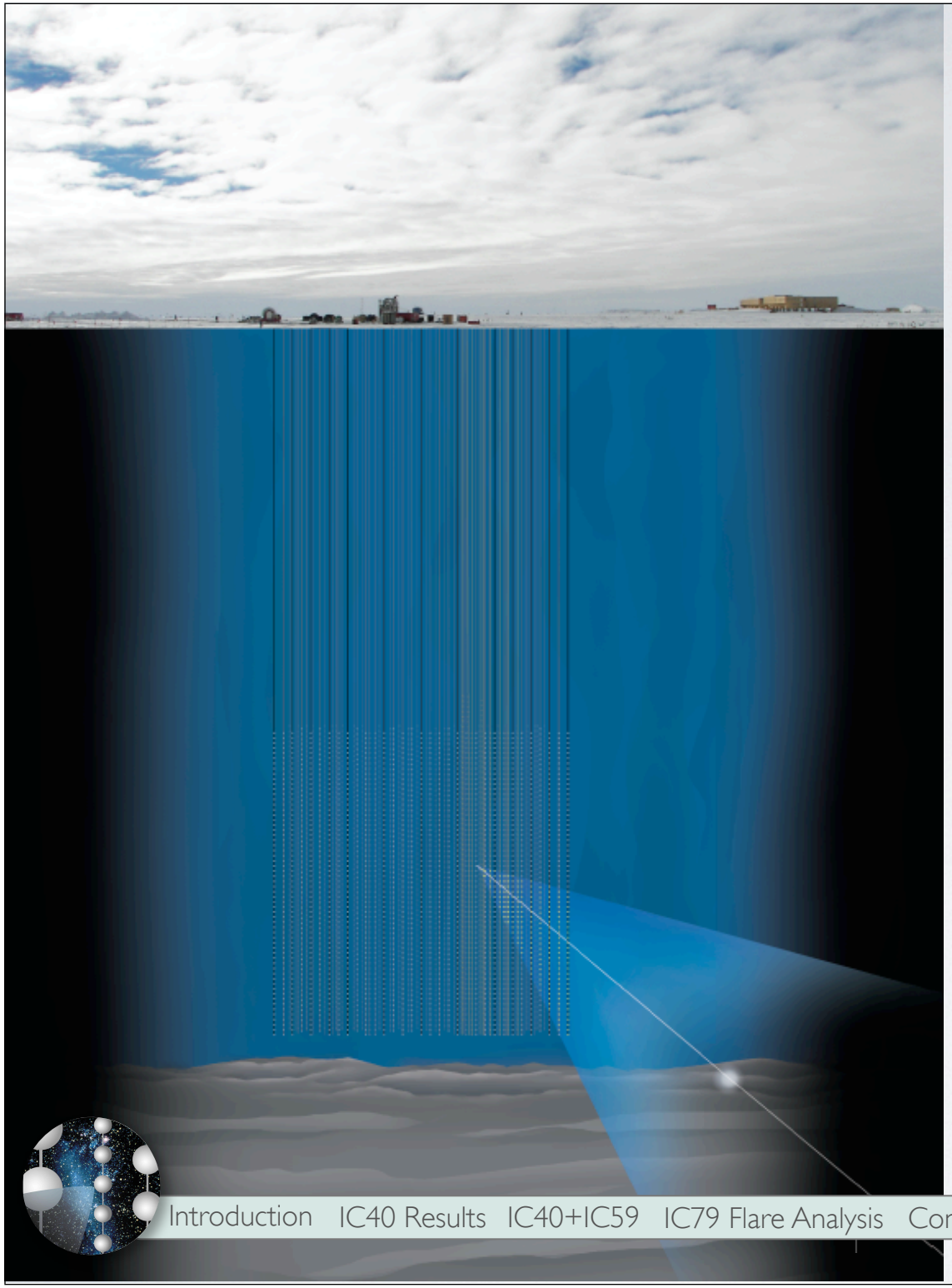


NEUTRINO POINT-SOURCE SEARCH IN ICECUBE

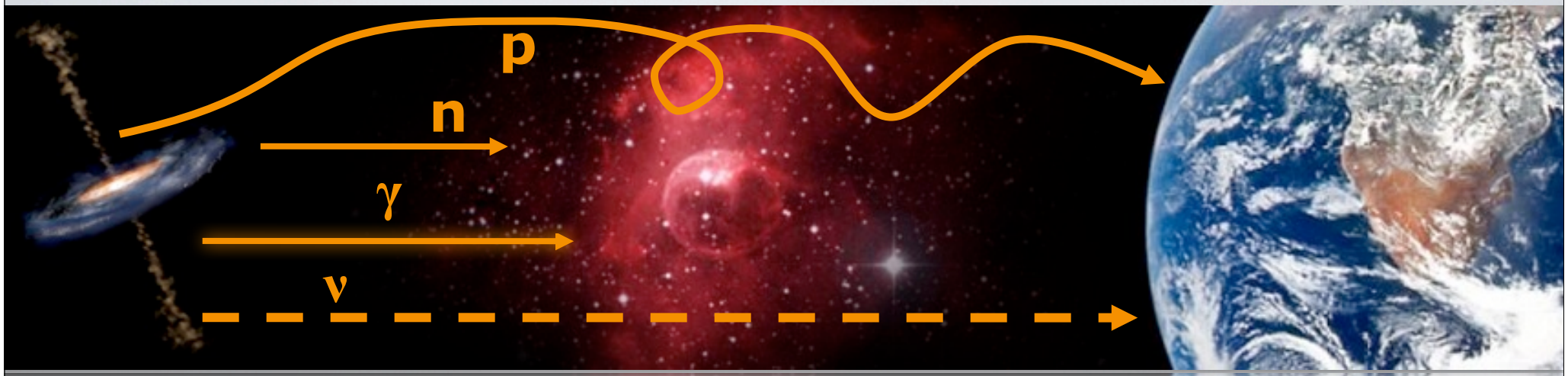
Juan Antonio Aguilar

Lake Louise Canada, 2011

THE UNIVERSITY of WISCONSIN MADISON

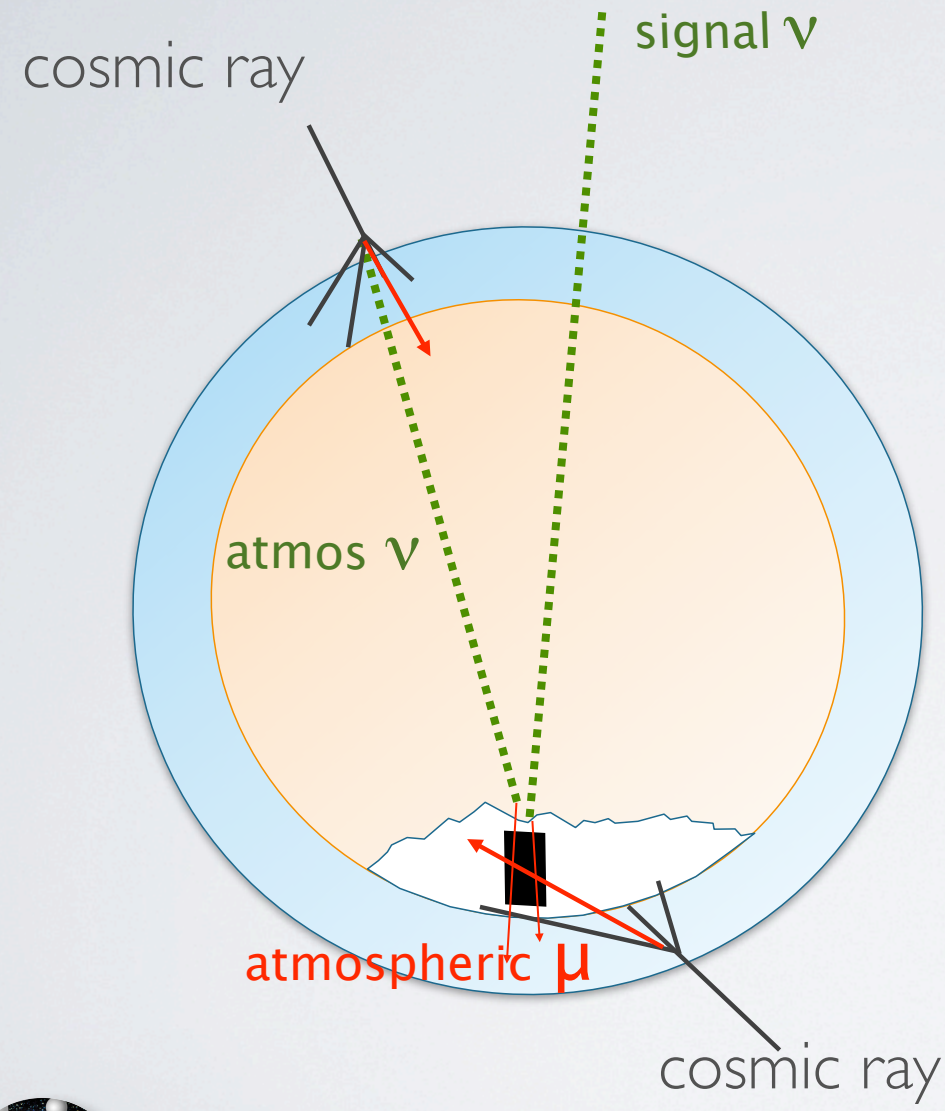
Neutrino Astronomy and IceCube

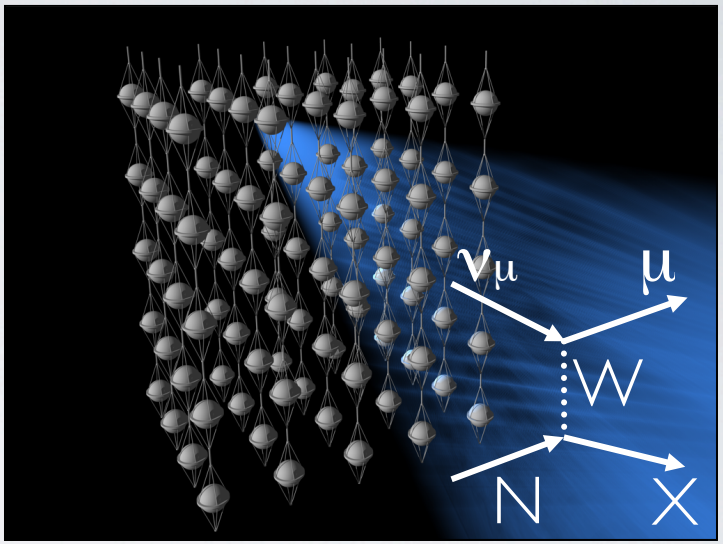
NEUTRINO ASTRONOMY

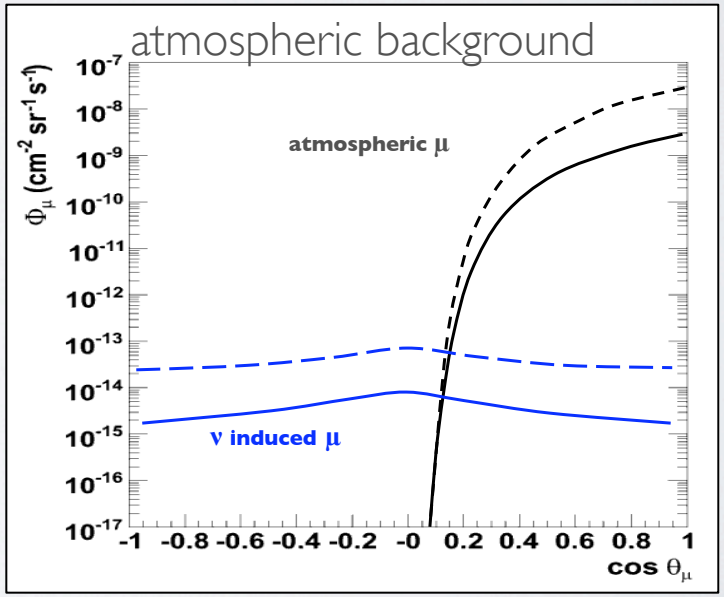


- Protons are deviated by magnetic fields ($E_p < 10^{19}$) and very energetic protons travel distances of a few Mpc.
- Neutrons reach distances of ~kpc at very high energy.
- Photons interact with the EBL (~100 Mpc) and CMB (~10 kpc).
- Neutrinos are neutral stable weakly interacting particles.

