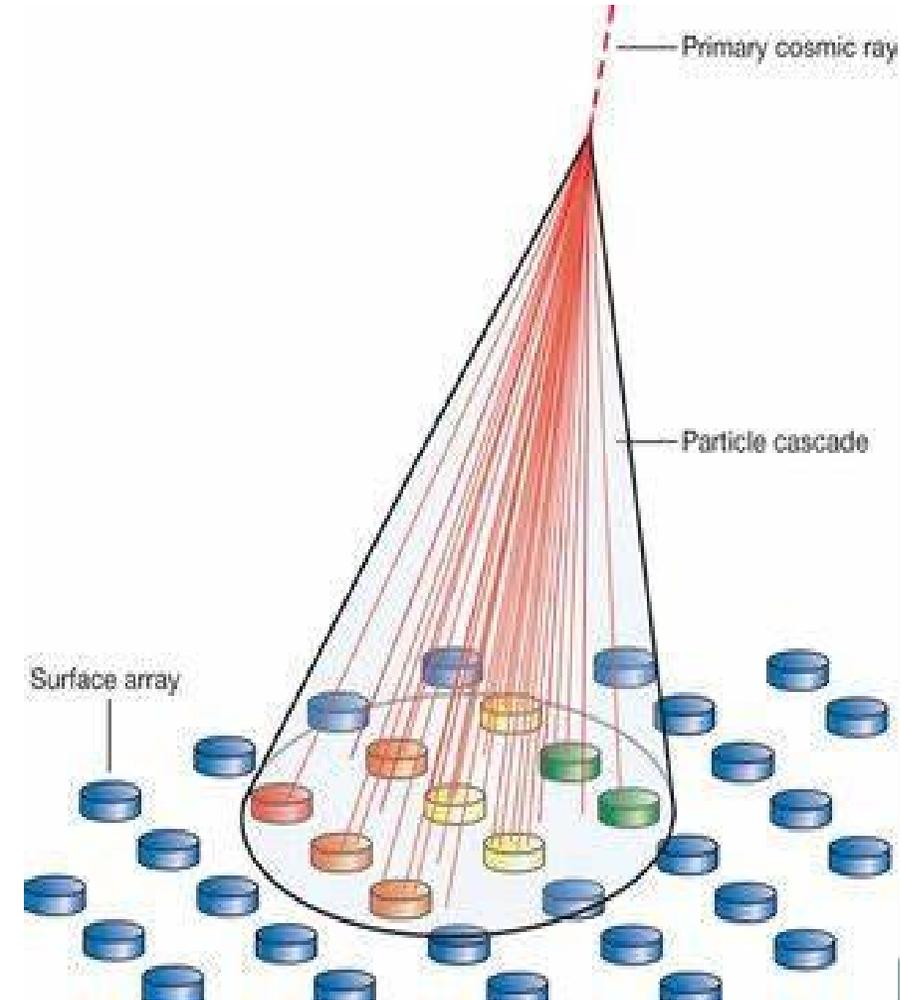
$Z$  and  $P$ ,  $E$  or  $R$  are measured independently by Tracker, ECAL, TOF and RICH



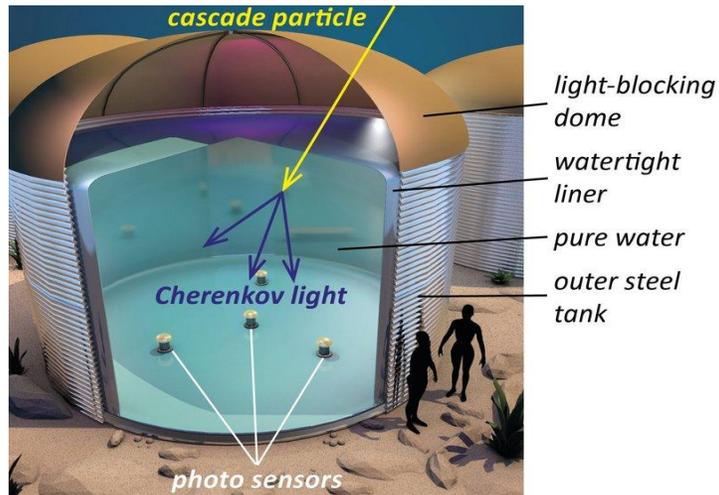
磁谱仪

量能器

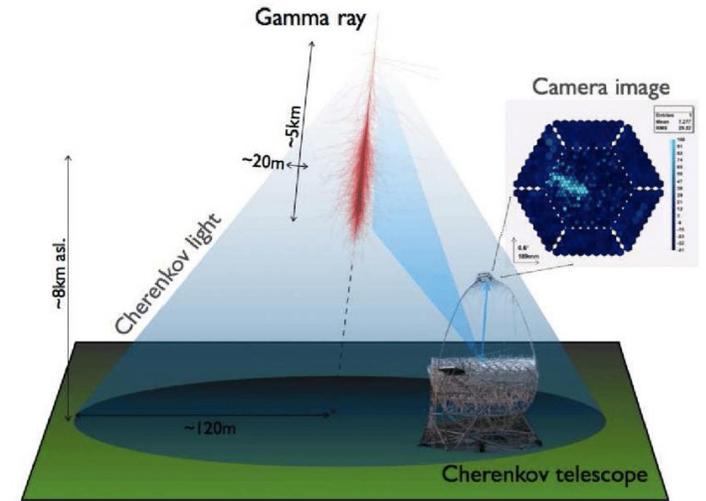
# 间接探测



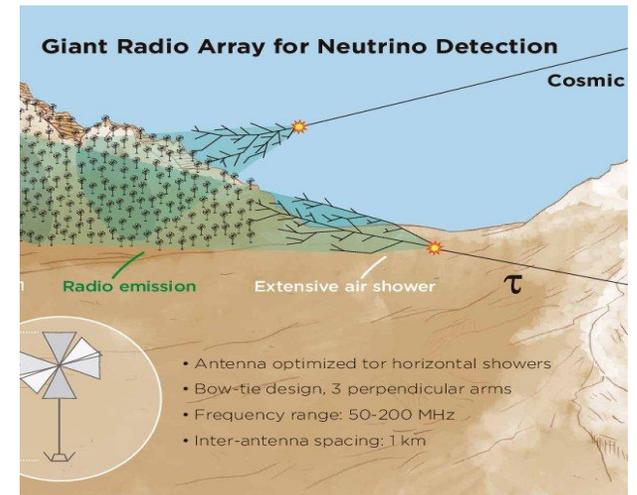
粒子探测阵列



水切伦科夫探测器



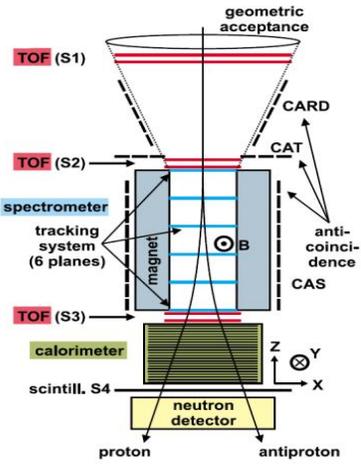
大气切伦科夫望远镜



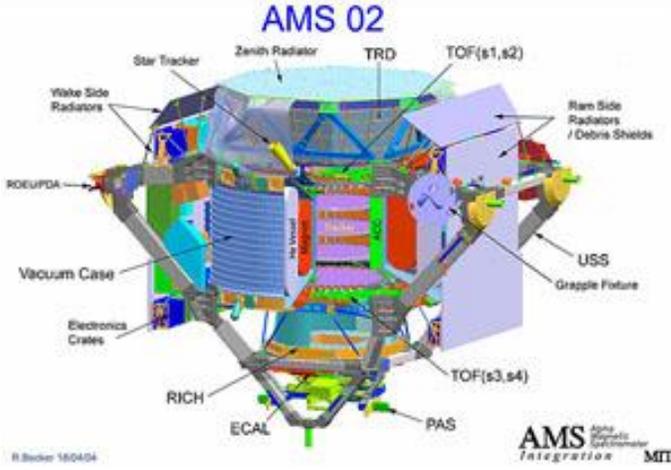
射电探测阵列

# 现有实验

## PAMELA(意)



## AMS-02(美欧中等)



## CALET(日美)



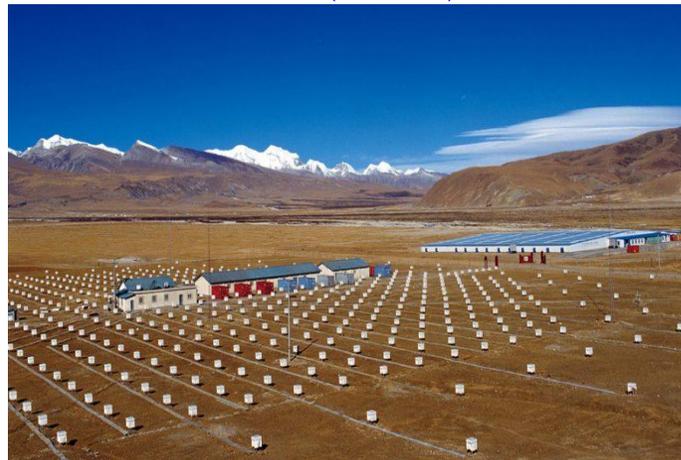
## ISS-CREAM(美)



## KSACADE(德)



## 羊八井(中日)



## HESS/MAGIC/VERITAS/CTA(美欧日)



## HAWC(美)



# 中国宇宙线研究



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

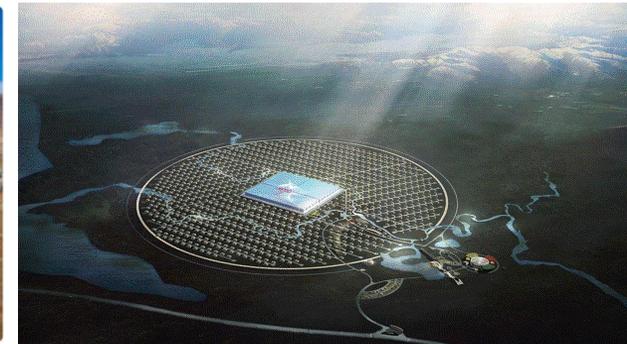
云南站(1950s)



西藏甘巴拉山(1970s)



西藏羊八井(1990s)



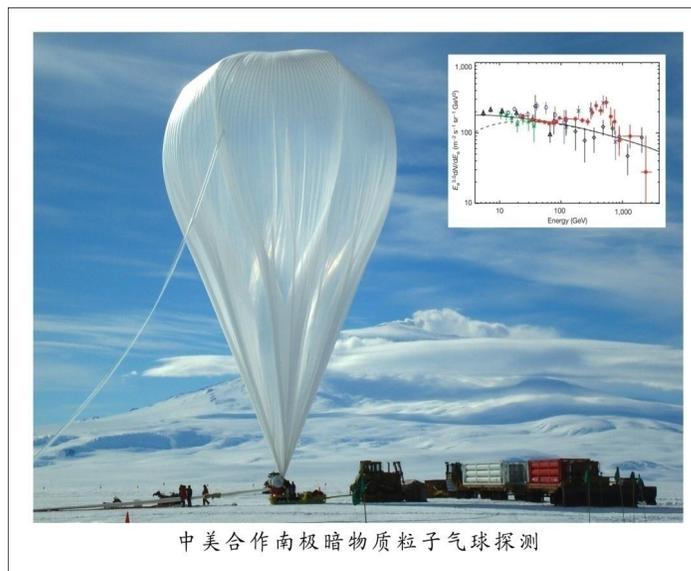
四川稻城(2010s)



气球实验(1970s)



载人航天(1990s)



国际合作气球(2000s)



悟空卫星(2010s)

# 中国宇宙线研究：云南站



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

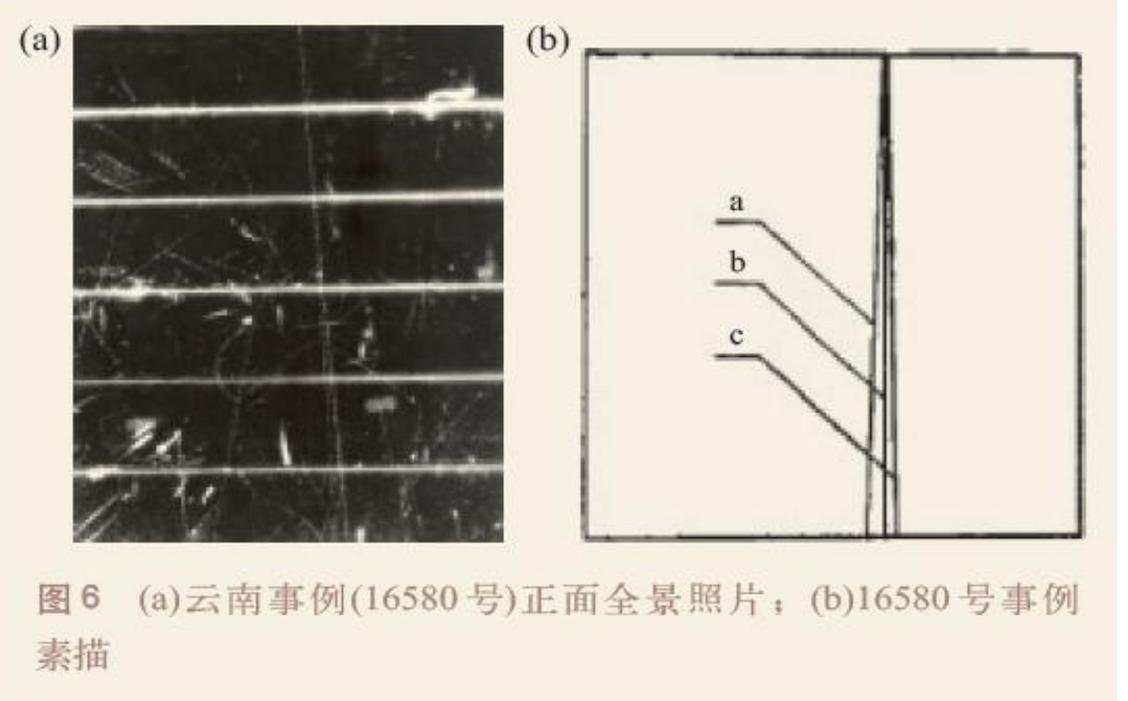


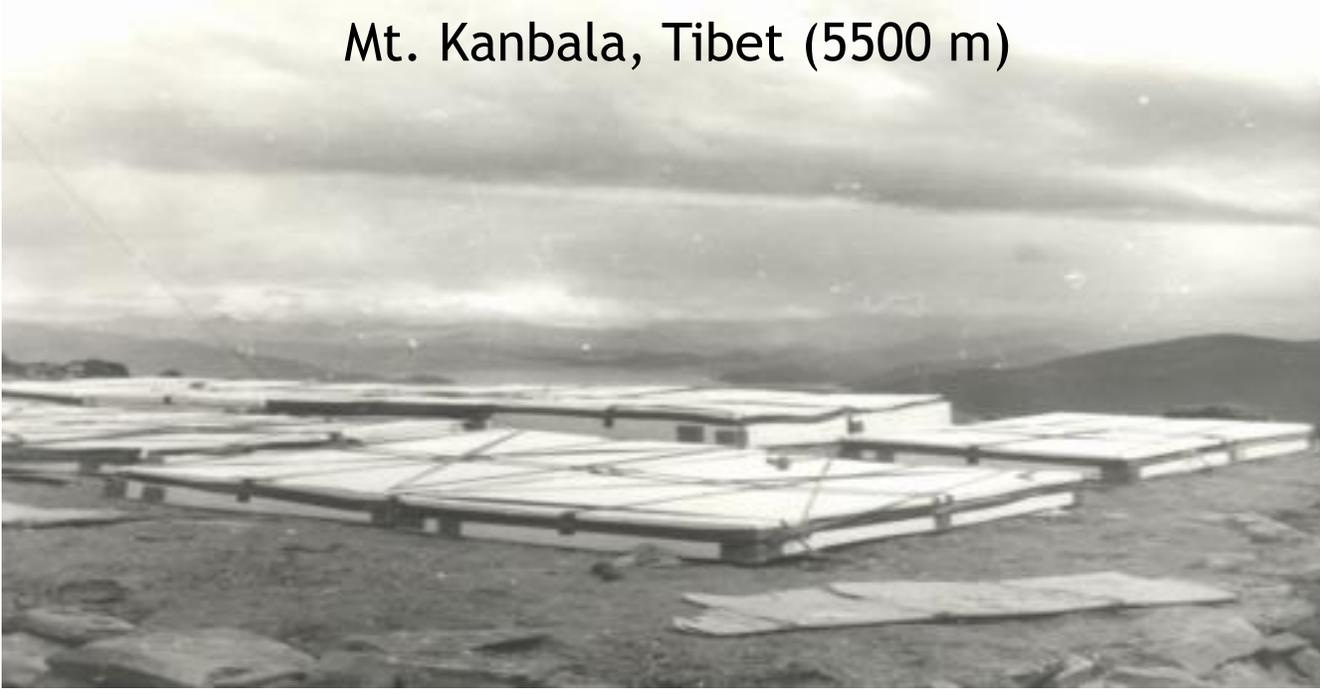
图6 (a)云南事例(16580号)正面全景照片；(b)16580号事例素描

利用云室探测到一个疑似重粒子 ( $m > 12 \text{ GeV}$ )

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

# 中国宇宙线研究：西藏甘巴拉山

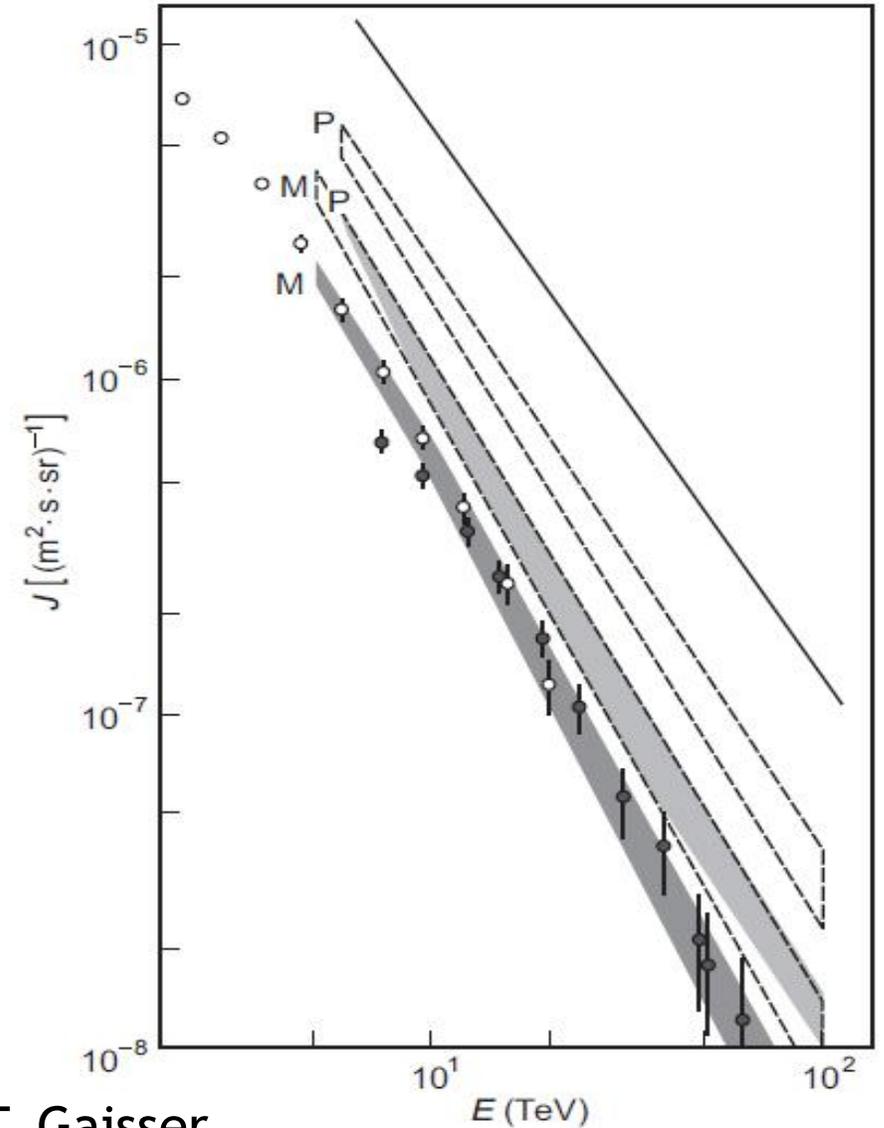
Mt. Kanbala, Tibet (5500 m)



$$\sigma_{p\text{-air}}^{\text{inel}} \approx 290 \text{ mb} \times \left( \frac{E_p}{1 \text{ TeV}} \right)^{0.06}$$

