

八年孕育知坎坷 五载研制铸辉煌

高海拔宇宙线观测站（LHAASO） ——从概念到实现

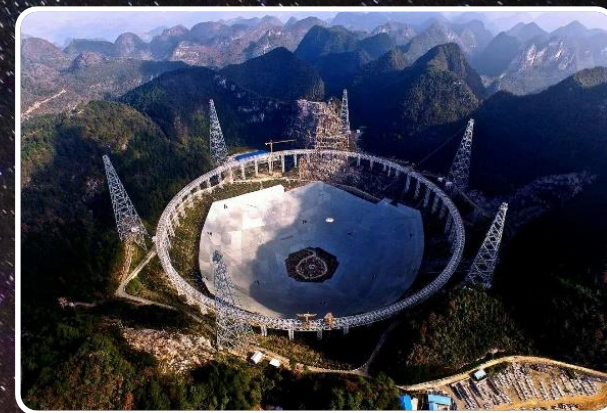
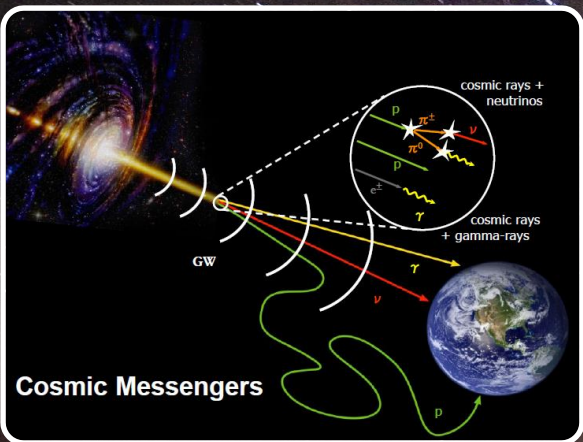
何会海

2023-08-25

内容

- 引子
- 探测器阵列设计
- 工艺设备研制
- 结语

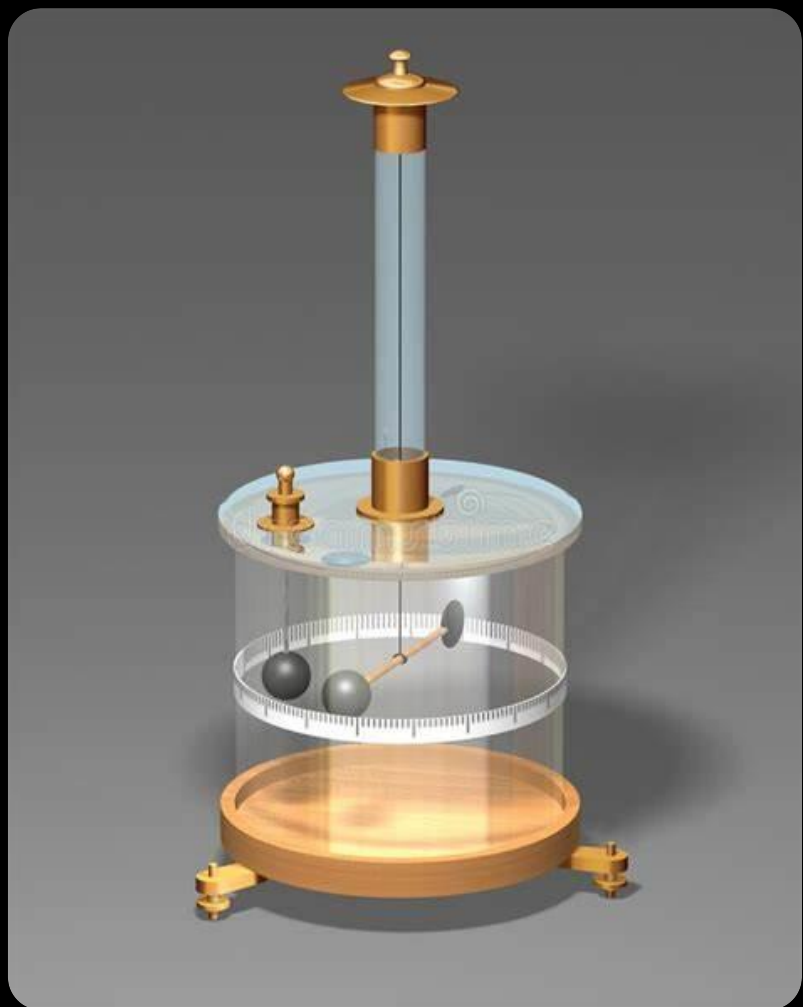
宇宙三信使——“两波一线”：电磁波、引力波、宇宙线



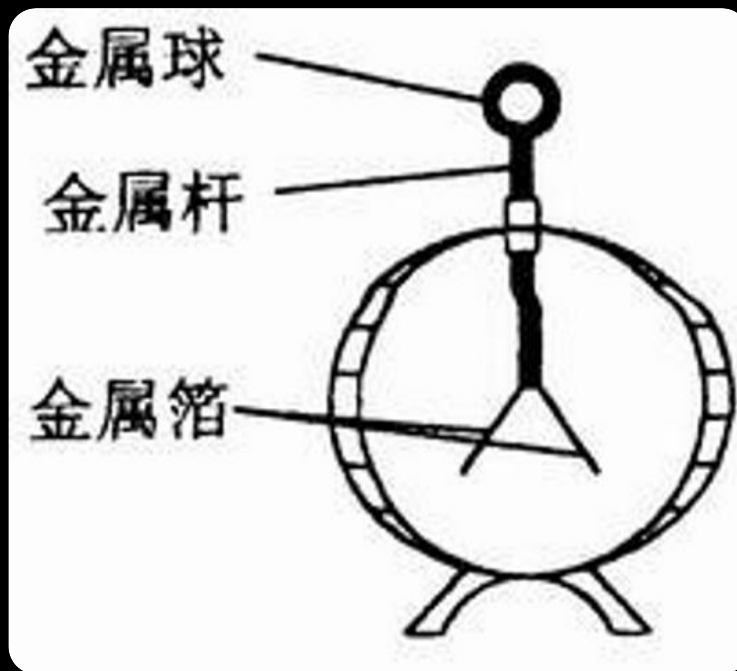
1785年，法国科学家库伦



➤利用**库伦扭秤**，测定了库伦力



他还发现了一个奇怪的现象……



验电器电荷消失之谜

验电器电荷消失之谜

150年

发现宇宙线



Important milestones

1785 Coulomb: *Spontaneous discharge*

1835 Faraday: *Confirms discharge*

1879 Crookes: *Discharge rate reduced with pressure*

1896 Bequerel, Curie's: *Radioactivity*

1900-1910: *A decade of intensive research*

1910 Wulf: *Climbes the Eiffel tower*

1910-11 Pacini: *Ionization under water*

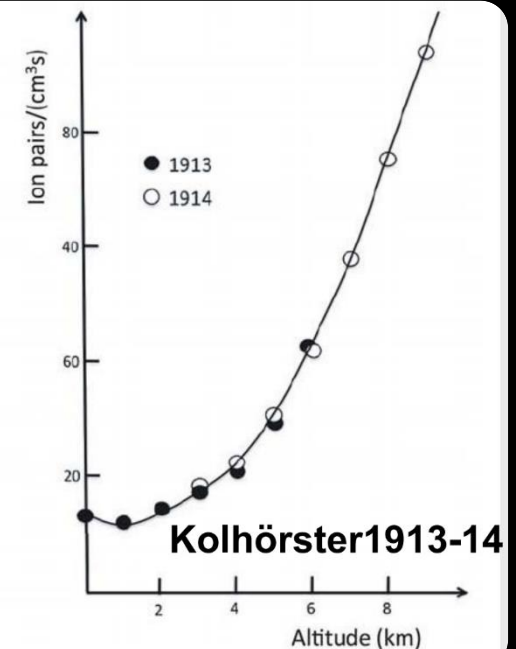
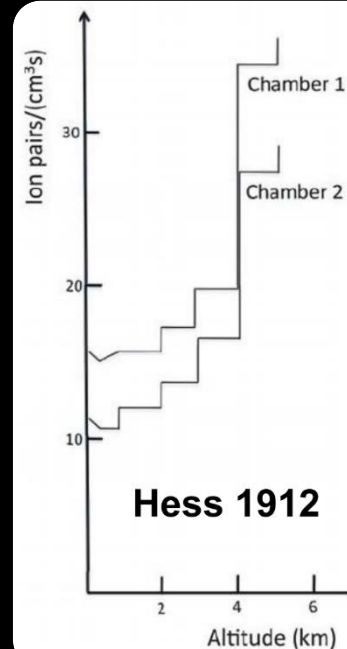
1912 Hess: *Ionization at high altitudes with balloon*

1914-18: *World War I*

1920s Compton, Millikan: *Cosmic rays*

1926: *General agreement on cosmic rays*

1936: *Nobel Prize to Anderson and Hess*



宇宙线的发现

1912年奥地利科学家赫斯发现了宇宙线，人类从此获得了一个新奇的科学宝藏和一种天然粒子炮弹，用以轰开原子核这个坚固的堡垒，探寻基本粒子的大千世界，开创了粒子物理学和高能天体物理学。

自上世纪三十年代起的20多年间，人类在宇宙线实验中相继发现了第一个反物质粒子 e^+ 、 μ 、 π 、 K 及 Λ 、 Σ 等基本粒子（一个诺贝尔奖引发了多个诺贝尔奖）。

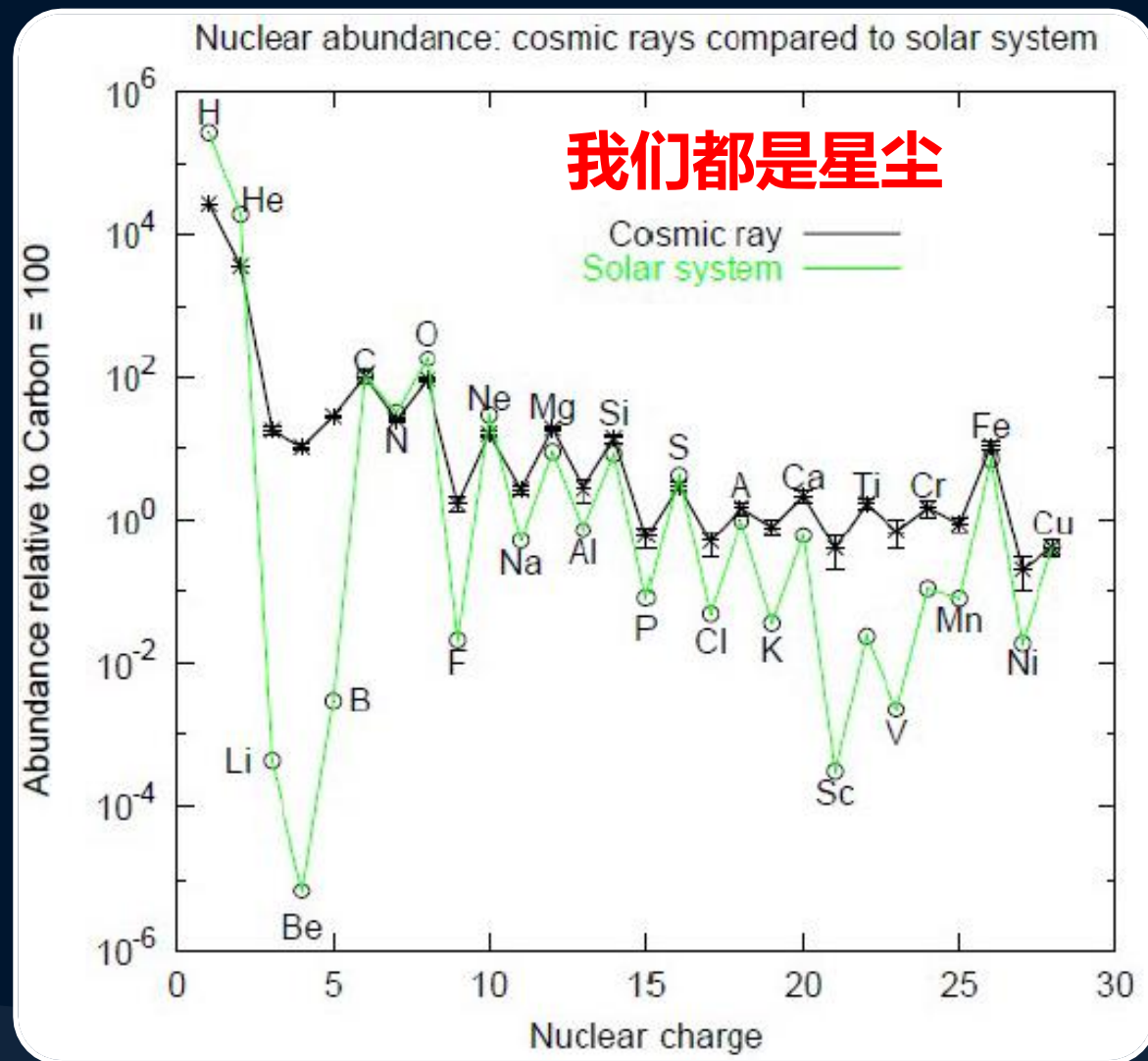


宇宙线是什么？

- 来自宇宙空间的**高能粒子**

- 元素周期表中质子到铁（以及更重）的原子核
- 电子
- 伽马射线
- 反物质粒子
- 中微子
- ...

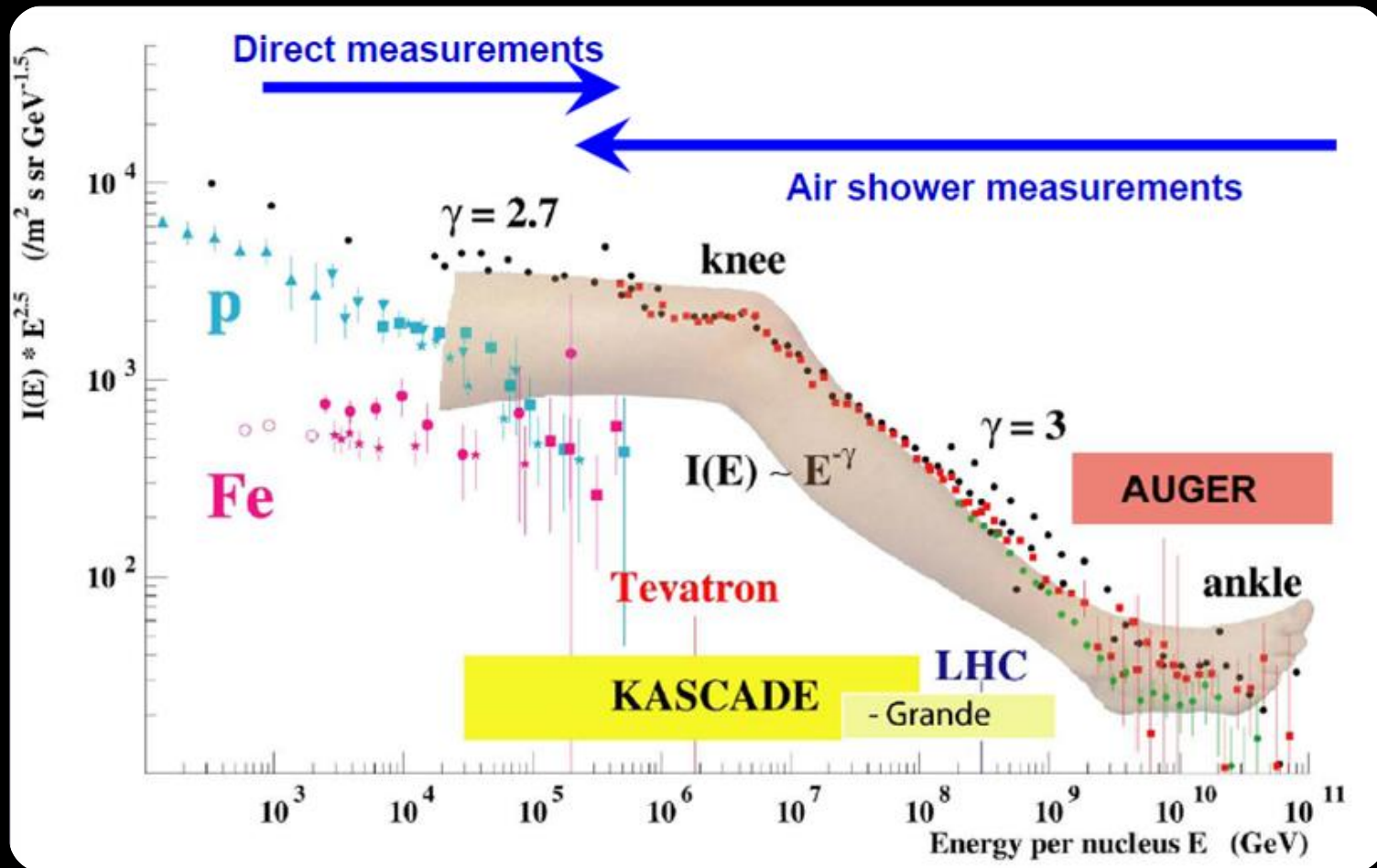
- 带电的、不带电的
- 强子、电磁粒子
- 物质、反物质
- 中微子



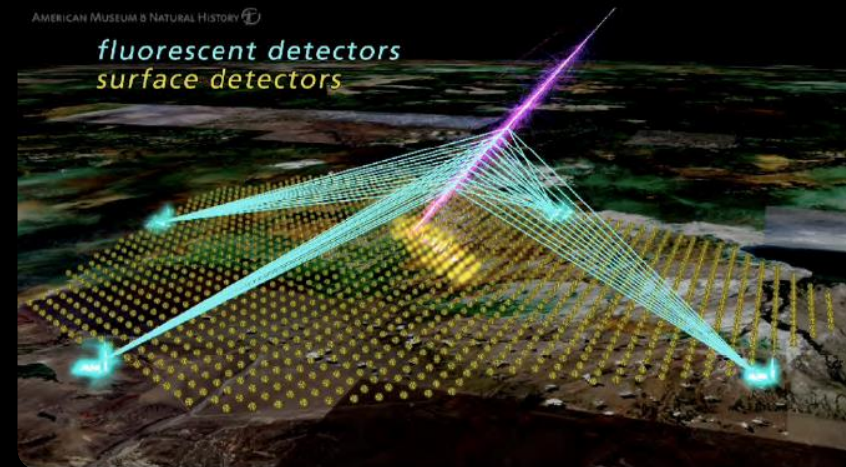
宇宙线有多少、能量有多高？



流强跨越30多个量级



能量覆盖10多个量级

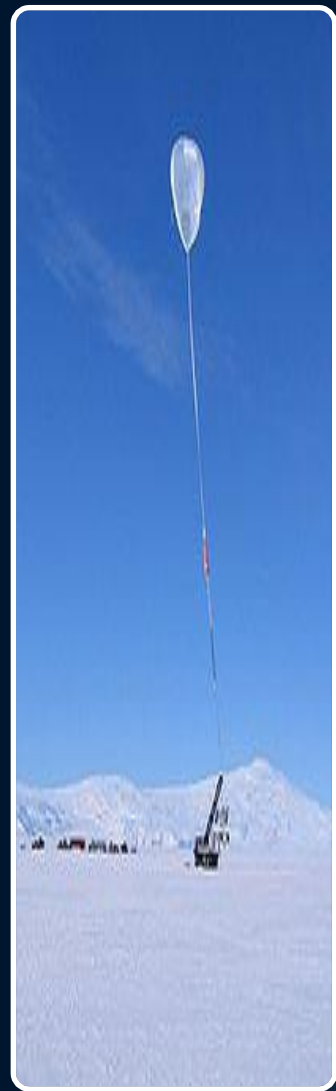


3,000平方千米

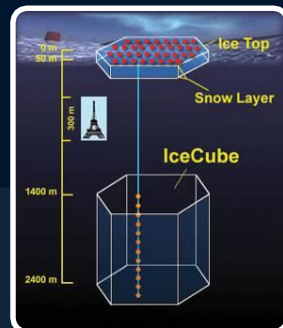
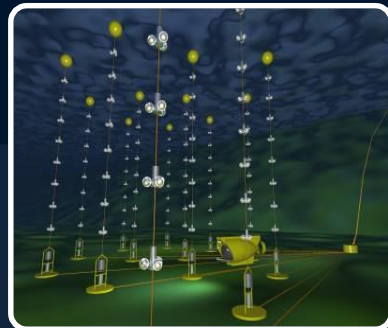
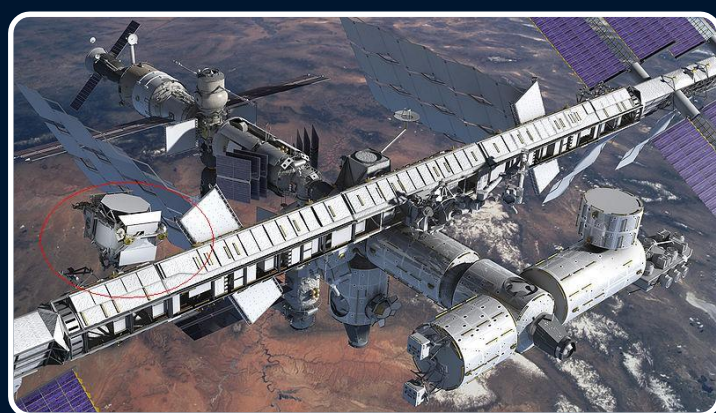
最高能量的宇宙线：