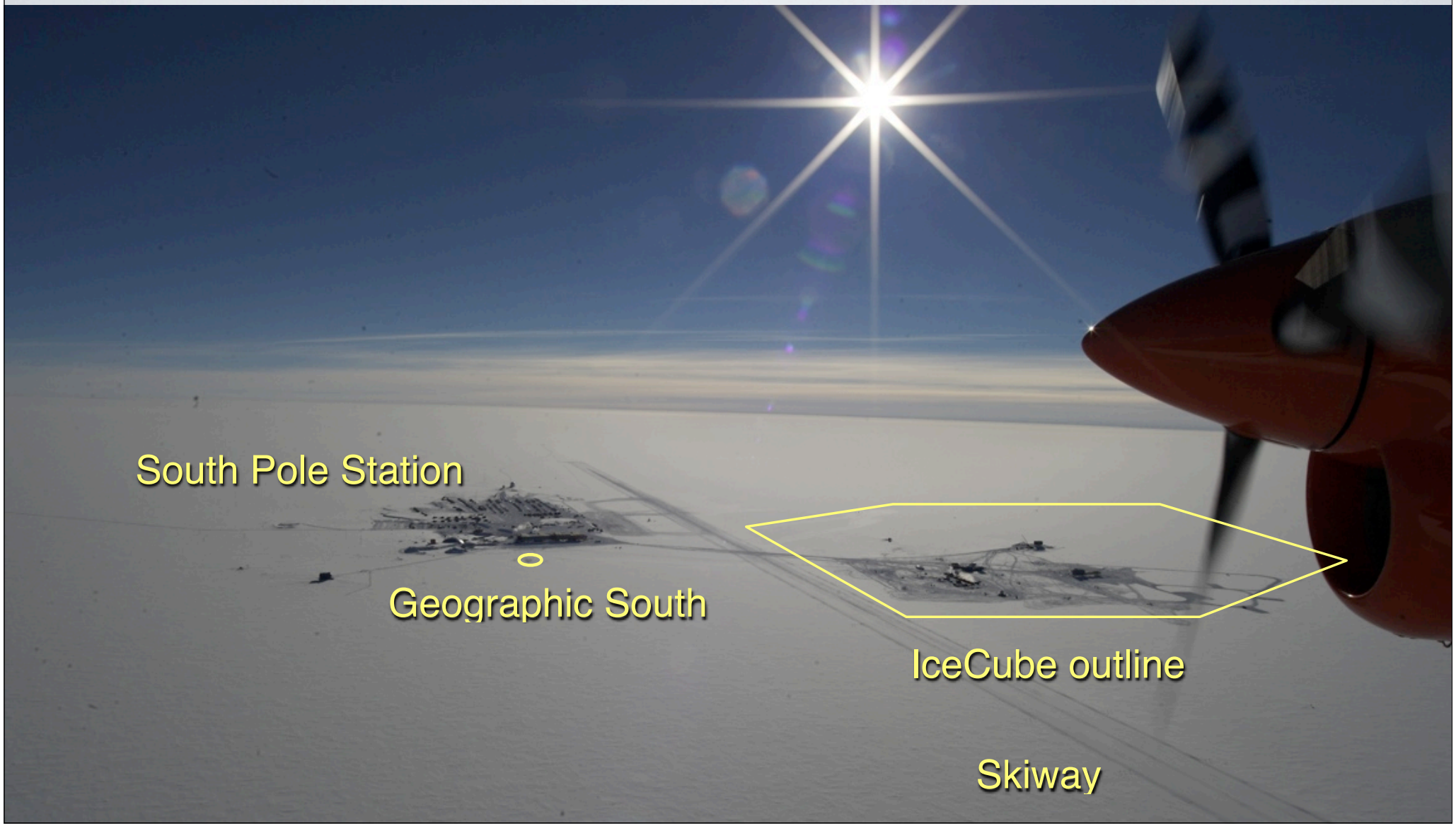
DETECTION PRINCIPLE



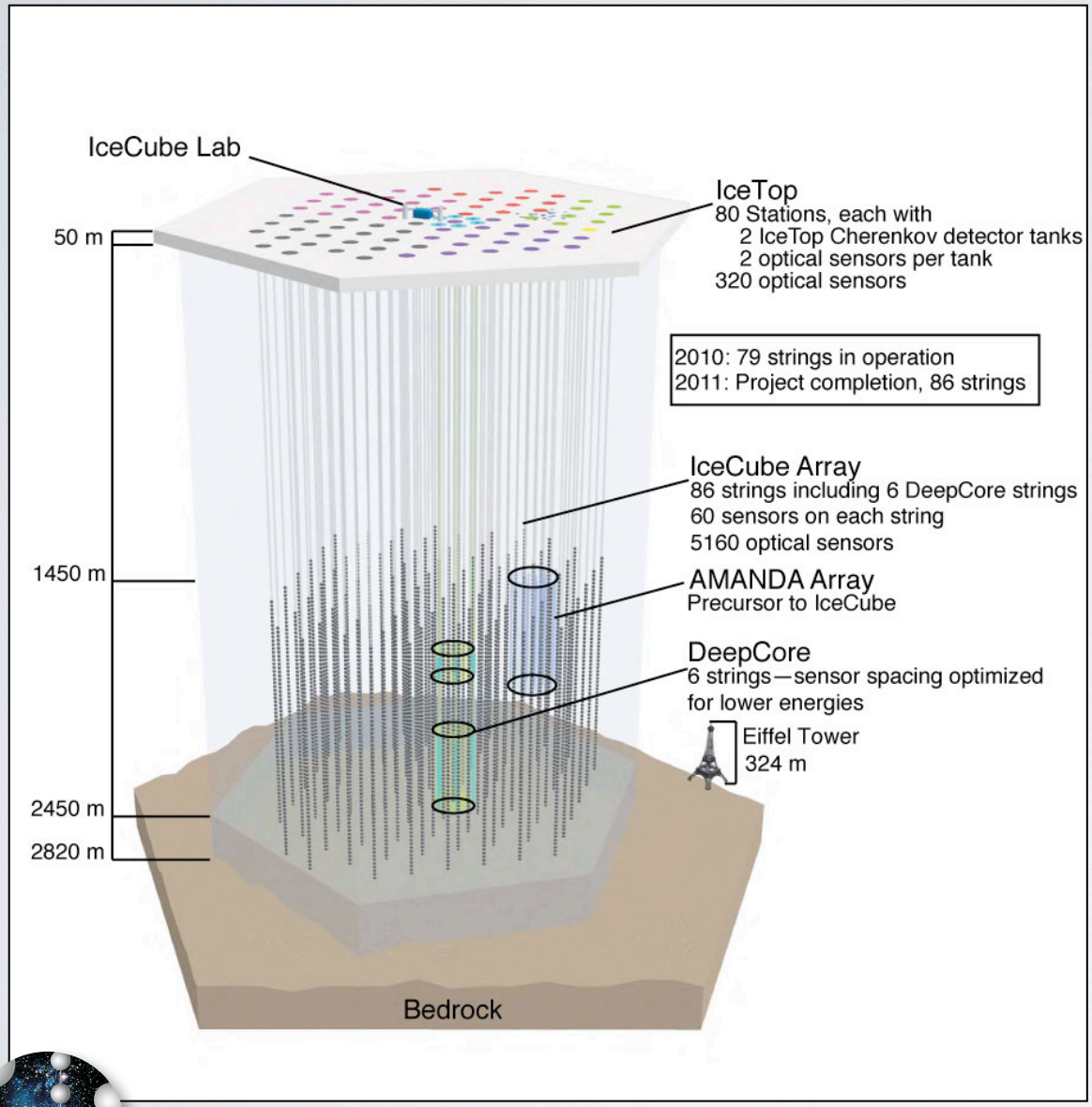




THE ICECUBE OBSERVATORY



ICECUBE



IceCube

Completion with 80 (+ 6) strings in January 2011

IceCube 79 (2010)

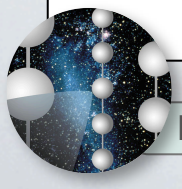
79 strings are in operation.

IceCube 59 (2009-10)

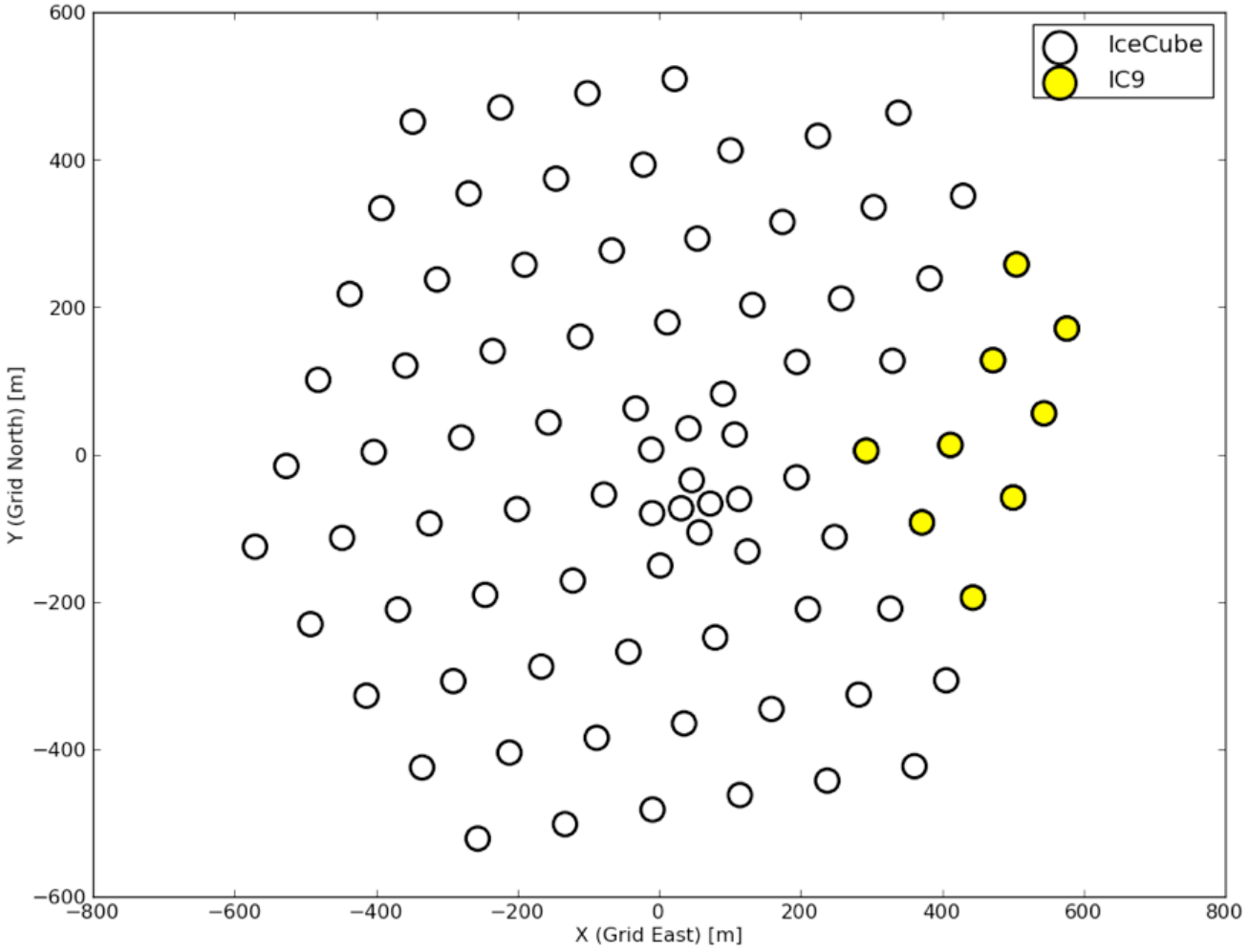
IceCube IC59 data is being processed. Analysis starting now.

IceCube 40 (2008-9)

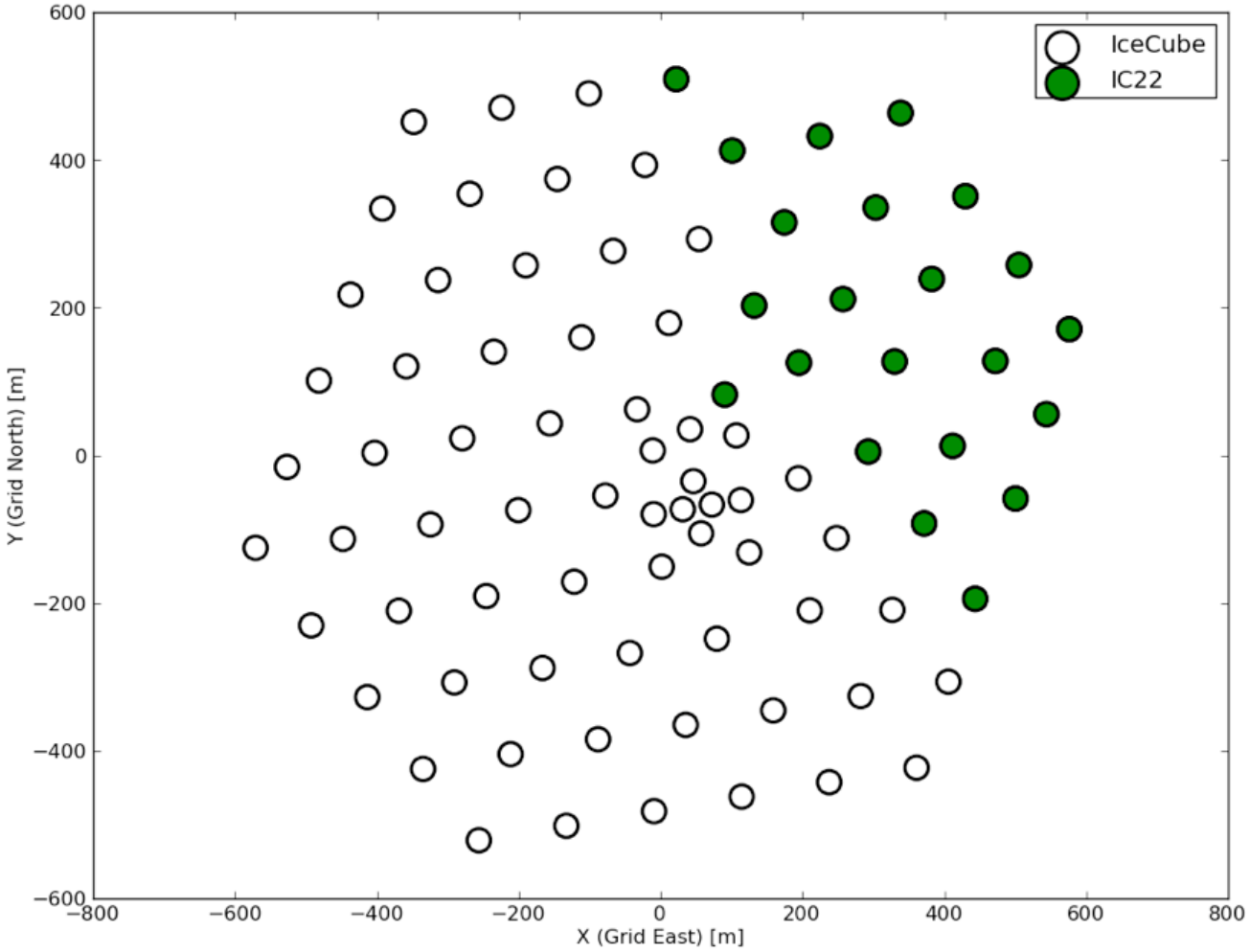
IC40 has approx. 2 x effective area of the previous IC22. IC40 data has been analyzed for point sources.