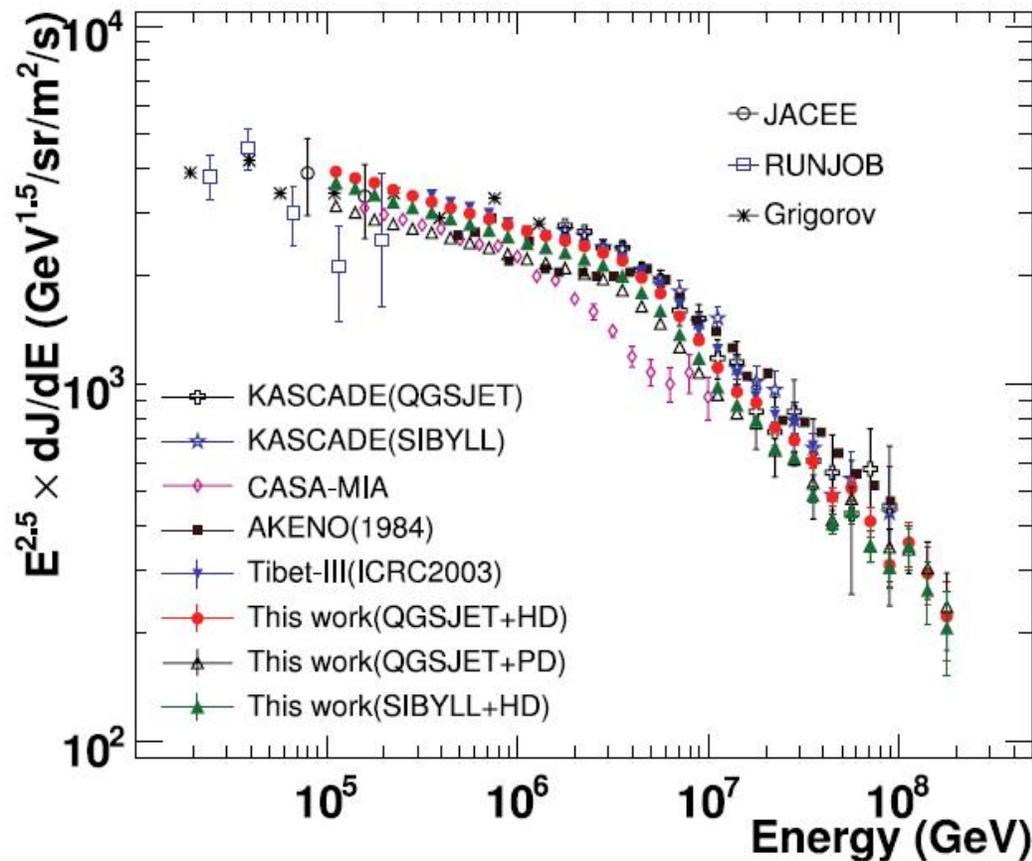
Ren et al. (1987, Nuovo Cim.C, 10, 43)

Recorded in textbook “Cosmic Rays and Particle physics” by T. Gaisser



# 中国宇宙线研究：西藏羊八井

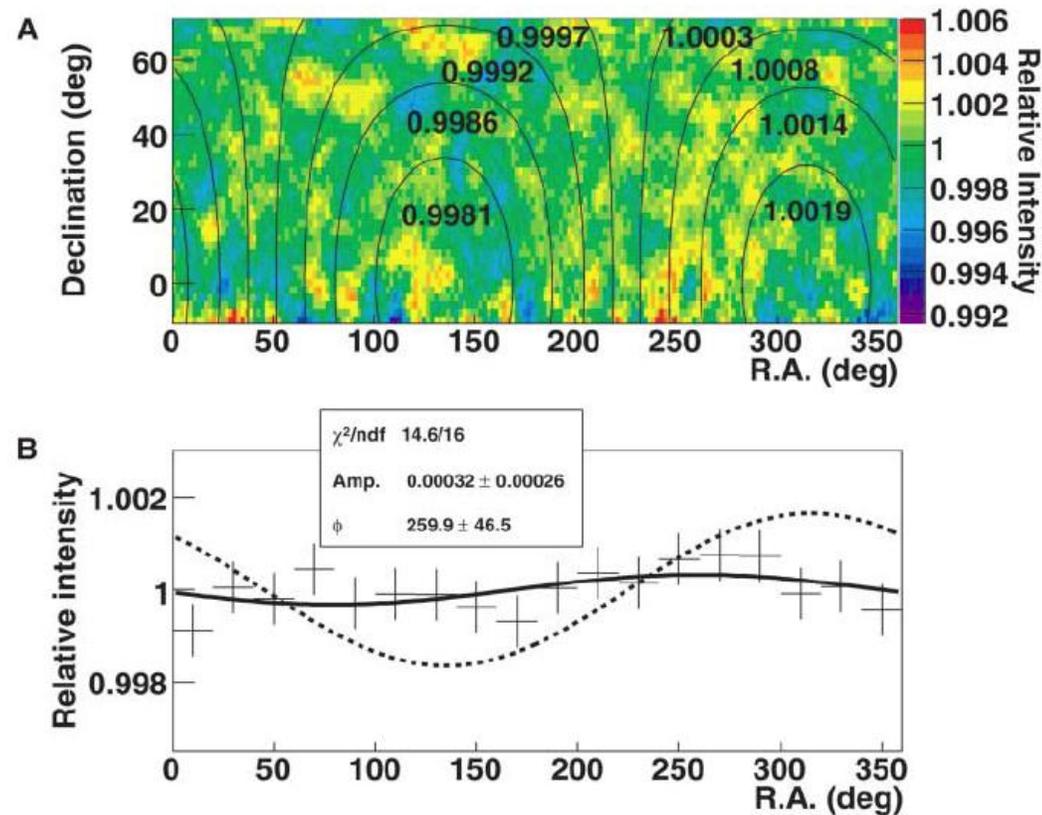
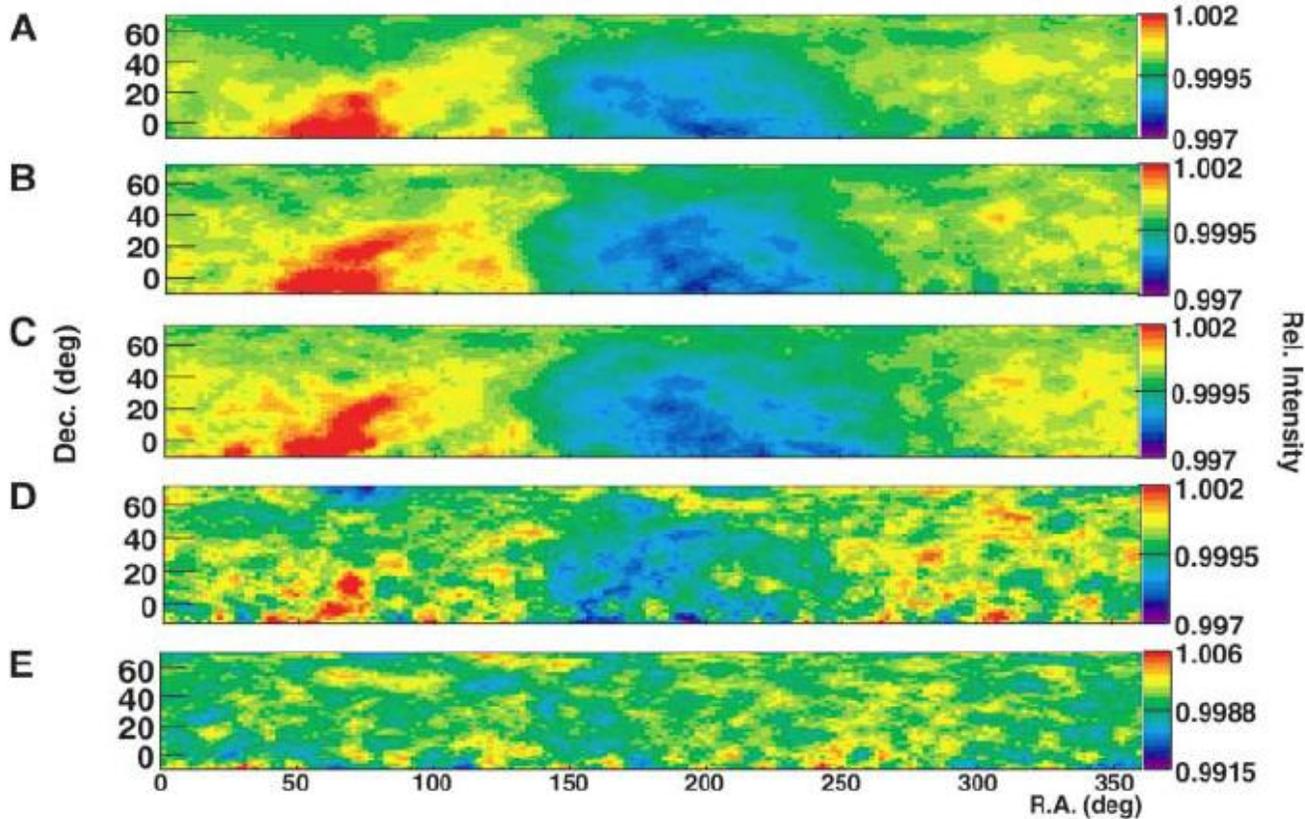
Yangbajing, Tibet (4300 m)



Precise measurements of CR spectra around the “knee” region

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

# 中国宇宙线研究：西藏羊八井



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

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

# 暗物质粒子探测卫星“悟空”

宇宙线质子

**NEWS IN FOCUS**

**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**

**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  $\gamma$ -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

24 | 31 DECEMBER 2015 | VOL 528 | NATURE | 443

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塑闪探测器PSD: 电荷



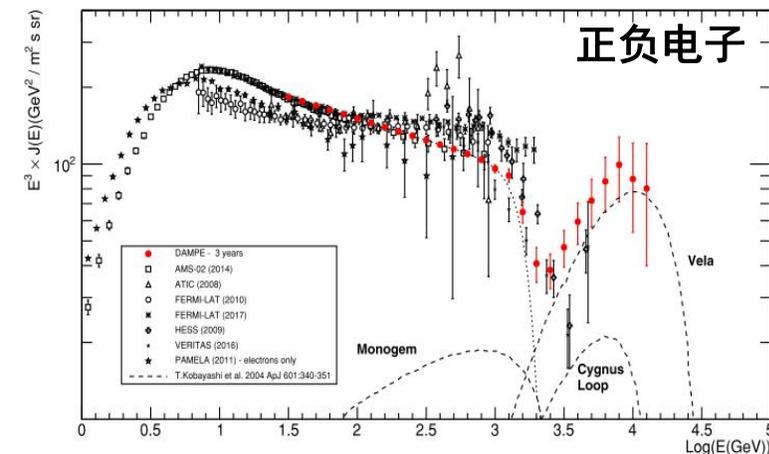
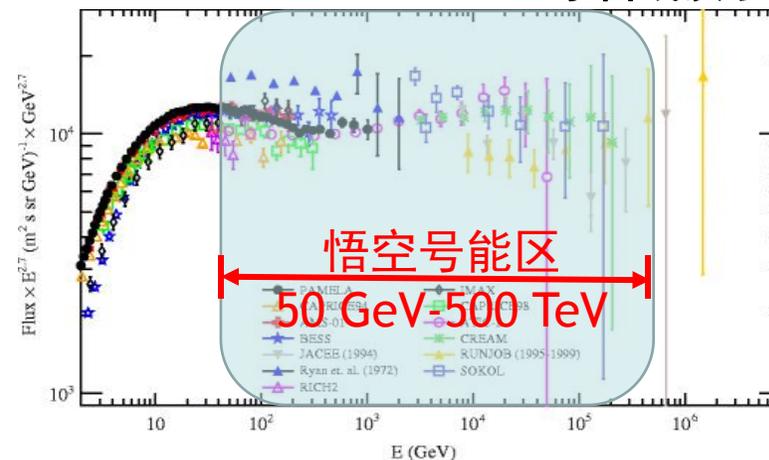
硅微条探测器STK: 径迹、电荷



BGO量能器: 能量、径迹、类别



中子探测器NUD: 粒子类别



“悟空”号卫星2015年底发射，其部分指标国际领先，为更好理解宇宙线相关科学问题提供了关键的机遇

# “悟空”探测器

塑闪探测器(近物所)



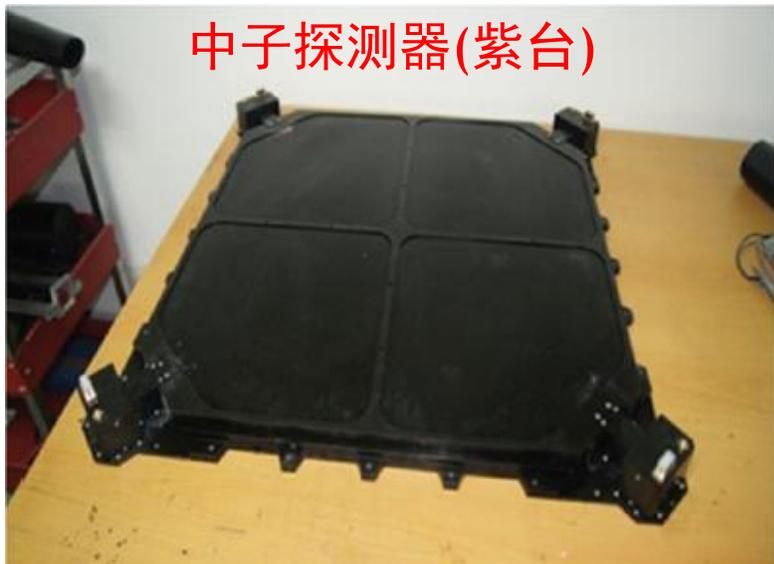
硅阵列探测器(高能所、意大利、瑞士)



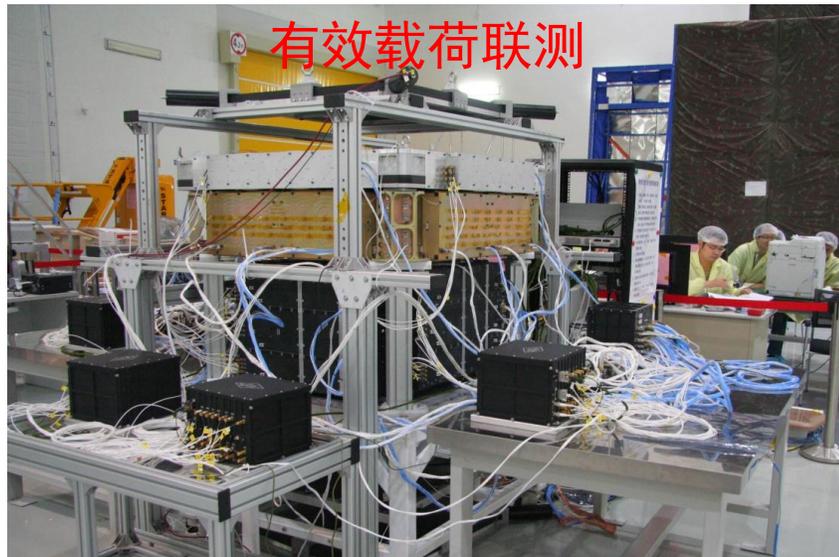
BGO量能器(科大、紫台)



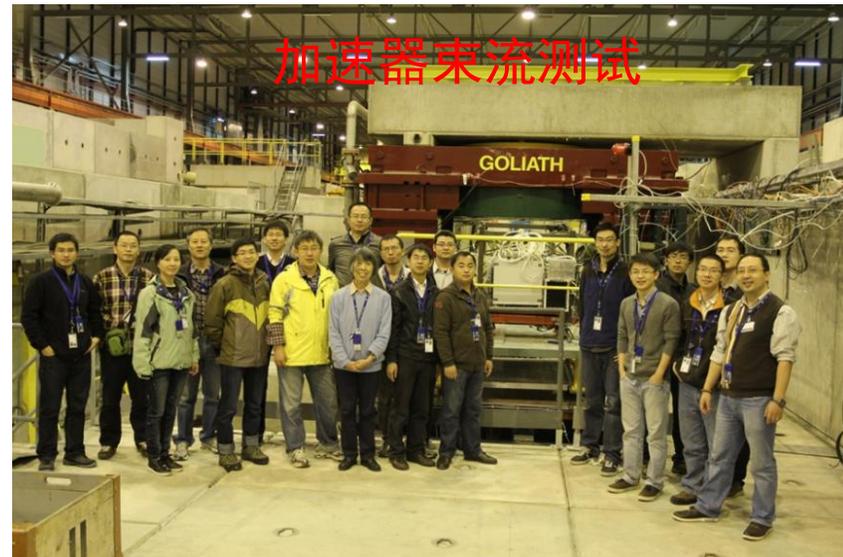
中子探测器(紫台)



有效载荷联测



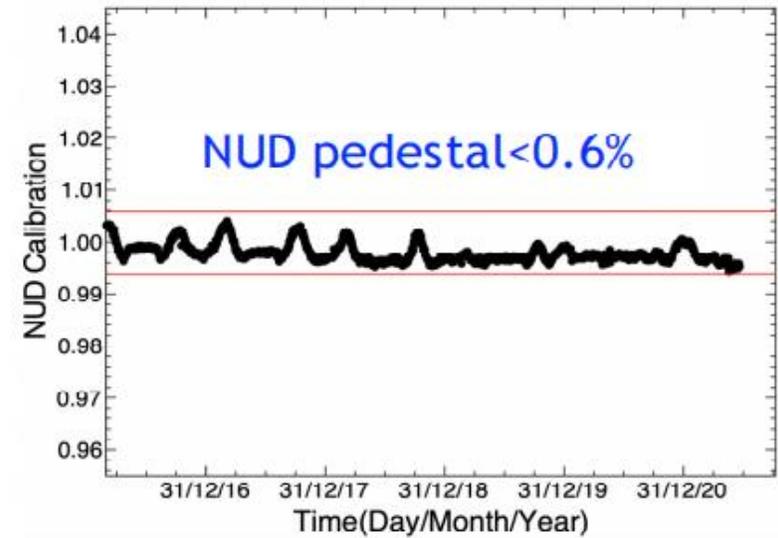
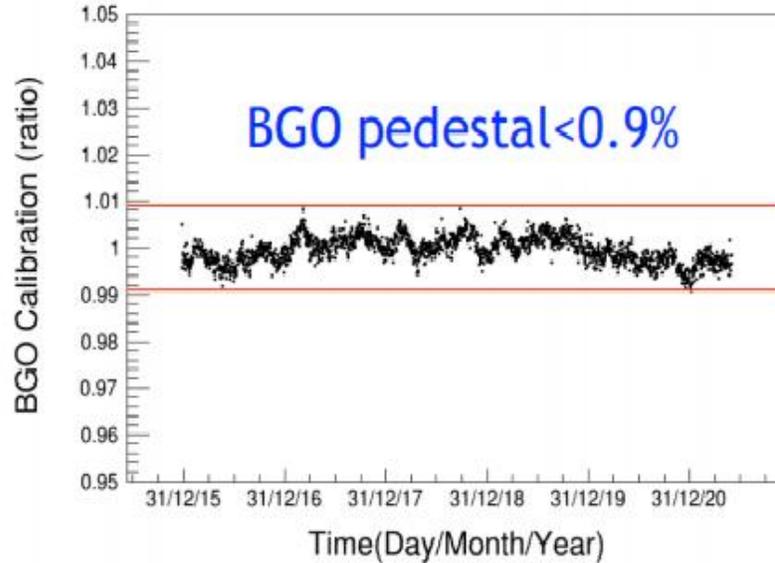
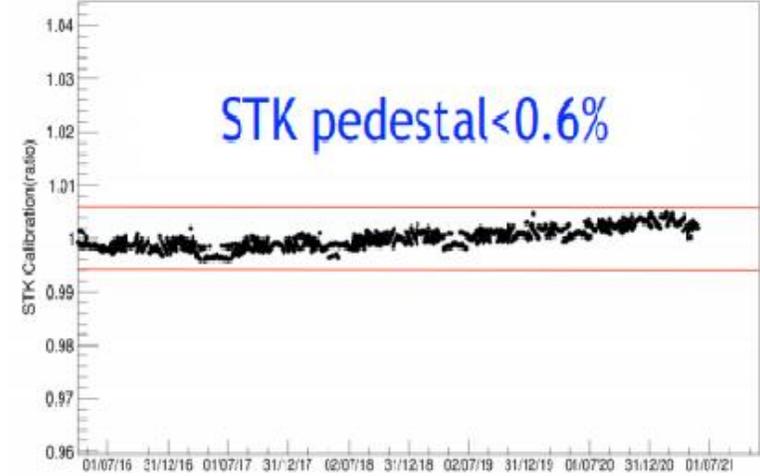
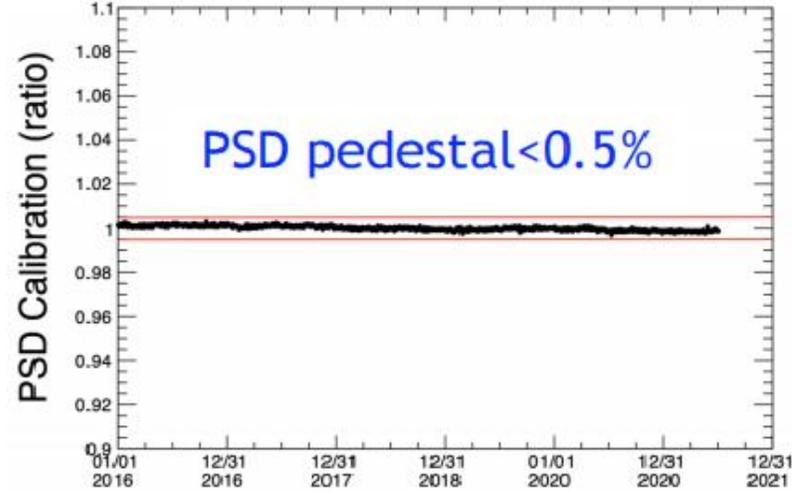
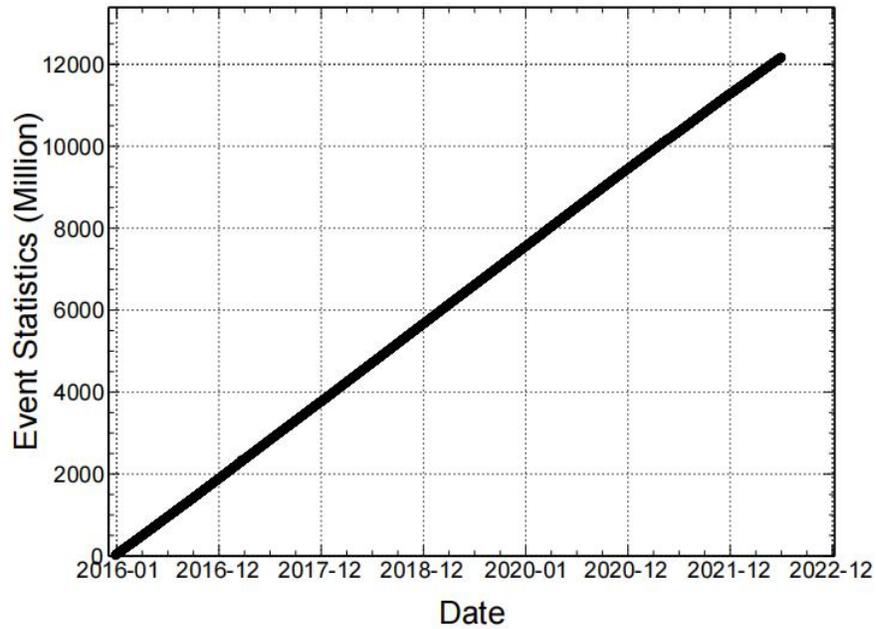
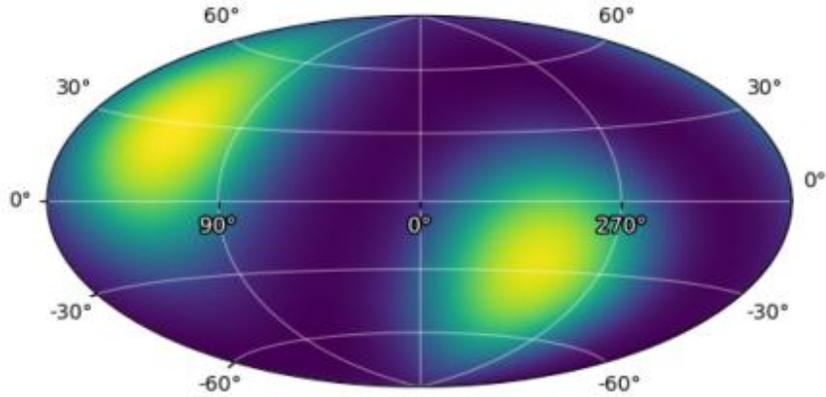
加速器束流测试