- 3万亿亿电子伏=48焦耳
- 每平方公里100年1个

宇宙线探测技术



“看” 粒子雨

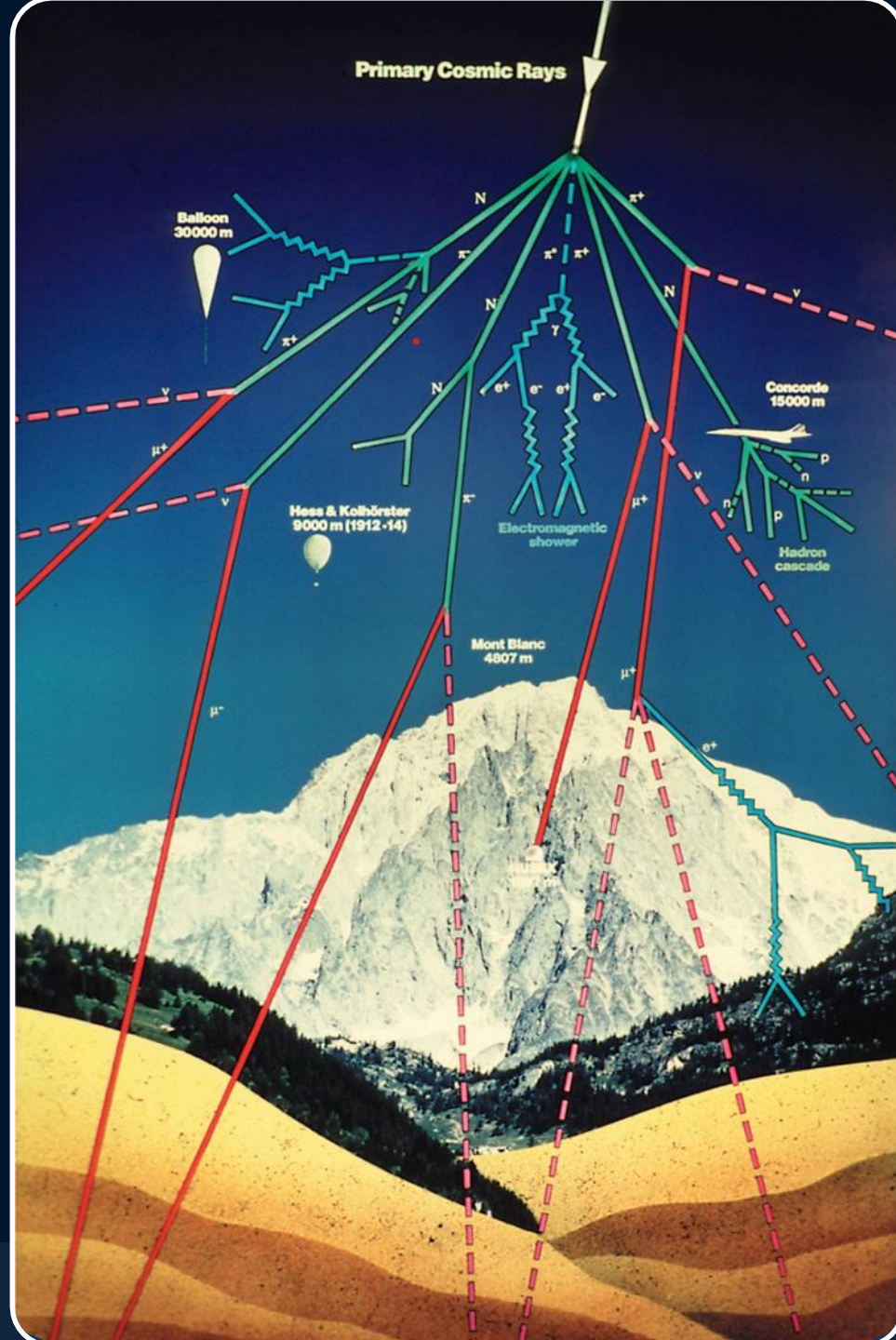


上天

攀山

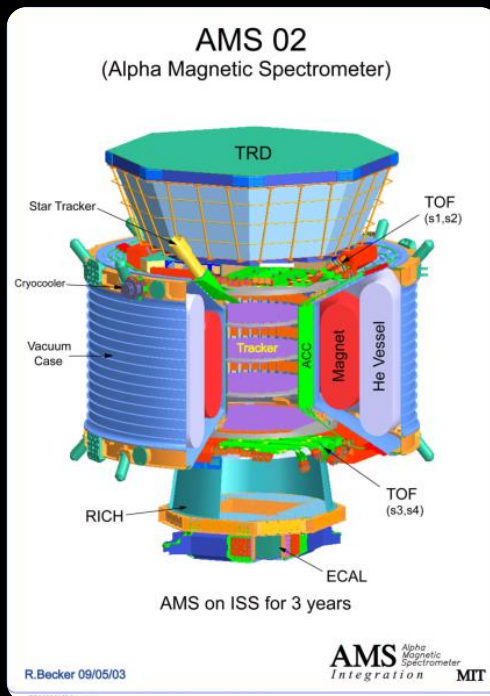
入地

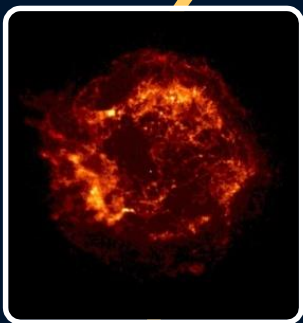
下海



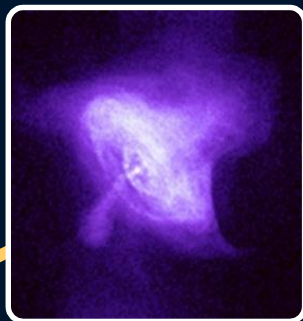
透过宇宙线看**极端相对论性**宇宙

- **宇宙线的起源、传播及加速机制—“世纪之谜”**
- **伽马射线天文—最高能量的电磁辐射窗口**
- 中微子天文
- 极高能粒子天文
- 反物质
- 暗物质
- 太阳物理及空间环境
- 粒子物理
- ...

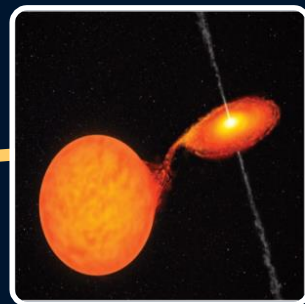




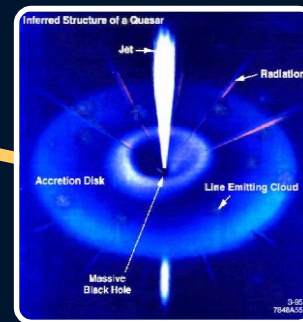
超新星遗迹



脉冲星



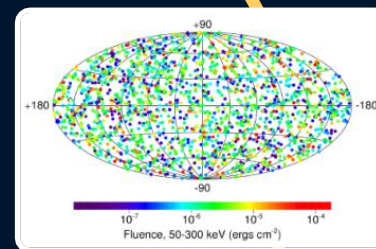
双星系统



活动星系核

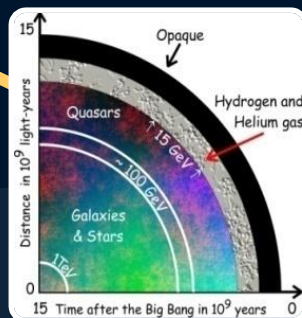


“世纪之谜”
高能宇宙线起源

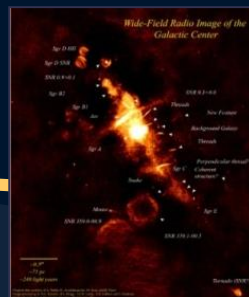


伽马暴

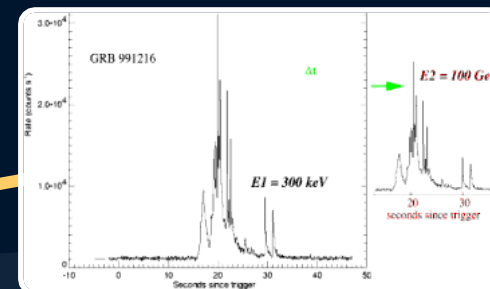
宇宙学
伽马射线视界



暗物质



检验相对论的基石
光速不变原理



中国70年宇宙线研究历史



王淦昌



张文裕



肖健



何泽慧



1987, 西藏, 海拔4300米



1977, 西藏, 5500米



高海拔宇宙线观测站 (LHAASO)

2021, 四川, 海拔4400米



1983, 北京



1989, 河北



羊八井宇宙线观测站

甘巴拉山乳胶室



1954, 云南, 海拔3,220米



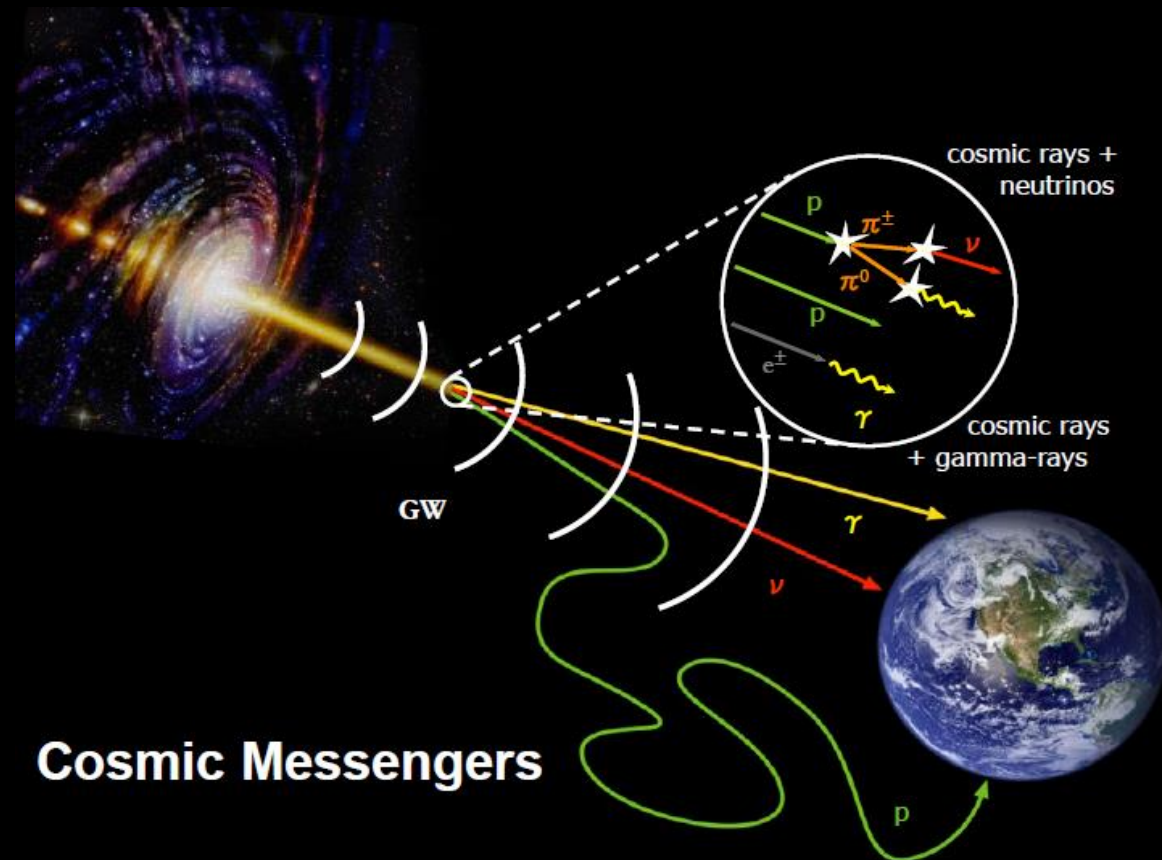
1987, 云南

落雪山宇宙线观测站

梁山裸管切伦科夫阵列

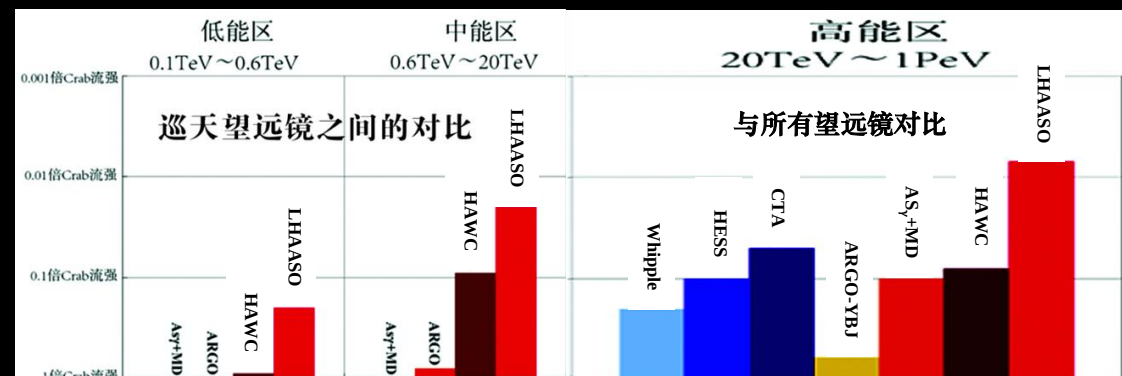
探索高能宇宙线起源的机遇与挑战

- 破解高能宇宙线起源“世纪之谜”的困境：
 - 宇宙线基本各向同性，透过宇宙线看宇宙是雾气茫茫的
 - 中微子是最直接的手段，但很难探测
 - 伽马射线容易探测，但存在二义性
- 超高能伽马辐射是最有效的手段
 - 流强极低
 - 巨大的宇宙线背景



LHAASO三大核心科学目标

- 探索“世纪之谜”高能宇宙线起源
- 发现高能辐射新现象、揭示新规律
- 新物理前沿探索
 - 暗物质间接测量
 - 量子引力/Lorentz对称性破坏效应
 - 超越LHC能标的新物理



- 超高能 γ 探测灵敏度世界最高
- 甚高能 γ 巡天灵敏度世界最高
- 宇宙线探测能量跨度最大

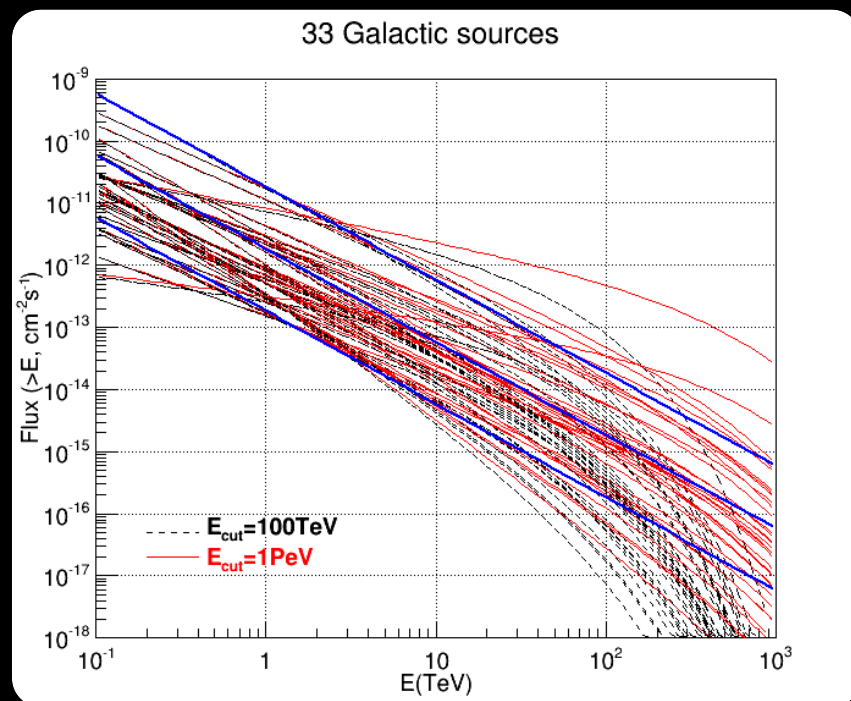
LHAASO建设目标

纸上谈兵

KM2A: 超高能伽马天文

- 大视场: 2 sr
- 能量分辨率: 20% @ 100 TeV
- 灵敏度: 1% I_{Crab} @ 100 TeV

10 photons/year/km²



年曝光量:
>2000 km²hr

阵列面积1 km²
ED覆盖率0.5%
• ~5千平米

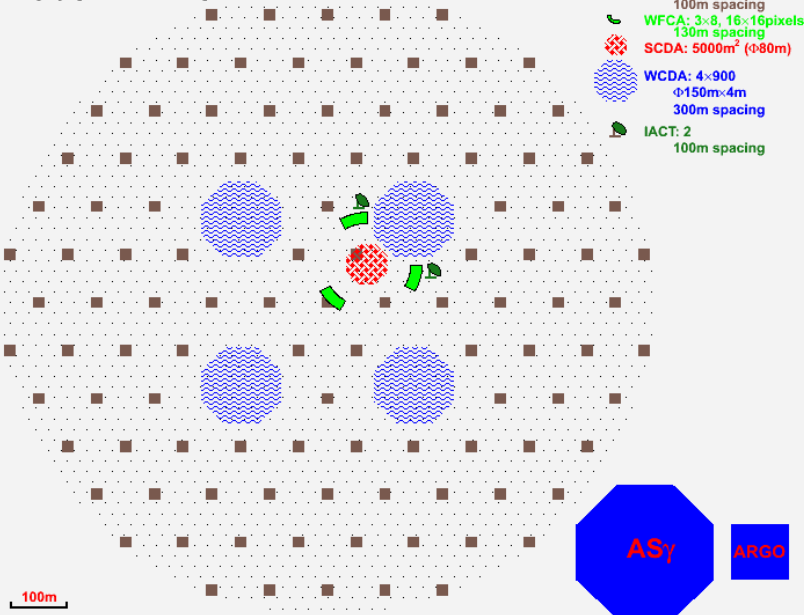
“零背景”

