Highlights and Plans from IceCube

Carsten Rott

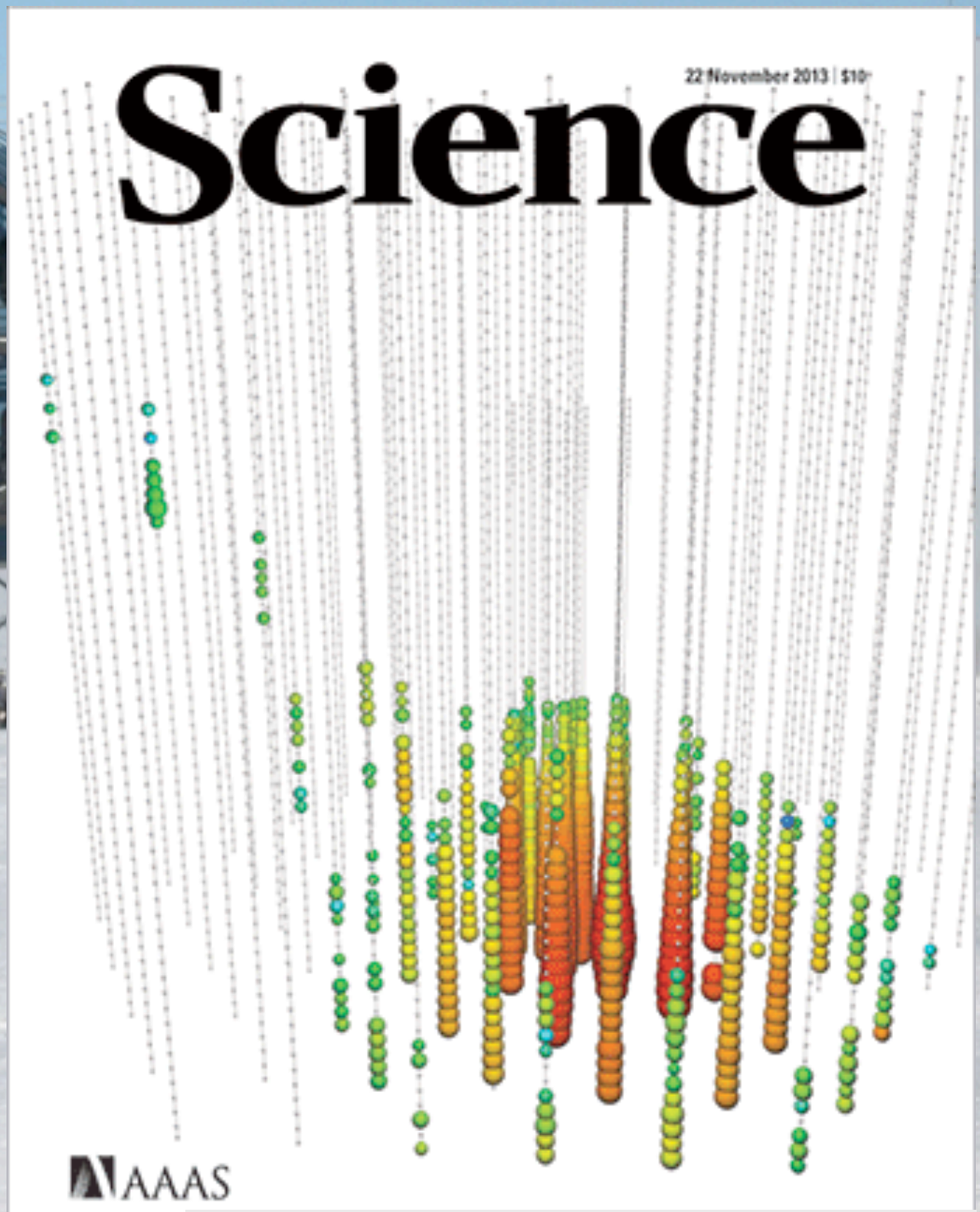
for the IceCube Collaboration

Sungkyunkwan University, Korea

rott@skku.edu

Outline

- Motivation
- The IceCube Detector
- Selected Results
- Outlook and Conclusions



http://www.sciencemag.org/content/342/6161/1242856

The IceCube Collaboration

IceCube

Stockholm University
Uppsala Universitet

University of Alberta

University of Oxford

Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal

Ecole Polytechnique
Fédérale de Lausanne
University of Geneva

Sungkyunkwan University
Chiba University

Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls

Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel

University of Adelaide
University of Canterbury

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube Collaboration

Sungkyunkwan University , Toronto and NBI latest additions 2013

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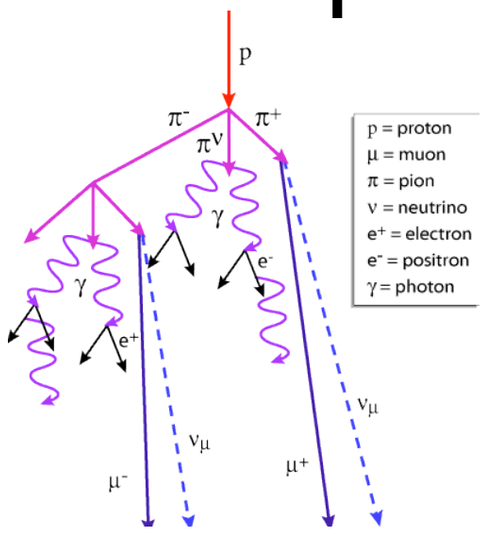
Sources of High Energy Neutrinos

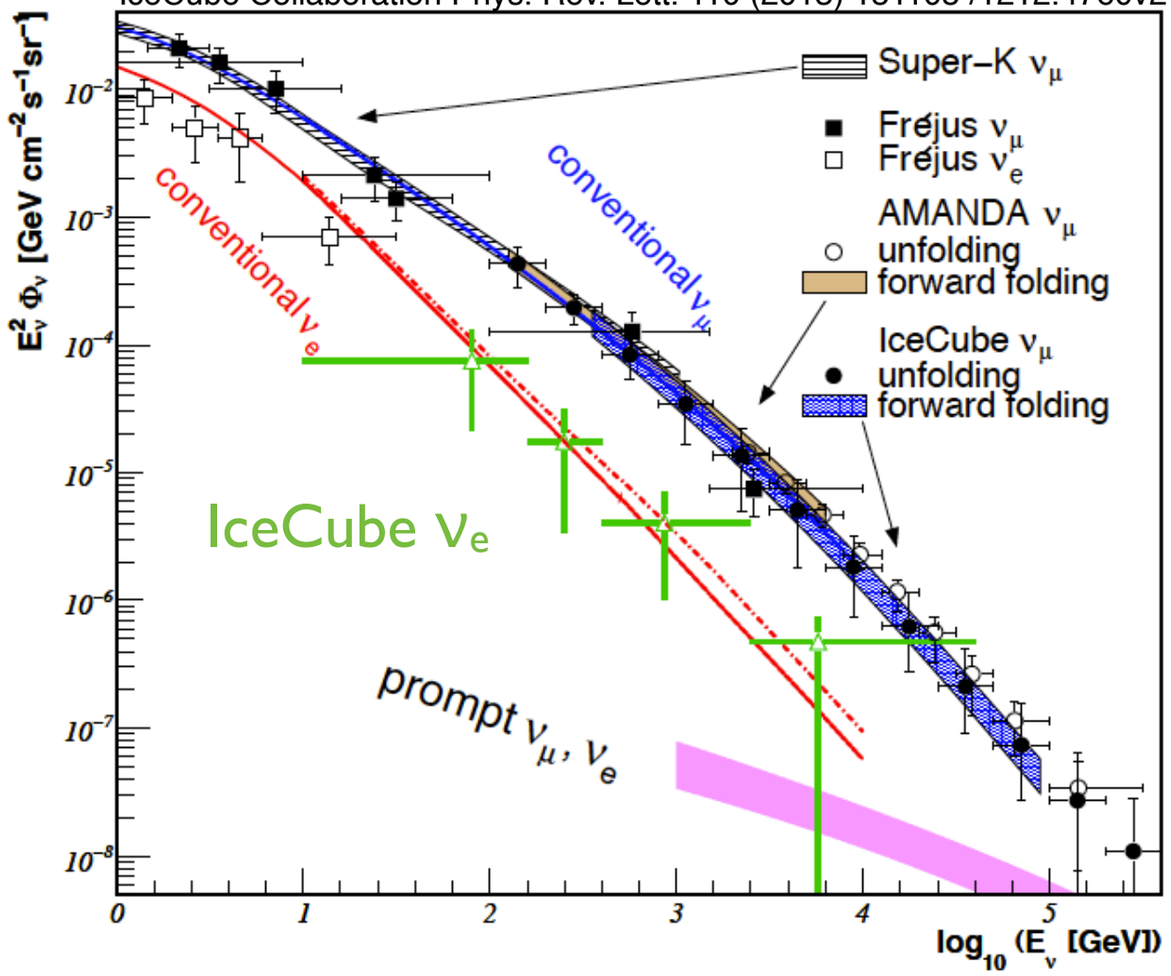
Atmospheric Neutrinos



Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^{\pm} (K^{\pm}) +$ other hadrons ... $\pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$

IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



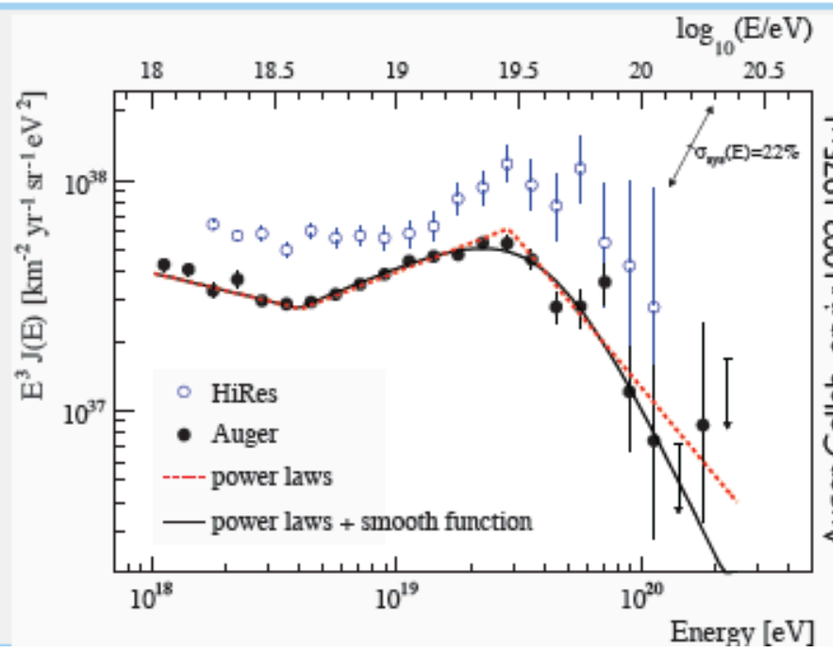
Astrophysical

$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

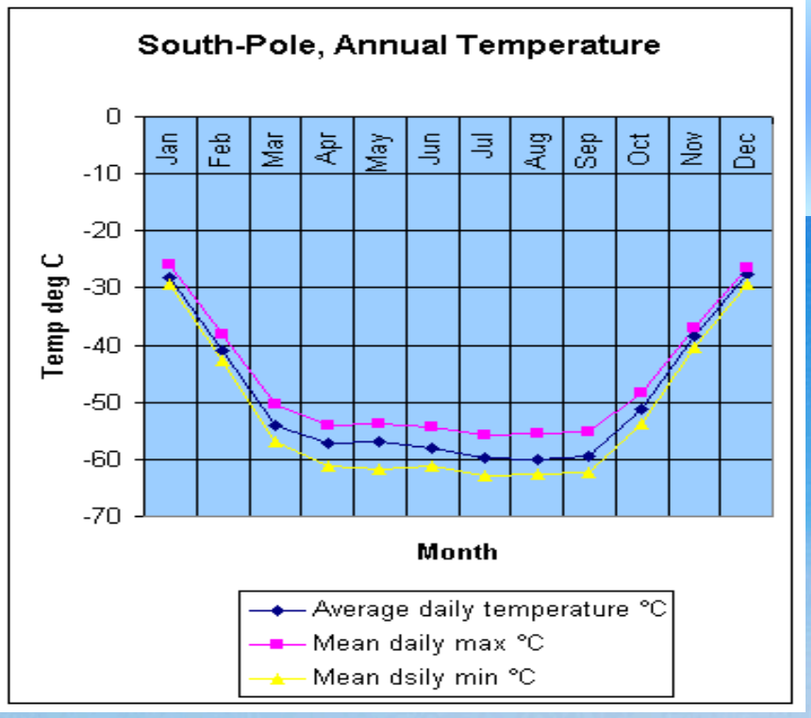
Active Galactic Nuclei

$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)



The IceCube Detector

Laboratory at the South Pole



Geographic South Pole

Amundsen Scott South Pole Station

Road to work

Skiway

1 km

IceCube

The IceCube Neutrino Telescope

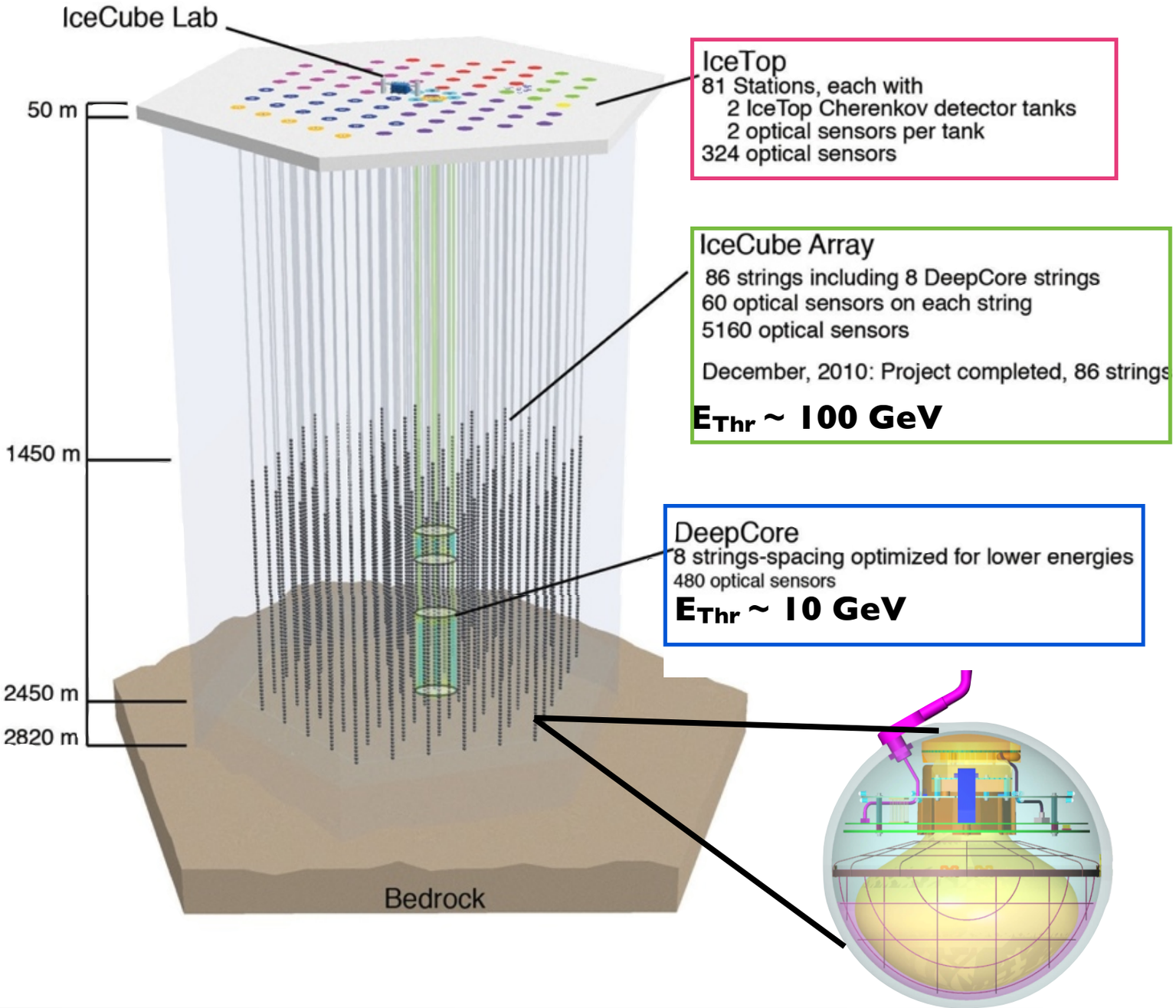
Gigaton Neutrino Detector at the Geographic South Pole

5160 Digital optical modules distributed over 86 strings

Completed in December 2010, start of data taking with full detector May 2011

Data acquired during the construction phase has been analyzed

Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice



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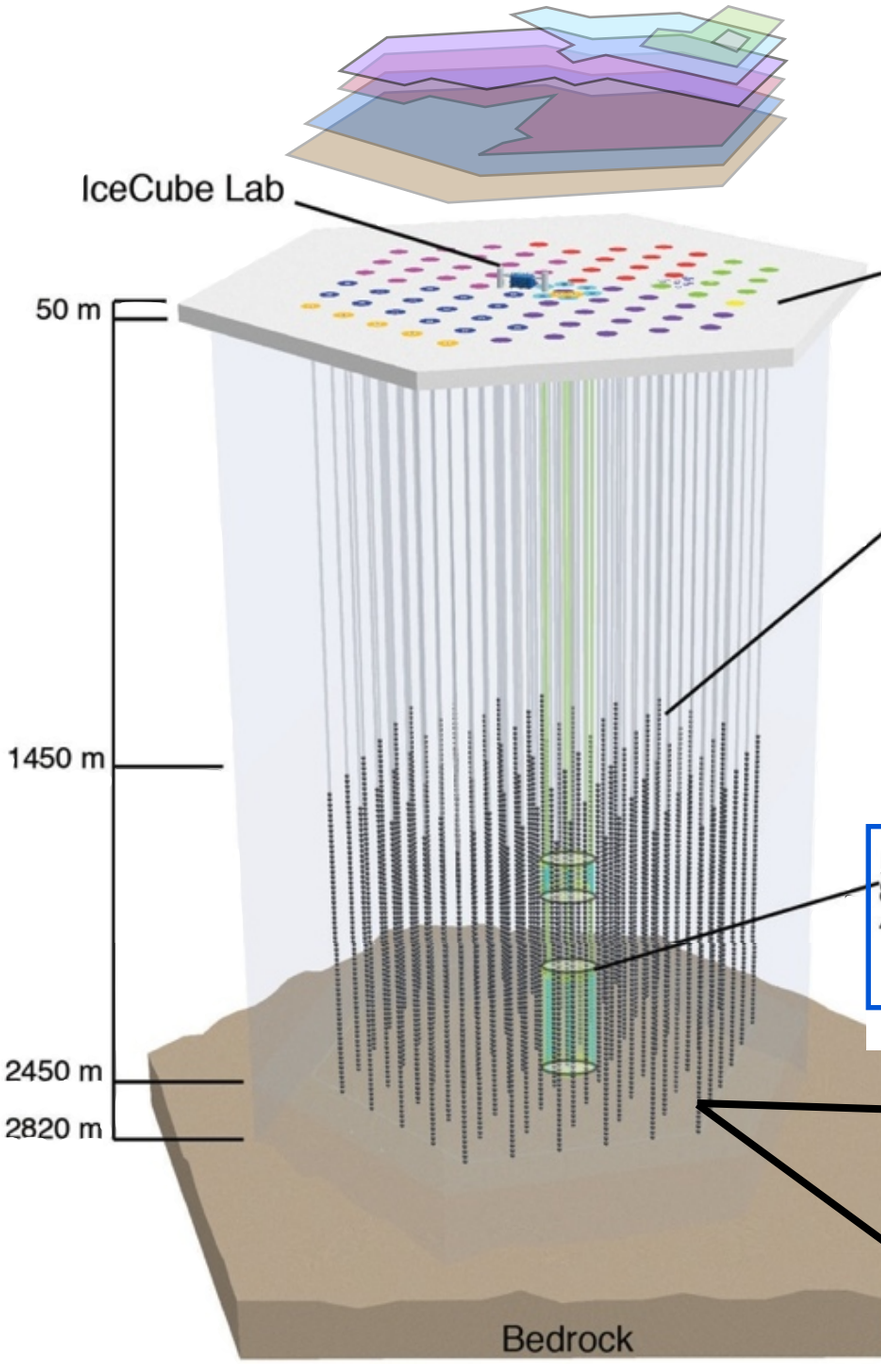
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



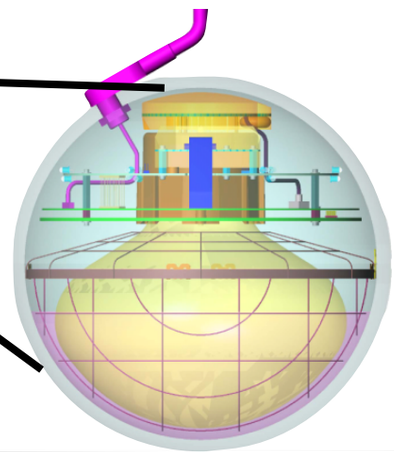
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

E_{Thr} ~ 100 GeV

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
E_{Thr} ~ 10 GeV



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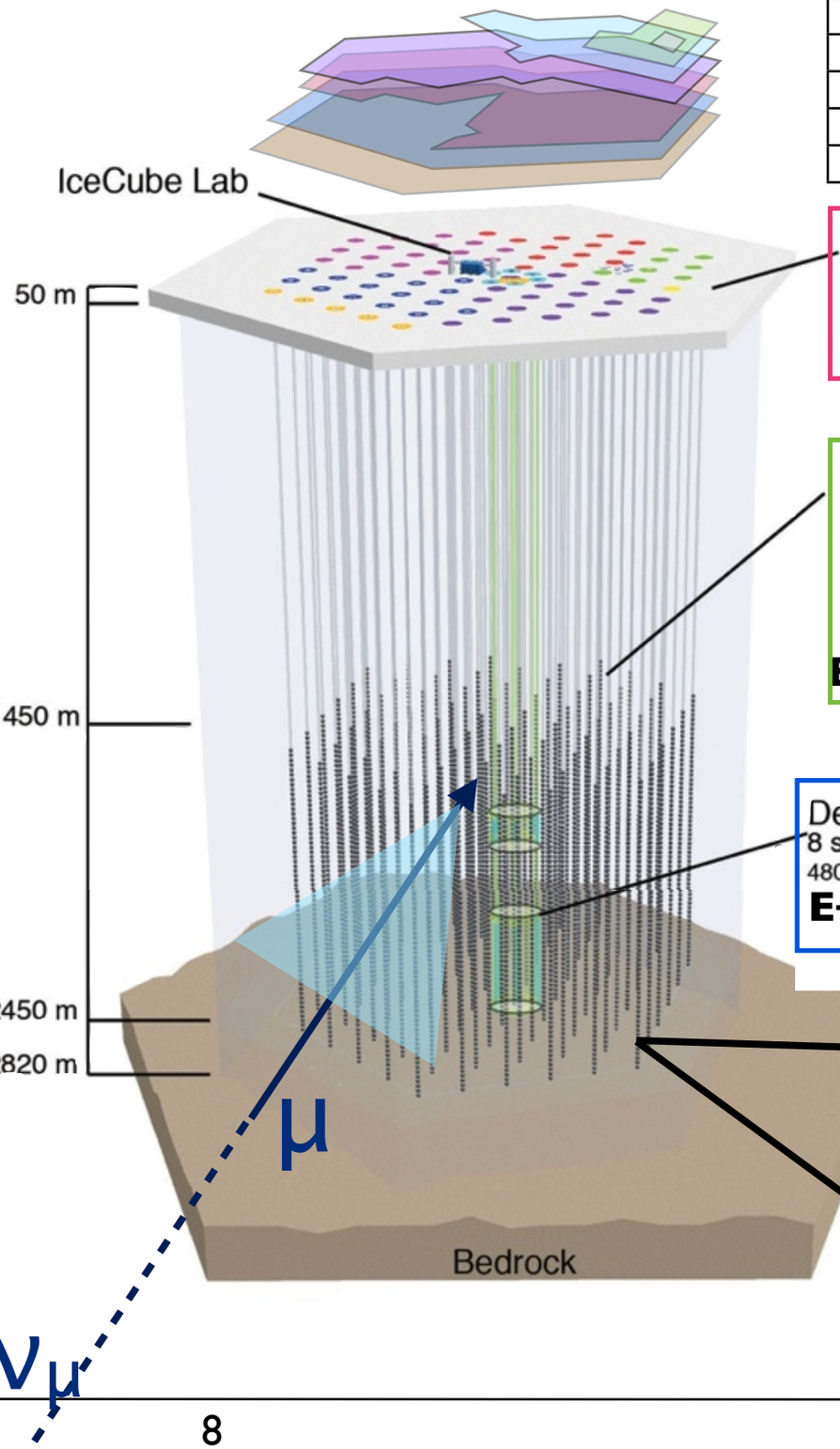

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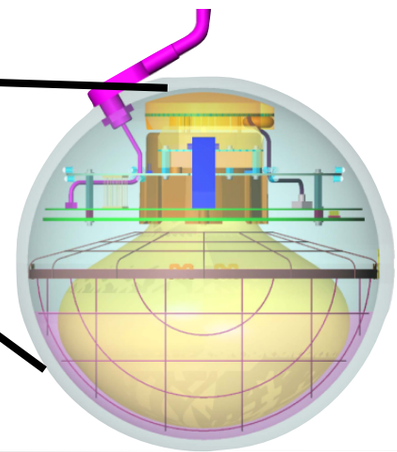


Signals in IceCube

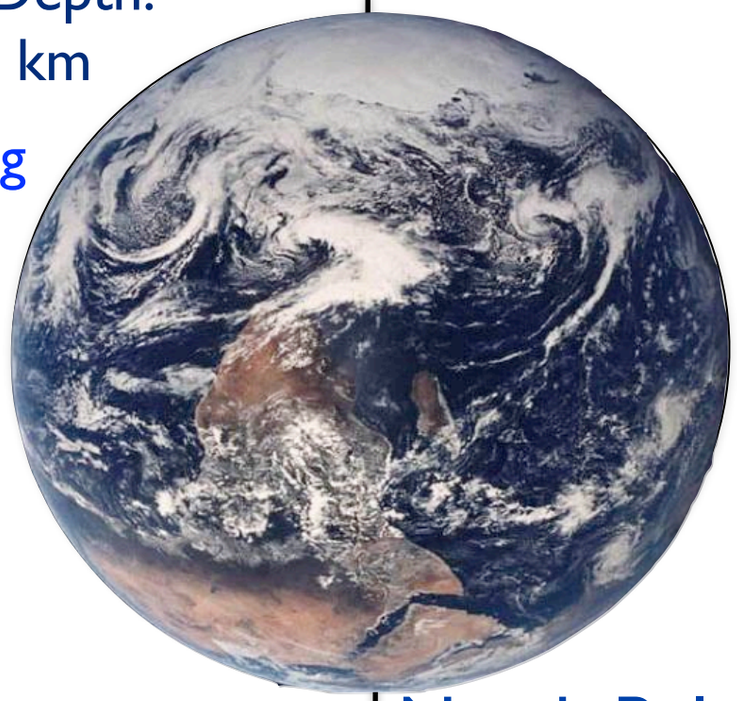
South Pole

$p + A \rightarrow \pi^{\pm} (K^{\pm}) +$ other hadrons ...

