Probing Cosmic Ray Anisotropy with Atmospheric Neutrinos

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A Different CRA Skymap

- History of many excellent measurements in the North:
  — Milaro, HAWC, Argo-YBJ, Super-K, Tibet Array, Auger
- IceCube has a high-statistics southern sky anisotropy measurement
- But there remains untapped potential:
  — For every cosmic ray, we get daughter neutrinos

$$\mathrm{p} \rightarrow \begin{cases} \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \end{cases}$$

Benefits of a Neutrino Search

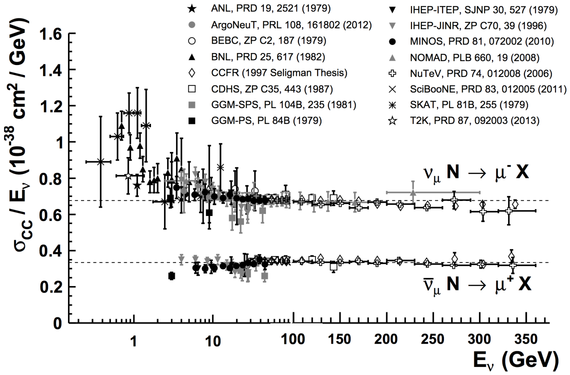
- Anisotropy yet unobserved in neutrinos
- Allows verification of expected particle production
  - Or maybe unexpected outcomes
- IceCube could observe the signal in both the North and South Skies
  - Pole-to-pole coverage
- Allows for first study of absolute pointing with neutrinos for IceCube

Can we observe the Northern Sky Cosmic Ray Anisotropy in atmospheric neutrinos?

Challenge: Neutrino Interaction Cross Section

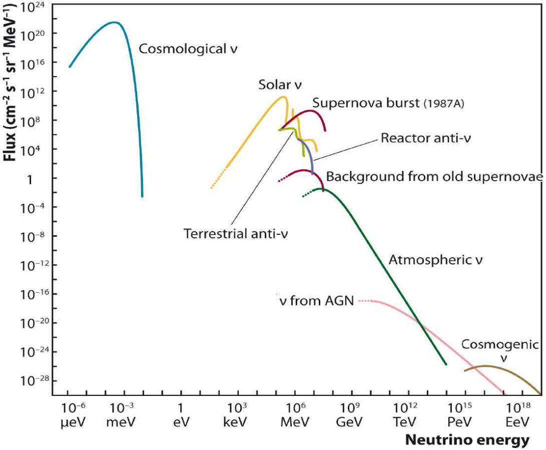
Neutrino detections are rare.

- Lower energy, less interations
- Higher energy, more interactions
  — Attenuated by the earth
- Lower fluxes at higher energies



Where does this leave us?

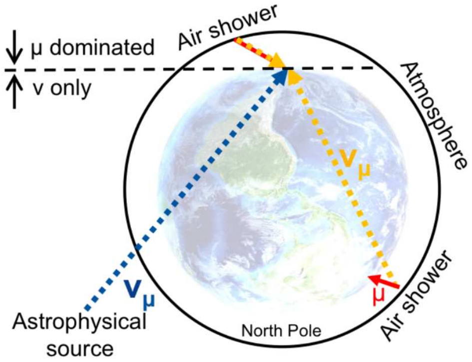
- 1 million events instead of billions
- Limited sample sizes only allow for larger feature studies
- Restricted in energy range



Detecting Atmospheric Neturinos

In Theory:

- It's easy!
- Anything from the North must be a neutrino
- Muons will interact as they traverse the earth
- IceCube sensitive to atmospheric neutrinos from 10-100 TeV primaries



Detecting Atmospheric Neutrinos

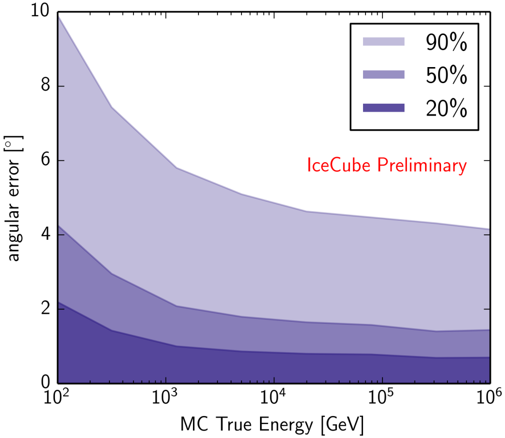
In Practice:

