

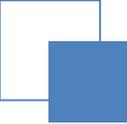
LHAASO与展望

—— 开启超高能 γ -天文学 及后续发展

张寿山

中国科学院高能物理研究所

第二十届全国核电子学与核探测技术学术年会
2022年11月10-11日



报告内容

- **LHAASO介绍**
- **LHAASO 物理分析进展**
- **未来探测器计划**
- **总结**

Bird's eye view of LHAASO, 2021-12

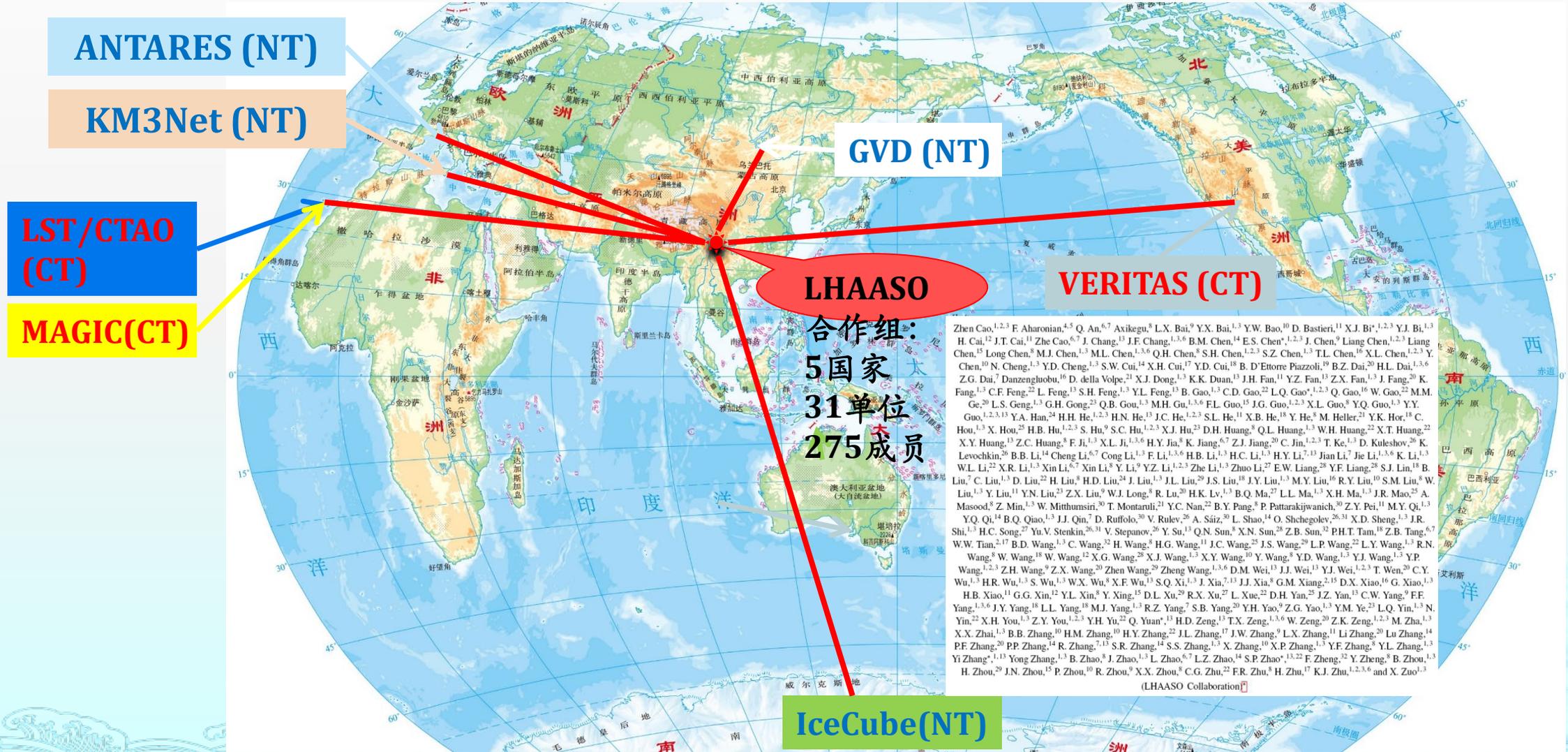
Location: 29°21' 27.6" N , 100°08'19.6" E

Altitude: 4410 m

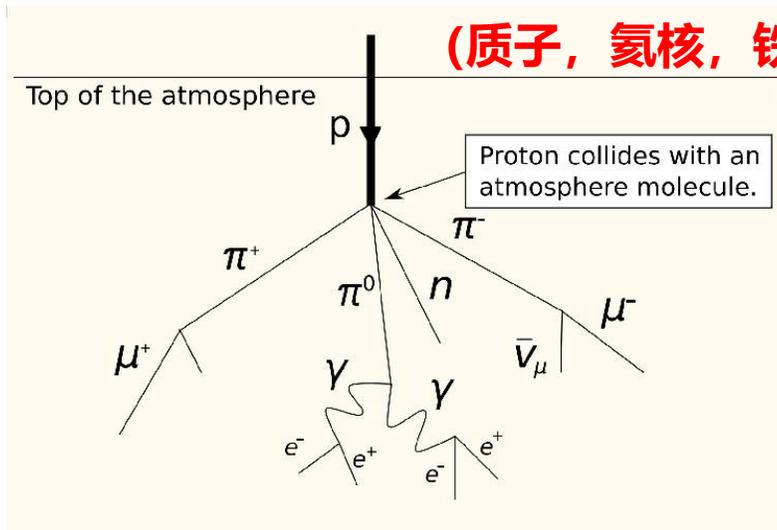
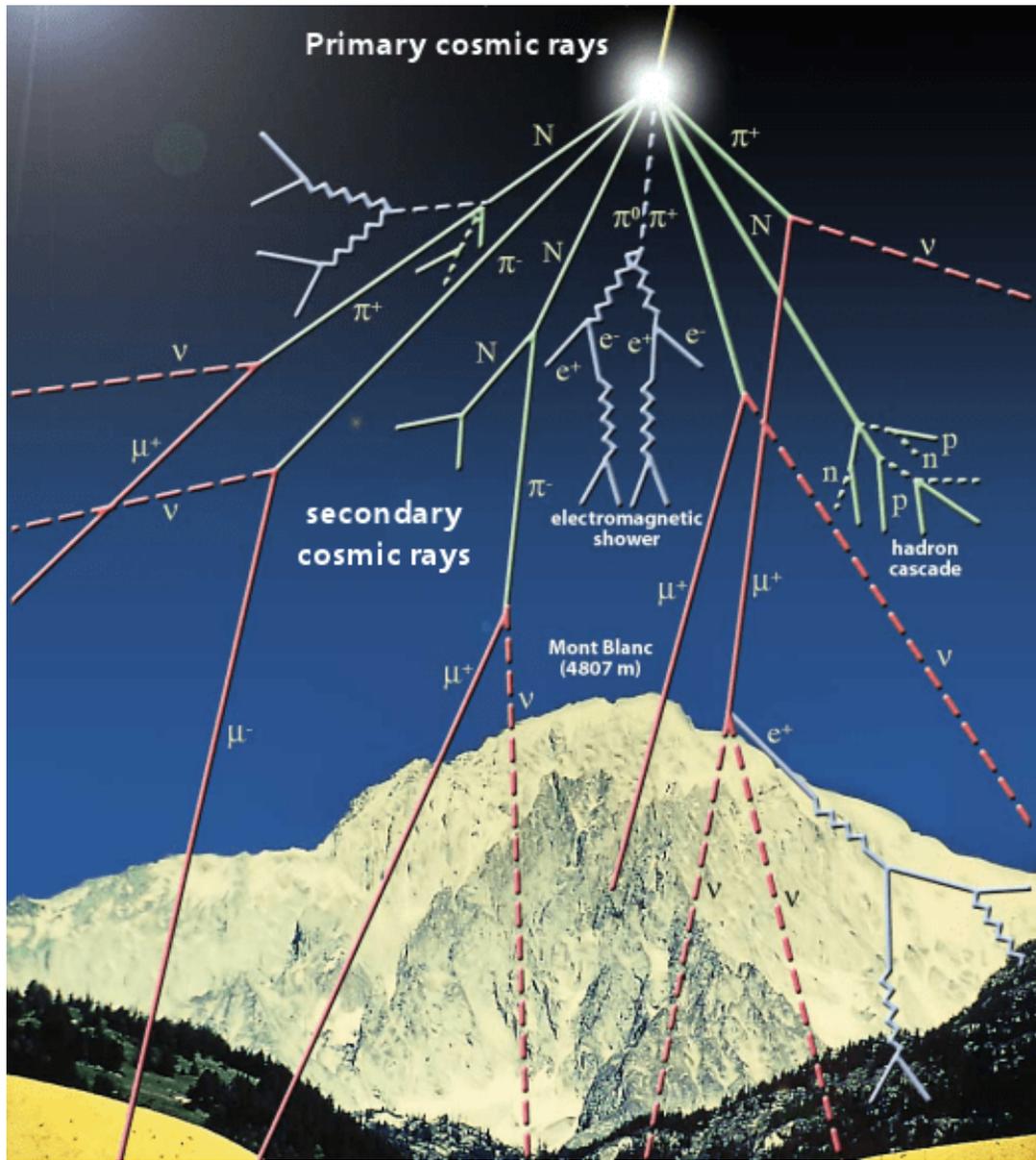
2021-07 completed built and in operation



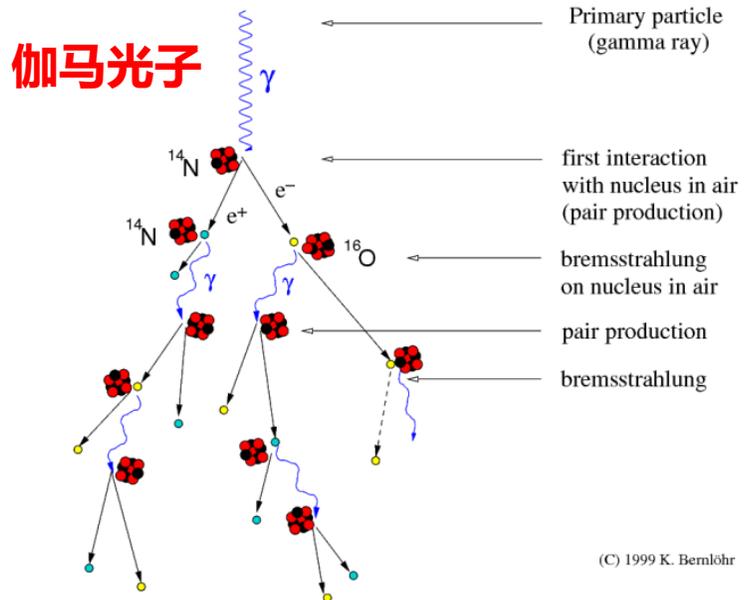
Multi-Messenger Collaboration Network



广延大气簇射



Development of gamma-ray air showers



(C) 1999 K. Bernlöhr

次级粒子：
正负电子、
伽马光子、
强子、
 μ 子、
中微子、
荧光、
Cherenkov光。

Hybrid Detection of EASs by LHAASO

CATCHING RAYS

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

LHAASO Physics Topics

- Gamma Ray Astronomy
- Charged CRs
- New Physics Frontier

18 wide-field-of-view air Cherenkov telescopes

5,195 scintillator detectors

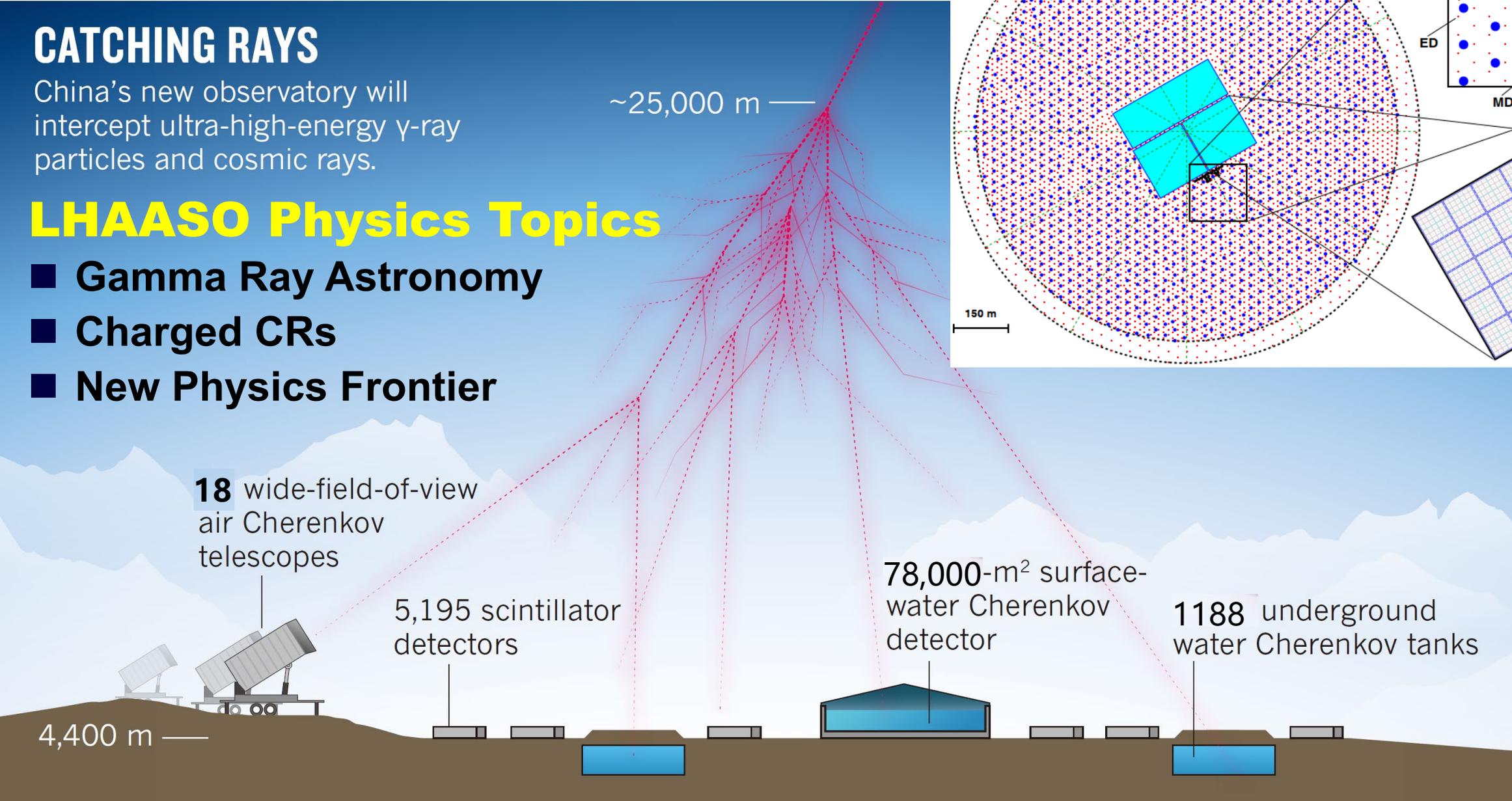
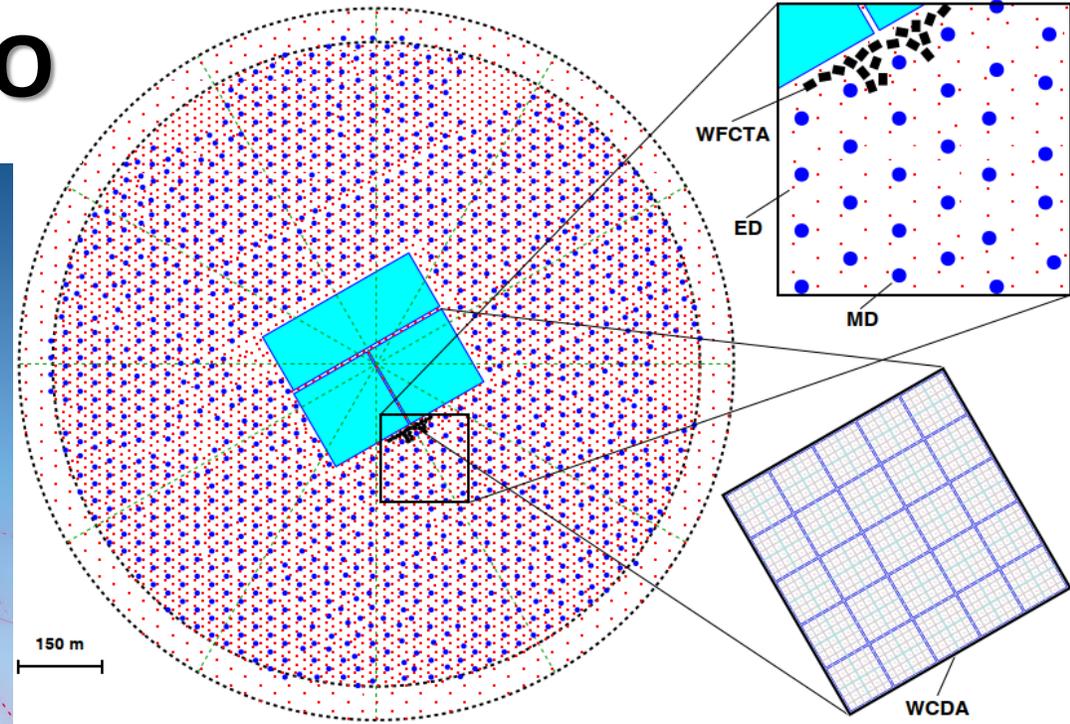
78,000-m² surface-water Cherenkov detector

1188 underground water Cherenkov tanks

4,400 m —

~25,000 m —

150 m

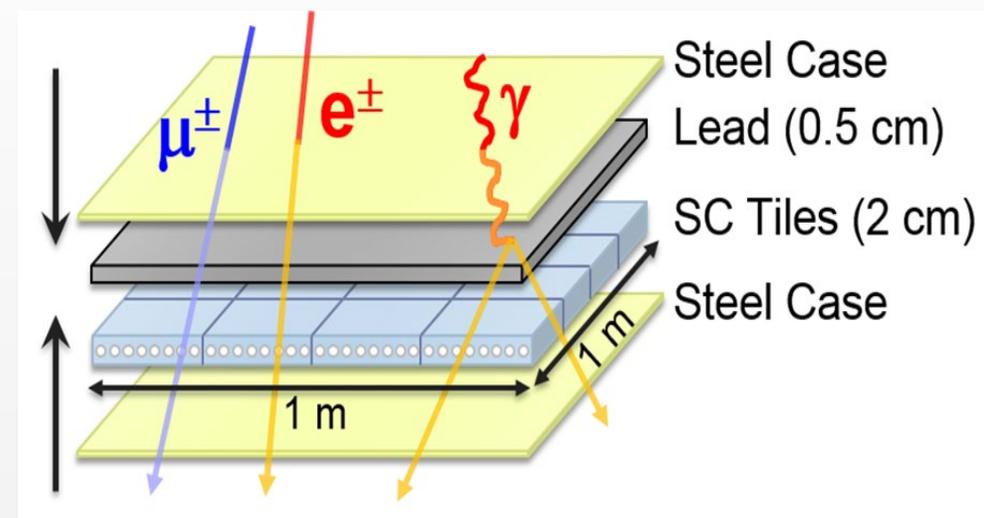




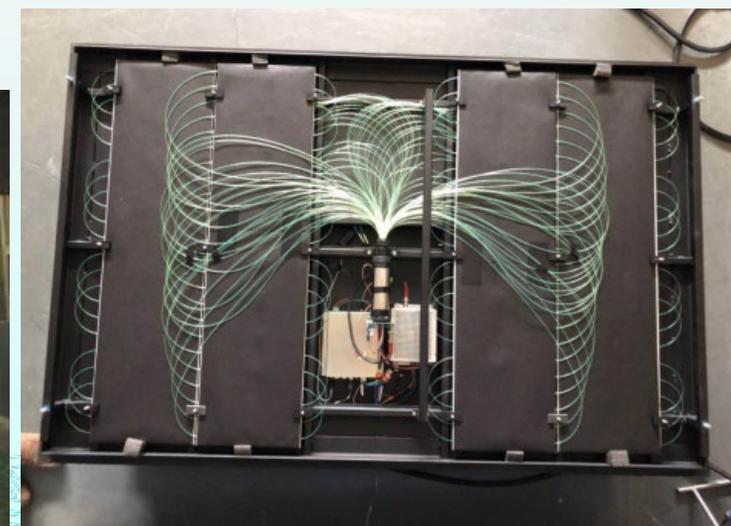
KM2A: 1.36 (km)²

- 5195 EDs
 - 1 m² each
 - 15 m spacing
- 1188 MDs
 - 36 m² each
 - 30 m spacing

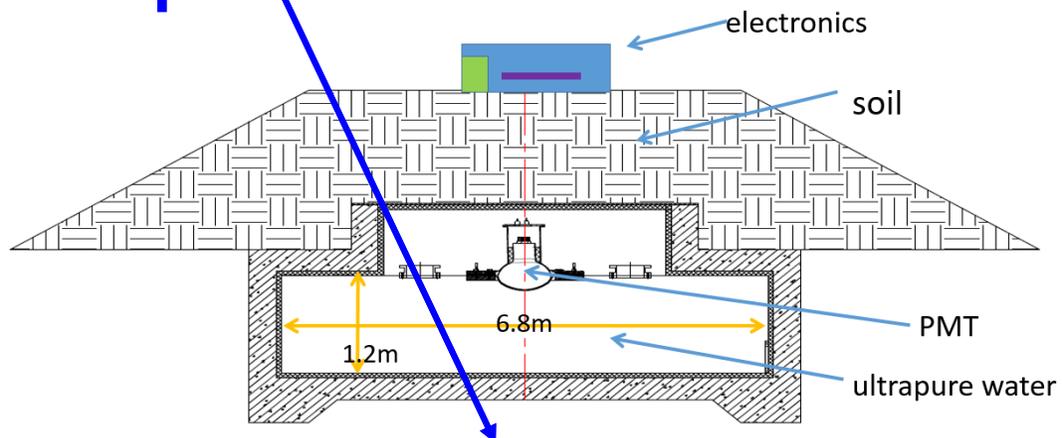
Scintillator Detectors (ED)



Inner View of one ED

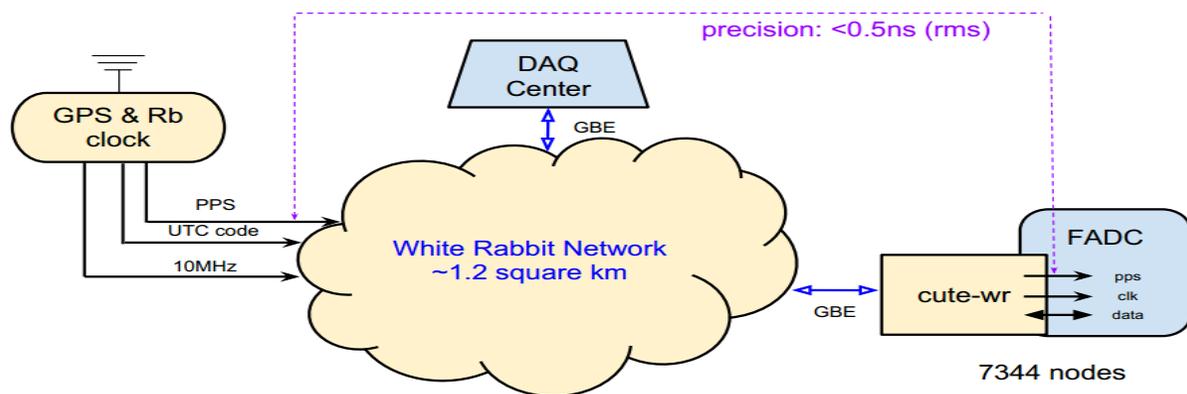


μ^\pm Muon detector (MD)



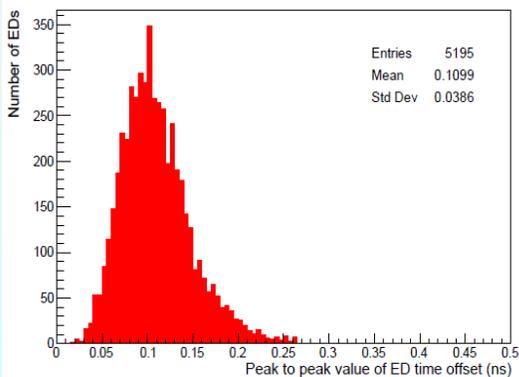
LHAASO定时系统

小白兔时钟同步系统：工业级无风扇，开源设计，自主可控



- 针对加速器控制应用开发
- 多实验室/公司合作研究
- OPEN hardware/Software
- 新一代网络同步标准

- 为分布在1平方公里范围的探测器节点提供统一的参考频率和绝对时间
- 支持数据传输，实现数据/控制链路复用
- 稳定可靠，易维护，造价低，适应野外工作环境



高精度

指向精度 <math>< 0.1</math> 度
角分辨 <math>< 0.5</math> 度

全局同步精度 <math>< 250\text{ ps}</math>

多节点

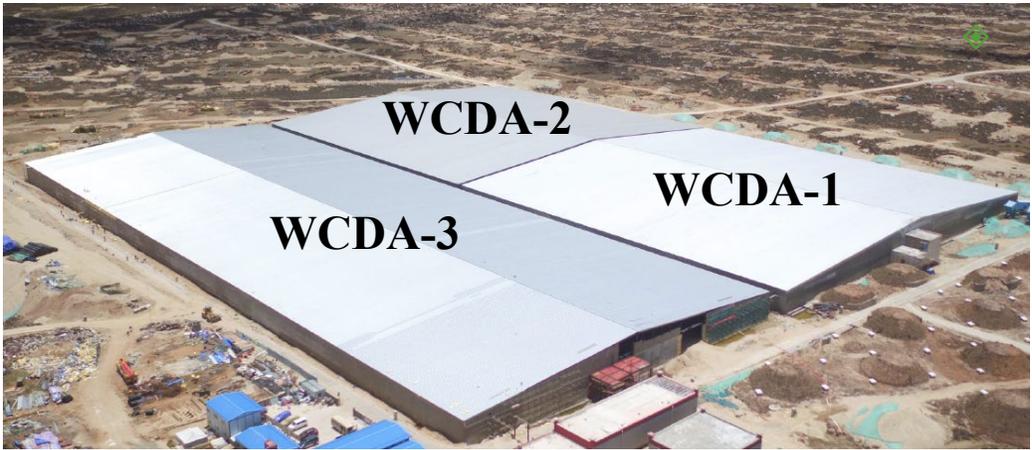
单点成本低
同步链路、数据链路复用
大阵列高精度标定
大量数据传输与处理

高可靠

温度变化: ± 30 摄氏度
10年损耗率 <math>< 20\%</math>

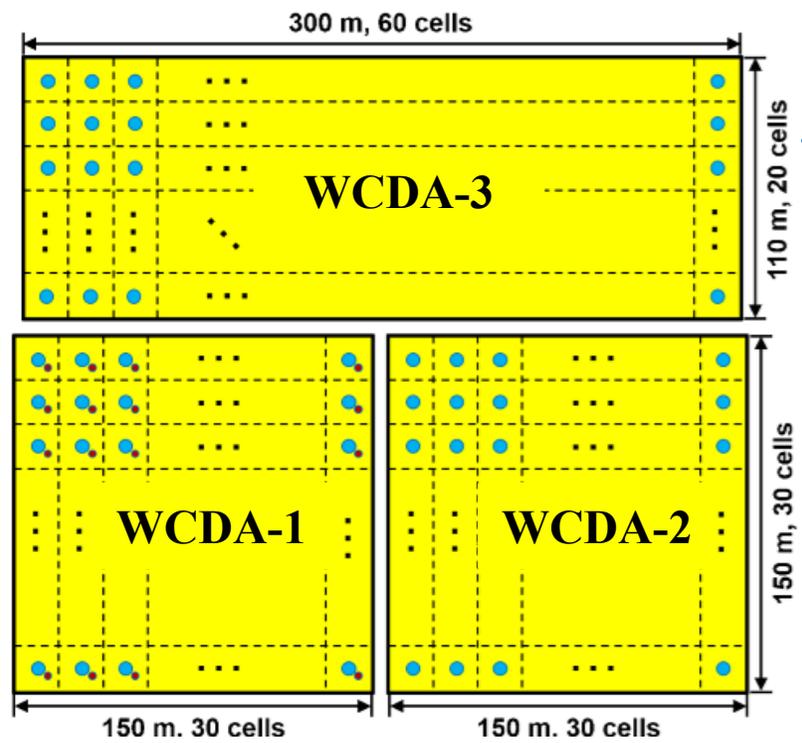
同步可靠性
网络可靠性

Water Cherenkov Detector Array (WCDA)