背景排除能力: 10⁴-10⁵

MD覆盖率5%
• ~5万平米

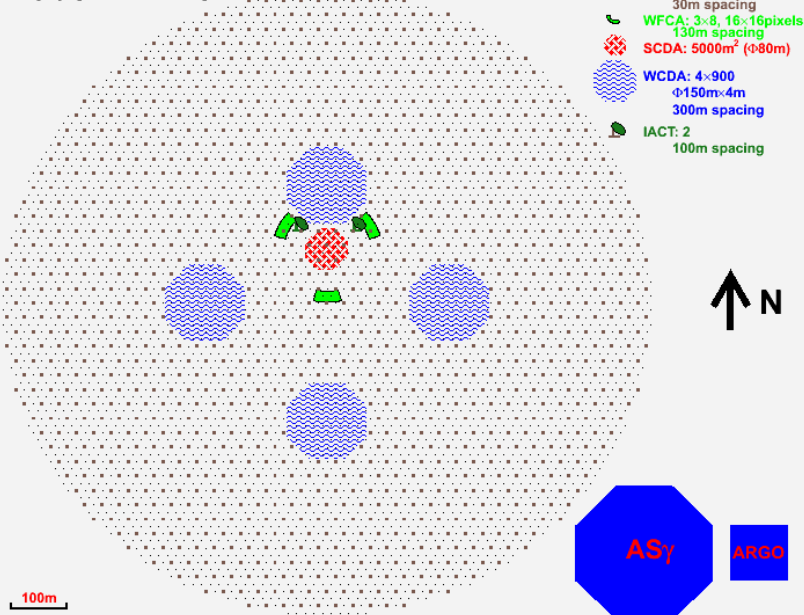
Large High Altitude Air Shower Observatory

Yangbajing, 4300m a.s.l., 606g/cm²



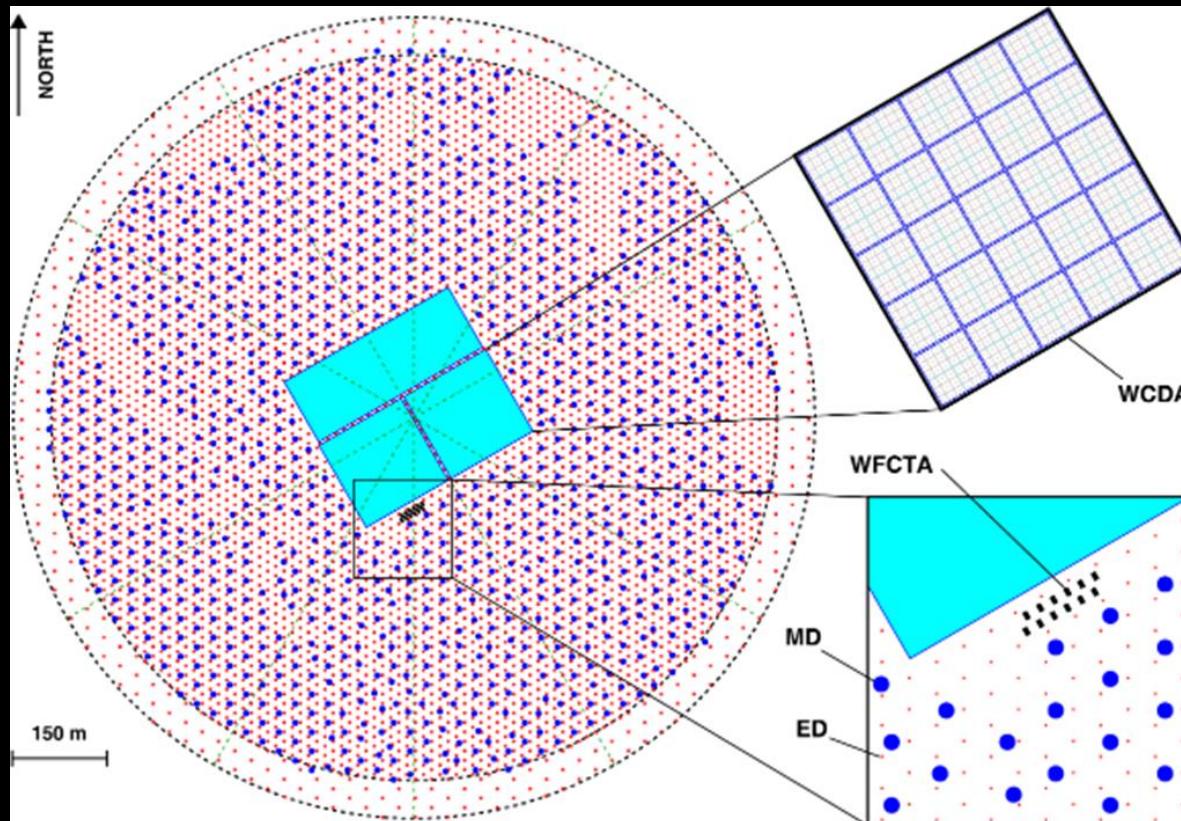
Large High Altitude Air Shower Observatory

Yangbajing, 4300m a.s.l., 606g/cm²



大型高海拔空气簇射观测站（LHAASO）@羊八井（4300 m a.s.l.），2009

不断优化



- 5195 EDs
 - 1 m² each
 - 15 m spacing
- 1171 MDs
 - 36 m² each
 - 30 m spacing
- 3000 WCDs
 - 25 m² each
- 12 WFCTs

高海拔宇宙线观测站（LHAASO）@稻城（4410 m a.s.l.），2017

大型高海拔空气簇射观测站（LHAASO）@羊八井（4300 m a.s.l.），2010

三地转战穷设计

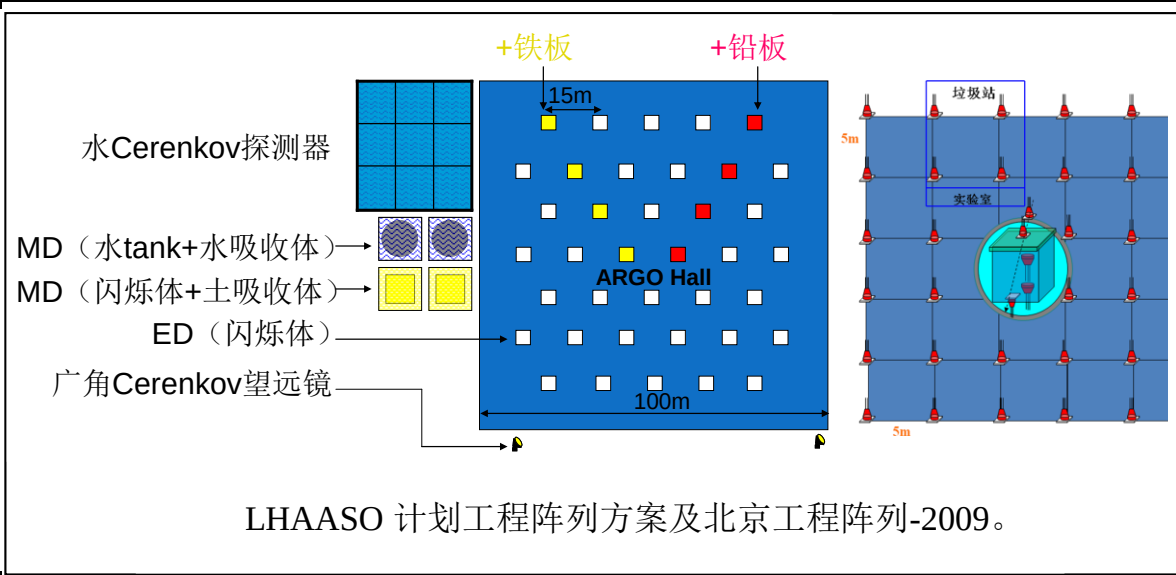
四川稻城



西藏羊八井

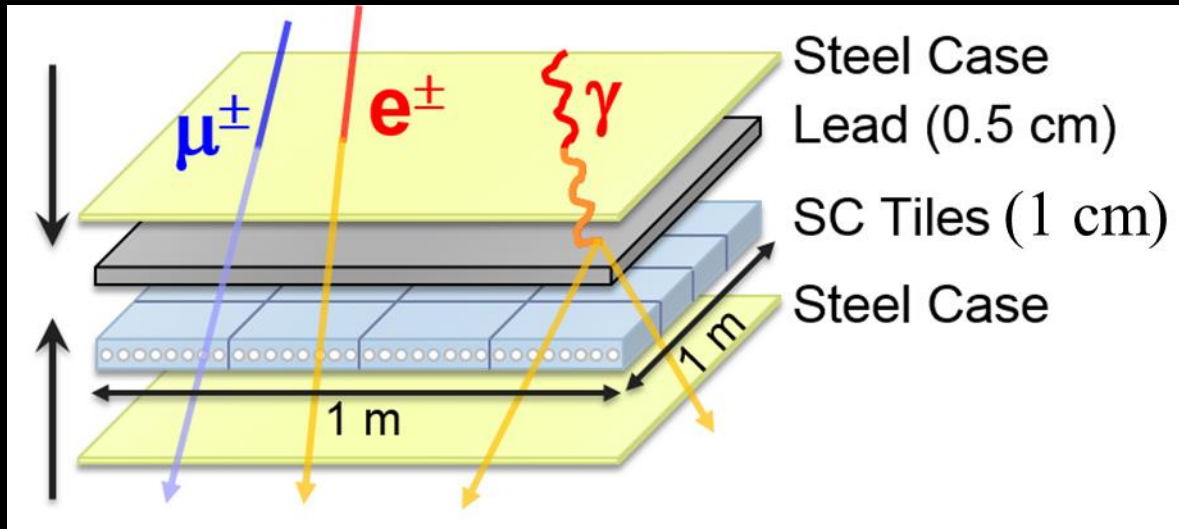


北京 IHEP



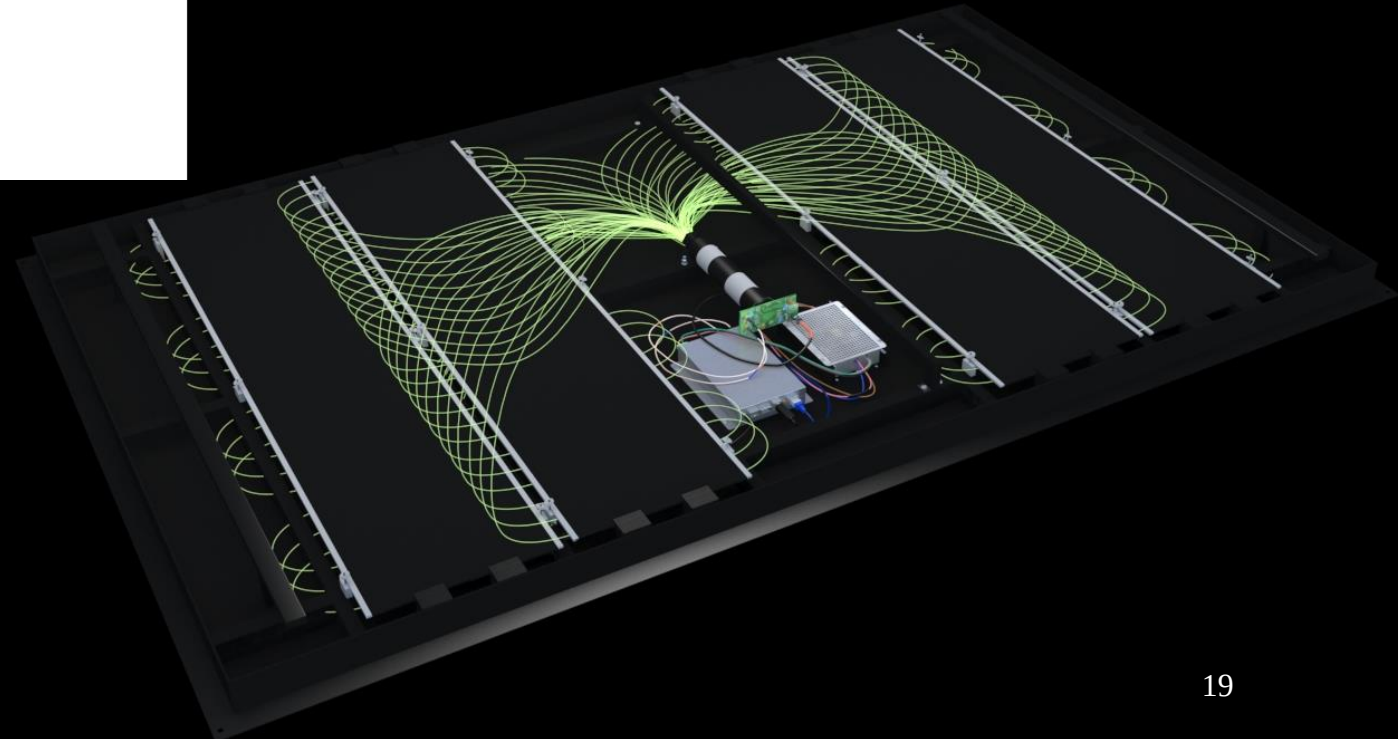


ED: Electromagnetic Particle Detector (ED)

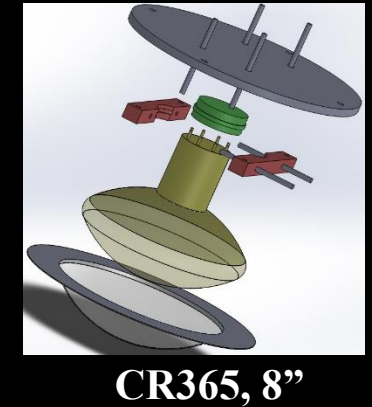
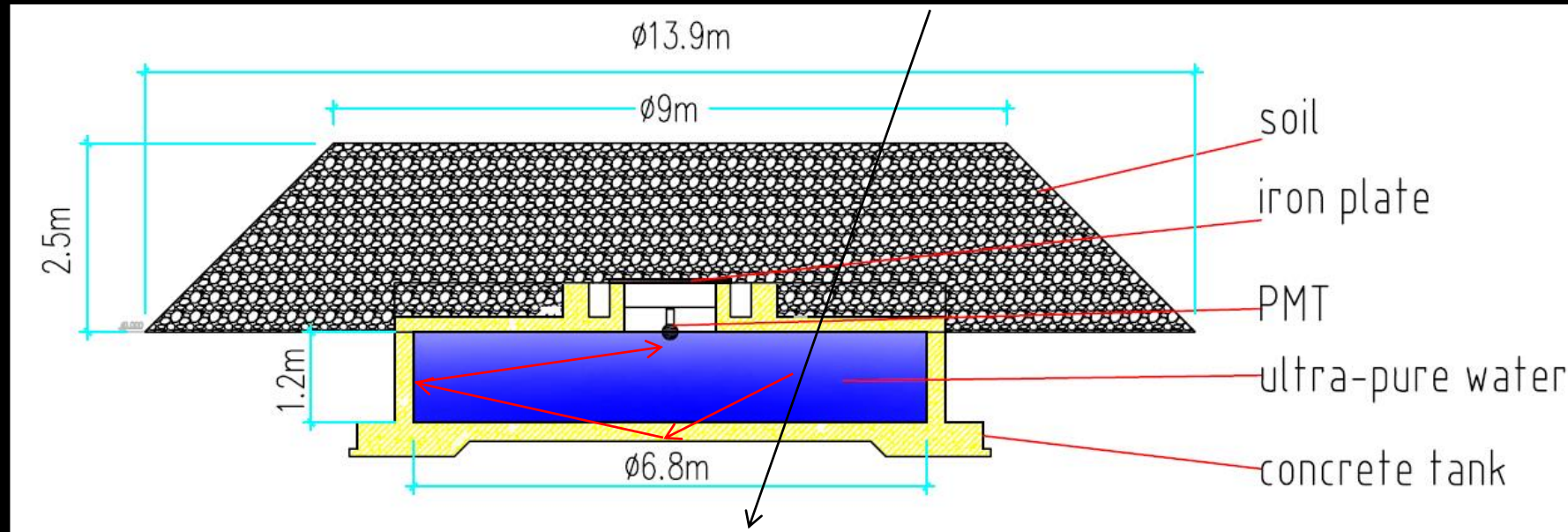


- **Uniformity for 5195 units: $< 10\%$**
- **Stability within $\pm 25^\circ\text{C}$: $\pm 5\%$**

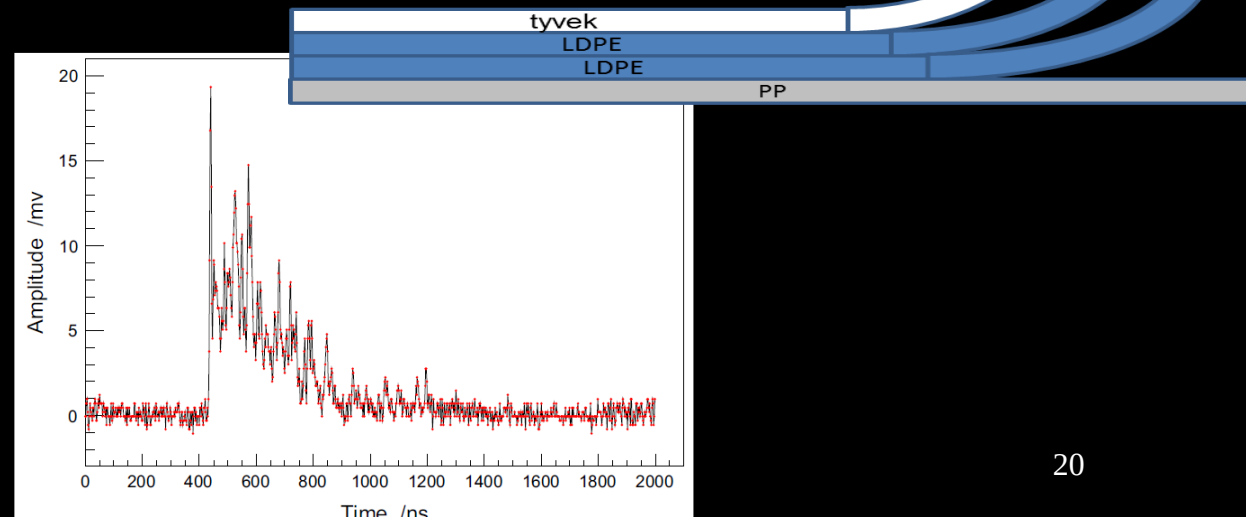
efficiency ($> 5 \text{ MeV}$)	$>95\%$
dynamic range	$1\text{-}10^4$ particles
time resolution	$<2 \text{ ns}$
particle counting resolution	25% @ 1 particle 5% @ 10^4 particles
aging ($<20\%$)	>10 years