- Main background is poorly-reconstructed muons from the south
  - Muon detection rate exceeds that of neutrinos
  - Misreconstructions: 10% of data
- Target Data Sample:
  - 1 million events per year of livetime
  - Final 10 year sample sensitive to cosmic ray anisotropy features from 10-100 TeV
- Maximizing signal acceptance by tolerating lower purity and larger angular error

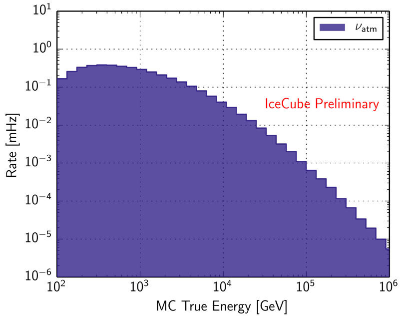
Data Selection Summary

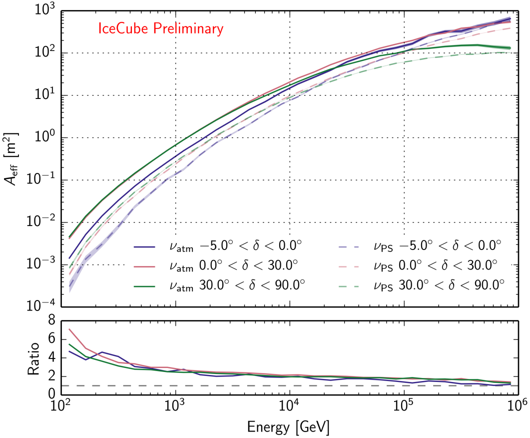
One Year: 132,895 events

	Final Data Rates
ExpData	4.50 mHz
MC Signal	3.98 mHz
MC Background	0.32 mHz
Signal/Data (%)	91.3
Background/Data (%)	7.28



North Sky ν_{atm} Data





Dipole Lower Energy Dependence (10-100 TeV)

IceCube

Astrophys.J. 826 (2016) no.2, 220

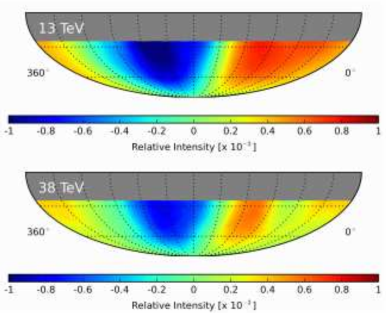
Tibet ASγ

inverted RA convention

ApJ, 836, 153 (2017)

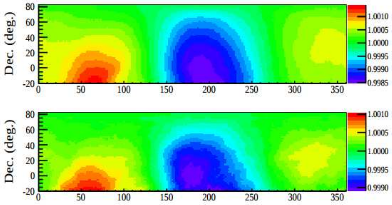
13 TeV

38 TeV



15 TeV

50 Tev



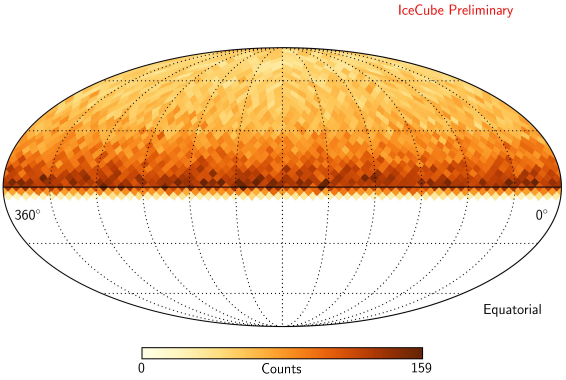
We are sensitive to an energy band with constant behaviour.

Insufficient statistics to allow for binning in energy.

