

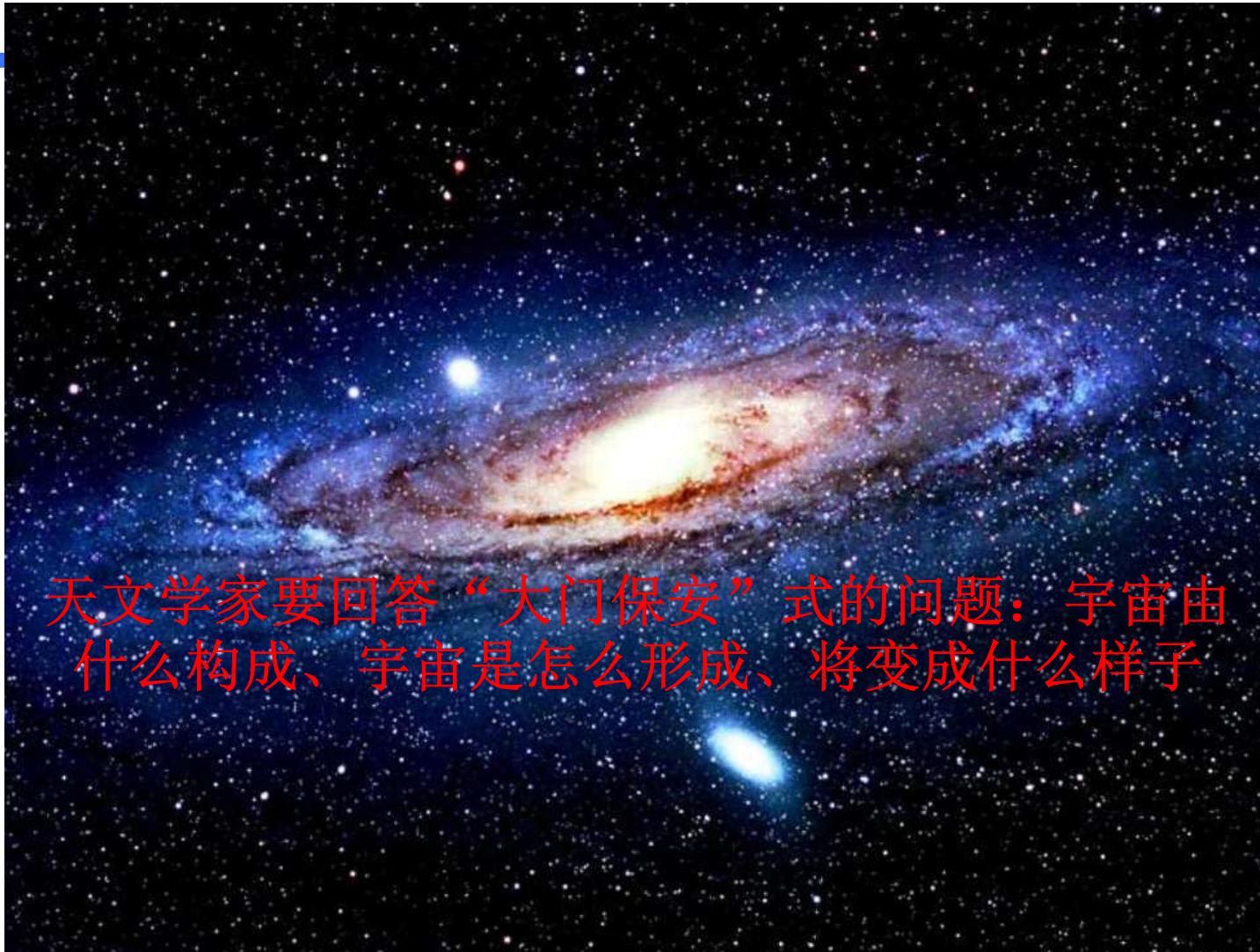


“悟空”号空间高能粒子 探测实验

郭建华

中科院紫金山天文台

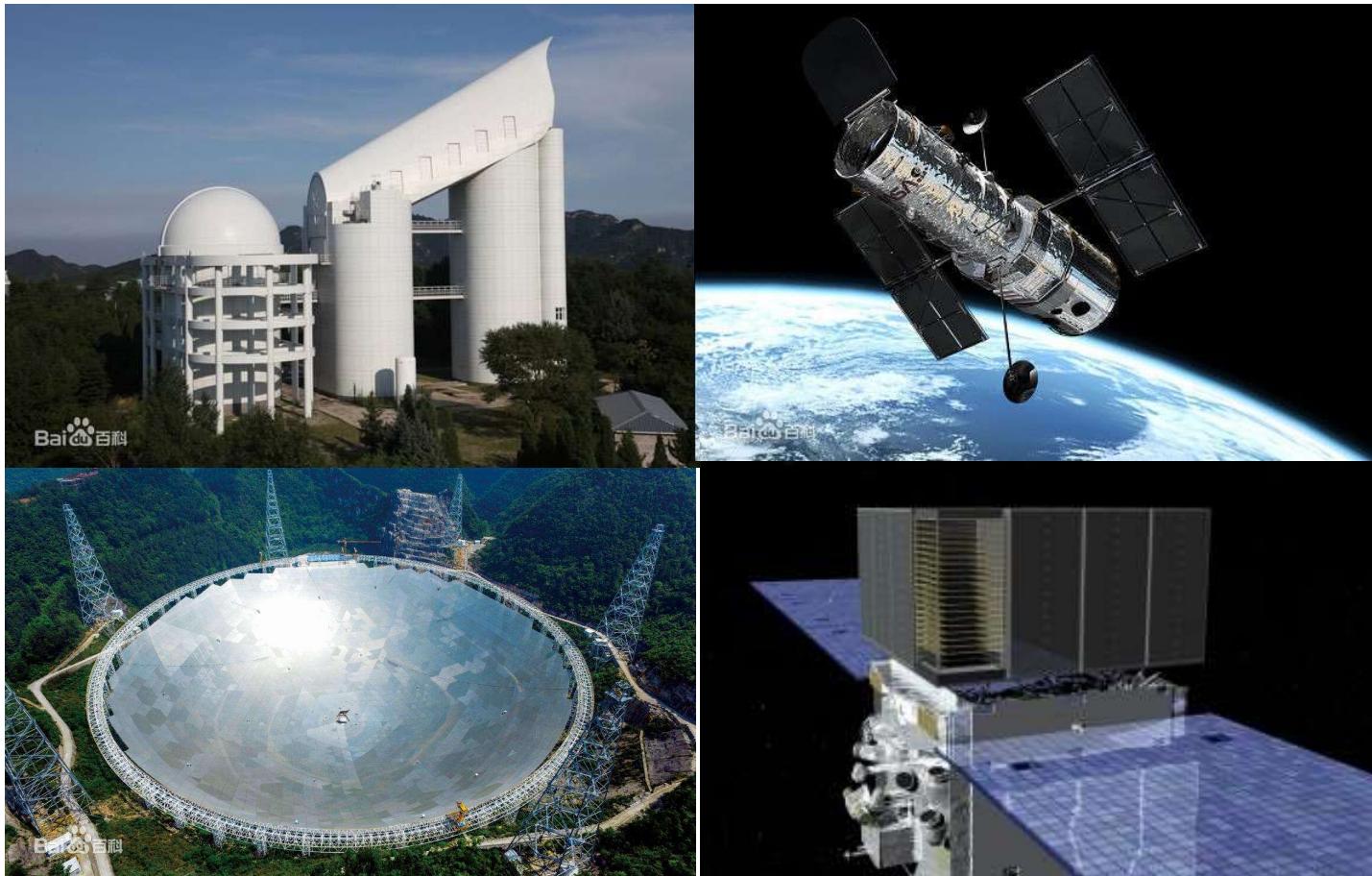
中国科学院暗物质与空间天文重点实验室



天文学家要回答“大门保安”式的问题：宇宙由什么构成、宇宙是怎么形成、将变成什么样子

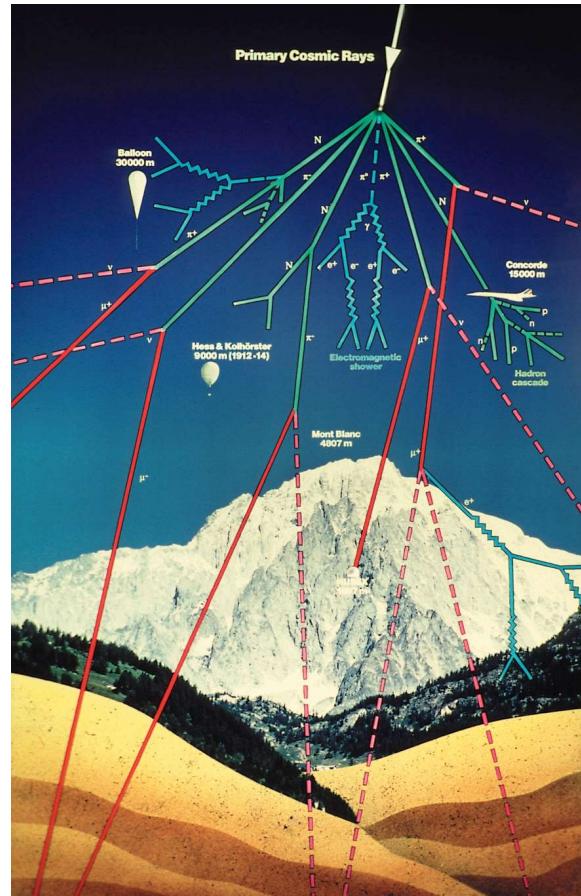


大部分天文发现由电磁波（光）观测得到





天文已经进入了多信使时代，宇宙中有大量的非光粒子：宇宙射线





宇宙线领域的诺贝尔奖



赫斯(1883-1964)
Victor Franz Hess



博特(1891-1957)
Walther Bothe



安德森(1883-1964)
Carl David Anderson



布拉开(1897-1974)
Lord Patrick M.S. Blackett



鲍威尔(1903-1969)
Cecil Frank Powell



贾科尼



戴维斯

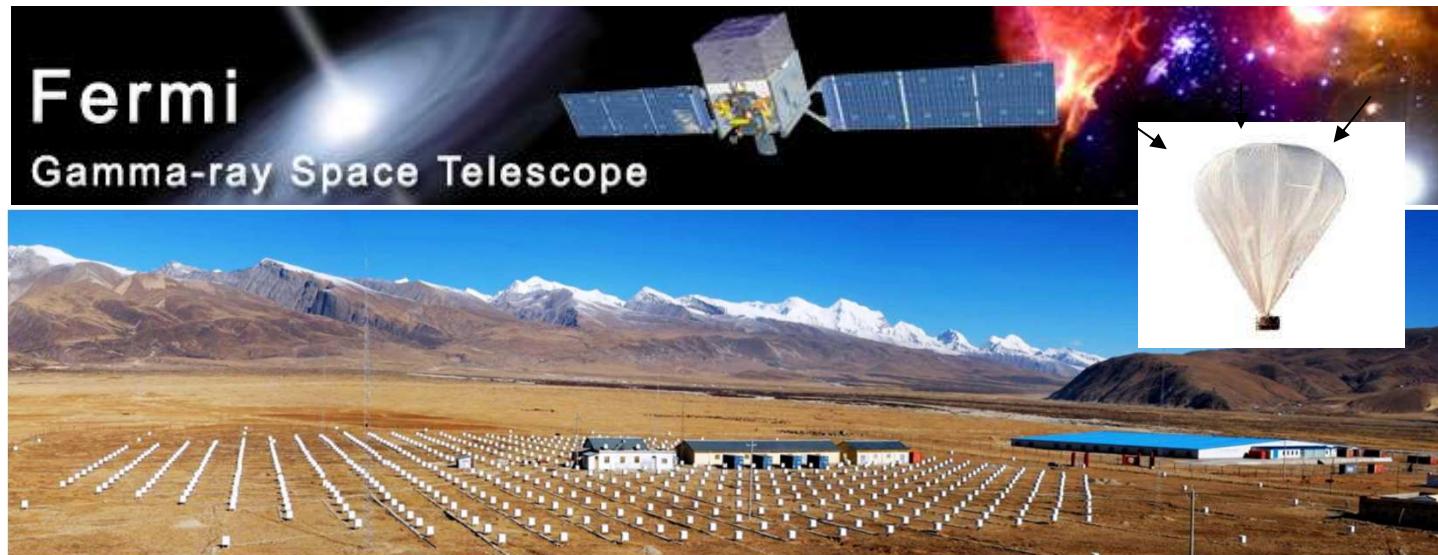


小柴昌俊

Hess (宇宙线的发现) ;
Bothe (符合方法证明宇宙线是带电粒子) ;
Anderson (正电子的发现) ;
Blackett (计数管控制云室技术及在宇宙线研究中的成就) ;
Powell (核乳胶, π 介子的发现) ;
Giacconi (X射线星的发现) ;
Davis 和 Koshiba (宇宙中微子)



宇宙射线的观测手段

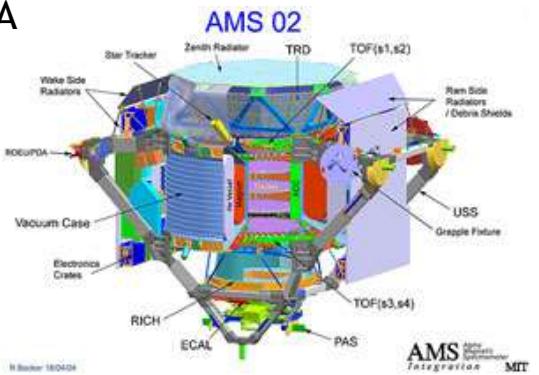
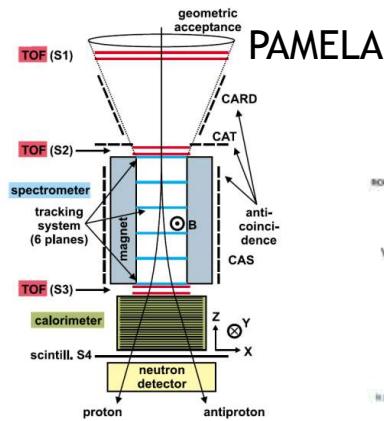


