ボリビア・チャカルタヤ山宇宙線観測所における高エネルギーγ線・宇宙線観測のための空気シャワー実験

東京大学宇宙線研究所
塙　隆志

2024年度ボリビア実験関係
共同利用研究採択課題一覧

- **ボリビア・チャカルタヤ山宇宙線観測所における高エネルギーγ線・宇宙線観測のための空気シャワー実験（継続）**

（常定芳基　大阪公立大学）

- **アンデス高原における雷雲からの高エネルギー放射線の研究（継続）**

（日比野欣也　神奈川大学）

- **南半球で観測する宇宙線中の太陽の影を用いた太陽磁場の研究　（継続）**

（川田和正　東京大学）

- **ボリビア・チャカルタヤ山宇宙線観測所における高エネルギー宇宙線異方性の研究（継続）**

（佐古崇志　東京大学 => 長野県工科短期大学）

- **ALPACA実験・ALPAQUITA実験で探る星質量ブラックホール連星におけるPeV宇宙線加速の可能性（新規）**

（加藤勢　東京大学 => パリ天体物理学研究所 IAP、ソルボンヌ大学）

ボリビア実験関係共同利用研究
経費執行状況

• 研究費：配分額 250万円

チャカルタヤ観測所運営分担金や
ALPAQUITA実験装置に使用

• 旅費：配分額 173万円

ボリビア出張・宇宙線研での国内研究打ち合わせに使用

ご支援、ありがとうございます！

活動状況

- **ボリビア渡航：延べ 7人（インフラ整備、装置調整、打ち合わせ）**

  2024/6/12-7/1 宇宙線研：さこ　　2024/11/23-11/30 宇宙線研：さこ・藤田
  2024/11/25-12/10 宇宙線研：Anzorena・杉本
  2024/11/25-12/18 宇宙線研：大西　　2025/1/27-2/14 宇宙線研：大西

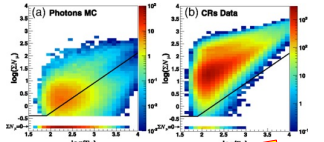
- **国際会議発表**

  22nd International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2024), 8-12 July (Mexico)
  TeV Particle Asrtrophyics (TeVPA) 2024, 26-30 August (Chicago)
  International Conference on High Energy Physics 2024 (ICHEP2024), 17-24 July (Prague)
  Space Climate9, ISEE Symposium, 1-4 October (Nagoya)
  7th International Symposium on Ultra High Energy Cosmic Rays 2024 (UHECR2024), 17-21 November (Malargue, Argentina)

- **国内学会発表**

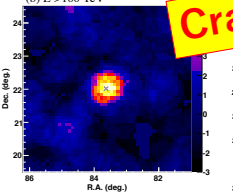
9月16日-19日	日本物理学会第79回年次大会（北海道大学）	6講演
9月11日-13日	日本天文学会2024年秋季大会（関西学院大学）	2講演
3月18日-21日	日本物理学会2025年春季大会（オンライン）	5講演（予定）
3月17日-20日	日本天文学会2025年春季年会（水戸市民会館）	2講演（予定）

Dawn of sub-PeV gamma-ray astronomy

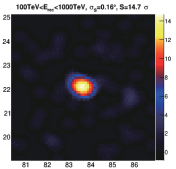


(b) $E>100$ TeV

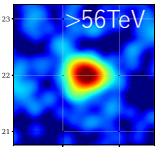
Crab



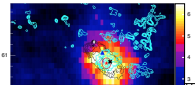
Tibet AS γ Collaboration, PRL 123, 051101 (2019)



LHAASO Collaboration, Chin. Phys. C45, 023002 (2021)

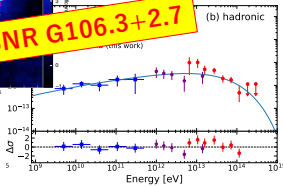


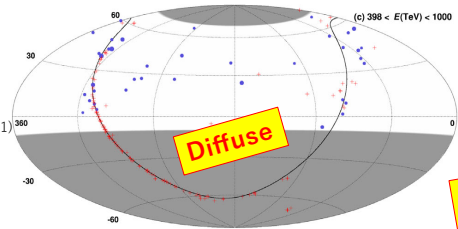
HAWC Collaboration, ApJ 881:134 (2019)



Tibet AS γ Collaboration, Nature Astron., 5, 460-464 (2021)

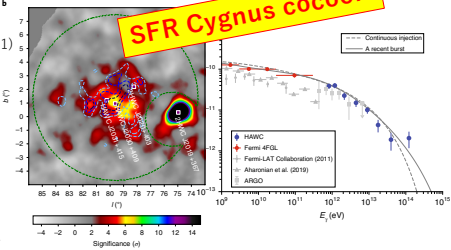
SNR G106.3+2.7



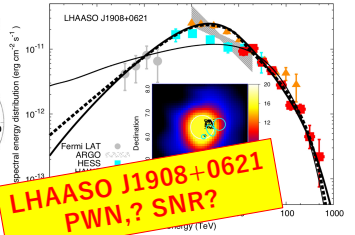


Tibet AS γ Collaboration, PRL 126, 141101 (2021)