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

IceCube Depth: 1.5-2.5 km

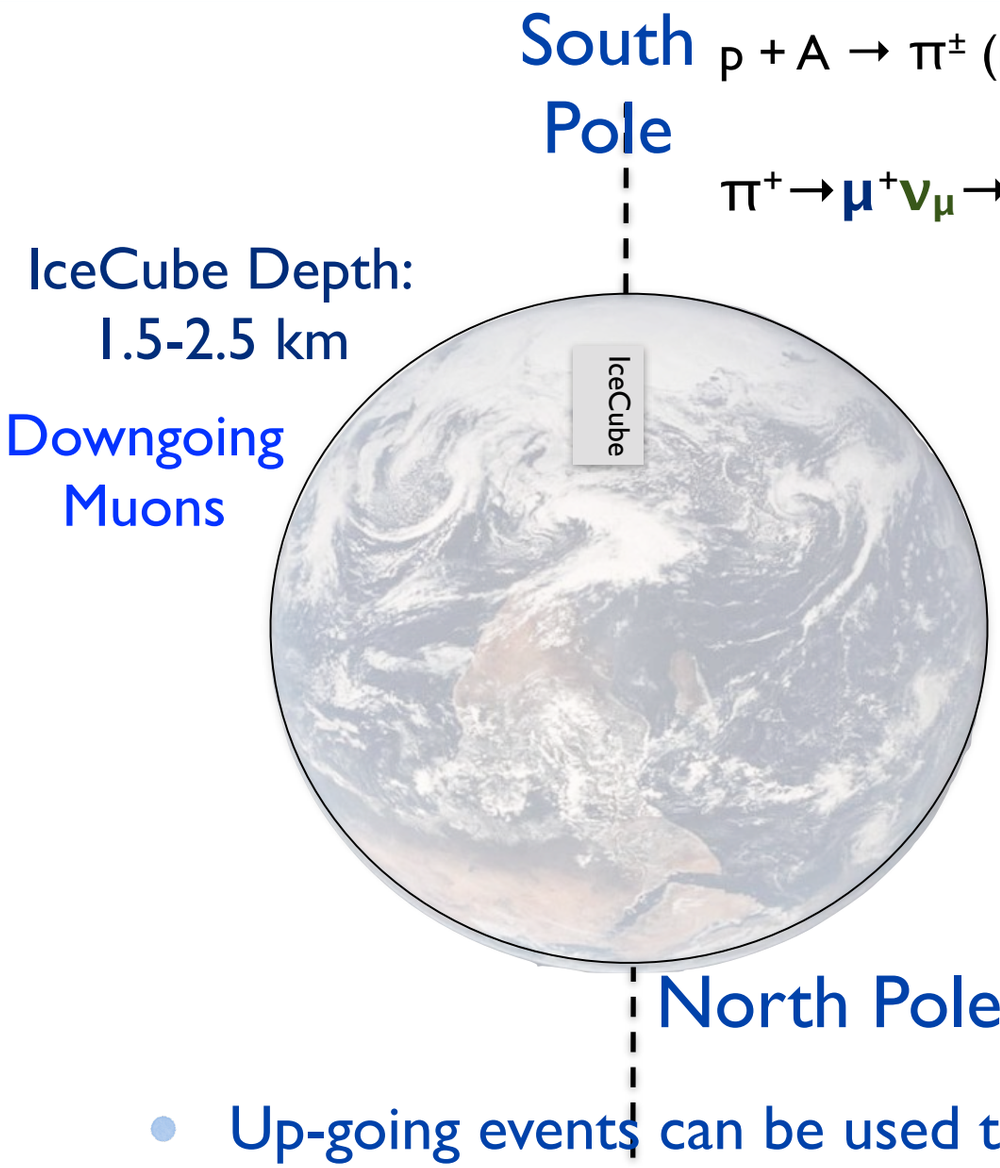
Downgoing Muons



North Pole

- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

Signals in IceCube



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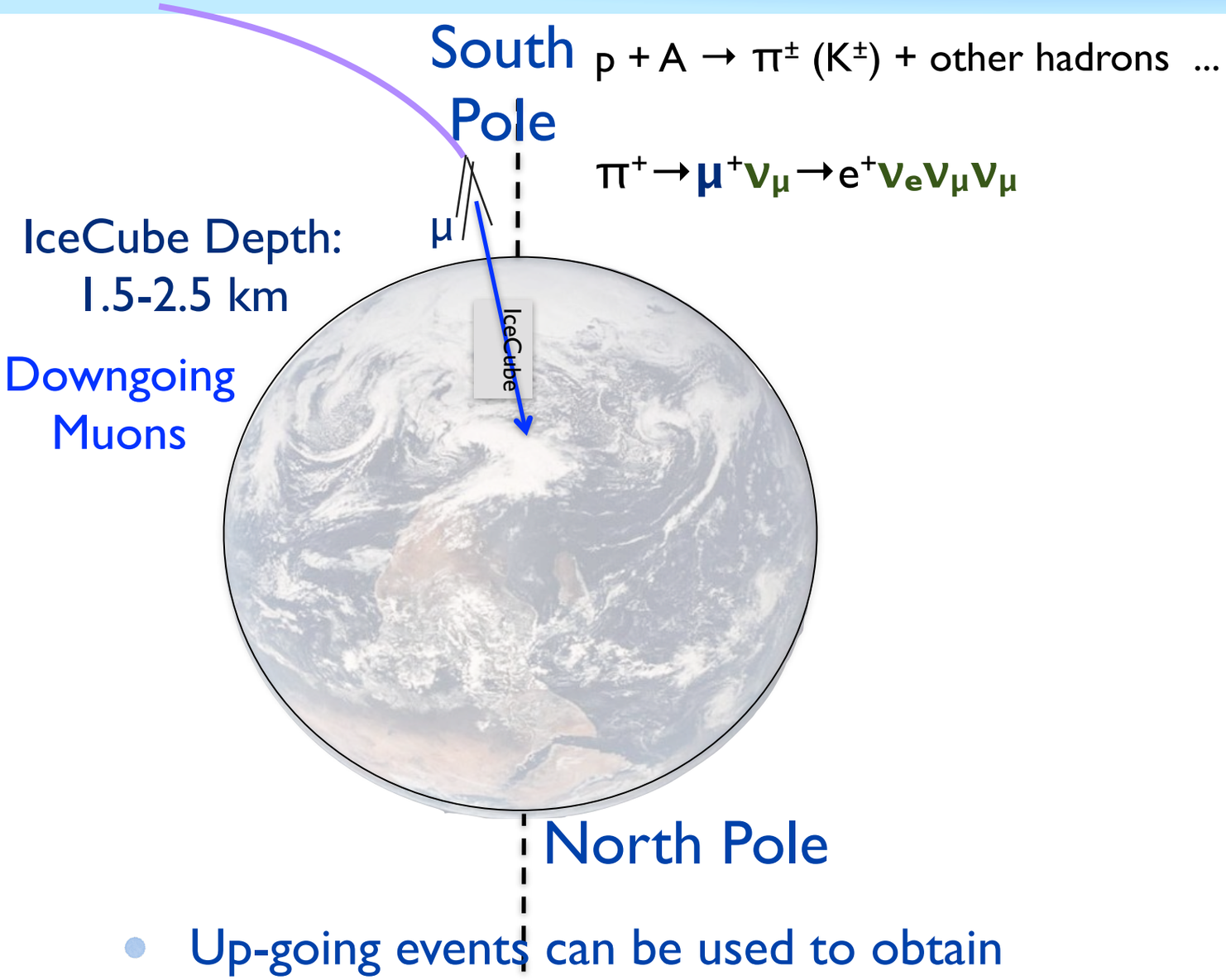

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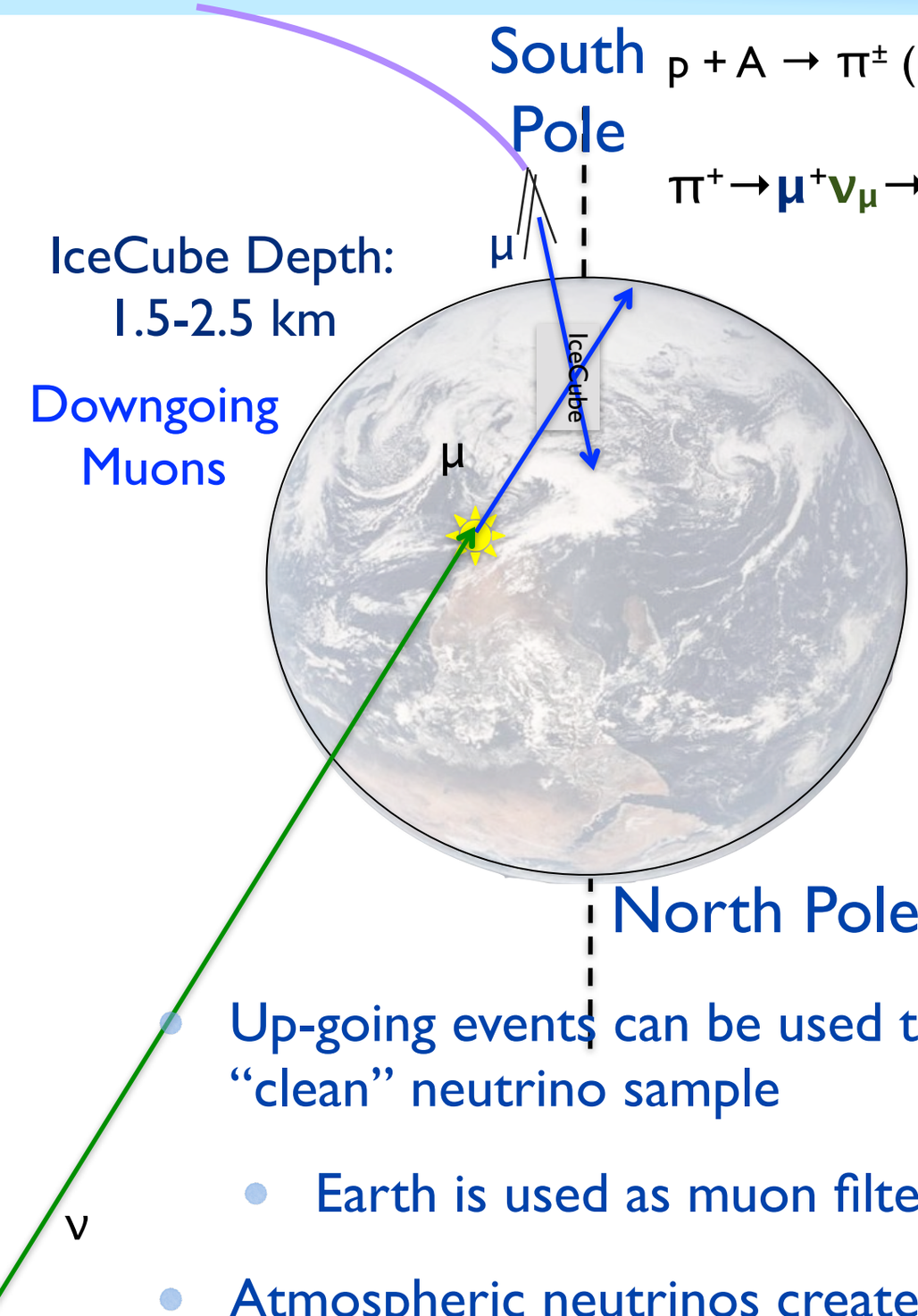

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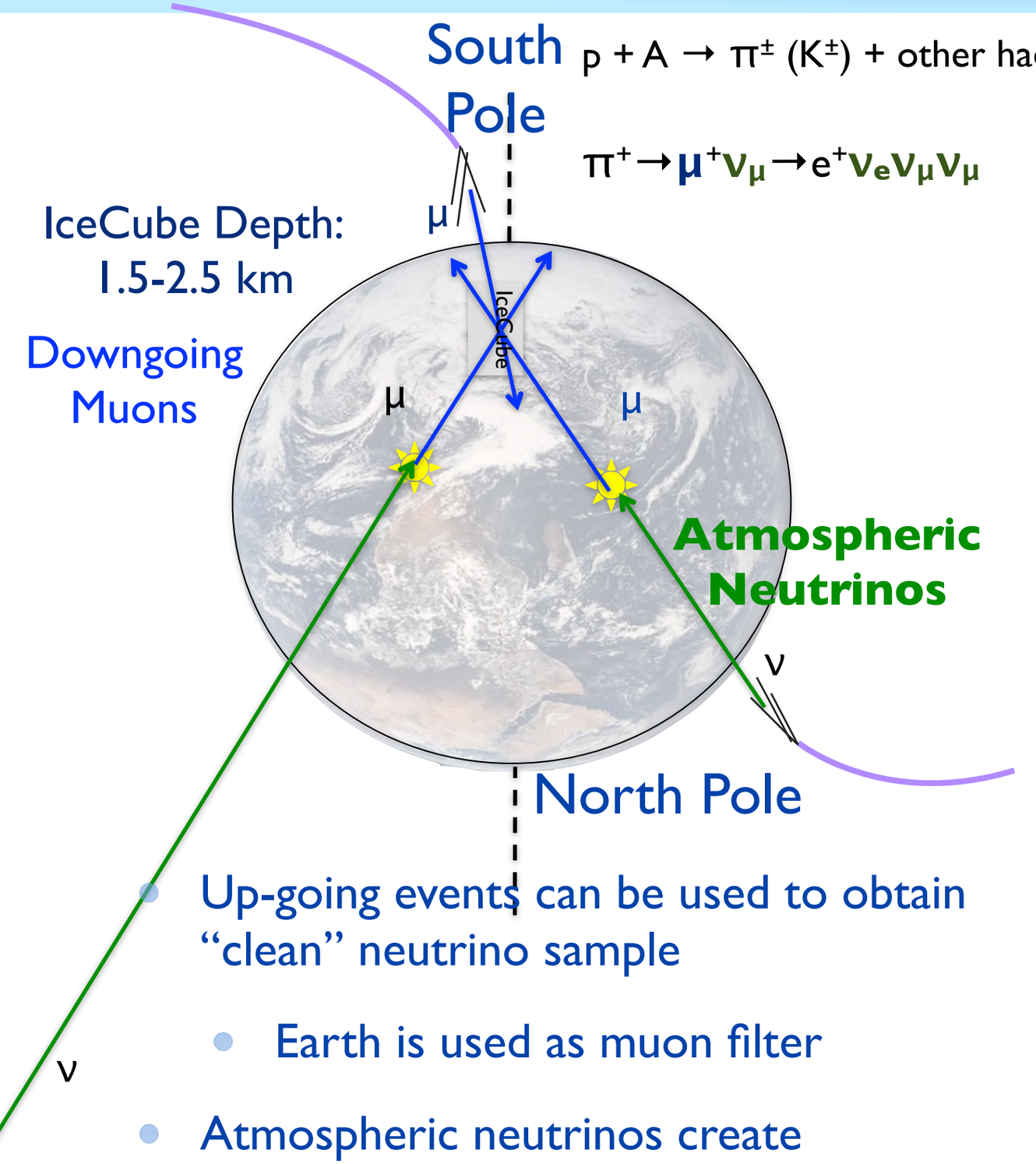

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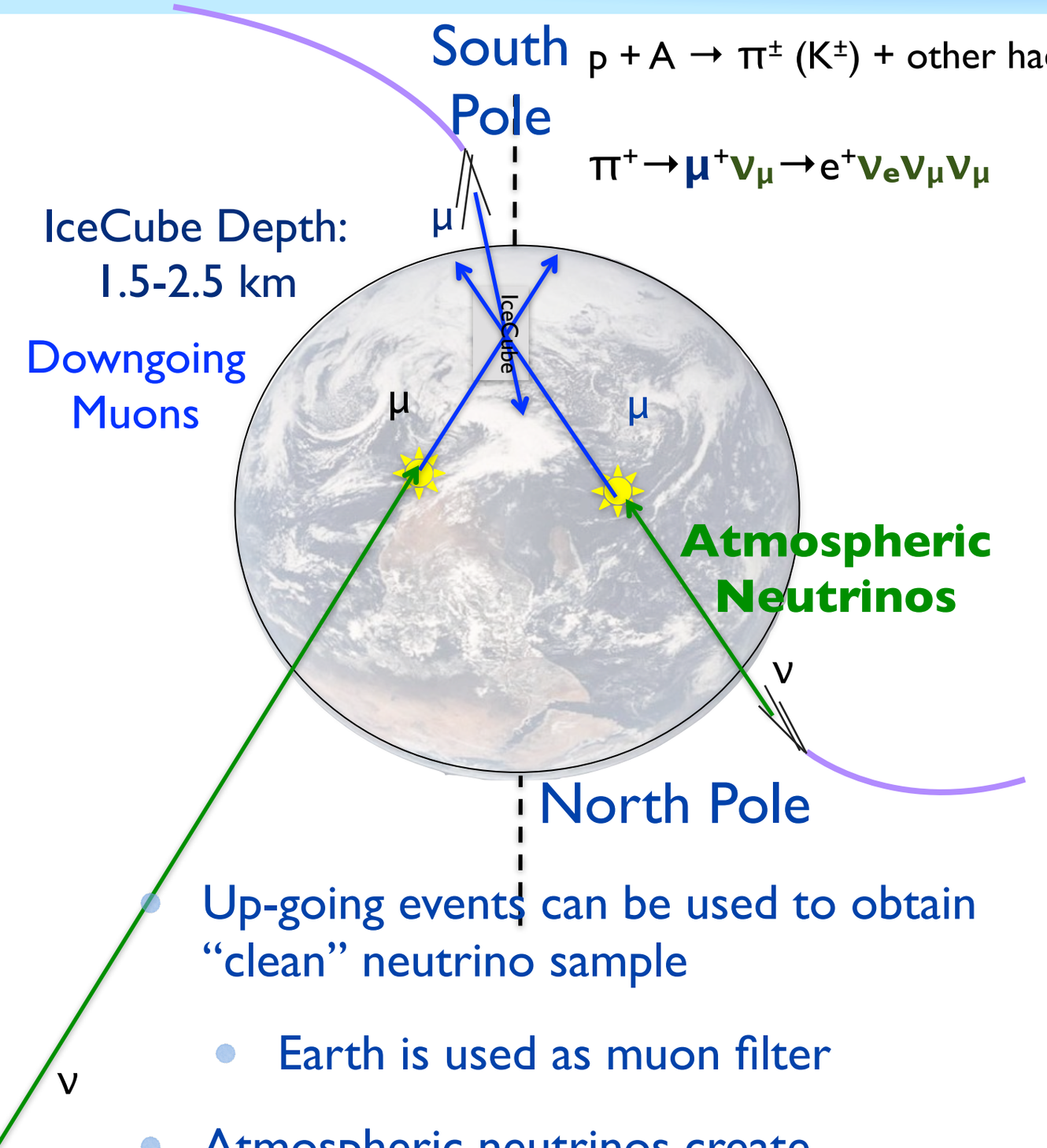

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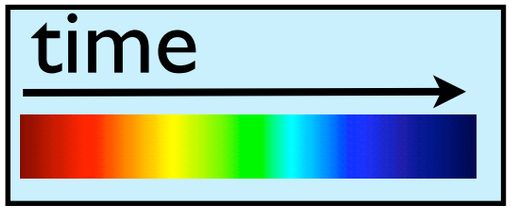

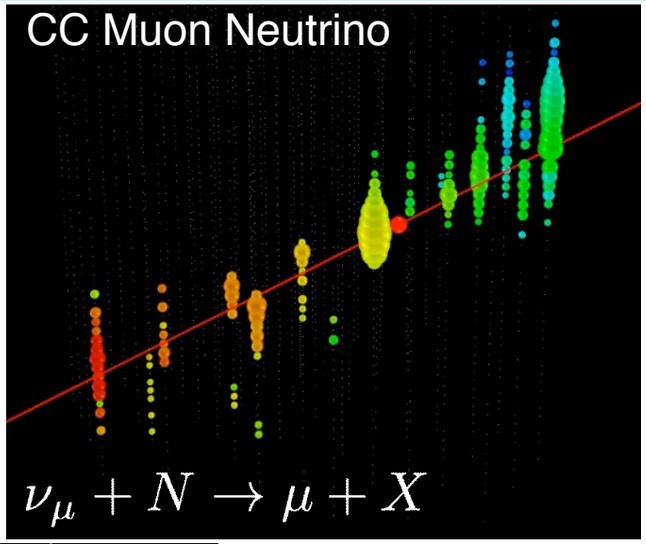

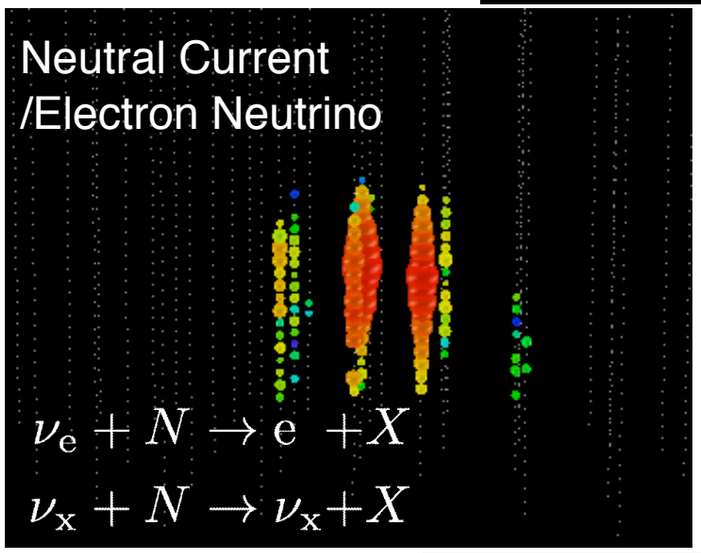

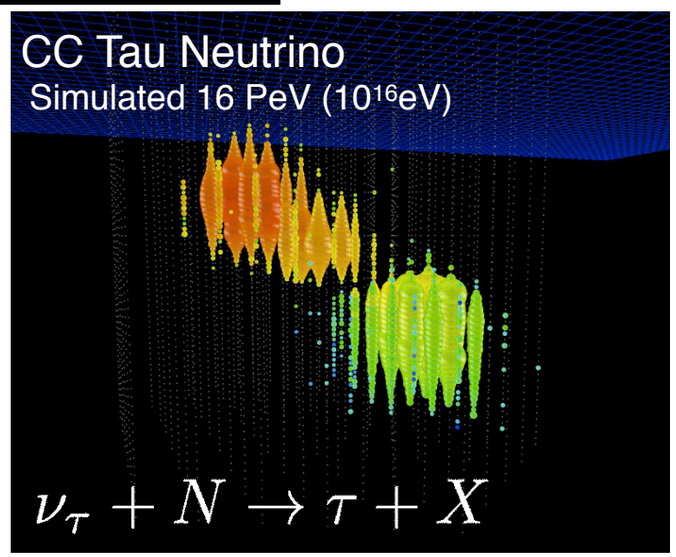

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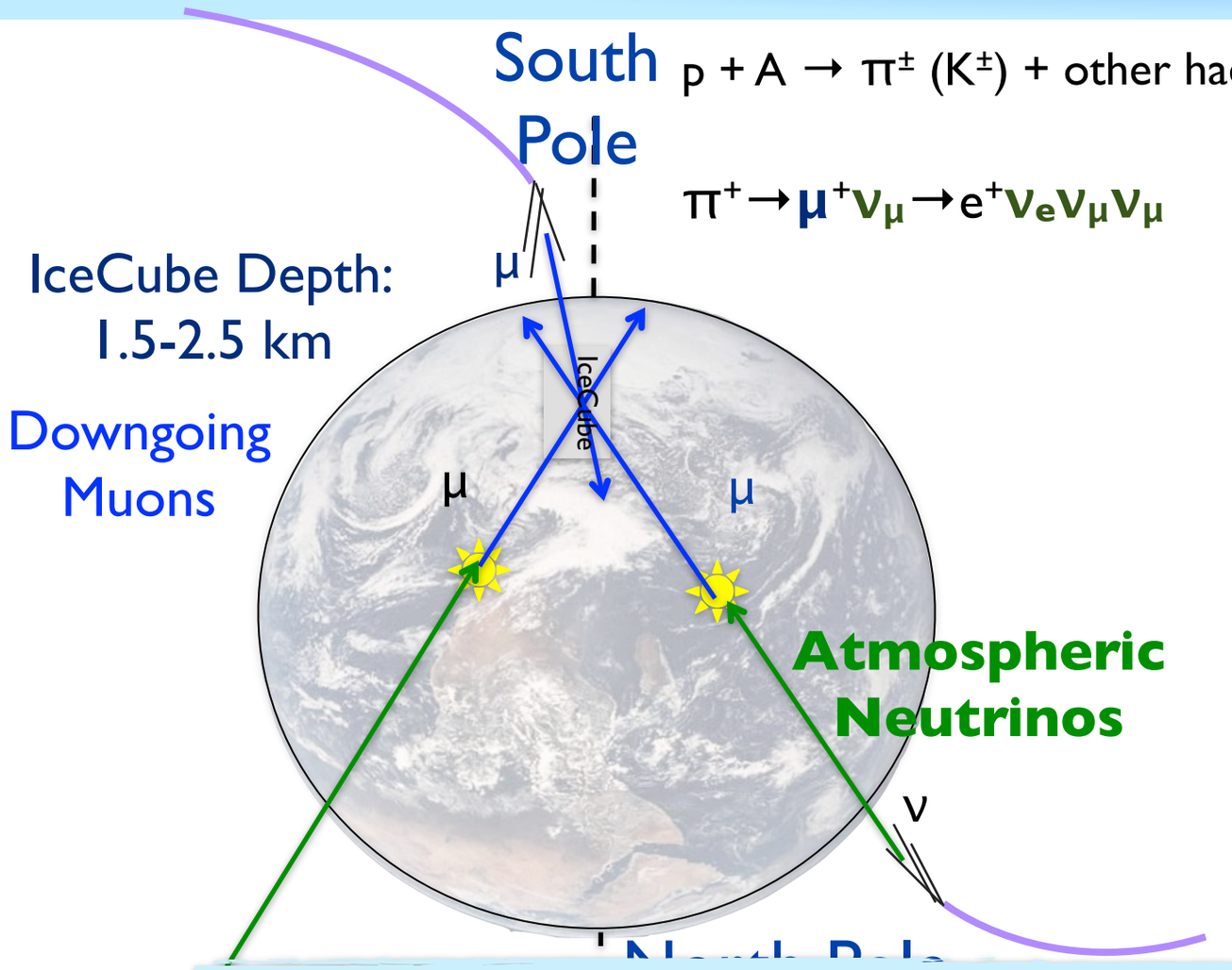

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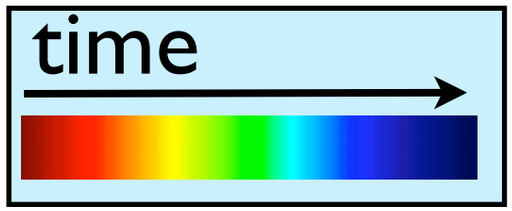