空间直接测量
IACT
地面粒子阵列

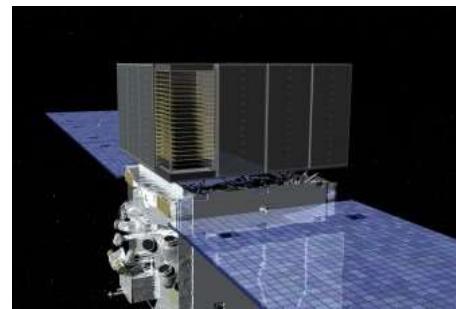




研究宇宙射线最好的场地是外太空



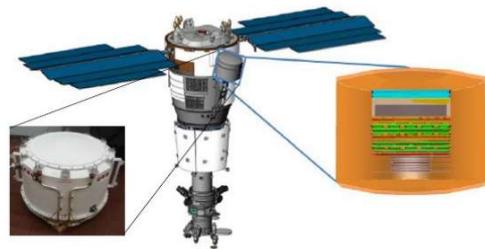
Fermi



CALET



NUCLEON

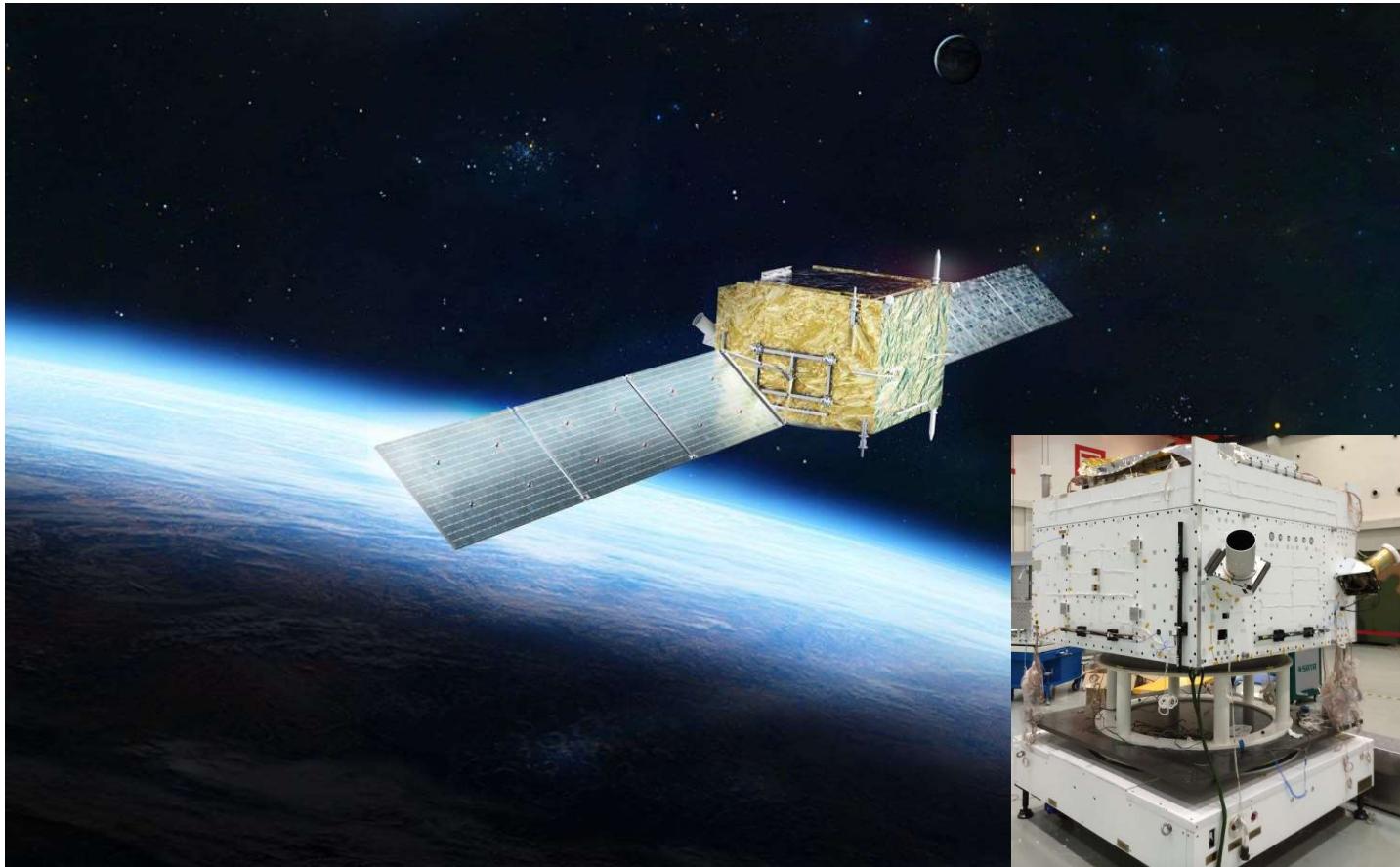


ISS-CREAM



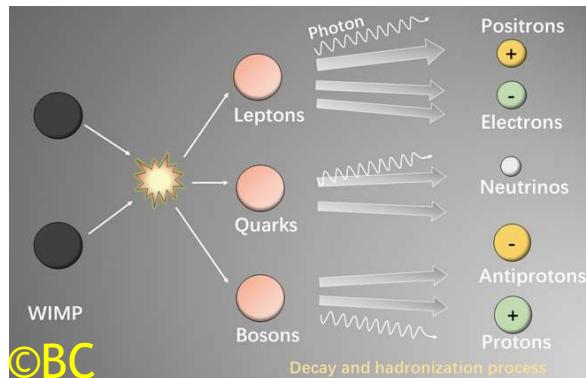


“悟空”号是中国首个TeV高能粒子空间探测器

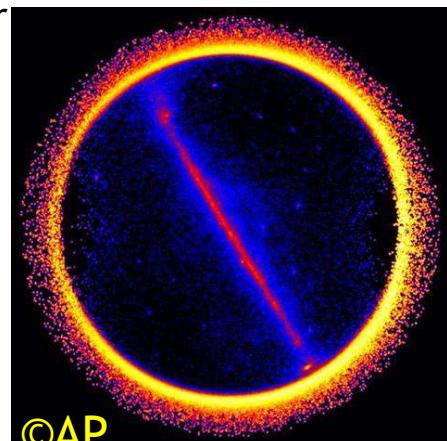




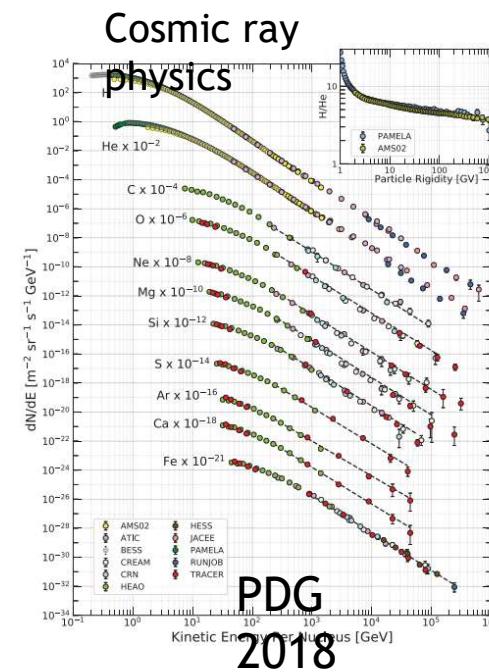
“悟空”号的三大科学目标



©BC
AS
Indirect detection of dark matter



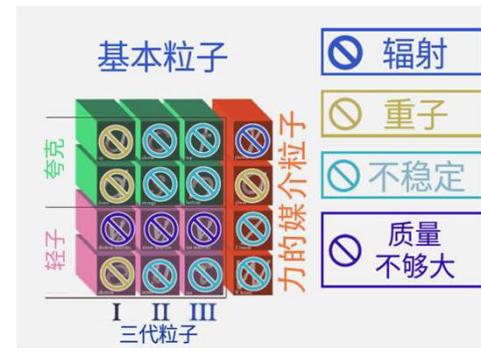
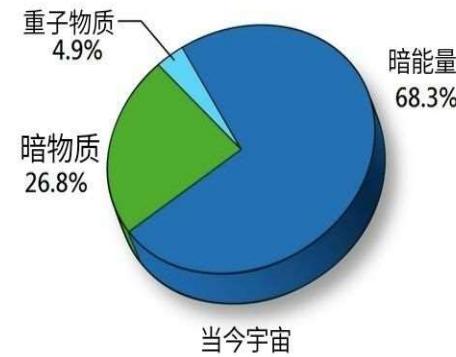
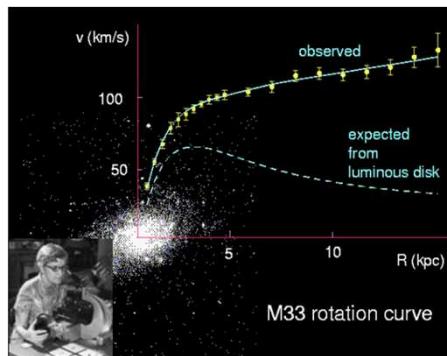
OD



Gamma-ray astronomy



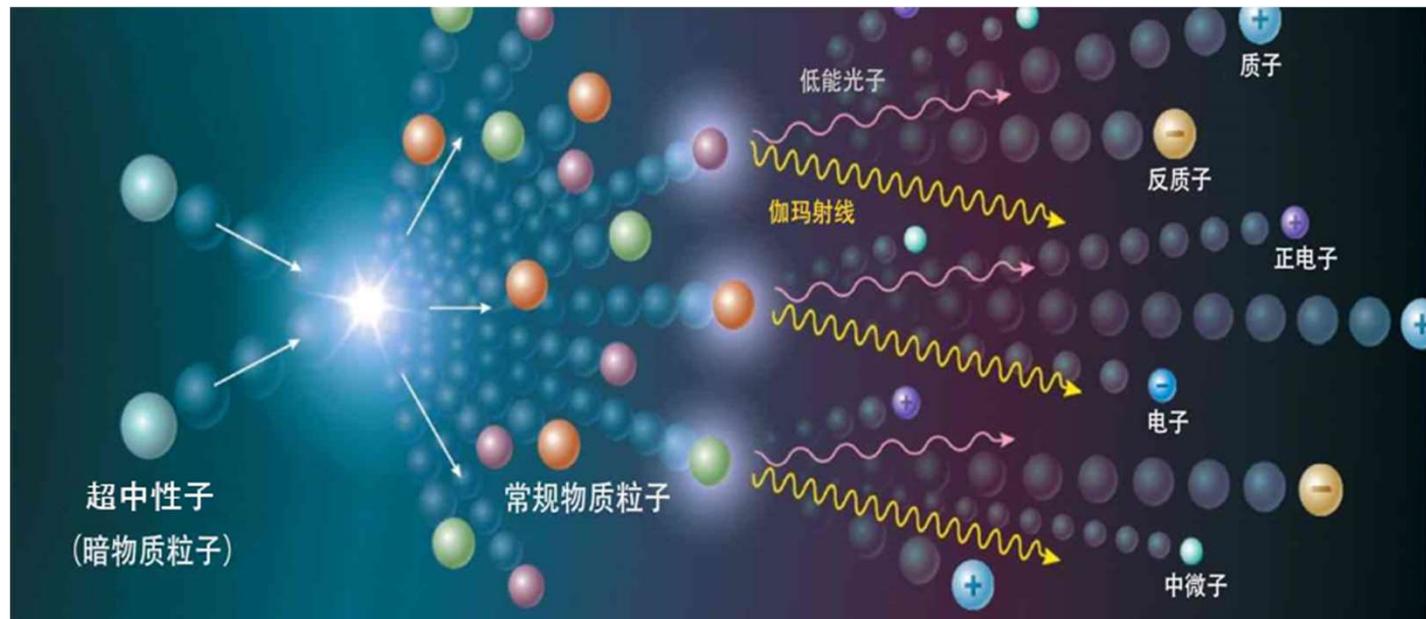
科学目标之一：寻找暗物质粒子



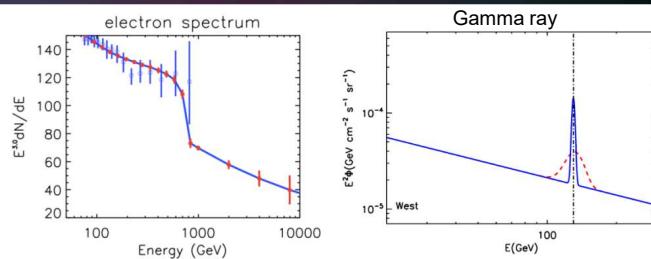
天文观测表明宇宙中存在大量的暗物质, 无法在粒子物理标准模型中得到解释。李政道: 暗物质是笼罩20世纪末和21世纪初现代物理学的最大乌云, 它将预示着物理学的又一次革命



如何探测暗物质粒子

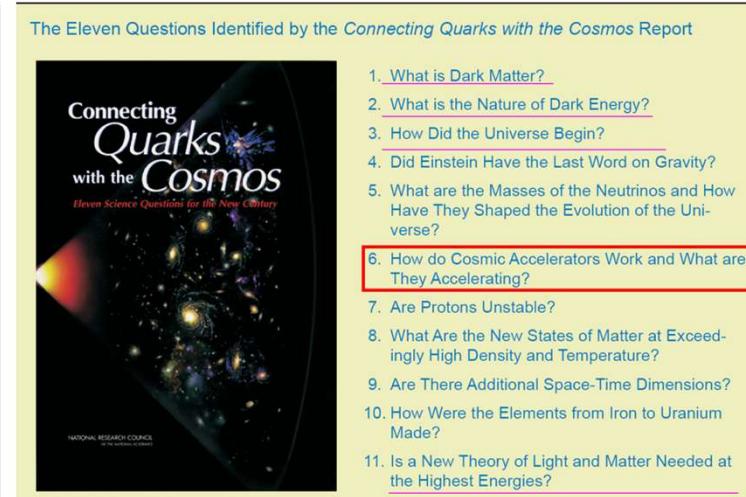
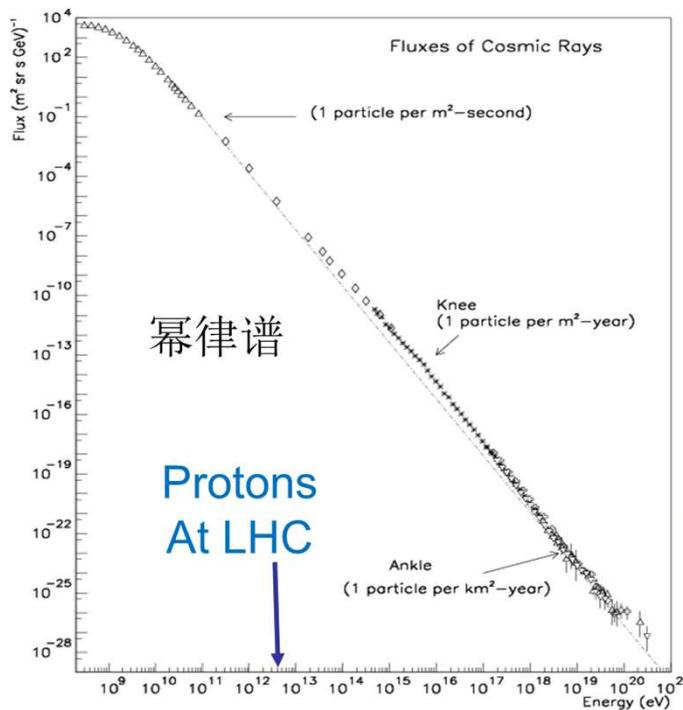


