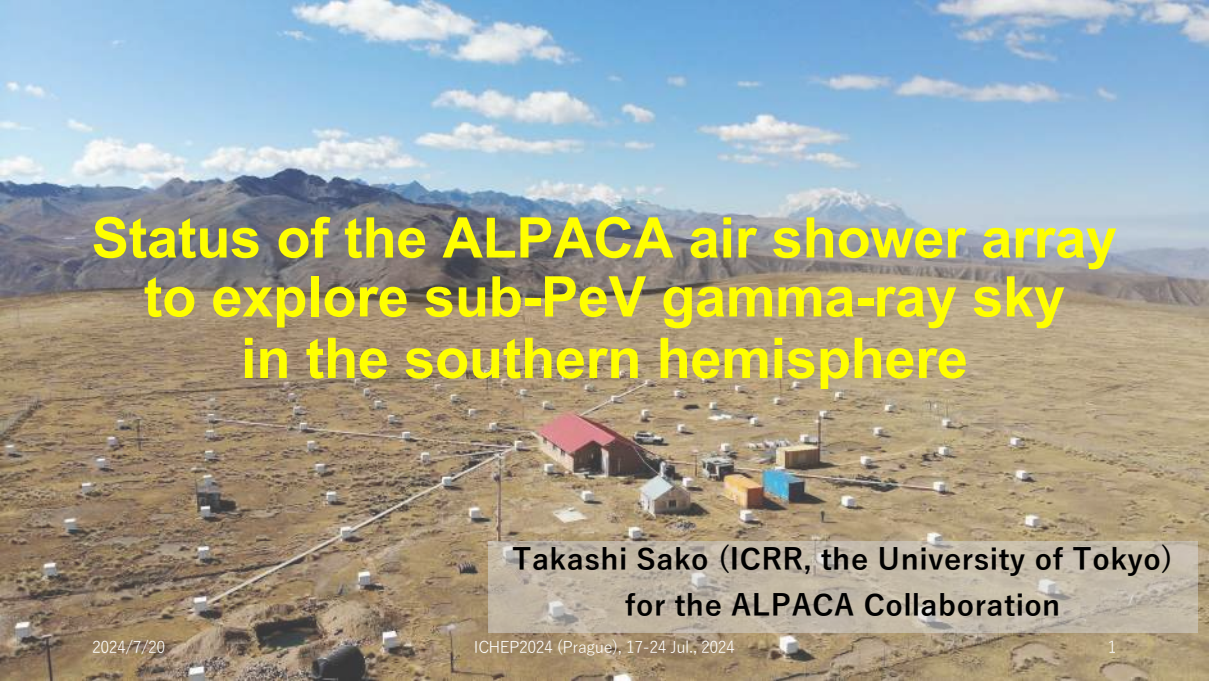
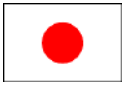
Status of the ALPACA air shower array to explore sub-PeV gamma-ray sky in the southern hemisphere



Takashi Sako (ICRR, the University of Tokyo)
for the ALPACA Collaboration

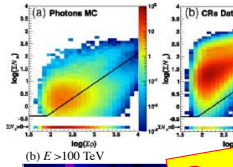
The ALPACA Collaboration



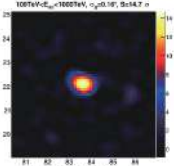
T. Sako[A], M. Anzorena[A], D. Blanco[B], E. de la Fuente[C], K. Goto[D], Y. Hayashi[E], K. Hibino[F], N. Hotta[G], G. Imaizumi[A], A. Jimenez-Meza[C], Y. Katayose[H], C. Kato[I], S. Kato[A], T. Kawashima[A], K. Kawata[A], T. Koi[J], H. Kojima[K], T. Makishima[H], Y. Masuda[I], S. Matsuhashi[H], M. Matsumoto[I], R. Mayta[B], P. Miranda[B], A. Mizuno[A], K. Munakata[I], Y. Nakamura[A], C. Nina[B], 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. K. Sako[N], J. Salinas[B], T. Shibasaki[O], S. Shibata[K], A. Shiomi[O], M. Subieta[B], F. Sugumoto[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], R. I. Winkelmann[B], G. Yamagishi[H], K. Yamazaki[J], Y. Yokoe[A] et al. (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]