Classic Analysis Methodology

One Year Signal Map

Signal acceptance and background contamination both peak near the horizon

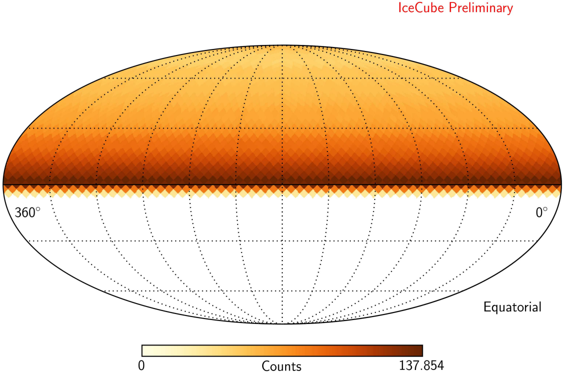


One Year Reference Map

Average of scrambled background maps

South Pole Scrambling:

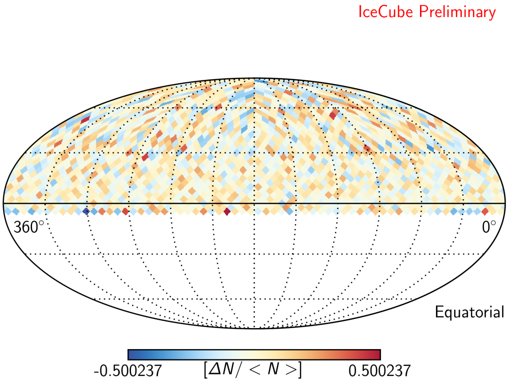
- Time Scrambling = RA Scrambling
- Event acceptance is declination dependent: $(\theta, \phi, t) \rightarrow (\alpha, \delta)$ $(\theta, \phi, t') \rightarrow (\alpha', \delta)$
- Scrambling to dipole resolution: 24 hrs



One Year Relative Intensity Map

$$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i\left(\alpha,\delta\right) - \langle N_i\left(\alpha,\delta\right)\rangle}{\langle N_i\left(\alpha,\delta\right)\rangle}$$

1 year results dominated by statistical fluctuations.



One Year Significance Map

$$\sigma = \sqrt{2(a+b)}$$

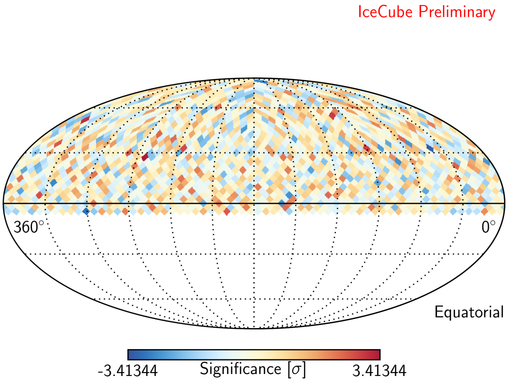
$$a = N_{\text{on}} \log\left[\left(\frac{1+\alpha}{\alpha}\right)\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]$$

$$b = N_{\text{off}} \log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]$$

$$\alpha = \frac{\text{exposure}_{\text{on}}}{\text{exposure}_{\text{off}}}$$

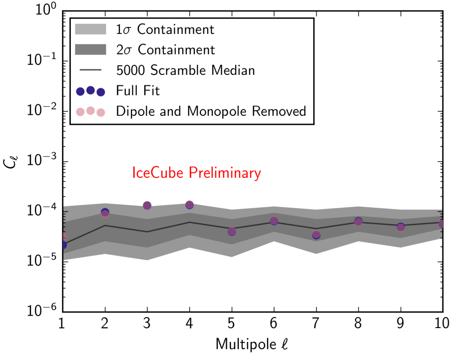
Li, Ma. 1983 ApJ 272

As expected, no significant signal in 1 year of data.