SFR Cygnus cocoon



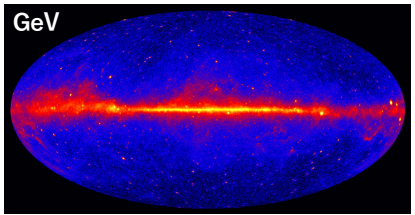
HAWC Collaboration, Nature Astron., 5, 465-471 (2021)



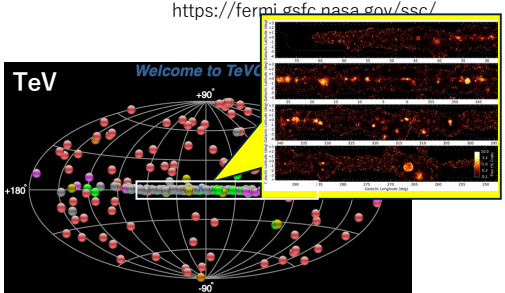
LHAASO J1908+0621 PWN,? SNR?

LHAASO Collaboration, Nature, 594, 33-36 (2021)

Gamma-ray sky

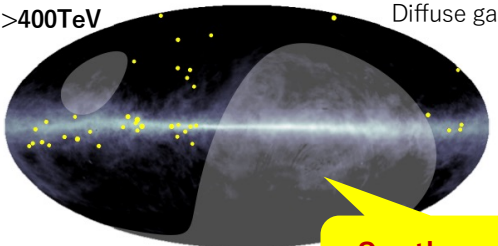


https://fermi.gsfc.nasa.gov/ssc/



http://tevcat.uchicago.edu

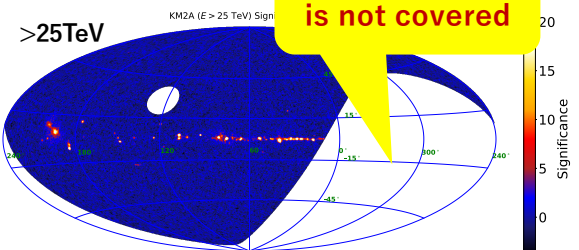
HESS: A&A 612, A1 (2018)



Diffuse gamma rays

Ti 2021)

Southern sky is not covered



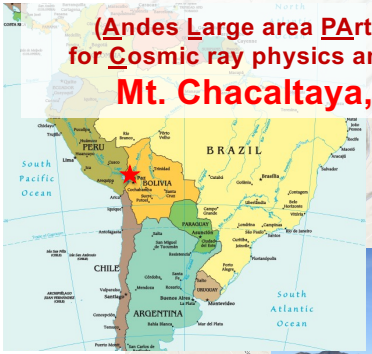
Gamma-ray sources

LHAASO Collaboration, arXiv:2305.1703v1 (2023)

ALPACA

(Andes Large area PArticle detector
for Cosmic ray physics and Astronomy)

Mt. Chacaltaya, Bolivia



UMSA CR Observatory
5200 m a.s.l.

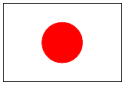
4600m

4400m

ALPACA site
4740 m a.s.l.

4,740 m above sea level
(16° 23′S, 68° 08′W)

The ALPACA Collaboration



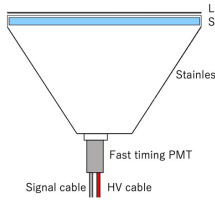
M. Anzorena[A], E. de la Fuente[C], K. Fujita[A], R. Garcia[A], K. Goto[D], Y. Hayashi[E], K. Hibino[F], N. Hotta[G], G. Imaizumi[A], A. Jimenez-Meza[C], Y. Katayose[H], C. Kato[I], S. Kato[A], T. Kawashima[A], K. Kawata[A], T. Koi[J], H. Kojima[K], T. Makishima[H], Y. Masuda[I], S. Matsuhashi[H], M. Matsumoto[I], R. Mayta[B], P. Miranda[B], A. Mizuno[A], K. Munakata[I], Y. Nakamura[A], M. Nishizawa[L], Y. Noguchi[H], S. Ogio[A], M. Ohnishi[A], S. Okukawa[H], A. Oshima[D,J], M. Raljevic[B], H. Rivera[B], T. Saito[M], T. Sako[A], T. K. Sako[N], T. Shibasaki[O], S. Shibata[K], A. Shiomi[O], M. Subieta[B], F. Sugimoto[A], N. Tajima[P], W. Takano[F], M. Takita[A], Y. Tameda[Q], K. Tanaka[R], R. Ticona[B], I. Toledano-Juarez[C], H. Tsuchiya[S], Y. Tsunesada[T,U], S. Udo[F], R. Usui[H], G. Yamagishi[H], K. Yamazaki[J], Y. Yokoe[A] (The ALPACA Collaboration)

