

Hybrid radio and particle detection of air showers:
potential for ultra-high-energy gamma-ray identification

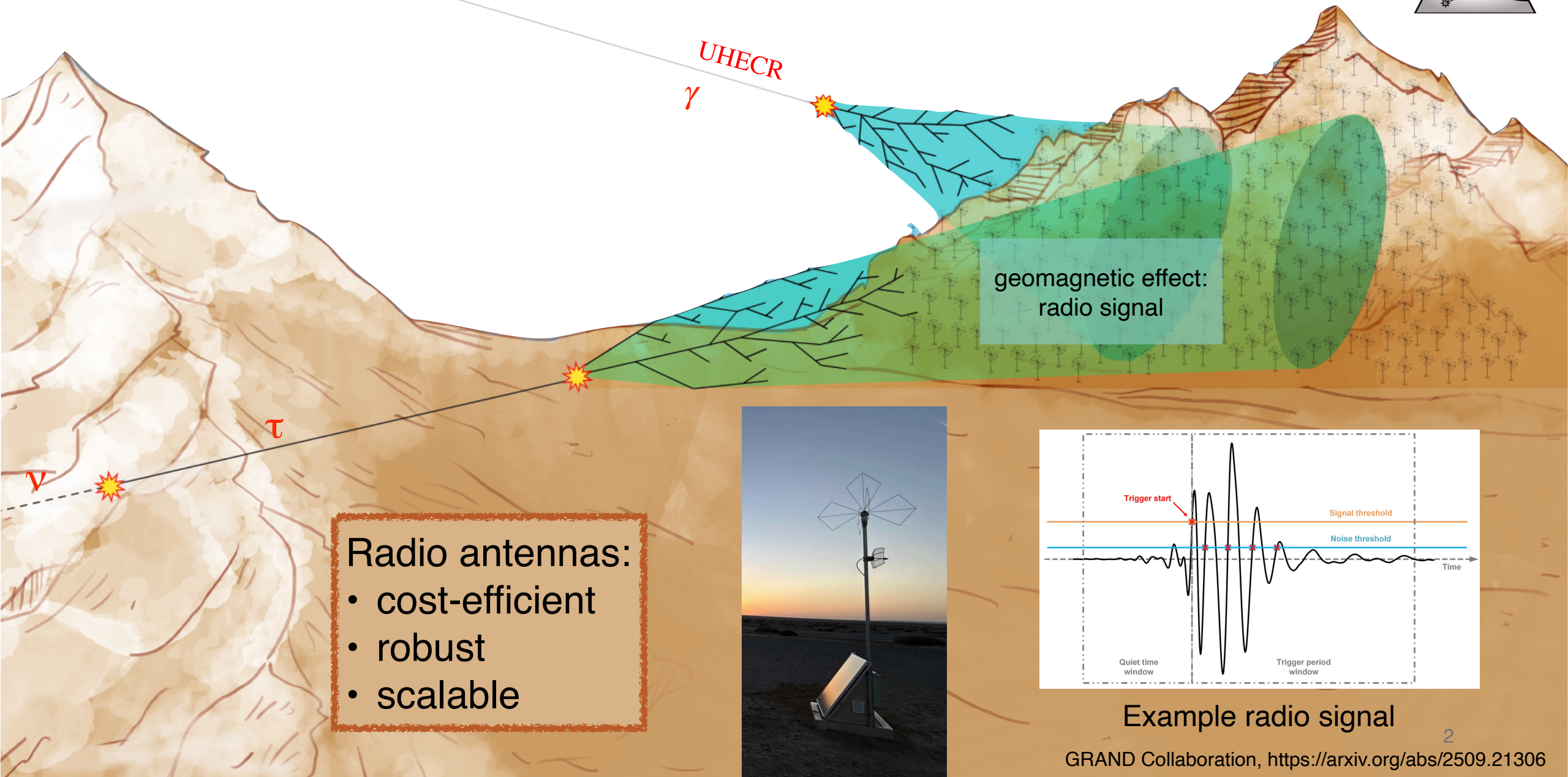
Paul Minodier¹ and Kumiko Kotera¹ from GRAND
Kaoru Takahashi² and Takashi Sako² from Telescope Array

PM, Takahashi, Kotera, Sako, in prep.

¹ Institut d'Astrophysique de Paris, CNRS UMR 7095, Sorbonne Université, 98bis bd Arago 75014, Paris, France

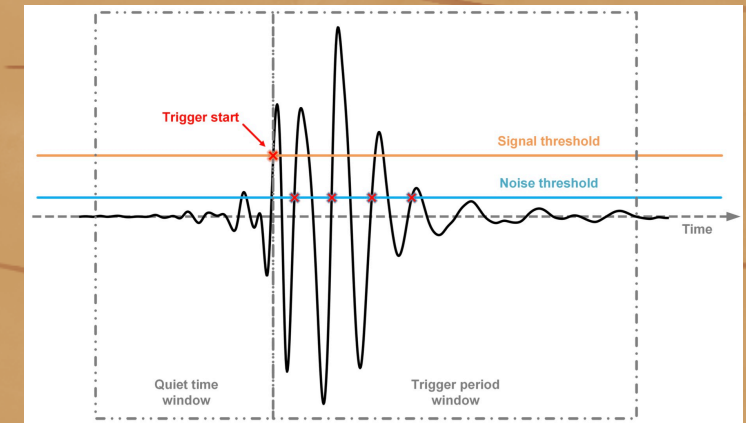
² ICRR, university of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba, 277-8582, Japan

The Giant Radio Array for Neutrino Detection (GRAND)



Radio antennas:

- cost-efficient
- robust
- scalable



Example radio signal

GRANDProto300 (China)

65 antennas deployed in the Gobi desert

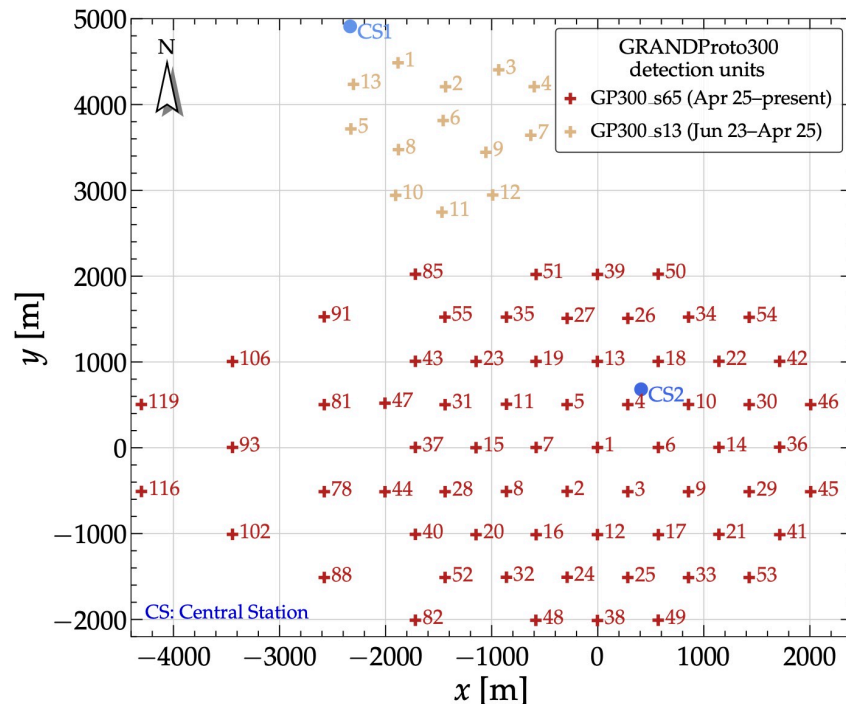
✓ Stable data collection

✓ Self-triggering on individual antennas +
online coincident triggering

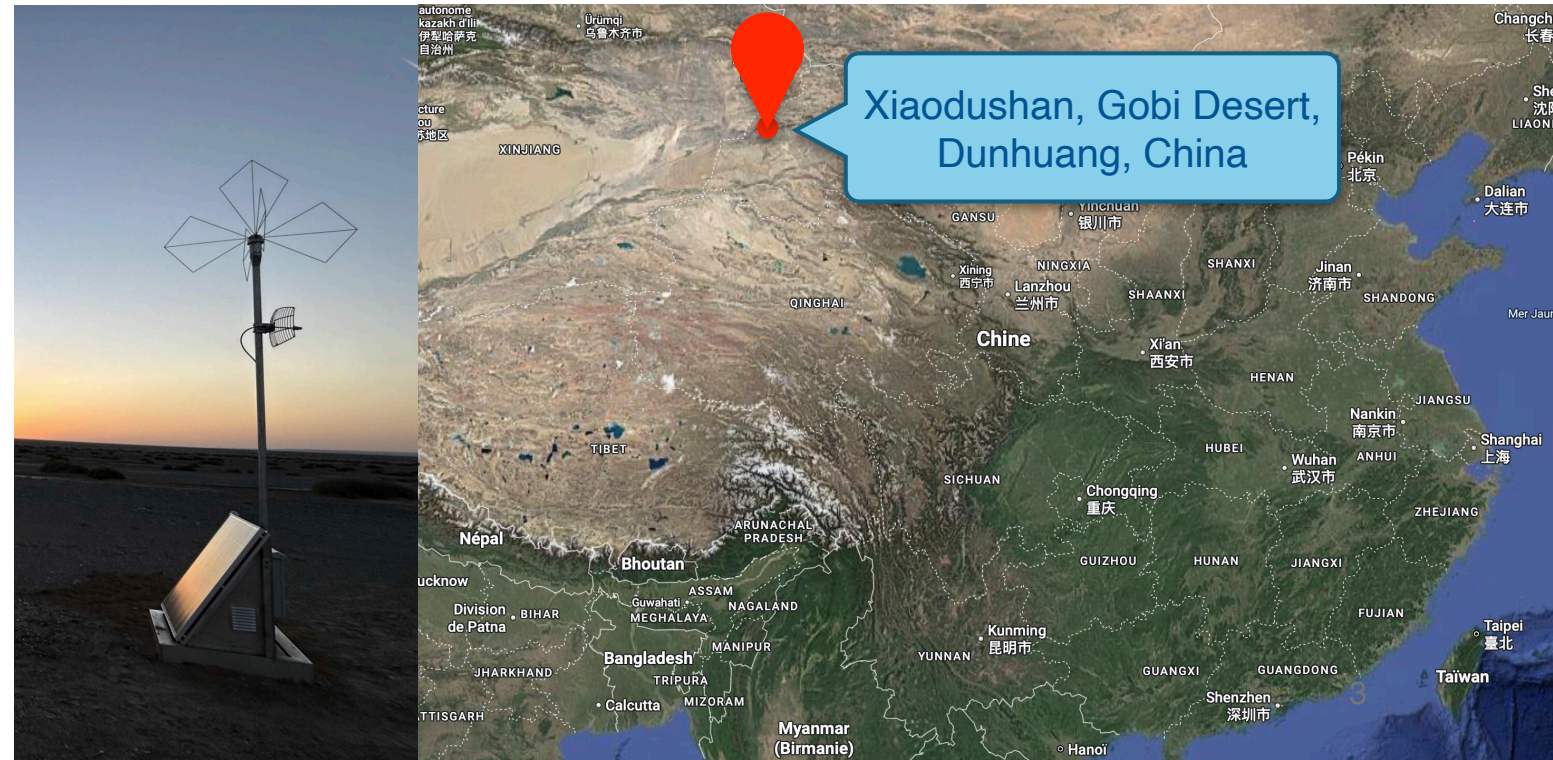
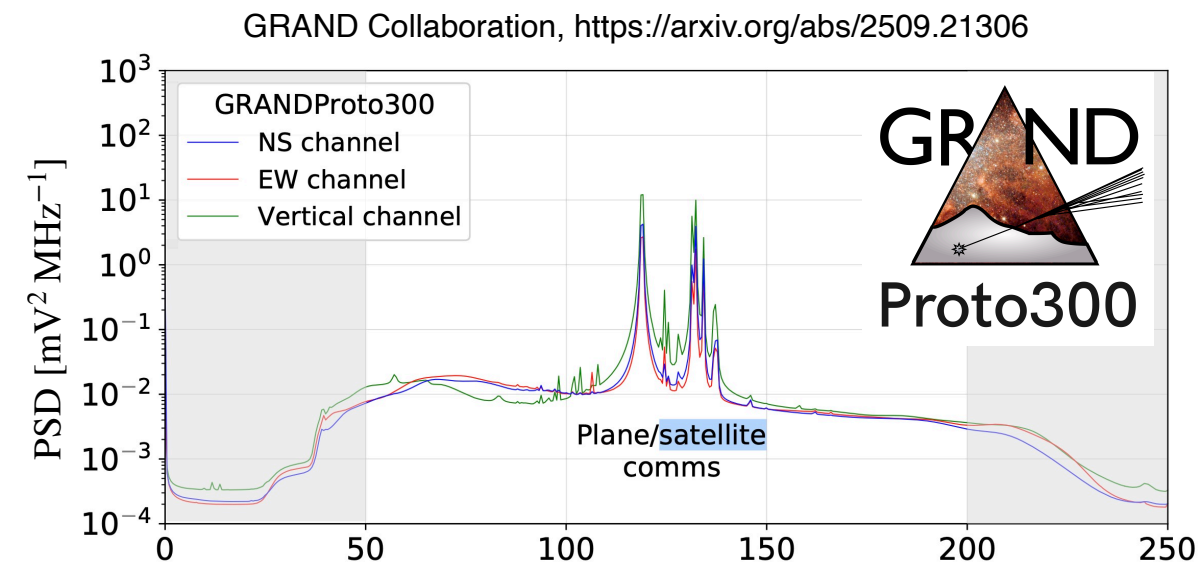
✓ Successful commissioning: plane tracks,
galactic noise, point sources

✓ **First cosmic rays detected!**

See Pengxiong Ma's talk



Current antenna layout of GRANDProto300

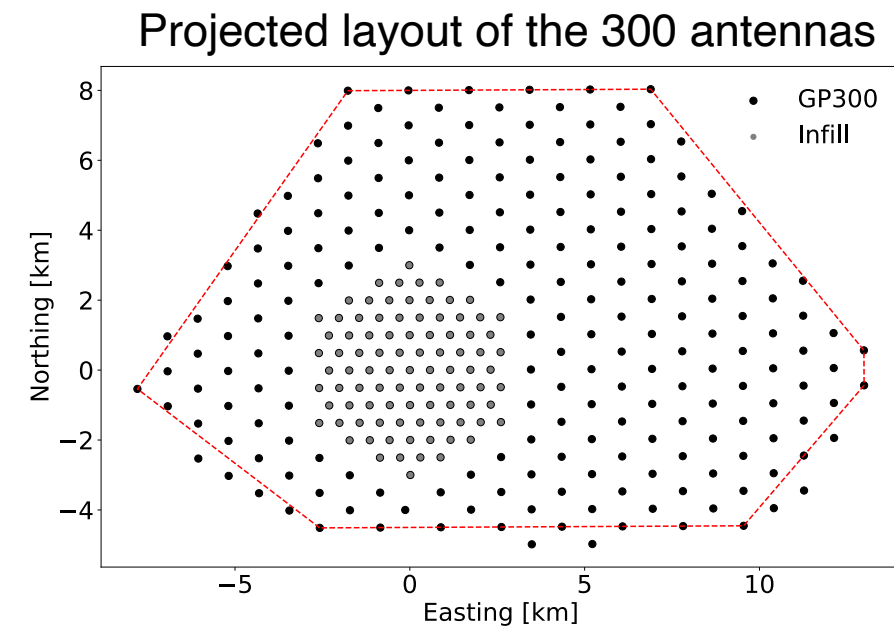


Next steps for GRANDProto300

Funding secured for the deployment of 300 antennas!

Next objectives:

- ❖ Understanding our detector
 - Quantify the detection performances: efficiency, purity, ...



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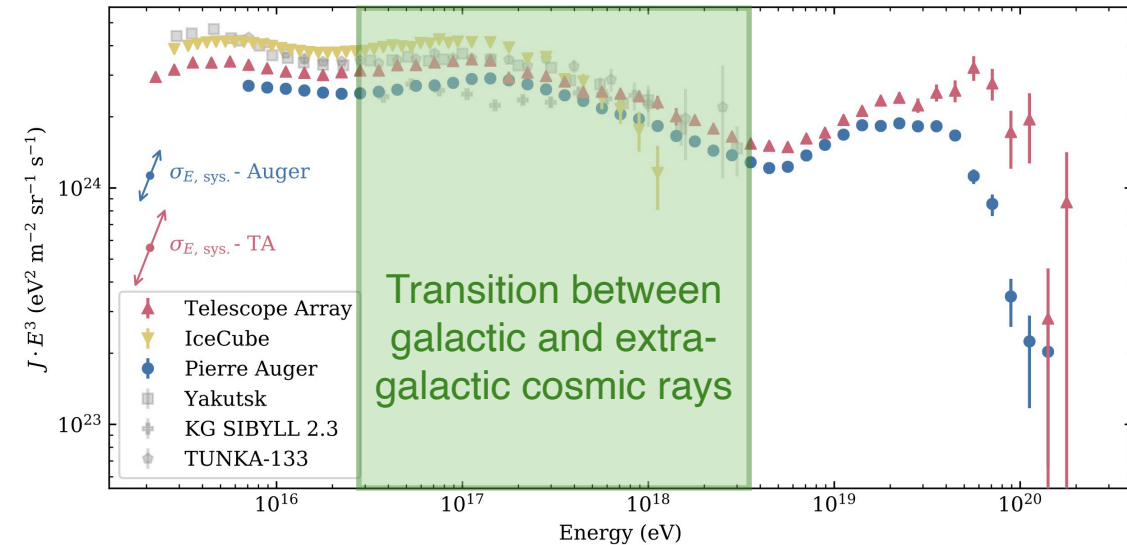
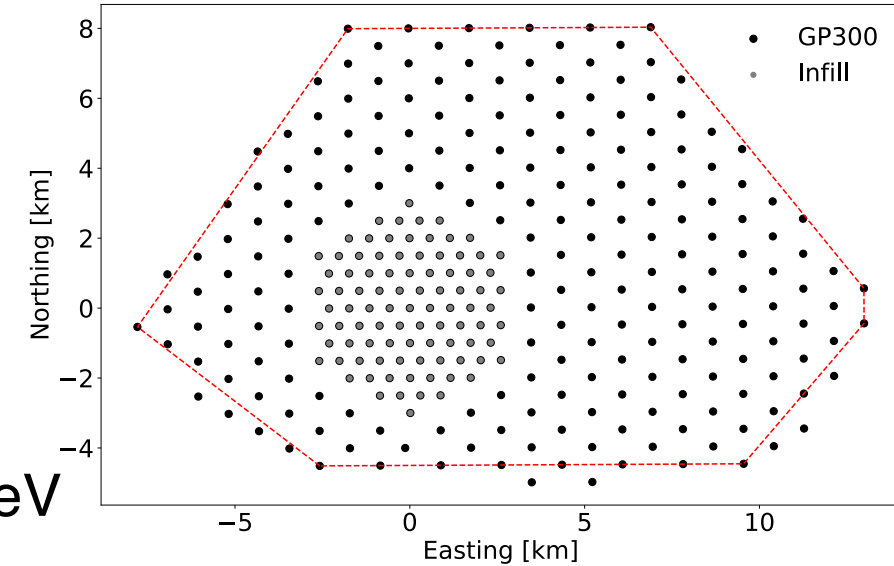
Next objectives:

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- ❖ Cosmic ray physics / astrophysics between $10^{16.5}$ - $10^{18.5}$ eV