暗物质粒子可衰变或相互湮灭，产生
“看得见”的普通高能宇宙线粒子





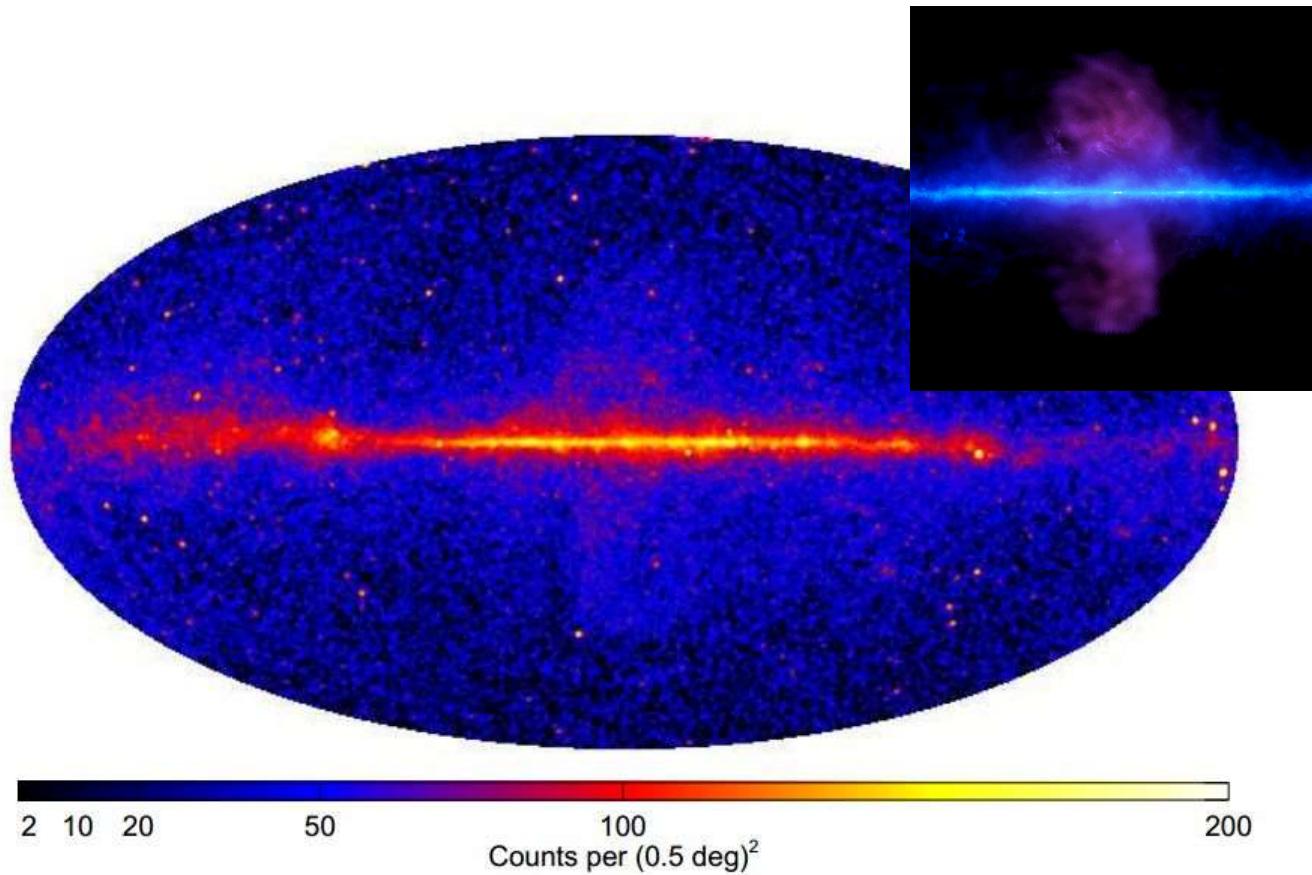
科学目标之二：宇宙线物理



2002年美国国家研究委员会确定的研究
前沿：《联结夸克和宇宙：新世纪11个科
学问题》

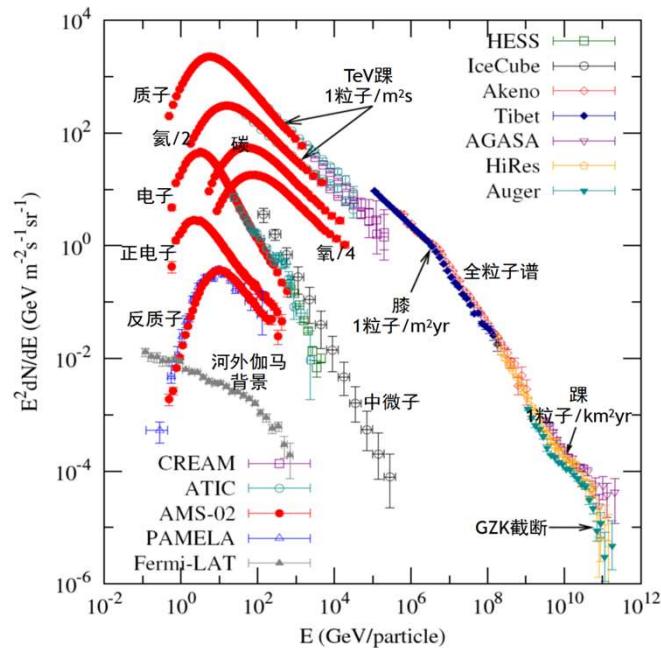


科学目标之三：伽马射线天文





“悟空”号的主要技术挑战



悟空号主要在电子宇宙线和伽马射线中寻找暗物质信号

挑战

电子和伽马信号流量极低：1TeV处质子、电子、弥漫伽马流量比 $\sim 10^6:10^3:1$ ，探测器需具备卓越的粒子鉴别能力

挑战

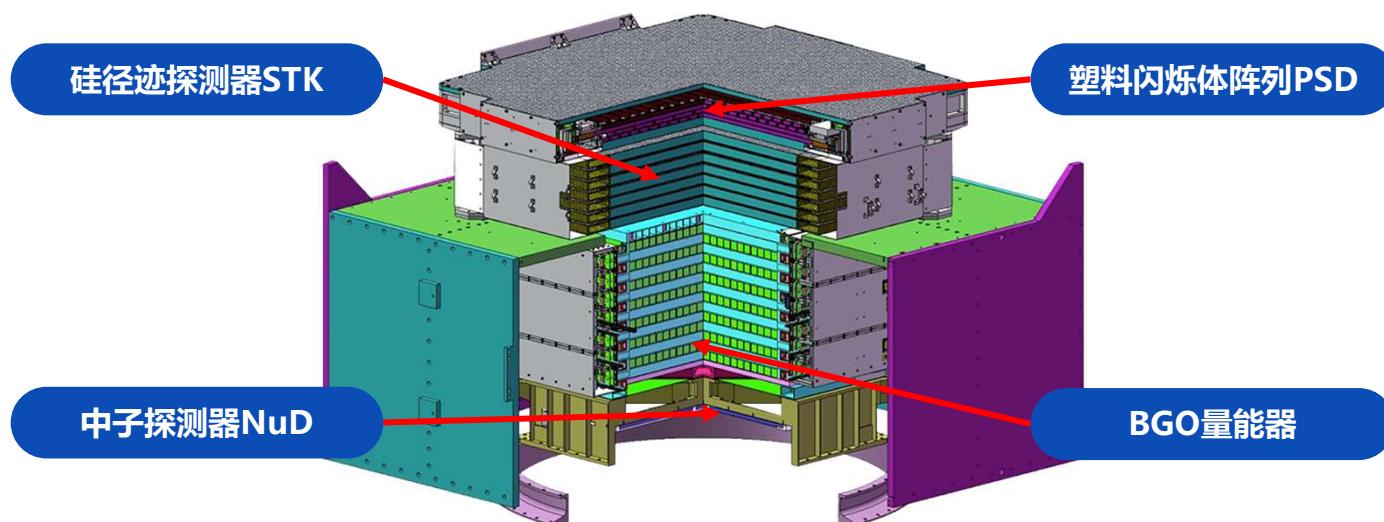
暗物质粒子质量未知：探测器应覆盖尽可能宽的能区以提高发现前景

挑战

卫星资源限制：有限重量、体积和功耗下实现7万多个探测单元信号测量



“悟空”号暗物质粒子探测器构造



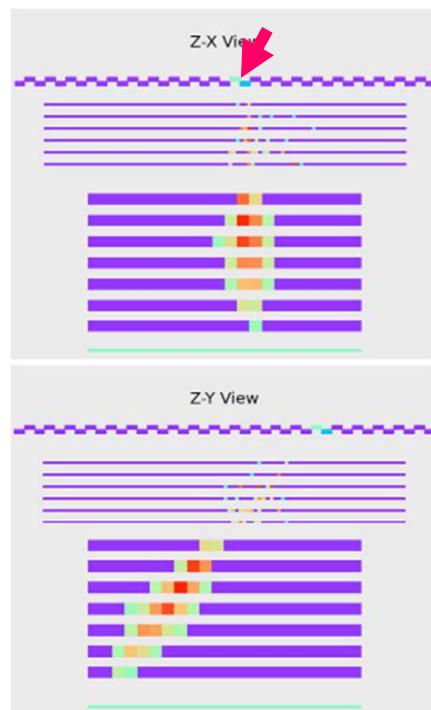
Chang (2014 Chin. J. Space Sci. 34, 550) & Chang et al. (2017 Astropart. Phys. 95, 6)

悟空号BGO量能器：大纵深(31个电磁辐射长度)、全吸收、成像型；国际空间实验中**最大单个量能器单元**(0.6米×0.6米；Fermi-LAT: 16个0.3米×0.3米单元组合)

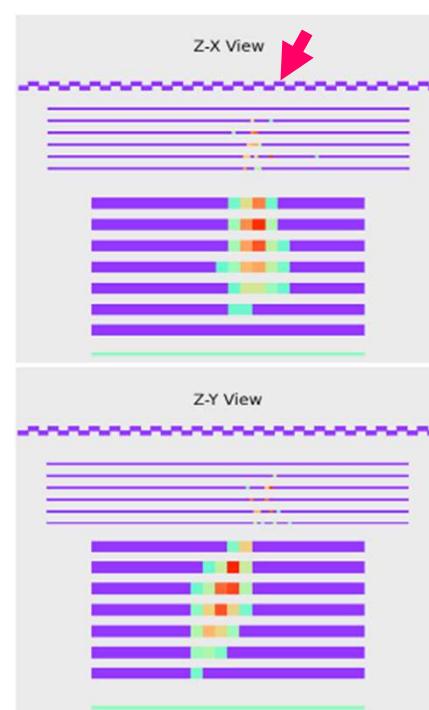


“悟空”号对入射粒子的测量

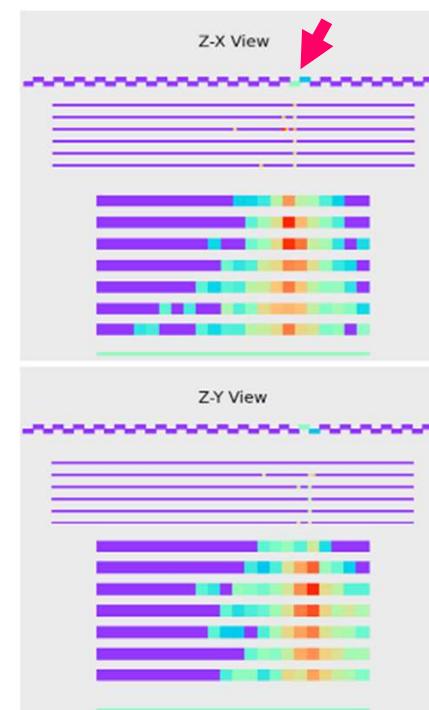
electron



gamma

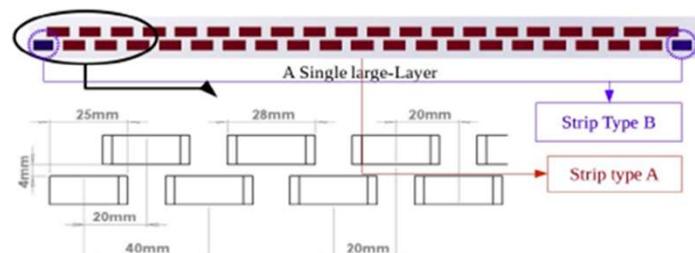


proton



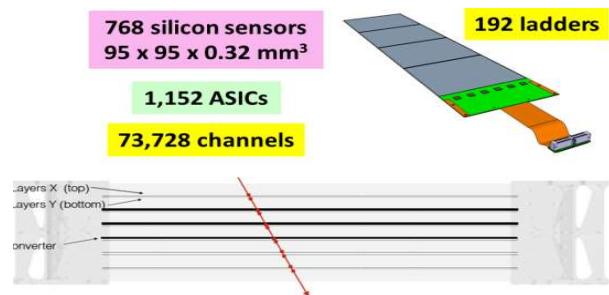


塑闪阵列探测器 (PSD)



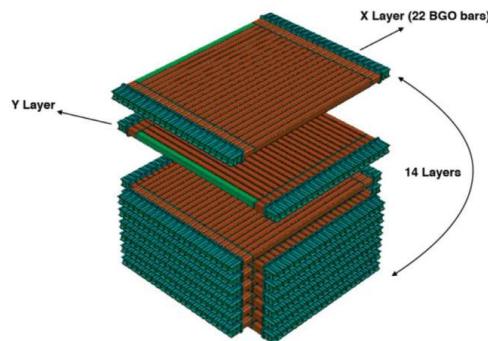
- 2 大层 (x,y), 塑闪条 $88.4 \text{ cm} \times 2.8 \text{ cm} \times 1 \text{ cm}$
- 有效面积: $82 \text{ cm} \times 82 \text{ cm}$
- 重量: $\sim 103 \text{ kg}$
- 功耗: $\sim 8.5 \text{ W}$

硅阵列探测器 (STK)



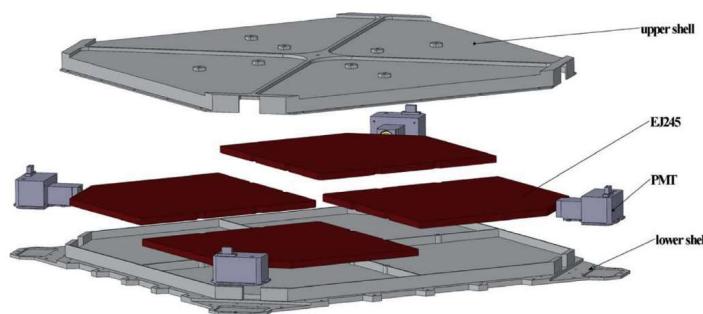
- 有效面积: $76 \text{ cm} \times 76 \text{ cm}$
- 重量 : $\sim 154 \text{ kg}$
- 功耗: $\sim 82 \text{ W}$
- 中间不同的层有1mm的钨板, 总辐射长度 $0.86X$

BGO量能器 (BGO CAL.)



- 包络: 100 cm x 100 cm x 50 cm
- 探测面积: 60 cm x 60 cm
- 总重量: ~1052 kg
- 功耗: ~ 41.6 W

中子探测器 (NUD)



- $n + {}^{10}\text{B} \rightarrow \alpha + {}^7\text{Li} + \gamma$
- 4 掺硼塑闪
- 有效面积: 60 cm x 60 cm
- 总重量: ~12 kg
- 功耗: ~ 0.5 W



载荷数管 (DAQ)



载荷数据
处理器

载荷管理器

DC-DC电源
机箱



DAMPE研制队伍



Purple Mountain Observatory, CAS
Institute of High Energy of Physics, CAS
Institute of Modern Physics, CAS
National Space Science Center, CAS
University of Science and Technology of China



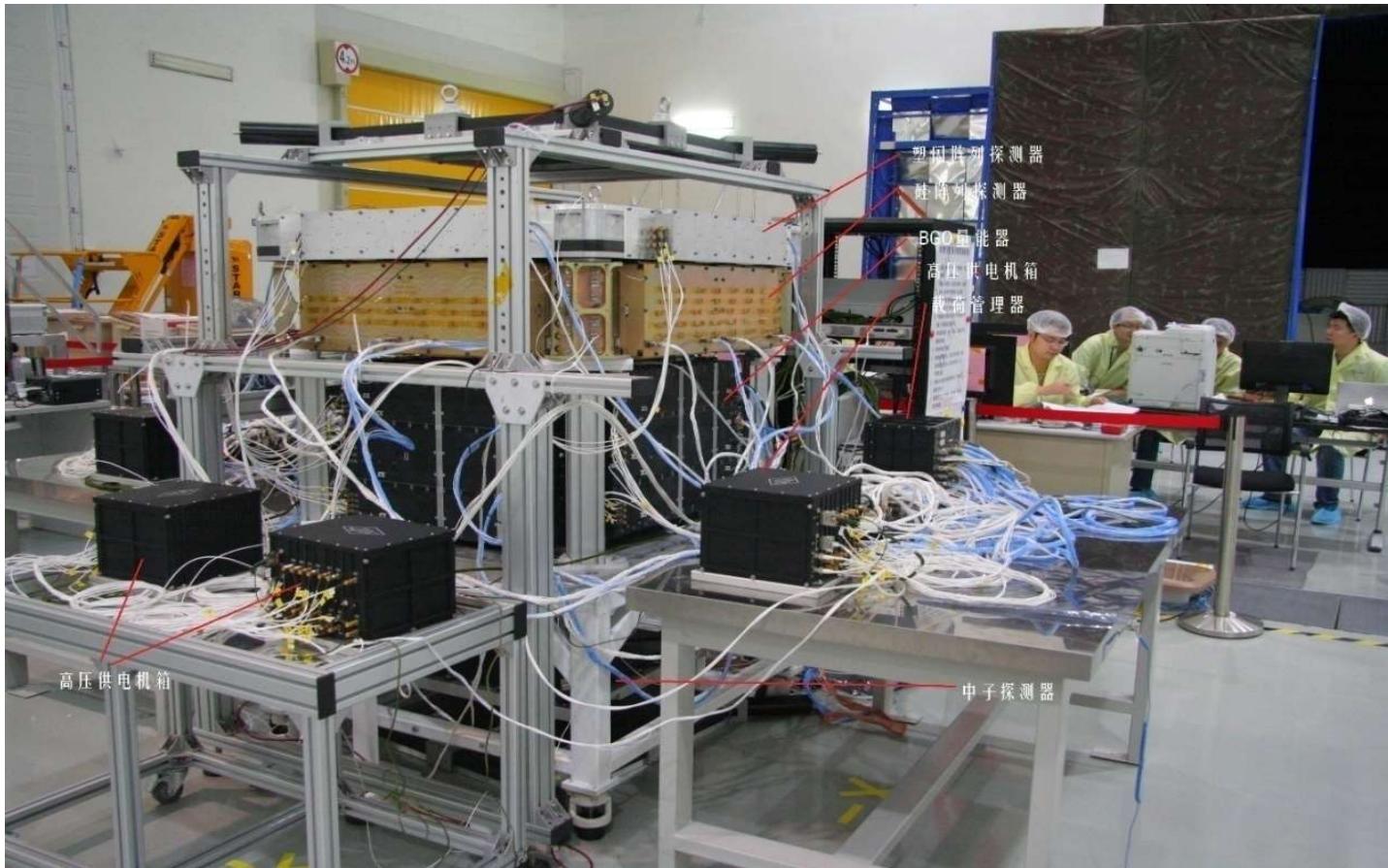
Geneva University



I.N.F.N. Sez. di Perugia, Perugia University
I.N.F.N. Sez. di Bari, Bari University