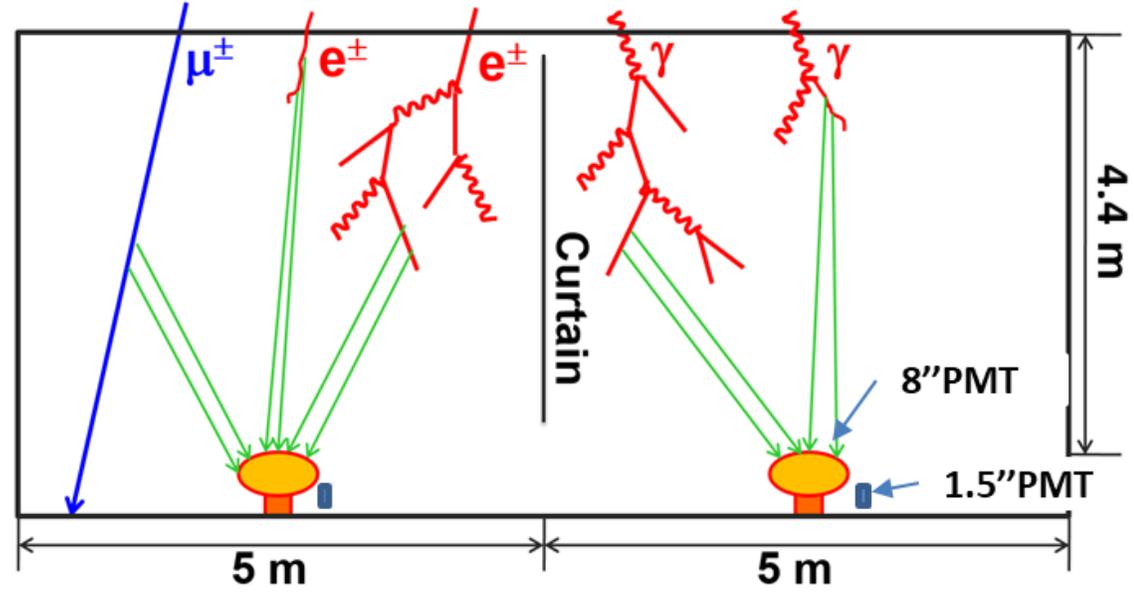


Energy rang

- ◆ WCDA-1
 - 300 GeV – 10 PeV
- ◆ WCDA-2 and WCDA-3
 - 100 GeV - 10 TeV

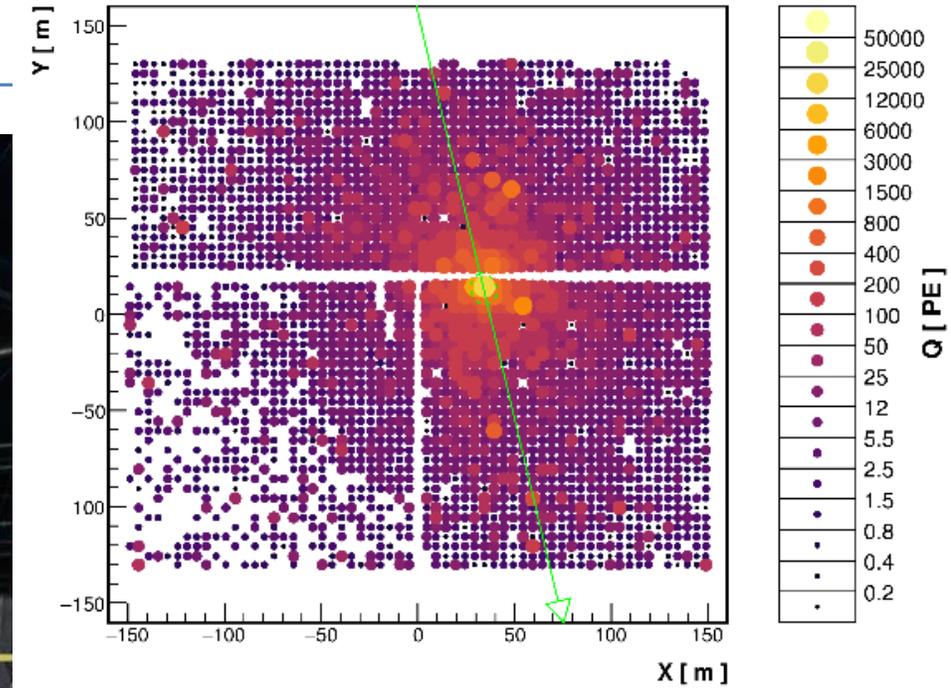
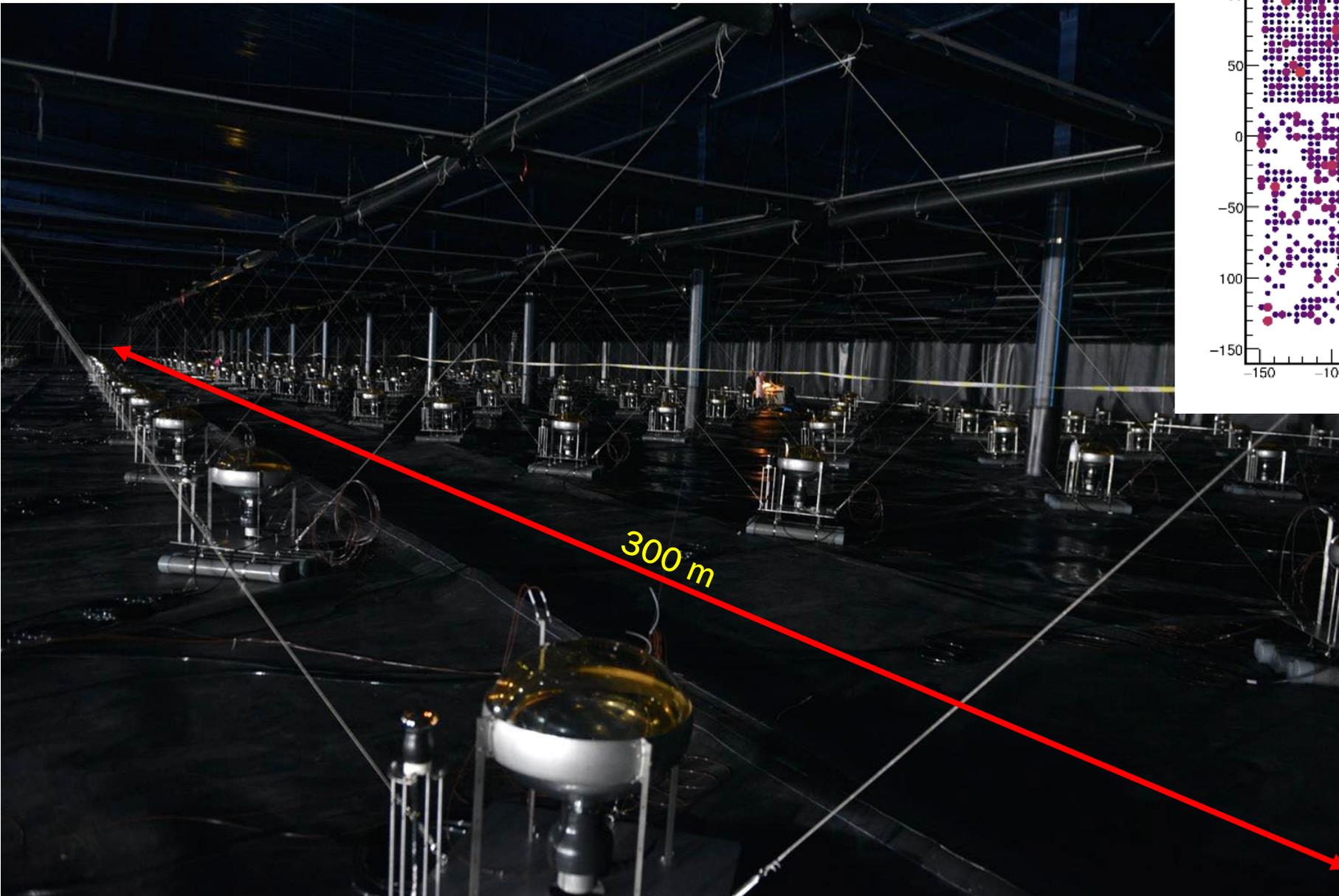


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two type of PMTs in each pool:
 - 8 inches and 1.5 inches for WCDA-1
 - 20 inches and 3 inches for WCDA-2 and WCDA-3



Inside of WCDA-3

20210511/131236/0.554789897: nTrig=-1, $\theta=37.81\pm 0.02^\circ$, $\phi=103.39\pm 0.02^\circ$



- ◆ WCDA-1 started operating in April 2019
- ◆ WCDA-2 started operating in January 2020
- ◆ WCDA-3 started operating in March 2021

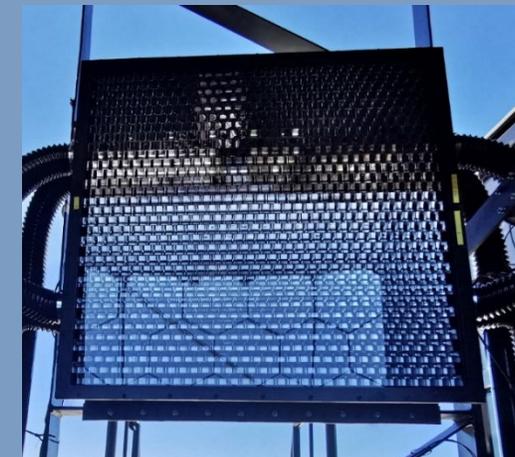
Wide Field of View Cherenkov Telescope (WFCTA)

◆ Telescope parameters:

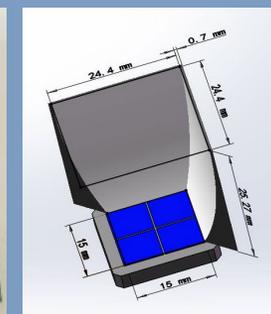
- $\sim 5 \text{ m}^2$ spherical mirror
- Camera: 32×32 SiPMs array
- FOV: $16^\circ \times 16^\circ$
- Pixel size: 0.5°



Mirror

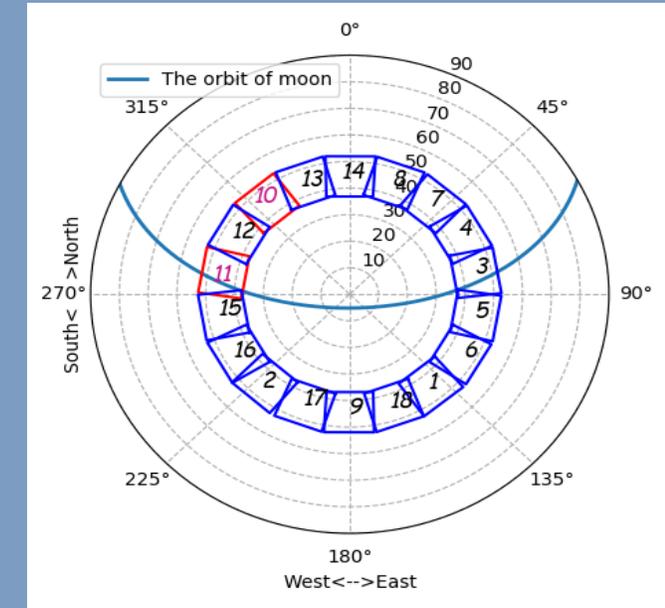
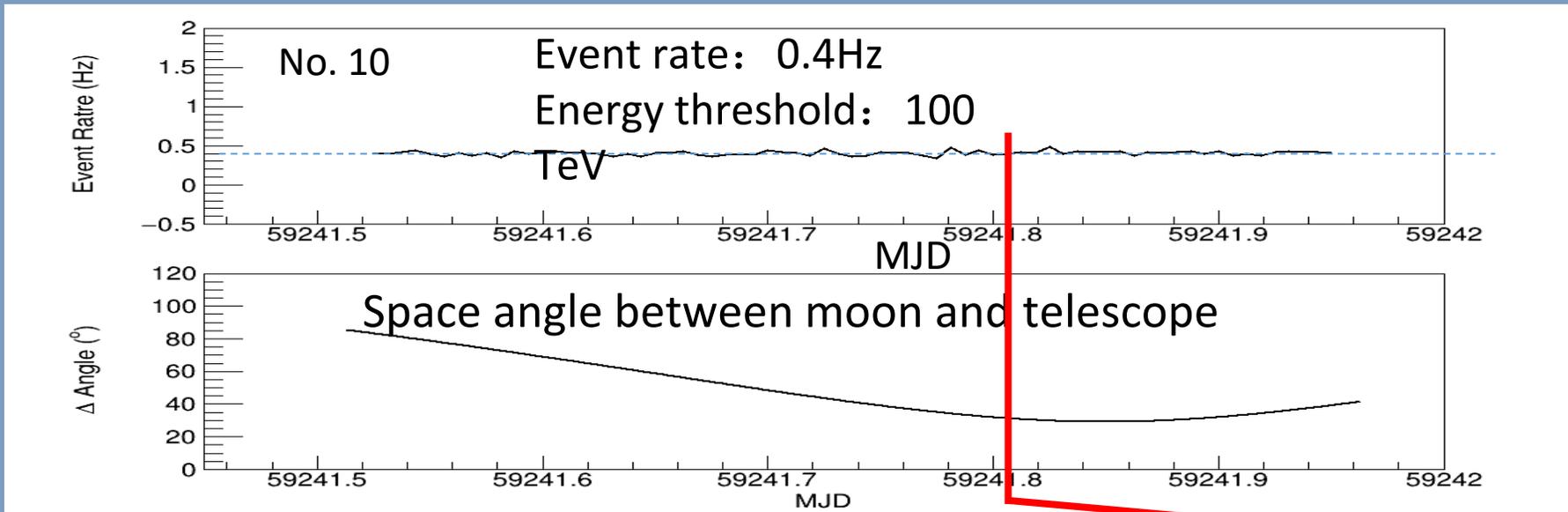


SiPM camera

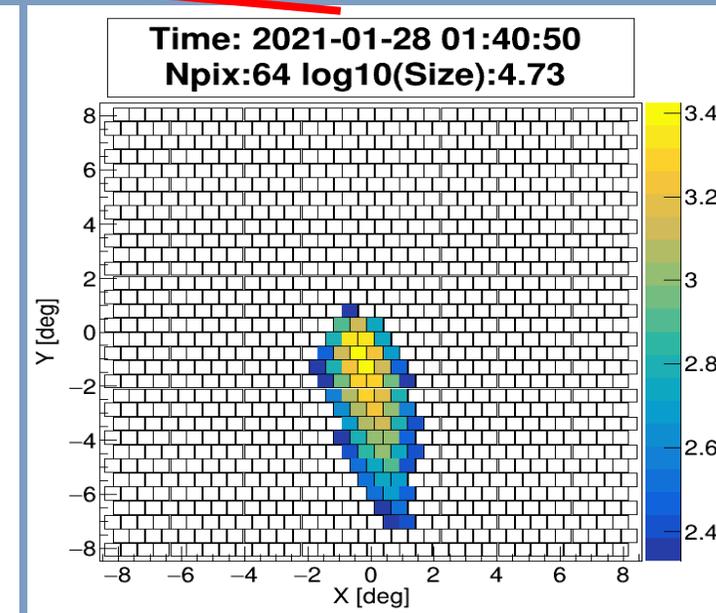
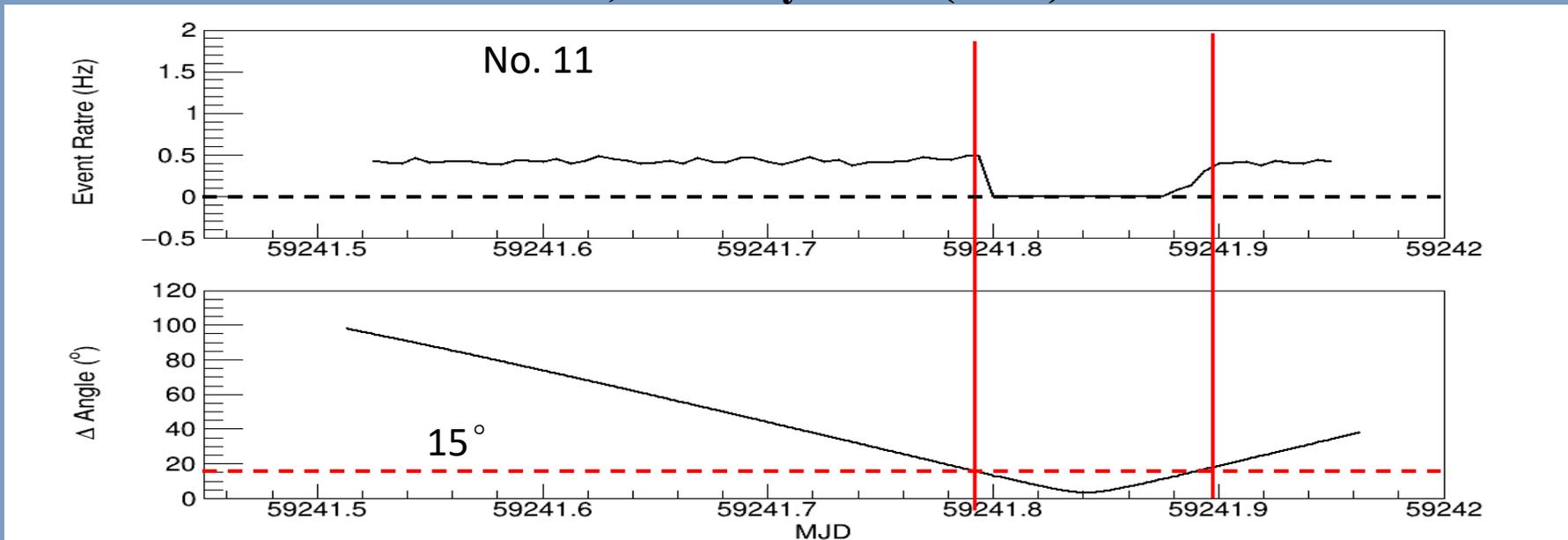


SiPM and Winstone cone

Telescope observation on the full moon night



SiPM camera: LHAASO Coll., Eur. Phys. J. C (2021) 81:657





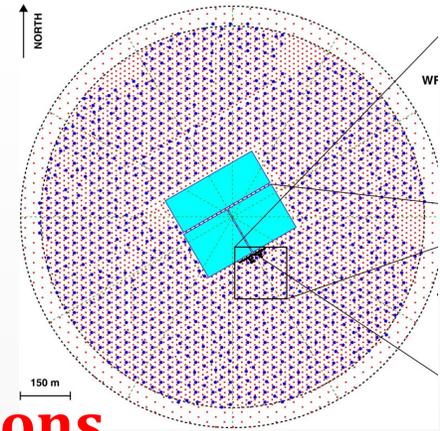
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KM2A

Selection of γ -rays out of CR background

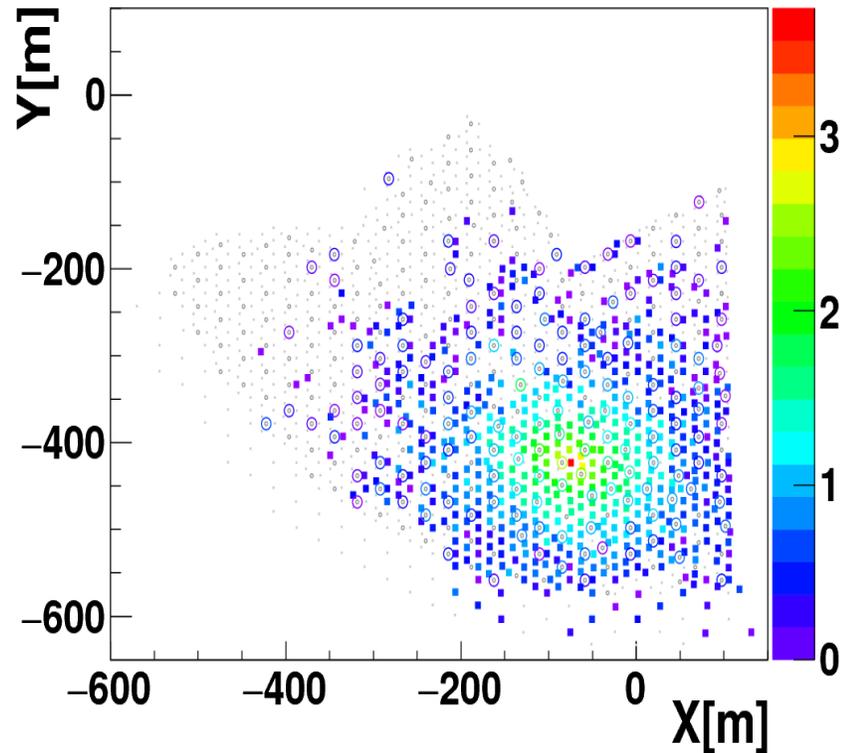
Active Area for Muons vs. Array Area: 4%



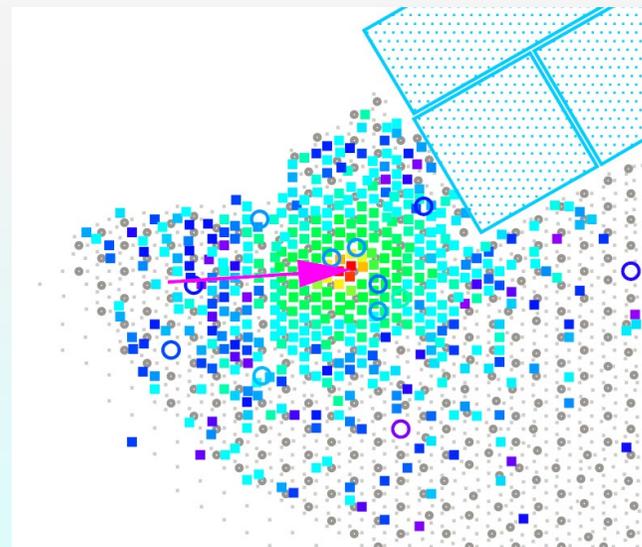
~1 PeV CR event: many muons

~ 1 PeV γ -ray event : very few muons

MJD:58788, NHitE:656, NHitM:154, Theta:31.2deg, Phi:284.0deg



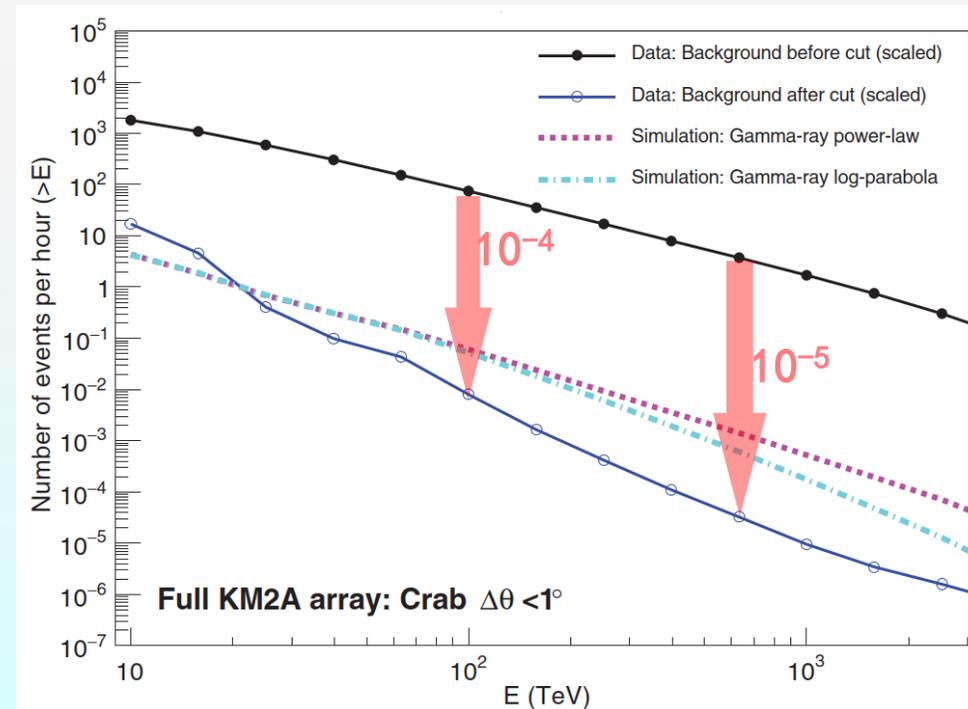
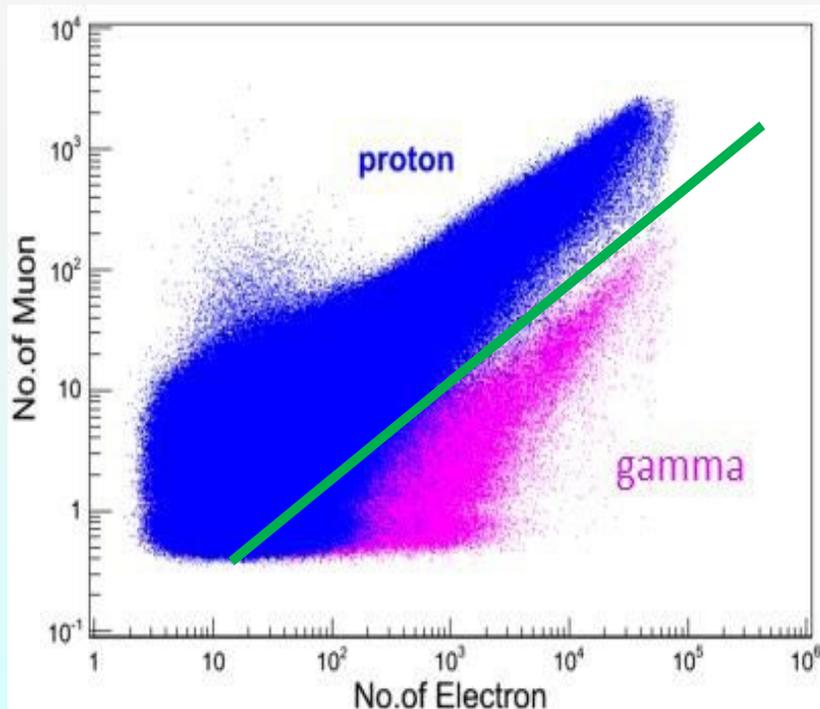
~1 PeV from the Crab