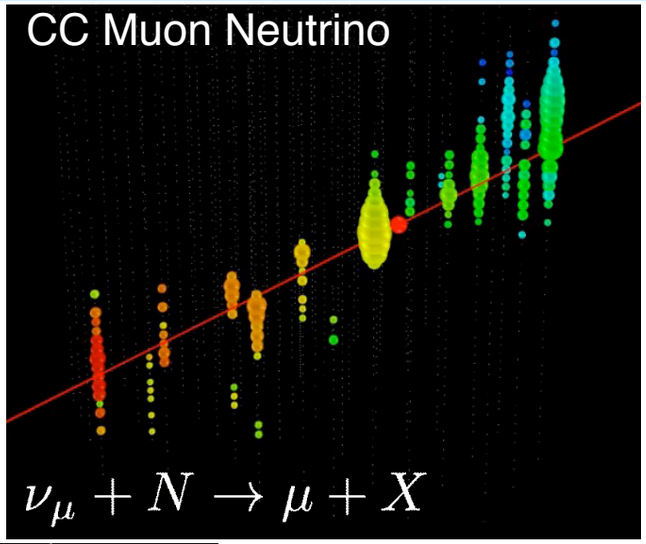

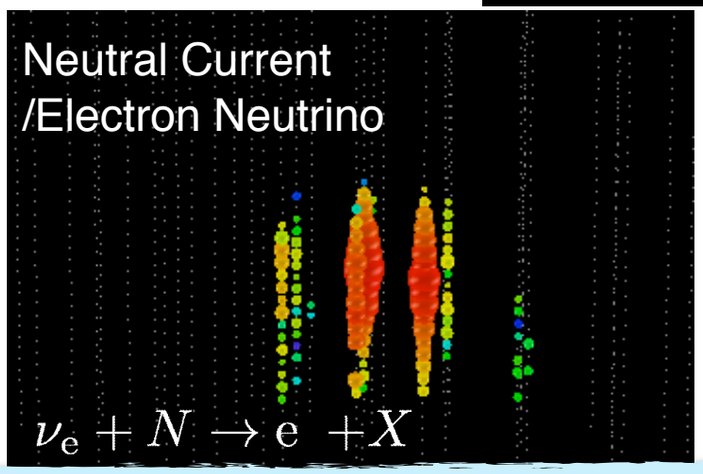

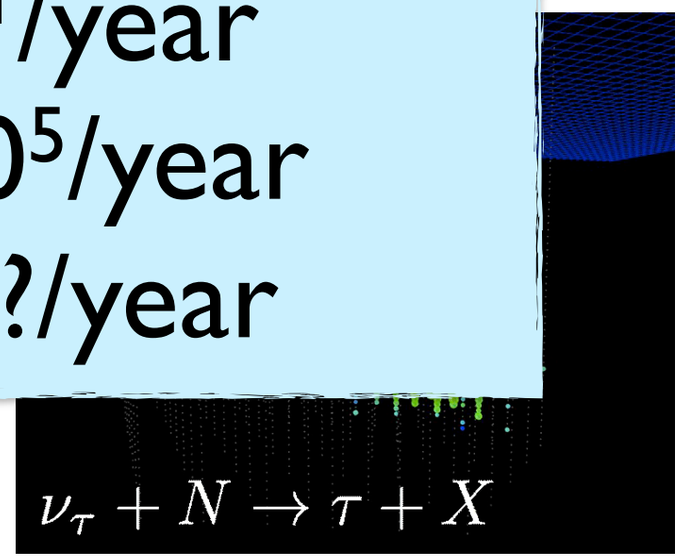

Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

Astrophysical neutrinos ~ ??/year

irreducible neutrino background to extra terrestrial neutrino fluxes

IceCube Science

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology
Cosmic ray composition	Atmospheric neutrino spectrum	Dark Matter	Supernovae monitoring	Earth density profile	GZK neutrinos
Arrival directions	Charm production	Neutrino oscillations	Transient events, GRBs, AGNs	Glaciology	
Origin	neutrino cross sections	Neutrino properties	Neutrino Point Sources	Atmospheric conditions	

Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

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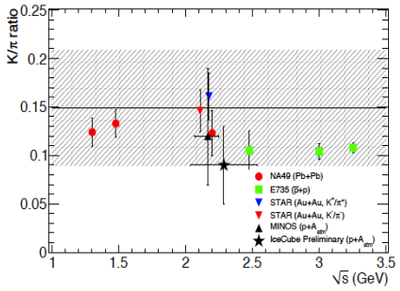	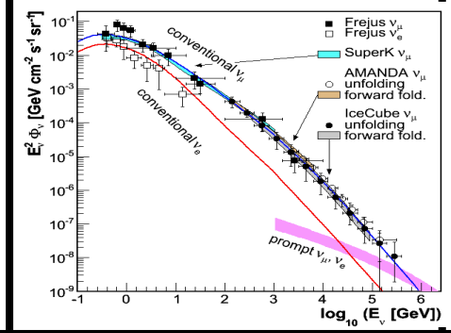	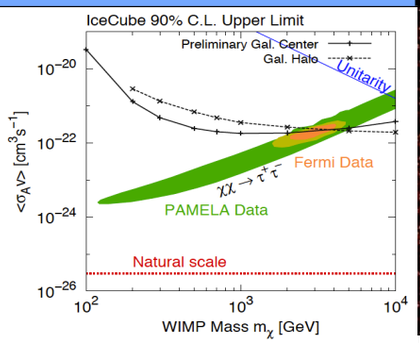	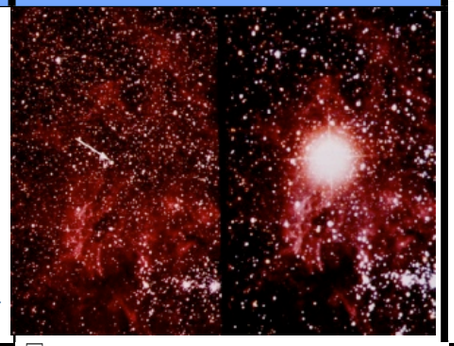	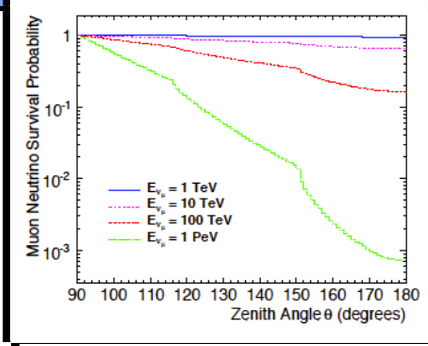	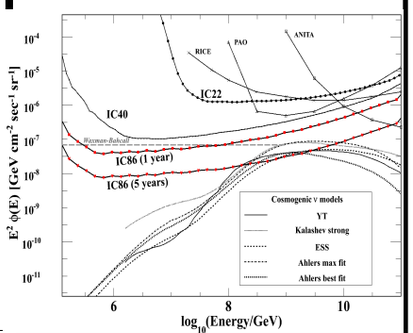
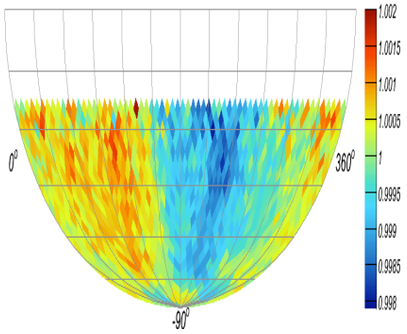	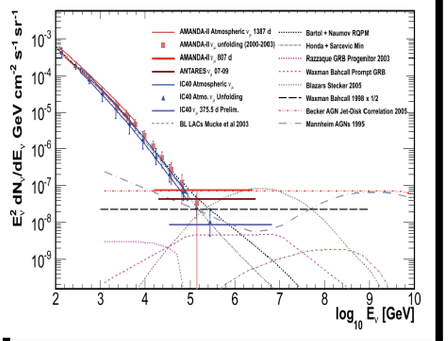	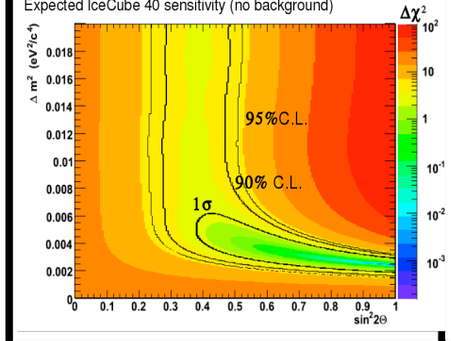	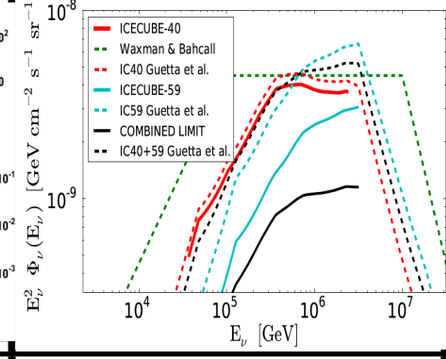	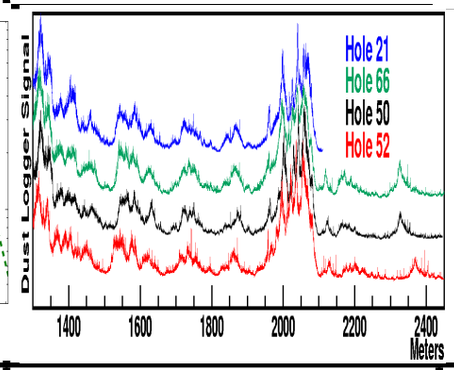	
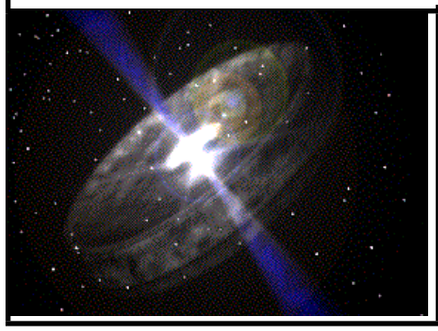	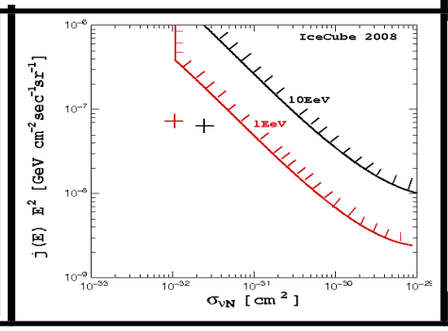	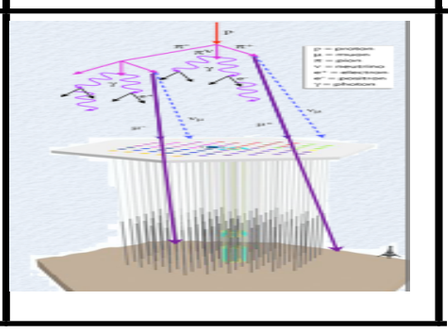	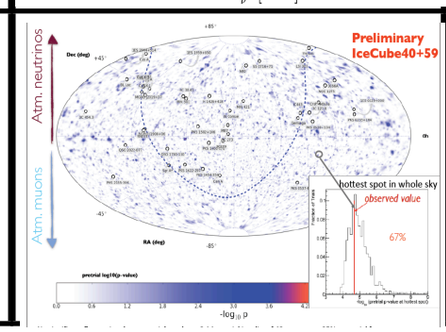	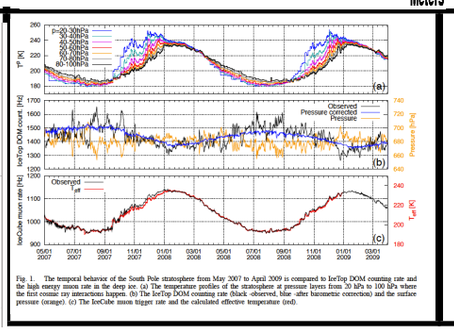	

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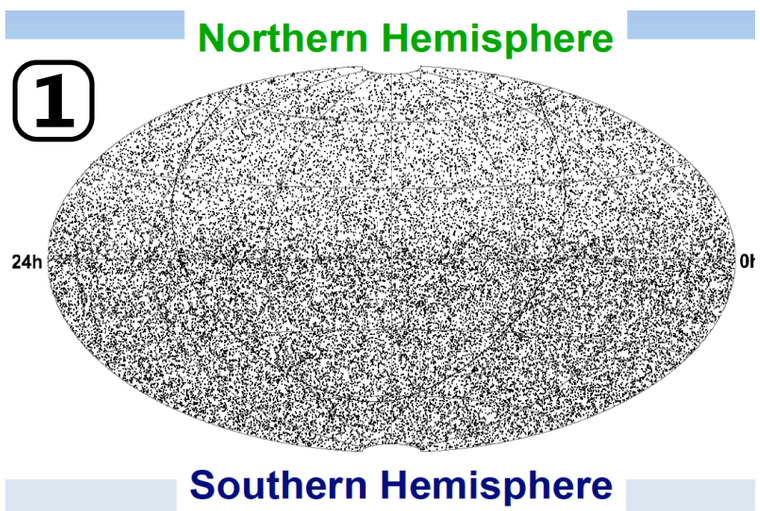
Selected Results

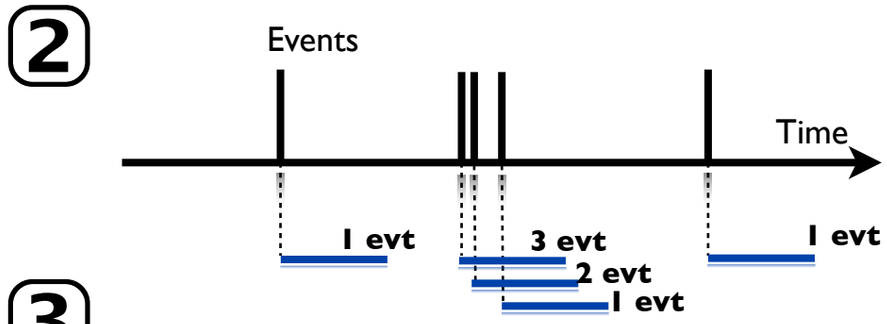
Finding Astrophysical Neutrinos

- How to overcome the large atmospheric neutrino background
- We need to rely on statistical methods to pick out neutrinos from this mess

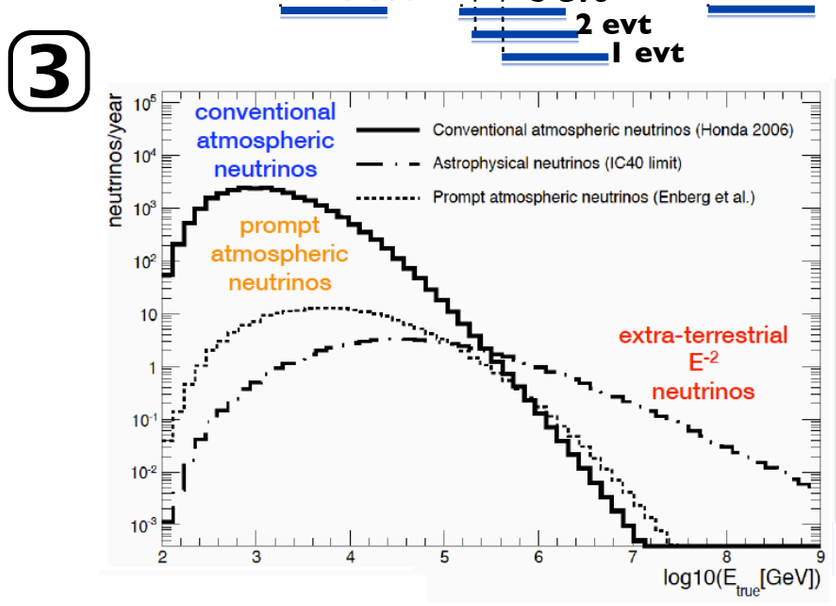
- Do neutrinos cluster anywhere in space, time, or arriving in coincidence with astronomical events or objects ?
- Do we see any spectral features ?



single source



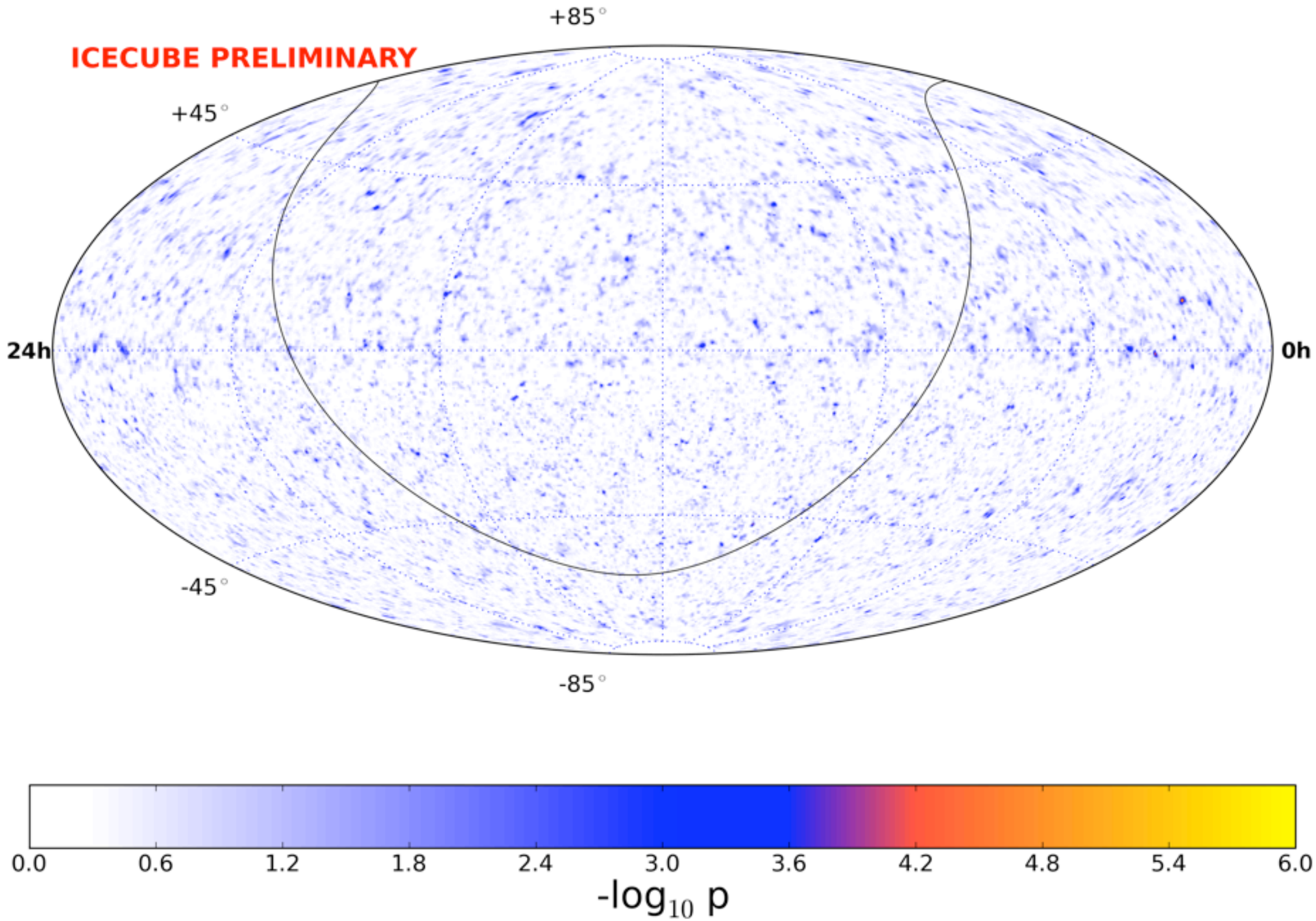
transient source



cumulative flux

Point Source Search

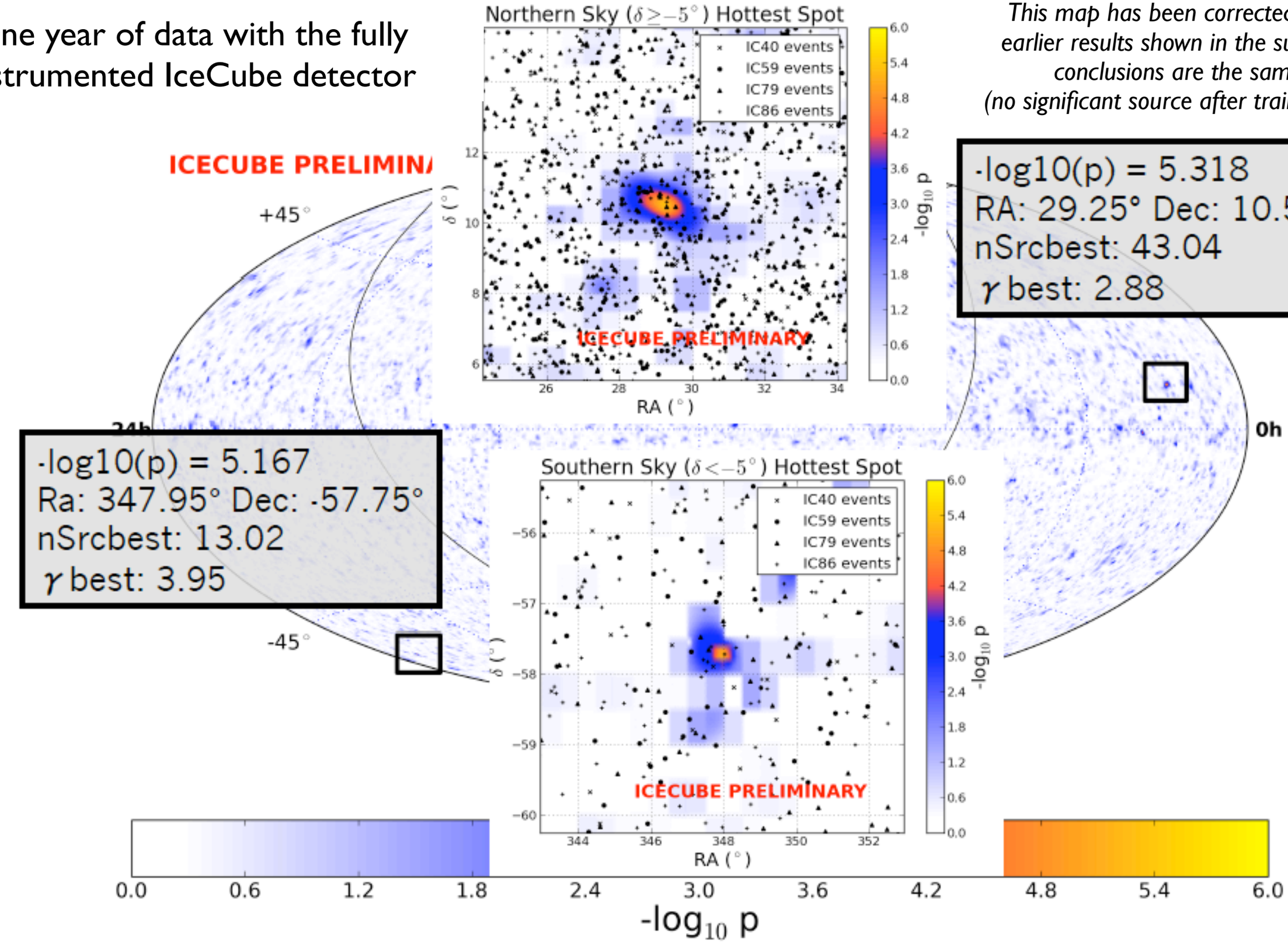
One year of data with the fully instrumented IceCube detector



Point Source Search

One year of data with the fully instrumented IceCube detector

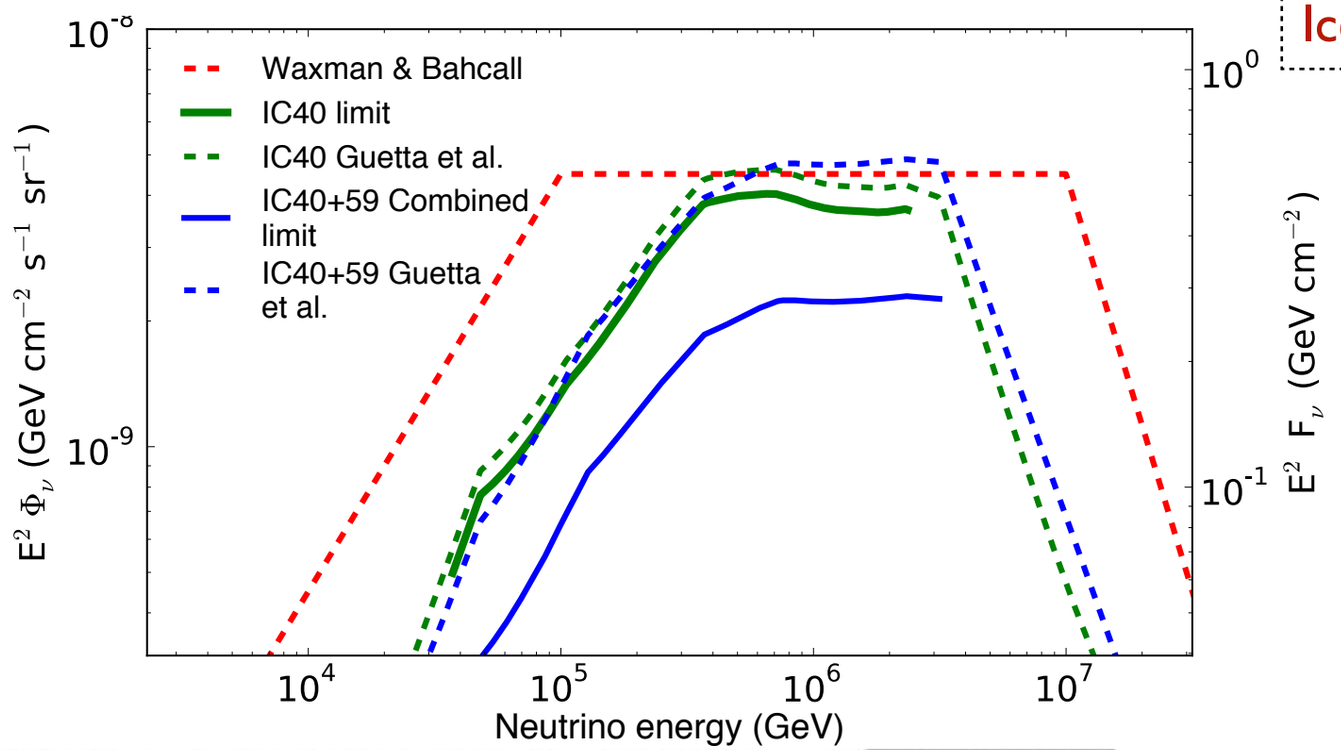
This map has been corrected from earlier results shown in the summer, conclusions are the same (no significant source after trail factors)



