

中国空间站高能宇宙辐射探测器 (HERD) 研制进展

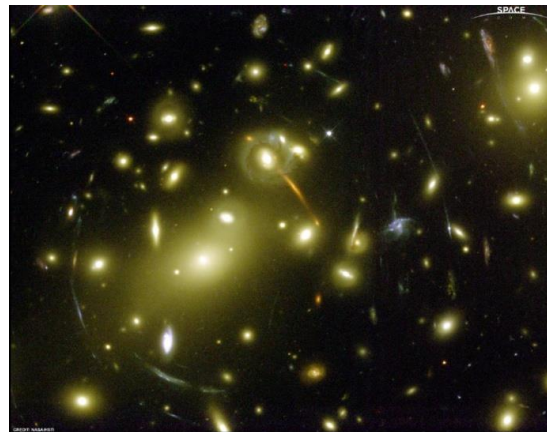
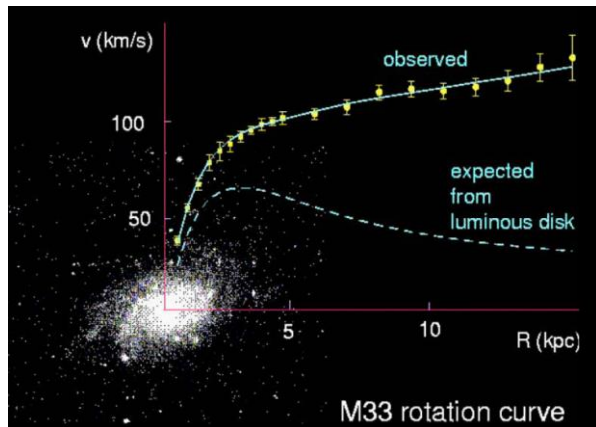
王志刚

2014.08.13

兰州

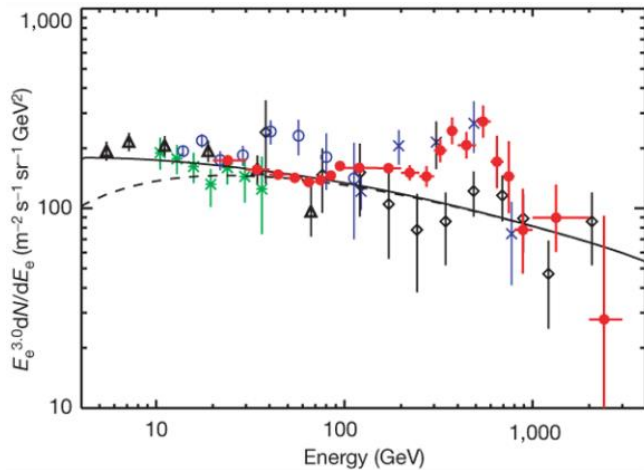
暗物质存在的证据

- 暗物质问题来源于天文学，至今已有70年历史
- 天文学家用各种动力学方法，通过引力效应反推出暗物质的分布
 - 星系的转动曲线
 - 引力透镜方法
 - X-射线方法
 - Sunyaev-Zeldovich 效应
 - 恒星与星系的运动
 -

