IceCube Point Source Searches with 6 years of data

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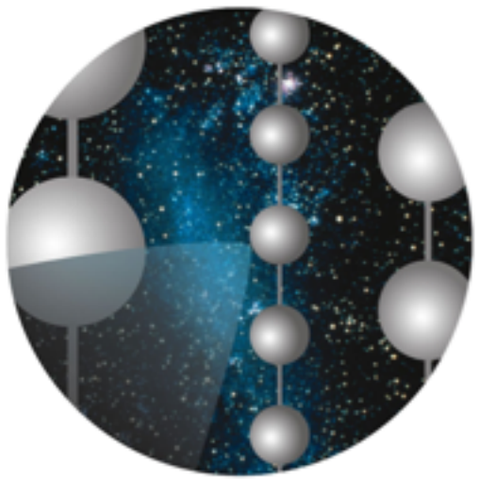
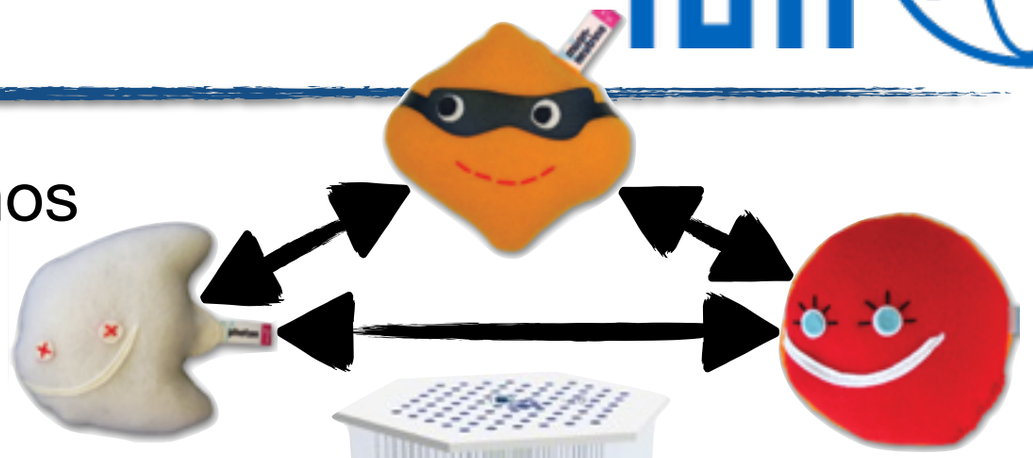
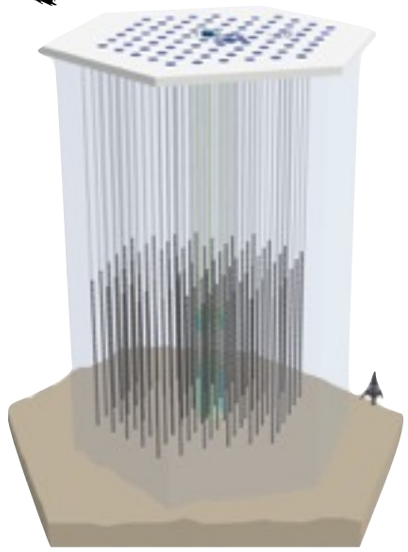


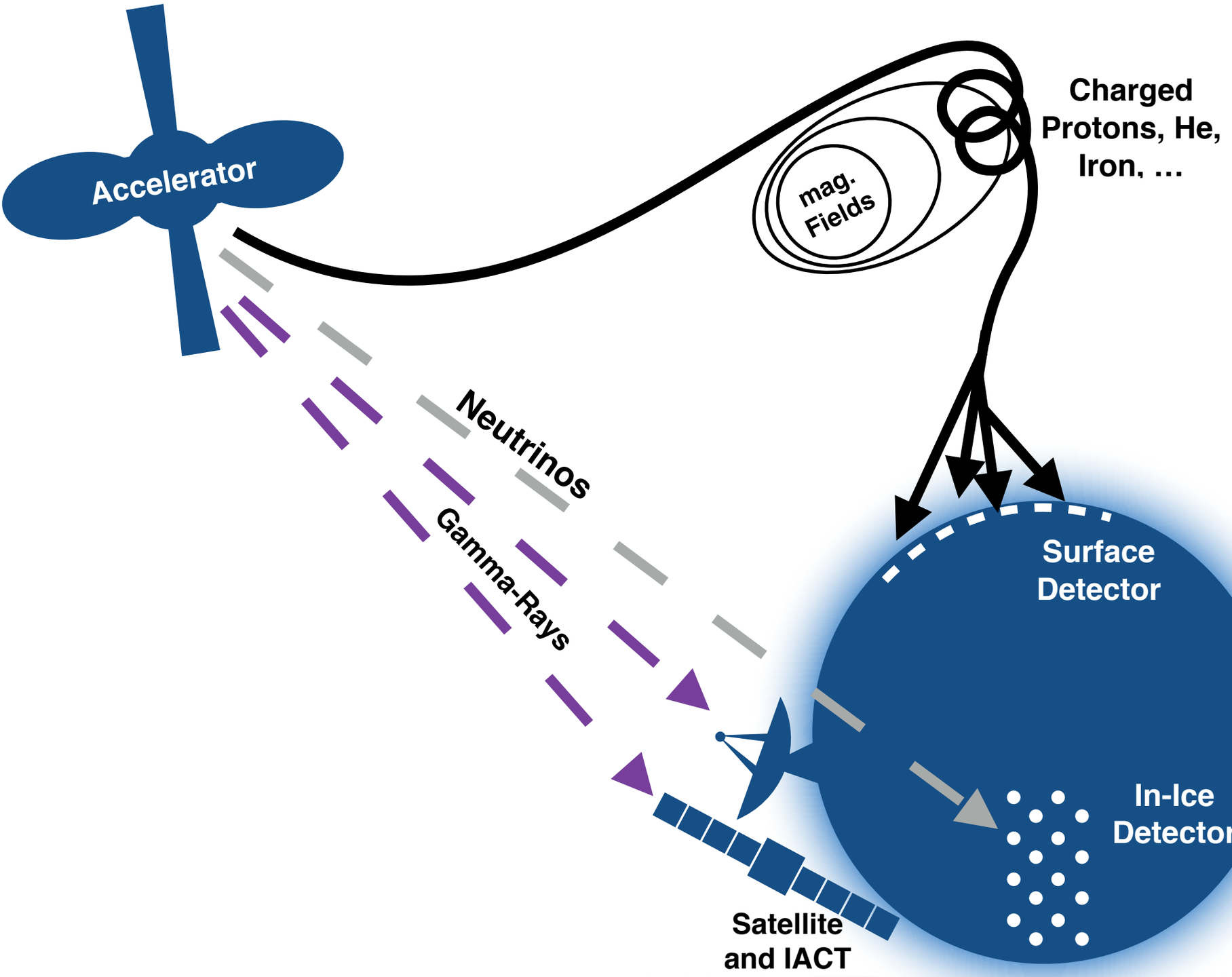
Contents

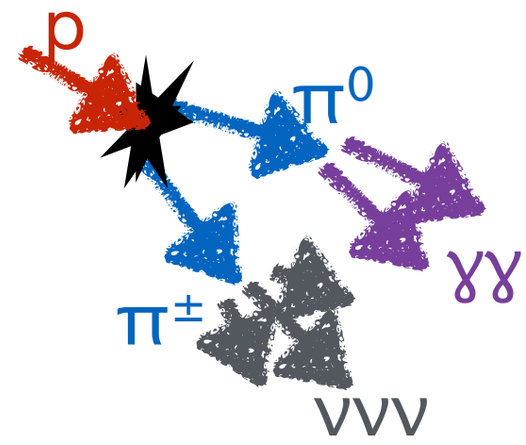


- Multi-Messenger Astronomy using neutrinos
- IceCube Neutrino Observatory
- Point Source Searches - New 6-year results
  - All-Sky Searches
  - Gamma-Ray Sources
- Outlook



Multi Messenger Astronomy

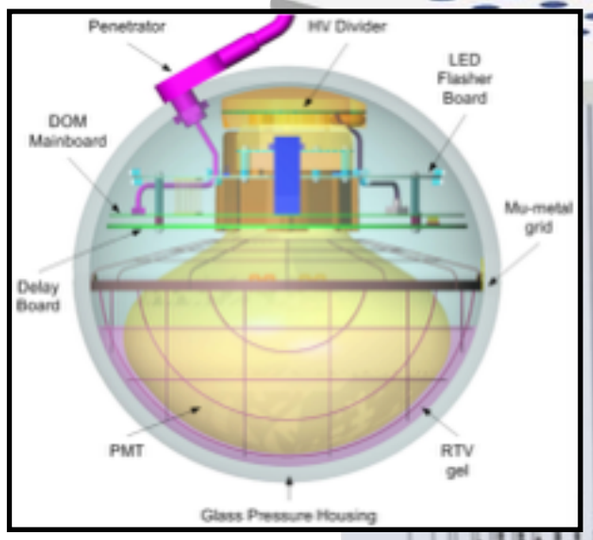




- Cosmic Rays
  - Deflected in mag. Fields
- Gamma Rays
  - Limited Range
  - Hadronic or leptonic origin
- Neutrinos
  - Hadronic origin
  - Large atm. backgrounds

