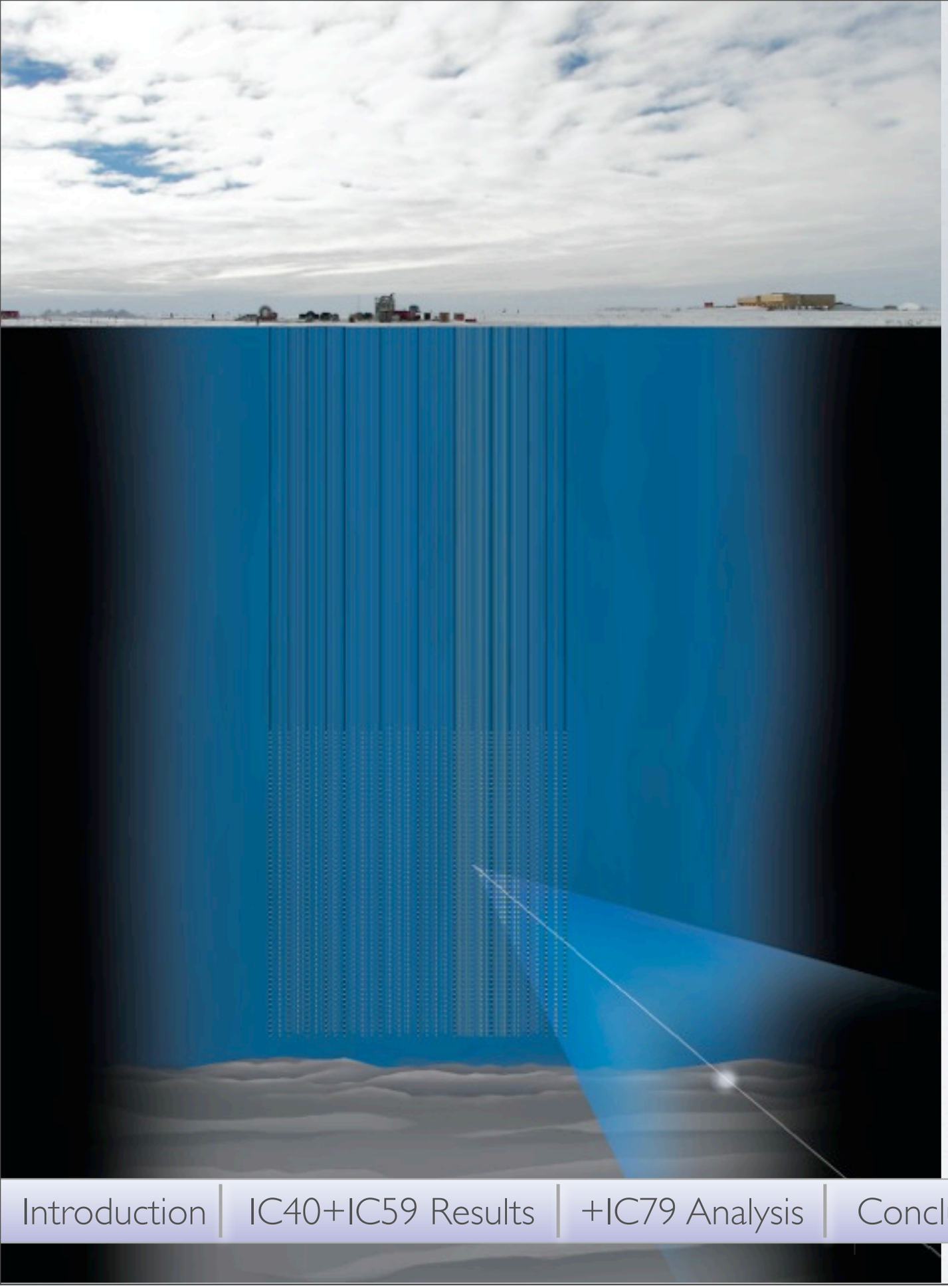


NEUTRINO POINT-SOURCE SEARCH IN ICECUBE

Juan Antonio Aguilar

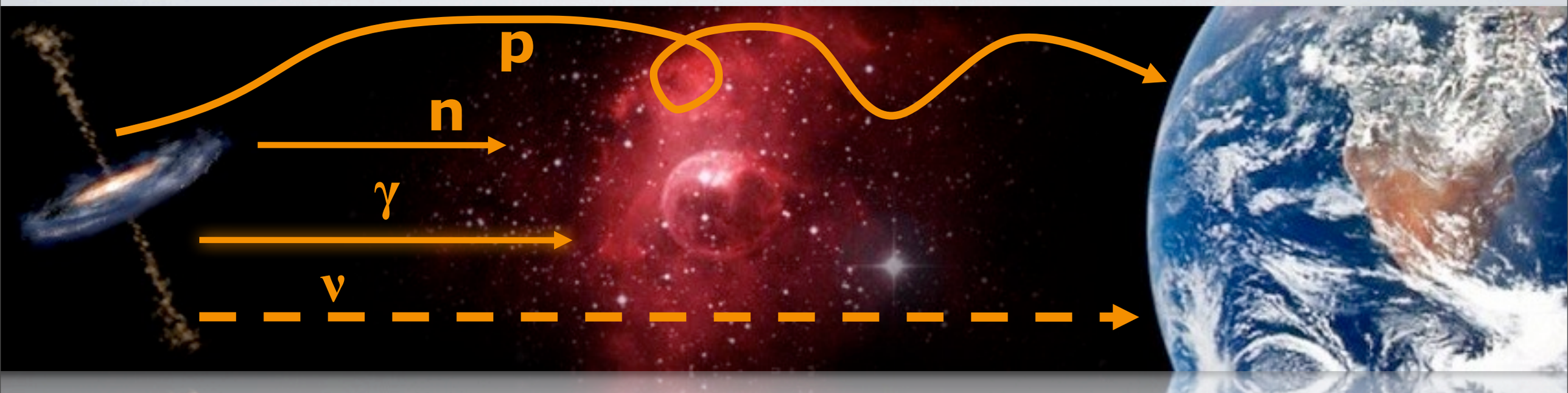
For the IceCube collaboration

UNIVERSITÉ DE GENÈVE

Introduction | IC40+IC59 Results | +IC79 Analysis | Conclusions

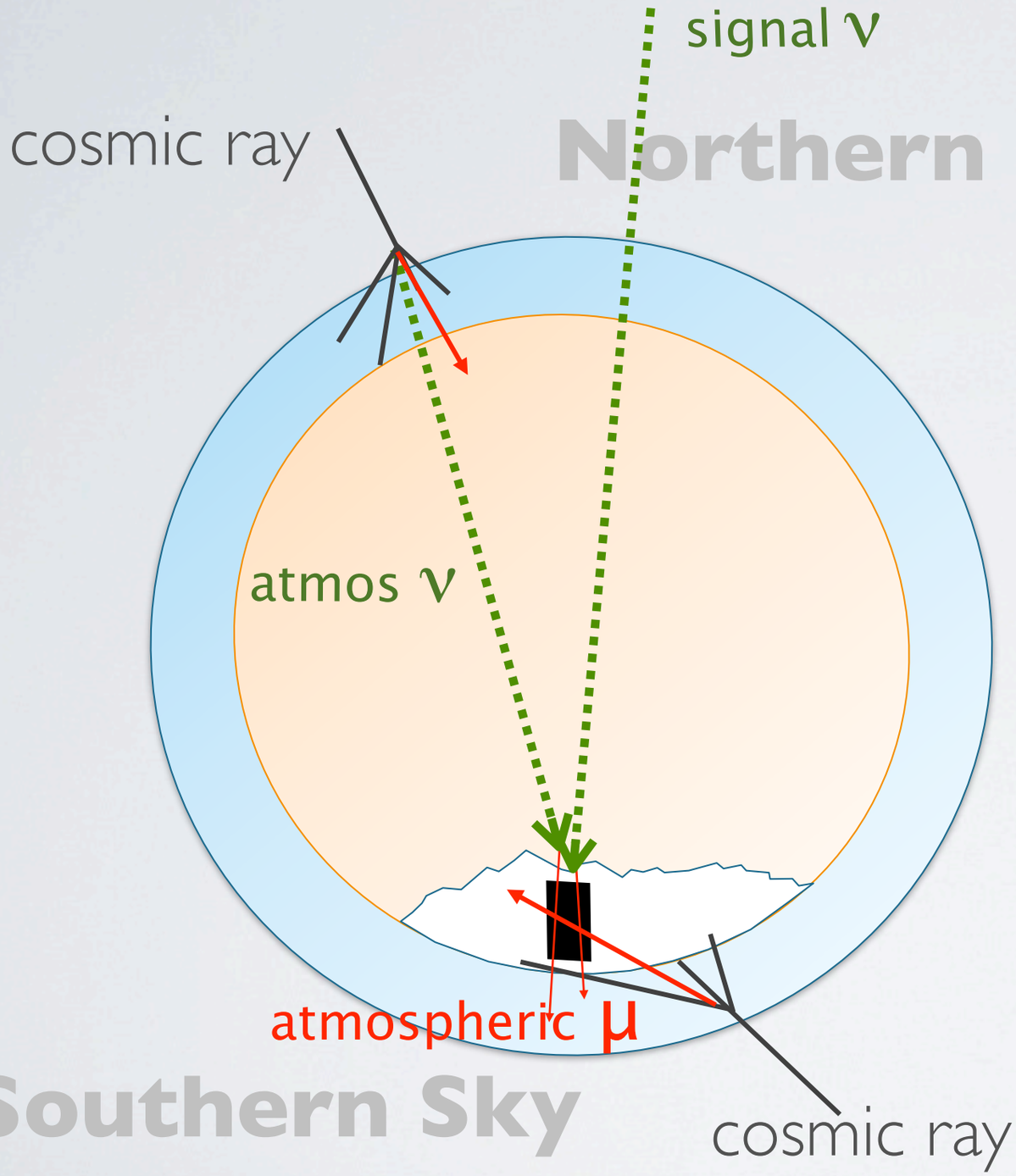
Neutrino Astronomy and IceCube

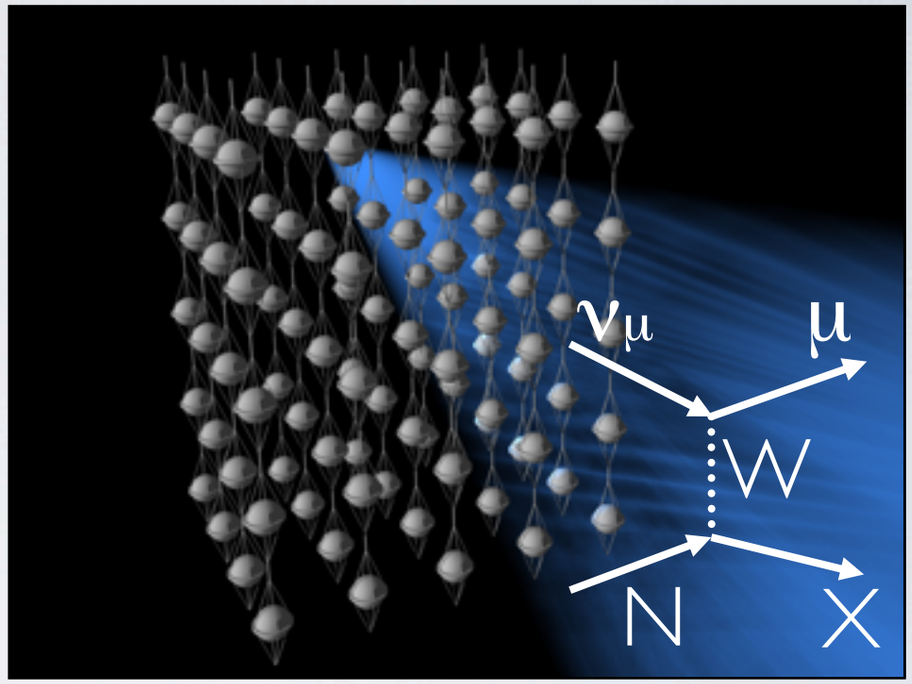
NEUTRINO ASTRONOMY

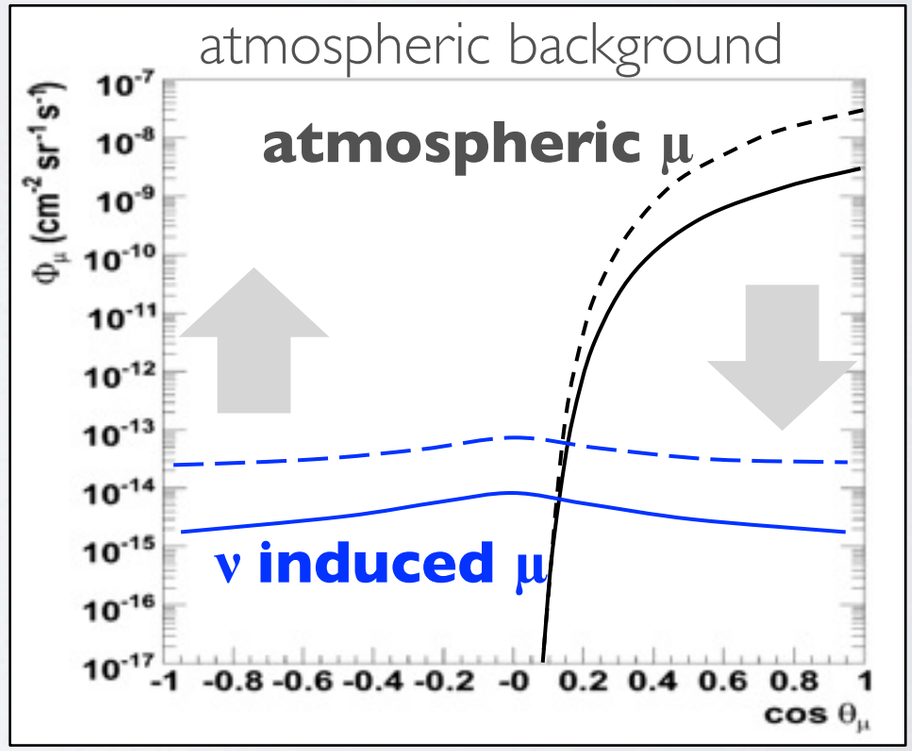


- Protons are deviated by magnetic fields ($E_p < 10^{19}$) and very energetic protons travel distances of a few Mpc.
- Neutrons reach distances of ~kpc at very high energy.
- Photons interact with the EBL (~100 Mpc) and CMB (~10 kpc).
- Neutrinos are neutral stable weakly interacting particles.