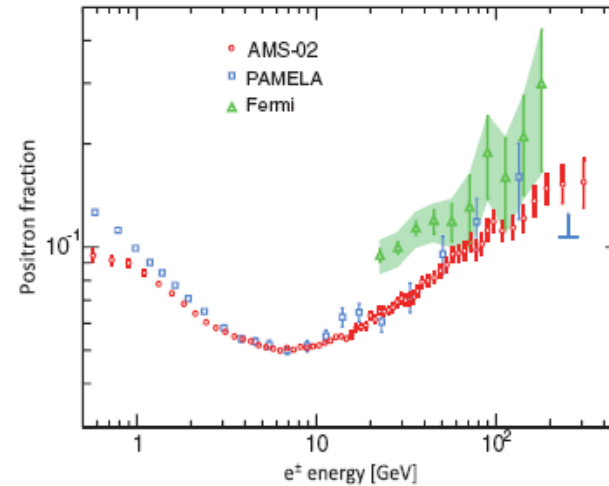


空间暗物质探测进展

ATIC 和 FERMI 电子能谱



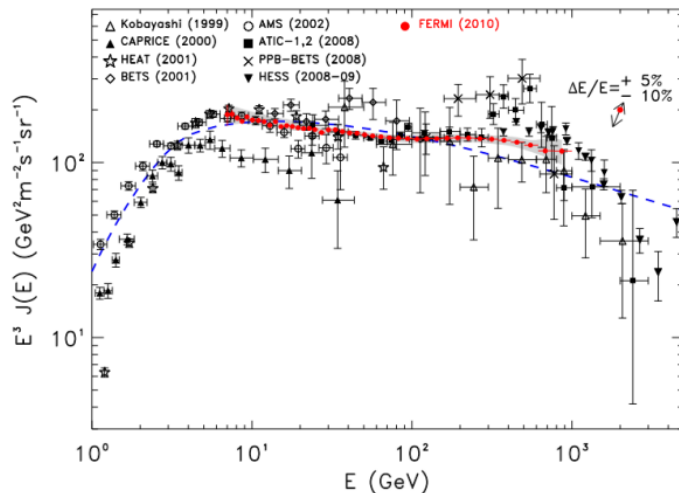
AMS02 正电子比例



ATIC and FERMI 电子在300GeV-800GeV范围存在“超出”结构。

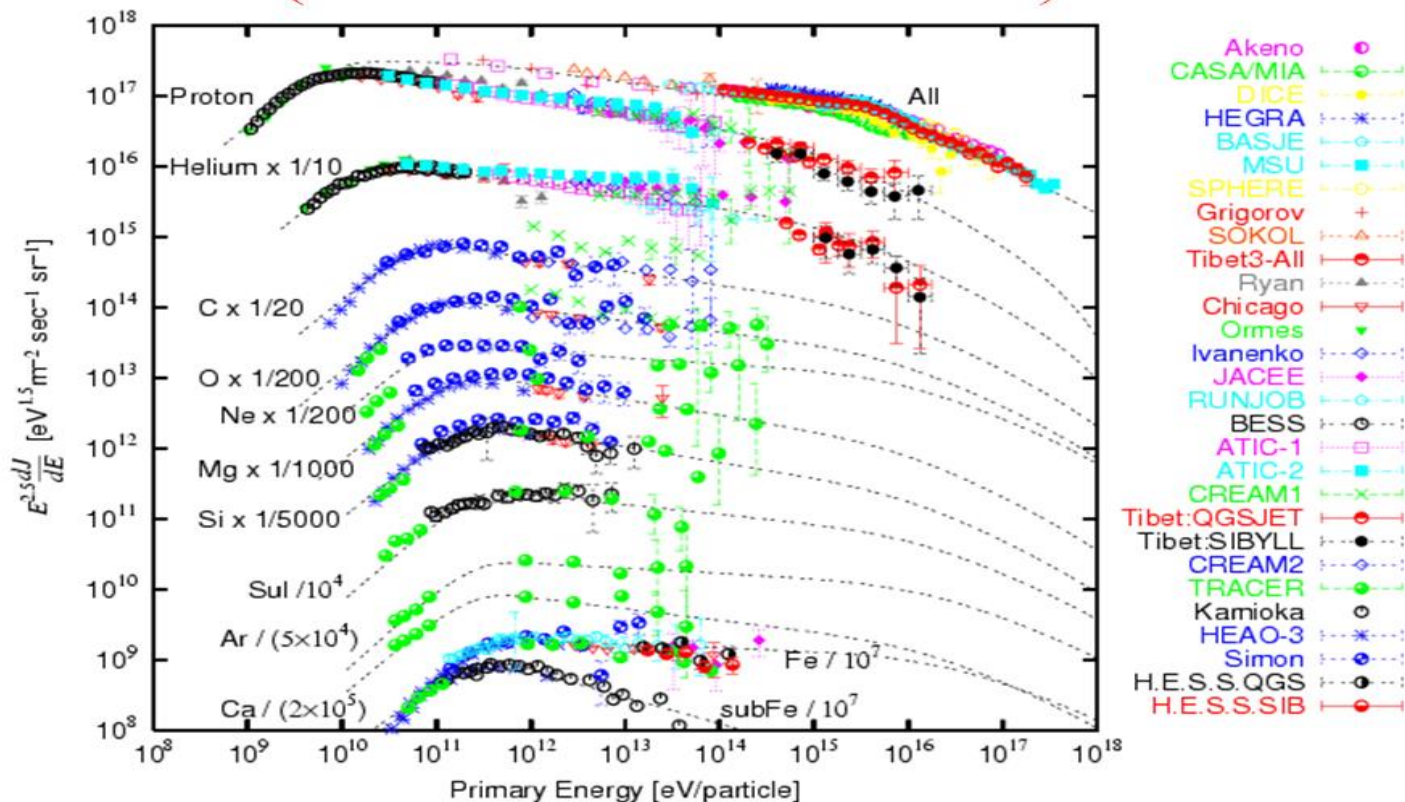
AMS02 正电子比例在10GeV-250GeV能区一直在增加。

这些实验观测到的异常信号都有可能是暗物质存在的特征。



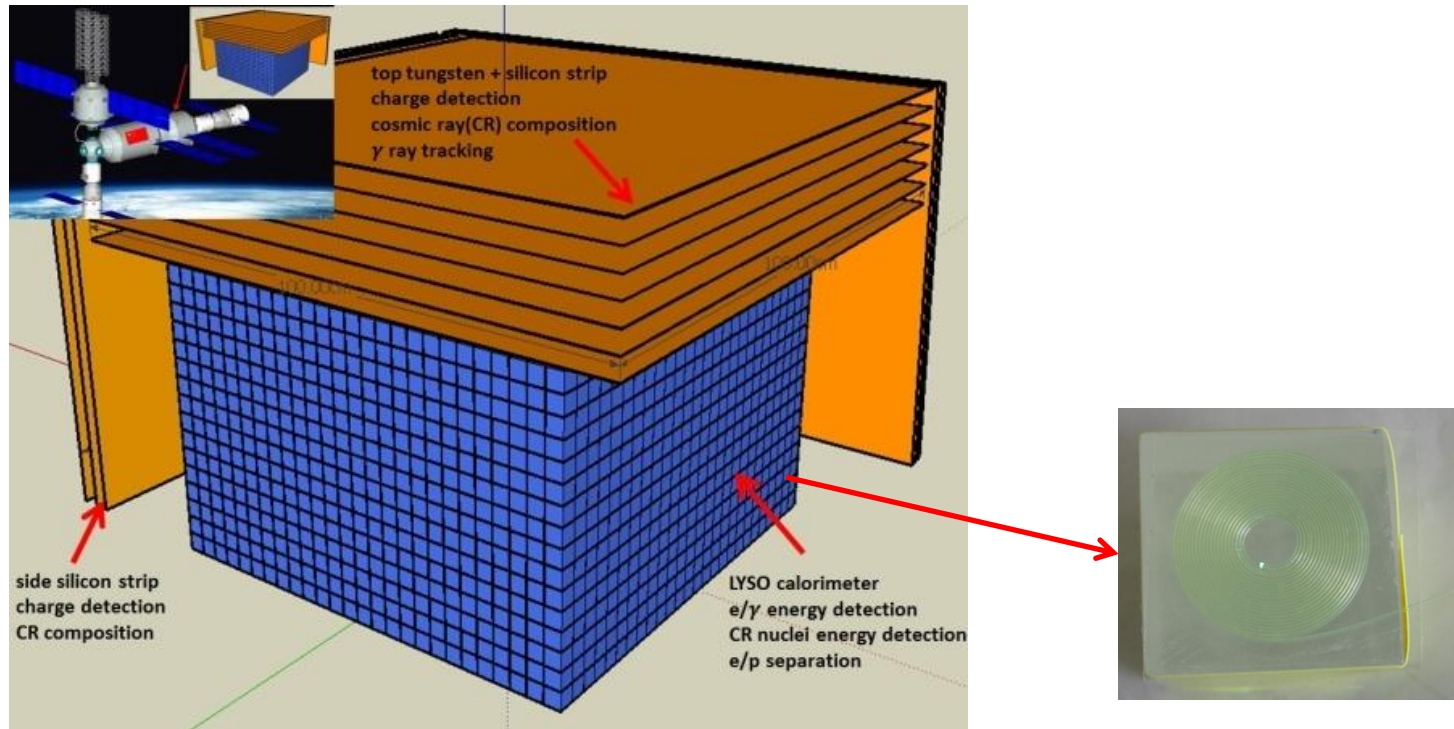
FERMI 电子能谱

高能宇宙线探测



对于宇宙线的观测和研究主要围绕三个基本问题展开：宇宙线从哪里来？宇宙线如何获得如此巨大的能量，其加速机制是什么？宇宙线在从源传播到地球的过程中，发生了怎样的变化和作用？解决这些问题需要更加精确的关于宇宙线的能谱和成分的观测。

HERD探测器结构



HERD探测器由中心量能器和五面硅微条探测器组成。
中心量能器是由LYSO晶体块组成的全灵敏型量能器，晶体发出的闪烁光由波长位移光纤引出到ICCD读出。
硅微条探测器由顶部和四周两部分组成。
目前处于预研阶段，有望在今年立项，预计2020年前后进入中国空间站。

探测器参数

	type	size	X0, λ	unit	main functions
tracker (top)	Si strips	70 cm \times 70 cm	2 X0	7 x-y (W foils)	Charge Early shower Tracks
tracker 4 sides	Si strips	65 cm \times 50 cm	--	3 x-y	Nucleon Track Charge
CALO	\sim 10K LYSO cubes	63 cm \times 63 cm \times 63 cm	55 X0 3 λ	3 cm \times 3 cm \times 3 cm	e/ γ energy nucleon energy e/p separation

探测器总重: \sim 2000 kg

探测器性能指标

γ/e energy range (CALO)	10GeV-100TeV
nucleon energy range (CALO)	100GeV-1000TeV
γ/e angular resol. (top Si-strips)	0.1°
nucleon charge resol. (all Si-strips)	0.1-0.15 c.u
γ/e energy resolution (CALO)	<1%@100GeV
proton energy resolution (CALO)	30%@1TeV
e/p separation power (CALO)	<10 ⁻⁵
electron eff. geometrical factor (CALO)	3.7 m ² sr@200 GeV
proton eff. geometrical factor (CALO)	2.6 m ² sr@100 TeV

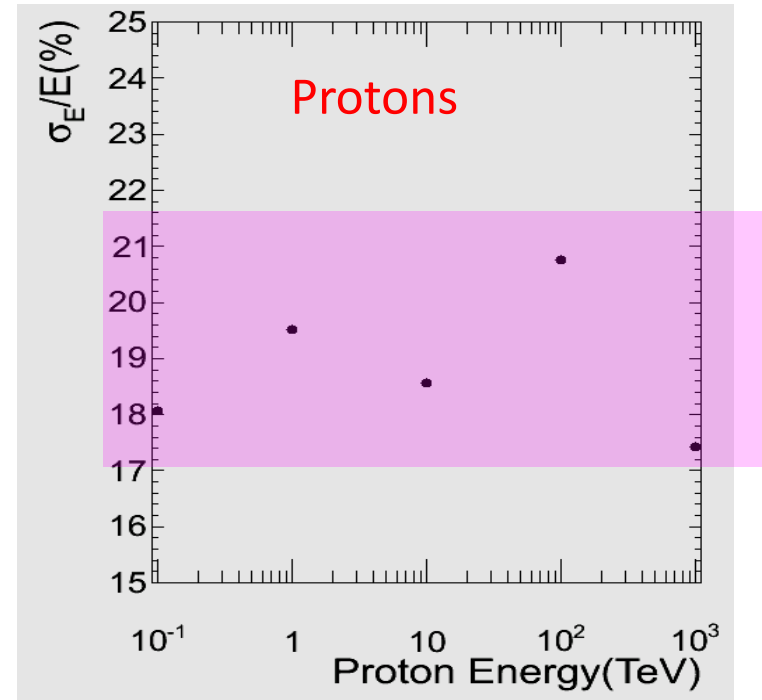
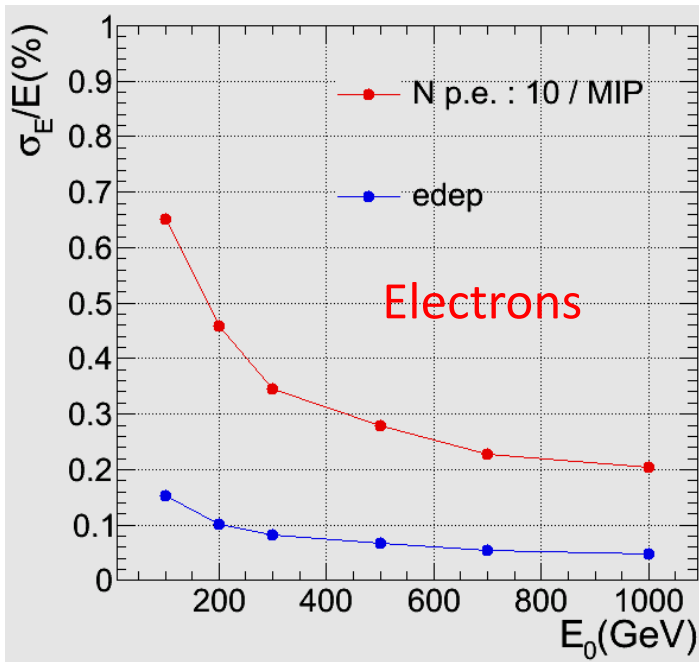
HERD探测器创新点

探测器	FERMI	AMS02	DAMPE	HERD
主要探测手段	量能器	量能器+磁谱仪	量能器	量能器
接收范围	顶面灵敏	顶面灵敏	顶面灵敏	五面灵敏
纵向深度（辐射长度）	10	18	31	55
类型	全吸收	取样	全吸收	全吸收
结构	三维	二维	二维	三维

空间中的入射粒子分布是各向同性的，传统的空间高能粒子载荷，主要使用顶面入射的量能器（或者加上磁谱仪）的模式，只能接受探测器顶面小角度入射的事例，如FERMI，AMS02以及DAMPE，因此载荷利用率极低。HERD的三维成像量能器为5面灵敏，极大的提高了探测的有效接收度，在同等的时间内取得的观测显著度要比传统载荷高很多。

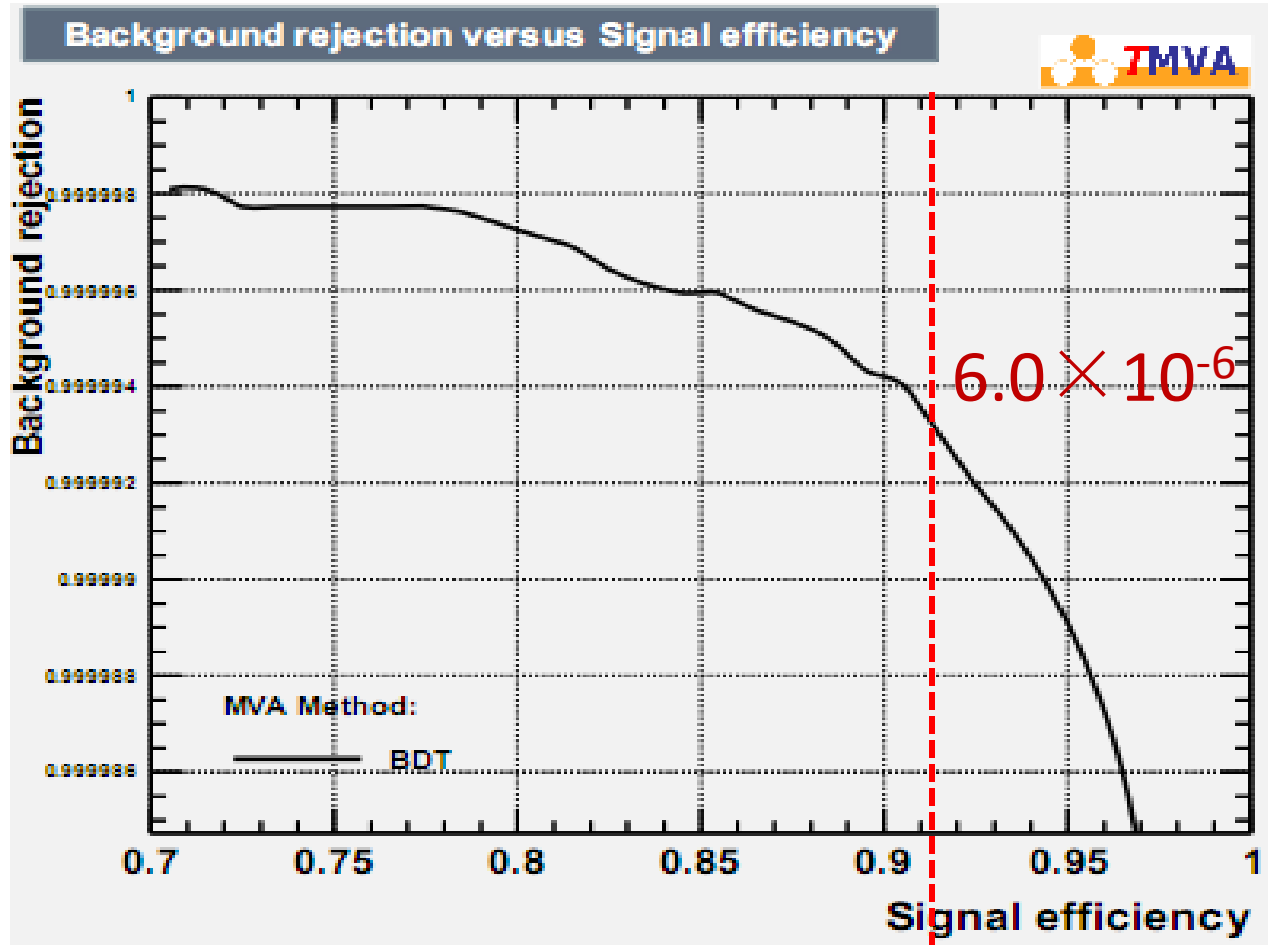
HERD使用近万个晶体颗粒组成三维的具有成像能力的量能器，每个量能器晶体的信号由波长转移光纤引出并汇聚到ICCD系统集中读出，此方案在量能器内部无热源，较容易实现在轨温控。