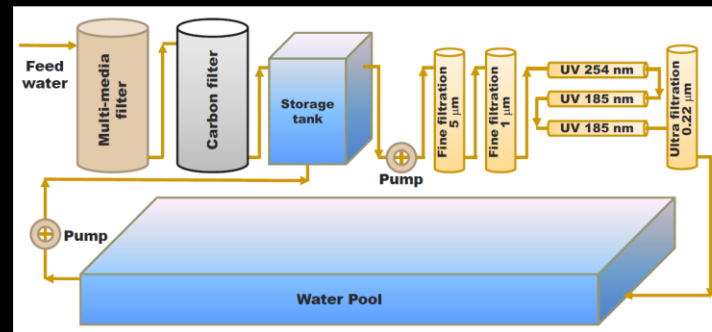
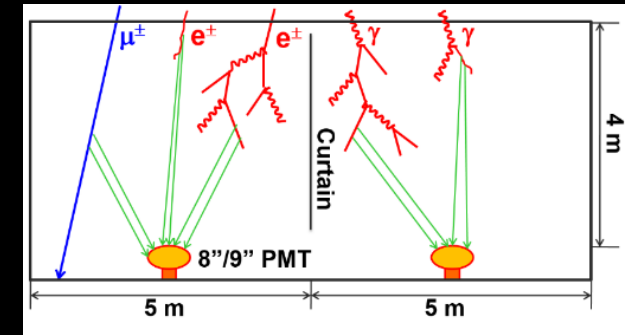
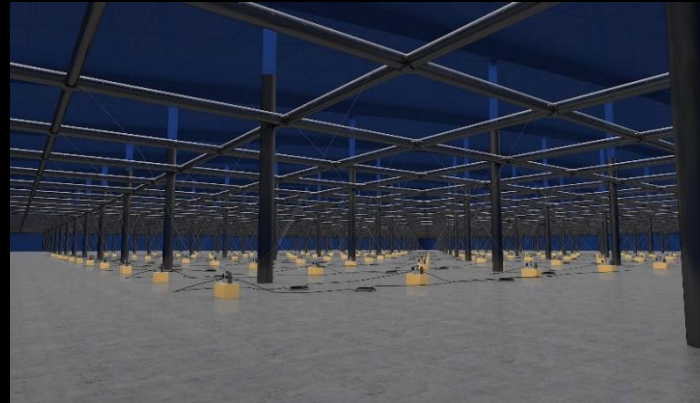
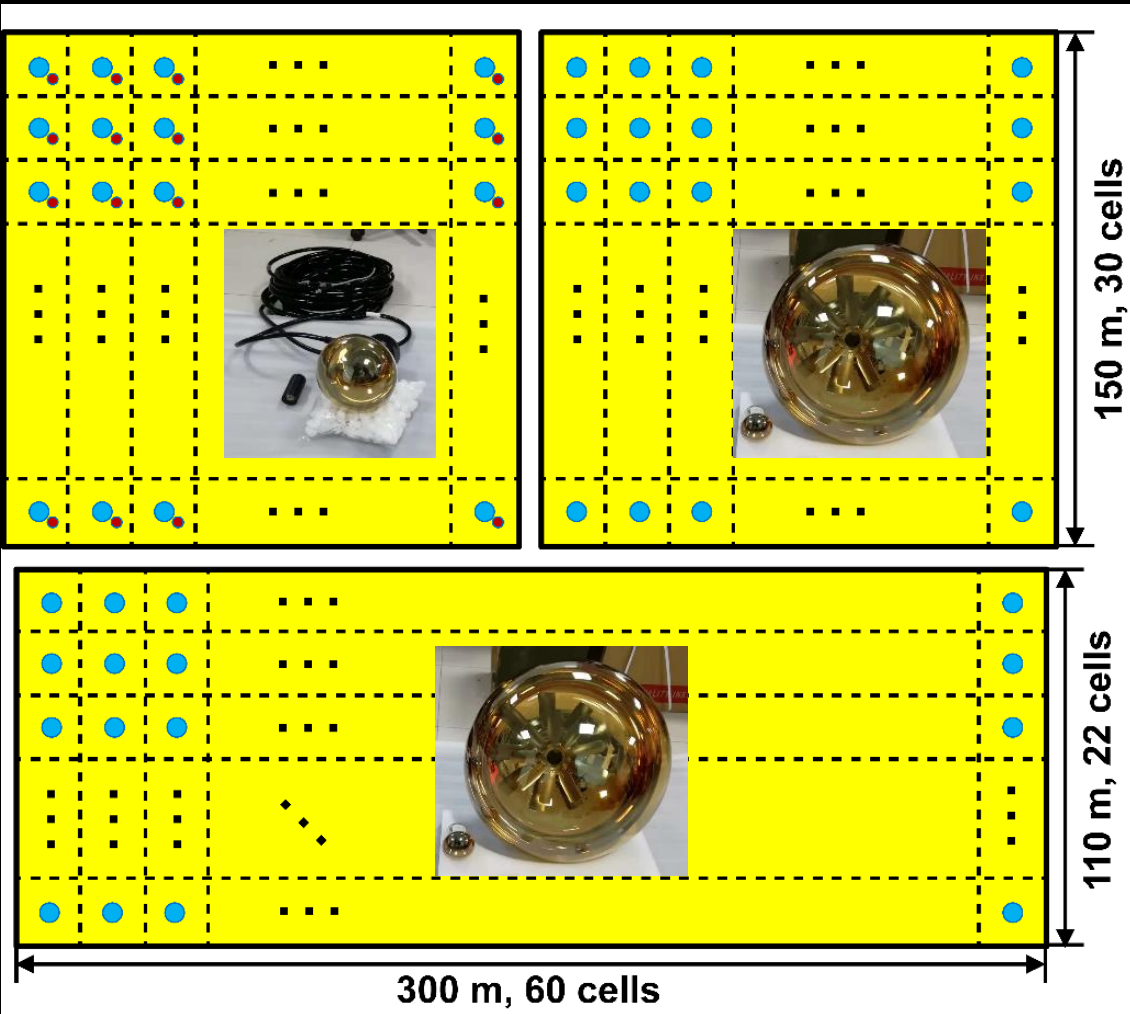
MD: Muon Detector



water att. len.	> 30 m (400 nm)
reflection coefficient	>95%
dynamic range	1-10 ⁴ particles
time resolution	<10 ns
particle counting resolution	25% @ 1 particle 5% @ 10 ⁴ particles
aging (<20%)	>10 years

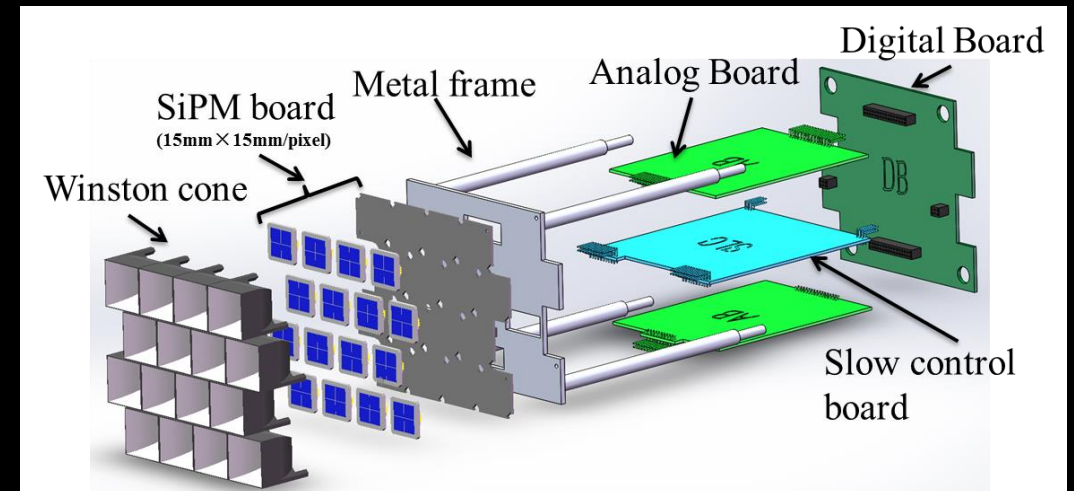
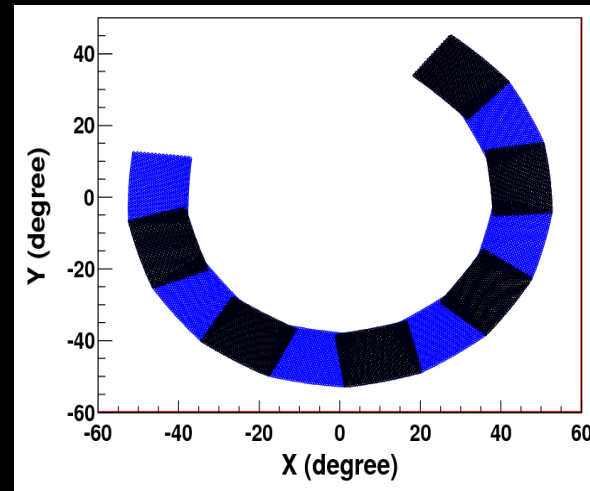
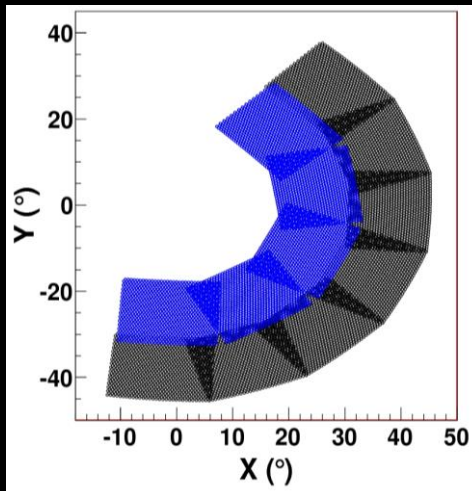
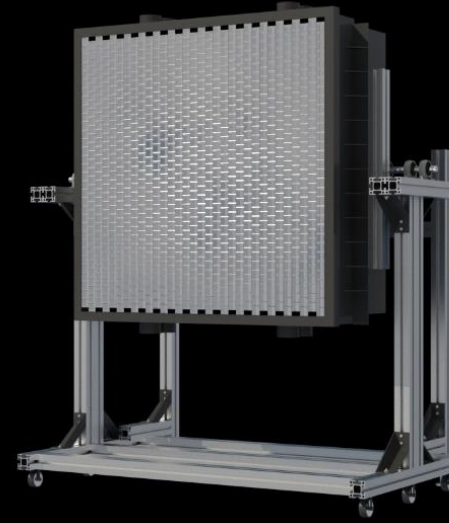
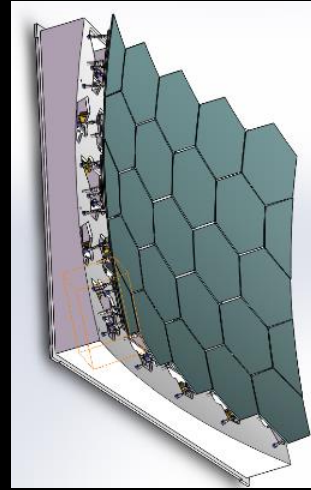


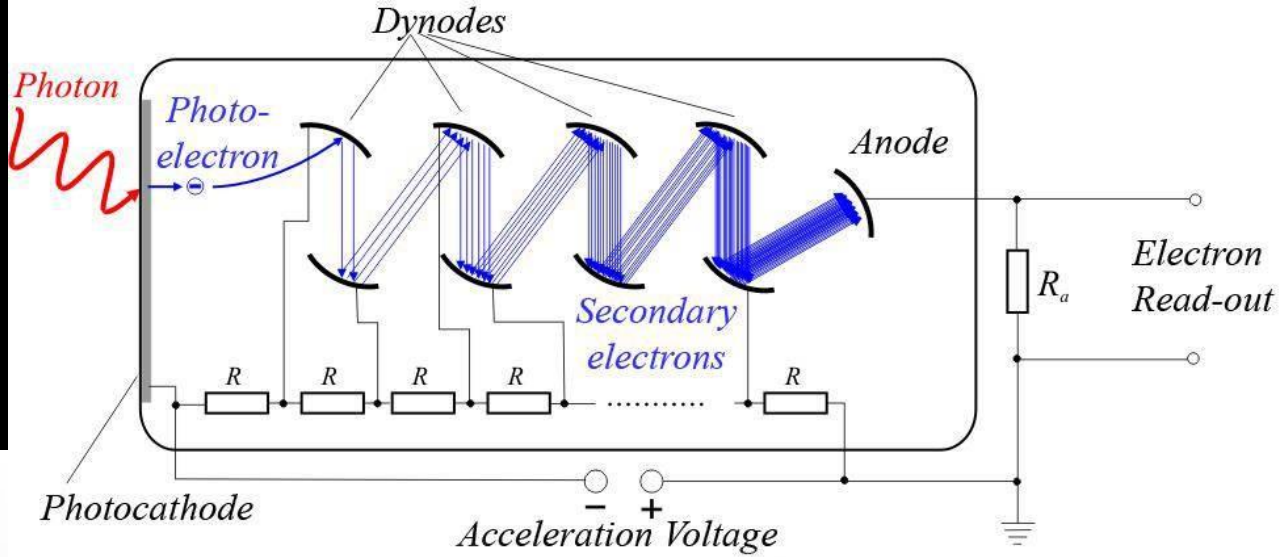
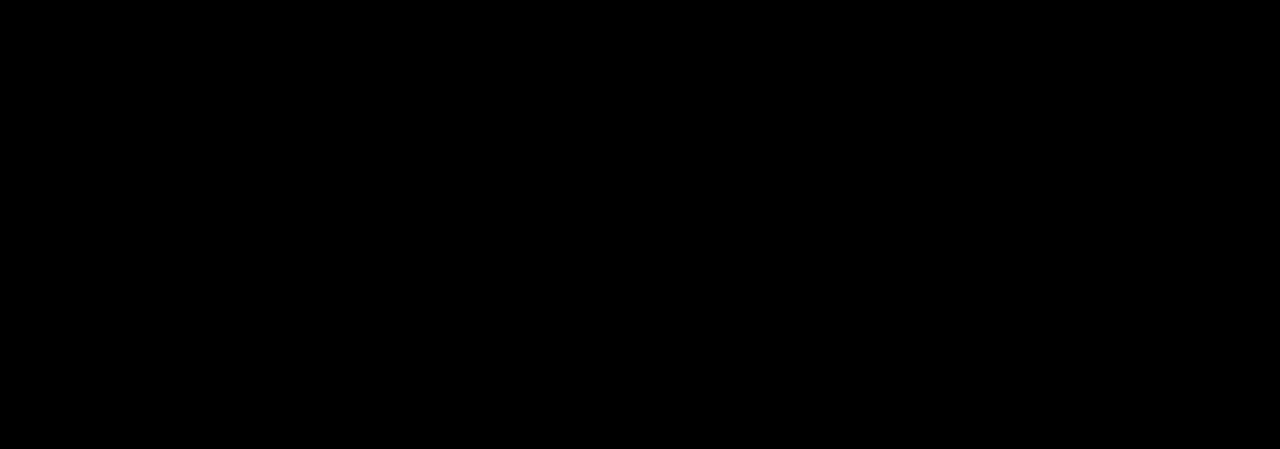
WCDA: Water Cherenkov Detector Array



WFCTA: Wide FoV Cherenkov Telescope Array

- 5m² spherical mirror
 - FOV: 16° × 16°
 - 32 × 32 SiPMs array
 - Pixel size 0.5° × 0.5°
- Portable design





世界上第一台兔耳探测器



Over 7,000 detector units
Spread around 1km² area

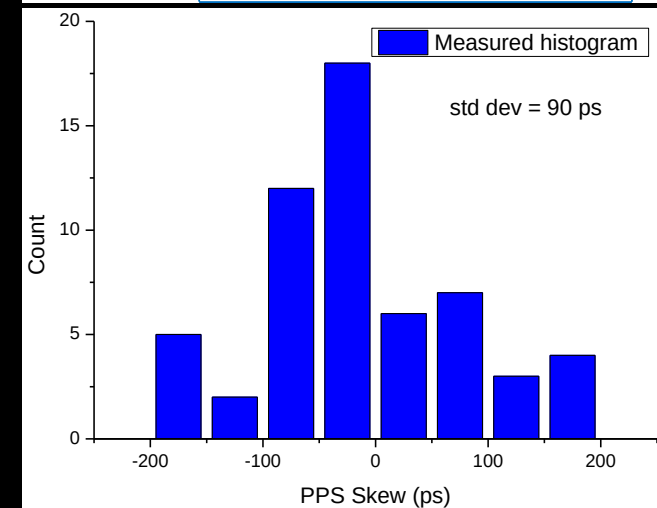
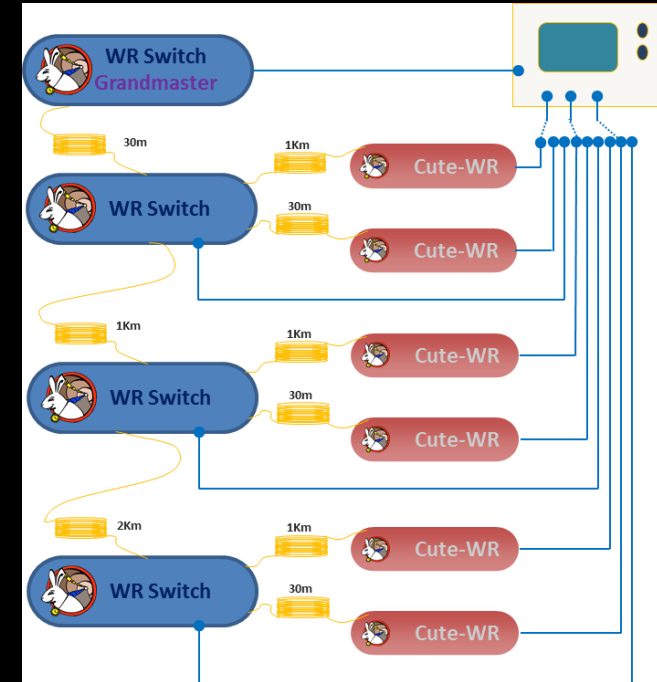
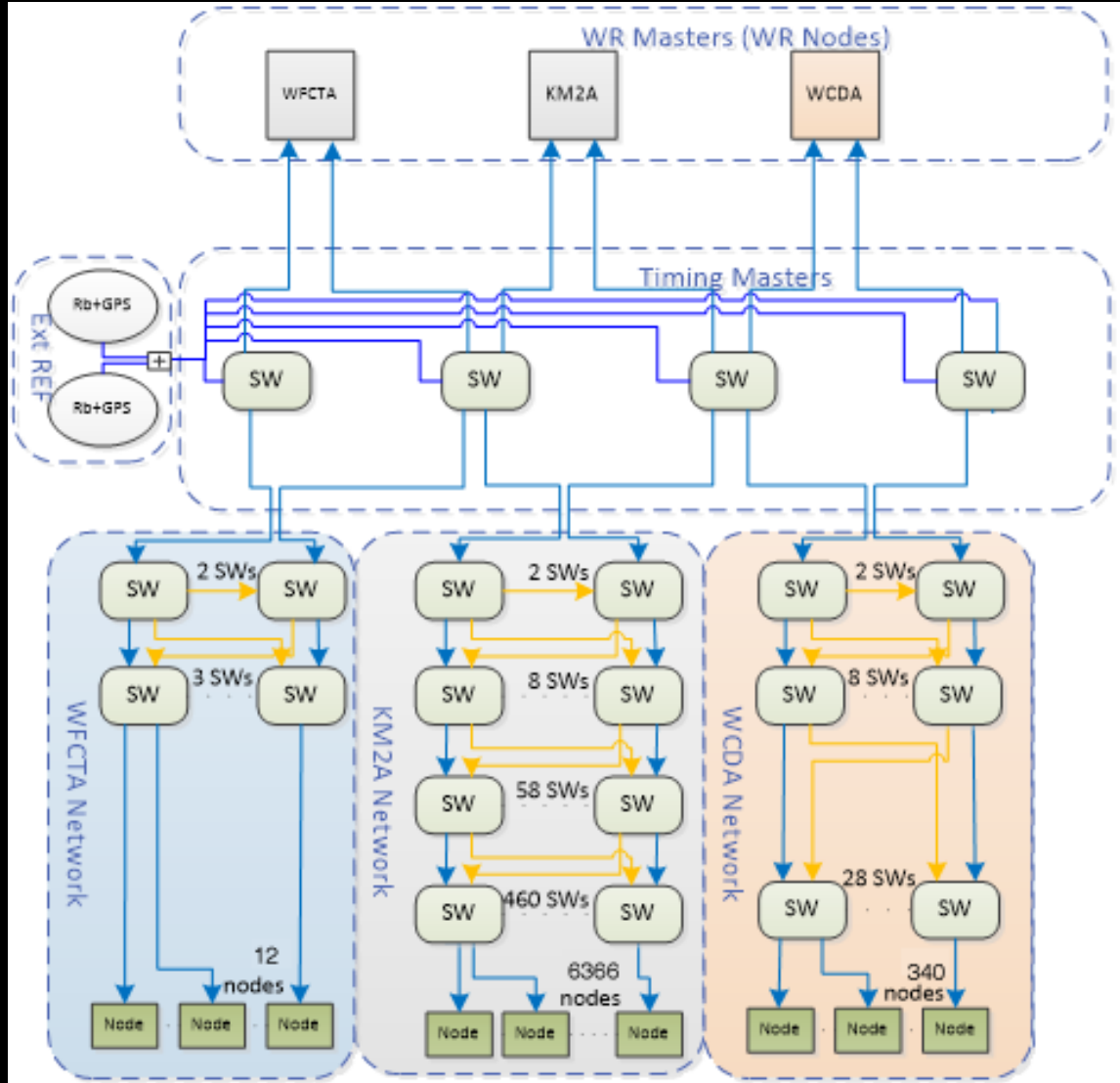
Synchronous timing with $\text{RMS} < 0.5\text{ns}$

0.5° Angular resolution for shower
reconstruct from *timing* of hits TOF

1000m coax cable in 30°C change, $\Delta \text{delay} = 15\text{ns}$!