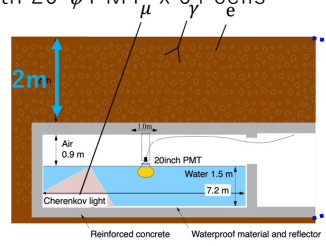
ICRR, Univ. of Tokyo[A], IIF, UMSA[B], Univ. de Guadalajara[C], Coll. of Engn., Chubu Univ.[D], Dept. of Sci. and Tech., Shinshu Univ.[E], Fac. of Engn., Kanagawa Univ.[F], Utsunomiya Univ.[G], Fac. of Engn., Yokohama Natl. Univ.[H], Dept. of Phys., Shinshu Univ.[I], Coll. of Sci. Engn., Chubu Univ.[J], Astro. Obs., Chubu Univ.[K], NII[L], Tokyo Metro. Coll. of Ind. Tech.[M], Dept. of Info. and Elec., Nagano Pref. Inst. of Tech.[N], Coll. of Ind. Tech., Nihon Univ.[O], RIKEN[P], Fac. of Engn., Osaka Electro-Comm. Univ.[Q], Fac. of Info. Sci., Hiroshima City Univ.[R], JAEA[S], Grad. Sch. of Sci., Osaka Metro. Univ.[T], NITEP, Osaka Metro. Univ.[U]

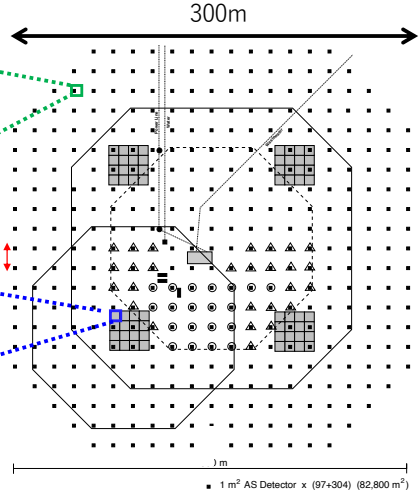
ALPACA Air Shower Array

1. **Array coverage 82,800m²**
   = 401 x 1m² plastic scintillators

2. **Underground water Cherenkov muon detector (MD) 3700m²**
   Soil over 2m (~16X_0)
   = 58m² with 20"ϕPMT x 64 cells



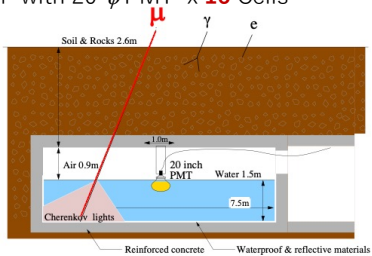


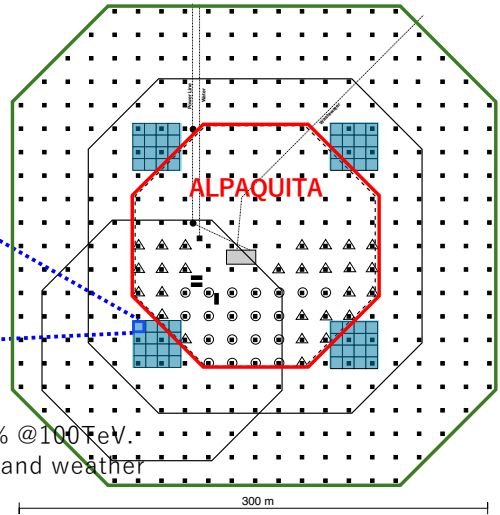


- ✓ Cosmic-ray BG rejection power >99.9% @100TeV.
- ✓ Angular resolution ~0.2° @100TeV, Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

ALPAQUITA

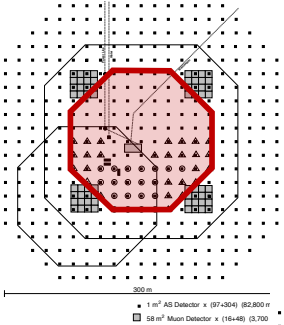
1. **Air Shower (AS) Array ~83,000m²**
   = **97** x 1m² Scintillation Detector
2. **Underground Muon Detector (MD) ~3600m²**
   = Water-Cherenkov-Type, 2.5m overburden (~19X_0)
   56m² with 20"ϕPMT x **16** Cells



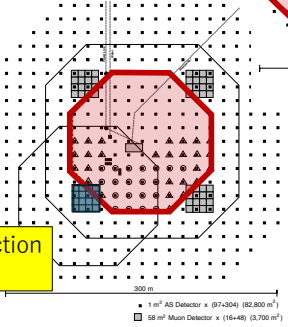


- ✓ Gamma-ray air shower has much less muons.
  Background cosmic rays can be rejected by >99.9% @100TeV.
- ✓ Wide FoV (~2sr) observation regardless day/night and weather
  - Angular resolution ~0.2° @100TeV
  - Energy resolution ~20% @100TeV