模拟结果 — 能量分辨率



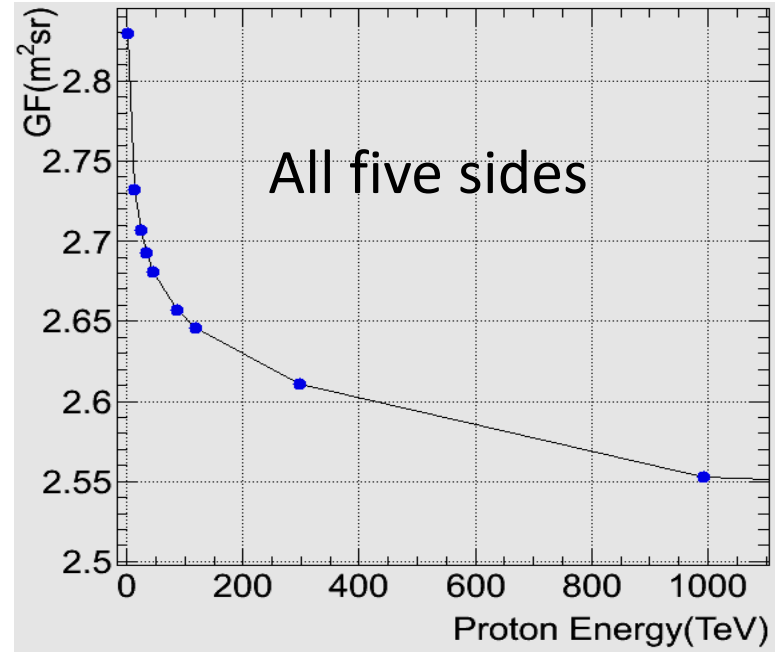
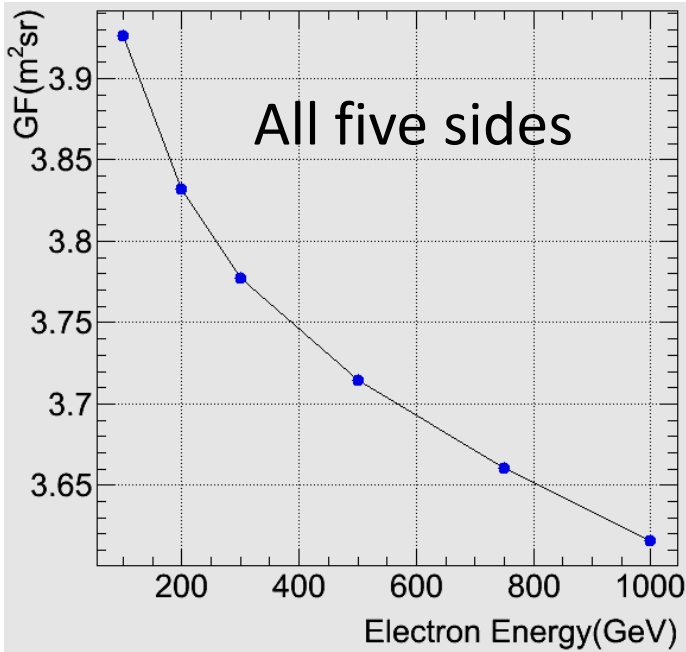
电子能量分辨率 < 1%; 质子能量分辨率 ~20%

e/p 分辨 (TMVA)



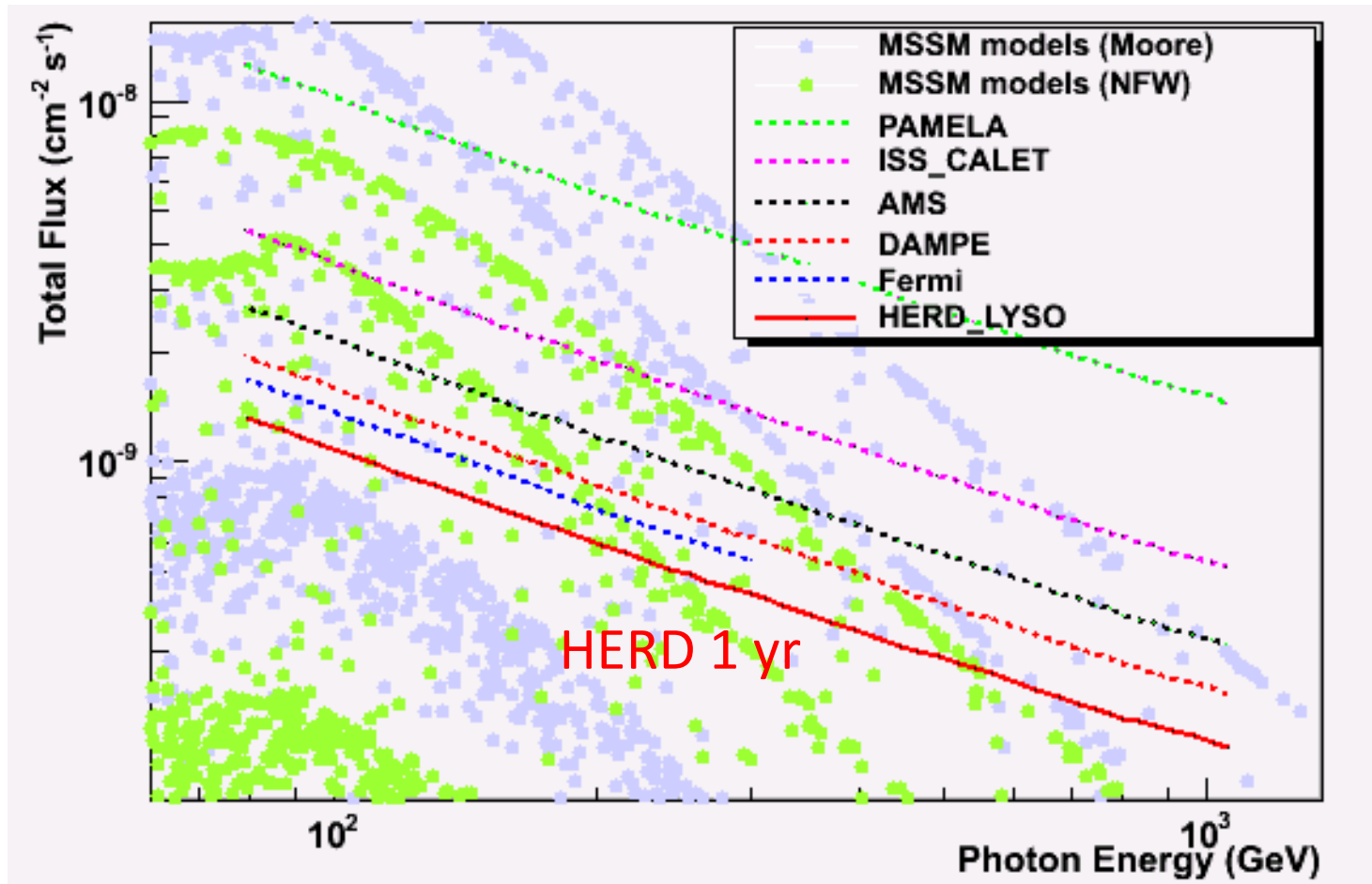
保持电子探测效率 $\sim 90\%$, 质子排斥效率 $> 10^5$

量能器有效几何因子



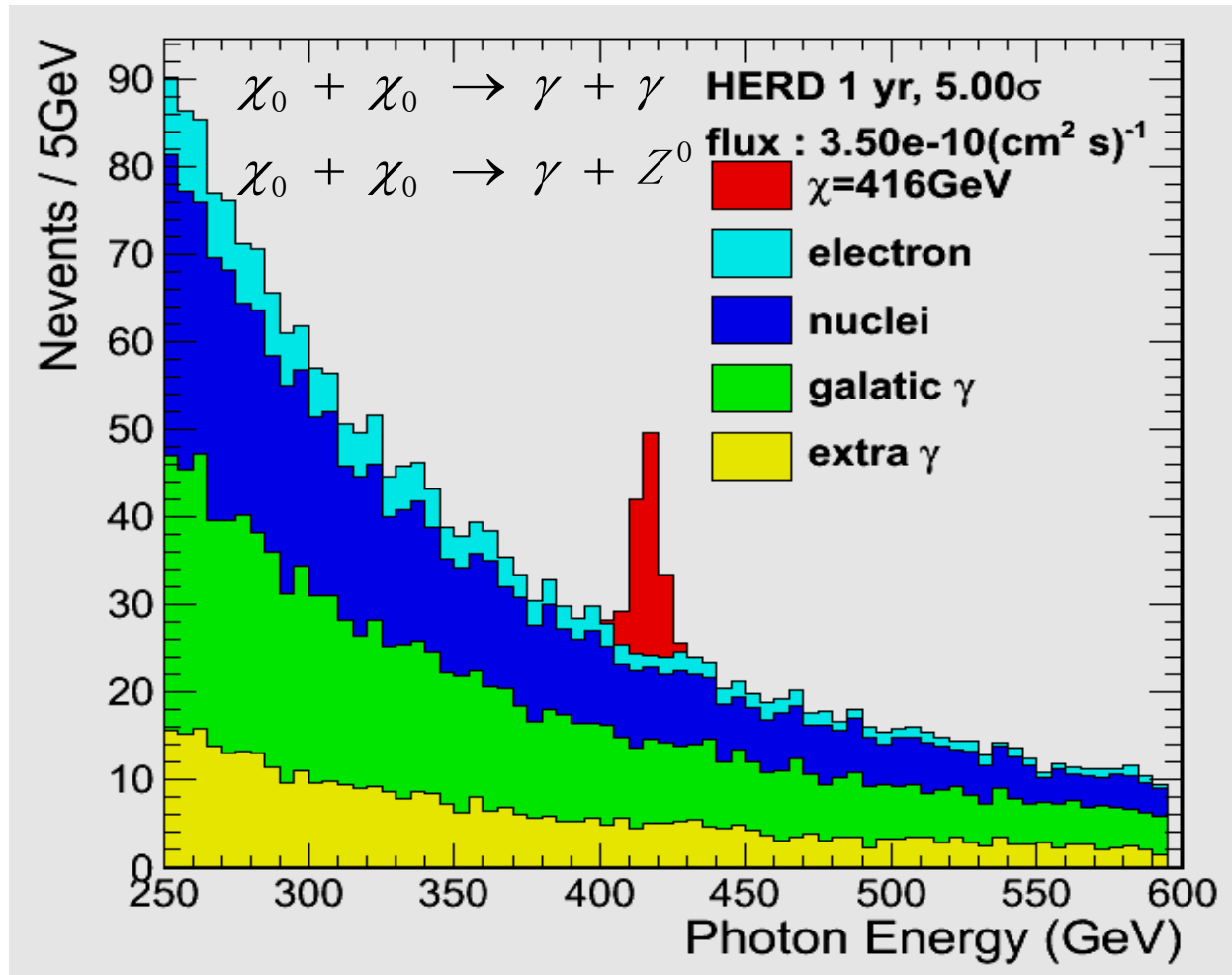
电子: $>3.7 \text{ m}^2\text{sr}@200 \text{ GeV}$ 质子: $>2.6 \text{ m}^2\text{sr}@100 \text{ TeV}$

