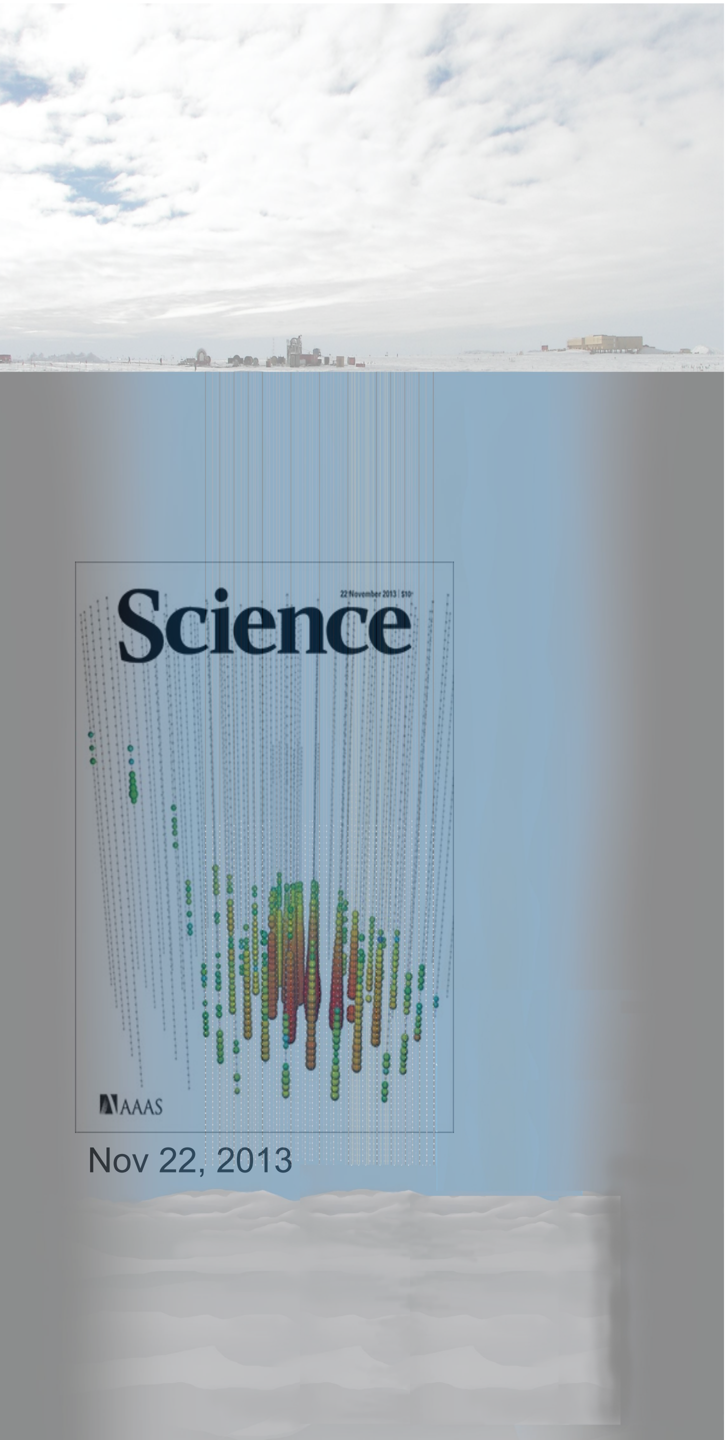
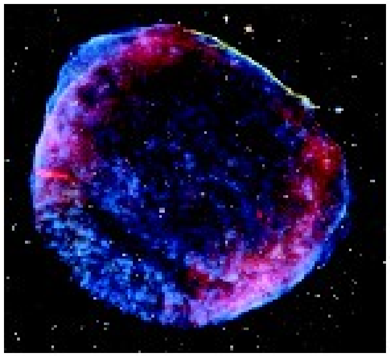


Evidence of extraterrestrial high-energy neutrinos from IceCube

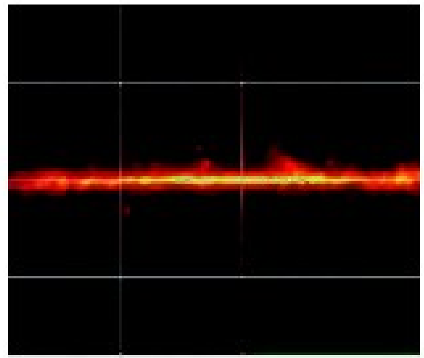
Carlos de los Heros
Uppsala University

CPAN 2013 meeting
Santiago de Compostela 25-28 November, 2013

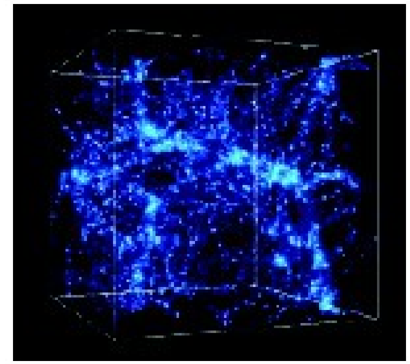
Cosmic accelerators



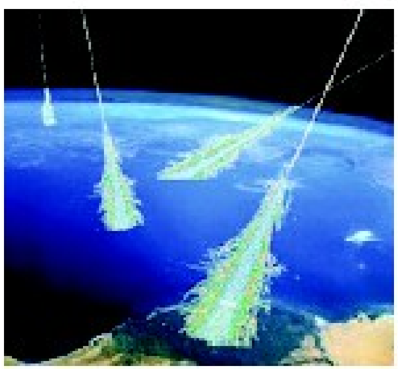
Diffuse fluxes



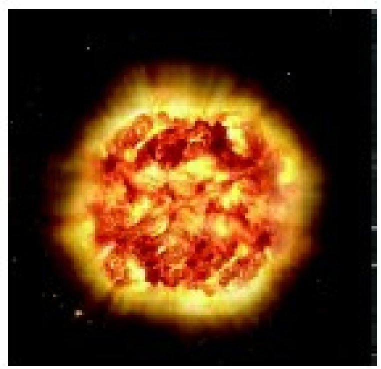
Dark Matter & Exotic Physics



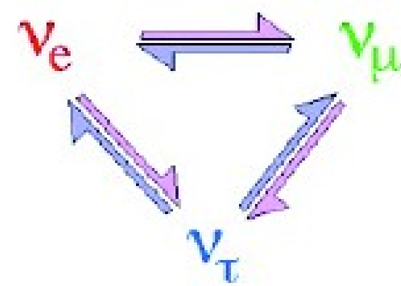
Cosmic rays



Supernovae



Neutrino Properties & Particle Physics



Cosmic accelerators

- Point-like sources (SNRs, Binaries ...)
- Extended sources
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
- Galactic plane
- Extended structures (e.g. Fermi-Bubbles)

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls
- Lorentz invariance violation

Cosmic rays

- Spectrum around "knee" (10^{15}–10^{17} eV)
- Composition
- Anisotropy

Supernovae

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

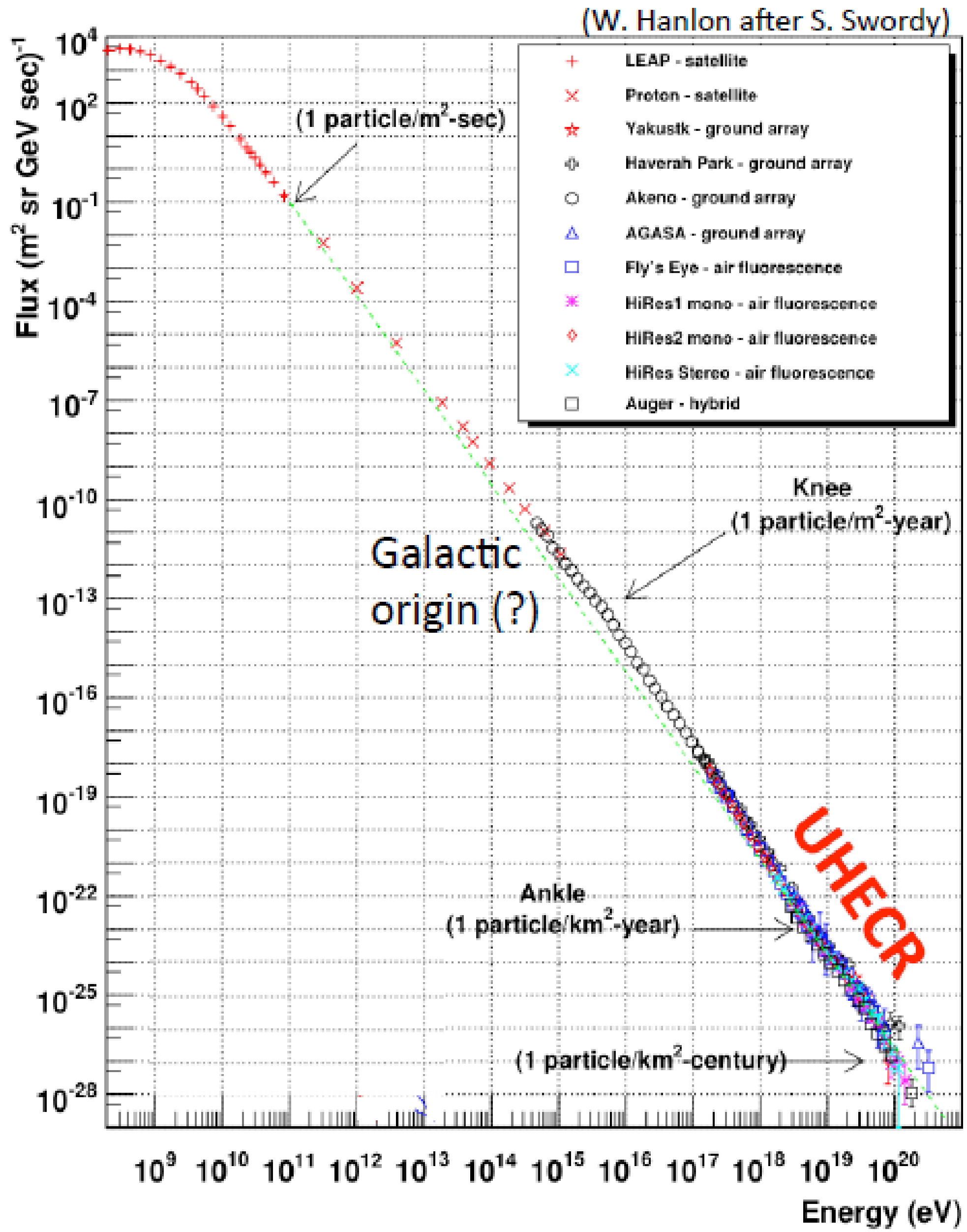
Neutrino Properties & Particle Physics

- Neutrino oscillations
- Charm in showers
- K/π ratio in showers
- Cross sections at very high energies

Challenge:
Understand UHE tail of the CR spectrum

We know Nature is accelerating particles to ~10^{20} eV

CR interactions with ambient matter and photons in the surroundings of the source MUST produce neutrinos through pion decay

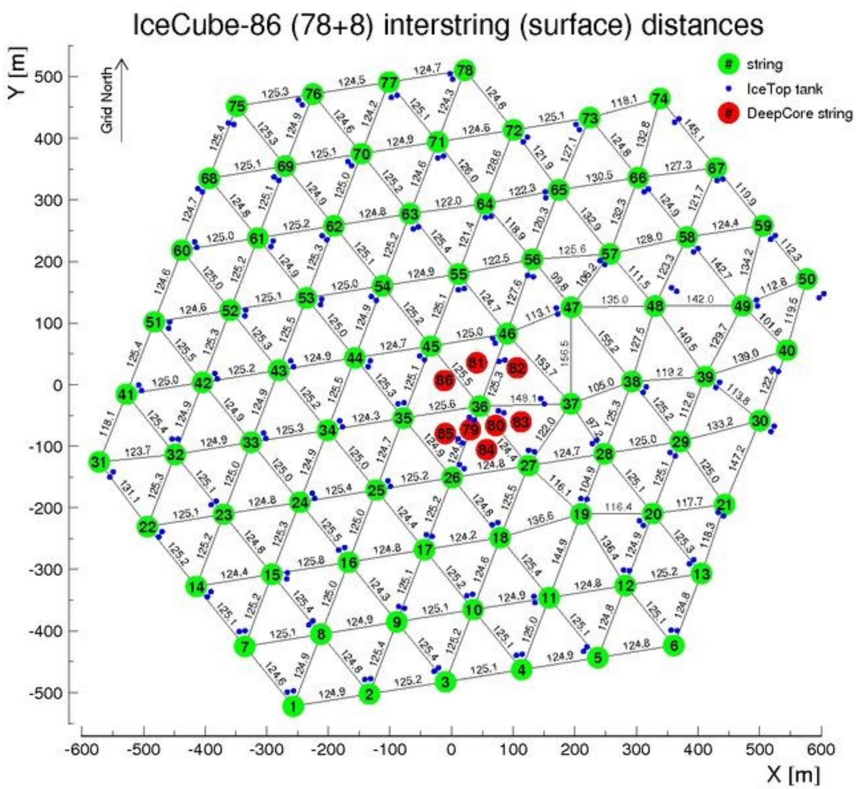


Detector completed December 2010

86 strings, 80 surface stations

Taking data in full configuration since May 2011

IceTop: Air shower detector
80 stations/2 tanks each
threshold ~ 300 TeV

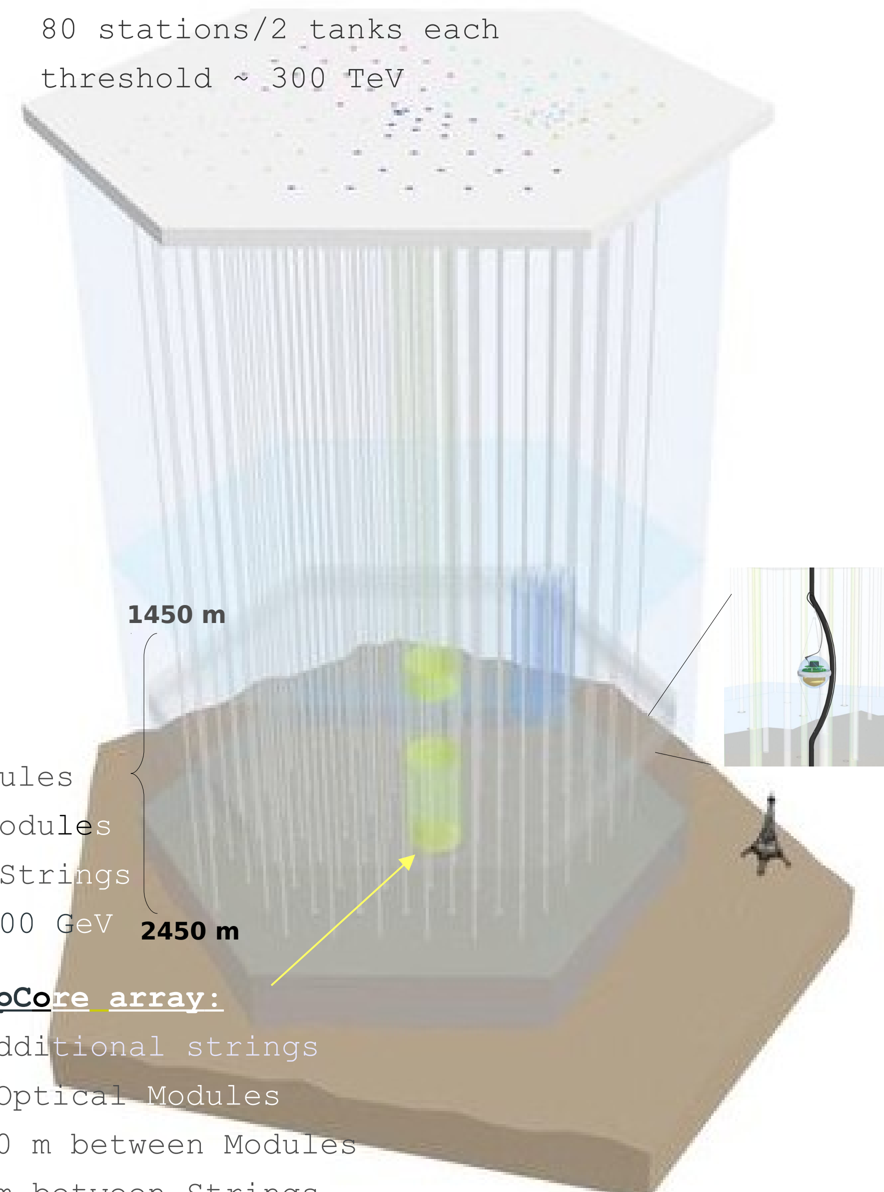


InIce array:

80 Strings
60 Optical Modules
17 m between Modules
125 m between Strings
E threshold ≲100 GeV

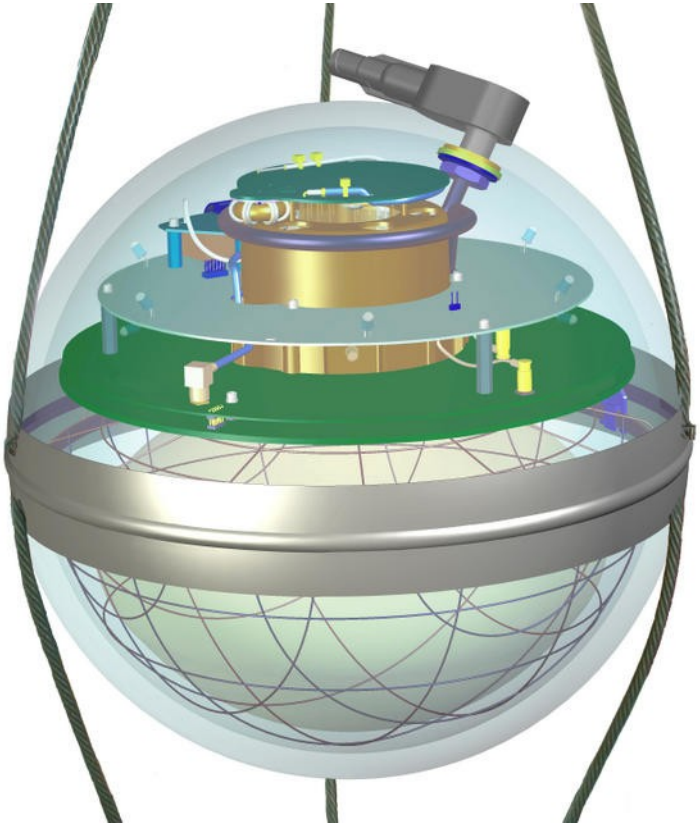
DeepCore array:

6 additional strings
60 Optical Modules
7/10 m between Modules
72 m between Strings
E threshold ~10 GeV



the Digital Optical Module

Each DOM is an autonomous data collection unit



- **PMT**: Hamamatsu, 10''

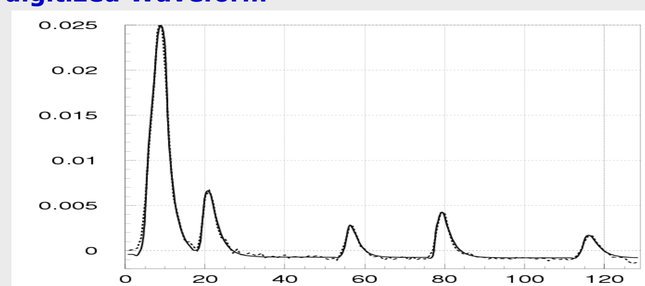
-**Digitizers**:

   ATWD: 3 channels. Sampling 300MHz, capture 400 ns

   FADC: sampling 40 MHz, capture 6.4 μs

Dynamic range 500pe/15 nsec, 25000 pe/6.4 μs

digitized Waveform

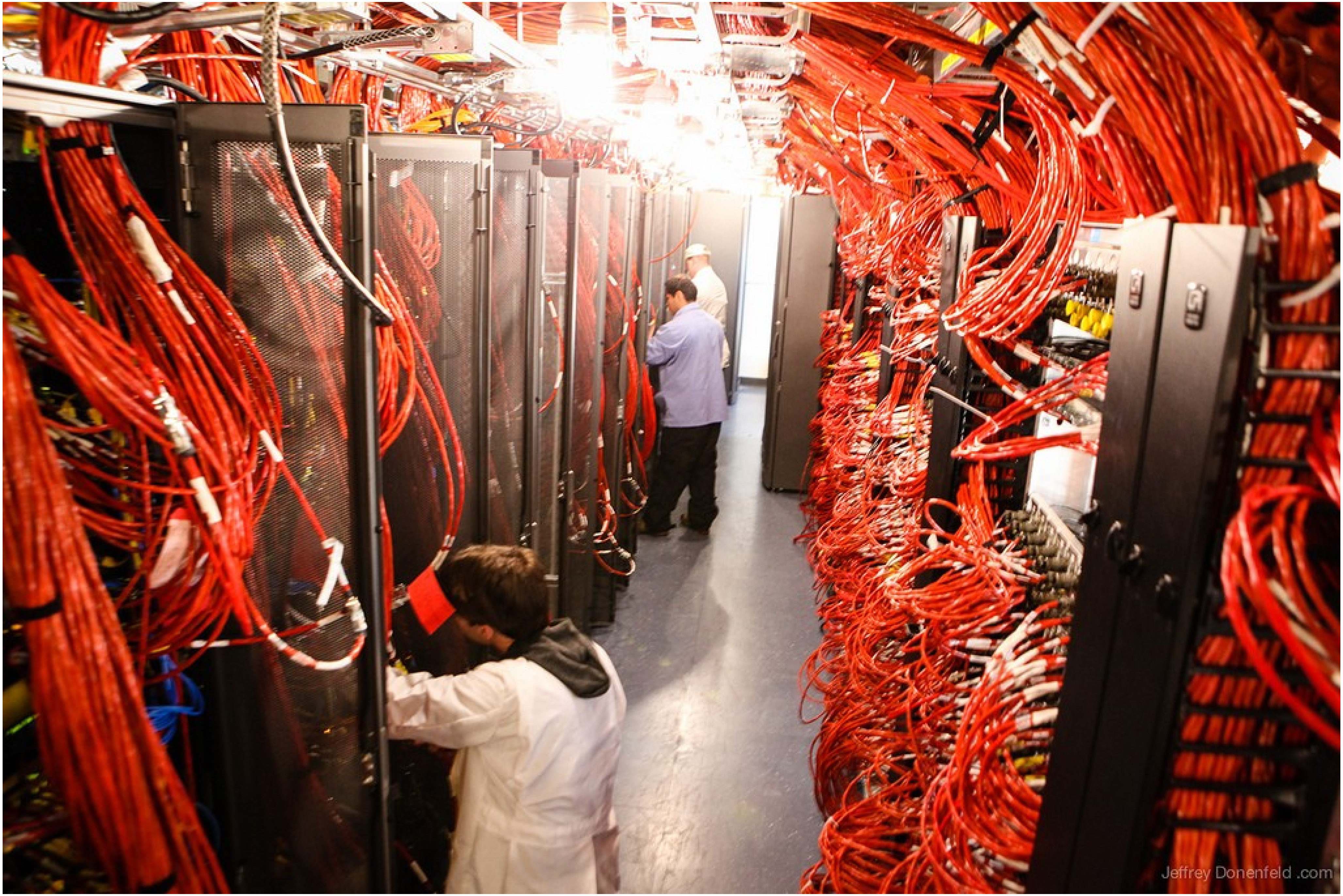


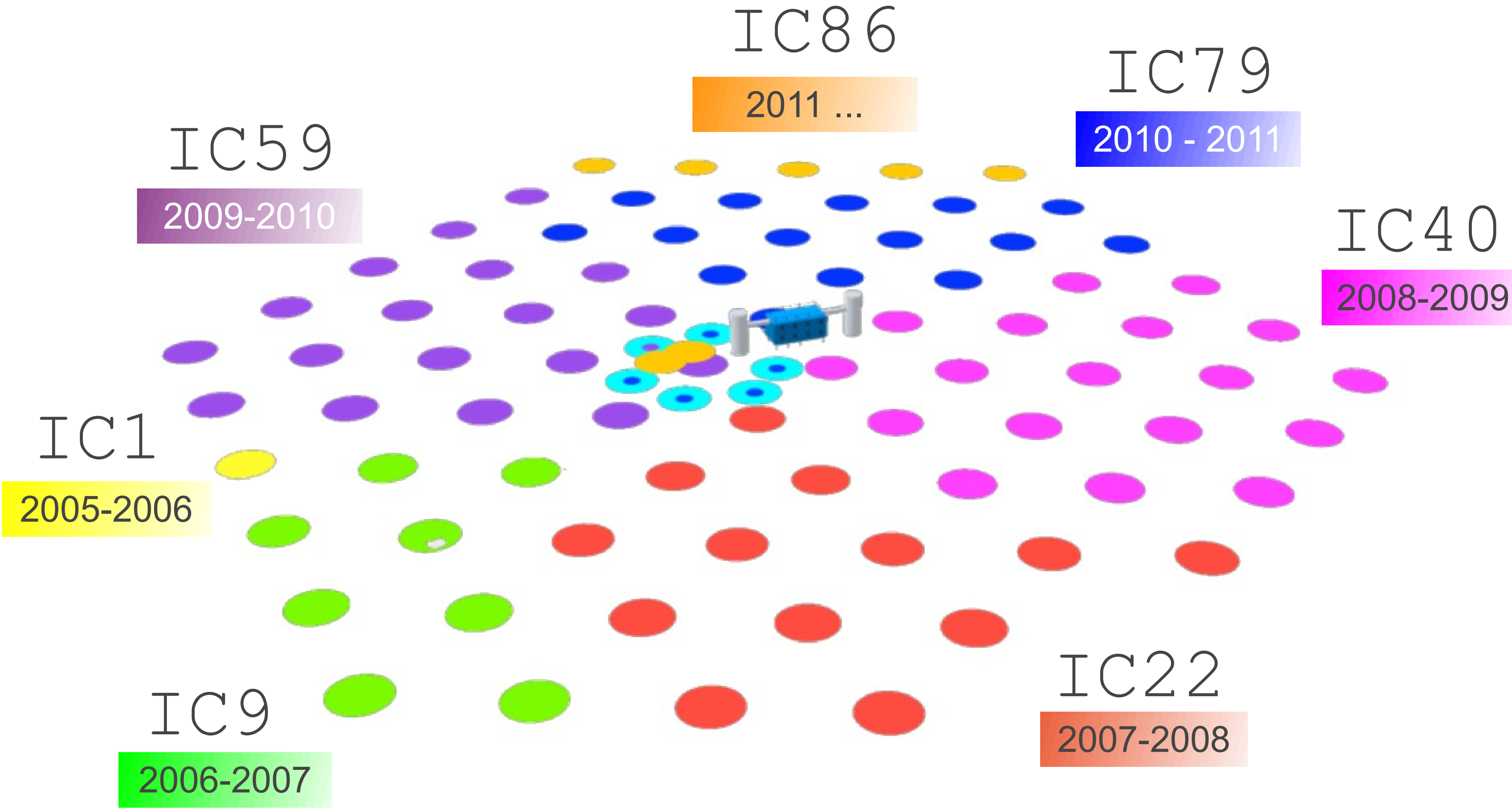
- **Flasher board**:

   12 controllable LEDs at 0° or 45°

- Dark Noise rate ~ 400 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns
- Power consumption: 3W

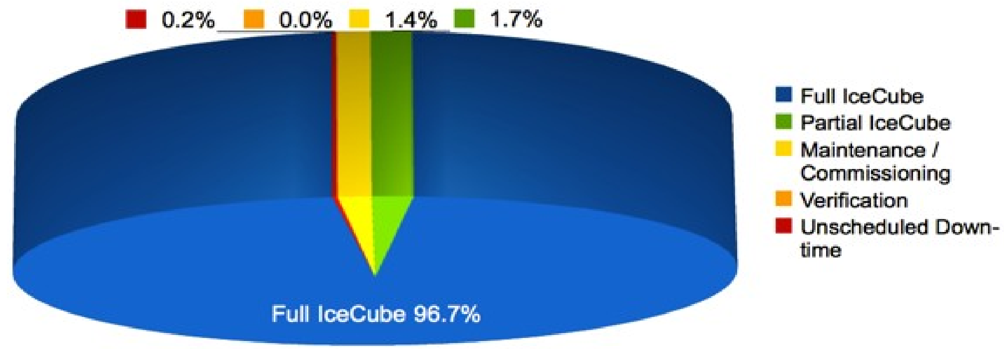
Clock stability: 10-10 ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec with 2 ns precision

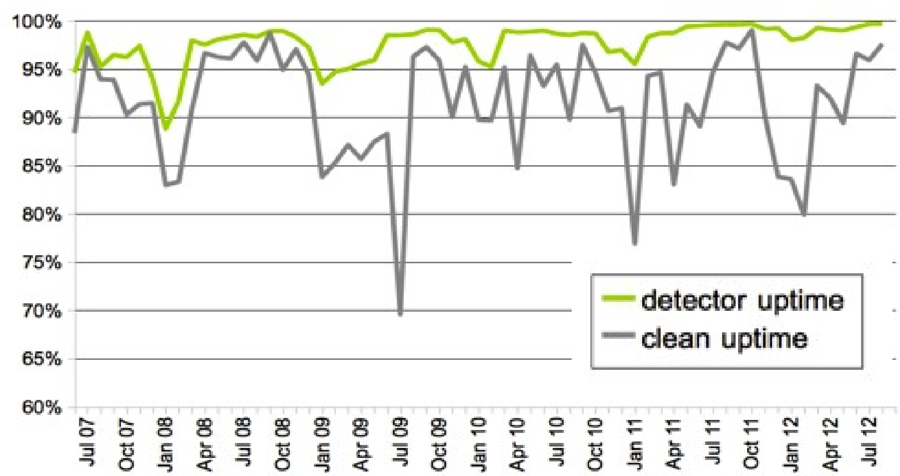

Jeffrey Donenfeld .com



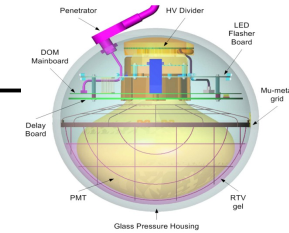
Data taking since 2005 – completed in 2010!

detector performance





Operation-time > 99.8 %
Physics data > 96.7%



DOM performance

- 99.1% (5435) DOMs have survived installation
- Failure rate: 2/year
- After 15 years operation (2025) we expect 97.2% +/- 0.4% of the detector operational

Muon rate: ~ 3 kHz
Neutrino rate: ~ 200/day

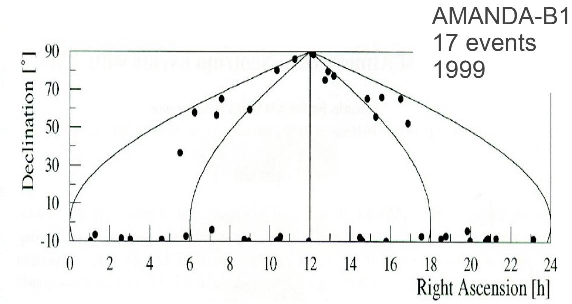
We record ~ 1 neutrino every 7 minutes

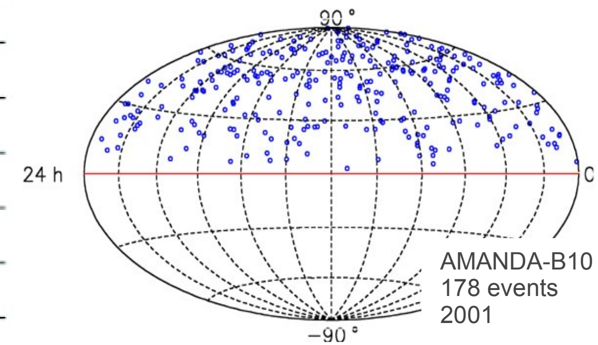
Well working detector delivering excellent data