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

Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
RWTH 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, UniGe, Switzerland

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

Chiba University, Japan

University of Canterbury,
Christchurch, New Zealand

THE ICECUBE OBSERVATORY

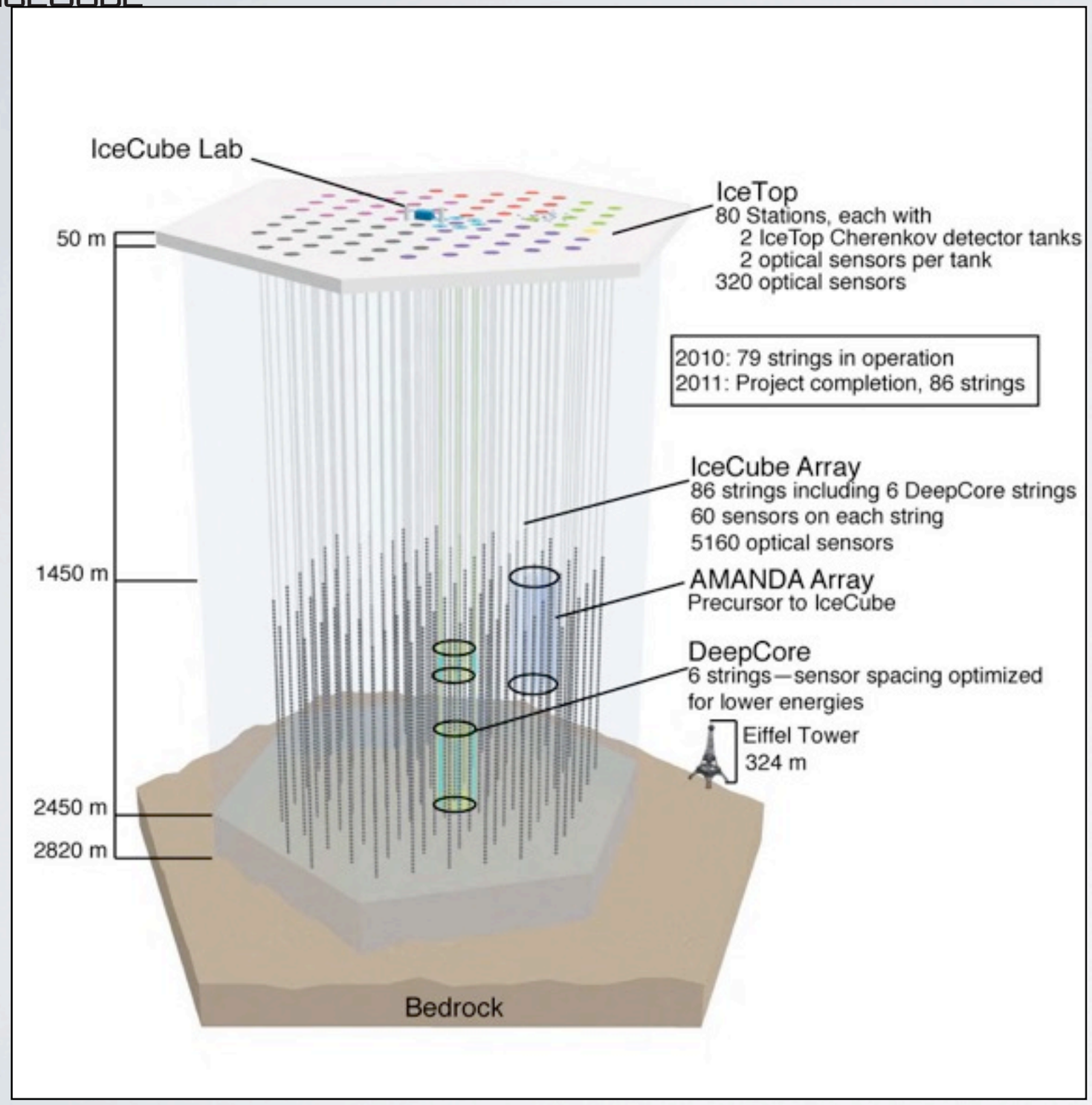
South Pole Station

Geographic South Pole

IceCube outline

Skiway

ICECUBE



IceCube

Completion with 86 strings in December 2010.

IceCube 79 (2010-11)

Pointsource analysis of this dataset is starting now.

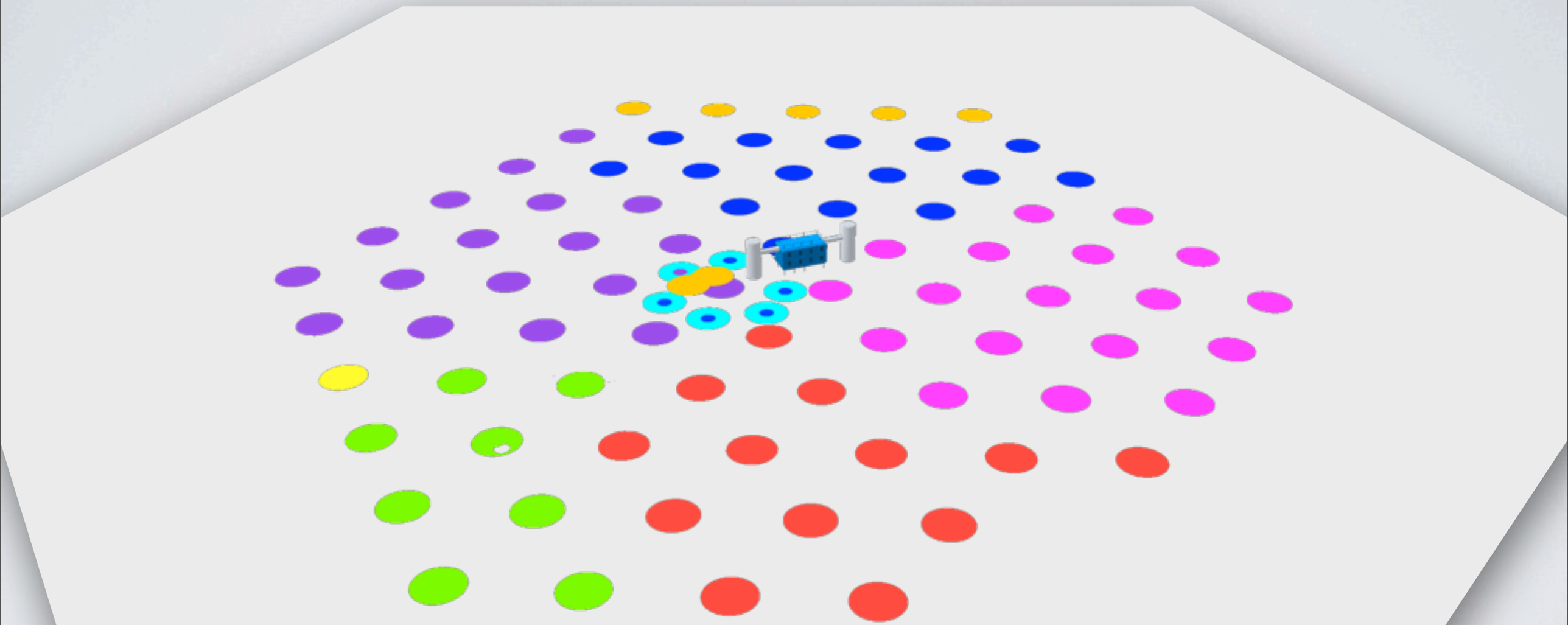
IceCube 59 (2009-10)

IceCube IC59 data has been analyzed, results presented here.

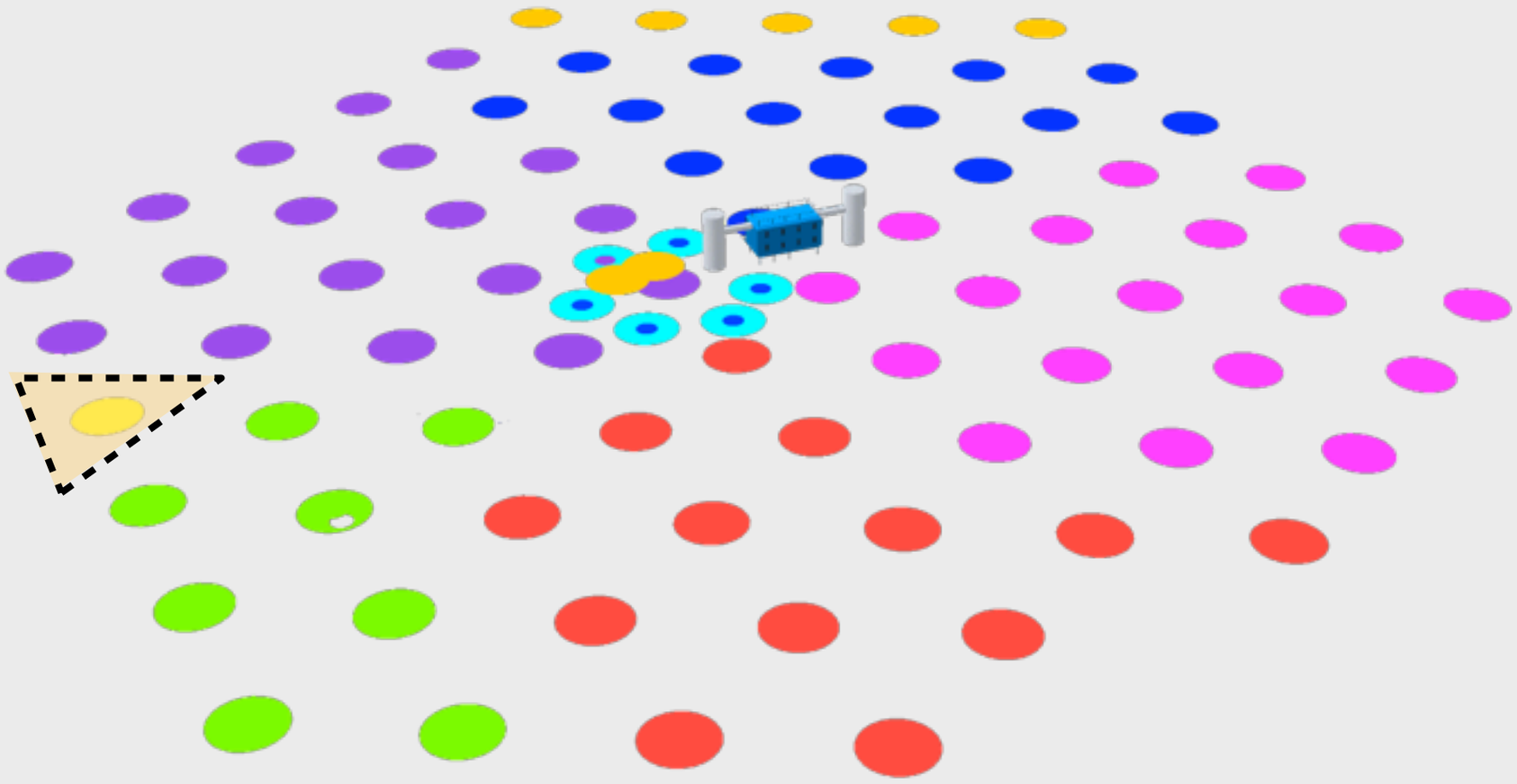
IceCube 40 (2008-9)

IC40 data has been analyzed and upper limits for point sources were published.

