Latest Results from IceCube

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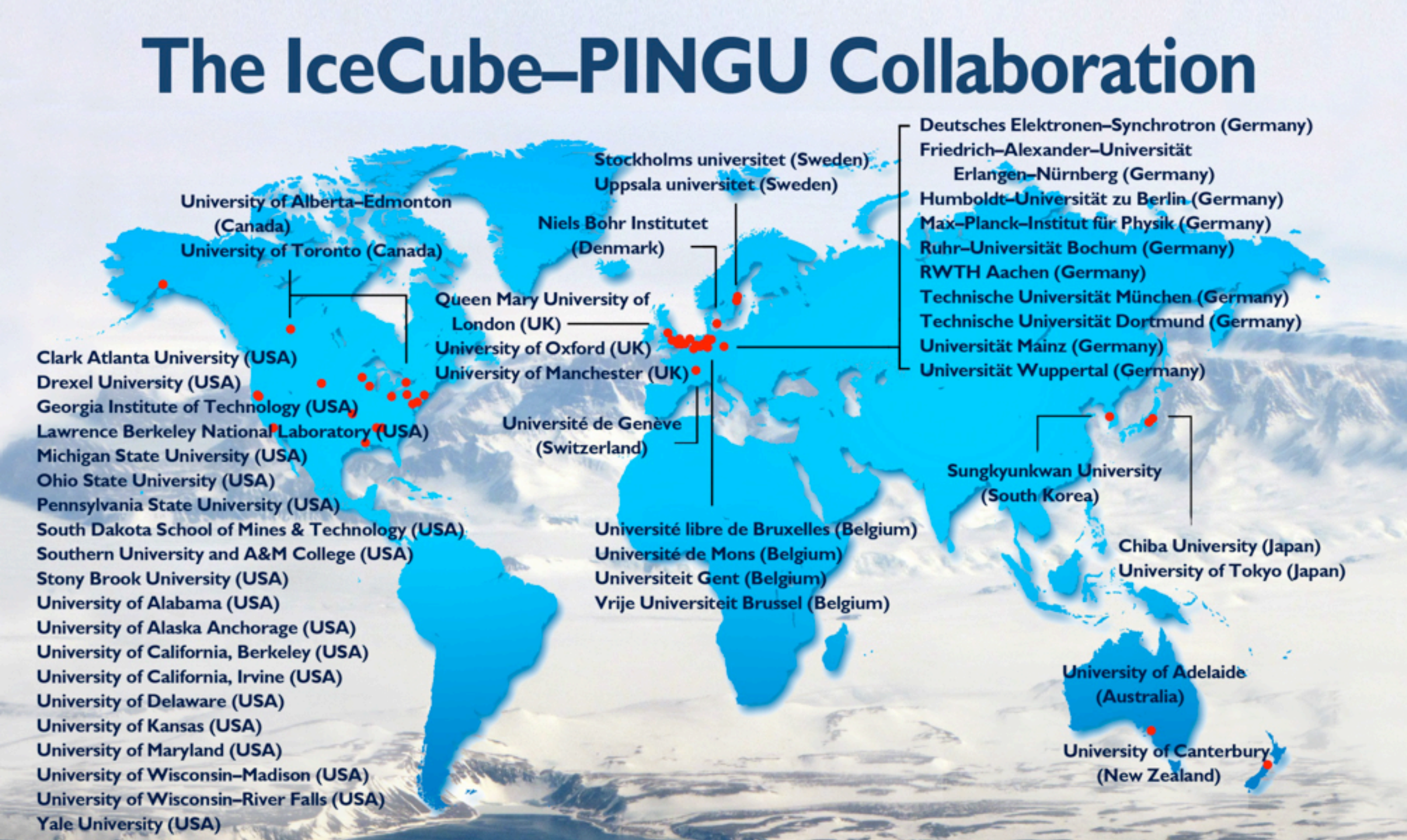
PPC2015
PARTICLE PHYSICS AND COSMOLOGY WORKSHOP

IceCube

* www.icecube.wisc.edu

1398

The IceCube–PINGU Collaboration



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
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

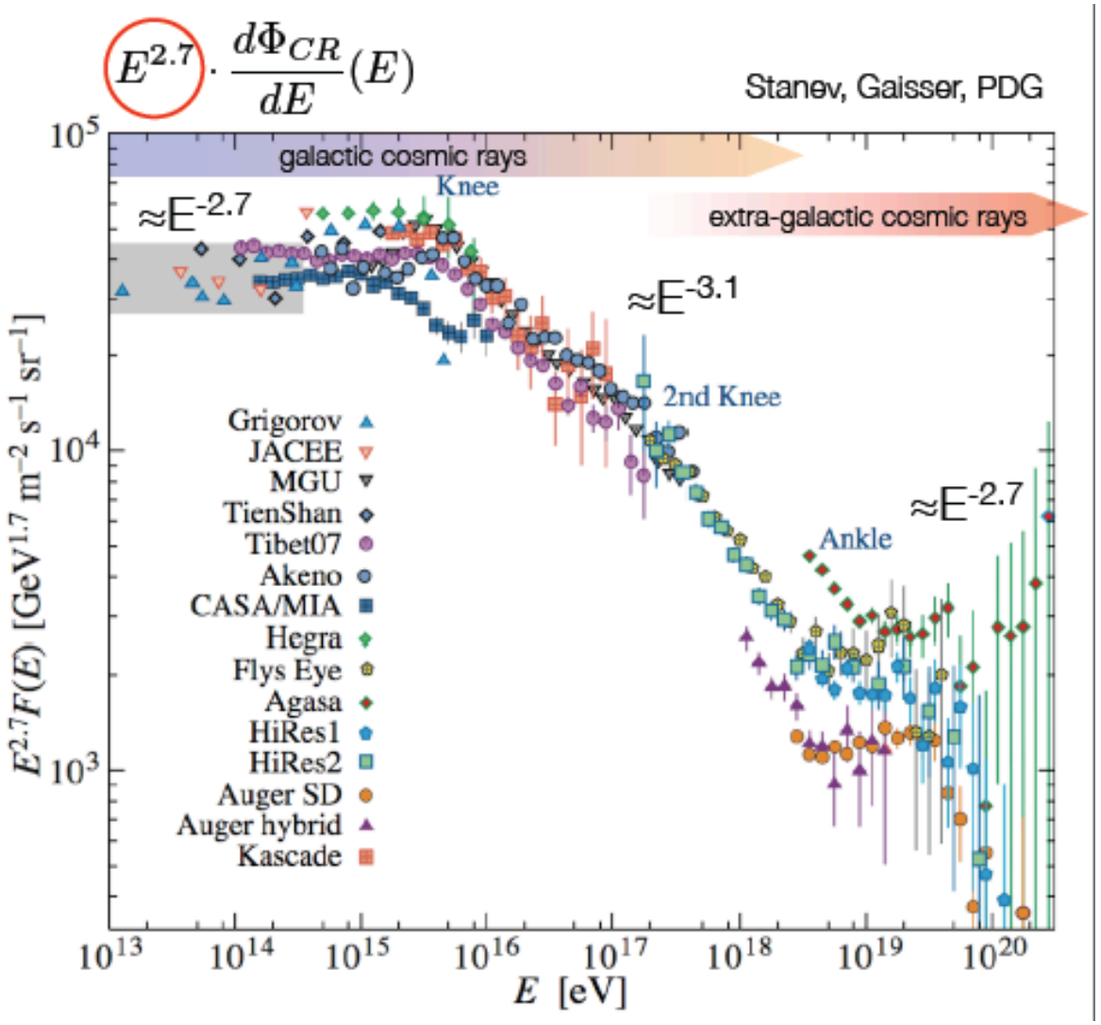
Outline

- Motivation
- The IceCube Neutrino Telescope
- Astrophysical Neutrinos
- Dark Matter
- Outlook and Conclusions

High Energy Cosmic Ray Mystery

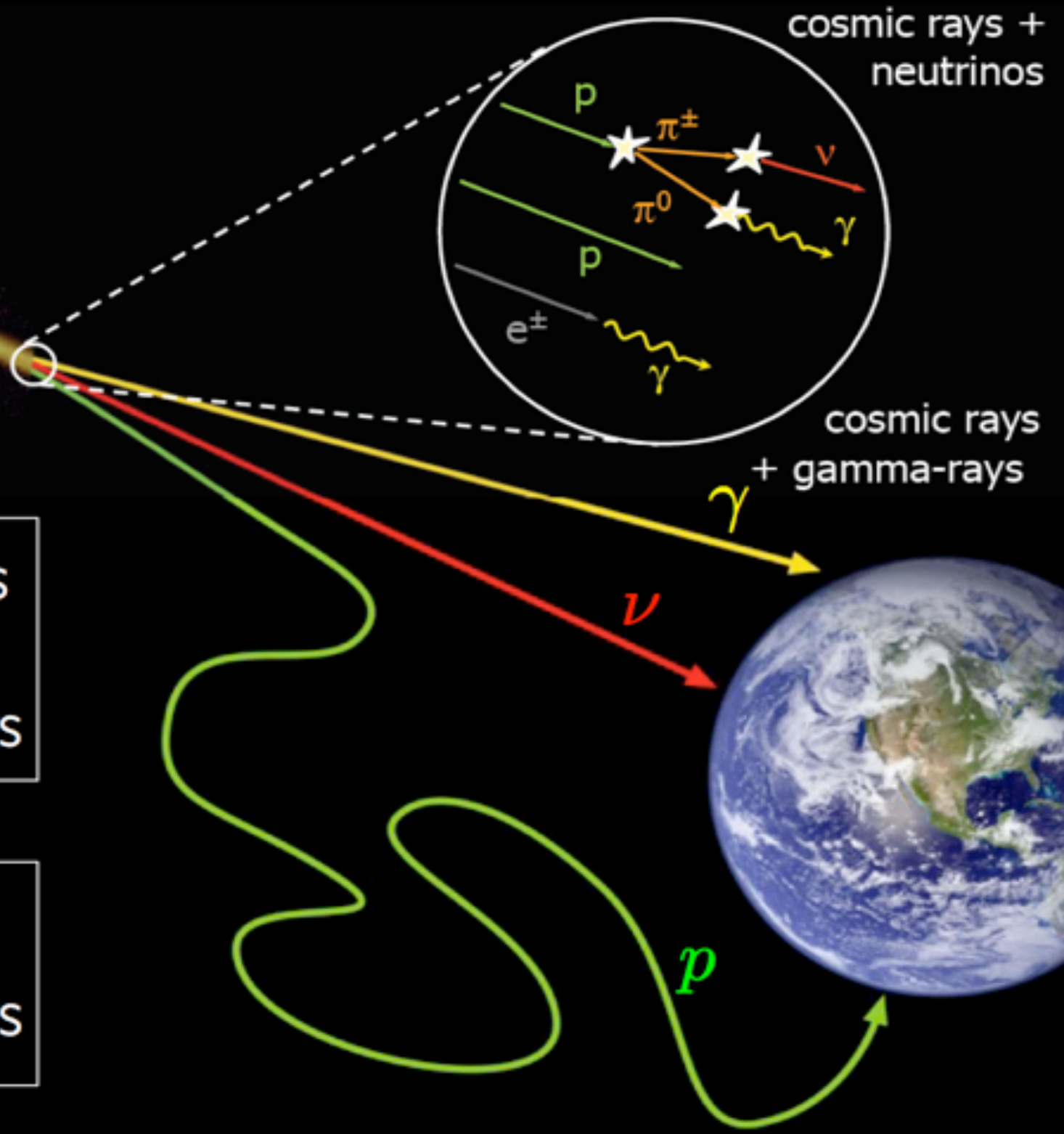
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.



- Where are they coming from ?
- What cosmic sources accelerate these particles to energies in the EeV range ?

Astrophysical Messengers

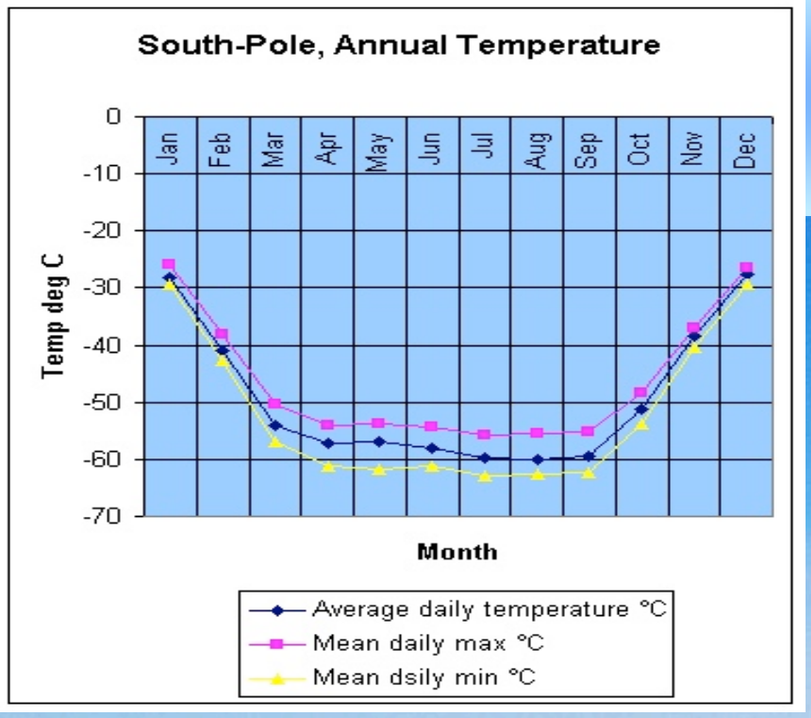


Hadrons *or* electrons can produce the observed gamma rays

Neutrinos only produced by hadrons

The IceCube Neutrino Telescope

Laboratory at the South Pole



Geographic South Pole

Amundsen Scott South Pole Station

Road to work

Skiway

1 km

IceCube

The IceCube Neutrino Telescope

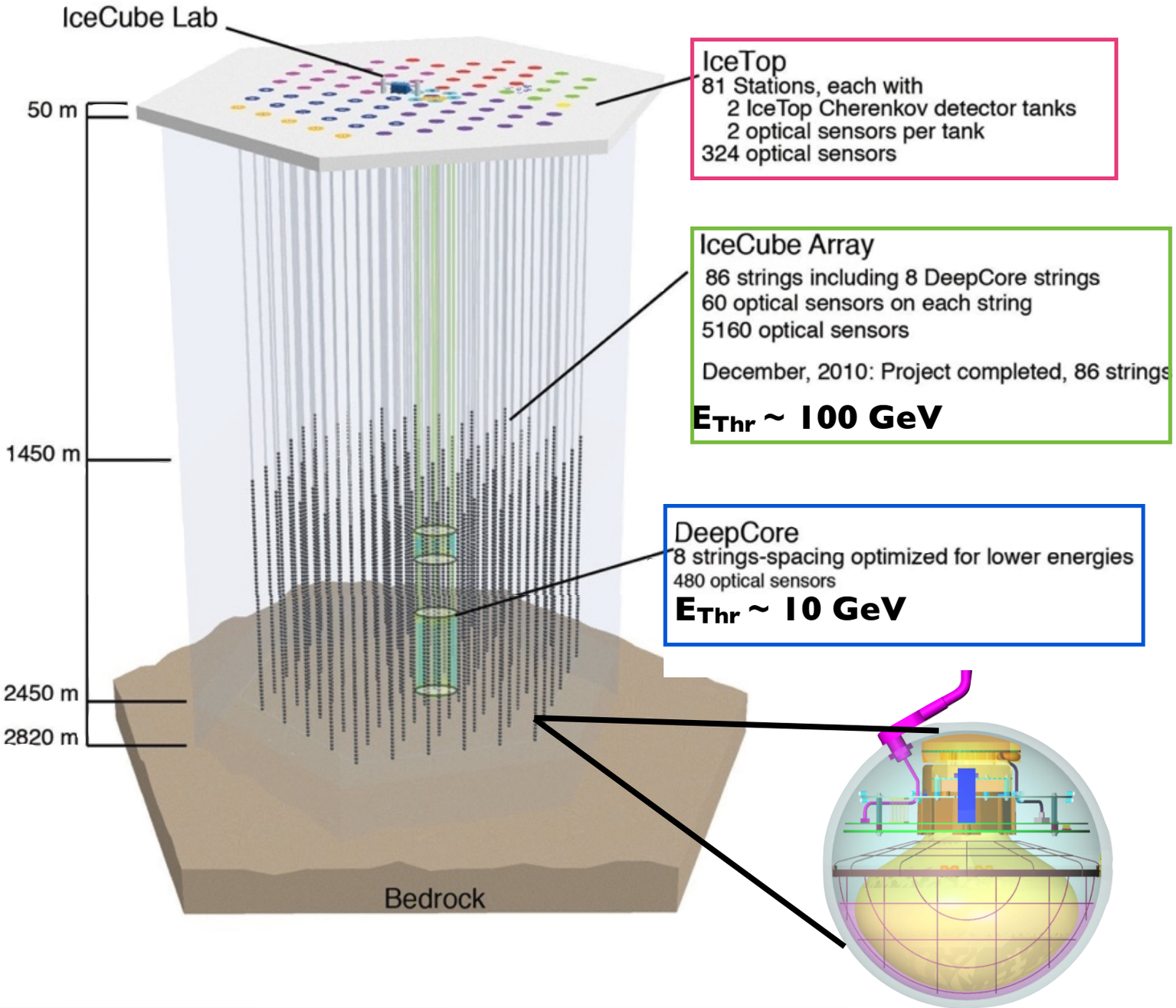
Gigaton Neutrino Detector at the Geographic South Pole

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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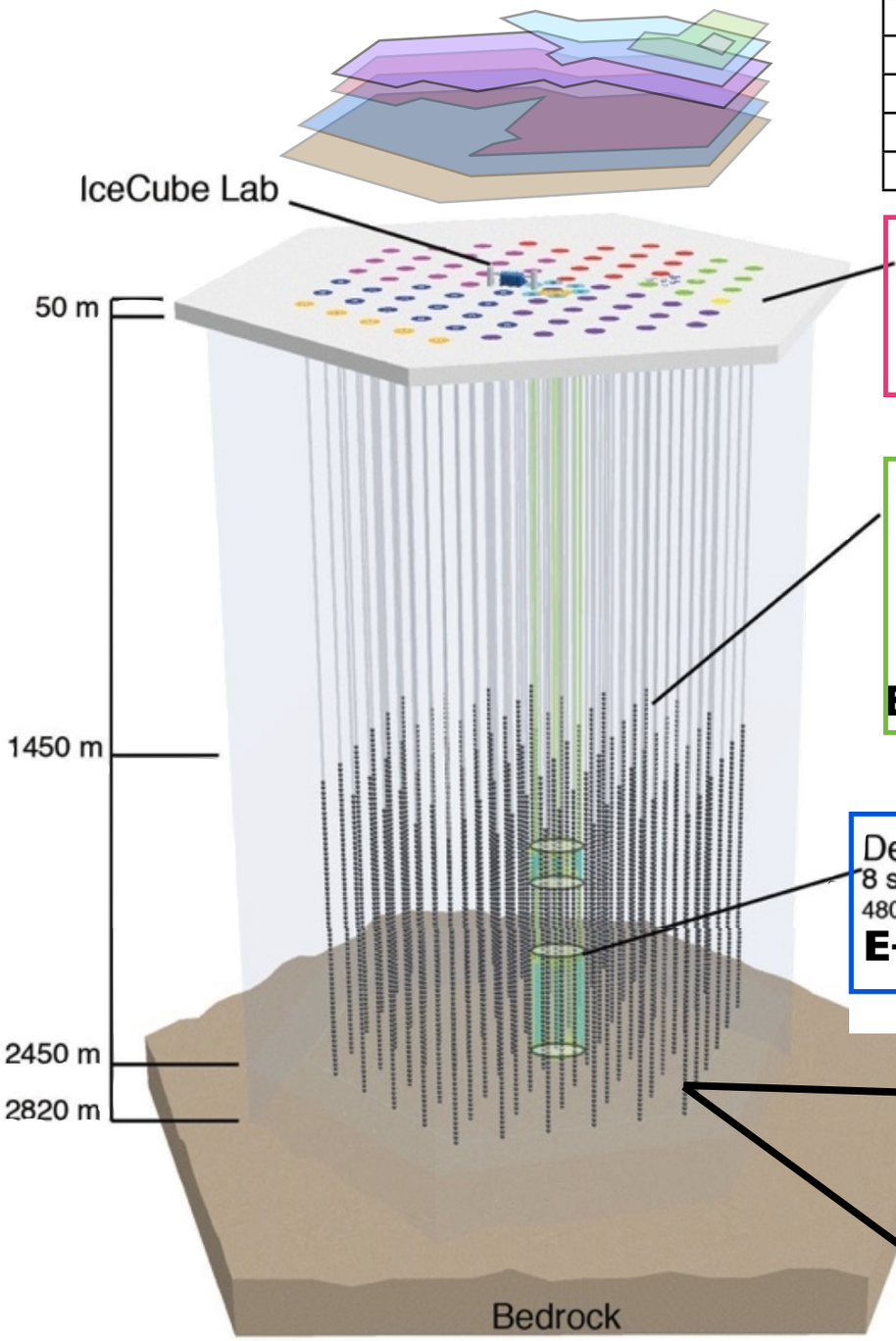
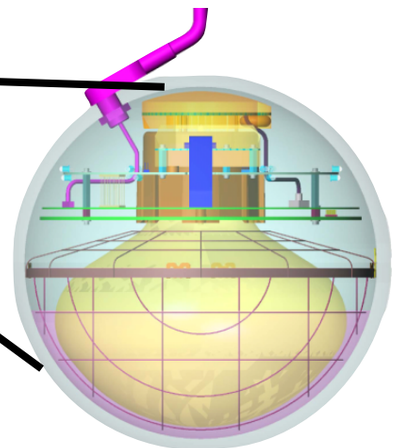
Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



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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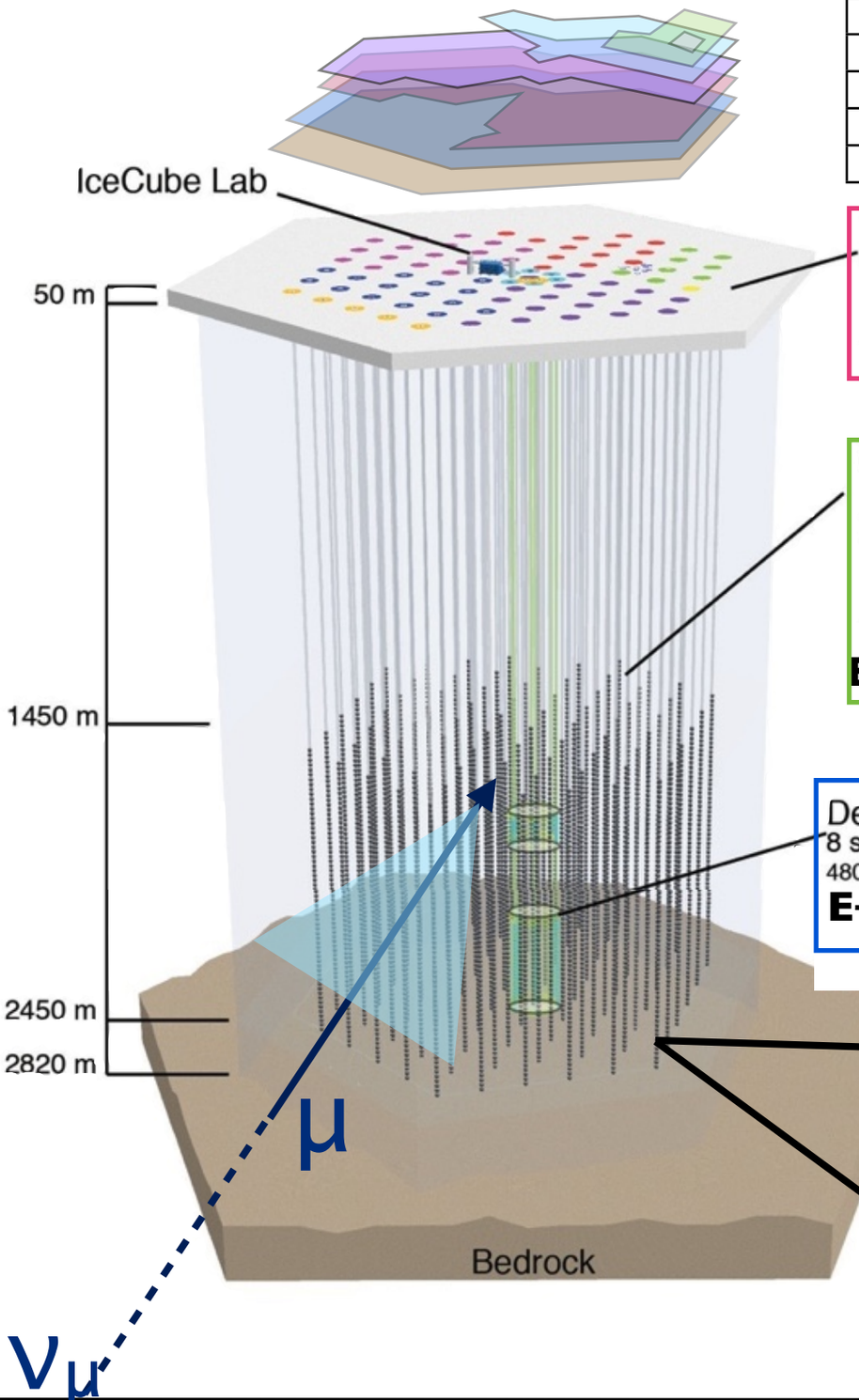

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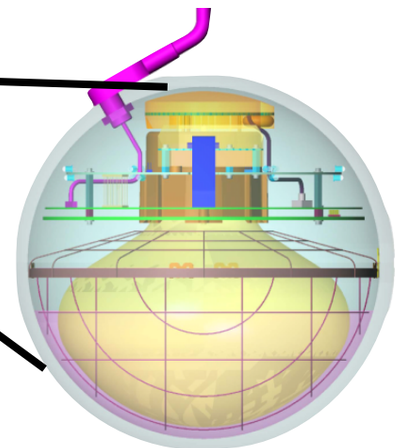
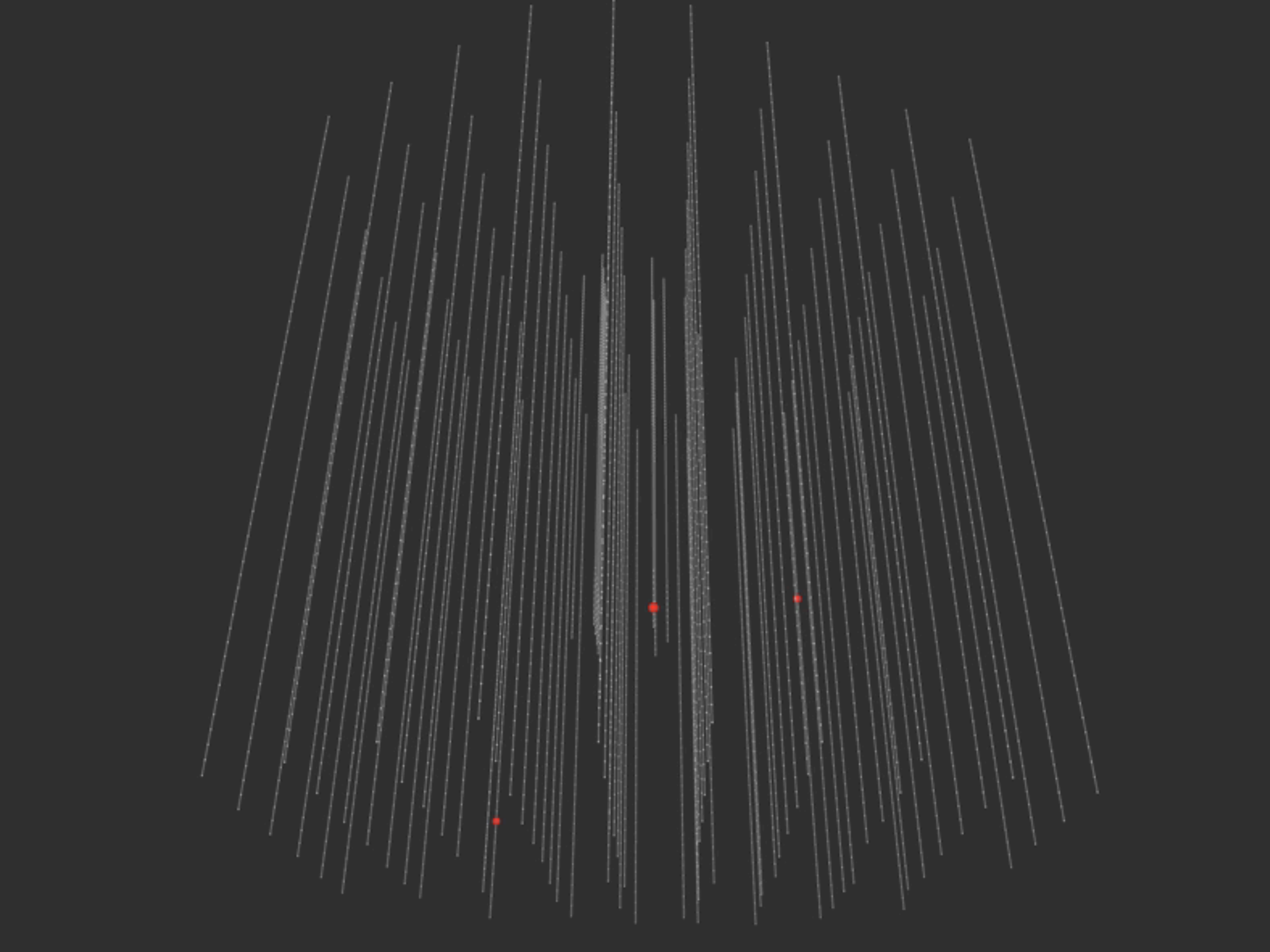
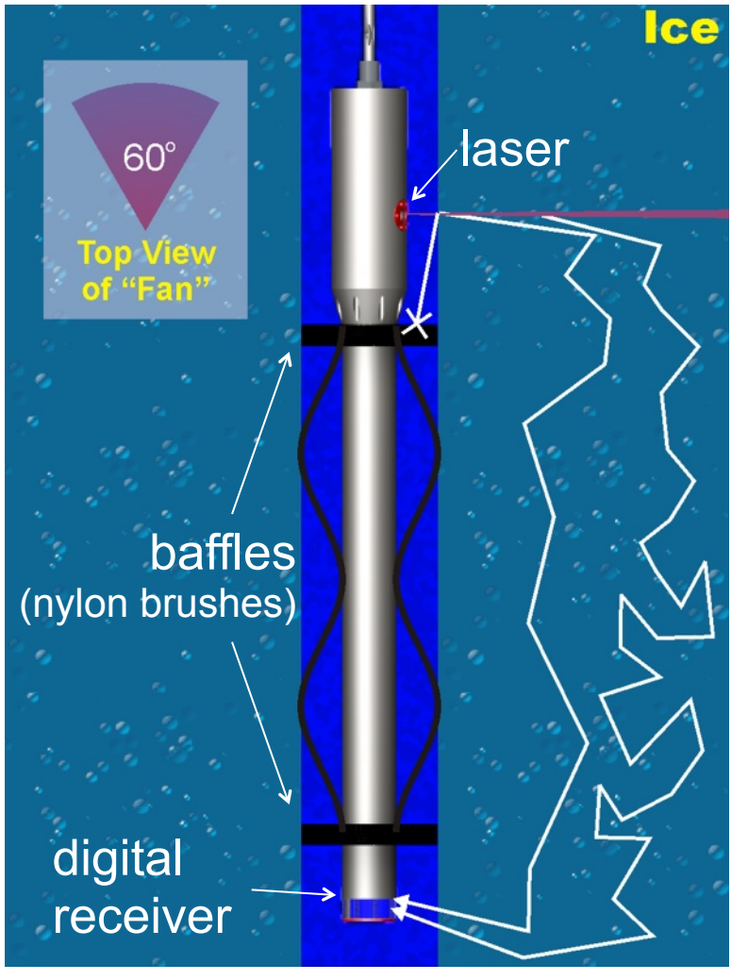




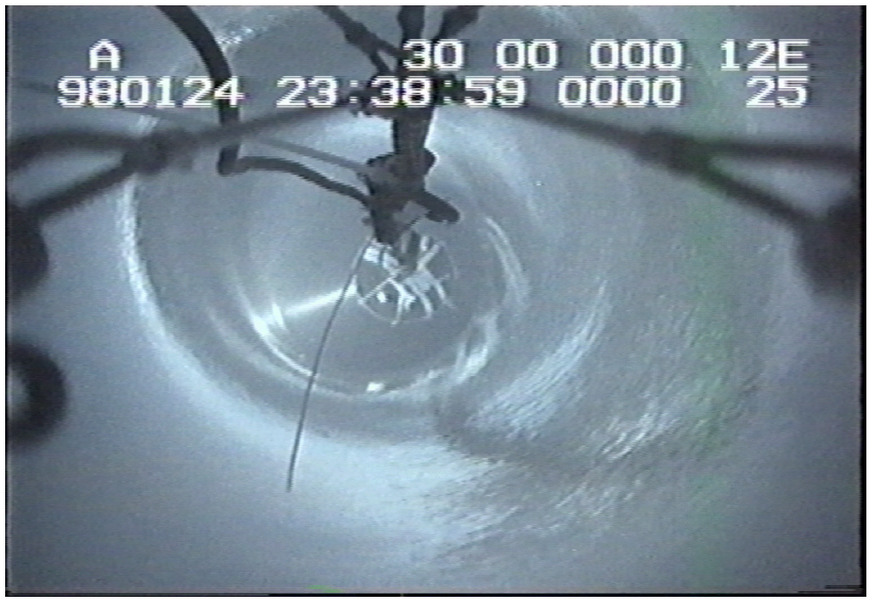
The Ice

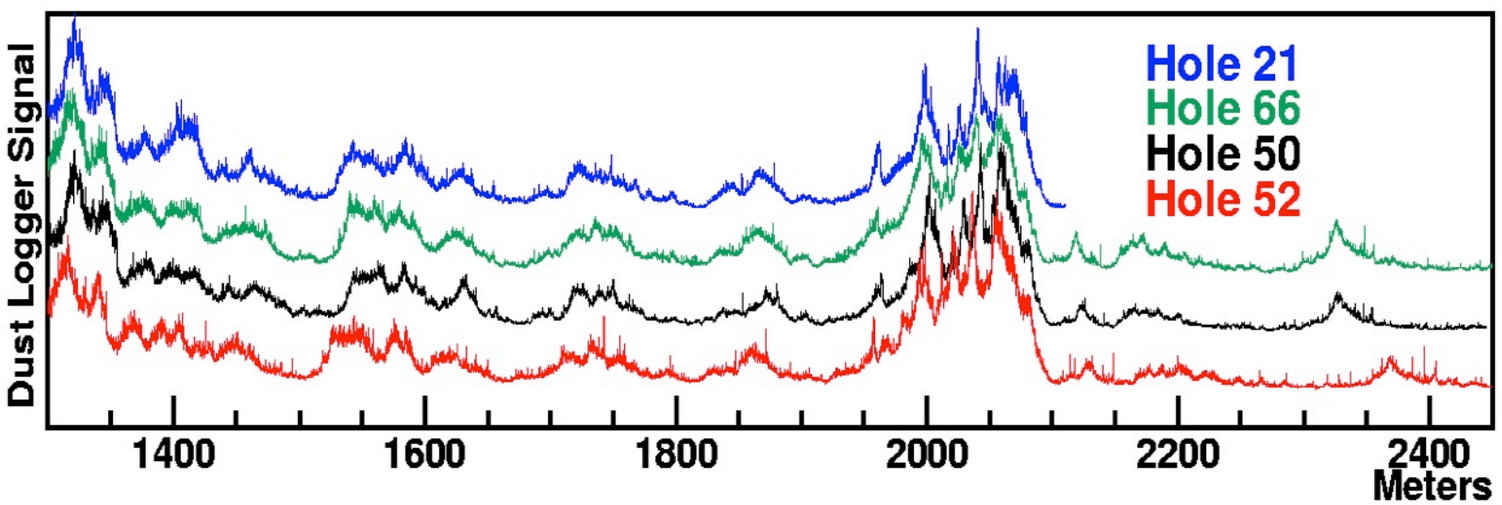


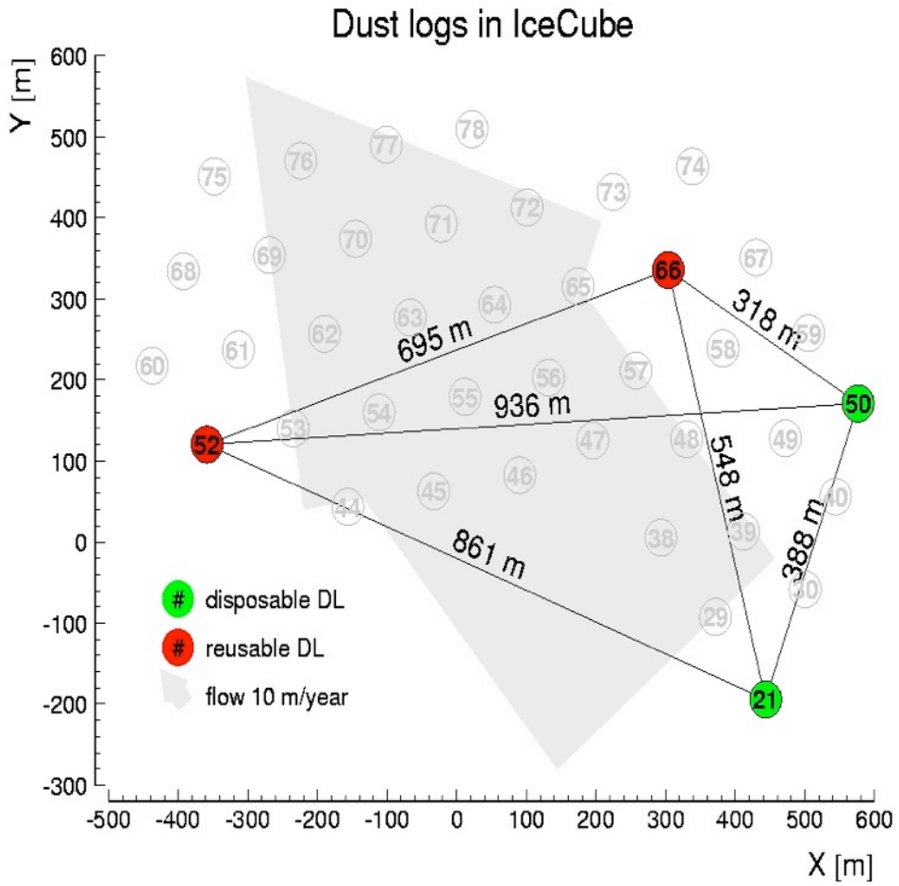
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - One pair of Camera DOMs

absorption length ~ 210m
scattering length ~20-40m







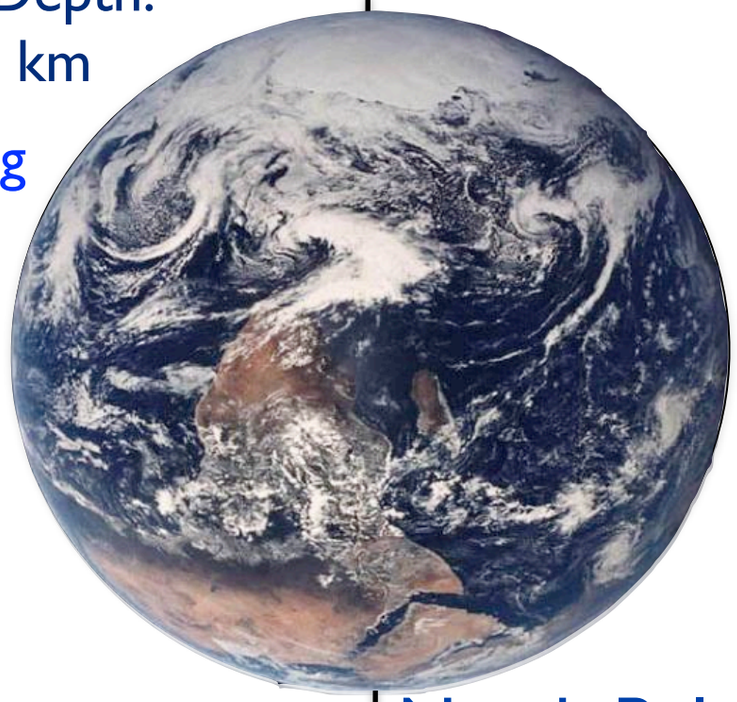
Signals in IceCube

South Pole

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

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

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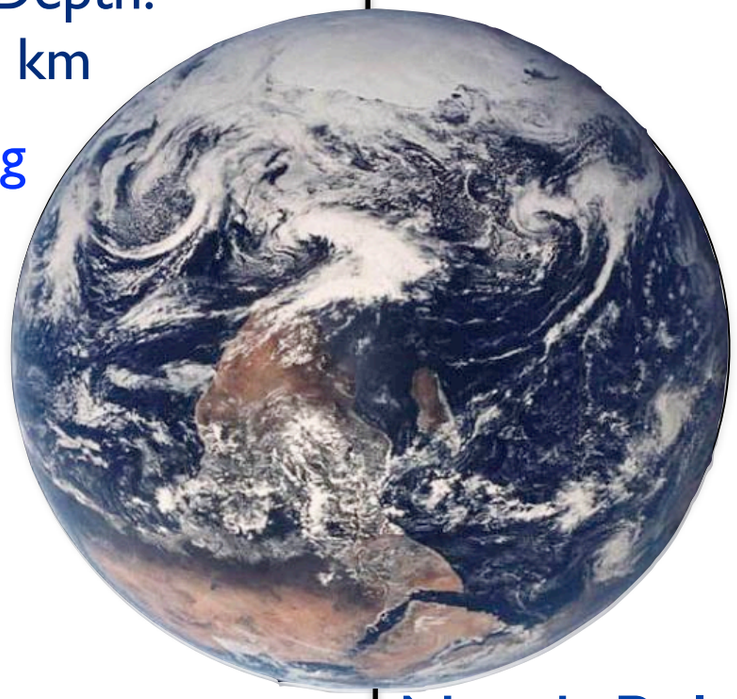