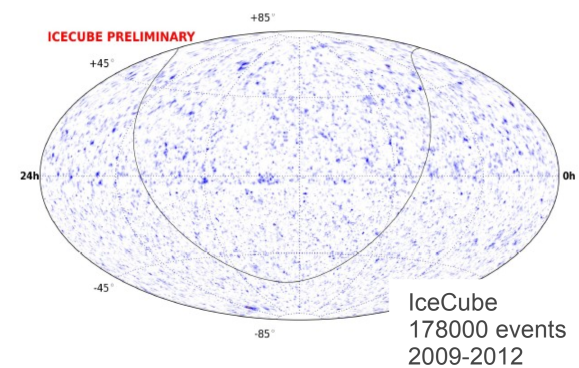
1991

2011

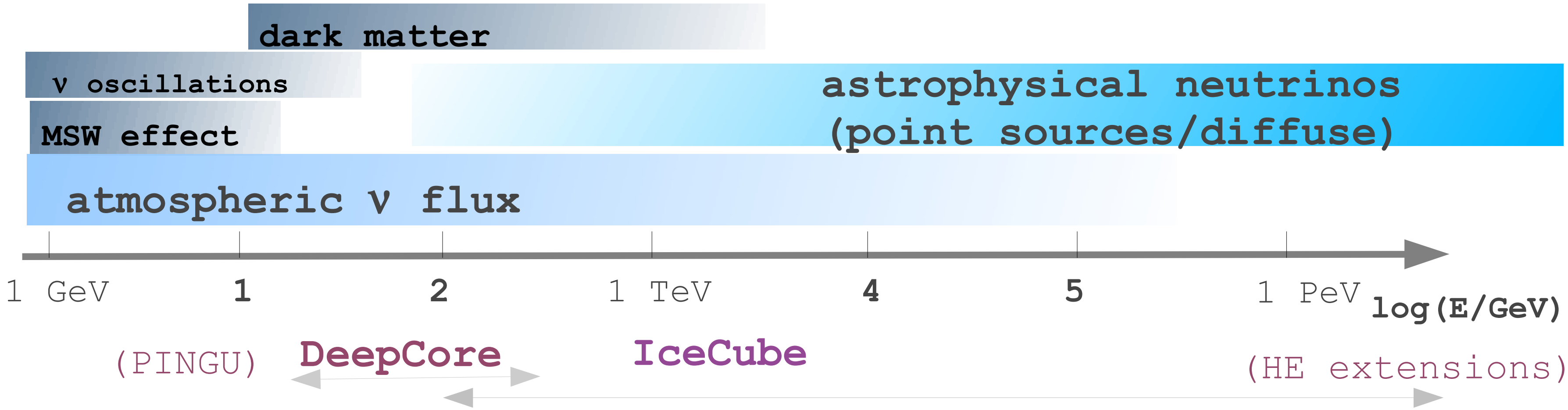
Season	Campaign	Sensors cum.	Strings	Depth (m)	Neutrinos per day	Resol. @100TeV
1991-1992	Exploratory	few		Shallow	-	
1992-1993						
1993-1994	AMANDA-A	80	4	800-1000	-	
1994-1995						
1995-1996	AMANDA-B4	86	4	1500-1950	$\sim$ 0.01	
1996-1997	AMANDA-B10	206	6/10	1500-1950	$\sim$ 1	4 $^\circ$
1997-1998						
1998-1999	AMANDA-II	306	3/13	1500-1950		
1999-2000	AMANDA-II	677	6/19	1500-1950	$\sim$ 5	2 $^\circ$
2001-2002						
2002-2003						
2003-2004	IceCube prep.					
2004-2005	IceCube 1	60	1/1	1450-2450		
2005-2006	IceCube 9	540	8/9	1450-2450		
2006-2007	IceCube 22	1320	13/22	1450-2450	18	1.5 $^\circ$
2007-2008	IceCube 40	2400	18/40	1450-2450	40	0.8 $^\circ$
2008-2009	IceCube 59	3540	19/59	1450-2450	120	0.6 $^\circ$
2009-2010	IceCube 79	4740	20/79	1450-2450	180	0.4 $^\circ$
2010-2011	IceCube 86	5160	7/86	1450-2450	>200	0.4 $^\circ$







a multipurpose detector



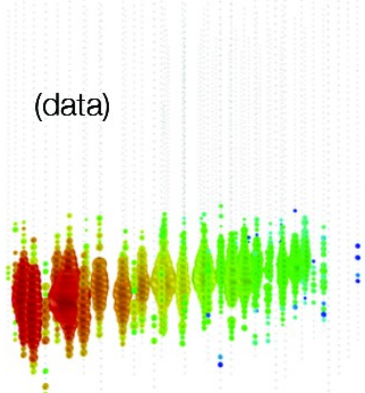
neutrino event signatures in IceCube:

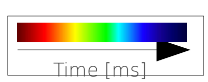
tracks:

ν_μ CC

angular resolution ~ 1°

can measure dE/dX only





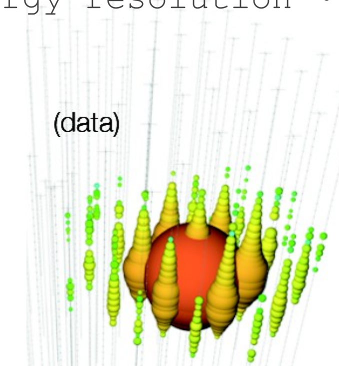
cascades:

ν_e, ν_τ CC

all flavours NC

angular resolution ≥ 10°

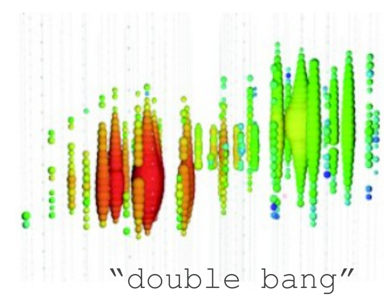
energy resolution ~ 15%



Tau neutrino, CC

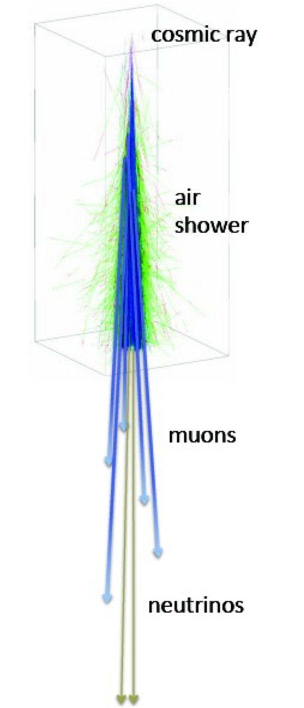
$$\nu_\tau + N \rightarrow \tau + X$$

(simulation)



τ production τ decay

- **atmospheric neutrinos.** Our "beam". Irreducible. Also our background



- **cosmic flux.** Even if individual sources not strong enough, contribution from all sources within Hubble radius can be detectable

→ diffuse cosmic flux

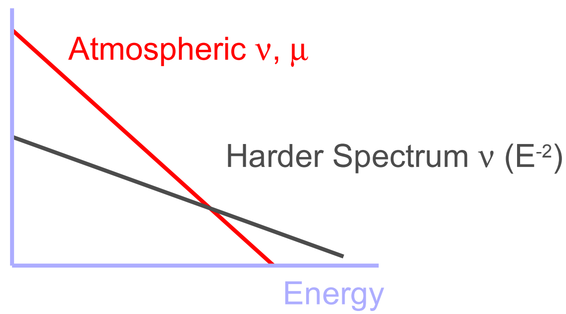
Assume hard spectrum 2.0 - 2.4 (production in shock acceleration)

Advantage over point-source search: can detect weaker fluxes

but: higher background

Signature:

excess of high energy neutrinos over irreducible background of atmospheric neutrinos

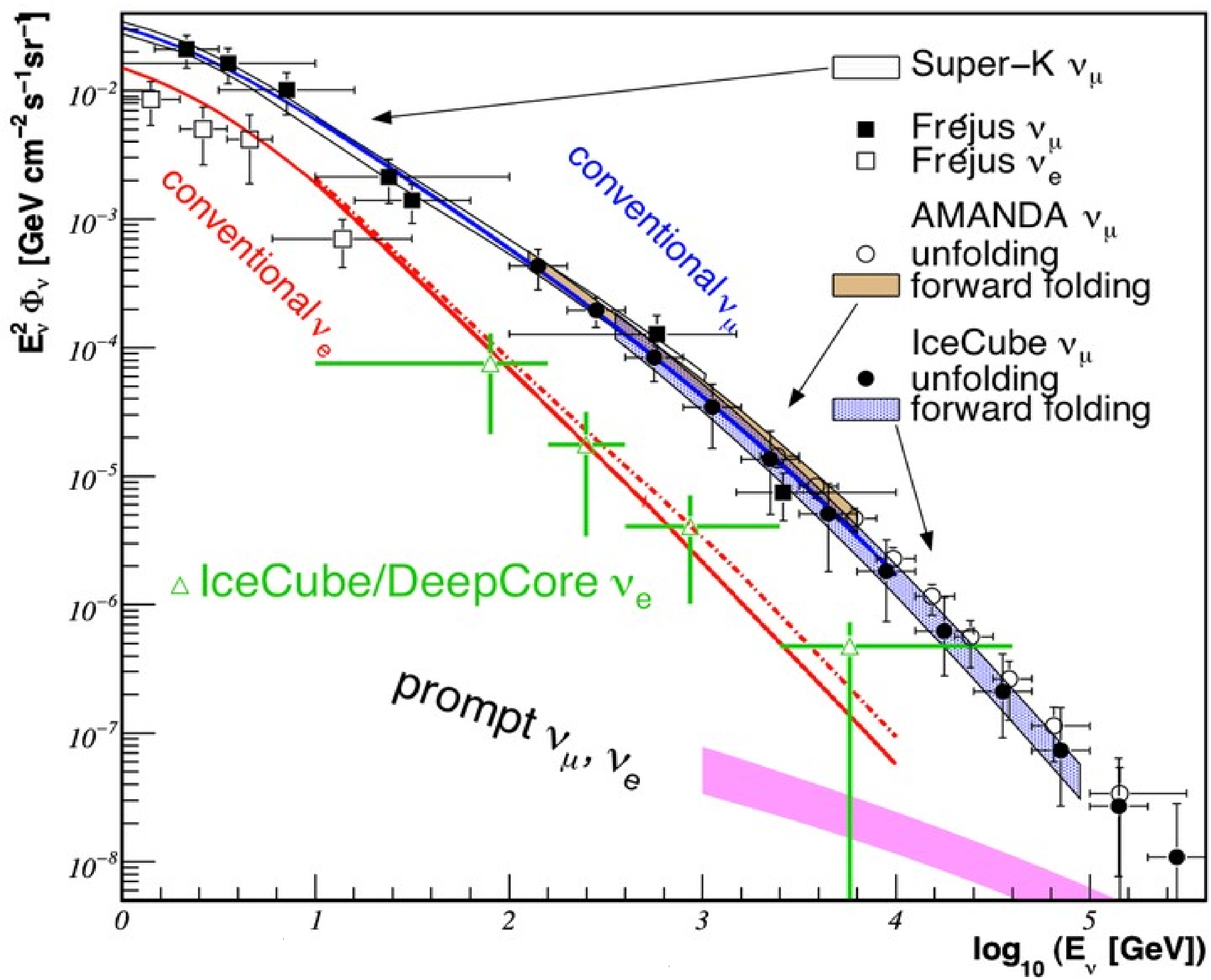


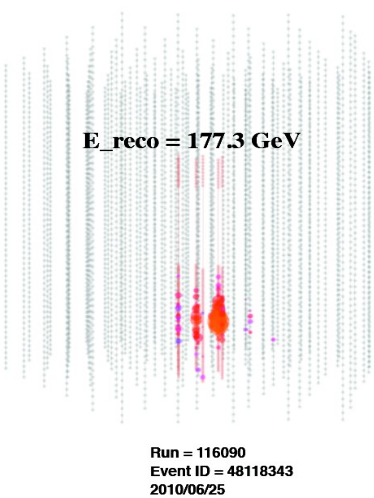
the measured diffuse neutrino flux up to 2012

use DeepCore with surrounding IceCube strings as a veto

define fiducial volume for starting events

measure νe-induced cascades





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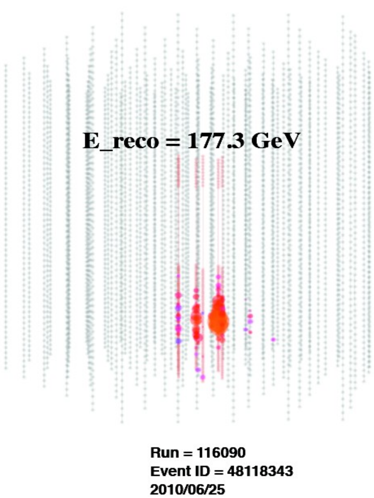
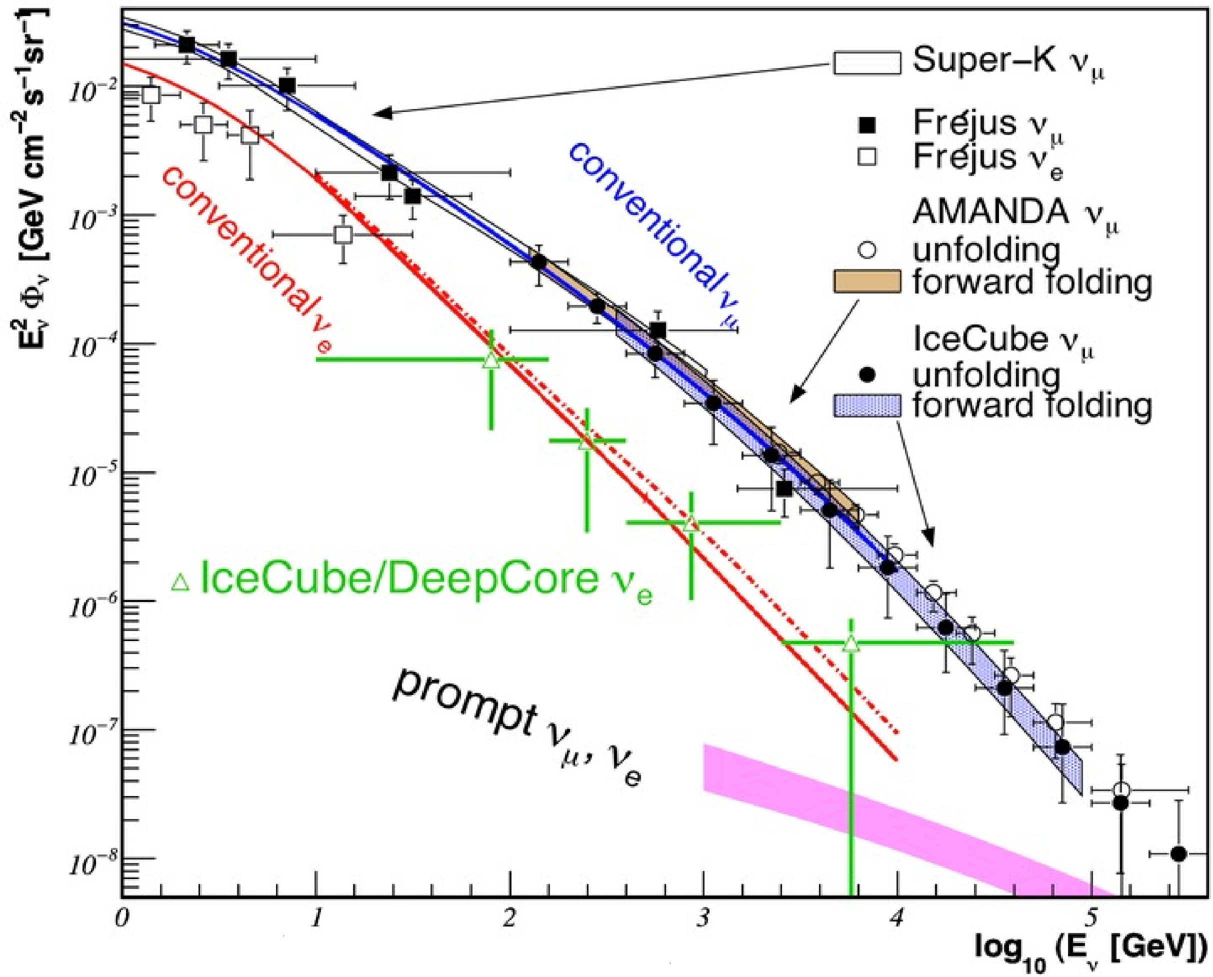
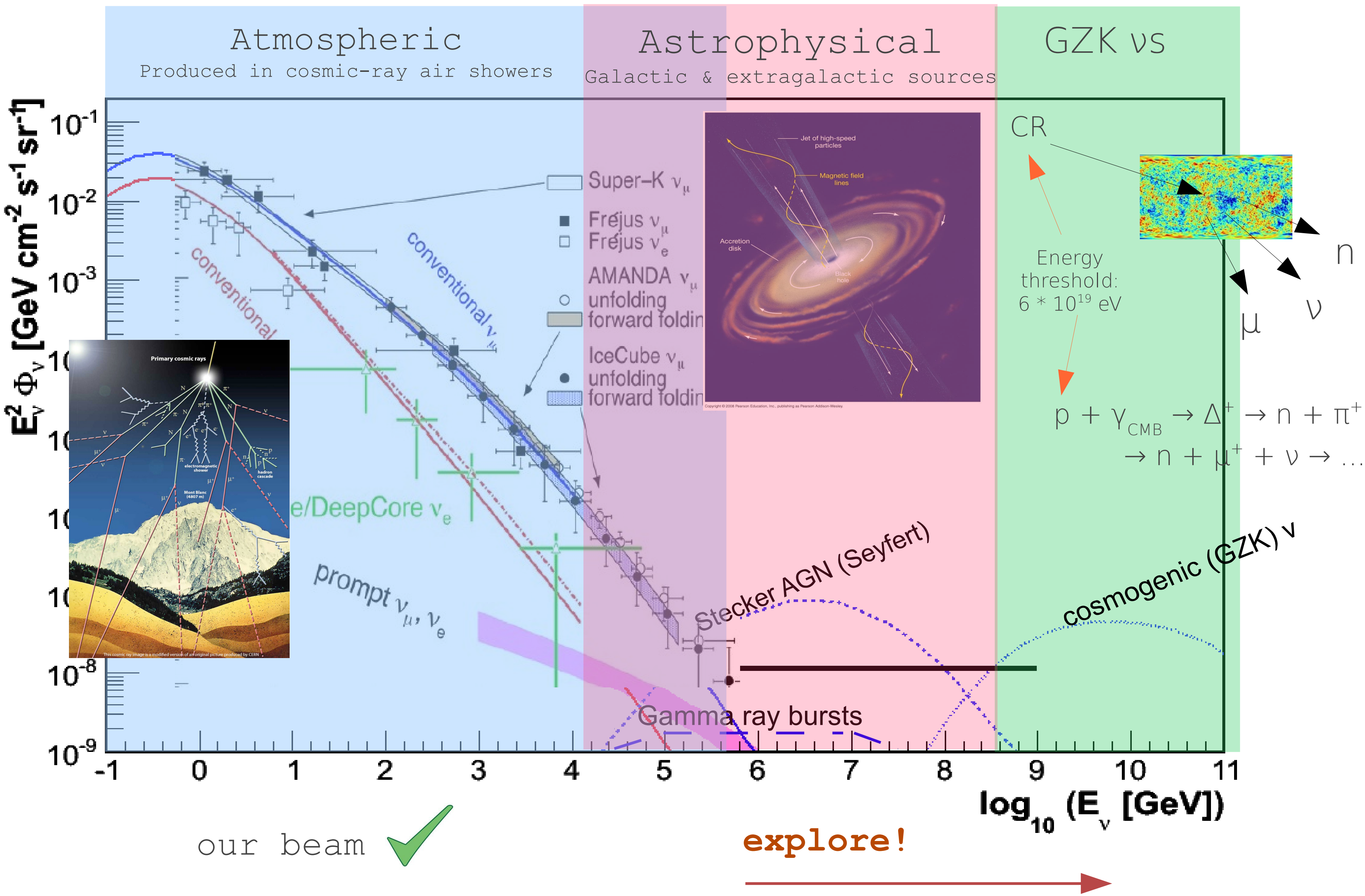




can we go higher in energy?

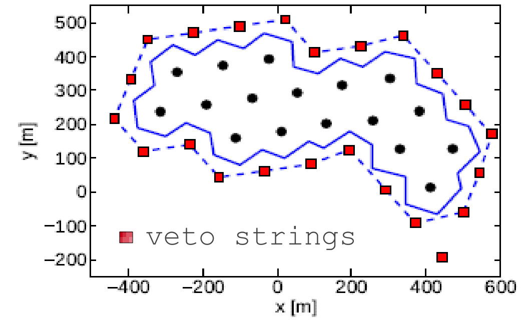
the diffuse neutrino flux

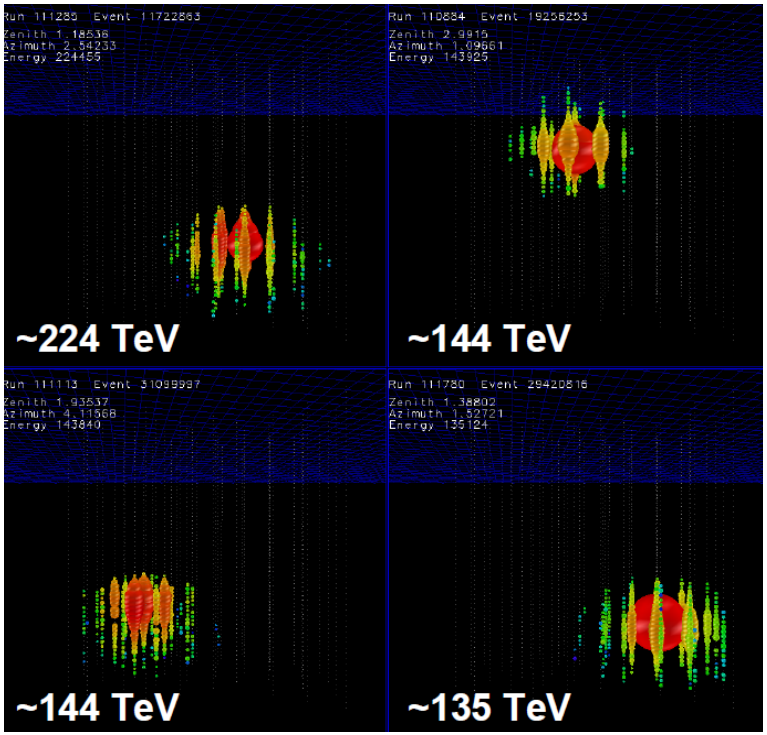


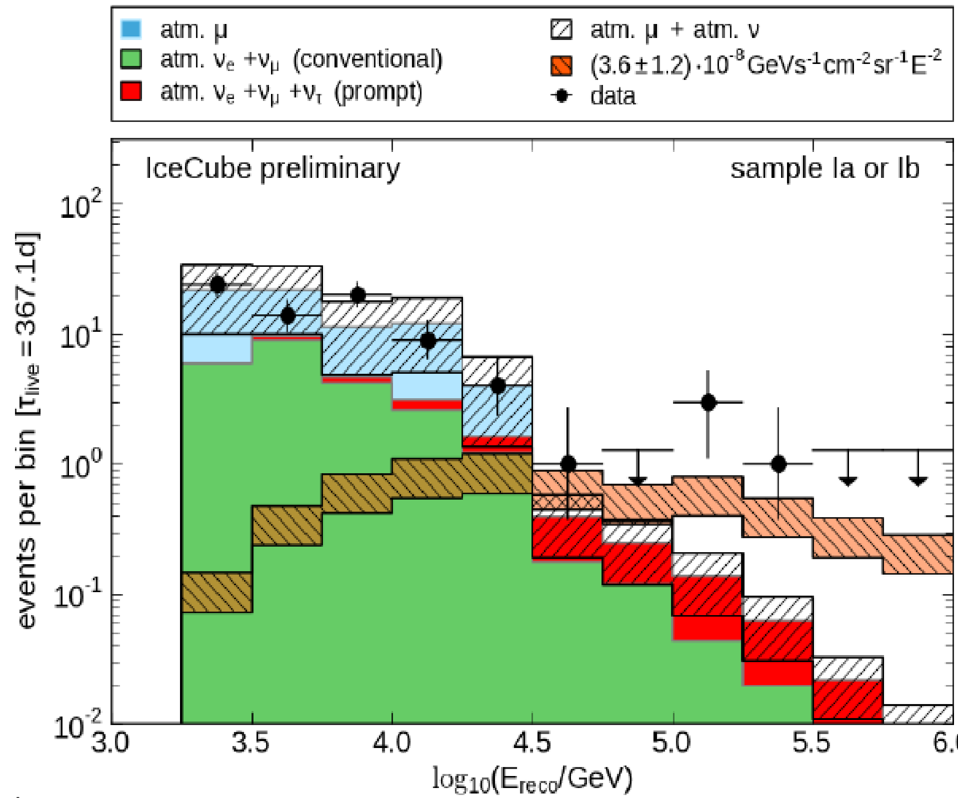
exploring higher energies

any signal over the atmospheric neutrino background?

cascade analysis using the partially deployed 40-string detector





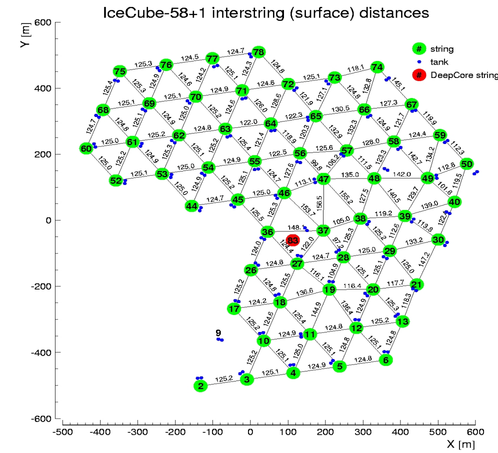


4 events above 100 TeV

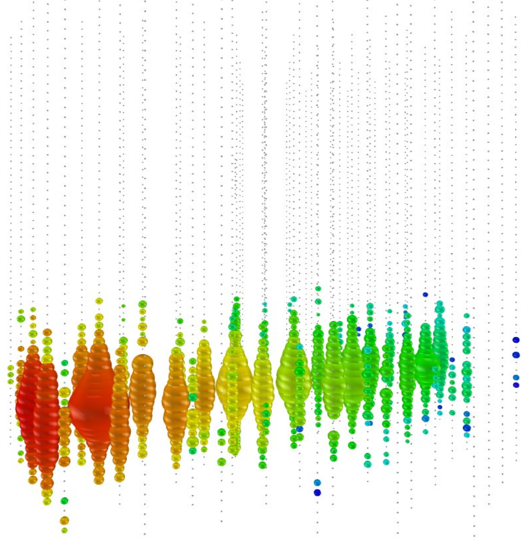
0.35 background events expected

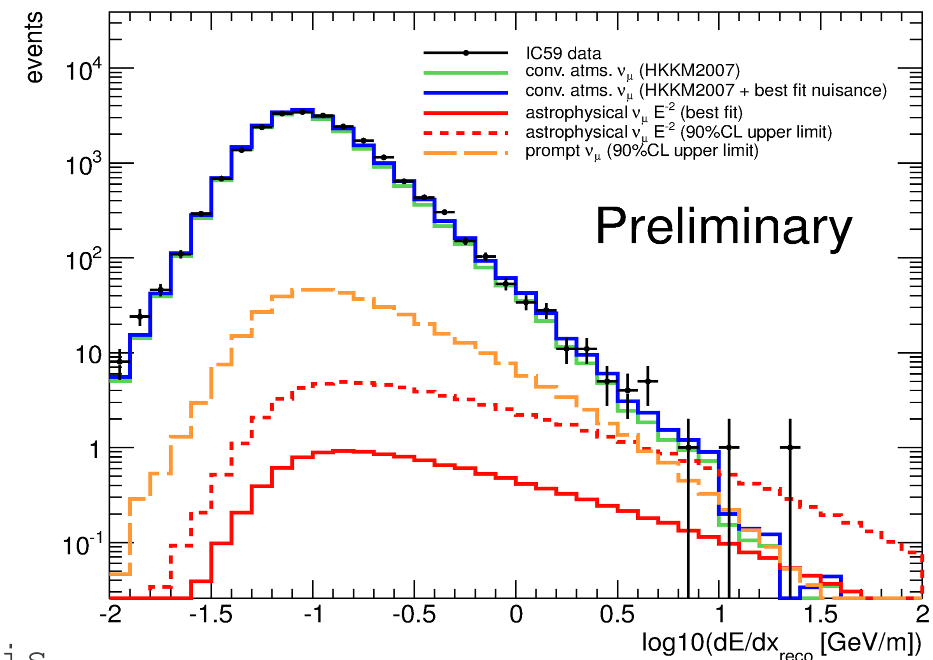
2.7σ excess over the backg-only hypothesis

muon analysis using the partially deployed
<u>59-string detector</u>

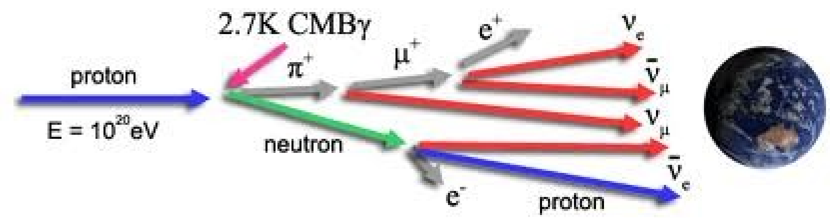


O(100) TeV muon





2 events observed
$O(10^{-1})$ background events expected
1.8σ excess over the backg-only hypothesis



Analysis aim:

Search for GZK neutrinos (related to the GZK cutoff)

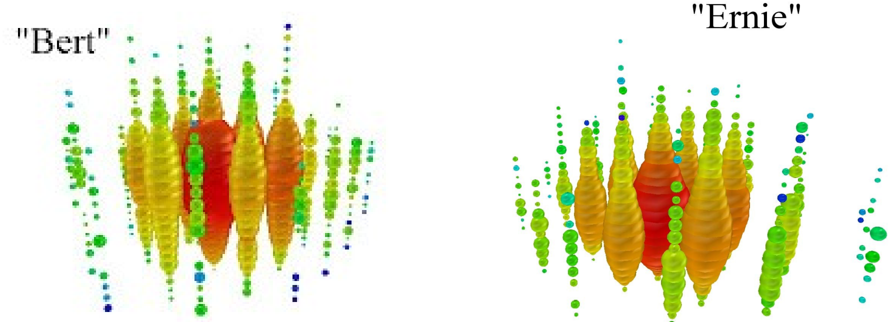
Analysis strategy:

Combined datasets of two years of data taking, 79-string data and first year of 86-string data

Use outer layer of strings as veto

Select starting events with a high number of photoelectrons (PE) in the detector (>60000 PE, depending on zenith angle)

Makes analysis sensitive to E_ν> PeV

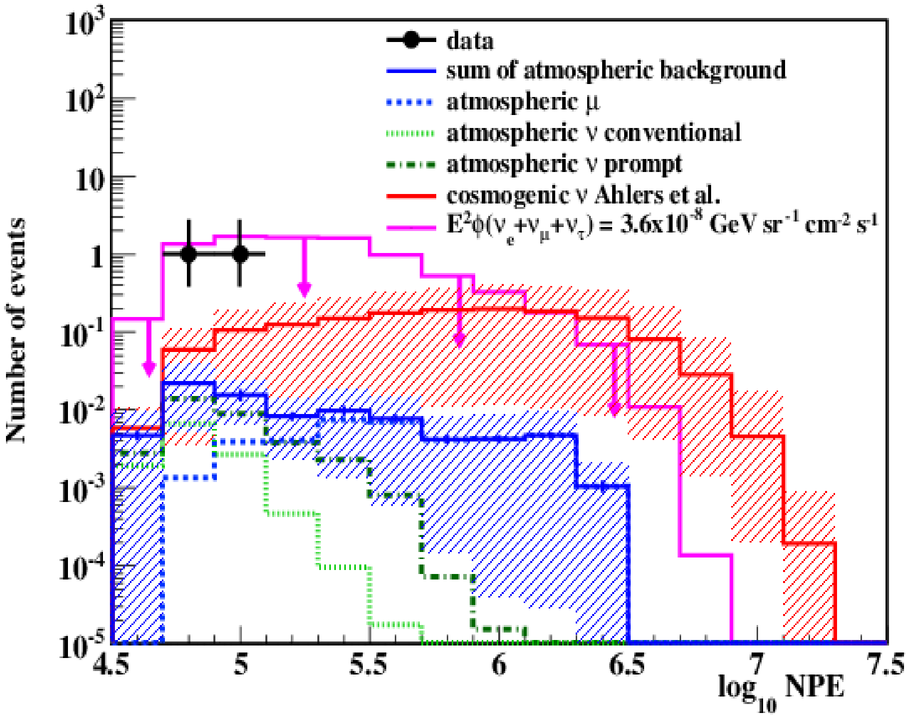


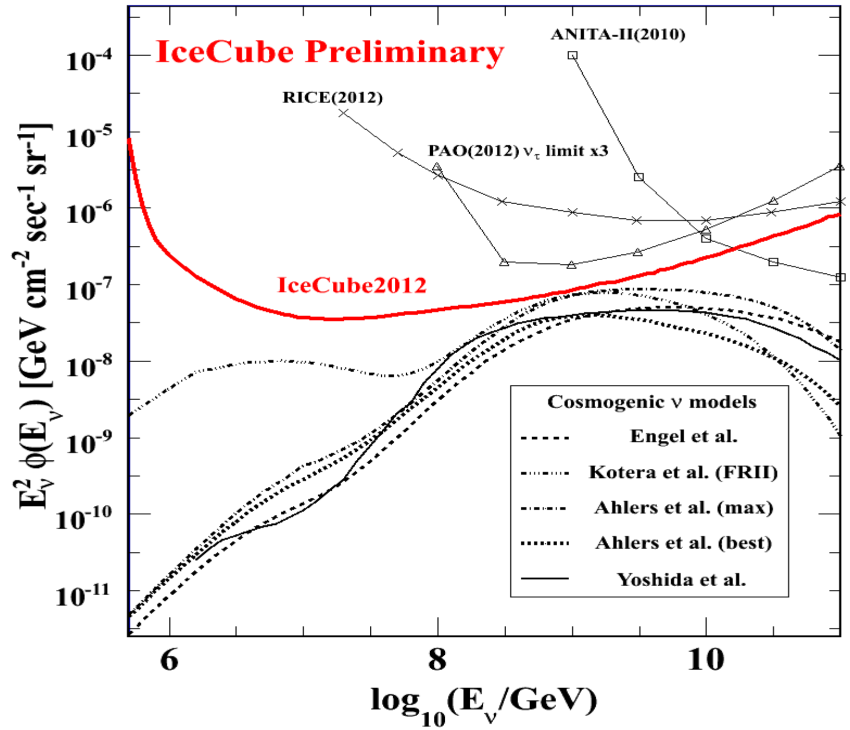
3)

What we found:

- 2 events in 616 days of livetime between May 2010- May 2012 (IC-79 and IC86)
- 0.08 events expected from atm μ + atm ν (including charm)
- significance (background-only hypothesis) including systematics: **2.8σ**

estimated energy (15% uncert.):
1.04 PeV & 1.14 PeV





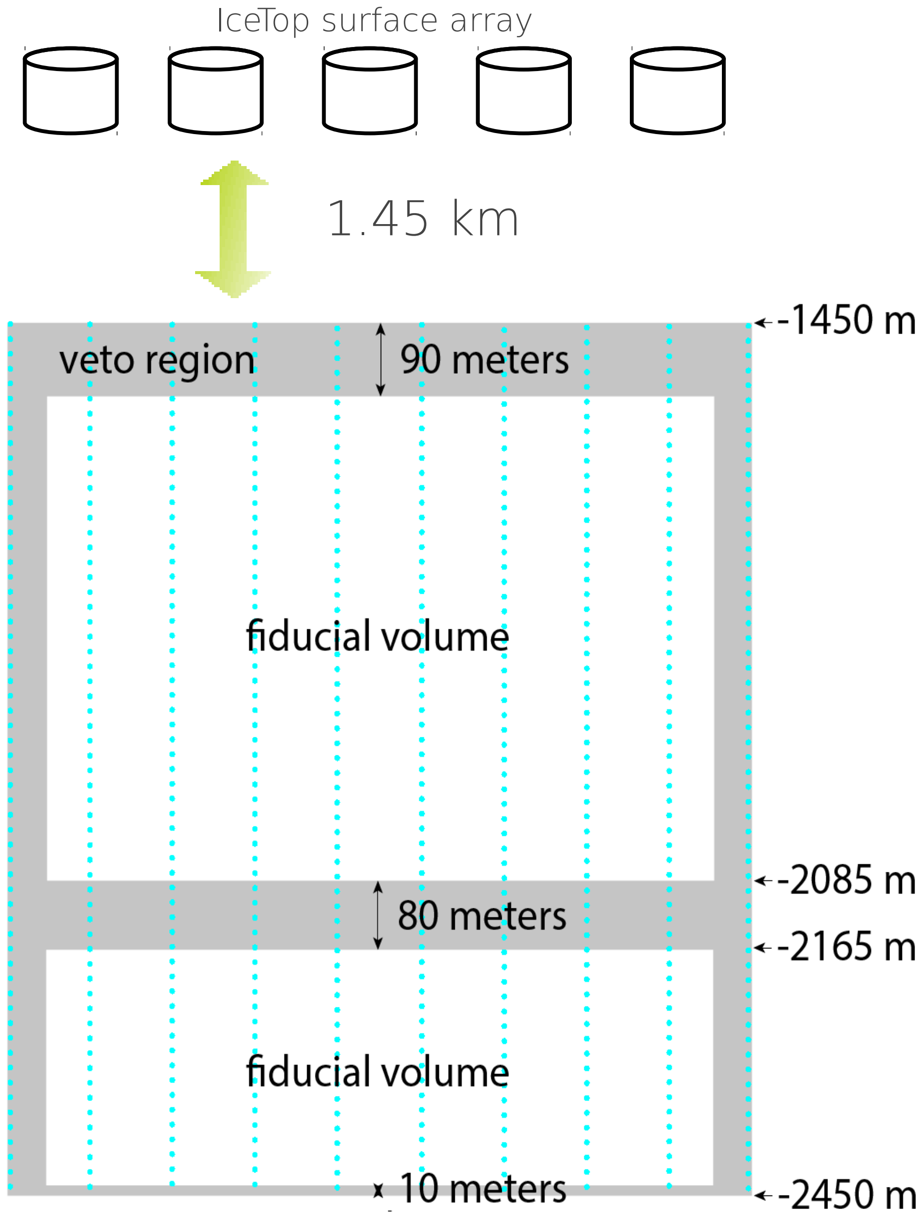
observed quantity.
proxy for energy

But: there should be more events if we relax the strong energy requirement...

search O(100TeV) neutrinos: veto strategy

Take advantage of completed, i.e. big, detector to define a veto:

- top 5 layers of modules (=90 m)
- bottom layer of modules (=10 m)
- outer layer of strings



- for atms. μ
  → reject tracks entering the detector from outside
- for atms. ν
  → accompanied by air showers with muons (detectable when coming from the Southern hemisphere)

Try to lower the threshold to ~50 TeV

Requirements:
All-sky

Challenge:
Atmospheric ν and μ background

search O(100TeV) neutrinos: veto strategy

Take advantage of completed, i.e. big, detector to define a veto:
- top 5 layers of modules (=90 m)
- bottom layer of modules (=10 m)
- outer layer of strings

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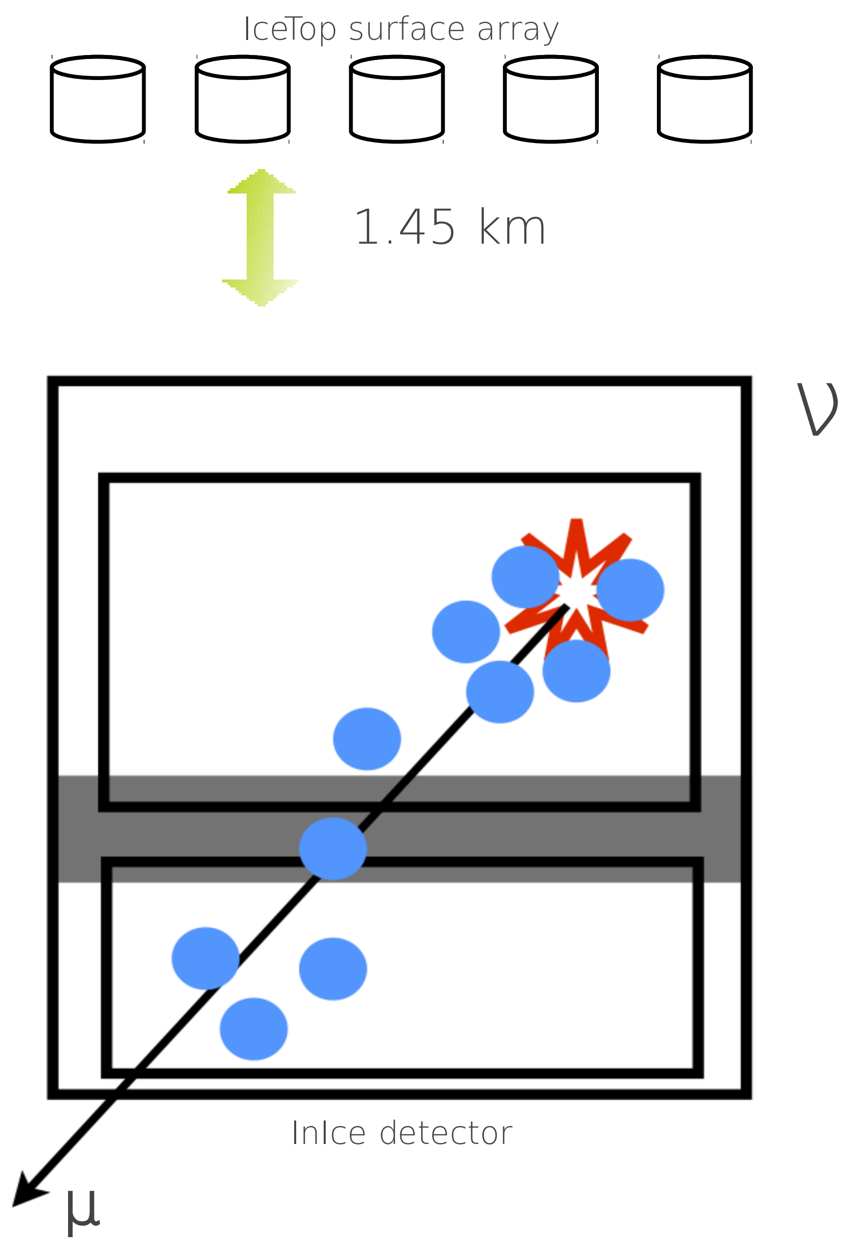
→ reject tracks entering the detector from outside

- for atms. ν
→ accompanied by air showers with muons (detectable when coming from the Southern hemisphere)



Try to lower the threshold to ~50 TeV

Requirements:
All-sky

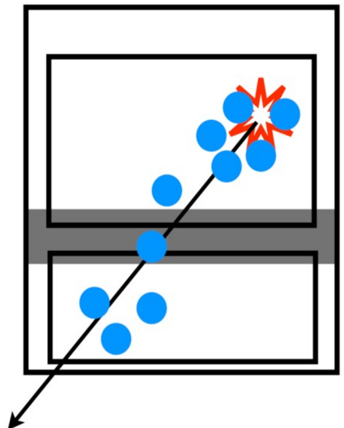
Challenge:
Atmospheric ν and μ background

Strategy:
Look for starting events in the detector

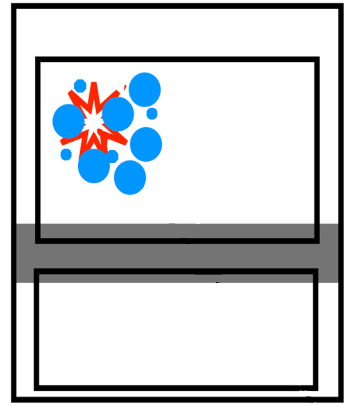
→ these must be neutrinos!!!

search O(100TeV) neutrinos: veto strategy

we want to select:

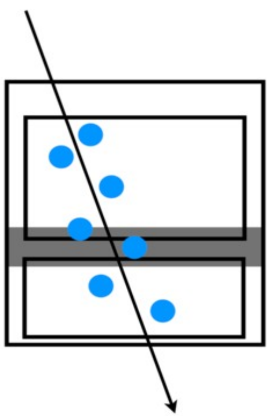


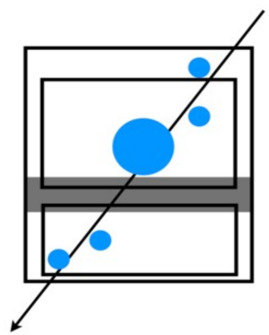
ν_μ CC

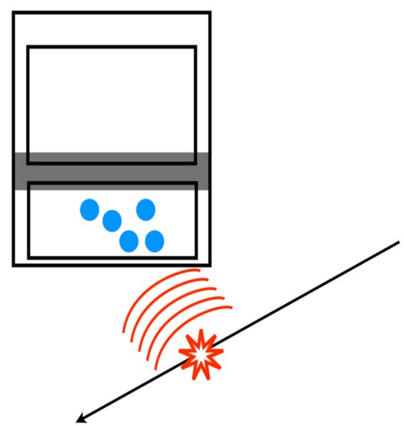


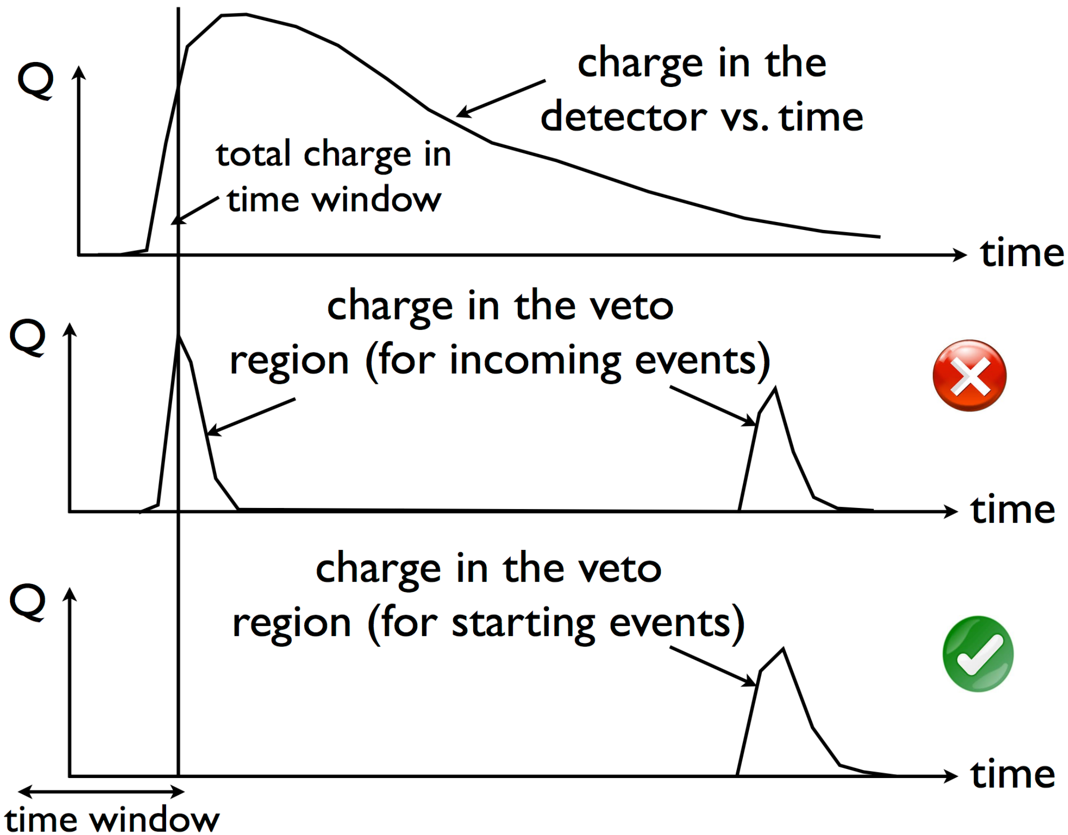
ν_e ν_τ CC
All-flavor NC

we want to reject:









Determining the Event Start Time:

Event start time determined from the rate of light deposition in the detector.

Not trigger on noise -> set a 250 PE threshold

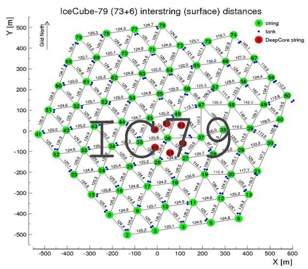
Evaluating containment:

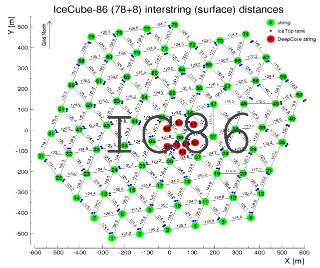
Require ≤ 3 PE in the veto region.

Otherwise discard as entering from outside

search O(100TeV) neutrinos: energy cut

Data samples May 2010 – June 2012





Expected background:

Atmospheric μ background

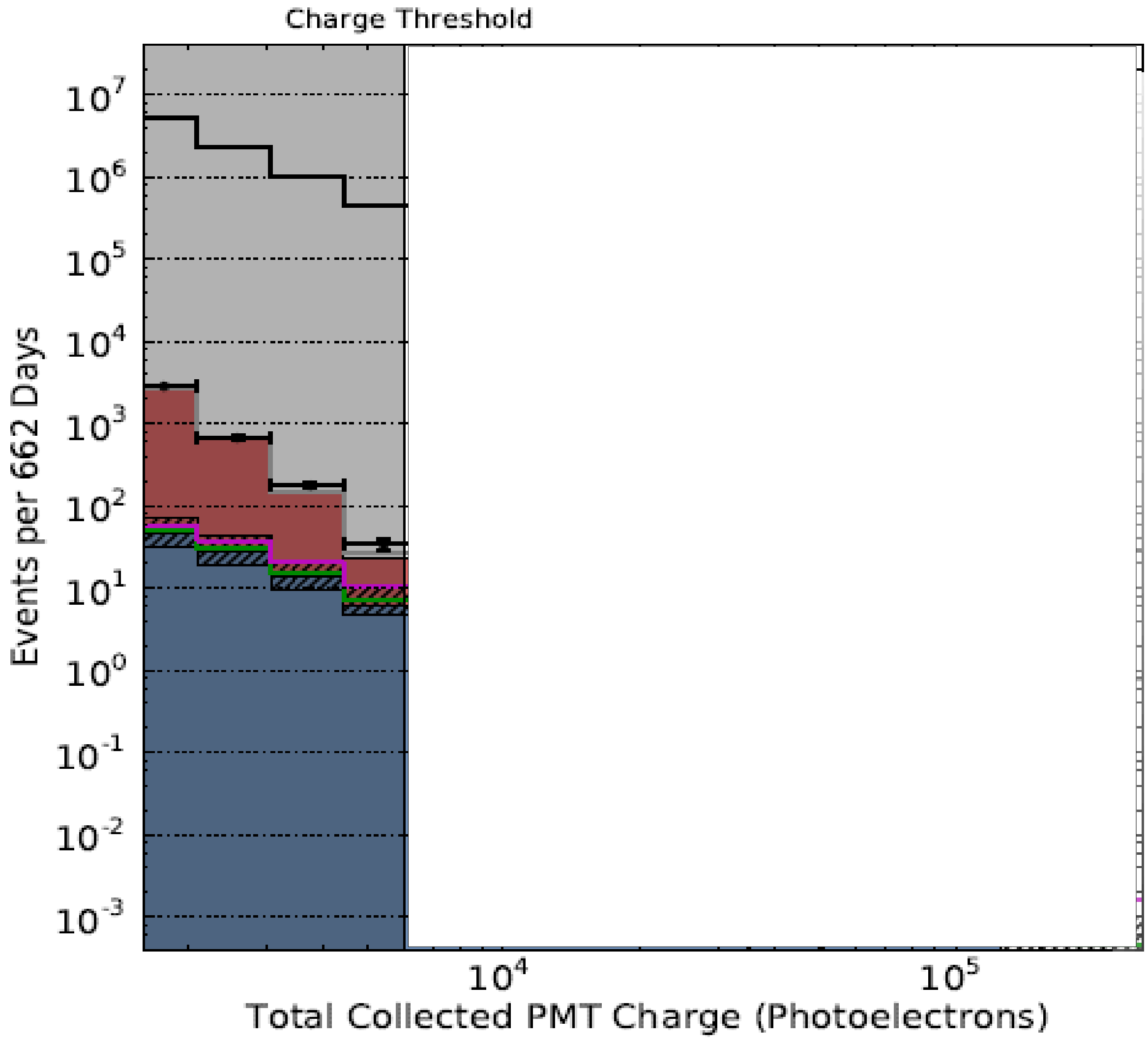
Determined from experimental data:
Define a second veto layer and tag events, which pass the first layer

6 ± 3.4

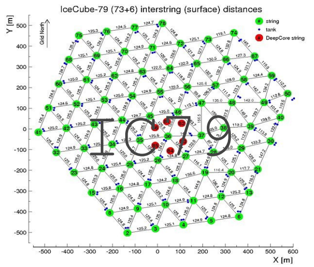
Atmospheric ν background

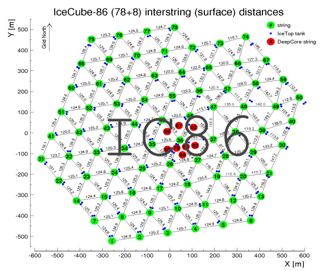
Based on MC simulation and previous IceCube measurements

$4.6^{+3.7}_{-1.2}$



Data samples May 2010 – June 2012





Expected background:

Atmospheric μ background

Determined from experimental data:
Define a second veto layer and tag events, which pass the first layer

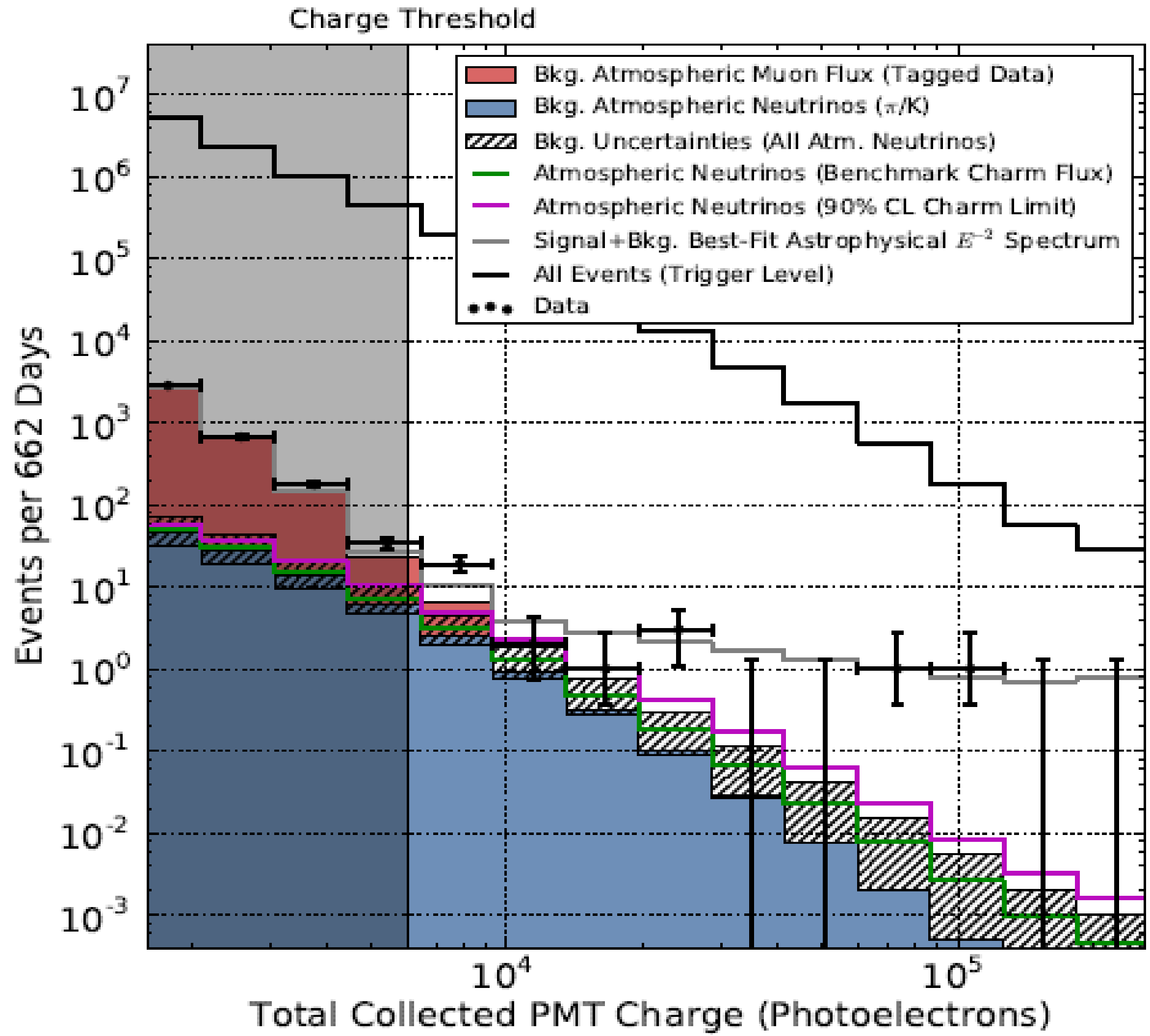
6 ± 3.4

Atmospheric ν background

Based on MC simulation and previous IceCube measurements

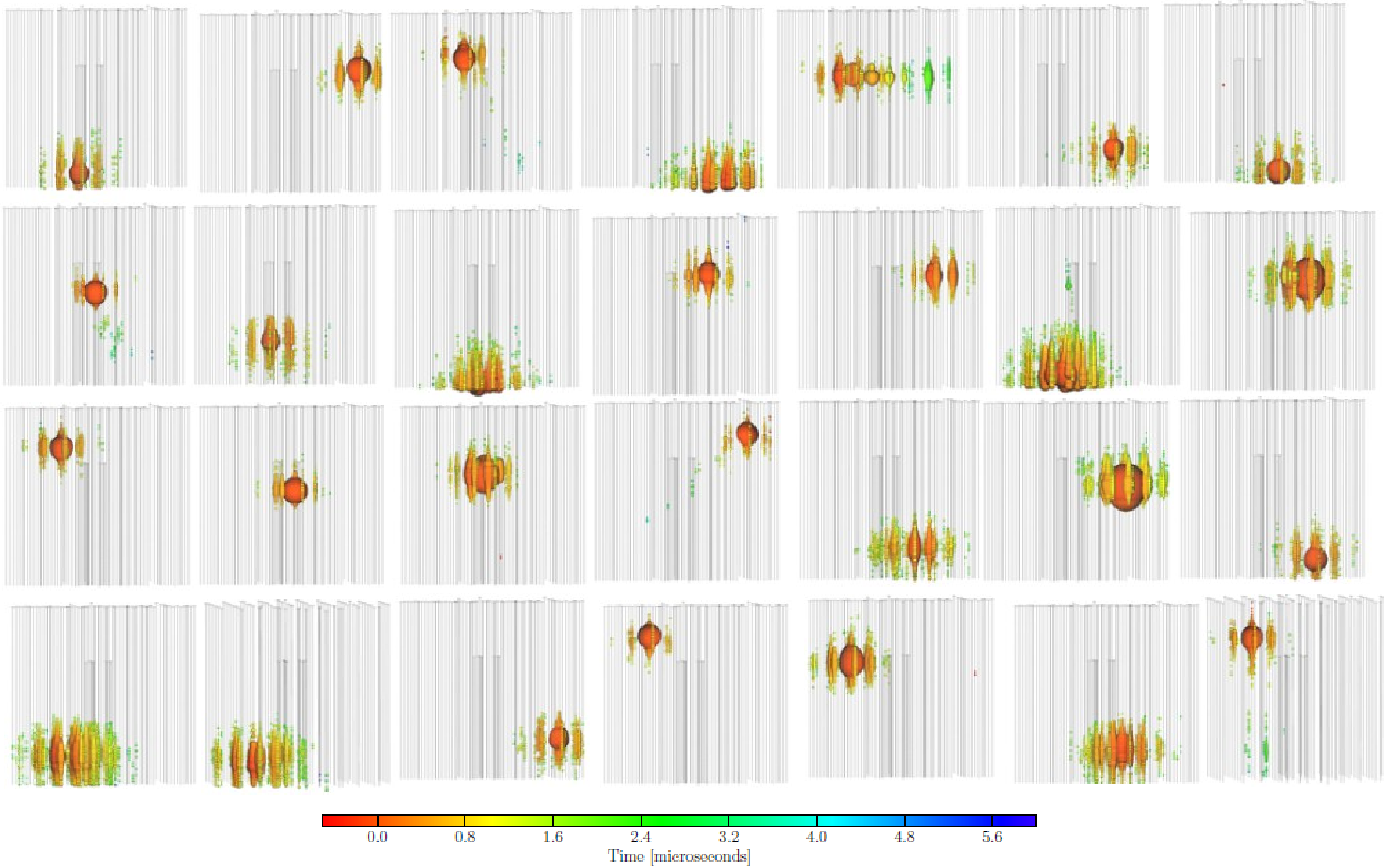
$4.6^{+3.7}_{-1.2}$

observed events: 28

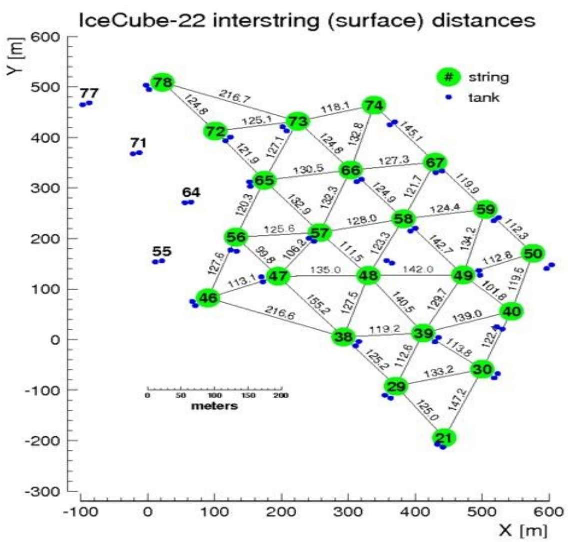


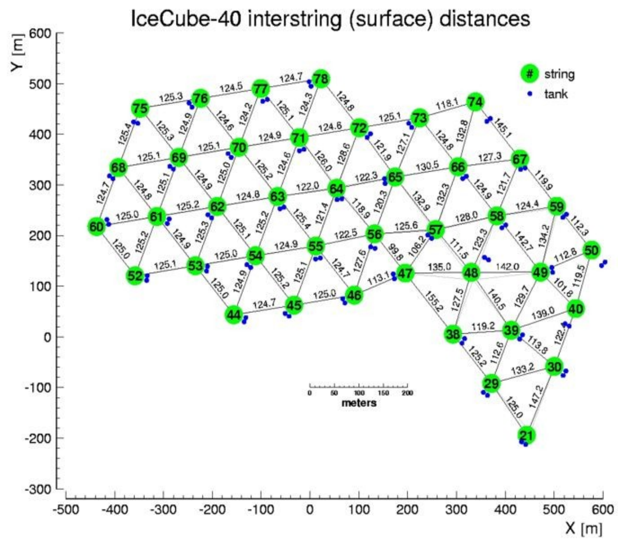
4.1σ deviation from expected atmospheric ν spectrum

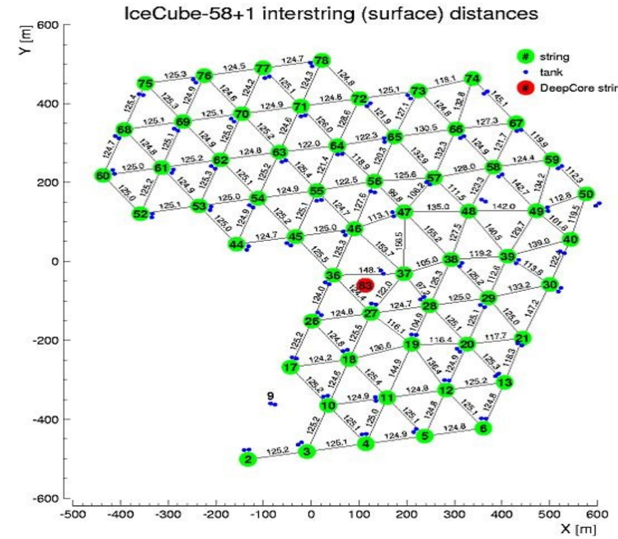
Re-discovery of Bert & Ernie (Epi y Blas)... + 26 more events!

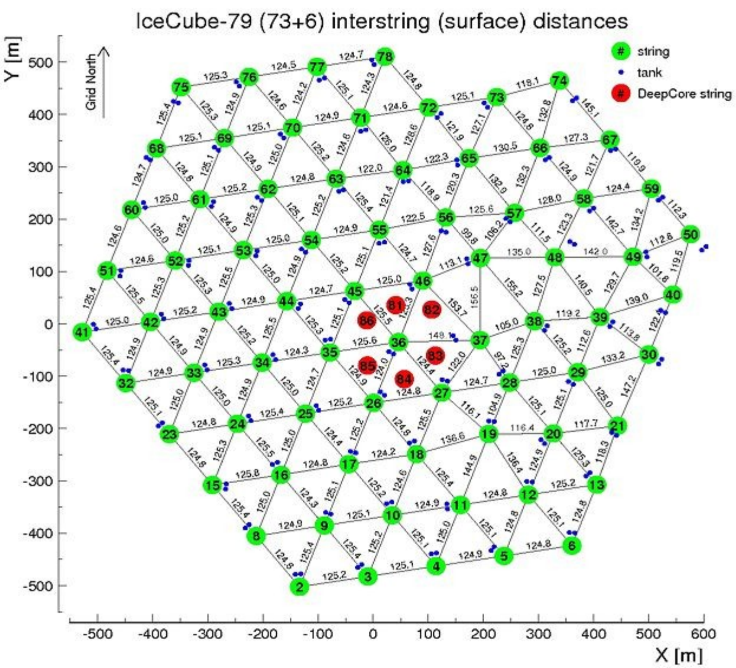


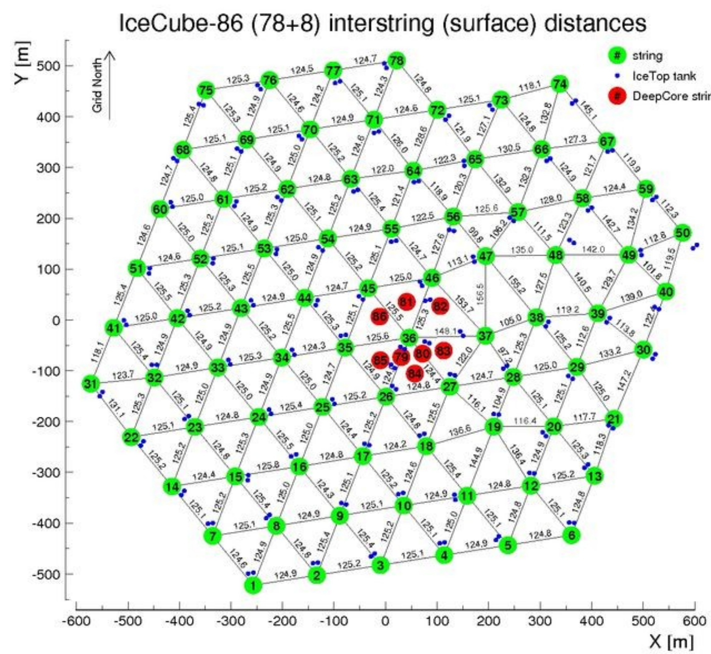
why now?