HERD 预期gamma-ray 线探测灵敏度

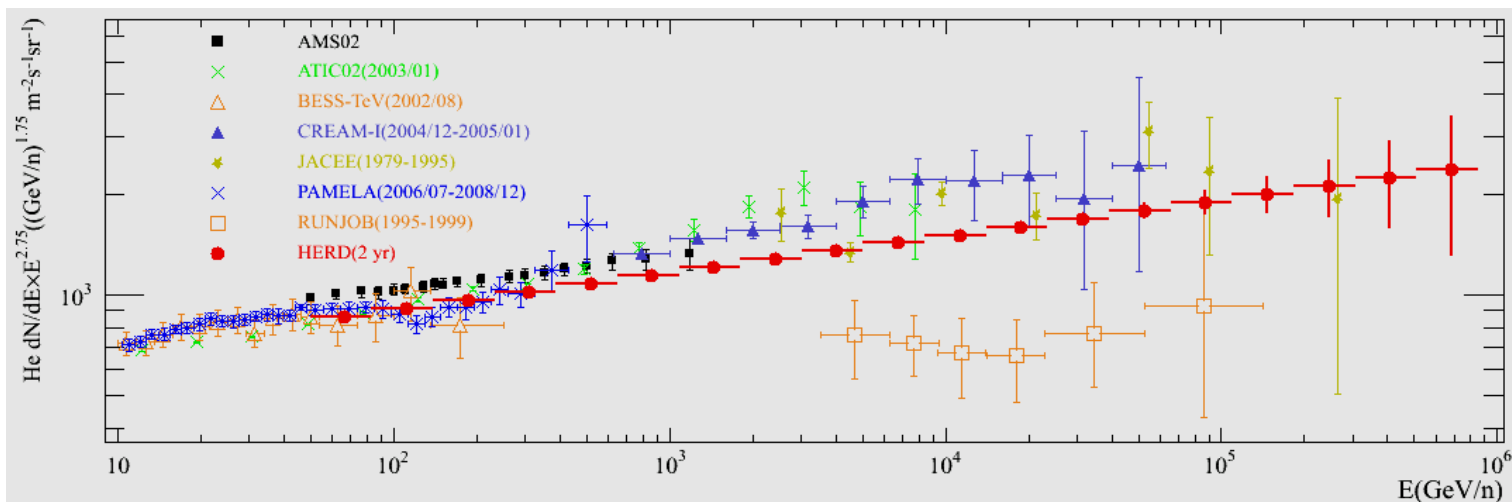
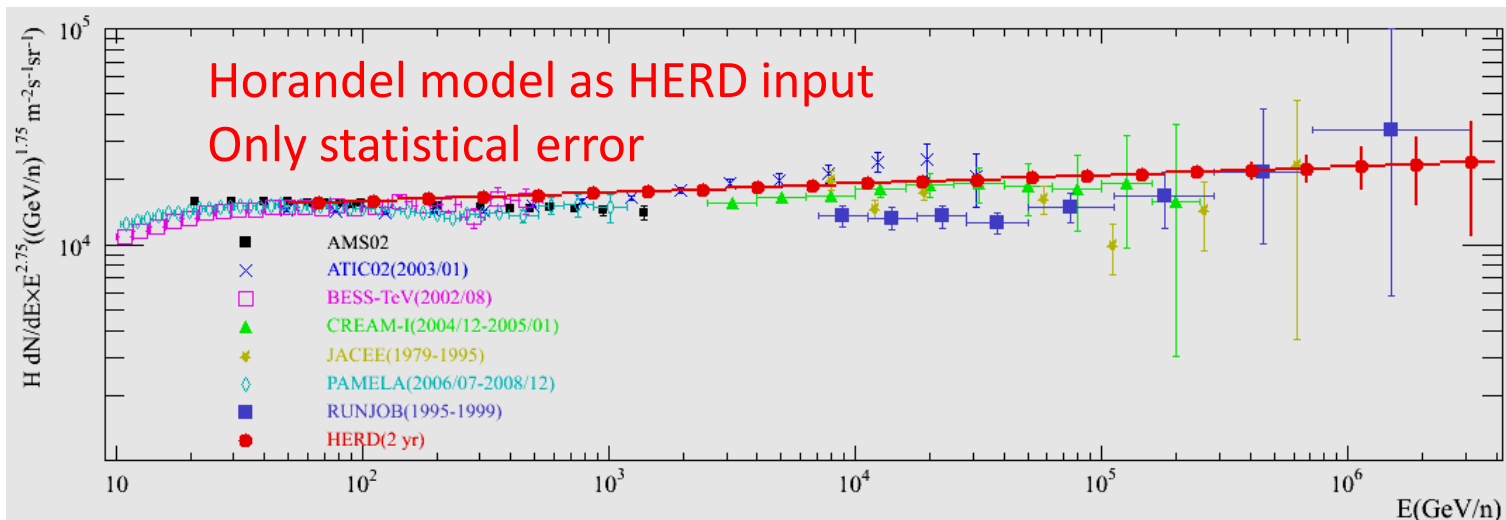


PAMELA: 2006-2016 CALET: 2015-2020; AMS: 2011-2021;
DAMPE: 2015-2020; Fermi: 2008-2018; HERD: 2020-2021

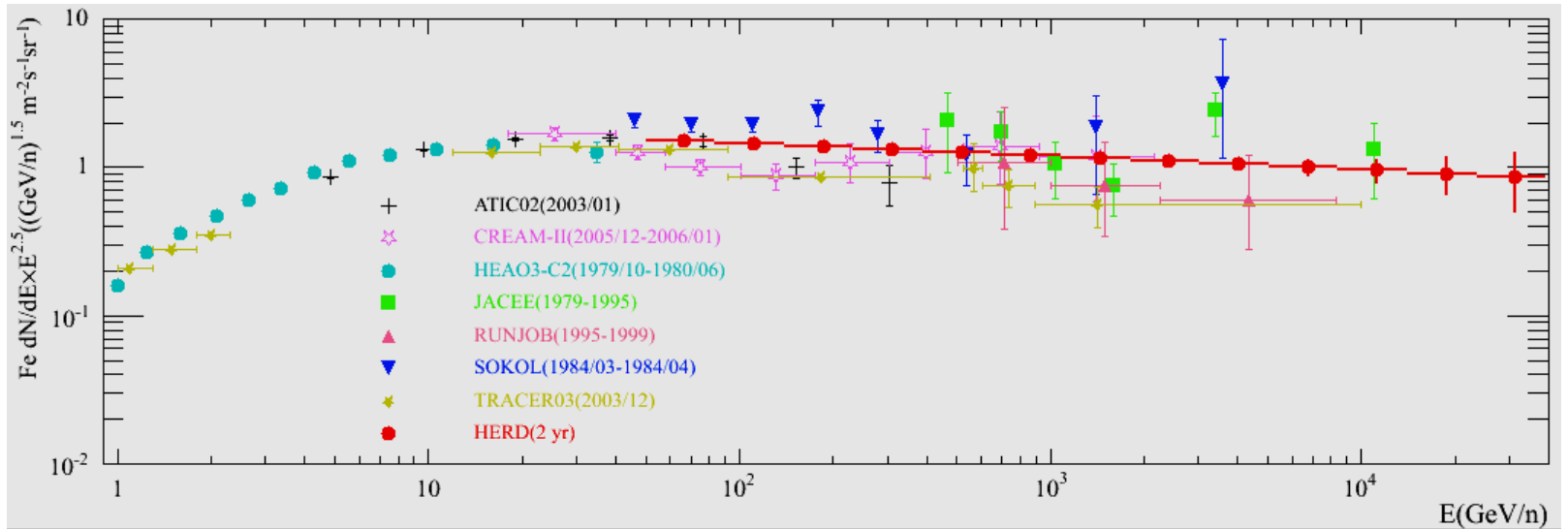
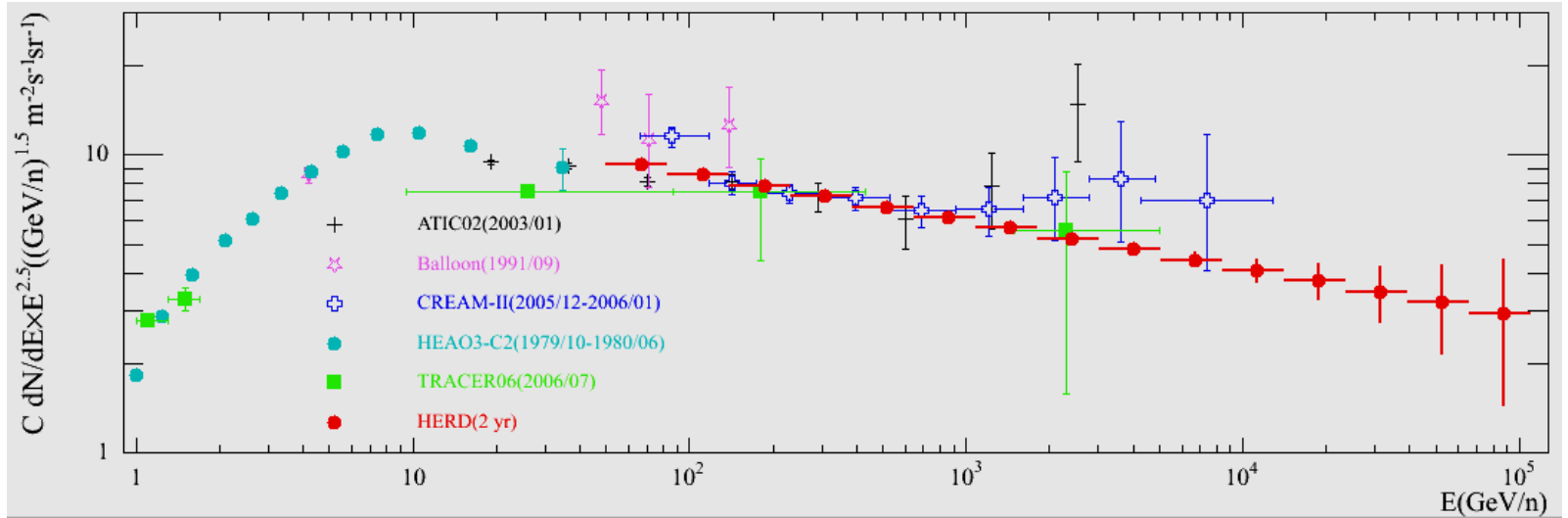
HERD预期DM 湮灭线