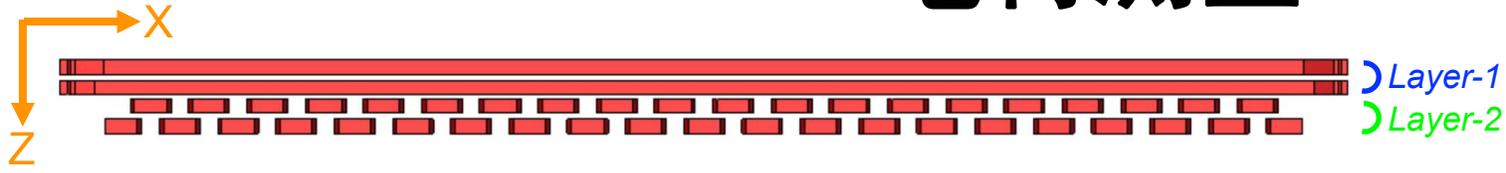
# “悟空”号性能指标优异，打开了TeV能段电子和伽马射线观测新窗口

卫星名称	观测能段	几何因子 ( $\text{m}^2\cdot\text{sr}$ )	能量分辨	本底抑制 @TeV	目前状况
PAMELA	~0.5 TeV	0.002	5-10%	$10^4$	停止 (10年)
FERMI	~2 TeV	2.5	5-15%	$10^3$	继续 (15年)
AMS-02	~2 TeV	0.05	2-3%	$10^5$	继续 (12年)
CALET	~5 TeV	0.1	3%	$10^5$	继续 (8年)
ISS-CREAM	~3 TeV	0.2	15%	$10^3$	停止 (1.5年)
DAMPE	~10 TeV	0.3	1%	$2 \times 10^5$	继续 (7.5年)

# 稳定运行7.5年



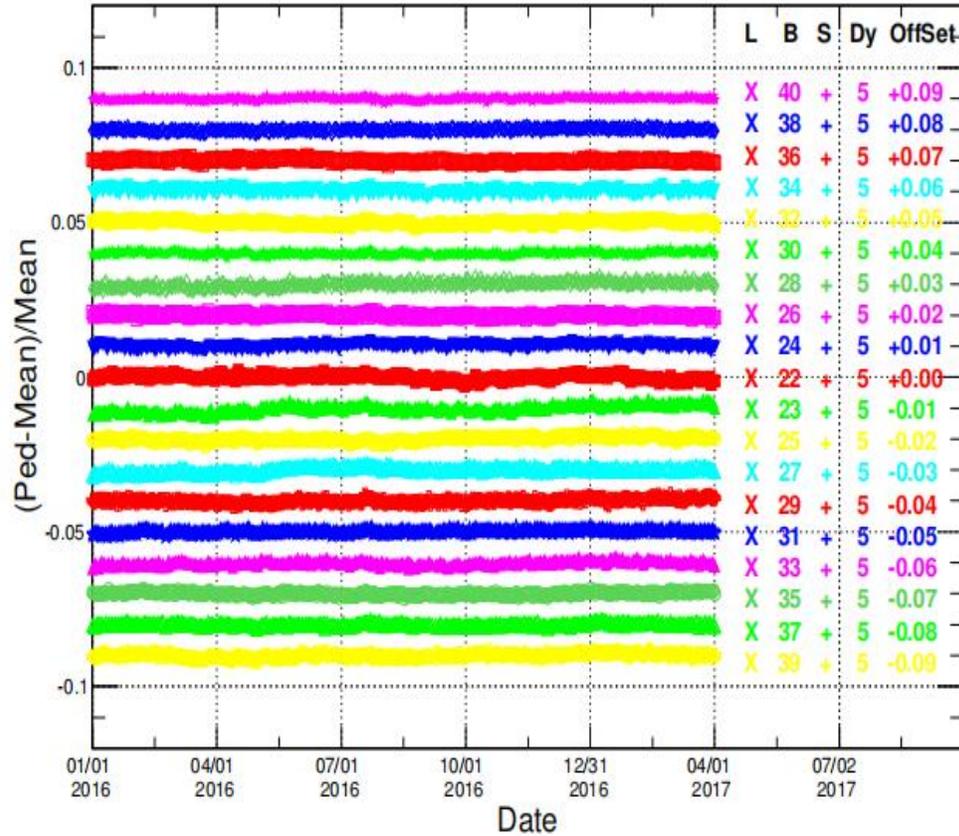
# 电荷测量



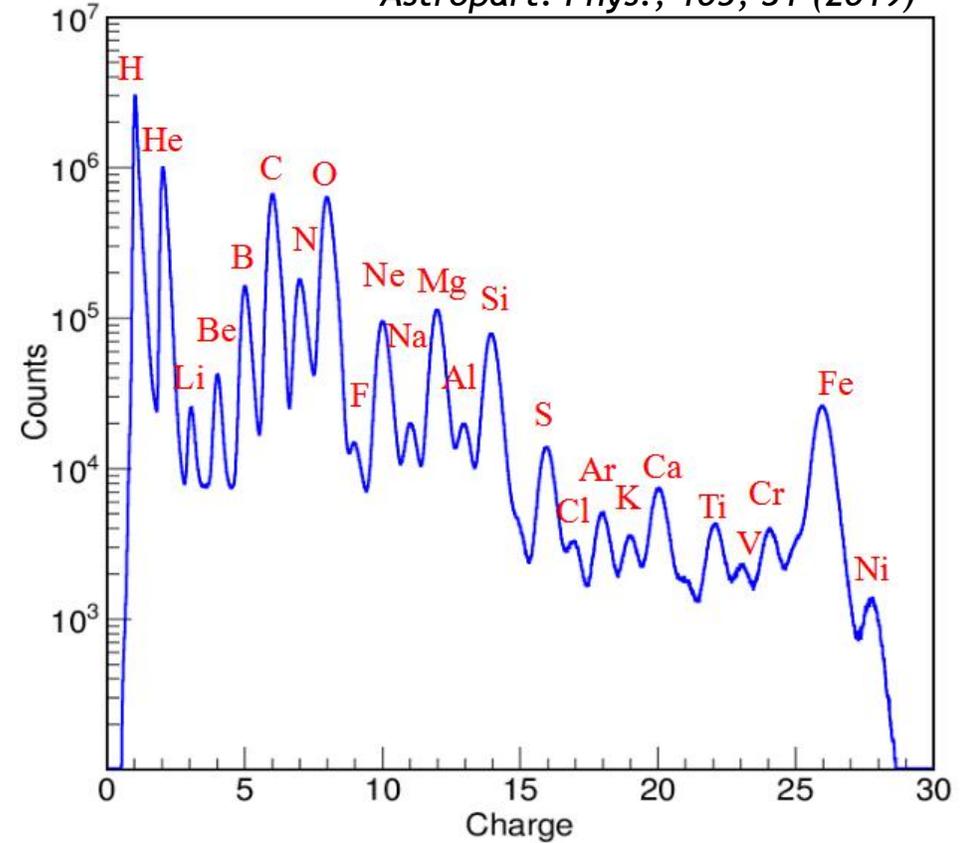
Bethe-Bloch formula

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

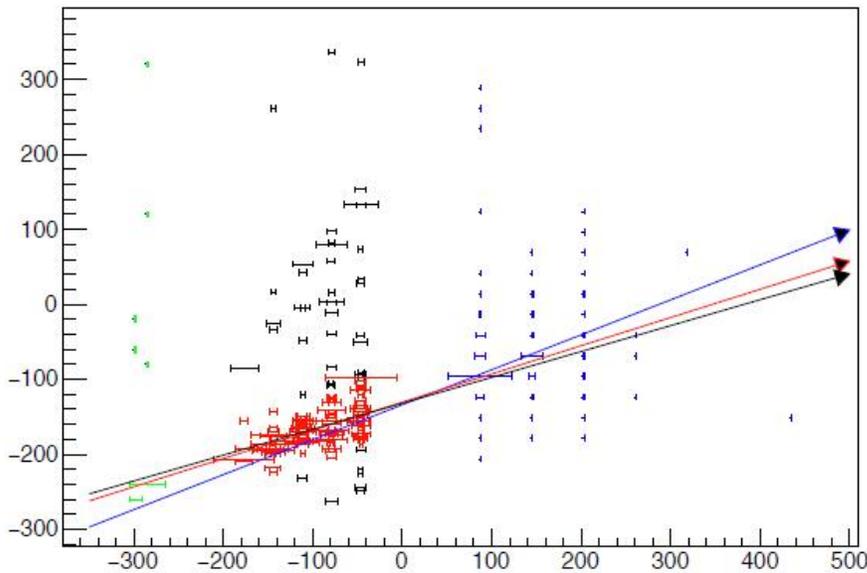
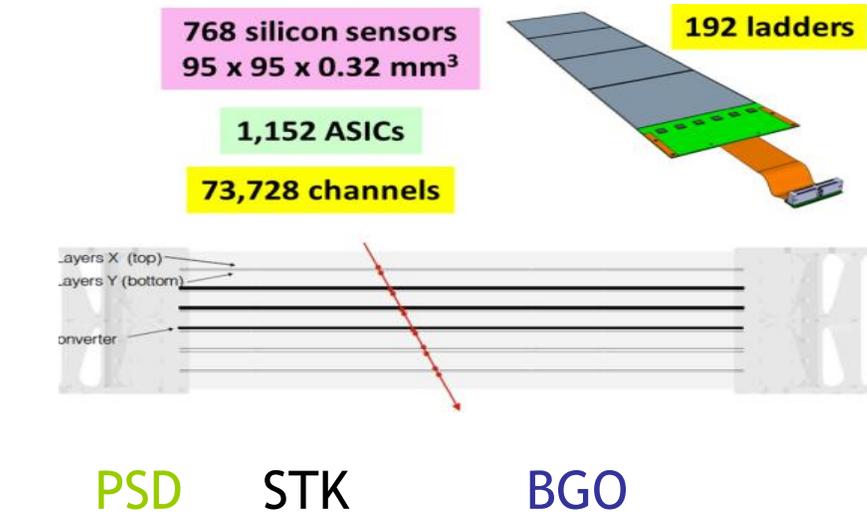
*Res. Astron. Astrophys.*, 19, 47 (2019)



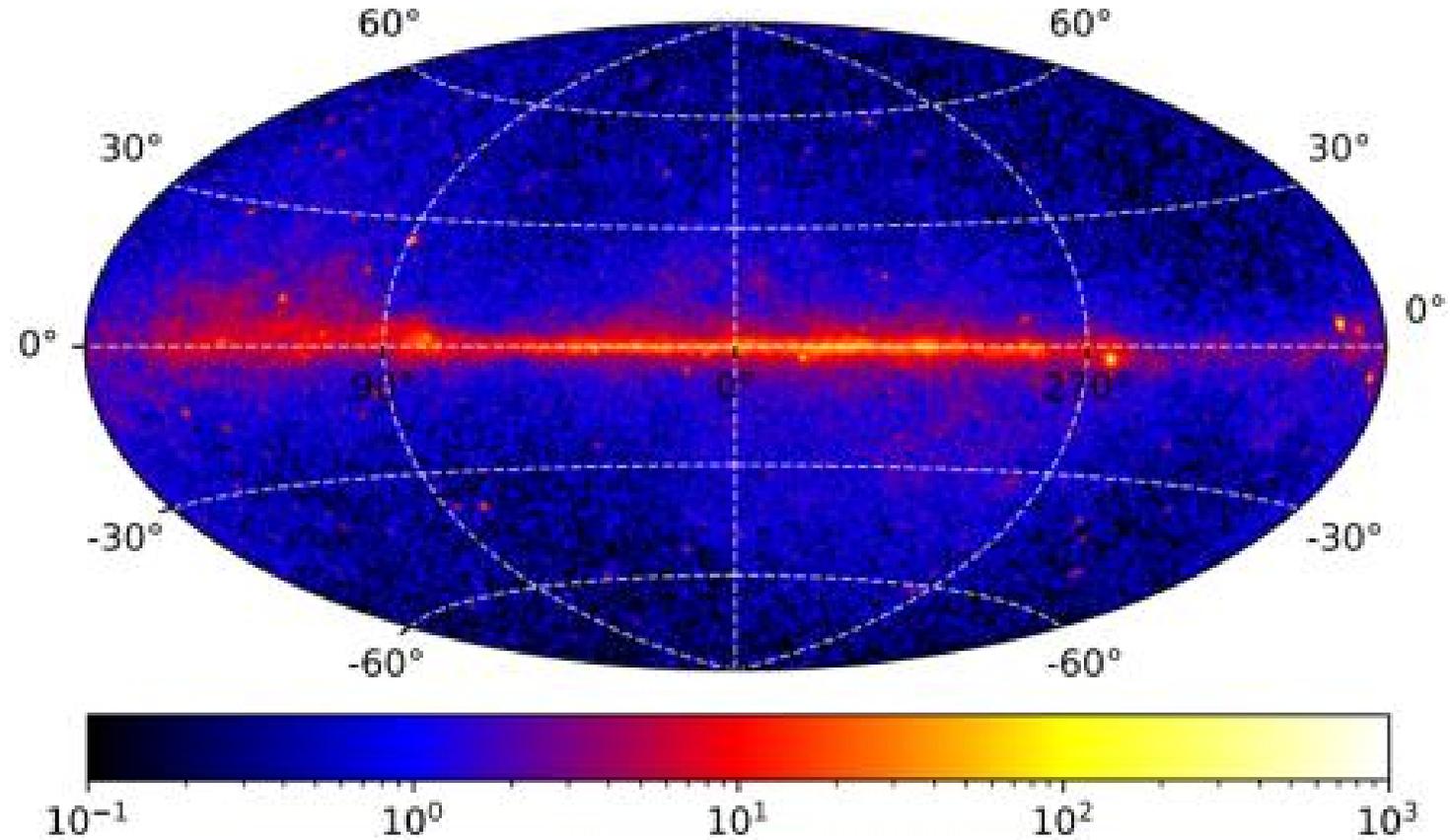
*Astropart. Phys.*, 105, 31 (2019)



# 方向測量



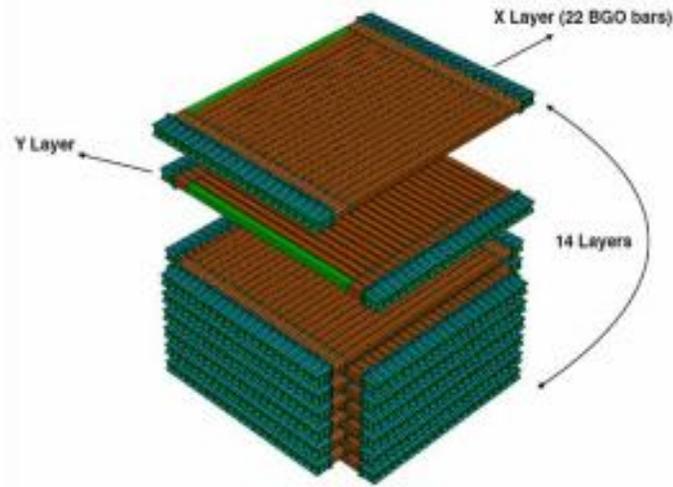
PoS, ICRC2021, 631 (2021)



Angular resolution is ~0.4 degrees @ 10 GeV  
as calibrated by  $\gamma$ -ray point sources

# 能量测量

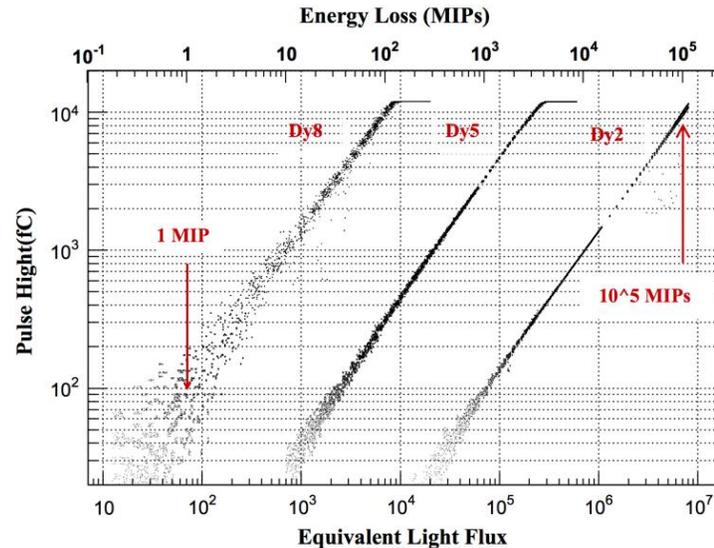
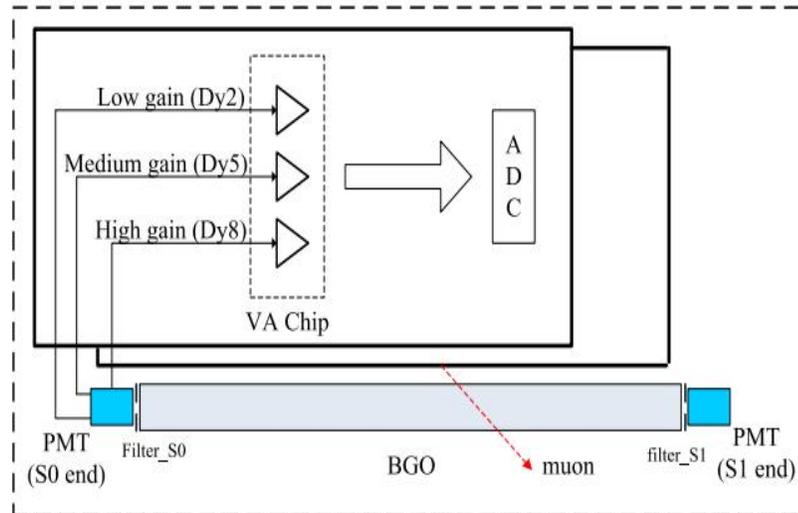
BGO calorimeter