Angular Spectrum Analysis

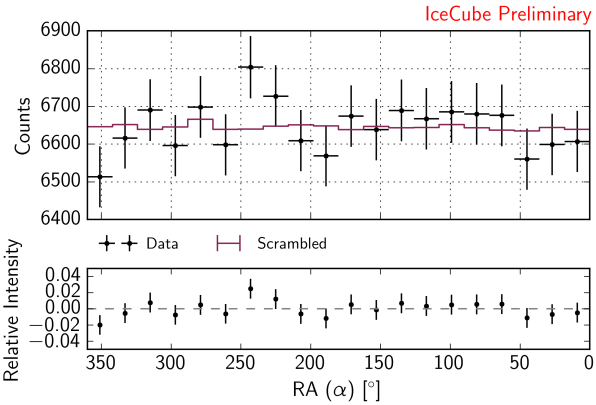
- Insensitive to orientation
- Does allow for detection of dipole or quadrupole



Low Statistics Analysis Methodology

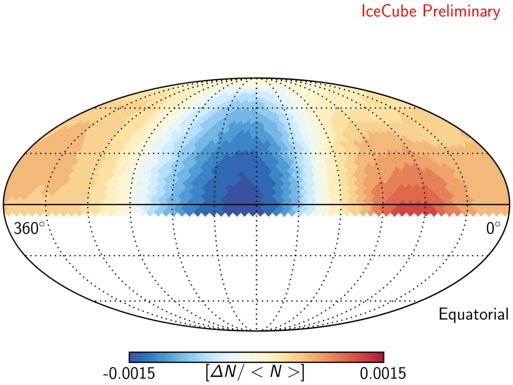
1D Fit

- Reduction of dimensionality increases statistical power
- Allows for measurement amplitude
- Allows for constraint of phase
- One year is consistent with isotropy



Binned Likelihood Ratio Test

- Binned log-likelihood method with skymaps
- Improve sensitivity by testing for a known signal hypothesis
- The averaged time-scrambled map is used as the null hypothesis
- Analysis templates: Tibet 15 TeV, Tibet 50 TeV, Pure Dipole with feature orientation



Background Modeling

- Likelihood here defined as the probability product across all pixels
- Poisson probabilities to observe (n_i) given signal hypothesis (θ_i) per pixel

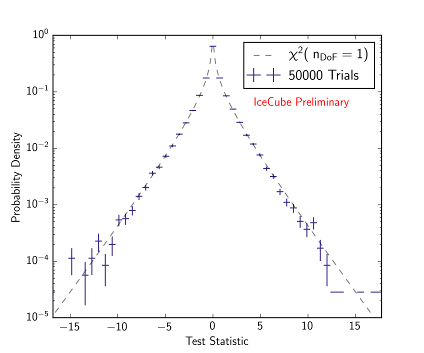
$$\mathcal{L} = \prod_i p_i = \prod_i \frac{\theta_i^{n_i} e^{\theta_i}}{n_i!}$$

- Test statistics for a null hypothesis:

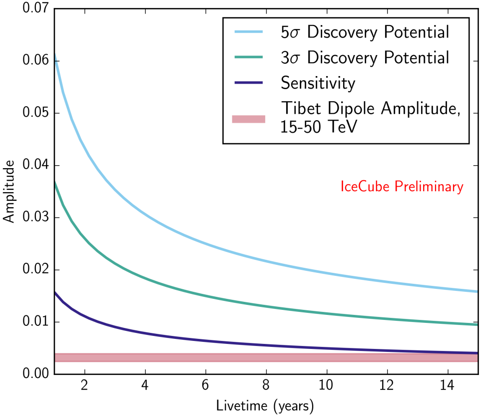
$$\mathrm{TS} = -2\log\frac{\mathcal{L}_{\mathrm{null}}}{\mathcal{L}_{\mathrm{template}}} = \chi^2_1$$

Wilk's Theorem: Ann. Math. Statist. Volume 9, Number 1 (1938), 60-62.