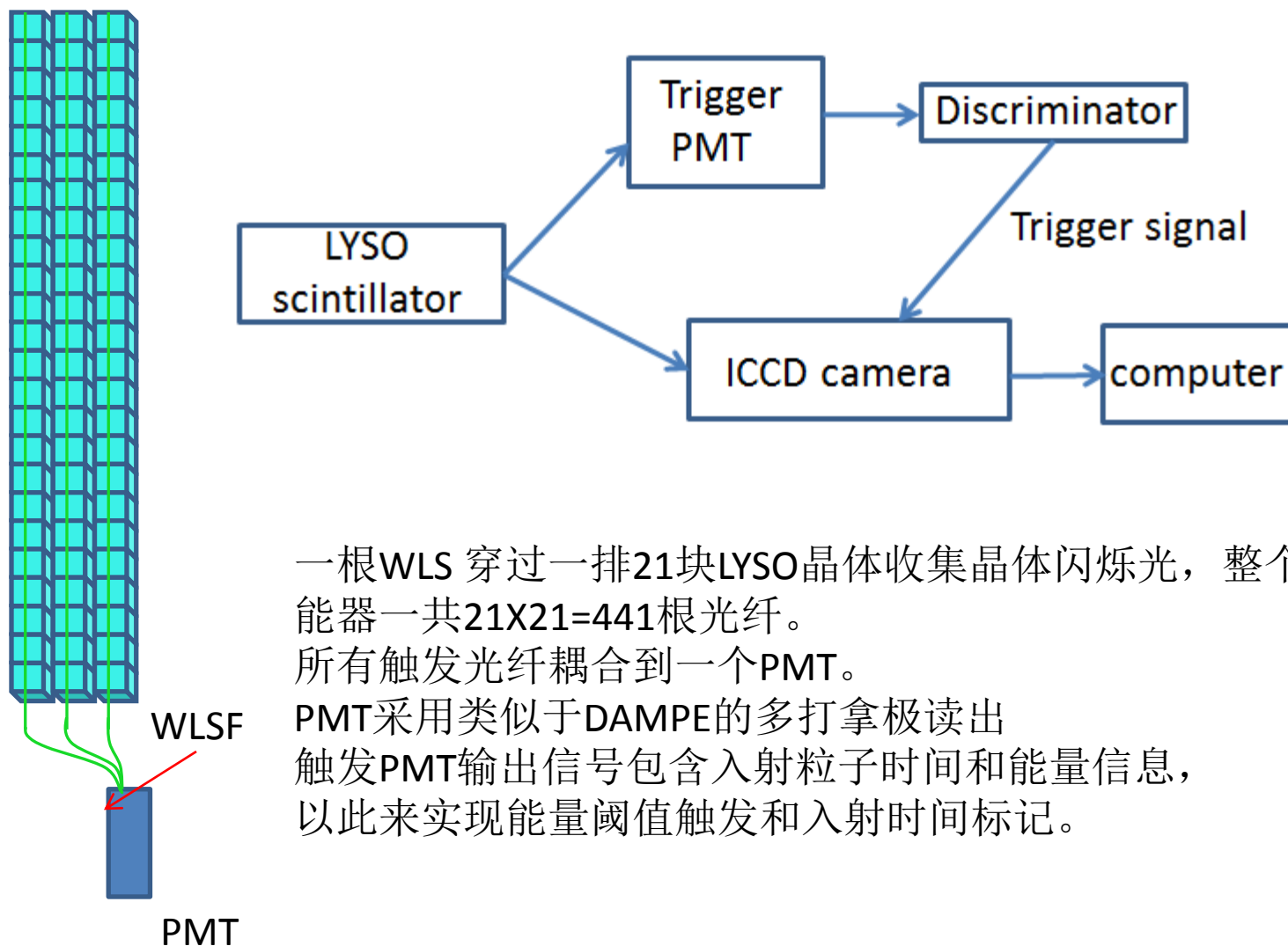
HERD预期Proton and He 能谱



HERD 预期 C and Fe能谱



量能器触发系统

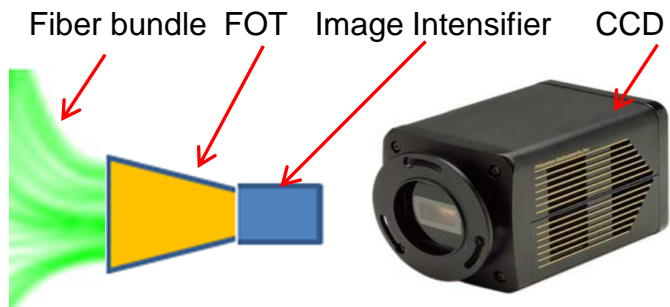


一根WLS 穿过一排21块LYSO晶体收集晶体闪烁光，整个量能器一共 $21 \times 21 = 441$ 根光纤。

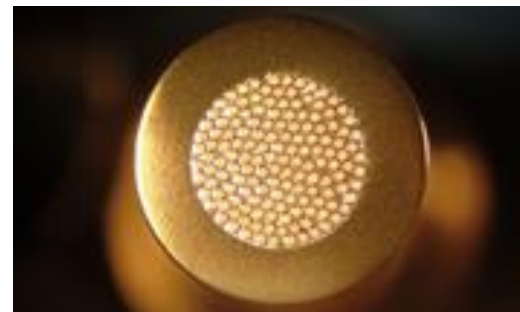
所有触发光纤耦合到一个PMT。

PMT采用类似于DAMPE的多打拿极读出
触发PMT输出信号包含入射粒子时间和能量信息，
以此来实现能量阈值触发和入射时间标记。

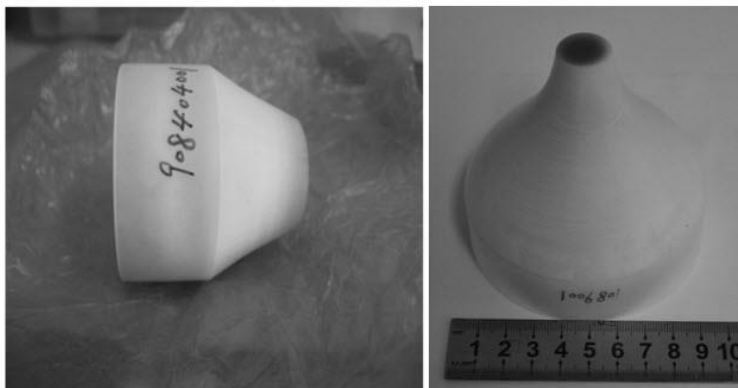
量能器读出系统



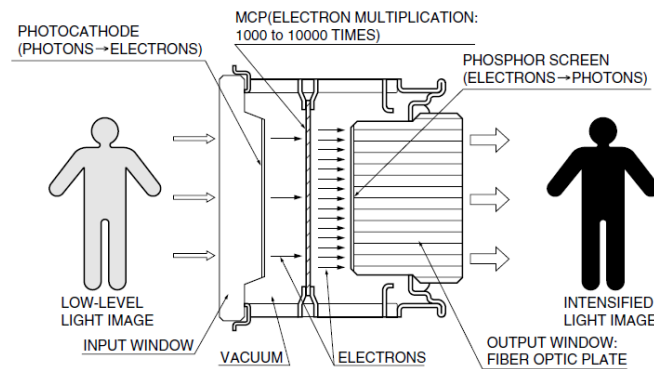
量能器ICCD读出系统



光纤束



光锥



像增强器工作原理

ICCD 读出帧频要求

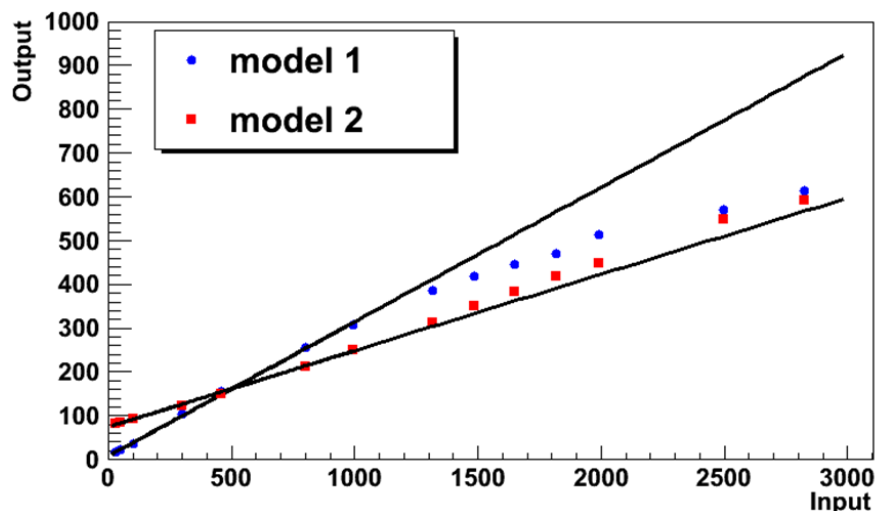
Trigger Threshold (GeV)	Counting Rate (Hz)	Detection Efficiency (200 frame)	Detection Efficiency (500 frame)	Detection Efficiency (1000 frame)
20	300	42%	63%	78%
30	100	70%	85%	92%
50	50	83%	92%	96%

为了获得较高的宇宙线探测效率，ICCD 读出帧频要达到1000。
ICCD 样机由西安光机所合作研制，目前交付了400帧地面样机。

量能器动态范围要求

▶ 动态范围估算

- cell MIP response (LYSO, 3cm cube) $\sim 30\text{MeV}$
- cell MAX Energy deposit response (PeV shower) $\sim 20\text{TeV}$
- dynamic range = $20\text{TeV} / (1/3 \text{ MIP}) = 2 \times 10^6$

