

高能宇宙线物理及下一代空间探测装置研讨会

甚大面积伽马射线空间望远镜 VLAST

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中国科学院紫金山天文台

2025.08.01 @乌鲁木齐

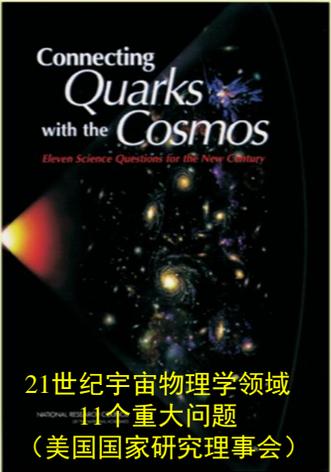


提纲

- 1. 甚大面积伽马射线望远镜VLAST**
- 2. VLAST技术预研进展**
- 3. 总结**

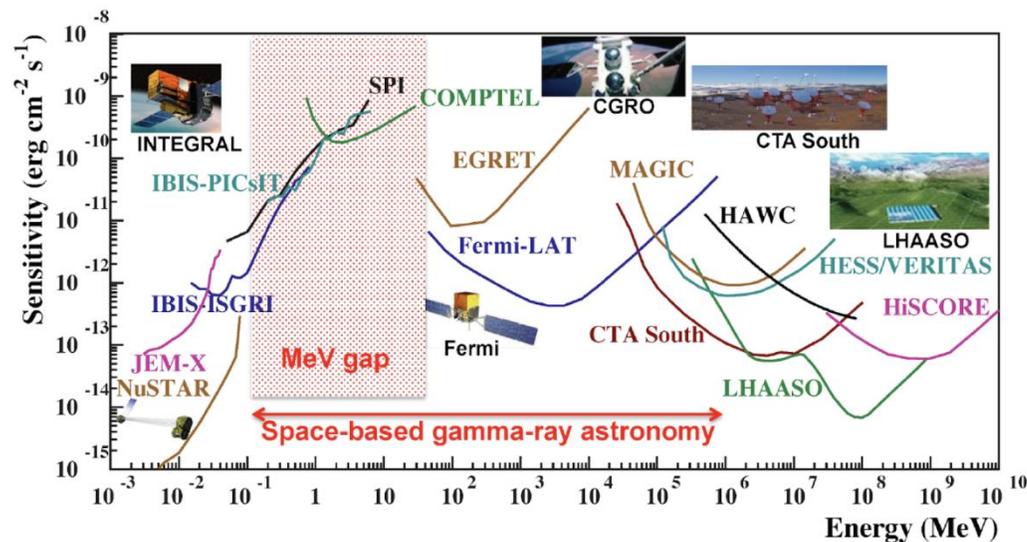
甚大面积伽马射线VLAST: 科学目标

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



21世纪宇宙物理学领域
11个重大问题
(美国国家研究理事会)

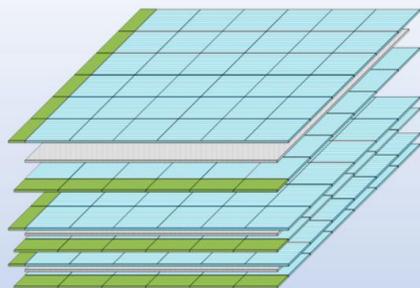
1. What is Dark Matter? **暗物质本质**
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable? **宇宙射线起源**
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? **超铁元素起源**
11. Is a New Theory of Light and Matter Needed at the Highest Energies?



MeV-TeV的空间伽马射线探测在**暗物质间接探测、宇宙线起源、超铁元素起源**等方面蕴含着重大科学机遇!

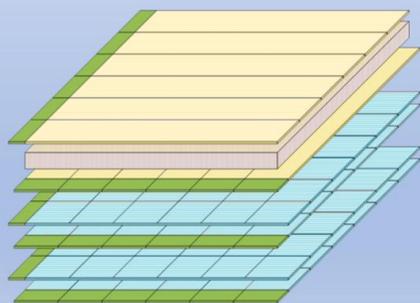
甚大面积伽马射线VLAST: 科学目标

DAMPE
硅阵列探测器

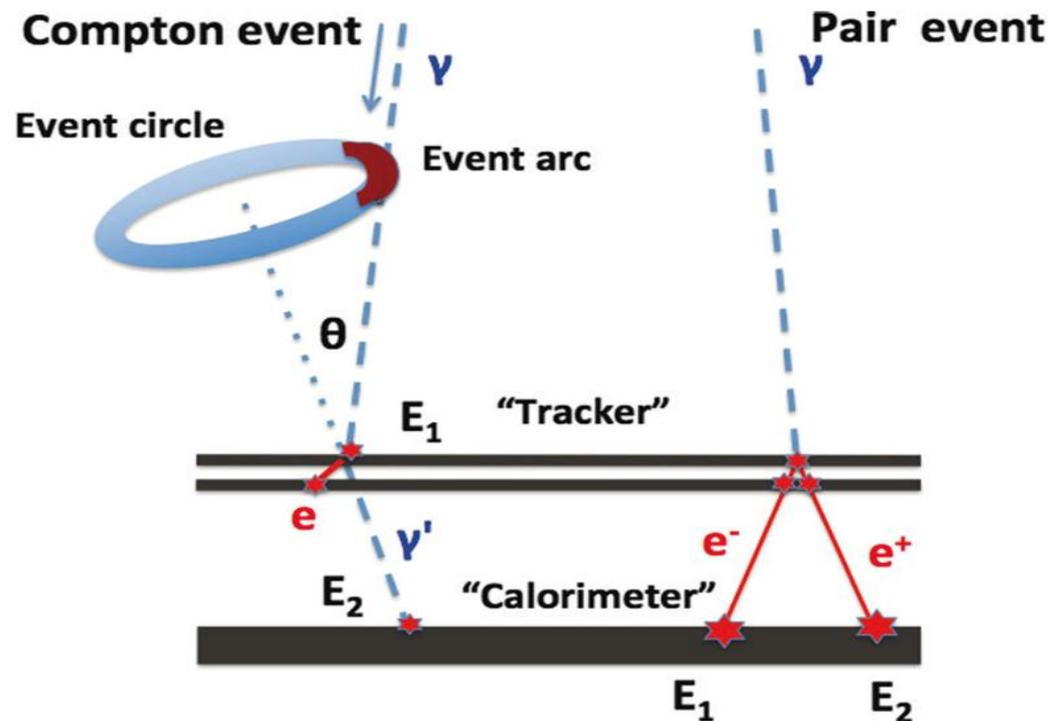


硅微条探测器-X
钨板
硅微条探测器-Y

VLAST
径迹及低能伽马
探测器



闪烁光纤探测器-X
CsI晶体探测器
闪烁光纤探测器-Y
硅微条探测器-X
硅微条探测器-Y
硅微条探测器-X
硅微条探测器-Y



关键创新: 径迹探测器中用CsI晶体代替传统的钨板, 利用康普顿效应进行MeV光子测量并有效提高100MeV以下伽马(利用电子对产生测量)的能量分辨, 实现1-100MeV伽马射线的高灵敏度探测

伽马探测能段: MeV-TeV (波段超级宽)

接受度 (峰值): ~10平方米球面度 (面积超级大)

主要技术基础: 悟空号卫星

综合性能预期比目前国际上最强大的同类设施Fermi-LAT(接受度~2平方米球面度)提升10倍以上

甚大面积伽马射线VLAST：科学目标

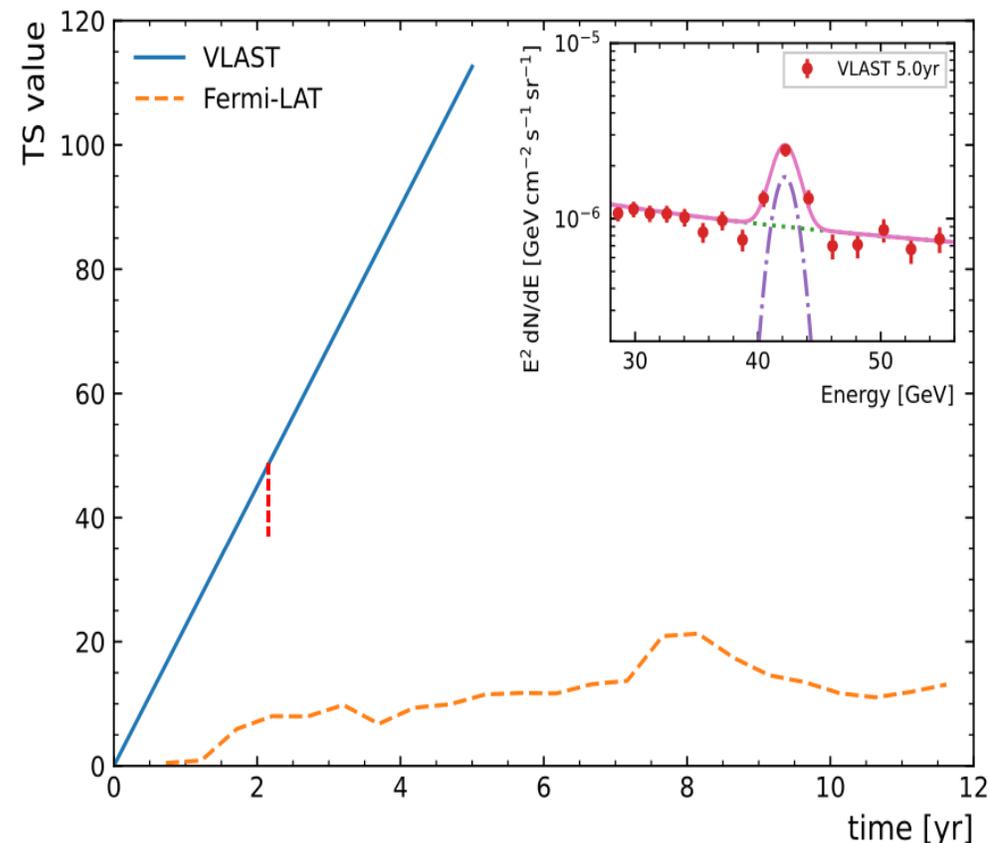
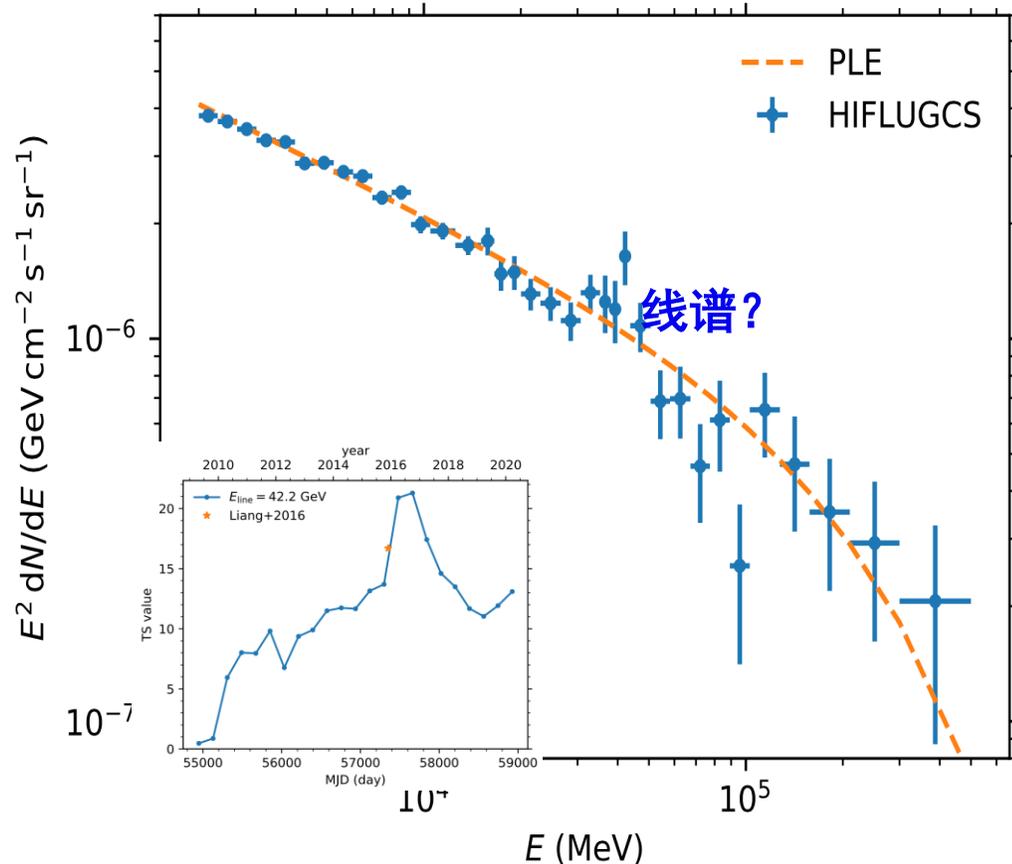
国内外正在运行或提议的一些相空间伽马探测项目

探测设施	伽马峰值接受度 ($\text{m}^2 \text{sr}$)	伽马能段范围	能量分辨率 (@10GeV)	角分辨本领 (@50GeV)
Fermi-LAT	~ 2	20 MeV-300 GeV	~6.0%	~ 0.10 deg
悟空号	~ 0.2	5 GeV-10 TeV	~1.5%	
AMS-100 (概念)	~30	0.1 GeV-10 TeV		~ 0.03 deg
APT	~20	1 MeV-10 TeV	~ 20%	~ 0.10 deg
HERD	~2	0.5 GeV-10 TeV	~1.5%	
VLAST	~10	1 MeV-10 TeV	~1.5%	~ 0.10 deg

甚大面积伽马射线VLAST: 科学目标

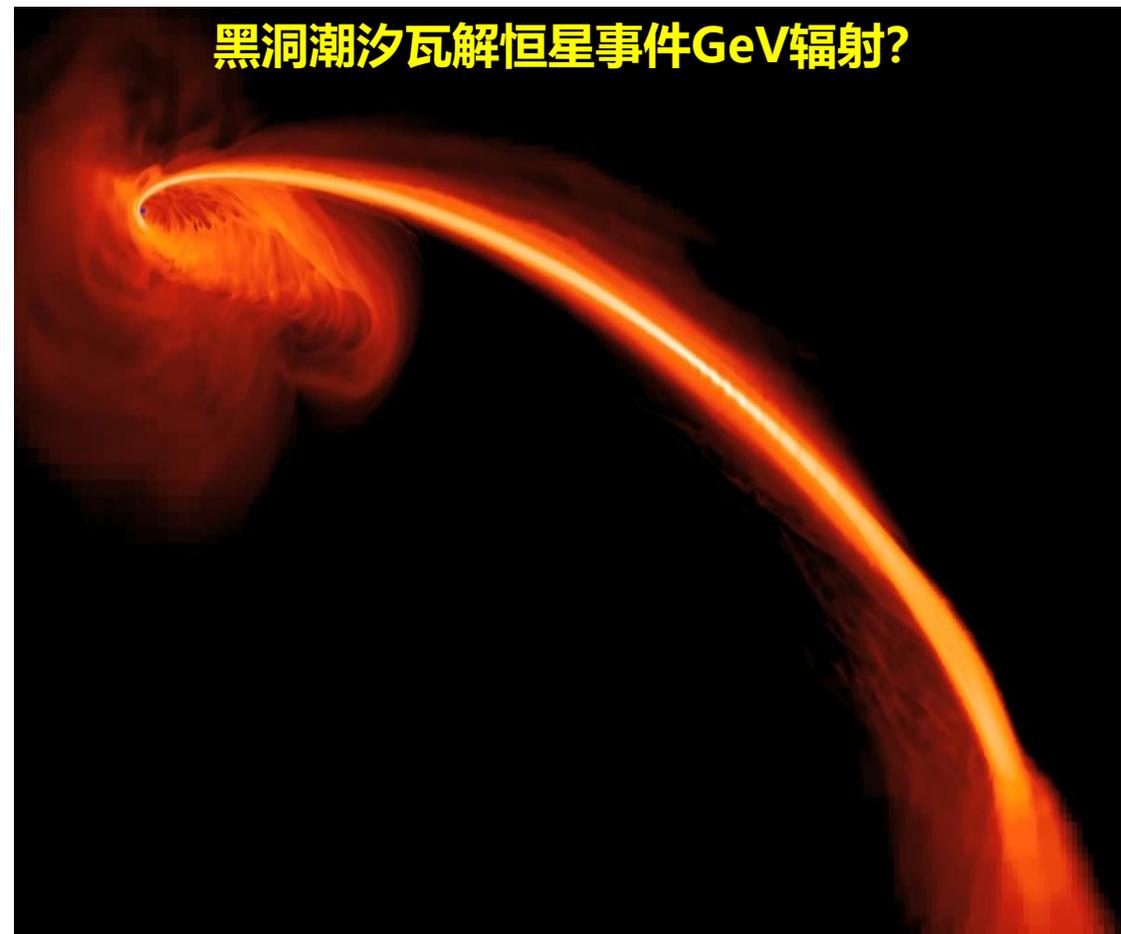
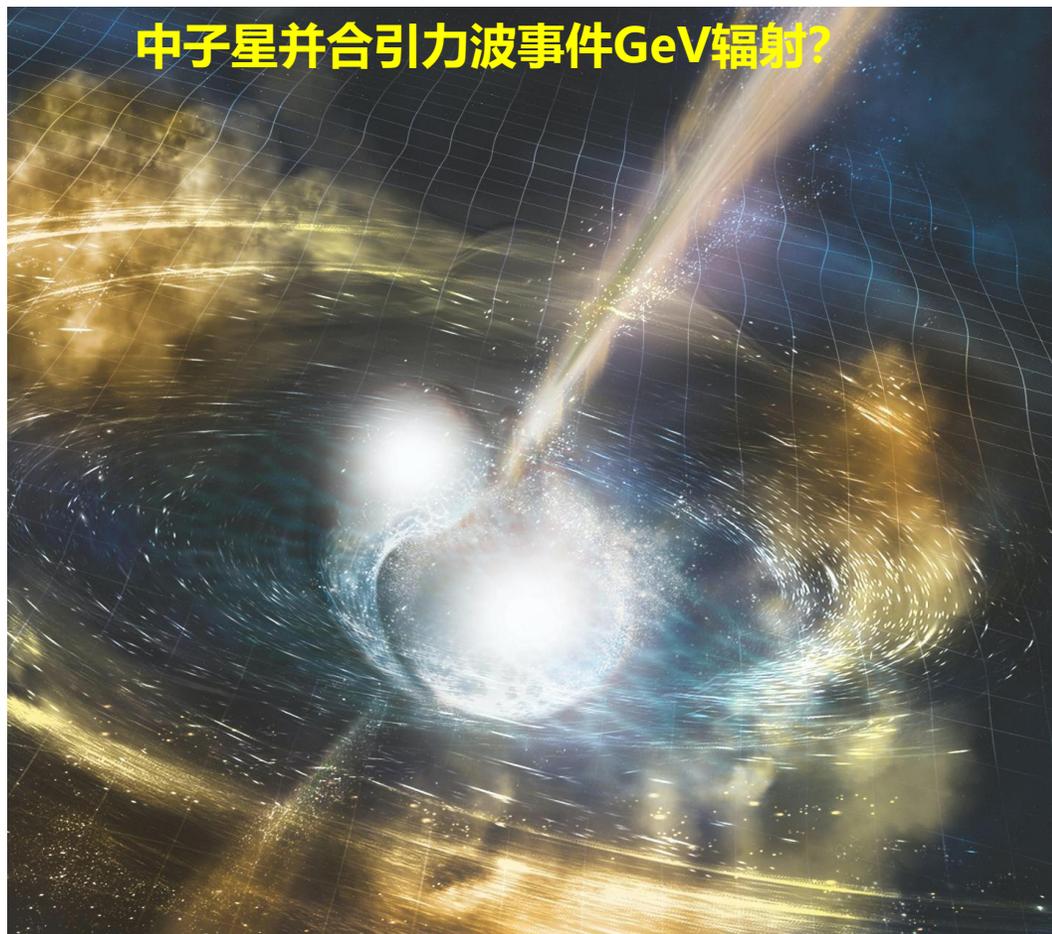
Shen, Xia & Fan 2021