Scrambles yield null hypothesis

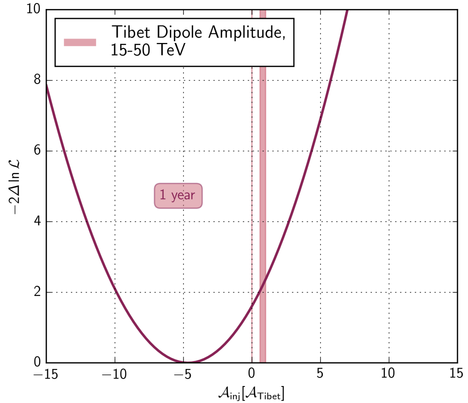


Projected Sensitivities and Discovery Potentials



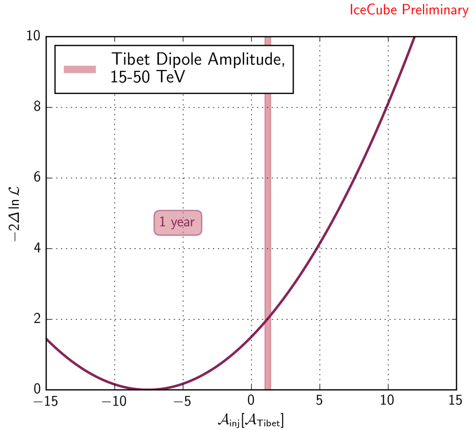
Tibet Template, 15 TeV

IceCube Preliminary



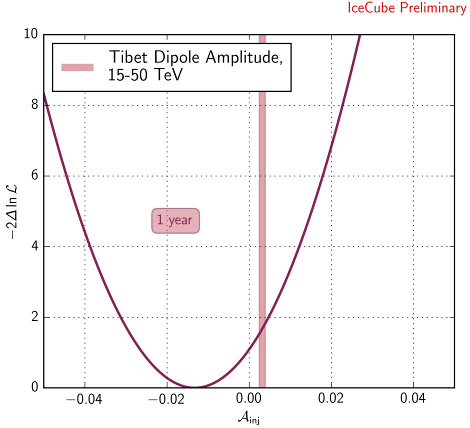
	Sidereal	Anti-Sidereal	Extended-Sidereal
TS	-1.60	2.07	-0.36
P-Value	0.89	0.07	0.72
Significance	-1.25σ	1.44σ	-0.60σ

Tibet Template, 50 TeV



	Sidereal	Anti-Sidereal	Extended-Sidereal
TS	-1.50	1.07	-0.23
P-Value	0.88	0.09	0.68
Significance	-1.22σ	1.30σ	-0.48σ

Pure Dipole, in Tibet Feature Orientation



	Sidereal	Anti-Sidereal	Extended-Sidereal
TS	−1.08	0.23	−0.50
P-Value	0.85	0.31	0.76
Significance	-1.04σ	0.48σ	-0.71σ

Summary

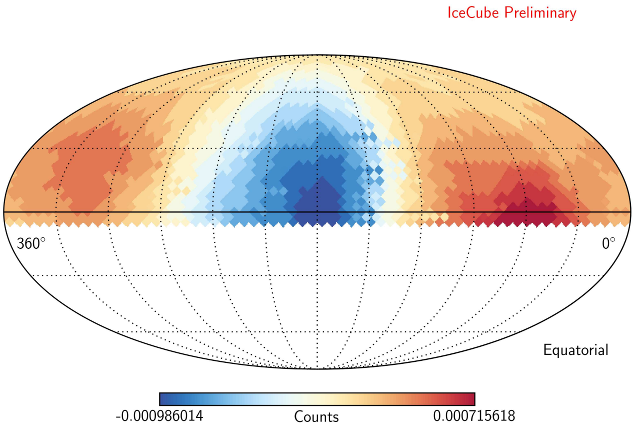
Physics Target: Dipole fit of North Sky Cosmic Ray Anisotropy with ν_{atm}

- High acceptance dataset achieved
- Classic methodology as due diligence
- 2D binned log-likelihood method implemented for lower-statistics treatment
- Approaching sensitivity to dipole in ten years of observation