IceCube-22 interstring (surface) distances
Y [m]
X [m]
string
tank
meters

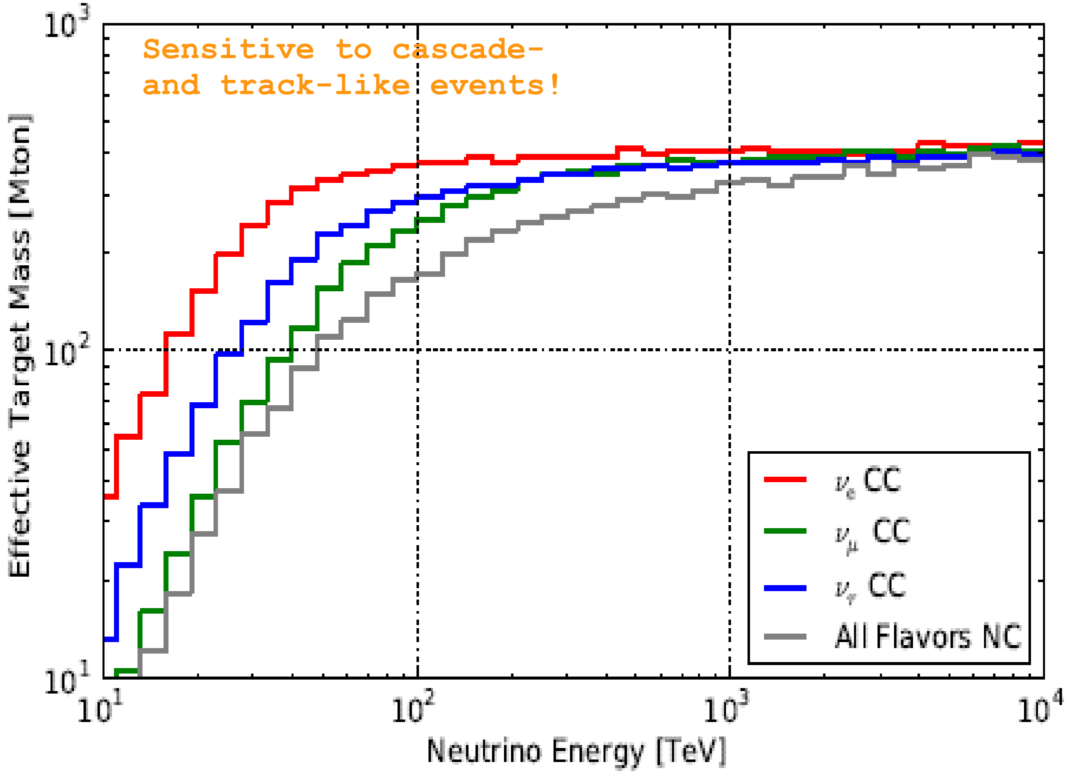

IceCube-40 interstring (surface) distances
Y [m]
X [m]
string
tank
meters


IceCube-58+1 interstring (surface) distances
Y [m]
X [m]
string
tank
DeepCore string


IceCube-79 (73+6) interstring (surface) distances
Y [m]
X [m]
Grid North
string
tank
DeepCore string


IceCube-86 (78+8) interstring (surface) distances
Y [m]
X [m]
Grid North
string
IceTop tank
DeepCore string

Effective target mass



- Largest sensitivity to ν_e CC:

  All energy deposited inside the detector.

- Smaller sensitivity for ν_τ and ν_μ CC:

  muon and tau decay products carry out part of the initial neutrino energy

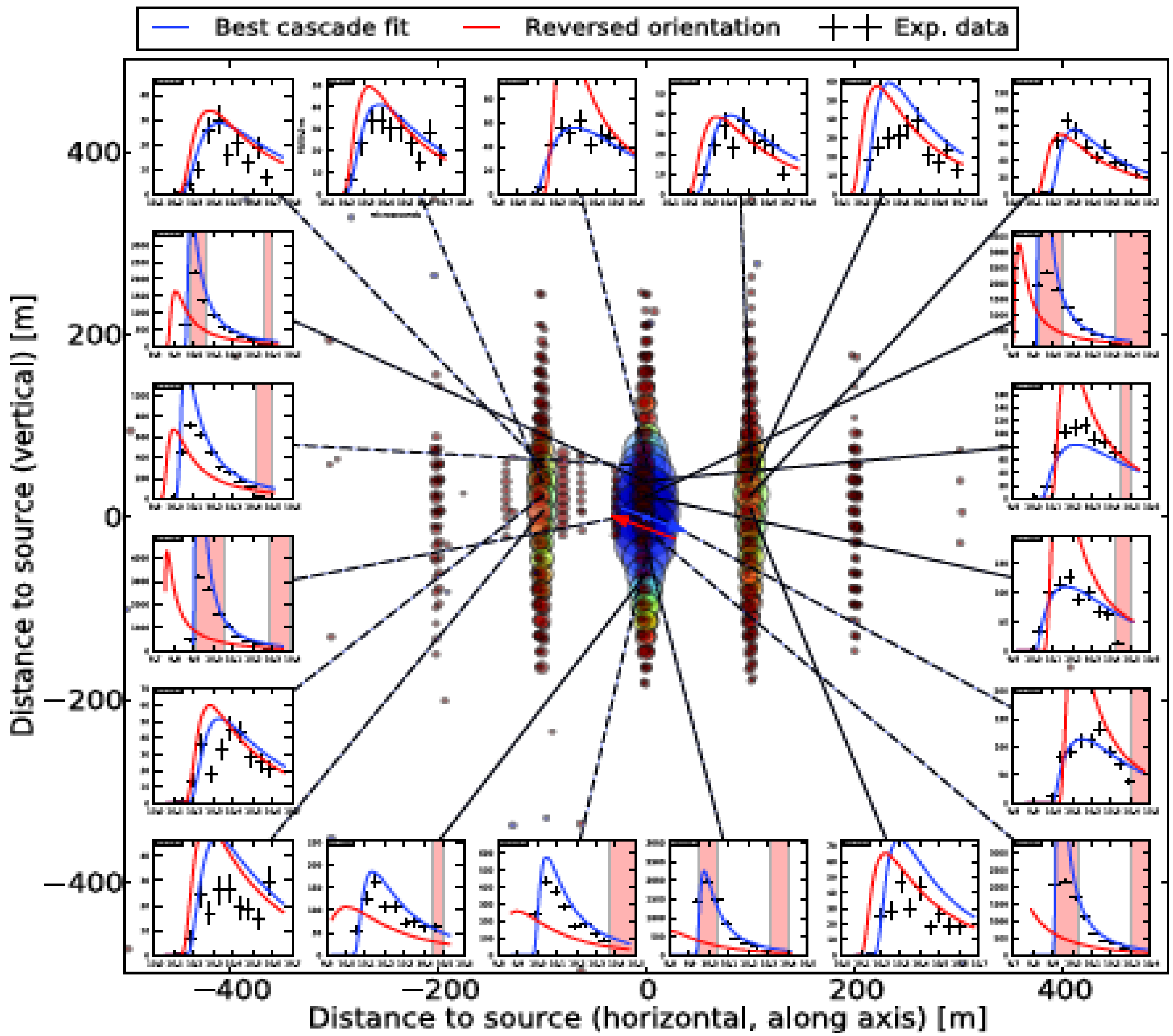
- Smallest sensitivity to NC interactions:

  Significant fraction of the total energy disappears with the neutrino

Check individual DOM waveforms for event direction

(bet fit blue, forced reverse direction red)

Width of waveforms tracks event time development



28 events:

7 clearly identifiable muon tracks

21 shower-like

4 of the track-like start in the detector

→ consistent with the 6.0 ± 3.4 atmospheric muon background expected

Starting point of the remaining 3 track-like events uniformly distributed in the detector

→ consistent with being ν_μ CC neutrino events

Most of the observed excess is in showers,

1 track / 4 showers, consistent with the expectation of a 1:1:1 neutrino flux of 1 track/ 5 showers

Increasing charm production to the level needed to explain the observations as atmospheric neutrinos, violates existing experimental bounds. It would require x4.5 larger flux than current 90% CL upper bounds

Besides, measured energy spectrum too hard to be charm

Calculate veto efficiency using the outermost two layers in anti-coincidence. Estimate 6.0 ± 3.4 sneaking atmospheric muons

Angular resolution:

For showers ≈ 10°-15°

For tracks ≤ 1°

Energy resolution

Energy measured is always energy deposited in the detector

Resolution: 10%-15% for showers

Fit to conventional atmospheric neutrino flux + charm + diffuse power law flux with free normalization is well described with an E^{-2} component, or $E^{-2.2}$ with a cutoff at PeV energies

Point sources:

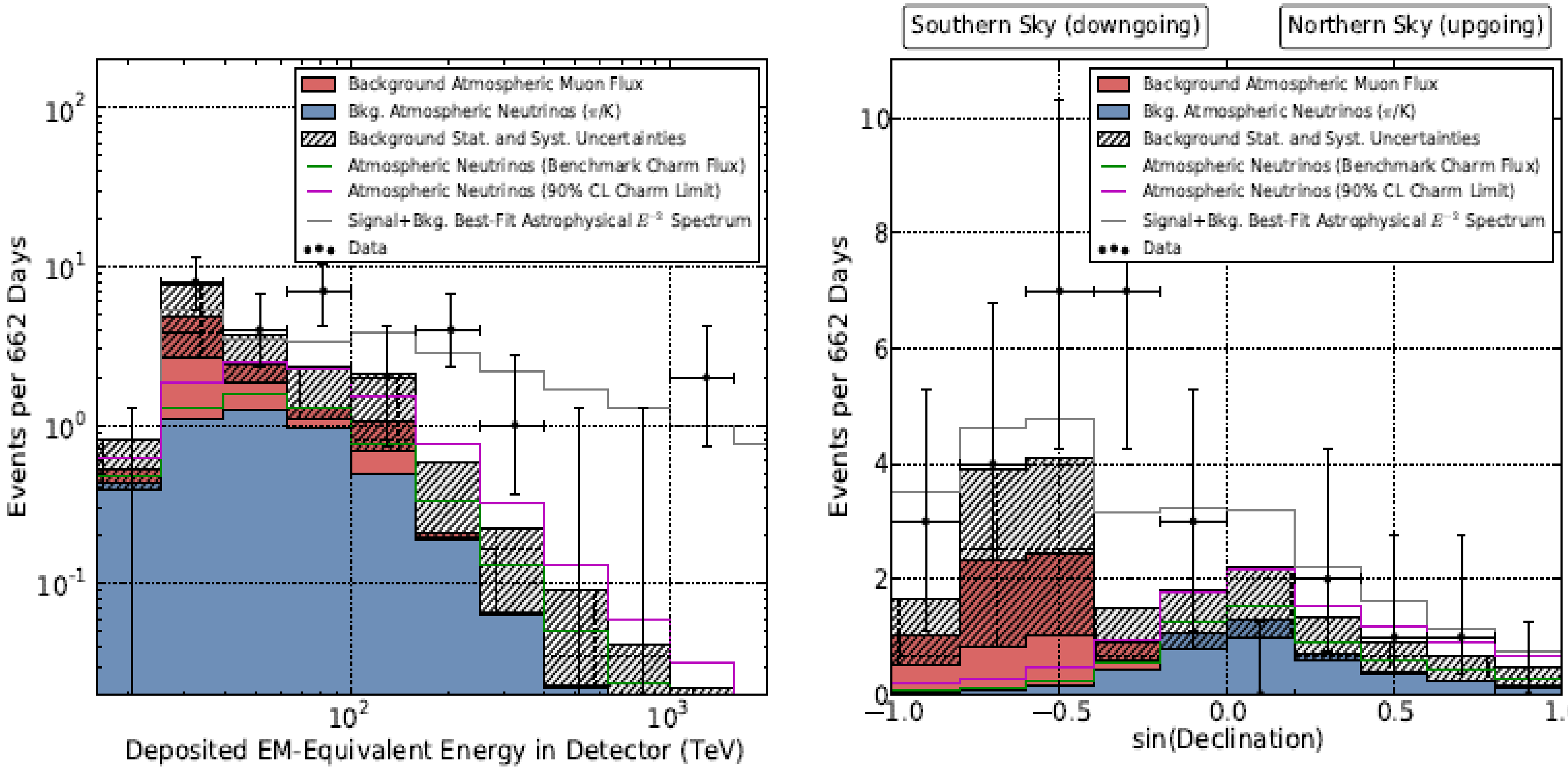
Test that all the events in the sample are uniformly distributed

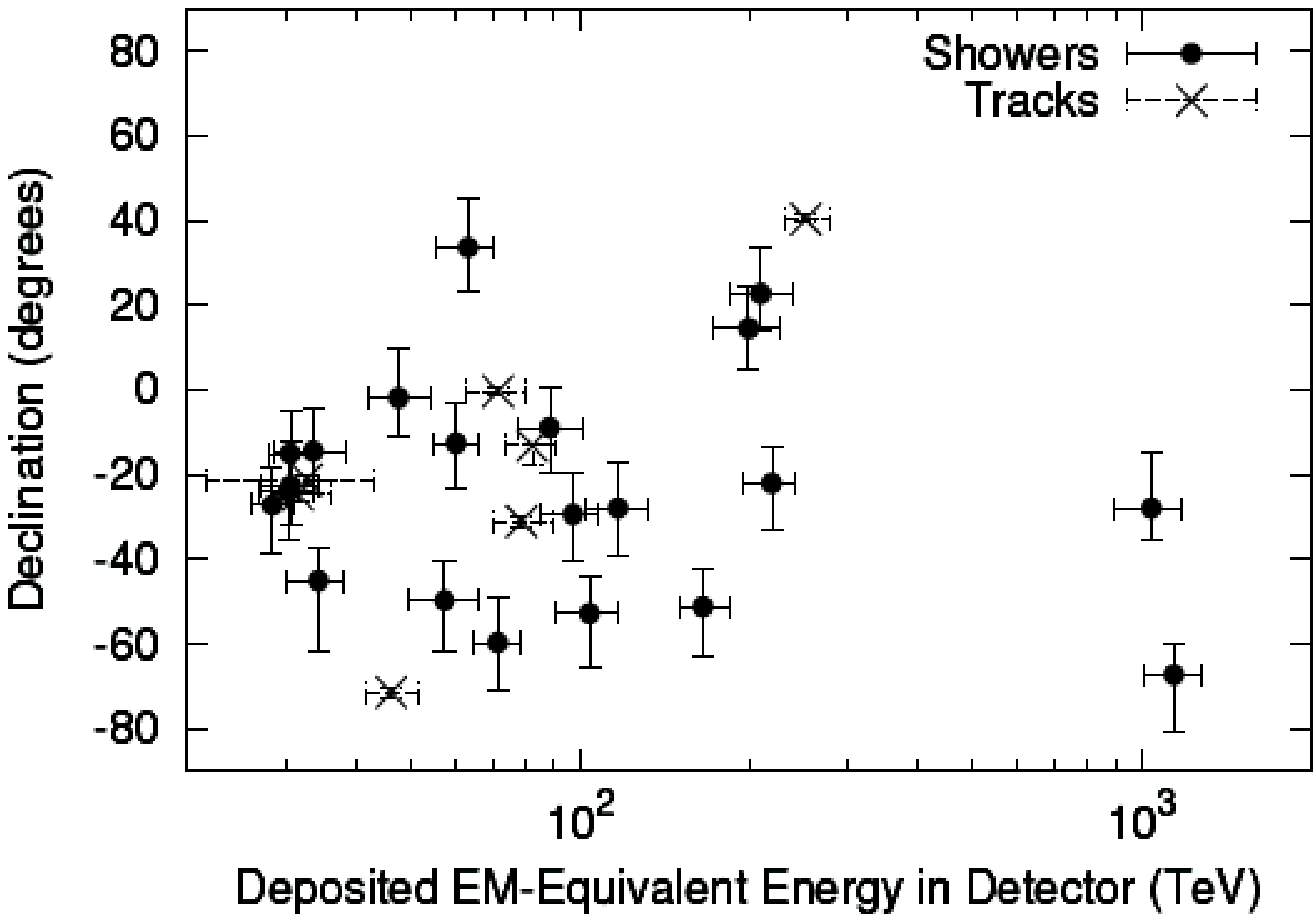
Test that events are clustered in time

Extended sources:

Test degree of correlation of arrival directions with the Galactic Plane

distribution in the sky





Showers
Tracks
80
60
40
20
0
-20
-40
-60
-80
Declination (degrees)
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

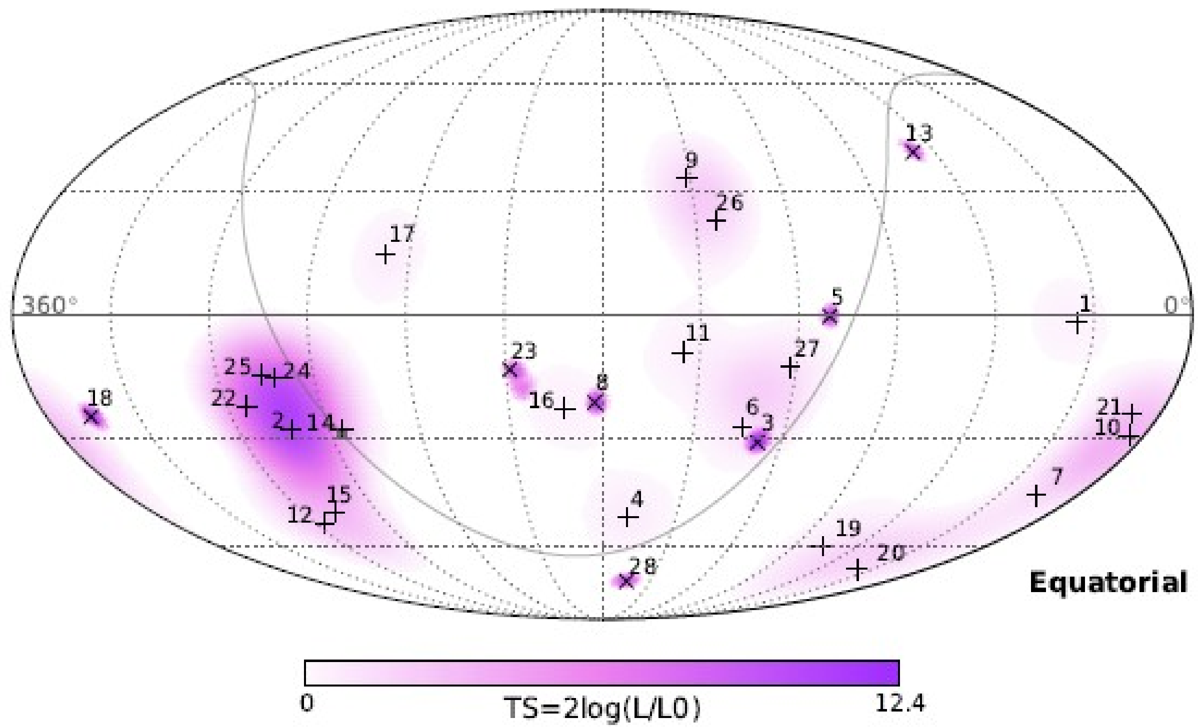
Event clustering analysis:

+ shower
X track

Problem:
tracks have a much better angular resolution than showers
→ dominate the significance

Solution:
analyze twice:
Just showers
& all events

Not significant



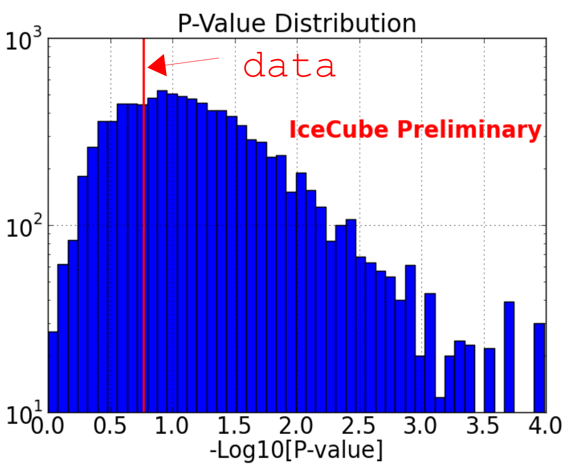
Other searches:
- Galactic plane correlation
- Time clustering

→ No statistically significant identification of any sources

Probability that a random skymap produces the clustering seen at the GC anywhere in the sky is 8%

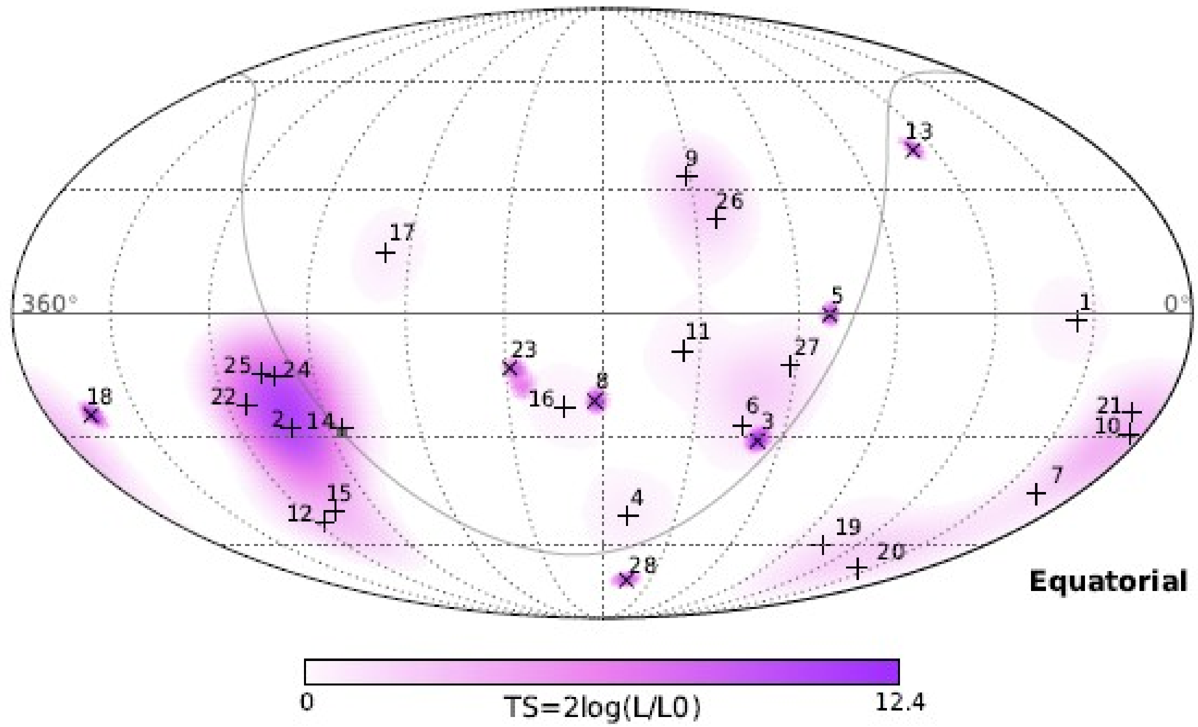
GRB correlation analysis:

Use temporal (±22 hrs window) and spatial (1°/10° for tracks/cascades) information to search for a correlation with 568 GRBs recorded during the analysis livetime



prob. accidental coincidences

+ shower
X track

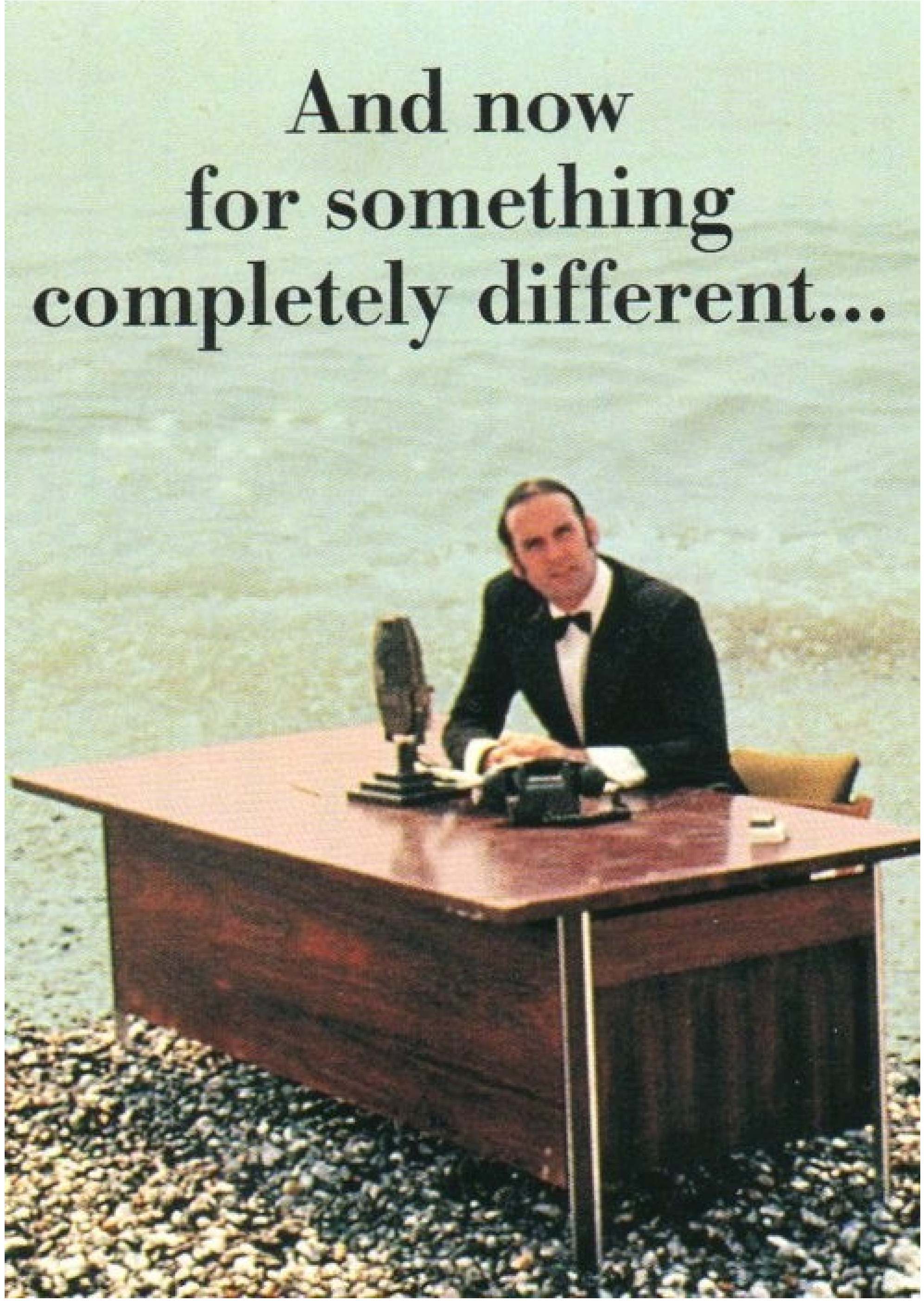


→ No evidence for any correlation with GRBs

interpretation of IceCube UHE results by the community

Title	Author(s)	Journal reference	ArXiv	Category
IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance	Barger, Learned, Pakvasa	PRD 87, 037302 (2013)	1207.4571	Glashow resonance
Neutrino decays over cosmological distances and the implications for neutrino telescopes	Baerwald, Bustamante, Winter	JCAP10(2012)020	1208.4600	Neutrino decay
On the interpretation of IceCube cascade events in terms of the Glashow resonance	Bhattacharya, Gandhi, Rodejohann, Watanabe	---	1209.2422	Glashow resonance
PeV neutrinos from the propagation of ultra-high energy cosmic rays	Roulet, Sigl, van Vliet, Mollerach	JCAP01(2013)028	1209.4033	GZK
Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos	Pakvasa, Joshipura, Mohanty	PRL 110, 171802 (2013)	1209.5630	Neutrino decay
On the origin of IceCube's PeV neutrinos	Cholis, Hooper	JCAP06(2013)030	1211.1974	Extragalactic (GRB)
Diffuse PeV Neutrinos from Gamma-ray Bursts	Liu, Wang	ApJ 766, 73 (2013)	1212.1260	Extragalactic (GRB)
Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons	Kistler, Stanev, Yuksel	---	1301.1703	Extragalactic
PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei	Kalashev, Kusenko, Essey	PRL 111, 041103 (2013)	1303.0300	Extragalactic (AGN)
Diffuse PeV neutrino emission from ultraluminous infrared galaxies	He, Wang, Fan, Liu, Wei	PRD 87, 063011 (2013)	1303.1253	Extragalactic (Infrared galaxies)
Stringent constraint on neutrino Lorentz invariance violation from the two IceCube PeV neutrinos	Borriello, Chakraborty, Mirizzi, Serpico	PRD 87, 116009 (2013)	1303.5843	Lorentz invariance
Neutrinos at IceCube from heavy decaying dark matter	Feldstein, Kusenko, Matsumoto, Yanagida	PRD 88, 015004 (2013)	1303.7320	Exotic (dark matter decay)
Galactic PeV Neutrinos	Gupta	---	1305.4123	Galactic
Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy	Fox, Kashiyama, Meszaros	ApJ 774, 74 (2013)	1305.6606	Galactic
Superheavy Particle Origin of IceCube PeV Neutrino Events	Barger, Keung	---	1305.6907	Exotic (Leptoquark)
PeV neutrinos observed by IceCube from cores of active galactic nuclei	Stecker	PRD 88, 047301 (2013)	1305.7404	Extragalactic (AGN)
TeV–PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars	Murase, Ioka	PRL 111, 121102 (2013)	1306.2274	Extragalactic (GRB)
Demystifying the PeV cascades in IceCube: Less (energy) is more (events)	Laha, Beacom, Dasgupta, Horiuchi, Murase	PRD 88, 043009 (2013)	1306.2309	
Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube	Murase, Ahlers, Lacki	---	1306.3417	Extragalactic
Pinning down the cosmic ray source mechanism with new IceCube data	Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weiler	---	1306.5021	Galactic
Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events	Stecker	---	1306.6095	Lorentz invariance
TeV-PeV neutrinos over the atmospheric background: originating from two groups of sources?	He, Yang, Fan, Wei	---	1307.1450	Two source populations
The Galactic Pevatron	Neronov, Semikoz, Tchernin	---	1307.2158	Galactic
Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube	Winter	---	1307.2793	Extragalactic
Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos	Joshipura, Mohanty, Pakvasa	---	1307.5712	
Are IceCube neutrinos unveiling PeV-scale decaying dark matter?	Esmaili, Sercipo	---	1308.1105	Exotic (dark matter decay)
Establishing the astrophysical origin of a signal in a neutrino telescope	Lipari	---	1308.2086	
Testing Relativity with High-Energy Astrophysical Neutrinos	Diaz, Kostelecky, Mewes	---	1308.6344	Lorentz invariance
A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube	Chen, Bhupal Dev, Soni	---	1309.1764	
The Galactic Center Origin of a Subset of IceCube Neutrino Events	Razzaque	---	1309.2756	Galactic
Probing the Galactic Origin of the IceCube Excess with Gamma-Rays	Ahlers, Murase	---	1309.4077	Galactic

an incomplete list by now

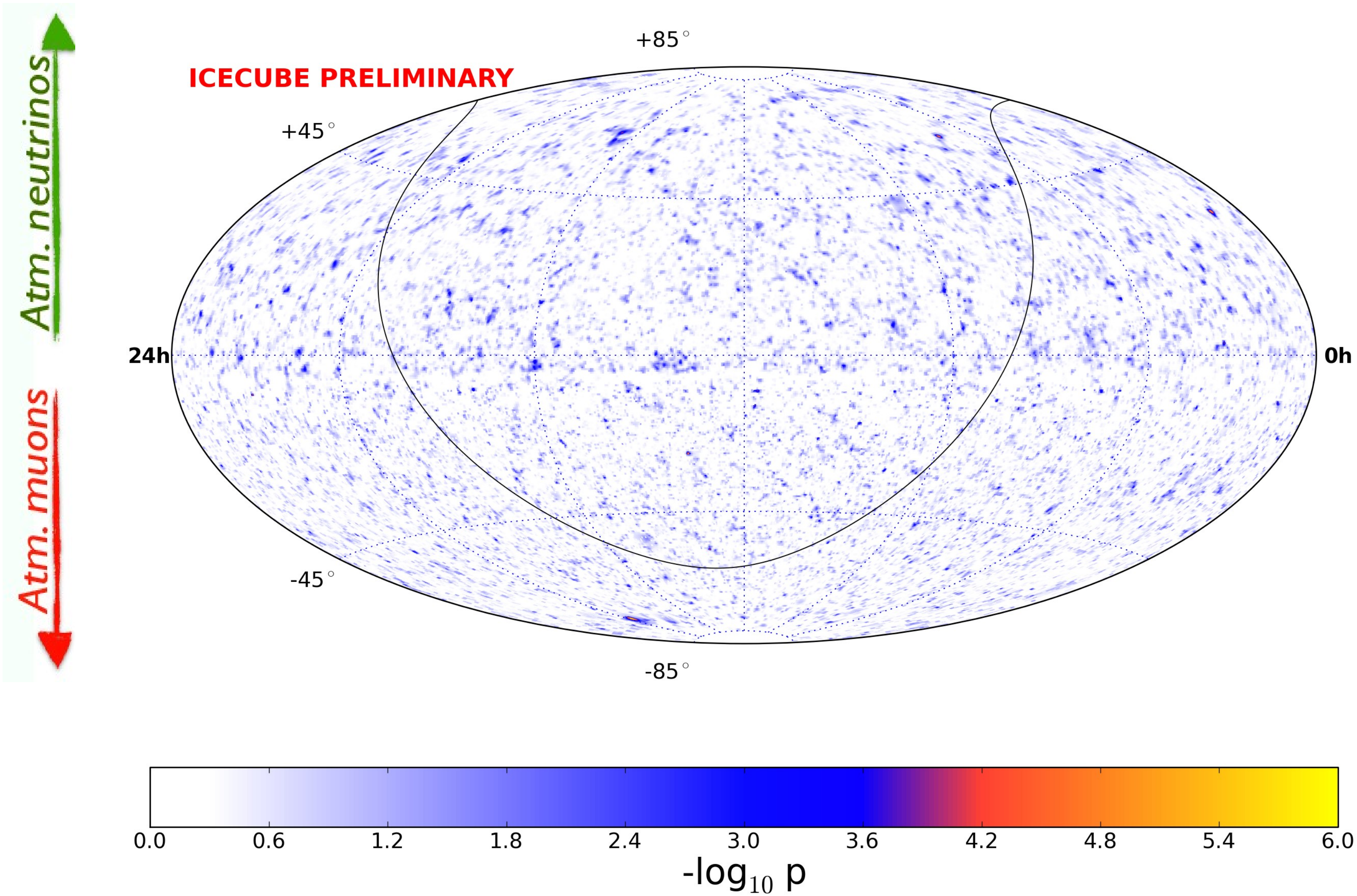

And now
for something
completely different...

4-year (IC40+IC59+IC79+IC86-I) neutrino sky.

