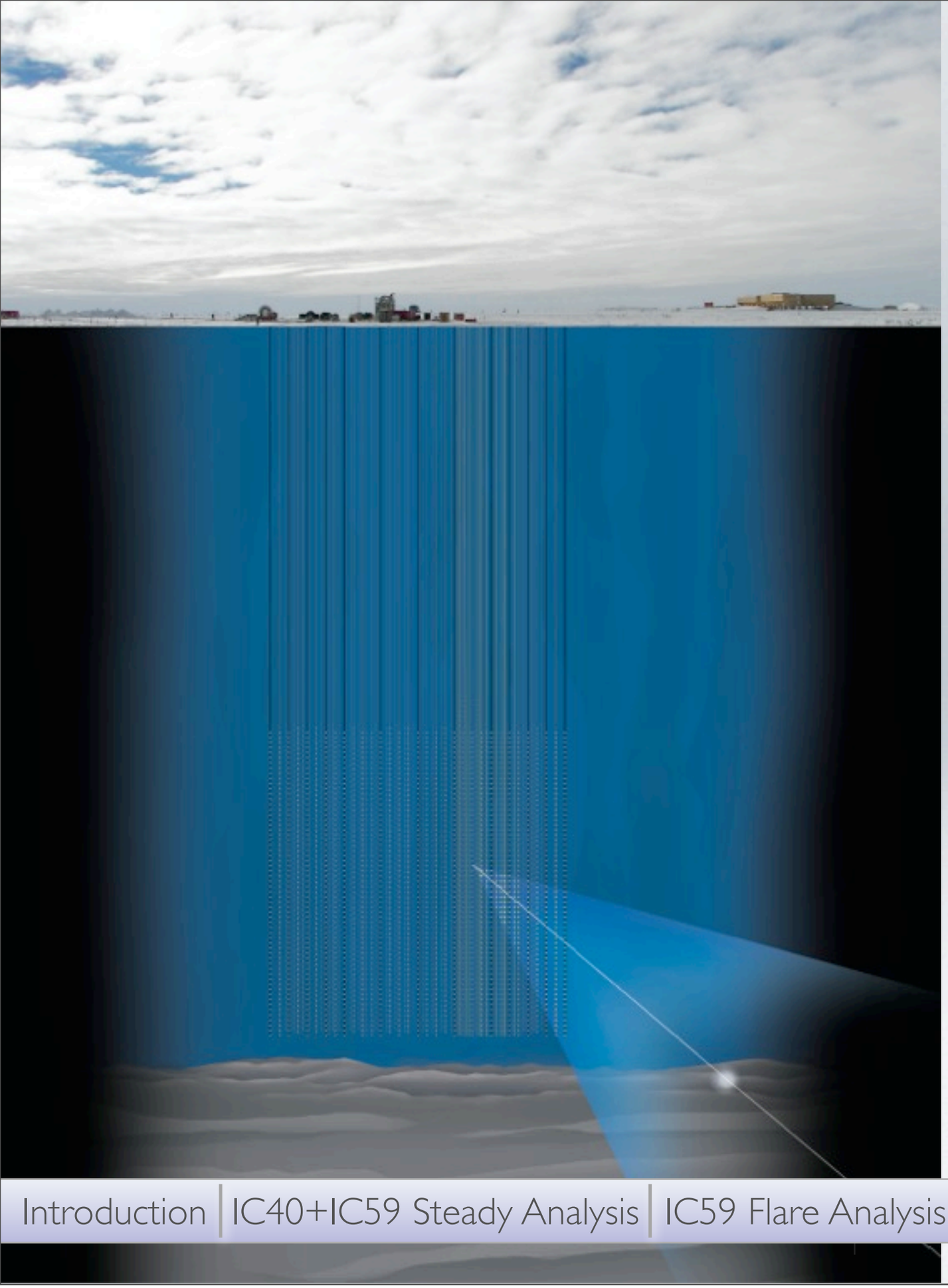


NEUTRINO POINT-SOURCE SEARCH IN ICECUBE

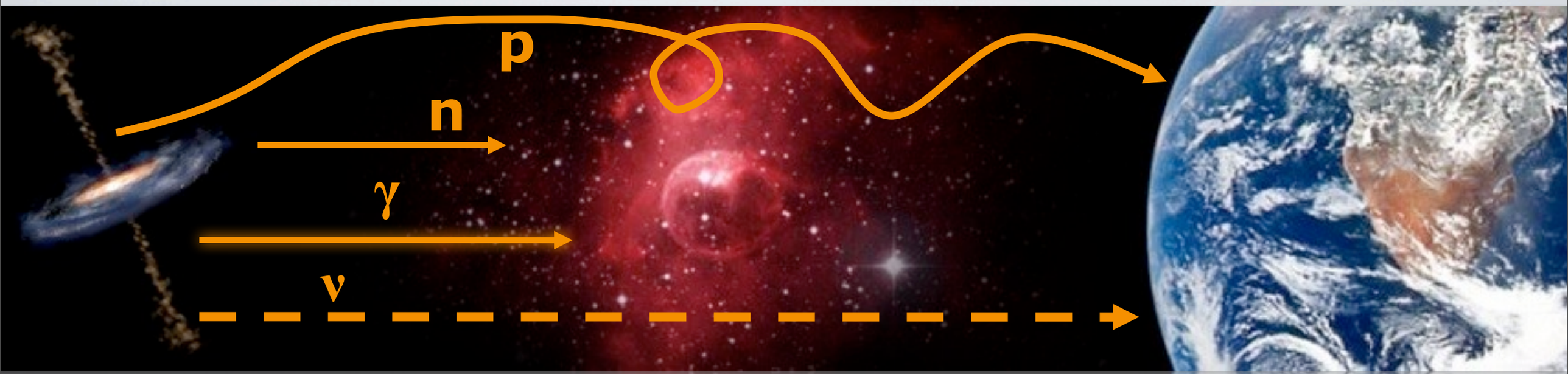
Juan Antonio Aguilar

TeVPA 2011 Stockholm, Sweden

Introduction | IC40+IC59 Steady Analysis | IC59 Flare Analysis | Conclusions

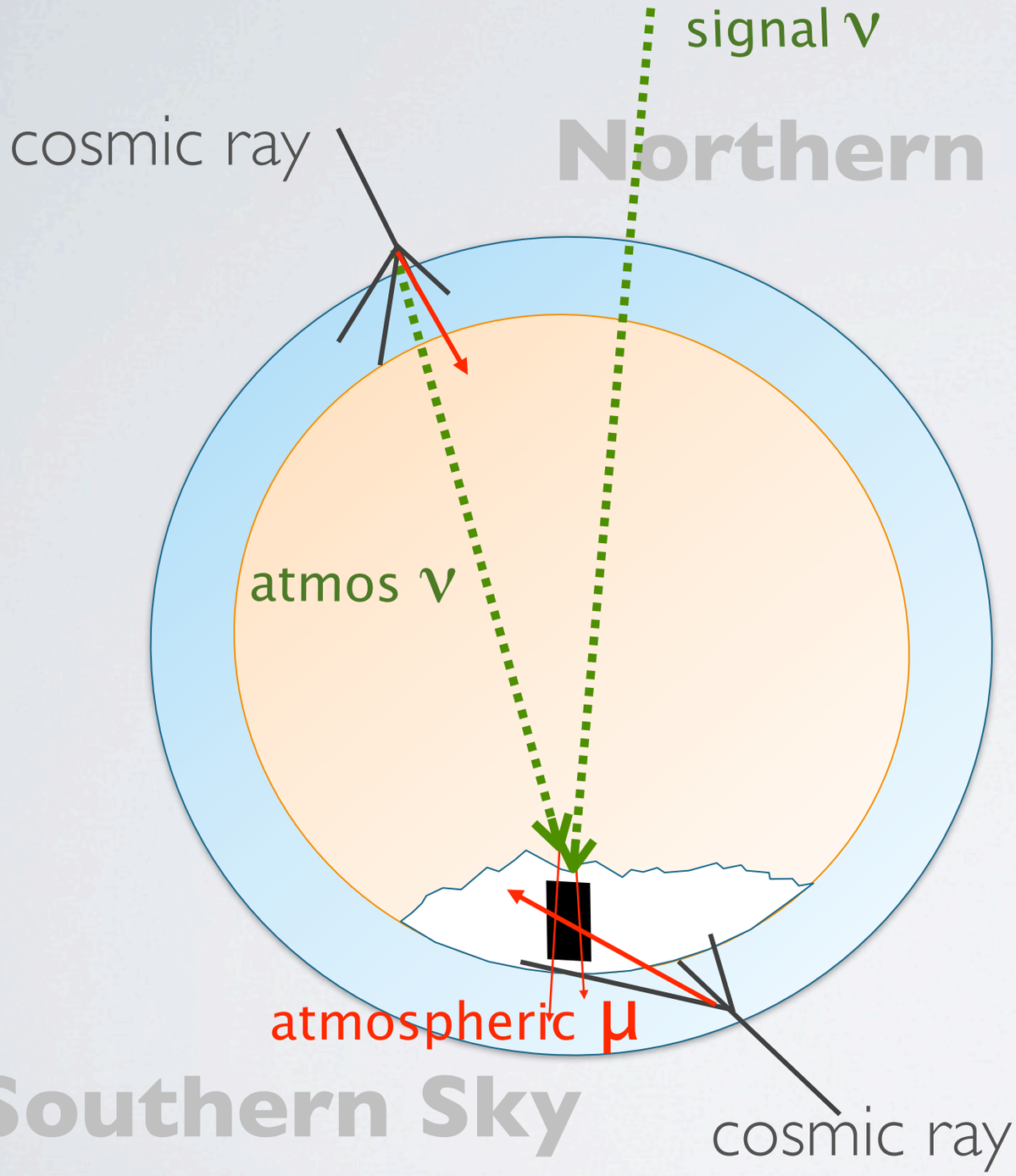
Neutrino Astronomy and IceCube

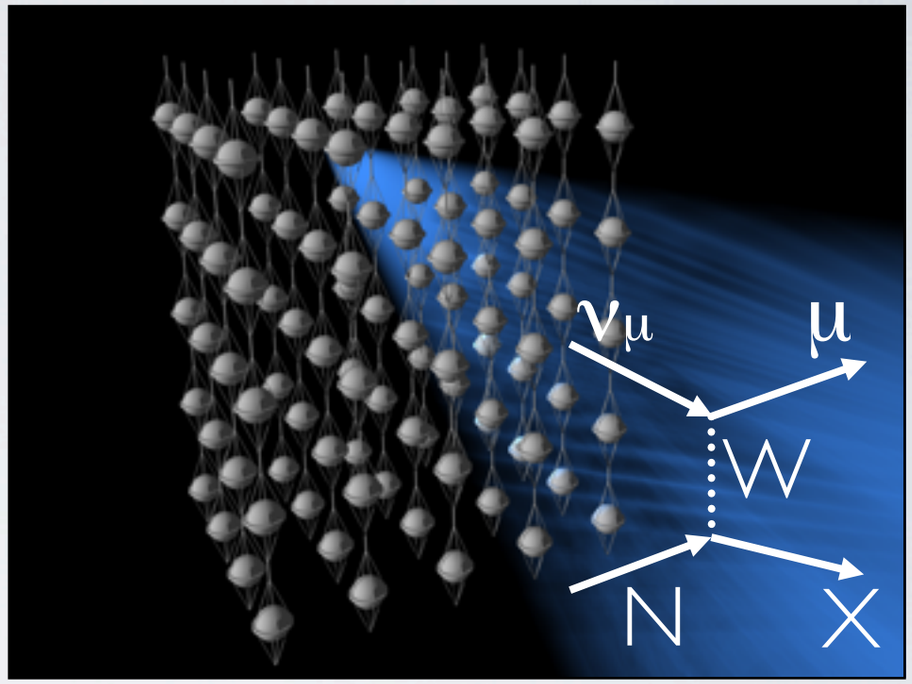
NEUTRINO ASTRONOMY

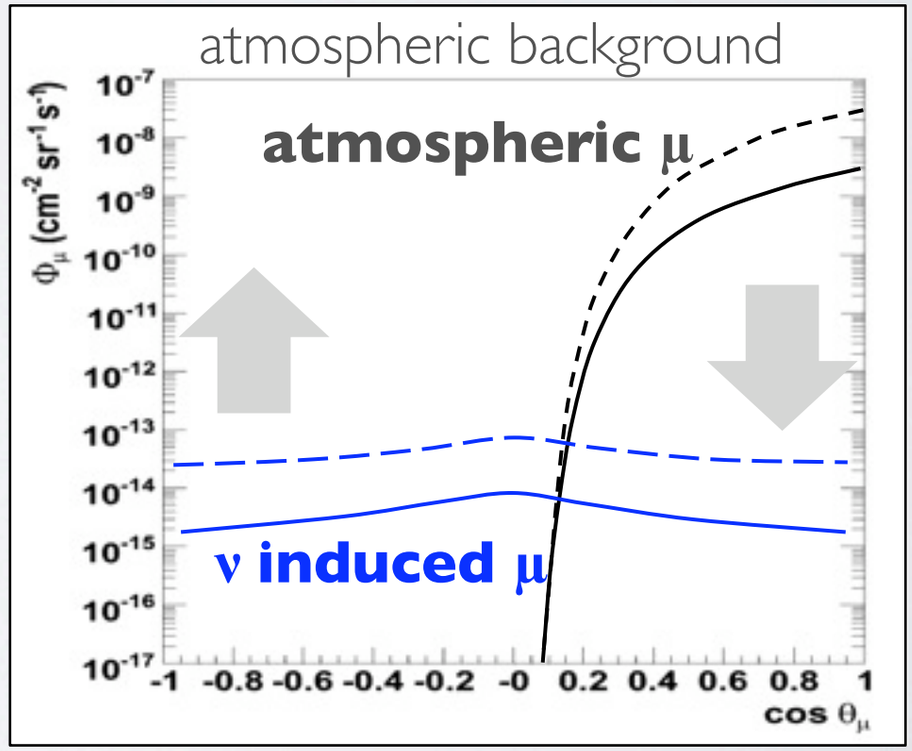


- Protons are deviated by magnetic fields ($E_p < 10^{19}$) and very energetic protons travel distances of a few Mpc.
- Neutrons reach distances of ~kpc at very high energy.
- Photons interact with the EBL (~100 Mpc) and CMB (~10 kpc).
- Neutrinos are neutral stable weakly interacting particles.