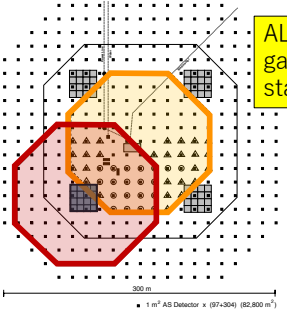
ALPACA Construction Plan



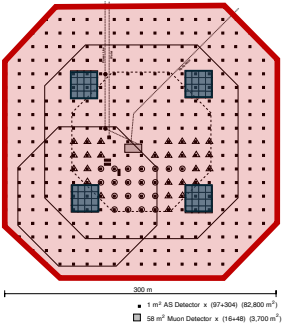
Current configuration



1st MD construction in 2025

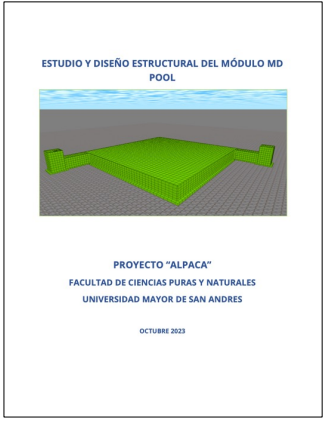


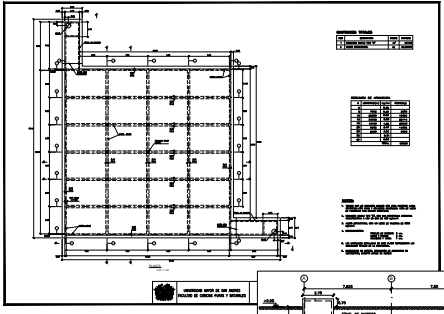
ALPAQUITA w/ MD
gamma-ray sensitive observation starts in 2025

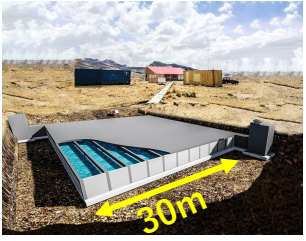


Full ALPACA construction in 2026

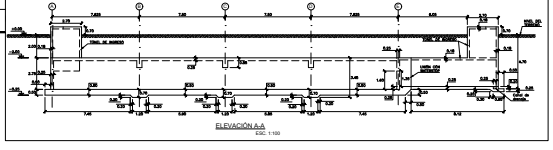
Heart of the experiment
~Underground muon detector~







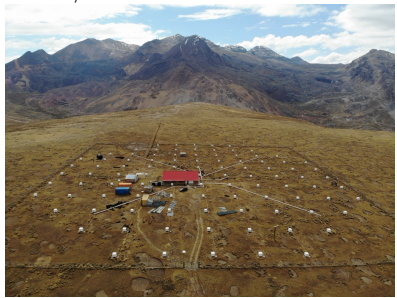
Site photo + CG image of MD by design company



- Long discussions with Bolivian design companies => fixed
- Public call for construction company soon
- Construction of the 1st MD will start in 2025
- First gamma-ray sensitive observation starts in 2025

ALPAQUITA Air Shower Array

¼ALPACA-scale air shower array
1m^2 scintillation detector x 97 with 15m spacing
Effective area ~18,000m^2



1m^2 5mm lead plate
1m^2 Scintillator
(50cm x 50cm x 5cm x4)

Inverse pyramid shape
Stainless steel box
(White painted inside)

2-inch PMT x1

Air Shower Trigger Condition：

Any 4 （Any3 since Jun 2024）detectors with >0.6 particles within 600ns

→ Rate ~280Hz @ CR mode energy ~7 TeV

Counting Mode Condition：

Any1, Any2, Any3, Any4 rates every 0.1 sec

Construction status:
2022 Jun. Deploy detectors
2022 Sep. Partial operation
2023 Apr. Full operation

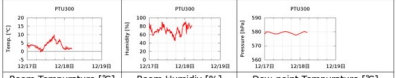
ALPAQUITA monitoring

Environment Monitor at 04:45:11_2024/12/18

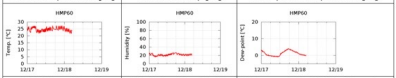
The ALPACA Experiment at Cerro Estuqueria, Bolivia (updated 04:45:11_2024/12/18)

Outside Air		Control Room (Inside)		Wind Speed		Wind Direction		Precipitation	
Ambient Temp.	1.8 ℃	Room Temp.	23.90 ℃	Ave.	m/s	Ave.	deg.	Duration	sec
Humidity	80.6 %	Humidity	20.77 %	Max	m/s	Max	deg.	Intensity	mm/h
Station Pressure	579.7 hPa	Dew-point Temp.	0.12 ℃	Min.	m/s	Min.	deg.	Peak Intensity	mm/h