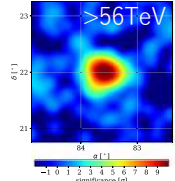
Dawn of sub-PeV gamma-ray astronomy



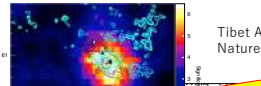
Tibet AS γ Collaboration, PRL 123, 051101 (2019)



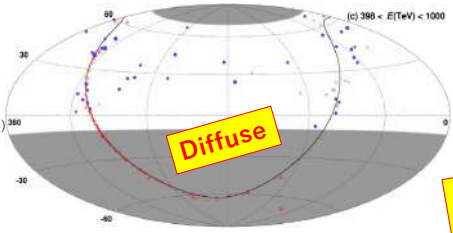
LHAASO Collaboration, Chin. Phys. C45, 023002 (2021)



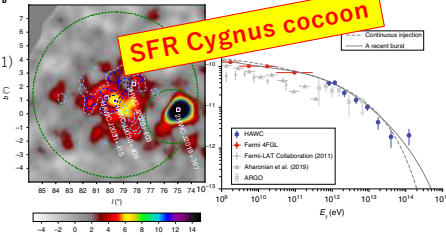
HAWC Collaboration, ApJ 881:134 (2019)



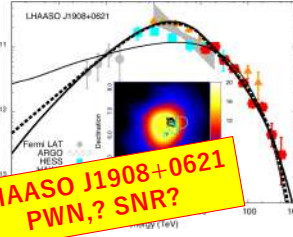
Tibet AS γ Collaboration, Nature Astron., 5, 460-464 (2021)



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

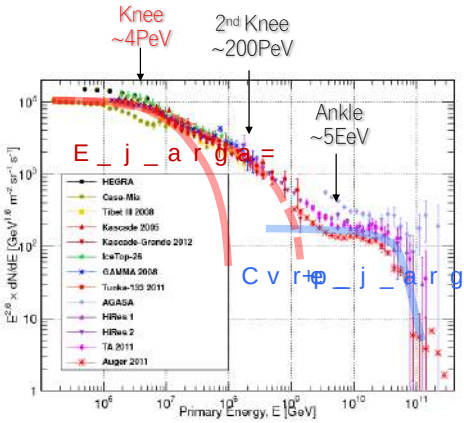


HAWC Collaboration, Nature Astron., 5, 465-471 (2021)
LHAASO Collaboration, Science Bulletin, 69, 449-457 (2024)



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

Why sub-PeV gamma rays?



Gaisser et al. Front.Phys.(Beijing) 8 (2013) 748

- Galactic protons are thought to be accelerated up to PeV (~knee)
  - Where are their origins?
  - Are CRs up to 100PeV (~2nd knee) heavy nuclei?
- Sub-PeV gamma rays point to the sources of PeV CRs

$$p(E) + ISM \rightarrow X + \pi^0 \rightarrow X + 2\gamma(\sim 0.1E)$$

- Diffuse gamma rays tell us the CR distribution in the galaxy.
- Highest energy gamma rays tell us the acceleration limit in energy/nucleon.

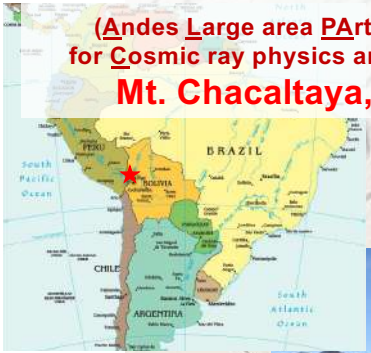
Especially in the **southern hemisphere**, near the Galactic center!!

U f c p c _ p c r f c A P q m s p a
U f _ r g q r f c k _ v g k s k _ a a c j c p _ r g m l c l c p e w & -
F m u b m r f c w n p m n _ e _ r c g l r f c e _ j _ v w =

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.

