Sensitivity Study of IceCube-Gen2 Surface Array for Cosmic-Ray Anisotropy

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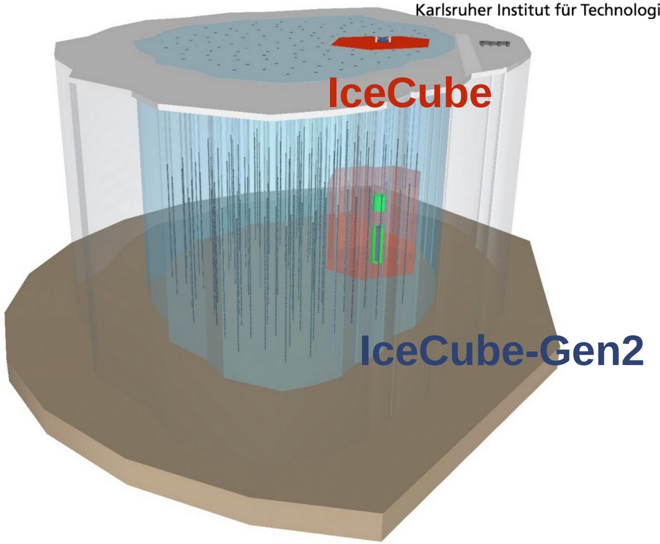
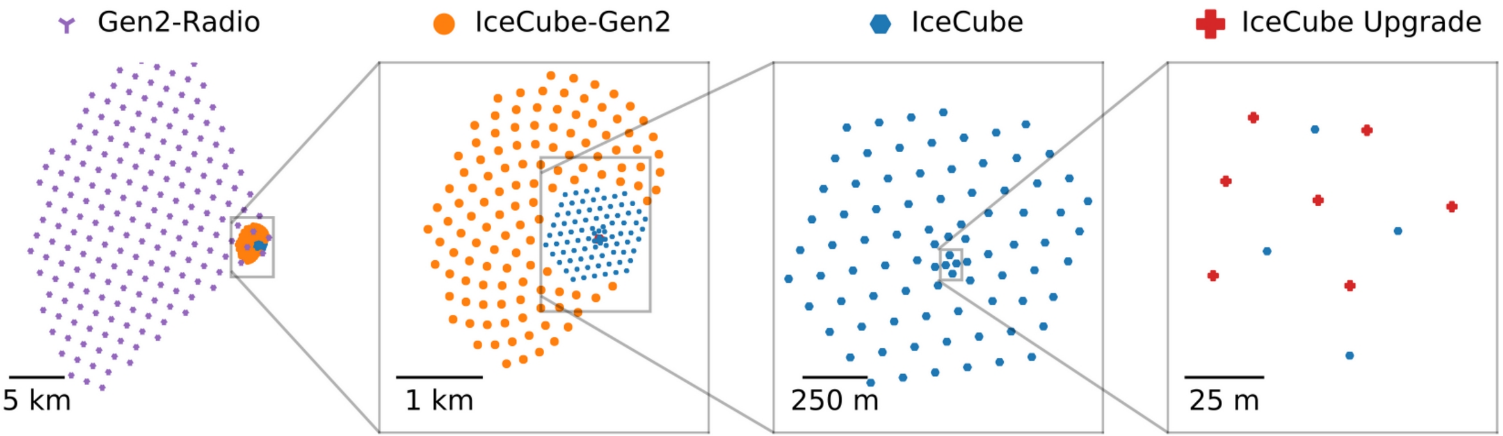
IceCube-Gen2: extending the IceCube Neutrino Obs.

- an order of magnitude larger *deep optical* and *surface* arrays
- sparse *in-ice radio* array for detection of Askaryan emission from ultra-high-energy neutrinos