ICECUBE CONFIGURATIONS

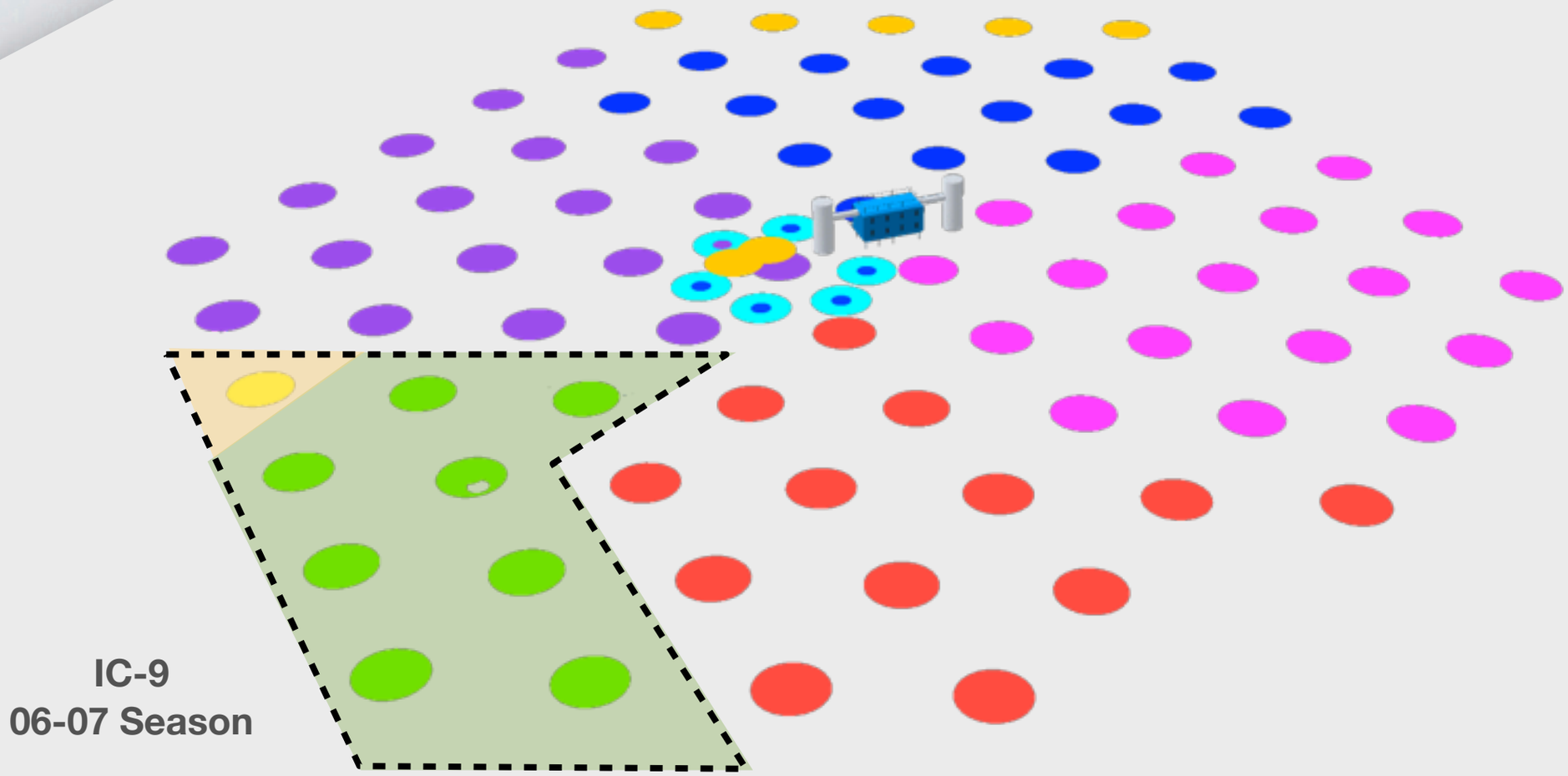


ICECUBE CONFIGURATIONS



IC-1
05-06 Season

ICECUBE CONFIGURATIONS



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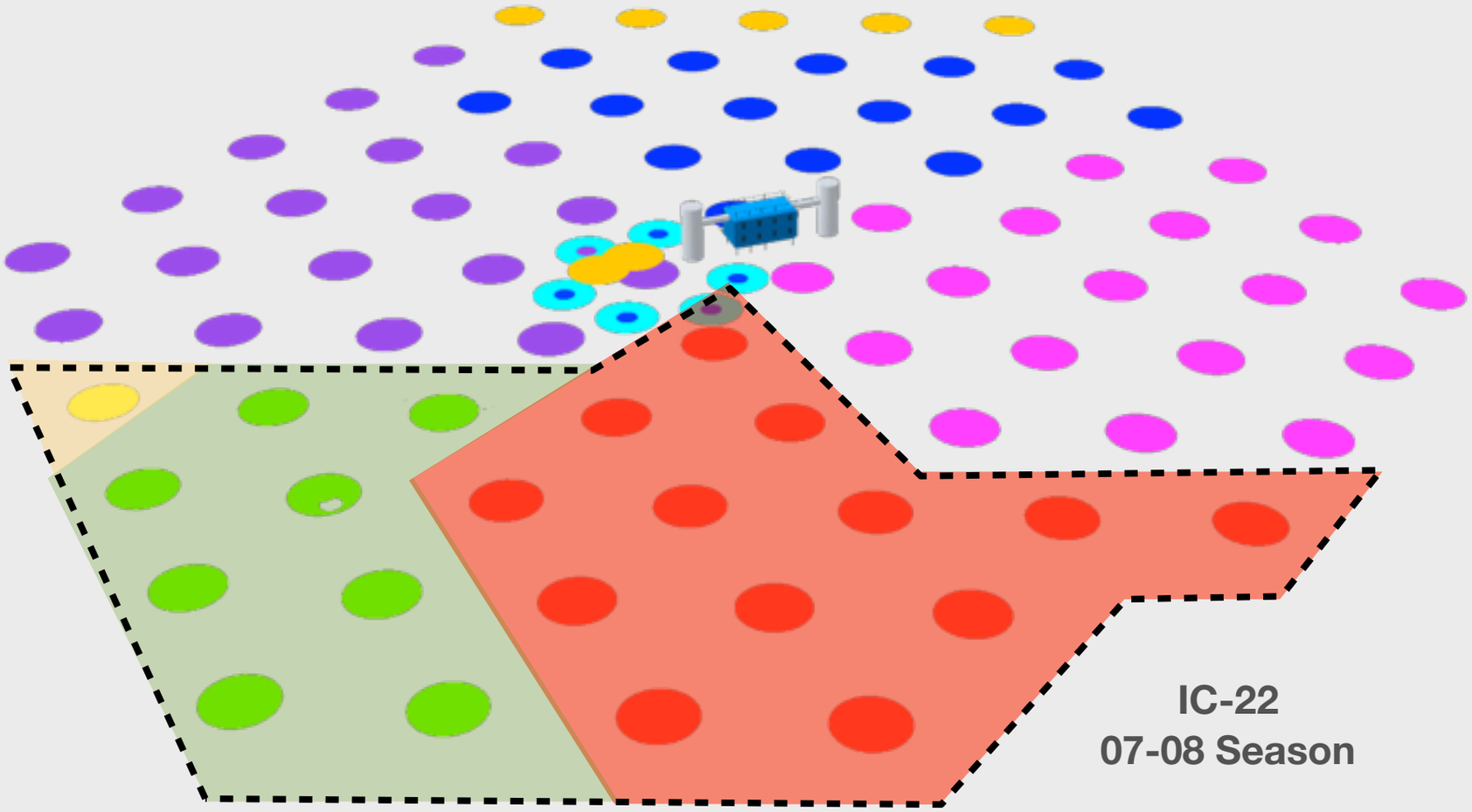

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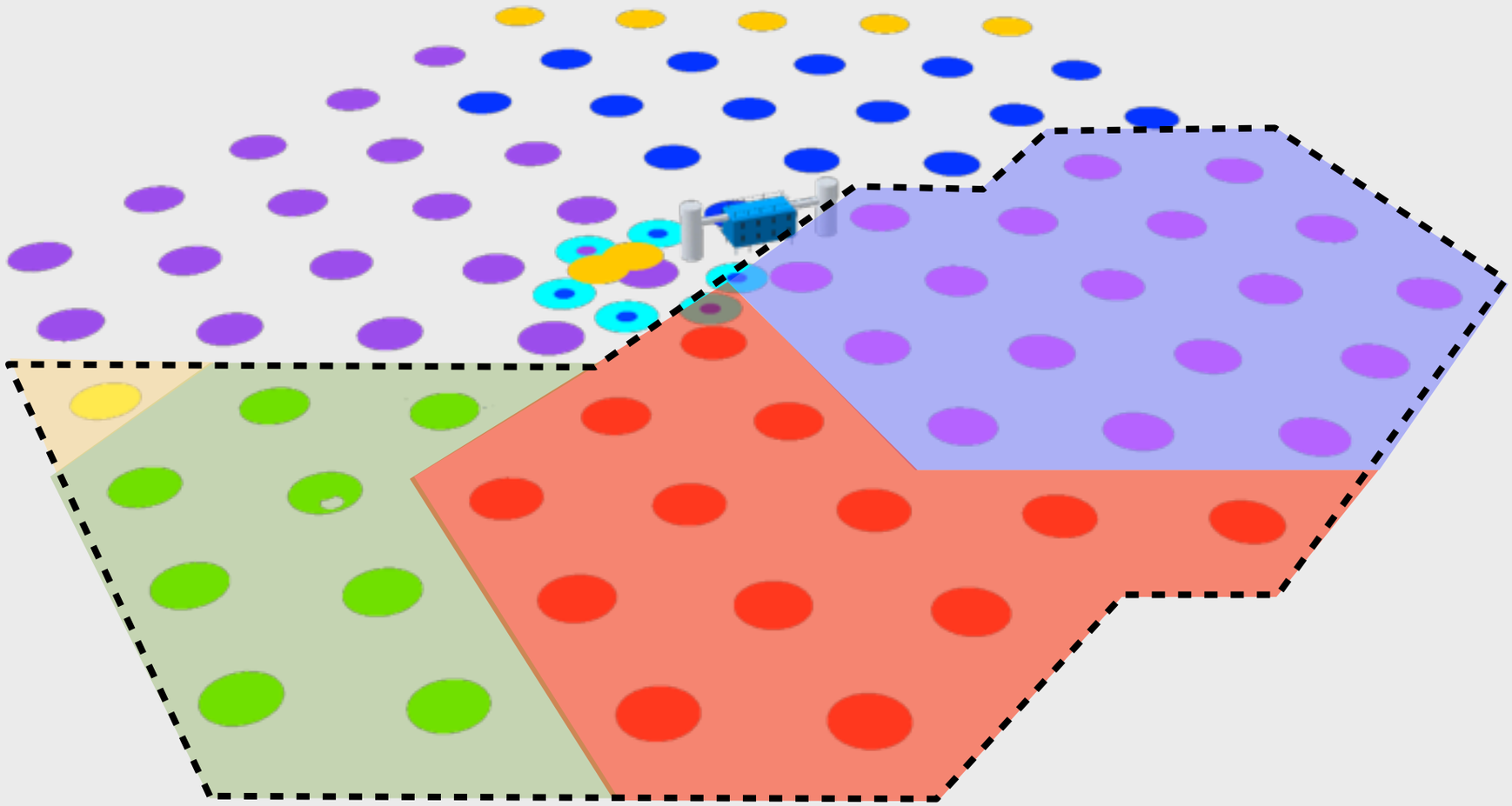
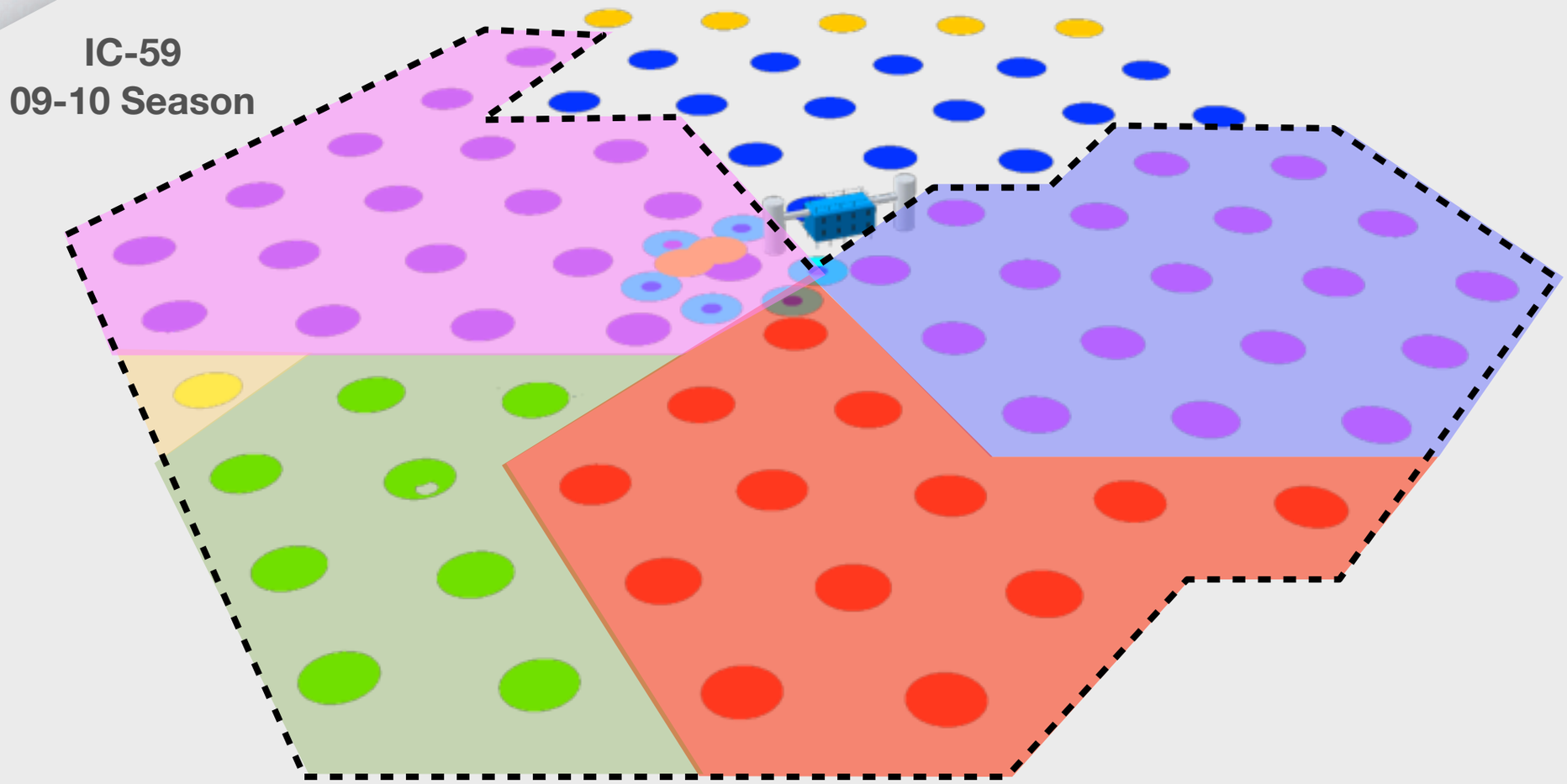
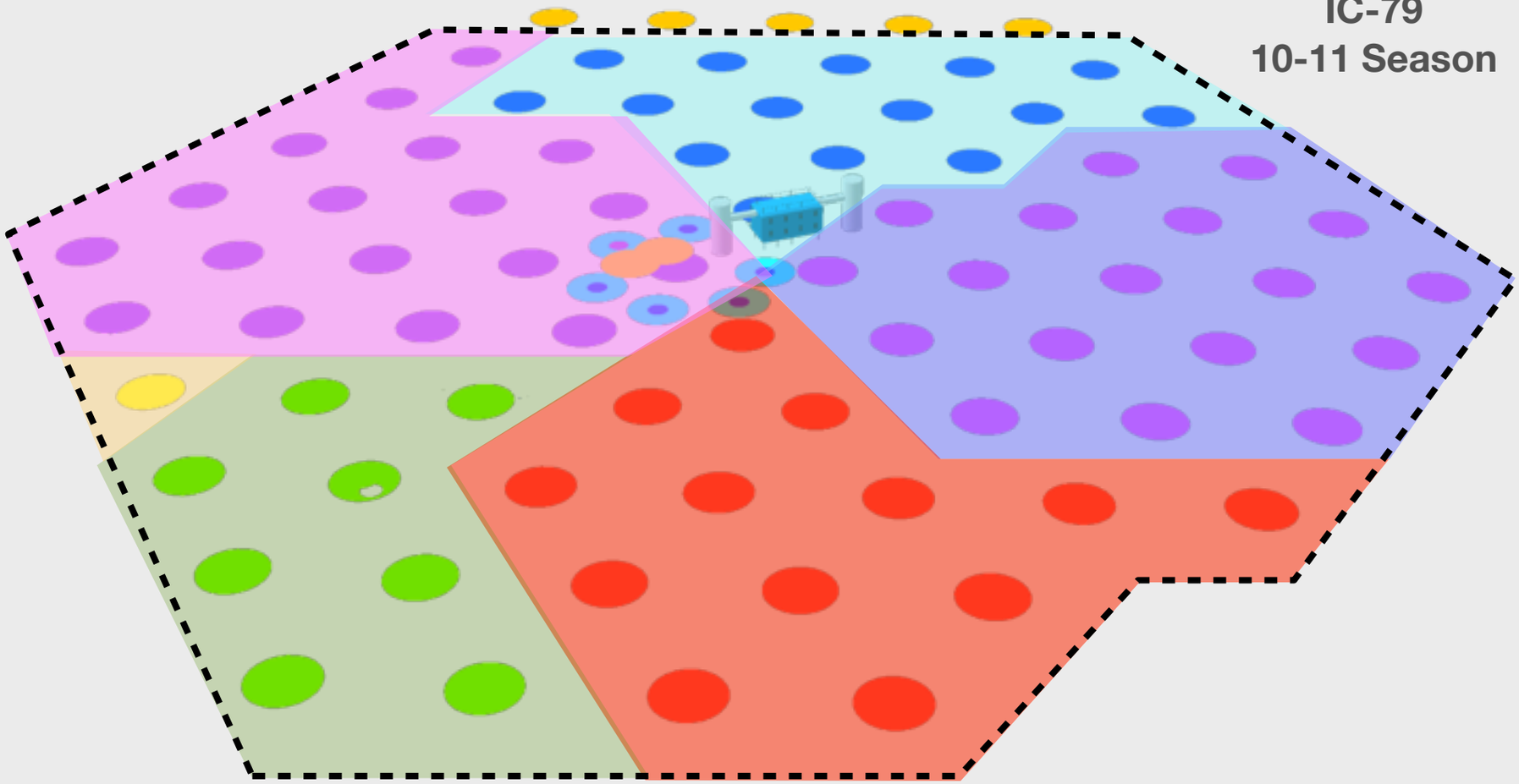


