超大型中微子射电探测阵列(GRAND)

进展和展望

张毅

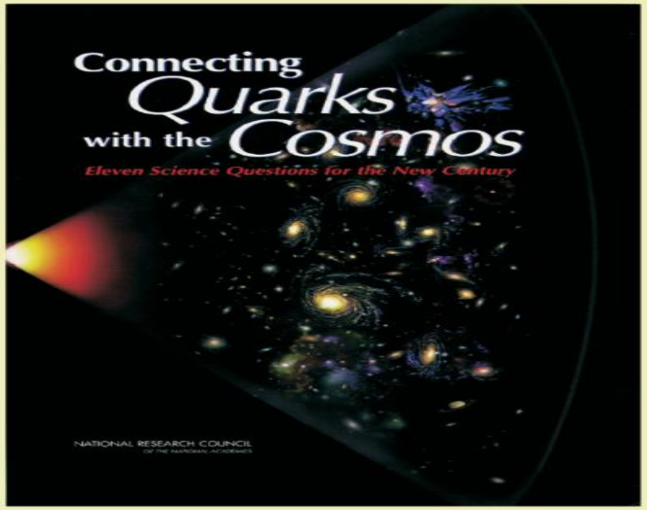
中国科学院紫金山天文台

On behalf of the GRAND collaboration




超高能宇宙粒子探测面向的科学问题

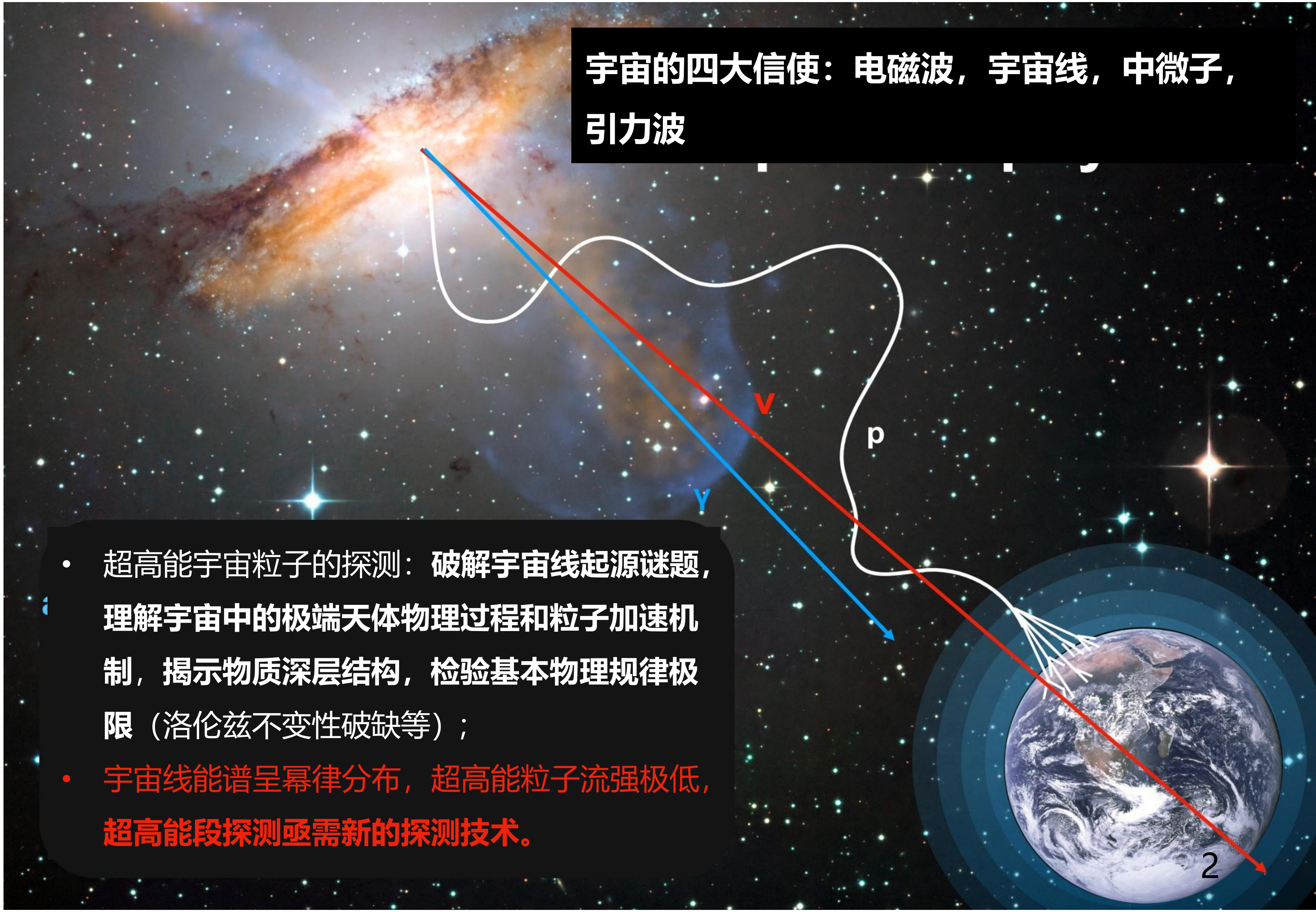
21世纪宇宙物理学11个重大前沿问题



1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protc
8. What Are ingly High Density and Temperature?
9. Are T
10. How Made
11. Is a New Theory of Light and Matter Needed at the Highest Energies?

宇宙加速器的原理

最高能量物理规律检验

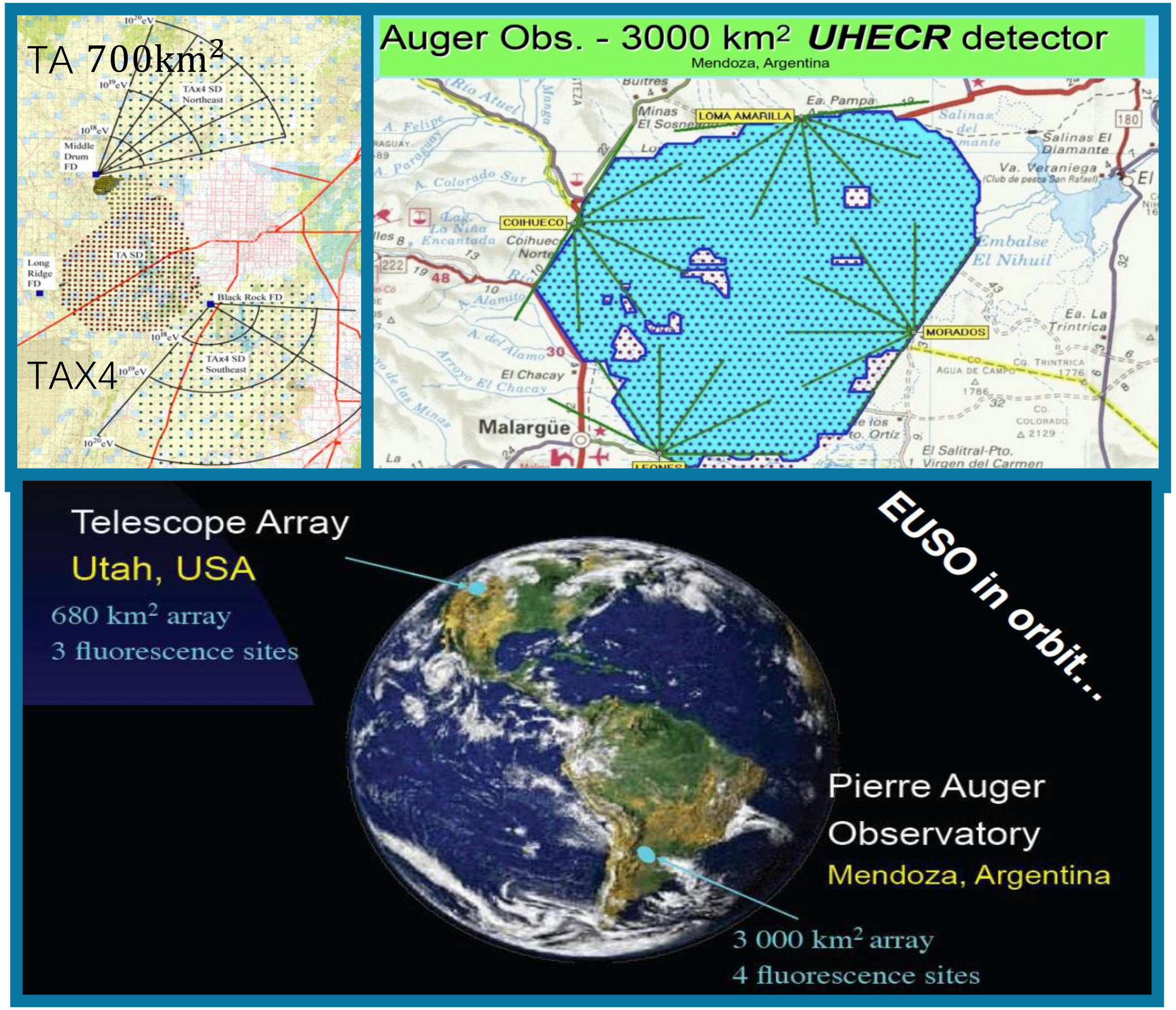


宇宙的四大信使：电磁波，宇宙线，中微子，引力波

- 超高能宇宙粒子的探测：**破解宇宙线起源谜题，理解宇宙中的极端天体物理过程和粒子加速机制，揭示物质深层结构，检验基本物理规律极限**（洛伦兹不变性破缺等）；
- 宇宙线能谱呈幂律分布，超高能粒子流强极低，**超高能段探测亟需新的探测技术。**

