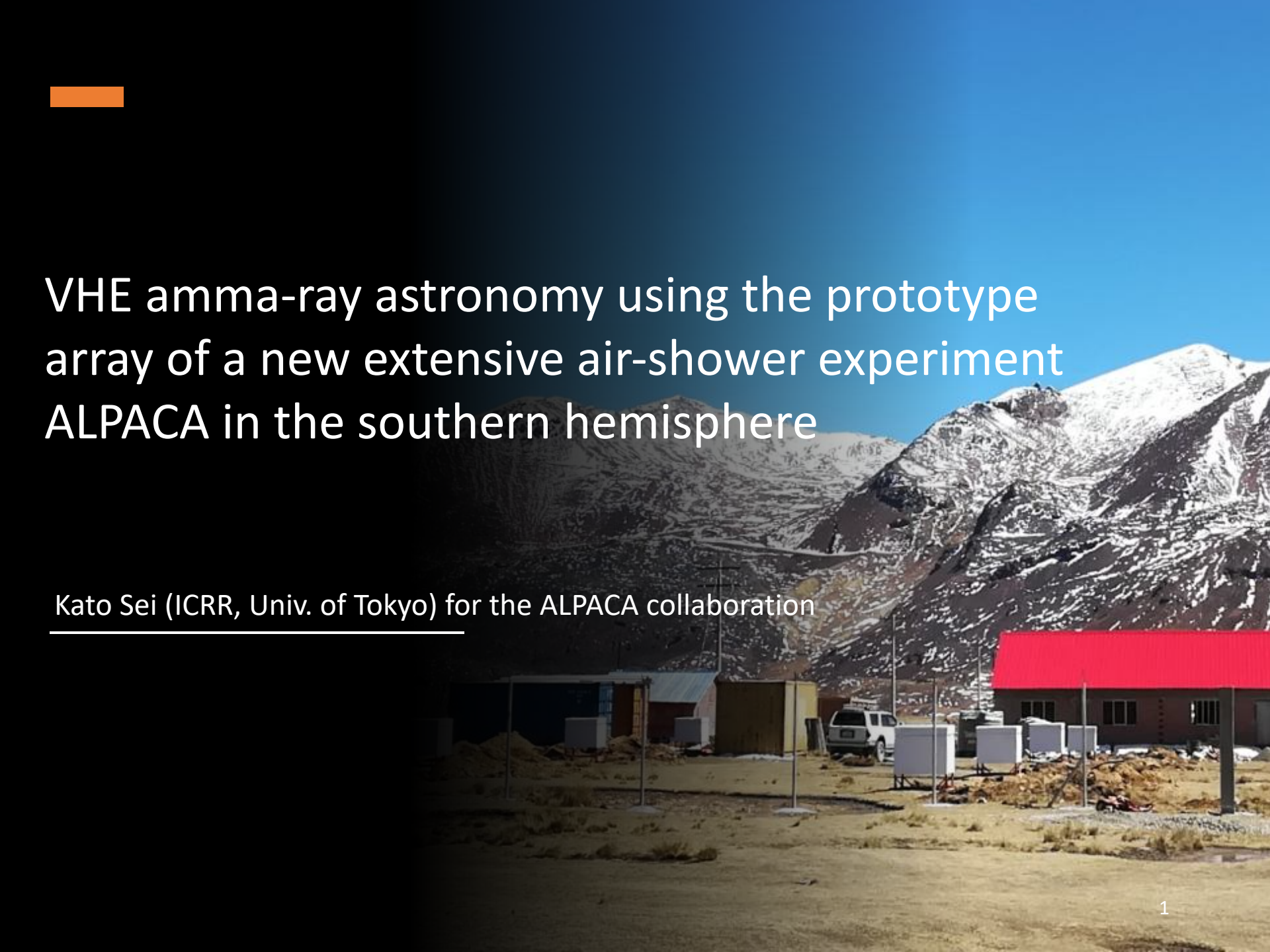
VHE amma-ray astronomy using the prototype array of a new extensive air-shower experiment ALPACA in the southern hemisphere

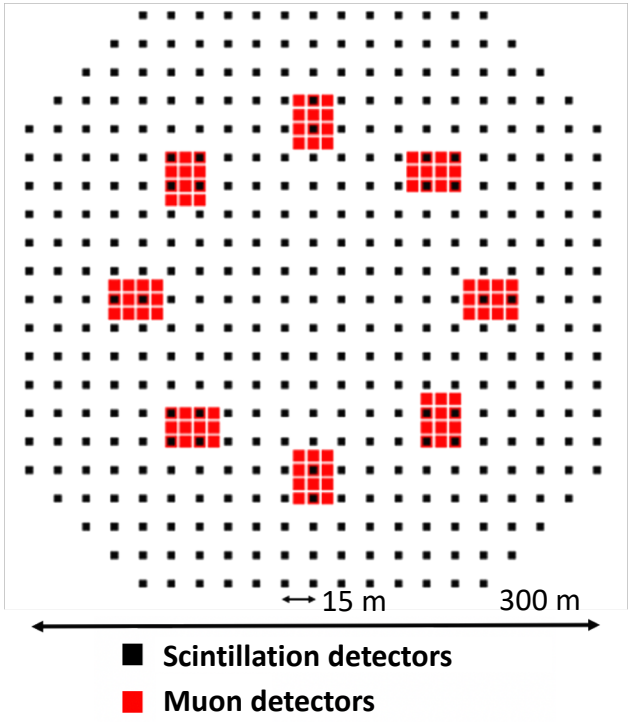
Kato Sei (ICRR, Univ. of Tokyo) for the ALPACA collaboration

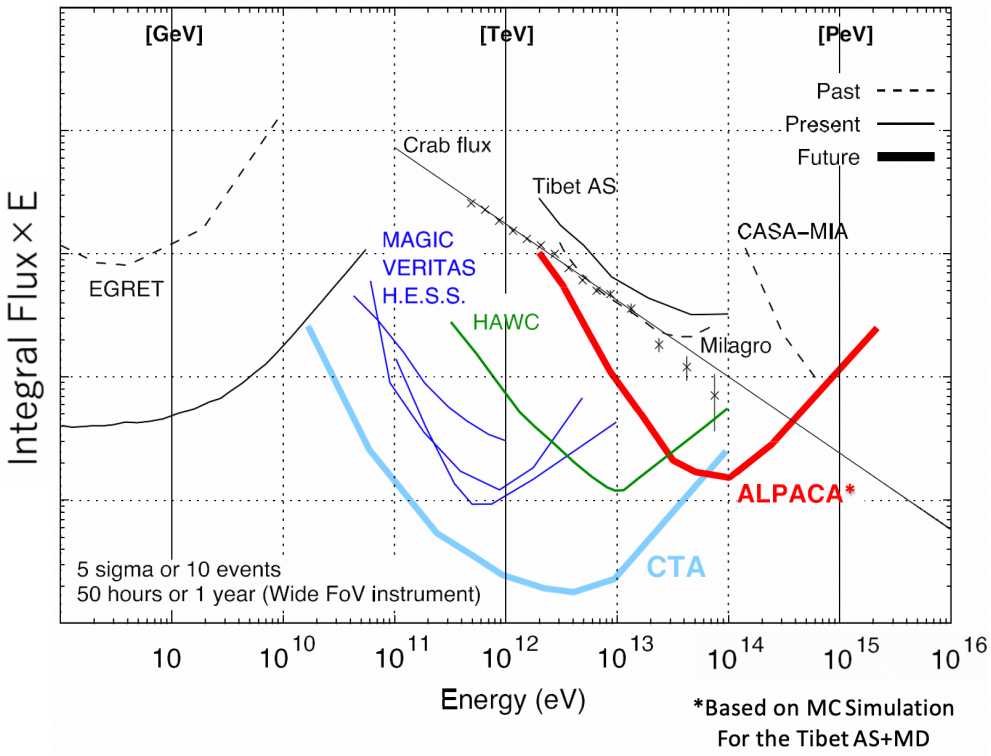


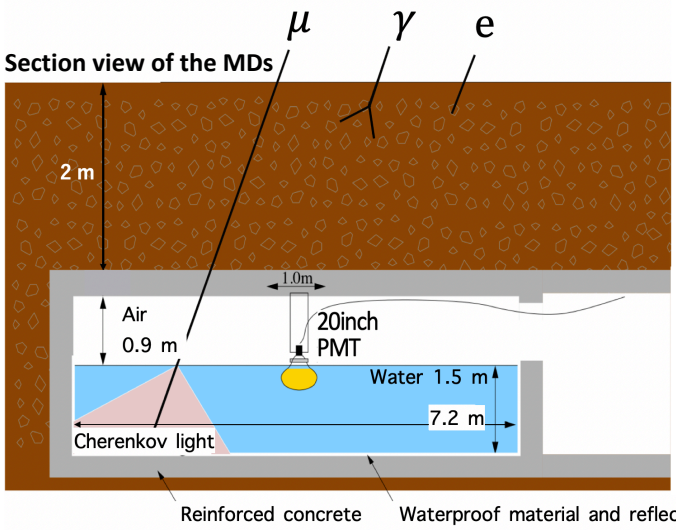
The ALPACA Experiment (Air Shower Array)

- Chacaltaya plateau ($16°\ 23'\ \mathrm{S}, 68°\ 08'\ \mathrm{W}$, Bolivia)
- Elevation : 4,740 m ($572.4\ \mathrm{g/cm^2}$)
- A surface air shower array (AS array : $83{,}000\ \mathrm{m^2}$)

  + an u/grd. muon detector array → BGCR rejection
- Main motivation: Southern VHE γ-ray astronomy beyond 100 TeV

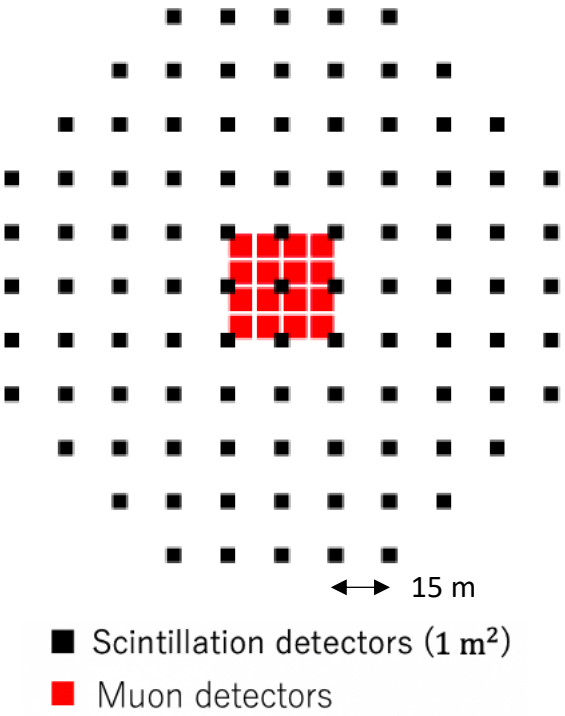


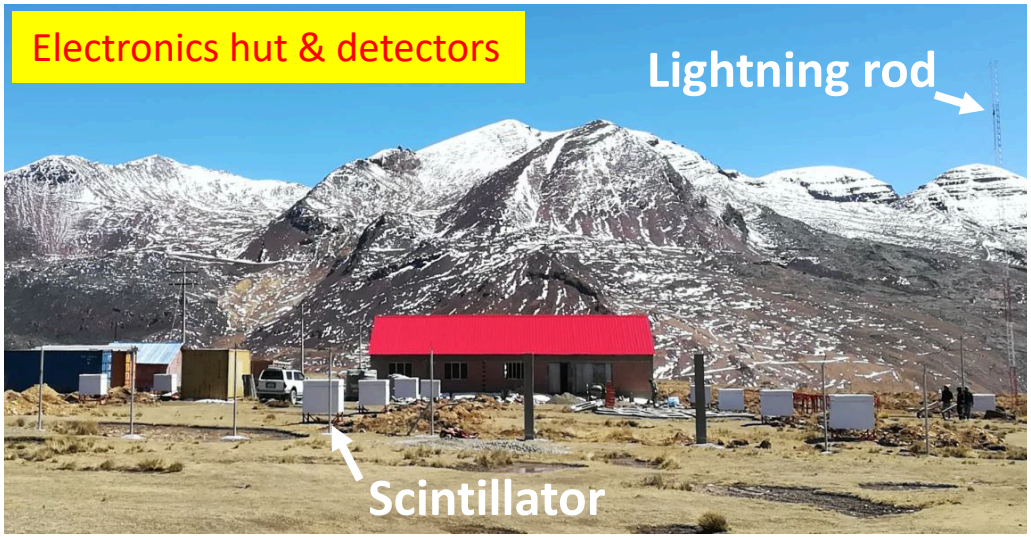




The ALPAQUITA Experiment

The prototype experiment of ALPACA





- Surface air-shower array: 18,450 m^2 (~1/4 of the ALPACA surface array)
- MD: 900 m^2 (56 m^2×16 cells)

Can ALPAQUITA explore southern 100 TeV γ-ray astronomy ?