DETECTION PRINCIPLE







ICECUBE COLLABORATION

10 countries, 36 institutions, ~260 collaborators

Bartol Research Inst, Univ of Delaware, USA
University of Alaska Anchorage, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

University of Alberta, Canada

Univ. of Alabama, USA
Clark-Atlanta University, USA
Georgia Tech
Ohio State University
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA

University of the West Indies, Barbados

Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
TWTH Aachen, Germany
Universität Bonn, Germany
Ruhr-Universität, Bochum, Germany
MPI, Heidelberg, Germany

Uppsala Universitet, Sweden
Stockholm Universitet, Sweden

Imperial College, London, UK
University of Oxford, UK

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons, Belgium
Universiteit Gent, Belgium

EPFL, Lausanne, Switzerland

Chiba University, Japan

University of Canterbury, Christchurch, New Zealand

THE ICECUBE OBSERVATORY

South Pole Station

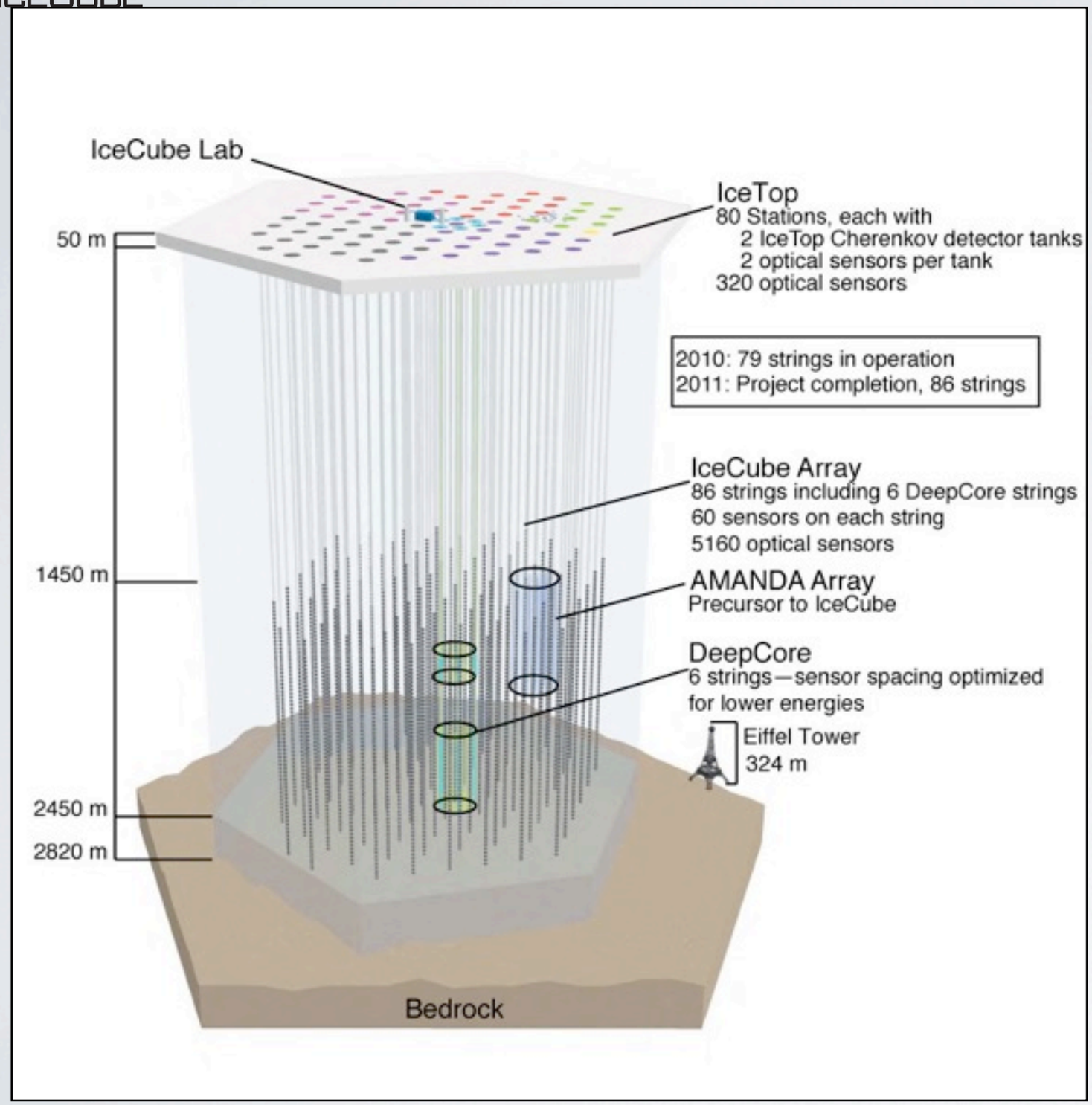
Geographic South Pole

IceCube outline

Skiway

Introduction | IC40+IC59 Steady Analysis | IC59 Flare Analysis | Conclusions

ICECUBE



IceCube

Completion with 86 strings in January 2011

IceCube 79 (2010-11)

79 strings are in operation.

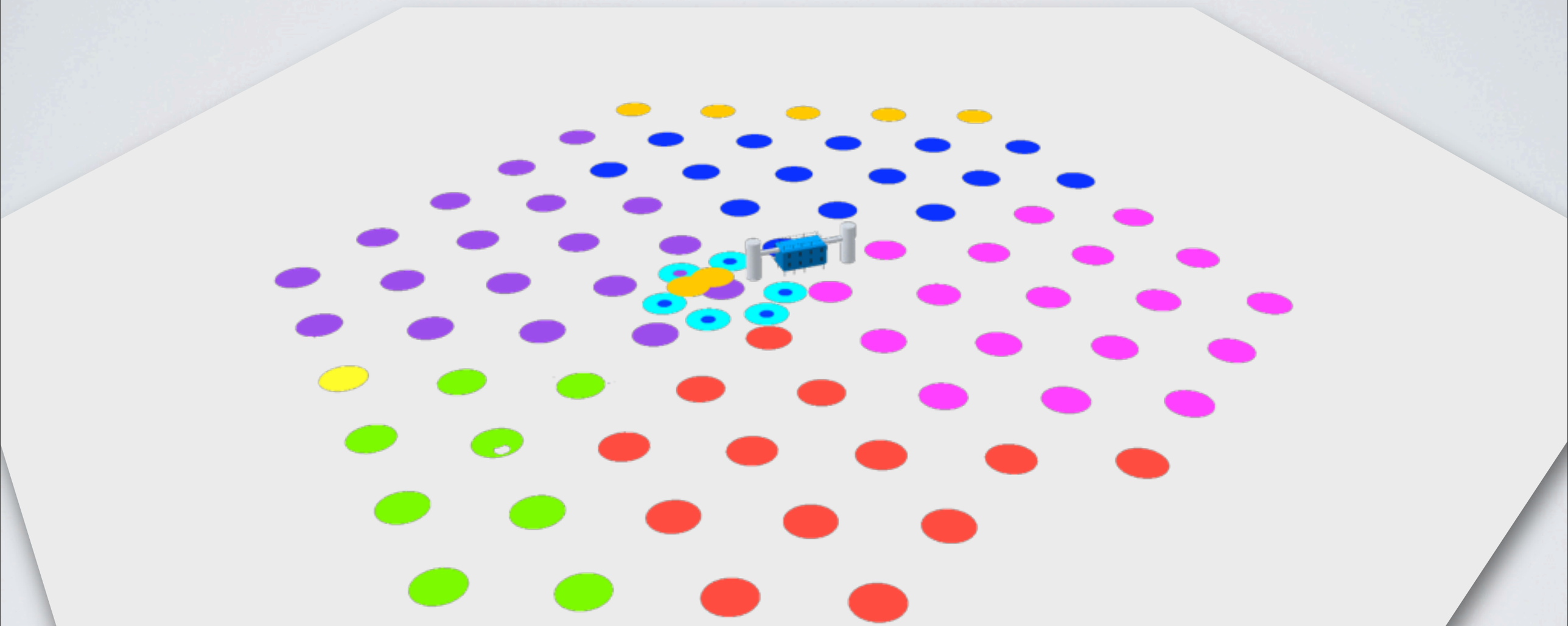
IceCube 59 (2009-10)

IceCube IC59 data is being processed. Analysis starting now.

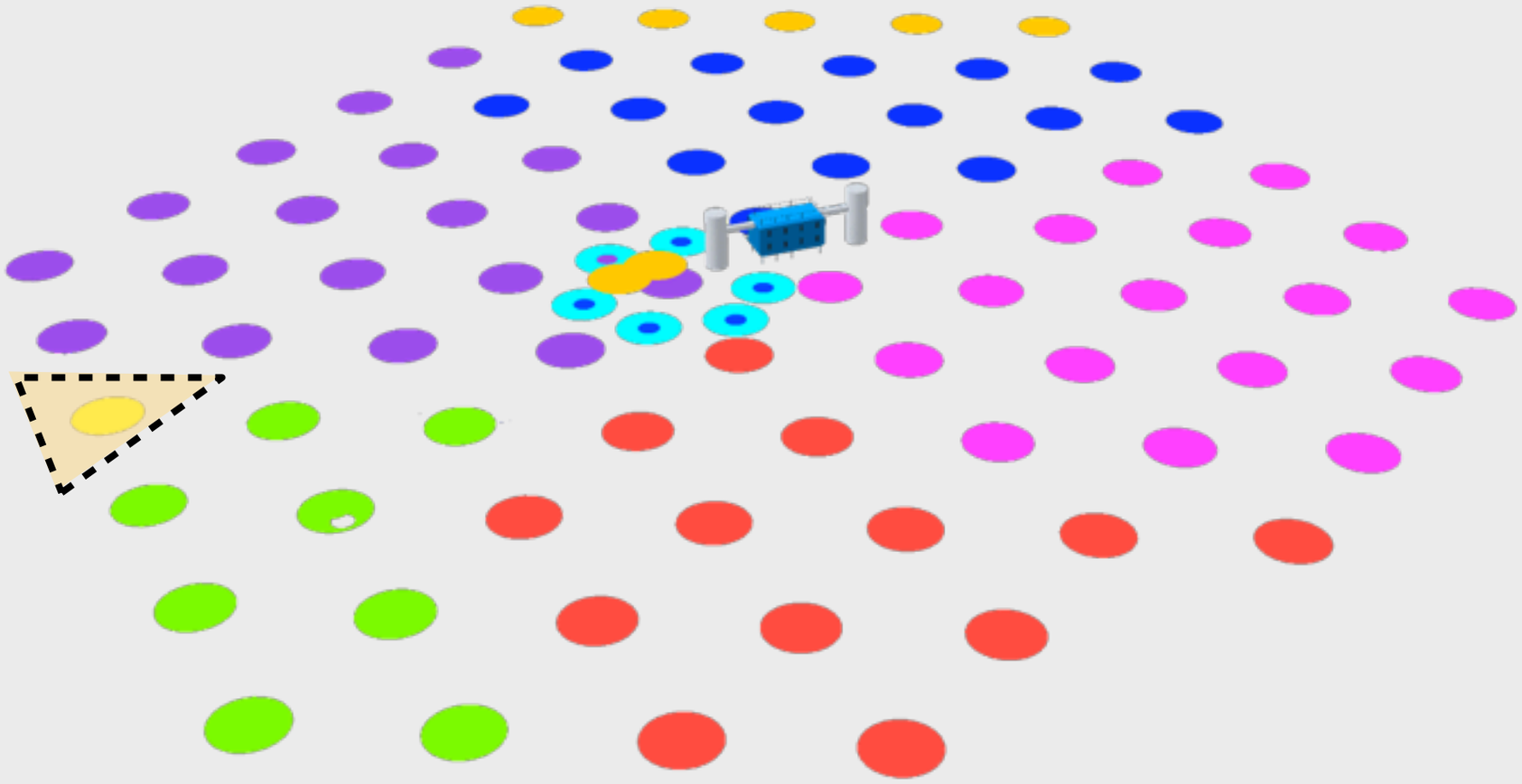
IceCube 40 (2008-9)

IC40 data has been analyzed for point sources.