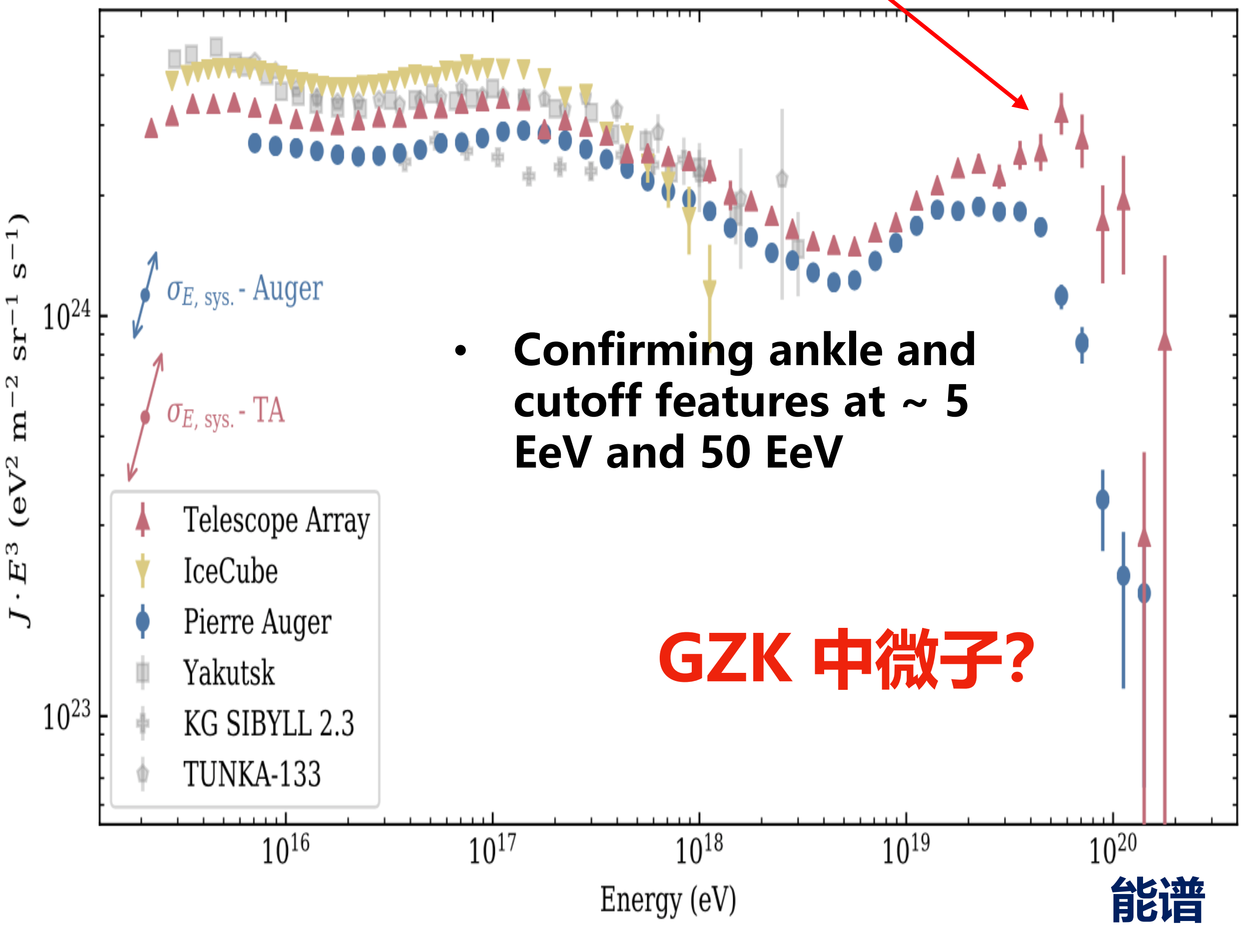
Current Knowledge on UHECRs

Auger and TA Experiments



Small statistics and composition discriminator being the main limiting factors

GZK + GR + E_max + 成分



- **Confirming ankle and cutoff features at ~ 5 EeV and 50 EeV**

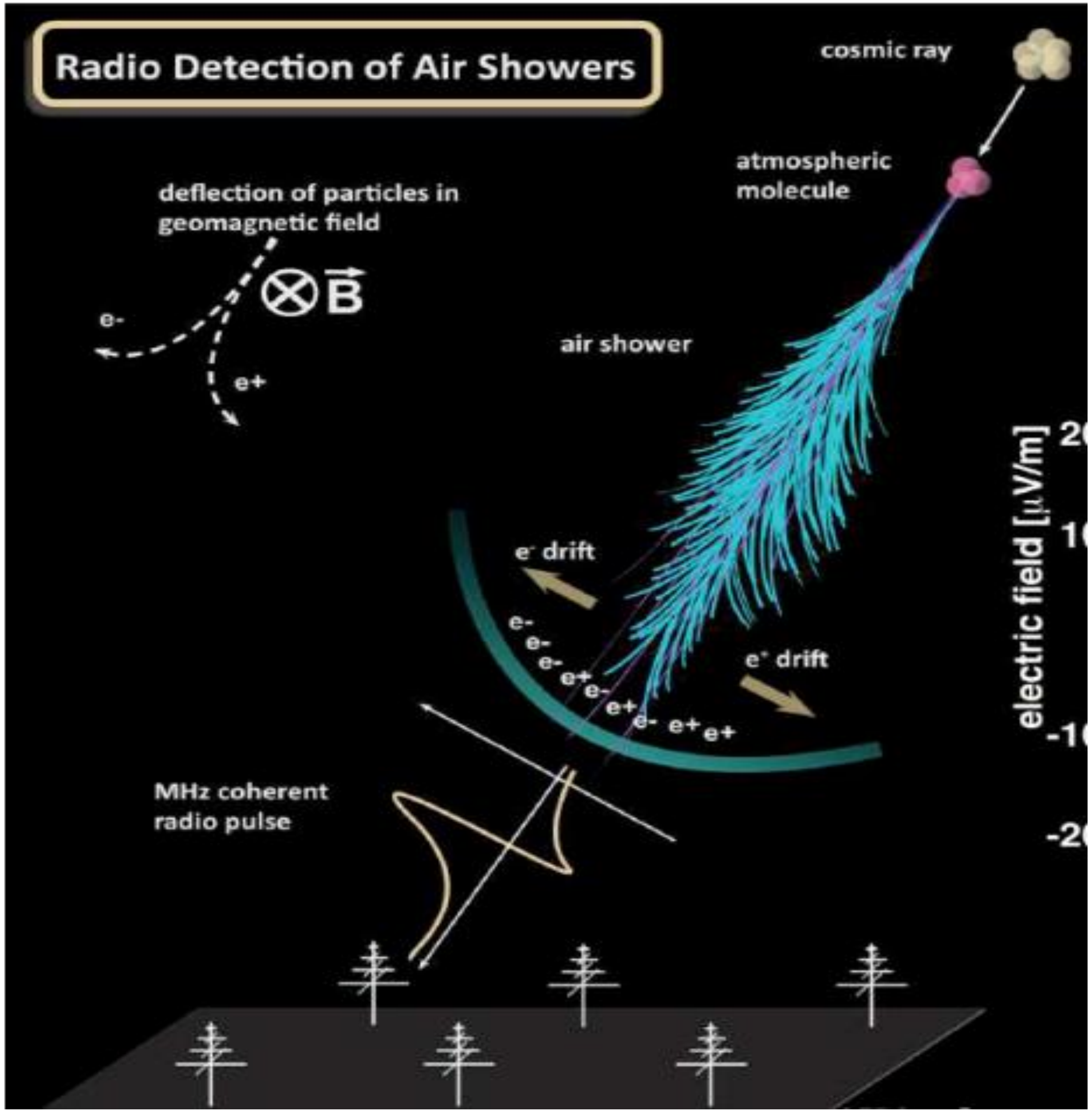
GZK 中微子?

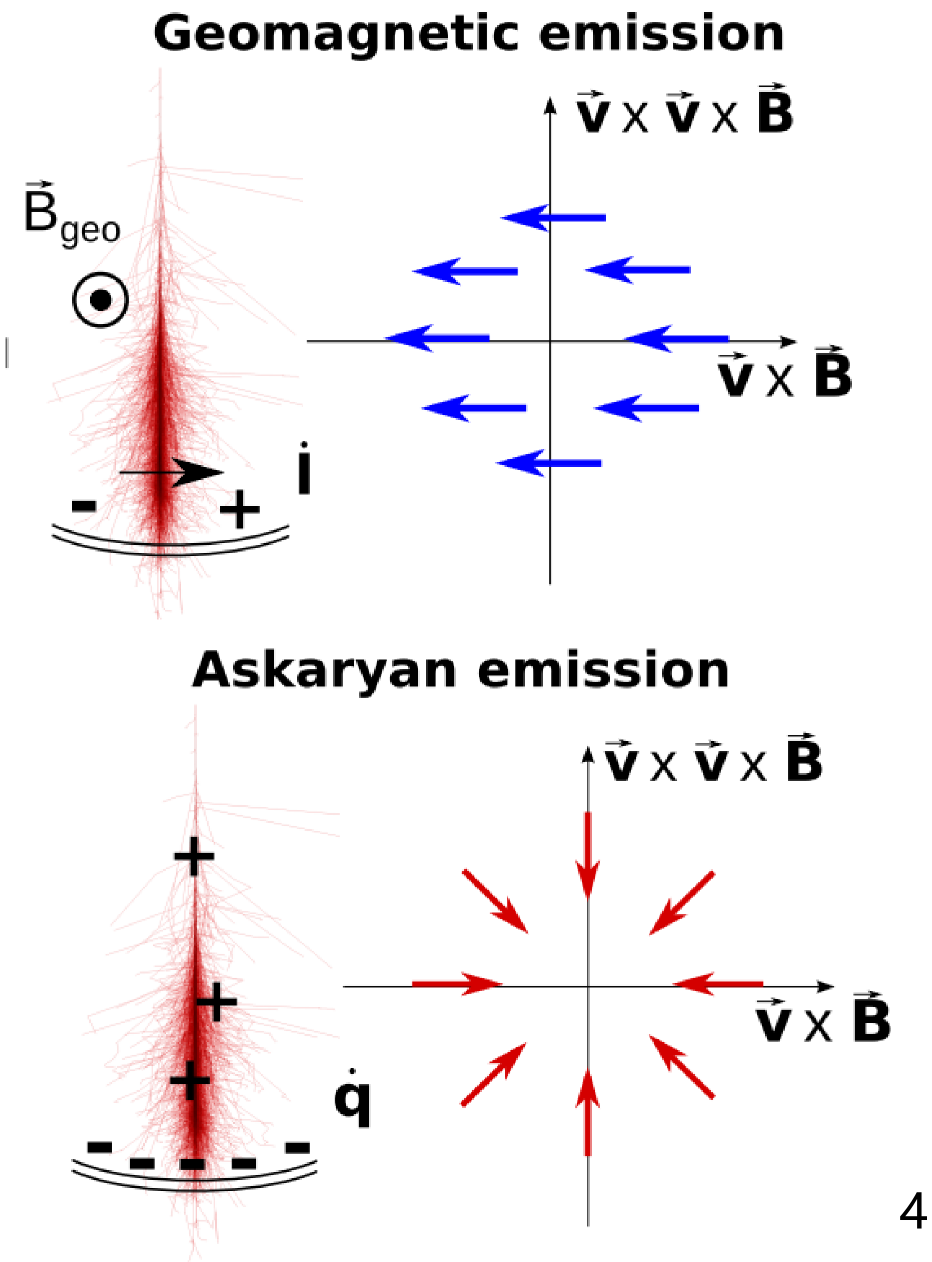
能谱

地面粒子探测器阵列对成分鉴别的困难?