LHAASO detector timing



和田地区

海西蒙古族
藏族自治州

西宁市 海东市 白银市

兰州市 定西市

果洛藏族自治州

黄河

青海玉树

玉树藏族自治州

阿坝藏族
羌族自治州

2013.09

四川稻城

眉山市

云南香格里拉

凉山彝族自治州

昭通市

攀枝花市

大理白族自治州

曲靖市

昆明市

玉溪市



西藏阿里
阿里地区

那曲市

昌都市

西藏羊八井

拉萨市

山南市

林芝市



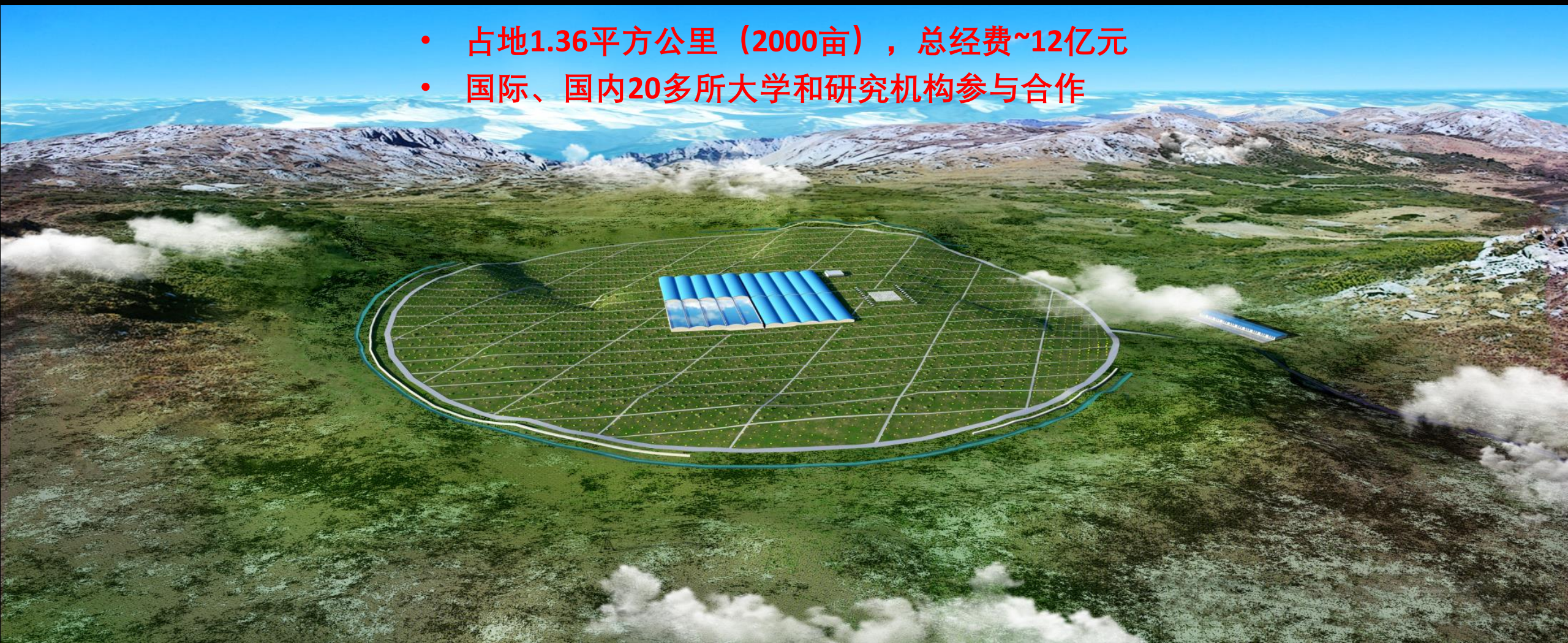
“四省五地”觅佳园



高海拔宇宙线观测站

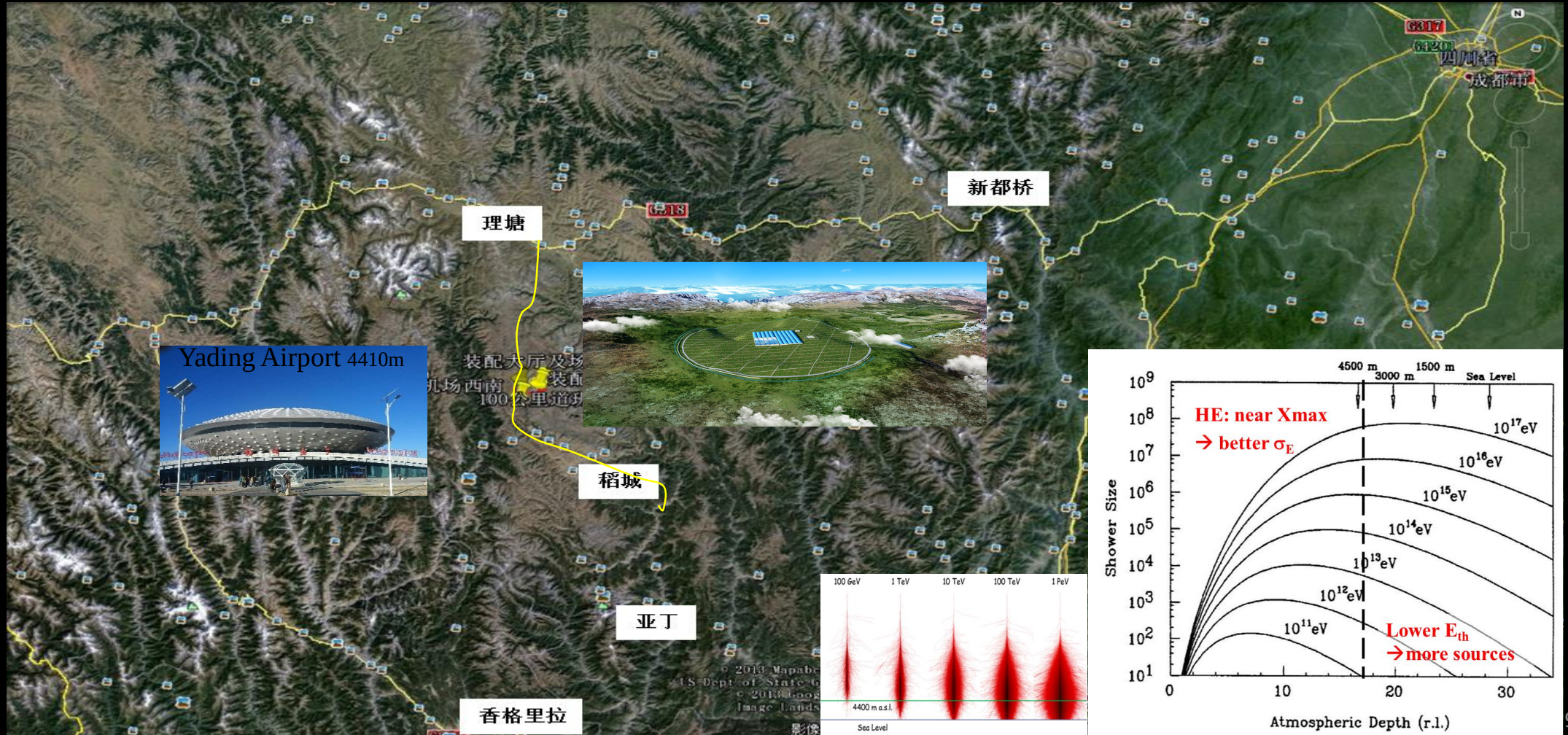
LHAASO: Large High Altitude Air Shower Observatory

- 占地1.36平方公里（2000亩），总经费~12亿元
- 国际、国内20多所大学和研究机构参与合作



大面积@高海拔

Mt. Haizi (4410 m a.s.l., 29°21' 27.6" N, 100°08'19.6" E), Sichuan, China



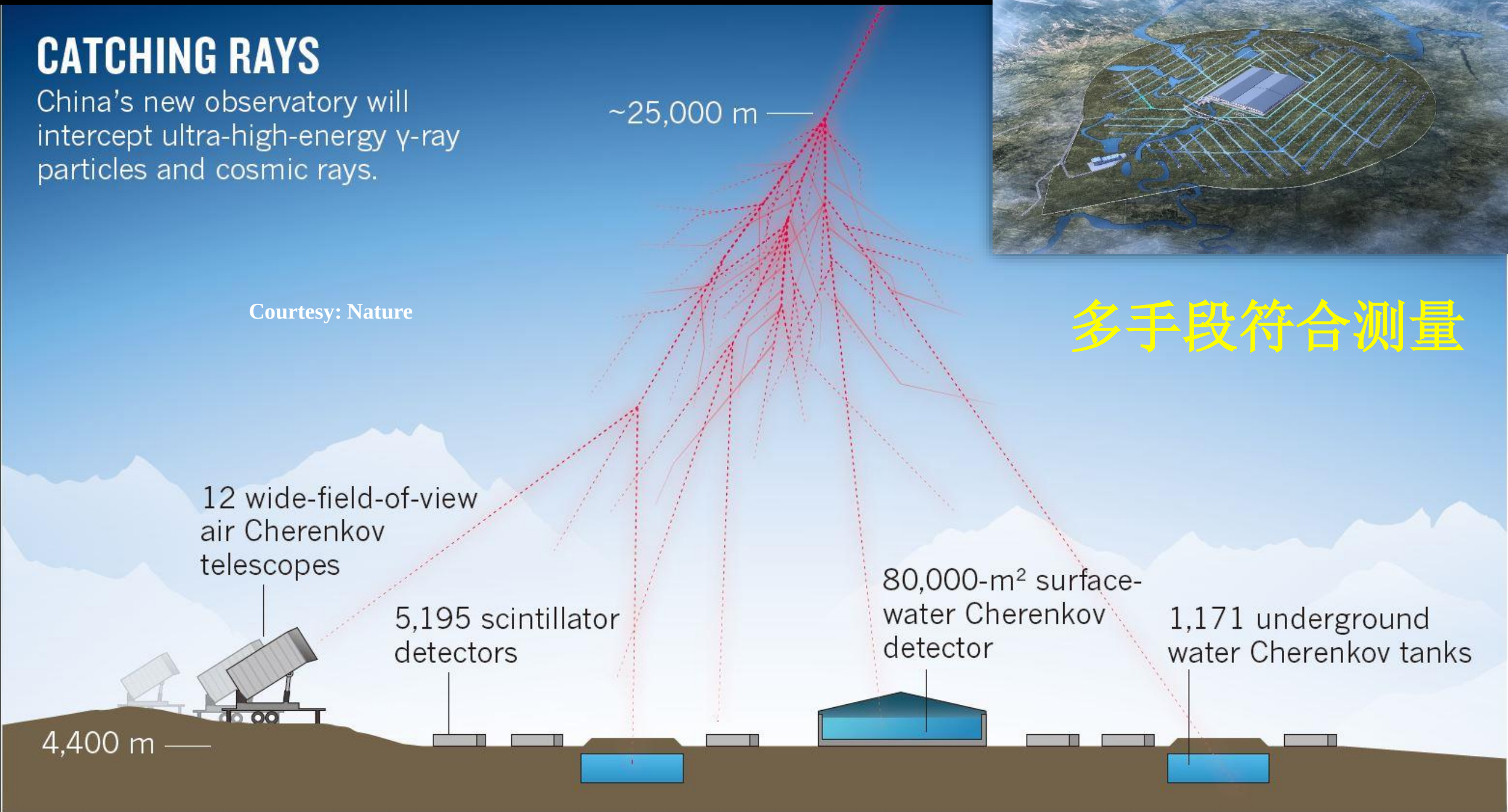
CATCHING RAYS

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

Courtesy: Nature

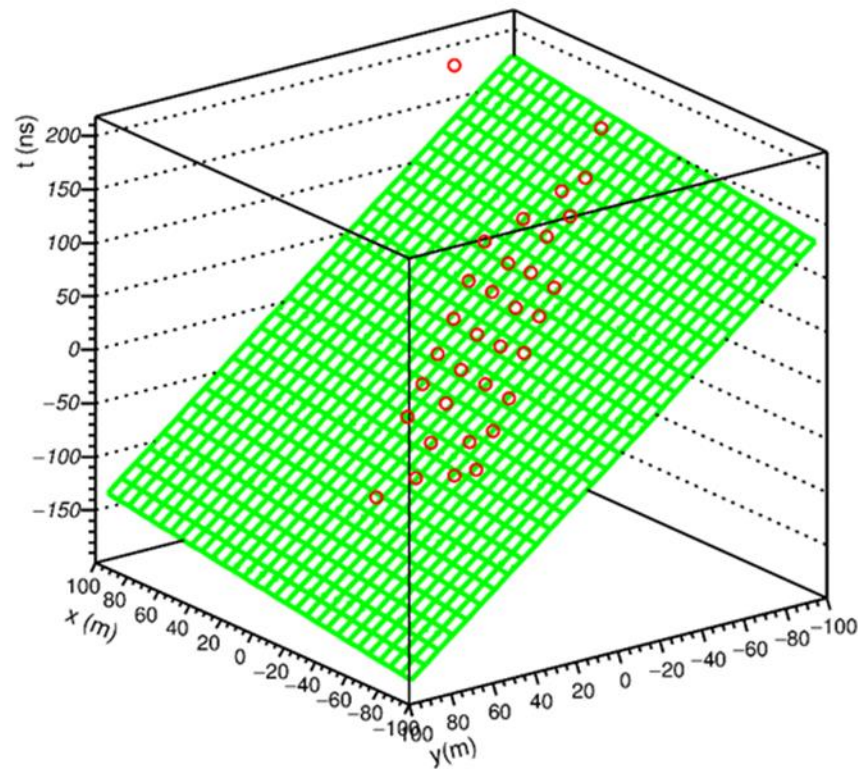


多手段符合测量

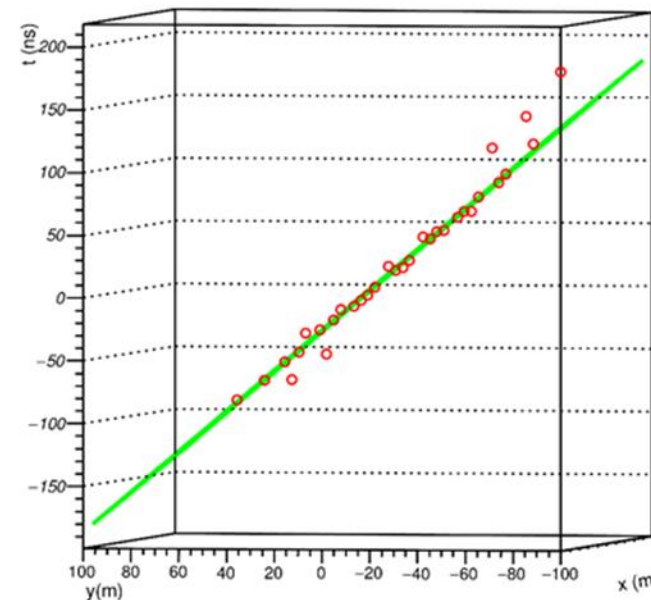


工艺设备研制

➤从科研到项目的角色转换，仿佛凤凰涅槃



2018年元月，完成首批33个ED的安装，打响了探测器现场安装的第一枪

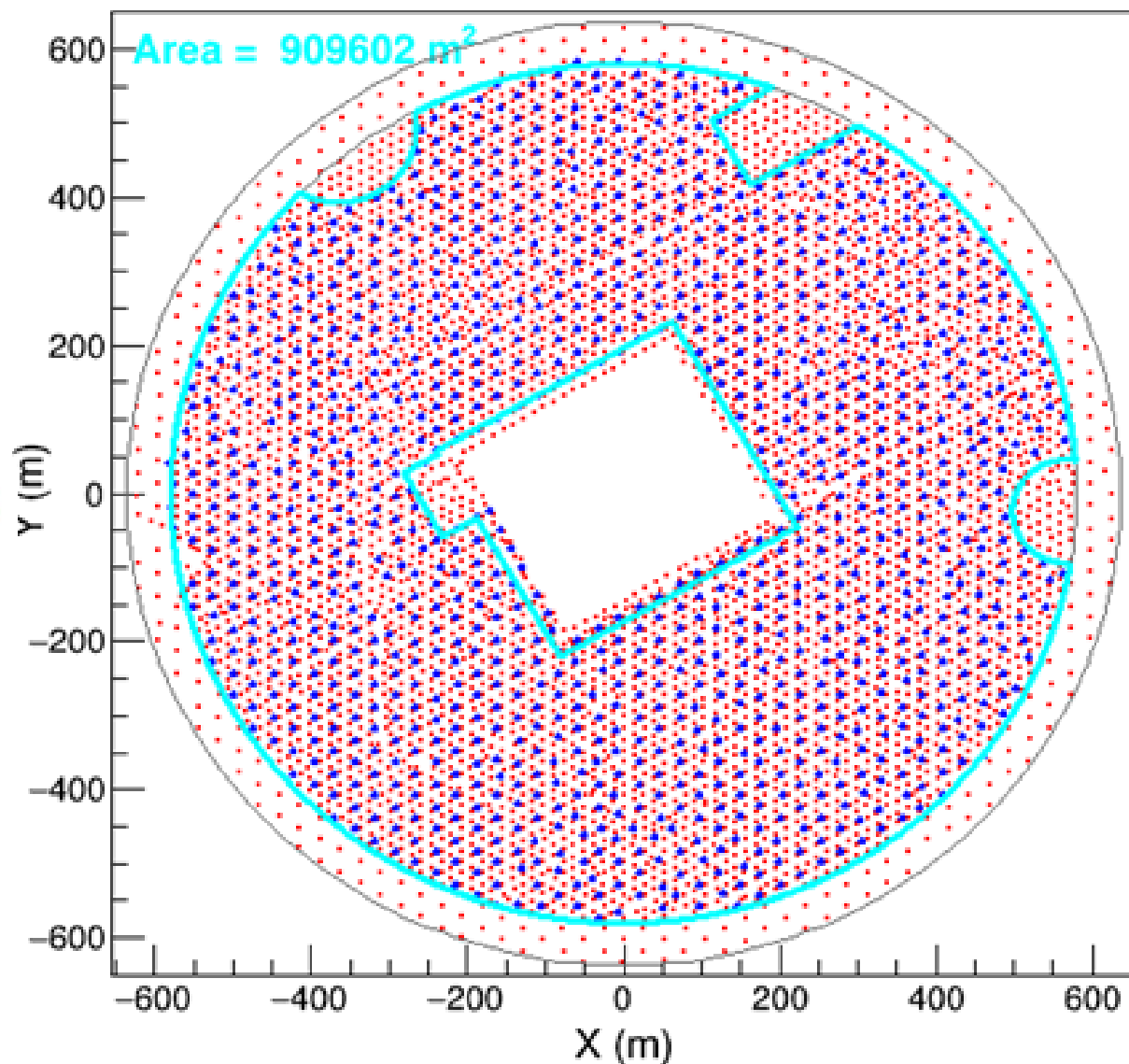
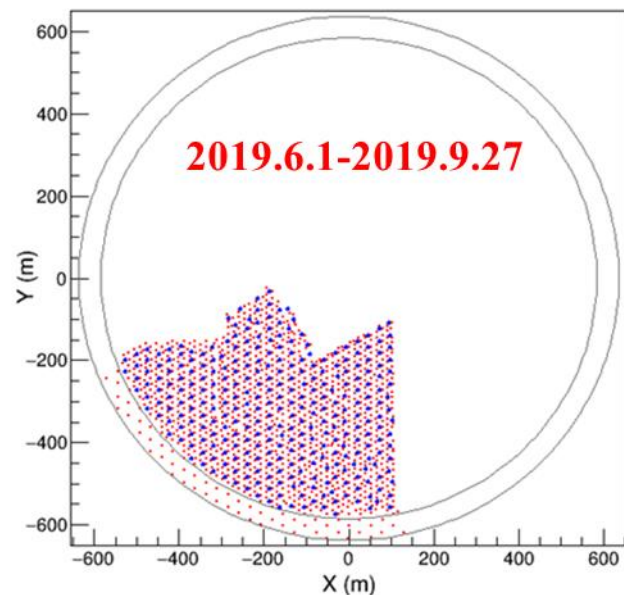


