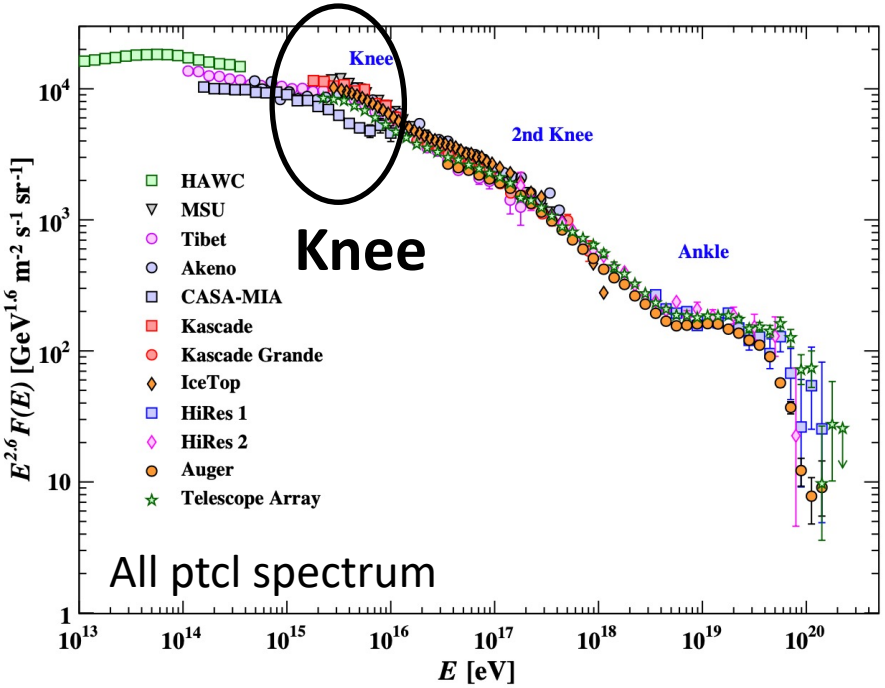
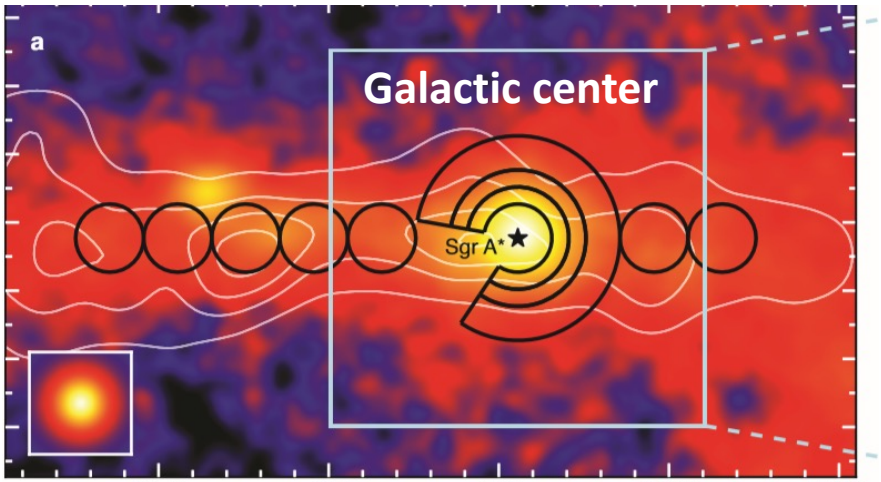
A simulation study on the performance of the ALPAQUITA experiment

(#857)

Kato Sei (ICRR, The Univ. of Tokyo)

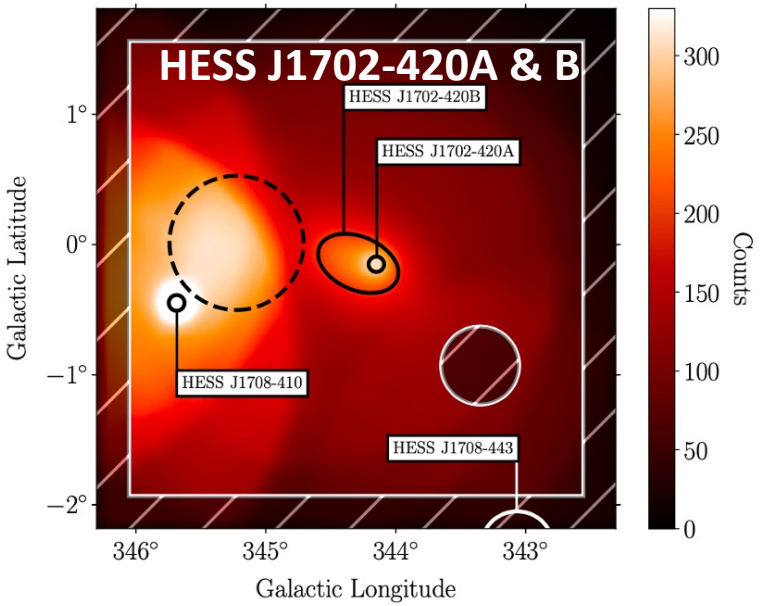
VHE Gamma-Ray Astronomy





$$p_{\mathrm{CR}} + p_{\mathrm{ISM}} \rightarrow p_{\mathrm{CR}} + p_{\mathrm{ISM}} + \pi^0 + \pi^{\pm}$$
$$\pi^0 \rightarrow \gamma + \gamma$$