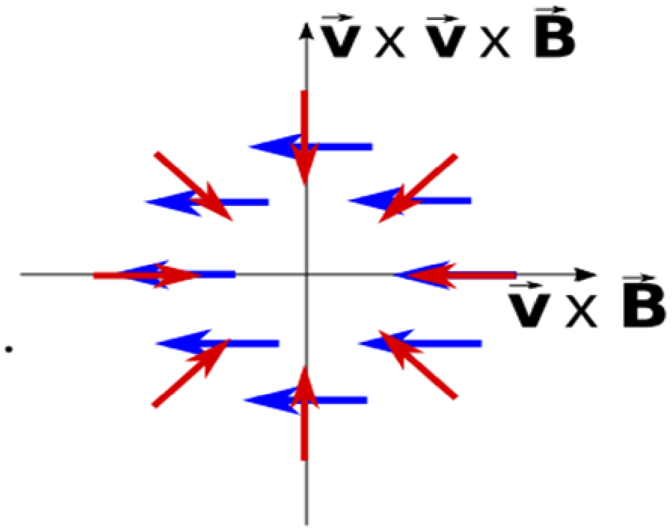
SNOWMASS review 2022, arXiv:2205.05845

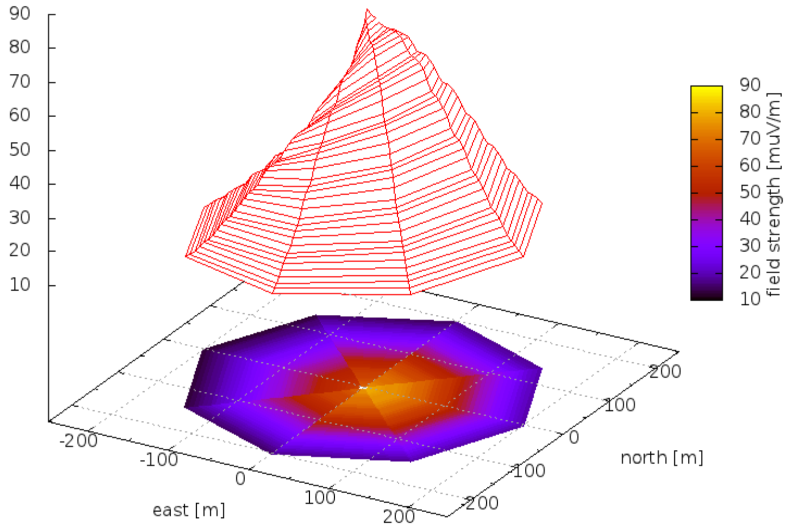
大气簇射产生射电信号的机制



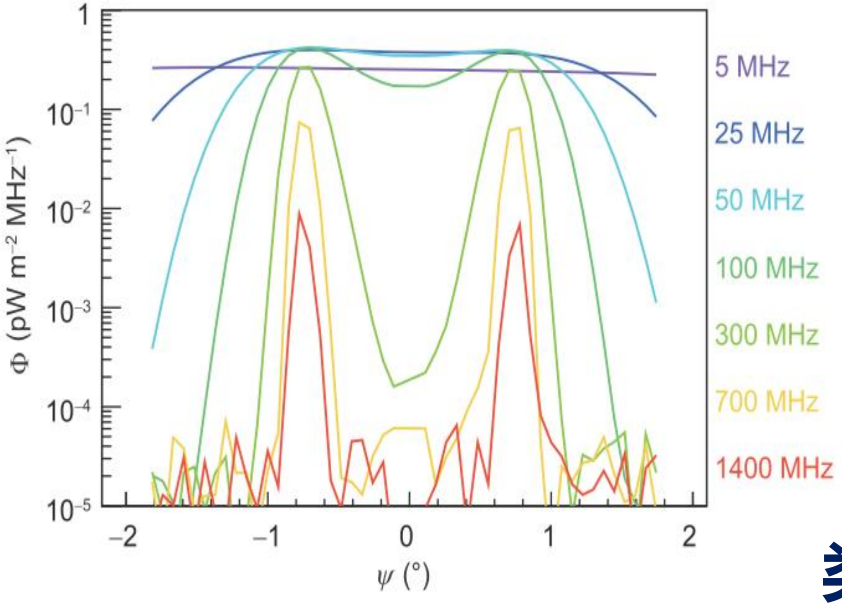


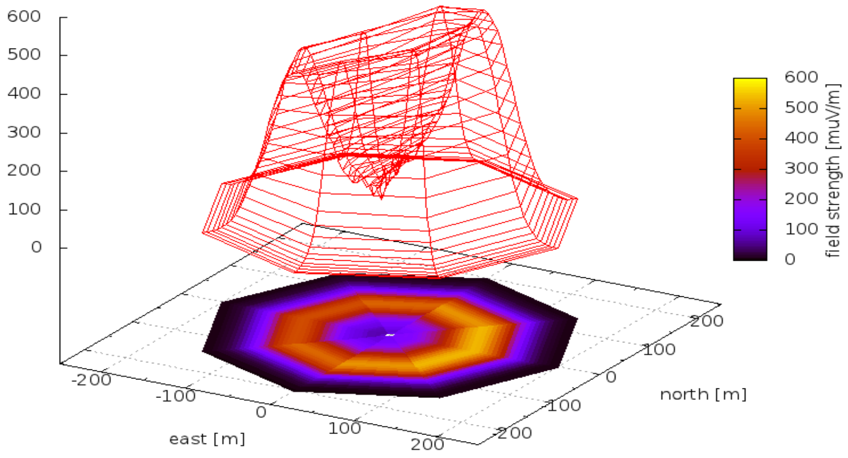
射电信号特征：不对称的横向分布





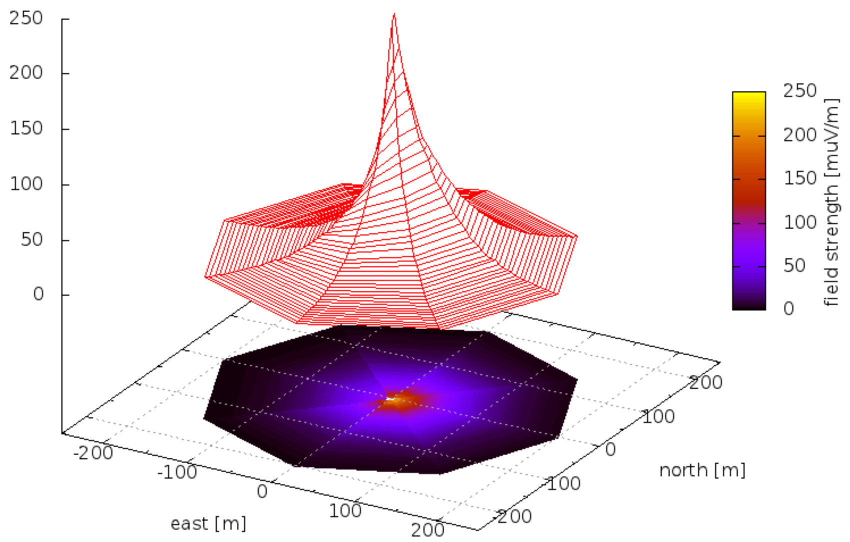
Vertical iron shower at LOPES frequencies simulated with CoREAS



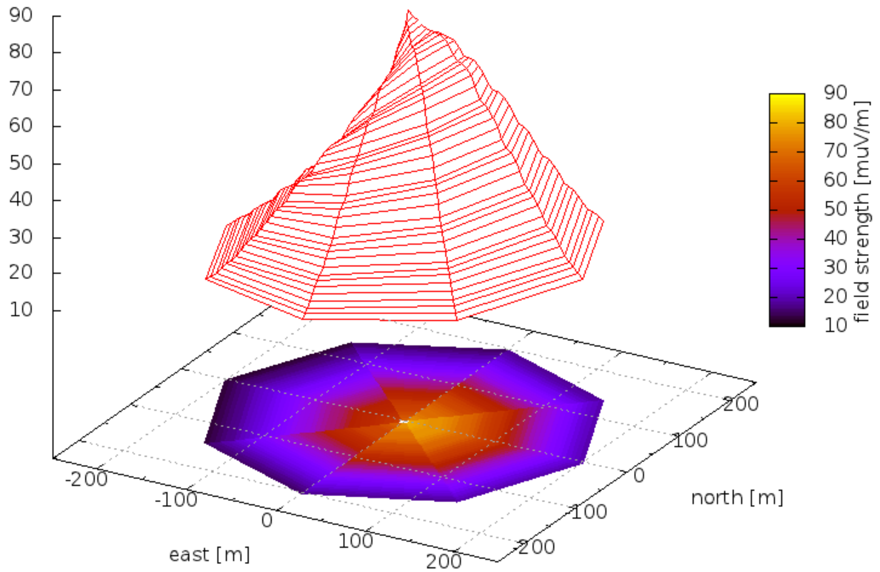


类切伦科夫环

- Relativistic forward beaming of emission: geometrical distance from source to observer influences emission pattern



Vertical proton shower simulated with CoREAS

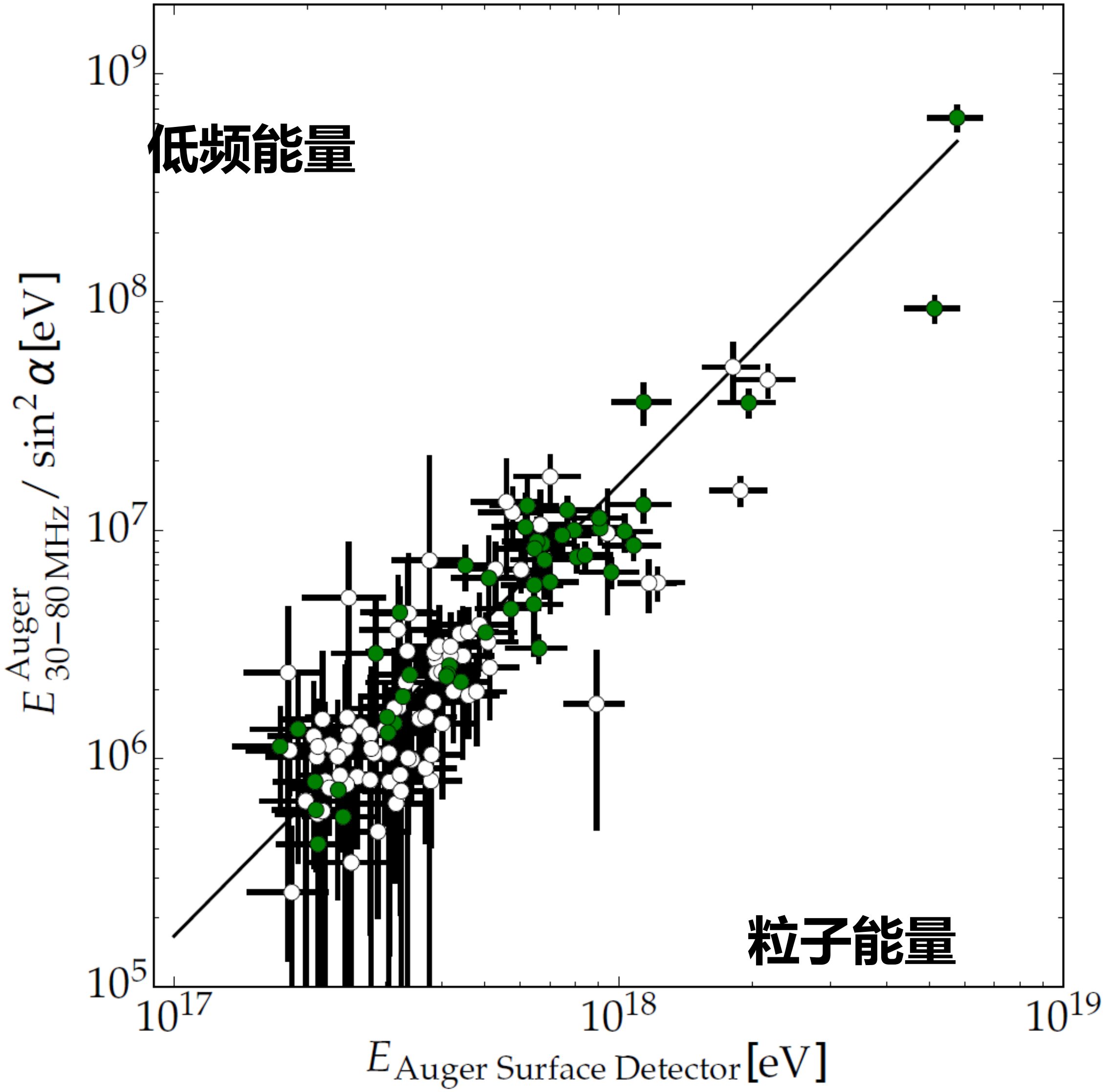


Vertical iron shower simulated with CoREAS

Data fit to CoREAS simulations gives Xmax to ~17 g/cm^2

S. Buitink et al., Phys. Rev. D 90 (2014) 082003, S. Buitink et al. Nature 435 (2016) 70

优势2：高精度能量分辨



Piere Auger Coll., Phys Rev. Lett. (2016), arXiv:1605.02564.

$$E_{30-80\,\mathrm{MHz}} = (15.8 \pm 0.7\,(\mathrm{stat}) \pm 6.7\,(\mathrm{sys}))\ \mathrm{MeV} \times \left(\sin\alpha\,\frac{E_{\mathrm{CR}}}{10^{18}\,\mathrm{eV}}\,\frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2 . \tag{10}$$