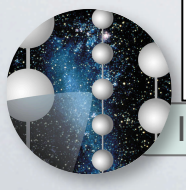


ICECUBE CONFIGURATIONS

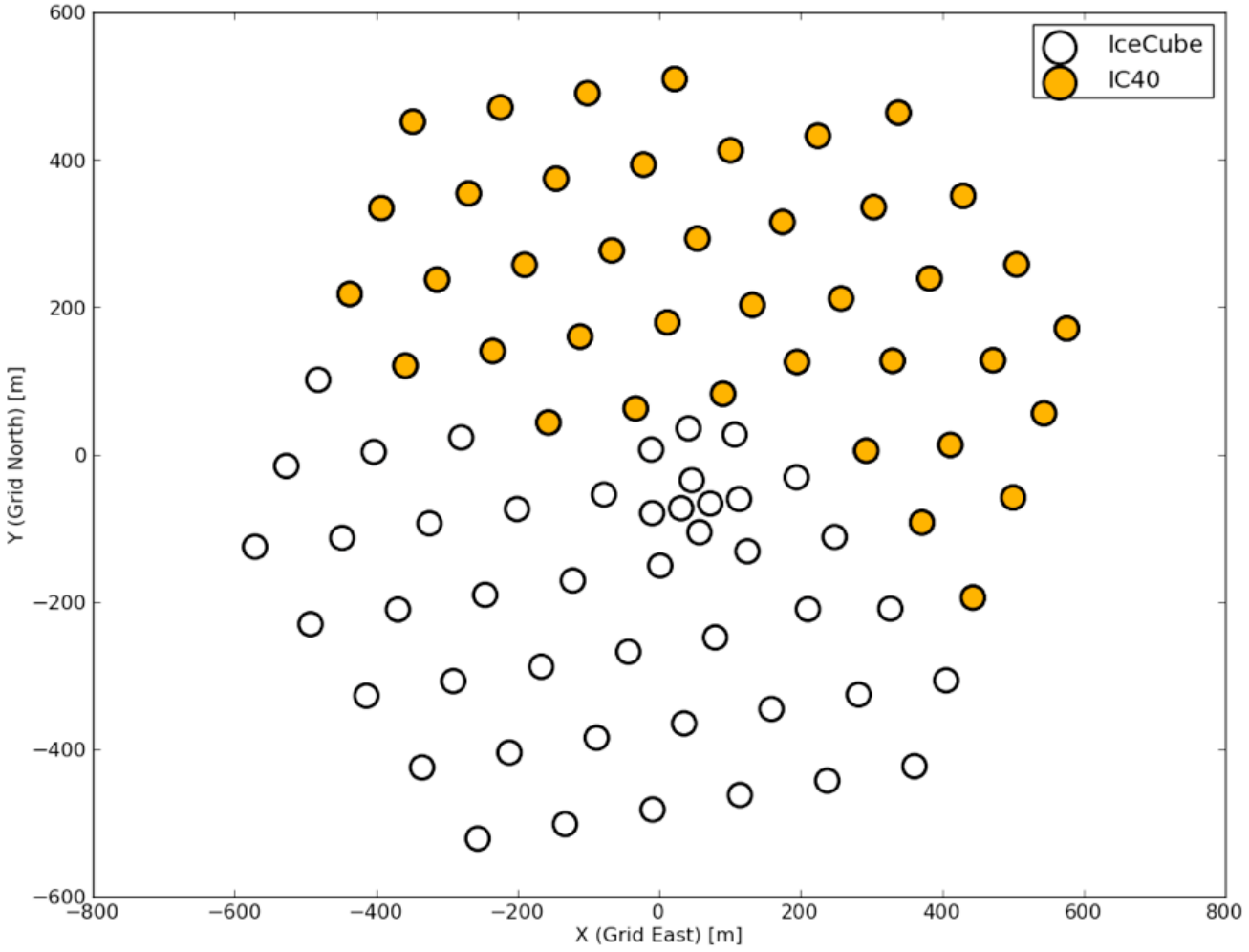


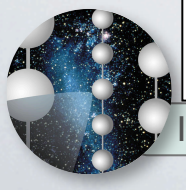
ICECUBE CONFIGURATIONS



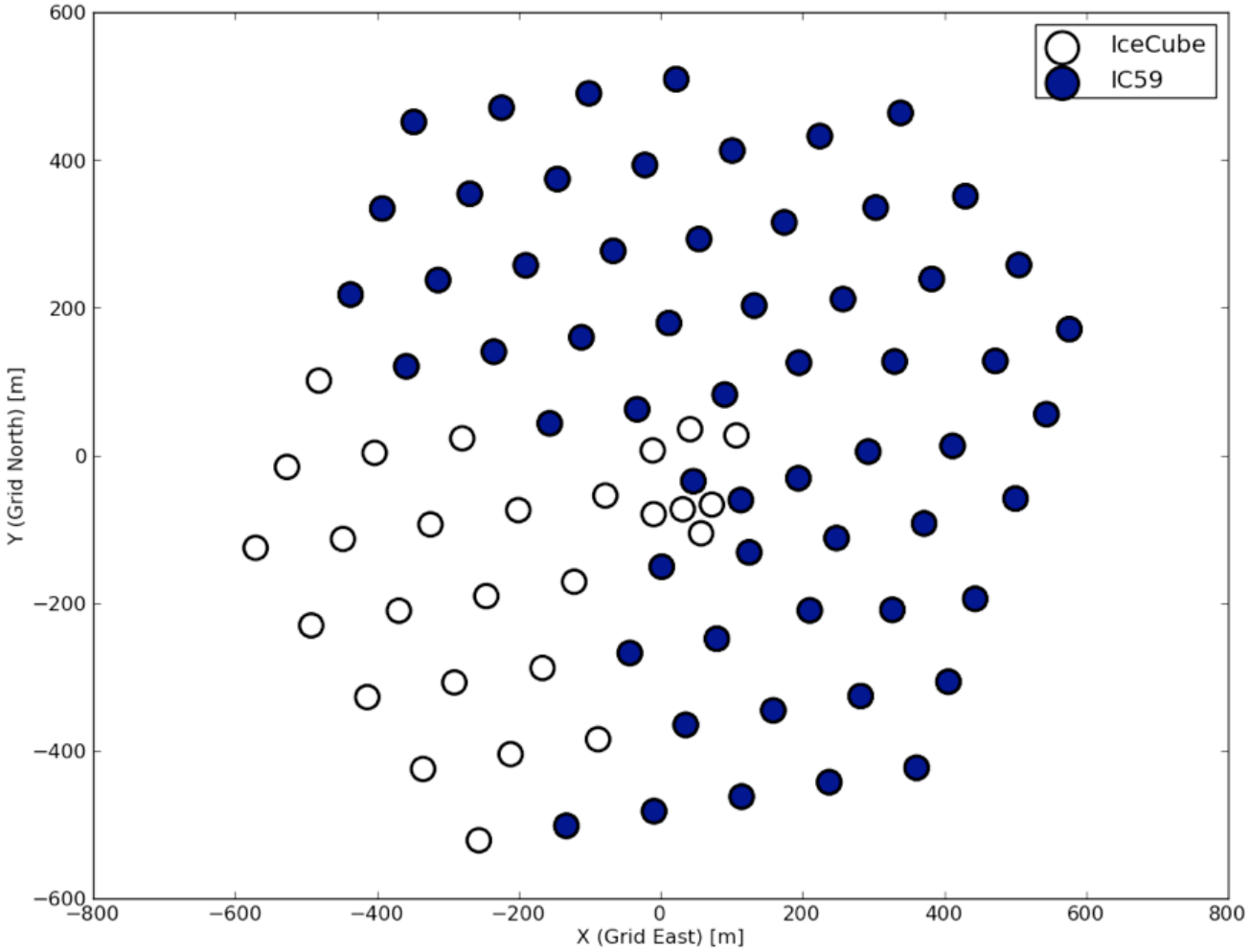


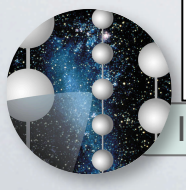
ICECUBE CONFIGURATIONS



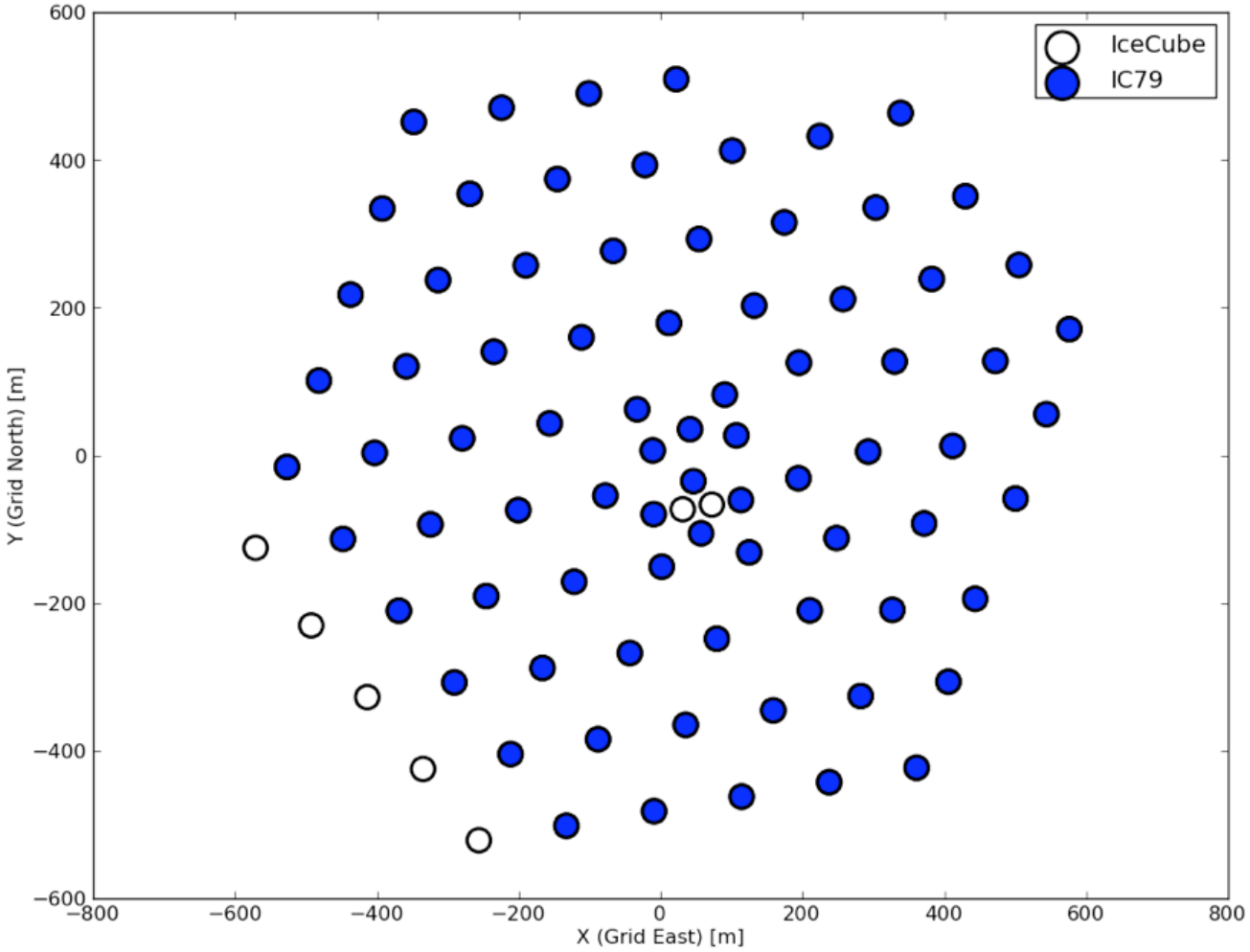


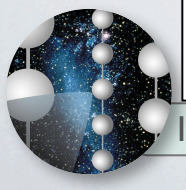
ICECUBE CONFIGURATIONS



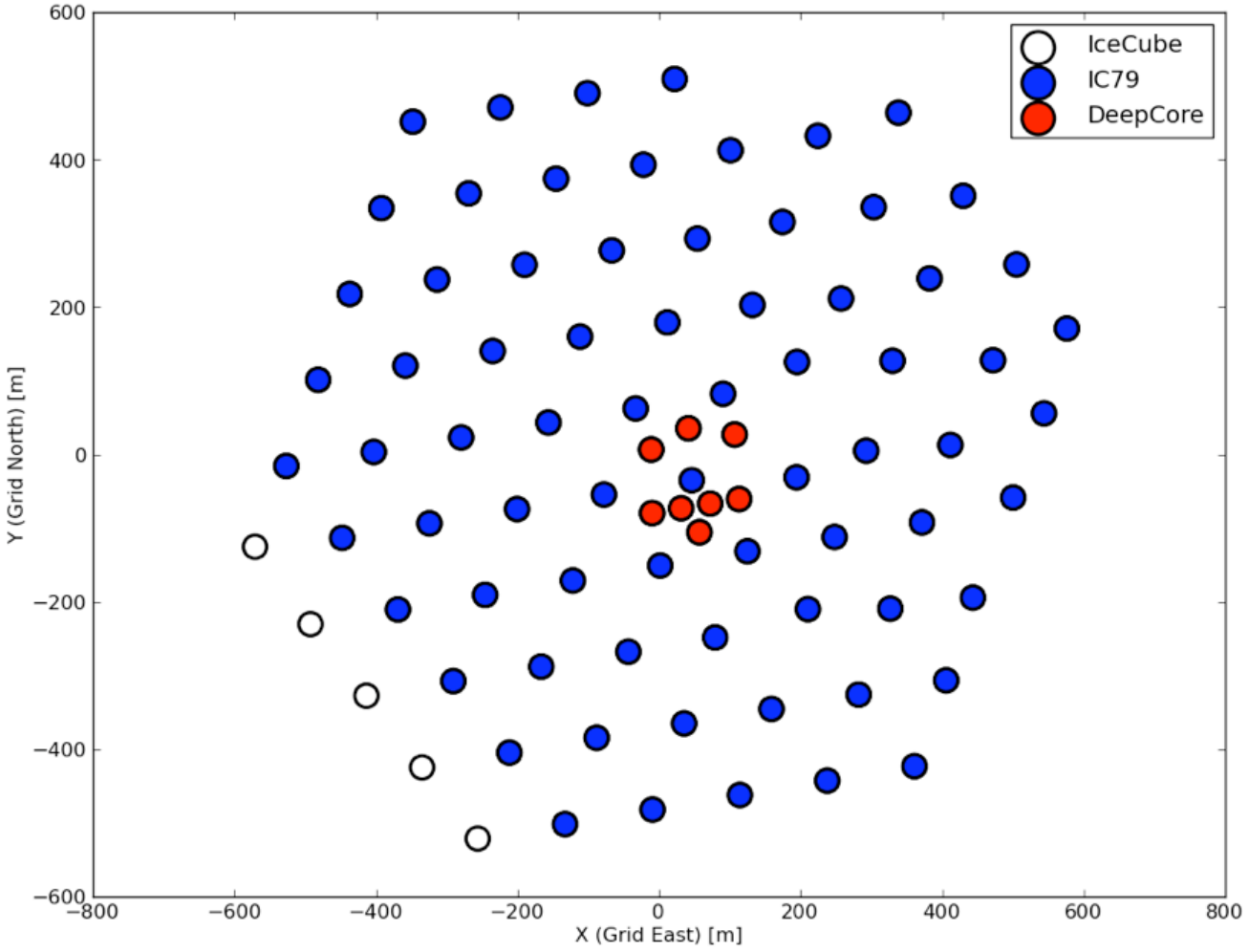


ICECUBE CONFIGURATIONS





ICECUBE CONFIGURATIONS

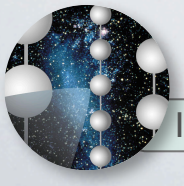


ICECUBE MUON SAMPLE

Detector rates:

Strings	Year	Livetime	SMT rate (Hz)	μ filter rate (Hz)	atm. ν final rate
9	2006	137 d	80	6	1.7
22	2007	276 d	450	20	18/d
40	2008	375.5 d	1100	23	40/d
59	2009	348 d	1900	24	120/d
79	2010		2300	40	> 120/d

- Low noise rates: ~500 Hz (SPE/sec)
- High duty cycle: >96%
- Event rates (59 strings): Trigger rate: ~1.9 kHz
  Neutrinos: ~120/day



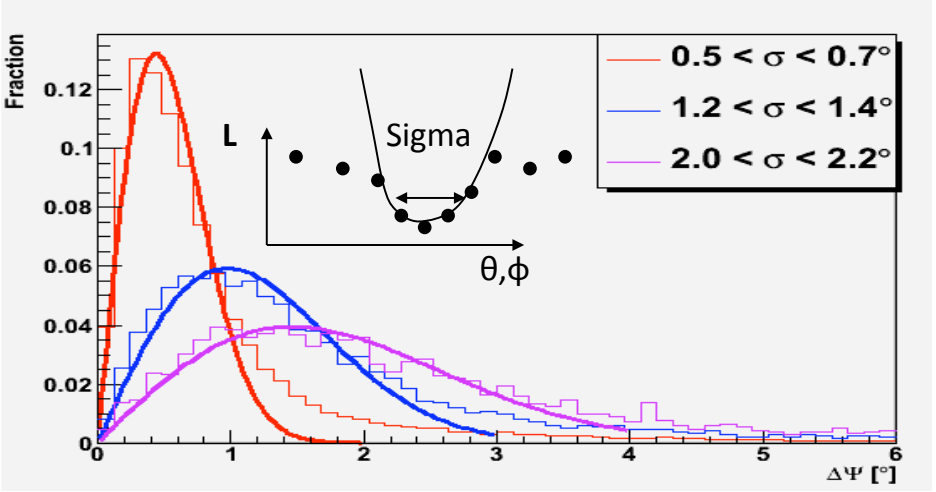
POINT SOURCE ANALYSIS

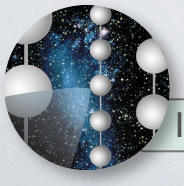
LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Likelihood Space around track solution fit to paraboloid: width = σ





LIKELIHOOD AND DENSITY FUNCTIONS

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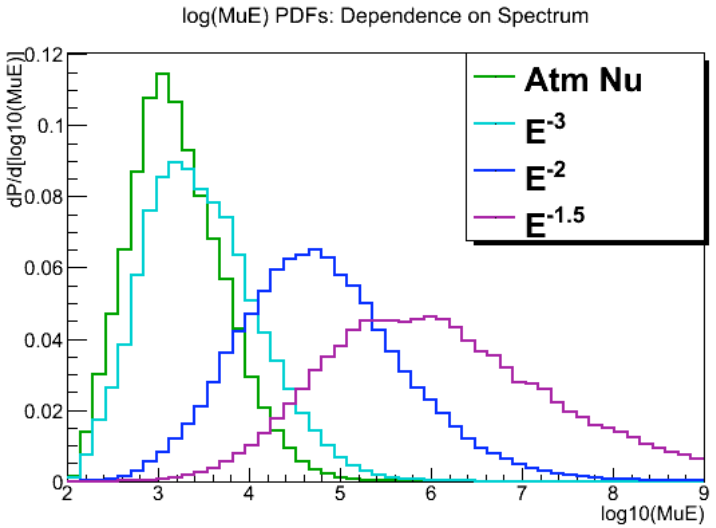


LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Background pdf:

$$\mathcal{B}_i = B_{\mathrm{zen}} \cdot P_{\mathrm{atm}}(E_i)$$

Scrambled real data

LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Background pdf:

$$\mathcal{B}_i = B_{\mathrm{zen}} \cdot P_{\mathrm{atm}}(E_i)$$

Likelihood:

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

LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Background pdf:

$$\mathcal{B}_i = B_{\mathrm{zen}} \cdot P_{\mathrm{atm}}(E_i)$$

Likelihood:

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

Maximization of the likelihood ratio:

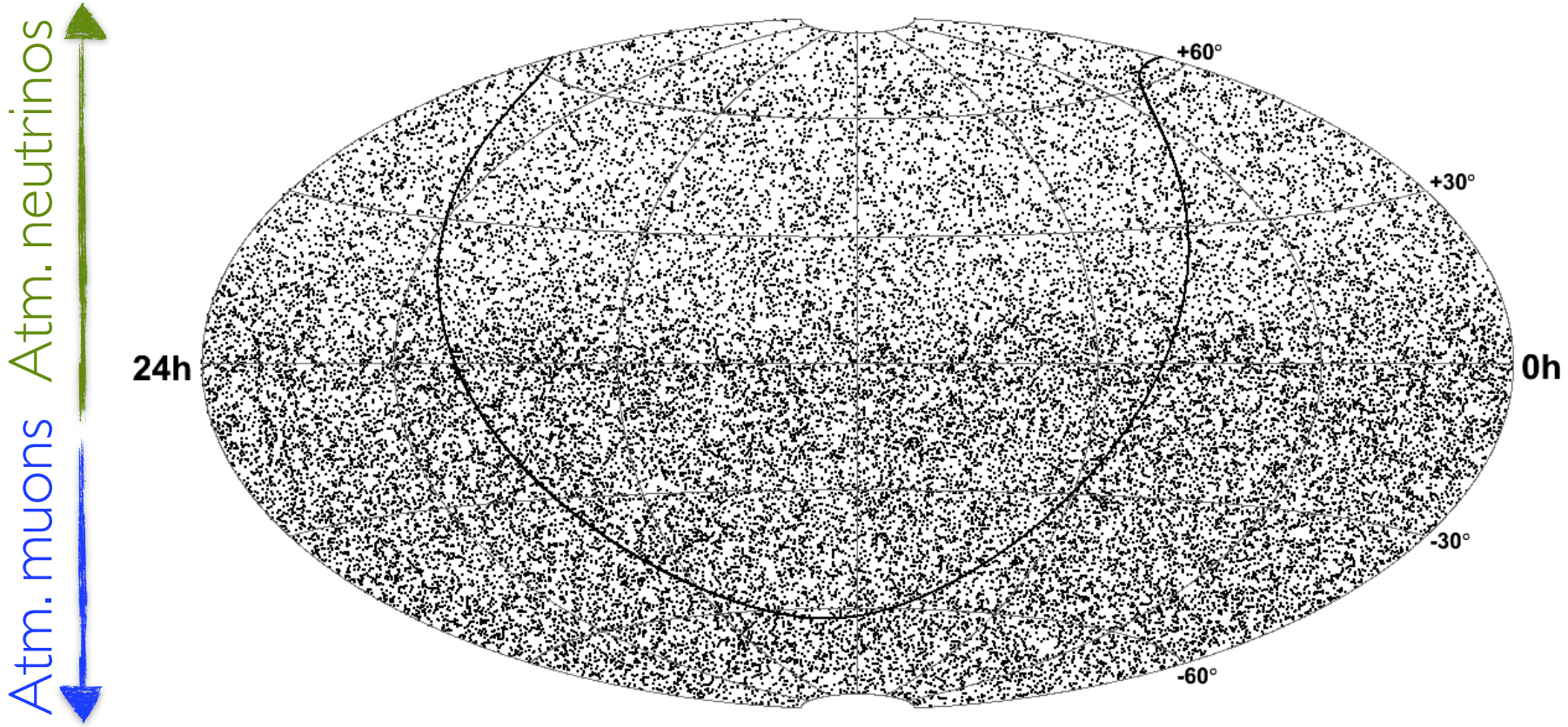
$$\log \lambda = \log \left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Estimates that maximize the Likelihood

The final significance is determined by scrambling the data in r.a. and repeating the analysis.

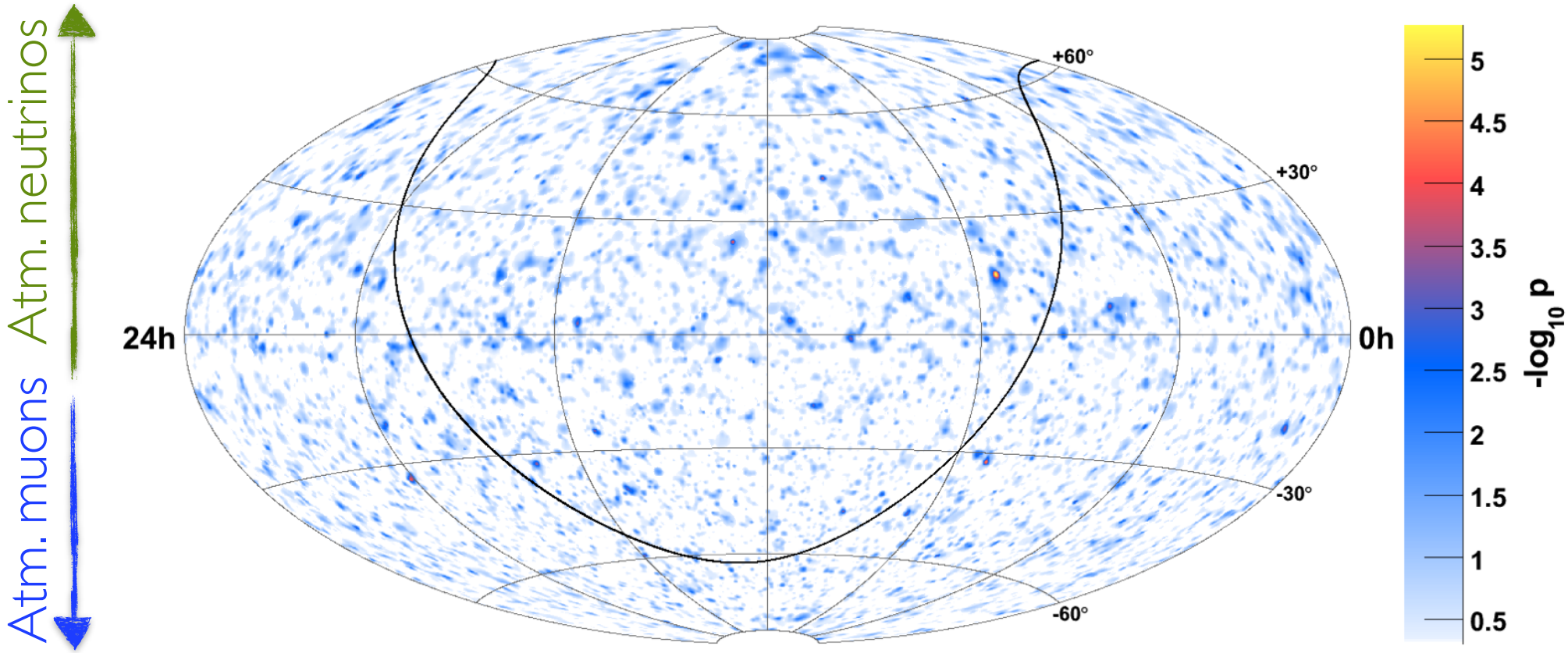
IC40 POINT SOURCES RESULTS

IC40 EVENT MAP



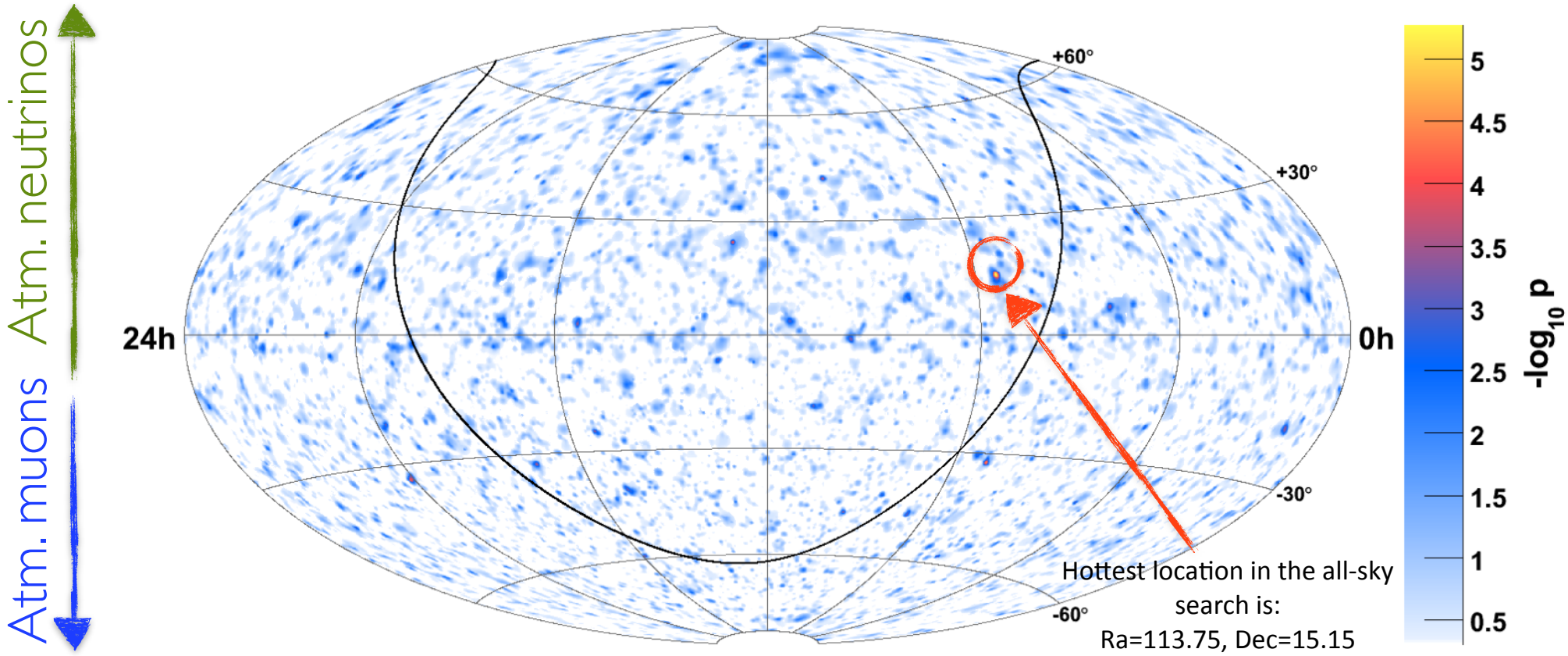
- Livetime: 375.5 days
- Events: 37290 (14139 up-going, 23151 down-going)