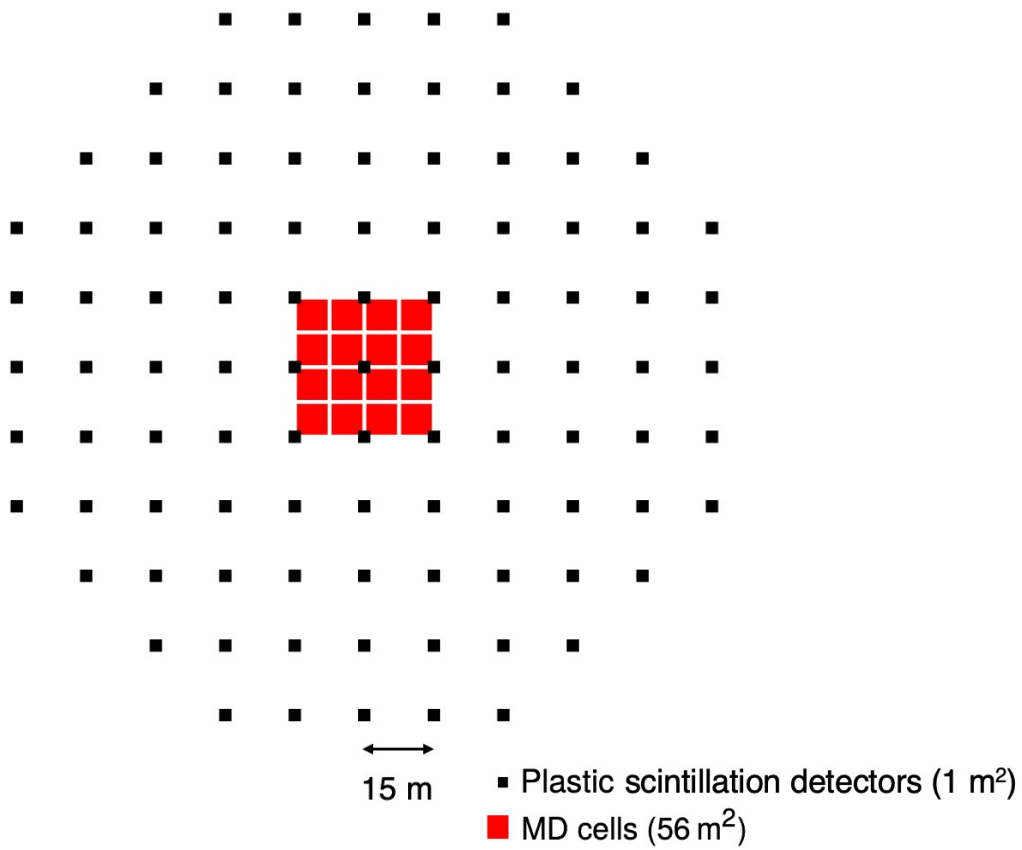
- VHE γ-ray astronomy > 100 TeV
- Many γ-ray sources & PeVatron candidates in the southern hemisphere



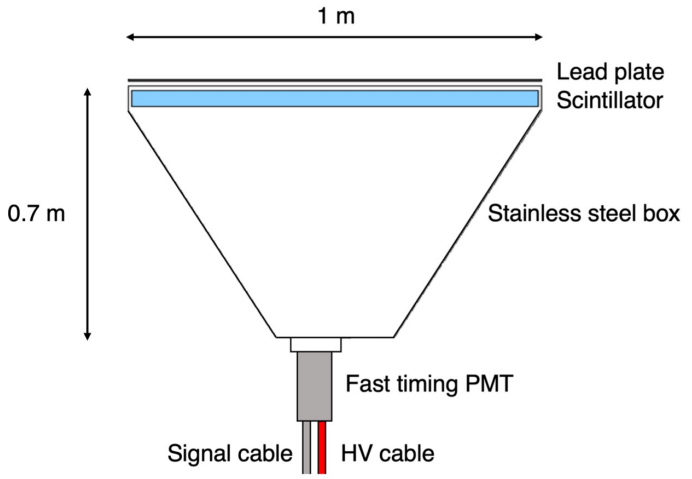
P.A. Zyla *et al.*, Prog. Theor. Exp. Phys. 2020, 083C01 (2020)
Nature 531, 476–479 (2016)
ArXiv:2106.06405v2 (2021)

The ALPAQUITA Experiment

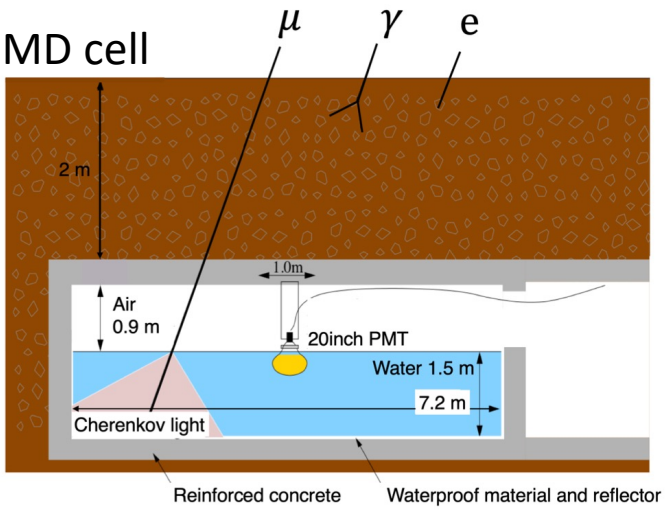
The prototype of the ALPACA experiment (See also T. Sako (#777) & Y. Yokoe (#947))



Scintillation detector



MD cell



- The prototype of ALPACA
- Mt. Chacaltaya plateau, Bolivia ($16°\ 23'\ \mathrm{S}, 68°\ 08'\ \mathrm{W}$)
- Elevation : 4,740 m ($572.4\ \mathrm{g/cm^2}$)
- AS array : 18,450 m² (97 detectors)
- Muon detector (MD) : 900 m² (16 cells)

