Neutrino Astroparticle Physics

"Astrophysics, cosmic-ray physics & particle physics with current generation neutrino telescopes"

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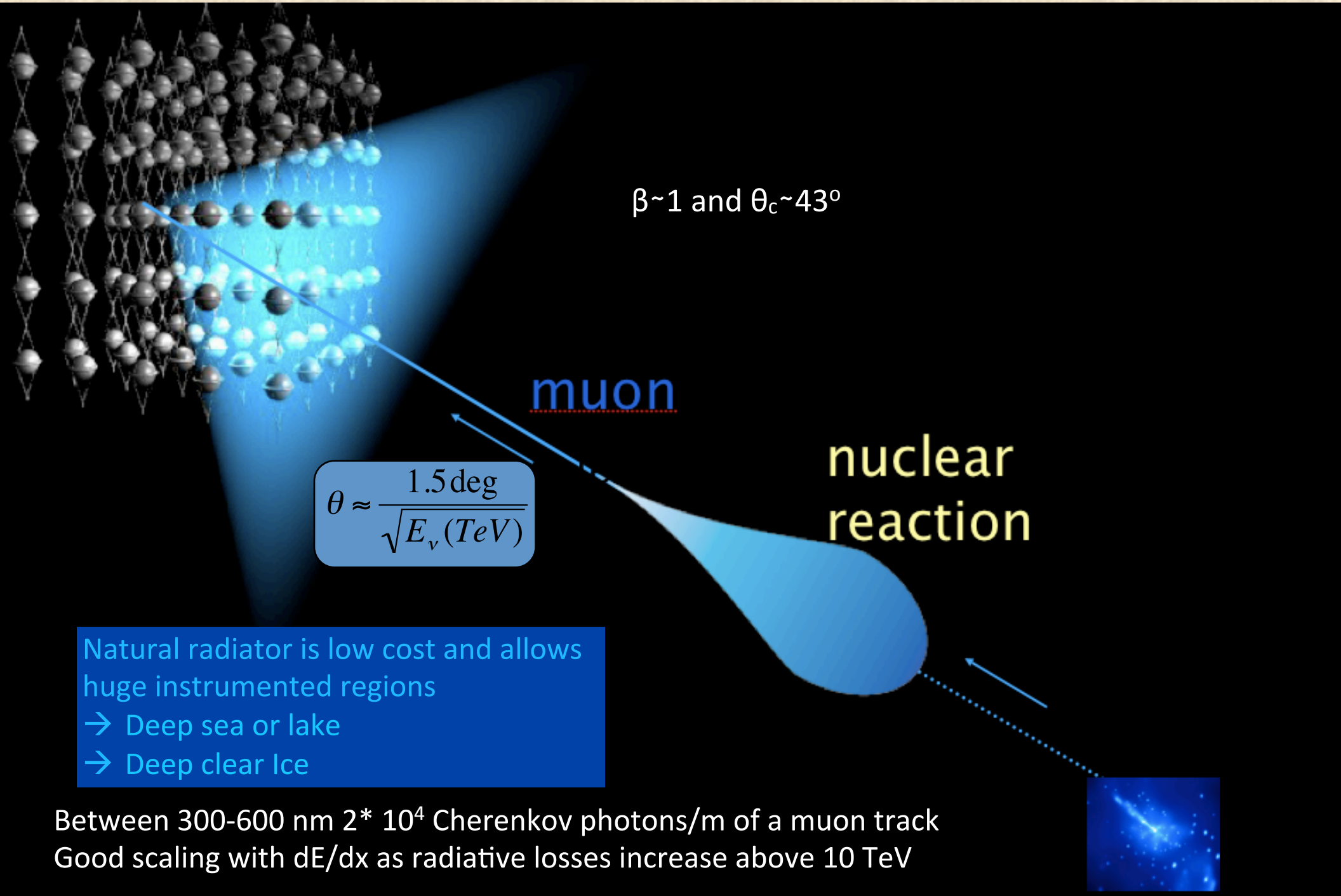
University of Maryland

Physics in Collision
Vancouver, Canada
1 Sept 2011

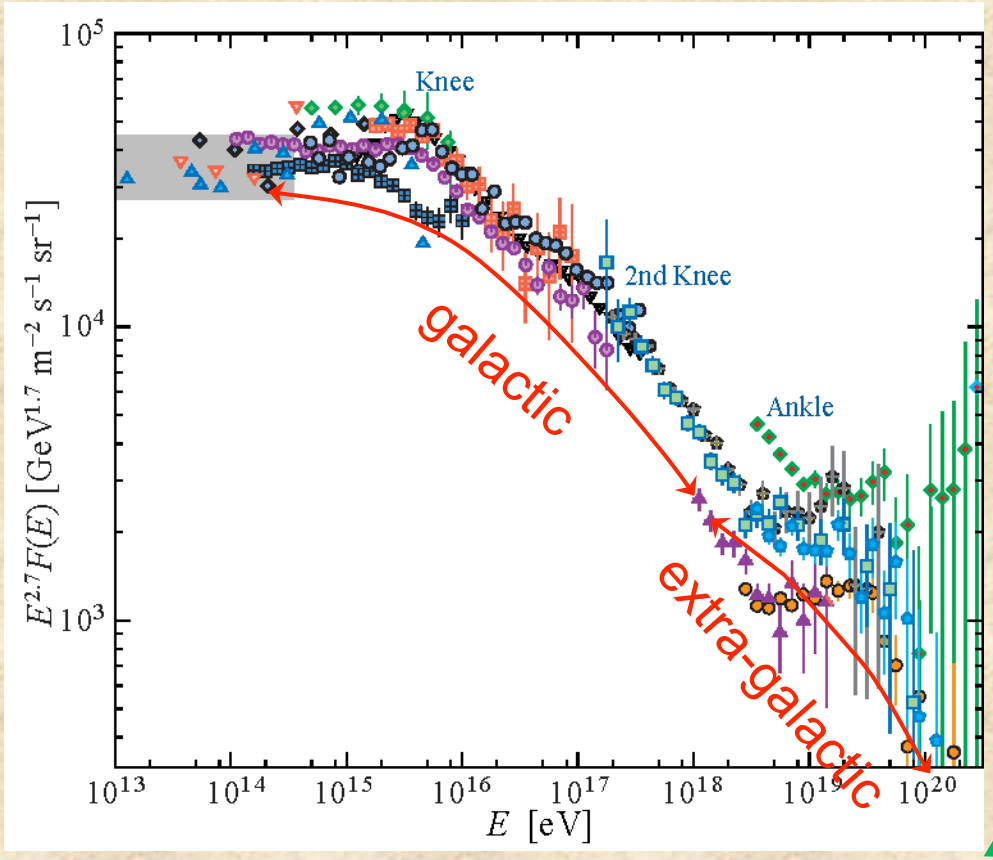
Concept of Large Neutrino Telescopes

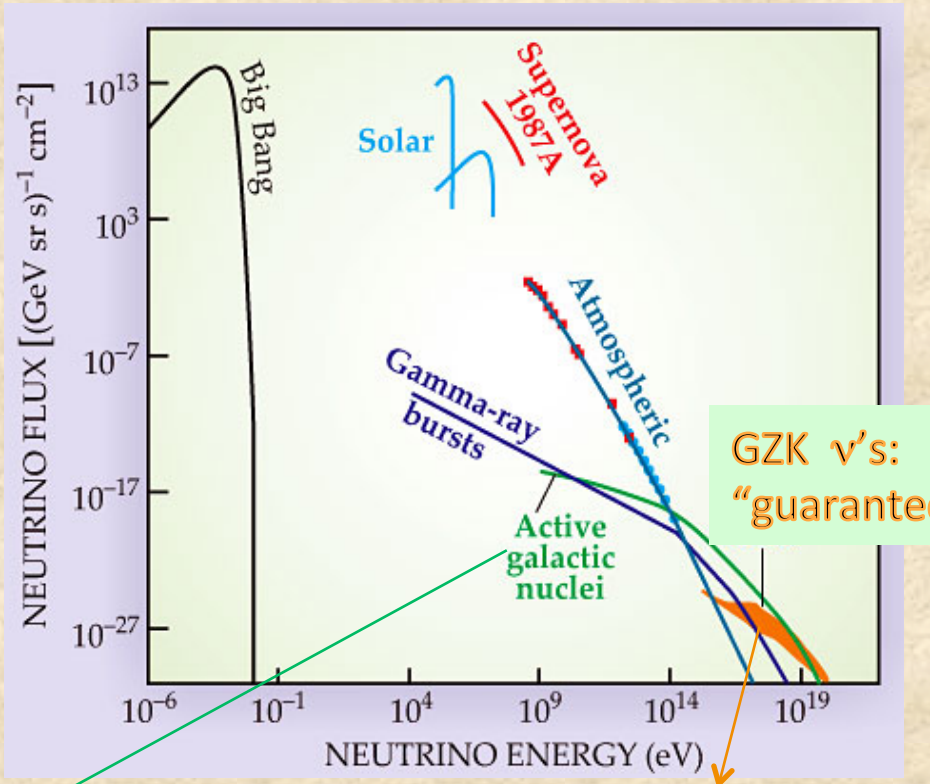


Between 300-600 nm 2* 10^4 Cherenkov photons/m of a muon track
Good scaling with dE/dx as radiative losses increase above 10 TeV

Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays

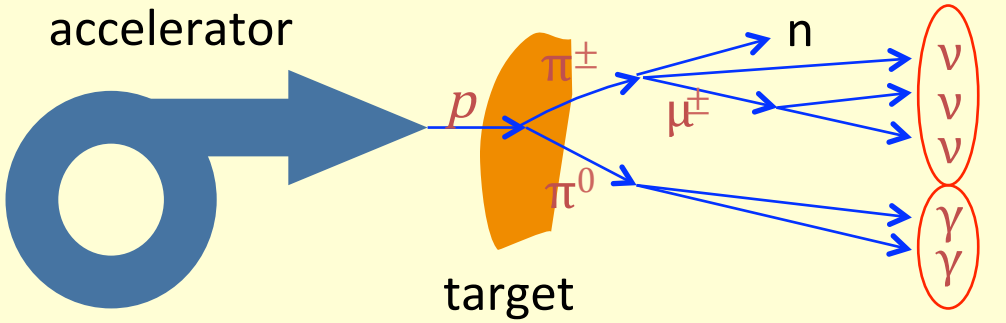




GZK ν's: "guaranteed"

$$\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} \rightarrow n\,\mu\nu \\ p\,\pi^{0} \rightarrow p\,\gamma\gamma \end{matrix}$$

CR – ν connection



the **γ – ν** connection for hadronic accelerators

Neutrinos Provide a Unique Window on the HE Universe

Universe opaque to to high energy (>10's TeV) photons:

$\gamma + \gamma_{EBL+CMB} \rightarrow e^+ + e^-$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\rightarrow \mu^+ + \nu_\mu$

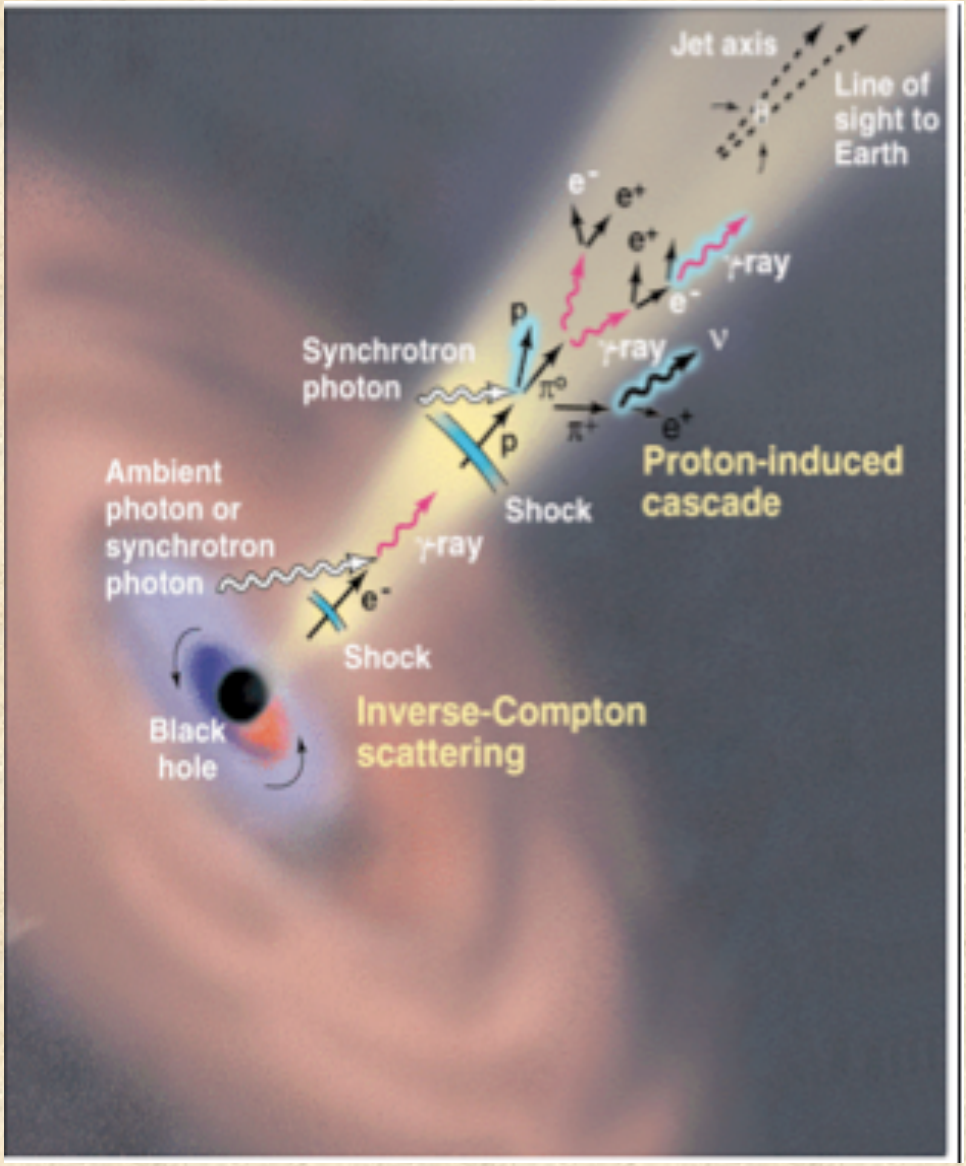
Cosmogenic "GZK" neutrinos

Protons deflected by magnetic field for $E < 10^{19}$ eV

- ***Not pointing back for distant sources***

1) Neutrinos are a candidate for high energy (>10TeV) cosmic astronomy!

2) Neutrinos provide unambiguous evidence of hadronic acceleration!

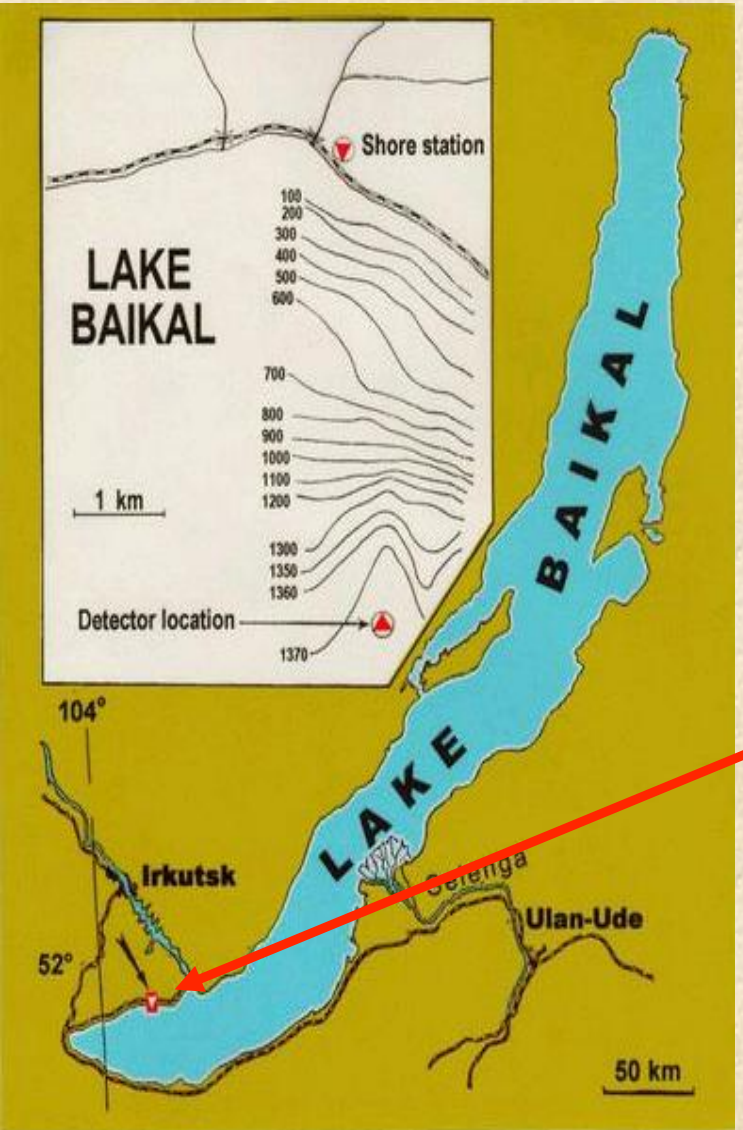


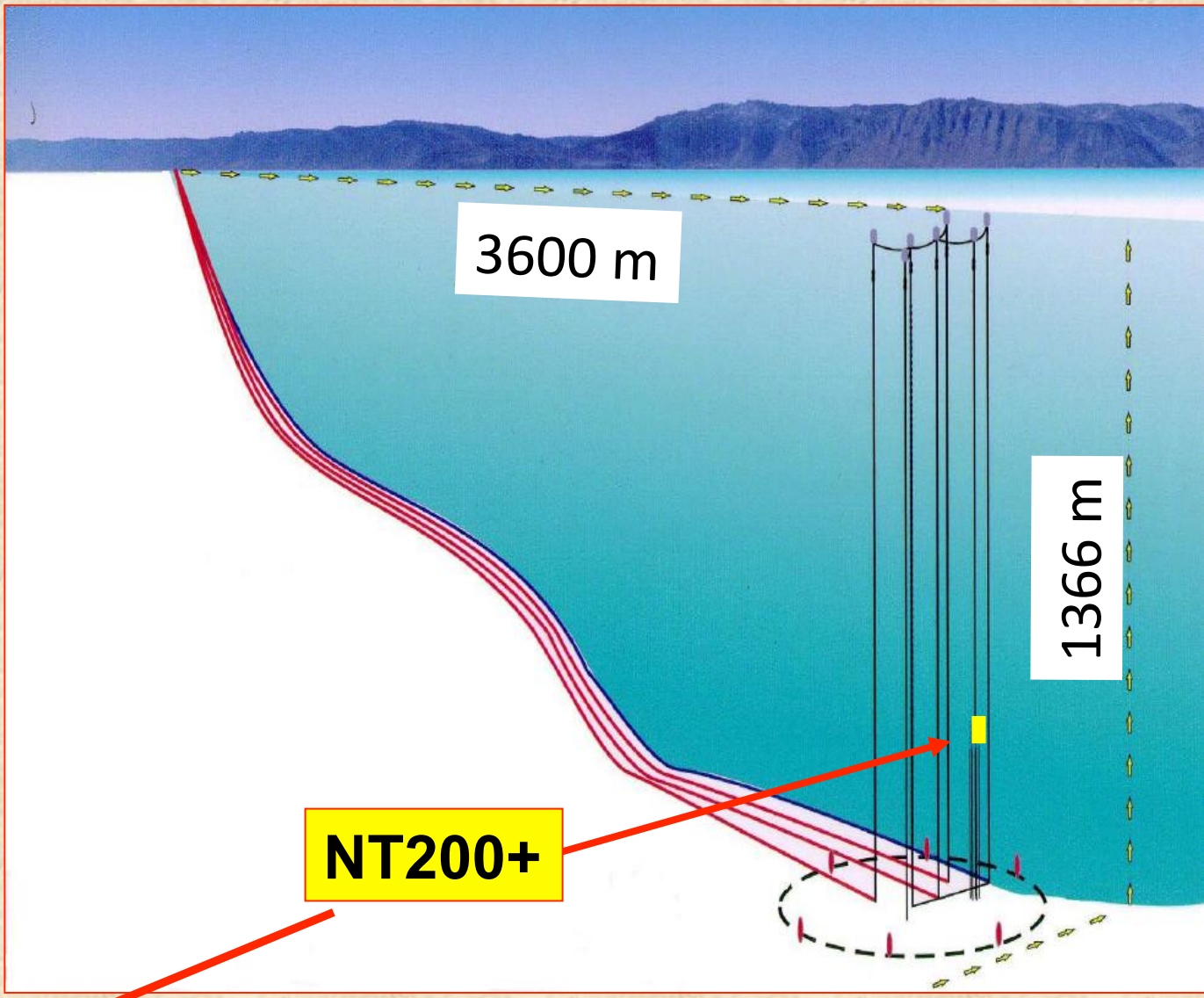
Neutrino Telescopes – A Brief Heritage

Telescopes for TeV energies:

- ***First envisioned by Greisen, Markov 1960***
- Pioneering effort: DUMAND near Hawaii
- First and second generation telescopes in 90's, proof of principle : Baikal, AMANDA (S Pole), NESTOR (Greece).
- Current generation experiments and initiatives:
  - 50000m^2 scale: ANTARES
  - Auger Detector (tau neutrinos, E > 10^{18} eV)
  - IceCube (data from 50-75% size)
- Coming generation: km^3 scale (and larger)
  - IceCube completed construction ***Dec 18, 2010 !***
    - *Data Taking Began May 13, 2011*
  - Based on NESTOR, NEMO, ANTARES experience's → km3NeT project, Mediterranean Sea. ***Multi-km^3 scale!***

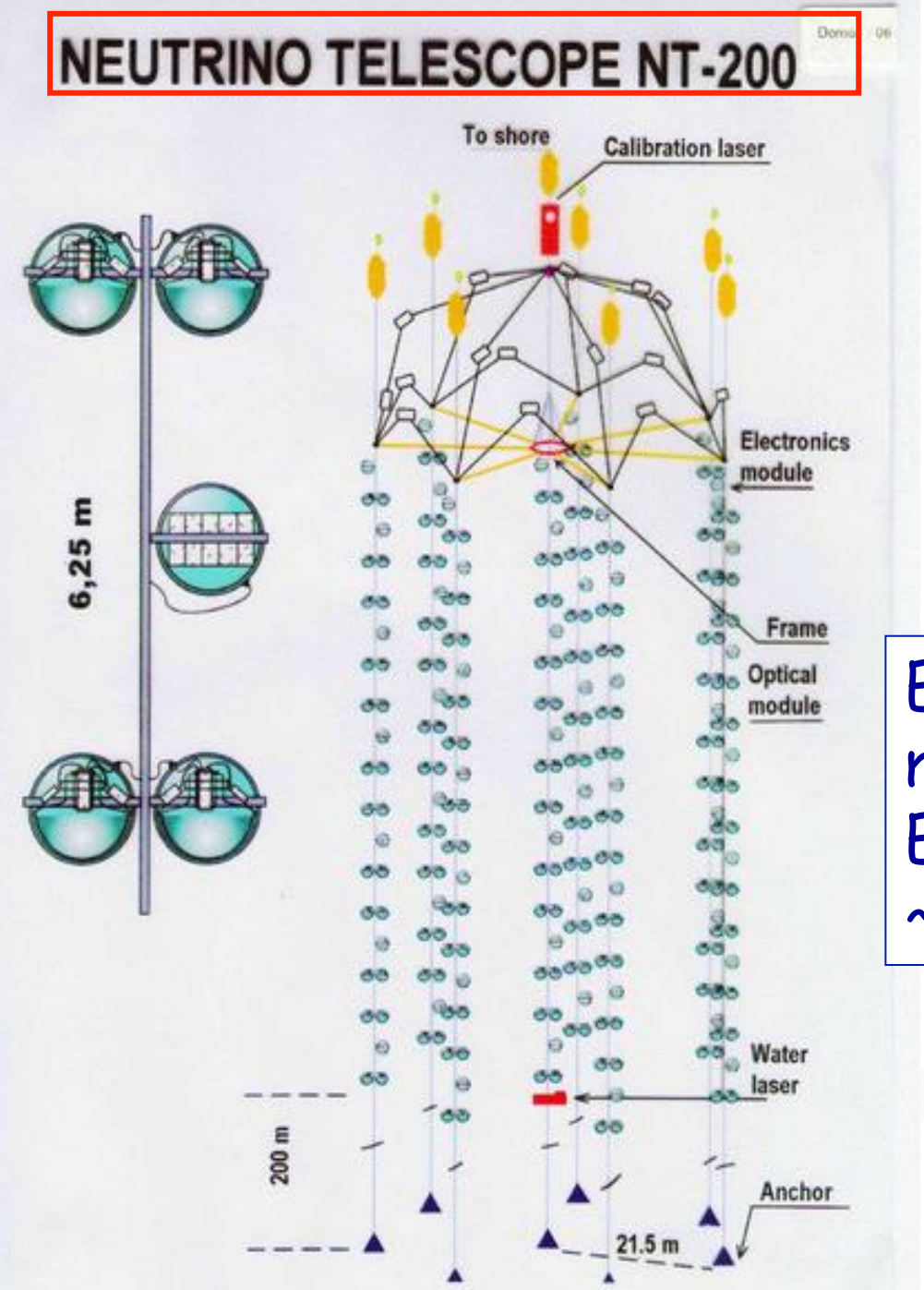
BAIKAL





- 4 cables x 4 km to shore.
- 1100m depth

NEUTRINO TELESCOPE NT-200



- 8 strings: 72m height
- 192 optical modules
  = 96 pairs (coincidence)
- measure T, Charge
  - σ_T ~ 1 ns
  - dyn. range ~ 1000 p.e.

Effective area: 1 TeV ~2000 m^2

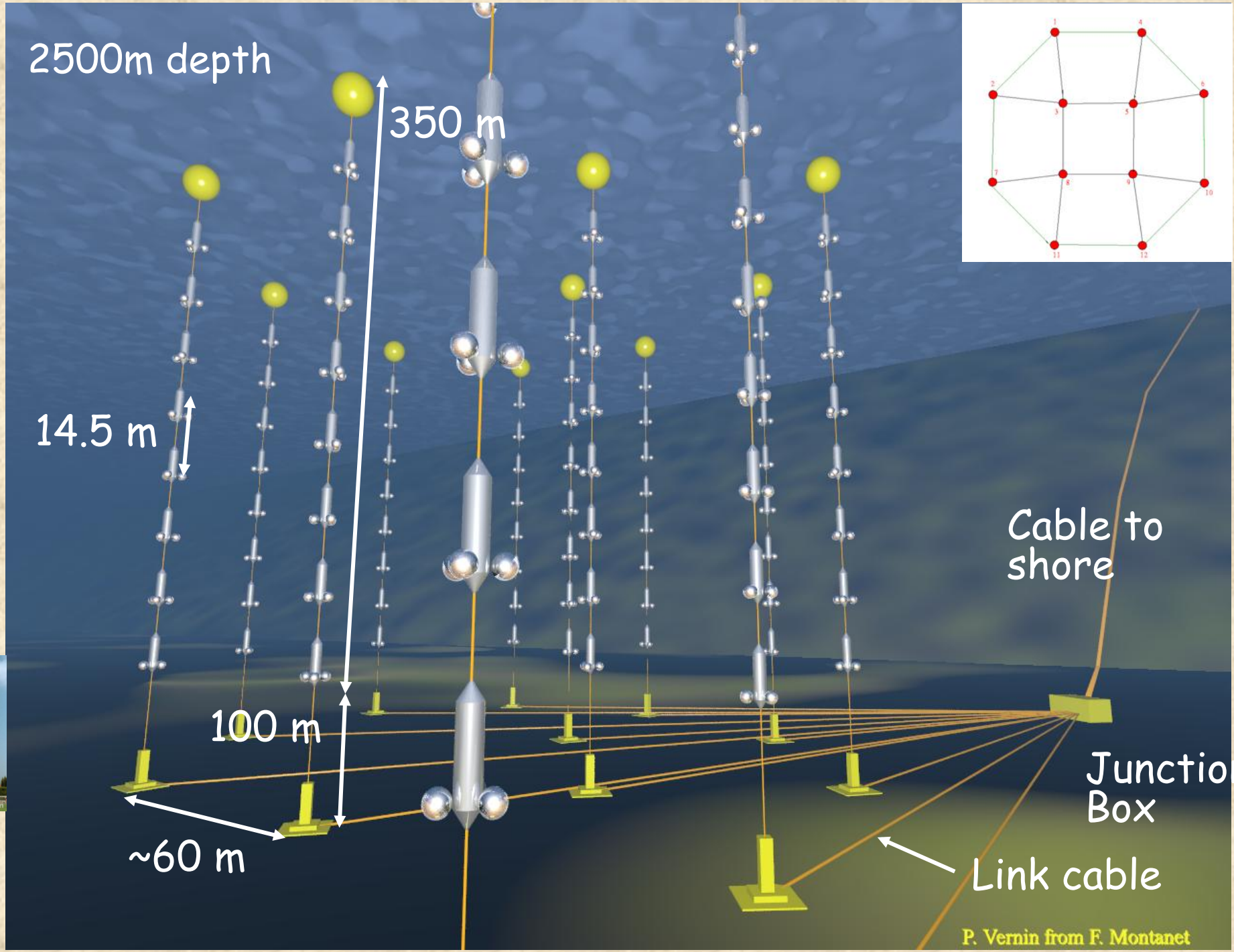
Eff. shower volume: 10TeV ~0.2Mt

Height x ∅ = 70m x 40m, $V_{inst}=10^5 m^3$

Quasar PM:

