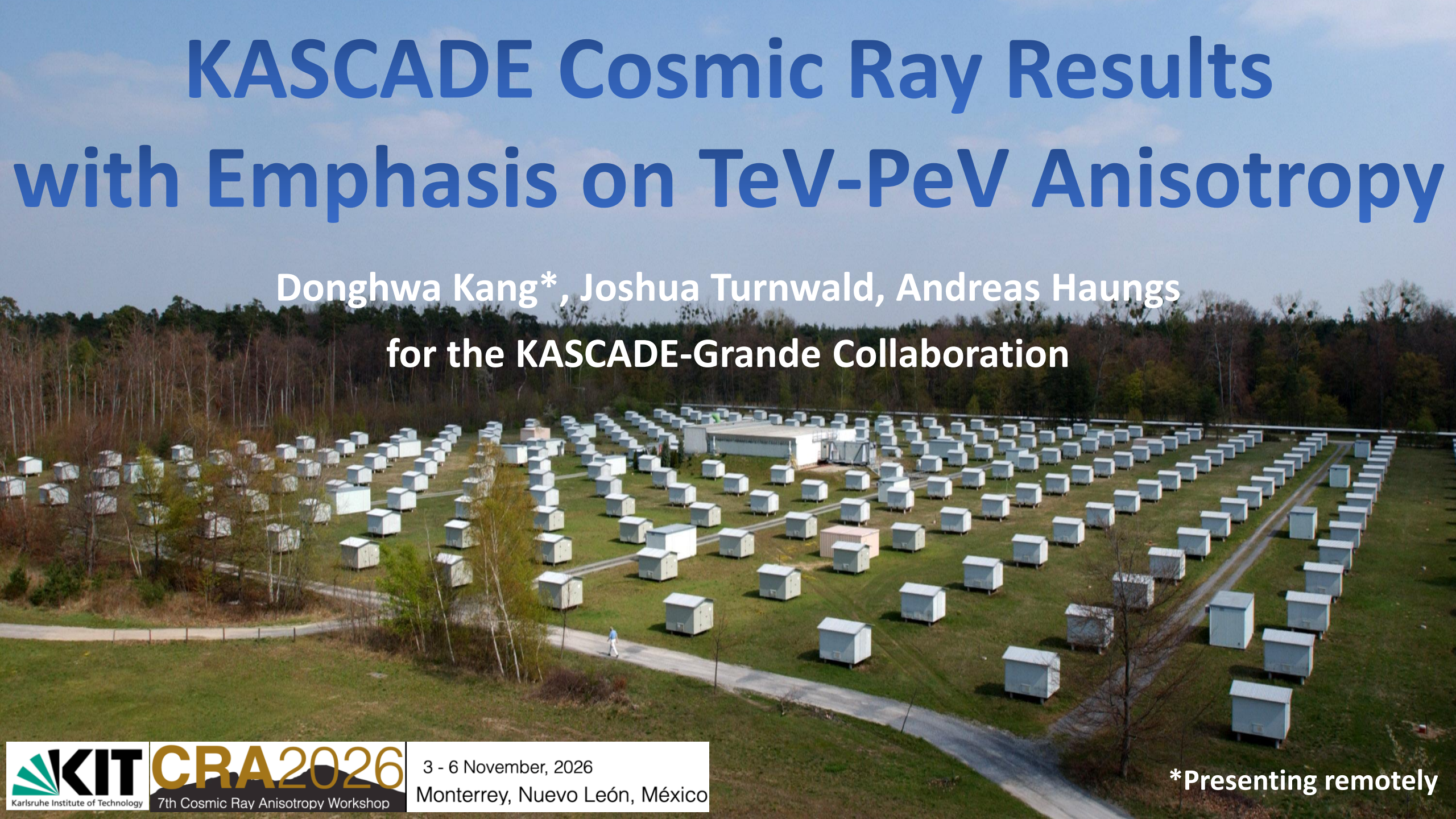
KASCADE Cosmic Ray Results with Emphasis on TeV-PeV Anisotropy

Donghwa Kang*, Joshua Turnwald, Andreas Haungs

for the KASCADE-Grande Collaboration



KIT Karlsruhe Institute of Technology

CRA2026 7th Cosmic Ray Anisotropy Workshop

3 - 6 November, 2026

Monterrey, Nuevo León, México

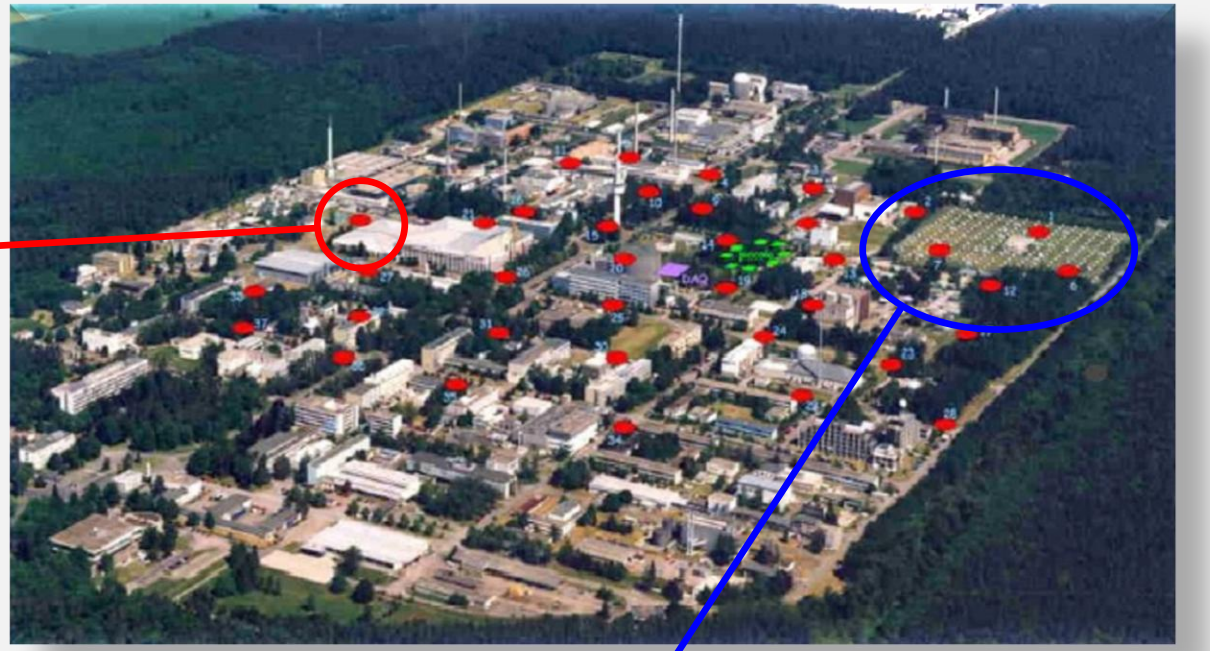
*Presenting remotely

KArlsruhe Shower Core and Array DEtector + Grande

[*Nucl. Instr. and Meth. A620 (2010) 202*]



- **10 PeV – 1 EeV**
- **0.5 km²**
- **37 stations (each 10 m²)**



Successfully completed data acquisition at the end of 2013

Data from more than 20 years of measurements are now available for public usage

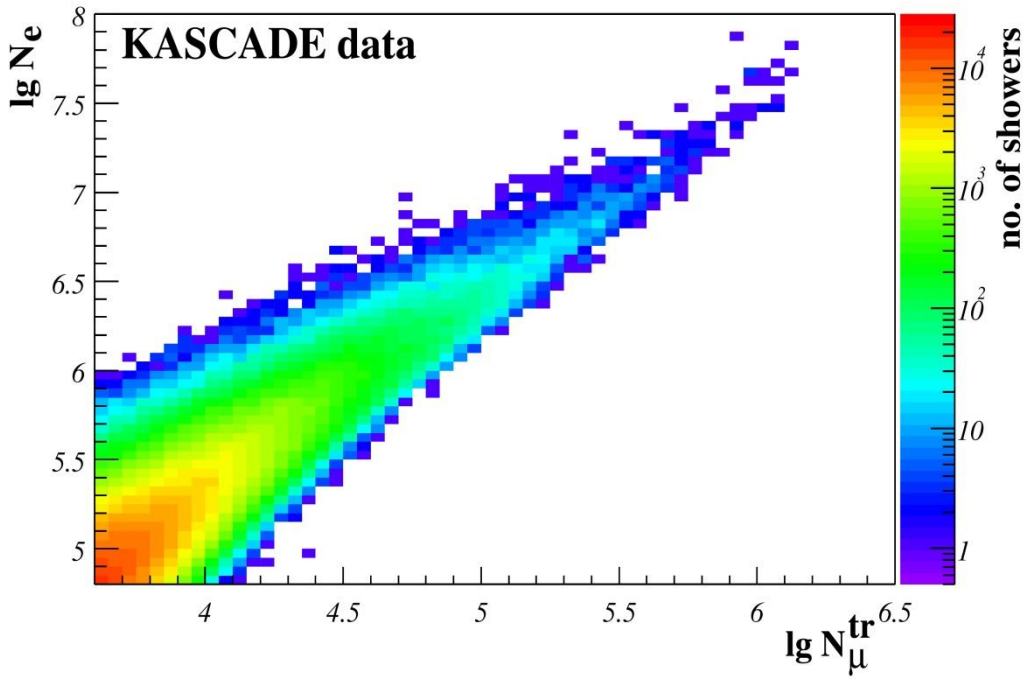
https://kcdc.iap.kit.edu/

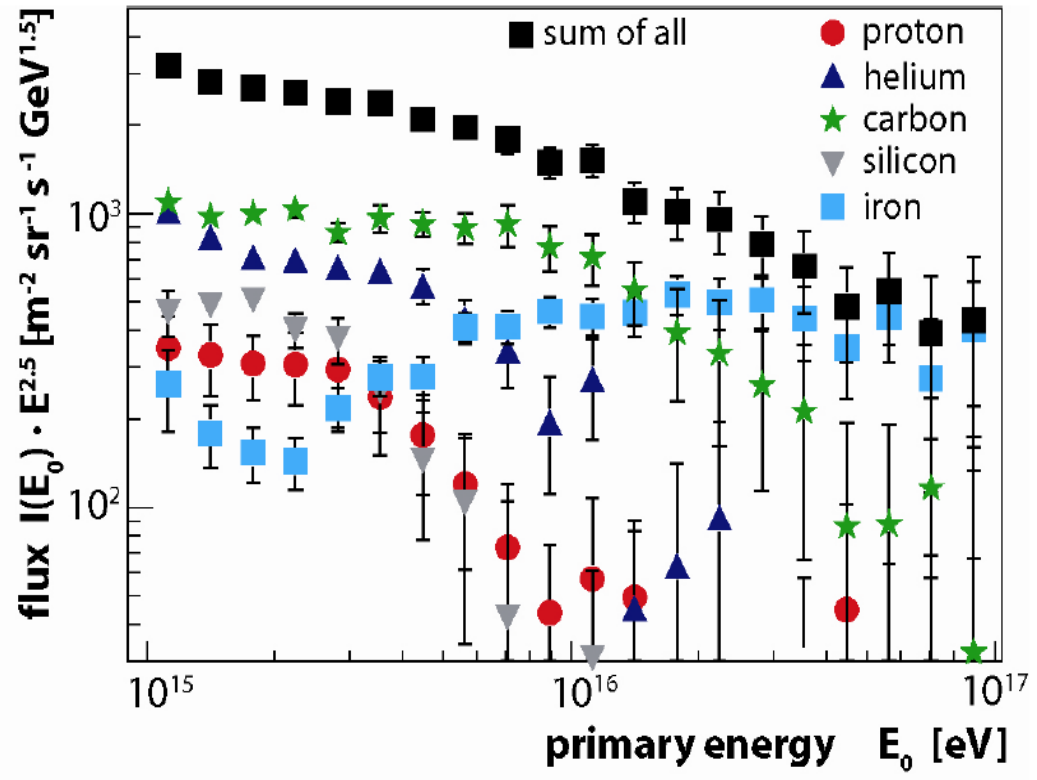


- **100TeV – 80PeV**
- **252 scintillation detector stations**
- **Large number of observables**

Energy Spectrum & Composition

KASCADE: Energy Spectra and Single Mass Groups





Searched: Energy and mass of the cosmic ray particles
Given: N_e and N_μ for each single event → solve the inverse problem