ICECUBE CONFIGURATIONS

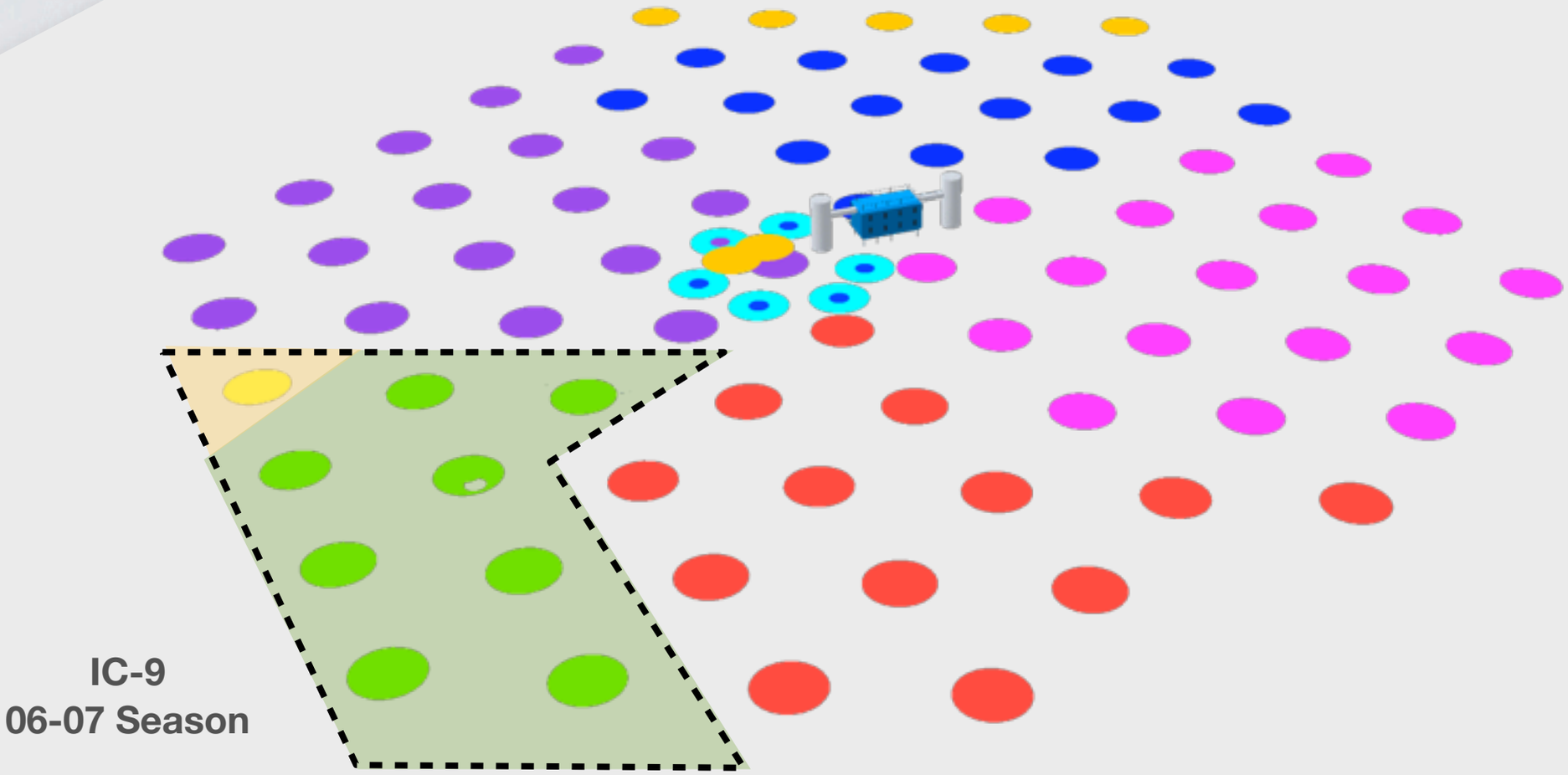


ICECUBE CONFIGURATIONS

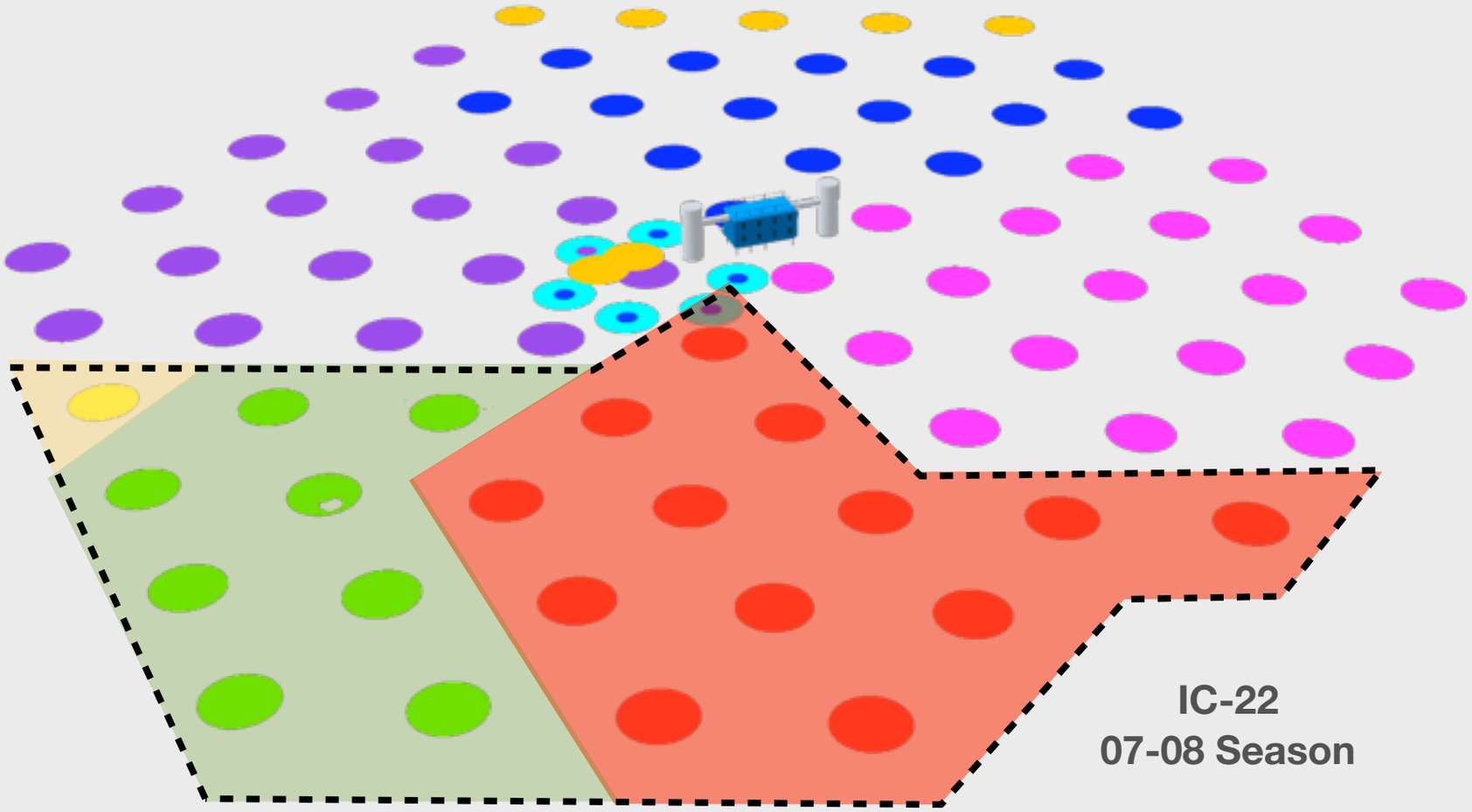


IC-1
05-06 Season

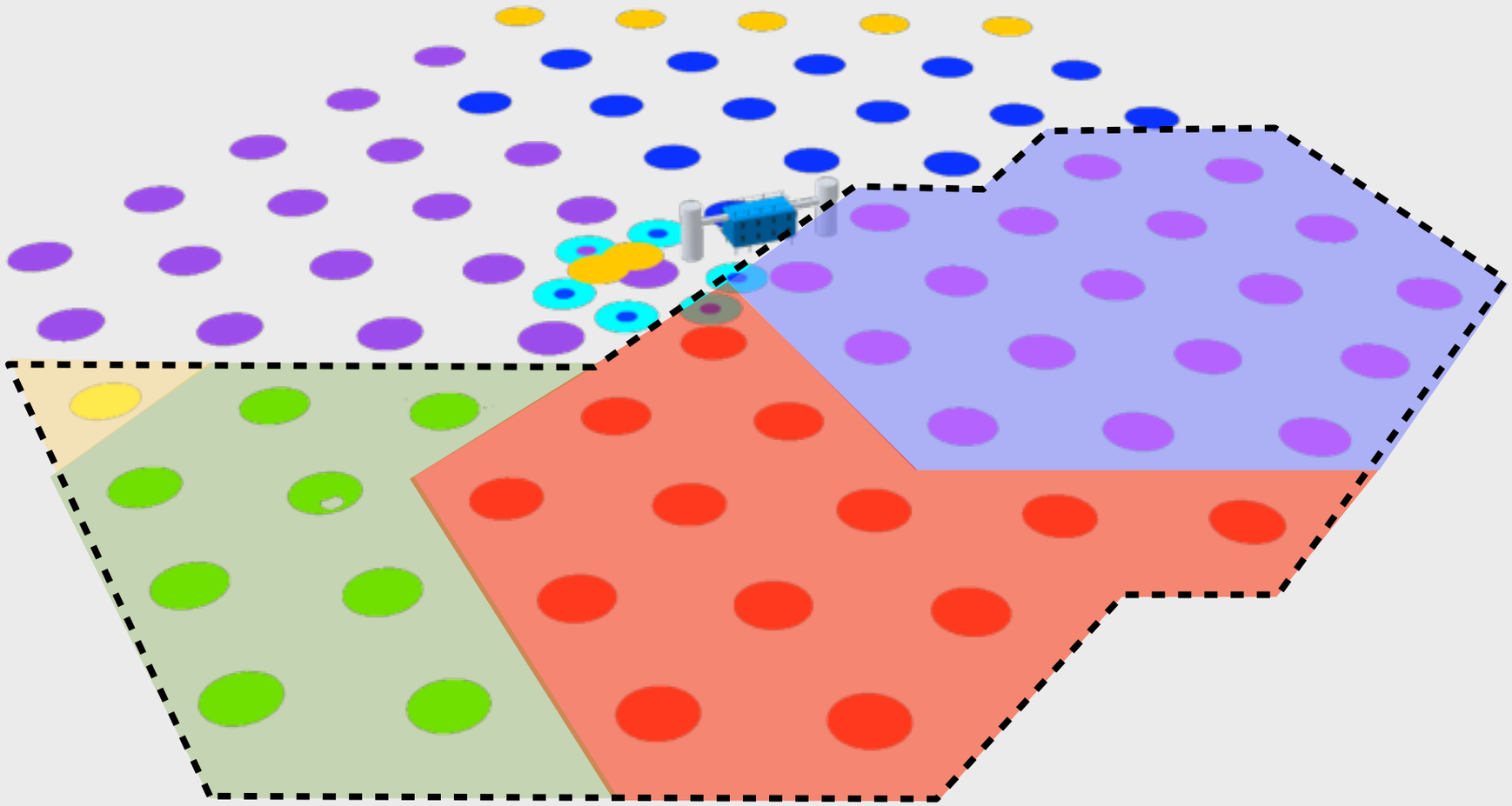
ICECUBE CONFIGURATIONS



ICECUBE CONFIGURATIONS

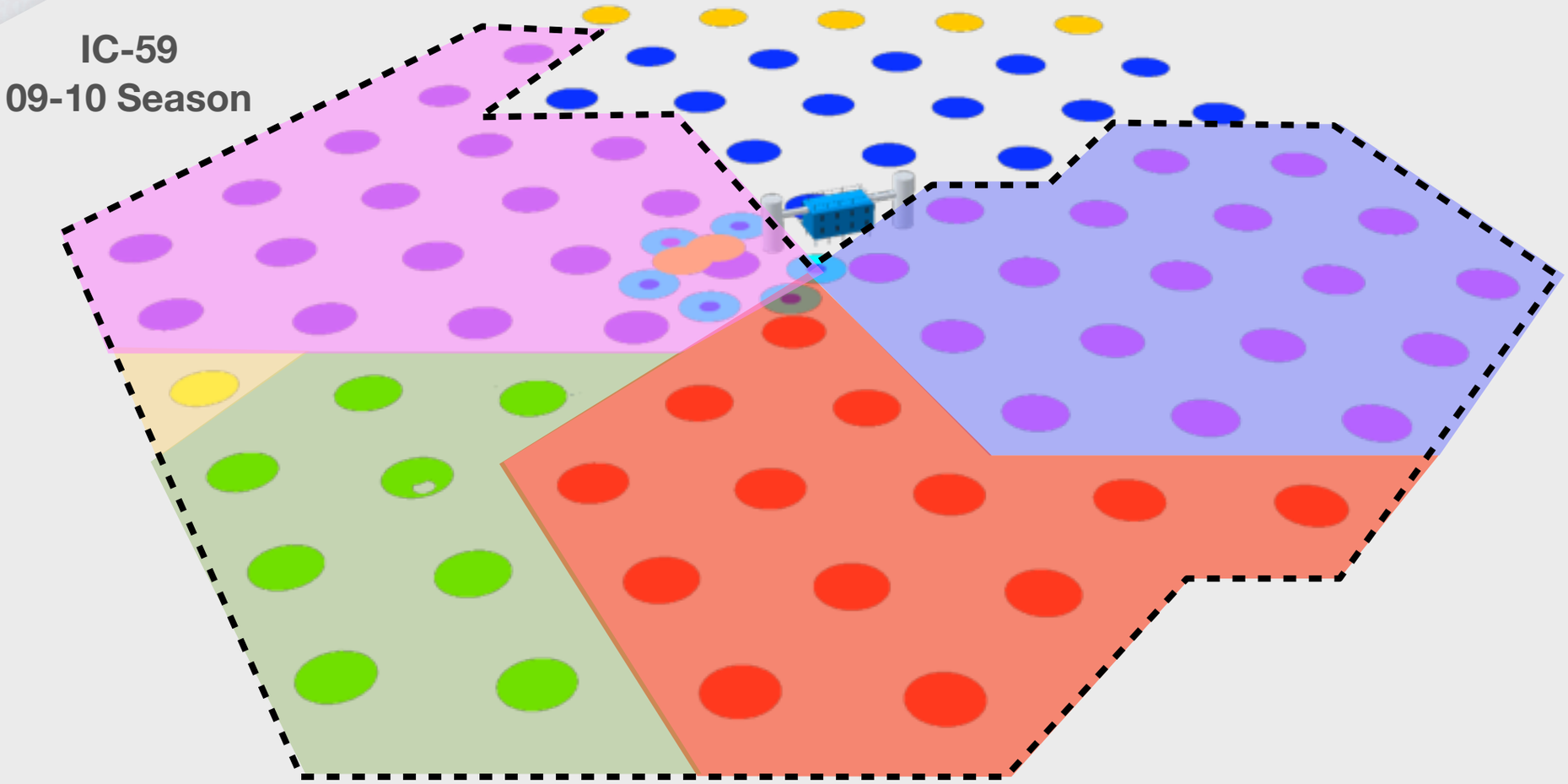


ICECUBE CONFIGURATIONS

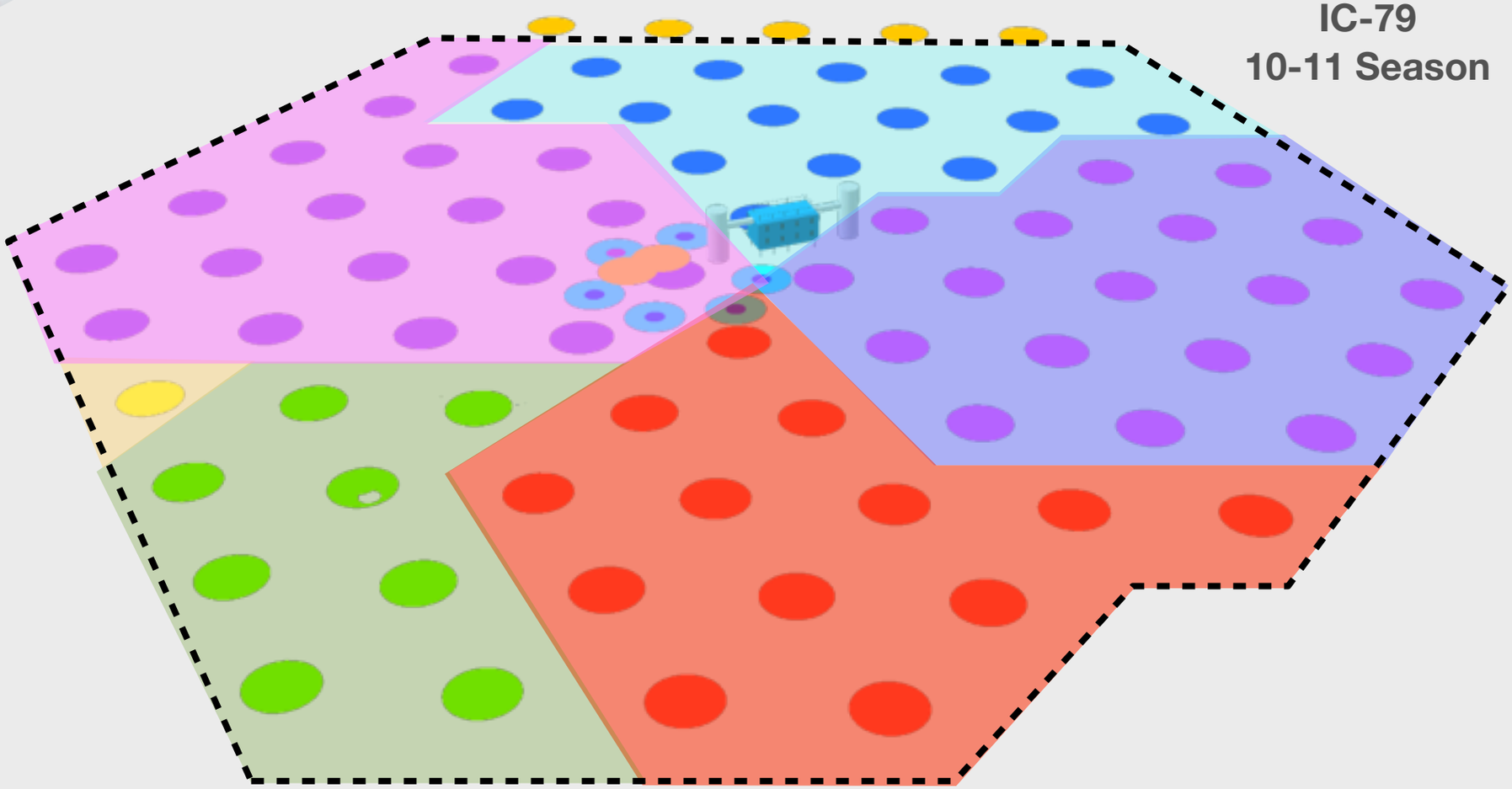


IC-40
08-09 Season

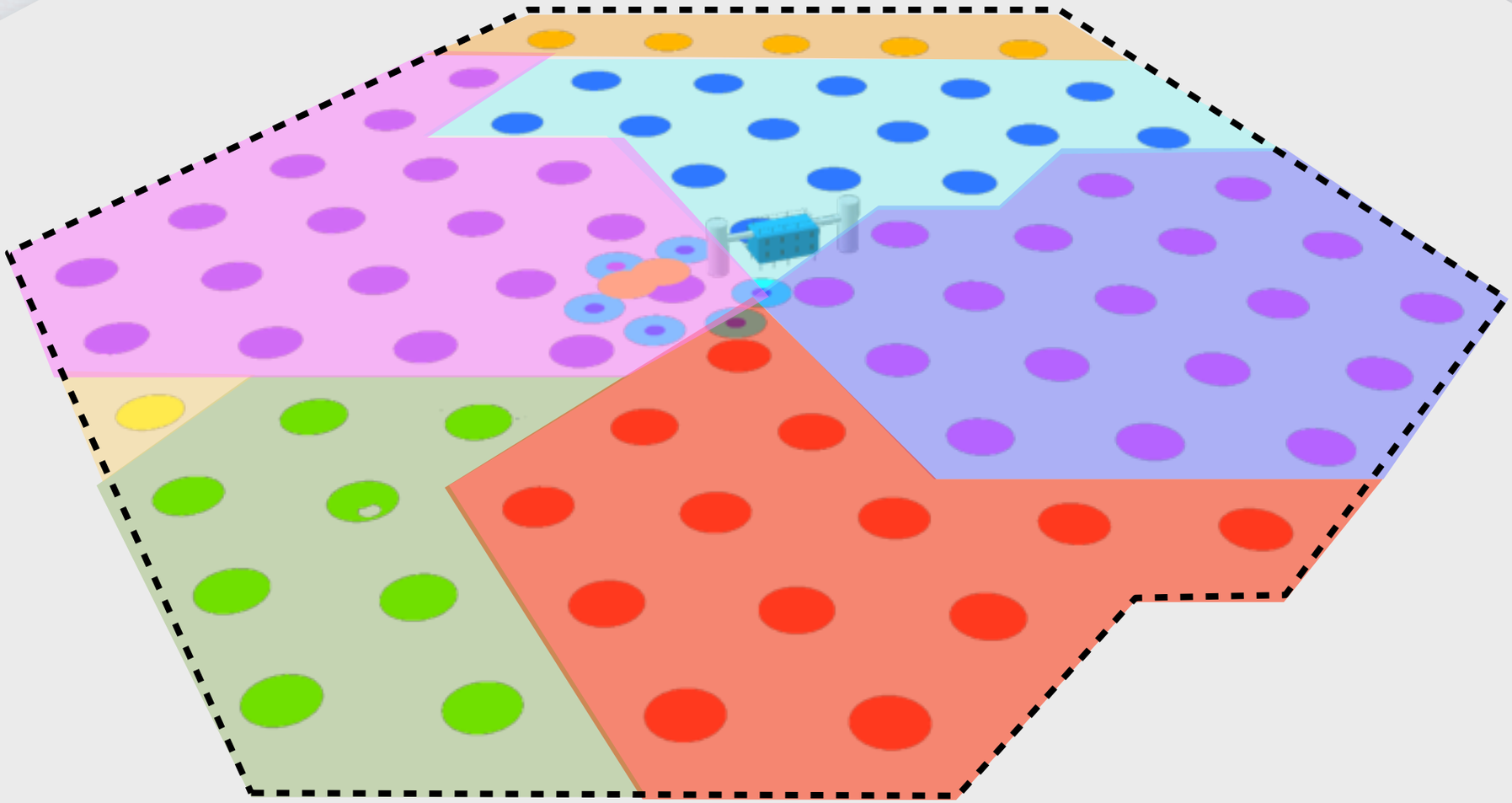
ICECUBE CONFIGURATIONS



ICECUBE CONFIGURATIONS



ICECUBE CONFIGURATIONS



Construction finished on January 2011

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	~ 170/d

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

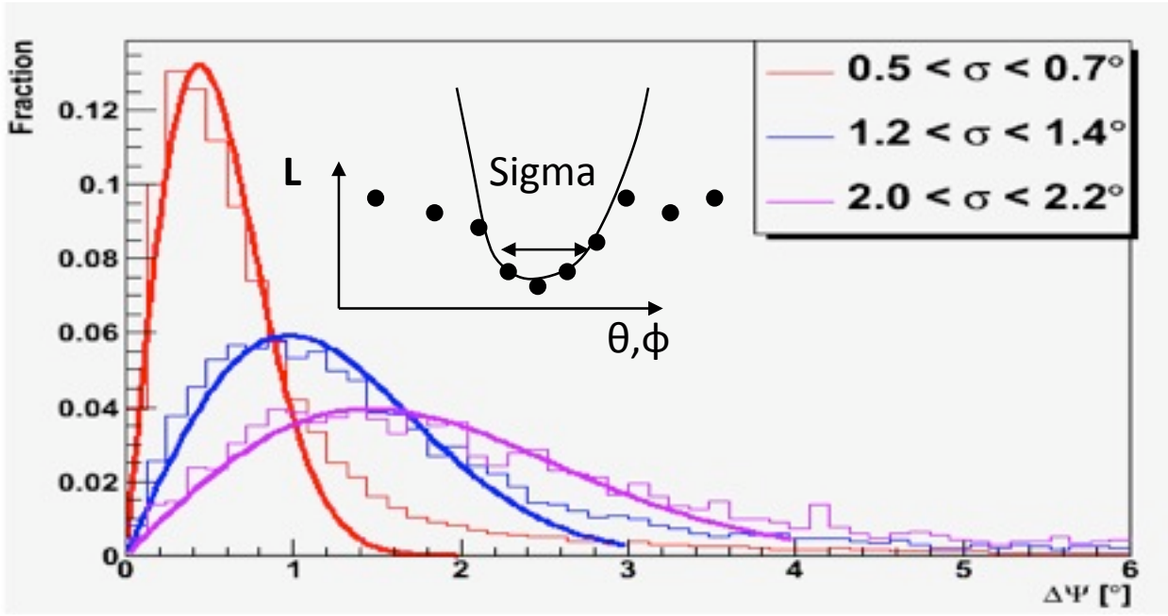
IC59+IC40 POINT SOURCE ANALYSIS

LIKELIHOOD AND DENSITY FUNCTIONS

Signal pdf:

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

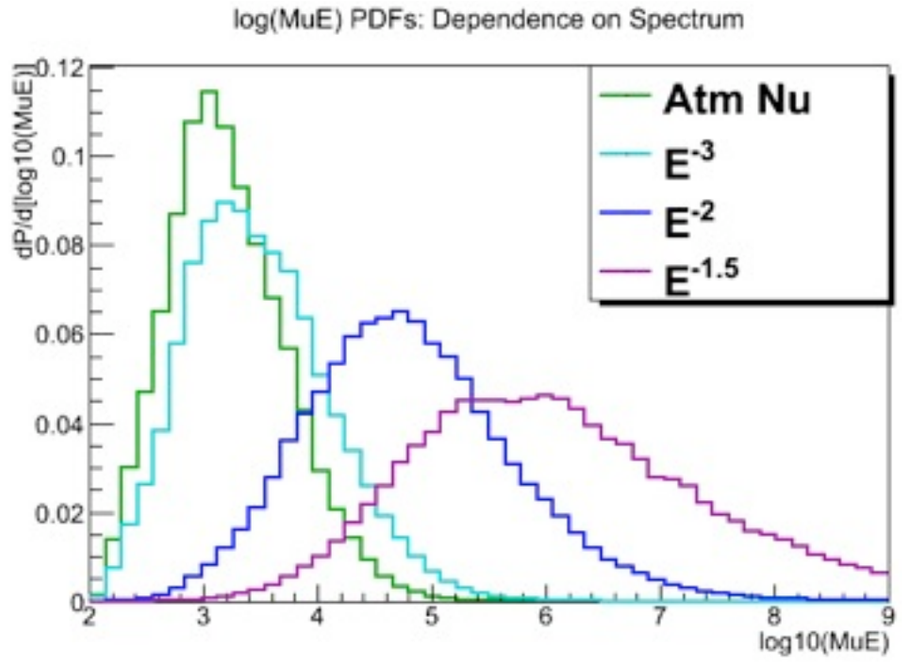
Likelihood Space around track solution fit to paraboloid: width = **σ**



LIKELIHOOD AND DENSITY FUNCTIONS

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 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:

$$\mathcal{B}_i = B(\theta_i) \cdot P_{atm}(E_i)$$

Scrambled real data.
(zenith dependence)

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:

$$\mathcal{B}_i = B(\theta_i) \cdot P_{atm}(E_i)$$