d=37cm

The ANTARES detector



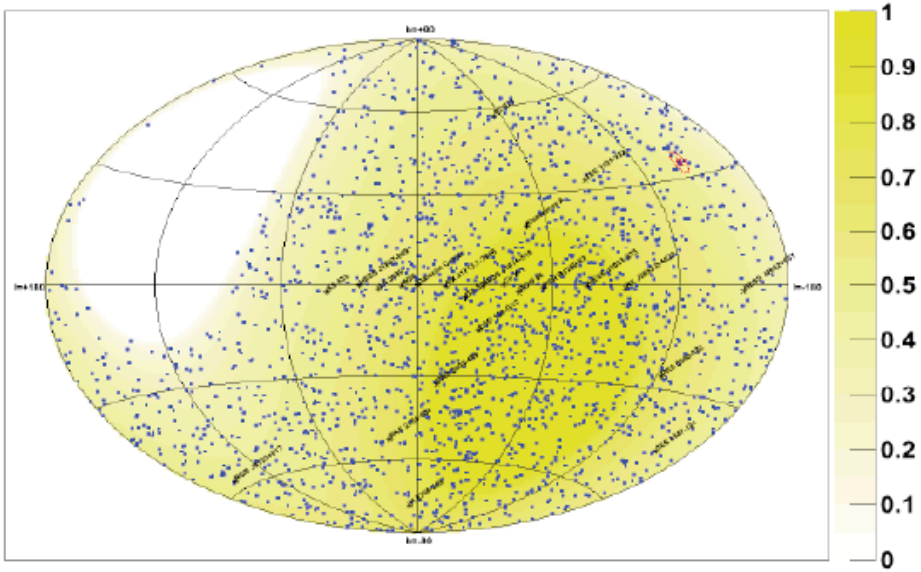
Mediterranean Projects

NESTOR

ANTARES

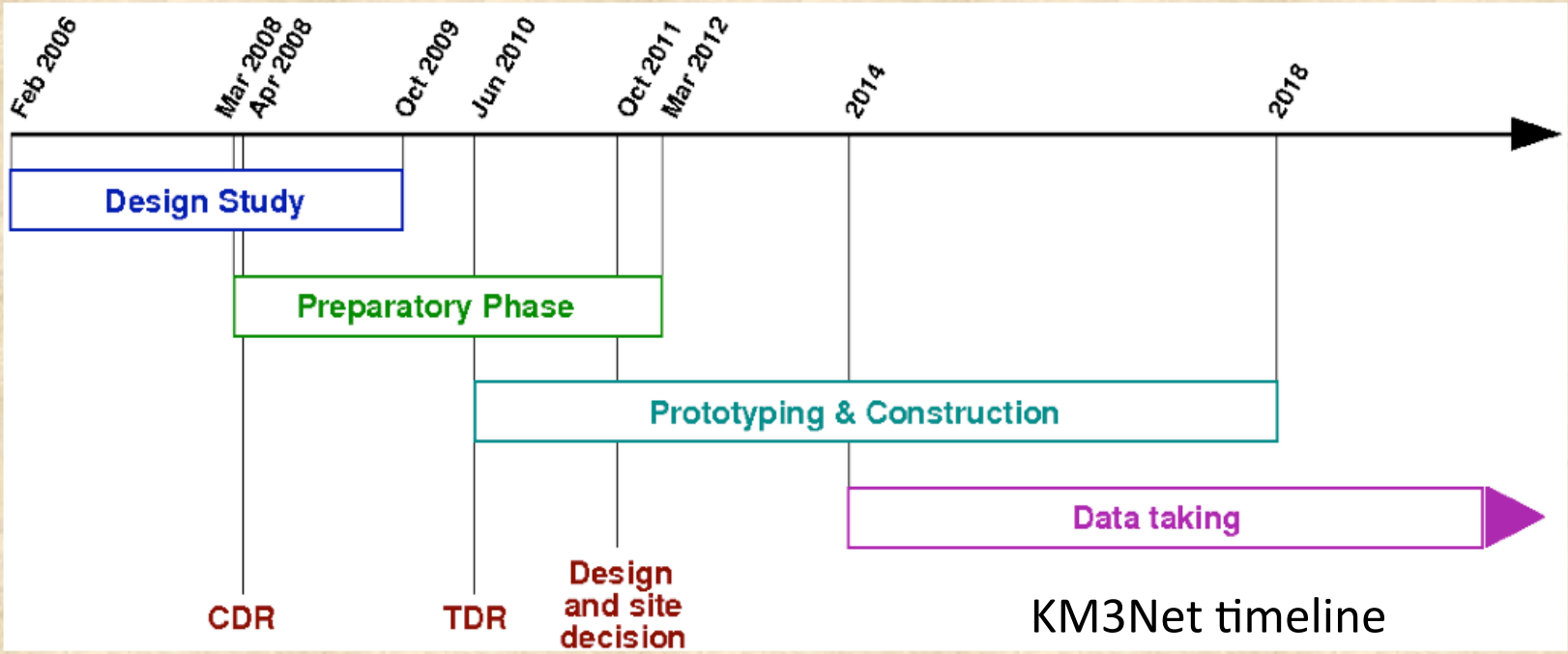
NEMO

Antares sky map

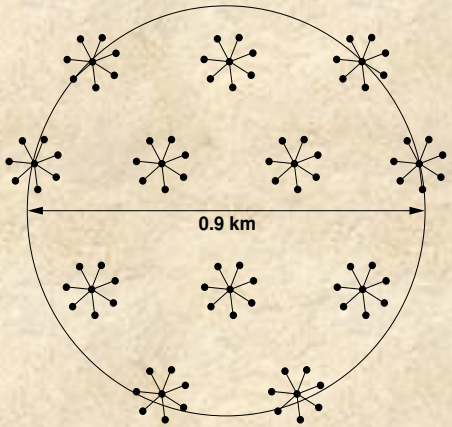


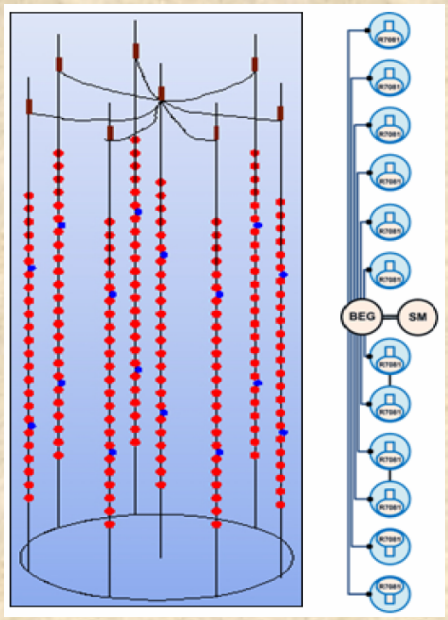
Since 2003: km3 initiative **KM3NeT**

Future projects at Baikal & Mediterranean



KM3Net timeline





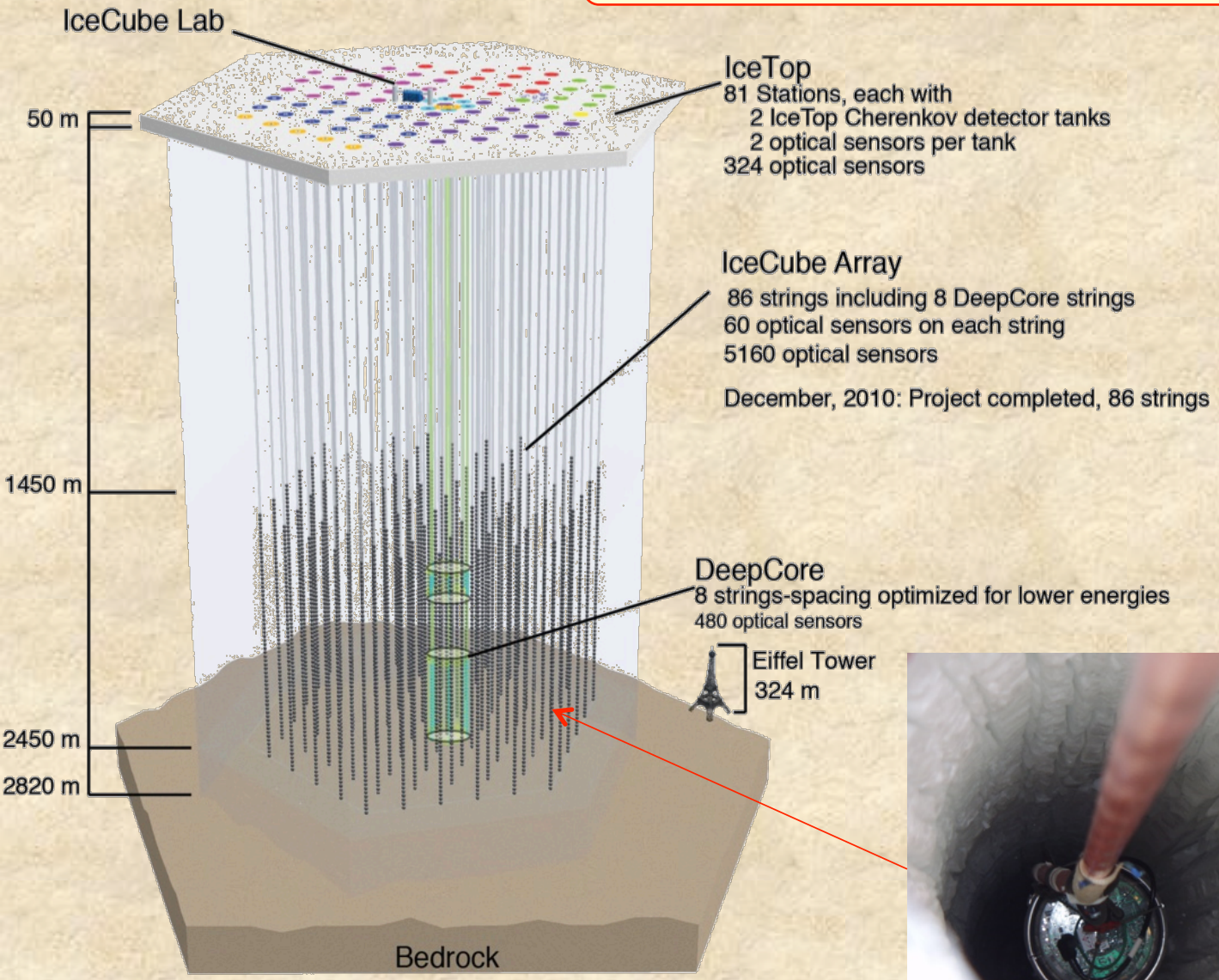
Possible extension beyond the NT200 detector in lake Baikal

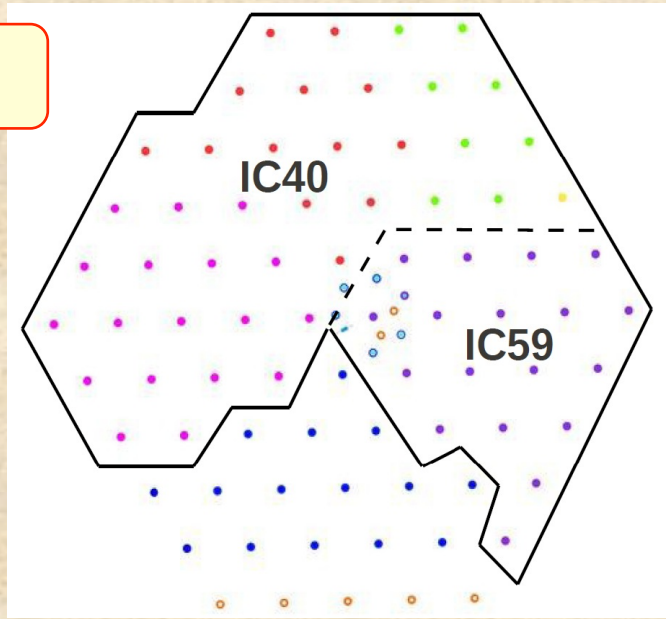
"GVD"

86 strings in 12 clusters of 8 strings over ~1km diameter

IceCube Detector

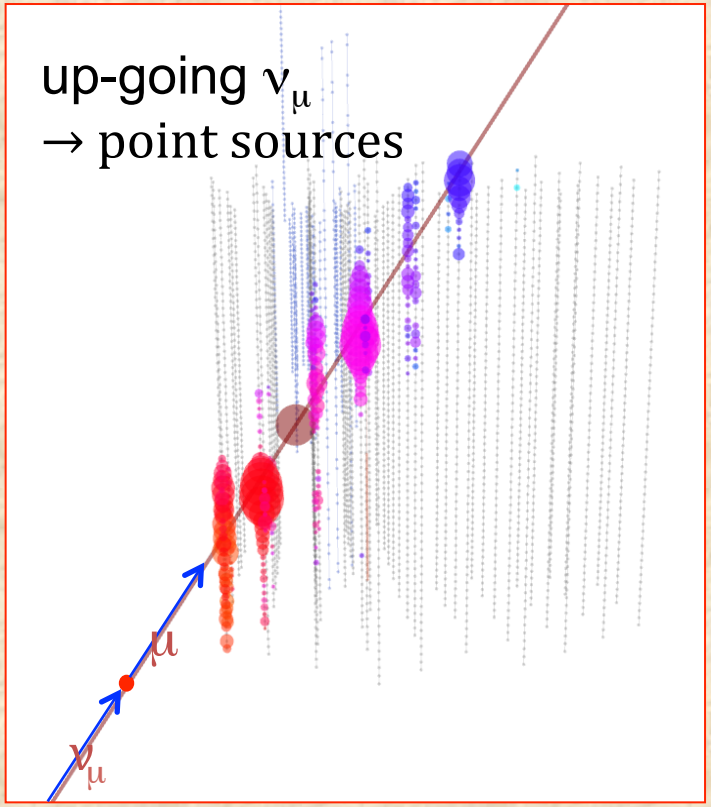
Detector Completion Dec 2010

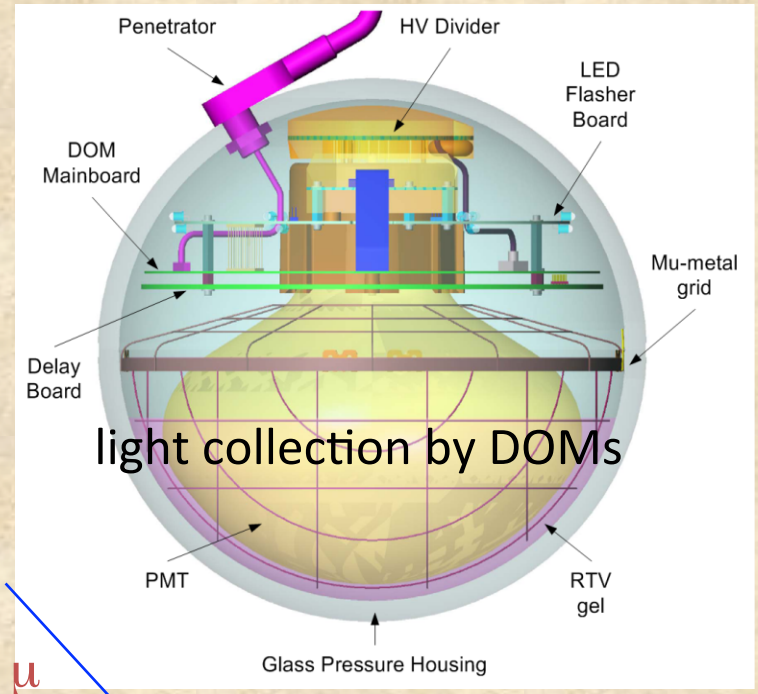


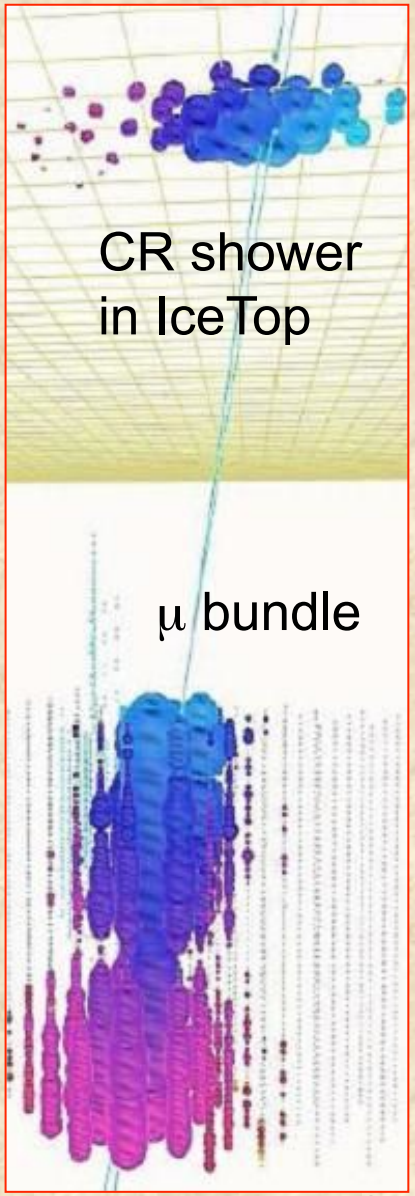


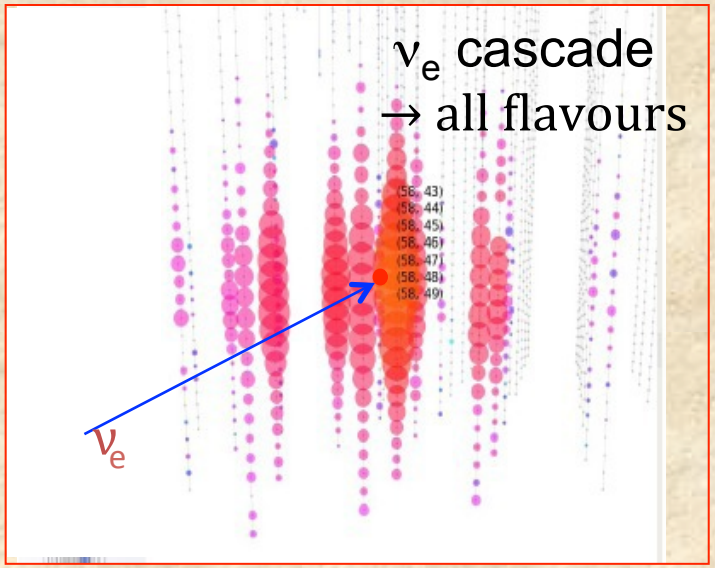
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

Detection Methods

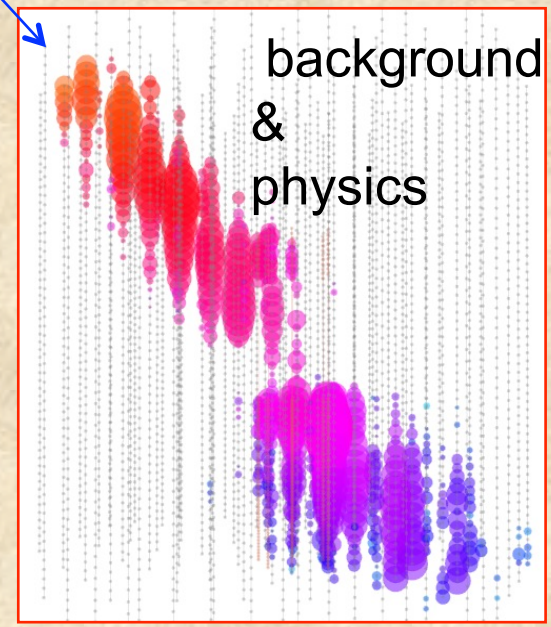




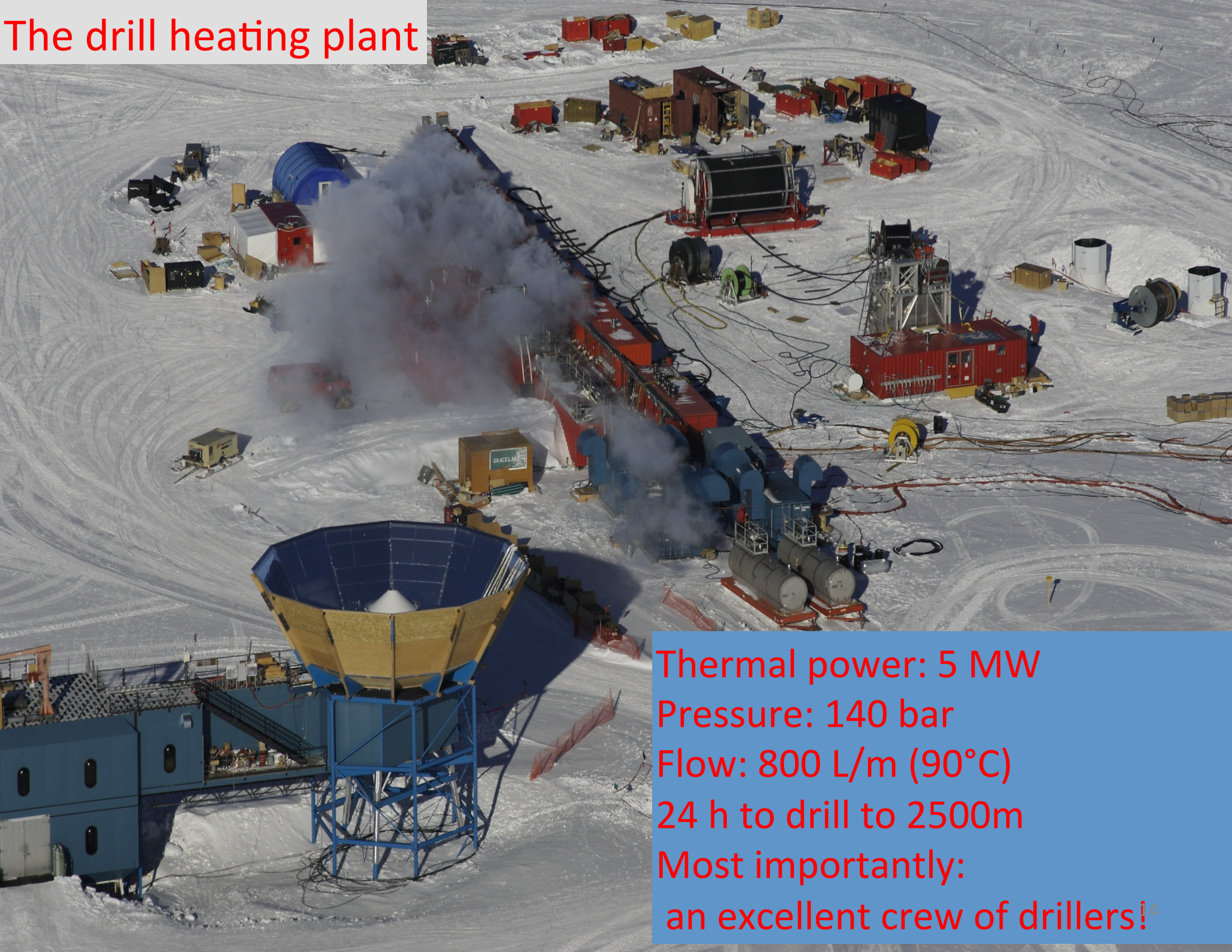




μ



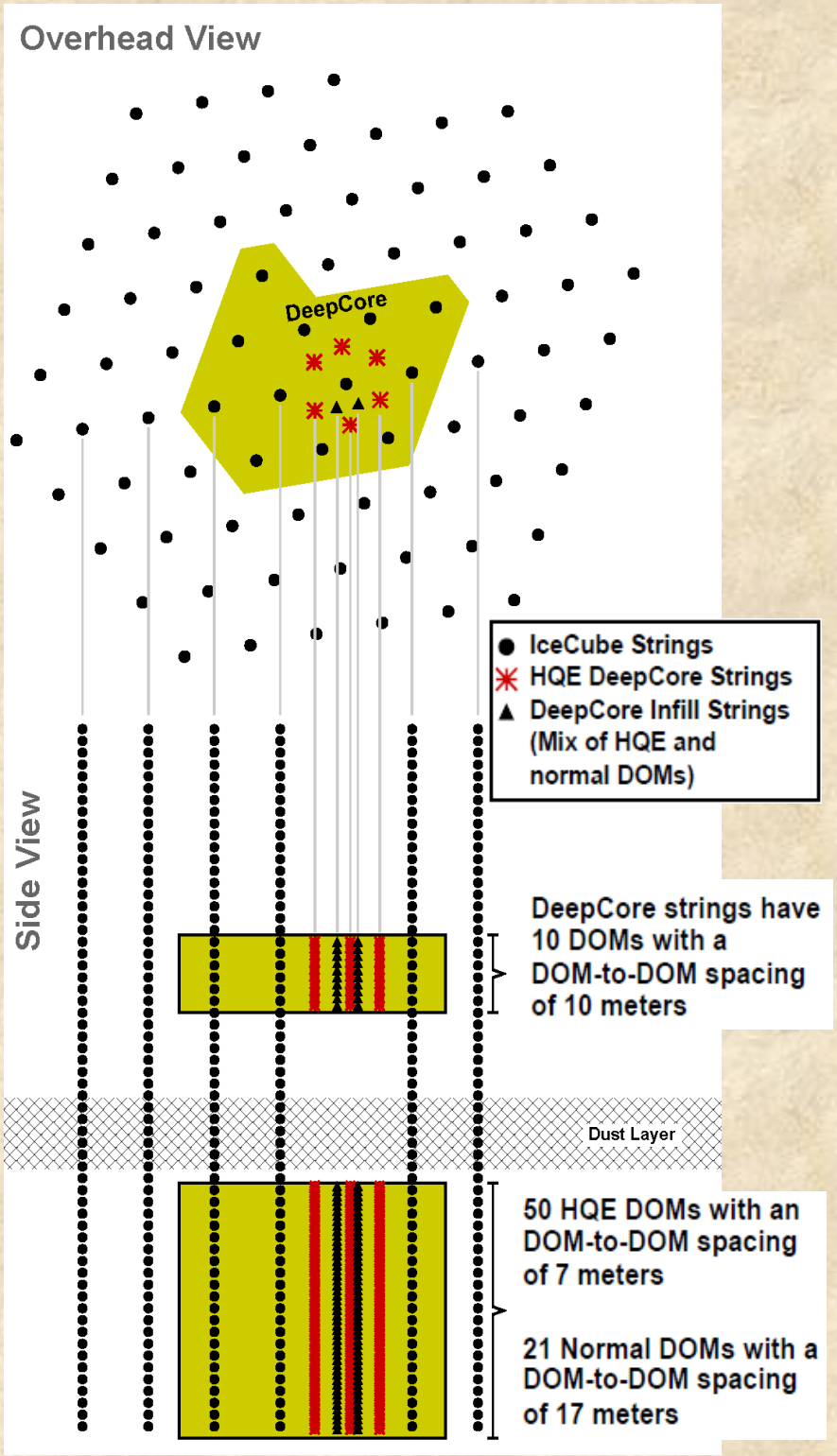
The drill heating plant



Thermal power: 5 MW
Pressure: 140 bar
Flow: 800 L/m (90°C)
24 h to drill to 2500m
Most importantly:
an excellent crew of drillers!

Operational support:
ICL maintenance
~60 kW power to electronics
90 GB/day filtered out and sent on satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)

DeepCore



8 high density plus the 12 standard strings in clear ice

(in IC79 equivalently 6 + 7 strings)

Energy range: down to 10 GeV
Extends physics:

- atm ν oscillations,
- low mass WIMPS
- SN/GRB physics
- Downgoing neutrinos
  - Contained events
  - 4π detector at LE

IceCube Detector Status, Rates

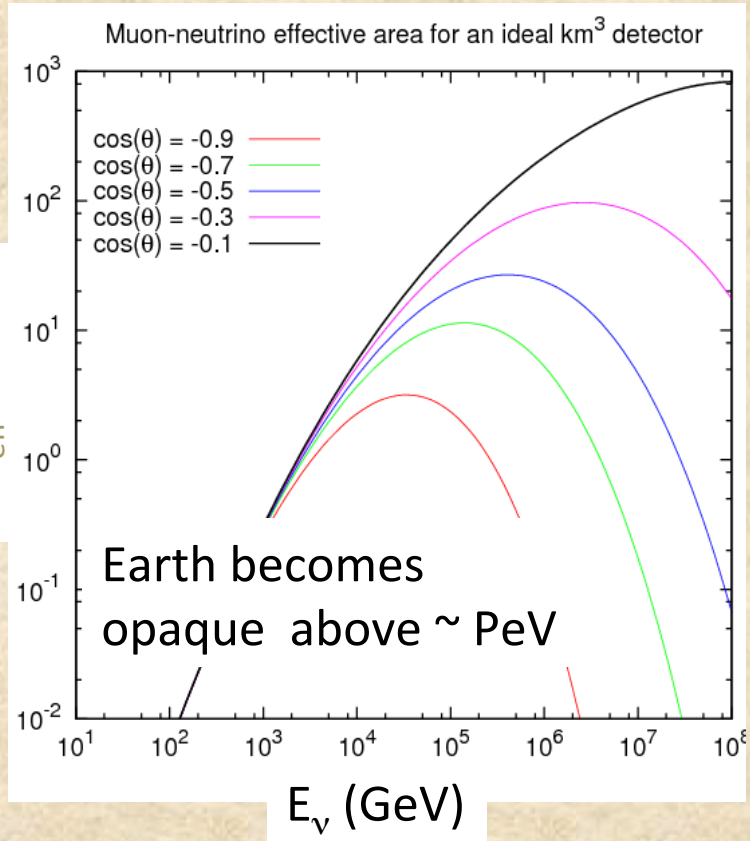
Strings	Data (year)	Livetime	μ rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	5 / day
IC40	2008-09	375 days	1100	38 / day
IC59	2009-10	360 days	1900	129 / day
IC79	2010-11	1 year	2250	analyzing
IC86	2011-	-	2700	running

