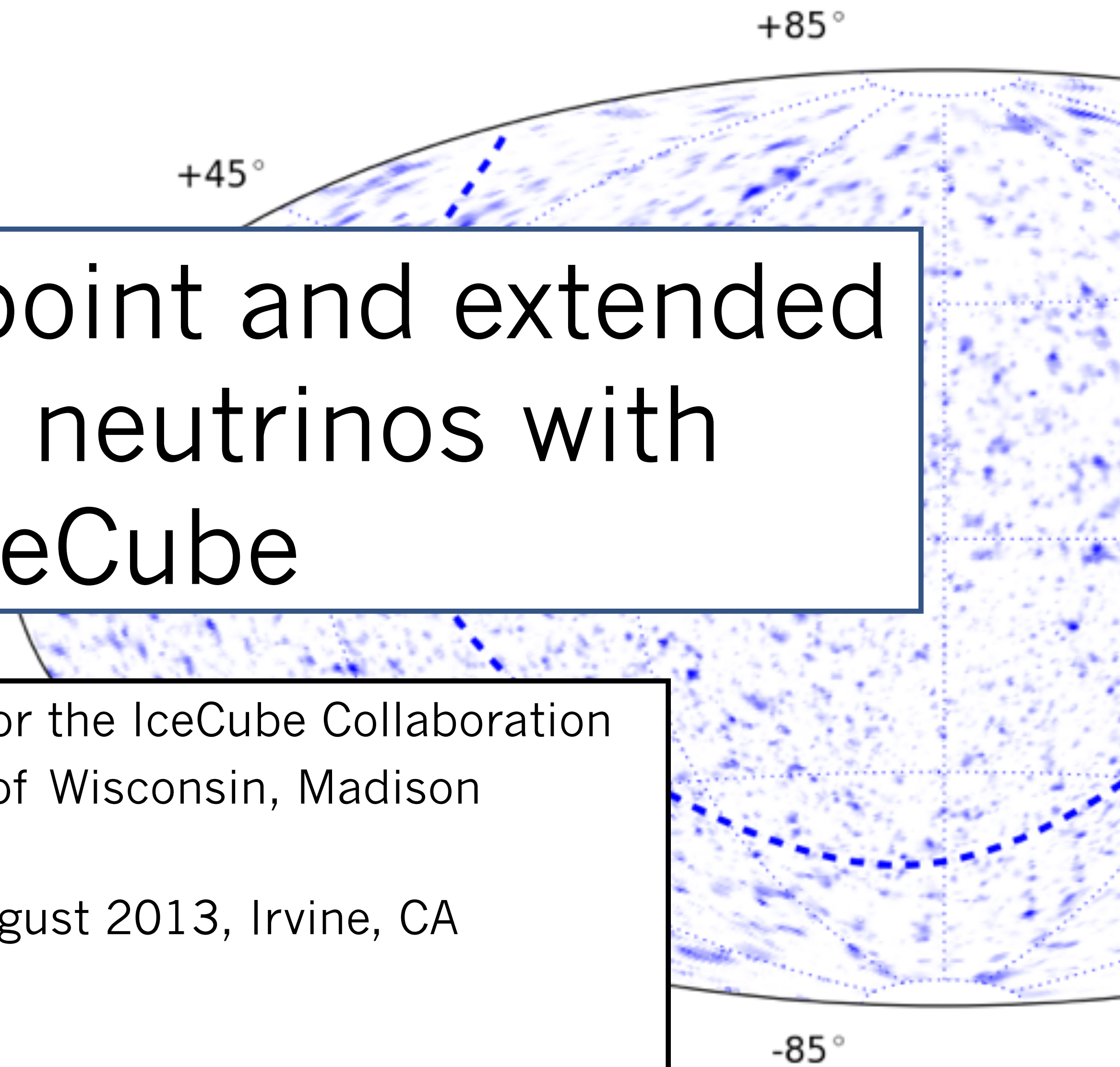


Searches for point and extended sources of neutrinos with IceCube

Jacob Feintzeig for the IceCube Collaboration
University of Wisconsin, Madison

TeVPA, August 2013, Irvine, CA

ICECUBE

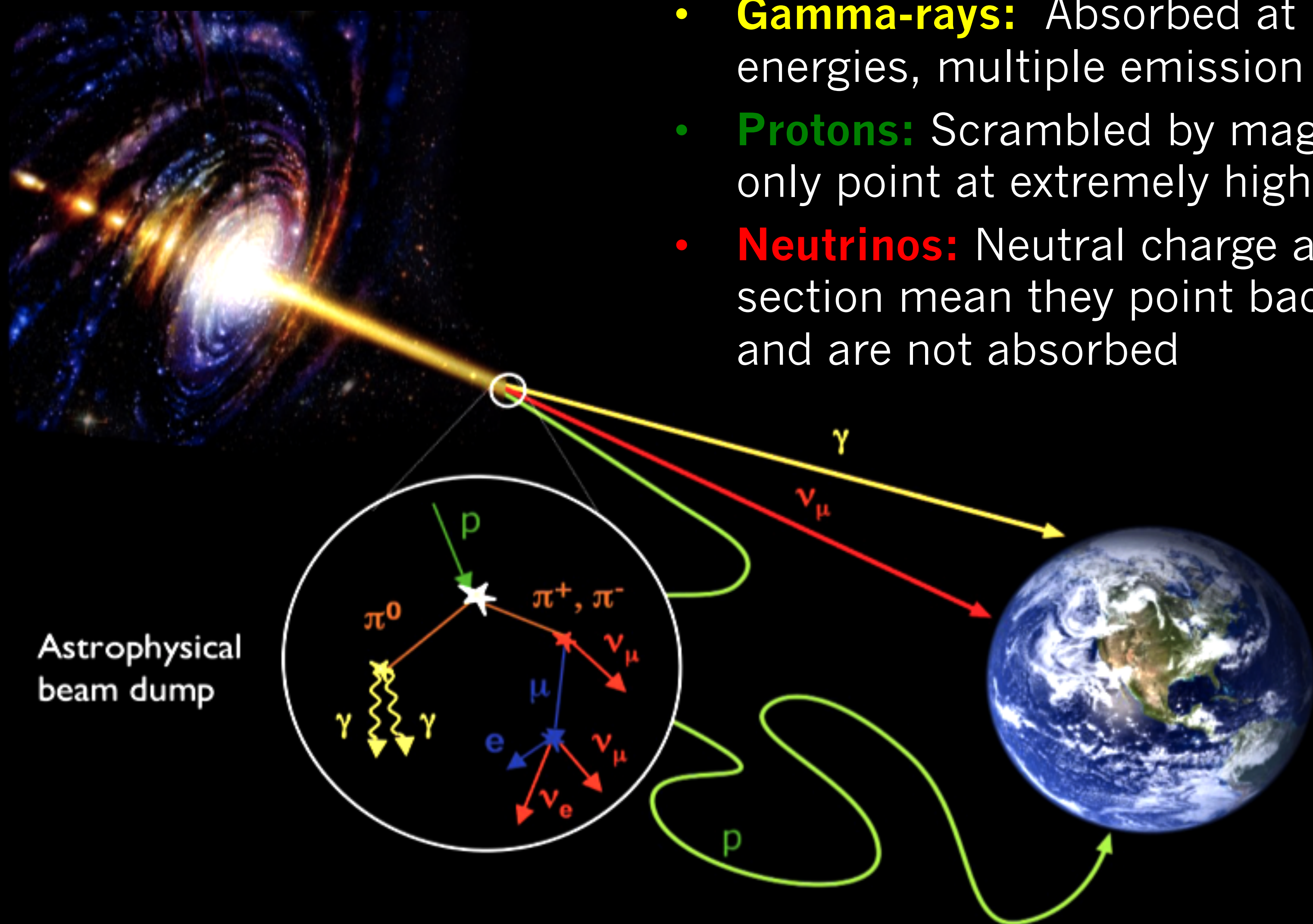
THE UNIVERSITY of WISCONSIN MADISON

Contents

- Neutrinos in the context of multi-messenger astronomy
- Point source analysis method in IceCube
- Recent results
  - All-sky scan and *a priori* source list search using 4 years of detector data
  - Targeted searches using stacked source catalogs with 3 years of detector data
  - All-sky scan using sample of contained vertex events
- Future outlook
  - Improvements in the Southern hemisphere

Neutrinos are excellent candidates for high-energy astronomy

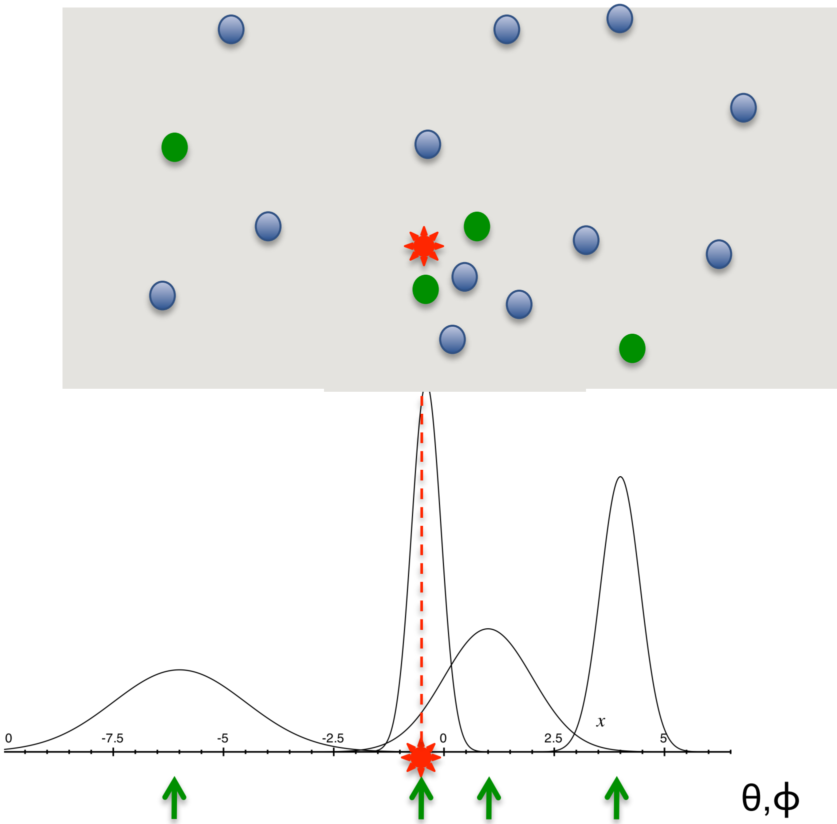
- **Gamma-rays:** Absorbed at highest energies, multiple emission mechanisms
- **Protons:** Scrambled by magnetic fields, only point at extremely high energies
- **Neutrinos:** Neutral charge and low cross-section mean they point back to source and are not absorbed



Contents

- Neutrinos in the context of multi-messenger astronomy
- Point source analysis method in IceCube
- Recent results
  - All-sky scan and *a priori* source list search using 4 years of detector data
  - Targeted searches using stacked source catalogs with 3 years of detector data
  - All-sky scan for low-background sample of high-energy neutrinos
- Future outlook
  - Improvements in the Southern hemisphere

To search for point sources, look for statistically significant spatial clustering of events

