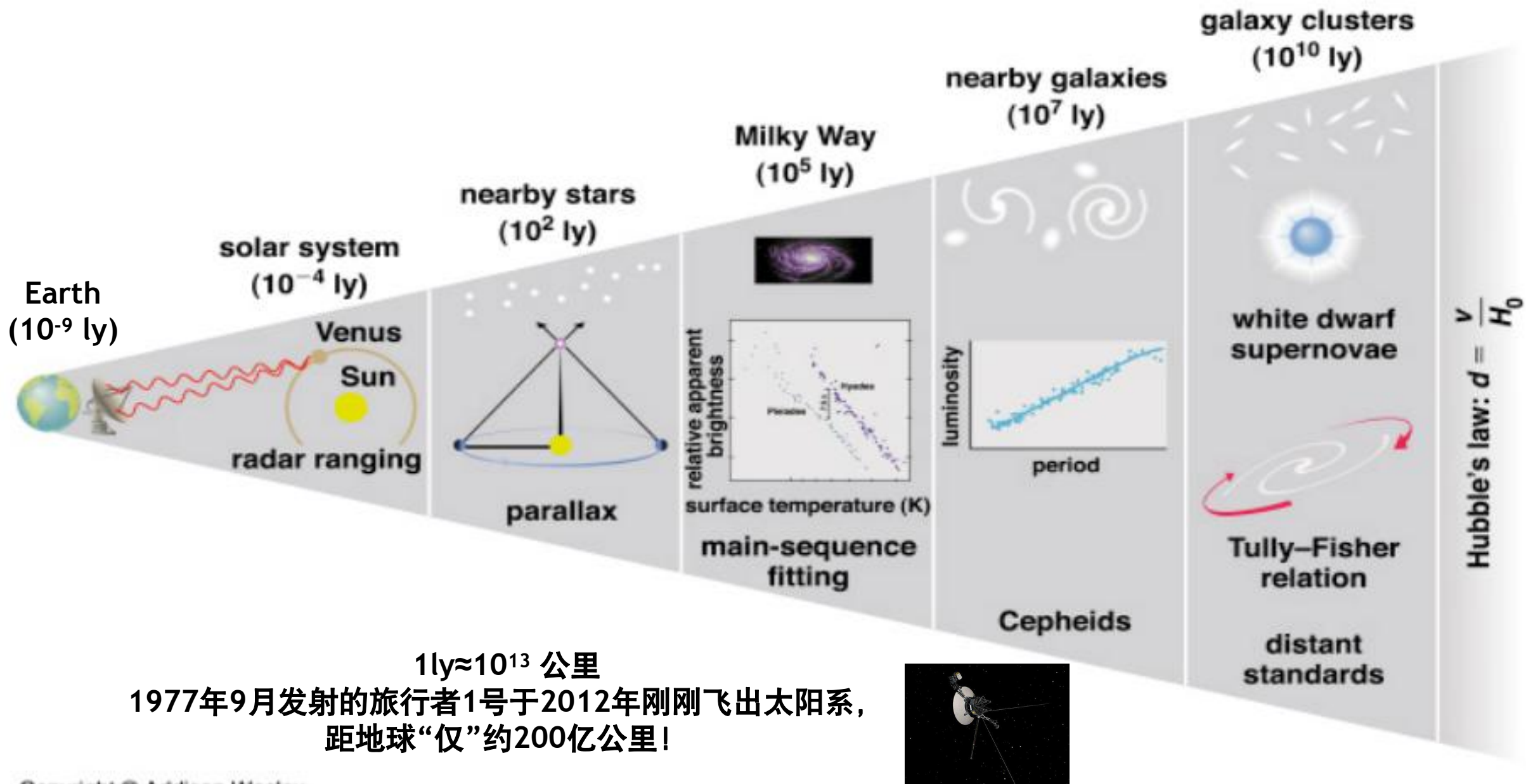


# 暗物质粒子空间间接探测

范一中  
(中国科学院紫金山天文台)  
2022年7月15日



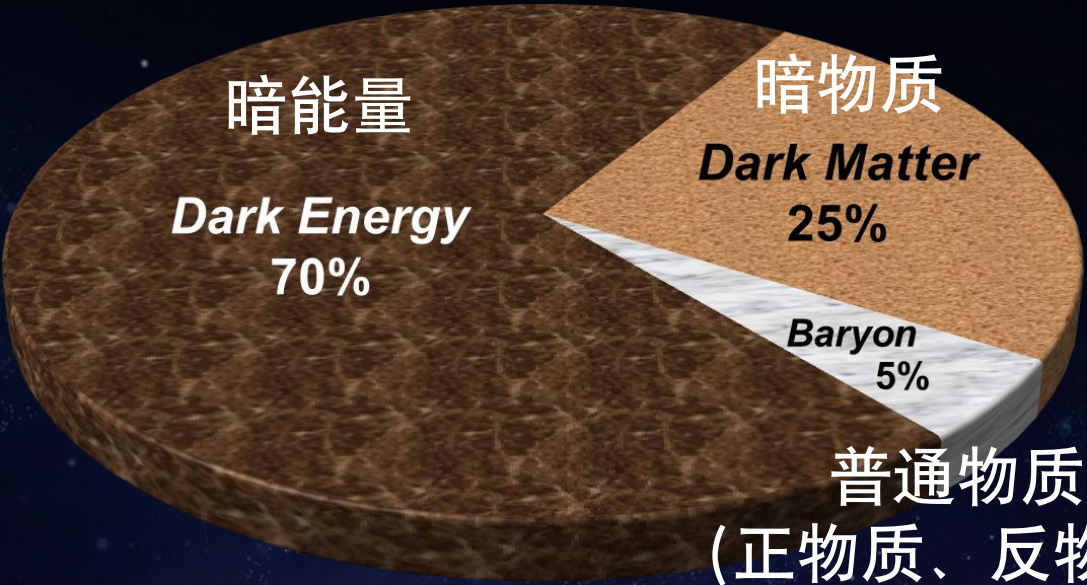
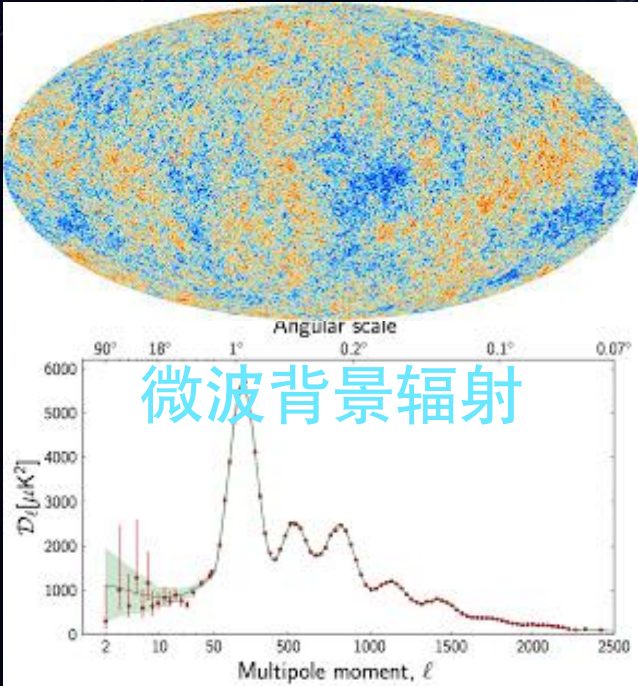
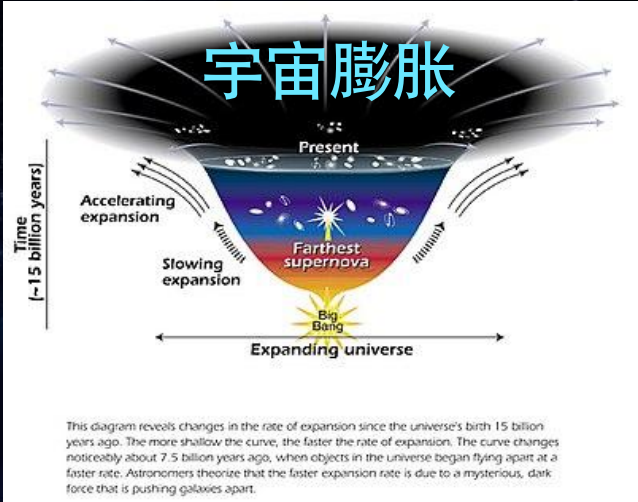
# 宇宙的层次结构



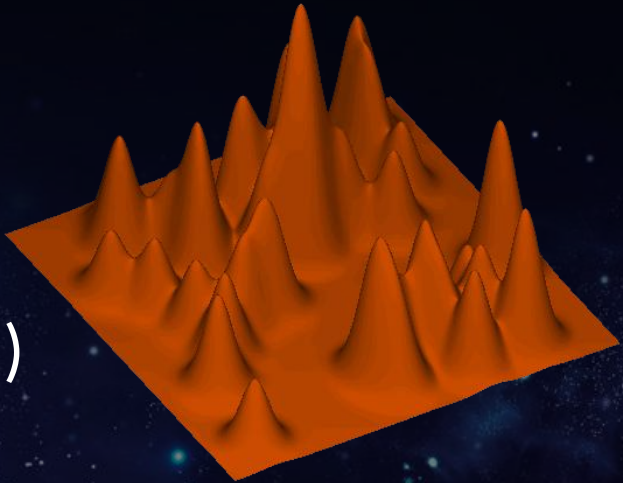
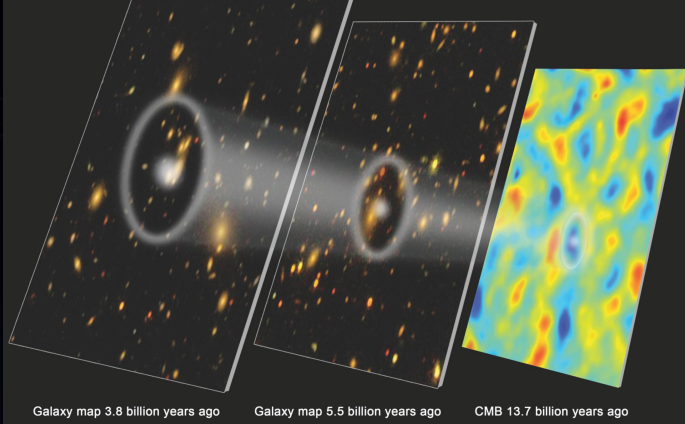
1ly $\approx$ 10<sup>13</sup> 公里

1977年9月发射的旅行者1号于2012年刚刚飞出太阳系，  
距地球“仅”约200亿公里！

# 当今宇宙的物质组分



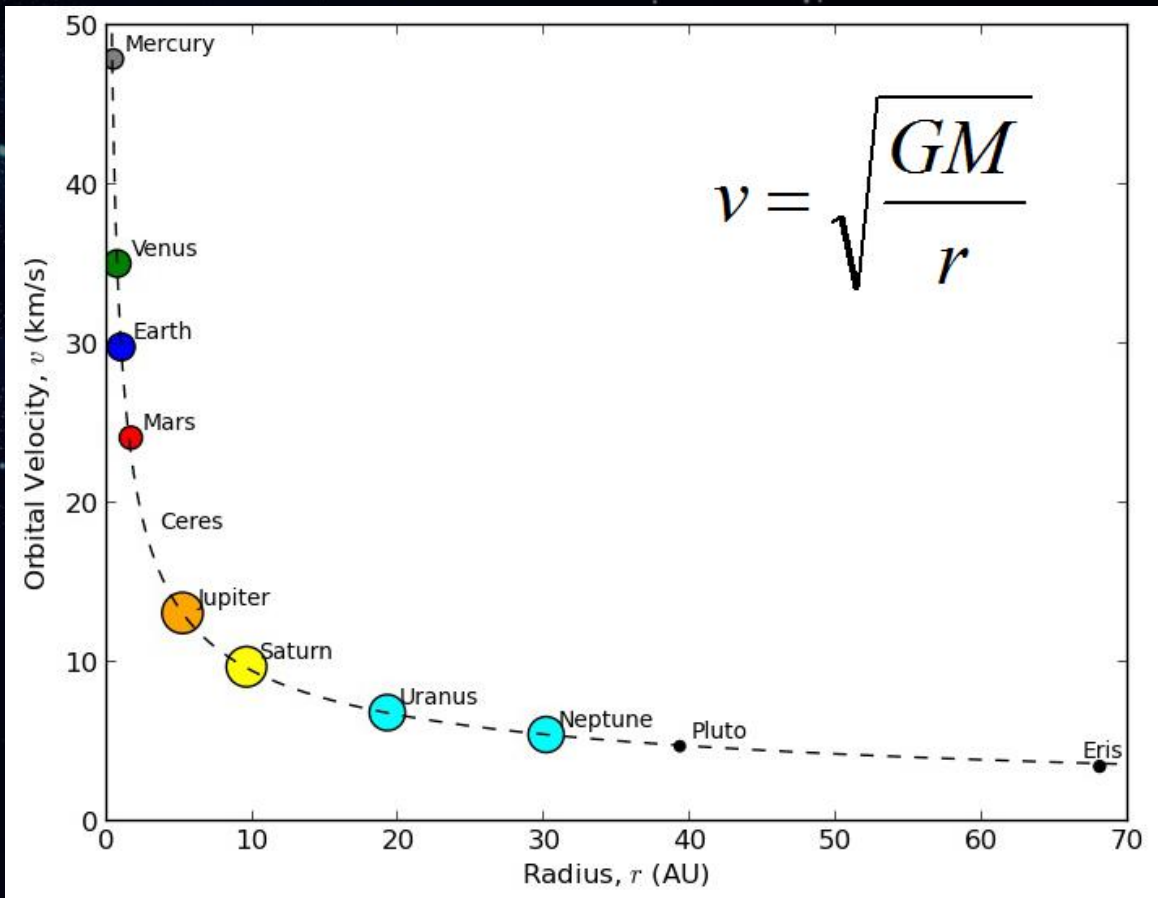
## 重子声波振荡



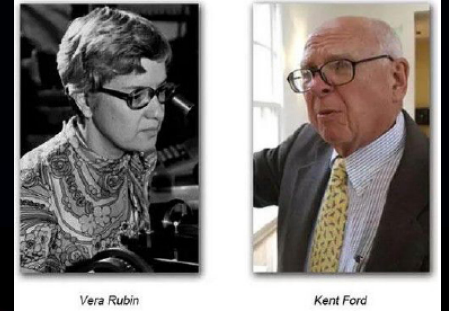
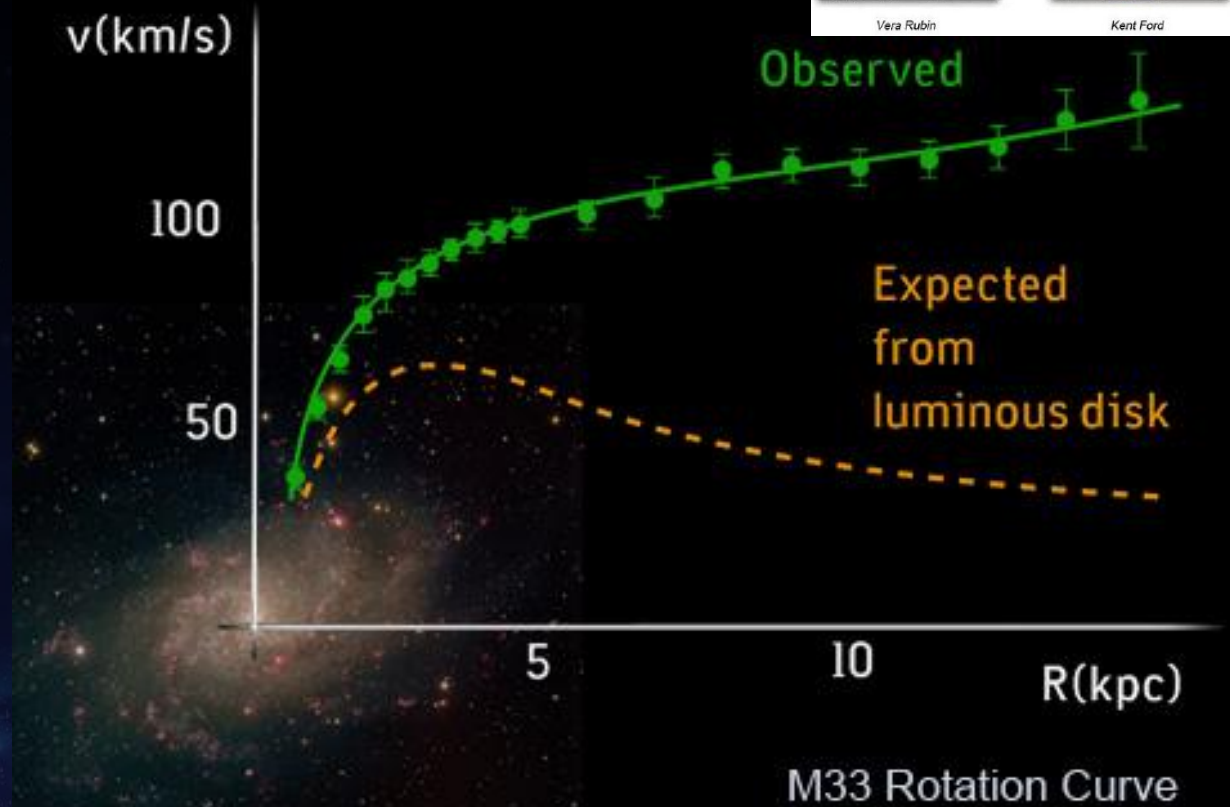


# 暗物质的观测证据

## 太阳系行星旋转曲线

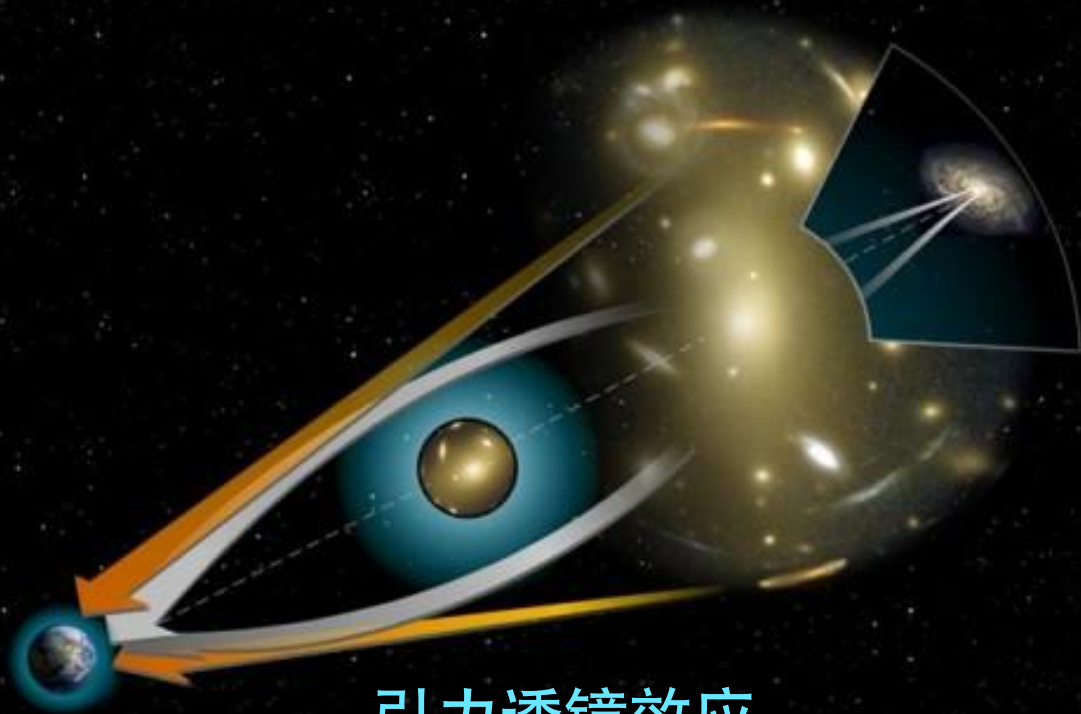


## M33星系旋转曲线





# 暗物质的观测证据



引力透镜效应



子弹星系团

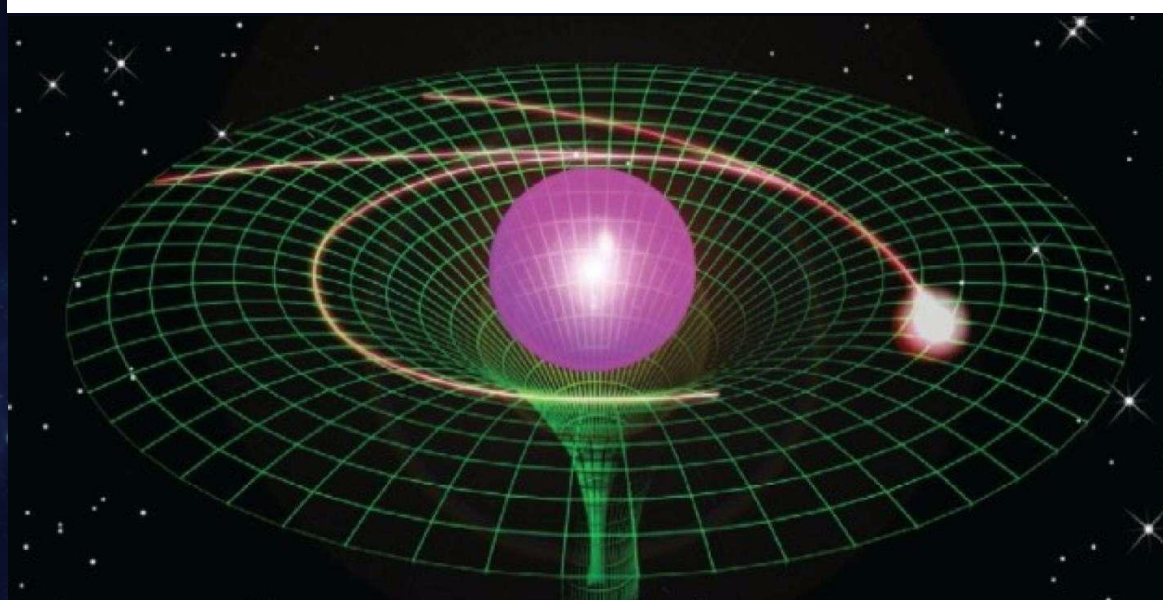
Clowe et al. (2006)



# 引力理论:牛顿万有引力定律与广义相对论

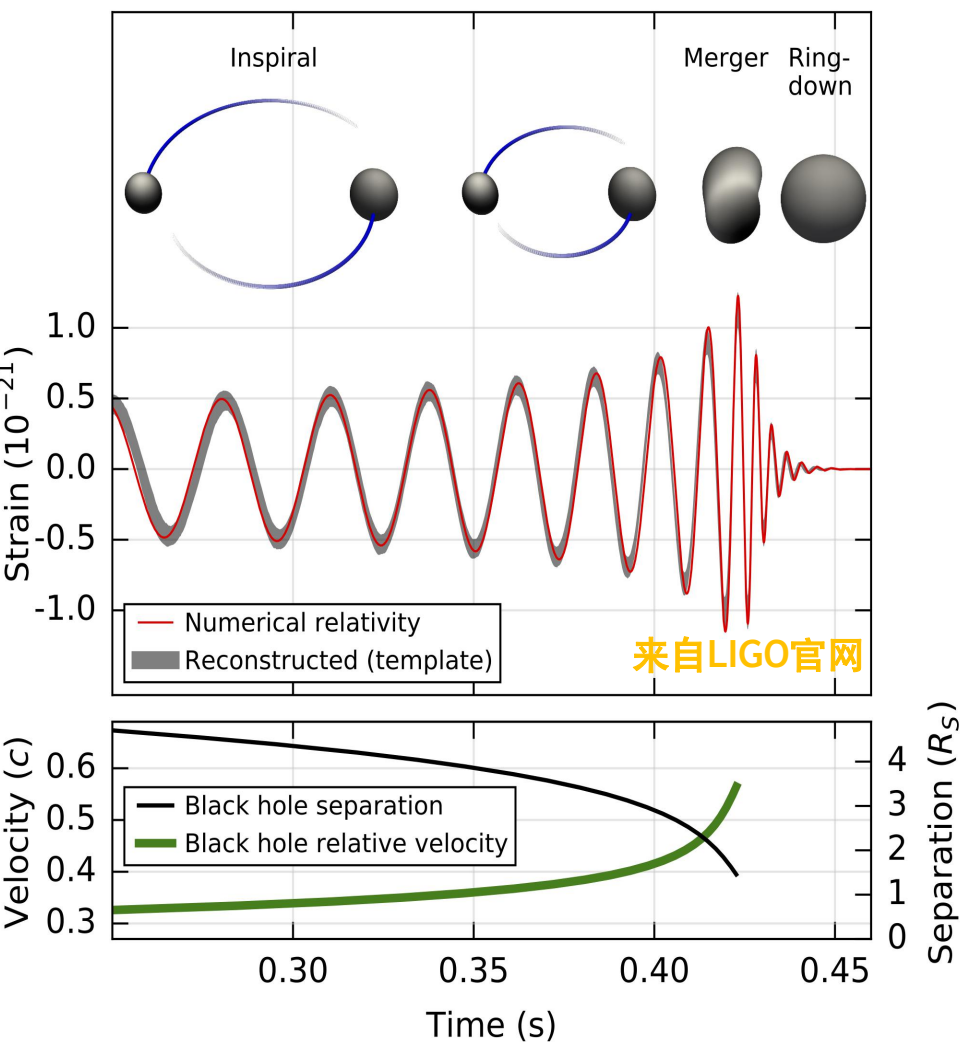


图片来自网络





# 广义相对论:引力波的预言及证实



1916年: 爱因斯坦基于广义相对论预言引力波

2015年: LIGO探测到GW150914

2016年: 文章发表后被评为年度世界十大科技进展之首,  
并被认为是二十一世纪十大科技进展之一!