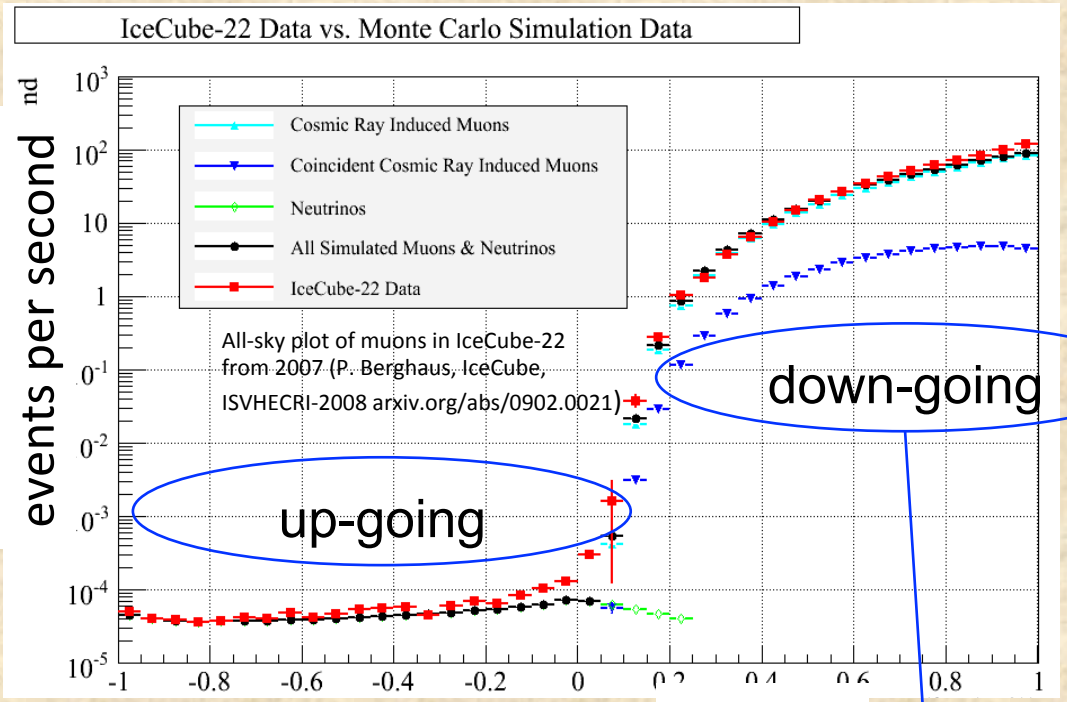
DeepCore Completed →

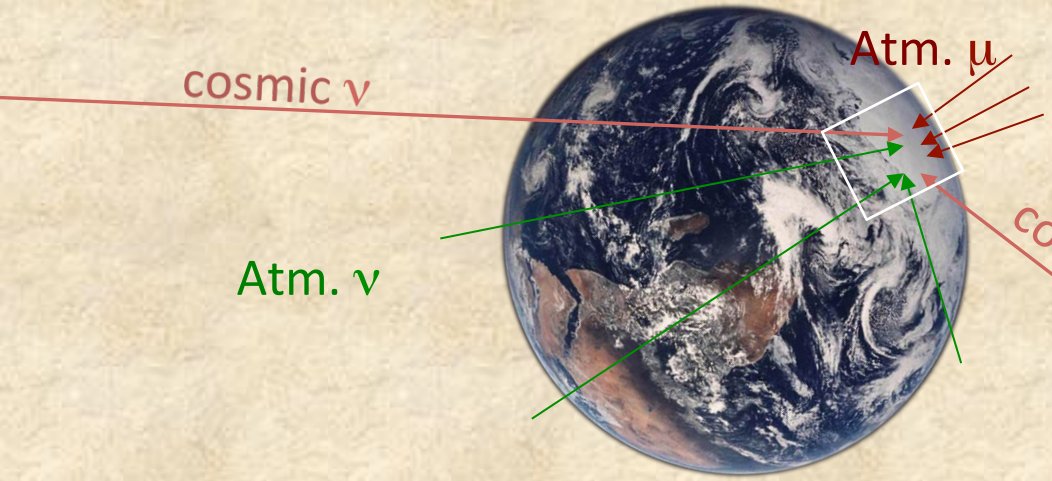
IC86 Run Start on May 13, 2011

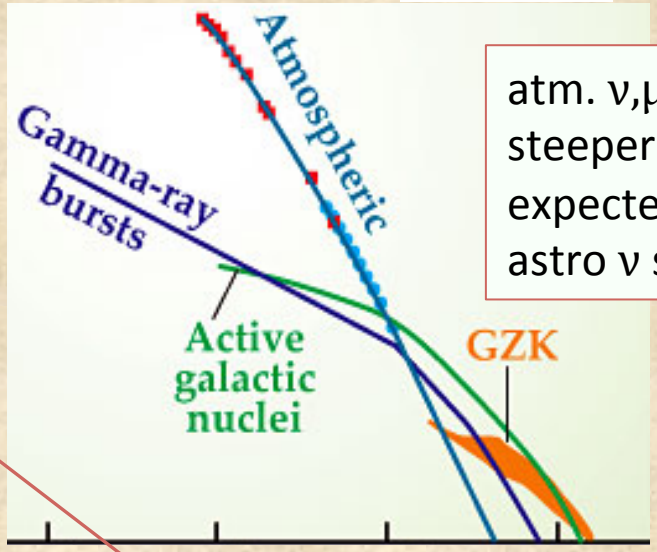
- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques

Muon Neutrino Effective Area



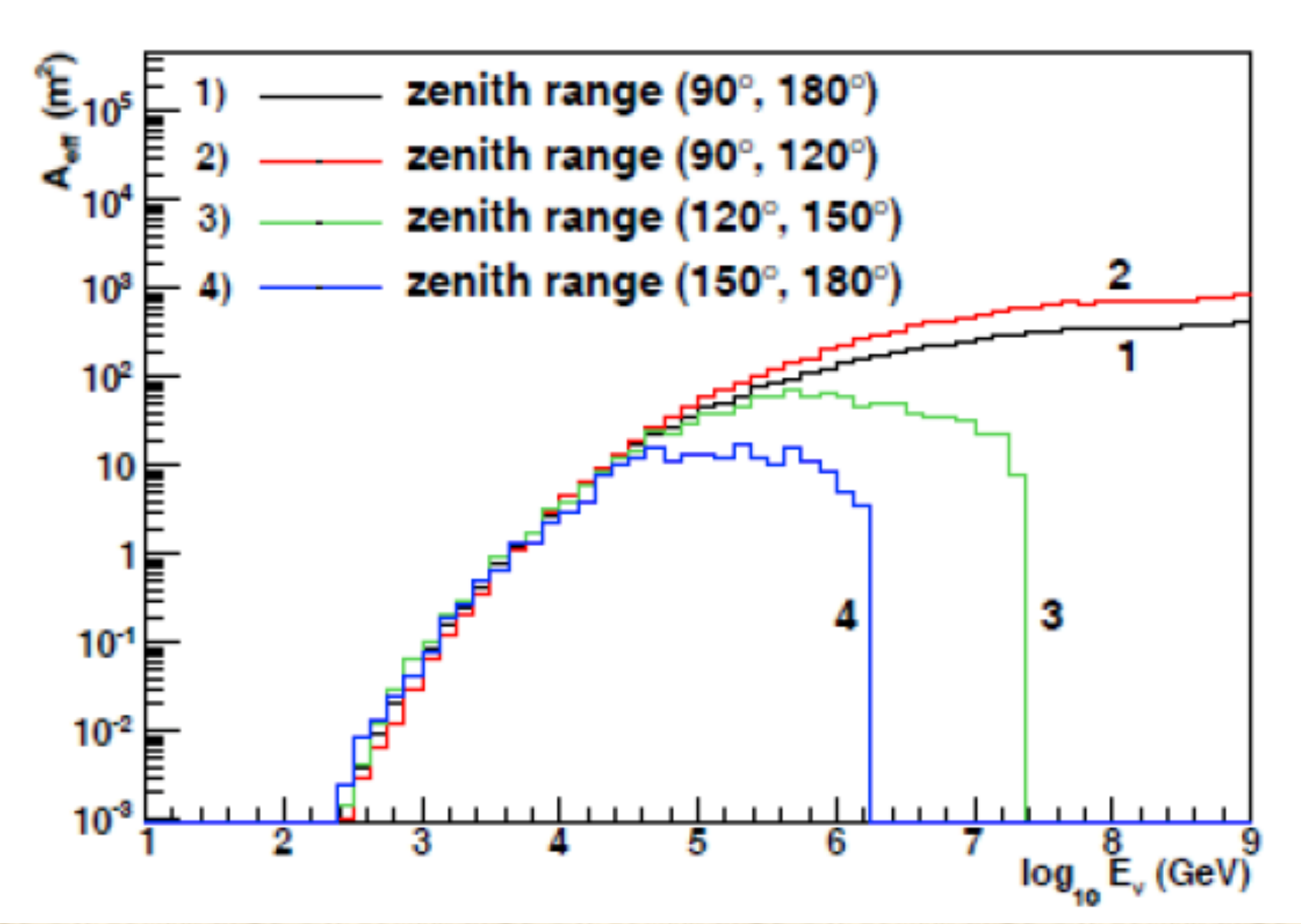




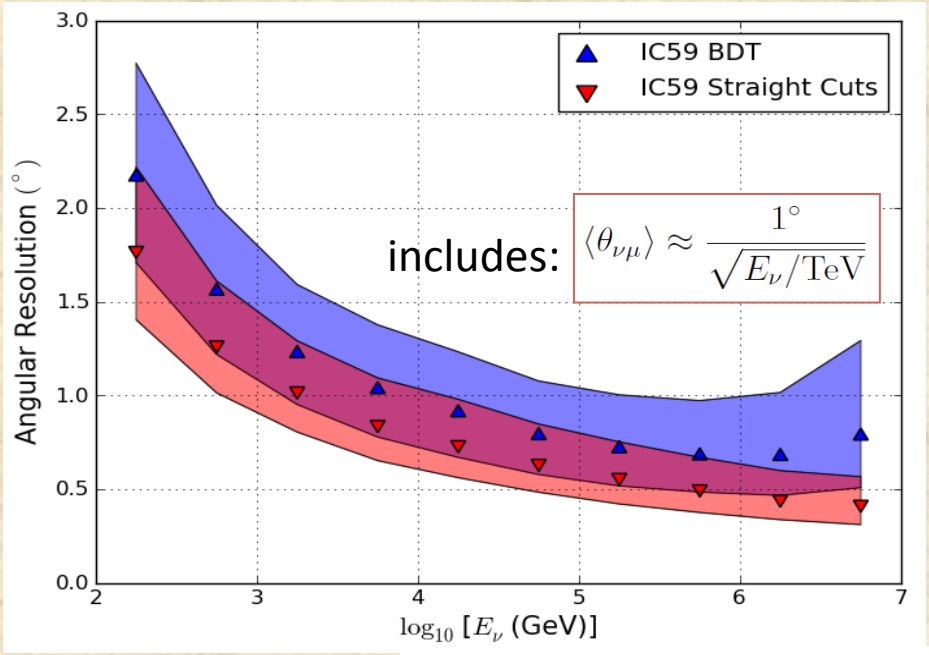


atm. ν,μ spectra steeper than expected astro ν spectrum

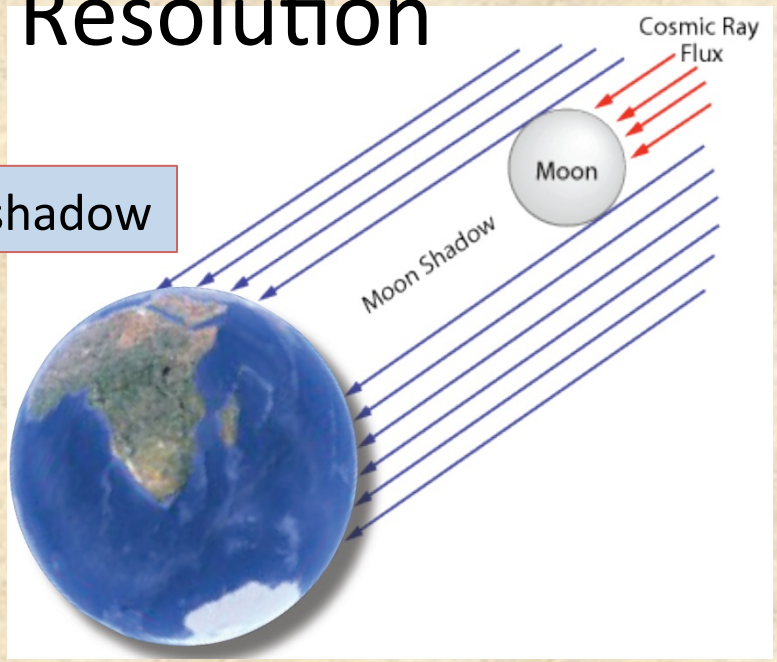
IceCube 40 string effective area



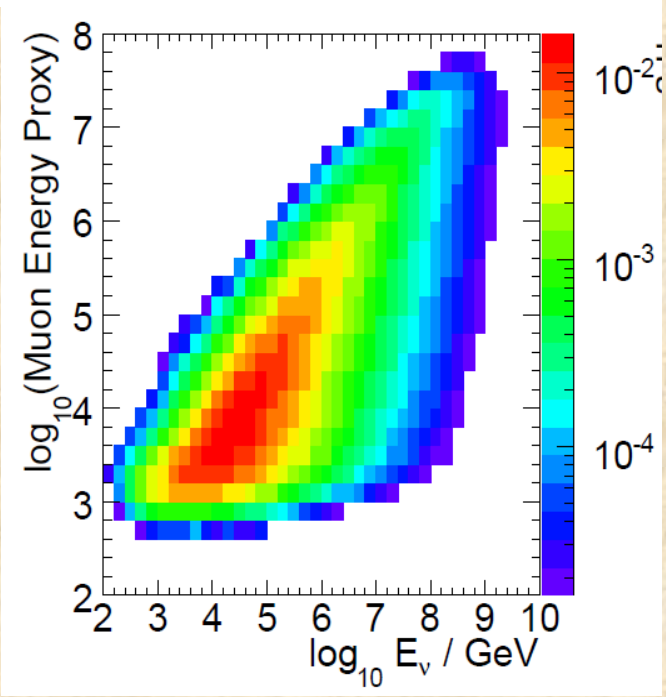
ν_μ Angular and Energy Resolution

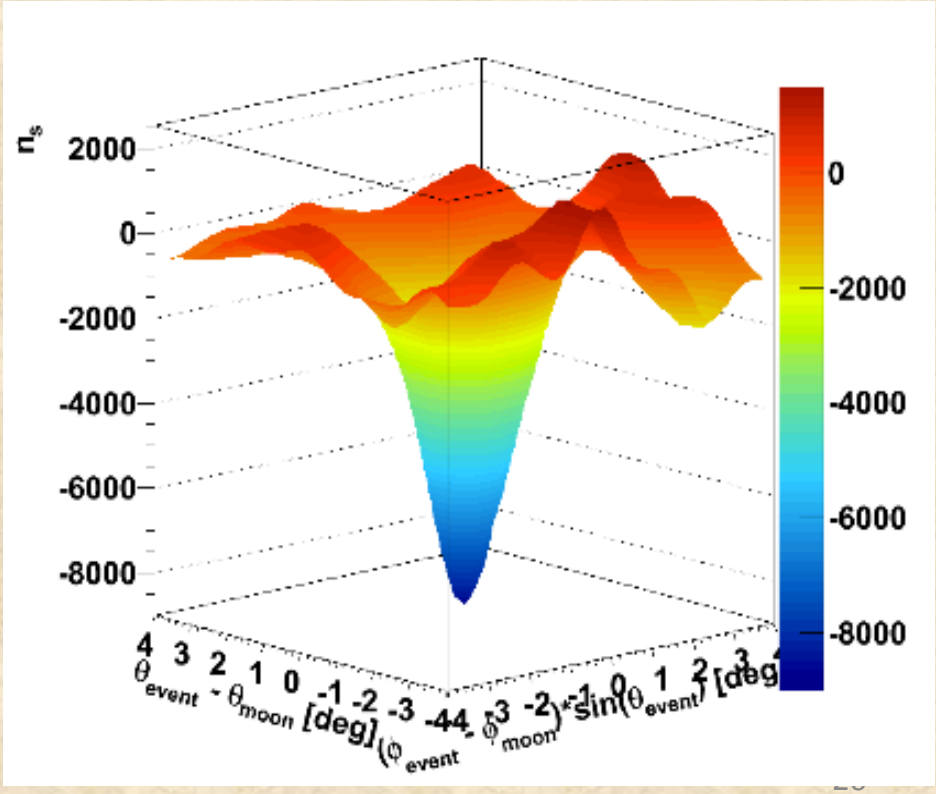


Moon shadow



ν_μ energy estimated from dE/dx of muon (bremsstr.)





Antares Run Status

Proposed official plots and numbers for Point Source Analysis with 2007-2010 data.

some numbers

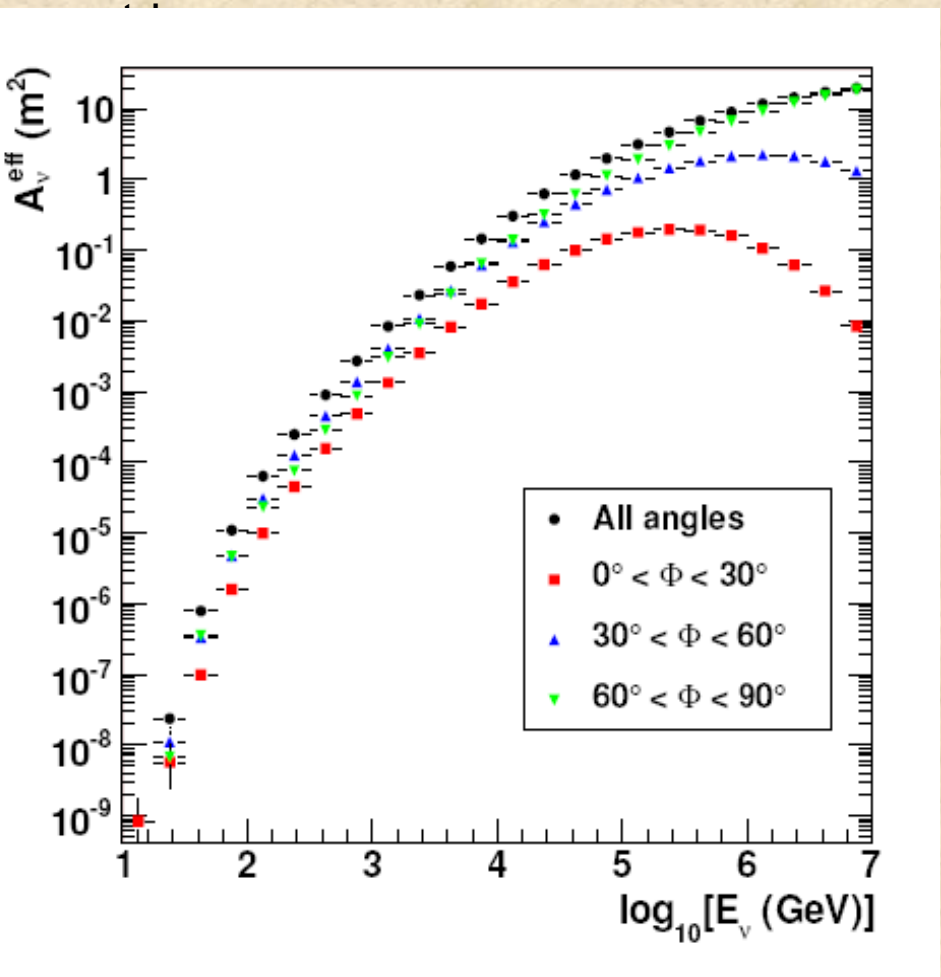
total livetime	**: 813 days**
number of neutrino candidates	**: 3058***
muons in the sample (estimated from MC)	**: 14%**
median angular resolution for E^{-2} neutrinos passing cuts	**: $0.46 \pm 0.1^{\circ}$**

* estimated number of neutrinos in the candidate sample increased by factor of 2.0 compared to 2007&8 analysis.

Expected Performance (12 lines detector)

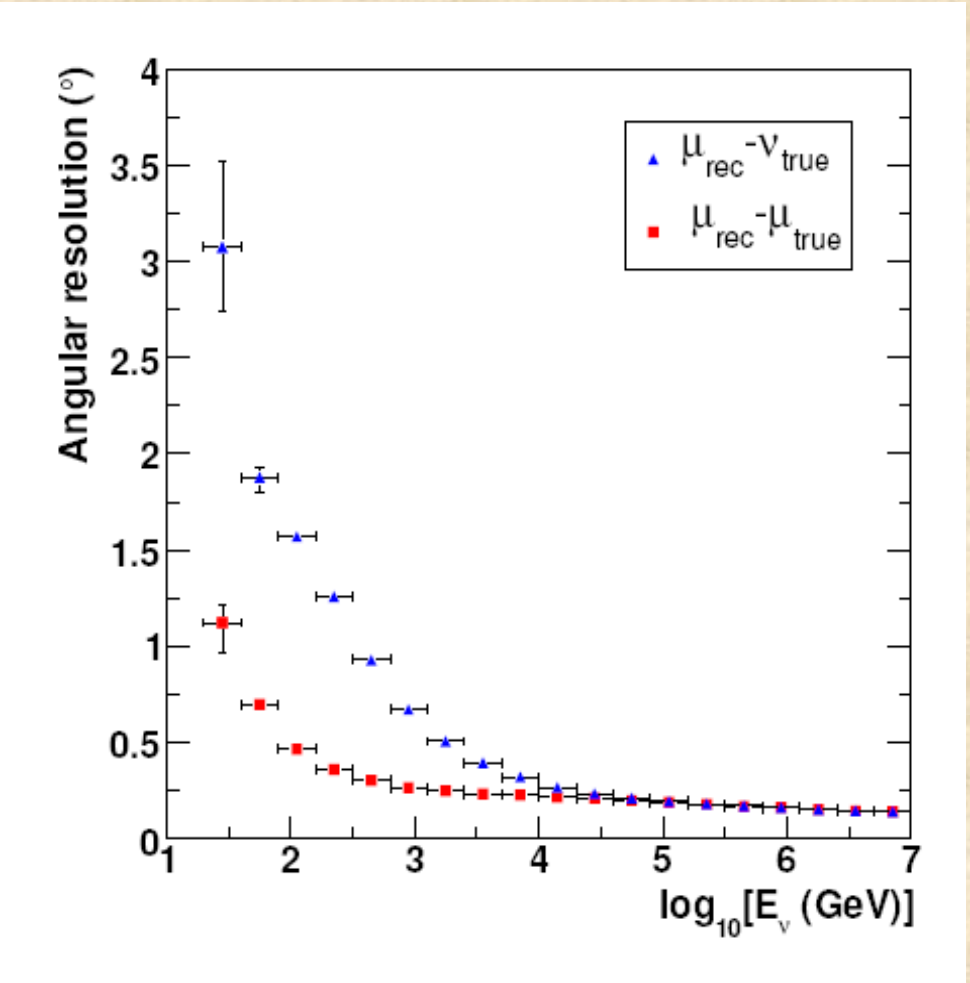
Neutrino effective area

For E_ν<10 PeV, A_{eff} grows with energy due to
the increase of σ_ν and the muon range.
For E_ν>10 PeV the Earth becomes opaque

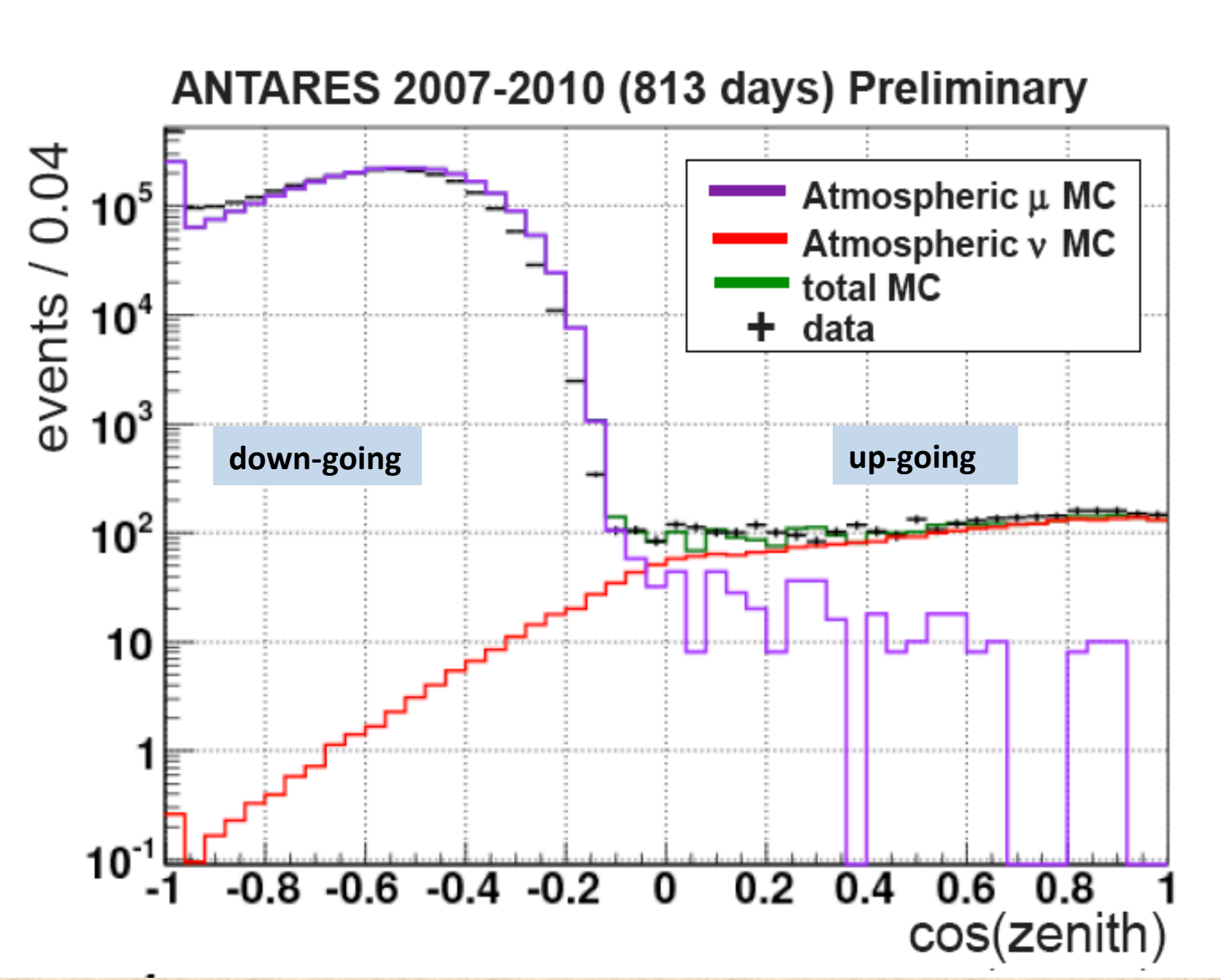


Angular resolution

For E_ν < 10 TeV, the angular resolution is dominated by the ν-μ angle.
For E_ν > 10 TeV, the resolution is limited by track reconstruction errors.



Antares Neutrinos

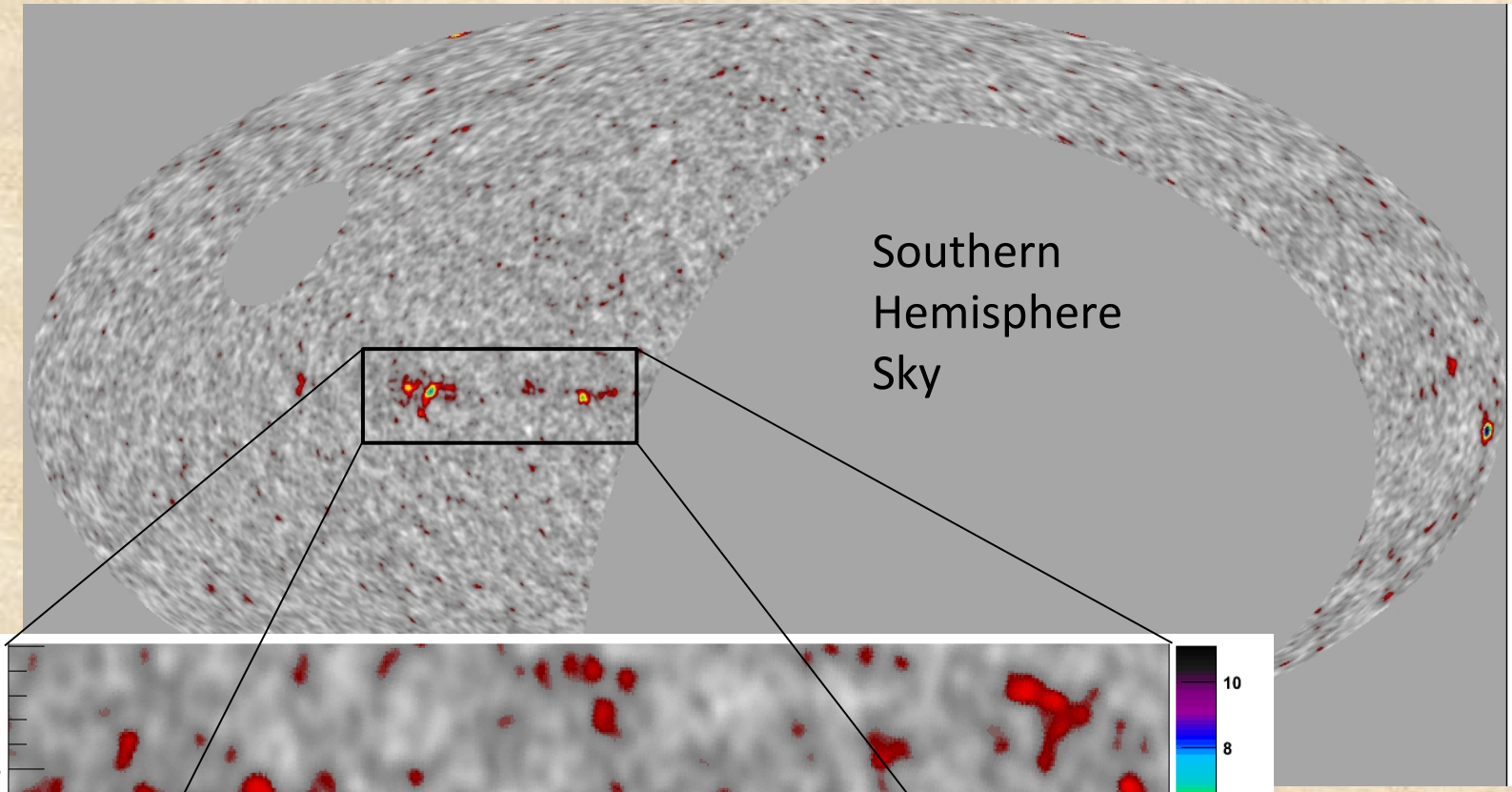


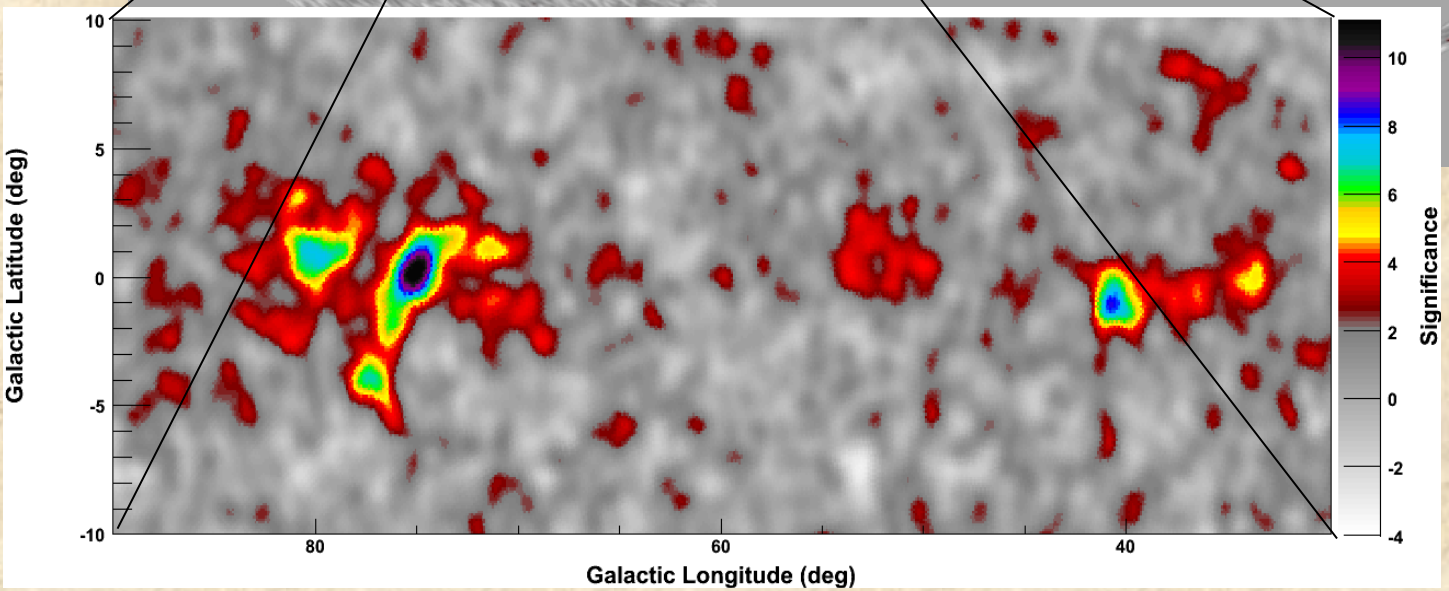
Sampling of IceCube Science Topics

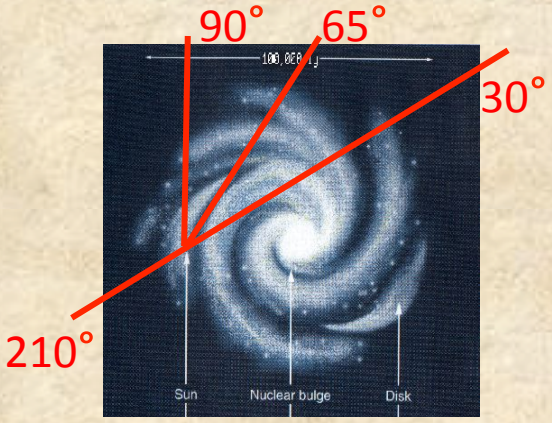
- **Search for sources of Galactic cosmic rays**
- Time integrated All sky point source
- Time dependent searches
  - Transient All Sky sources
  - Gamma-Ray Bursts
- Atmospheric neutrino spectrum
- Search for HE diffuse neutrinos
  - muons
  - Cascades
- IceCube at low energy with Deep Core
  - Indirect Search for Dark Matter
  - Low energy cascade events
- Cosmic Ray anisotropy

galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions

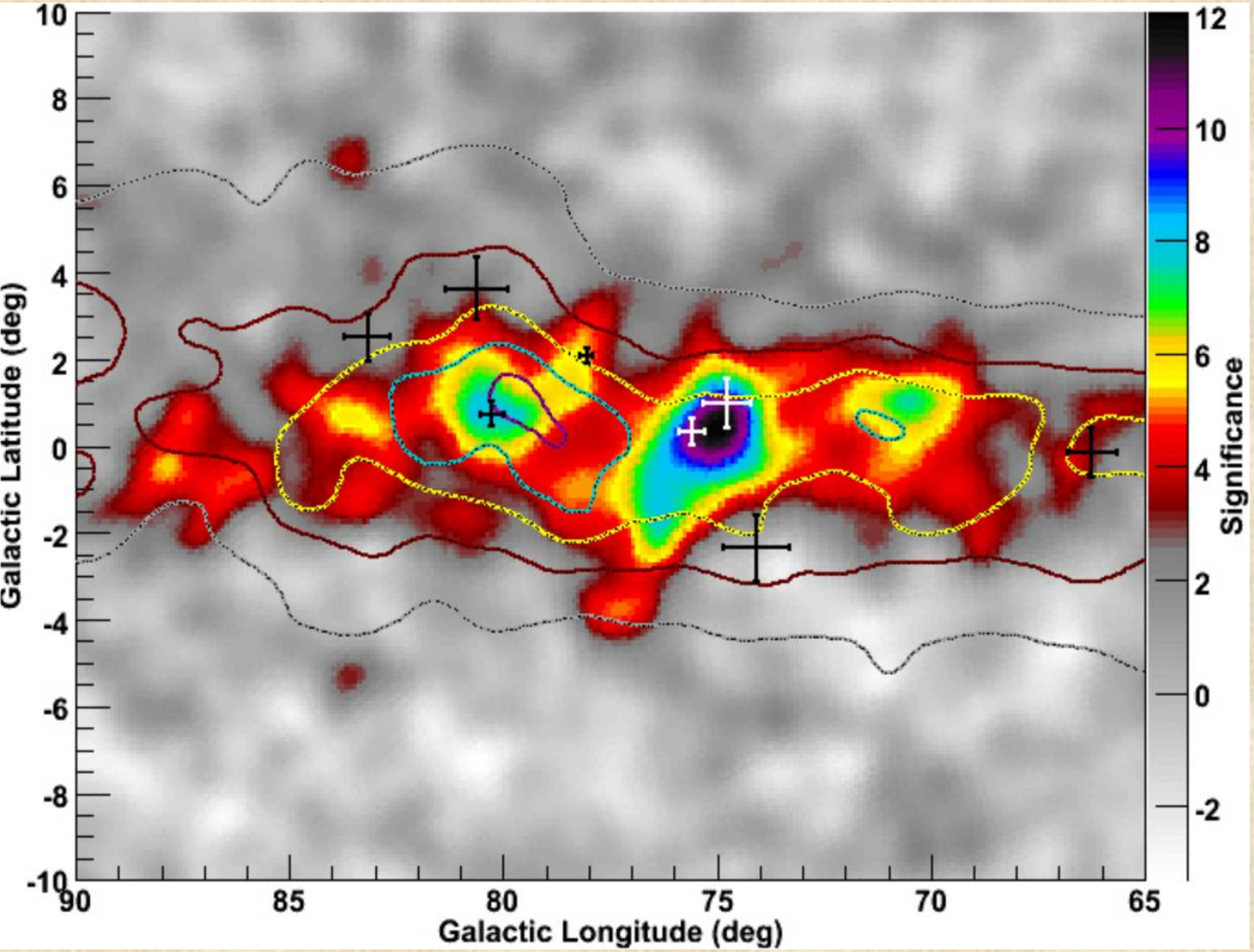






milagro

cygnus region : Milagro



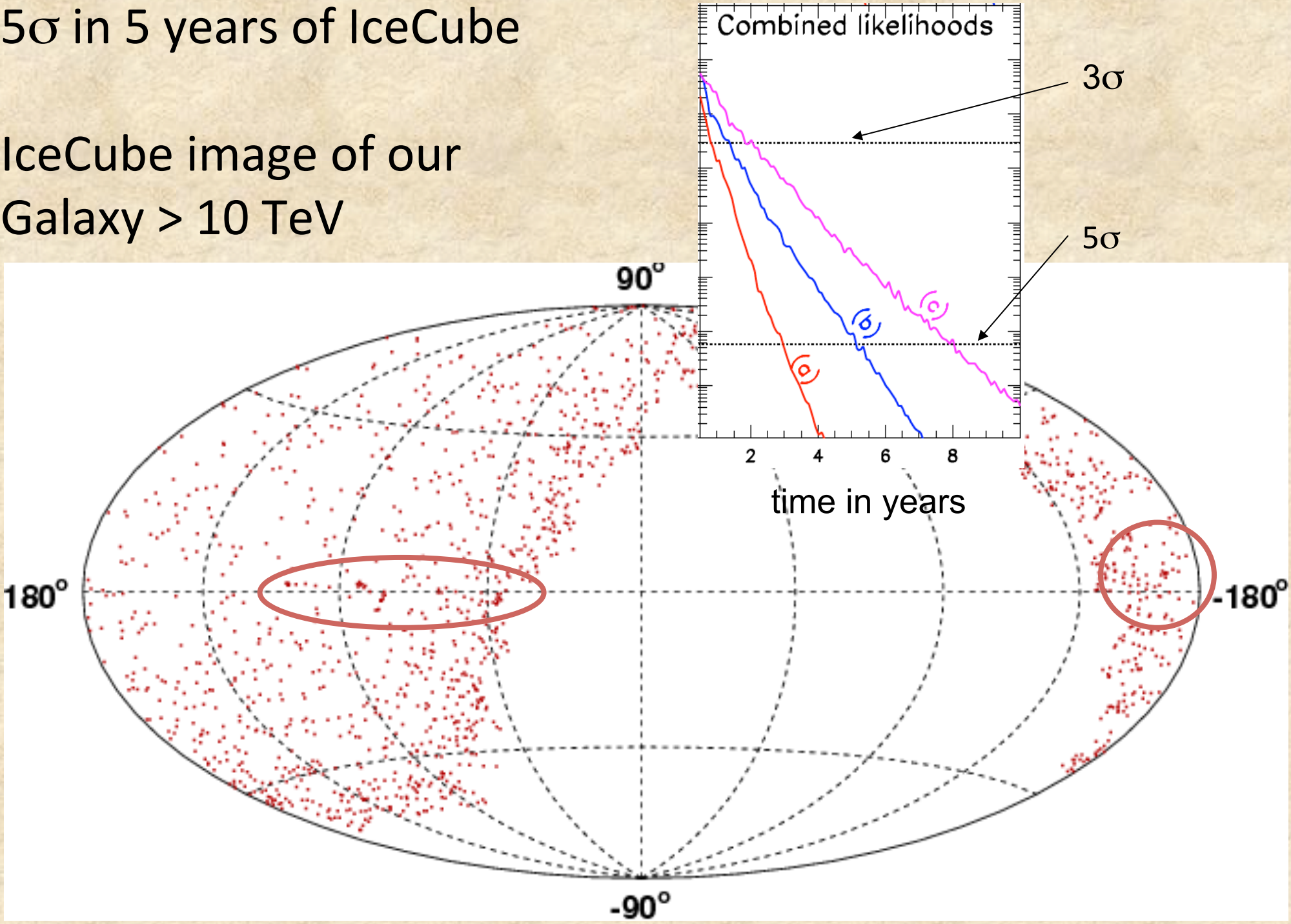
Milagro

translation of
TeV gamma rays
into
TeV neutrinos

3 ± 1 ν per year in IceCube per source

5σ in 5 years of IceCube

IceCube image of our Galaxy > 10 TeV



M. C. Gonzalez-Garcia, F. Halzen, and S. Mohapatra, Astropart. Phys. **31**, 437 2009; e-print arXiv:0902.1176.

20,000 atmospheric neutrinos later …

Preliminary

STACKING 6 MILAGRO SNR

IC40 Stacking Search	Med. Sensitivity	90% Upper Limit
Milagro 6 SNR	2.05 * prediction	5.50 * prediction

3.0 events in IC40 predicted by flux from Halzen, Kappes, O'Murchadha (2008)

p-values of 6 Milagro SNR stacked searches:

AMANDA 7-yr	22-strings	40-strings
20%	27%	2.3%

59-strings

>50%

(a posteriori)

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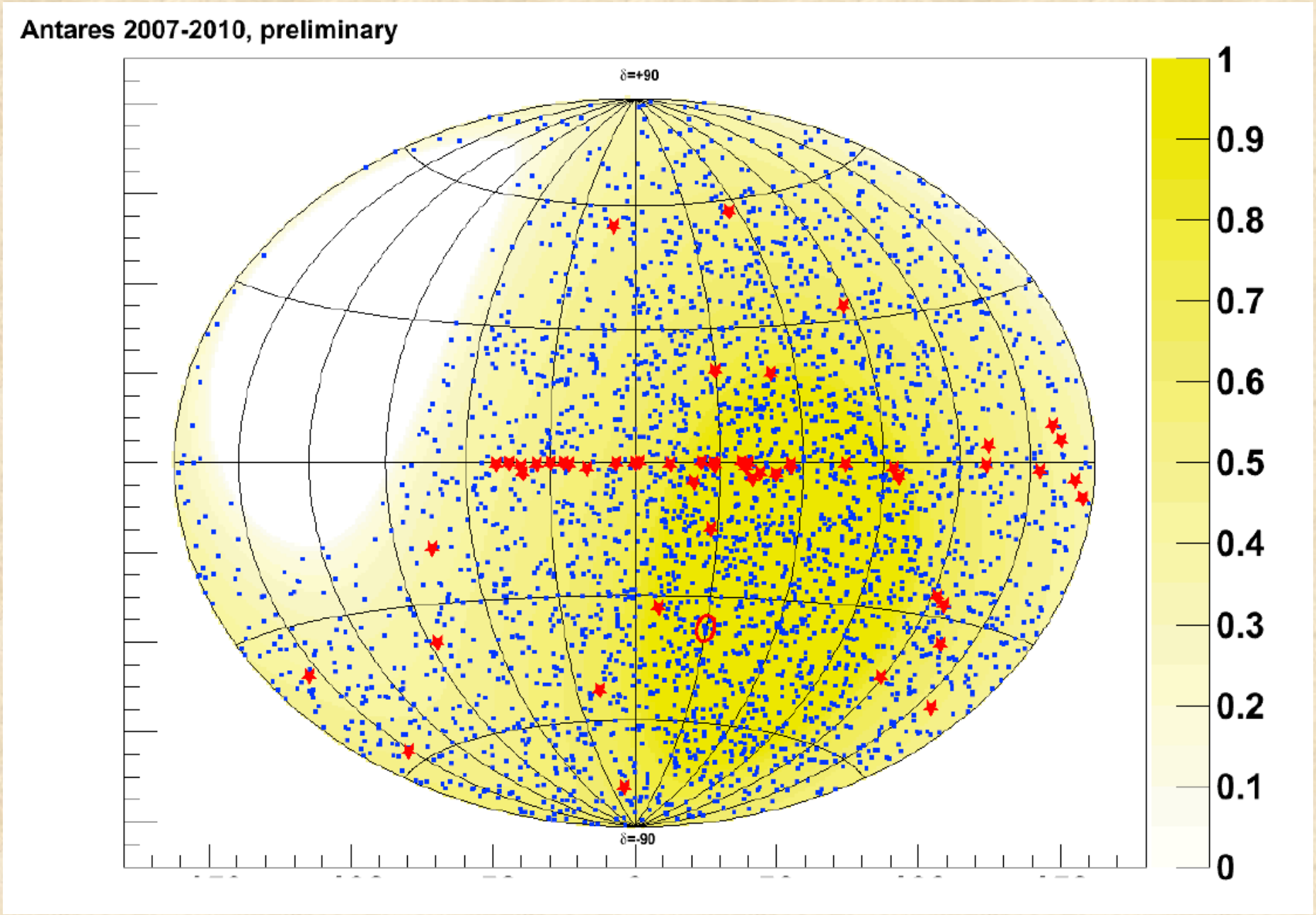
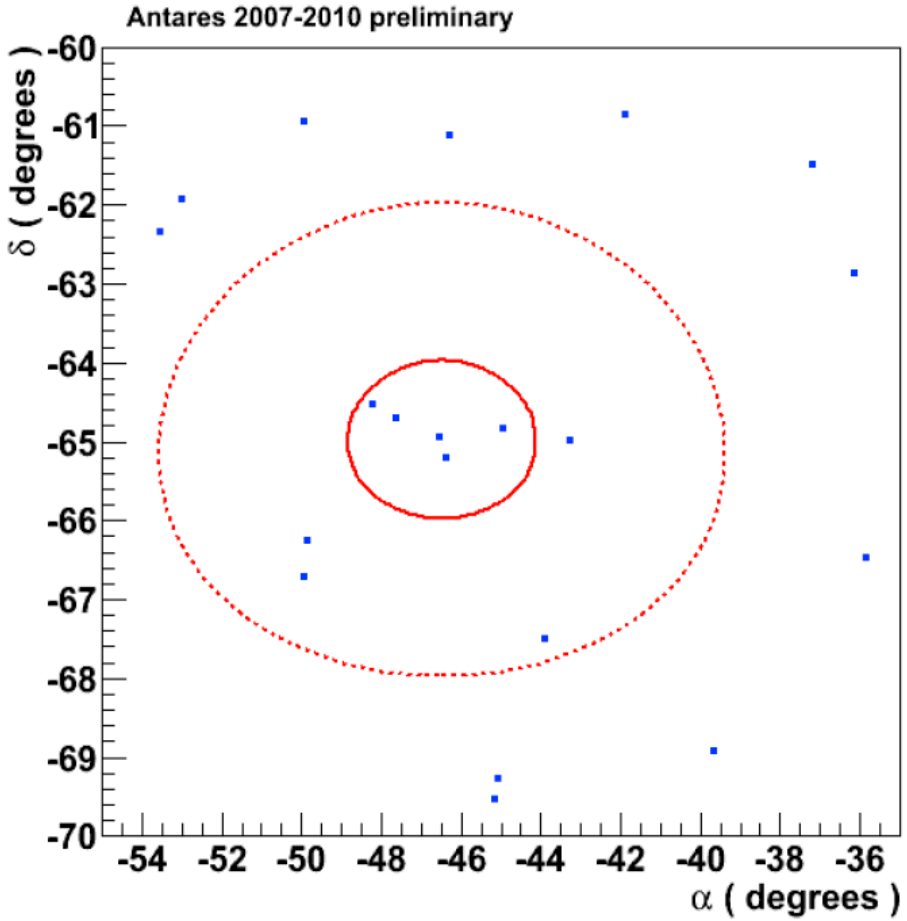
Antares All-Sky Point Source Search



Antares All-sky



The solid (dashed) circle is centered on the fitted source position and has a radius of 1(3) degrees.

in the full-sky search, we find this set of events as most significant cluster.

fitted coordinates :

location	: -46.49, -64.97
Q-value	: 13.02
p-value	: 0.026 (2.2σ)
# events	: 9
Nsig fitted	: 5.1

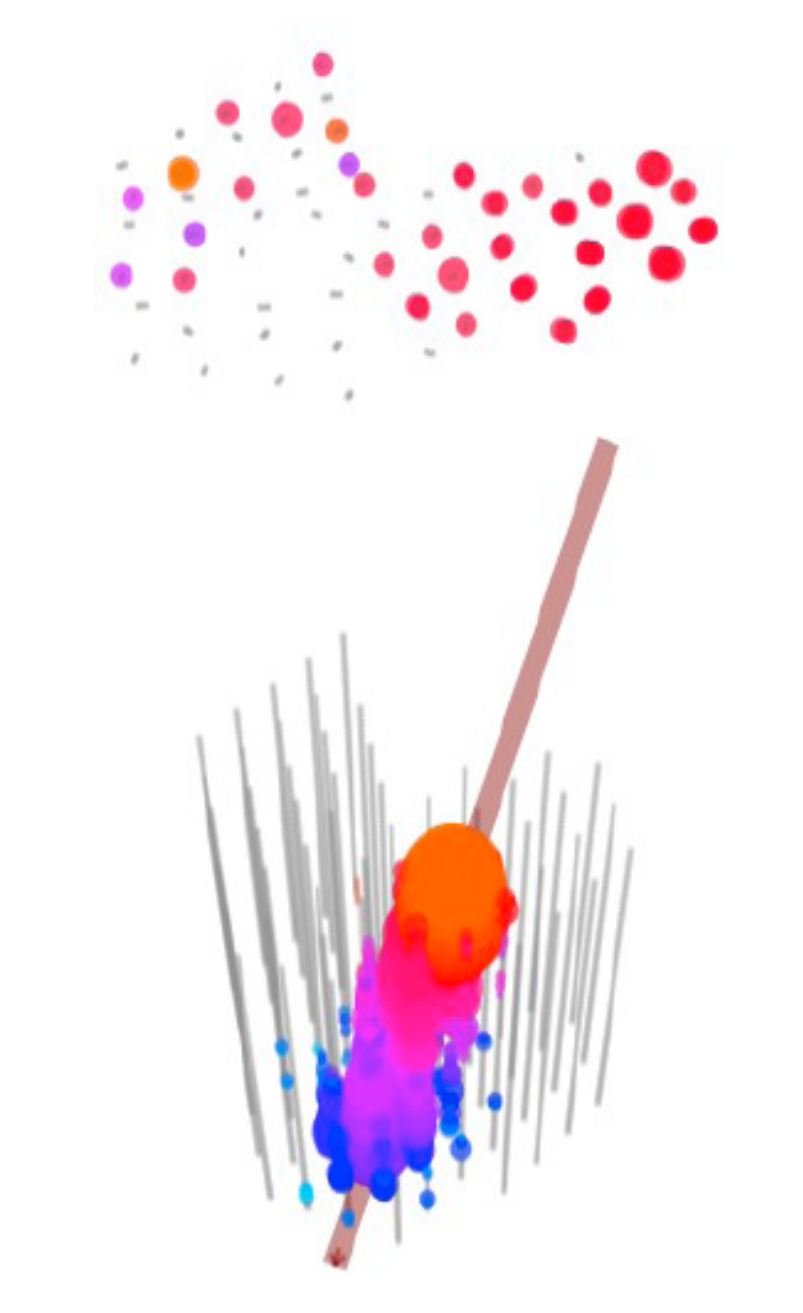
The EM metthod has found the same cluster with roughly equal significance

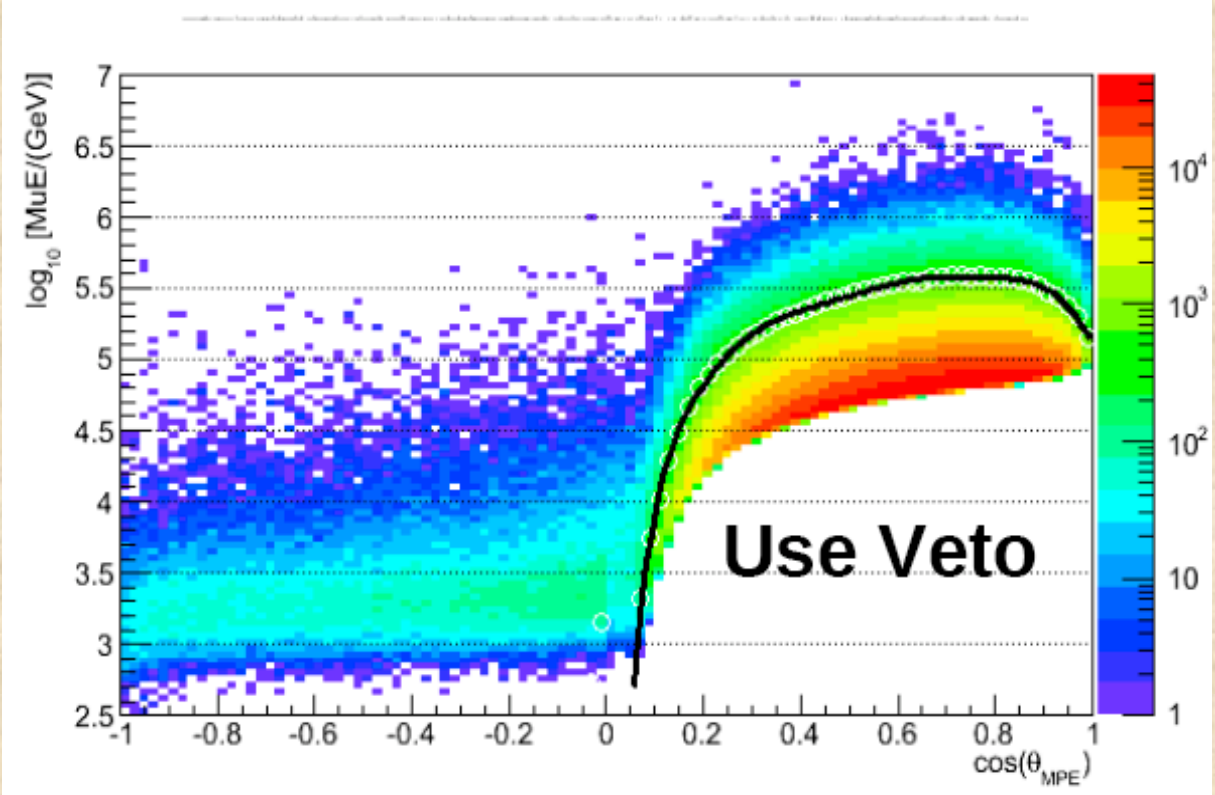
Antares 813 day Point Source

Table of the 11 most-signal-like candidate sources

name	ra	decl	Nsigfit	Q	p-value	nsigma	lim_Nsig	lim_flux
HESS J1023-575	155.83	-57.76	1.97	2.35	0.41	0.82	5.62	6.6e-08
3C 279	-165.95	-5.79	1.11	2.15	0.48	0.71	5.35	1.0e-07
GX 339-4	-104.30	-48.79	1.26	1.49	0.72	0.36	5.10	5.8e-08
Cir X-1	-129.83	-57.17	1.52	1.31	0.79	0.27	5.00	5.8e-08
MGRO J1908+06	-73.01	6.27	0.90	1.22	0.82	0.23	4.59	1.1e-07
ESO 139-G12	-95.59	-59.94	0.98	0.76	0.94	0.08	4.63	5.4e-08
HESS J1356-645	-151.00	-64.50	0.76	0.49	0.98	0.03	4.37	5.1e-08
PKS 0548-322	87.67	-32.27	0.77	0.39	0.99	0.02	4.23	7.1e-08
HESS J1837-069	-80.59	-6.95	0.59	0.26	0.99	0.01	4.12	8.0e-08
PKS 0454-234	74.27	-23.43	0.39	0.09	1.00	0.00	3.83	7.0e-08
ICECUBE	75.45	-18.15	0.34	0.07	1.00	0.00	3.83	7.0e-08

IceCube IC59 search - Improvements

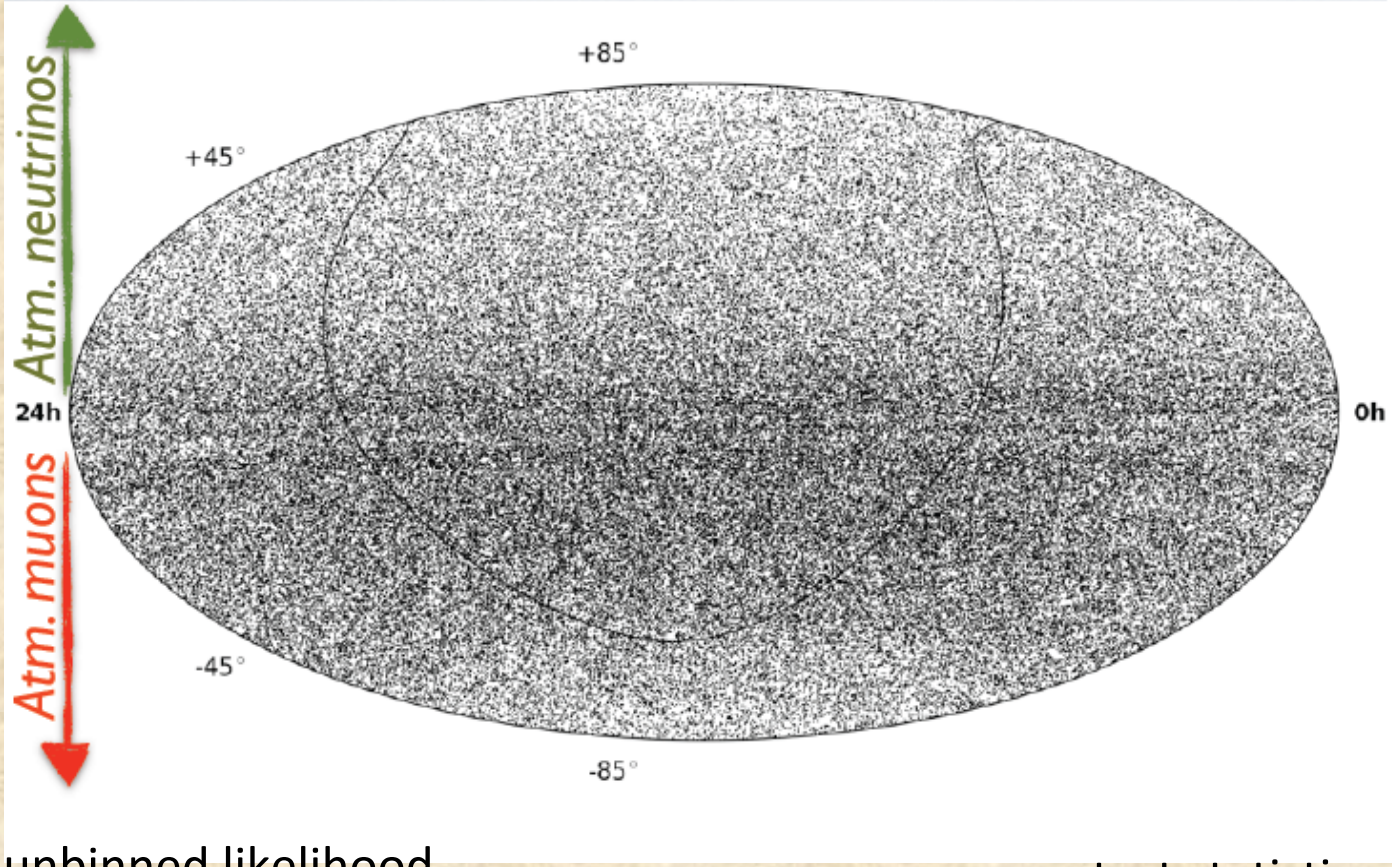


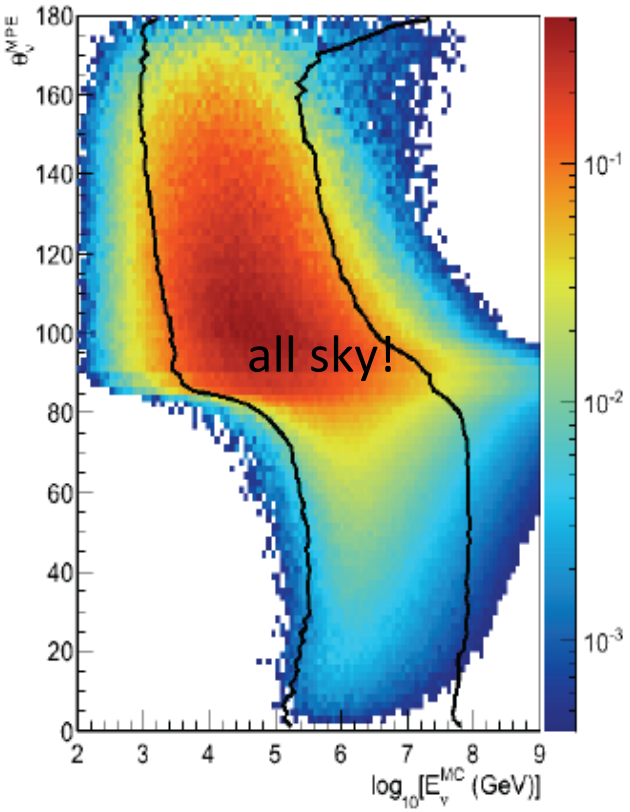


- Use IceTop as veto to reduce energy “cut” for down-going
- Improved sensitivity using BDT
- Improved reconstruction

Point Source Search in Skymap (IC40+59)