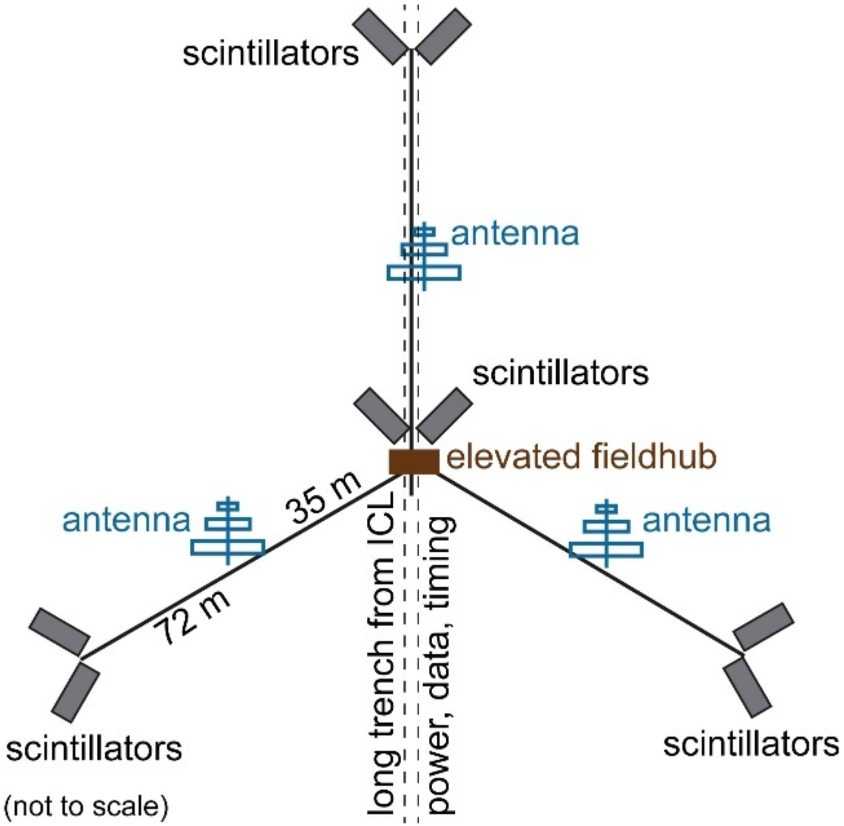




arXiv:2008.04323

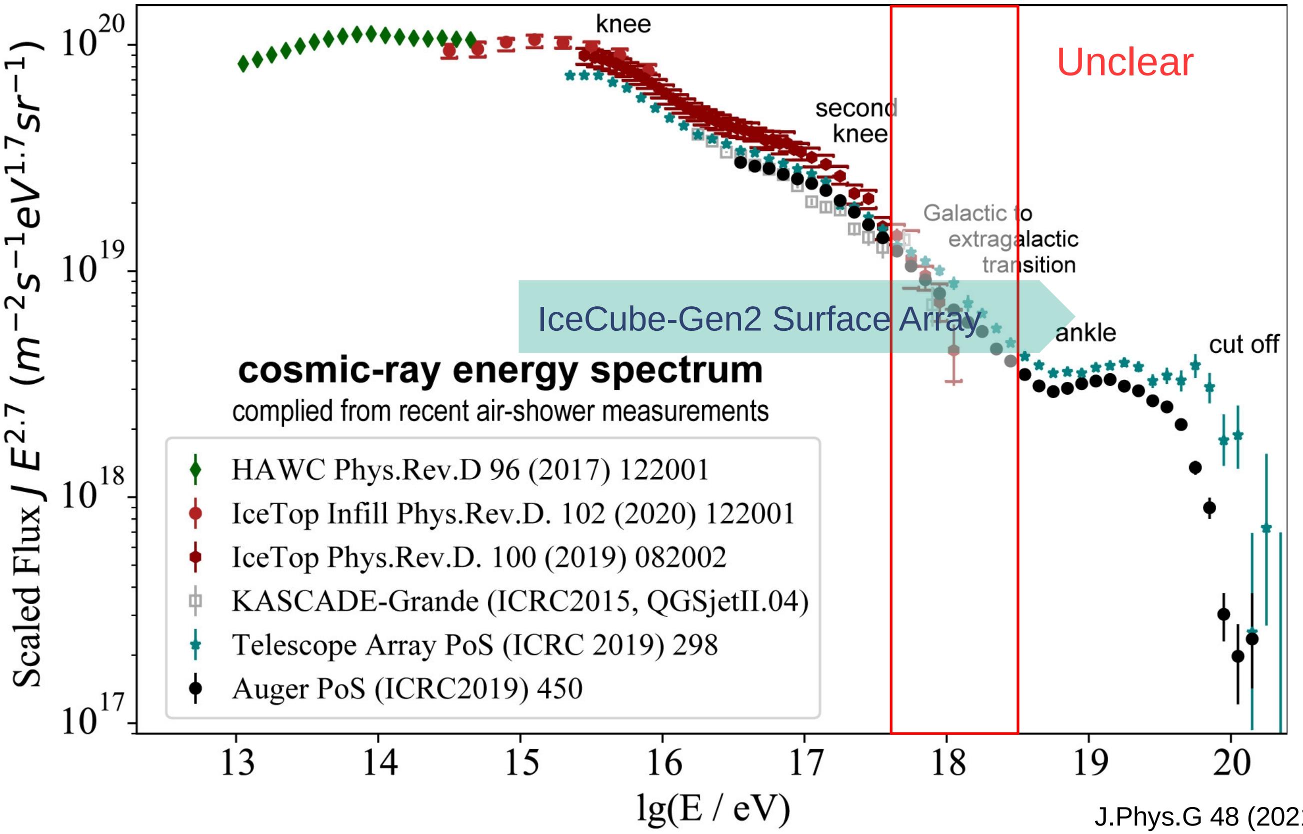
Surface array of IceCube-Gen2

- 1 surface station per optical string (120), 240m spacing between stations
  - + extra stations as surface enhancement of IceTop, the surface array of IceCube
- Gen2 surface array: bigger aperture with increase in max. energy and accuracy for mass
  - ×8 aperture surface only (8 km^2), ~6.6 km^2 eff.
  - > 30× aperture for coincidences with optical in-ice part



IceCube-Gen2 surface array: energy

- **Energy reach until Ankle: Galactic-to-extragalactic Transition (unsolved problem)**



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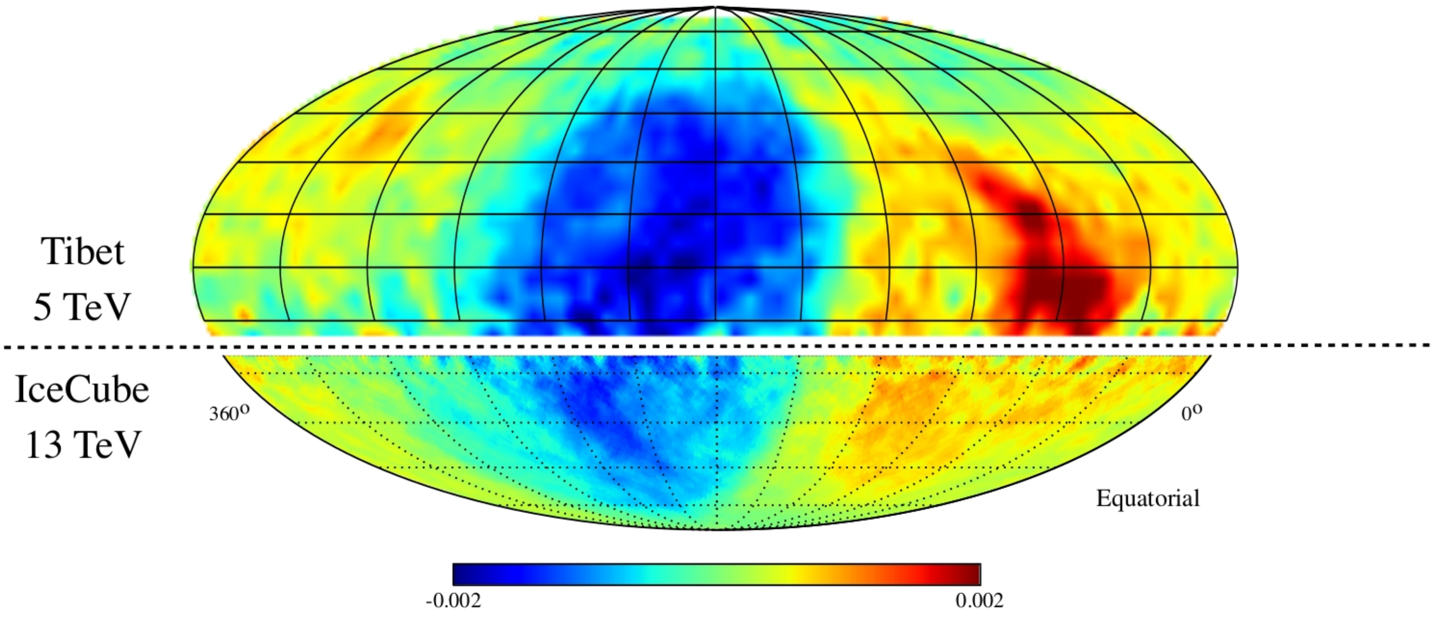
Cosmic-ray dipole anisotropy