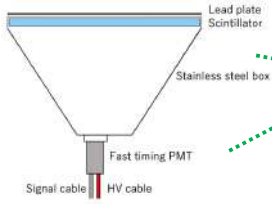
4,740 m above sea level
(16° 23′S, 68° 08′W)

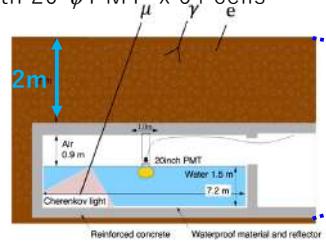
La Paz

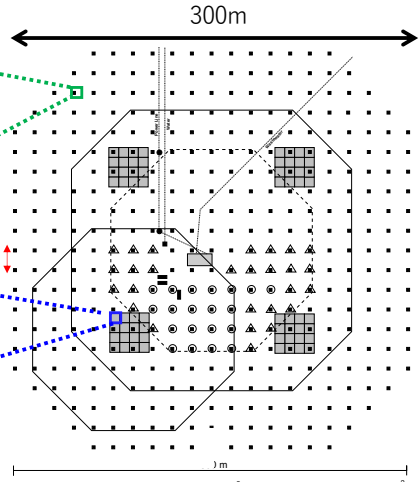
ALPACA Array

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







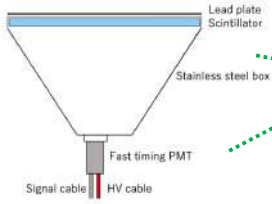
- ✓ Cosmic-ray BG rejection power >99.9% @100TeV.
- ✓ Angular resolution ~0.2° @100TeV, Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

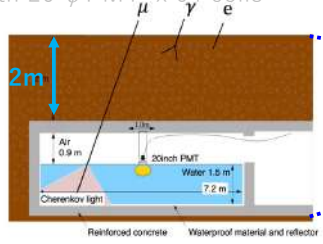
97 detectors

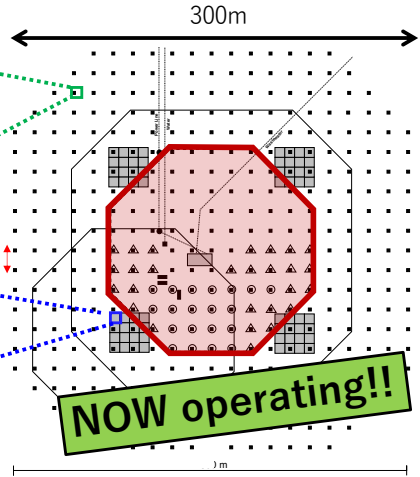
ALPA**QUITA** surface array

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.
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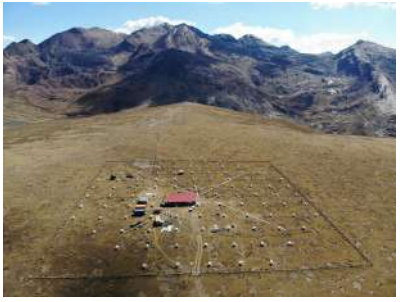
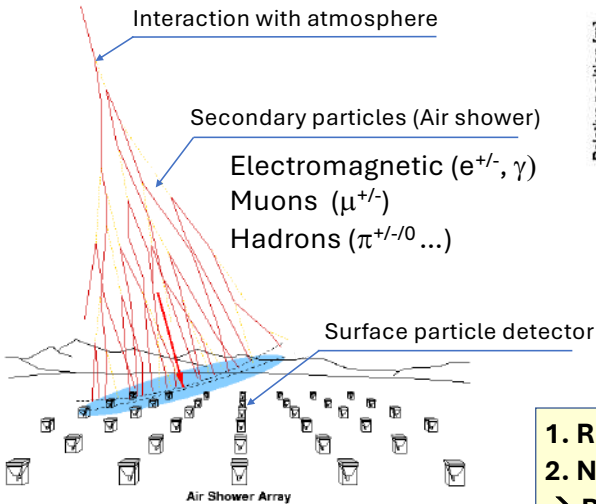
ALPAQUITA in operation