The IceCube Neutrino Observatory

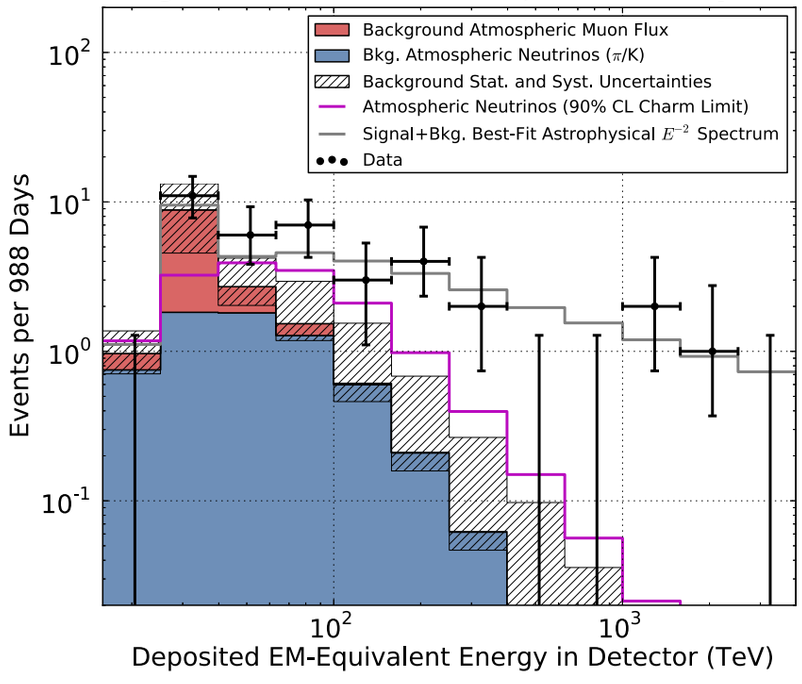
- **5160** Digital Optical Modules (DOMs)
  - 60 each on **86** strings
  - 1km^3 in depth from 1.5 to 2.5 km
  - Full detector operational since 2011, partial detectors running before (ICxx)
- Relativistic charged particles emit Cherenkov light along path + stochastic losses
- Use light pattern detected to reconstruct *direction* and *deposited energy* of particles
- Surface Array (**IceTop**) can be used as active veto for very down-going events

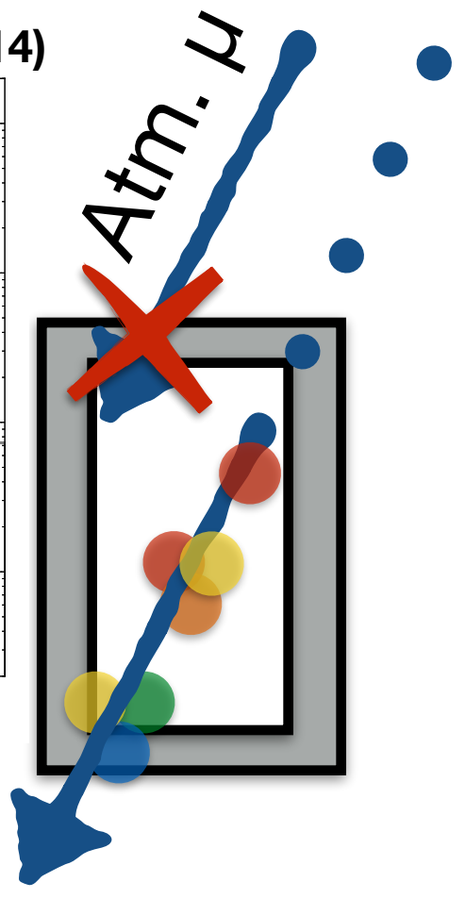


Astrophysical Neutrinos

- Events starting in IceCube
  - Use outer layers of IceCube as veto against incoming μ
  - Small sample with high purity
  - Dominated by shower-type events
- Origin unknown
  - large uncertainties in ang. direction
  - low statistics
- Use track-like events for point source studies

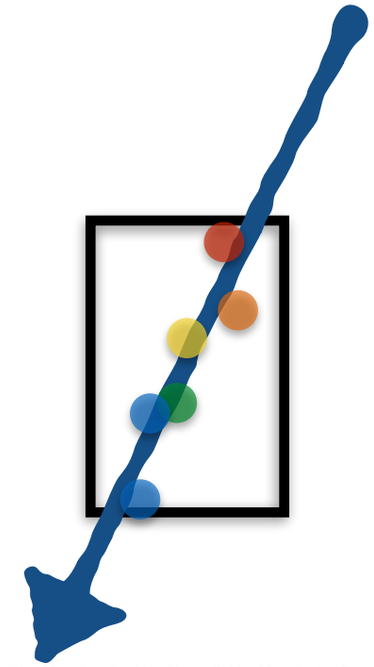
Phys. Rev. Lett. 113, 101101 (2014)



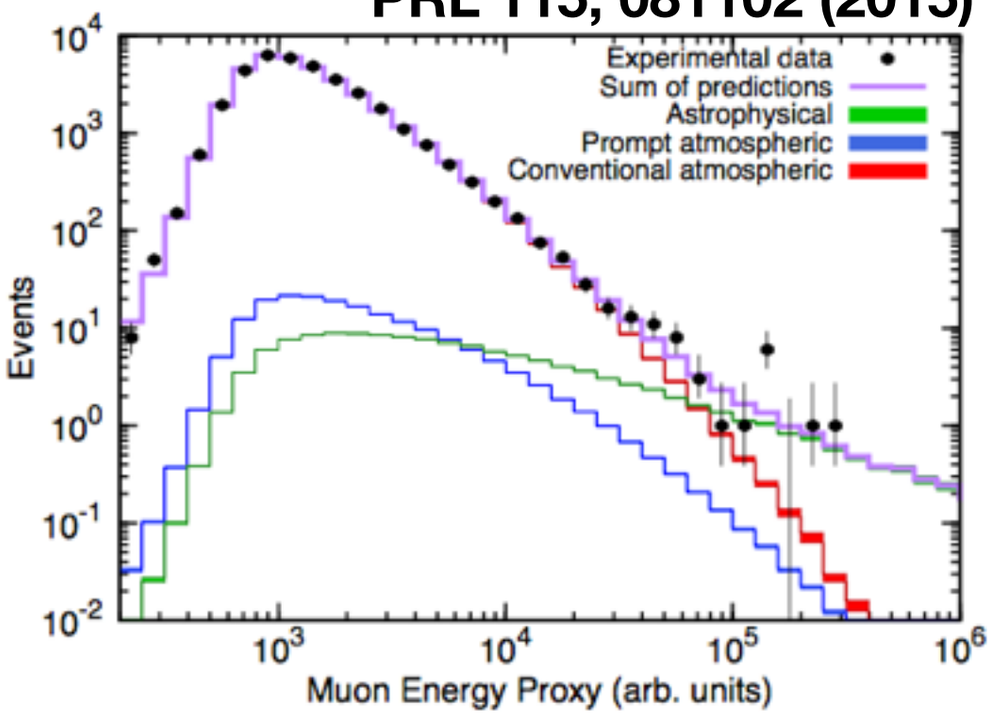


Through-going μ searches

- Muons travel long distance before being detected
  - Collection volume much larger than instrumented one
  - Track-signature of muons gives long lever-arm
- Astrophysical ν_μ observed in north by IceCube
- Background of atmospheric μ+ν
  - point-signal clusters on small angular scales
  - large off-source regions

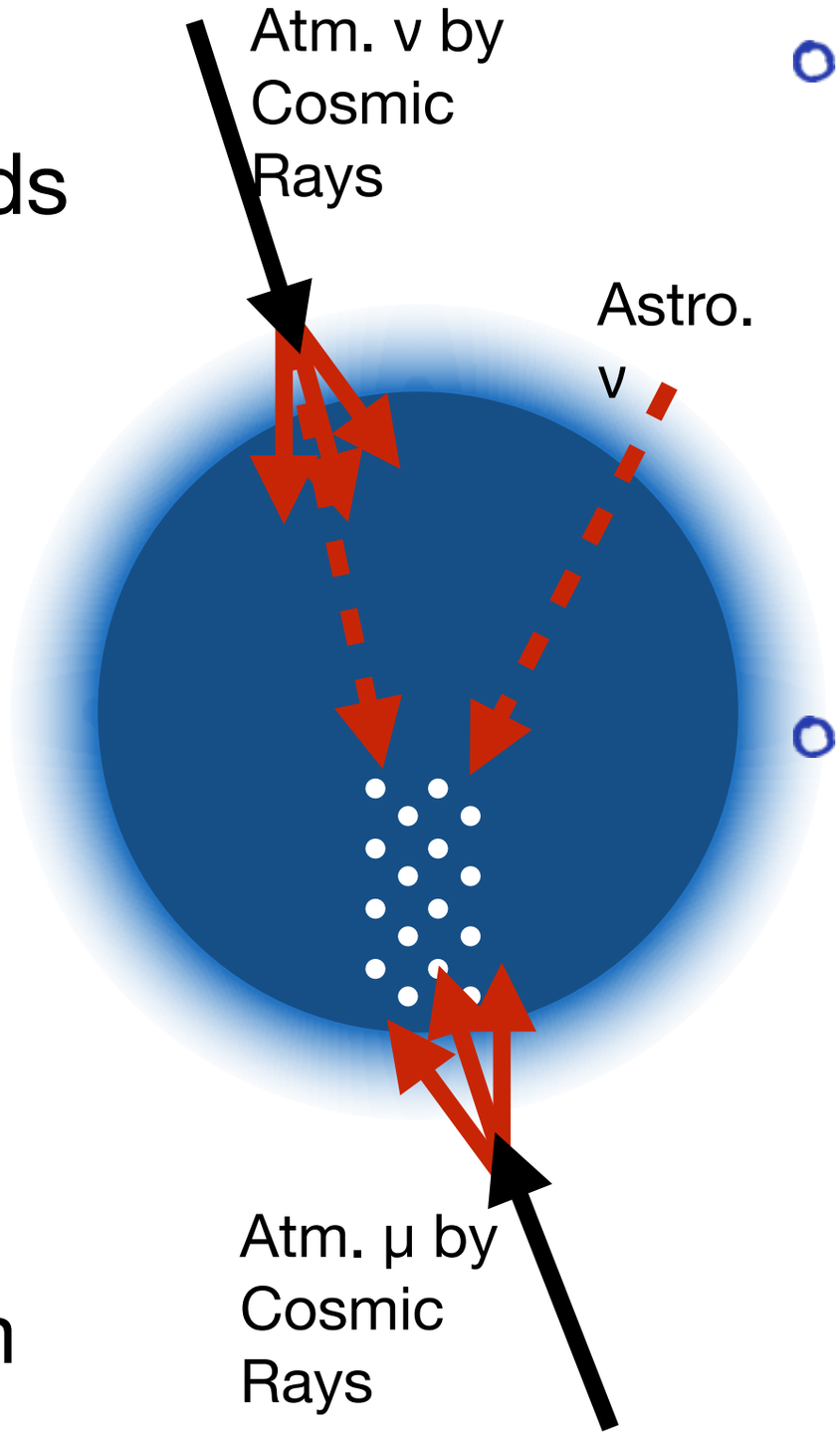


PRL 115, 081102 (2015)



