A Search for Cosmic-ray Proton Anisotropies with the Fermi Large Area Telescope

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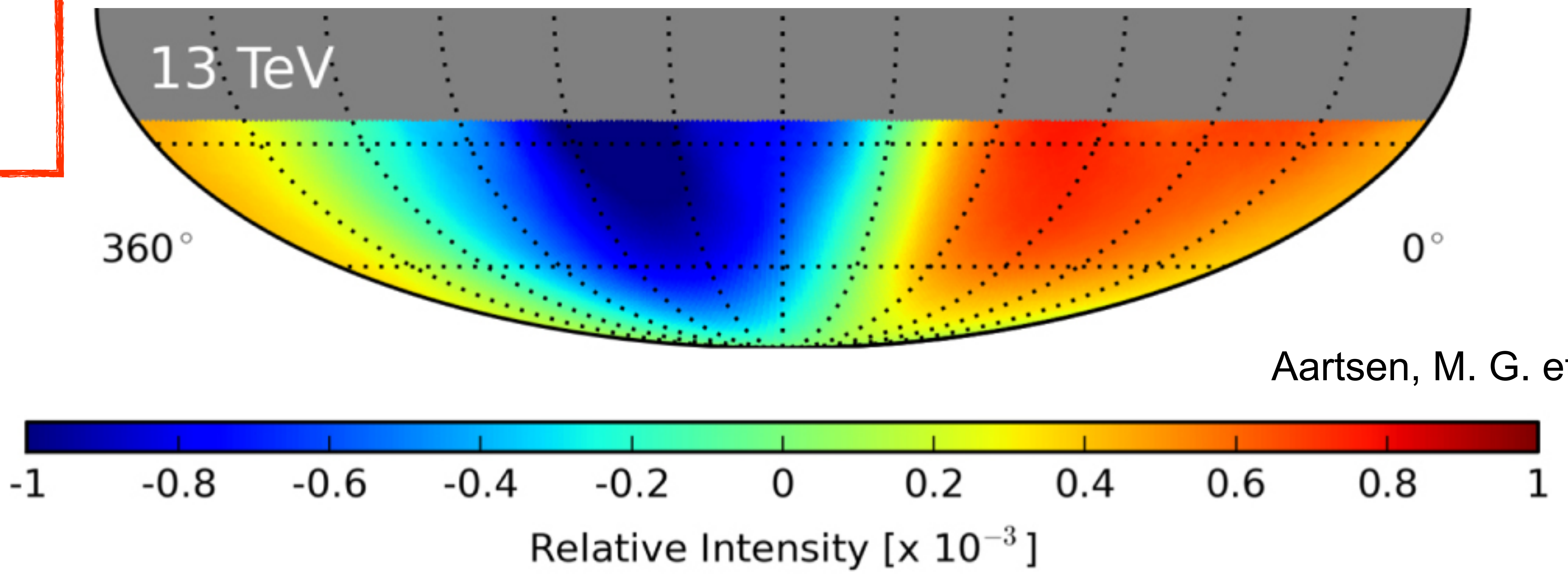
Outline

- Motivation
- Fermi Large Area Telescope
- Event selection
- Anisotropy search
- Initial results
- Outlook and sensitivity

Anisotropy Measurements

IceCube

Large-scale (dipole)



Aartsen, M. G. et al. 2016, *ApJ*, **826**, 220

Anisotropy measurements

- Dipole amplitude O(10^{-4} - 10^{-3})
- Contains information about sources and local interstellar environment
- No consensus on origin

Limitations of ground-based observations

- Declination dependence unconstrained
- Mixed species
- Partial sky coverage

Fermi Large Area Telescope

Fermi Gamma-ray Space Telescope

Fermi Gamma-ray Space Telescope launched in June 2008

- Low earth orbit (565 km)

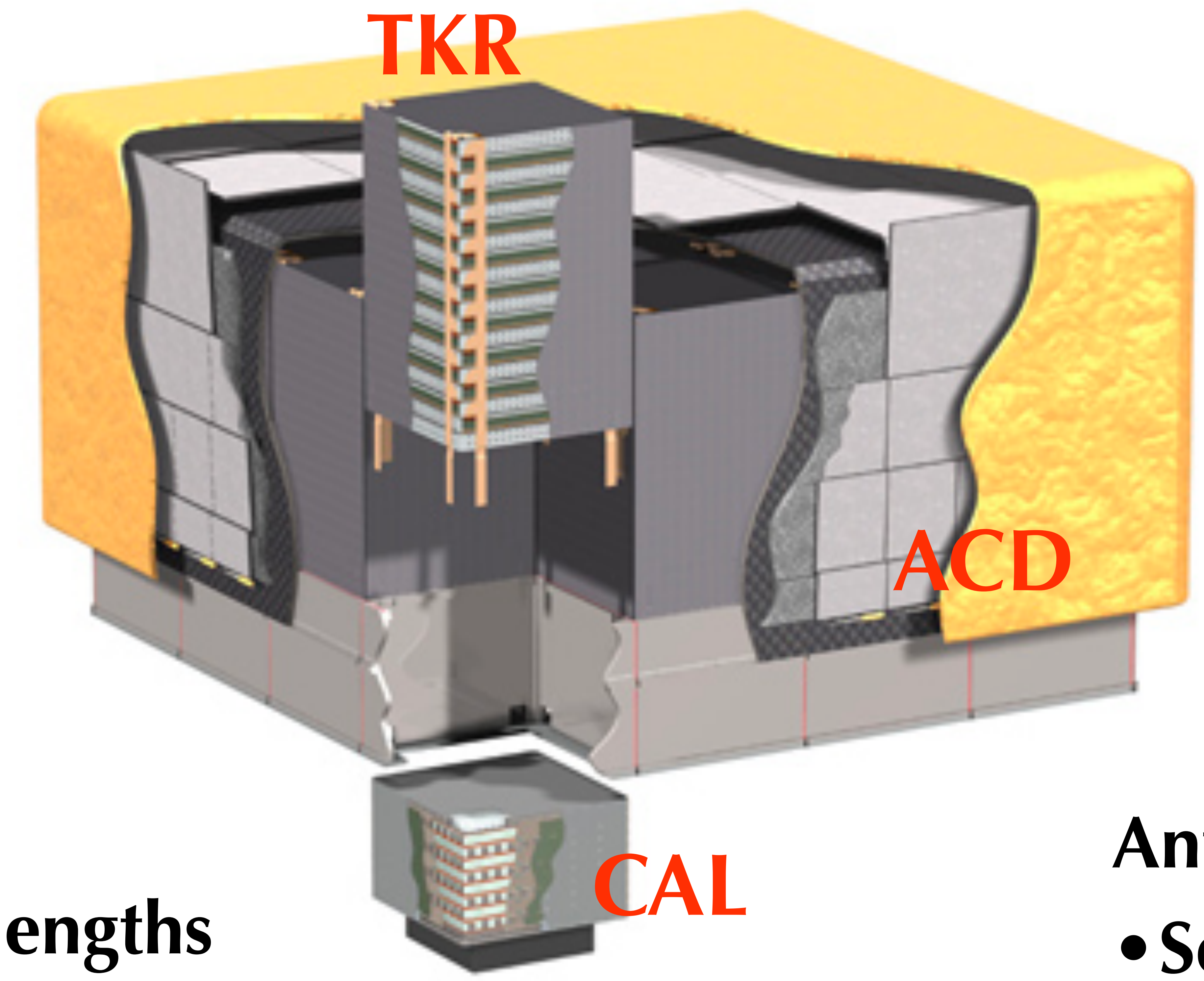
Two Instruments

- Large Area Telescope (LAT)
- Gamma-ray Burst Monitor (GBM)

Large Area Telescope

- Pair conversion gamma-ray telescope
- 2.4 sr instantaneous field of view
- Full-sky coverage every ~3 hrs