LHAASO最大的“拼图”是这样建成的

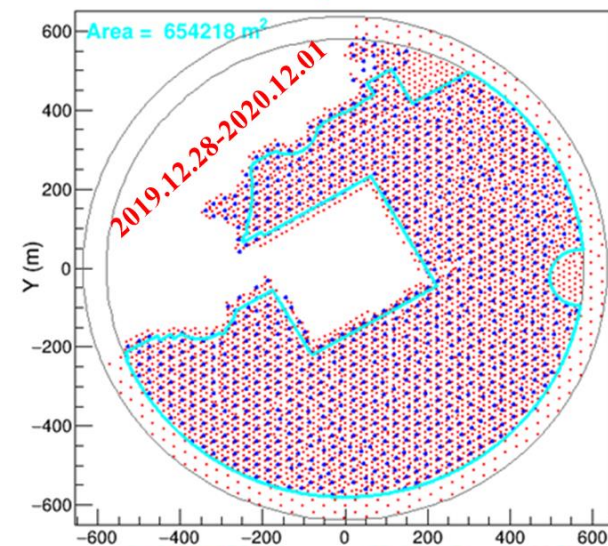
LHAASO-KM2A Layout: 5249 EDs + 1188 MDs



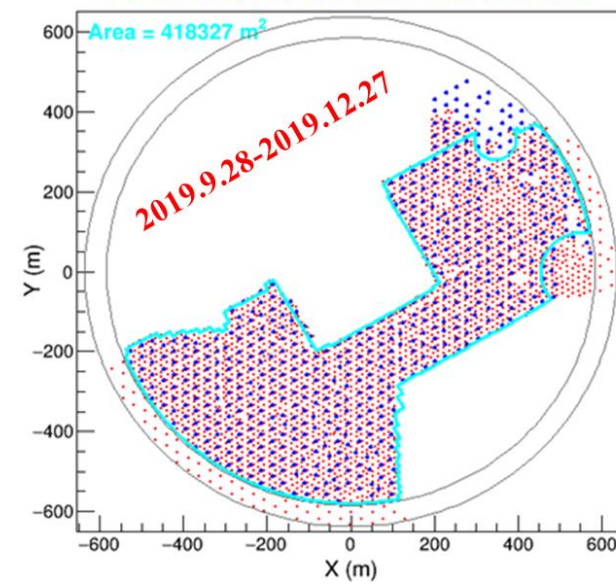
1/4 LHAASO Layout: 1286 EDs + 307 MDs



3/4 LHAASO-KM2A Layout: 3978 EDs + 917 MDs



1/2 LHAASO Layout: 2365 EDs + 578 MDs



WCDA #1水池: 150m×150m

2018-1

2017-12

2017-11







净水泛舟





2017-05-03

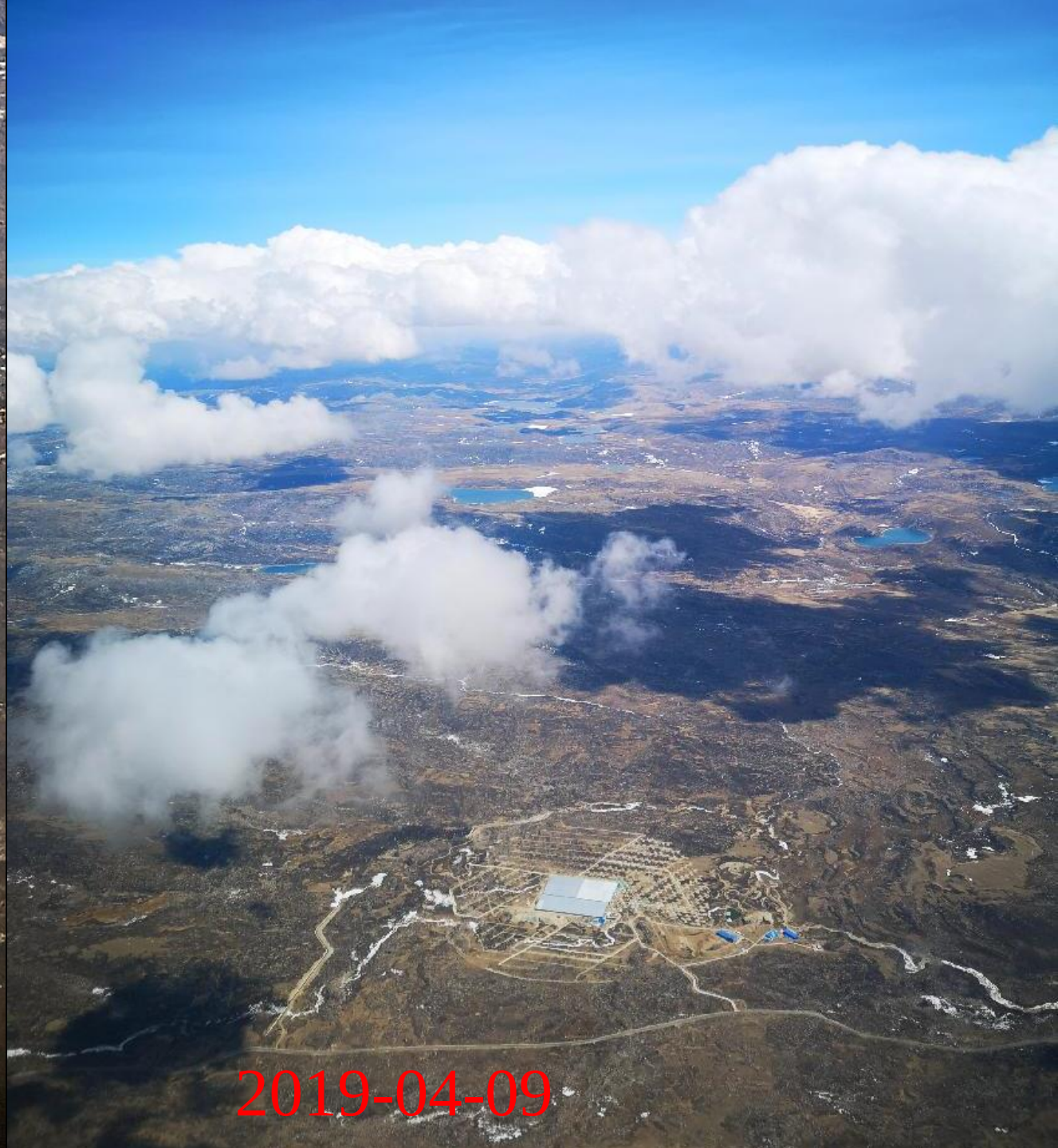


2018-10-25





2019.1.24



2019-04-09

2019-07-10



2020-06-13



2020-11-18



2021-03





2021年10月



2023年5月10日 LHAASO通过国家验收



LHAASO工艺设备研制大事记

- 2018-01-15, ED开始安装
- 2018-08-11, MD开始安装
- 2018-08-24, WRS-FL鉴定件验收
- 2018-09-16, 计算环境就绪
- 2018-10-10, WFCTA开始安装
- 2018-10-22, WCDA开始安装
- 2018-12-10, 1号配电室通电。
- 2019-04-26, 首批探测器投入运行
- 2019-09-19, 数据获取1/4系统验收
- 2019-12-26, 1/2规模阵列投入运行
- 2020-09-02, 工艺供配水系统完成
- 2020-12-06, 3/4阵列投入运行
- 2021-07-20, 全阵列投入运行
- 2021-10-16, 工艺设备验收
- 2023-05-10, 通过国家验收

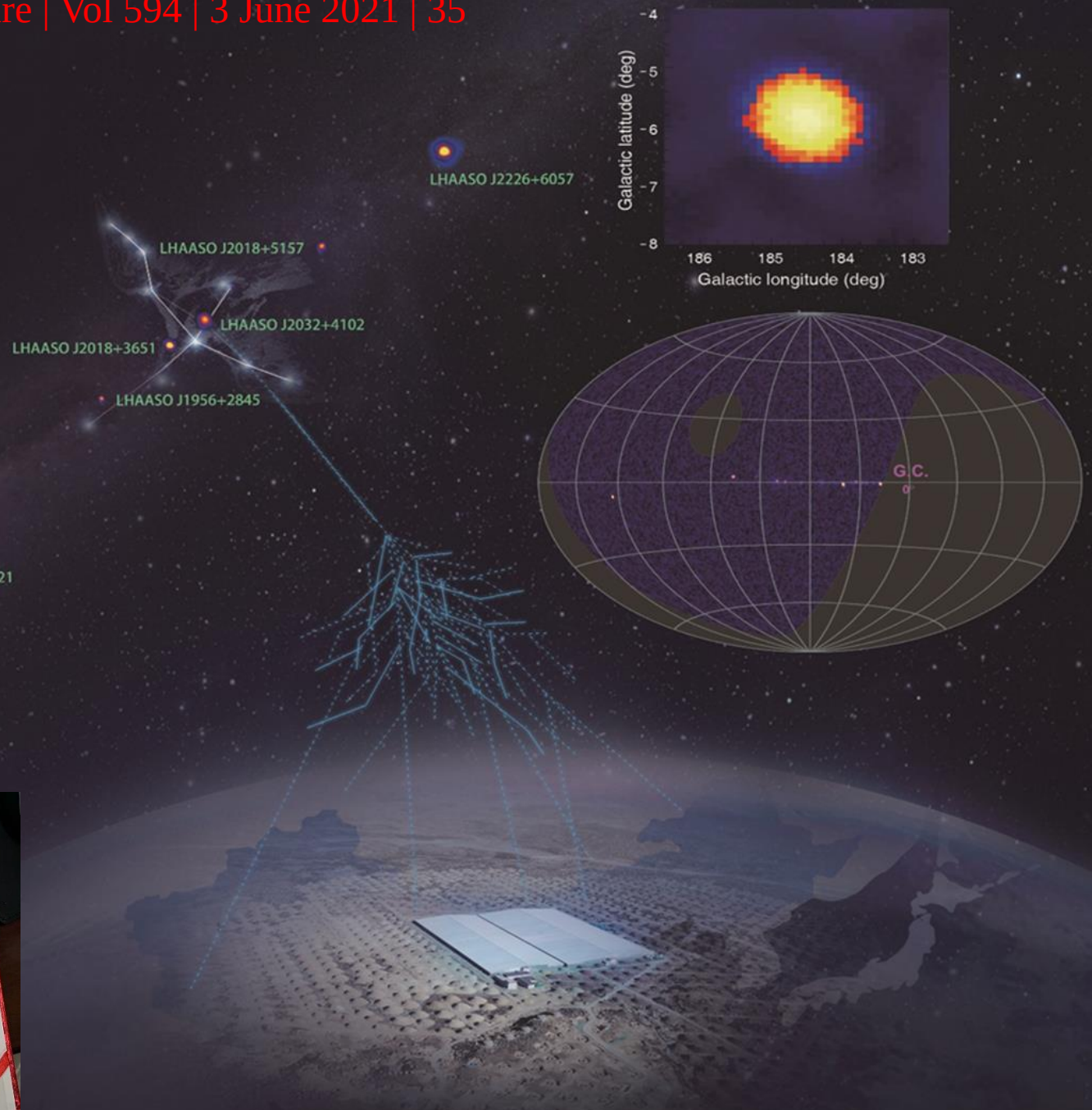
2019-04-26



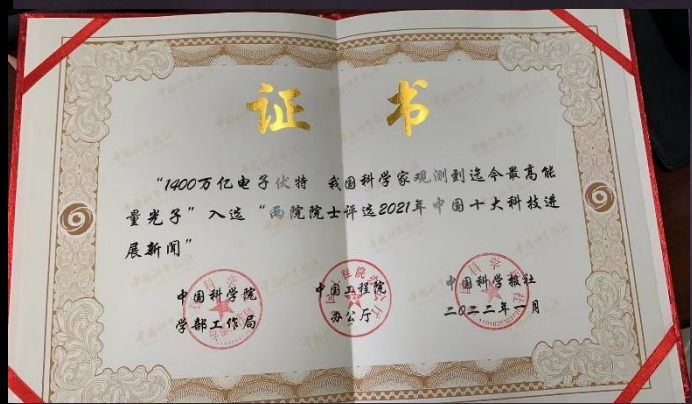
首批探测器投入科学运行



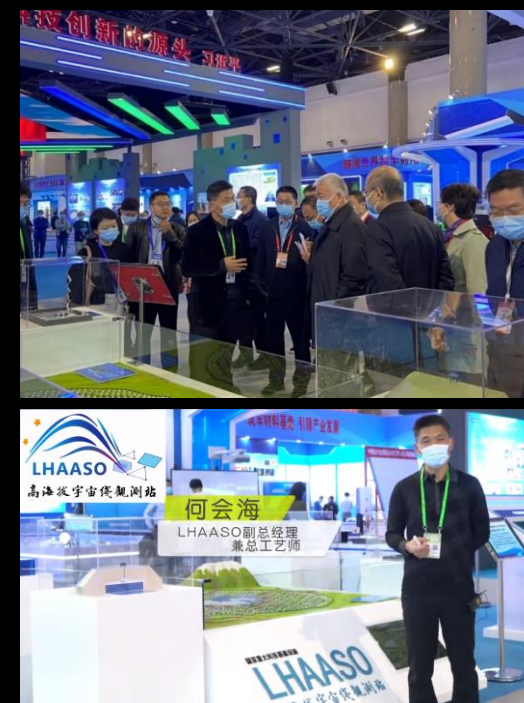
Nature | Vol 594 | 3 June 2021 | 35



1/2-KM2A不到
一年运行数
据打开了超
高能伽马天
文这一人类
观测宇宙的
最高能量电
磁辐射窗口

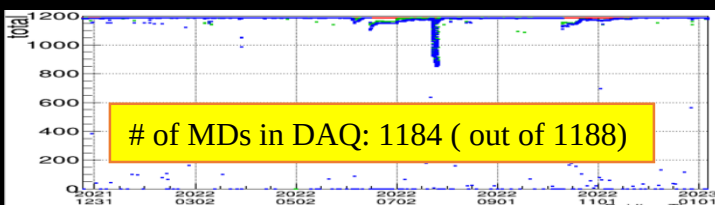
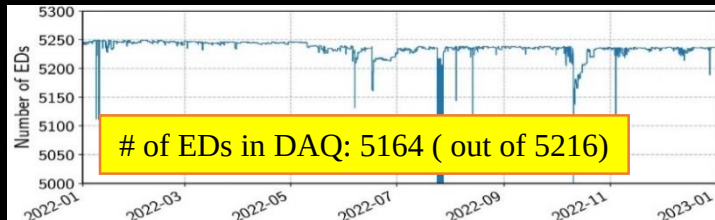
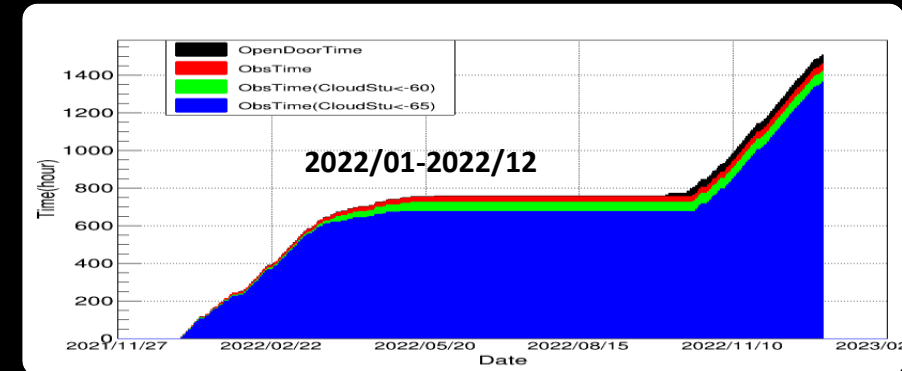
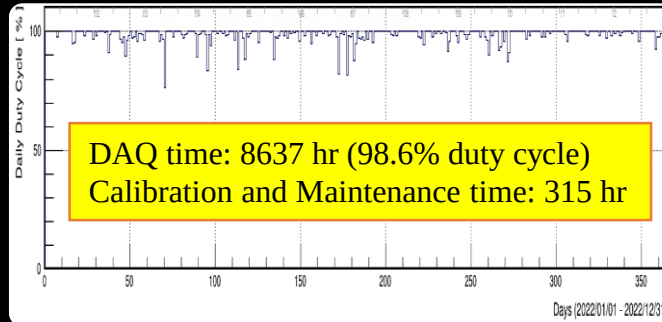
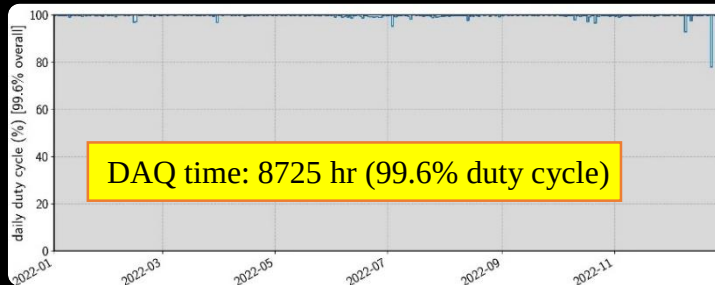


国家“十三五”科技创新成就展



国家“十三五”科技创新成就展入选项目

Operation of the LHAASO detectors



Reconstruction and Analysis

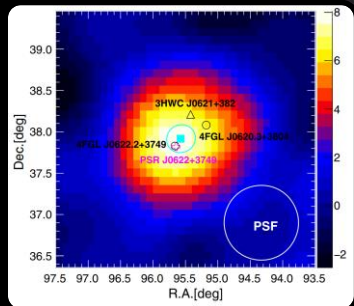
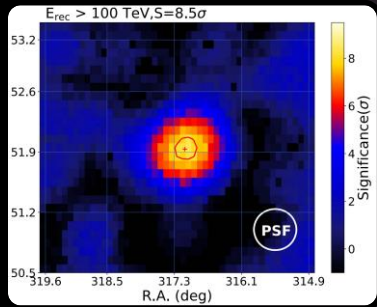
- **Data procession**
 - # of events: 1 trillion LE、70 billion HE、70 million hybrid
 - Amount: 11 PB
- **Simulation**
 - # of events: 1 billion LE、0.7 billion HE、150 million hybrid
 - Amount: 4 PB
- # of jobs: 10M for data, 50M for simulation