Projected layout of the 300 antennas



A. Coleman et al., <https://arxiv.org/pdf/2205.05845> (2023)

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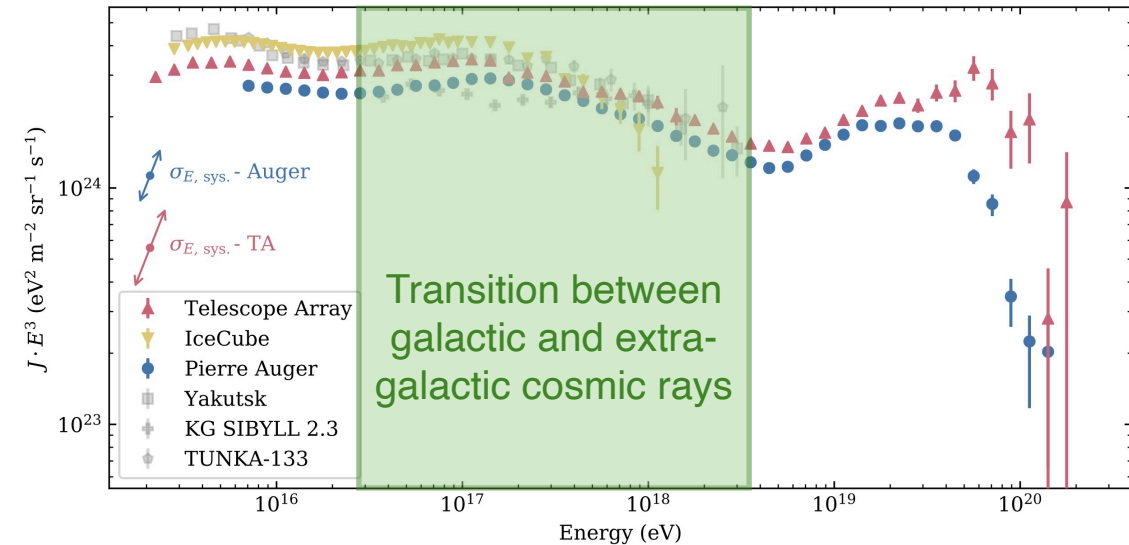
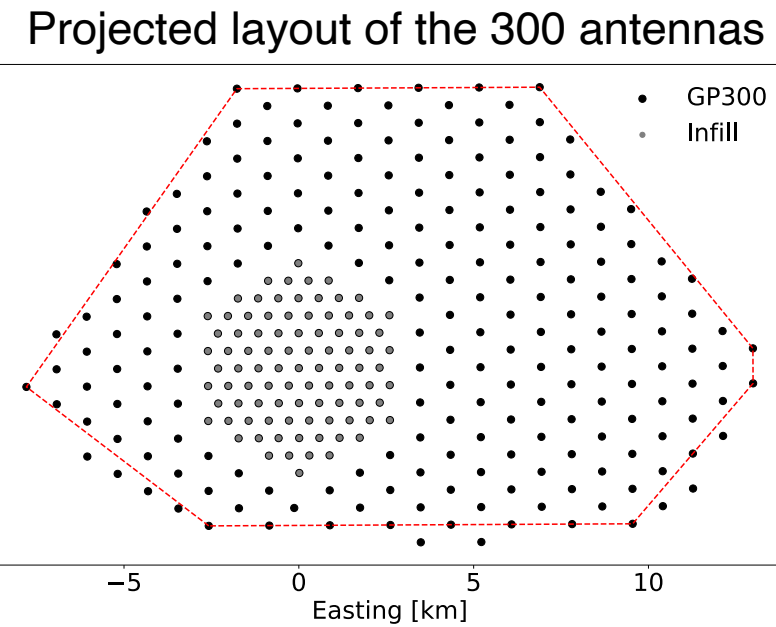
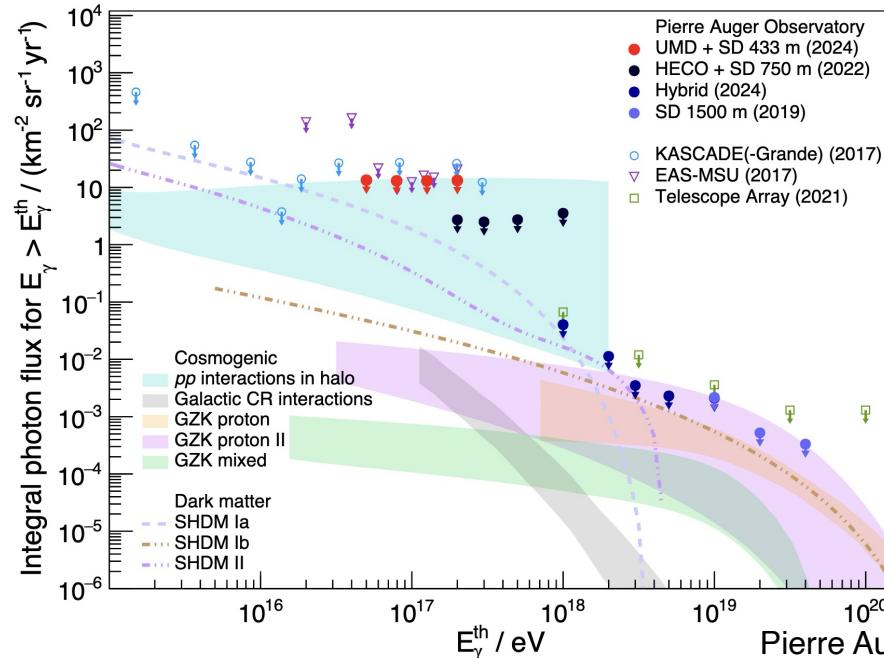
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❖ Understanding our detector

► Quantify the detection performances: efficiency, purity, ...

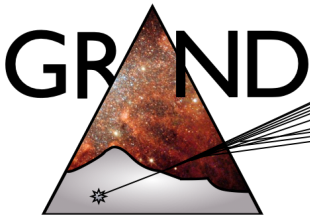
❖ Cosmic ray physics / astrophysics between $10^{16.5}$ - $10^{18.5}$ eV

❖ UHE ($> 10^{16}$ eV) gamma ray astrophysics?



A. Coleman et al., <https://arxiv.org/pdf/2205.05845> (2023)

Ultra-high-energy very inclined extensive air showers



Very inclined Extensive Air Showers (EAS) :

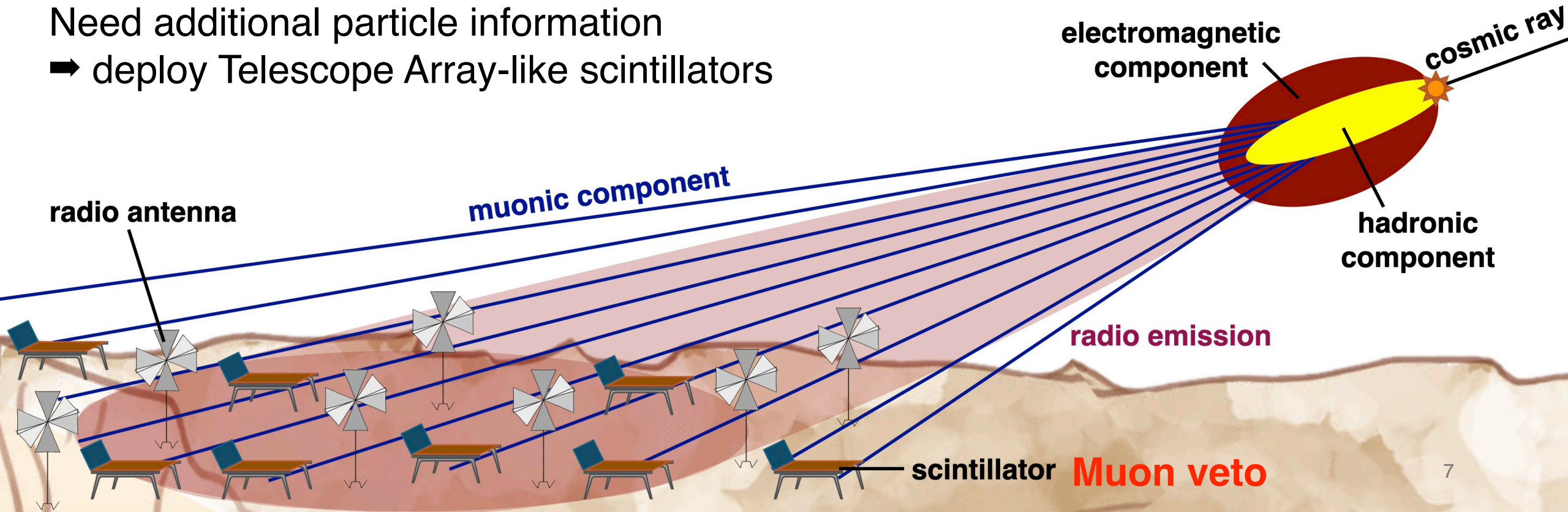
- Particle content absorbed except for muons
- Radio emission prominent

Difference between cosmic rays and gamma rays ?

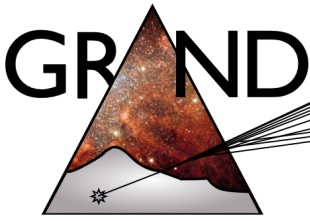
➡ muon content

Need additional particle information

➡ deploy Telescope Array-like scintillators



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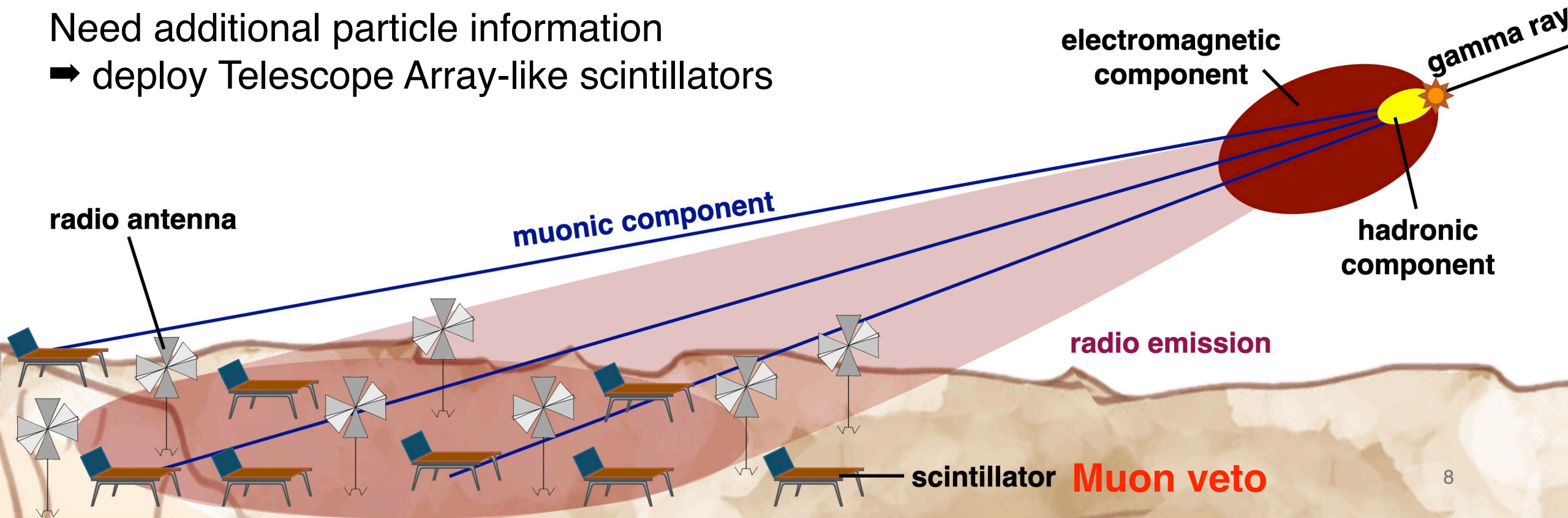
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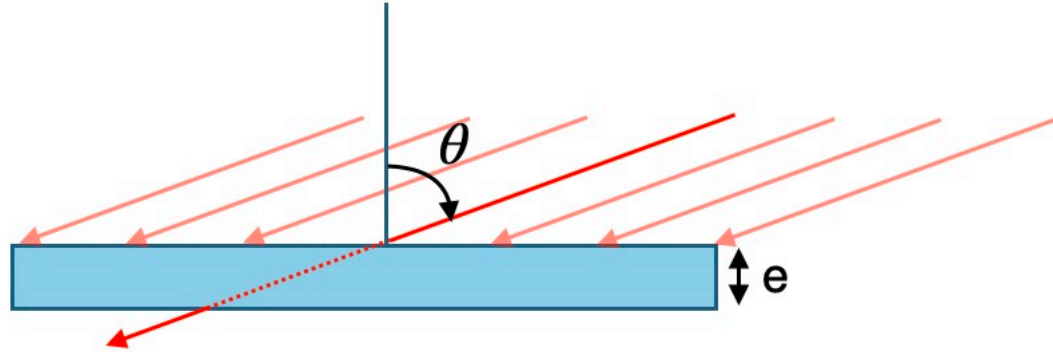
Inclined scintillators to detected very inclined showers?

Intuitively, inclined, or pyramidal scintillators, would allow to catch more particles.

Flat

Small effective area: $A \cos \theta$

Effective area effect

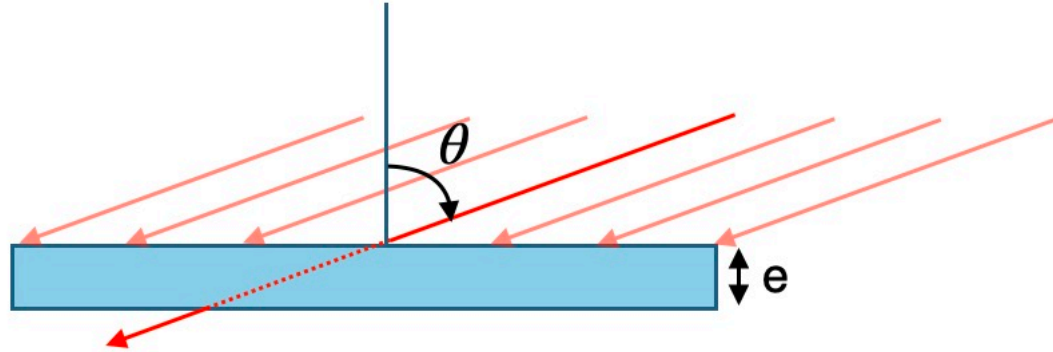


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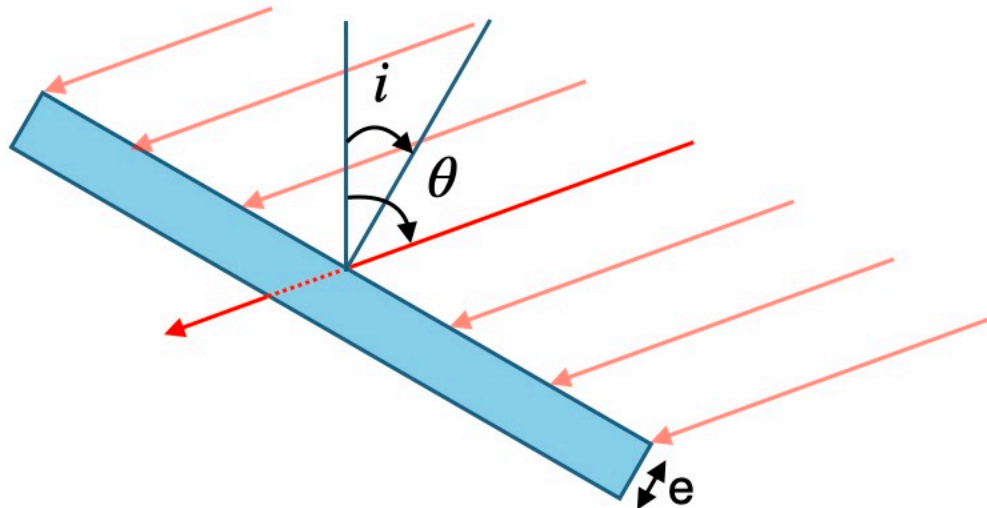
Flat

Small effective area: $A \cos \theta$



Inclined

Larger effective area: $A \cos(\theta - i)$

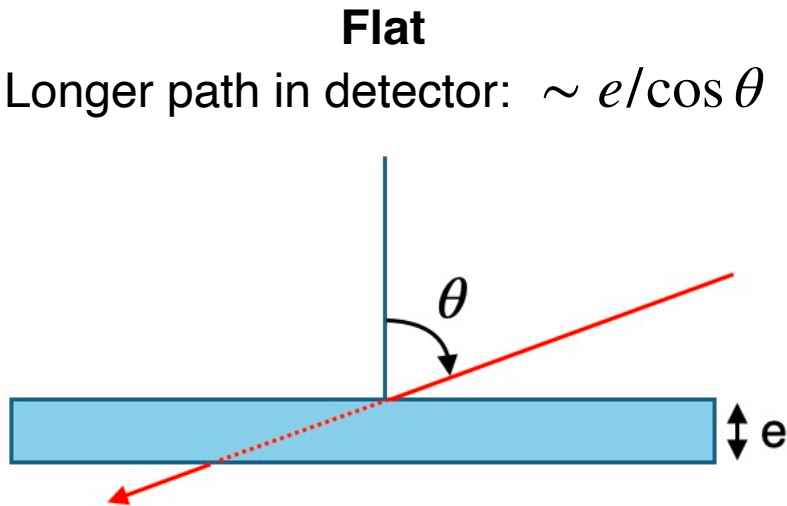
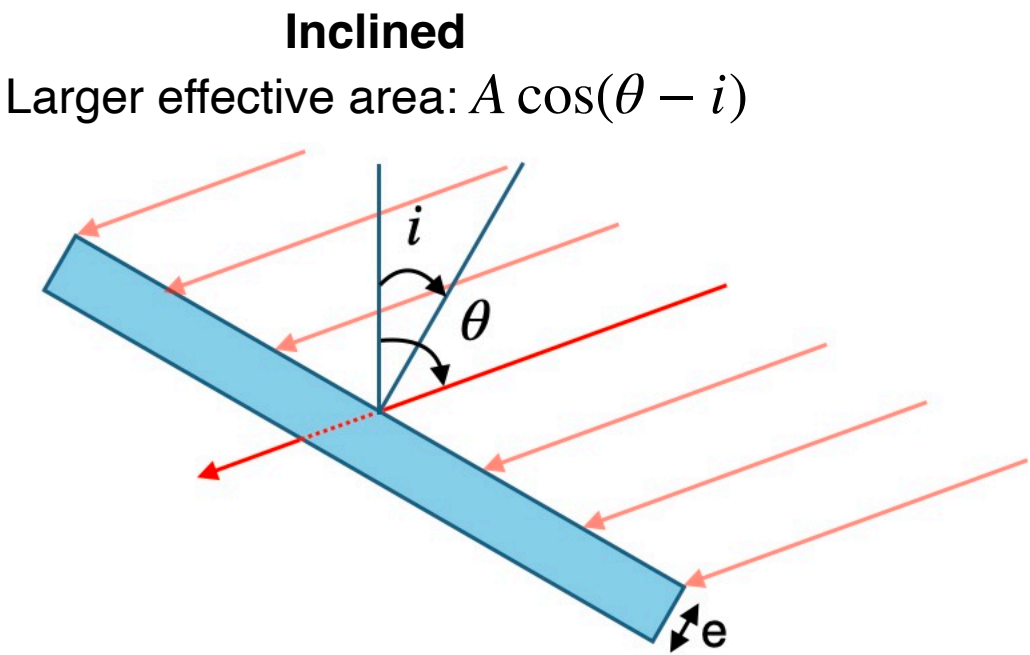
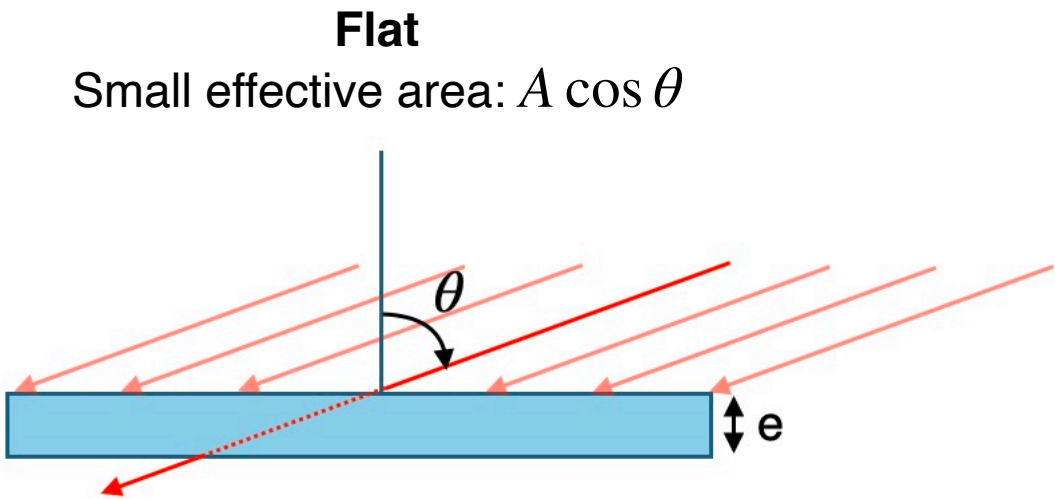


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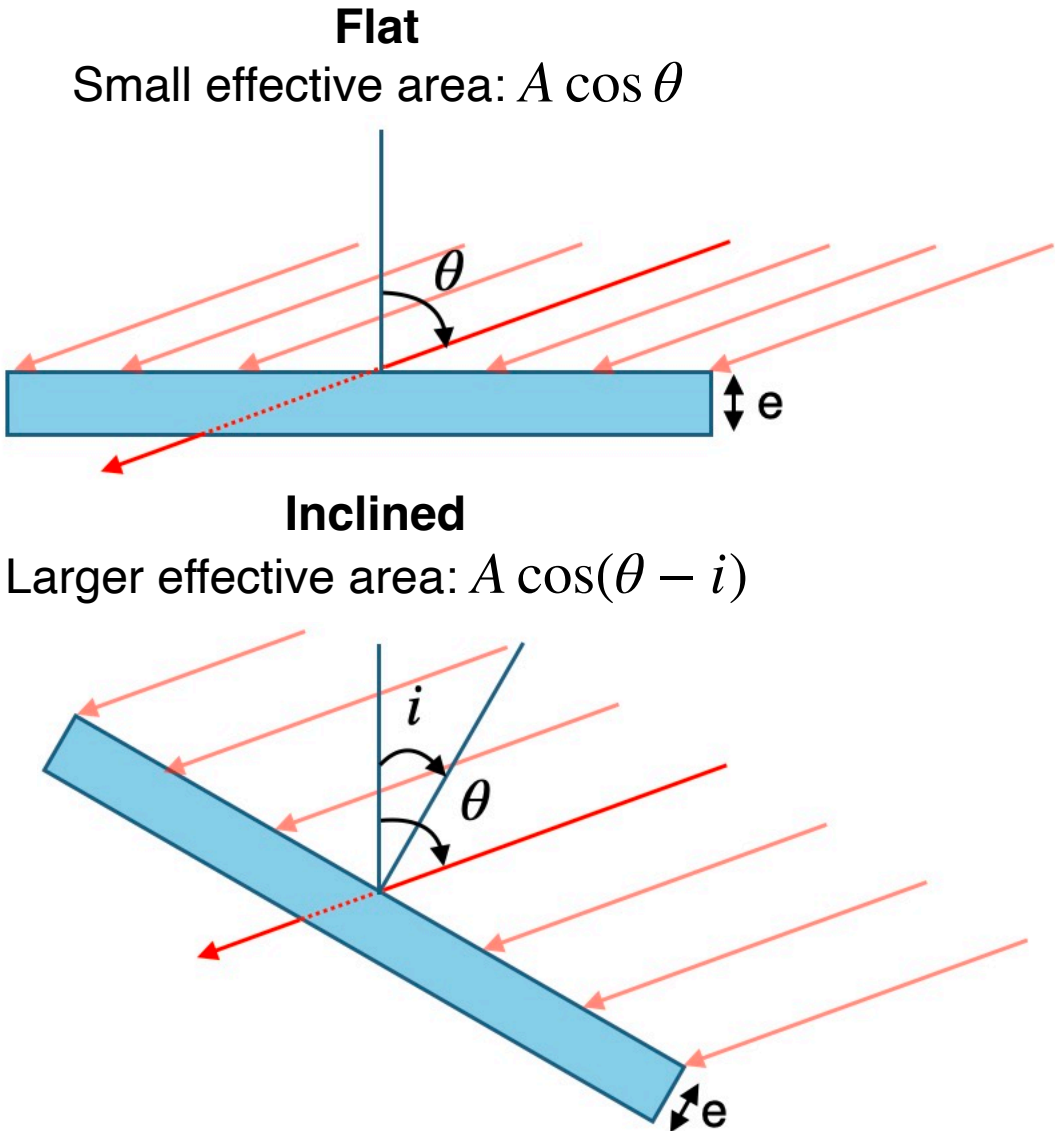