43339 up-going + 64230 down-going from 723 days





unbinned likelihood

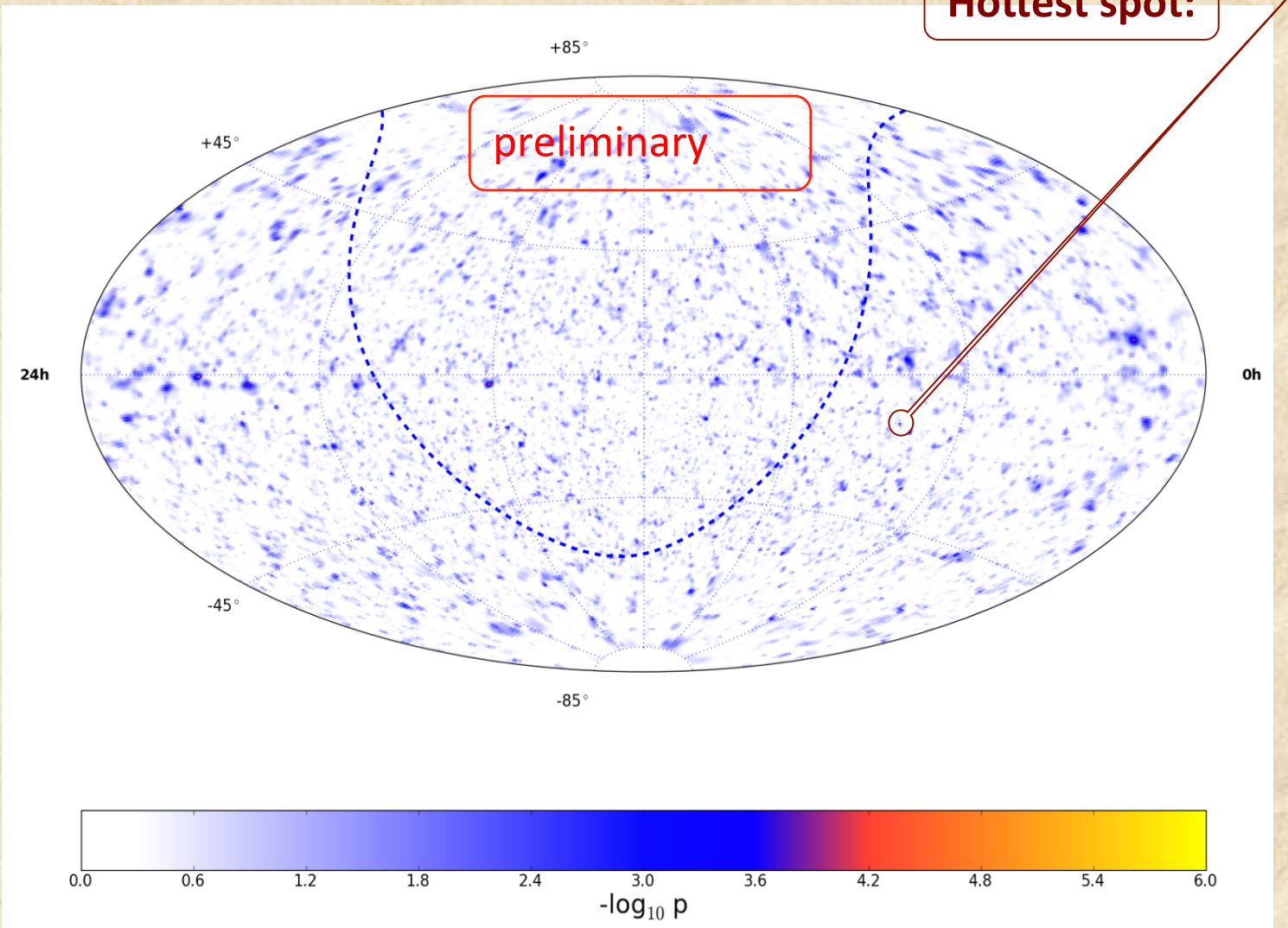
$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

signal term contains angular and energy pdf

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \mathrm{p-value}$$

Significance Skymap (IC40+59)



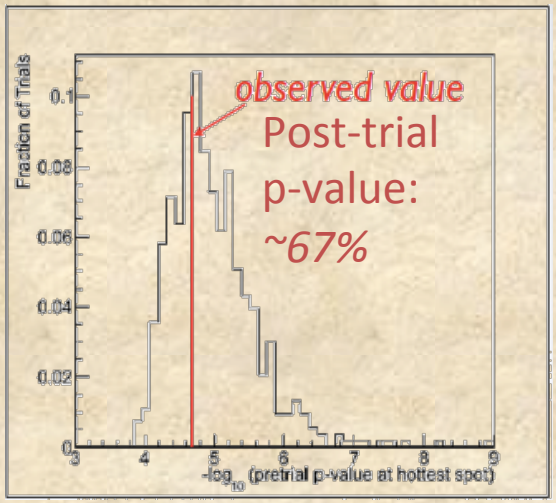
ra: 75.45 dec: - 18.15

$-\log_{10} p = 4.65$

$\hat{n}_s = 18.3$

$\hat{\gamma} = 3.9$

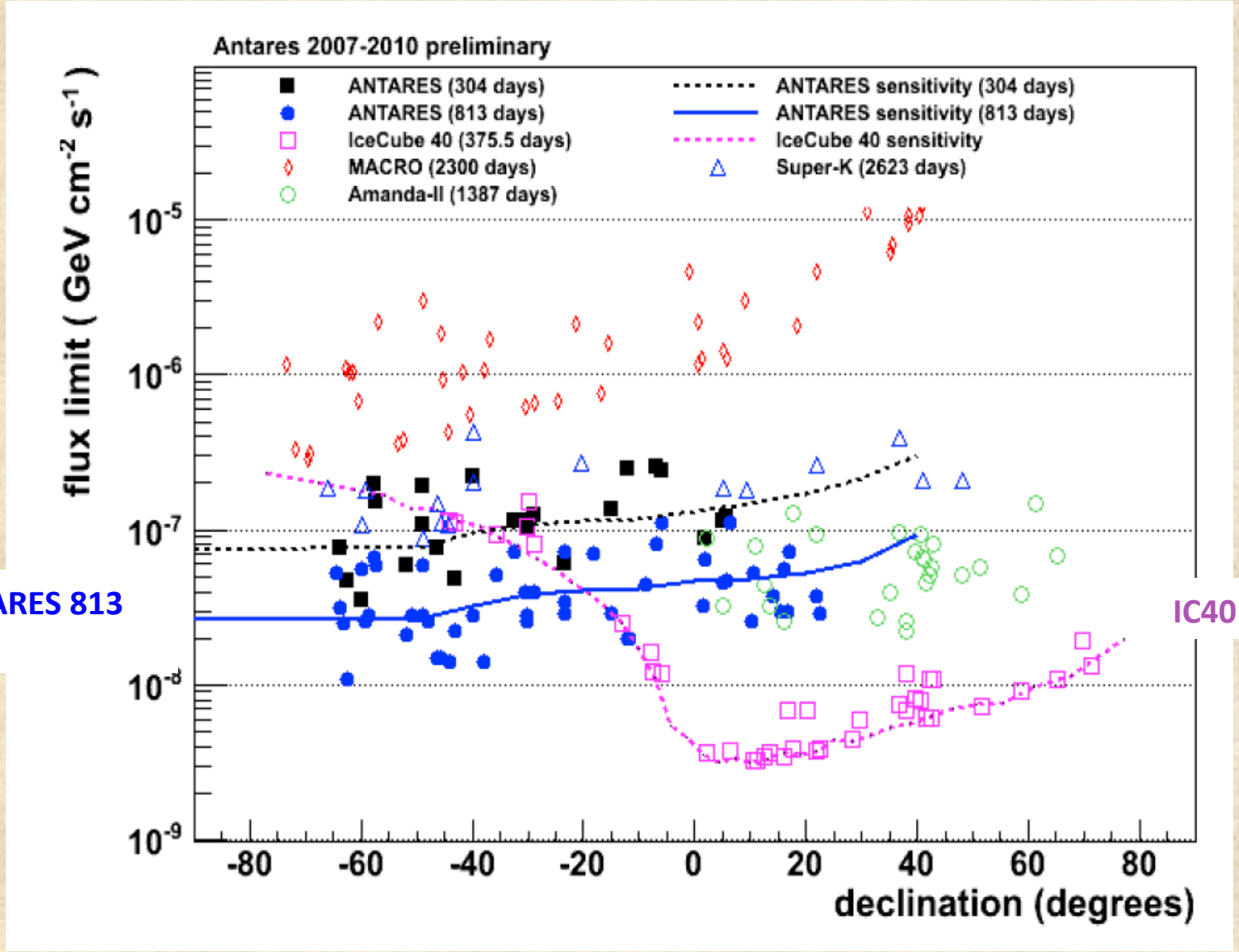
but: $\mathcal{O}(100000)$ **trials**



IceCube selected sources

(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

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

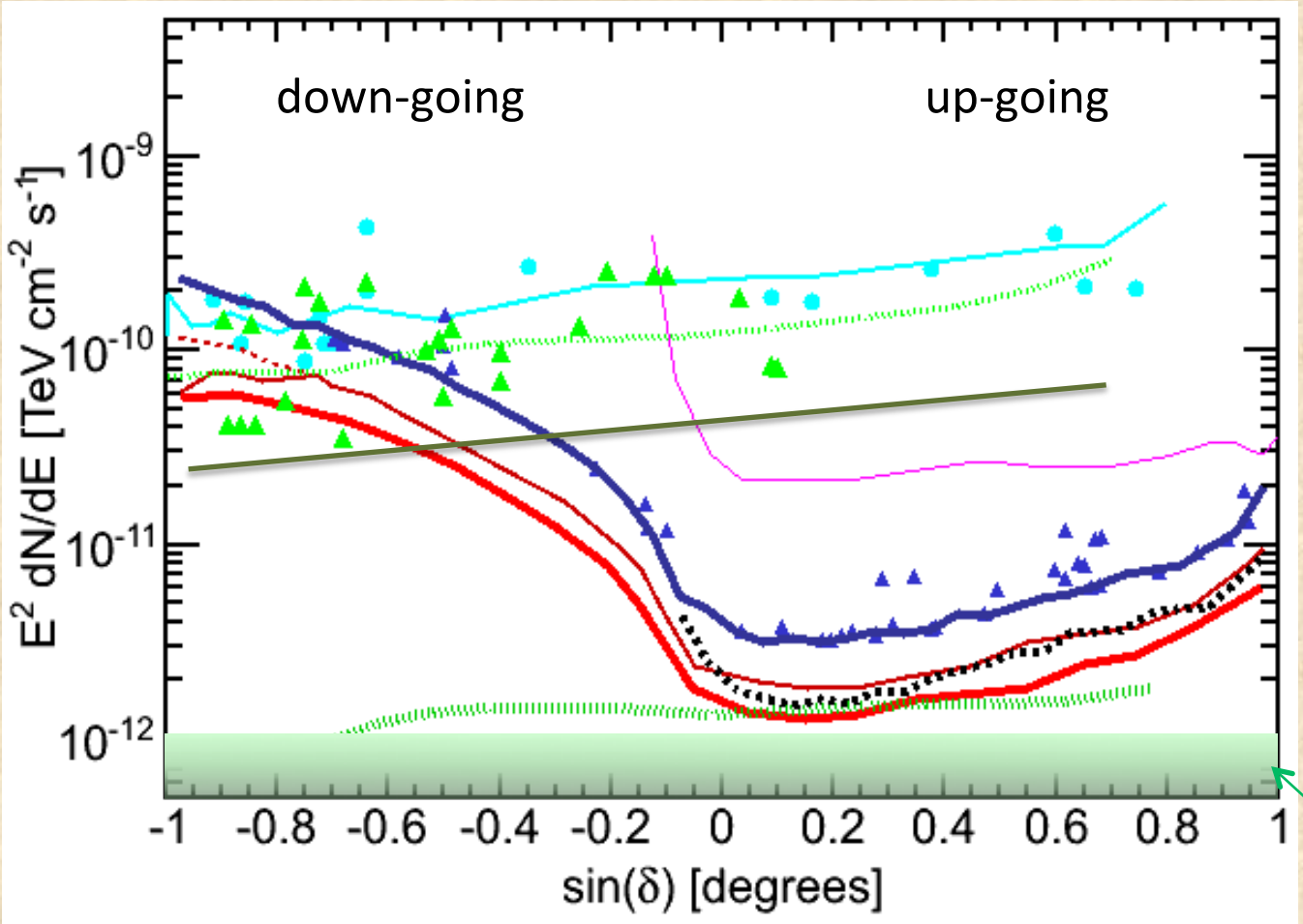


ANTARES 813 days

IC40 1 year

Neutrino Point Source Upper Limits

90% CL sensitivity for E-2 spectrum



SuperK
ANTARES (304 days)

Antares (813 day)
(*my approximation*)

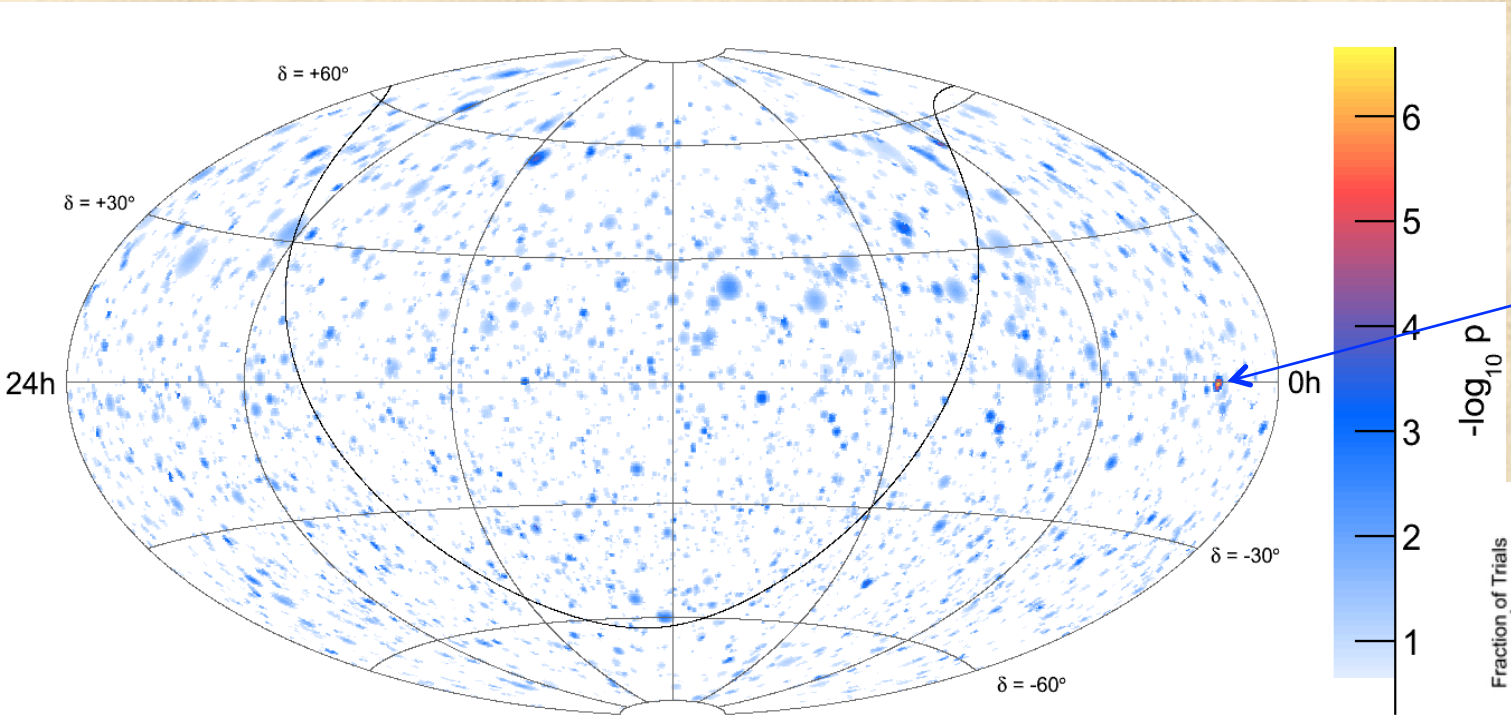
AMANDA
IceCube 40
IceCube 80 (predicted)
IceCube 40+59
KM3NeT
(predicted)

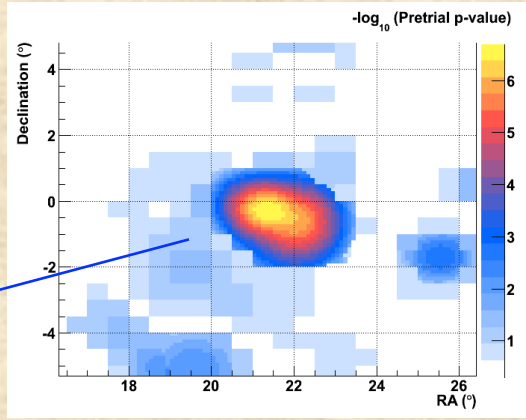
sensitivity to models

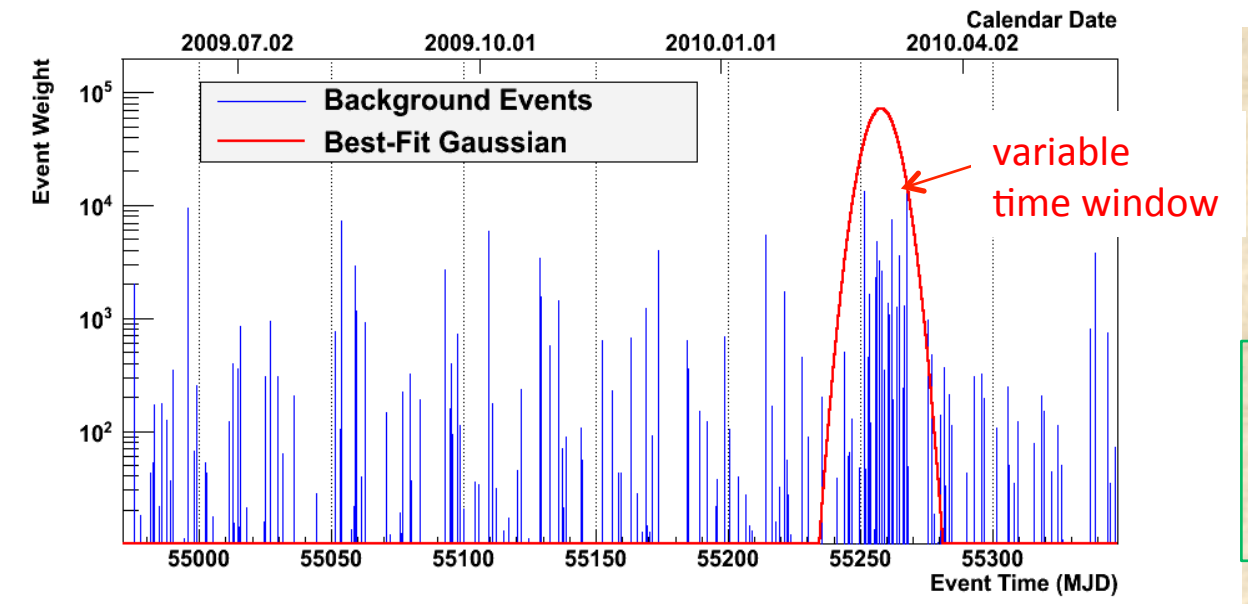
Sampling of IceCube Science Topics

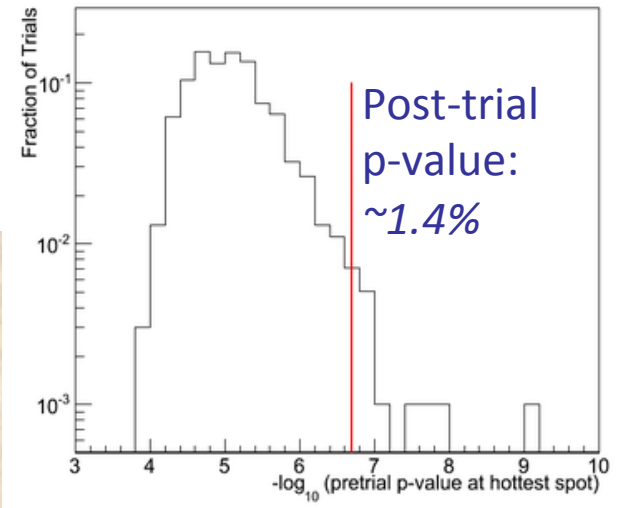
- Search for sources of Galactic cosmic rays
- Time integrated All sky point source
- **Time dependent searches**
  - **Transient All Sky sources**
  - **Gamma-Ray Bursts**
- Atmospheric neutrino spectrum
- Search for HE diffuse neutrinos
  - muons
  - Cascades
- IceCube at low energy with Deep Core
  - Indirect Search for Dark Matter
  - Low energy cascade events
- Cosmic Ray anisotropy

Time Dependent Point Source Searches









interesting fluctuation!
however, no known object found
in this region of sky

Follow-Up Programs

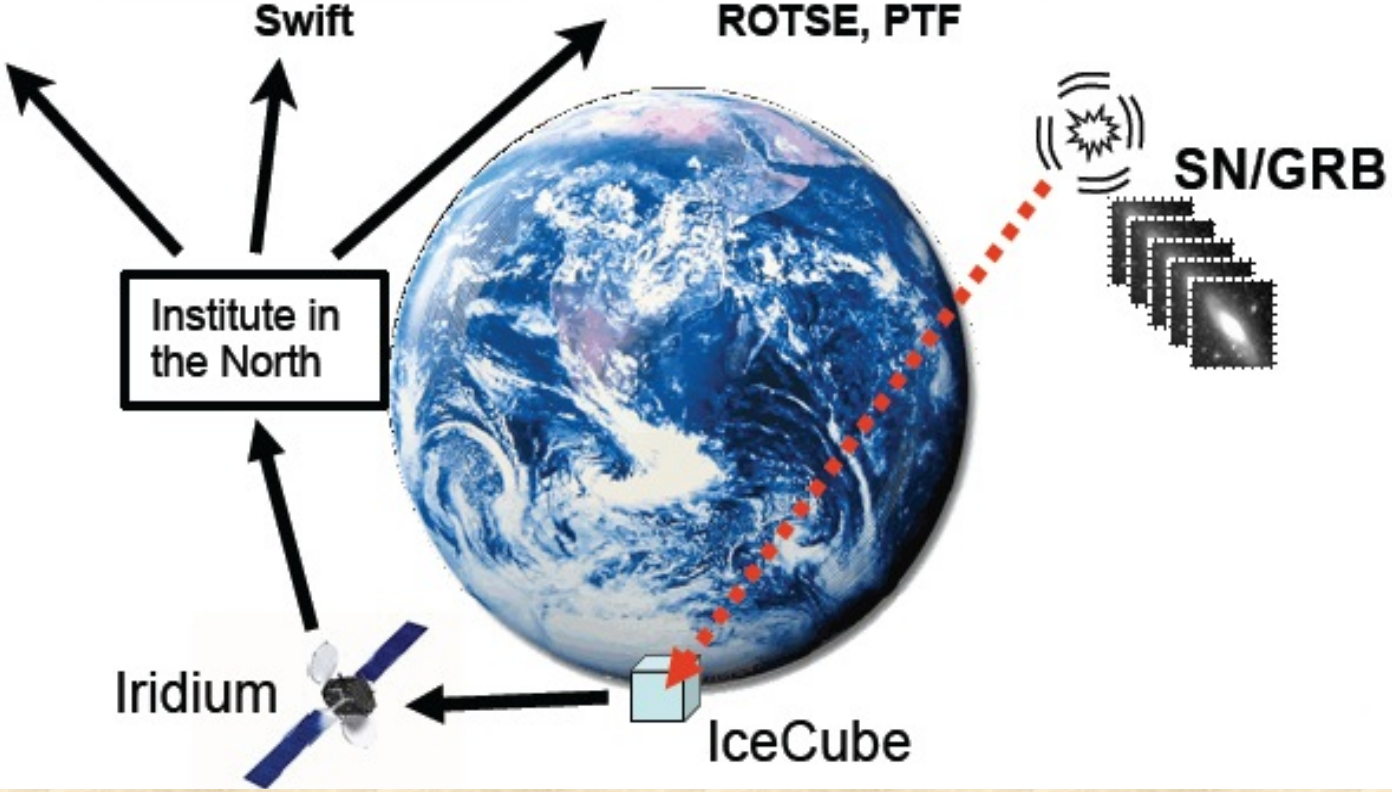
- **Trigger other instruments** (IACTs, X-ray satellites, optical telescopes . . .)

MAGIC

Swift

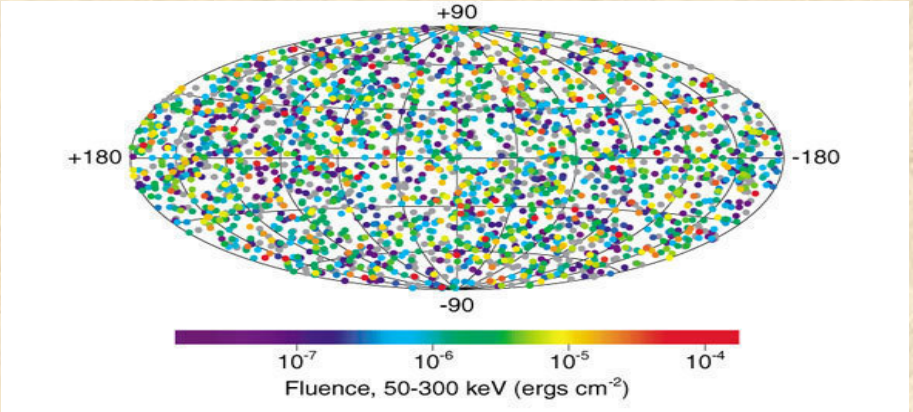
ROTSE, PTF

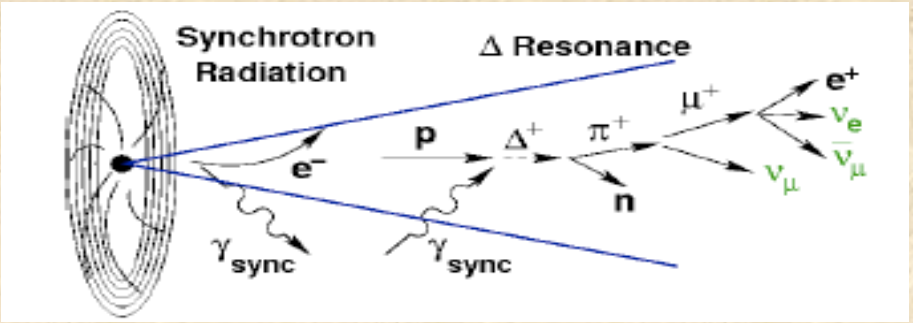
- **Multiplet trigger:**
  (example optical)
  - angular window 4°
  - time window 100 s
  - Delay < 5 min



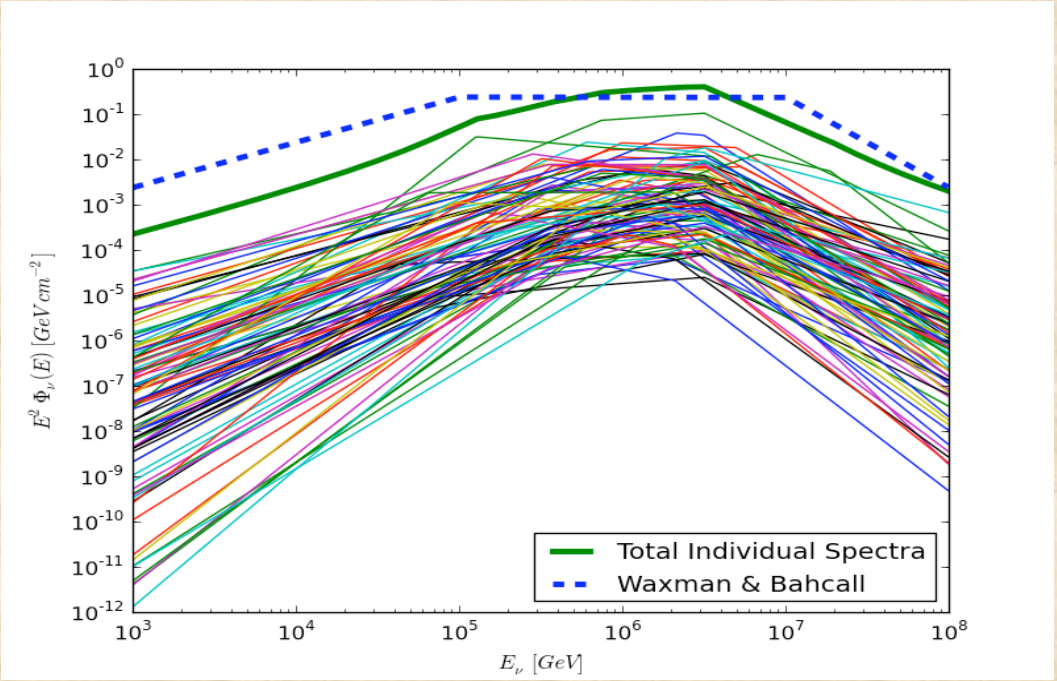
Gamma Ray Bursts

- Gamma-Ray Bursts are short bursts of gamma rays, a few seconds in duration
- Brighter than rest of gamma ray sky
- Afterglow lasting much longer
- First observed in Vela satellites (1960s)
- Several generations of satellite-based observations have shown:
- Extra-galactic origin
- Gamma-ray emission beamed