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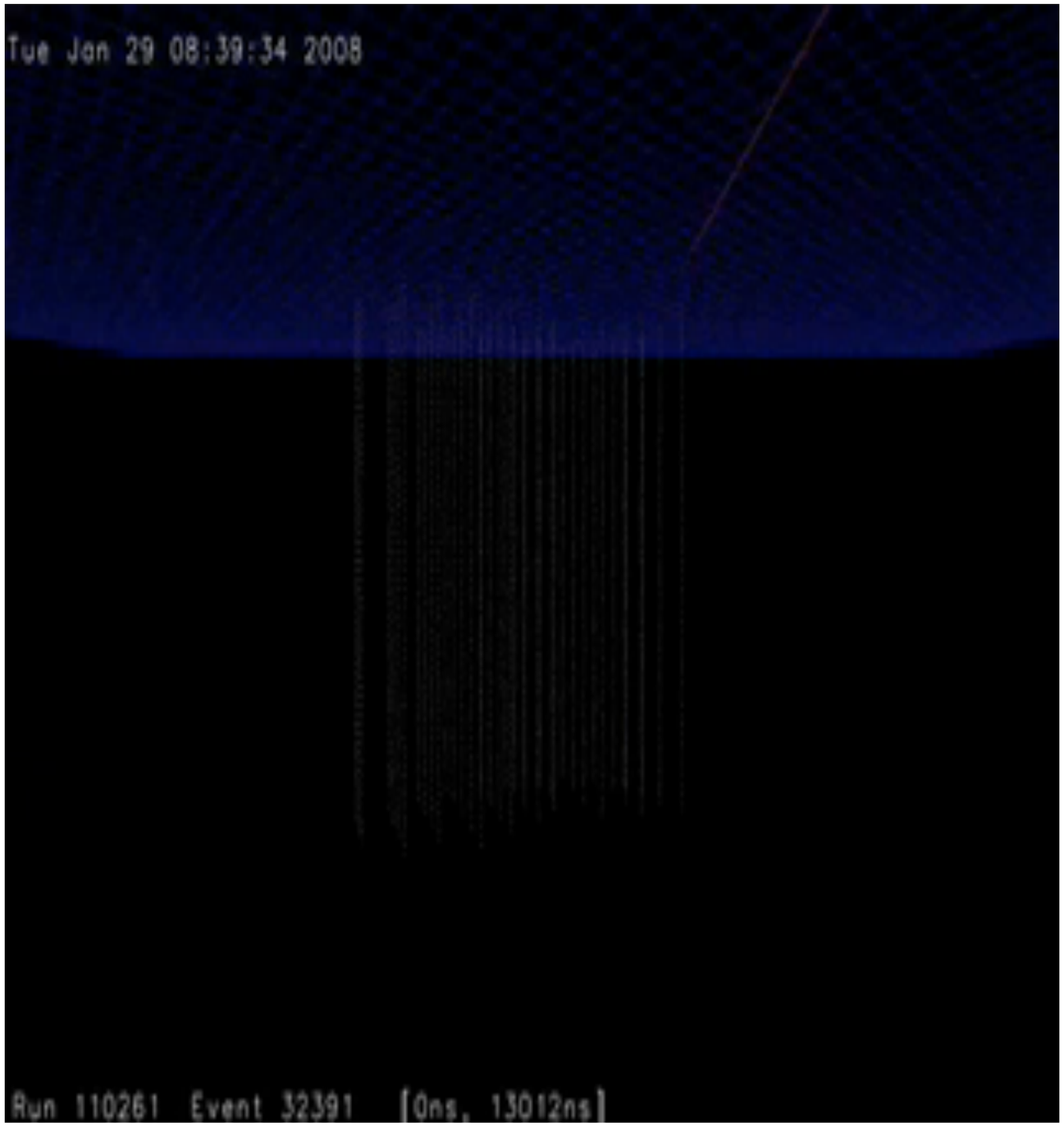

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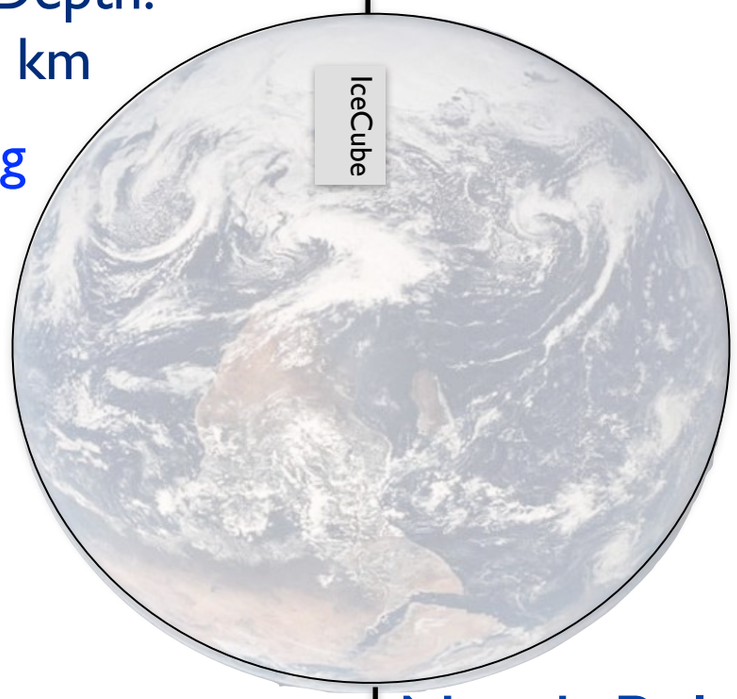

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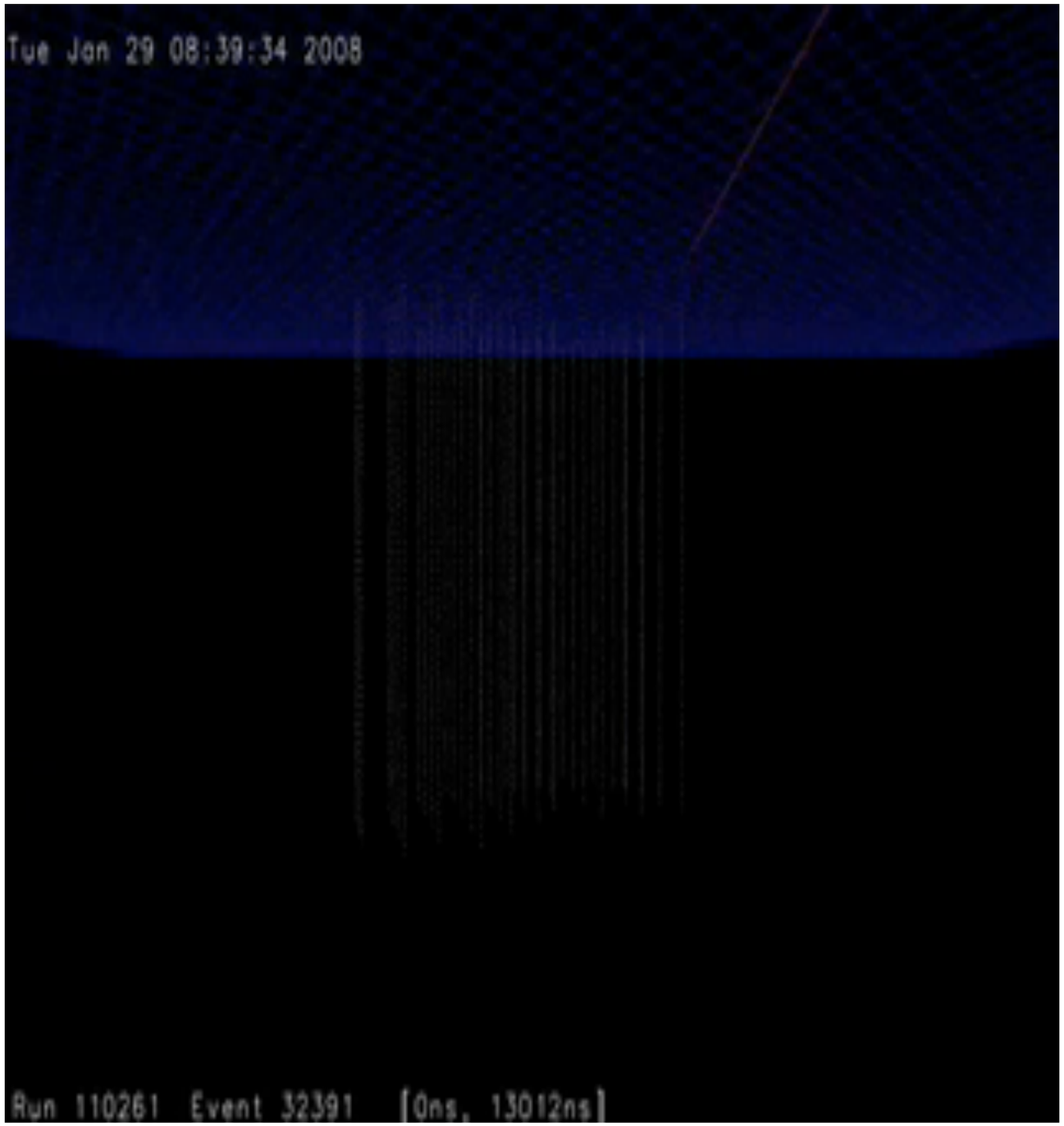

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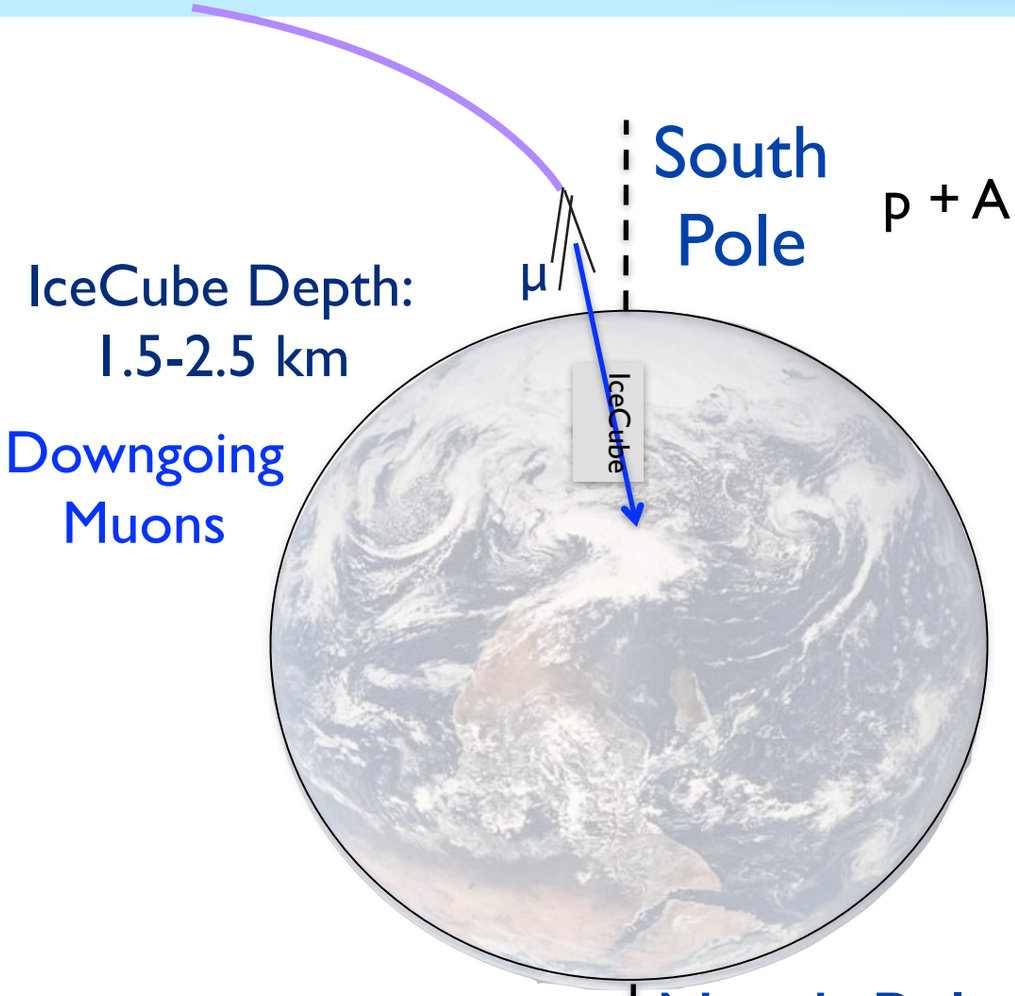

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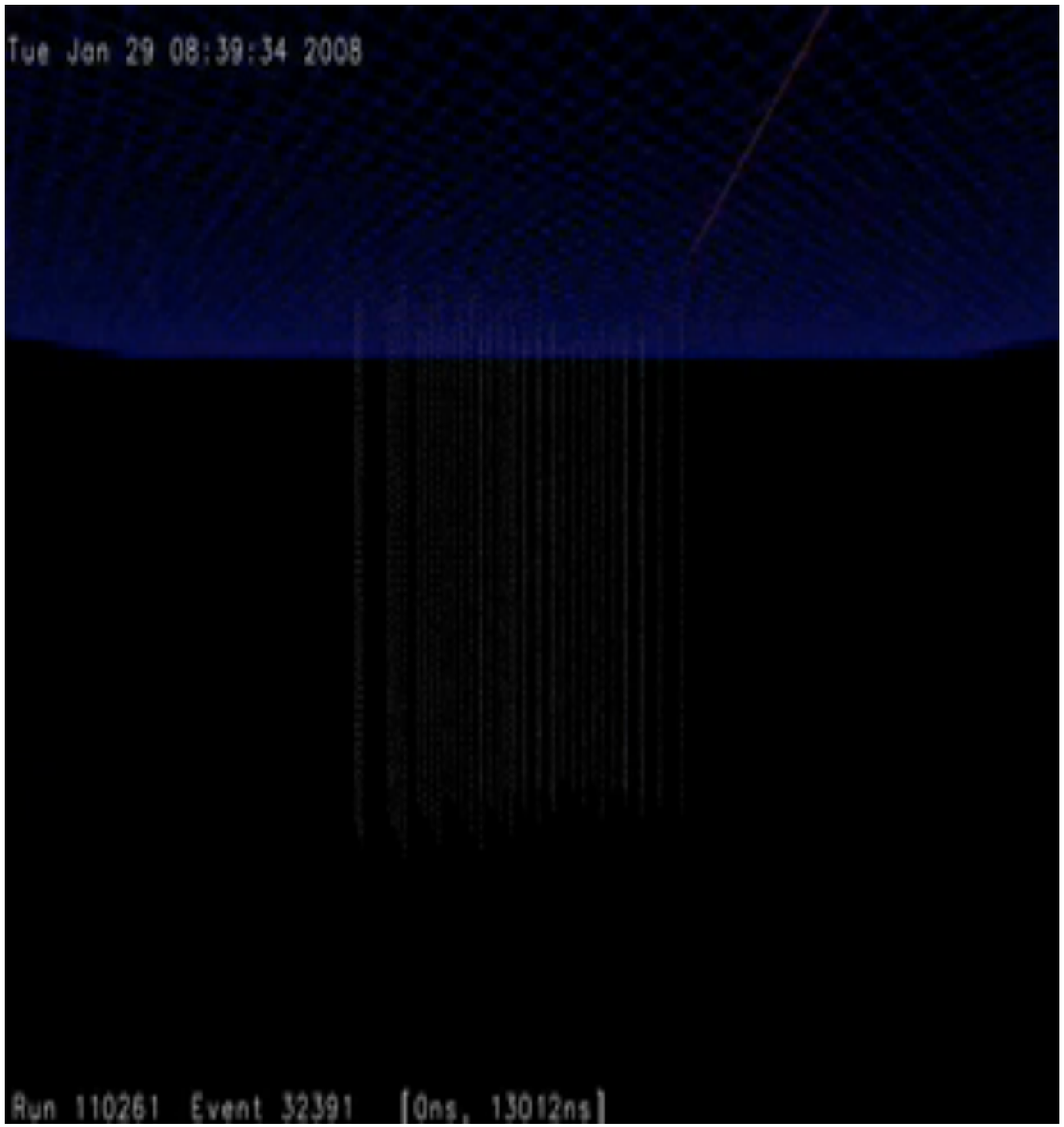

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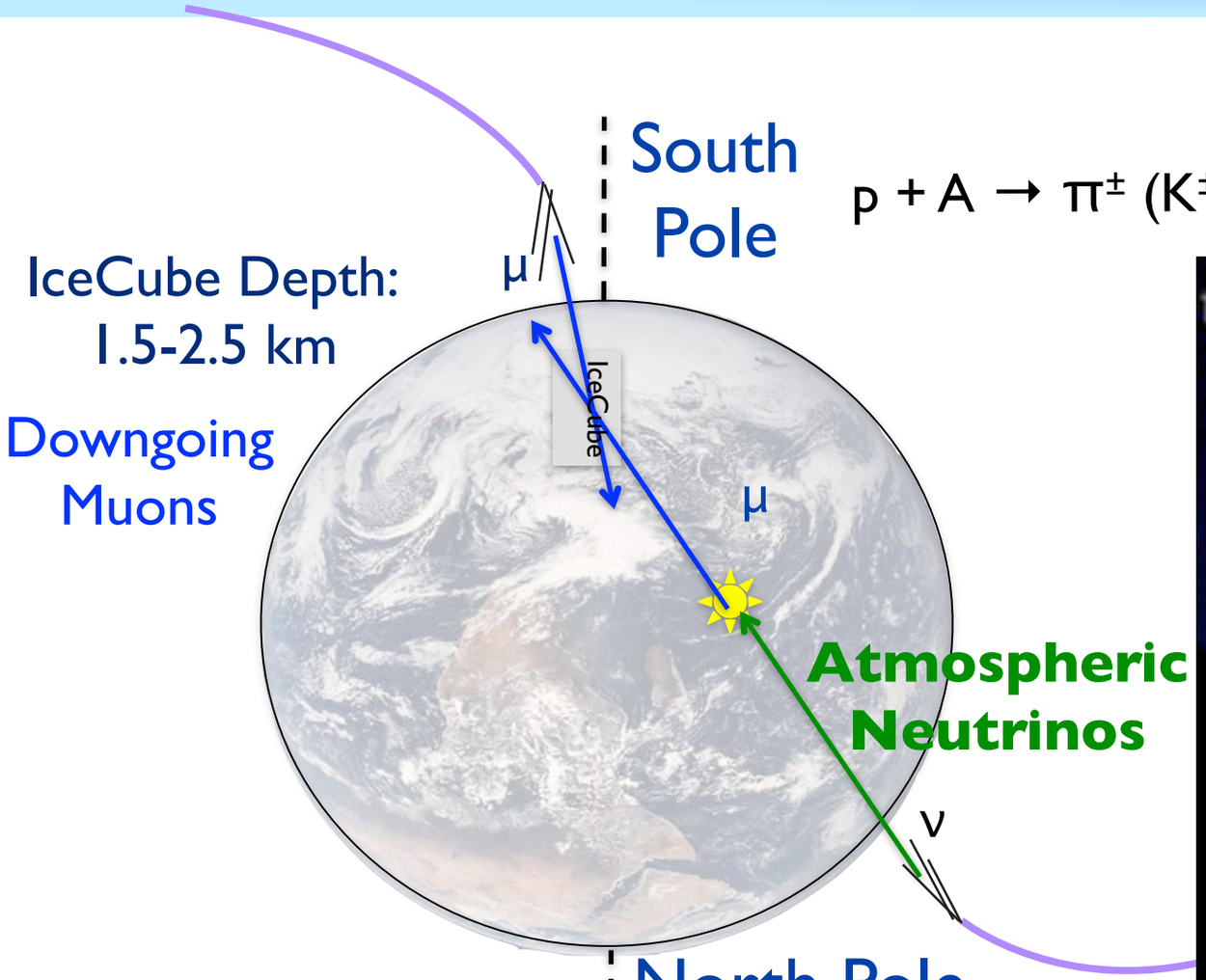

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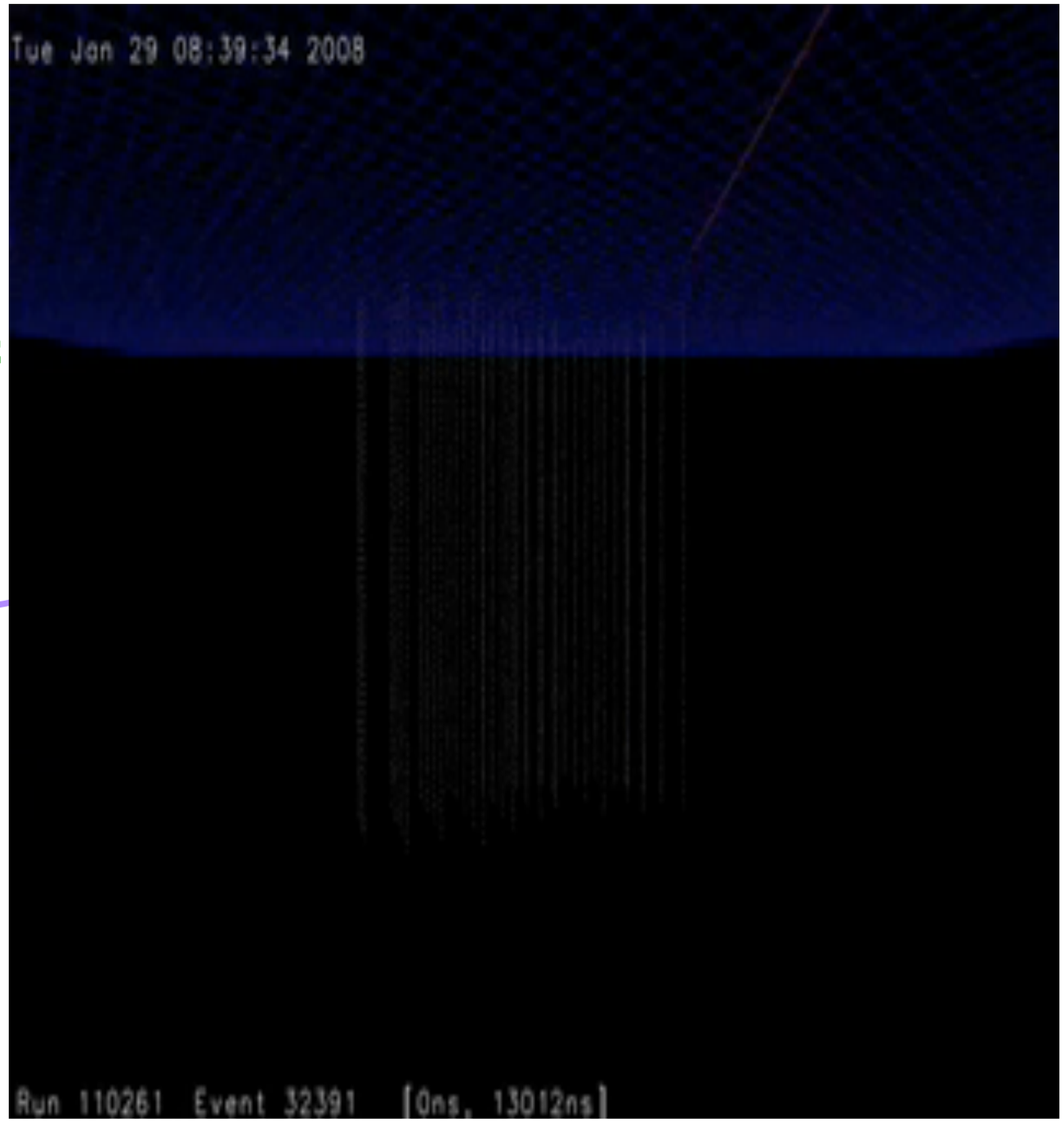

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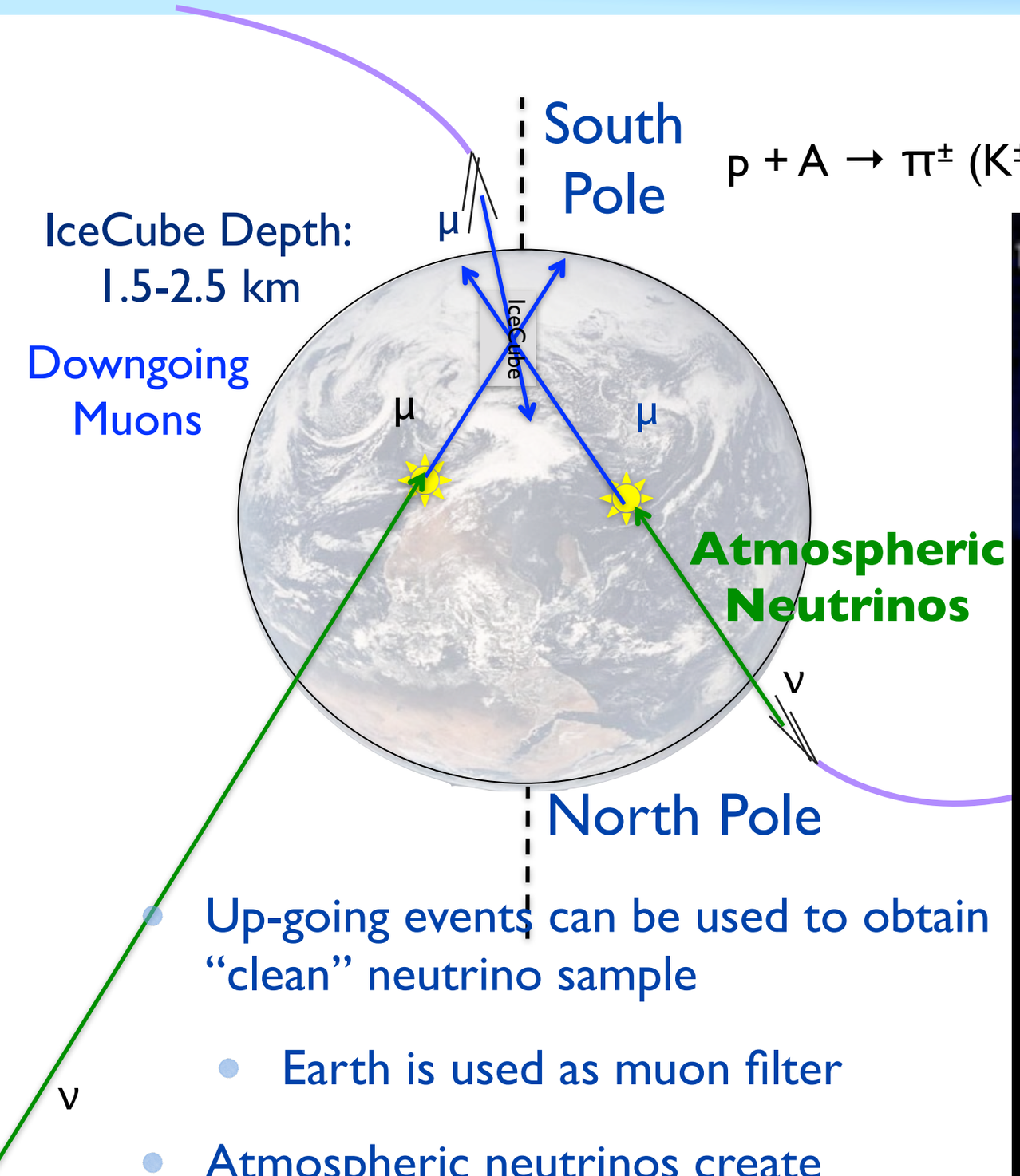

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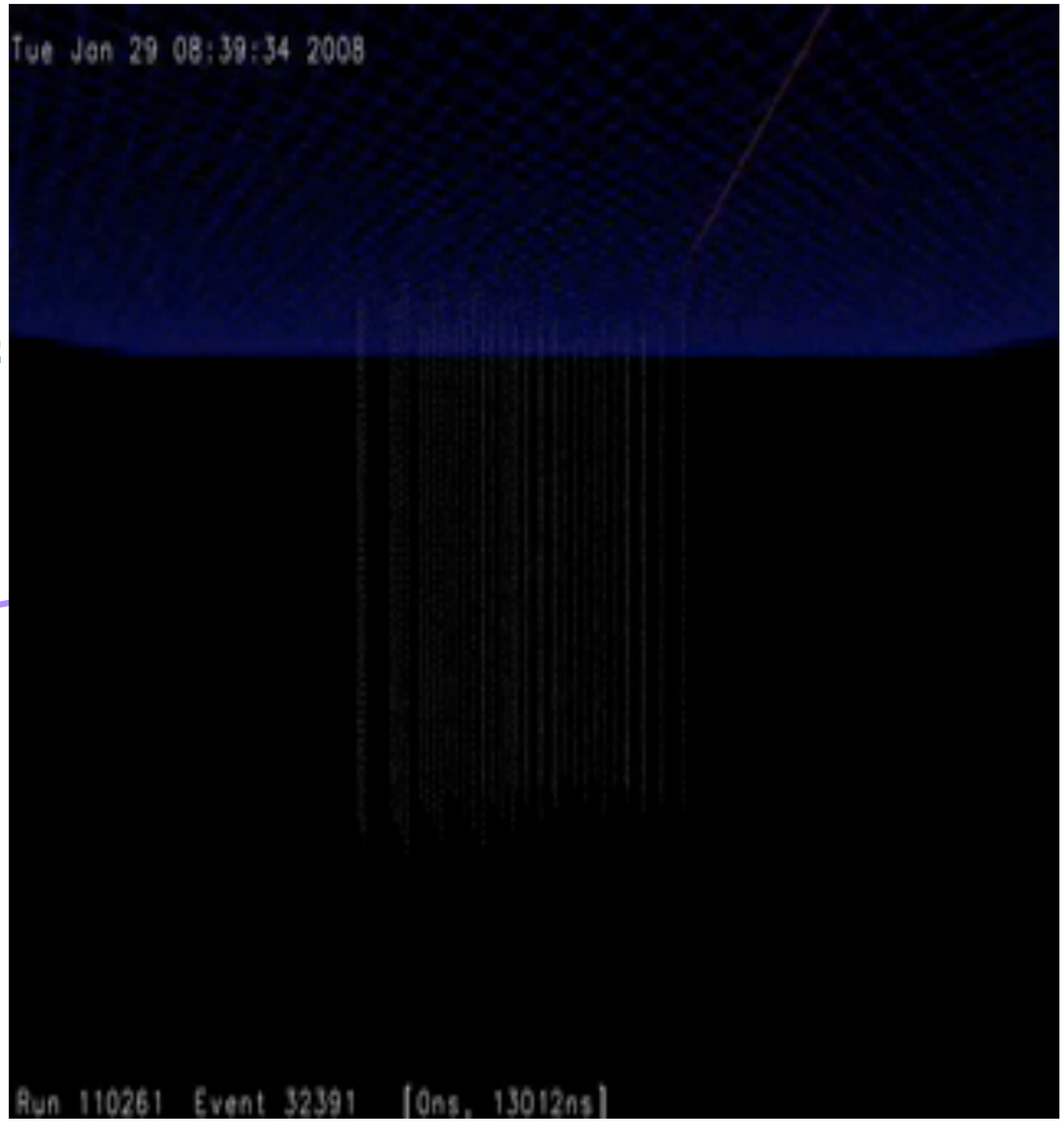

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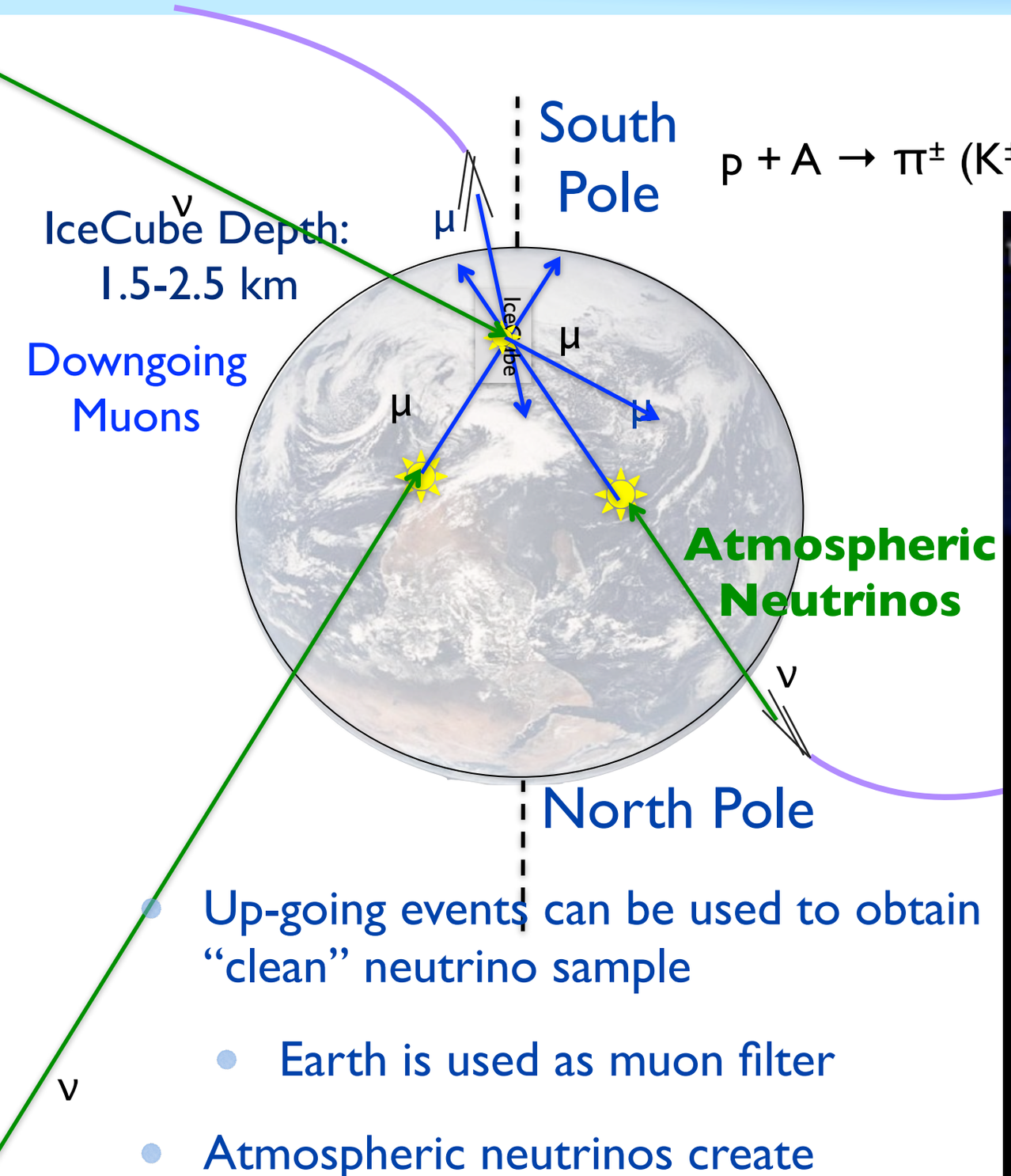