Simulation Settings

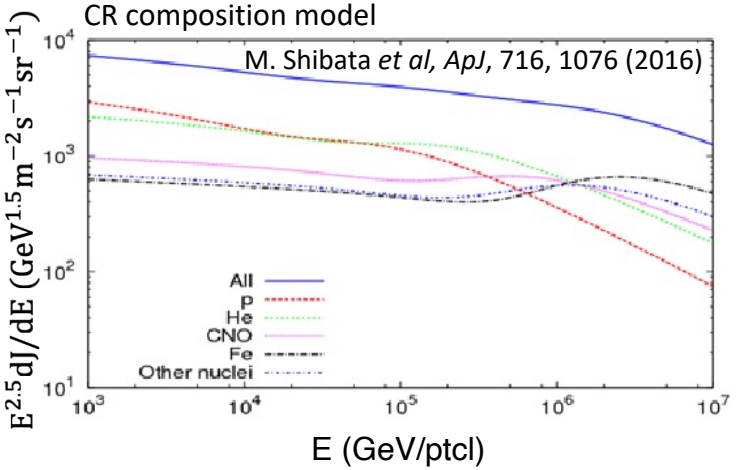
Corsika7.6400 & Geant4 v10.04.p02

D. Heck, J. Knapp, J. N. Capdevielle, G. Schats, T. Thouw, Report FZKA (1998) 6019
S. Agostinelli, et al., Nucl. Instrum. Methods Phys. Res. A 506 (2003) 250

Primary particle generation with Corsika

Primary particles	Gamma rays	Cosmic rays
Interaction model	EGS4	FLUKA & EPOS-LHC
Spectrum	$\propto E^{-2}$	Refer to the right
Path in the sky	RX J1713.7-3946 ($\theta_{\rm min} = 23.4°$)	
Simulation area	Circular region with a 300 m radius from the AS array center	

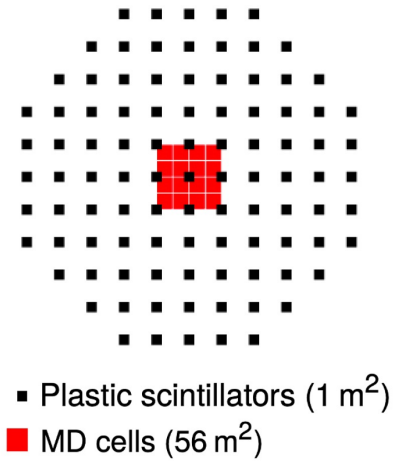
CR composition model



Detector response with Geant4

AS array: **Energy loss of shower particles in a plastic scintillator**

- 18,450 m^2 in total (consists of 97 scintillation detectors)
- 1 ptcl is defined as 9.4 MeV
- Trigger condition : 0.5 ptcl any 4 w/i 600 ns
- # of shower ptcls & detection timing are recorded

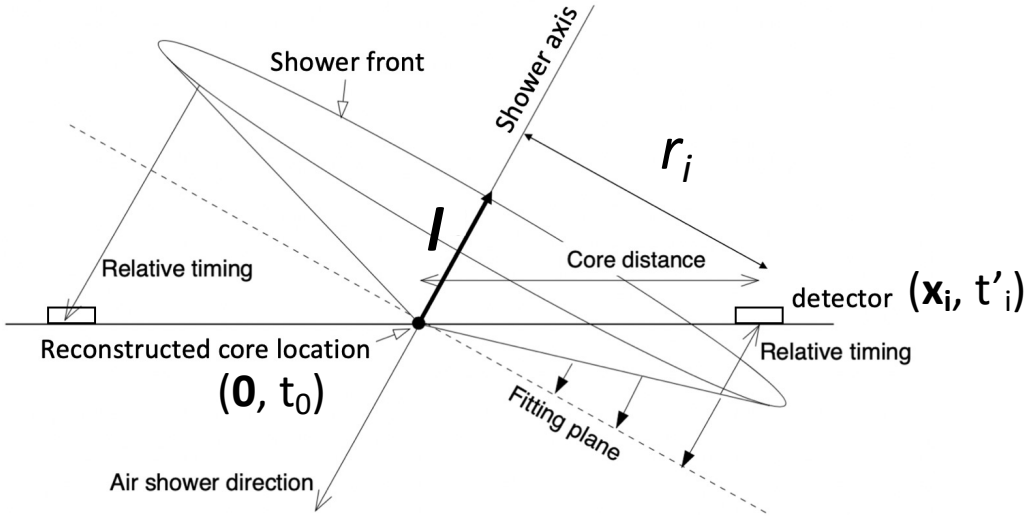


Muon detector (MD): **Cherenkov light emission of shower particles**

- 900 m^2 in total
- 2 m Soil overburden: 16 r. l. => muons w/ E $\gtrsim$ 1.2 GeV can reach MD

Reconstruction of Shower Core Position & Direction

- Shower core position: $\left(\frac{\sum_i \rho_i^{1.5} x_i}{\sum_i \rho_i^{1.5}}, \frac{\sum_i \rho_i^{1.5} y_i}{\sum_i \rho_i^{1.5}}\right)$ (ρ_i: number density of particles recorded with the i-th scintillation detector)
- Direction:
  1. Assume that a shower front is in a conical shape with a slope b $(\mathrm{ns/m})$ and modify the detection timing of the i-th scintillation detector as
  $$t_i' = t_i - b\, r_i \ .$$
  2. Calculate "residual error" χ as
  $$\chi^2 = \sum_i w_i \left(\boldsymbol{l} \cdot \boldsymbol{x}_i + c(t_i' - t_0)\right)^2, \quad \left(w_i = \frac{\rho_i}{\sum_j \rho_j}\right).$$
  3. Iterate 1. & 2. and finally determine $\boldsymbol{l}$.