IC40 SIGNIFICANCE MAP



- Log-likelihood is calculated on a fine grid: 0.1° x 0.1°
- Significance comes from the hottest single spot, calculated as the fraction of scrambled trials with equal or higher significance – robust result

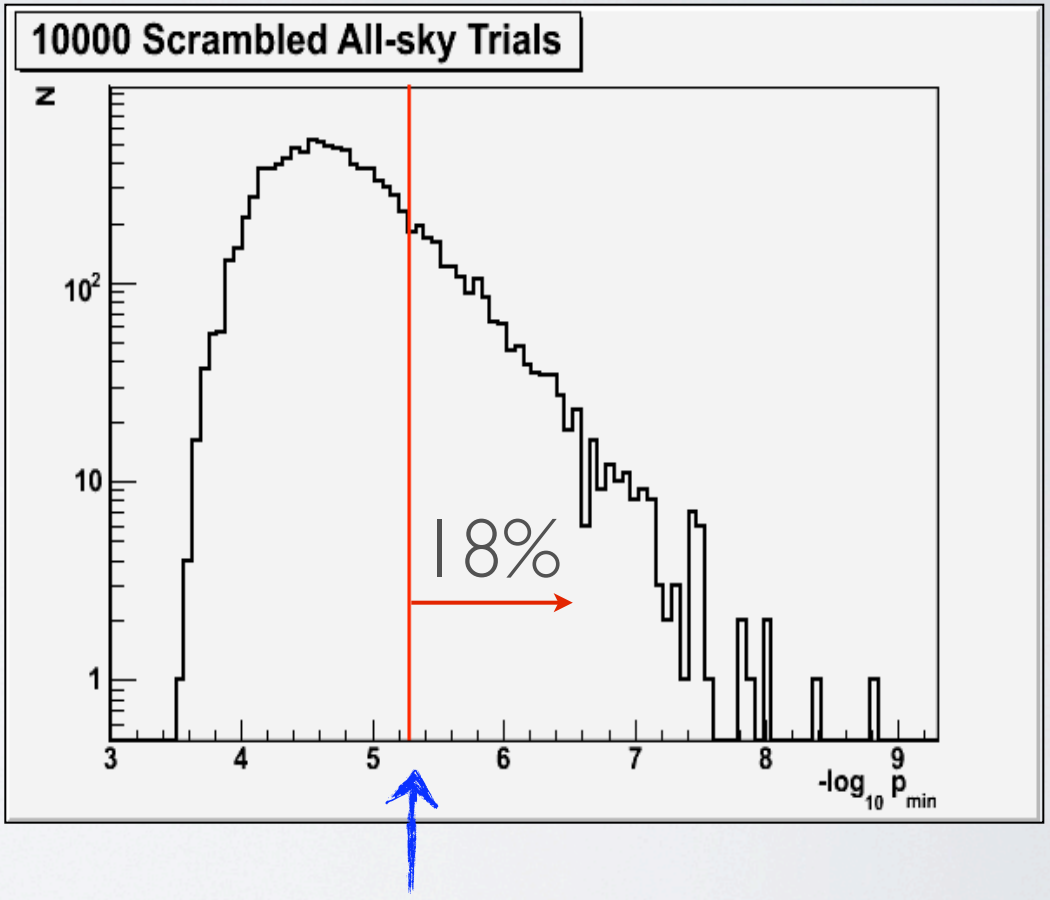
IC40 SIGNIFICANCE MAP



- Log-likelihood is calculated on a fine grid: 0.1° x 0.1°
- Significance comes from the hottest single spot, calculated as the fraction of scrambled trials with equal or higher significance – robust result

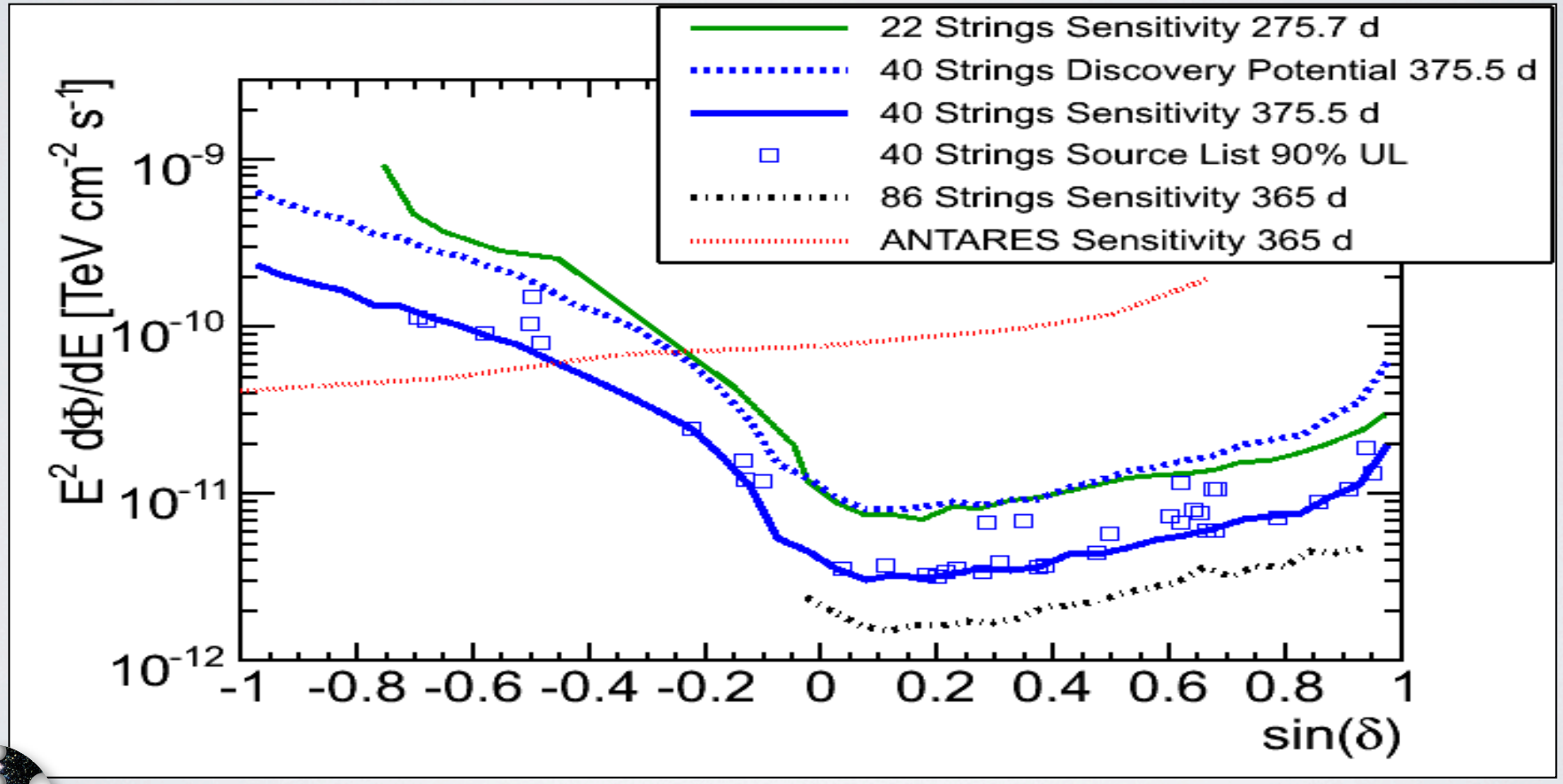
IC40 ALLSKY RESULTS

- The distribution of results for 10000 scrambled skymaps.
- For each scrambled trial, the same analysis is performed.
- The hottest spot in each trial yields the $-\log_{10}(p_{min})$ that goes into this histogram. 1817 of the 10000 scrambled skymaps had a $-\log_{10}(p_{min})$ equal or greater than that of the real dataset ➜ **all-sky p-value = 18%**.



IC40 UPPER LIMITS (90% CL)

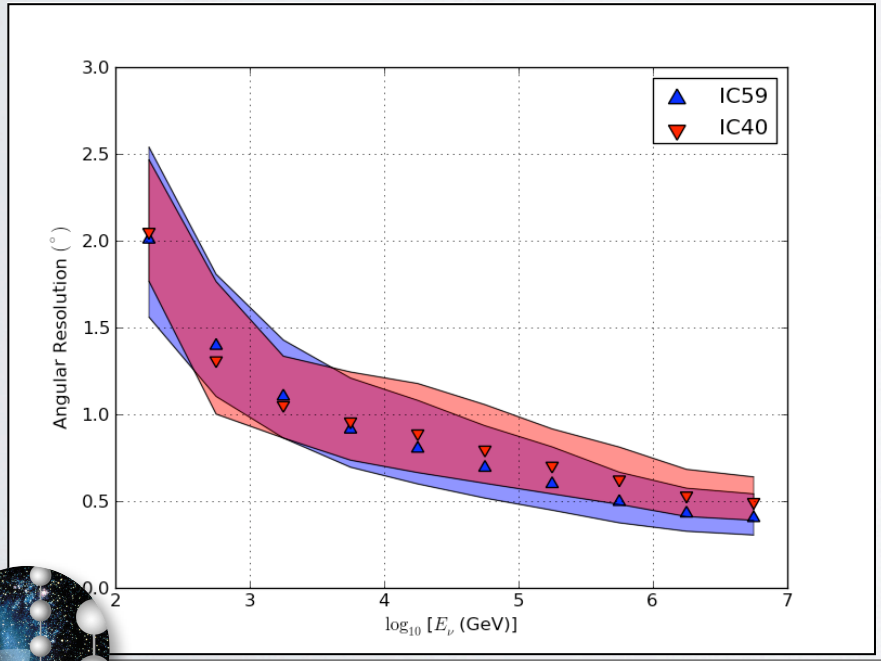
- Median sensitivities/UL for E^{-2} neutrino spectrum
- Discovery potential at 5σ (P = 50%) takes ~3x more flux
- IceCube (IC86) ~2x better than IC40

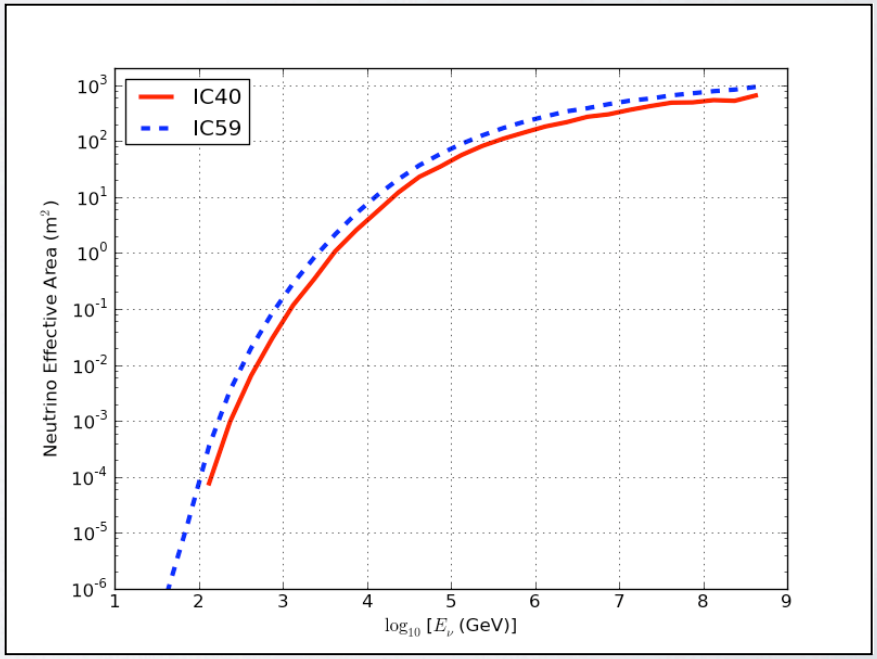


IC40 + IC59 ANALYSIS

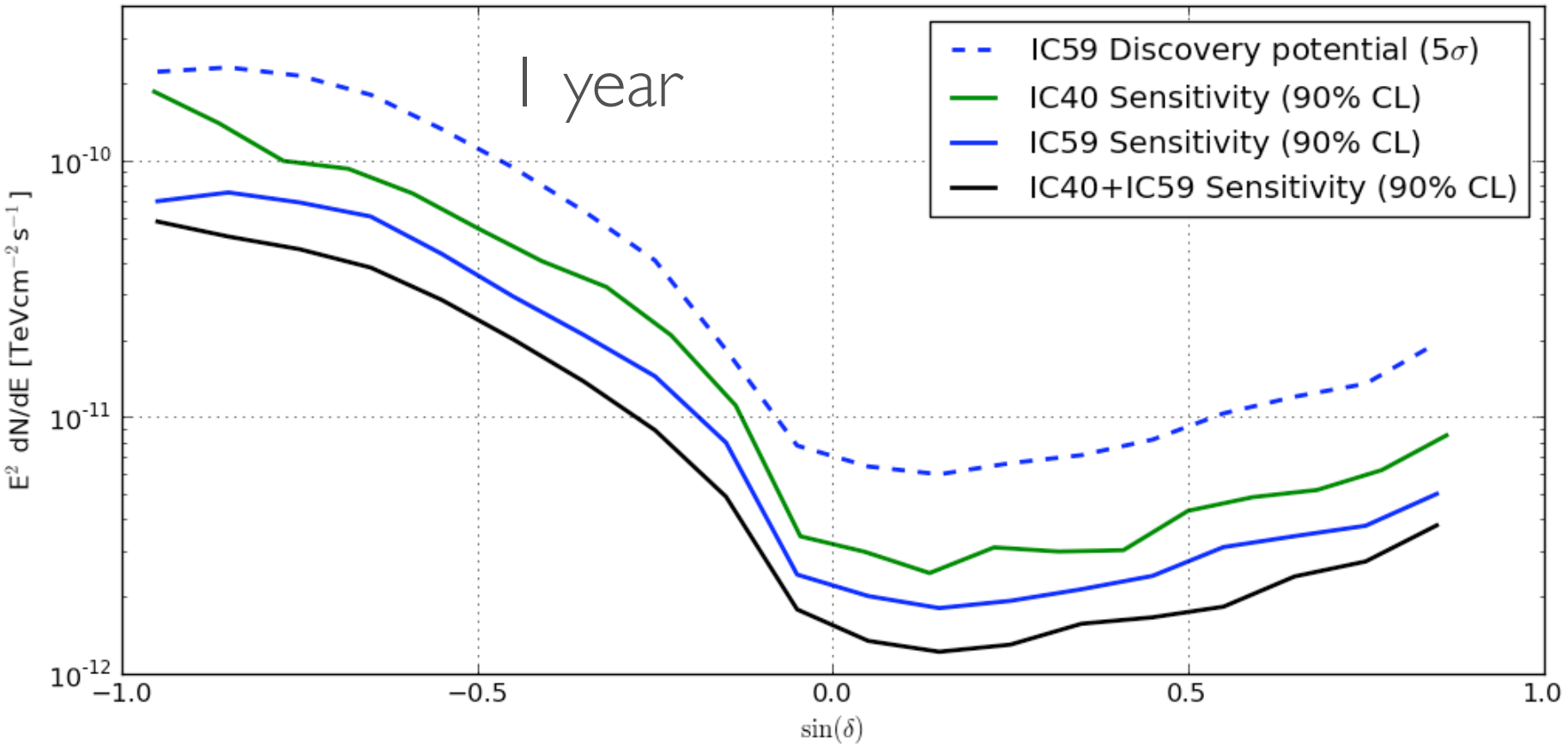
IC40+IC59 ANALYSES

- Unbinned likelihood methods are ideal to combine different datasets from detectors.
- Each event carries its own pdf and background can be estimated for each sample.
- The likelihood is maximized for the combined datasets for the same signal hypothesis.





