### Probing Cosmic Ray Anisotropy with Atmospheric Neutrinos

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CRA2017

Overview
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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

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

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## 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

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

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### Challenge: Neutrino Interaction Cross Section ANL, PRD 19, 2521 (1979) IHEP-ITEP, SJNP 30, 527 (1979) cm<sup>2</sup> / GeV) ArgoNeuT, PRI, 108, 161802 (2012) IHEP-JINR, ZP C70, 39 (1996) BEBC, ZP C2, 187 (1979) MINOS, PRD 81, 072002 (2010) BNL PRD 25, 617 (1982) NOMAD, PLB 660, 19 (2008) 1.4 CCFR (1997 Seligman Thesis) NuTeV PRD 74 012008 (2006) CDHS\_ZP\_C35\_443 (1987) SciBooNE, PRD 83, 012005 (2011) 1.2 GGM-SPS, PL 104B, 235 (1981) SKAT, PL 81B, 255 (1979) GGM-PS, PL 84B (1979) T2K, PRD 87, 092003 (2013) (10<sup>-38</sup> ( $\nu_{\mu} \mathbf{N} \rightarrow \mu^{-} \mathbf{X}$ 0.8 0.8 10 0.6 0 0 0.4 0.2

100 150 200

Λ 250

10



E<sub>v</sub> (GeV)

300 350

Neutrino detections are rare.

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

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### Data Selecti

Methods & Results

### Where does this leave us?

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





Methods & Results

### 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



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# 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  ${\rm TeV}$
- Maximizing signal acceptance by tolerating lower purity and larger angular error

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### 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



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### North Sky $\nu_{\rm atm}$ Data







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Data Selection 00000

### Dipole Lower Energy Dependence (10-100 TeV) IceCube



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

13 TeV







We are sensitive to an energy band with constant behaviour. Insufficient statistics to allow for binning in energy.

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## Classic Analysis Methodology

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One Year Signal I	Мар		ICECLIBE DICEXE
		IceCube	Preliminary
Signal acceptance a contamination both	nd background peak near the		

horizon



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Classic One Year Reference Map Average of scrambled background maps IceCube Preliminary South Pole Scrambling: ■ Time Scrambling = **RA** Scrambling Event acceptance is declination dependent:  $(\theta, \phi, t) \rightarrow (\alpha, \delta)$ 360°  $(\theta, \phi, t') \rightarrow (\alpha', \delta)$ Scrambling to dipole Equatorial resolution: 24 hrs 137.854 Counts

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One Year Re	elative Intensity Map		ICECUBE
		IceCube F	Preliminary
$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i}{\langle N \rangle_i}$	$rac{\left(lpha,\delta ight)-\left\langle \textit{\textit{N}}_{i}\left(lpha,\delta ight) ight angle }{\left\langle \textit{\textit{N}}_{i}\left(lpha,\delta ight) ight angle }$		
1 year results statistical flue	dominated by ctuations.	360°	0°

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Equatorial

0.500237

 $[\Delta N / < N >]$ 

-0.500237

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One Year Sig	nificance Map		CEDJE ONVERSITY
$\sigma = \sqrt{2(a+b)}$	<u>b)</u>	IceCube Pi	reliminary
$a=N_{\rm on}\log[$	$\left(\frac{1+\alpha}{\alpha}\right) \left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)$		~
$b = N_{\text{off}} \log \left[ \right]$	$(1{+}\alpha) \Big( rac{N_{ m off}}{N_{ m on} + N_{ m off}} \Big) \Big]$		
$\alpha {=} \frac{\mathrm{exposure_{on}}}{\mathrm{exposure_{off}}}$	L F	360°	0°
Li, Ma. 1983 ApJ 272			Equatorial
As expected, r	no significant signal		
in 1 year of da	ita.	-3.41344 Significance $[\sigma]$ 3.41344	

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## Angular Spectrum Analysis



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



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### Low Statistics Analysis Methodology

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### 1D Fit

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



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BinnedLLH				
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### 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





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### Background Modeling

- Likelihood here defined as the probability product across all pixels
- Poisson probabilities to observe (n<sub>i</sub>) given signal hypothesis (θ<sub>i</sub>) 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:

$$\mathsf{TS} = -2\log\frac{\mathcal{L}_{\mathsf{null}}}{\mathcal{L}_{\mathsf{template}}} = \chi_1^2$$

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



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Projected Sen	sitivities and Discove	ery Potentials	ICECLIEE DIVERSITY
	0.07 0.06 0.05 emilieuv 0.03 0.02 0.01 0.00 2 4 6	5σ Discovery Potential         3σ Discovery Potential         Sensitivity         Tibet Dipole Amplitude,         15-50 TeV         IceCube Preliminary         8       10       12       14         Livetime (years)	
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### 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	$-1.25\sigma$	$1.44\sigma$	$-0.60\sigma$

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### Tibet Template, 50 TeV



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ICC.	Cu	De -				

	Sidereal	Anti-Sidereal	E x t e n d e d e r e a l
TS	-1.50	1.07	-0.23
P-Value	0.88	0.09	0.68
Significance	$-1.22\sigma$	$1.30\sigma$	$-0.48\sigma$

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Methods & Results



# Summary

Physics Target: Dipole fit of North Sky Cosmic Ray Anisotropy with  $\nu_{\rm atm}$ 

- 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

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# **Backup Slides**

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 $\nu_{\rm atm}$  Dataset

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Skymap Templates

Cross Checks

### Anti-Sidereal Cross-Check Results



# Tibet 15 TeV





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Skymap Templates

### Extended-Sidereal Cross-Check Results



# Tibet 15 TeV





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### LogLikelihood Analysis - Asimov Predictions

All amplitudes are multiples of the observed Tibet Amplitude



### Injection Test



### Injection test on 5000 trials with one year of data.



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### Expected Test Statistics - Asimov Predictions







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Skymap Templates

### Expected PValues - Asimov Predictions







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## Expected Significance - Asimov Predictions







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