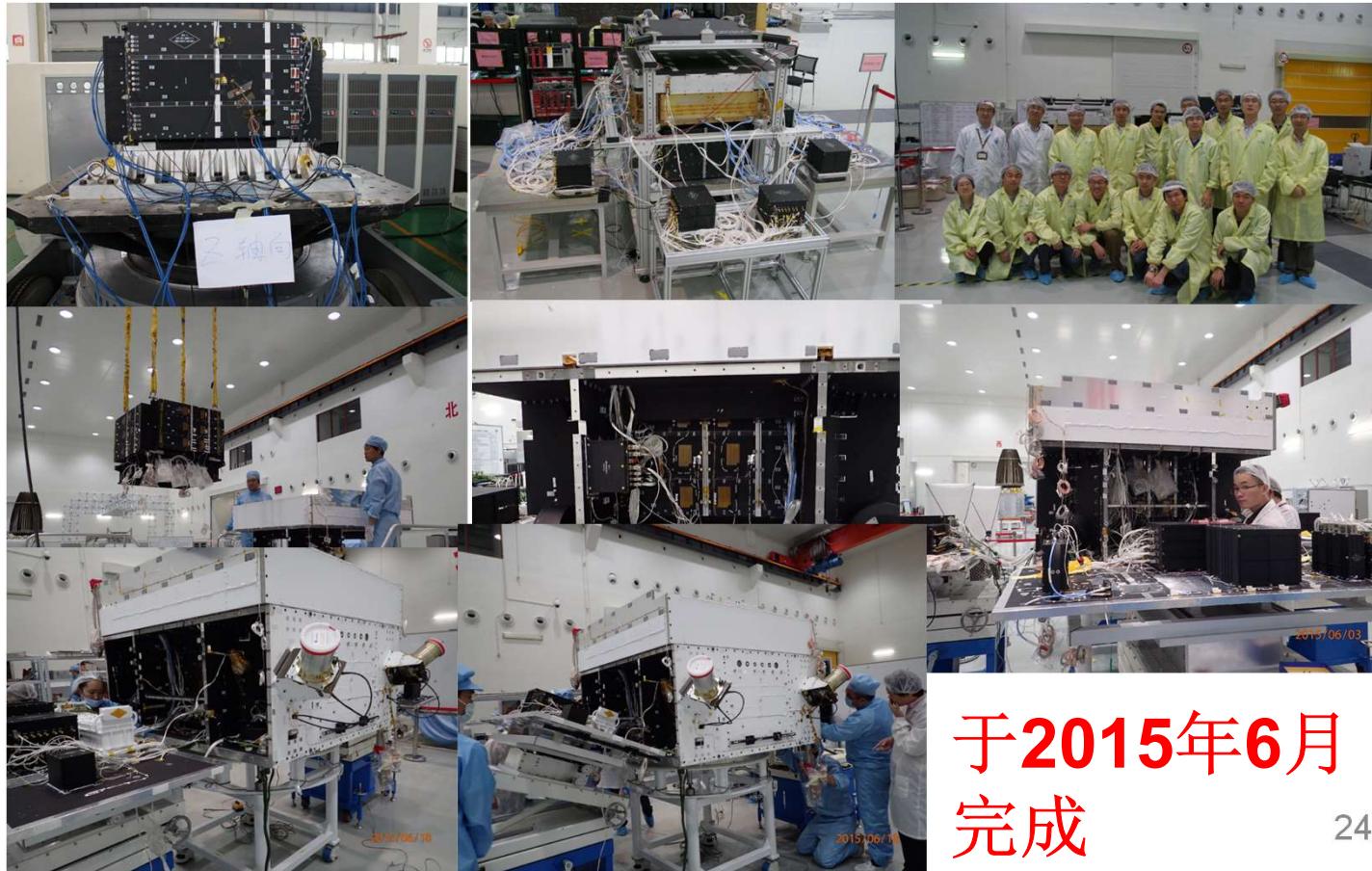


载荷完成联试 (2015. 05)





在上海微小卫星工程中心完成组装



于2015年6月
完成



在上海微小卫星工程中心进行EMC试验



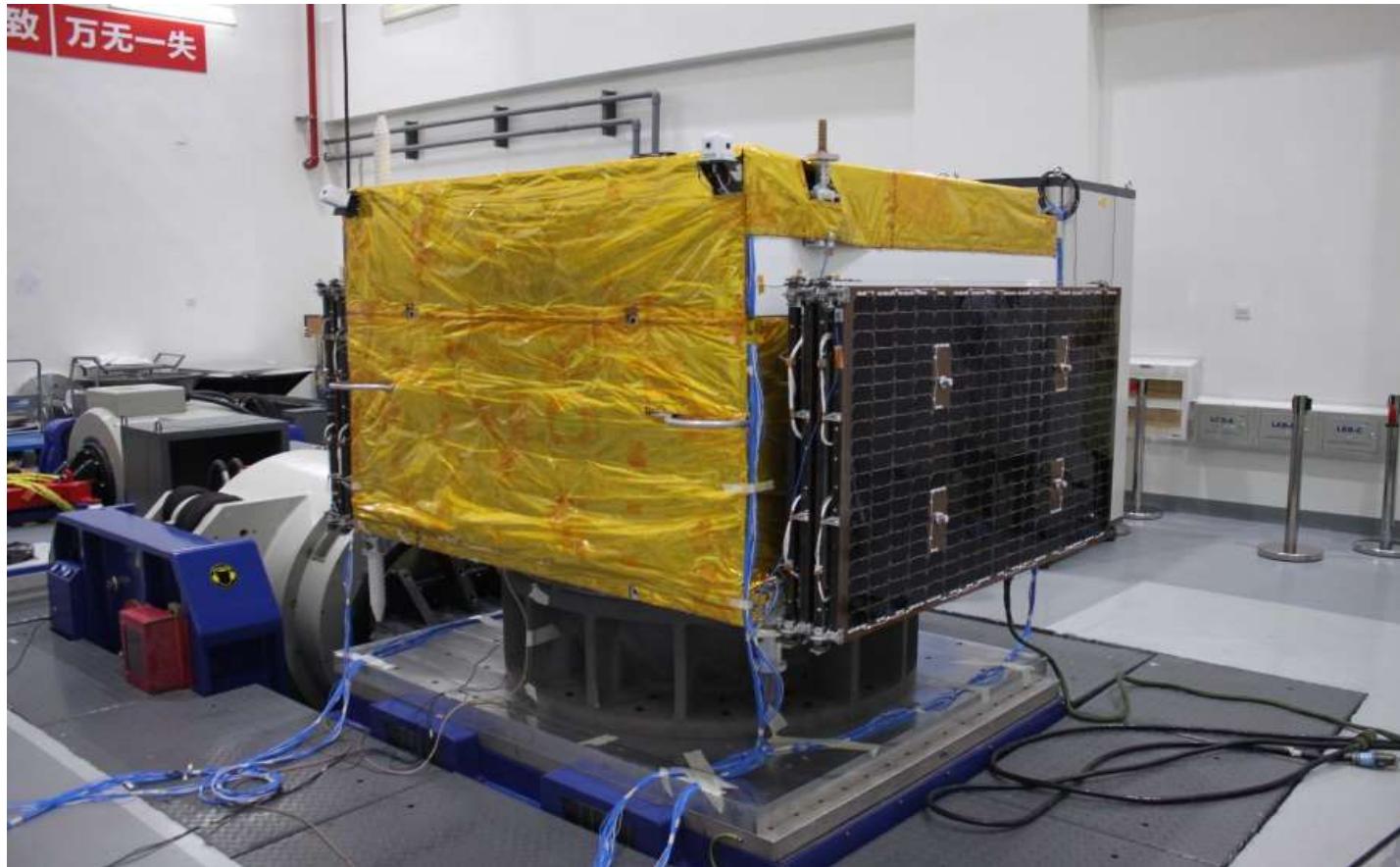


在上海卫星工程研究院进行热真试验





在上海微小卫星工程中心进行力学振动试验



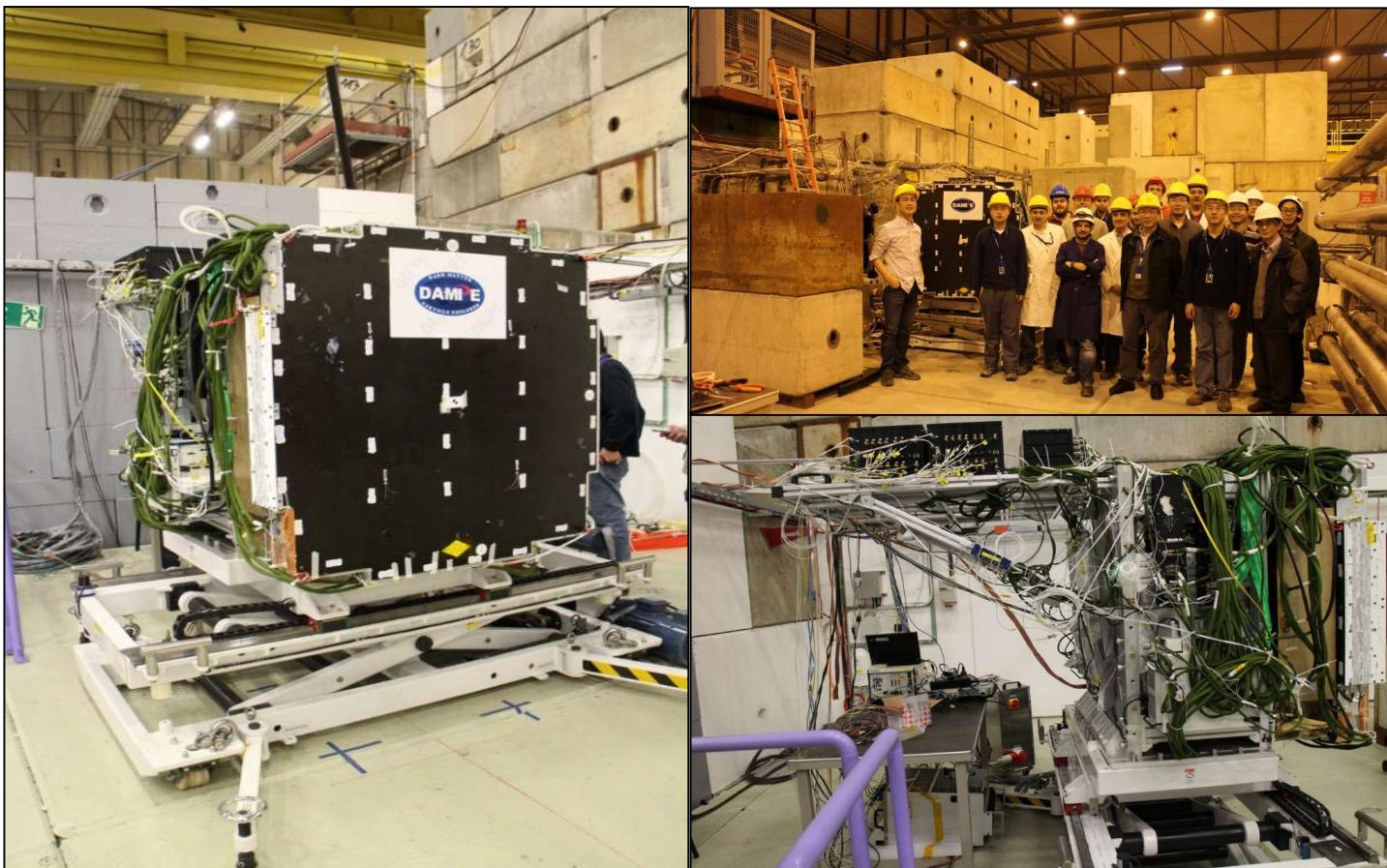


在海南三亚进行的数传对接试验





在欧洲核子中心进行束流试验





束流试验结果



Recognized Experiments

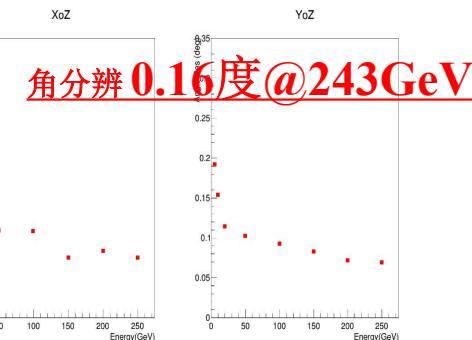
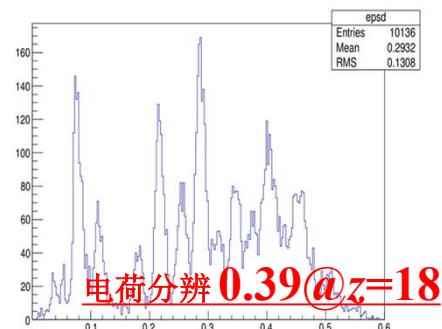
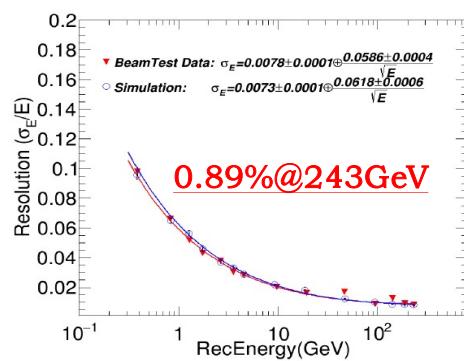
由于2012年出色的束流标定结果，2013年：DAMPE被列为欧洲核子中心认可实验，并入选国内十大天文进展。

RE 29 DAMPE

Link

2014

31-DEC-2016



所有指标均达到或者好于预期！！

30

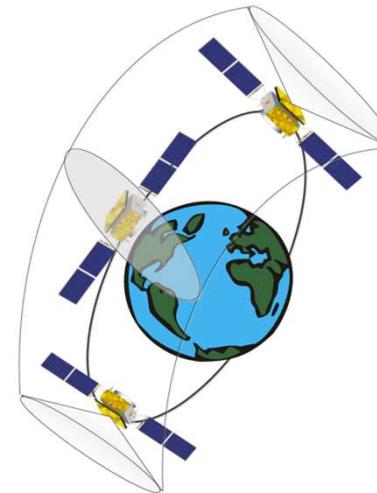
30

卫星运往发射塔





“悟空”号发射



- 轨道高度: 500 km
- 倾角: 97.4°
- 周期: 95 minutes
- 太阳同步轨道

32

32



开启中国空间科学“新”时代

NEWS IN FOCUS

POLITICS Canada's first science minister brings air of change p.445 **STOKE 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.450

COLUMNIST

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 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 a significant 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 exotic 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 that 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 basic 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.)

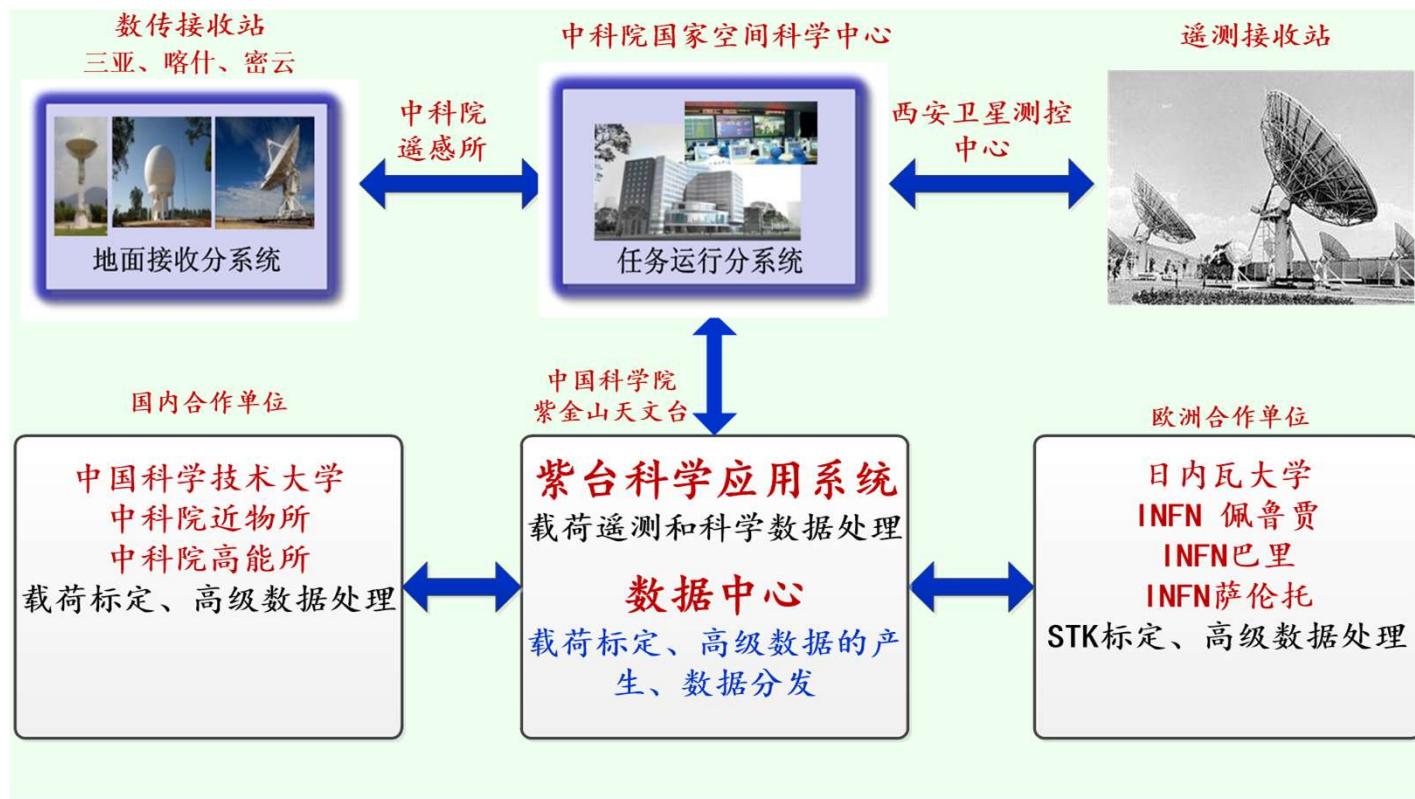
The DAMPE lift-off from the Jiuquan Satellite Launch Center in northern China will be followed by the launch of the Quantum Satellite in 2016, the world's first quantum-communications satellite and an X-ray telescope observing in