308 BGO bars

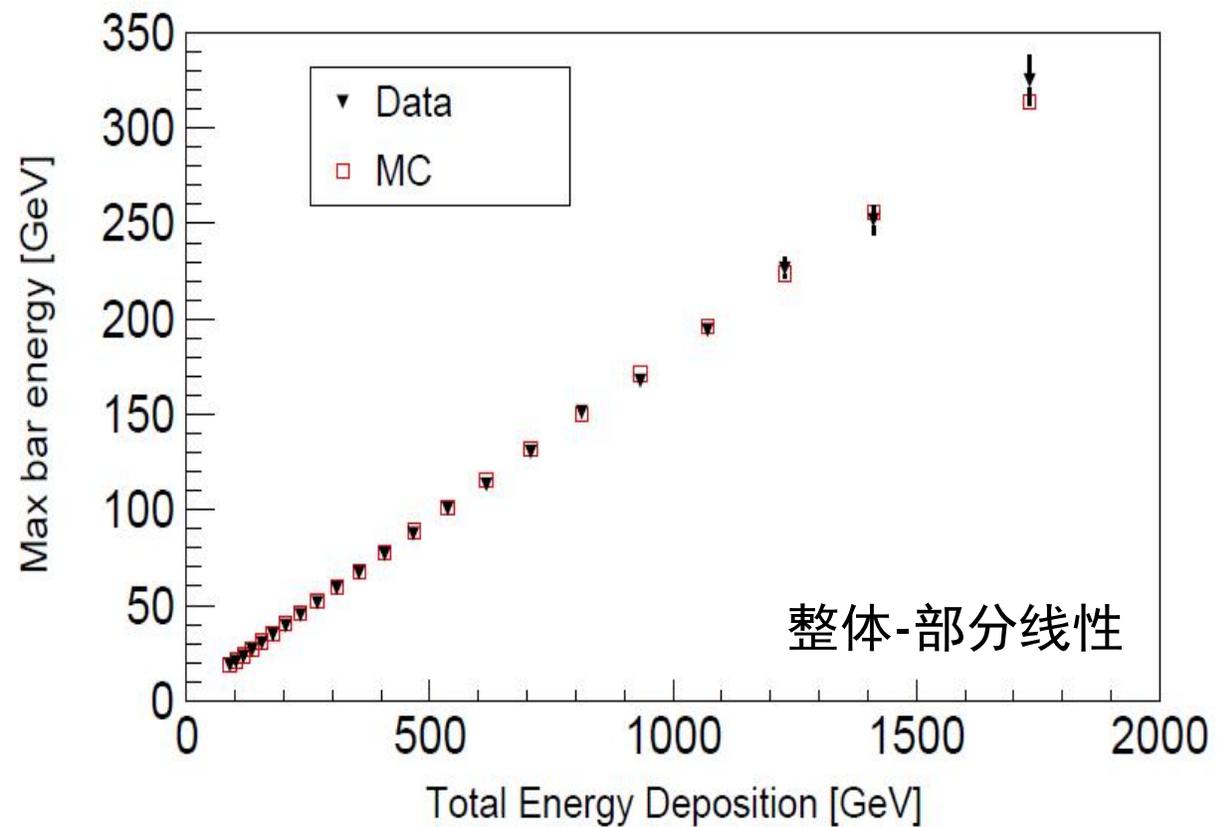
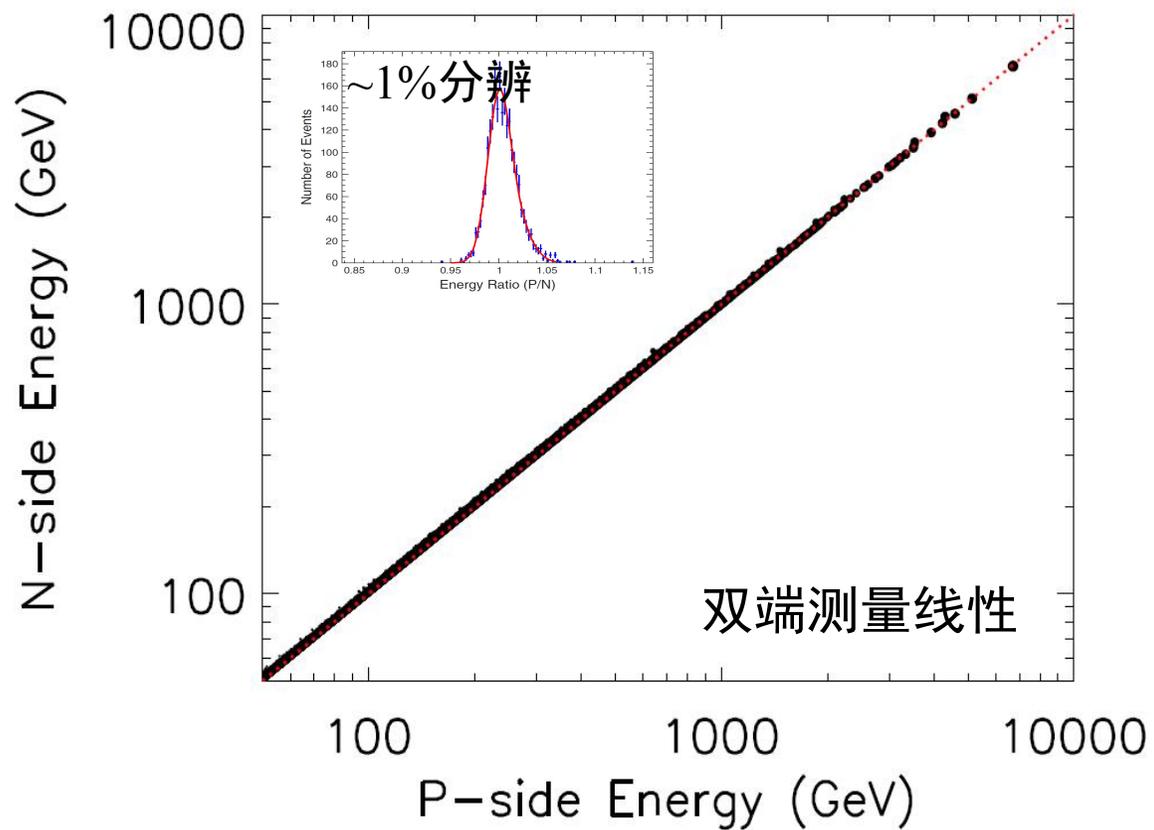


616 PMTs



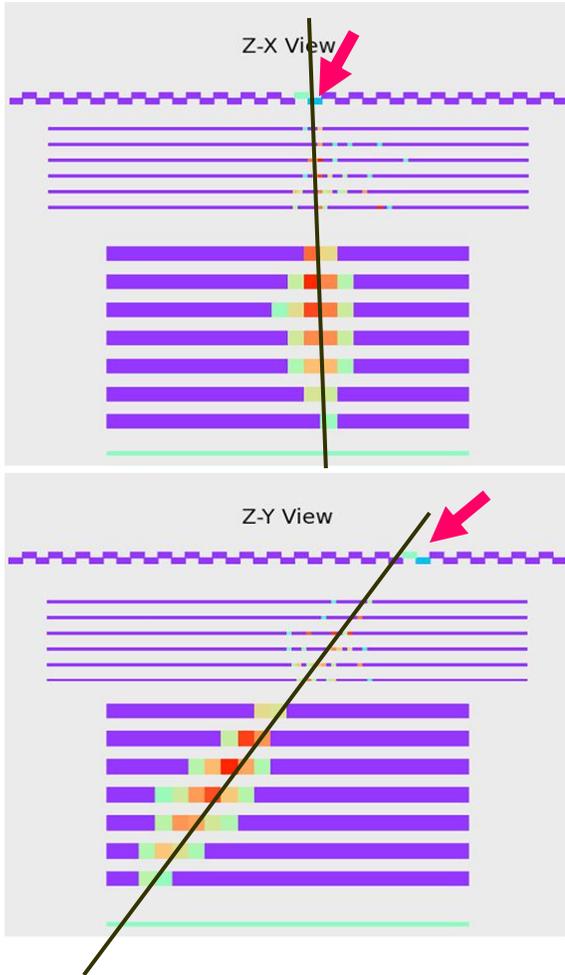
- Thick calorimeter ( $32 X_0$ ): high-resolution
- Two-side readouts
- Three dynode outputs enable a  $>10^6$  dynamic range

# 能量测量

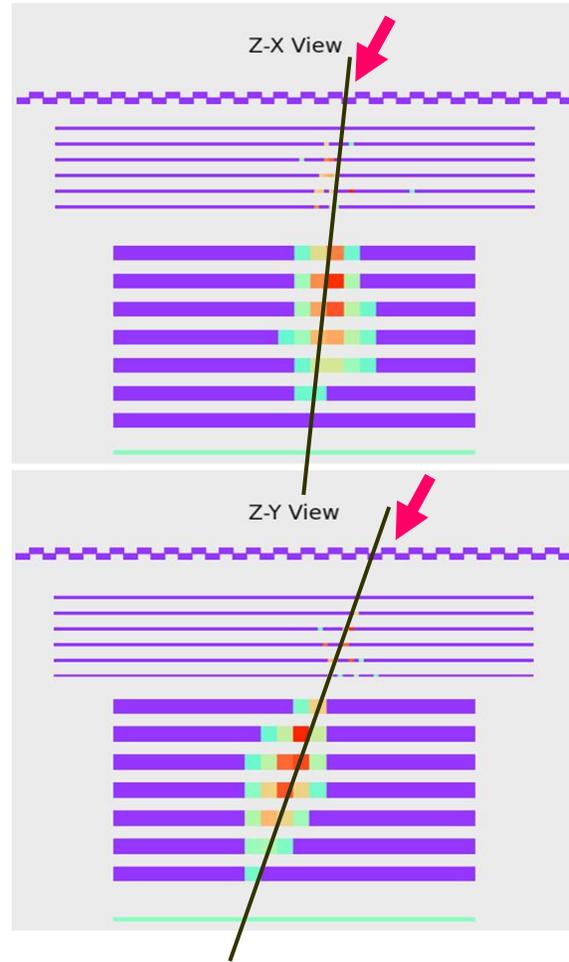


# 粒子鉴别

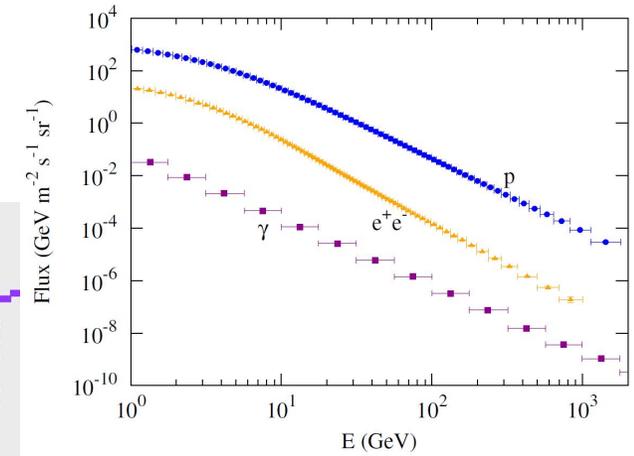
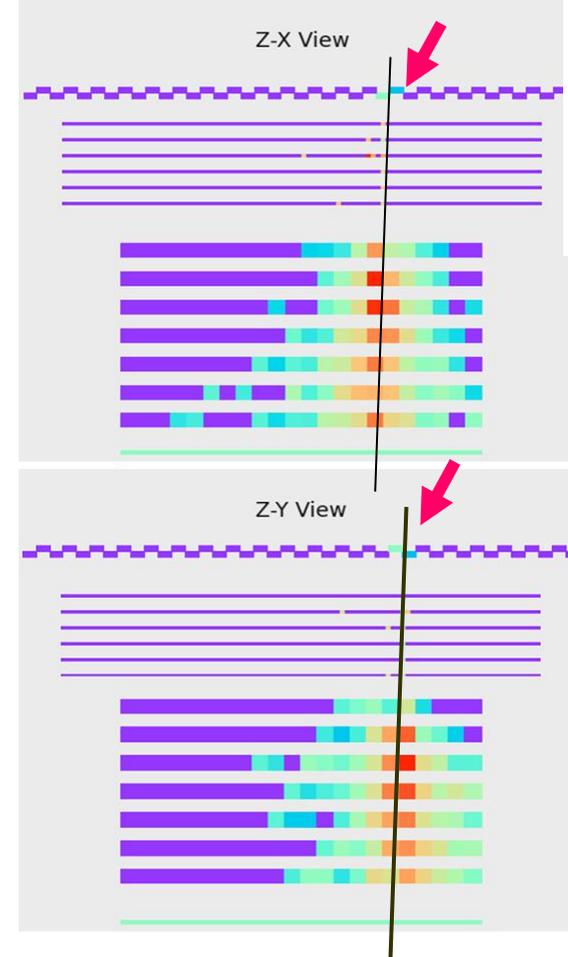
电子



伽马



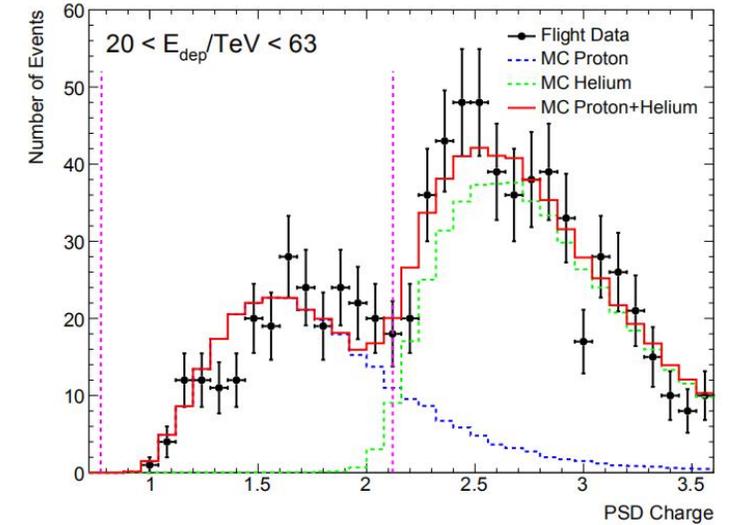
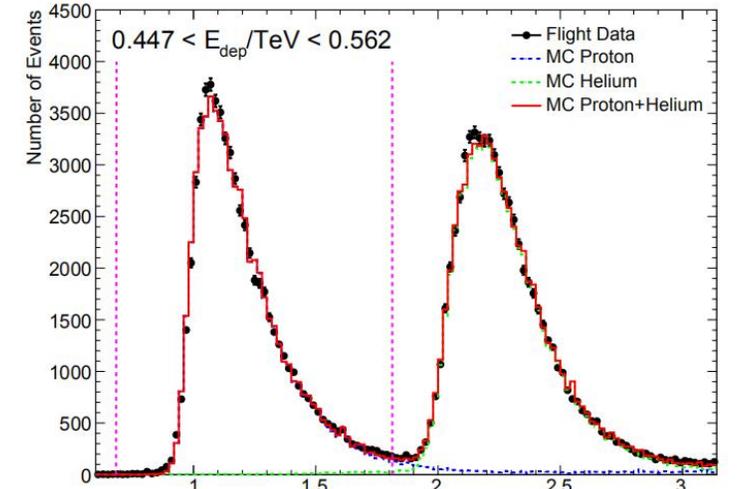
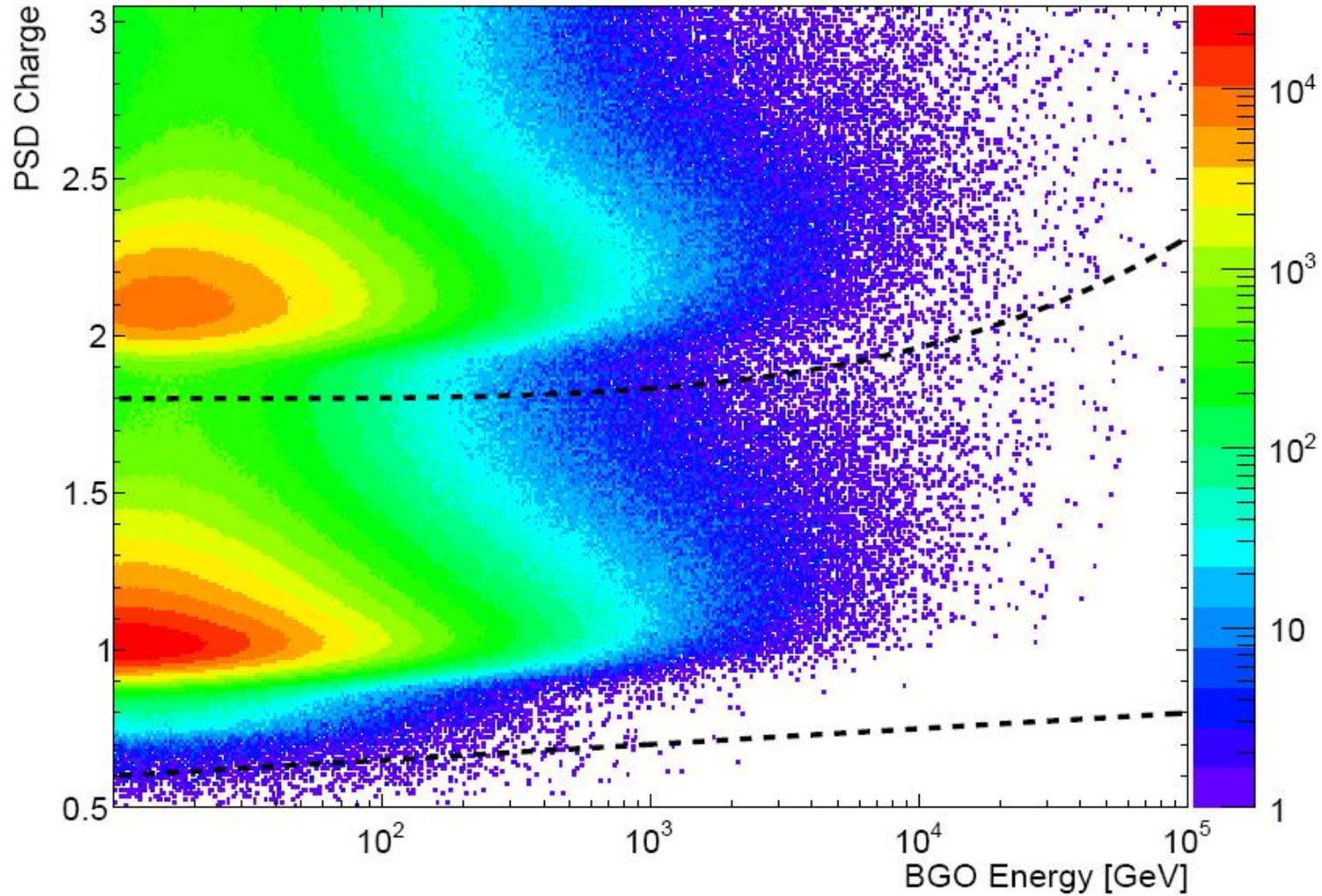
质子