- 能量分辨率 ~17% （荧光探测20%）
- 辐射能量可对电磁级联中的能量进行量能器式测量

比现有技术更好的能量分辨

GRAND Concept

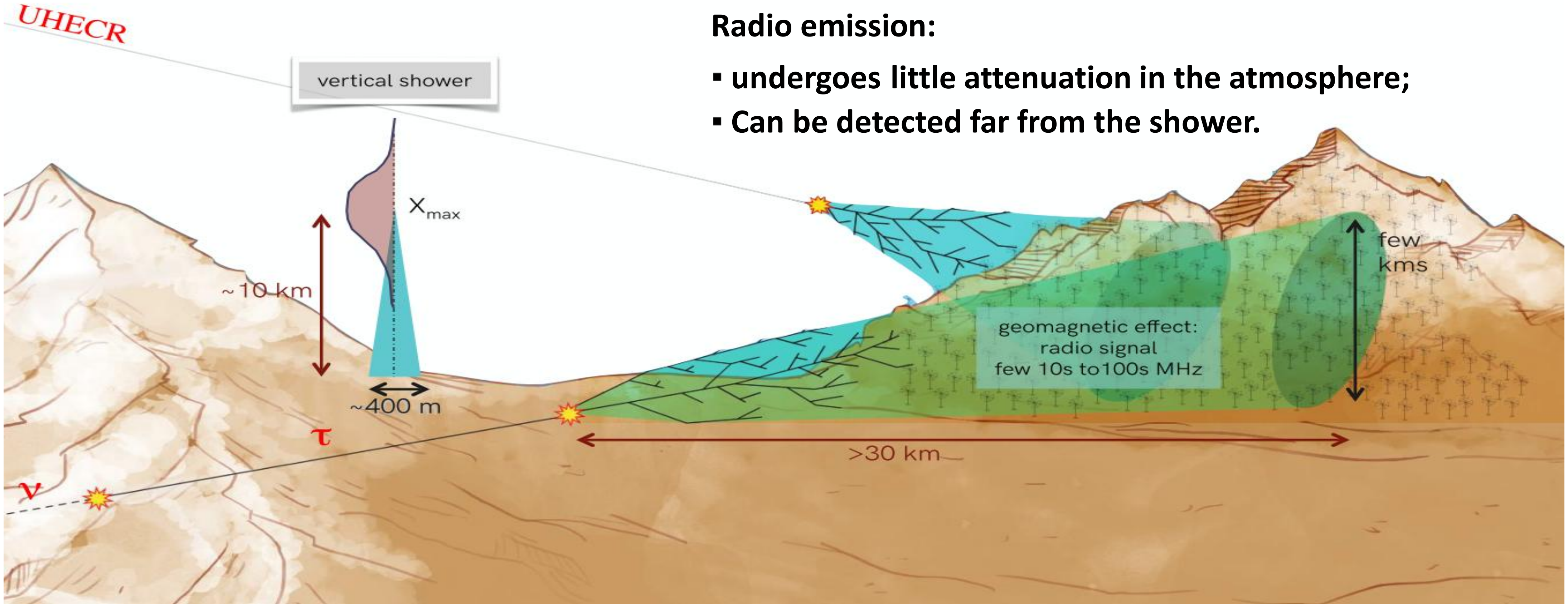
超高能宇宙线的起源和τ中微子的天体起源

CRs hit the atmosphere
Vτ interact with mountains->τ decay

Air showers (radio emission due to Geomagnetic filed)

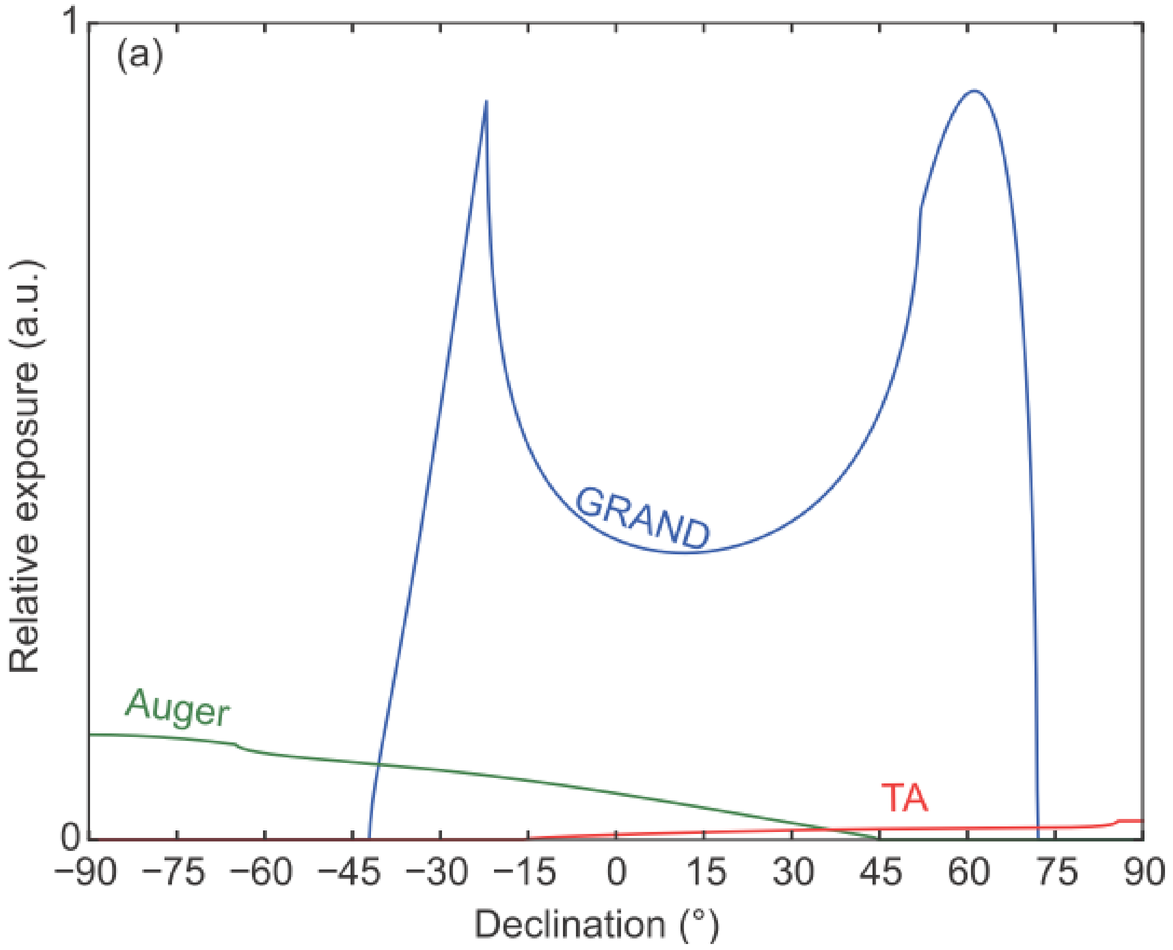
Radio emission:

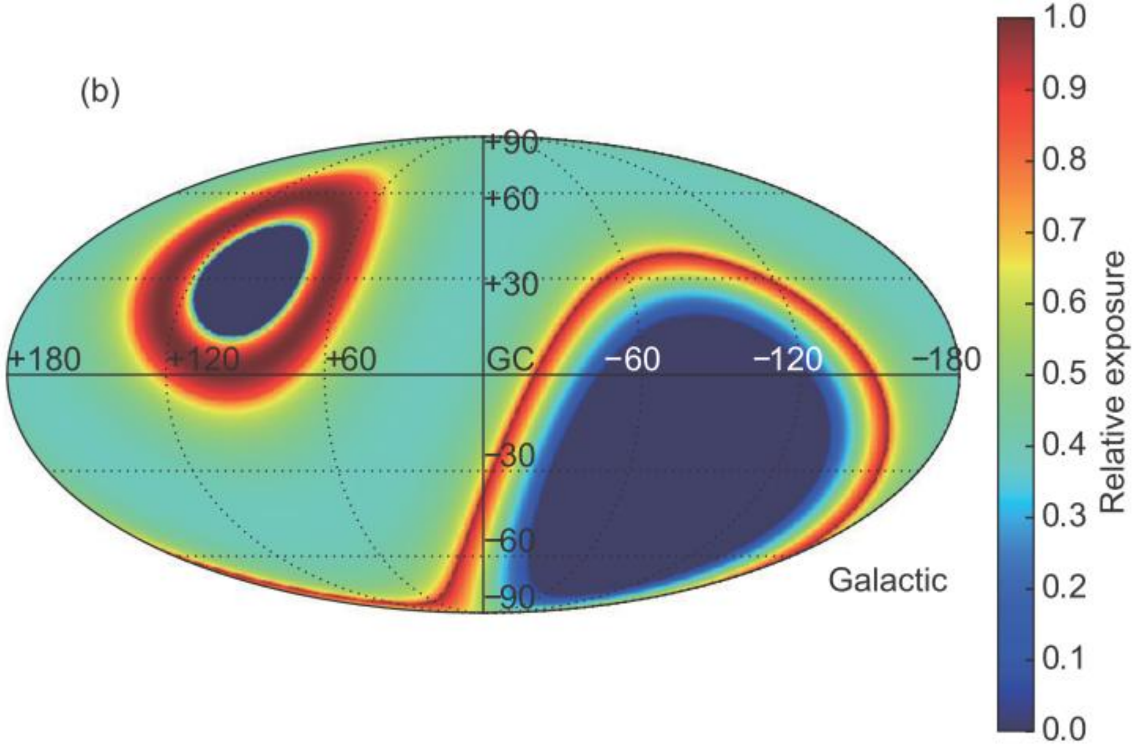
- **undergoes little attenuation in the atmosphere;**
- **Can be detected far from the shower.**



Advantages of Radio antennas: **scalable, cheap**, robust, ideal for giant arrays