24/12/2015 | VOL 328 | NATURE | 442

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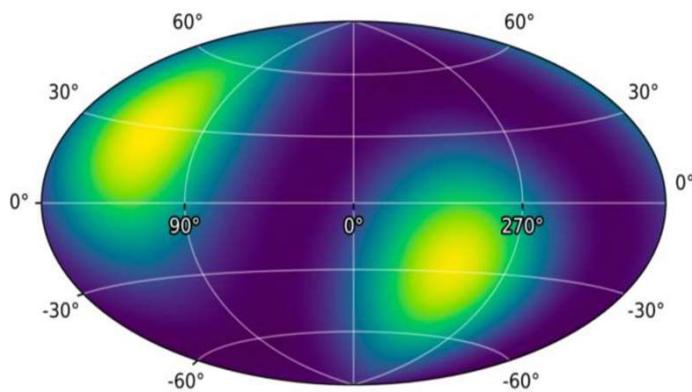


星地数据链路

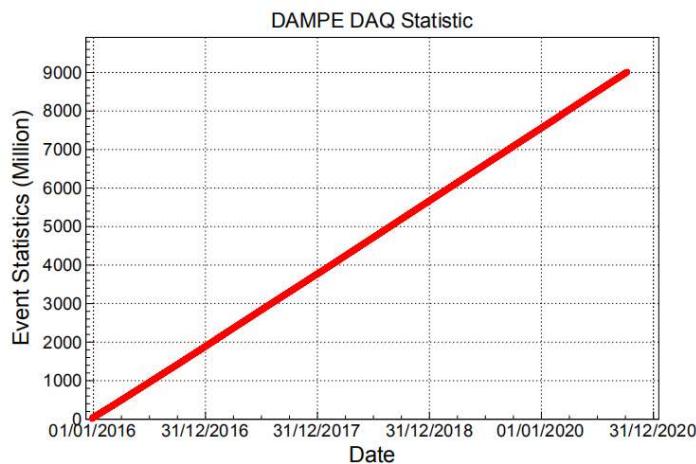


运行情况

DAMPE 5 year exposure map



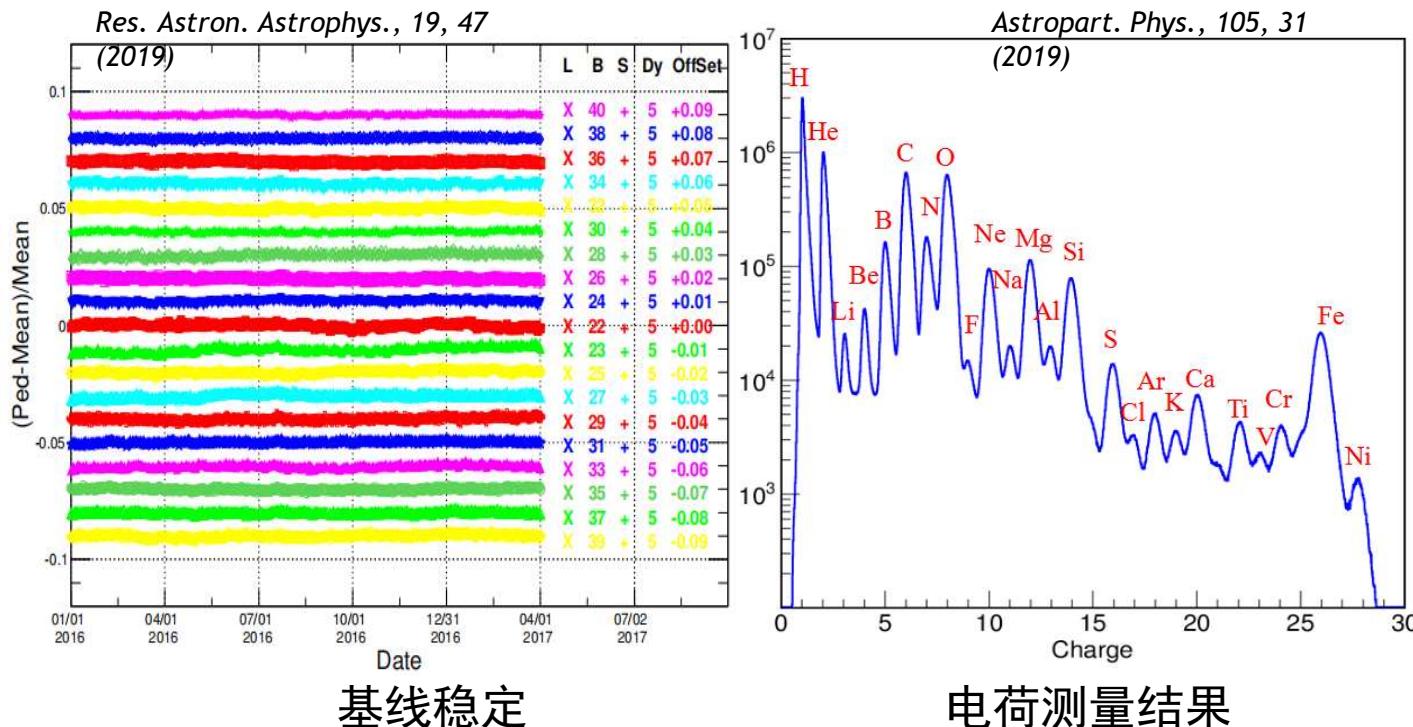
9+ billion events



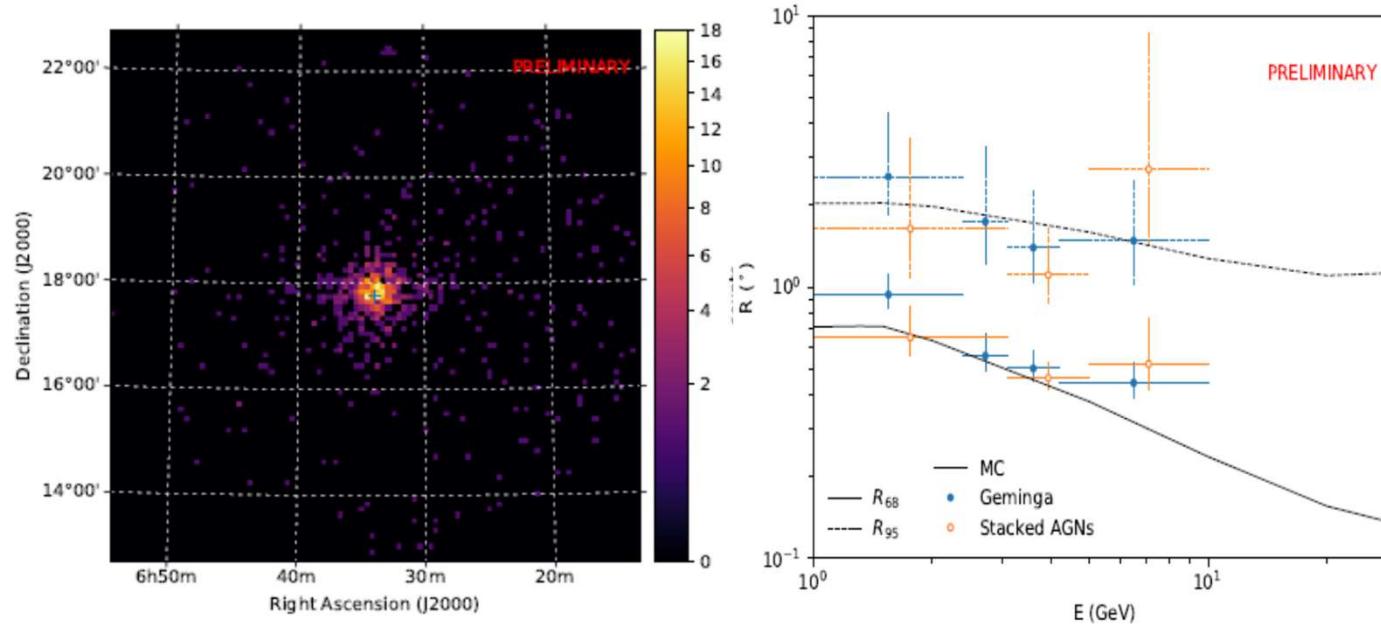
从2015年12月发射至今已近稳定运行将近5年半，扫描天区10次，累计了90亿以上的事例



电荷测量性能

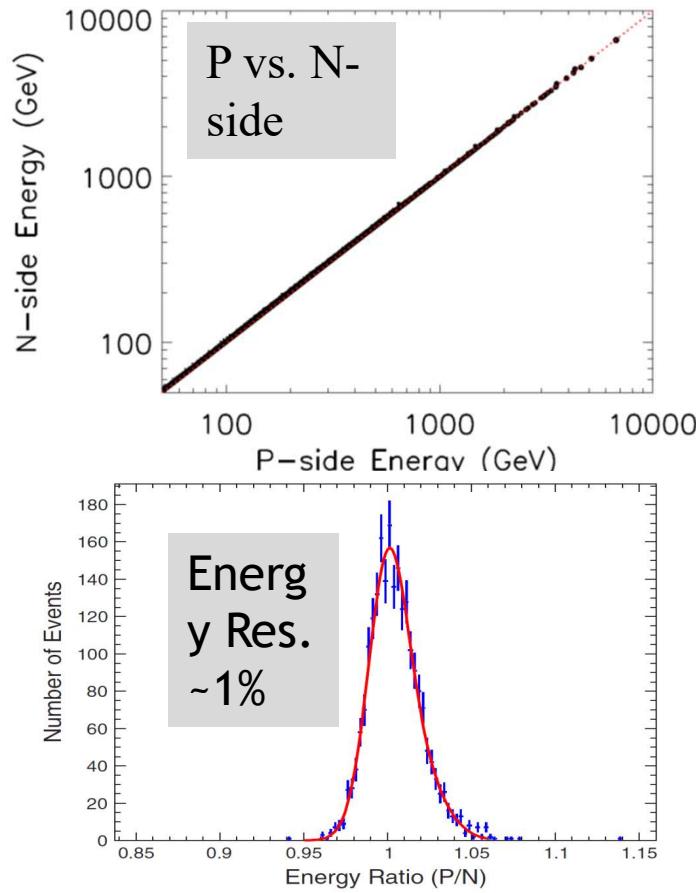
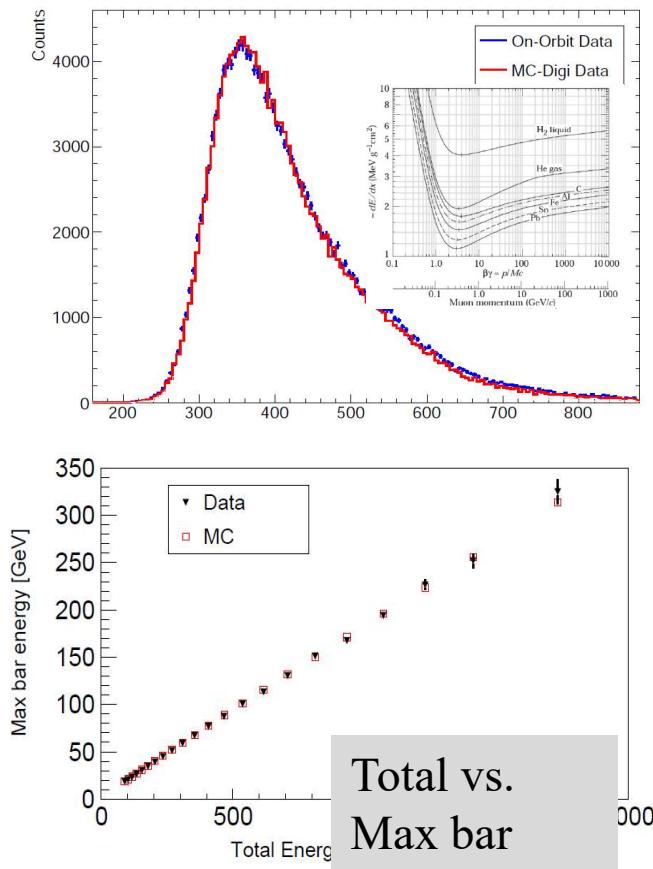


方向（角）分辨

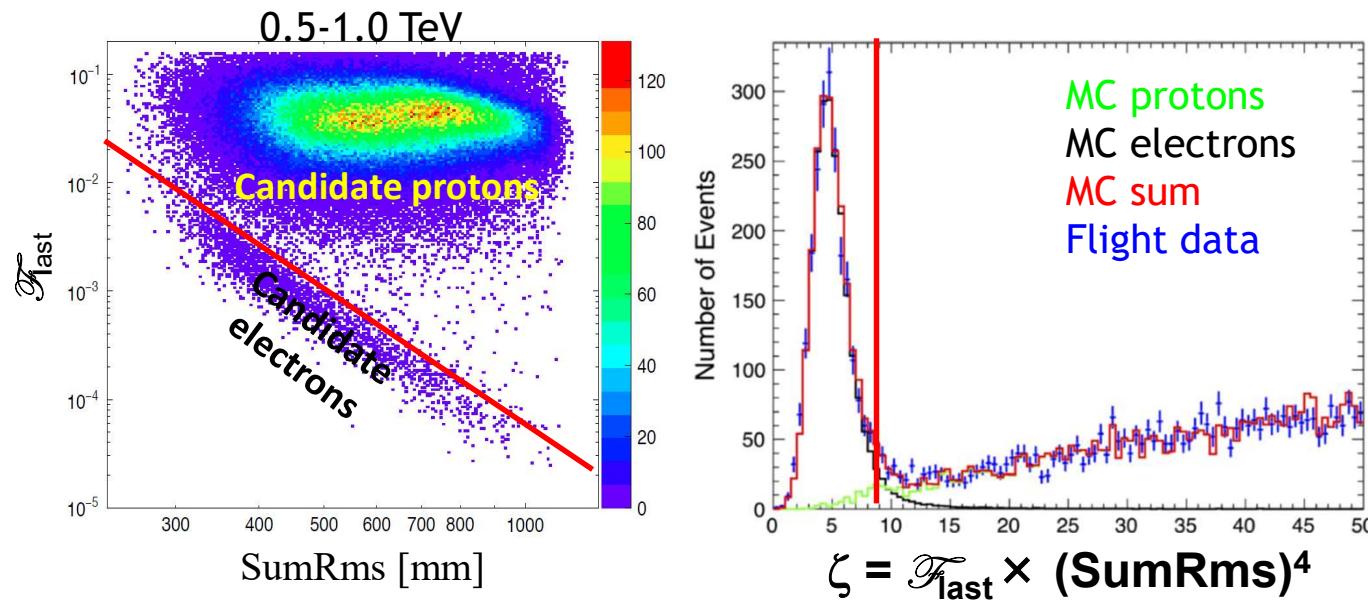


角分辨（通过脉冲星和AGN标定） ~0.5 degrees @ 5 GeV

能量测量性能



粒子分辨能力



- 利用横向的簇射扩展(SumRMS)和纵向簇射深度发展 ((8×10^6) energy ratio in last layer) 从质子中区分电子
- 在保证90% 电子探测效率的基础上, 质子背景的混入比例 ~2% @ TeV, ~5% @ 2 TeV, ~10% @ 5 TeV

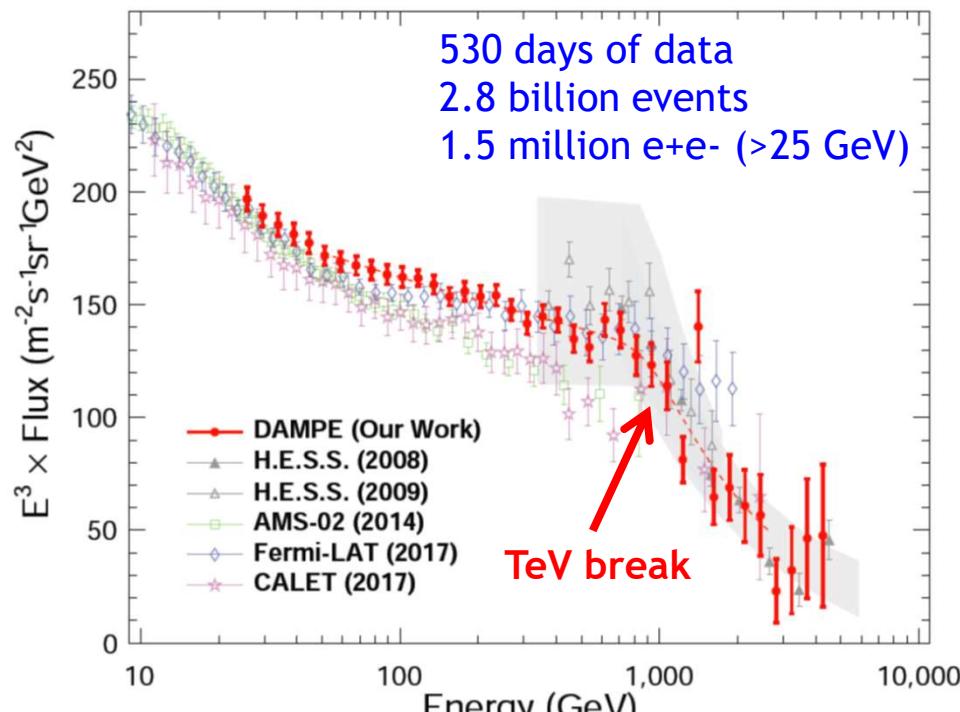
Nature, 552, 63 (2017)