Likelihood:

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

Maximize:

- γ , the neutrino spectral index
- $\mathbf{n_s}$, number of signal events

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:

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Maximize:

- γ , the neutrino spectral index
- $\mathbf{n_s}$, number of signal events

Maximization of the likelihood ratio:

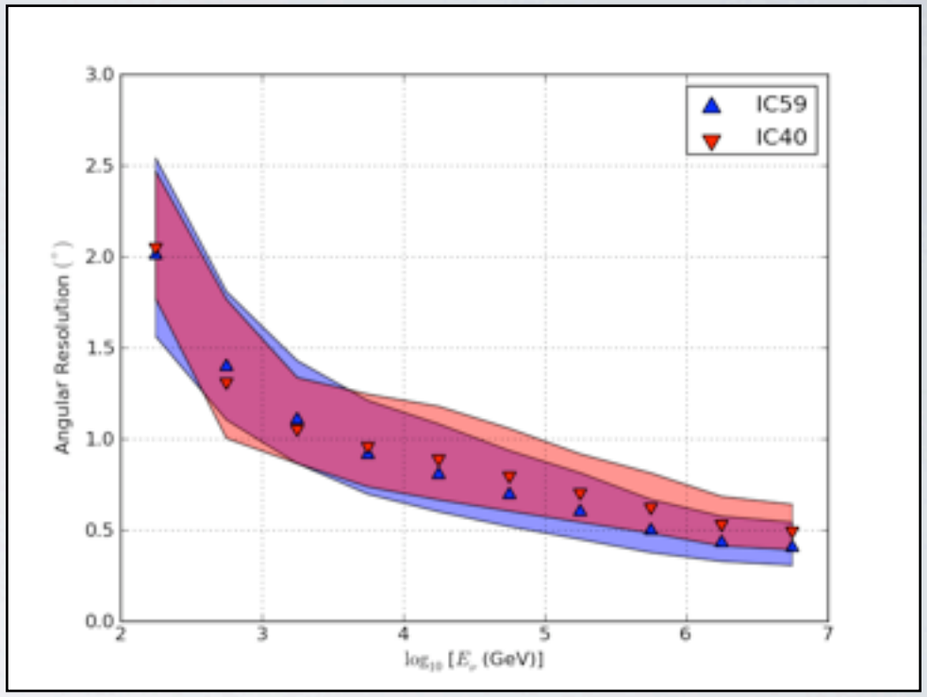
$$\log \lambda = \log \left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Estimates that maximize the Likelihood

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

COMBINING DATASETS

- We combined the IC59 data and IC40 data into one likelihood analysis.
- Each dataset has its own background distribution and detector performance.

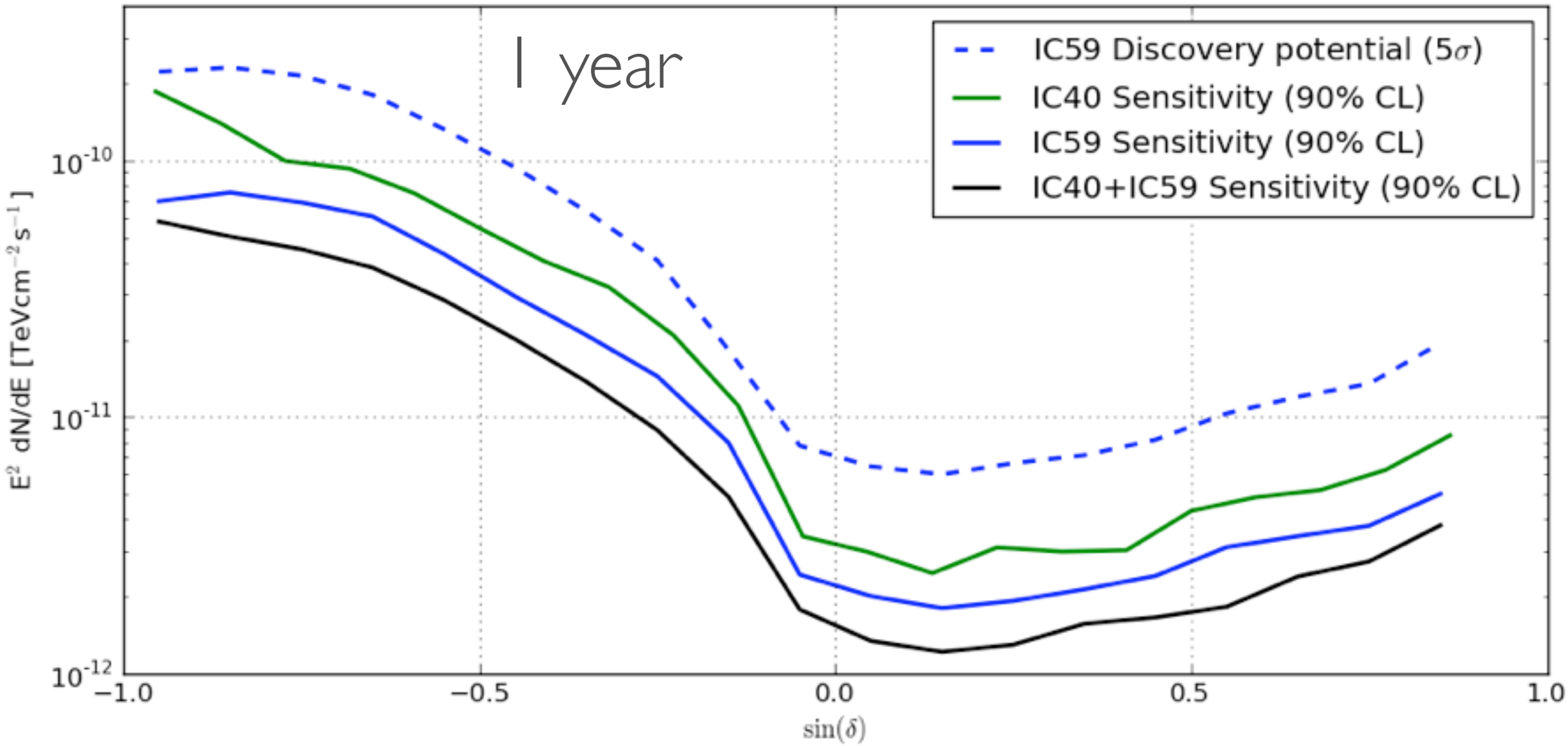


$$\mathcal{L}(n_s,\gamma) = \prod_{i=1}^{N}\left(\frac{n_s^j}{n_{tot}^j}\mathcal{S}_i^j + \left(1-\frac{n_s^j}{n_{tot}^j}\right)\mathcal{B}_i^j\right)$$

where j = {IC40, IC59}
and $N = n_{tot}^{IC40} + n_{tot}^{IC59}$

- The signal hypothesis is the same: $\gamma = \gamma_{IC40} = \gamma_{IC59}$
- The expected number of signal events depend on the detector acceptance, livetime and event selection: $n_s = n_s^{IC40} + n_s^{IC59}$