- studying the anisotropy in the arrival directions of cosmic rays
- $\longrightarrow$ strong constraints (the energy of the transition from Galactic to extra-galactic origin of cosmic rays)
- e.g.:

relative intensity map

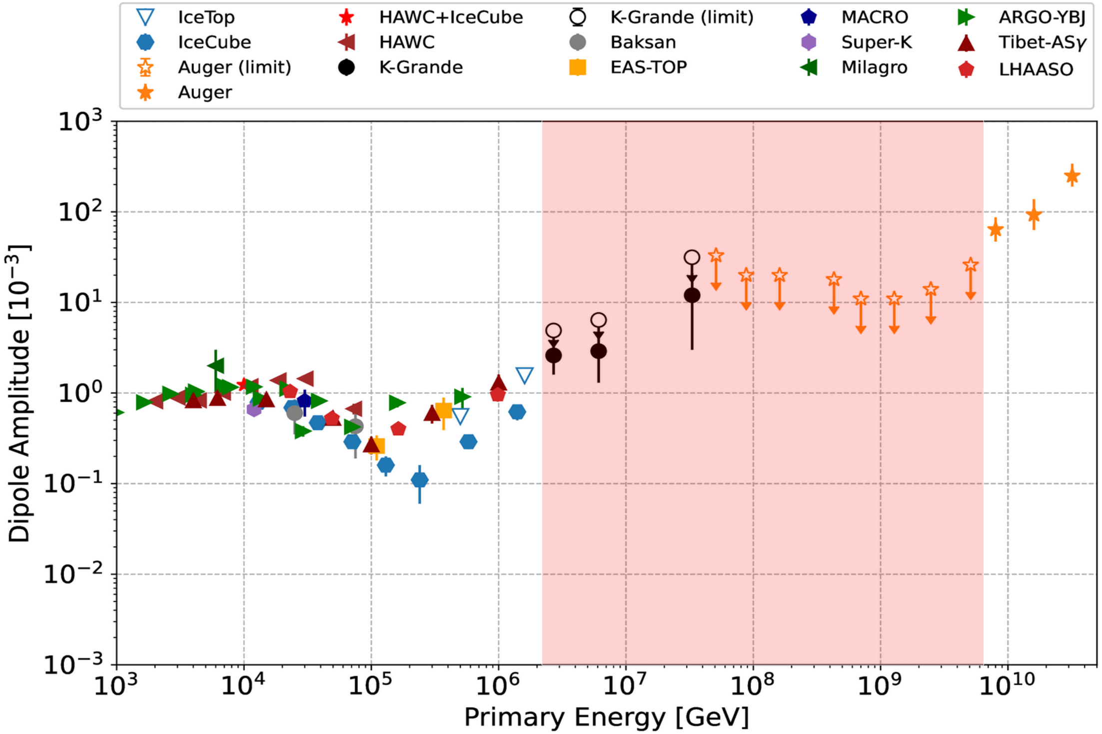


[Makus Ahlers & Mertsch, 2016]

Motivation of this work

- Reconstructed dipole amplitude
  - missing part on the reconstructed dipole amplitude plot with the main experiments data
  - Gen2 will be able to fill in a part of the gap on the dipole anisotropy plot
  - be able to know the **sensitivity of Gen2 for CR anisotropy** before the detection 10 years latter
  - compare with the up limits by the observations of KASCADE and Pierre Auger Obs.

dipole anisotropy



CORSIKA simulations of cosmic ray air showers

- IceCube-Gen2 surface array simulation
  - Hadronic interaction model: Sibyll 2.3d
  - Sim1: log10(E/GeV): (4, 8), zenith: $\sin^2\theta \leq 0.6$
  - Sim2: log10(E/GeV): (4, 7.5), zenith: $\sin^2\theta \leq 0.8$
  - The efficiency plots: *Sim1* + *Sim2 ($\sin^2\theta$ of 0.6-0.8)*

- Steps for getting **reconstruction efficiency**
  - 100 m cut along the surface array edge (polygon)
  - Scintillator triggered times ≥ 5
  - Fit with 2d function (or by LLH)
  - Estimation of Helium, Nitrogen, Aluminum by lnA (logarithmic mass dependence of the cosmic-ray primaries)

Cosmic-ray air shower reconstruction efficiency

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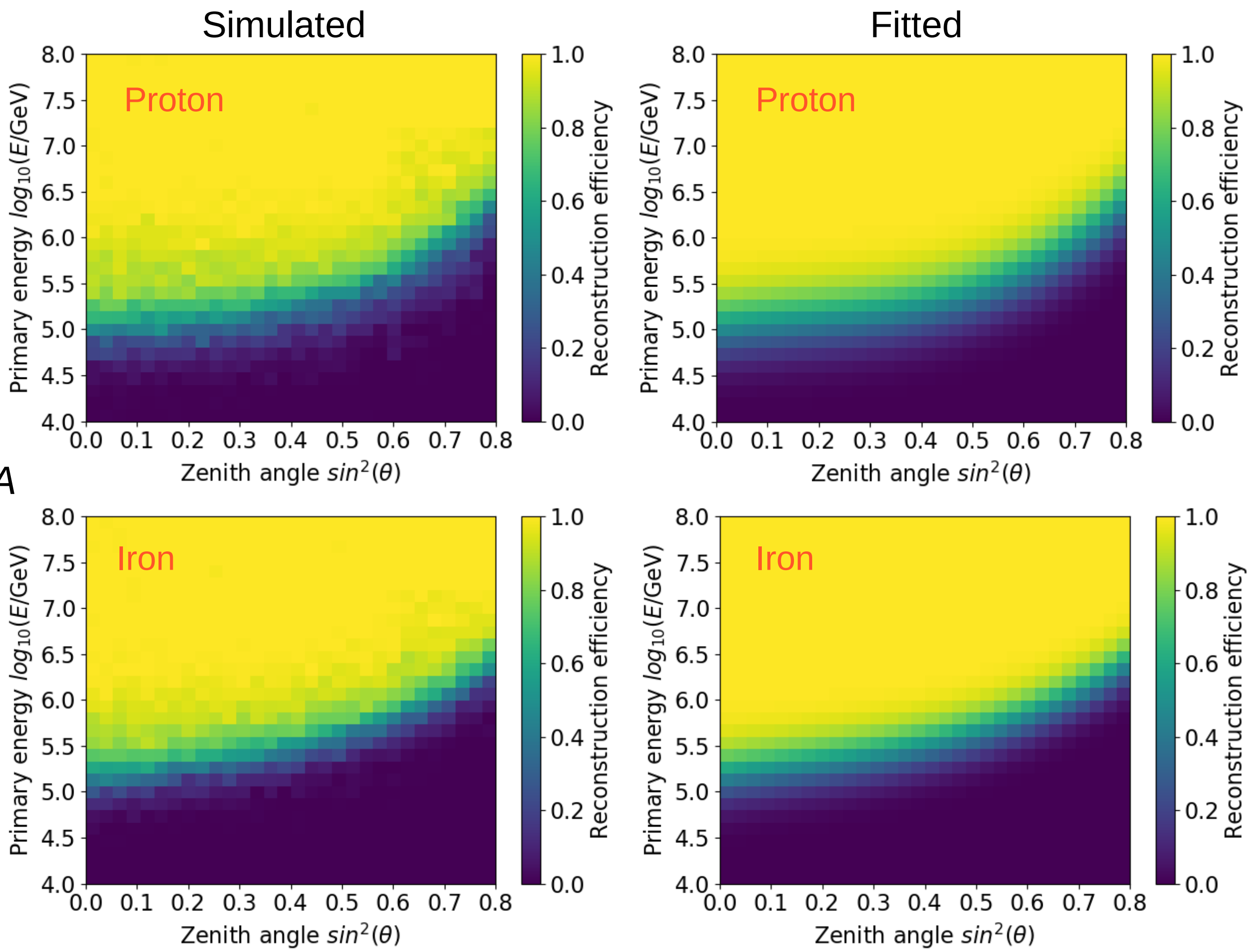
- 2d fit function of the 2d histogram:
  - A modified error function (erf)

$$\epsilon = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{E-(\mu_0+\mu_1 z+\mu_2 z^2+\mu_3 z^3)}{\sigma_0+\sigma_1 z}\right)\right]$$