Point Source Search: Signal(s) and Background

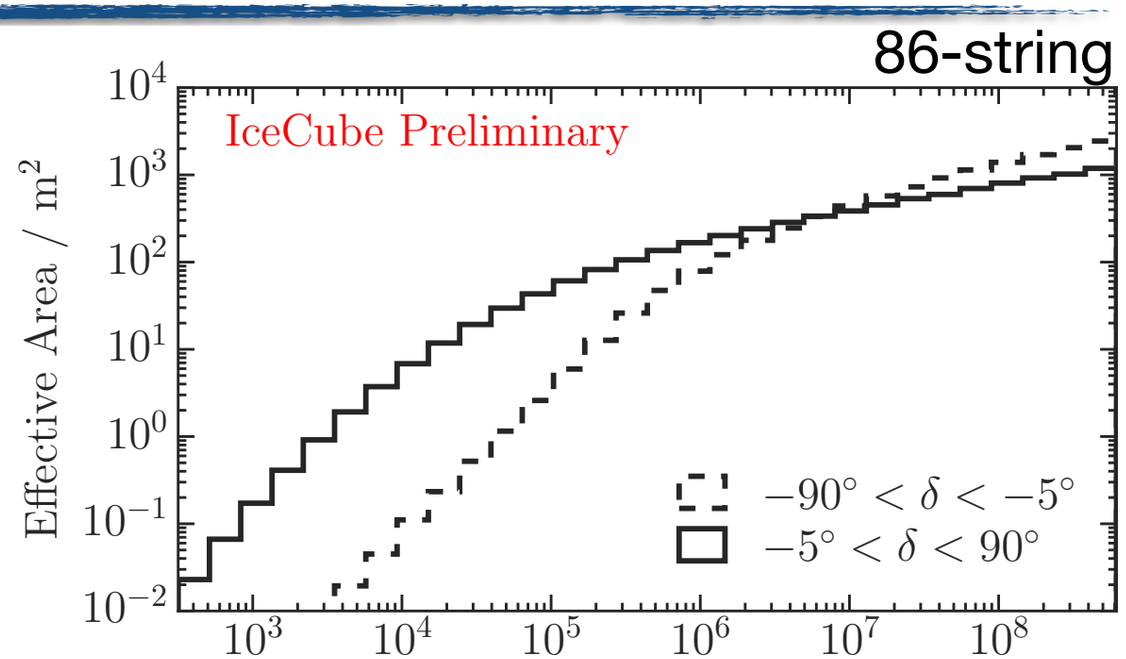
- Overwhelming atm. backgrounds
  - Atmospheric ν produced in air showers
  - Atm. μ enter IceCube from above
- Expected signal follows hard energy spectrum

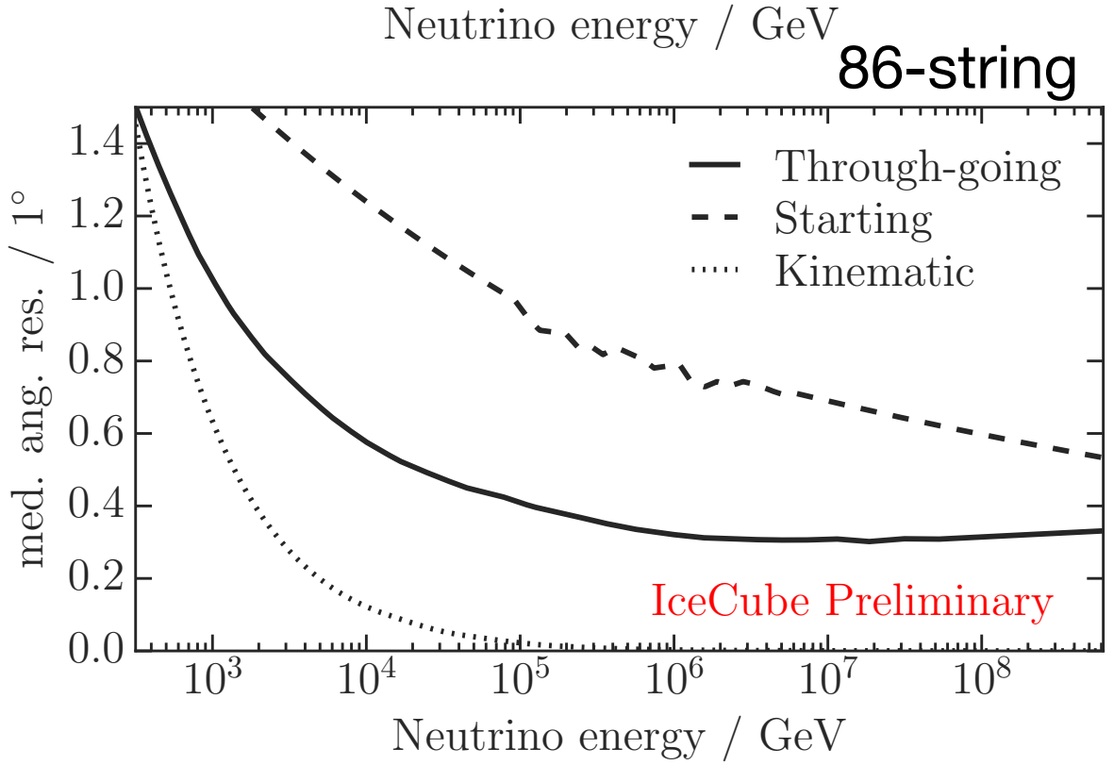


- North (TeV - PeV)
  - Clear neutrino signal
  - Absorption at highest energies
- South (PeV - EeV)
  - Bundles of muons look like high-energy single muon
  - Starting events help to identify astro. ν

Event Sample of Point Source Searches

- Multivariate event selection to select most promising signal
  - Muons induced by high-energy neutrinos
  - Best reconstruction (long-lever arm)
- North: ~70k ν_μ's per year
- South: ~35k μ's per year
- Total: 6 years = **600,000+** events
  - First 2 years in partial configuration (IC40 & IC59)
  - 4 years with full detector (IC79 + 3xIC86)