范一中等 2022



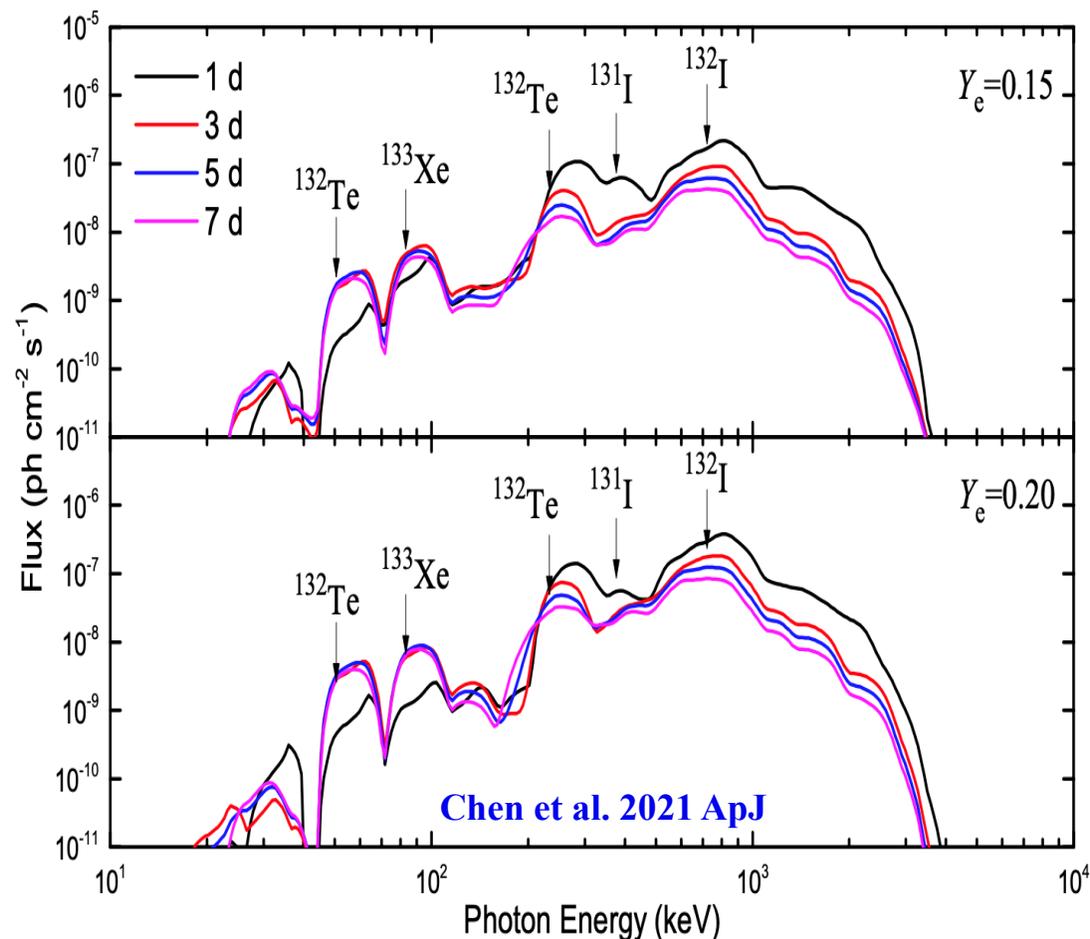
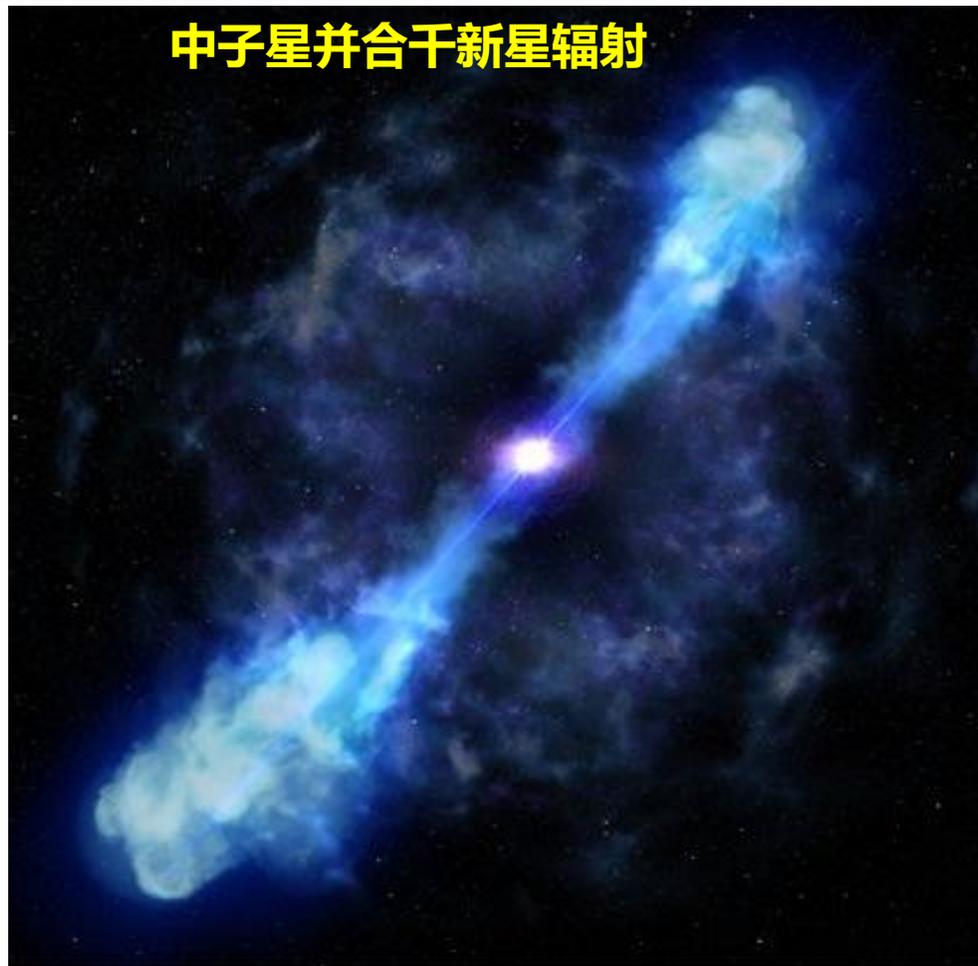
A. 引领基于伽马射线的国际暗物质间接探测研究，精确测量或高精度限制暗物质粒子主要物理参数 (GeV以上线谱，如果探测到，将是暗物质的确定性信号；2年VLAST观测将判定Fermi-LAT的伽马线谱迹象是否真实)

甚大面积伽马射线VLAST：科学目标



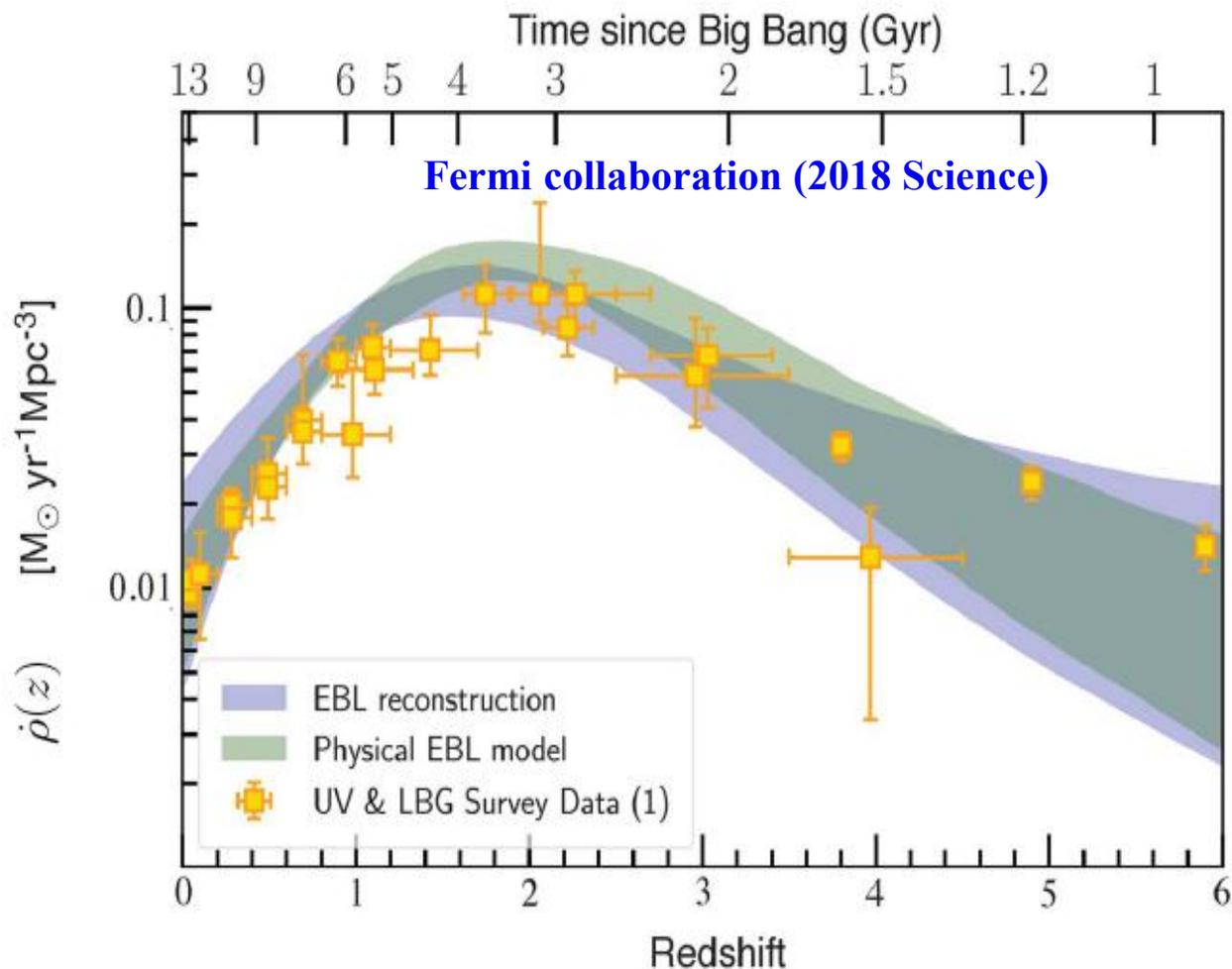
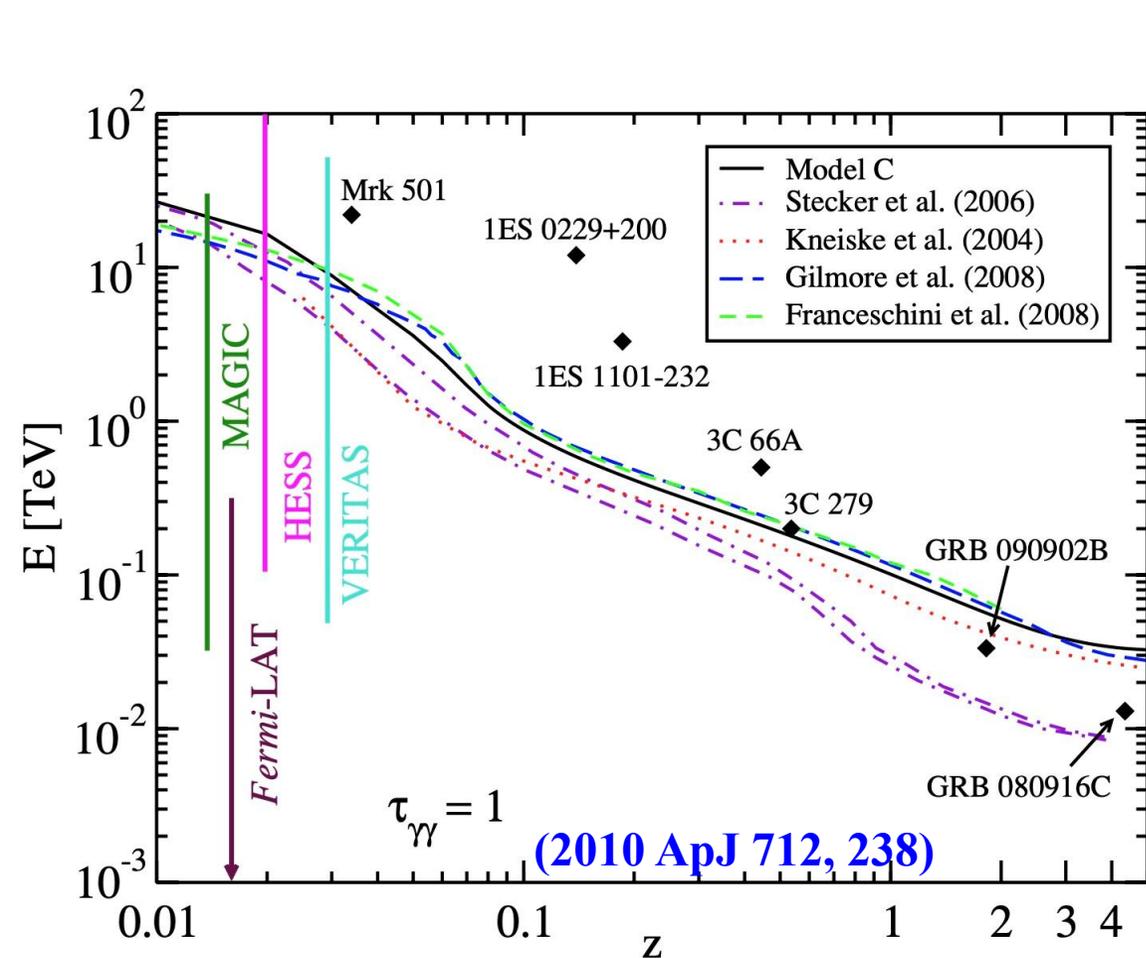
B1. 监测引力波、黑洞潮汐瓦解恒星等重要天文事件的GeV辐射，证认高能中微子的辐射源，发现新型GeV爆发现象；与SVOM，EP等X射线探测设施协同，进行keV-TeV超宽波段观测。预计前3年共探测到~7000个源！