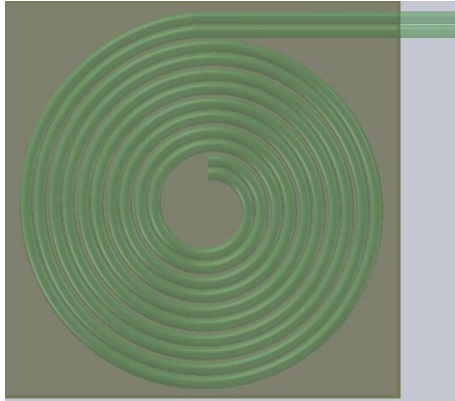


不同工作状态下，ICCD动态范围测试结果

ICCD样机线性范围： ~ 300

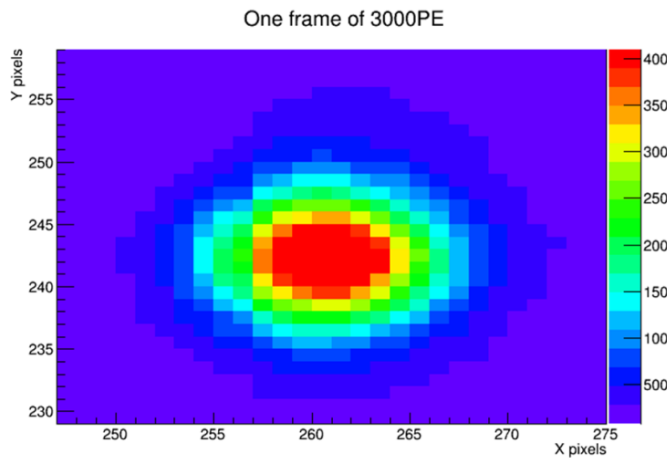
一级读出无法满足要求

大动态范围读出设计

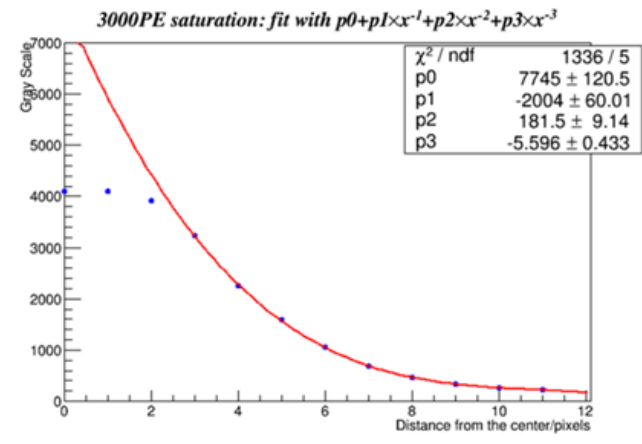


晶体信号双光纤读出

- 1, 每块晶体由两根光纤读出, 其中一路通过衰减, 实现高低两个量程读出。
- 2, 大信号在CCD上的形状呈高斯分布, 中心饱和。正在研究利用边缘没有饱和的信号进行外推, 得到原始信号幅度。



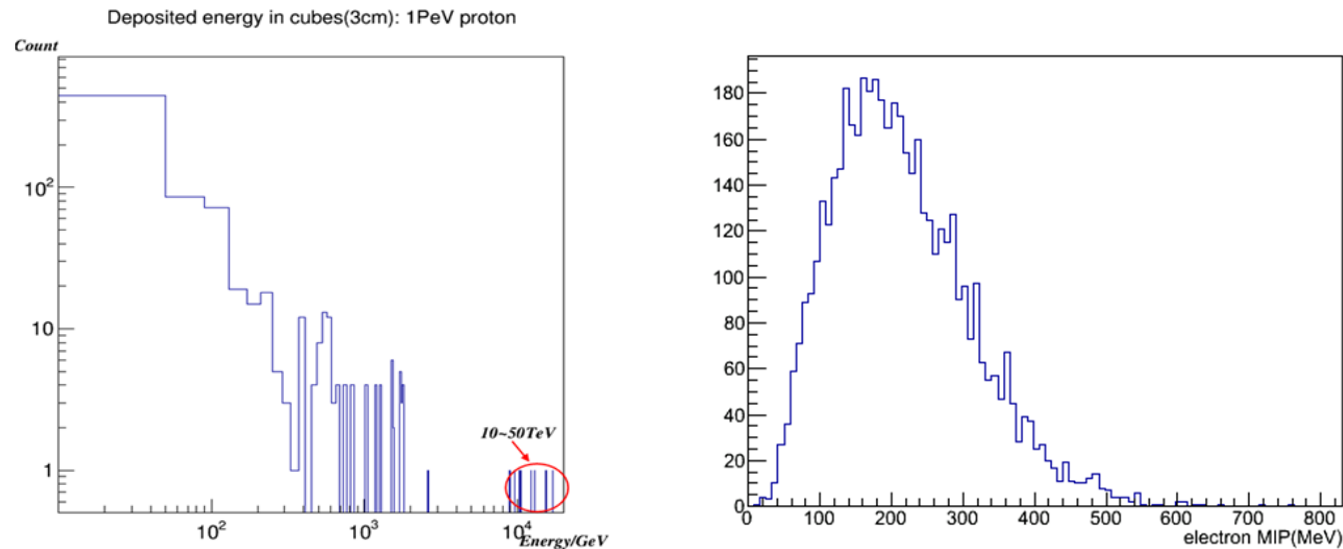
3000P.E 在CCD上的信号分布



饱和信号外推

LYSO 晶体光输出线性测试

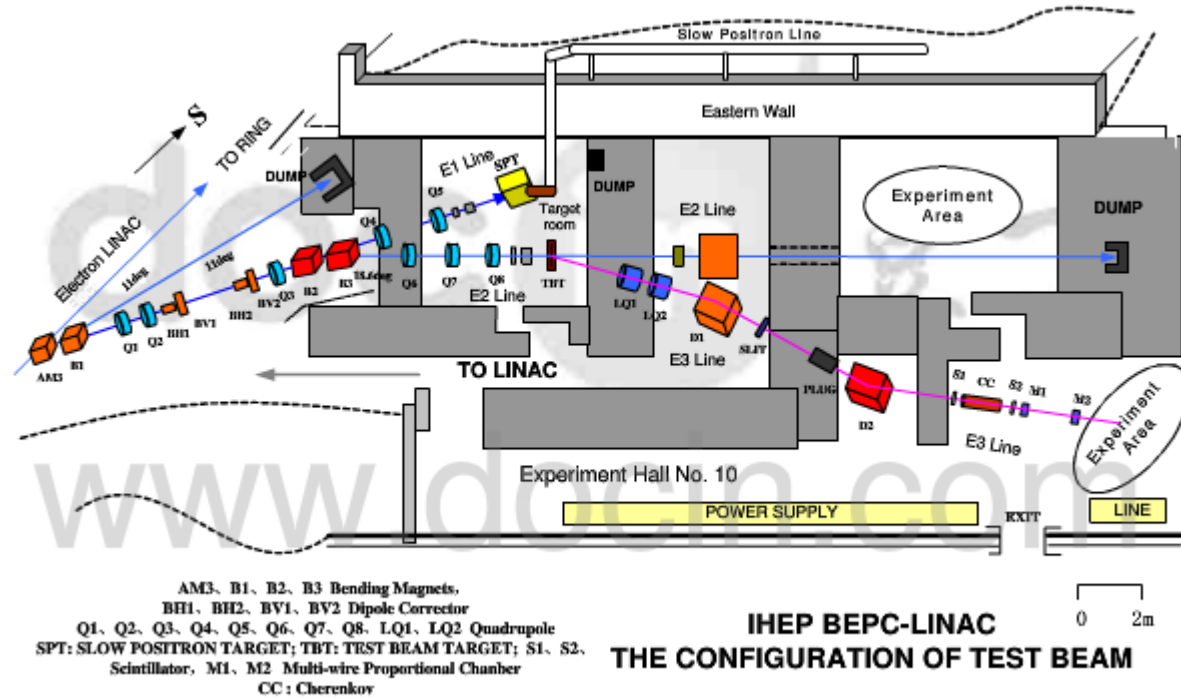
- 无机闪烁体用作直接测量高能宇宙线时，簇射中心区域会沉积极高的能量，可能会出现发光饱和，有必要研究其响应线性



1PeV质子簇射中心区域沉积能量~20TeV。

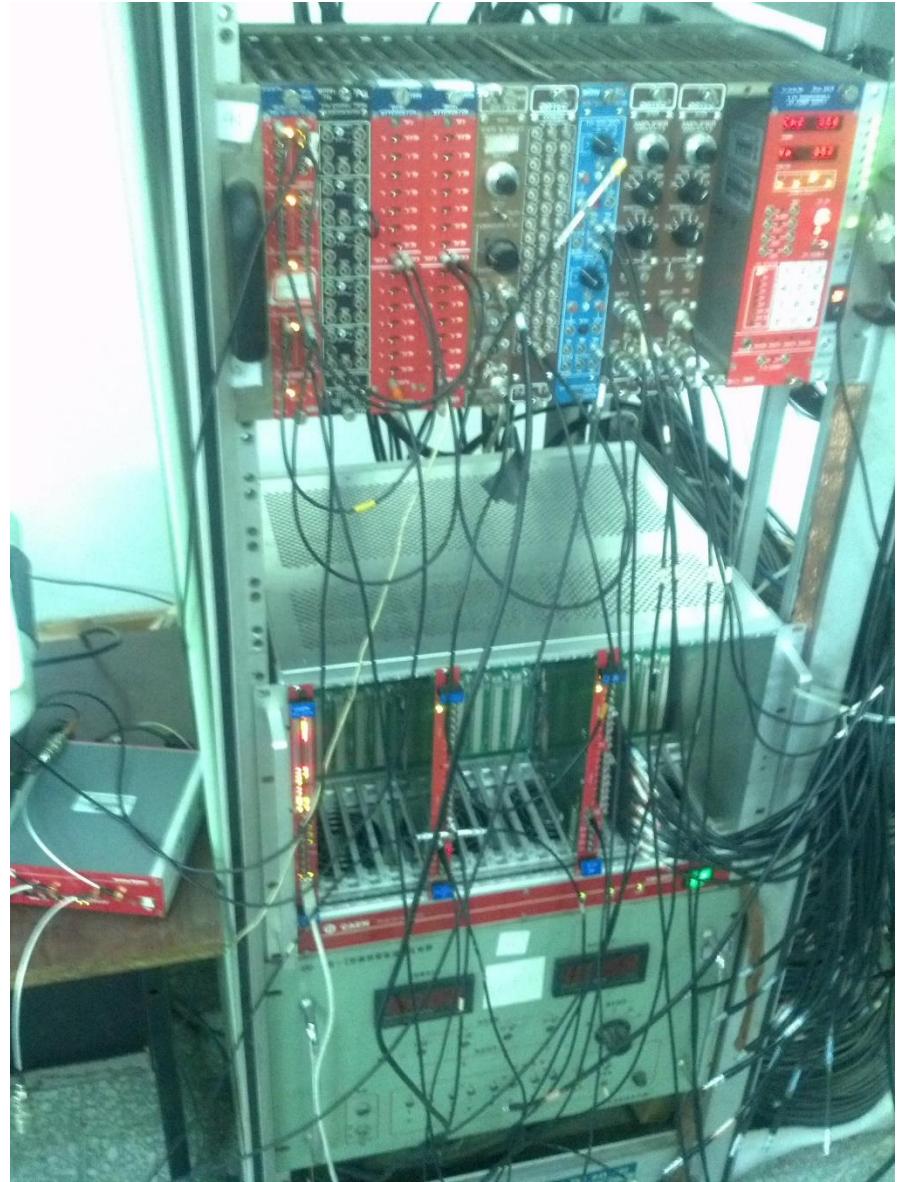
2.5 GeV 电子穿过3cm LYSO沉积能量~200MeV，利用多束团电子瞬时沉积的累积能量模拟高能粒子入射, 20TeV相当于~10⁵电子在LYSO中沉积能量。

