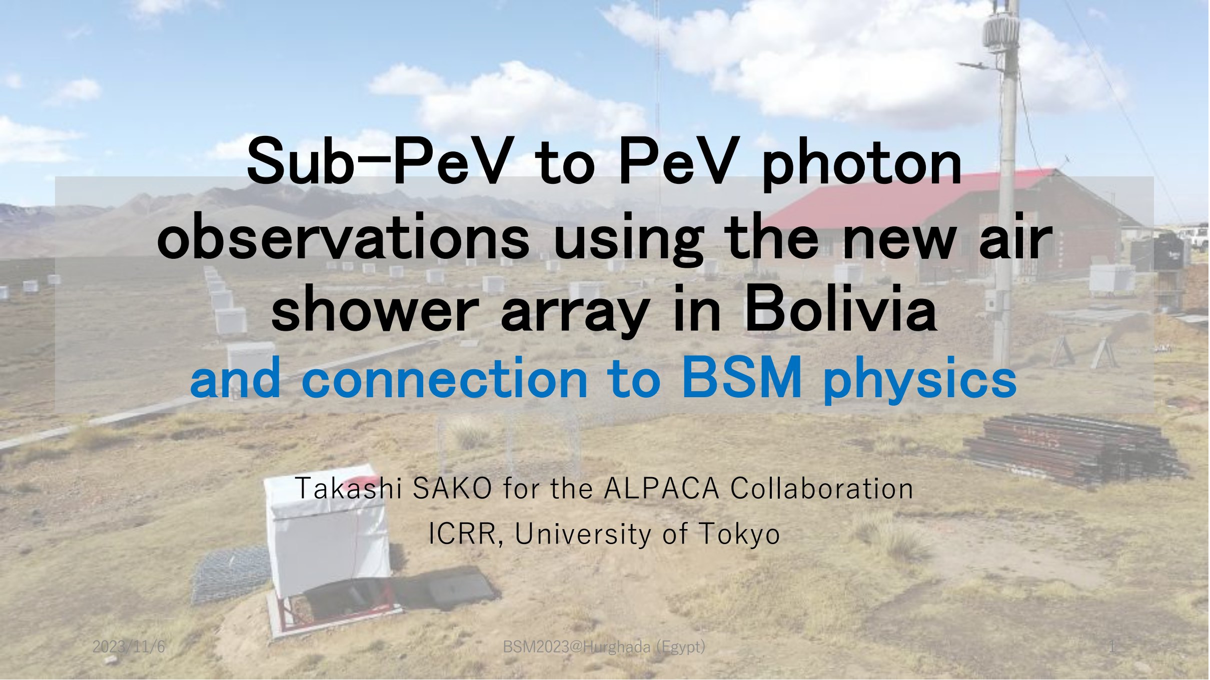
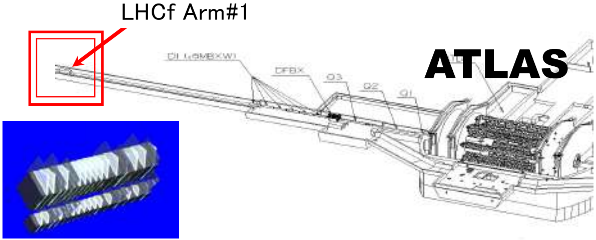


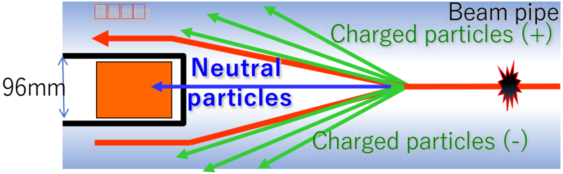
Sub-PeV to PeV photon observations using the new air shower array in Bolivia and connection to BSM physics

Takashi SAKO for the ALPACA Collaboration
ICRR, University of Tokyo

Highest energy photon in the laboratory

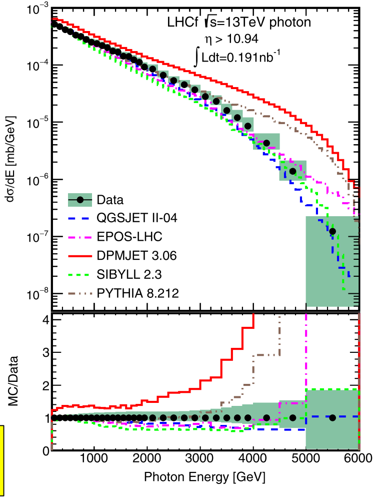
LHCf Collaboration, PLB 780 (2018) 233-239





Astrophysical photons provide a unique opportunity to study physics at PeV scale

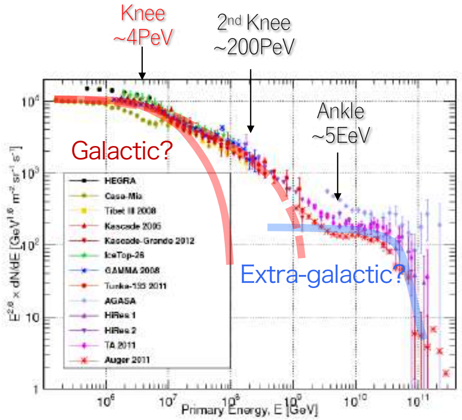
Photon production cross section at 0 degree of $\sqrt{s}$=13TeV $p+p$ collisions