Expected performances for UHE Cosmic Rays



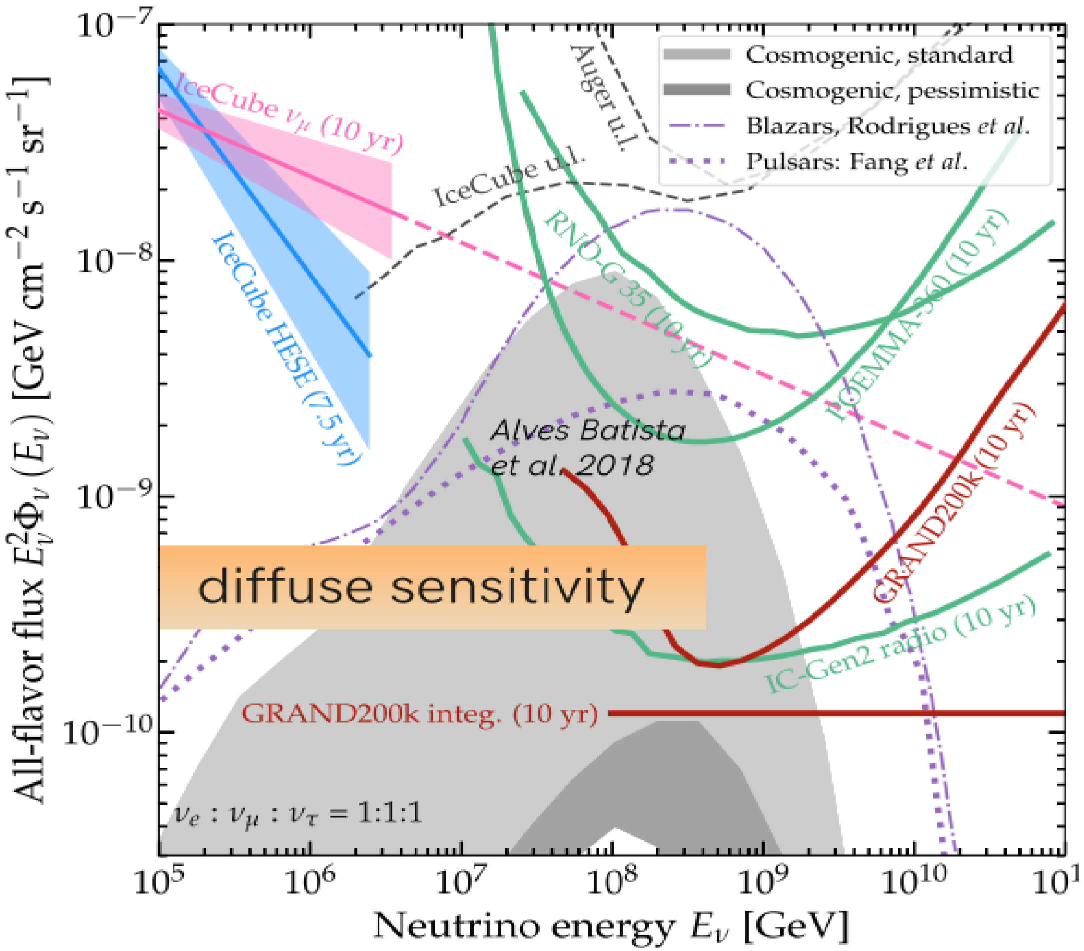


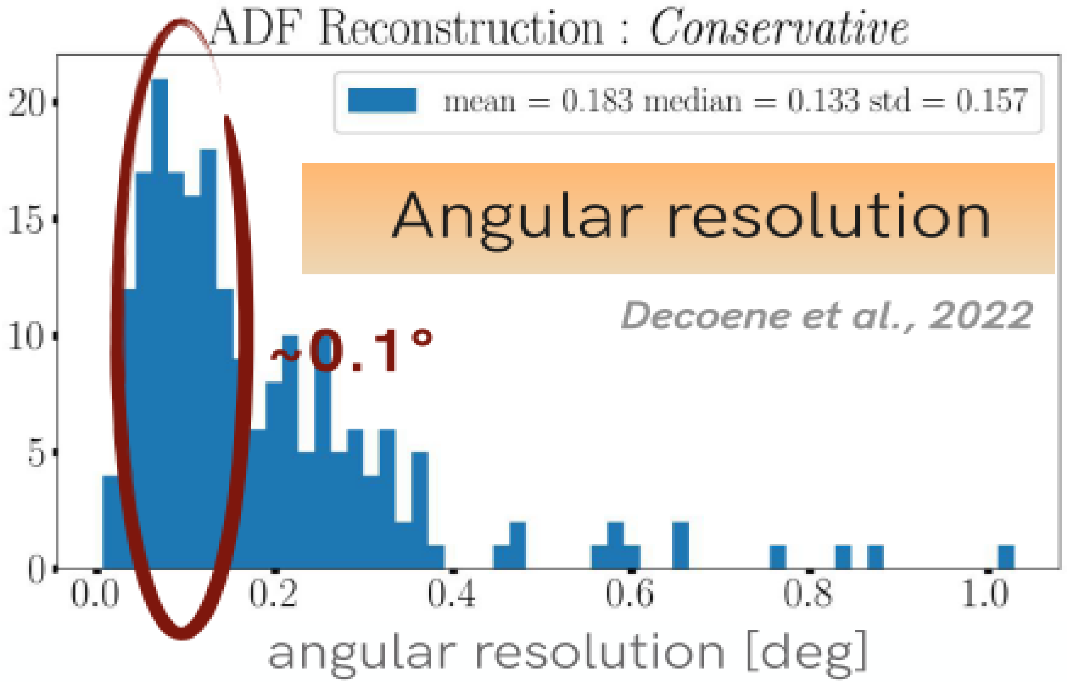
$65^\circ \leqslant \theta_z \leqslant 85^\circ$ for UHE CRs

One year, 6400 events above $10^{10.5}$ GeV Vs **the combined ~ 750 collected events of Auger and TA to date.**

Expected performances for Neutrinos

中国科学院紫金山天文台
Purple Mountain Observatory,Chinese Academy of Sciences



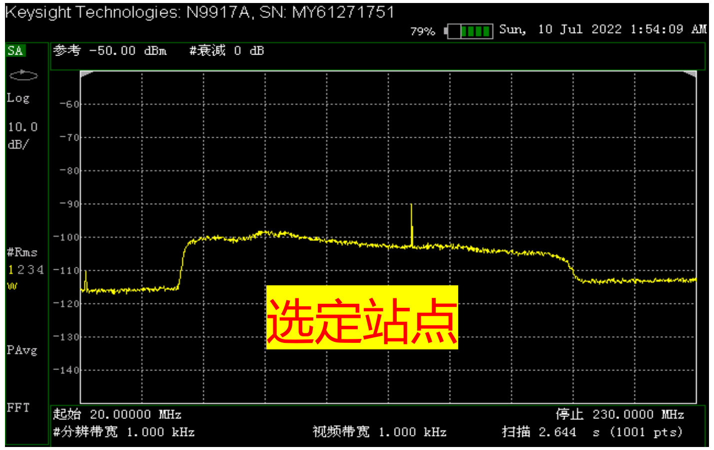


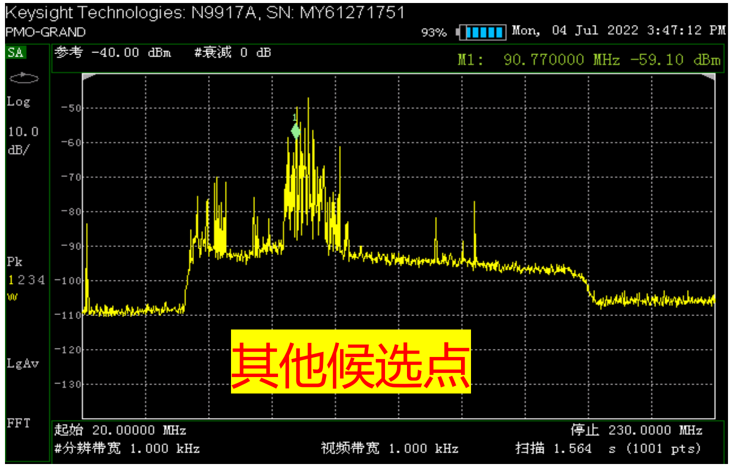
Diff. sens. lim. in GeV cm⁻² s⁻¹ sr⁻¹	iFoV in sky %	dFoV in sky %	ang. res.	2021 / 2025 / >2030
4.2×10^{-8} in 30 d	6	19	<2.8°	PUEO
3.6×10^{-9} (2030)	35	20	5°	ARA
1×10^{-8} in 5 yr	30	35	2°×10°	RNO-G
8×10^{-9} in 5 yr	50	>50	2.9−3.8°	ARIANNA-200
3×10^{-10} in 5 yr	50	>50	?	RET-N
4×10^{-10} in 5 yr	43	43	2°×10°	IceCube-Gen2 Radio
1.2×10^{-8} in 5 yr	6	19.5	0.3°−1°	BEACON
1×10^{-8} in 5 yr	6	80	0.1°	**GRAND10k**
4×10^{-10} in 5 yr	45	100	0.1°	**GRAND**
[1.5×10^{-8} (2019)]	30	92.8	<1°	Auger
?	27	62	1°	TAMBO
7×10^{-8} in 5 yr	0.6	18−36	0.4°	POEMMA Cerenkov
1×10^{-10} in 5 yr	6	62	<1°	Trinity

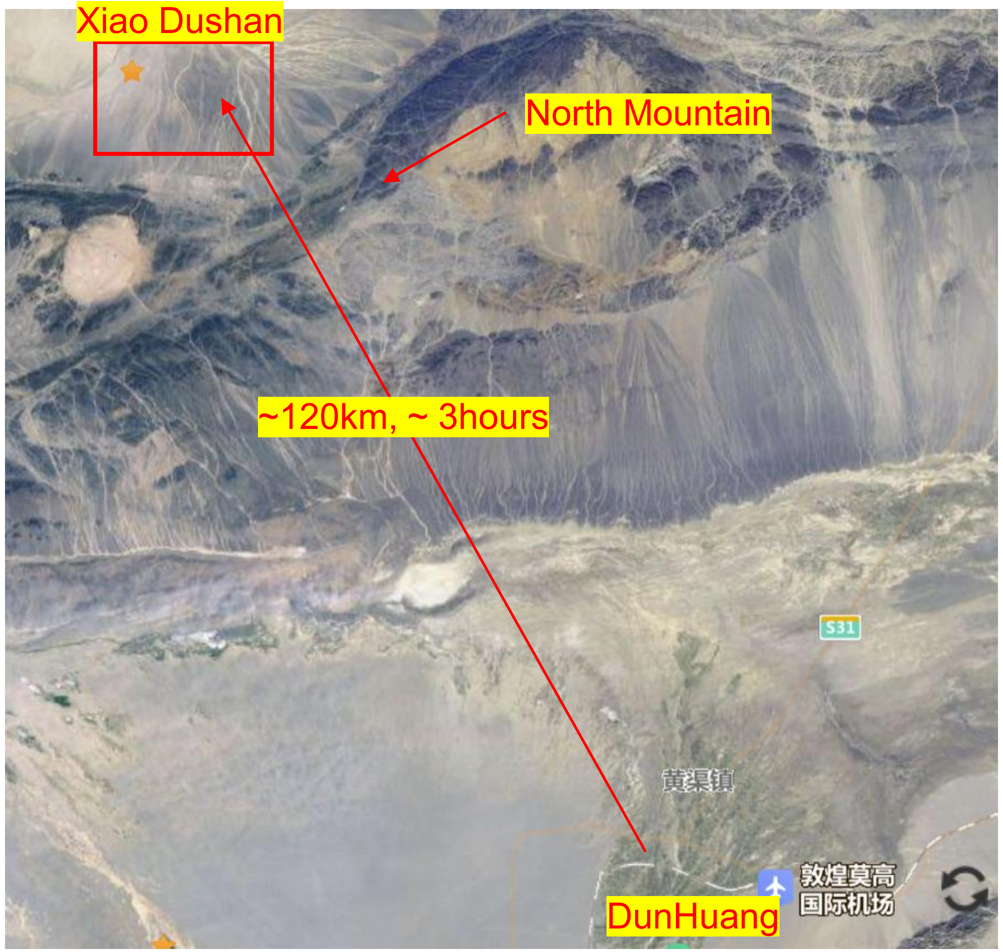
GRAND could potentially detect a large number of cosmogenic neutrinos. The event rate in the 10^8 - 10^{11} GeV energy range is about 1-18 events per year for the standard model.

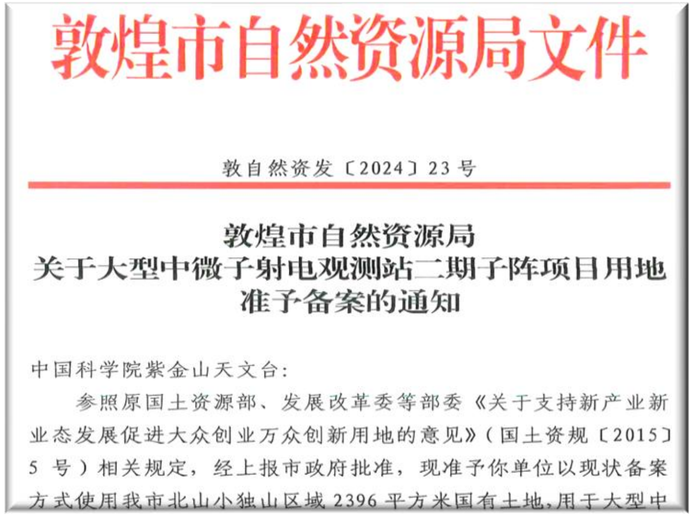
Grand will potentially observe the UHE neutrino sources at 5 σ in 3 years.