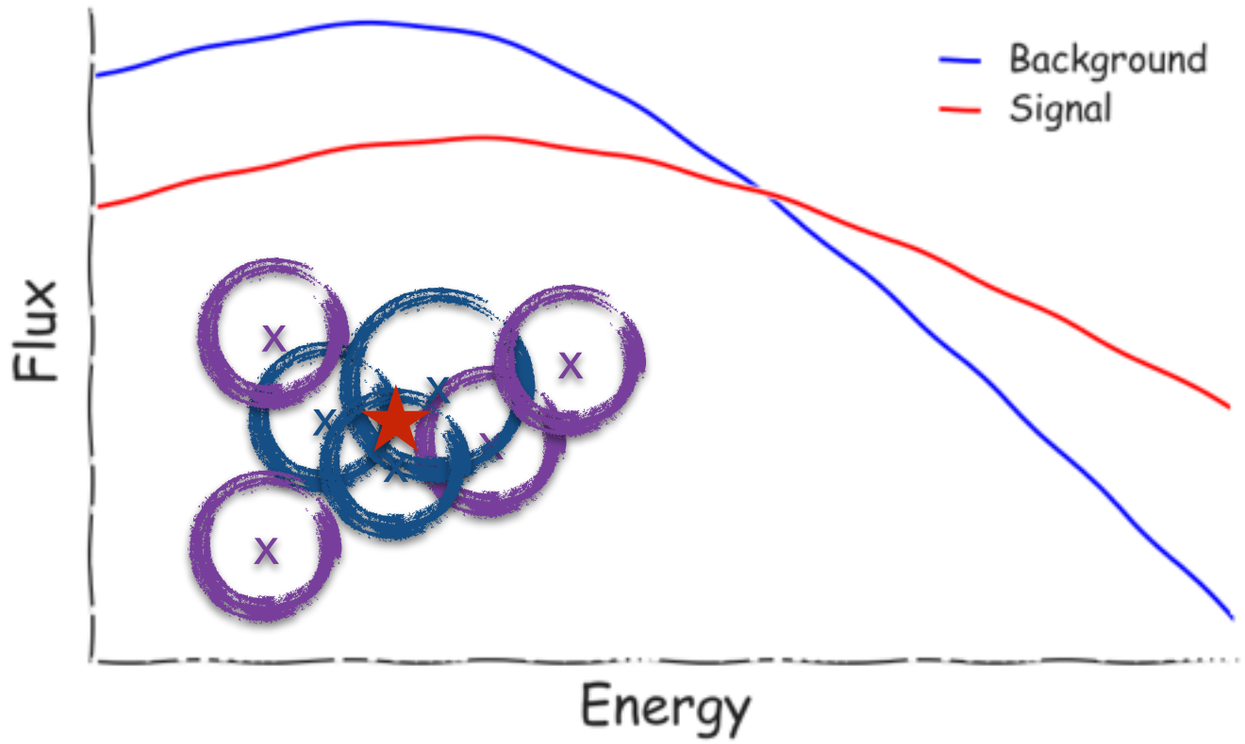


Point Source Searches in IceCube

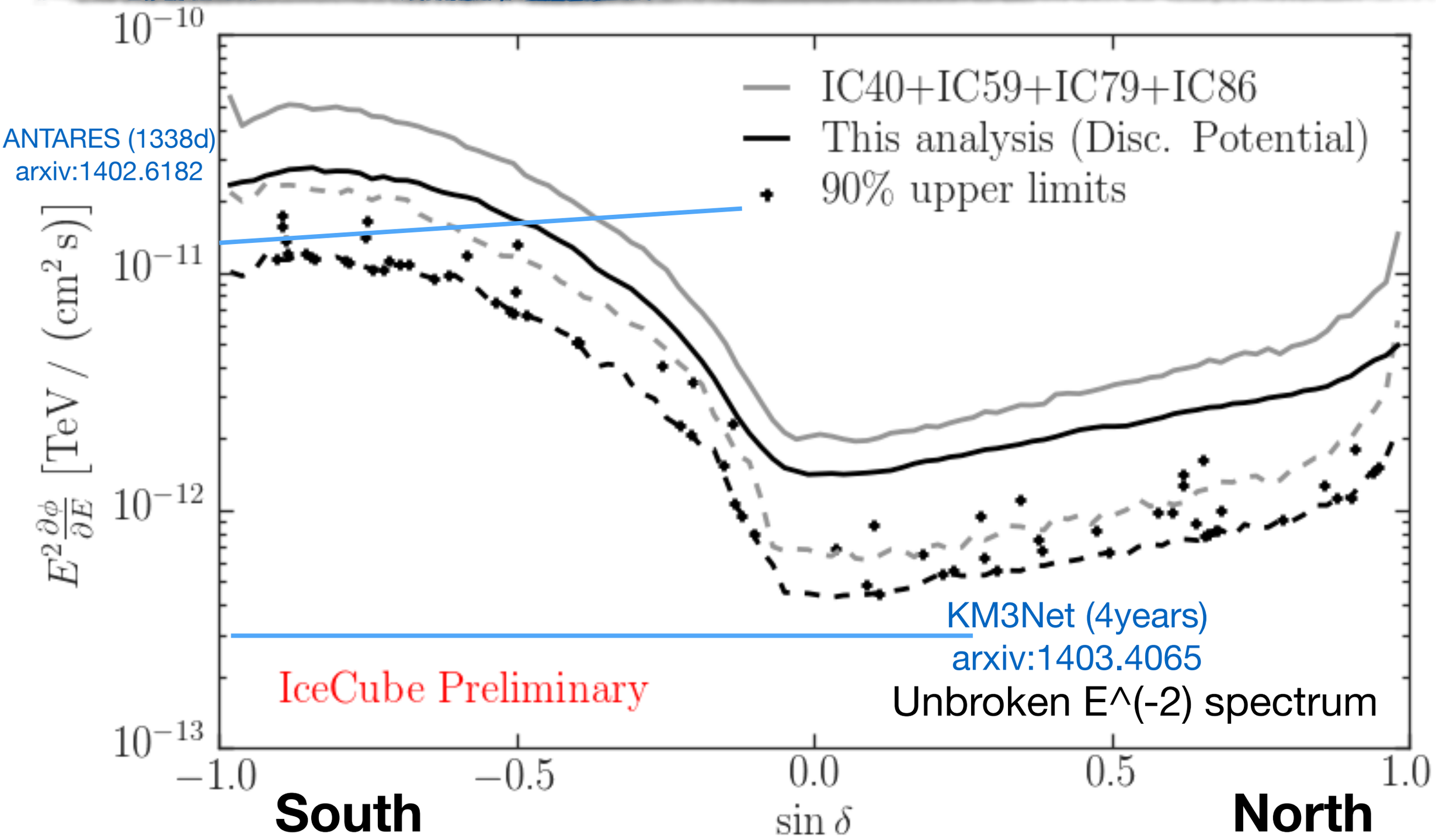
$$\mathcal{L} = \prod_i \left(\frac{n_s}{N} \mathcal{S}\left(\Delta\Psi_i, \sigma_i, E_i; \gamma\right) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}\left(\delta_i, E_i\right) \right)$$

$$\mathcal{S}\left(\Delta\Psi_i, E_i; \gamma\right) \propto \mathrm{e}^{-\frac{\Delta\Psi^2}{2\sigma_i^2}} \, \mathcal{P}_E^{\mathcal{S}}\left(E_i|\delta_i;\gamma\right) \qquad \mathcal{B} \propto \mathcal{P}_{\mathbf{x}}\left(\delta_i\right) \mathcal{P}_E^{\mathcal{B}}\left(E_i|\delta_i\right)$$

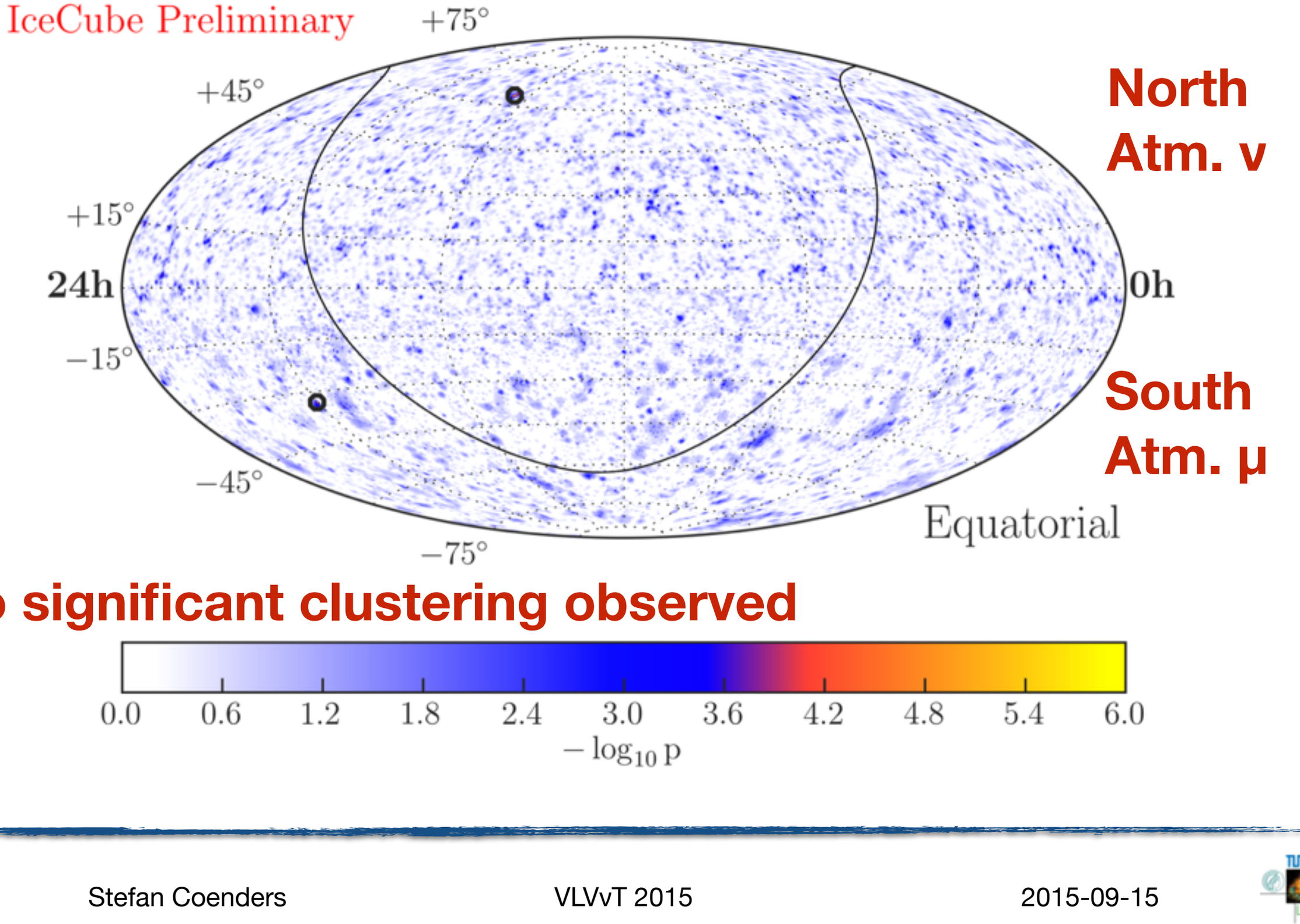
- PSF modelled Gaussian on sphere with event-wise uncertainty
- Background: declination (δ) -dependent
- Energy information: P(E) of signal harder than atm. background
- Find maximum LLH over the entire sky
- Previous analyses: 4 year (ApJ 796, 109)
  3 year (ApJ 779 132)