(where, $z = \sin^2\theta$)

  - Proton: ϵ_P Iron: ϵ_{Fe}

- Estimation of other 3 primaries with *lnA*
  - (by logarithmic mass dependence)
  - Helium: $\epsilon_{He} = 0.653\ \epsilon_P + 0.653\ \epsilon_{Fe}$
  - Nitrogen: $\epsilon_{Ni} = 0.340\ \epsilon_P + 0.660\ \epsilon_{Fe}$
  - Aluminum: $\epsilon_{Al} = 0.176\ \epsilon_P + 0.824\ \epsilon_{Fe}$



[W. Hou PoS ICRC2023 354]

Reconstruction efficiency and Arrival directions

- Efficiency of total primaries:

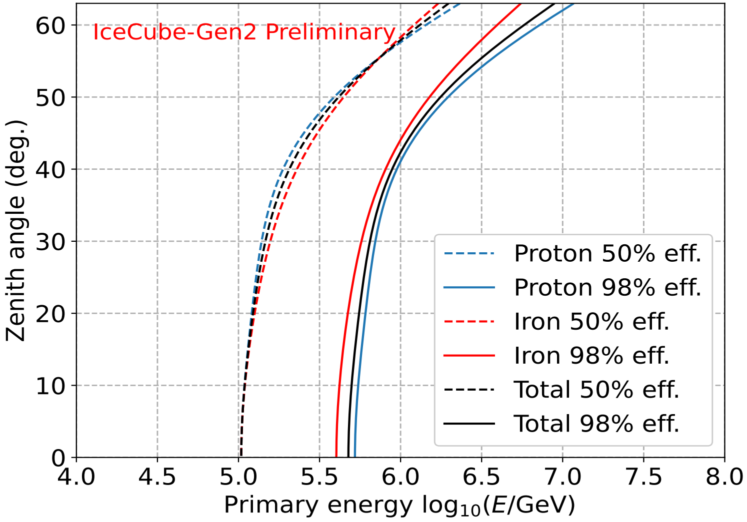
$$\epsilon_{\text{tot}}\left(E,\theta\right) = \frac{\Sigma_{i=1}^{5}\epsilon_i\left(E,\theta\right)\phi_{\text{H4a},i}\left(E\right)}{\Sigma_{i=1}^{5}\phi_{\text{H4a},i}\left(E\right)}$$

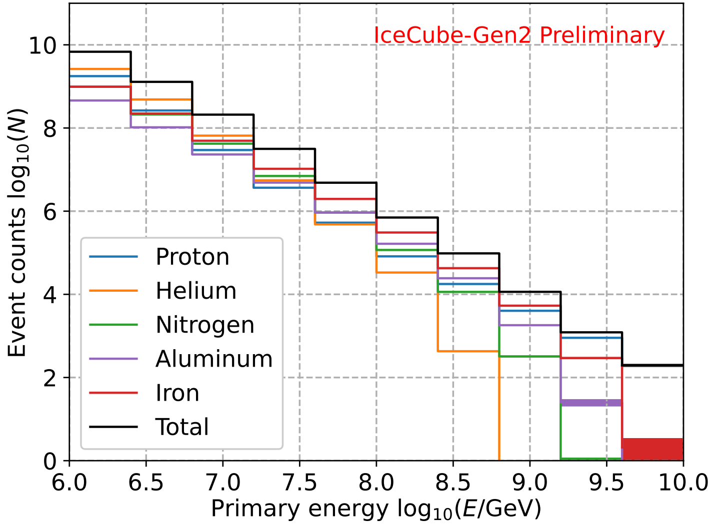
  - *i*: 5 primary particles

- 2d fit function of the 2d histogram:

$$N_{\text{eff},ij} = \int_{\theta_{\min}}^{\theta_{\max}}\int_{E_{j-1}}^{E_j}\epsilon_i\left(E,\theta\right)N_{\text{H4a},i}\left(E\right)dE\,d\theta$$

  - *j*: 10 energy bins
  - N_{H4a}: number of arrival directions with reco. Eff & 10 years exposure





Sensitivity studies of CR anisotropy: MC simulation

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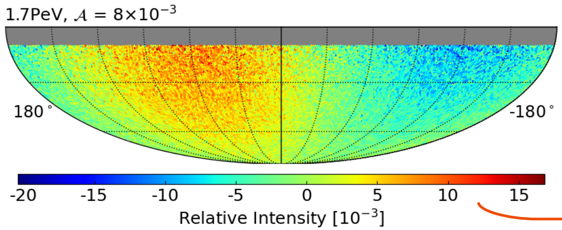
- Injected arrival directions of primary particles (with dipoles):
  - Gen2 surface array exposure + Gaisser H4a flux model
  - Air shower reconstruction efficiency
  - Energy range: 1 PeV ~ 175 PeV, bin size: 0.4 ($\log_{10}$E/GeV)
  - Exposure time: 10 years
  - Total events: ~ 8.4 billion
- Dipole setup of arrival directions
  - Dipole location: right ascension: 270°, declination: (-80°, 80°)
  - declination bin size: 10° dipole amplitudes: 15 A per bin
  - Dipole amplitude input (true dipole): (7×10^{-3}, 9.56×10^{-1})

Reconstructed dipole amplitudes

Relativity intensity and dipole amplitude

- Dipole maps
  - data maps & background maps
  - 15 amplitude input & 15 maps with large significance in each energy bins
  - selection of amplitude input (6 E bins):
    from 7×10^{-3} up to 9.56×10^{-1}
  - different energy bins covering different ranges of the amplitude
- relative intensity: $\delta I = \dfrac{N_{ipix} - \langle N \rangle_{ipix}}{\langle N \rangle_{ipix}}$

- Relative intensity sky maps: e.g. E1 (1.7 PeV)



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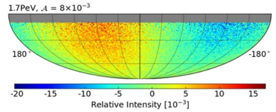