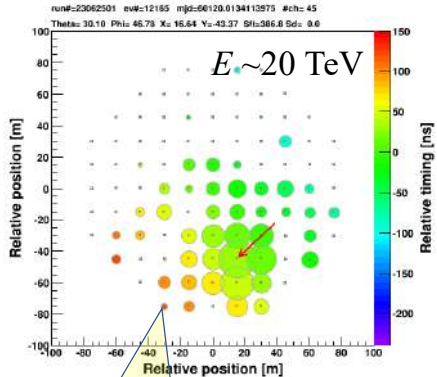


- Installation of 97 ground detectors completed in 2022.
- Full operation since April 2023.

ALPAQUITA analysis

γ-ray/cosmic ray

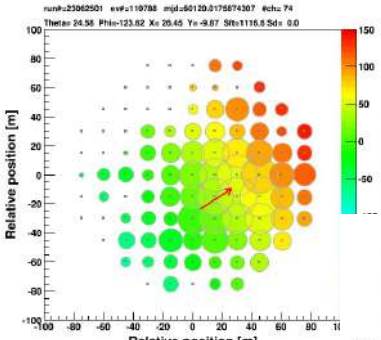


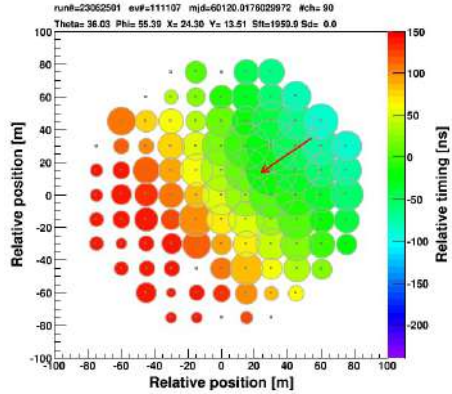


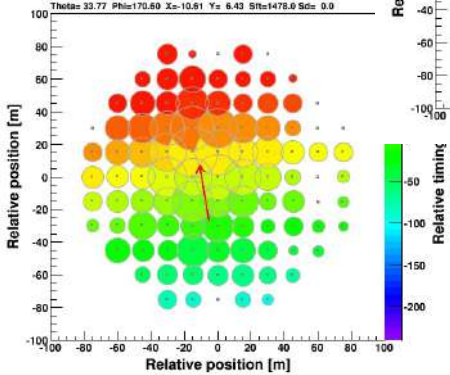
Red arrow:
head → core position
direction → arrival direction
length → zenith angle

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

Big Events!



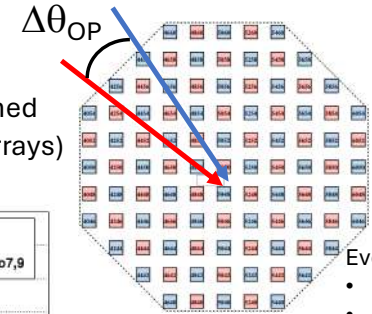


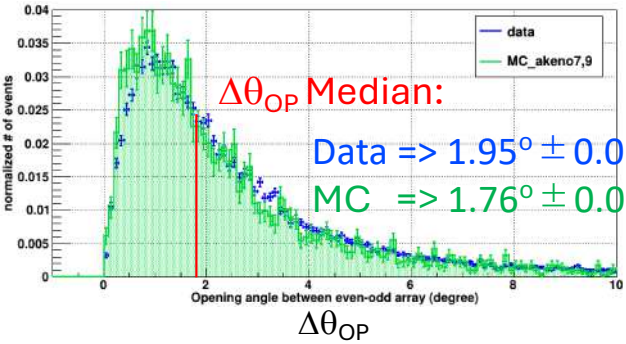


E >100 TeV

Data-driven angular resolution

Even-Odd opening angle $\Delta\theta_{OP}$:
Opening angle between directions determined by two independent arrays (even and odd arrays)