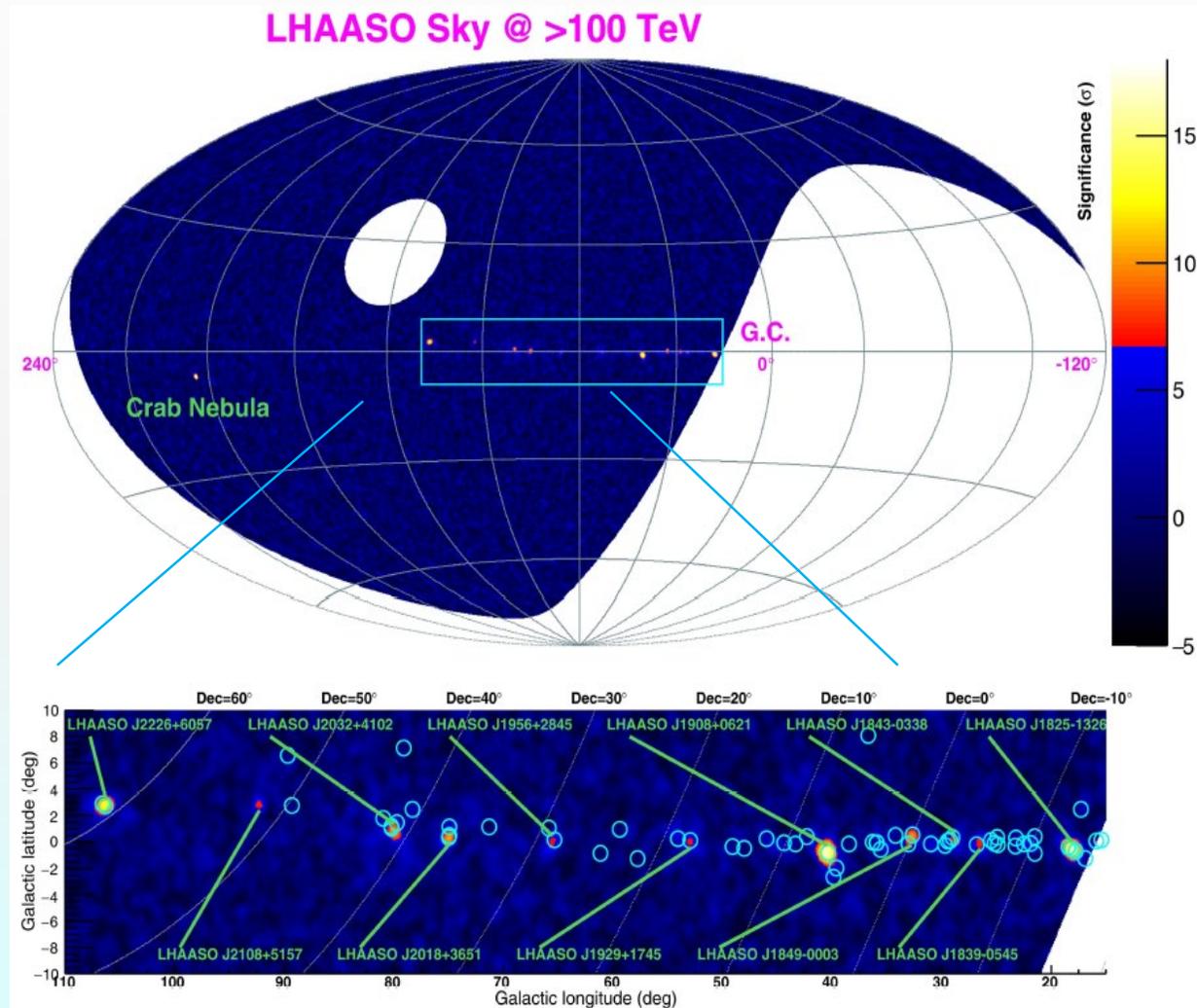
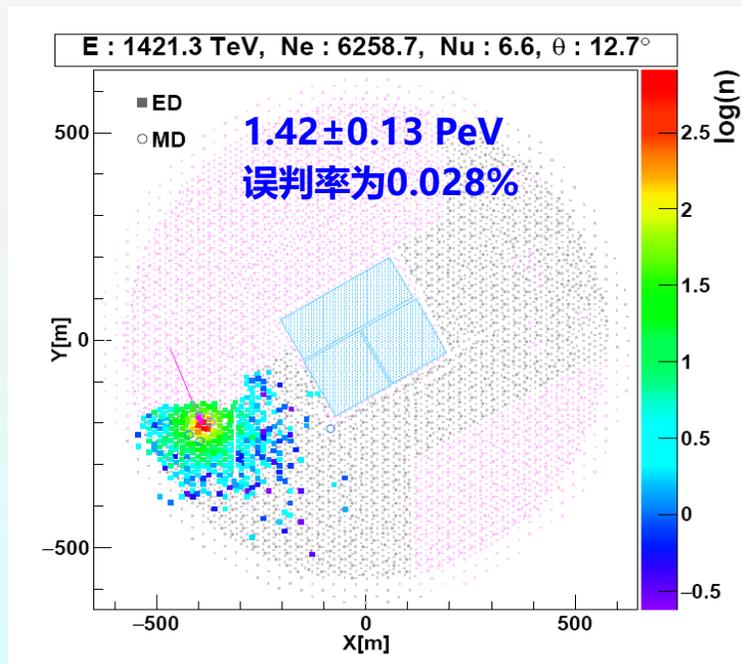
- ◆ Area:
1.3 km²
- ◆ Detectors:
5242 ED
1188 MD
- ◆ Energy Range:
0.01-10 PeV

CR background Rejection Power

- ◇ Counting number of measured muons in a shower
- ◇ Cutting on ratio $N_{\mu}/N_e < 1/230$
- ◇ BG-free ($N_{\gamma} > 10N_{CR}$) Photon Counting for showers $E > 100$ TeV from the Crab

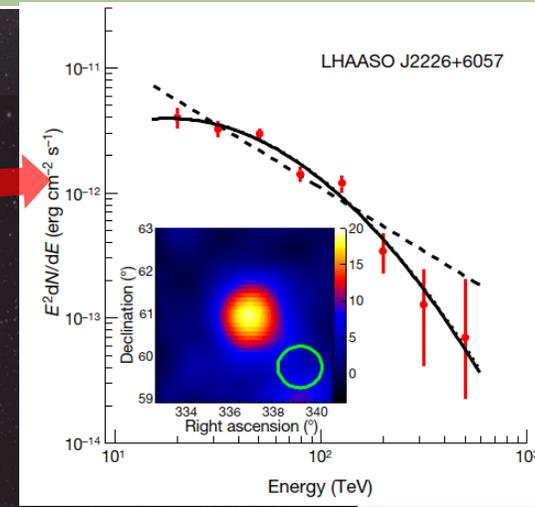
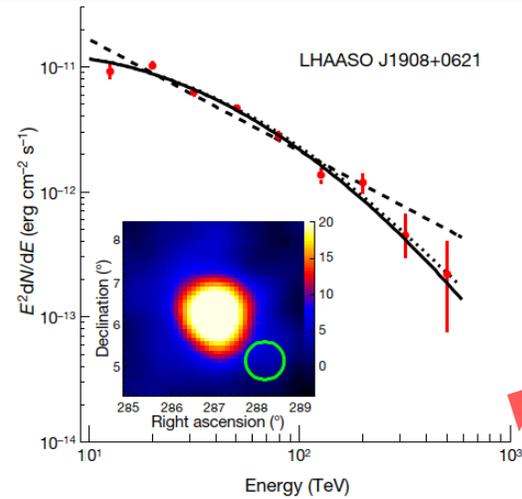


- ◆ 发现首批**12**个拍电子伏加速器
- ◆ **1.4PeV**最高能量光子，预示超级拍电子伏加速器

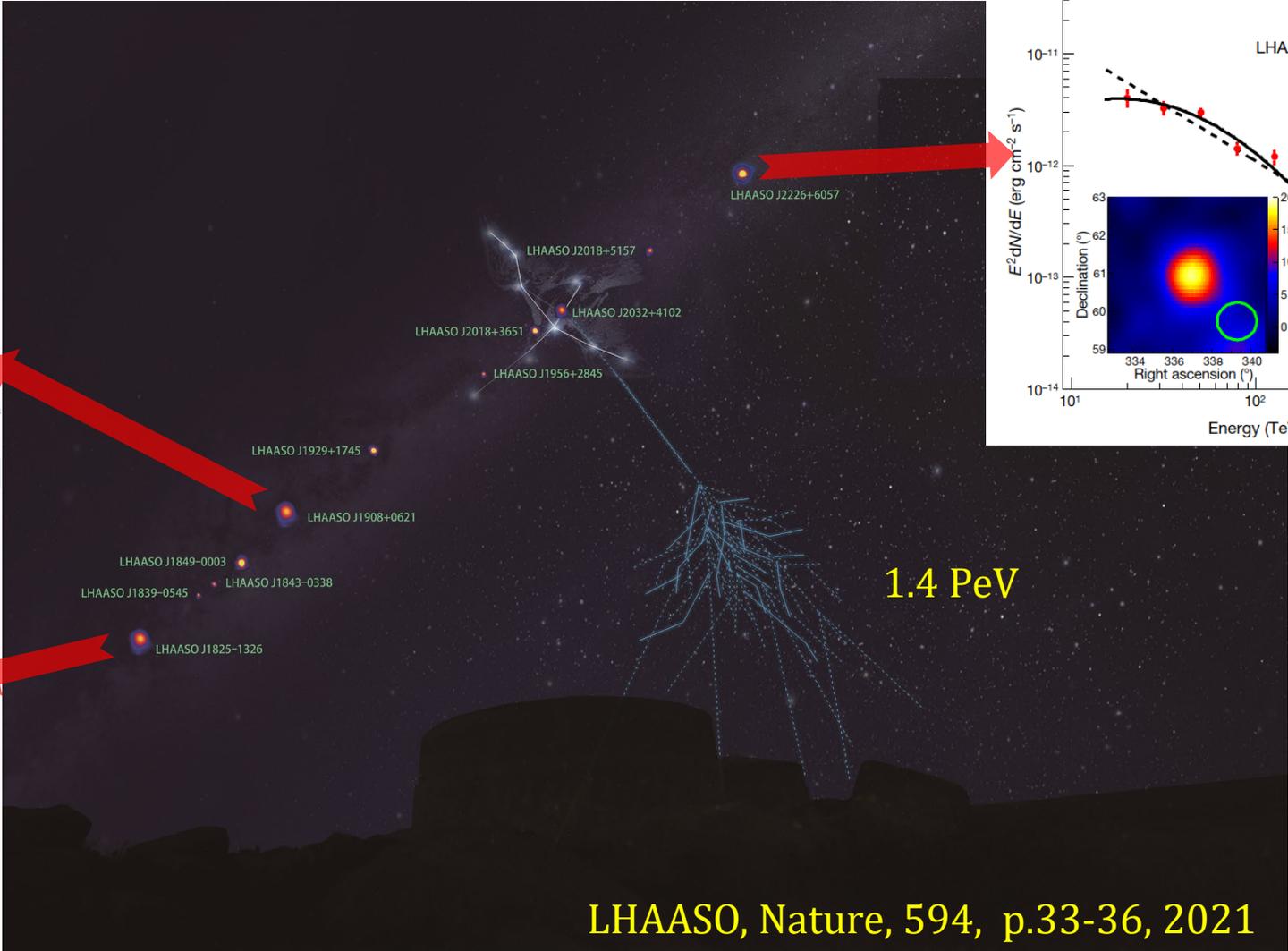
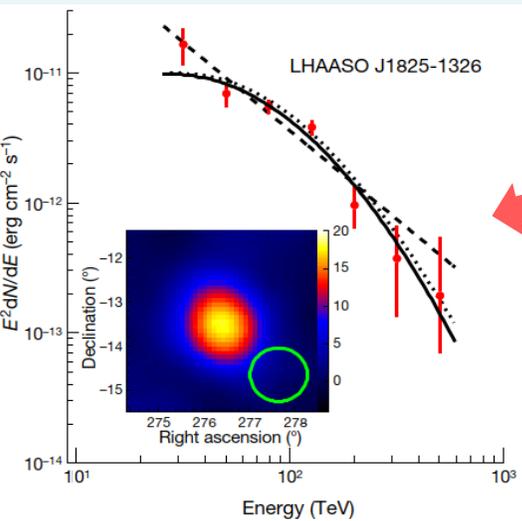


Discovery in KM2A Survey

Do not observe clear cut-off up to ~ 1 PeV



河内存在许多PSR, 都是宇宙线源候选天体!



- Three brightest PeVatrons
- ◆ No trend of cut-off in SED of γ -ray sources
 - ◆ Updates using newer data show continuous extension to higher energies

超高能LHAASO星表(11个未认证)

◆ 高显著性:

$>7\sigma$

◆ 高统计量:

534个光子

(~65个背景)

◆ 最高能量:

超过1PeV

Source name	Significance	E_{\max} (PeV)
LHAASO J0534+2202	17.8	1.12 ± 0.09
LHAASO J1825-1326	16.4	0.42 ± 0.16
LHAASO J1839-0545	7.7	0.21 ± 0.05
LHAASO J1843-0338	8.5	$0.26^{+0.16}_{-0.10}$
LHAASO J1849-0003	10.4	0.35 ± 0.07
LHAASO J1908+0621	17.2	0.44 ± 0.05
LHAASO J1929+1745	7.4	$0.71^{+0.16}_{-0.07}$
LHAASO J1956+2845	7.4	0.42 ± 0.03
LHAASO J2018+3651	10.4	0.27 ± 0.02
LHAASO J2032+4102	10.5	1.42 ± 0.13
LHAASO J2108+5157	8.3	0.43 ± 0.05
LHAASO J2226+6057	13.6	0.57 ± 0.19

Crab Nebula

Nature 594:33-36 (2021)



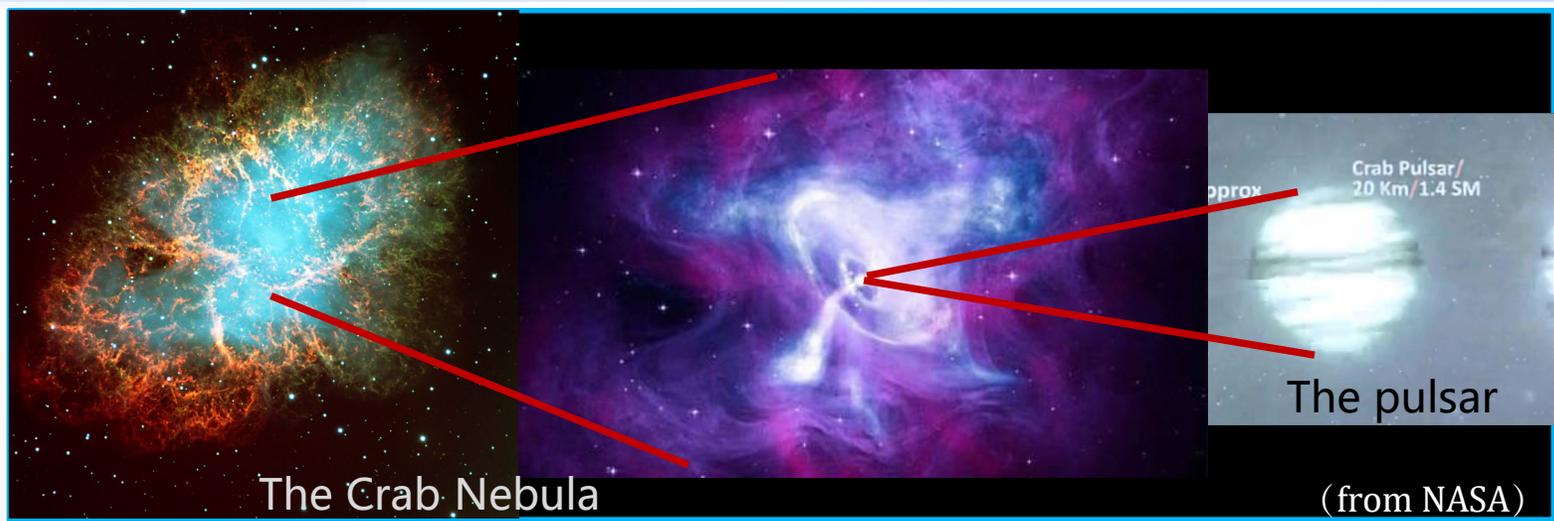
高

Standard candle observation

出於東井下戊子客星別出子端門內近屏星 四月丙午東井下
 客星沒 五月客星出端門內客星沒壬午客星如掌在南十天
 昭宗乾寧三年有客星三一大二小在屋危間乍合作離相隨東行
 狀如闕經三日二小星沒其大星後沒虛危齊分也 光化三年
 正月客星出 宦者旁大如桃光炎射 宦者不見 天復
 二年正月客星出 宦者在紫宮華蓋下漸行至 宦者不見 天復
 昌黎客星客星動 已外星在在守之 宦者不見 天復
 出兵

梁太祖乾化二年正月客星出 宦者不見 天復
 宋太祖太宗實二年朝客星出 宦者不見 天復
 市垣宗人星事 有客星三 宦者不見 天復
 至七星沒大平興國八年二月甲辰客星出 宦者不見 天復
 北行占曰主嗣臣失禮免端 二年七月丁亥客星出北河星西北
 稍暗微有芒 西南南淳化元年正月辛巳客星出 宦者不見 天復
 七十日經四 宦者不見 天復
 甲辰客星出 宦者不見 天復
 十一日沒占 宦者不見 天復
 南方大中 宦者不見 天復
 親祀汾陰后 宦者不見 天復
 如挑速如經 宦者不見 天復
 七十五日入 宦者不見 天復
 仁宗明道元年 宦者不見 天復
 于凡十三日 宦者不見 天復
 歲餘消沒

神宗熙寧元年 宦者不見 天復
 民飢大臣有長 宦者不見 天復
 三年十一月丁



The coverage of 3.5 orders of magnitudes of energy

0.5 - 12 TeV

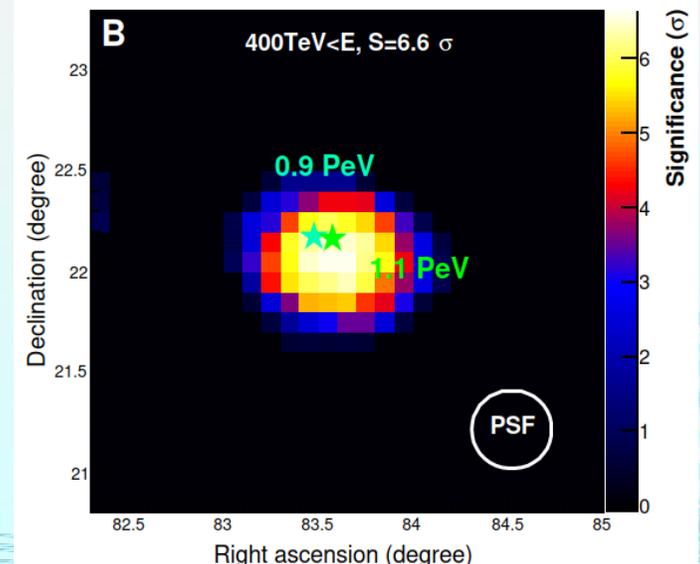
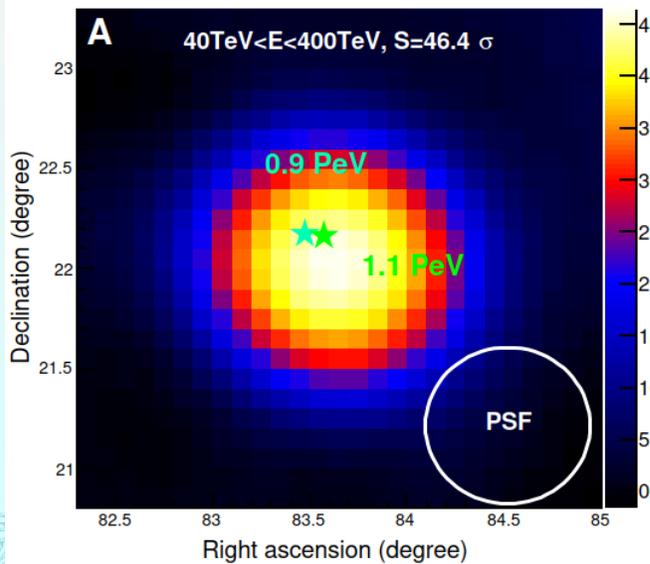
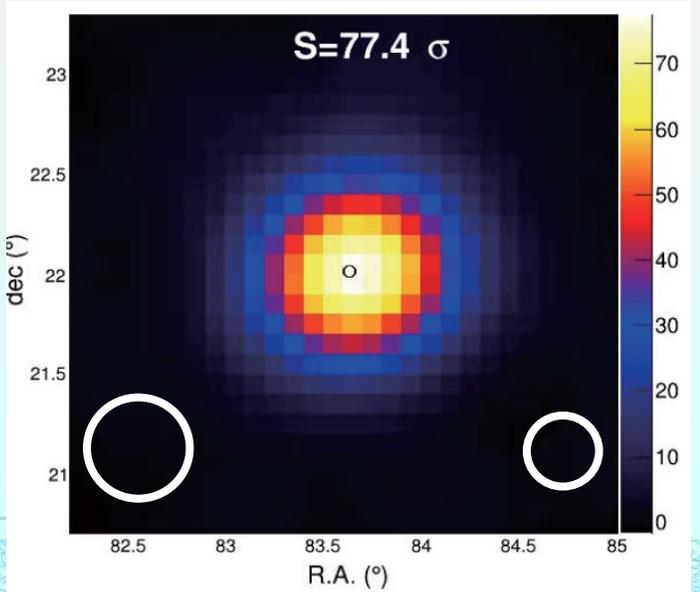
PSF: 0.22°

40-400 TeV

0.26°

0.4-1.2 PeV

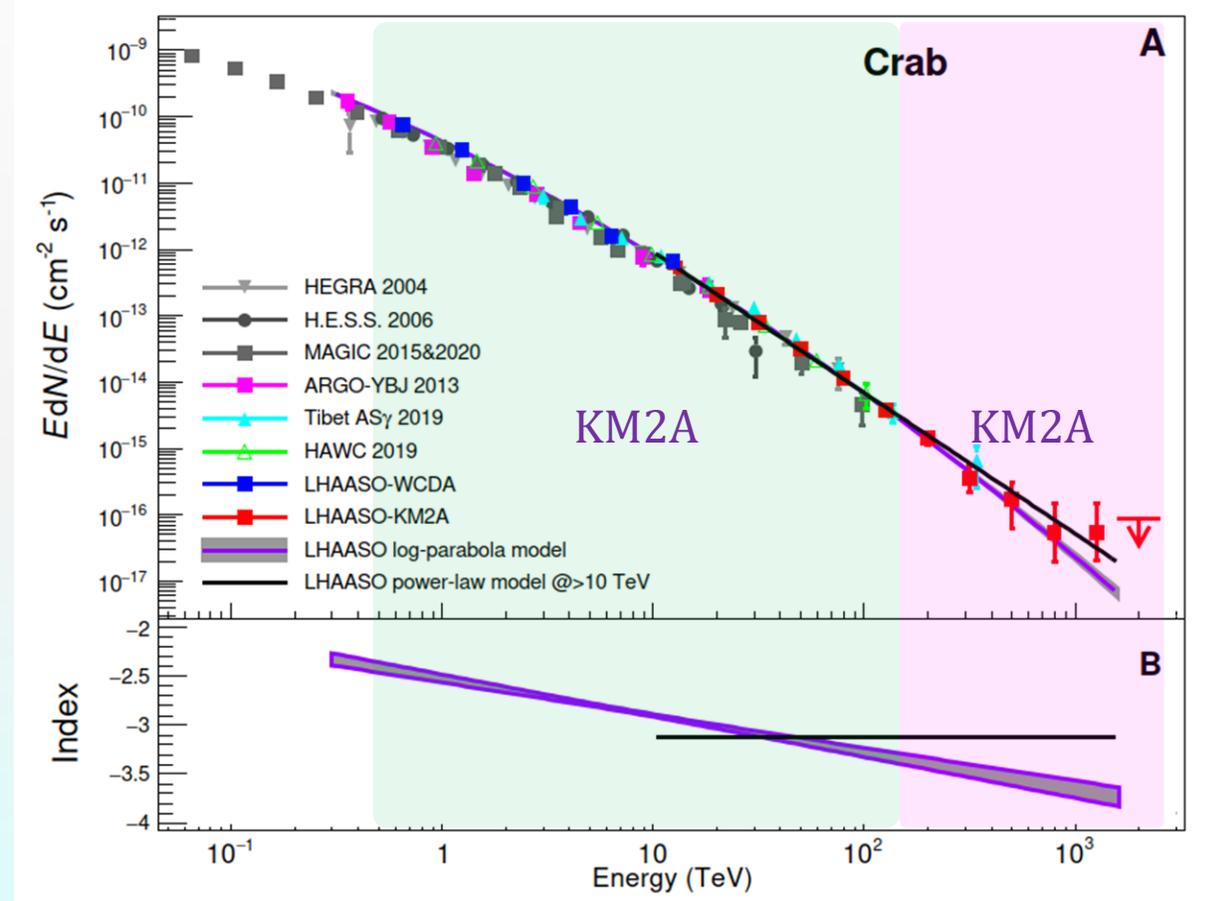
0.15°



SED of the Crab: “standard Candle” & PeVatron

LHAASO, Science, Science, 373, 425 (2021)

- ◇ **LHAASO:**
 - Covering 3.5 decades of energy
 - Agreeing with other experiments below 100 TeV
 - Self cross-checking between WCDA & KM2A
- ◇ **LHAASO-KM2A:**
 - Unique **UHE SED**
 - A **PeVatron** without ambiguity
 - Clear **origin**: a well-known PWN
- ◇ **An extreme e-accelerator:**
 - 2.3 PeV electrons
 - in **~0.025 pc** core region
 - accelerating efficiency of **15%** ($1000\times$ better than SNR shock waves)

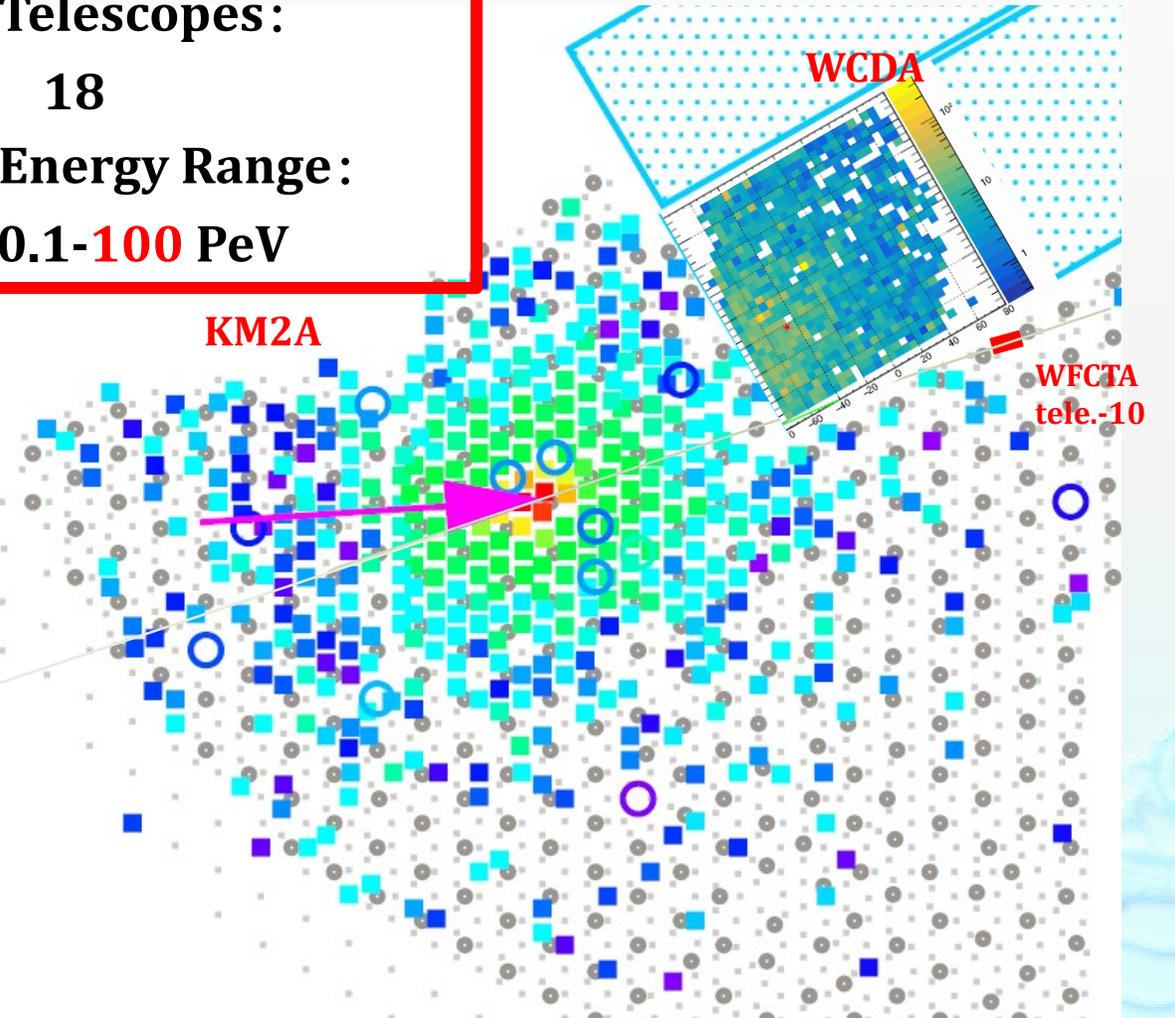


Wide FoV C-Telescope Array (WFCTA)