Fermi LAT Subsystems



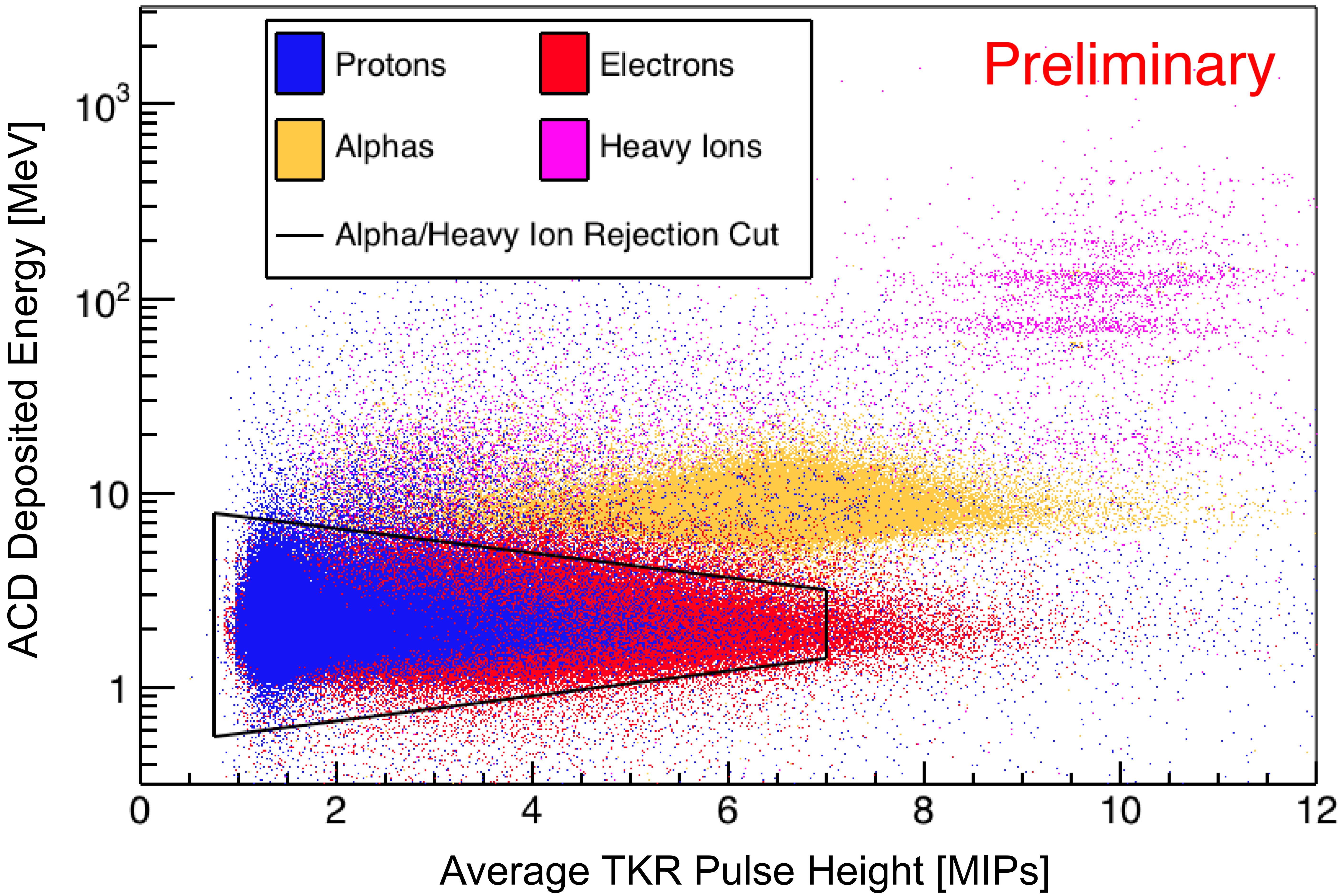
Tracker (TKR)
- 18 layers X and Y Si strips
- Tungsten layers to promote pair conversion

Calorimeter (CAL)
- 8 layers of CsI crystals
- 3D image of shower
- 8.5 radiation lengths
- 0.5 nuclear interaction lengths

Anti-Coincidence Detector (ACD)
- Segmented scintillator tiles
- Charged particle identification

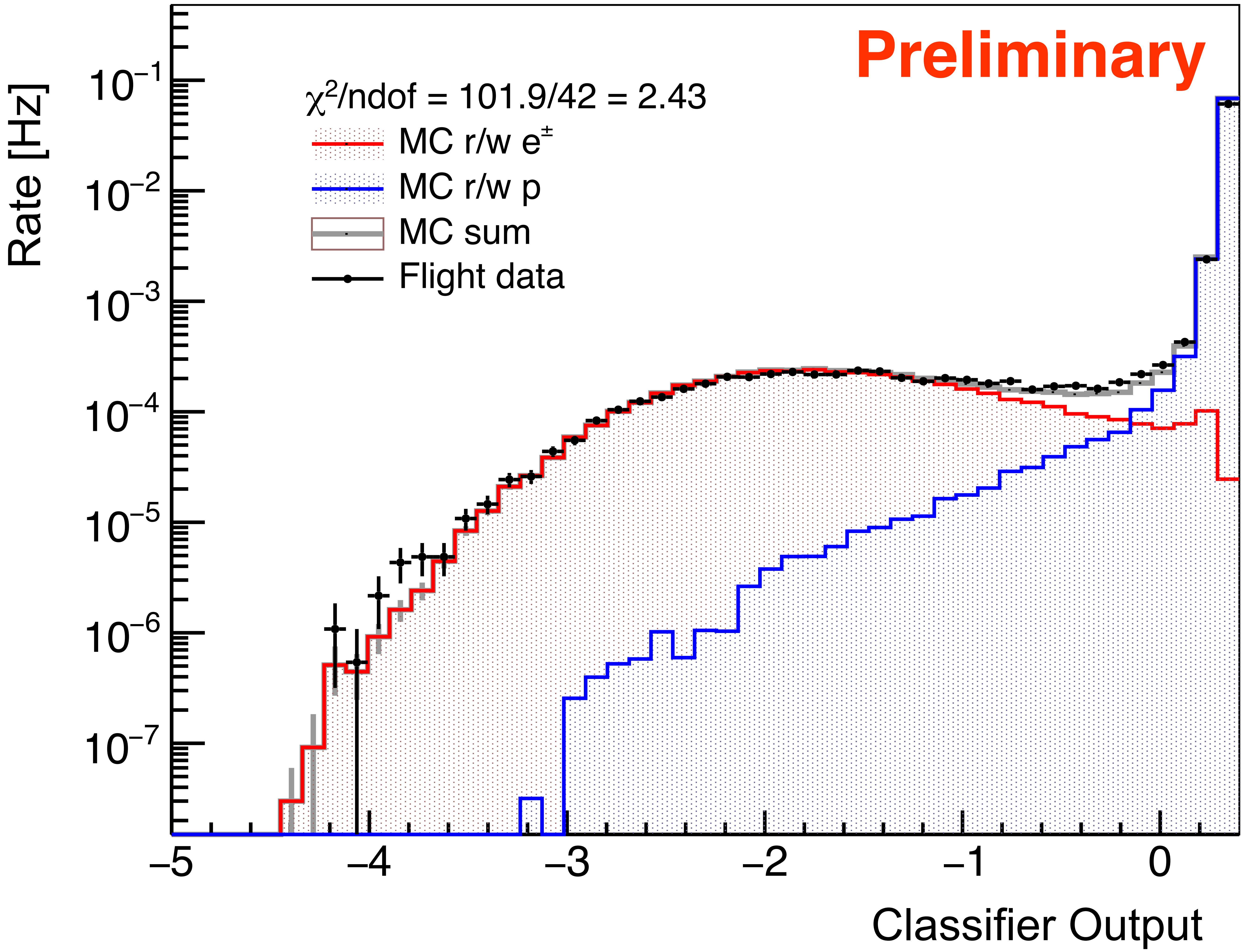
Event Selection

- 8 years of Pass 8 data (final analysis)
  - 1 year only (this talk)
- 100 GeV - 10 TeV
- Quality cuts
  - Deposit > 20 GeV in the CAL
- Use ACD and TKR to measure charge (right)
  - Residual Z>1 contamination < 1%



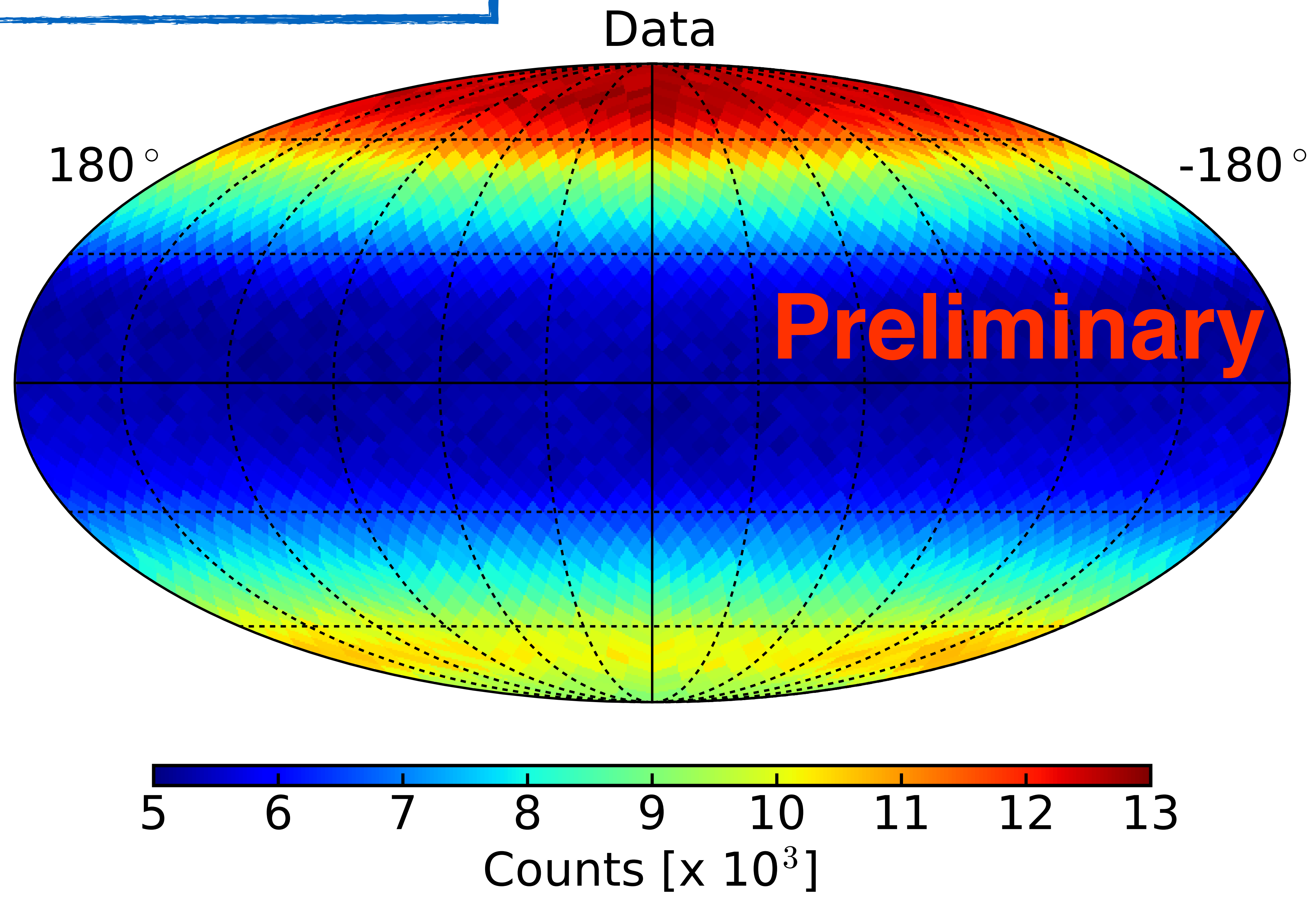
Lepton-Hadron Separation

- Dedicated classifier developed for Fermi LAT e+/e- analyses
- Uses differences in leptonic vs. hadronic showers
  - e.g. hadronic showers are wider in transverse direction
- 8 energy bins
  - 178 - 316 GeV (shown)
- Residual lepton contamination < 1%