Outline

- **Introduction to the Astrophysics in sub-PeV to PeV**
  - Origin of galactic cosmic rays
  - sub-PeV photon observations with air shower arrays
- **ALPACA**: first sub-PeV astrophysics in the southern hemisphere
- **BSM physics with sub-PeV to PeV photons**
  - LIV/ALP/DM/PBH…
- **Summary**

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

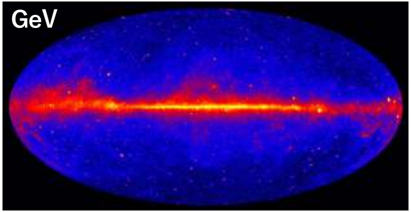
$$p(E) + ISM \rightarrow X + \pi^0 \rightarrow X + 2\gamma(\sim 0.1E)$$

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

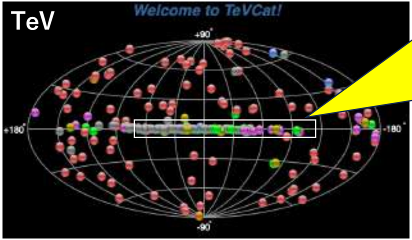
Especially in the **southern hemisphere**, near the Galactic center!!

- Where are the CR sources?
- What is the maximum acceleration energy (/nucleon)?
- How do they propagate in the galaxy?

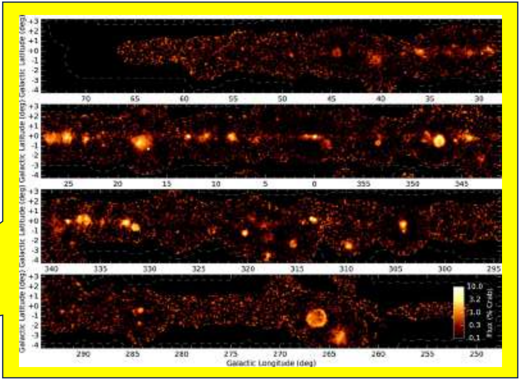
Gamma-ray sky



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



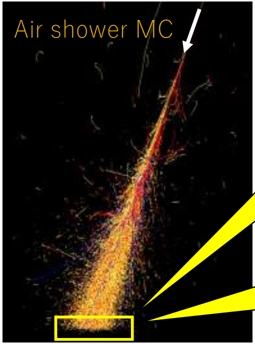
http://tevcat.uchicago.edu



HESS: A&A 612, A1 (2018)

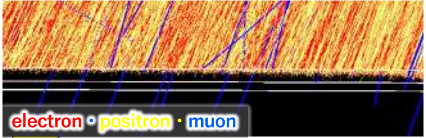
Air shower measurements and PID

- Air shower observation is essential to detect low flux sources
- 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

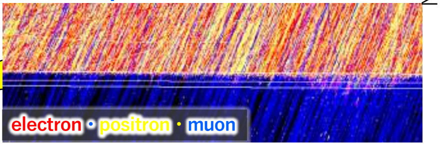


Ground surface

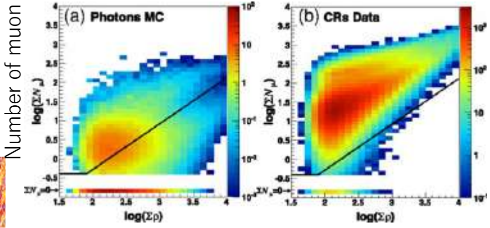
200TeV gamma shower



200TeV proton shower

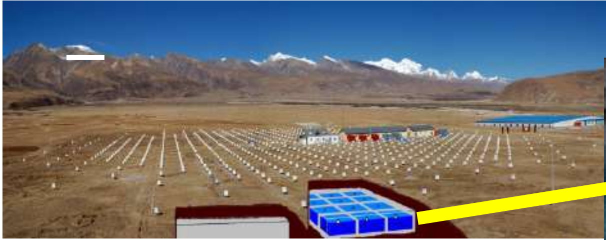


Crab analysis by Tibet AS γ Collaboration
PRL 123, 051101 (2019)

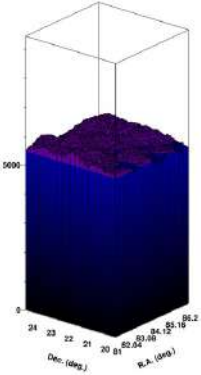


Shower size measured by the ground array

PID in the Tibet experiment

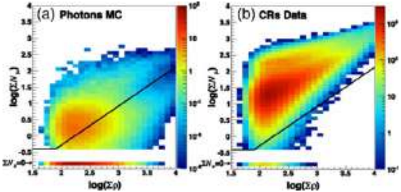


w/o PID

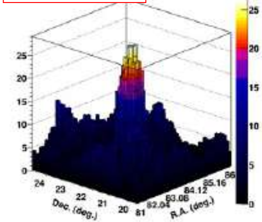


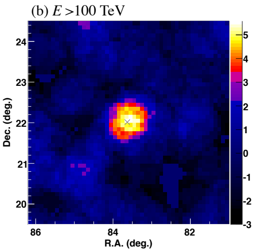
EM showers

Hadronic showers



w/ PID

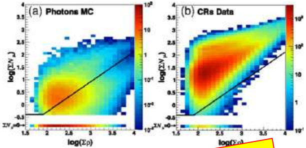


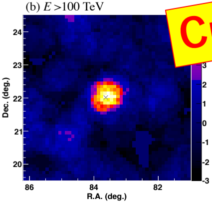


First >100TeV detection from Crab in 2019

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

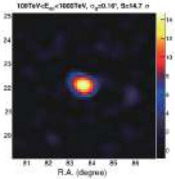
Dawn of sub-PeV gamma-ray astronomy



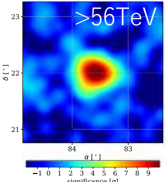


Crab

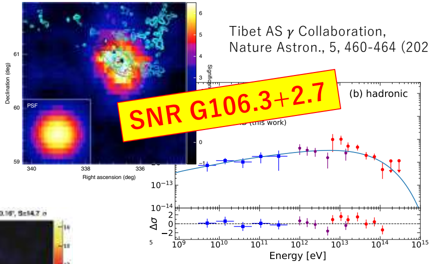
Tibet AS γ Collaboration,
PRL 123, 051101 (2019)