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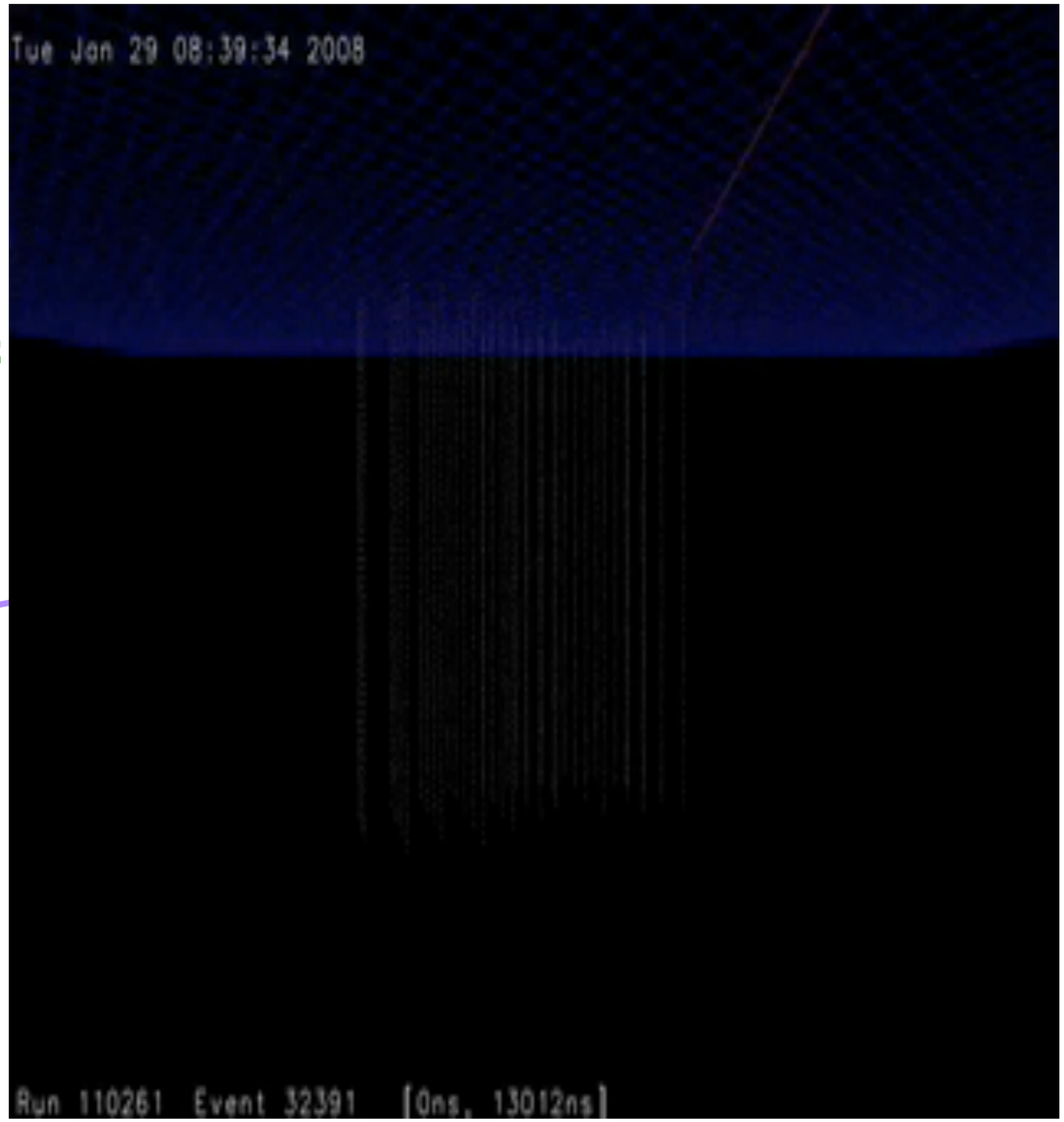

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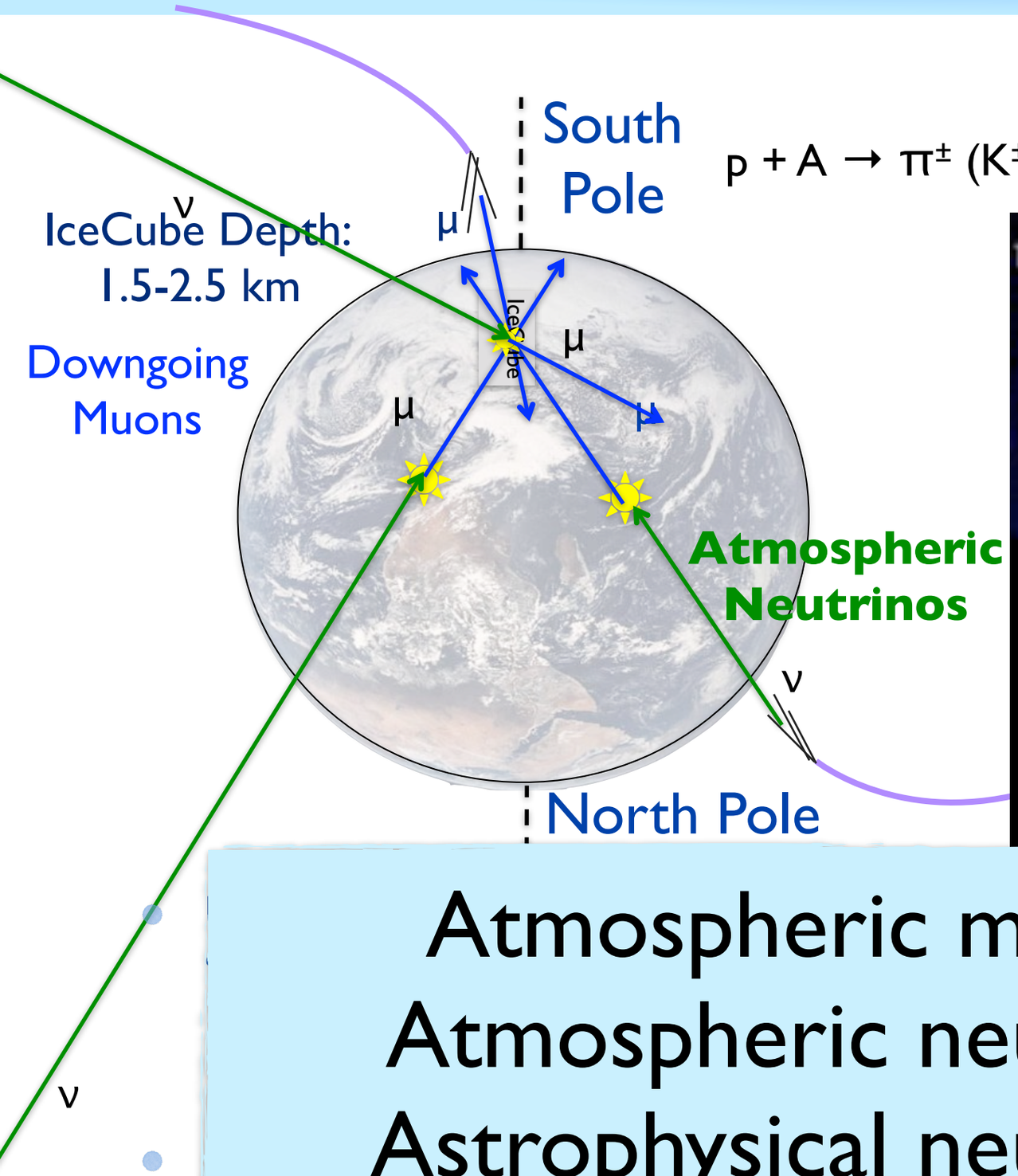

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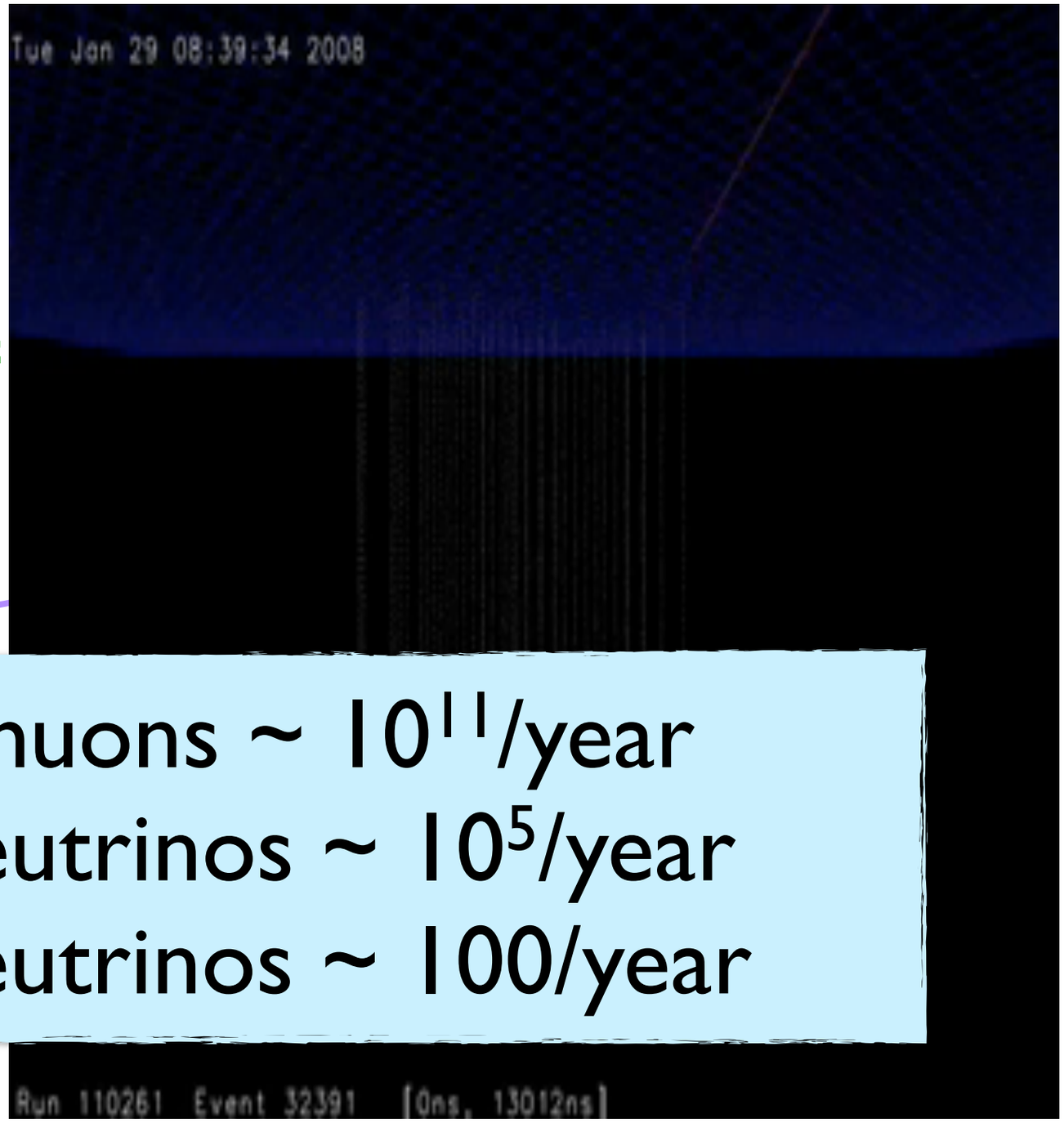


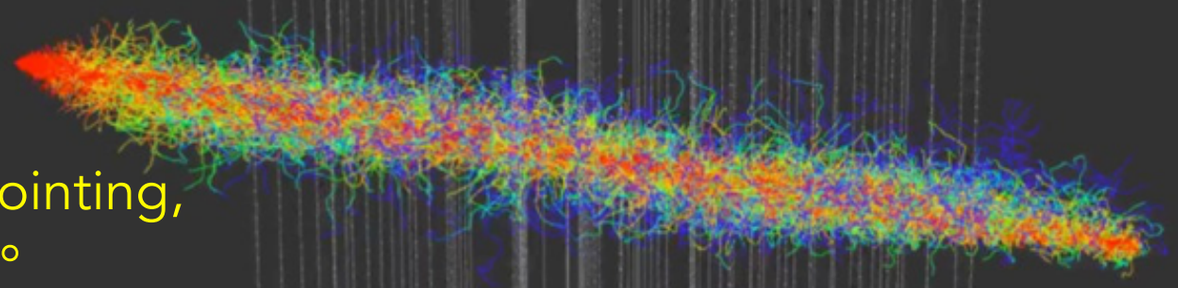
Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

irreducible neutrino background to
extra terrestrial neutrino fluxes

Event Topologies in IceCube

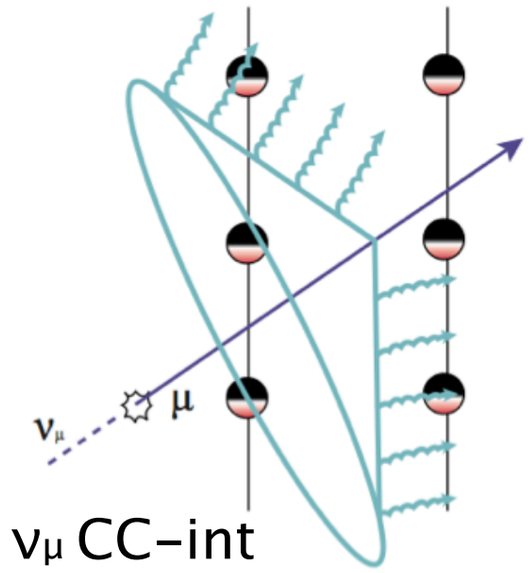
Track topology

(e.g. induced by muon neutrino)



Good pointing,
0.2° - 1°

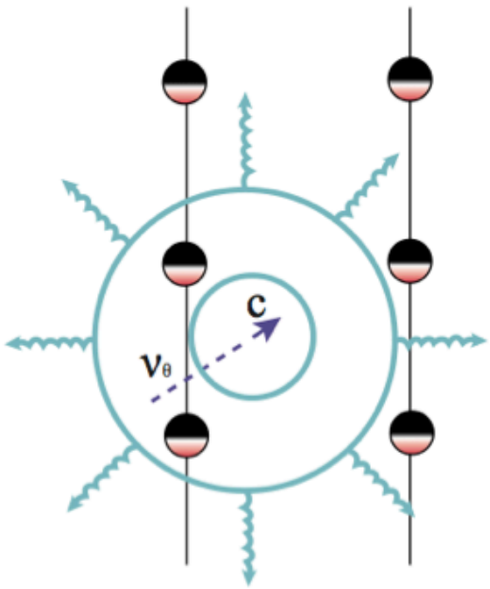
Lower bound on energy for through-going events



ν_μ CC–int

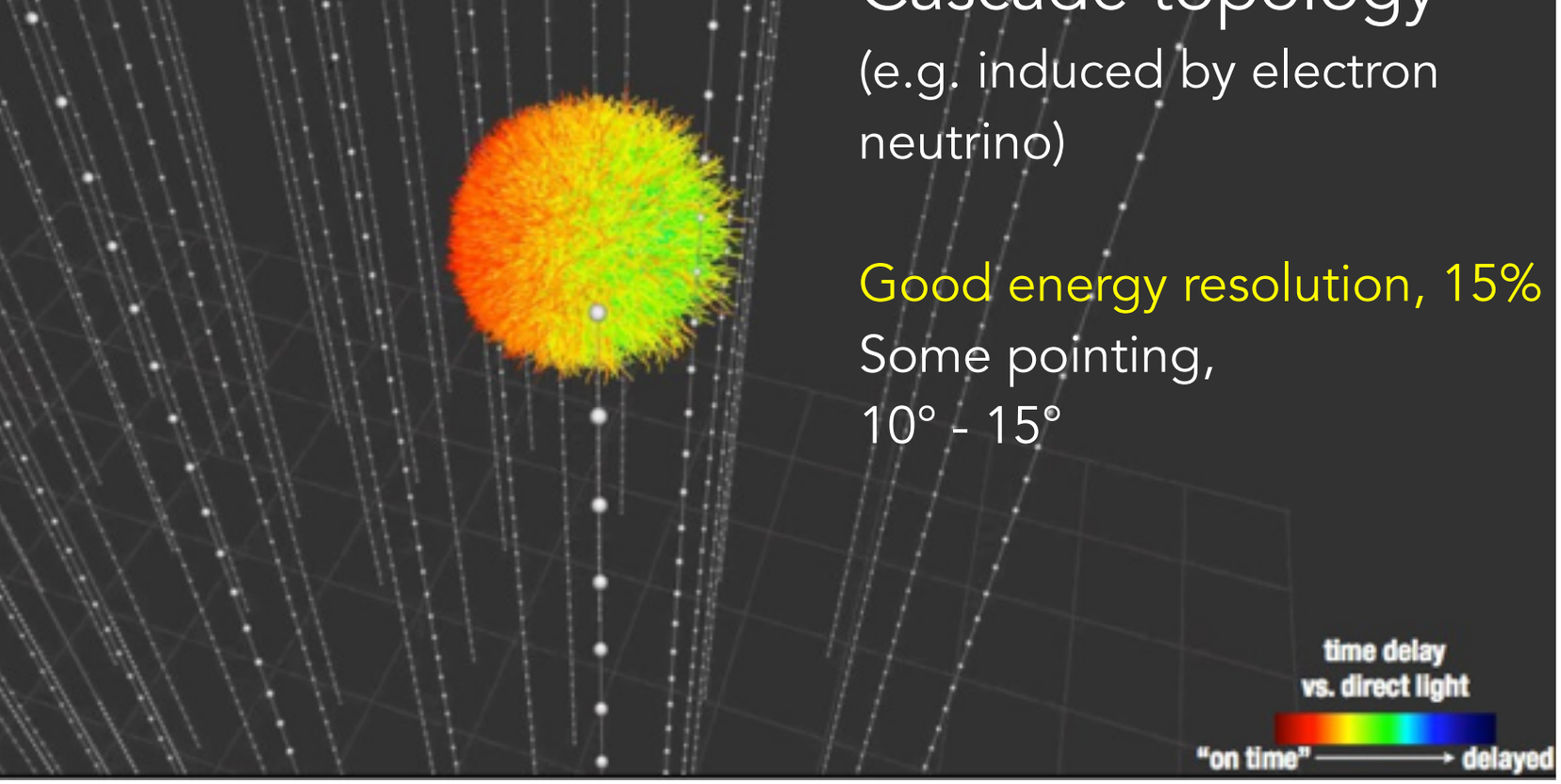
Cascade topology

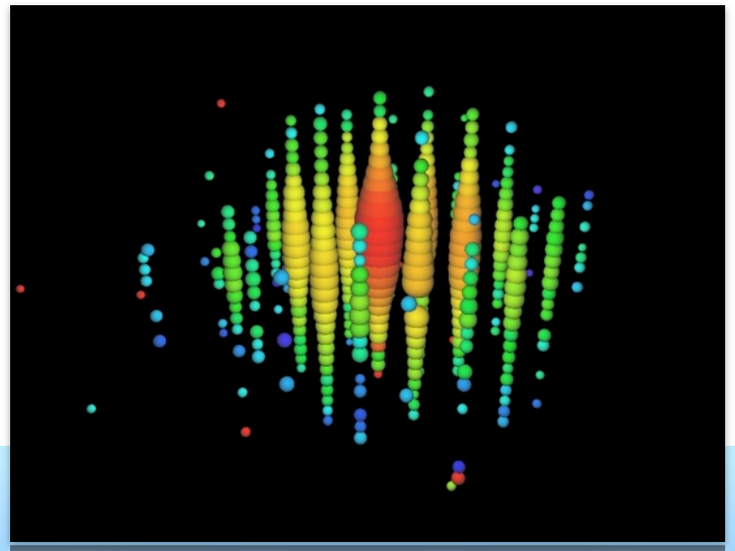
(e.g. induced by electron neutrino)



ν_e ν_τ CC–int & ν_i NC–int

Good energy resolution, 15%
Some pointing,
10° - 15°

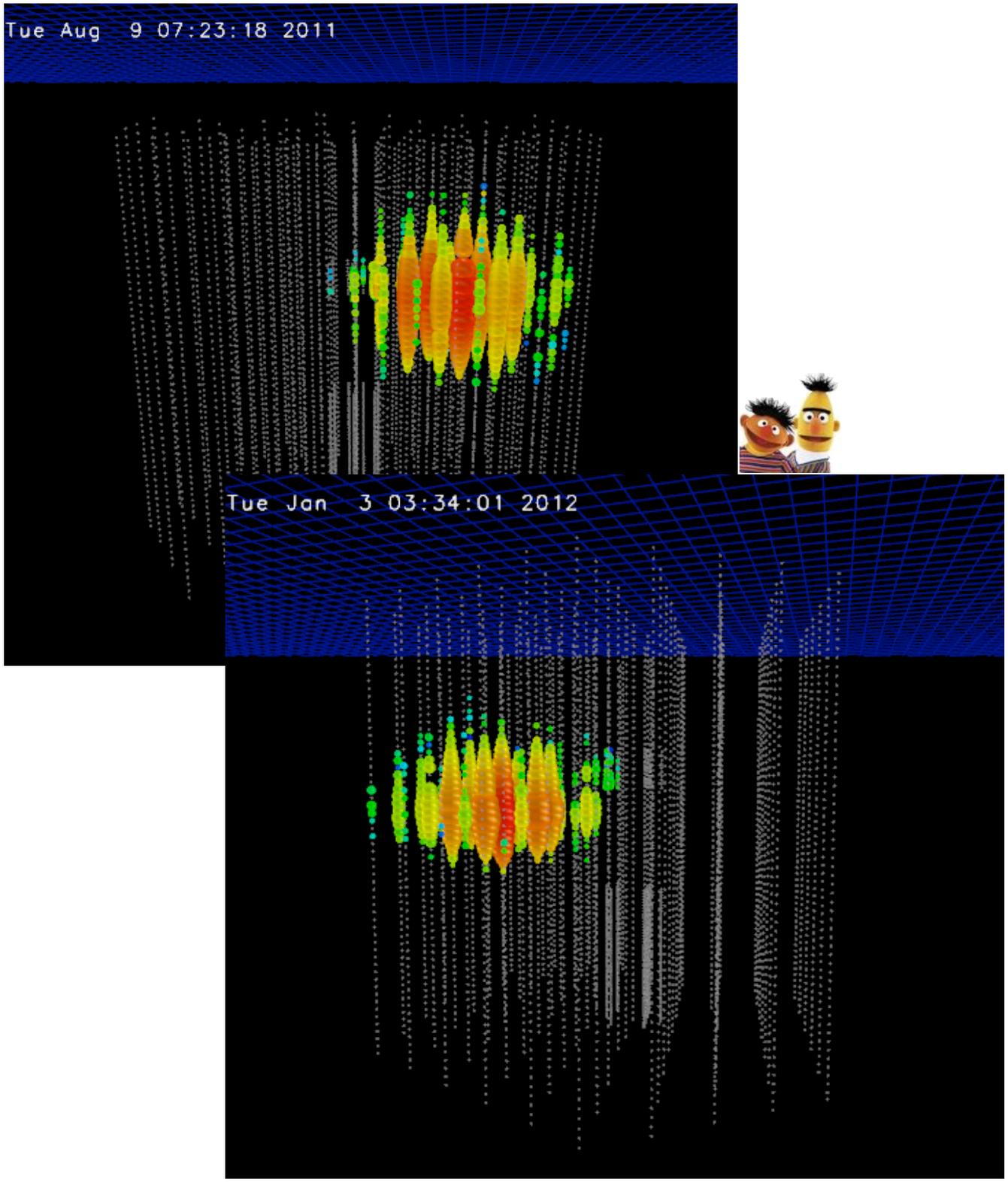




Astro-physical Neutrino Search

Search for highest energy neutrinos

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



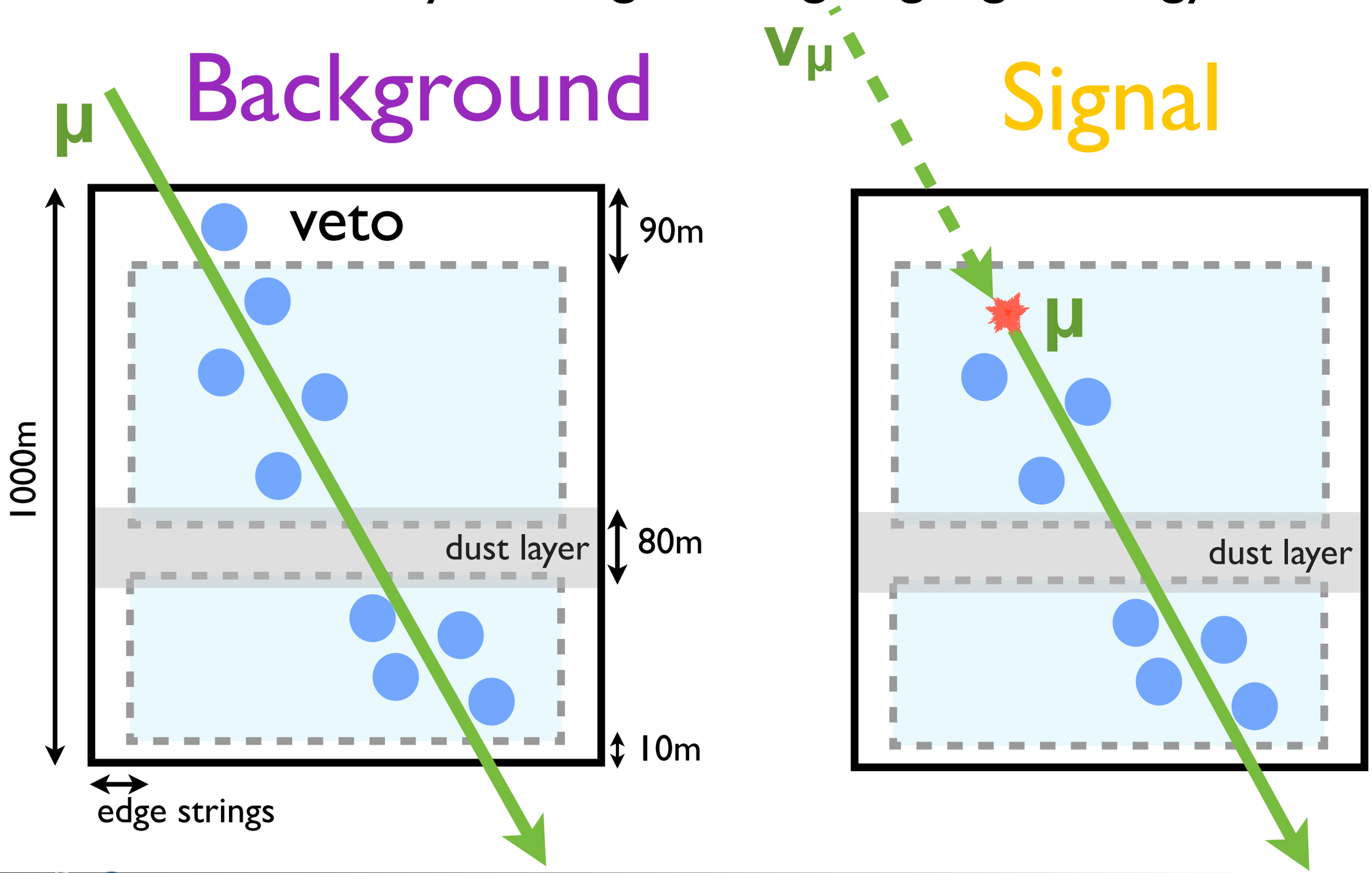
Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events (→ 2.7σ)

- 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_T CC, or ν_e CC
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

Ernie & Bert are not GZK, but ...

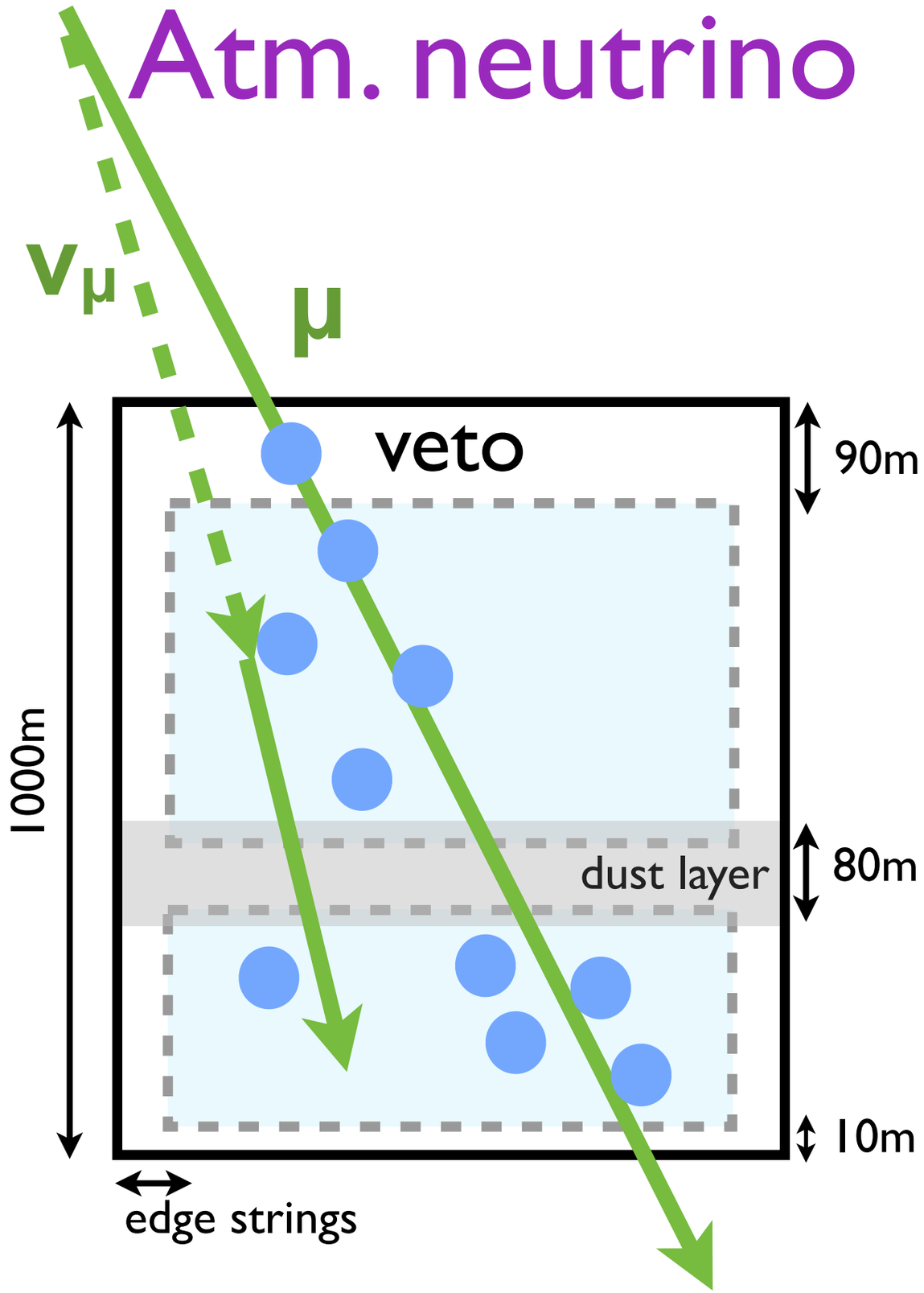
Follow up analysis to trace high-energy excess

- Probe the energy region of about 30TeV to 1PeV, all flavors and all directions, by vetoing down-going high-energy muons

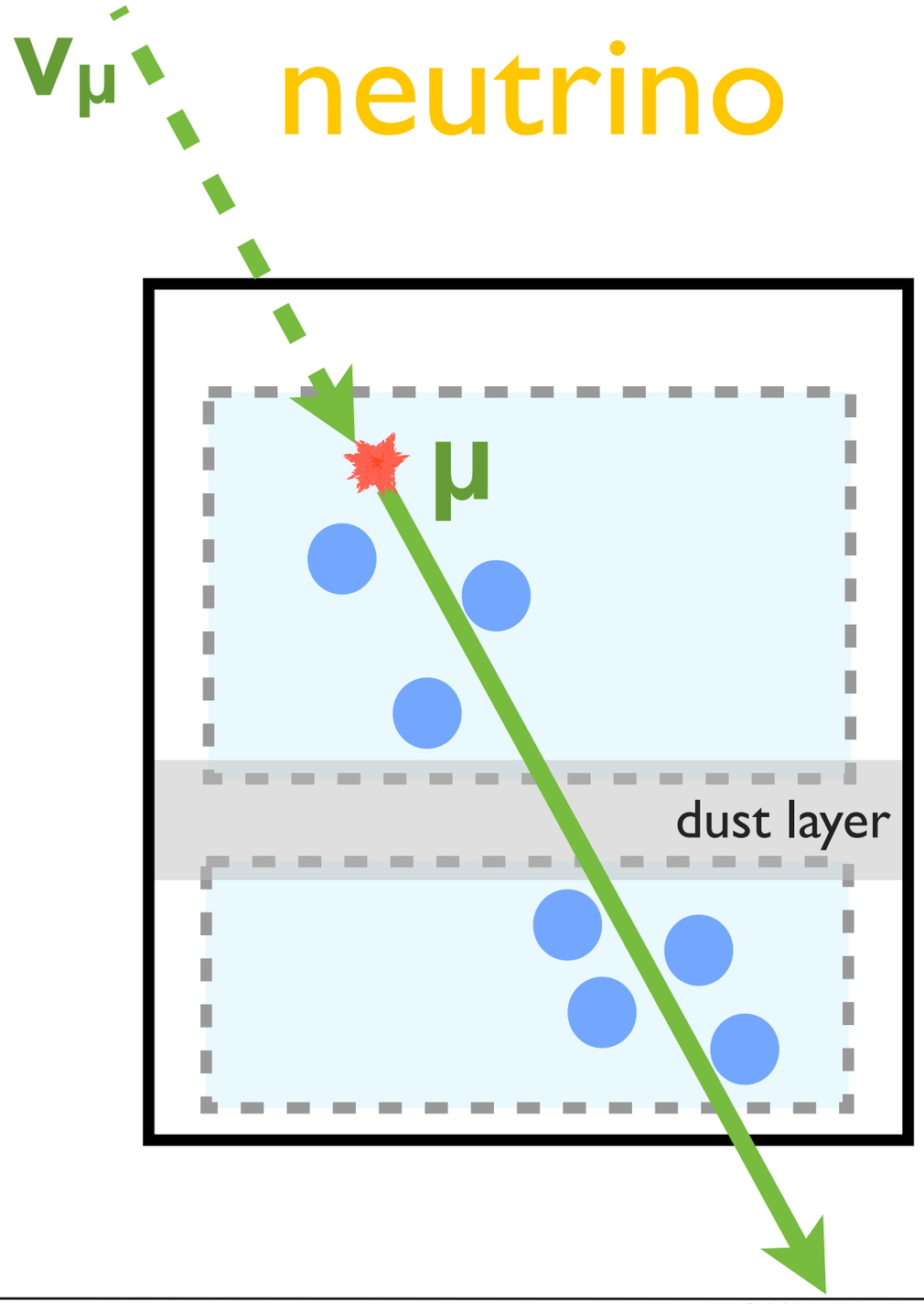


Veto and Self-veto

Atm. neutrino

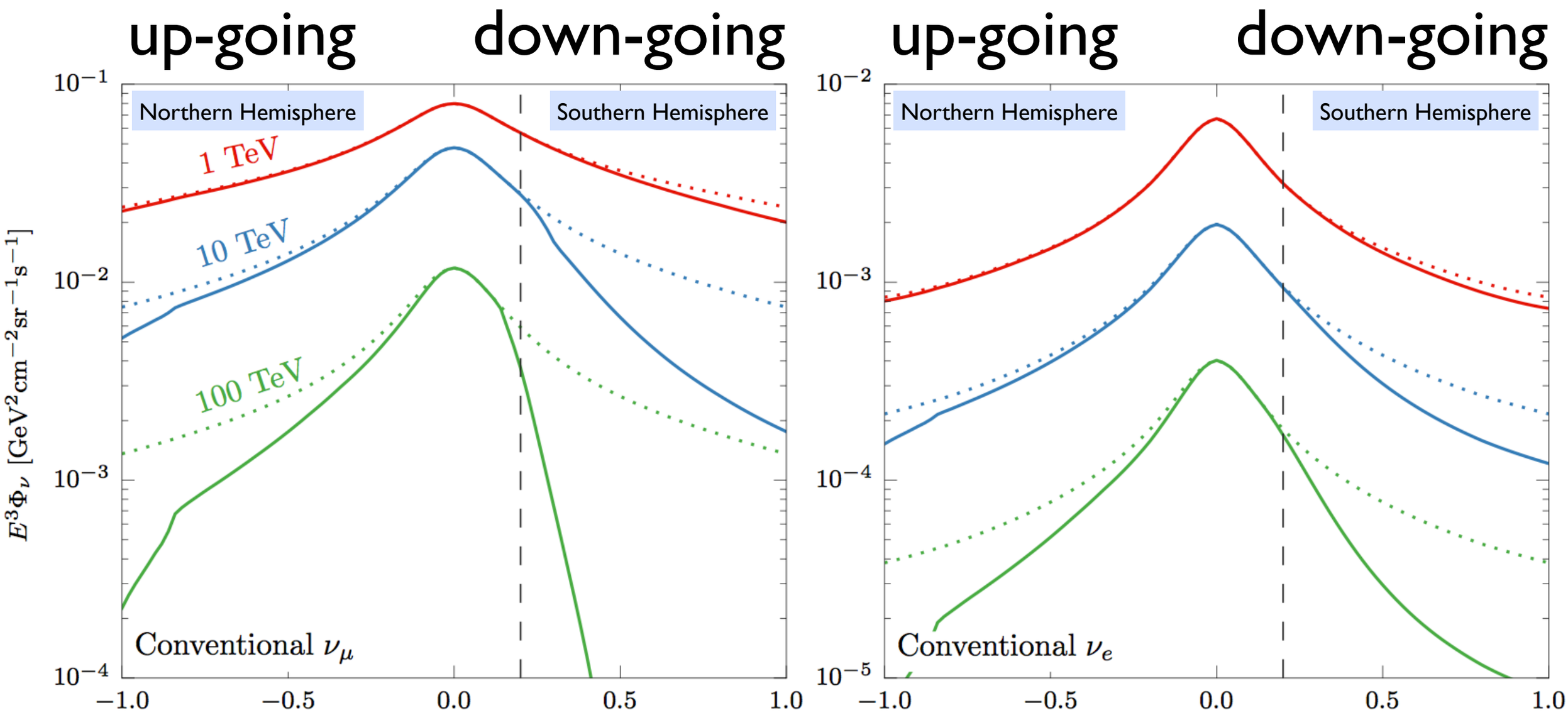


Astro-physical neutrino

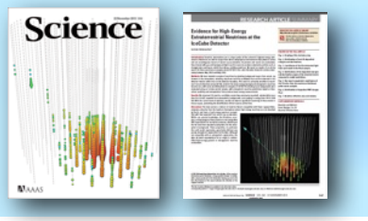


IceCube Collaboration
arxiv:1410.1749

Veto and Self-veto



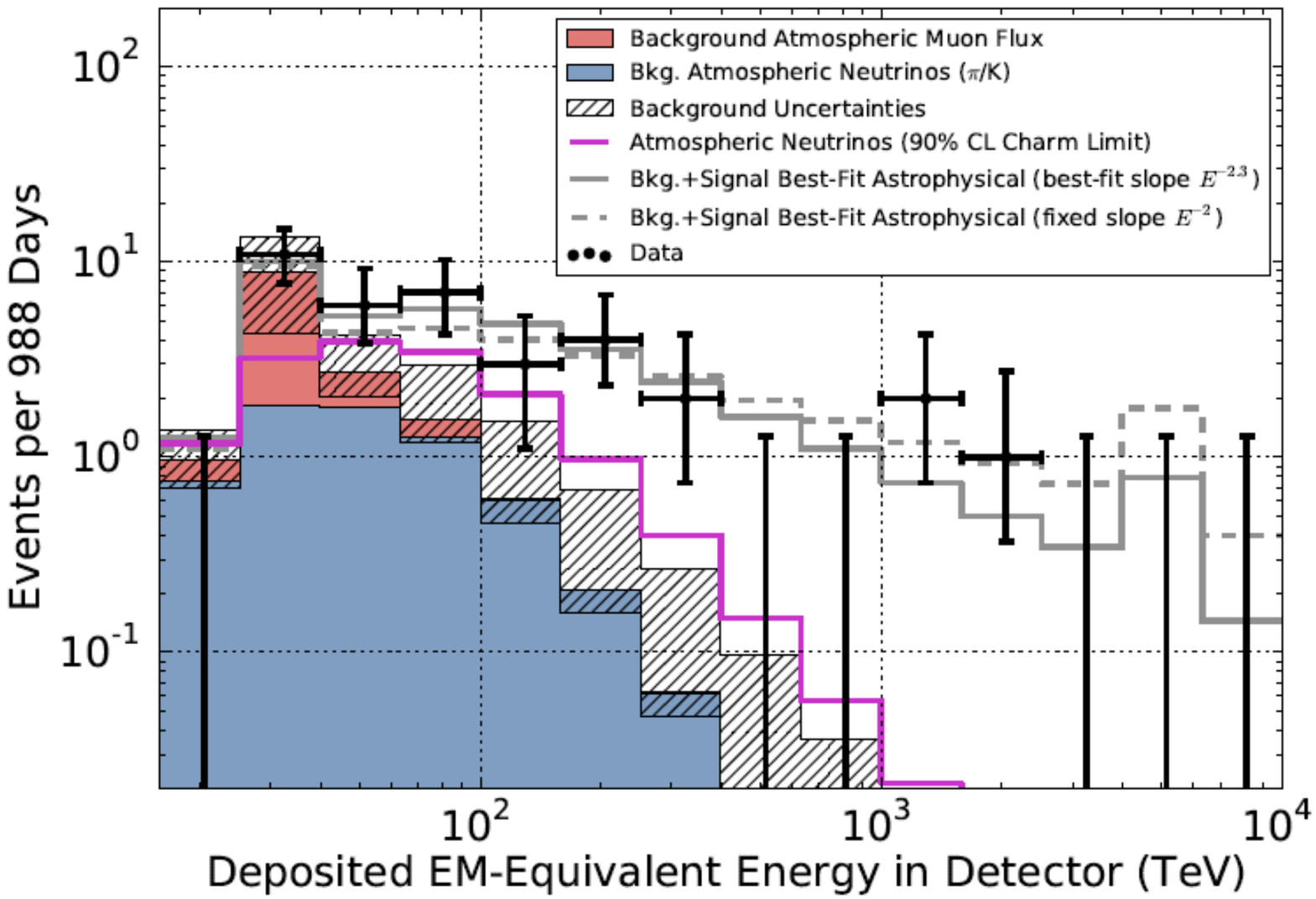
Down-going high-energy neutrinos are can be nearly background free identified as astro-physical neutrinos