Sensitivity & Discovery Potential



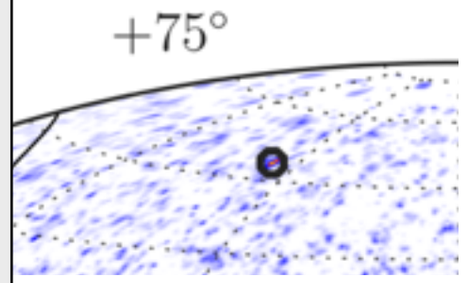
Results of 6 year analysis

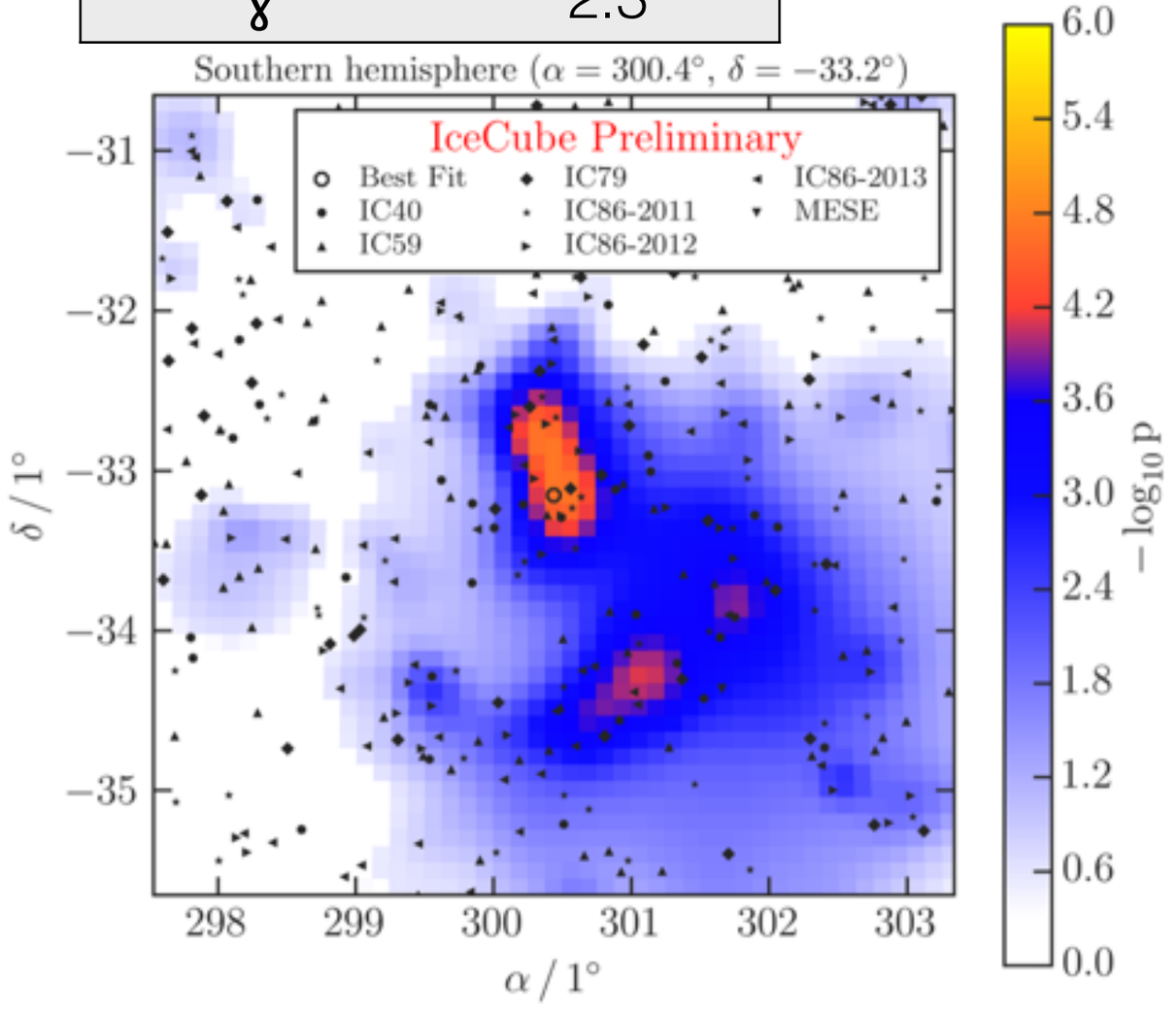


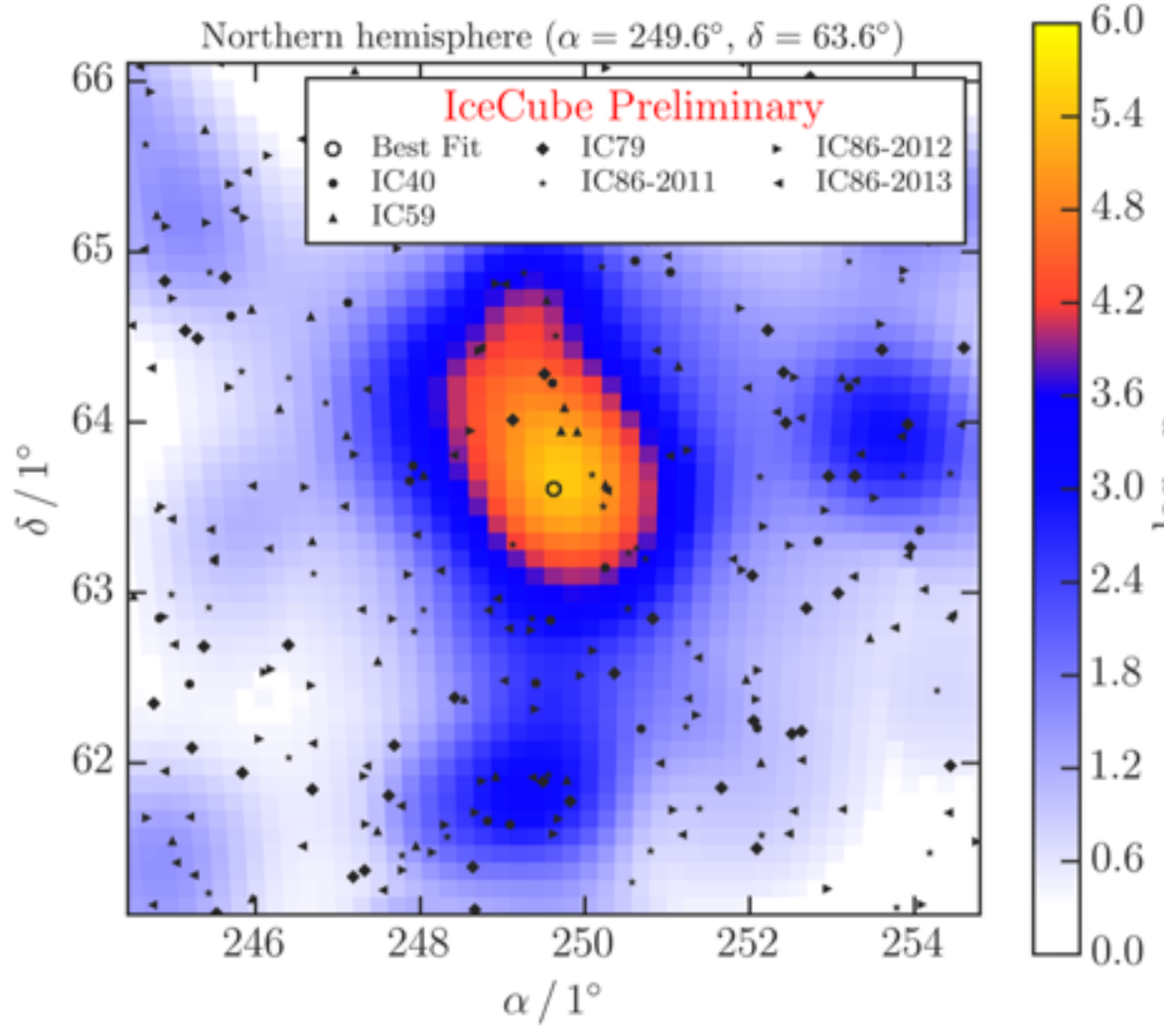
No significant clustering observed

Results of 6 year analysis - Hottest Spots

South	
$-\log_{10}(p)$	4.74
Post-Trial	87%
n_s	19.4
γ	2.3



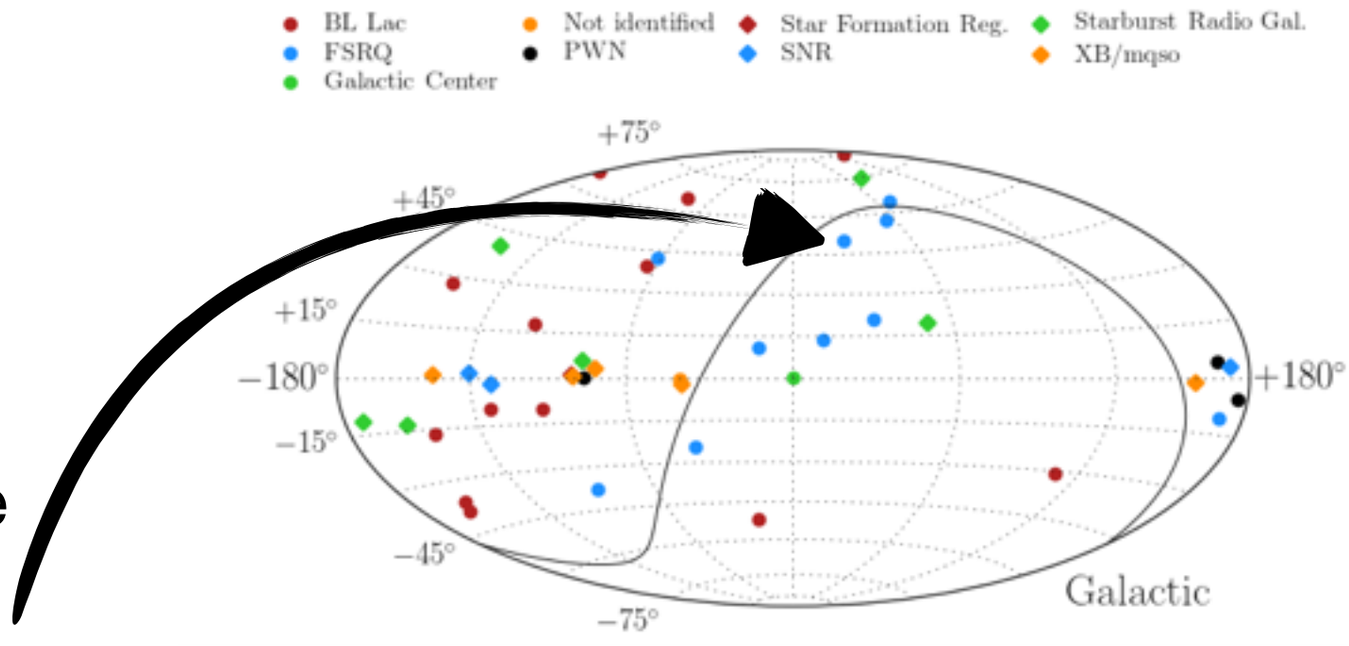




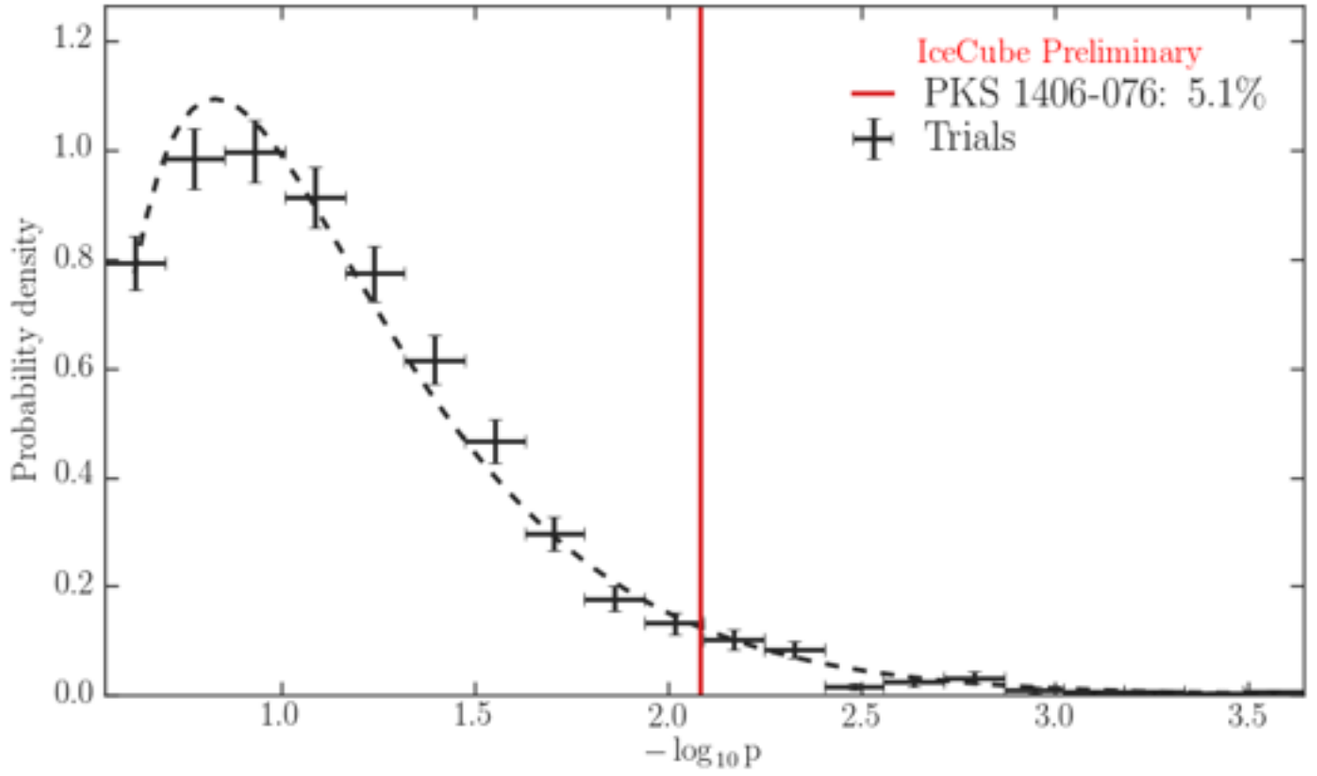
North	
$-\log_{10}(p)$	5.51
Post-Trial	35%
n_s	28.4
γ	2.1

A-Priori Source lists