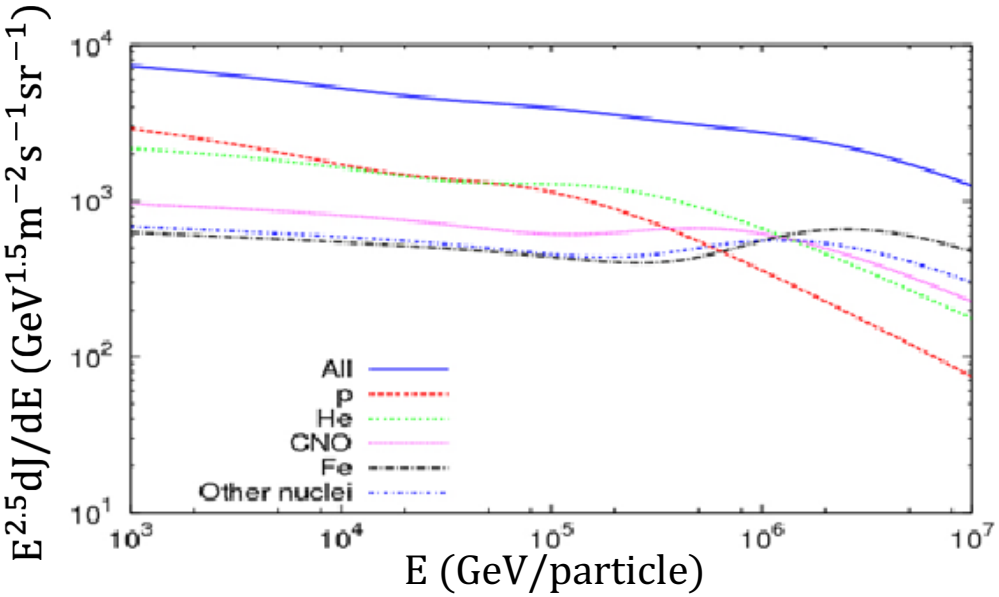
Air Shower Generation (Corsika7.6400)

Simulation condition

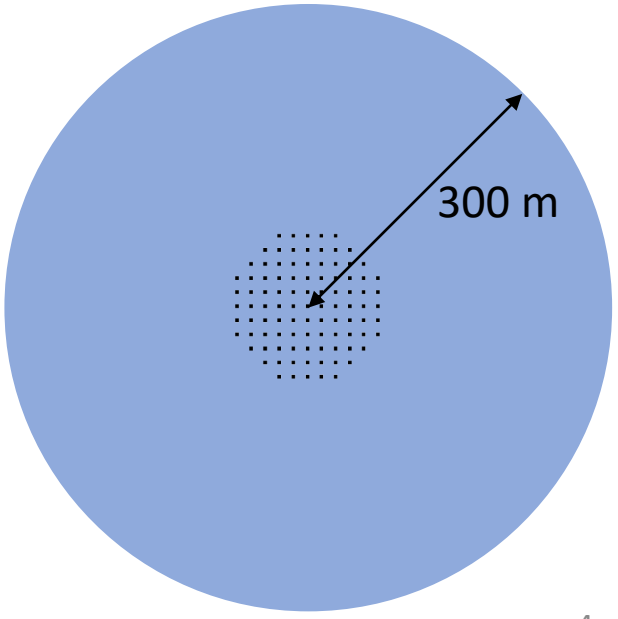
D. Heck, J. Knapp, J. N. Capdevielle, G. Schats, T. Thouw, Report FZKA (1998) 6019

Simulation condition	γ rays	BGCR (FLUKA & EPOS-LHC)
Energy range	$300\,\mathrm{GeV} \leq E < 10\,\mathrm{PeV}$	1. $300\,\mathrm{GeV} \leq E < 10\,\mathrm{PeV}$ & 2. $10\,\mathrm{TeV} \leq E < 10\,\mathrm{PeV}$
Total number of events	3.7×10^{7}	1.1×10^{8} & 7.7×10^{7}
Spectrum	$\propto E^{-2}$ *	Lower-left figure
Orbit	RX J1713.7-3946 (minimum zenith angle = 23.4°)	
Simulated area	Lower-right figure	

* The index is changed with an appropriate weighting procedure depending on analyses

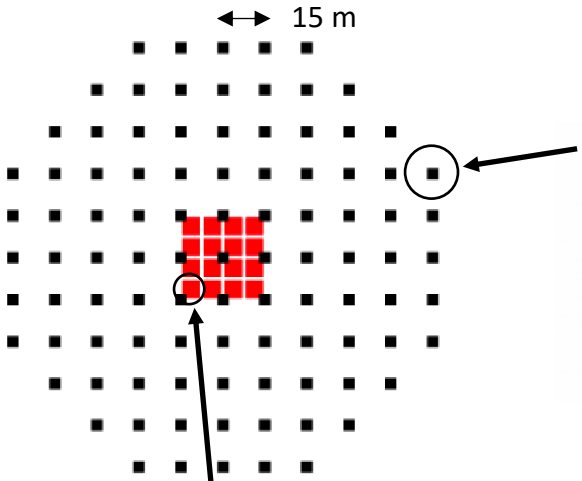


M. Shibata *et al, ApJ*, 716, 1076 (2010)

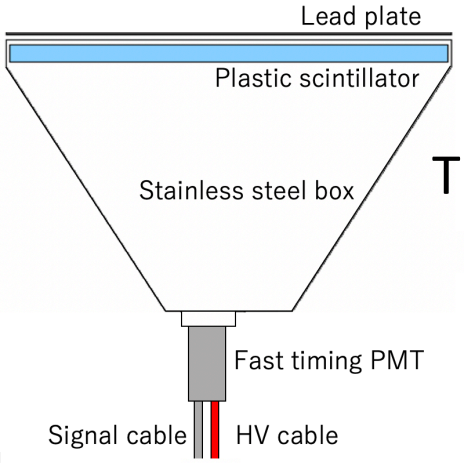


Detector Responses (Geant4 v10.04.p02)

S. Agostinelli, et al., Nucl. Instrum. Methods Phys. Res. A 506 (2003) 250



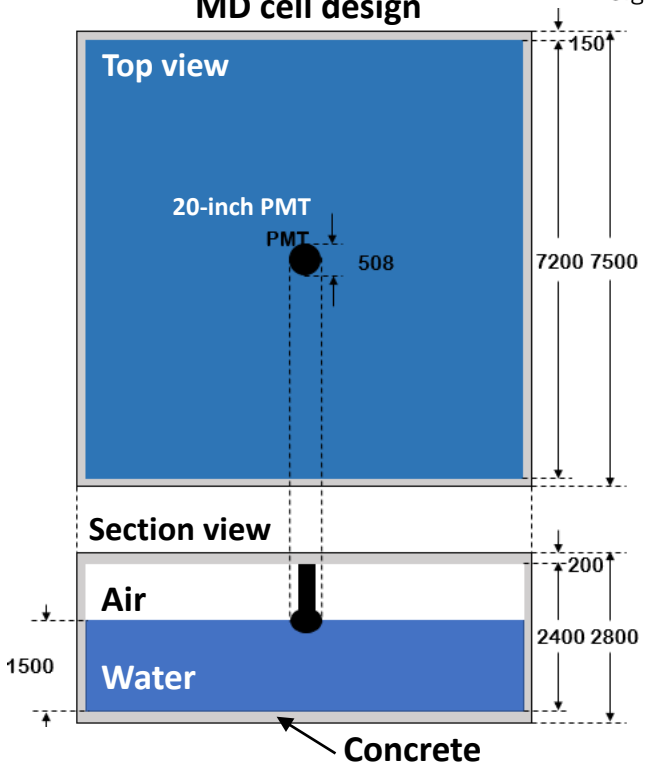
Scintillation detector design



The surface array:

- 97 scintillation detectors ($1\ \mathrm{m}^2$ each)
- Total geometrical area: $18{,}450\ \mathrm{m}^2$
- $1\ \mathrm{ptcl} \equiv 9.4\ \mathrm{MeV}$
- Trigger condition: 0.5 ptcl any 4 w/i 600 ns

MD cell design



The Muon detector:

- 2.0 m soil overburden
- Consists of 16 cells ($56\ \mathrm{m}^2$ each)
- Total geometrical area: $900\ \mathrm{m}^2$
- 2 m soil + 20 cm concrete ceiling ($470\ \mathrm{g/cm}^2$)
  -> Only muons w/ E $\gtrsim$ 1.2 GeV can reach MD
- 1 muon $\equiv$ 24 p.e.

Analysis Conditions

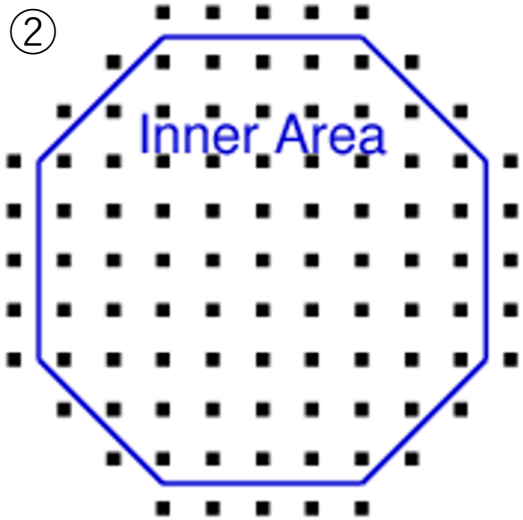
Event selection criterion

For surface array performance

① 0.8 ptcl any 4

② “IN” event : 3 out of 4 hottest detectors locate in the inner area

③ Residual error < 1 m (indicator of the quality of direction reconstruction)



For the sensitivity to gamma rays

① + ② + ③ &

④ Reconstructed zenith angle $\theta < 40°$

⑤ Inside the analysis window of radius

$$r = \begin{cases} 1.5° & (\Sigma\rho < 15) \\ 5.8°/\sqrt{(\Sigma\rho/\mathrm{m}^{-2})} & (15 \le \Sigma\rho \le 135) \\ 0.5° & (135 < \Sigma\rho) \end{cases}$$