High-energy neutrino search 3yrs

37 events (9 track-like, 28 showers) observed

Expectation from conventional atm. muons and neutrinos ~15.0



- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (8.4±4.2), Conv. Neutrino ($6.6^{+5.9}_{-1.6}$),
- Over 60 TeV < E < 2000 TeV, the spectrum consistent with E^{-2} or $E^{-2.3}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

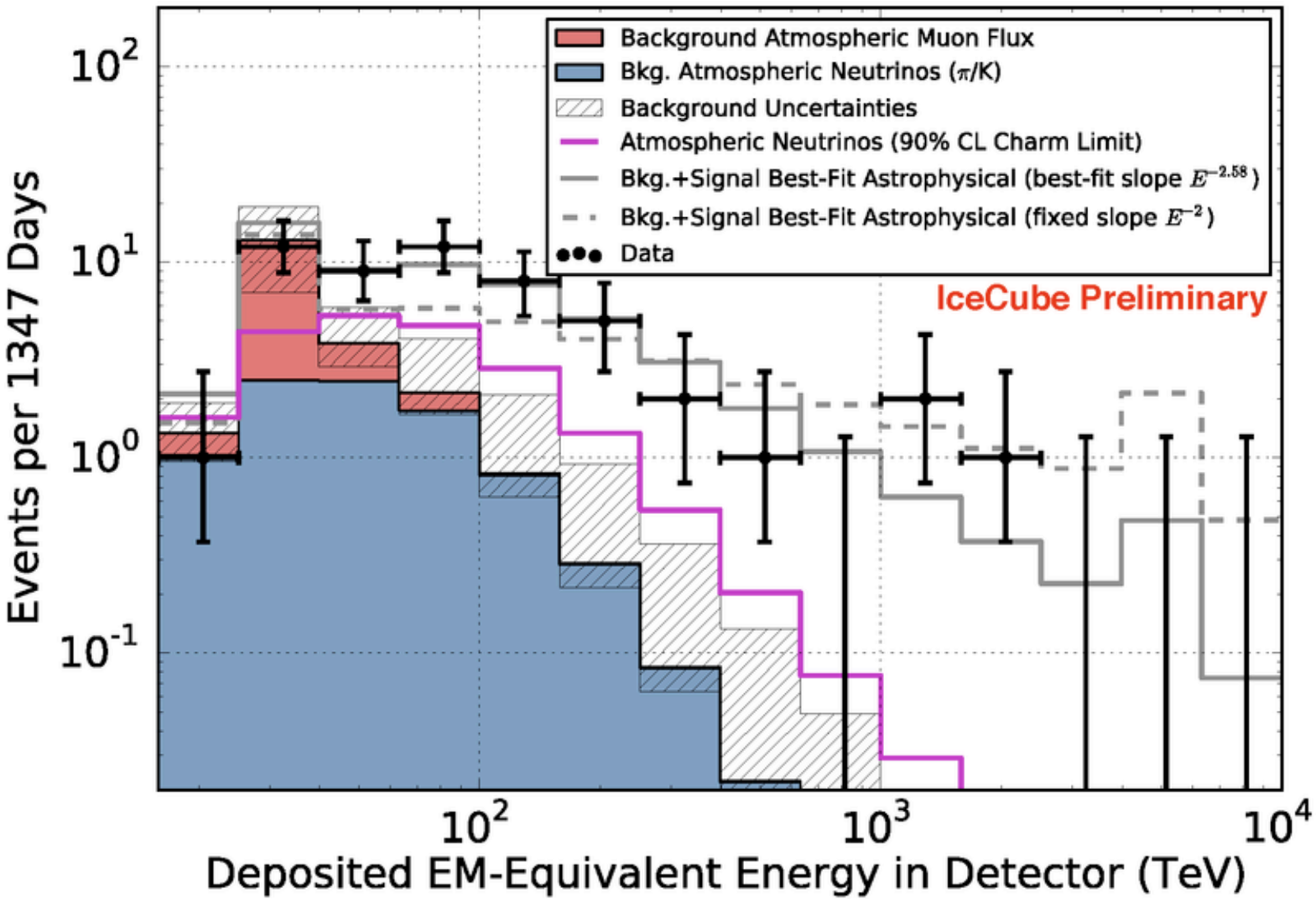
5.7 sigma rejection of atmospheric-only hypothesis

IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

High-energy neutrino search 4yrs

54 events (15 track-like, 39 showers) observed

Expectation from conventional atm. muons and neutrinos ~21.6

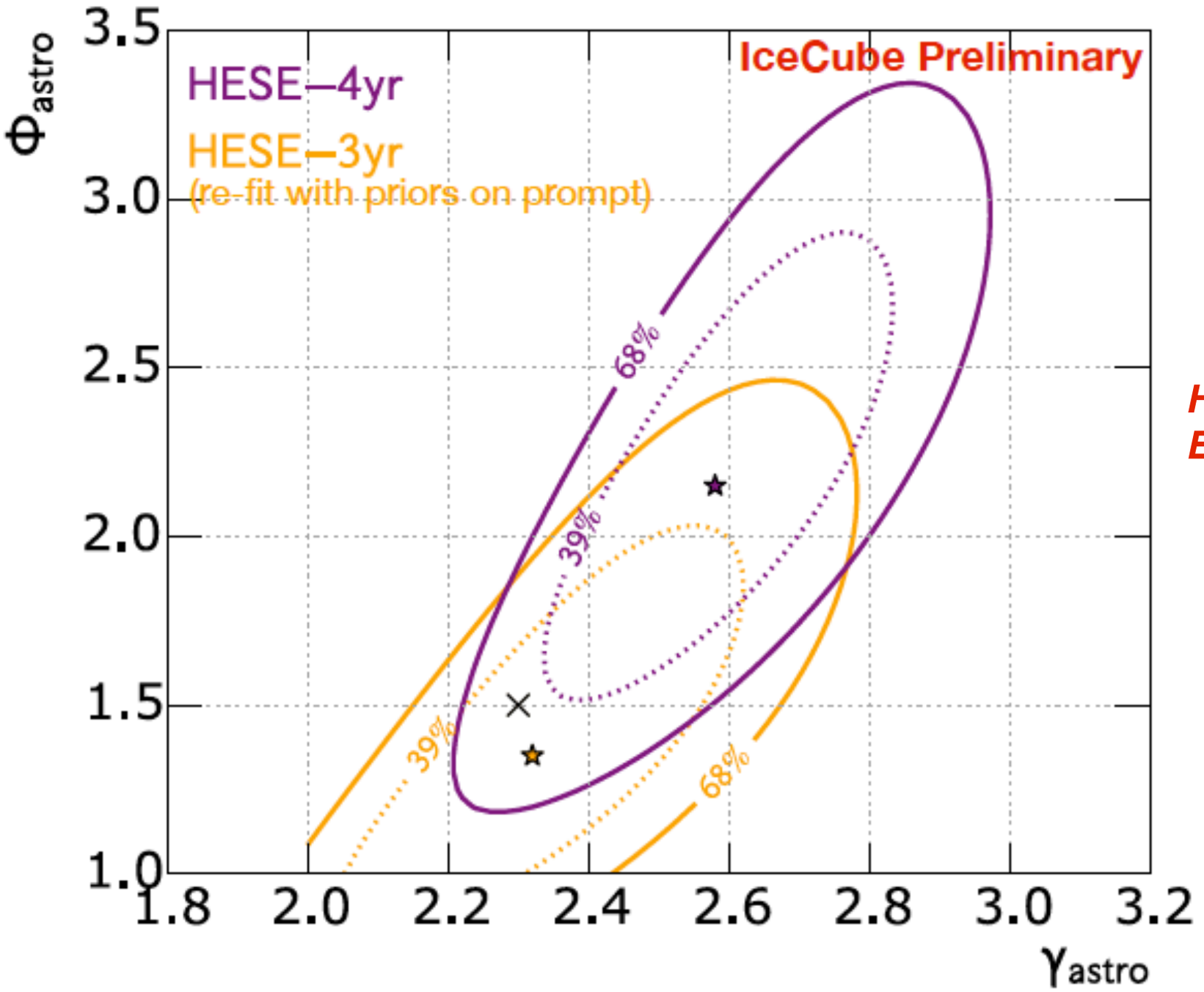


- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (12.6±5.1), Conv. Neutrino ($9.0^{+8.0}_{-2.2}$),
- Over 60 TeV < E < 2000 TeV, the spectrum best fit with $E^{-2.58}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

~7 sigma rejection of atmospheric-only hypothesis

forthcoming ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

Spectral index and flux

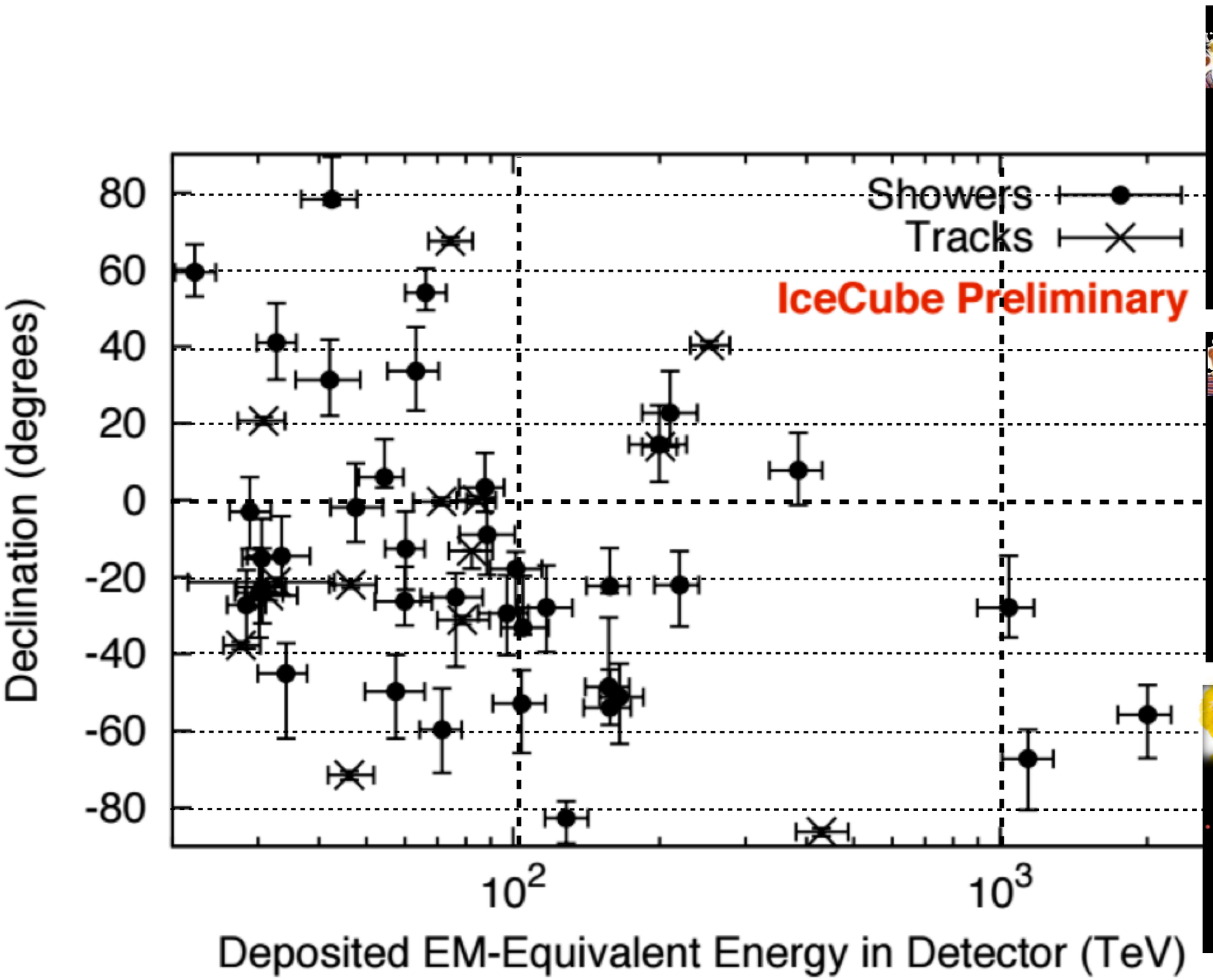


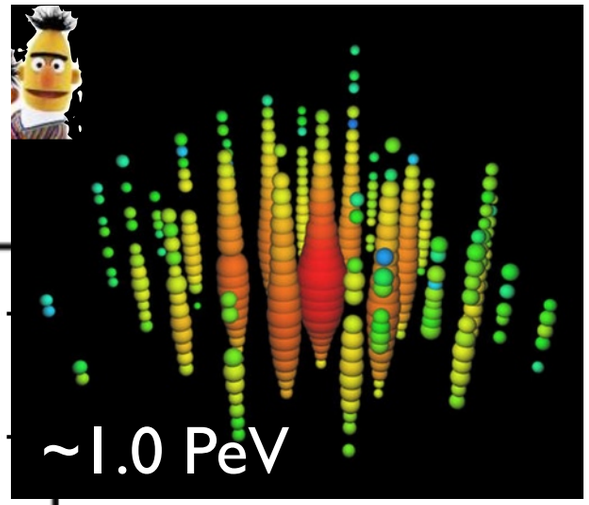
Contour plot in spectral index vs. normalization at 100TeV

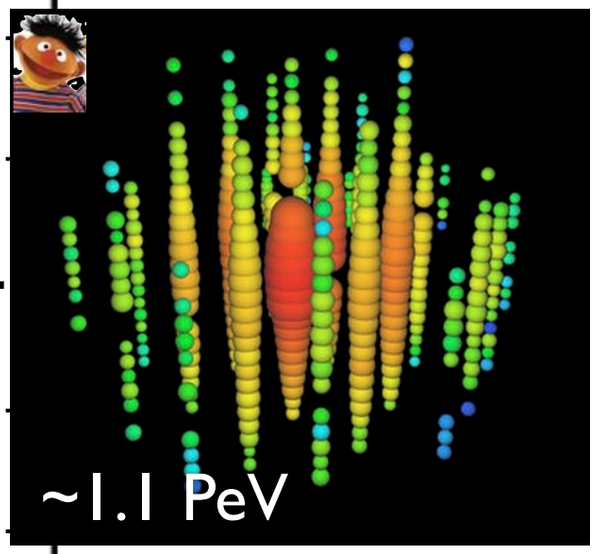
HESE-4yrs best fit flux:
$E^2\Phi$ = ~2.2 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

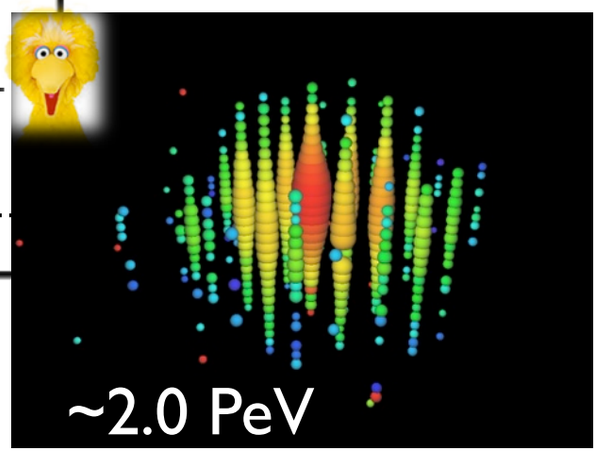
Spectral index has steepened
(no new PeV events but relatively large number in TeV)

Distribution



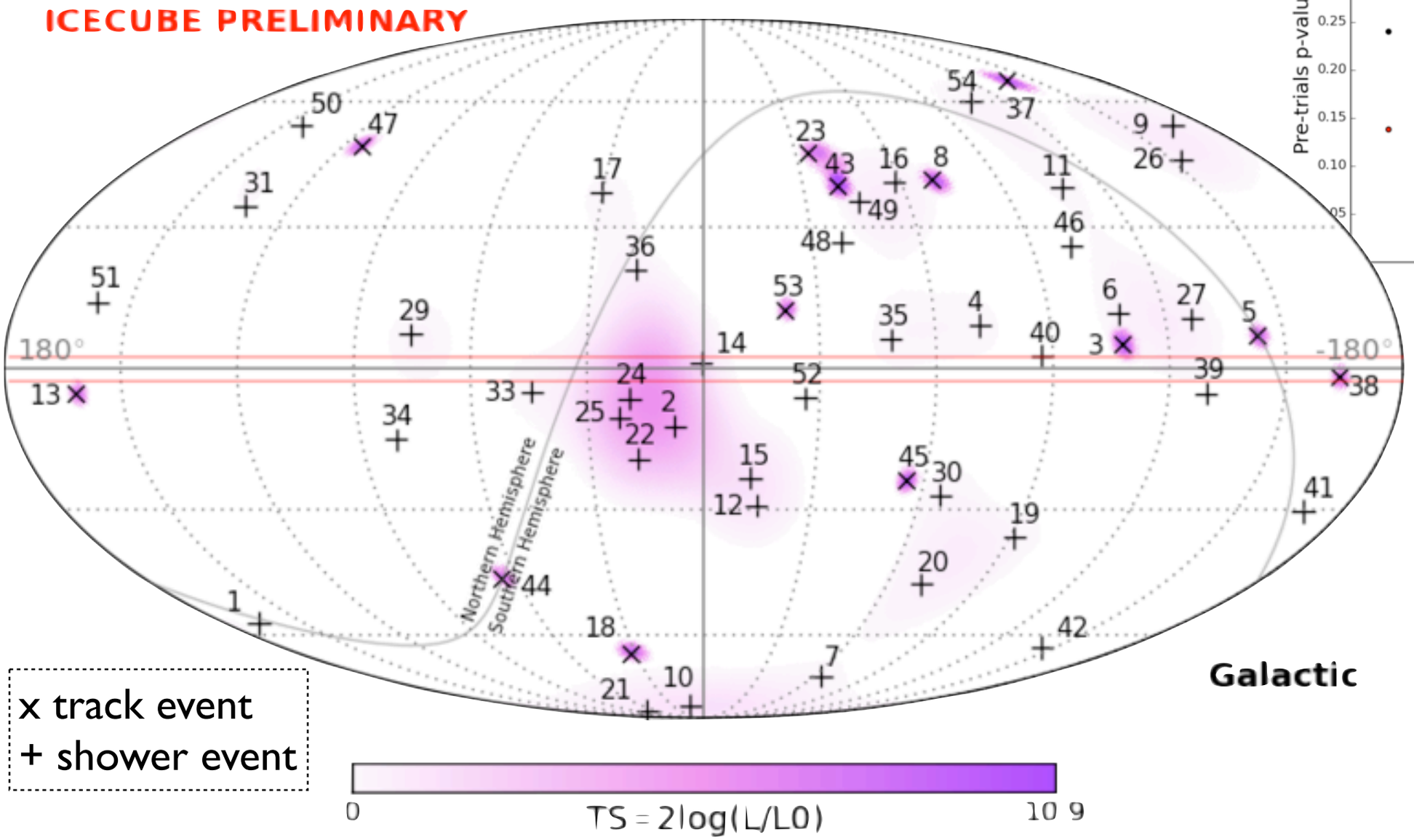


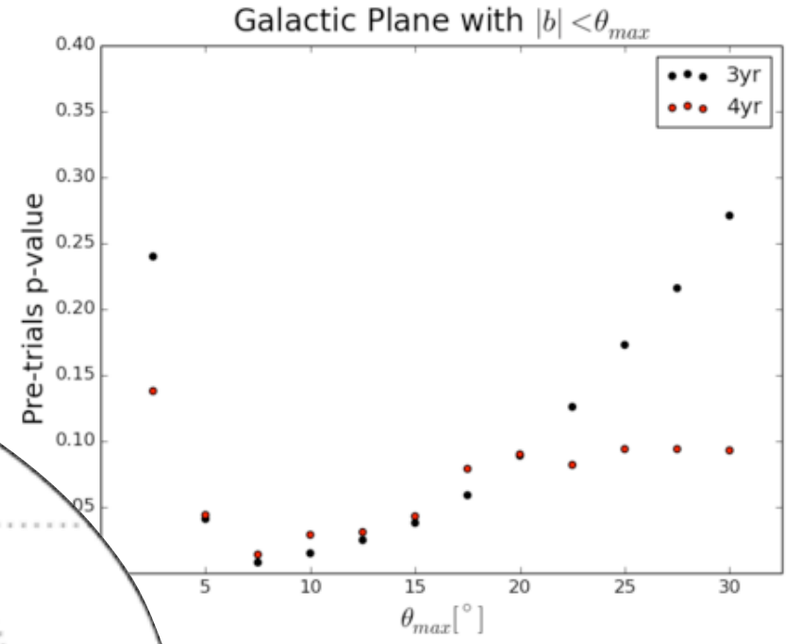




IceCube Collaboration, *Science* 342, 1242856 (2013)

Skymap HESE-4yrs

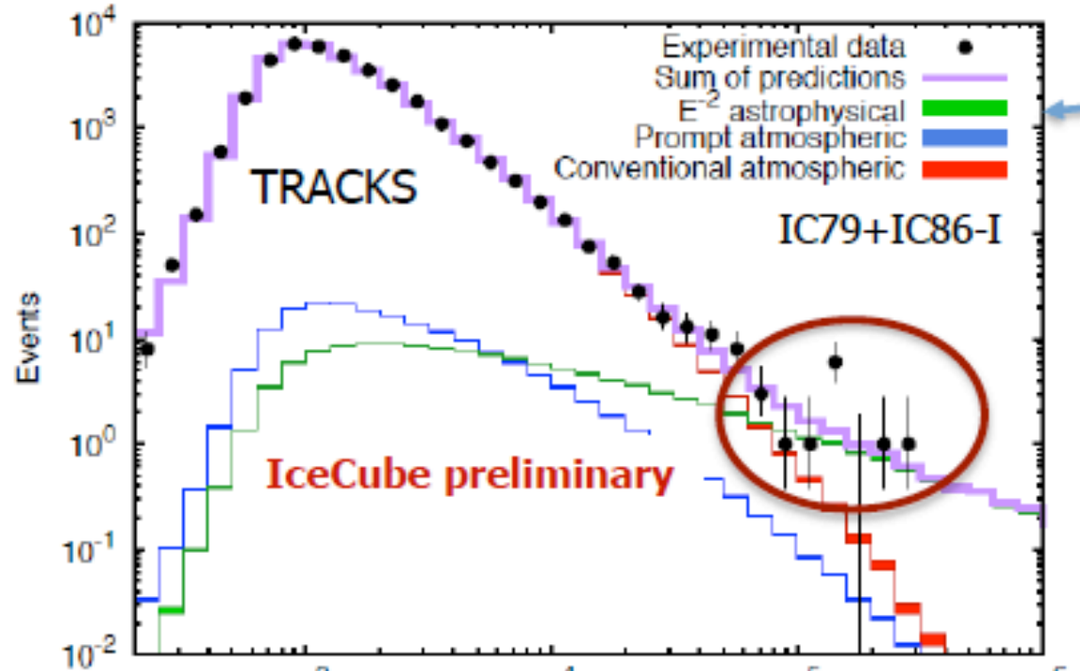




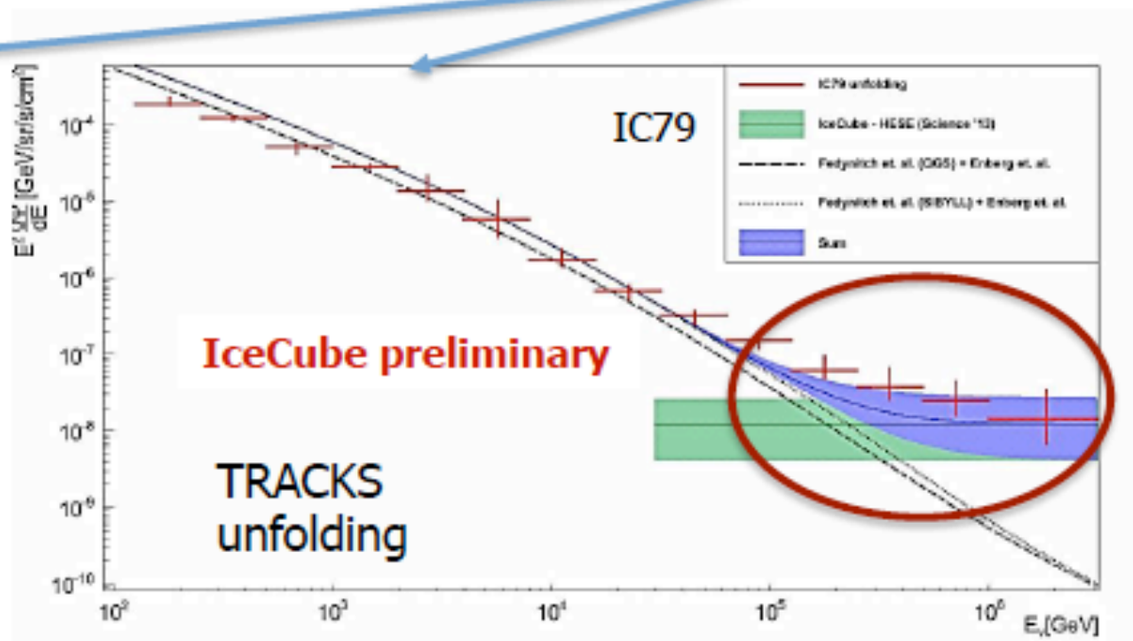
no significant correlations -- spacial or temporal

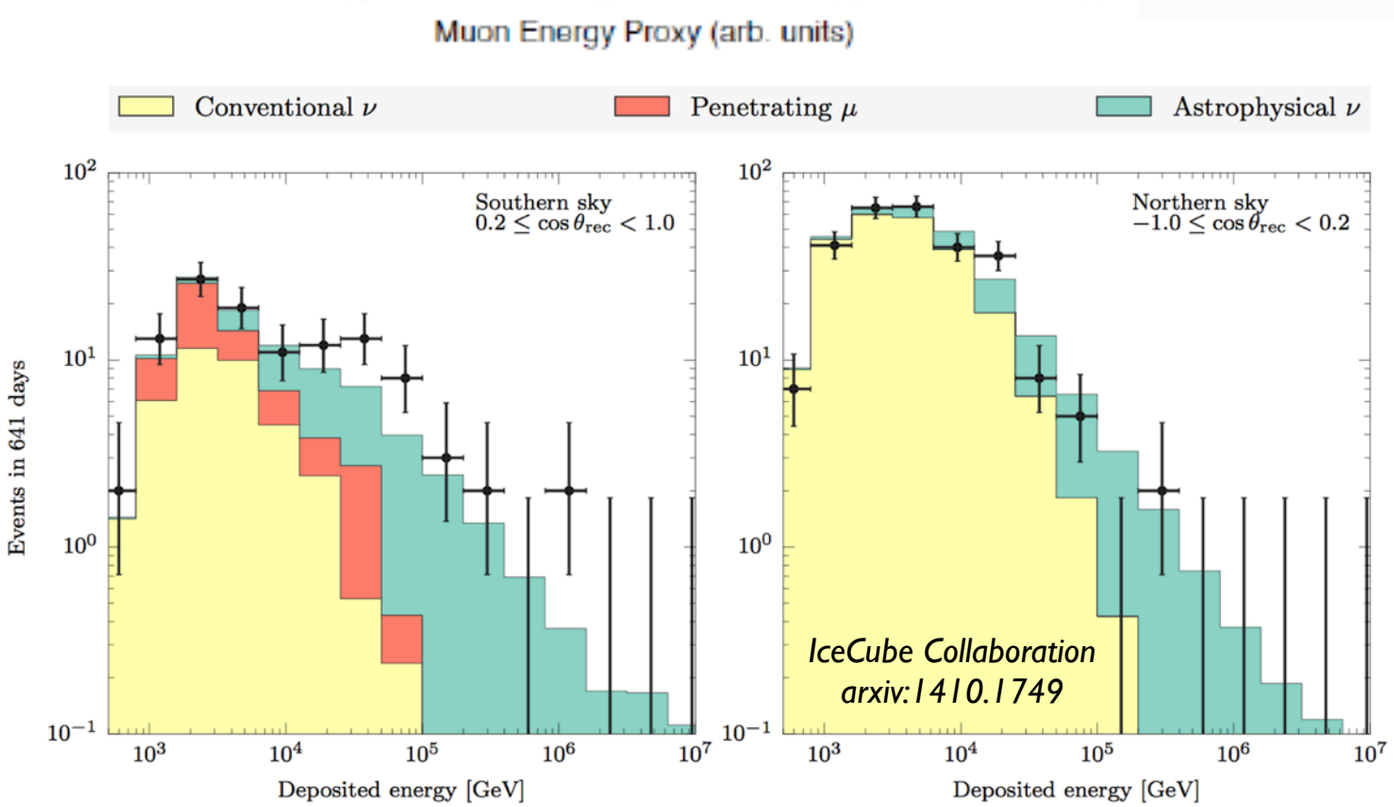
p-value for cascade events "clustering" 18%