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

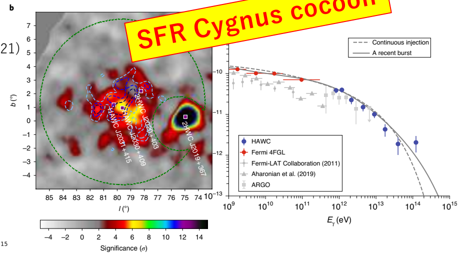


HAWC Collaboration,
ApJ 881:134 (2019)



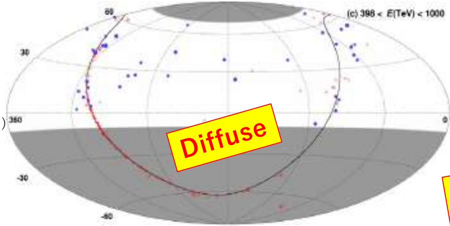
Tibet AS γ Collaboration,
Nature Astron., 5, 460-464 (2021)

SNR G106.3+2.7



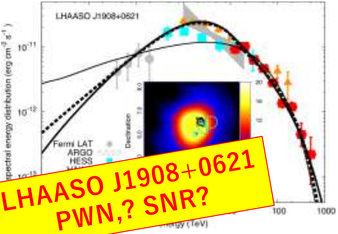
SFR Cygnus cocoon

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



Diffuse

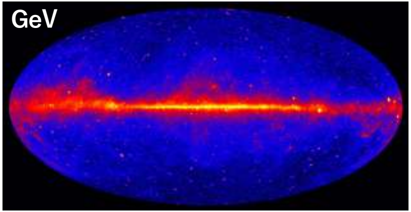
Tibet AS γ Collaboration, PRL 126, 141101 (2021)



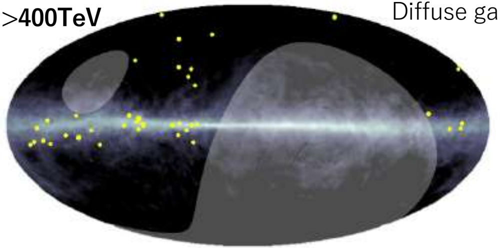
LHAASO J1908+0621
PWN,? SNR?

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

Gamma-ray sky

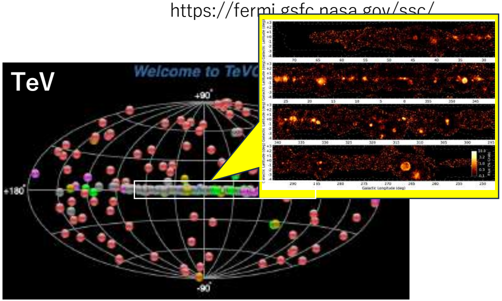


https://fermi.gsfc.nasa.gov/ssc/



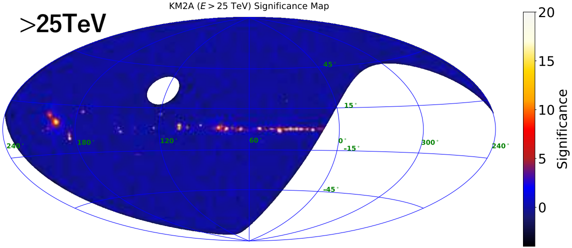
Diffuse gamma rays

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



http://tevcat.uchicago.edu

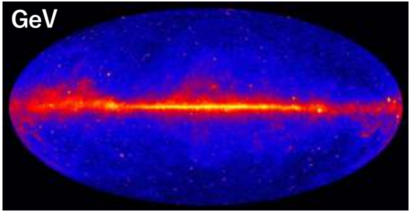
HESS: A&A 612, A1 (2018)



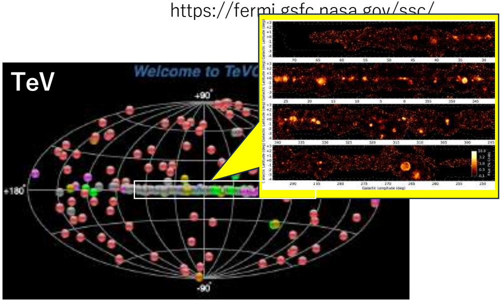
Gamma-ray sources

LHAASO Collaboration, arXiv:2305.1703v1 (2023)

Gamma-ray sky

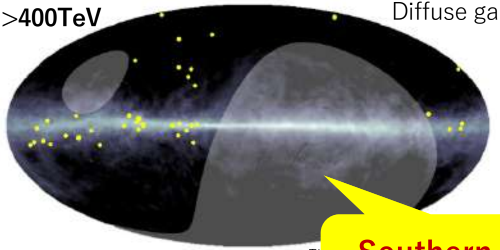


https://fermi.gsfc.nasa.gov/ssc/



http://tevcat.uchicago.edu

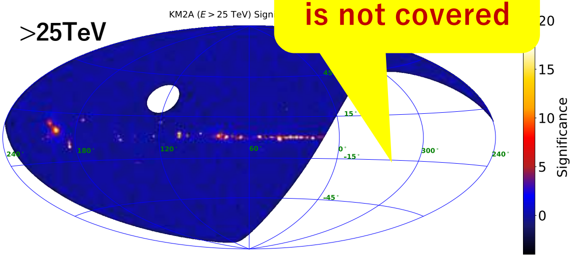
HESS: A&A 612, A1 (2018)



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.