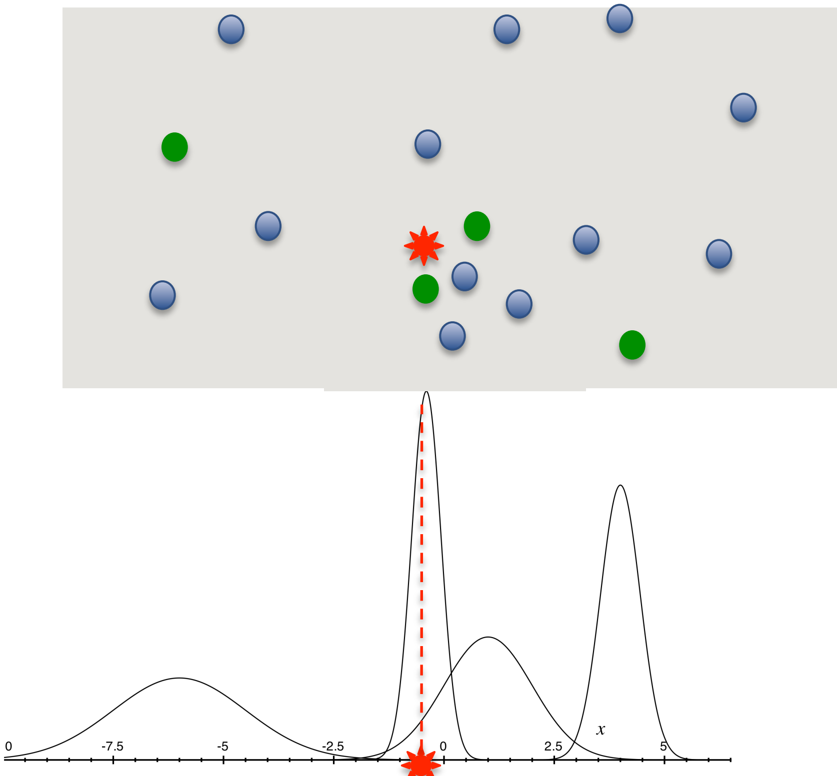


Location of candidate neutrino event on the sky

Test point source hypothesis here

- Signal: Astrophysical neutrinos clustering in space
- Background: Isotropic atmospheric neutrinos
- Un-binned maximum likelihood method
  - Spatial probability distribution function for signal modeled as a 2D gaussian
  - Width from reconstruction uncertainty
  - Energy information used to weight events
  - Signal expected to be higher energy than background

To search for point sources, look for statistically significant spatial clustering of events

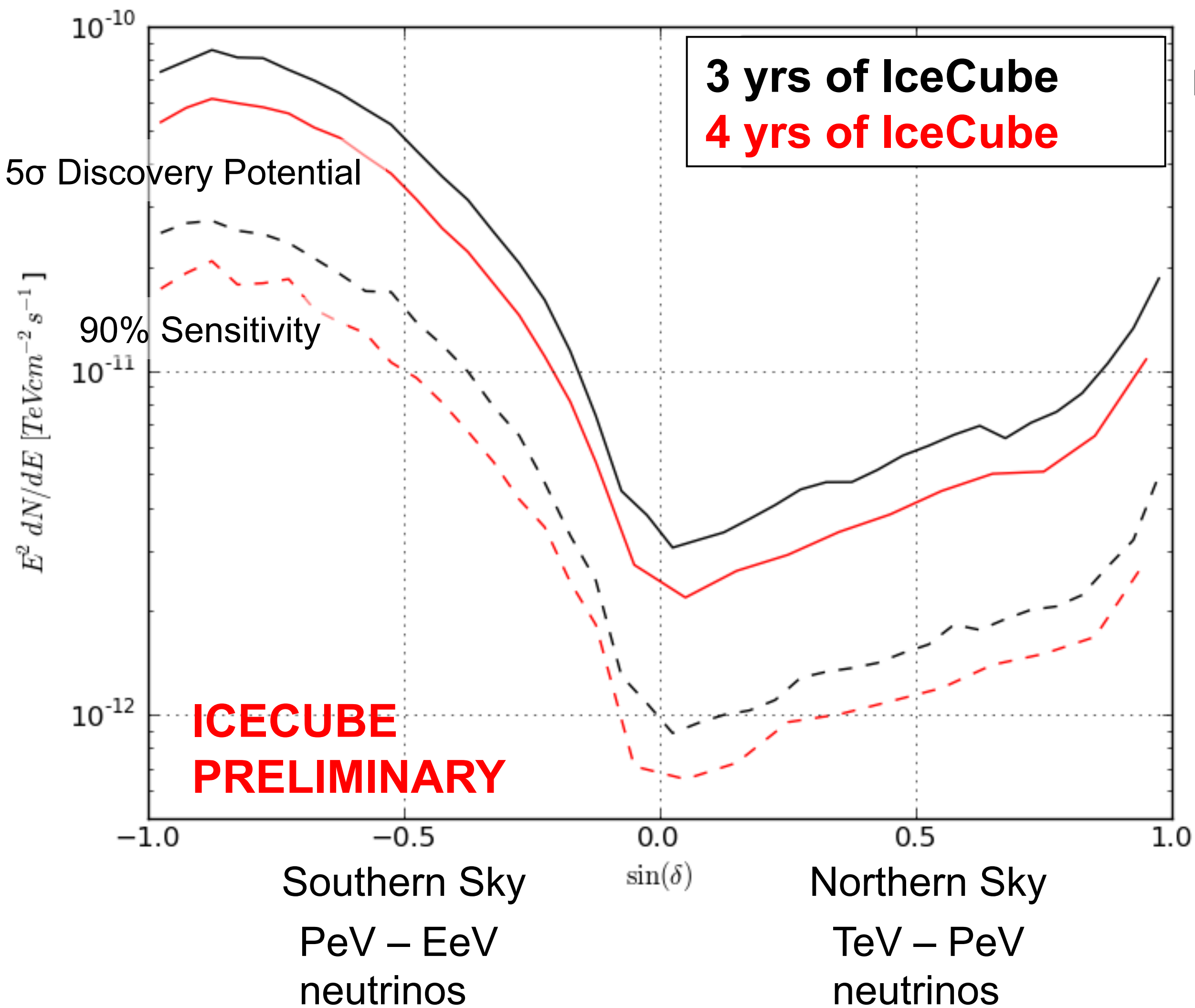


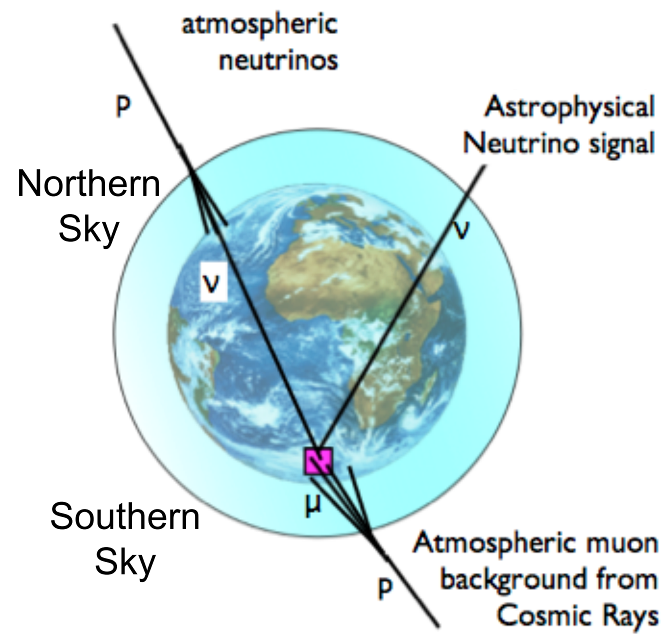
- Signal: Astrophysical neutrinos clustering in space
- Background: Isotropic atmospheric neutrinos
- Un-binned maximum likelihood method
  - Spatial probability distribution function for signal modeled as a 2D gaussian
  - Width from reconstruction uncertainty
  - Energy information used to weight events
  - Signal expected to be higher energy than background

At each point in the sky, use likelihood to fit for # of signal events and neutrino spectral index

Likelihood translates events on the sky into probabilities

Discovery potential for 4 years of IceCube





Discovery potential improves because of:

- More livetime
- Better angular resolution
- Bigger effective area
  - detector size, event selection
- Improved understanding of systematics

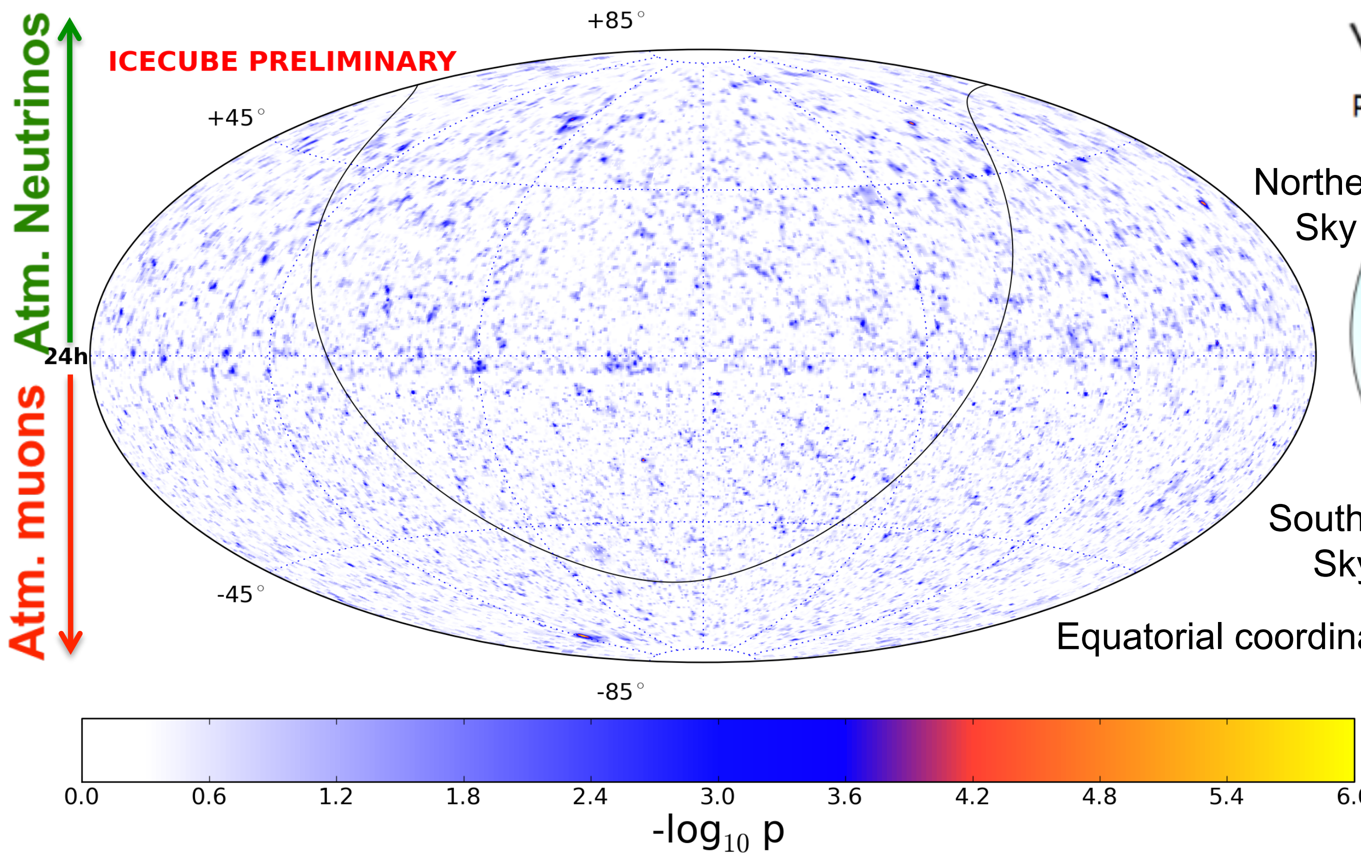
Contents

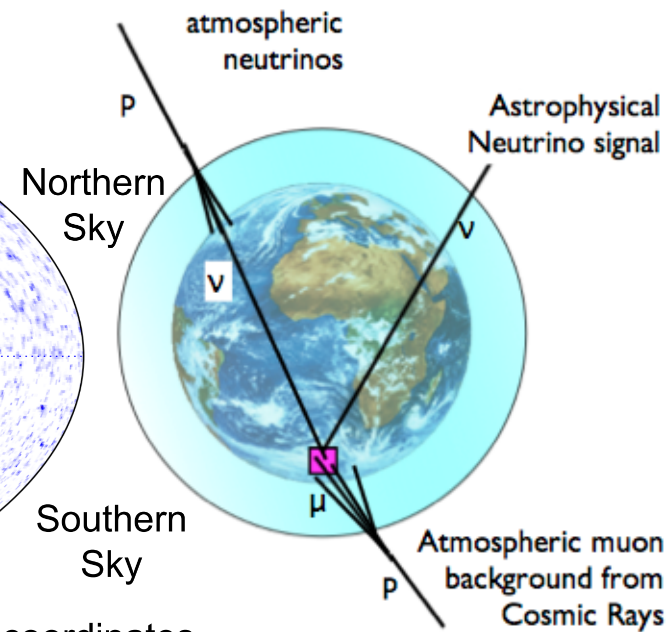
- Neutrinos in the context of multi-messenger astronomy
- Point source analysis method in IceCube
- Recent results
  - All-sky scan and *a priori* source list search using 4 years of detector data
  - Targeted searches using stacked source catalogs with 3 years of detector data
  - Spatial clustering of 2 year contained vertex event sample
- Future outlook
  - Improvements in the Southern hemisphere