甚大面积伽马射线VLAST：科学目标



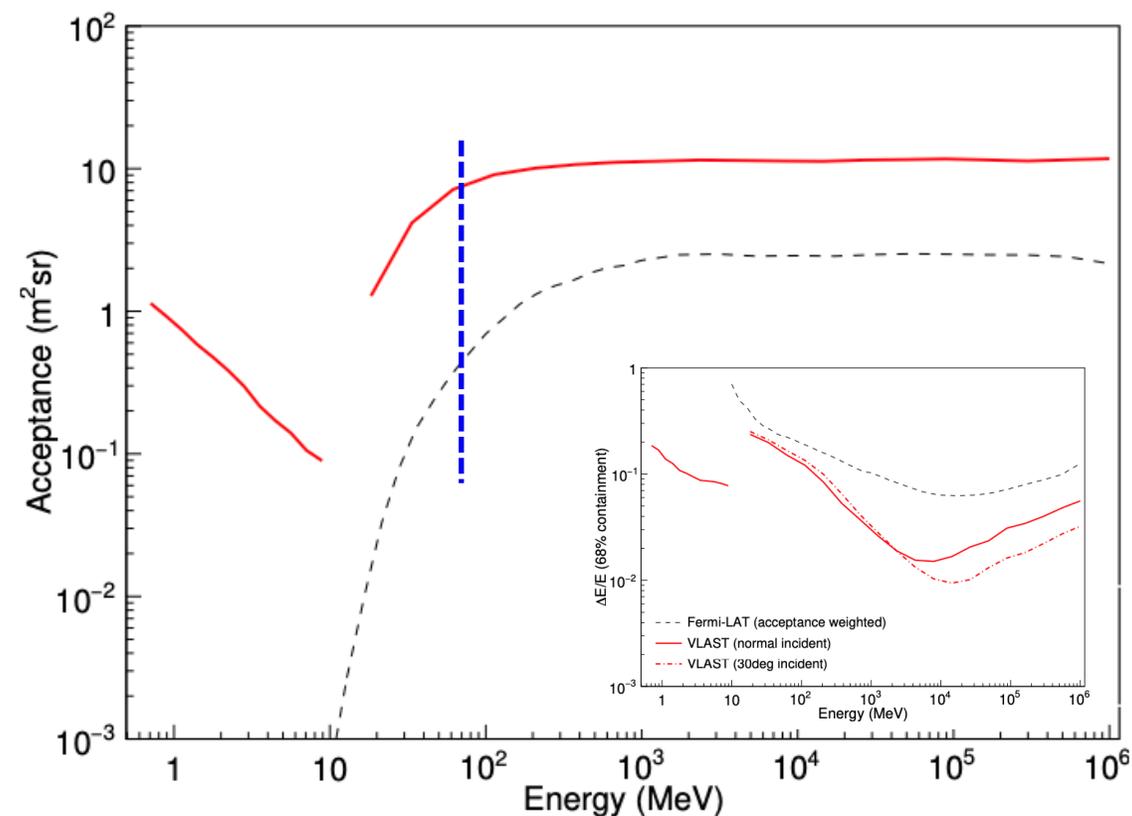
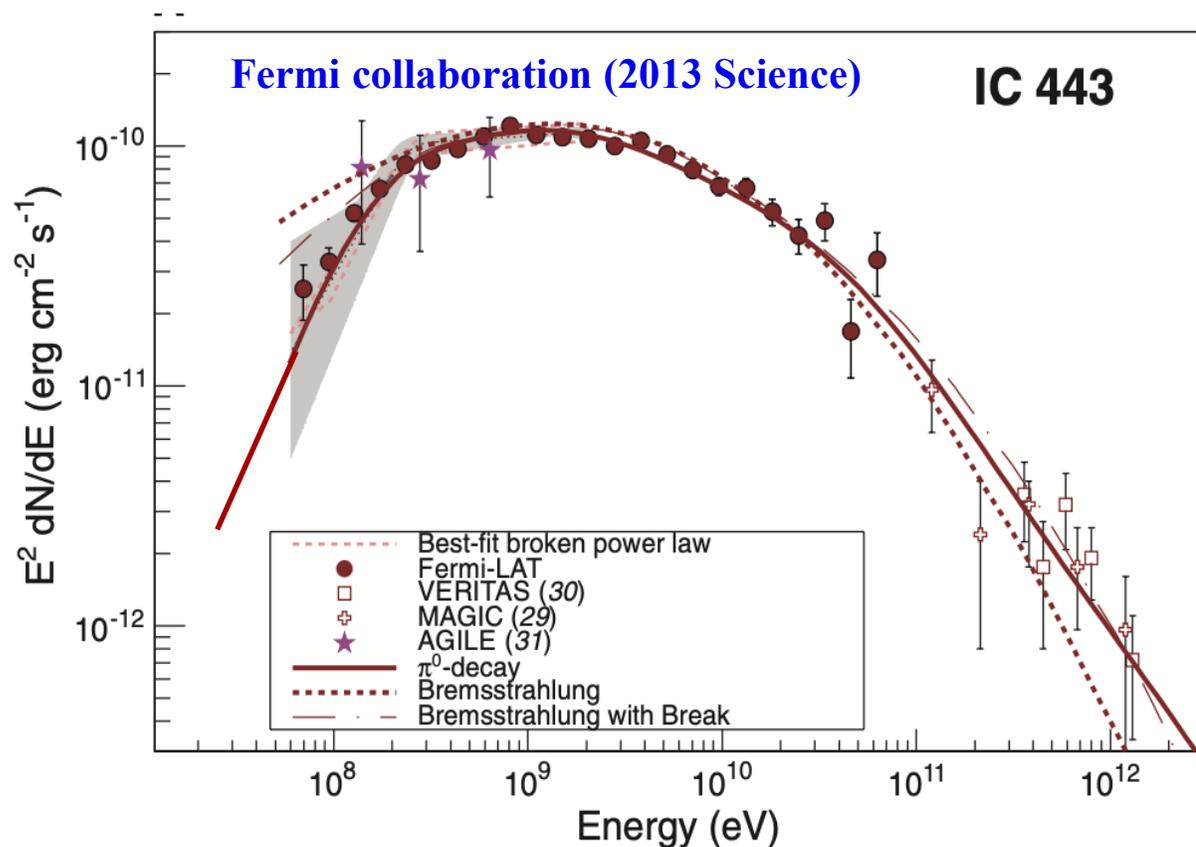
B2. 探测中子星并合事件/千新星晚期MeV线谱，直接证认超铁元素起源地

甚大面积伽马射线VLAST: 科学目标



C. 发现高红移(> 6)宇宙中的GeV爆发事件、精确测量宇宙伽马射线视界, 重建河外背景光(EBL)及恒星形成的红移演化

甚大面积伽马射线VLAST: 科学目标



D. 精确测量超新星遗迹的宽波段能谱，通过70MeV的中性 π 介子鼓包证认强子宇宙线源；获得银河系宇宙线三维空间分布，揭示宇宙线传播机制

甚大面积伽马射线VLAST： 载荷配置

关键科学目标与对应的探测器需求简表

科学目标或功能	信号(可能)能段	Fermi-LAT (接受度)	VLAST (接受度)	VLAST探测器
伽马射线鉴别		是	是	反符合探测器
暗物质间接探测	~ GeV-TeV	~ 2 m ² sr	>10 m ² sr	高能成像量能器
宇宙线源证认	~ 70 MeV	~ 0.4 m ² sr	~ 7 m ² sr	径迹及低能量能器
超铁元素衰变	1-10 MeV	无	~ 0.5 m ² sr (探测40Mpc源)	径迹及低能量能器

甚大面积伽马射线VLAST： 载荷配置

三大主载荷:

(a)反符合探测器:

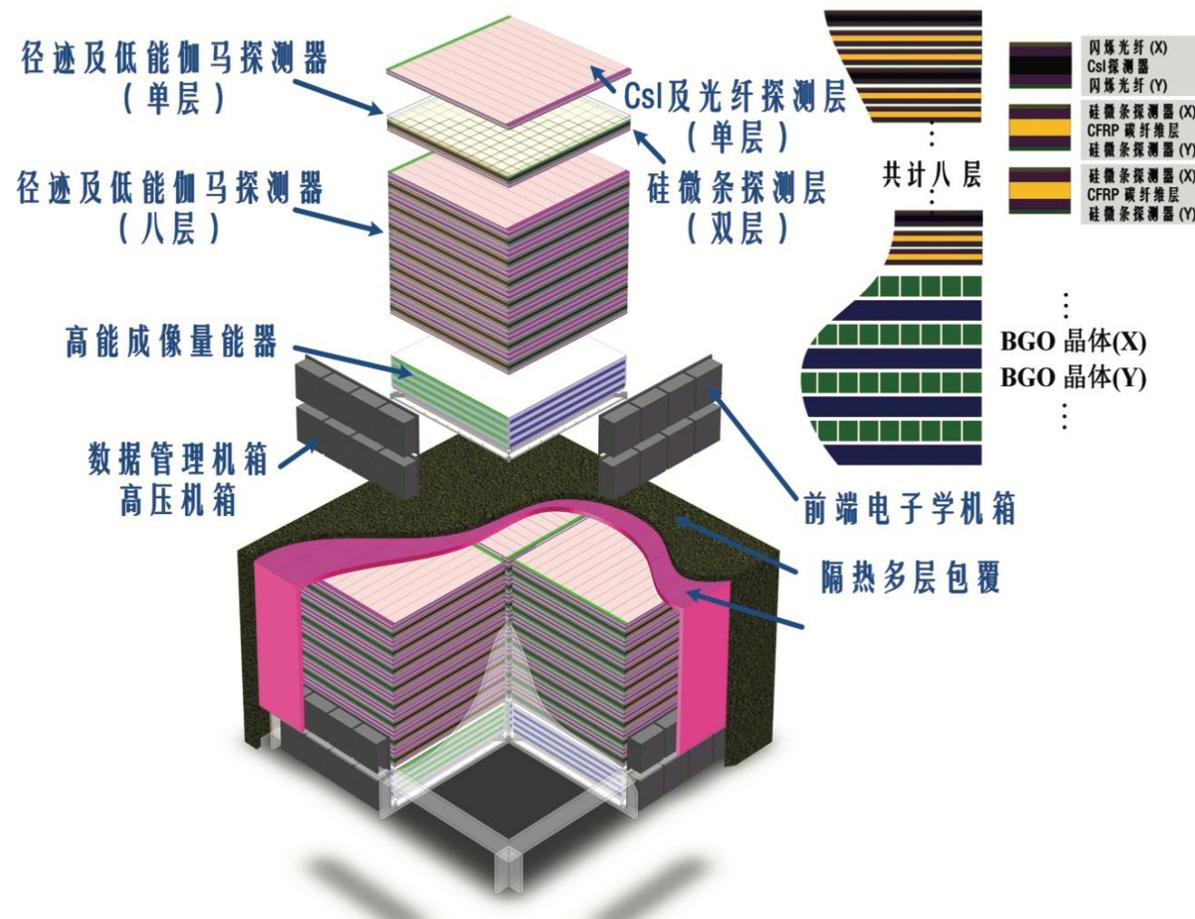
- 位于探测器的顶部及四周，用于区分光子和带电粒子

(b)径迹及低能伽马探测器:

- 用于测量高能光子（电子对）径迹和低能康普顿效应光子

(c)高能成像量能器:

- 位于探测器的底部，用于测量入射高能粒子能量

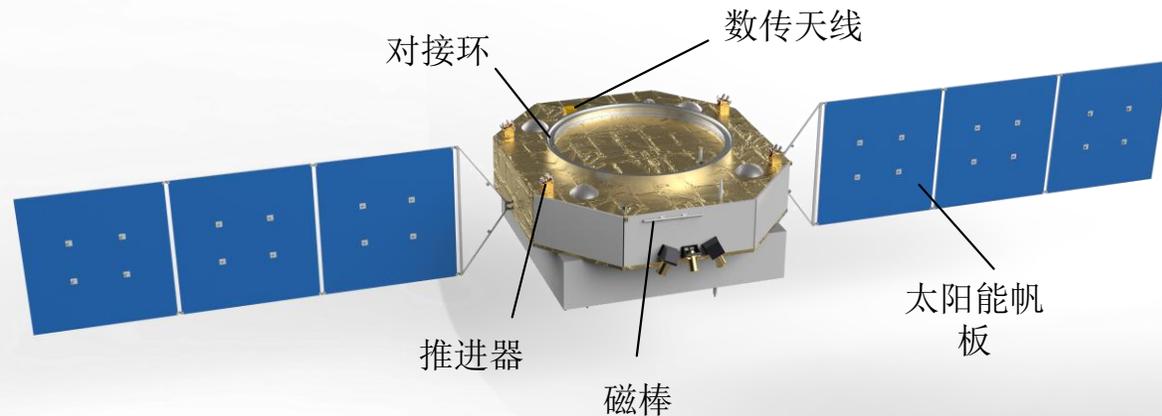
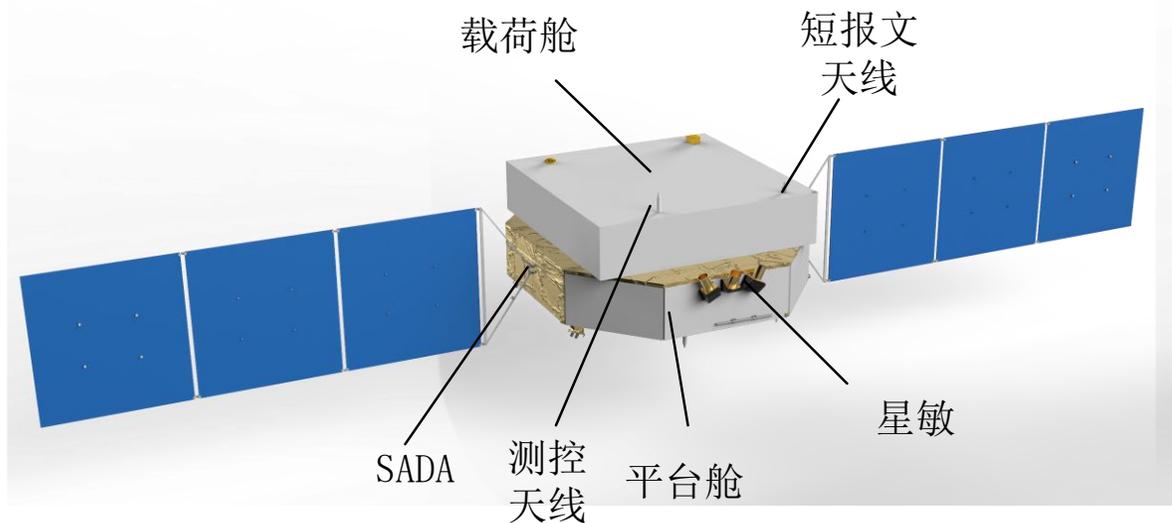
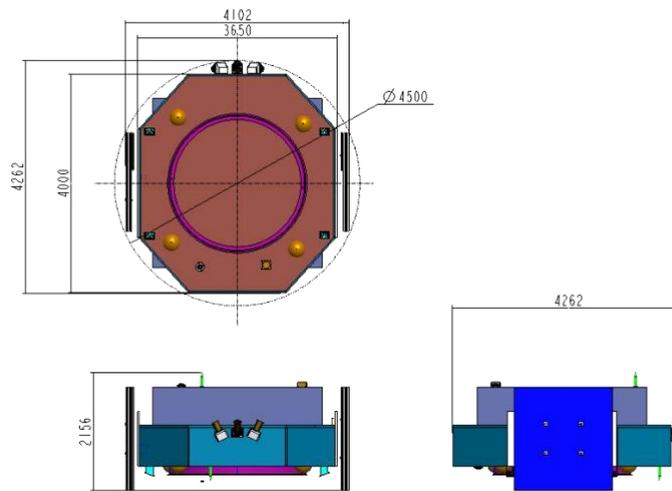


VLAST是2×2的阵列，每个单元尺寸为1.2米!