15 sky maps

- 1d projection fit to the first harmonic
- ⟶ 15 **reconstructed amplitude** in each energy bin
  $\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_4, \ldots, \mathcal{A}_{15}$
- ⟶ Error bars from covariance matrix of fitting
  (standard deviation 1σ)

Dipole sensitivity to the cosmic ray anisotropy

- Sensitivity: number of sigmas
  - Common approach: $n_\sigma = (X_i - \mu)/\sigma$
  - This work: $n_\sigma = (\mathcal{A}_{reco} - \mathcal{A}_{hypo})/\sigma_\mathcal{A}$ with $\mathcal{A}_{hypo}=0$

    ⟶ *significance of a dipole deviation from a null hypothesis*

    ⟶ $\sigma_\mathcal{A}$ *from the covariance matrix in the corresponding first harmonic fit of the 1D projected map*
  - $\sigma_\mathcal{A} \propto 1/\sqrt{N}$ verified by MC, a similar case in paper [1]
  - $n_\sigma = S(\delta_d, \delta_{obs.})\, \mathcal{A}\sqrt{N}$ (S is the sensitivity coefficient)
  - True dipole: $n_\sigma = S_{true}\, \mathcal{A}_{true}\sqrt{N}$
  - The corresponding reconstructed dipole: $n_\sigma = S_{reco}\, \mathcal{A}_{reco}\sqrt{N}$
- Sensitivity coefficients
  - Plot: scatter points ($n_\sigma/\sqrt{N}$, $\mathcal{A}$)
  - ⟶ **Sensitivity coefficient** is the slope of the points

[W. Hou PoS ICRC2023 354]

[1]. P. Sommers, Astropart. Phys. 14(2001)271

Dipole sensitivity to the cosmic ray anisotropy

- Sensitivity coefficients: $n_\sigma = \mathcal{S}\left(\mathcal{A}, E, \theta_{\max}, \delta_{\mathrm{d}}, \delta_{\mathrm{Gen2}}\right) \mathcal{A}\sqrt{N},$

$$\mathcal{S}(\mathcal{A}, E) = \lambda_1(E) + 2\lambda_2(E)\mathcal{A} + 3\lambda_3(E)\mathcal{A}^2$$

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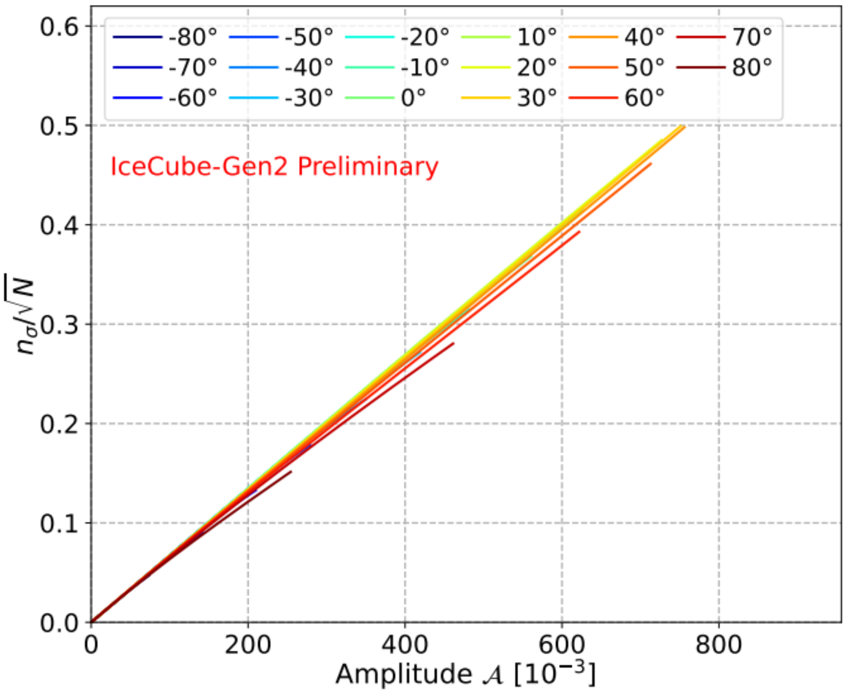
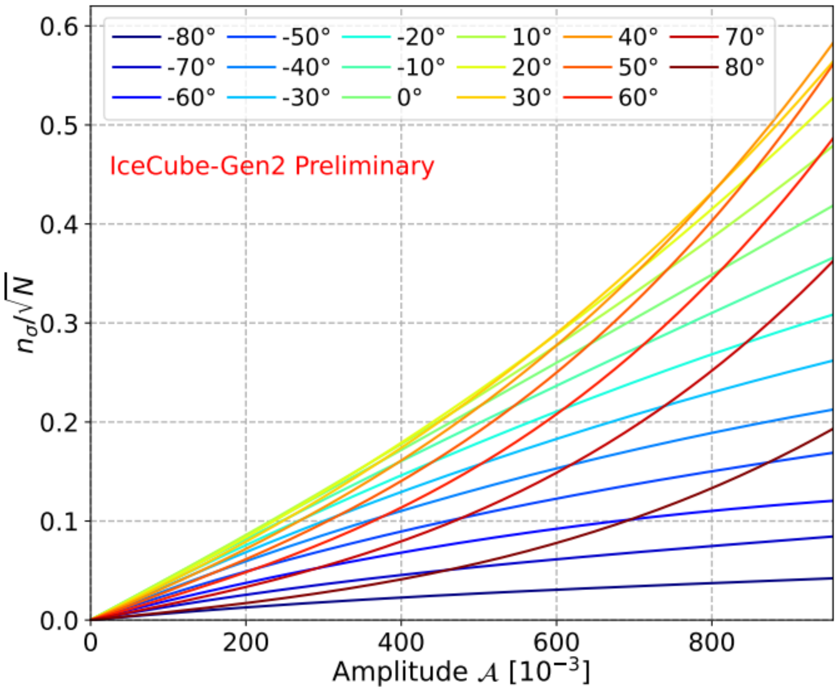
Sensitivity coefficient (S) of reco. dipole