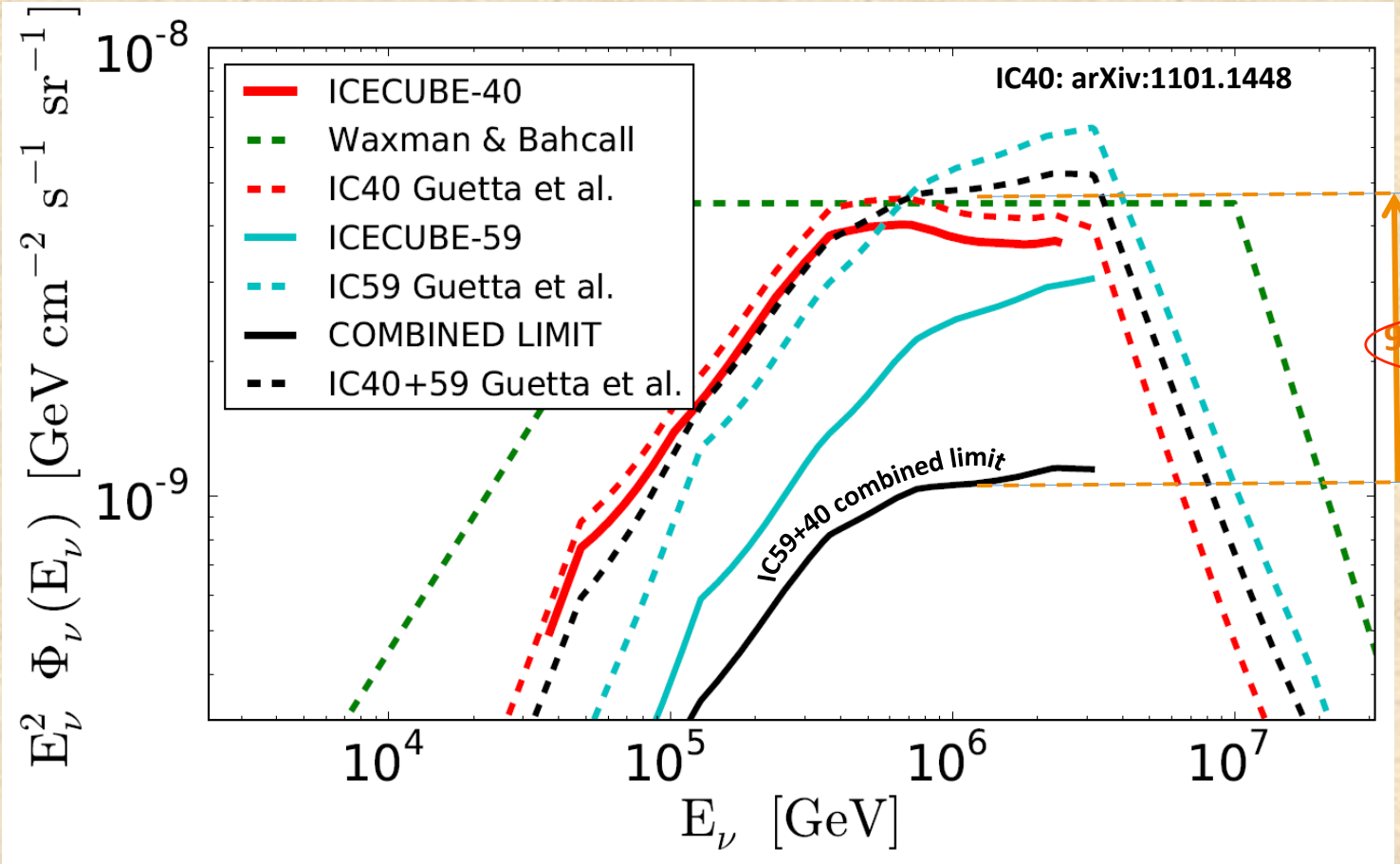


- Internal shocks in GRBs are a compelling candidate for the source of acceleration for UHECRs.
- Acceleration conditions required to produce the observed gamma rays would also be sufficient for UHECR production
- Observed gamma-ray burst energy injection rate into Universe well matched to observed UHECR energy
- Waxman-Bahcall modeled neutrino production from photon-hadron interactions in fireball



IceCube GRB search

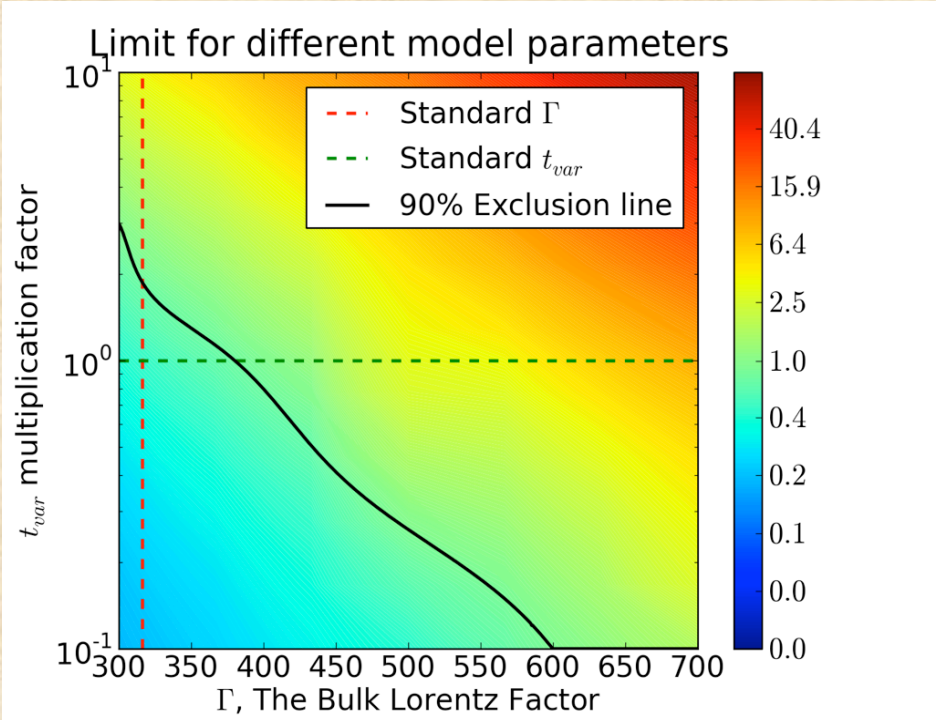
- IceCube performs a stacked for a neutrino signal in coincidence with observed GRB gamma signals
  - All Northern hemisphere GRB bursts are considered.
- Combination of spatial and time correlation yields very low background ***(~Background Free Search)***
- Per-burst neutrino fluence and spectra are calculated based on the measured gamma-ray spectra. Parameterization of Guetta, et al. (Astropart.Phys. 20 (2004) 429-455)

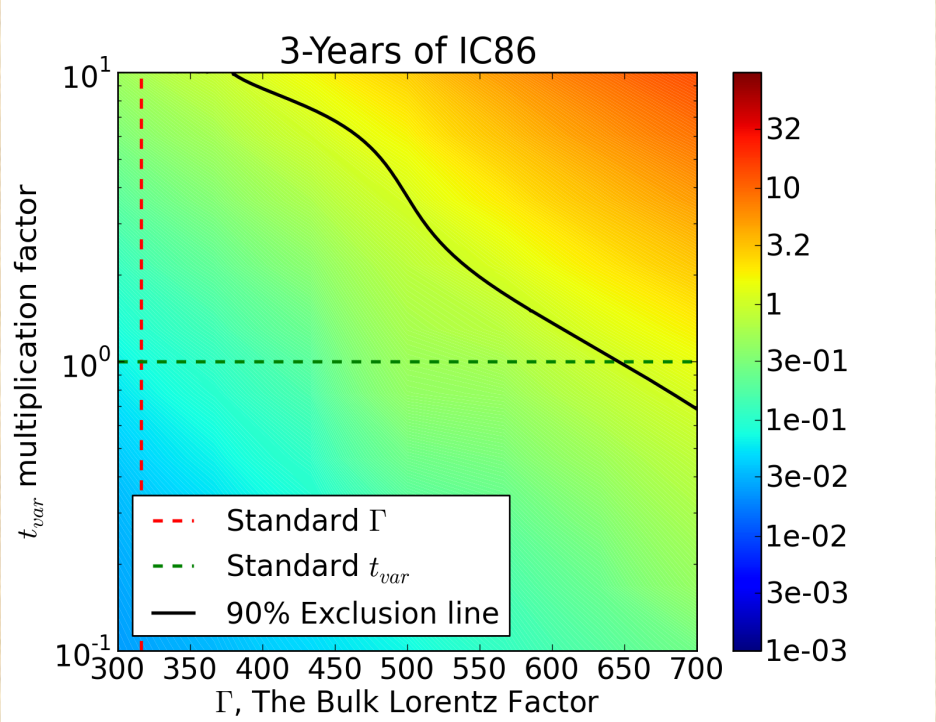


IceCube GRB Summary

- Three successive seasons without a GRB neutrino discovery
- IC40 90% CL upper limit: 0.82 modeled flux
- IC59 90% CL upper limit: 0.46 modeled flux
- Combined search results
  - Expect 8 neutrinos from model, see 0
  - Combined limit is 0.22 modeled flux
- ***Where are the neutrinos?***
- ***Do we already rule out GRB as CR source?***
- Input assumptions in modeled GRB neutrino flux
  - Bulk Lorentz factor, fraction of energy in electrons relative to protons, dynamics of time structure
- Ongoing work to place limits on UHECR production in GRBs
  - ***Km^3 detector gives sensitivity of Astrophysical Interest!***

GRB astrophysics in IceCube
Current & Future





3 years of IceCube will see neutrinos from GRBs or rule out the fireball model!

Sampling of IceCube Science Topics

- Search for sources of Galactic cosmic rays
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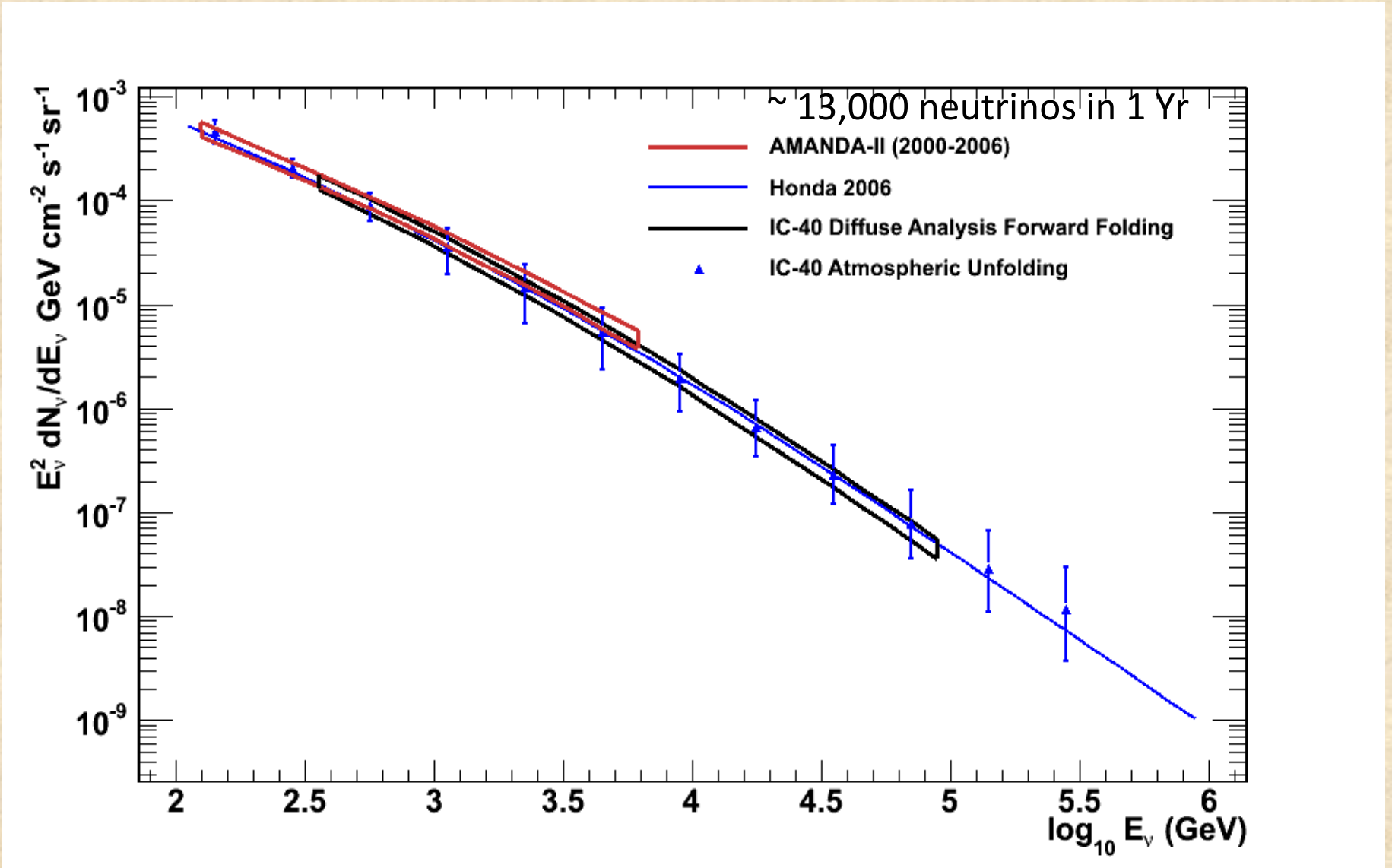
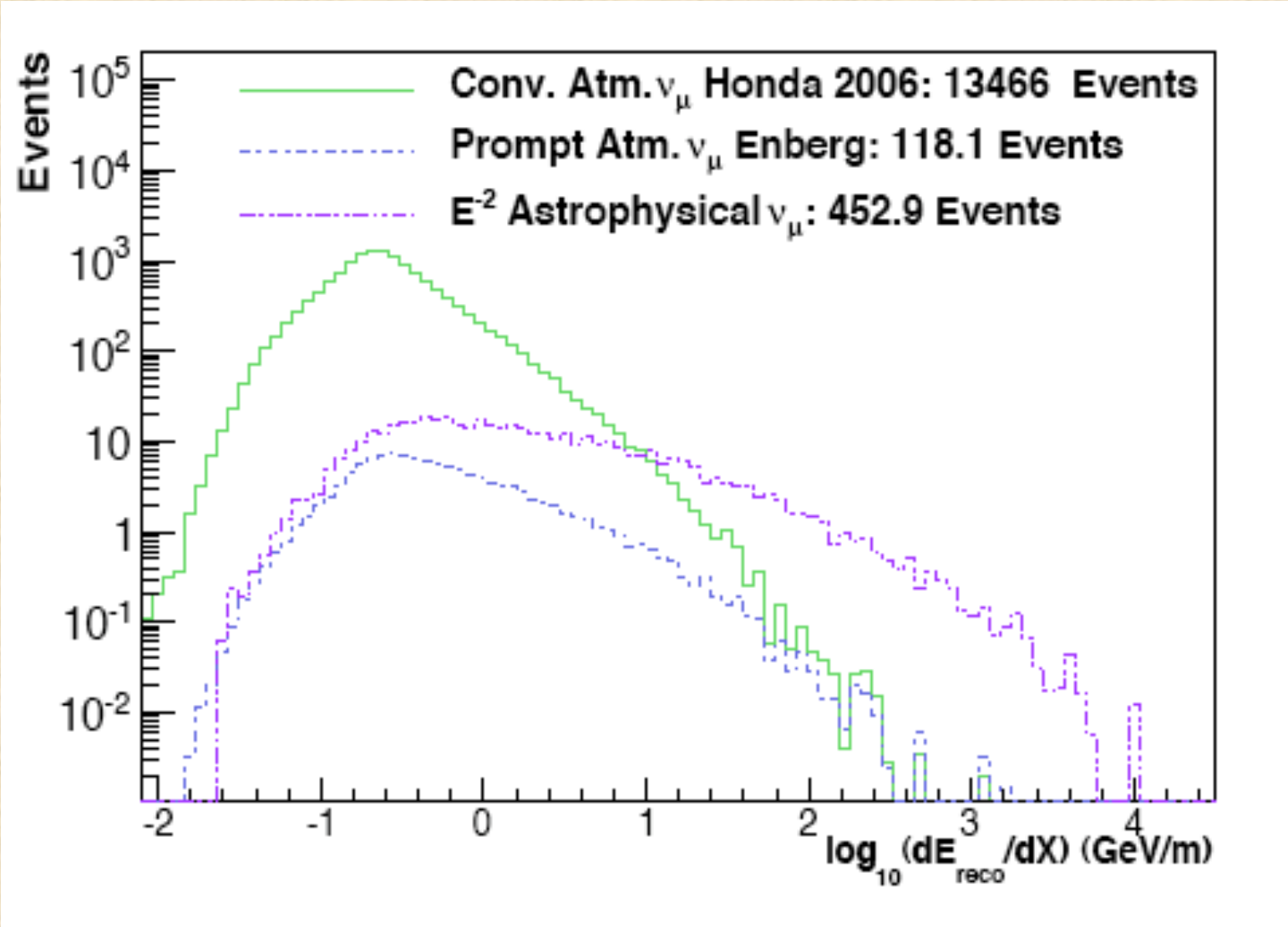
  - Transient All Sky sources
  - Gamma-Ray Bursts
- **Atmospheric neutrino spectrum**
- **Search for HE diffuse neutrinos**
  - **muons**
  - **Cascades**
- IceCube at low energy with Deep Core
  - Indirect Search for Dark Matter
  - Low energy cascade events
- Cosmic Ray anisotropy

Atmospheric Neutrino Spectrum

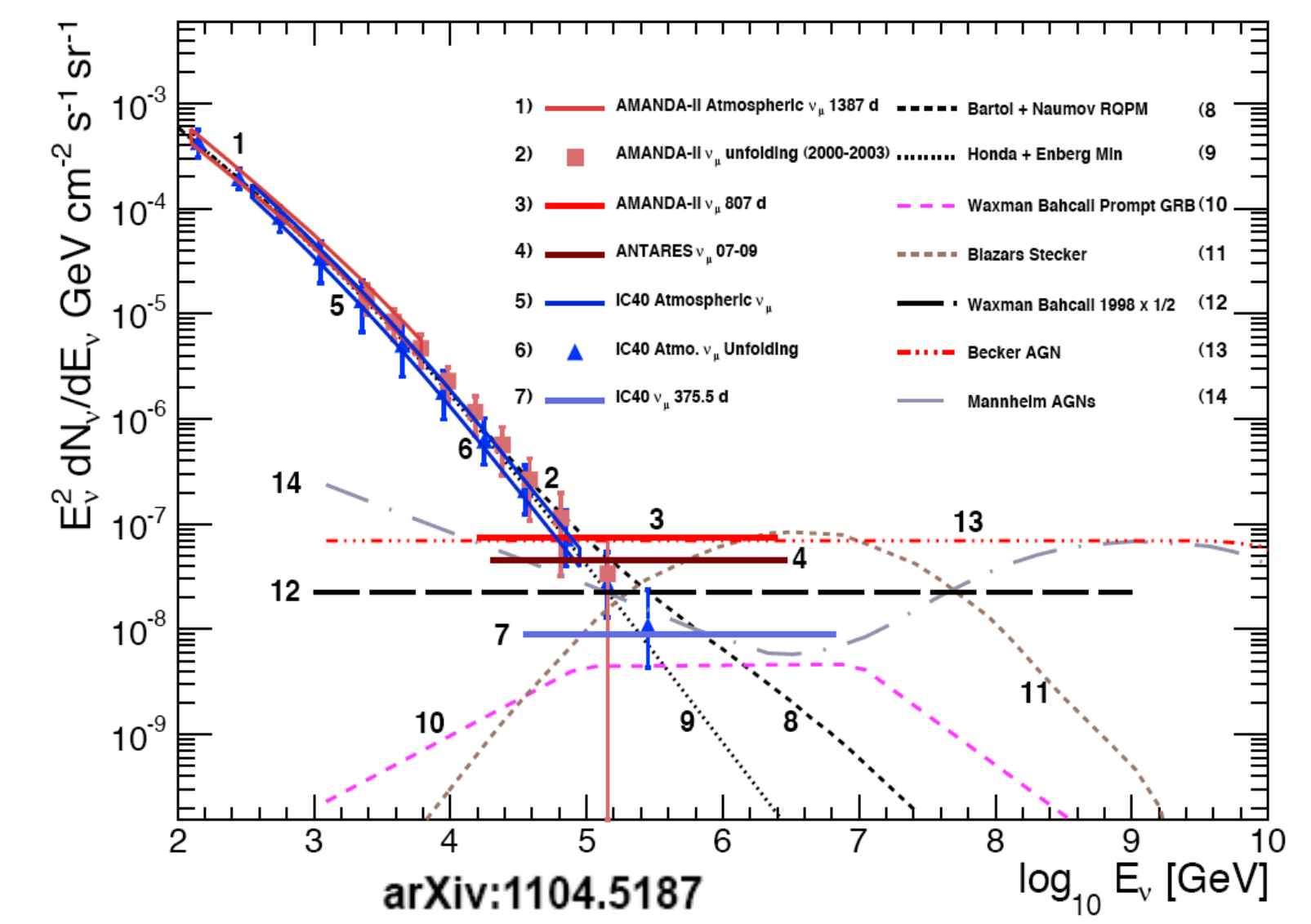


PHYSICAL REVIEW D 83, 012001 (2011)

Search for Diffuse Neutrino flux with Muon neutrinos



IC40 muon neutrino diffuse flux limit



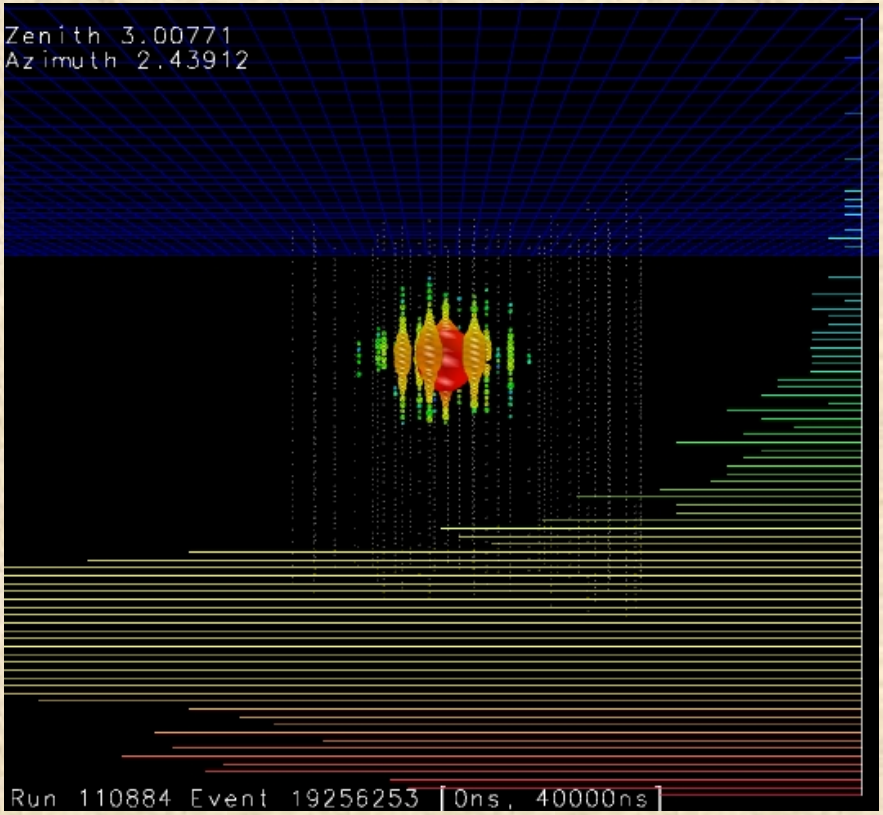
IceCube 40 has Reached the Waxman-Bahcall bound!

HE Cascades in IceCube

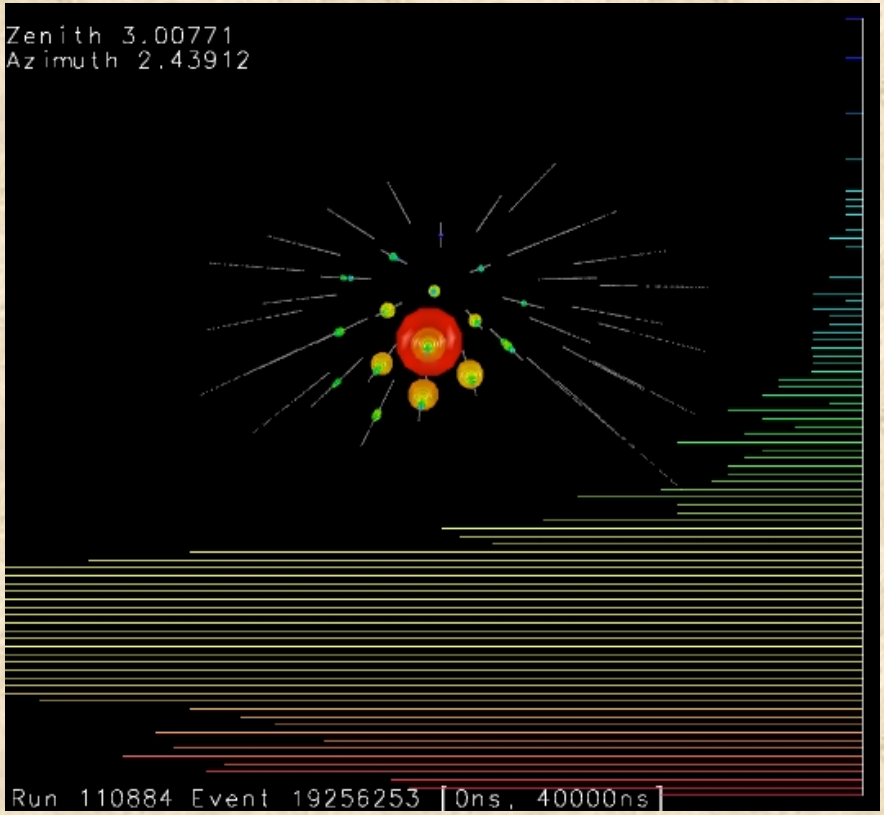
- The volume of IceCube is qualitatively different then previous generations of detectors
  - Ability to contain high energy cascade events
  - Advantage is that all sky is covered at all energies
    - Muon astronomy constrained to low energy contained events and higher energy events (above cr induced muon spectrum)
  - Disadvantage is reduced ability to point for astronomy
  - But, for diffuse analysis pointing not critical!
- IC40 is sufficient to start sensitive searches using cascades
  - Not yet as mature as muon neutrino, but getting there
  - Preliminary results → work in progress

IC40 HE cascade event displays

Energy estimate = 175 TeV

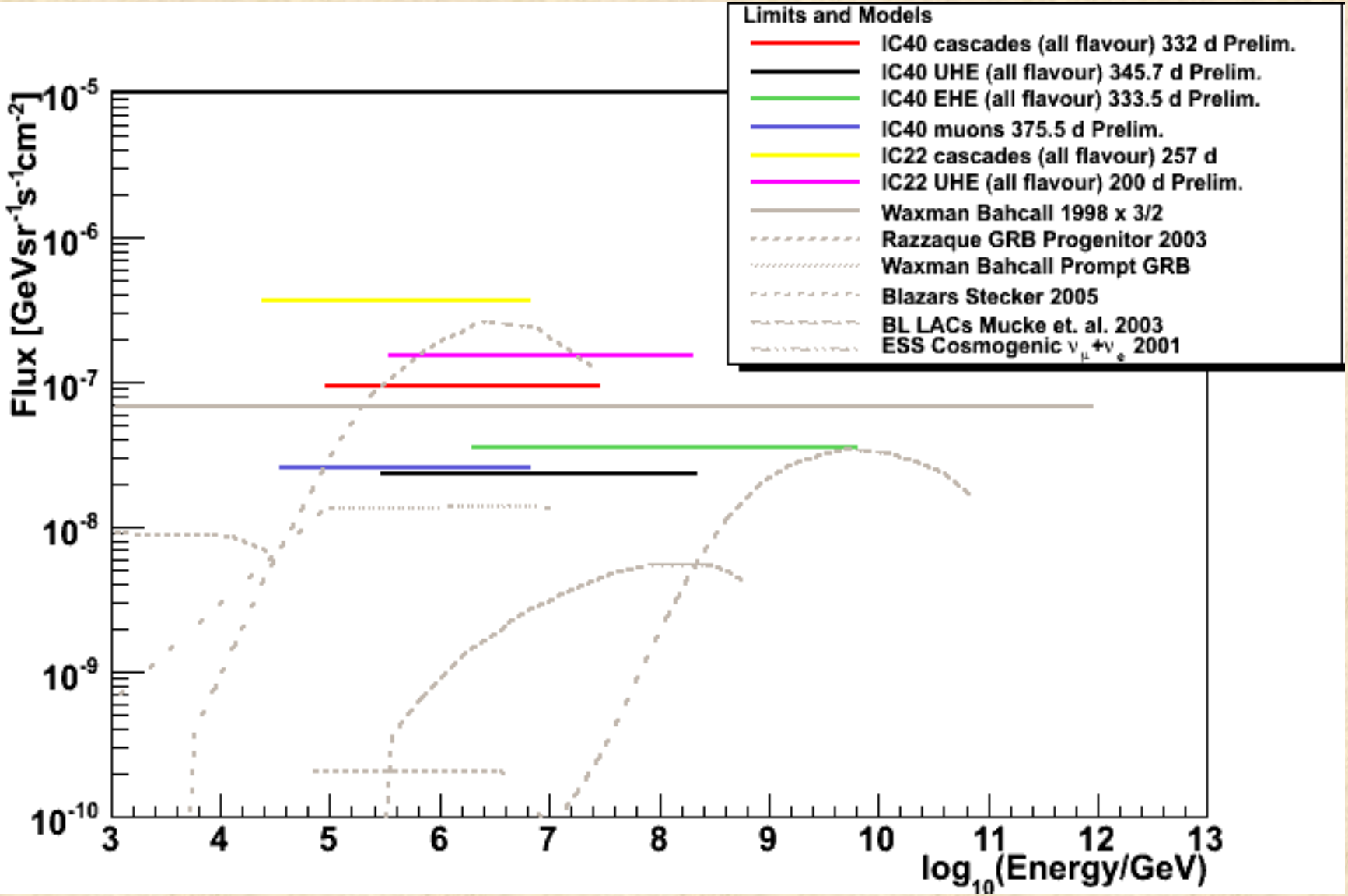


Side view



Top view

All-Flavour Diffuse Flux of Astrophysical Neutrinos

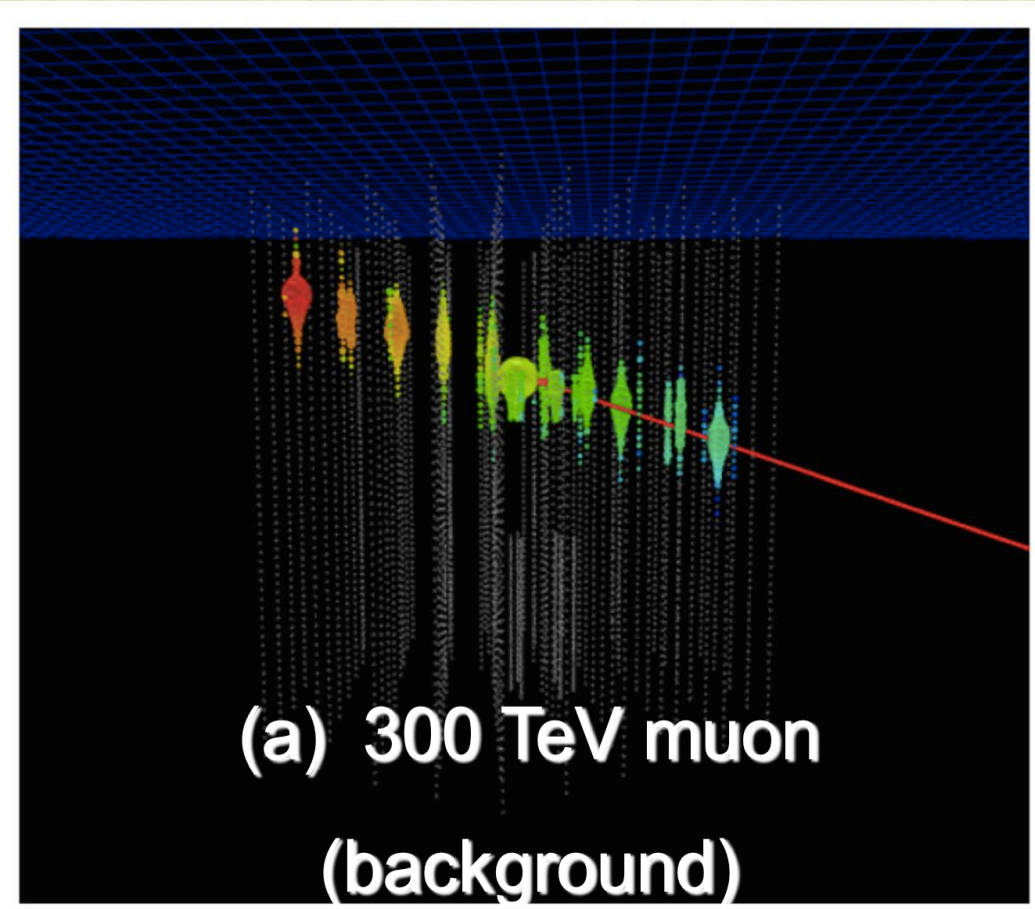


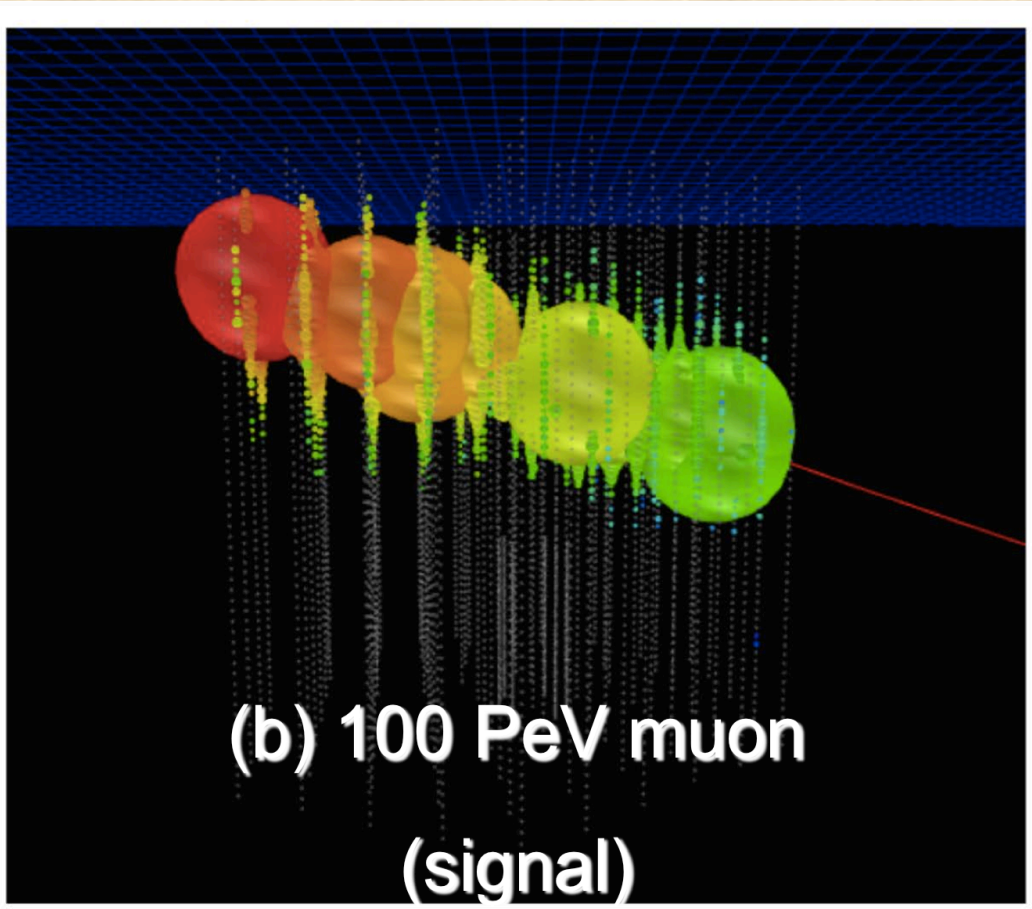
All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Cosmogenic Neutrinos (GZK)