高能所E2束流线

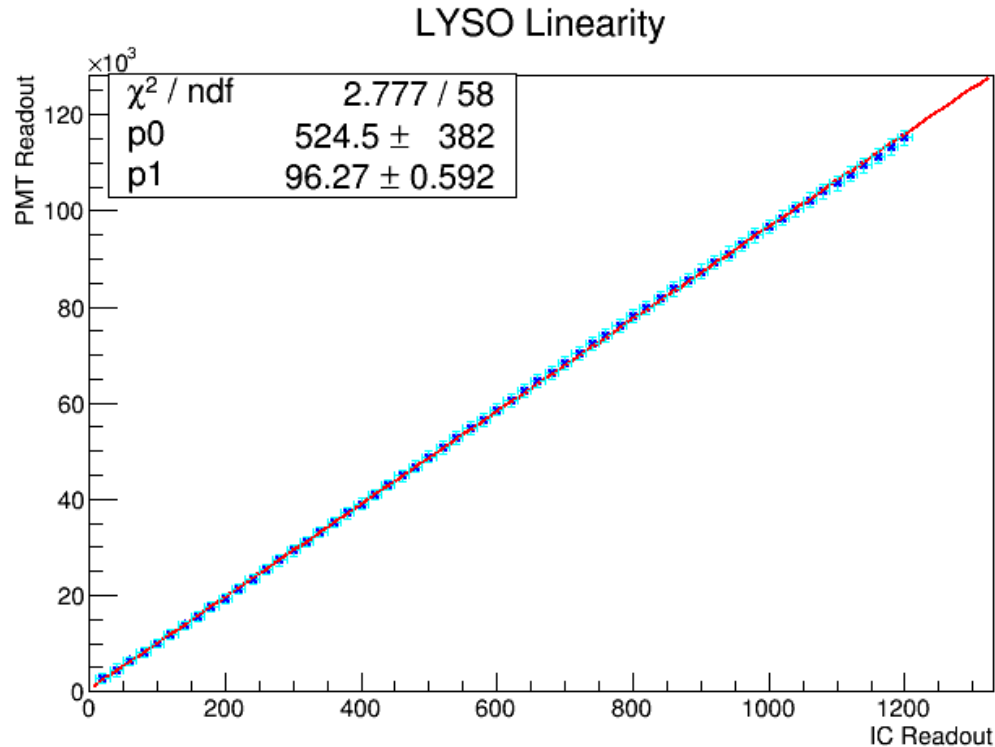


BEPC E2 Line 参数:

2.5GeV 单能电子束, 12.5Hz, 脉宽20ps, 每束团电子数 $10^3 \sim 10^{10}$

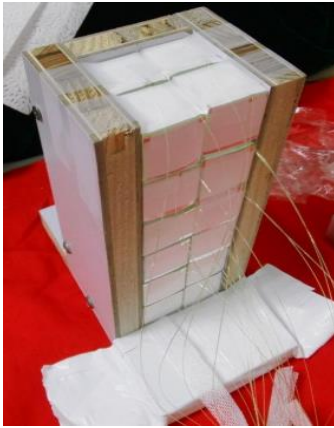


LYSO晶体响应测试结果

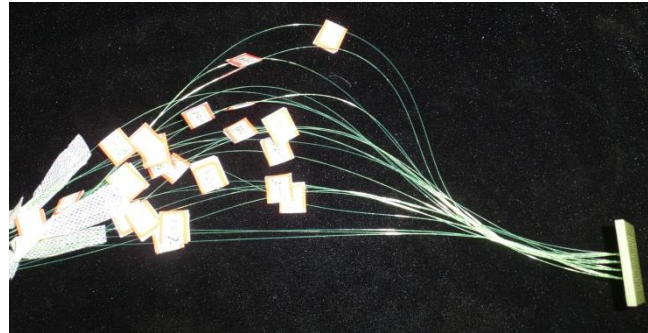


晶体光输出响应线性范围： 5×10^3 - 10^6 电子
低能端受限于束流条件没有测试，
正在改进实验方案，准备下一次实验

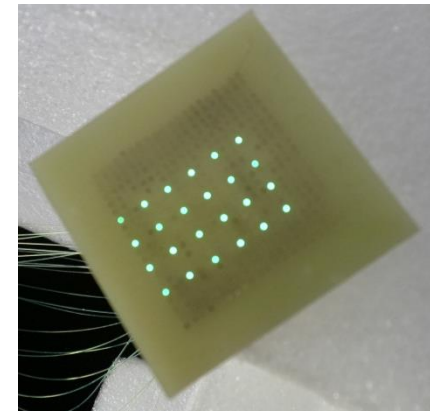
量能器模型宇宙线测试 (1)



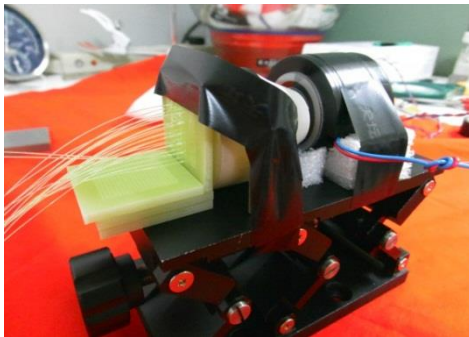
2 × 2 × 4 CsI(Na) module
2.5cm × 2.5cm × 2.5cm



24 fibers with number



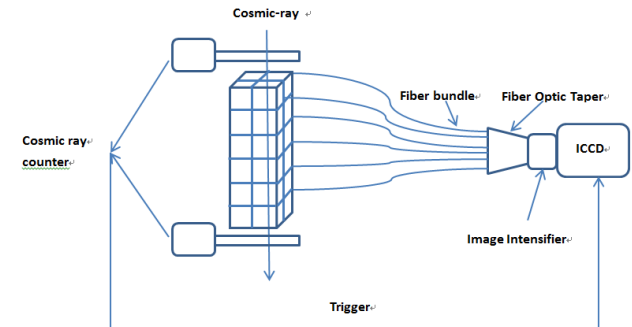
24 fibers fixed on a
micropore plate



Fibers coupled to II through
fiber Optical taper

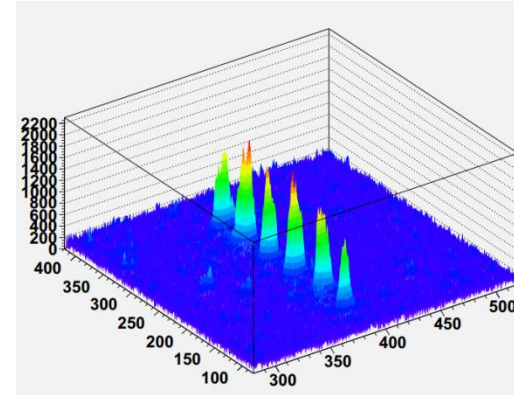
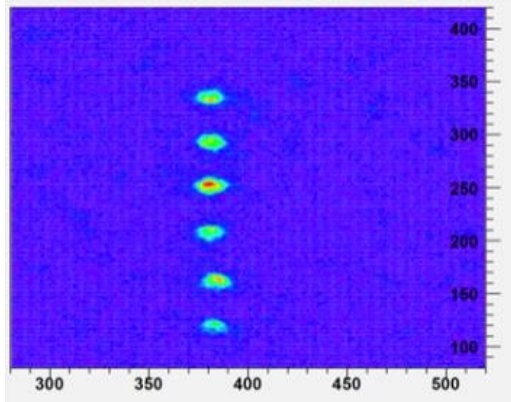


ICCD system and
cosmic ray counter

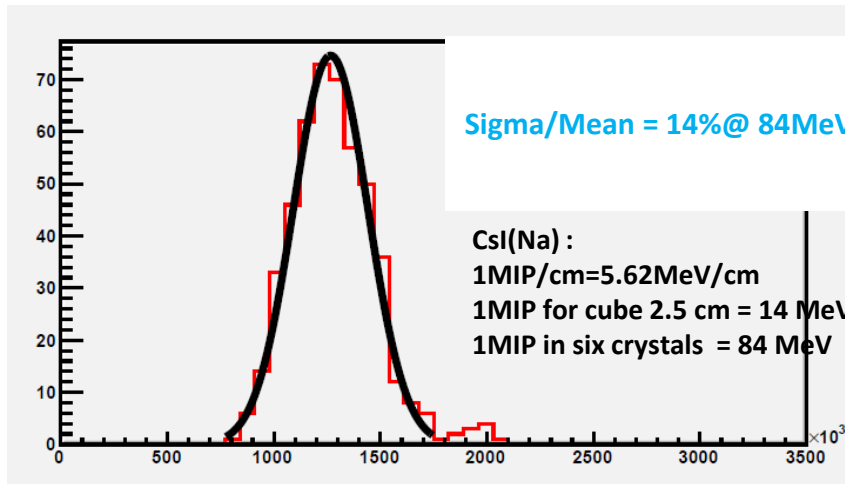


Schematic presentation of
cosmic ray test

量能器模型宇宙线测试 (2)



Display of a typical cosmic muon event passing through six crystals read out by ICCD



**Energy resolution meet
the requirement of HERD
to e/γ .**

Energy resolution of MIPs in six crystals

HERD 团队

- Current Chinese member institutions
 - Institute of High Energy Physics, China
 - Purple Mountain Observatory, China
 - Xi'an Institute of Optical and Precision Mechanics, China
 - University of Science and Technology of China
- Current international member institutions (**tentative**)
 - University of Geneva, Switzerland
 - Università di Pisa and INFN, Italy
 - IAPS/INAF, Italy
 - University of Florence and INFN Firenze, Italy
 - University of Perugia/Trento and INFN, Italy
 - University of Bari and INFN, Italy
 - KTH, Sweden

1st HERD workshop, Oct.17-18, 2012, IHEP, Beijing



2nd HERD workshop, Dec.1-4, 2013, IHEP, Beijing

总结

HERD探测器具有：
大几何因子

> $3\text{m}^2\text{sr}$ for electron

> $2\text{m}^2\text{sr}$ for proton

- 高能量分辨率($\sim 1\%$)
- 高e/p 识别能力 ($< 10^{-5}$)
- 晶体量能器和ICCD读出系统正在进一步深入研究和不断改进中。

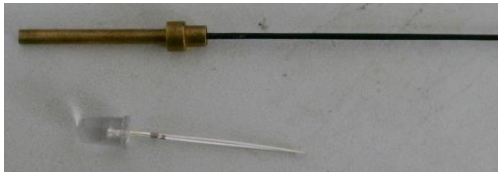
Thank You!