GrandProto300








敦煌市自然资源局文件

敦自然资发〔2024〕23号

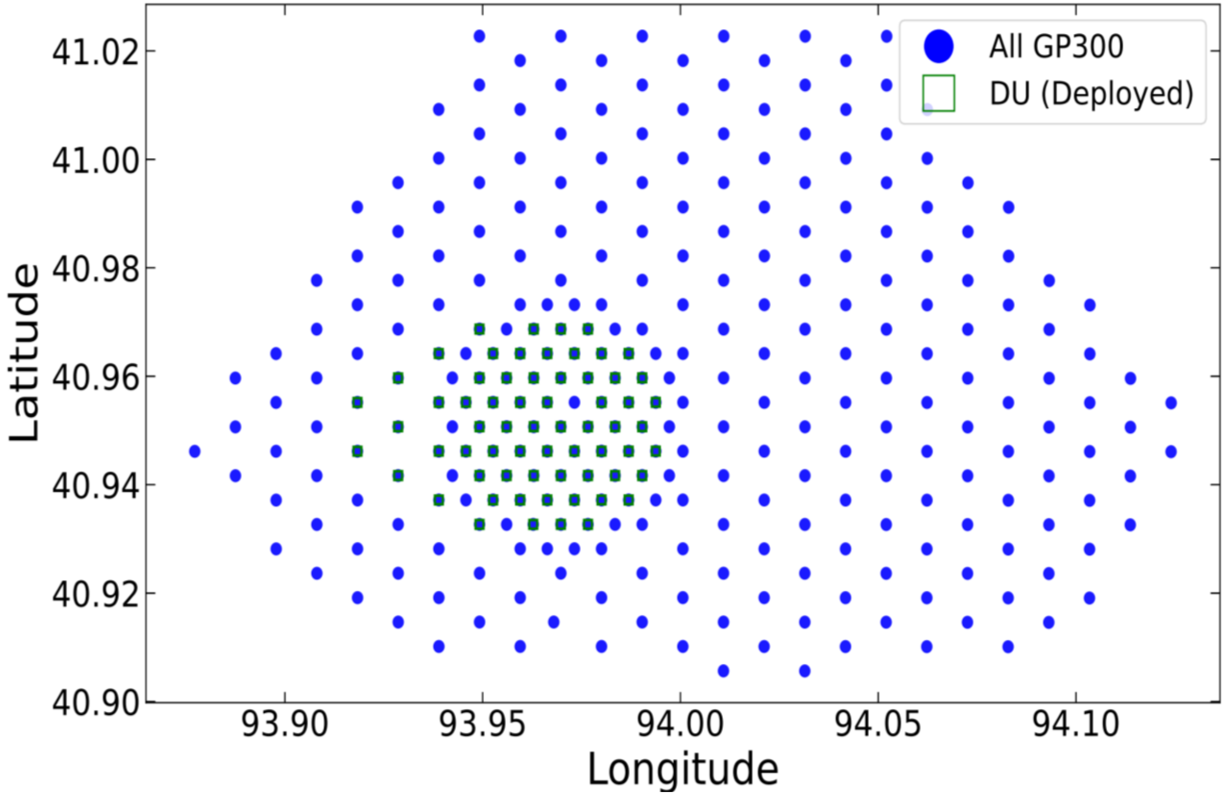
敦煌市自然资源局
关于大型中微子射电观测站二期子阵项目用地准予备案的通知

中国科学院紫金山天文台：

参照原国土资源部、发展改革委等部委《关于支持新产业新业态发展促进大众创业万众创新用地的意见》(国土资规〔2015〕5号)相关规定，经上报市政府批准，现准予你单位以现状备案方式使用我市北山小独山区域2396平方米国有土地，用于大型中

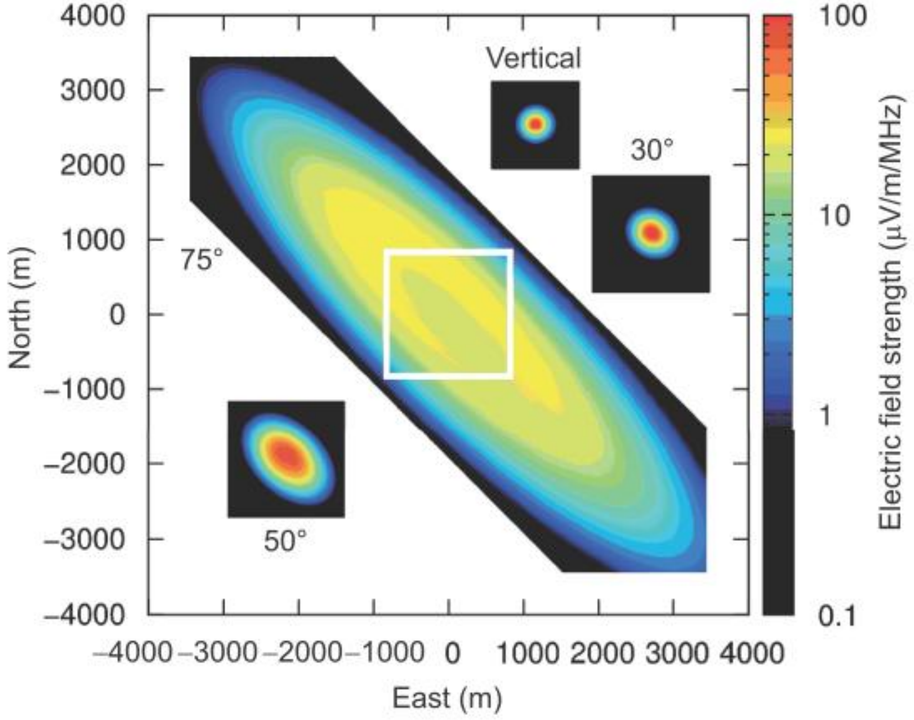
- ✓ 锁定无线电宁静的优越站址;
- ✓ 获授约200平方公里范围内300个单元的点位用地许可。

GrandProto300



自触发技术：

- **技术优势**：摆脱对粒子探测阵列效率的依赖
- **前提条件**：需具备优良的射电环境
- **核心任务**：宇宙射线（CR）的甄别与识别
- ※ 国际尚无稳定实现



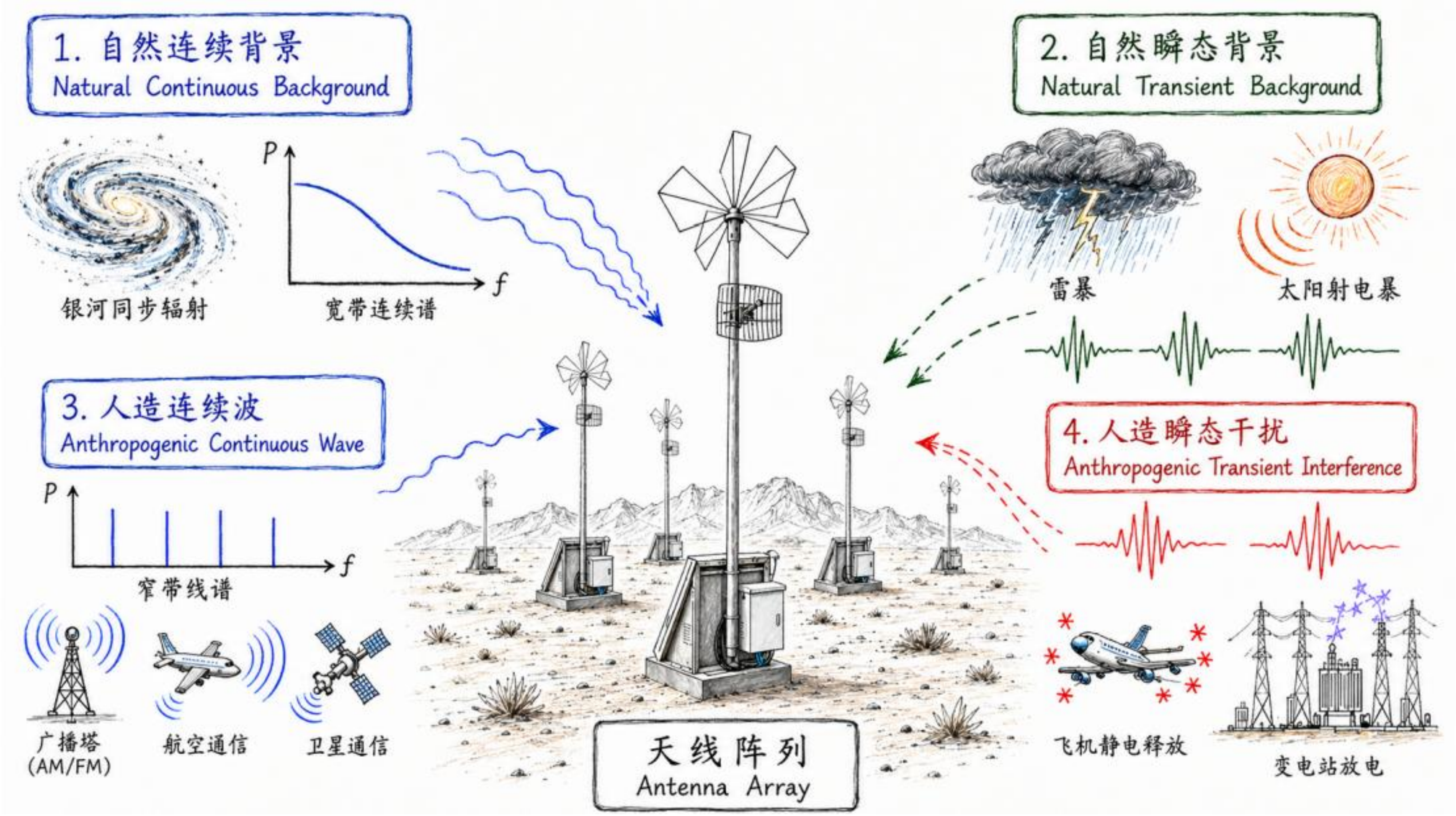
大倾角宇宙射线事例的自触发探测

能量范围：$10^{16.5} - 10^{18}$ eV

- 采用**自触发技术**
- 重建能谱、到达方向与成分
- 为GRAND后续阶段提供试验平台

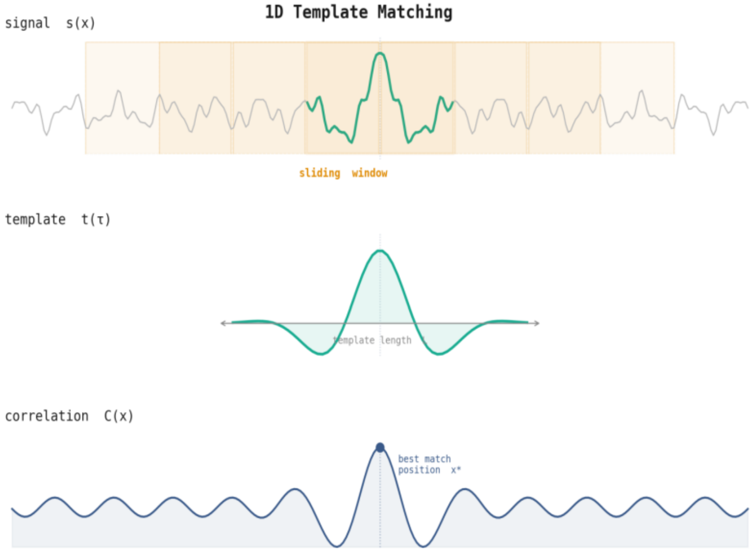
大倾角+低衰减+自触发→ 有效探测面积大

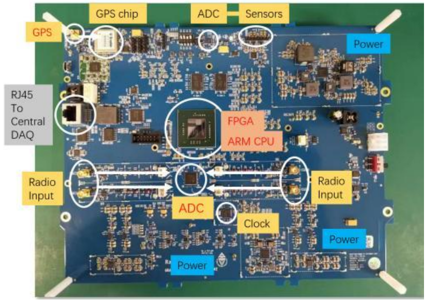
自触发的困难：噪声干扰


1. 自然连续背景
Natural Continuous Background
P
f
银河同步辐射
宽带连续谱
2. 自然瞬态背景
Natural Transient Background
雷暴
太阳射电暴
3. 人造连续波
Anthropogenic Continuous Wave
P
f
窄带线谱
广播塔
(AM/FM)
航空通信
卫星通信
4. 人造瞬态干扰
Anthropogenic Transient Interference
飞机静电释放
变电站放电
天线阵列
Antenna Array