No evidence of point sources was found in four years of detector data

- Search for time-independent sources
- 394,000 total events
  - 178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days, including first year of completed detector

See 2013 ICRC proceeding # 0550





Equatorial coordinates

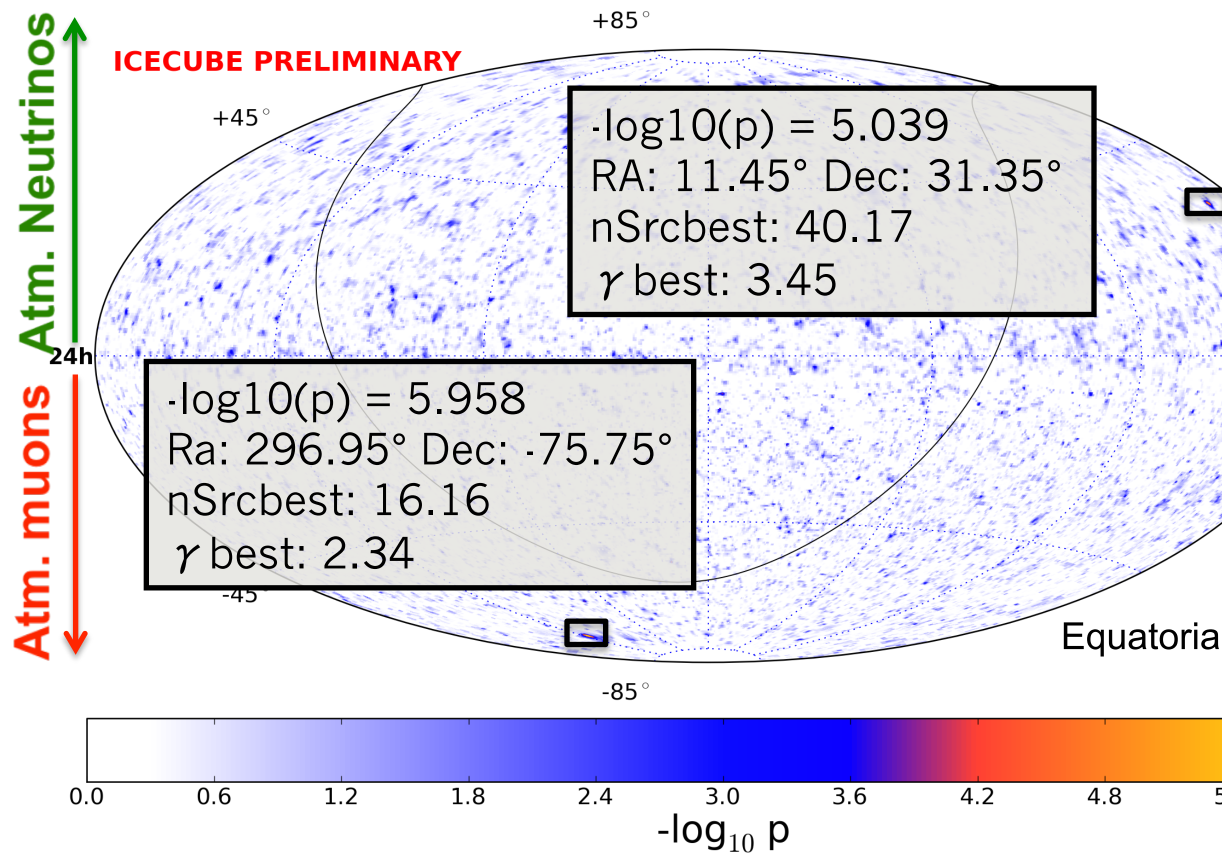
No evidence of point sources was found in four years of detector data

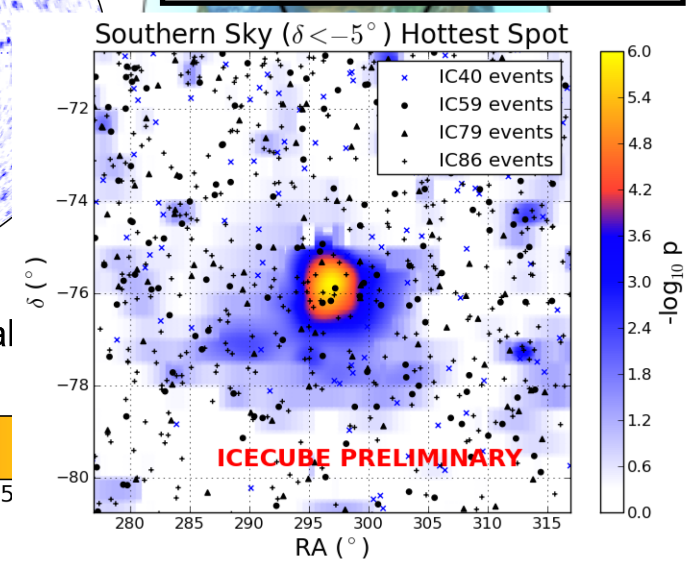
- Search for time-independent sources
- 394,000 total events
  - 178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days, including first year of completed detector

See 2013 ICRC proceeding # 0550

Most significant spots

Post trials p-values:
Northern Sky: 37.6%
Southern Sky: 9.3%

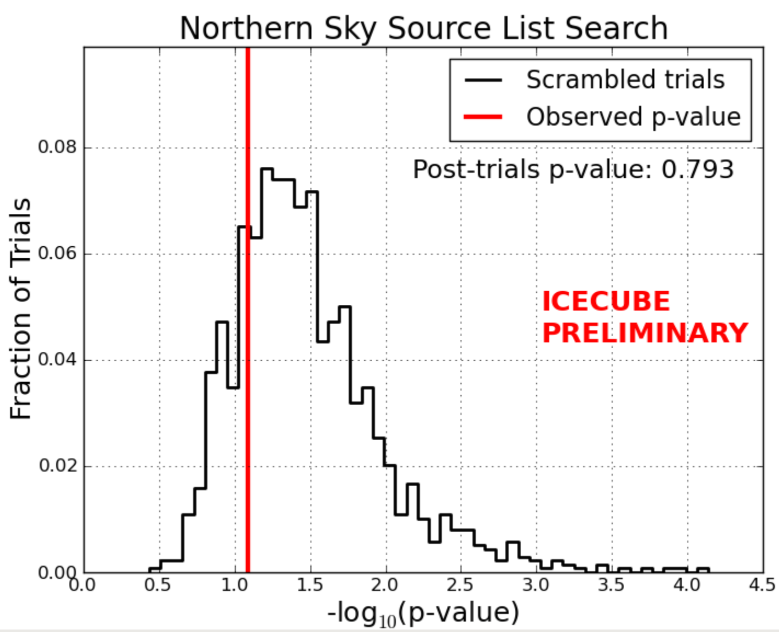


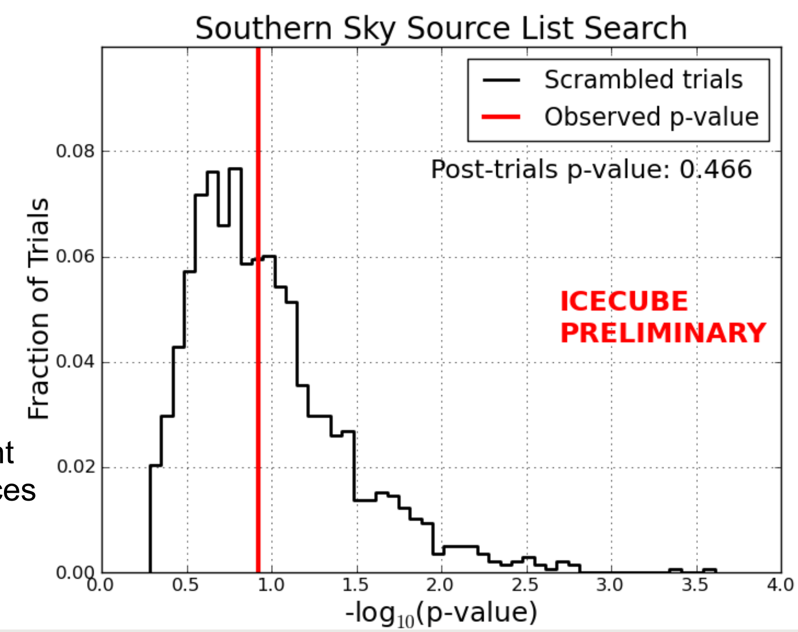


Search using *a priori* list of sources is consistent with background

- List consists of 44 promising sources
  - Supernova remnants, active galactic nuclei, etc. that are observed in gamma rays or for which models predict neutrino emission

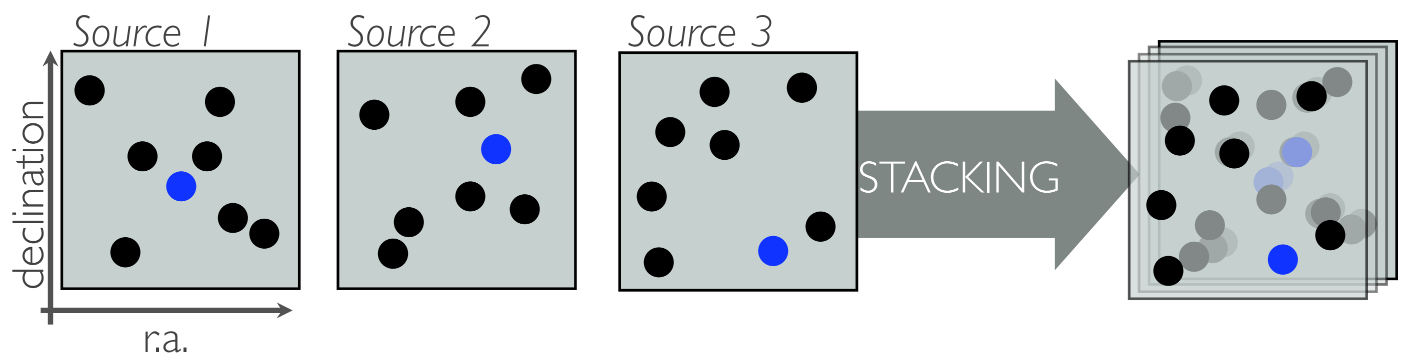
Most significant source in:	Source	n_s best	γ best	Pre-trials p-value	Post-trials p-value
Northern sky	3C 123.0	12.54	3.95	0.081	0.793
Southern sky	PKS 1406-076	7.50	3.95	0.12	0.466