Energy Reconstruction

Kamata, K., Nishimura, J., Prog. Theor. Phys. ***6****, 93 (1958)*
Greisen, K.,Ann. Rev. Nucl. Part. Sci. ***10****, 63 (1960)*
K. Kawata et al., Exp Astron 44, 1 (2017)

#Det is defined as # of detectors used for the direction reconstruction

1. #Det < 30:

   Estimate energies with $\Sigma\rho$ and r_{rec}

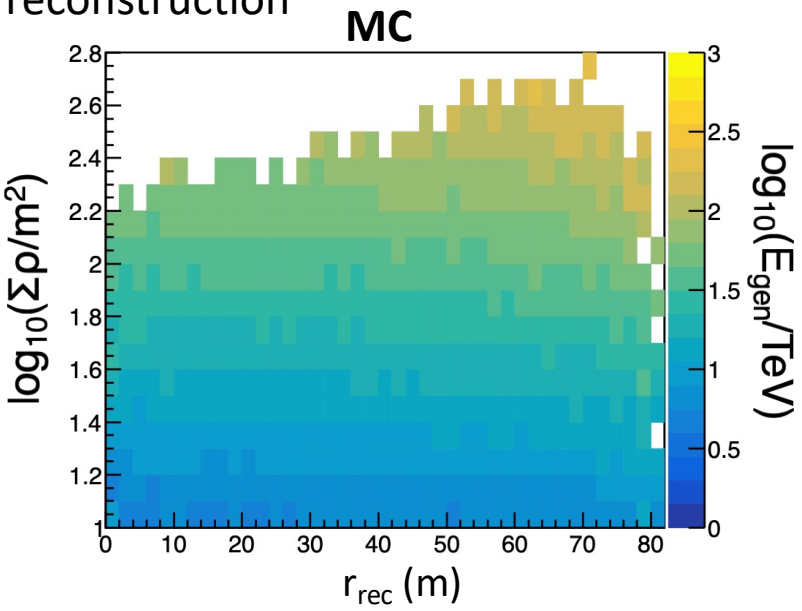
   where

   $\Sigma\rho = \Sigma_i \rho_i - \rho_{max}$

   (ρ_i: # density of particles recorded w/ the i-th detector)

   and

   r_{rec} : distance w/ the array center & the reconstructed shower core position



2. #Det >= 30:

   Fit a lateral distribution of ptcl density w/ NKG function;

$$S(r)\ (\text{ptcls/m}^2) = \frac{N_e}{r_m^2} \frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r}{r_m}\right)^{s-2} \left(1+\frac{r}{r_m}\right)^{s-4.5}$$

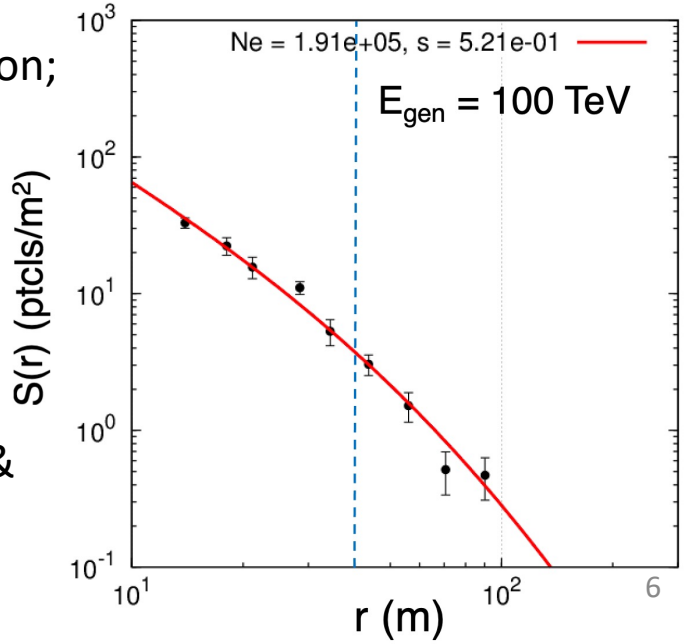
   where

   N_e: total # of shower electrons,

   s: shower age

   r_m(=125 m): Molière length @ the ALPAQUITA site, &

   r: distance from a shower axis



S(r=40m) is adopted in this study.

Event Selection Criteria

For AS array performance

1. 0.8 ptcl any 4
2. The detector that records the largest ptcl density is inside the inner area
3. Residual error $\chi < 1$ m
4. Reconstructed age < 1.3 for events w/ energies estimated w/ S40
5. Reconstructed zenith angle < 40°

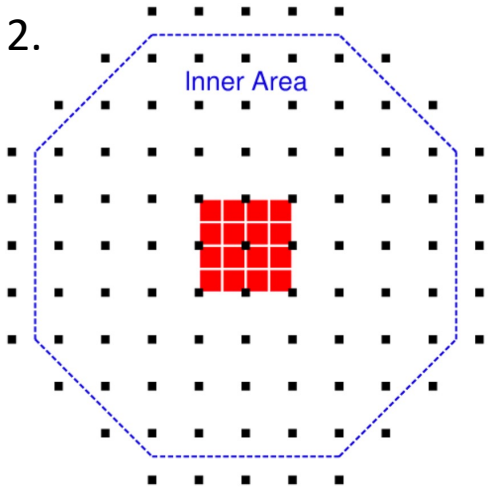
For the analysis using the muon detector (sensitivity to point gamma-ray sources)

6. Inside the analysis window with a angular radius of

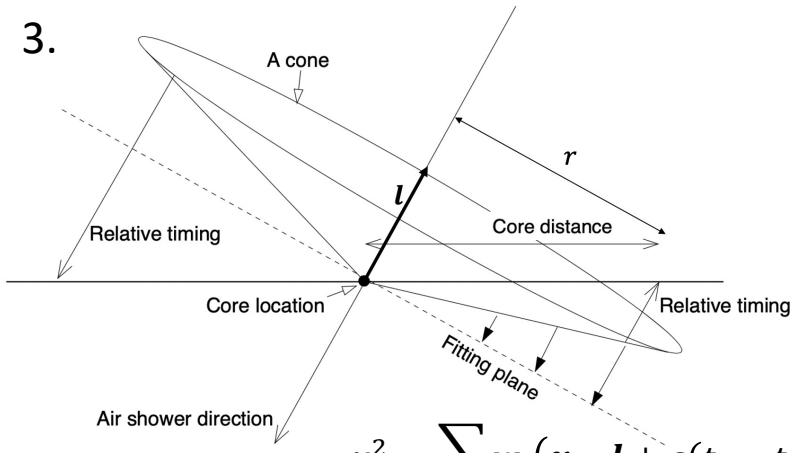
$$r = \begin{cases} 1.5^\circ & (\Sigma\rho < 15\,\mathrm{m}^{-2}), \\ \dfrac{5.8^\circ}{\sqrt{\Sigma\rho/\mathrm{m}^{-2}}} & (15\,\mathrm{m}^{-2} < \Sigma\rho < 135\,\mathrm{m}^{-2}), \text{ and} \\ 0.5^\circ & (135\,\mathrm{m}^{-2} < \Sigma\rho). \end{cases}$$

$\Sigma\rho = \Sigma_i \rho_i - \rho_{max}$

2.