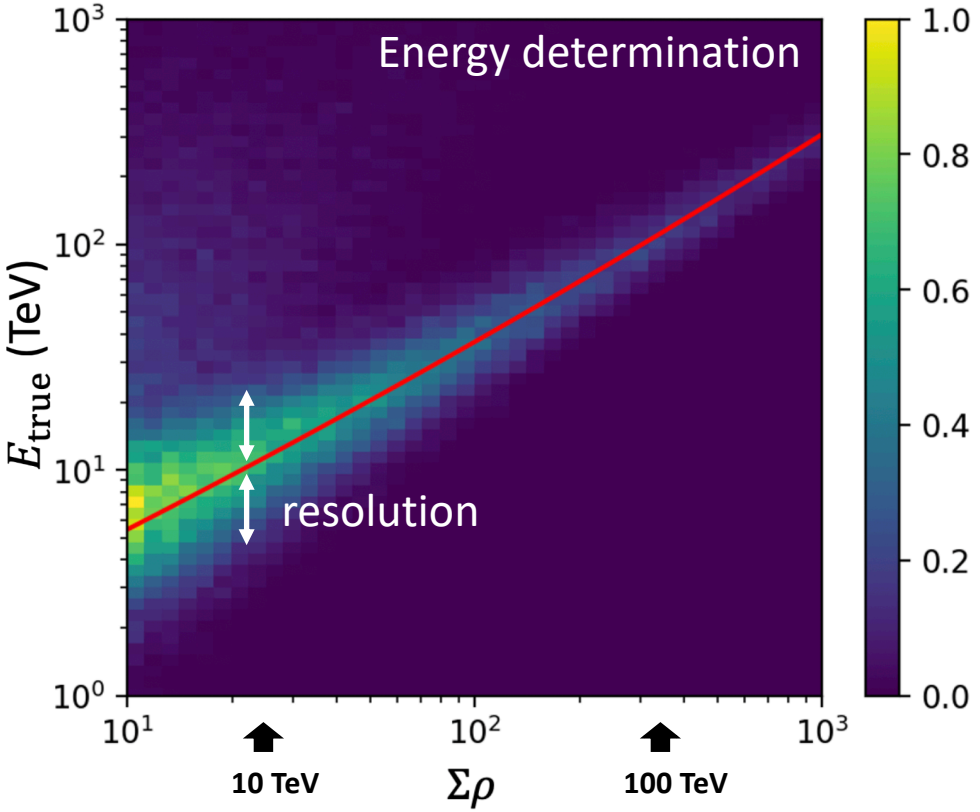
($\Sigma\rho$: sum of the density of detected ptcl)

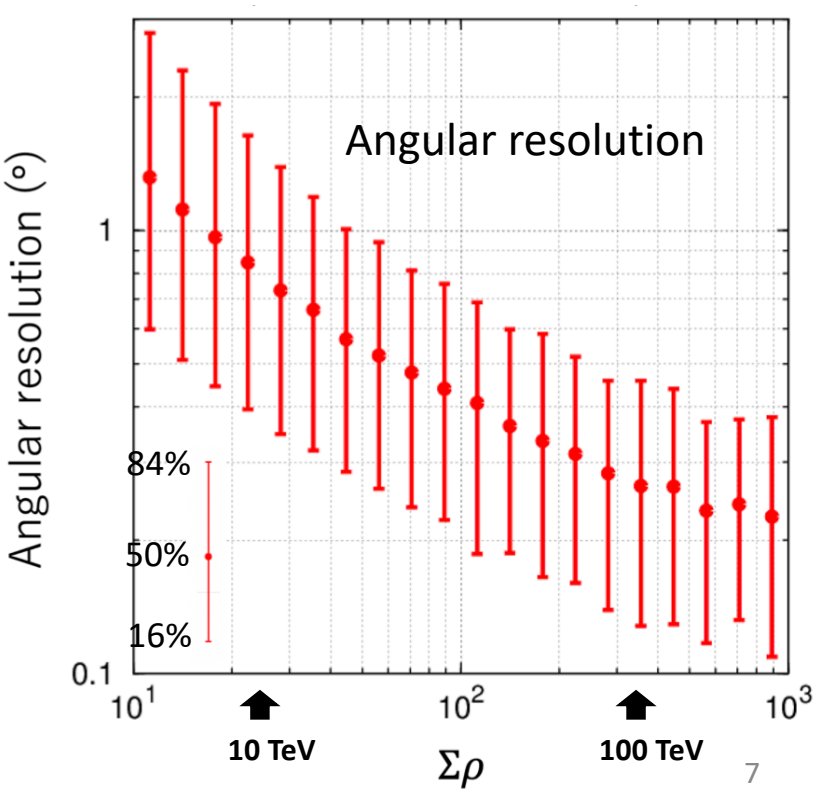
ALPAQUITA AS Array Performance for Gamma Rays

Target events: Gamma rays w/ $\Gamma = -2.5$ & $\theta_{\rm true} < 40°$

Trigger efficiency*	100% ≥20 TeV
Energy resolution	$+27\% \ -21\%$ @ 100 TeV
Angular resolution	$\simeq 0.3°$ @ 100 TeV

*Efficiency for the events w/ the true cores inside the AS array

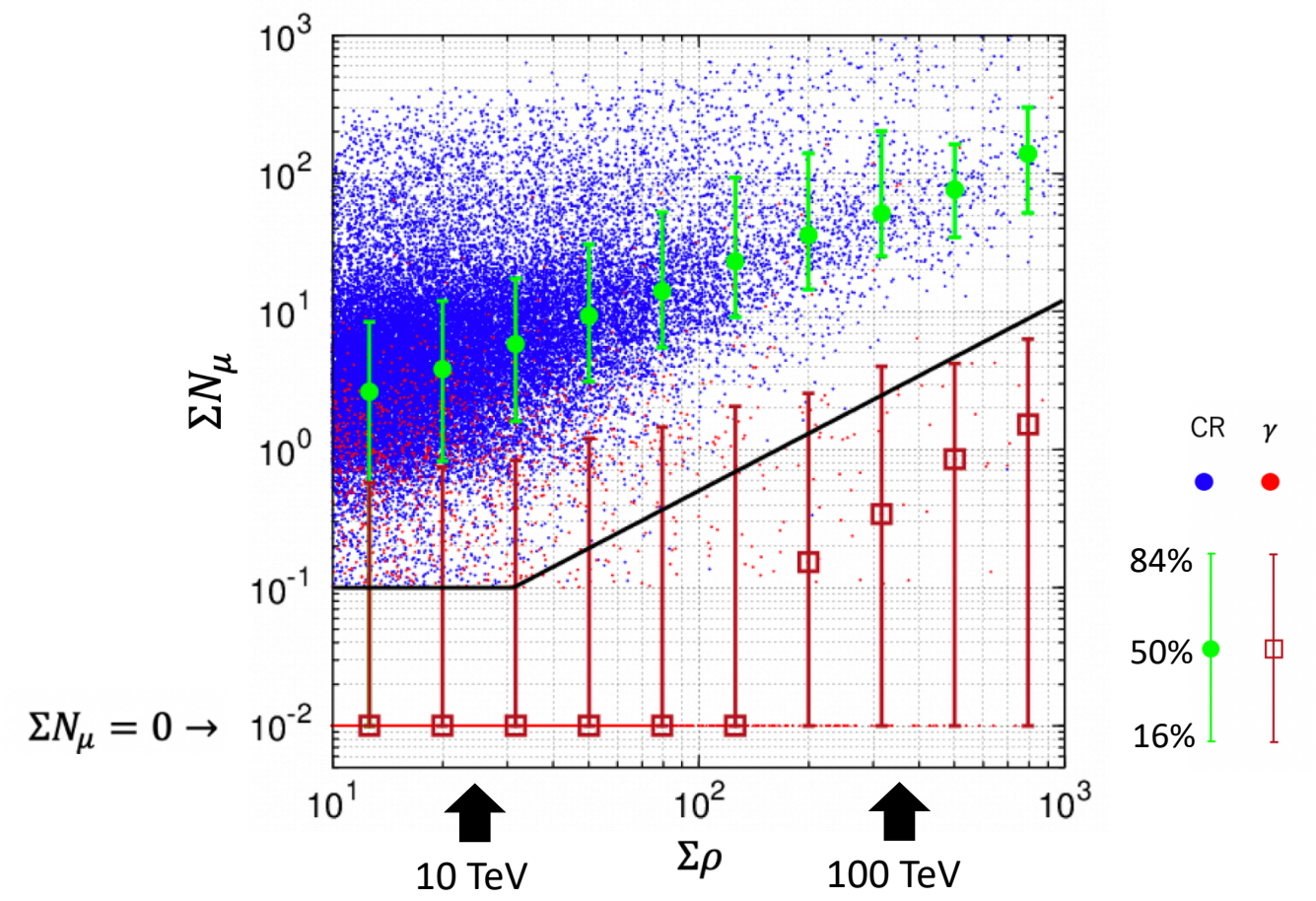




Muon Cut Line

To maximize the detection significance of signal γ rays

ΣN_μ : Total number of muons detected with the muon detector

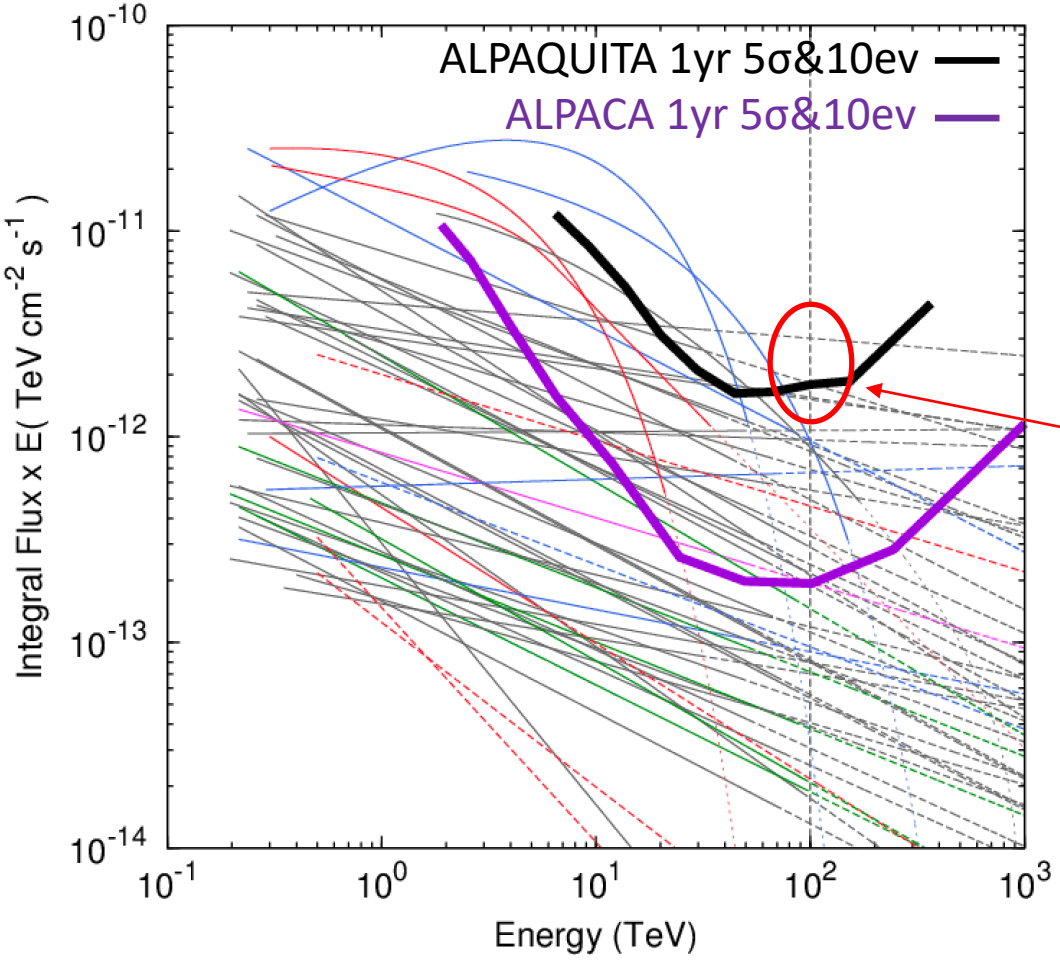


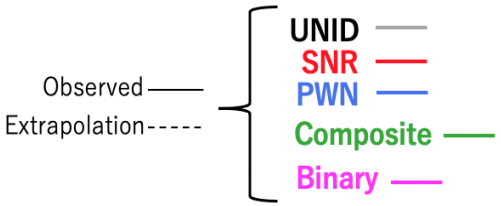
Survival ratio of gamma rays $\simeq$ 79 % @100 TeV

Rejection power for BGCRs $\simeq$ 99.9% @100 TeV γ. eq.