ALPACA site
4740 m a.s.l.

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

La Paz

The ALPACA Collaboration

Japan Bolivia Mexico

M. Anzorena[1], D. Blanco[2], E. de la Fuente[3,4], K. Goto[5], Y. Hayashi[6], K. Hibino[7], N. Hotta[8], A. Jimenez-Meza[9], Y. Katayose[10], C. Kato[6], S. Kato[1], I. Kawahara[10], T. Kawashima[1], K. Kawata[1], T. Koi[11], H. Kojima[12], T. Makishima[10], Y. Masuda[6], S. Matsuhashi[10], M. Matsumoto[6], R. Mayta[13,14], P. Miranda[2], A. Mizuno[1], K. Munakata[6], Y. Nakamura[1], C. Nina[2], M. Nishizawa[15], R. Noguchi[10], S. Ogio[1], M. Ohnishi[1], S. Okukawa[10], A. Oshima[5,11], M. Raljevich[2], T. Saito[16], T. Sako[1], T. K. Sako[1], J. Salinas[2], T. Sasaki[7], T. Shibasaki[17], S. Shibata[12], A. Shiomi[17], M. A. Subieta Vasquez[2], N. Tajima[18], W. Takano[7], M. Takita[1], Y. Tameda[19], K. Tanaka[20], R. Ticona[2], I. Toledano-Juarez[21,22], H. Tsuchiya[23], Y. Tsunesada[13,14], S. Udo[7], R. Usui[10], R. I. Winkelmann[2], K. Yamazaki[11] and Y. Yokoe[1]

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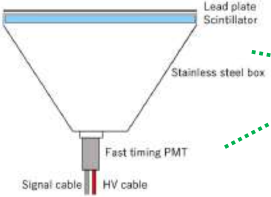
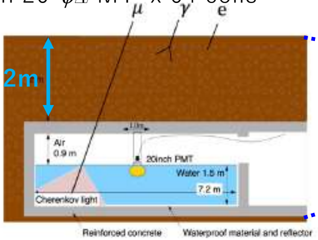
[23]Japan Atomic Energy Agency, Tokai-mura 319-1195, Japan.

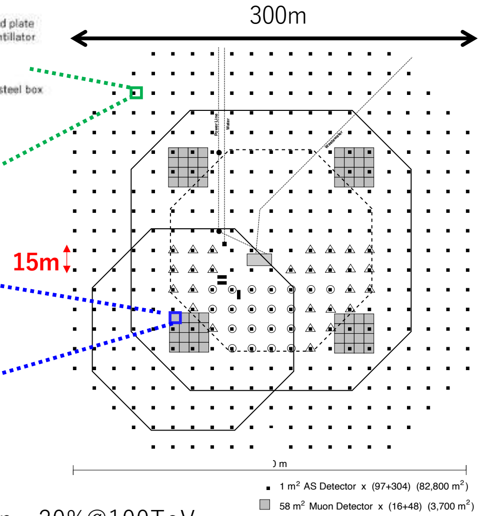
ALPACA Array

1. **Array coverage 82,800m^2**
   = 401 x 1m^2 plastic scintillators

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



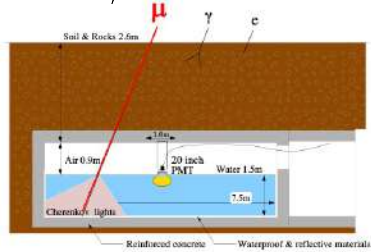


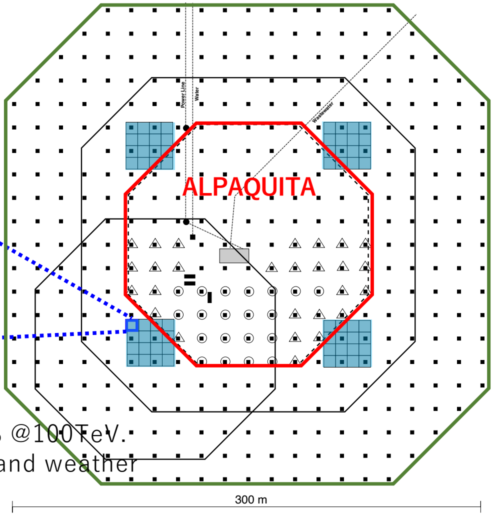


- ✓ Cosmic-ray BG rejection power >99.9% @100TeV.
- ✓ Angular resolution ~0.2° @100TeV, Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

ALPACA Project

1. **Air Shower (AS) Array ~83,000m^2**
   = 401 x 1m^2 Scintillation Detector
2. **Underground Muon Detector (MD) ~3600m^2**
   = Water-Cherenkov-Type, 2.5m overburden (~19X_0)
   56m^2 with 20”ϕPMT x 96 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