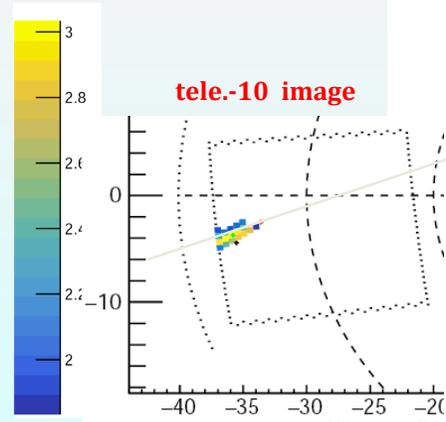
Cross-checking inside Collaboration



- ◆ Telescopes:
18
- ◆ Energy Range:
0.1-100 PeV

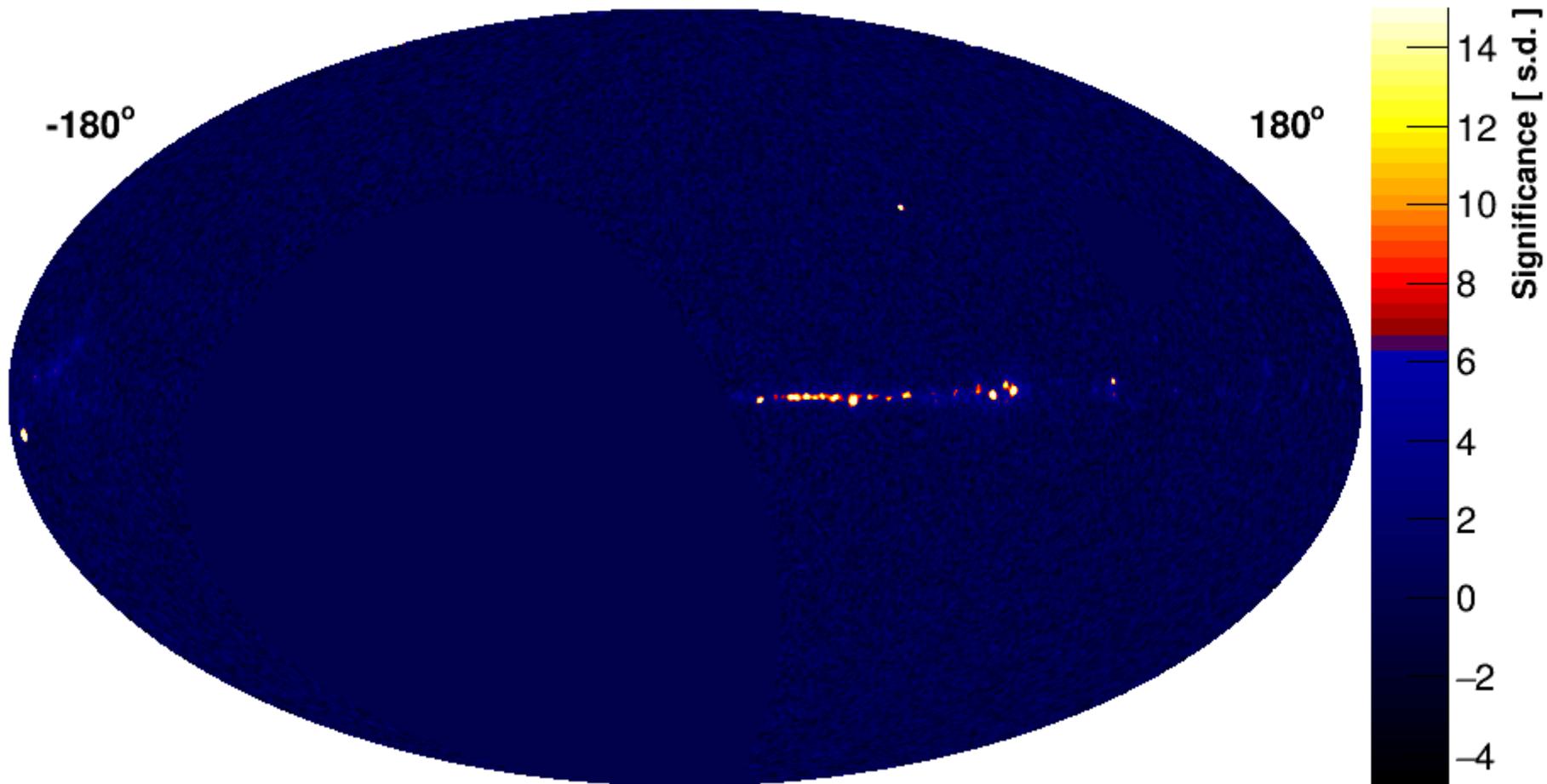


- ◆ WFCTA measured the event simultaneously
 $L/W \sim 2.6$, $N_{pe} \sim 9100$ in 11 pixels
- ◆ **Energy: 0.9 ± 0.2 PeV**
- ◆ KM2A measured the event
 $N_{particle} \sim 4574$ in 395 EDs
- ◆ **Energy: 0.9 ± 0.1 PeV**
- ◆ **Chance probability: $< 0.1\%$**
- ◆ $N_{\mu} \sim 15$ in 11 MDs



New TeV Catalog

◆ WCDA New Sky Map



LHAASO首个甚/超高能星表将在2023年发布

探索洛伦兹对称破缺LIV

- 洛伦兹对称性破坏会导致一些奇异现象，如光速不是常数，而有能量依赖
- 高能光子若超过光速，则不稳定会衰变到正负电子对或者三个光子

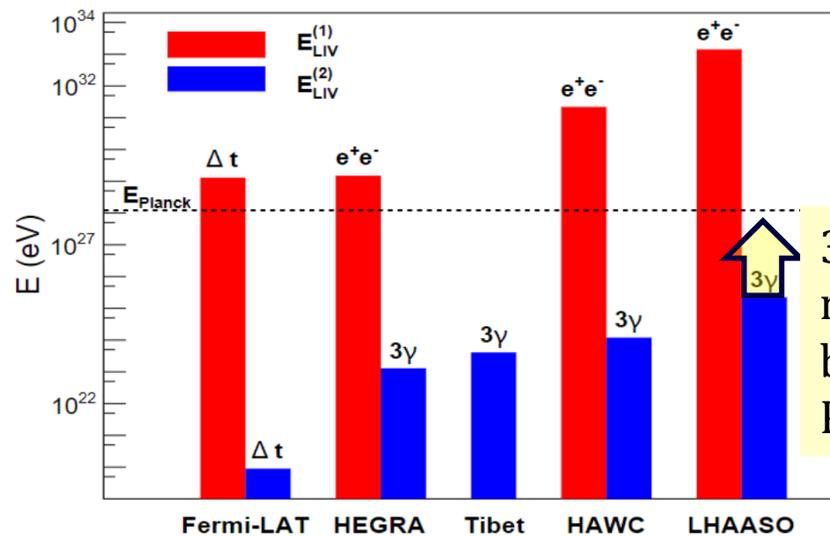
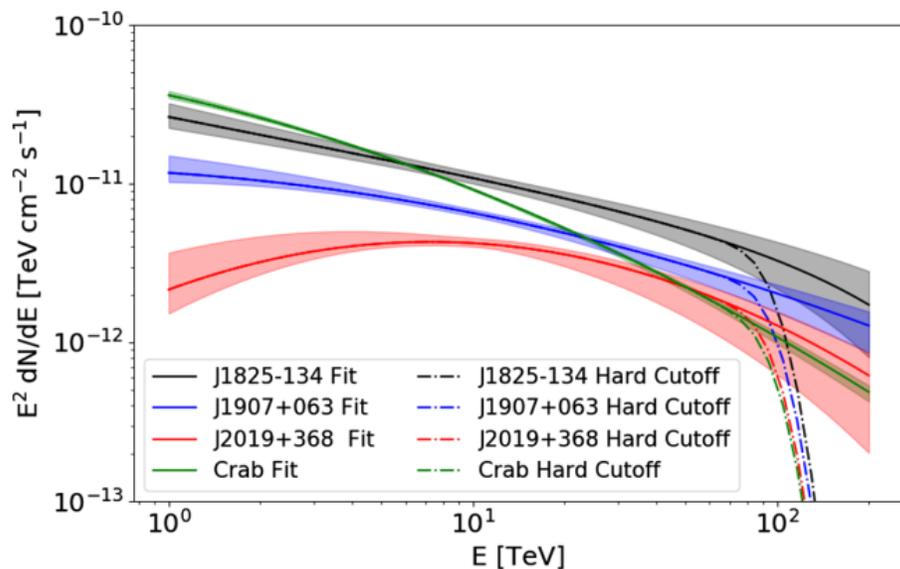
Process: $\gamma \rightarrow e^+e^-$

Process: $\gamma \rightarrow 3\gamma$

$$E_\gamma^2 - p_\gamma^2 = \pm |\alpha_n| p_\gamma^{n+2},$$

$$E_{LIV}^{(n)} = \alpha_n^{-1/n} \cdot (n > 0)$$

- 高能光子衰变的后果是伽马射线谱有高能硬截断；
- 分析了LHAASO观测的两个最高能量的源LHAASO J0534+2202和LHAASO J2032+4102
- LHAASO观测到目前最高能量的伽马事例，能对LIV给出最强的检验，比以前的限制提高了一个量级多。

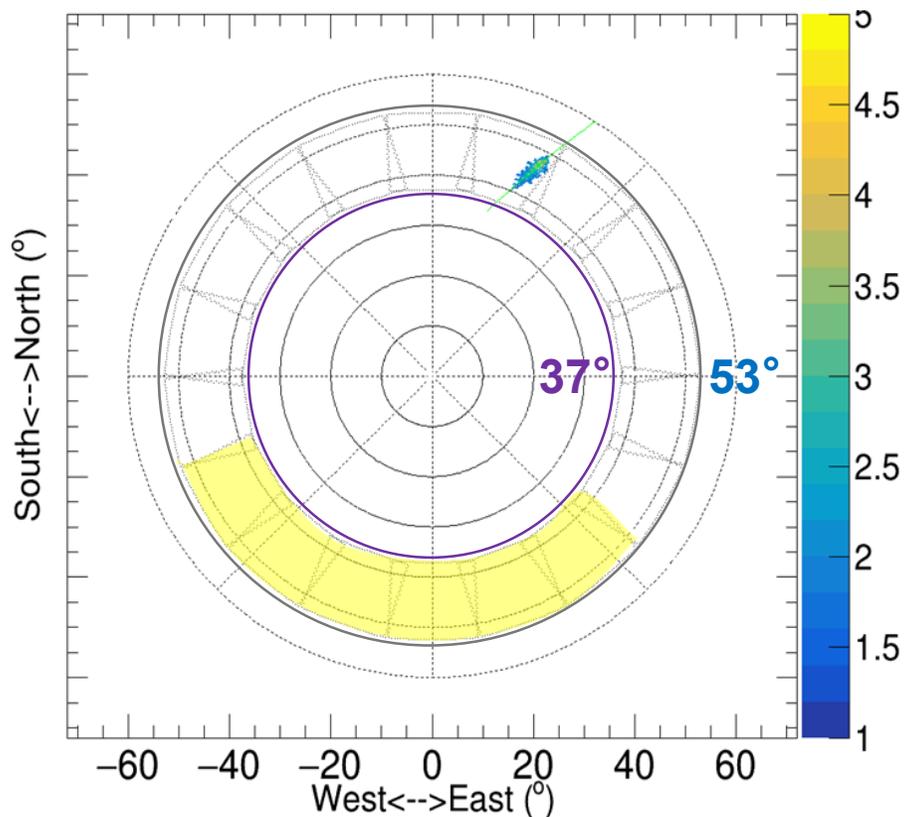
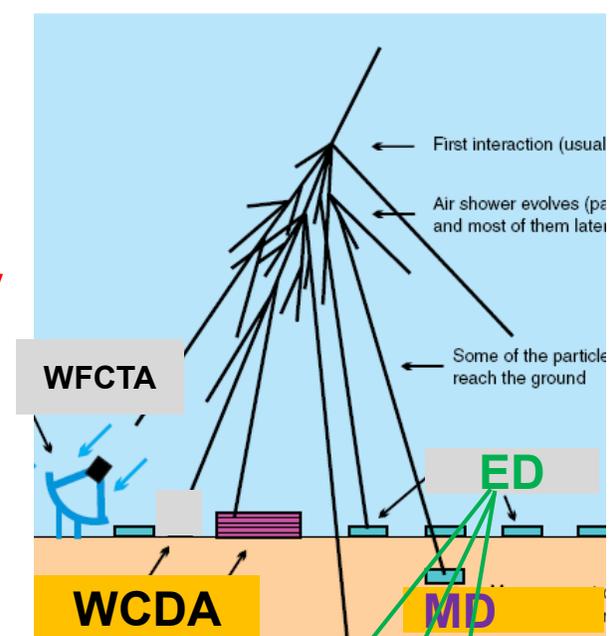


3 orders of magnitudes below the Planck-scale

Charged Cosmic Rays

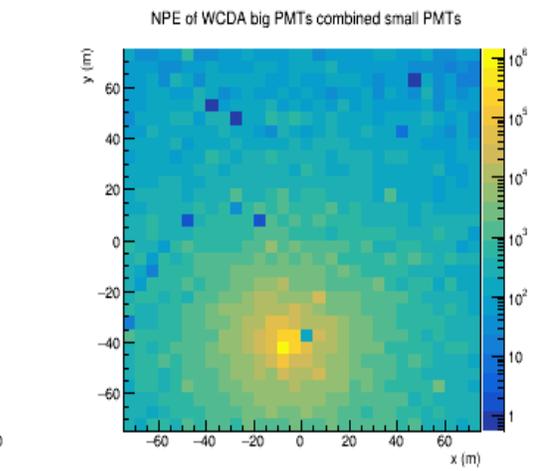
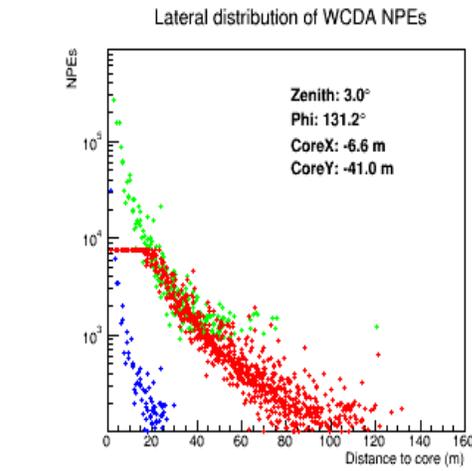
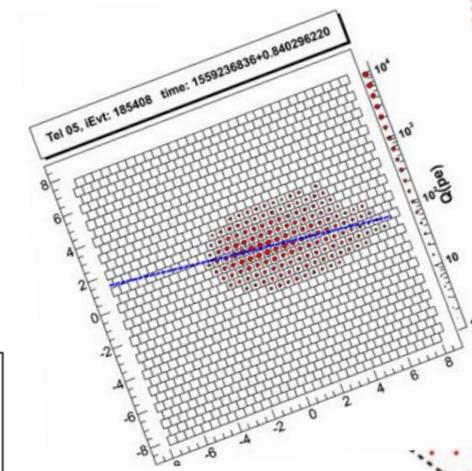
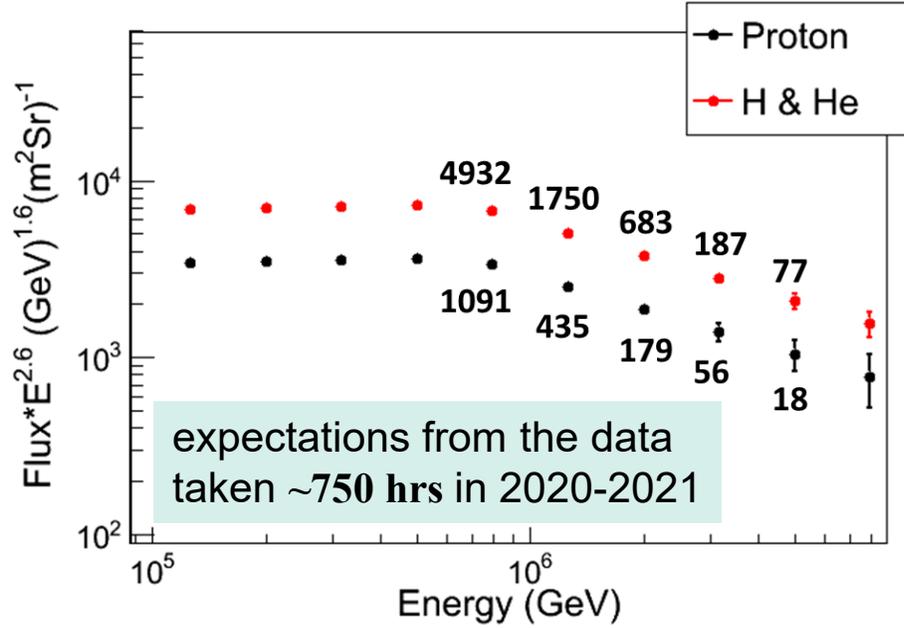
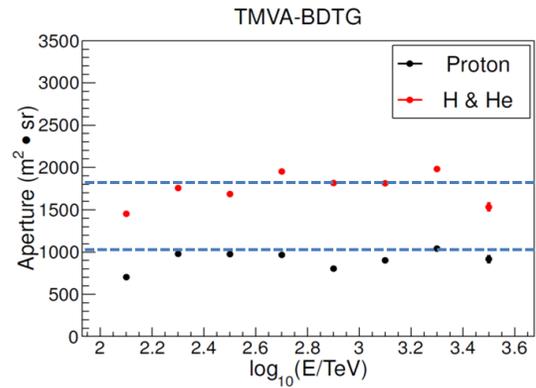
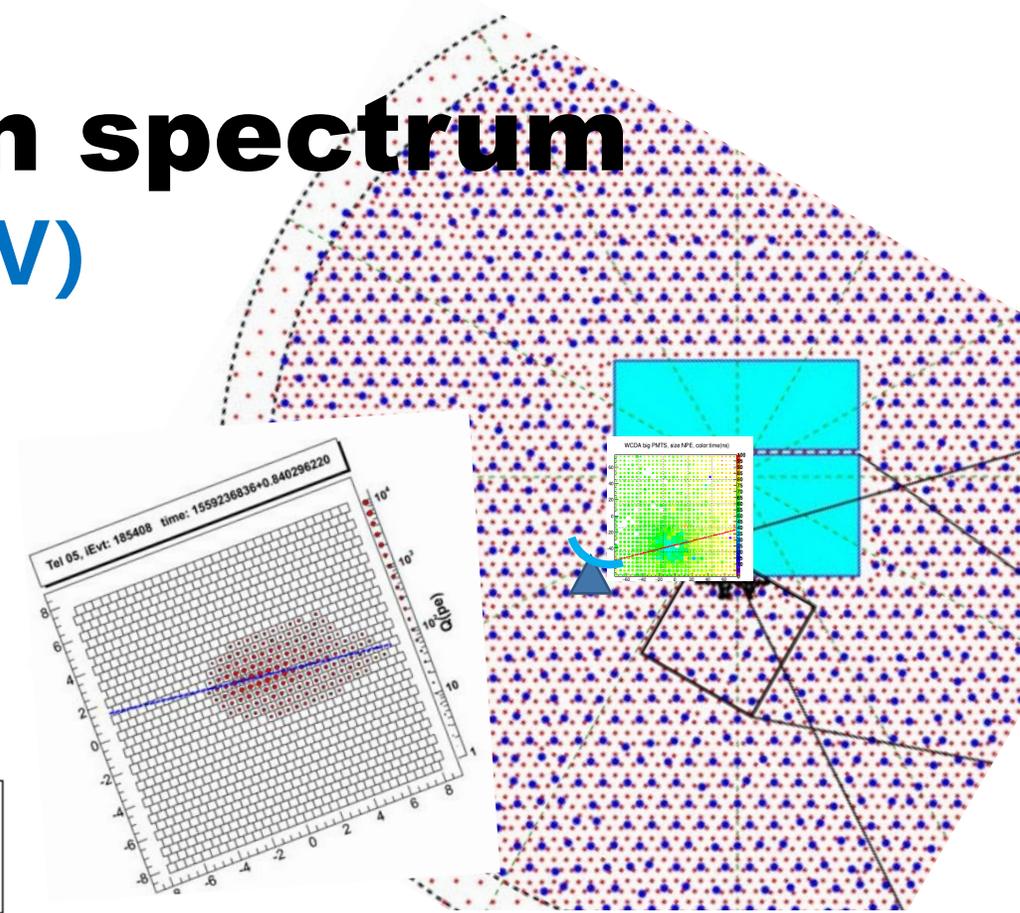
- Measuring **AS front** by **WCDA** or **ED** array (0.2°)
- Measuring **E-flux** near core by **WCDA** (2m)
- Measuring **μ -content** by **MD array** ($1-10^4$ each)
- Measuring **X_{\max}** by **WFCTA** (40 g/cm^2)
- Measuring **AS Energy** by **WFCTA** (15%)

- Calibrate **E-scale** using moon shadow by **WCDA** at $6 < E < 30 \text{ TeV}$
- **$\Delta E/E$** currently 30% dominated by Statistics and **<10%** in 4 yrs
- Propagating the **E-scale** to **WFCTA** by using commonly triggered CRs



The knee of Proton spectrum

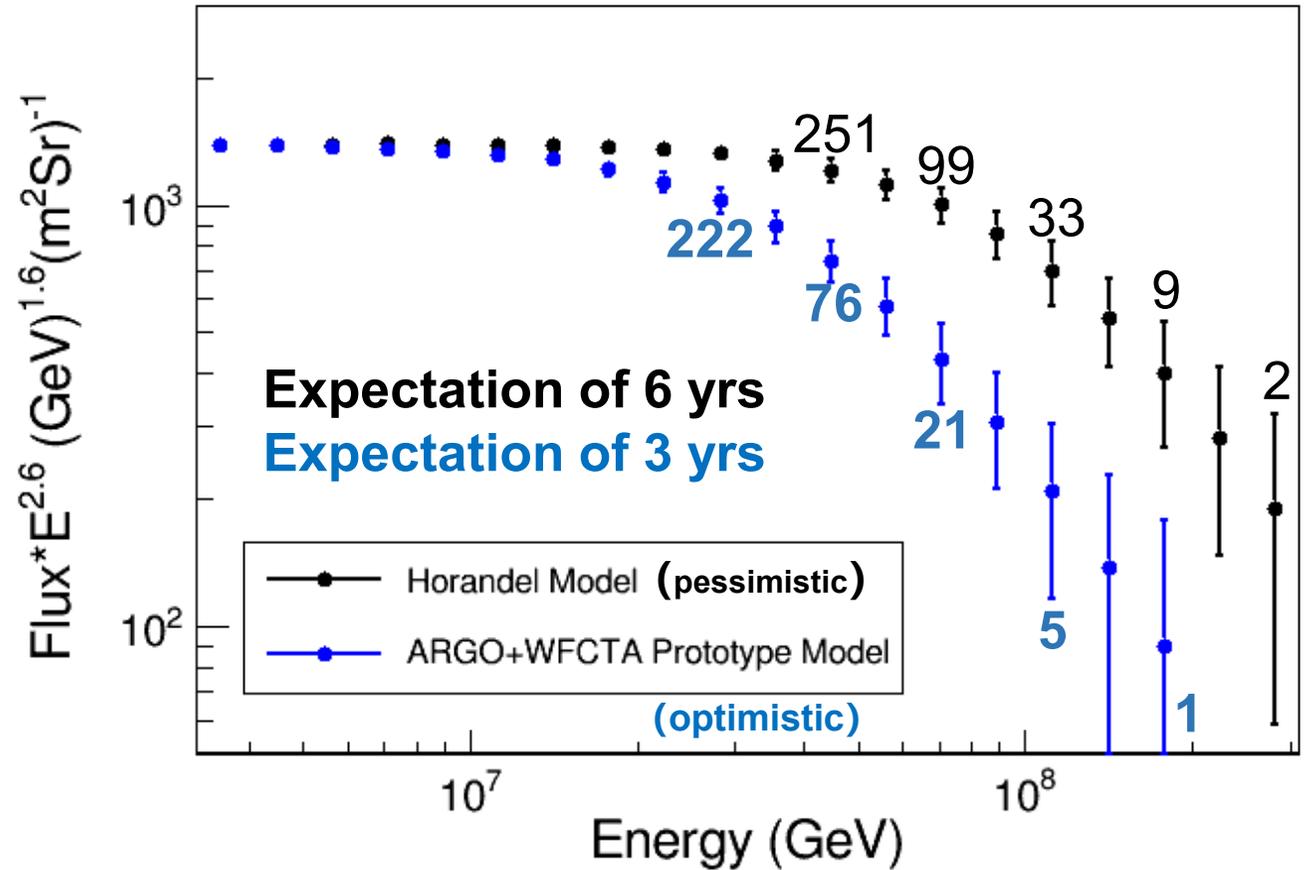
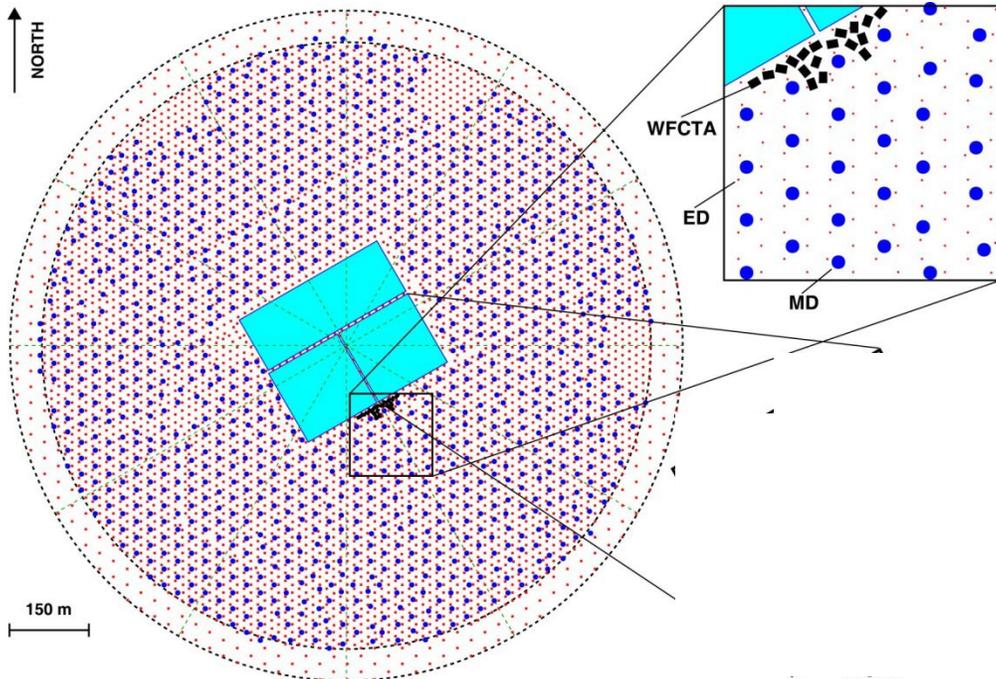
- Coincident events by **WCDA** and **($E_b \sim 0.7$ PeV)**
6 telescopes (phase I)
- Shower cores in **WCDA-1**
- Selecting pure **proton** showers by 4 parameters: aperture of **1000** m² sr
- **H+He** showers: aperture of **1800** m² sr