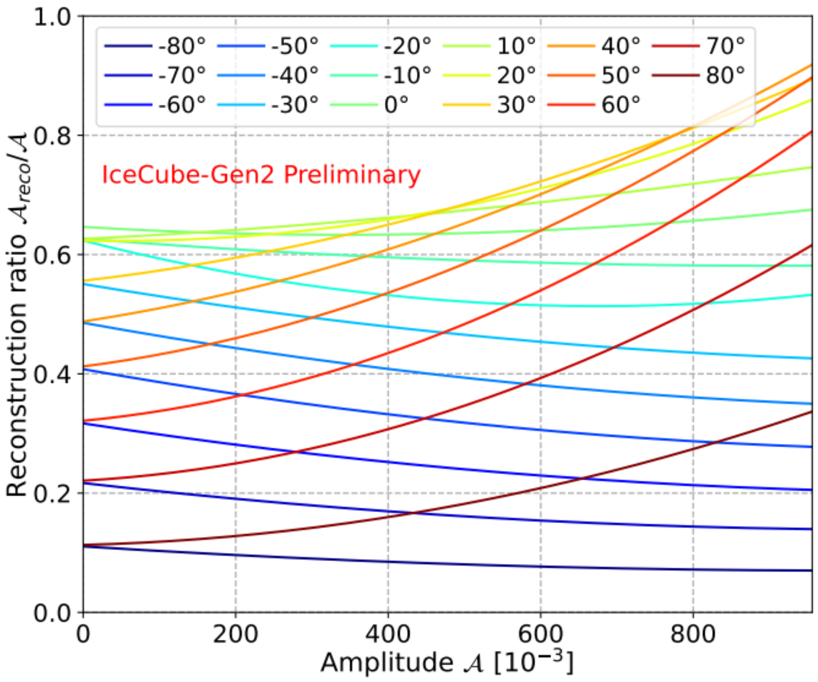


Sensitivity coefficient (S) of true dipole



Dipole sensitivity to the cosmic ray anisotropy

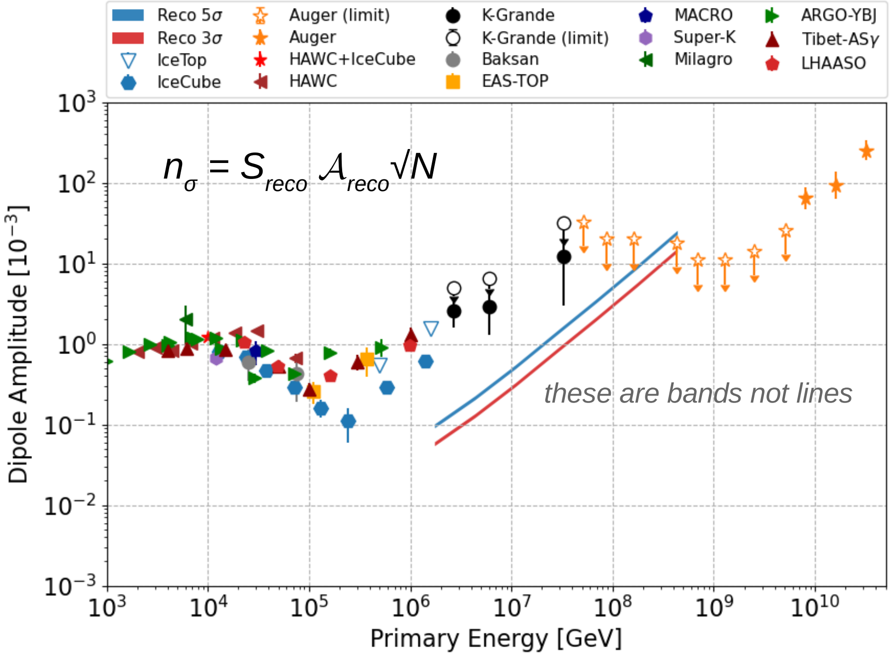
- Ratio between reconstructed dipole and the corresponding true dipole: A_{reco}/A_{true}
- Small reconstruction ratio for larger declinations of dipole



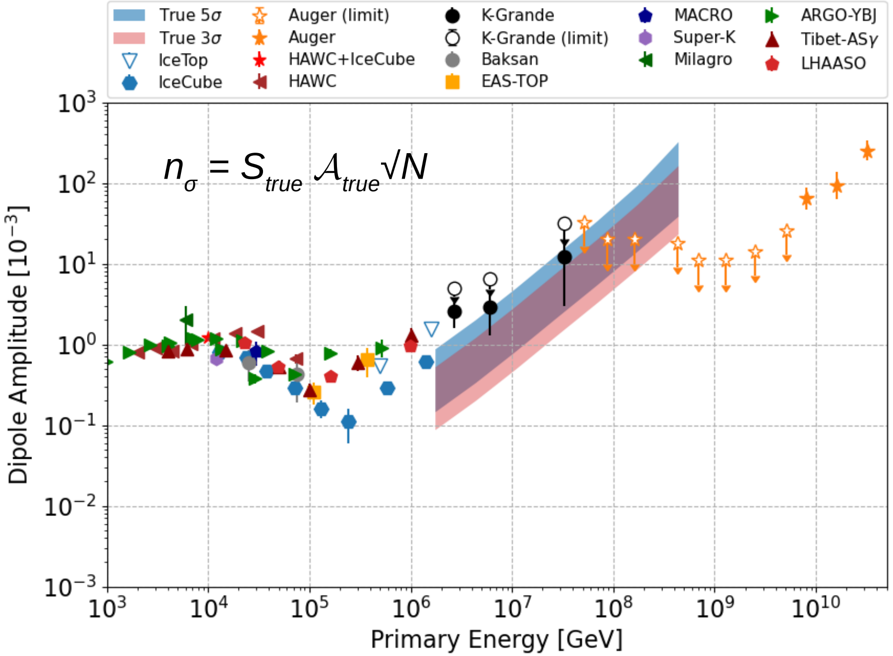
Sensitivity plot

- Fill in between the top and bottom of A(dec) at each energy bin
  - Left: sensitivity with reco. A compared with reco. data of obs., but different reco. ratio A_{reco}/A_{true}
  - Right: sensitivity with true A, (KA: small FoV ⟶ small reco. ratio, Auger: large FoV ⟶ A_{reco} close to A_{true})

Sensitivity band with reco. A

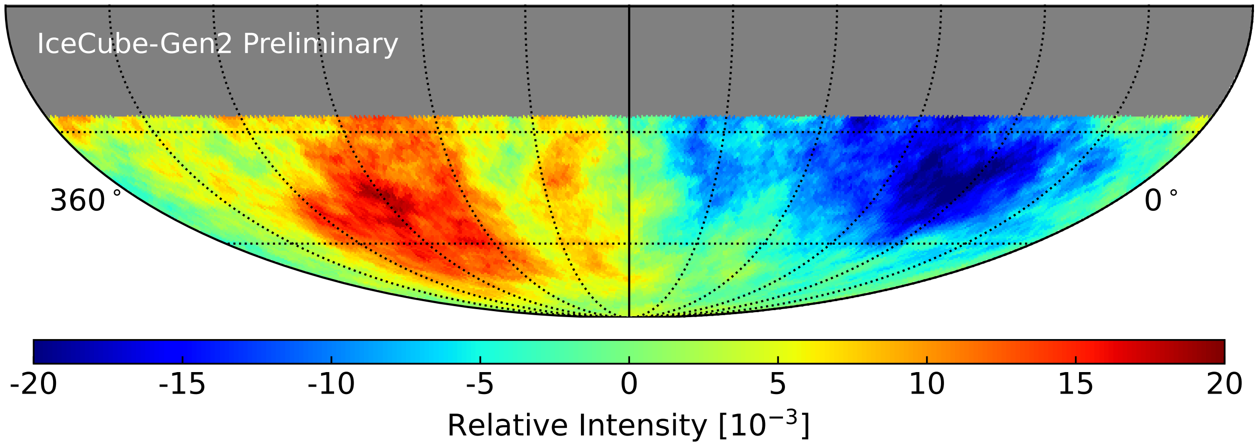


Sensitivity band with true A



An example: sky map with a certain dipole sensitivity

- Injected relative intensity map: significance: 5σ
- dipole orientation: $(270°, -10°)$
- median energy: 176 PeV
- Injected true dipole amplitude: 0.0144
- reconstructed amplitude 9×10^{-3}
- with 20° top hat smoothing