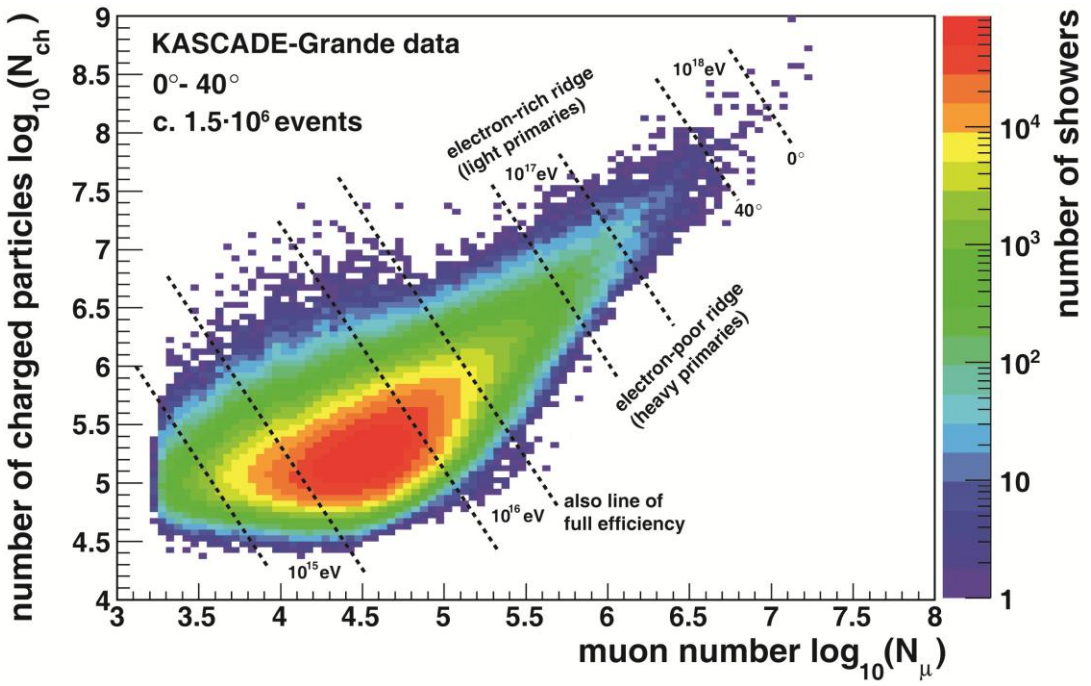
$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

- Kernel function obtained by Monte Carlo simulations (CORSIKA)
- Contains: shower fluctuation, efficiencies, reconstruction resolution

- Knee caused by light primaries at ~ $3 \cdot 10^{15}$ eV (He dominant)
- Relative abundancies depend strongly on high-energy interaction model

Astropart. Phys. 24 (2005) 1-25

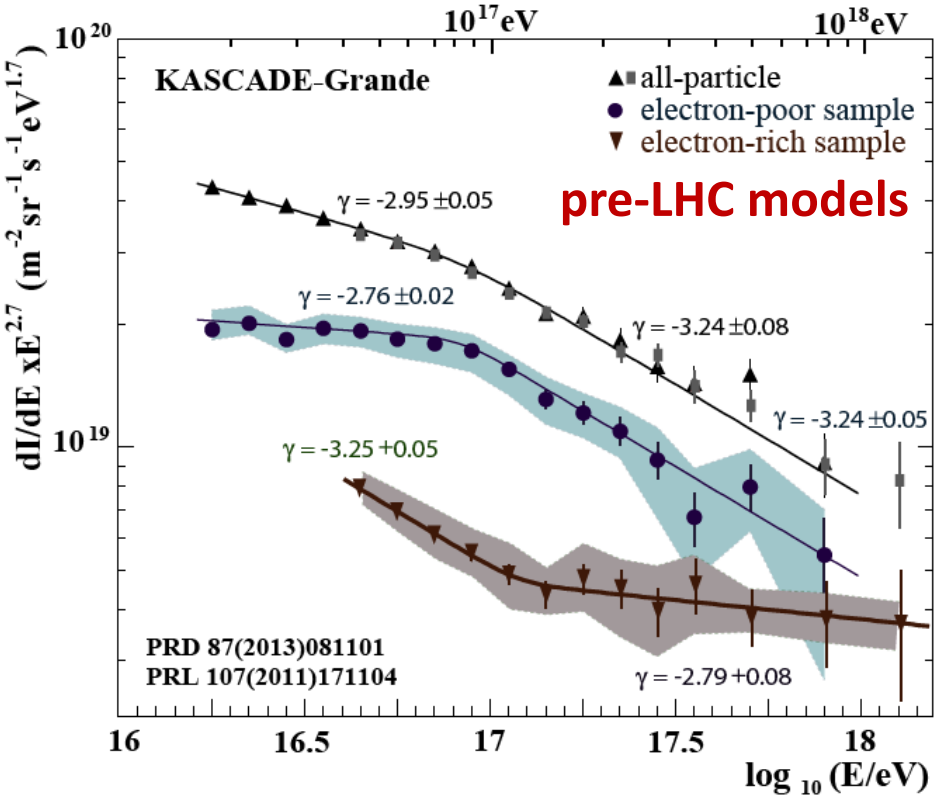
KASCADE-Grande: Energy and Elemental Composition



- 2-dim. shower size distribution → determination of primary energy
- Separation in *electron-rich* and *electron-poor* events

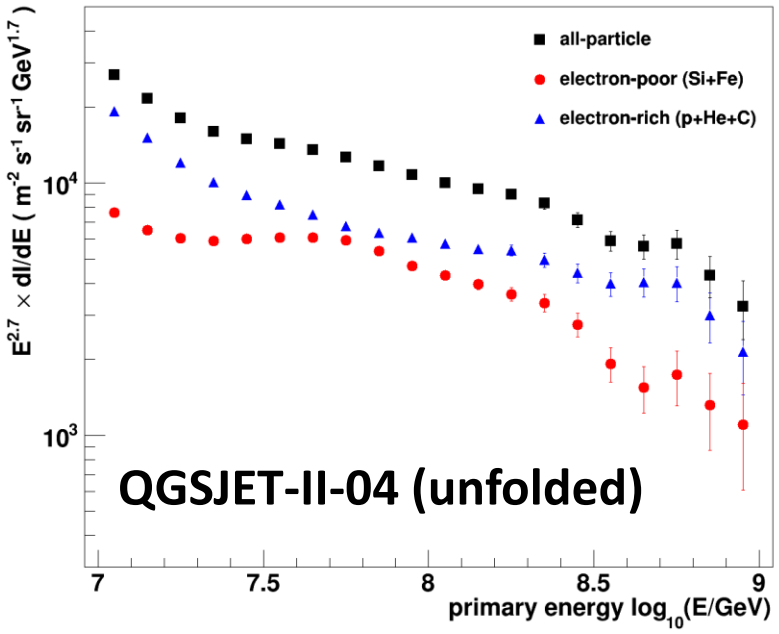
$$\log_{10}(E/\mathrm{GeV}) = [a_H + (a_{Fe} - a_H)\cdot k]\cdot \log_{10}(N_{ch}) + b_H + (b_{Fe} - b_H)\cdot k$$

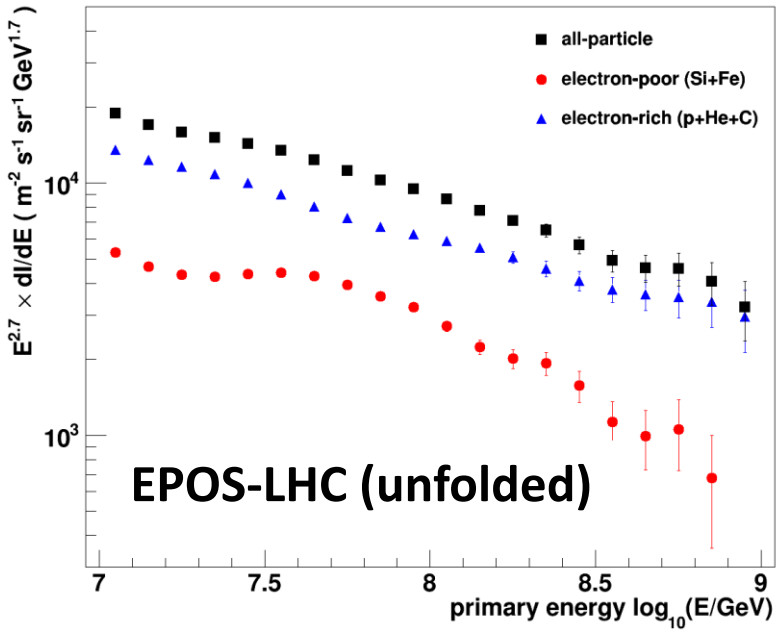
$$k = \frac{(\log_{10}(N_{ch}/N_\mu) - \log_{10}(N_{ch}/N_\mu)_H)}{(\log_{10}(N_{ch}/N_\mu)_{Fe} - \log_{10}(N_{ch}/N_\mu)_H)}$$

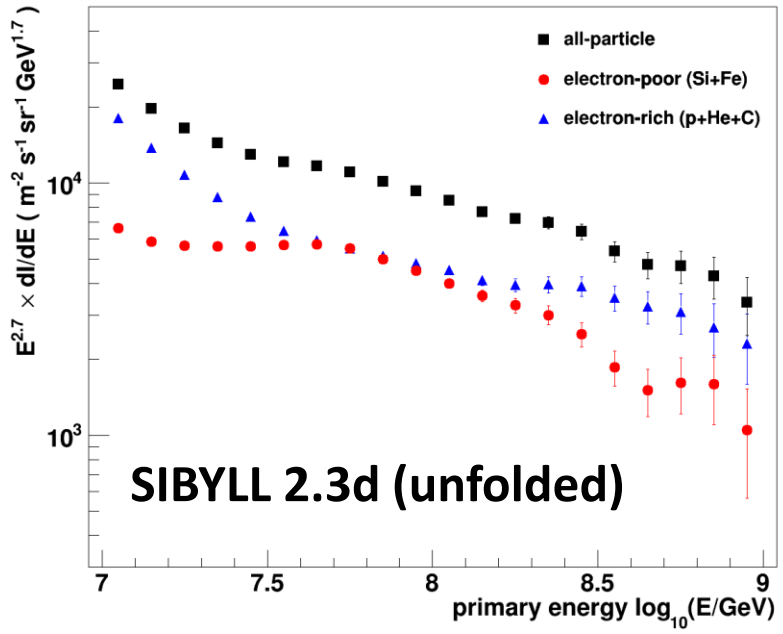


- Spectra of individual mass groups
- Steepening close to 10^{17} eV (2.1σ) in all-particle spectrum
- Knee of heavy primaries at ~$9\cdot10^{16}$ eV (3.5σ)
- Hardening at $10^{17.08}$eV (5.8σ) in light spectrum: slope change from γ = -3.25 to γ=-2.79

KASCADE-Grande: Spectra with post-LHC Models



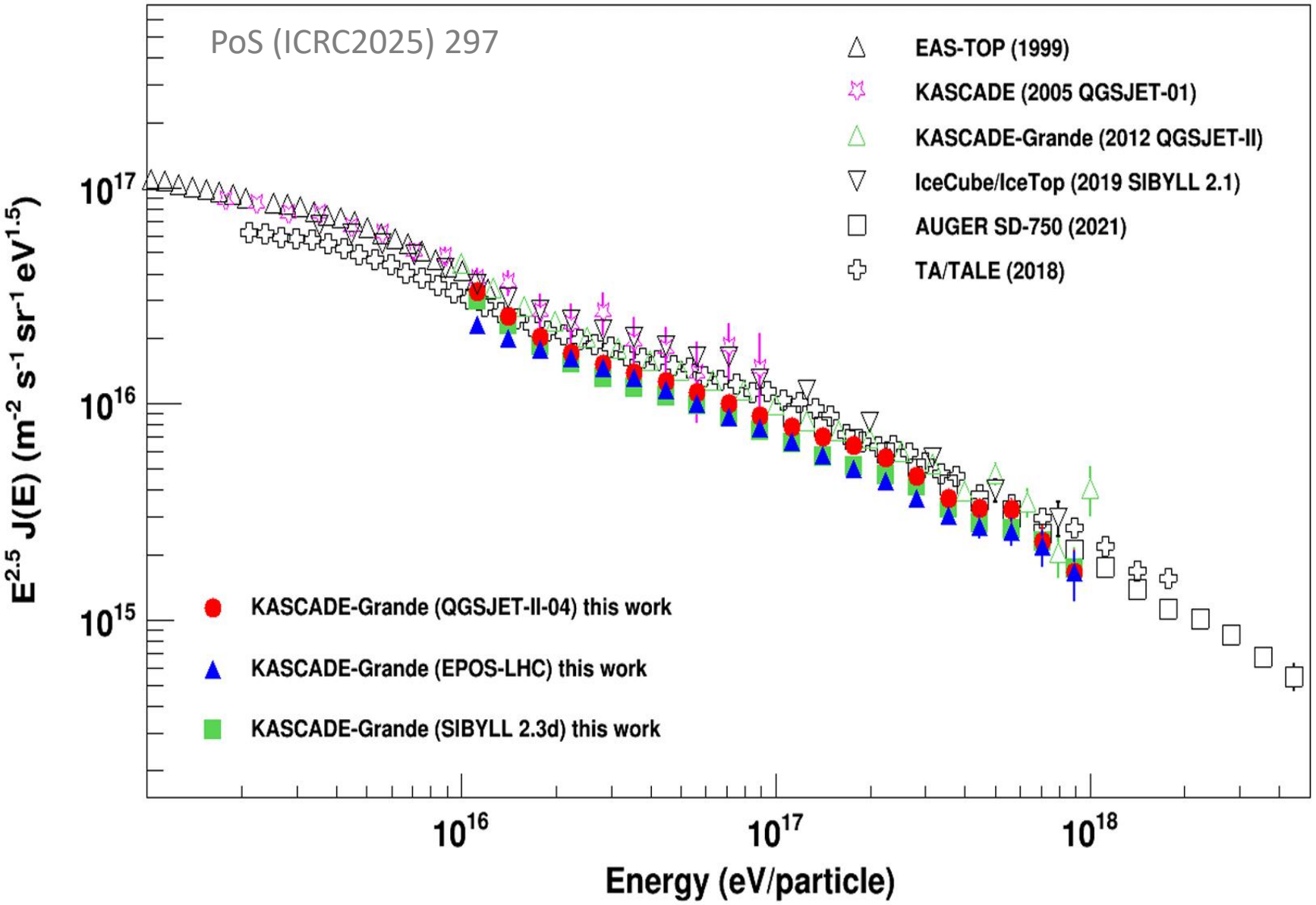




- Relative abundancies (composition) depend strongly on hadronic interaction model
- Reconstructed energy spectra for heavy (Si+Fe) and light (p+He+CNO) primary mass groups
- Data selection by attenuation corrected shower size ratio N_{ch}/N_{μ}
- Accounted shower-to-shower fluctuation based on the Bayesian unfolding algorithm
- Knee-like structure of heavy primaries below 10^{17} eV, hardening of light primaries is significant
- Muon discrepancy: KASCADE-Grande observes fewer muons than predicted by simulations for near-vertical showers