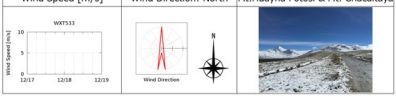
Ambient Tempurature [℃] | Ambient Humidity [%] | Station Pressure [hPa]

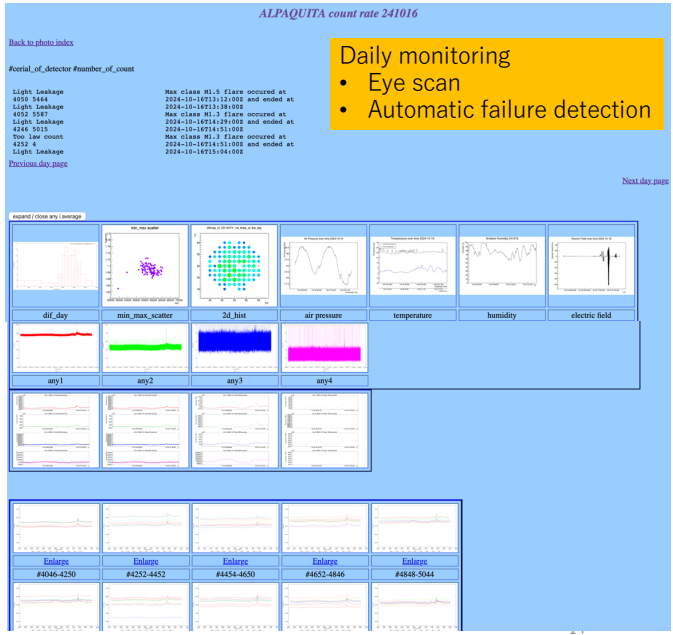


Room Tempurature [℃] | Room Humidity [%] | Dew-point Tempurature [℃]

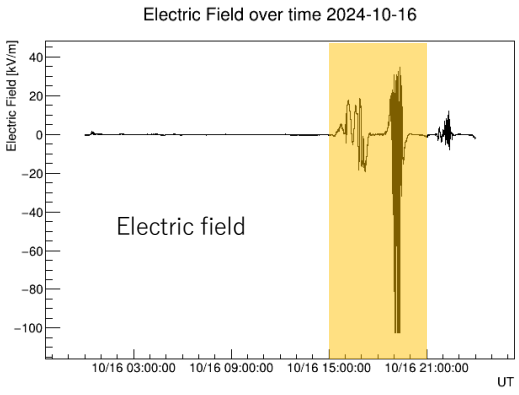


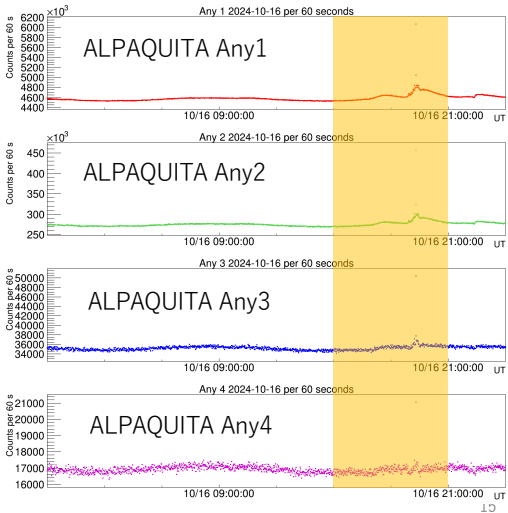
Wind Speed [m/s] | Wind Direction: North | Mt.Huayna Potosi & Mt. Chacaltaya





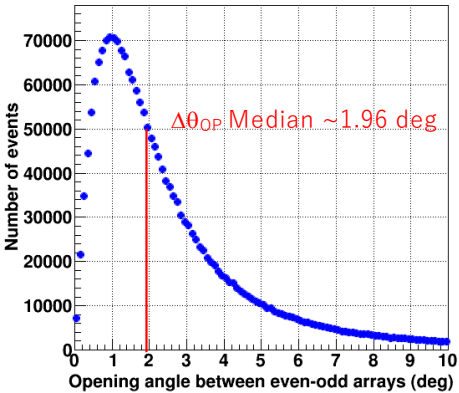
Electric field correlation?