Sensitivity to VHE Gamma-ray Sources

Sensitivity curves in 1yr5σ





- ~7 sources in 1-yr obs. above 10 TeV
- 4 sources will be detected above 100 TeV !
  HESS J1616-508
  HESS J1702-420
  HESS J1708-443
  HESS J1843-033

For the energy spectra of the sources:
H.E.S.S. A&A 612, A1 (2018) & HAWC Phys. Rev. Lett 124, 021102 (2020)

Summary

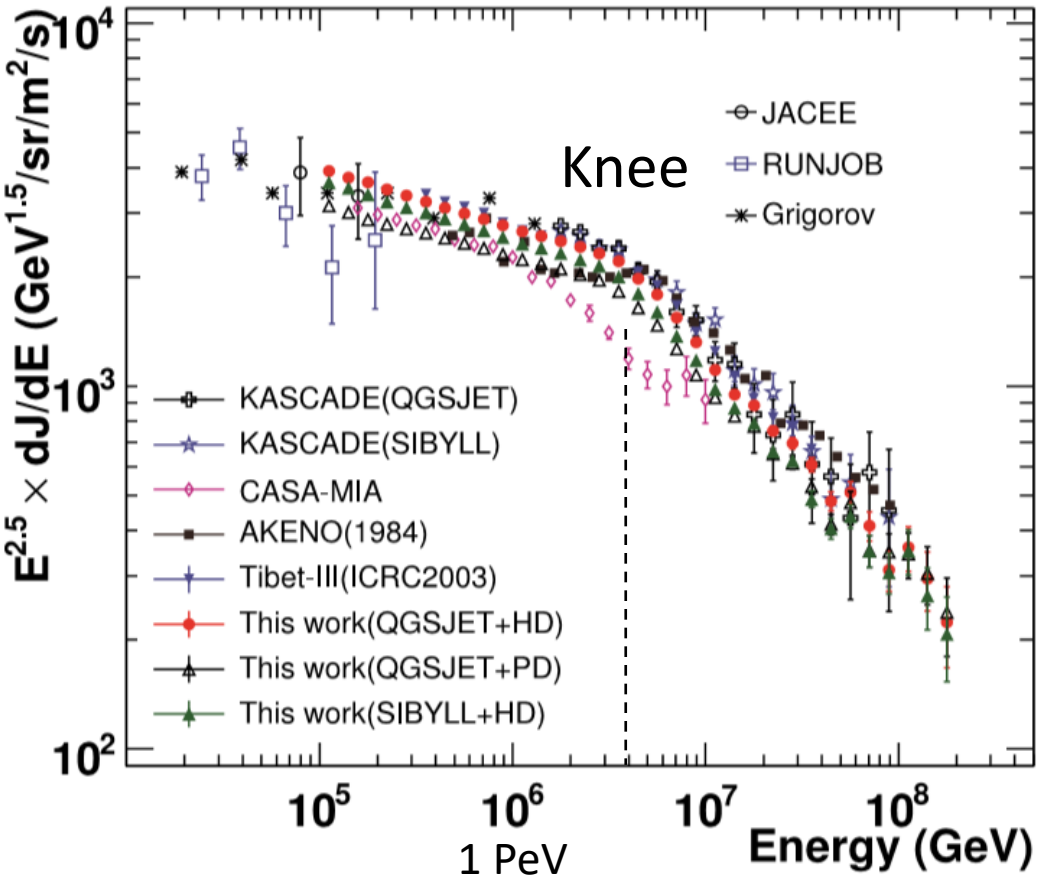
- The ALPACA experiment: A new air-shower array experiment
  - Researchers from Bolivia, Mexico, and Japan
  - Main motivation: Southern VHE γ-ray astronomy beyond 100TeV
- The prototype exp. ALPAQUITA: The array is under construction
  - Size: $\sim 1/4$ of the ALPACA arrays
  - Starting DAQ: expect in 2021
- ALPAQUITA performance (MC simulation)

Trigger efficiency	100% @ $\geq$20 TeV
Energy resolution	$+27\%$ -21% @100 TeV
Angular resolution	$\simeq 0.3^{\circ}$ @100 TeV
Survival ratio of gamma rays	$\simeq 79$ % @100 TeV
Rejection power of BGCRs	$\simeq 99.9\%$ @100 TeV γ eq.
TeV source detectability	~ 4 sources in 1-yr obs. $\geq$ 100 TeV

Origin of Cosmic Rays at the knee

A motivation for very high-energy (VHE) gamma-ray astronomy

All-particle spectrum



Index: $\sim 2.7 \rightarrow \sim 3.1$@ the knee

Accelerators of CRs at the knee ??

→ Implication of PeVatrons

Indirect observation of CRs:

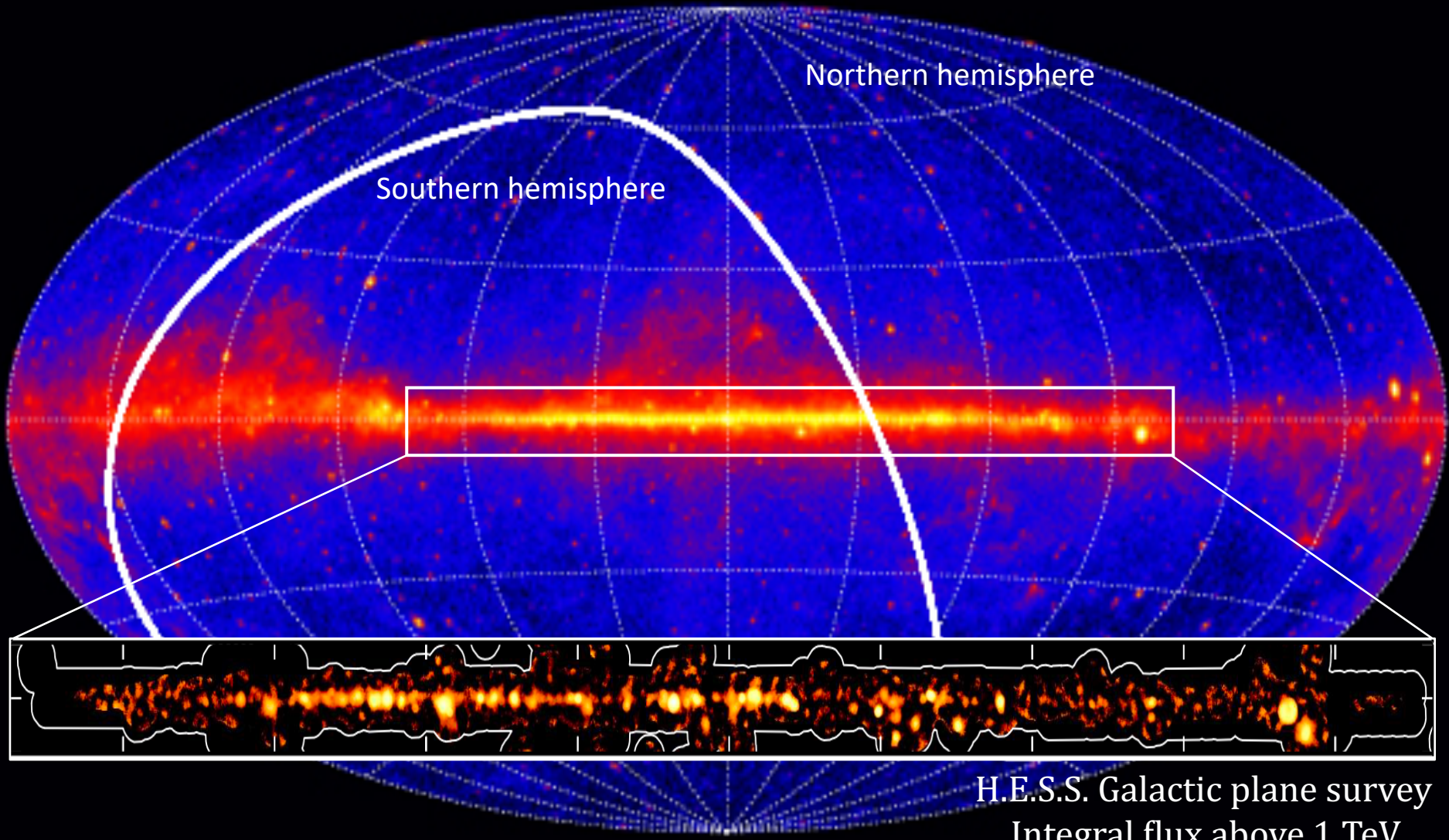
$$p + p \rightarrow p + p + \pi^0 + \pi^{\pm}$$
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\frac{E^{\gamma}_{max}}{E^{p}_{max}} \sim O(1/10)$$

→ Obs of 100 TeV γ rays

M. Amenomori *et al. ApJ*, 678, 1165 (2008)

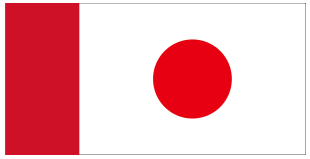
Gamma-Ray Sky



H.E.S.S. Galactic plane survey
Integral flux above 1 TeV

NASA/DOE/Fermi LAT Collaboration
H. Abdalla et al., Astronomy & Astrohysics 612, A1, 2018





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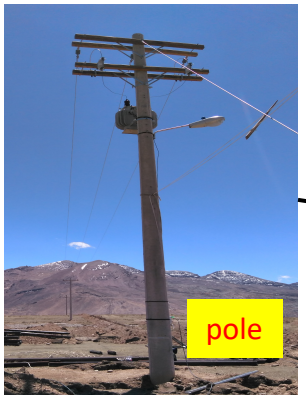
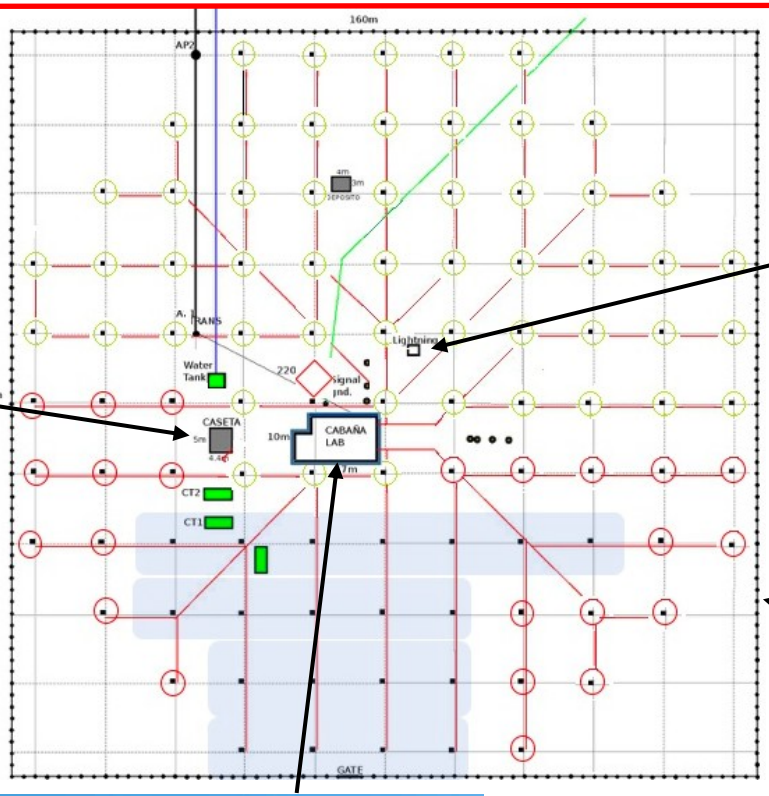
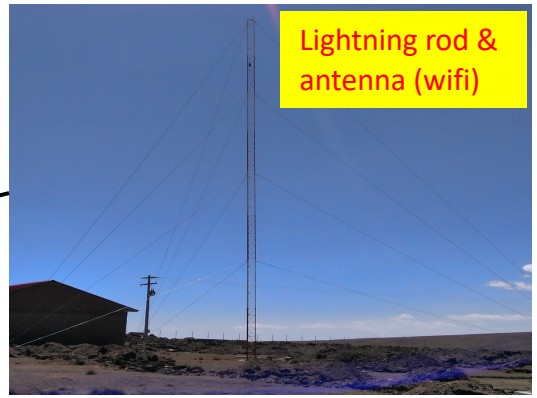
ALPATQUITA Construction (the Current Status)