➤ 电荷测量区分伽马、质子电子、重离子

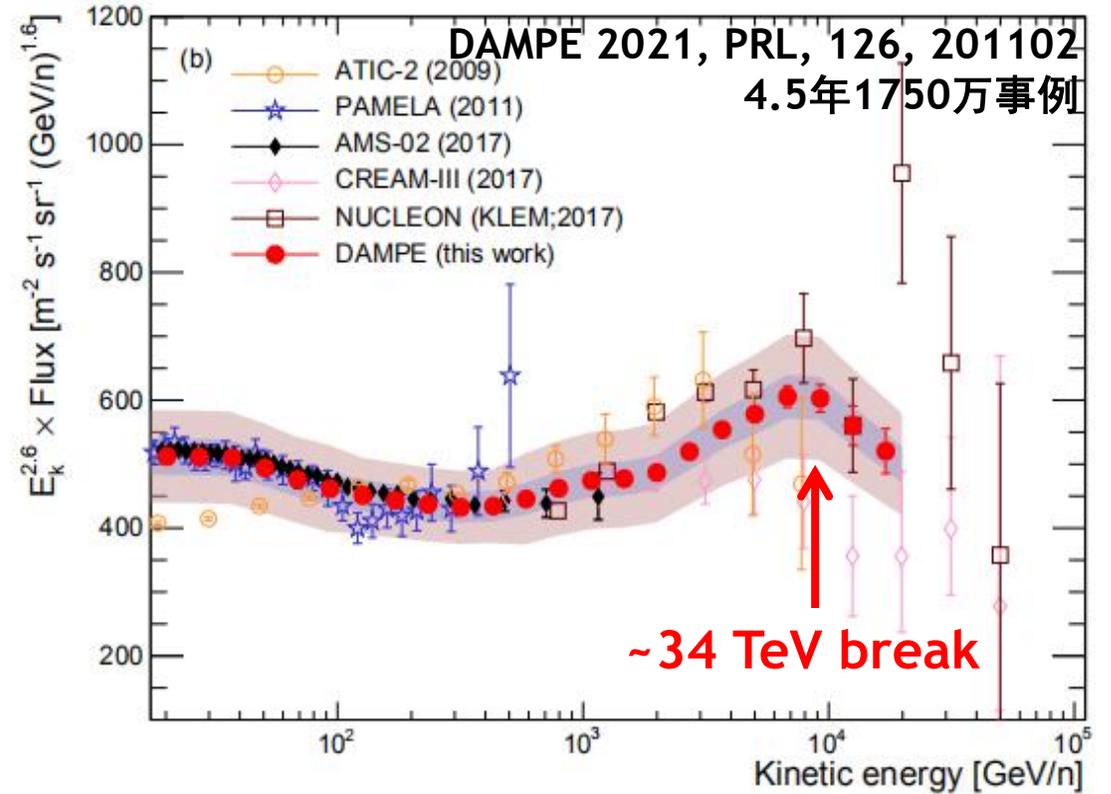
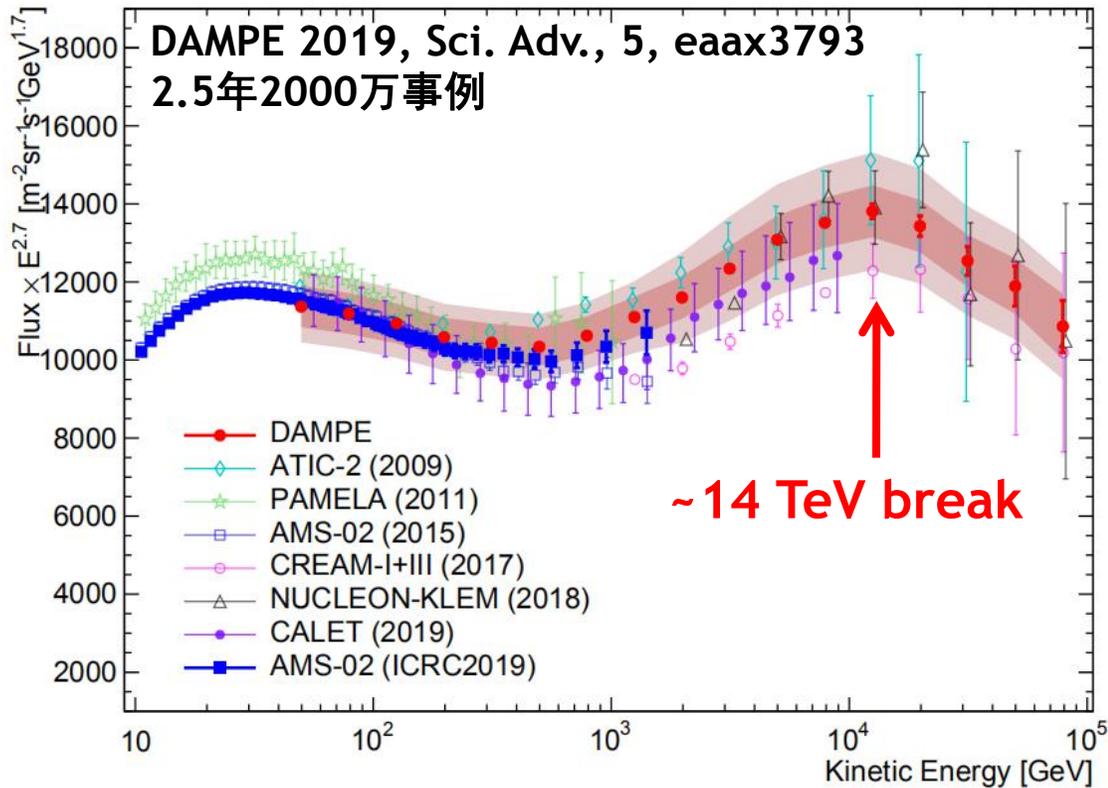
➤ 簇射形态区分质子和电子：强子相互作用和电磁相互作用的差异

# 质子氦核鉴别



*Sci. Adv.*, 5, eaax3793 (2019)

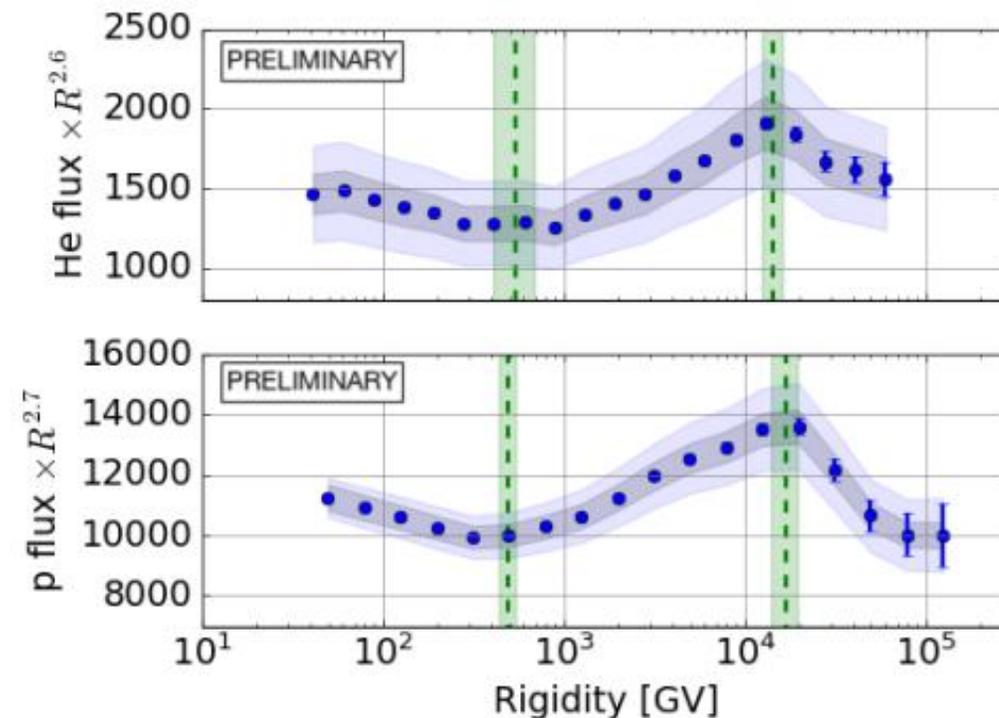
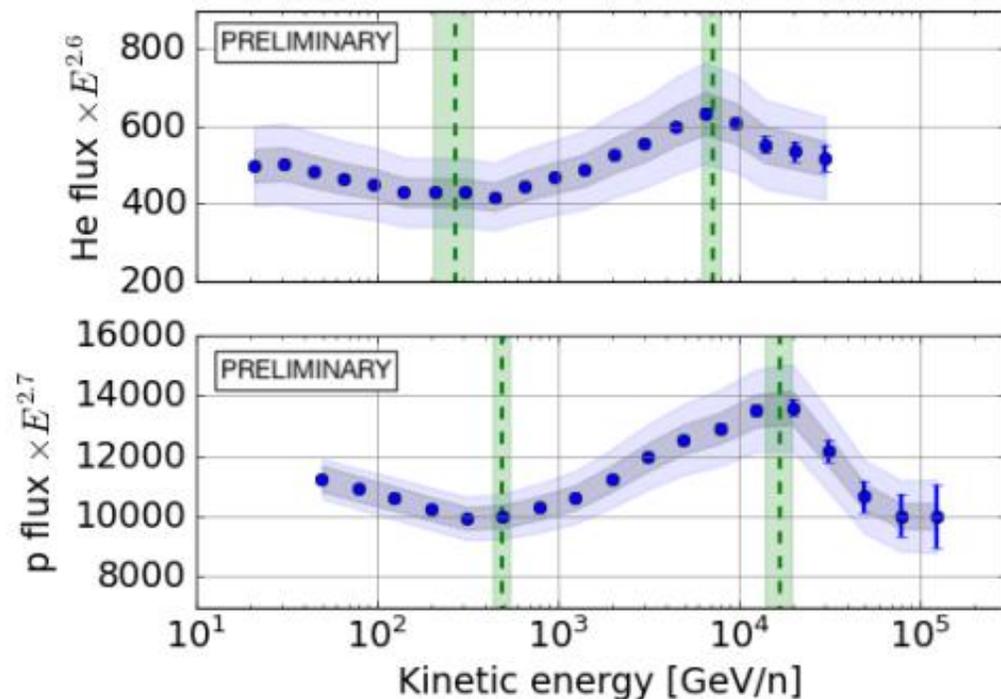
# 质子和氦核能谱测量



- 质子和氦核能谱显示出非常类似的变硬+变软的结构；变软的结构首次由“悟空”号以高置信度测得
- 质子和氦核变软能量近似正比于粒子电荷Z

# 质子和氦核能谱测量

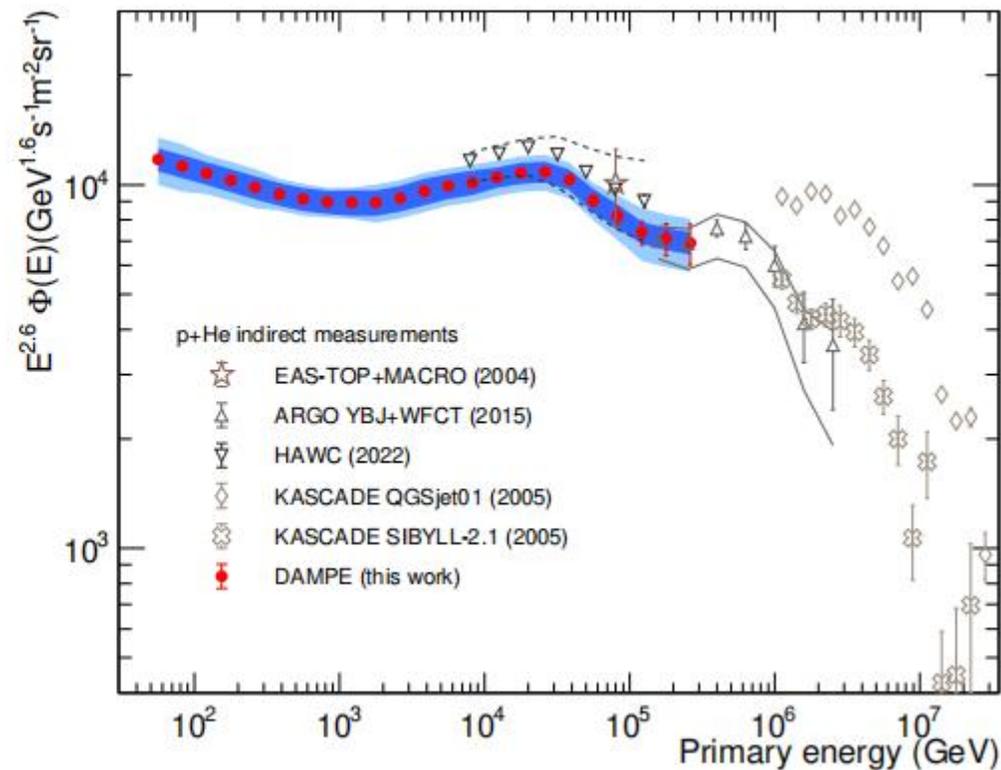
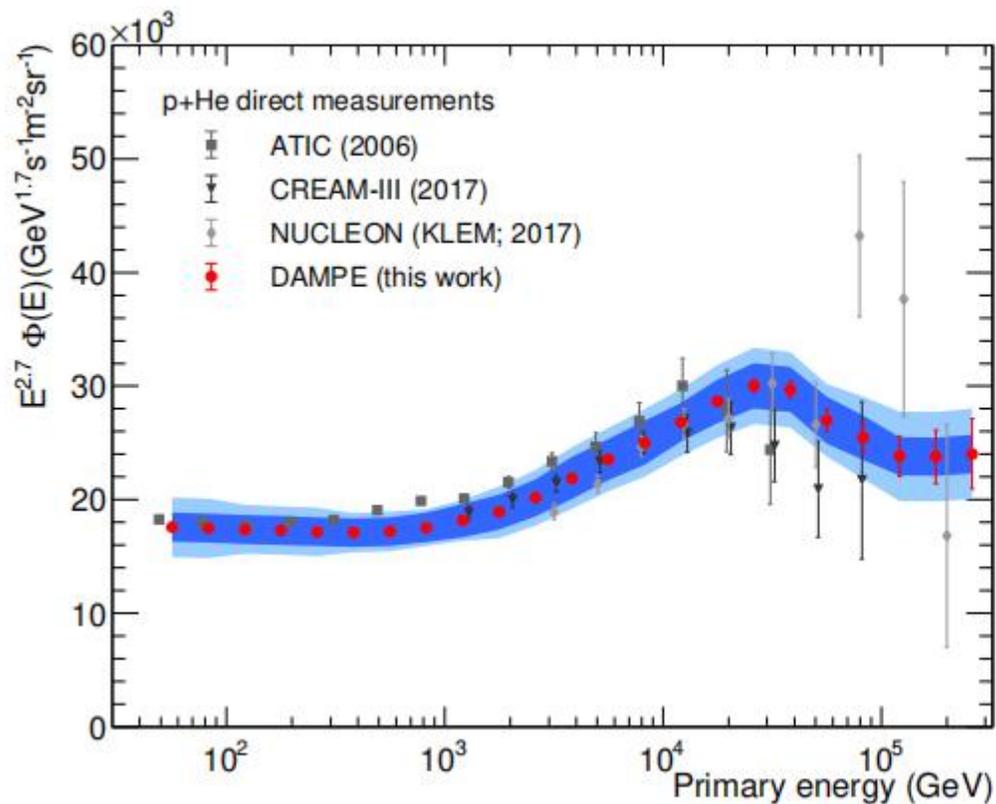
DAMPE 2023, ICRC



质子和氦核结构出现在相同磁刚度处：加速或传播机制？

# 质子+氦核能谱测量

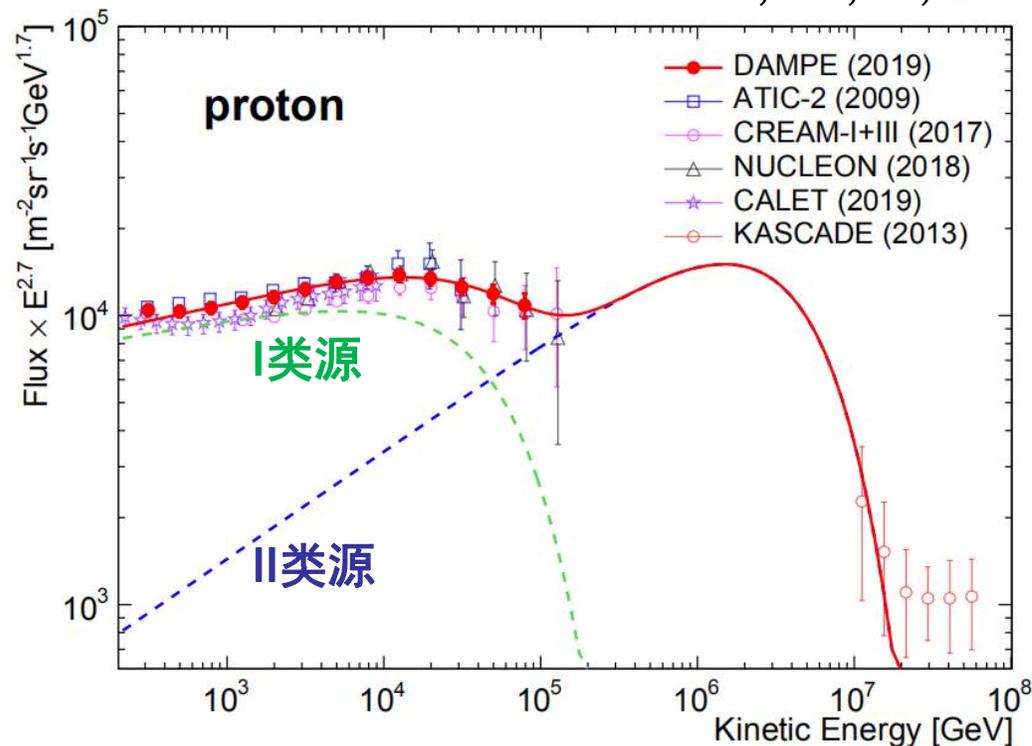
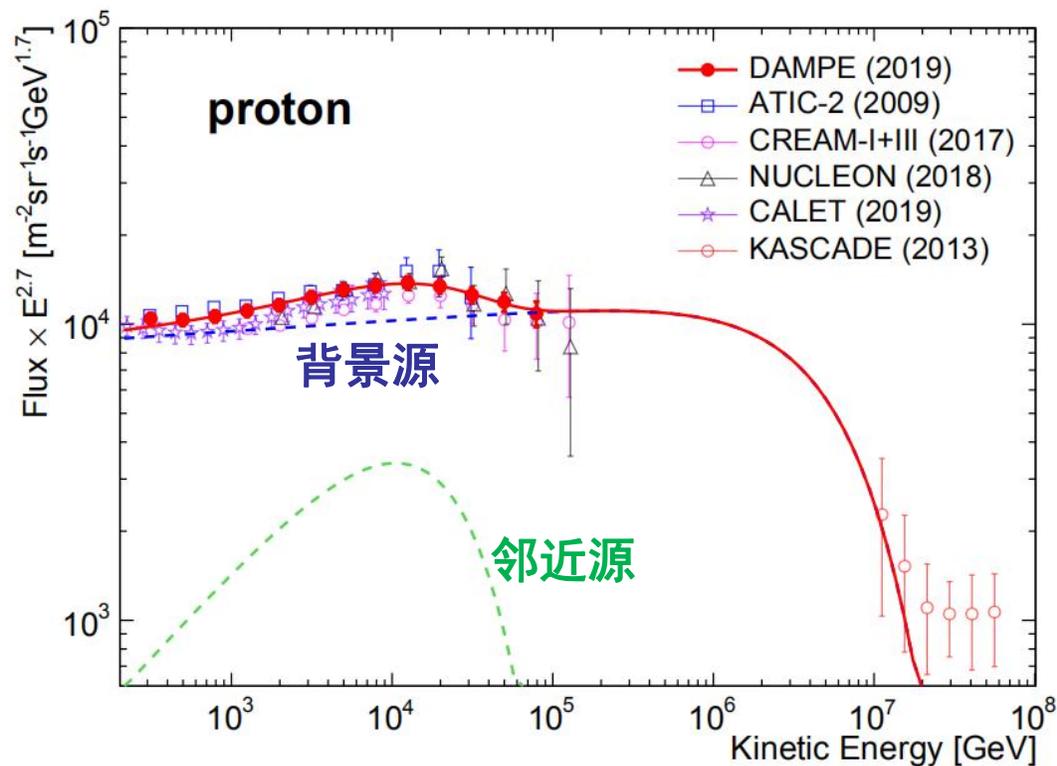
DAMPE 2023, 2304.00137