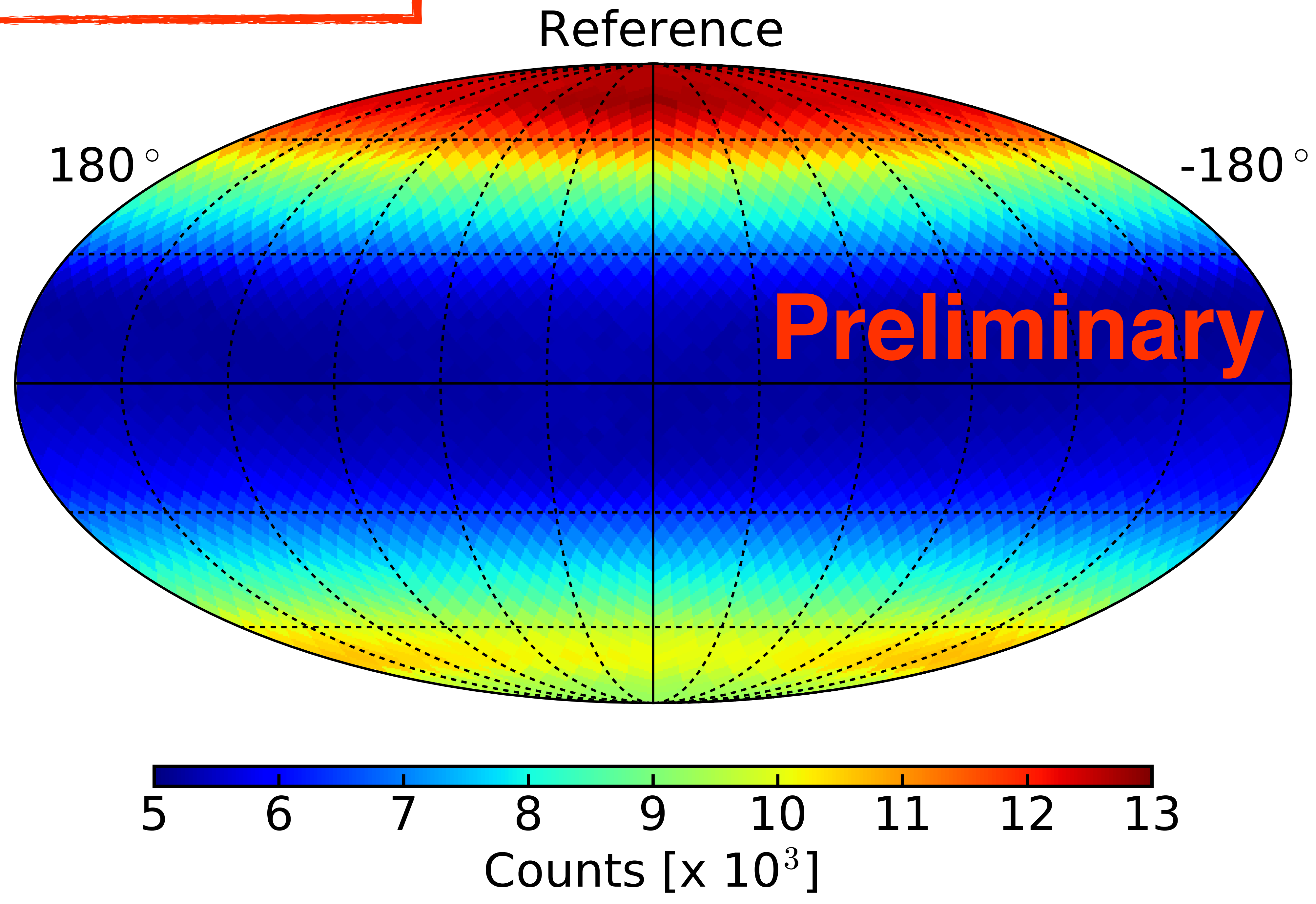


Equatorial Sky Maps

Counts map
1 year of flight data



Reference Map
10 map average



Expected anisotropy O(10^{-4} - 10^{-3})
- Cannot estimate exposure from simulation!

Data-driven method of creating reference map
- Detector response to an isotropic sky

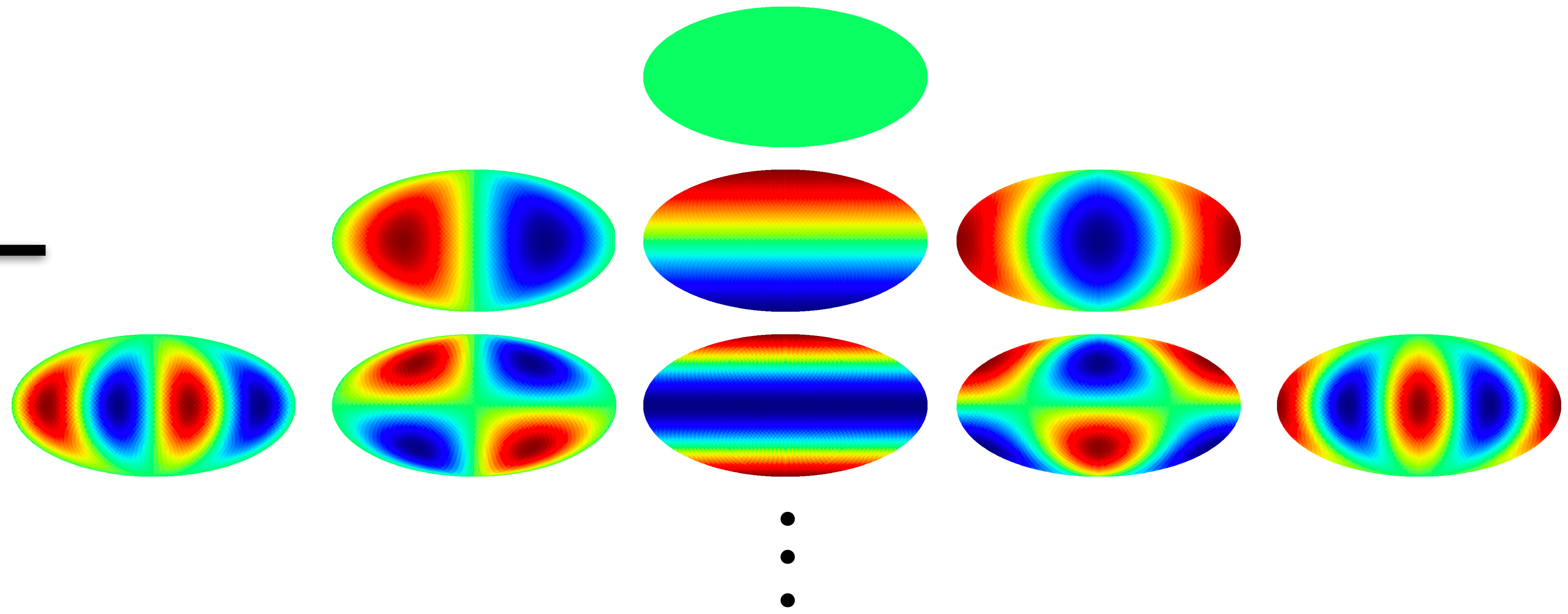
Anisotropy Search Method

Analyze relative intensity →

$$\delta I_i(\alpha,\delta) = \frac{\Delta N_i}{\langle N_i \rangle} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$