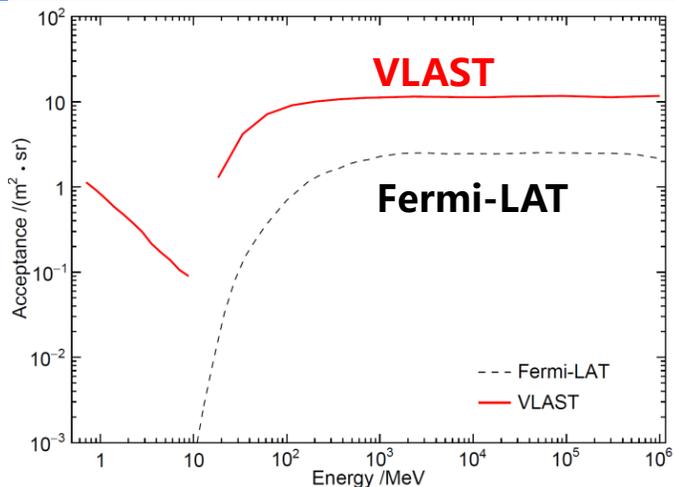
甚大面积伽马射线VLAST: 卫星平台

— 卫星构型设计

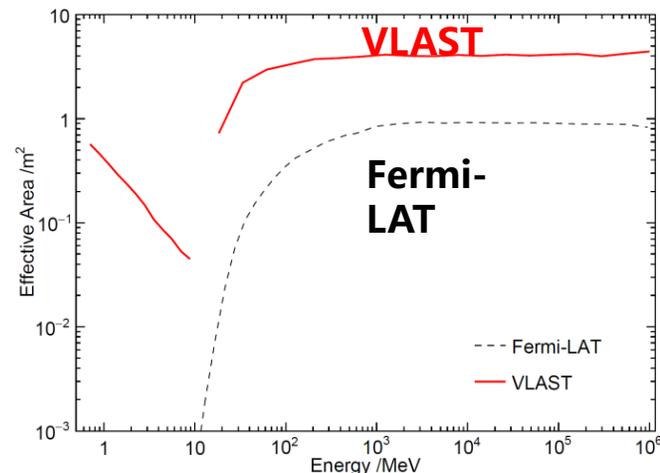
- 发射包络: 4102mm×4262mm×2156mm
- 帆板展开包络: 16304mm×4262mm×2156mm
- 配置6个25Nms控制力矩陀螺支撑大惯量下卫星姿态控制
- 短报文快速收发ToO及Alert
- 帆板配置SADA转动机构保证能源获取



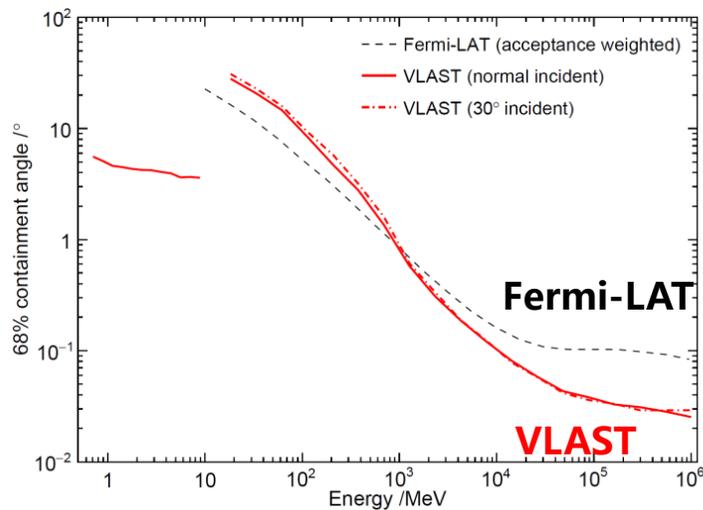
甚大面积伽马射线VLAST: 性能预期



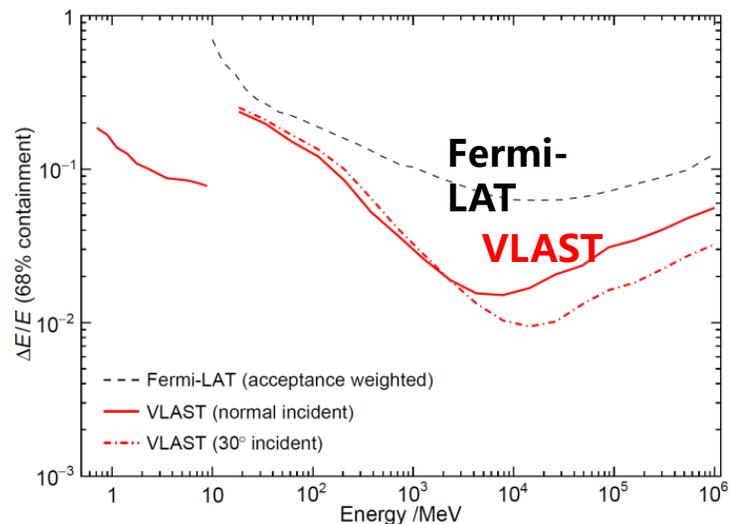
有效接受度大



探测面积大



角度分辨本领强



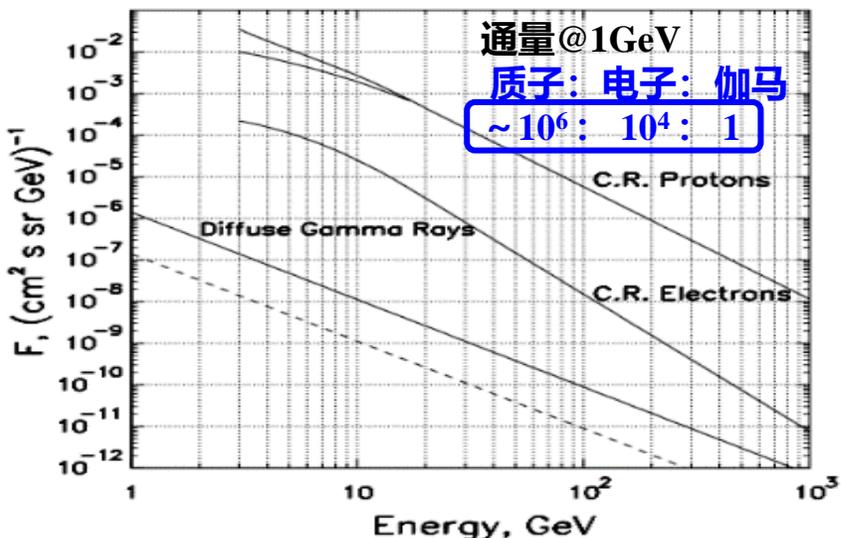
能量分辨率高

提纲

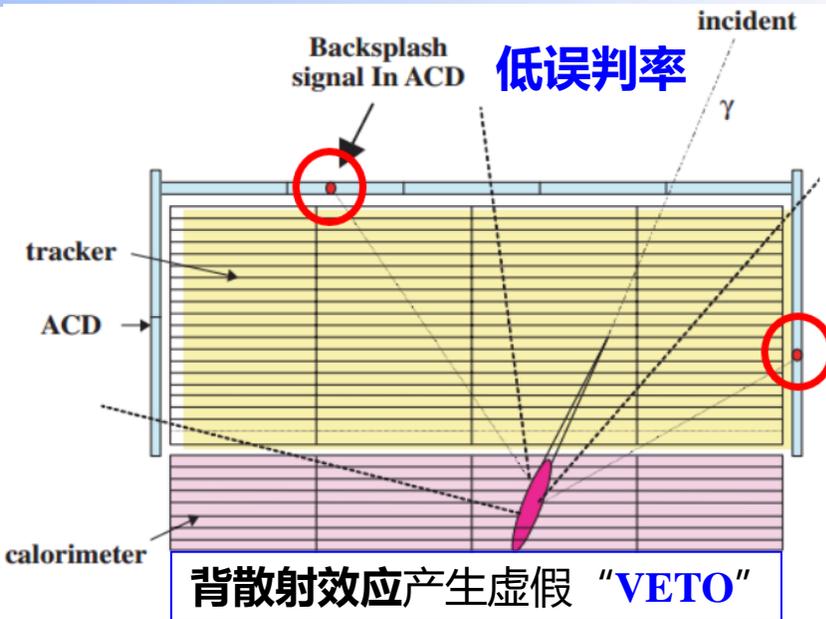
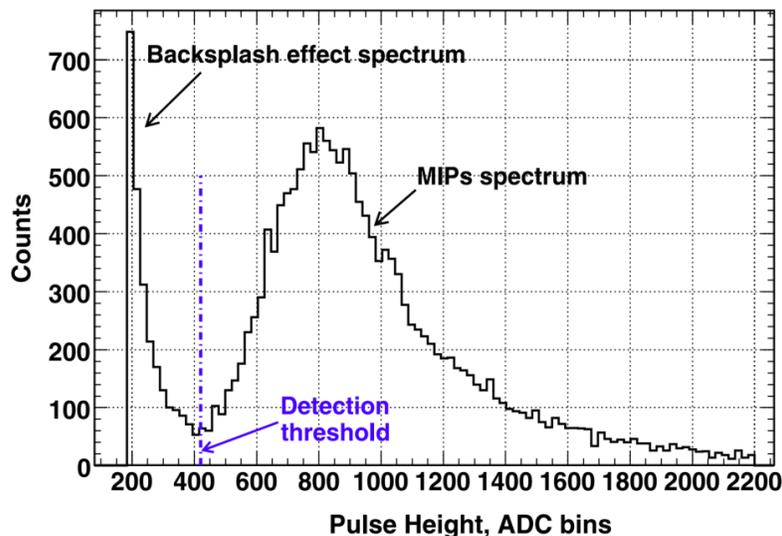
1. 甚大面积伽马射线望远镜VLAST
2. **VLAST技术预研进展**
3. 总结

VLAST技术预研进展：反符合探测器

高探测效率



ACD对MIPs的响应幅度谱



总体构型设计原则：在可接受的探测效率和背散射效应范围内尽可能增加ACD面积，降低ACD工程建造成本。

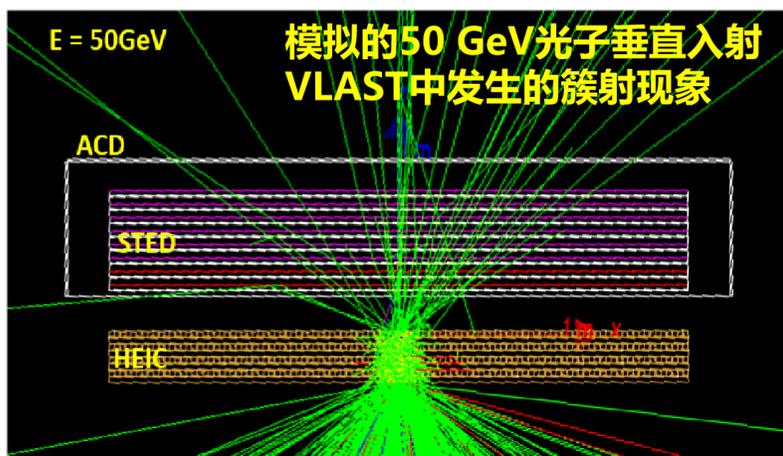
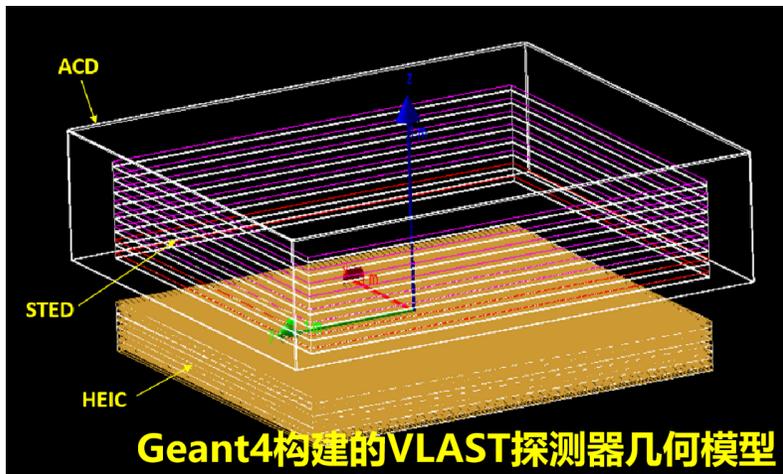
矛盾点

探测效率，阈值，动态范围
经济性，重量，功耗

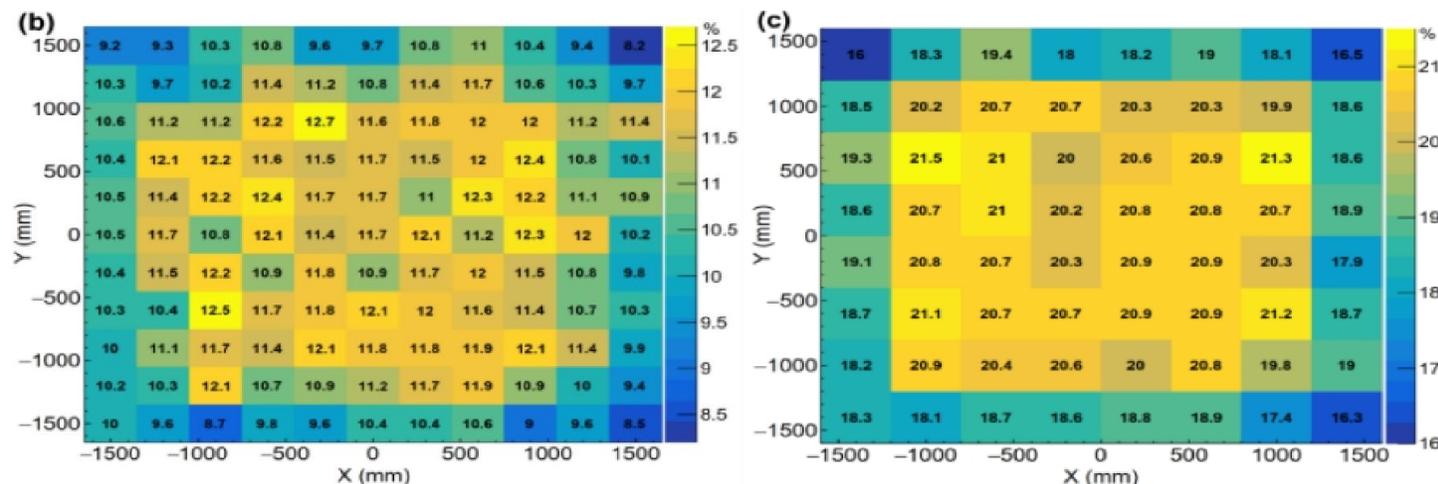
- 电荷测量和反符合由不同的功能单元完成。电荷探测仅在卫星顶部，尽可能继承DAMPE的成熟技术；
- 反符合探测器五面包络径迹探测器，增加卫星接受度；
- 反符合探测器采用模块化构型设计，降低由背散射效应带来的伽马误判率；

VLAST技术预研进展：反符合探测器

总体构型设计

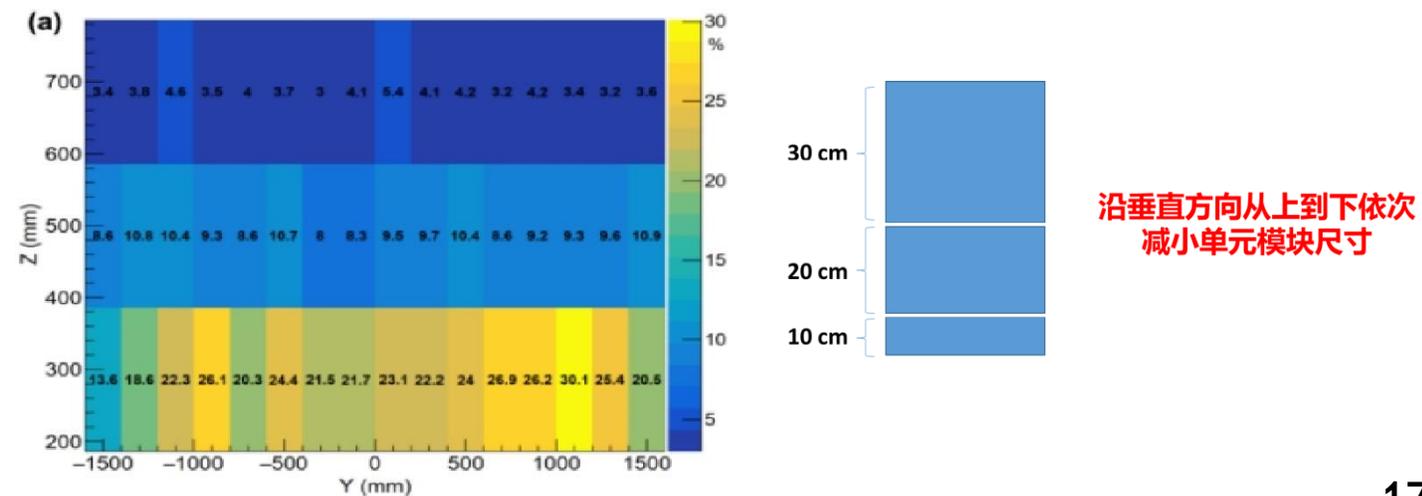


顶部

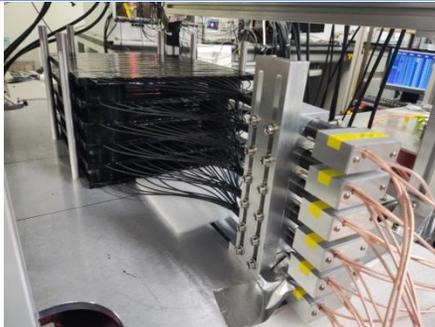


选择30cm作为单元模块尺寸，此时顶部ACD的整体FVR约为11% (阈值: 0.3MIPs)

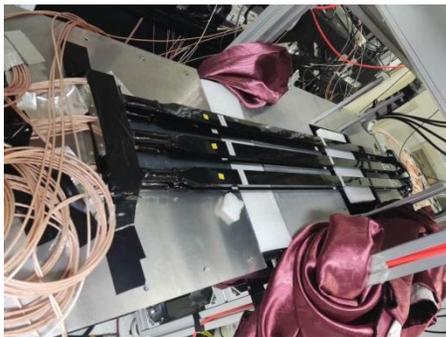
侧面



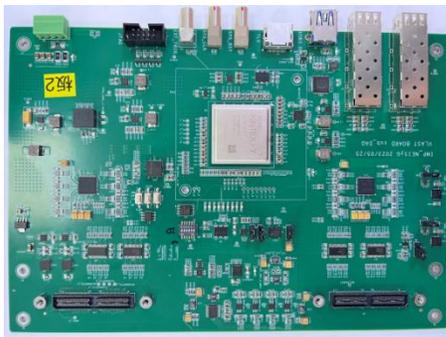
VLAST技术预研进展：反符合探测器



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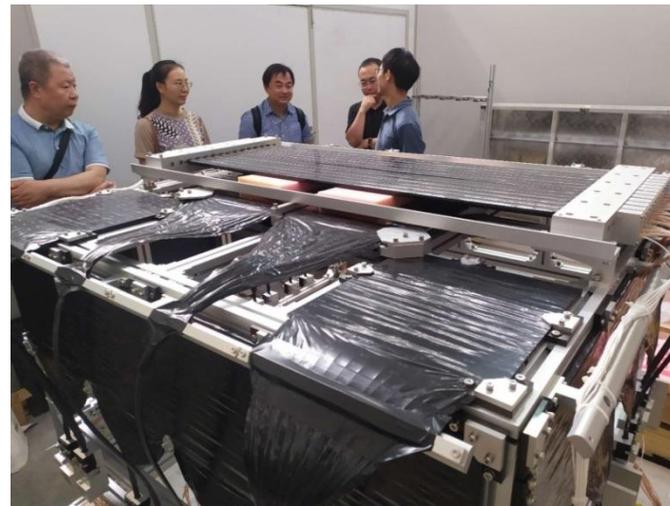