- Source list of possible neutrino emitters
  - 44 sources of various type
  - Mostly northern hemisphere

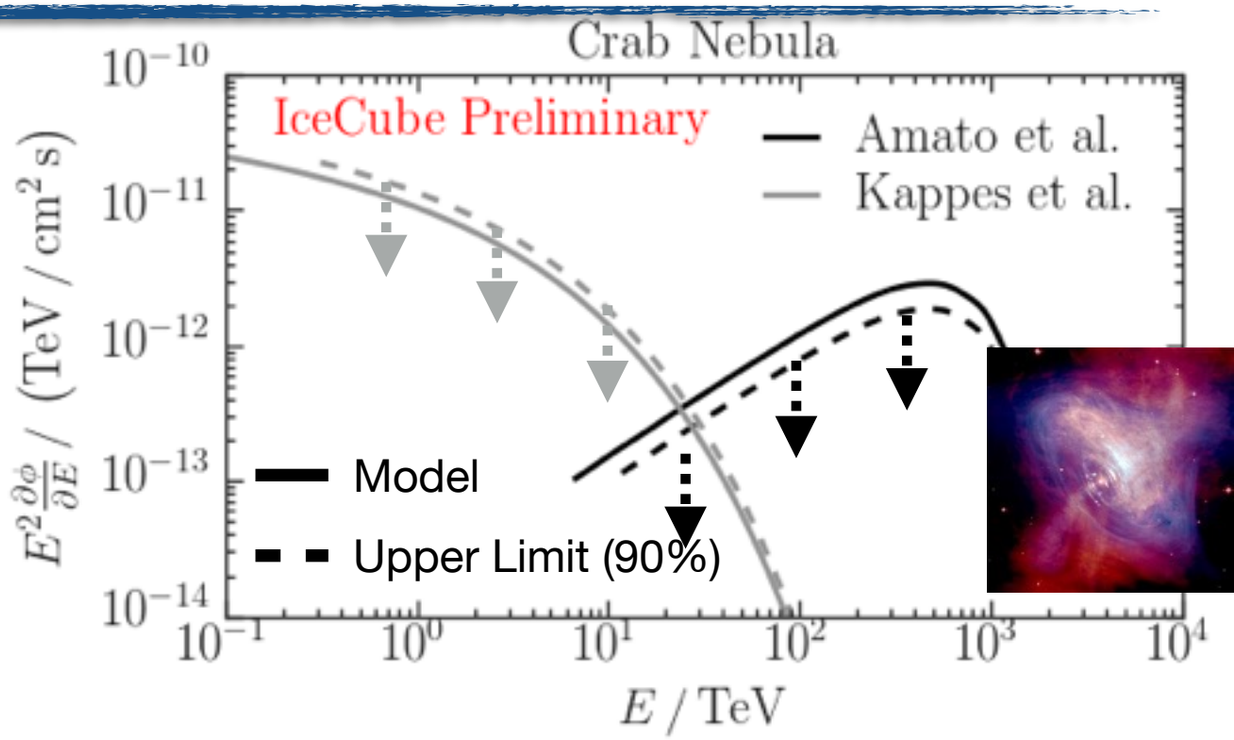


- Best Source: PKS1406-076
  - Post Trial Significance: 5.1%
  - n_Src = 12.9, ɣ = 2.8
- Complete source list at ApJ 796, 109 (2014)

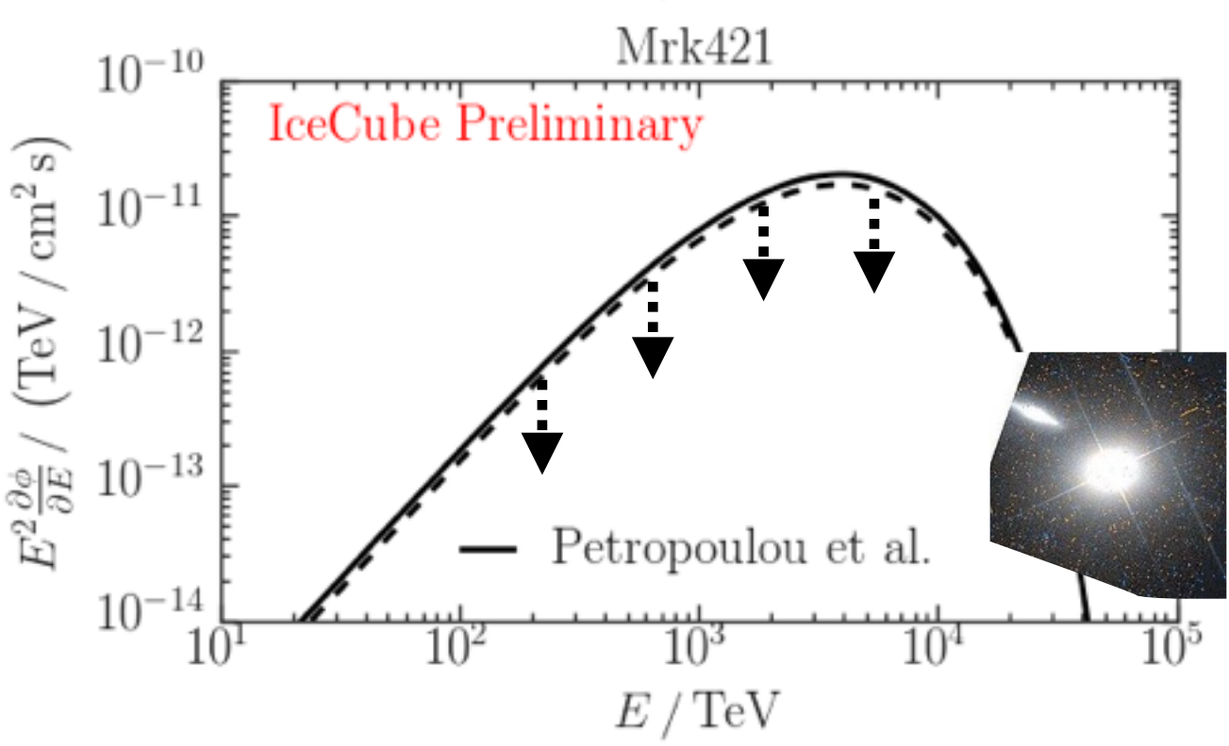


Gamma-Ray sources: Model Predictions

- Using ɣ-ray observations
  - ɣ-rays and ν's connected in π-decays
  - Use SED of gamma-rays to estimate neutrino flux