IC-40
08-09 Season

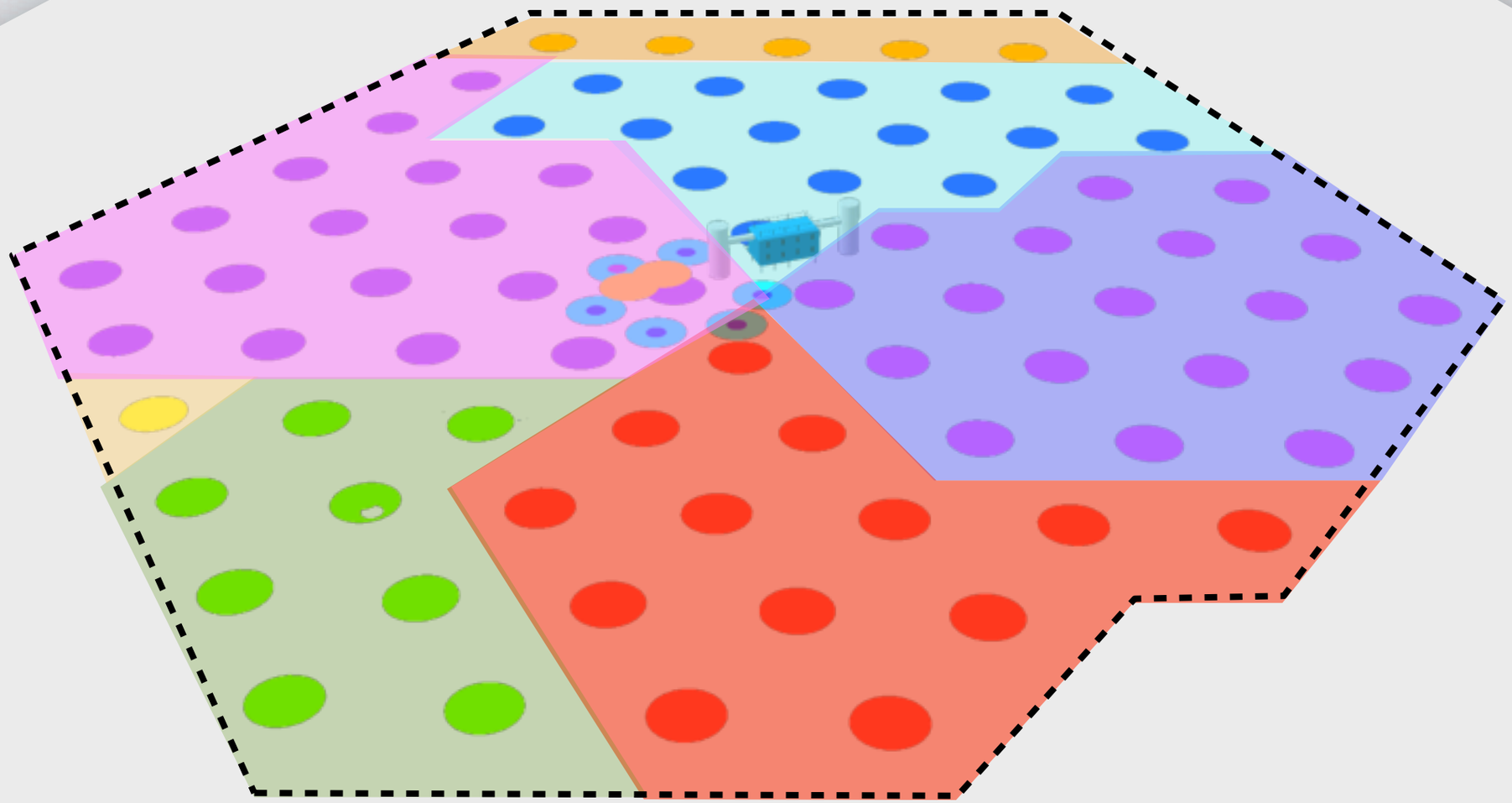
ICECUBE CONFIGURATIONS



ICECUBE CONFIGURATIONS



ICECUBE CONFIGURATIONS



Construction finished on December 2010

ICECUBE MUON SAMPLE

- Low noise rates: ~500 Hz (SPE/sec)
- High duty cycle: > 96% (analysis level)

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	347 d	2300	40	207/d

- ***IC-40:***
  - 14 121 northern events
  - 22 779 southern events
  - 36 900 total events
- ***IC-59:***
  - 43 339 northern events
  - 64 230 southern events
  - 107 569 total events
- ***IC-79:***
  - ~60 000 northern events
  - t.b.d. southern events
  - t.b.d. total events

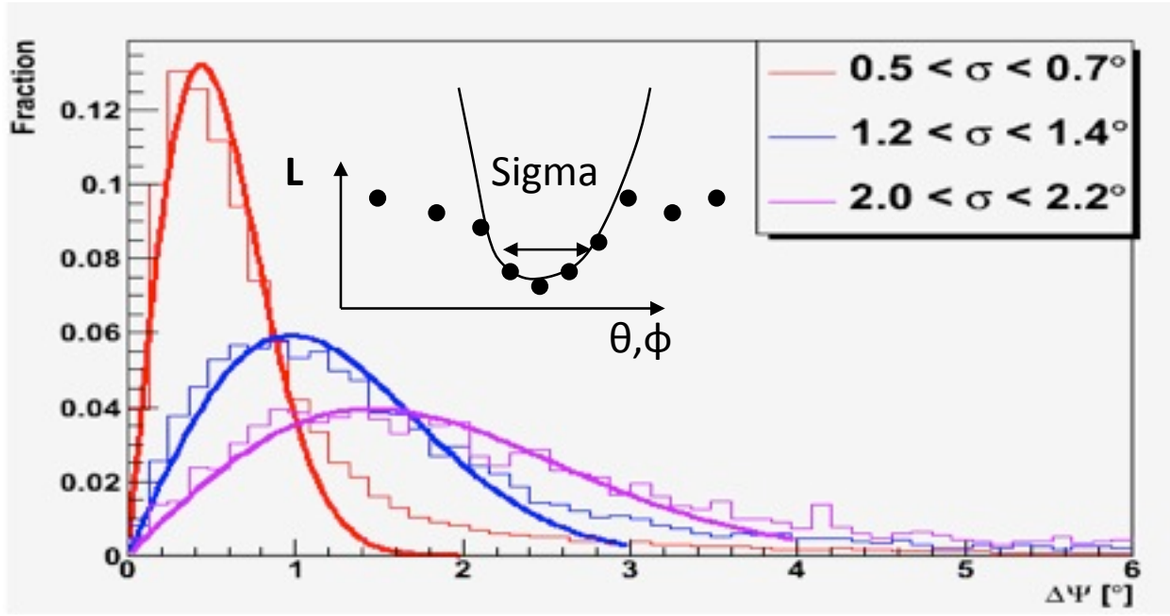
IC59+IC40 POINT SOURCE ANALYSIS

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**



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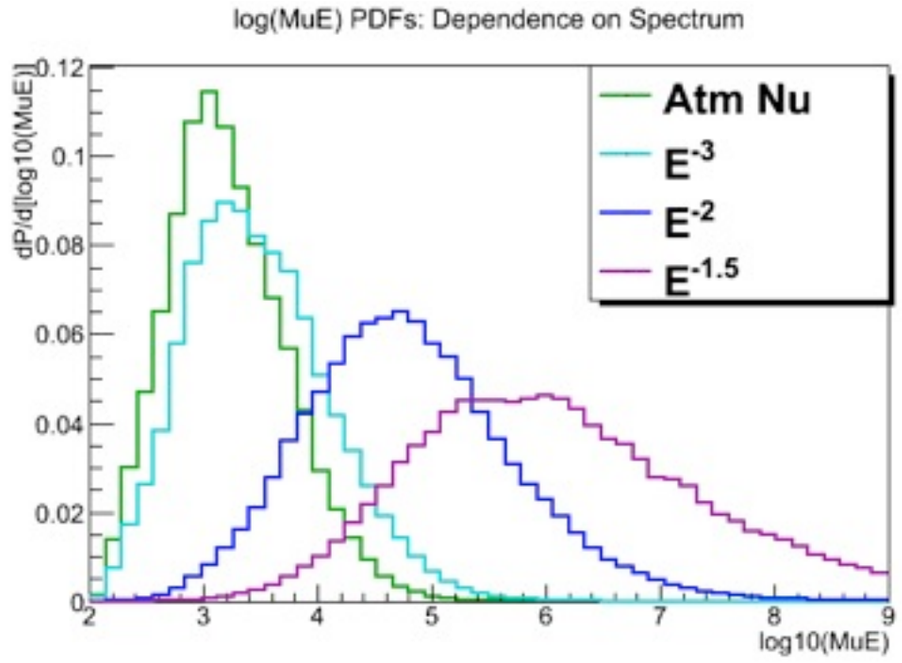

LIKELIHOOD AND DENSITY FUNCTIONS

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:

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

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 wrt:

- 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:

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

Likelihood:

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Maximize wrt:

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

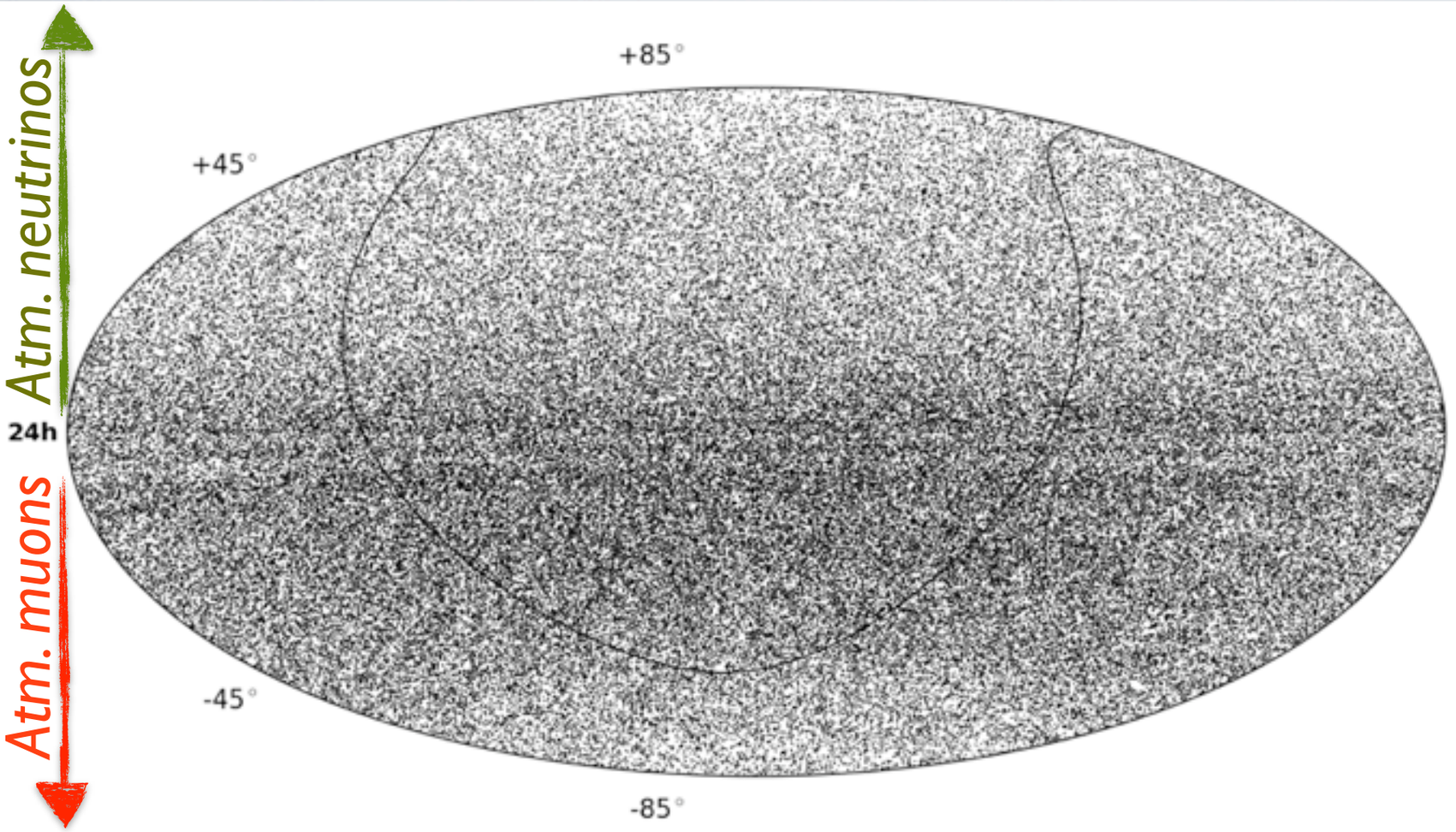
Maximization of the likelihood ratio:

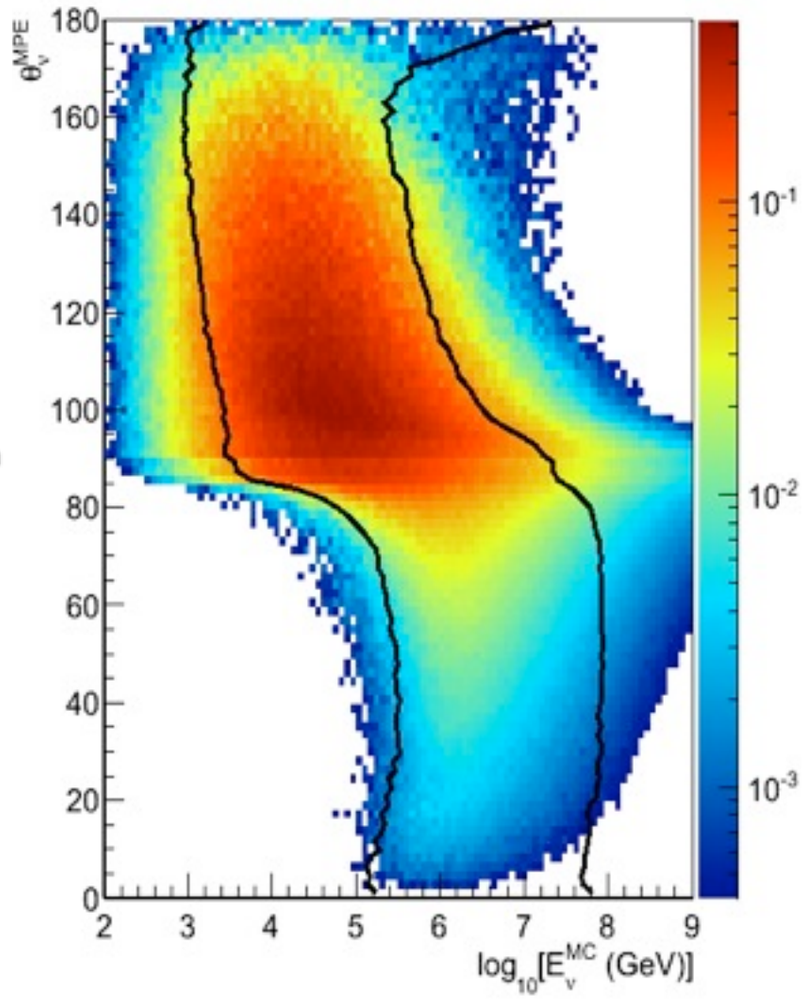
$$\log \lambda = \log \left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Estimates that maximize the Likelihood