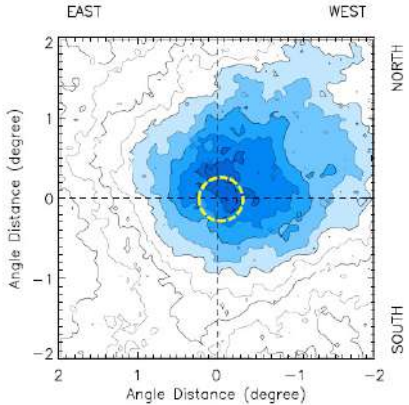




Event selection criteria:
- Zenith angle < 40deg
- In Array flag = on
- 1.25 Any 4 flag = on
- Residual error < 1.0

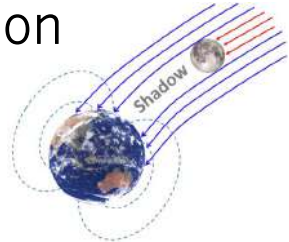
✓ Angular resolution
σ_{50} ~ ($\Delta\theta_{OP}$ Median) / 2 = **~1°**
(Mode energy ~ several TeV)

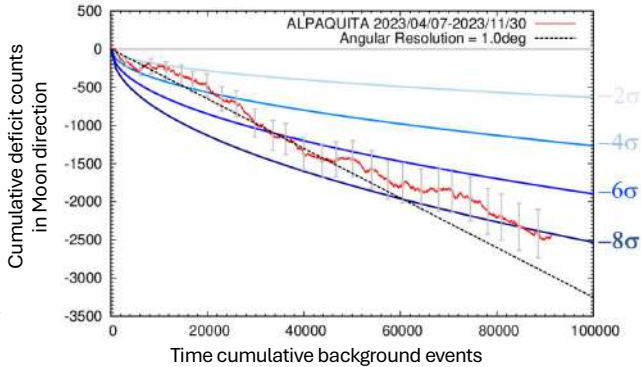
Shadow of the Moon



Displacement
by geomagnetic field:

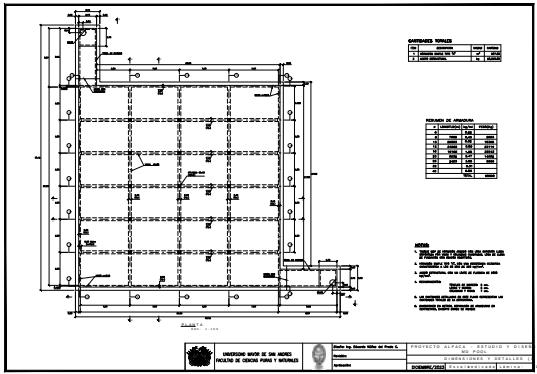
$$\Delta\theta \sim \frac{1.6^o}{E[\mathrm{TeV}]}$$

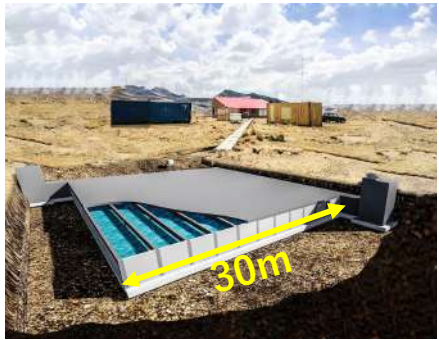




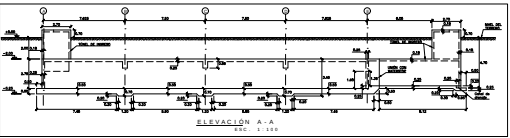
- April 7 – November 30, 2023（225 days）
- Successful detection at 8.0σ
- Shift westward ~0.2 degrees as expected.
- Confirmed ~1 degree resolution

Underground Muon Detector (MD)





Site photo + CG image of MD by design company



- Total 4 units, each composes of 16 cells of 7.5mx7.5m.
- 2m soil overburden allows >1GeV muon penetration.
- Design finalizing with Bolivian construction design company.
- Construction of first MD starts in this year.