Trials account for # of sources on each list

Stacking specific source classes enhances discovery potential

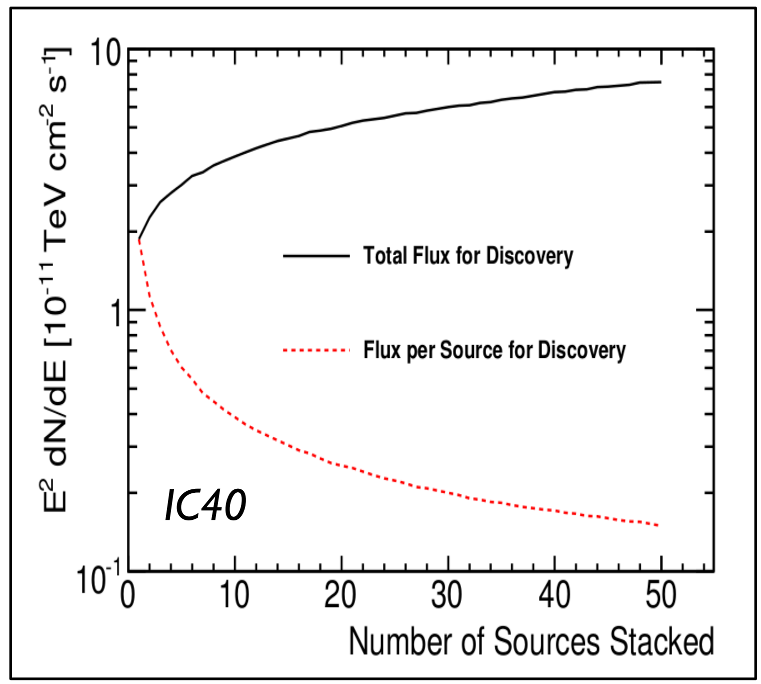


- Look at known collection of sources, with known extensions.
- Constrain specific astrophysical models.

$$\mathcal{S}_i = \sum_{j=1}^{N} W^j R^j(\gamma) S_i^j(r_i, E_i)$$

relative efficiency

theoretical weight



Results from five catalogs consistent with background

astro-ph/1307.6669

Catalog	Sources	Theoretical Weighting	Sample	p-value
6 Milagro SNRs	6	No	IC79+IC59	20.4 %
Starburst Galaxy	127	Yes, FIR observation	IC79+IC59+IC40	≥ 50 %
Galaxy Cluster	5	Yes, 4 models tested	IC79+IC59+IC40	All ≥ 50 %
Molecular Cloud SNR	4	Yes, integrated γ-flux	IC79+IC59+IC40	≥ 50 %
Black Hole	233	Yes, FIR observations	IC79+IC59+IC40	44. 31%

- Milagro 6 was *a-posteriori* positive fluctuation in IC40.
- Starburst catalog based on Becker et al. (arXiv:0901.1775)
- Galaxy Cluster different models depend on how the CRs are distributed.
- Molecular Cloud catalog includes IC443 and W44: *Fermi in Science 15/2/2013*

90% C.L. upper limits for 6 Milagro SNR associations

astro-ph/1307.6669

<u>MODEL</u>

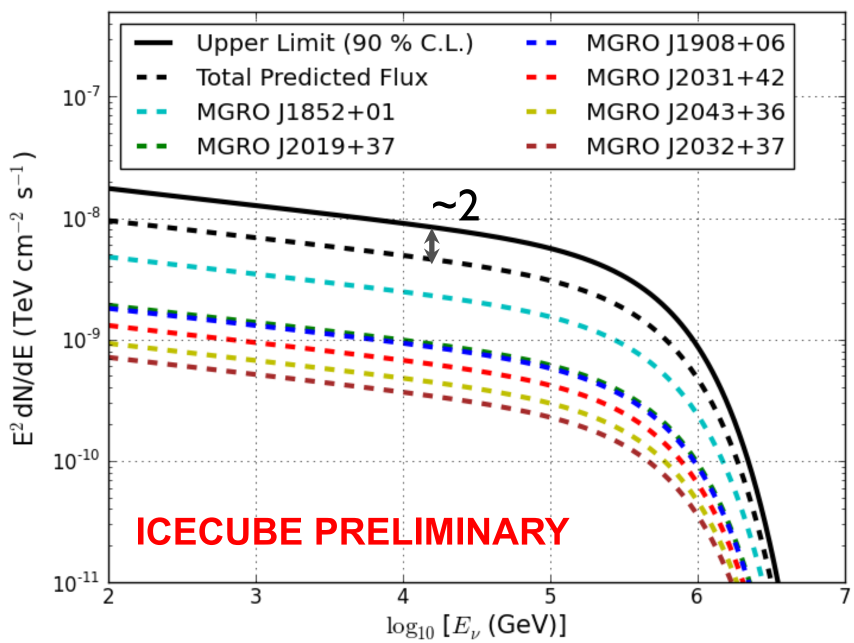
•F. Halzen, A. Kappes and A. O'Murchadha (Phys. Rev. D78:063004, 2008).

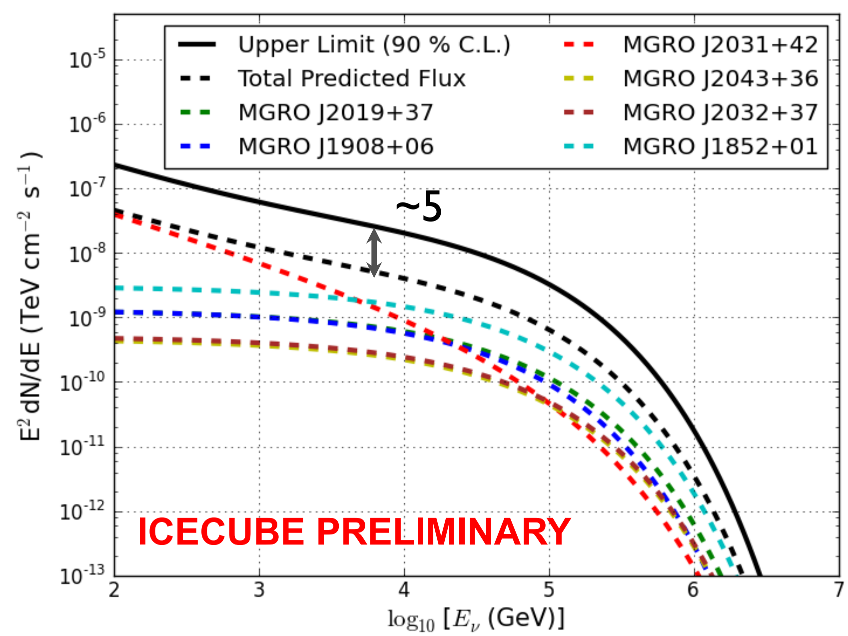
•Based on published TeV Gamma-ray at that time ($E_{cut\text{-}off}$ ~ 300 TeV.)

<u>MODEL</u>

•Update on the model prediction with recent gamma-ray observation ($E_{cut\text{-}off}$ ~ 30 TeV).

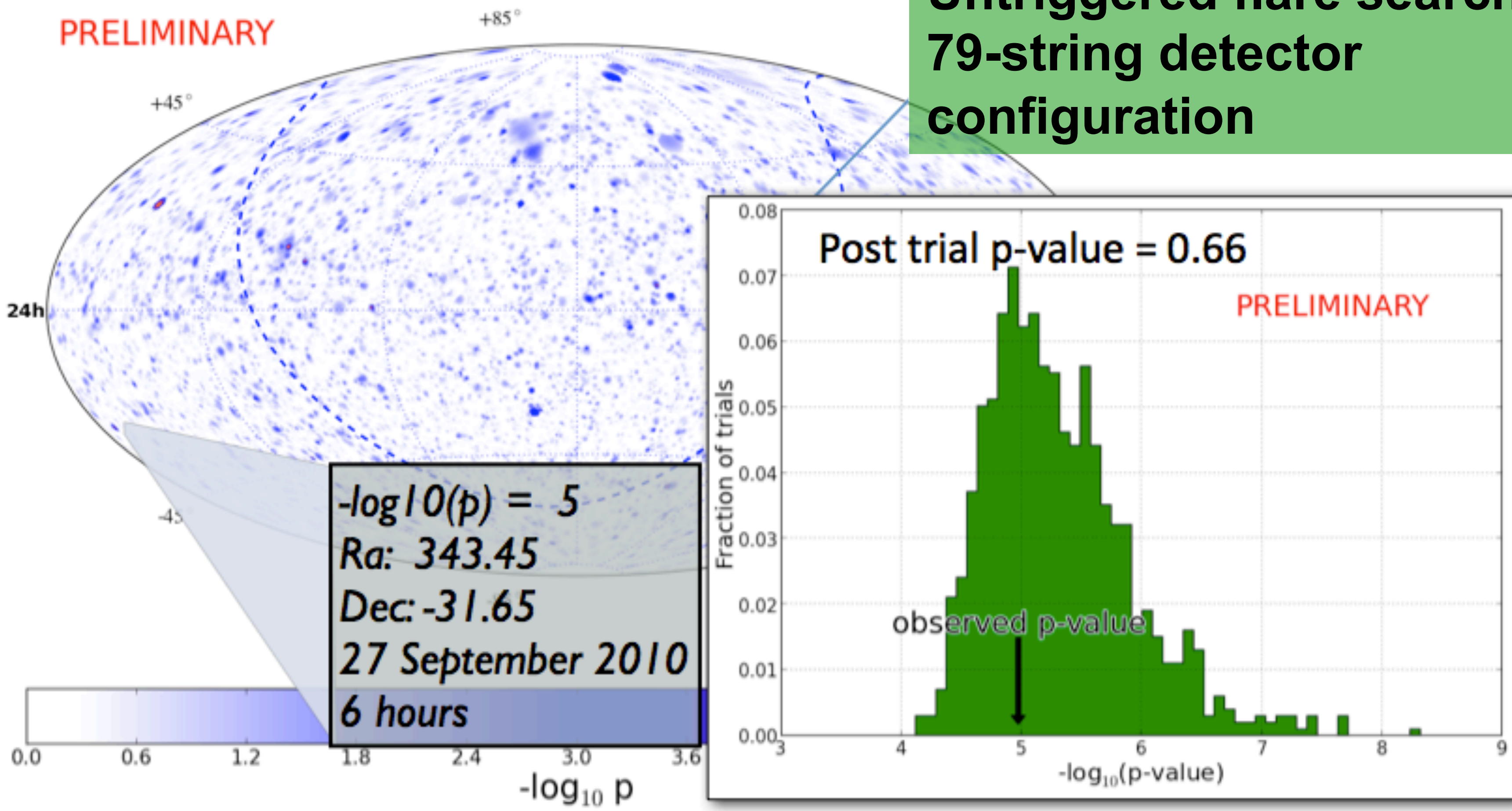
•For those sources with no measurement and spectral index of 2 and $E_{cut\text{-}off}$ = 31 TeV