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➤ 高性能反符合/电荷探测器

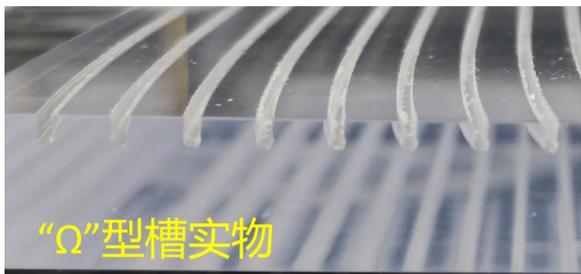
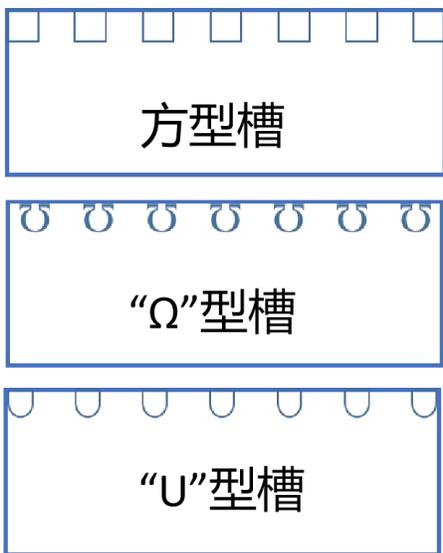
- 两种方案：块状和条状的塑闪探测器
- 特色：预埋波长位移转换光纤，降低探测效率对粒子击中位置的依赖性，消除模块化构型设计带来的探测灵敏死区；
- 特色：多打拿极读出，兼顾核素测量；



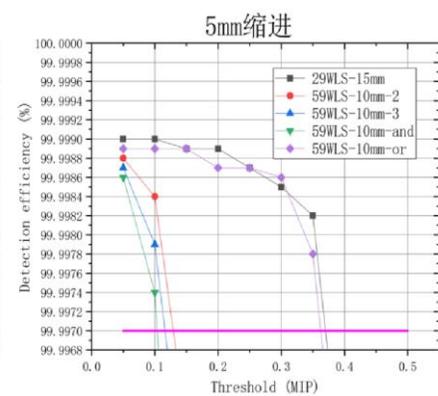
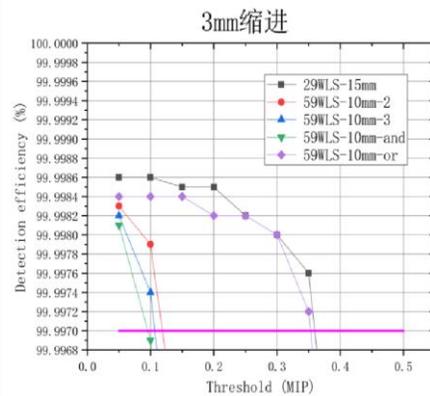
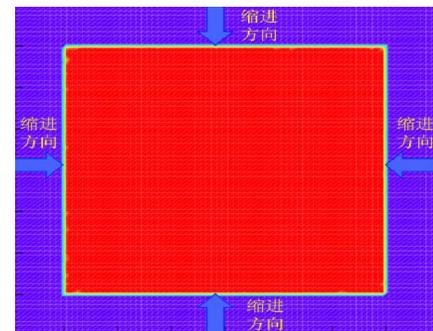
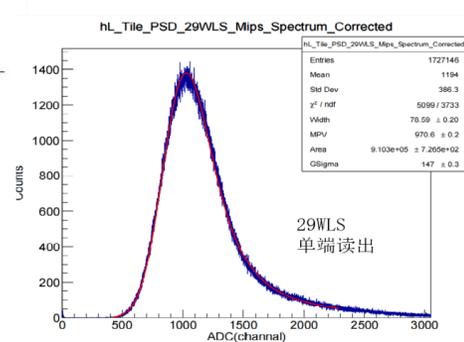
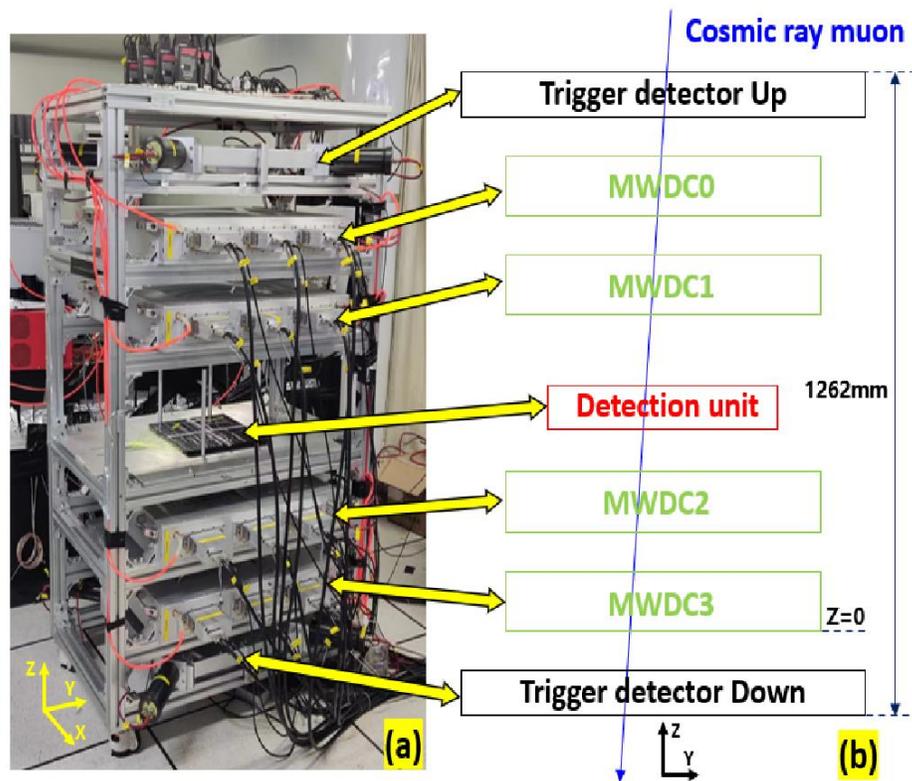
VLAST技术预研进展：反符合探测器

探测单元研制

光纤嵌入构型工艺研究



搭建宇宙线μ子测试平台，测试ACD单元的MIPs探测效率

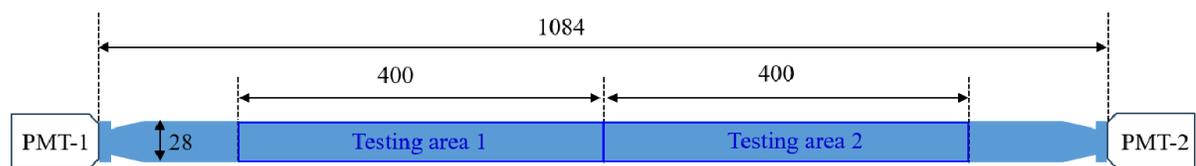


对于MIPs事件，单元可以在阈值为0.3MIPs情况下实现0.9997的极高探测效率指标！

VLAST技术预研进展：反符合探测器

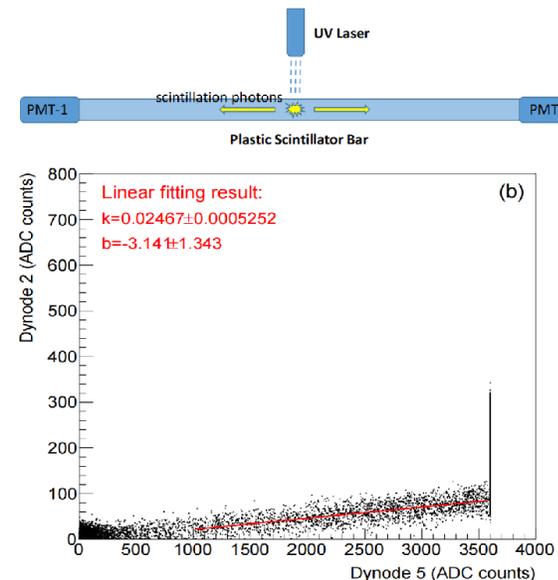
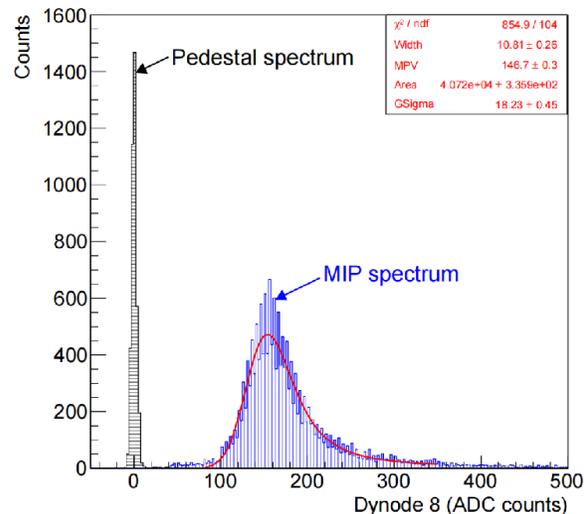
探测单元研制

电荷探测器单元的大动态范围设计

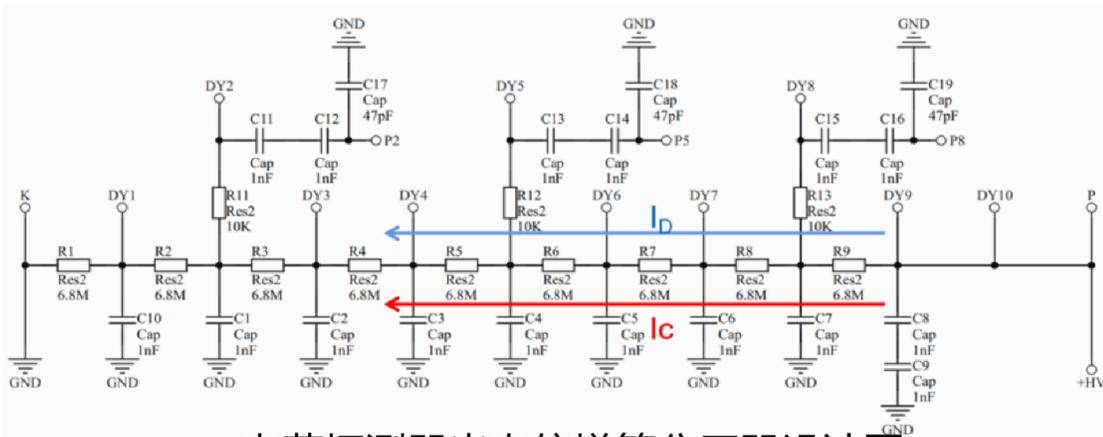
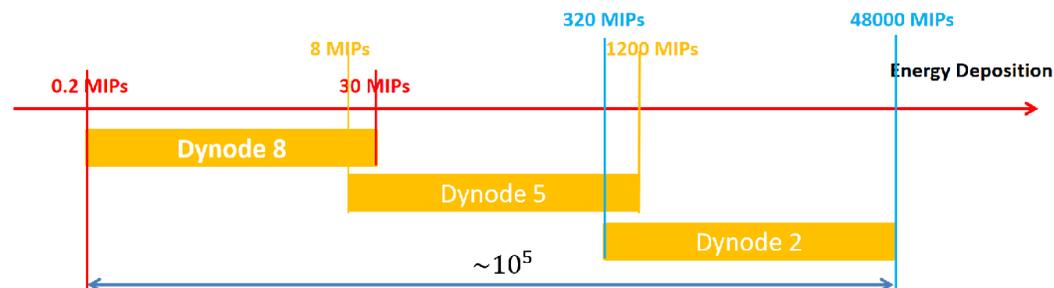


电荷探测器几何尺寸示意图

Unit: mm

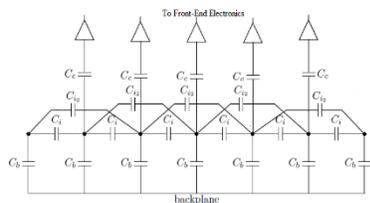
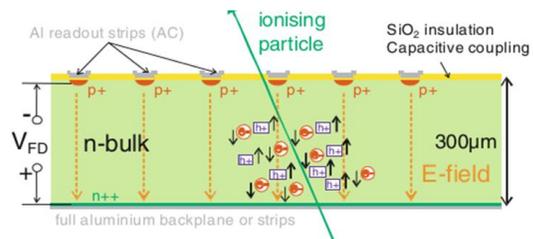


宇宙线测试结合激光测试得到电荷探测器的动态范围



电荷探测器光电倍增管分压器设计图

VLAST技术预研进展：径迹探测器

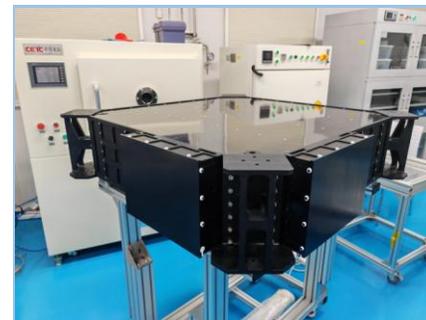


➤ 径迹探测器：

- 转换体：采用CsI晶体+波长位移光纤读出
- 径迹测量：硅微条（性能），闪烁光纤（价格）

➤ 高灵敏的硅微条径迹探测器：

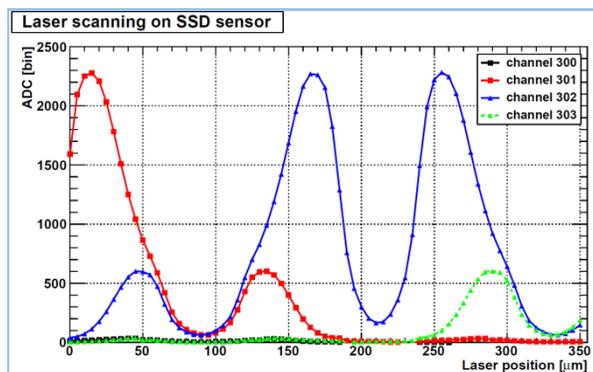
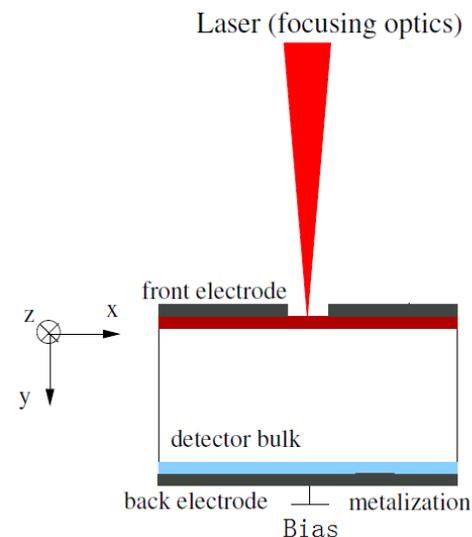
- “悟空”号原有的一体化工装，硅微条越长平面度越差，超过100um的差异
- 采用“分体式”设计，配合光学导轨，通过三坐标仪测量校准平面度，获得高精度的封装工艺
- 多通道低噪声读出电子学的研制



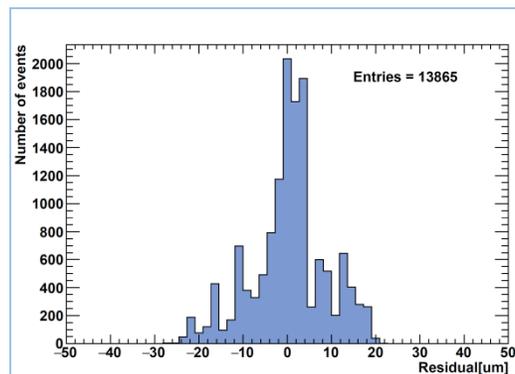
VLAST技术预研进展：径迹探测器

➤ 通过激光和束流测试探测器模块的位置分辨

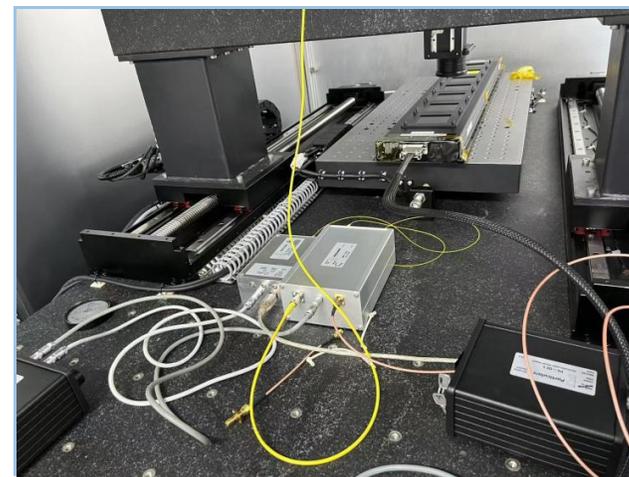
- 实验室条件下，激光模拟带电粒子，在硅探测器中沉积能量
- 通过移动，扫描不同的硅微条的位置对激光信号的响应
- 通过计算信号的在不同微条间的分配 η 计算位置分辨 ($<40\mu\text{m}$)