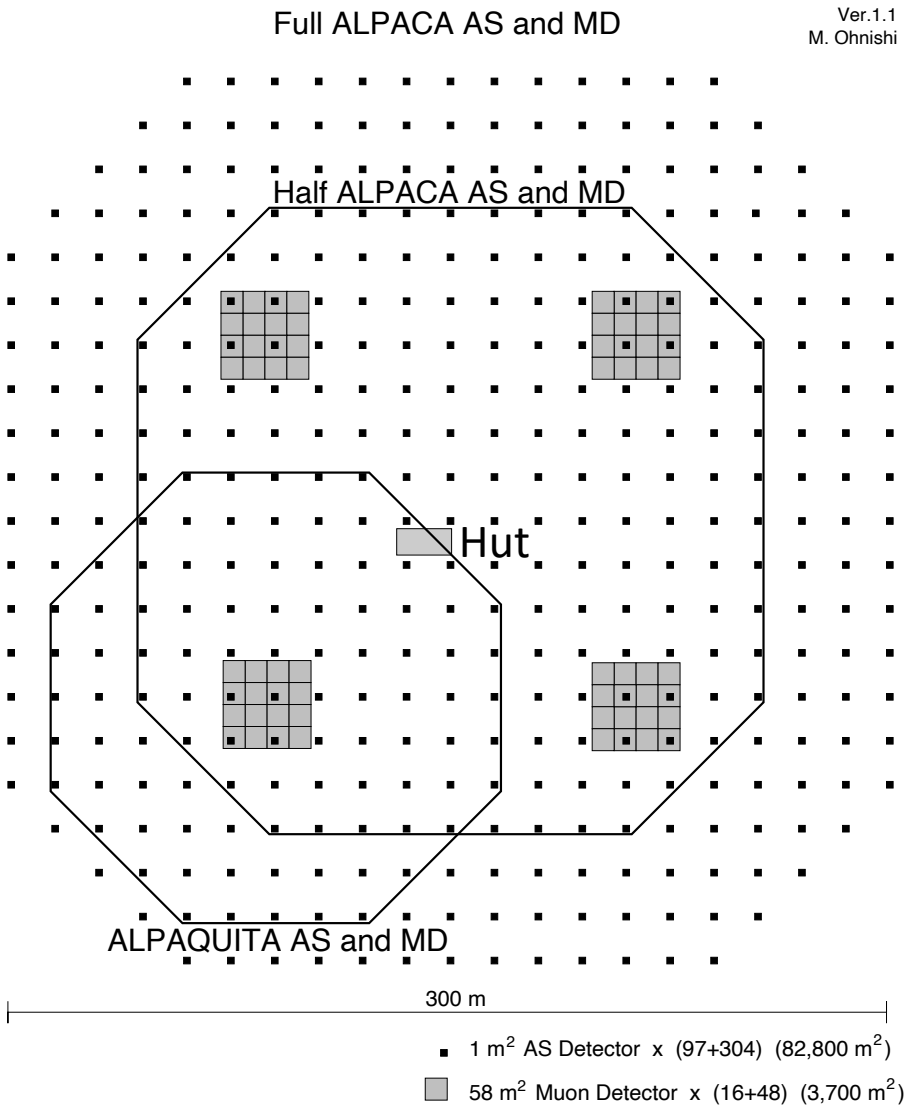






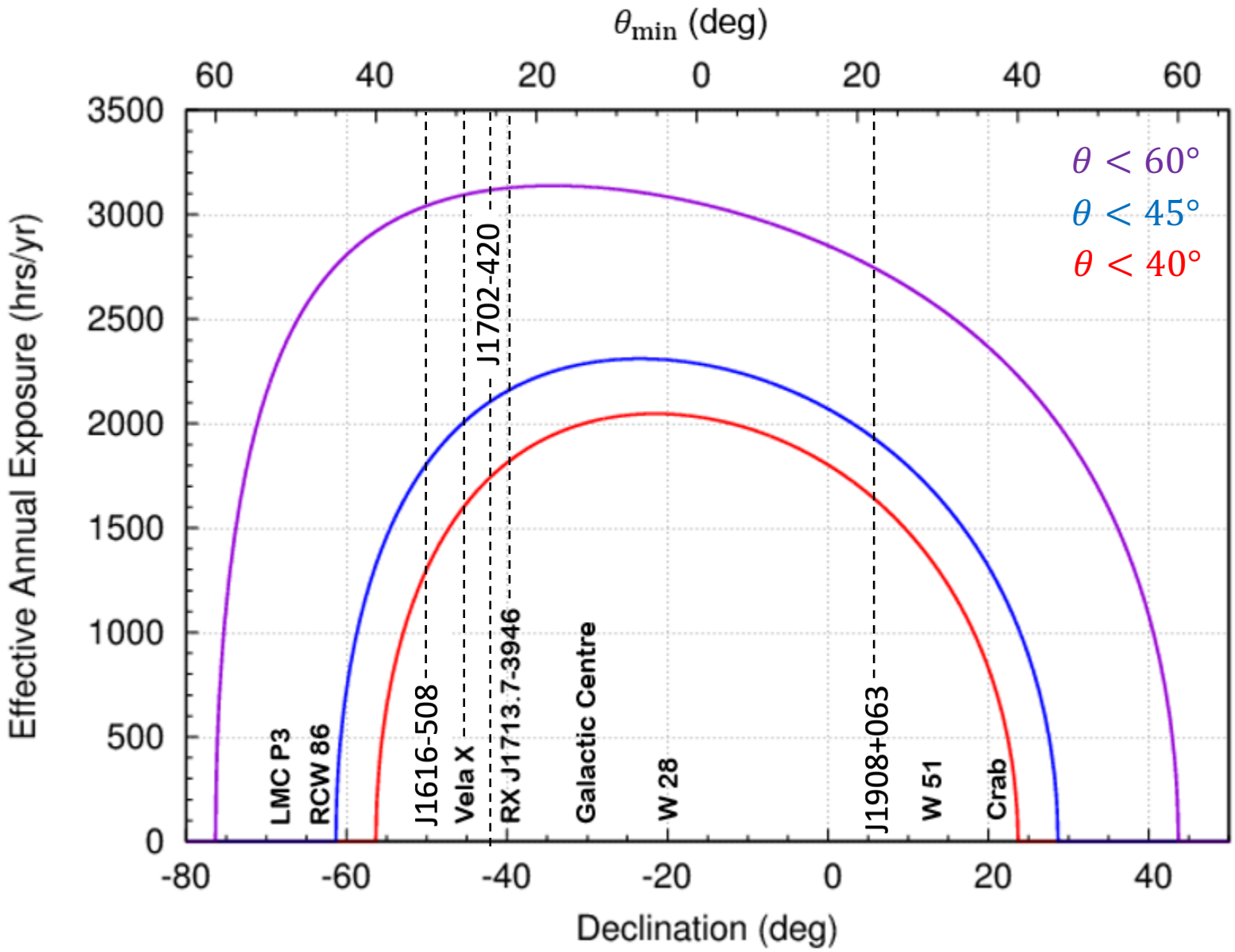
Position of ALPAQUITA

Take the expansion to ALPACA into account



$\theta_{\min}$ & Exposure to Several Objects

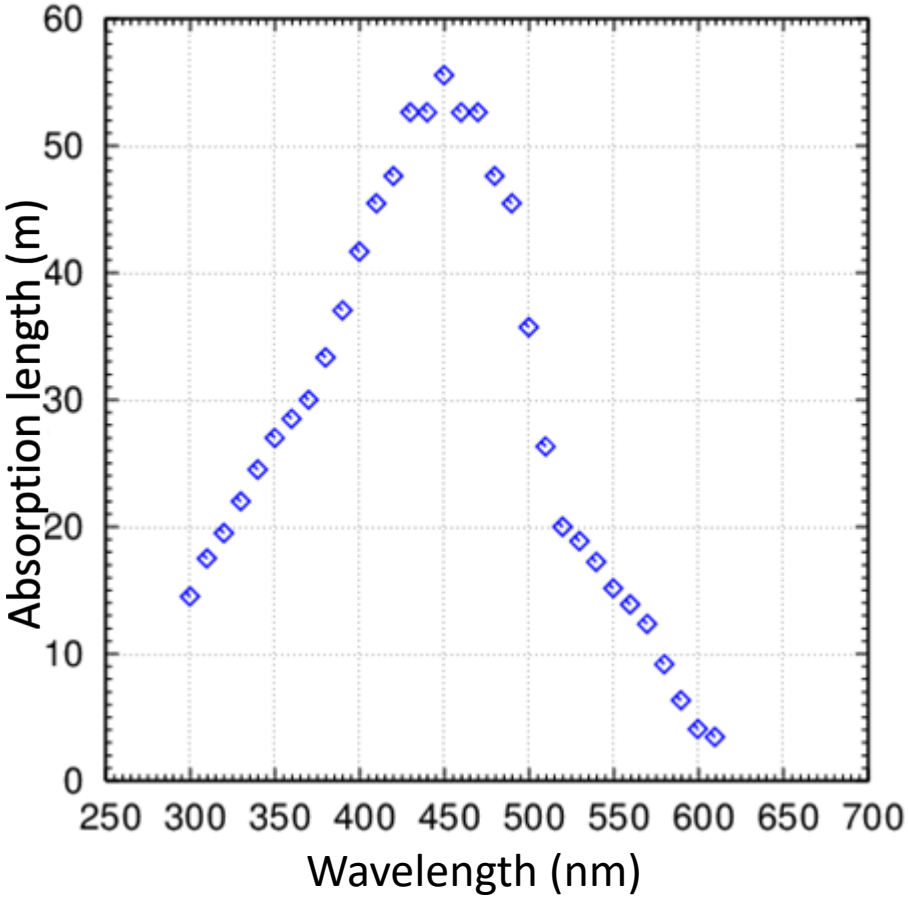
Not corrected by zenith angle



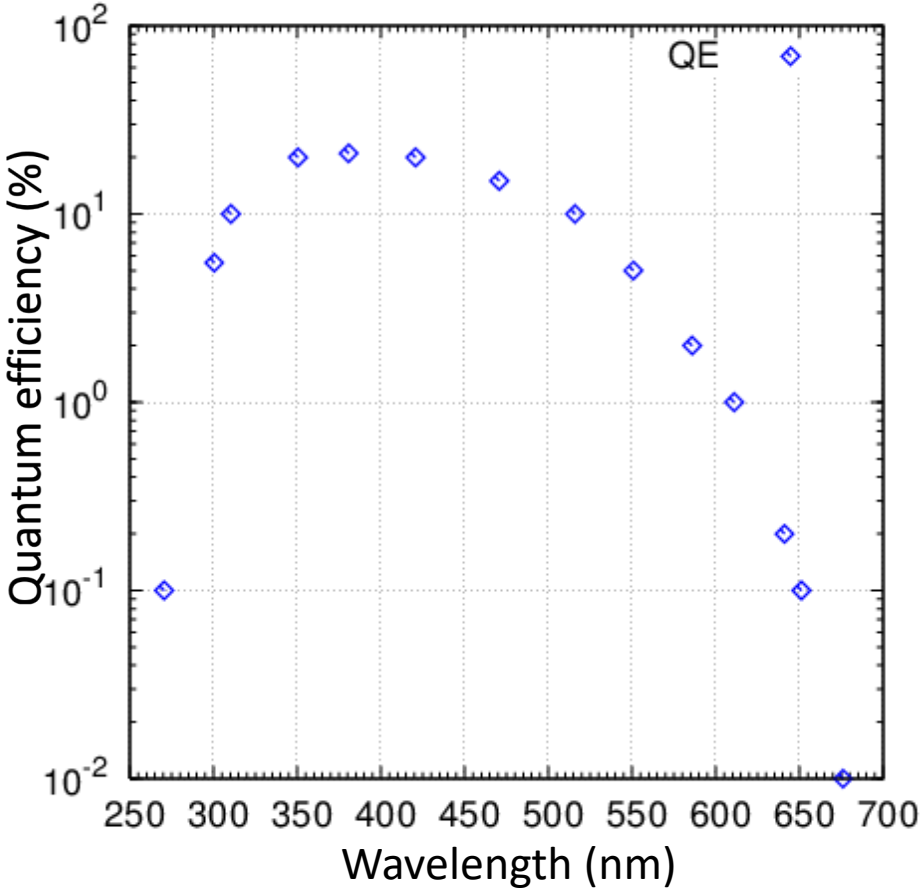
Other Parameters in MD Simulation

Input parameters to Geant 4 simulation

Absorption length

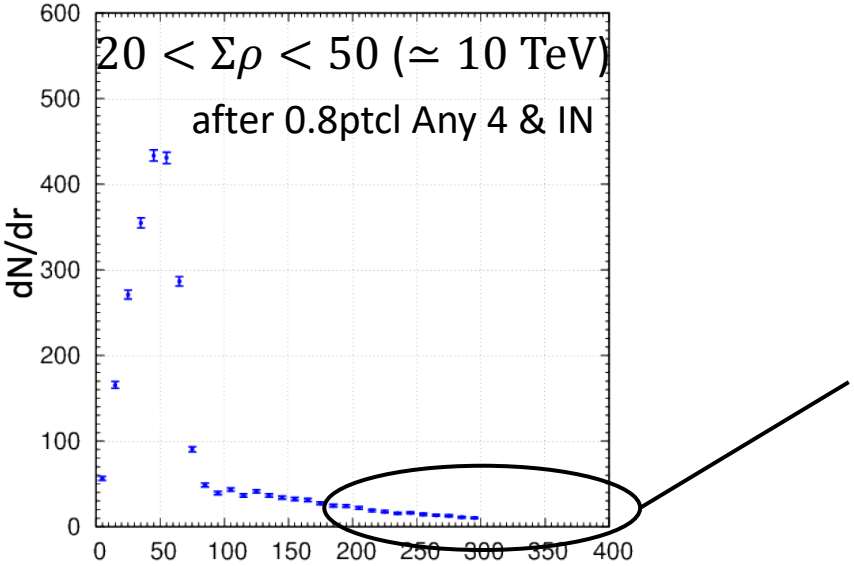


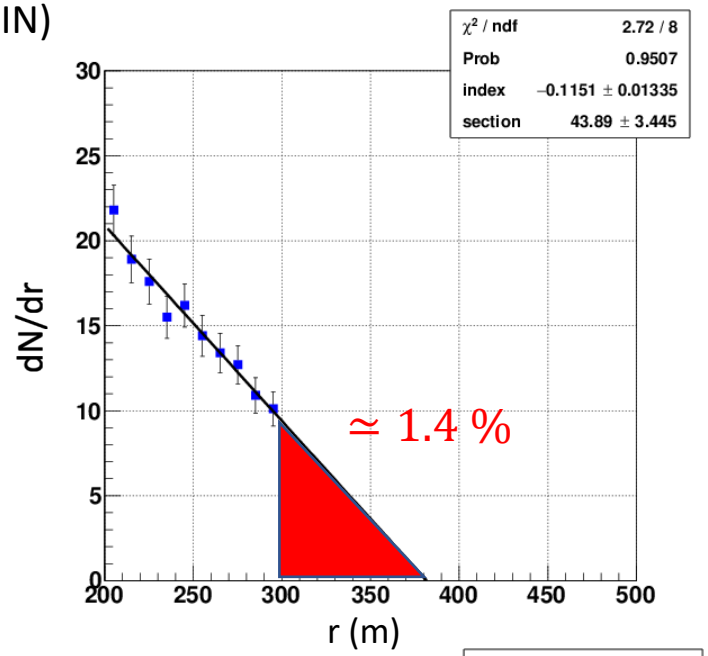
Q.E. of PMT



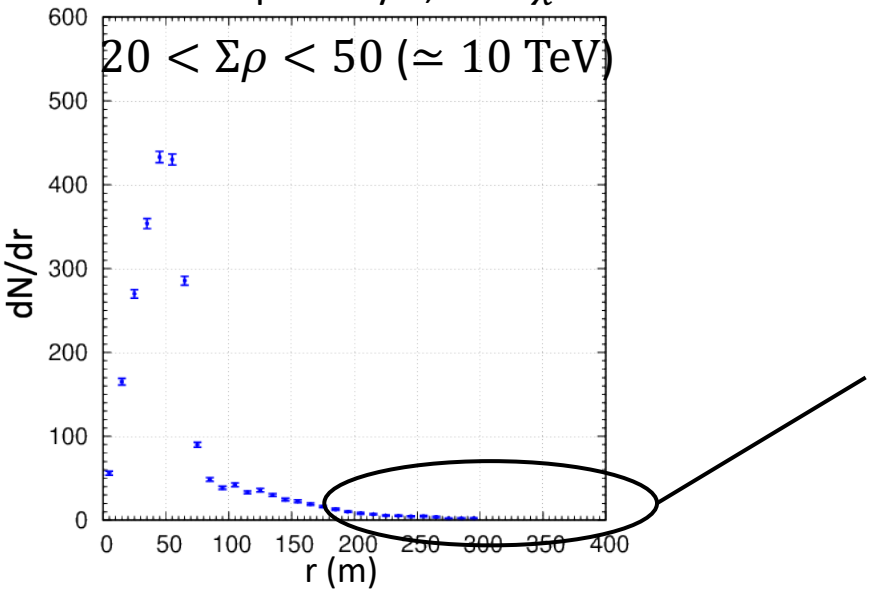
Radial Distribution of Events After Selection Cuts