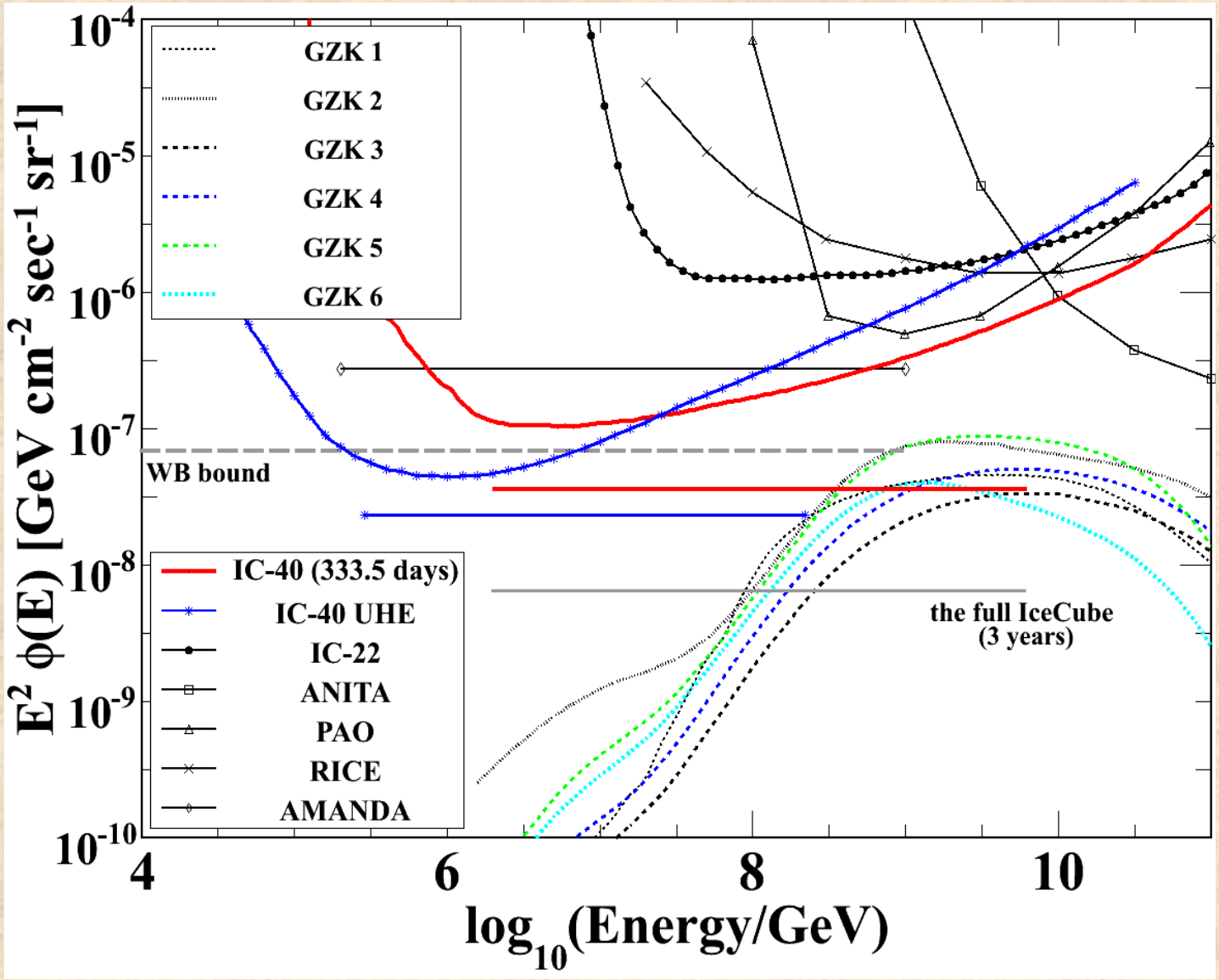
- Cosmogenic neutrinos "guaranteed" flux
  - Interaction of cosmic rays with CMB
- Very high energy events (>10 PeV)
  - Very bright events
  - Near the horizon
- Extension of diffuse (astrophysical) neutrino search to higher energies
- Flux predictions have large uncertainty
  - Fraction of event per year for lower predictions assuming protons as highest energy cosmic rays

Cosmogenic neutrino signatures



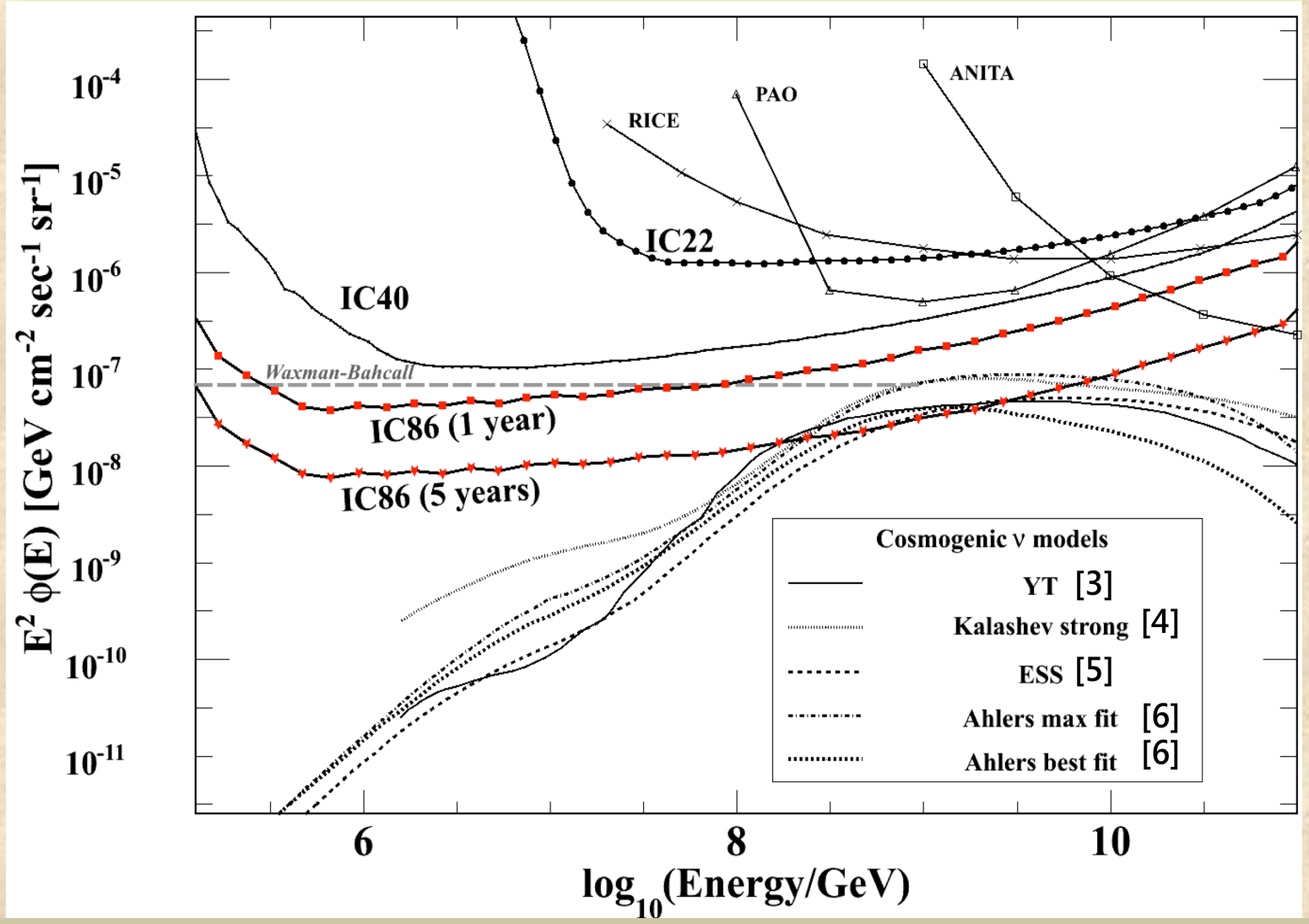


Constraints on the Extremely-high Energy Cosmic Neutrino Flux with the IceCube 2008-2009 Data



limits are touching GZK predictions of “guaranteed” EHE neutrinos

IceCube 86 sensitivity



Several Analyses in progress with IceCube Data
HE atmoshepric neutrino/diffuse, EHE, GZK

Stay tuned!

Sampling of IceCube Science Topics

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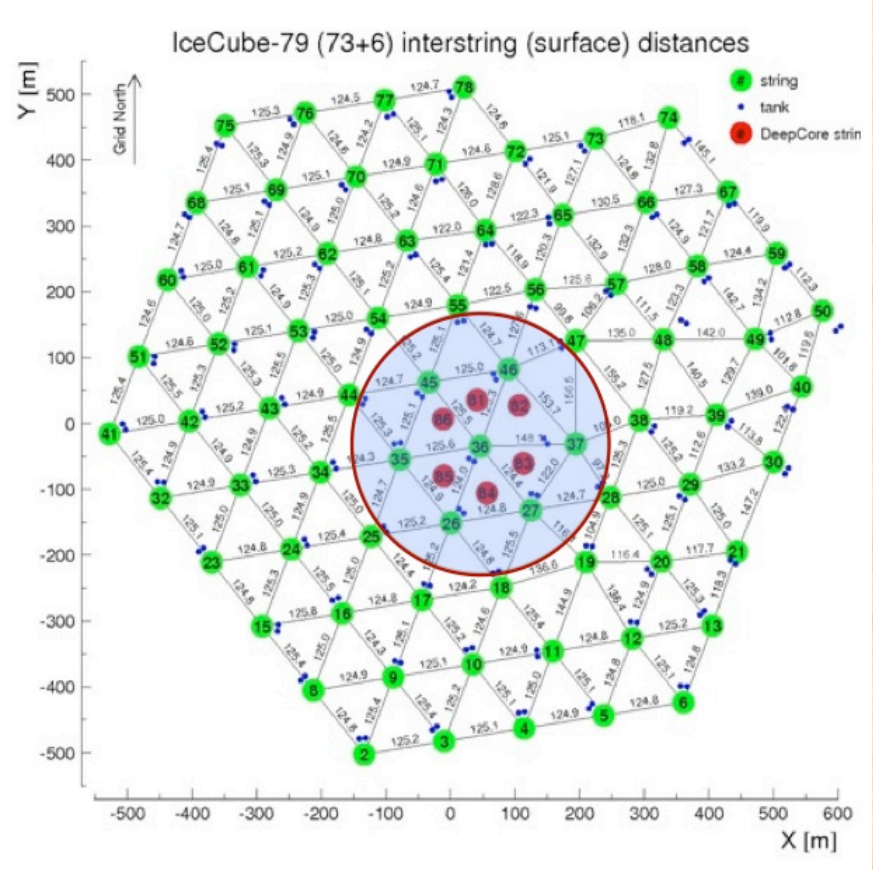
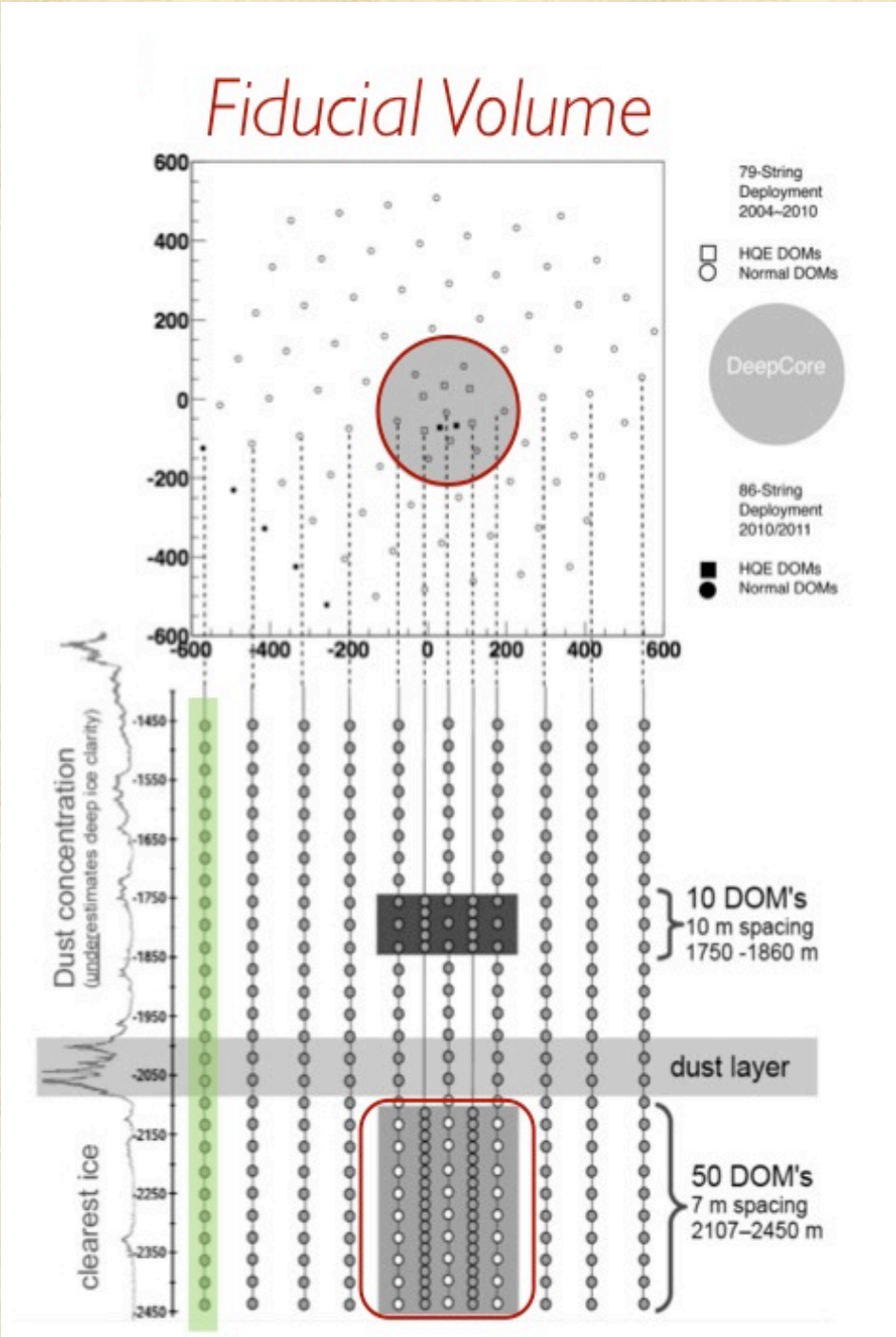
  - muons
  - Cascades
- **IceCube at low energy with Deep Core**
  - **Low energy cascade events**
- Cosmic Ray anisotropy

IceCube Deep Core (low energy & contained events)

Motivation:
- Low mass WIMP search (indirect DM)
- Neutrino oscillation physics
  - extend LE, ν_μ disappearance, ν_τ appearance
- southern hemisphere →4π detector

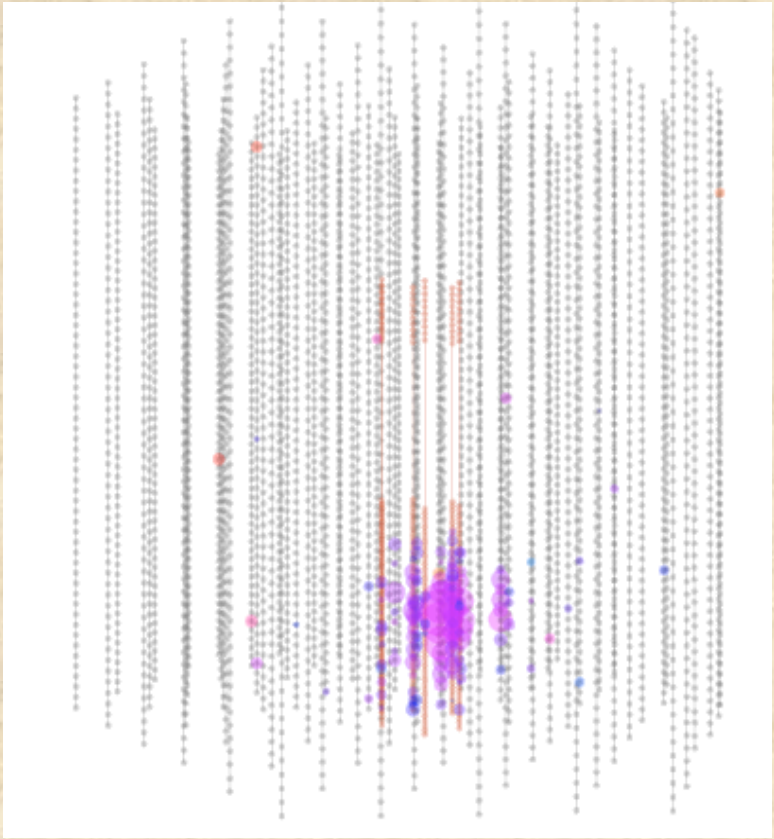




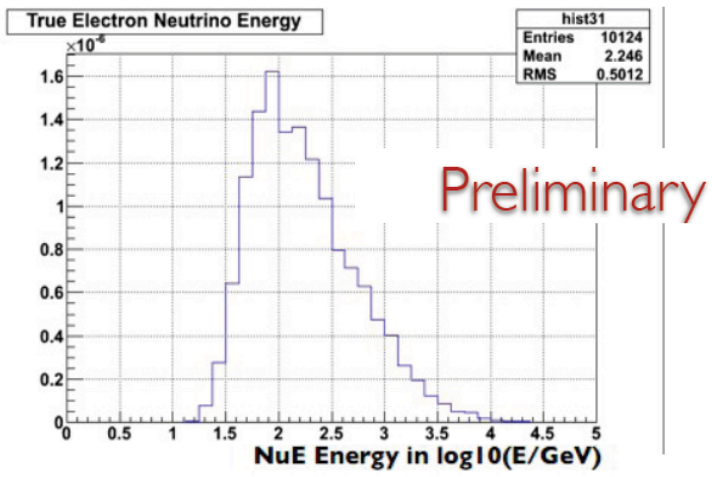
Observation of low energy Neutrino Cascades

- Disappearing ν_μ should appear in IceCube as ν_τ cascades
  - Effectively identical to neutral current or ν_e CC events
  - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background

Preliminary



Harsh Cut



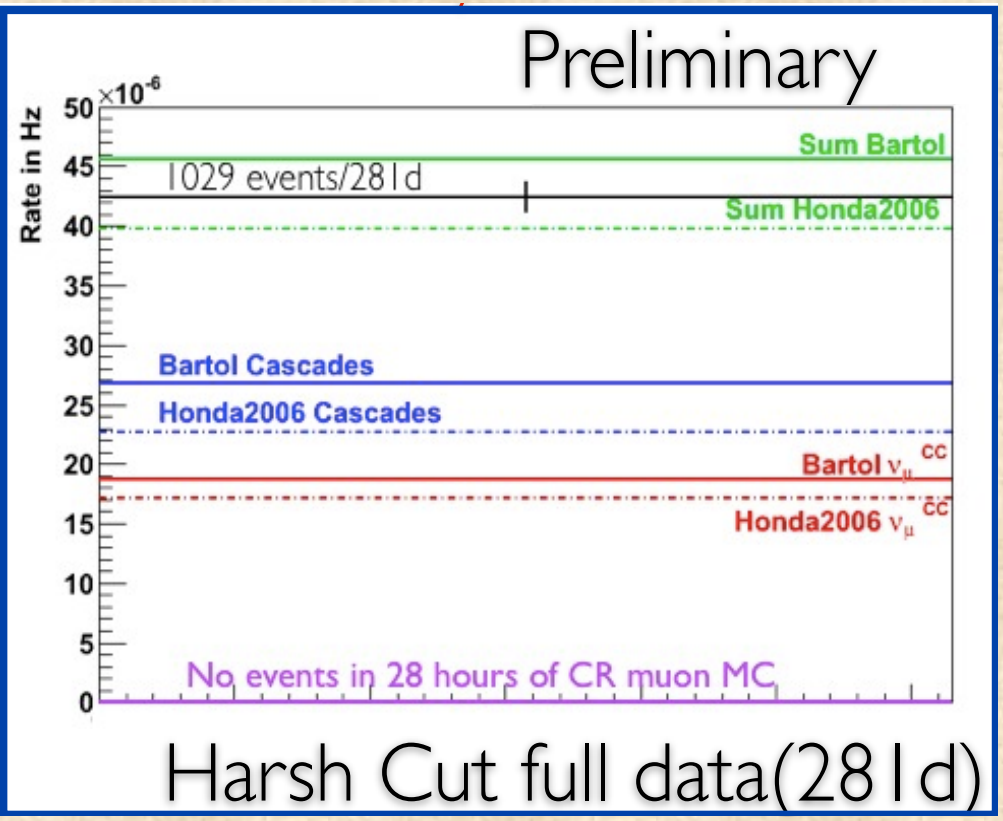
<NuE> ~180 GeV

$$C^{sig} = \nu_\mu^{NC} + \nu_e^{CC} + \nu_e^{NC}$$
$$C^{bg} = \nu_\mu^{CC}$$
$$N^{sig} = \nu_e^{CC} + \nu_e^{NC}$$
$$N^{bg} = \nu_\mu^{CC} + \nu_\mu^{NC}$$

← cascades

← ν_e

Low energy cascades in IceCube DeepCore



Preliminary

	N^{obs}	C^{sig} (C'^{sig})	C^{bg}(C'^{bg})
#Events (281 days)	1029	650.2 (551.2)	454.0 (415.4)

N^{obs} = Number of observed events in real data
C^{sig} = Cascade Signal from Bartol model $\nu_e^{CC} + \nu_e^{NC} + \nu_\mu^{NC}$
C^{bg} = Remaining Background from Bartol model ν_μ^{CC}
(C'^{sig} and C'^{bg} = expected rates from Honda 2006 model)

First clear observation of LE cascades in IceCube at 10-300 GeV
➔ First steps in oscillation studies

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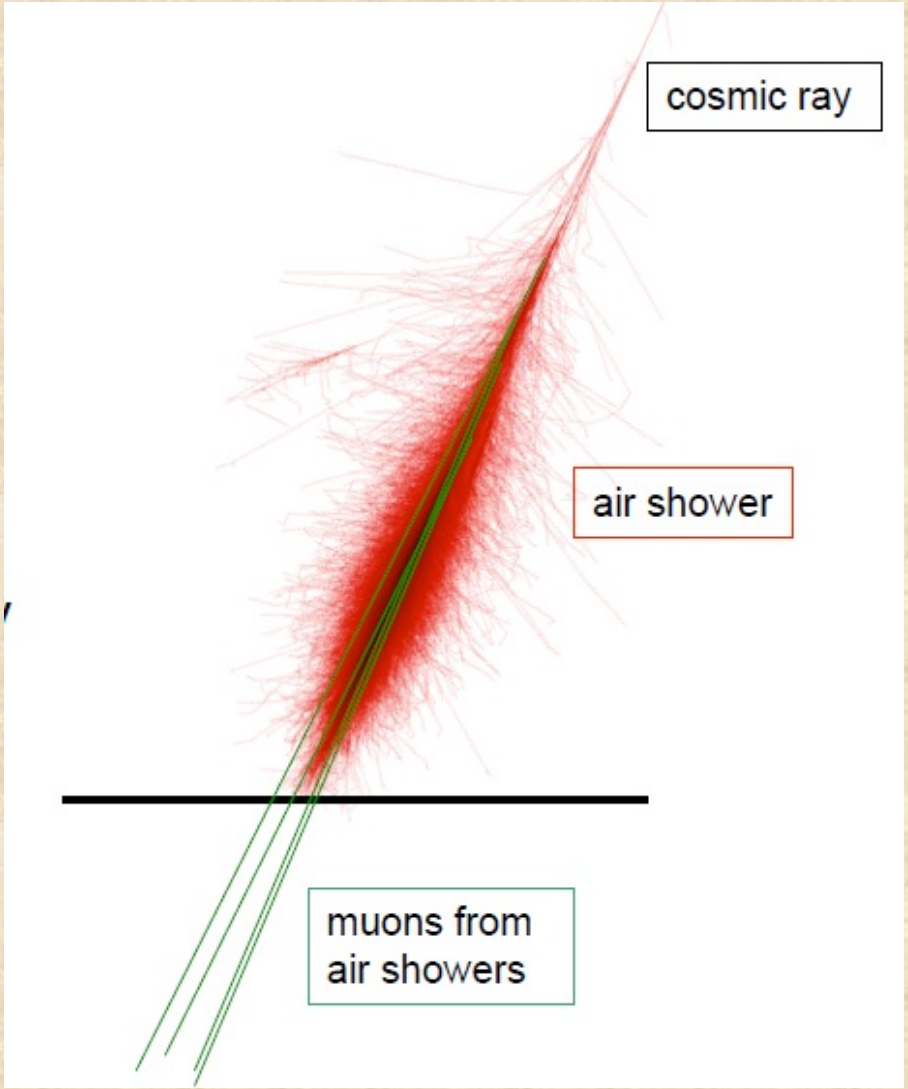
CR Muon Astronomy