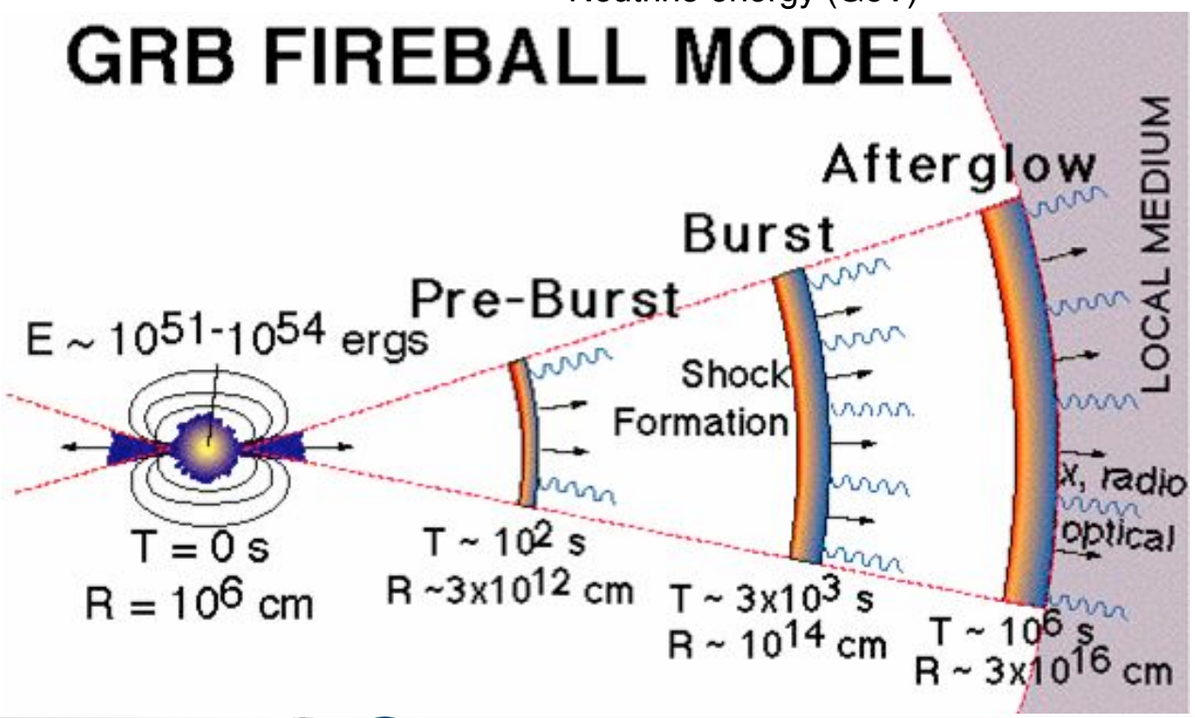
Transient Search

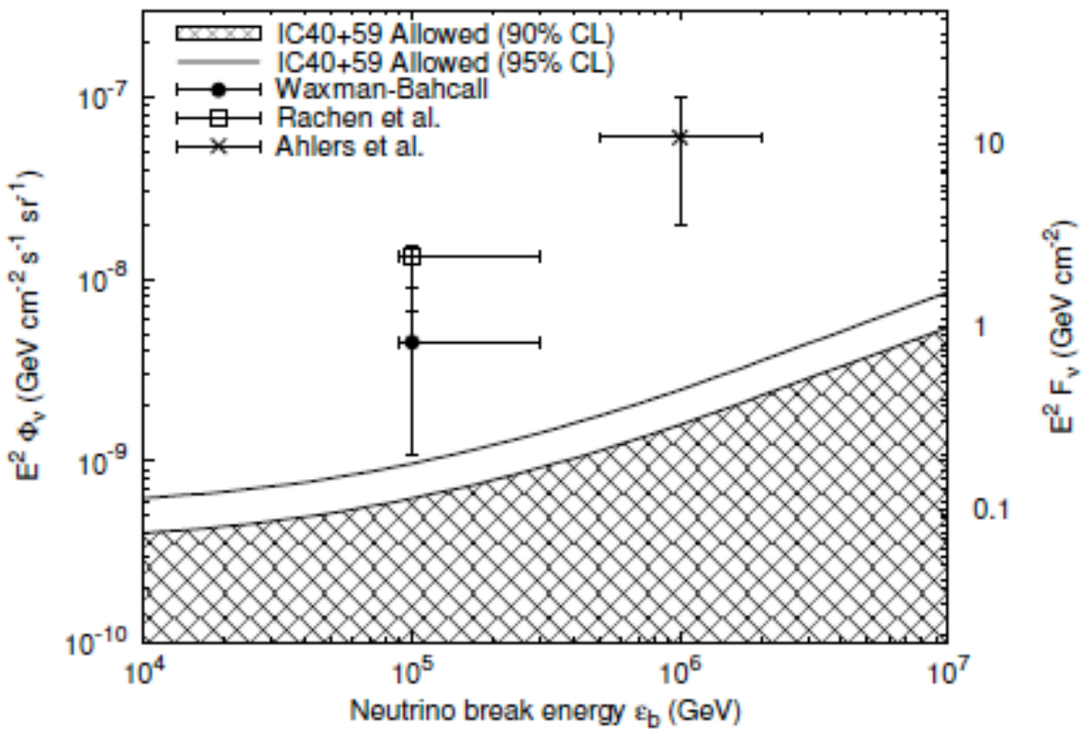
IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern and 85 from southern sky) analyzed. **No coincidence found**

IceCube Collaboration - Nature Vol **484**, 351 (2012)



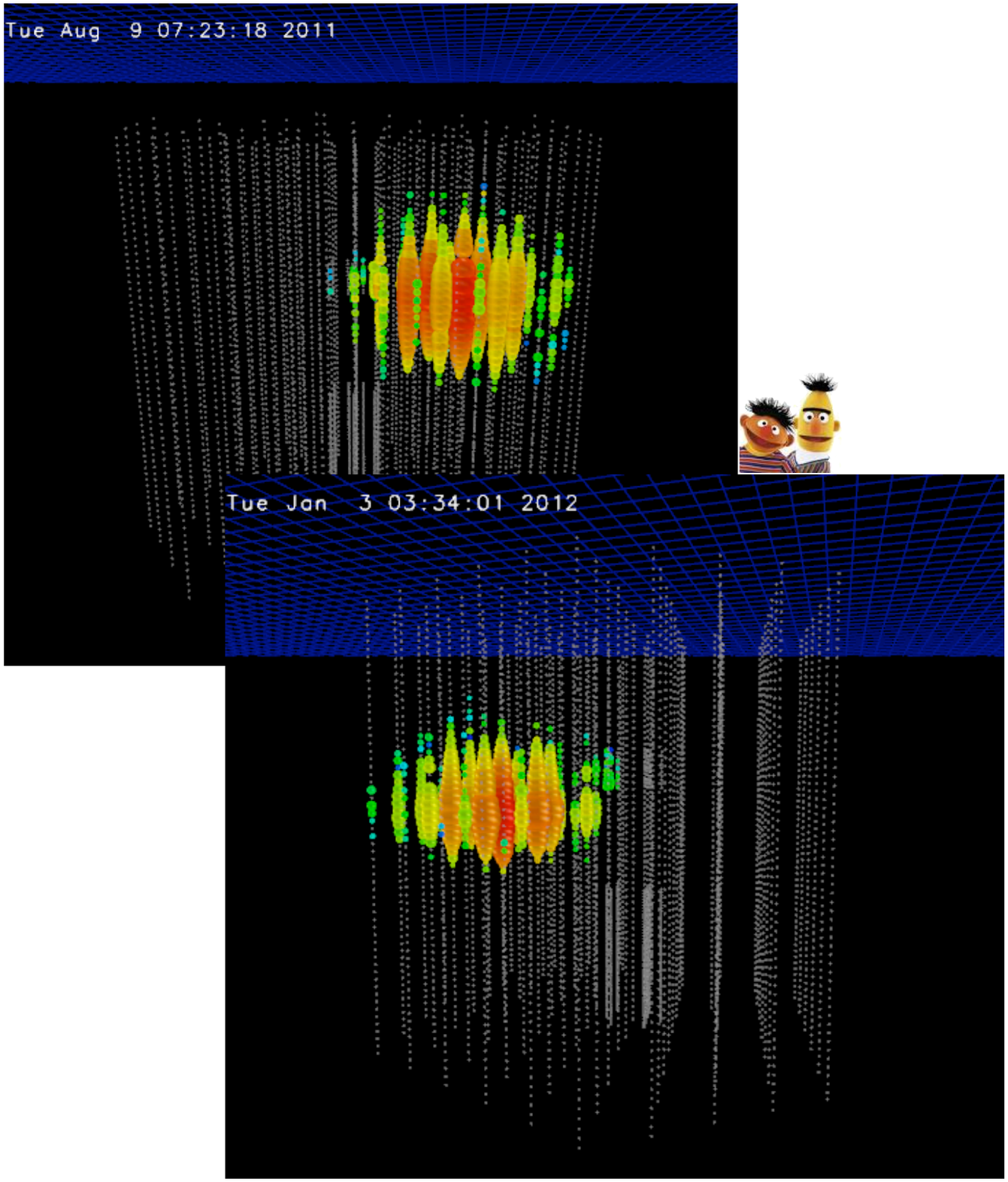
5.2 event expected
0 events observed





Search for highest energy neutrinos

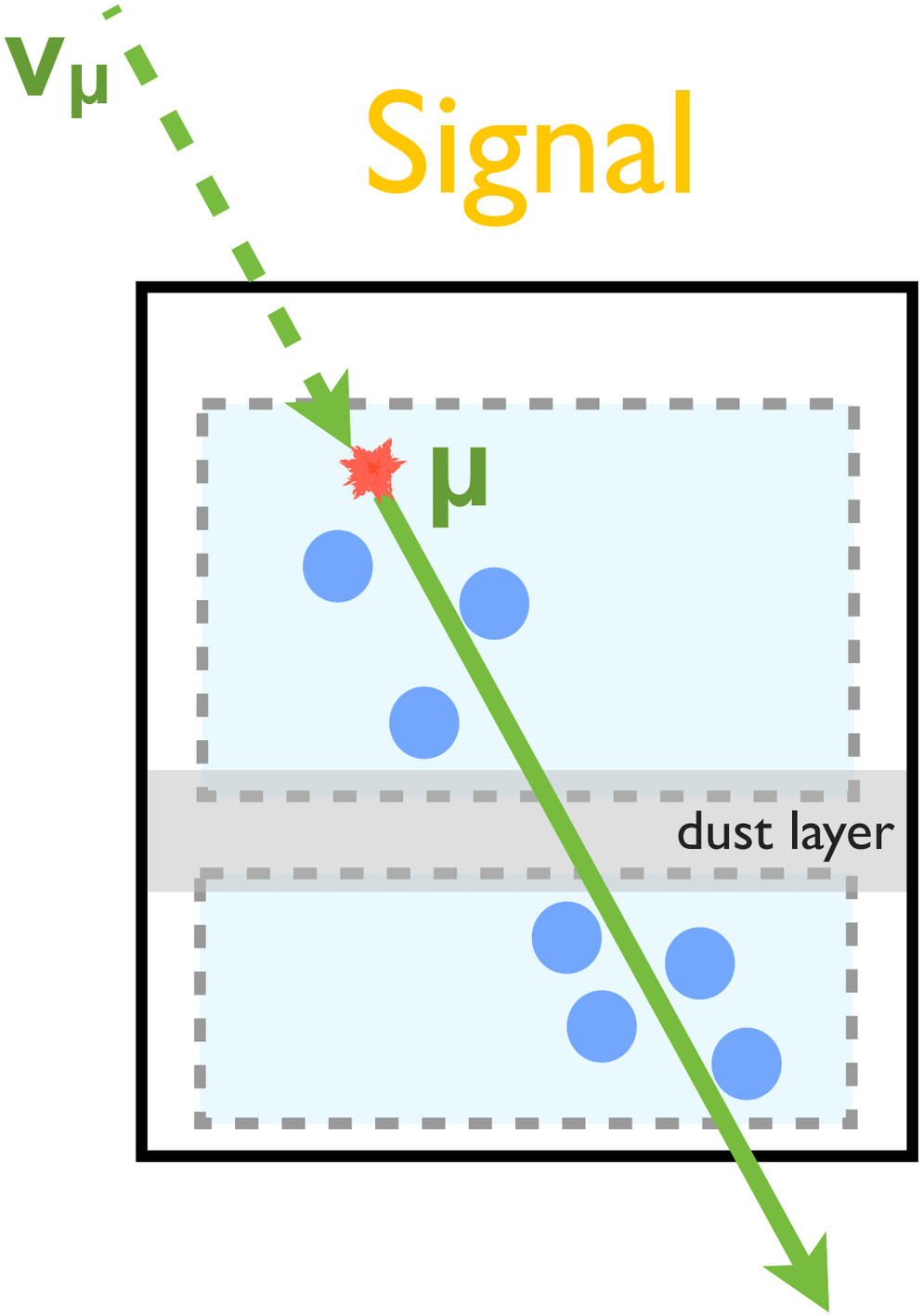
IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



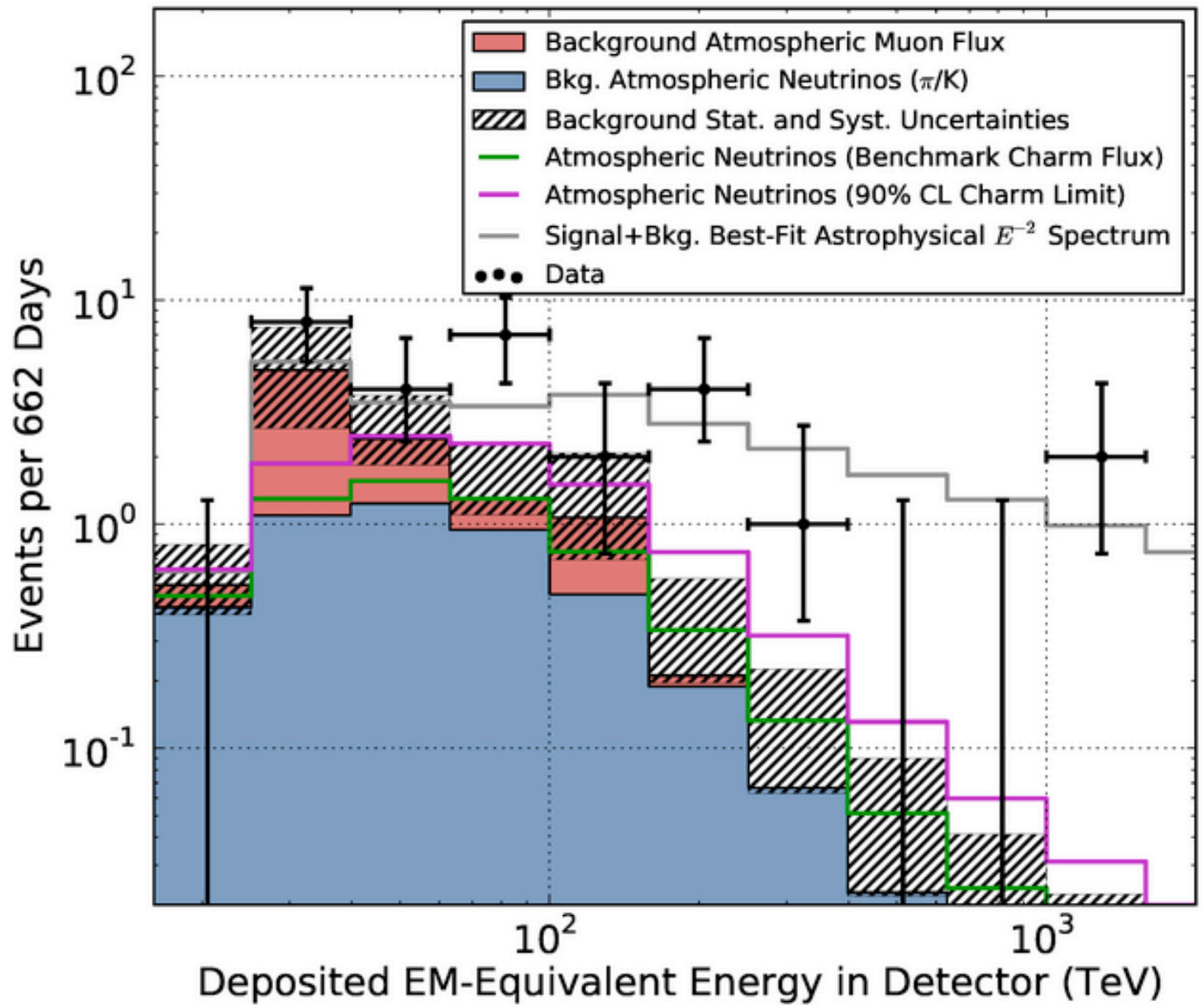
Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events (→ 2.7σ)

- Ernie ~1.15 PeV (~$1.9 \cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~$1.7 \cdot 10^{-4}$J)
- Energy is the visible energy of the cascade, could originate from NC event, ν_τ CC, or ν_e CC
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

High-energy neutrino search



IceCube Collaboration, *Science* 342, 1242856 (2013)



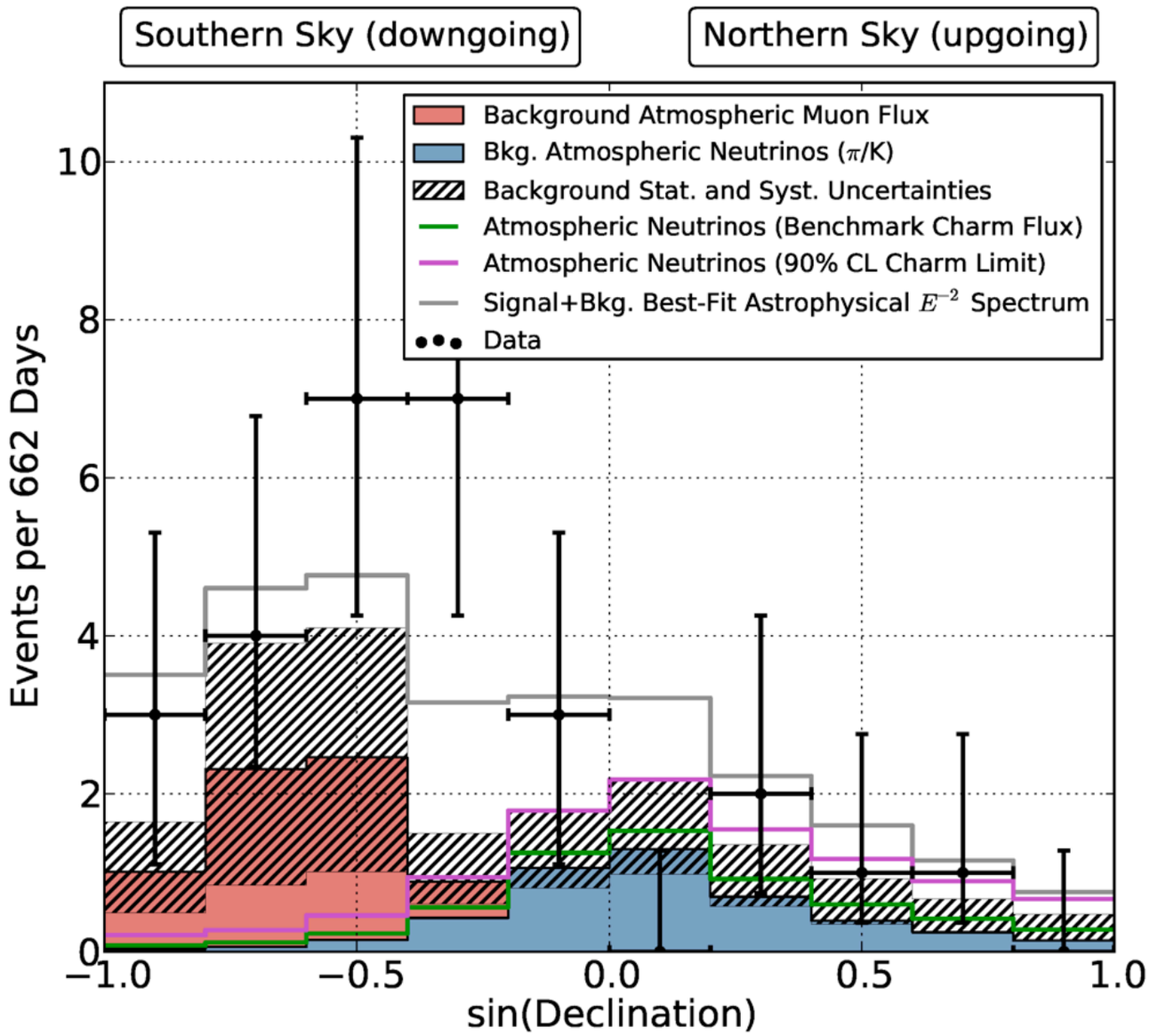
28 events (7 track-like, 21 showers) observed

Expectation from conventional atm. muons and neutrinos $10.6\ ^{+5.0}_{-3.6}$

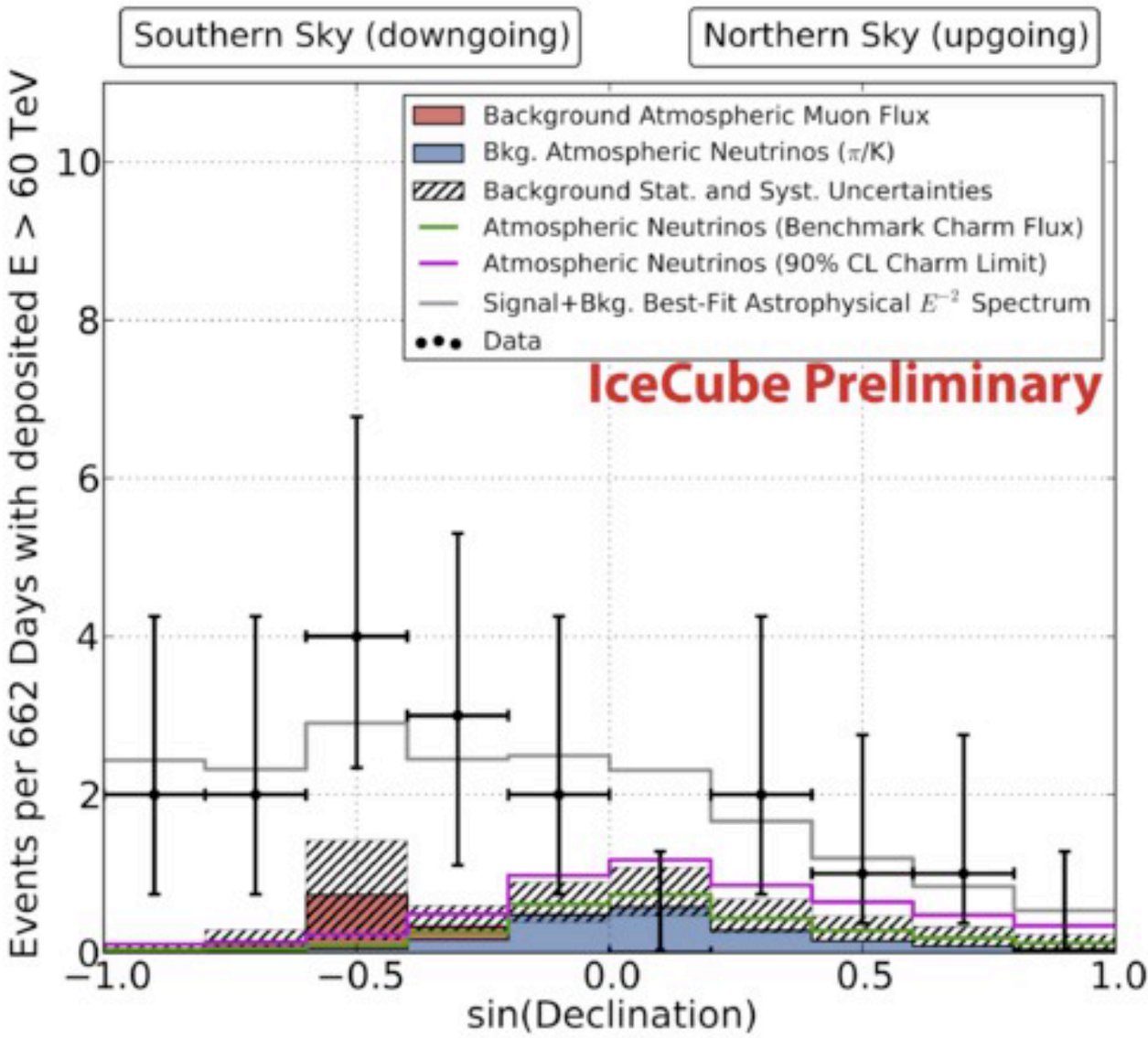
Declination Distribution

IceCube Collaboration, *Science* 342, 1242856 (2013)

All Events

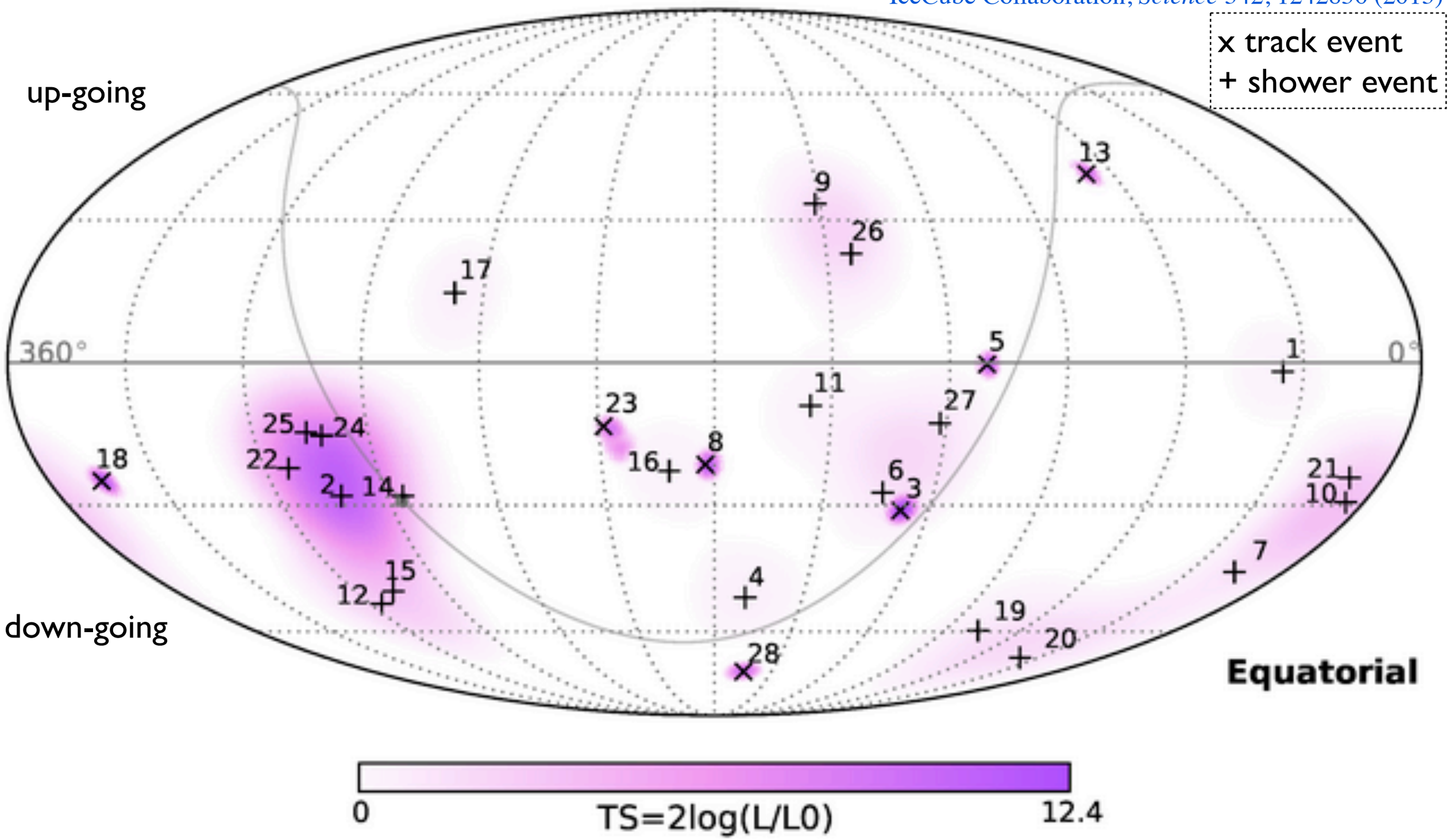


Event Energy > 60TeV



High-energy neutrino search

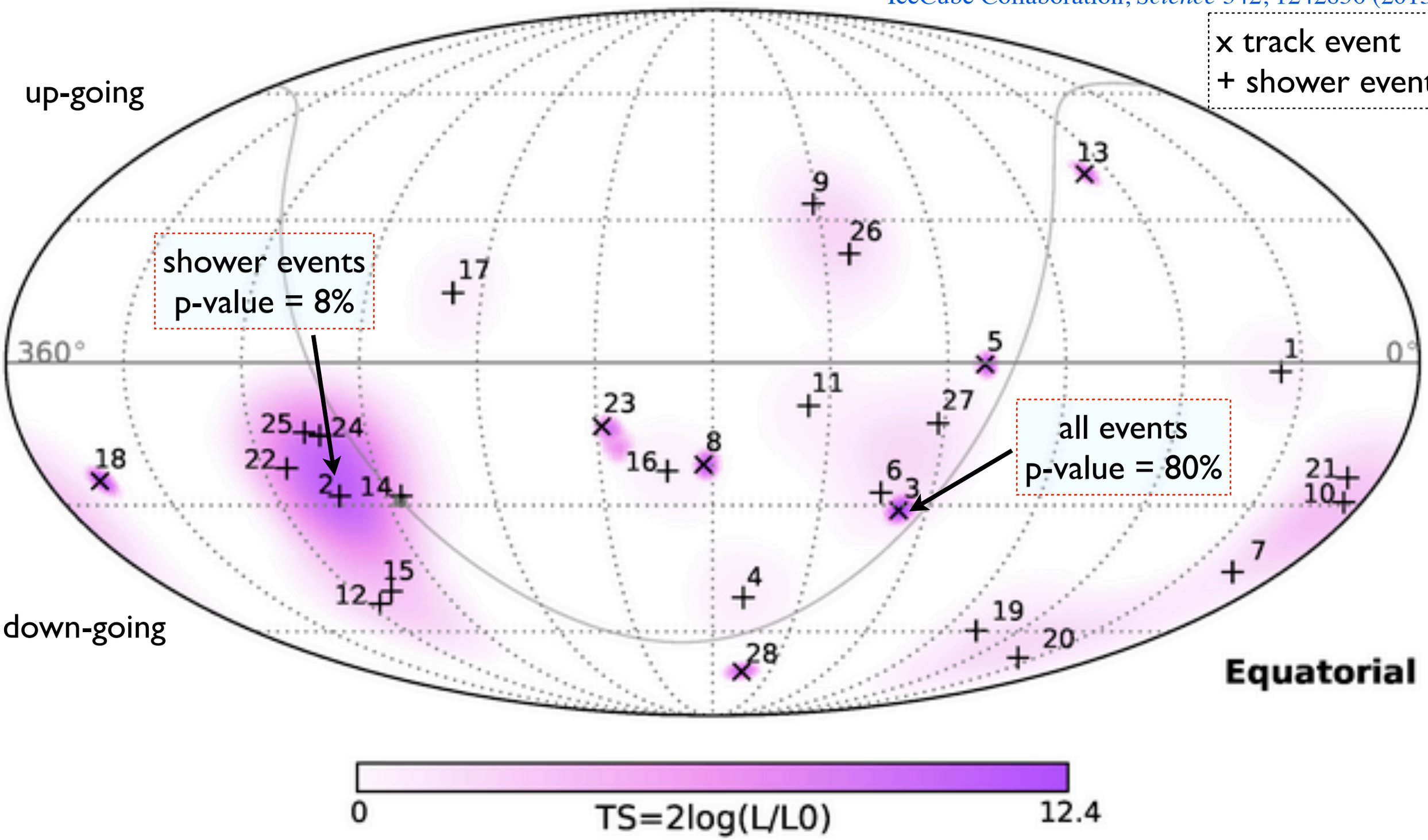
IceCube Collaboration, *Science* 342, 1242856 (2013)