The Nobel Prize in Physics 2017

## Nobelpriset i fysik 2017

KUNGL. VETENSKAPS-AKADEMIEN  
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Med ena hälften till  
With one half to:

och med den andra hälften gemensamt till  
and with the other half jointly to:

**Rainer Weiss**  
LIGO/VIRGO Collaboration

**Barry C. Barish**  
LIGO/VIRGO Collaboration

**Kip S. Thorne**  
LIGO/VIRGO Collaboration

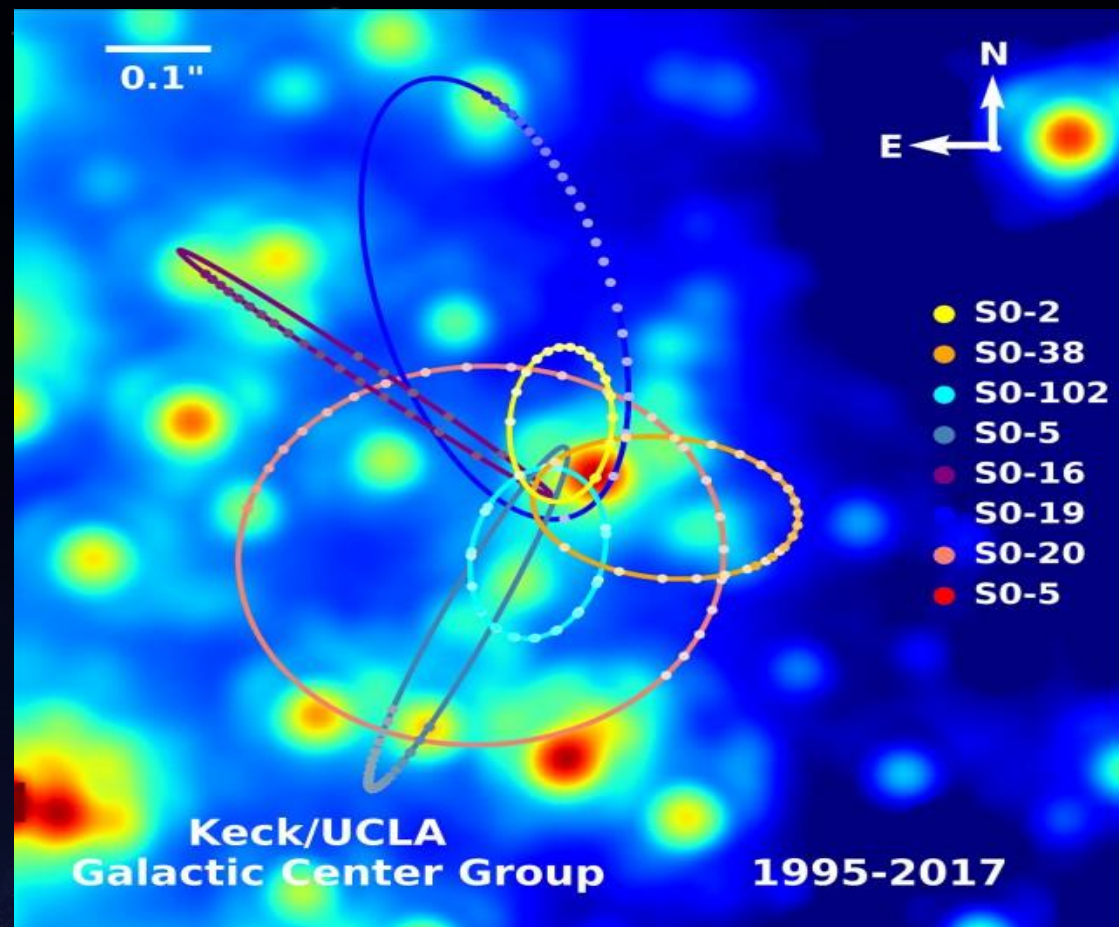
*"för avgörande bidrag till LIGO-detektorn och observationen av gravitationsvågor"*  
*"for decisive contributions to the LIGO detector and the observation of gravitational waves"*

3 October 2017

WWW.NEWS.CN  
Kungl. Vetenskapsakademien



# 广义相对论:黑洞的预言及证实



1964-1970年: 彭罗斯与霍金基于广义相对论从数学上证实了黑洞的存在

1995-2016年: 根策尔和盖兹发现并确认银河系中心的超大黑洞

2020年: 彭罗斯、根策尔和盖兹获得诺贝尔物理学奖



# 科学家普遍认可暗物质的存在

$z = 47.3$

$T = 0.05 \text{ Gyr}$

500 kpc

Aquarius模拟

- 目前科学家普遍认可暗物质的存在
- 暗物质是由天文观测推断存在的一种未知物质，它们不带电、寿命长、不发射/反射或吸收光(电磁波)，通过引力在**大尺度**上影响着天体和宇宙
- 暗物质分布不均匀，形成大大小小的结构。宇宙整体而言暗物质是普通物质质量的5倍，但各个地方差异很大



# 我们身边的暗物质

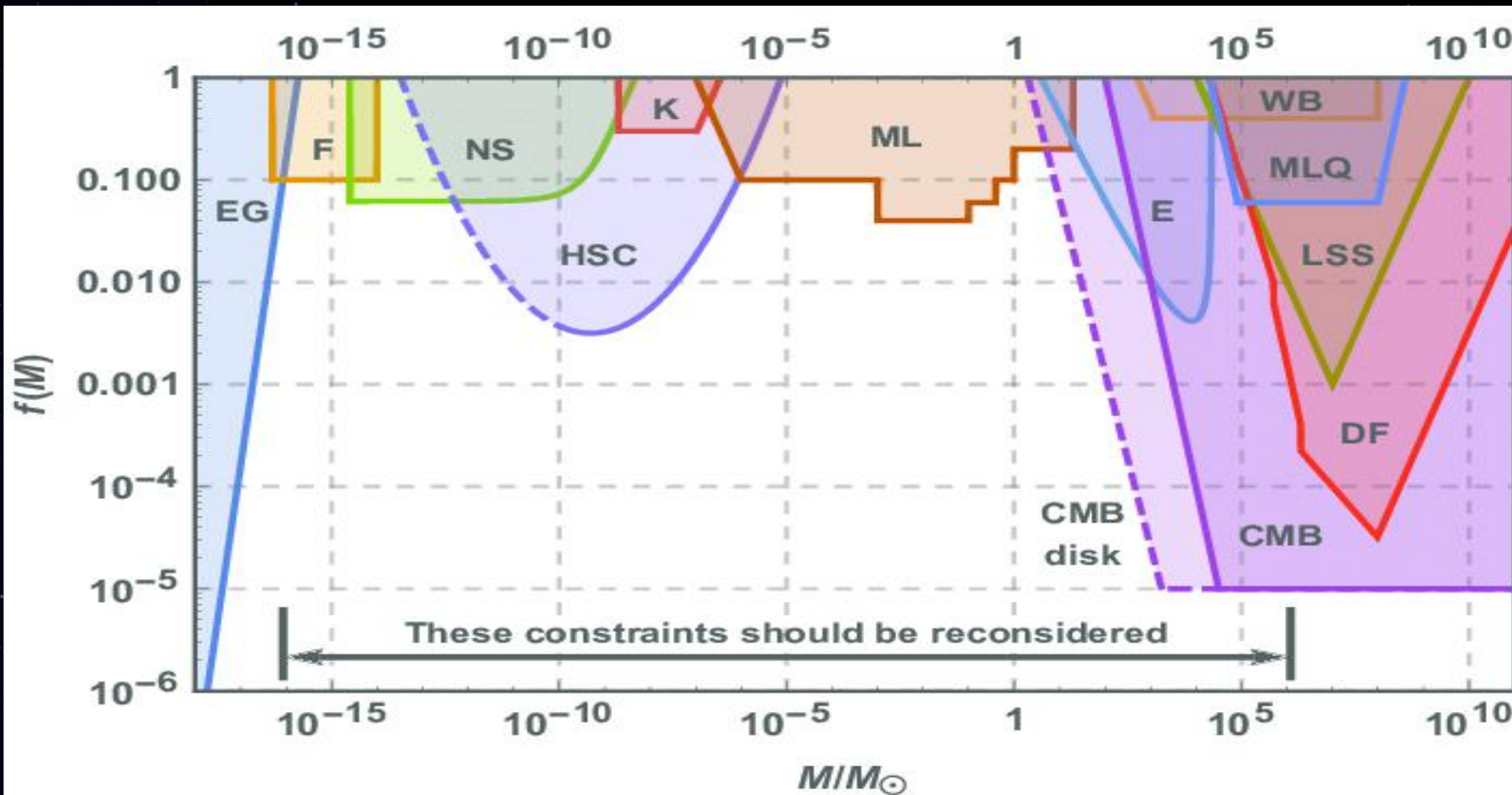
ccce51.net



- 暗物质密度大约0.3个氢原子质量每立方厘米
- 假设暗物质粒子质量为100倍氢原子质量，则一个茶杯里平均有大约1个暗物质粒子，每秒钟约有1亿个暗物质粒子穿越我们身体
- 地球体积内的暗物质总质量约0.5公斤
- 银河系中暗物质质量大约是恒星、气体物质质量的10倍



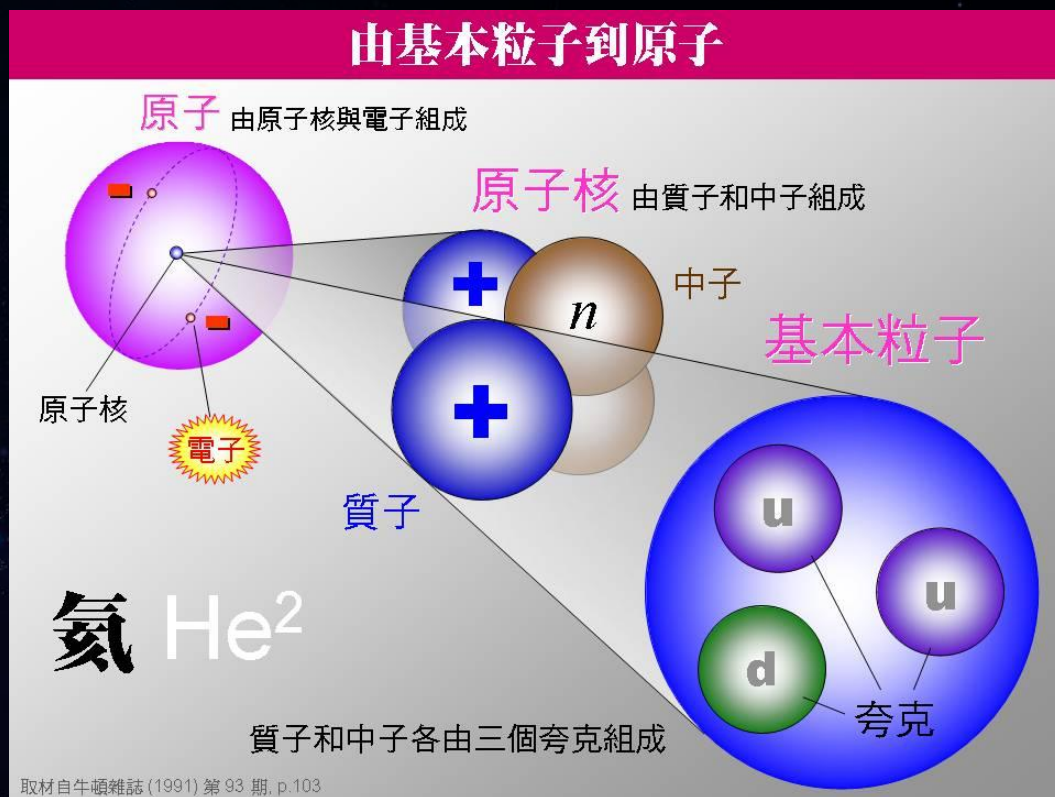
# 暗物质是黑洞吗？



黑洞最多仅占宇宙中暗物质的一小部分(Ketov & Khlopov 2019)



# 暗物质:人类未知的全新粒子



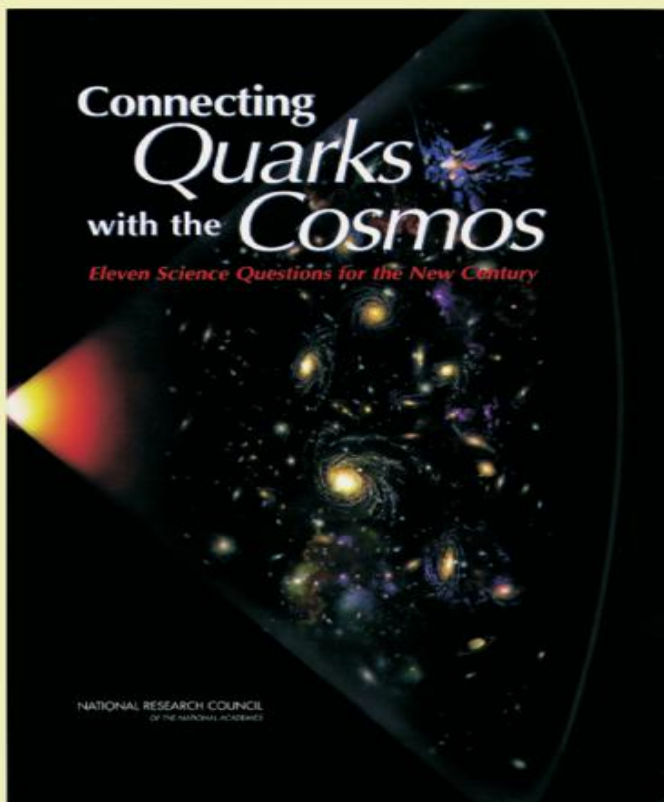
标准粒子物理模型预言的61种基本粒子已经被成功探测到，  
但其中没有任何一种可以合理地解释暗物质！



# 暗物质的本质已经成为当今重大前沿科学问题

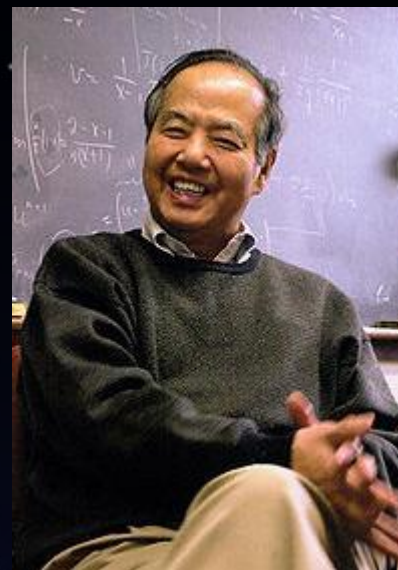
美国国家研究理事会遴选出21世纪宇宙物理学11个重大前沿问题

The Eleven Questions Identified by the *Connecting Quarks with the Cosmos* Report



## 什么是暗物质?

1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies?



李政道，华裔物理学家，诺贝尔奖获得者

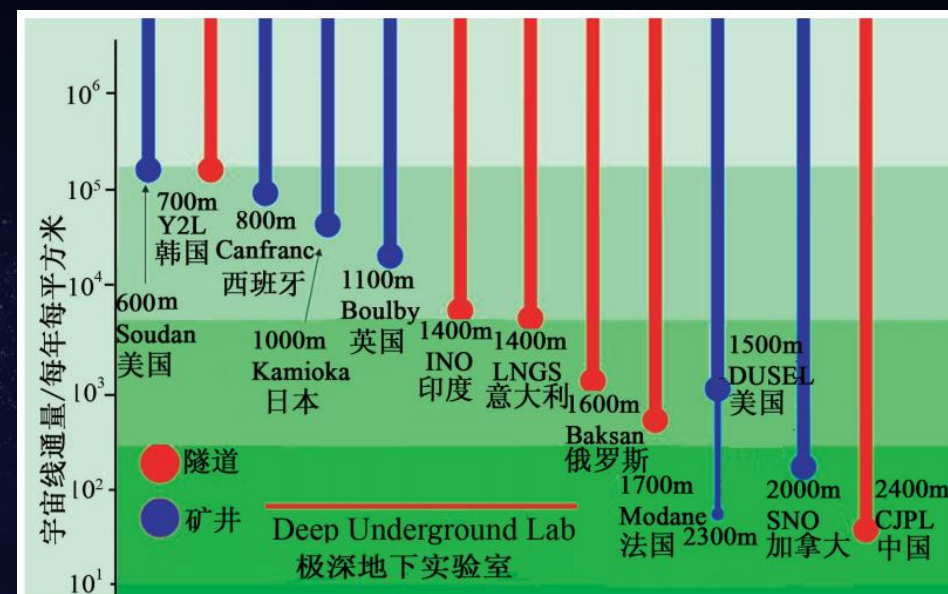
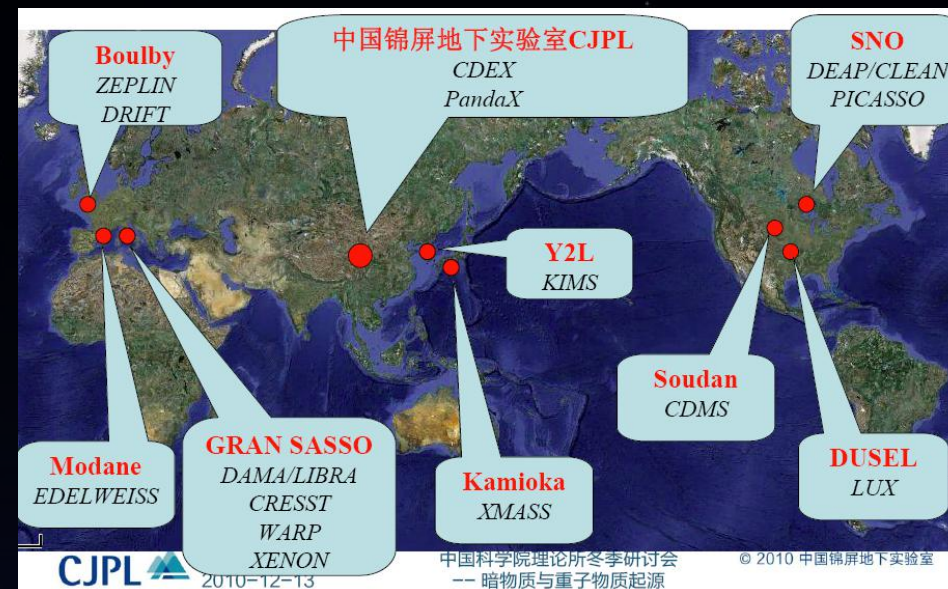
暗物质是笼罩20世纪末和21世纪初现代物理学的最大乌云，它将预示着物理学的又一次革命



# 入地探测暗物质(锦屏深地实验室)

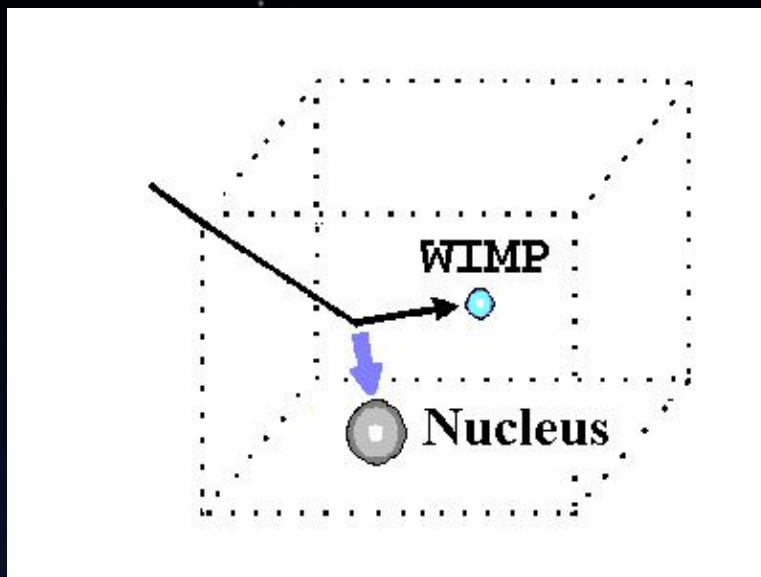


(图来自中国锦屏地下实验室)

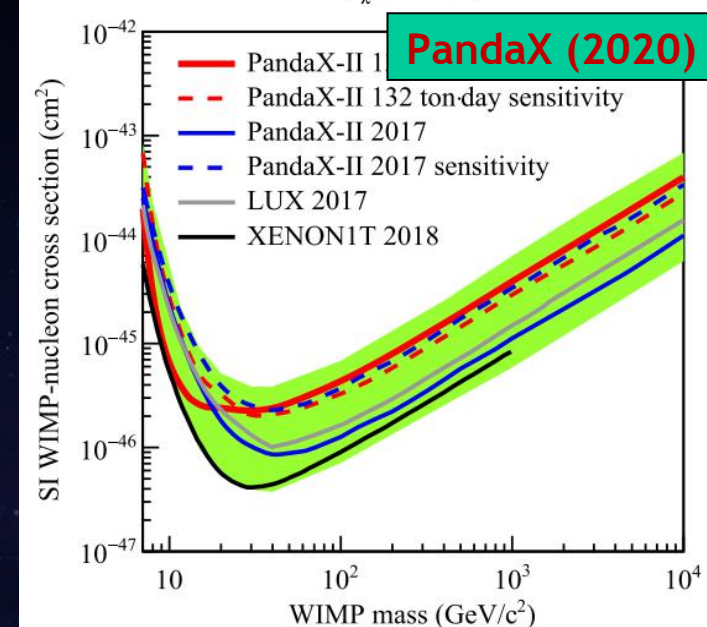
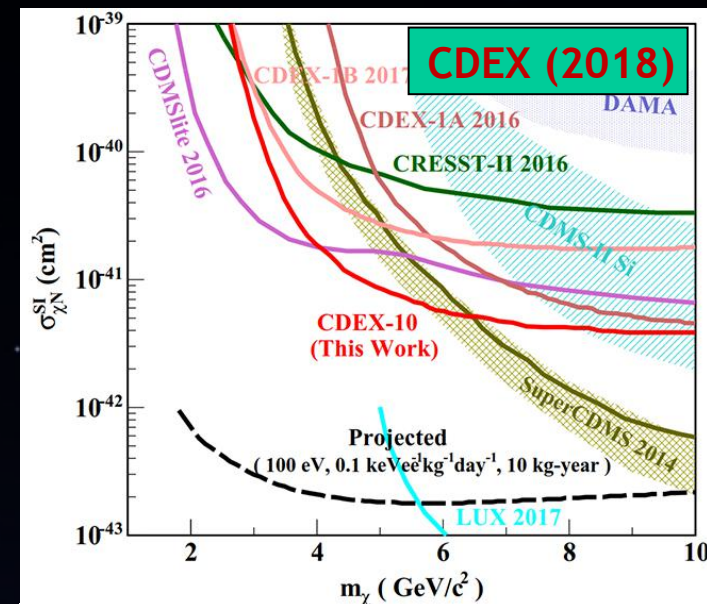




# 入地探测暗物质(锦屏深地实验室)

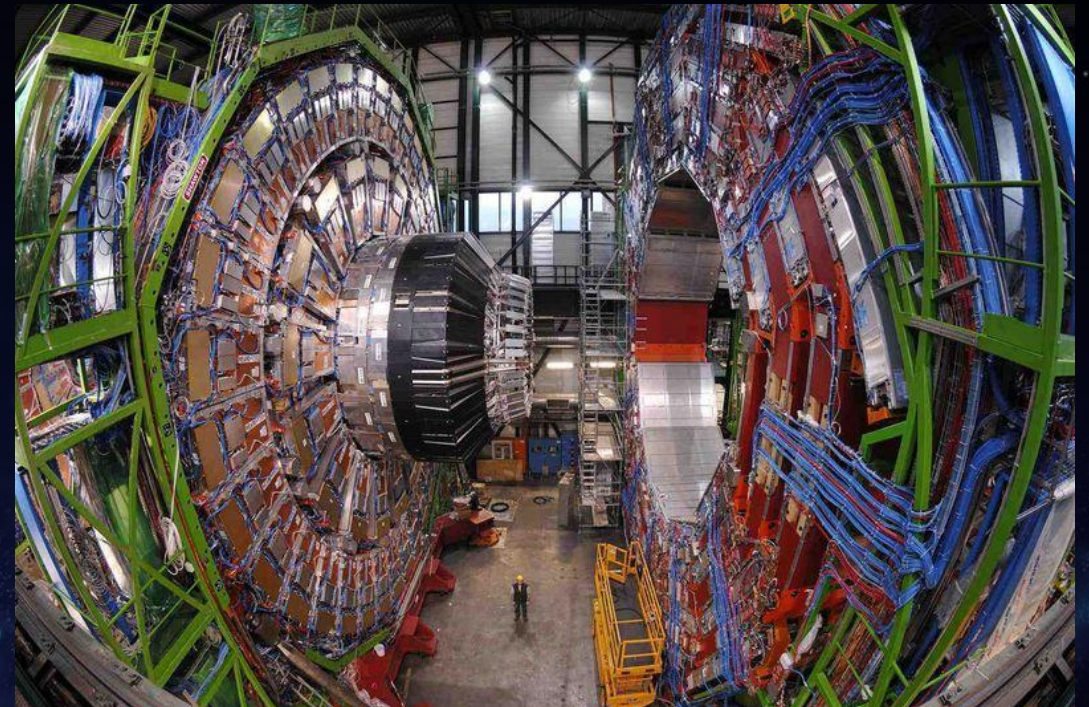
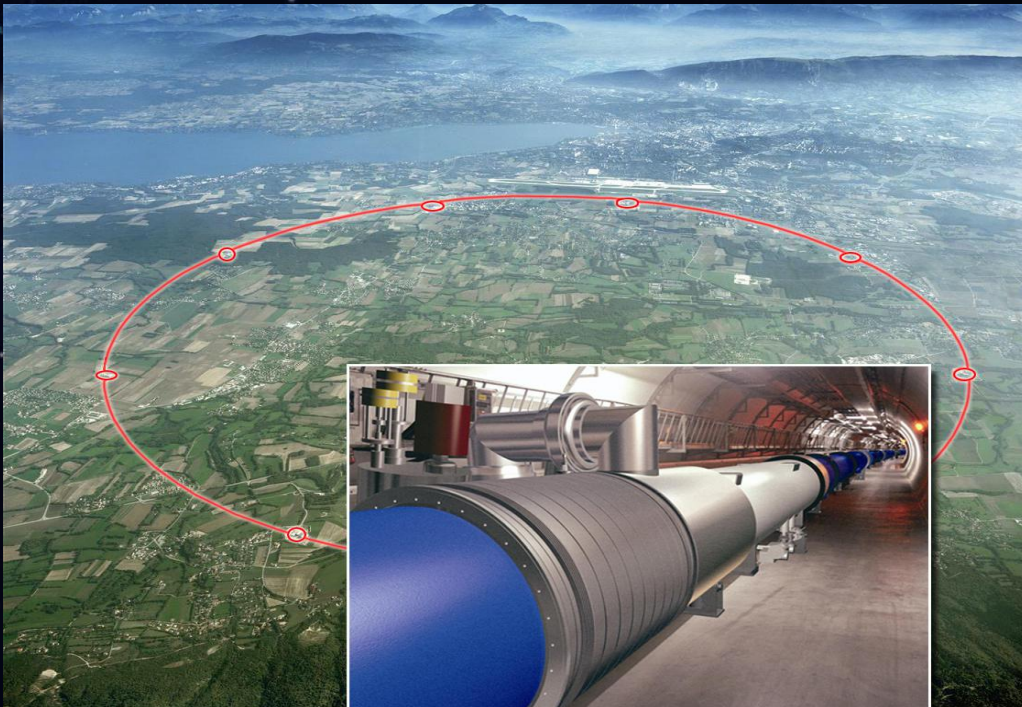
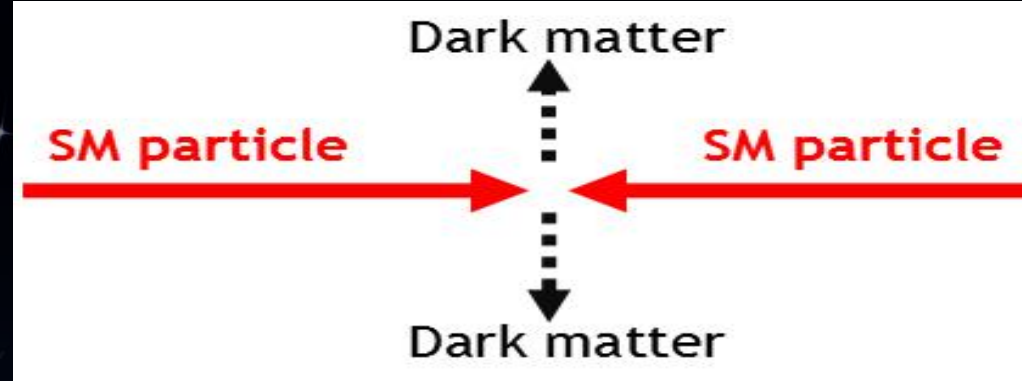