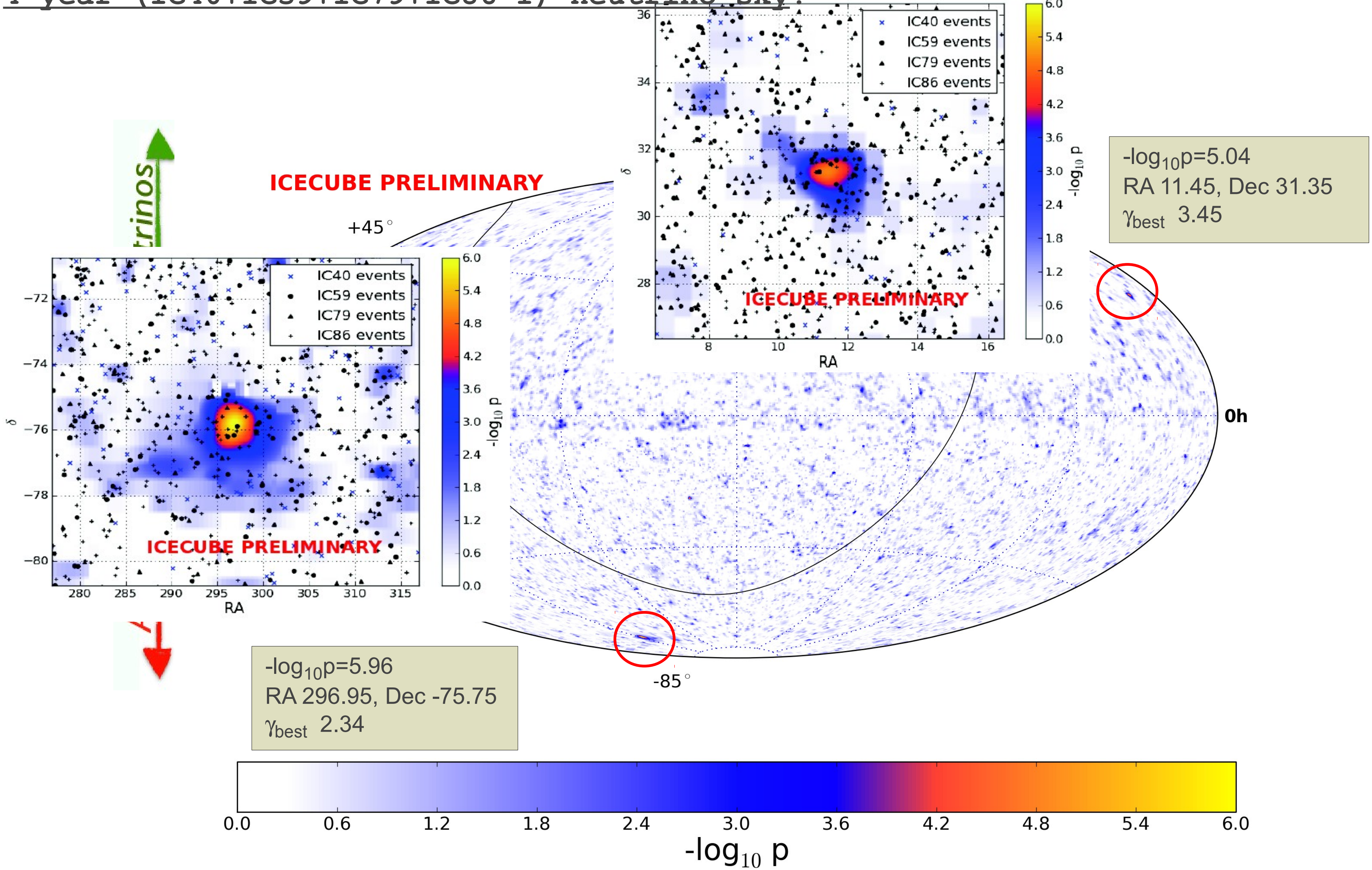
total livetime 1371.7 d

total number of events: 178000 upgoing

216000 downgoing (atm muons)



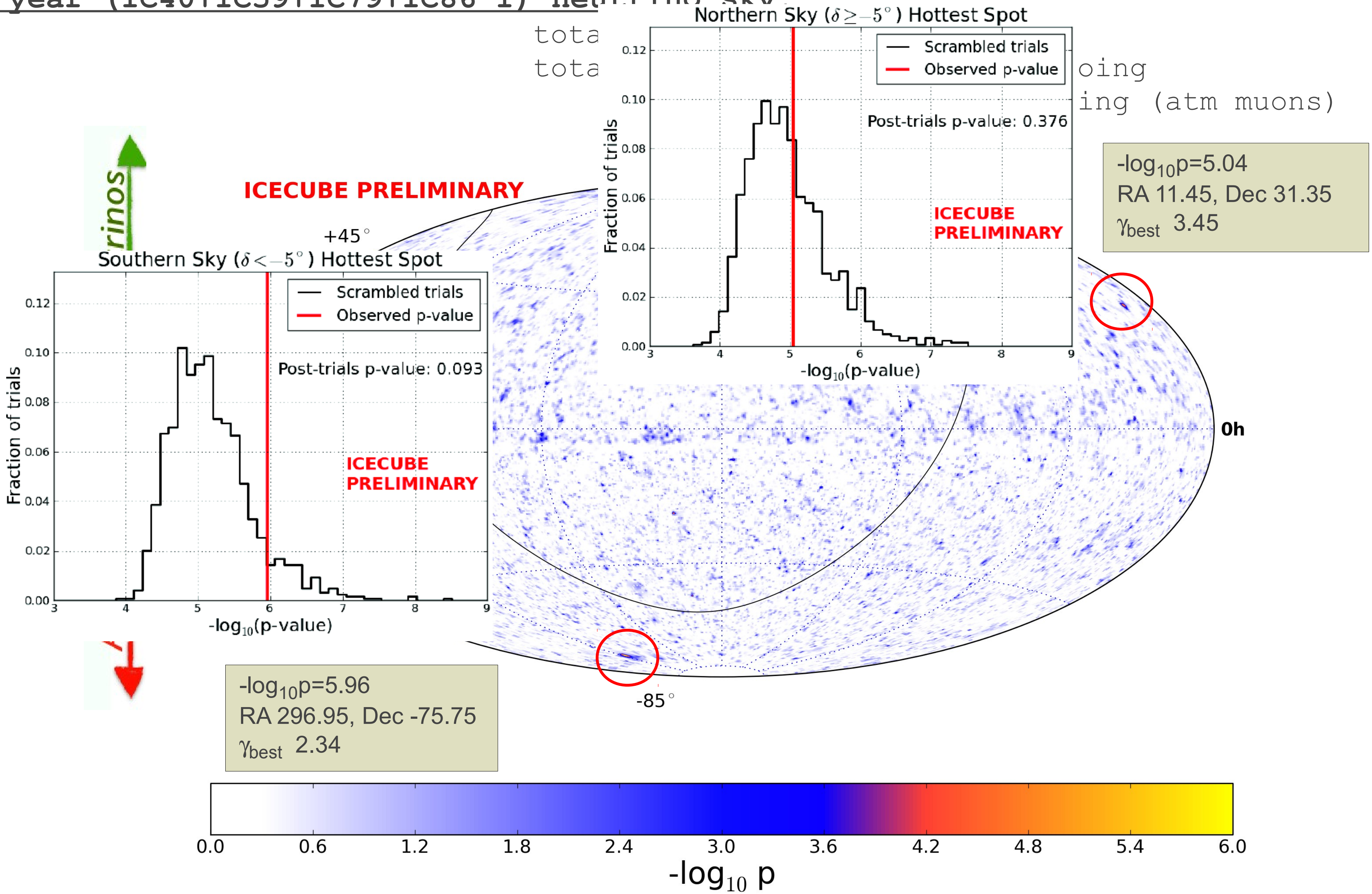
4-year (IC40+IC59+IC79+IC86-I) neutrino sky.



4-year (IC40+IC59+IC79+IC86-I) neutrino sky

tota oing

tota ing (atm muons)



Two Complementary searches:

"Model-Dependent" search:

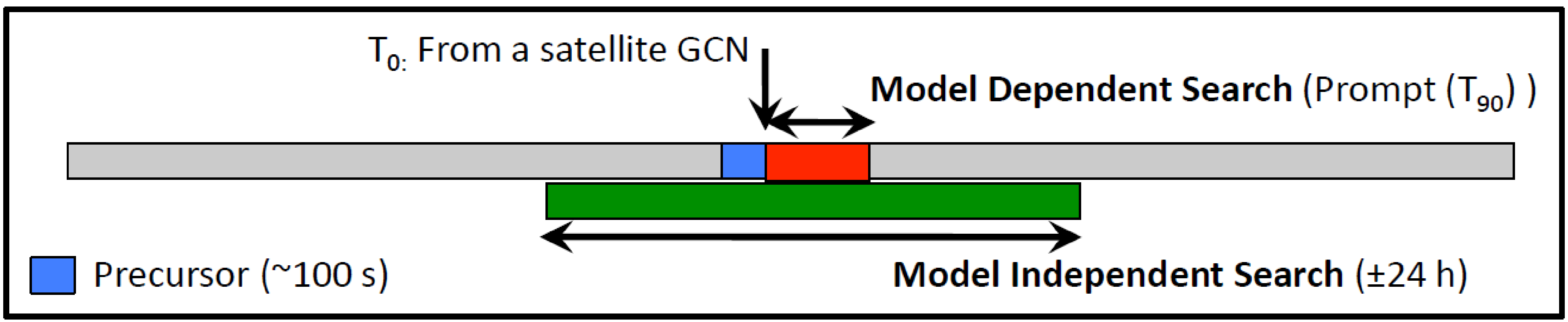
- **Time-window** defined by start and end of observed gamma emission (**T_{90} typically ~ 30 s**)
- Use model predictions of neutrino flux and energy spectrum to weight the search

⇒Most sensitive if models are right

"Model-Independent" search:

- **Time window** expands from **± 10 s to ± 1 day** (NB: neutrinos closer to GRB T_0 given more significance)
- No specific weighting to model predictions, search at all neutrino energies

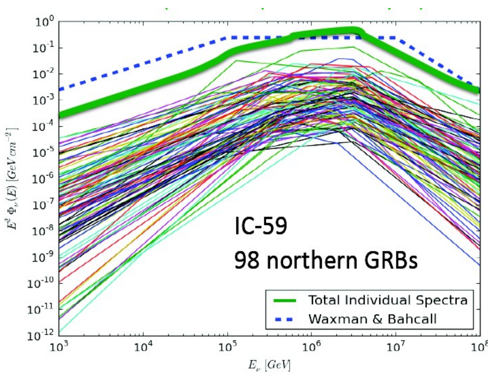
⇒"Catch-all" analysis



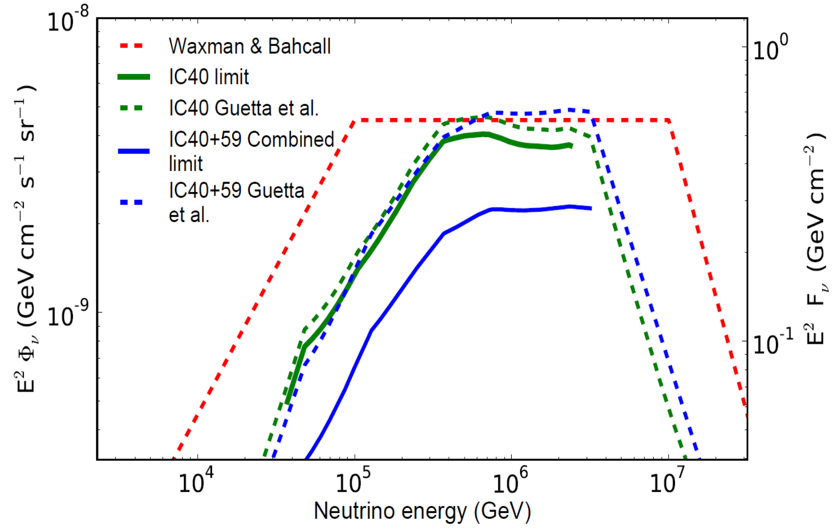
IceCube-40 + IceCube-59 results:

2008-09 data (40-string)
117 GRBs in northern sky

2009-10 data (59-string)
95 GRBs in northern sky
85 GRBs in southern sky

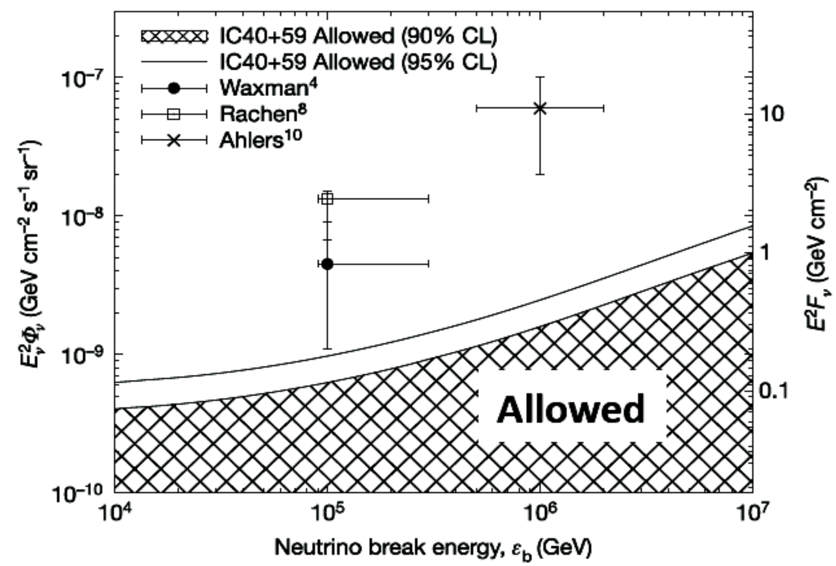


model dependent analysis



Because short duration, searches are very low background

model independent analysis



Nature, vol 484, 351 (2012)

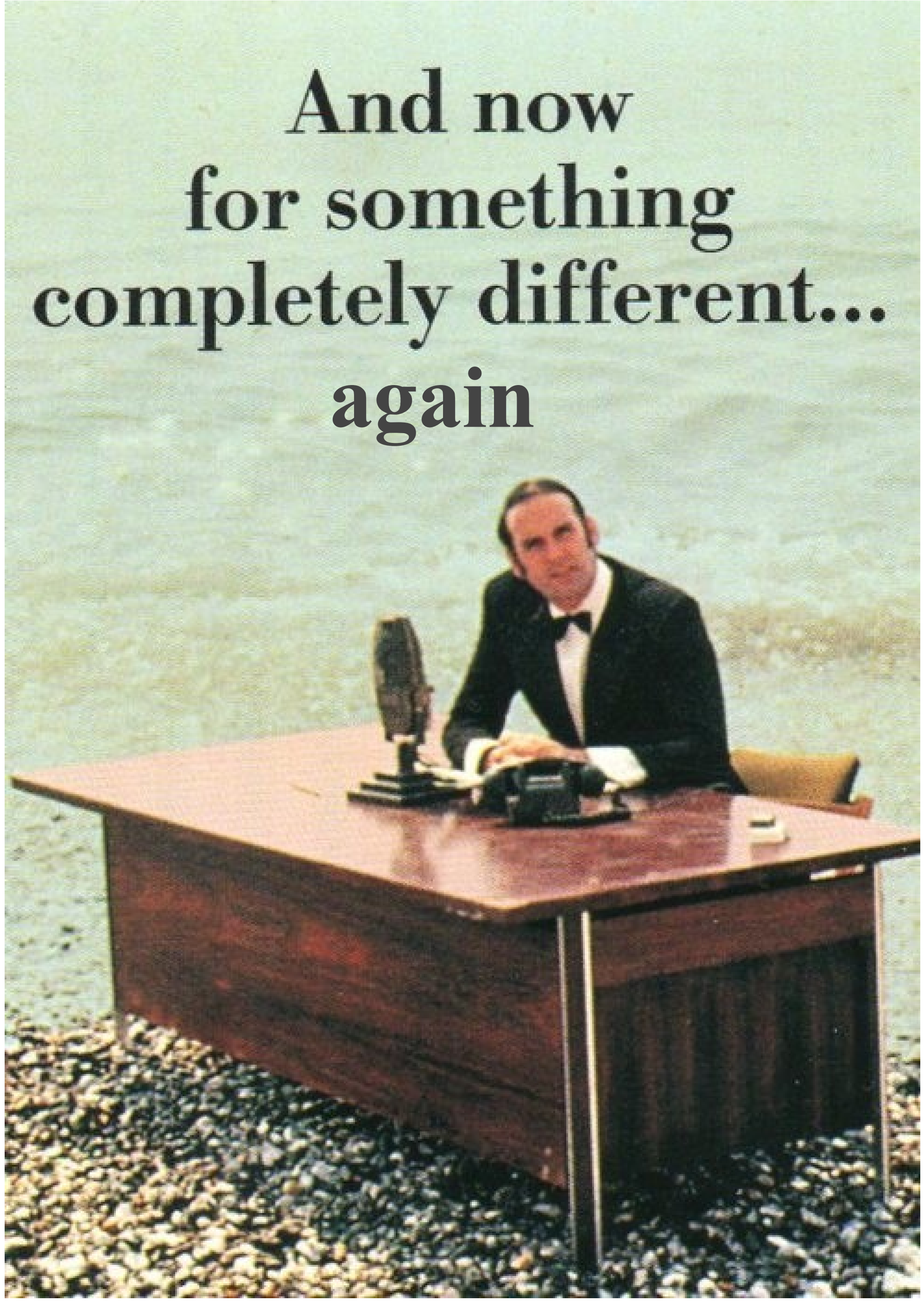
Results:

0 events observed

5.2 events expected (Guetta et al.)

model disfavored at > 3σ

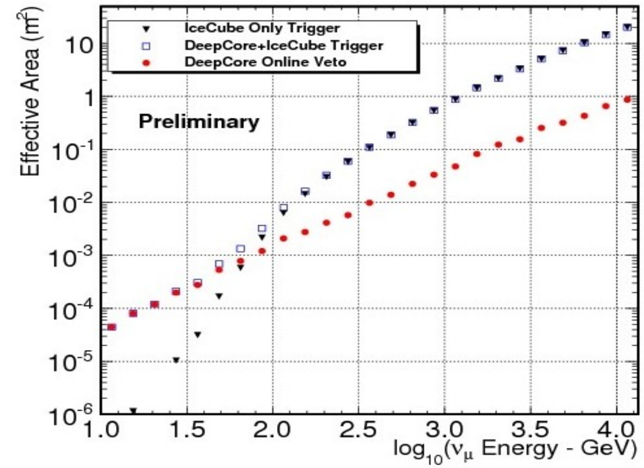
→ revisit theory
Some models strongly excluded already

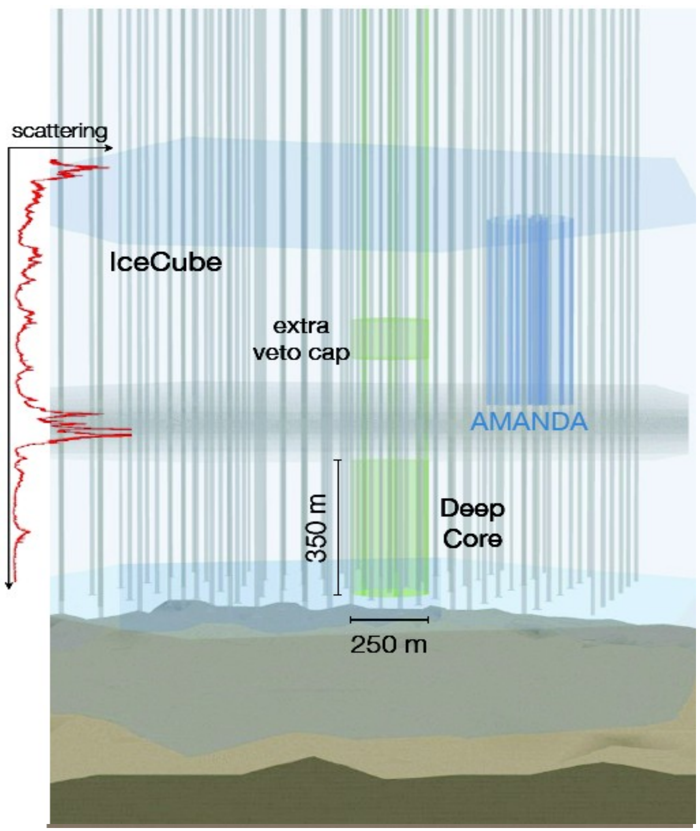

And now
for something
completely different...
again

full sky sensitivity using IceCube surrounding strings as a veto:

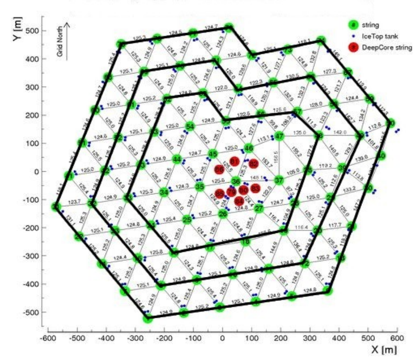
375m thick detector veto: three complete IceCube string layers surround DeepCore

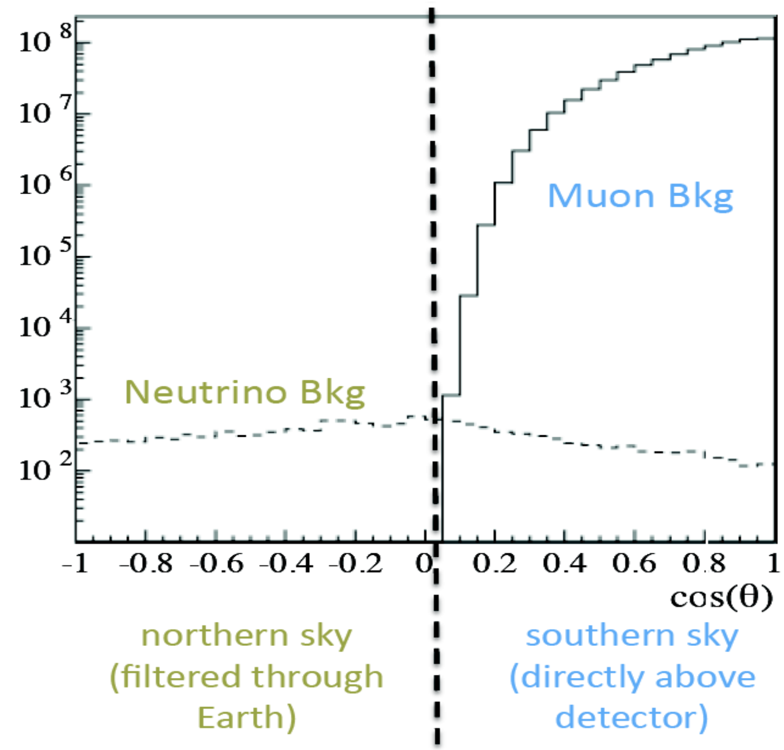
--> access to southern hemisphere, galactic center and all-year Sun visibility





can use IceCube outer string layers to define starting and througoing tracks





towards lower energies: DeepCore

full sky sensitivity using IceCube surrounding strings as a veto:

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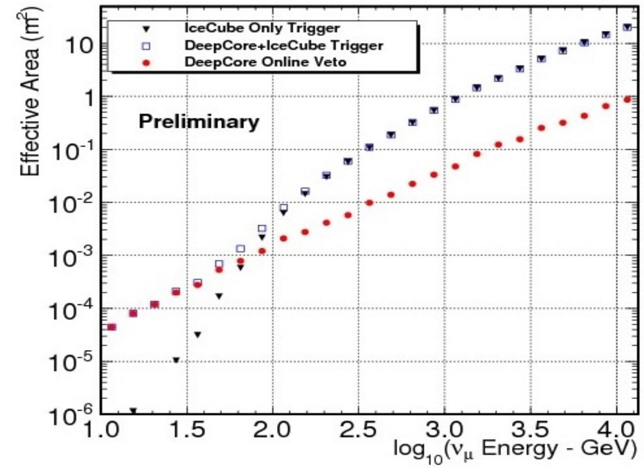

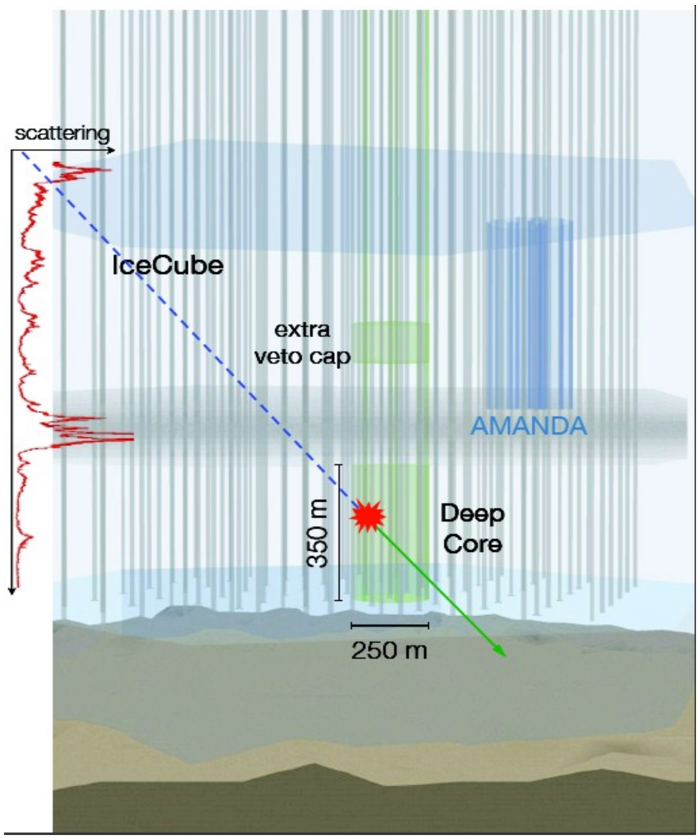

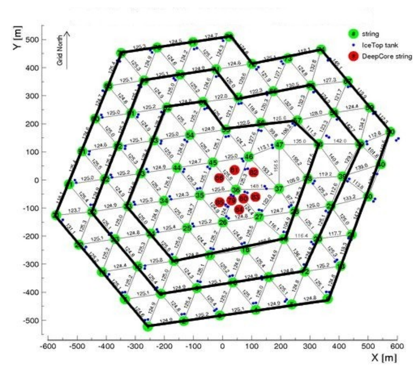

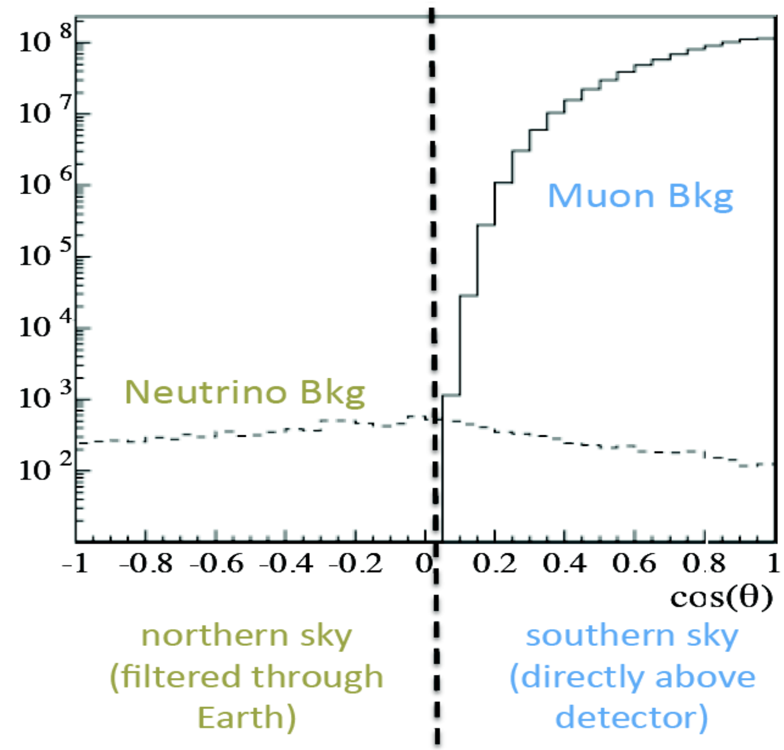

full sky sensitivity using IceCube surrounding strings as a veto:

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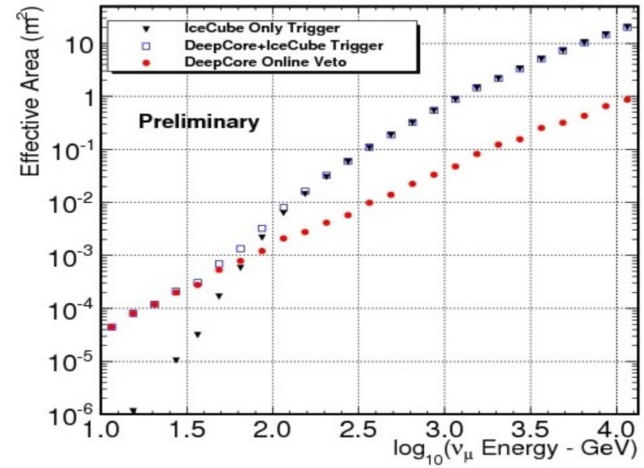
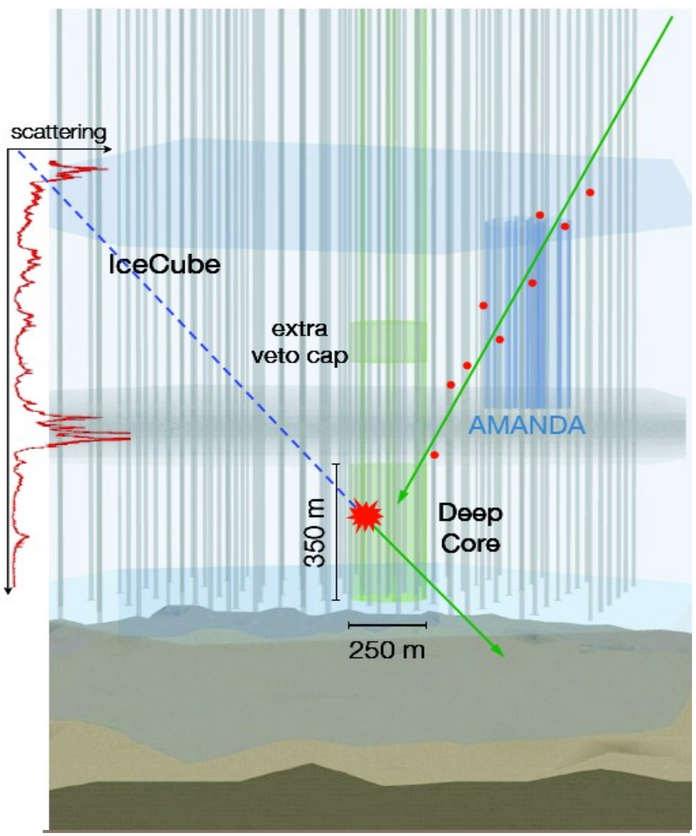
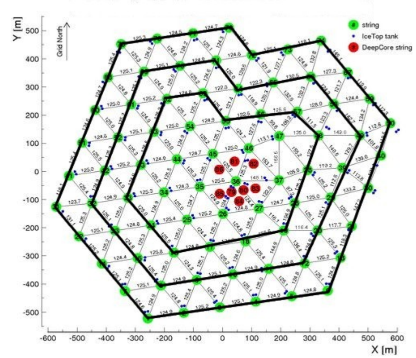
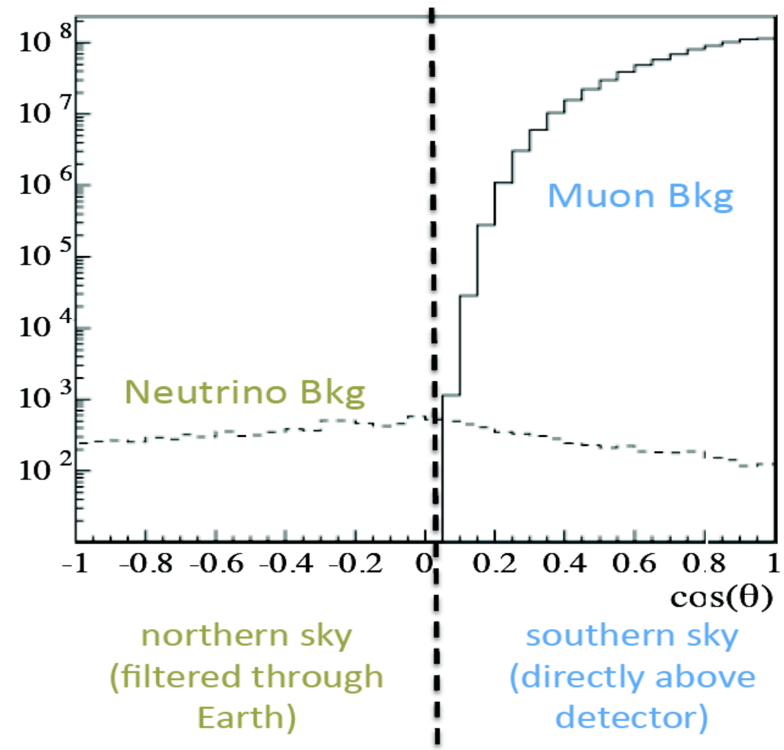