同样揭示出先变硬再变软的拐折结构，在100 TeV以上可能有再拐折的迹象

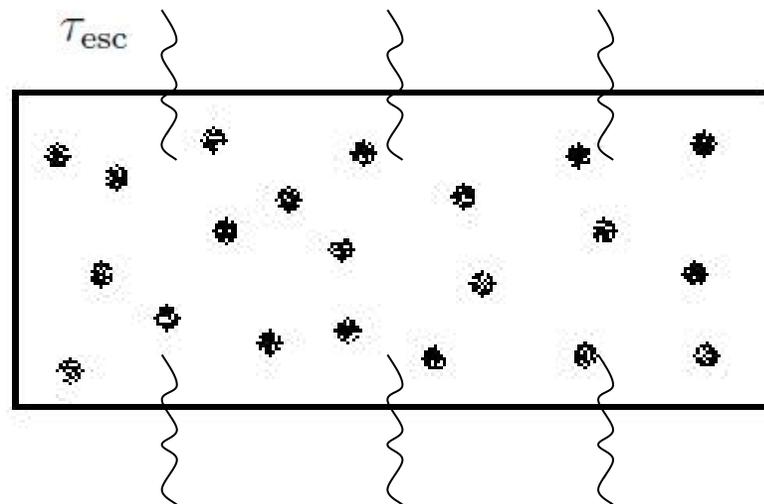
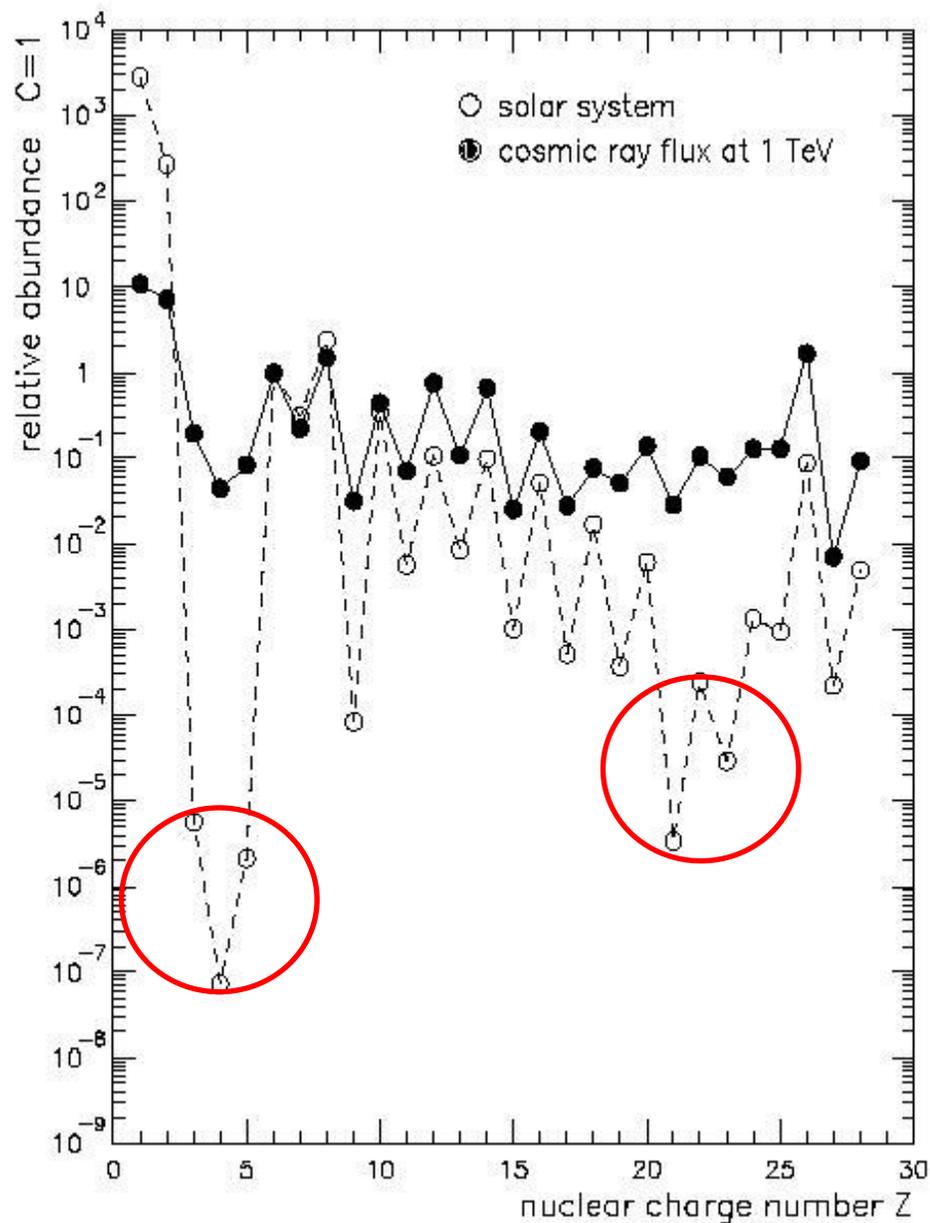
# 宇宙线能谱拐折的物理含义

Yue et al., FoP, 15, 24601 (2020)



- 该处拐折行为可能是**邻近**地球的一处**宇宙线加速源**留下的印记，拐折能量对应于该源的加速能力上限(左图)
- 也可能是宇宙线源存在**不同类别**，例如Ia型超新星和II型超新星(右图)

# 次级宇宙线：宇宙线传播探针



$$\frac{\partial N(E, t)}{\partial t} = Q(E, t) - \frac{N(E, t)}{\tau_{\text{esc}}(E)} - \frac{N(E, t)}{\tau_i(E)} - \frac{N(E, t)}{\gamma\tau_d}$$

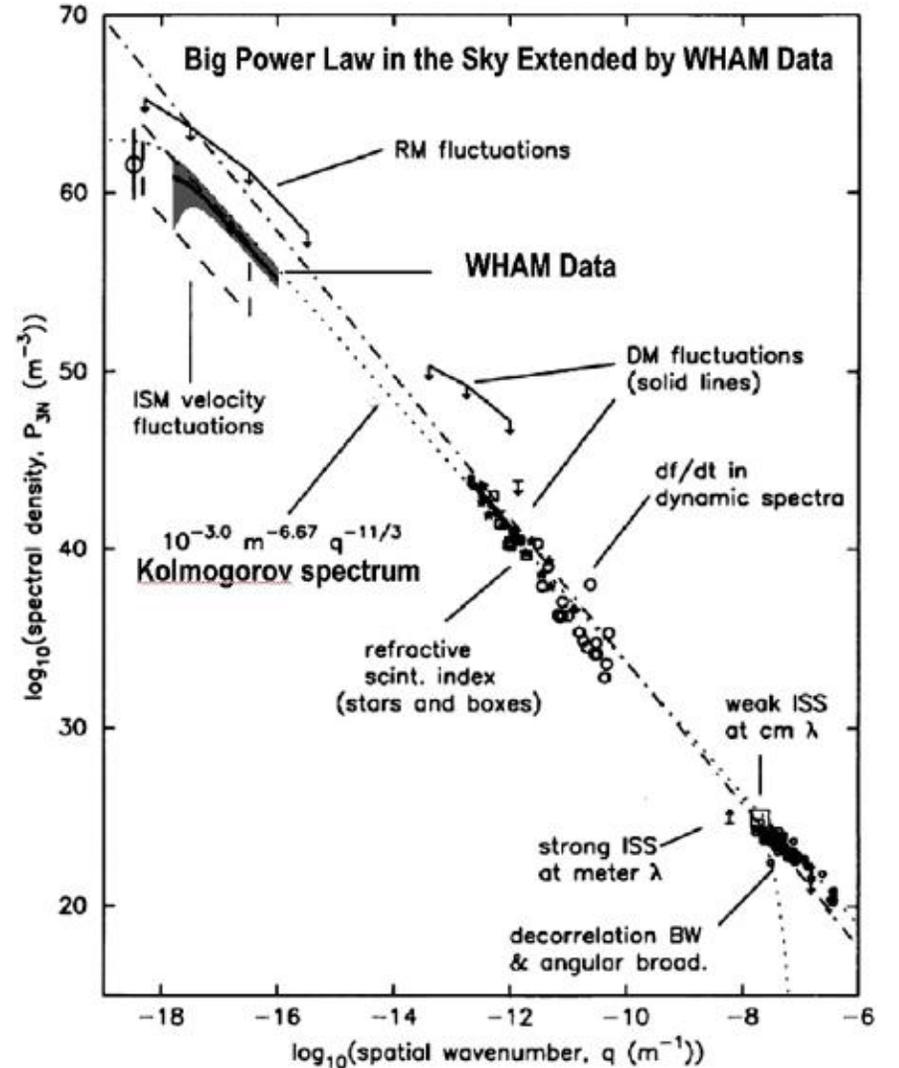
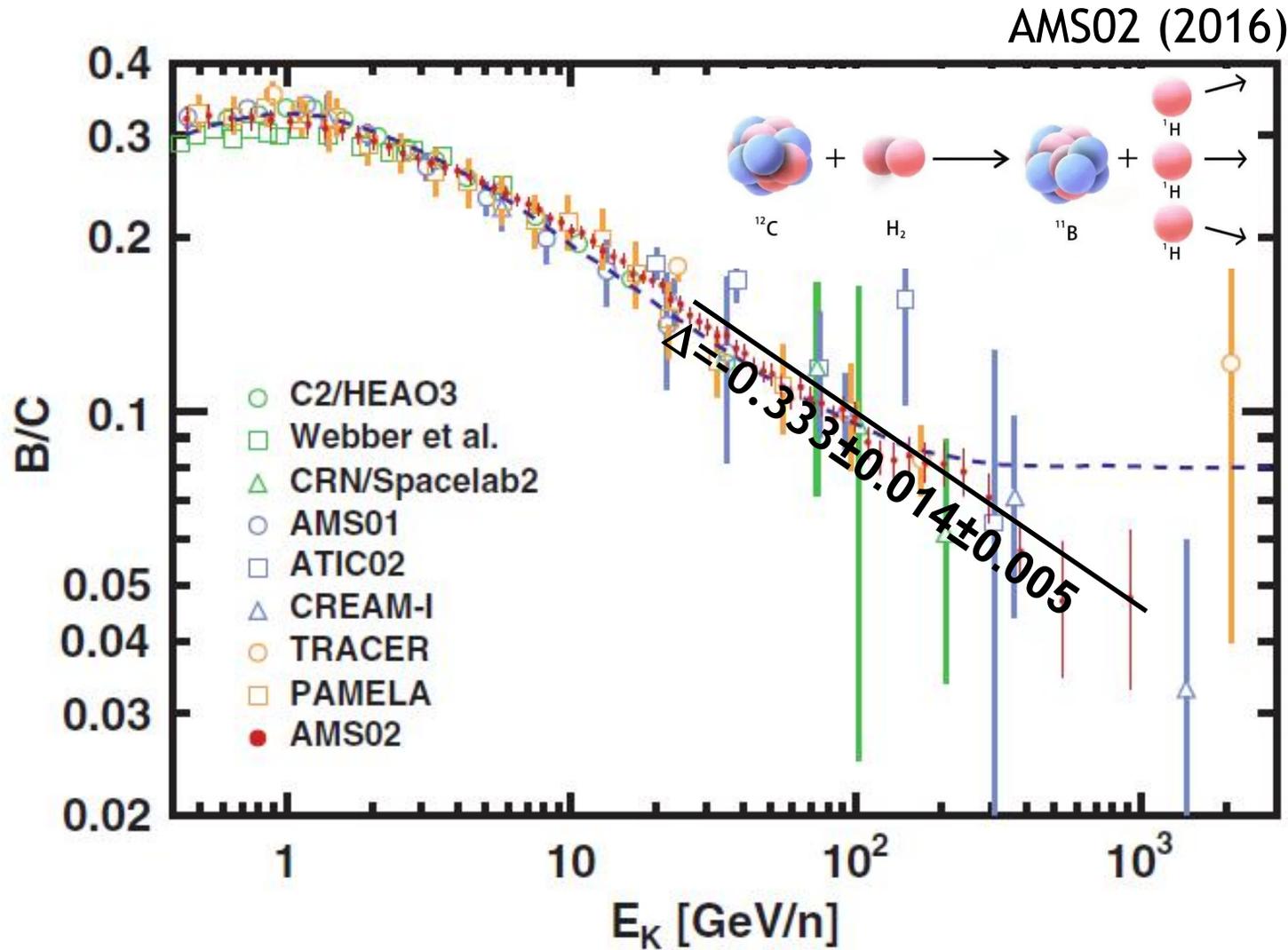
$$N(E) = Q(E) \times \left( \frac{1}{\tau_{\text{esc}}(E)} + \frac{1}{\tau_i(E)} + \frac{1}{\gamma\tau_d} \right)^{-1}$$

$$\frac{N_S}{N_P} = \frac{\tau_{\text{tot}}}{\tau_{P \rightarrow S}}, \quad \tau_{P \rightarrow S} = \frac{1}{n\sigma v}$$

$$\tau_{\text{tot}} = \left( \frac{1}{\tau_{\text{esc}}} + \frac{1}{\tau_i} + \frac{1}{\gamma\tau_d} \right)^{-1}$$

# 次级宇宙线：宇宙线传播探针

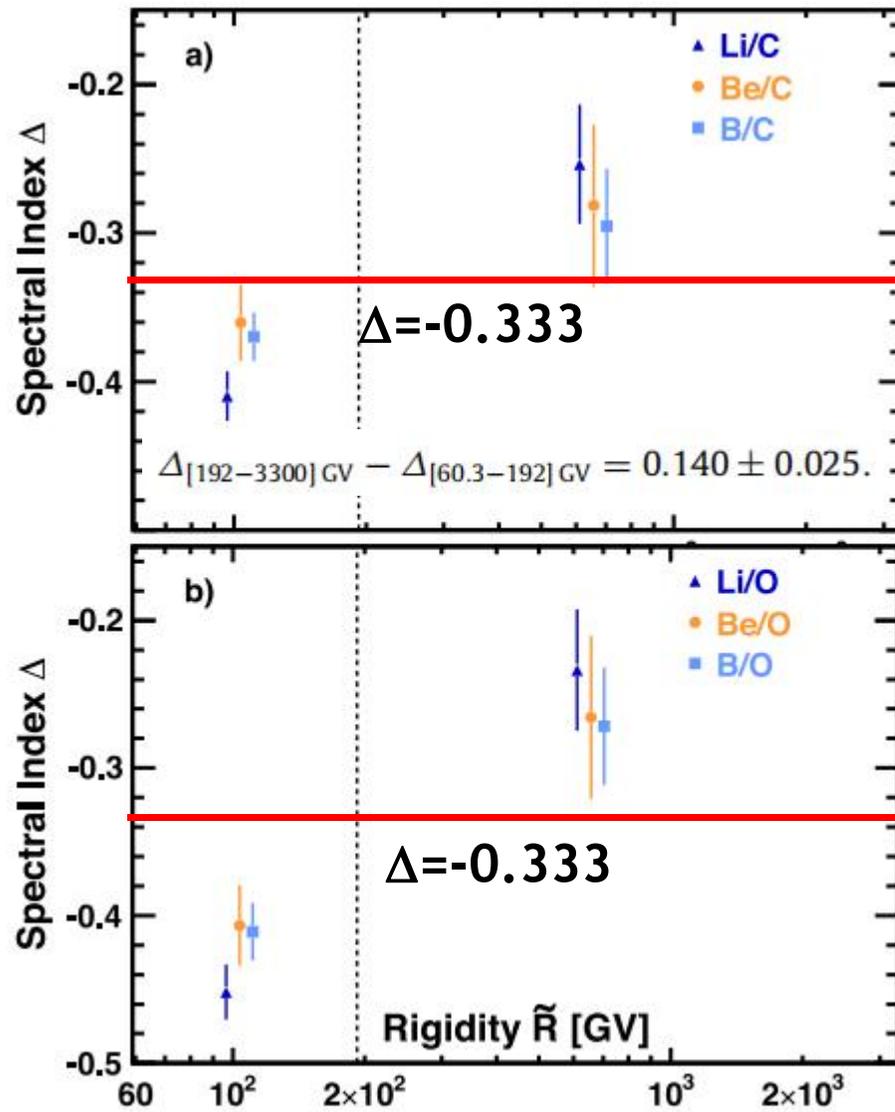
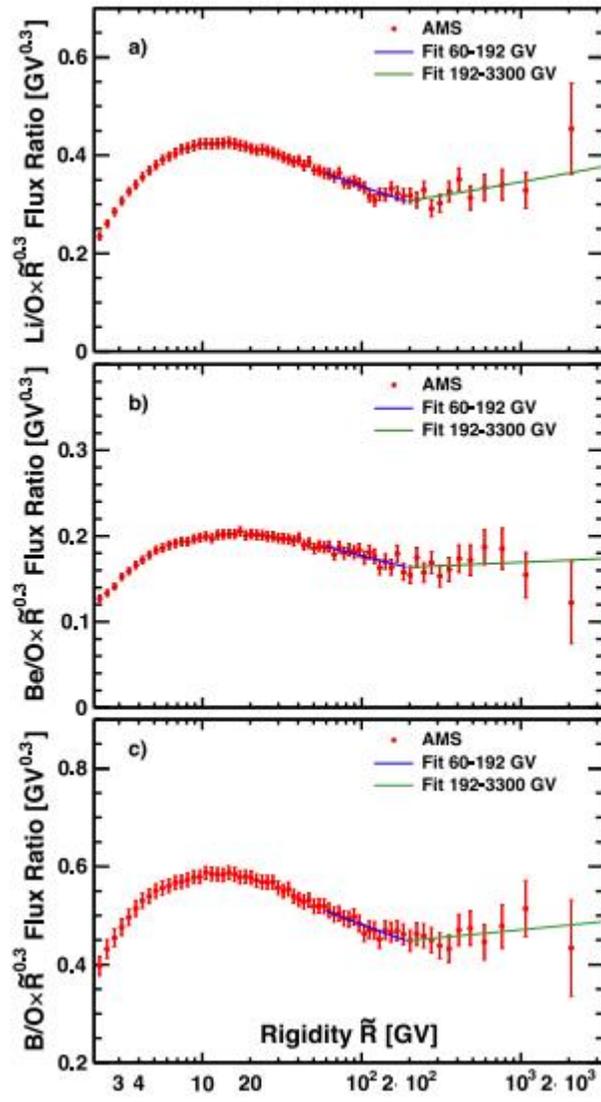
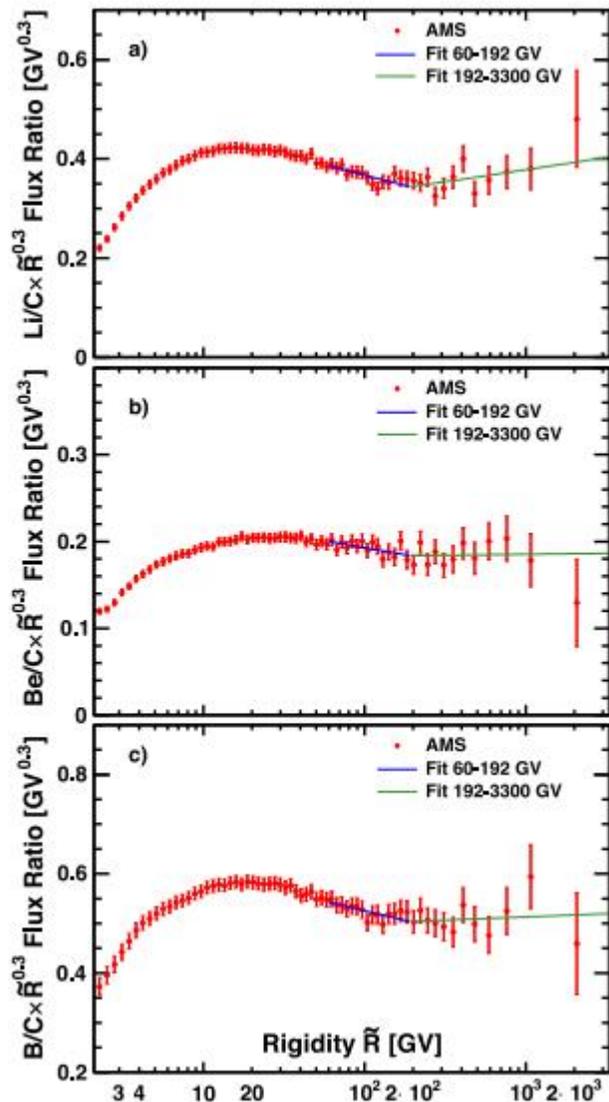
Browning & Lazarian (2013)