Path length effect

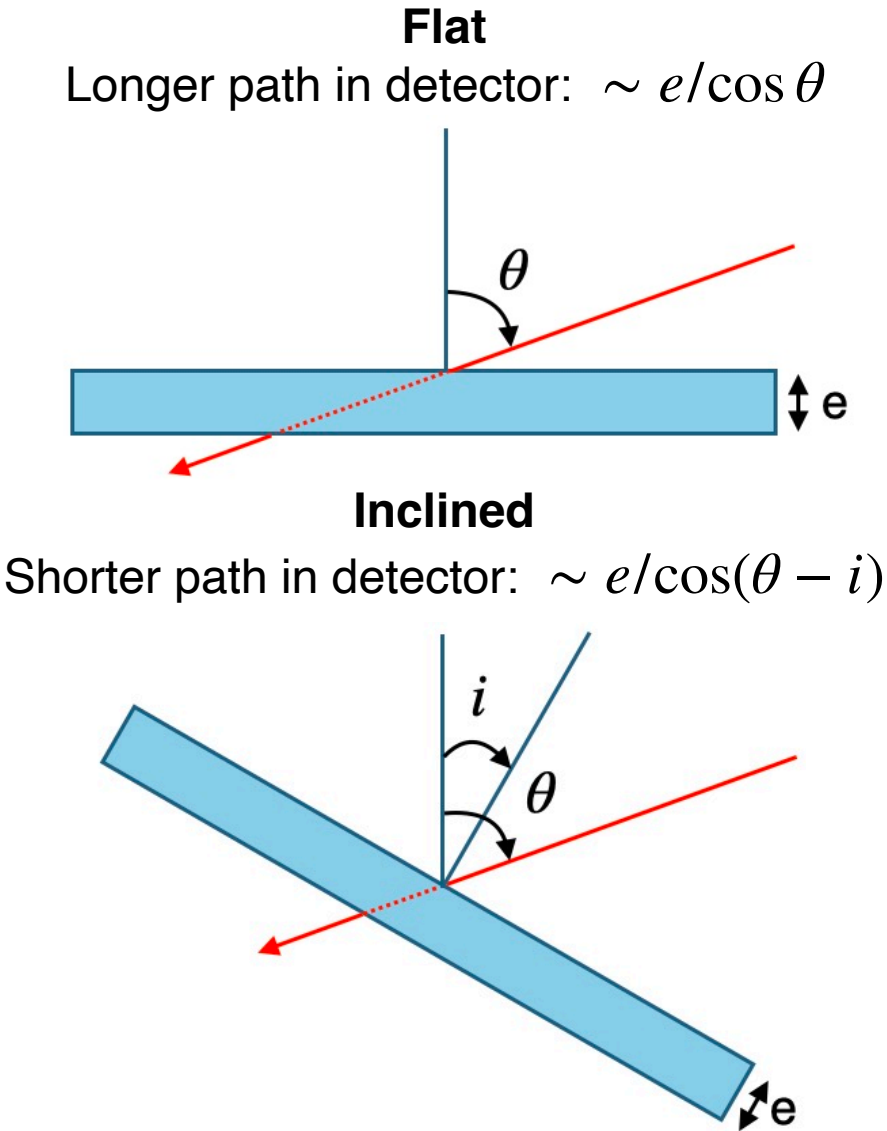
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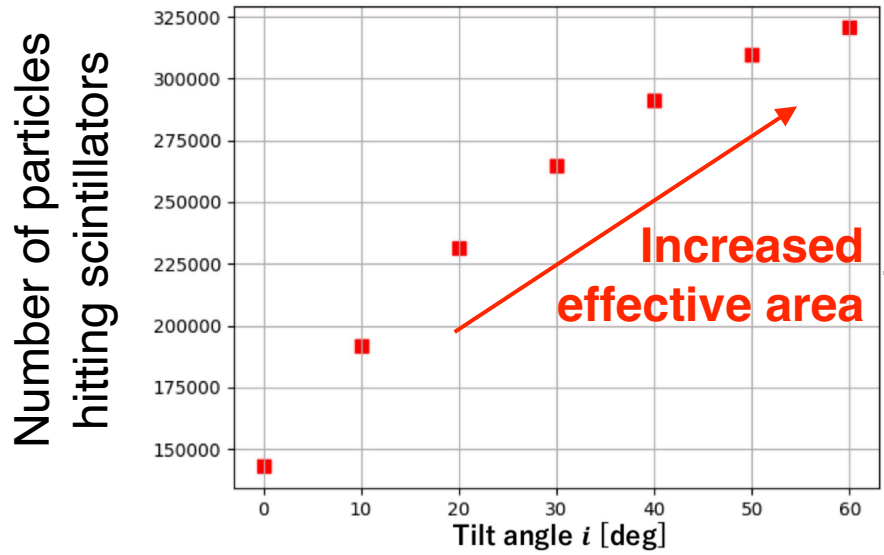
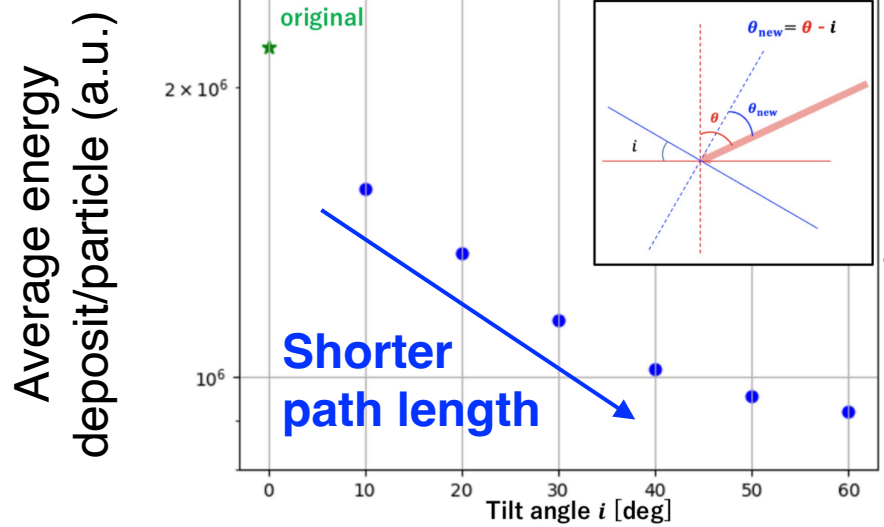


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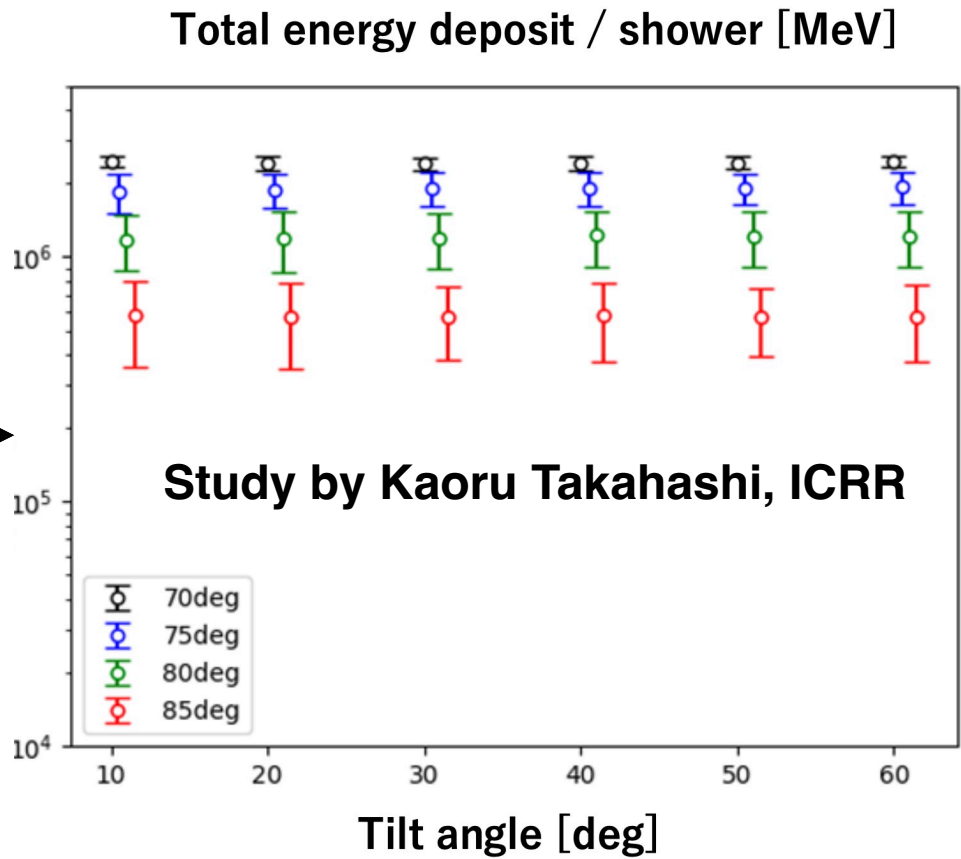
Effect 1



Effect 2

Two opposite effects:

- effect 1: effective area increased
- effect 2: shorter path, i.e. smaller energy deposit



Detection depends on total energy deposit

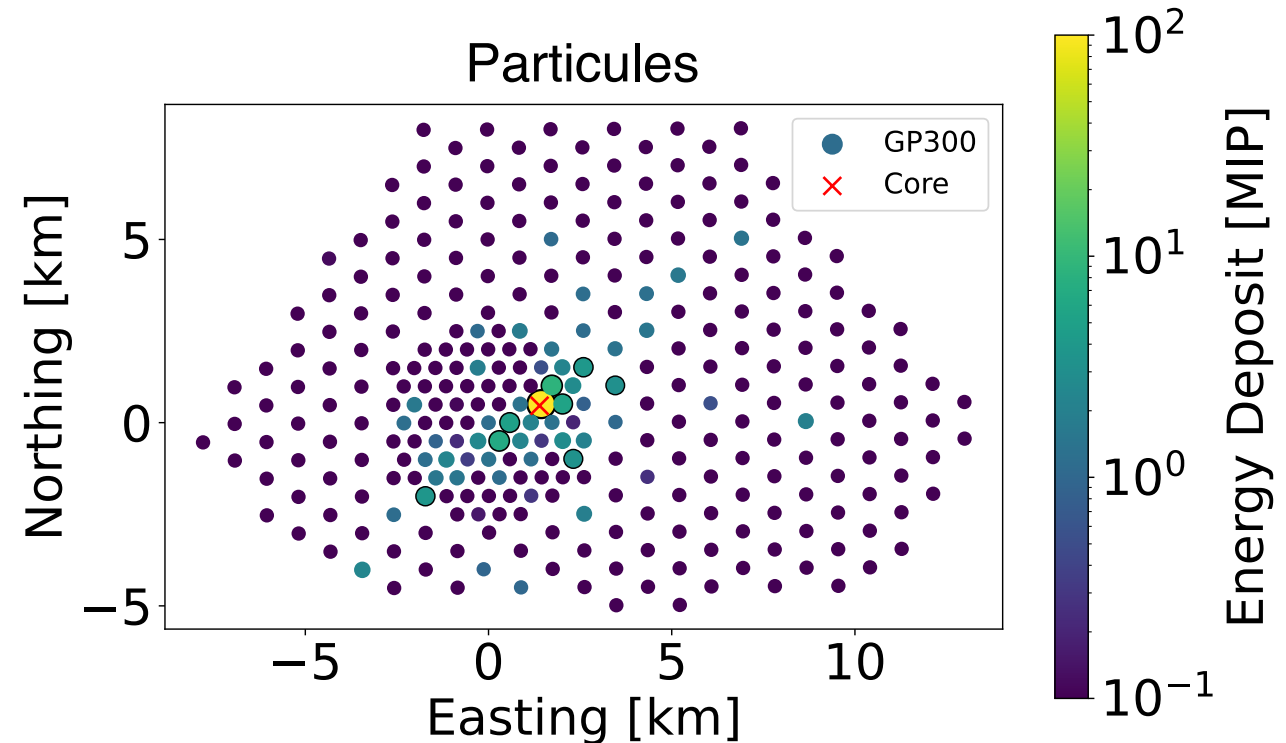
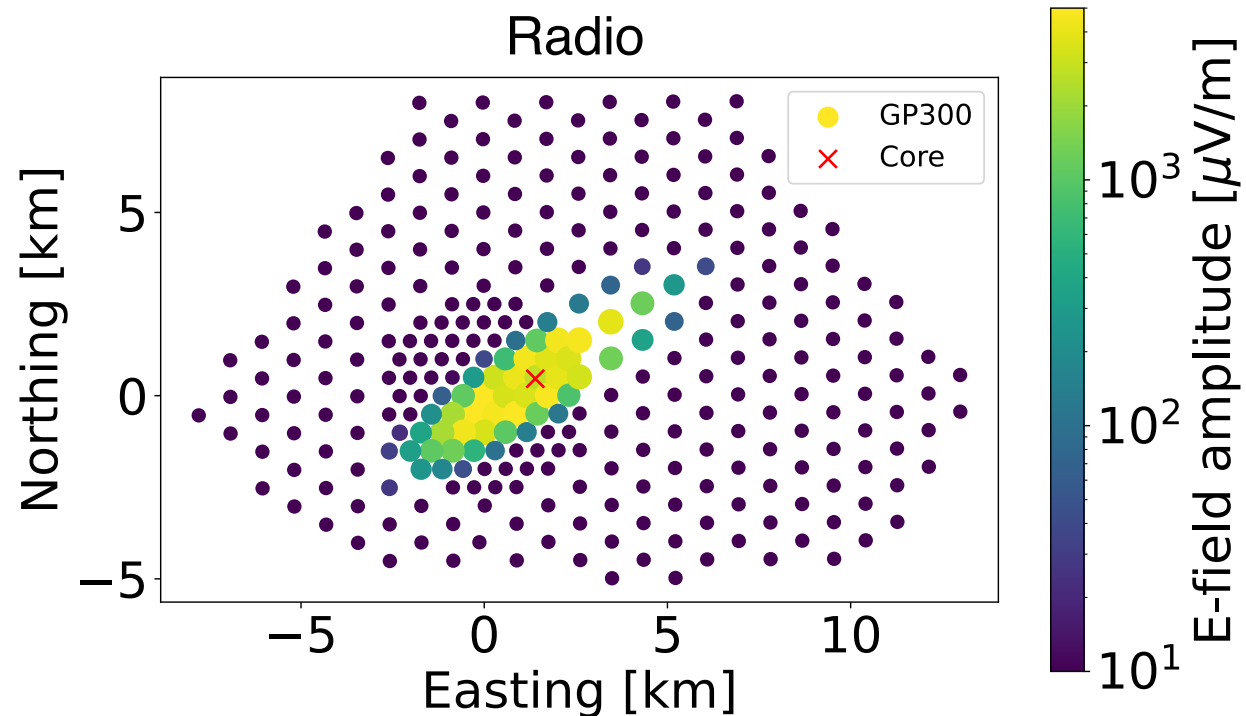
Total energy deposit mostly independent of the tilt angle

Characteristics of inclined showers

- Simulations with CORSIKA and CoREAS
- Energy deposit computation with GEANT4-based Telescope Array Surface Detector simulation package

Antennas + Scintillators at GP300 positions

Proton with $\log_{10}(E/\text{eV}) = 18.5$, $\theta = 76^\circ$, $\phi = 303.9^\circ$



Trigger parameters

Radio

- Filtered between 50-200 MHz
- **4 antennas** with amplitude $\geq 75 \mu\text{V/m}$

Particles

- **3 scintillators** with energy deposit ≥ 3 MIP (Minimum Ionising Particles)

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Photon with $\log_{10}(E/\text{eV}) = 18.5$, $\theta = 76^\circ$, $\phi = 291.4^\circ$

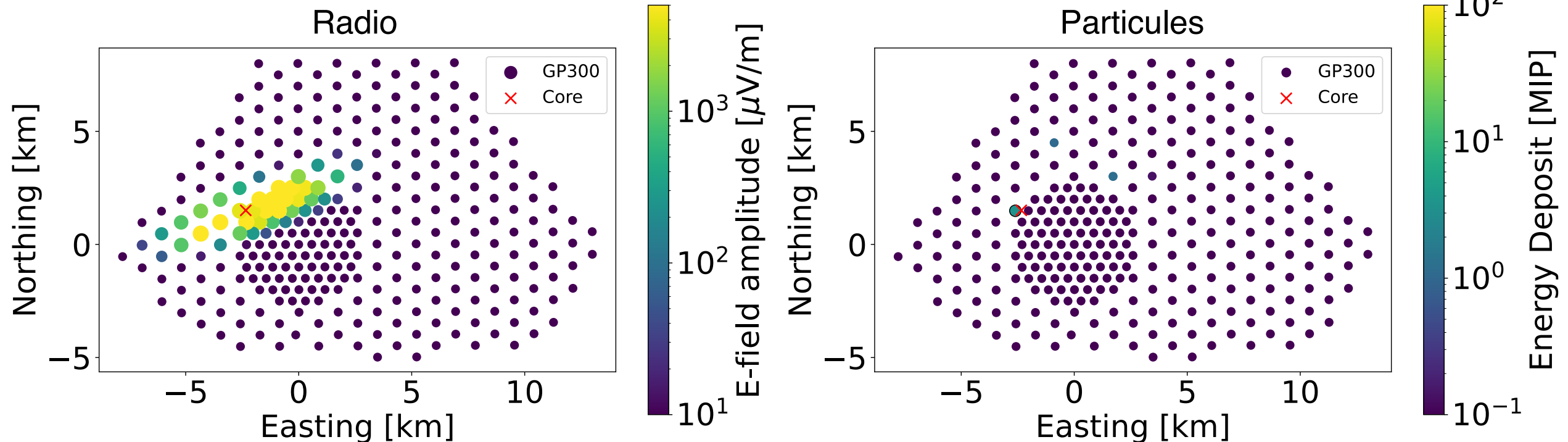
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Proton-gamma discrimination