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

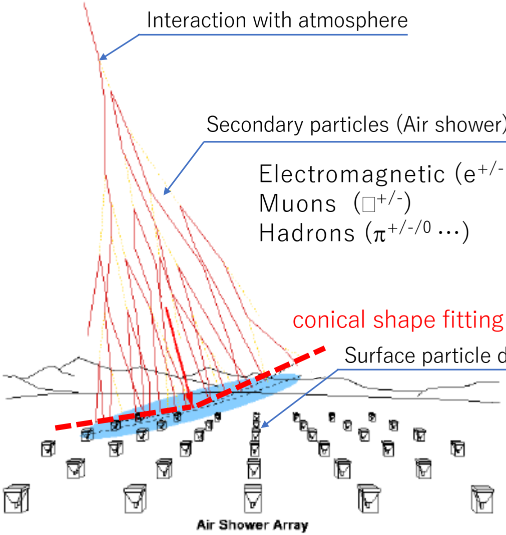
Air Shower Trigger Condition：

Any 4 detectors with >0.6 particles within 600ns
→ Air shower trigger rate ~280Hz
Cosmic-ray mode energy ~7 TeV

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

ALPAQUITA Air Shower Analysis

γ-ray/cosmic ray



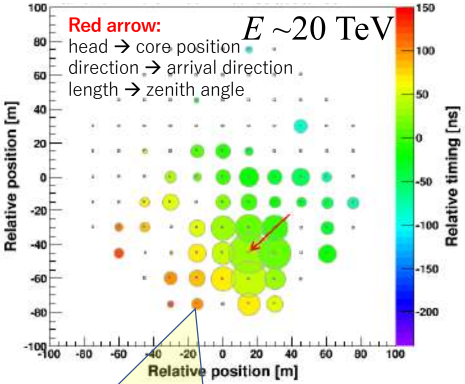
Interaction with atmosphere

Secondary particles (Air shower)

Electromagnetic ($e^{+/-}$, γ□
Muons (□$^{+/-}$)
Hadrons ($\pi^{+/-/0}$ …)

conical shape fitting

Surface particle detector

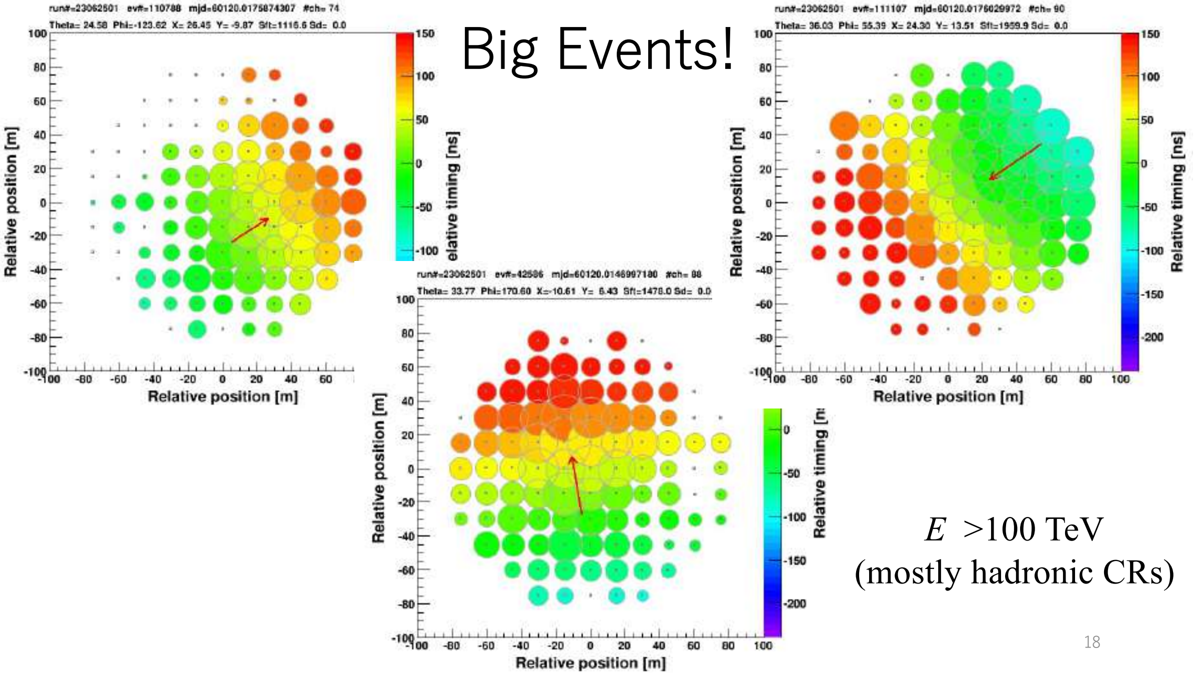


Red arrow:
head → core position
direction → arrival direction
length → zenith angle

E ~20 TeV

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

Big Events!