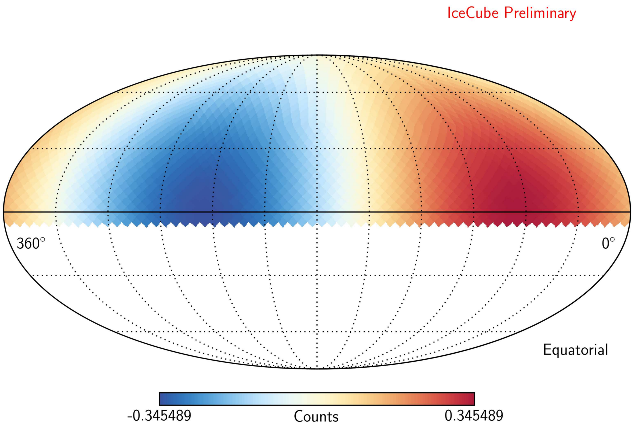
- Method successfully tested and validated on one year of data
- Full 10 year analysis to be completed in 6 months as PhD thesis

Backup Slides

Tibet, 50 TeV

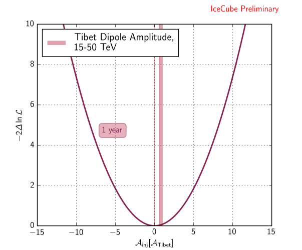

IceCube Preliminary
360°
0°
Equatorial
-0.000986014
Counts
0.000715618

Pure Dipole

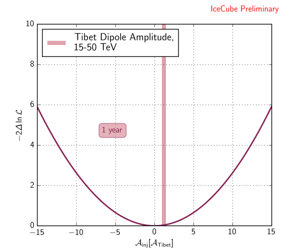

IceCube Preliminary
360°
0°
Equatorial
-0.345489
Counts
0.345489

Anti-Sidereal Cross-Check Results

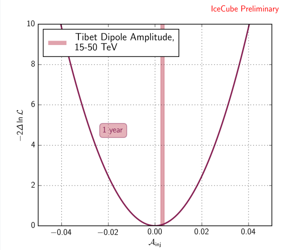
Tibet 15 TeV



Tibet 50 TeV

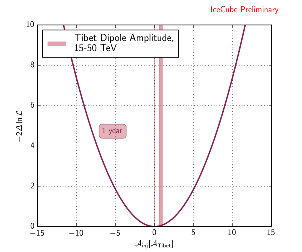


Dipole

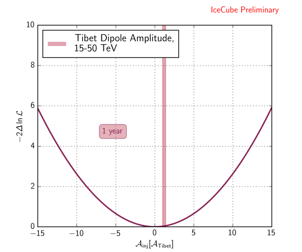


Extended-Sidereal Cross-Check Results

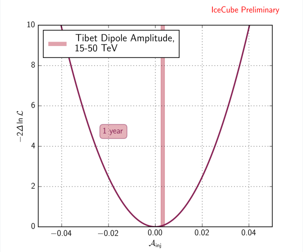
Tibet 15 TeV



Tibet 50 TeV



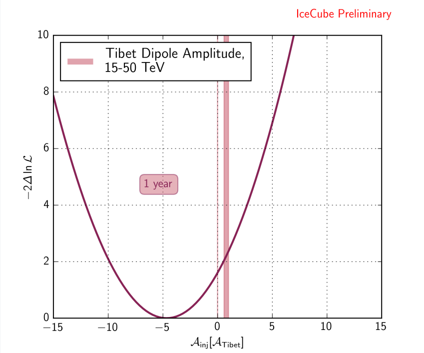
Dipole



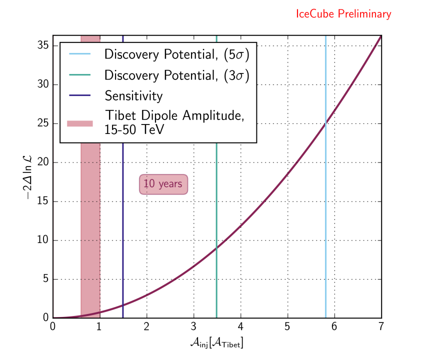
LogLikelihood Analysis - Asimov Predictions