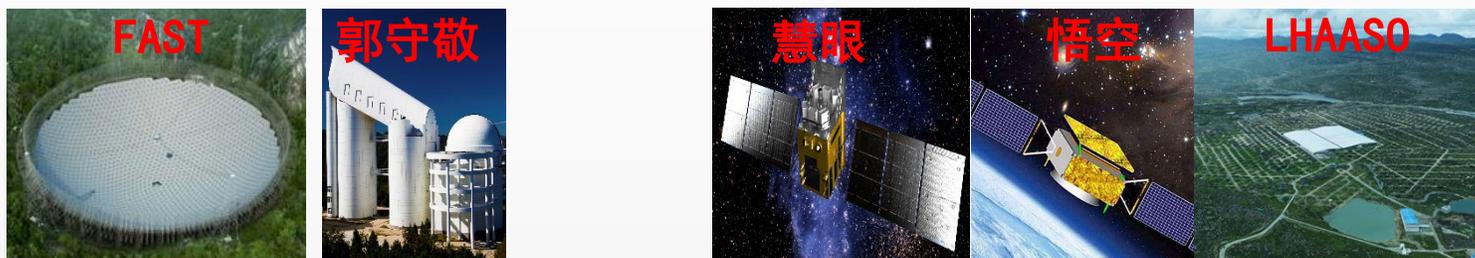
The knee of Fe spectrum

($E_b \sim 24$ or 50PeV)

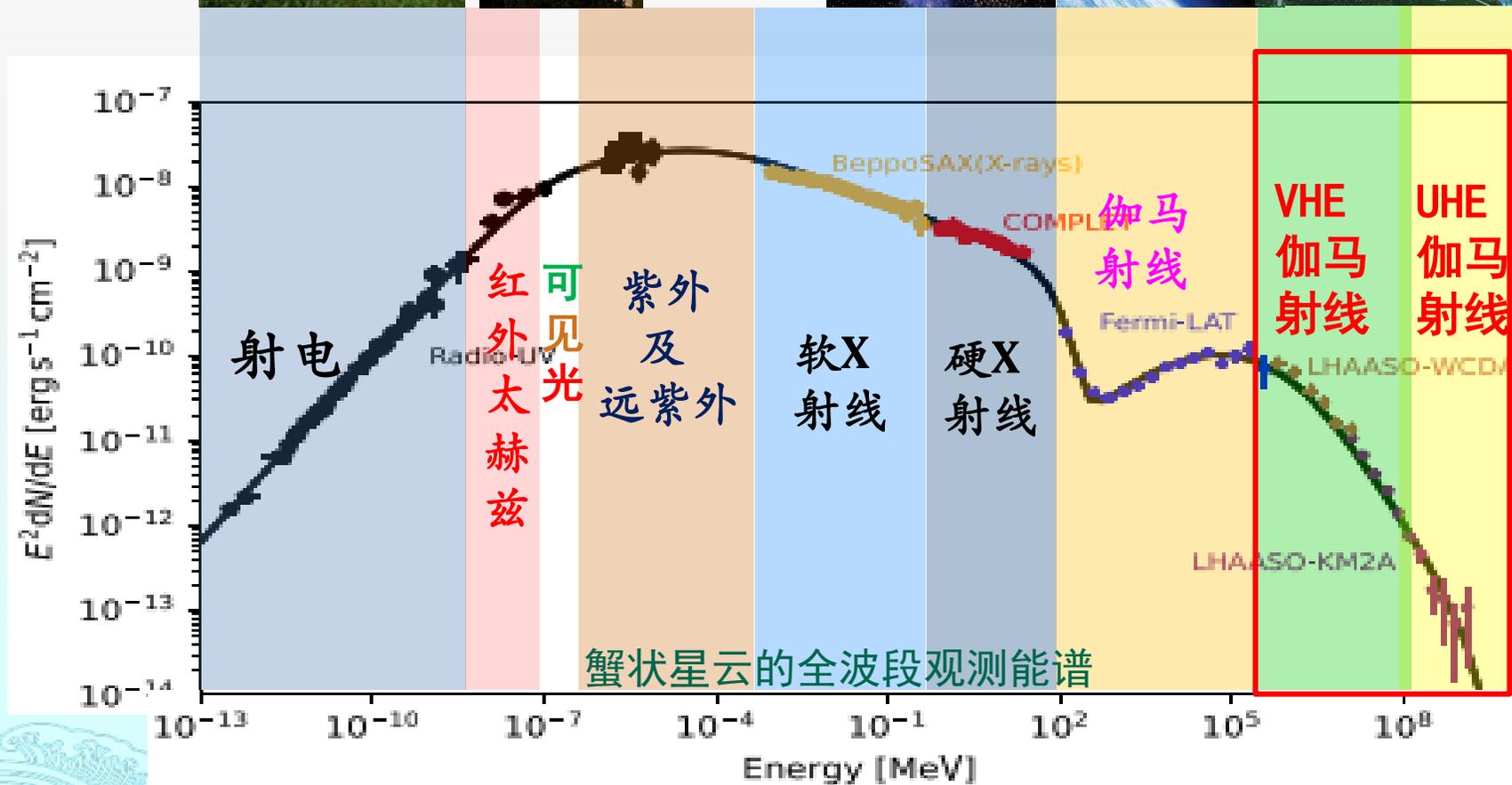
- Coincident events by both **WFCTA** and **full KM2A (phase-II)**
- Shower cores are in 1 km^2
- Incline shower with depth of 840 g/cm^2



LHAASO开启UHE γ -天文学新时代



LHAASO的建成，突破了国际上长期没有超高能伽马射线望远镜的瓶颈，使我国天文观测领域拥有了几乎全波段的观测能力。



采用“边建设、边运行”模式，LHAASO运行一年即发现人类历史上从未观测到的最高能伽马光子，达1.4拍（拍=千万亿）电子伏；发现一批亚拍电子伏以上银河系伽马源，揭示了银河系内广泛存在“拍电子伏粒子加速器”，其加速能力突破了传统认知，加速能力超过人类最大的加速器1千到1万倍，开启了“超高能伽马天文学”时代。



报告内容

- LHAASO介绍
- LHAASO 物理分析进展
- 未来探测器计划
- 总结

我国宇宙线实验历程与展望

LHAASO仍然需要扩展

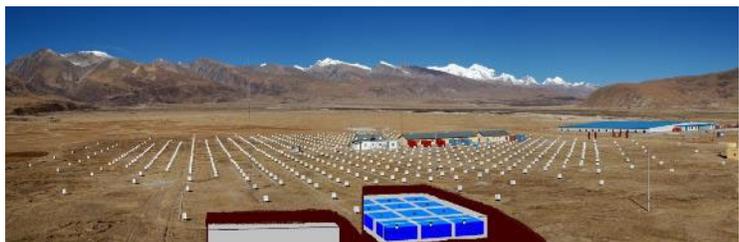
国际领先的大科学装置

- 2019 –: 稻城海子山, LHAASO



下一代?

需要多项关键技术攻关
目标: 敲定宇宙线起源



- 1980s –: 羊八井, Tibet AS γ , ARGO-YBJ



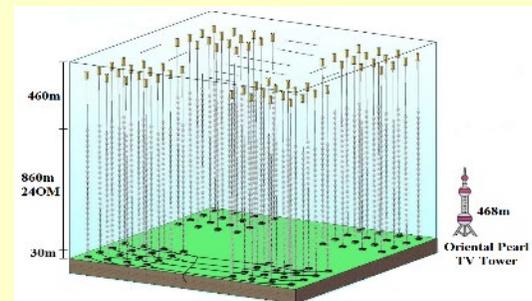
- 1970s – 1980s: 甘巴拉山, 乳胶室



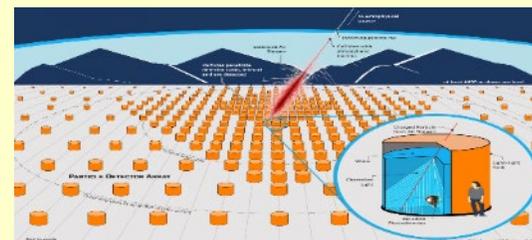
- 1960s – 1970s: 云南落雪山, 大型云雾室



- LACT: 大型空气切伦科夫望远镜



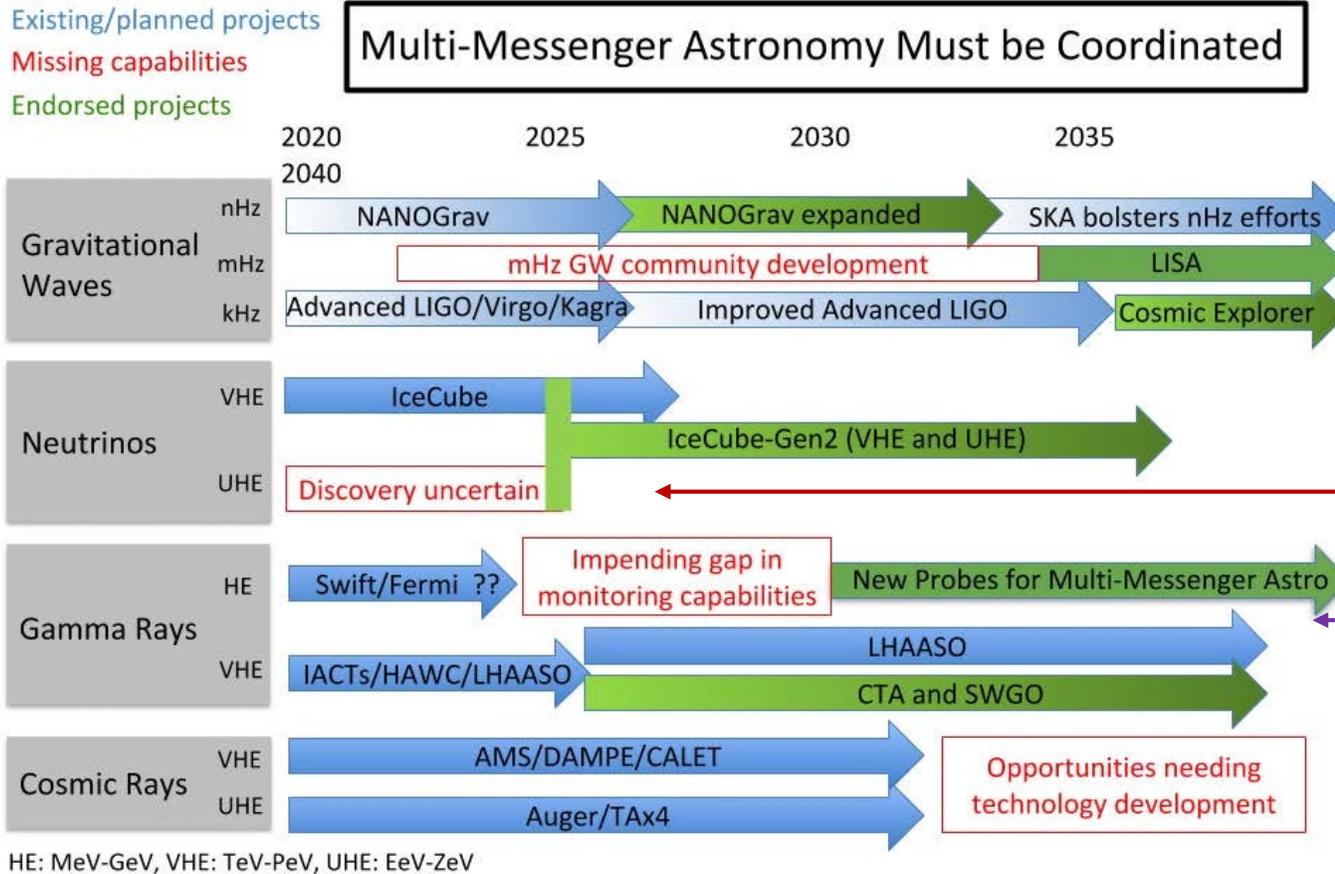
- H ν T: 高能中微子望远镜



- SWGO: 南方宽视场伽马天文台

美国天文和天体物理的十年规划报告 (ASTRO2020) :

多信使项目的发展情况 和 LHAASO的国际地位



蓝色：存在的实验
绿色：计划的项目
红色：尚缺失的能力

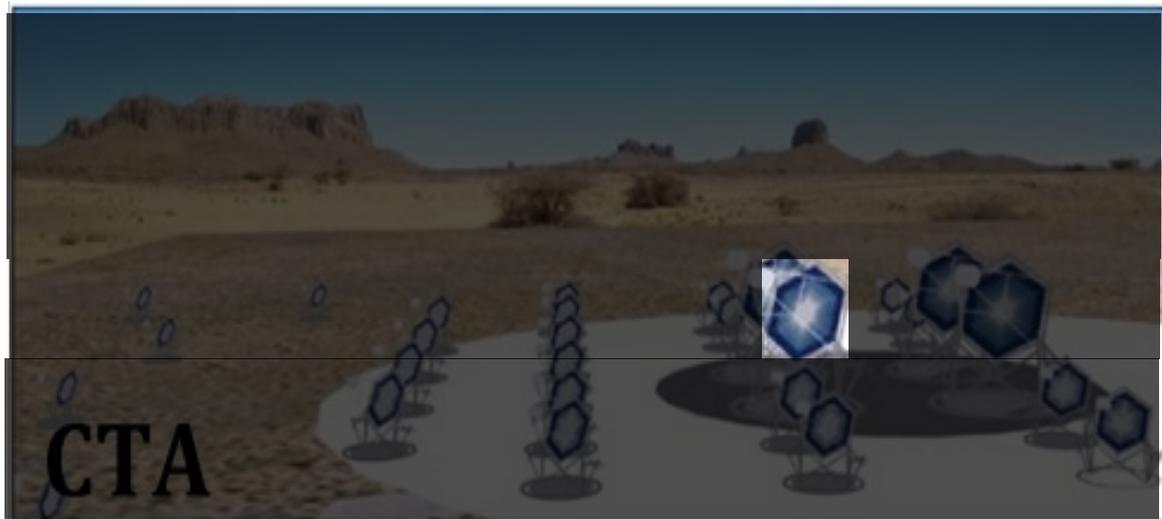
现在对超高能中微子信使观测缺失
实施IceCube-Gen2，保持领导地位

在未来至少15年里，LHAASO一家独大的局面
将由CTA的建成而改变；
SWGO具有重大意义：我们已经正式加入，
目标是 4 X LHAASO in Peru/Chili

2020年代伽马天文学研究的“国际分工”

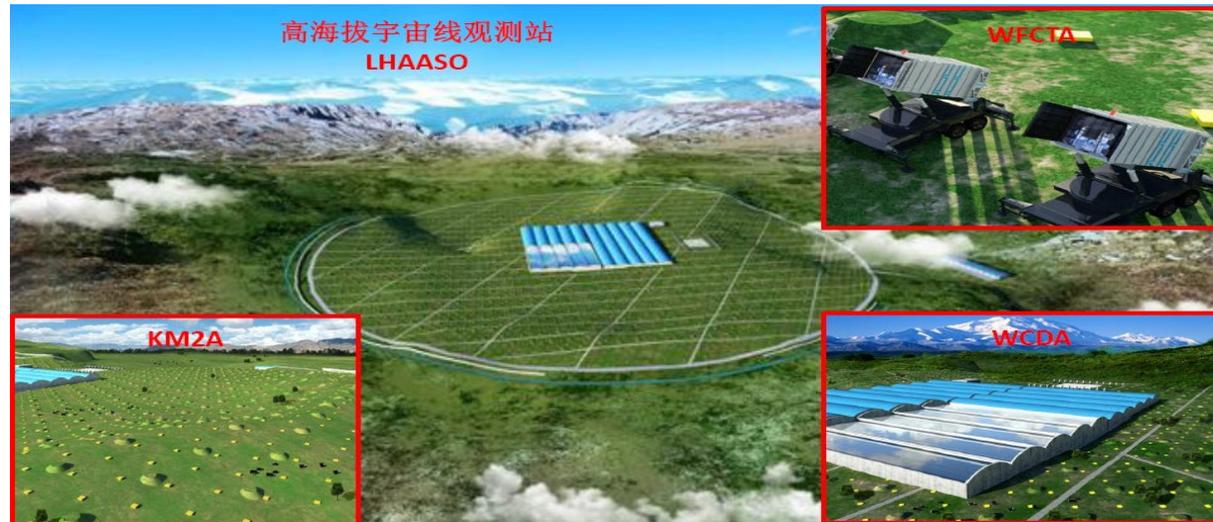
- 中国的LHAASO：巡天普查、**精确测量能谱**
- 欧洲的CTA：定点观测、**精确测量光源内部结构**

2004年，欧洲科学家提出CTA计划
建设10平方公里**百台**望远镜阵列



2021年，一台LST！

2009年，中国科学家提出LHAASO计划
建设1平方公里地面探测器阵列

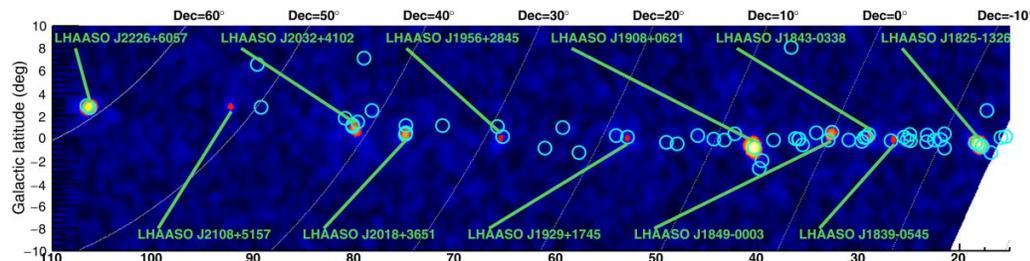


2021年7月，全阵列建成，
2021年10月，工艺验收，投入运行！

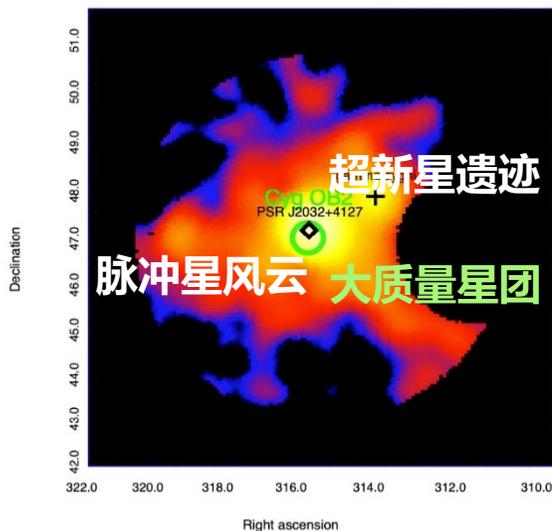
LHAASO开启“超高能伽马天文学”

LHAASO发现的12个超高能伽马源

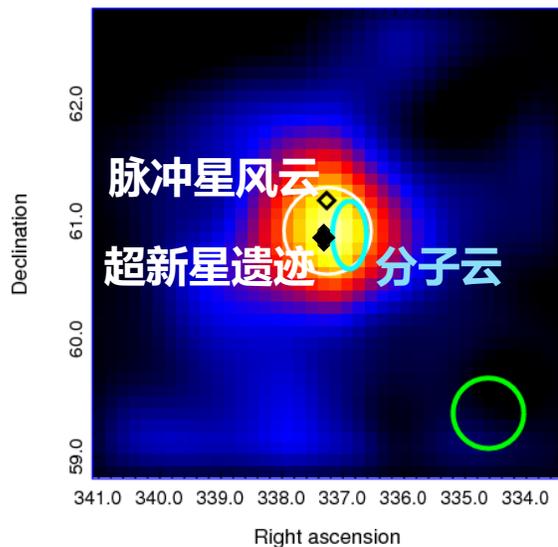
Nature, 594, 33-36, 2021



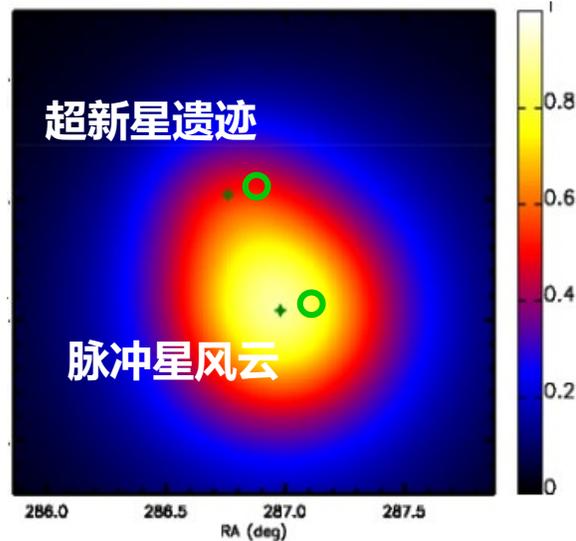
天鹅座: LHAASO J2032+4102



LHAASO J2226+6057



LHAASO J1908+0621



➤ LHAASO角分辨: $\sim 0.3^\circ$

➤ 不能精确定位伽马射线来自哪个天体源

➤ 不能确定伽马辐射机制, 得不到粒子加速的准确信息

➤ 亟需高角分辨伽马源观测设备: $< 0.05^\circ$

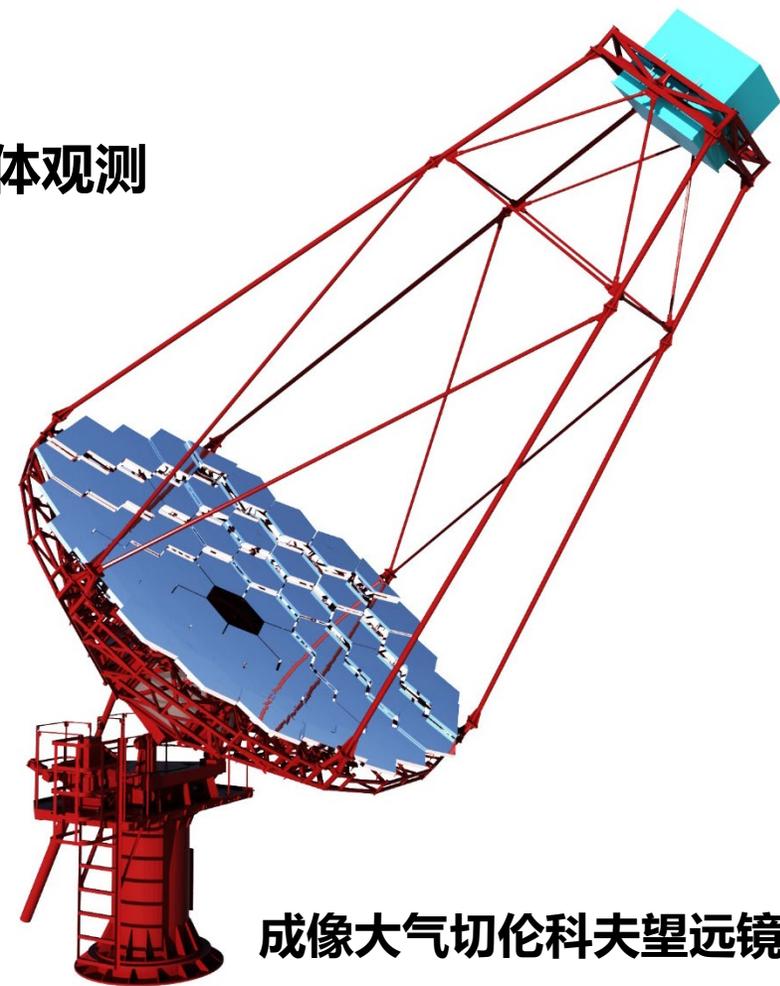
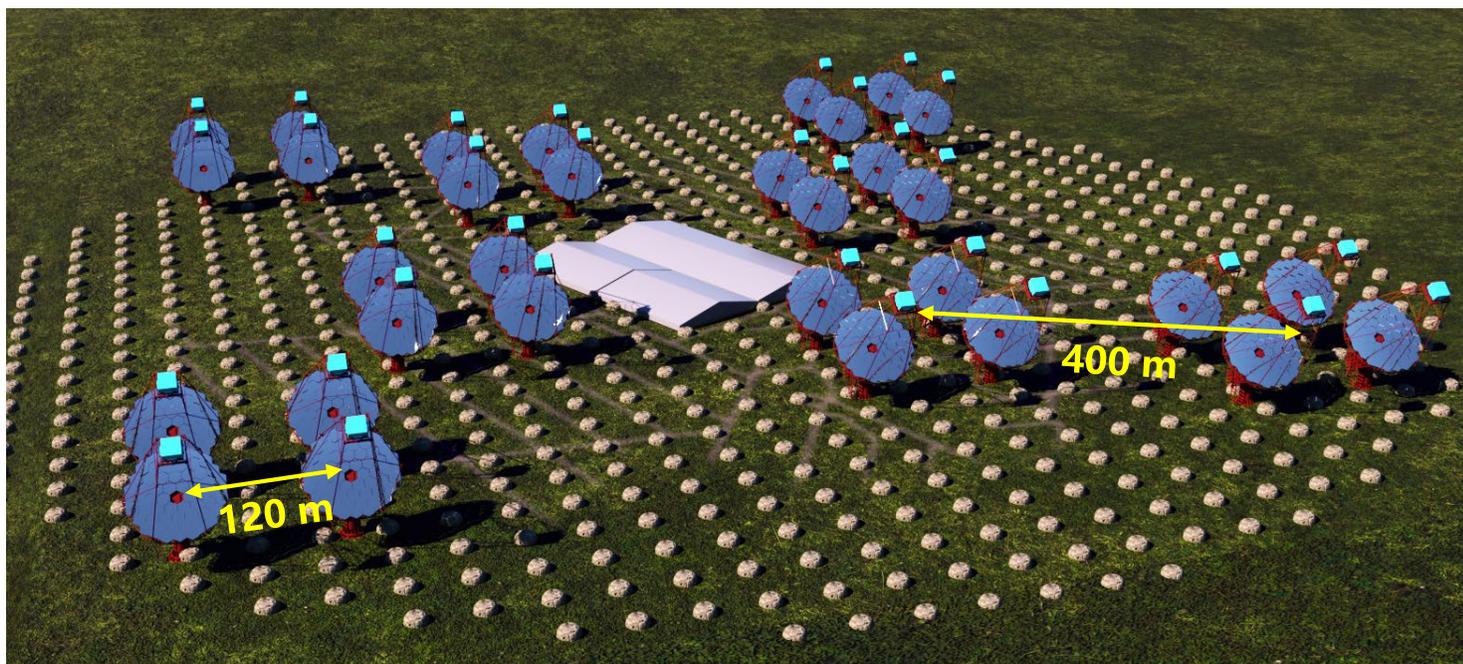
➤ 辐射位置精确定位以确定辐射和加速机制

➤ 目前一代设备 (HESS、VERITAS) 的灵敏度不够

LACT总体结构

➤ LACT由32台望远镜组成

- 分成8组，每组间隔400米：实现最大面积覆盖
- 每组4台（~HESS），望远镜间隔120米：实现高分辨的立体观测
- 同时跟踪观测同一伽马源，有效观测面积达到1.6平方公里