Identify photon events in the dominant proton background

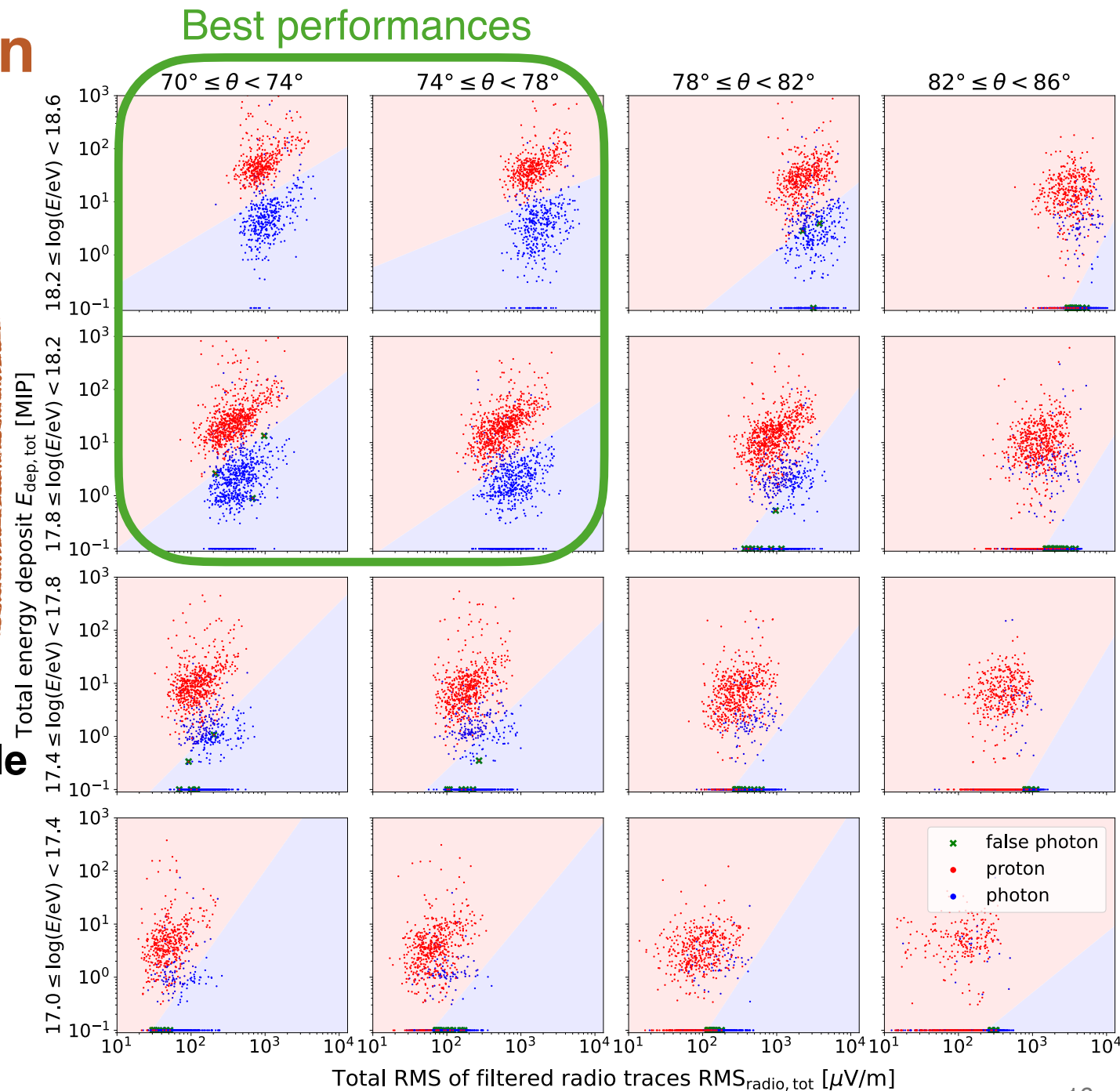
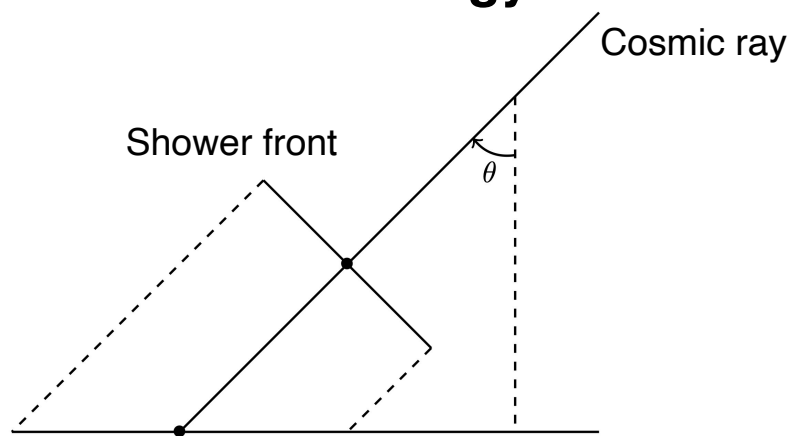
Classification based on **two observables**:

- the **total energy deposit** (particles)
- the **total radio signal** (sum of the RMS of the filtered radio traces)

$$\text{RMS}_{\text{radio,tot}} = \sum \left[\sum_{j=x,y,z} \frac{1}{N} \sum_{i=0}^N E_j^2(t_i) \right]^{\frac{1}{2}}$$

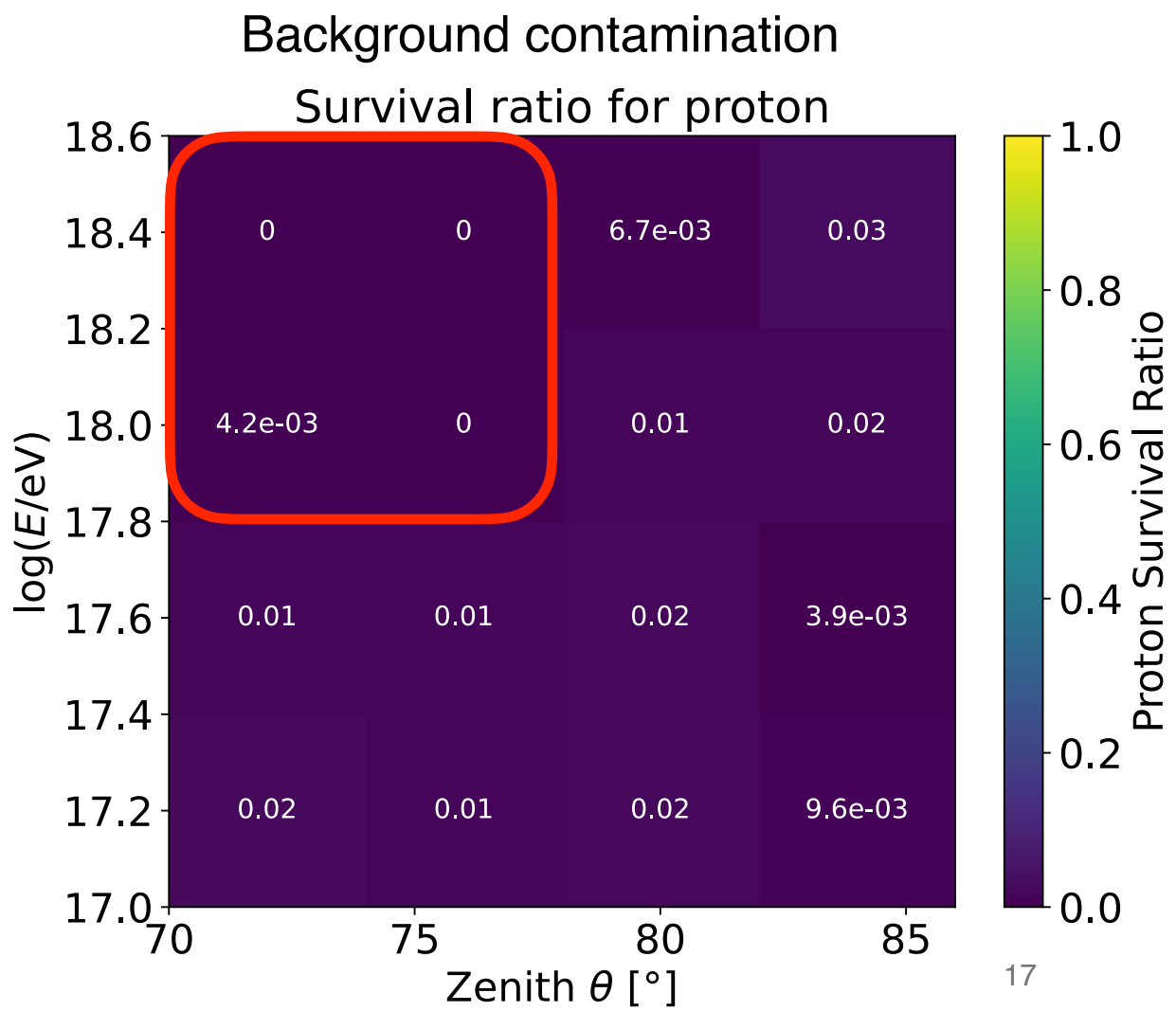
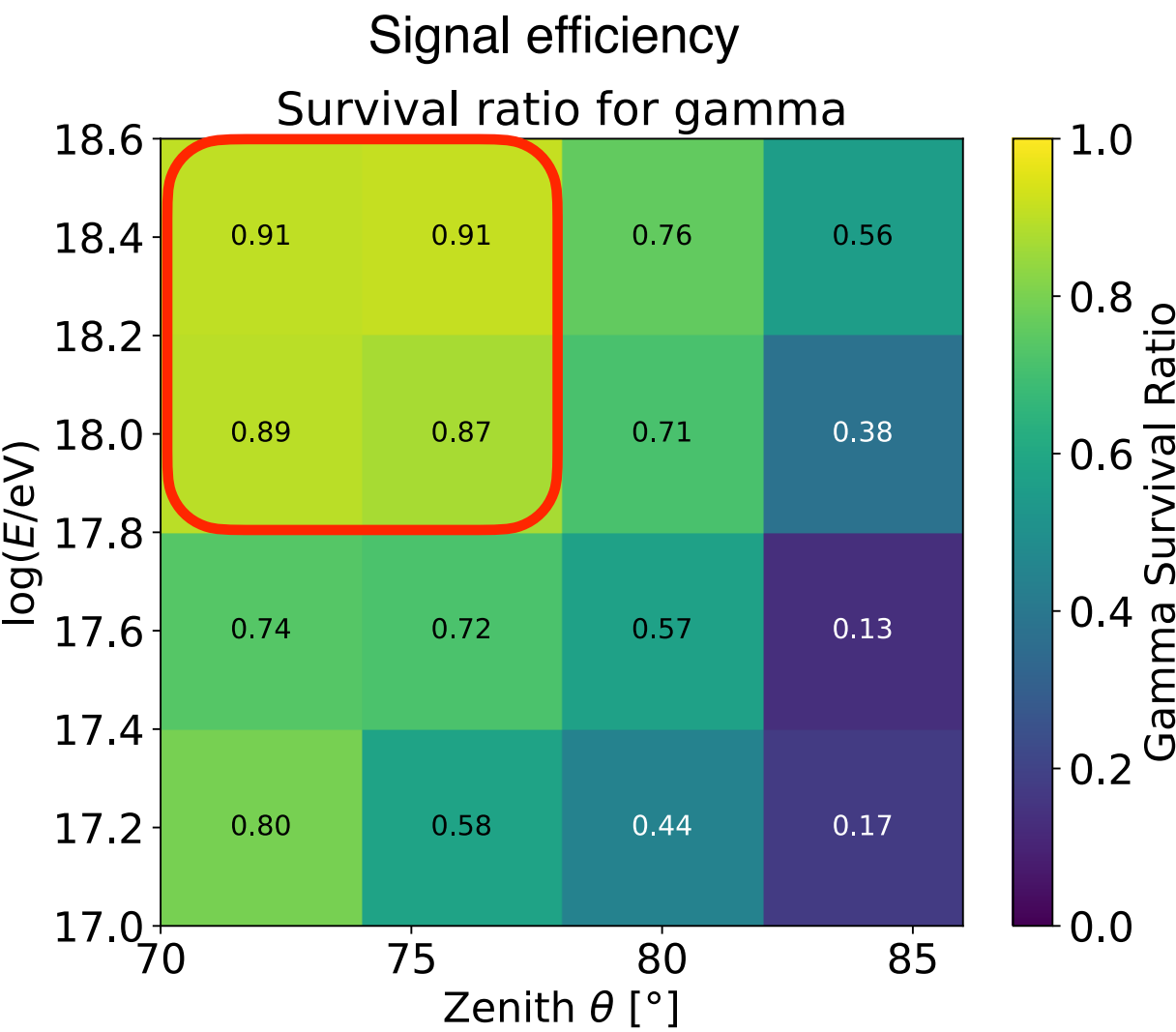
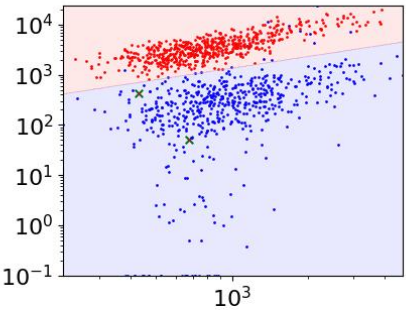
with $E_j(t)$ the electric field along direction j at time t , and N the number of time steps.

Split events based on **energy** and **zenith angle**



Performances

Survival ratio: ratio of events identified as photons

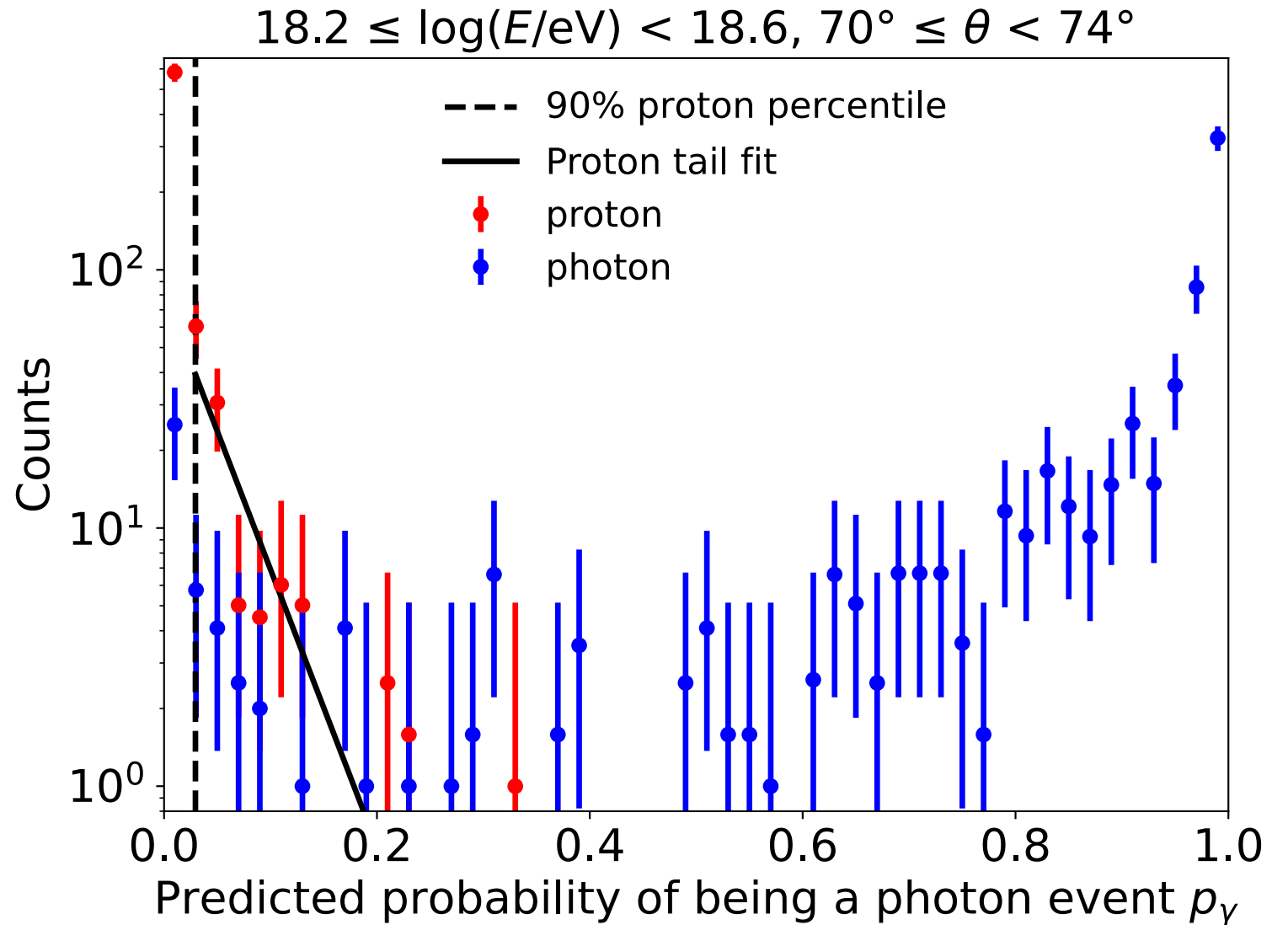


Varying threshold

Vary the cut on the predicted probability to be a photon event $p_{\gamma,\text{cut}}$

For each bin:

- fit of the tail (10%) of the proton distribution
- integrate the fitted line to compute background contamination

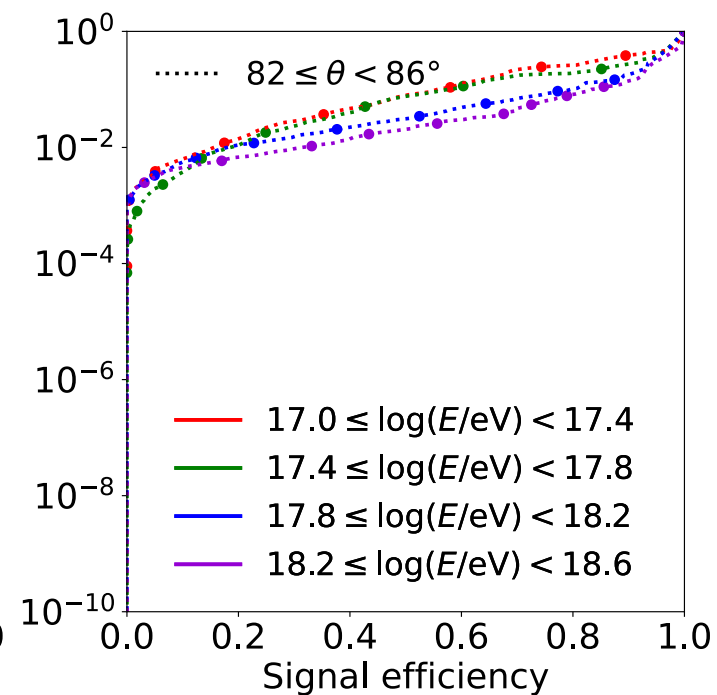
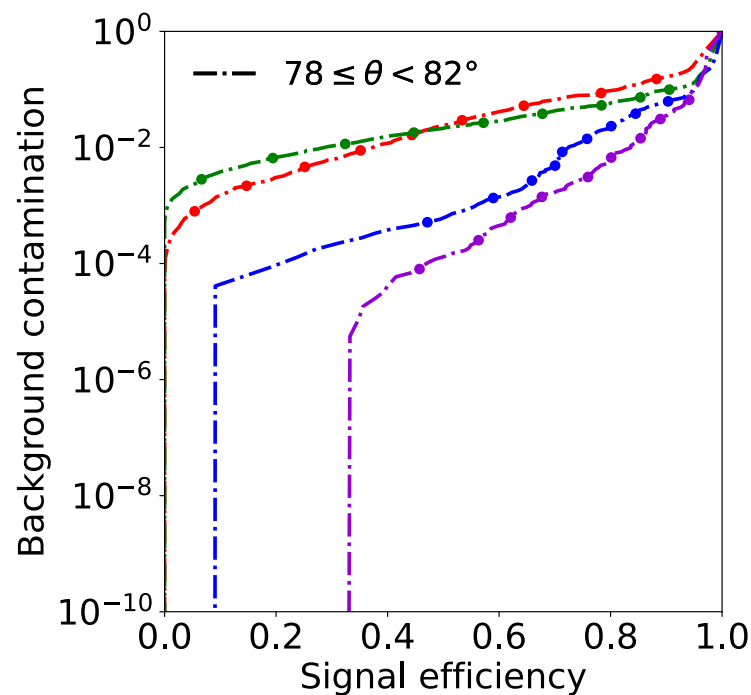
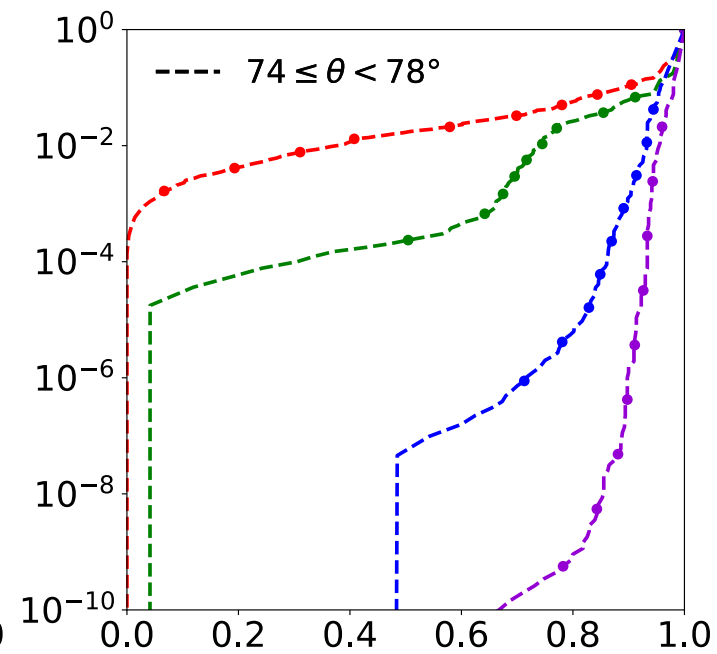
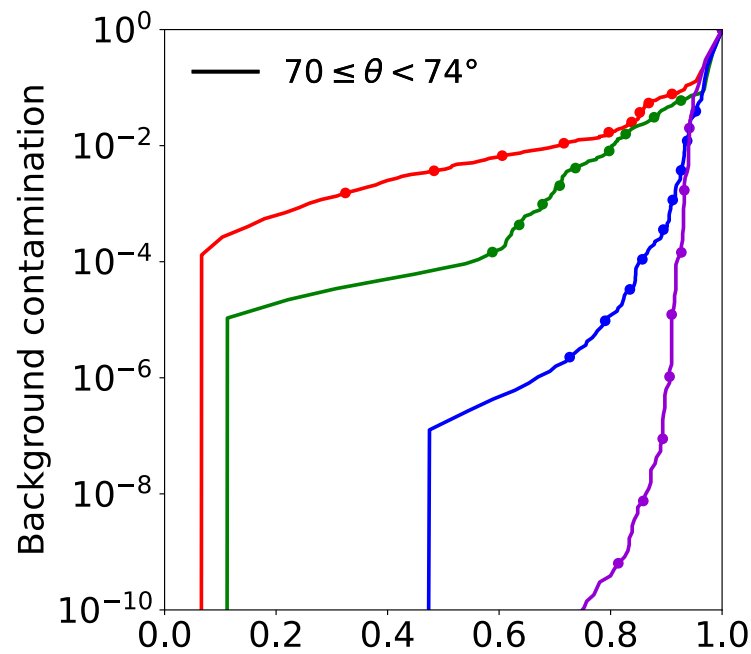


Varying threshold

Good performances at high energies and low zenith

At lower energies:

- lower particle content detected
 - At higher zenith angles:
 - very large and sparse footprints
 - poor particle detection efficiency
- ➡ Poor discrimination



Choice of threshold

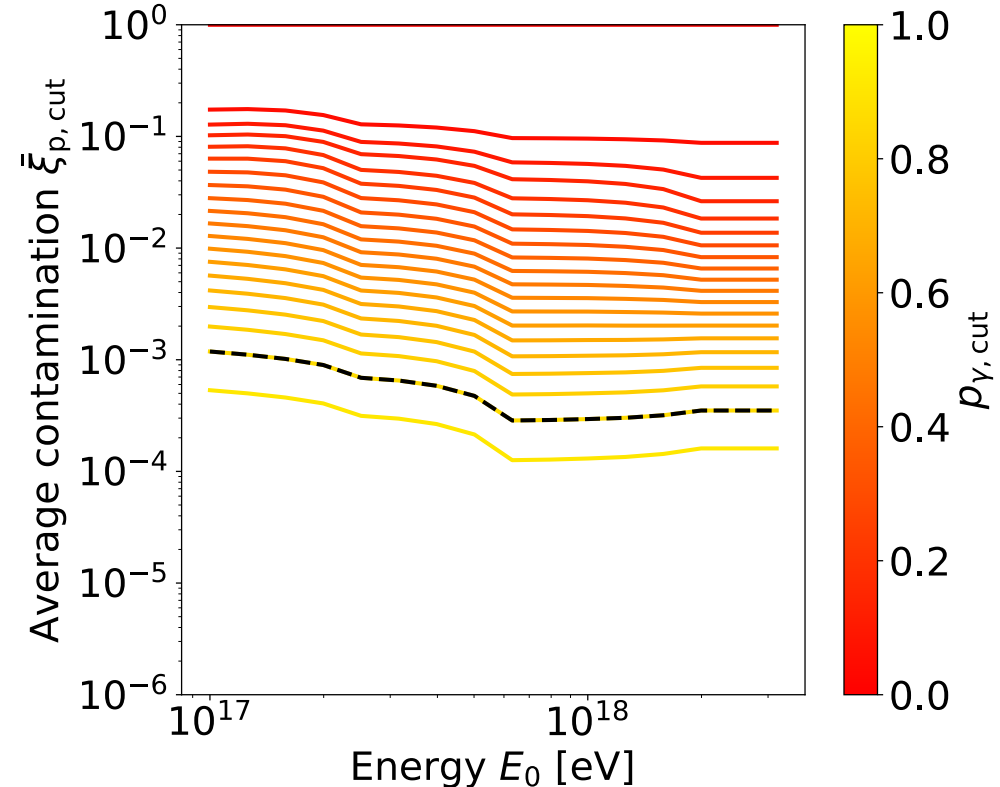
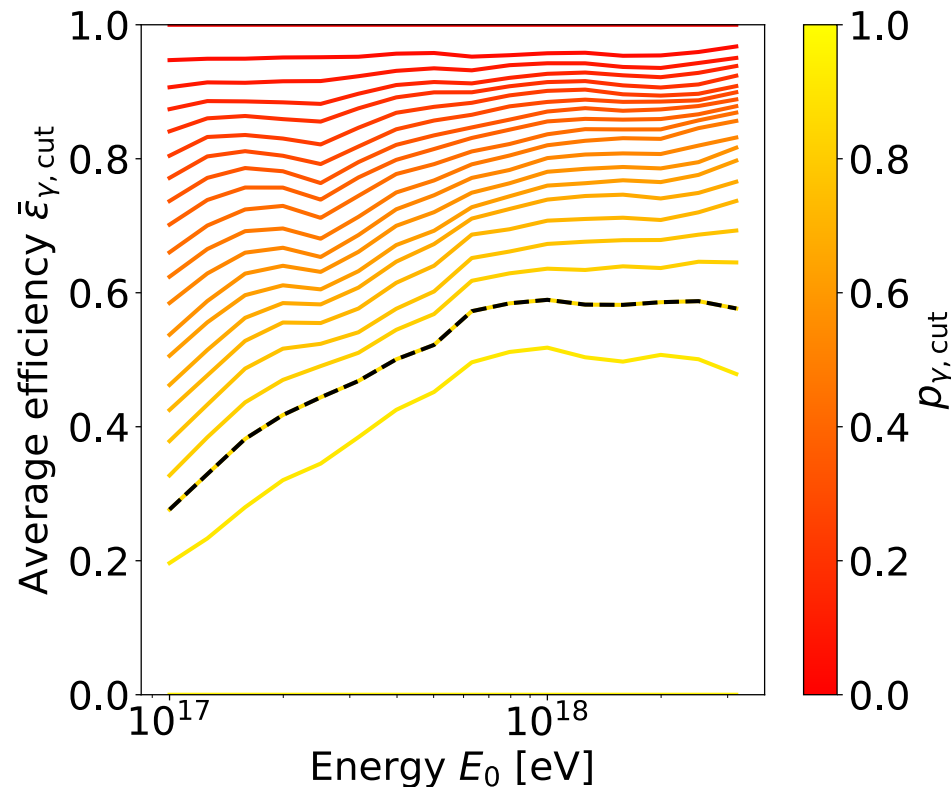
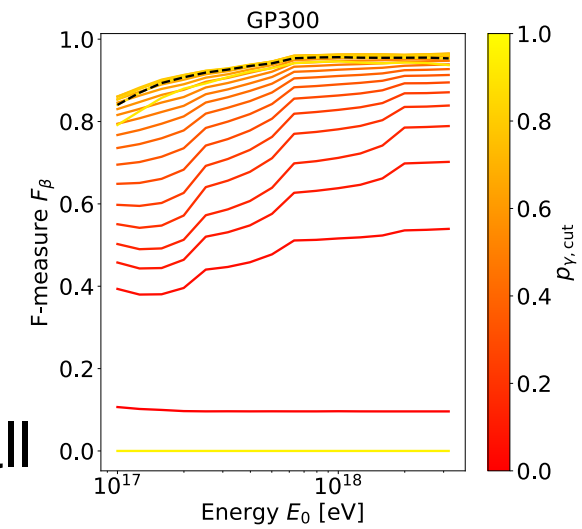
$$F(\beta) = \frac{(1 + \beta^2)pr}{\beta^2 p + r} = \frac{(1 + \beta^2) \text{TP}}{(1 + \beta^2) \text{TP} + \beta^2 \text{FN} + \text{FP}}$$

Compromise between:

- reducing the background contamination
- maintaining high signal efficiency

Use $F(\beta)$ -measure: weighted harmonic mean of precision and recall

Threshold chosen: $p_{\gamma, \text{cut}} = 0.9$



Limits on the photon flux at UHE

Threshold for the photon identification cut
 $p_{\gamma,\text{cut}} = 0.9$

Constraints on the gamma ray flux?

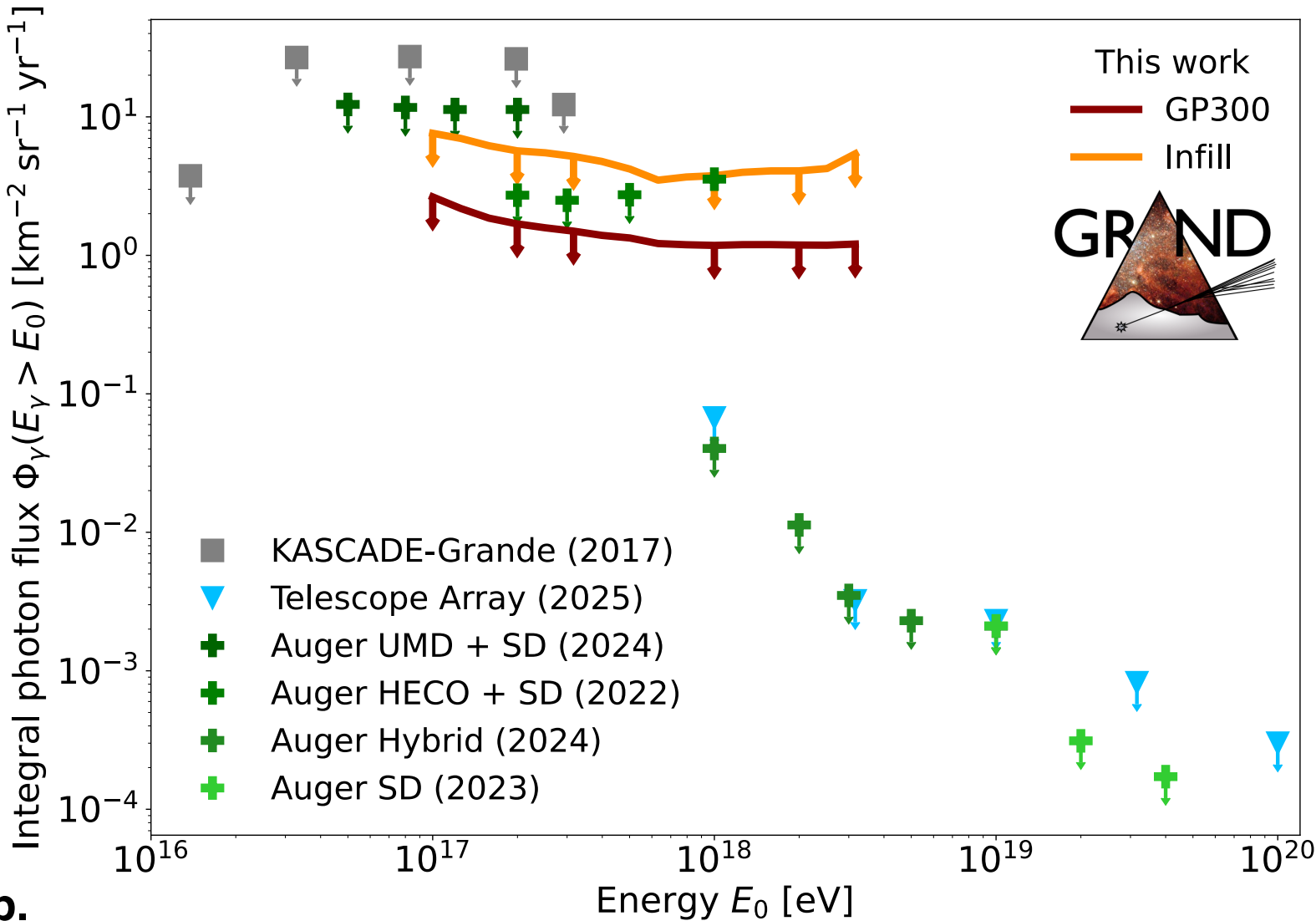
Feldman-Cousins upper limit at C.L. confidence level on the number of events

$$\Phi_{\gamma,\text{U.L.}}^{\text{C.L.}}(E_{\gamma} > E_0) = \frac{N_{\gamma}^{\text{C.L.}}}{\bar{\epsilon}_{\gamma,\text{cut}} \mathcal{E}_{\gamma}}$$

Average efficiency of the photon identification cut

Detector exposure to photons

PM, Takahashi, Kotera, Sako, in prep.



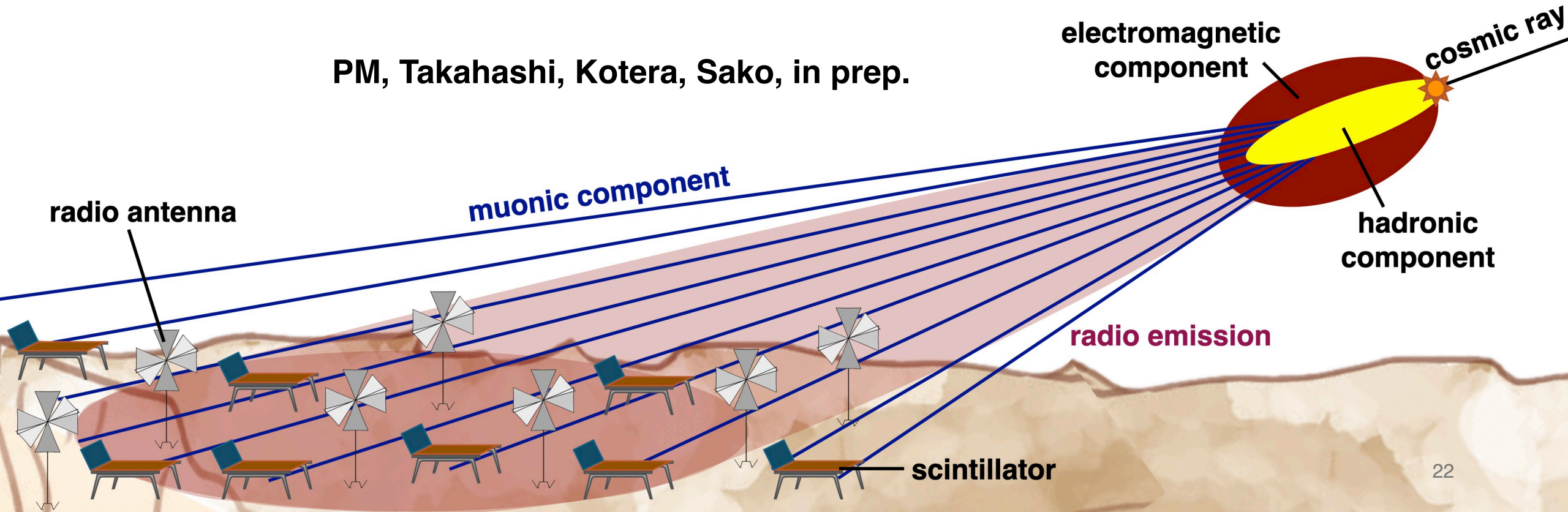
Conclusion

Use **scintillators** to act as **muon veto** for proton-gamma discrimination

- Study on GP300 layout
- Discrimination efficiency below 10^{-4} for $10^{18-18.5}$ eV, and 70° - 78°

Competitive limits with existing experiments
Different parameter range, with zenith above 70°

PM, Takahashi, Kotera, Sako, in prep.



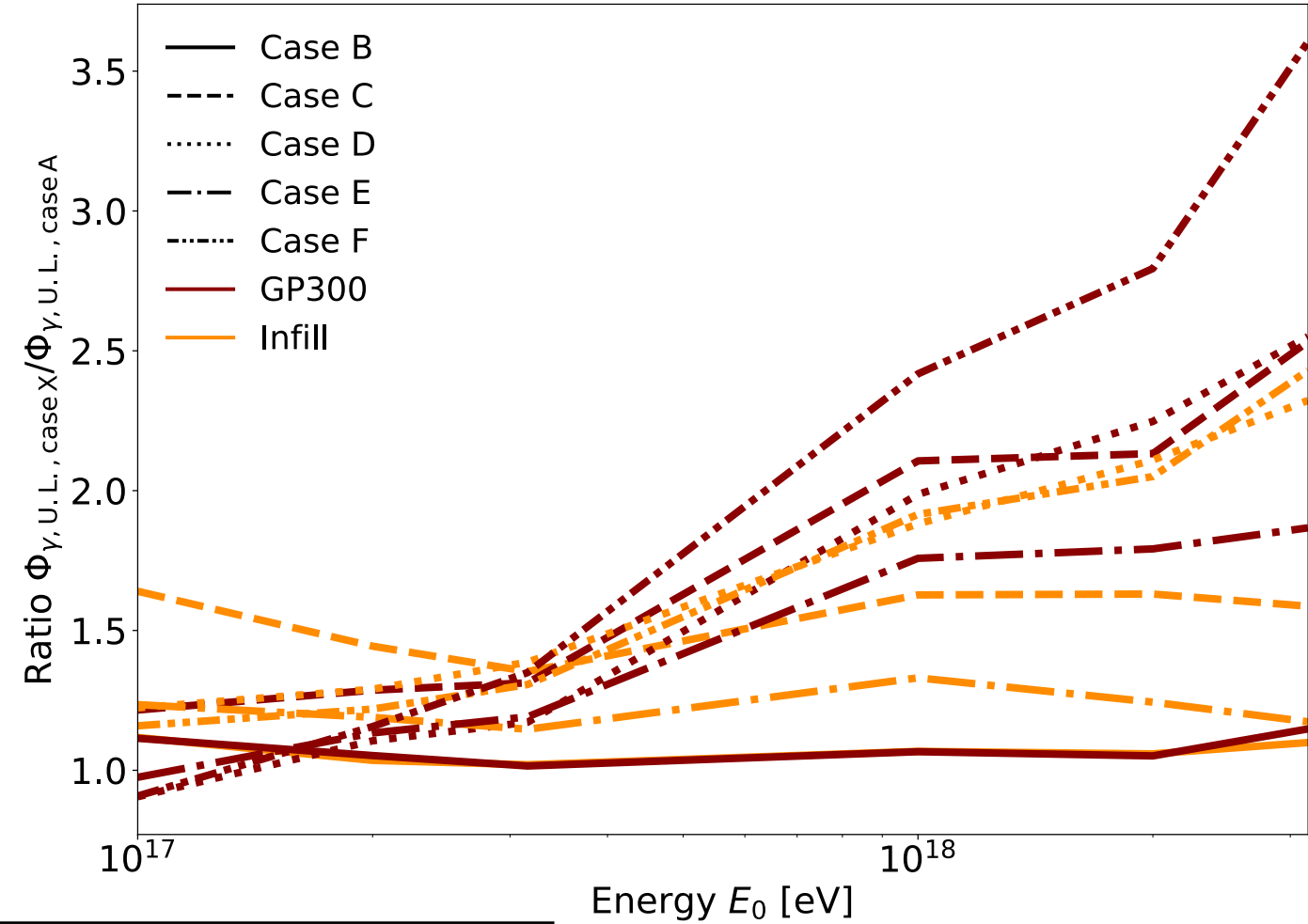
Back-up slides

Impact of reconstruction resolution

Energy and zenith resolution not perfect

- Test different cases:
- with/without energy binning
 - with broad/thin zenith bins
 - with/without sample weighting

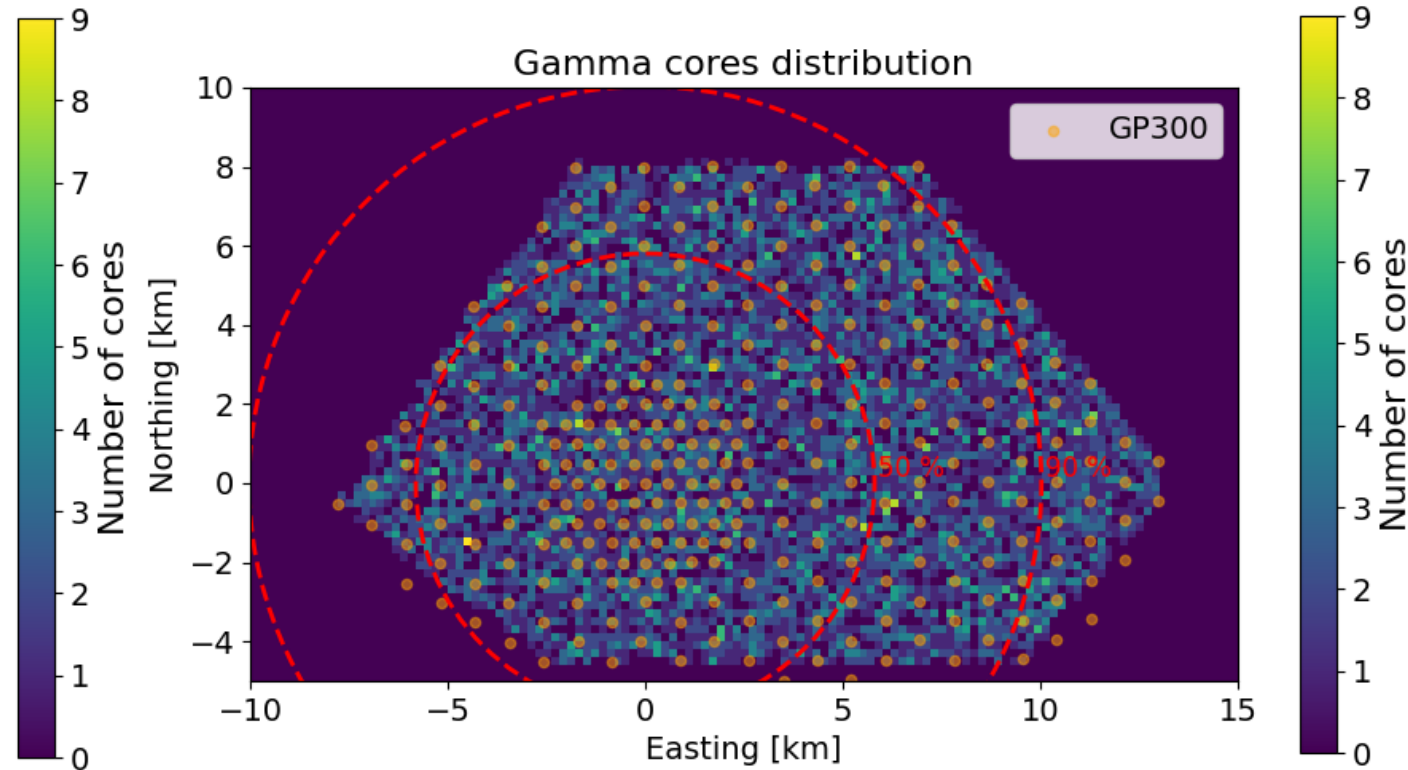
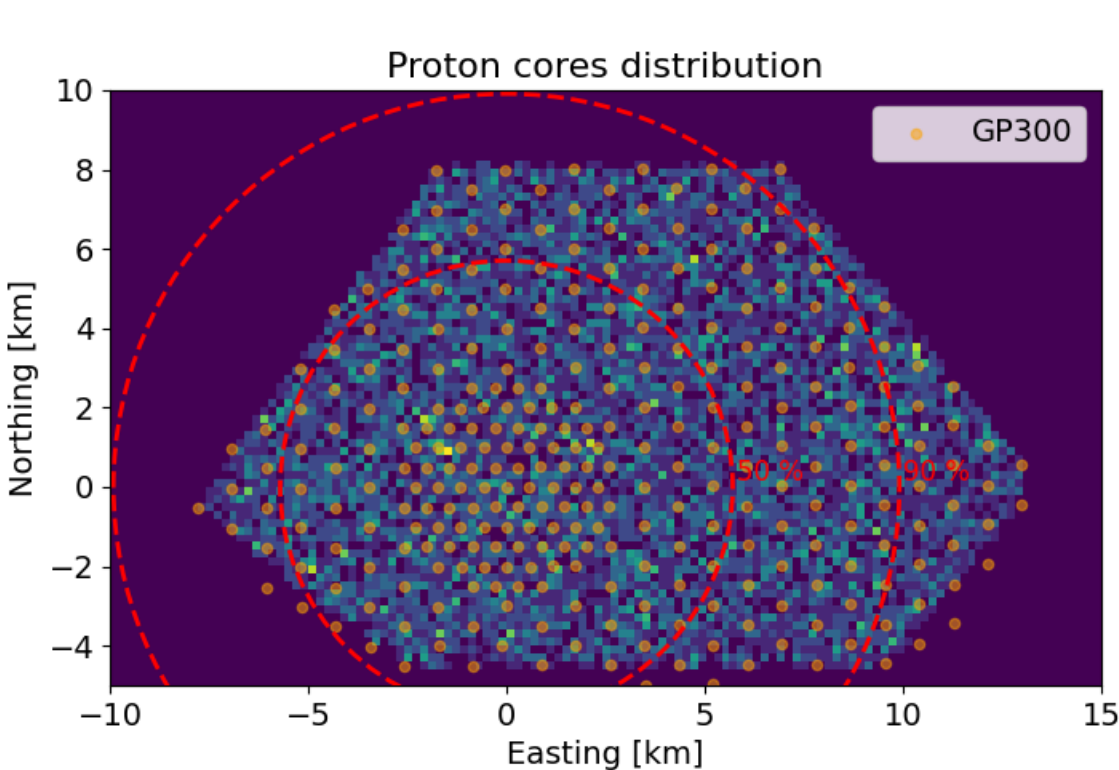
Impact on the flux limits achievable?