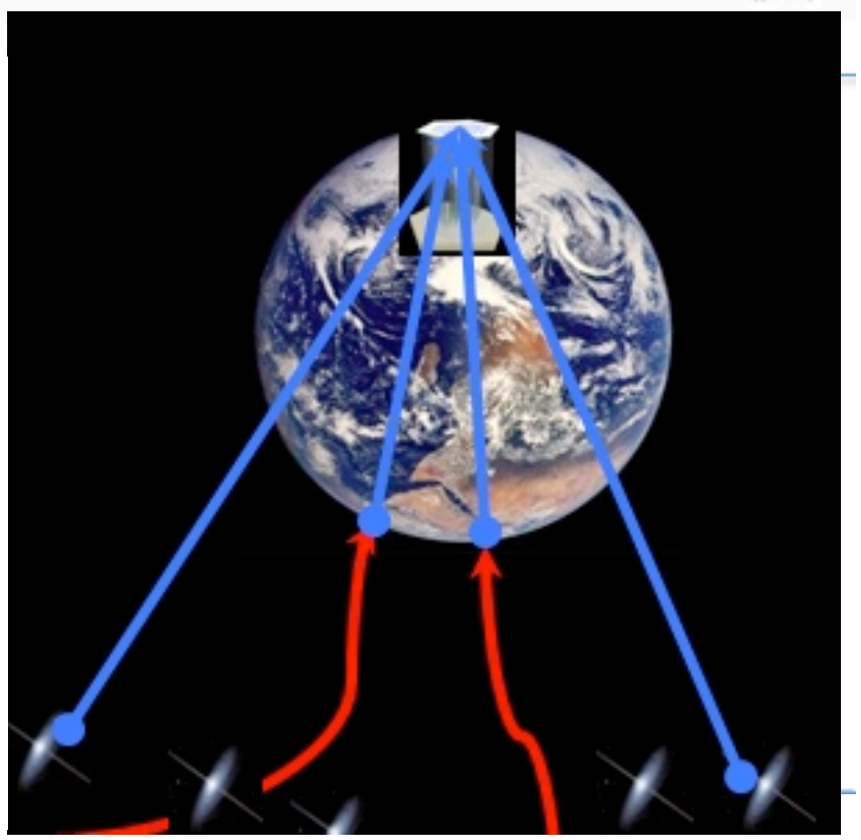
Up-going muon analysis



through-going tracks from ν_μ CC





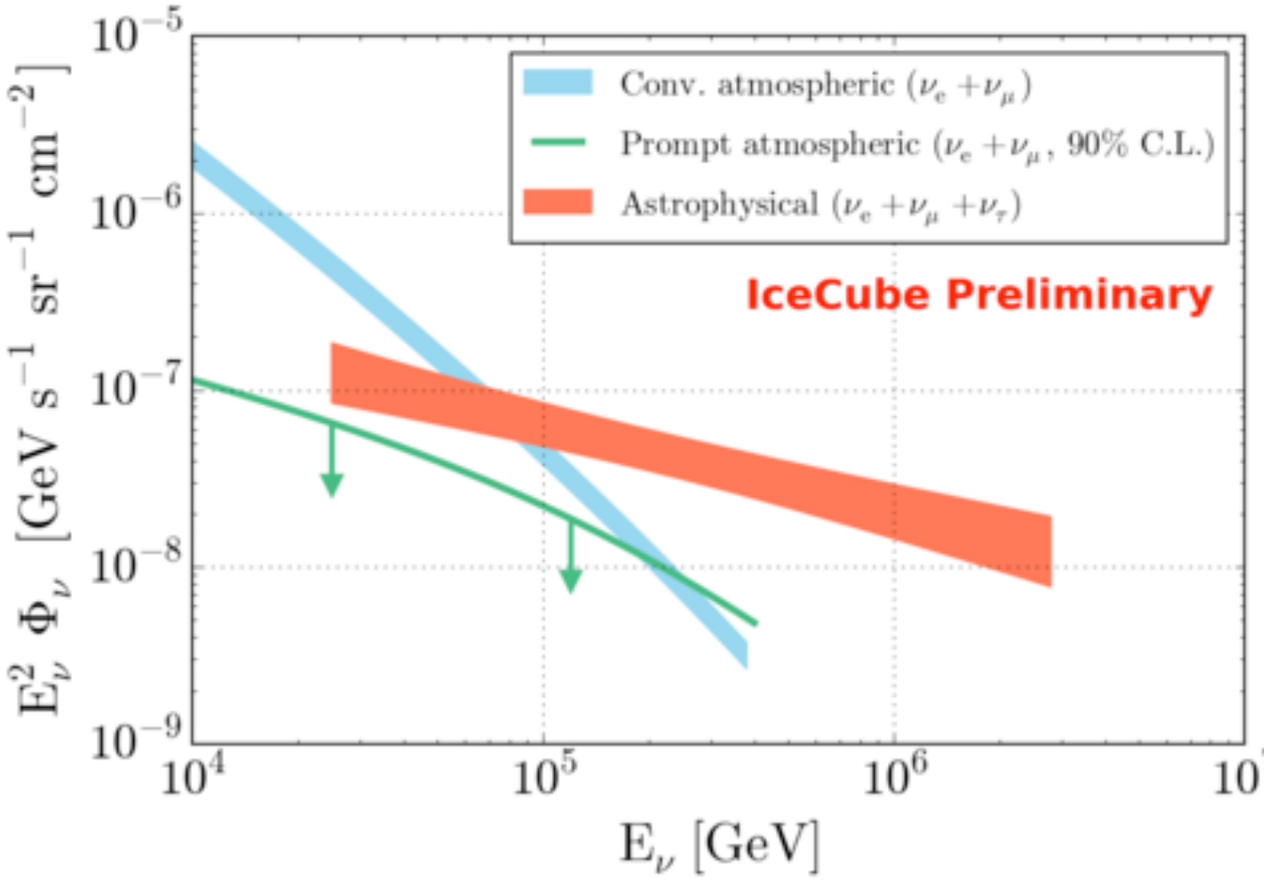


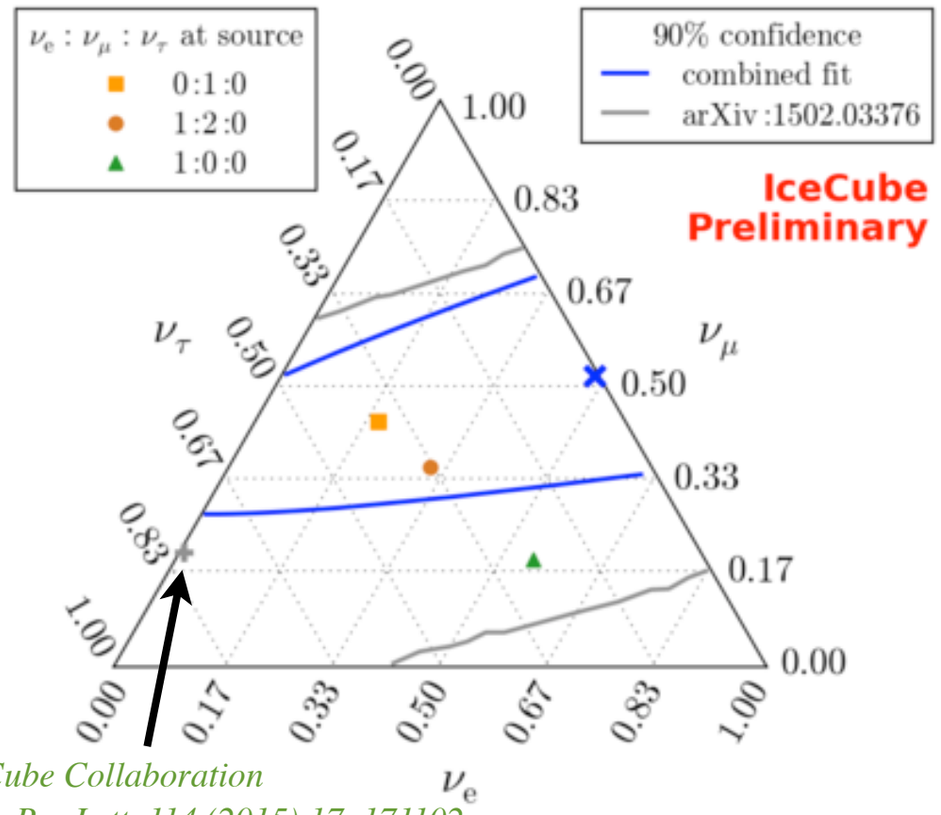
Global fit

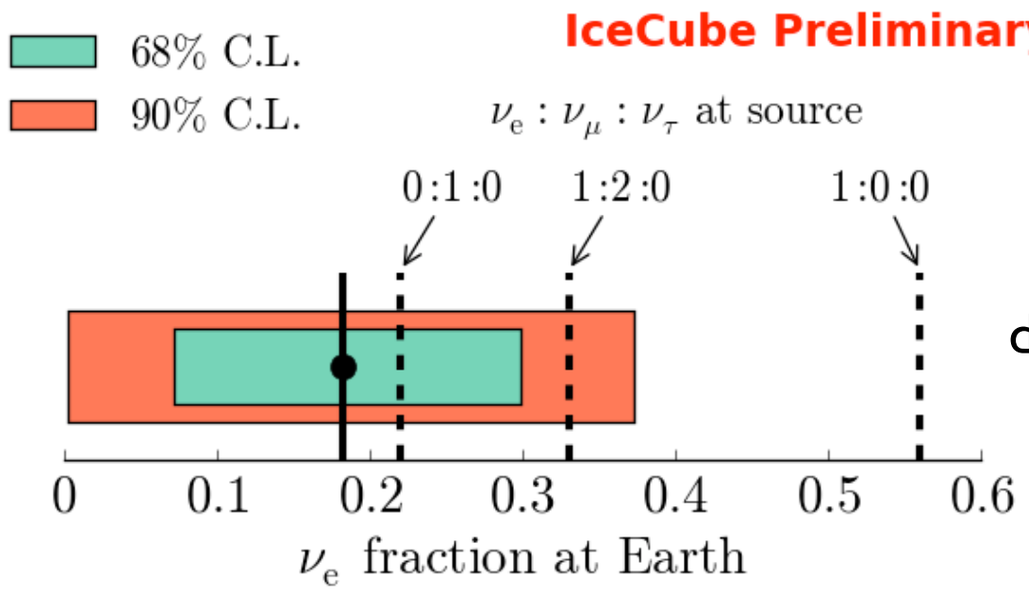
submitted ApJ

- Global fit of several IceCube analyses
  - Variety of selection criteria for both shower-like and track-like events
  - Data are fit to three observables
    - Energy, zenith angle, event topology

1:2:0 pion-decay
0:1:0 muon-damped
1:0:0 neutron-beam







neutron-decay dominated source rejected at 3.6σ

IceCube Collaboration
Phys.Rev.Lett. 114 (2015) 17, 171102

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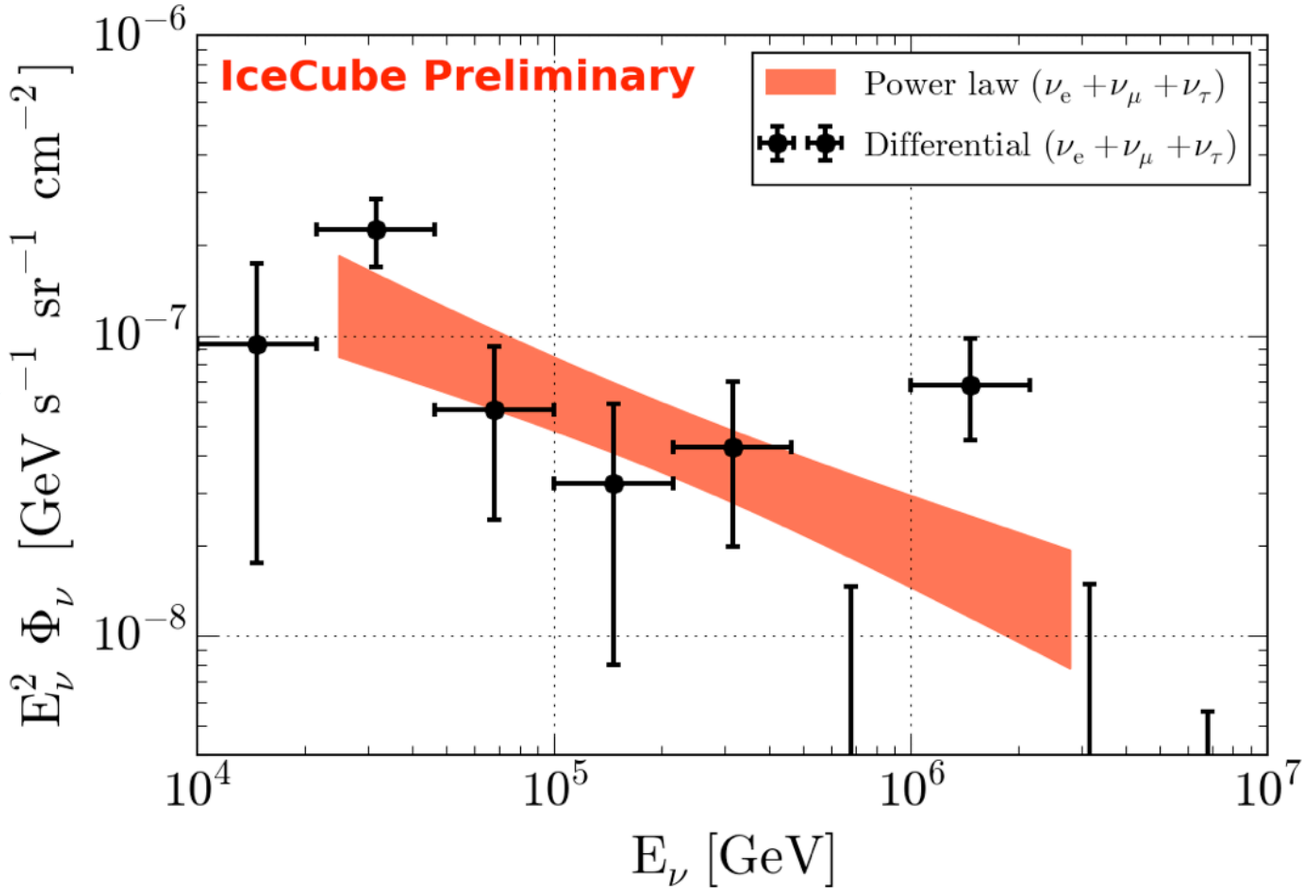

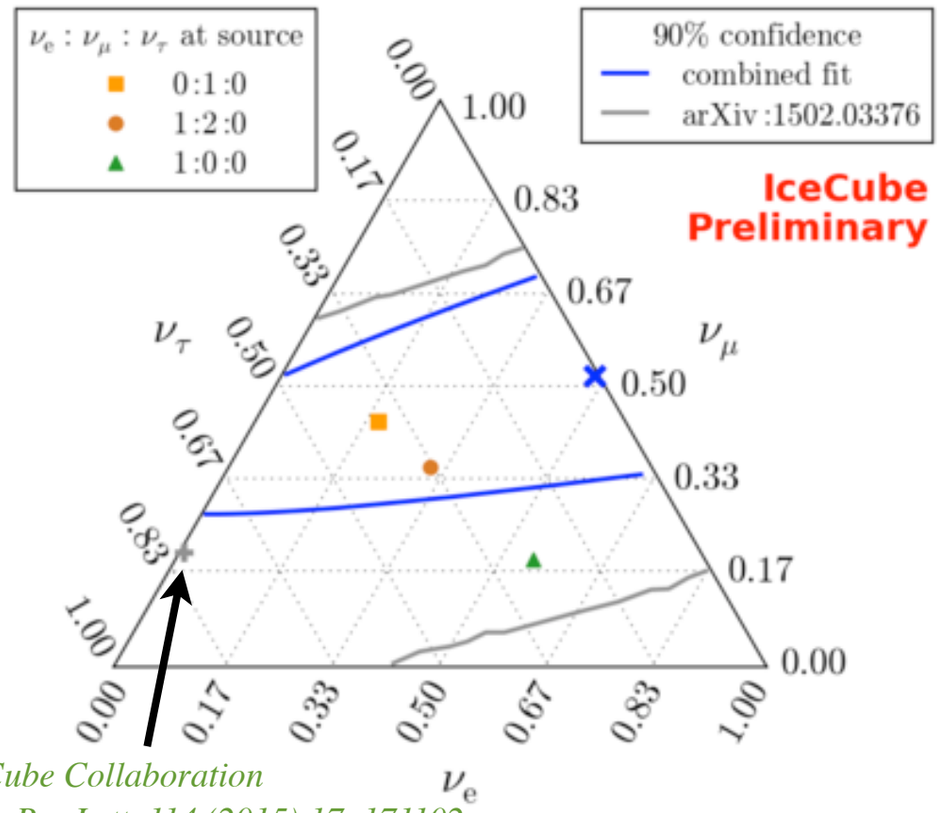

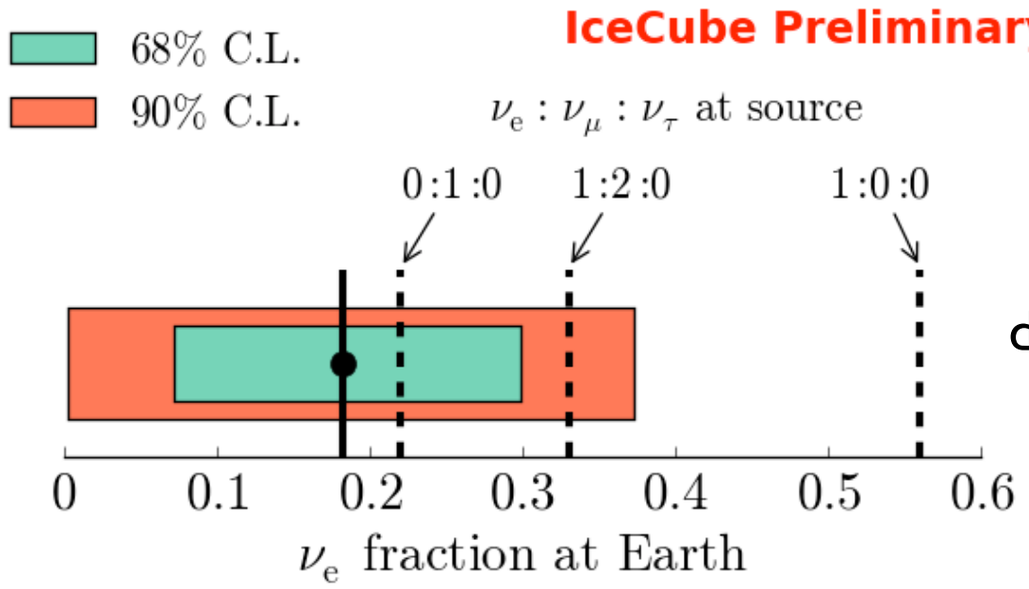

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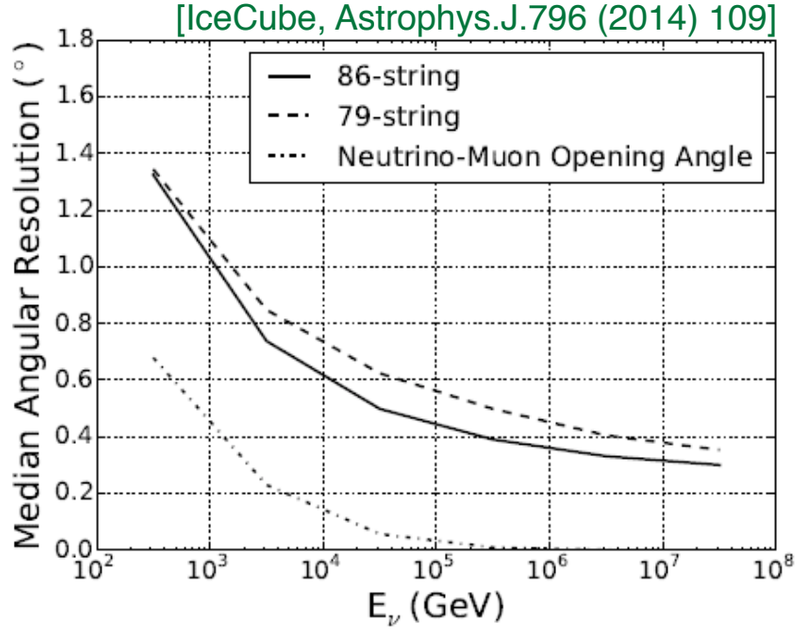
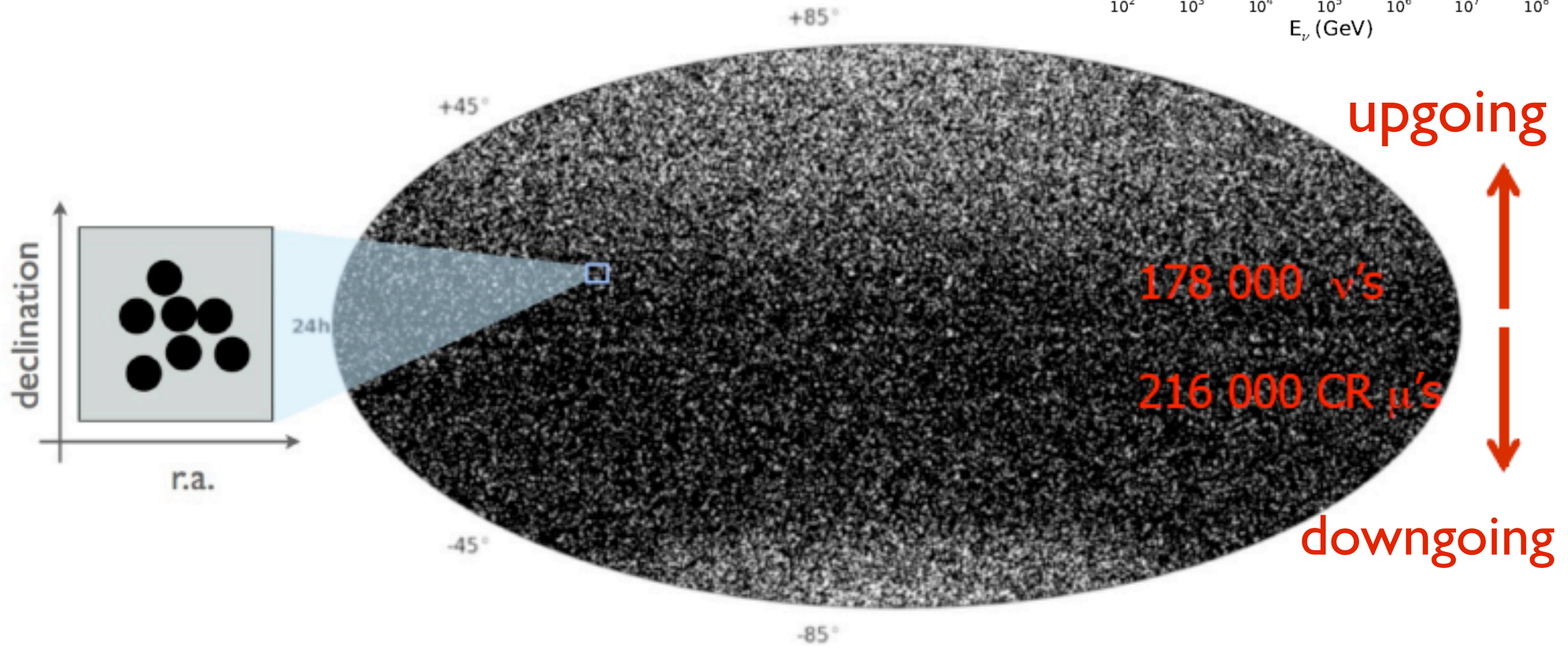
IceCube Collaboration
Phys.Rev.Lett. 114 (2015) 17, 171102

Point Source Search (2008-2012)

- 4yrs (1373days livetime) with loose cut optimization for well-reconstructed muon tracks
- Background estimate based on off-source data from same declination band
- unbinned maximum likelihood test for a fine grid of potential sources

[IceCube, Astrophys.J.796 (2014) 109]

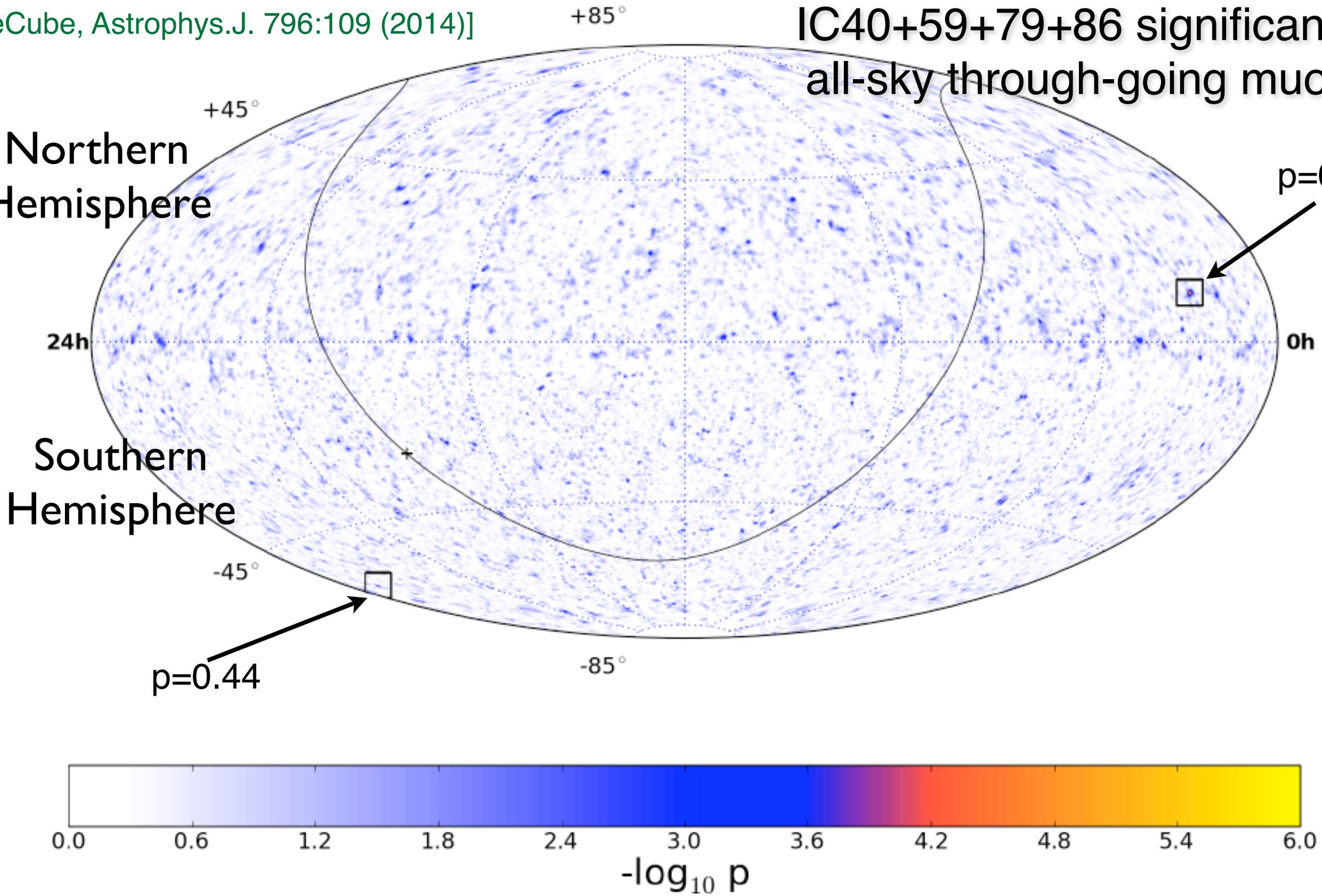




Point Source Search

[IceCube, Astrophys.J. 796:109 (2014)]

IC40+59+79+86 significance:
all-sky through-going muons



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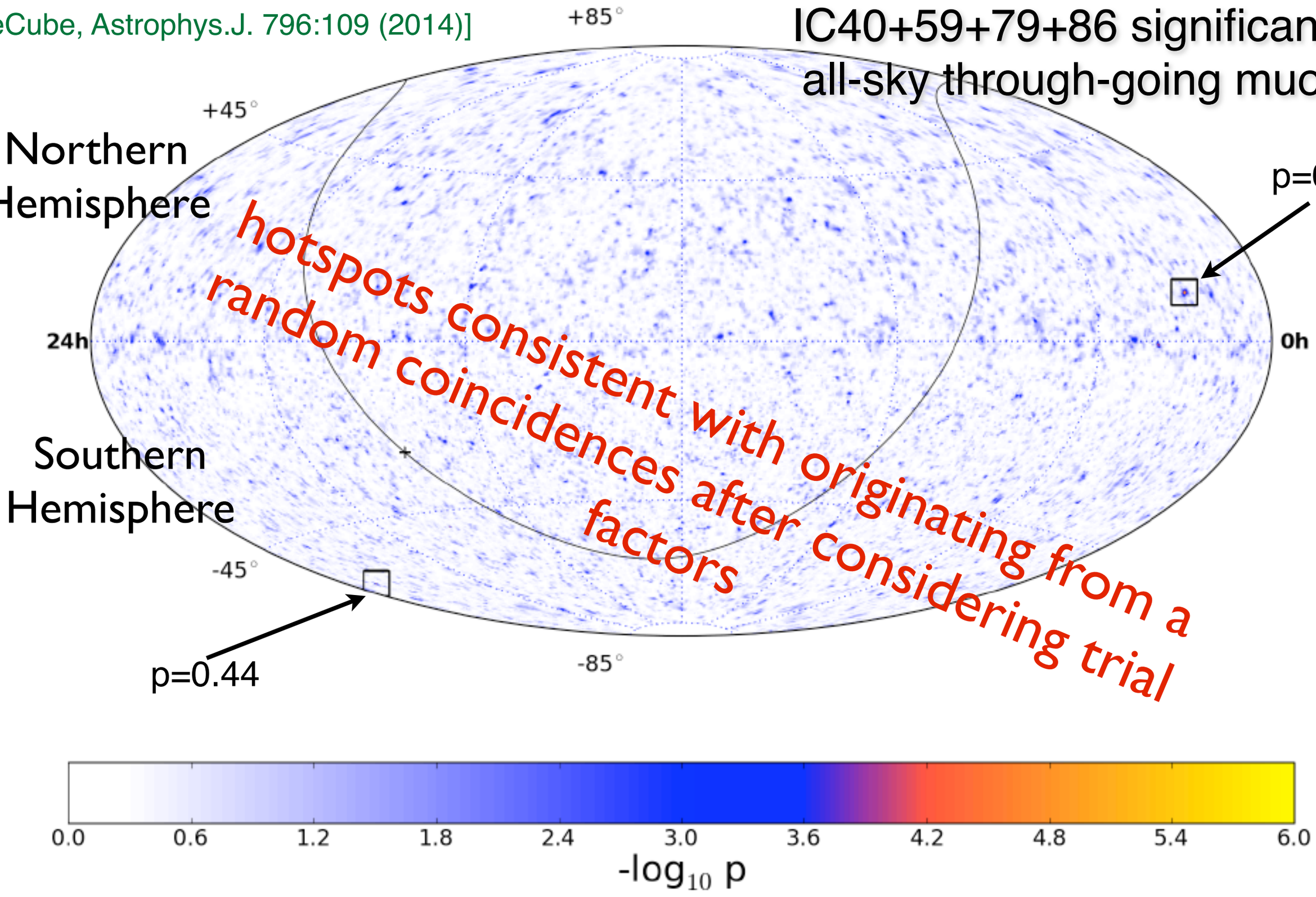


Neutrinos in coincidence with gamma-ray bursts?

IceCube

ν

γ, ν

Gamma-ray satellites

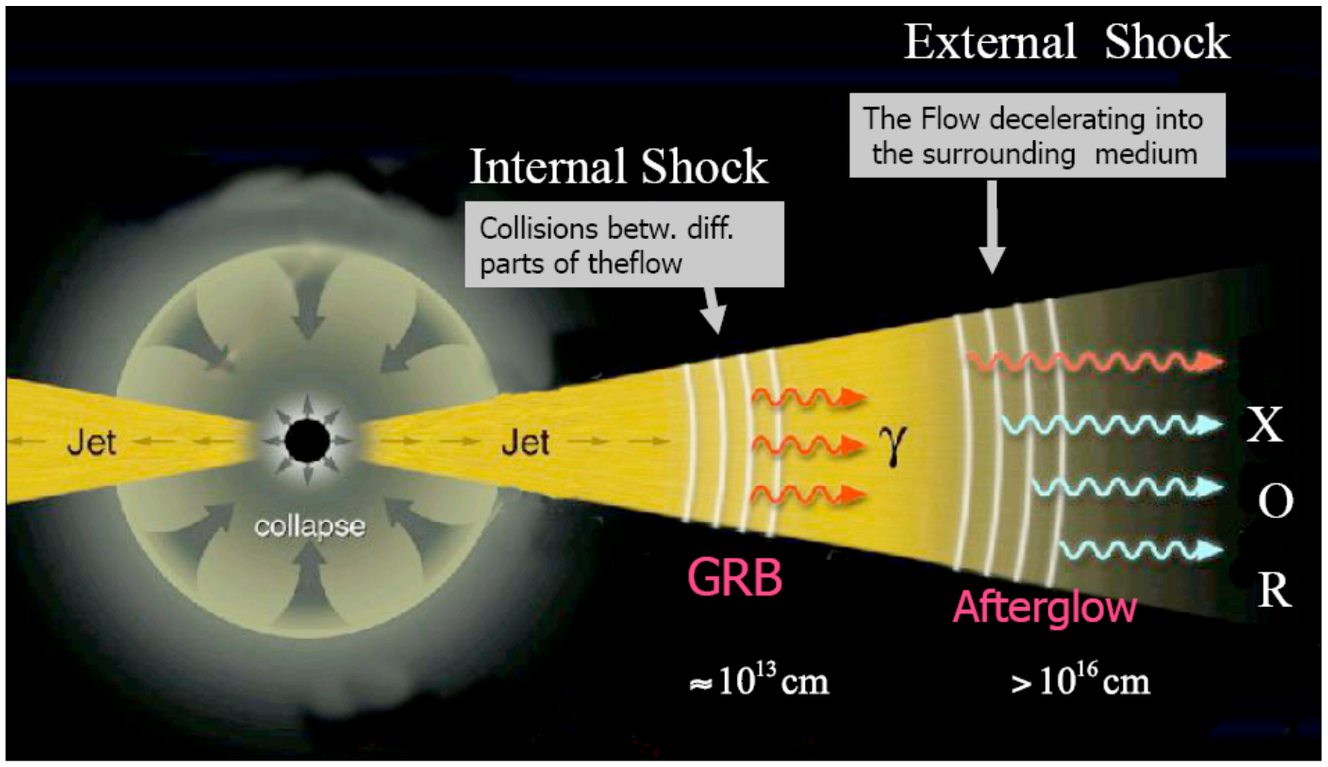
GRB timing/localization information from correlations among satellites

Where are the neutrinos? Are GRBs really cosmic ray sources?

distant GRB

Direction plus time (10-100s) cuts – much reduced background

Transient Search GRBs



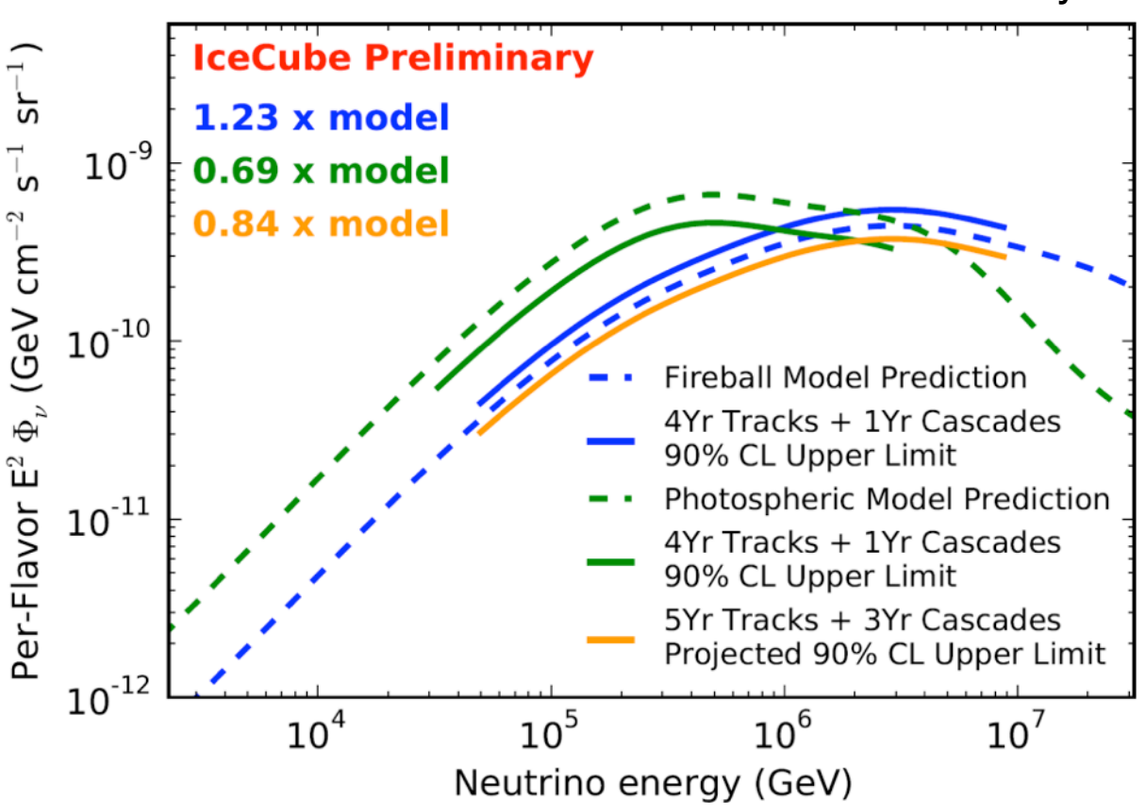
IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern and 85 from southern sky) analyzed. **No coincidence found**

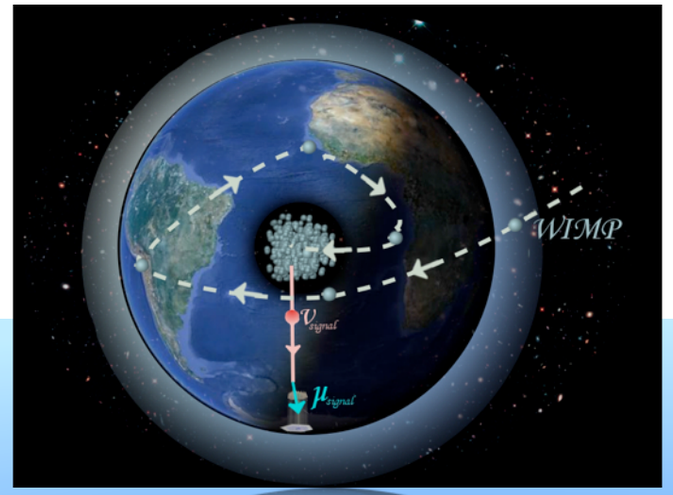
IceCube Collaboration - Nature Vol **484**, 351 (2012)

- upgoing ν_μ track search – 506 bursts in 4yrs
- all-flavor cascade search – 257 bursts in 1yr