CDEX和PandaX以及国外系列地下直接实验没有发现暗物质信号，对暗物质属性给出严格限制





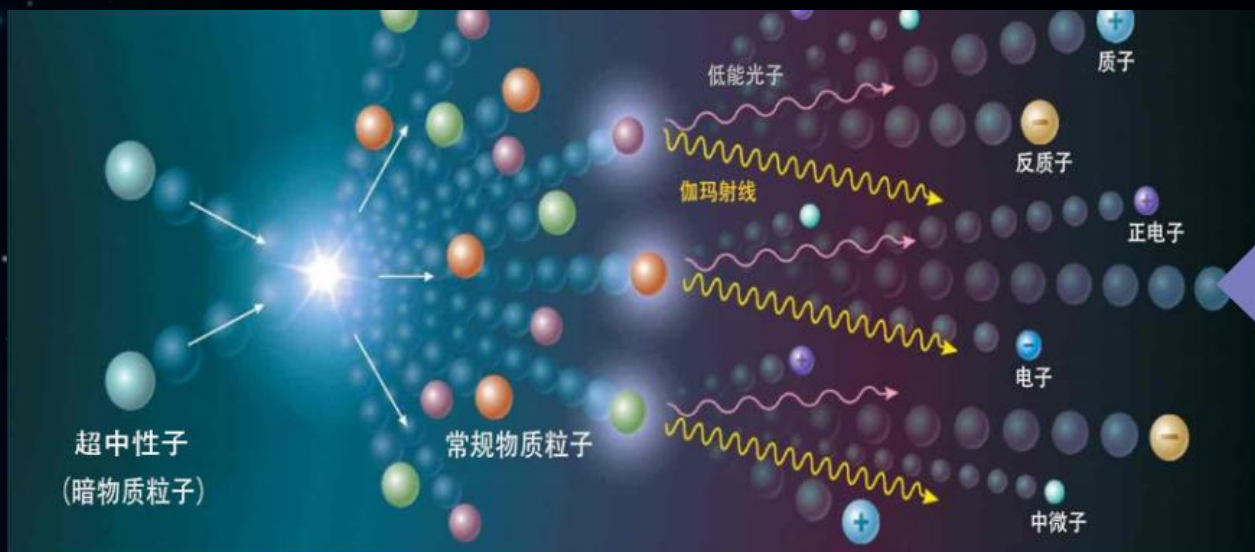
# 入地探测暗物质(大型强子对撞机)



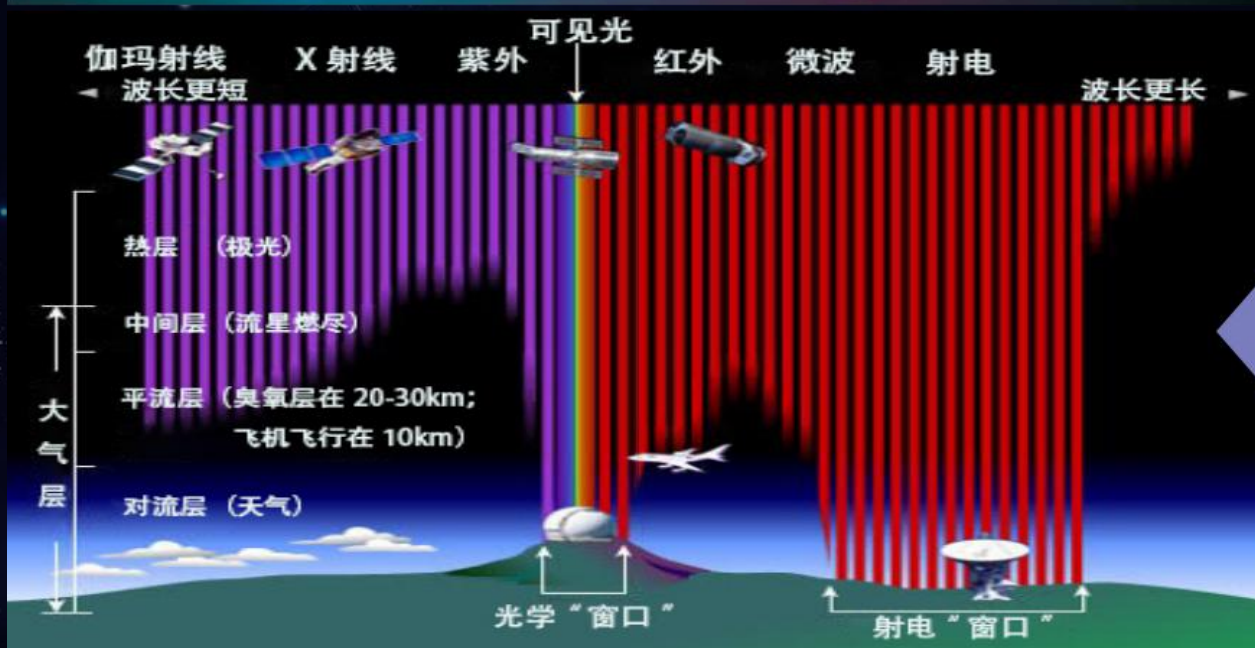
大型强子对撞机尚未发现明确的暗物质信号(图取自LHC官网)



# 上天探测暗物质(空间间接探测实验)



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；它们会被大气吸收，因此需在外太空进行探测



悟空卫星：通过观测高能(电子)宇宙线和伽马射线来间接探测暗物质粒子、研究天体物理



# 我国暗物质空间探测已走过二十年历程



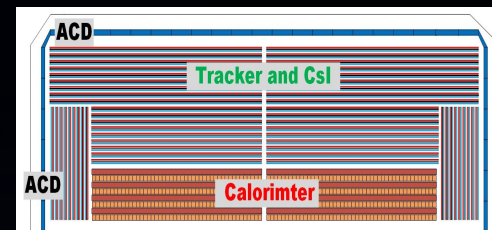
1999 加速器  
验证ATIC



2008 南极气球  
观测成果发布



2015 暗物质  
卫星发射



2019 提出下  
一代卫星项目

1998

1999

2006

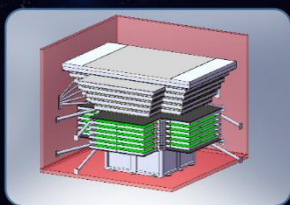
2008

2011

2015

2017

2019



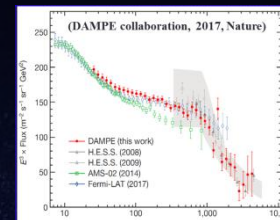
1998 探测  
方法提出



2006 乳胶室  
暗物质探测



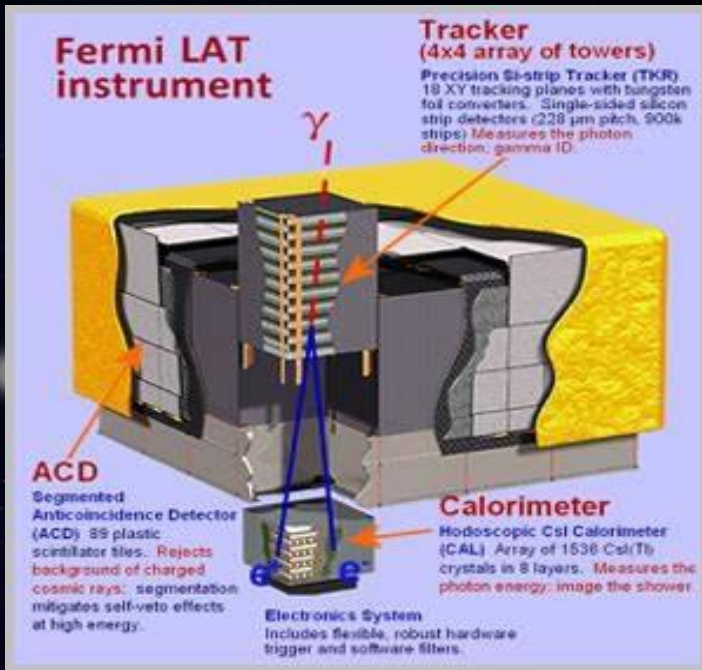
2011 暗物质粒子  
探测器立项研制



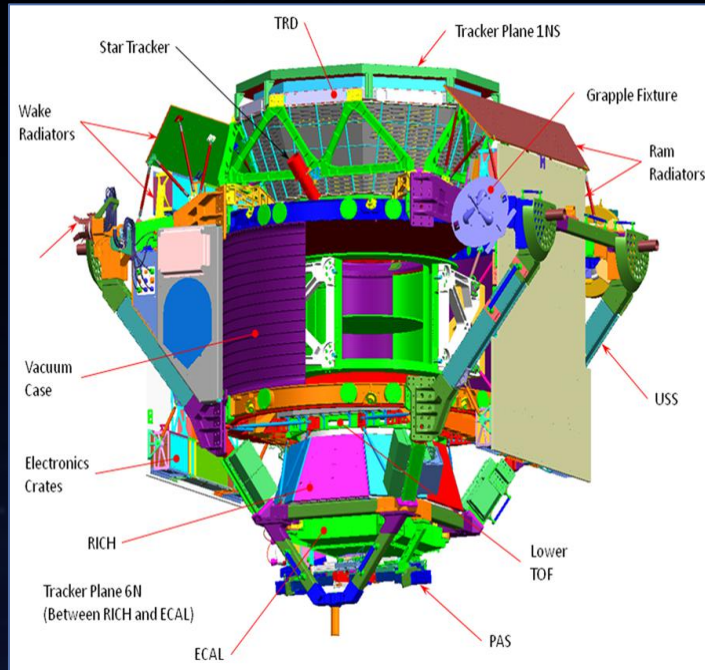
2017 首批电  
子成果发布



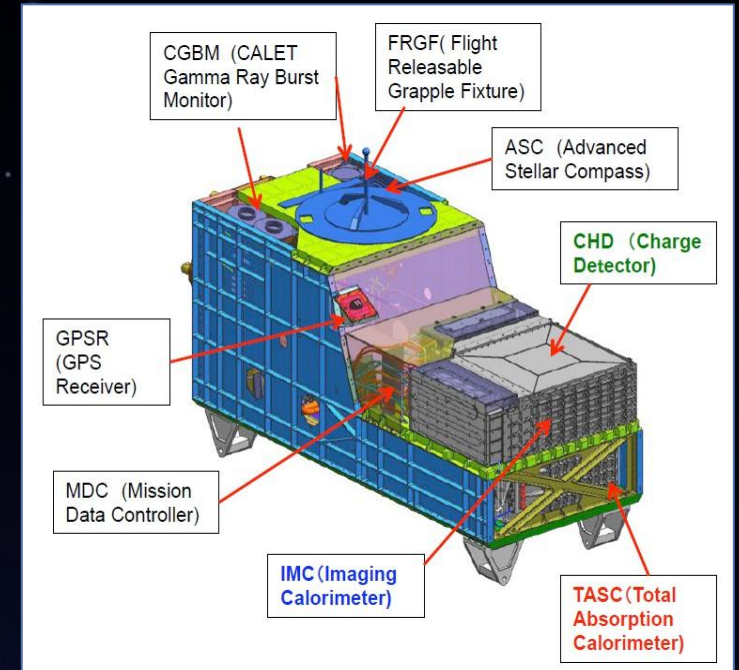
# 暗物质空间探测实验:国际竞争特别激烈



Fermi-LAT (7亿美元, 2008)



AMS-02 (20亿美元, 2011)



CALET (未报道, 2015)