Case	Energy bins $\Delta \log_{10}(E/\text{eV})$	Zenith bins $\Delta \theta$ (°)	Sample weighting $w(E)$
A (Reference)	0.4	4	E^{-2}
B (No weights)	0.4	4	1
C (No energy bins)	—	4	E^{-2}
D (No energy bins, no weights)	—	4	1
E (No energy bins, thin zenith bins)	—	1	E^{-2}
F (No energy bins, thin zenith bins, no weights)	—	1	1

Simulation library

- Proton and gamma primary : 8972 events for each primary
- Energie range: 10^{17} eV to $10^{18,5}$ eV (included)
- Zenith between 70° and 85° (included) with uniform distribution
- Random azimuth between 0° and 360°
- Layout of GP300 (official)
- Random core contained



Particle footprint analysis: Methodology

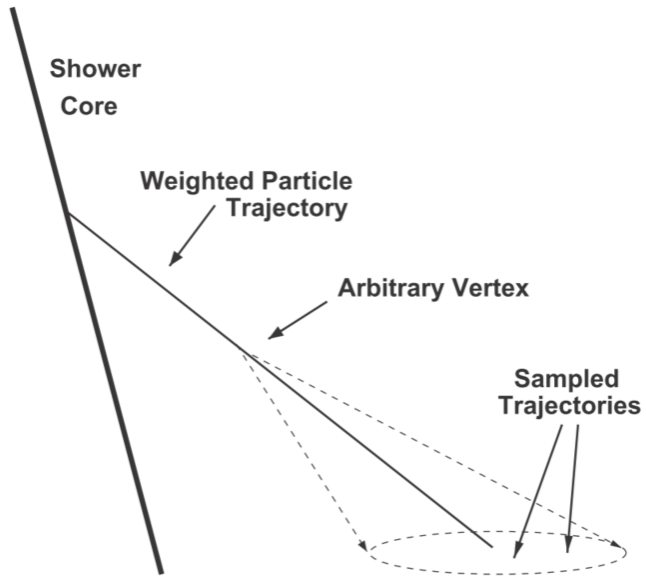
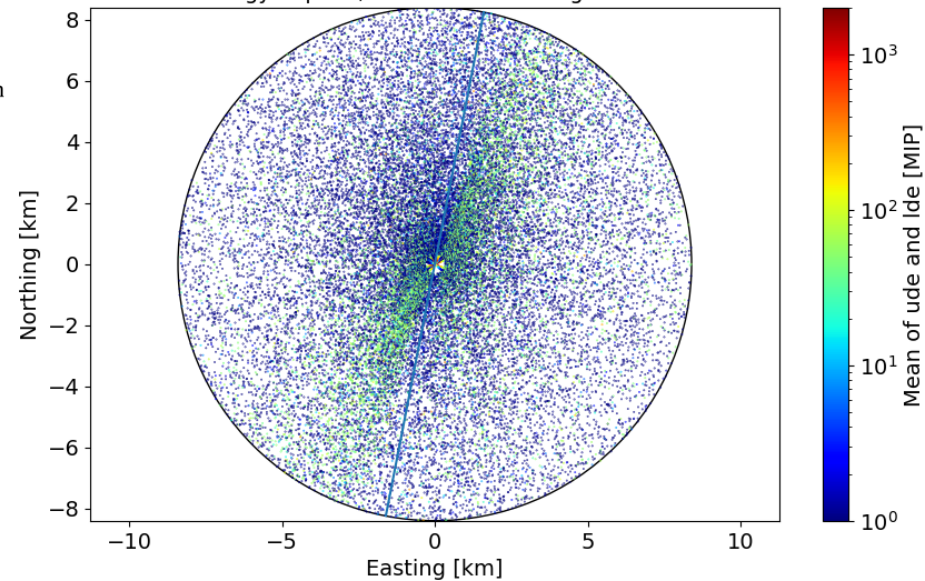


Fig. 1. Geometry for a "Gaussian cone" with a vertex placed at arbitrary position on the trajectory of the weighted particle.

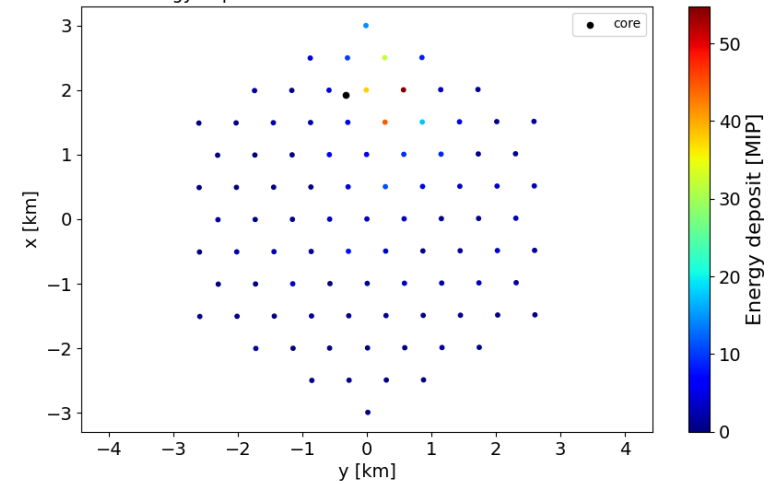
1st step: DETHINNING

2nd step: GEANT4 energy deposits

Proton air shower with $\log_{10}(E/\text{eV}) = 18.5$, $\theta = 87.0$, $\phi = 169.0$
Total energy deposit, 1st interaction height = $2.9\text{e}+06$



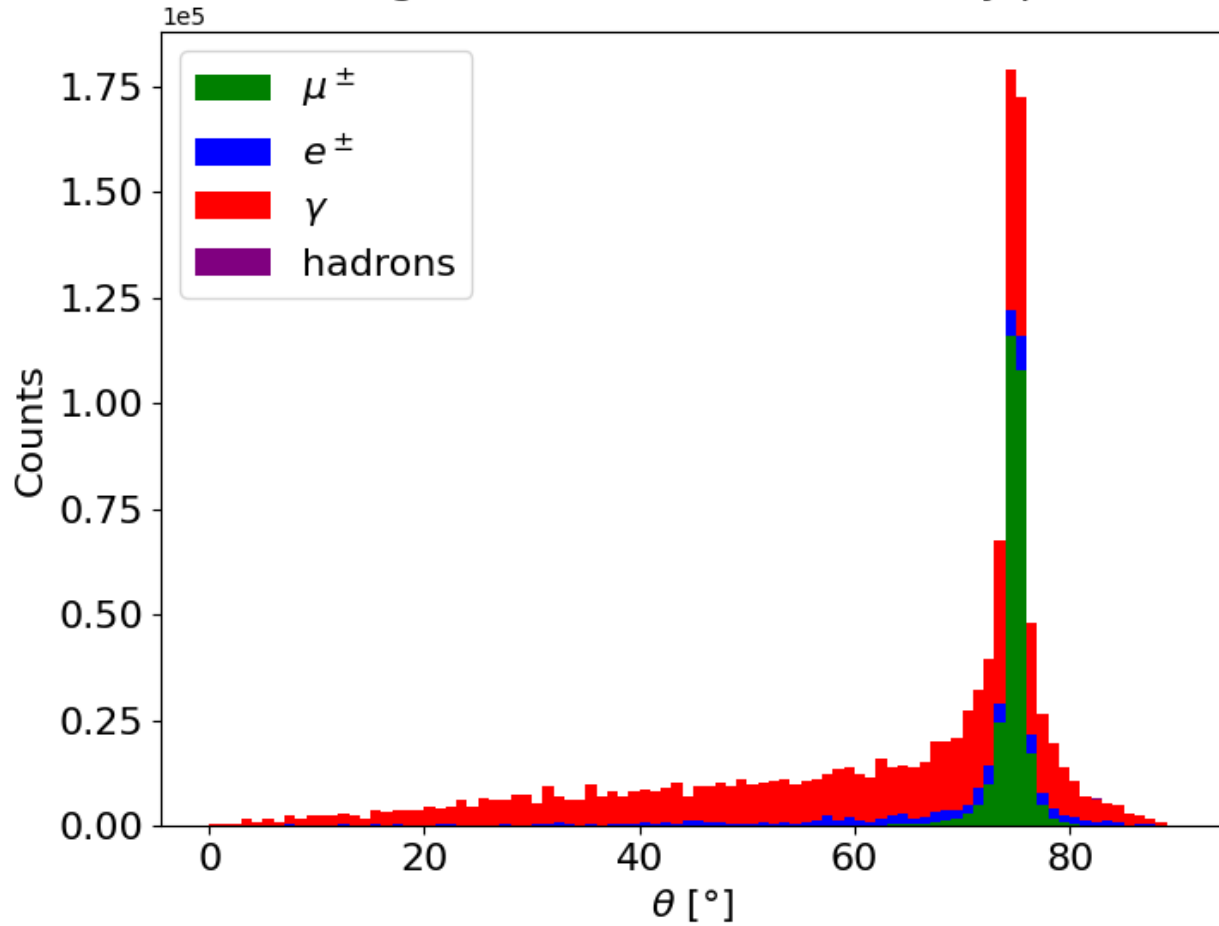
Proton air shower with $\log_{10}(E/\text{eV}) = 18.5$, $\theta = 63.0$, $\phi = 12.124246059007898$
Energy deposit for scintillation detectors on the infill



3rd step: « real » particle footprint

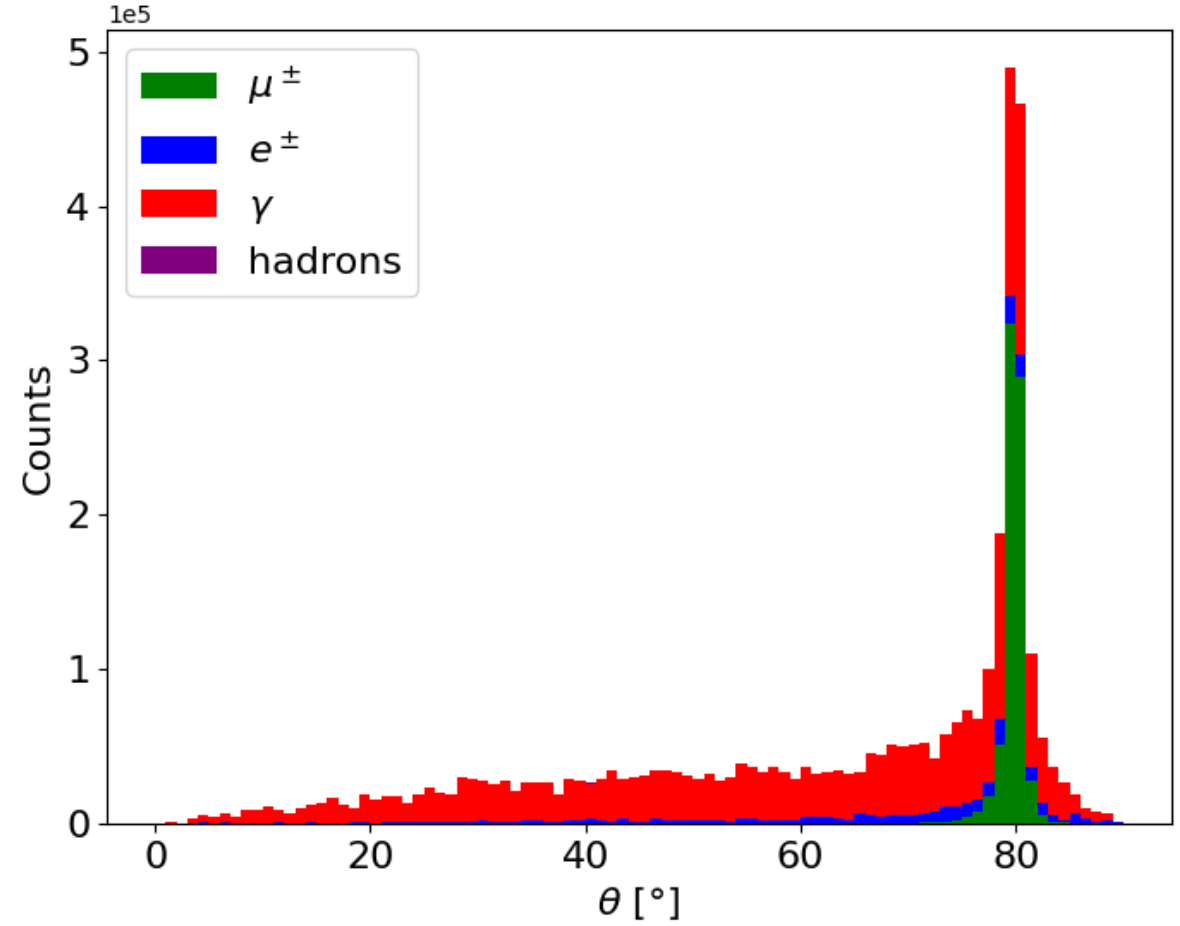
Proton: $\log_{10}(E/\text{eV}) = 17.5, \theta = 75^\circ, \phi = 0^\circ$