Spherical harmonic decomposition

– **Multipole coefficients a_{lm}**

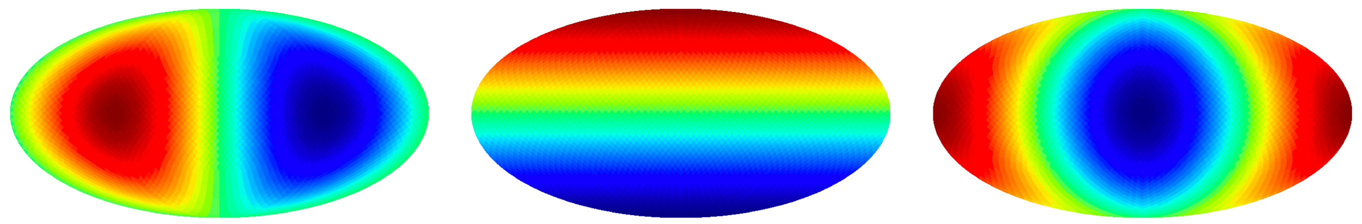


Study angular power spectrum and dipole

– **Sensitive to anisotropies at all angular scales**

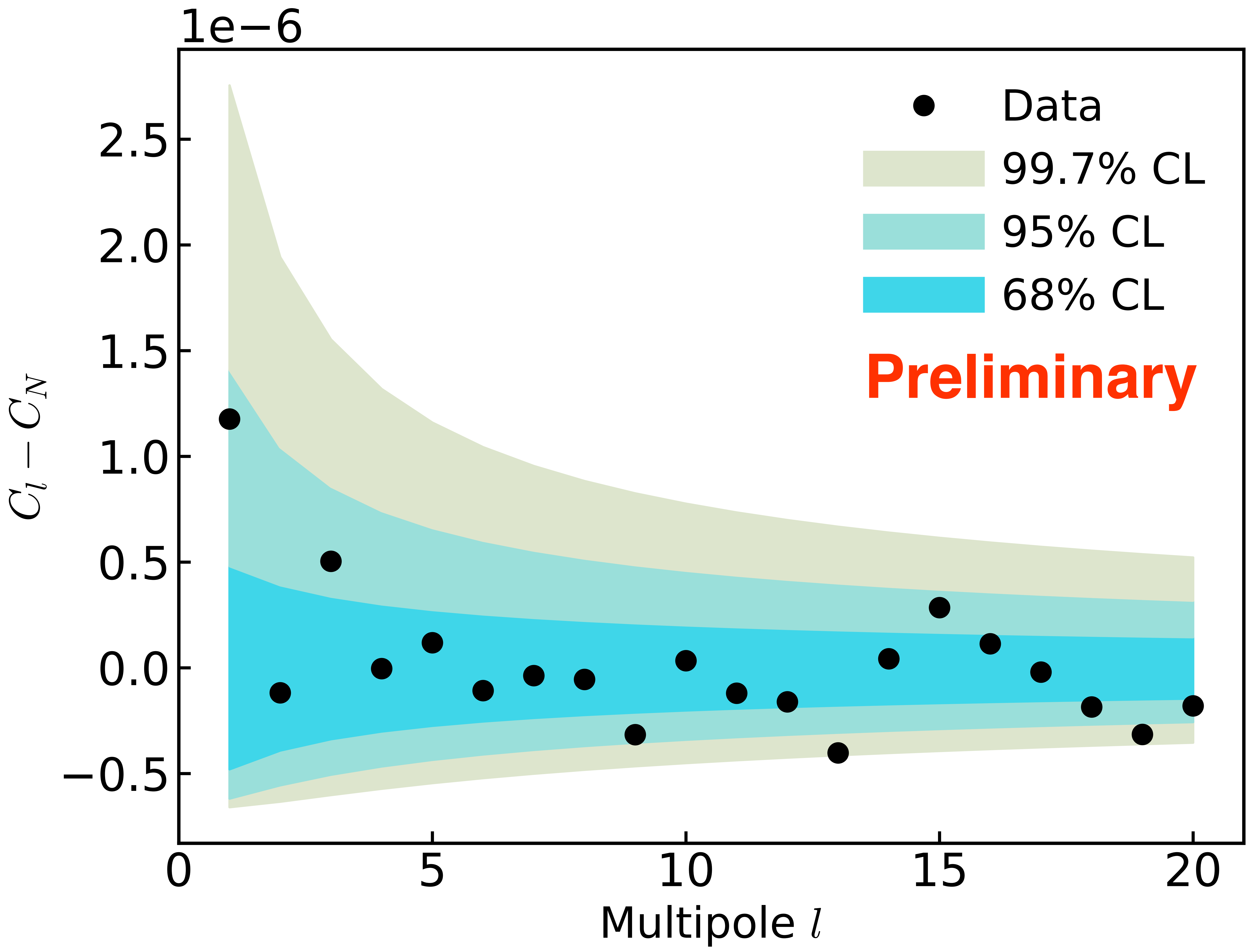
dipole amplitude

$$\boxed{\delta = \sqrt{\frac{3}{4\pi}}\sqrt{(a_{1-1}^2 + a_{10}^2 + a_{11}^2)}}$$



Angular Power Spectrum

- **1 year analysis of flight data**
  - Blind to full, 8 year data set
- **Angular scale ~ 180°/l**
- **Consistent with isotropy**
  - Expected with 1 year of data
- **Full analysis will have 8x statistics**



C_l = measured power

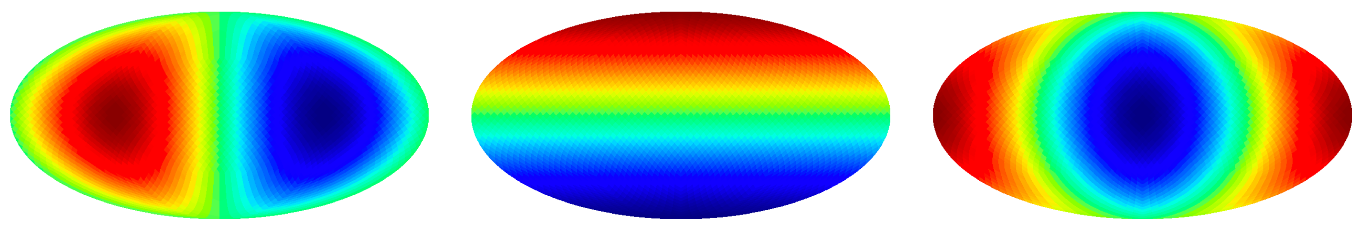
C_N = power due to poisson noise

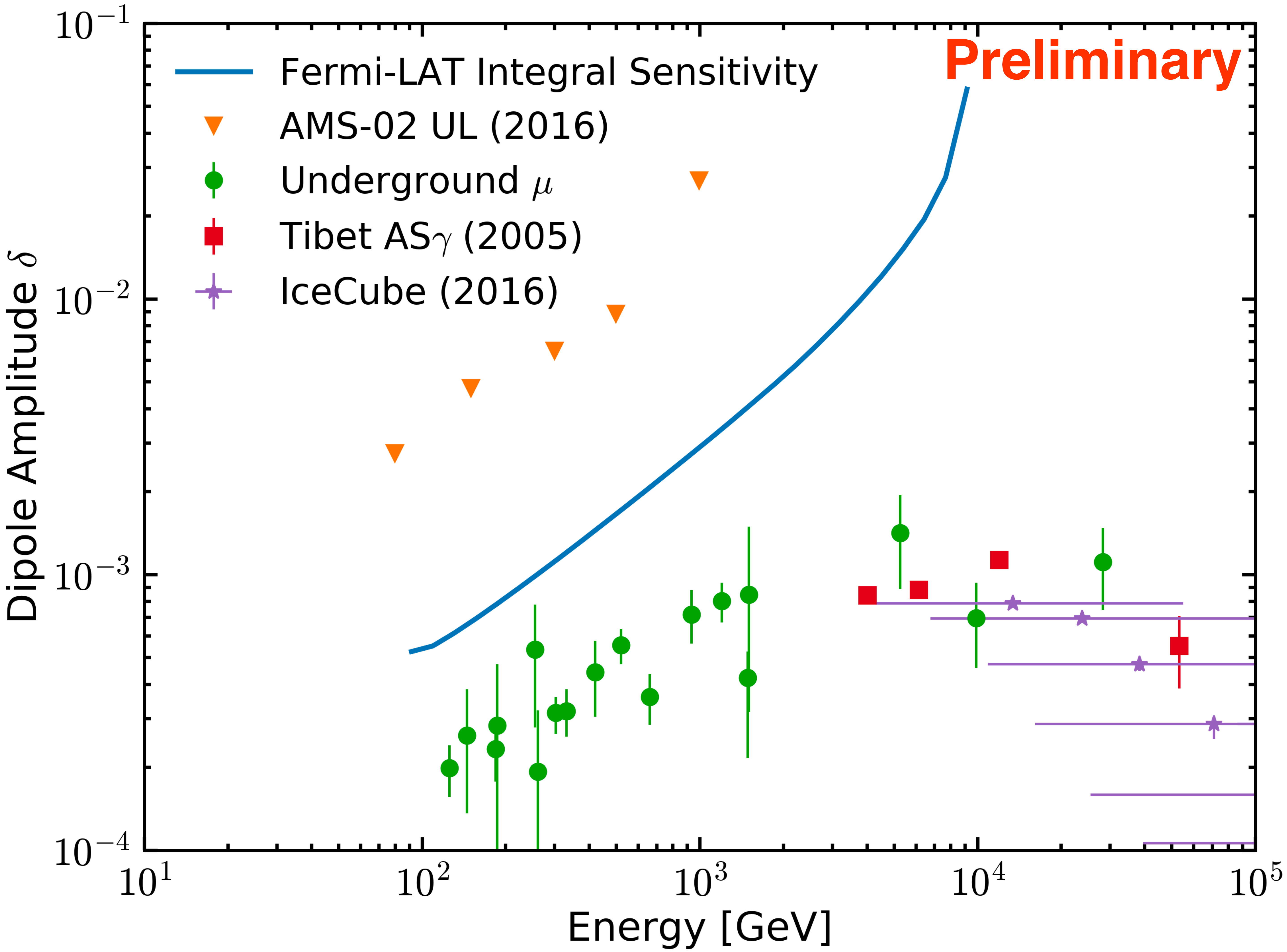
$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |\hat{a}_{lm}|^2$$