“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 ($m^2 \cdot sr$)	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 (12年)
AMS-02	~2 TeV	0.05	2-3%	10^5	继续 (9年)
CALET	~5 TeV	0.1	3%	10^5	继续 (5年)
ISS-CREAM	~3 TeV	0.2	15%	10^3	停止 (1.5年)
DAMPE	~10 TeV	0.3	1%	2×10^5	继续 (5年)

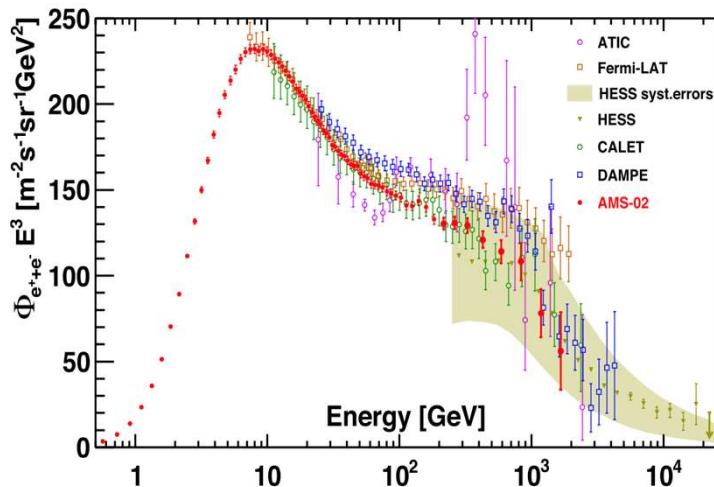
TeV的宇宙线电子



- 三种不同的粒子鉴别方法得到了非常一致的结果
- 直接探测器1TeV存在能谱截断（ 6.6σ 置信度）
- TeV拐折：国际上第一次直接探测到；对于理论家判断sub-TeV的正电子超出是否来自于暗物质起源有关键意义



宇宙线电子结果入选中国科学十大进展



- Fermi-LAT合作组2017没有发现拐折
- 日本CALET合作组2018没有发现拐折
- AMS-02合作组(2021 Phys. Rep. 894, 1): 在~0.9TeV处发现了电子能谱的拐折(见上图)



Results reported today by a China-led space science mission provide a tantalizing hint—but not firm evidence—for dark matter. Perhaps more significantly, the first observational data produced by China's first mission dedicated to astrophysics shows that the country is set to become a force in space science, says David Spergel, an astrophysicist at Princeton University. China is now "making significant contributions to astrophysics and space science," he says.

Science评论:

中国暗物质空间探测器测量到一个诱人信号
(结果凸显了中国在空间科学方面的崛起)

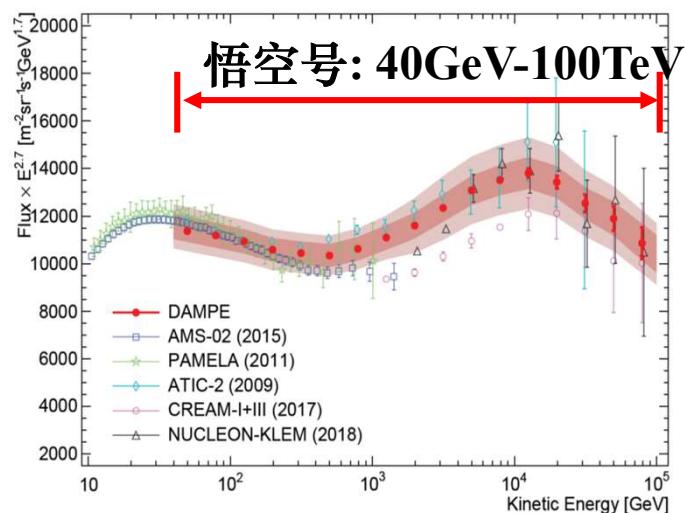


入选2018年度中国科学
十大进展

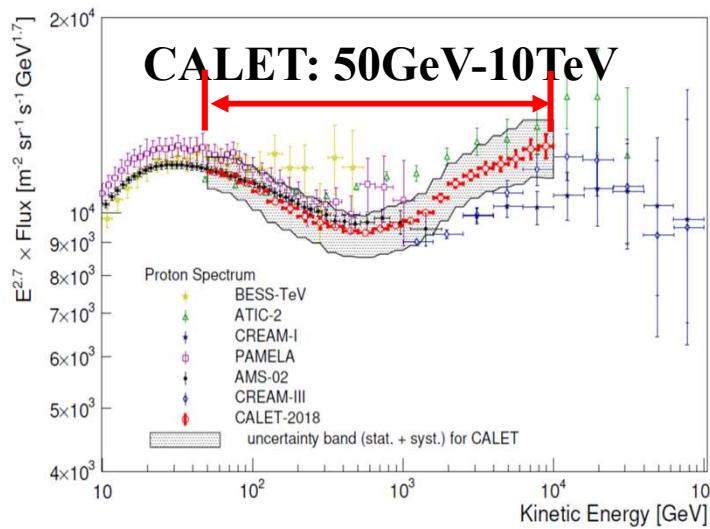


宇宙线质子

. Adv. (2019, 5, eaax3793)

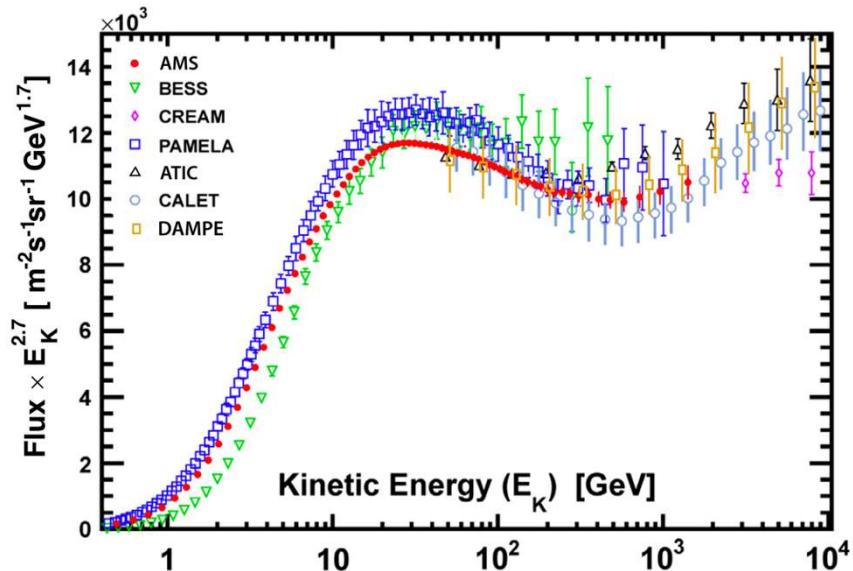


Phys. Rev. Lett. (2019, 122, 181102)



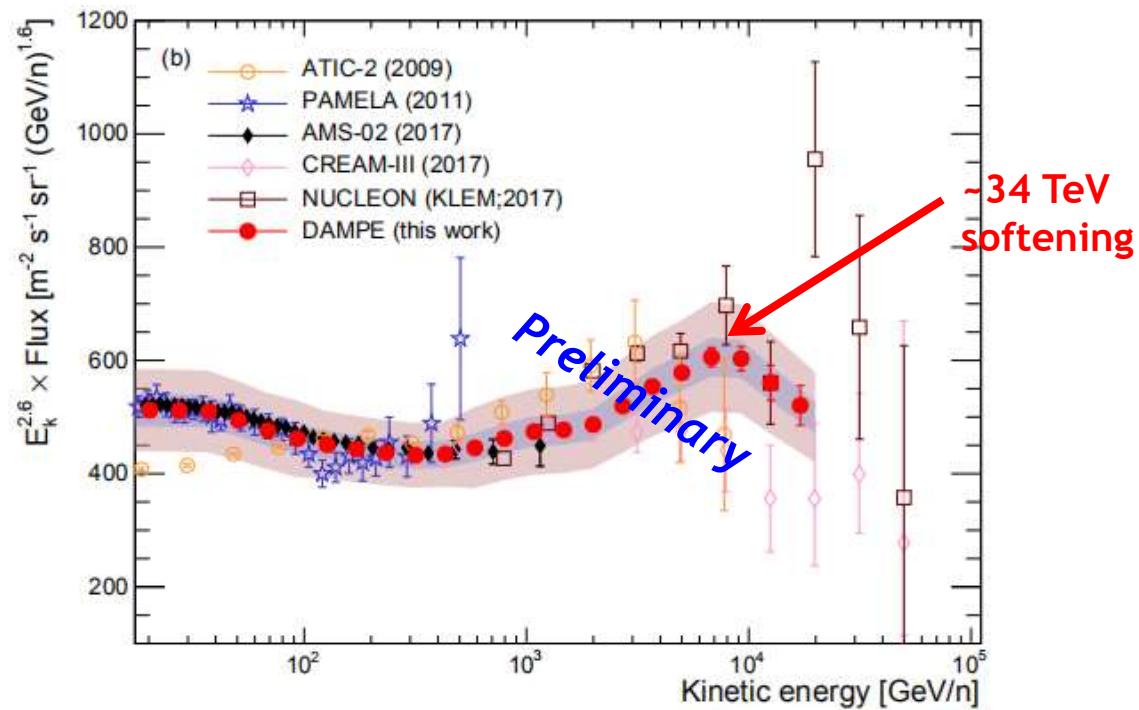
悟空号发表的质子能谱的测量能段范围超过CALET的10倍！
高置信度发现14 TeV处的能谱拐折，可能是地球附近宇宙线加速源的印记

宇宙线质子



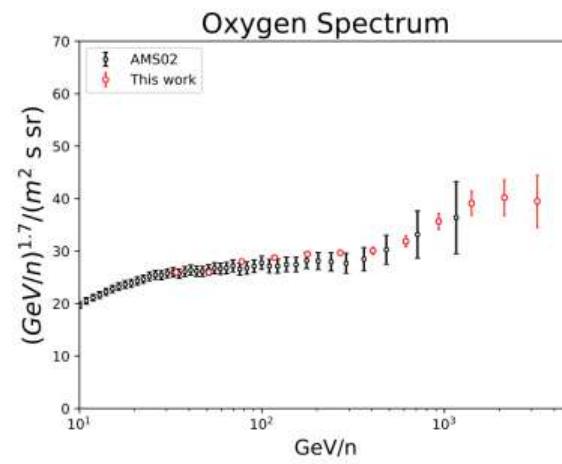
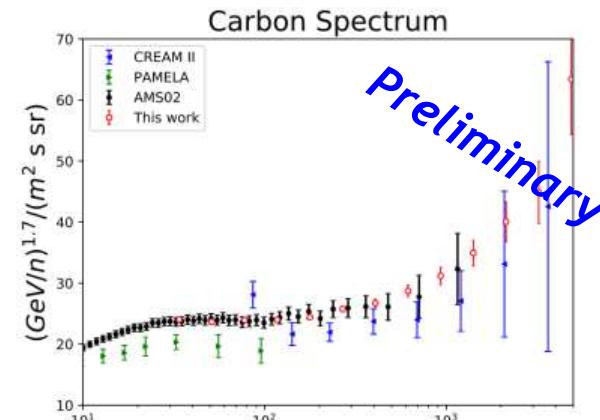
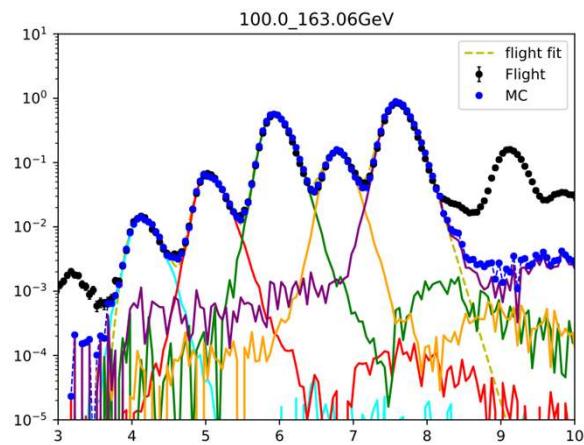
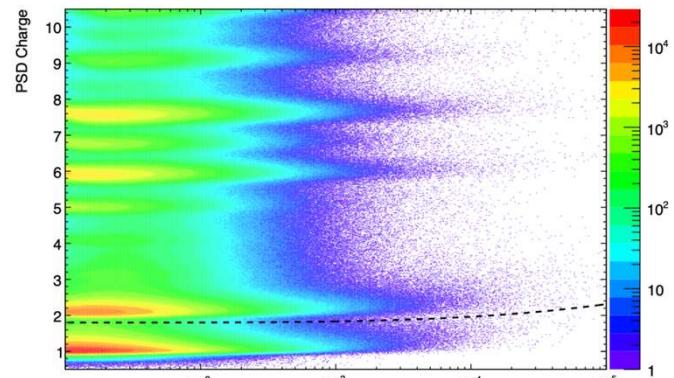
➤ 2021 Phys. Rep.
894, 1: AMS-02 合作
组最新质子能谱测量
结果与“悟空”号一
致（见左图）