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

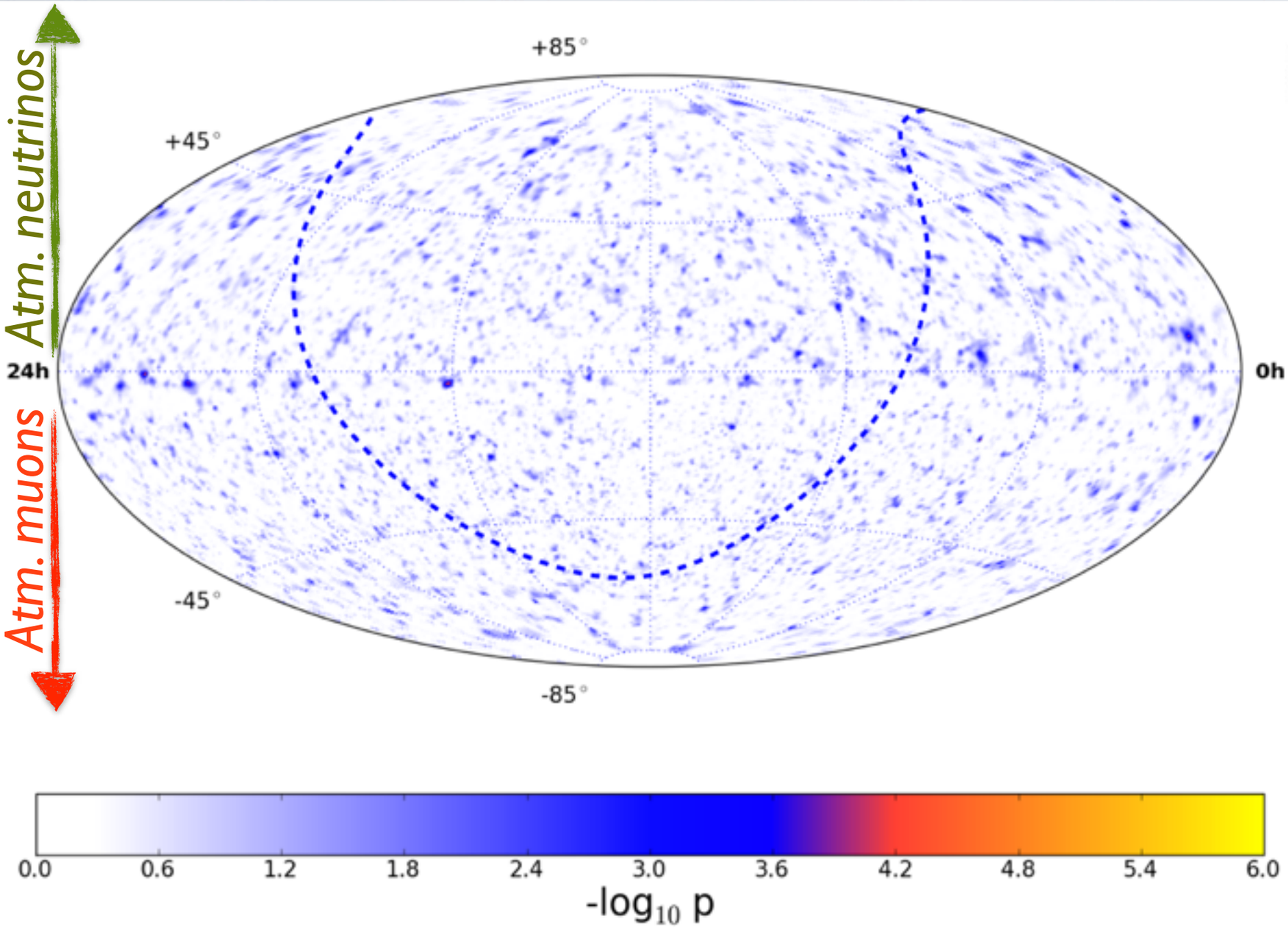
COMBINING DATASETS

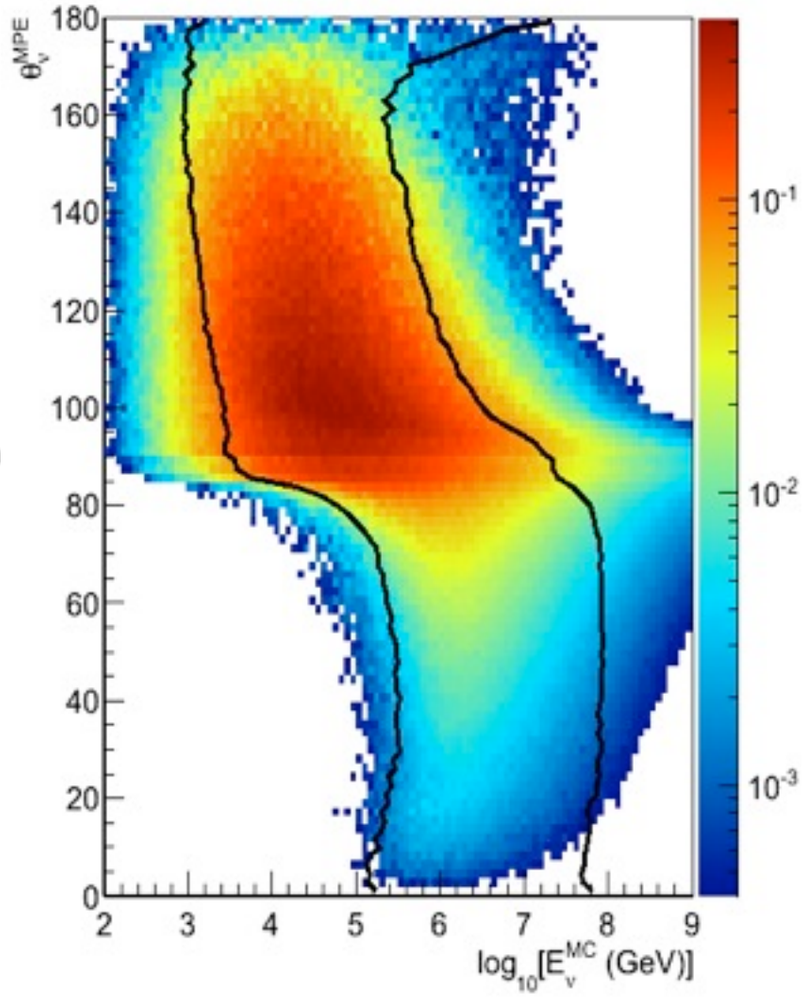




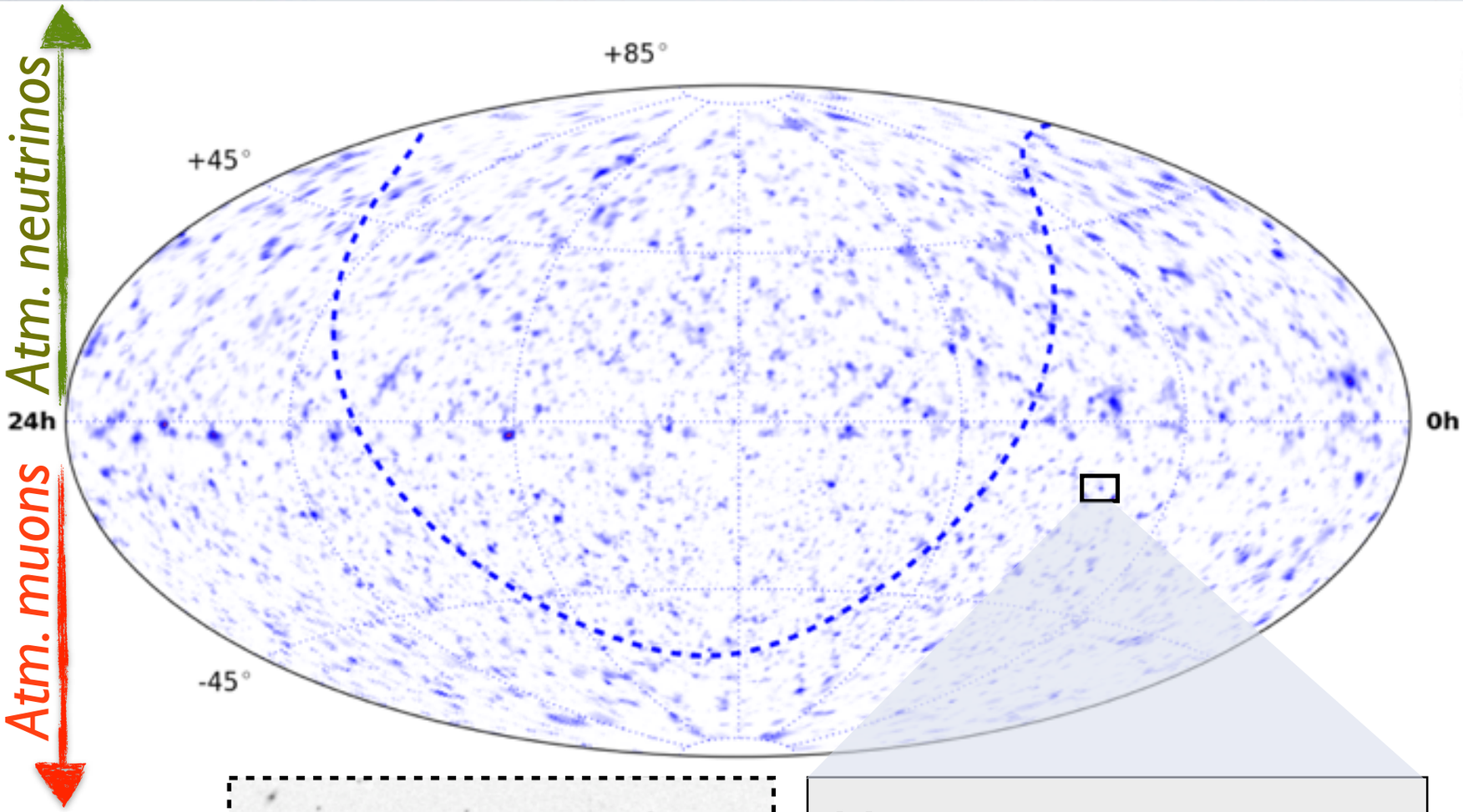
- *Total events (IC40+IC59): 57460 (upgoing) + 87009 (downgoing)*
- *Livetime: 348 days (IC59) + 375 days (IC40)*