PoS(ICRC2023)307
PoS(ICRC2025)297
PoS(ICRC2025)224

All-Particle Energy Spectrum



- Comparison of all-particle spectrum (unfolded) derived from different post-LHC models with results from other experiments
- Relatively small dependence among post-LHC interaction models in use
- Absolute flux measured by KASCADE-Grande is up to 10% lower than that reported by other experiments, possibly due to near sea level observation altitude

Cosmic-ray Anisotropy with KASCADE and KASCADE-Grande

[J. Turnwald (2026), Master's thesis, KIT]
DOI: 10.5445/IR/1000192932

Data-Driven Likelihood Reconstructions

- Data can be analyzed to simultaneously reconstruct
  - Relative acceptance $A(\varphi, \theta)$ in local coordinates
  - Relative intensity $I(\alpha, \delta)$ in equatorial coordinates
  - Background rate $N(t)$ in sidereal time

- Expected number of CRs observed in sidereal time bin τ and local coordinate i :

$$\mu_{\tau i} \cong I_{\tau i}\, N_{\tau}\, A_i$$

- Reconstruction via maximum likelihood:

$$\mathcal{L}(n|I, N, A) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

- Maximum can be reconstructed by iterative method:

$$\lambda = \frac{\mathcal{L}(n|I, N, A)}{\mathcal{L}\left(n\middle|I^{(0)}, N^{(0)}, A^{(0)}\right)}$$

ApJ 886 (2019) no.1 L18

Dipole Estimation

- Calculate relative intensity with likelihood method
- 1D harmonic fit: Fits the right-ascension projection of the unsmoothed anisotropy

$$F(\varphi) = A\cos(\varphi + \alpha)$$

- 2D harmonic fit: Fits the unsmoothed two-dimensional relative intensity map

$$F(\varphi, \delta_i) = \sum_{n=1}^{3} A_n \cos^n(\delta_i)\cos(n\varphi_i + \alpha_n)$$

- Direct dipole likelihood:
  - Express relative intensity as: $\delta I(\alpha, \delta) = d_x \cos\alpha \cos\delta + d_y \sin\alpha \cos\delta$
  - Maximize likelihood ratio, which depends on dipole parameters d_x and d_y

$$\lambda = 2\ln\frac{\mathcal{L}\left(n\middle|d_x^*, d_y^*, N_\tau^*, A_i^*\right)}{\mathcal{L}\left(n\middle|0,0, N_\tau^{(0)}, A_i^{(0)}\right)}$$

  - Likelihood can be used to estimate significance of results

ApJ 981 (2025) 192

Significance Tests

- Sky map significance: generalized Li & Ma method

  Test local deviations relative to an isotropic reference distribution, using 20° smoothing
  → pre-trial and post-trial map significance

$$\tilde{S}_a = \sqrt{2(-\tilde{\mu}_a + \tilde{\mu}_a^{BG} + \tilde{n}_a \log(1 + \delta \tilde{I}_a))}$$

- Dipole significance: Direct maximum-likelihood method

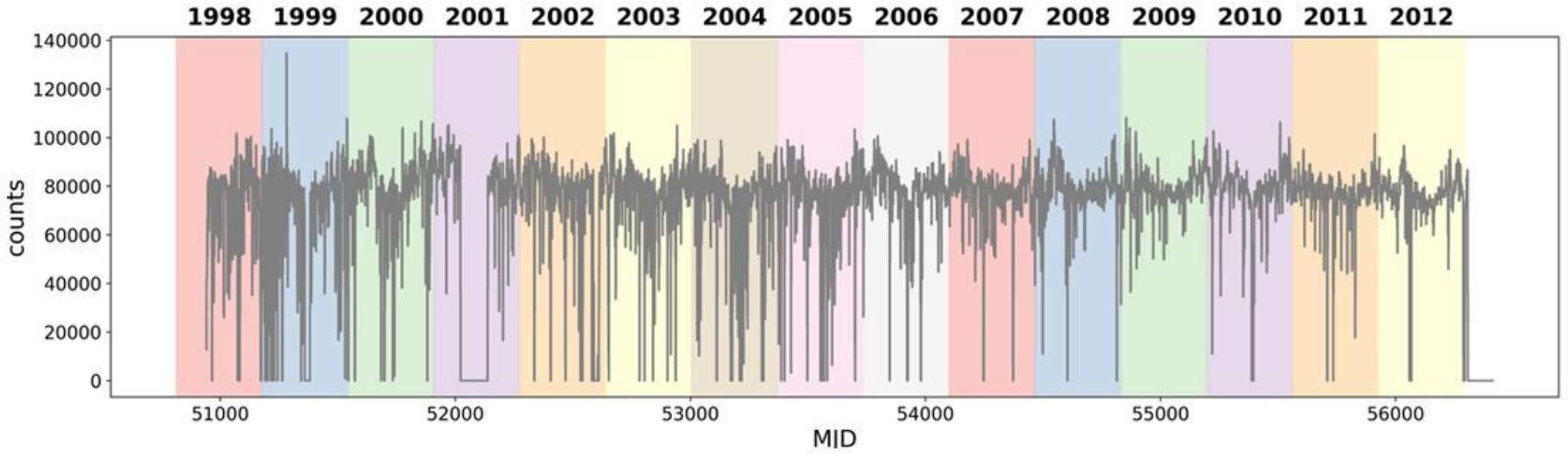
  Evaluate the statistical significance of a dipole anisotropy compared with isotropy
  → likelihood-ratio p-value

$$\lambda = 2 \ln \frac{\mathcal{L}_{\text{dipole}}}{\mathcal{L}_{\text{isotropic}}}, \qquad p = e^{-\lambda/2}$$

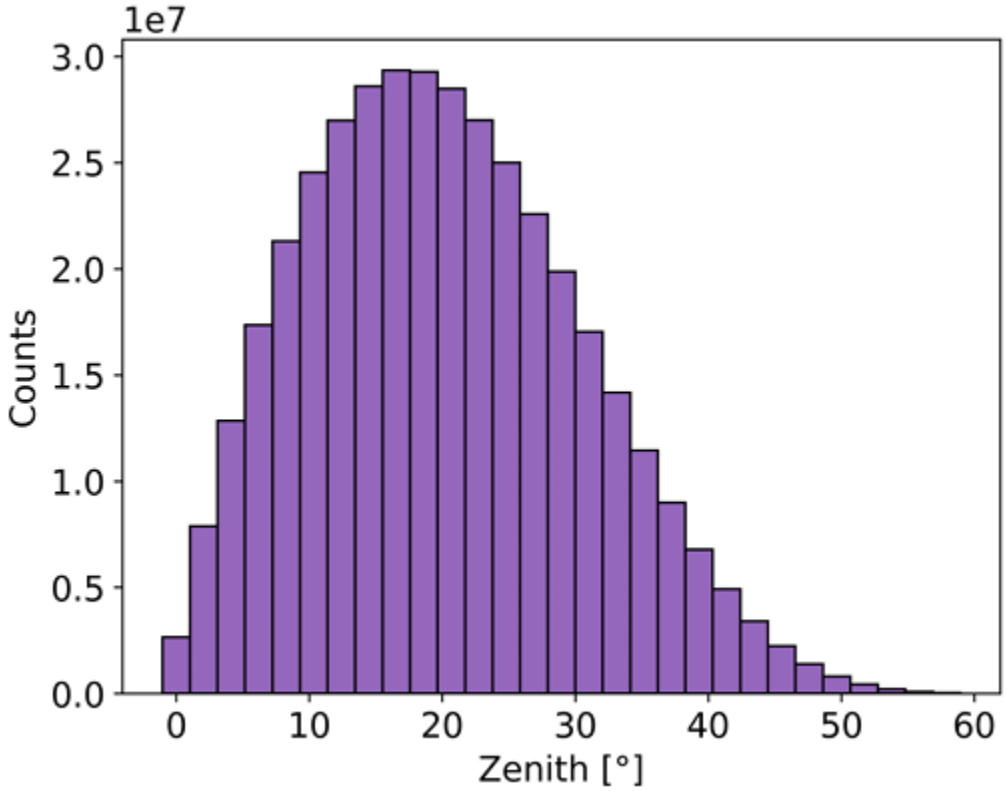
ApJ 981 (2025) 192
ApJ 886 (2019) no.1 L18

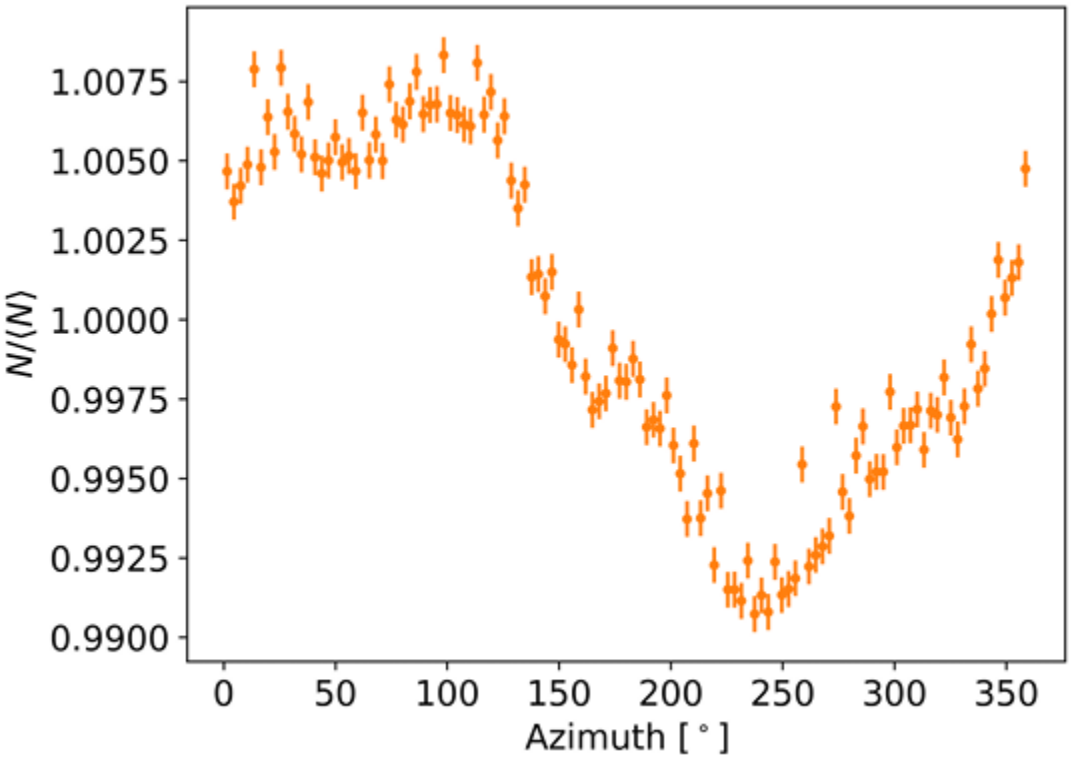
KASCADE Dataset

- KASCADE in Karlsruhe (49.1° N, 8.4° E) at 100 m a.s.l.
- Full KASCADE dataset (1998 – 2013), ca. 371 Million events after quality cuts
- Data from kcdc.iap.kit.edu
- Only events with zenith angles lower than 40° were considered → declination coverage of approximately 9° to 89°
- KASCADE events per day over measurement time per Modified Julian Date (MJD)