Burst data from Fermi-BAT and Swift provide precise time stamp and location

Difficult to attribute diffuse neutrino flux with GRB bounds

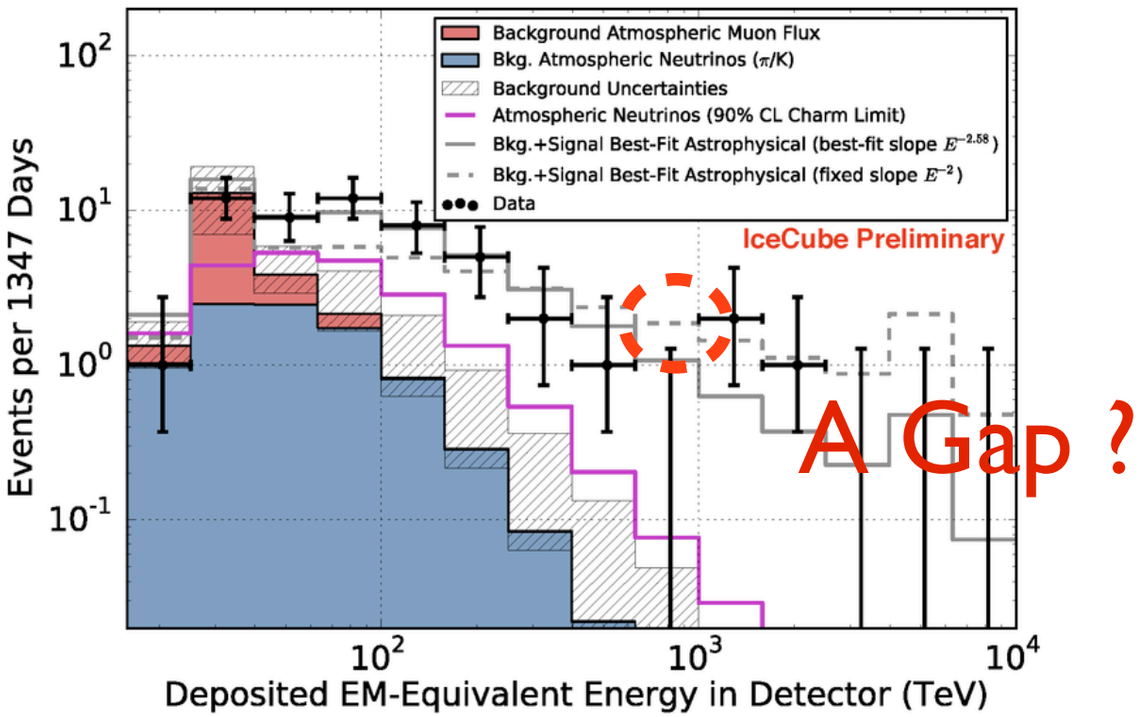




Hunt for Dark Matter with Neutrinos

Heavy Dark Matter Decay

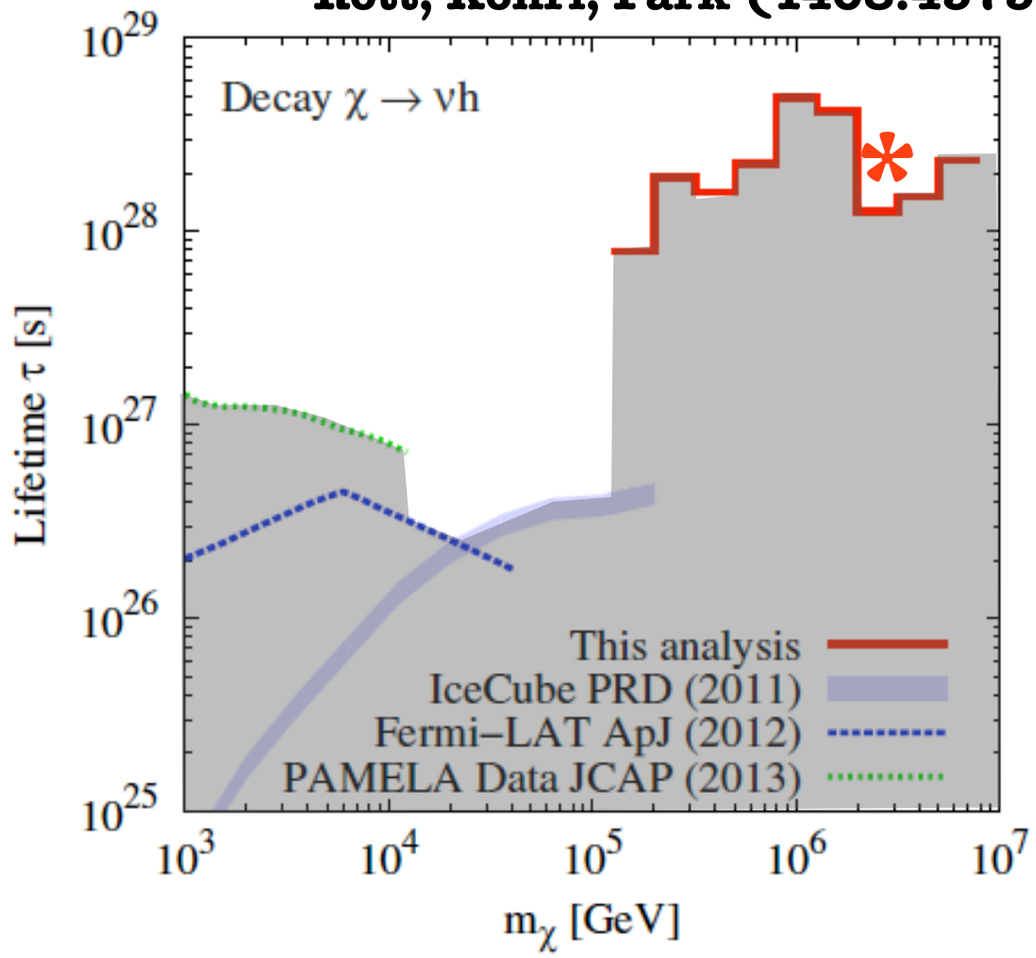
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*



- Consider Heavy Decaying Dark Matter (example $\chi \rightarrow \nu h$)
- Focus on most detectable feature (neutrino line)
- Backgrounds steeply falling with energy, highest energy events provide best sensitivity
- Continuum and spacial distribution could help identify a signal
- Bounds from Fermi-LAT and PAMELA derived from search for bb annihilation channel (dominant decay channel of Higgs).
- IceCube Gravitino Decay analysis forthcoming (ICRC2015)

Derived bound on lifetime ~10^{28}s

Rott, Kohri, Park (1408.4575)



Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
El Aisati, Gustafsson, Hambye 1506.02657

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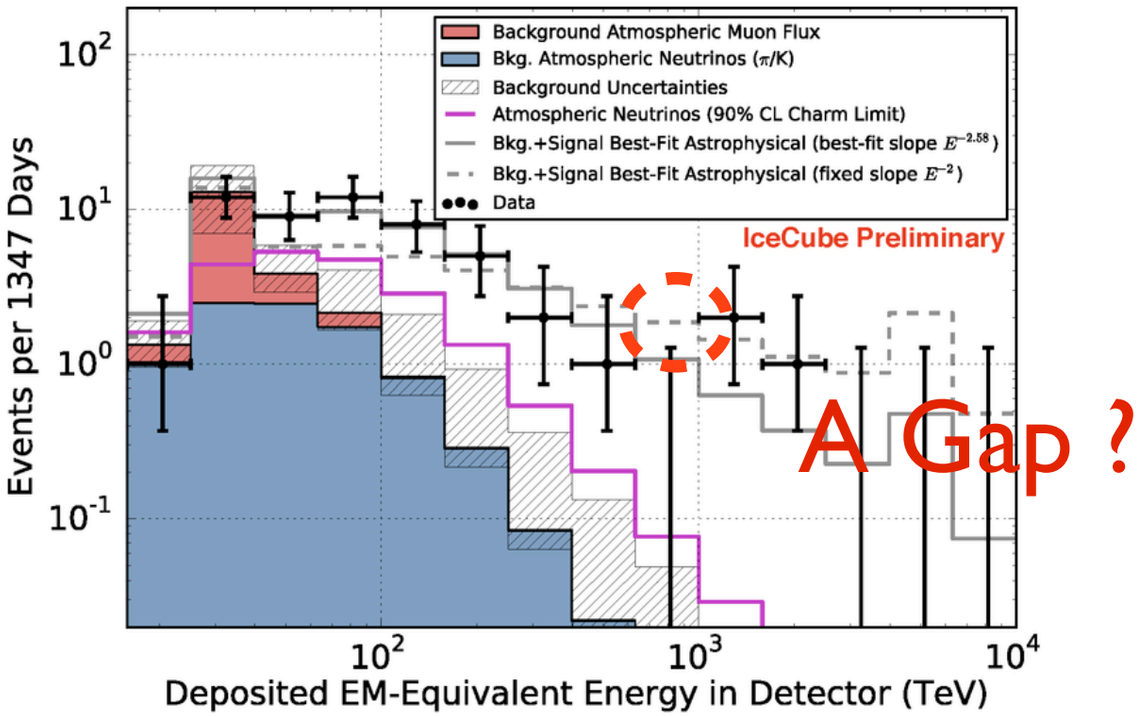

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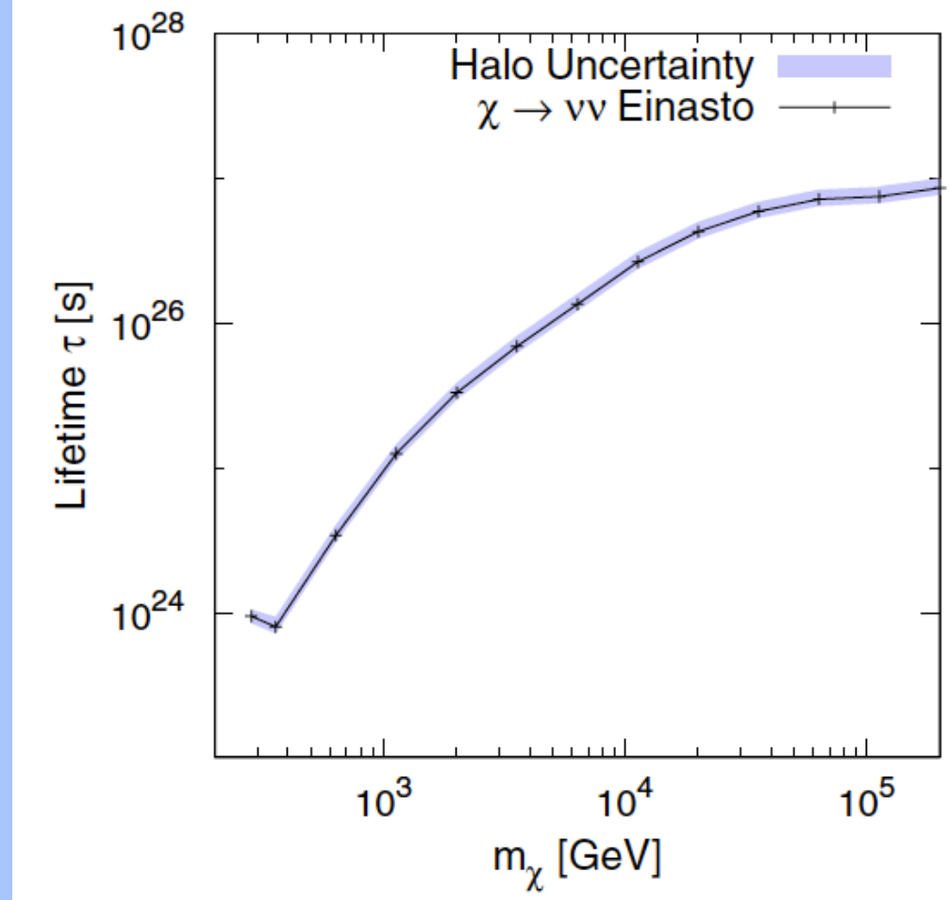
IceCube Bound on lifetime ~10^{27}s

Phys.Rev.D84:022004,2011



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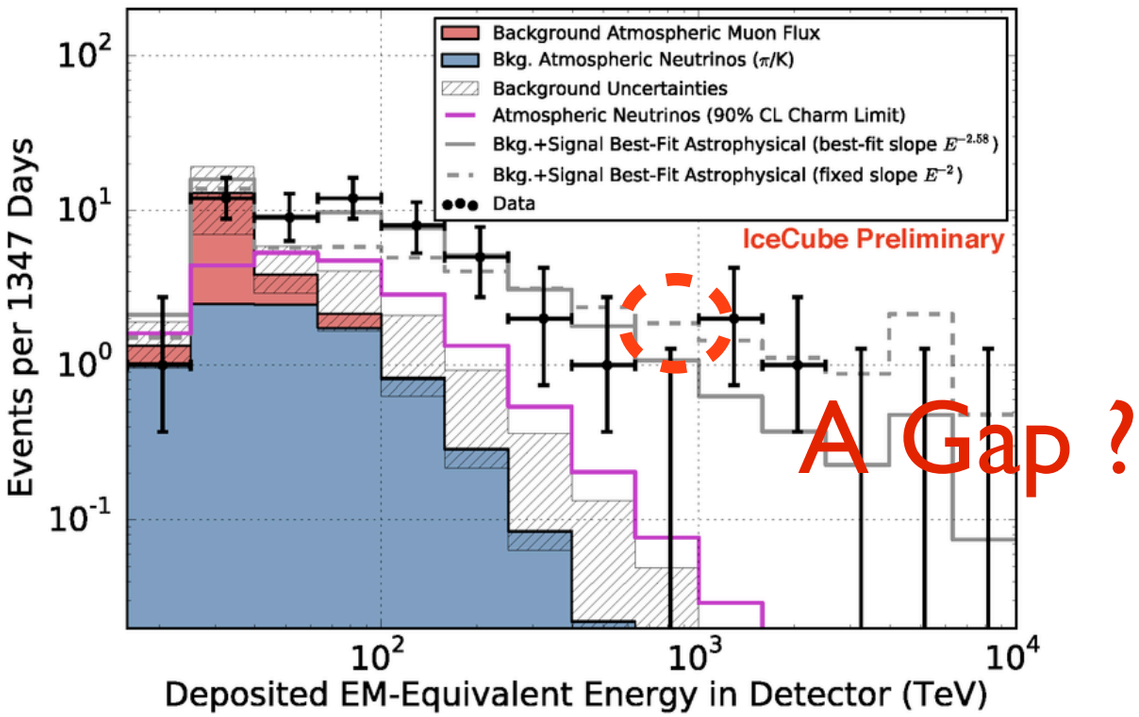

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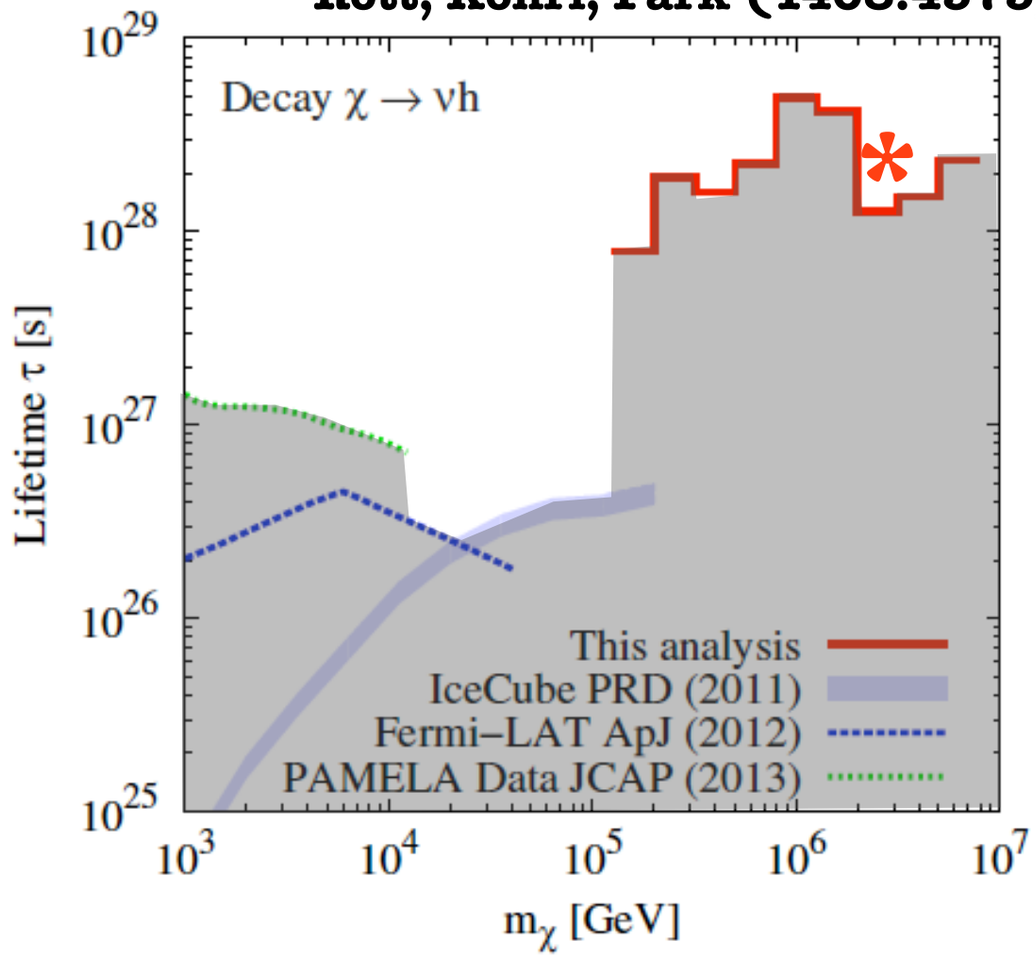

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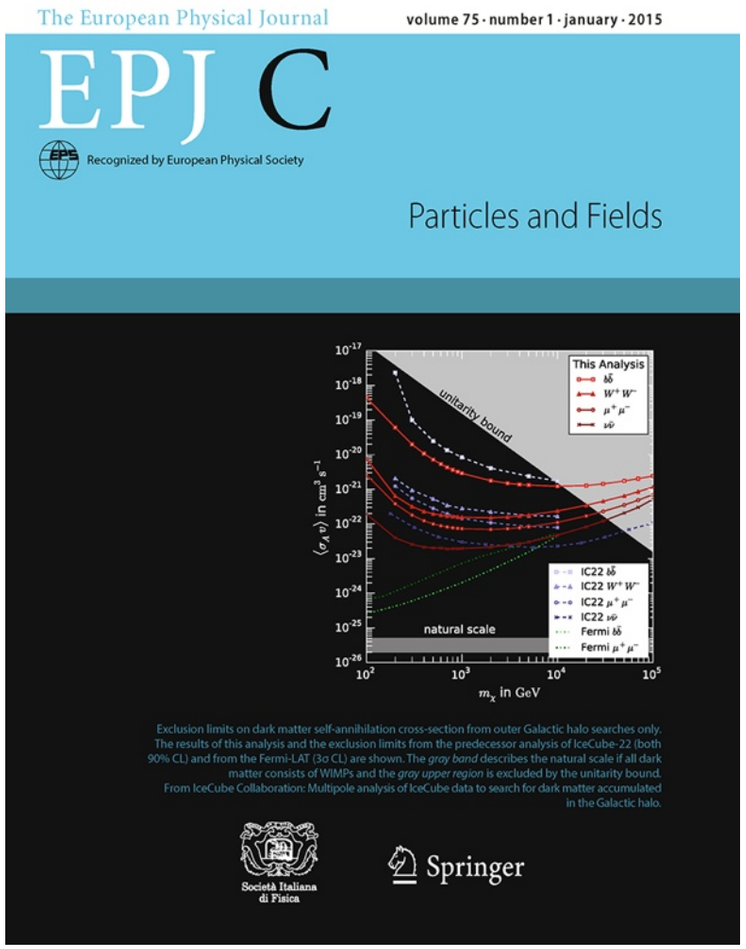
Galactic Halo

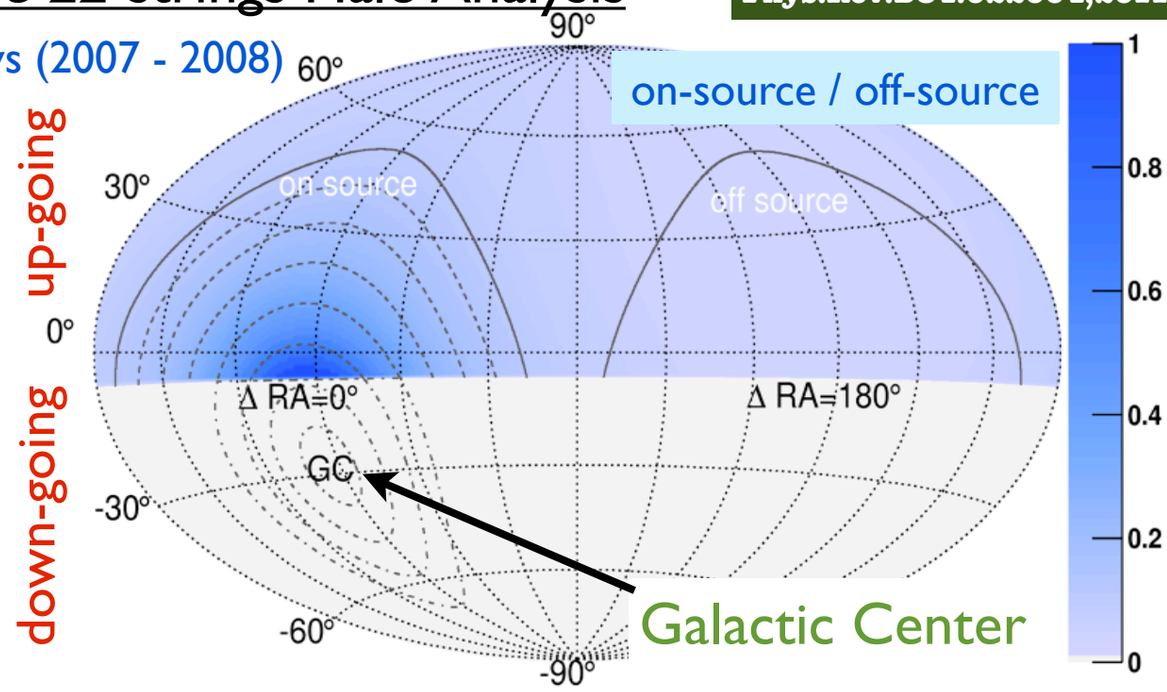
- Galactic Center (GC) on the southern hemisphere
  - large backgrounds from down-going muons
- Search for anisotropy on Northern hemisphere
  - high-purity neutrino sample (up-going muon events)
- Assume annihilation into νν, bb, μμ, ττ, WW



IceCube 22-strings Halo Analysis

Phys.Rev.D84:022004,2011

276 days (2007 - 2008)



IceCube 79-strings multipole analysis

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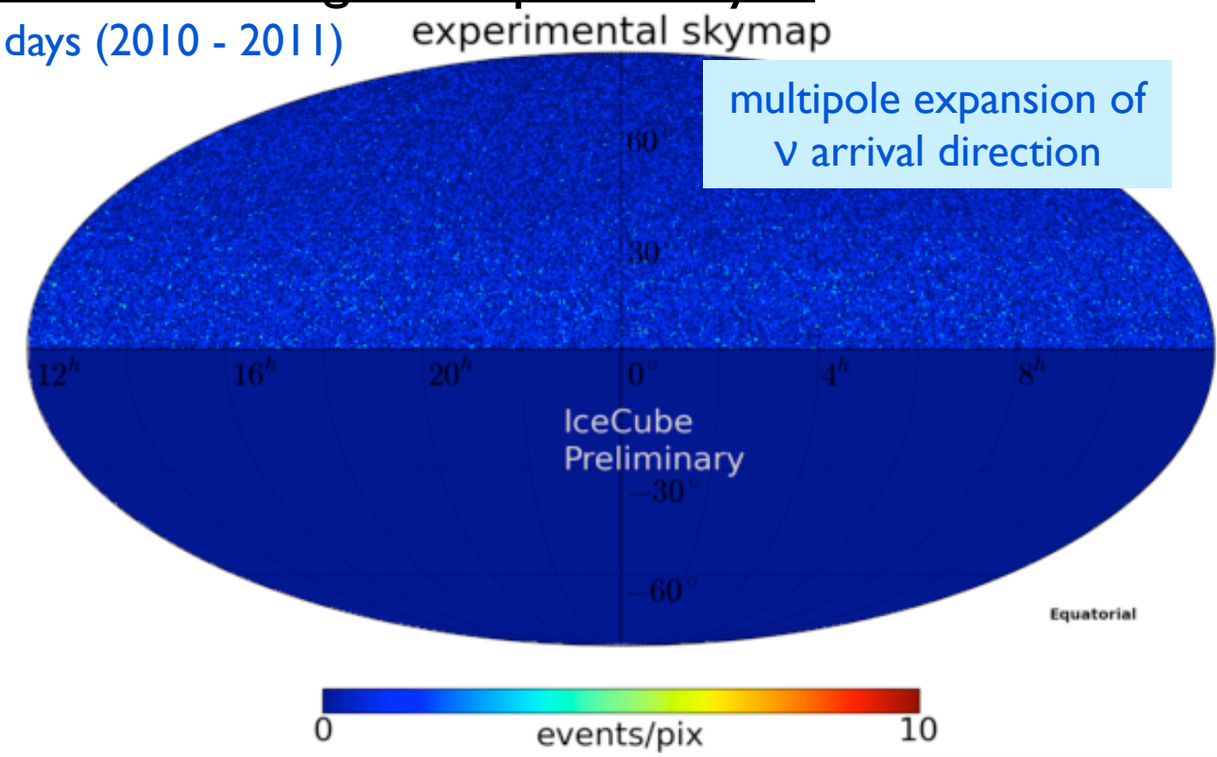

Eur. Phys. J. C75, 20 (Jan 2015)

R. Abbasi et al., Phys. Rev. D 84 (2011) 022004.
M. Ackermann et al., Astrophys. J. 761 (2012) 91.

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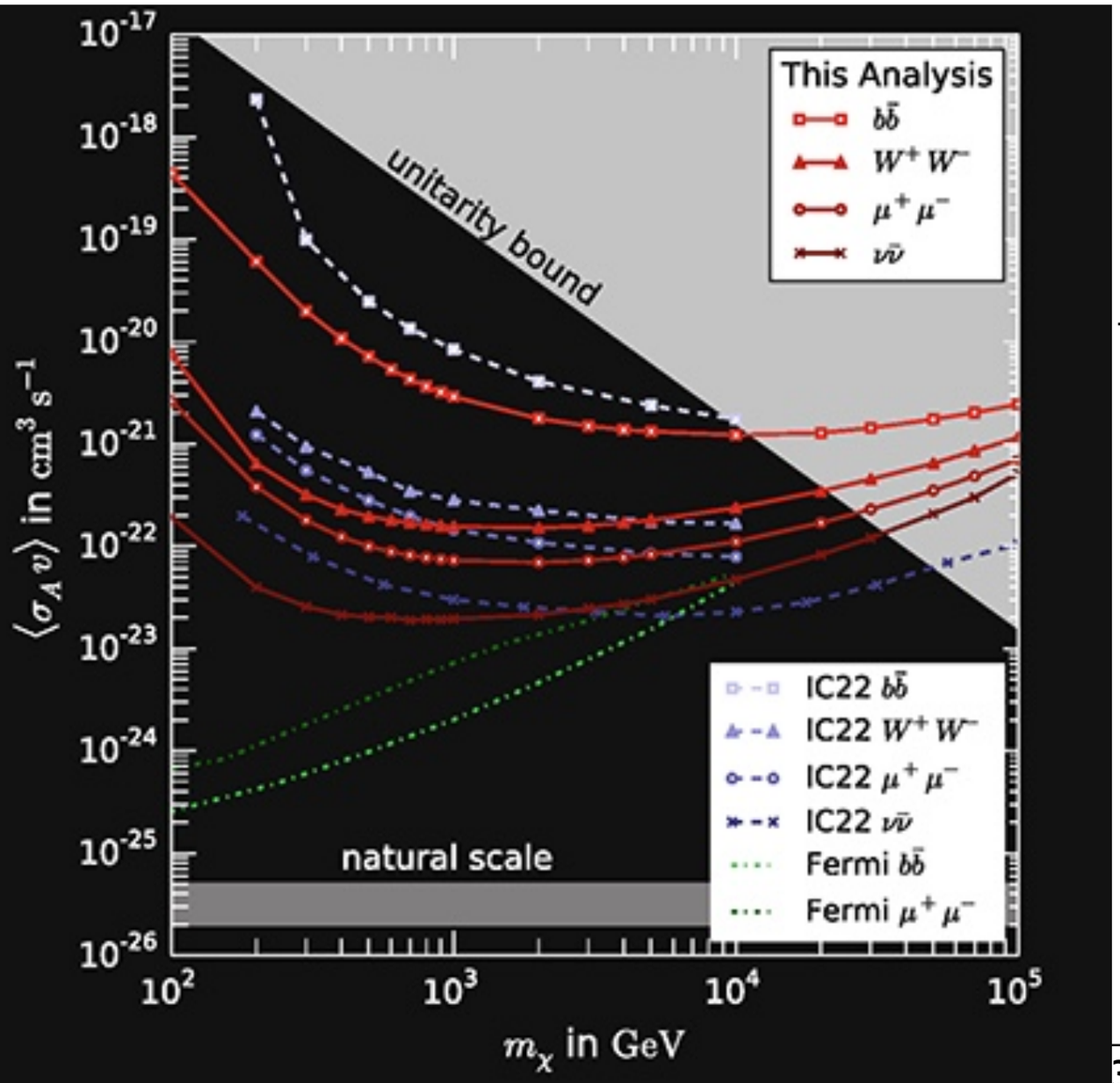

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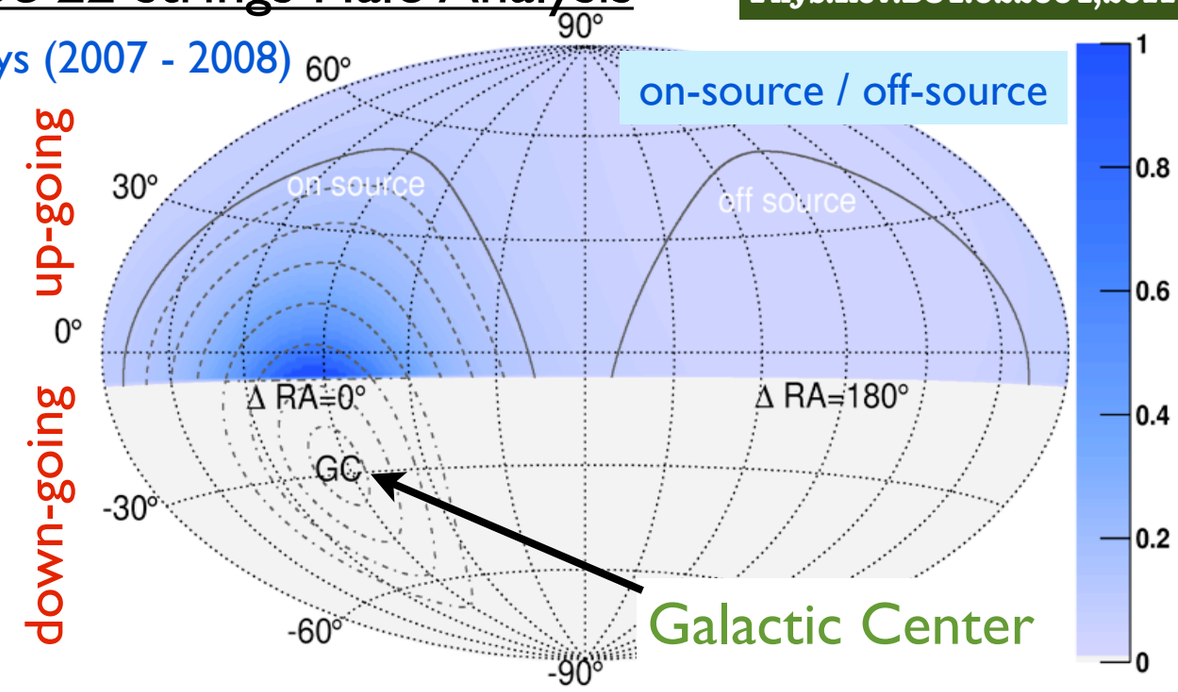

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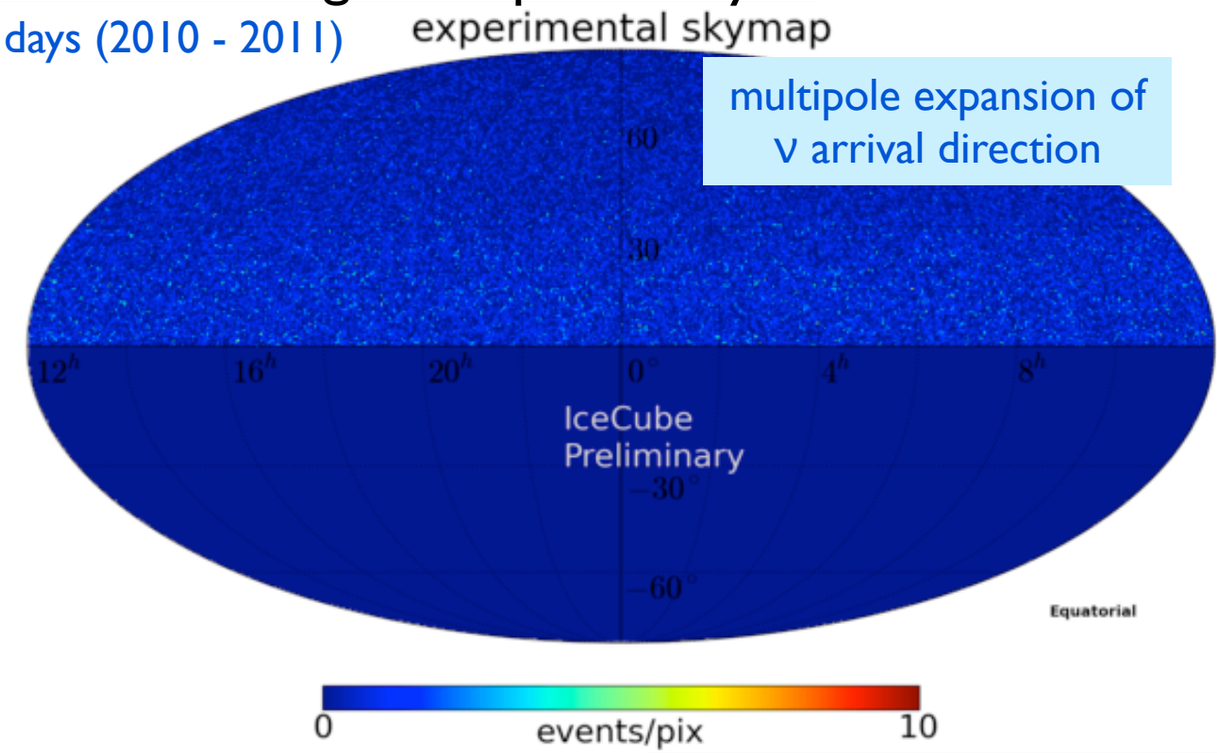
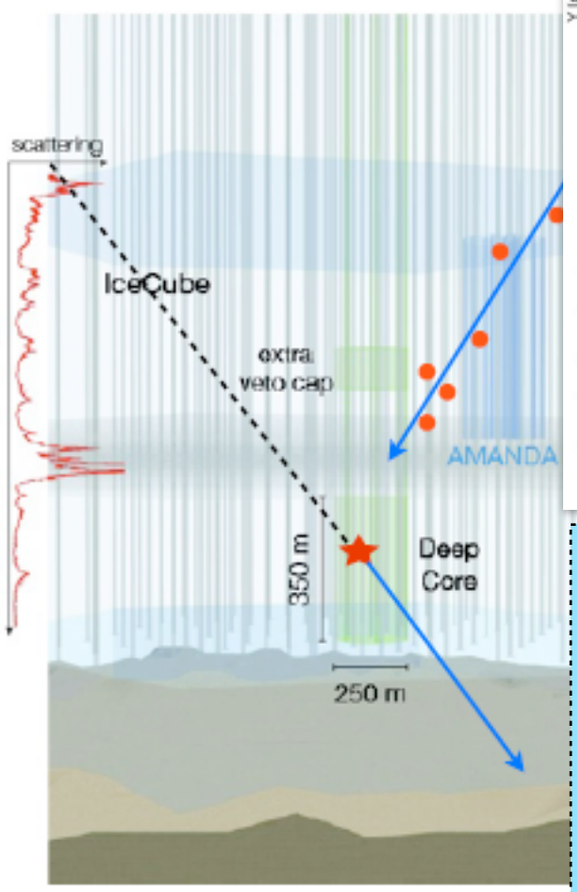


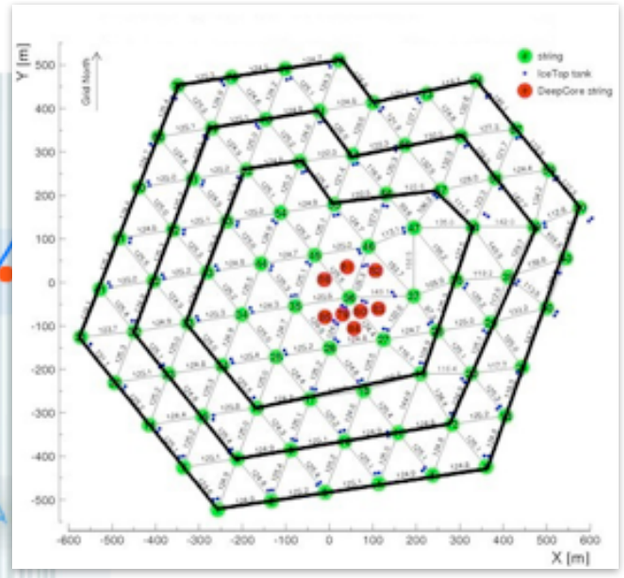
Eur. Phys. J. C75, 20 (Jan 2015)

IceCube Collaboration
arXiv1505.07259
submitted EPJC

Galactic Center

Use IceCube external strings as a veto:
- 3 complete layers around DeepCore (~ 375m)
- Full sky sensitivity: access to southern hemisphere





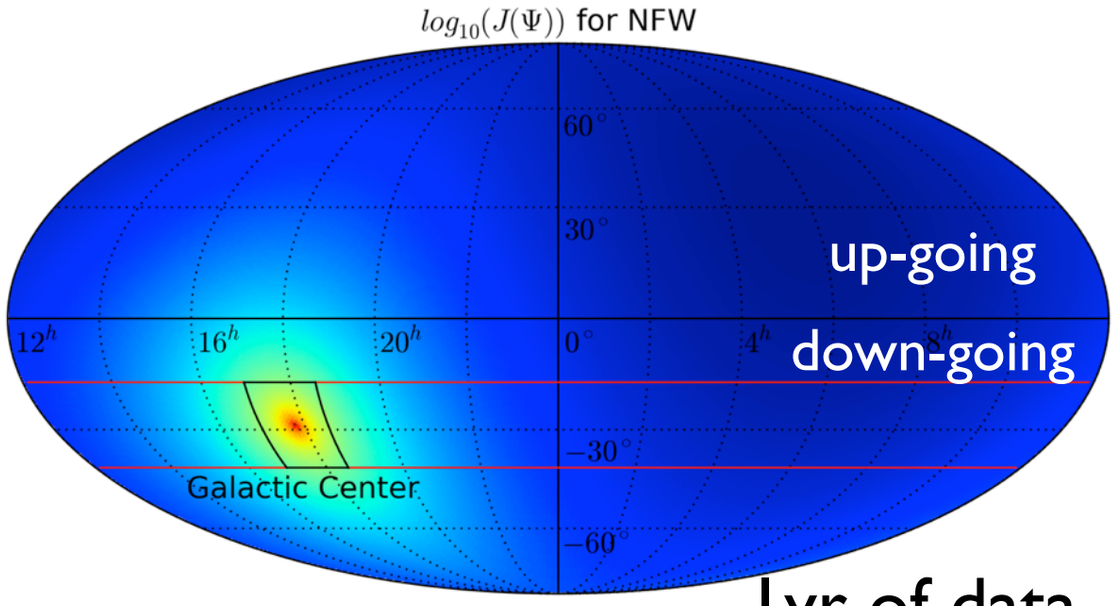
Two analyses, combined based on best sensitivity (dotted).