国际竞争空前激烈，必须在关键技术指标方面取得领先，才能获得重要成果！



# “悟空”探测器由数百人花4年时间研制完成

塑闪探测器



硅阵列探测器



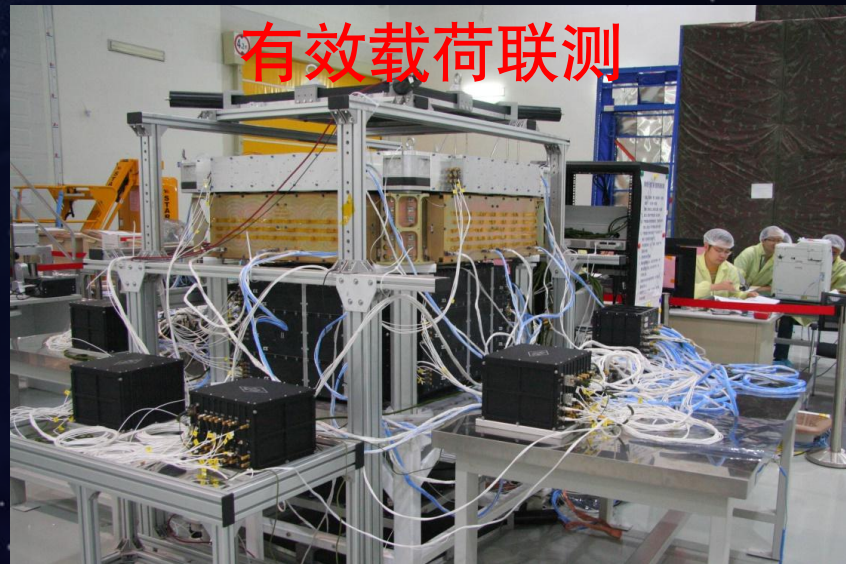
BGO量能器



中子探测器



有效载荷联测

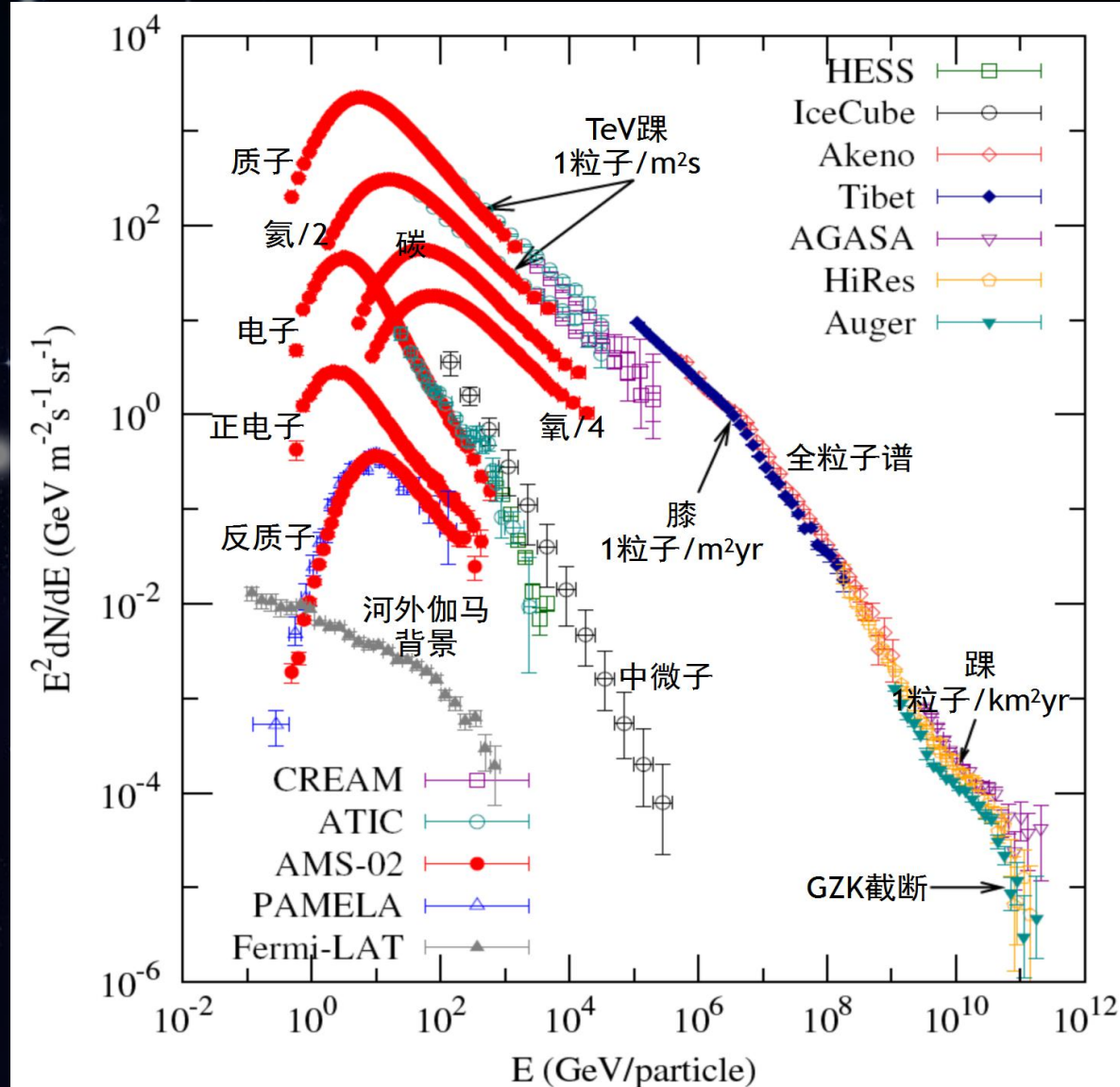


加速器束流测试





# “悟空”号卫星实验面临的主要技术挑战



悟空号主要在电子宇宙线和伽马射线中寻找暗物质信号

## 挑战一

电子和伽马信号流量极低：1 TeV处质子、电子、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

## 挑战二

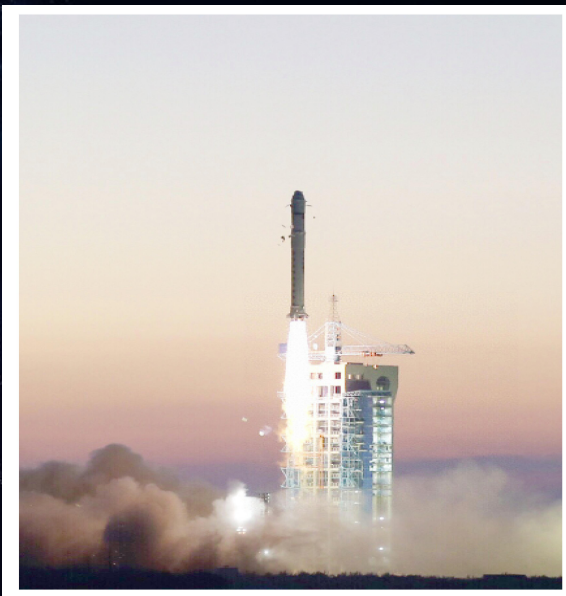
暗物质粒子质量未知：探测器应覆盖尽可能宽的能区以提高发现前景

## 挑战三

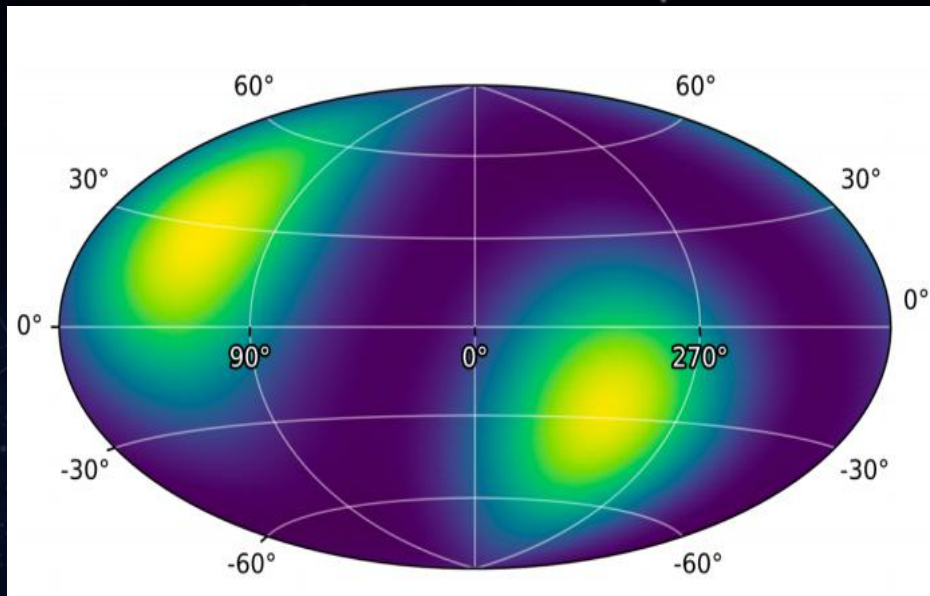
卫星资源限制：有限重量、体积和功耗下实现7万多个探测单元信号测量



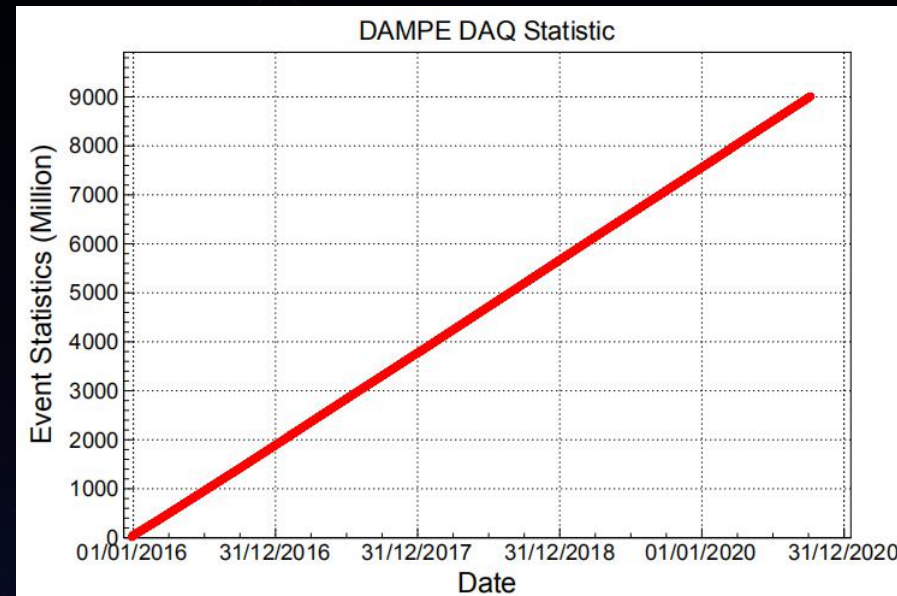
# “悟空”号卫星已平稳在轨运行超过6年时间



2015.12.17发射



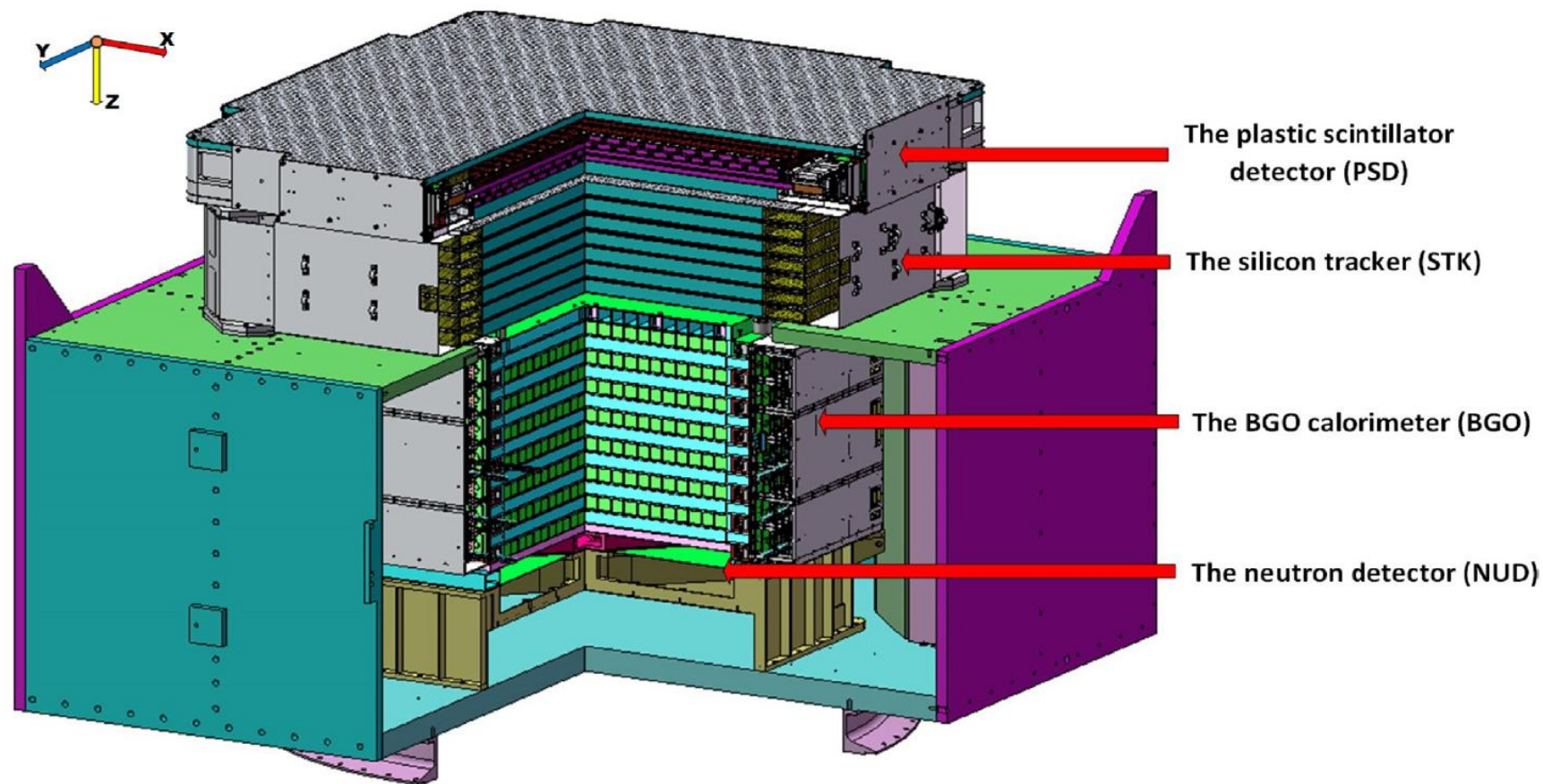
完成全天扫描观测13次



积累120+亿高能事例



# 探测器配置

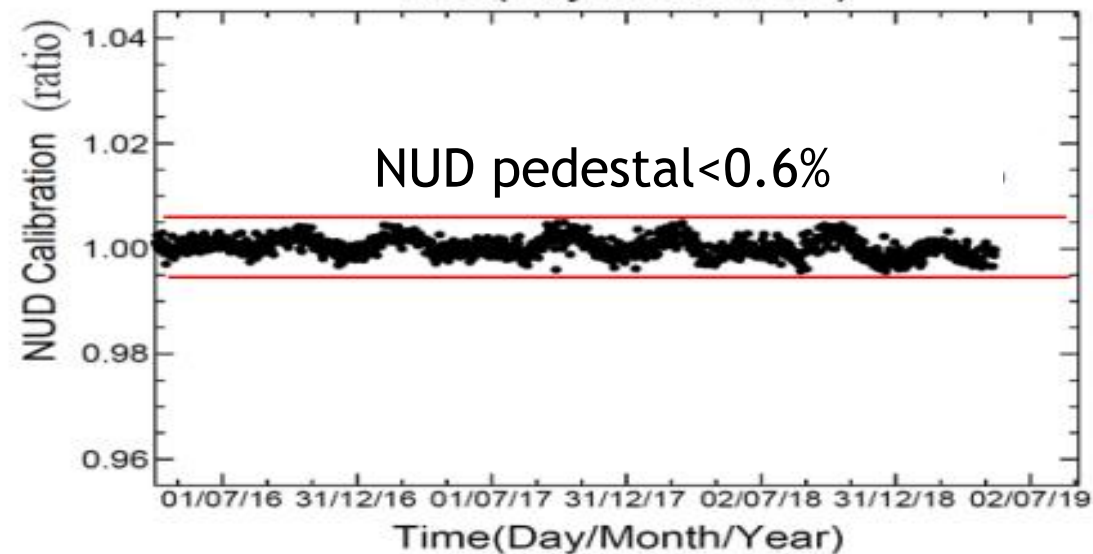
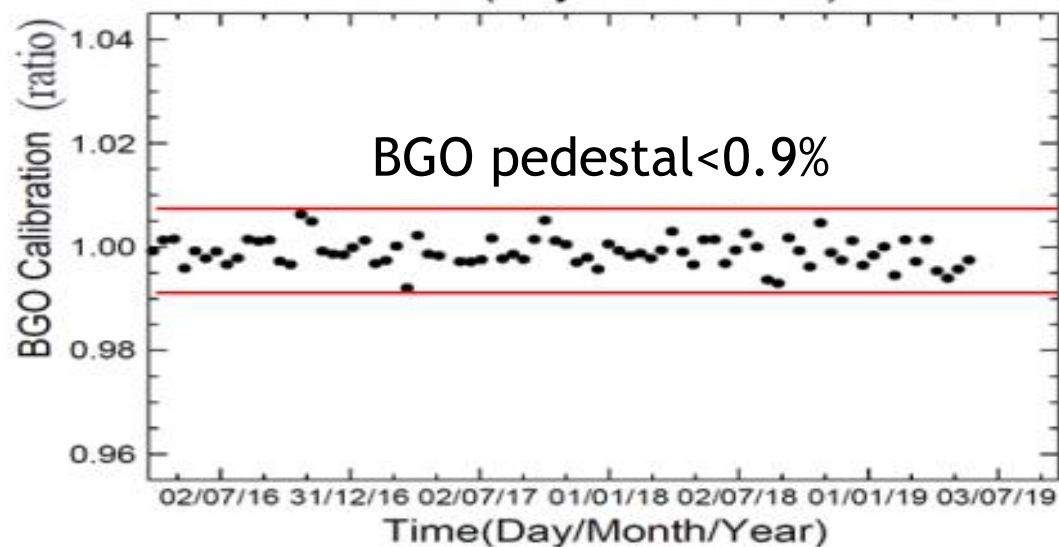
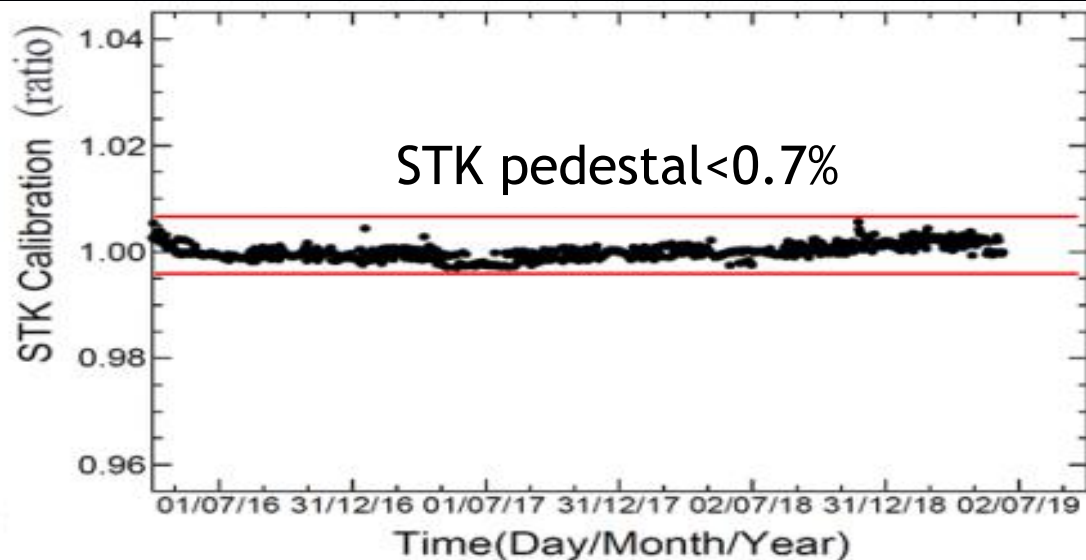
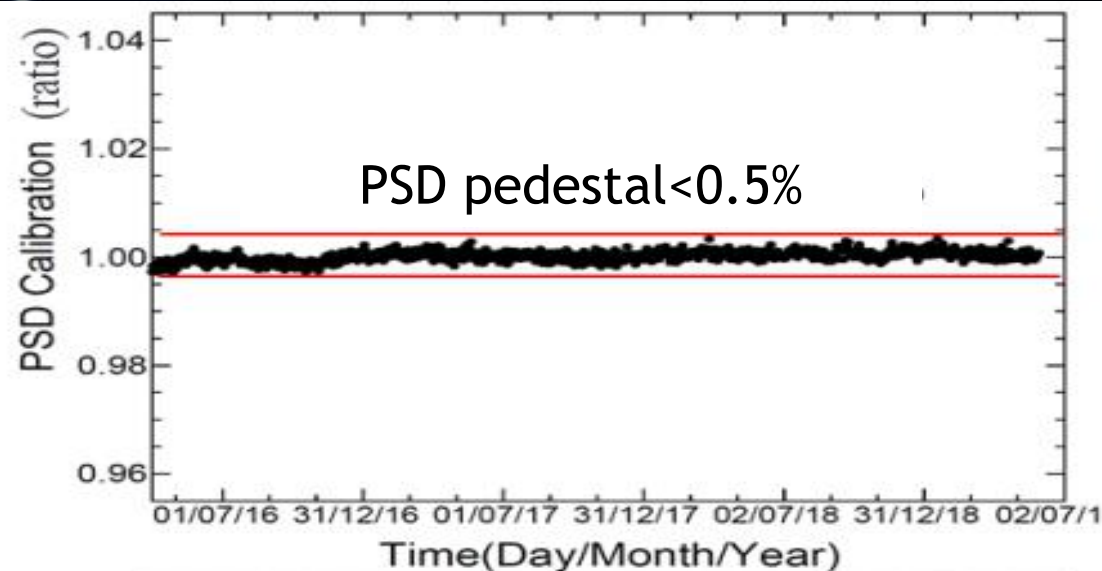


- 塑闪阵列探测器PSD：电荷测量
- 硅阵列探测器：径迹和电荷测量
- BGO量能器：能量、径迹测量和粒子鉴别
- 中子探测器：粒子鉴别

*Astropart. Phys.*, 95, 6 (2017)



# 四大子探测器工作都非常稳定

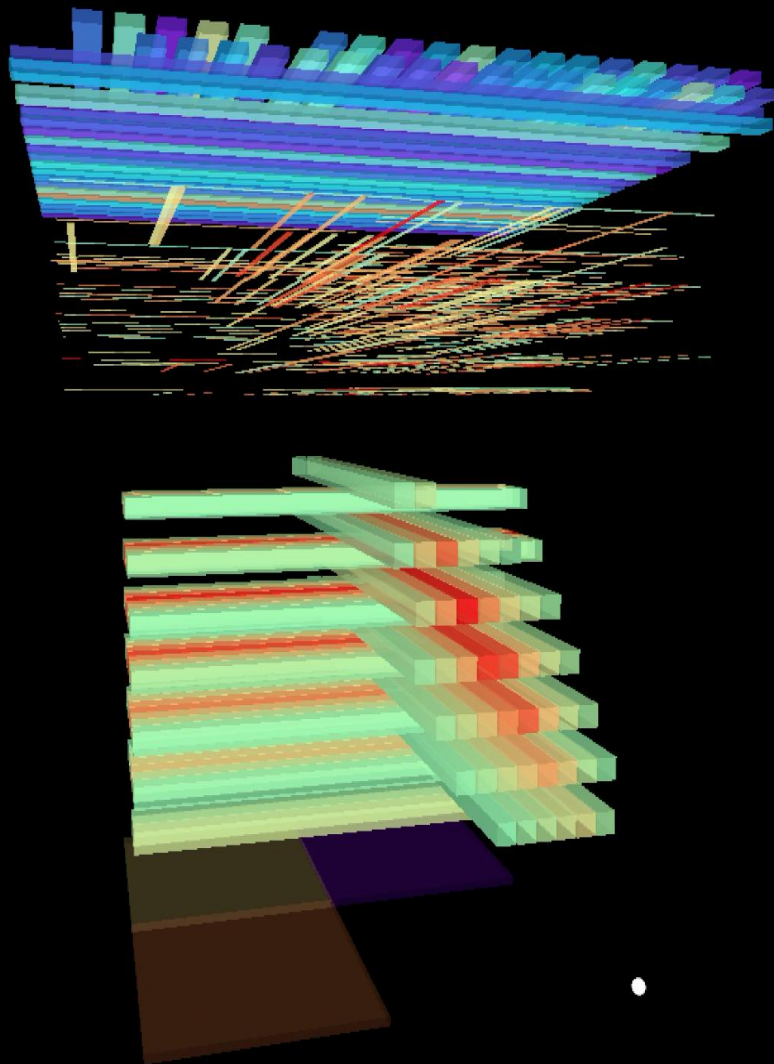




# “悟空”号性能指标优异，打开了TeV能段电子和伽马射线观测新窗口

| 卫星名称      | 观测能段     | 几何因子<br>(m <sup>2</sup> .sr) | 能量分辨  | 本底抑制<br>@TeV        | 目前状况      |
|-----------|----------|------------------------------|-------|---------------------|-----------|
| PAMELA    | ~0.5 TeV | 0.002                        | 5-10% | 10 <sup>4</sup>     | 停止 (10年)  |
| FERMI     | ~2 TeV   | 2.5                          | 5-15% | 10 <sup>3</sup>     | 继续 (14年)  |
| AMS-02    | ~2 TeV   | 0.05                         | 2-3%  | 10 <sup>5</sup>     | 继续 (11年)  |
| CALET     | ~5 TeV   | 0.1                          | 3%    | 10 <sup>5</sup>     | 继续 (6.5年) |
| ISS-CREAM | ~3 TeV   | 0.2                          | 15%   | 10 <sup>3</sup>     | 停止 (1.5年) |
| DAMPE     | ~10 TeV  | 0.3                          | 1%    | 2 × 10 <sup>5</sup> | 继续 (6.5年) |





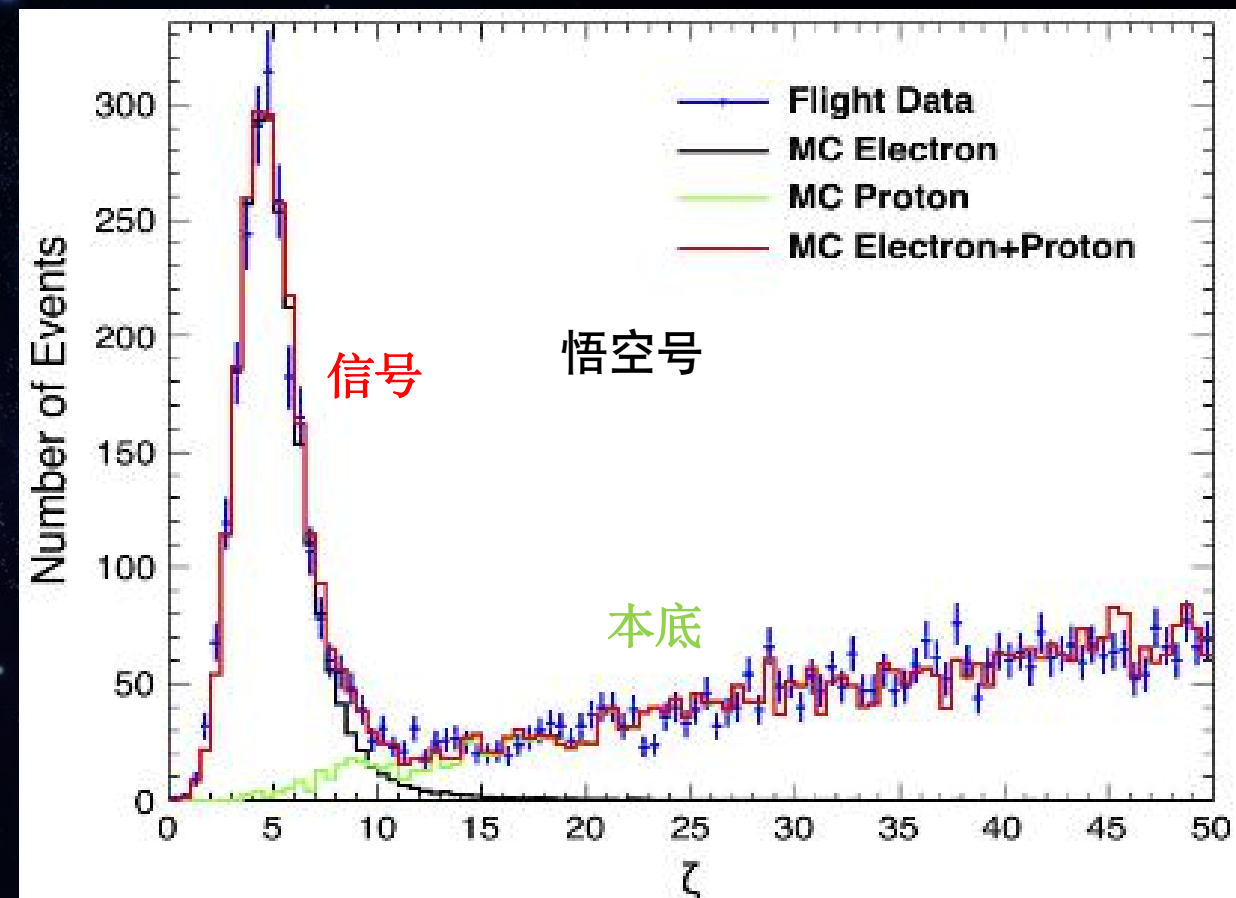
7.6 TeV电子!

“悟空”卫星通过高精度观测宇宙射线粒子的能量、方向、电荷和种类以研究:

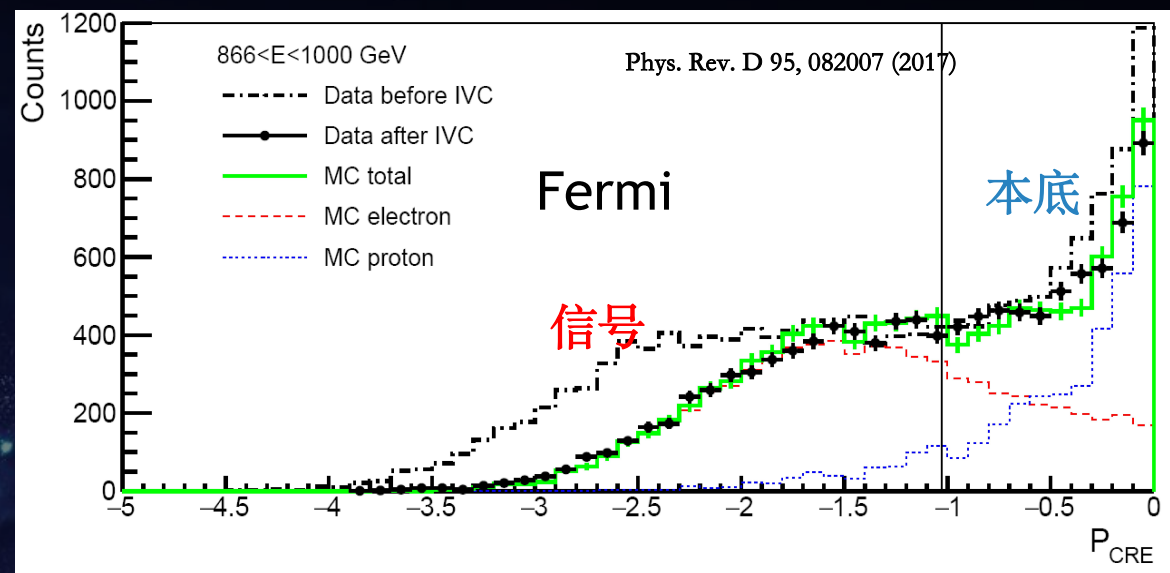
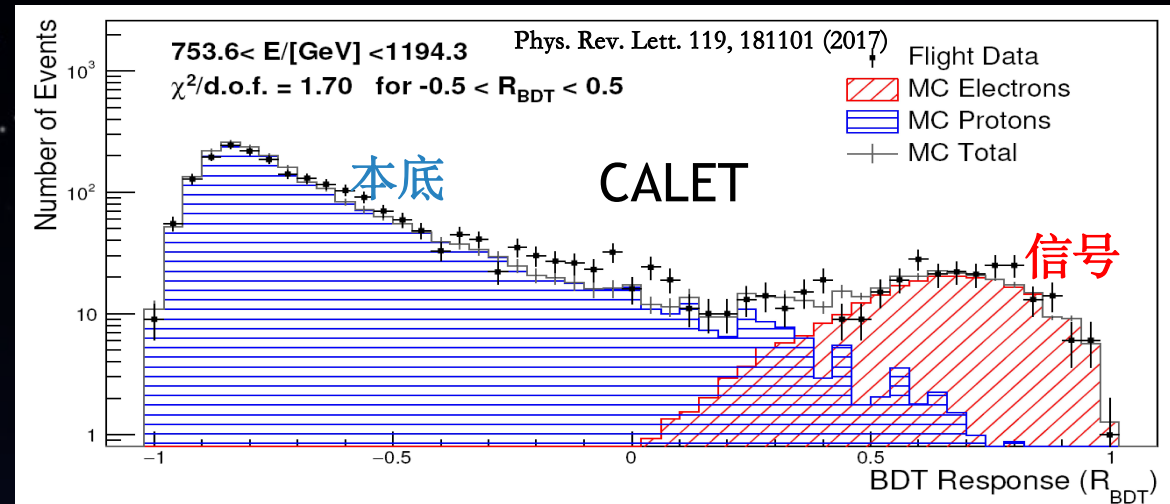
- 暗物质粒子
- 宇宙射线物理
- 伽马射线天文



# 优异的粒子鉴别

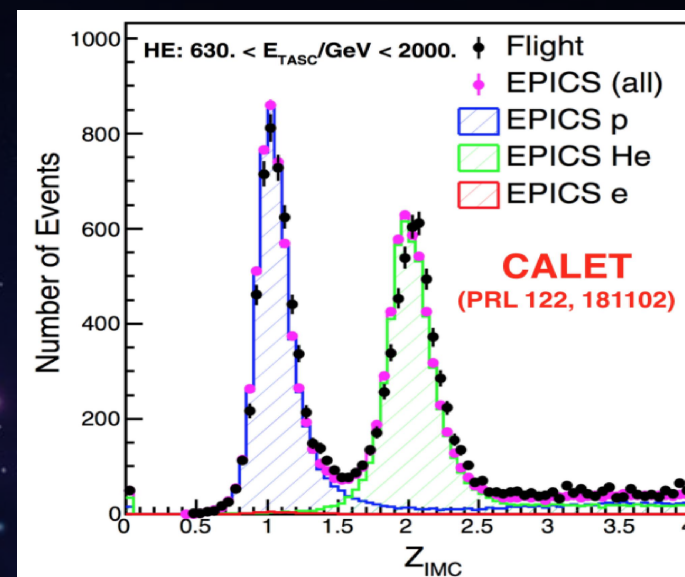
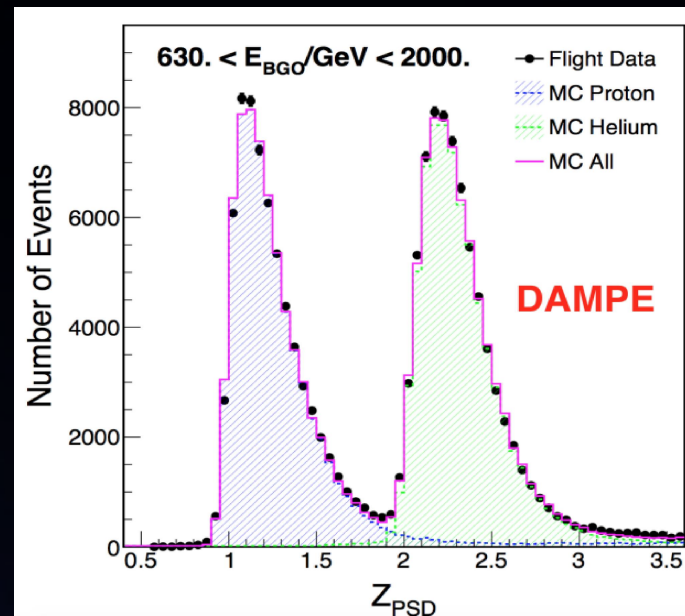
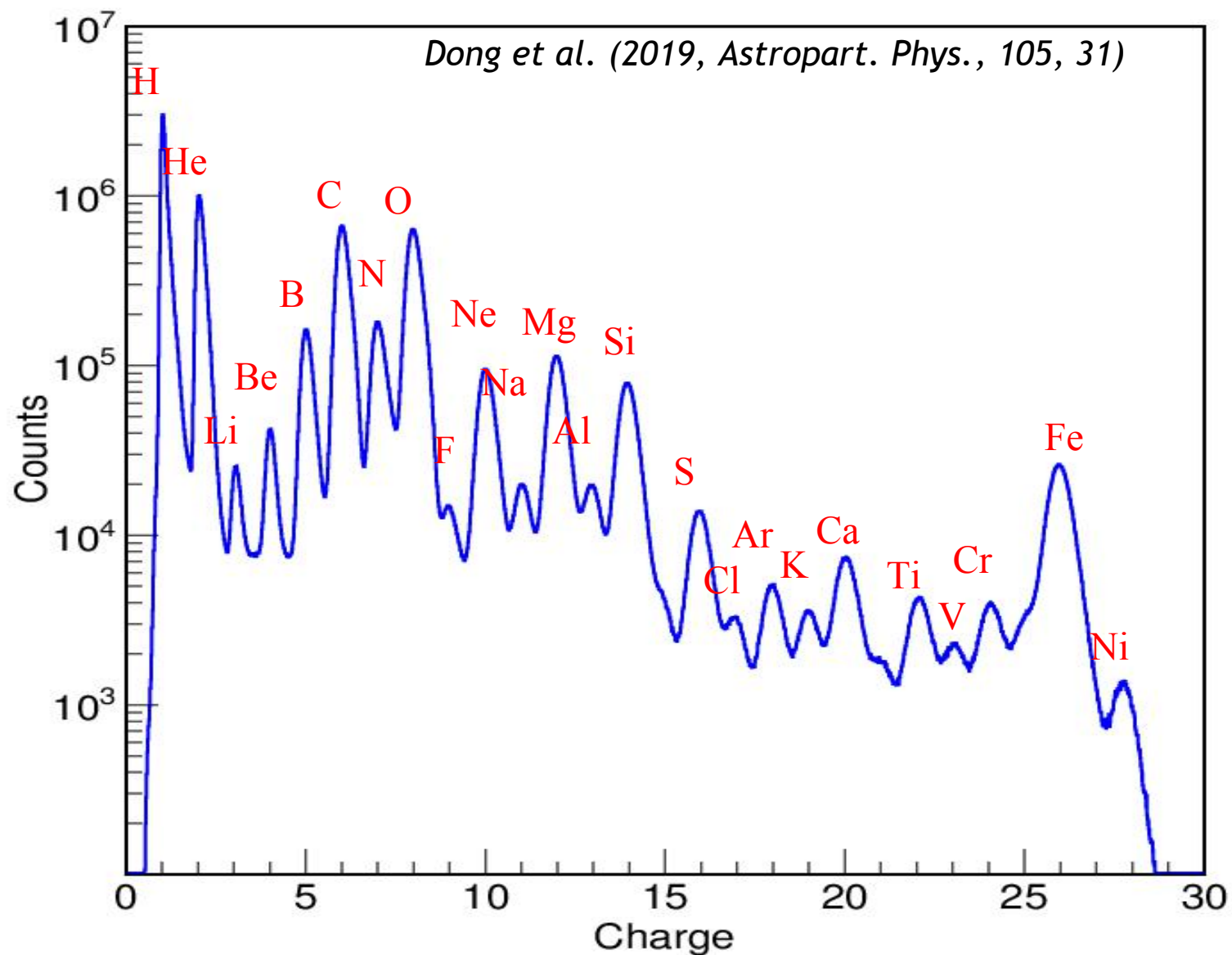


质子-电子鉴别能力为国际同类探测器最好水平

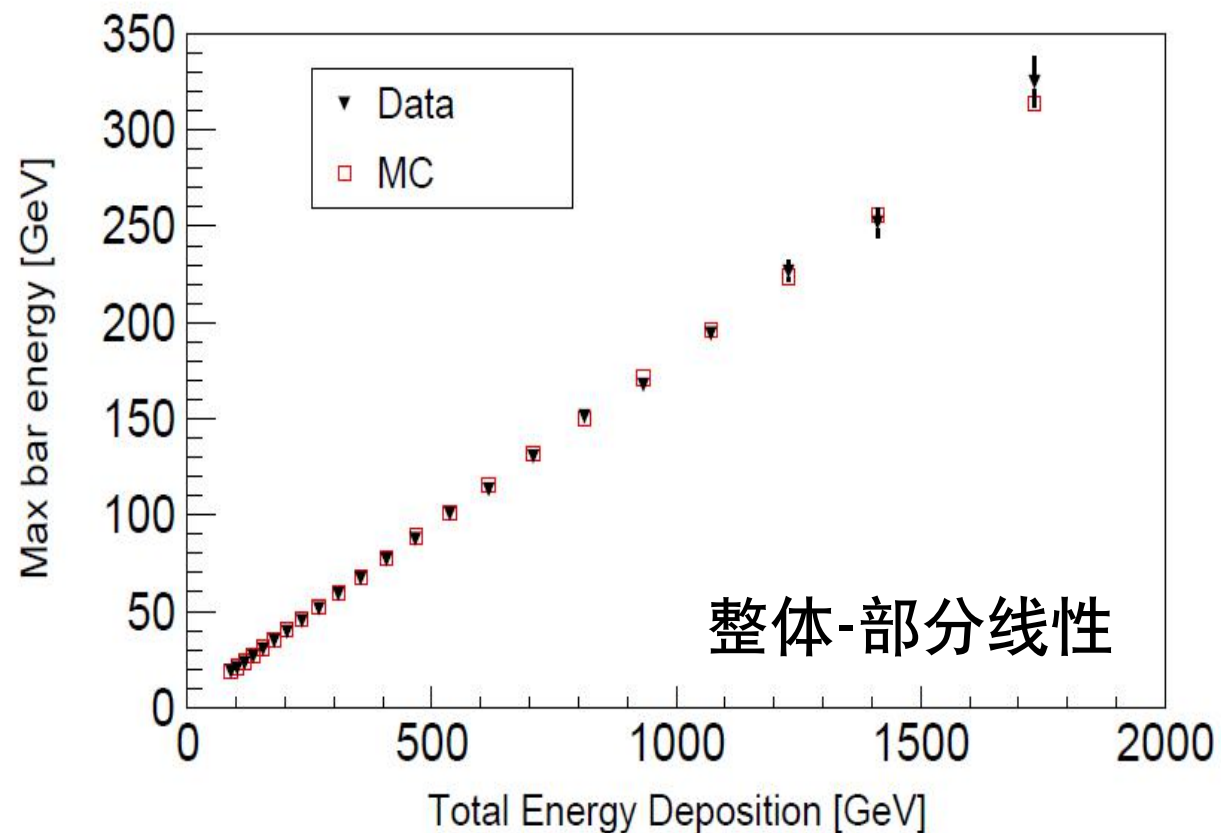
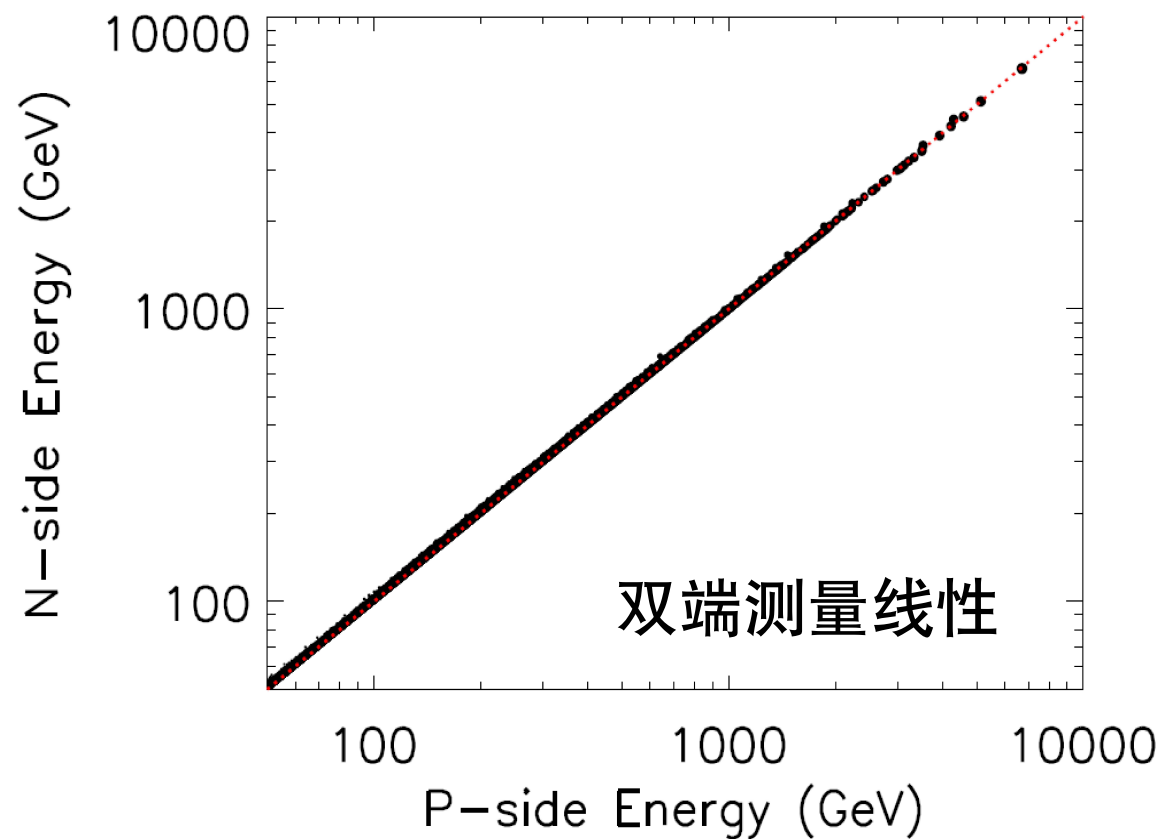