KASCADE

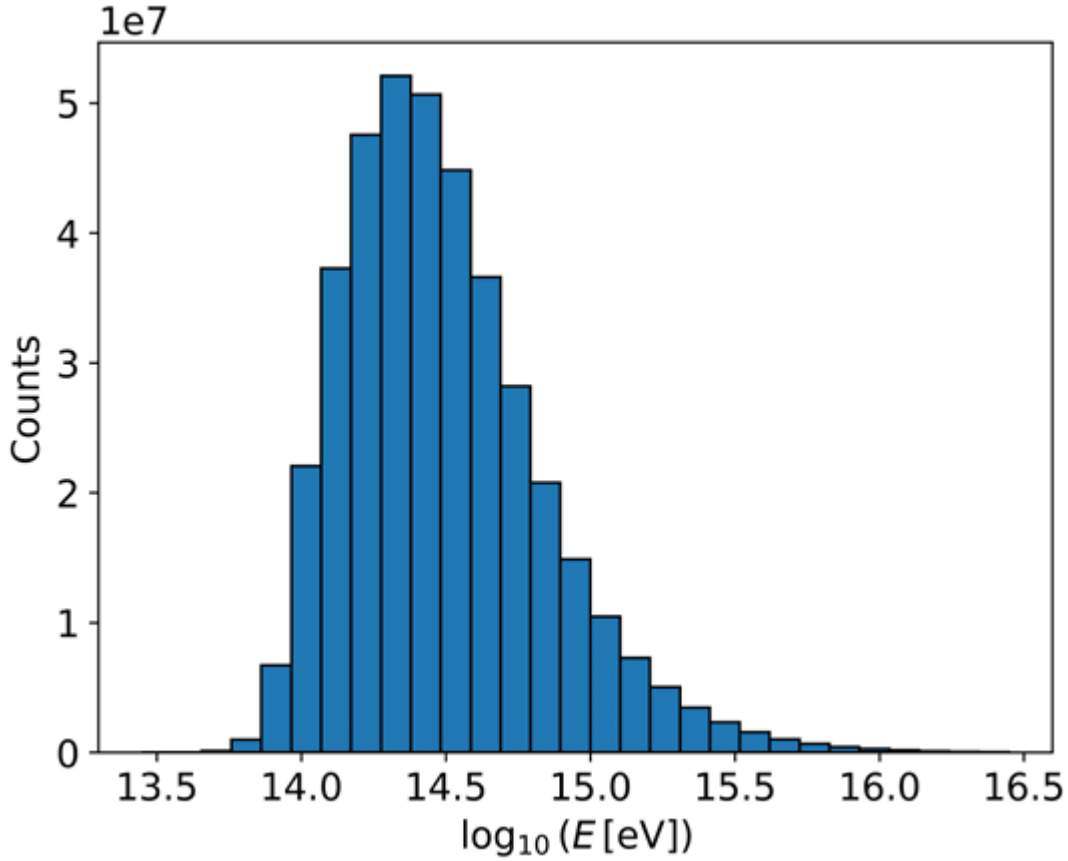




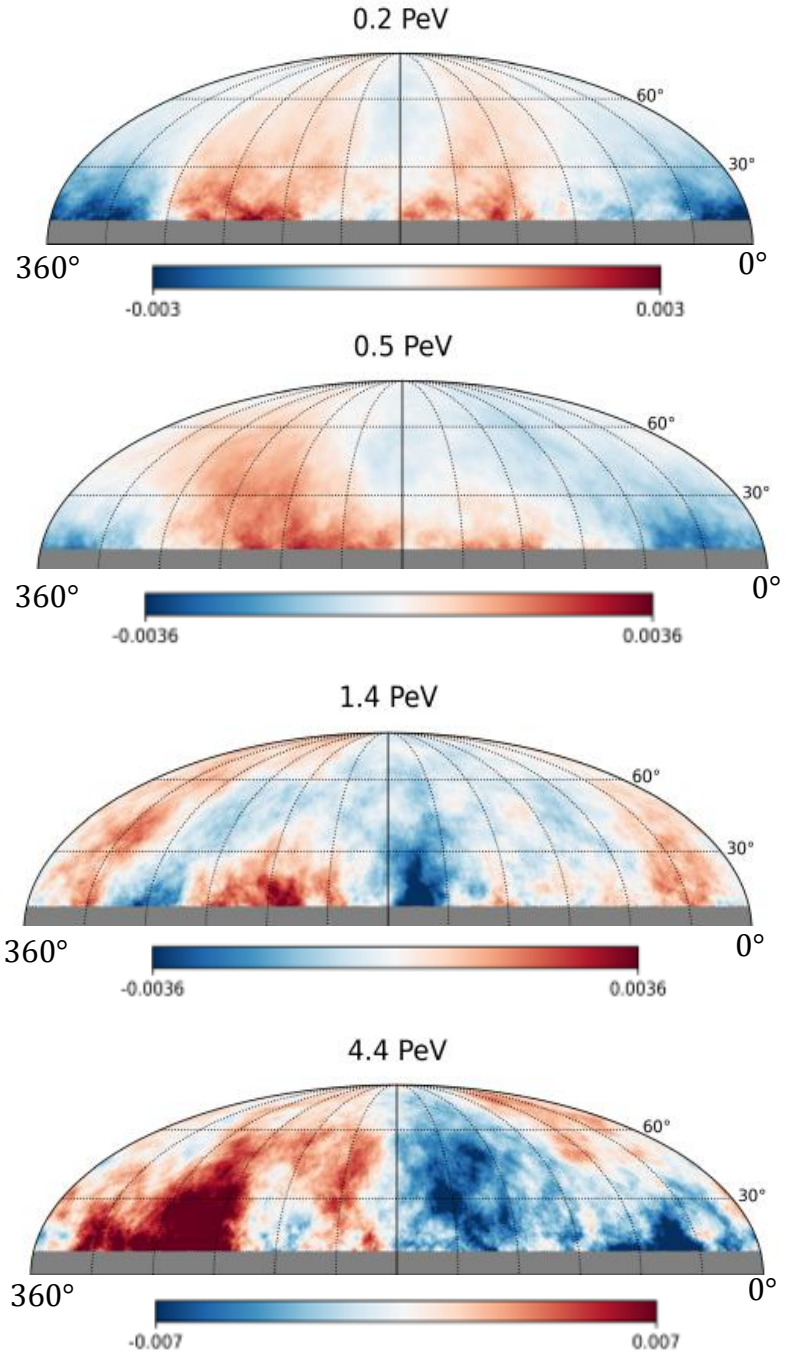
- Distributions of the zenith and azimuth angles
- A non-isotropic azimuth distribution with a maximum deviation of about 1% is observed due to detector site effects and the influence of the Earth's magnetic field
- This does not bias the anisotropy analysis, as the ϕ- and θ-dependent detector acceptance $A(\phi, \theta)$ is estimated by the likelihood method

KASCADE Energy Bins

- Energy range from 10^{14} to 10^{16} eV, divided four energy bins



	Energy range	E_{median} [TeV]	N [10^6]
bin 1	$[10^{14.0}, 10^{14.5})$	180	194.70
bin 2	$[10^{14.5}, 10^{15.0})$	439	147.05
bin 3	$[10^{15.0}, 10^{15.5})$	1374	26.48
bin 4	$[10^{15.5}, 10^{16.0})$	4248	3.12
complete data	$[10^{14.0}, 10^{16.0})$	225	371

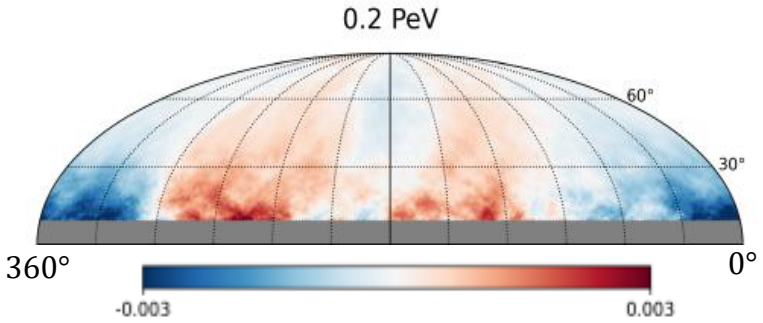


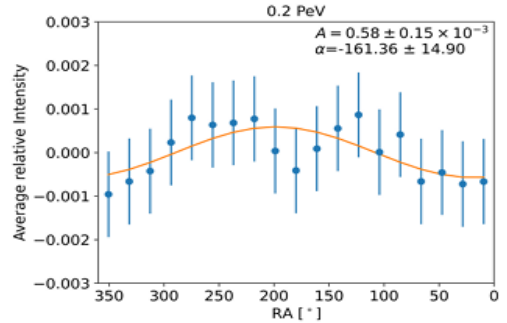
Sky maps

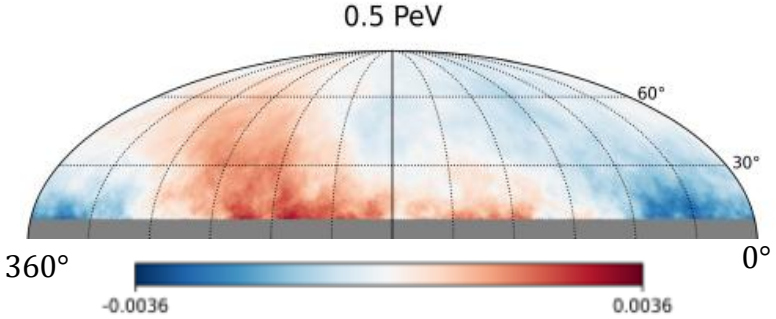
- Iterative likelihood method used to reconstruct sky maps and detector acceptance

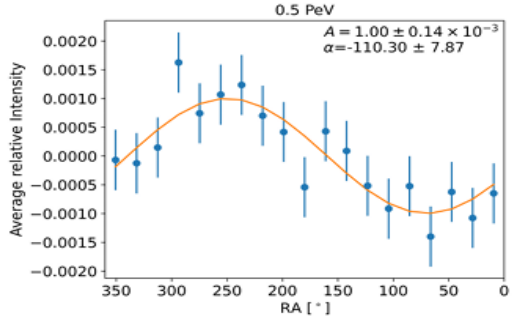
$$\delta I = \frac{N_i - \langle N_i \rangle}{\langle N_i \rangle}$$

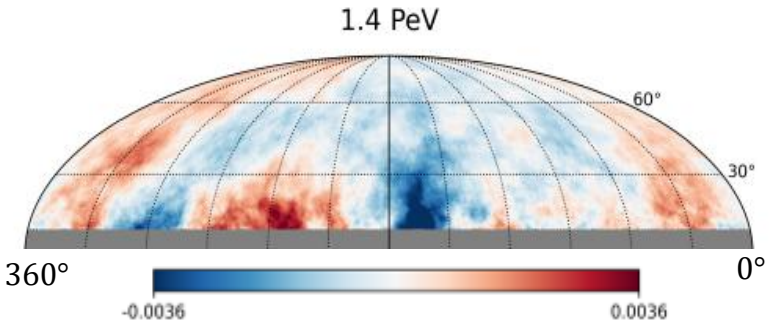
Relative Intensity

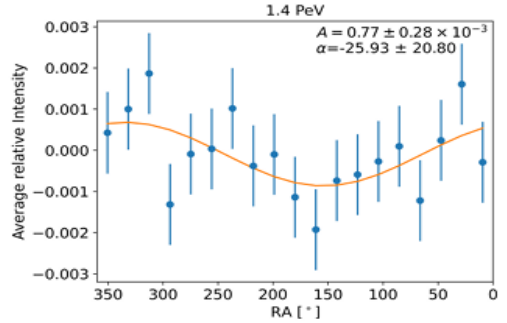


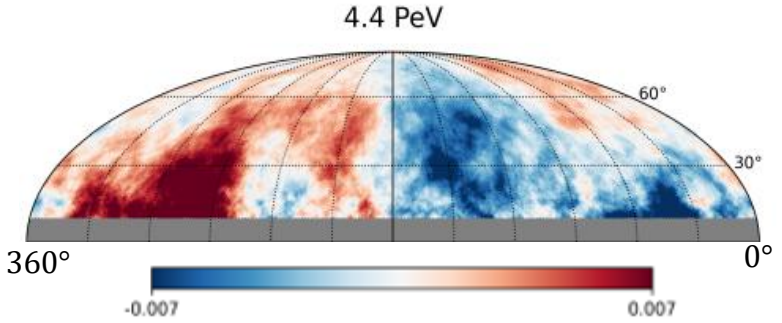


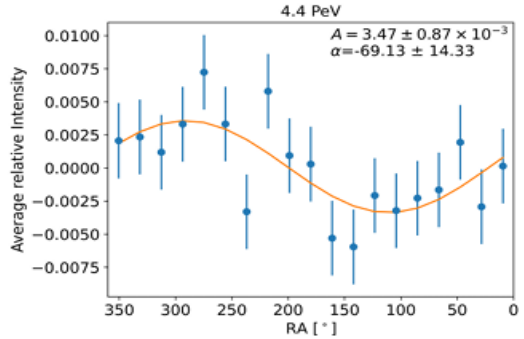








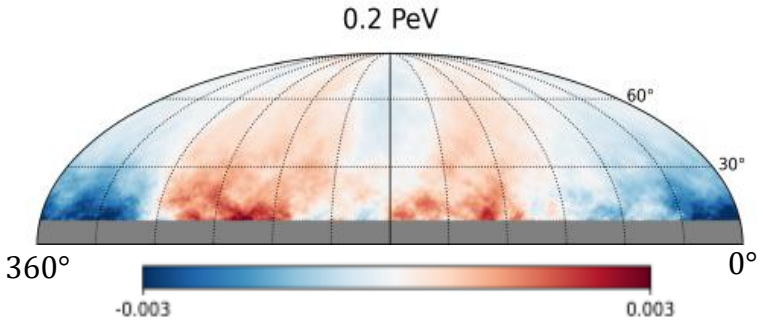


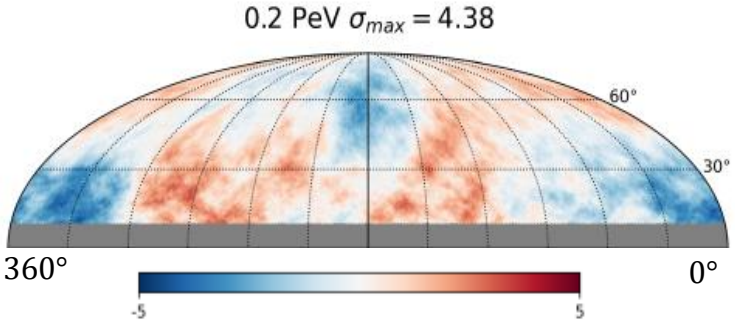


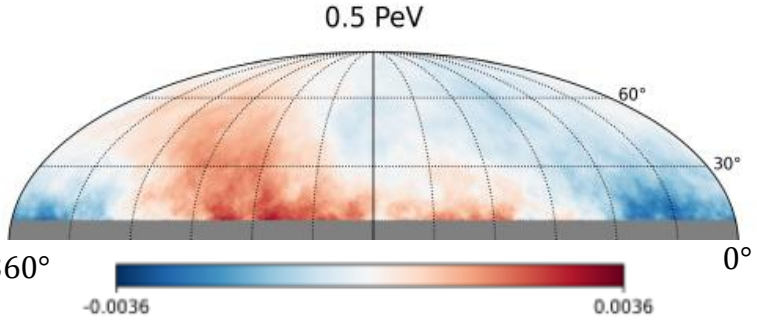
- Iterative likelihood method used to reconstruct sky maps and detector acceptance