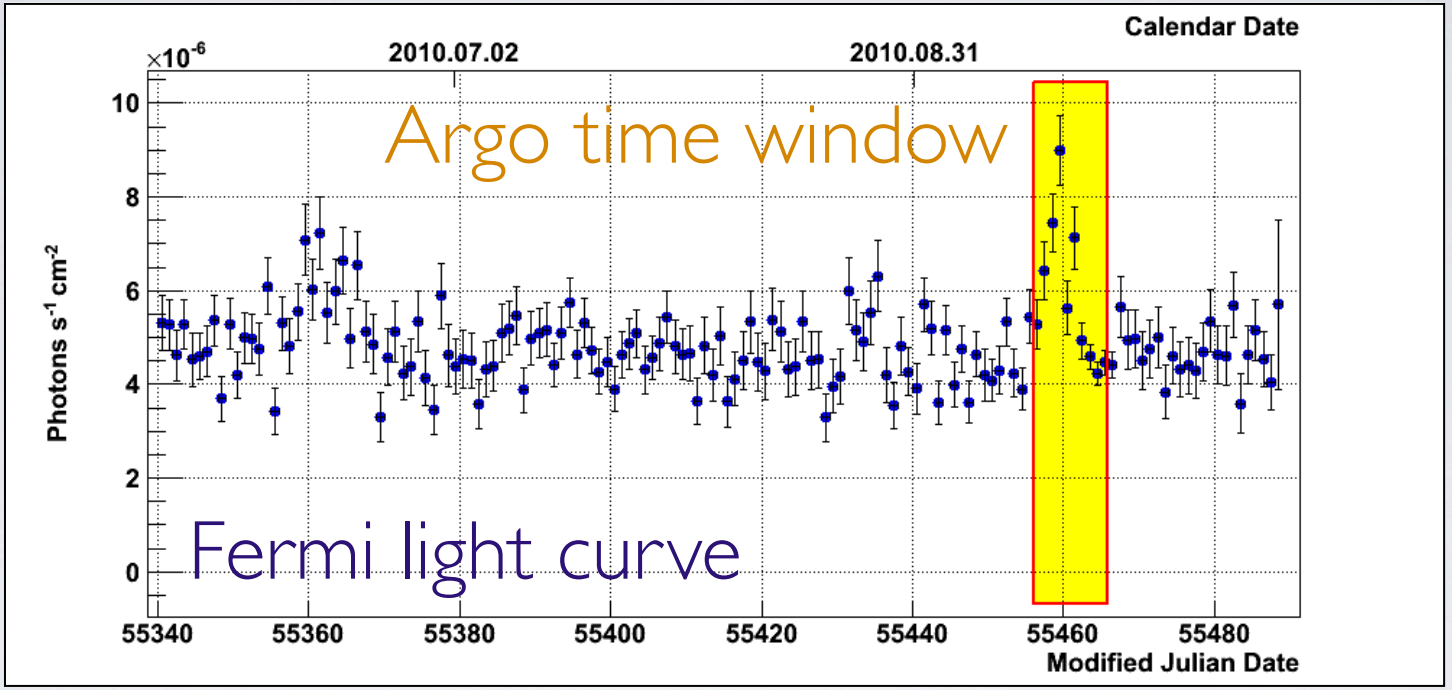
SENSITIVITY IC40+IC59



- The IC59 has a factor **~1.5x** better sensitivity compared to IC40.
- We can improve the sensitivity even more by combining the two data sets and reach the IC86 expected sensitivity.

IC79 CRAB FLARE

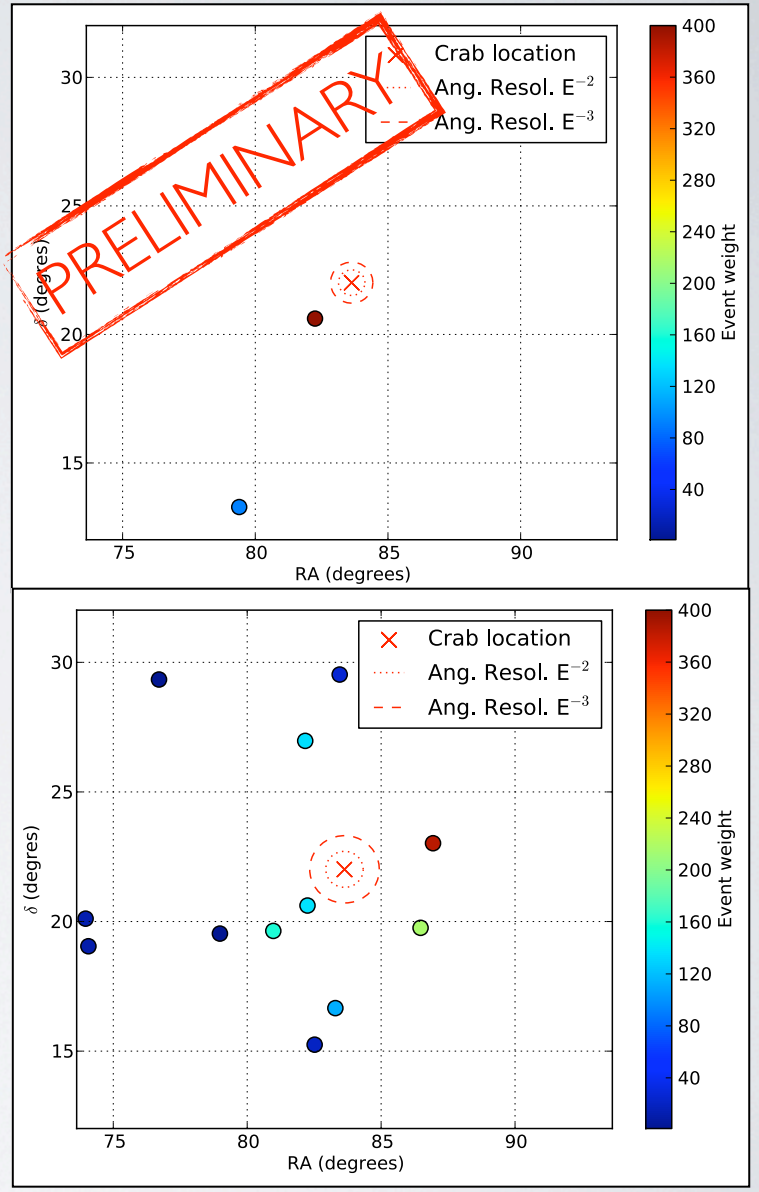
CRAB NEBULA FLARE



- A flare of 4-5 days from the Crab Nebula was reported in the GeV region from Fermi and AGILE on September 2010.
- ARGO claimed an enhanced TeV emission in a **10 days** interval.

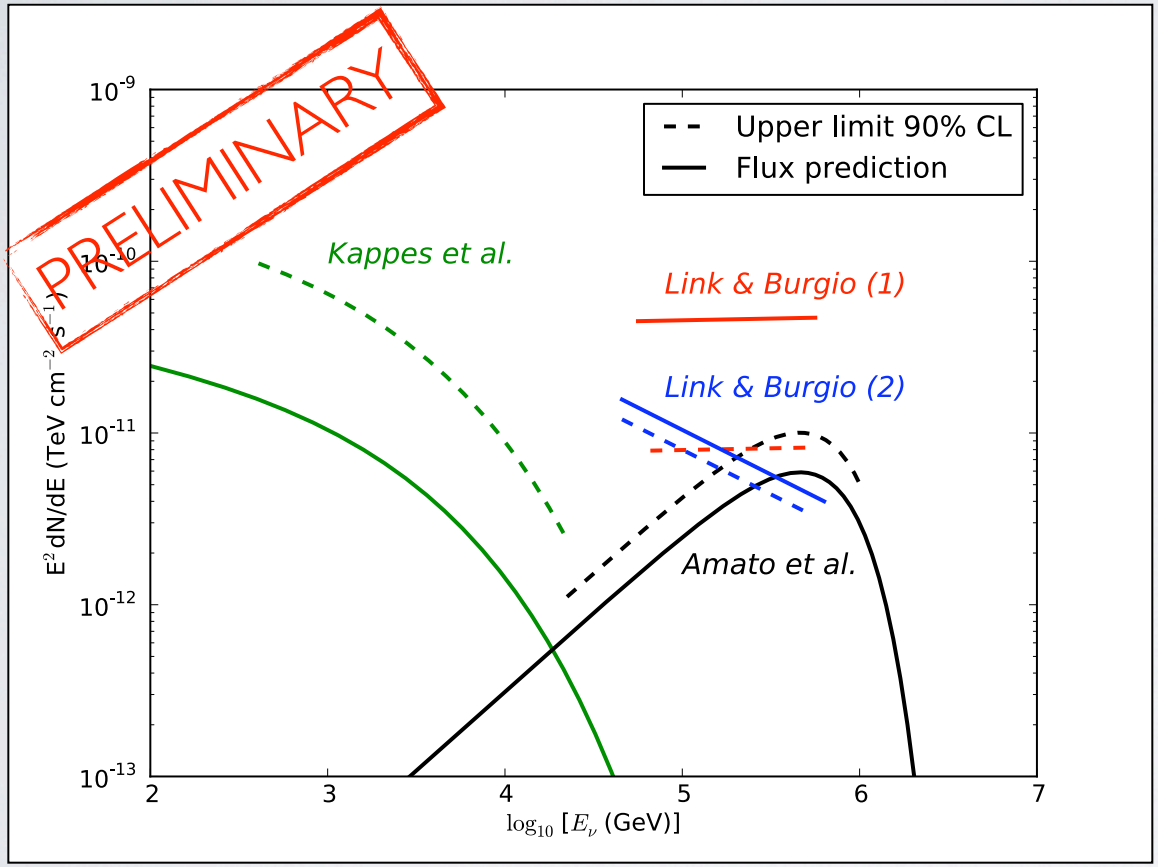
FLARE NEUTRINO ANALYSIS

- During Sep 2010 IceCube was running with **IC79** configuration.
- Data is still being processed so an online event selection was used for this analysis.
- An unbinned analysis was performed using the time of the events as an extra information (Time PDF) and two datasample were analyzed (Straight cuts and BDT).
- In both samples the best fit of n_s is **0** (under-fluctuations).



Spectrum	$\Phi^{90\%CL}$ (TeV$^{\gamma-1}$ cm^{-1}s^{-1})
E^{-2}	4.74×10^{-11}
$E^{-2.67}$	2.50×10^{-10}
E^{-2} (100 TeV)	7.91×10^{-11}
E^{-2} (1000 TeV)	5.39×10^{-11}

IC40 UPPER LIMITS ON CRAB STEADY EMISSION MODELS

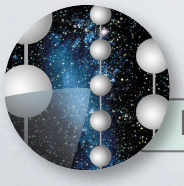


- Due to the livetime, the best upper limits come from **time integrated** searches.
- **IC40** upper limits already exclude the upper region of some models.

CONCLUSIONS

CONCLUSIONS

- The whole year of IC40 has been analyzed for point-source and no evidence of a neutrino point source has been found.
- The IC59 data analysis has started and it will be the first time to combine data-samples from previous geometries to enhance the discovery potential and sensitivities.
- Data from the IC79 period is being processed but the online data has been analysis in a rapid response to an astronomical event like the gamma-ray flare from the Crab Nebula.
- IceCube is finally complete and IC86 will start to take data soon.