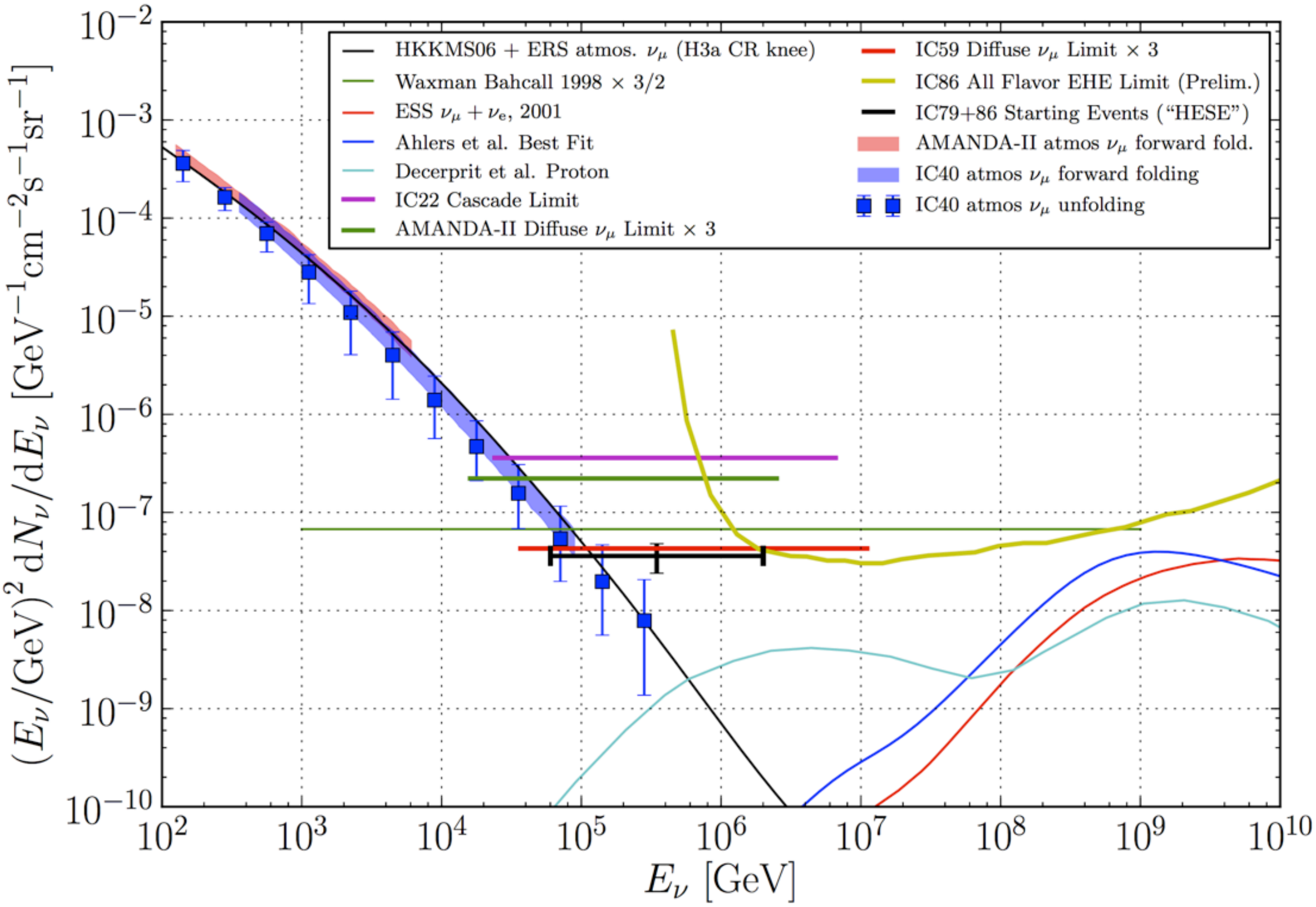


High-energy neutrino search

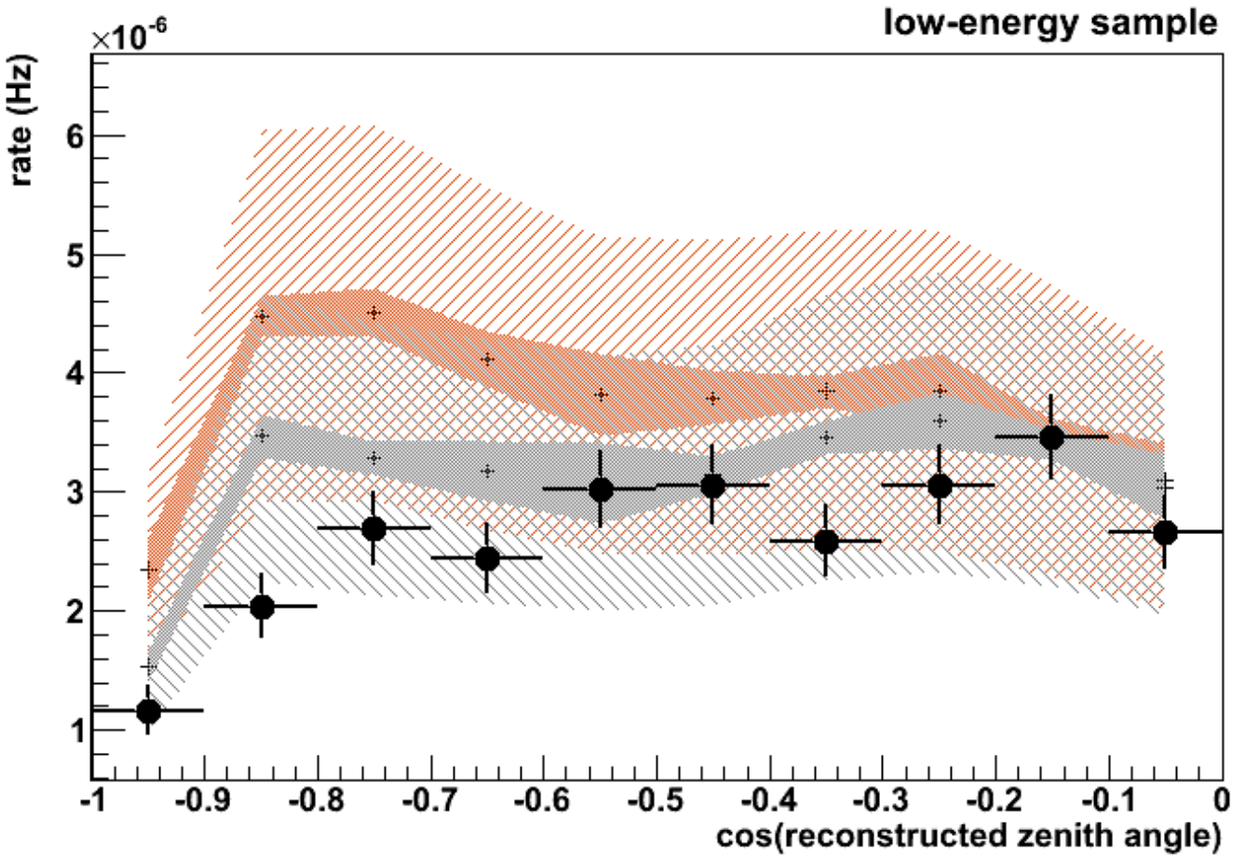
All p-values are post trial

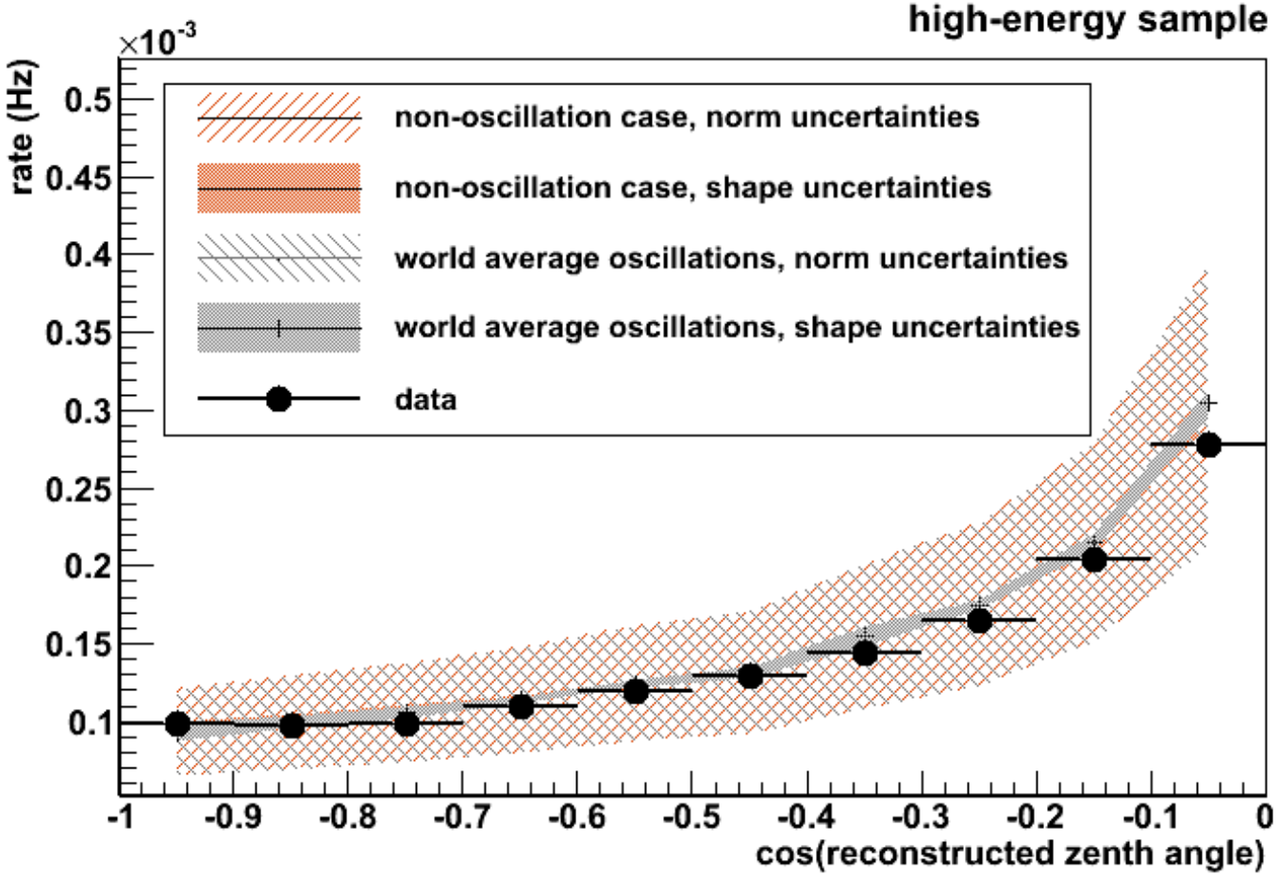
IceCube Collaboration, *Science* 342, 1242856 (2013)

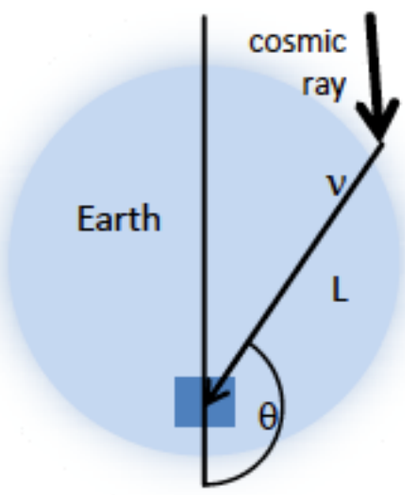


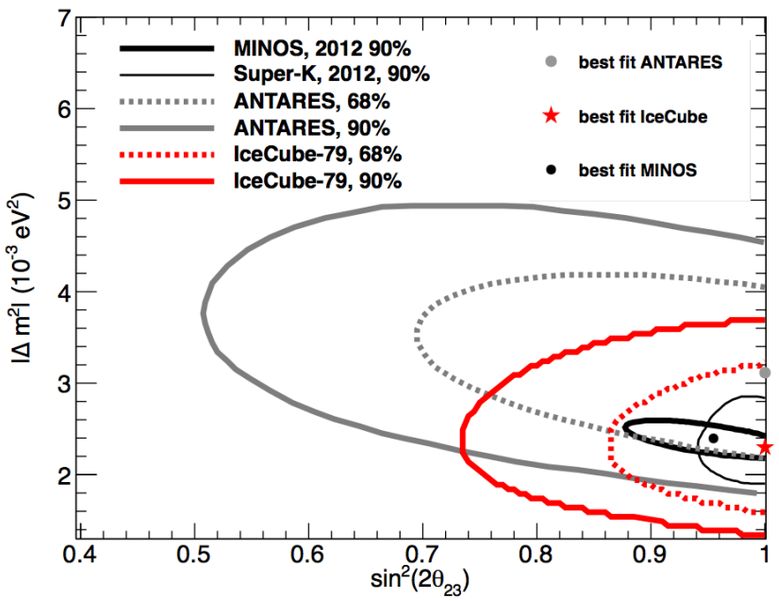

HKKMS06 + ERS atmos. ν_μ (H3a CR knee)
Waxman Bahcall 1998 × 3/2
ESS $\nu_\mu + \nu_e$, 2001
Ahlers et al. Best Fit
Decerprit et al. Proton
IC22 Cascade Limit
AMANDA-II Diffuse ν_μ Limit × 3
IC59 Diffuse ν_μ Limit × 3
IC86 All Flavor EHE Limit (Prelim.)
IC79+86 Starting Events ("HESE")
AMANDA-II atmos ν_μ forward fold.
IC40 atmos ν_μ forward folding
IC40 atmos ν_μ unfolding
$(E_\nu/\mathrm{GeV})^2\,\mathrm{d}N_\nu/\mathrm{d}E_\nu$ [GeV^{-1}cm^{-2}s^{-1}sr^{-1}]
E_ν [GeV]

Atmospheric Neutrino Oscillations









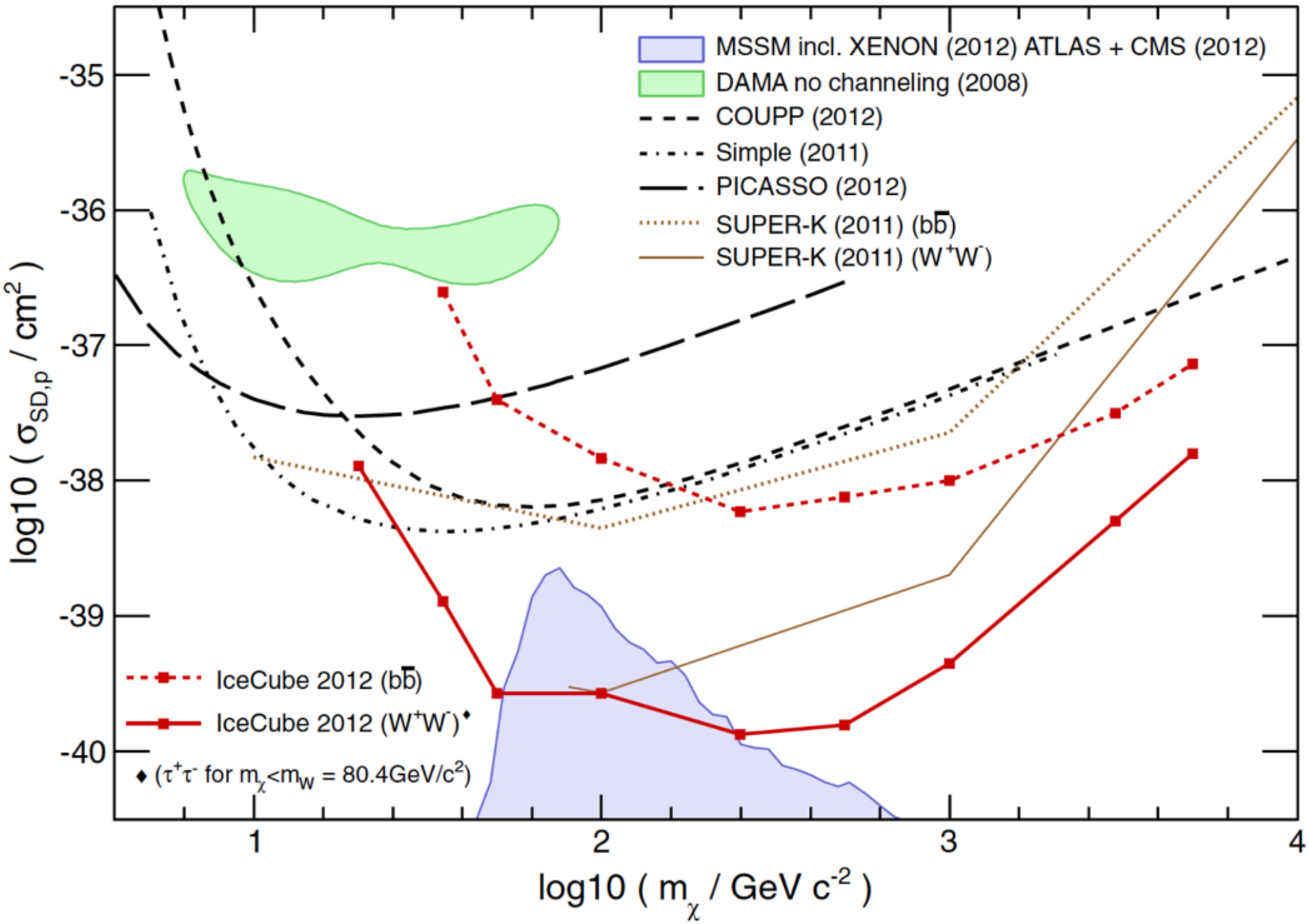
Phys. Rev. Lett. 111, 081801 (2013)

Neutrino oscillation with high significance but not high precision yet

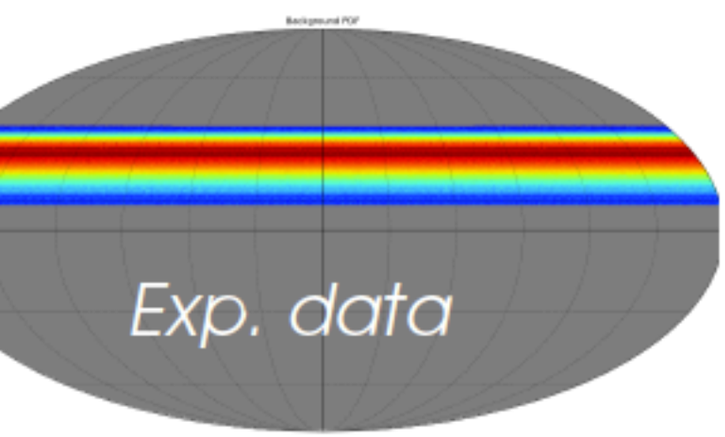
- $|\Delta m^2| = [2.5 \pm 0.5(\text{stat}) \pm 0.3(\text{sys})]\ 10^{-3}\ \text{eV}^2$
- $\sin^2(2\theta_{32}) > 0.92$ (68% CL)

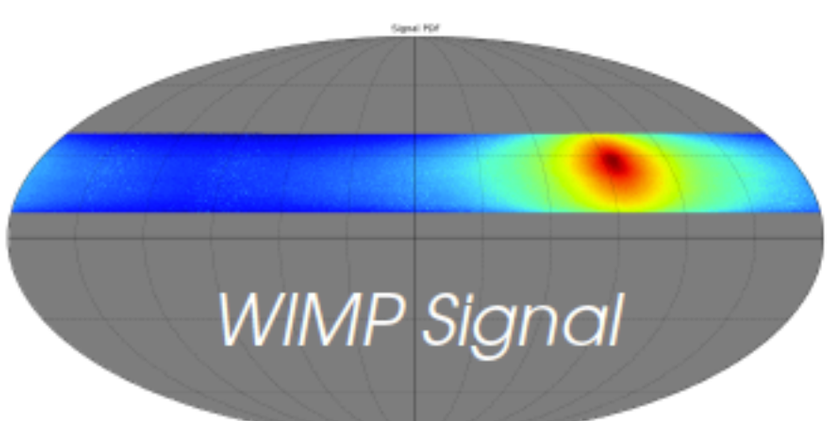
IceCube Dark Matter Search

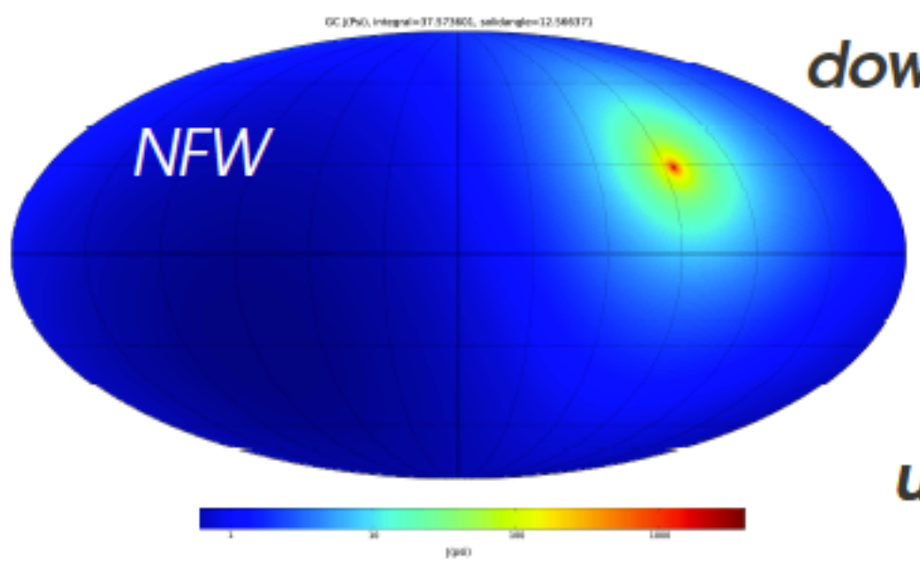
IceCube Coll. PRL 110, 131302 (2013)