微条的信号分布

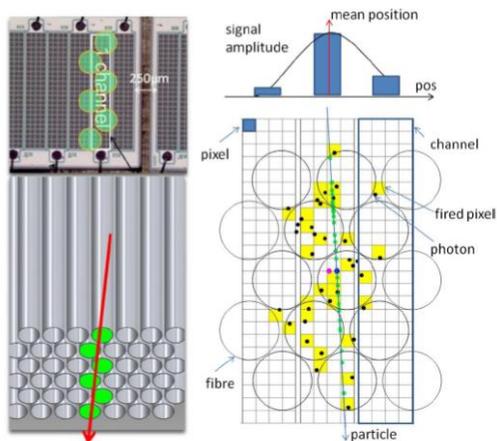


计算得到位置和移动位置的残差

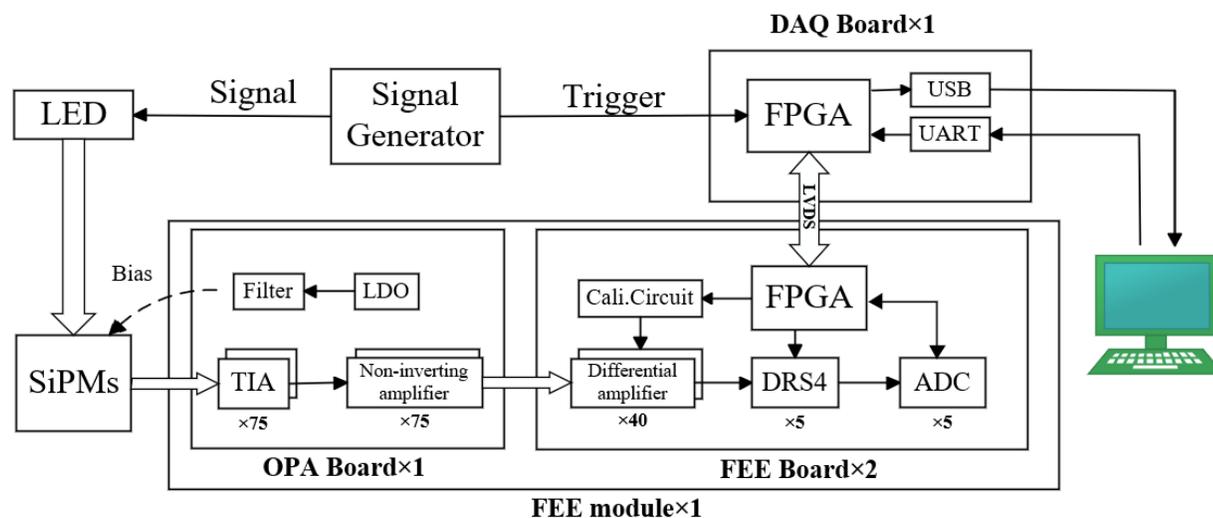


激光测试

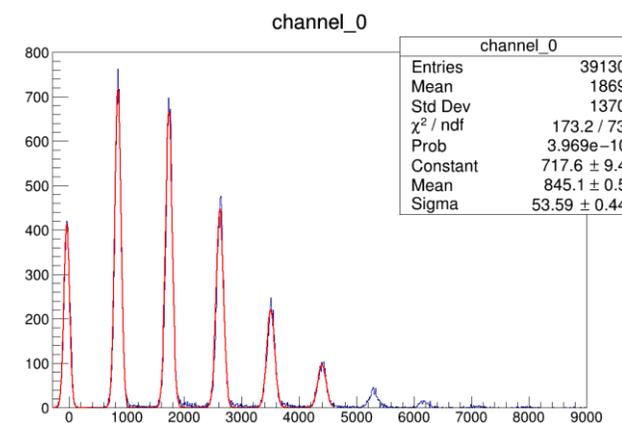
VLAST技术预研进展：径迹探测器



闪烁光纤模块试制

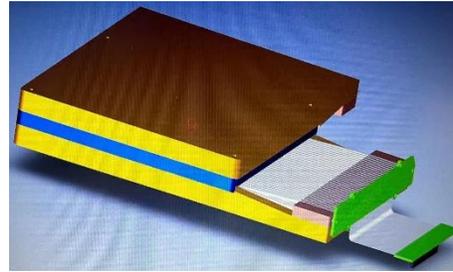
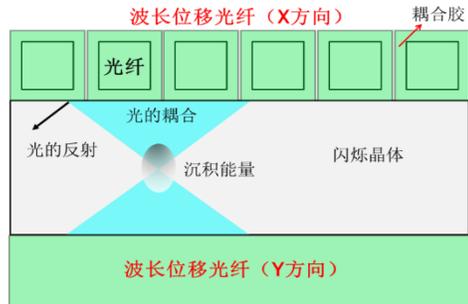


读出电子学



单光子 (热噪声) 的测量

VLAST技术预研进展：径迹探测器



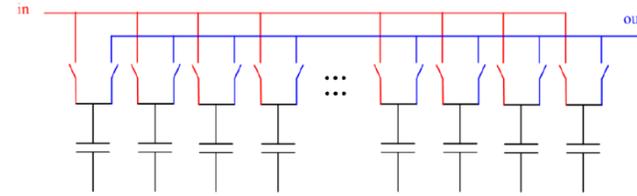
闪烁体模块：CsI闪烁体和波长位移光纤

闪烁探测器的阵列读出

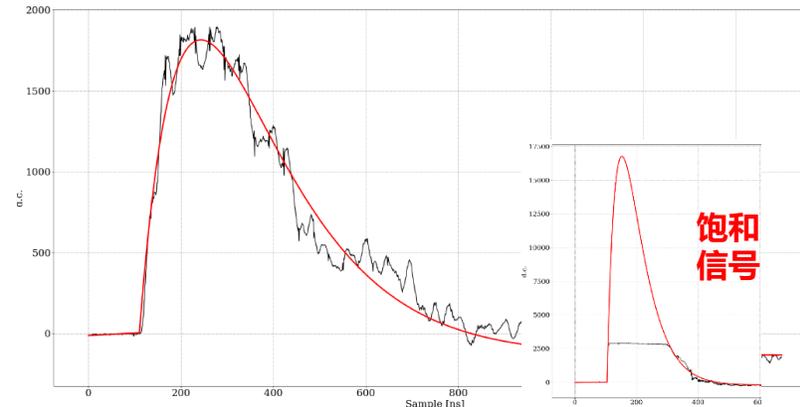
- CsI闪烁体和光纤的耦合的不同方案分析和测试
- SiPM光电阵列的实现单光子探测
- 探索新的编码方式减少电子学

功耗波形采样技术

- 基于开关电容的波形采样技术，降低功耗；
- 研究波形鉴别算法，识别CsI闪烁体信号，利用波形中“尾巴”部分重建原始信号，增大动态范围

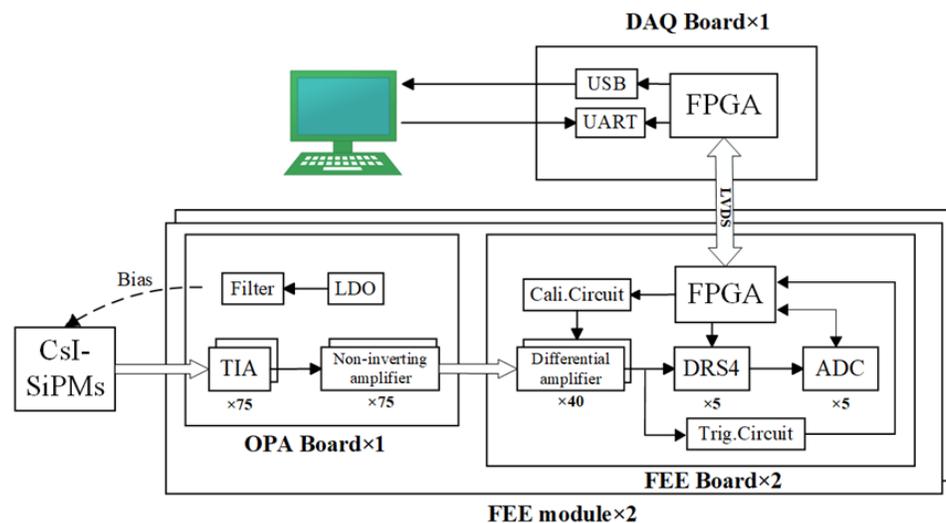
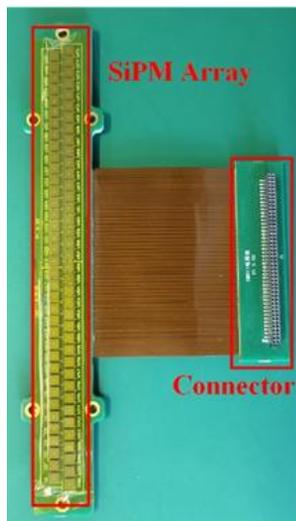
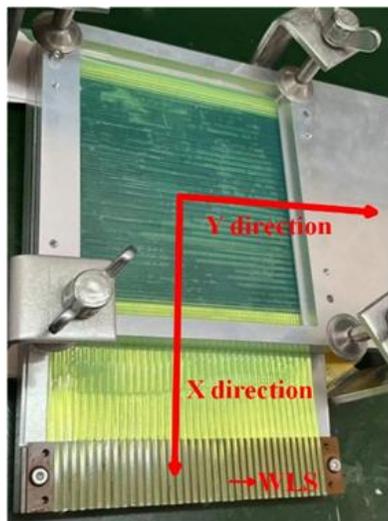


基于开关电容阵列的波形数字化原理

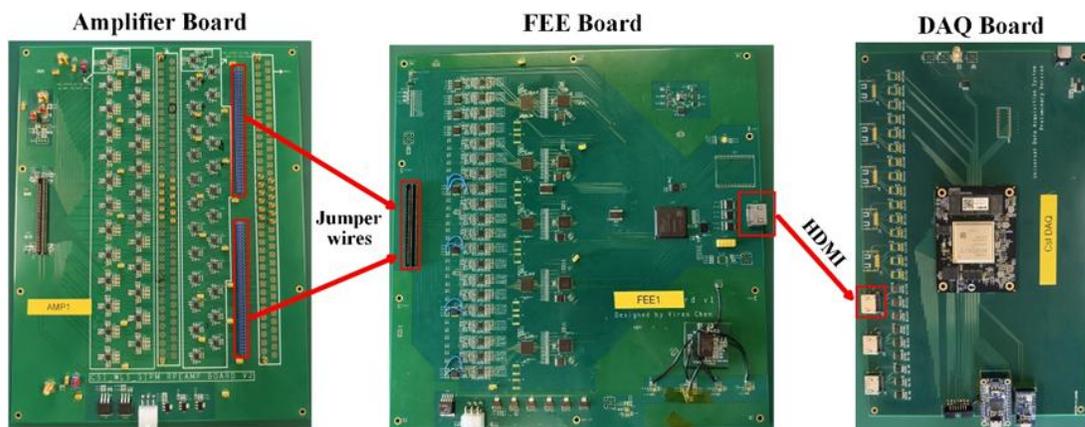


闪烁体信号的采集和重建

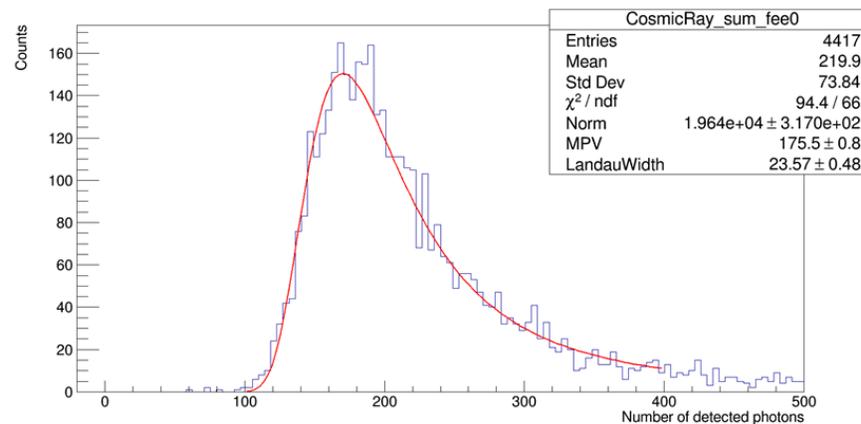
VLAST技术预研进展：径迹探测器



2mm波长位移光纤读出

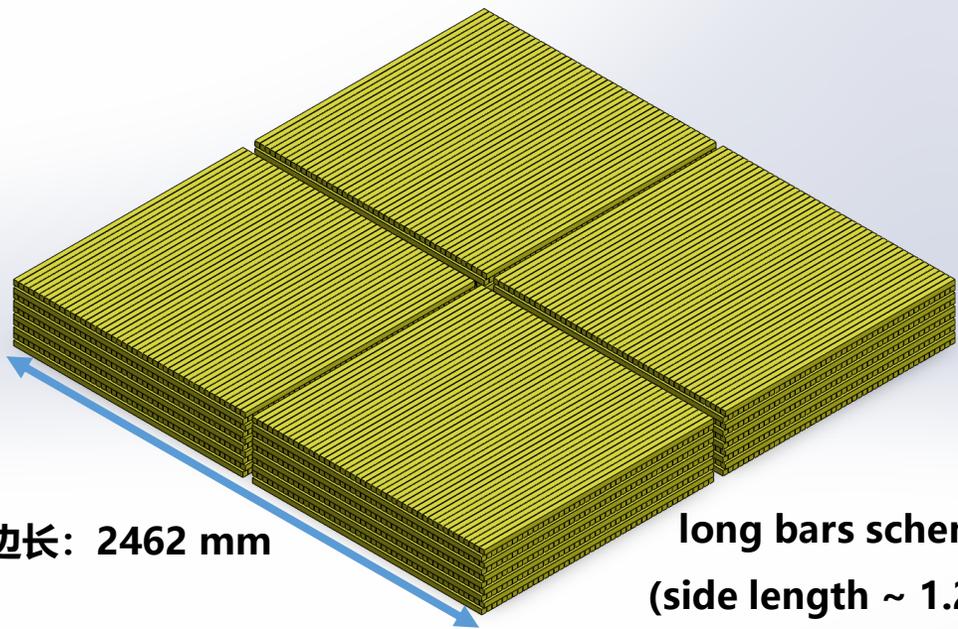


读出电子学



宇宙线测试结构

VLAST技术预研进展：电磁量能器

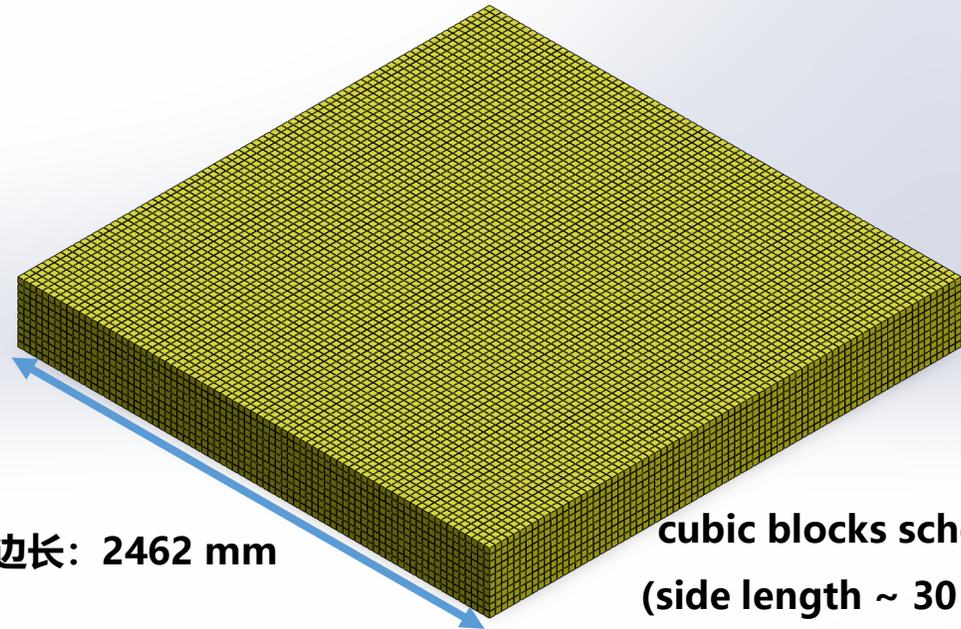


边长: 2462 mm

long bars scheme
(side length ~ 1.2 m)

- **长条状晶体方案:**

- 晶体间死区少, 能量分辨更好;
- 1米长晶体的生长工艺比较复杂;
- 单根晶体造价很高;



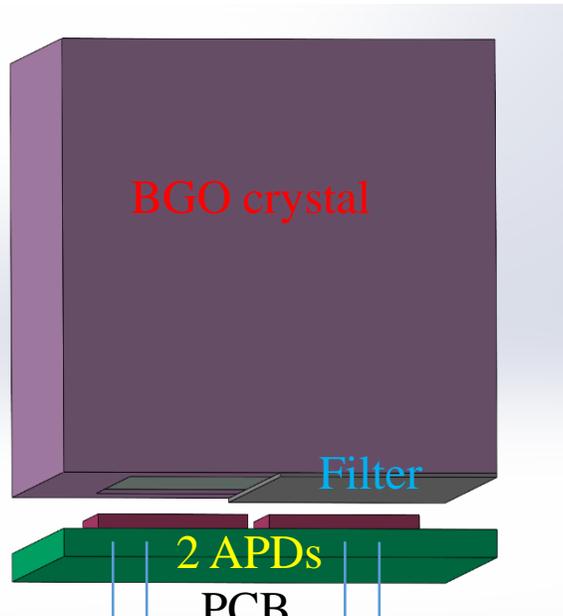
边长: 2462 mm

cubic blocks scheme
(side length ~ 30 mm)