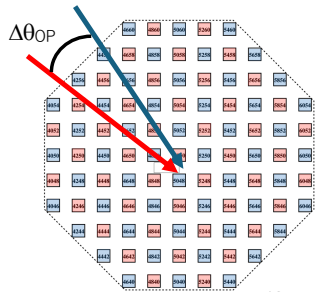


Performance of ALPAQUITA Even-Odd Method

Event selection criteria:
- Zenith angle < 40deg
- In Array flag = on
- 1.25 Any 4 flag = on
- Residual error < 1.0

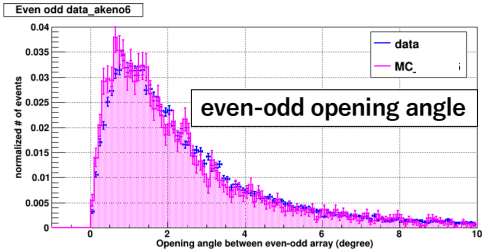


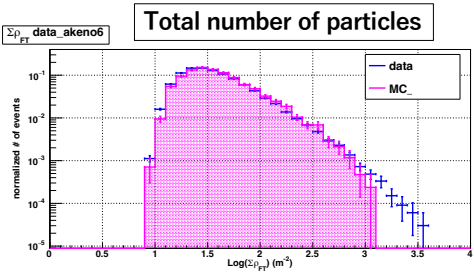
Even-Odd opening angle：
Opening angle between directions determined by two independent arrays (even and odd arrays)

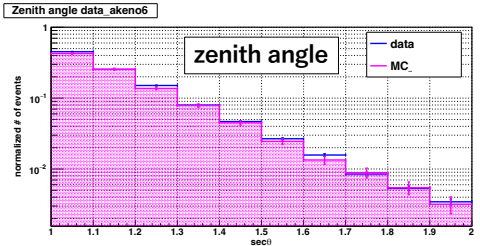


Angular resolution
$\sigma_{50} = \Delta\theta_{OP} / 2 = \sim 1^{o}$

Data-MC comparison

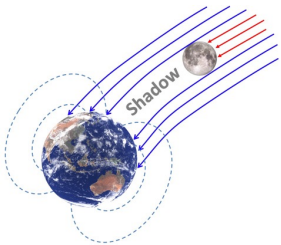


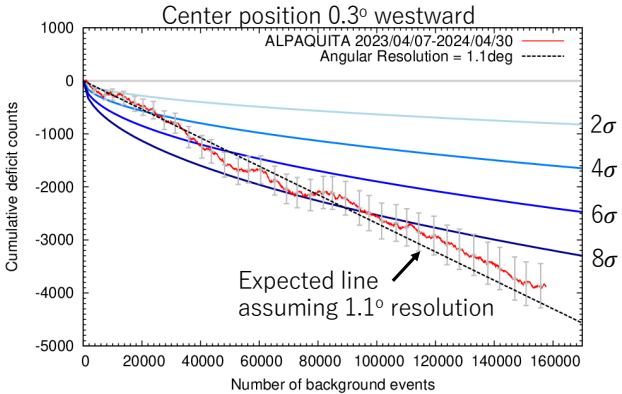




- Detector calibration data are taken into account
- Good agreement between experimental data and MC
- Air shower array shows expected performance

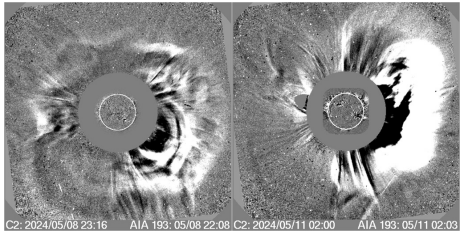
Moon Shadow

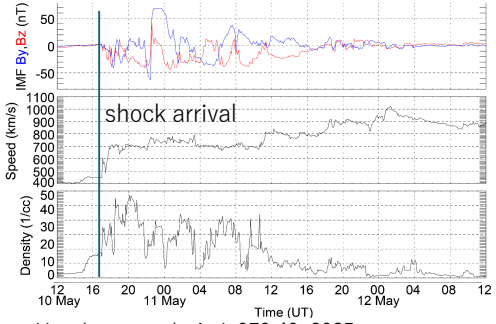


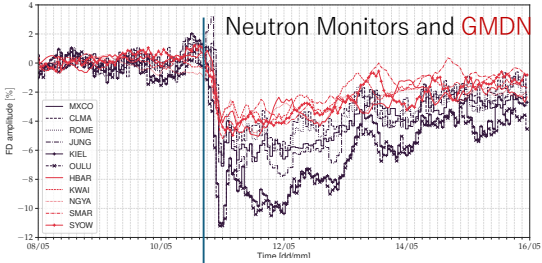


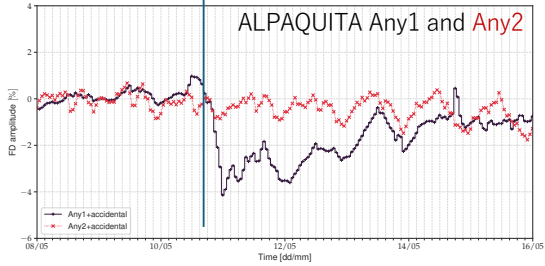
- Shadow of the moon is clearly detected at >8σ
- Evolution of the deficit depth suggests the angular resolution of 1.1 degree (mode energy = a few TeV)