LHAASO: opening the UHE γ sky

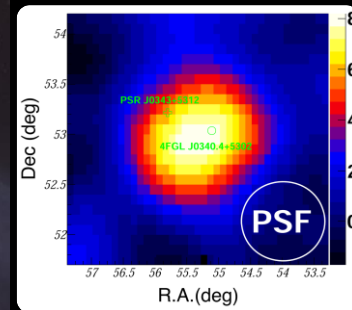
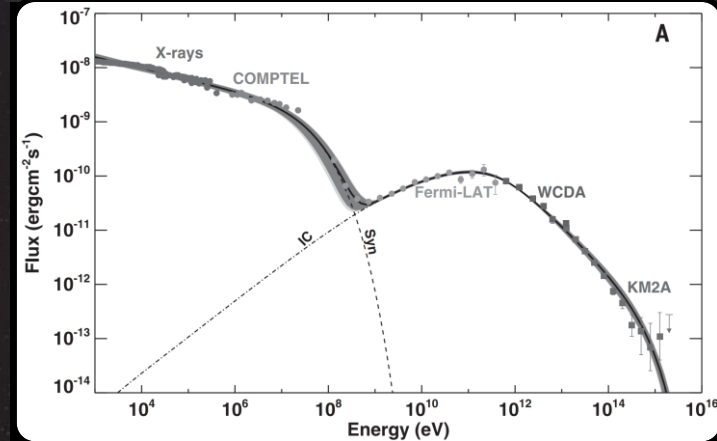
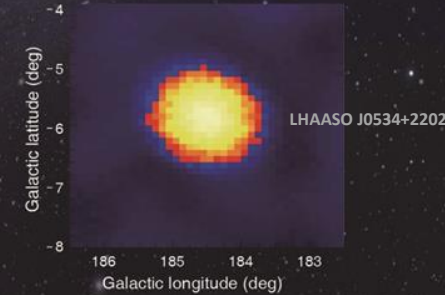
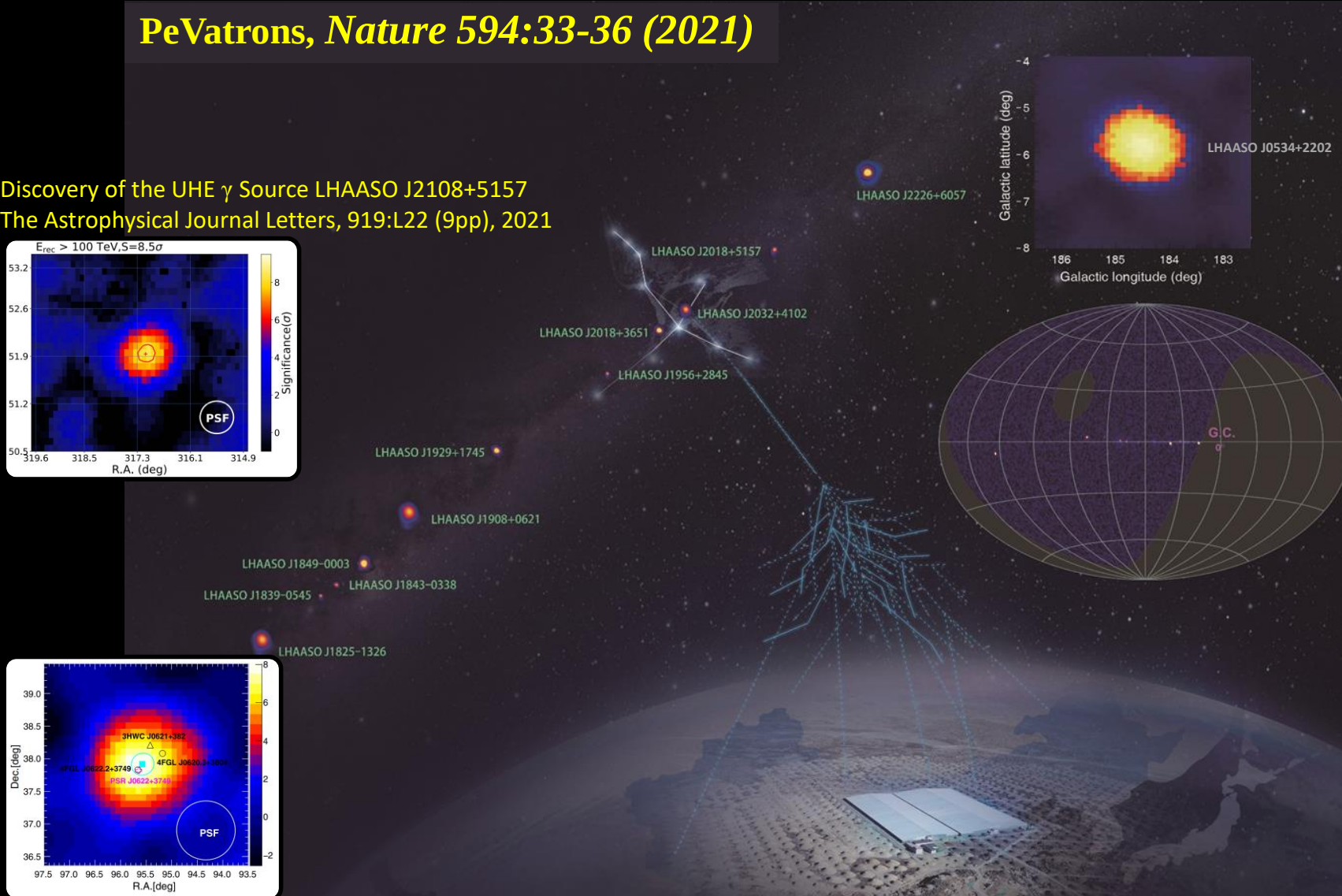
PeVatrons, *Nature* 594:33-36 (2021)

Crab Nebula, *Science*, 373, 425 (2021)

Discovery of the UHE γ Source LHAASO J2108+5157
The Astrophysical Journal Letters, 919:L22 (9pp), 2021



Extended γ Emission Surrounding PSR J0622 + 3749 Observed by LHAASO-KM2A
Phys. Rev. Lett. 126, 241103 (2021)



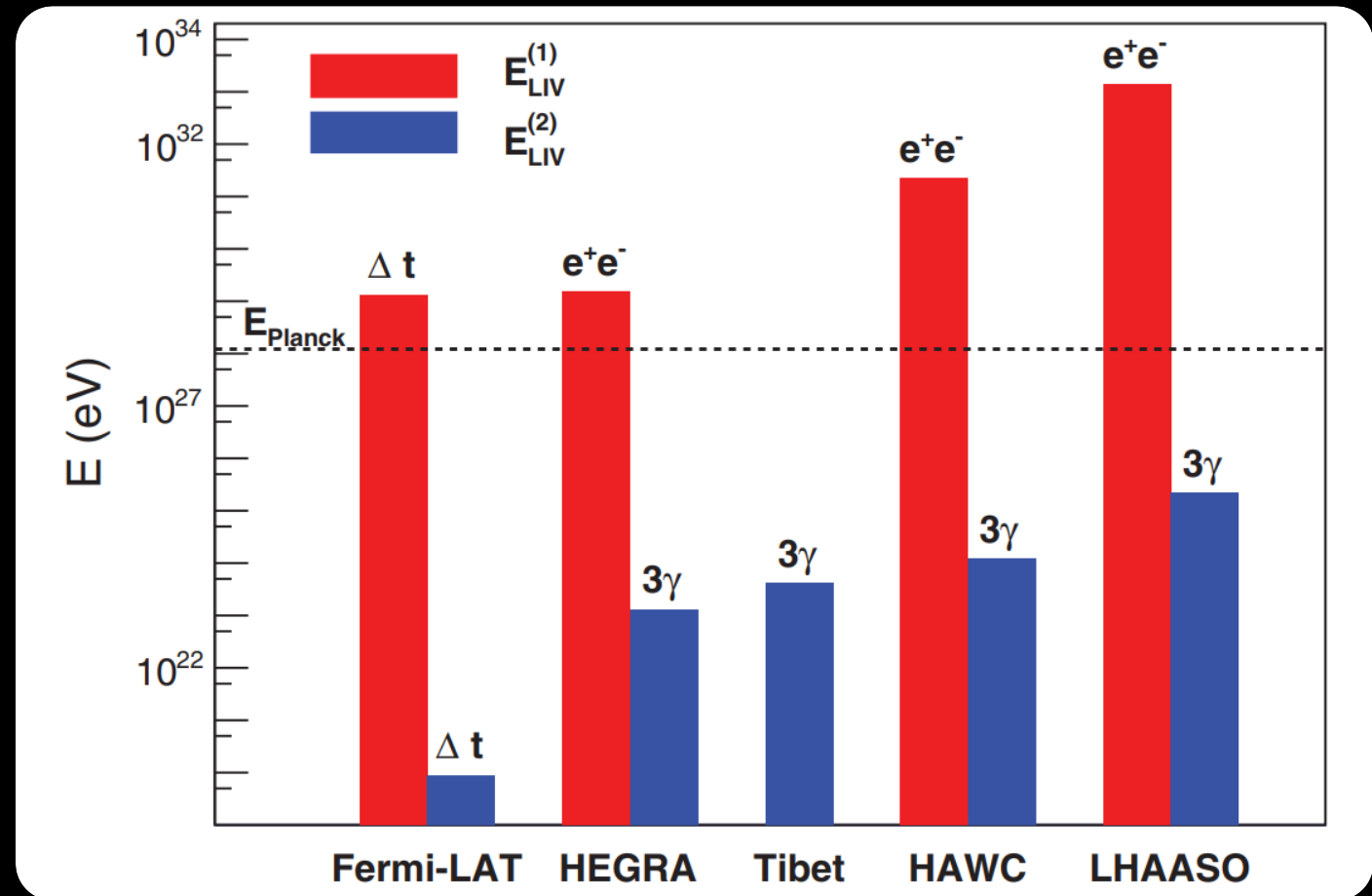
Discovery of LHAASO J0341+5258, with Emission up to 200 TeV
The Astrophysical Journal Letters, 917:L4 (7pp), 2021

“Einstein's relativity theory passes strict test based on LHAASO observation”—physics.org

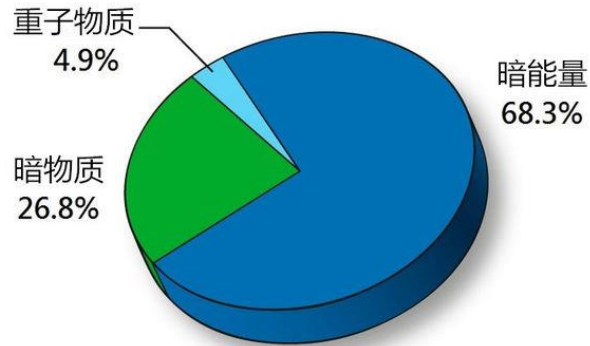
$$E_\gamma^2 = p_\gamma^2 \left[1 + \xi_n \left(\frac{p_\gamma}{E_{\text{Pl}}} \right)^n \right]$$

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

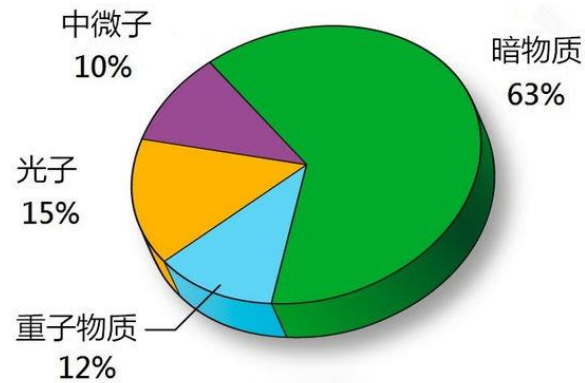
$$\gamma \rightarrow 3\gamma$$



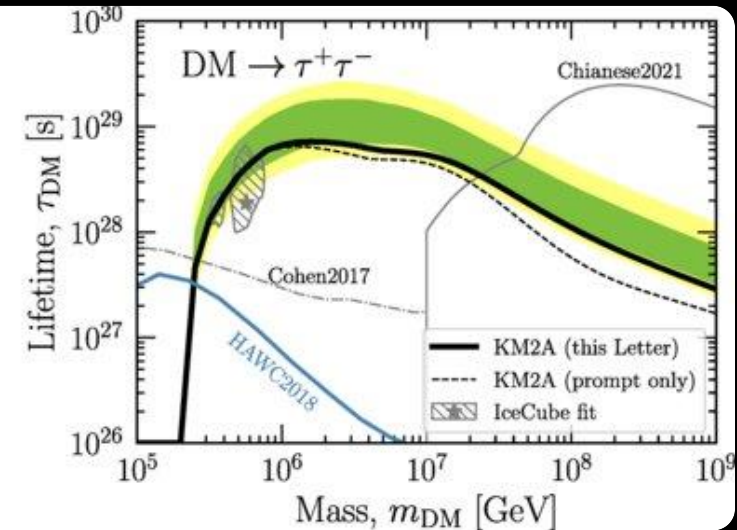
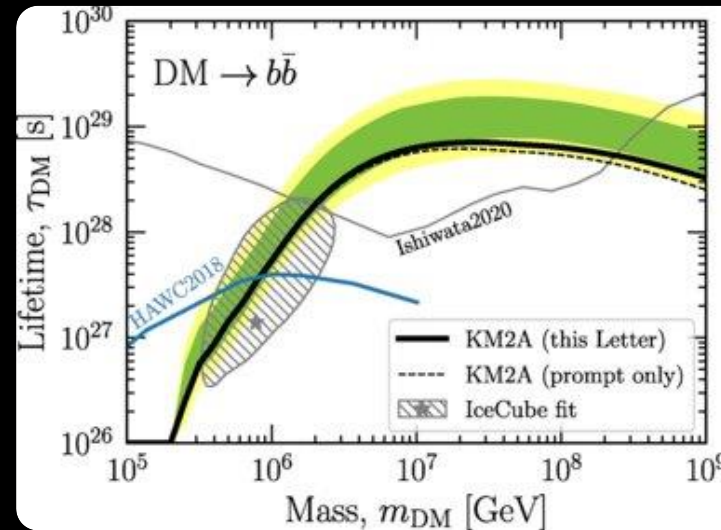
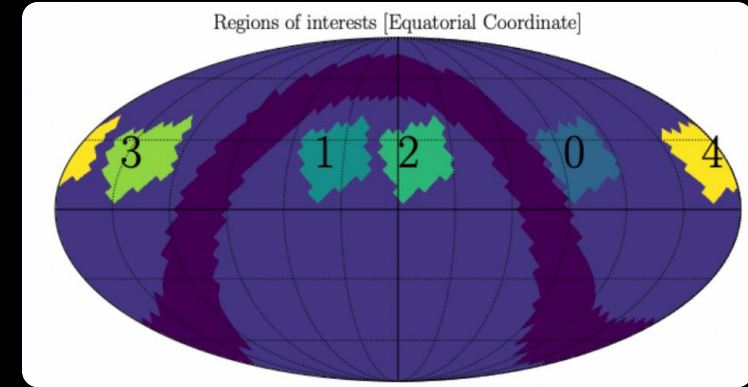
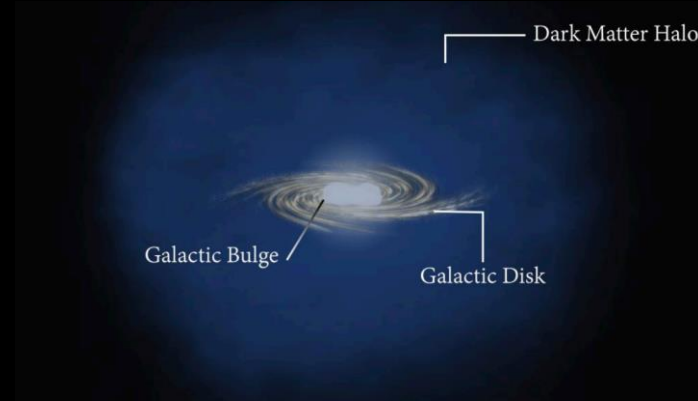
Constraints on heavy decaying dark matter



当今的宇宙

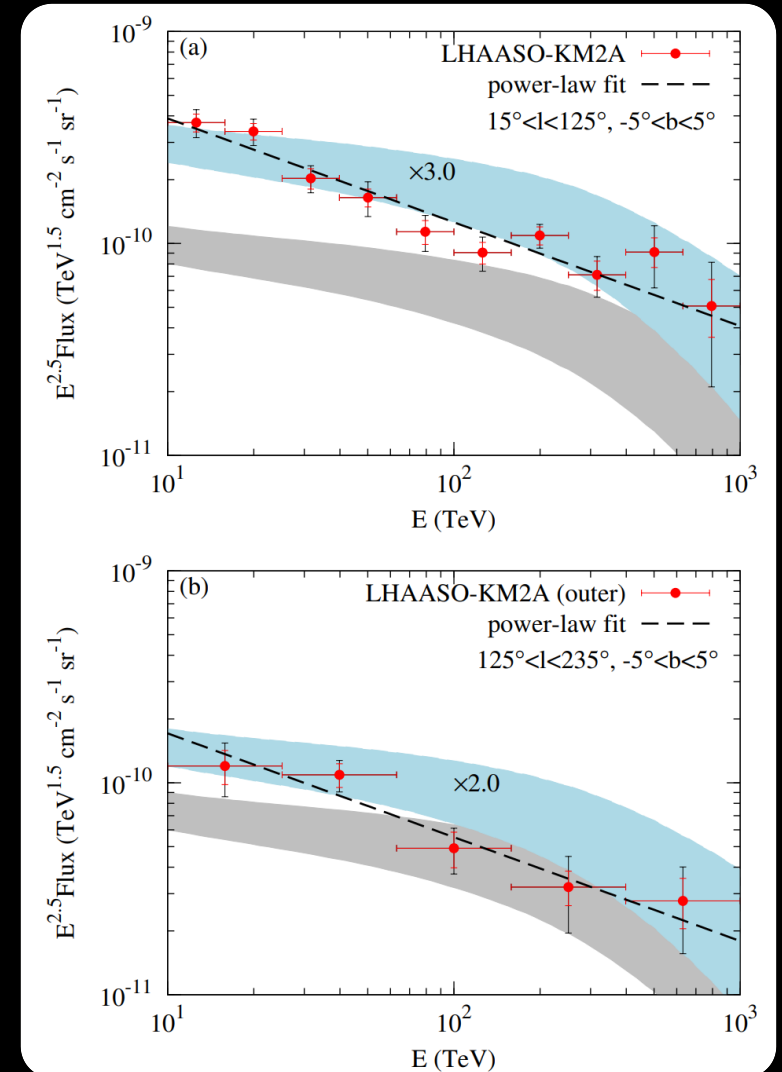
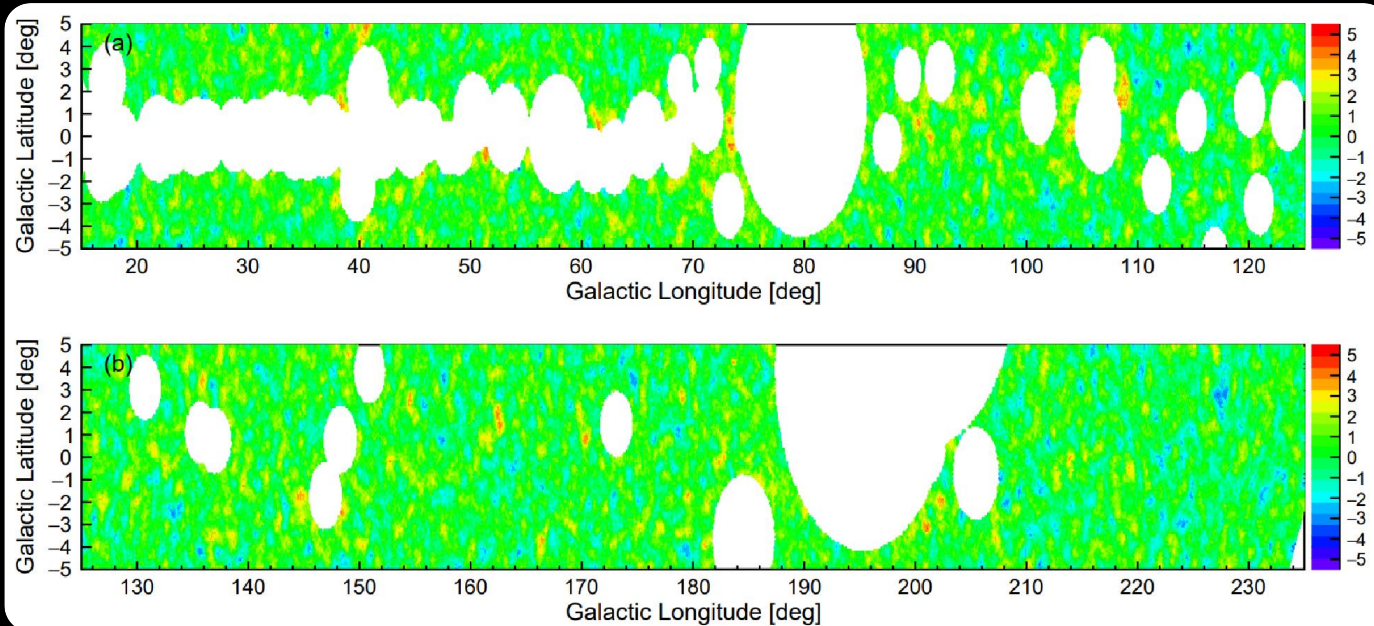