# 精确的粒子电荷测量

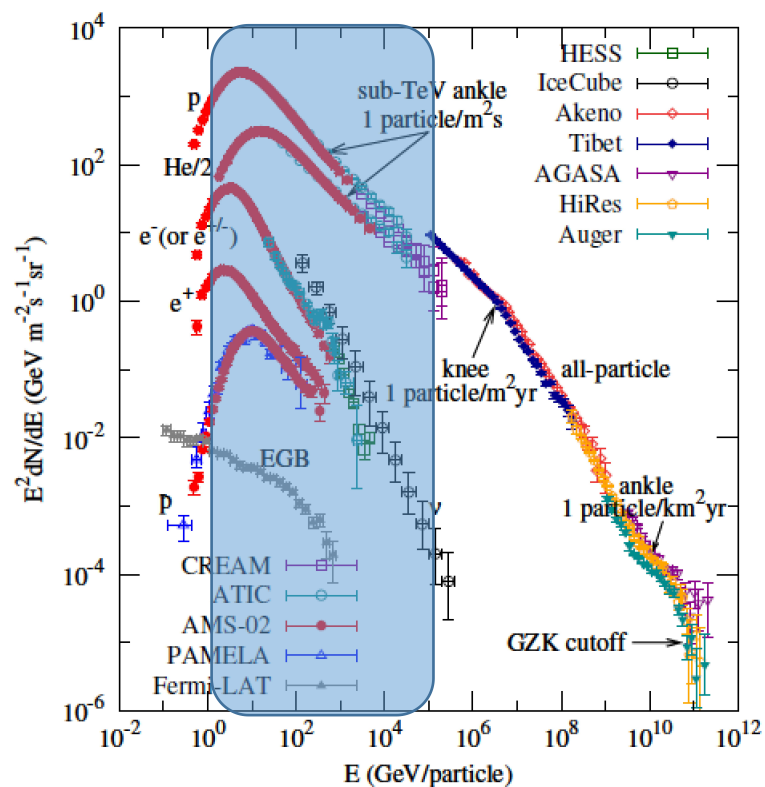


# 准确的粒子能量测量

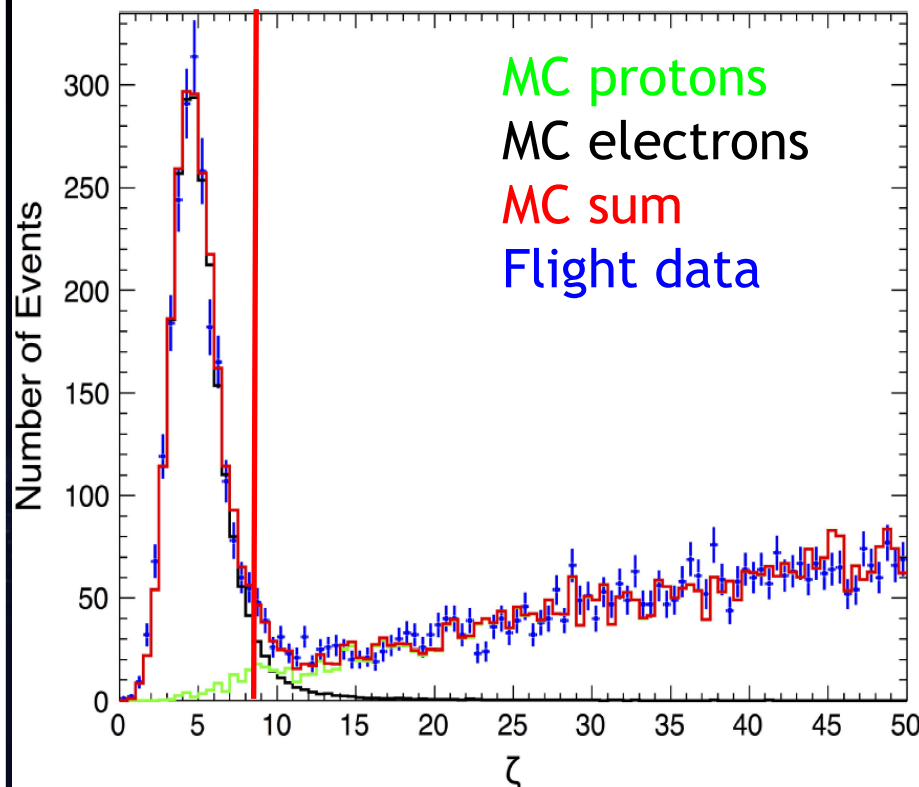




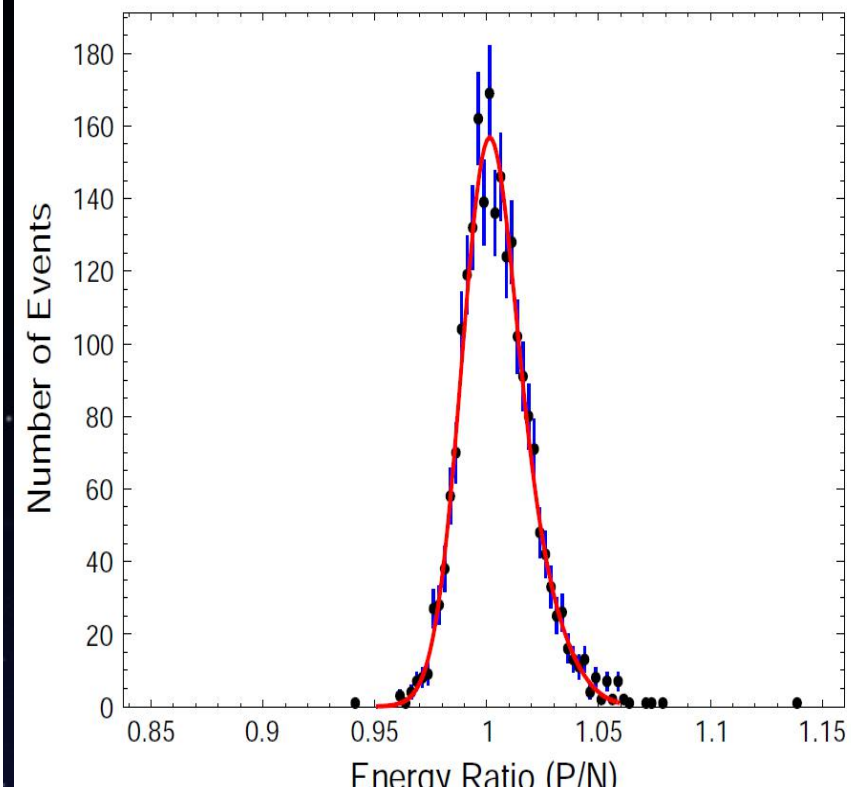
# “悟空”号卫星的三大法宝



覆盖能段宽

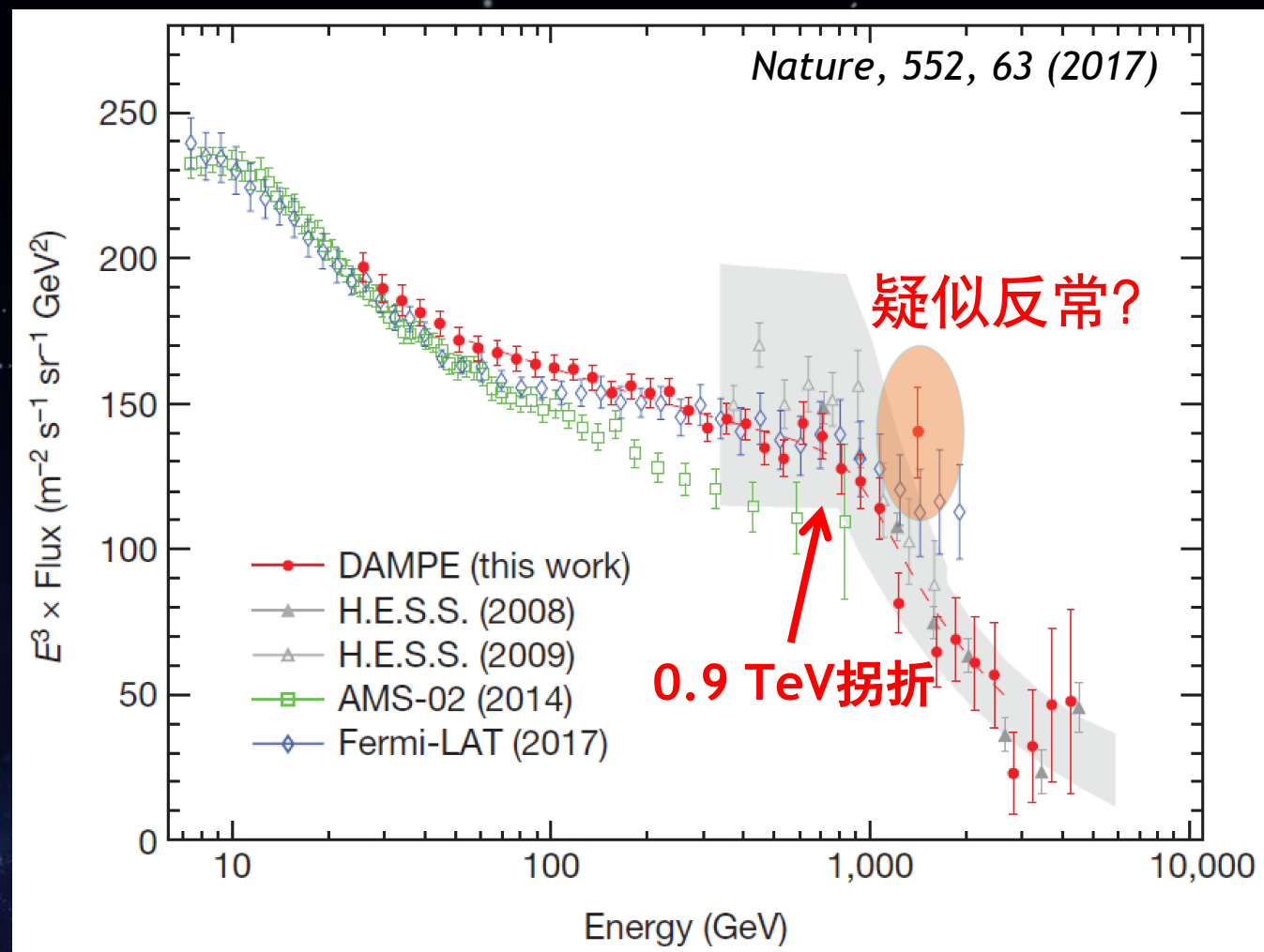
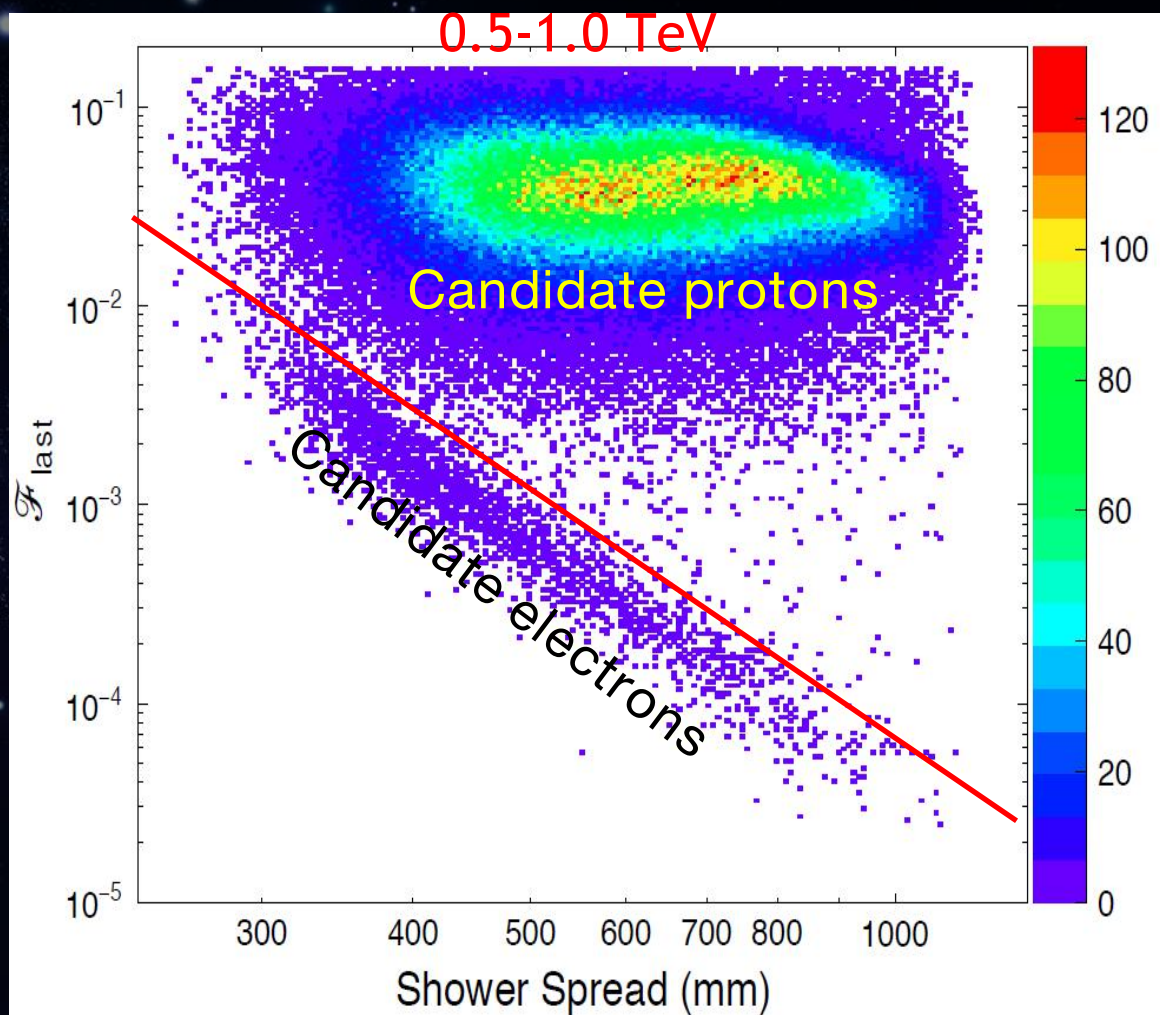


粒子鉴别强(自主创新方法)



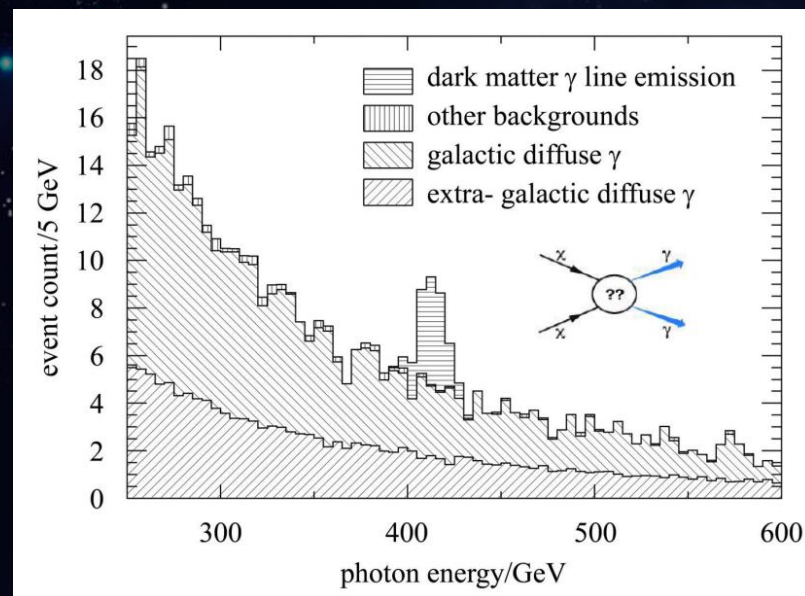
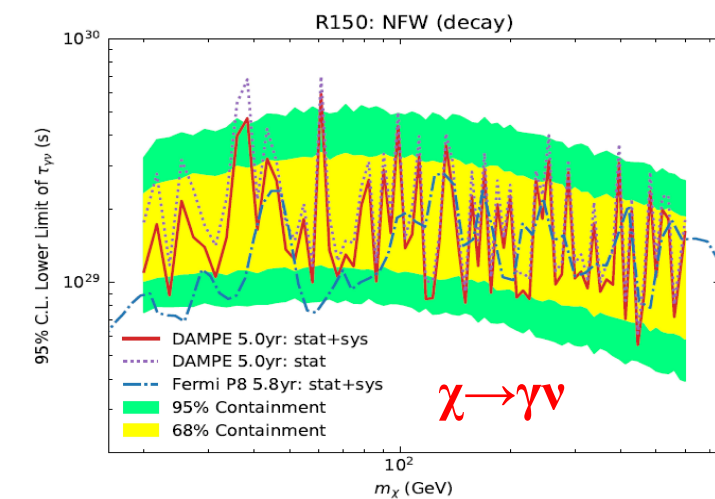
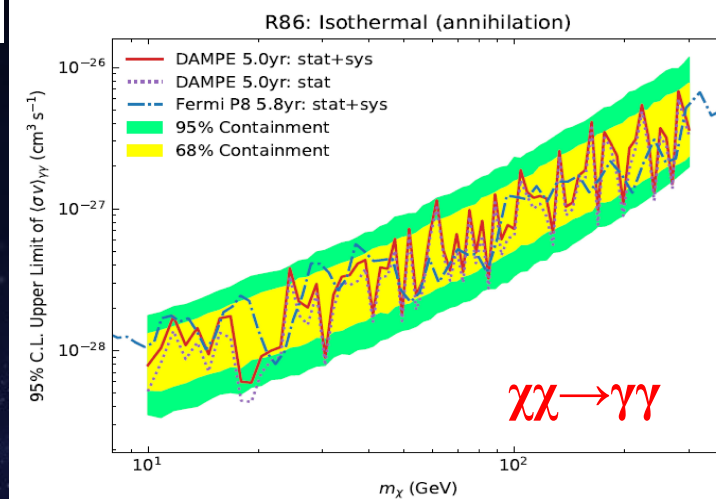
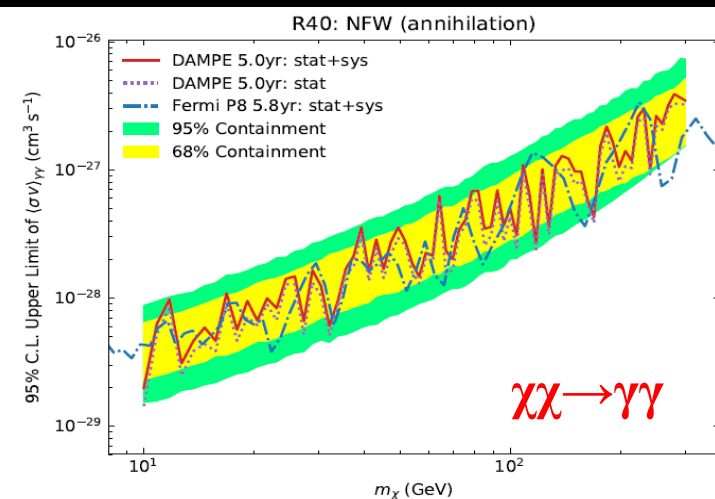
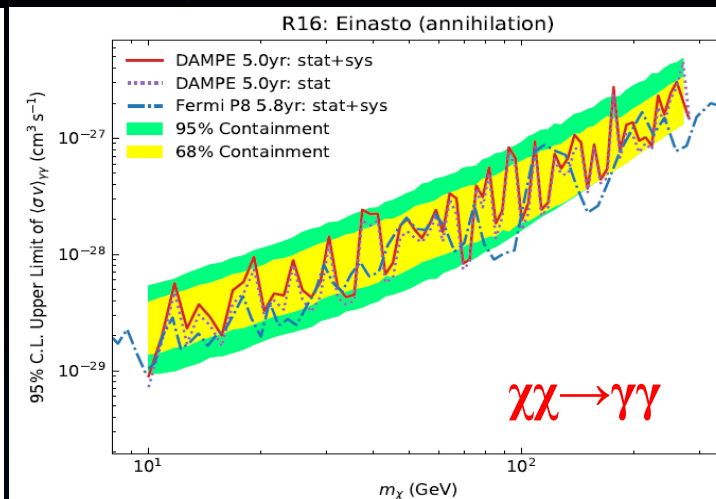
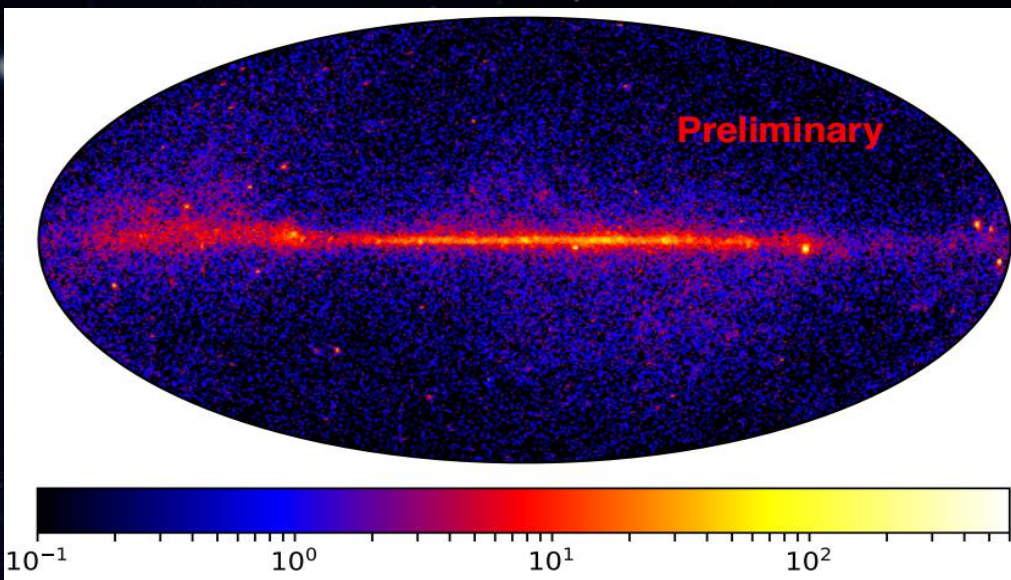
能量分辨率高

# “悟空”号获得精确宇宙射线电子能谱测量





# 获得国际上最灵敏单能伽马线谱搜寻结果



“悟空”卫星能量分辨为国际最高水平，尤其适合探测伽马射线线谱(2022 Sci. Bull.)

# “悟空”号获得国际社会的广泛关注

## NEWS IN FOCUS

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

**STRUNG 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**



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 DAVIDE CA

A gain of too dark-matter (or Monkey century CH

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

missions to emerge from the Chinese Academy of Sciences' Strategic Priority Program on Space Science, which kicked off in 2011.