宇宙线事例的识别

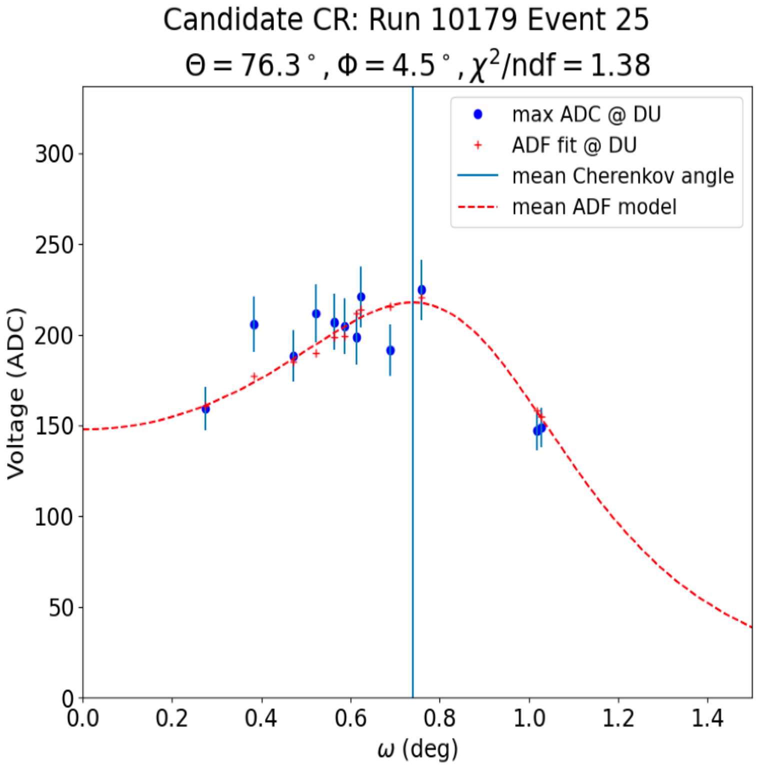
波形匹配(Matching)