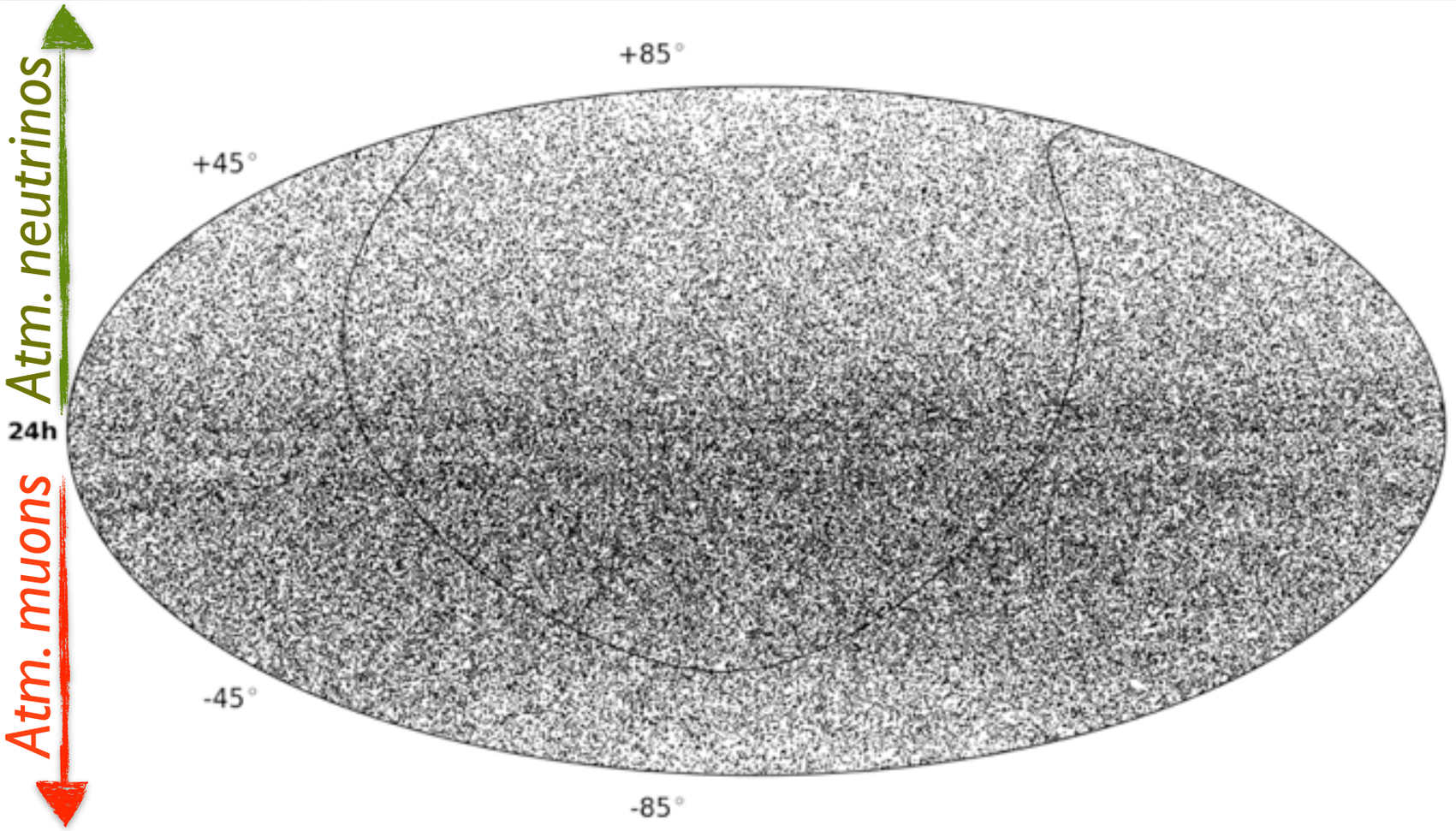
SENSITIVITY IC40+IC59

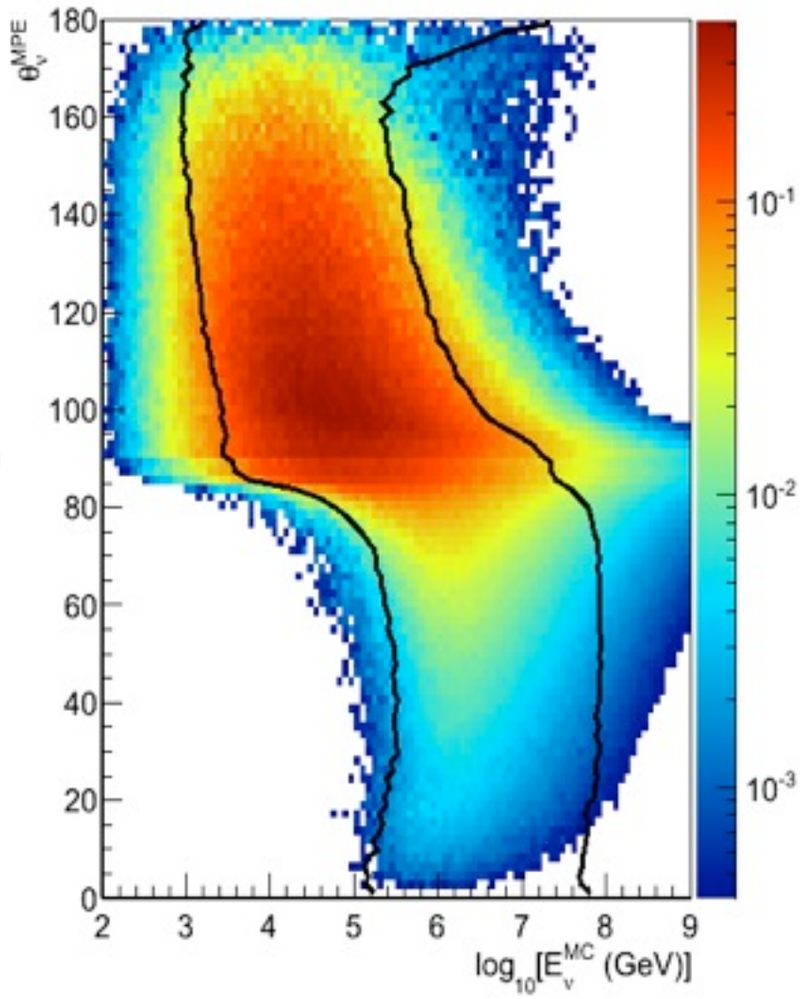


- The IC59 has a factor **~1.5x** better sensitivity compared to IC40.
- We can improve the sensitivity even more by combining the two data sets and reach the IC86 expected sensitivity.

IC40+IC59 POINT SOURCES RESULTS

COMBINING DATASETS

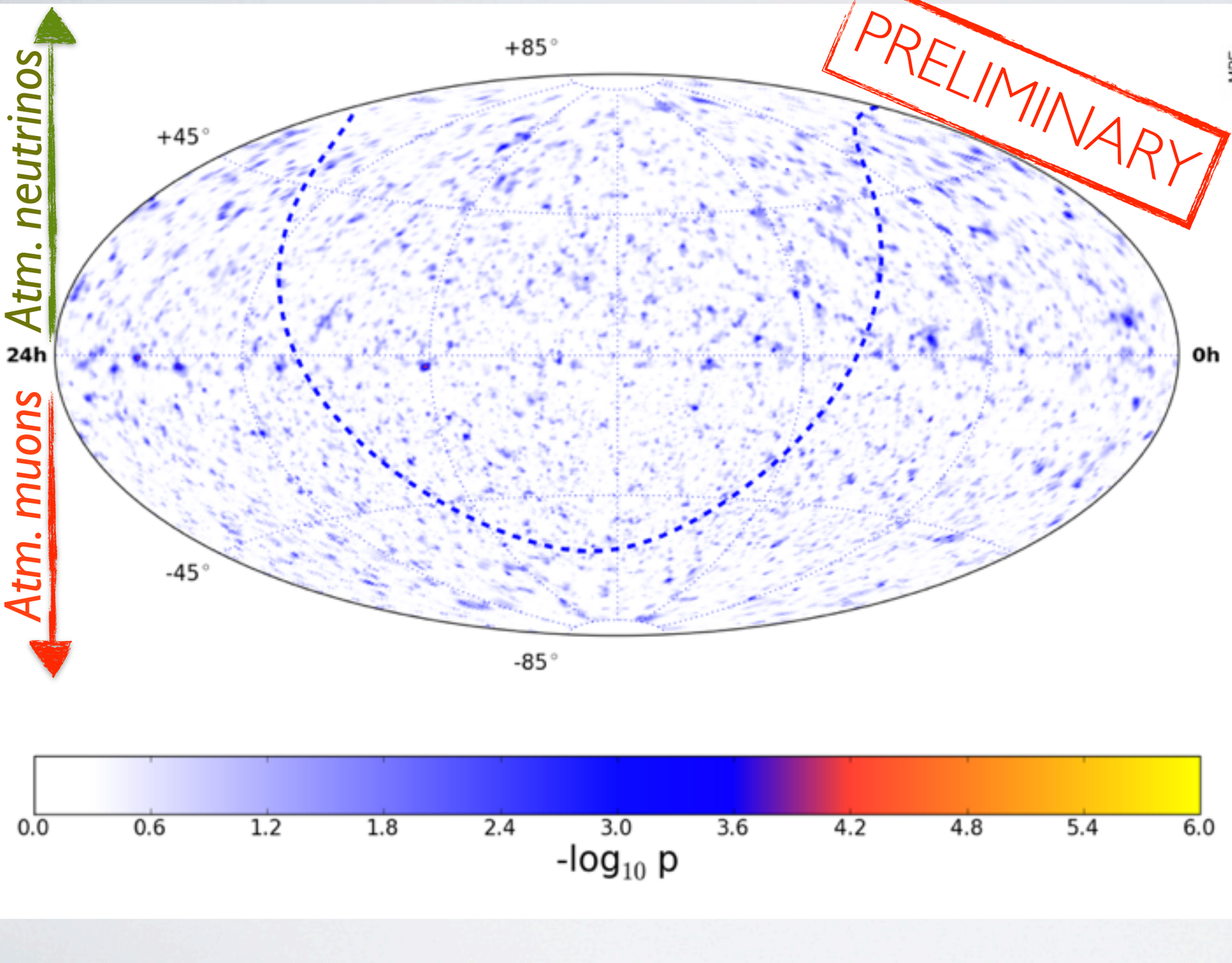


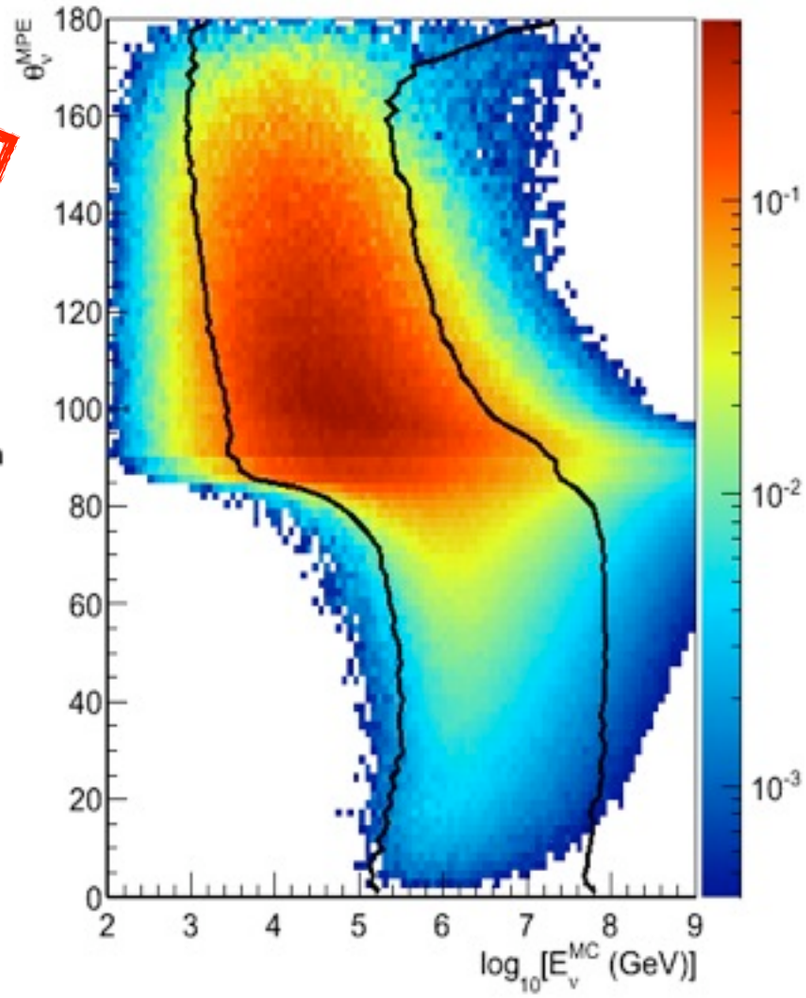


- *Total events: 43339 (upgoing) + 64230 (downgoing)*
- *Livetime: 348 days (IC59) + 375 days (IC40)*