E >100 TeV
(mostly hadronic CRs)

Moon Shadow Detection

- April 7, 2023 – July 16, 2023 (83 days)
- With cable length correction

→ Successfully detected at 6.7σ

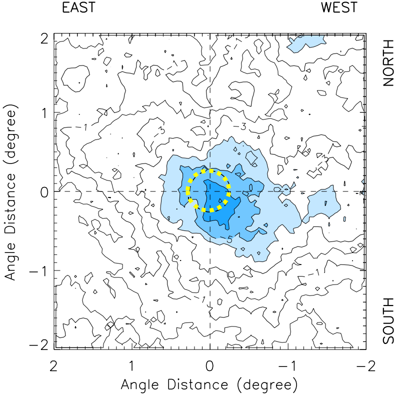
→ Westward shift ~0.2° as expected

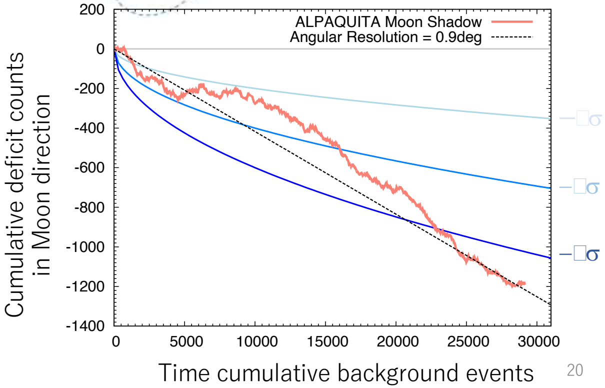
→ Moon shadow verified ~0.9° resolution

Displacement
by geomagnetic field

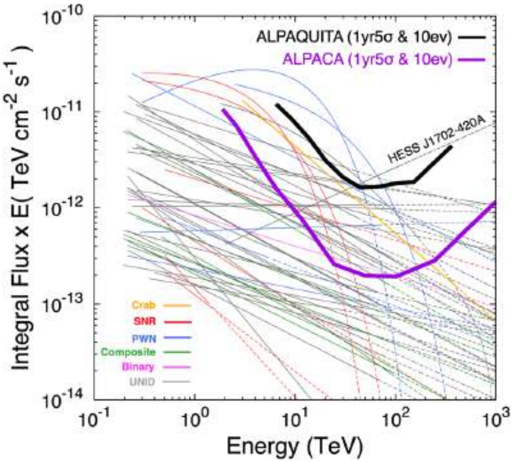
$$\Delta\theta \sim \frac{1.6^o}{E[\mathrm{TeV}]}$$

We can check
✓ Angular resolution
✓ Pointing accuracy
✓ Absolute energy scale

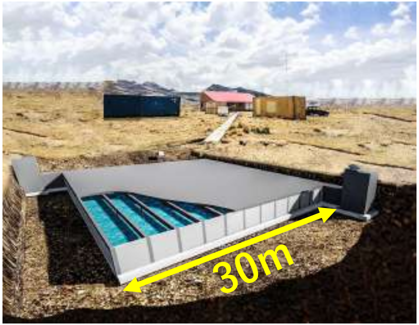




ALPAQUITA sensitivity



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



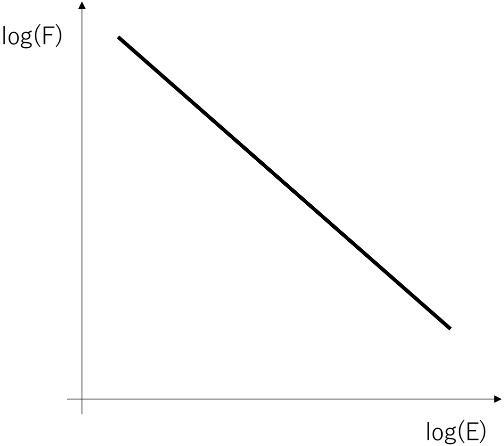
Site photo + CG image of MD by design company

- Construction of underground muon detector starts in 2024 => completion of ALPAQUITA
- Completion of full ALPACA in 2025
- A few bright TeV sources are within the ALPAQUITA 1yr sensitivity
- Half of the known southern TeV sources are within ALPACA 1yr sensitivity

Many sub-PeV sources will be discovered in the coming years.

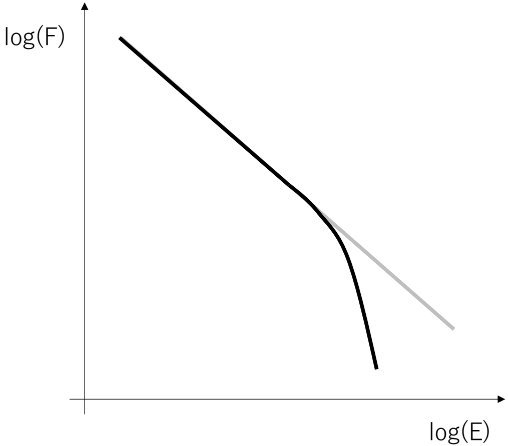
BSM physics
with sub-PeV to PeV photons

How Astro photons tell us BSM?



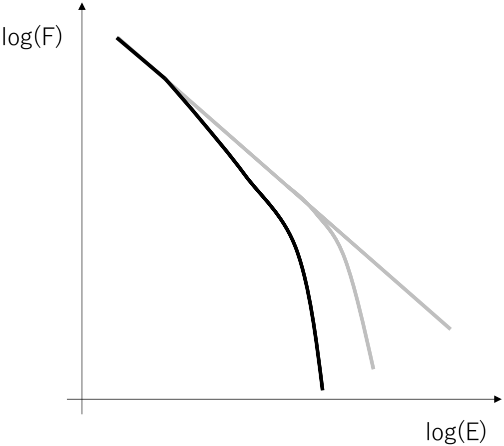
Astro photons have generally power law energy spectrum

How Astro photons tell us BSM?



High-energy cutoff is expected due to the acceleration limit

How Astro photons tell us BSM?