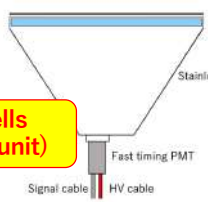
ALPA**QUITA** Array

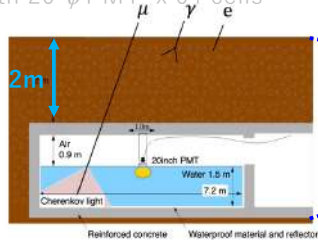
97 detectors

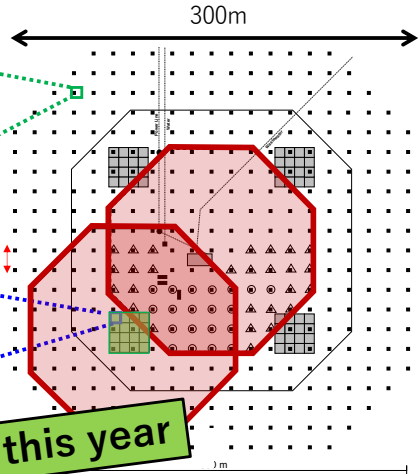
1. **Array coverage 82,800m²**
   = 401 x 1m² plastic scintillators

2. **Underground water Che… muon detector (MD) 37…**
   Soil over 2m (~16X_0)
   = 58m² with 20"ϕPMT x 64 cells

16 cells (1 MD unit)



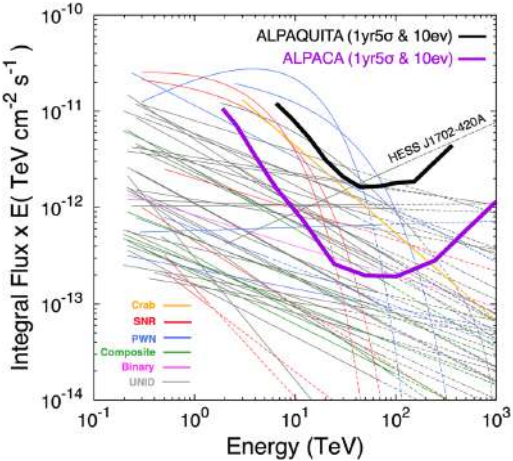




MD construction starts in this year

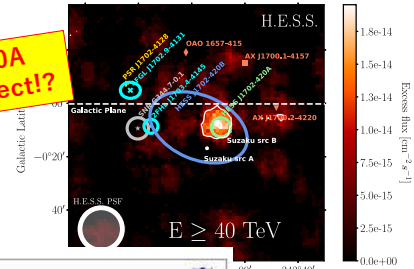
- ✓ Cosmic-ray BG…
- ✓ Angular resolut… Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

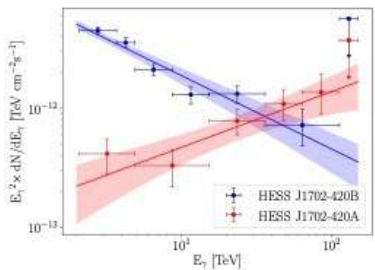
Sensitivities of ALPACA/ALPAQUITA



S.Kato et al., Experimental Astronomy (2021) 52:85-107

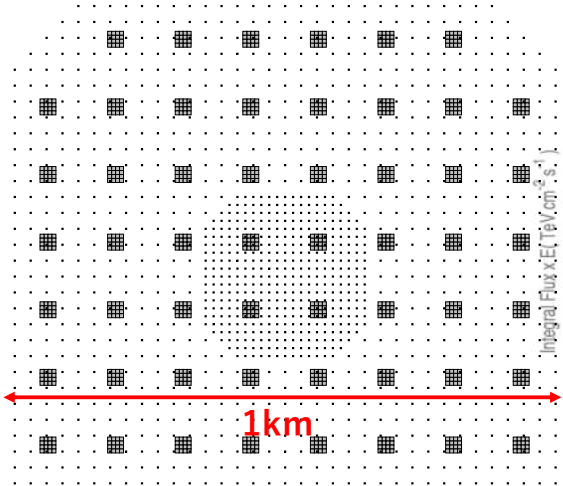
HESS J1702-420A
Mysterious object!?