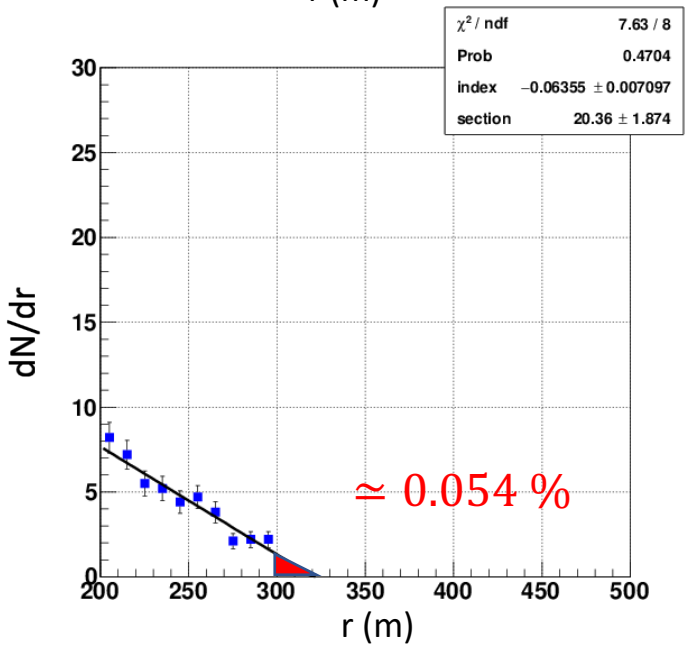
Radial Distribution of events (after 0.8ptcl Any 4 & IN)





after 0.8ptcl Any 4, IN & $\chi^2 < 1\ \mathrm{m}^2$





Reconstruction Methods

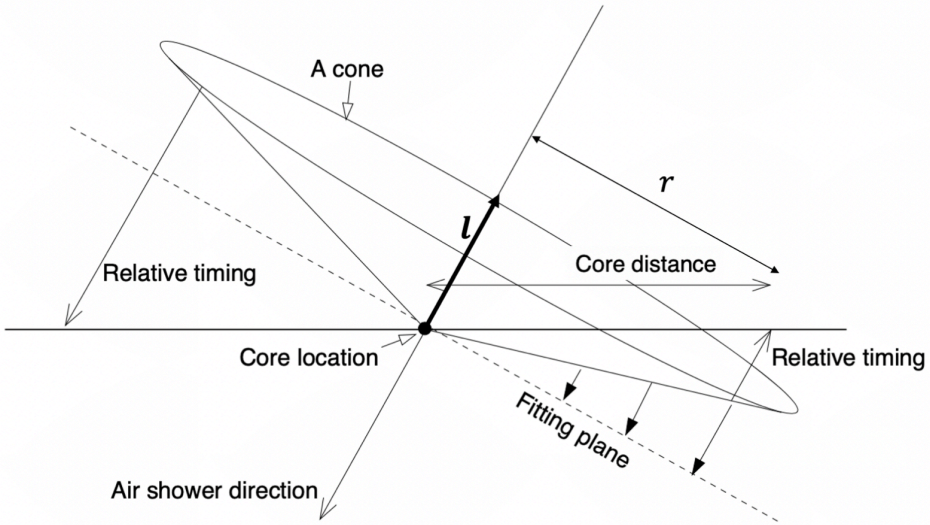
For events w/ 0.8 ptcl any 4

Core estimation: $\left(\frac{\sum_i {\rho_i}^w x_i}{\sum_i {\rho_i}^w}, \frac{\sum_i {\rho_i}^w y_i}{\sum_i {\rho_i}^w} \right)$ (w=2)

Direction estimation:

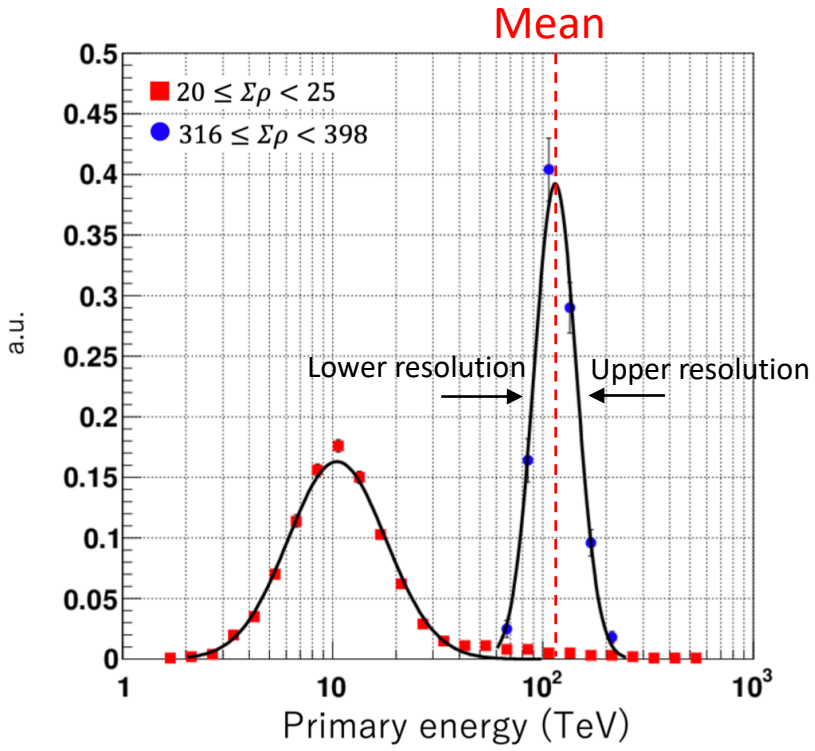
$$\chi^2\,(\mathrm{m}^2) = \sum_i w_i (\boldsymbol{l} \cdot \boldsymbol{x}_i + c(t_i - t_0))^2 \qquad \left(w_i = \rho_i / \Sigma_i \rho\right)$$