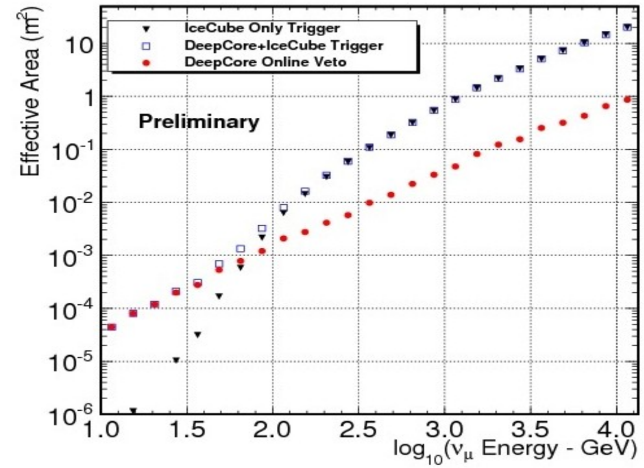


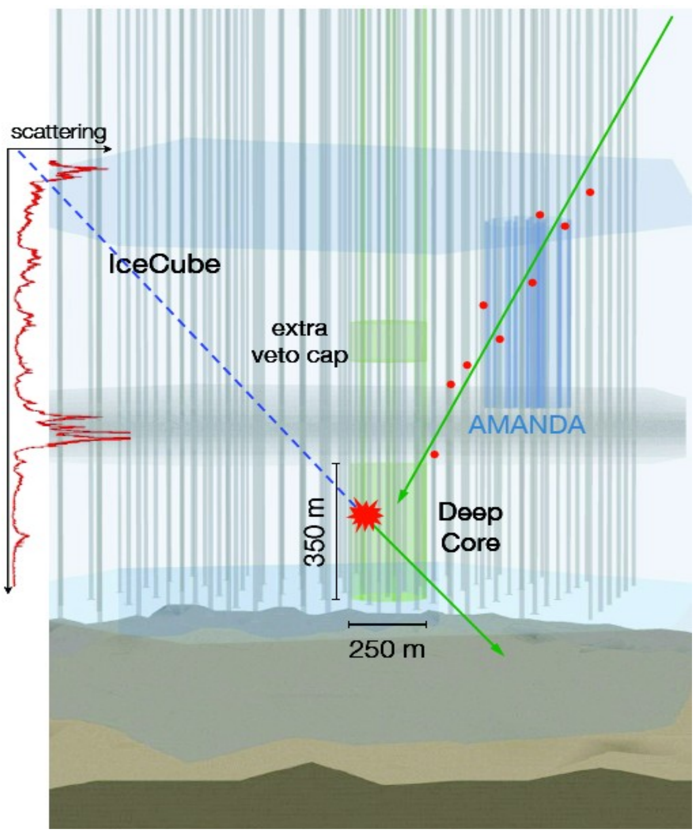
full sky sensitivity using IceCube surrounding strings as a veto:

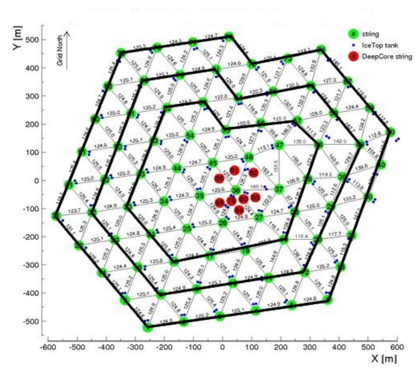
375m thick detector veto: three complete IceCube string layers surround DeepCore

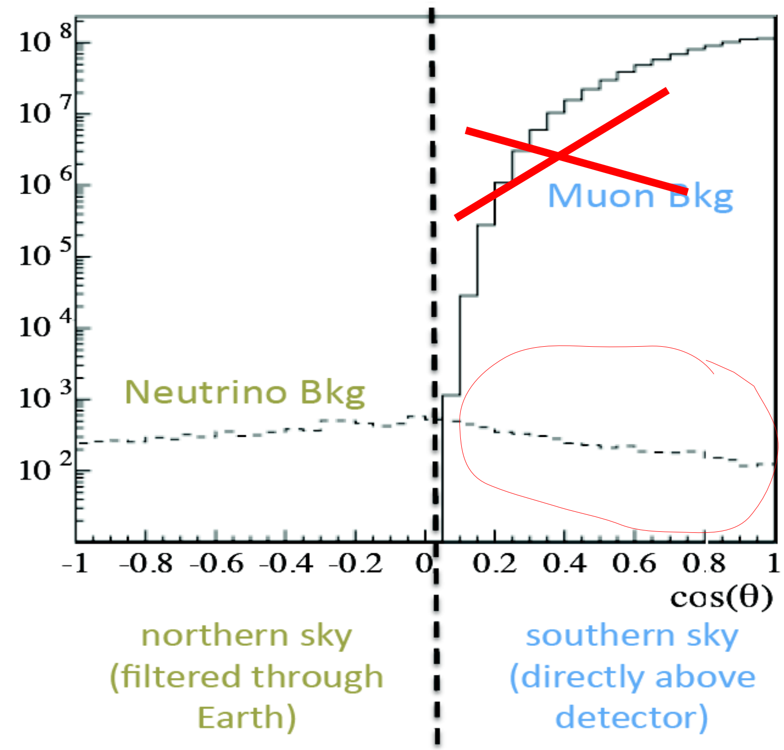
--> access to southern hemisphere, galactic center and all-year Sun visibility

IceCube is a 4π detector also at low energies









<u>WIMPS</u>

- Arise in extensions of the Standard Model
- Assumed to be stable: relics from the Big Bang
- weak-type Xsection gives needed relic density

$$\Omega_\delta h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann} v \rangle_{fr}} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- mass from few GeV to few TeV
- MSSM candidate: lightest neutralino,

$$\tilde{\chi}^0_1 = N_1\mathbf{B} + N_2\mathbf{W}^3 + N_3 H^0_1 + N_4 \mathbf{H}^0_2$$

- UED: lightest 'rung' in the Kaluza-Klein ladder

<u>SIMPZILLAS</u>

- Non-thermal, non-weakly interacting stable relics

$$\chi\chi \rightarrow \left\{ \begin{matrix} q\bar{q} \\ \ell^+\ell^- \\ W, Z, H \end{matrix} \right\} \rightarrow \nu, \gamma, e^+e^-, \bar{p}$$

...

Kaluza-Klein modes an additional useful channel:

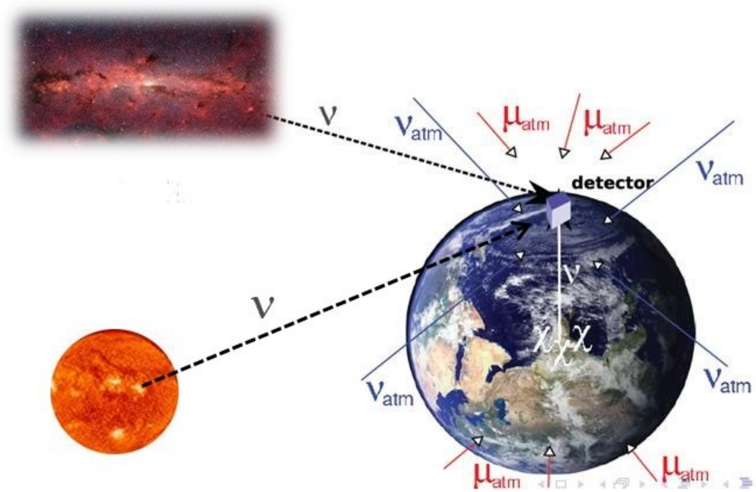
$$\kappa\kappa \rightarrow \nu\nu$$

<u>signature</u>:

ν excess over background from Sun/Earth/Galactic Halo/nearby galaxies

Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

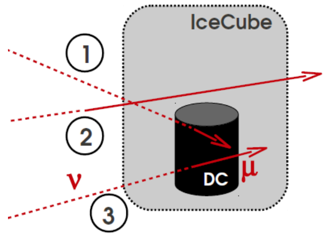
Sun, Earth, Galactic Halo/Center, dwarf spheroids



note astrophysical / hadronic uncertainties

IceCube results from 317 days of livetime between 2010-2011:

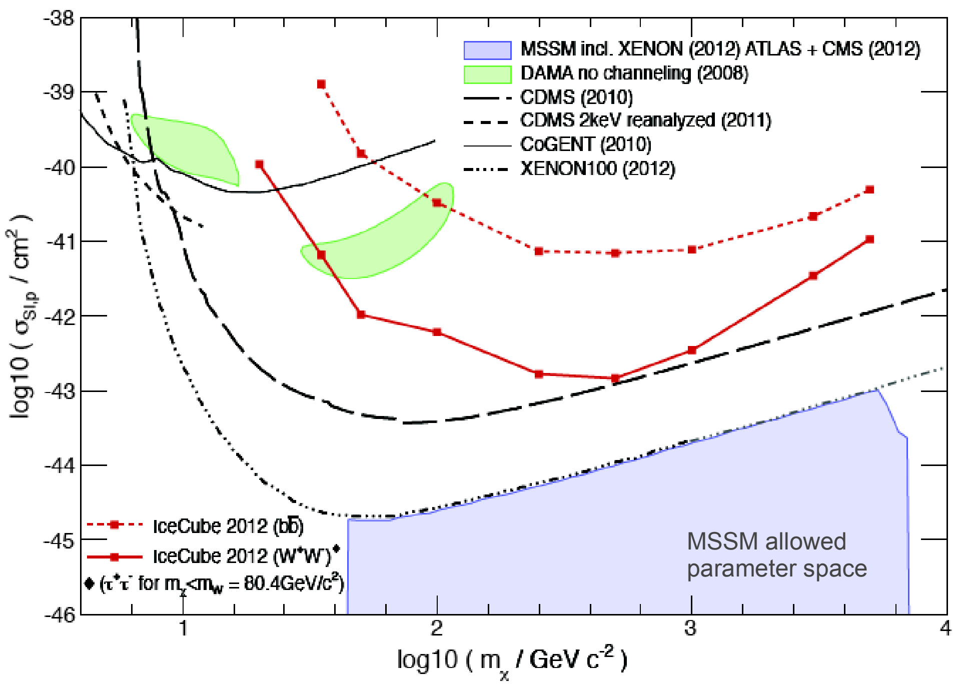
All-year round search: Extend the search to the southern hemisphere by selecting starting events



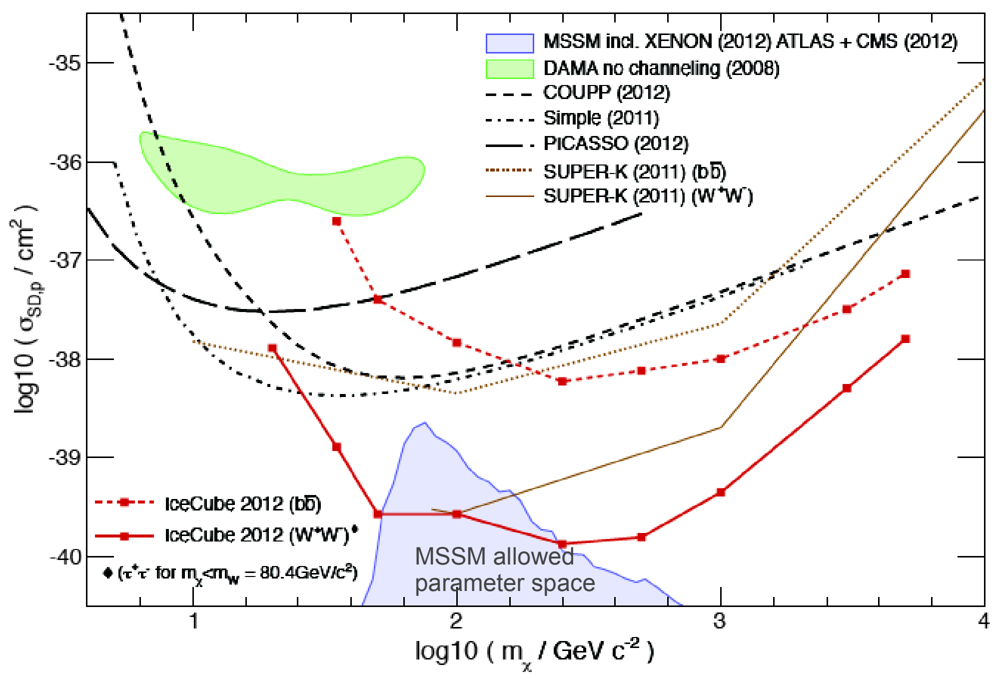
→ Veto background through location of interaction vertex
- muon background: downgoing, no starting track
- WIMP signal: require interaction vertex within detector volume

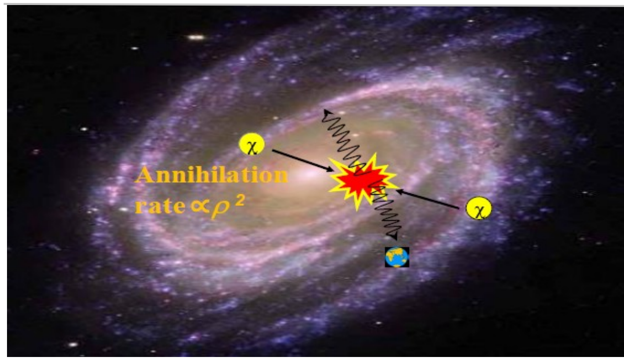
$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$$

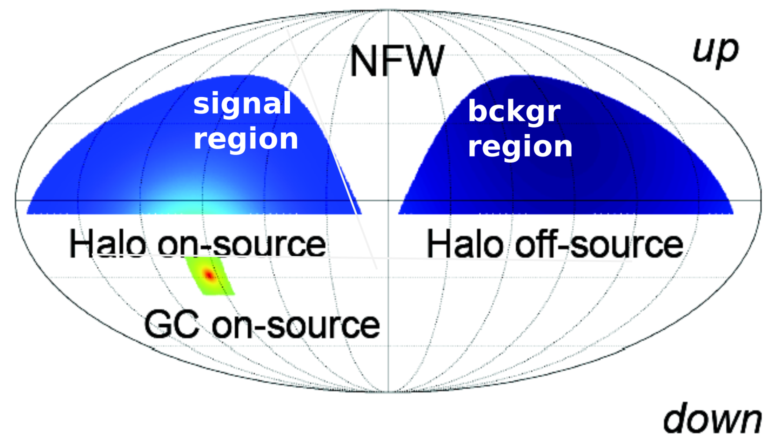
90% CL **neutralino-p SI Xsection** limit



90% CL **neutralino-p SD Xsection** limit







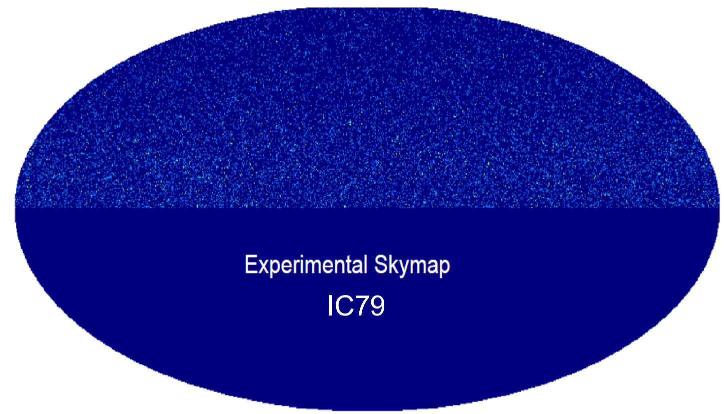
- Look for an excess of events in the on-source region w.r.t. the off-source

or,

- Use a multipole analysis 'a la' CMB in search for large-scale anisotropies

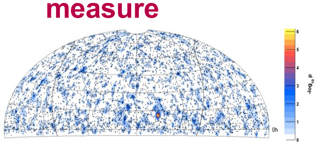
Need expected neutrino flux from SUSY and halo model.

- Limit on the self-annihilation cross section:



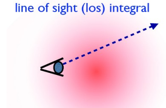
$$\varphi_\nu = \frac{dN}{dE\, dA_{eff}\, dt\, d\Omega} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle J_\Omega R_{SC}\frac{\rho_{SC}^2}{m_\chi^2}\frac{dN_\nu}{dE}$$

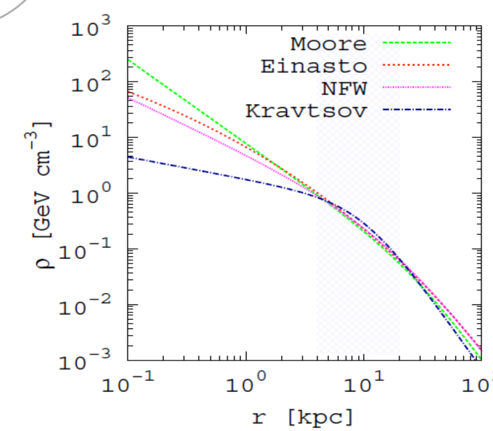
measure

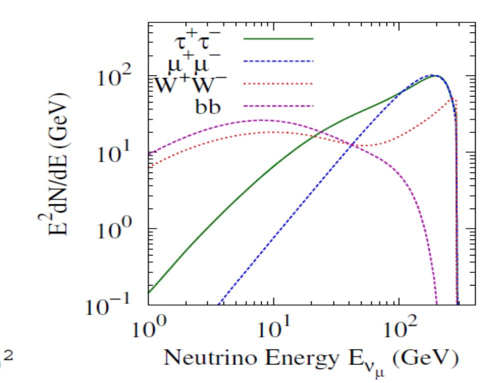


halo model

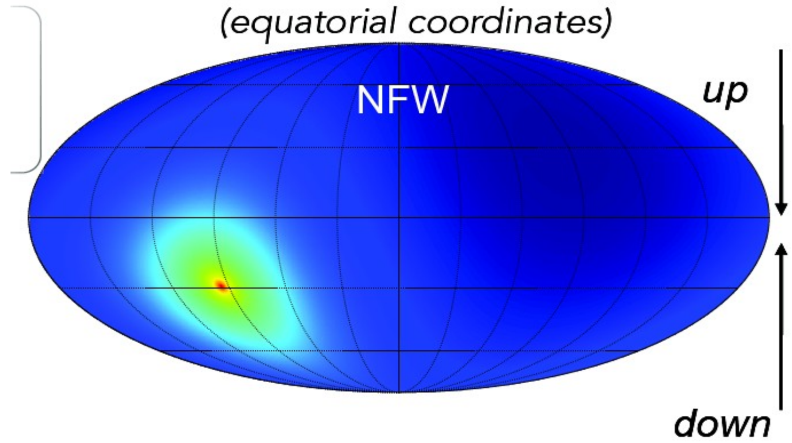
particle physics

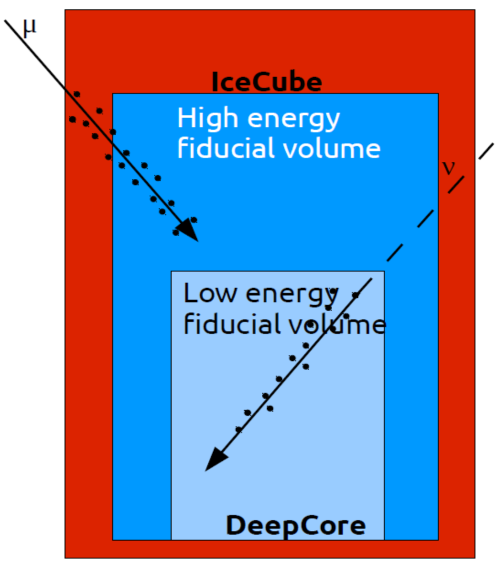






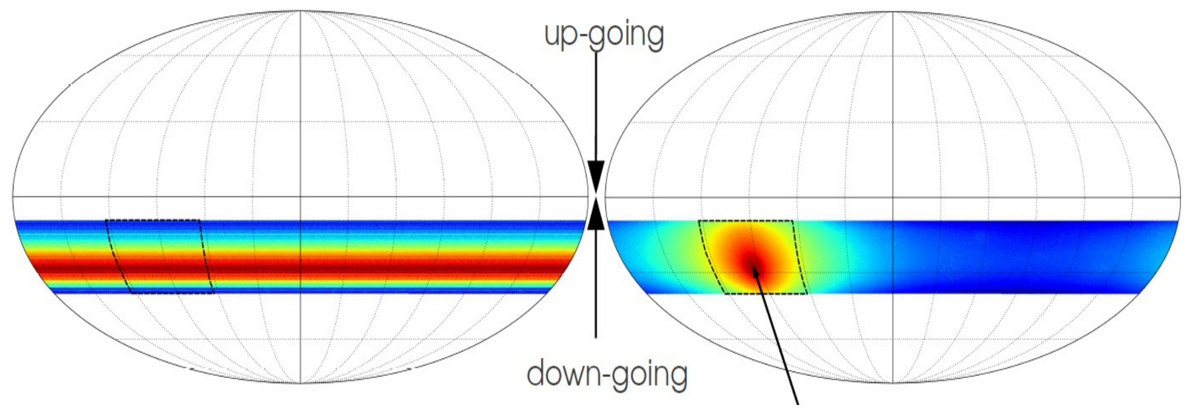
- 79-string configuration
- Use DeepCore to lower the energy threshold to ~10 GeV
- Analysis rely on veto methods to reject incoming tracks
- Use scrambled data for background estimation





scrambled background

signal

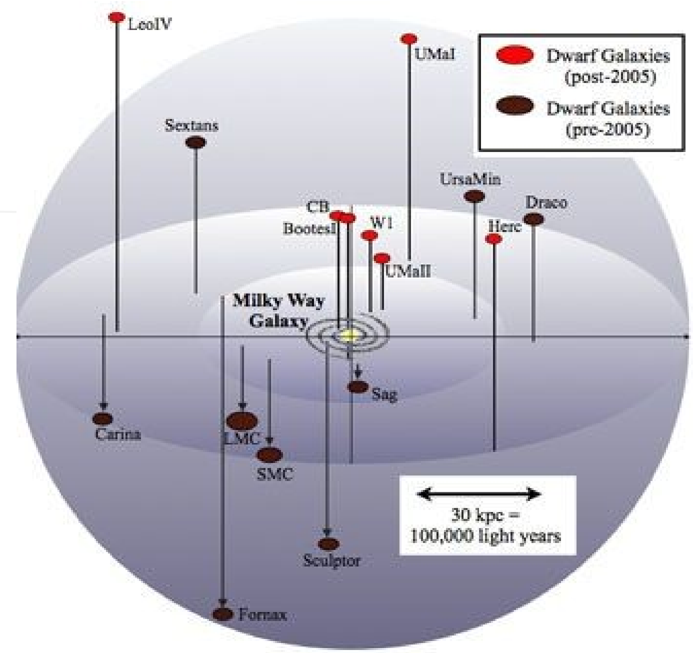


Galactc Center

DM search from dwarf galaxies and galaxy clusters

- Dwarf galaxies: high mass/light ratio
- → high concentration of DM in the halos
- known location. Distributed both in the north and southern sky.
  - Point-like search techniques: stacking
  - known distance -> determination of absolute annihilation rate if a signal is detected
- Galaxy clusters: enhance signal due to accumulation of sources

  But: extended sources with possible substructure
- Same expected neutrino spectra as for the galactic center/halo
- IceCube results from various sources



Galactic Halo:

IC22 PRD 84, 022004 (2011)

IC79 in preparation

Galactic Center

IC40 arxiv:1210.3557

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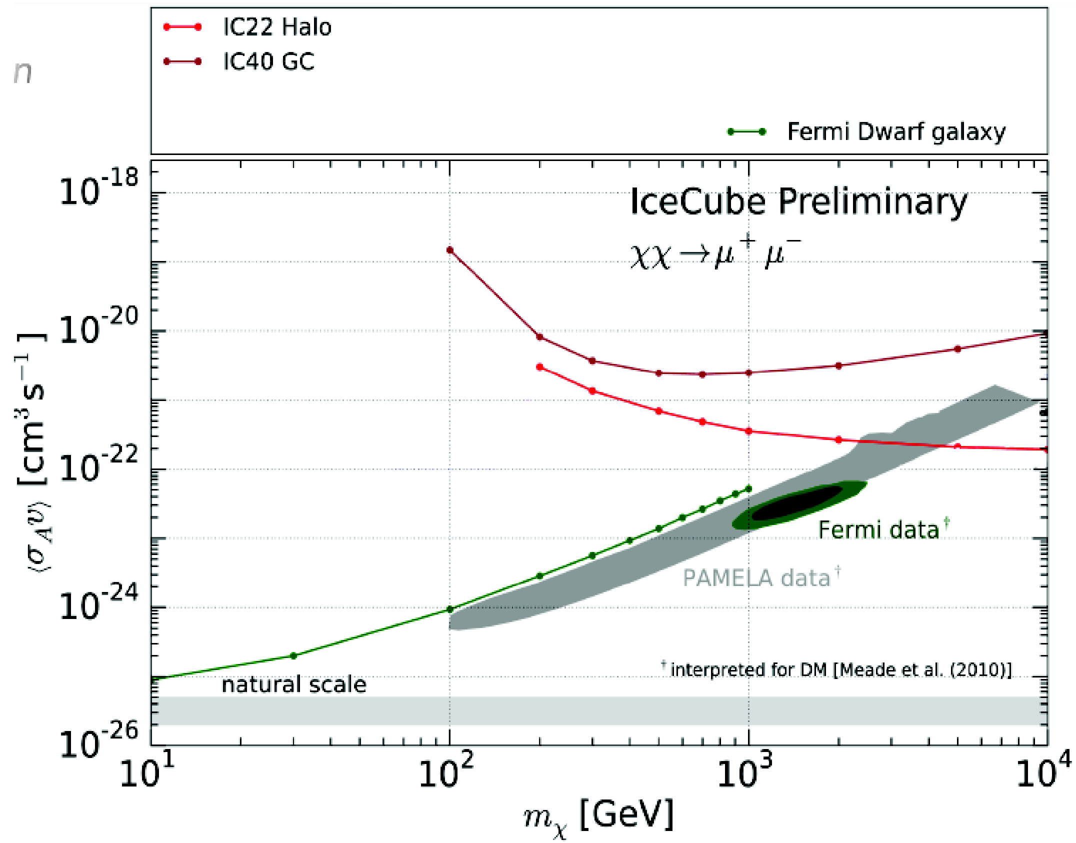
Dwarf spheroids:

IC59 submitted

Clusters of galaxies

IC59



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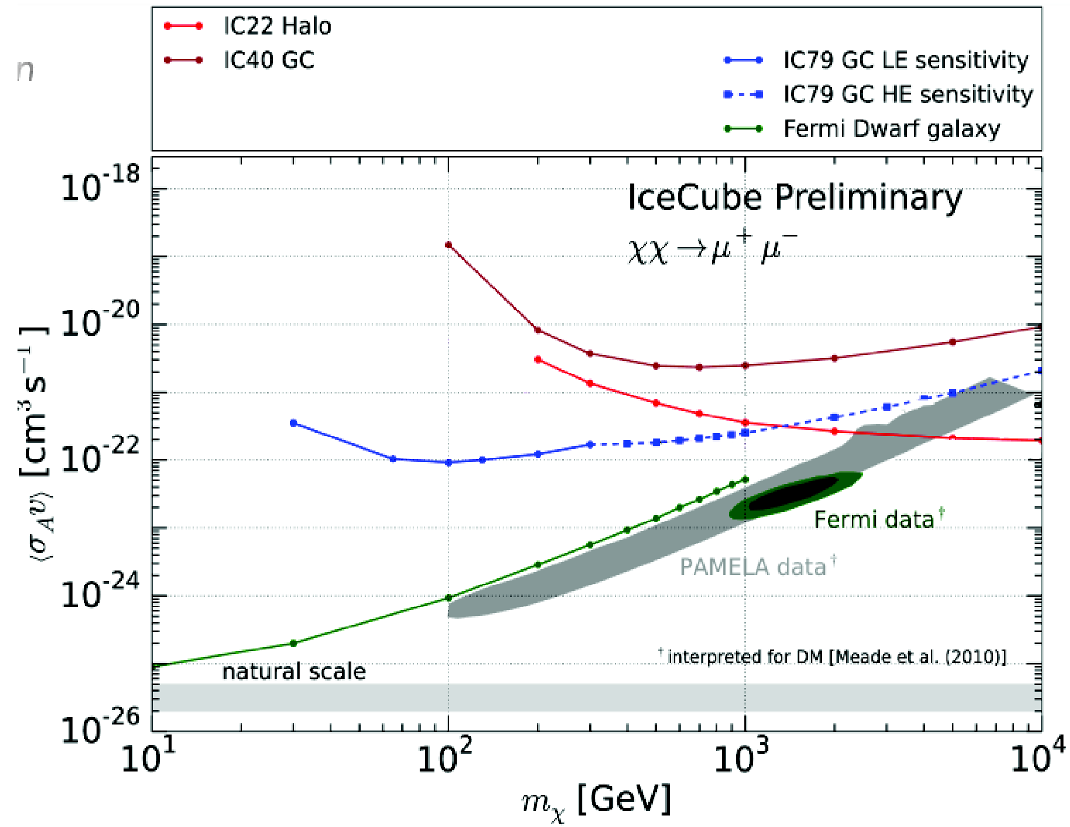

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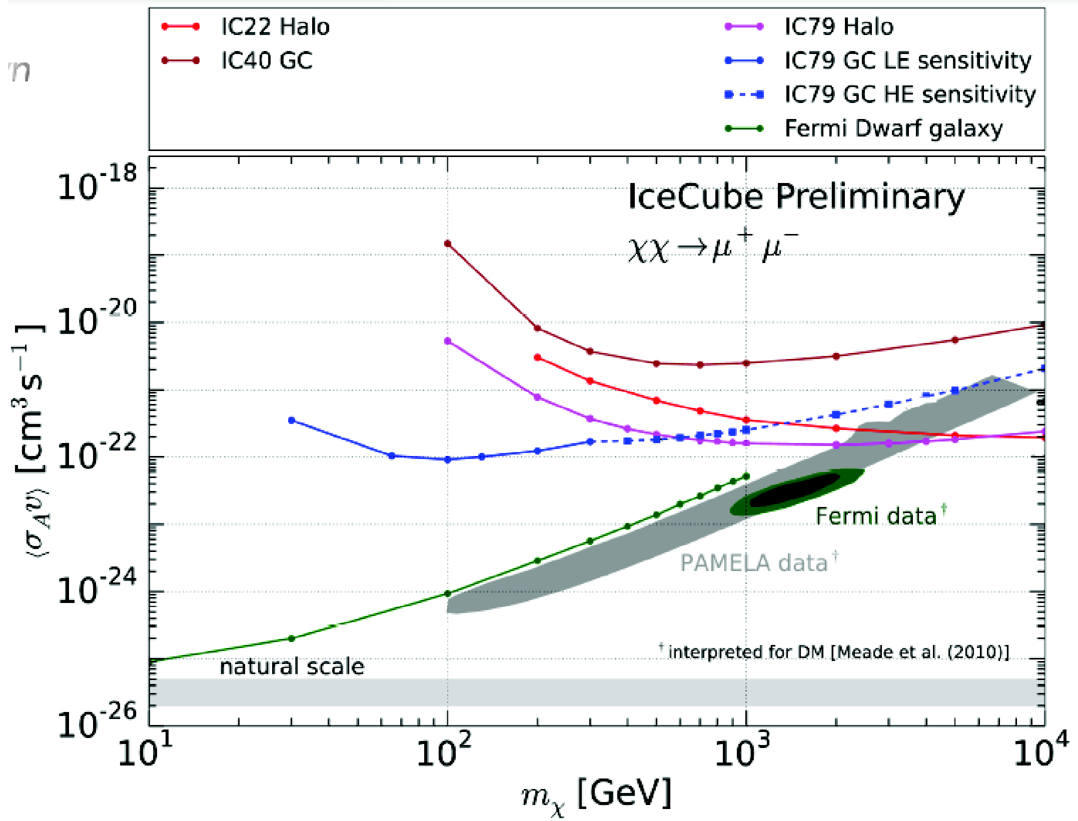

DM search from Galaxies: results

Galactic Halo:

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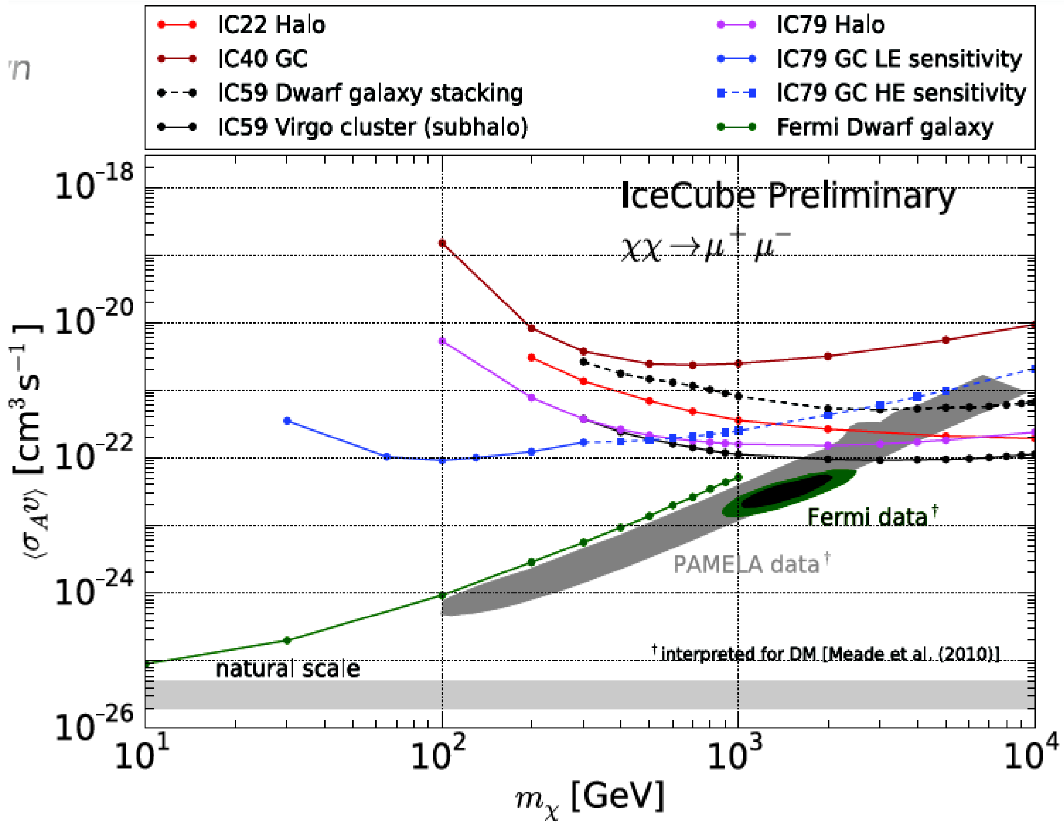


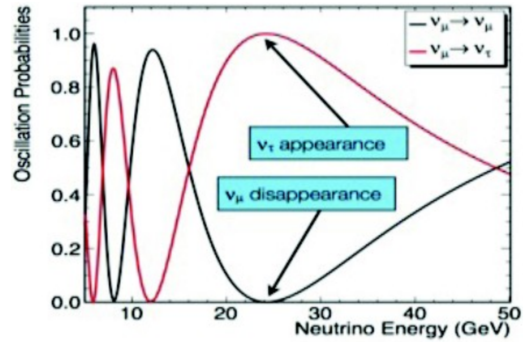
DeepCore Energy threshold at trigger level ~20 GeV

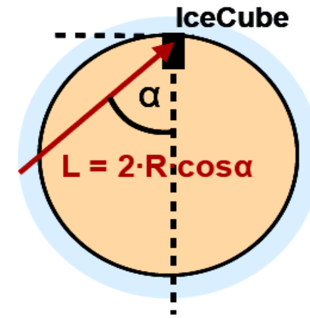
Covers first oscillation maximum @25 GeV

High statistics available

→ measure atmospheric muon rate as

a function of angle and energy



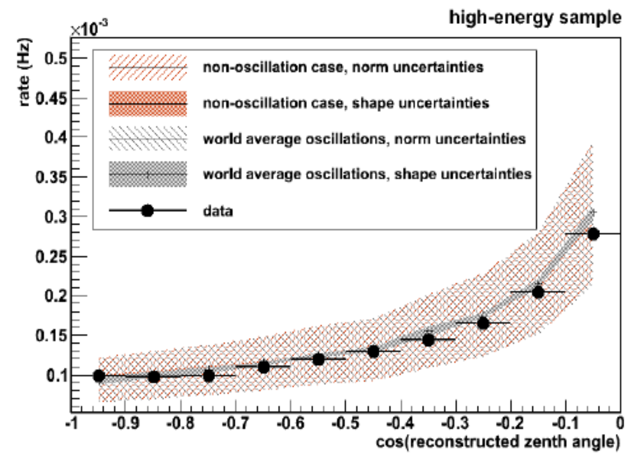


Challenges:

angular reconstruction

systematics

Results with IC79: Phys. Rev. Lett. 111, 081801 (2013)



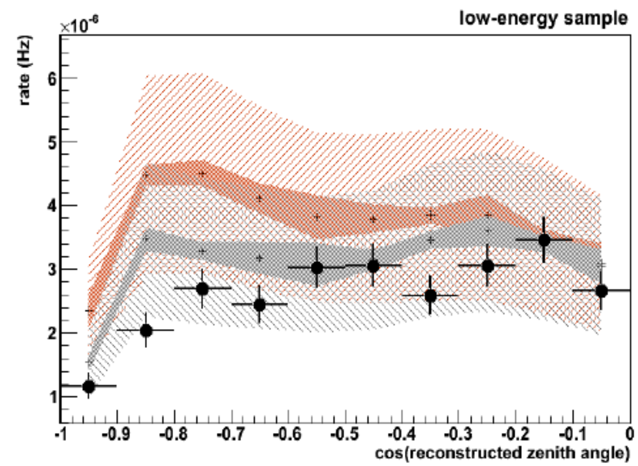
IceCube sees neutrino oscillations @5.6σ

consistent with world-average best fit.