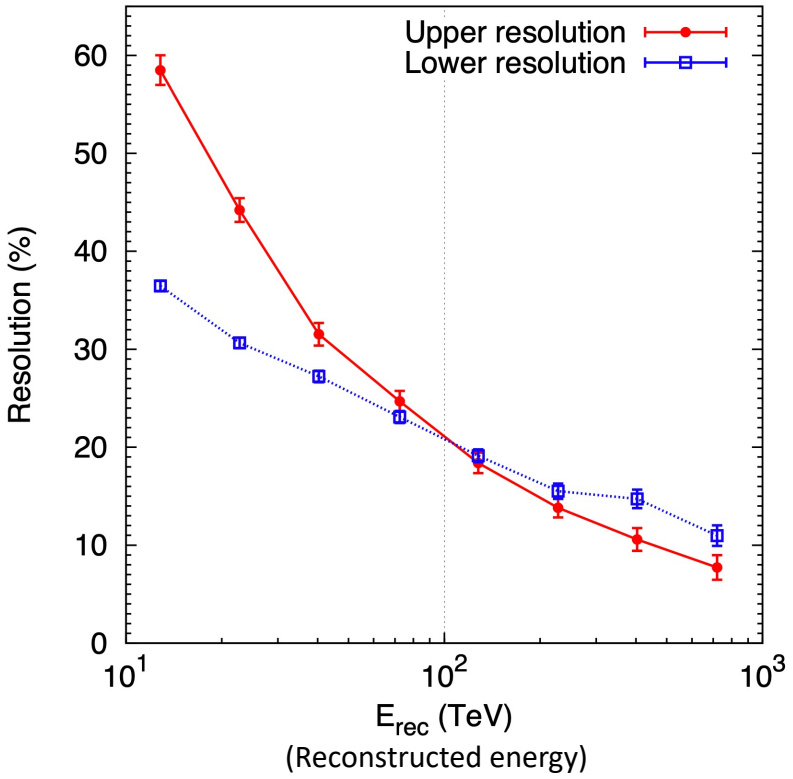
3.

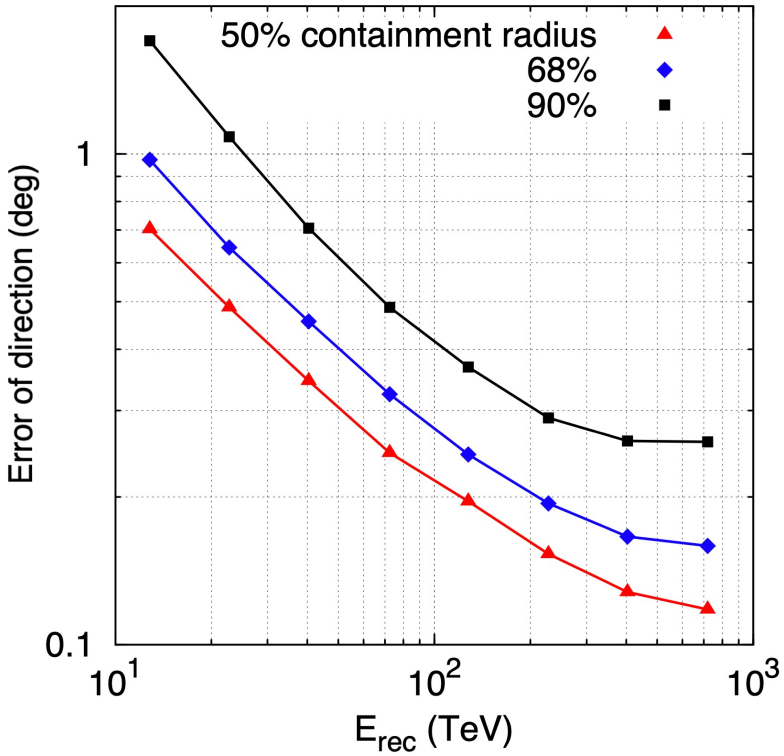


$$\chi^2 = \sum_i w_i \left(\boldsymbol{x}_i \cdot \boldsymbol{l} + c(t_i - t_0)\right)^2$$

Energy & Angular Resolutions for Gamms Rays

Performance to gamma rays following a PL spectrum w/ index=2.5





E_{rec} (TeV)	10 TeV	100 TeV
Energy resolution	$+59\% - 37\%$	$+21\% - 21\%$
Angular resolution	$^*0.70^\circ$	0.21°