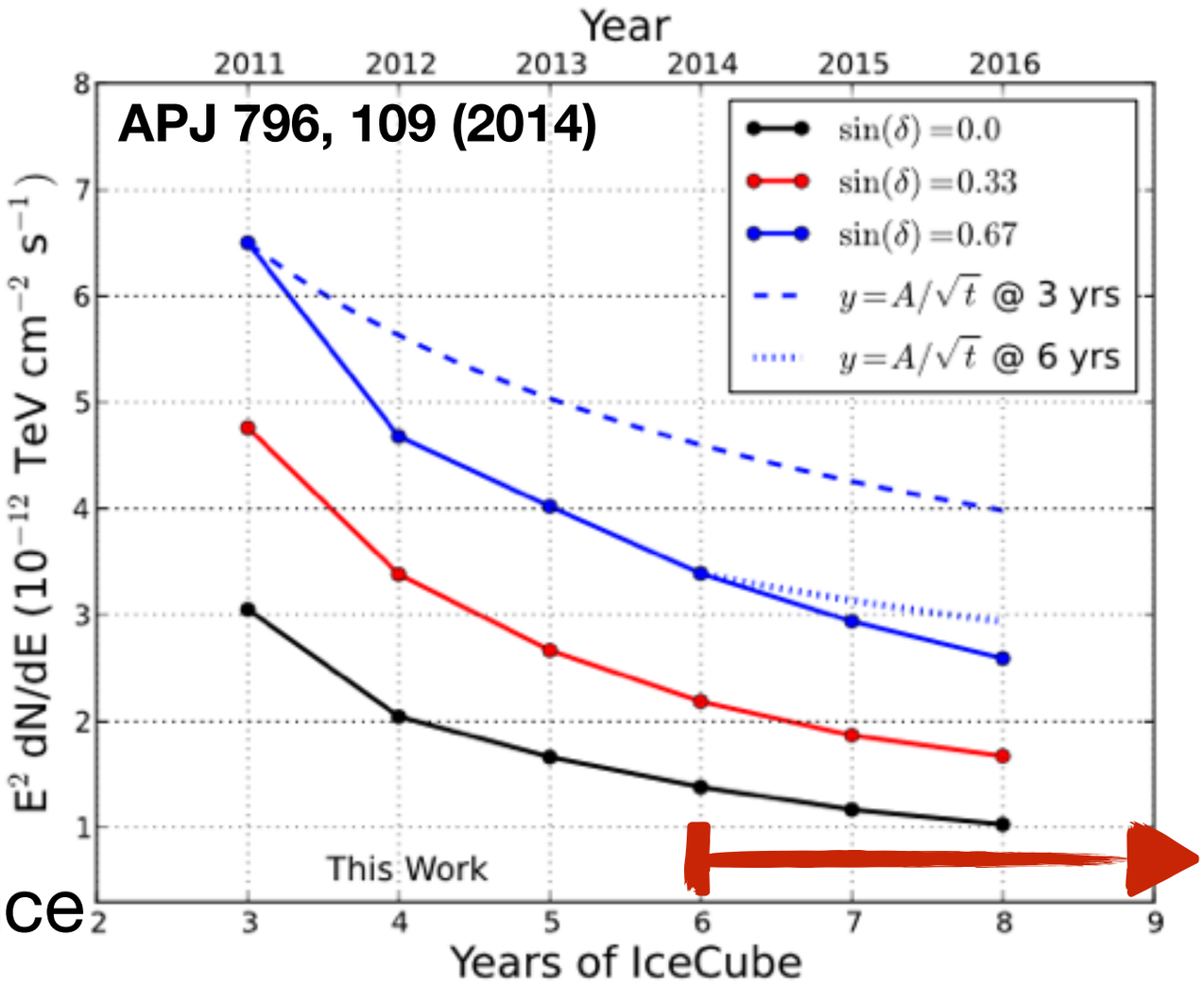


- Crab & Mrk 421
  - IceCube observes small over-fluctuations at source locations
  - 90% upper limits below or close to model predictions



Outlook on future performance

- Discovery Potential grows faster than square-root
  - 2 additional years: Disc. Potential reaches 10^{-12} TeV / cm^2 s
  - Stronger gain for South: Starting events
- Gen-2 development
  - Better pointing and geom. Area
  - Additional gain in performance



Conclusion

- No steady clustering observed with 6 years of data
  - Scan of full sky - Large trial factor reduces p-value from 3×10^{-6} to 35%
  - Source List: Best fit for PKS 1406-076, consistent with background at 5.1% after accounting for trials of 10 sources in the south
- 2014-15 data in preparation, another year of detector livetime
  - >700k events
  - PeV neutrino track event
  - Starting events use full detector only - livetime increase from 988 to ~1700 days
- Current best limits on point like sources in *northern* hemisphere set by IceCube
  - Strong constraints on model prediction: Crab Nebula & Mrk 421
  - South: Best limits above PeV energies (no cutoff)

The IceCube Collaboration

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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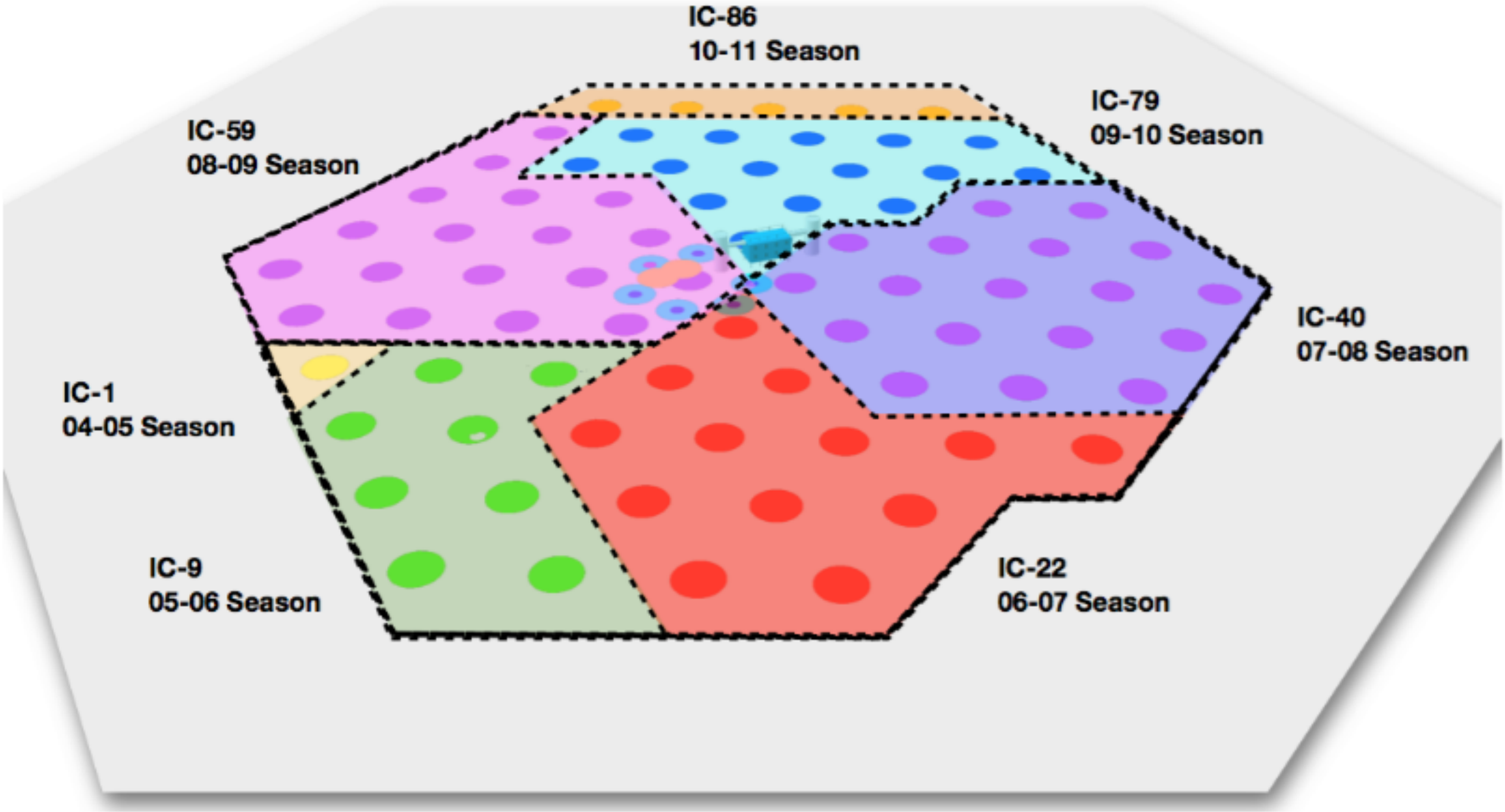
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

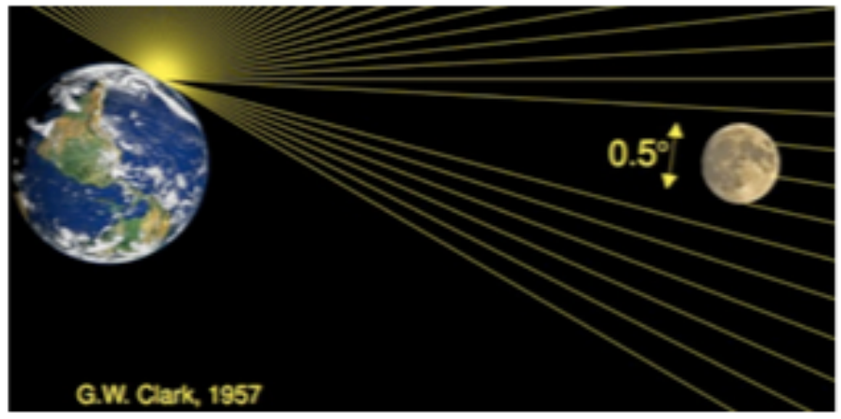
Thank You!