Zenith angle distribution of secondary particles

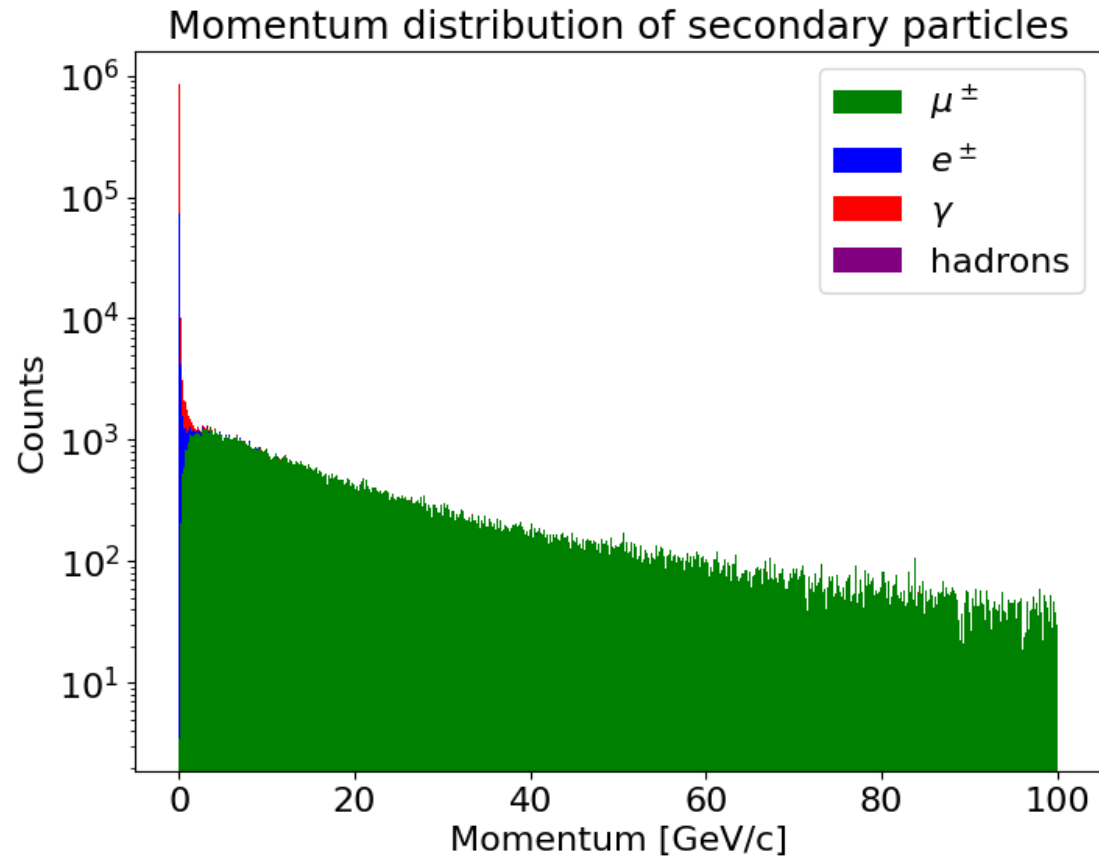


Proton: $\log_{10}(E/\text{eV}) = 18, \theta = 80^\circ, \phi = 0^\circ$

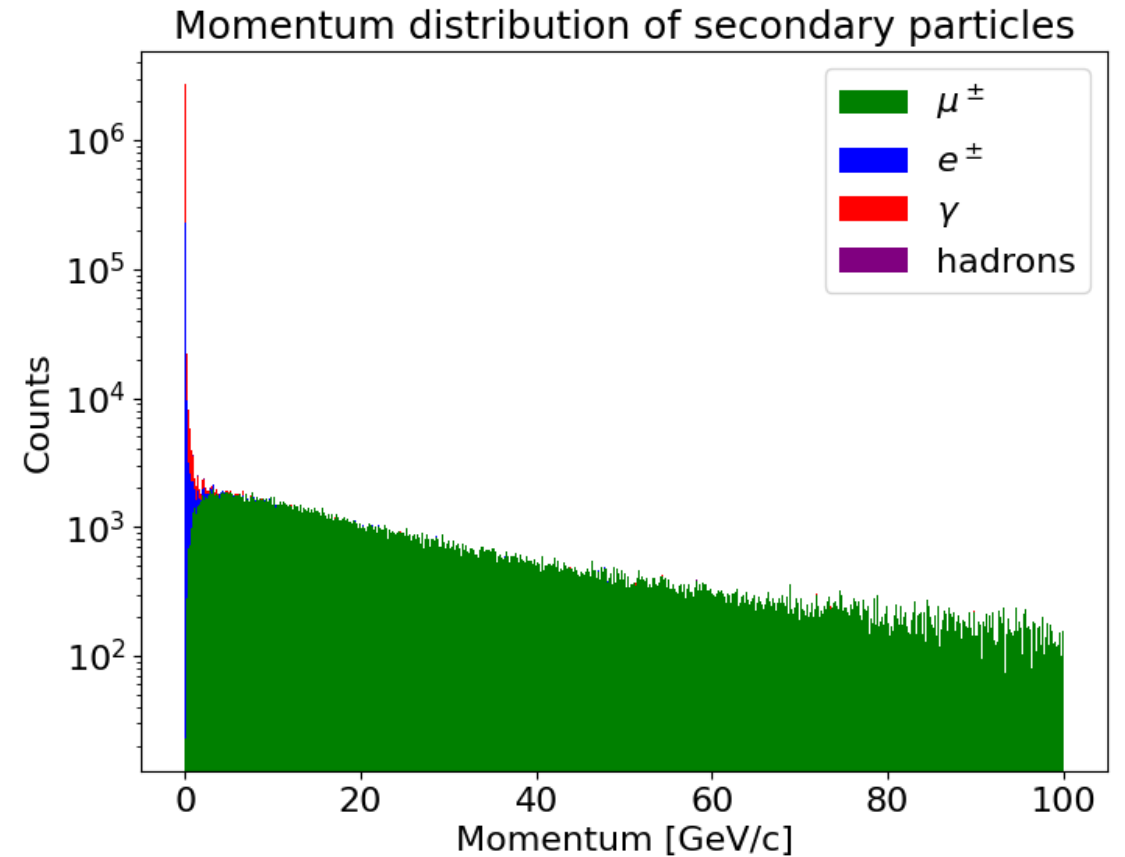
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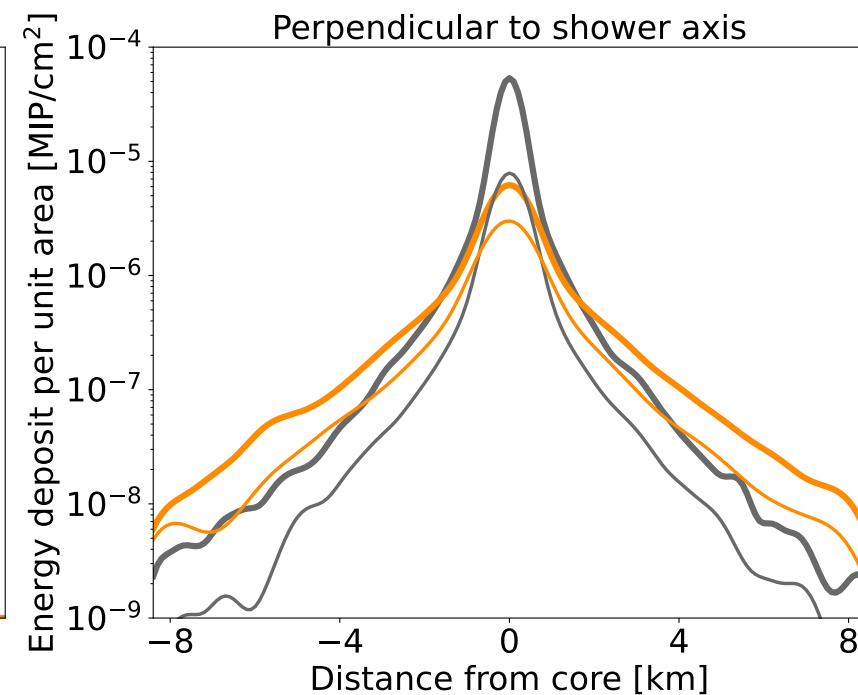
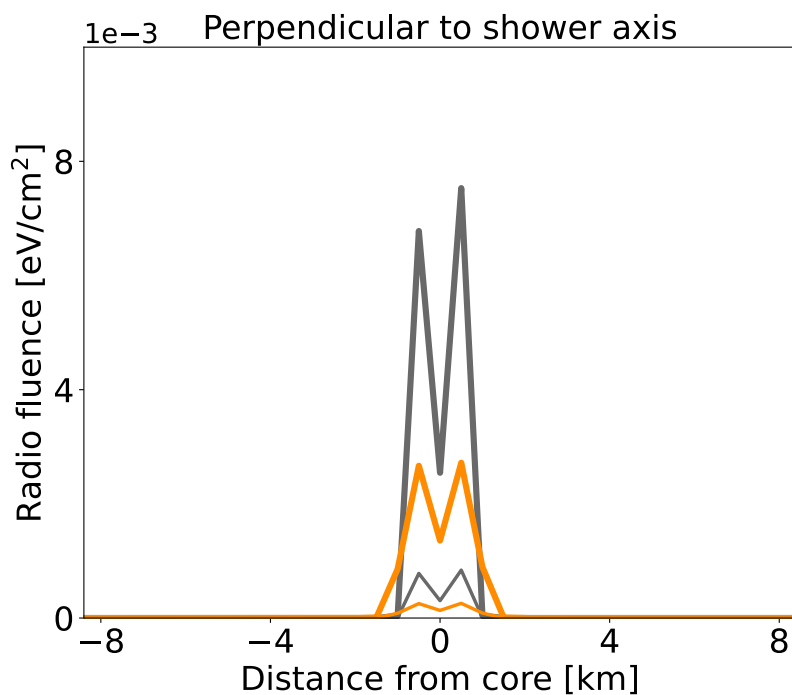
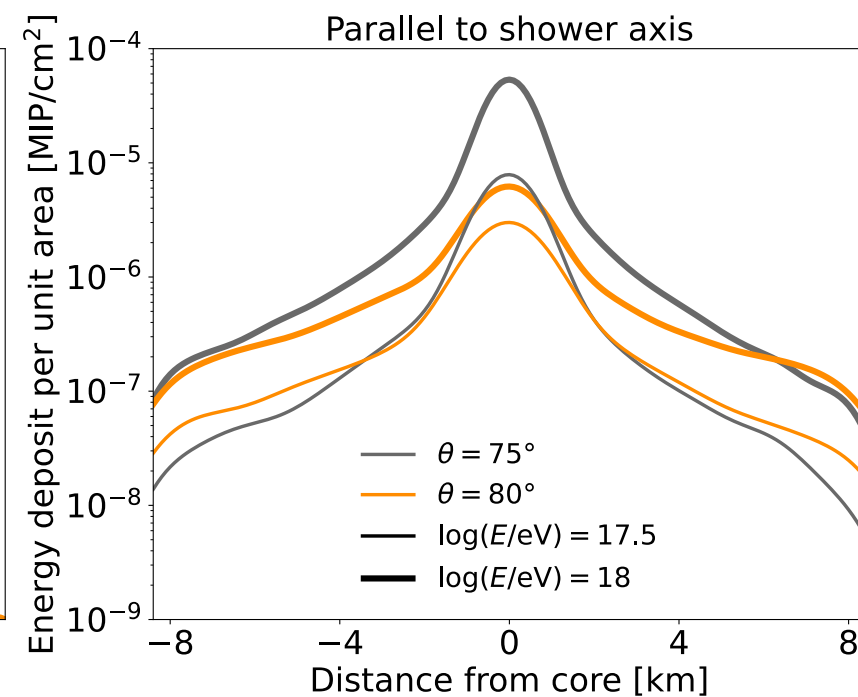
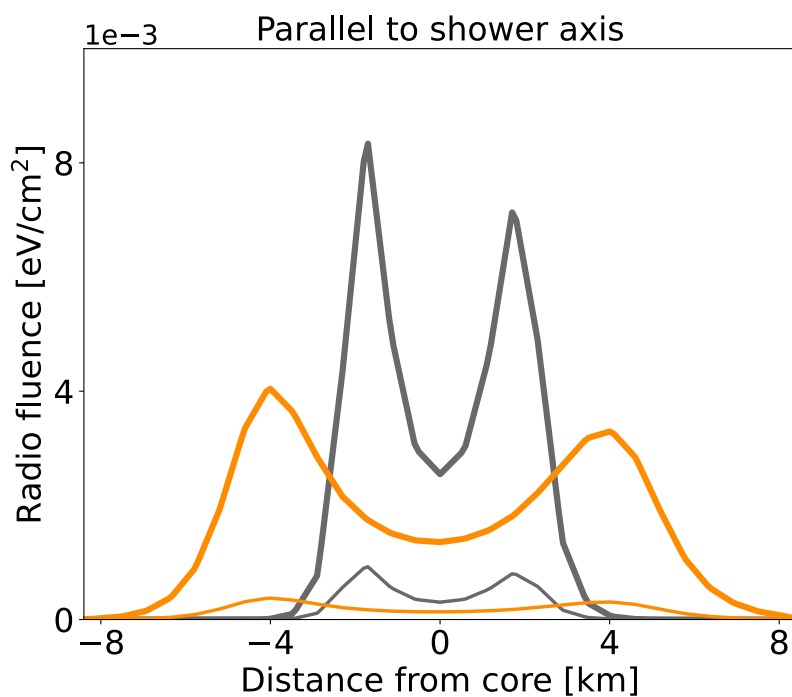


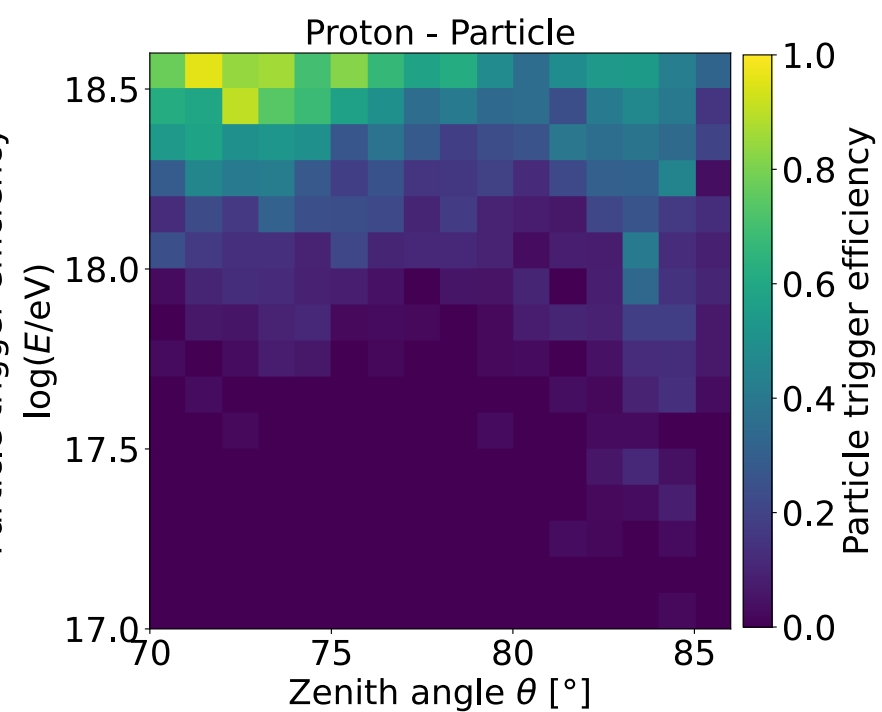
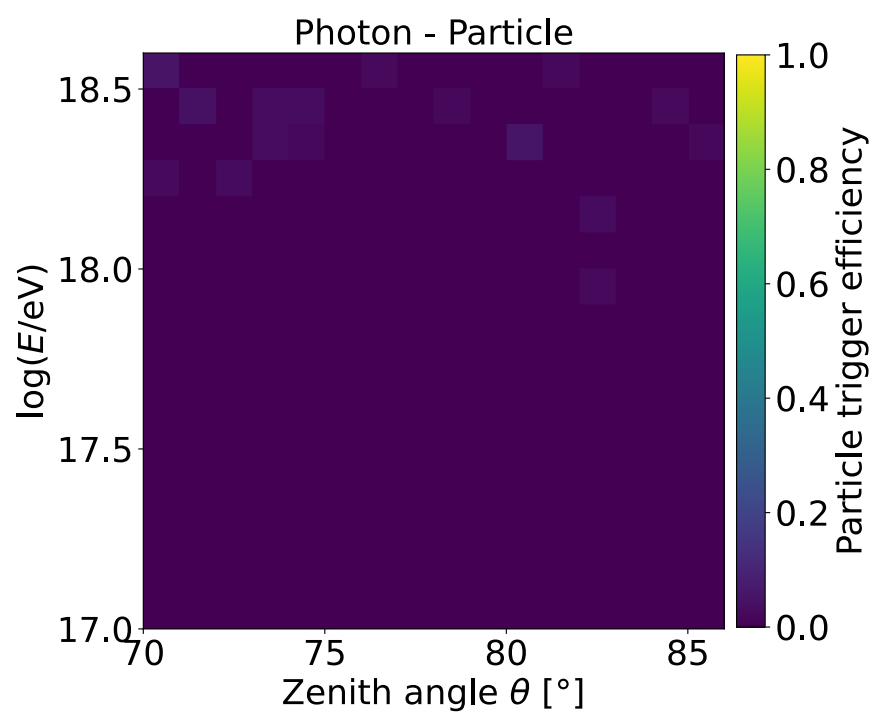
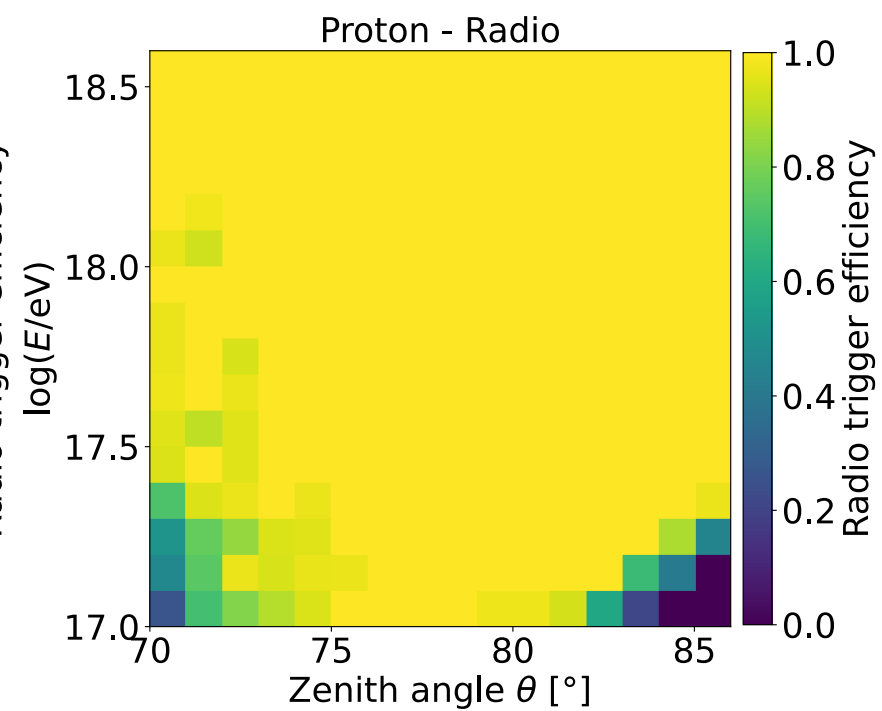
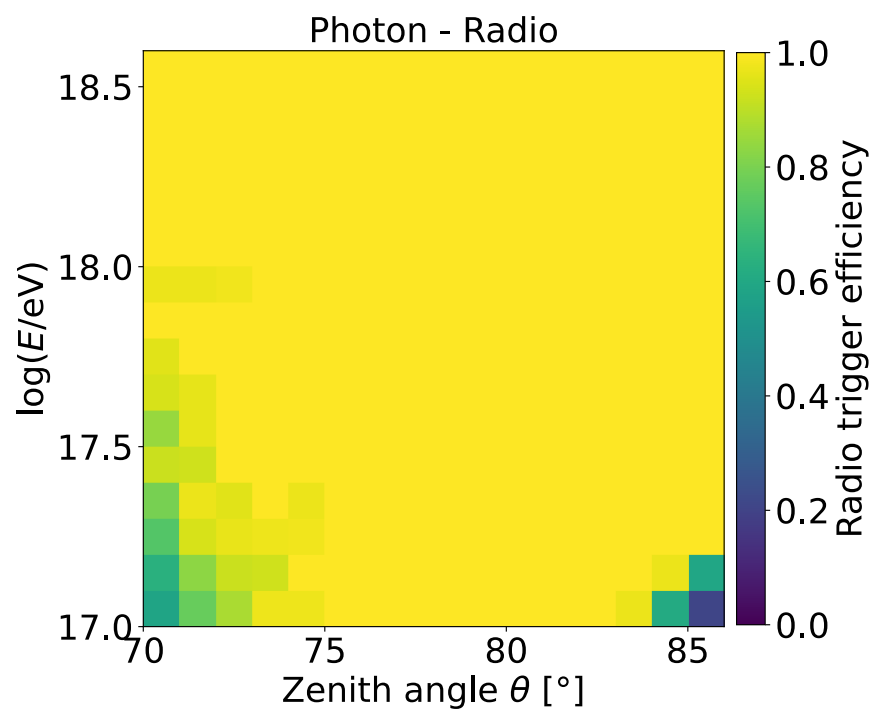
Proton: $\log_{10}(E/\text{eV}) = 17.5$, $\theta = 75^\circ$, $\phi = 0^\circ$

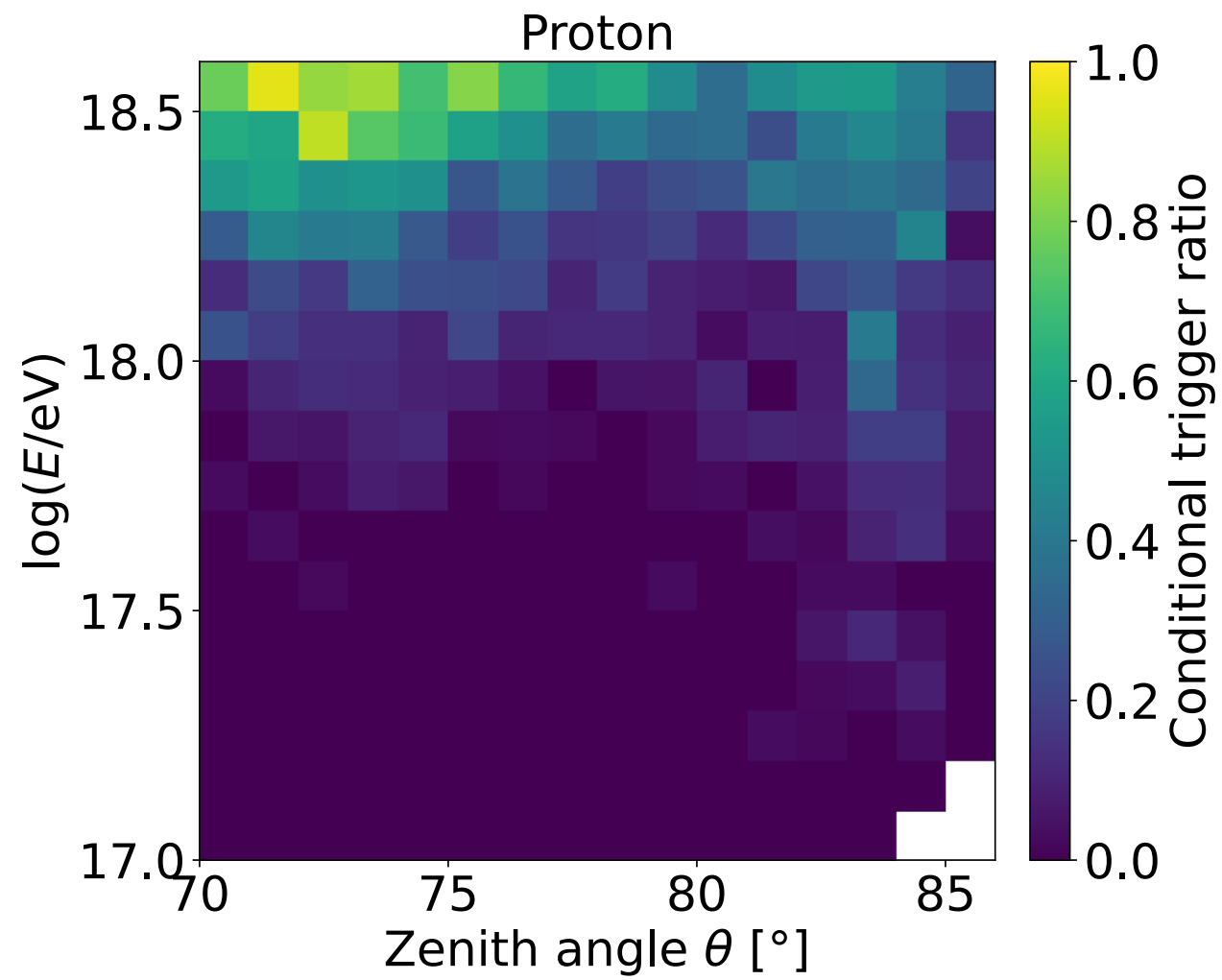
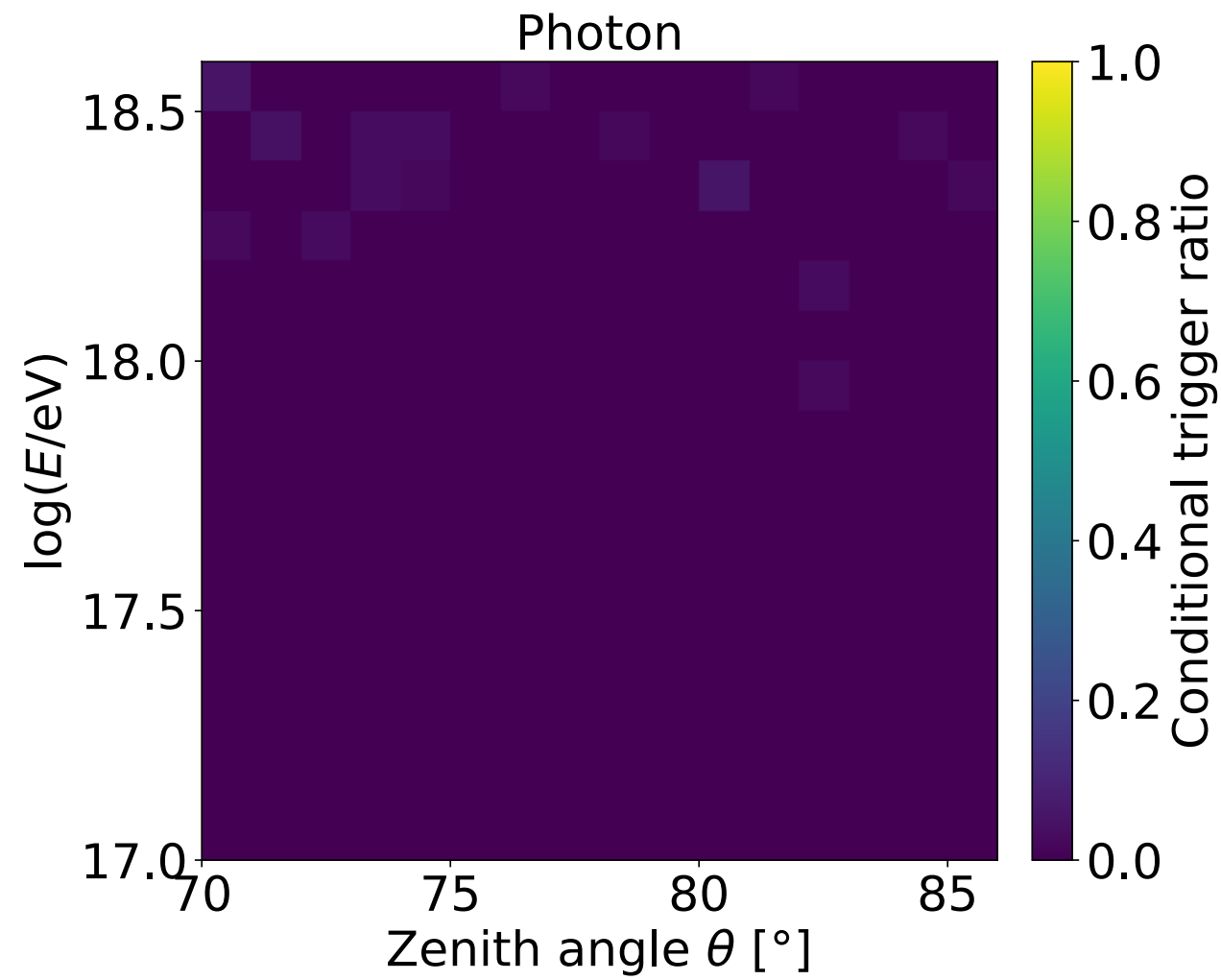