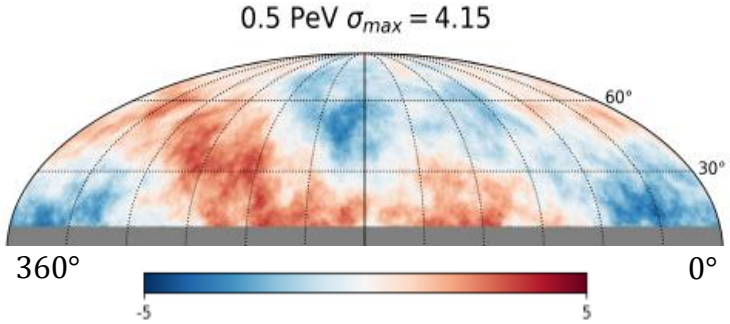
$$\delta I = \frac{N_i - \langle N_i \rangle}{\langle N_i \rangle}$$

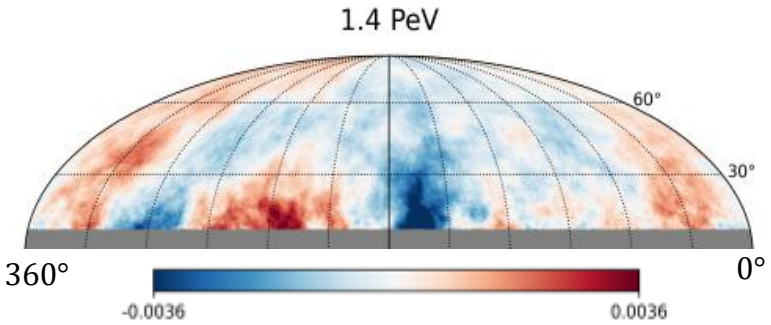
- Dipole anisotropy extracted using three independent methods:
  - 1D right ascension fit
  - 2D harmonic fit
  - Direct likelihood fit

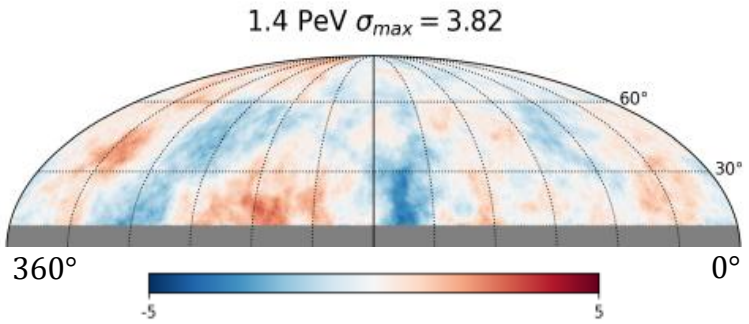


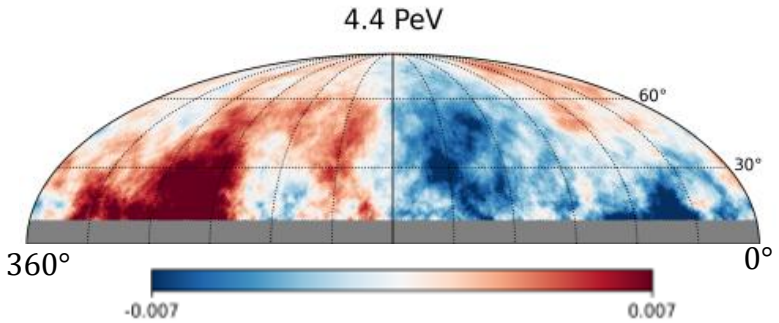


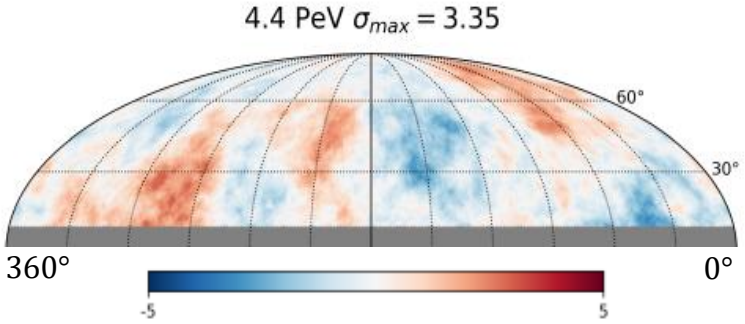








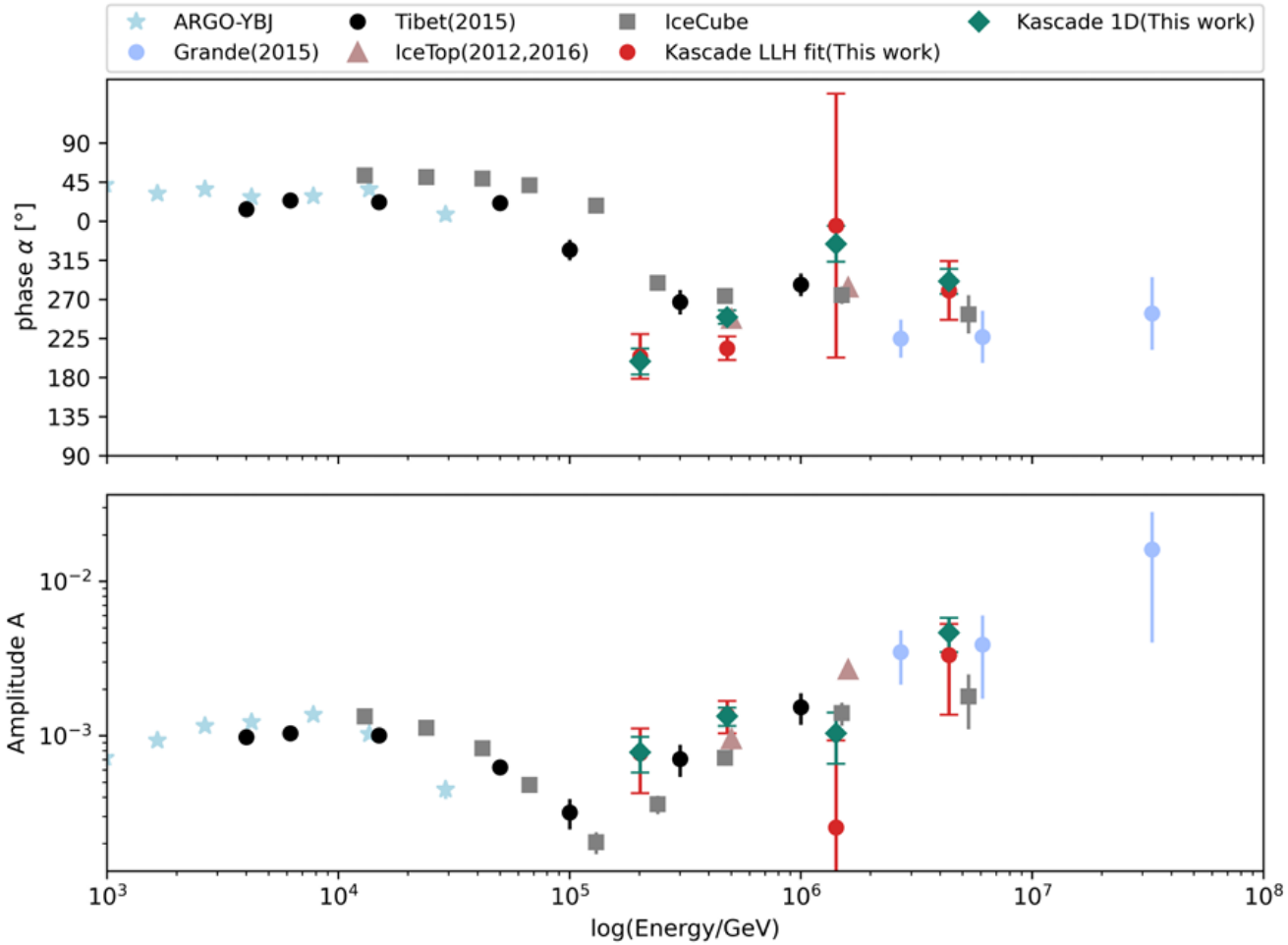




Significance

- Li & Ma pre-trial significances with 20° smoothing
- Largest dipole significance at 0.5 PeV with $p = 1.2 \times 10^{-4} (\sim 3.7\sigma)$
- Full KASCADE dataset: $p = 3.0 \times 10^{-5} (\sim 4\sigma)$

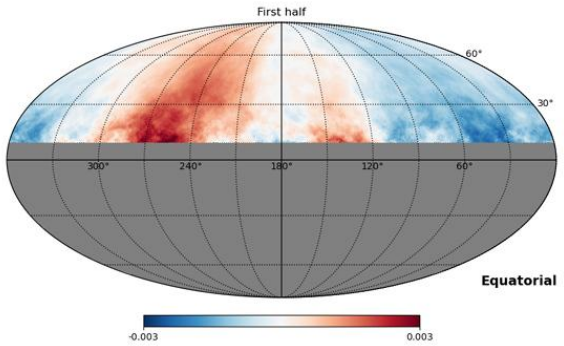
Dipole Amplitude and Phase

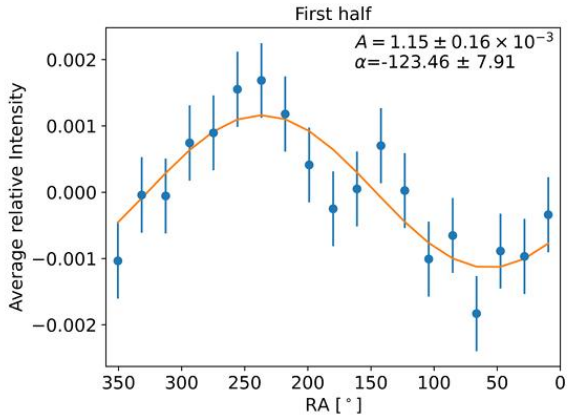


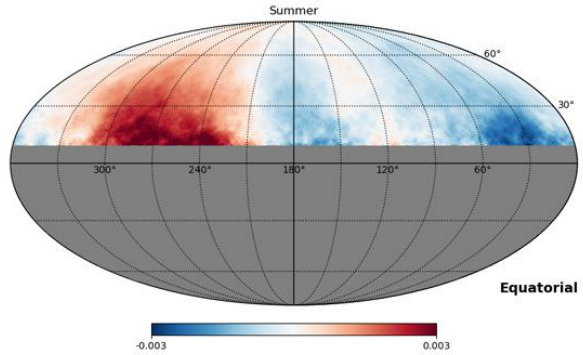
E_{median} [PeV]	1D amplitude [10^{-3}]	1D phase [°]	Dipole likelihood p-value
0.2	0.78 ± 0.20	199 ± 15	0.077
0.5	1.34 ± 0.18	250 ± 8	0.00012
1.4	1.04 ± 0.38	334 ± 21	0.931
4.4	4.66 ± 1.16	291 ± 14	0.237

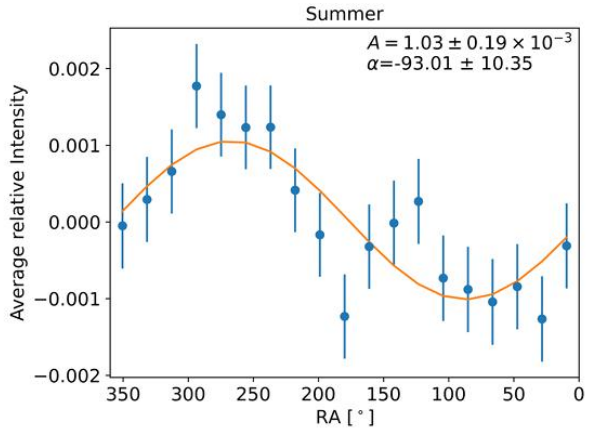
- 1.37 PeV, the 1D fit suggests a dipole-like intensity variation, but the direct dipole likelihood finds no significant dipole (p = 0.93), possibly due to a more complex anisotropy pattern.