COMBINING DATASETS

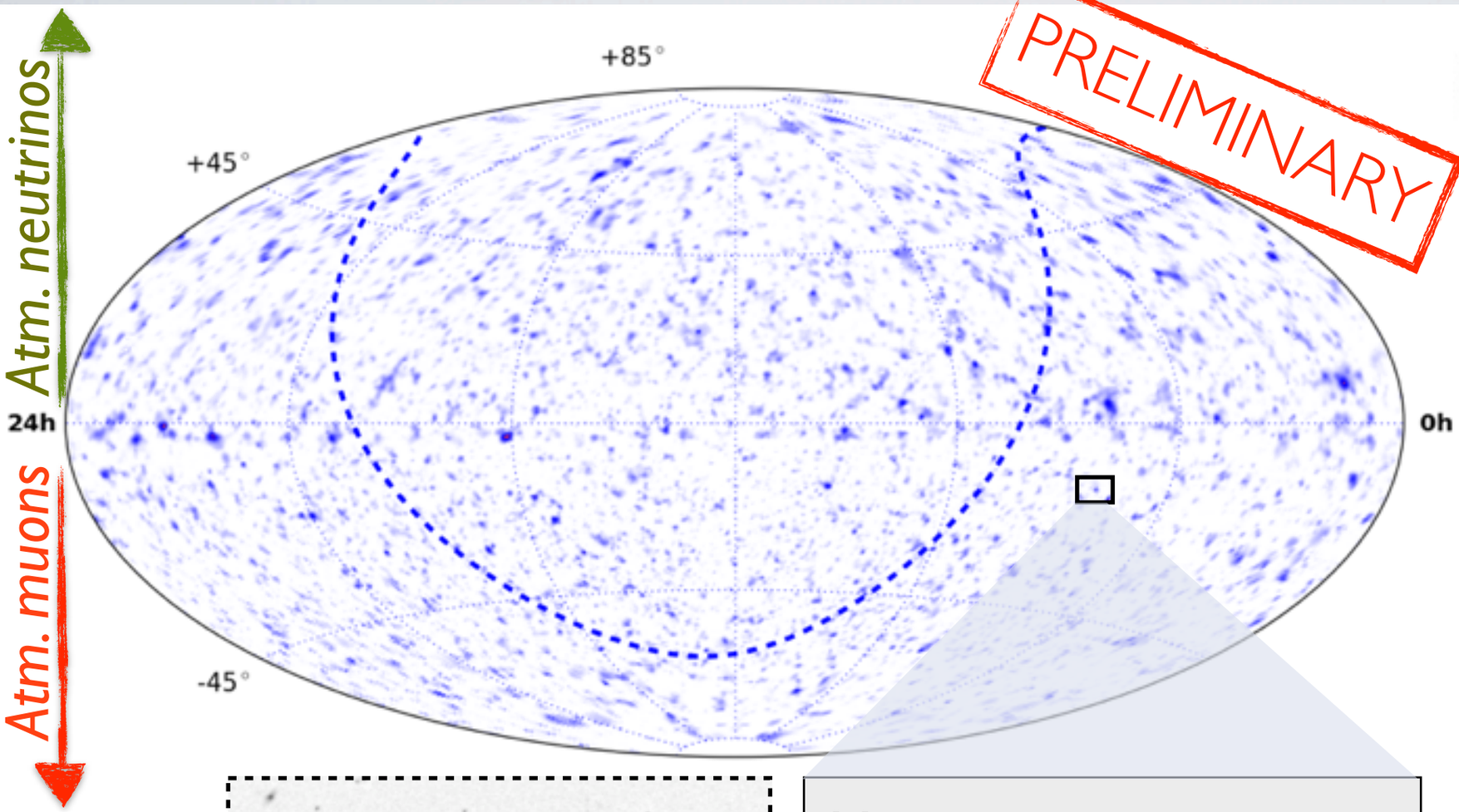
PRELIMINARY

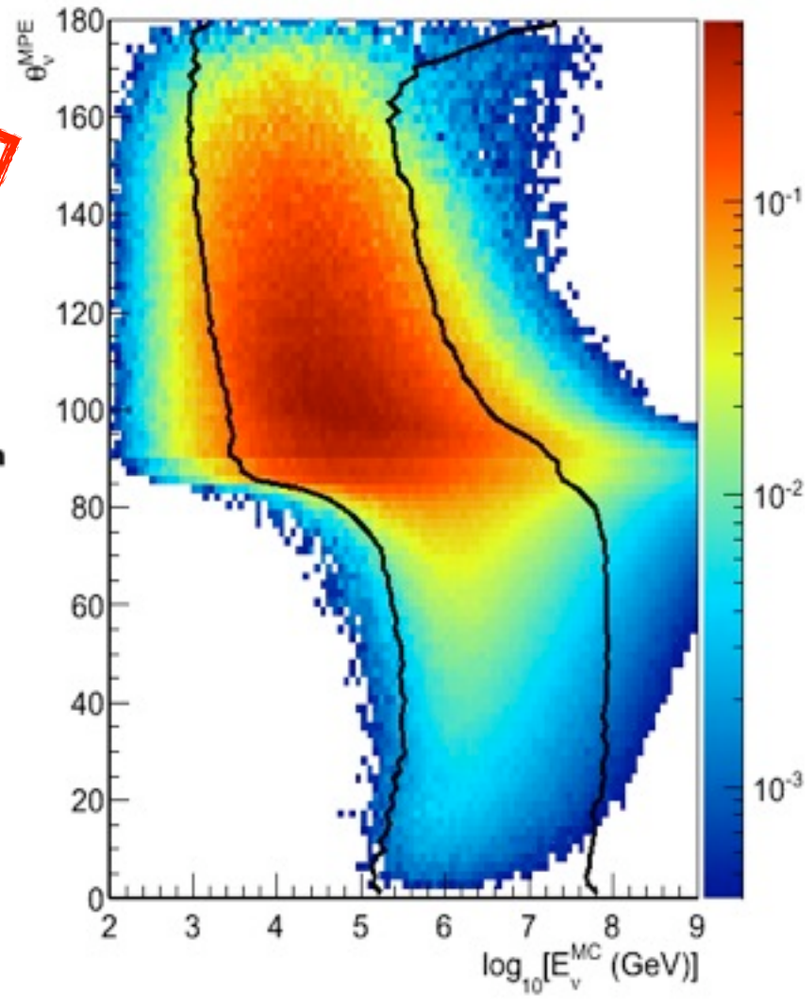




COMBINING DATASETS

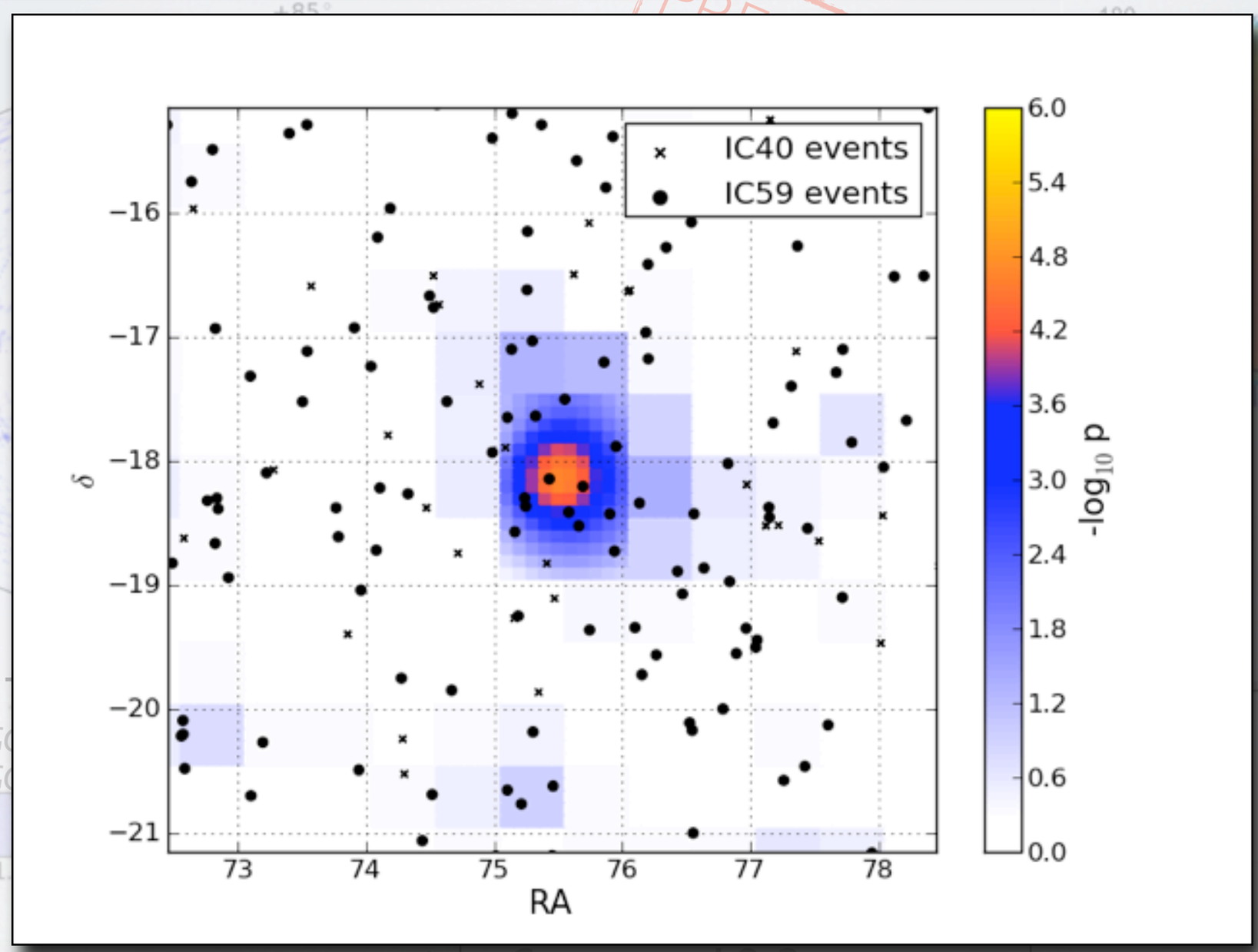
PRELIMINARY

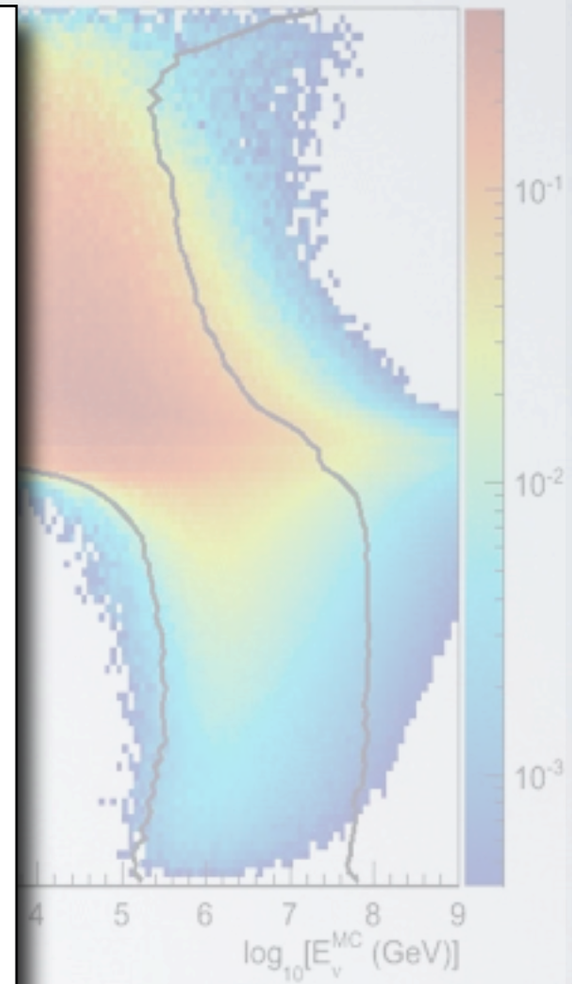




Hottest spot:
ra: 75.45
dec: - 18.15
$-\log_{10}$(p-value) = 4.65
$nSrc_{best}$ = 18.3
γ_{best}= 3.9

COMBINING DATASETS





Atm. neutrinos

Atm. muons

$nSrc_{best} = 18.3$

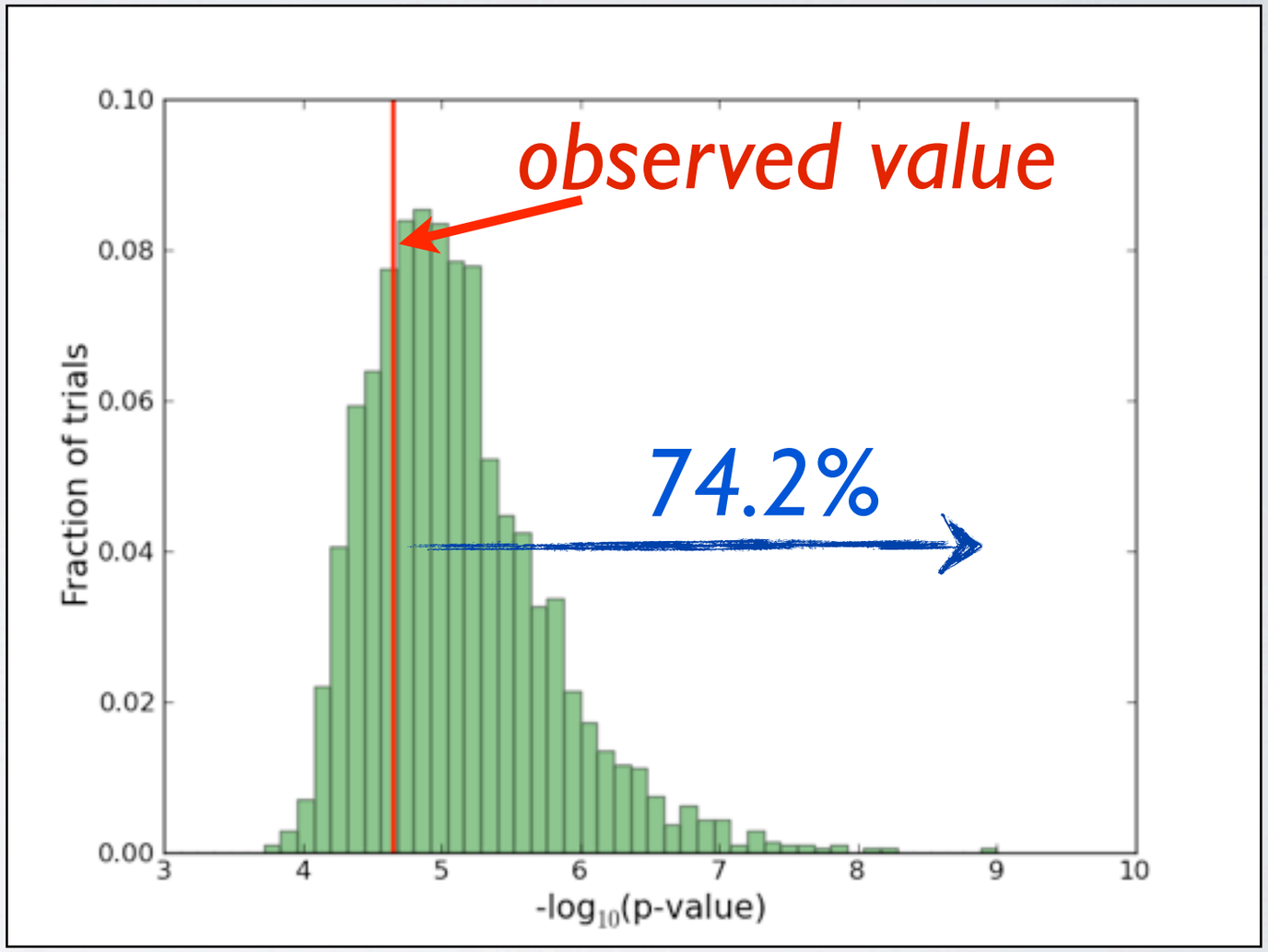
$\gamma_{best} = 3.9$

IC40 ALLSKY RESULTS

- We compare the outcome of the all sky survey with an ensemble of identical (on average) scrambled skymaps.