- **块状小晶体方案:**

- 工艺成熟, 易于生产和加工;
- 簇射轮廓描述更简单和清晰;
- 模块间无空隙, 便于扩展更大规模;

VLAST技术预研进展：电磁量能器

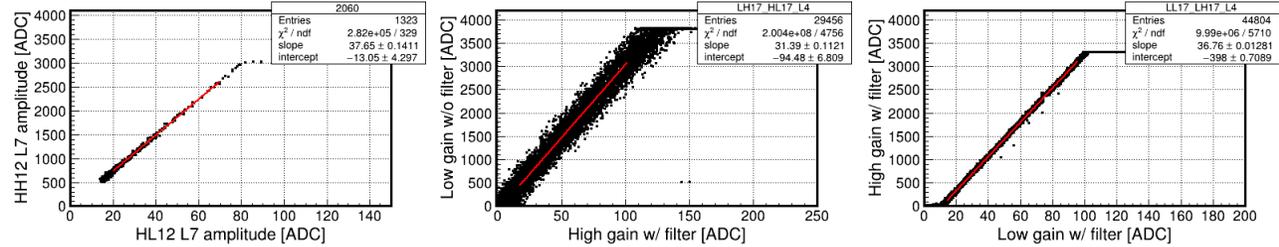


bare high gain (HH)

covered high gain (LH)

bare low gain (HL)

covered low gain (LL)



借助遮光片和电子学增益，可以实现的动态范围：

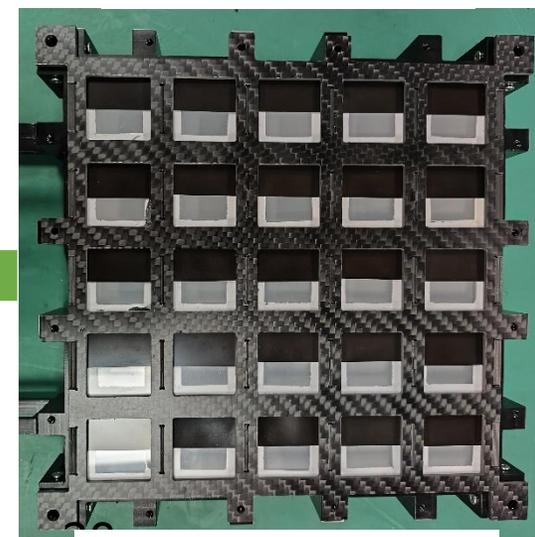
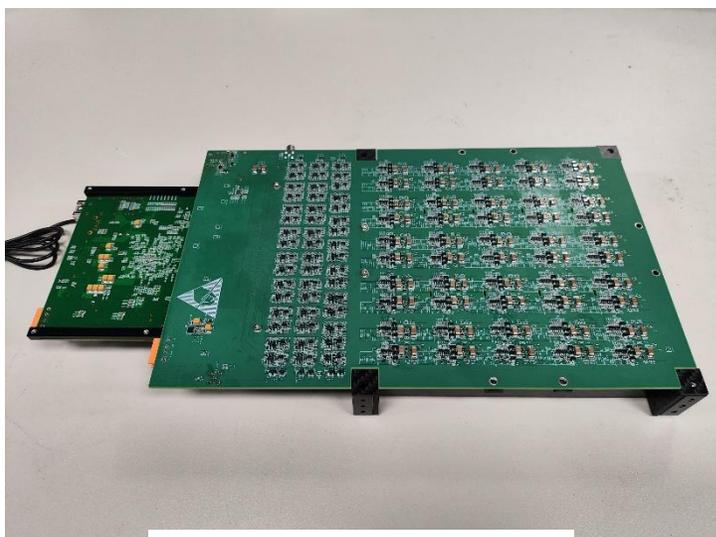
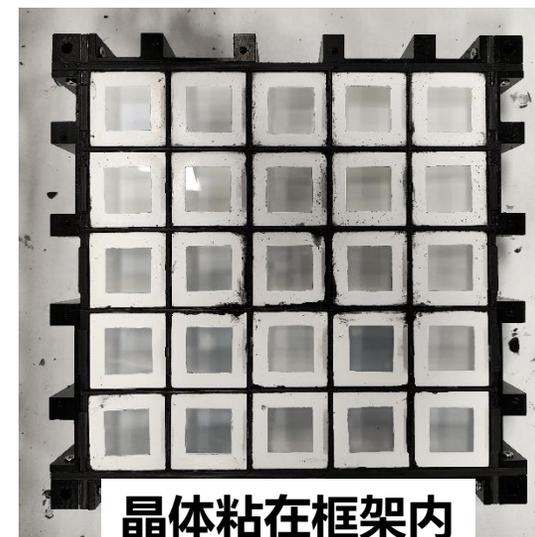
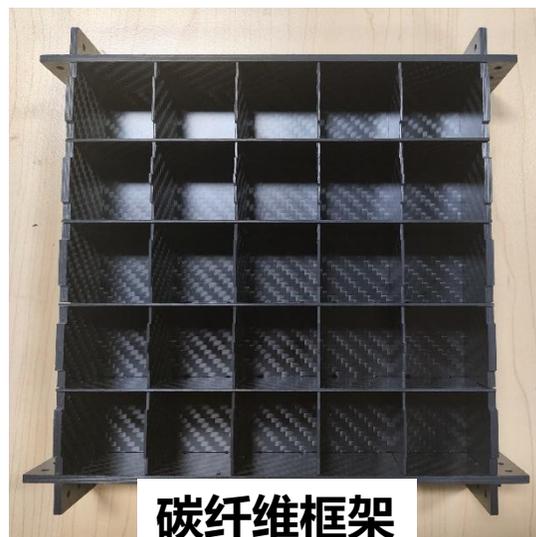
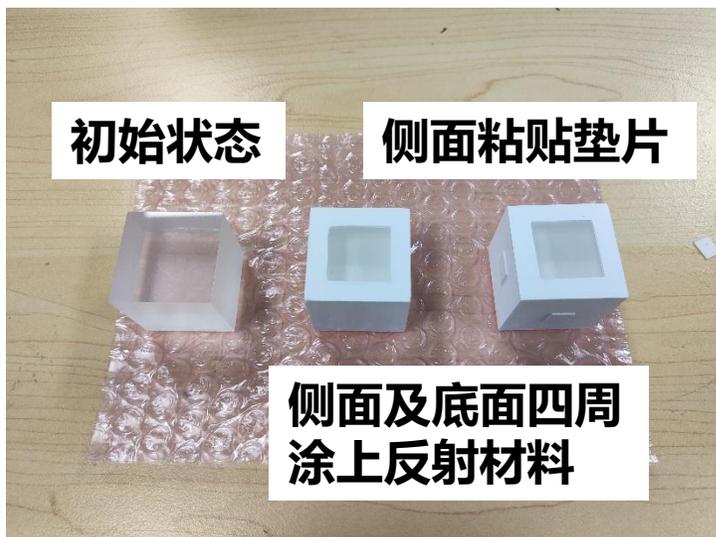
$$\frac{4096 - 1000}{5 \times 10} \times 37.65 \times 31.39 \times 36.76 = 2.69 \times 10^6$$

各种增益对应的动态范围

Readout channel	Electronic dynamic range	System dynamic range
HH	3 fC – 150 fC	0.1 MIPs – 5 MIPs
HL	10 fC – 7 pC	0.3 MIPs – 240 MIPs
LH	3 fC – 150 fC	100 MIPs – 5000 MIPs
LL	10 fC – 7 pC	330 MIPs – 240000 MIPs

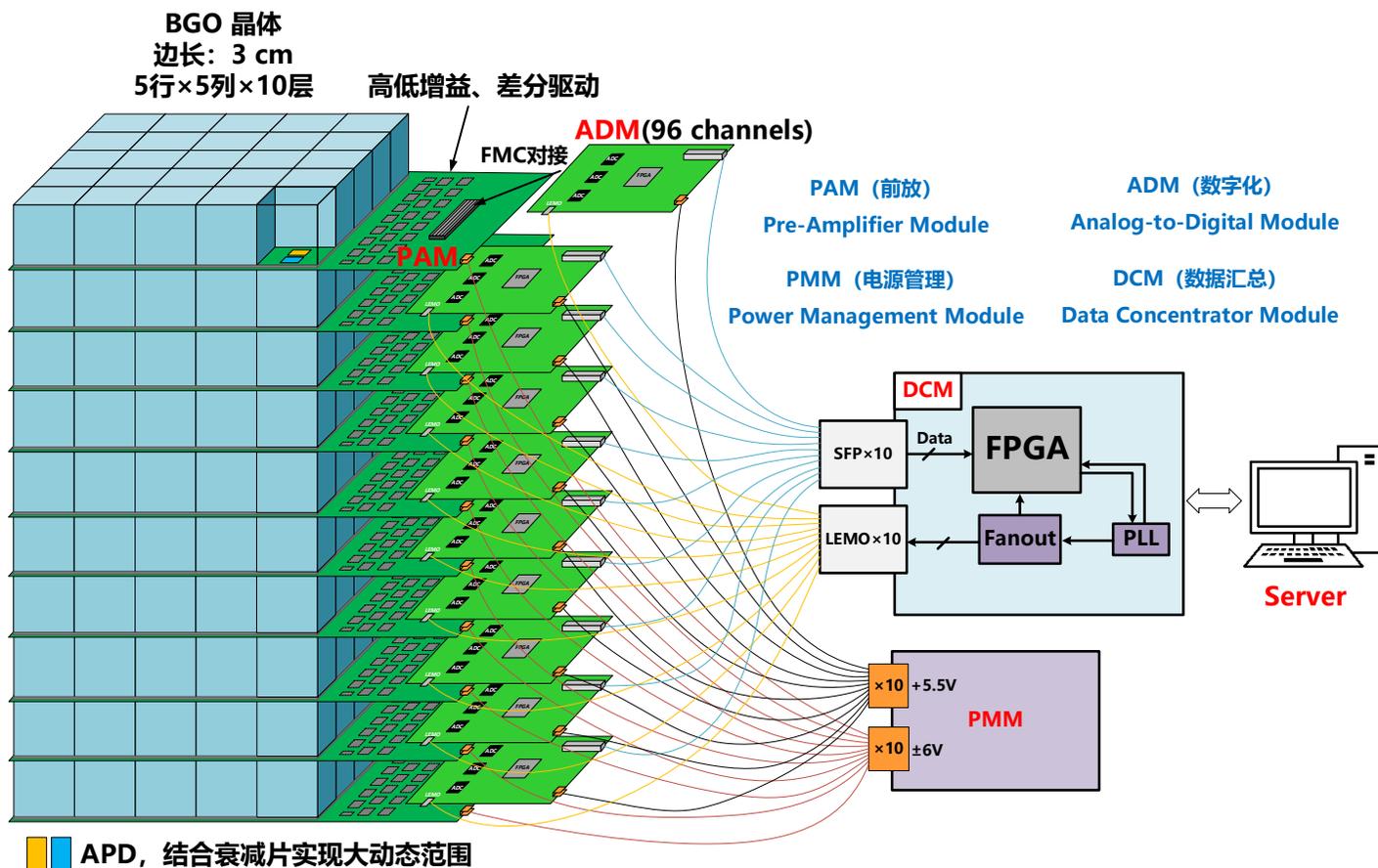
36 倍
30 倍
36 倍

VLAST技术预研进展：电磁量能器



VLAST技术预研进展：电磁量能器

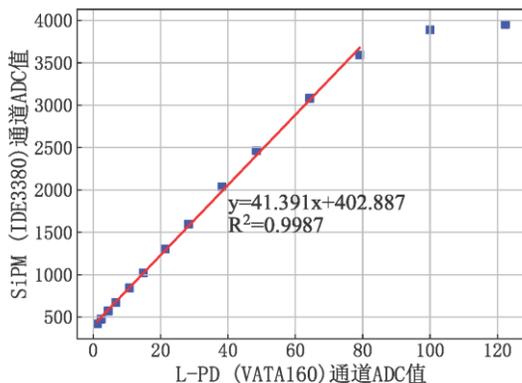
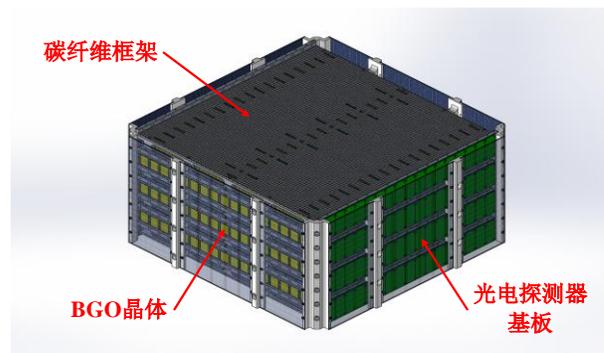
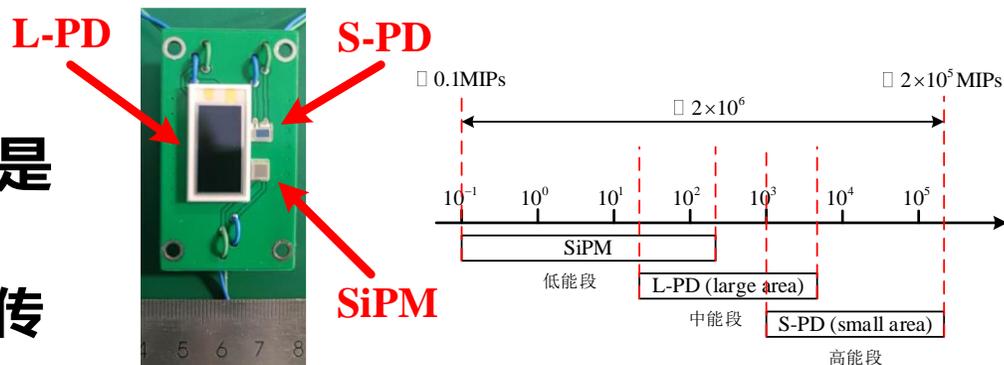
探测器部分的尺寸：192 mm × 192 mm × 417 mm；
以 BGO 晶体计算，中心垂直入射时，
横向尺寸约合 3.3 个莫里哀半径，纵向尺寸约合 26.8 个辐射长度；



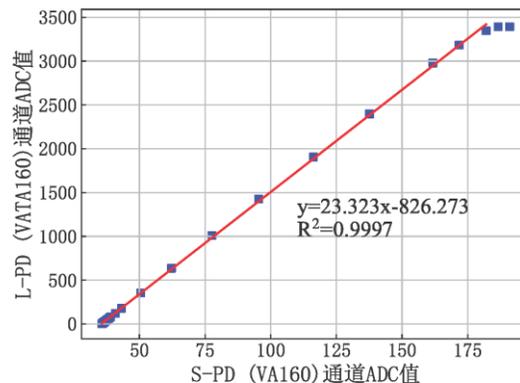
VLAST技术预研进展：电磁量能器

➤ 条形的“准3D”量能器单元优势是需要相对少的读出电子学

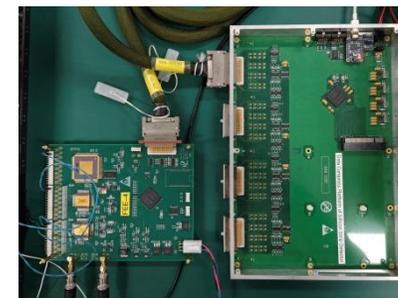
- **特色：**利用3种不同增益的光电传感器实现大动态范围 ($> 10^6$)
- 解决串扰、测量范围的线性扩展、标定等问题