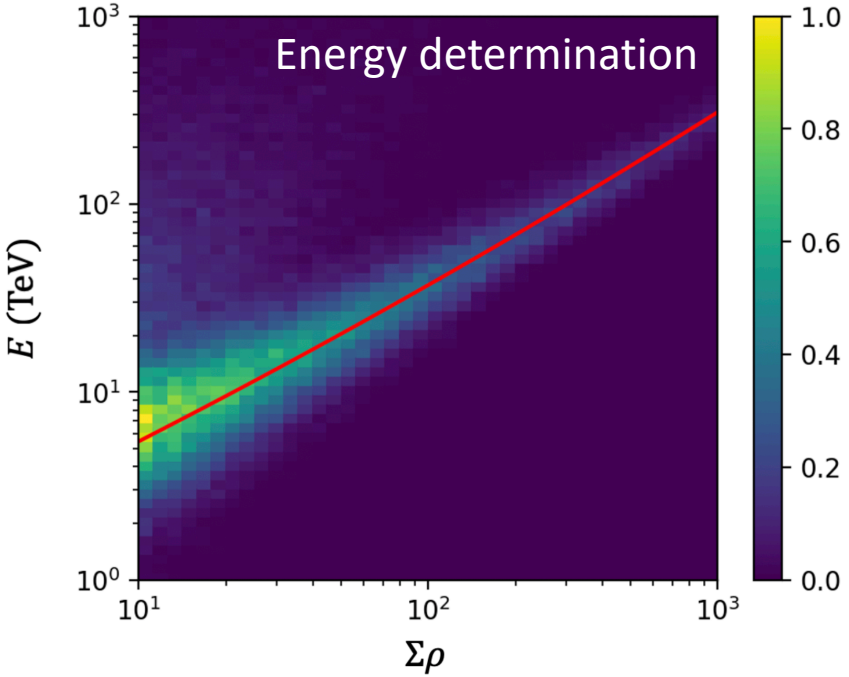
($\boldsymbol{x}_i$: position of the detector that detected particles
t_i: timing of the detection)



Energy resolution & relation b/w energy & $\Sigma\rho$

$\Sigma\rho$: Total number density of ptcls detected with the AS array



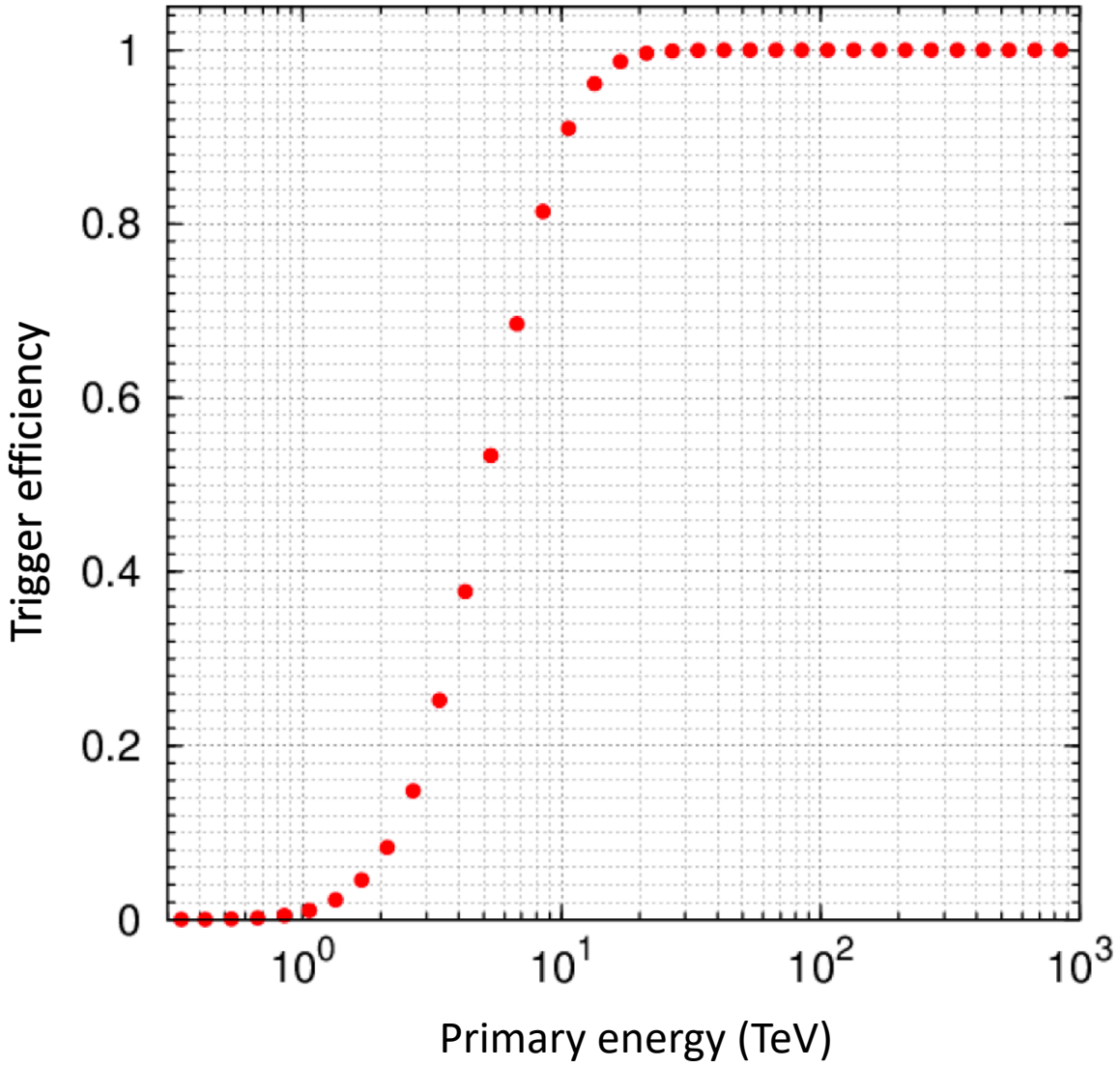


$$\log_{10}\left(\frac{E}{\mathrm{TeV}}\right) = 4.4\times10^{-2}\left(\log_{10}\left(\frac{\Sigma\rho}{\mathrm{m}^{-2}}\right)\right)^2 + 0.7\left(\log_{10}\left(\frac{\Sigma\rho}{\mathrm{m}^{-2}}\right)\right) + 7.6\times10^{-3}$$

Trigger efficiency

Target events

Gamma rays w/ $\Gamma = -2.5$, $\theta_{\mathrm{sim}} < 40°$ & true core inside the AS array



Reconstruction methods

For events w/ 0.8 ptcl any 4

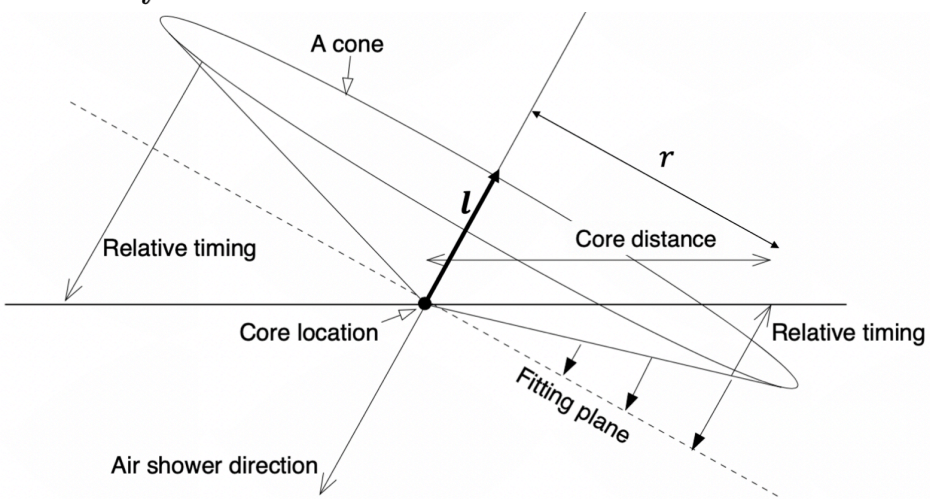
Core estimation: $\left(\frac{\sum_i {\rho_i}^w x_i}{\sum_i {\rho_i}^w}, \frac{\sum_i {\rho_i}^w y_i}{\sum_i {\rho_i}^w} \right)$ (w=2)

Direction estimation:

$$b = 0.0125 \log_{10}\left(\frac{\Sigma\rho}{\mathrm{m}^{-2}}\right) + 0.0625 \ (\mathrm{ns/m}), \qquad \text{where } 0.075 \leq b \leq 0.12$$

$$\Rightarrow \qquad t_i \rightarrow t_i - br$$

$$\Rightarrow \quad \chi^2 \ (\mathrm{m}^2) = \sum_i w_i (\boldsymbol{l} \cdot \boldsymbol{x} + c(t_i - t_0))^2 \qquad \left(w_i = \rho_i / \Sigma_i \rho\right)$$