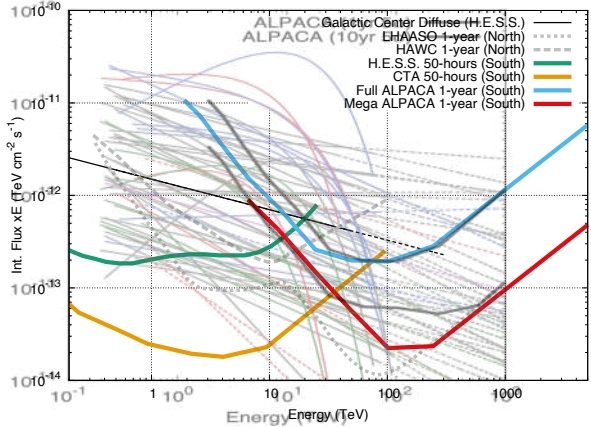




HESS Collaboration, A&A 653, A152 (2021)

Beyond PeV – Mega (m^2) ALPACA





Where is the highest energy accelerator in our Galaxy?

Summary

- **Sub-PeV gamma-ray astronomy opened a new window to reveal the highest energy CR accelerators in the Galaxy**
  - Successful experiments in the northern hemisphere
  - Southern sky is yet unexplored
- **ALPACA is a new air shower array constructed in Bolivia**
  - First sub-PeV observation in the southern hemisphere
  - Underground MD technic established by the Tibet AS γ collaboration
- **Observation started!**
  - Observation with 97 ground detectors, **ALPAQUITA**, is on going
    - Even-odd test and Moon's shadow confirm expected performance
  - Construction of the **first MD** will start in this year
  - Extension to 401 ground detectors + 4 MDs (full **ALPACA**) follows in 2025
  - Idea of **Mega ALPACA** to reach PeV is proposed

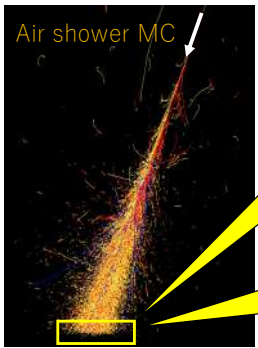
Backup

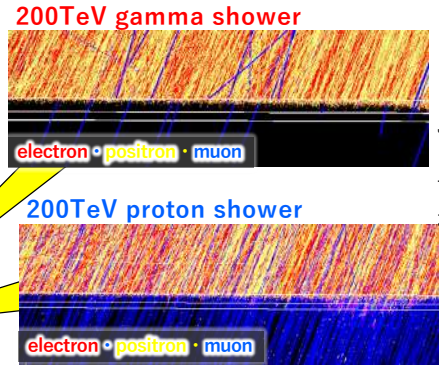
Status of the ALPACA air shower array to explore sub-PeV gamma-ray sky in the southern hemisphere

Takashi Sako (ICRR, the University of Tokyo)
for the ALPACA Collaboration

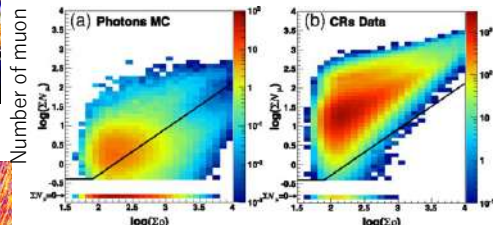
Particle ID

- BG is enormous hadronic CR showers
- Number of penetrating muons 2m underground is used for hadronic/EM shower separation
- Technic is established by the Tibet ASγ Collaboration