BACKUP

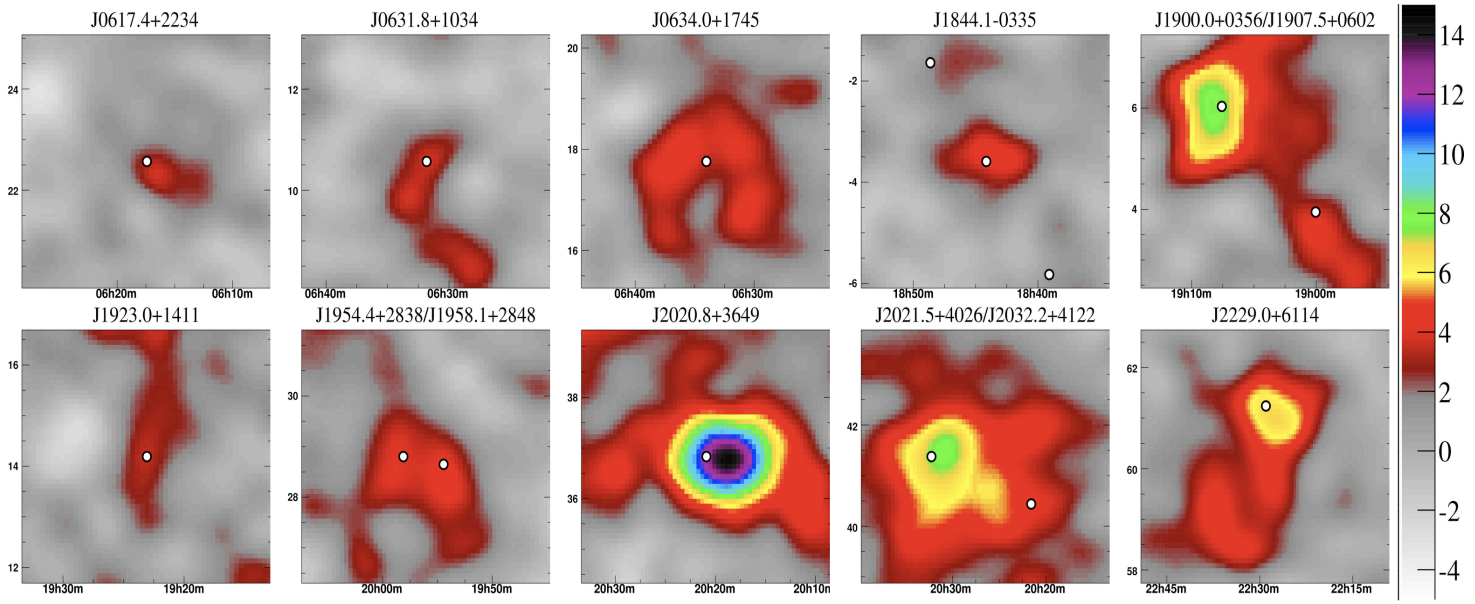
ADVANTAGE OF STACKING

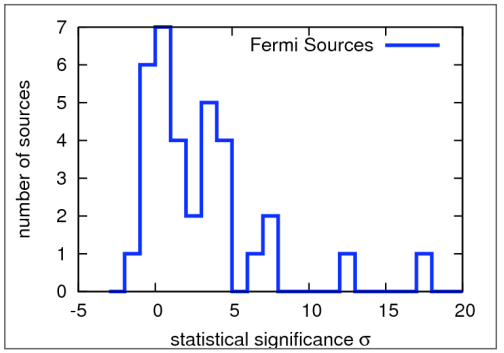
Catalog	E^{-2} Sensitivity (10^{-12} TeV^{-1} cm^{-2} s^{-1})	Improvement (wrt point-source analysis)
One source at $\delta = 25°$ (average δ)	3.4	1x
Stacking 6 Milagro SNR sources	5.7 total or 0.95 *per source*	3.6x
Stacking 17 Milagro sources	6.8 total or 0.40 *per source*	8.5x

The gain by adding more identical sources is somewhere between:

- sqrt(nSources) ➜ expectation for high background
- nSources ➜ expectation for low background

MILAGRO-FERMI SOURCES: THE GEV – TEV CONNECTION



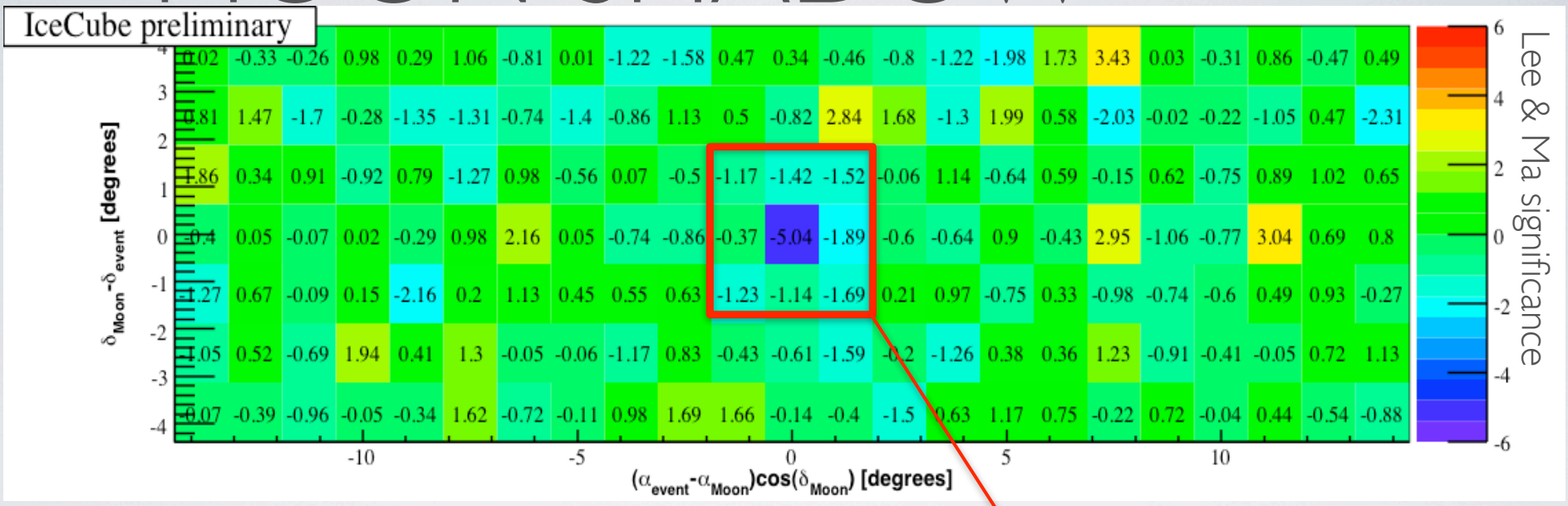


Abdo et al. 2009, arXiv:0904.1018v3

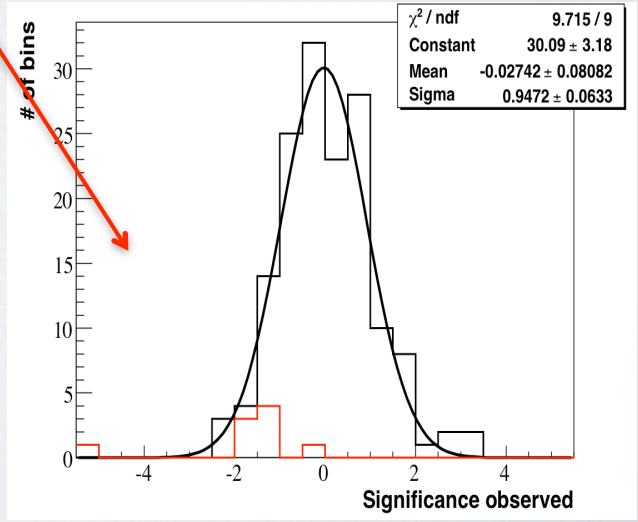
- Milagro showed that many Fermi GeV gamma ray sources extend to TeV
- Of 34 galactic Fermi BSL sources in Milagro 6 (14) are observed with > 5 (3) σ
- Probability of 4 or more excesses > 3 σ in 34 trials is $p = 1.5 \times 10^{-7}$
- Strong evidence for multi-TeV emission from Galactic BSL sources as a class.

MGRO J1852+01

IC40 RESULTS OF THE MOON SHADOW

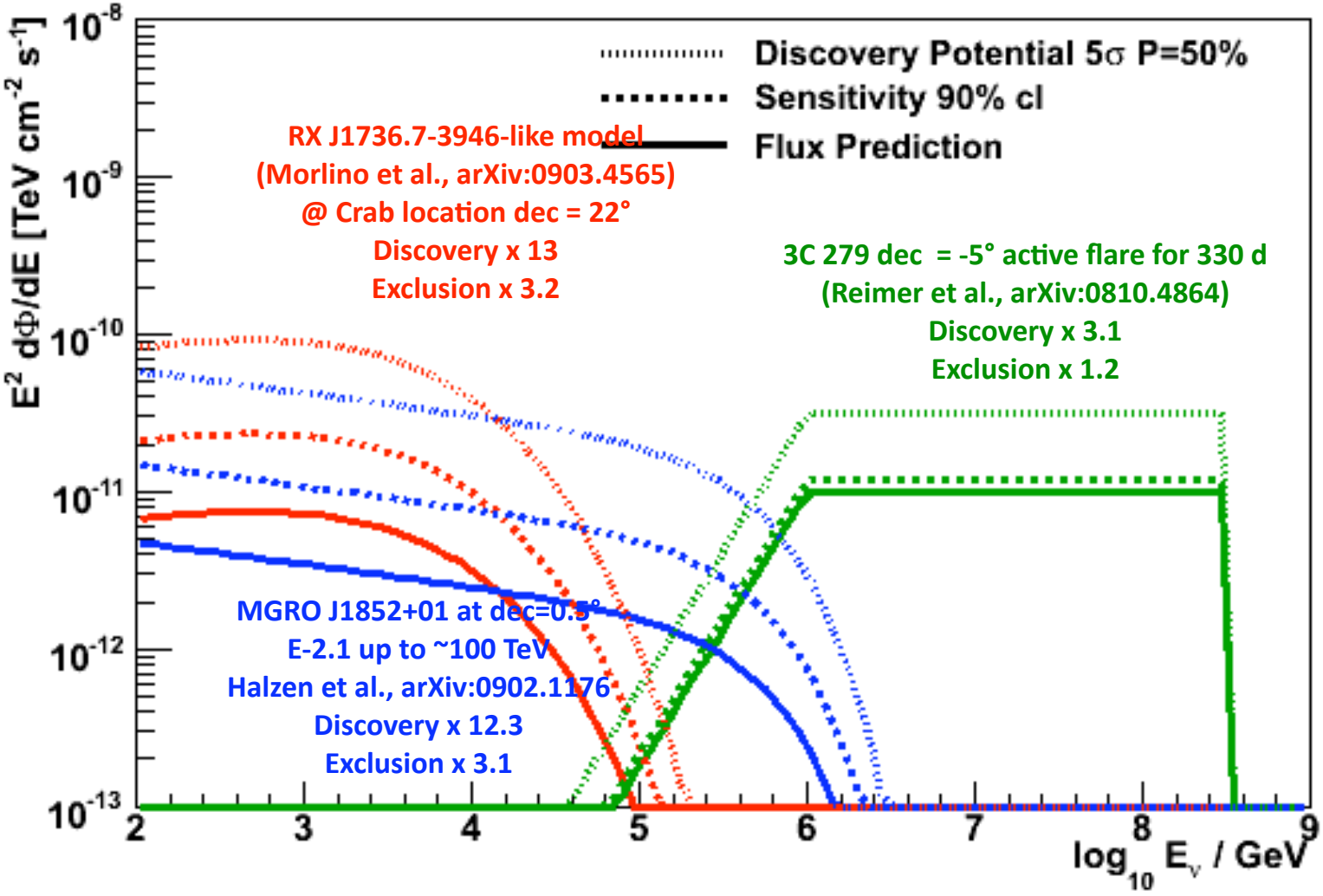


- Cosmic rays blocked by the moon lead to a point-like deficit in the distribution of down-going muons in the detector.



- Moon shadow observed as a deficit in CR muon rate using 8 months of IC40 data.
- Deficit of 5σ (~900 events of ~28000) consistent with expectation.
- **Important verification of angular resolution and absolute pointing.**

MODEL TESTING



40-string Source List Results

Northern Sky **Sources:**

Highest significance comes from southern sky (see next slide)

P-values >=0.5 (downward fluctuations) are given as "---"

Source Name	Ra , Dec (deg)	p-value
Cyg_OB2	(308.083, 41.510) :	---
MGRO_J2019+37	(305.220, 36.830) :	0.42759
MGRO_J1908+06	(286.976, 6.269) :	---
Cas_A	(350.850, 58.815) :	---
IC443	(94.179, 22.529) :	---
Geminga	(98.476, 17.770) :	0.47413
Crab_Nebula	(83.633, 22.014) :	---
1ES_1959+650	(299.999, 65.149) :	---
1ES_2344+514	(356.770, 51.705) :	---
3C66A	(35.673, 43.043) :	0.23808
H_1426+428	(217.136, 42.672) :	---
BL_Lac	(330.680, 42.278) :	0.22601
Mrk_501	(253.468, 39.760) :	0.42262
Mrk_421	(166.114, 38.209) :	0.14000
W_Comae	(185.382, 28.233) :	---
1ES_0229+200	(38.202, 20.287) :	0.15528
M87	(187.706, 12.391) :	---
S5_0716+71	(110.473, 71.343) :	---
M82	(148.967, 69.680) :	0.39095
3C_123.0	(69.268, 29.671) :	0.43538
3C_454.3	(343.491, 16.148) :	0.45811
4C_38.41	(248.815, 38.135) :	0.47329
PKS_0235+164	(39.660, 16.620) :	0.13602
PKS_0528+134	(82.735, 13.532) :	0.48542
PKS_1502+106	(226.104, 10.494) :	0.10331
3C_273	(187.278, 2.052) :	---
NGC_1275	(49.951, 41.512) :	---
Cyg_A	(299.868, 40.734) :	0.44191
IC-22_maximum	(153.375, 11.375) :	---

22-string hottest spot is now a downward fluctuation →

← …Southern Sky sources continue on next slide

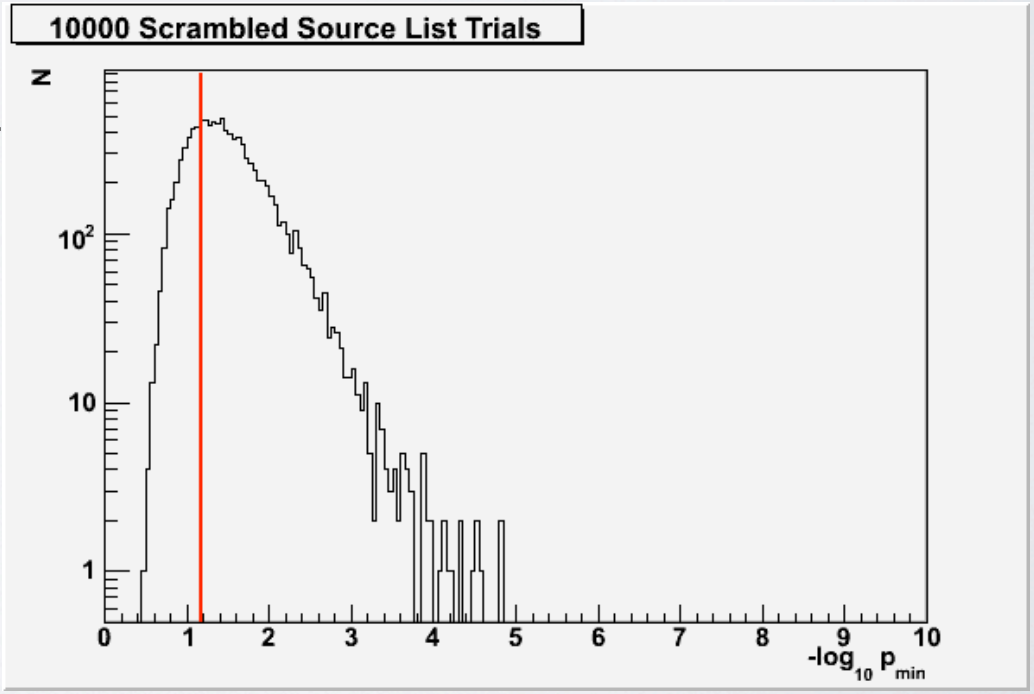
40-string Source List Results (cont.)