成像大气切伦科夫望远镜

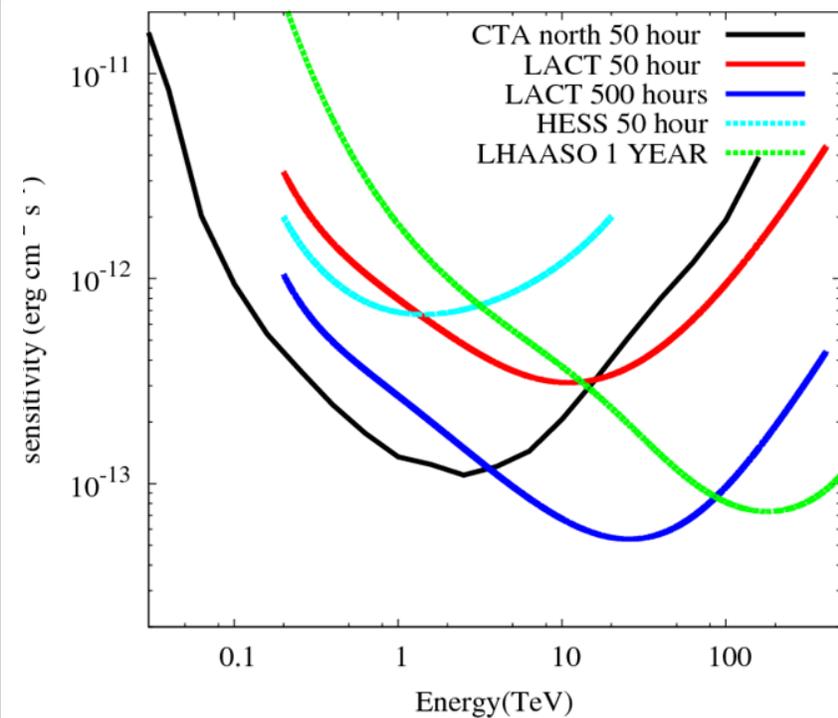
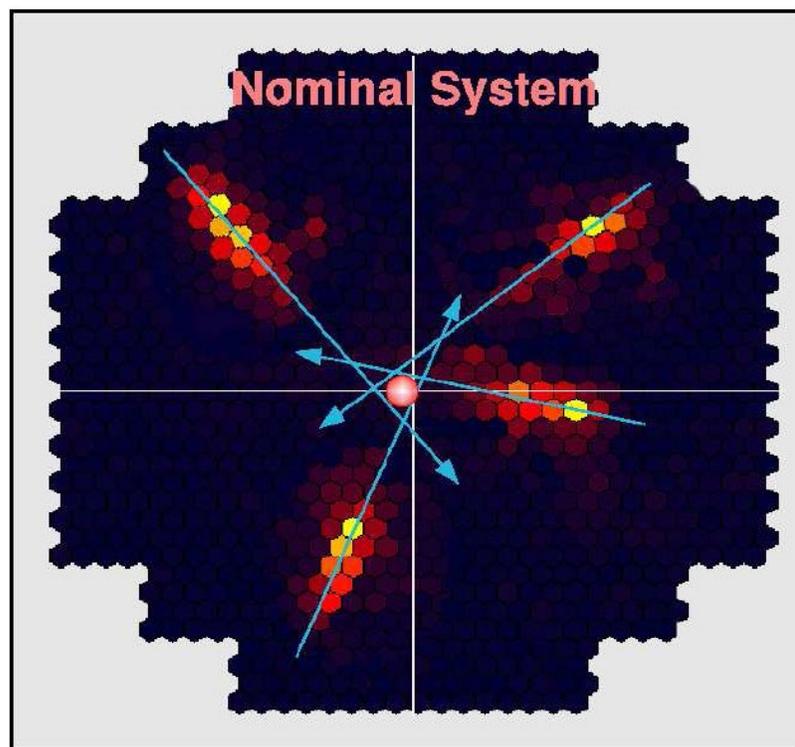
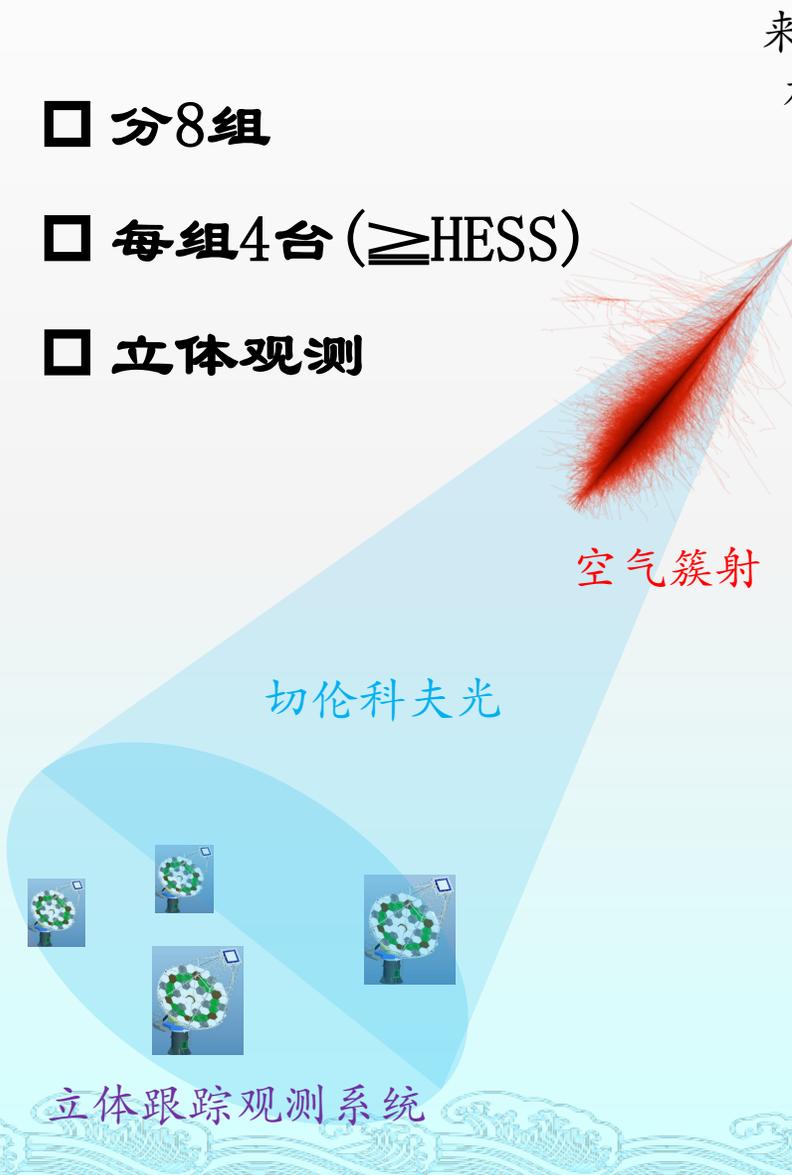
大型超高能伽马源立体跟踪观测设备 (LACT)

- 分8组
- 每组4台 (\geq HESS)
- 立体观测

来自宇宙
加速器
 γ 射线

➤ **LACT总体性能指标:**

角分辨率 @10TeV	灵敏度 @10TeV	能量 分辨率
<0.05°	<3% Crab	<15%



LACT样机关键技术预先研究

- 2016年启动我国大口径切伦科夫望远镜方案论证
- 2020年1月国际论证确定方案
- 2020年秋季成立攻关小组
 - 主结构
 - 主反射面
 - 核心专用集成芯片及其读出电路
- 8个单位参与攻关：

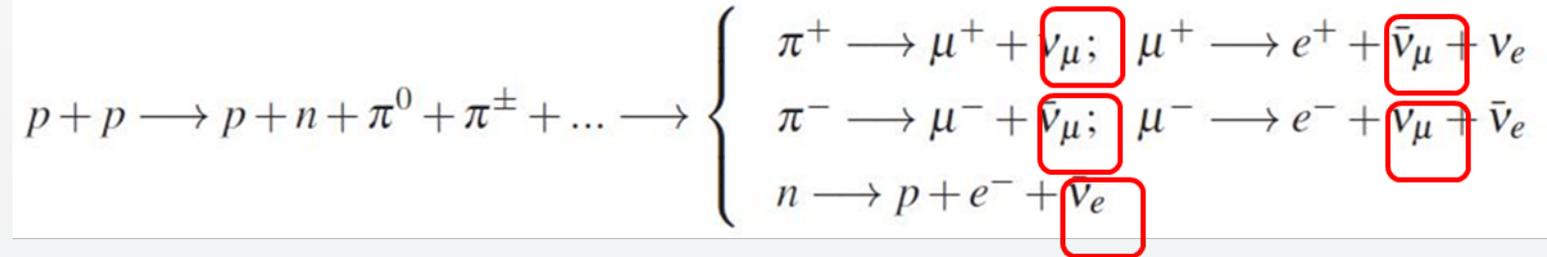
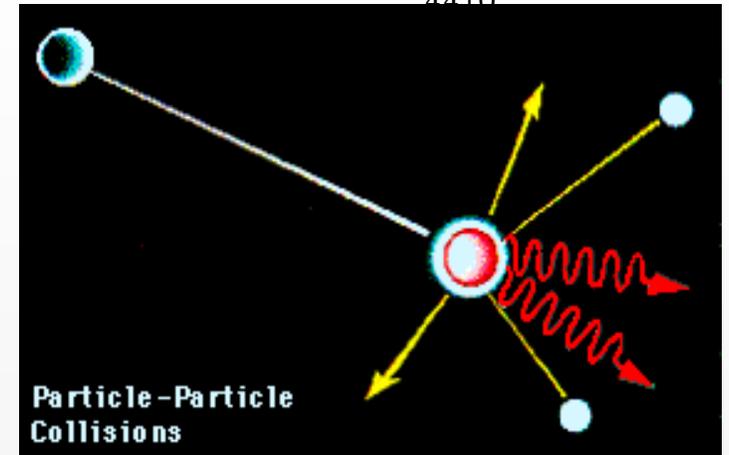
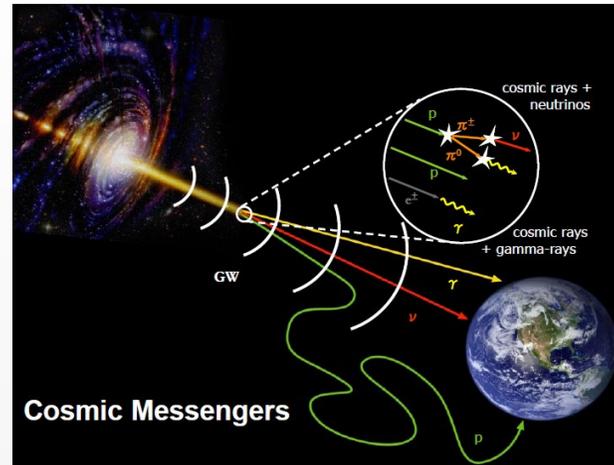
高能物理研究所
南京大学
电子科技集团39所
航天科工集团23所

中国科学技术大学
云南天文台
云南大学
中山大学

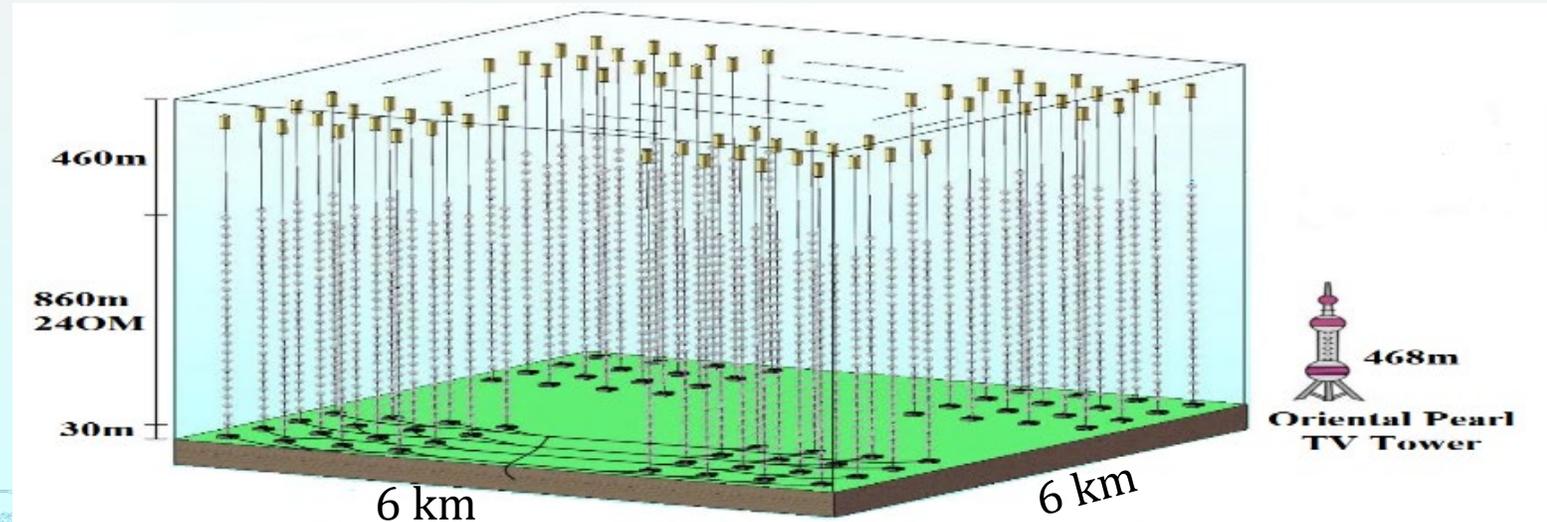


高能中微子望远镜

- 宇宙线源发出的高能伽马光子，必然存在相伴生的中微子
- 一锤定音，高能宇宙线起源问题的最后一块拼图！



- 利用贝加尔湖或南海的优势，占领中微子学科领域的制高点
- 建设 $>30 \text{ km}^3$ 中微子望远镜，超越IceCube-Gen2，实现探测单源灵敏度

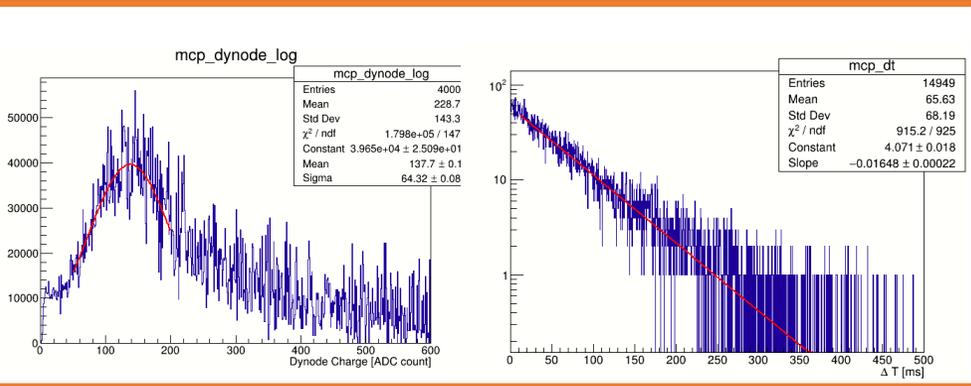


高能中微子望远镜预先研究

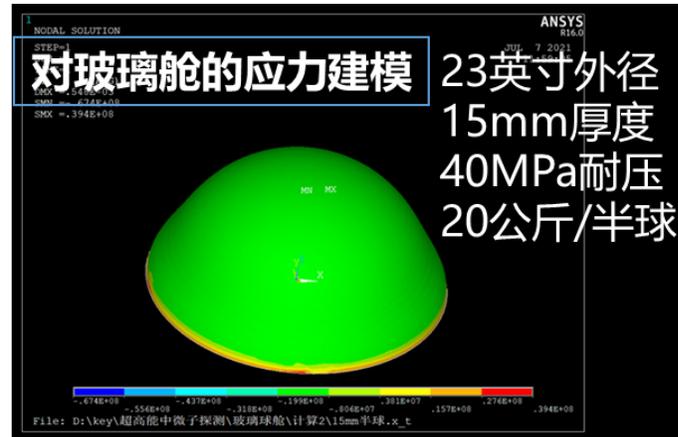


完成首个单元探测器模型下水试验
(20寸玻璃舱内含8寸PMT)

- 关键技术攻关：
 - GPU算法的模拟程序
 - SiPM倍增极的PMT优化工作
 - PMT膨胀节缩短工作
 - 玻璃舱国产化工作。
- 预先研究：
 - 在南海进行深海内含PMT玻璃舱的投放；
 - 在南海或贝加尔湖投放水文检测系统



8寸PMT测量到的电荷谱和事例时间差分布

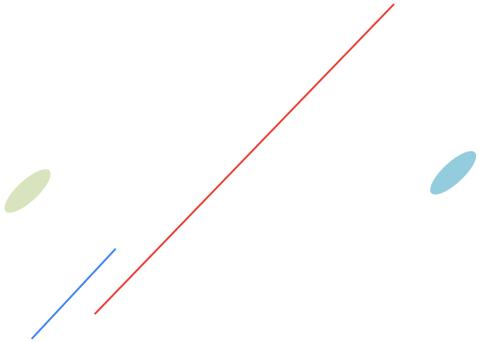


吸引到国内外多方积极参与：

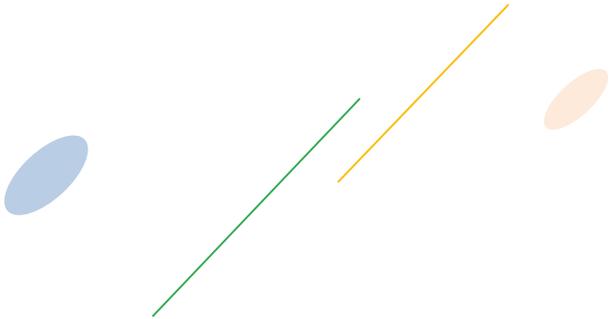
- 国内已有七家单位参与，约30人。
- 得到俄Baikal-GVD合作组积极支持，并建立紧密联系。

Conclusion

- ◇ LHAASO is completely built, and in full operation since July 2021
- ◇ Open-up “**UHE (>0.1 PeV) Astronomy**”
 - ① 12 PeVatrons are discovered in our galaxy
 - ② A photon at 1.4 PeV is recorded toward Cygnus constellation
- ◇ **First Discoveries:**
 - ① Our galaxy is full of **PeVatrons** accelerating particles over 1 PeV
 - ② Potential **CR origins**: many type of candidates
 - ③ The Crab: extreme e-PeVatron emitting 1.1 PeV γ posing challenges
- ◇ **Fundamental rules, e.g. LIV, are tested in extreme condition**
- ◇ **Precision Measurements of individual species CRs around knees will be measured at first time**
- ◇ **Lookout for future:**
 - ① PSF \sim 0.05 $^\circ$ for identifying for CR sources by **LACT**
 - ② ν -telescope with the sensitivity for single-PeVatron: **30 km³** in LB or SCS



谢谢!



LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr) ^a	L_s (erg/s) ^b	Potential TeV Counterpart ^c
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130, 2HWC J1825-134
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069, HESS J1841-055
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063, ARGO J1907+0627, VER J1907+062, 2HWC 1908+063
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188, HESS J1930+188, VER J1930+188
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}{}^d$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}{}^l$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368, VER J2016+371
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157, MGRO J2031+41, 2HWC J2031+415, VER J2032+414
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	
	SNR G79.8+1.2	SNR candidate	—	—	—	
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

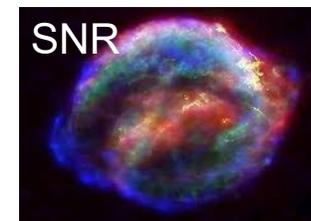
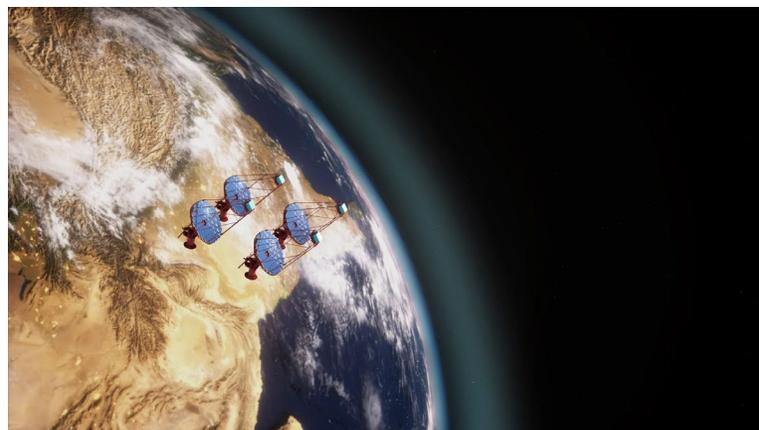
伽马射线立体成像测量技术

■ 跟踪观测+立体重建方案

- 4台望远镜测量同一伽马射线
- 望远镜指向标定和监测方案

■ 角分辨大幅度提升

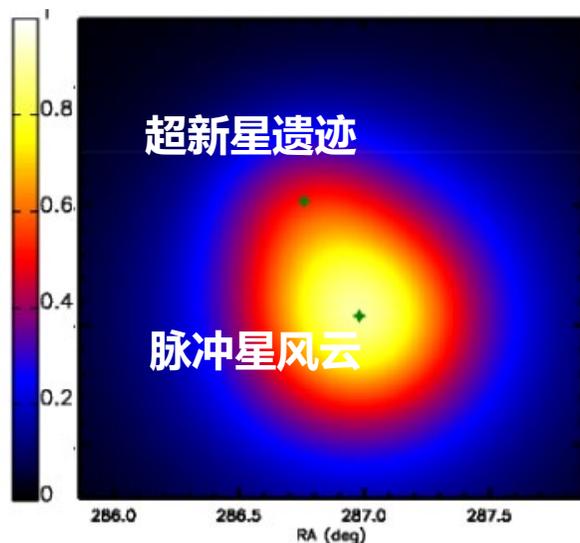
角分辨: $<0.05^\circ$ @ 能量 >20 TeV



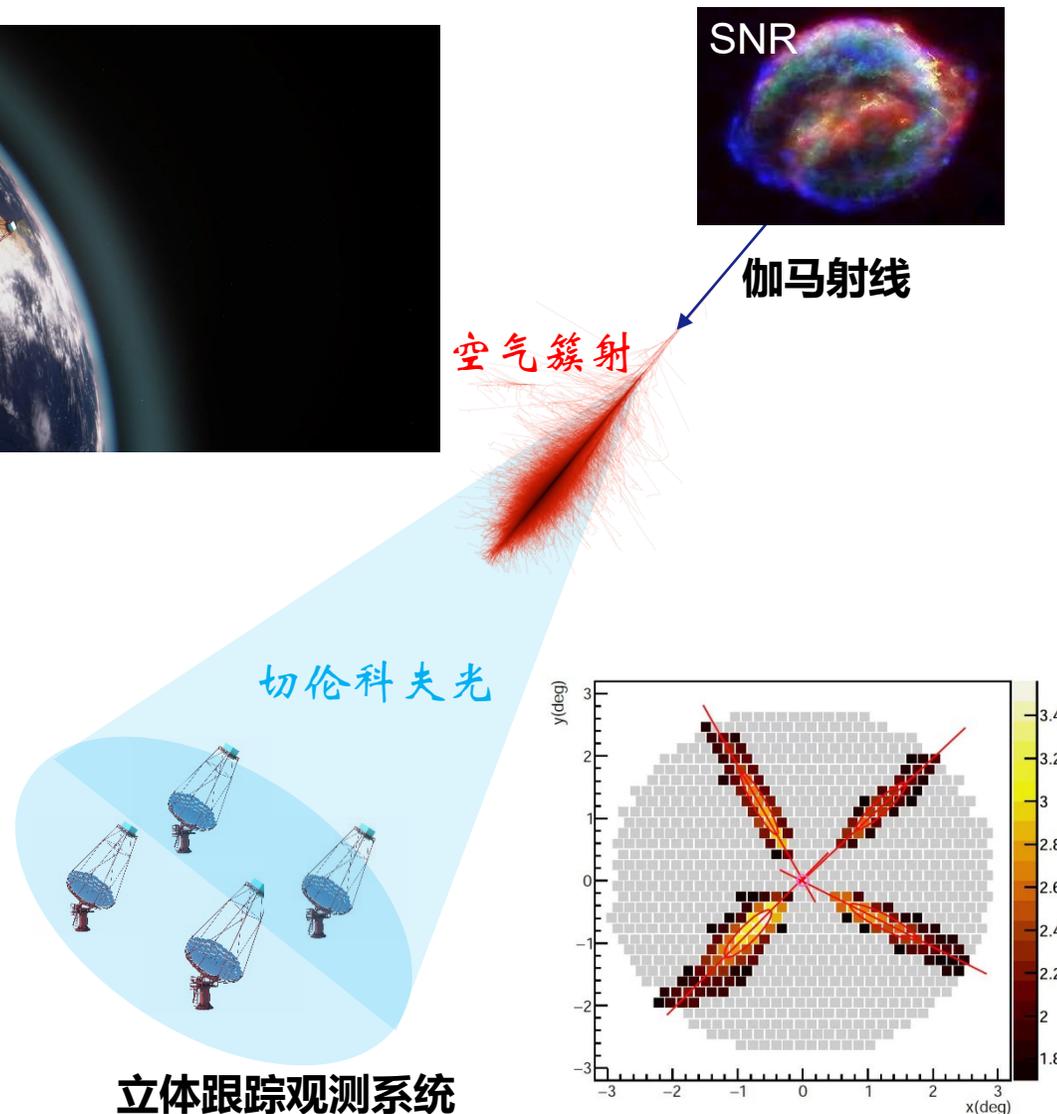
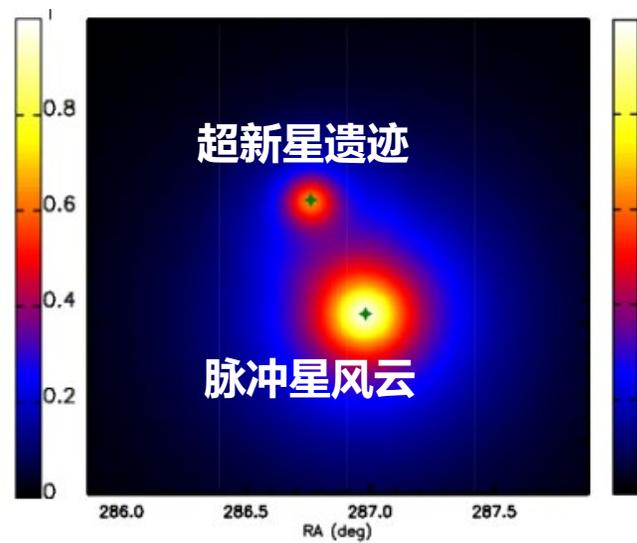
伽马射线

空气簇射

LHAASO J1908+0621



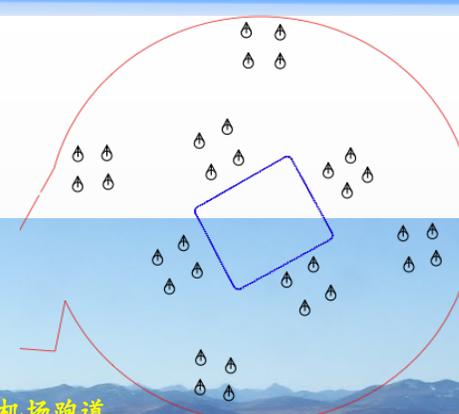
LACT观测预期



立体跟踪观测系统

LACT 设计的核心思想

- 32台成像C-望远镜: $\phi 6\text{ m}$ (@HESS)
~ $\phi 12\text{ m}$ (@LACT)
- 分8组覆盖 1km^2 面积: 8×HESS 升级换代



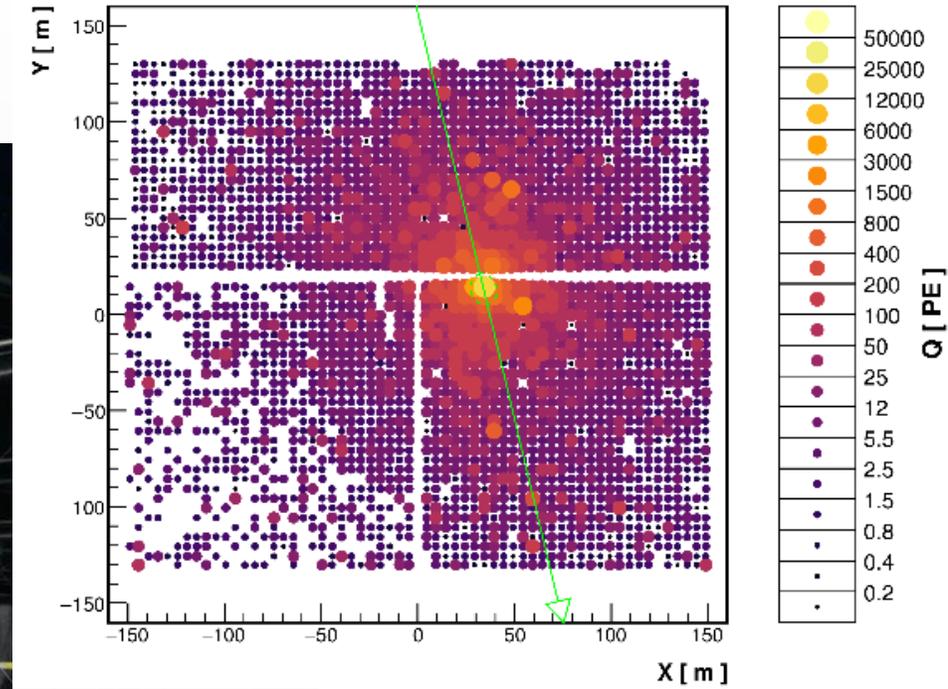
亚丁机场跑道



Water Cherenkov Detector Array (WCDA)



20210511/131236/0.554789897: nTrig=-1, $\theta=37.81\pm 0.02^\circ$, $\phi=103.39\pm 0.02^\circ$