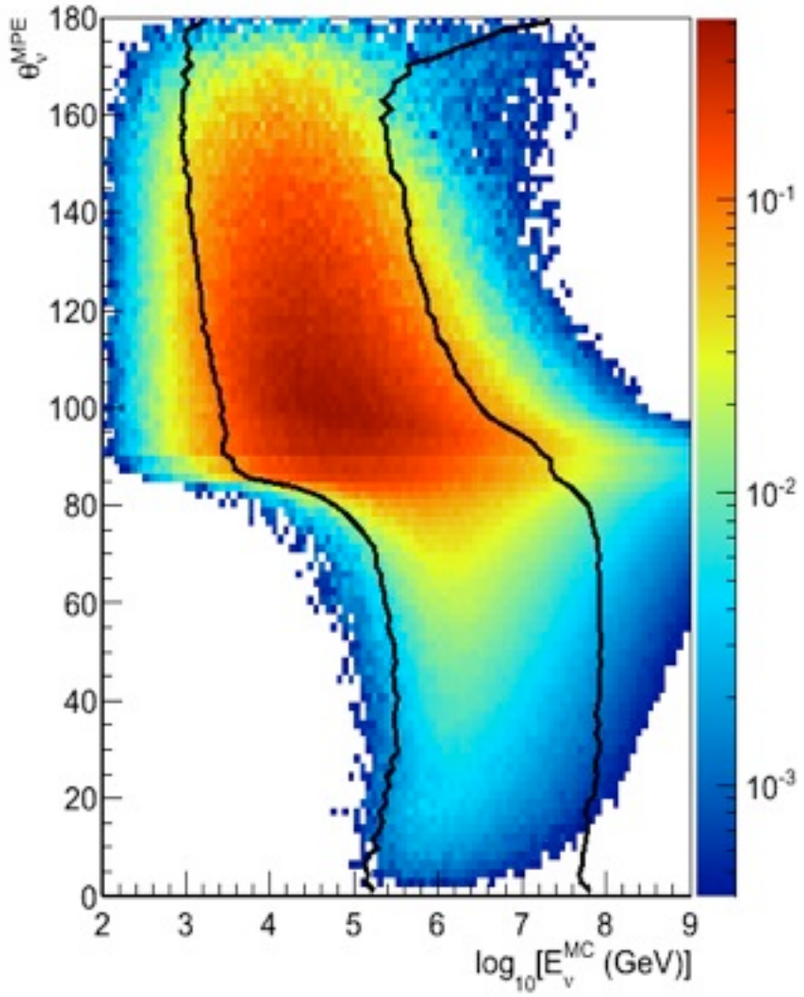
COMBINING DATASETS

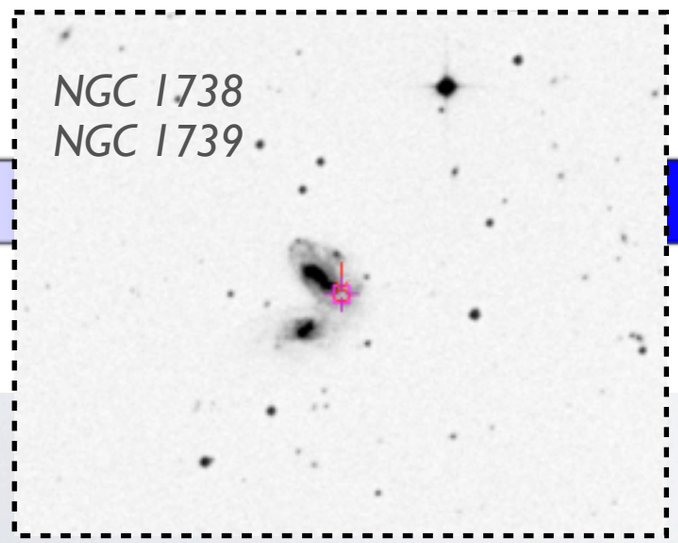




COMBINING DATASETS

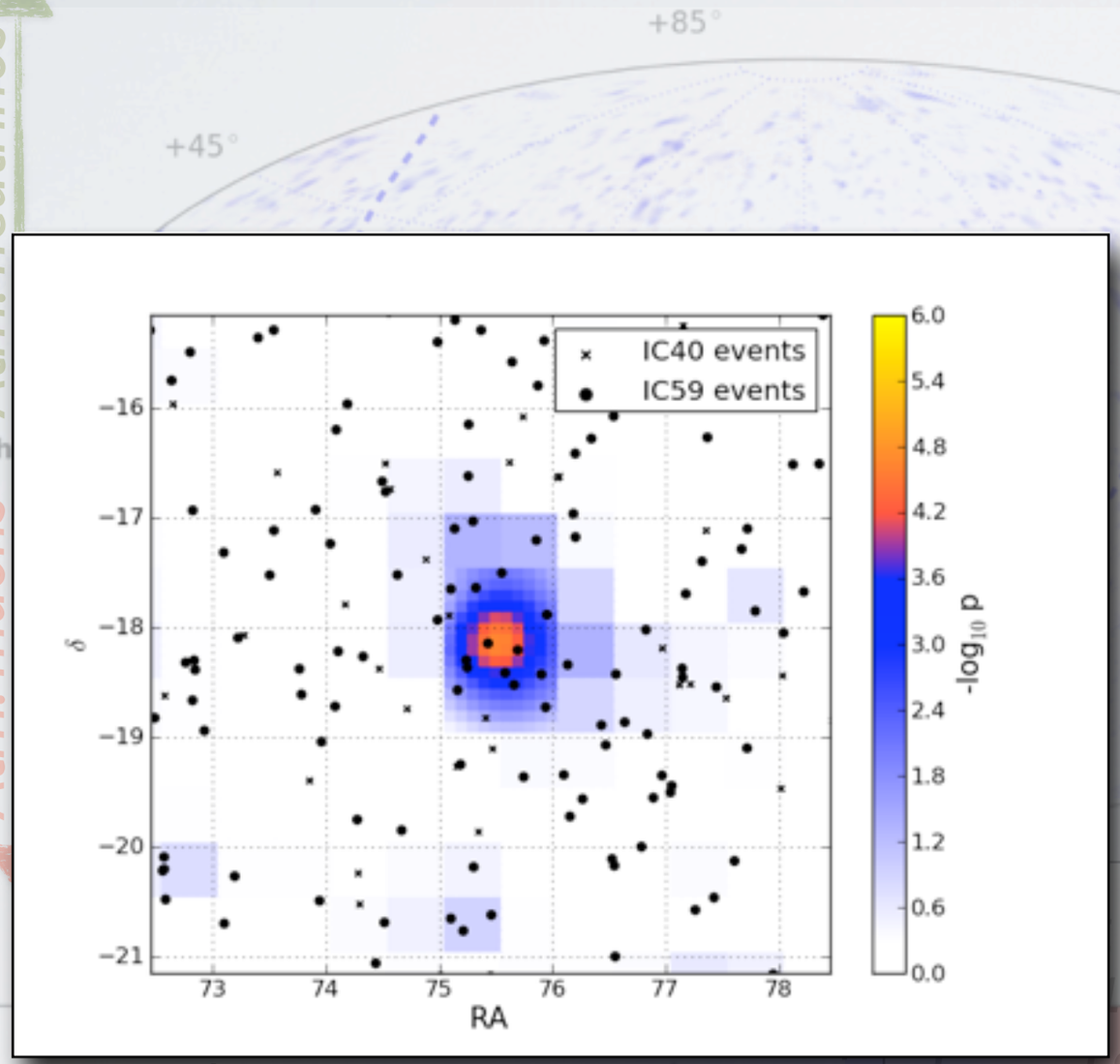


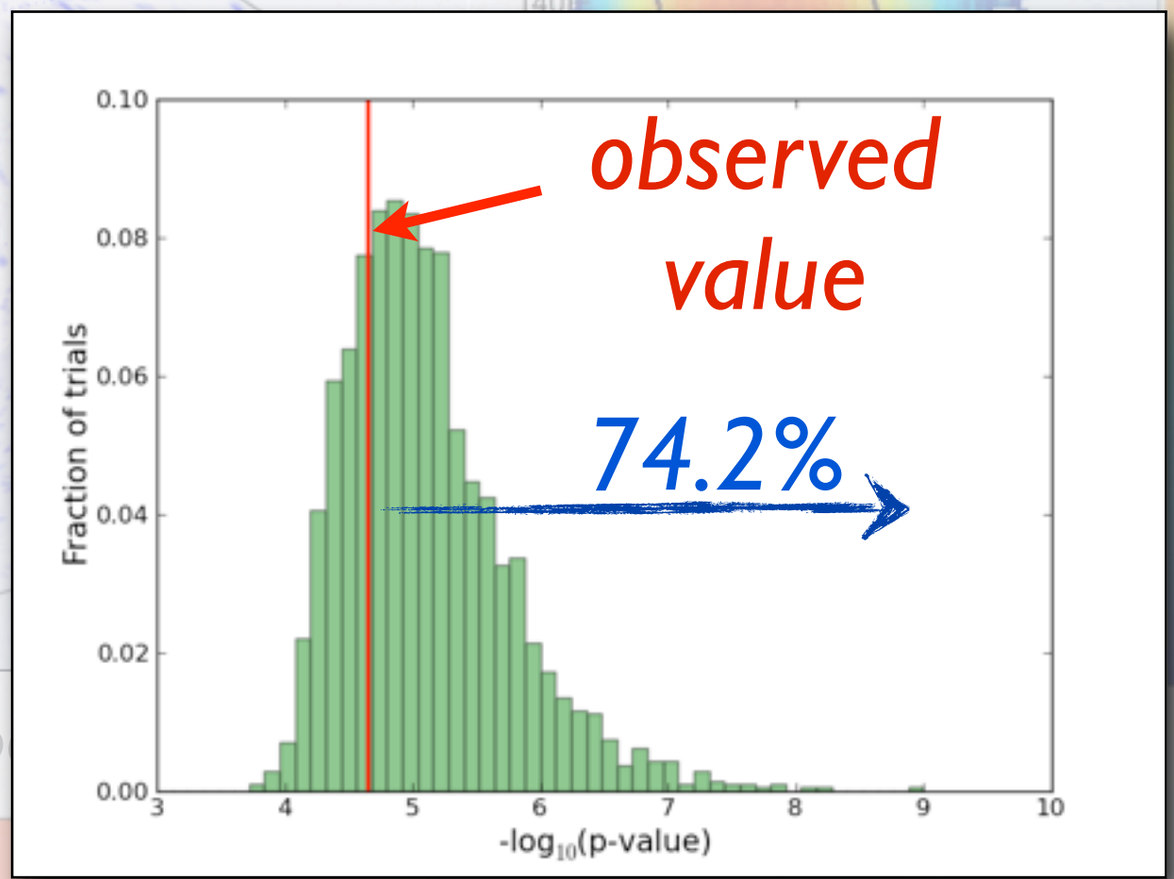




Hottest spot:
ra: 75.45
dec: - 18.15
$-\log_{10}$(p-value) = 4.65
$nSrc_{best}$ = 18.3
γ_{best}= 3.9

COMBINING DATASETS





-log10 p

-log10(p-value) = 4.65

nSrcbest = 18.3

γbest = 3.9

IC40+IC59 SOURCE LIST

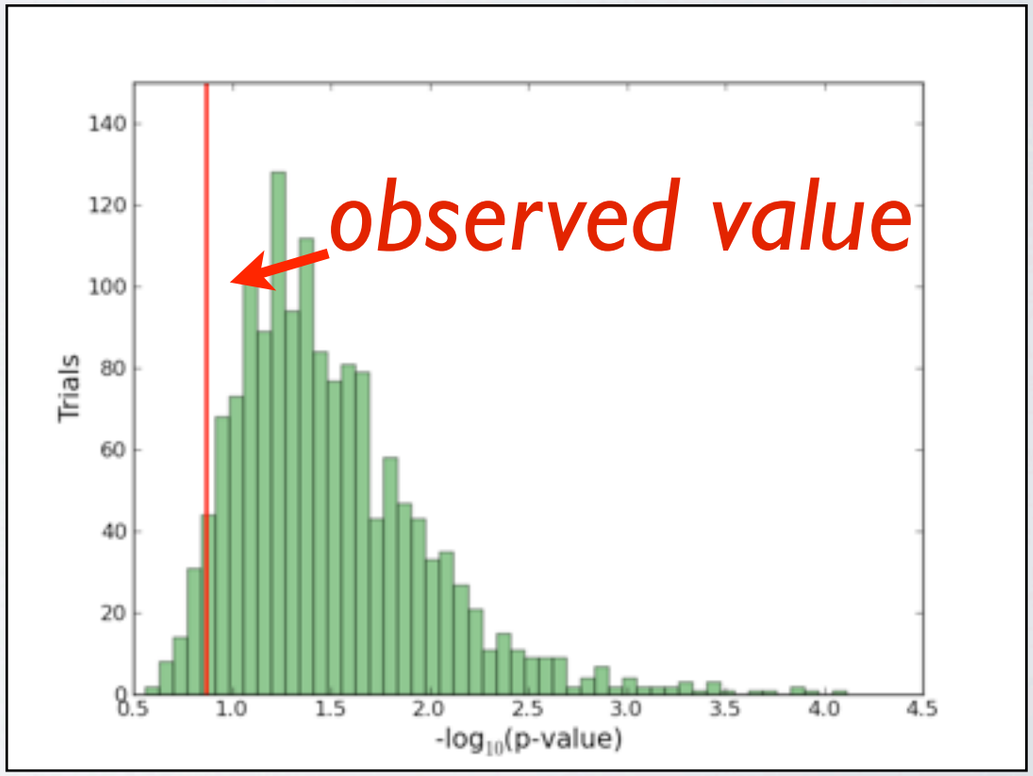
- We can reduce the number of trials by looking at pre-define directions in the sky.

- 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

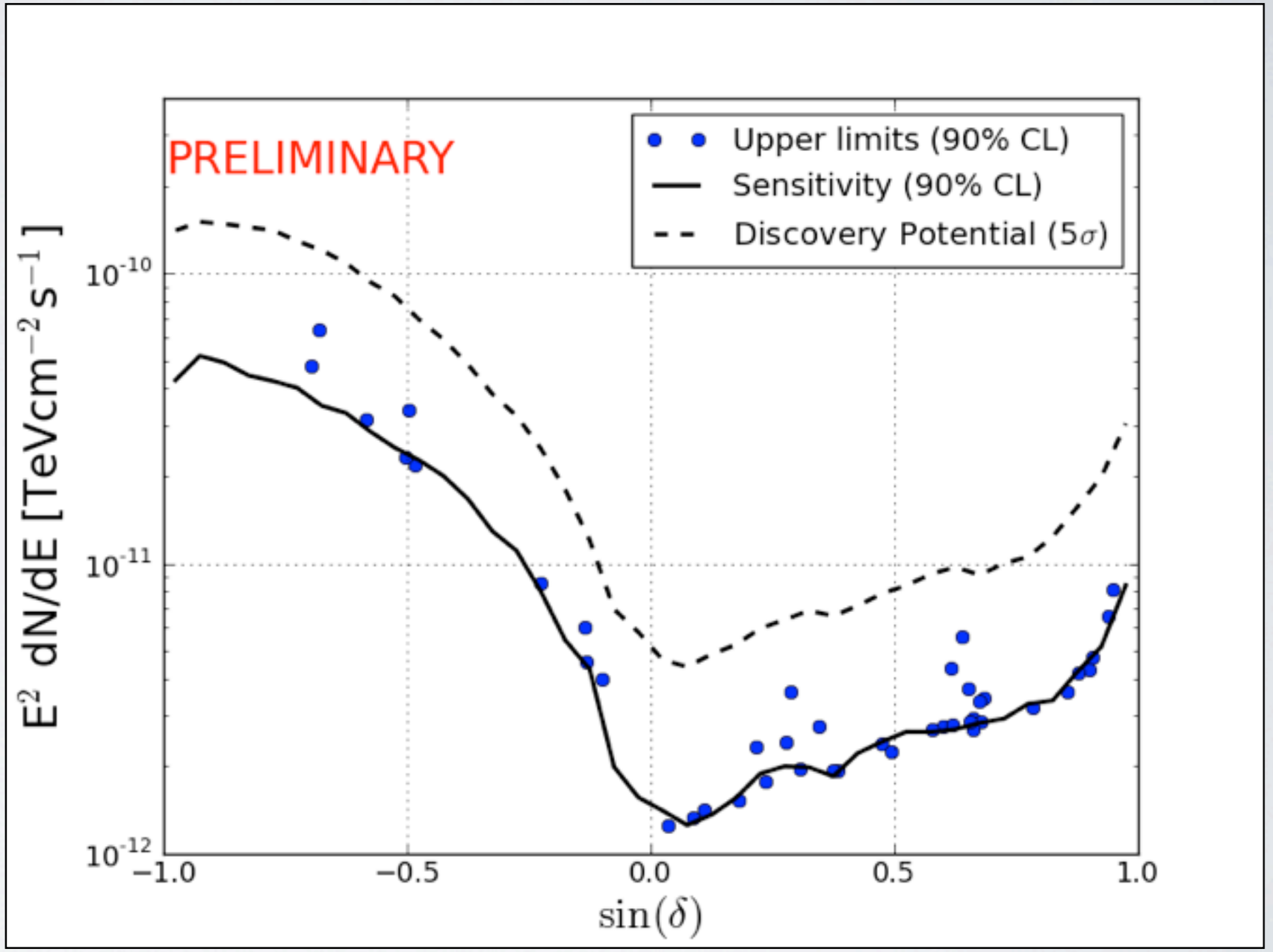
PKS 0235+164	39,66	16,62	LBL	z = 0.94	0,18
PKS 0528+134	82,73	13,53	FSRQ	z = 2.060	0,49
PKS 1502+106	226,10	10,49	FSRQ	z = 0.56/1.839	--
3C 273	187,28	2,05	FSRQ	z = 0.158	--
NGC 1275	49,95	41,51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299,87	40,73	Radio-loud Galaxy	z = 0.056146	0,44
Sgr A*	266,42	-29,01	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%***



IC40+IC59 SOURCE LIST

- Source list upper limits based on the classical (frequentist) construction of upper limits (Neyman 1937).
- Upper limit is minimum flux that produces higher log-likelihood in 90% of simulated trials than the log-likelihood observed for the data.
- Systematics errors not included in these limits.



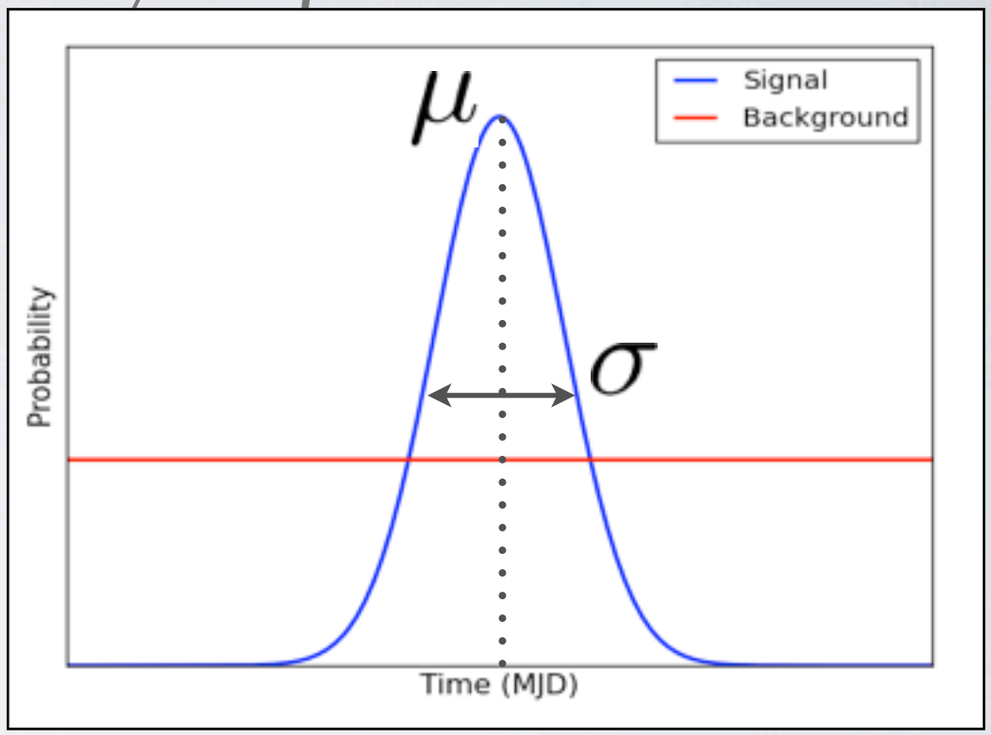
TIME DEPENDENT ANALYSIS

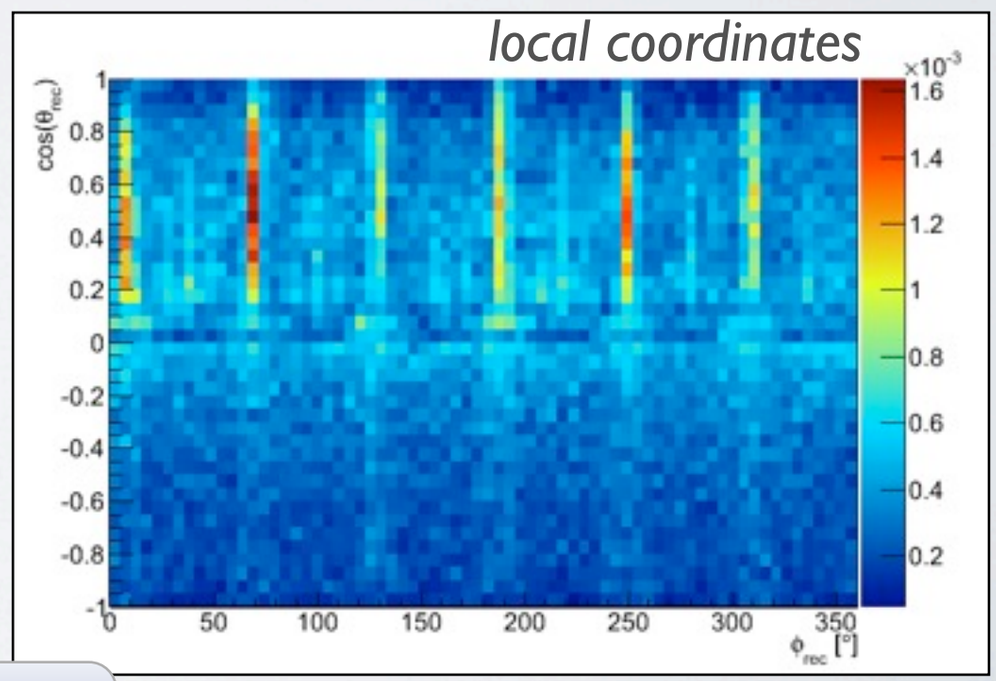
- ***Goal:*** Look for accumulation of events not only in ***space*** but also in ***time***.