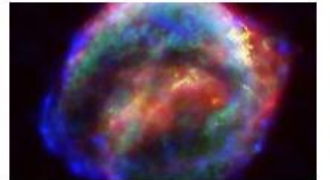
followed next year by a further two missions: the world's first quantum-communications satellite and an X-ray telescope observing in ▶

**Nature焦点新闻：暗物质探测器开启中国空间科学时代**

← → ↺ 🏠 [www.sciencemag.org/category/space?page=5](http://www.sciencemag.org/category/space?page=5)

## China's dark matter space probe detects tantalizing signal

By Dennis Normile | Nov. 29, 2017



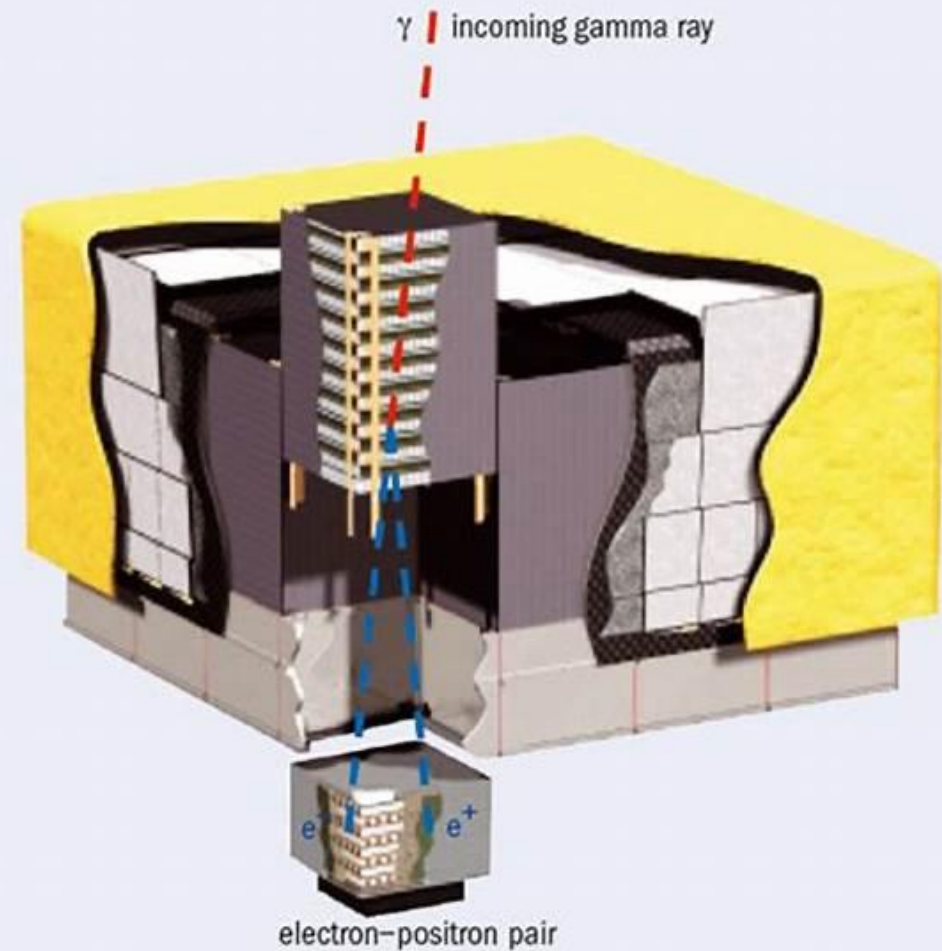
Results highlight country's rise in space science

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新闻：中国暗物质空间探测器测量到了一个诱人的信号(结果表明中国在空间科学方面的崛起)**

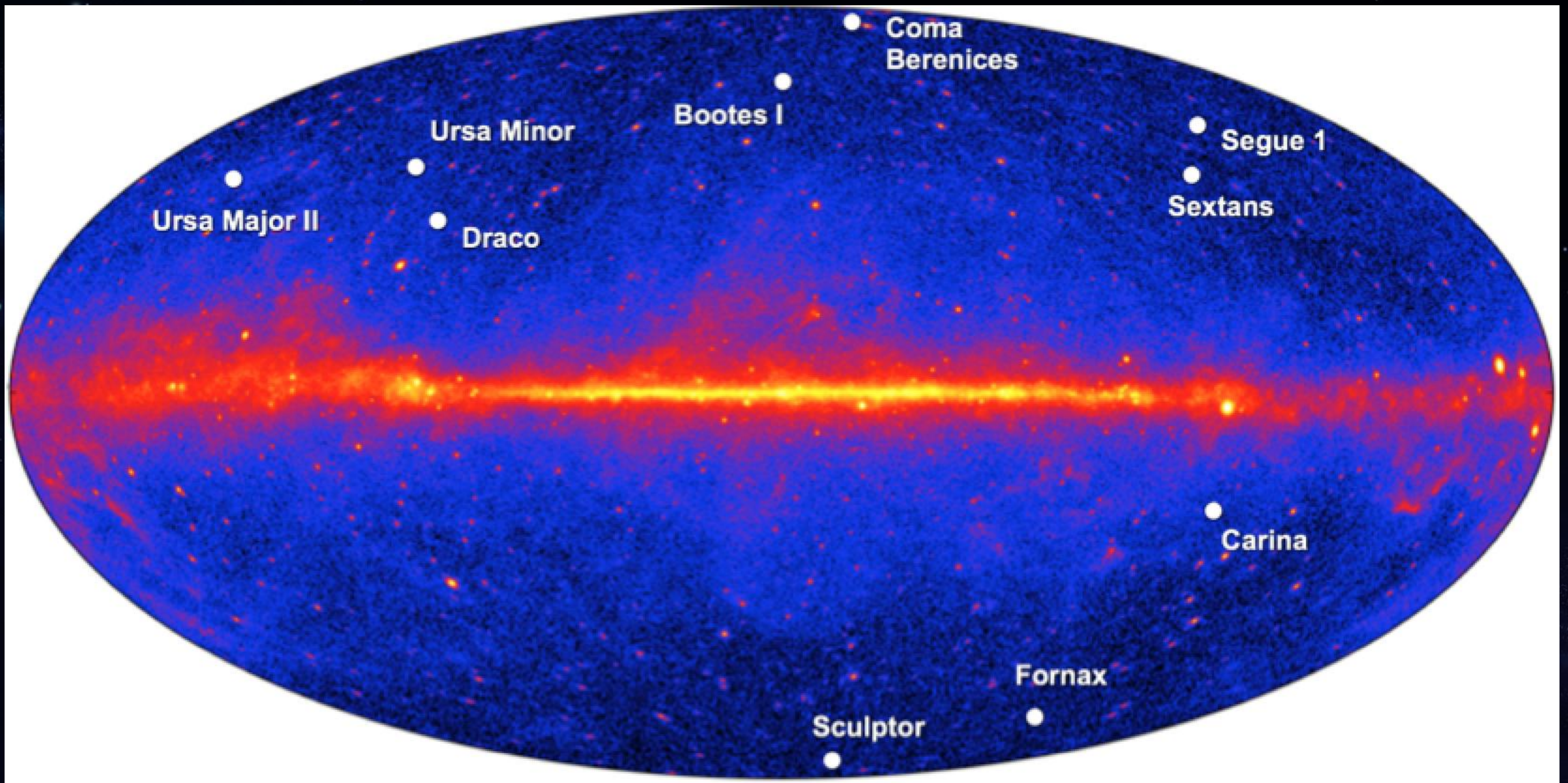


# 基于伽马射线的暗物质间接探测



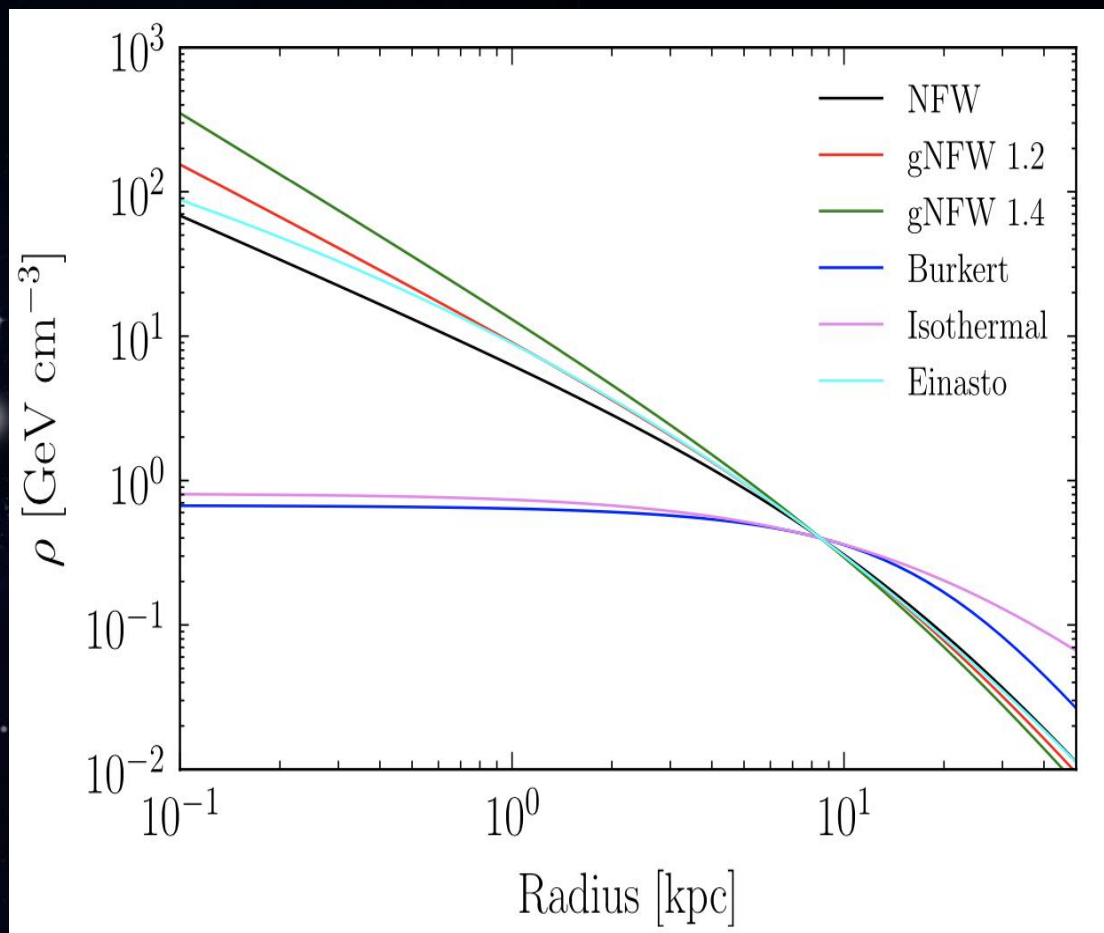


# 基于伽马射线的暗物质间接探测

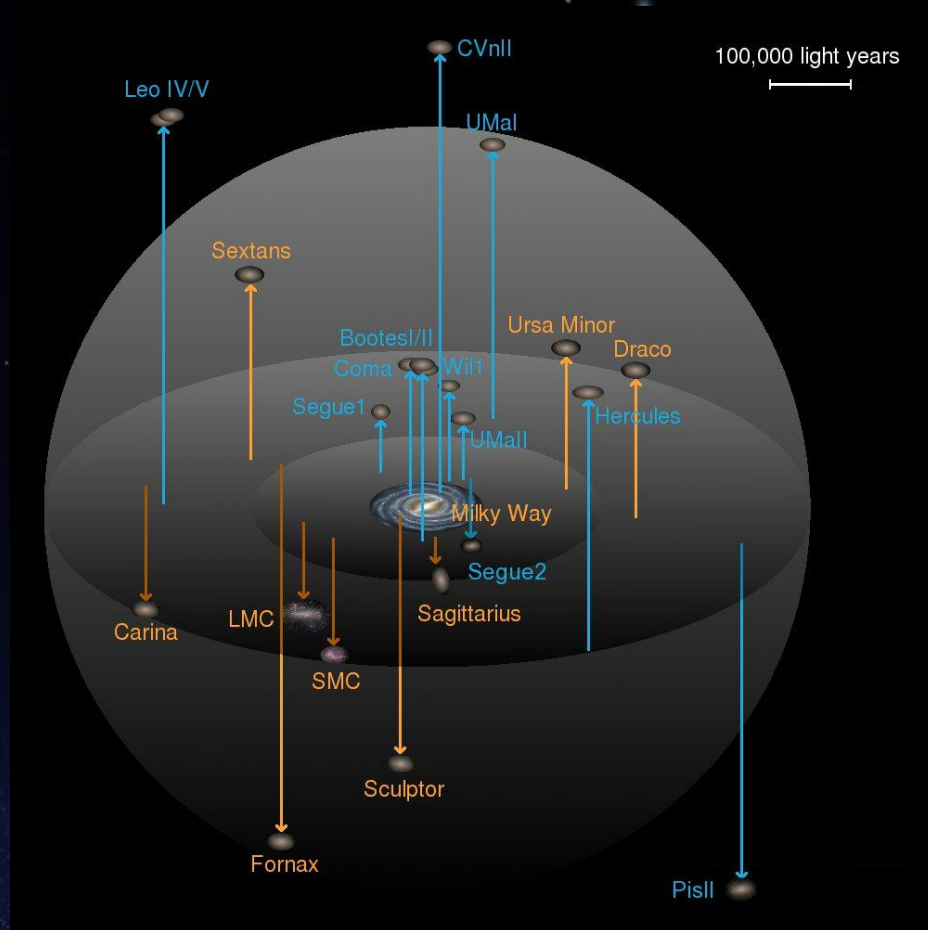




# 基于伽马射线的暗物质间接探测

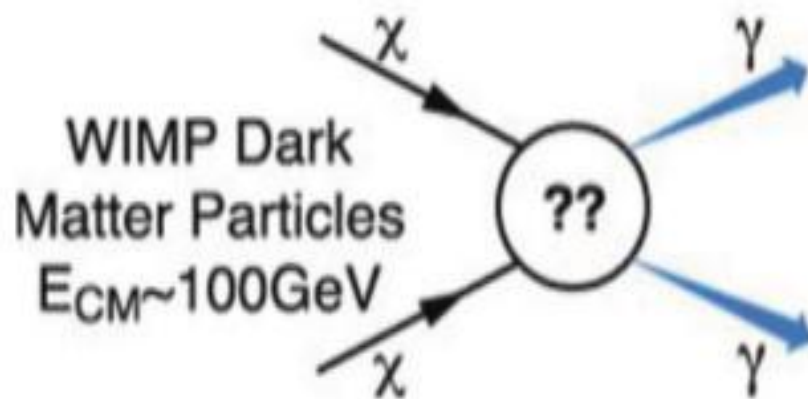
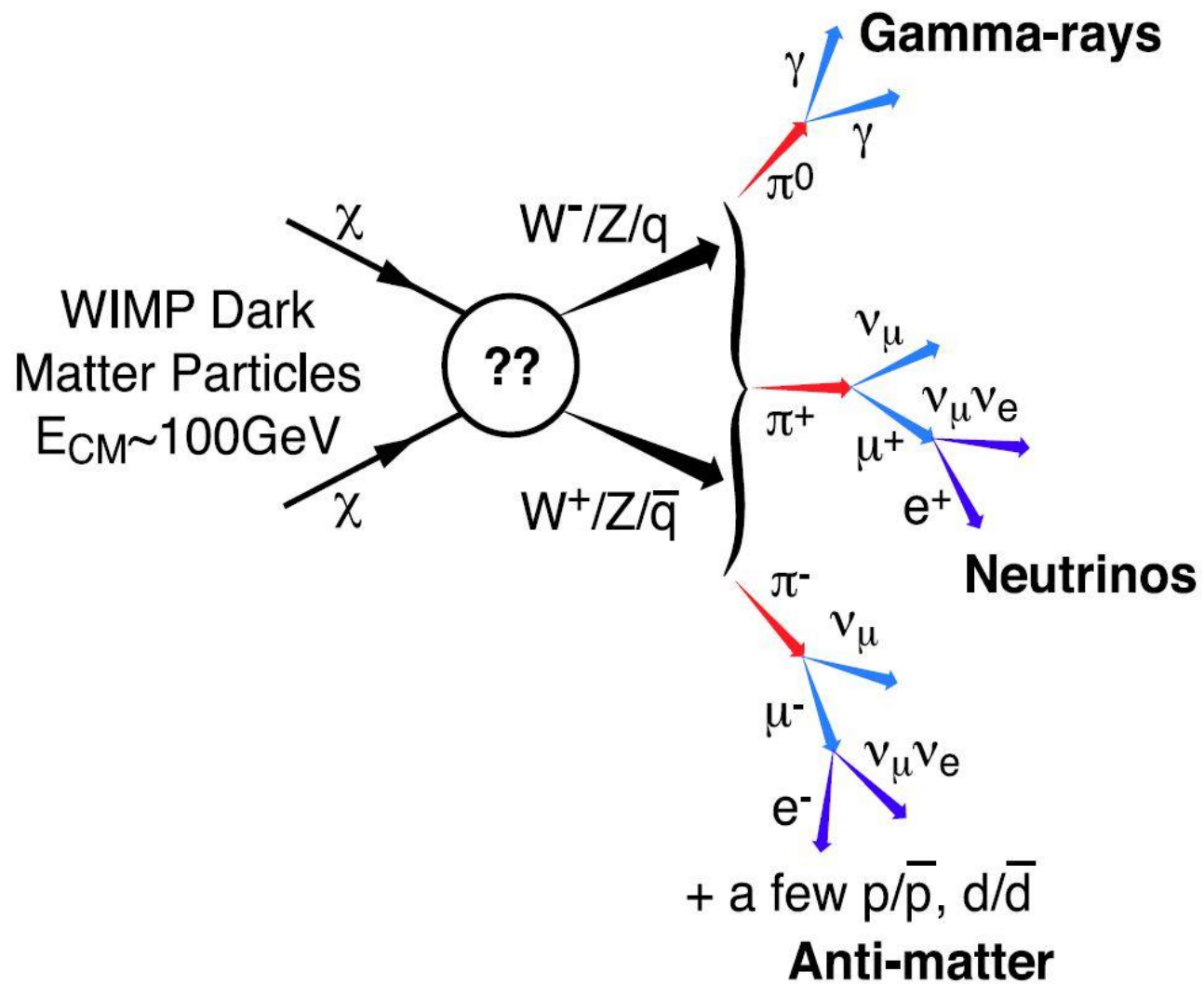


银河系中心: 宇宙中最明亮的暗物质湮灭信号区域



银河系矮星系: 暗物质湮灭信号最纯净的区域

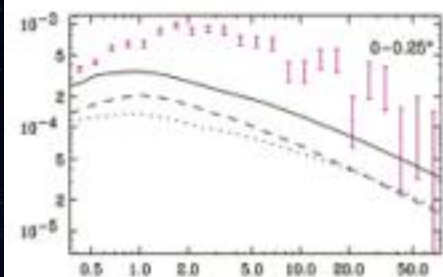
# 基于伽马射线的暗物质间接探测



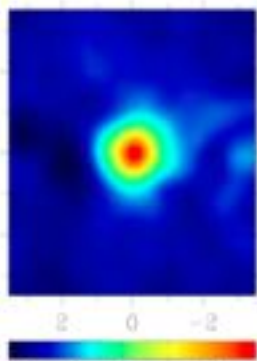


# 基于伽马射线的暗物质间接探测

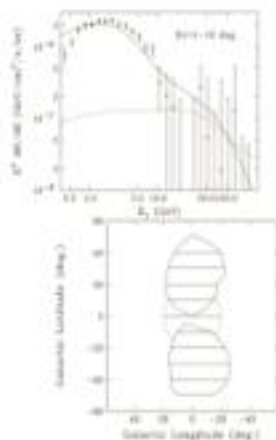
## Excess emission spectrum peaks around 3 GeV



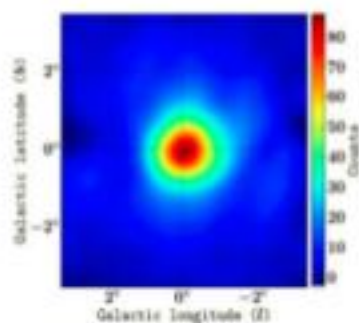
Goodenough &  
Hooper  
Phys.Lett. B697  
(2011)



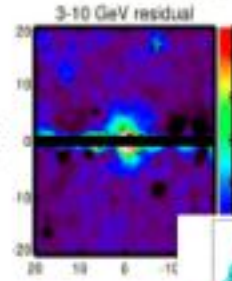
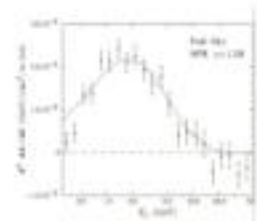
Abazajian &  
Kaplinghat  
PRD 87 129902  
(2012)



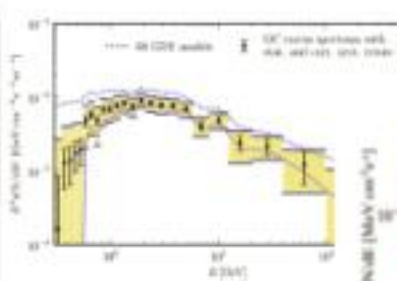
Hooper & Slatyer  
Phys.Dark Univ.  
2 (2013)



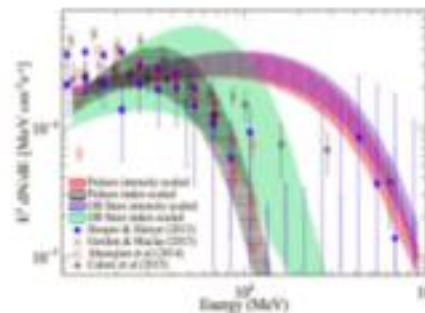
Gordon & Macias  
PRD 88, 083521  
(2013)



Daylan et al.  
Phys. D  
12 (2016)



Calore et al.  
JCAP 1503  
(2015)



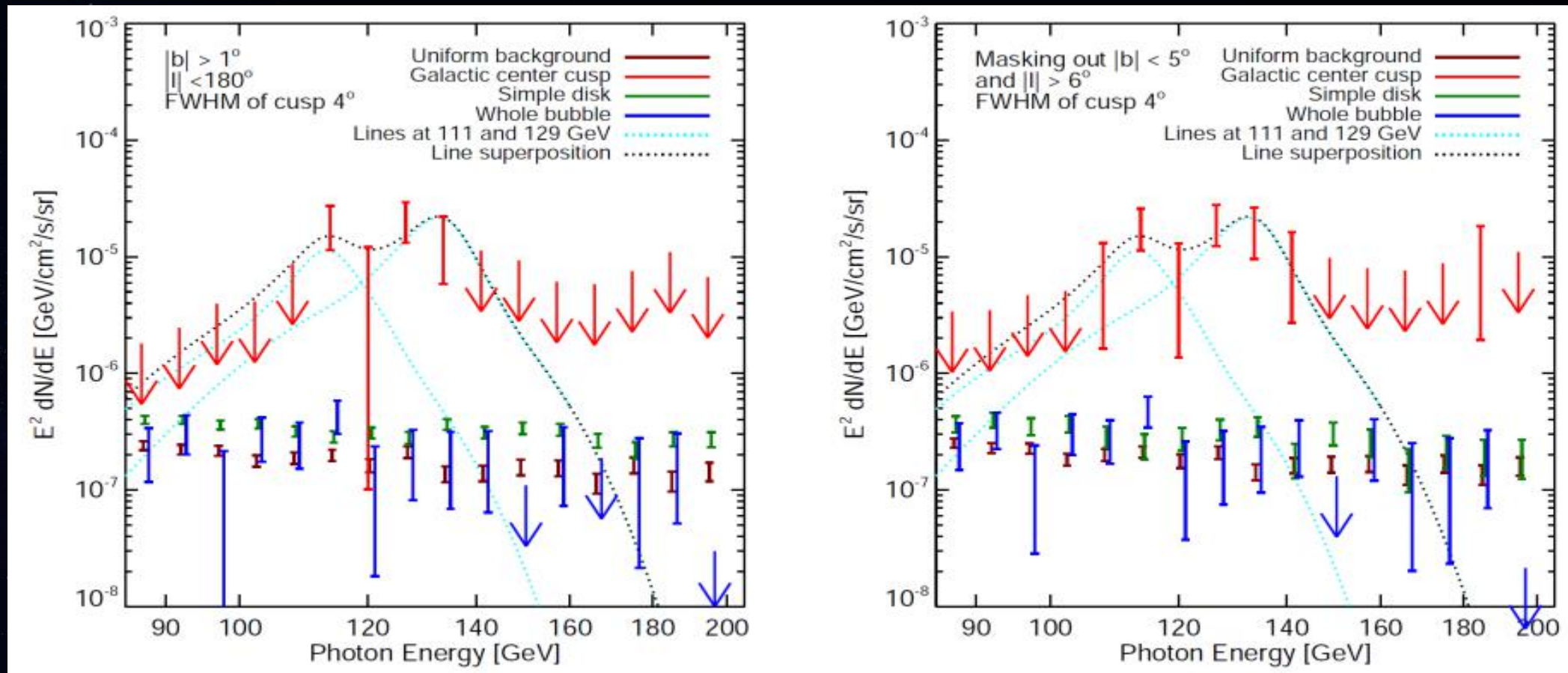
Ajello et al.  
(The Fermi-LAT  
Collaboration)  
ApJ 819 1 44 (2016)

Zhou et al. PRD  
91, 123010 (2015)

## Dark matter annihilation, unresolved sources, CR electrons?

银河系中心方向的GeV波段存在一个重要的超出，但是否来自于暗物质尚无定论

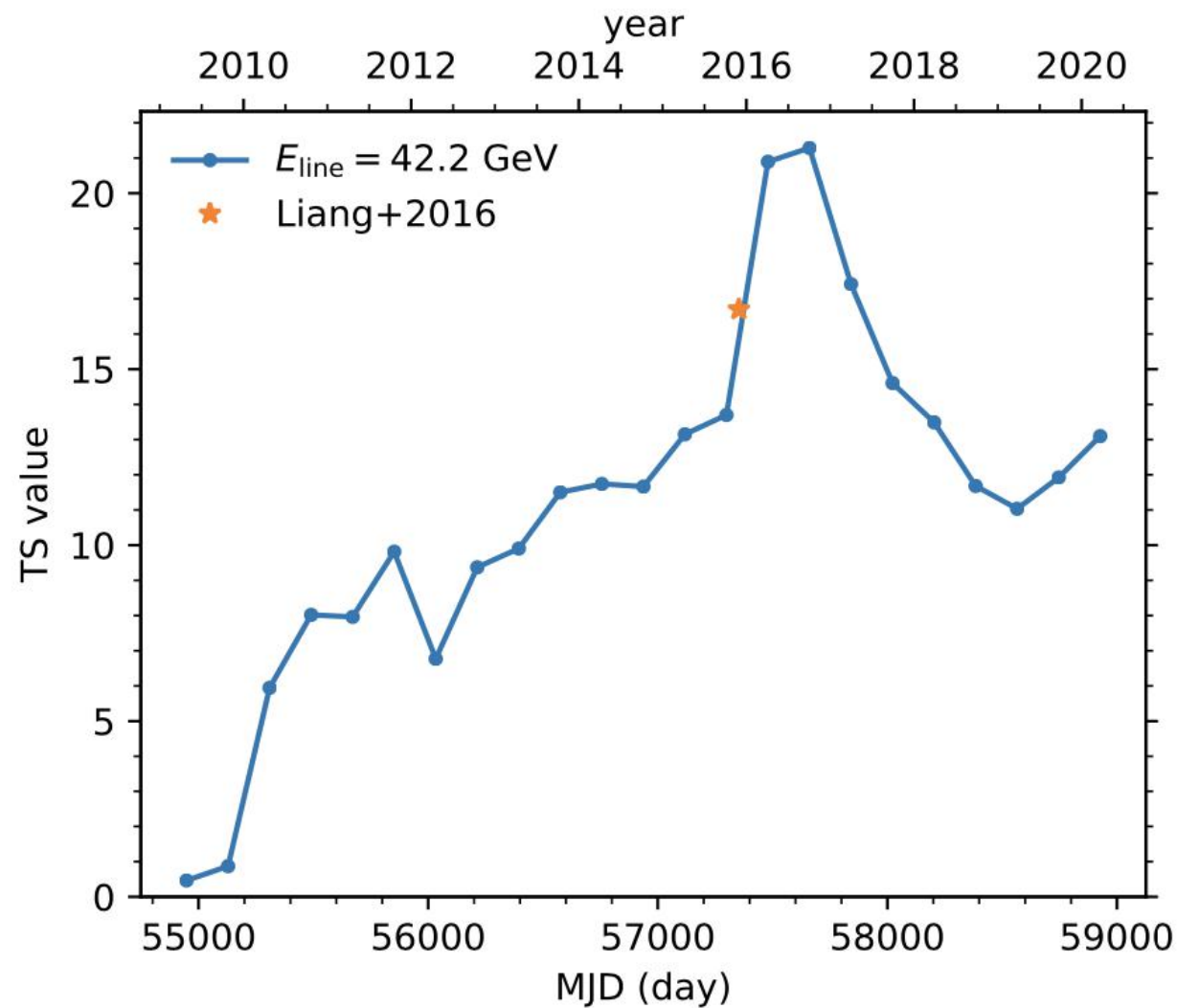
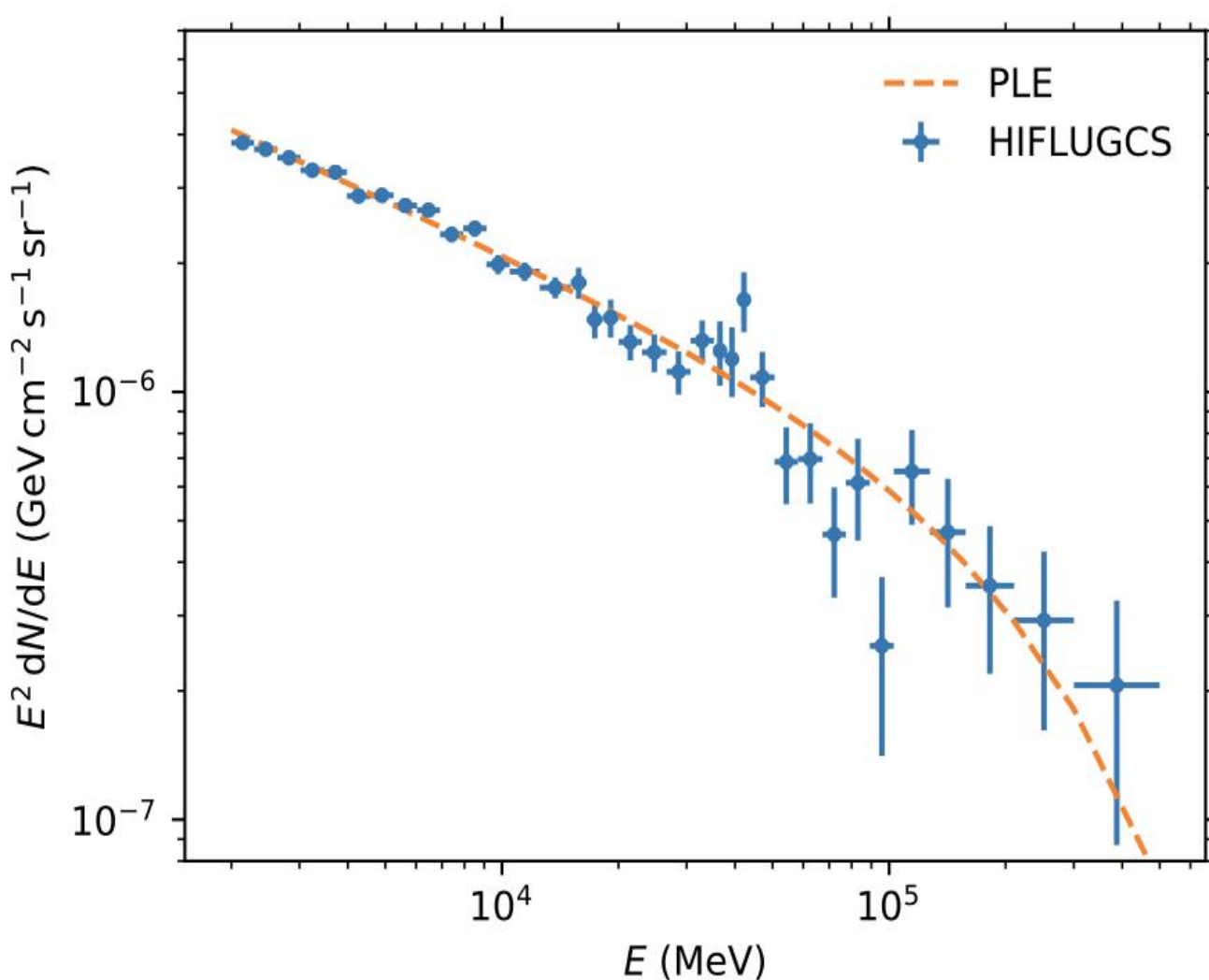
# 基于伽马射线的暗物质间接探测



Fermi-LAT的数据中呈现出 $\sim 130\text{GeV}$ 的线状谱(Su & Finkbeiler 2012: 双线谱)?