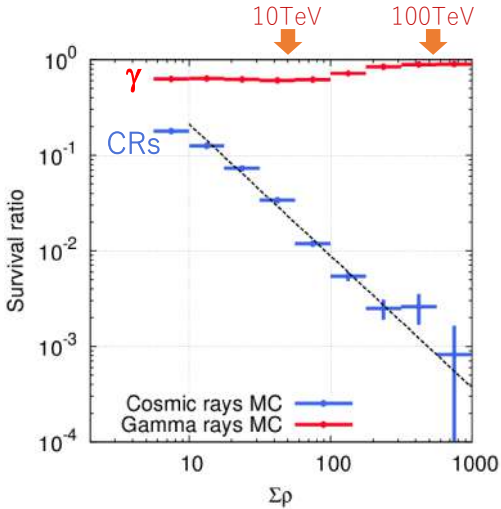




Crab analysis by Tibet AS γ Collaboration
PRL 123, 051101 (2019)

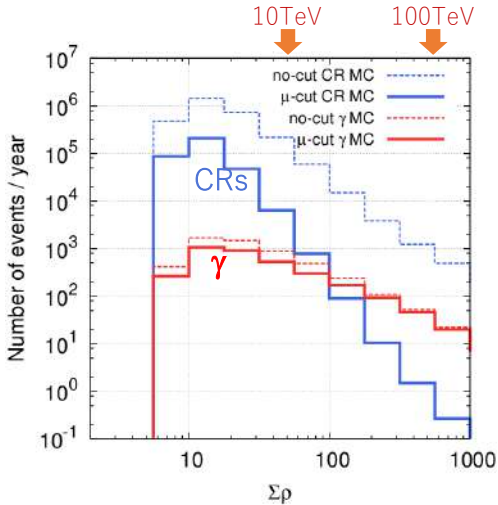


Shower size measured by the ground array



ALPACA full MC simulation
(AS 83000m^2 + MD 5400m^2)
Muon cut is optimized
assuming Crab-like source

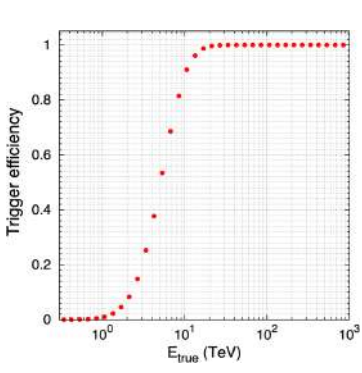
- ✓ Cosmic rays will be rejected by ~99.9% @100TeV
- ✓ Gamma rays will be retained over 90% @100TeV

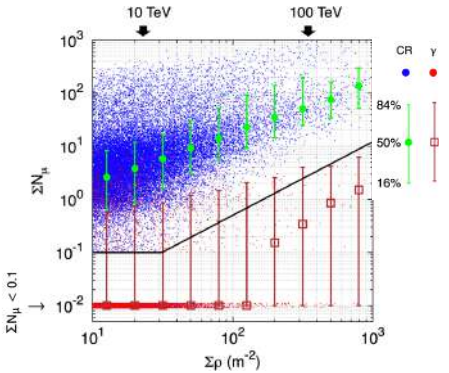


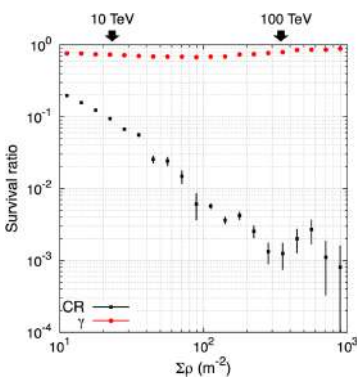
ALPACA full MC simulation
(AS 83000m^2 + MD 5400m^2)
Muon cut is optimized
assuming Crab-like source

- ✓ # of cosmic rays ~1 /year >100TeV
- ✓ # of gamma rays ~50 /year >100TeV

ALPAQUITA Performance







S.Kato et al., Experimental Astronomy (2021) 52:85-107

- CORSIKA (FLUKA + EPOS-LHC)+ GEANT4 simulation
- Trajectory of RXJ1713.7-3946 (23.4 deg zenith angle at culmination)
- Full efficiency > 20TeV
- 99.9% BG rejection while keeping 80% of photons @ 100TeV