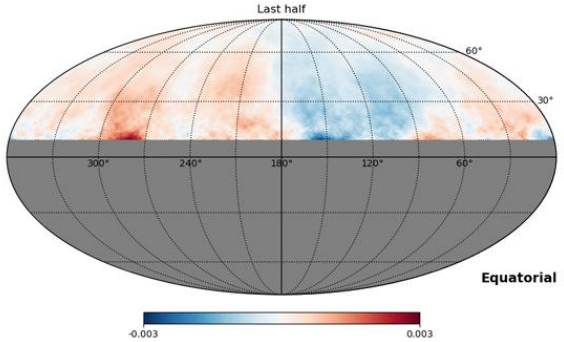
KASCADE: Systematic Checks

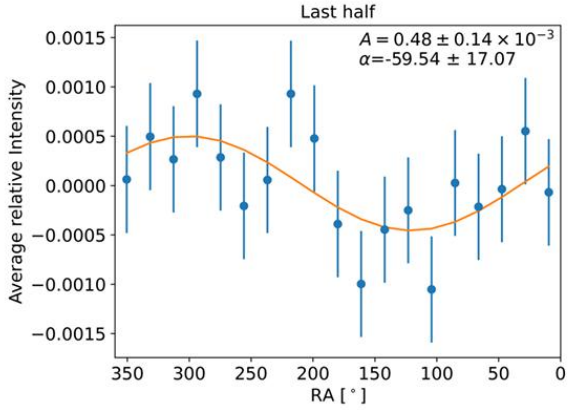


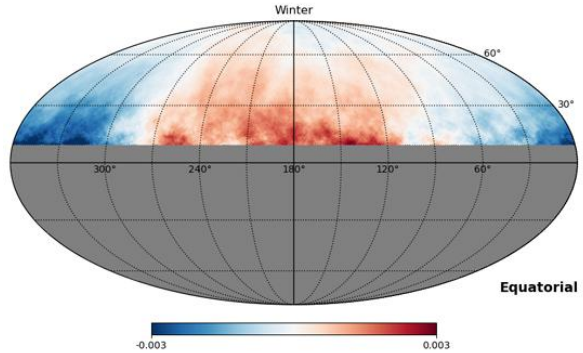


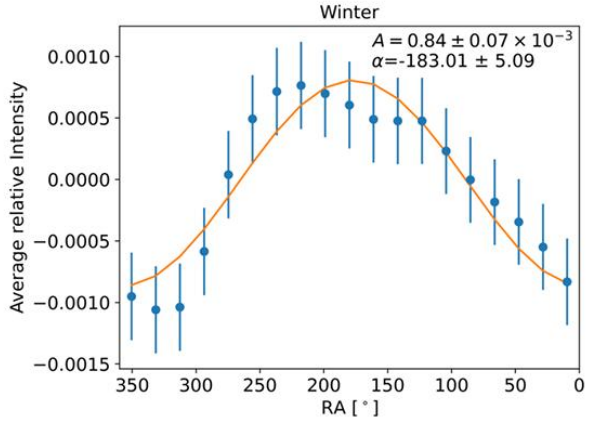












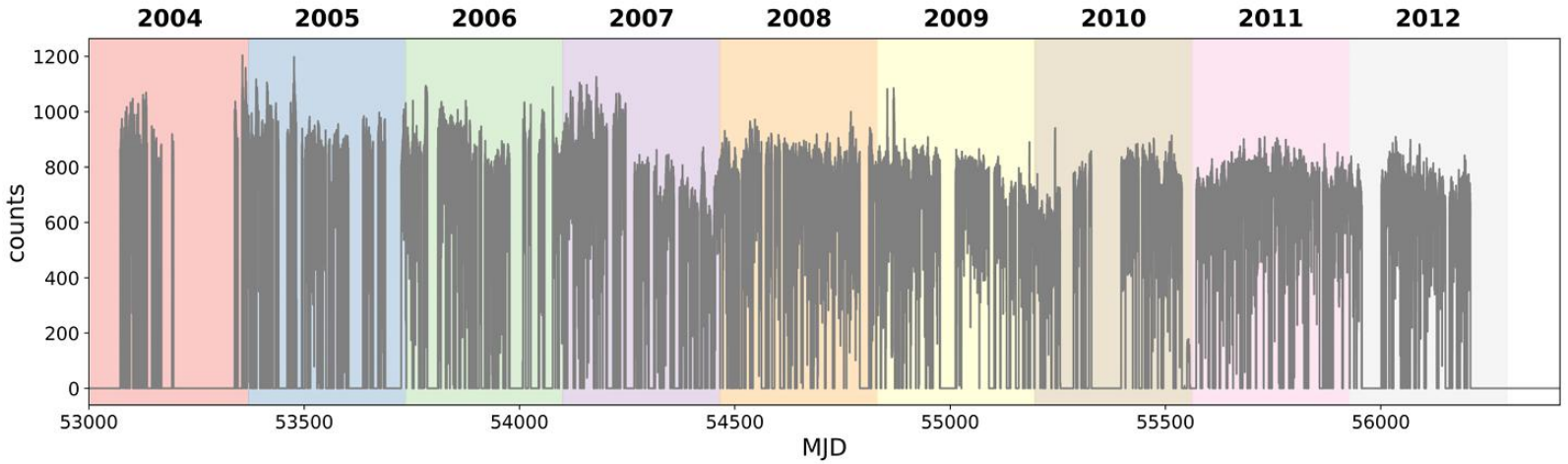
- Extensive systematic tests: solar, sidereal, anti-sidereal, day/night, seasons, detector uptime
- The anisotropy remains stable under multiple systematic checks, although detector uptime introduces measurable systematic effects that must be considered

KASCADE Systematic Checks

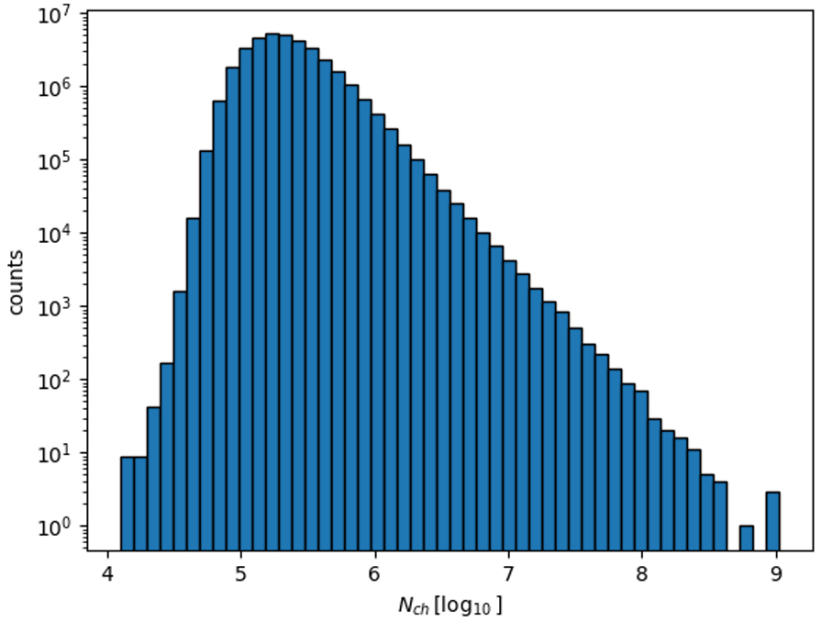
	Definition	N_{Events} $[10^6]$	A_{1D} $[10^{-3}]$	α_{1D} [°]
Sidereal	complete data	371.36	0.67 ± 0.11	230.69 ± 9.79
Solar	complete data	371.36	0.56 ± 0.1	43.38 ± 9.89
Anti-Sidereal	complete data	371.36	1.13 ± 0.09	233.55 ± 4.65
Ext-Sidereal	complete data	371.36	0.56 ± 0.09	1.49 ± 8.78
Day	between 6.00 am and 18 pm	184.69	1.76 ± 0.23	174.36 ± 7.38
Night	between 18.00 pm and 6 am	190.39	1.35 ± 0.16	303.89 ± 6.92
Summer	01.04 to 31.09	179.12	1.03 ± 0.19	266.99 ± 10.35
Winter	01.10 to 31.03	195.95	0.84 ± 0.14	177.11 ± 9.41
Unix even	Unix time is even	185.68	0.62 ± 0.18	243.05 ± 17.04
Unix odd	Unix time is odd	185.67	0.74 ± 0.13	220.41 ± 9.99
First half	01.01.1999 to 01.01.2006	168.57	1.15 ± 0.16	236.54 ± 7.91
Last half	01.01.2006 to 01.01.2013	186.01	0.48 ± 0.14	300.46 ± 17.07
Mondays and Tuesday	each from 00:00:00 to 23:56:04	104.49	0.37 ± 0.16	260.85 ± 23.85
Wednesday and Thursday	each from 00:00:00 to 23:56:04	106.80	0.90 ± 0.20	222.94 ± 12.63
Saturday and Sunday	each from 00:00:00 to 23:56:04	105.36	0.83 ± 0.23	228.25 ± 15.91

- The one dimensional results A_{1D} are not corrected for the FOV for systematic checks.
- Remark: Anti-sidereal and extended-sidereal amplitudes indicate possible contamination from time-dependent detector effects.

KASCADE-Grande Dataset

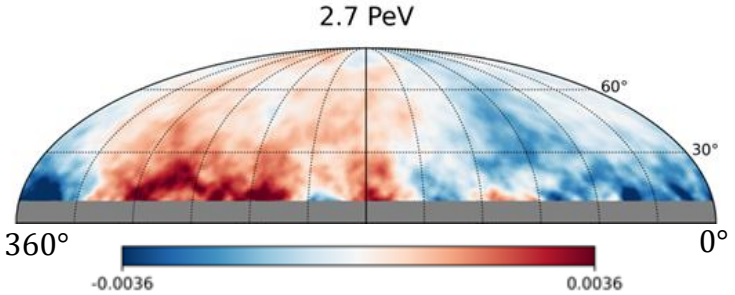


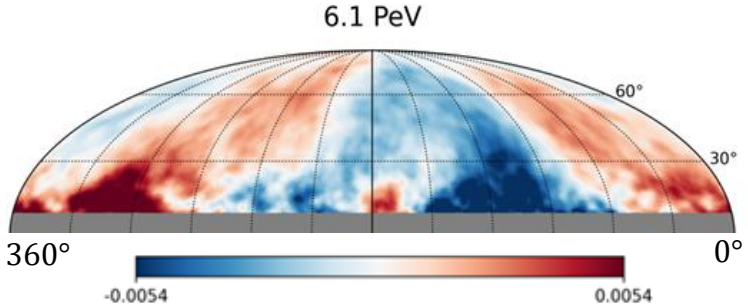
- Extending anisotropy measurements to higher energy
- Full KASCADE-Grande dataset (March 2004 – October 2012), ca. 35 Million events after quality cuts

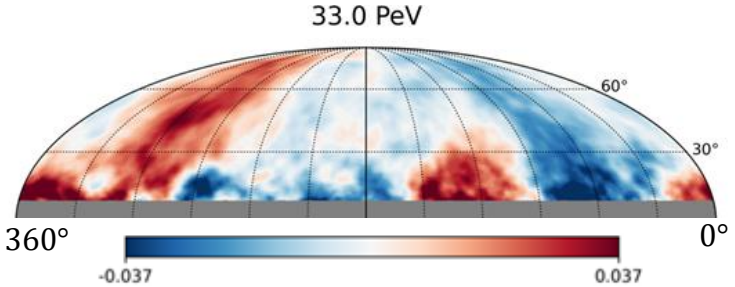


	N_{ch} cuts	E_{med} [PeV]	N [10^6]
bin 1	$[10^{5.2}, 10^{5.6})$	2.7	17.43
bin 2	$[10^{5.6}, 10^{6.4})$	6.1	6.07
bin 3	$\geq 10^{6.4}$	33	0.146