- ***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.

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

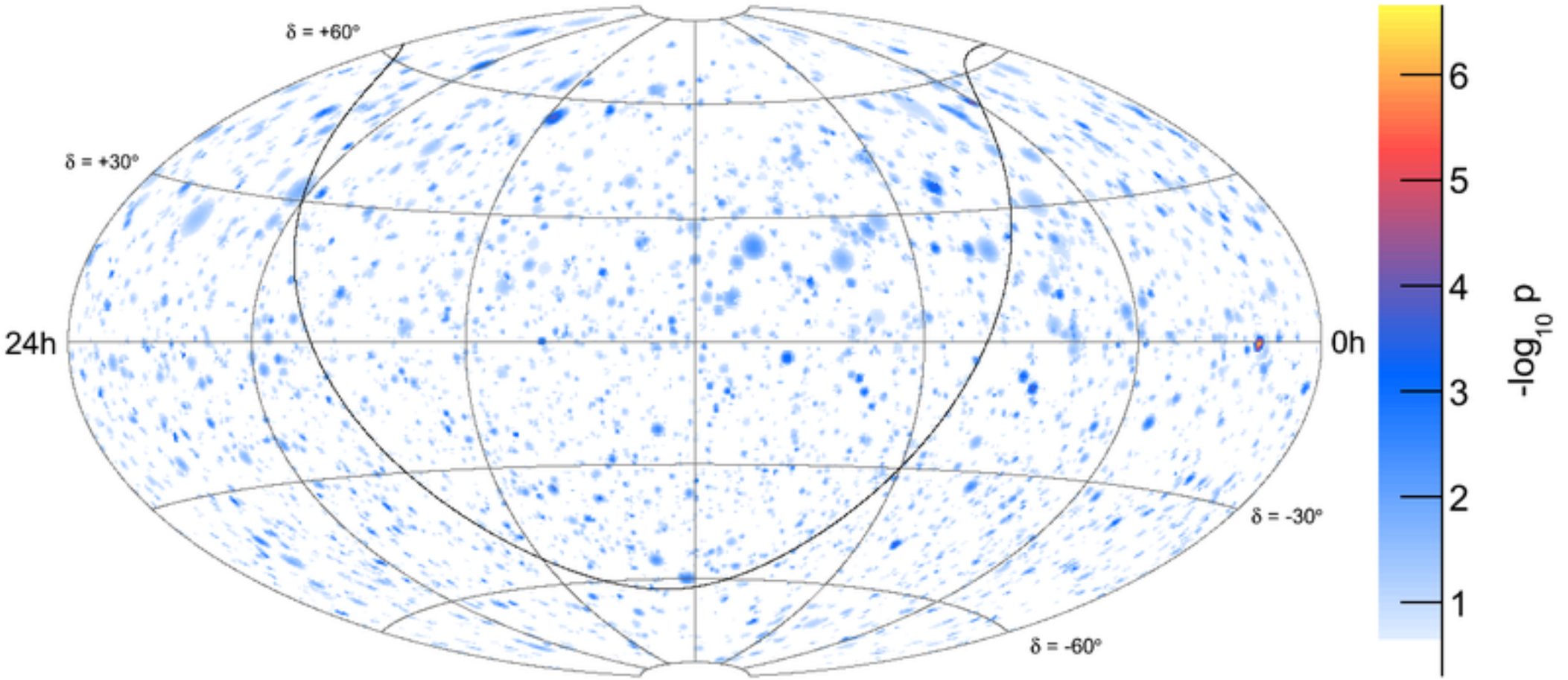
At low time scales (< 1 day) the background depends not only on zenith but on the local coordinates of the arrival track directions.





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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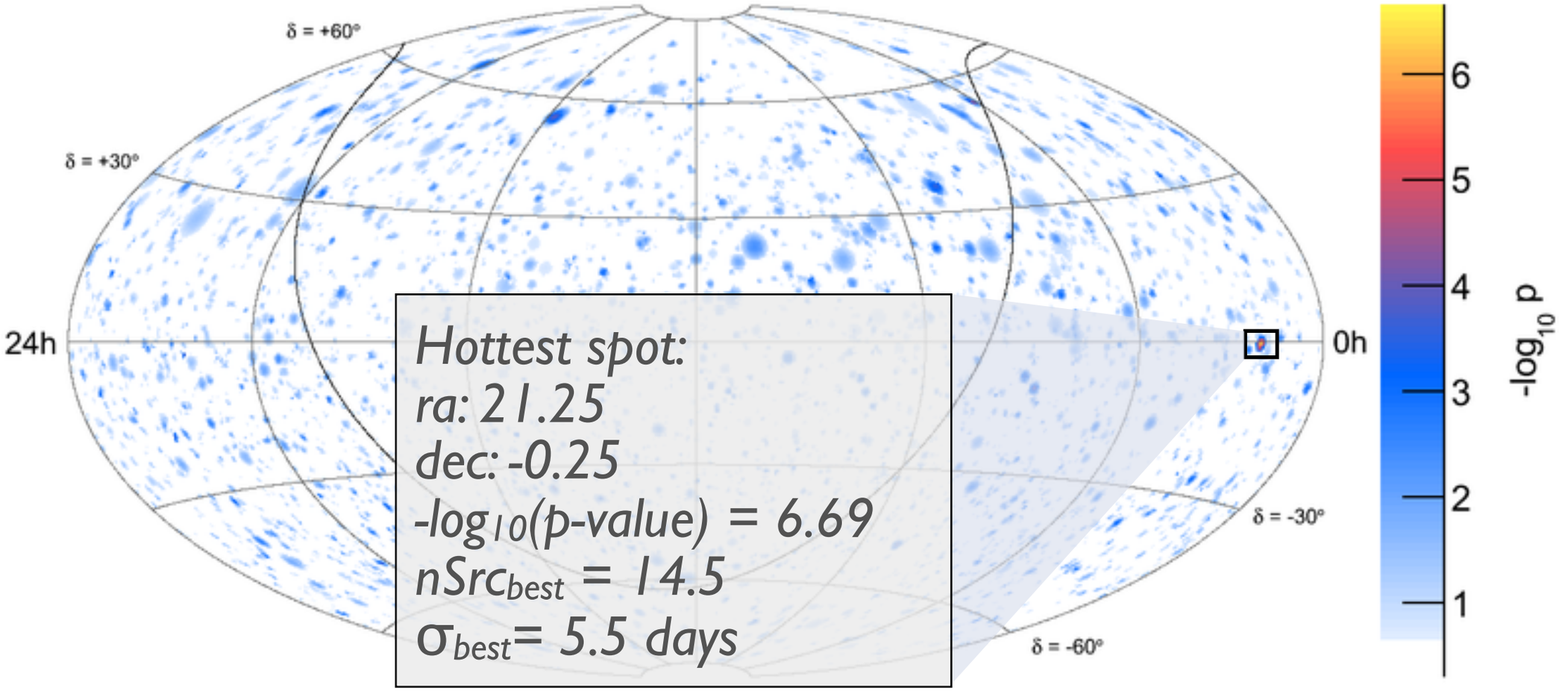
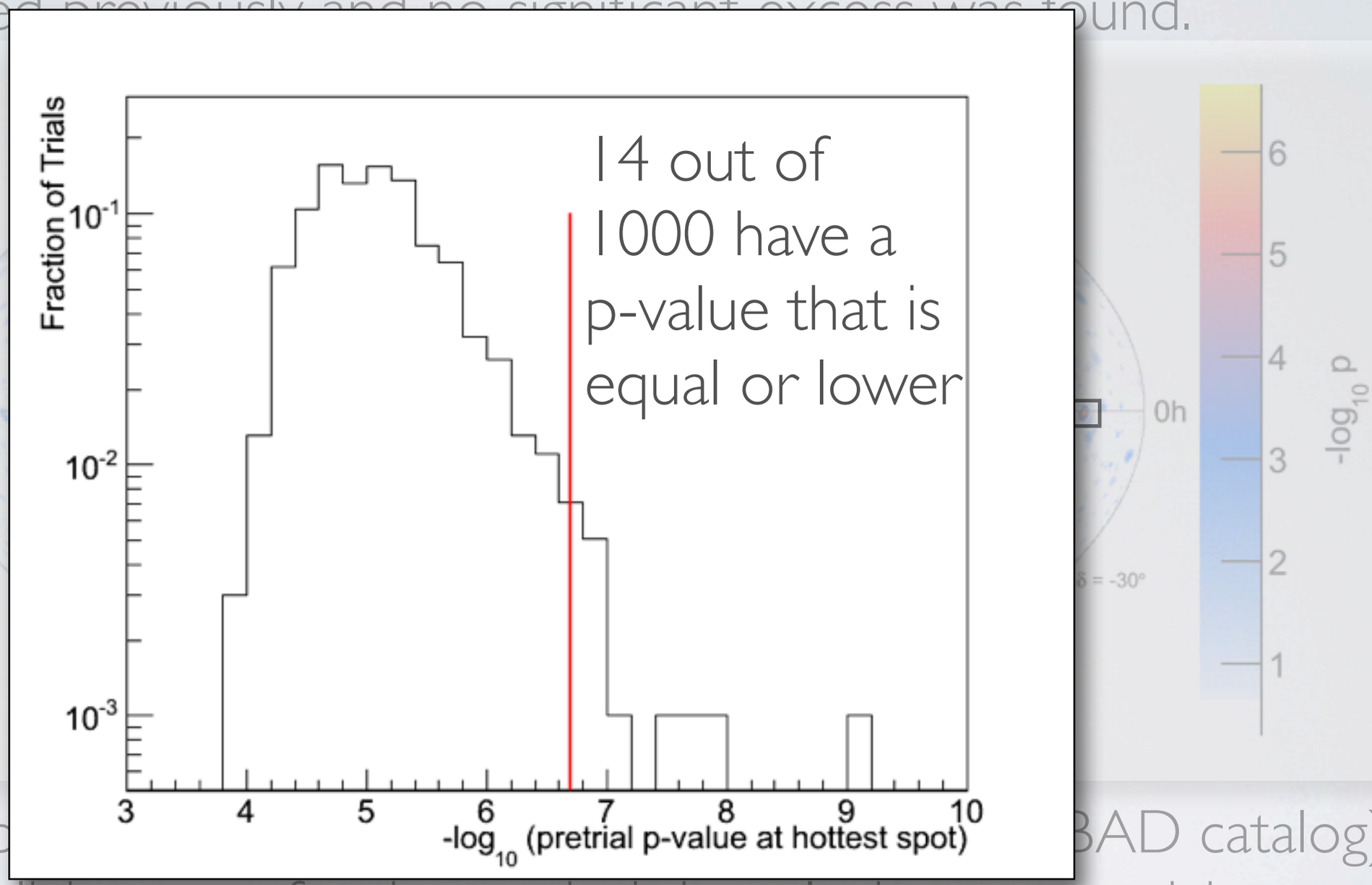


- No correspondence with any known source (SIMBAD catalog)
- Fermi light curve for that period doesn't show any activity.

FLARE ANALYSIS RESULTS

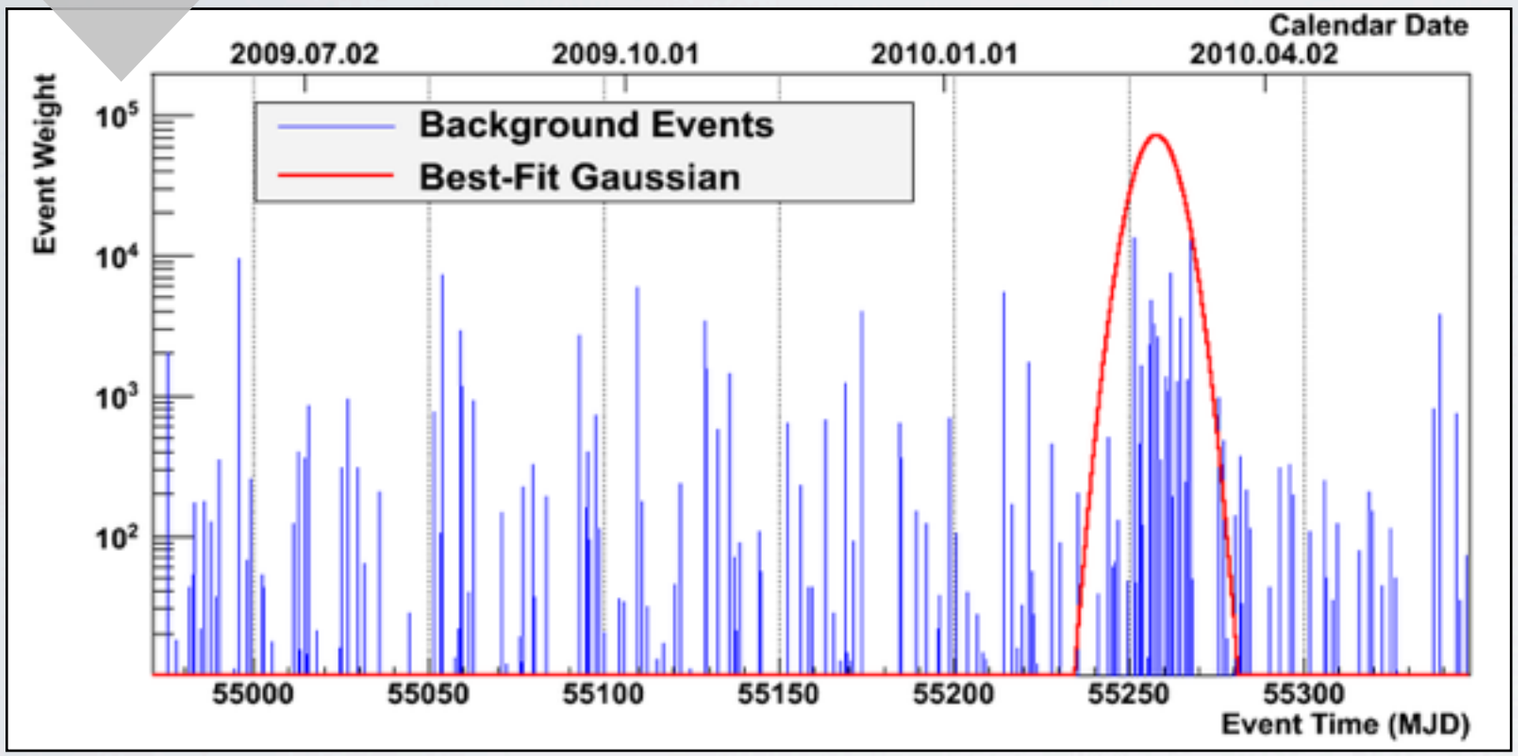
- Only IC59 data was used for the flare analysis. Data from IC40 was analyzed previously and no significant excess was found.