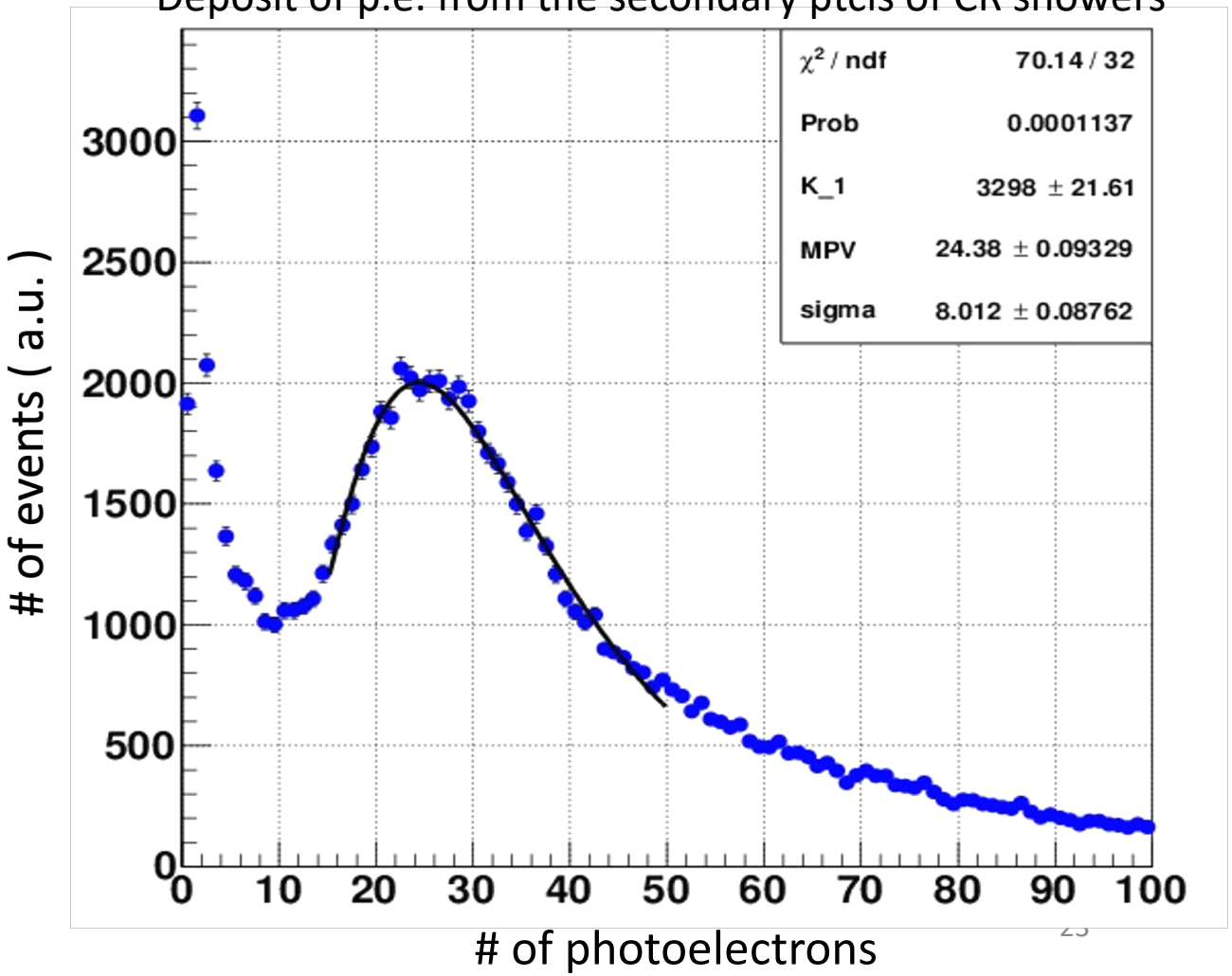


Definition of 1 Muon

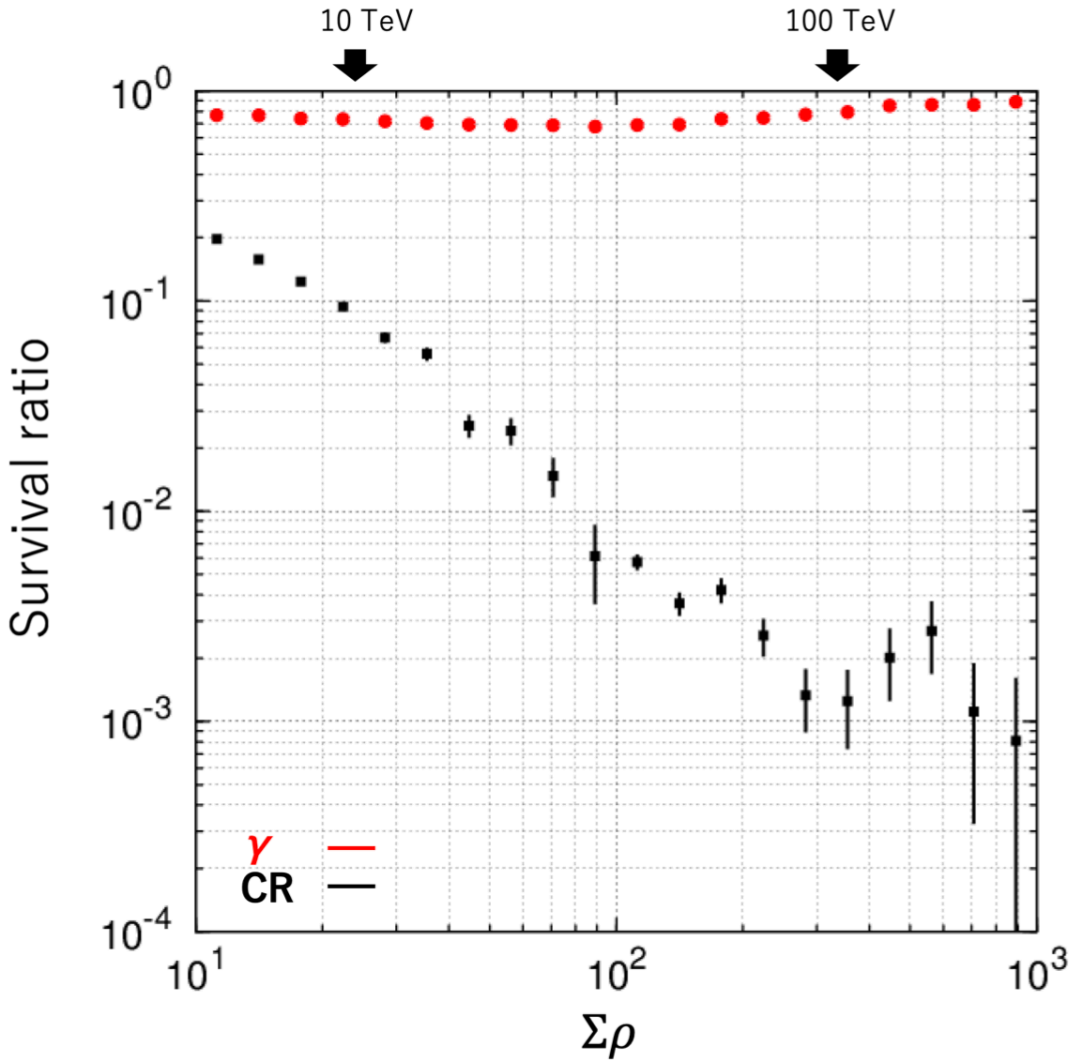
Photoelectron → muon

1muon ≡ 24 photoelectron for in all MD cells

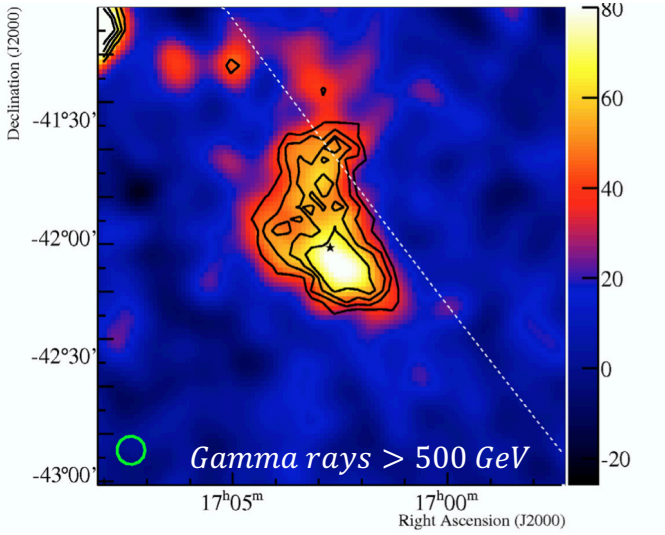
Deposit of p.e. from the secondary ptcls of CR showers

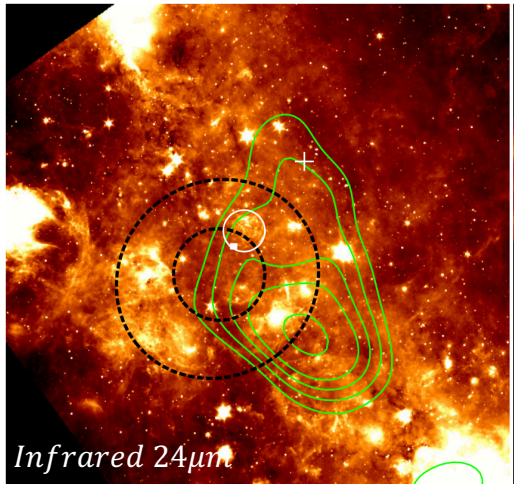


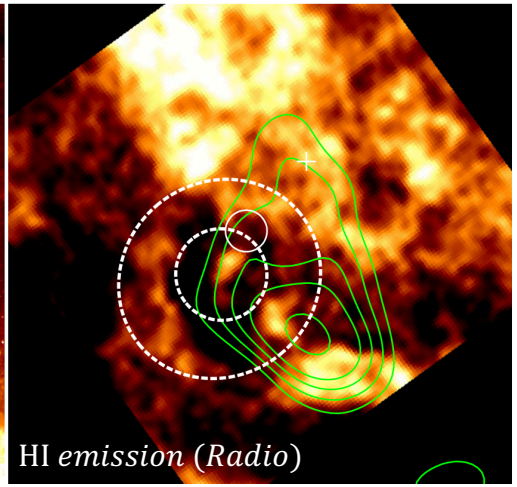
Survival ratio of gamma rays & Rejection power of BGCRs

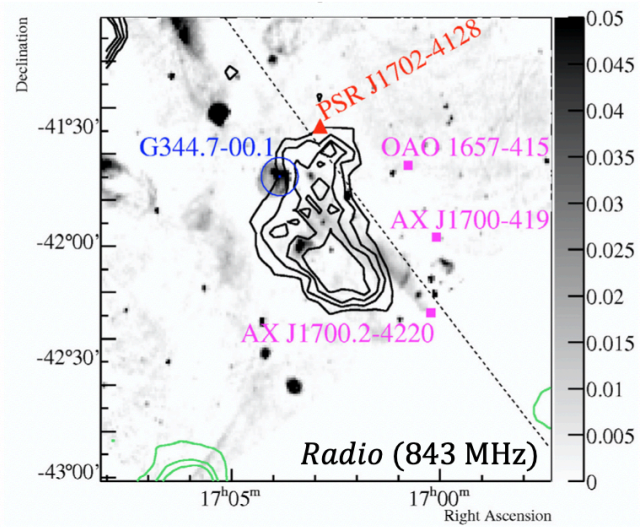


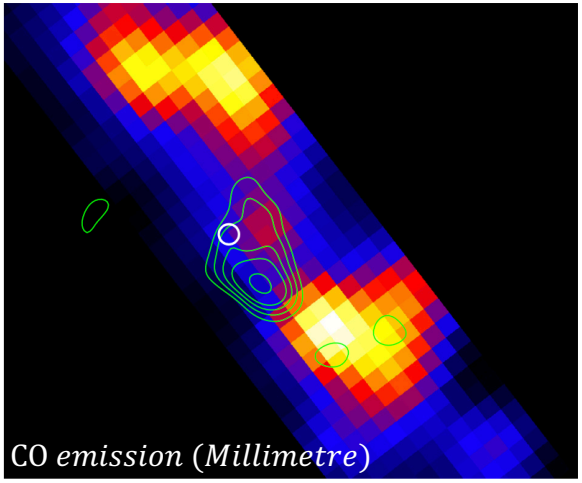
HESS J1702-420: Dark Accelerator

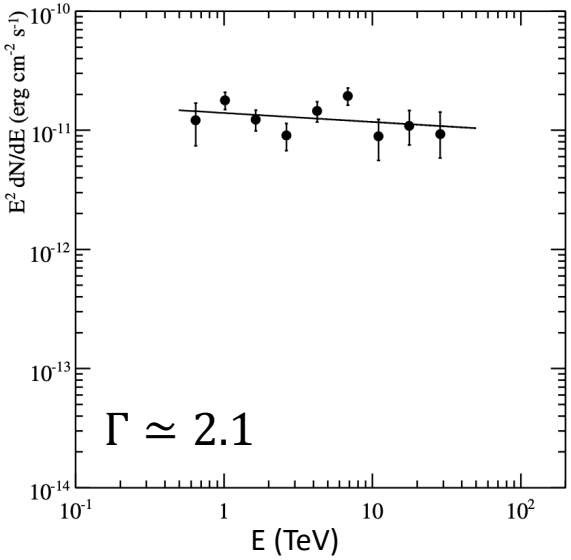












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