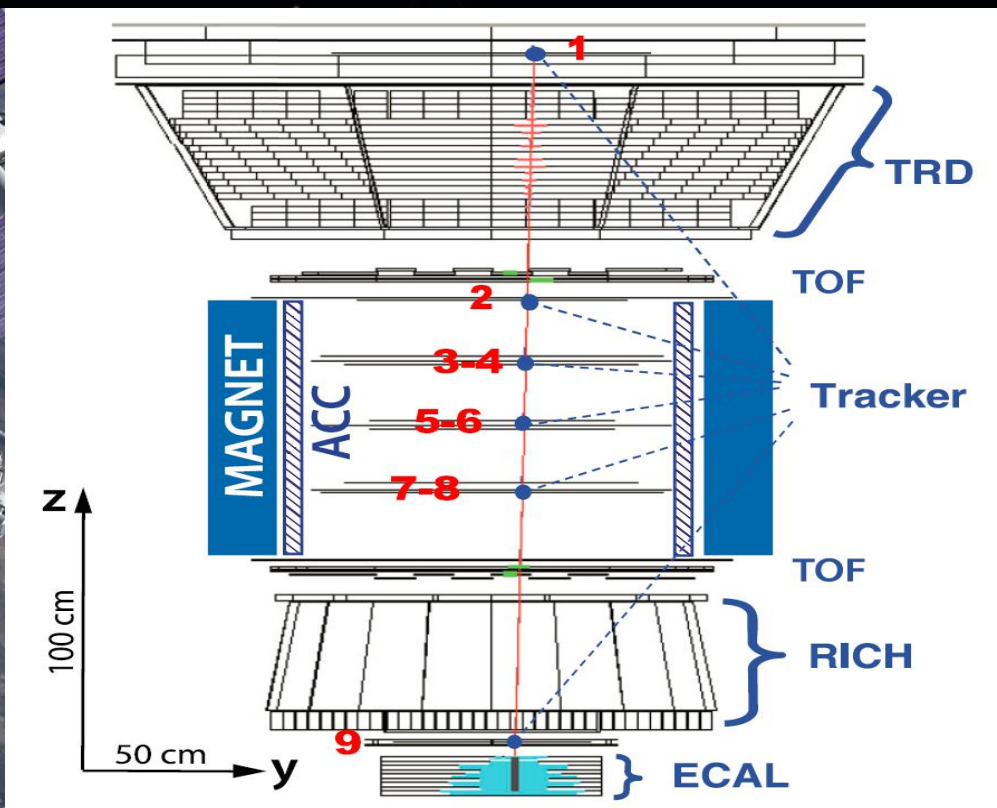
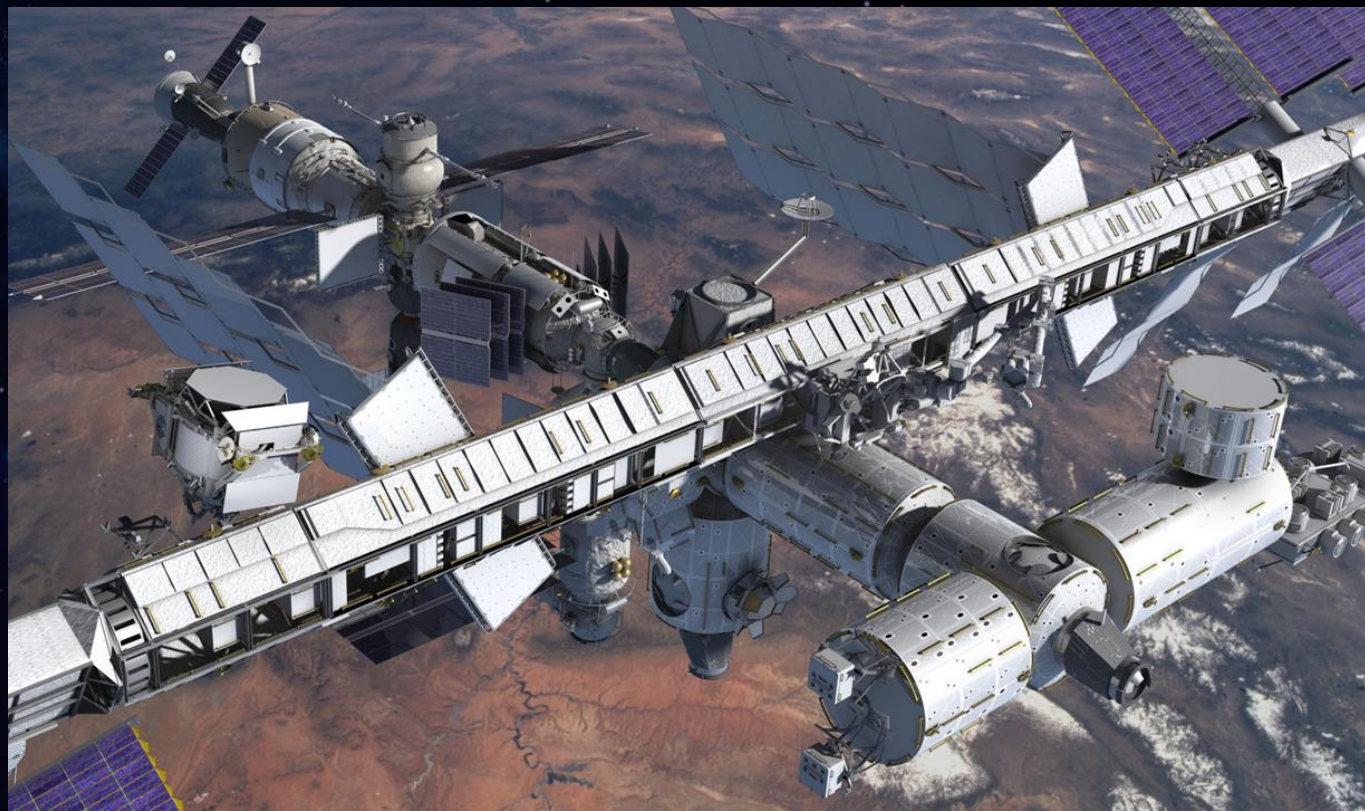


# 基于伽马射线的暗物质间接探测



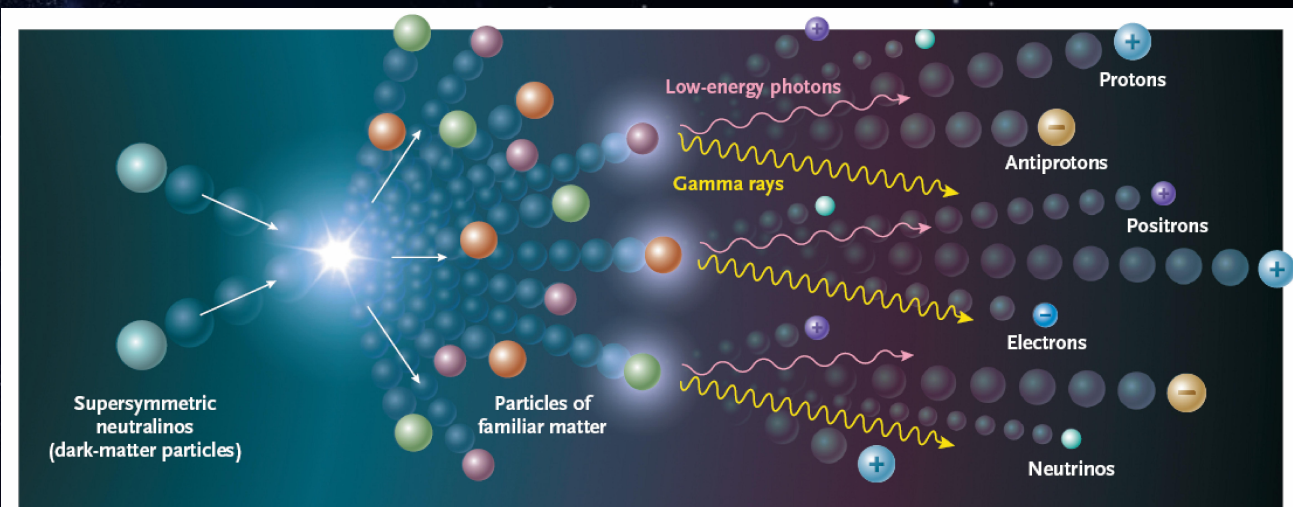
Shen, Xia & Fan (2021 ApJ): 在星系团方向搜寻暗物质线谱, 没有可靠信号

# 基于反物质宇宙线的暗物质间接探测



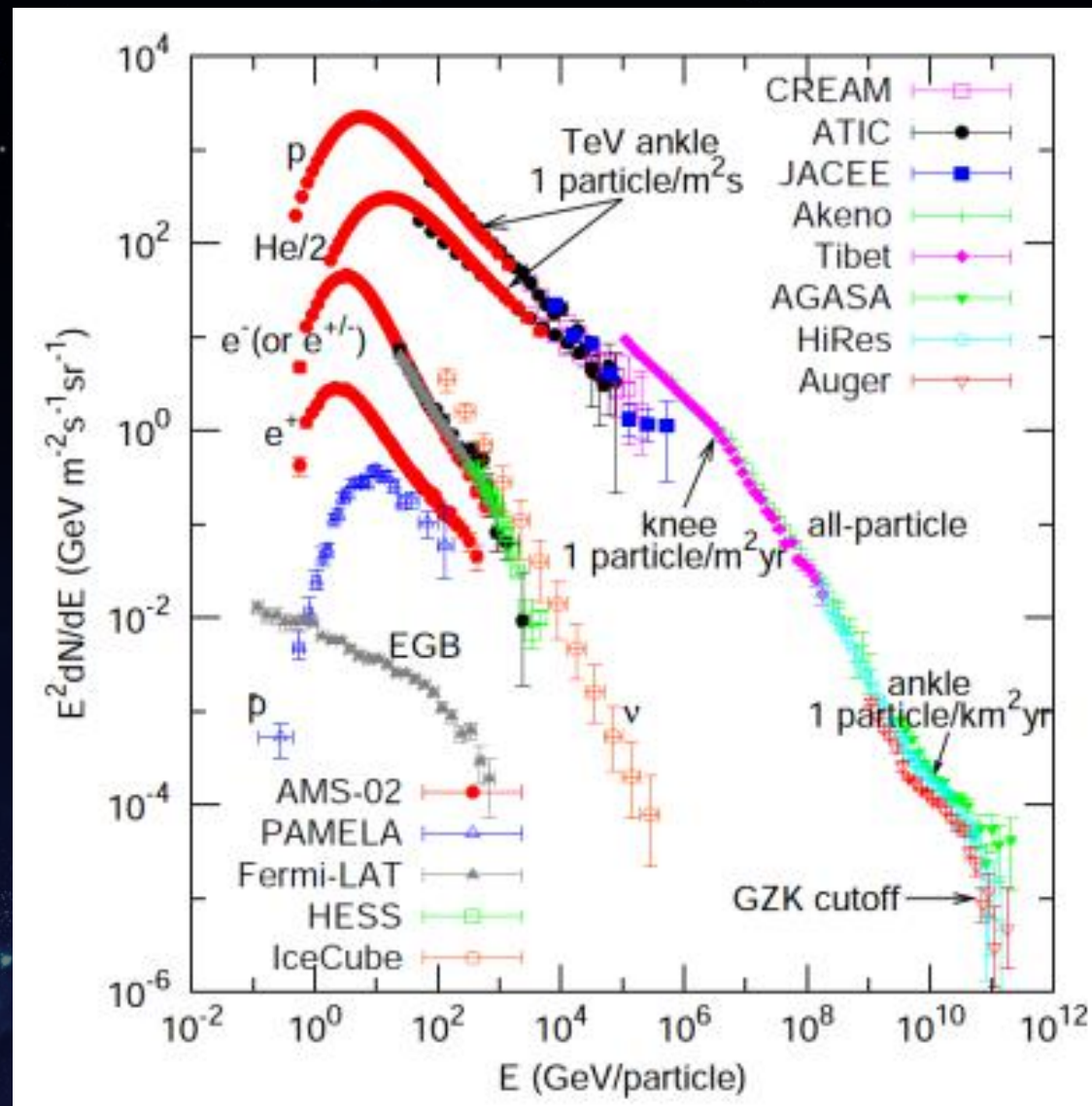


# 基于反物质宇宙线的暗物质间接探测



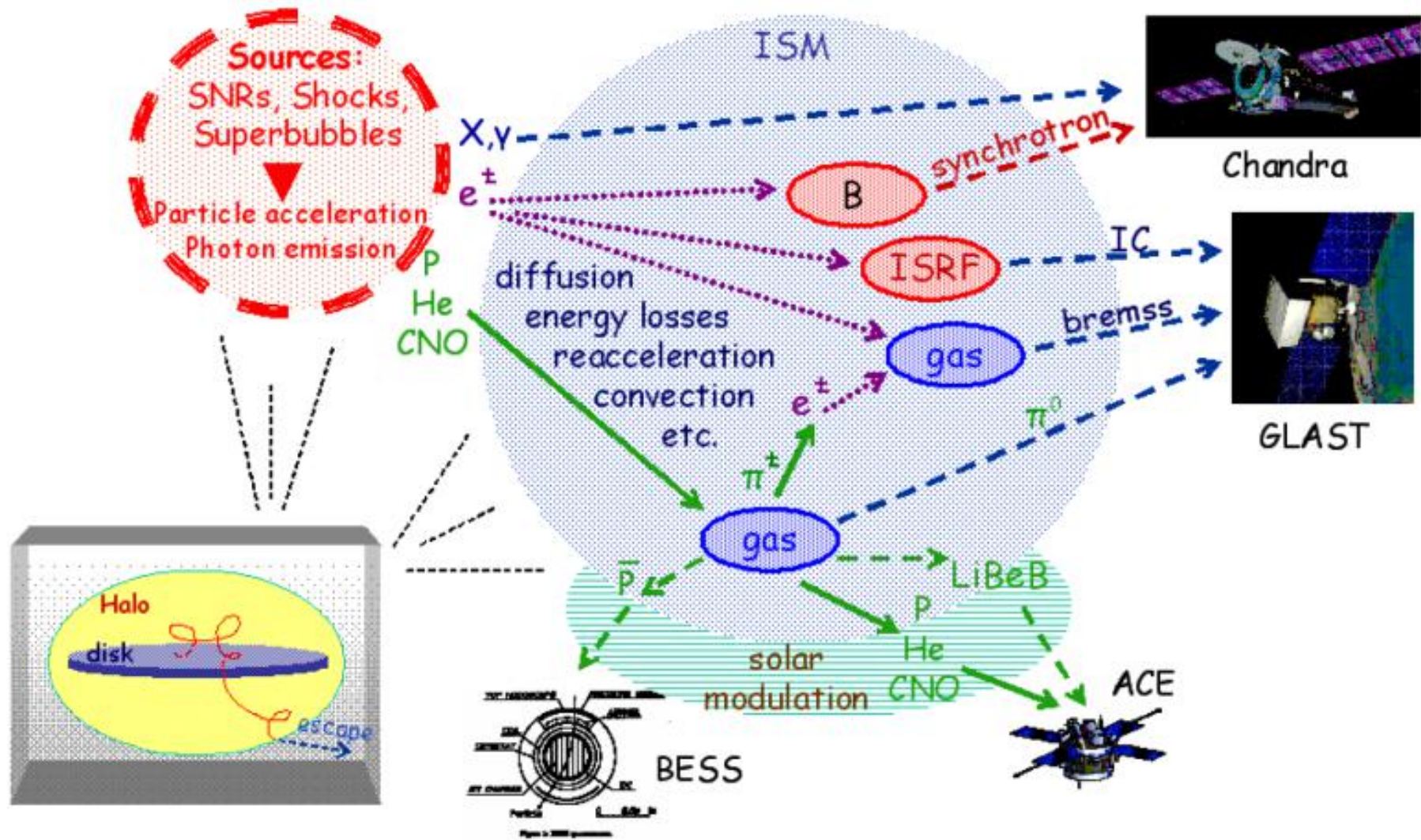
暗物质粒子湮灭成为伽玛射线、正负电子、正反质子对等 (e.g., Bergström & Snellman 1988, Turner & Wilczek 1990)

反物质宇宙线由于天文本底低，  
是搜寻暗物质的主要研究对象之一



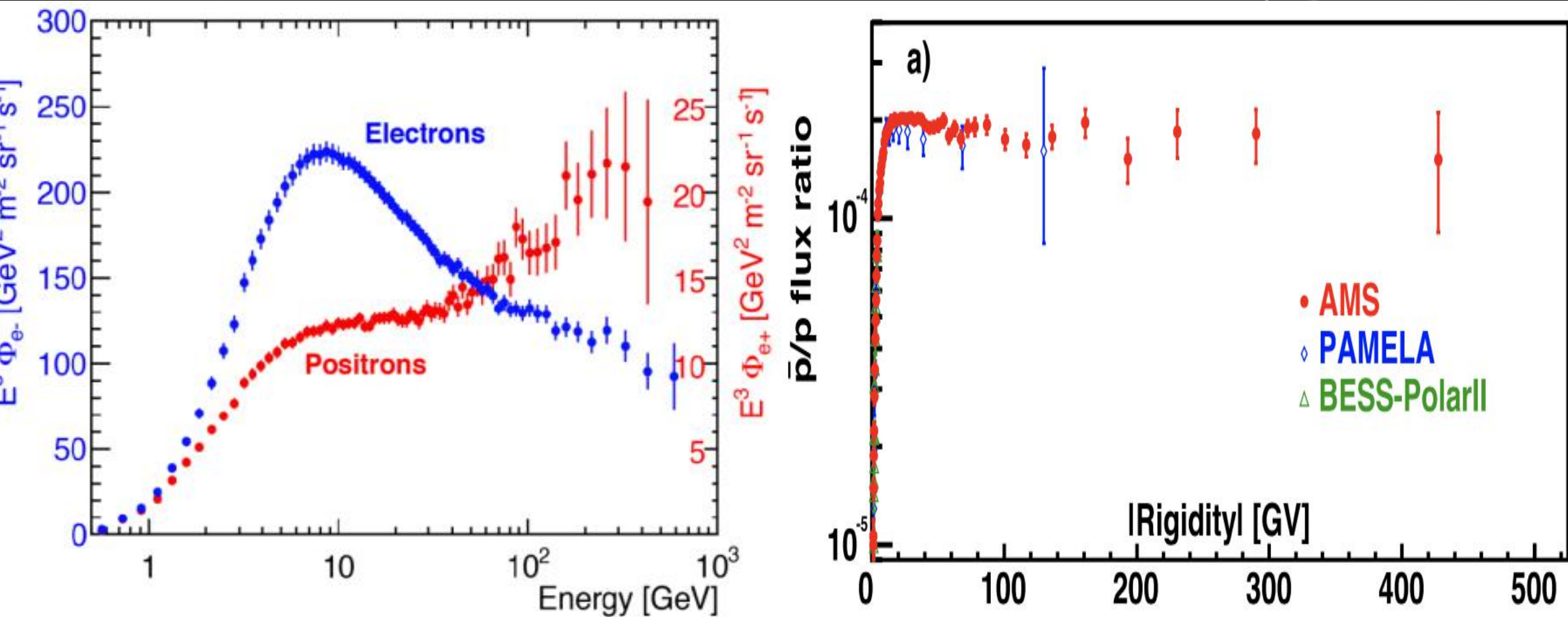


# 基于反物质宇宙线的暗物质间接探测



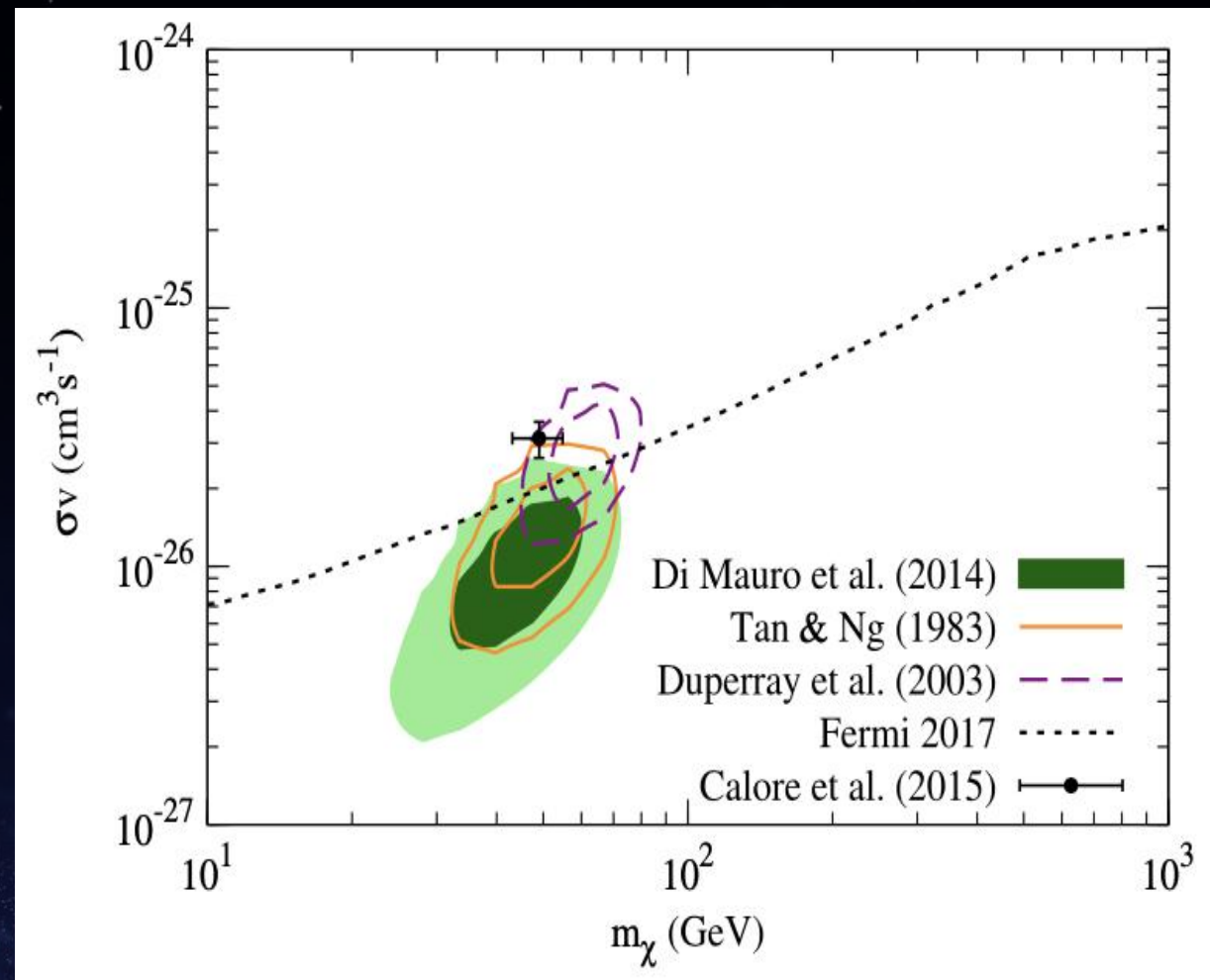
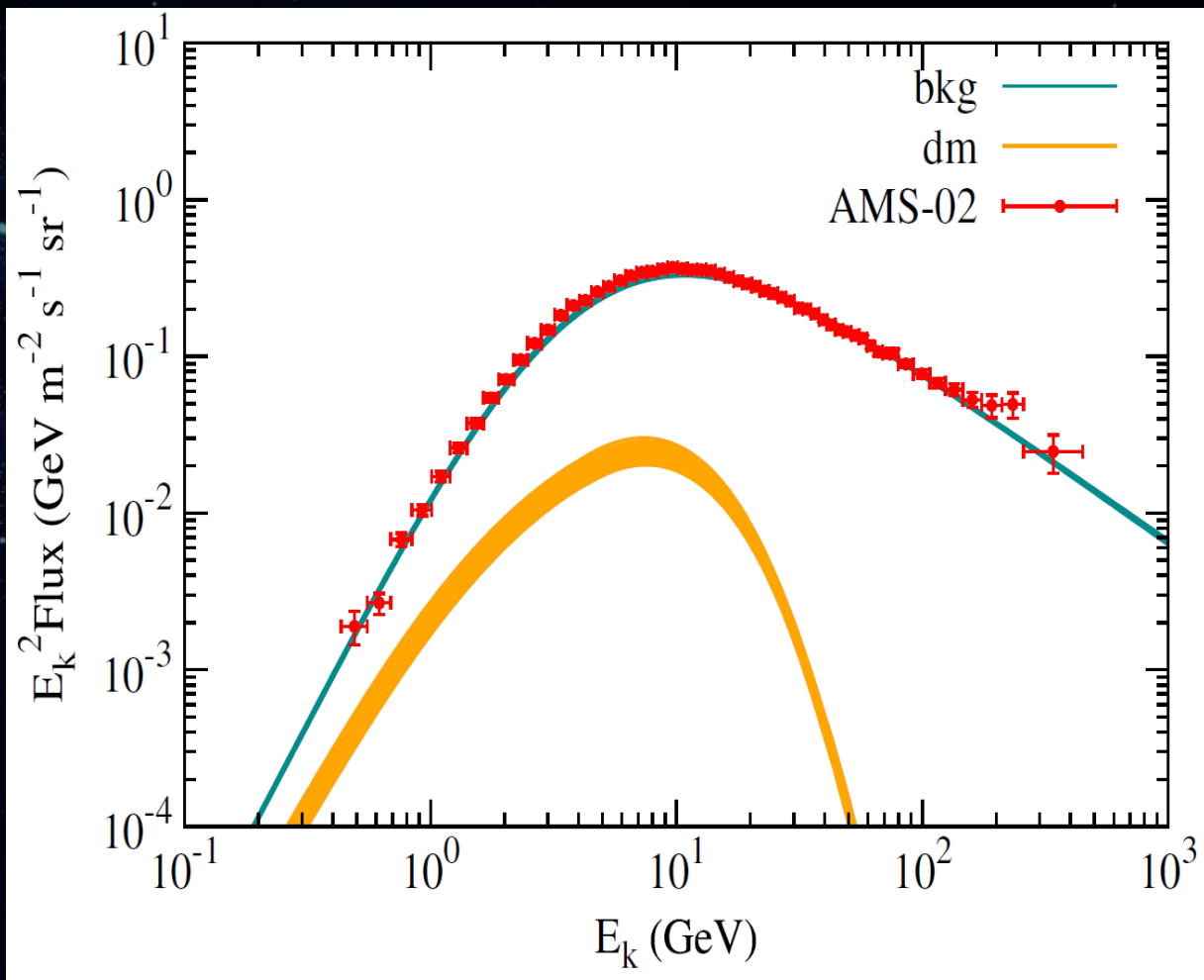


# 基于反物质宇宙线的暗物质间接探测



AMS-02 collaboration (2021 Phys. Rep.)