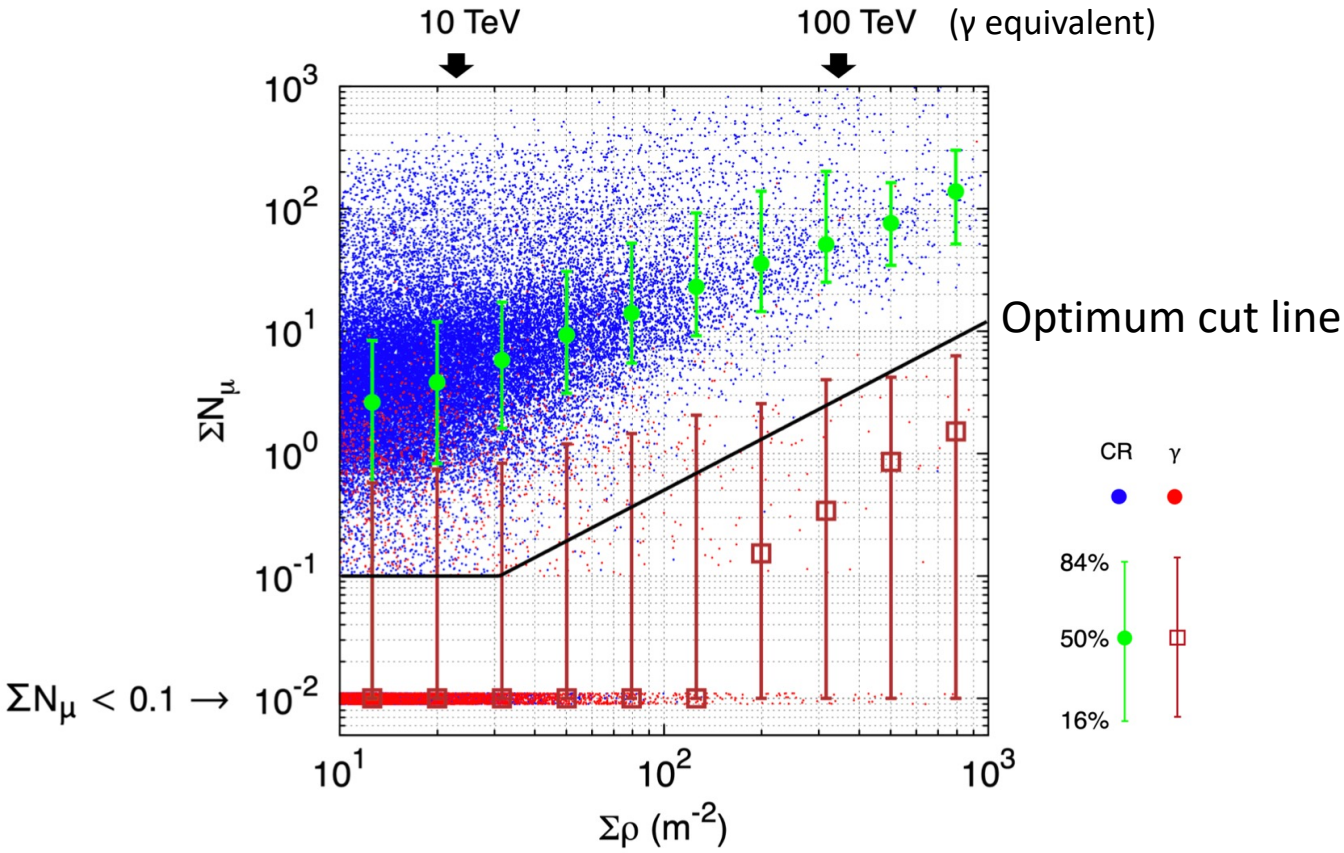
* 50% containment radius

Event Selection Criterion Using the Muon Detector (MD)

To maximize the detection significance of signal γ rays

ΣN_μ : Total number of muons detected with MD

(1muon is defined as 24 photoelectron for all MD cells)