137亿年前 (宇宙诞生38万年时) 的宇宙



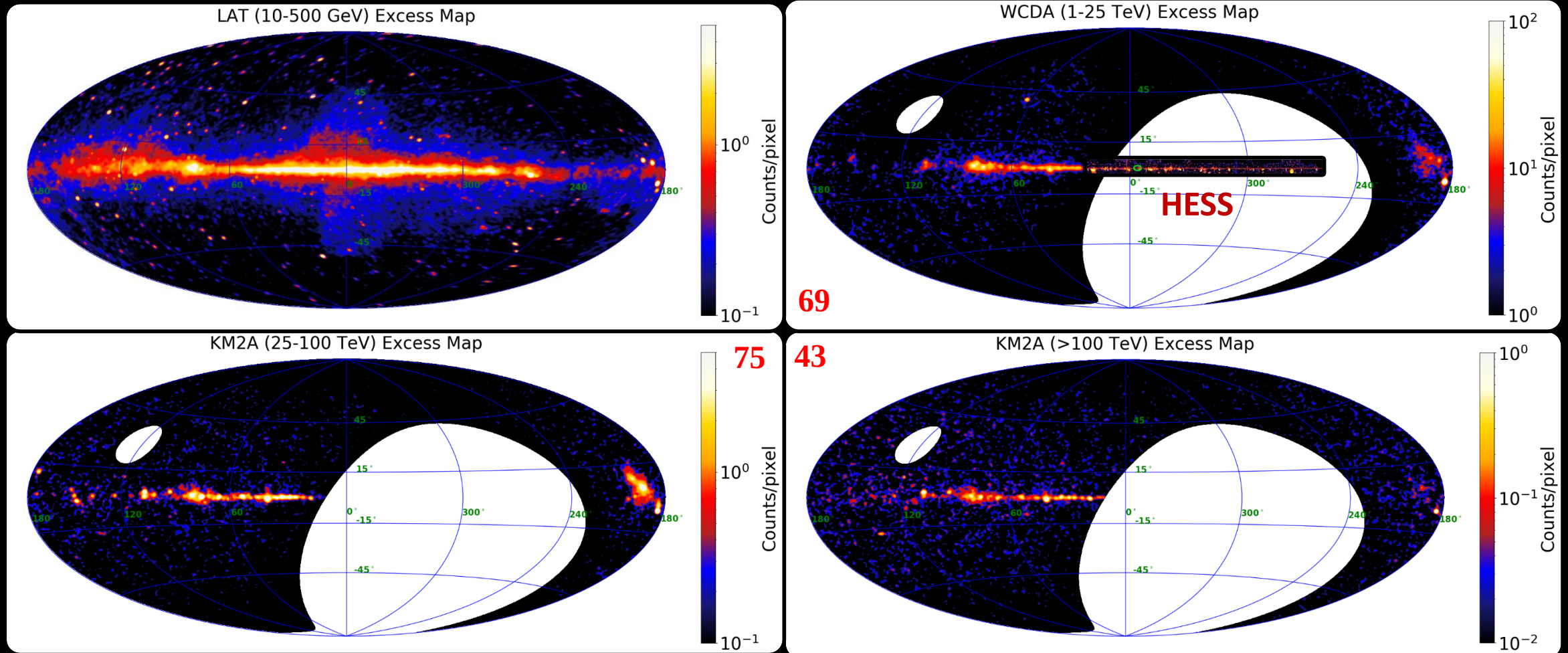
UHE diffuse γ emission of the GP with KM2A

detected with 29.1σ and 12.7σThe energy spectrum.....is different from the curved spectrum as expected.....flux is higher by a factor of ~ 3 than the prediction.imply that either additional emission sources exist or cosmic ray intensities have spatial variations.



VHE-UHE γ -ray astronomy: 1st LHAASO Catalog

- 90 in total: 32 new sources, 43 UHE
- 82 with $|b| < 12^\circ$, 8 with $|b| > 12^\circ$



GRB: the brightest explosions in the Universe

- Every time a GRB goes off, a black hole is born
- Excellent laboratories of the universe's most extreme processes

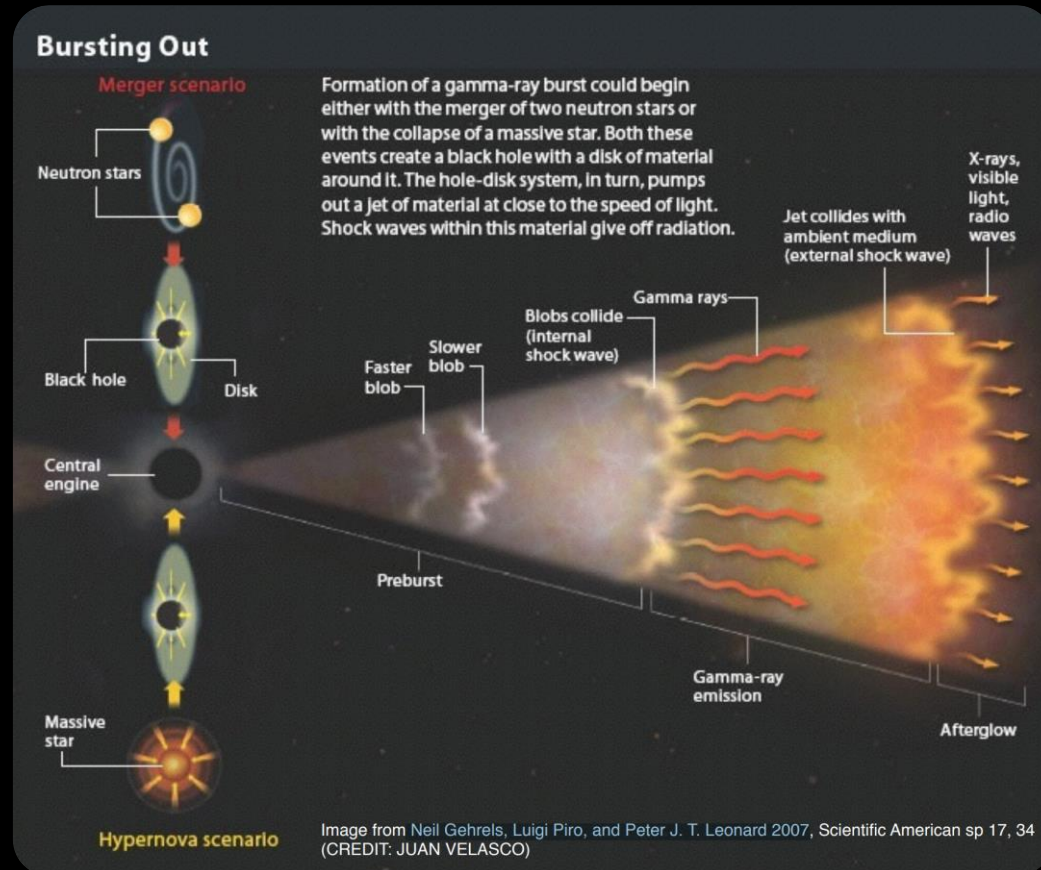
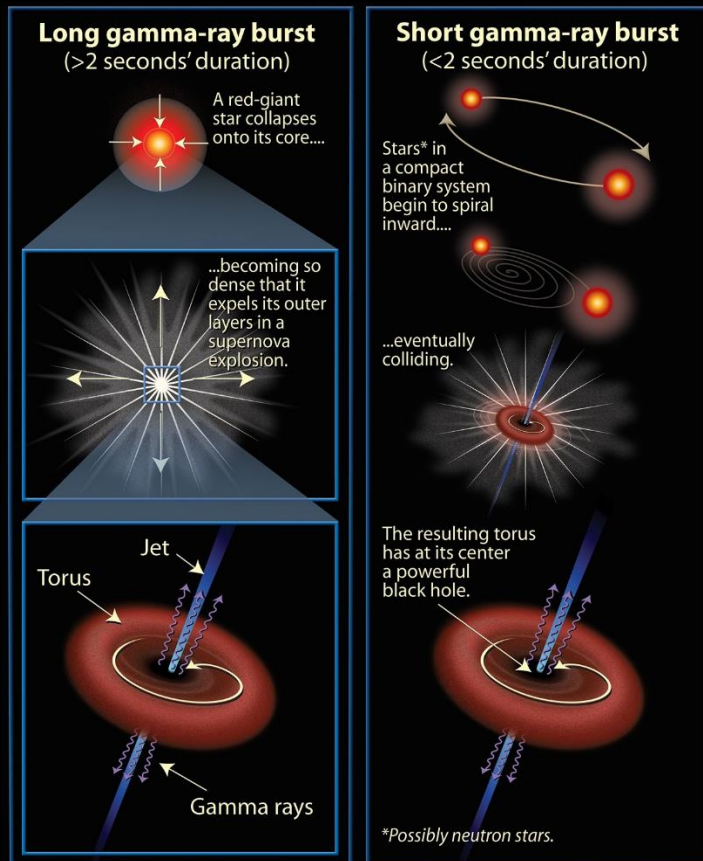


Image from Neil Gehrels, Luigi Piro, and Peter J. T. Leonard 2007, Scientific American sp 17, 34 (CREDIT: JUAN VELASCO)

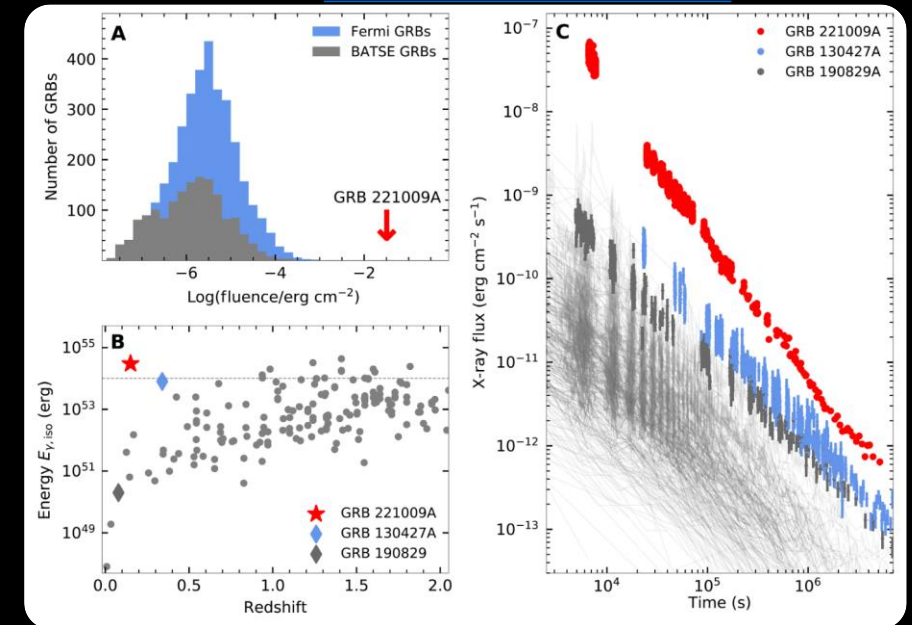
GRB221009A: the Brightest Of All Time (BOAT)

- a dust-filled galaxy in the constellation Sagitta
- ~2.4 billion light years from Earth
- 1 per 1000 yr

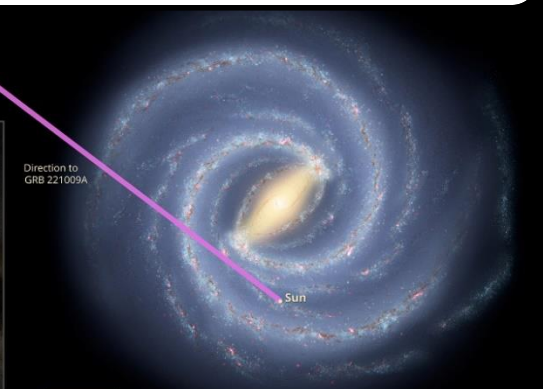


A view of GRB221009A from the Gemini South telescope in Chile. (Image credit: Gemini Observatory/NOIRLab/NSF/AURA/B. O'Connor (UMD/GWU) & J. Rastinejad & W. Fong (Northwestern University))

[DOI: 10.1126/sciadv.adi1405](https://doi.org/10.1126/sciadv.adi1405)



View from Earth



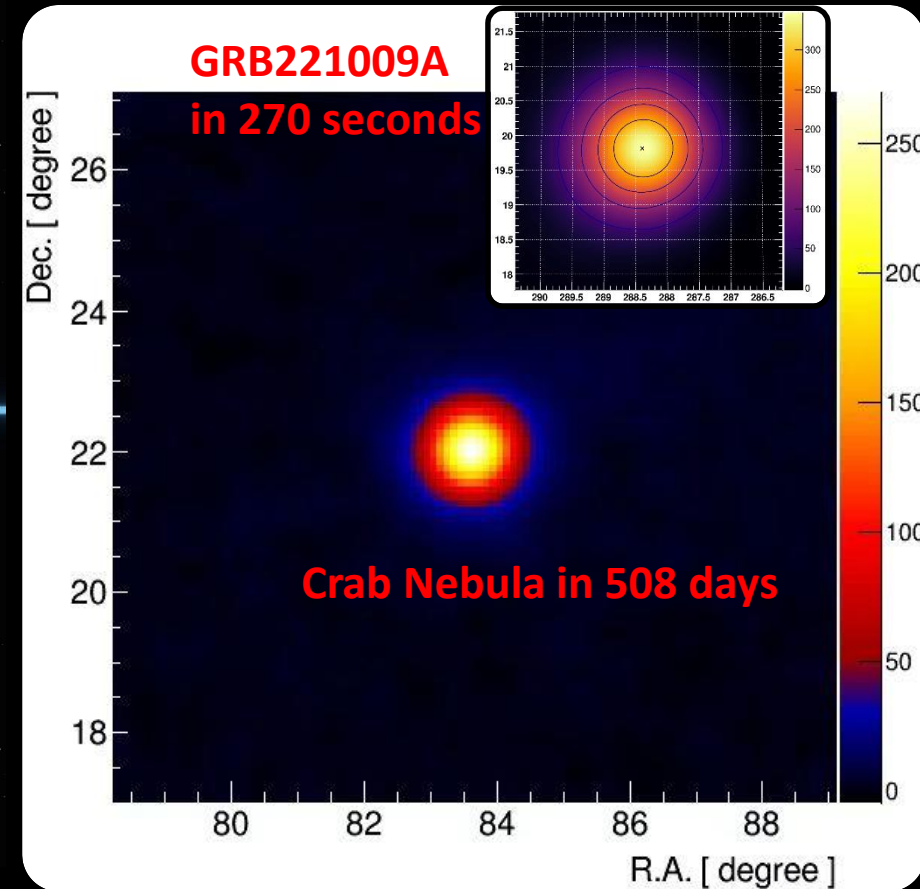
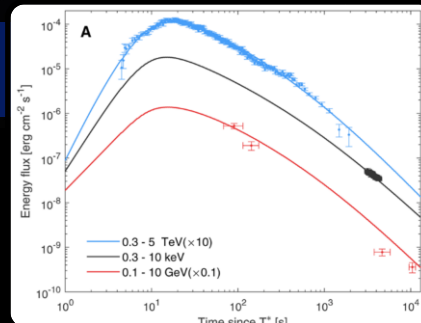
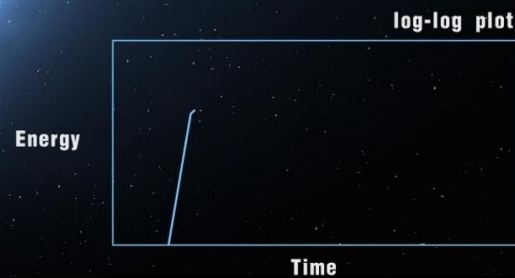
20,000 light-years

Credit: NASA's Goddard Space Flight Center

GRB221009A@the highest energies by LHAASO

GRB221009A-I, [DOI:10.1126/science.adg9328](https://doi.org/10.1126/science.adg9328) (2023)

GRB221009A-II, submitted



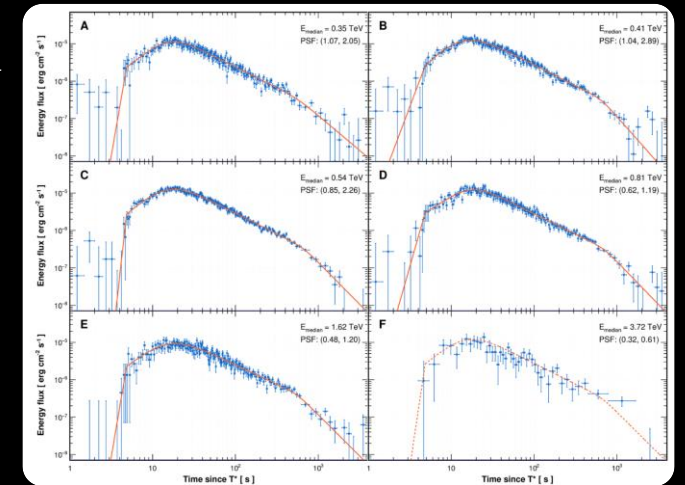
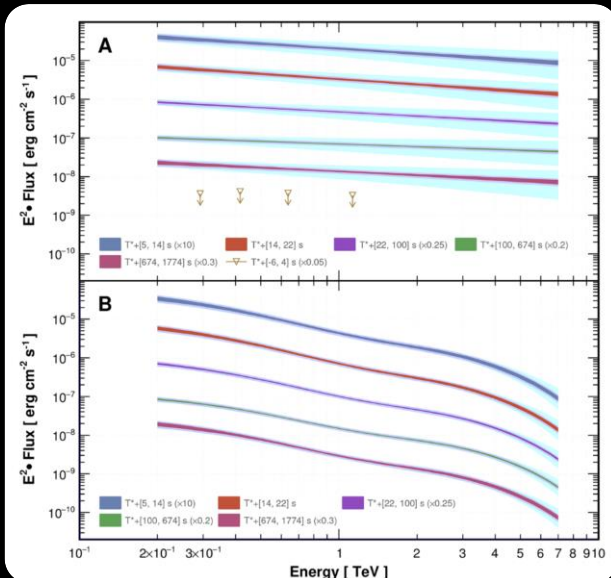
GRB physics on LHAASO BOAT

➤ Test of LIV: the fundamental symmetry of Einstein's relativity

$$E^2 \simeq p^2 c^2 \left[1 - \sum_{n=1}^{\infty} s \left(\frac{E}{E_{\text{QG},n}} \right)^n \right] \quad \text{Planck scale } E_{\text{Pl}} = (\hbar c^5/G)^{1/2} \simeq 1.22 \times 10^{19} \text{ GeV}$$

$$v(E) = \frac{\partial E}{\partial p} \approx c \left[1 - s \frac{n+1}{2} \left(\frac{E}{E_{\text{QG},n}} \right)^n \right]$$

$$\Delta t_{\text{LIV}} = s \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{\text{QG},n}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$



➤ Extragalactic background light (EBL)

➤ Axion-like particles (ALPs)

走，到海子山看粒子雨！