Protheroe & Meyer Phys. Let. B, 493, 1 (2000)

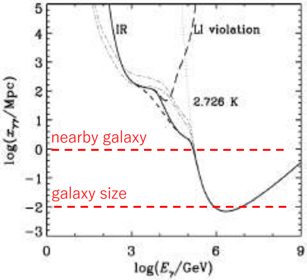
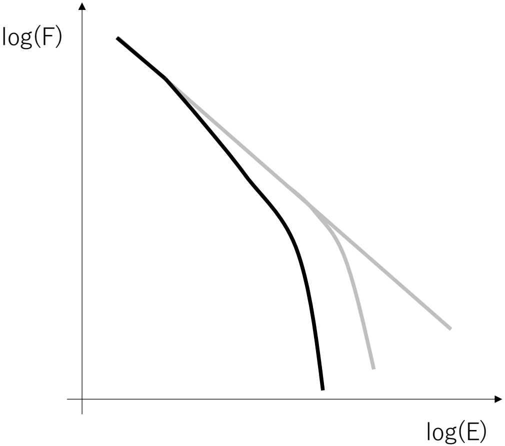


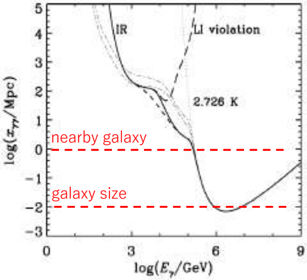
Fig. 2. Mean free path for photon–photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz invariance violation discussed in Section 4 is shown by the long dashed curve.

Photon-photon interaction leads more suppression at high energy (distance dependent)

How Astro photons tell us BSM?



Protheroe & Meyer Phys. Let. B, 493, 1 (2000)



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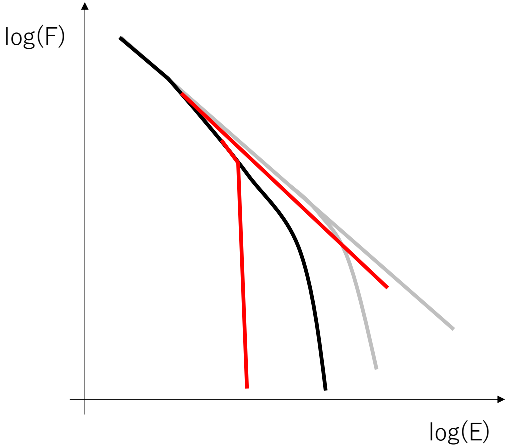
Test of QED at PeV

How Astro photons tell us BSM?



Protheroe & Meyer Phys. Let. B, 493, 1 (2000)

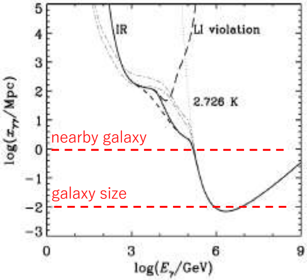


Fig. 2. Mean free path for photon–photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz invariance violation discussed in Section 4 is shown by the long dashed curve.

- Some BSM scenarios predict a sharp cut off
- Some BSM scenarios predict less attenuation

=> **Detection or non-detection of high-energy photon can constrain the BSM scenarios**

Lorentz Invariance Violation (LIV)

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

$$E_{\rm LIV}^{(n)} = \alpha_n^{-1/n}.$$

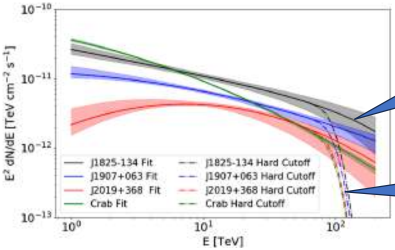
- Photon decay is predicted
- Photon decay predicts a mean free path and a sharp cutoff above threshold

$$\Gamma_{\gamma\to 3\gamma} = 5\times 10^{-14}\,\frac{E_\gamma^{19}}{m_e^8 E_{\rm LIV}^{(2)10}},$$

$$E_{\rm LIV}^{(2)} > 3.33\times 10^{19}\ {\rm eV}\left(\frac{L}{\rm kpc}\right)^{0.1}\left(\frac{E_\gamma}{\rm TeV}\right)^{1.9}.$$

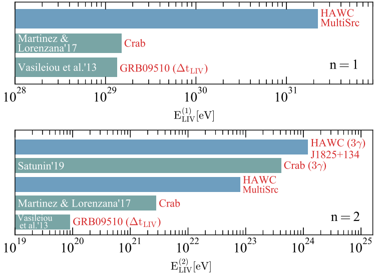
- E_{LIV} can be constrained by the actually observed photon energy E_γ and the distance to the source L

HAWC Collaboration, PRL 124, 131101 (2020)