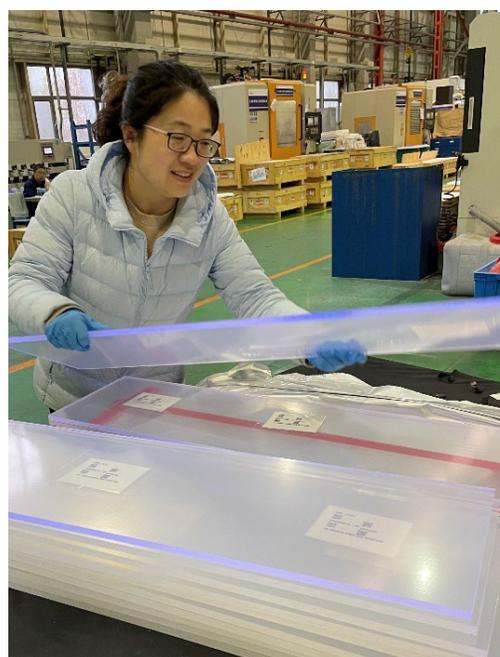
- ◆ Area:
78,000 m²
- ◆ Detector units:
3120
- ◆ Energy Range:
0.1-10 TeV

ED建设照片

正在测试新安装的ED



正在进行ED组装工作

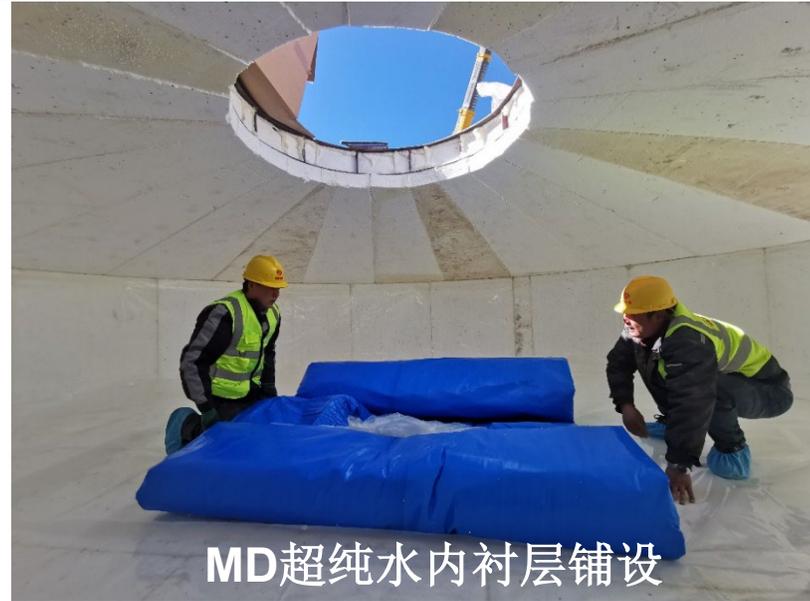


正在进行塑料闪烁体加工

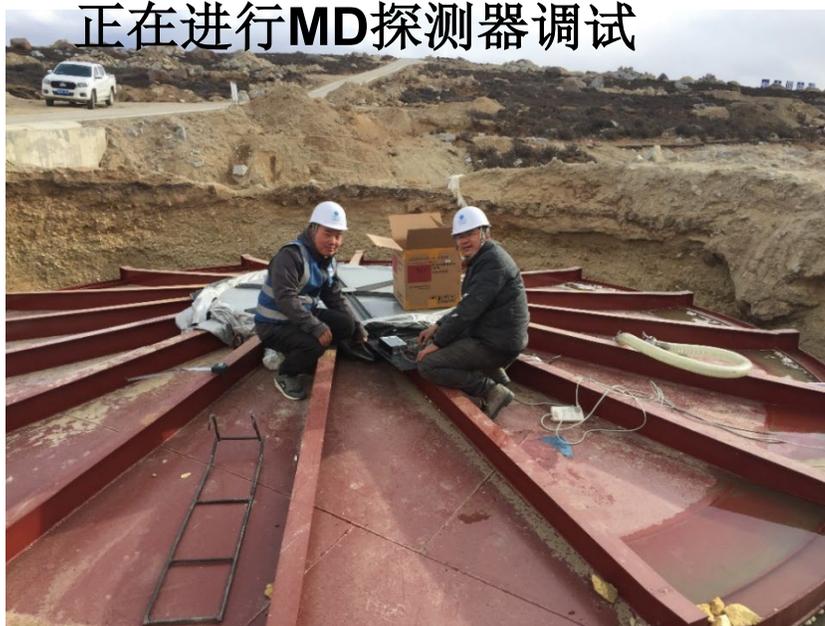
MD建设照片



MD探测器定位



MD超纯水内衬层铺设



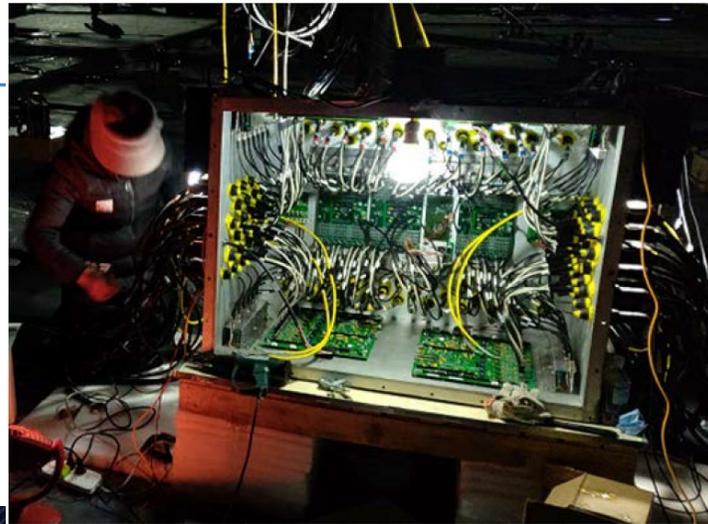
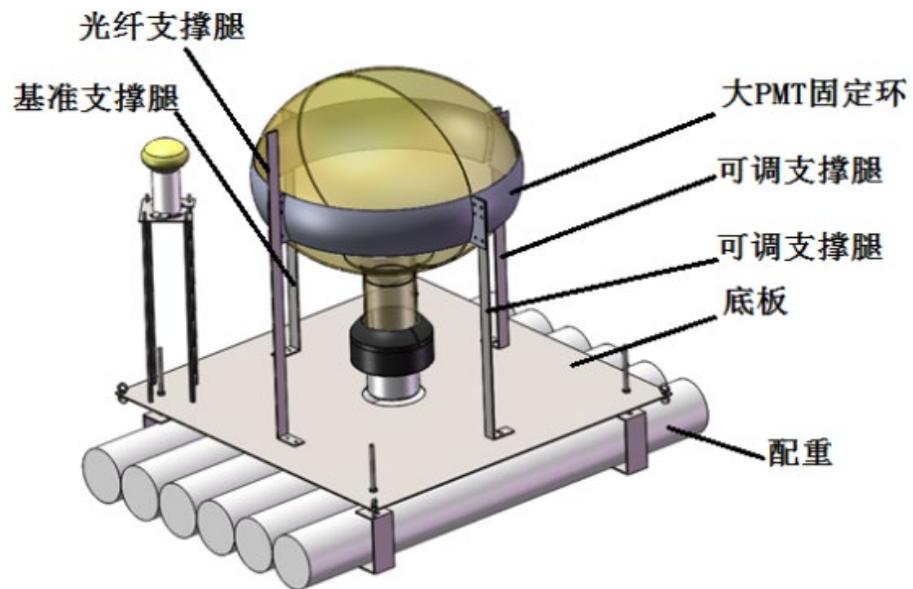
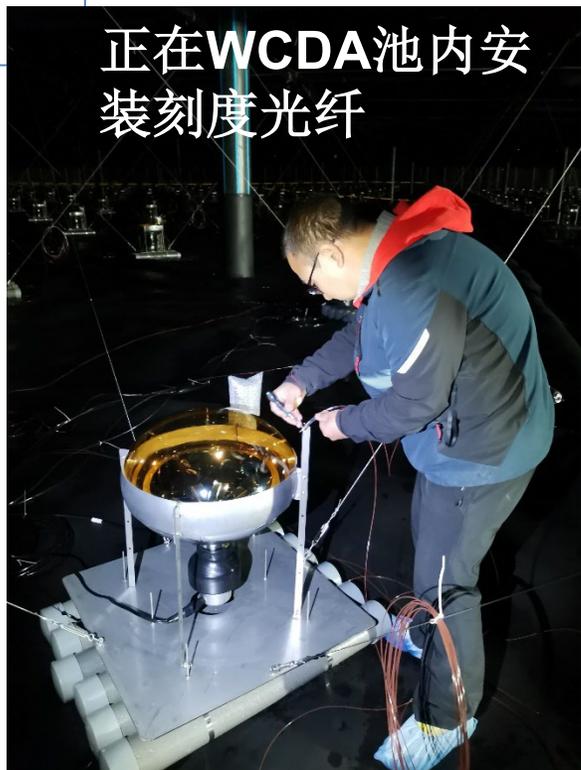
正在进行MD探测器调试

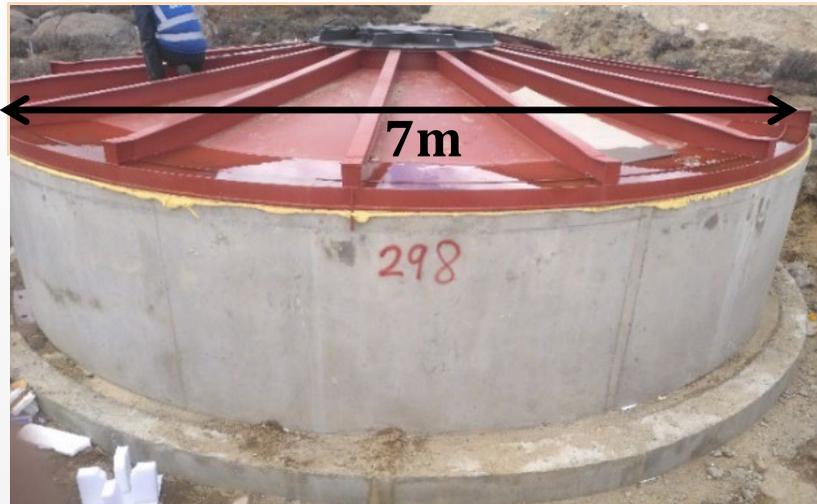


正在进行超纯水灌注

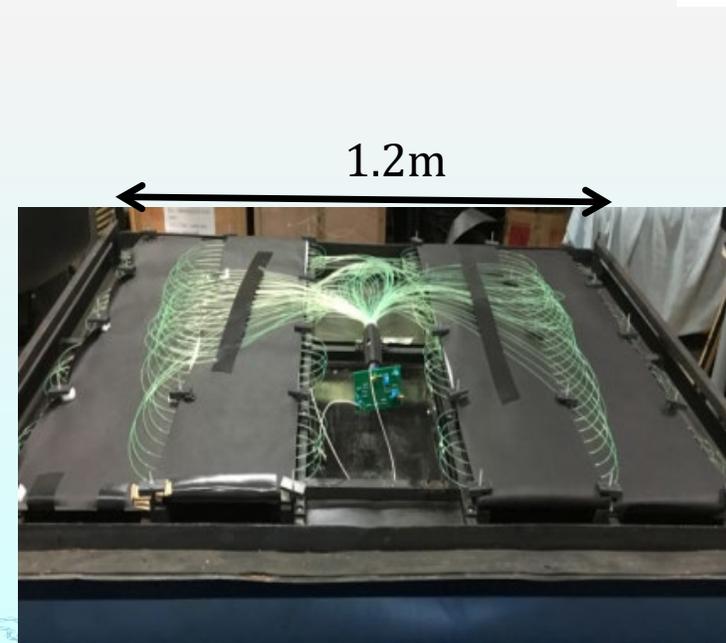
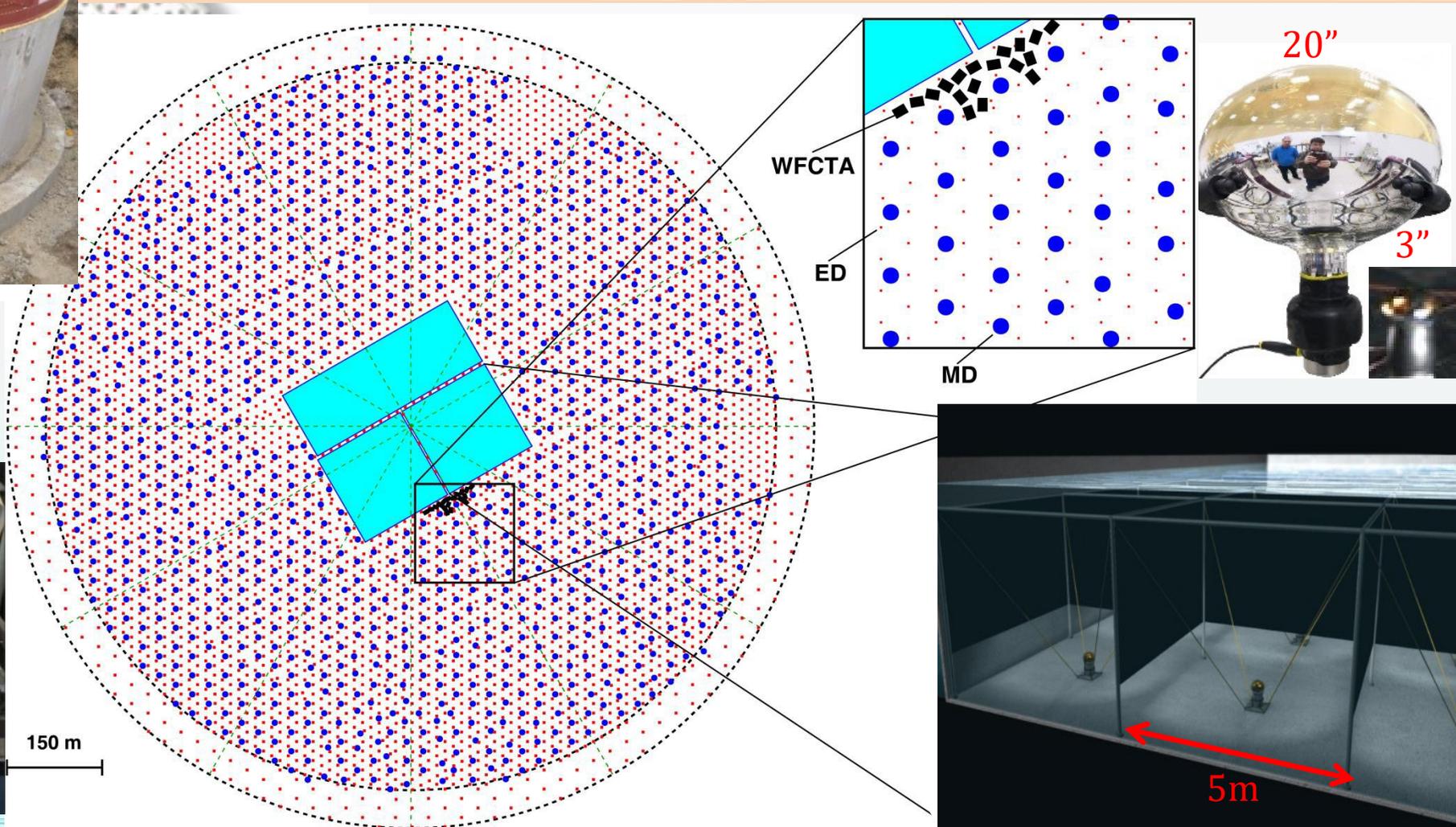
WCDA建设照片

正在WCDA池内安装刻度光纤





LHAASO Layout

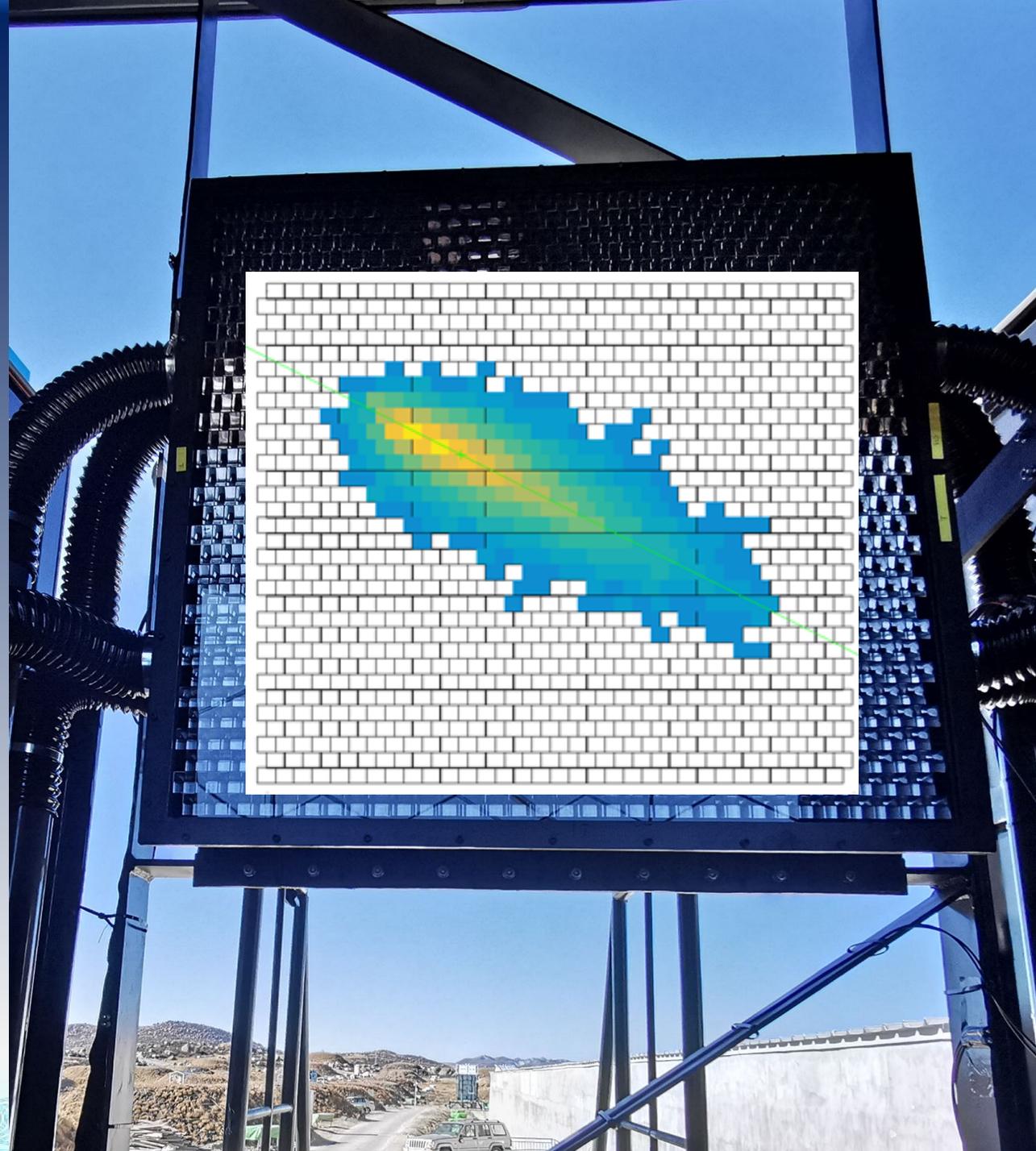
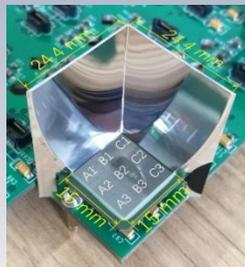




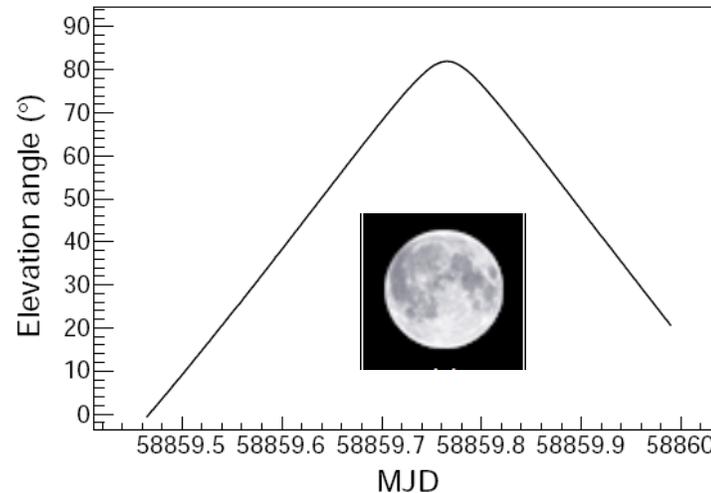
大面积硅光电管应用于切伦科夫望远镜

在世界上首次大面积采用硅光电管（SiPM）取代了传统的PMT

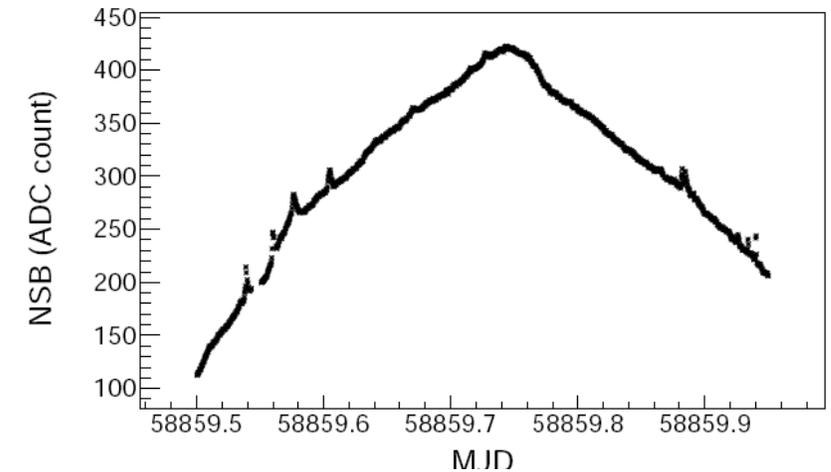
在满月的晚上也能正常观测，有效观测时间一下就提升了2倍



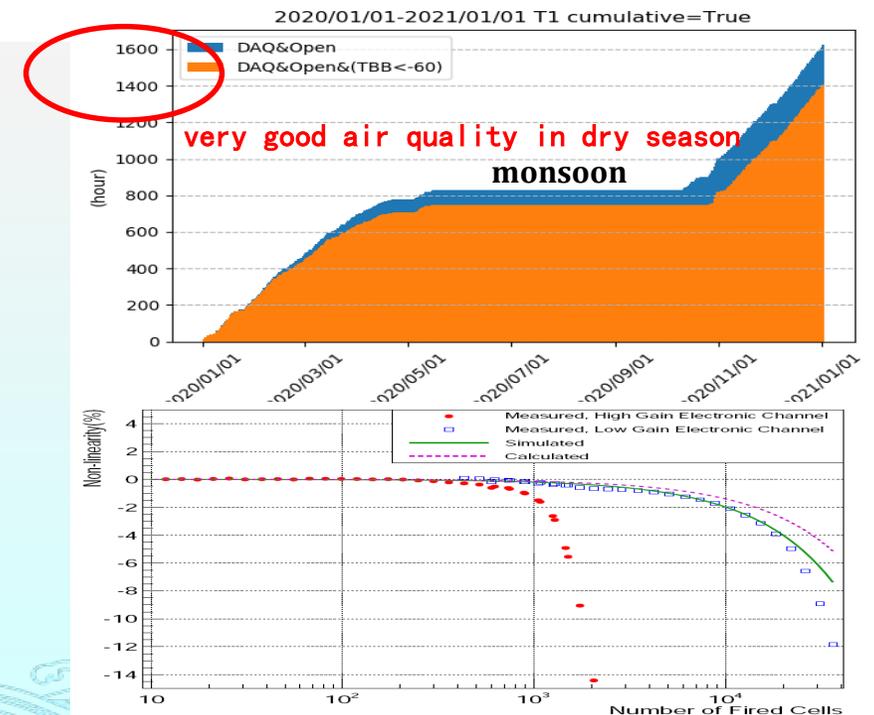
LHAASO WFCTA SiPM Camera



European Physical Journal C, accepted, 2021



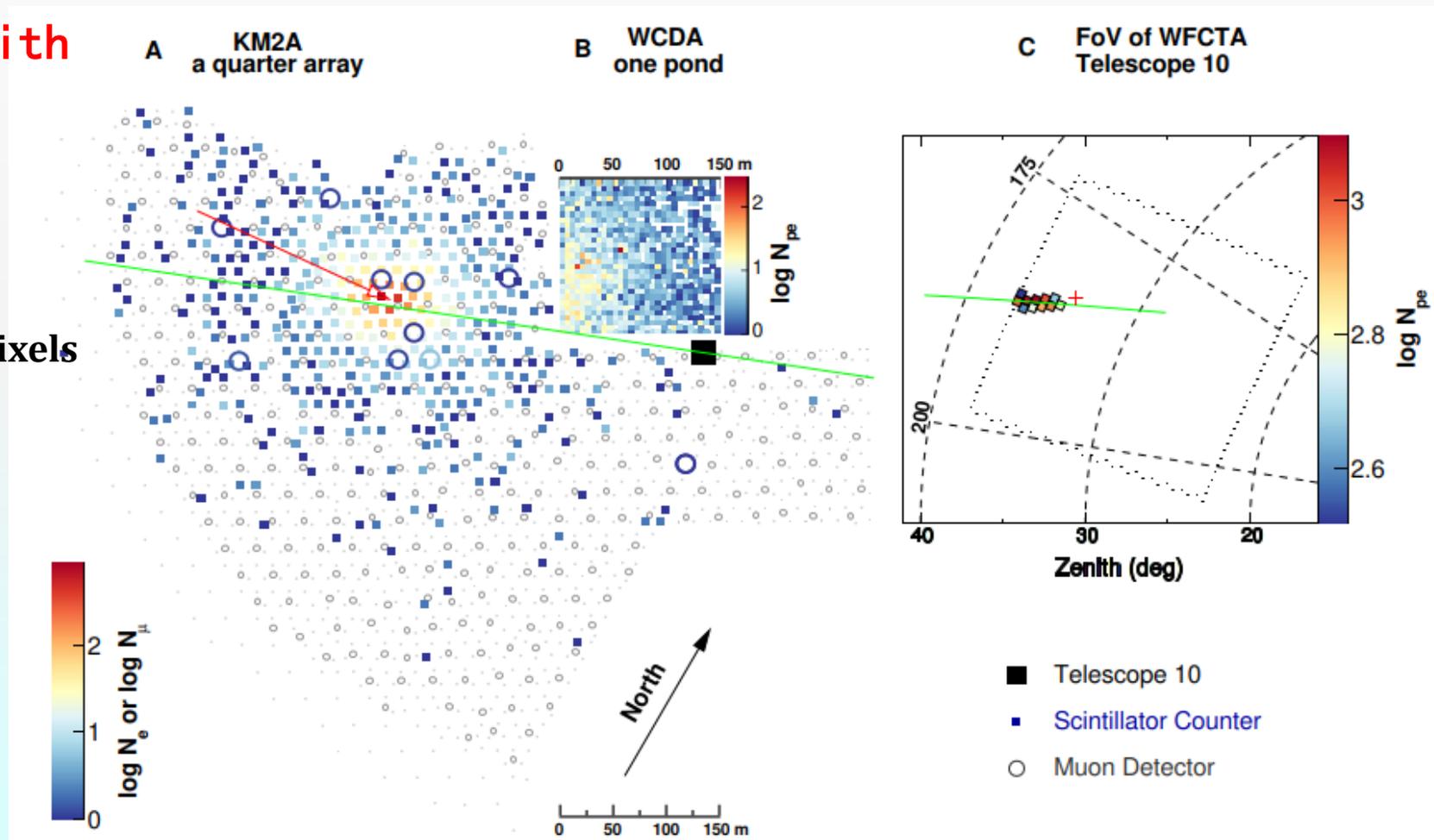
- SiPM enables an operation of WFCTA with full moon
- Effective Operational time **1400 hrs** per year
- 0.5° pixels with dynamic range 10–32,000 pe enable a coverage 100 TeV – 100 PeV