Dipole Sensitivity

- **Fermi LAT 8 year sensitivity**
  - Integral energy bins
- **AMS-02 UL**
  - Integral energy bins
- **Ground-based measurements**
  - Projection onto right ascension (i.e. no sensitivity to a_{10})
  - Lower limit on true anisotropy on sky

$$\delta = \sqrt{\frac{3}{4\pi}}\sqrt{(a_{1-1}^2 + a_{10}^2 + a_{11}^2)}$$

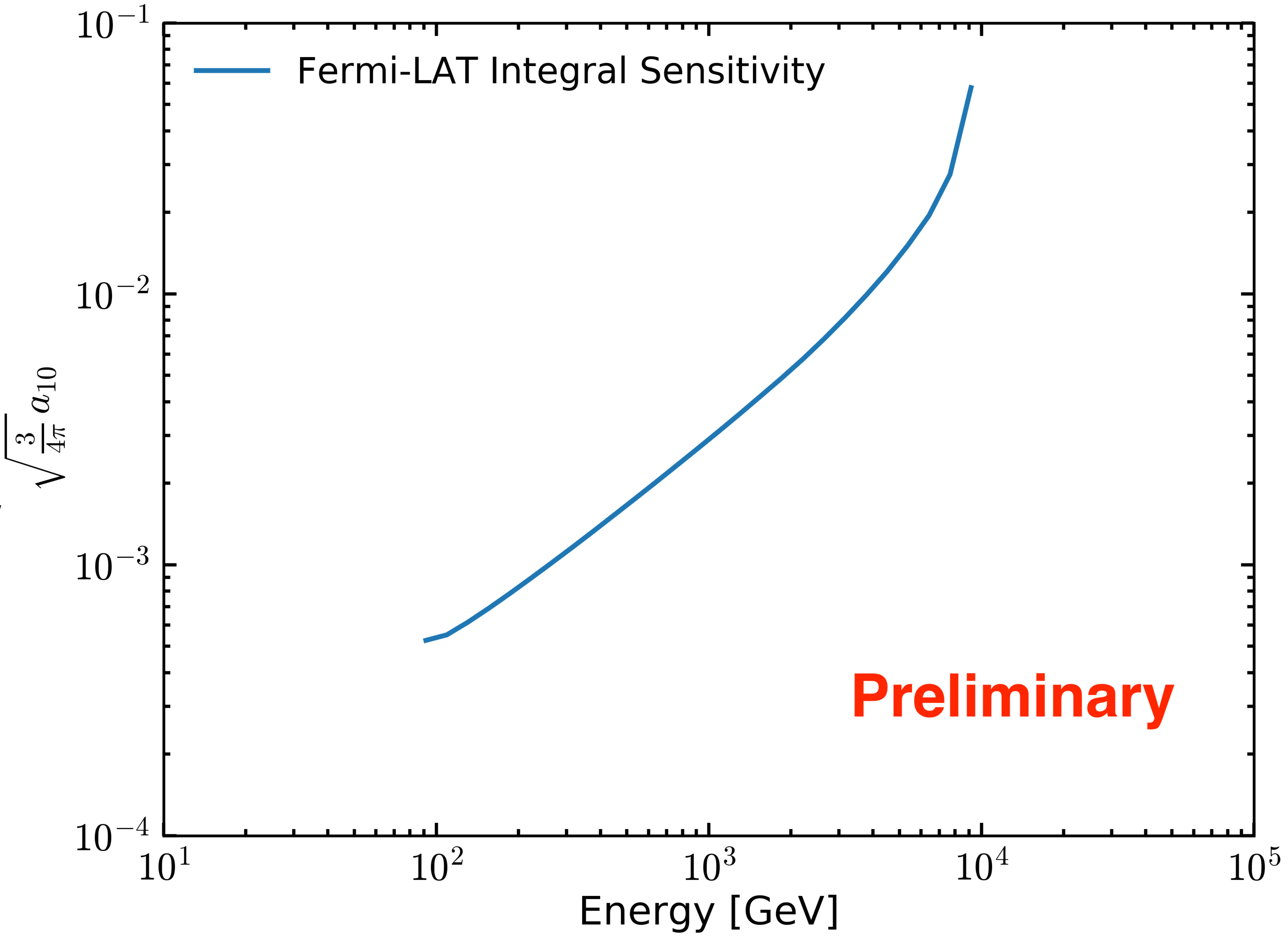




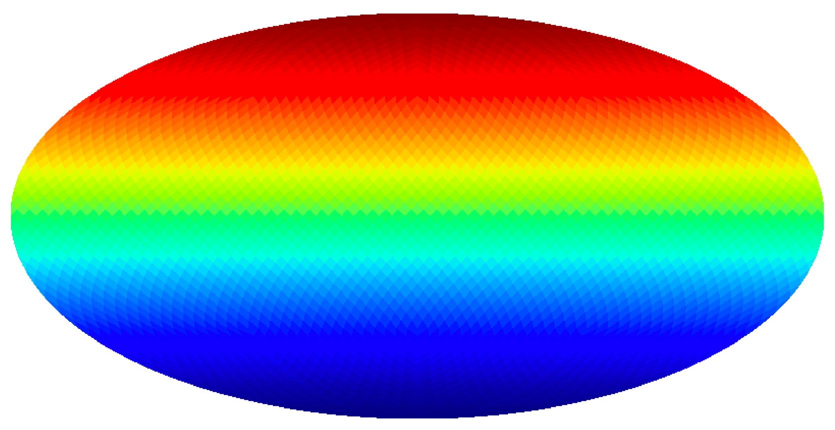
First Constraints on Declination Component

Fermi LAT sensitivity to a_{10} component of dipole anisotropy compared to previous measurements

- Ground-based observatories not sensitive to this component
- We will constrain full-sky phase of dipole

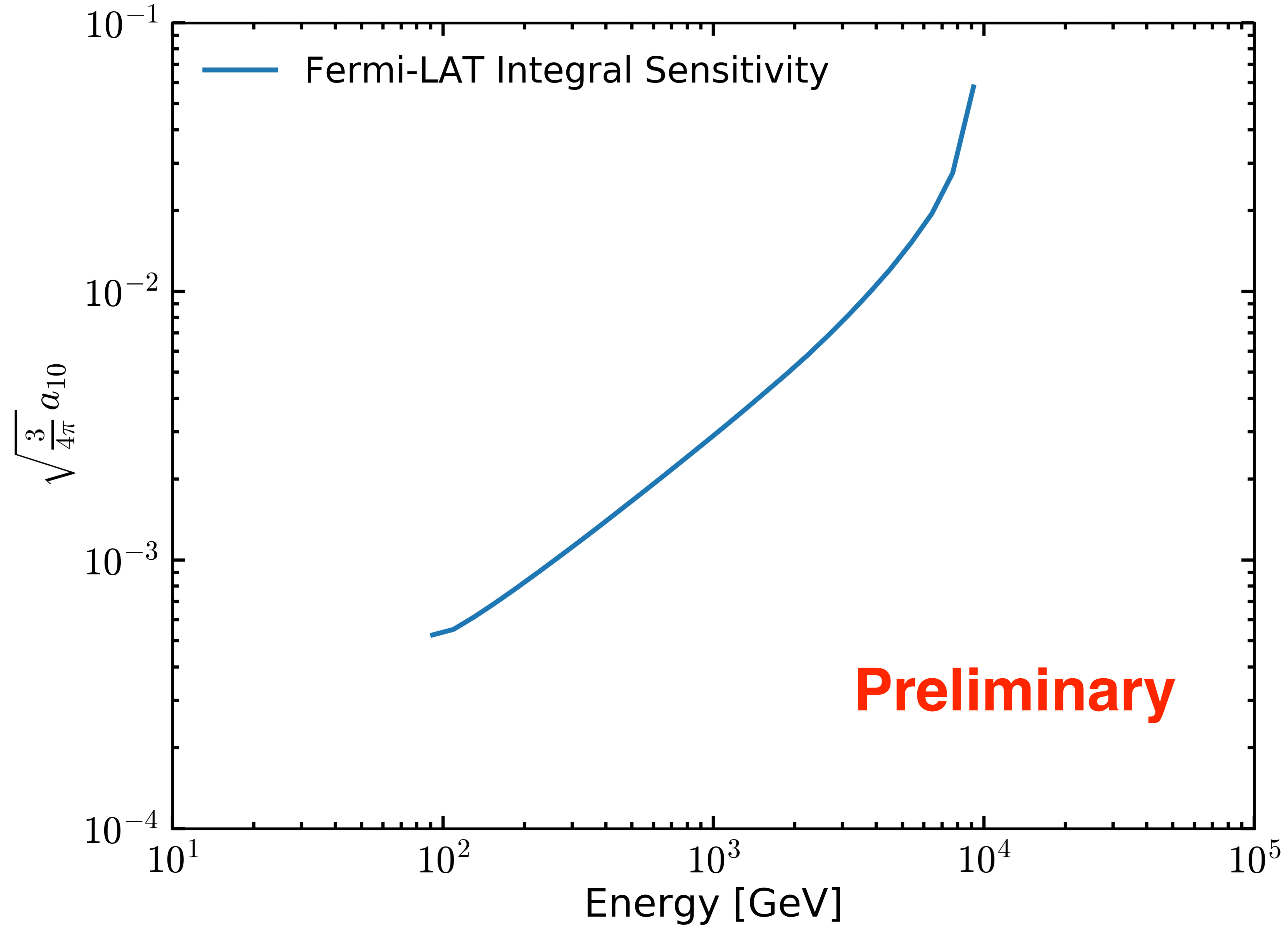


Declination component of dipole



Summary and Outlook

- **Fermi LAT well-suited to studying anisotropy**
  - **Wide FoV, full-sky survey**
- **Unique measurement**
  - **Full-sky**
  - **Proton-only**
  - **Sensitive to anisotropy in *both* right ascension and declination**
- **We are developing analysis on 1 year and will then unblind to 8 year data set**
- **Thanks!**