IceCube Partial Configuration

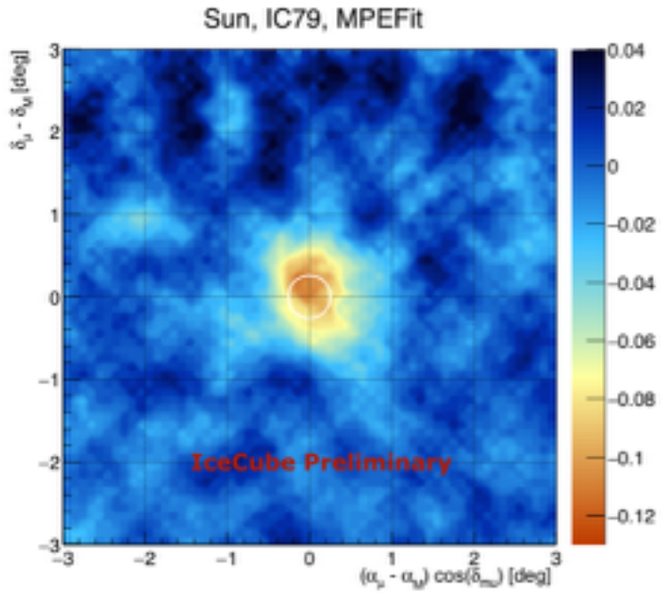


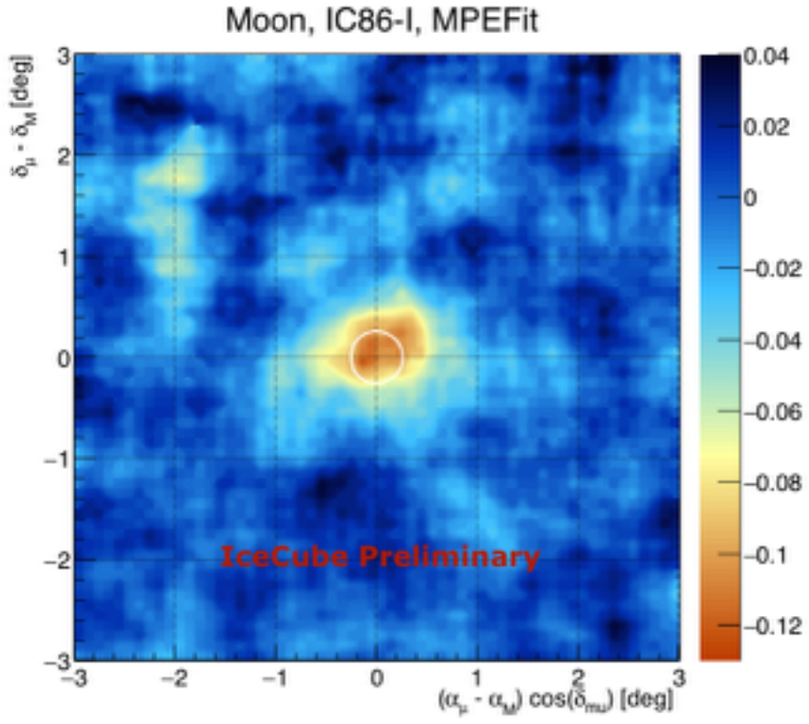
IceCube Angular Resolution

- Use the Moon (Sun) as negative point source
  - Cosmic rays blocked by moon
  - Lack of atmospheric μ



- 0.8° width of source
- very good MC agreement for muon energies





Source List Results

Table 1: Source list in Southern hemisphere

Type	Source	α	δ	p-Value	n_S	γ	B_{1°	Φ
BL Lac	PKS 2005-489	302.37	-48.82	0.13	0.9	1.2	33.8	14.22
BL Lac	PKS 0426-380	67.17	-37.93	—	0.0	—	34.9	—
BL Lac	PKS 0548-322	87.67	-32.27	—	0.0	—	38.8	—
BL Lac	H 2356-309	359.78	-30.63	—	0.0	—	39.3	—
BL Lac	1ES 1101-232	165.91	-23.49	—	0.0	—	40.3	—
BL Lac	1ES 0347-121	57.35	-11.99	—	0.0	—	42.9	—
FSRQ	PKS 0454-234	74.27	-23.43	—	0.0	—	40.3	—
FSRQ	PKS 0727-11	112.58	-11.70	0.037†	6.6	3.9	42.9	3.46
NI	HESS J1507-622	226.72	-62.34	0.24	2.2	2.5	30.0	12.14
NI	HESS J1503-582	226.46	-58.74	—	0.0	—	32.3	—
NI	HESS J1741-302	265.25	-30.20	0.18	2.7	2.3	39.7	8.32
NI	HESS J1834-087	278.69	-8.76	0.21	2.7	3.1	39.7	1.55
PWN	HESS J1356-645	209.00	-64.50	—	0.0	—	28.8	—
PWN	PSR B1259-63	197.55	-63.52	0.059	4.7	2.3	29.3	17.40
PWN	HESS J1303-631	195.74	-63.20	0.10	4.1	2.1	29.1	15.73
PWN	MSH 15-52	228.53	-59.16	—	0.0	—	31.6	—
PWN	HESS J1023-575	155.83	-57.76	—	0.0	—	33.5	—
PWN	HESS J1616-508	243.78	-51.40	—	0.0	—	33.6	—
PWN	HESS J1632-478	248.04	-47.82	—	0.0	—	33.5	—
PWN	Vela X	128.75	-45.60	0.26	1.6	2.5	33.8	11.19
PWN	HESS J1837-069	279.41	-6.95	—	0.0	—	37.5	—
SNR	RCW 86	220.68	-62.48	0.18	2.6	2.2	29.8	13.62
SNR	RX J0852.0-4622	133.00	-46.37	—	0.0	—	33.9	—
SNR	RX J1713.7-3946	258.25	-39.75	—	0.0	—	34.2	—
SNR	W28	270.43	-23.34	—	0.0	—	40.2	—
XB/mqso	Cir X-1	230.17	-57.17	—	0.0	—	33.3	—
XB/mqso	GX 339-4	255.70	-48.79	0.072	5.3	2.0	33.9	16.45
XB/mqso	LS 5039	276.56	-14.83	0.075	7.2	3.1	42.4	4.08
cluster	HESS J1614-518	63.58	-51.82	—	0.0	—	33.3	—

† Most significant source in this list. Post trial correction yields a p-Value of 64%.

Table 2: Traditional Source List

Type	Source	α	δ	p-Value	n_S	γ	B	Φ
BL Lac	PKS 0537-441	84.71	-44.09	—	0.0	—	33.8	—
BL Lac	PKS 2155-304	329.72	-30.23	—	0.0	—	39.7	—
BL Lac	PKS 0235+164	39.66	16.62	0.38	7.0	3.1	43.5	0.63
BL Lac	1ES 0229+200	38.20	20.29	0.10	16.4	3.2	39.8	1.11
BL Lac	W Comae	185.38	28.23	0.37	0.9	1.3	36.2	0.82
BL Lac	Mrk 421	166.11	38.21	0.15	5.5	2.0	31.7	1.27
BL Lac	Mrk 501	253.47	39.76	0.37	5.1	3.7	31.6	0.88
BL Lac	BL Lac	330.68	42.28	—	0.0	—	29.9	—
BL Lac	H 1426+428	217.14	42.67	—	-0.0	—	30.2	—
BL Lac	3C66A	35.67	43.04	0.34	1.9	2.1	30.1	1.00
BL Lac	1ES 2344+514	356.77	51.70	—	0.0	—	27.7	—
BL Lac	1ES 1959+650	300.00	65.15	0.13	7.0	2.8	26.0	1.81
BL Lac	S5 0716+71	110.47	71.34	—	0.0	—	23.0	—
FSRQ	PKS 1454-354	224.36	-35.65	0.13	3.4	2.2	36.5	11.85
FSRQ	PKS 1622-297	246.53	-29.86	0.017	8.1	2.3	39.9	13.23
FSRQ	QSO 1730-130	263.26	-13.08	—	0.0	—	41.9	—
FSRQ	PKS 1406-076	212.24	-7.87	0.0083‡	12.9	2.8	39.4	2.32
FSRQ	QSO 2022-077	306.42	-7.64	—	0.0	—	39.4	—
FSRQ	3C279	194.05	-5.79	—	0.0	—	40.0	—
FSRQ	3C 273	187.28	2.05	0.21	12.1	3.2	53.9	0.69
FSRQ	PKS 1502+106	226.10	10.49	0.35	4.7	2.6	45.8	0.65
FSRQ	PKS 0528+134	82.73	13.53	0.45	2.7	3.8	44.4	0.56
FSRQ	3C 454.3	343.49	16.15	0.13	3.6	2.0	43.9	0.95
FSRQ	4C 38.41	248.81	38.13	0.10	6.9	2.4	31.7	1.41
GC	Sgr A*	266.42	-29.01	—	0.0	—	39.4	—
NI	MGRO J1908+06	286.98	6.27	—	0.0	—	49.1	—
PWN	Geminga	98.48	17.77	—	0.0	—	41.8	—
PWN	Crab Nebula	83.63	22.01	0.35	6.8	3.8	39.7	0.75
PWN	MGRO J2019+37	305.22	36.83	0.35	5.9	4.0	31.8	0.99
SFR	Cyg OB2	308.30	41.32	—	0.0	—	30.0	—
SNR	IC443	94.21	22.50	0.42	3.7	4.0	39.4	0.68
SNR	Cas A	350.81	58.81	0.30	3.7	4.0	26.3	1.27
SNR	TYCHO	6.36	64.18	—	0.0	—	25.8	—
SRG	Cen A	201.37	-43.02	0.28	0.3	1.1	34.3	10.89
SRG	M87	187.71	12.39	—	0.0	—	45.2	—
SRG	3C 123.0	69.27	29.67	—	0.0	—	34.9	—
SRG	Cyg A	299.87	40.73	0.065†	4.0	1.9	30.7	1.63
SRG	NGC 1275	49.95	41.51	—	0.0	—	29.9	—
SRG	M82	148.97	69.68	—	0.0	—	23.6	—
XB/mqso	SS433	287.96	4.98	0.43	4.1	4.0	50.9	0.49
XB/mqso	HESS J0632+057	98.24	5.81	0.083	18.4	3.3	49.5	0.87
XB/mqso	Cyg X-1	299.59	35.20	0.29	6.8	4.0	32.4	0.98
XB/mqso	Cyg X-3	308.11	40.96	0.50	0.6	4.0	30.8	0.78
XB/mqso	LSI 303	40.13	61.23	—	0.0	—	26.1	—

† Most significant source in this list for the northern hemisphere, the post-trial p-Value yields 89%.
‡ Most significant source in this list for the southern hemisphere. The post-trial p-Value yields 5.1%.

Sensitivity to different spectra