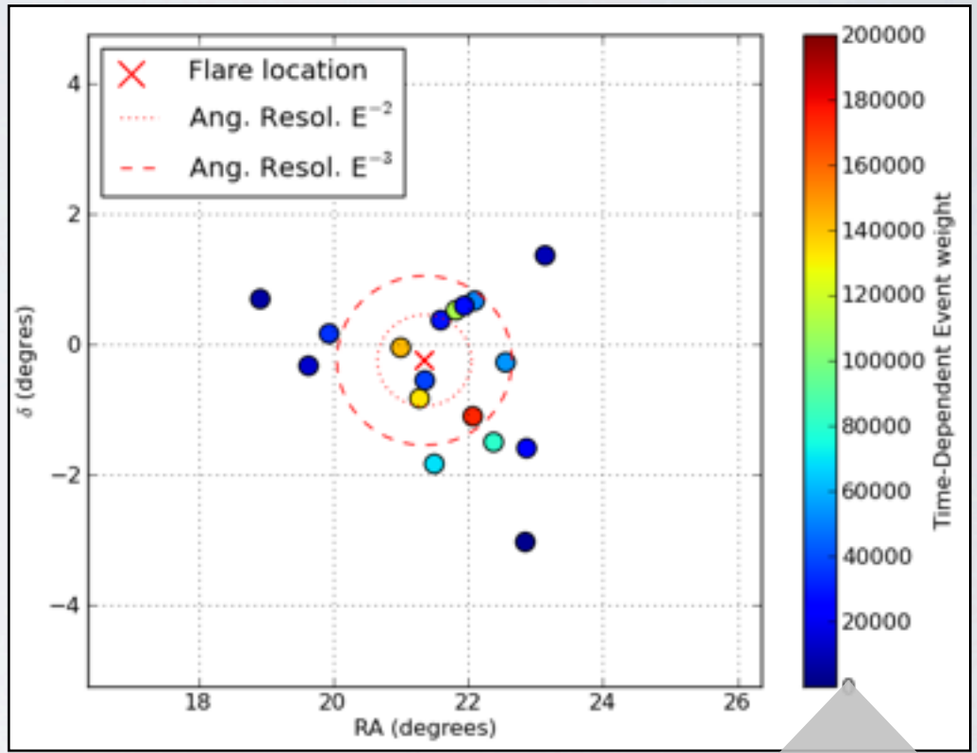


- No co… BAD catalog)
- Fermi light curve for that period doesn't show any activity.

FLARE EVENTS

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



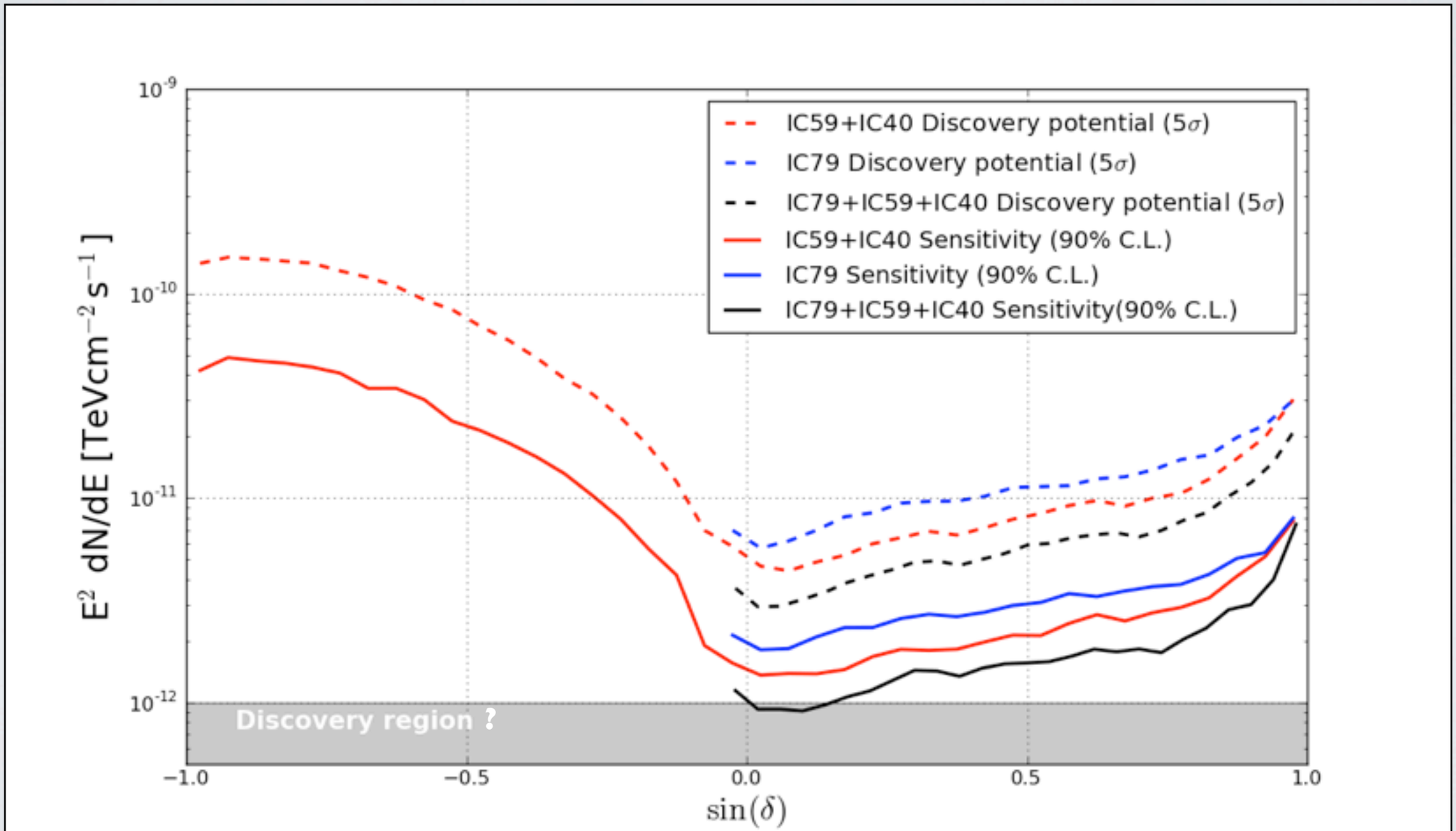


- Events that form part of the *flare* all have fairly low energy and are ~1 degree away, and only stand out in terms of their timing properties.

+IC79 ANALYSIS

+IC79 ANALYSIS

- This year analysis starts to get into a *discovery* (?) region.



CONCLUSIONS

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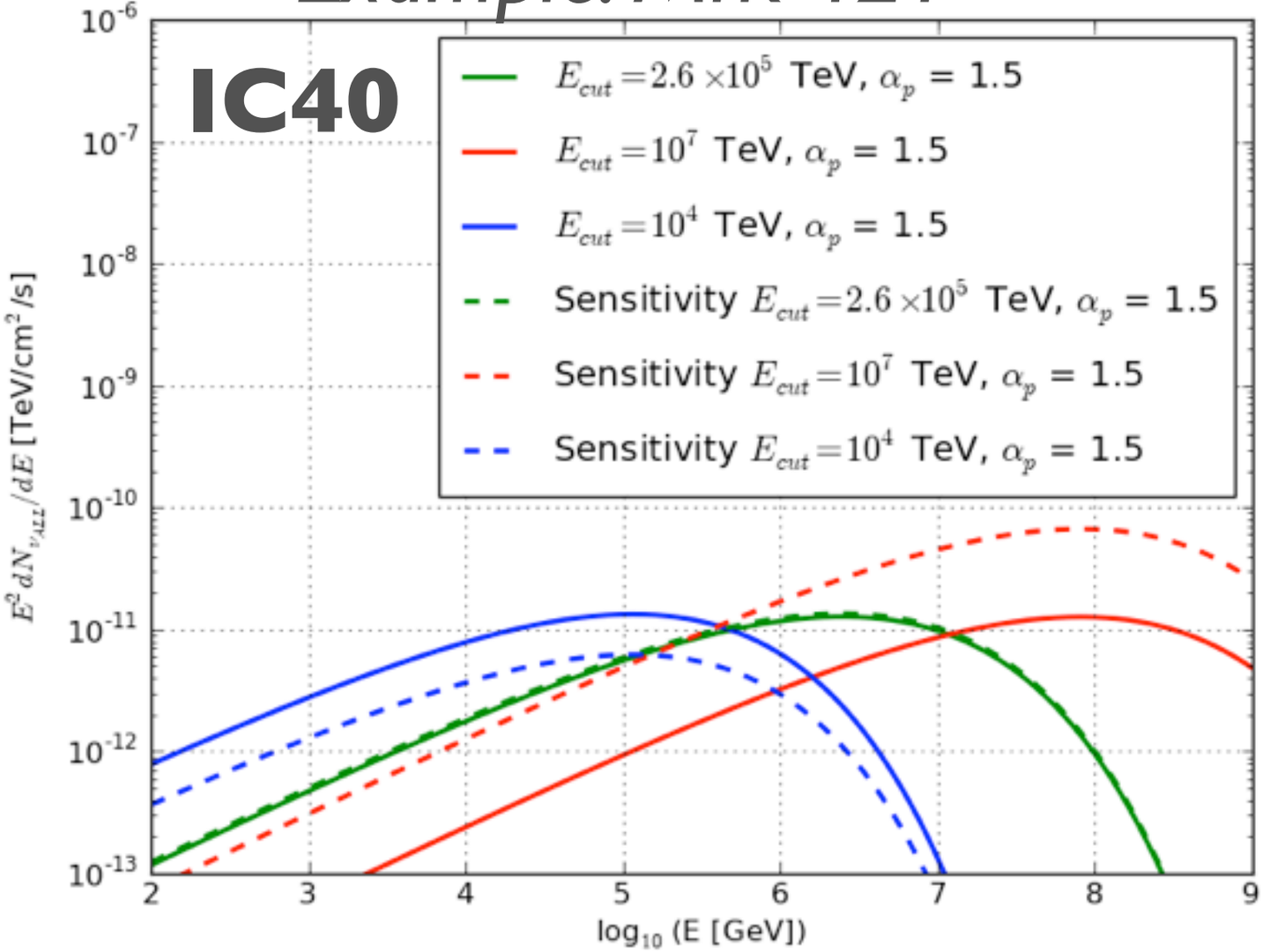
- What can we already say on AGN models, for instance:

Example: Mrk 421



Andrii Neronov, Celine Tchernin, ISDC

- Use a proton spectrum with free normalization, E_{cut} and α_p:

$$\frac{dN_p}{dE_p} = AE^{-\alpha_p}\exp\left(\frac{E_p}{E_{cut}}\right)$$

- In pp interactions for cascade dominated γ-ray total electromagnetic power is needed to estimate the total neutrino flux.

Kelner et al, PHYSICAL REVIEW D 74, 034018 (2006)

CONCLUSIONS

- The whole year of IC59 was analyzed for point-source and no evidence of a neutrino point source has been found.

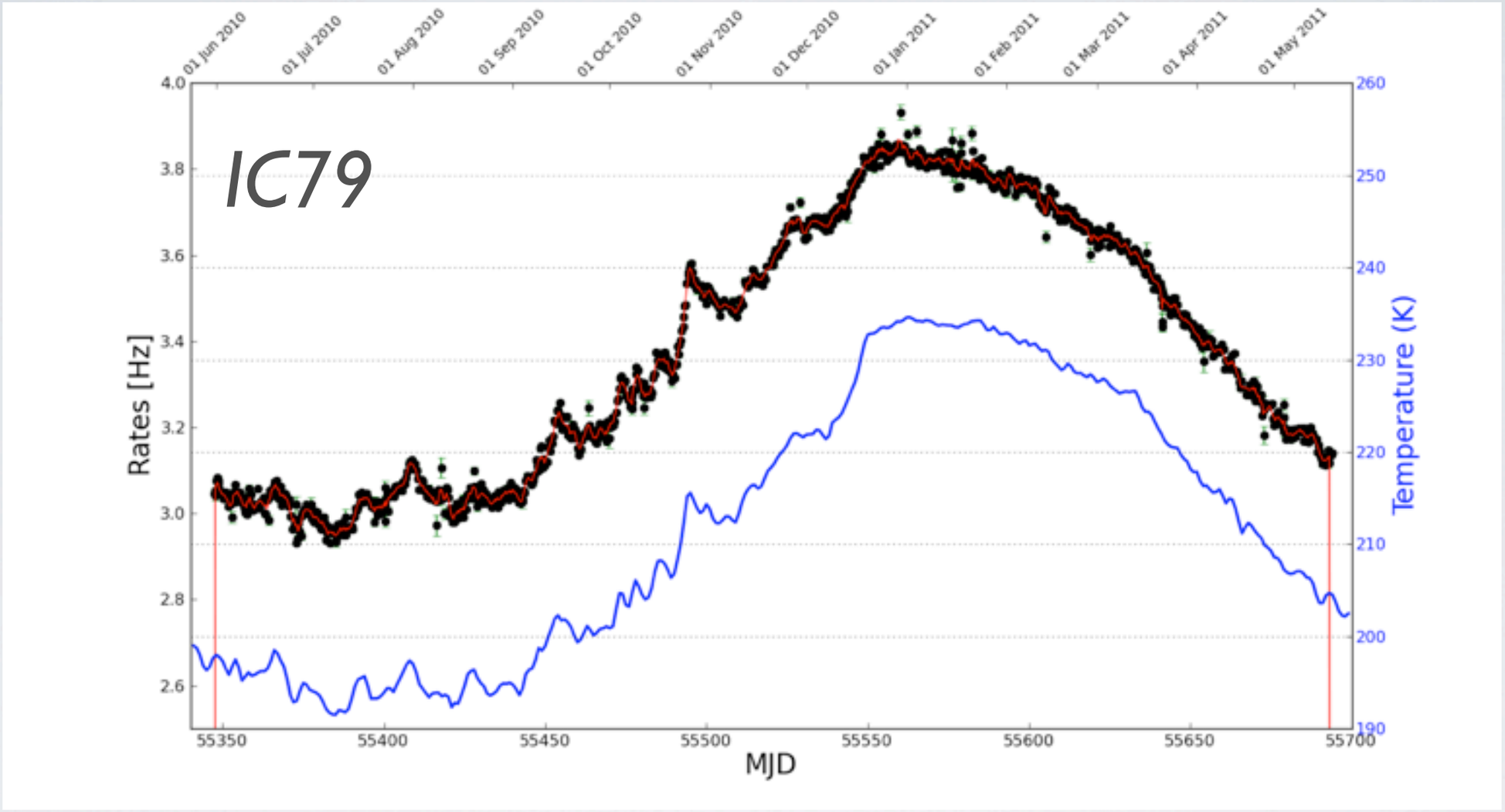
- We performed the combination of the IC59 and the previous IC40 data to enhance the discovery potential and sensitivities.

- This year combination of IC79 data with previous years will allow us to reach new levels of sensitivity and we expect to get interesting years ahead.

- IC86 data is being processed and analyzed.

BACK UP

MUON LEVEL 3



- The level3 is common for the muon group.
- Still muon dominated: ~ 3 - 4 Hz
- The detector up-time at this analysis level is 95 %