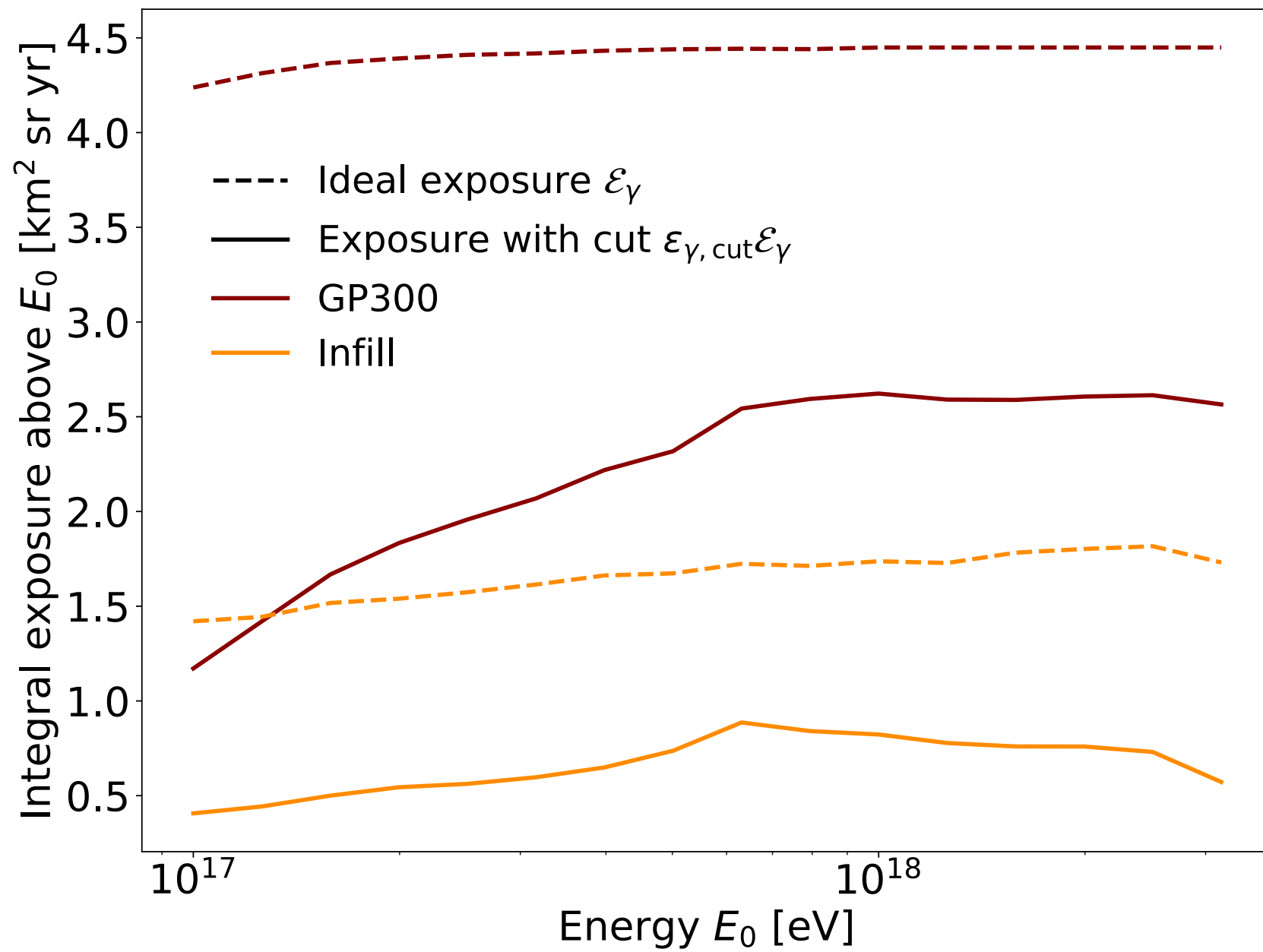
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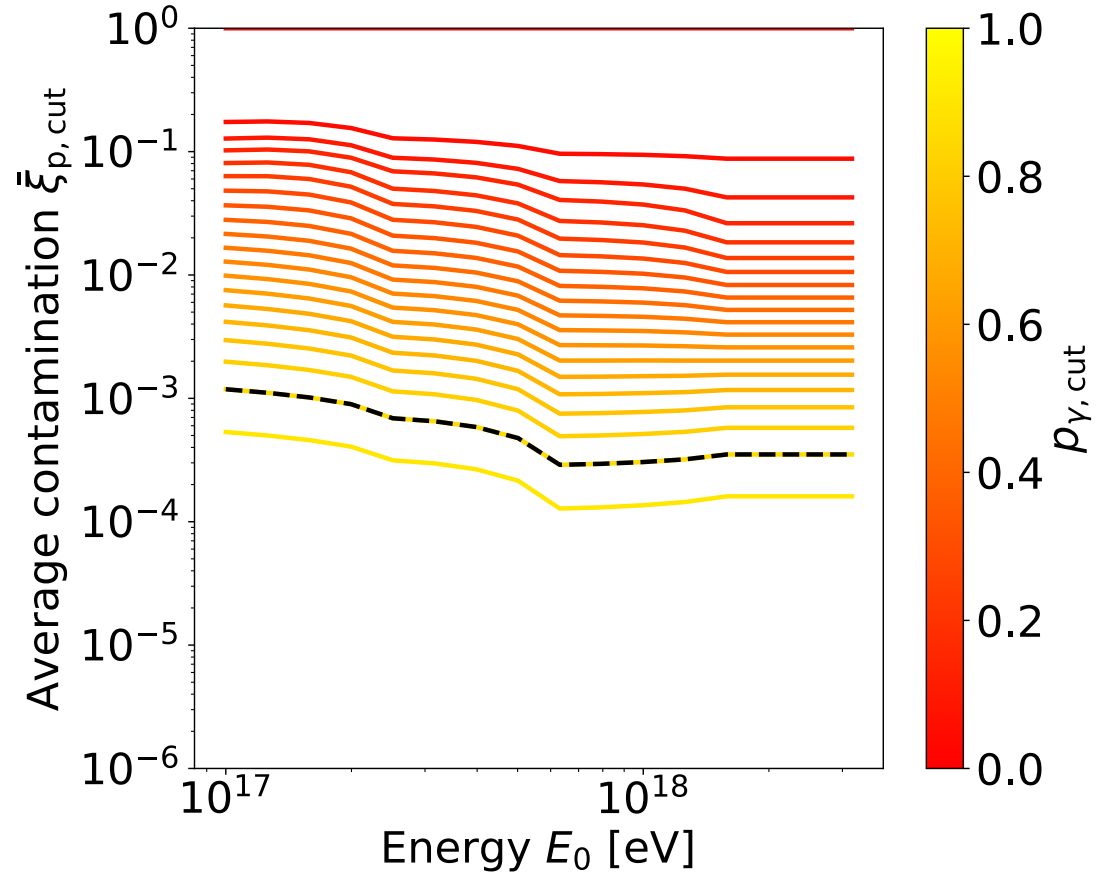
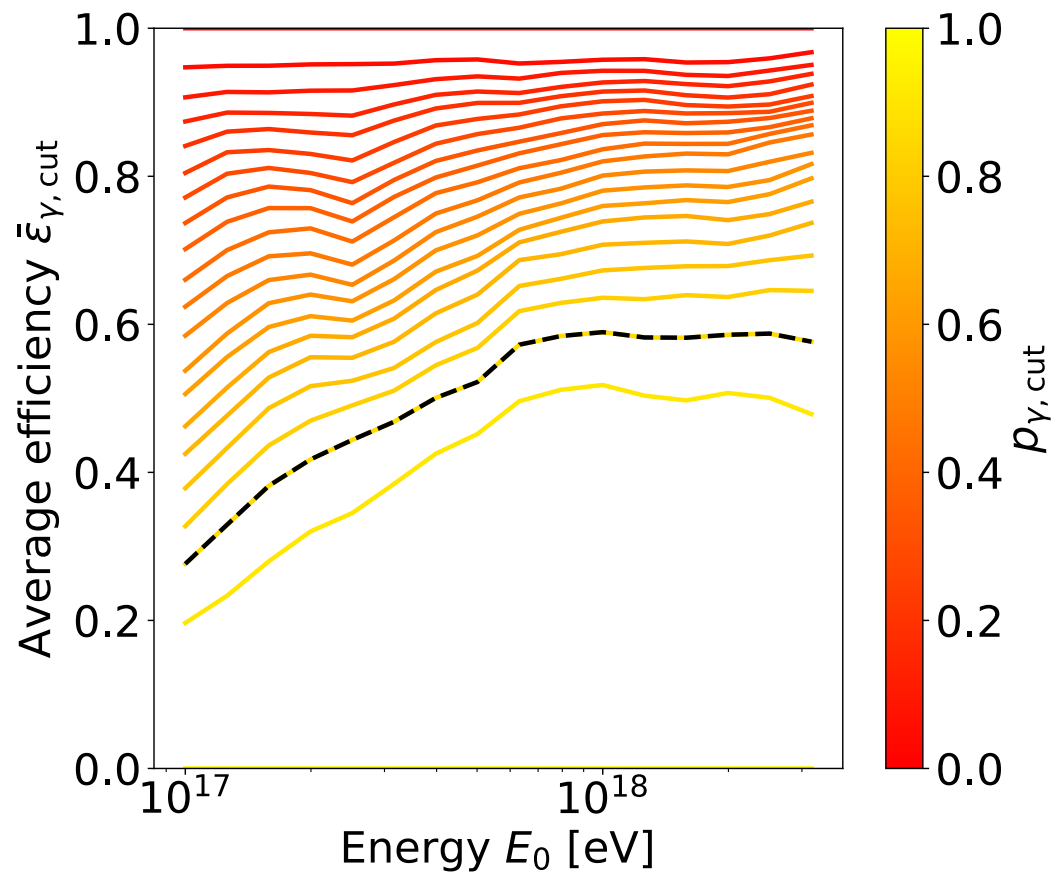






$$\bar{\varepsilon}_{\gamma,\text{cut}}(E_\gamma > E_0) = \frac{\int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_\gamma^{-\Gamma} \tau(E_\gamma, \theta) \varepsilon_{\gamma,\text{cut}}(E_\gamma, \theta) \cos \theta \sin \theta \, d\theta \, dE_\gamma}{\int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_\gamma^{-\Gamma} \tau(E_\gamma, \theta) \cos \theta \sin \theta \, d\theta \, dE_\gamma}$$

$$\bar{\xi}_{\text{p},\text{cut}}(E_{\text{p}} > E_0) = \frac{\int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_{\text{p}}^{-\Gamma_{\text{p}}} \tau_{\text{p}}(E_{\text{p}}, \theta) \xi_{\text{p},\text{cut}}(E_{\text{p}}, \theta) \cos \theta \sin \theta \, d\theta \, dE_{\text{p}}}{\int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_{\text{p}}^{-\Gamma_{\text{p}}} \tau_{\text{p}}(E_{\text{p}}, \theta) \cos \theta \sin \theta \, d\theta \, dE_{\text{p}}}$$

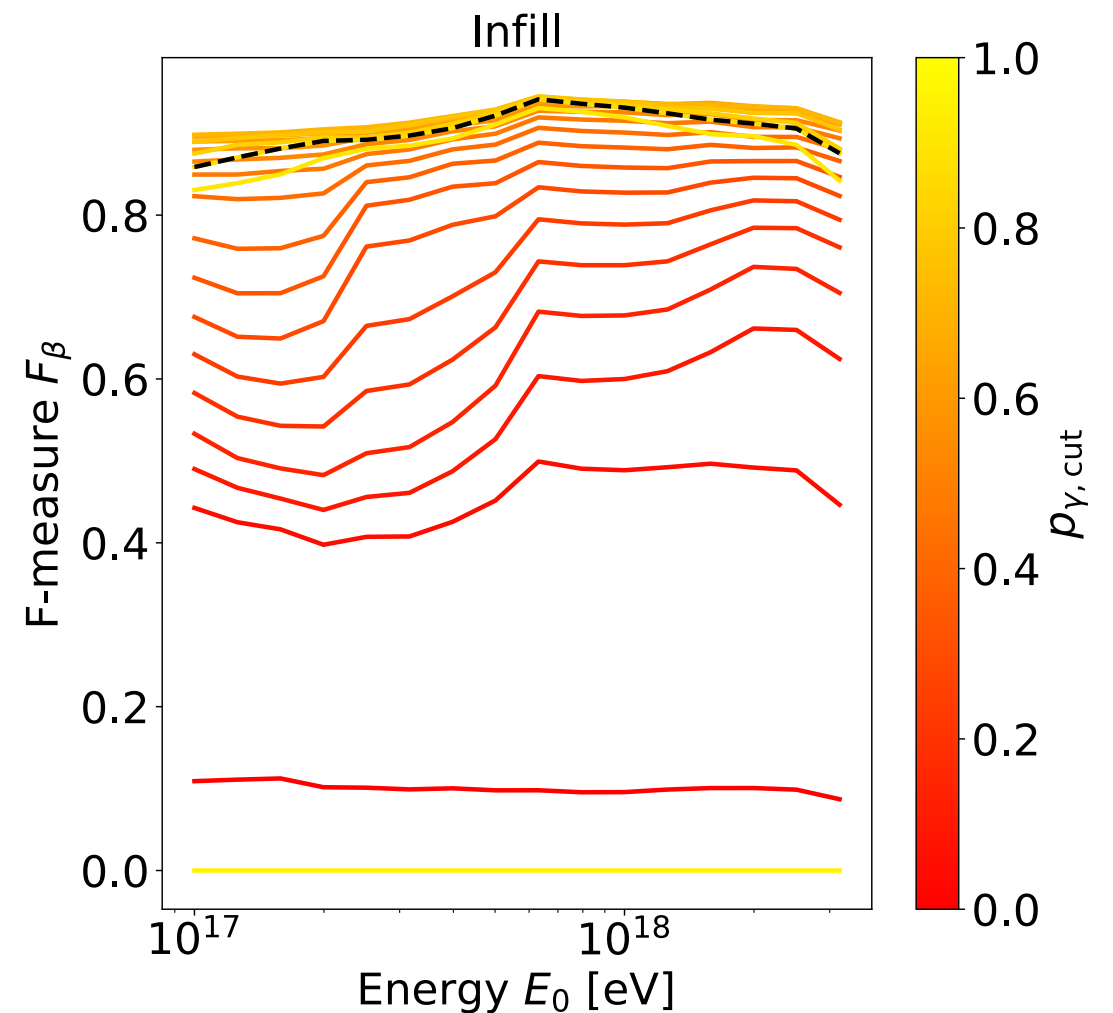
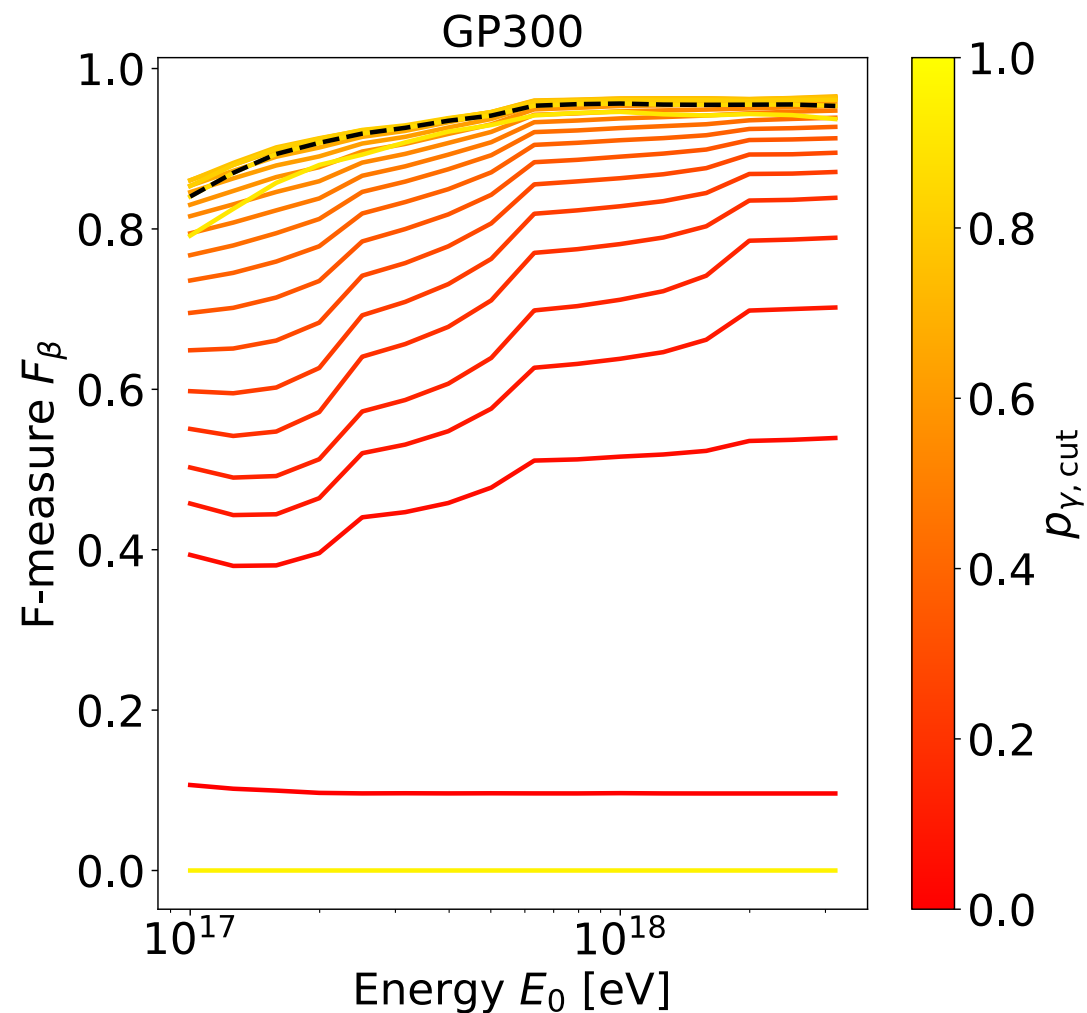


$$\text{TP} = \frac{1}{c_E(\Gamma)} \int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_{\gamma}^{-\Gamma} \tau(E_{\gamma}, \theta) \varepsilon_{\gamma, \text{cut}}(E_{\gamma}, \theta) \cos \theta \sin \theta \, d\theta \, dE_{\gamma} ,$$

$$\text{FN} = \frac{1}{c_E(\Gamma)} \int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_{\gamma}^{-\Gamma} \tau(E_{\gamma}, \theta) (1 - \varepsilon_{\gamma, \text{cut}}(E_{\gamma}, \theta)) \cos \theta \sin \theta \, d\theta \, dE_{\gamma} ,$$

$$\text{FP} = \frac{w_p}{c_E(\Gamma_p)} \int_{E_0}^{\infty} \int_0^{\frac{\pi}{2}} E_p^{-\Gamma_p} \tau_p(E_p, \theta) \xi_{p, \text{cut}}(E_p, \theta) \cos \theta \sin \theta \, d\theta \, dE_p ,$$

$$F(\beta) = \frac{(1 + \beta^2)pr}{\beta^2 p + r} = \frac{(1 + \beta^2) \text{TP}}{(1 + \beta^2) \text{TP} + \beta^2 \text{FN} + \text{FP}}$$



Threshold choice

$$\begin{aligned}\tilde{R}(p_{\gamma,\text{cut}}) &= \max_{E_0} \frac{R(p_{\gamma,\text{cut}} + \Delta p_{\gamma,\text{cut}}, E_0)}{R(p_{\gamma,\text{cut}}, E_0)} \\ &= \max_{E_0} \left[\frac{\bar{\varepsilon}_{\gamma,\text{cut}}(p_{\gamma,\text{cut}} + \Delta p_{\gamma,\text{cut}}, E_0)}{\bar{\varepsilon}_{\gamma,\text{cut}}(p_{\gamma,\text{cut}}, E_0)} \frac{\bar{\xi}_{\text{p, cut}}(p_{\gamma,\text{cut}}, E_0)}{\bar{\xi}_{\text{p, cut}}(p_{\gamma,\text{cut}} + \Delta p_{\gamma,\text{cut}}, E_0)} \right]\end{aligned}$$