Backup

Anisotropy Search Method

1. **Analyze relative intensity**
2. **Spherical harmonic decomposition**
3. **Angular power spectrum**
   - Sensitive to anisotropies at all angular scales
4. **Dipole amplitude**
   - Sensitive to dipole anisotropy in both right ascension and declination

$$\delta I_i(\alpha,\delta) = \frac{\Delta N_i}{\langle N_i \rangle} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle} \quad \textbf{(1)}$$

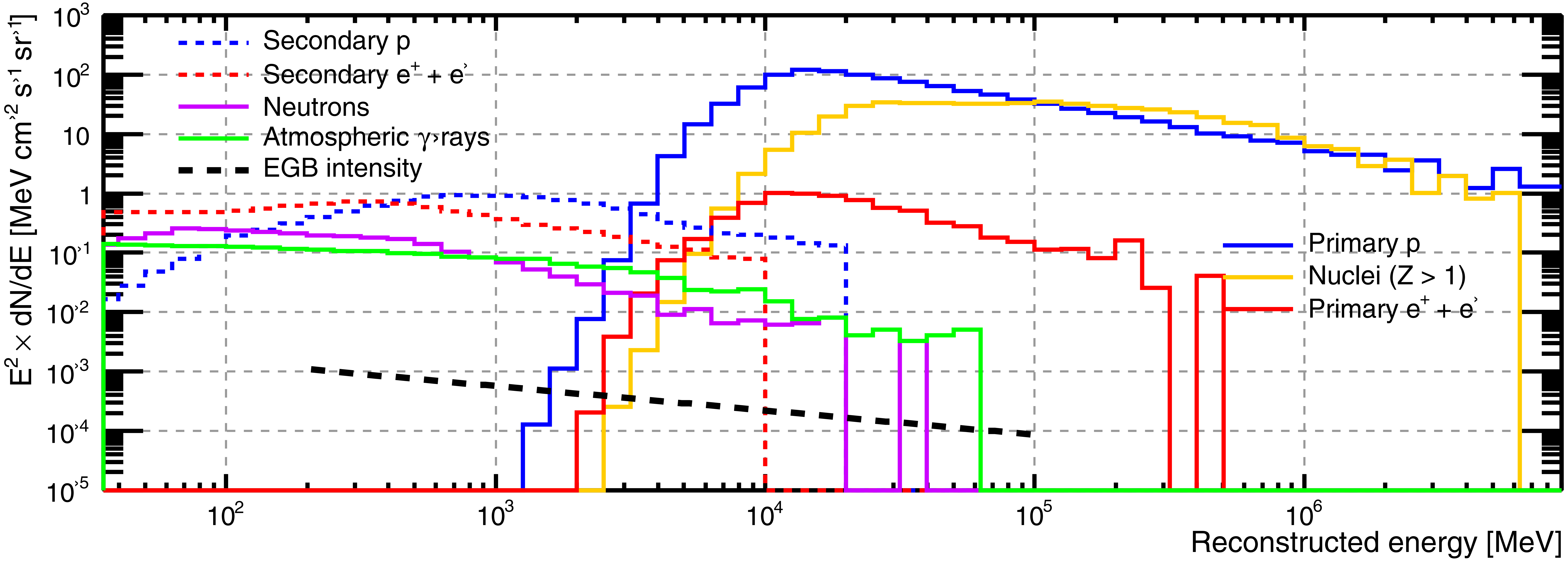
$$\hat{a}_{lm} = \frac{4\pi}{N_{pix}} \sum_{i=1}^{N_{pix}} Y^*_{lm}(\pi - \delta_i, \alpha_i)\delta I_i(\alpha_i, \delta_i) \quad \textbf{(2)}$$

$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |\hat{a}_{lm}|^2 \quad \textbf{(3)}$$