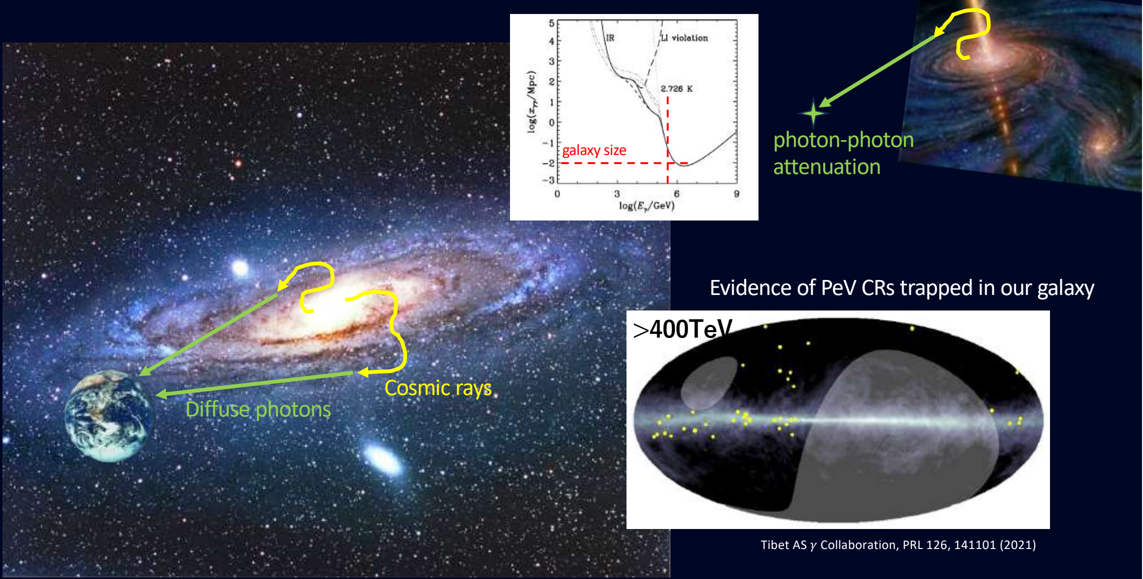


Measured spectrum

Sharp cutoff by LIV



Diffuse photons and BSM



Evidence of PeV CRs trapped in our galaxy

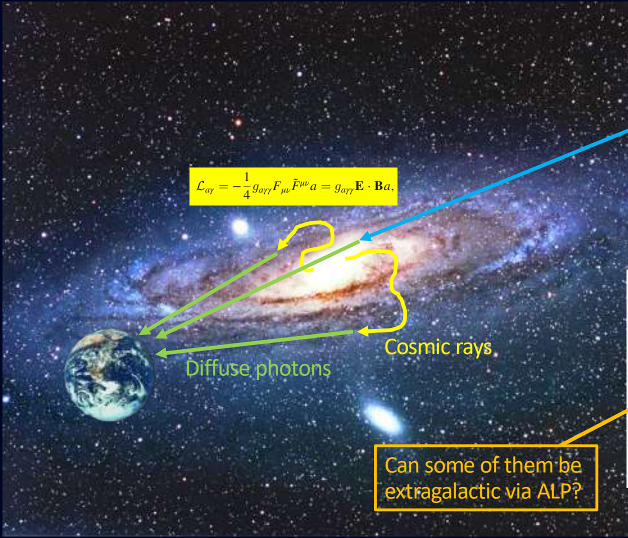
Tibet AS γ Collaboration, PRL 126, 141101 (2021)

Diffuse photons and Axion-Like Particle (ALP)

C. Eckner and F. Calore, PRD 106, 083020 (2022)

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}a,$$

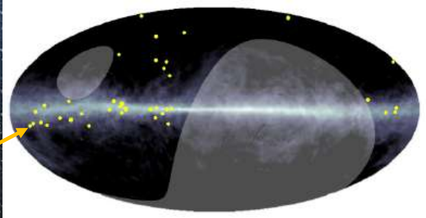
ALP



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}a,$$

Can some of them be extragalactic via ALP?

Evidence of PeV CRs trapped in our galaxy



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

Diffuse photons and ALP

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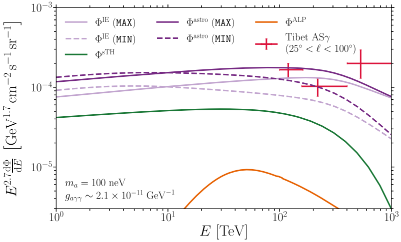
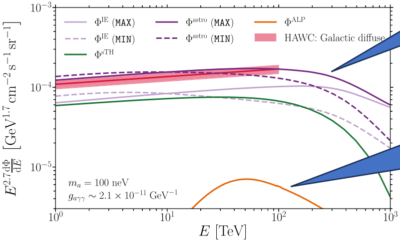
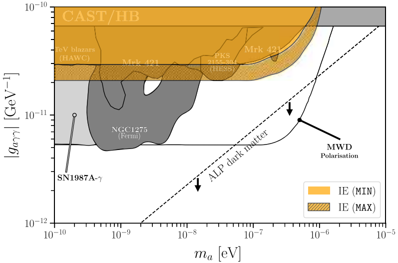




Astrophysical flux (model)

ALP flux (model) normalized by IceCube ν flux



- Interstellar Emission (IE; diffuse emission) and contribution from sub threshold sources (sTH) are modeled
- ALP contribution is modeled assuming star-forming galaxy sources, its evolution, normalization by IceCube ν flux with m_a and $g_{a\gamma\gamma}$ free parameters
- Limit in $g_{a\gamma\gamma}$ as a function of m_a

Summary

- **Astrophysics reach sub-PeV to PeV photons since 2019**
  - Tibet, HAWC and LHAASO
  - individual source and diffuse emission
  - all observatories in the northern hemisphere
- **First southern observatory ALPACA**
  - many sub-PeV to PeV sources will be revealed
  - some of them will be PeV CR accelerators
- **sub-PeV to PeV photons test new physics BSM**
  - LIV/ALP/DM(annihilation and decay)/PBH/…
  - ALPACA can provide *"PeV beams"* to test BSM scenarios