IceCube Search for Dark Matter at the Galactic Center







2D PDFs generated with healpix

$$\frac{d\Phi}{dE}(E,\phi,\theta) =$$

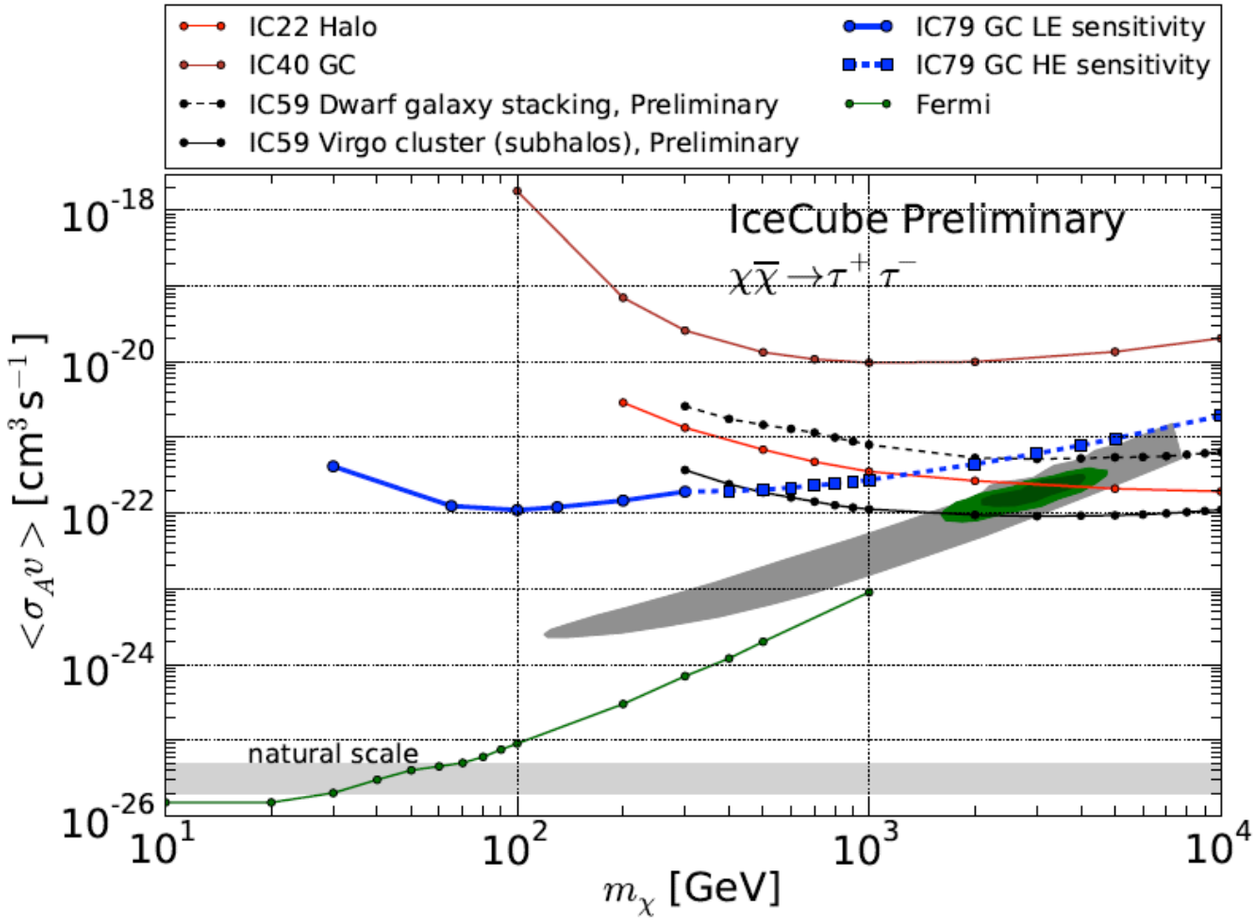
Particle Physics

$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\sum_f Br(f)\frac{dN_f}{dE}$$

$$\times$$

Dark Matter Distribution

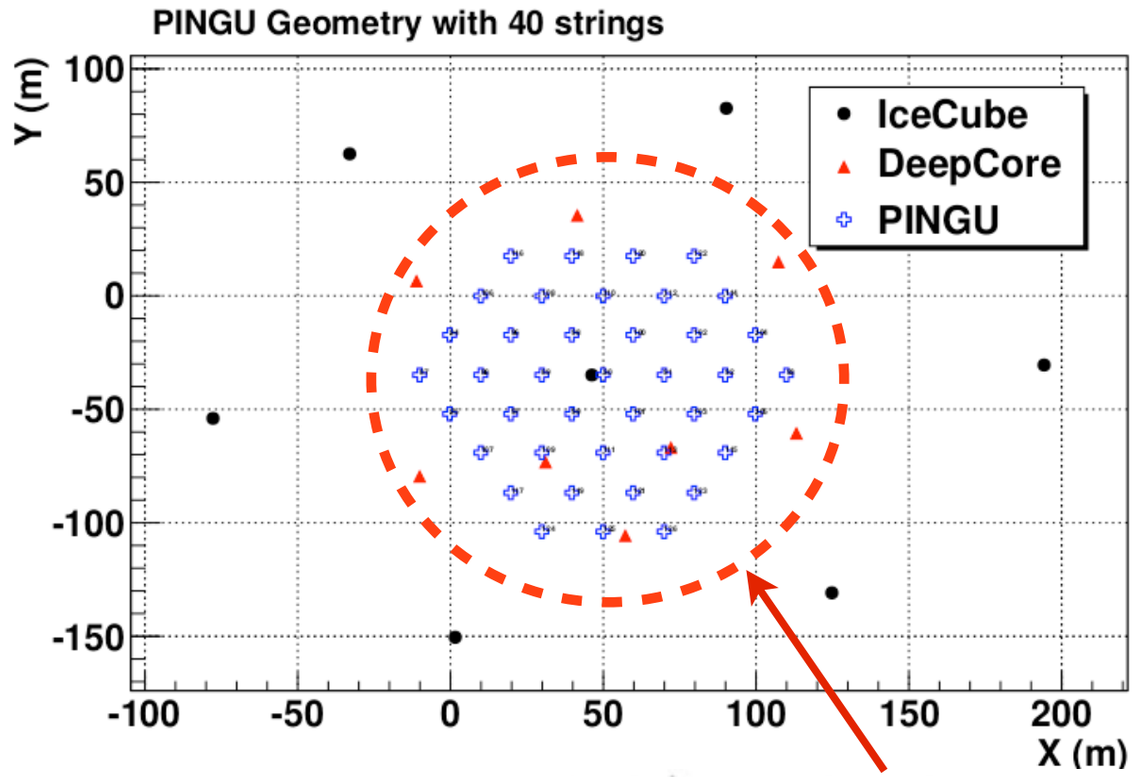
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



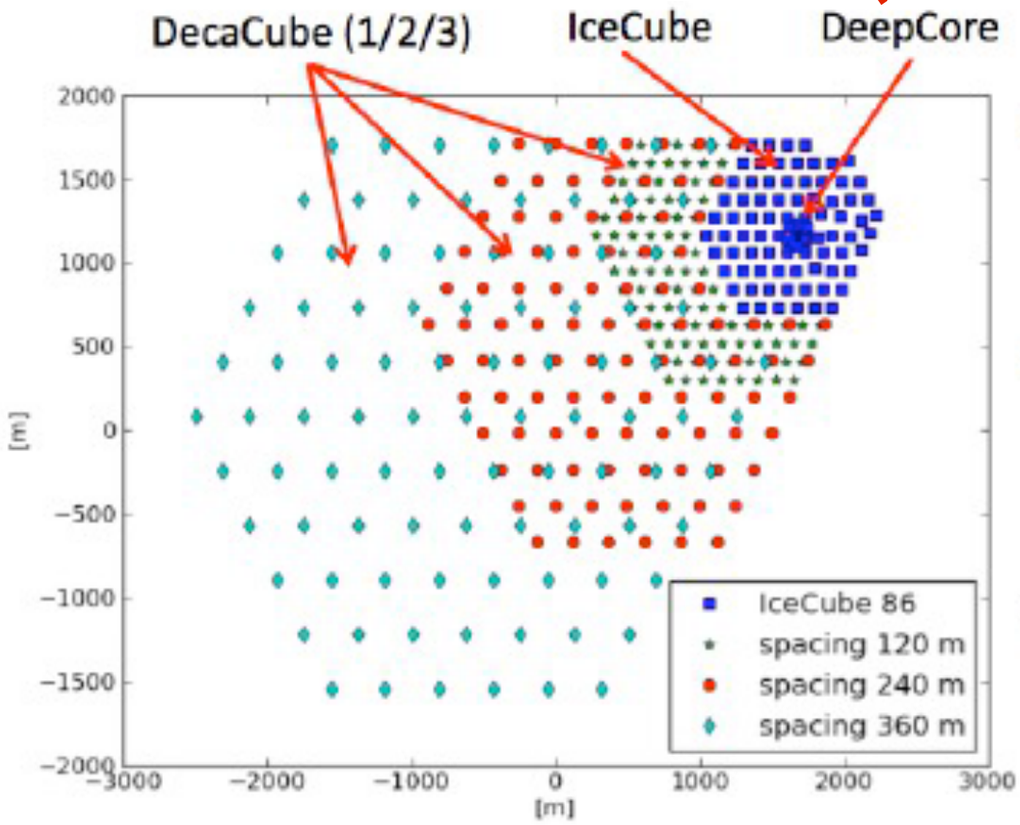
Future Plans

Future of IceCube

- Make it better
  - Precision detector with ~GeV threshold



- Make it bigger



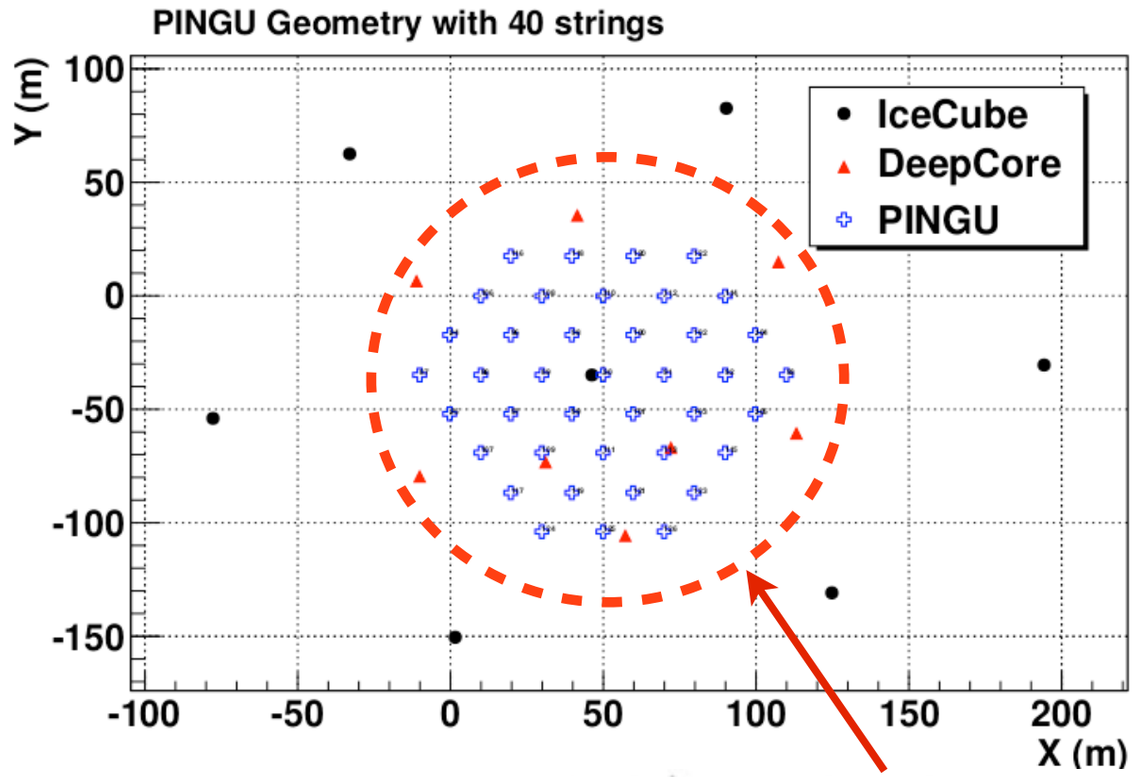
Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

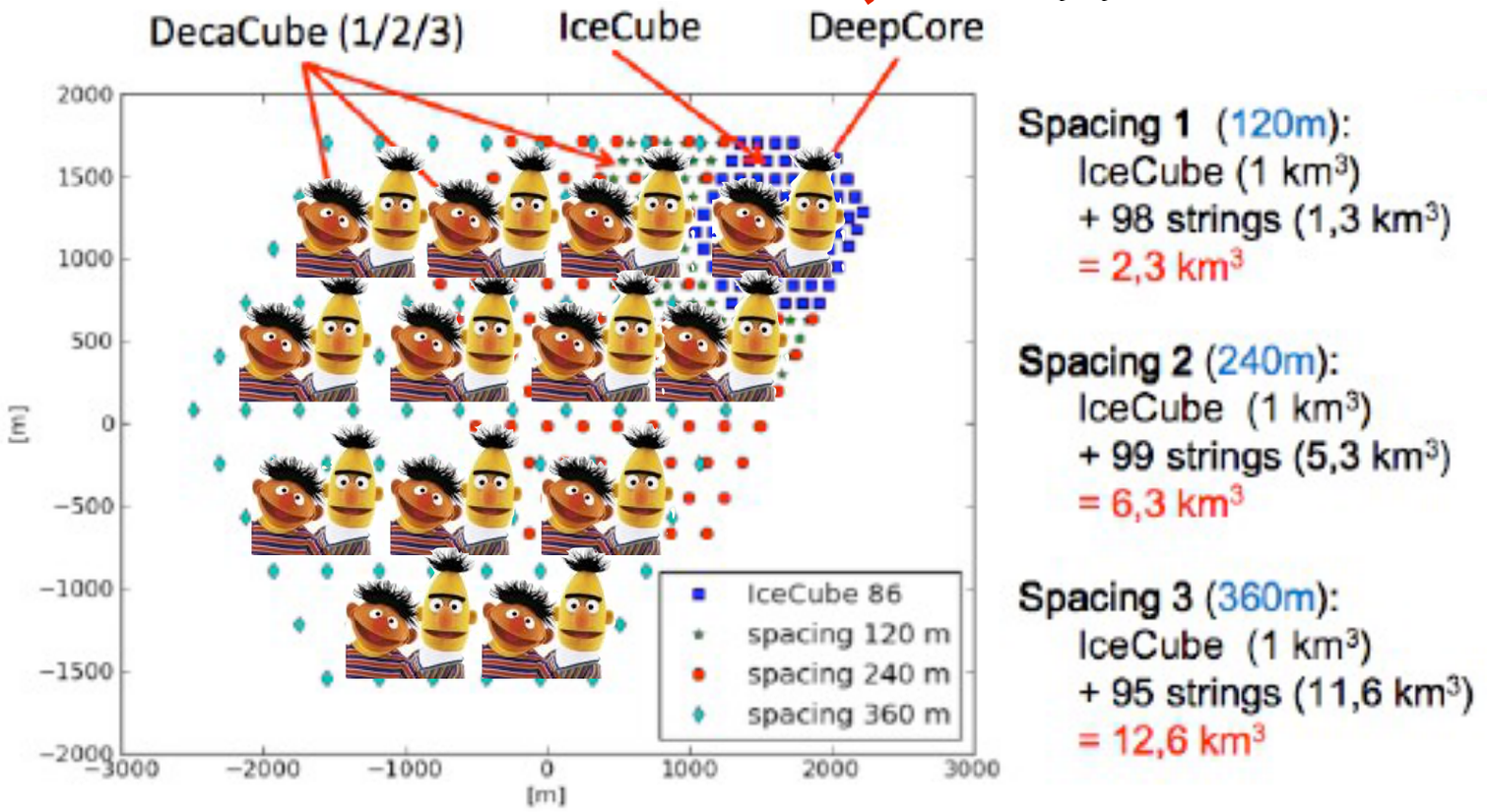
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

Future of IceCube

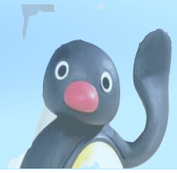
- Make it better
  - Precision detector with ~GeV threshold



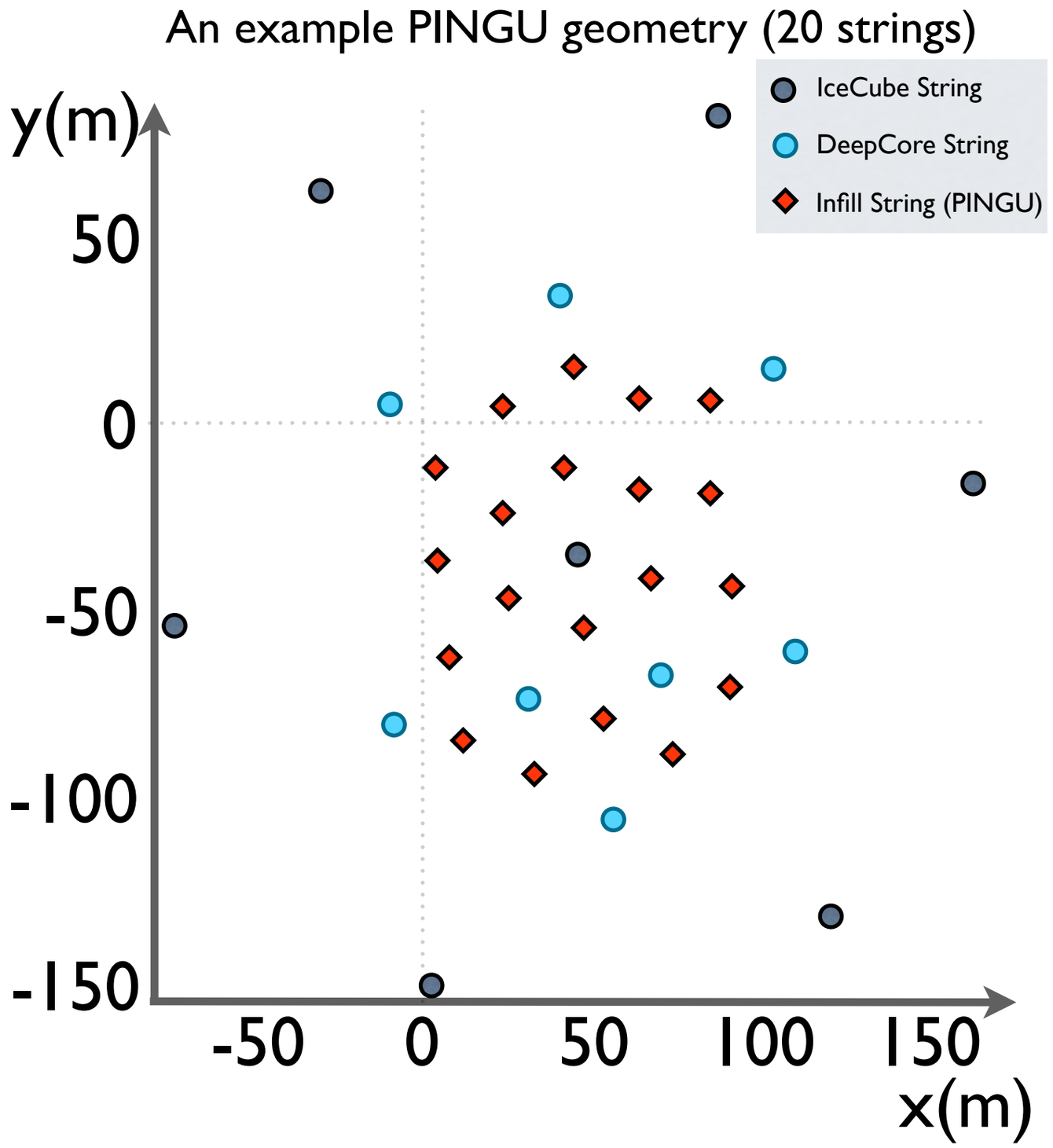
- Make it bigger



PINGU - Precision IceCube Next Generation Upgrade



- Developing a proposal to further in-fill DeepCore, called PINGU
  - Instrument a volume of about 10MT with ~40 strings each containing 60-100 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models



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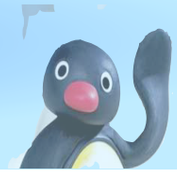

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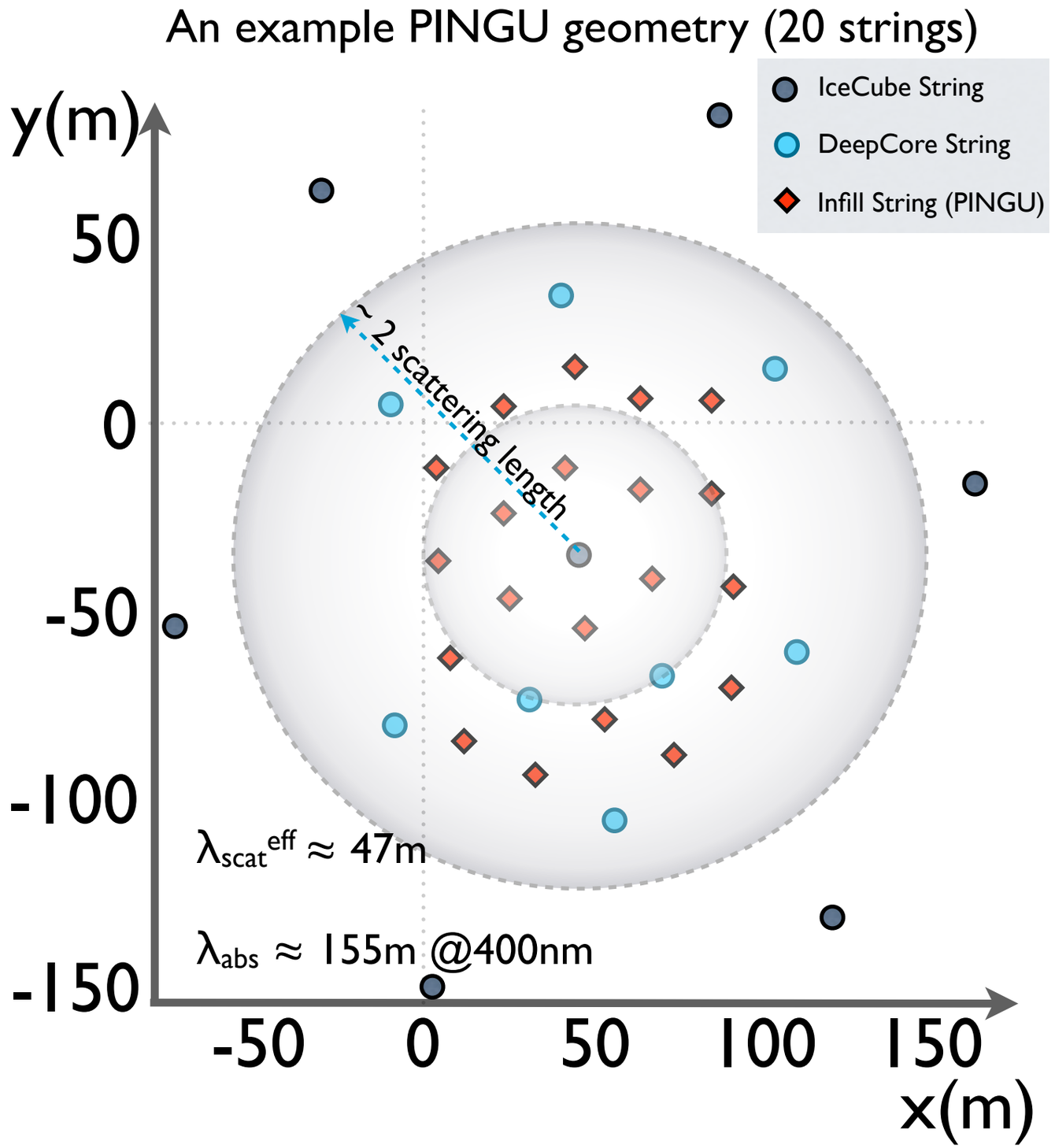
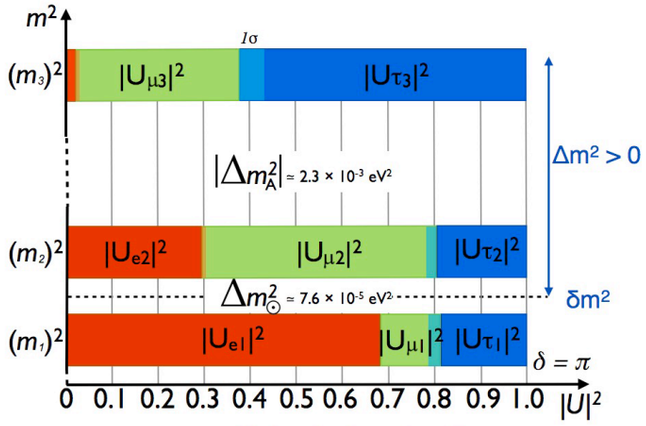


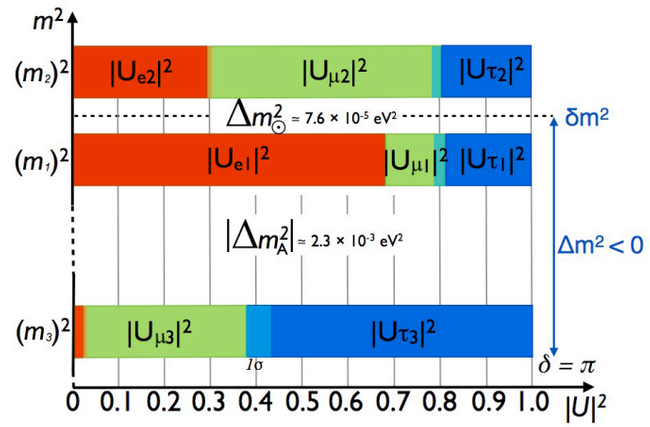
PINGU Physics Potential

Neutrino Mass Hierarchy



Fogli et al. convention, $\delta m^2 = \Delta m^2 = m^2 - m^2$

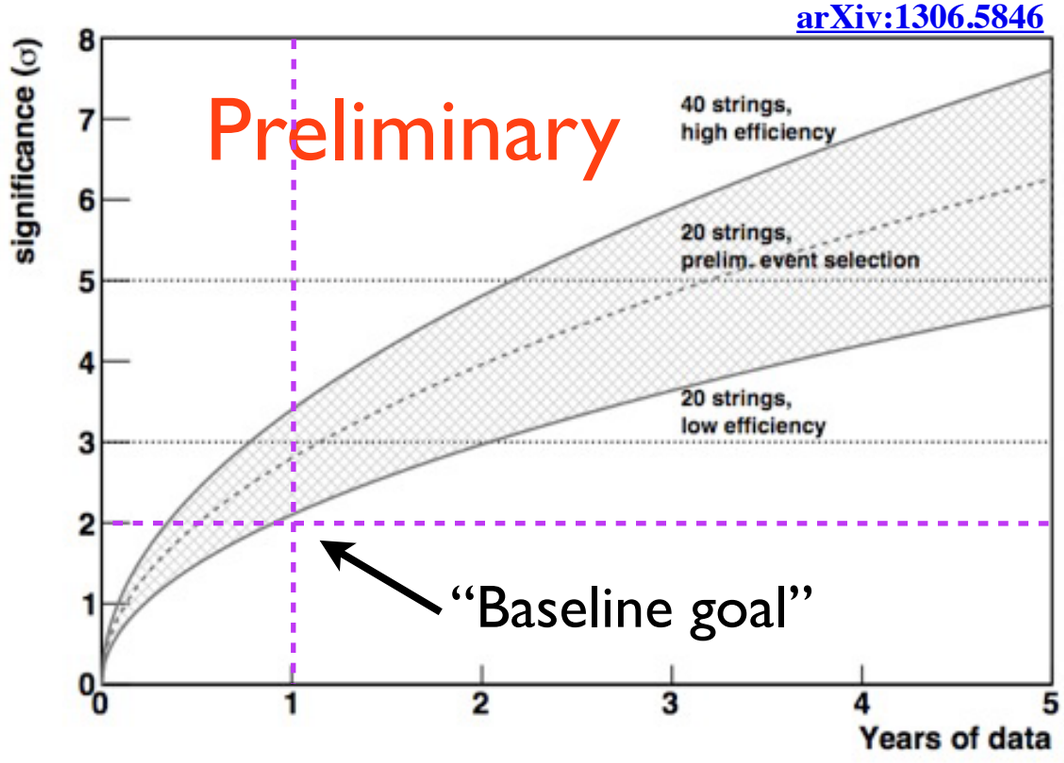
$\Delta m^2 = m_3^2 - (m_1^2 - m_2^2)/2$



Fogli et al. convention, $\delta m^2 = \Delta m^2_\odot = m_2^2 - m_1^2$

$\Delta m^2 = m_3^2 - (m_1^2 - m_2^2)/2$

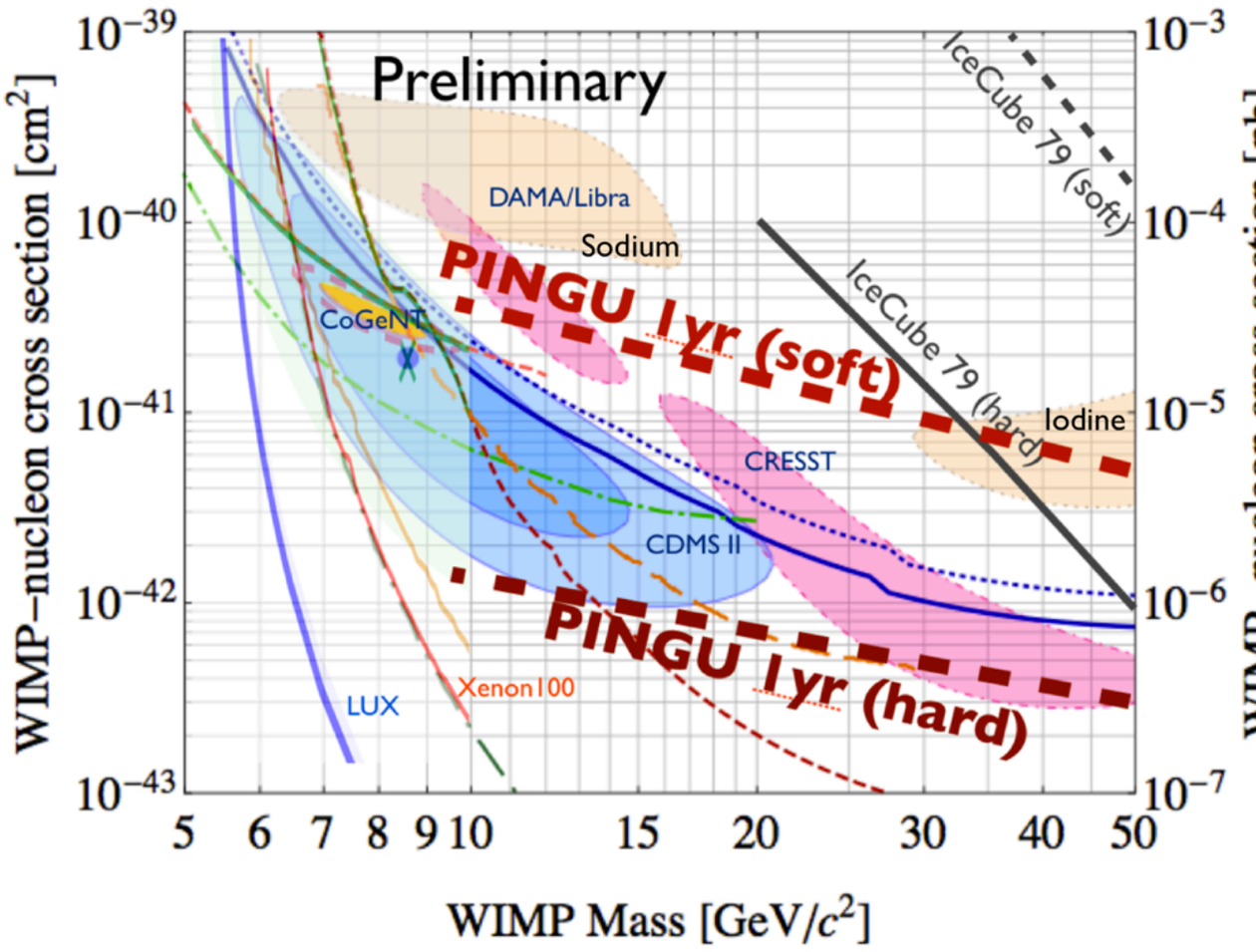
arXiv:1306.5846



Estimated significance for determining the neutrino mass hierarchy with PINGU. The top of the range is based on a 40 string detector with a high assumed signal efficiency in the final analysis; the bottom uses a 20 string detector and assumed a lower signal efficiency.