All searches for transient sources are also consistent with background

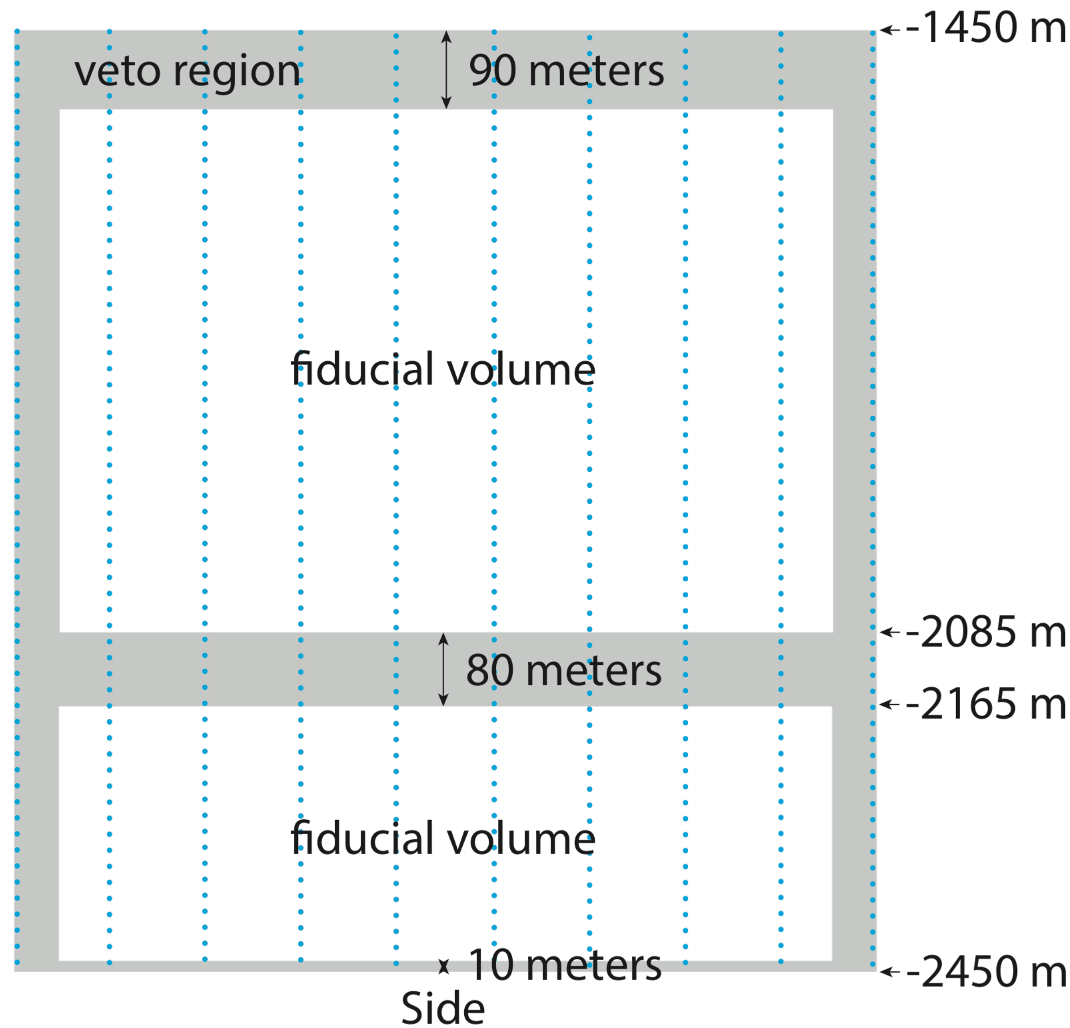
Untriggered flare search, 79-string detector configuration



See 2013 ICRC, contribution #0649

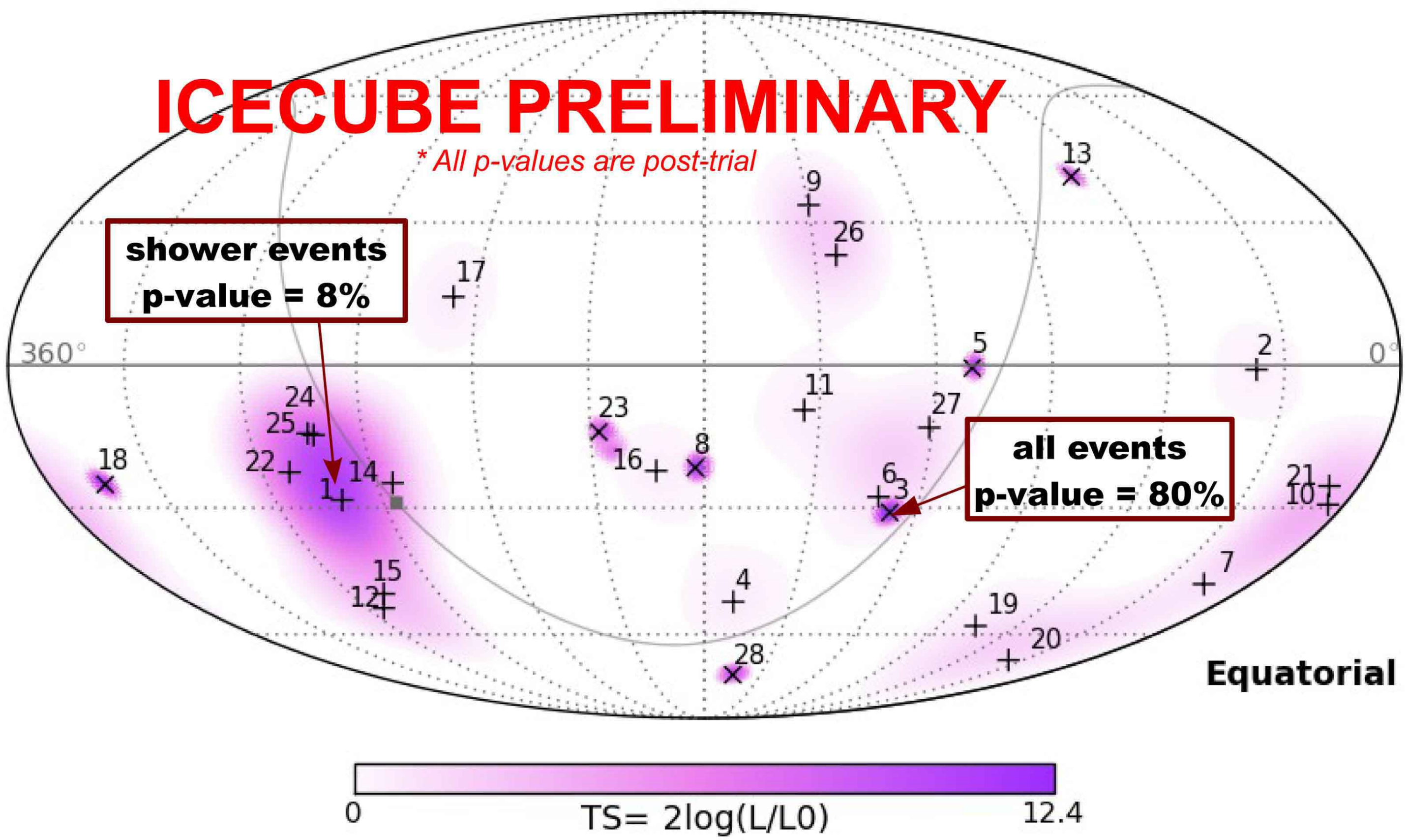
Point source search using sample of 28 events with contained vertices

- 2 years of data
  - Charge>6000 & vertex inside fiducial volume
- Compared to previous searches, this analysis has:
  - Much lower background (28 total events instead of 400k)
  - Lower energy threshold in the Southern hemisphere
  - Track (<1° pointing) and cascade (poor angular resolution) events



No evidence of spatial clustering found in contained vertex event sample

- Searched for:
  - Point source in sample of all 28 events
  - Point source in subsample of 21 cascade events

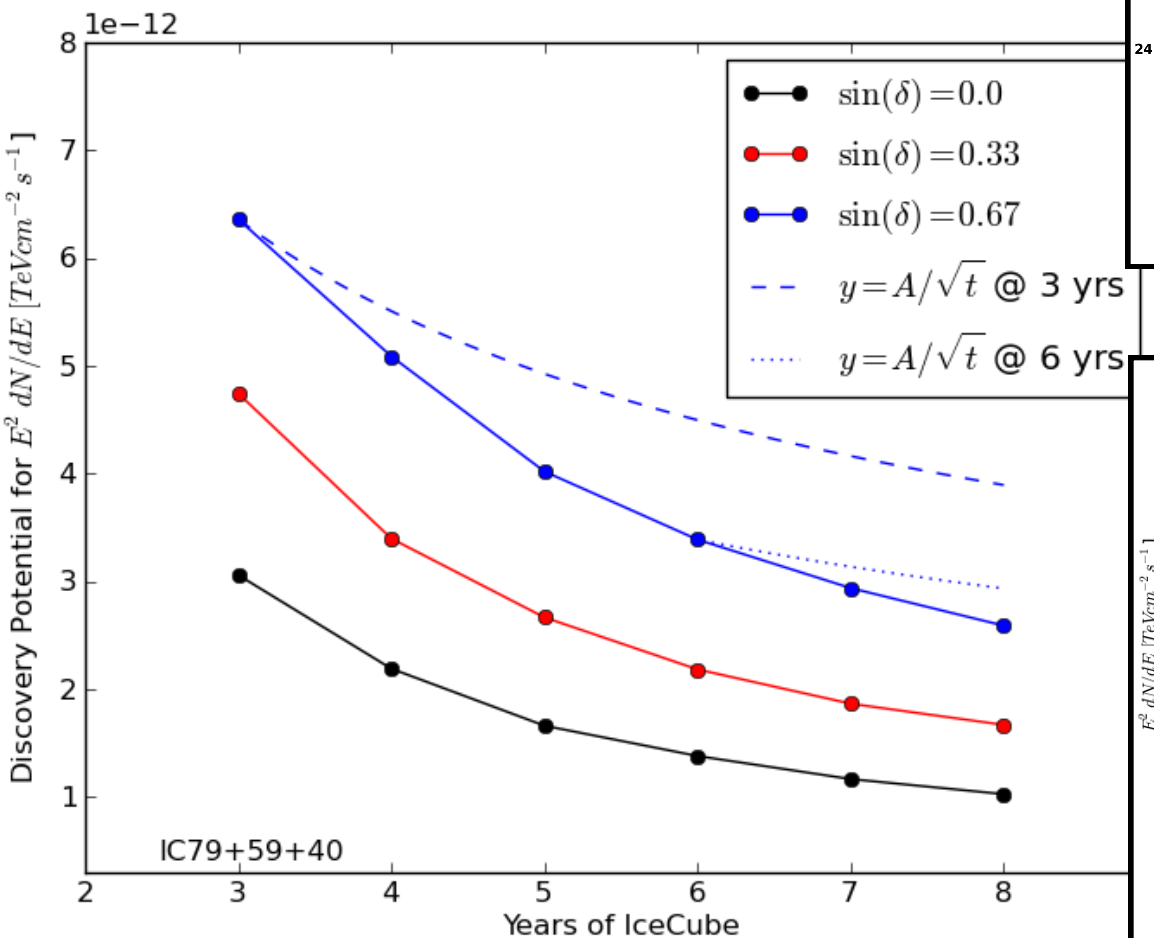


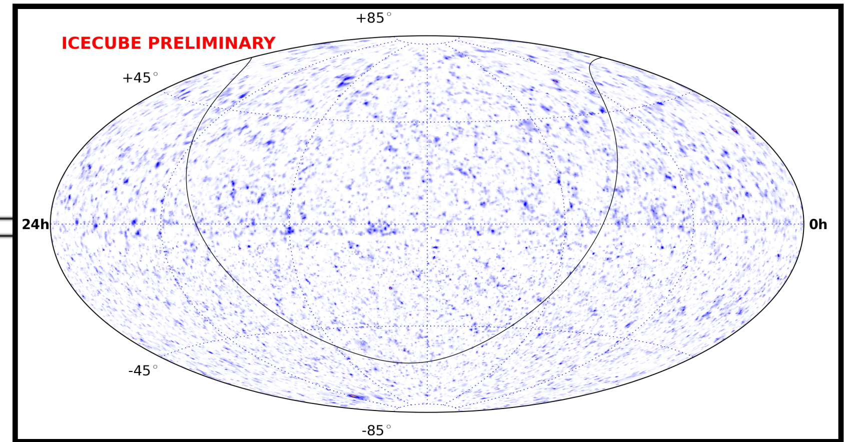
Contents

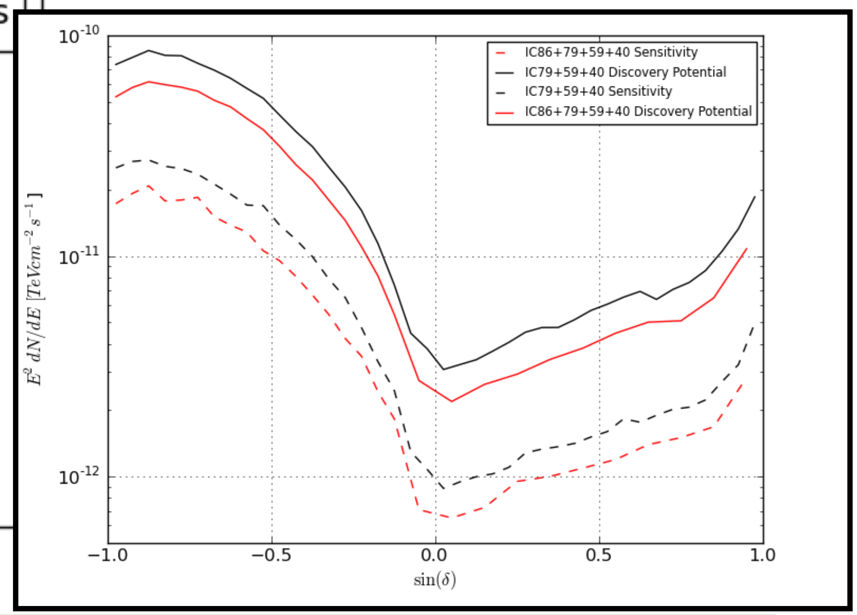
- Neutrinos in the context of multi-messenger astronomy
- Point source analysis method in IceCube
- Recent results
  - All-sky scan and *a priori* source list search using 4 years of detector data
  - Targeted searches using stacked source catalogs with 3 years of detector data
  - All-sky scan for low-background sample of high-energy neutrinos
- Future outlook
  - Improvements in the Southern hemisphere