In a two-flavour scenario:

$$|\Delta m^2_{32}| = (2.3^{+0.6}_{-0.5}) \times 10^{-3}\ \mathrm{eV}^2 \text{ and } \sin^2(2\theta_{23}) > 0.93$$

(no energy measurement used in the fit)



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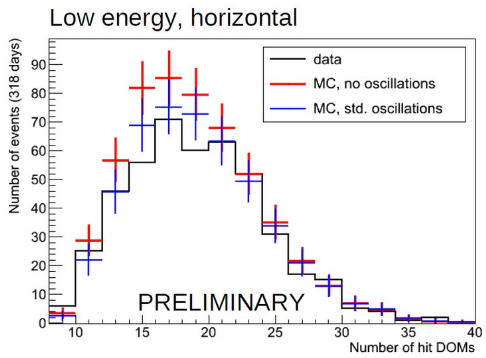

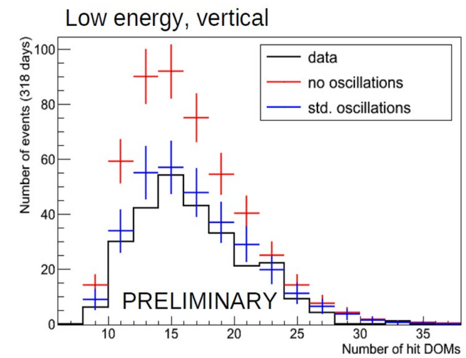

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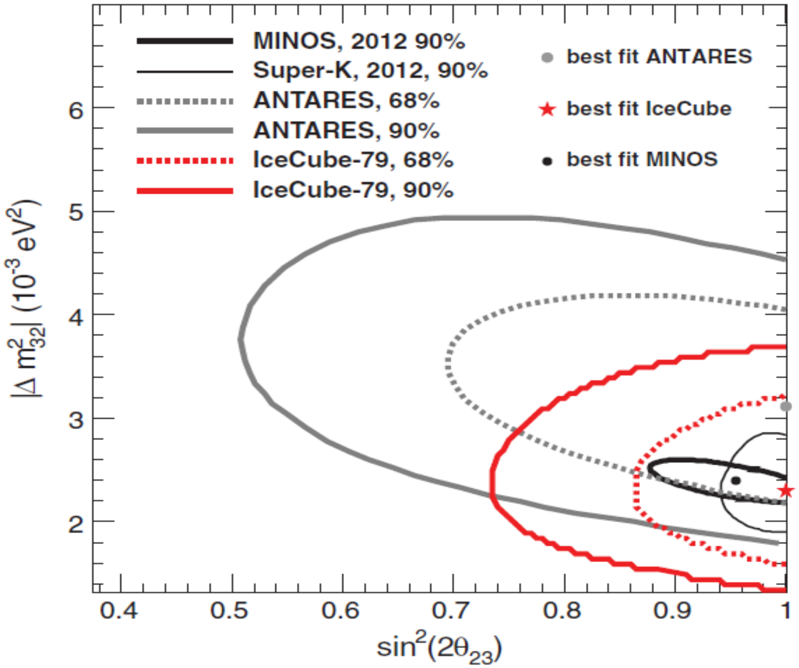


Phys. Rev. Lett. 111, 081801 (2013)

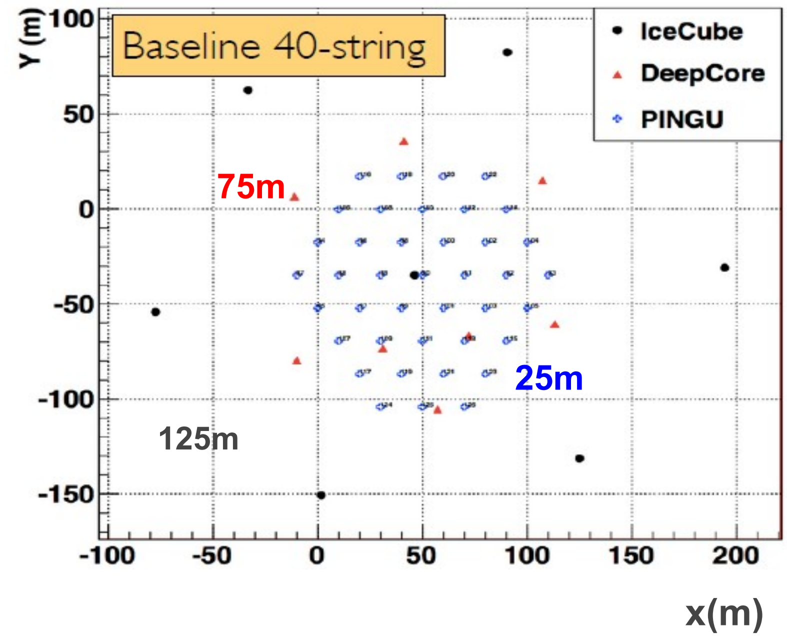
DeepCore showed the potential of going down in energy.

How low could we go?

Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV)

→ **PINGU:**

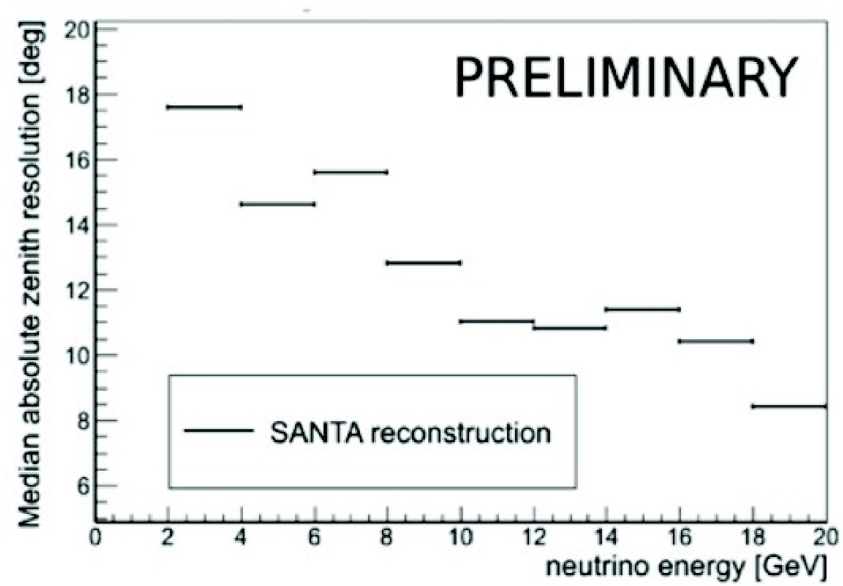
Precision **I**cecube **N**ext **G**eneration **U**pgrade



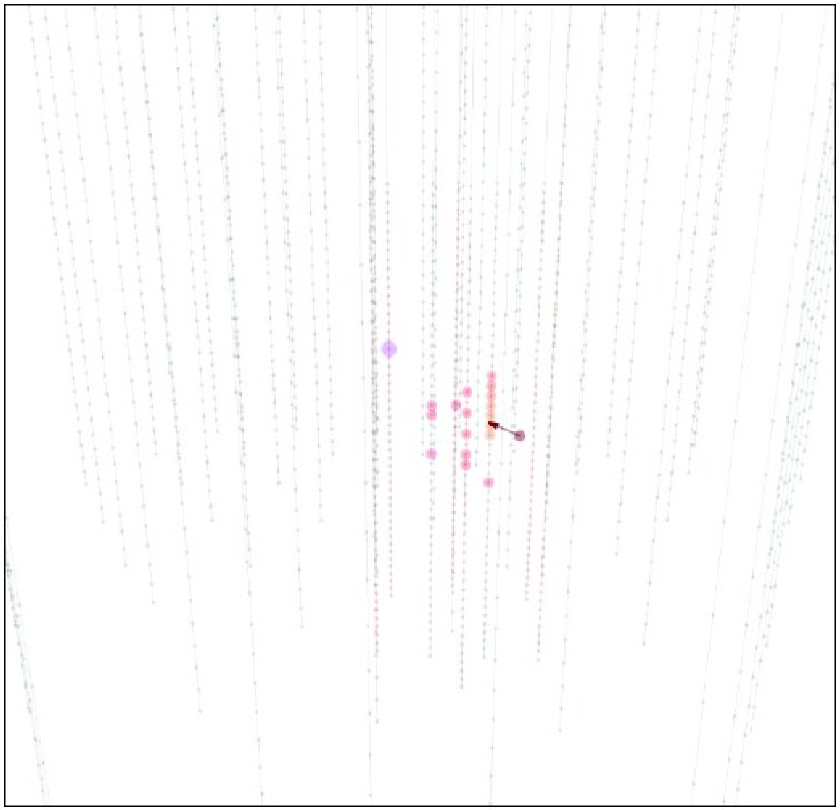
Aims:

Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay and high statistics SuperNova detection



9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade



DeepCore only

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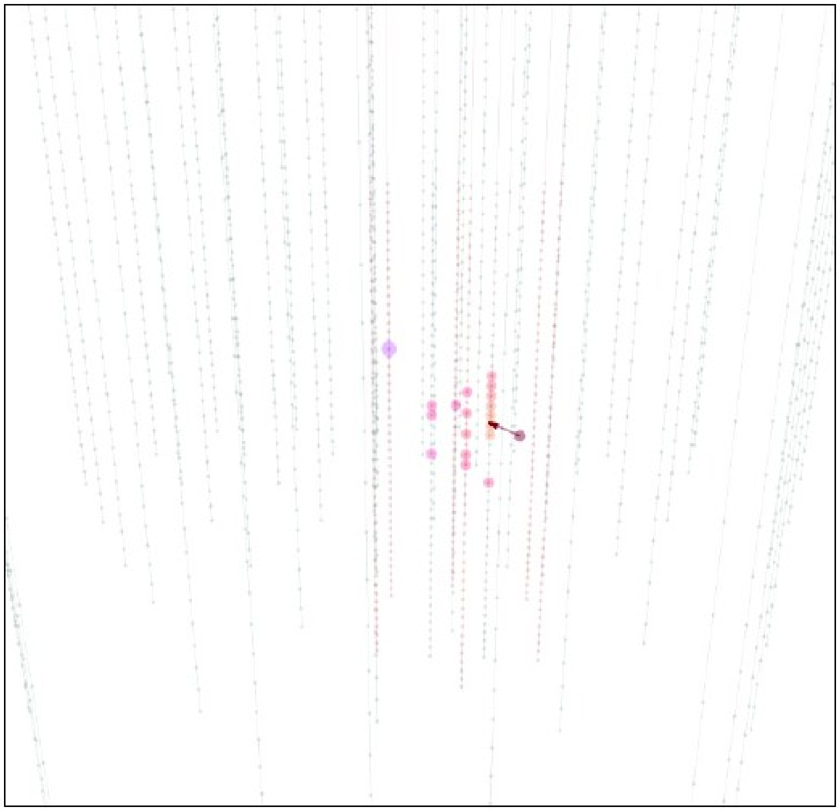
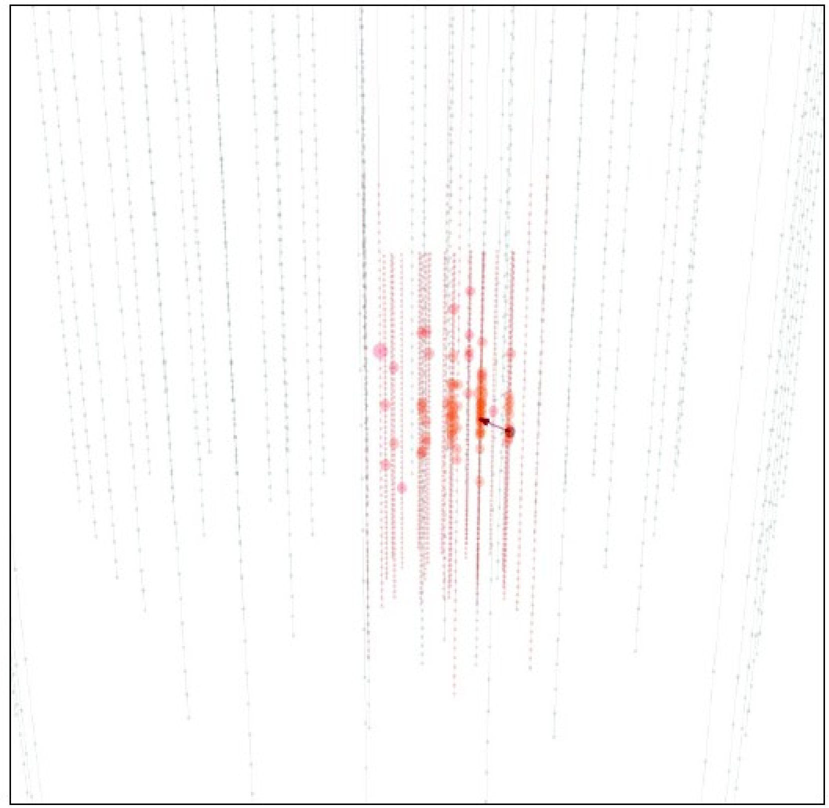


DeepCore only

20 DOMs hit



DeepCore + PINGU

50 DOMs hit

IceCube highlights

- Detector completed on December 2010
- Full operation with 86 strings starts in May 2011
- Full detector → Veto techniques possible.

  IceCube becomes a 4π detector with access to the Galactic Center and whole southern sky

- **Recent results**:
  - dark matter: competitive spin-dependent limits above WIMP mass 35 GeV (PRL 110, 131202 (2013))
  - atmospheric electron neutrinos (PRL 110, 151105 (2013))
  - highest energy neutrinos ever observed (PRL 111, 021103 (2013))
  - follow up on high energy neutrinos (Science 342, 6161 (2013)) 342 no. 6161
  - neutrino oscillations at high energies (PRL 111, 081801 (2013))

Many of these results only possible with the low-energy extension, DeepCore.... which paves the ice for PINGU, an even lower-energy extension under study (E_ν threshold of ~ O(1 GeV))

We got them.

28 events with energies above 50 TeV in one year of IceCube operation with the nearly complete detector and one year with the complete detector

Inconsistent at more than 4 sigma with background-only hypothesis

Compatible with astrophysical origin, but no evidence of clustering

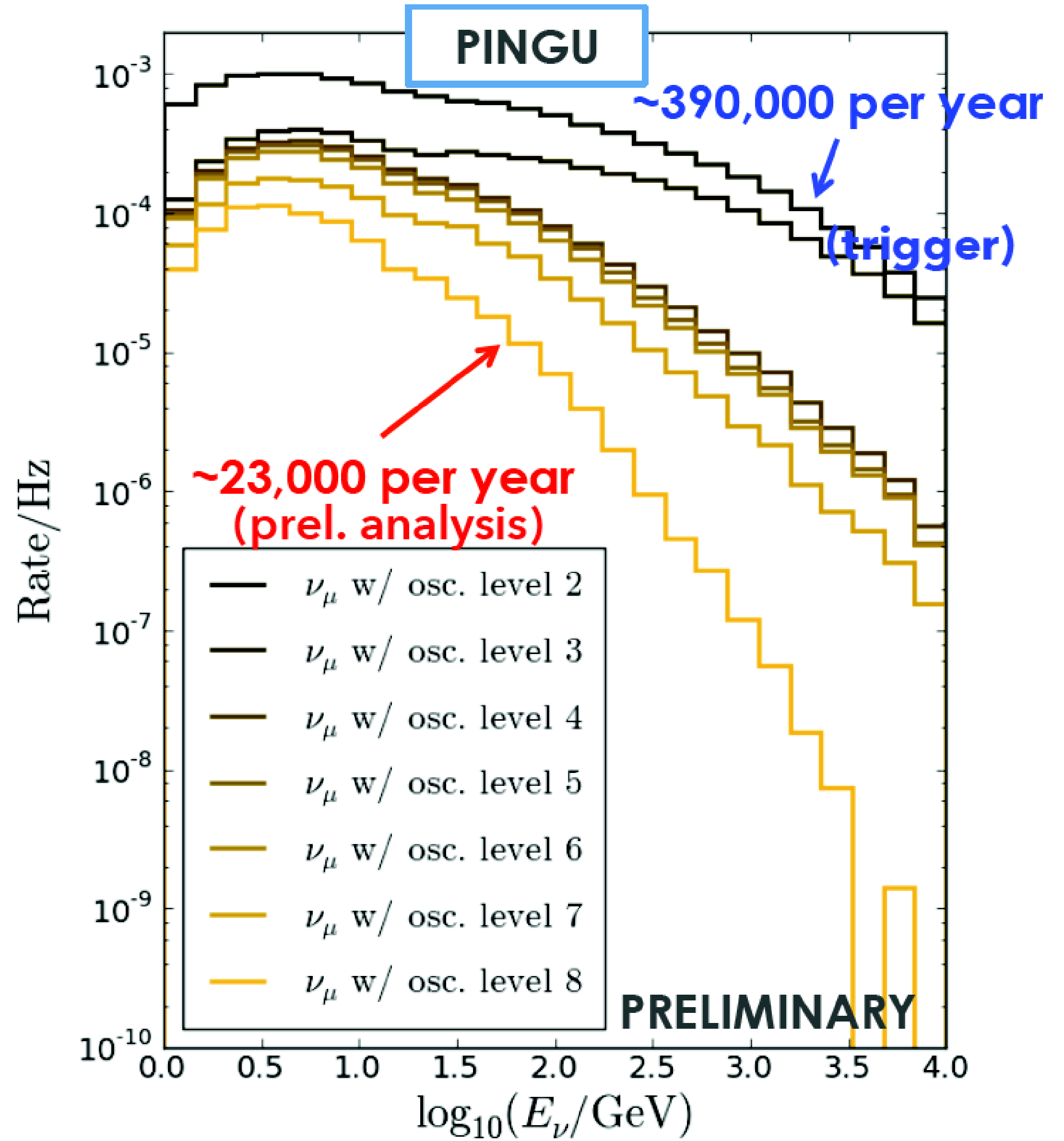
One more year of data already taken and being analyzed

slides from D. Grant, TAUP13

- Gain sensitivity to atmospheric neutrinos in the region below 10 GeV with very high statistics
    - **provide a definitive measurement of the neutrino mass hierarchy (NMH)**
    - will help pin down $(\Delta m_{23})^2$ and test maximal mixing
- Probe lower mass WIMPs
- Gain increased sensitivity to supernova neutrino bursts
- Initiate an extensive calibration program to improve systematics knowledge
- Pathfinder technological R&D for the Megaton Ice Cherenkov Array (MICA)

Precise geometry currently under study

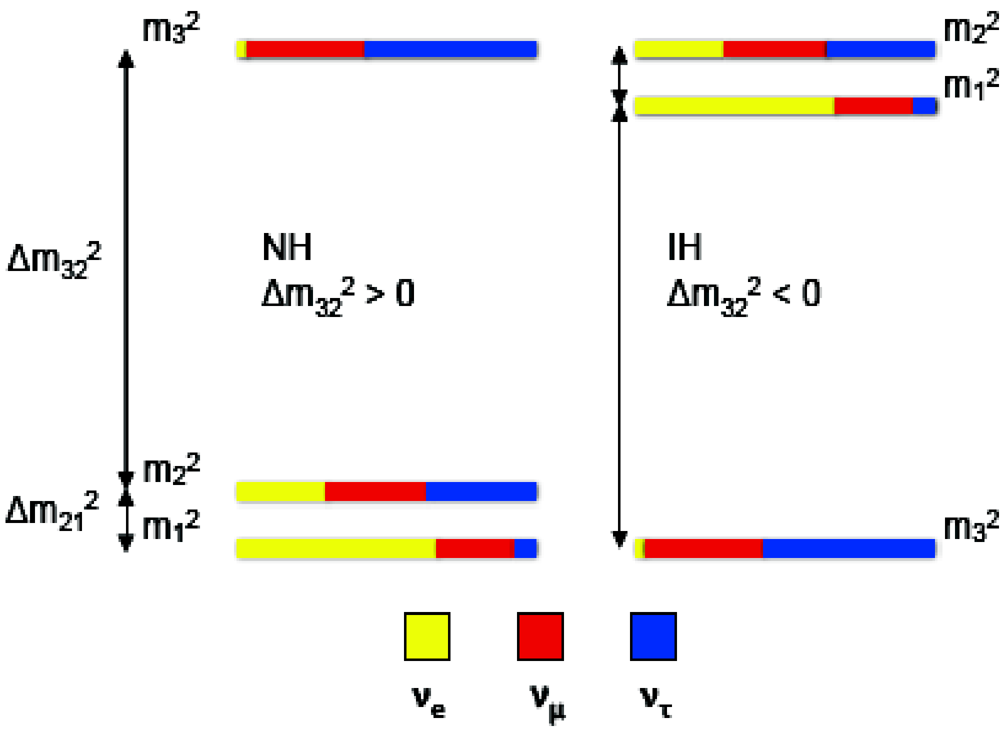
- A preliminary event selection based on DeepCore analysis
  - 23,000 muon neutrinos per year after oscillations
  - Oscillation signature is the disappearance of 12,000 events per year
- Sufficient to measure neutrino mass hierarchy via matter effects in the 5-20 GeV range without direct $\nu_\mu - \bar{\nu}_\mu$ discrimination
  - Exploit asymmetries in cross sections and kinematics



- Sign Δm_{21}^2 known from MSW effect in Sun
- Sign of Δm_{32}^2 (atmospheric muon neutrinos) still unknown

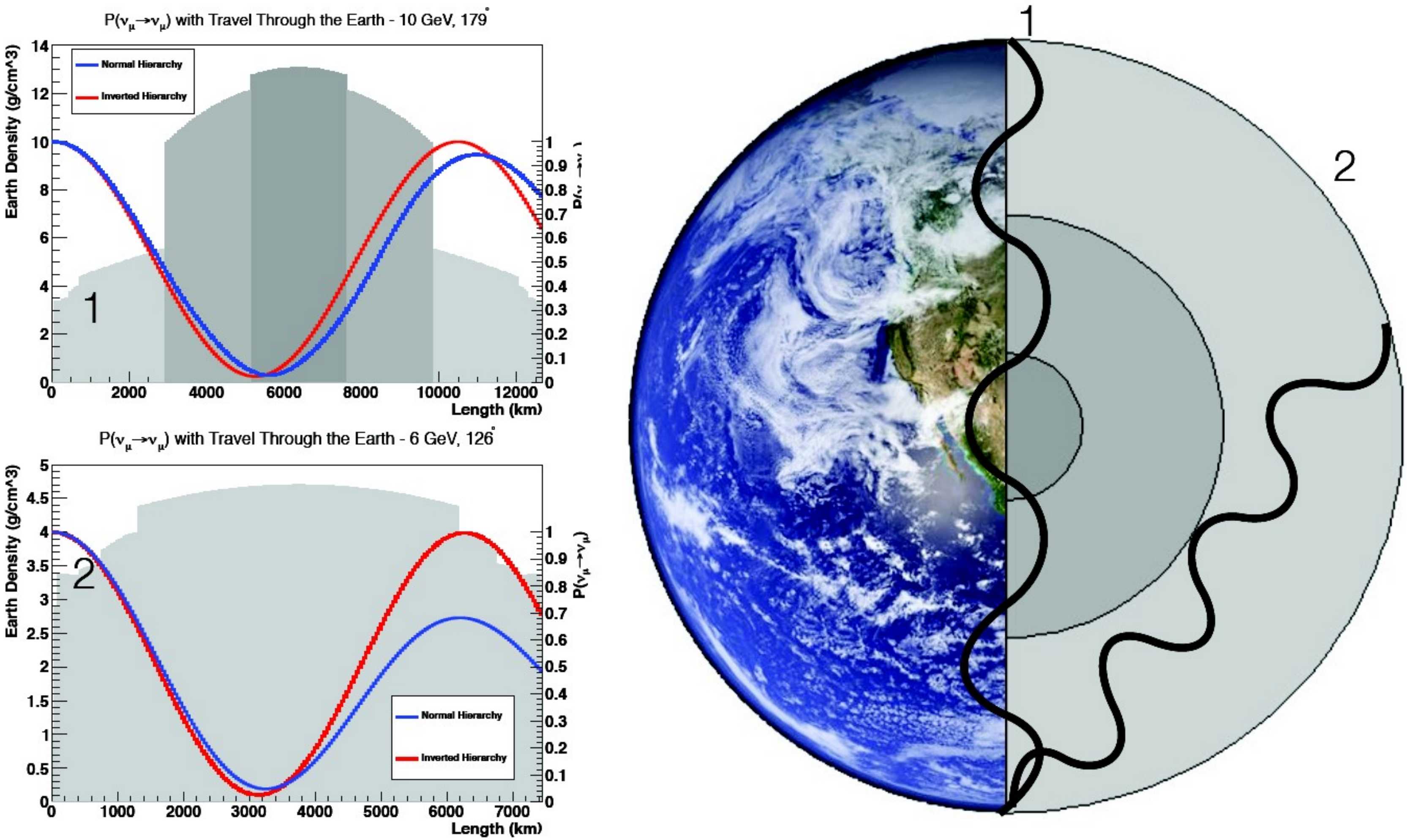
  $\Delta m_{32}^2 > 0 \rightarrow$ Normal hierarchy (NH)

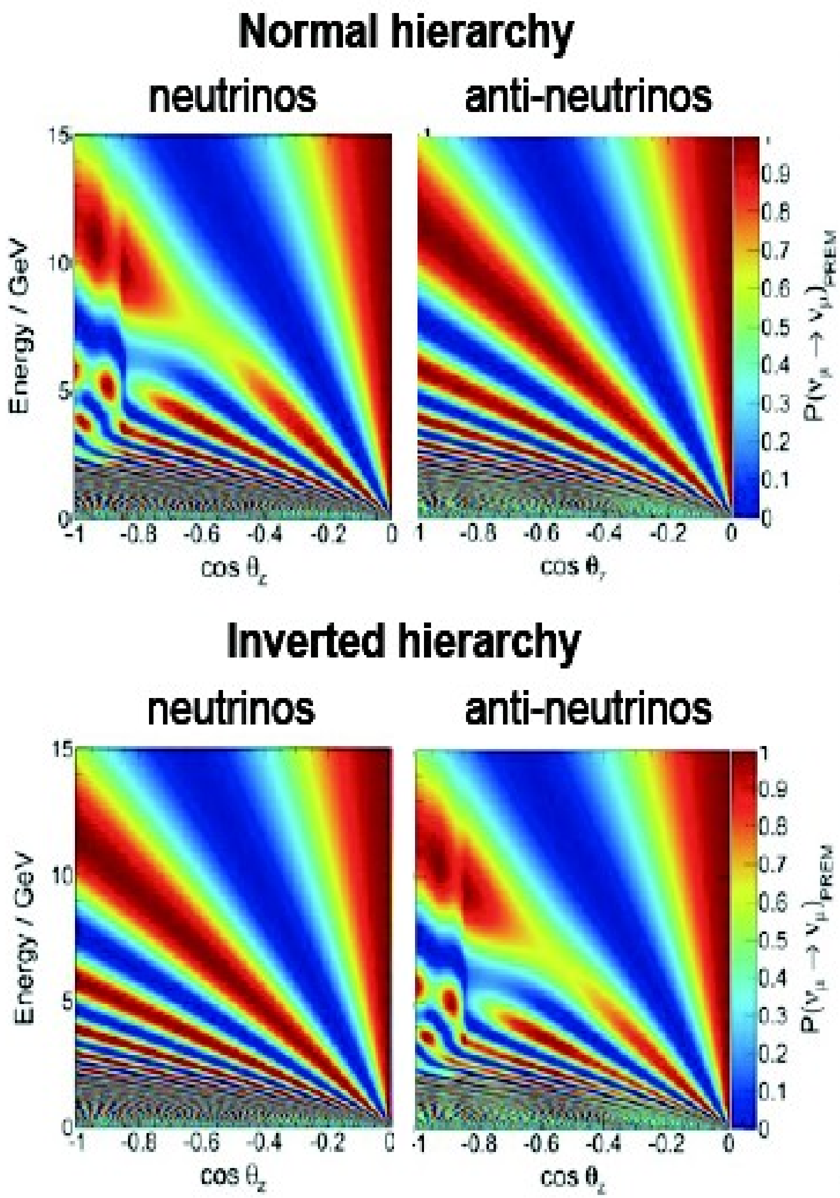
  $\Delta m_{32}^2 < 0 \rightarrow$ Inverted hierarchy (IH)



Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy





- Maximum effect NH ↔ IH for θ=130° at 7 GeV
- For $\bar{\nu}$ NH and IH approximately swapped

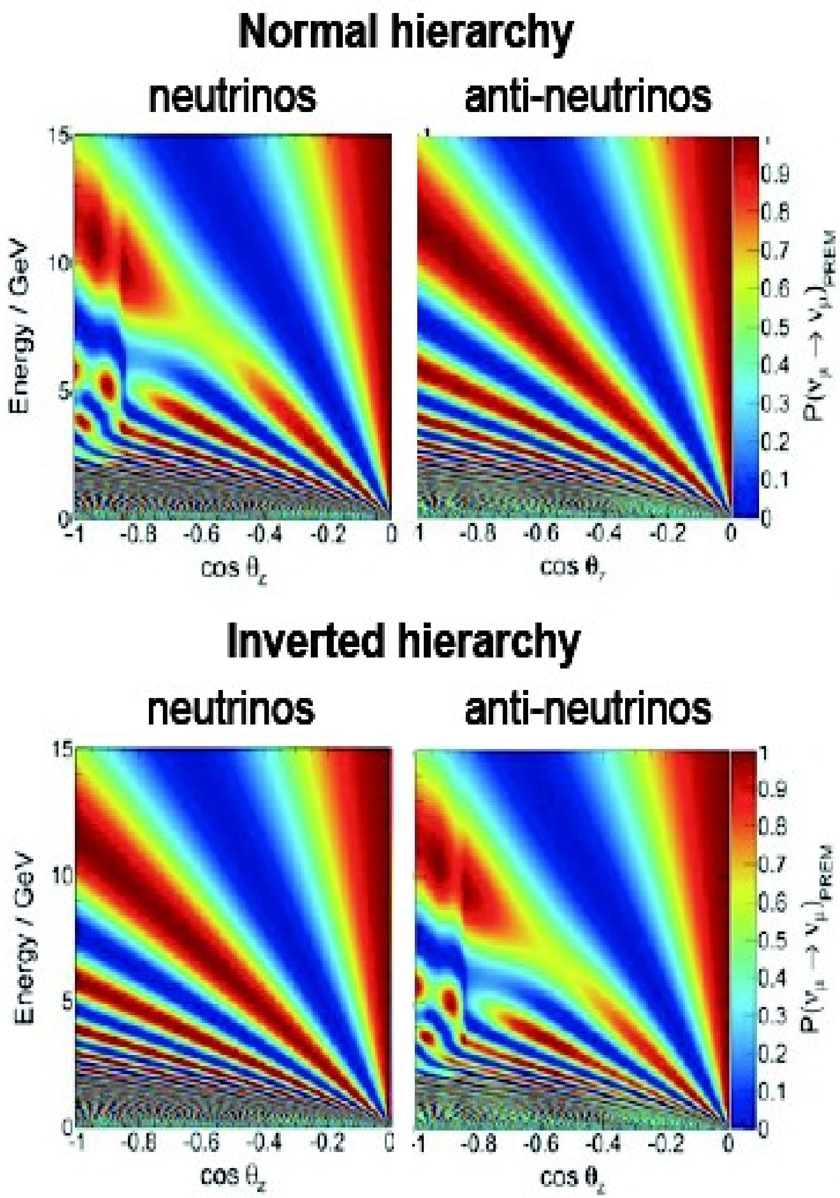
Recap: $\xi = \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \frac{A_{CC}}{\Delta m^2}\right)^2}$