Distribution of ISM turbulence

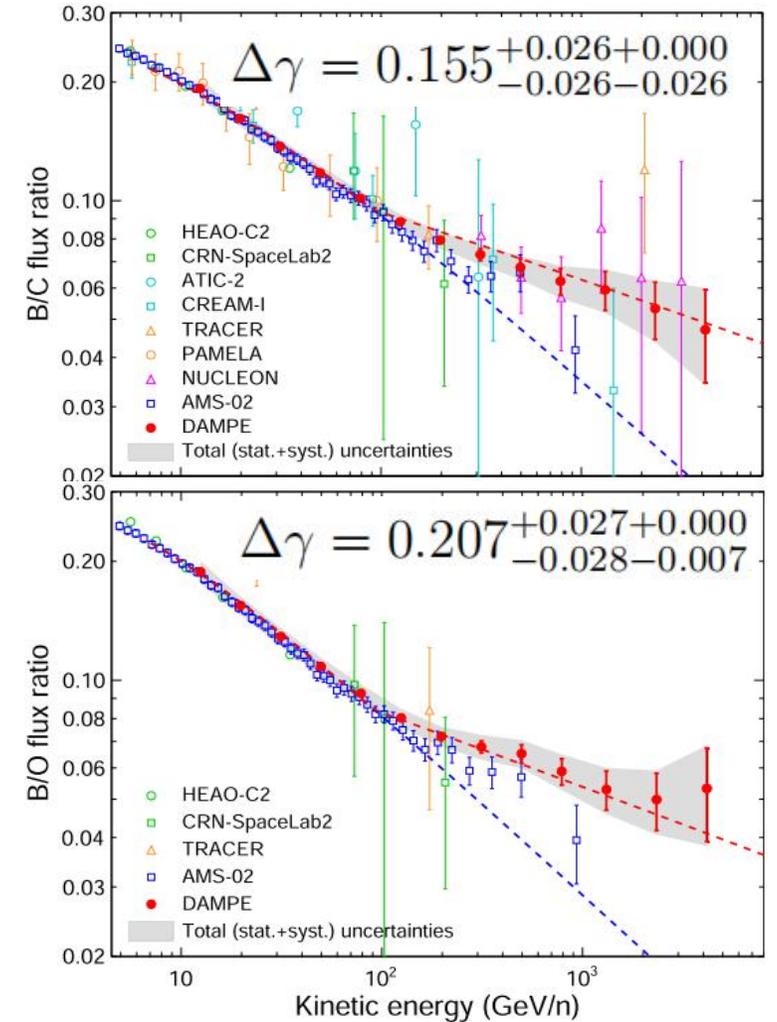
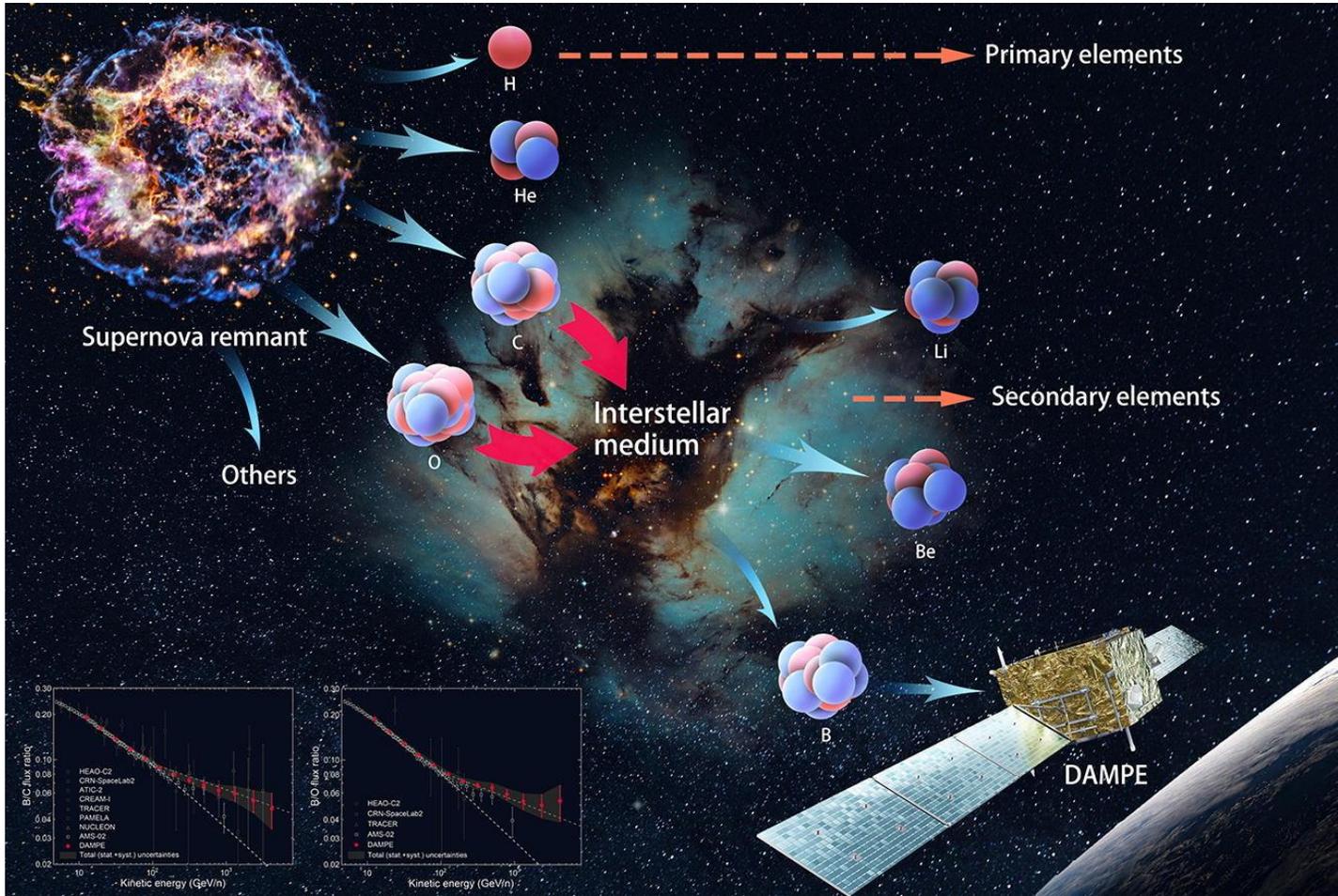
# 次级/初级宇宙线比例

AMS02 (2021, Phys. Rept.)



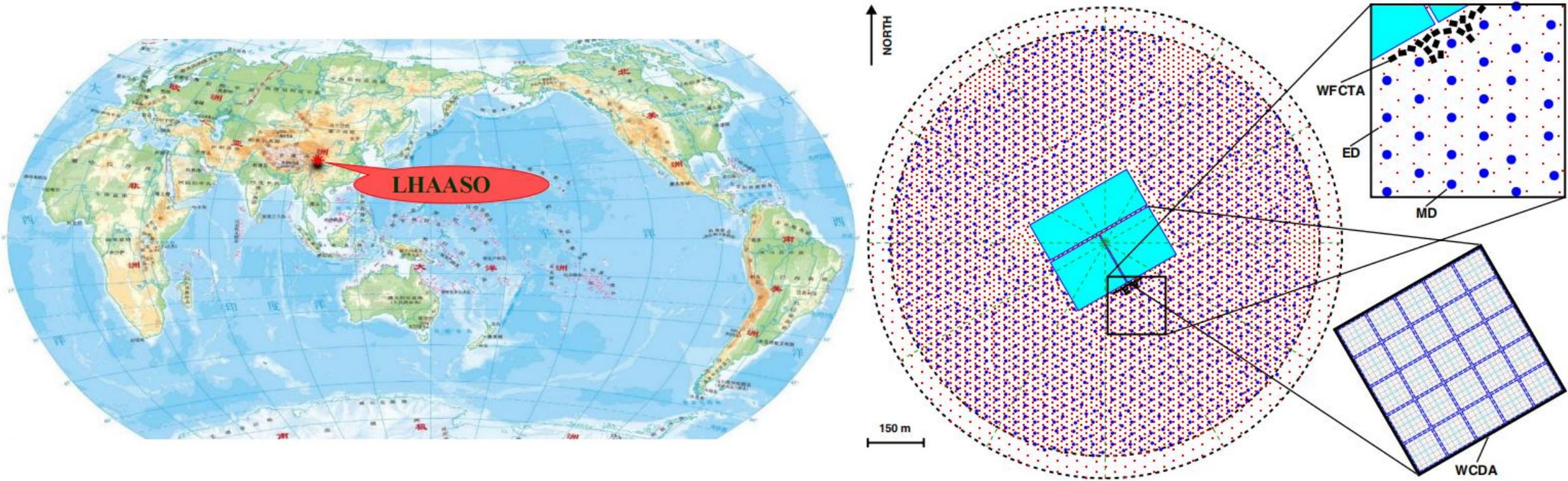
# DAMPE精确测量B/C和B/O的拐折

2022, Sci. Bull., 67, 2162



- DAMPE以高置信度观测到B/C和B/O的拐折行为，二者拐折位置均为~100 GeV/n
- 可能反映了宇宙线扩散传播的能量依赖性质的变化（对应于星际介质湍动性质的变化）

# 高海拔宇宙线观测站——LHAASO

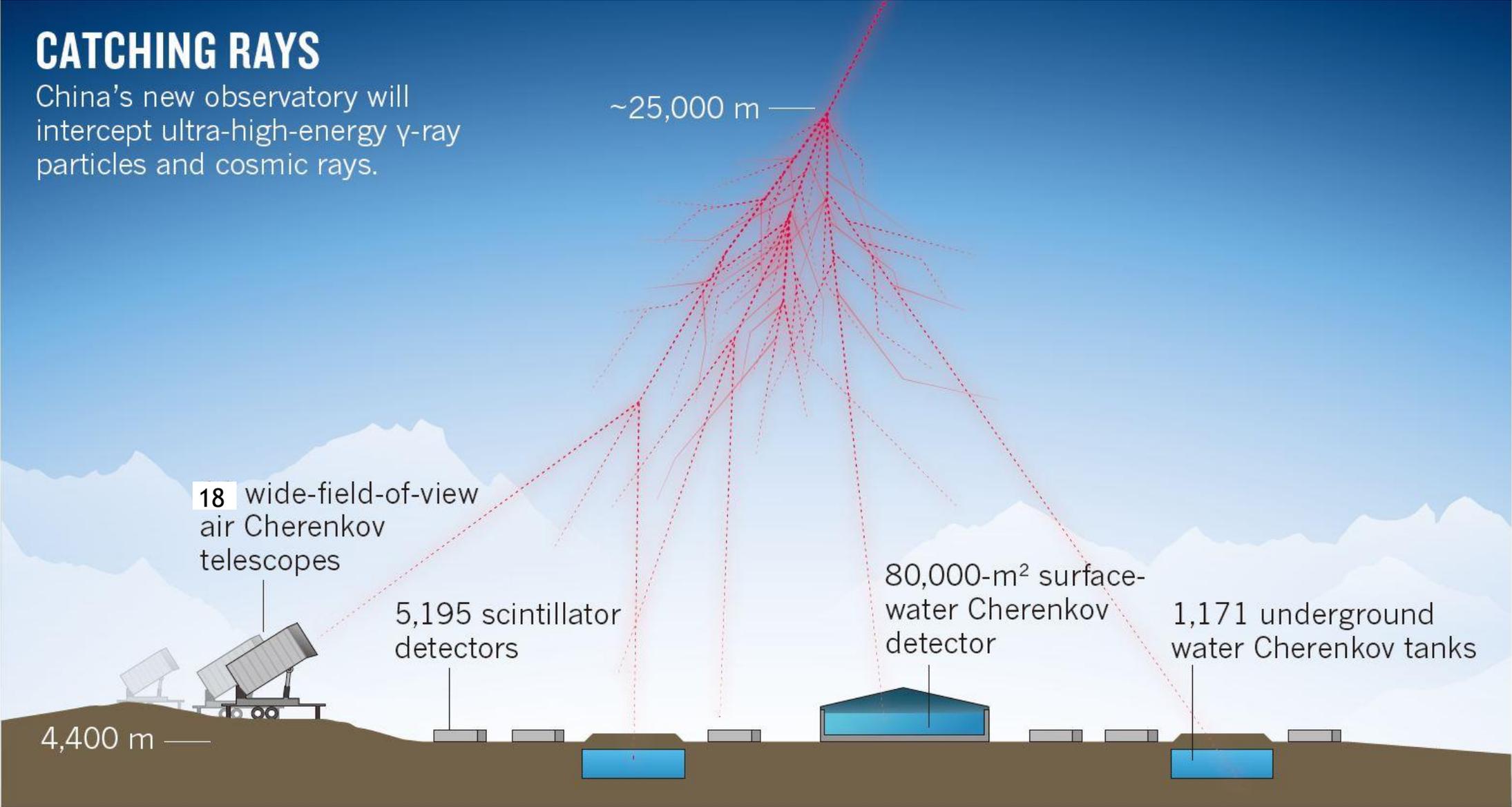


- Haizi mountain, Sichuan, China, 4410 m above the sea level
- LHAASO uses hybrid detector arrays: the square kilometer array (KM2A), the water Cherenkov detector array (WCDA), and the wide field-of-view Cherenkov telescope array (WFCTA)
- Full operation since July 2021

# LHAASO复合探测阵列

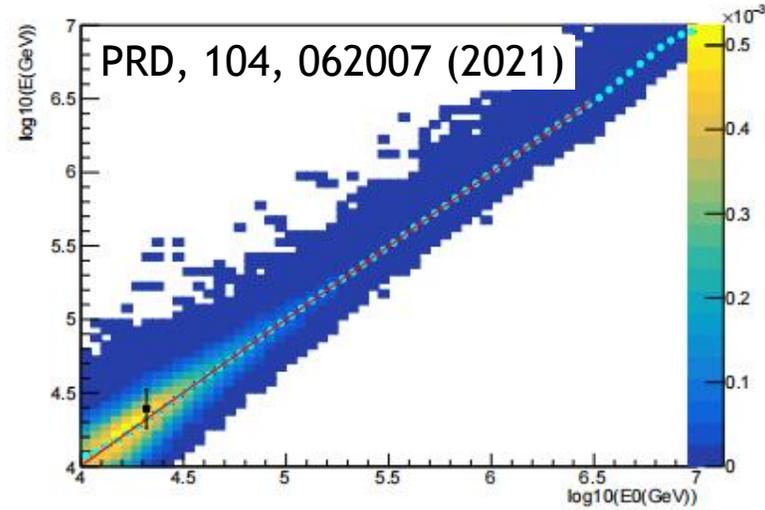
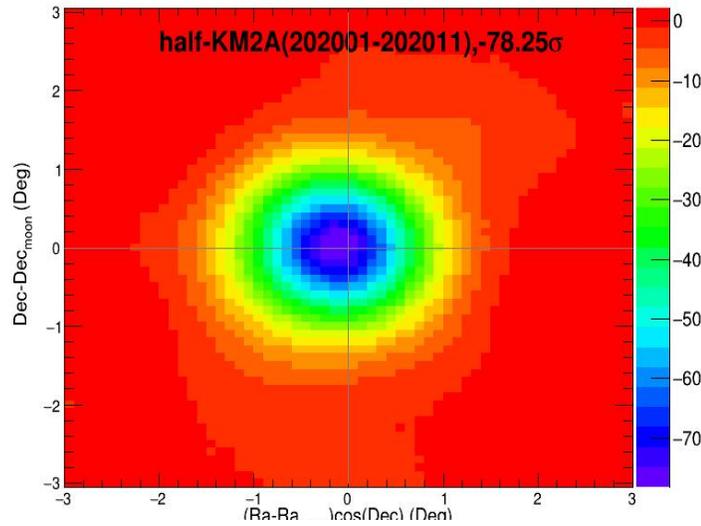
## CATCHING RAYS

China's new observatory will intercept ultra-high-energy  $\gamma$ -ray particles and cosmic rays.

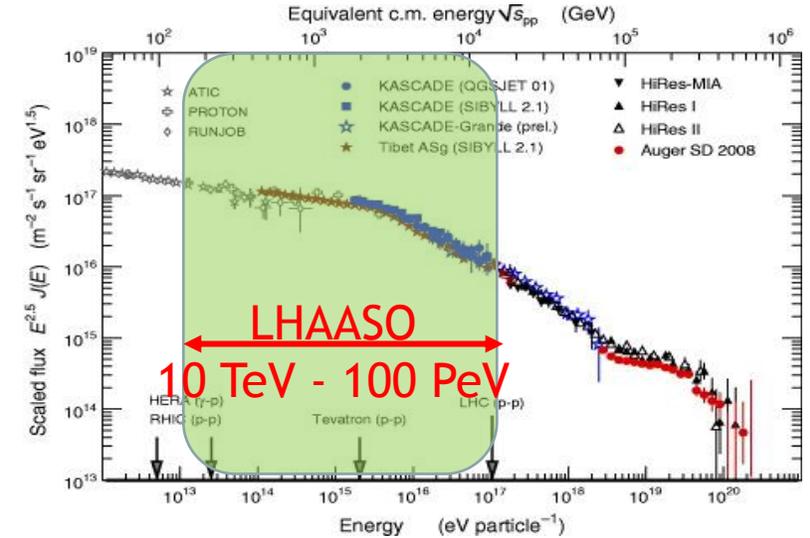


# LHAASO性能指标

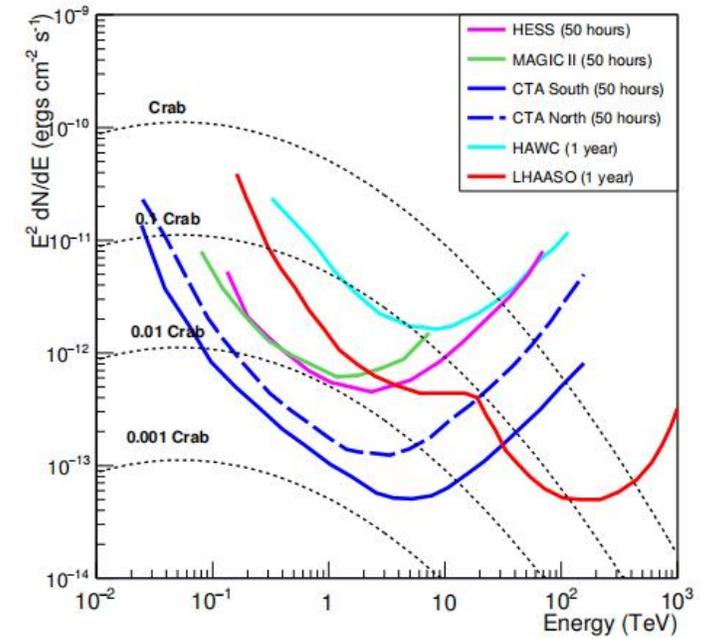
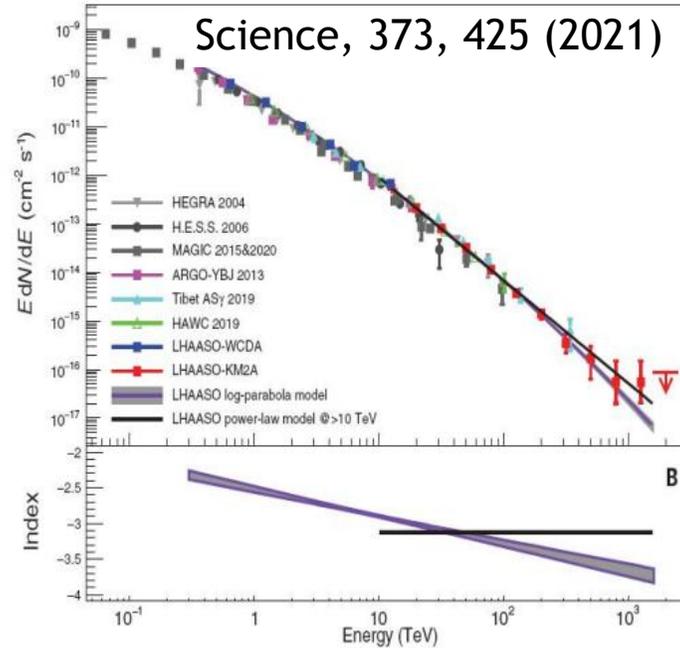
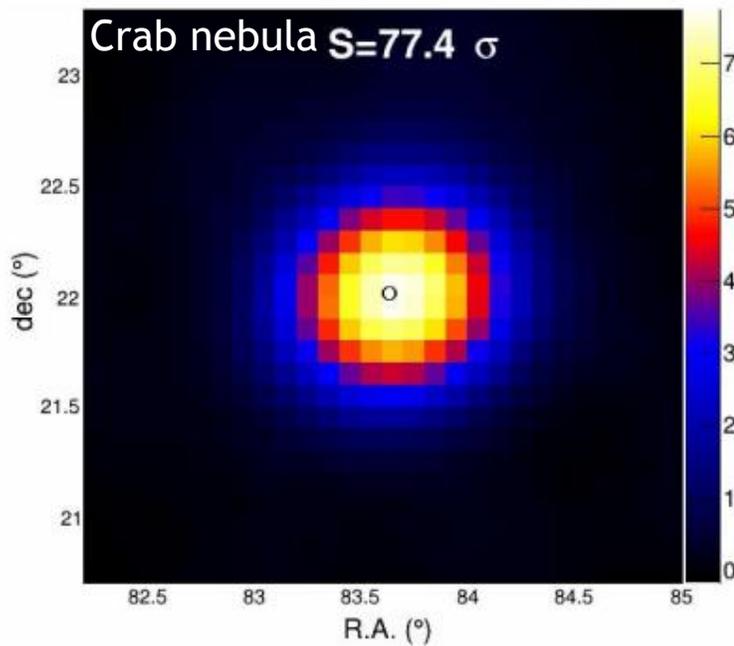
Moon shadow



Chin. Phys. C, 46, 035002 (2022)



Crab nebula  $S=77.4 \sigma$



# LHAASO开启PeV窗口

LHAASO, Nature, 594, 33 (2021)

## Article

# Ultrahigh-energy photons petaelectronvolts from 12 sources

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

Received: 21 October 2020

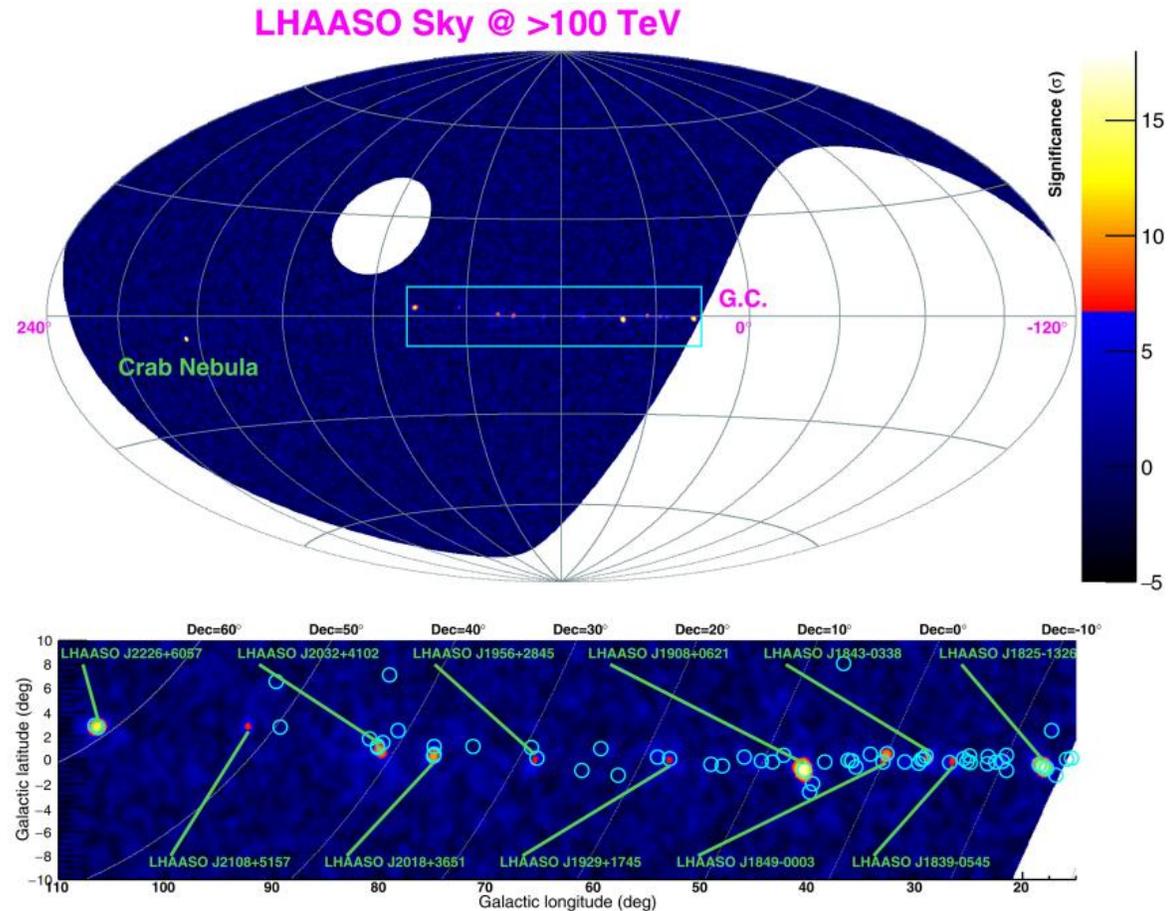
Accepted: 26 March 2021

Published online: 17 May 2021

 Check for updates

A list of authors and affiliations appears at the end of this article.