$$\delta = 3\sqrt{\frac{C_1}{4\pi}} \quad \textbf{(4)}$$

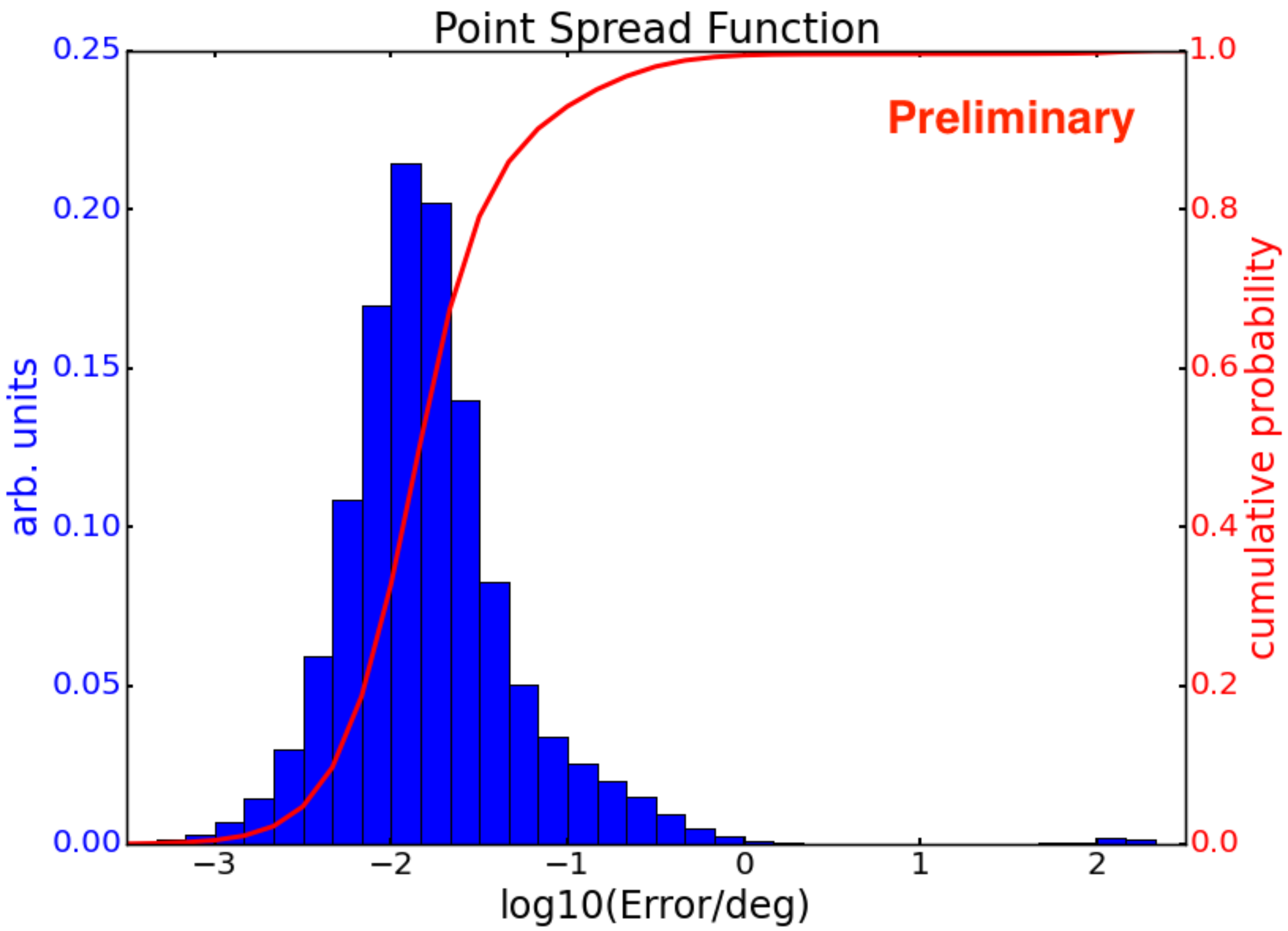
Cosmic-ray intensities

Ackermann, M., et al. 2012. *ApJS*, ***203***, 4



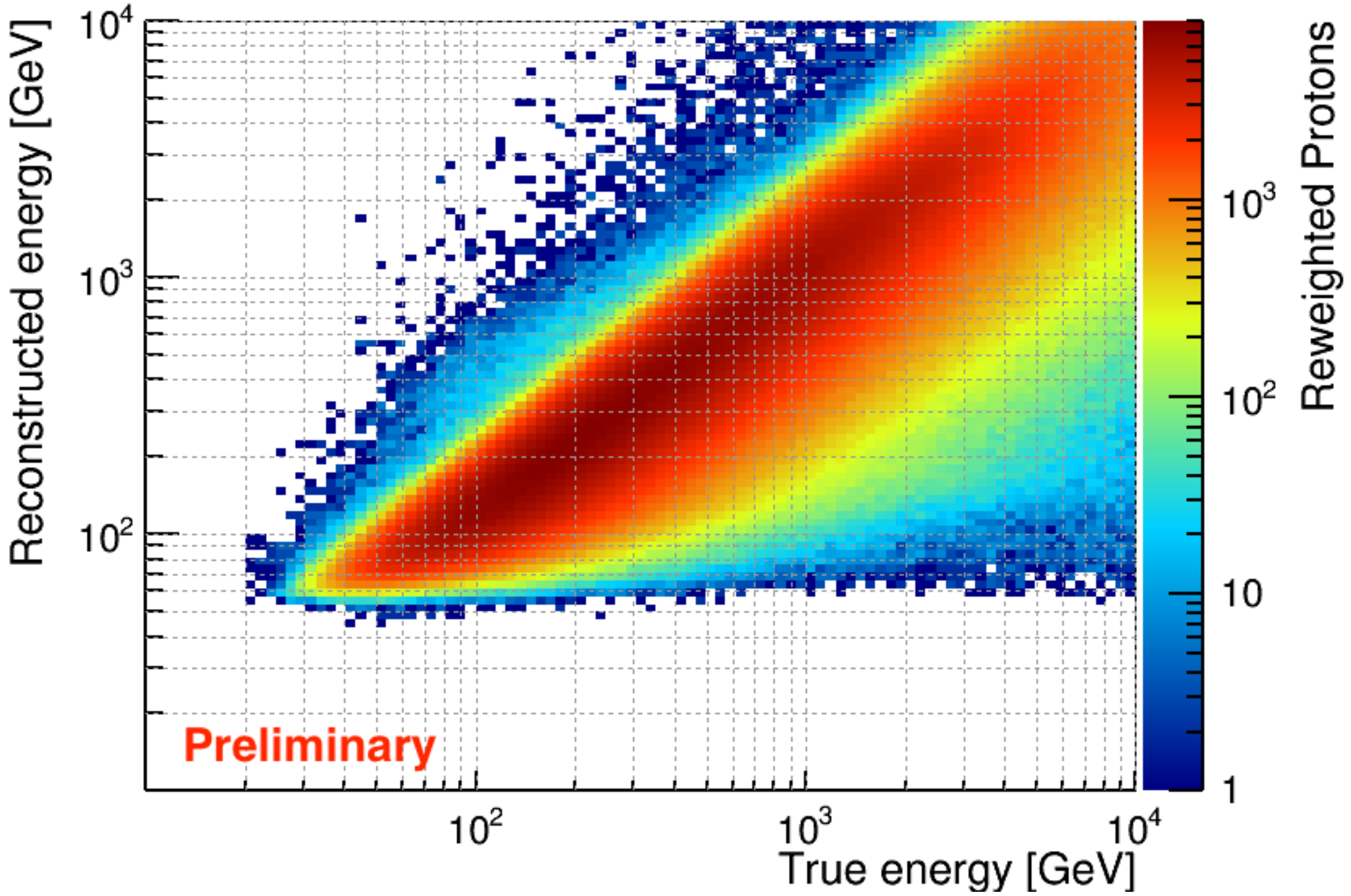
Model of the cosmic-ray particles fluxes from background-simulation. Note that particle energy is reconstructed under the gamma-ray hypothesis and does not necessarily represent actual energy for hadrons in this plot.

Instrument response



Angular error between true track direction and reconstructed track direction from simulation

68% containment = 0.02°



Energy smearing matrix comparing reconstructed energy to true energy from simulation

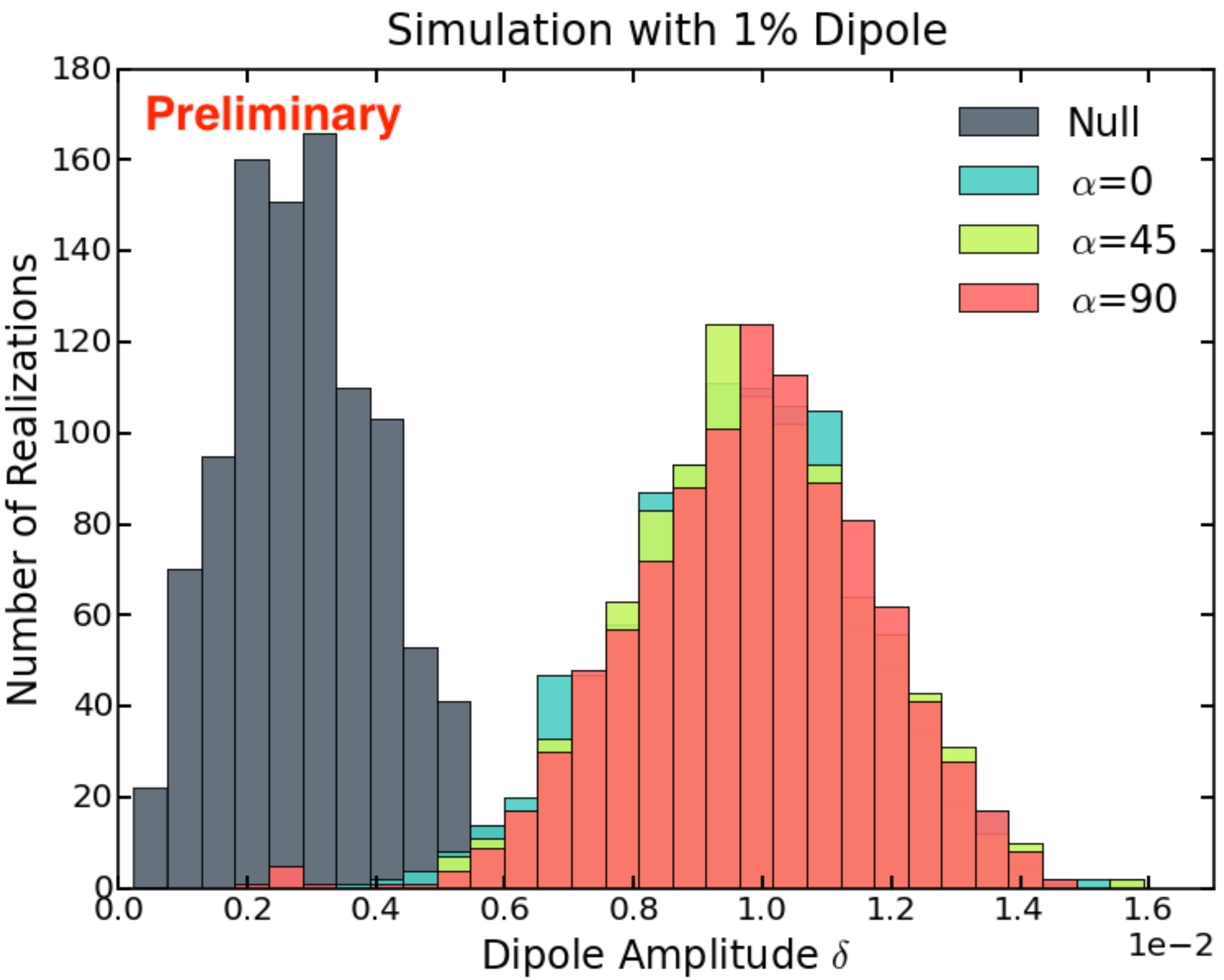
Dipole orientation

Dipole amplitude

$$\delta = \sqrt{\frac{3(|a_{1-1}|^2 + |a_{10}|^2 + |a_{11}|^2)}{4\pi}}$$

Unconstrained by ground-based measurements

- **Simulation (right)**
  - **1% dipole injected at different dipole orientations**
  - **α = angle between dipole and declination axis**
- **Reconstructed dipole independent of orientation on sky**



Sensitivity estimate

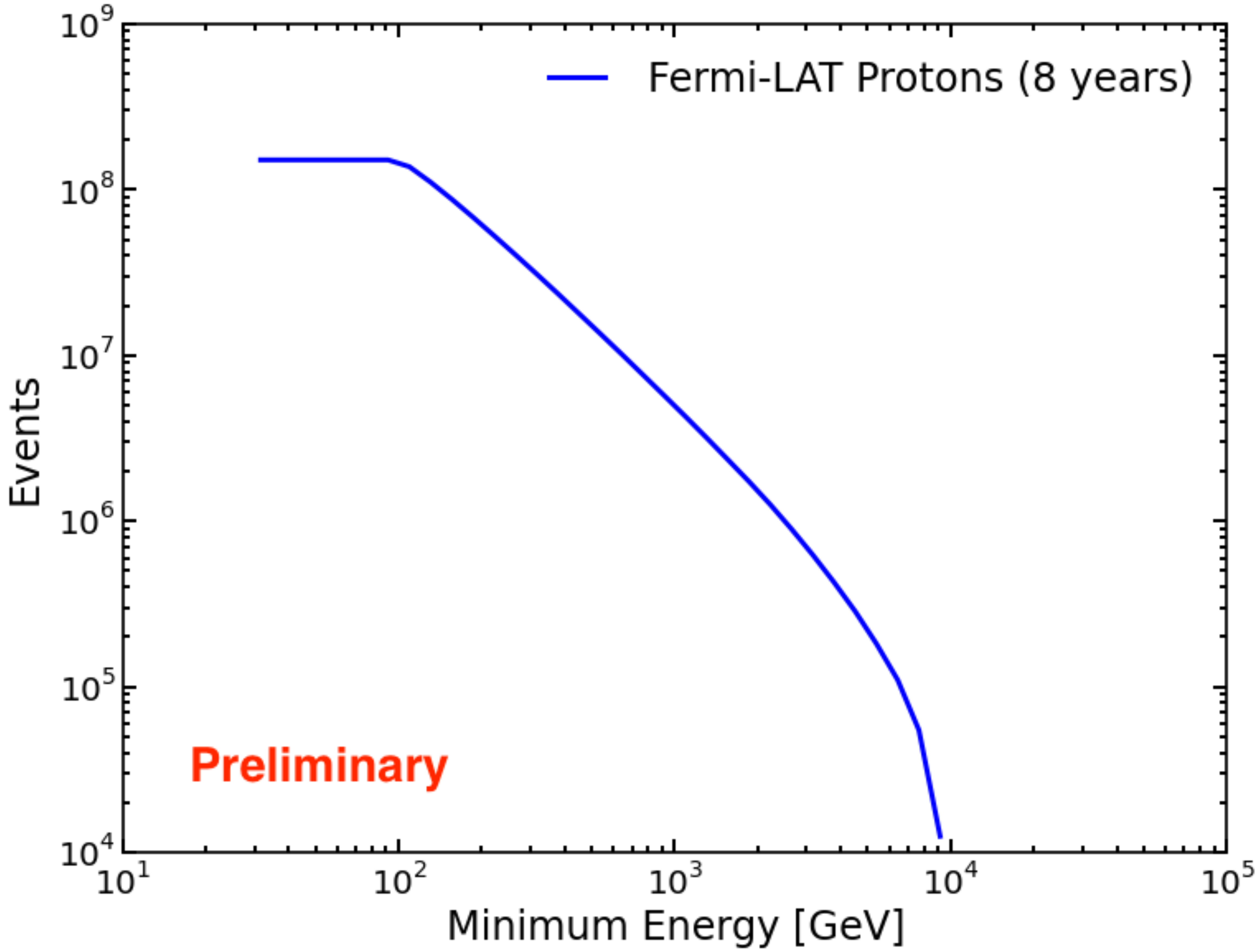
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