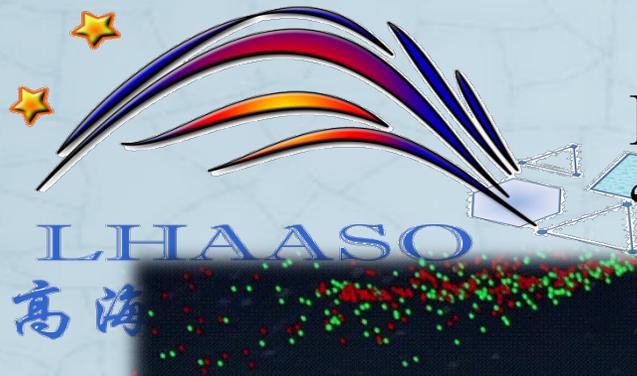


The Crab as Electron PeVatron, *Science*

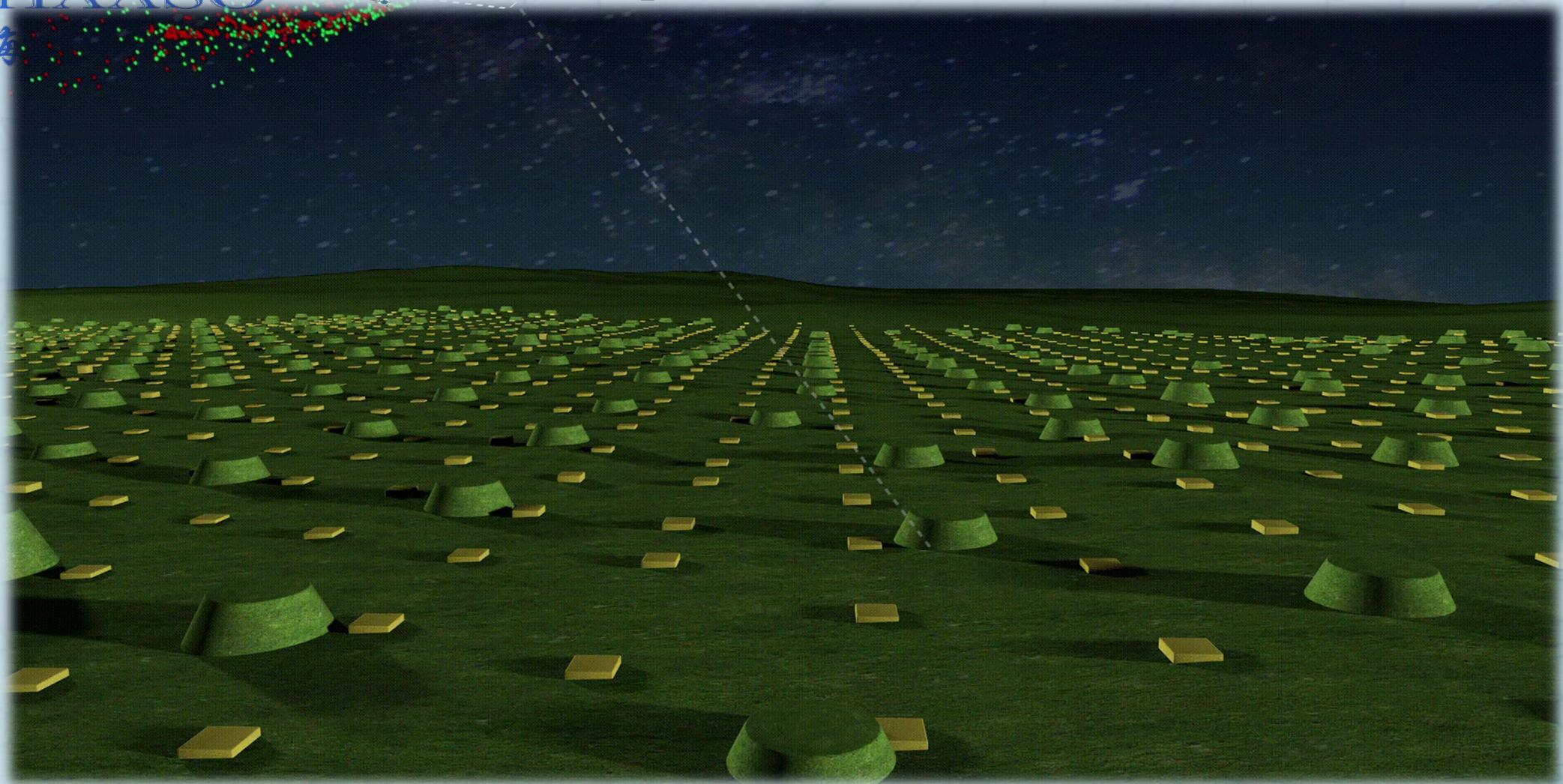
Special capability of self cross-checking with multiple techniques

- WFCTA measured the event simultaneously
L/W~2.6, $N_{pe} \sim 9100$ in 11 pixels
- **Energy: 0.9 ± 0.2 PeV**
- KM2A measured the event
 $N_{particle} \sim 4574$ in 395 EDs
- **Energy: 0.9 ± 0.1 PeV**
- **Chance probability: $< 0.1\%$**
 $N_{\mu} \sim 15$ in 11 MDs

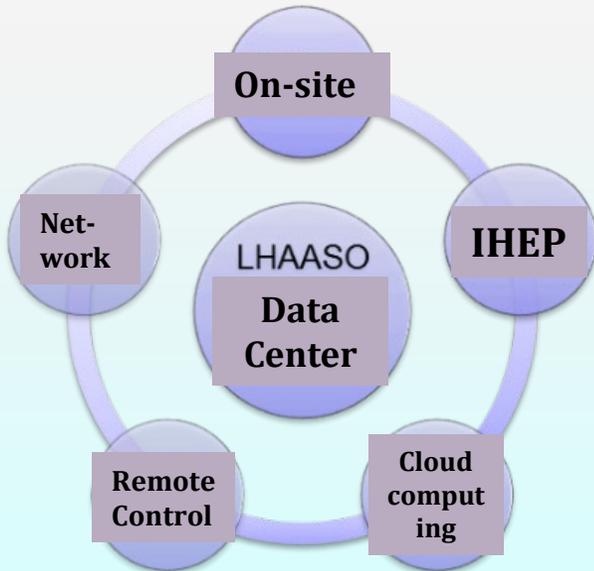
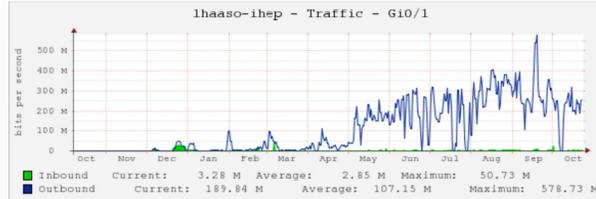




Enter the atmosphere, cascade interaction generates a “shower of particles” which last few nanoseconds



- Full functional computing room
- # of CPU Cores:
3000
- Temp Storage:
2.5 PByte
- Data Band Width:
2.4 Gbit/sec

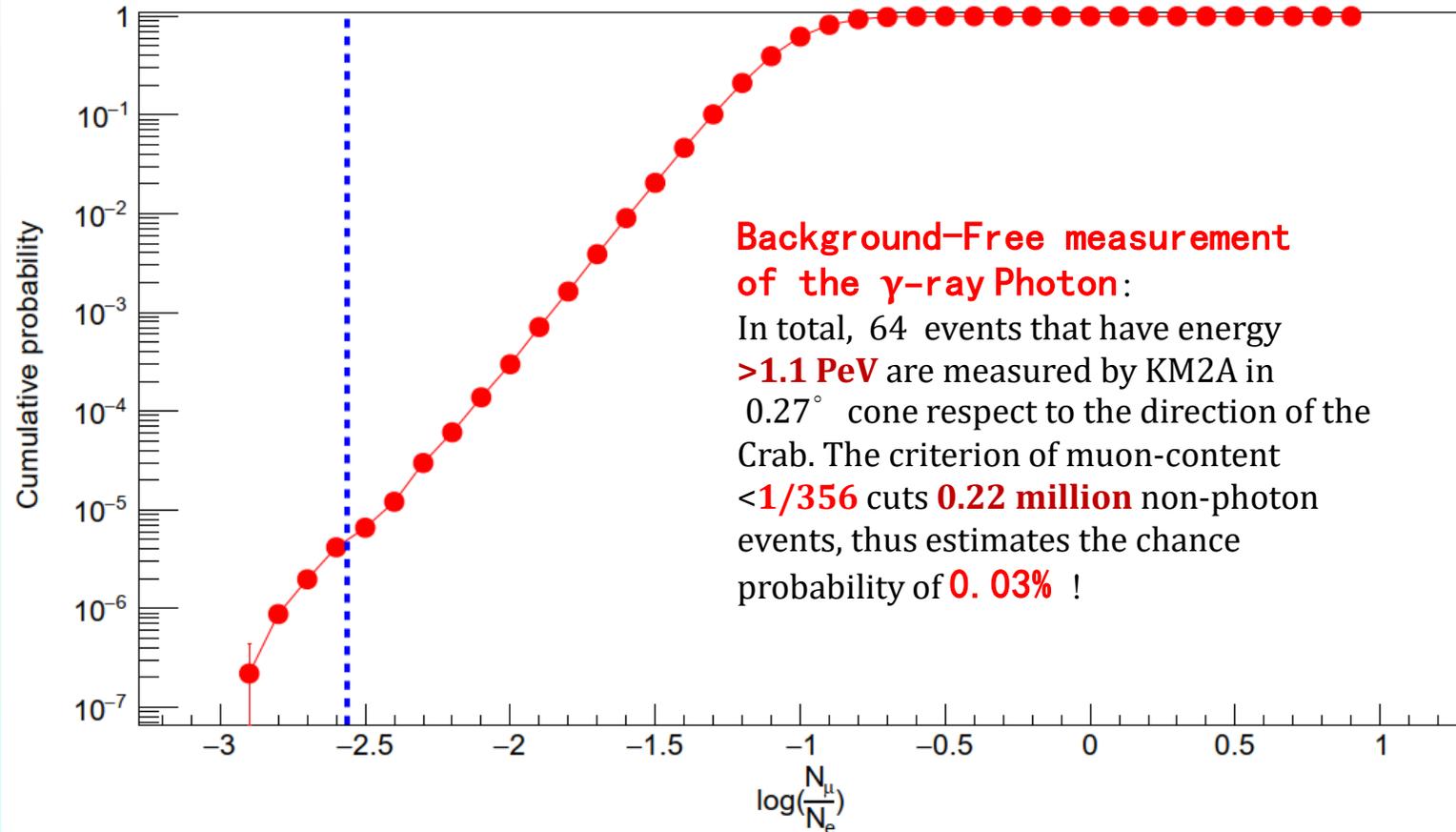
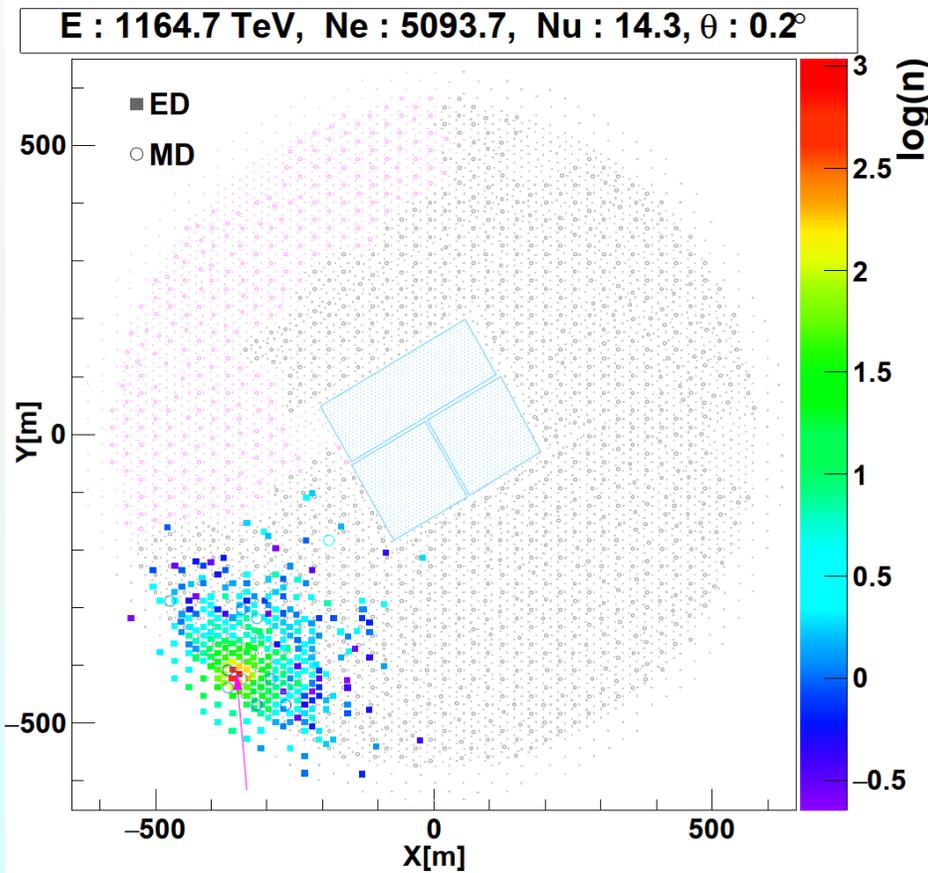


On-site Facility

1.1 PeV Photon

from the Crab Direction Record by KM2A

LHAASO, Science, 373, 425-430, 2021



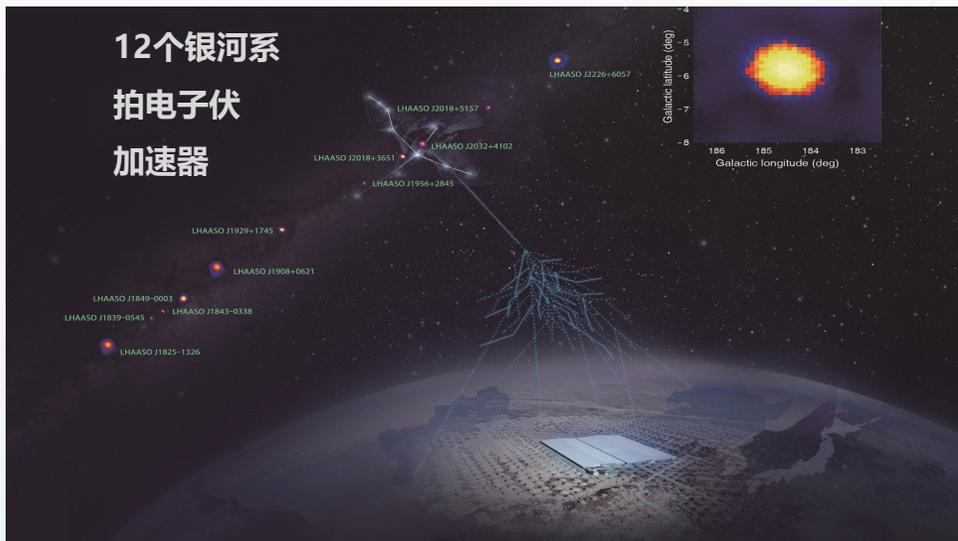
洛伦兹协变性破坏
量子引力等
新物理前沿探索

LHAASO的科学问题

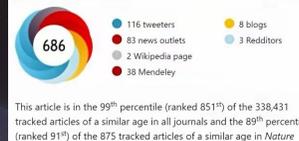
γ -ray astronomy

发现银河宇宙线起源的候选天体、揭示超高能伽马辐射机制及宇宙线的加速原理

12个银河系
拍电子伏
加速器



Online attention



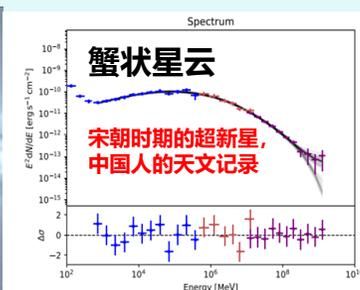
This article is in the 99th percentile (ranked 851st) of the 338,431 tracked articles of a similar age in all journals and the 89th percentile (ranked 91st) of the 875 tracked articles of a similar age in *Nature*

View more on Altmetric

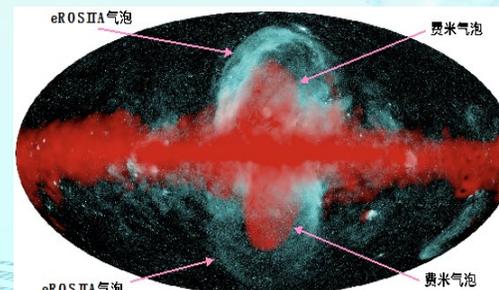
Altmetric calculates a score based on the online attention an article receives. Each coloured thread in the circle represents a different type of online attention. The number in the centre is the Altmetric score. Social media and mainstream news media are the main sources that calculate the score. Reference managers such as Mendeley are also tracked but do not contribute to the score. Older articles often score higher because they have had more time to get noticed. To account for this, Altmetric has included the context data for other articles of a similar age.

《自然》：Zhen Cao, *et al.*, LHAASO Coll., *Nature*, 594, 33-36, 2021

《科学》：Zhen Cao, *et al.*, LHAASO Coll., *Science*, 373, 425 (2021)



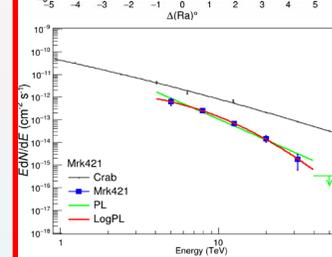
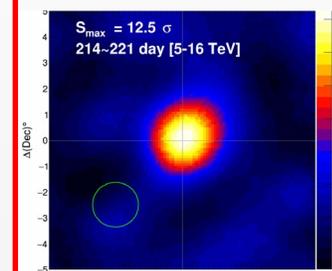
银河系的X射线和伽马射线泡



伽马暴几秒钟内
释放 10^{52} 尔格



星系中央超大质量黑洞



Discovery in KM2A Survey

Our Galaxy is full of PeVatrons

LHAASO, Nature, 594, p.33-36, 2021

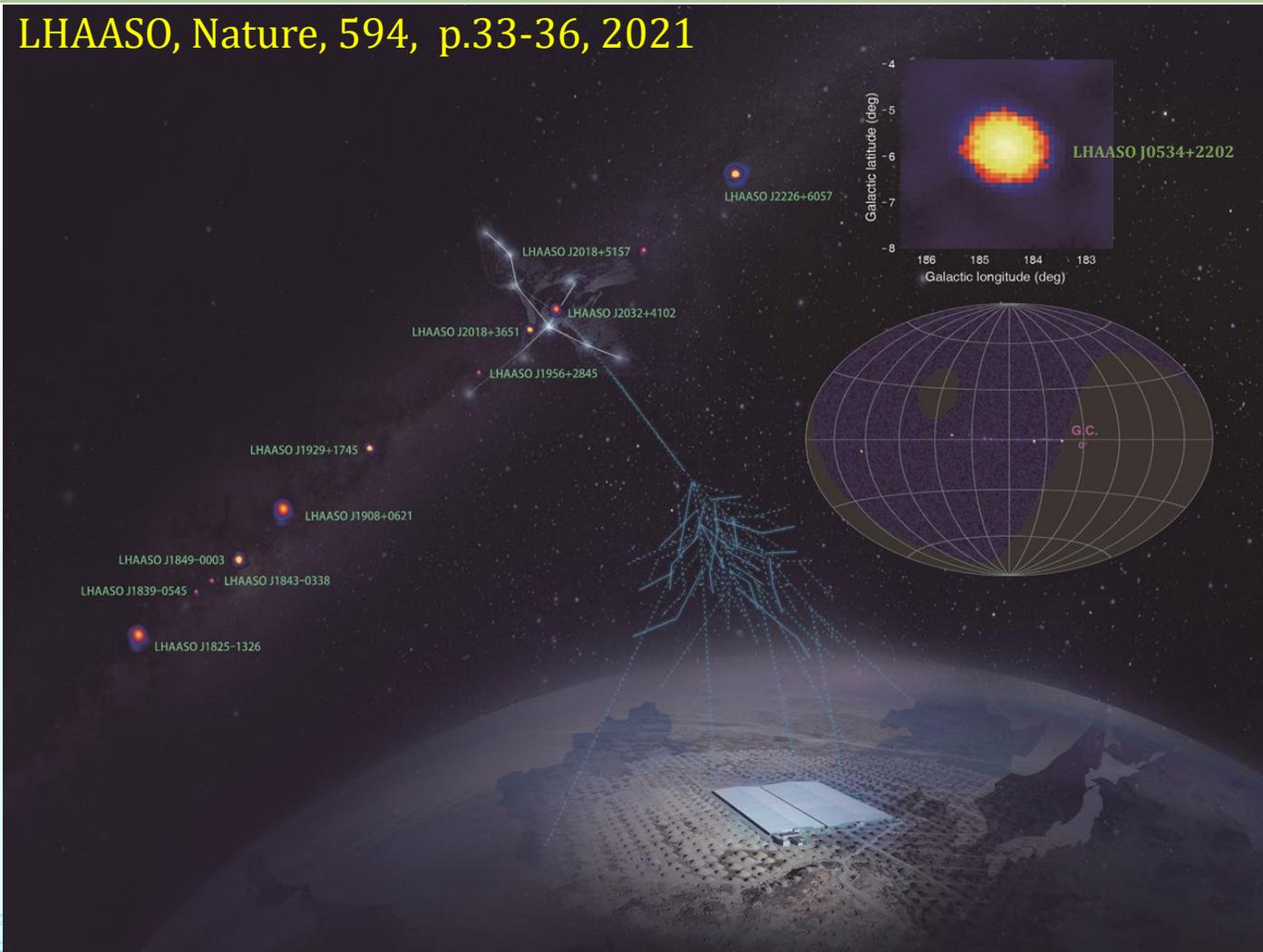


Table 1 | UHE γ -ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV ($\times\sigma$)	E_{\max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

12 PeVatrons are discovered

◆ High Standard: significance $>7\sigma$

◆ BG-free: Cosmic Ray background rejection rate $<10^{-4}$

◆ High Statistics: 530 UHE photons

◆ Multiple Type of Sources

Discovery Using **KM2A**

Onset of UHE γ -ray Astronomy

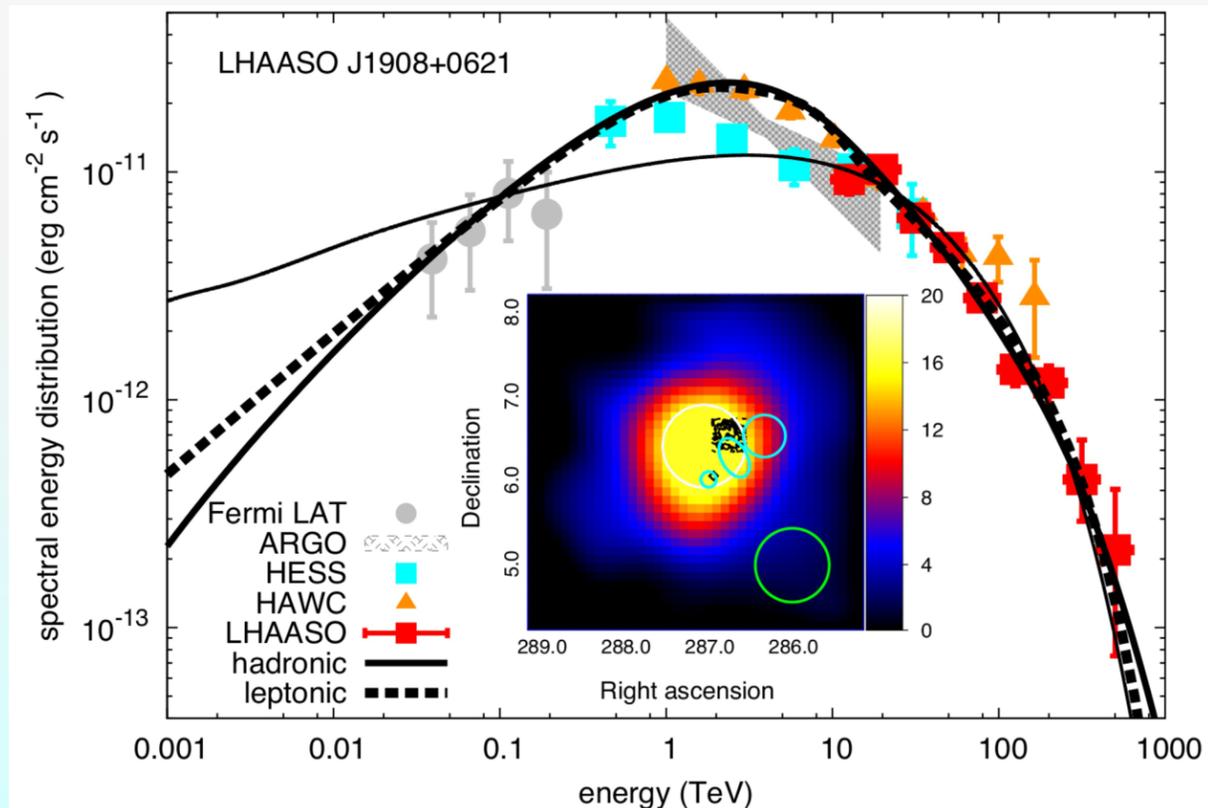
这只用到
LHAASO设计
灵敏度的
~1/20!

$E > 0.1$ PeV: all types of candidates

◆ Spectroscopy: 15% resolution

◆ Morphology: 0.25° PSF

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr) ^a	L_s (erg/s) ^b	Potential TeV Counterpart ^c
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334 PSR J1826-1256	PSR	3.1 ± 0.2^d 1.6	21.4 14.4	2.8×10^{36} 3.6×10^{36}	HESS J1825-137, HESS J1826-130, 2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604 PSR J1838-0537	PSR	4.8 1.3 ^e	33.8 4.9	2.0×10^{36} 6.0×10^{36}	2HWC J1837-065, HESS J1837-069, HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001 W43	PSR YMC	7 ^g 5.5 ^h	43.1 —	9.8×10^{36} —	HESS J1849-000, 2HWC J1849+001
LHAASO J1908+0621	SNR G40.5-0.5 PSR 1907+0602 PSR 1907+0631	SNR PSR PSR	3.4 ⁱ 2.4 3.4	$\sim 10 - 20^j$ 19.5 11.3	— 2.8×10^{36} 5.3×10^{35}	MGRO J1908+06, HESS J1908+063, ARGO J1907+0627, VER J1907+062, 2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746 PSR J1930+1852 SNR G54.1+0.3	PSR PSR SNR	4.6 6.2 $6.3^{+0.8}_-0.7^d$	82.6 2.9 $1.8 - 3.3^k$	1.6×10^{36} 1.2×10^{37} —	2HWC J1928+177, 2HWC J1930+188, HESS J1930+188, VER J1930+188
LHAASO J1956+2845	PSR J1958+2846 SNR G66.0-0.0	PSR SNR	2.0 2.3 ± 0.2^d	21.7 —	3.4×10^{35} —	2HWC J1955+285
LHAASO J2018+3651	PSR J2021+3651 Sh 2-104	PSR H II/YMC	$1.8^{+1.7}_-1.4^l$ $3.3 \pm 0.3^m/4.0 \pm 0.5^n$	17.2 —	3.4×10^{36} —	MGRO J2019+37, VER J2019+368, VER J2016+371
LHAASO J2032+4102	Cygnus OB2 PSR 2032+4127 SNR G79.8+1.2	YMC PSR SNR candidate	1.40 ± 0.08^o 1.40 ± 0.08^o —	— 201 —	— 1.5×10^{35} —	TeV J2032+4130, ARGO J2031+4157, MGRO J2031+41, 2HWC J2031+415, VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7 PSR J2229+6114	SNR PSR	0.8 ^p 0.8 ^p	$\sim 10^p$ $\sim 10^p$	— 2.2×10^{37}	VER J2227+608, Boomerang Nebula



20" PMTs used in 70% WCDA

◆ Enhancement of the sensitivity below 300 GeV

◆ Transient Phenomena: GRB, AGN-flares, multi-messenger astronomy ...