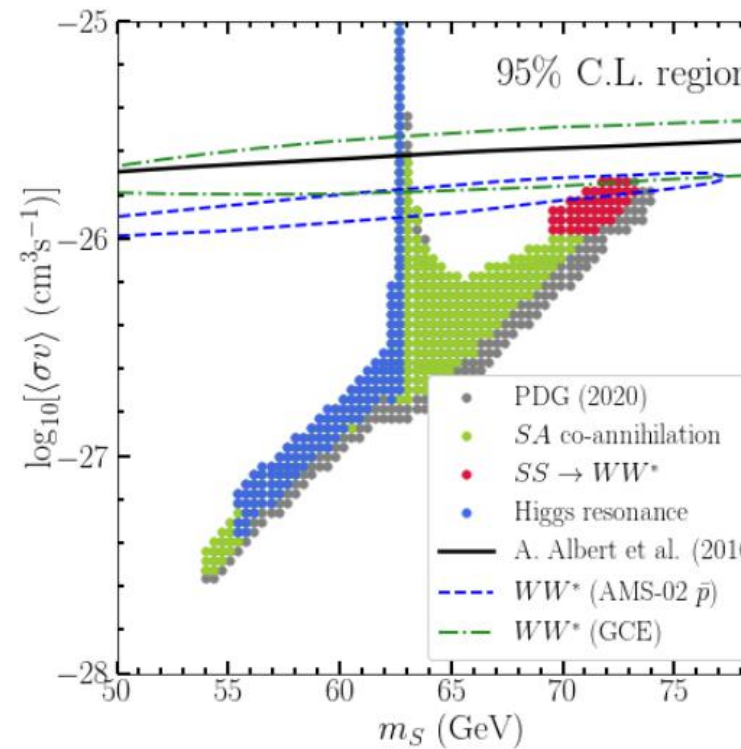
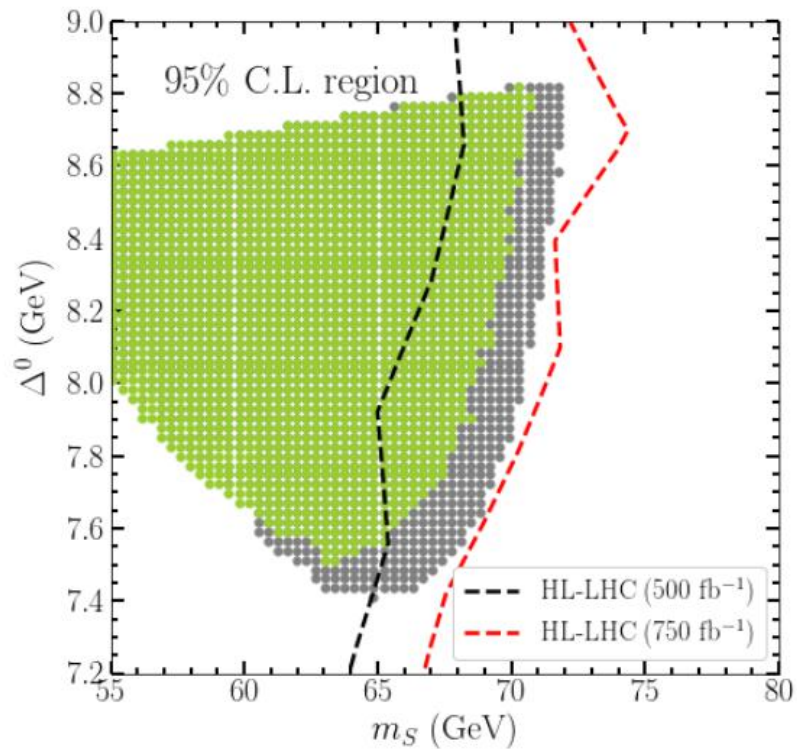
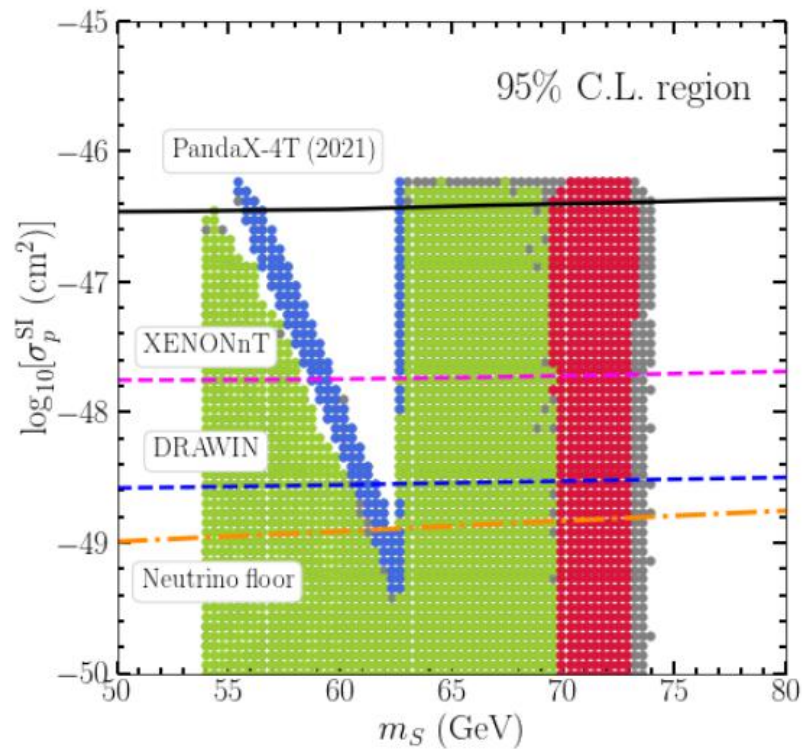
# 基于反物质宇宙线的暗物质间接探测



Cui et al. (2017 PRL) : 反质子能谱中可能存在超出, 可用50-100GeV的暗物质模型解释



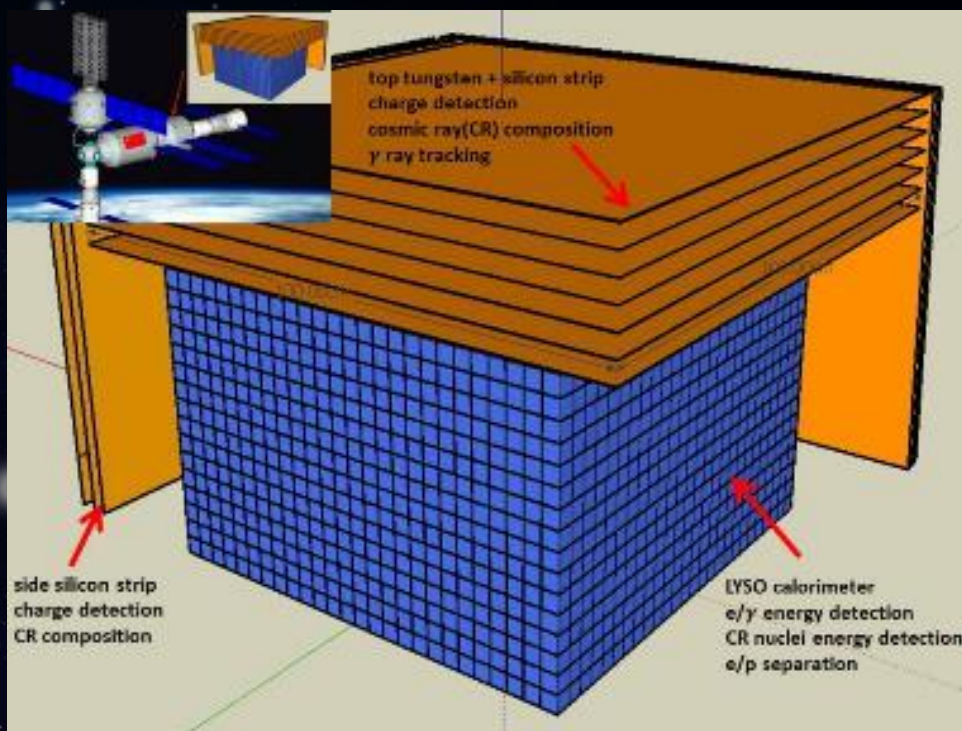
# 暗物质和宇宙线空间探测的未来?



i2HDM model for W-boson mass excess: 暗物质质量为54-74GeV?  
(Fan, Tang, Tsai & Wu 2022 PRL in press; <https://arxiv.org/abs/2204.03693>)

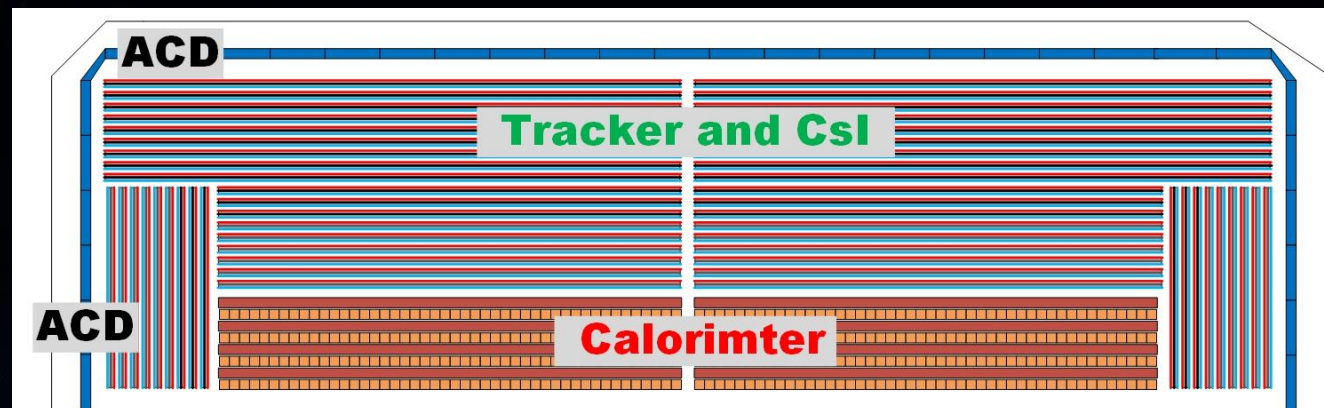


# 暗物质和宇宙线空间探测的未来

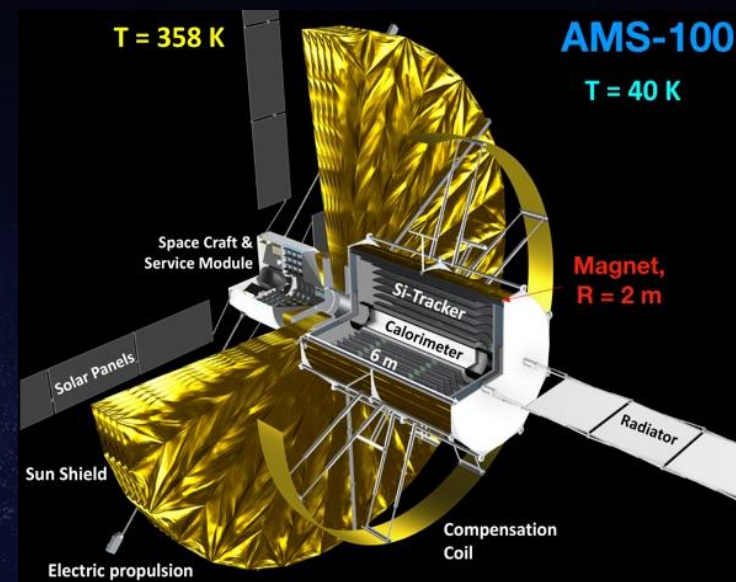


## 中国空间站高能辐射探测设施HERD

- 增大接受度和统计量，往更高能段延伸
- 提高分辨率（能量分辨、角分辨）



## 甚大面积伽马射线天文台VLAST



## 大型超导磁谱仪AMS-100

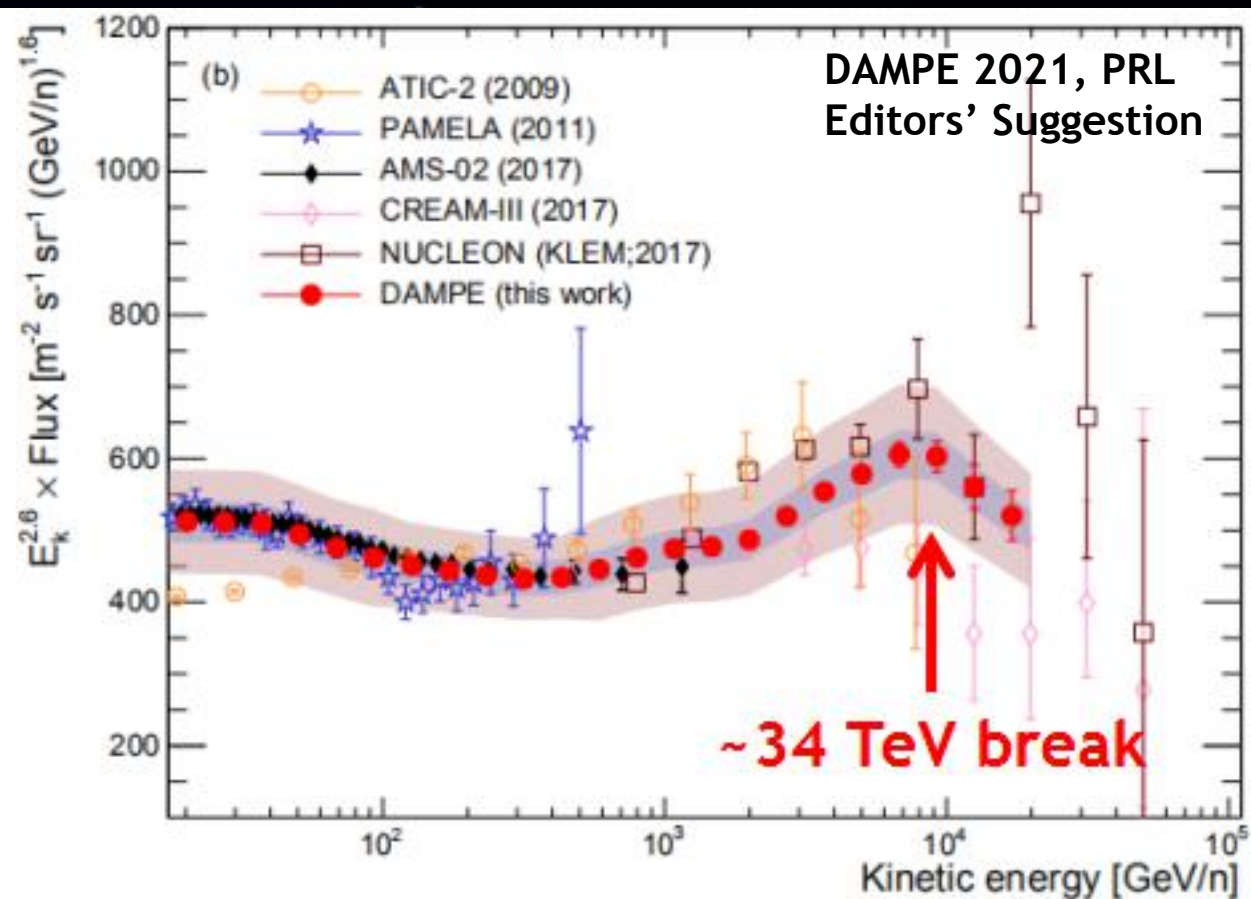
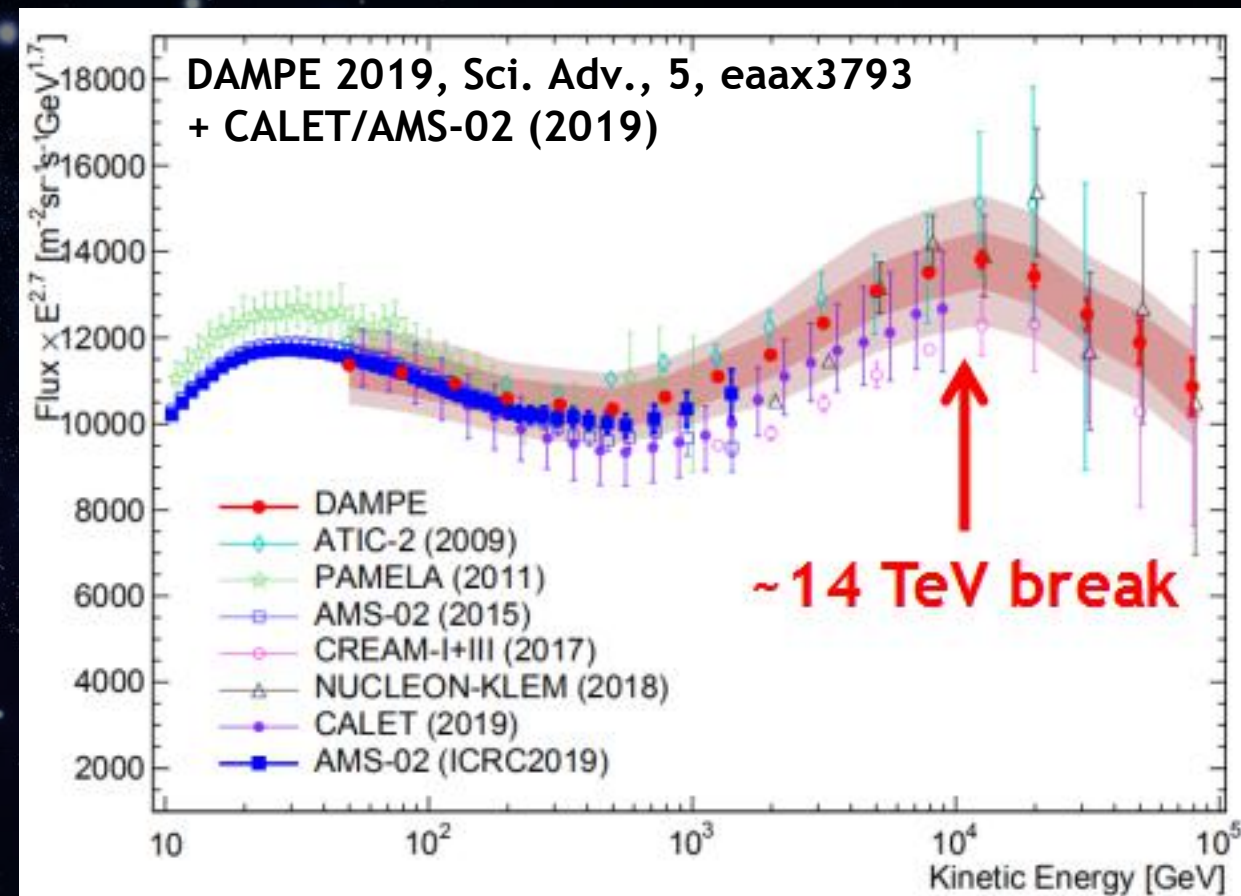


# 总 结

- 暗物质的本质是现代科学面临的重大前沿问题，将有望带来新一轮物理学（基础科学）的革命
- “悟空”号卫星在宇宙线正负电子、核素和伽马射线的观测中都取得了阶段性进展，为暗物质物理参数给出严格限制.其它的试验数据中也出现了一些有趣的迹象
- 为全面了解暗物质粒子，应当积极布局下一代暗物质空间探测实验

# 谢谢

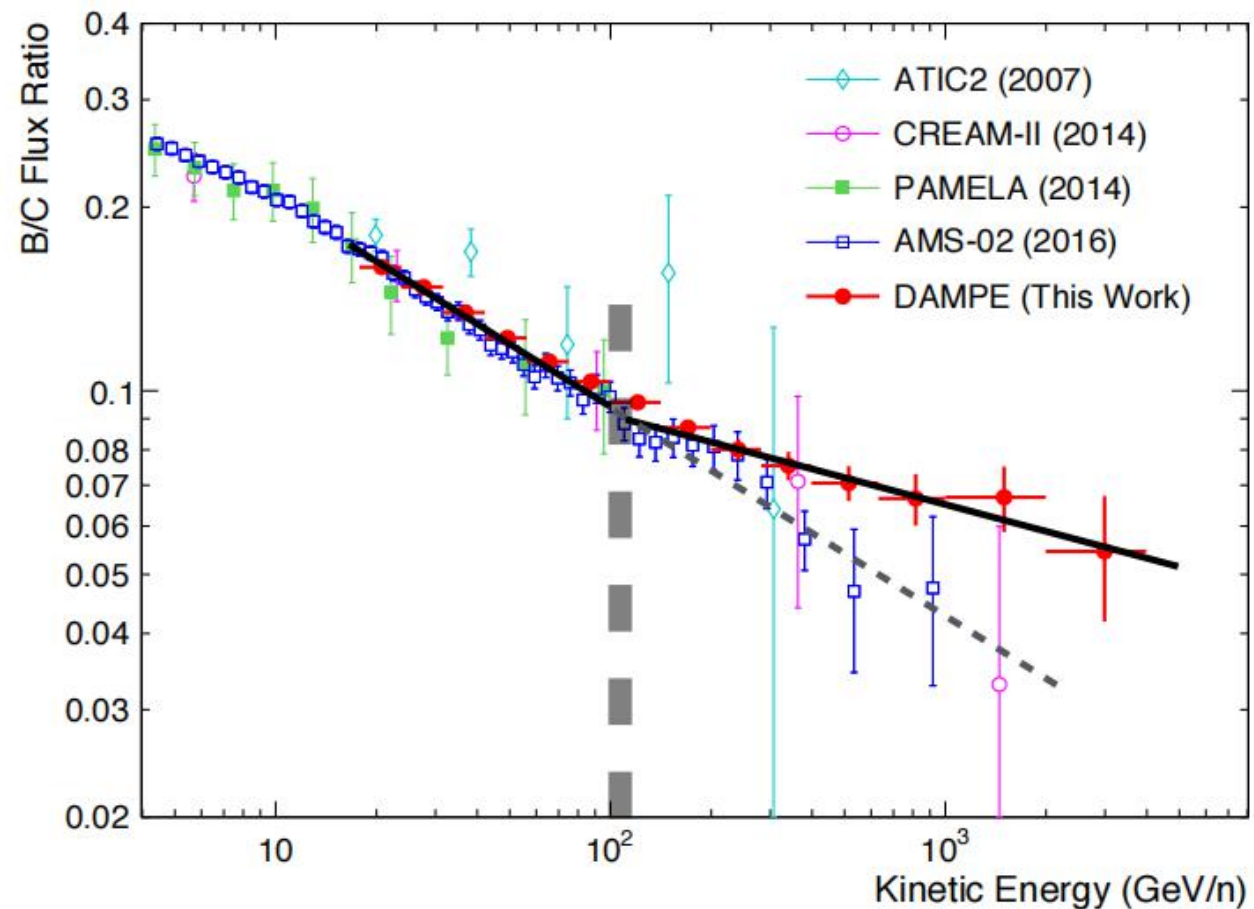
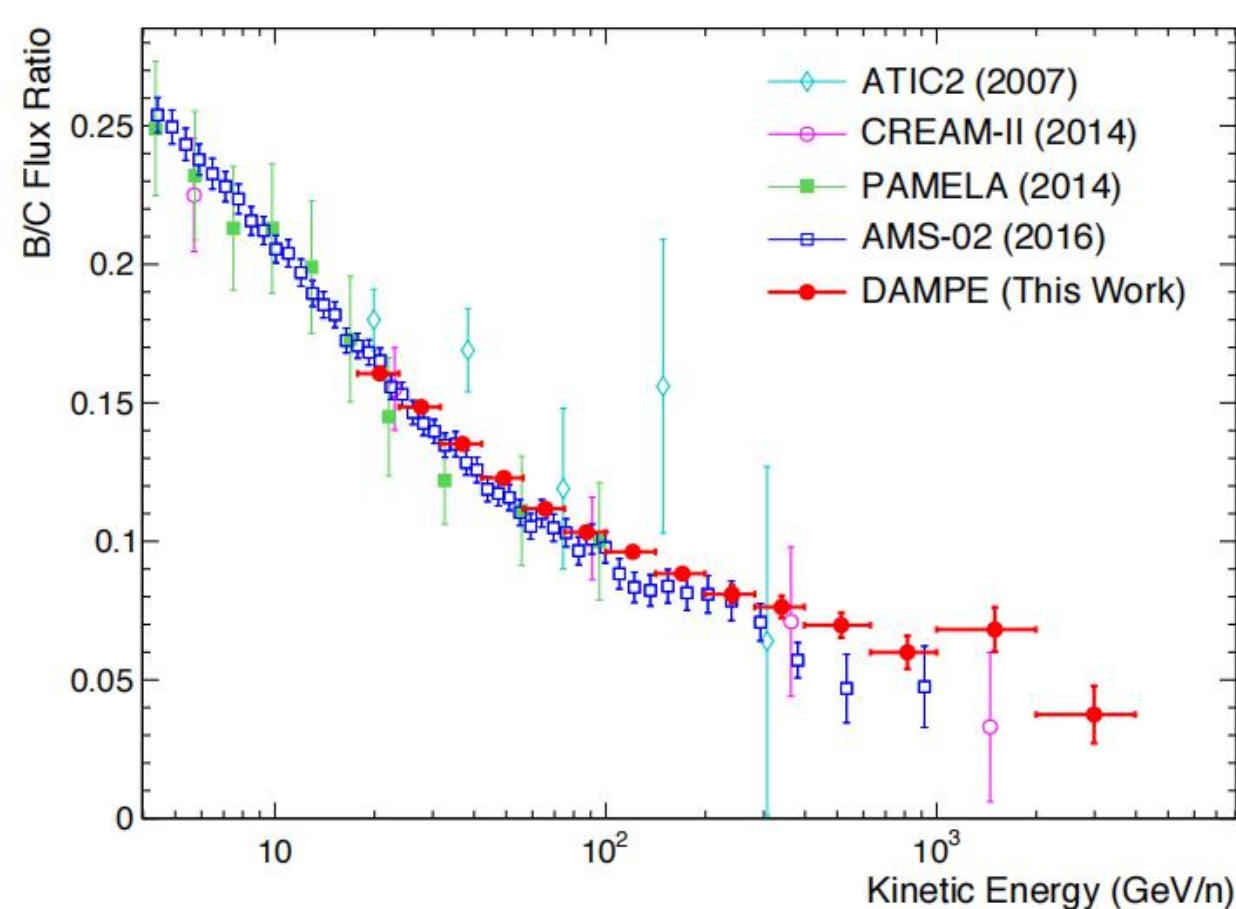
# 宇宙射线能谱测量助力天体物理研究



“悟空”号卫星精确测量了质子和氦核宇宙射线能谱，发现能谱变软的新结构，可能来自邻近地球的宇宙射线加速源



# 宇宙射线能谱测量助力天体物理研究



硼碳比例是研究宇宙射线传播过程的重要物理量，“悟空”号的初步观测结果揭示出硼碳比例存在有意思的新特征