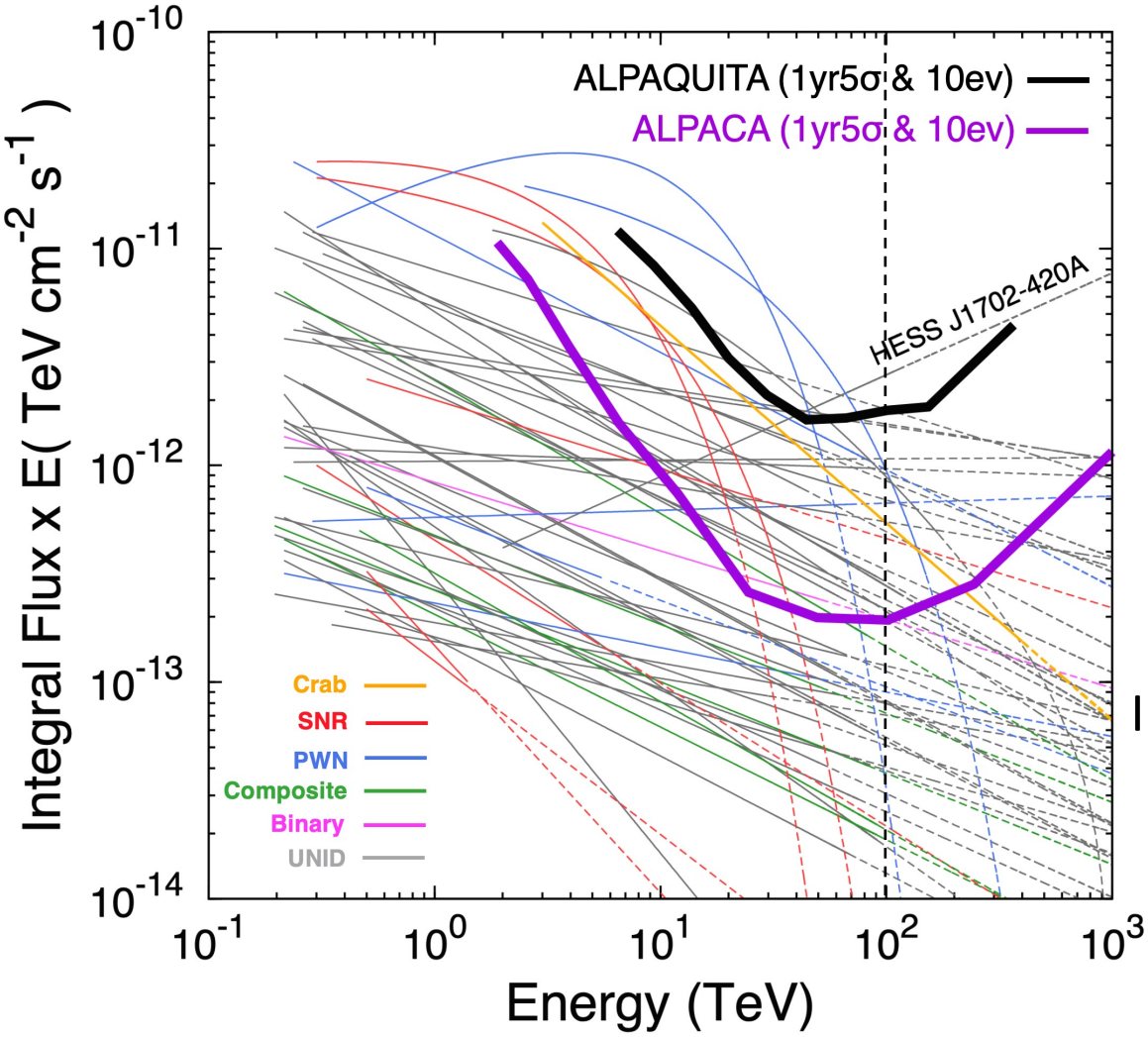


@ E > 100 TeV (γ equivalent), Survival ratio of γ : $\simeq 80\%$

Rejection power of BGCR : $\simeq 99.9\%$

# of CR events < 1 event/yr (for point src.)

ALPAQUITA Sensitivity to Gamma-Ray Point Sources



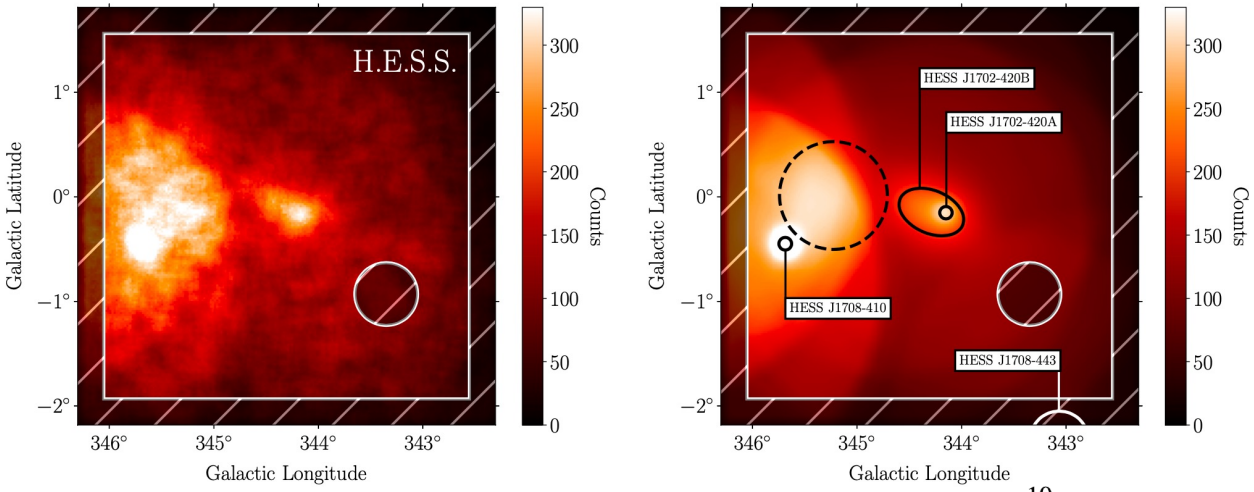
In 1 calendar year obs.,
5 sources byd O(10 TeV) &
HESS J1702-420A byd 100 TeV

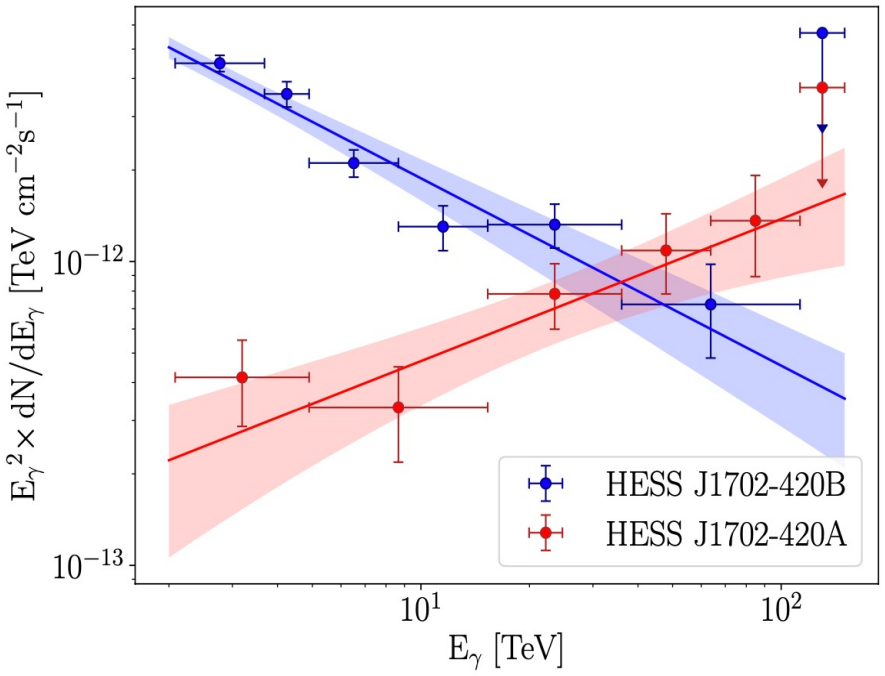
*For the energy spectra, absorption of γ-ray due to the interstellar radiation filed is not considered.