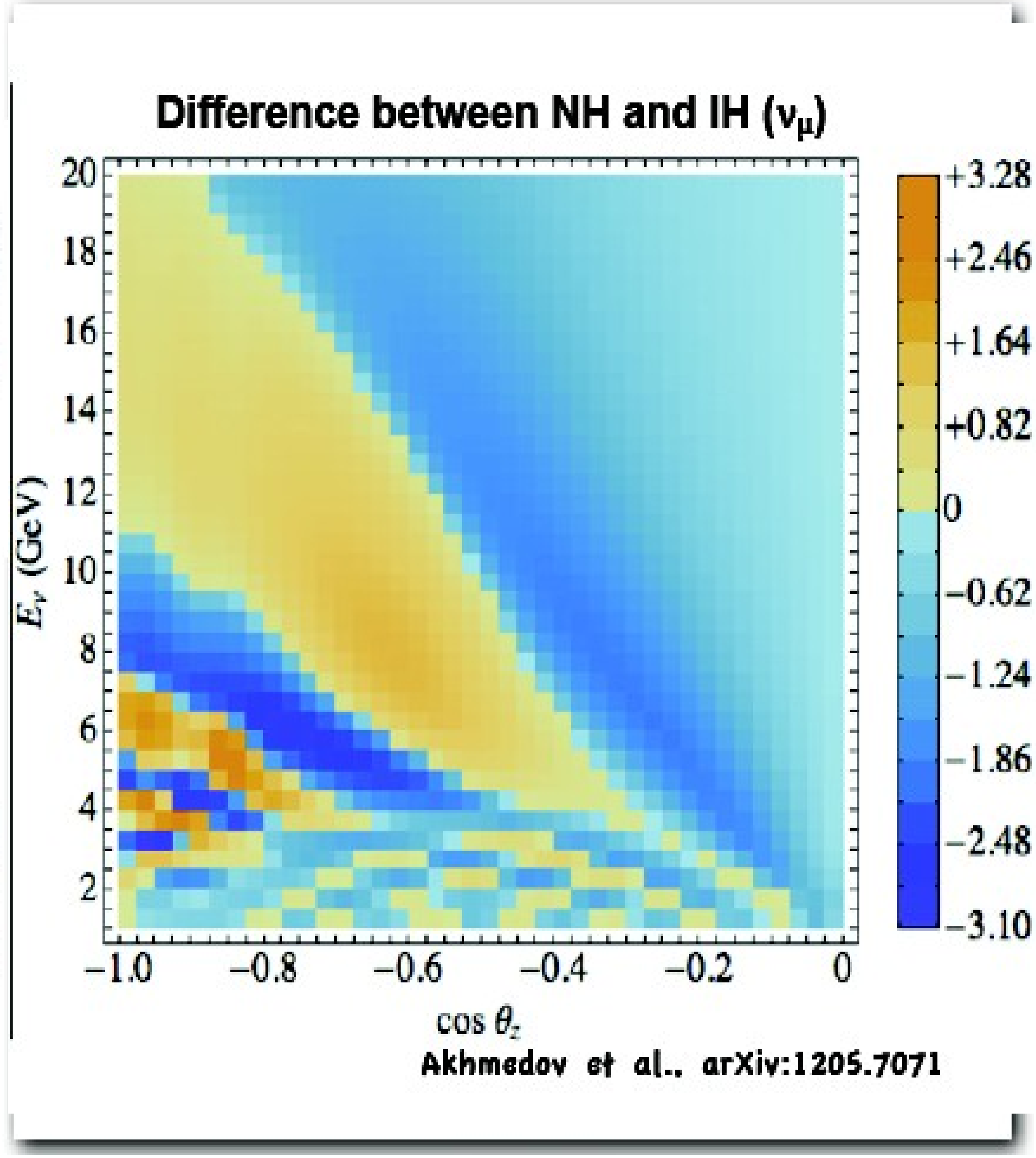
→ effect cancels if detected $N(\nu) = N(\bar{\nu})$

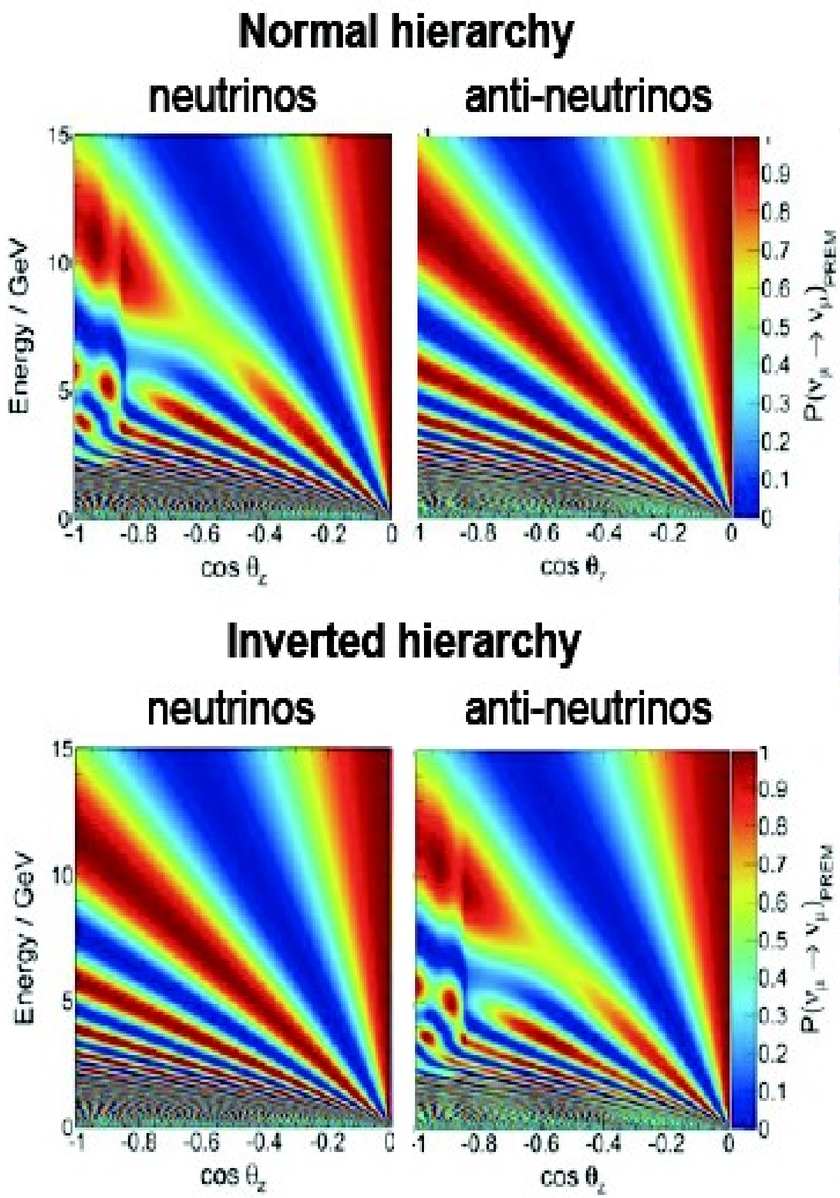
- Fortunately, $\text{flux}(\nu_{atm}) \approx 1.3 \times \text{flux}(\bar{\nu}_{atm})$
  and $\text{xsec}(\nu) \approx 2 \times \text{xsec}(\bar{\nu})$

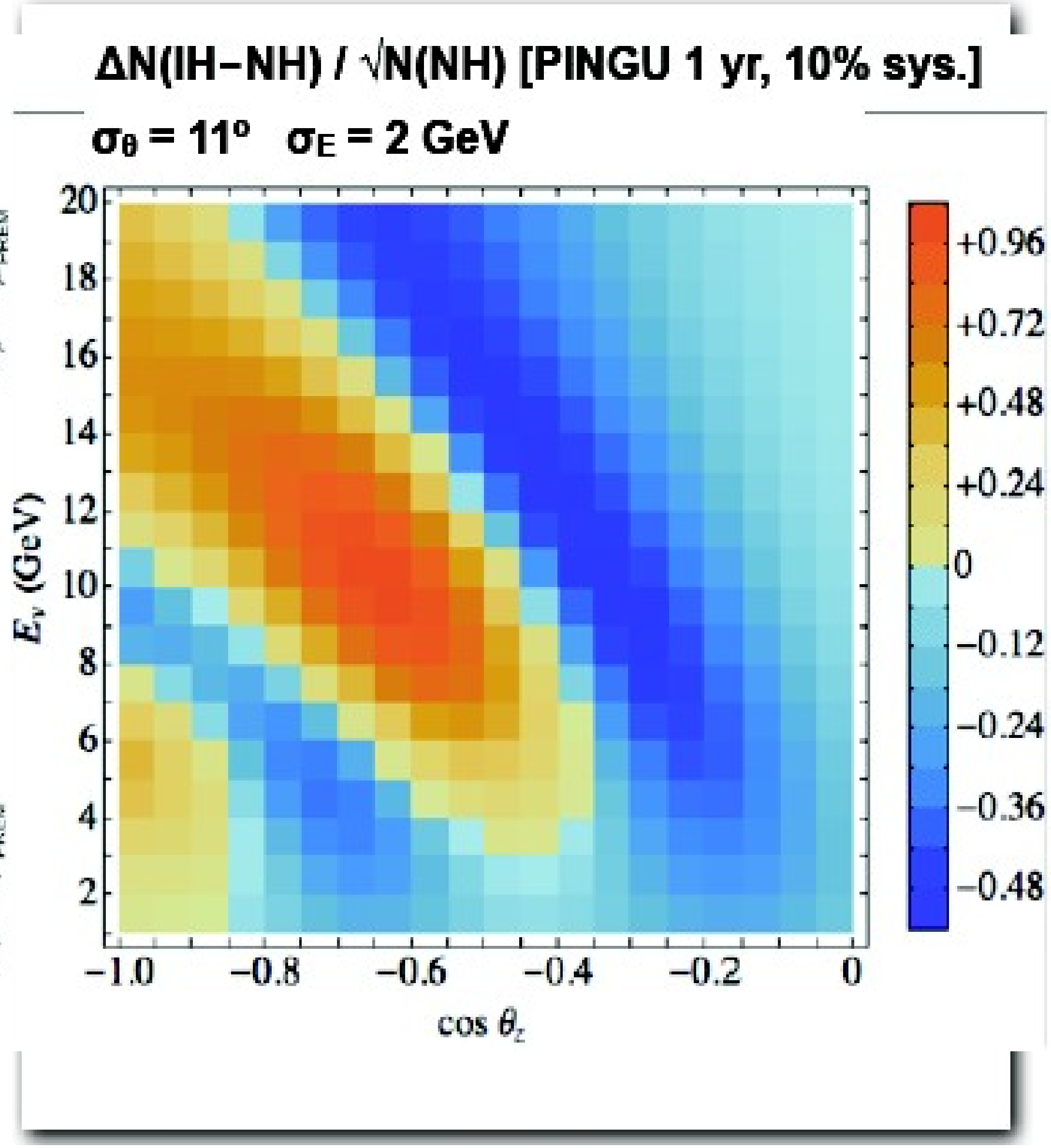
⇒ Count $N_\mu(E,\theta)$ from $\nu_\mu + N \to \mu + X$
and compare with NH / IH predictions

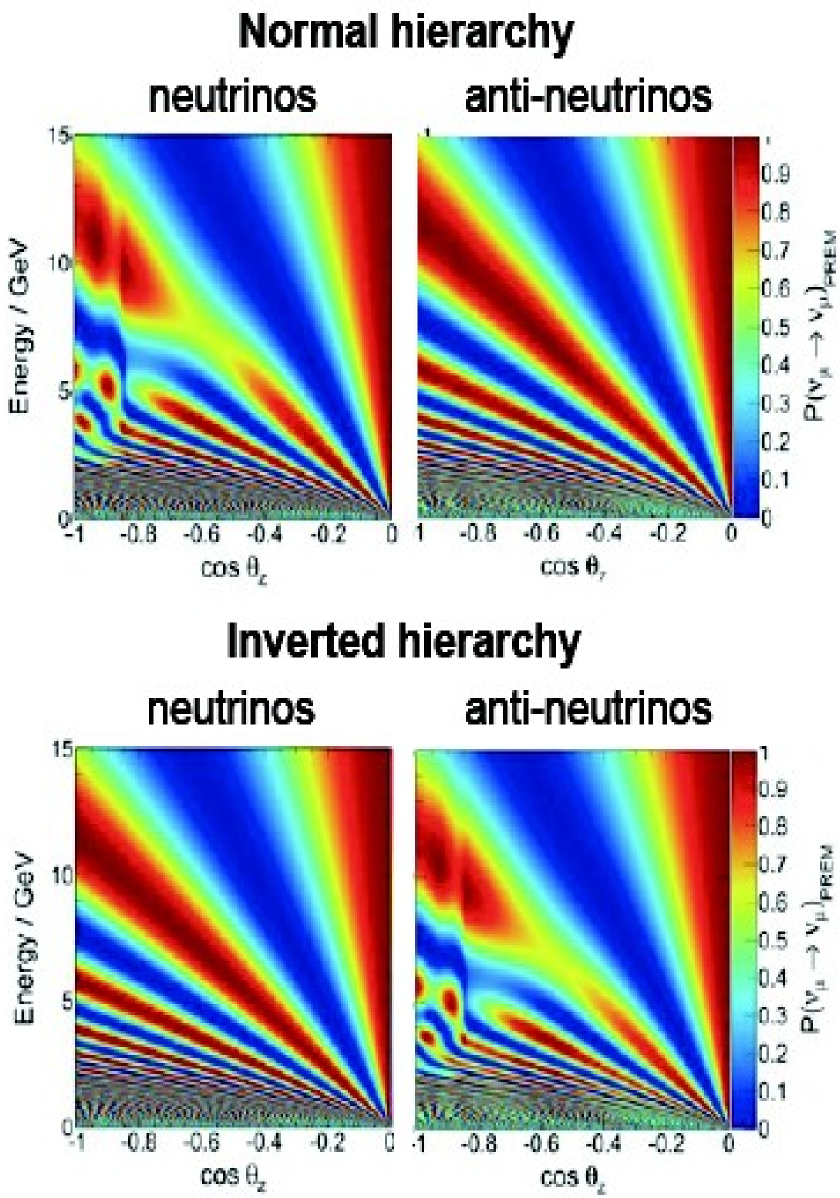
Remark:
neutrino telescopes inherently insensitive to $\nu \leftrightarrow \bar{\nu}$

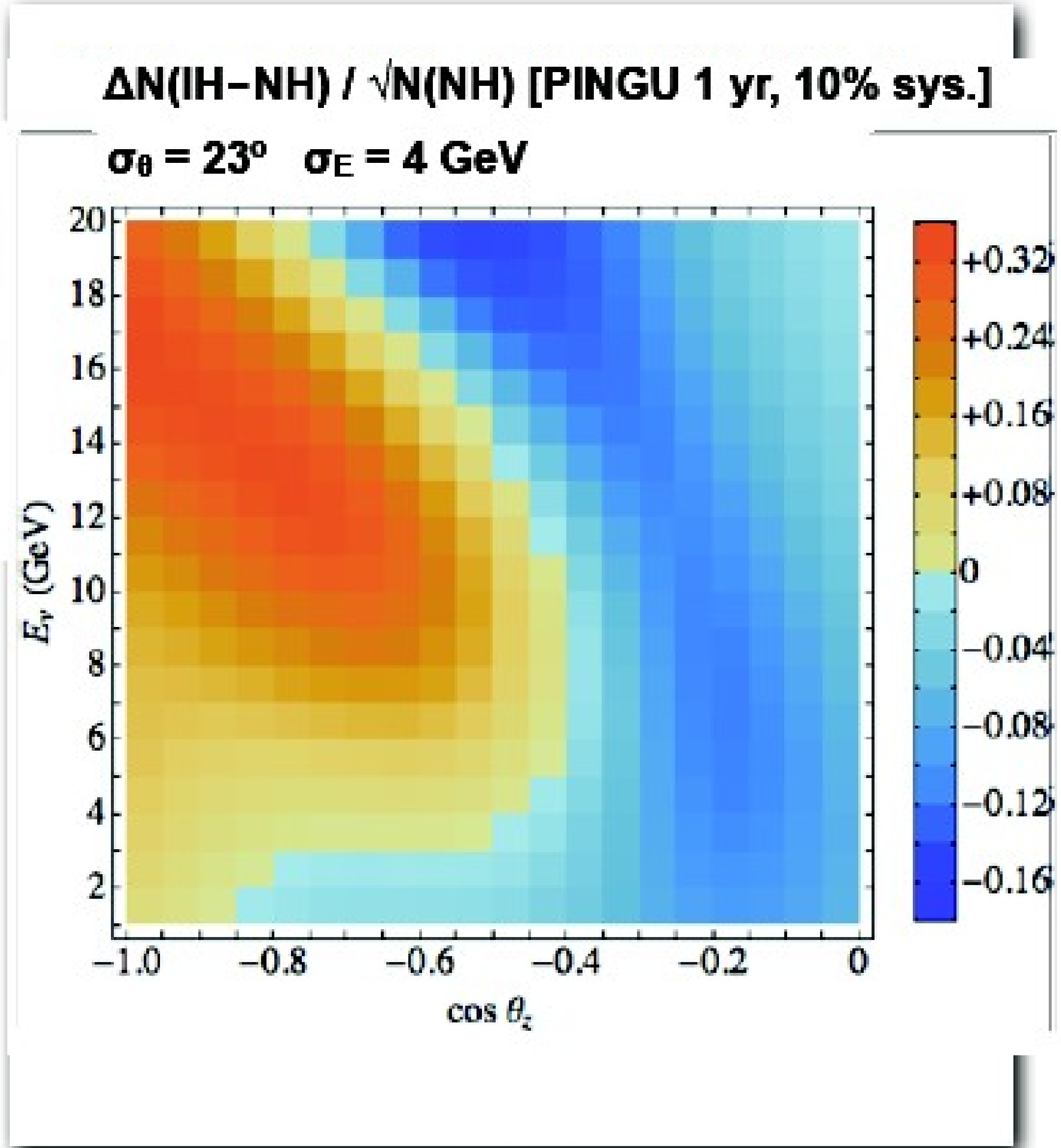

Normal hierarchy
neutrinos
anti-neutrinos
Inverted hierarchy
neutrinos
anti-neutrinos
Energy / GeV
cos θz
P(νμ → νμ)PREM


Difference between NH and IH (νμ)
Eν (GeV)
cos θz
+3.28
+2.46
+1.64
+0.82
0
−0.62
−1.24
−1.86
−2.48
−3.10
Akhmedov et al., arXiv:1205.7071


Normal hierarchy
neutrinos
anti-neutrinos
Energy / GeV
cos θz
Inverted hierarchy
neutrinos
anti-neutrinos
Energy / GeV
cos θz

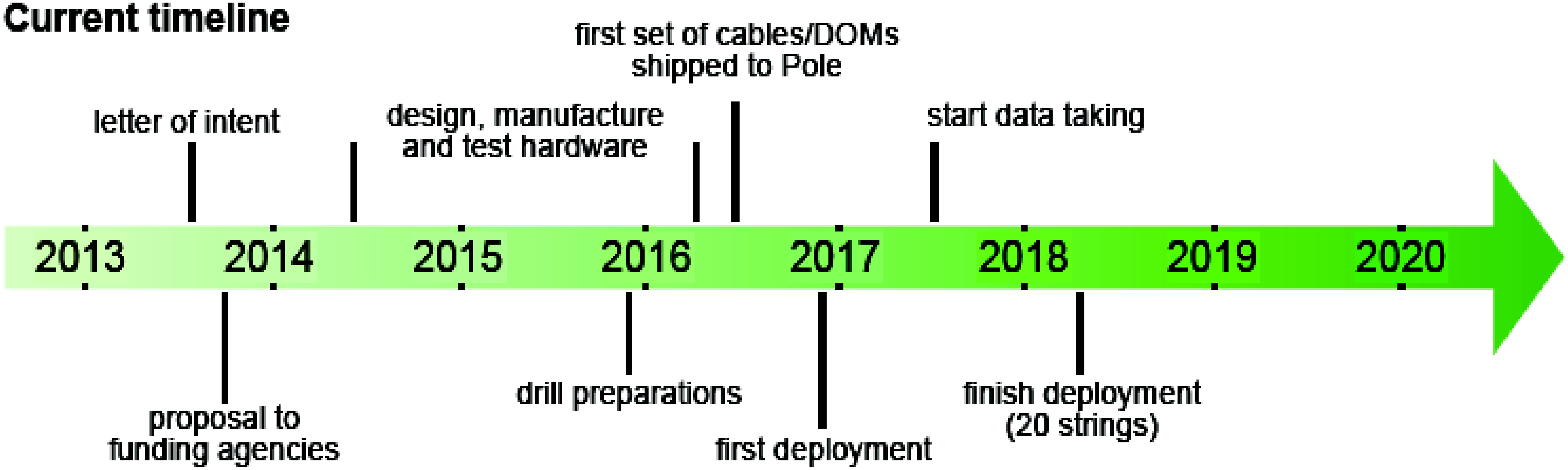

ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]
σθ = 11°   σE = 2 GeV
Eν (GeV)
cos θz
+0.96
+0.72
+0.48
+0.24
0
−0.12
−0.24
−0.36
−0.48


Normal hierarchy
neutrinos
anti-neutrinos
Inverted hierarchy
neutrinos
anti-neutrinos
Energy / GeV
cos θz
P(νμ → νμ)PREM

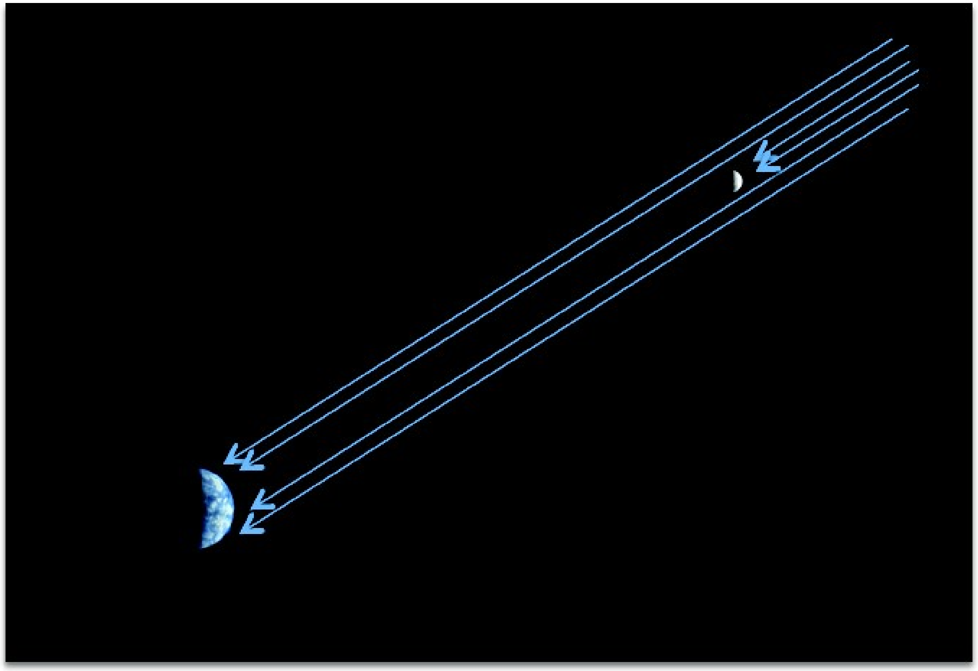

ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]
σθ = 23°   σE = 4 GeV
Eν (GeV)
cos θz

- Moderate timeline of ~10 years (data taking could start in 2017)
- Overall low risk for construction and operation (IceCube experience)
- Costs: ~10 M$ for startup (includes drill reactivation) + 1.25 M$ per string

Current timeline

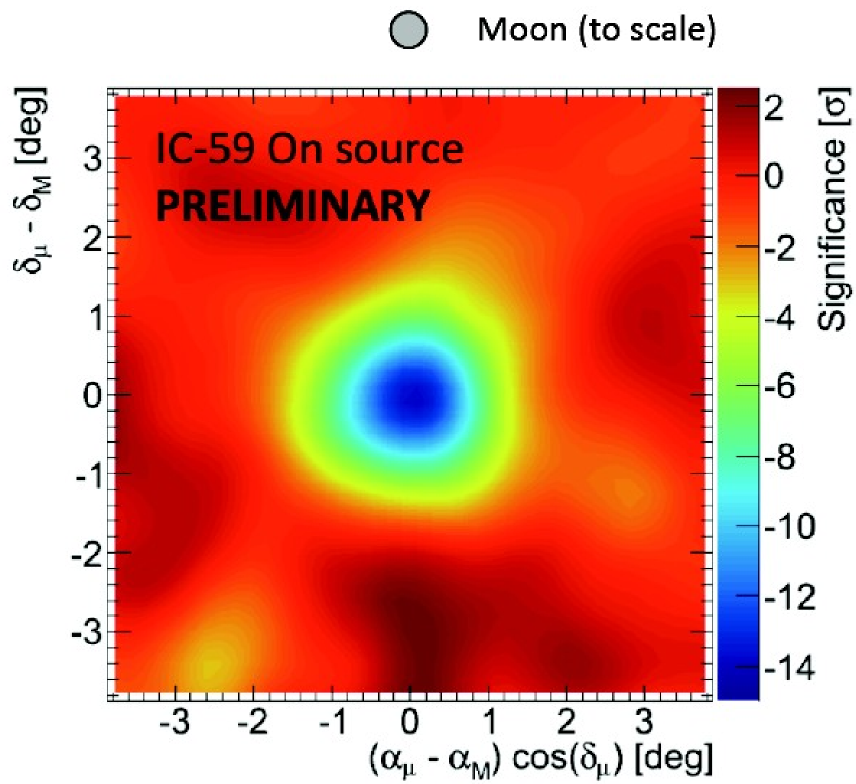


Cosmic Ray Moon Shadow



Cosmic rays are blocked by the moon (radius 0.25°)

Causes small point-like deficit of cosmic ray showers detected by IceCube

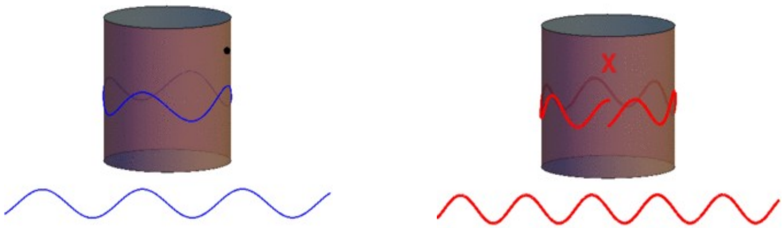


Spoiler alert: there are no neutrino sources bright enough to calibrate pointing with!

But, cosmic ray moon shadow "negative" source is used to verify:

- absolute pointing is correct
- ~1° typical point spread function (size of deficit and shape agree with sim.)

- **Universal Extra Dimensions**:



$$n\frac{\lambda}{2} = 2\pi R, \qquad n\frac{h}{2p} = 2\pi R \;\Rightarrow\; p = n\frac{h}{4\pi R}$$

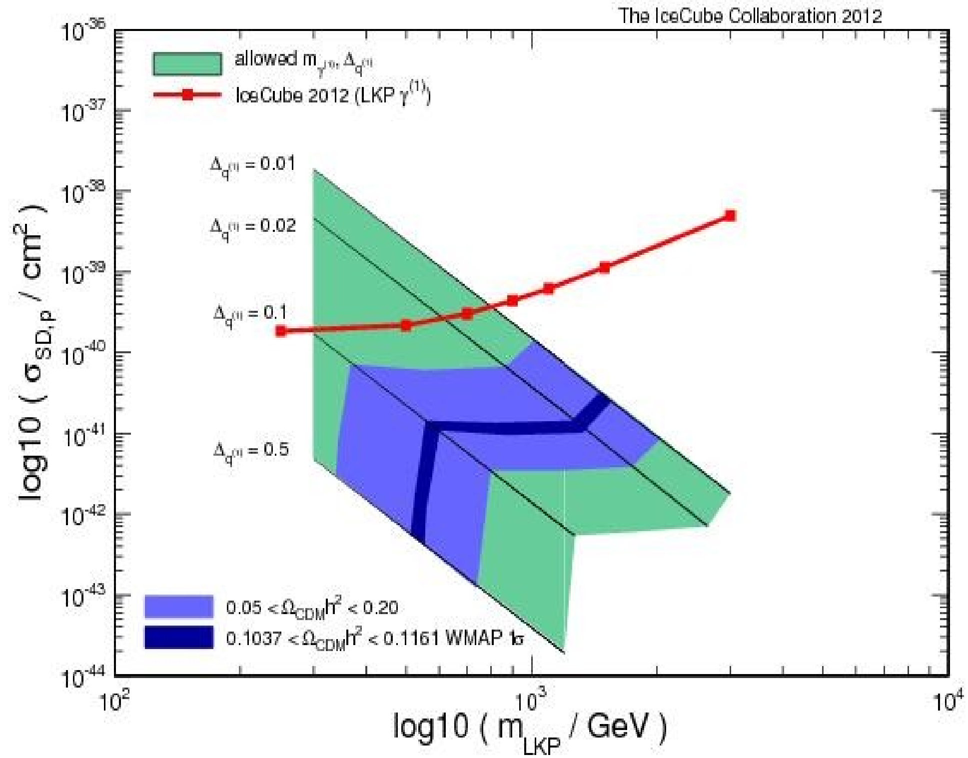
$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

$$m_n^2 = \frac{n^2}{c^2R^2} + m_o^2$$

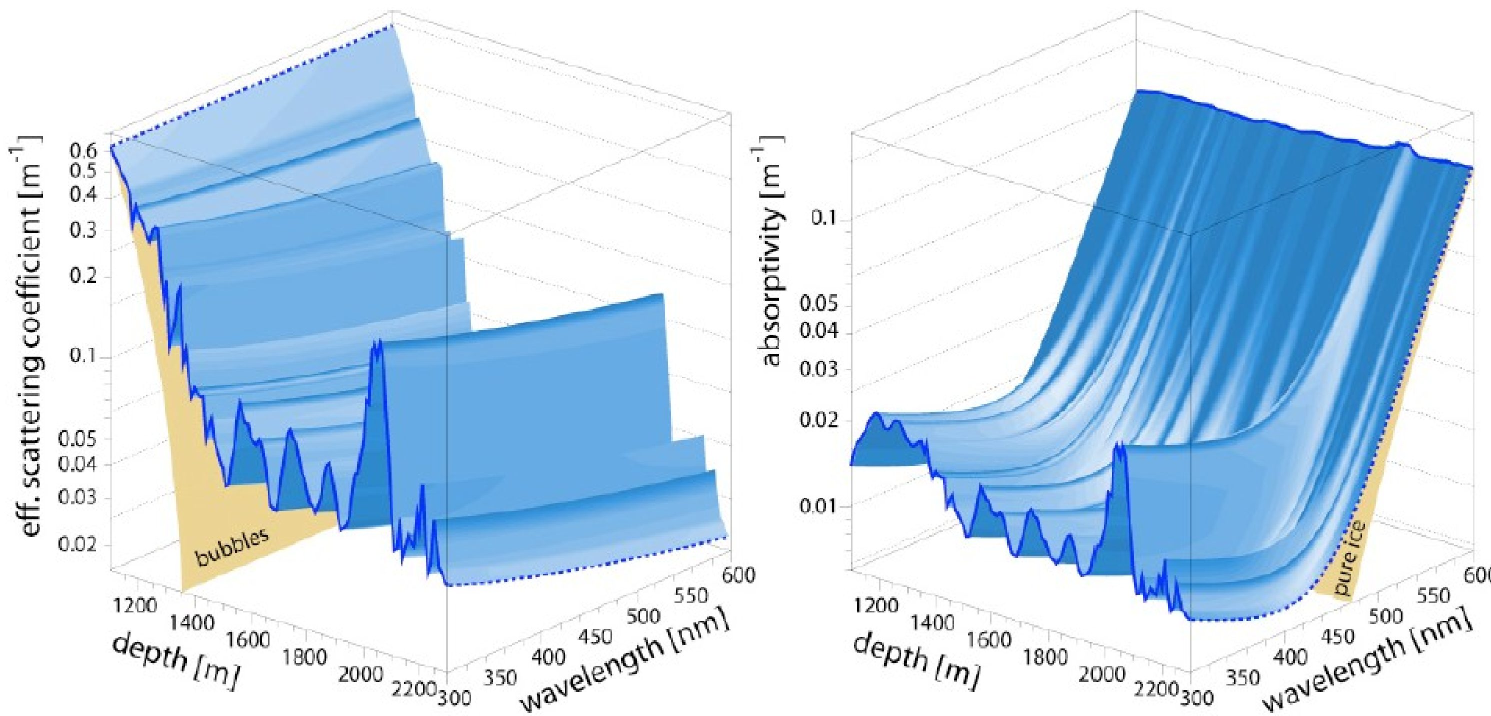
n=1 → Lightest Kaluza-Klein mode, **B**[1]

good DM candidate

90% CL LKP-p Xsection limit vs LKP mass



- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $\langle\lambda_{eff}\rangle \sim 47$ m, $\langle\lambda_{abs}\rangle \sim 155$ m



- Constant temperature ~ -35C