- For each of the 2000 scrambled trial, the same analysis is performed.

- **1484** of the **2000** scrambled skymaps had a significance equal or greater than that of the real dataset
  ➜ all-sky p-value (post-trial) = 74.2%.



IC40+IC59 SOURCE LIST

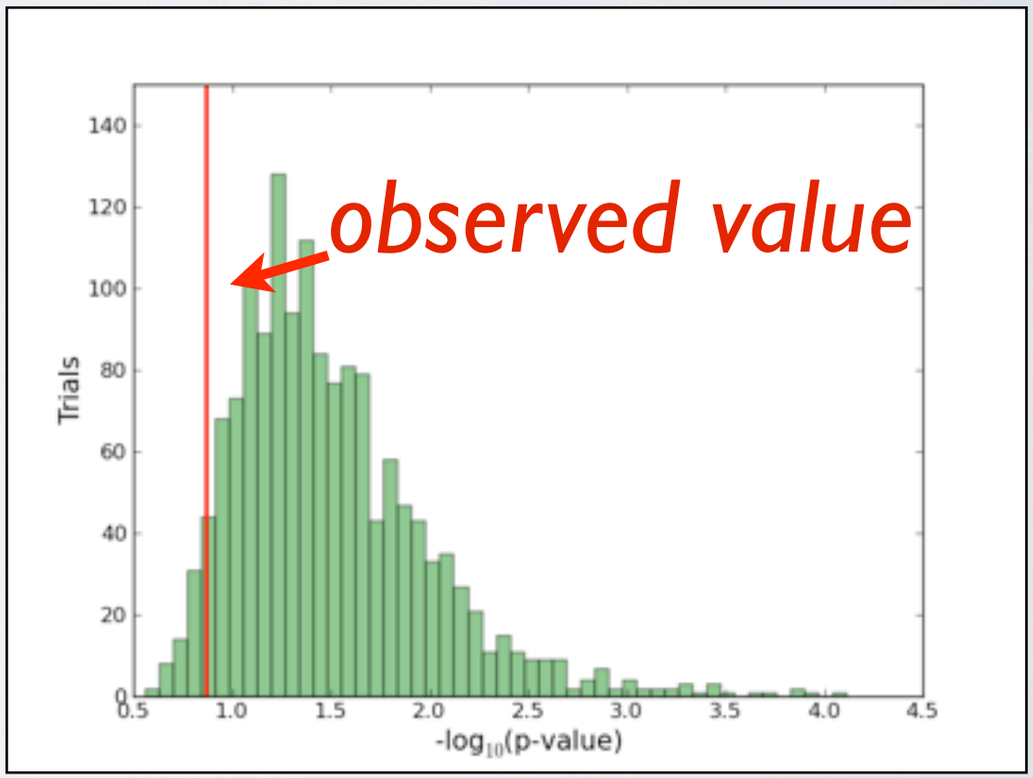
- We can reduce the number of trials by looking at pre-define directions in the sky.

- A set of candidate source is selected *a-priori*. The likelihood method is evaluated in position. Post-trial p-value is calculated using scrambled trials.

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	--
MGRO J2019+37	305.22	36.83	PWN	-	--
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	--
IC443	94.18	22.53	SNR	1.5 kpc	--
Geminga	98.48	17.77	Pulsar	100 pc	--
Crab Nebula	83.63	22.01	SNR	2 kpc	--
1ES 1959+650	300.00	65.15	HBL	z = 0.048	--
1ES 2344+514	356.77	51.70	HBL	z = 0.044	--
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	--
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	--
W Comae	185.38	28.23	HBL	z = 0.1020	--
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starbust	3.86 Mpc	--
3C 123.0	69.27	29.67	FRII	1038 Mpc	--
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3

PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	--
3C 273	187.28	2.05	FSRQ	z = 0.158	--
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	***201.37***	***-43.02***	***FRI***	***3.8 Mpc***	***0.14***
PKS 1454-354	***224.36***	***-35.65***	***FSRQ***	***z = 1.42***	***0.14***
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	--
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	--
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	--
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	--
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	--
Cyg X-3	308.11	40.96	MQSO	9 kpc	--
LSI 303	40.13	61.23	MQSO	2 kpc	--
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

- The most significant source is ***PKS 1454-354:***
  - ***-p-value$_{obs}$ = 0.136***
- ***1431*** trials out of ***1496*** p-value ≥ p-value$_{obs}$
  - ***-p-value(post) = 95.7%***



IC59 FLARE ANALYSIS

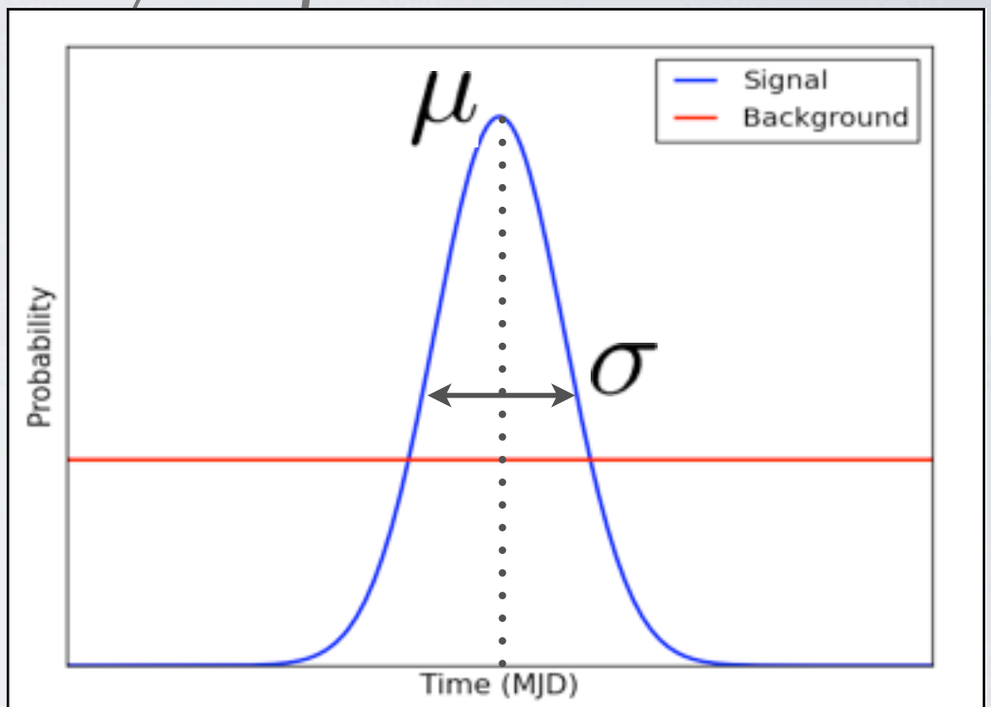
TIME DEPENDENT ANALYSIS

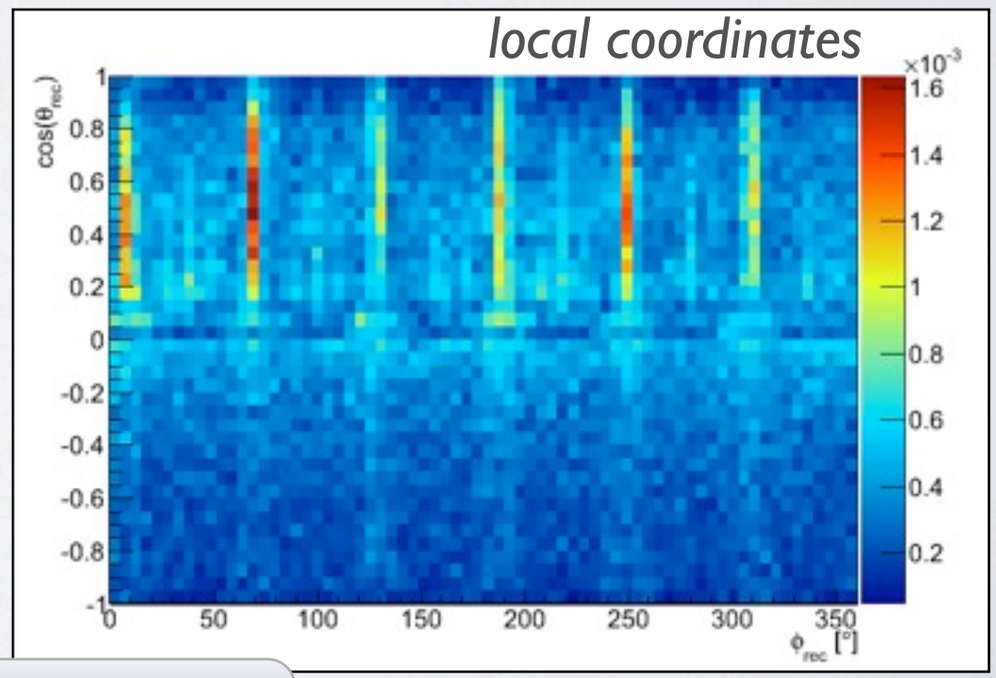
- ***Goal:*** Look for accumulation of events not only in ***space*** but also in ***time***.

- ***Method:*** The analysis method uses the same ***unbinned*** maximum likelihood by adding two additional search parameters: the ***mean*** and a ***width*** of a Gaussian function in time.

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

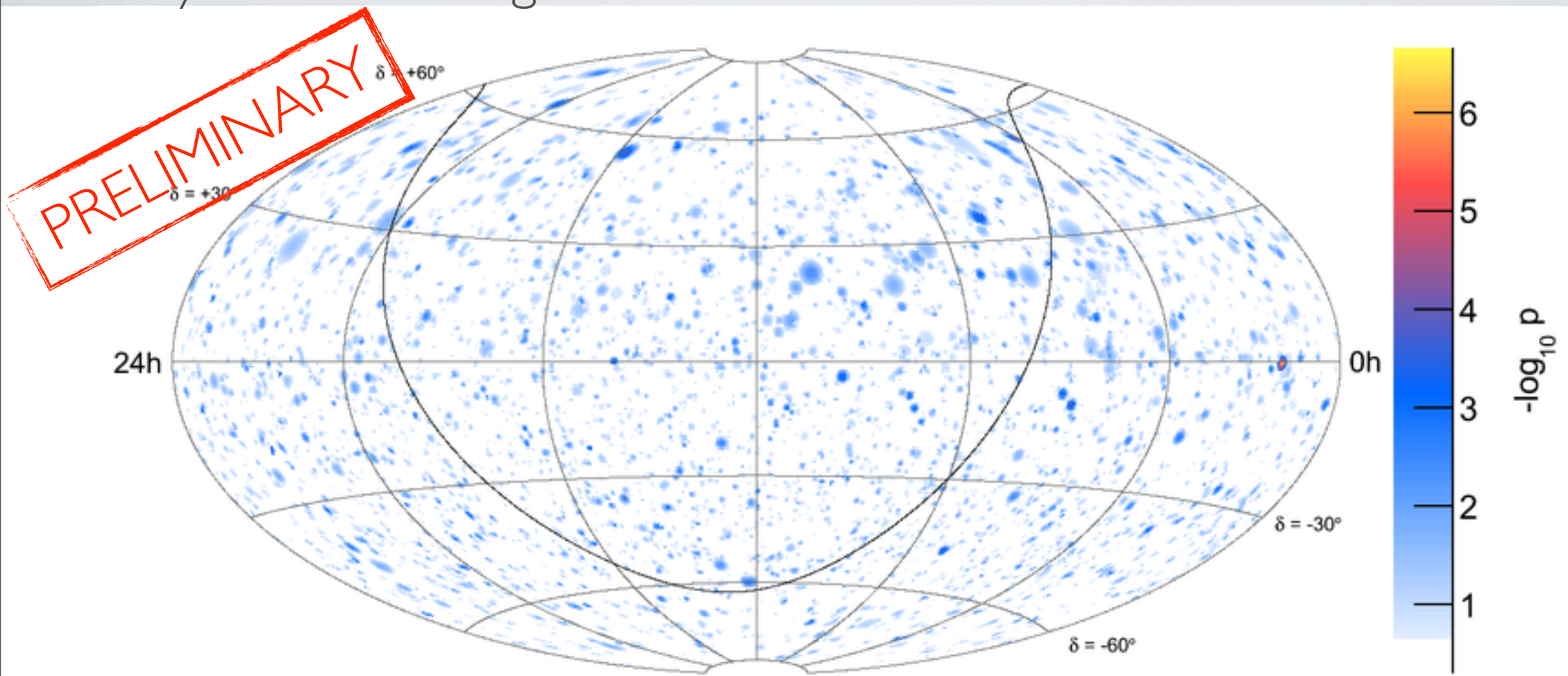
At low time scales (< 1 day) the background depends not only on zenith but on the local coordinates of the arrival track directions.





FLARE ANALYSIS RESULTS

- Only IC59 data was used for the flare analysis. Data from IC40 was analyzed and no significant excess was found.