Back Up

Linearity study of image intensifier

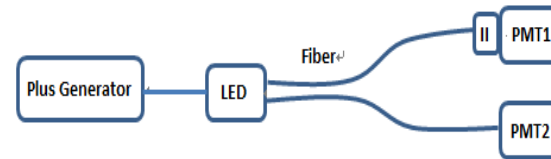


18mm diameter Image intensifier



LED and quartz fiber

The gain of II is 30



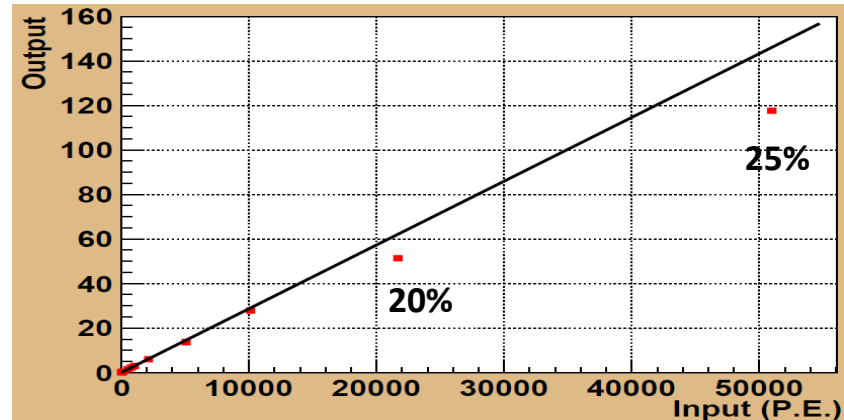
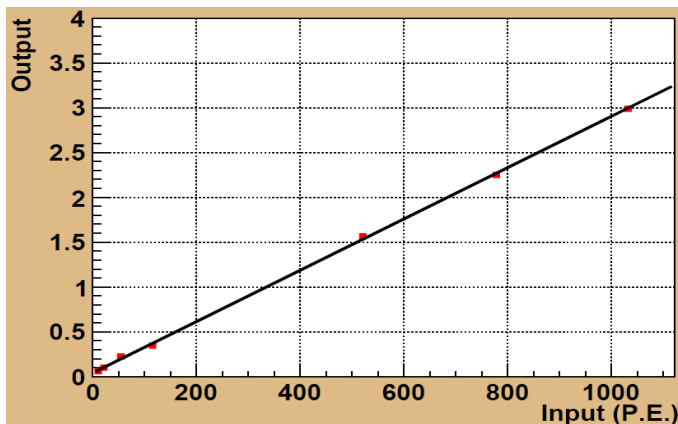
Schematic presentation of the test

LED : wave length 505-510nm, close to WLS output light

Fiber: 0.4mm diameter quartz fiber

PMT1: test detector

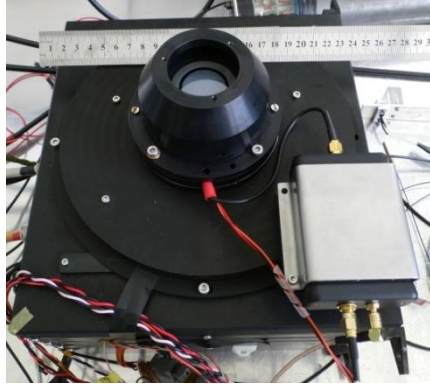
PMT2: monitor the stability of the LED



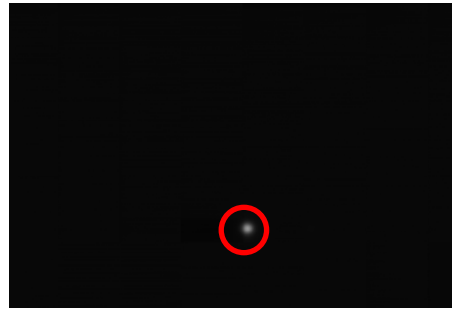
Fitting data from 10 P.E. to 1000P.E. , and then extrapolated the fitted curve to 50000 P.E.

The divergence at 20000 P.E. and 50000 P.E. is 20% and 25% respectively.

Linearity study of ICCD prototype

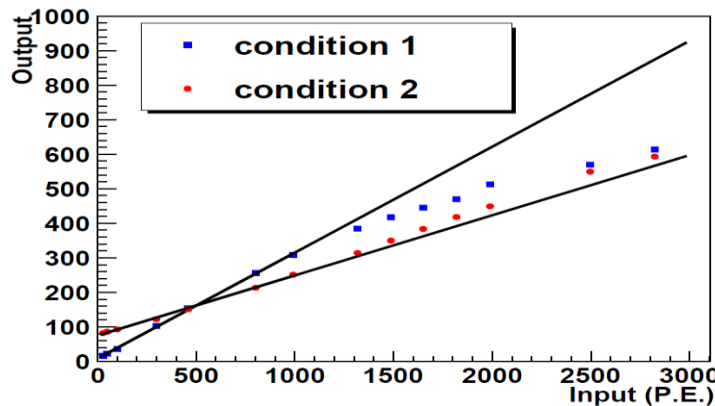


The ICCD prototype



The fiber image in the ICCD

The test setup is identical to the linearity study of image intensifier, one fiber used to test the ICCD, another used to monitor the stability of the LED



Linearity of the ICCD prototype with different II gain

In condition 1, the gain of II is 1.5×10^5 , the linearity range of ICCD is 100.

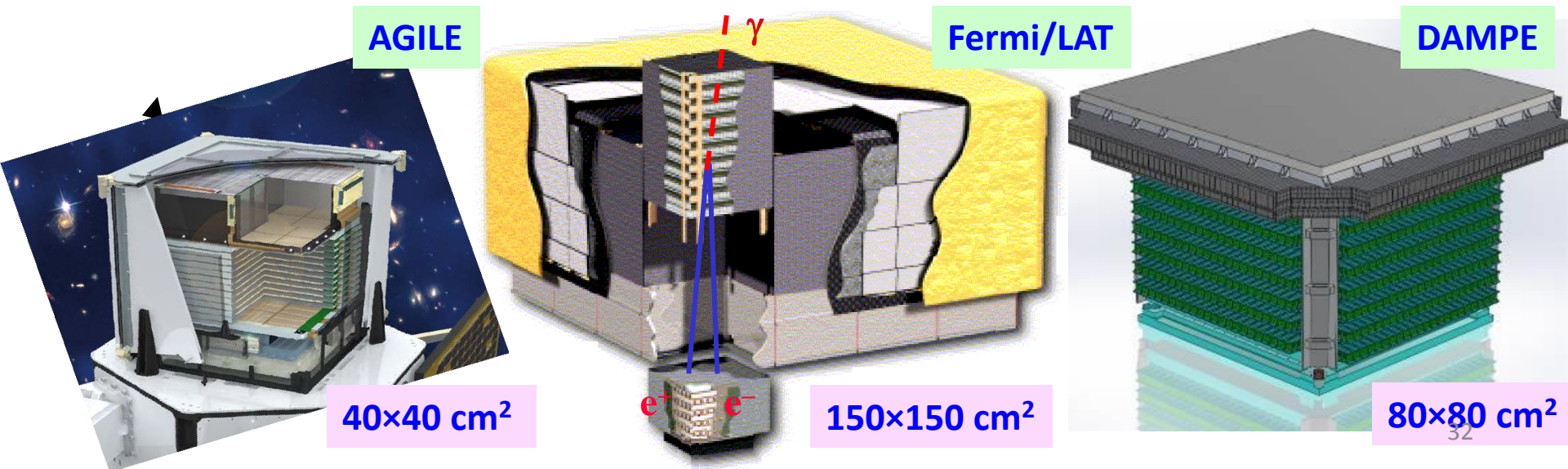
In condition 2, the gain of II is 1.0×10^4 , the linearity range of ICCD is 300.

II with lower gain can obtained larger linearity.

In linearity study of Image Intensifier and ICCD, the PMT's non-linear response is not exclude, this issue will be studied in future.

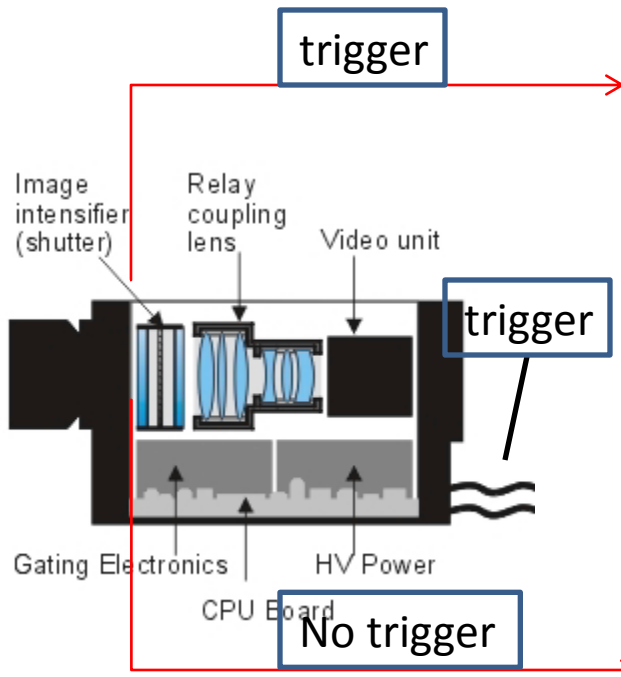
Silicon Tracker-Converter

- Integrated Tungsten converter plates into a tracker with Si strip detectors
 - γ converts in W plate to e^+e^- \rightarrow detected in subsequent Si detectors
 - Unambiguous identification of γ -ray , superior pointing resolution
- Silicon tracker-converter successfully used in AGILE and Fermi/LAT
 - Became standard design of γ -ray space telescope
- Silicon strip detectors is a mature technology, including space applications
 - PAMELA (2006), AGILE (2007), Fermi/LAT (2008), AMS-02(2011)
 - Excellent performance, well beyond the typical 3 year design lifetime

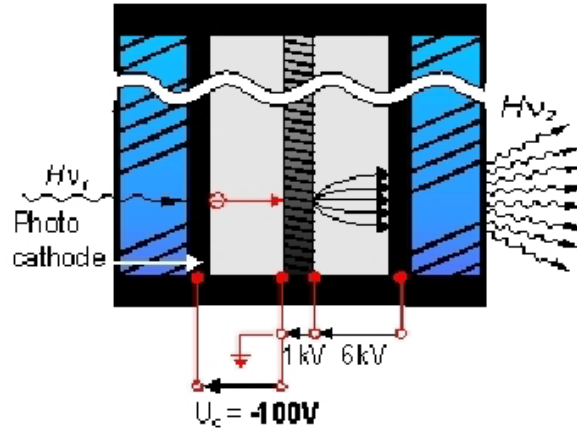


ICCD system

Gating:
a crucial feature of high speed ICCD cameras

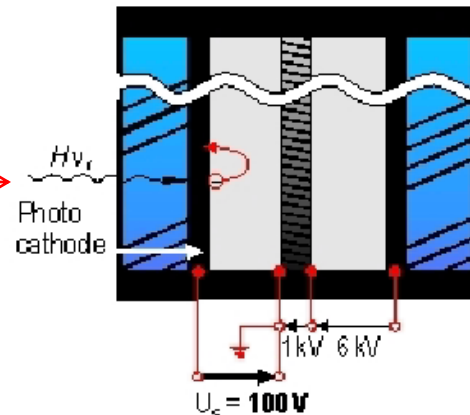


shutter is open



If the voltage U_c between photocathode and multichannel plate is negative, the photoelectrons are accelerated towards the multi channel plate. This means that the shutter is open.

shutter is closed



If the voltage U_c is positive, the photoelectrons are kept at the photoathode, thus the shutter is closed