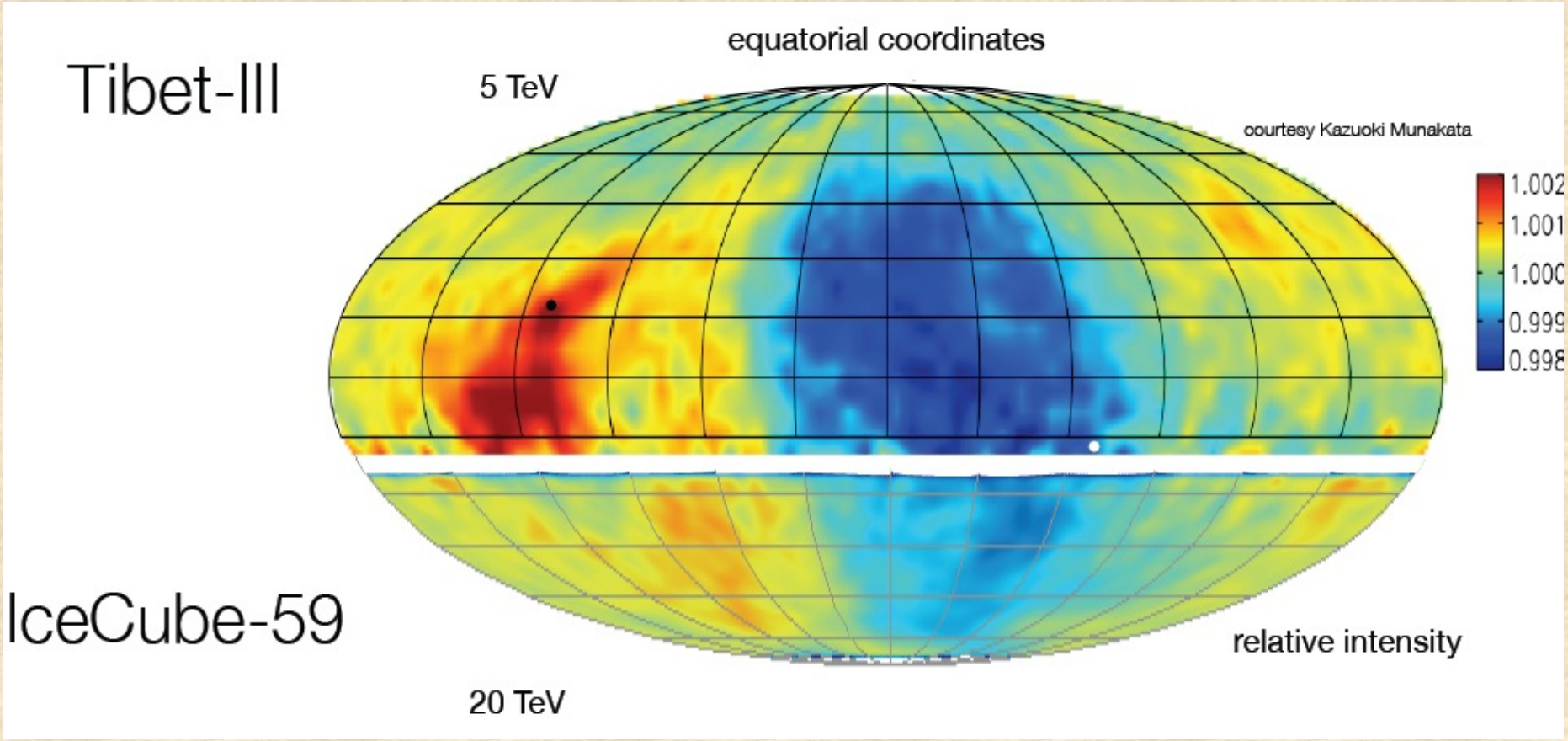
Use large sample (~2 kHz) of down going cosmic ray muons to make a map of the southern hemisphere

Recall the Moon Shadow



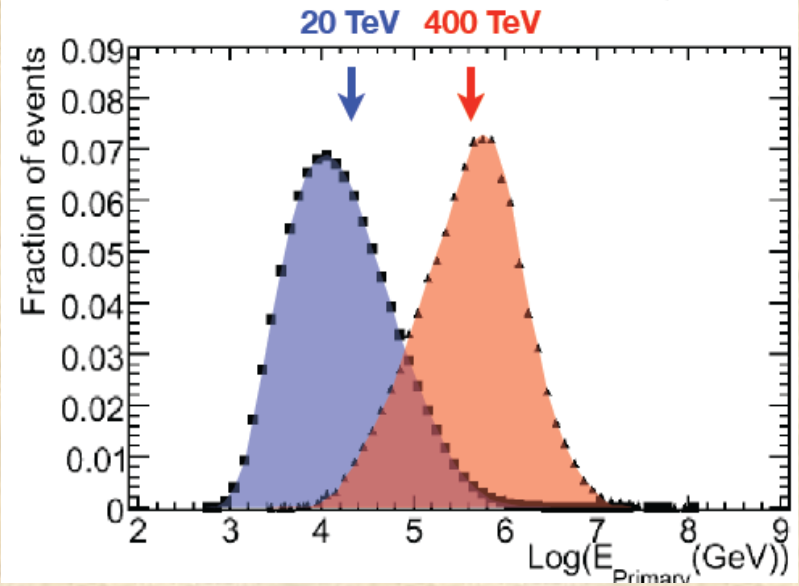
Cosmic Ray Anisotropy

Compared to Northern Sky

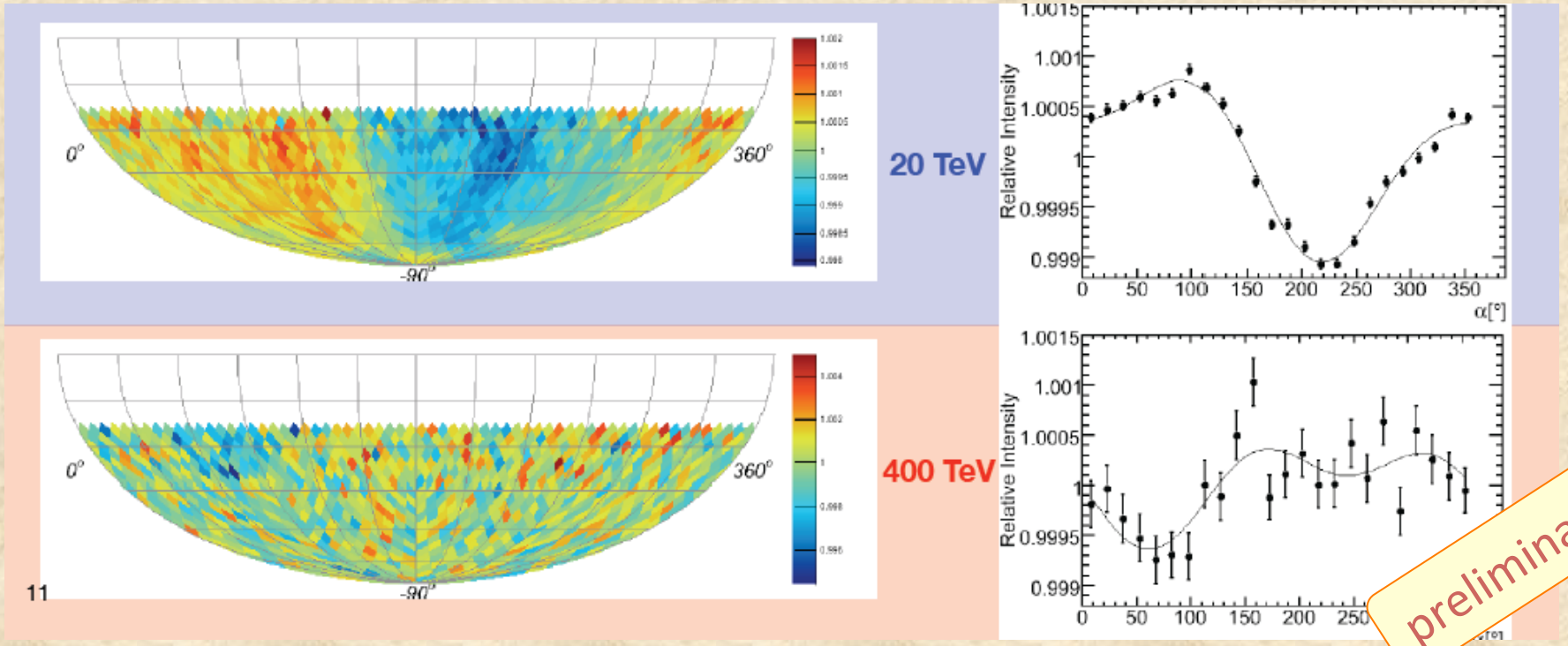


the orientation of the dipole moment
does **not** correspond to the relative motion
in the Galaxy (Compton-Getting effect)

Cosmic Ray Anisotropy vs Energy in IceCube-59

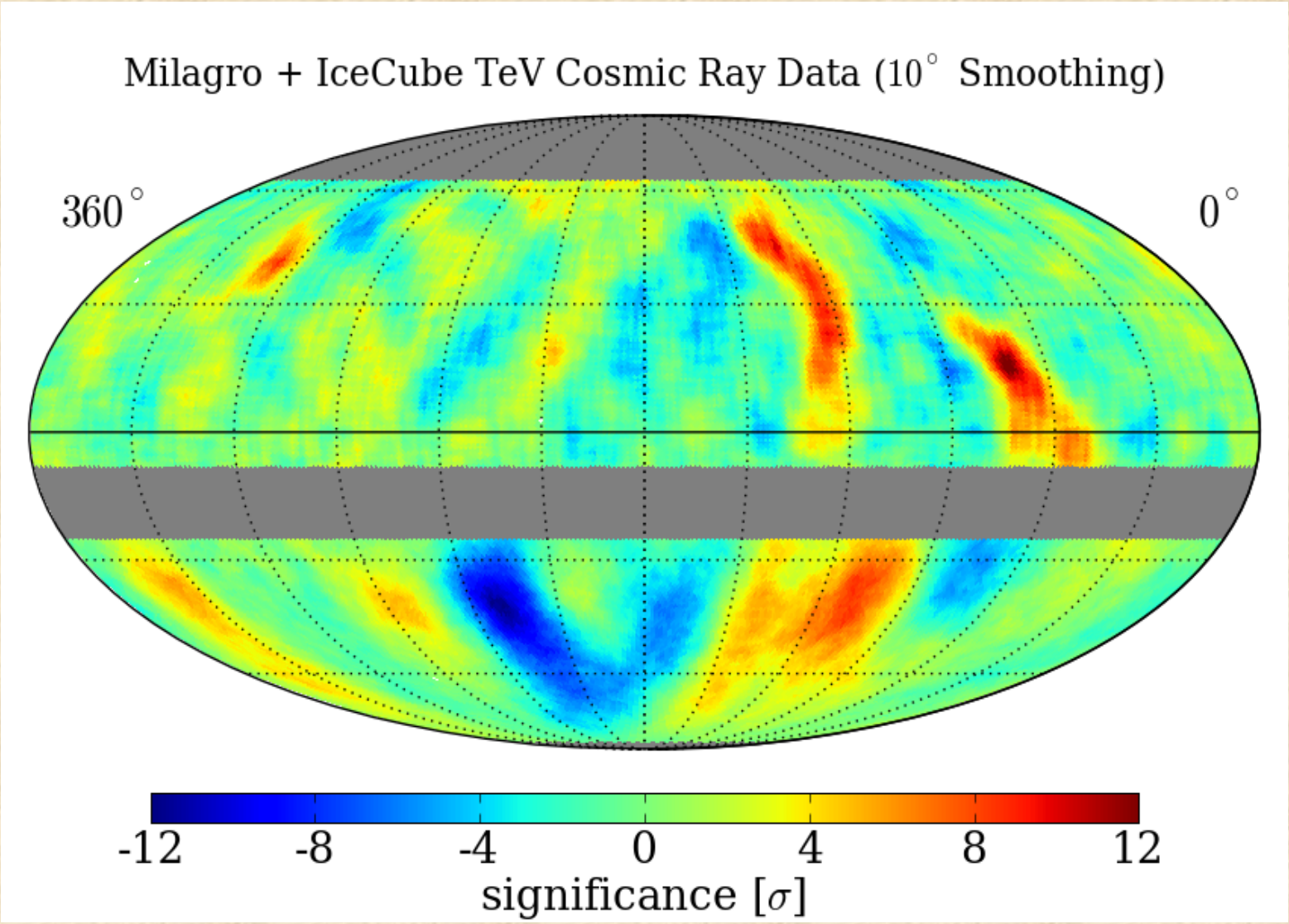


- first time structure at higher energy observed
- structures at 20 TeV and 400 TeV differ



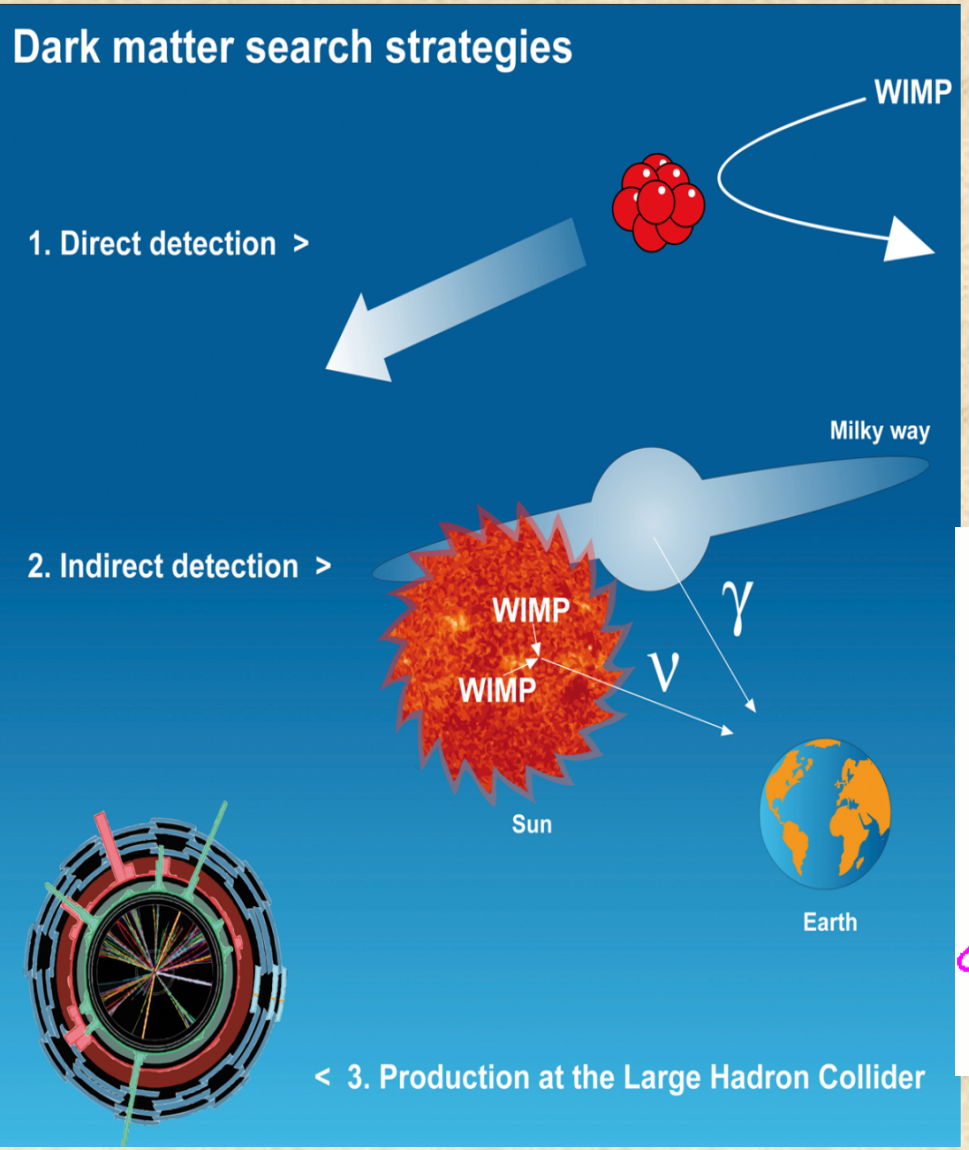
- *Nearby CR sources?*
- *Something Else?*

Equatorial sky maps in HEALPix with NSide= 64, ***pix resol ~ 0.9˚***



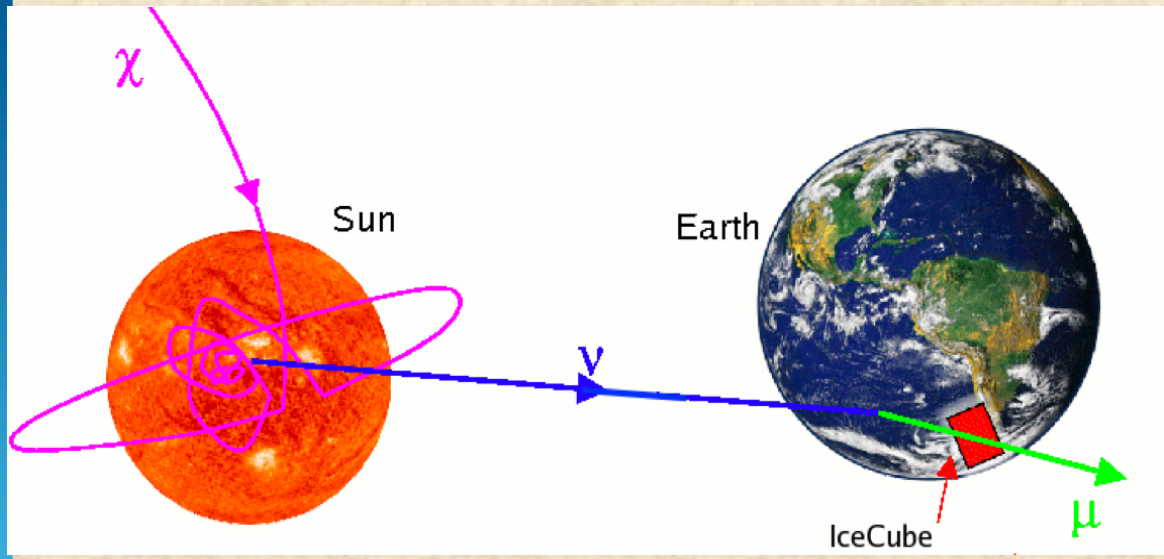
[submitted to ApJ: **arXiv:1105.2326**]

Exotics: Dark Matter, Monopoles ....



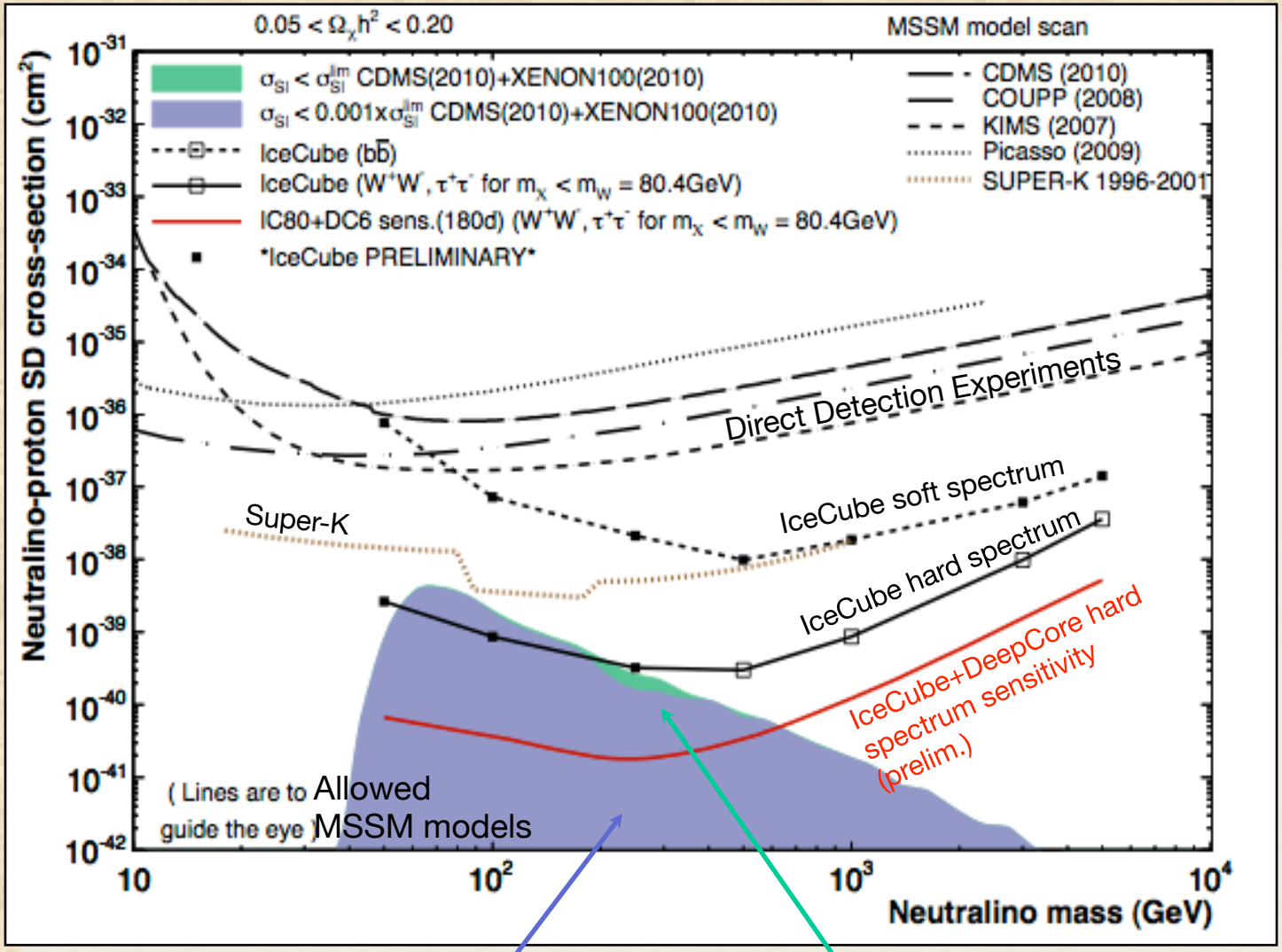
cosmology constraint for DM:

Dark Matter Searches: SUSY, WIMPS, KK



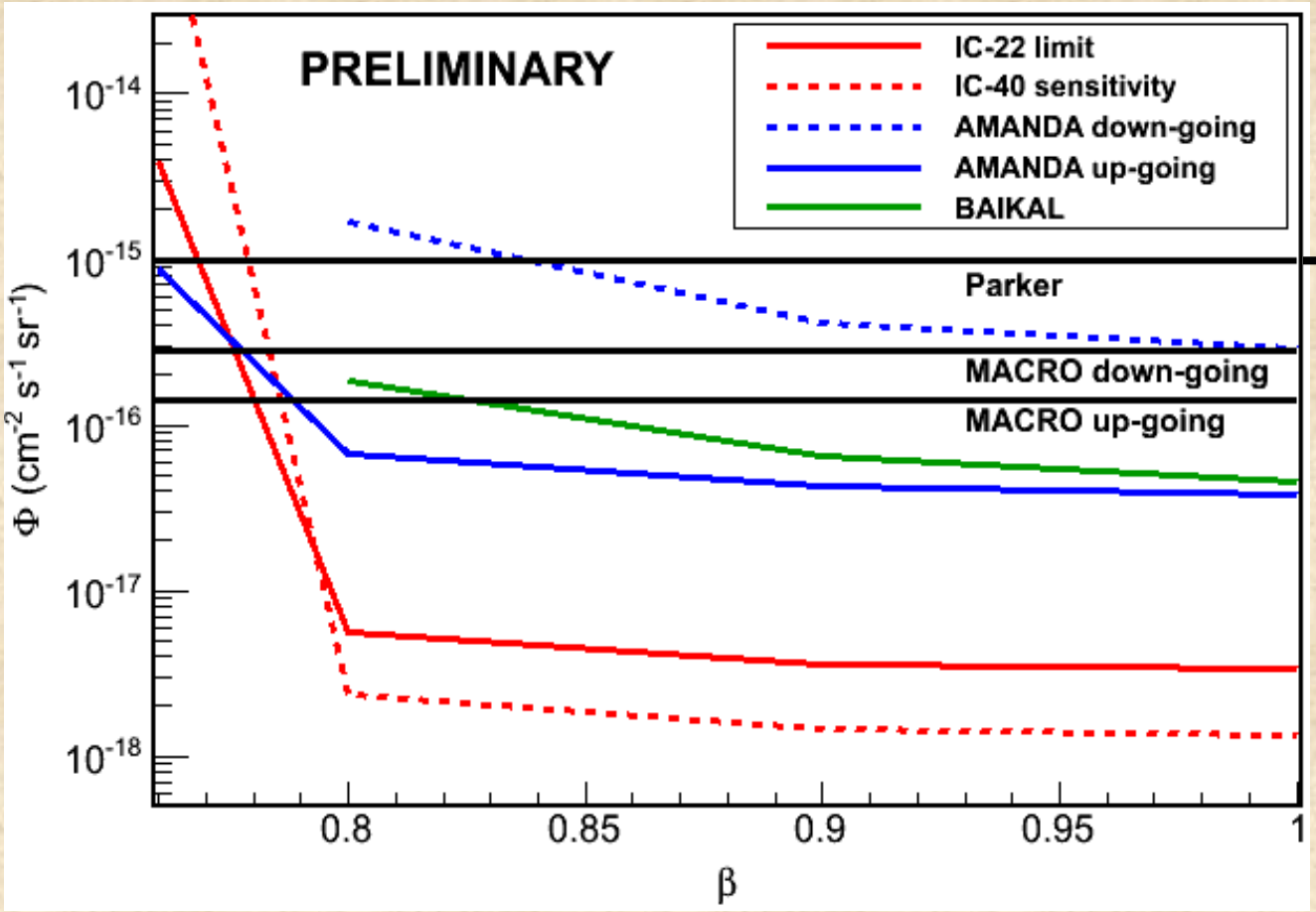
Sensitivity to MSSM WIMPs

- Solar WIMP dark matter searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



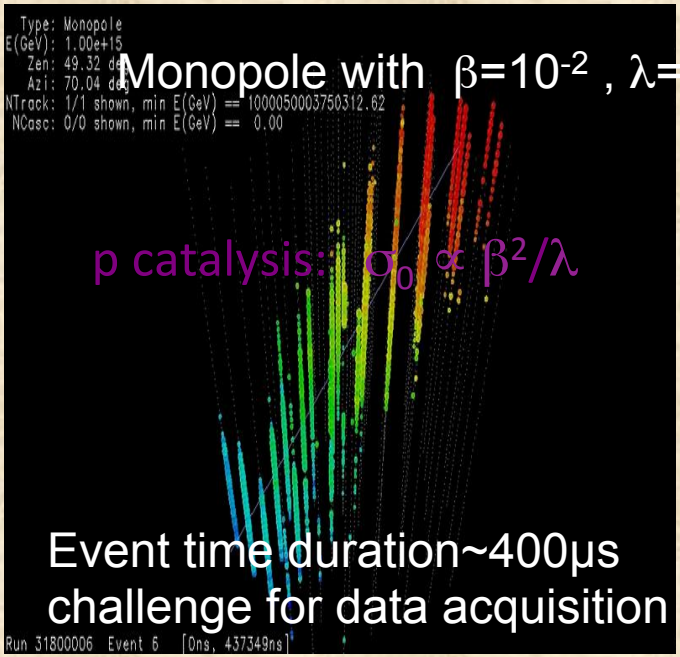
Relativistic Monopole Search

Monopole flux limits assuming an isotropic flux at the detector



existence of cosmic B-fields

future: slow monopoles



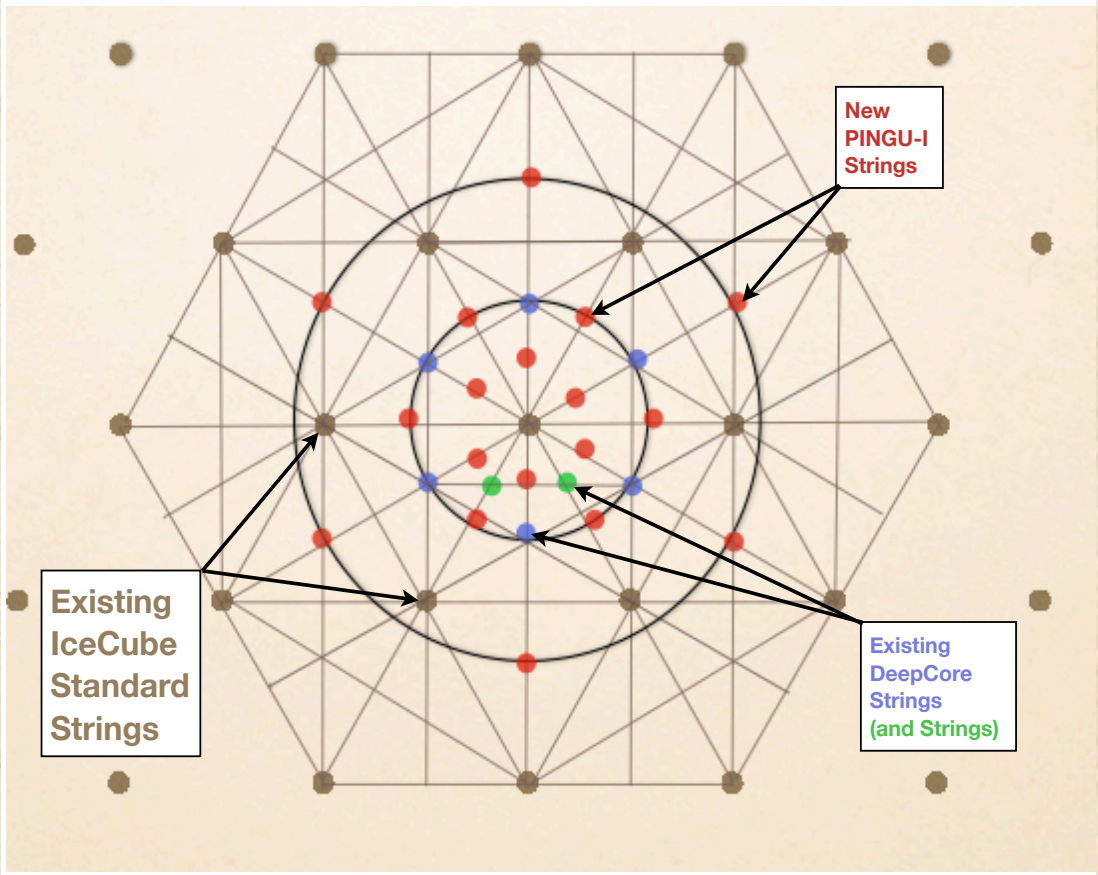
- O(1000) below bound from existence of galactic B-field (Parker)
- Limits seriously constraint GUT models

Future

HE: radio, acoustics, ...
- cosmogenic neutrinos
- Under construction

DM-Ice: Dark matter
- Bckgrnd measure in IceCube
- Proposal

LE: DeepCore + extension (PINGU)
- oscillations
- galactic sources
- dark matter
- SN neutrinos



Pingu-I
18 additional strings with about 1000 DOMs
in the 30 MT DeepCore ➔ Cherenkov imaging

Summary

- ***Large Neutrino Telescopes now operating in both hemispheres***
  - IceCube is complete and has already surpassed expected performance.

    The era of km^3 neutrino telescopes is just beginning!
- ***Results from Antares the partly completed IceCube detector (IC22,40,56,79) reached sensitivities which are starting to seriously challenge some models:***
  - point source limits all sky, time (in)dependent, candidate list,
  - GRB limits challenging the fireball model
  - WIMP limits extended, Monopole limit well below "Parker Bound"
  - Diffuse: factor 4 below W&B bound; EHE: in the range of GZK predictions
  - pre-selected candidate sources (single or stacking), transients/time dep.: flares, GRB, SN ...
  - follow-up program (optical, X-ray, γ-ray)
- ***Measurements:***
  - atmospheric neutrino and muon spectrum, lorentz invariance, non-standard oscillations
  - cosmic ray anisotropy on various angular scales, CR composition: IceCube/IceTop has unique capabilities
- ***Future: exploit existing facility and infrastructure:***
  - DeepCore: low energy extension, atm. Oscillations, low mass WIMPS
  - high energy extensions: radio, Low energy: Cherenkov imaging?, DM-Ice

Stay tuned over the next decade!