All amplitudes are multiples of the observed Tibet Amplitude

1 Year

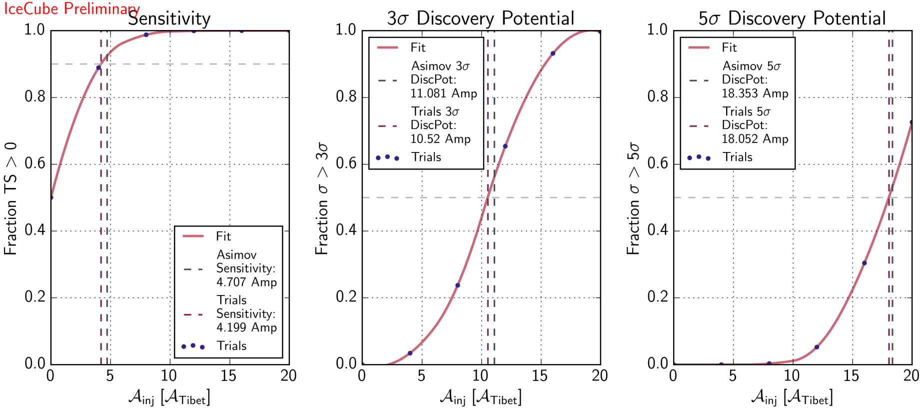


10 Years



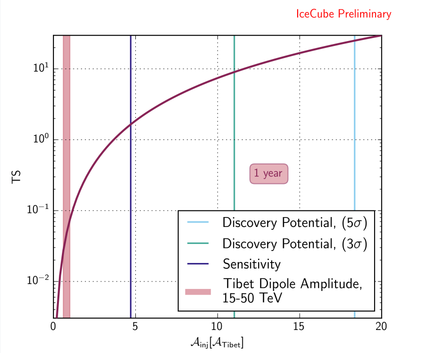
Injection Test

Injection test on 5000 trials with one year of data.

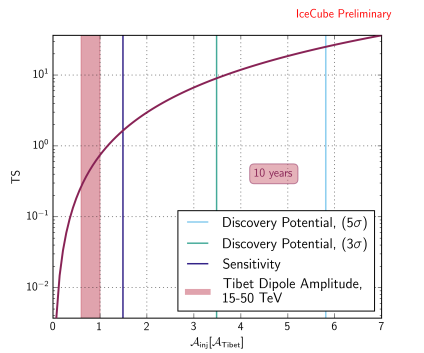


Expected Test Statistics - Asimov Predictions

1 Year

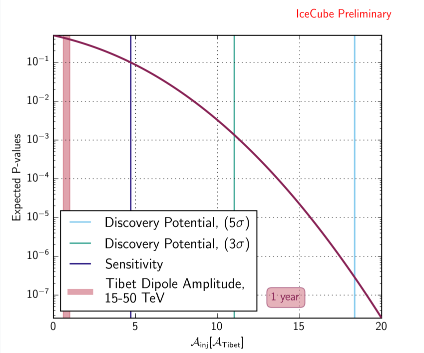


10 Years

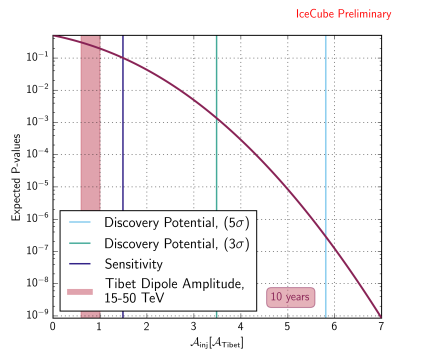


Expected PValues - Asimov Predictions

1 Year

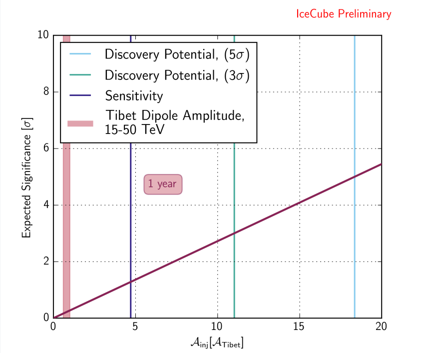


10 Years



Expected Significance - Asimov Predictions

1 Year



10 Years