Both analyses observed underfluctuations

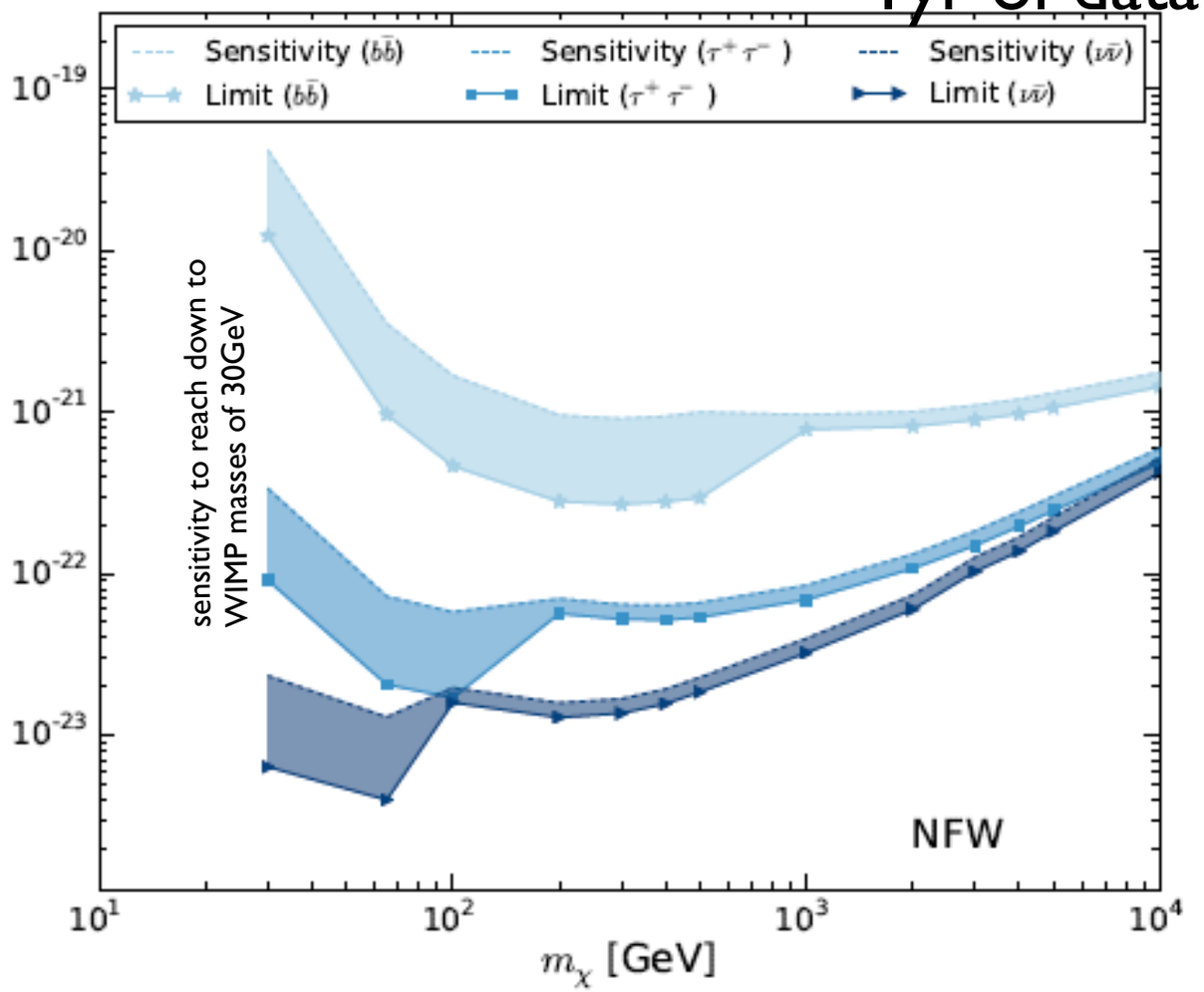
"High energy" analysis: 0.5 σ

"Low energy" analysis: 2σ

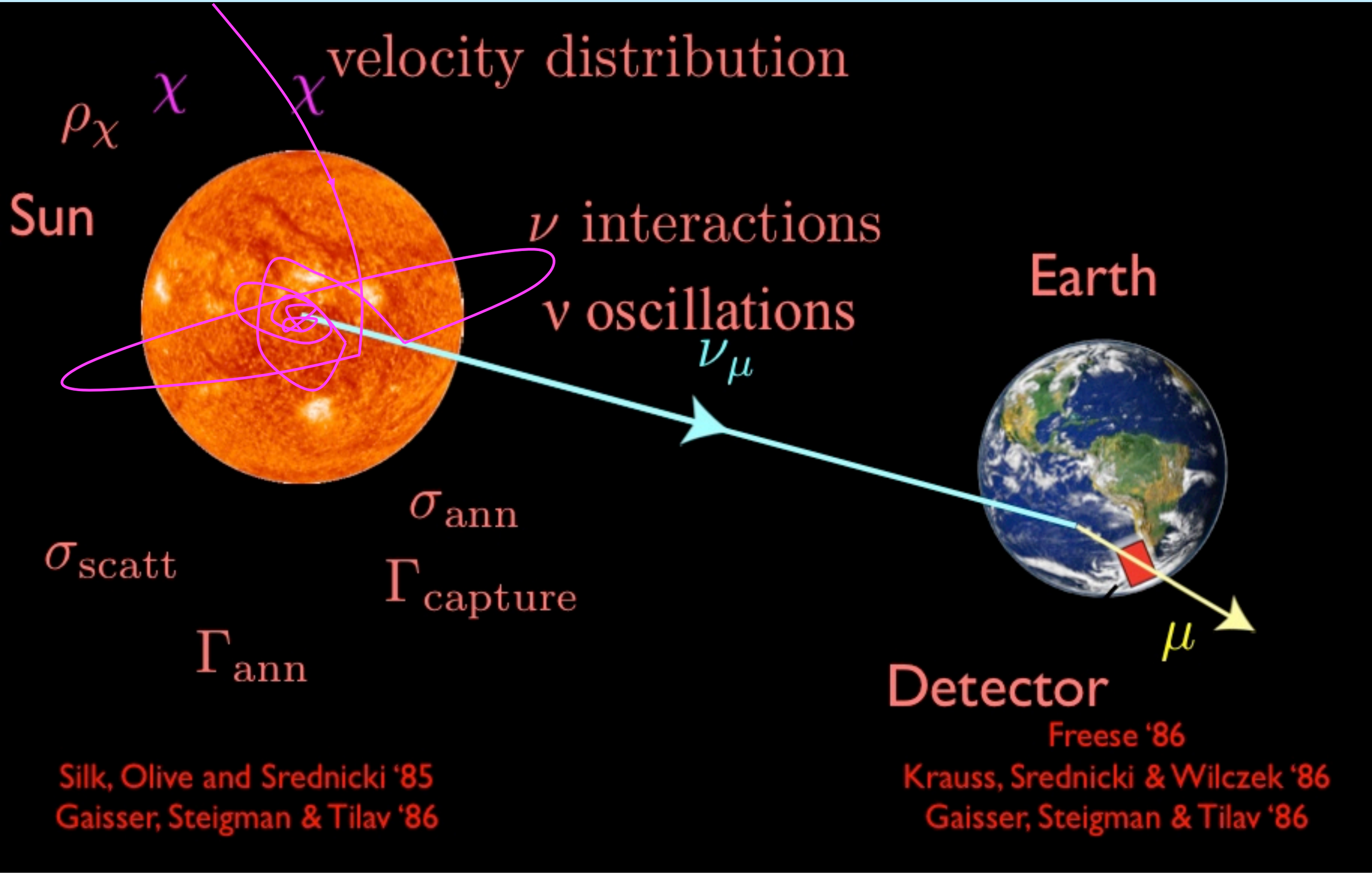
Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation



1yr of data



Solar WIMPs

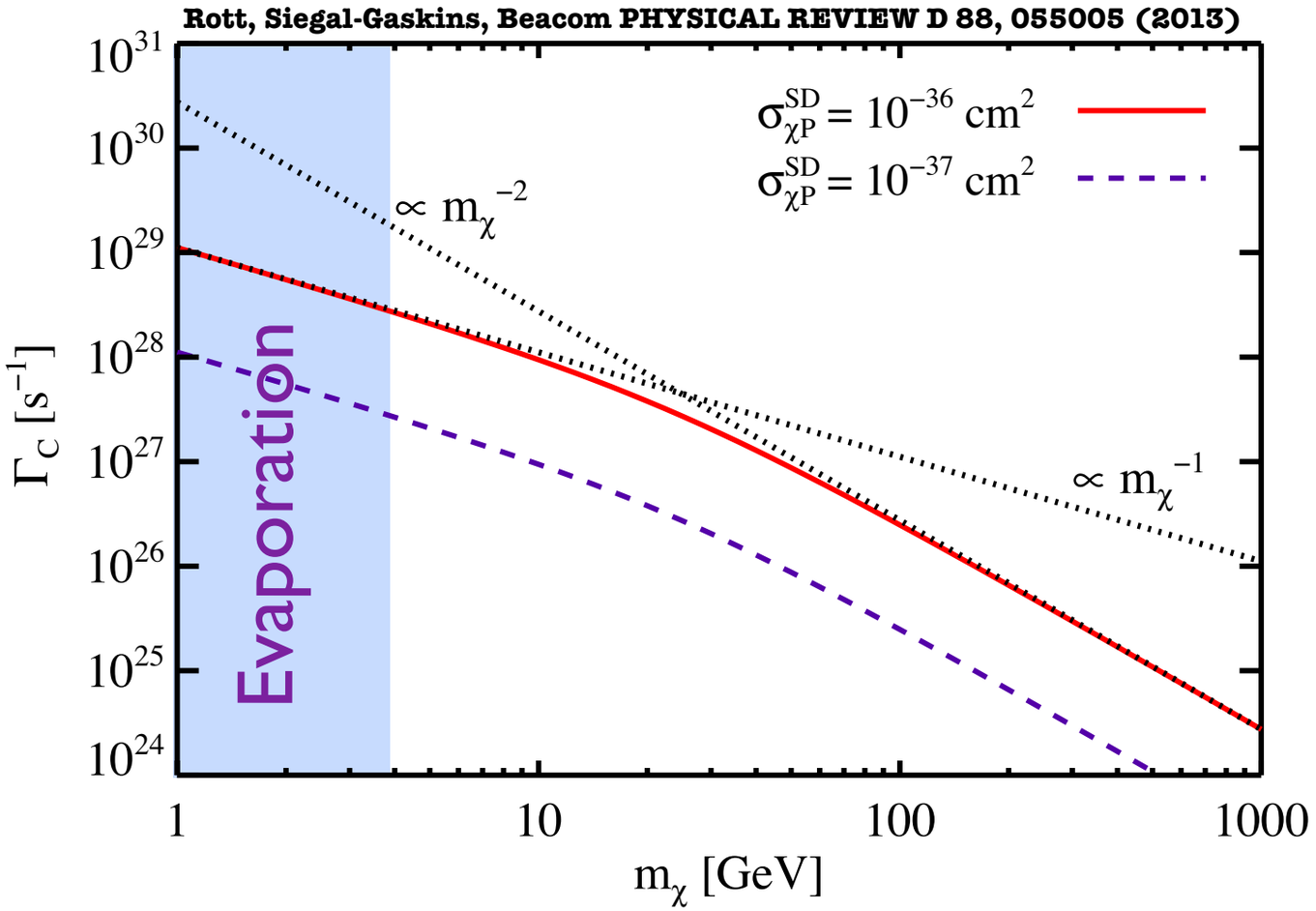


Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, Γ_C ,depends on WIMP-nucleon scattering cross section
- Dark Matter accumulates and starts annihilating
  - → Only neutrinos can make it out
- Equilibrium: The capture rate regulates the annihilation rate ($\Gamma_A=\Gamma_C/2$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section



The capture rates scales as:

$\Gamma_C \sim \rho_\chi m_\chi^{-1} \sigma_A$ for $m_\chi \sim m_A$

$\Gamma_C \sim \rho_\chi m_\chi^{-2} \sigma_A$ for $m_\chi >> m_A$

number density + kinematic suppression

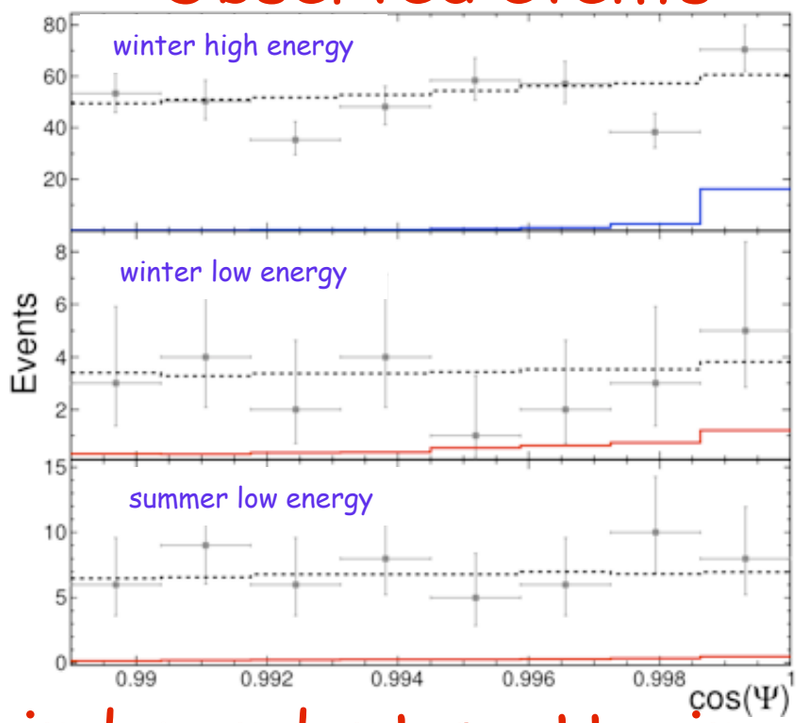
m_A - is the target mass

IceCube Solar WIMP Limits

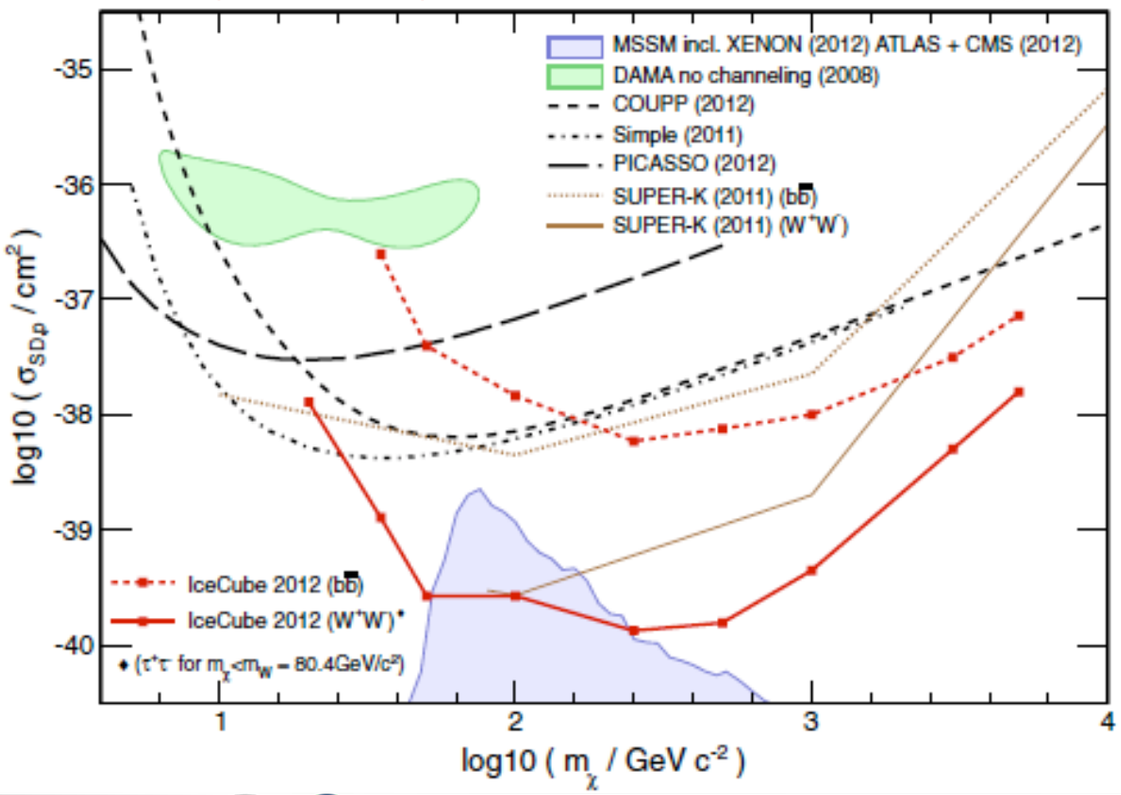
PRL 110, 131302 (2013)

- IceCube 79-strings configuration (partially completed DeepCore)
  - 318 days (May 2010 - May 2011)
- Search for an excess of events from the direction of the Sun
  - use track events for better pointing
- Separate summer and winter analysis
  - use outer detector to veto down-going muons for summer analysis

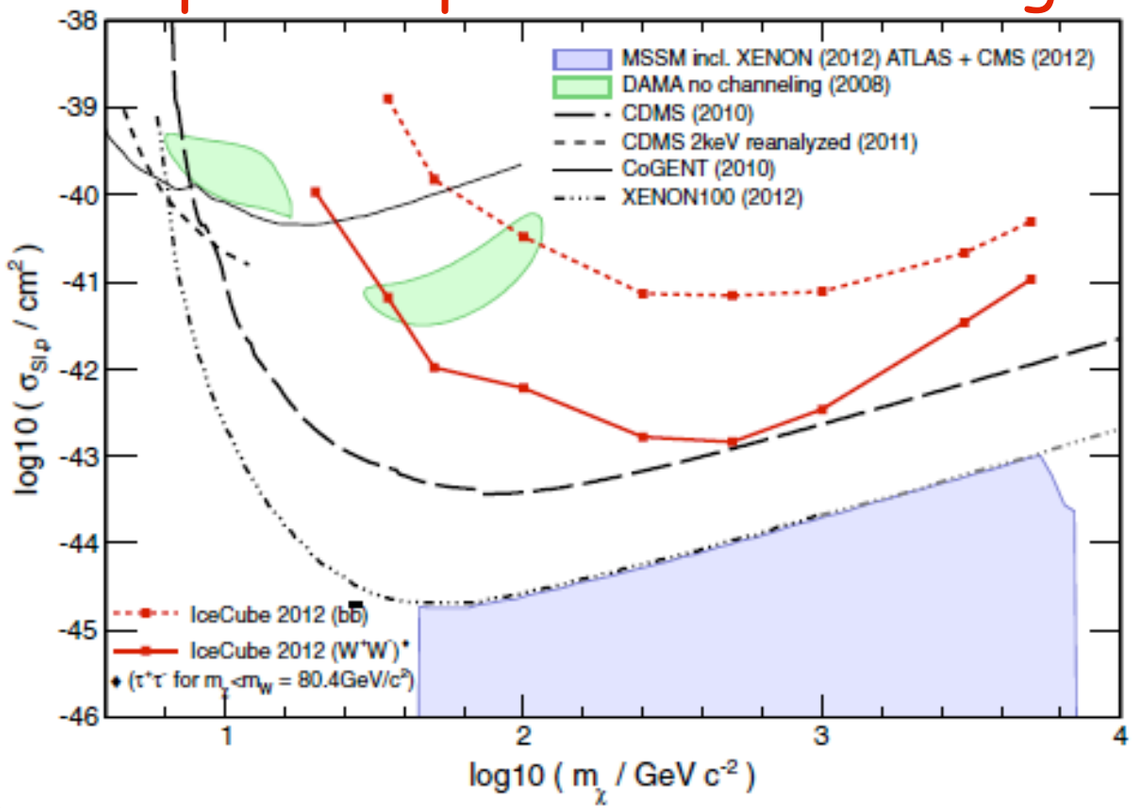
Observed events



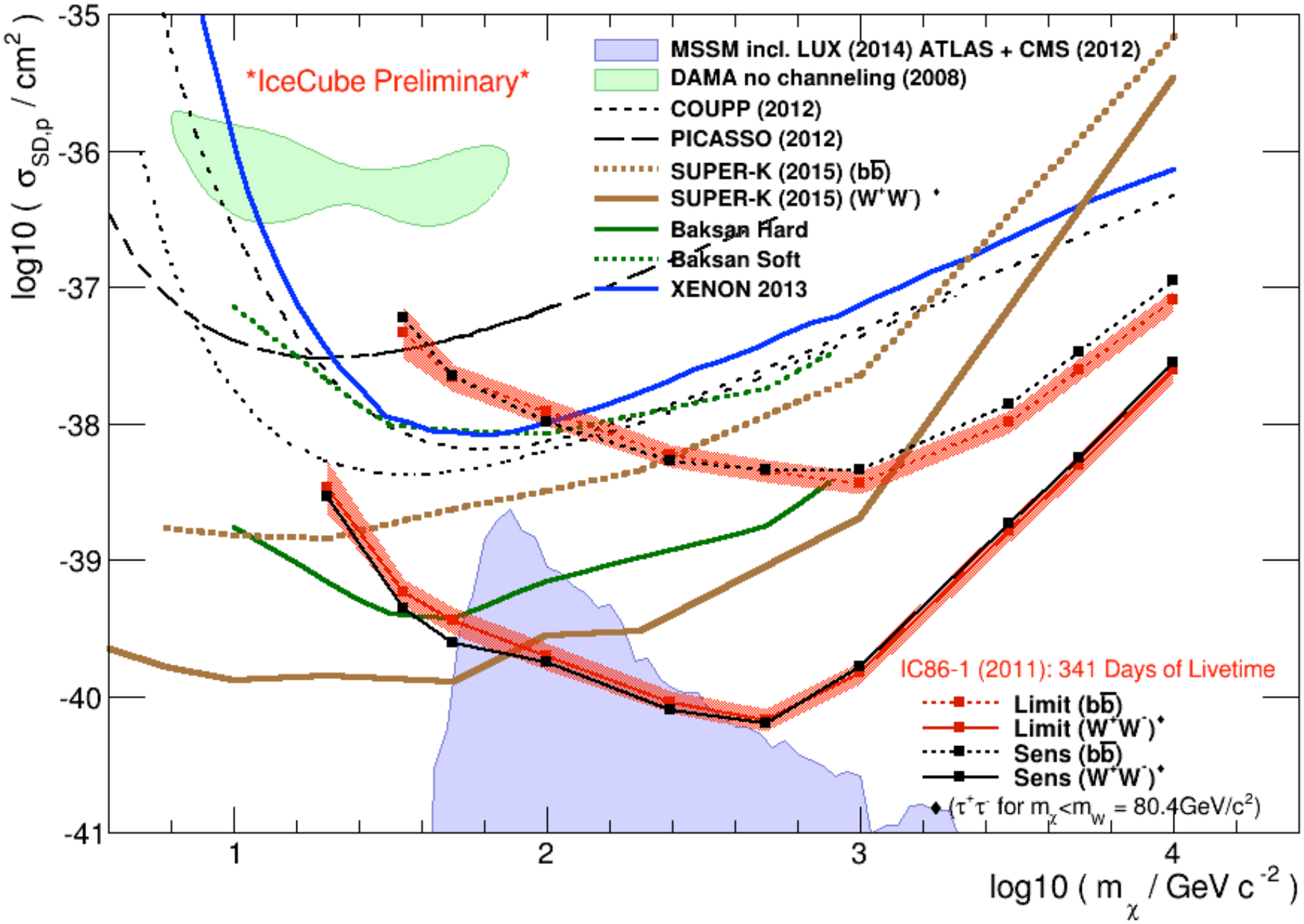
Spin-dependent scattering



Spin-independent scattering

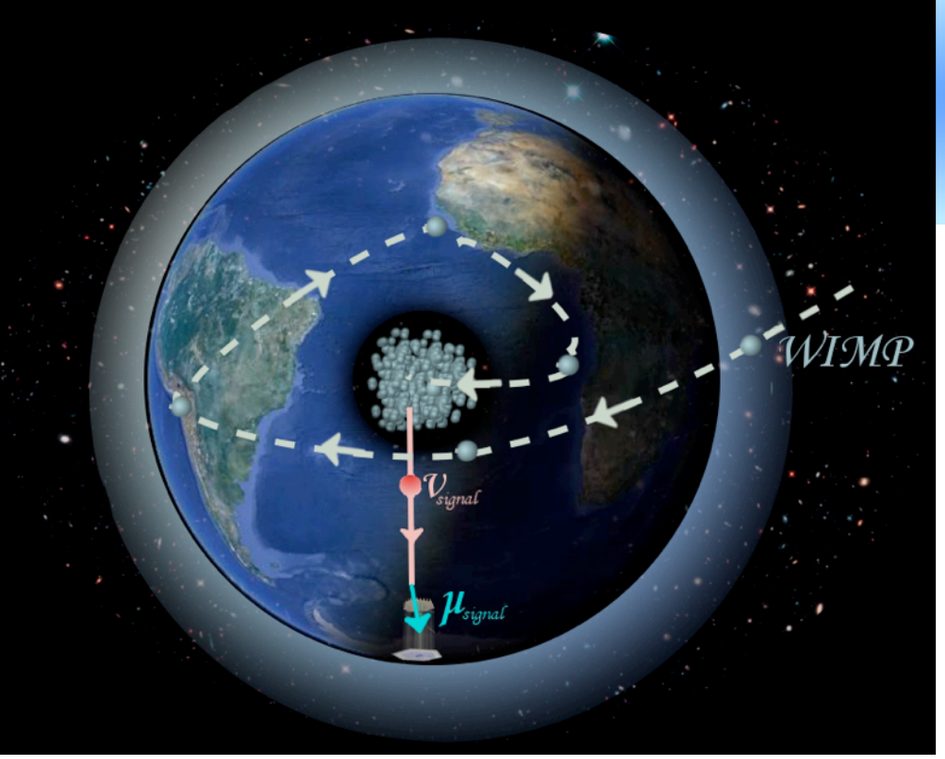


Preliminary Solar WIMP Limits IC86

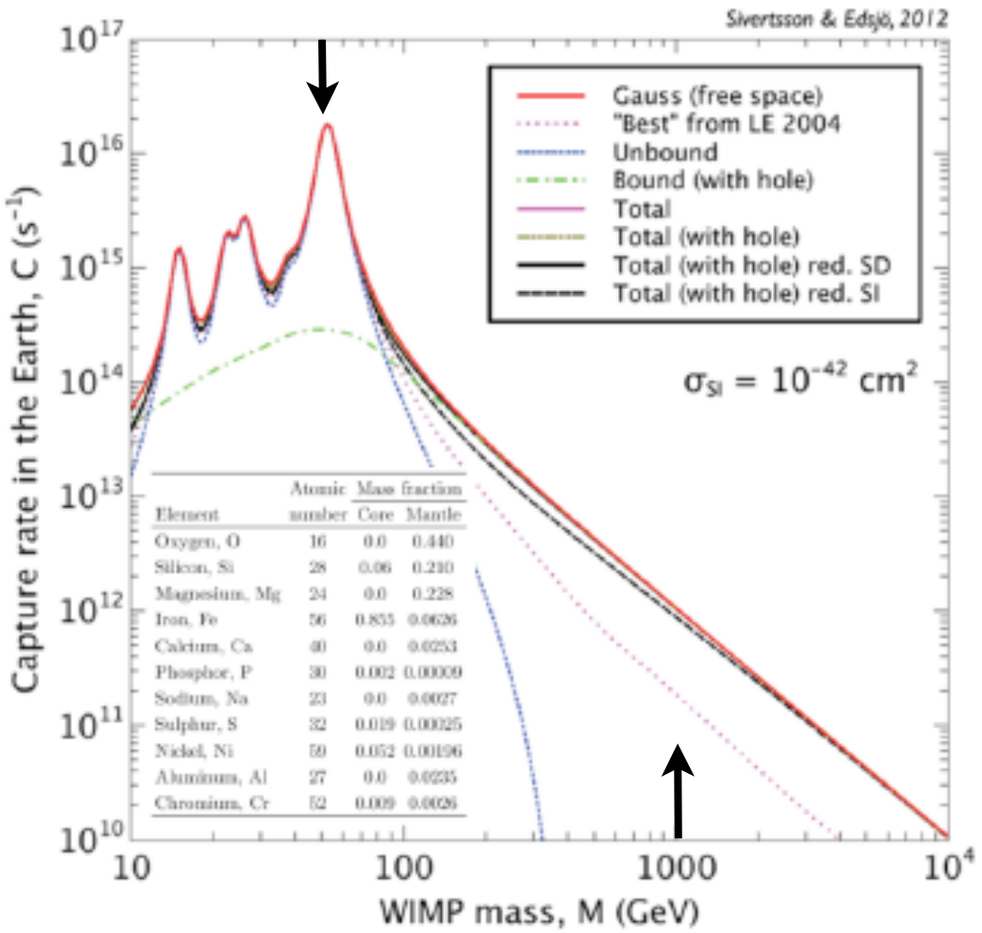


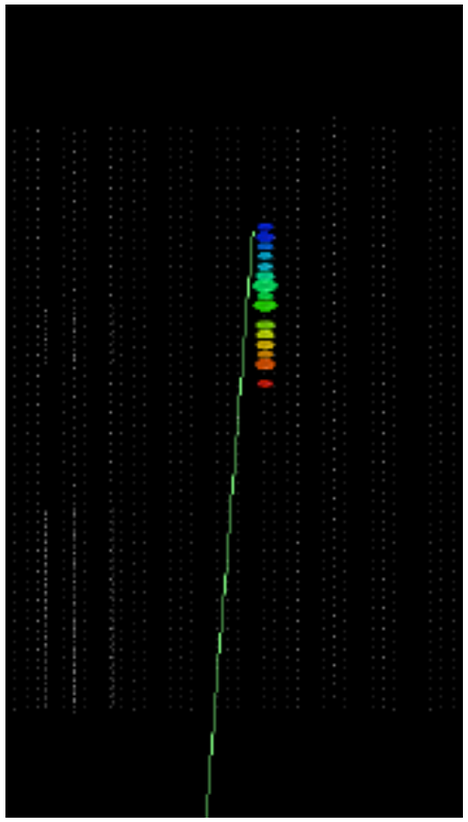
- Two independent analyses (1yr of IceCube data)
- Result with 3yrs of IceCube data expected for ICRC 2015

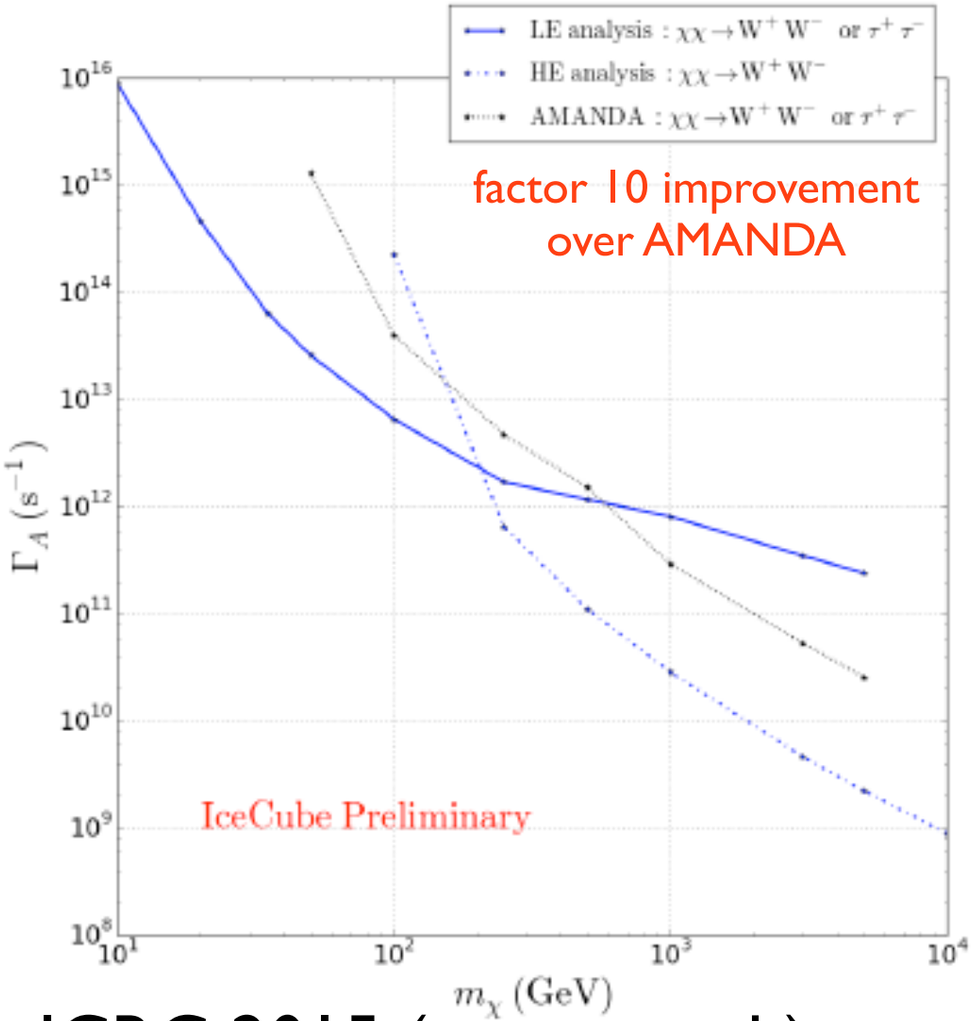
Earth WIMPs



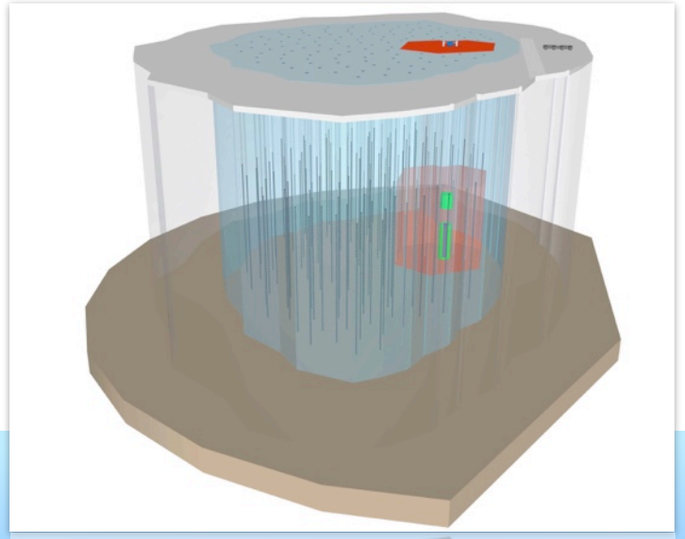
- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- IC86-1 dataset: 2 statistically independent analyses
  - Low energy & High energy







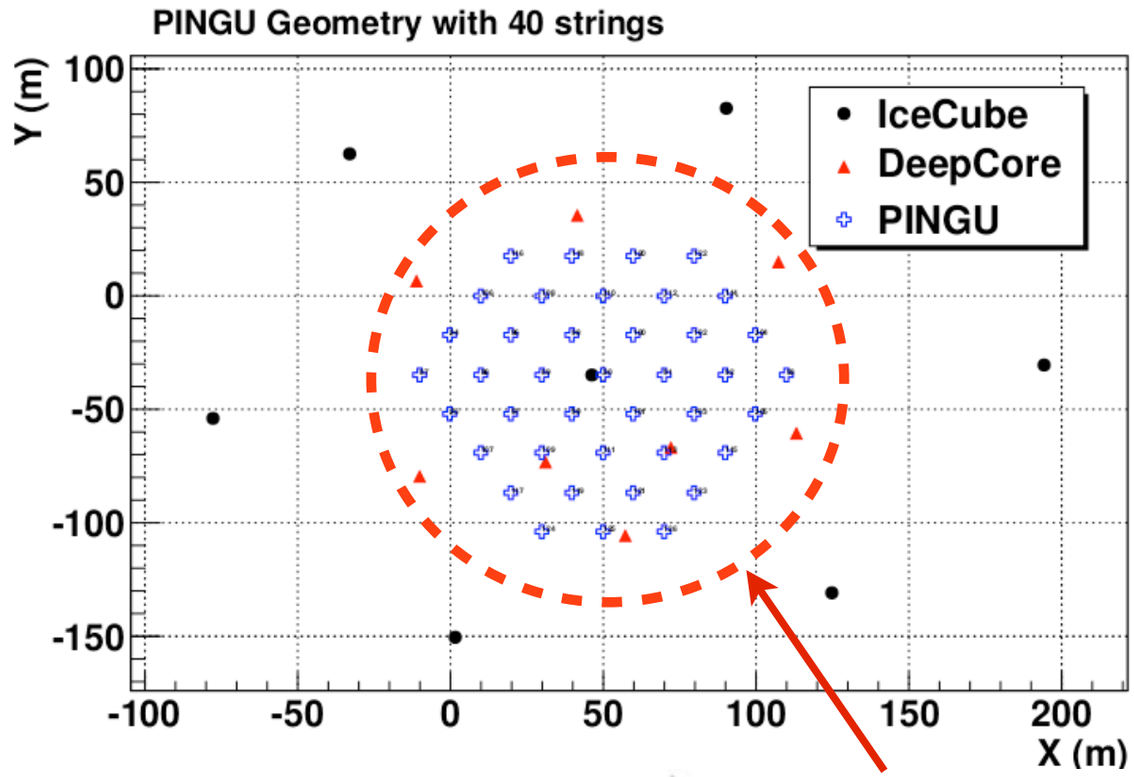
- First result of Earth WIMP analysis expected at ICRC 2015 (next month)