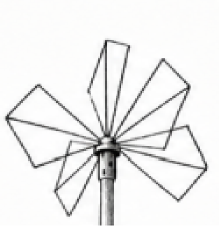
电子学层

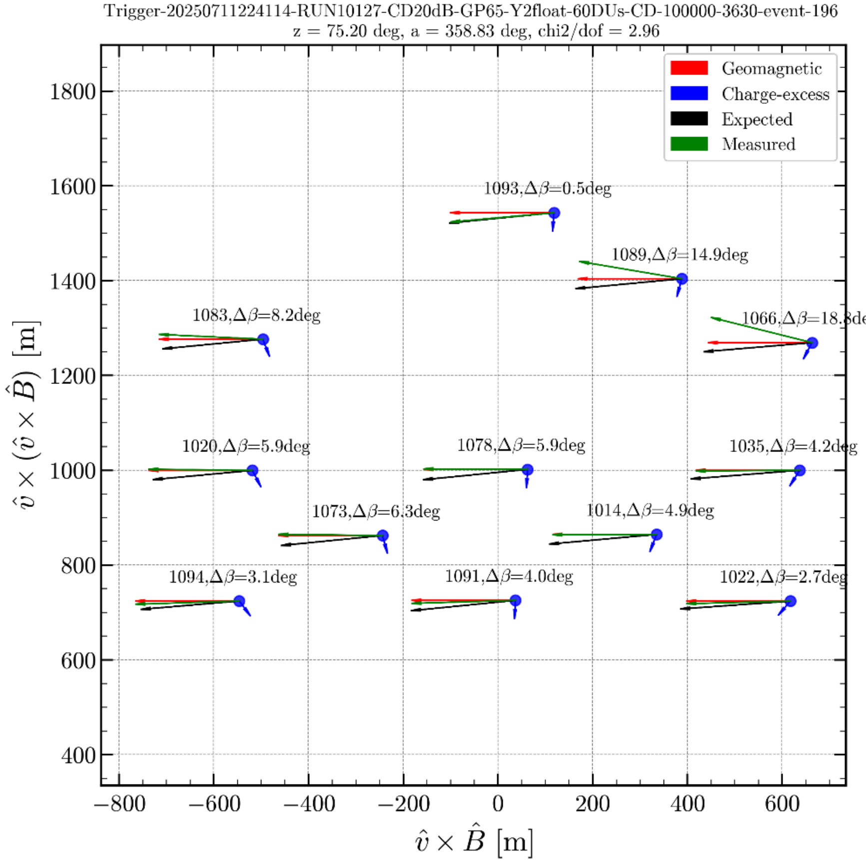
横向分布测试



阵列level

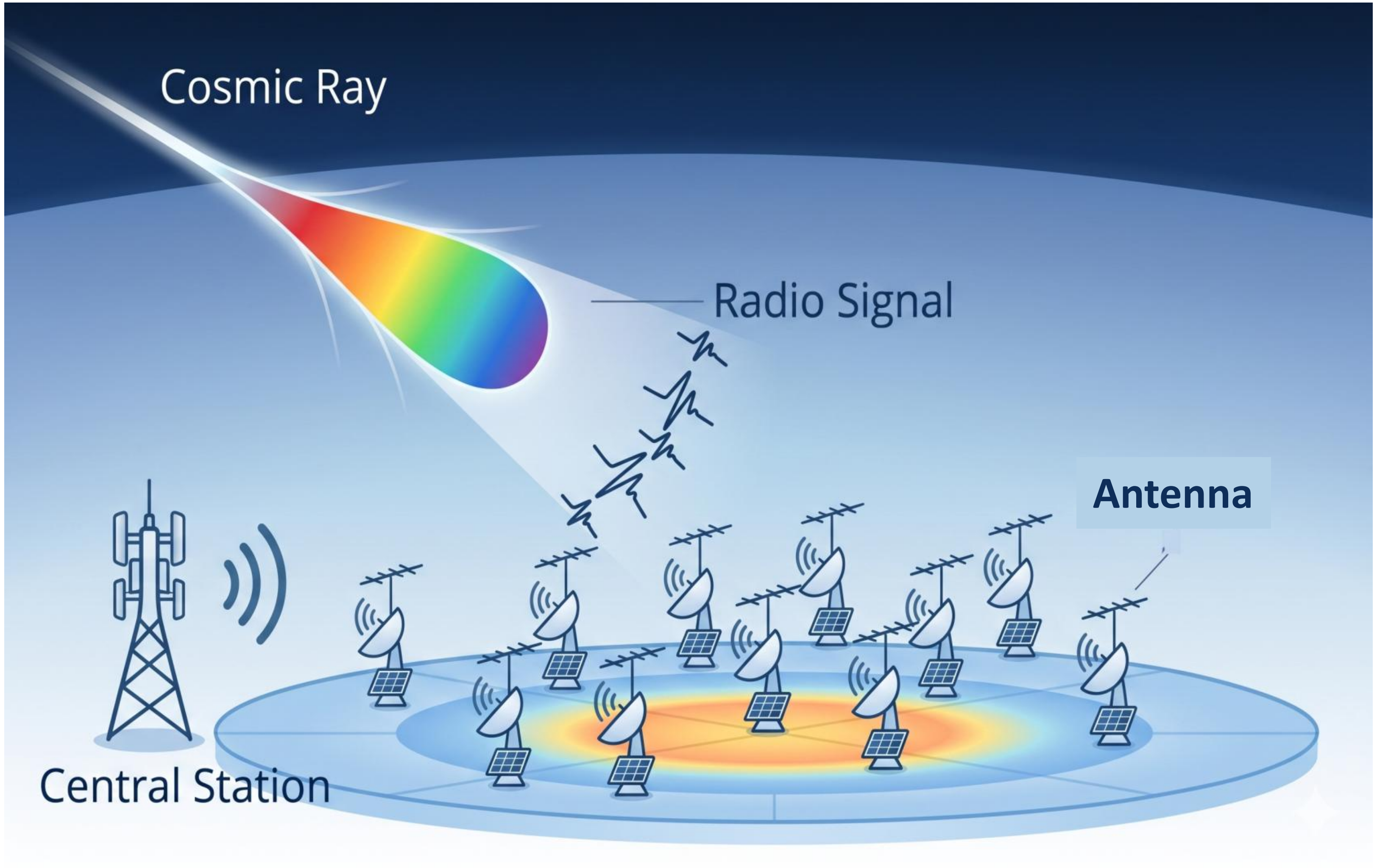
偏振检验

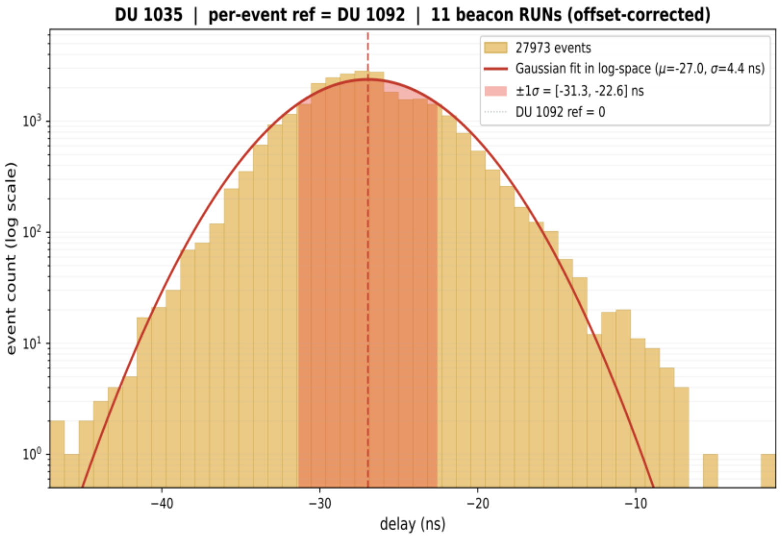




极化天线

无线大阵列的时间同步和标定

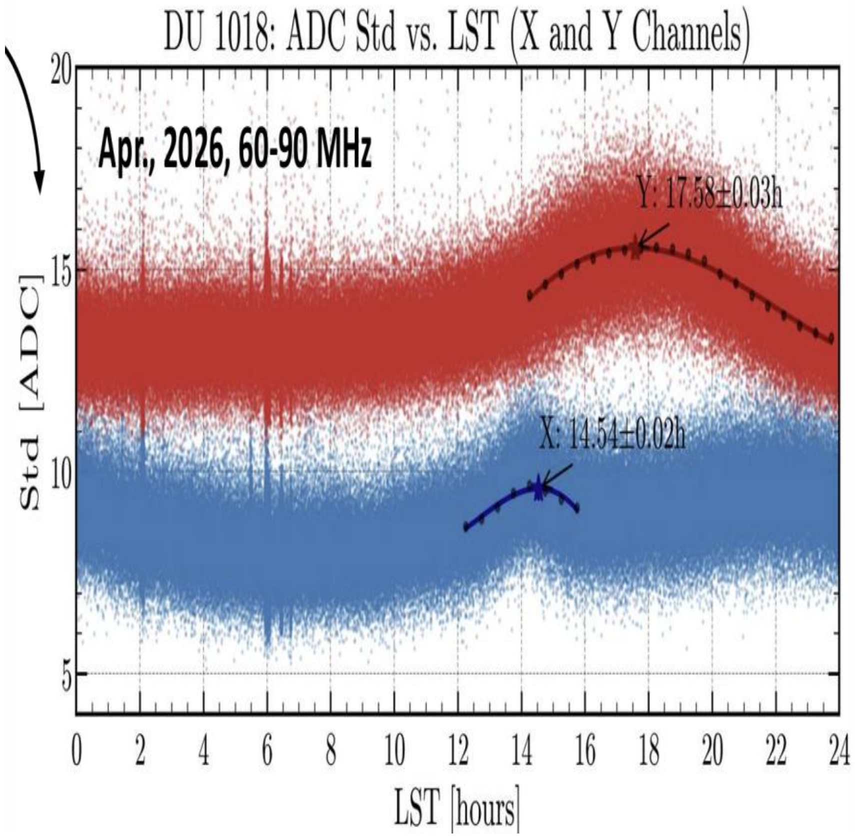


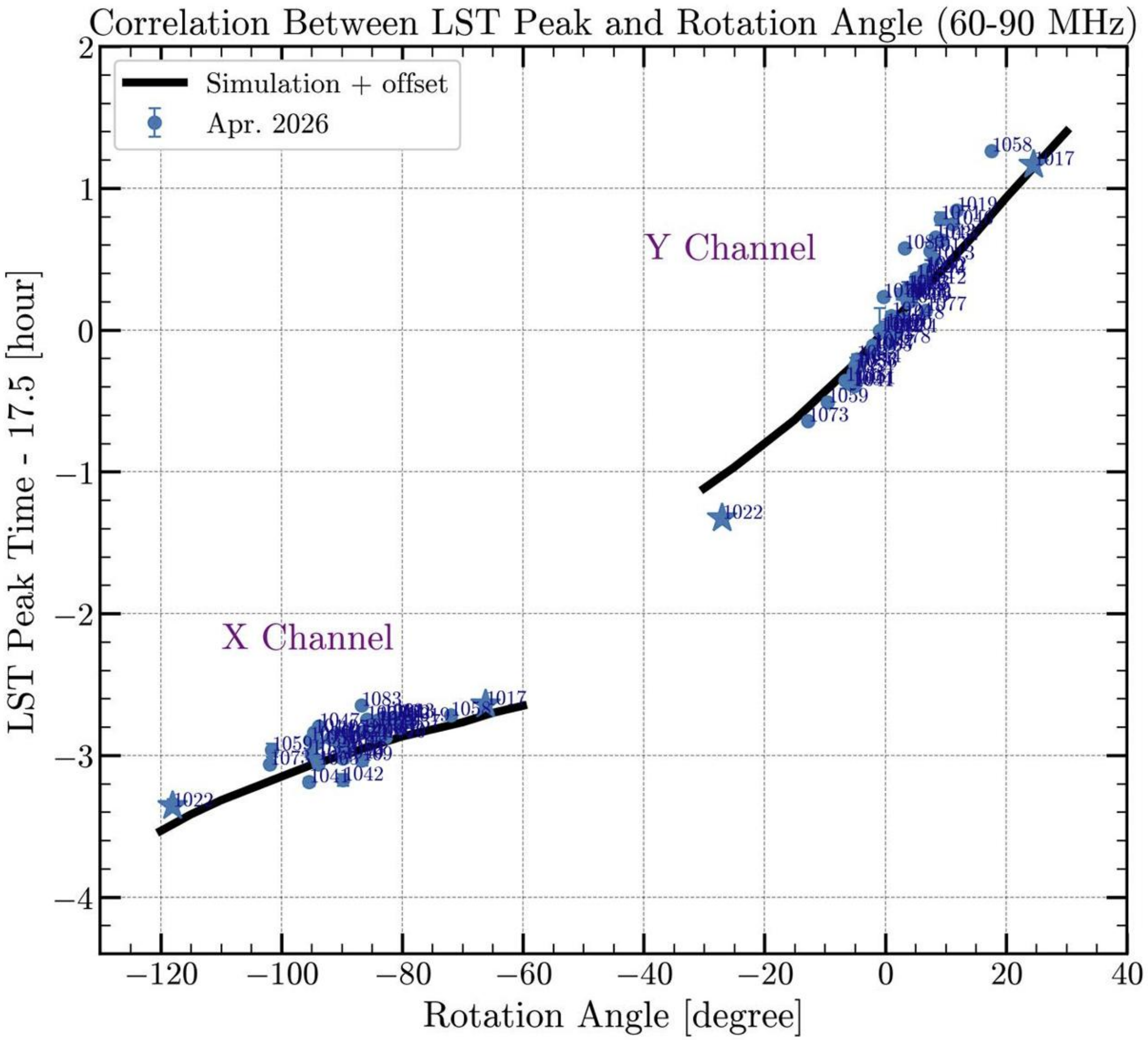


单元的时间分辨，~5ns (GPS)

改进Beacon的设计和开发算法，时间同步精度好于2ns

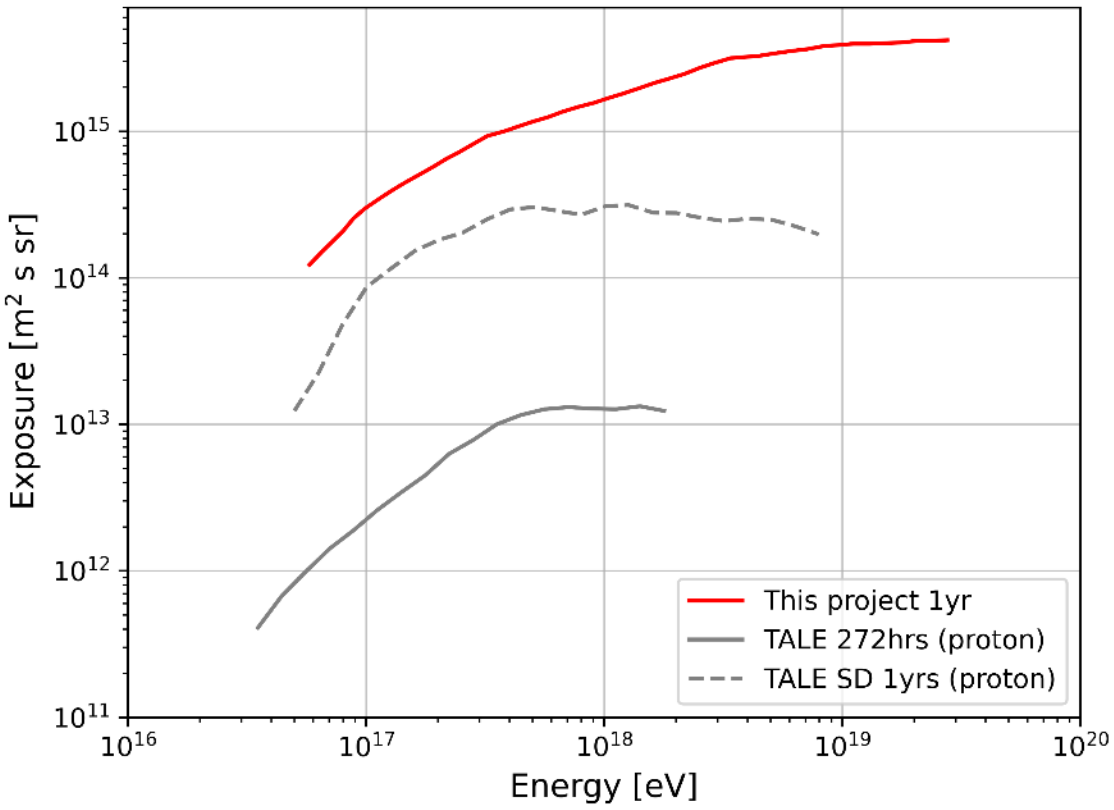
天线转向的标定


DU 1018: ADC Std vs. LST (X and Y Channels)
Apr., 2026, 60-90 MHz
Y: 17.58±0.03h
X: 14.54±0.02h
Std [ADC]
LST [hours]

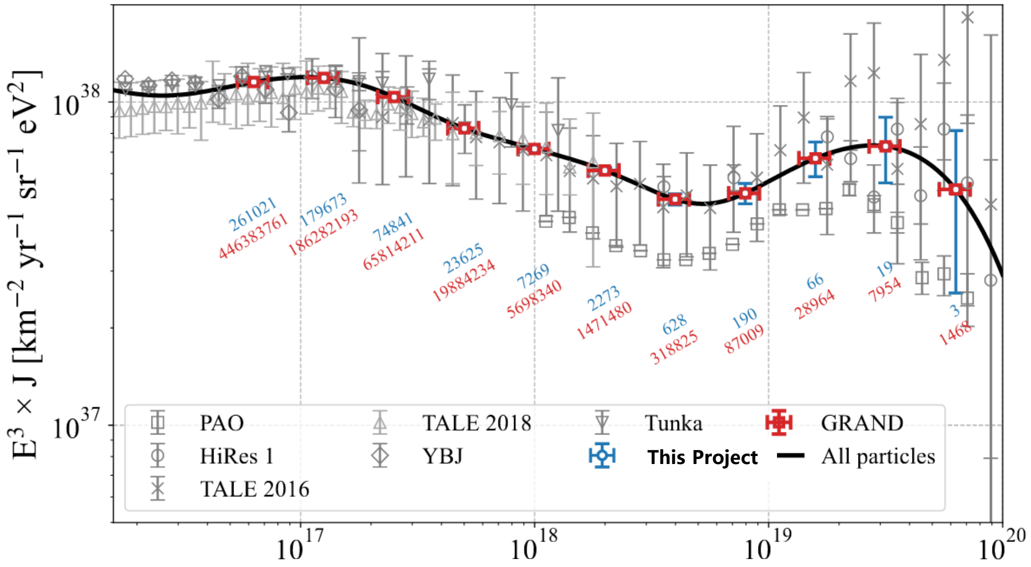

Correlation Between LST Peak and Rotation Angle (60-90 MHz)
Simulation + offset
Apr. 2026
Y Channel
X Channel
LST Peak Time - 17.5 [hour]
Rotation Angle [degree]

GrandProto300预期性能

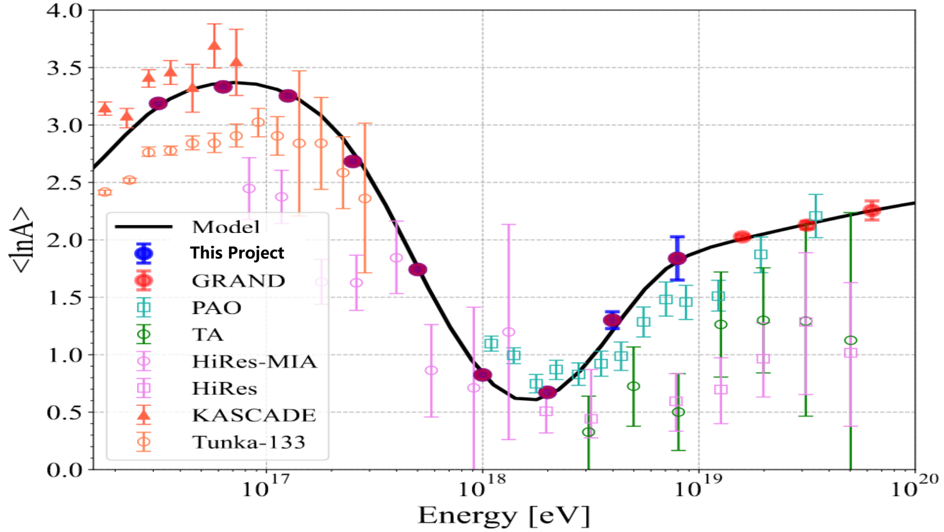
样机阵列的预期有效曝光



10^{17}eV能量以上最好的有效探测曝光



预期的宇宙射线能谱测量

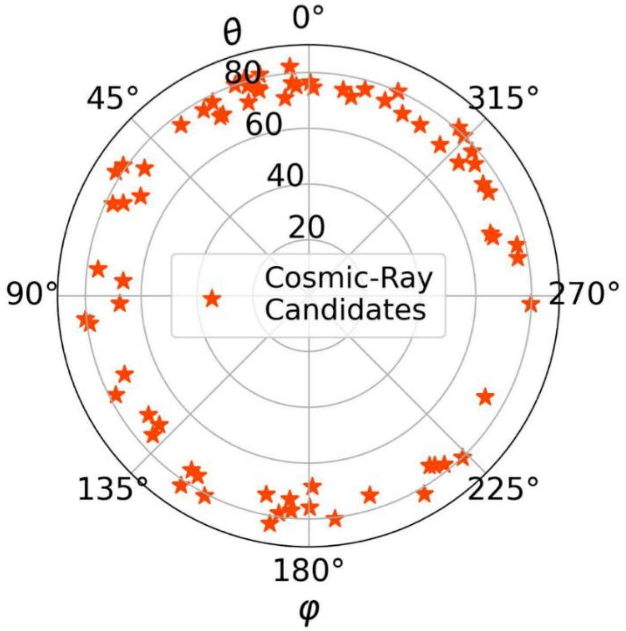


预期的宇宙射线成分测量

Zhang, *ApJ* **991**, 123 (2025).

Summary

- **GRAND**：已成功通过自触发技术观测到宇宙射线
- **GP65**：已完成部署，取数中
- **GP300（2029）**：预计2029年全面建成，持续测量 **100 PeV – 10 EeV** 能段宇宙射线
- 新的技术研究同步开展



GRAND Collaboration Meeting @Dunhuang, May 2026

Working on the first UHECR spectrum with GP300!


谢谢！
Thank you!