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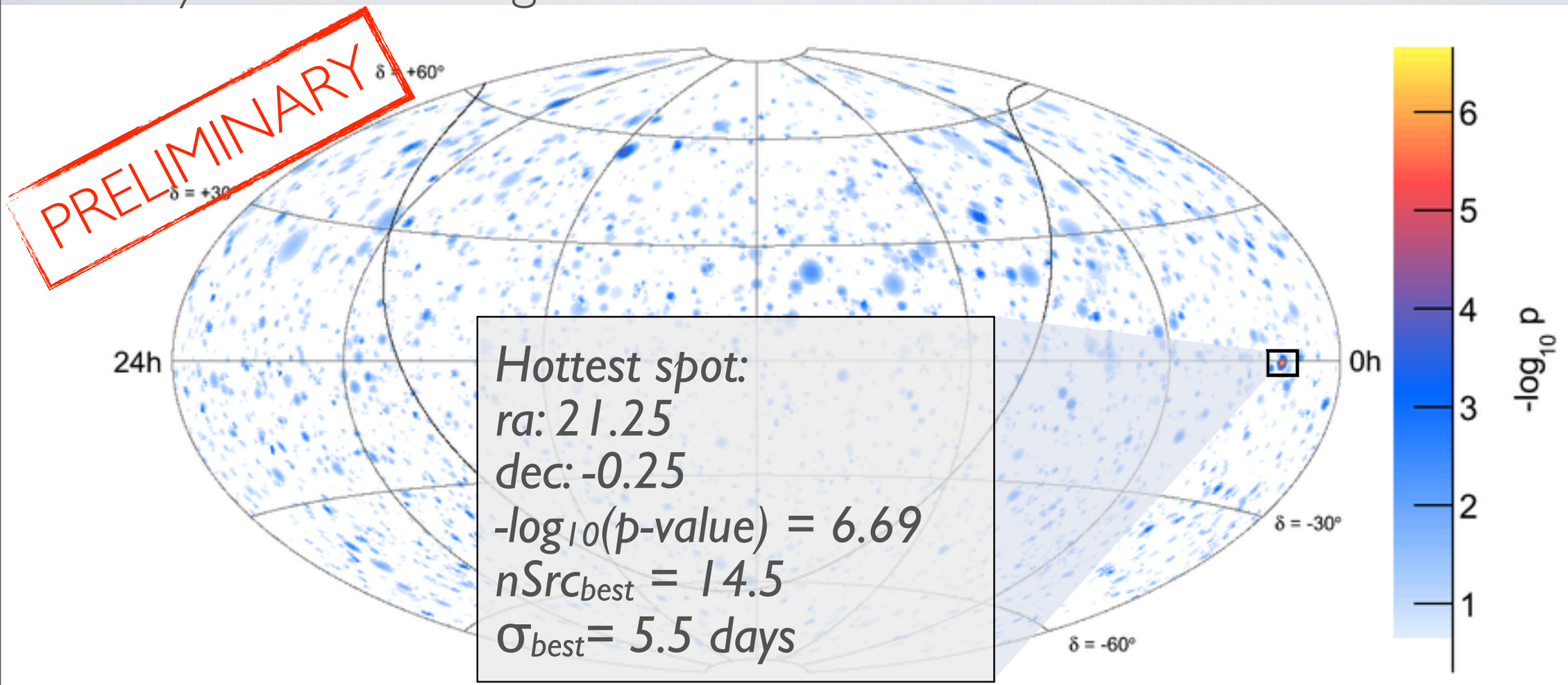
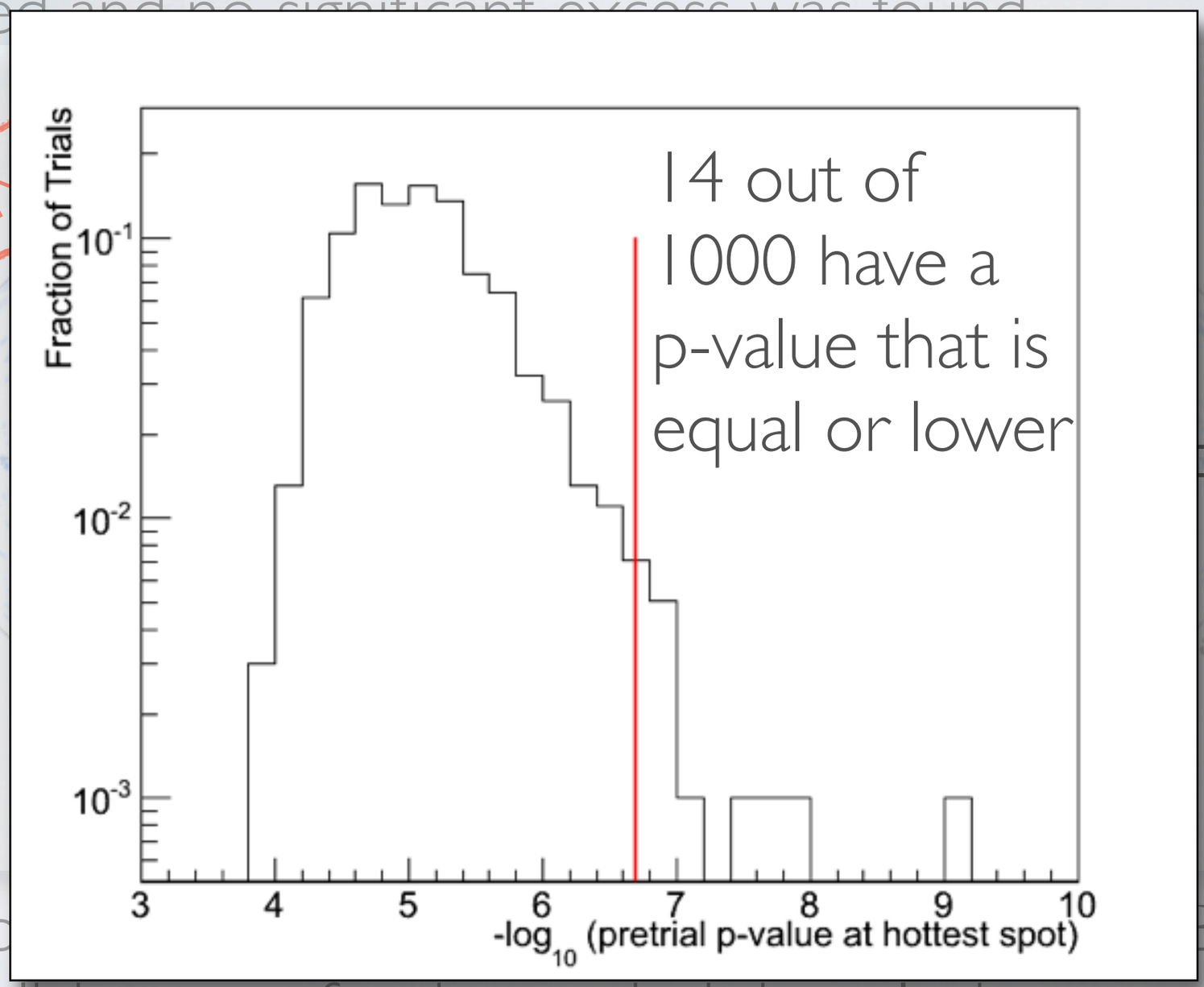
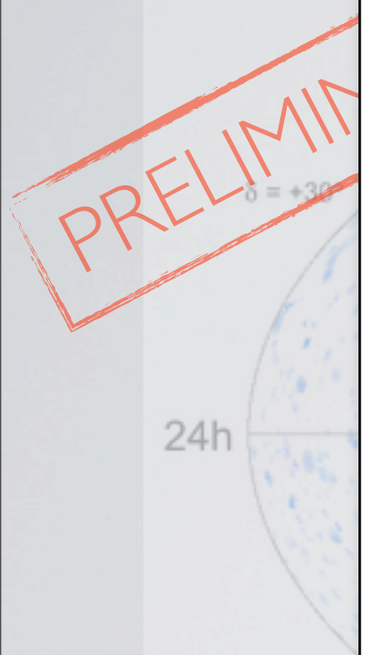


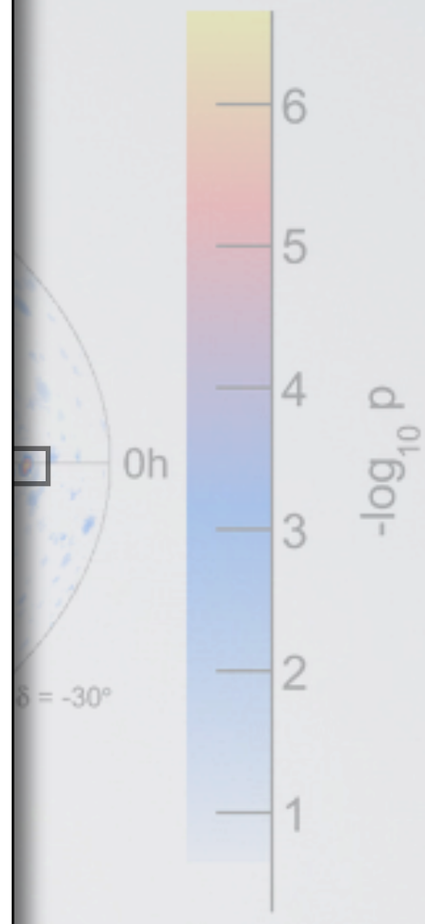
- No correspondence with any known source (SIMBAD catalog)
- Fermi light curve for that period doesn't show any activity.

FLARE ANALYSIS RESULTS

- Only IC59 data was used for the flare analysis. Data from IC40 was analyzed and no significant excess was found



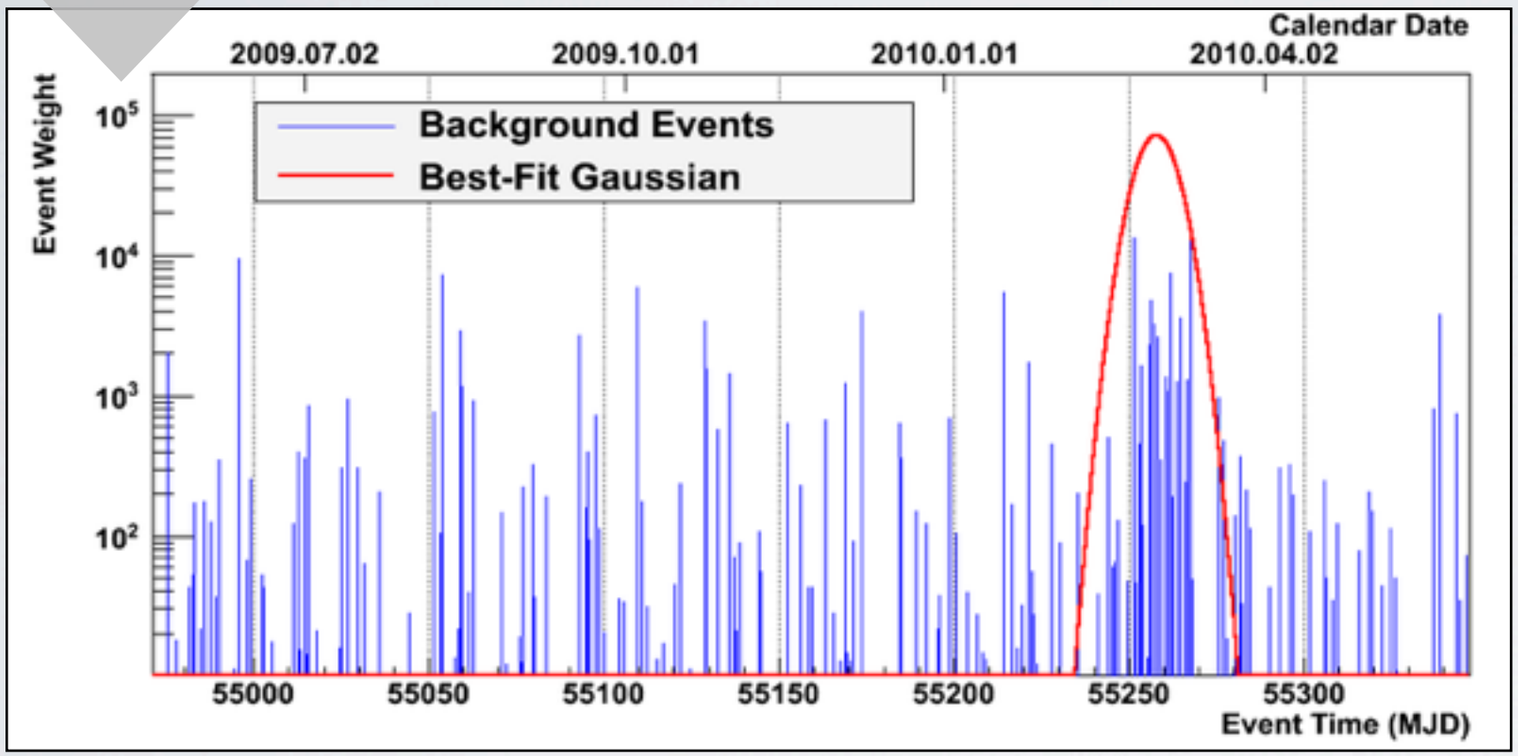


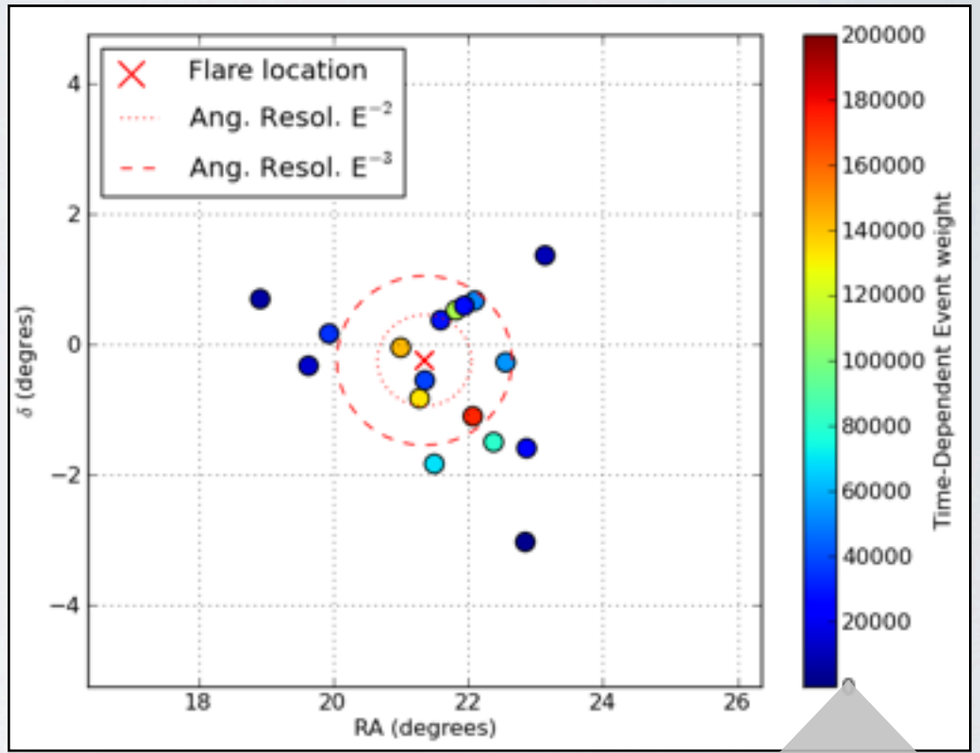


- No co BAD catalog)
- Fermi light curve for that period doesn't show any activity.

FLARE EVENTS

- By considering only the spatial and energy S/B ratio, the accumulation of events is only visible in time.





- Events that form part of the *flare* all have fairly low energy and are ~1 degree away, and only stand out in terms of their timing properties.

CONCLUSIONS

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- The whole year of IC59 has been analyzed for point-source and no evidence of a neutrino point source has been found.
- We performed the combination of the IC59 and the previous IC40 data to enhance the discovery potential and sensitivities.
- Time dependent analysis was performed to search for untriggered flares. An excess in significance has been found with a p-value of ***~1.4%*** still compatible with a background fluctuation.
- More analysis (periodic analysis, triggered flares, stacking, and extended sources) are on the way.
- IceCube is finally ***complete*** and taking data.