宇宙线氦核



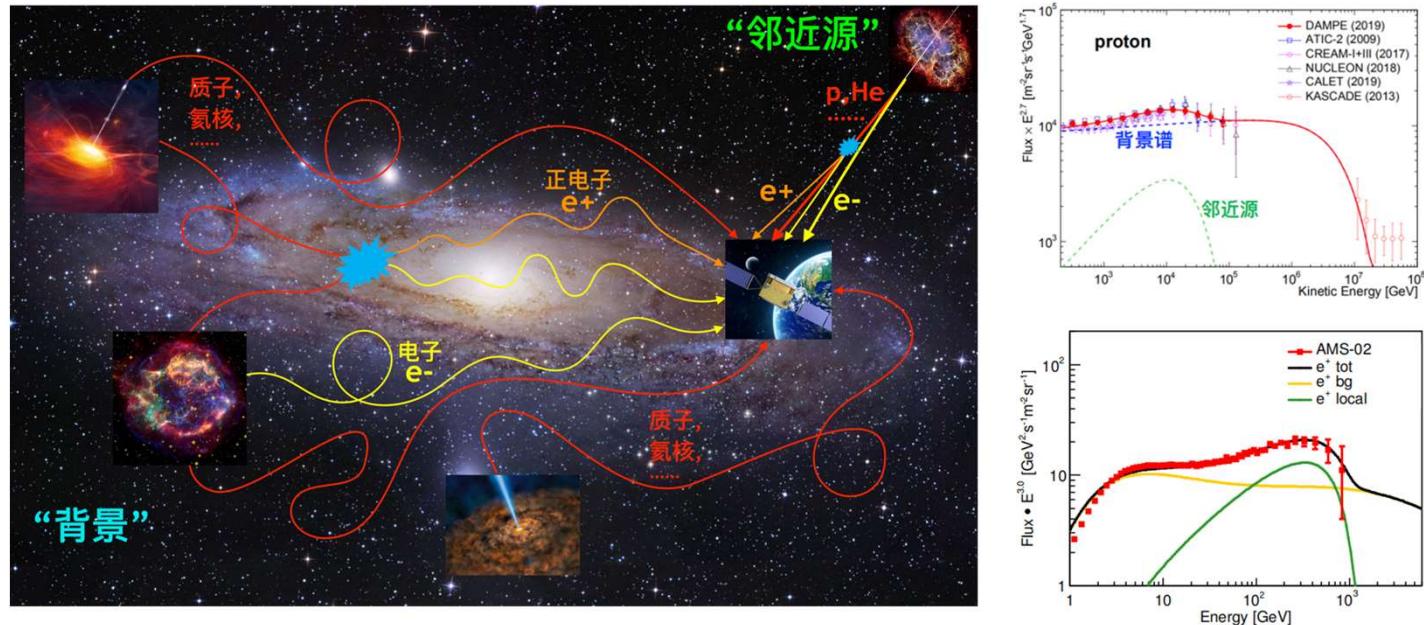
Accepted by
PRL

重荷的测量

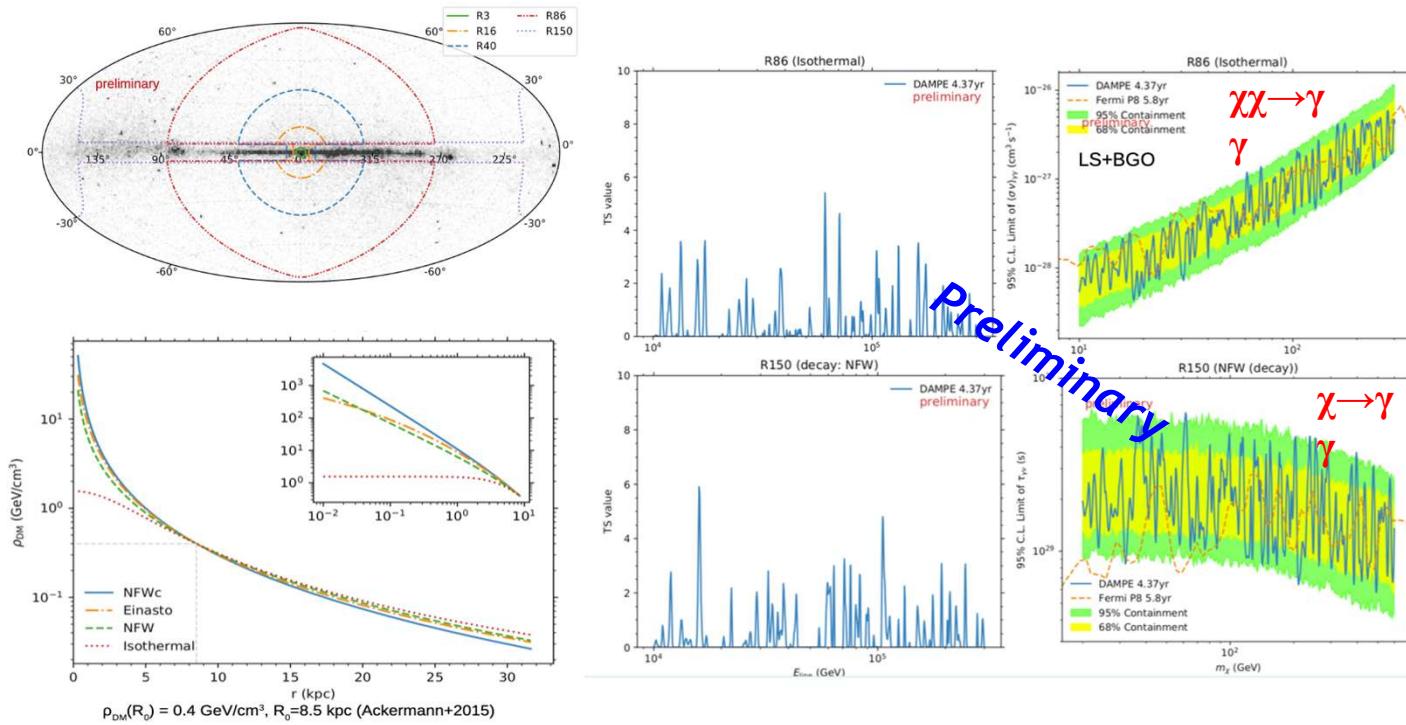




基于“悟空”号以及其他实验的观测结果，可以建立起一个“背景+邻近源”的宇宙射线模型

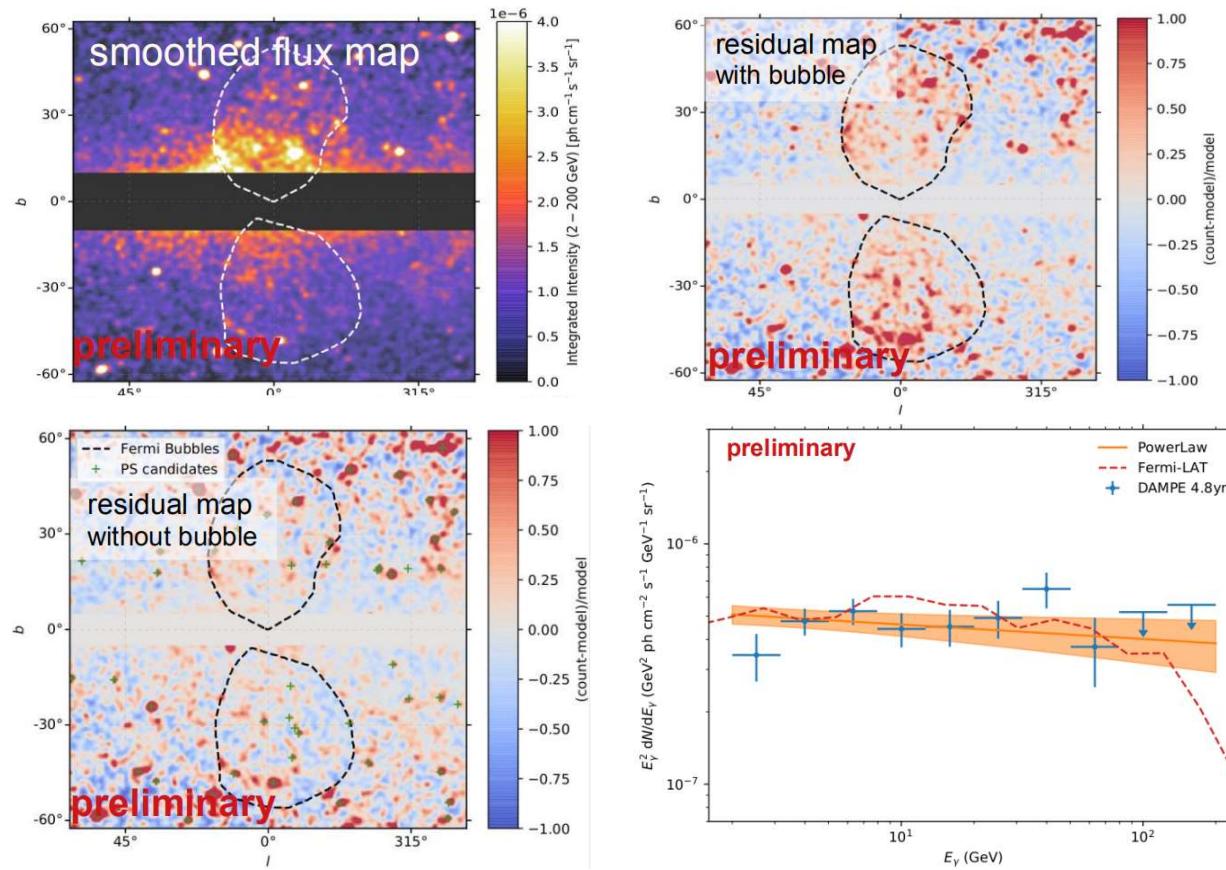


伽马射线



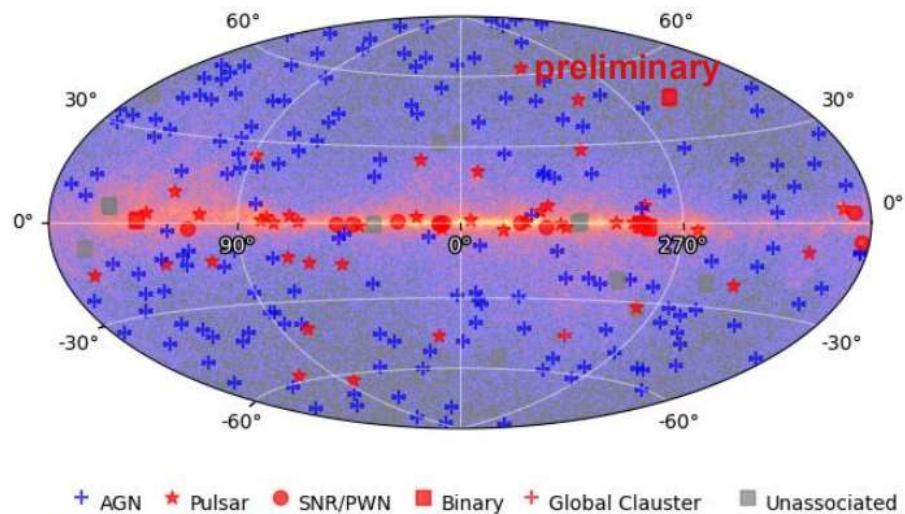
线谱是暗物质粒子的最佳信号。“悟空”号比Fermi-LAT相比探测面积小，运行时间短，但得益于其卓越的能量分辨能力，在线谱搜寻能力与Fermi-LAT相当

伽马射线



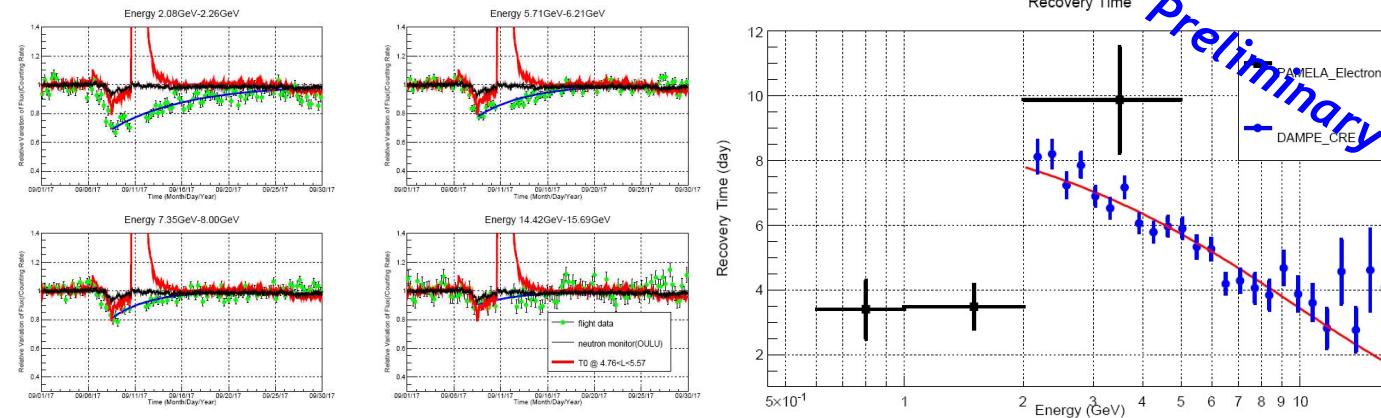


伽马射线



Source Type	Number
AGN	175
Pulsar	45
SNR/PWN	11
Binary	4
Globular cluster	1
Unassociated	13
Total	249

其他“收获”



- “悟空”号观测到 e^+e^- 的“Forbush”下降过程
- 观测到恢复时间和能量的相关性



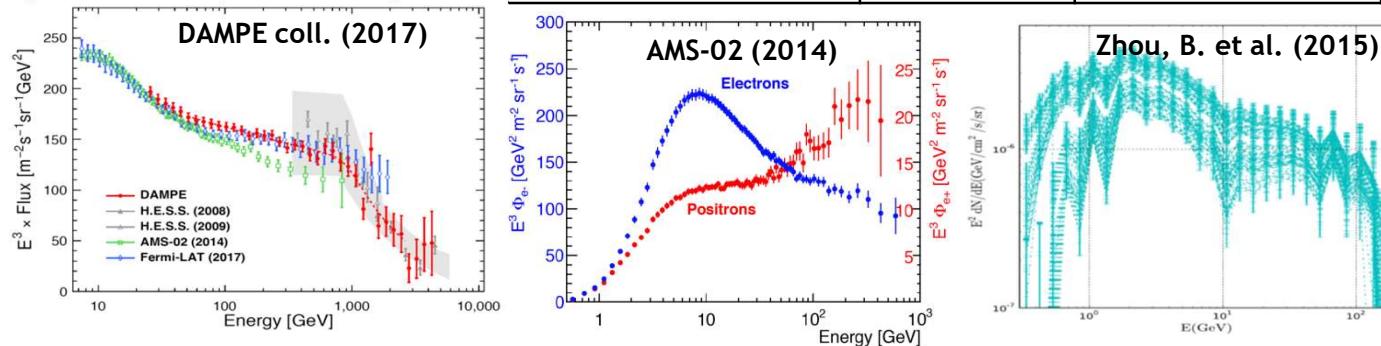
小结

- 悟空号目前已经平稳运行5年多，打开了TeV的观测窗口
- 精确地测量了正负电子能谱在TeV处的截断
- 精确地测量质子（氦核）在 ~ 14 (34) TeV处变软
- 给出了暗物质湮灭、衰变到到伽马射线限制
- 预计悟空号还能够运行3-5年，将会有宇宙线和伽马射线的更多结果

“悟空”号的伽马探测能力弱，特别是灵敏度低于Fermi-LAT，而伽马射线是暗物质的smoking gun

目前的宇宙线探测结果

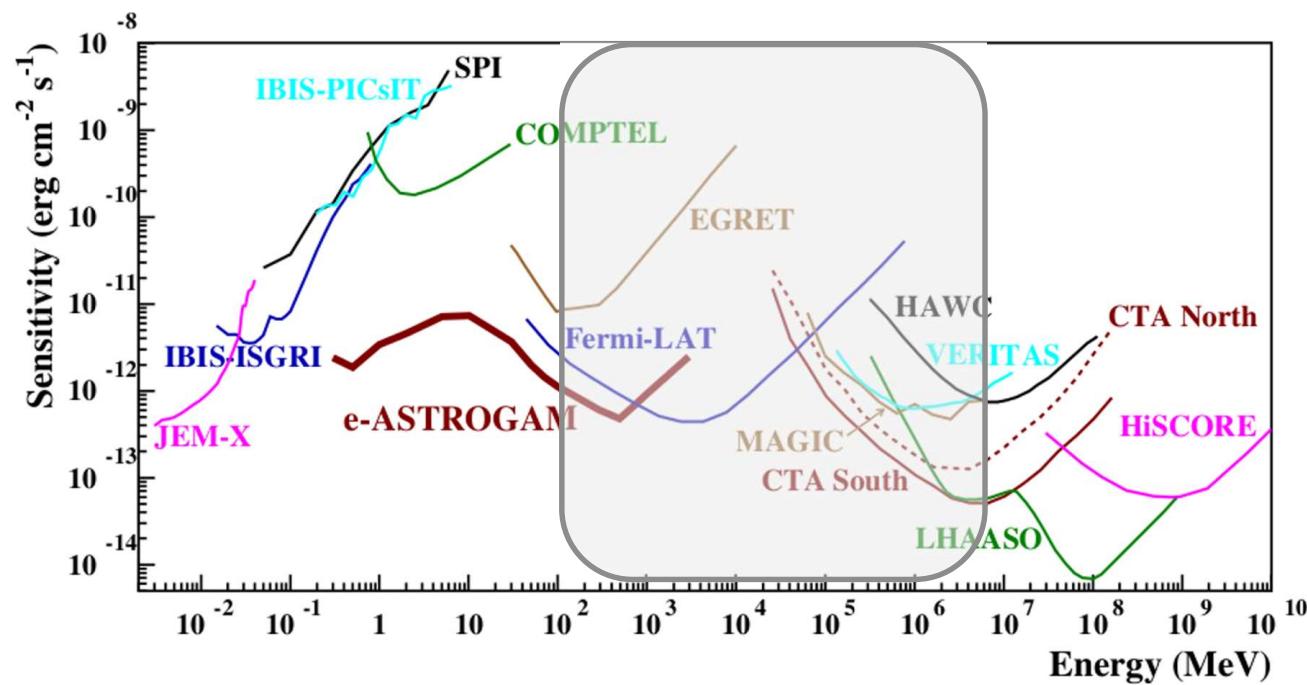
研究对象	探测现状	不确定性	疑似信号的能区
正负电子宇宙线	与宇宙线模型预言比有超出	大	TeV
反质子宇宙线	AMS-02数据中似乎有超出	大	GeV
伽玛射线	银心	存在重要的GeV超出	GeV
	矮星系	个别近源有微弱的信号	GeV