Summary

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- We present the 2D function of the air shower reconstruction efficiency of proton and iron primaries for the IceCube-Gen2 surface array based on CORSIKA simulation, estimate the helium, nitrogen, and aluminum
- Simulate the CR arrival directions for the surface array using Monte-Carlo simulation by injecting 15 different dipoles at declinations ranging from $-80°$ to $80°$ for 7 energy bins
- We compare the actual sky map of an injected dipole with a reference map without a dipole, make the sky maps of relative intensity and perform 1D projections of the sky maps and fit them with first harmonic functions
- To assess the sensitivity of IceCube-Gen2 surface array to a dipole anisotropy, we consider a null hypothesis and the propagation of the sigmas
- We get the sensitivity function and show the 3σ and 5σ sensitivity to the CR dipole anisotropy with curves and bands for the surface array


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Thank you!
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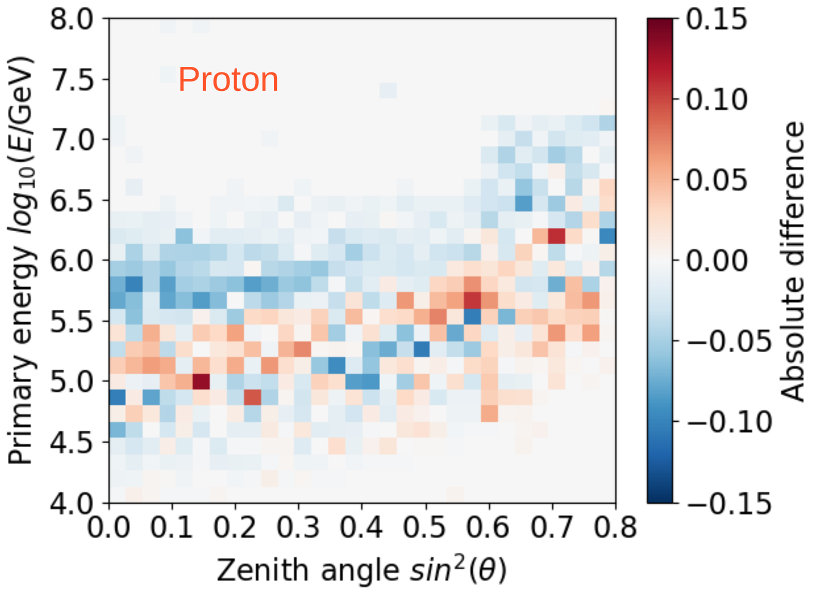
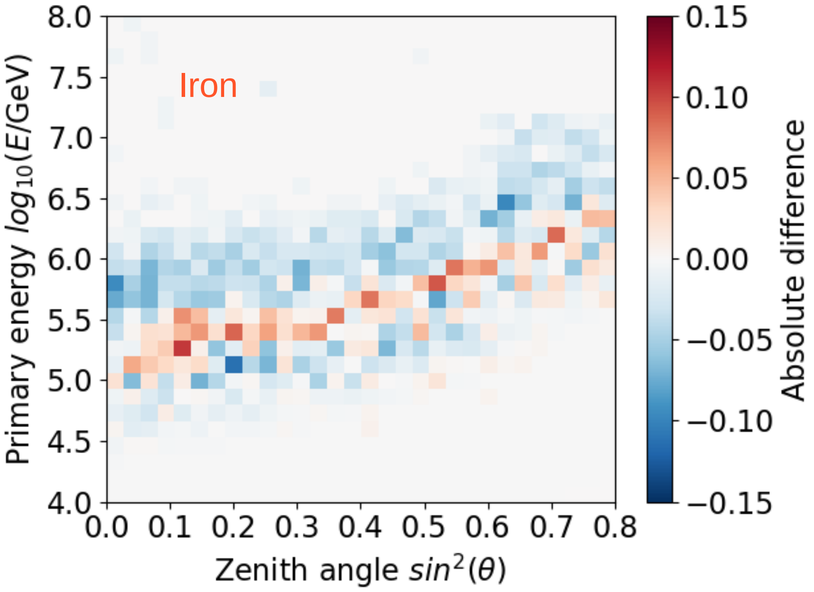
Absolute difference between simulations and the fits: *diff = sim-fit*