Forbush decrease in May 2024



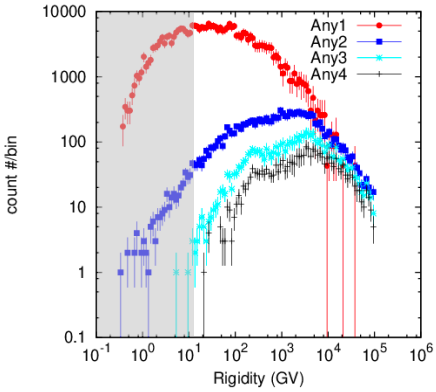


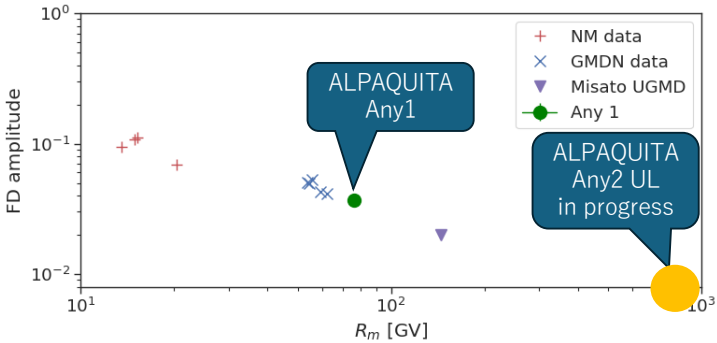




Hayakawa et al., ApJ, 979:49, 2025.

Median rigidity and amplitude

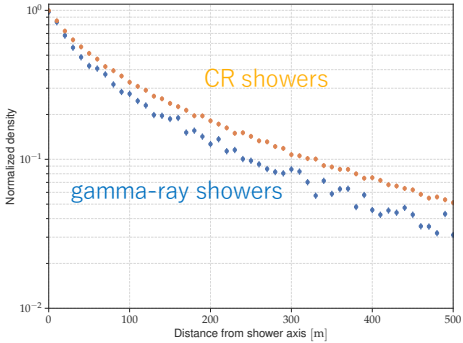




- ALPAQUITA response function in CR rigidity
- MC simulation with a model CR spectrum and composition
- Median rigidity above 12GV geomagnetic cutoff
  Any1:76GV, Any2:960GV

- Median rigidity and FD amplitude
- ALPAQUITA Any1 aligns with the traditional experiments
- ALPAQUITA Any2 will give a strong constraints at highest rigidity (UL determination in progress)

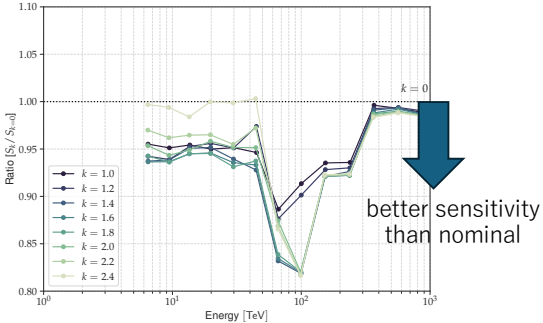
PID with Muon lateral (MC study)



$$m_k = \sum_j N_j \times \left(\frac{R_j}{R_n}\right)^k$$

lateral distance weighted N_{mu}
k=0 : nominal

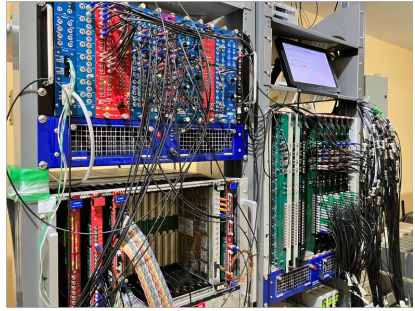
Experimental Astronomy, accepted (2025)



sensitivity improvement w.r.t. k=0 (nominal)

Summary

- 南半球でsub-PeVガンマ線を観測するALPACA実験を進行中
- ¼サイズのALPAQUITA地上アレイが稼働中
  - 雷同期事象を観測か
  - 基本特性（天頂角、$\sum\rho$、even-odd開き角）をMCで再現
  - 月の影を10シグマで確認
  - Counting modeで Forbush decreaseを検出。~1TVで制限。
  - Muon lateral分布を利用したガンマ線検出感度向上
- 2025年に地下ミューオン検出器1号機を建設し、ガンマ線天文学を開始
- 2026年に Full ALPACA (w/ 4 MDs)を完成し、本格的な観測を開始



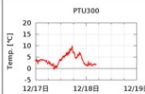
ALPAC

Environment Monitor at 04:45:11_2024/12/18

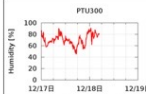
The ALPACA Experiment at Cerro Estuqueria, Bolivia (updated 04:45:11_2024/12/18)