Discovery potential will improve as more data is added to analysis

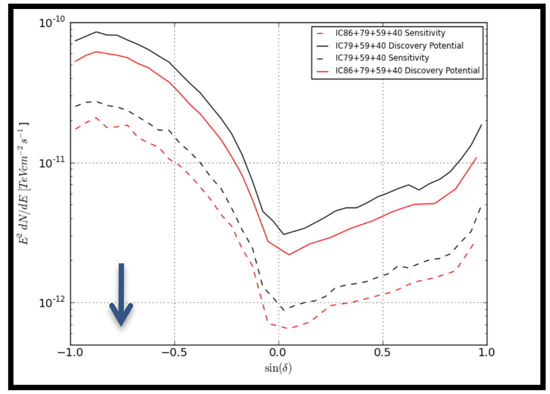
Analysis is not yet background dominated (gaussian regime), not yet in σ ~ √t regime



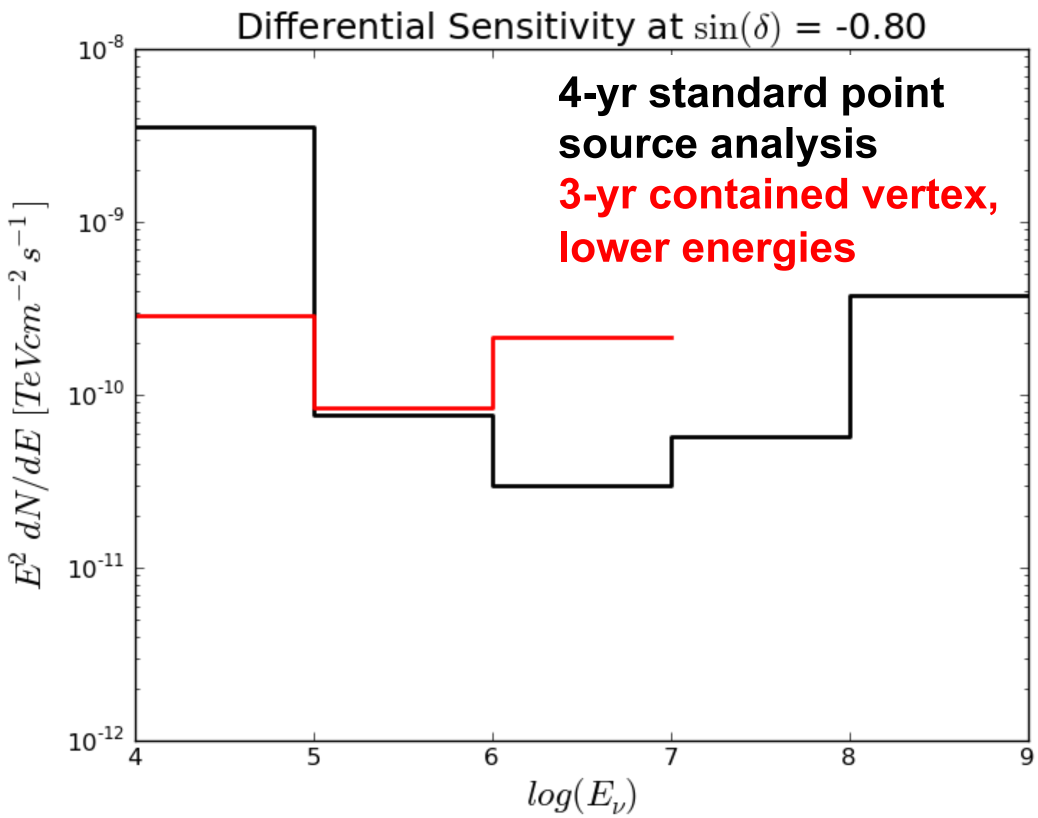




Improving the sensitivity in the Southern sky



- Method of spatial clustering for contained vertex events
  - Combining tracks and cascades
  - Background estimation
- Extend contained vertex event selection to lower energies
  - More signal, more tracks
  - More background
  - Combine with 4 year "standard analysis" for most statistical power

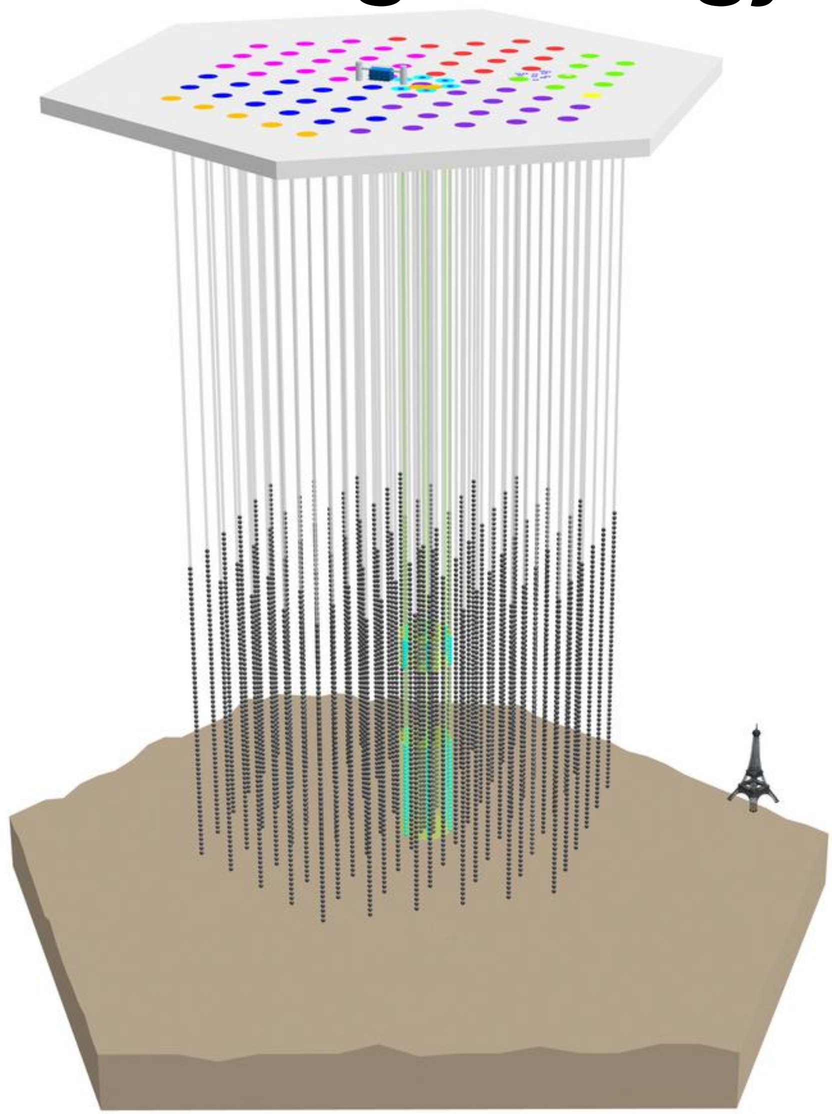


Conclusion

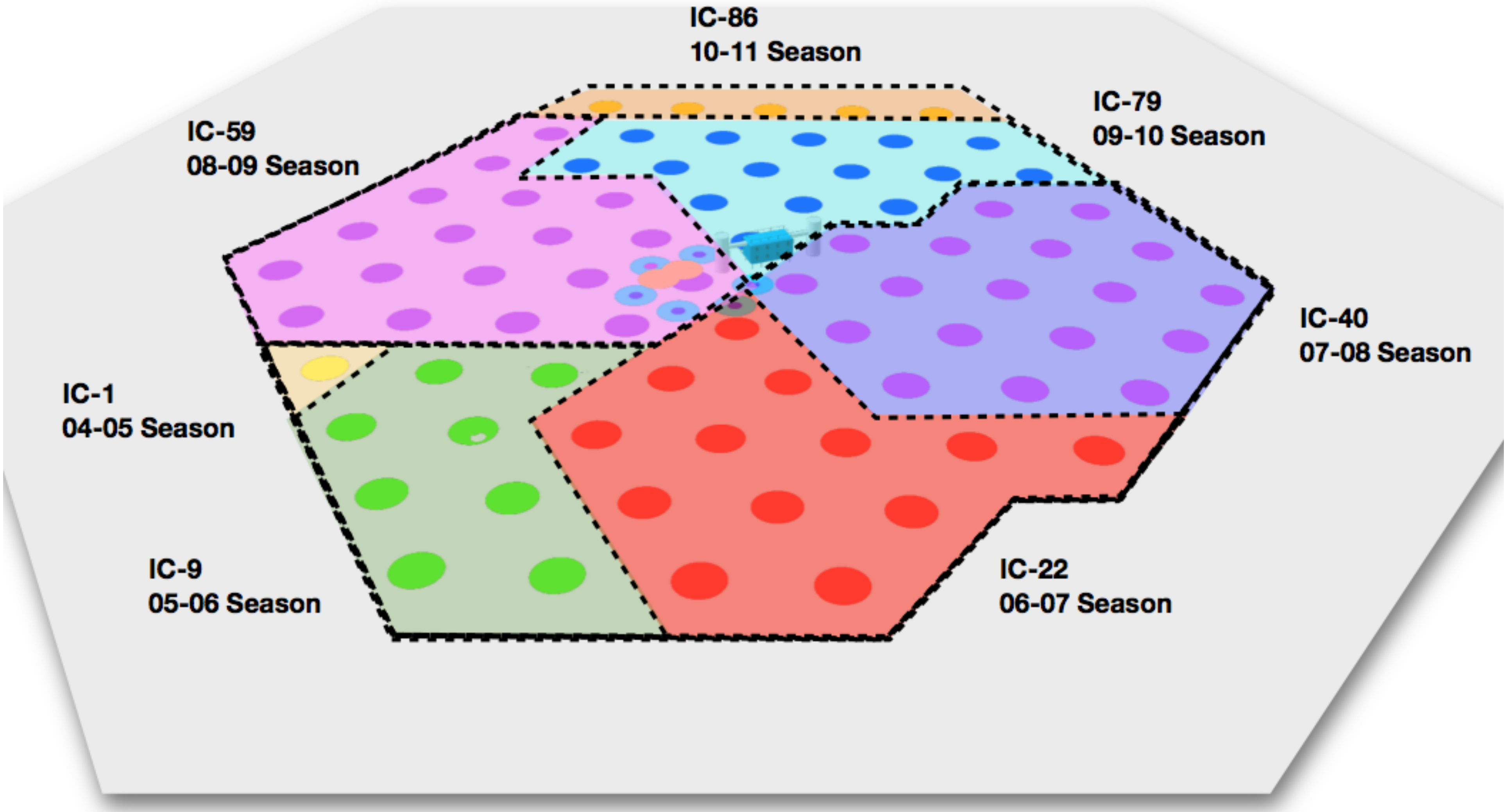
- So far, no search has found significant clustering of neutrino events or association with sources
  - All-sky search and *a priori* source list using 4 years of detector data
  - Stacking analyses using 3 years of data
    - Milagro supernova remnants (SNRs)
    - Starburst galaxies
    - Galaxy clusters
    - SNRs associated with molecular clouds
    - Black hole candidates
  - Spatial clustering analysis of 28 contained vertex events
- Discovery potential will continue to improve – stay tuned for more results!