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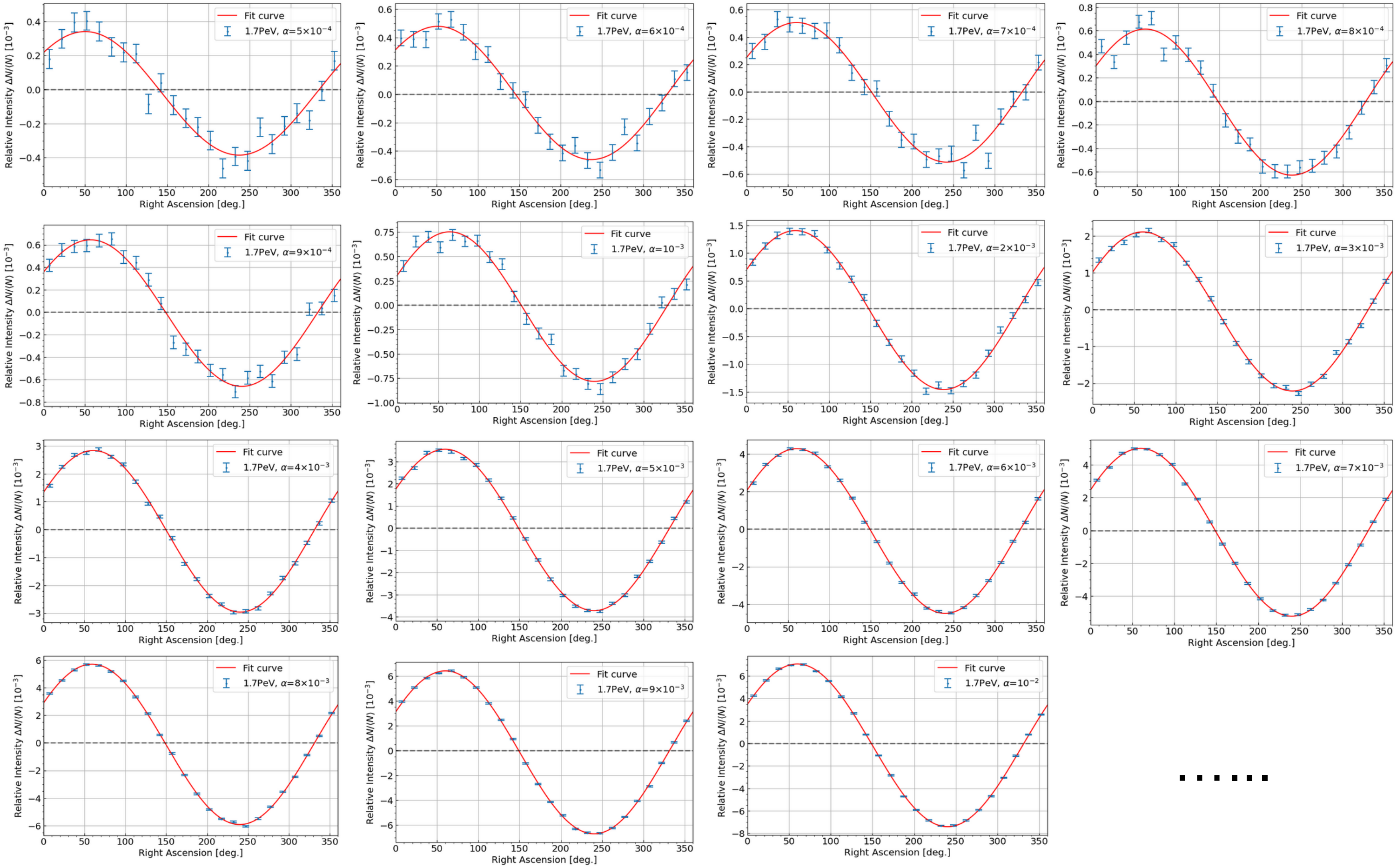
e.g.: 1.7PeV RI 1d projection



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Estimated reconstruction efficiencies

- The reconstruction efficiencies for helium, nitrogen, and aluminum using the natural logarithm of their mass number, denoted as ln A.
- This estimation is based on the logarithmic mass dependence of the cosmic-ray primaries
- The reconstruction efficiency for helium, nitrogen, and aluminum can be written as

$$\epsilon(A_i, E, z) = \frac{\ln A_i}{\ln A_{\mathrm{Fe}} - \ln A_{\mathrm{P}}} \left[\epsilon_{\mathrm{Fe}}(E, z) - \epsilon_{\mathrm{P}}(E, z)\right] + \epsilon_{\mathrm{P}}(E, z),$$

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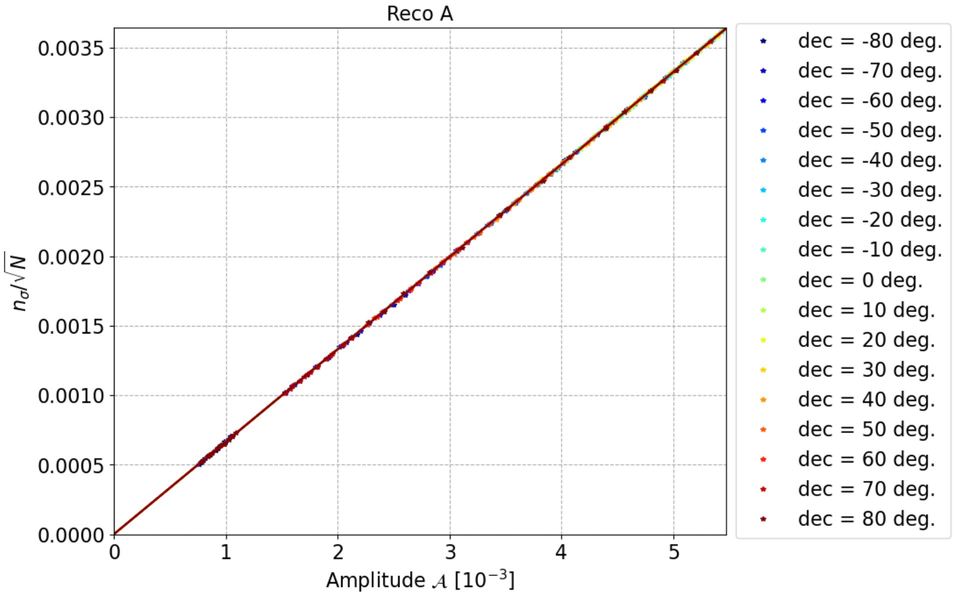
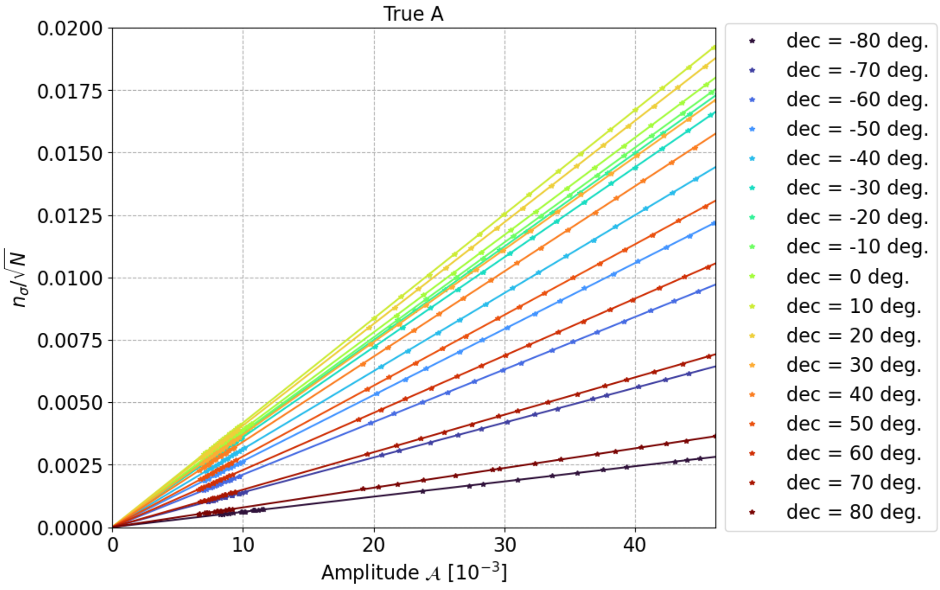
Zoom-in dipole sensitivity plot

- In the first two energy bins





- S_{reco} shows nearly consistent results with all dec (in the first two energy bins)

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Sensitivity band with reco. A and true A

- Combined sensitivity plot