KASCADE-Grande: Sky maps

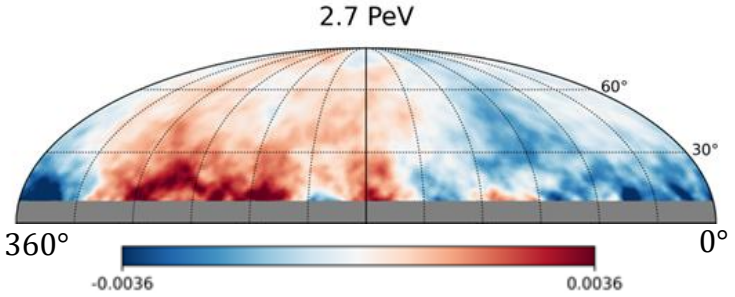


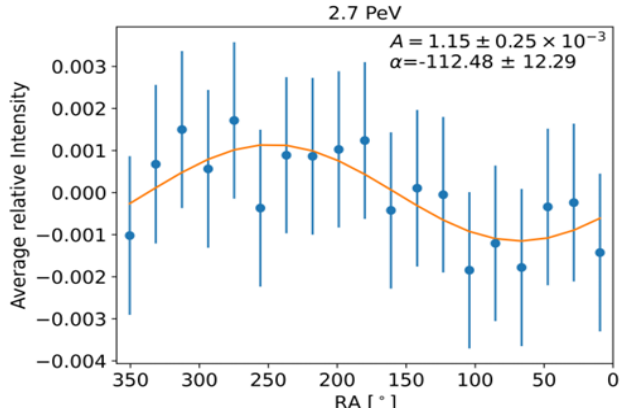


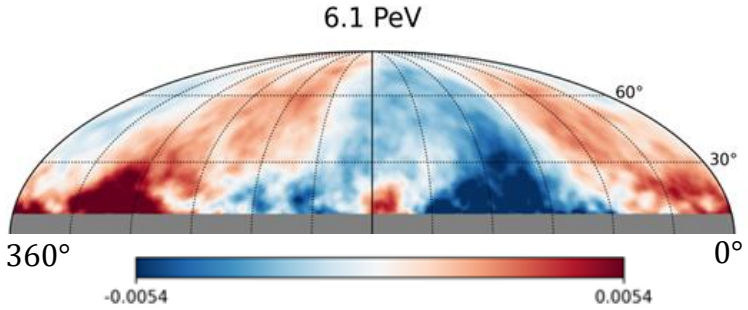


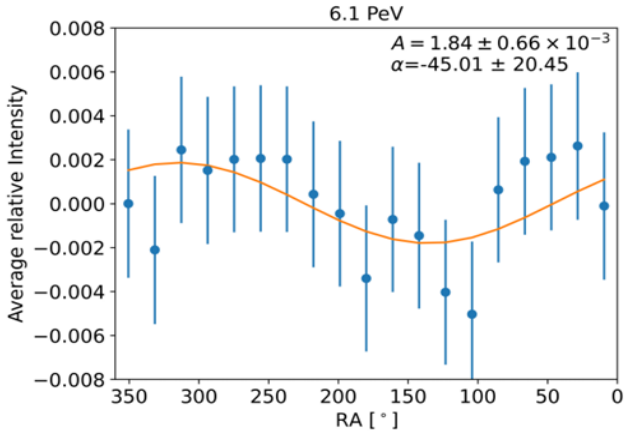
- Same method used to reconstruct sky maps

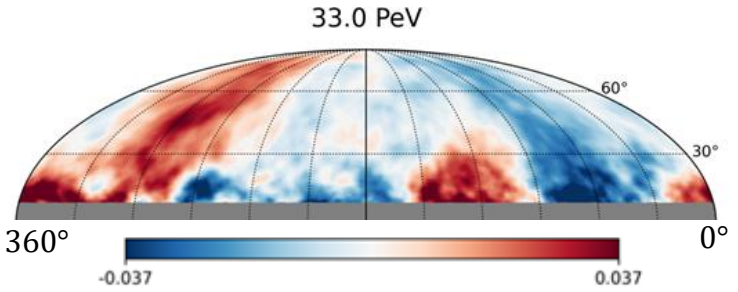
KASCADE-Grande: Relative Intensity

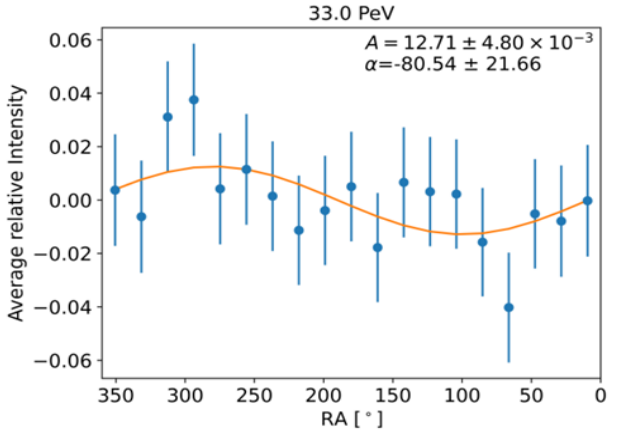






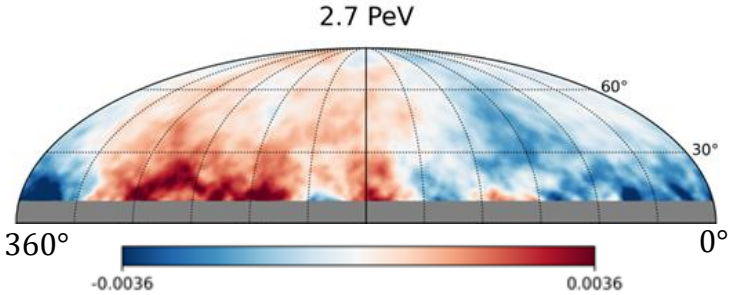


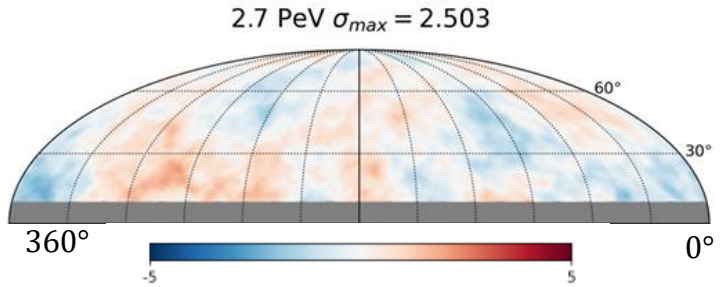


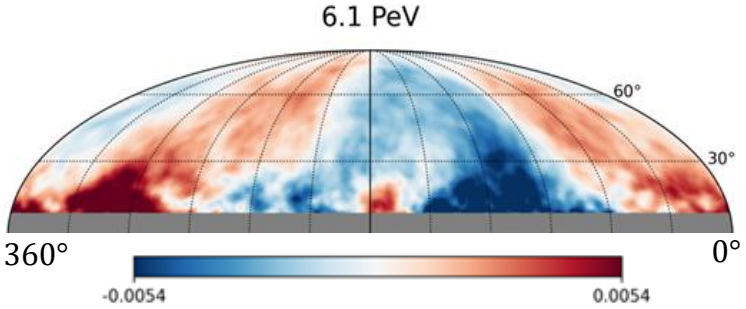


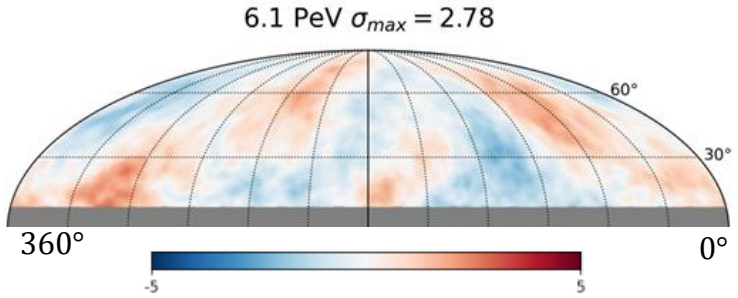
- Same method used to reconstruct sky maps

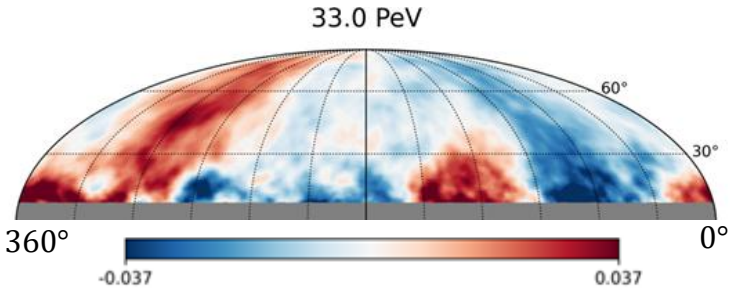
KASCADE-Grande: Significance

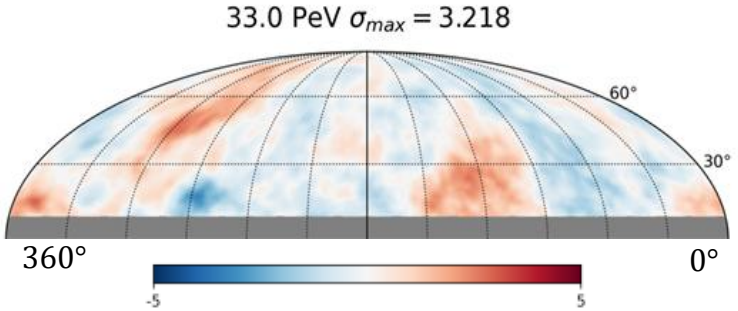






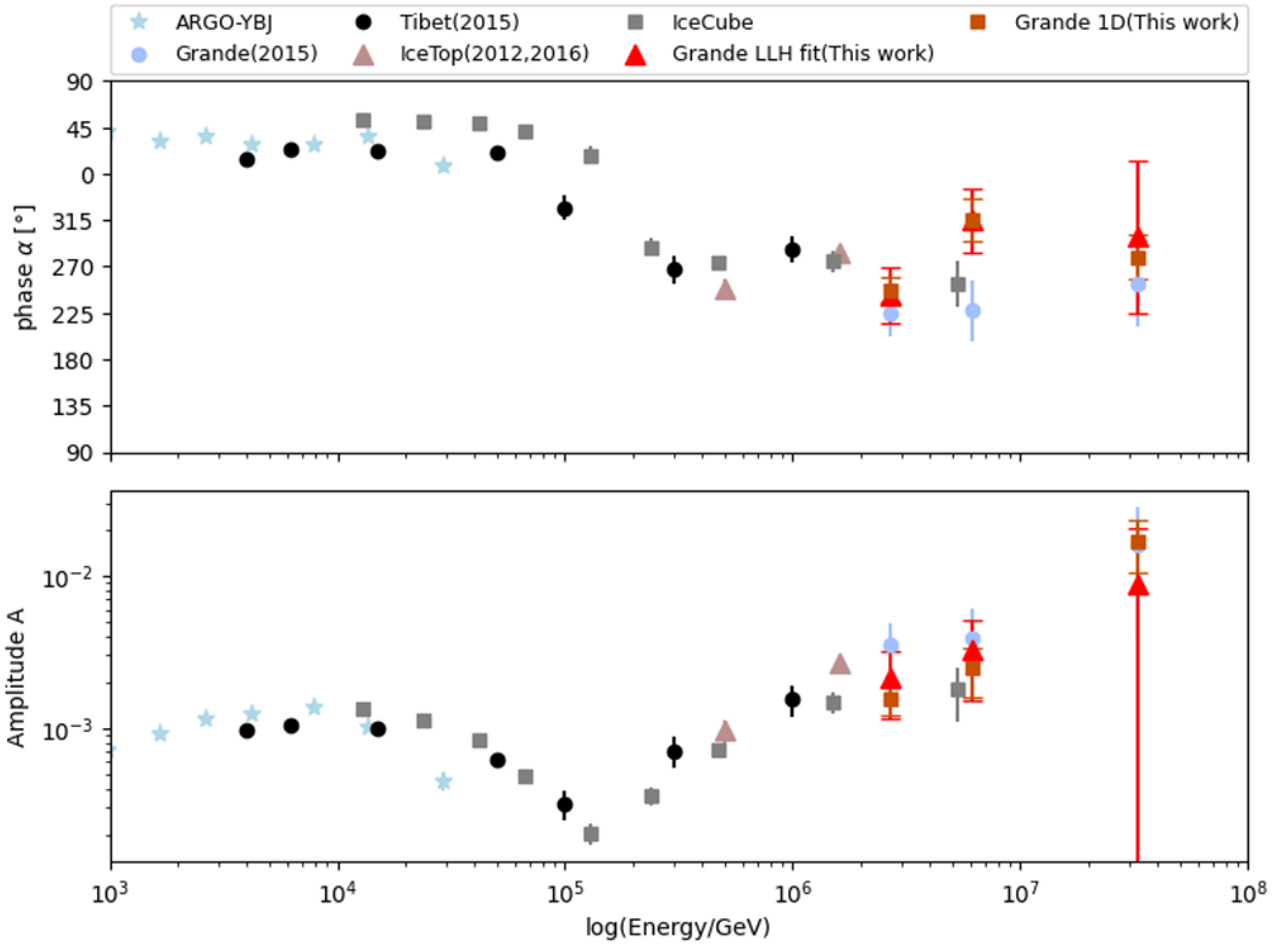






- Same method used to reconstruct sky maps
- Li & Ma pre-trial significances with 20° smoothing
- KASCADE-Grande: No significant large- or medium-scale anisotropy observed
- The highest post-trial map significance is 2.37σ at 33 PeV