暗物质仍有很大可能性落入GeV-TeV波段，大面积伽马射线望远镜具有重要的发现机遇、发现后也具有精测的必要

53

伽马探测器的灵敏度



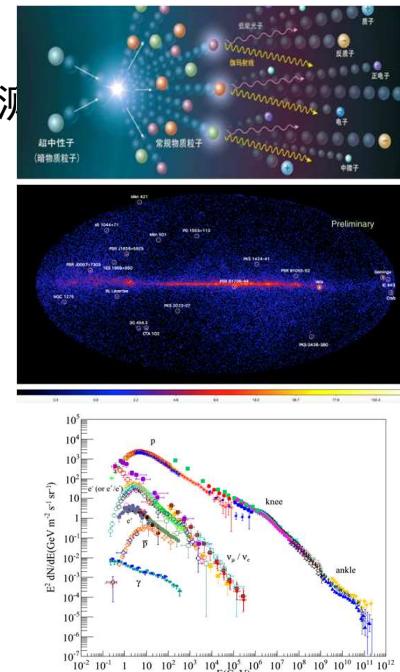
GeV-TeV能段一个显著超越Fermi的仪器非常必要！



VLAST (悟空2号) 科学目标

甚大面积伽马射线空间望远镜VLAST(Very Large Area gamma-ray Space Telescope)致力于暗物质间接探测和GeV时域天文！

- 暗物质粒子(WIMP, ALP)的间接探测
 - 矮星系等区域的暗物质湮灭产生的GeV辐射探测
 - 暗物质湮灭(类)线谱探测
 - 在伽马射线源能谱中搜寻ALP信号
 - 在电子宇宙线中搜寻暗物质信号
- 伽马射线天文
 - 引力波、中微子事件的高能辐射对应体
 - 新的GeV(爆发)源、高红移GeV辐射源
 - 测量宇宙的伽马射线视界
- 宇宙线物理(大张角入射粒子)
 - 邻近电子宇宙线源的证认
 - 高能段能谱的精确测量及新能谱结构的证认





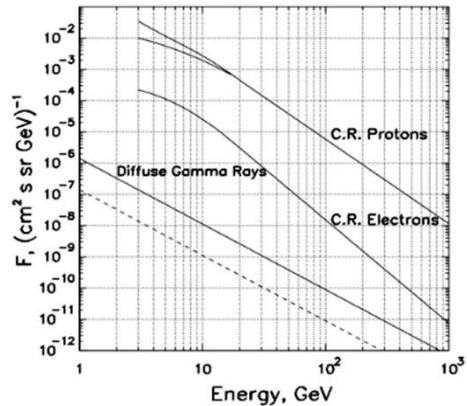
VLAST vs. “悟空”号：特色

- ◆ DAMPE: 对高能电子、伽马的能量分辨率国际领先
- ◆ VLAST: GeV伽马的探测灵敏度世界第一
- ◆ DAMPE: (探测器)厚、(能量分辨)高、(粒子鉴别)准
- ◆ VLAST: (探测器)薄、(有效面积)大、(观测天区)广

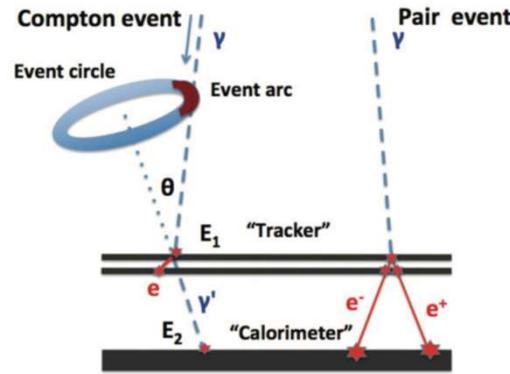
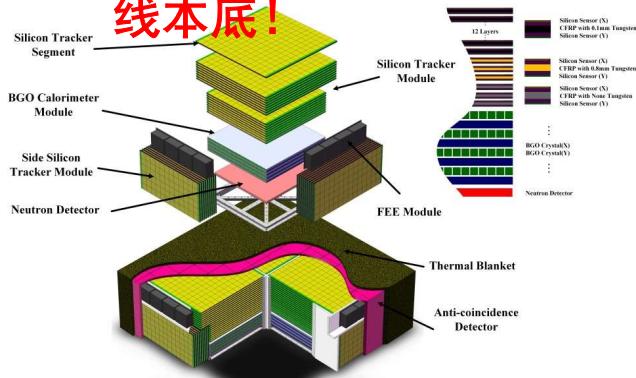
γ 探测设备	工作能段	接受度@10GeV (m ² sr)	能量分辨@50GeV
Fermi-LAT	0.1GeV-0.5TeV	2	6.5%
DAMPE	2GeV-10TeV	0.2	1.5%
HERD(在研)	5GeV-20TeV	~2	2.0%
VLAST	0.3GeV-20TeV	~10	1.5%

VLAST是国际首颗10 m² sr级的高能探测卫星，
将以前所未有的灵敏度对GeV γ 进行高能量分辨观测！

VLAST初步设计



光子流量远低于宇宙线本底!



高能光子探测原理

VLAST探测原理：

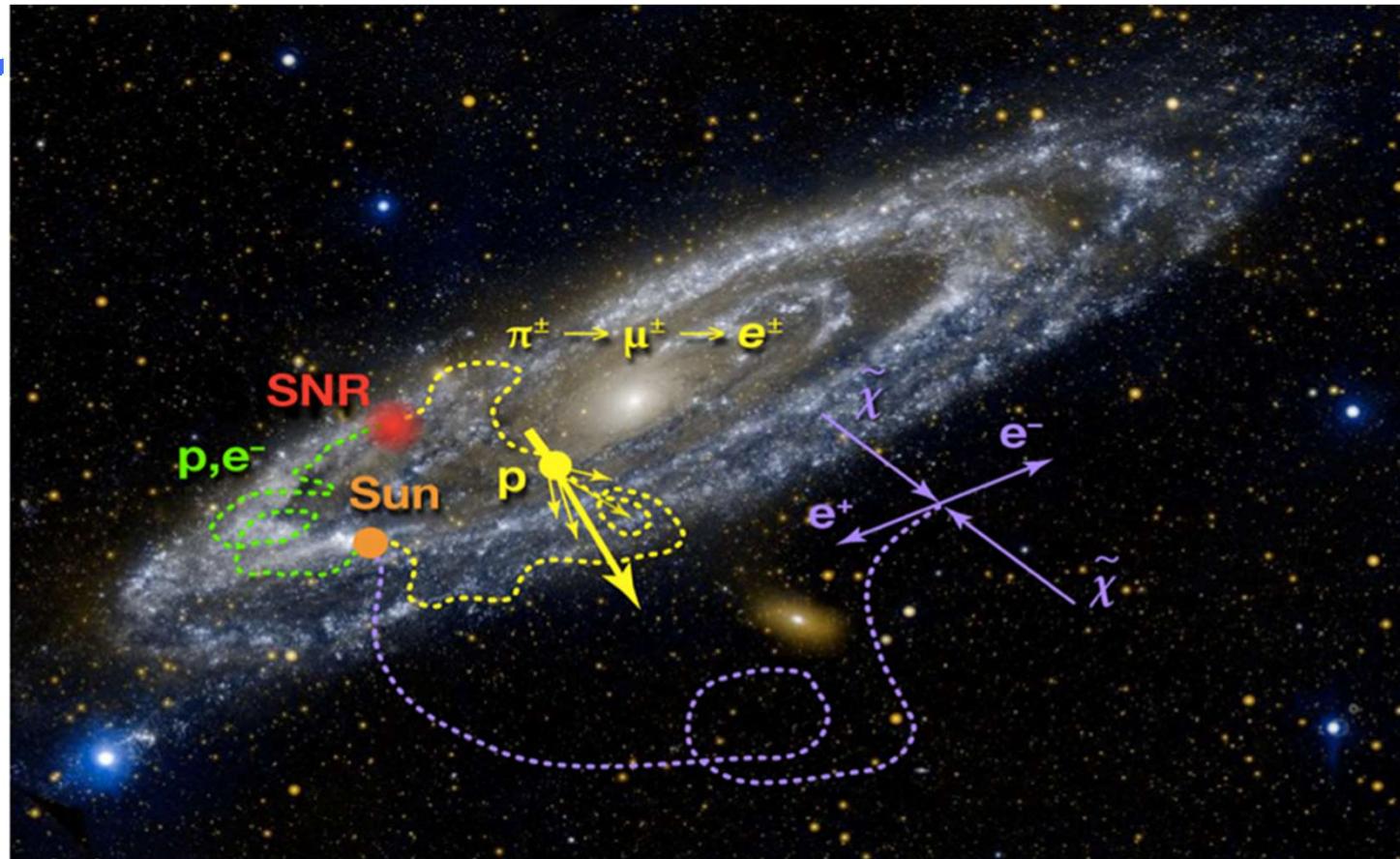
- 反符合探测器：剔除带电粒子
- 径迹探测器：测量光子方向
- 量能器：粒子能量+e/p鉴别
- 中子探测器：粒子鉴别加强



VLAST：技术挑战和创新

指标项	“悟空” DAMPE	VLAST (预期)	跨越度
伽马探测效率@1GeV	5%	60%	约12倍
探测单元动态范围	200,000	1,000,000	约5倍
探测器单元通道数	75,908	1,500,000	约20倍
原始触发率	100Hz (>5GeV)	20kHz (>0.3GeV)	约200倍
技术挑战与创新：			

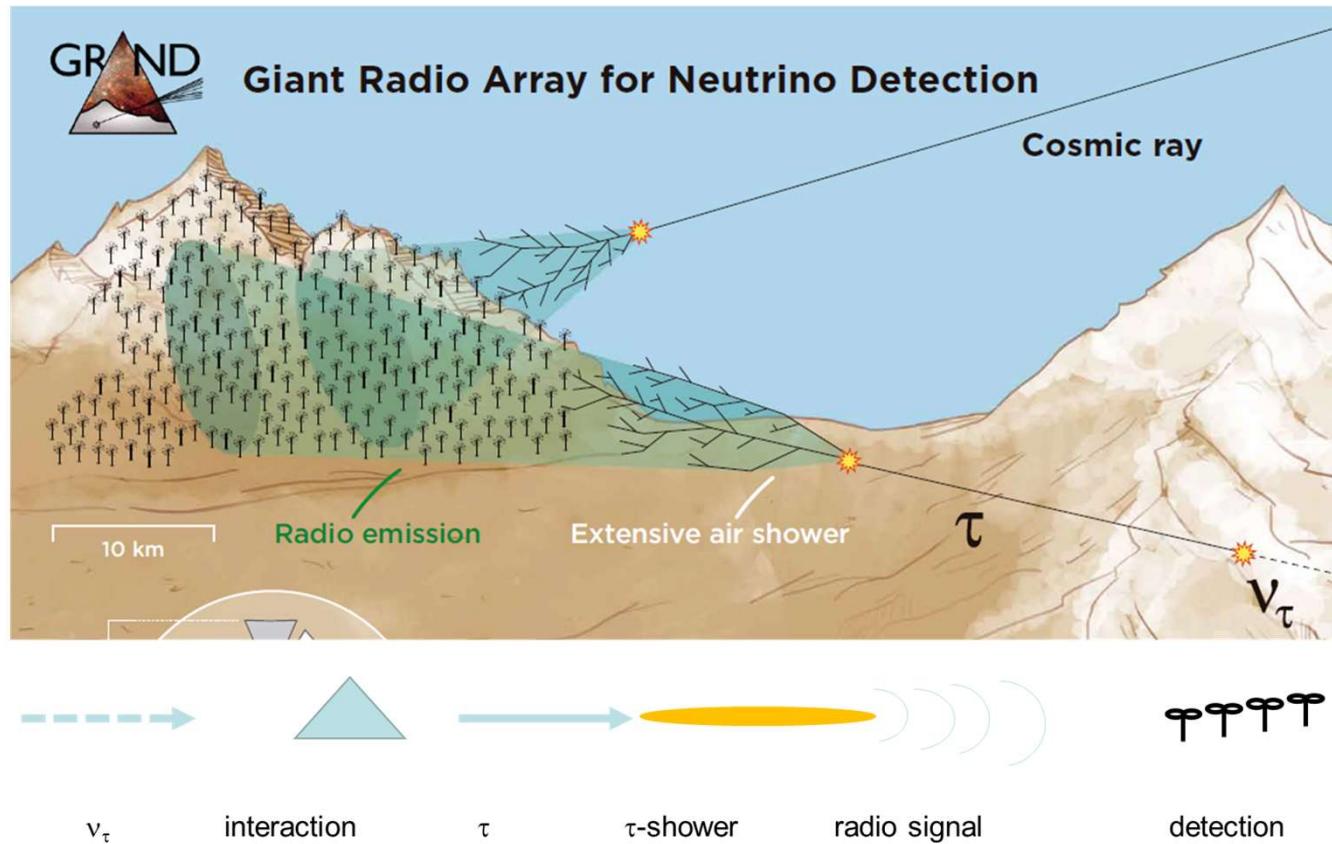
- 超大面积的高位置分辨径迹探测器（总约280 m²）
- 低串扰、大动态范围的光电探测（动态范围>10⁶）
- 高效率的反符合探测（探测效率优于99.9%，事件率>10⁴Hz）
- 高效的在轨数据压缩和触发判选 (>100:1)



宇宙射线最高能量比目前的最大加速器高一亿倍以上！宇宙空间是人类最后的实验室！

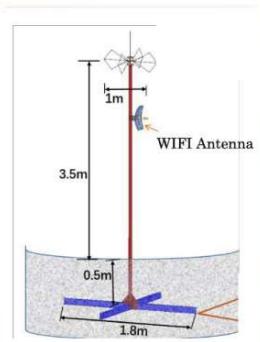
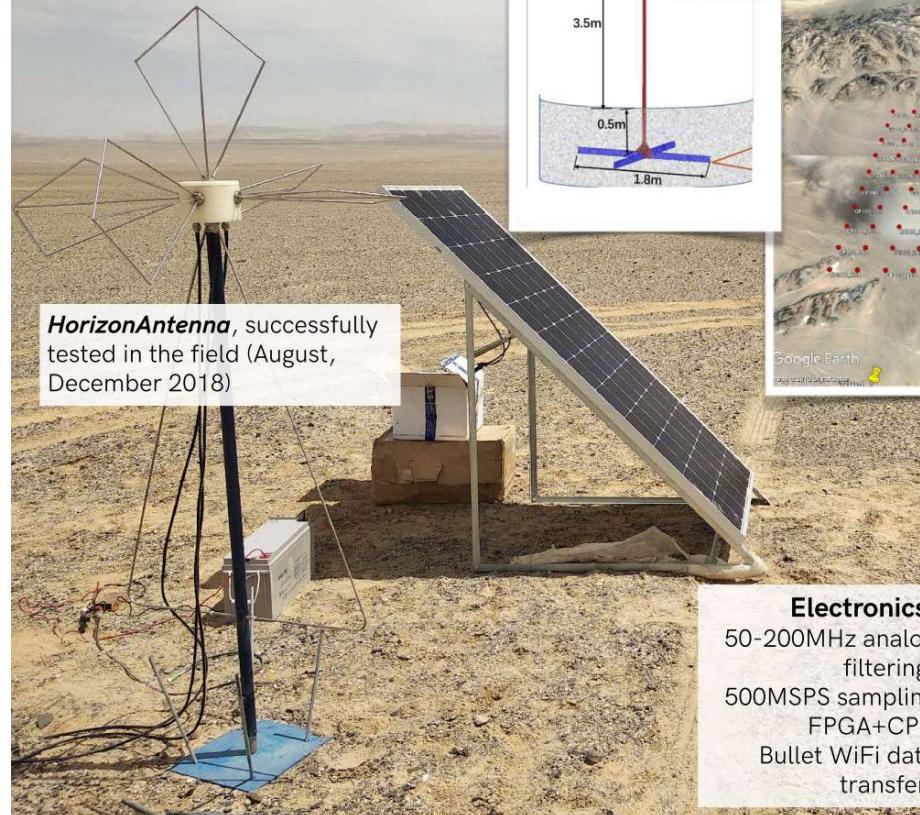


衷心感谢

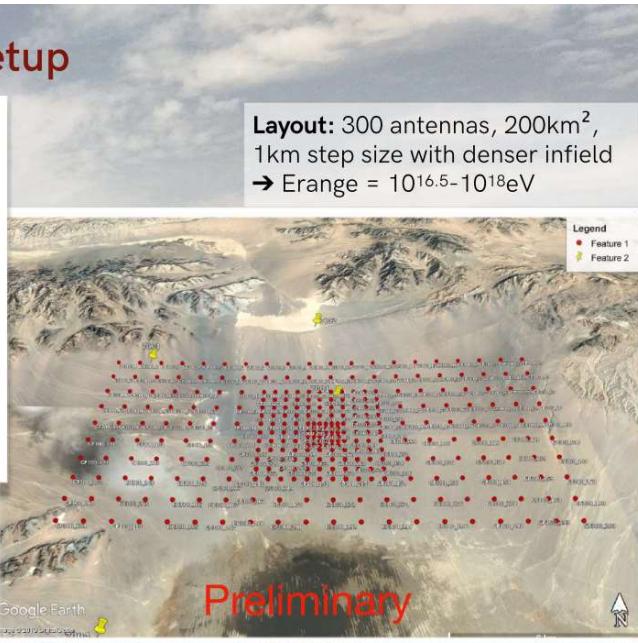


GRANDProto300: experimental setup

Antenna set-up: (Xidian University) antenna simulations, nut design, unit design. First prototypes to be installed on site before end of year 2019



Layout: 300 antennas, 200km^2 , 1km step size with denser infield
 $\rightarrow \text{Erange} = 10^{16.5}\text{--}10^{18}\text{eV}$



Electronics:
50-200MHz analog filtering,
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