Backup

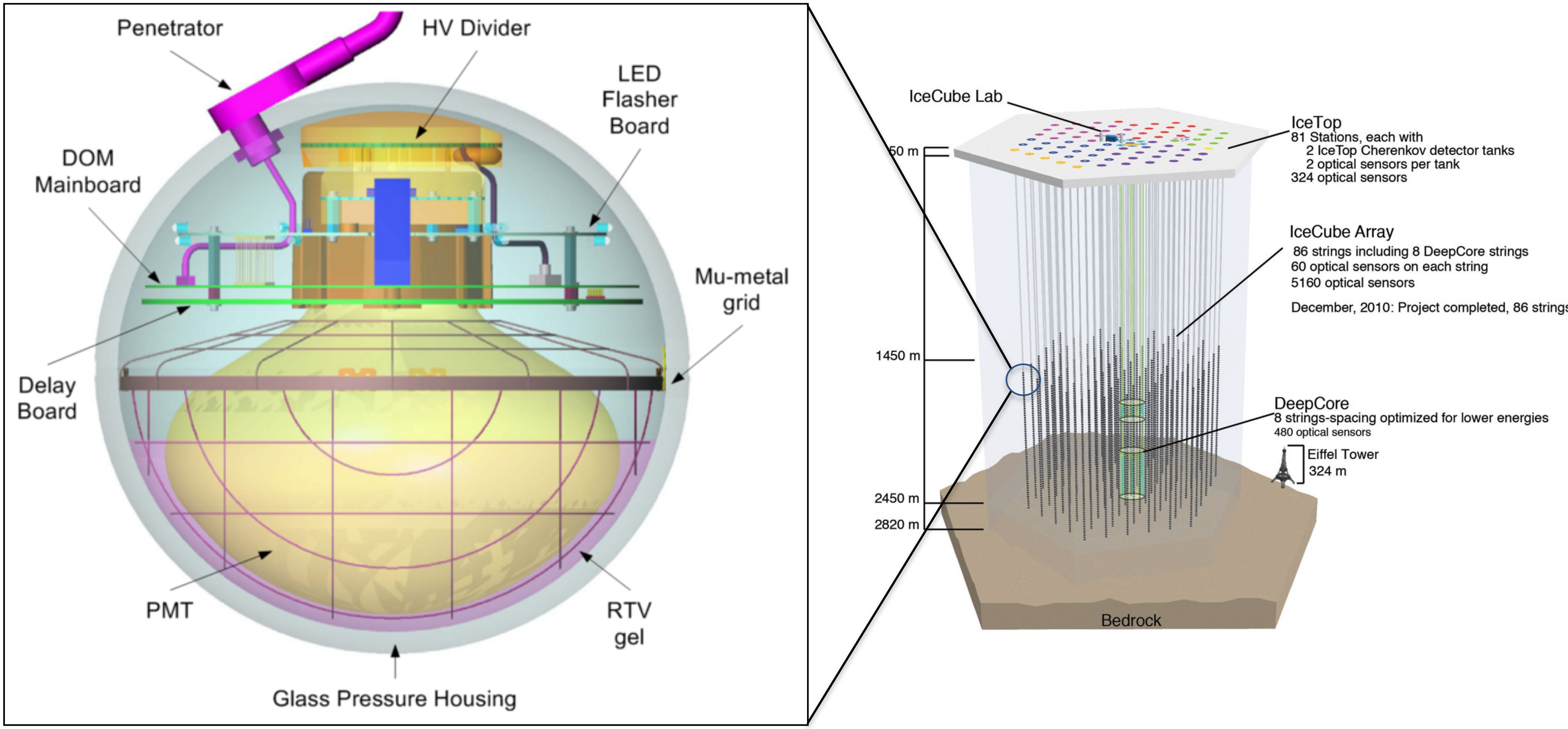
IceCube uses a fully-instrumented km^3 of ice to detect high-energy particles



During construction, IceCube ran in partial detector configurations



Light is detected via photomultiplier tubes, waveforms are digitized and read out to surface



Digital **O**ptical **M**odule

The IceCube Collaboration

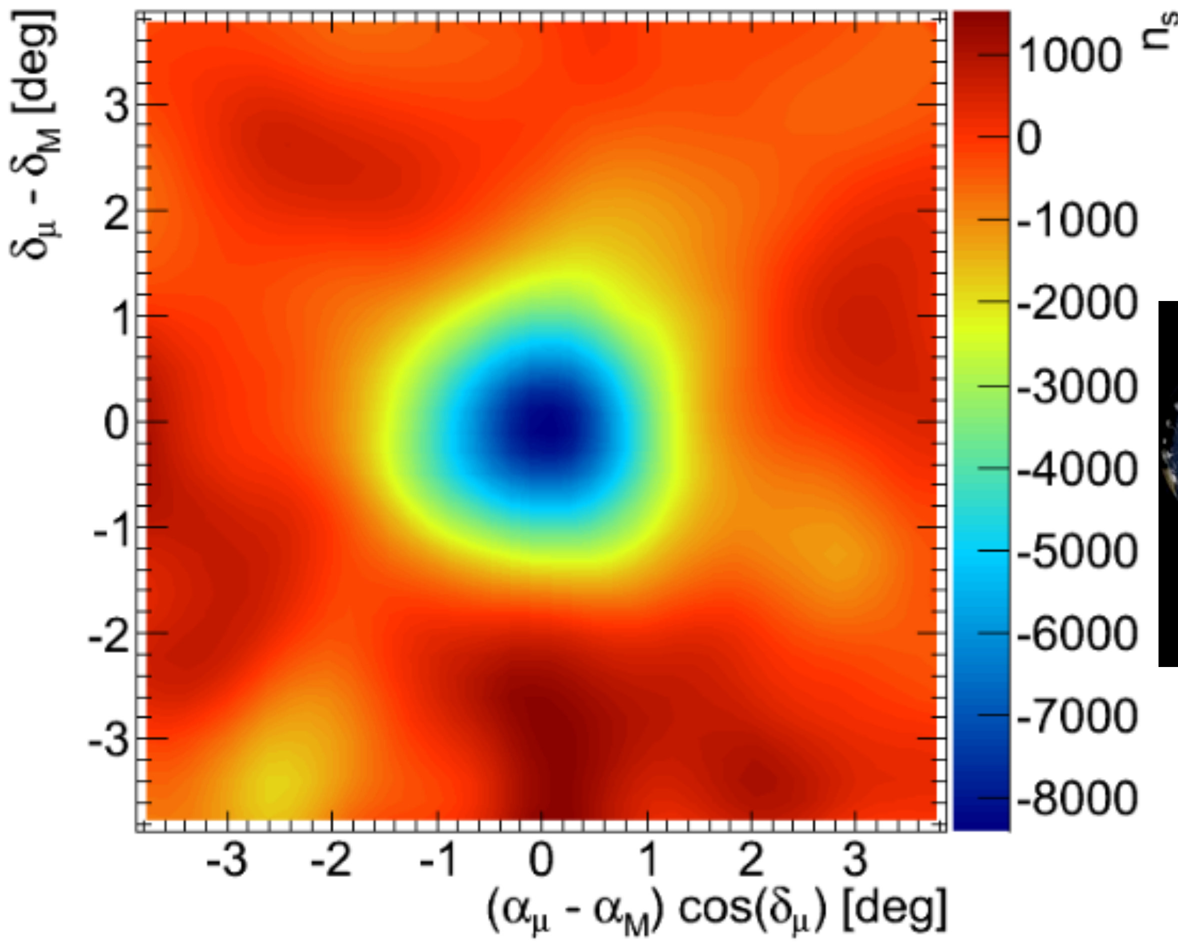
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)

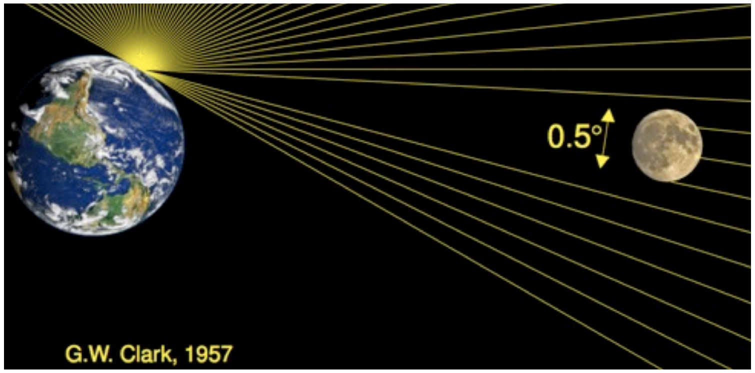
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Using geometry and timing of detected photons, neutrino directions are reconstructed to less than 1°



Shadow of the moon observed in cosmic rays



E_{CR} ~ 40 TeV
Absolute pointing ~ 0.1°
Angular resolution ~ 1°, agrees well with expectations from simulation

Likelihood method translates events on the sky into p-values

Signal: Astrophysical neutrinos clustering in space
Background: Isotropic atmospheric neutrinos

Maximize the likelihood function:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Braun et. al., arXiv: 0801.1604

Test statistic:

$$\lambda = \log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Obtain **p-value** by comparing test statistic for real data to random trials from scrambled data

Fit for:
- **n_s**, # of signal events
- **γ**, neutrino spectral index

Complete source list results – northern sky

Source	RA (°)	Dec (°)	$\hat{n}_s$	$\hat{\gamma}$	$B_{2°}$	p-value	$\Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu}$
S5 0716+71	110.47	71.34	1.38	3.95	66.0	0.49	3.21
M82	148.97	69.68	0.00	2.61	65.8	–	2.93
1ES 1959+650	300.00	65.15	10.22	3.95	70.4	0.11	4.48
TYCHO	6.36	64.18	7.92	3.95	71.0	0.22	3.55
LSI 303	40.13	61.23	0.00	3.02	71.3	–	1.98
Cas A	350.85	58.81	0.00	2.70	71.4	–	1.77
1ES 2344+514	356.77	51.70	5.84	3.95	76.6	0.29	2.20
3C66A	35.67	43.04	0.00	2.51	82.1	–	1.31
H 1426+428	217.14	42.67	0.00	2.58	83.1	–	1.30
BL Lac	330.68	42.28	6.06	3.25	83.1	0.37	1.77
NGC 1275	49.95	41.51	0.00	3.32	83.8	–	1.32
Cyg OB2	308.08	41.51	0.00	3.21	83.8	–	1.27
Cyg X-3	308.11	40.96	6.41	3.95	85.5	0.29	2.09
Cyg A	299.87	40.73	1.36	1.35	85.5	0.21	2.43
Mrk 501	253.47	39.76	11.43	3.95	88.3	0.12	2.76
Mrk 421	166.11	38.21	2.31	1.75	89.7	0.34	1.85
4C 38.41	248.81	38.13	0.00	2.53	89.7	–	1.29
MGRO J2019+37	305.22	36.83	4.53	3.95	92.1	0.43	1.62
Cyg X-1	299.59	35.20	4.82	3.95	93.7	0.34	1.76
3C 123.0	69.27	29.67	12.54	3.95	102.9	0.081	2.54
W Comae	185.38	28.23	3.43	1.85	103.8	0.23	1.89
IC443	94.18	22.53	6.26	3.00	111.5	0.31	1.44
Crab Nebula	83.63	22.01	0.00	2.73	111.5	–	0.91
1ES 0229+200	38.20	20.29	12.58	3.95	114.5	0.16	1.90
Geminga	98.48	17.77	3.06	3.95	123.1	0.47	1.05
PKS 0235+164	39.66	16.62	10.45	3.85	125.6	0.23	1.55
3C 454.3	343.49	16.15	9.81	2.91	125.6	0.22	1.55
PKS 0528+134	82.73	13.53	0.00	2.52	128.9	–	0.84
M87	187.71	12.39	0.00	2.66	129.9	–	0.82
PKS 1502+106	226.10	10.49	5.17	2.35	132.7	0.28	1.30
MGRO J1908+06	286.98	6.27	0.00	3.05	145.0	–	0.66
HESS J0632+057	98.25	5.80	12.98	3.15	148.0	0.19	1.24
SS433	287.96	4.98	0.00	2.53	151.0	–	0.70
3C 273	187.28	2.05	0.73	3.95	155.4	–	0.63