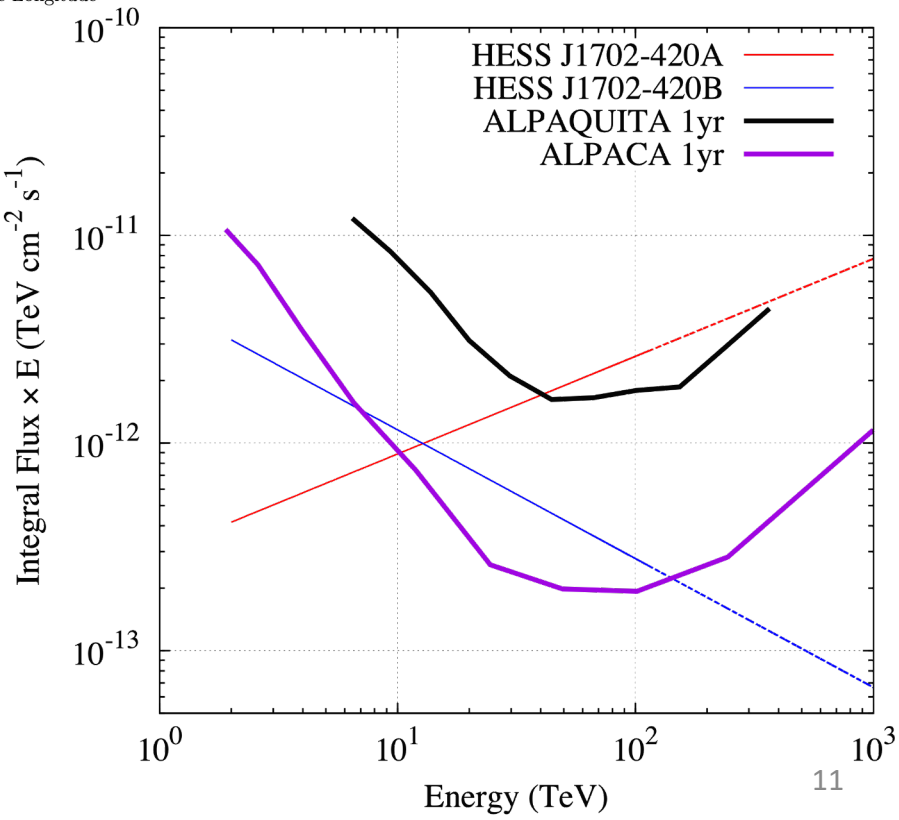
*The spectra are cited from *A&A 612, A1 (2018)* and *PRL 124.021102 (2020)*

HESS J1702-420A: Dark Accelerator

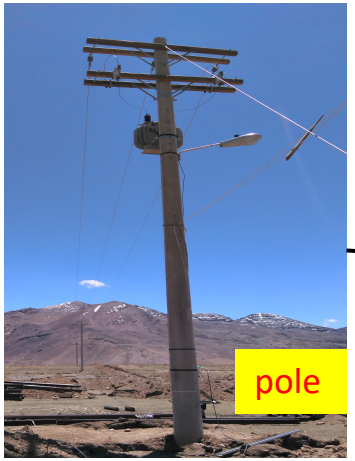
(ArXiv:2106.06405v2)

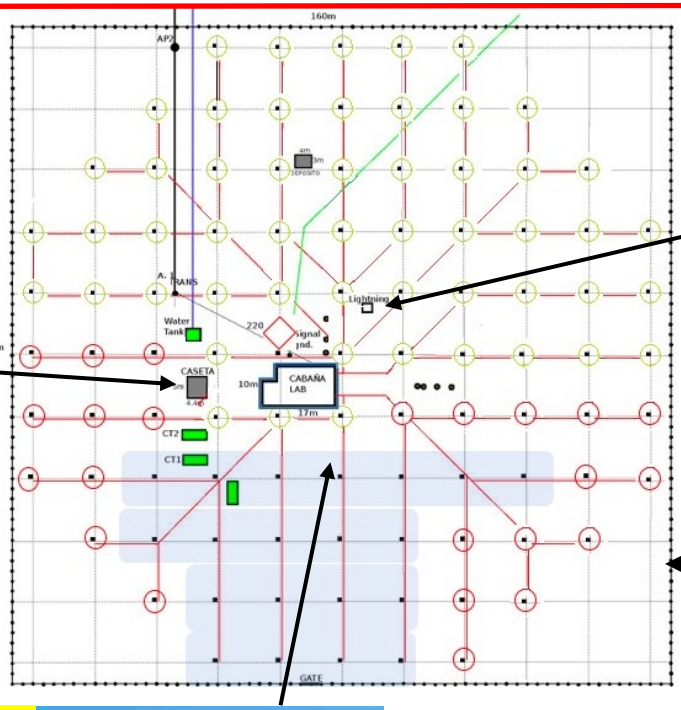


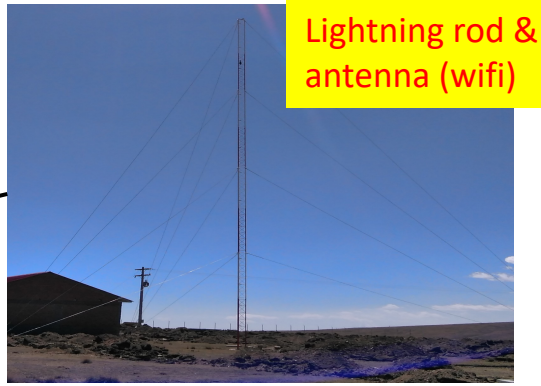




ALPAQUITA Construction (Current Status)


pole




Lightning rod & antenna (wifi)


fence


Electronics hut & detectors


Dwells for cables

For further information, go to **T. Sako's talk (#777)**

Summary

ALPAQUITA: The prototype of ALPACA

- Elevation: 4,740 m (572.4g/cm^2)
- AS array: 18,450 m^2 (97 scintillation detectors)
- MD total: 900 m^2
- Main motivation: Experimental verification & γ-ray astronomy byd. 100 TeV

AS array performance (for 100TeV γ)

- Energy resolution: +21% & -27%
- Angular resolution: $\simeq 0.2^\circ$
- Detection area: $\simeq$ 12,600 m^2 (Inner area geometrical)

MD array performance (for 100TeV γ-equivalent)

- Survival ratio of gamma rays: $\simeq$ 80%
- Rejection power of BGCRs: $\simeq$ 99.9%

Source Detectability (w/ one calendar year obs.)

- 5 sources byd. O(10 TeV)
- HESS J1702-420A byd. 100 TeV

=> Enable us to discuss a hot topic