Outside Air		Control Room (Inside)		Wind Speed		Wind Direction		Precipitation	
Ambient Temp.	1.8 ℃	Room Temp.	23.90 ℃	Ave.	m/s	Ave.	deg.	Duration	sec
Humidity	80.6 %	Humidity	20.77 %	Max	m/s	Max	deg.	Intensity	mm/h
Station Pressure	579.7 hPa	Dew-point Temp.	0.12 ℃	Min.	m/s	Min.	deg.	Peak Intensity	mm/h

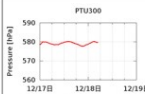
Ambient Tempurature [℃]



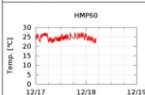
Ambient Humidity [%]



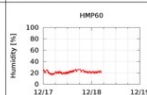
Station Pressure [hPa]



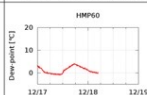
Room Tempurature [℃]



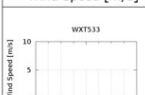
Room Humidiy [%]



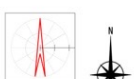
Dew-point Tempurature [℃]



Wind Speed [m/s]

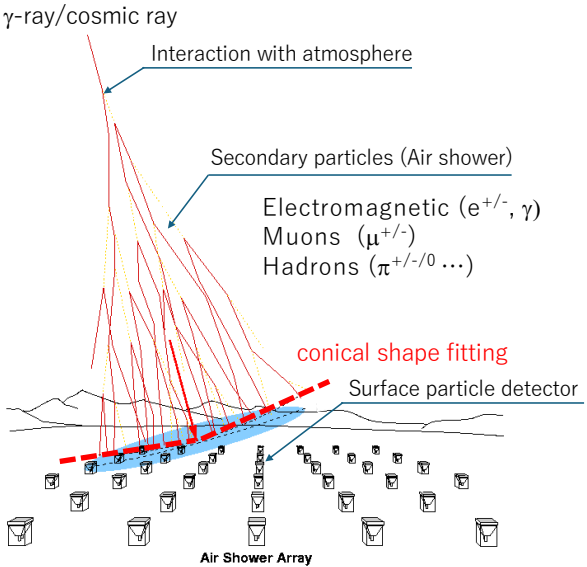


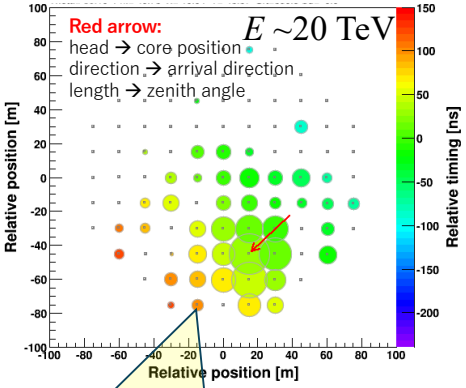
Wind Direction: North



Mt.Huayna Potosi & Mt. Chacaltaya

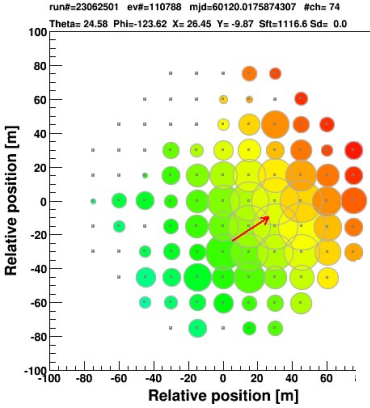
ALPAQUITA Air Shower Analysis

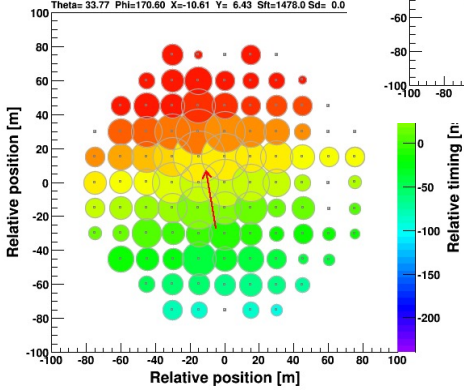


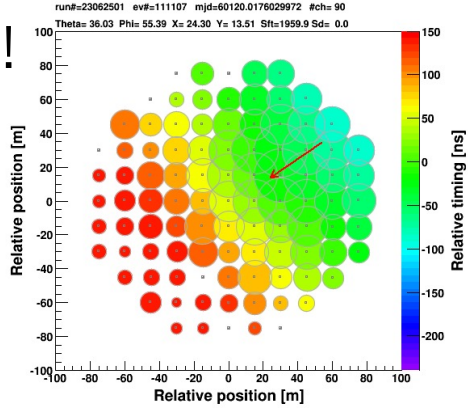


1. Relative arrival timing (Color scale)
2. Number of particles (Circle size)
→ Reconstruct direction and energy

Big Events!







E >100 TeV
(mostly hadronic CRs)