$$\delta = 3\sqrt{\frac{C_1}{4\pi}}$$

$$C_l \sim \chi^2_{2l+1}$$

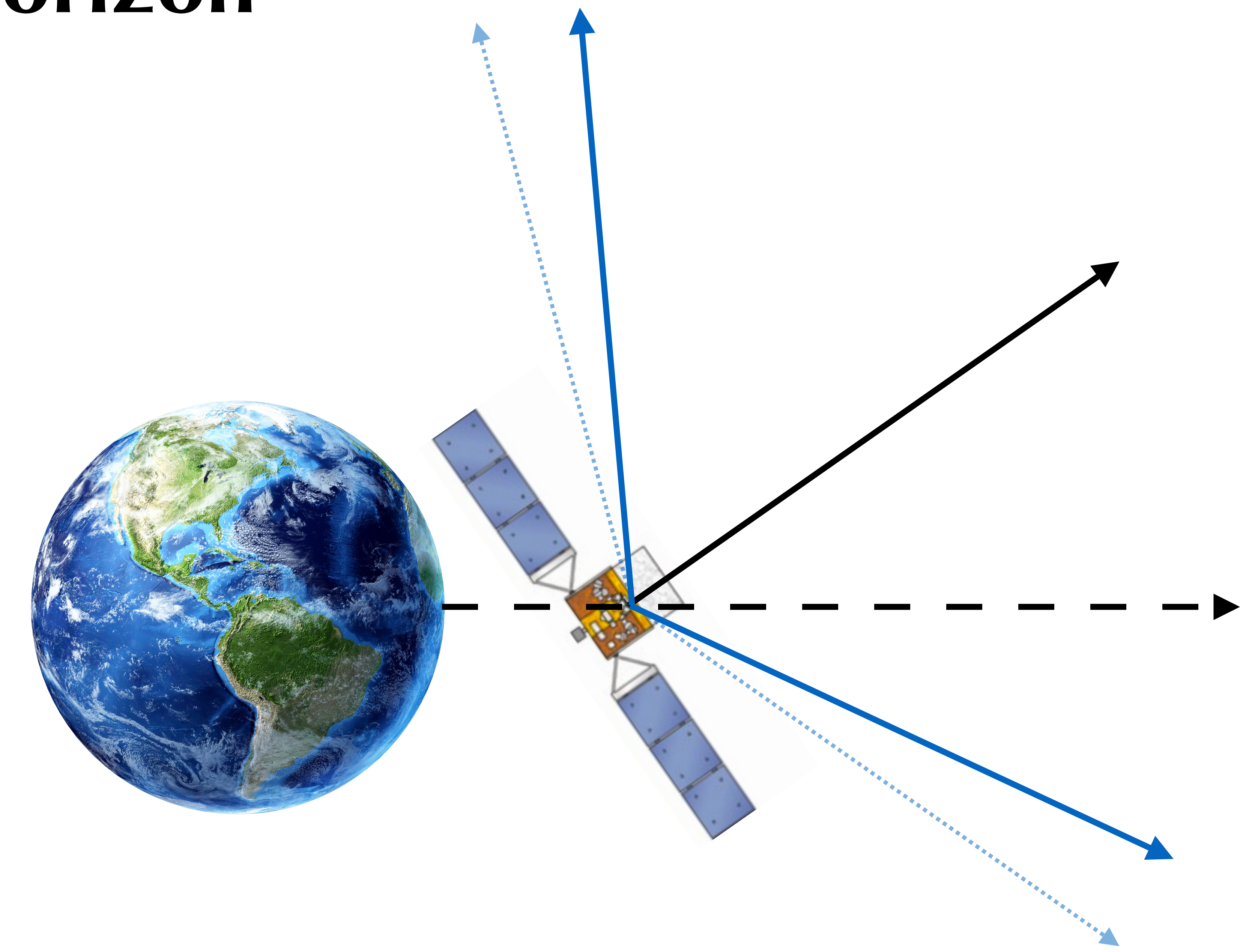
$$P(\delta)d\delta = \frac{8\pi\delta^2}{9}\sqrt{\frac{6}{C_N^3}} \exp\left(-\frac{2\pi\delta^2}{3C_N}\right) d\delta$$

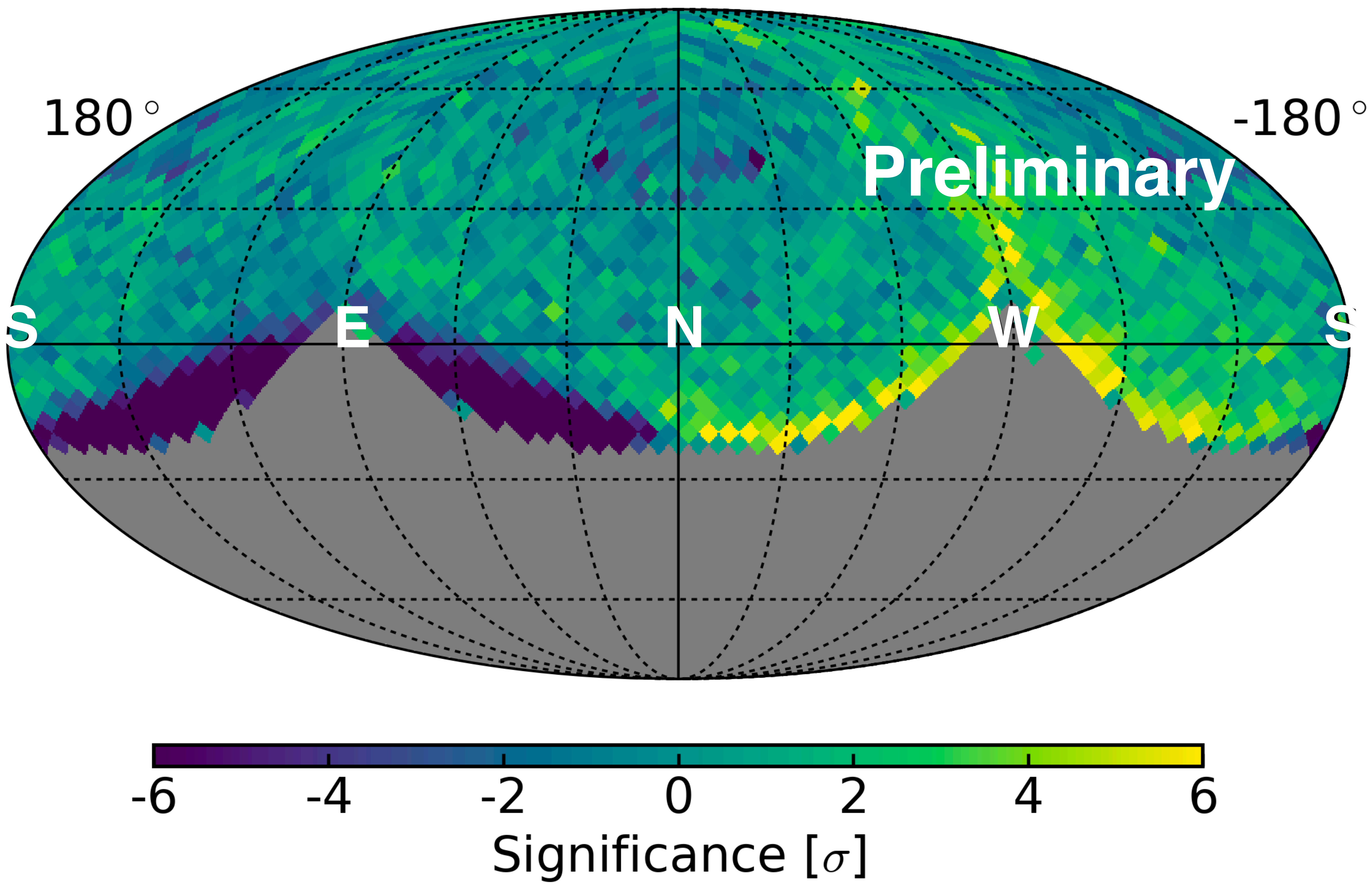
$$C_N = \frac{4\pi}{N}$$



Geomagnetic contamination

- Geomagnetic deflection can create false positive in anisotropy search
- E-W effect present in horizontal coordinates
  - Perform analysis in this coordinate system
- Make energy-dependent instrument theta cuts to remove CRs arriving from near earth's horizon





4.50 < LogE < 4.75 GeV

Instrument theta < 30°