Highest significance from list of 39 sources comes from PKS 1622-297

Southern Sky **Sources:**

Source Name	Ra , Dec (deg)	p-value
Sgr_A*	(266.417, -29.008) :	---
PKS_0537-441	(84.710, -44.086) :	---
Cen_A	(201.365, -43.019) :	---
PKS_1454-354	(224.361, -35.653) :	---
PKS_2155-304	(329.717, -30.225) :	0.31679
PKS_1622-297	(246.525, -29.857) :	0.06622
QSO_1730-130	(263.261, -13.08) :	0.44807
PKS_1406-076	(212.235, -7.874) :	0.36176
QSO_2022-077	(306.420, -7.640) :	---
3C279	(194.050, -5.790) :	0.48659

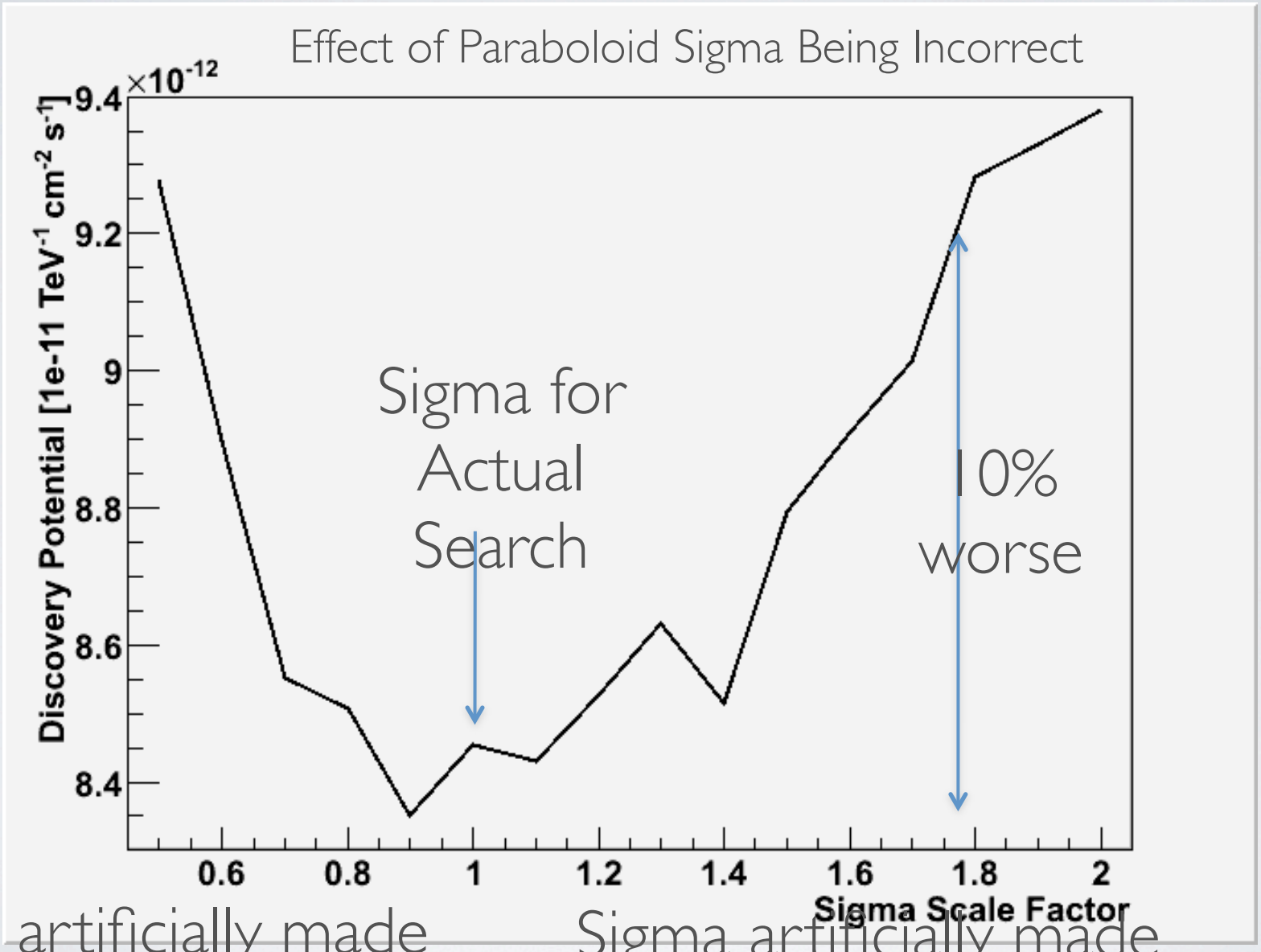
Pretrial p-value of 6.6% or less for any of the 39 sources happens in 75% of scrambled skymaps => **source list final p-value = 75%**



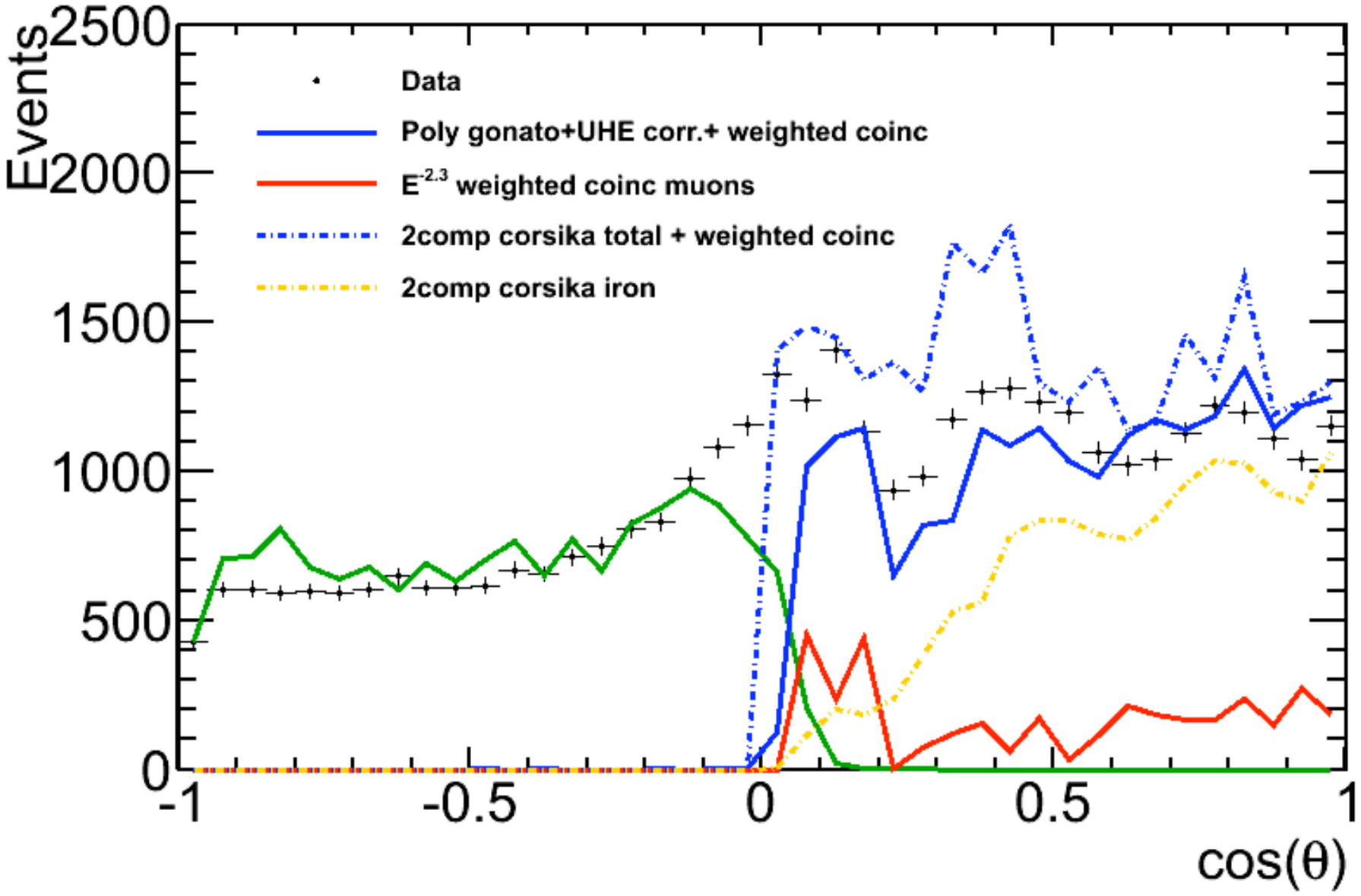
Systematic errors total

For fluxes we consider error on eff area:
Nsel/Ngen (detector response) x cross section x muon range
asymmetric error from S pdf (method) due to main source of discrepancy between data and MC (including DOM sensitivity 8%, ice properties):
NCh
-13% sensitivity (90%cl)
-18% disc potential(5 sigma)
sigma: ±8%
Cross section: ±2%
Muon prop: ±3%

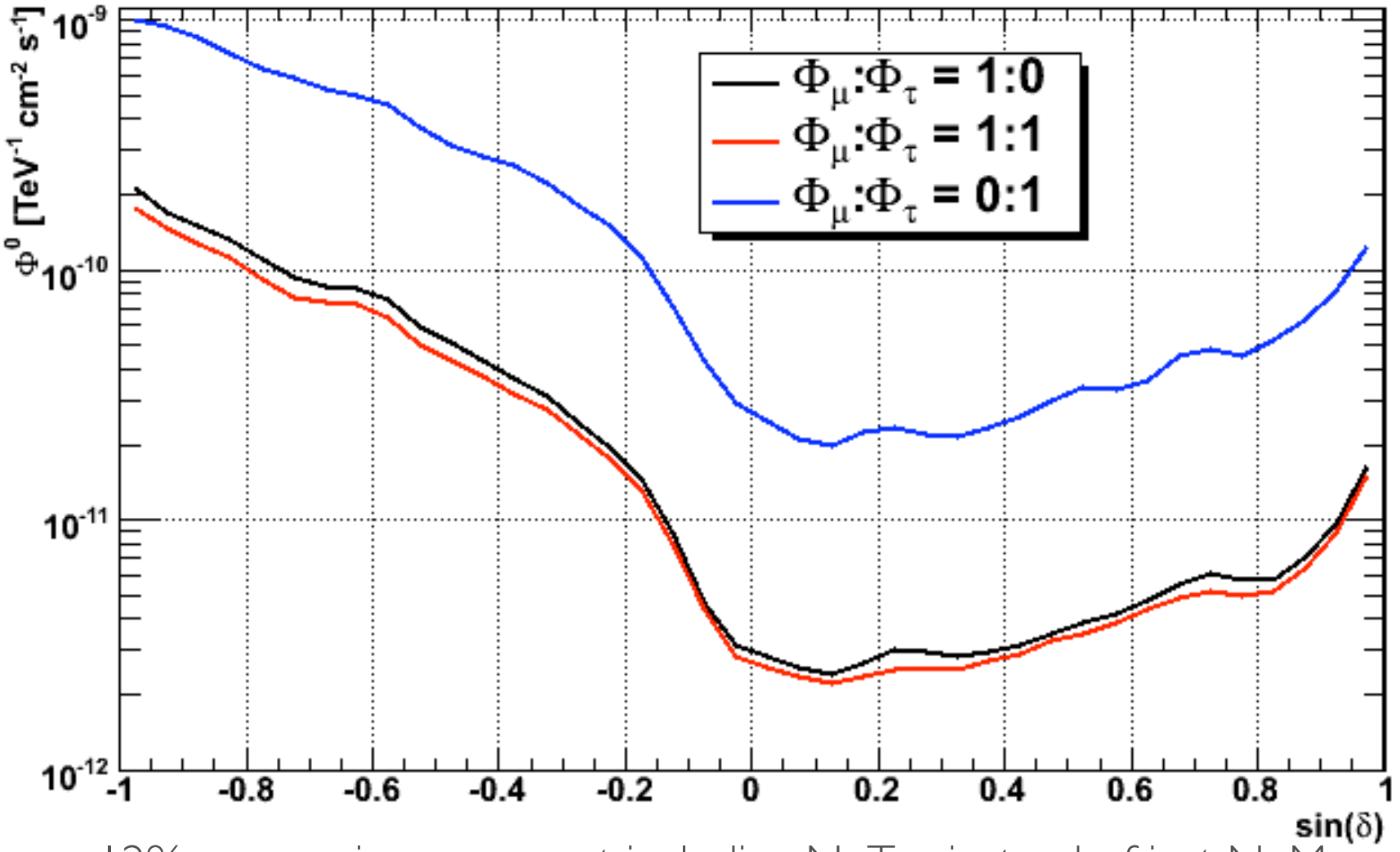
SYSTEMATICS – PSF



IC40 FINAL ZENITH – CR



E^{-2} SENSITIVITY INCLUDING



- 12% average improvement including NuTau instead of just NuMu
- More improvement near up-going (Tau regeneration) and down-going (some UHE Tau tracks)

Nearby Clusters of Galaxies

CR Distribution Model	Median Sensitivity (IC40)
Uniform inside shock radius	2.8 * prediction
Uniform inside virial radius	4.3 * prediction
Trace hot gas (X-rays)	4.6 * prediction
Central AGN Model	1.9 * prediction

Could begin to rule out CR sources and CR propagation models in ~ 1 yr of full IceCube, or start to see Clusters in neutrinos

Murase et al. 2008, arXiv:0805.0104v2