The extension of the cosmic-ray spectrum (to energies up to 1.4 petaelectronvolts) indicates the existence of particle acceleration factories that accelerate particles to these energies. We search for objects to find the origin of Galactic cosmic rays.

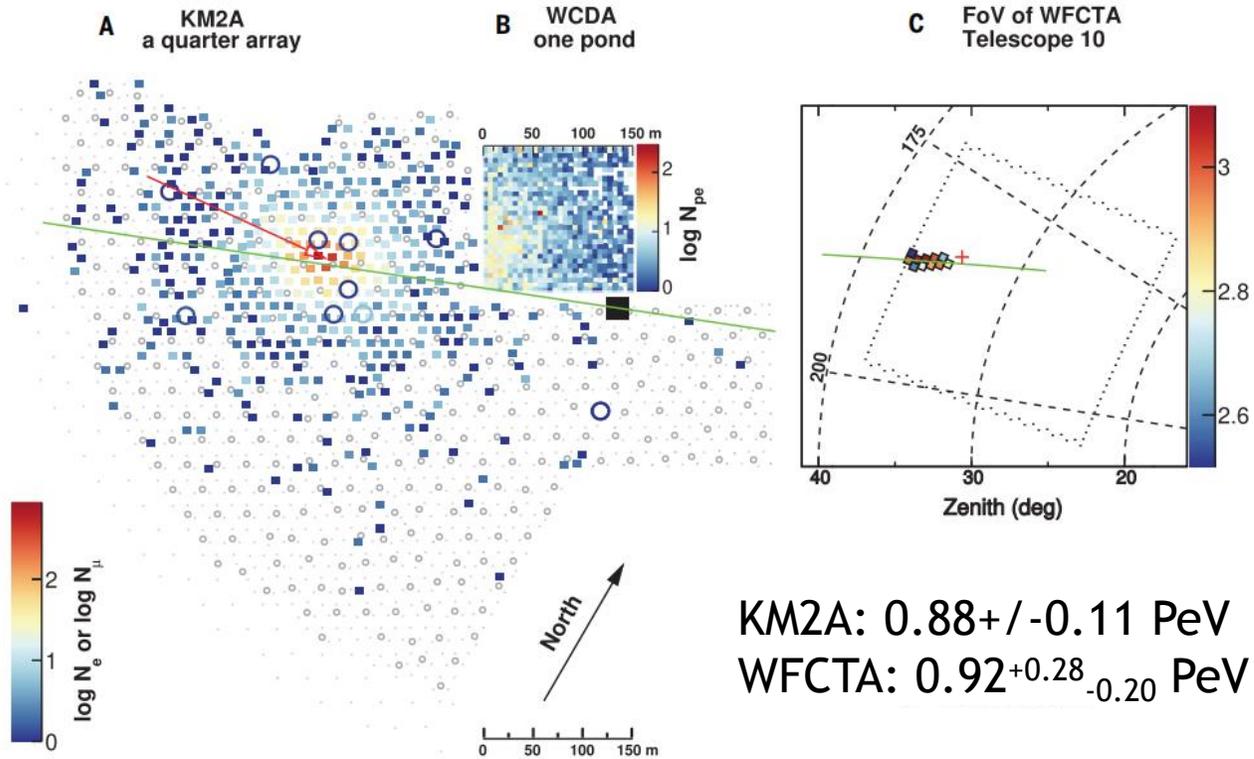


LHAASO discovered a number of PeVatrons, successfully opens the PeV window

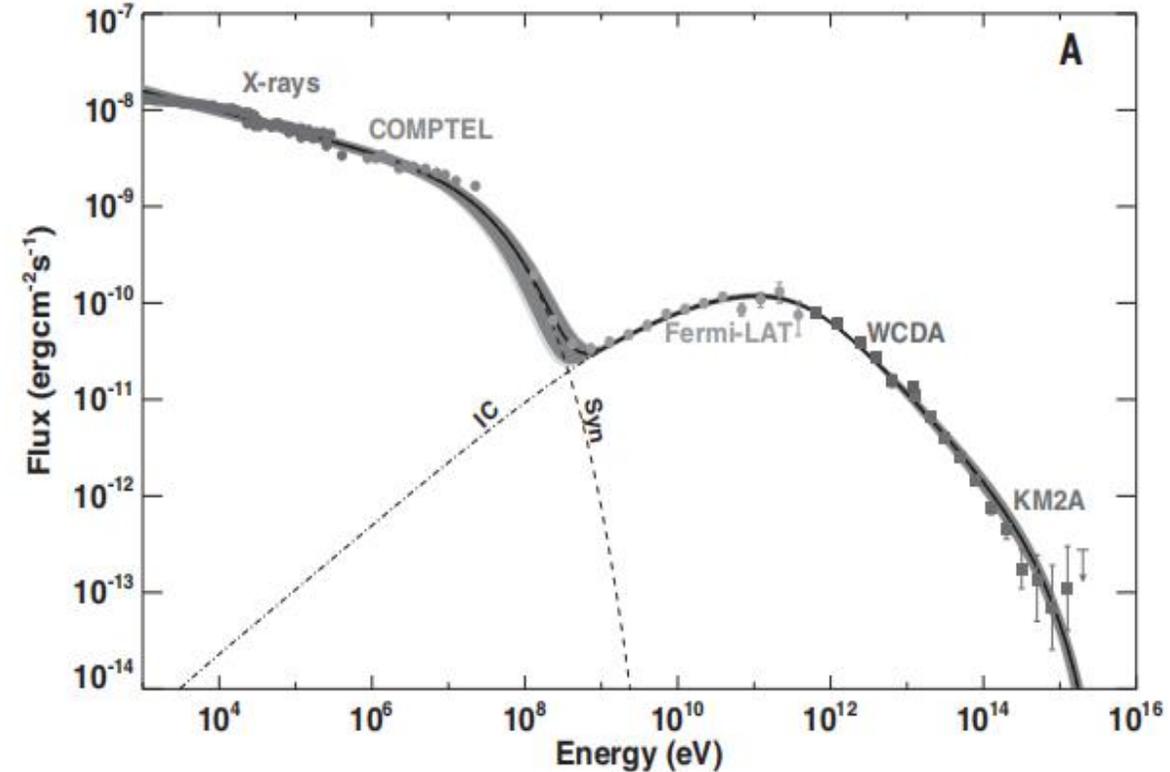
# LHAASO观测到crab PeV光子

Acceleration of PeV electrons by Crab nebula

LHAASO, Science, 373, 425 (2021)



KM2A:  $0.88 \pm 0.11$  PeV  
WFCTA:  $0.92^{+0.28}_{-0.20}$  PeV



LHAASO measurement of the Crab nebula spectrum extends to PeV, revealing PWNe as PeV electron accelerator

# LHAASO揭示出脉冲星附近的慢扩散

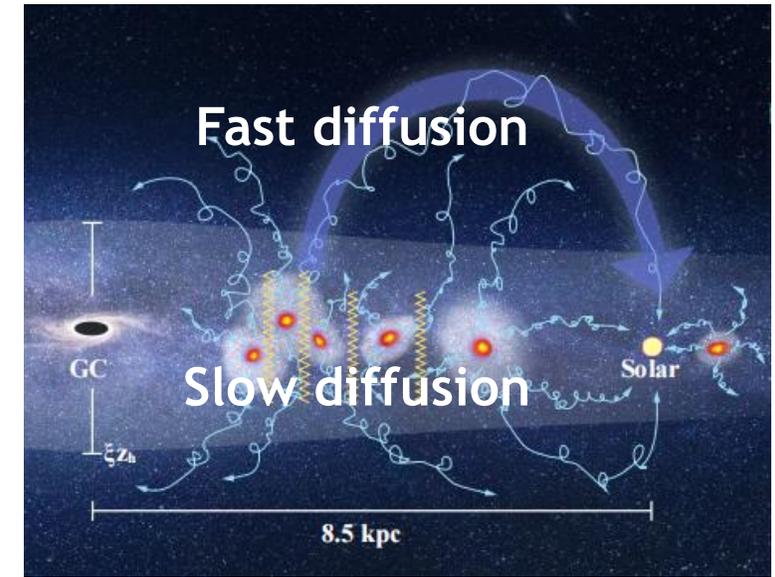
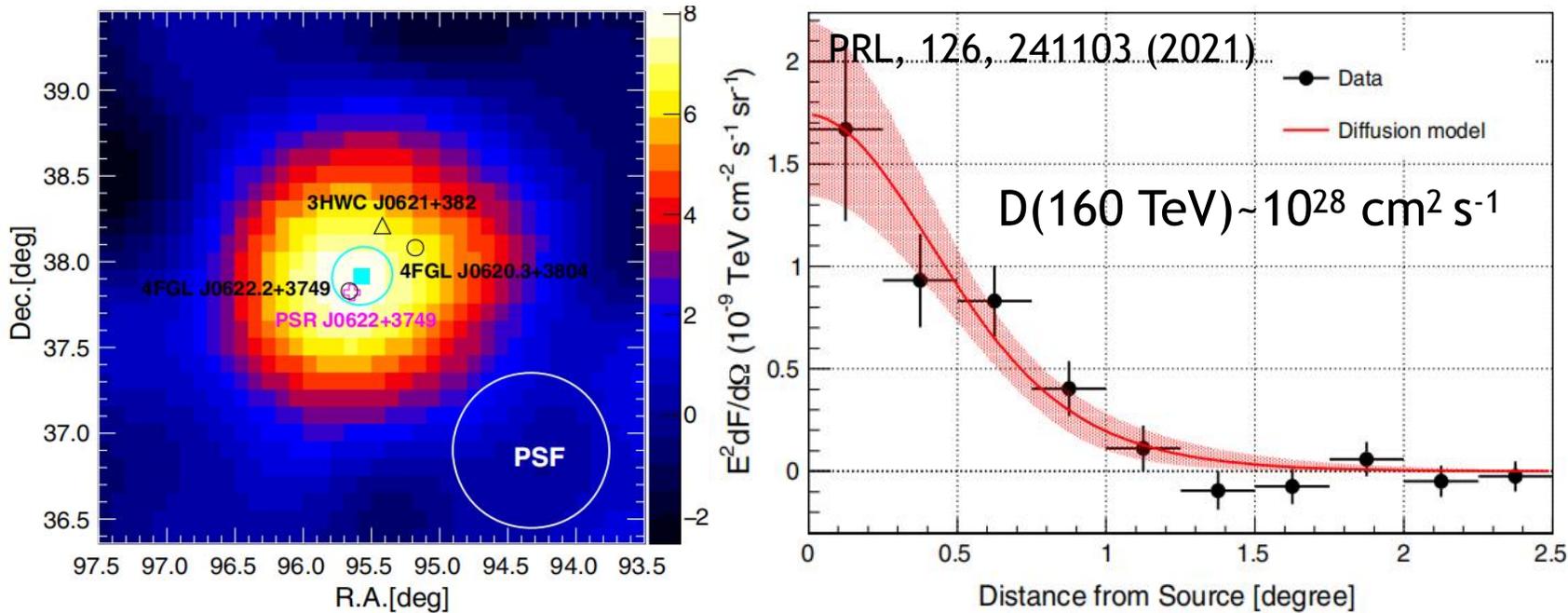


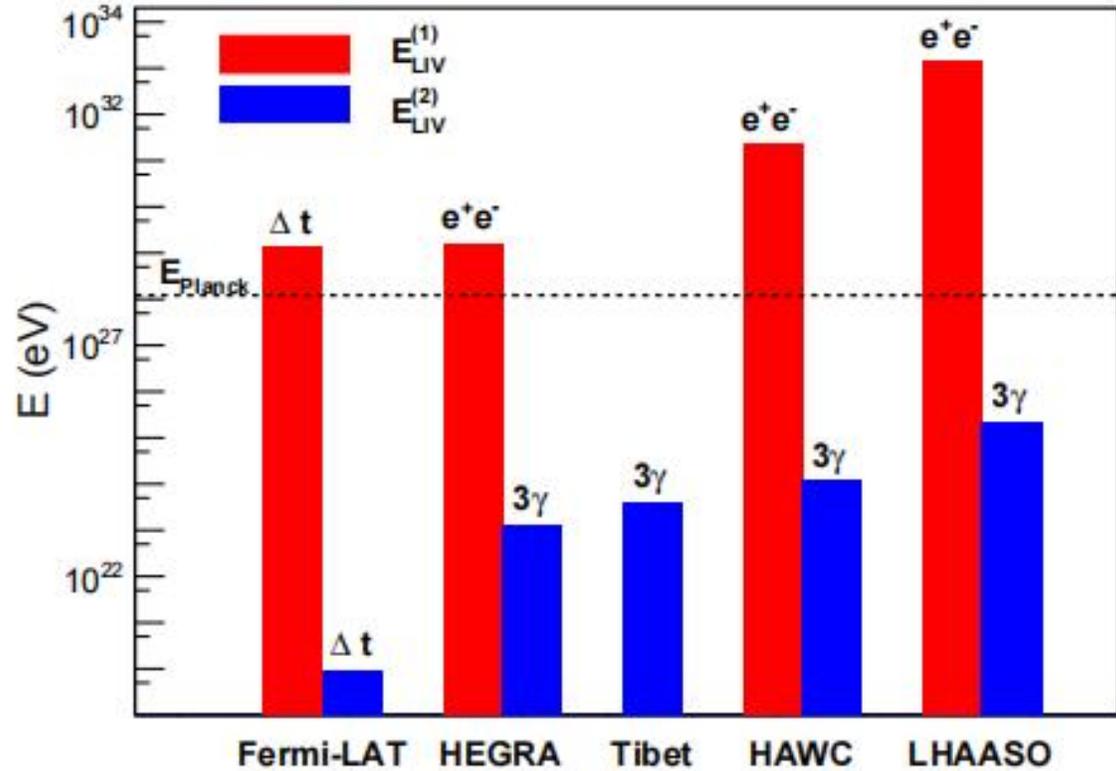
TABLE II. Comparison of the properties of pulsars J0622 + 3749, Geminga, and Monogem.

Name	$P$ (s)	$\dot{P}$ ( $10^{-14}$ $\text{s s}^{-1}$ )	$L_{\text{sd}}$ ( $10^{34}$ $\text{erg s}^{-1}$ )	$\tau$ (kyr)	$d$ (kpc)	Ref.
J0622 + 3749	0.333	2.542	2.7	207.8	1.60	[25]
Geminga	0.237	1.098	3.3	342.0	0.25	[59]
Monogem	0.385	5.499	3.8	110.0	0.29	[59]

LHAASO discovered extended emission from a pulsar, indicating a very slow diffusion (slower by  $\sim 100$  times) compared with that inferred from B/C

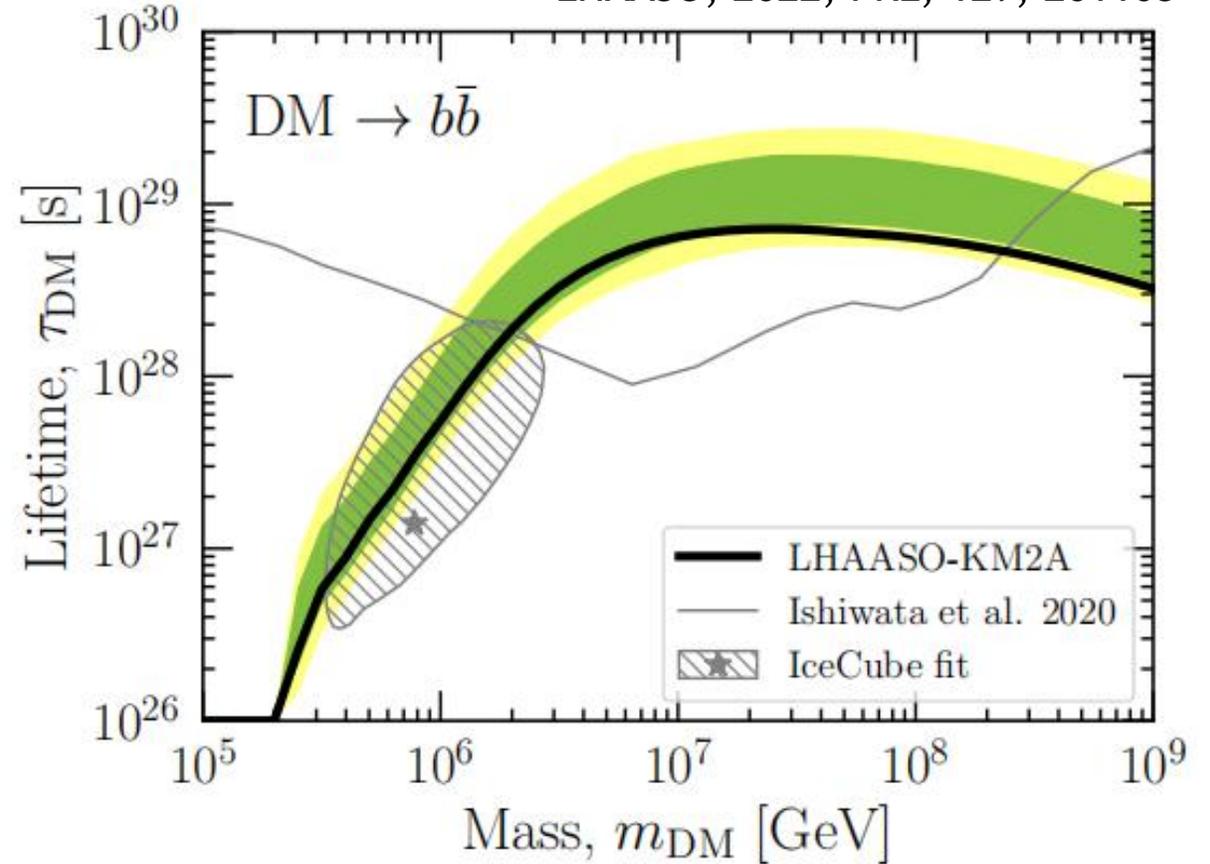
# LHAASO新物理探索

LHAASO, 2022, PRL, 128, 051102



The strongest constraints on Lorentz invariance violation via highest energy photon (1.4 PeV)

LHAASO, 2022, PRL, 129, 261103



The strongest constraints on heavy decaying dark matter parameters

# 总结

- 宇宙线的研究已有超过百年的历史，关于宇宙线起源、加速、传播等过程仍然有许多未解之谜，是当前的物理和天文学研究前沿
- 以DAMPE和LHAASO为代表的中国宇宙线实验研究已跻身国际先进行列，有望在该领域取得突破性进展
- DAMPE实验发现了一系列核素宇宙线能谱结构；LHAASO成功地开启了PeV伽马射线观测窗口，发现一大批PeV粒子加速器；这些结果为理解宇宙线起源和传播带来了新的知识
- 随着DAMPE和LHAASO数据的积累和分析的深入，预期将取得更多的新发现，有效推动宇宙线物理学学科的发展

**谢谢！**