ICECUBE PRELIMINARY

Upper limits in 10^{-12} $TeV^{-1}cm^{-2}s^{-1}$

← Most significant source in northern sky

Complete source list results – southern sky

2

ICECUBE PRELIMINARY

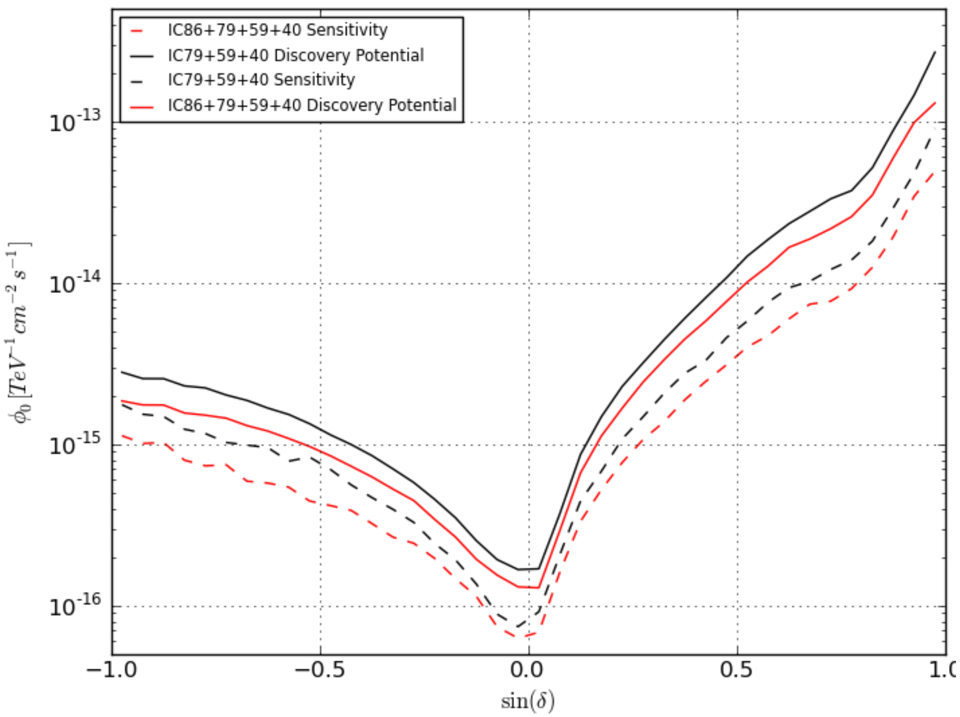
Source	RA (°)	Dec (°)	$\hat{n}_s$	$\hat{\gamma}$	B_{2°	p-value	$\Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu}$
3C279	194.05	-5.79	0.00	2.50	134.3	–	1.61
QSO 2022-077	306.42	-7.64	0.00	2.50	136.9	–	1.63
PKS 1406-076	212.24	-7.87	7.50	3.95	136.9	0.12	3.24
QSO 1730-130	263.26	-13.08	0.00	2.51	148.5	–	3.48
Sgr A*	266.42	-29.01	2.71	2.85	145.8	0.32	12.33
PKS 1622-297	246.53	-29.86	1.28	3.30	145.8	0.47	10.64
PKS 2155-304	329.72	-30.23	0.00	2.54	147.1	–	9.02
PKS 1454-354	224.36	-35.65	0.00	3.34	141.7	–	10.81
Cen A	201.37	-43.02	0.00	3.13	141.6	–	12.99
PKS 0537-441	84.71	-44.09	0.00	2.52	140.8	–	13.88

Most significant source in southern sky

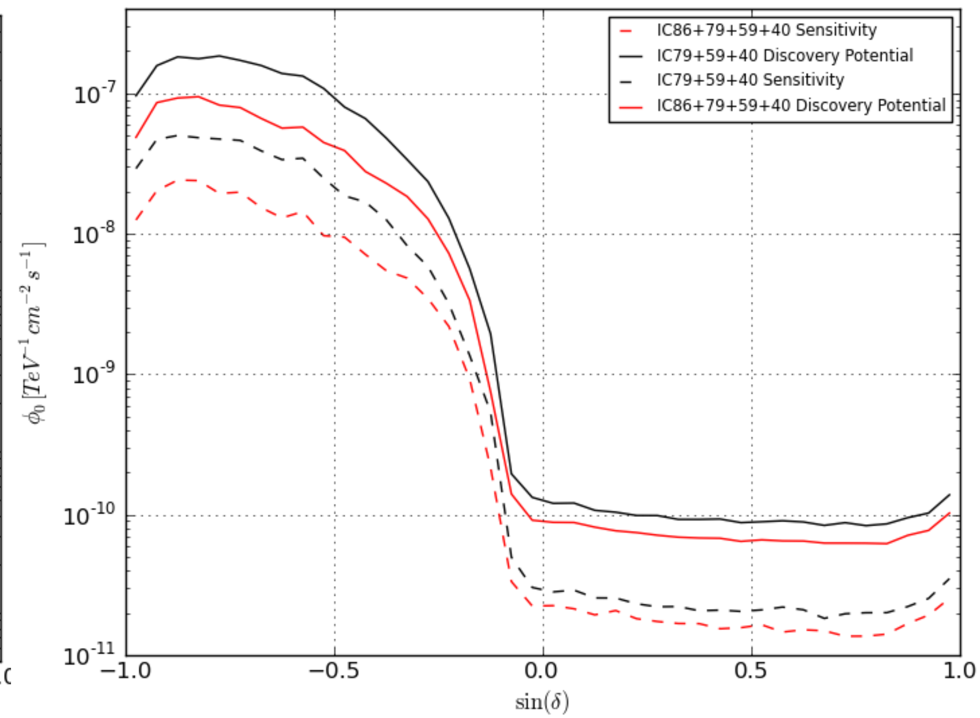
Upper limits in 10^{-12} $TeV^{-1}cm^{-2}s^{-1}$

Discovery Potentials for 4 Years of IceCube

E^{-1} injection spectrum



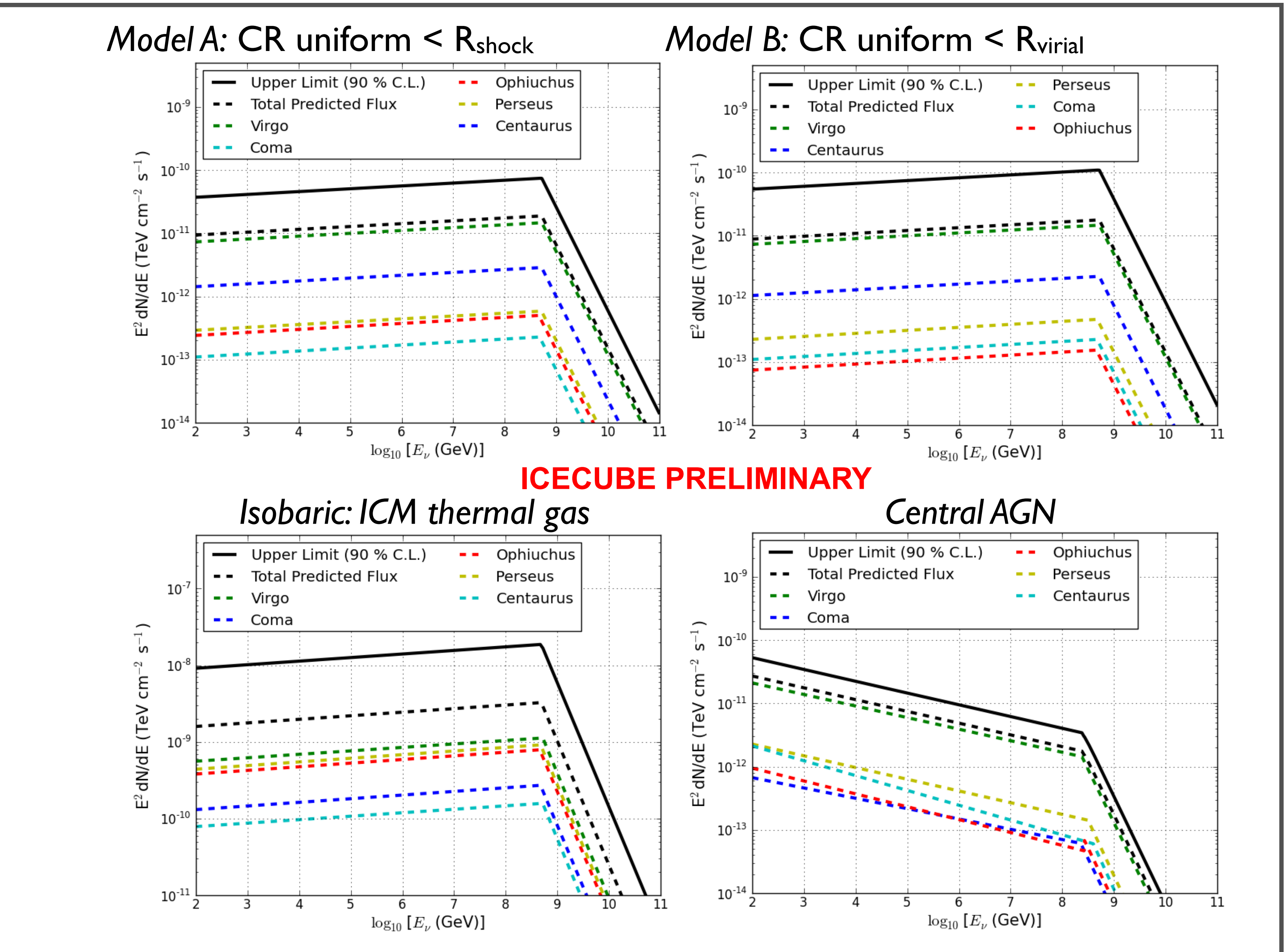
E^{-3} injection spectrum



Catalogs for stacking searches

- *6 sources with SNR associations, reported by Milagro:* Motivated by a posteriori study of IC40 Milagro 17 Stacking. IC 40 hence excluded to avoid bias. Described by Halzen, Kappes and O'Murchada.
- *Starburst Galaxies:* Catalog of 127 sources described by Becker, Biermann, Dreyer, Kneiske
- *Galaxy Clusters:* Five nearby clusters with flux models varying according to the model of CR acceleration as described by Murase, Inoue, Nagataki.
- *Molecular Cloud Associated SuperNova Remnants:* 4 Sources as per the Catalog defined by T. Montaruli, J. Becker and F Schuppan
- *Black Hole Candidate Stacking:* 233 Candidates within the GZK radius, as per catalog defined by L. Caramete and J Biermann

Galaxy Cluster: Upper limits



Upper limits calculated for the 4 different models based on the CR distribution in the Galaxies.

Improving the analysis via better angular resolution

- New event reconstruction techniques use detailed information on photon propagation in the glacial ice
- Results in improved angular resolution at all energies