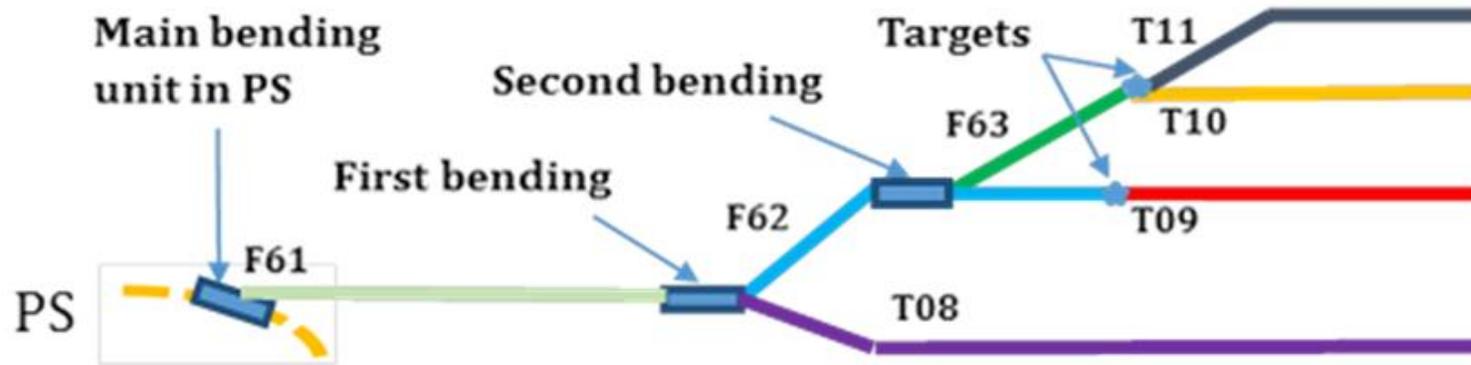
低能段与中能段增益



中能段与高能段增益



VLAST技术预研进展：束流试验

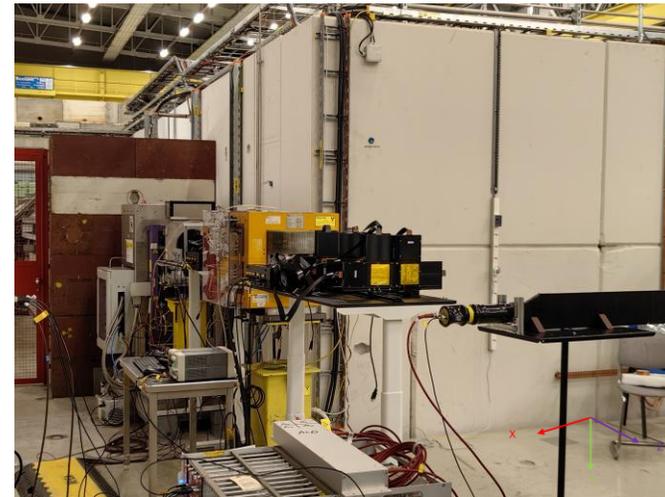
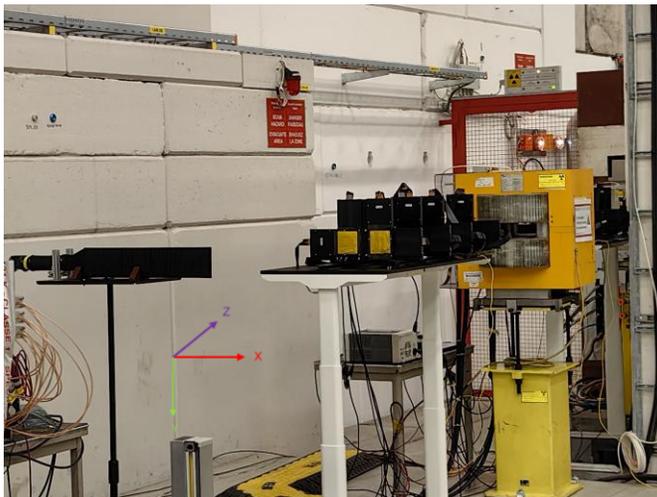
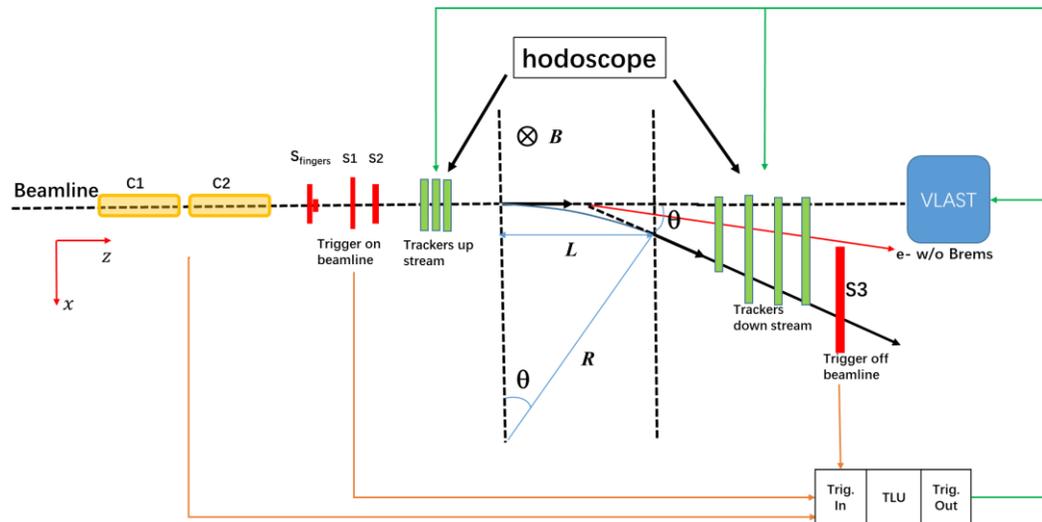


Spill duration: 0.4 second flat top

Usually : 1-2 cycles per minute per East Destination, Max 6 East cycles / 40 seconds

Parameter	T09 Target	T10/T11 Target	
Beam Line	T09	T10	T11
Secondary beam Max Momentum (GeV/c)	15	11.5	3.5
$\Delta p/p$ (%)	± 0.7 to ± 15.0	± 0.7 to ± 15.0	± 0.7 to ± 15.0
Maximum intensity/spill (hadrons/electrons)	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$
Available particle types	Pure electrons (T09) or mixed/pure hadrons or pure muons		

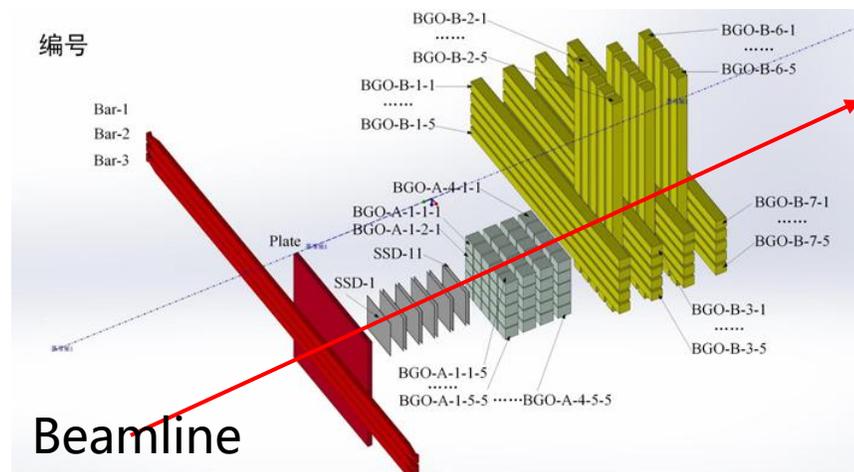
VLAST技术预研进展：束流试验



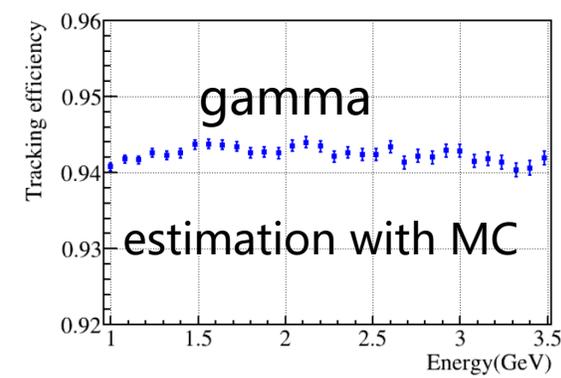
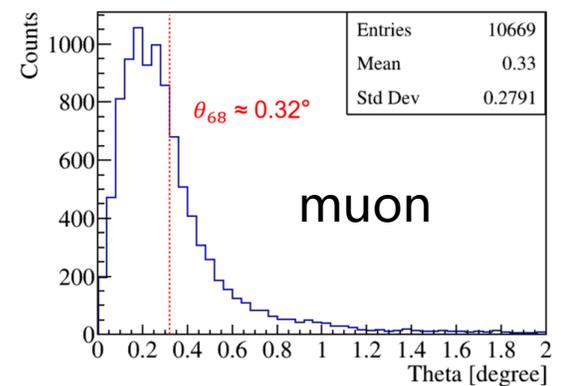
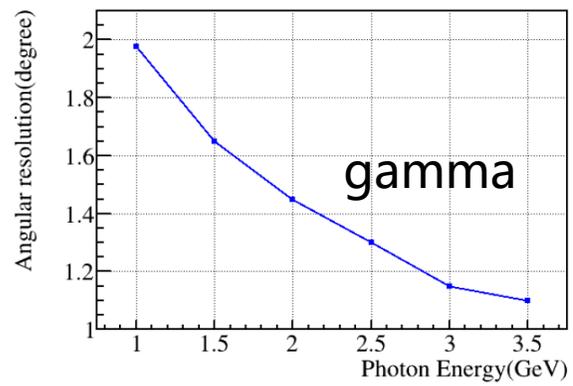
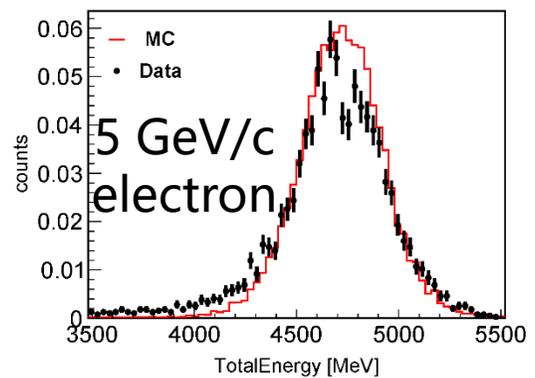
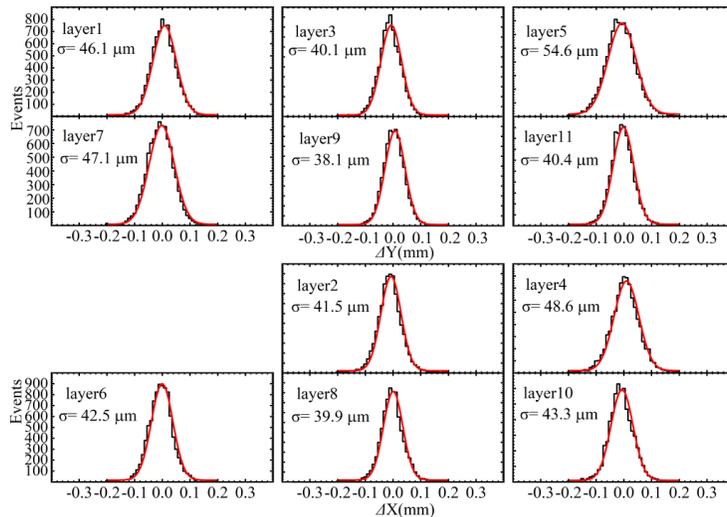
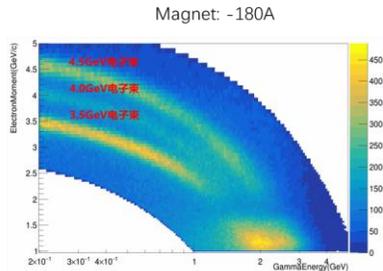
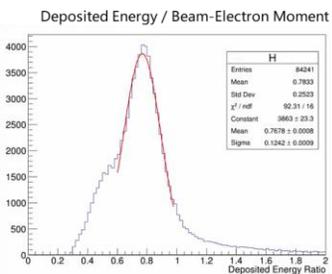
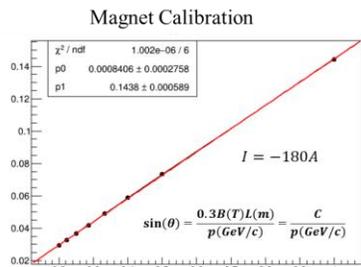
Material Budget

	材料	厚度(mm)	辐射长度(mm)	等效辐射长度(X0)	占比
C1	铝膜	1.4	88.97	0.015736	0.060364
	二氧化碳	3280	1.97E+05	0.016692	0.064033
	铝膜	1.4	88.97	0.015736	0.060364
	空气	1685	3.04E+05	0.005545	0.02127
C2	mylar	0.25	88	0.002841	0.010898
	二氧化碳	3115	1.97E+05	0.015852	0.060812
	mylar	0.25	88	0.002841	0.010898
触发	塑闪	5	2.70E+02	0.018519	0.07104
丝室	丝室	0.005	1	0.005000	0.019181
finger	塑闪	10	270	0.037037	0.142079
S2	塑闪	10	270	0.037037	0.142079
S1	塑闪	10	270	0.037037	0.142079
SSD*14	硅(320um)	4.48	94	0.047660	0.182829
铝膜*14	铝(20um)	0.28	88.97	0.003147	0.012073
大厅空气	空气	7965	303900	0.026209	0.100543
			总厚度	0.260679	

编号



VLAST技术预研进展：束流试验

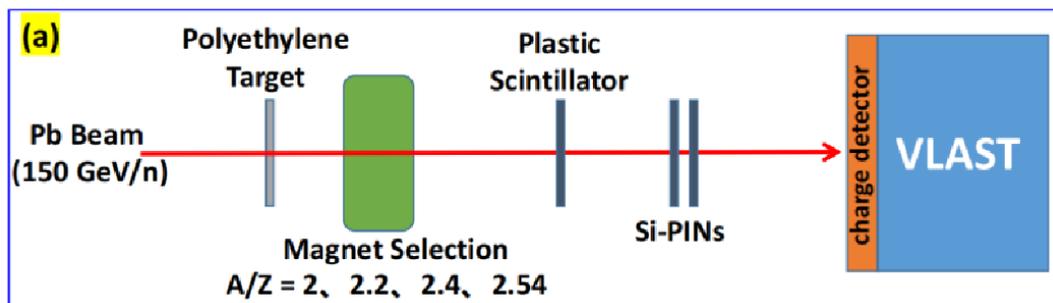


VLAST技术预研进展：束流试验

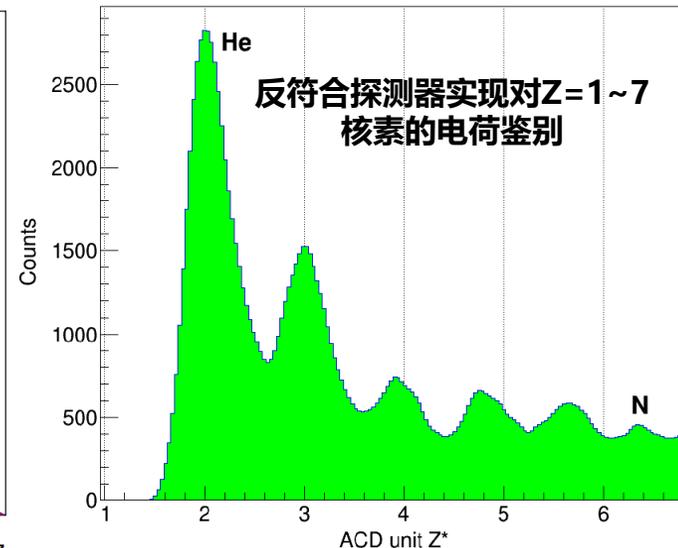
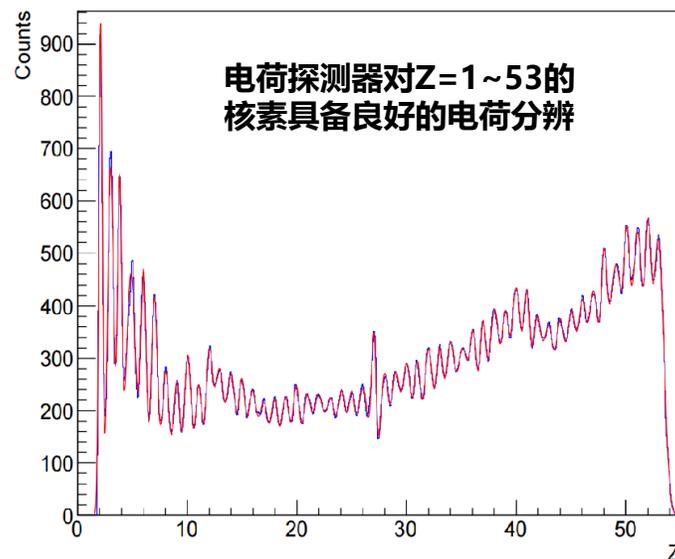
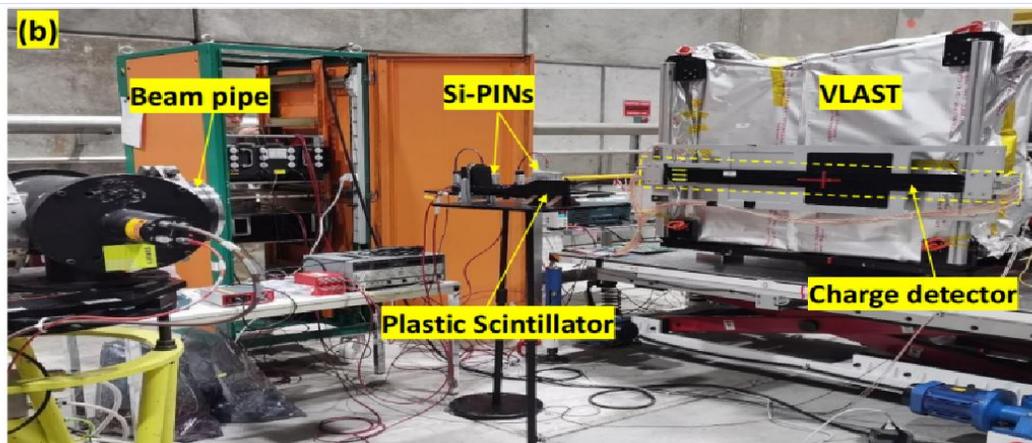
实验目标：利用SPS-H8束流线产生的核碎片研究电荷测量能力及QUENCH效应

束流： $A/Z=2$ 的Pb碎片

外触发设置：



Si1、Si2为硅Pin探测器，用于标记碎片粒子。



电荷分辨($0.15e@He$)满足 $Z=1\sim 40$ 电荷测量指标要求!

总结

- **甚大面积伽马射线空间望远镜(VLAST) :**
 - 大面积高分辨碘化铯CsI读出及康普顿散射光子数据处理技术
 - 暗物质探测、高能时域天文、伽马射线视界、宇宙线起源
- **搭建一个小型原理样机, 进行束流试验**
- **研制探路者载荷, 预计2026年底发射**
- **深入凝练科学目标, 完成VLAST工程方案的设计、技术见底**
- **壮大科学及技术队伍, 为工程立项做好全方位准备**