KASCADE-Grande

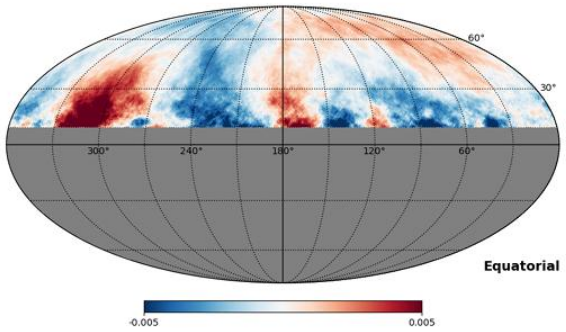


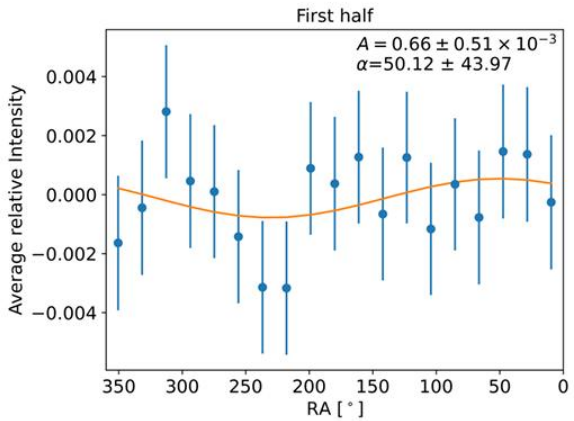
- Previous KASCADE-Grande results with the East-West method [ApJ 870 (2019) 91] are in agreement
- One-dimensional measurements of the amplitude were corrected for their limited FOV

E_{med} [PeV]	A_{1D} [10^{-3}]	α_{1D} [°]	A_{LLH} [10^{-3}]	α_{LLH} [°]	Dipole likelihood p-value
2.7	1.54 ± 0.33	248 ± 12	2.16 ± 1.02	243 ± 27	0.10
6.1	2.46 ± 0.88	315 ± 20	3.30 ± 1.78	315 ± 31	0.17
33	17.04 ± 6.44	279 ± 22	8.92 ± 11.49	299 ± 74	0.73

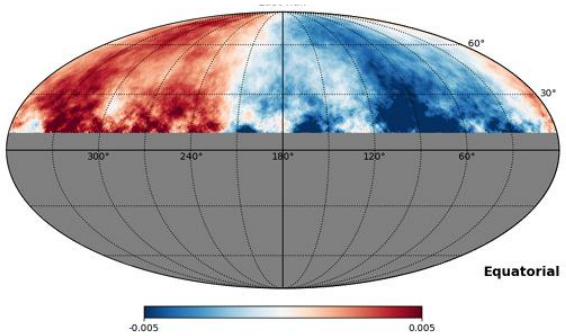
KASCADE-Grande: Systematic Checks

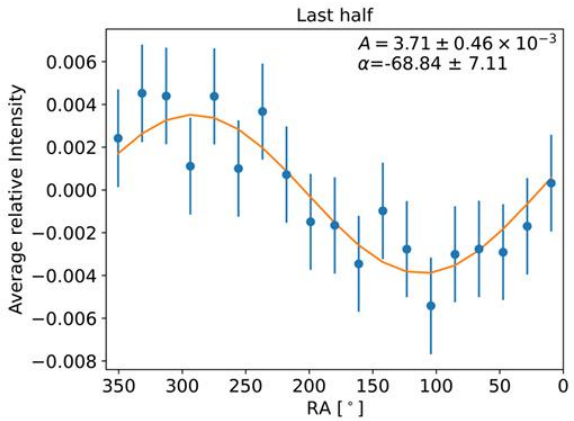
01.01.2005 – 01.01.2009



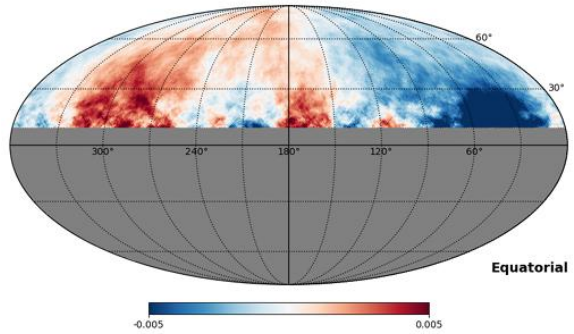


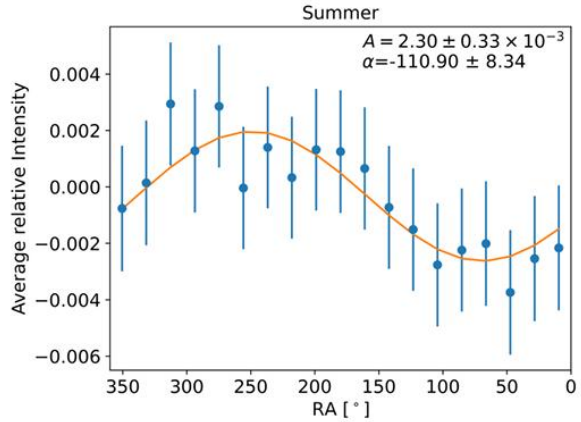
01.01.2009 – 01.01.2013



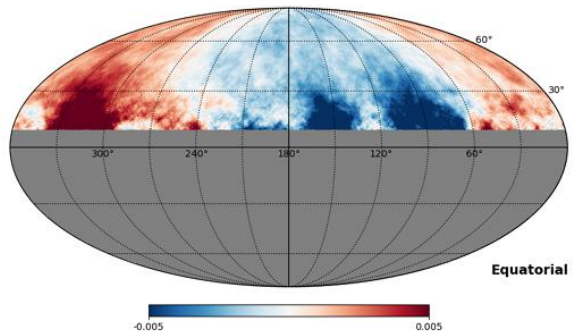


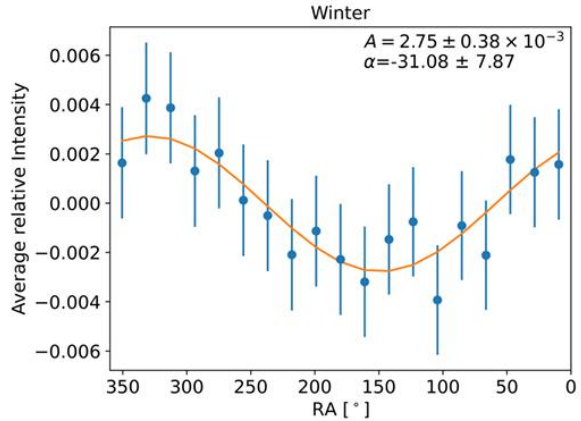
Summer





Winter



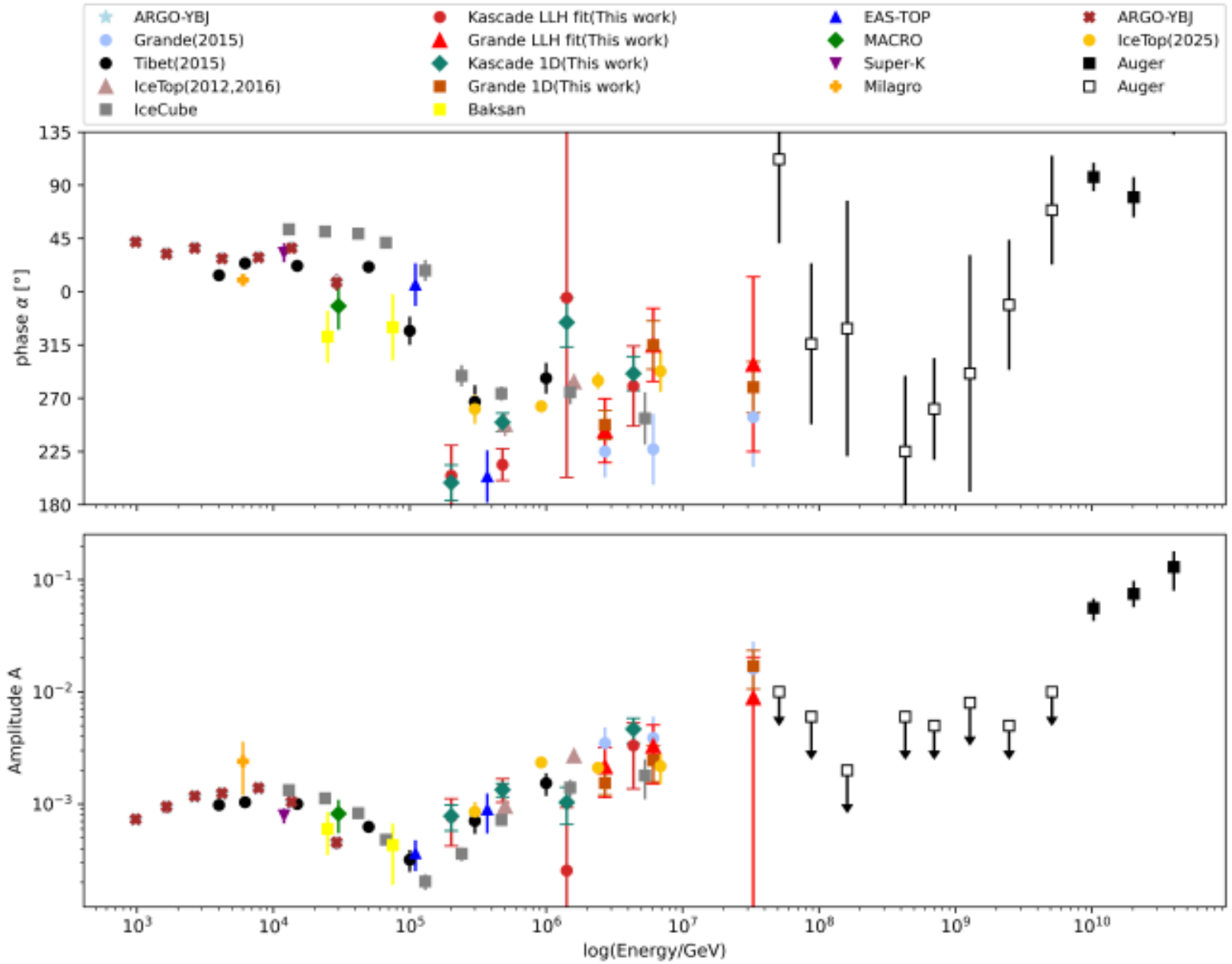


- Systematic tests: solar, sidereal, anti-sidereal, day/night, seasons, detector uptime
- The temporal systematic variations in KASCADE-Grande, particularly between the first and last halves of the dataset

KASCADE-Grande: Systematic Checks

	Definition	N_{Events} $[10^6]$	A_{1D} $[10^{-3}]$	α_{1D} $[^\circ]$
Sidereal	complete data	23.63	1.91 ± 0.29	292.81 ± 8.61
Solar	complete data	23.63	0.39 ± 0.38	142.52 ± 56.36
Anti-Sidereal	complete data	23.63	1.21 ± 0.40	196.86 ± 18.84
Ext-Sidereal	complete data	23.63	2.26 ± 0.31	120.63 ± 7.83
Day	between 6.00 am and 18 pm	11.70	3.19 ± 0.37	283.47 ± 6.73
Night	between 18.00 pm and 6 am	11.93	0.88 ± 0.40	326.38 ± 26.06
Summer	01.04 to 31.09	12.09	2.30 ± 0.33	249.1 ± 8.34
Winter	01.10 to 31.03	11.53	2.75 ± 0.38	328.92 ± 7.87
Unix even	Unix time is even	11.81	2.55 ± 0.43	329.43 ± 9.51
Unix odd	Unix time is odd	11.82	2.33 ± 0.49	252.14 ± 12.16
First half	01.01.2005 to 01.01.2009	11.40	0.66 ± 0.51	50.12 ± 43.97
Last half	01.01.2009 to 01.01.2013	11.32	3.71 ± 0.46	291.16 ± 7.11
Mondays and Tuesday	each from 00:00:00 to 23:56:04	6.52	2.29 ± 0.62	241.7 ± 15.47
Wednesday and Thursday	each from 00:00:00 to 23:56:04	6.65	3.86 ± 0.42	4.27 ± 6.28
Saturday and Sunday	each from 00:00:00 to 23:56:04	6.83	2.89 ± 0.6	268.32 ± 11.87

Combined TeV – PeV Anisotropy



- Energy-dependent anisotropy
- Dipole amplitude gradually increases with energy from 0.2 PeV to ~ 33 PeV
- Dipole phase evolves with energy, consistent with the phase transition near 10^{14} – 10^{15} eV
- Results are consistent with previous measurements
- Further work: combine KASCADE and IceTop/IceCube for a wider-sky analysis to better constrain systematic effects

Summary and Outlook

Full KASCADE dataset analyzed
Large- and medium-scale anisotropy reconstructed in four energy bins from 180 TeV to 4.25 PeV. The direct dipole likelihood yields its strongest energy-bin result at 439 TeV. (publication in preparation)

KASCADE-Grande extends the measurements to 33 PeV
Results are broadly consistent with earlier measurements, but no significant large- or medium-scale anisotropy is established in the analyzed KASCADE-Grande energy bins.

Systematics and future measurements
Time-dependent detector effects and reference-map choices influence the interpretation. Combining northern- and southern-sky data offers a promising direction for future work.

The Experiment Ended.
The Science Continues.
Thank you!



Image generated by ChatGPT