Dark Matter Searches

- Assume that atmospheric muon backgrounds can be effectively rejected (not included in the sensitivity)
- Low-mass WIMP scenarios well testable



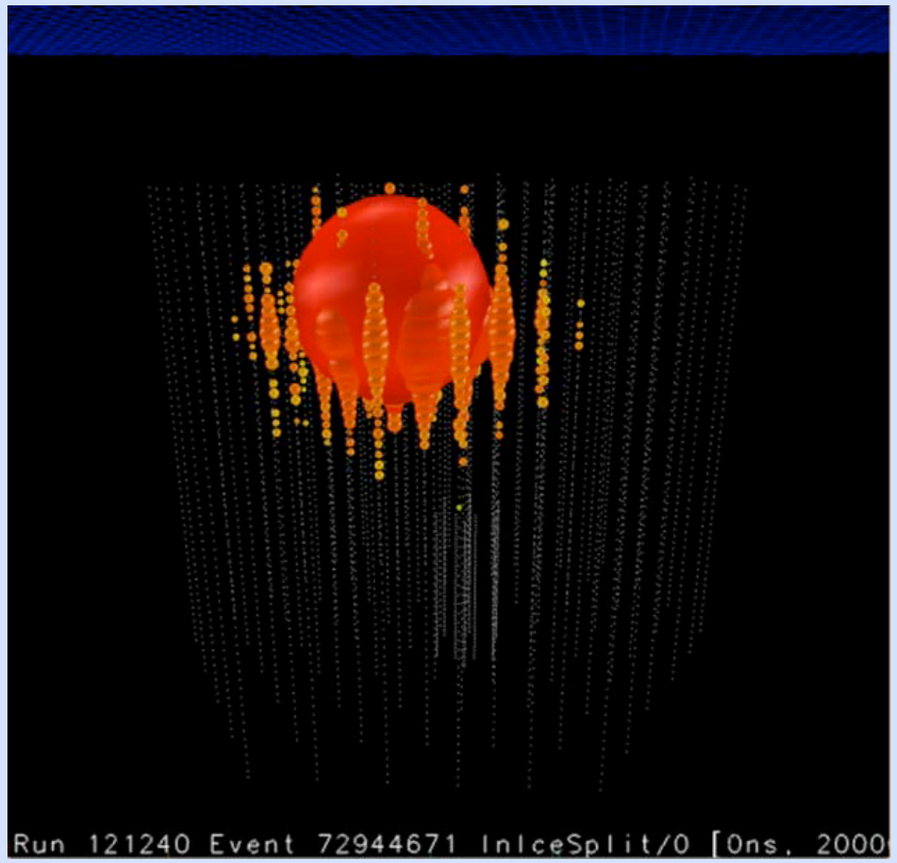
Adapted Rott, Tanaka, Itow JCAP09(2011)029 to PINGU.

Advantages of PINGU

- Well-established detector and construction technology (low risk)
- Relatively low cost: ~$10M design/startup plus ~$1.25M per string
- Rapid schedule: deployment could be complete by 2017-18, depending on final scope
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors
- PINGU LOI forthcoming

Conclusions

- IceCube has reigned in a new era in astro-particle physics
  - What's the origin of the high-energy neutrino excess ?
- Great prospect for future upgrades
  - PINGU in-fill aims at creating a large volume detector with a threshold of few GeV
    - Ideal for precision neutrino measurements (Neutrino Mass Hierarchy, ...)



IceCube continues to collect and analyze data

One very high energy event appeared in the 10% of the 2012 data used to develop the analysis – "Big Bird"

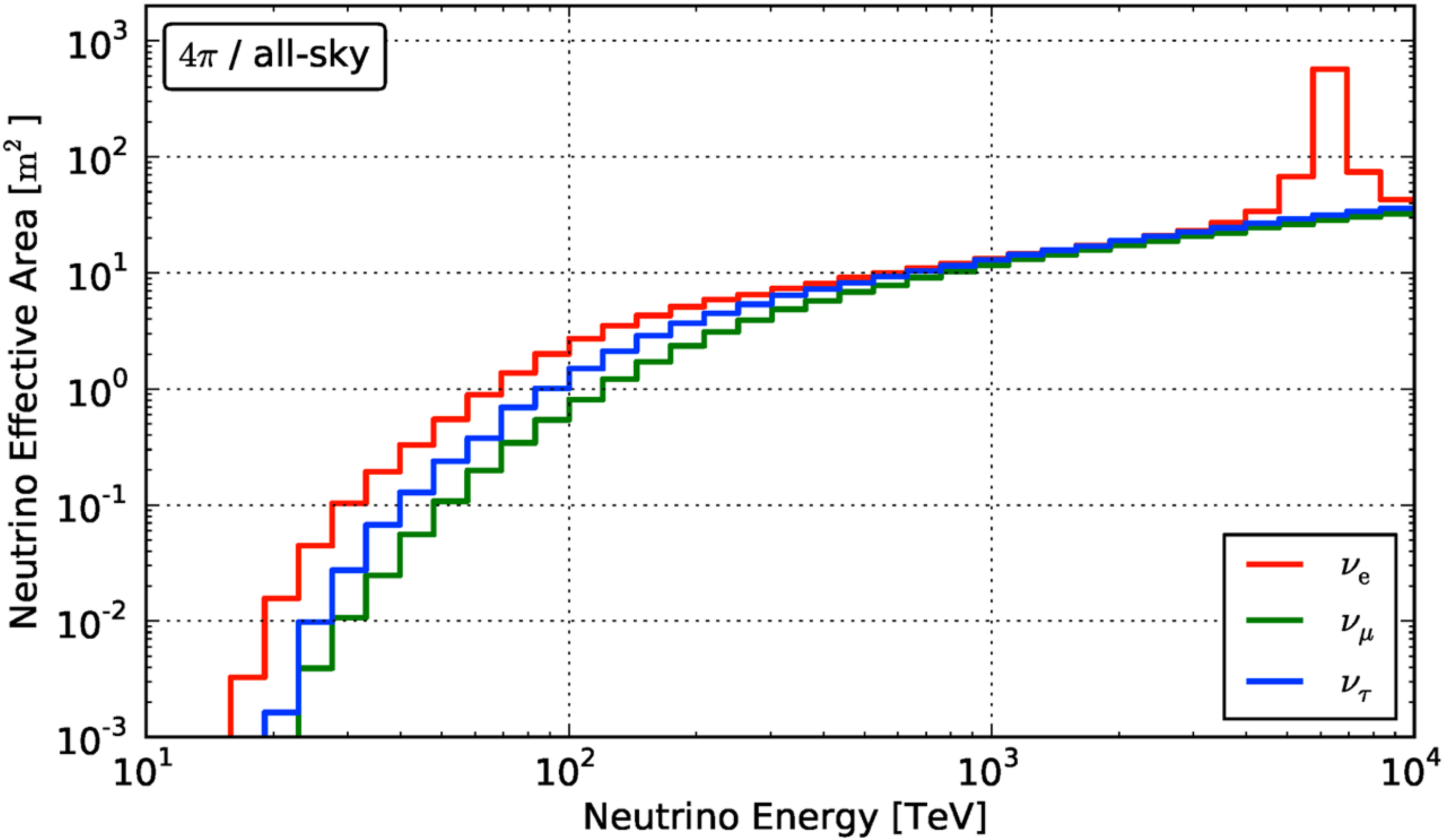
378 hit DOMs

Bert and Ernie are the not only PeV neutrinos

Backup

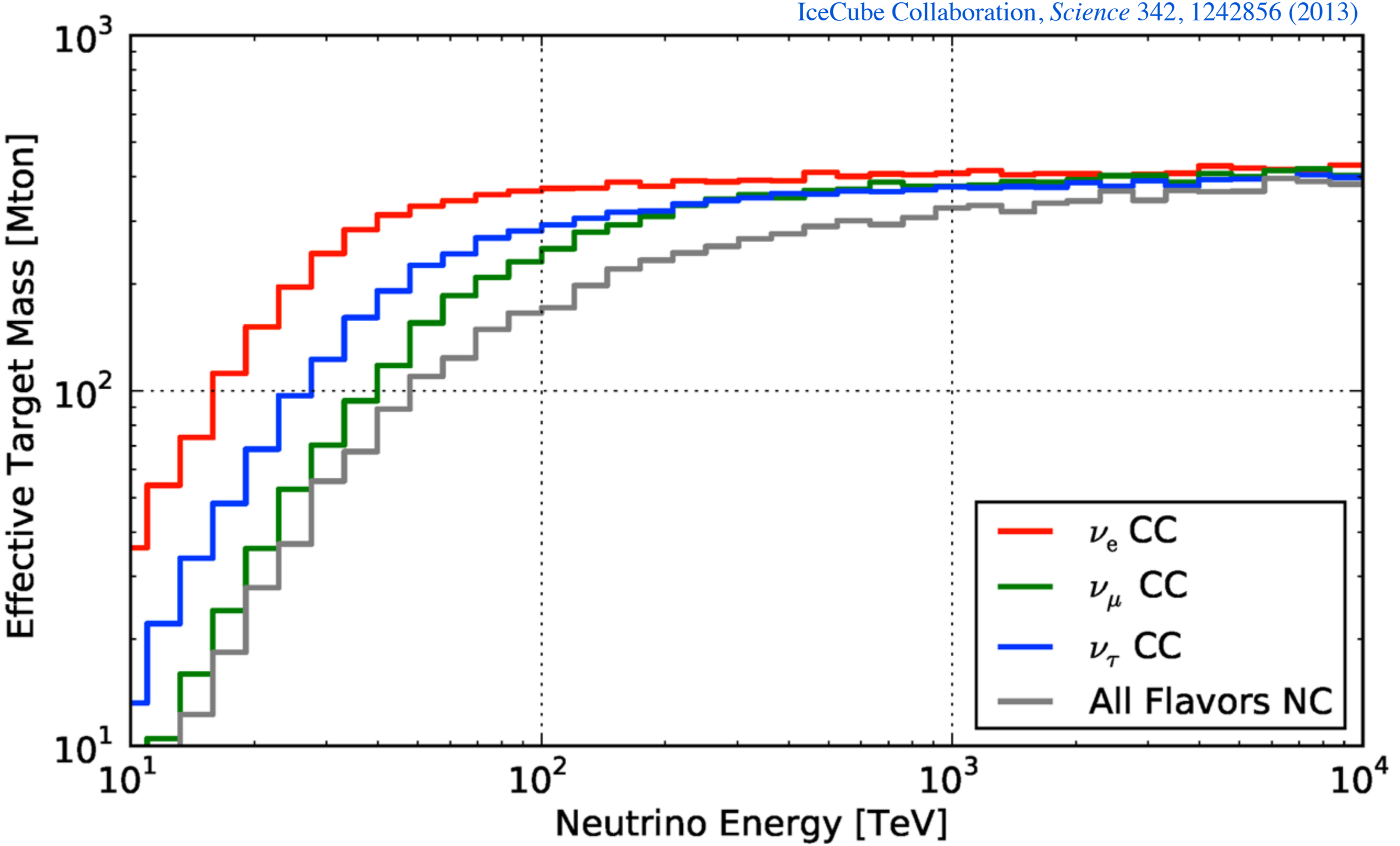
Effective Area

IceCube Collaboration, *Science* 342, 1242856 (2013)

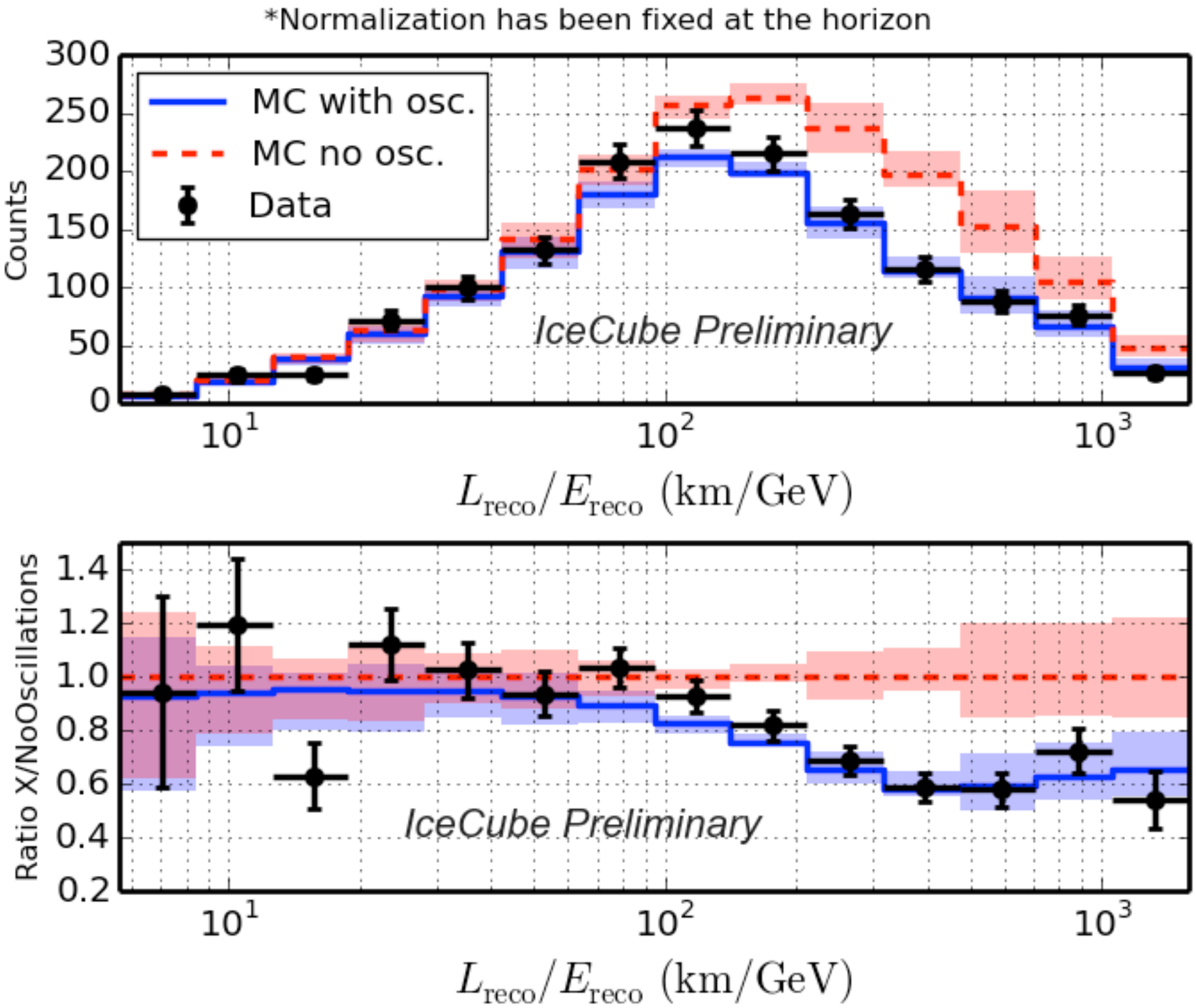


Effective Target Mass

IceCube Collaboration, *Science* 342, 1242856 (2013)



IceCube 86 strings oscillations analysis



Improvements: new reconstruction techniques using unscattered photons

Good angular resolution at lowest energies

Highest event rates at ~10 GeV

ICRC2013 Proceedings: IceCube Coll. arxiv:1309.7008

Likelihood Search for a Point Source - Test Statistics (TS) Calculation

Maximize the likelihood L at every point in the sky x

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

- n_{tot}: Total # of events = 28
- n_s: # of events from source, Varied to maximize L
- $S_i(x)$: Reconstruction map value at position x from event i
- $B_i(x)$: Uniform value for each event at every position

* *Events' energies not used in the likelihood*

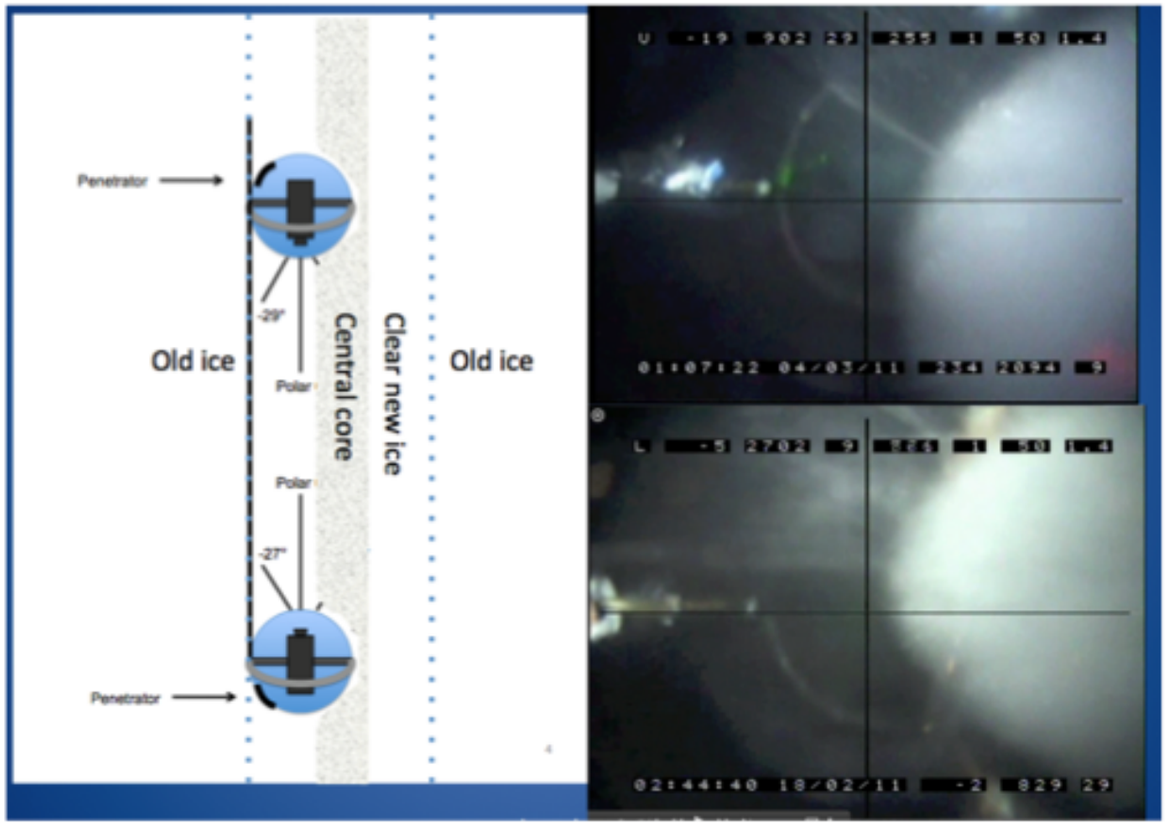
TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) / L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

Calibrations

- The goal is improved overall precision. IceCube methods already perform well (5-10% level); aim is to reach few % level via:
  - Improved in lab measurements for calibration of the PMTs and the DOM itself. Complete a full circular test to obtain the absolute efficiency in the ice.
  - Advanced understanding of the hole ice and methods to reduce the impact (drill water degassing).
  - Improvement of LED flasher control and precision calibration of the LED output
  - Full simulations studies are underway



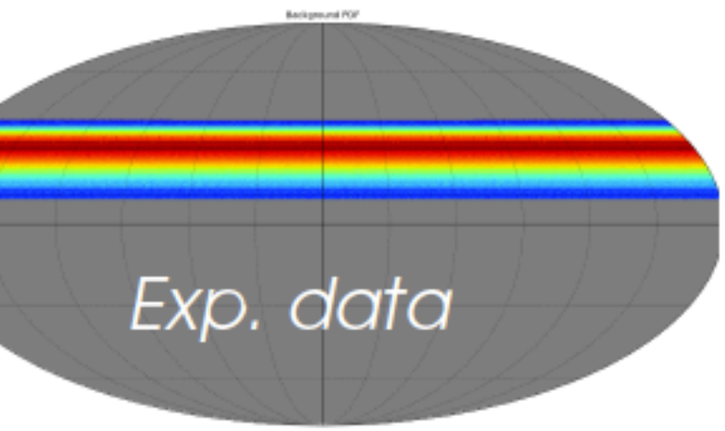
Low-cost on-board cameras for PINGU

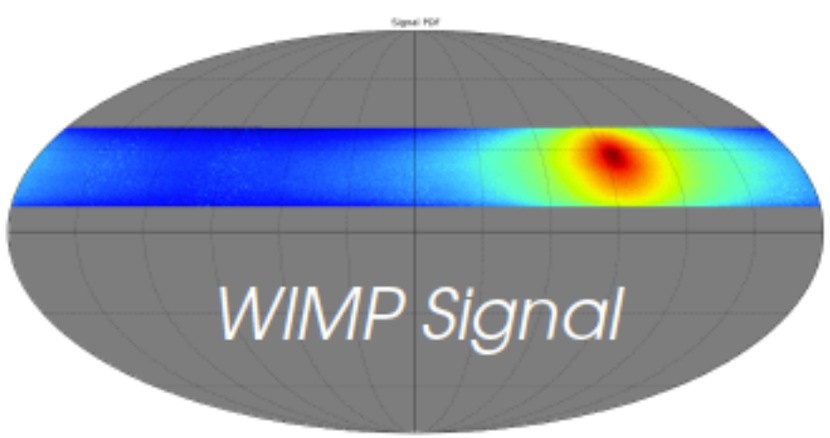
- Low-cost on-board camera system
  - complementary to the more sophisticated camera systems.
  - The merit of the system:
    - can be deployed on a large fraction or all of PINGU Sensors
  - determine the exact positioning of individual DOMs with respect to the drill hole and refrozen ice
  - understand local ice properties after freeze in

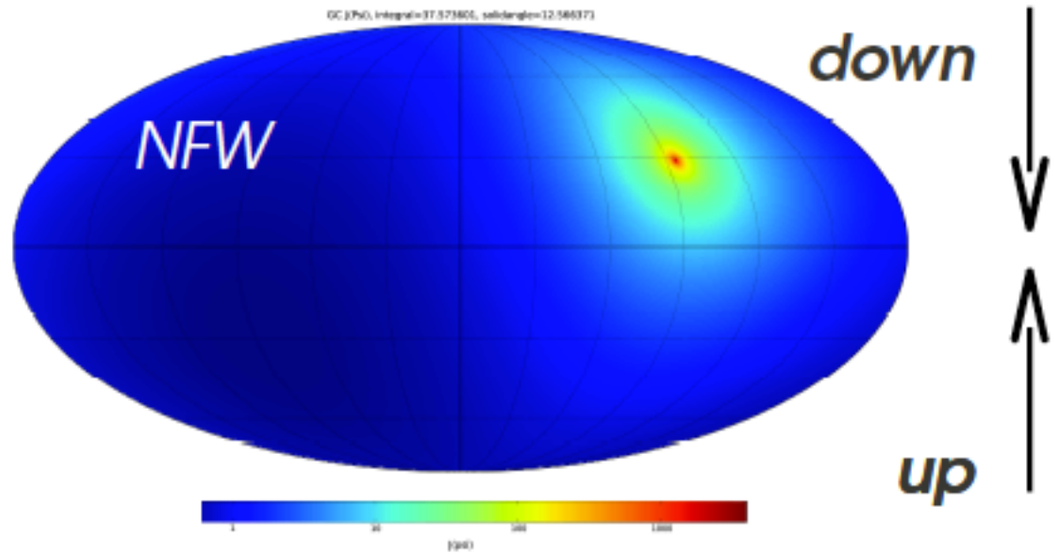
Bert over Seoul

Gyeongbokgung Palace

Search for Dark Matter in the Milky Way

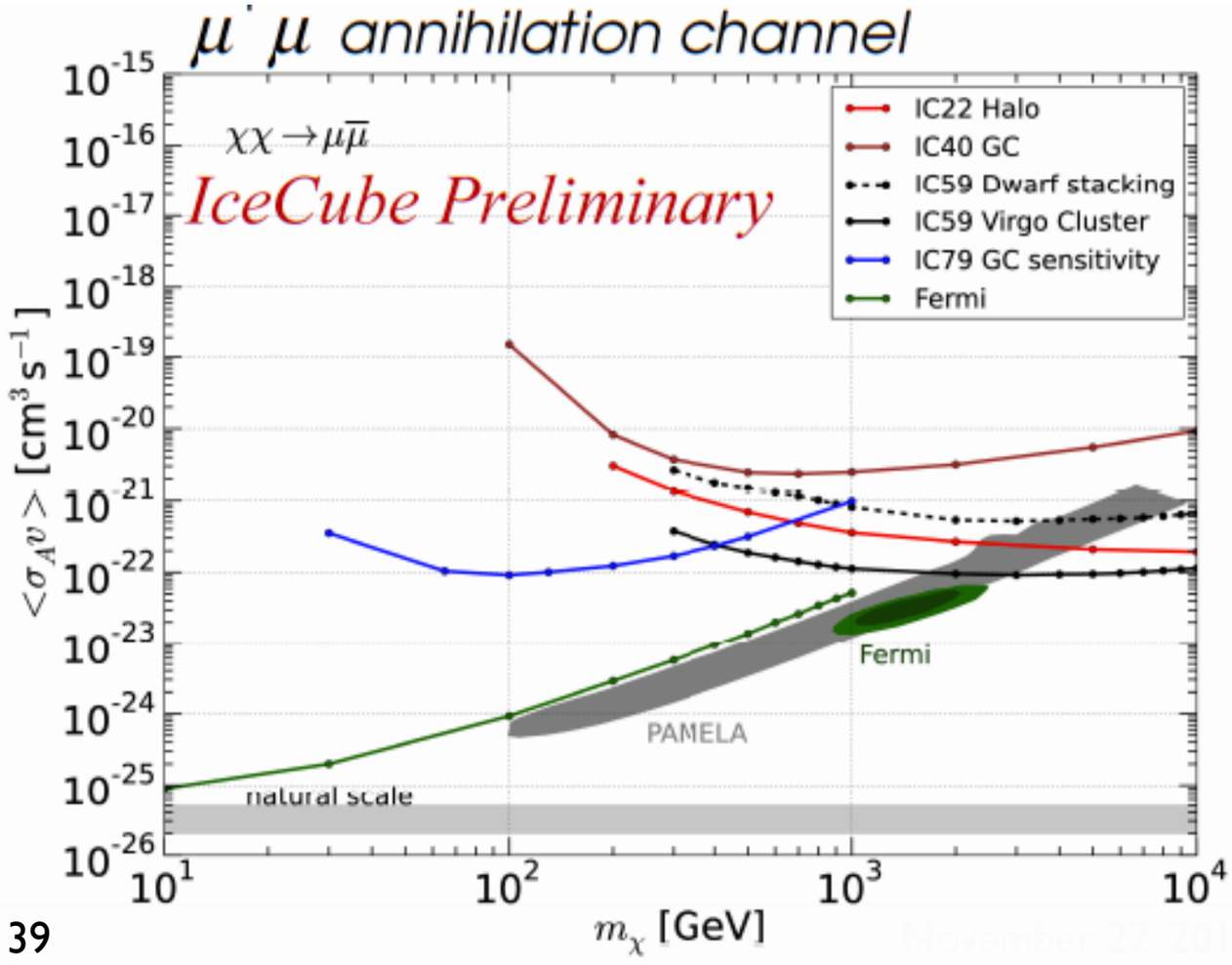




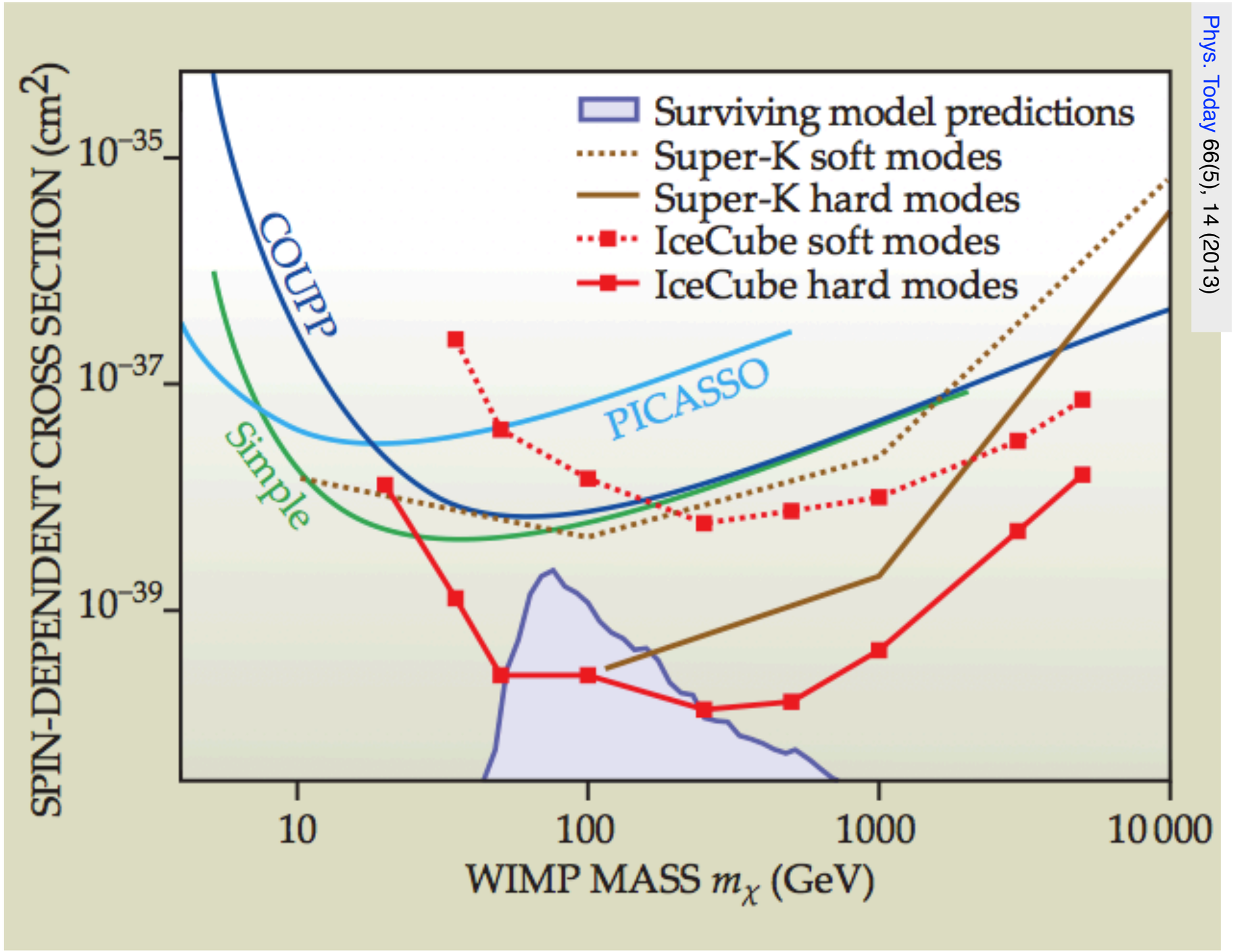


2D PDFs generated with healpix

- IceCube achieves sensitivity to reach down to WIMP masses of 30GeV



IceCube Dark Matter Search



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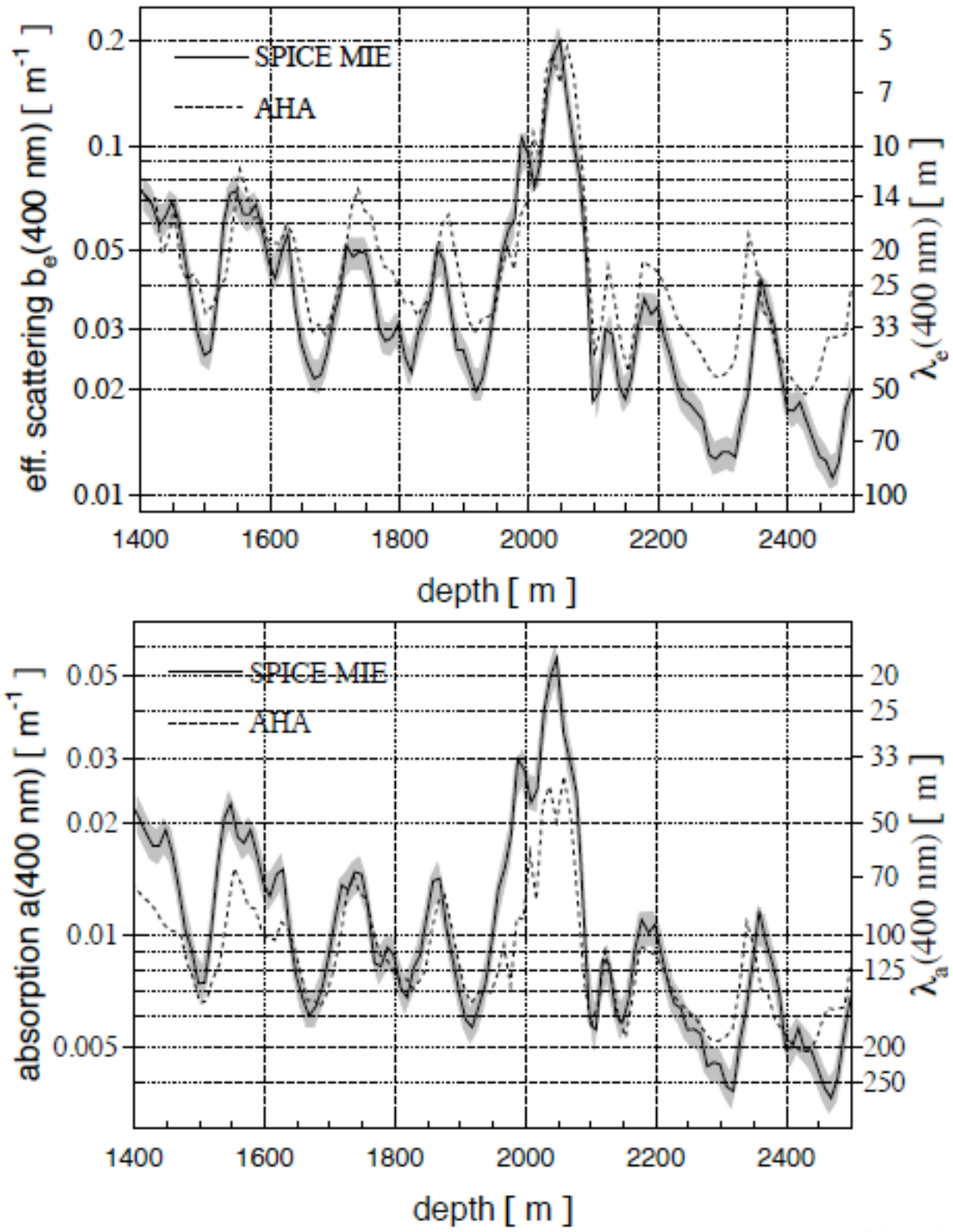
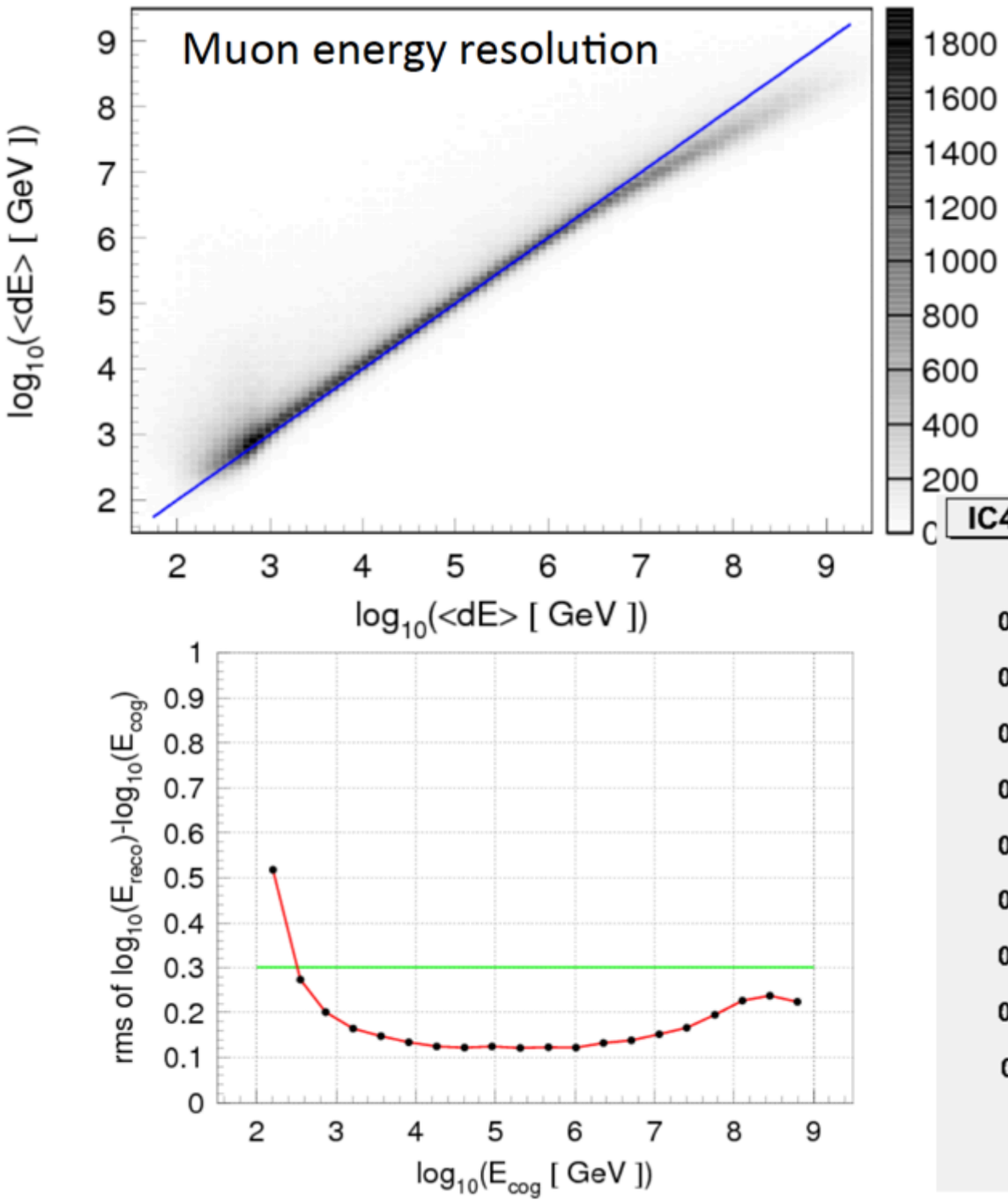
Ice and Detector Response

- Important to model light propagation and detector precisely to reduce systematic uncertainties
- Calibration system allows to map second order effects:
  - Vertical variations (up to 50m/km)
  - Azimuthal anisotropy of scattering length (up to ~10% / 100m)



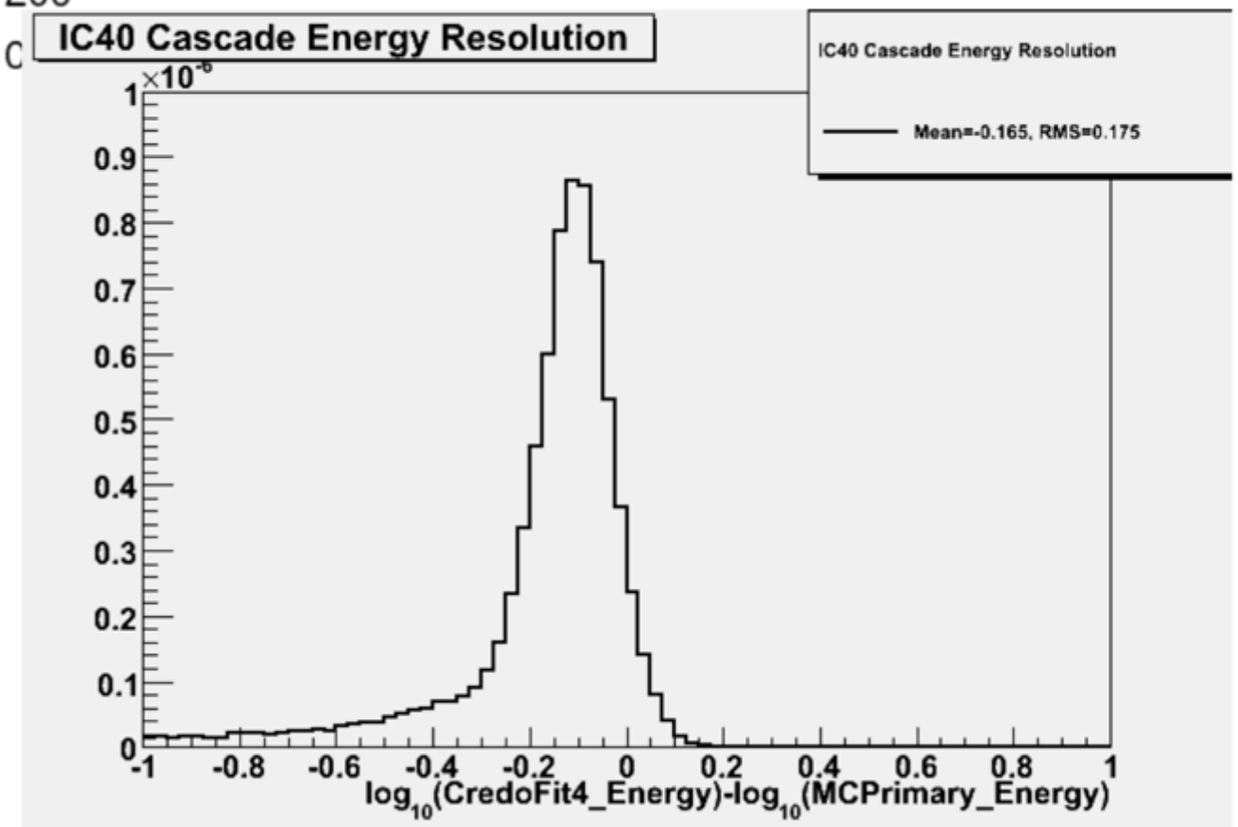
Measurement of South Pole ice transparency with the IceCube LED calibration system,
Aartsen et al., (IceCube Coll.), NIMA55353
http://arxiv.org/abs/1301.5361

Resolution



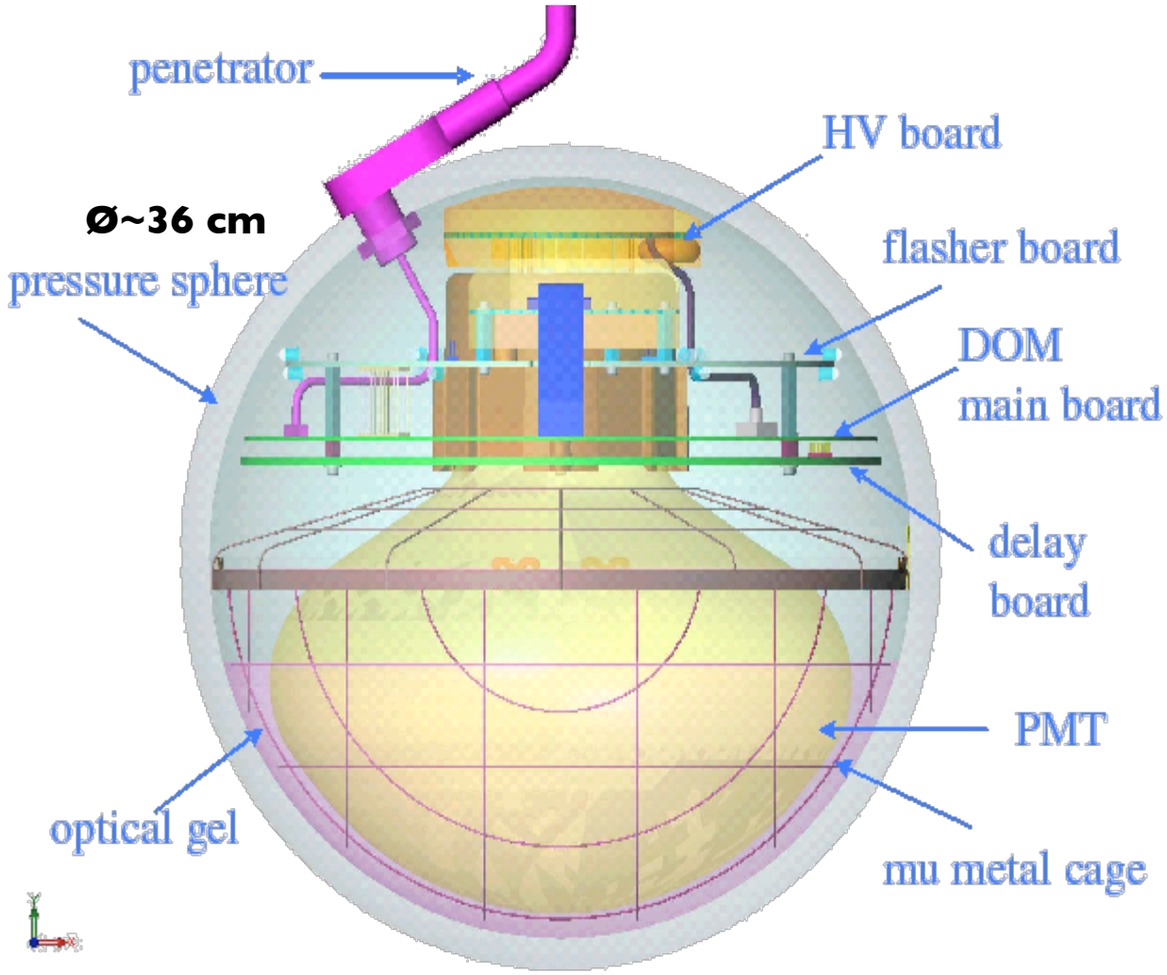
Muon energy: rms of log(E) ~ 0.15
Muon neutrino: 0.3 (inevitable physics fluctuations from neutrino energy to muon energy at detector)

Electron neutrino cascades:
rms of log(E): ~ 0.175
sigma of peak: 0.07



Digital Optical Module (DOM)

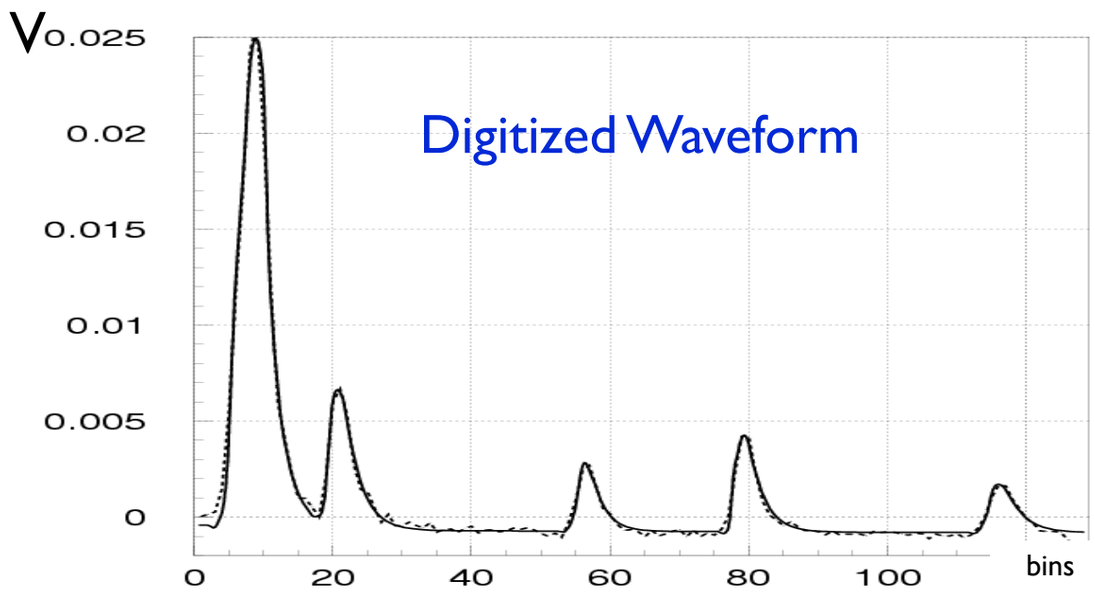
10 inch Hamamatsu PMT (R-7081-02)

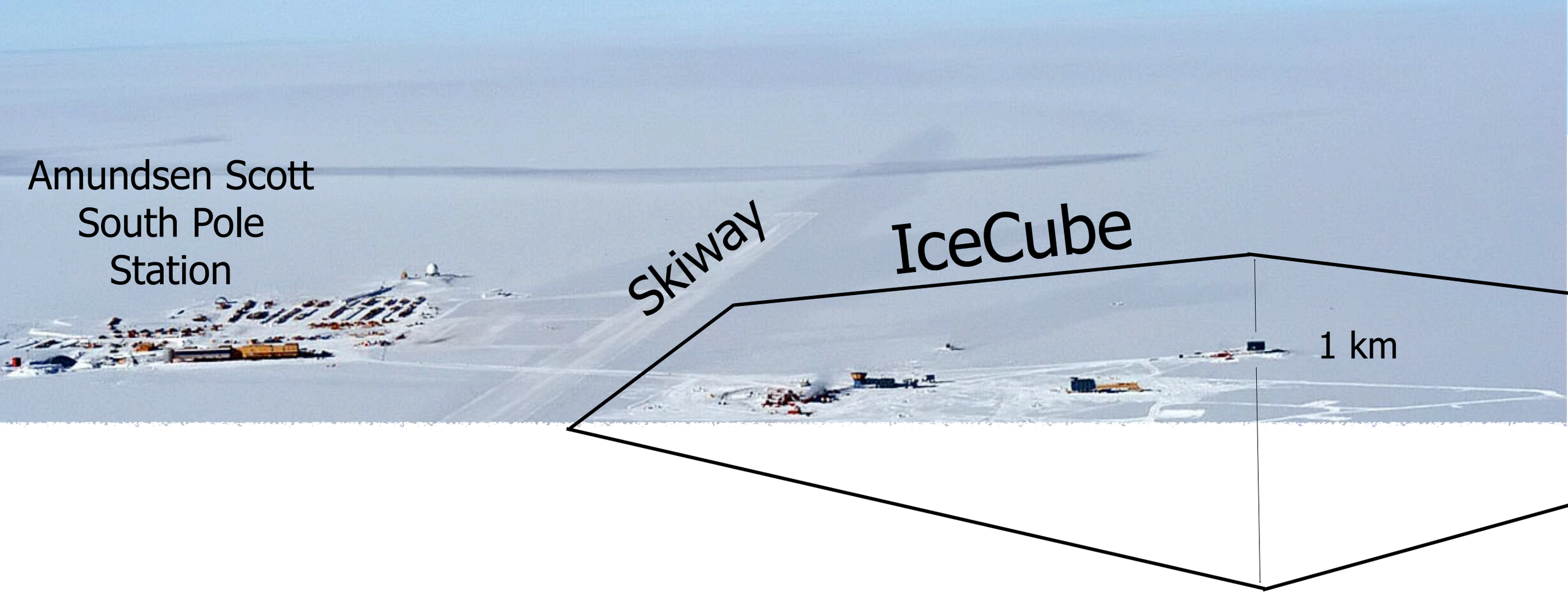


- Dark Noise rate ~ 350 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2 ns

Measure individual photon arrival time:
2 ping-ponged four-channel ATWDs:
- Analog Transient Waveform Digitizer
- 200-700 Megasamples/s
- 400 ns range
- 400 pe / 15 ns

- fADC (fast 'ADC'):
  - 40 Megasamples/s
  - 6.4 μs range




Amundsen Scott
South Pole
Station
Skiway
IceCube
1 km