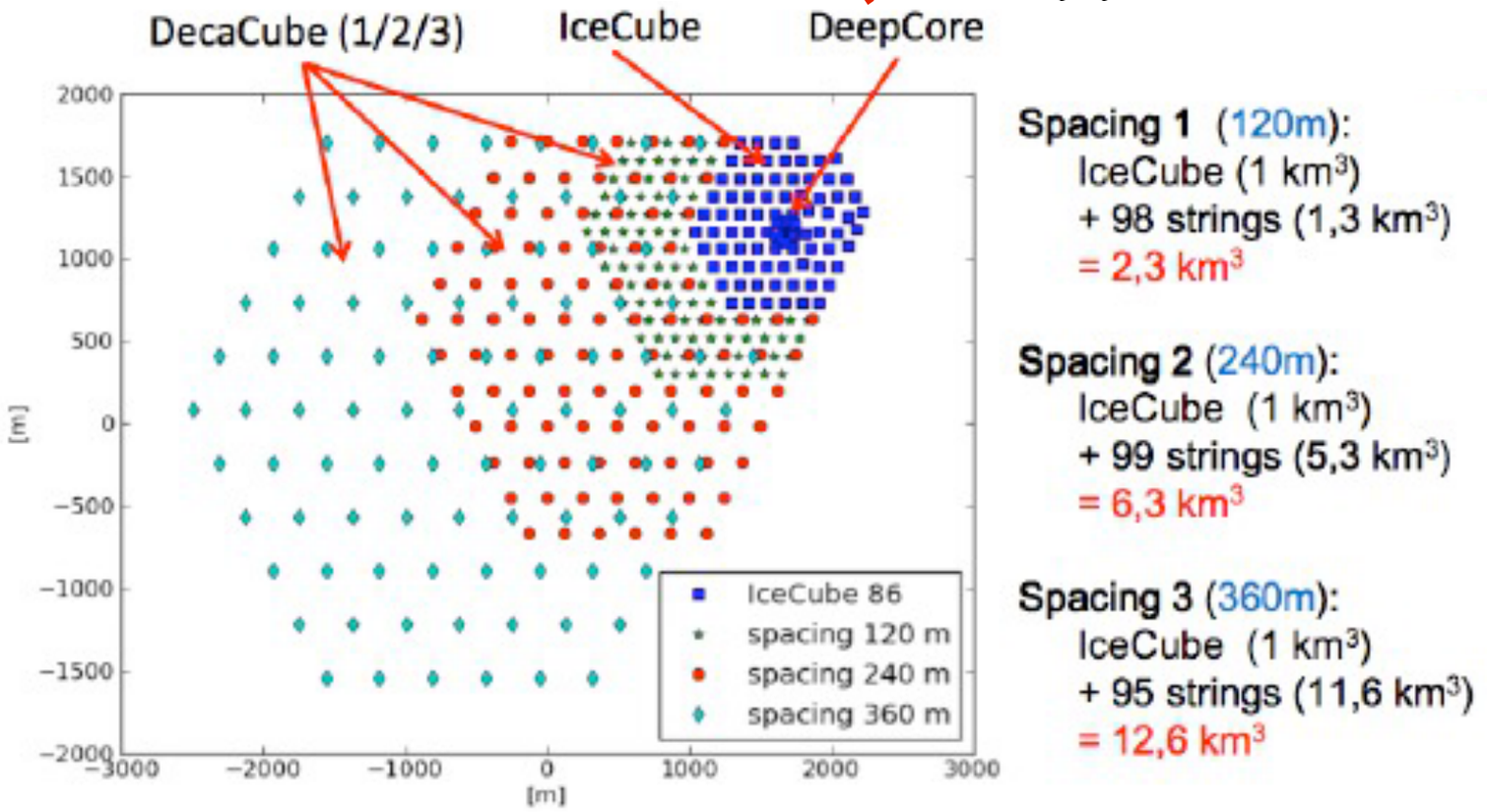
Future Plans

Future of IceCube

- Precision physics with ~GeV threshold



- Large volume: acquire high statistics astrophysical neutrino sample



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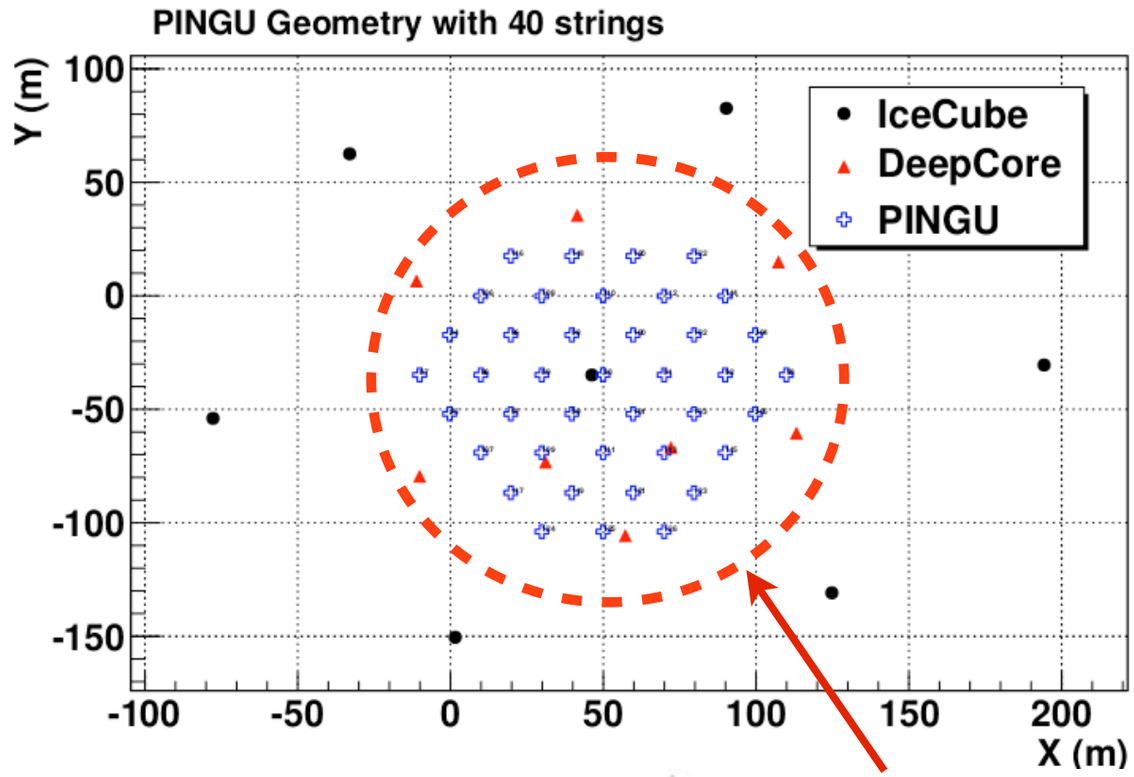

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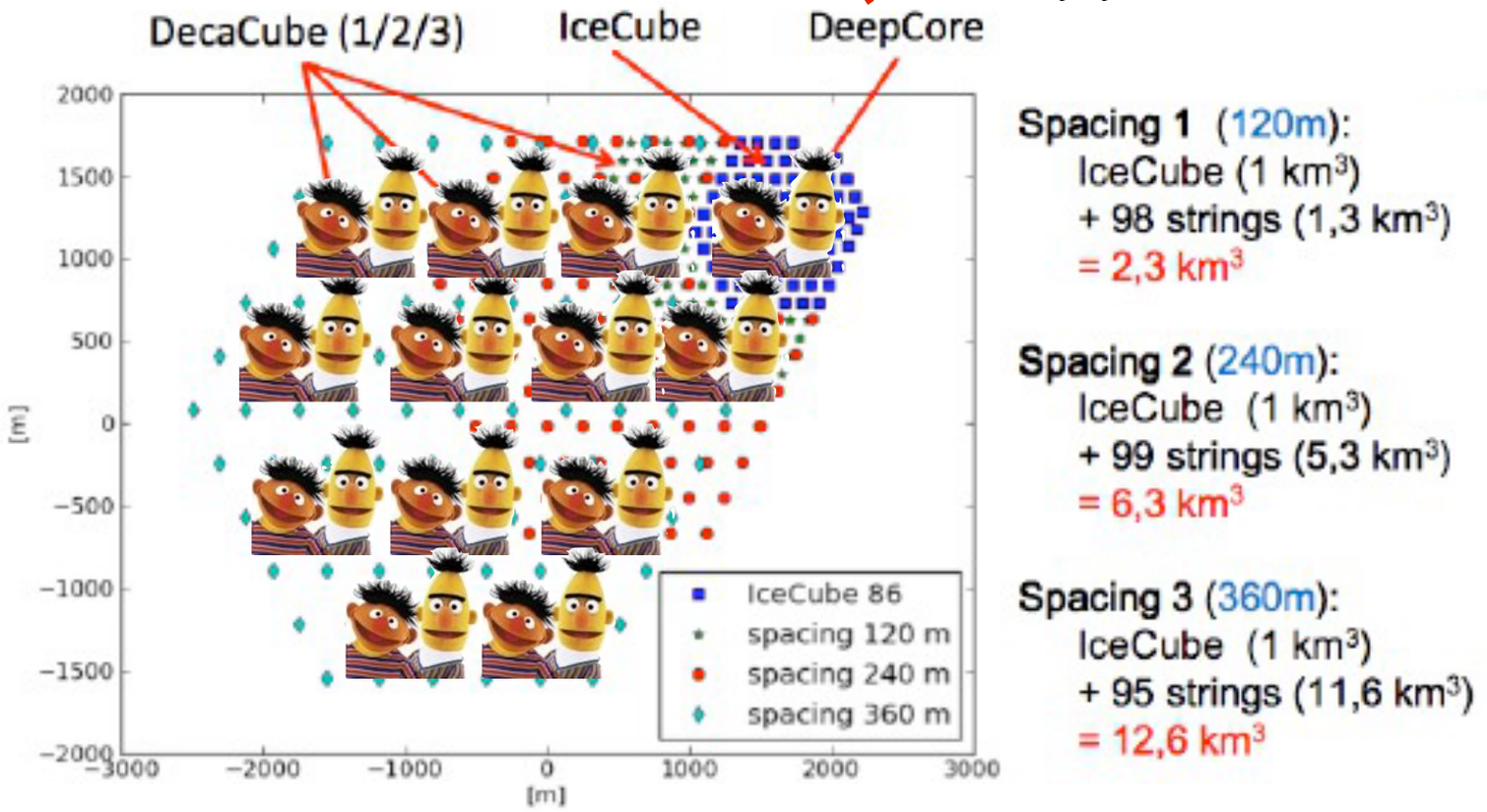
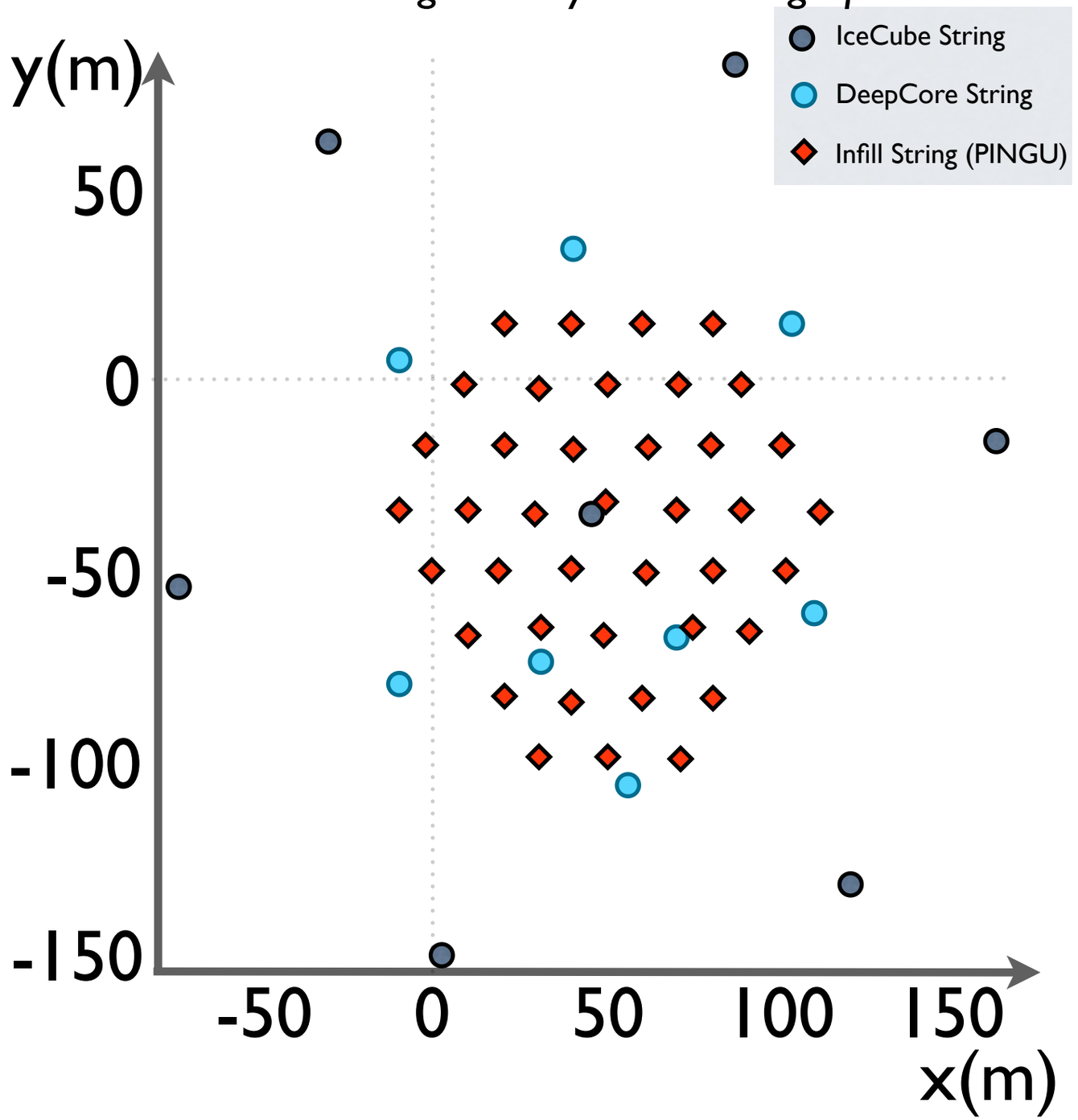


PINGU - Precision IceCube Next Generation Upgrade

- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 96 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

An example PINGU geometry (40 strings)
Note: PINGU geometry is still being optimized



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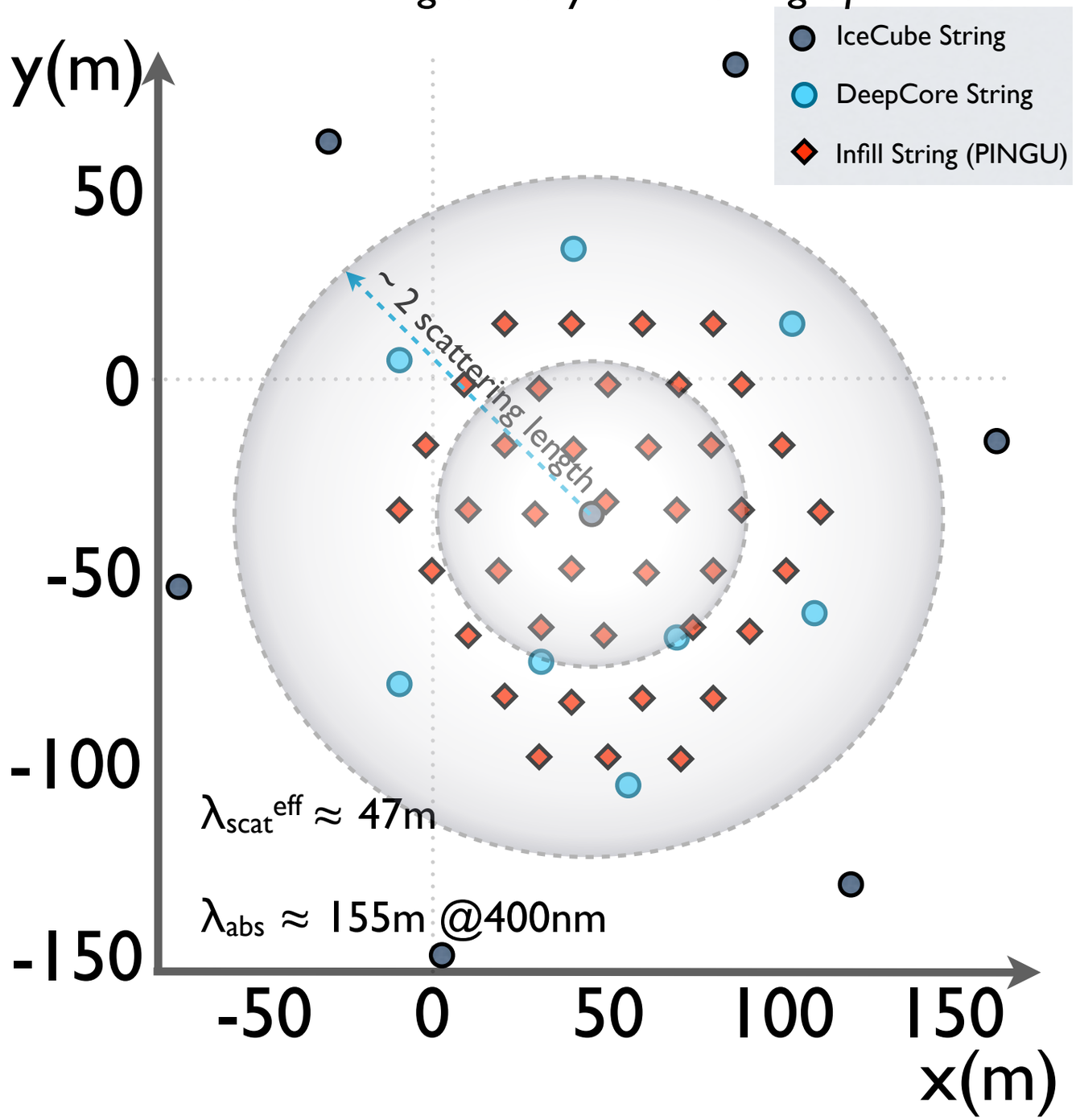
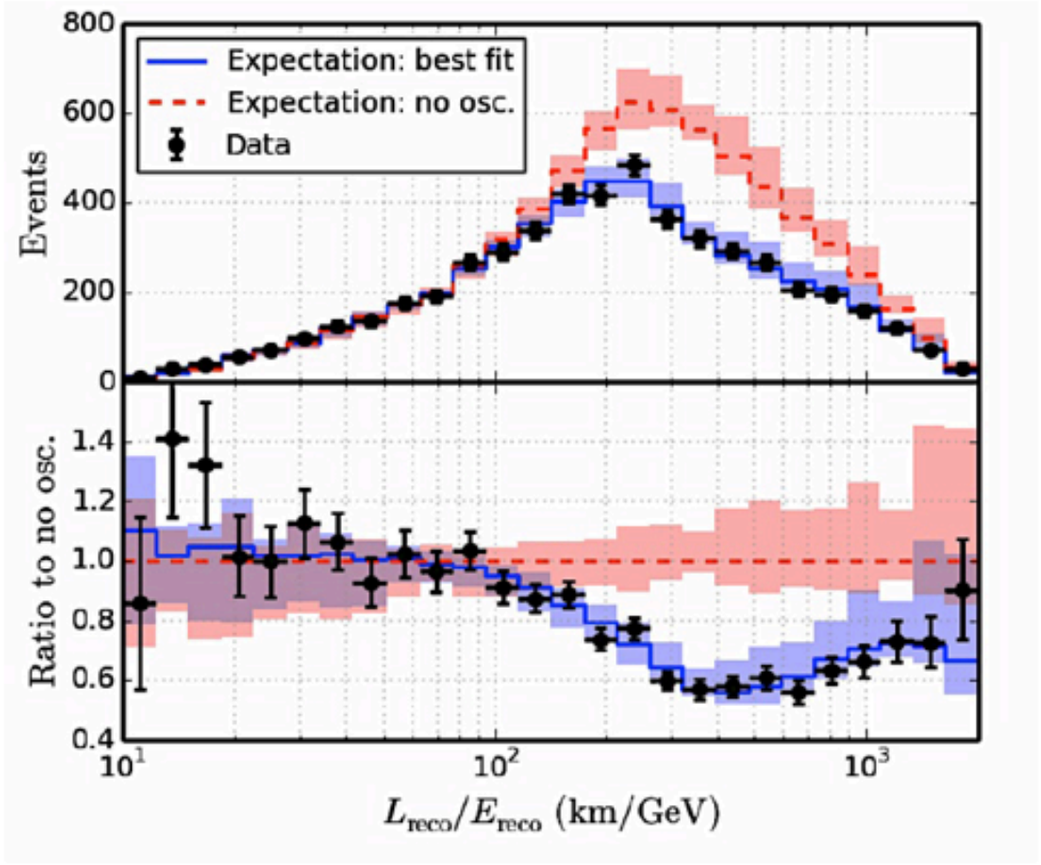


IceCube Neutrino Oscillations

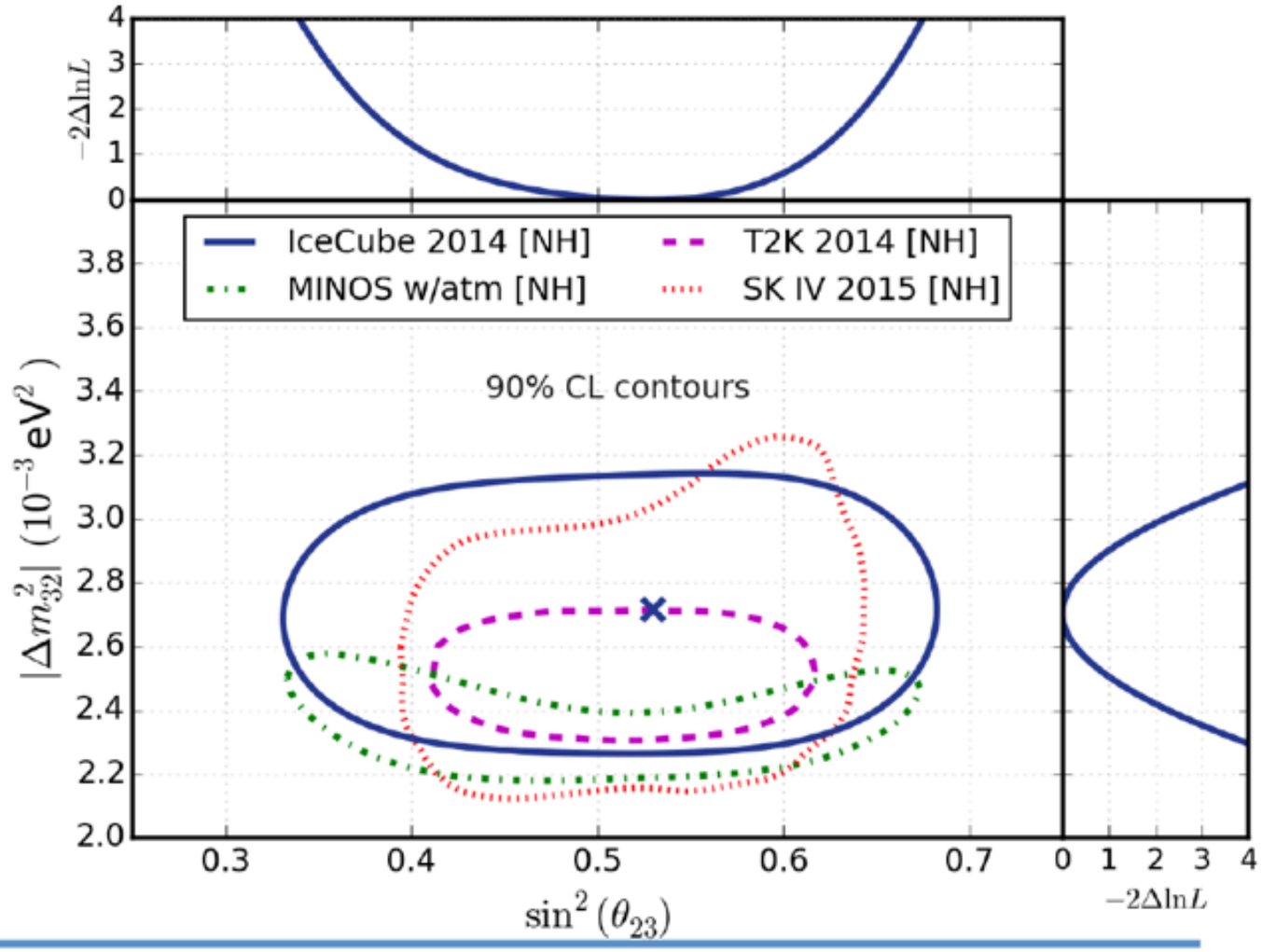


- select
  - starting events
  - clear μ tracks
  - rely on direct photons
- 5174 events observed cf. 6830 expected if no oscillation
- perform 2D fit in *E* and *cos(θ)*

[*IceCube, Phys.Rev.D91:072004 (2015)*]

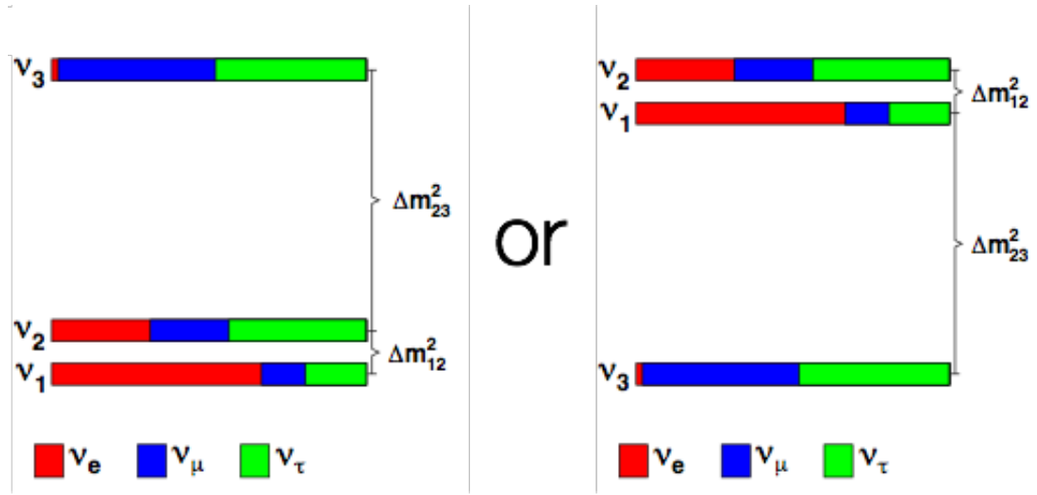
- competitive result (3 years)
- will improve further

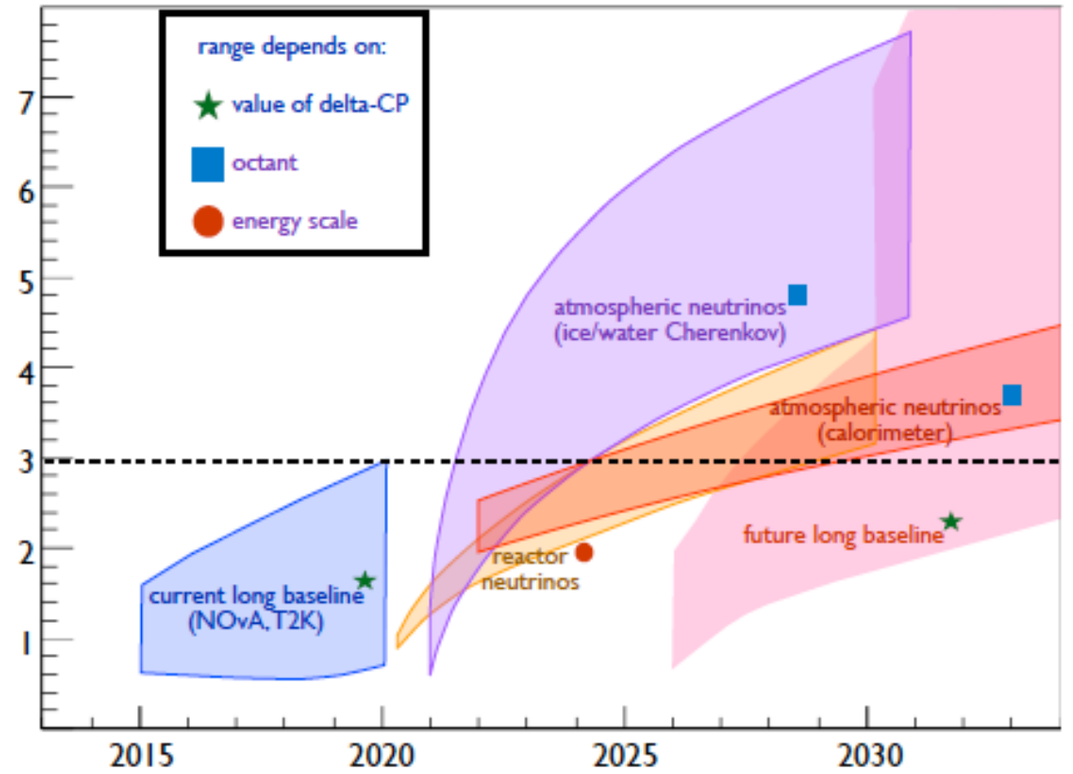
$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$



Advantages of PINGU

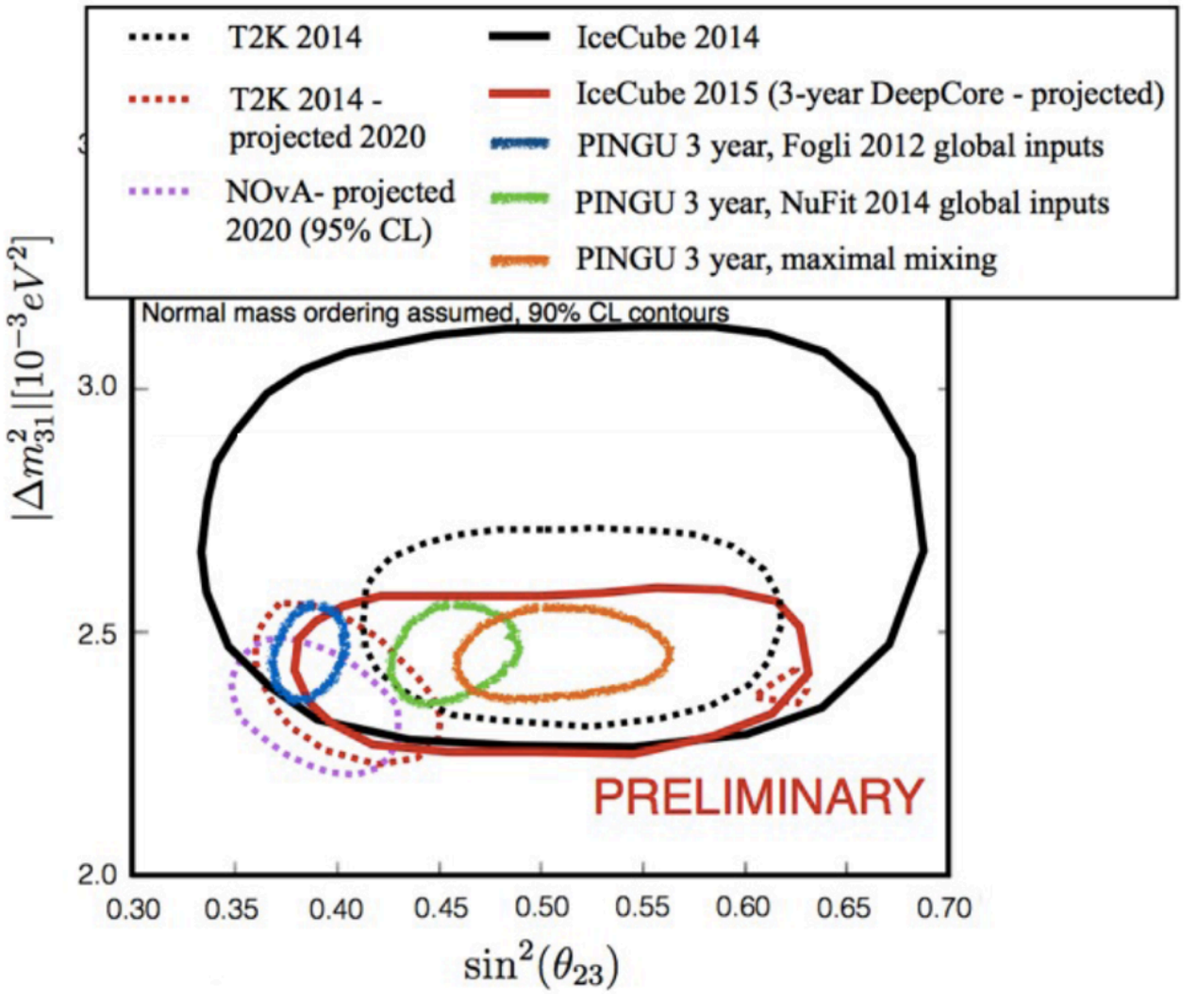
- Well-established detector and construction technology (low risk)
- Relatively low cost: ~$10M design/startup plus ~ $1.25M per string
- Rapid schedule
  - 3 seasons (first deployments in 2017/2018 ?)
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration 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 released *arXiv:1401.2046*
  - update this summer

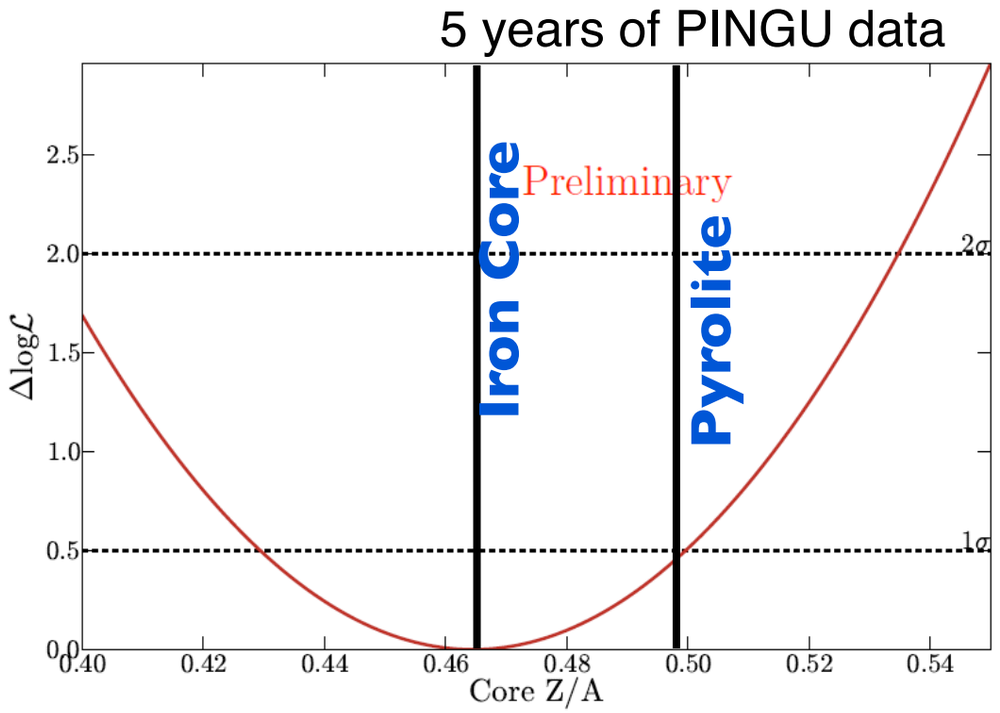


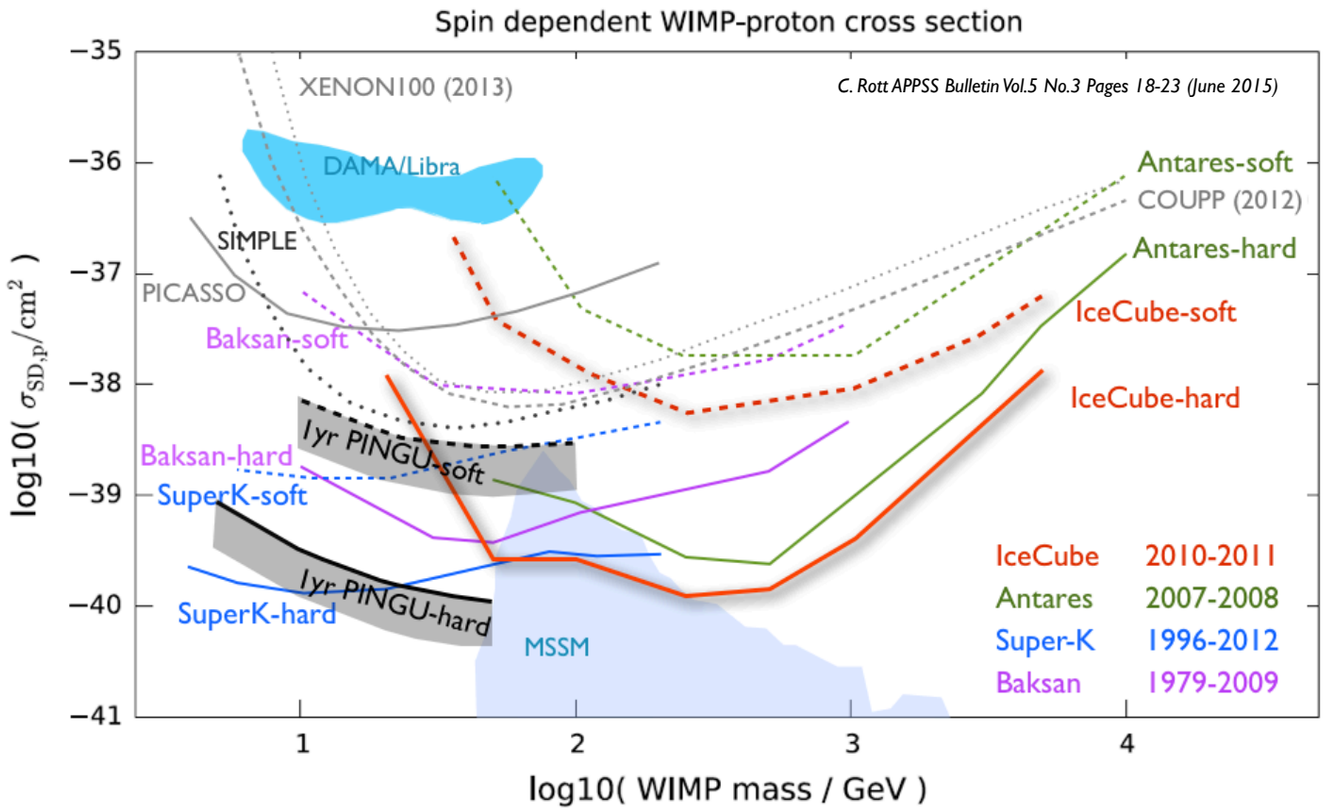


PINGU Multi-purpose experiment

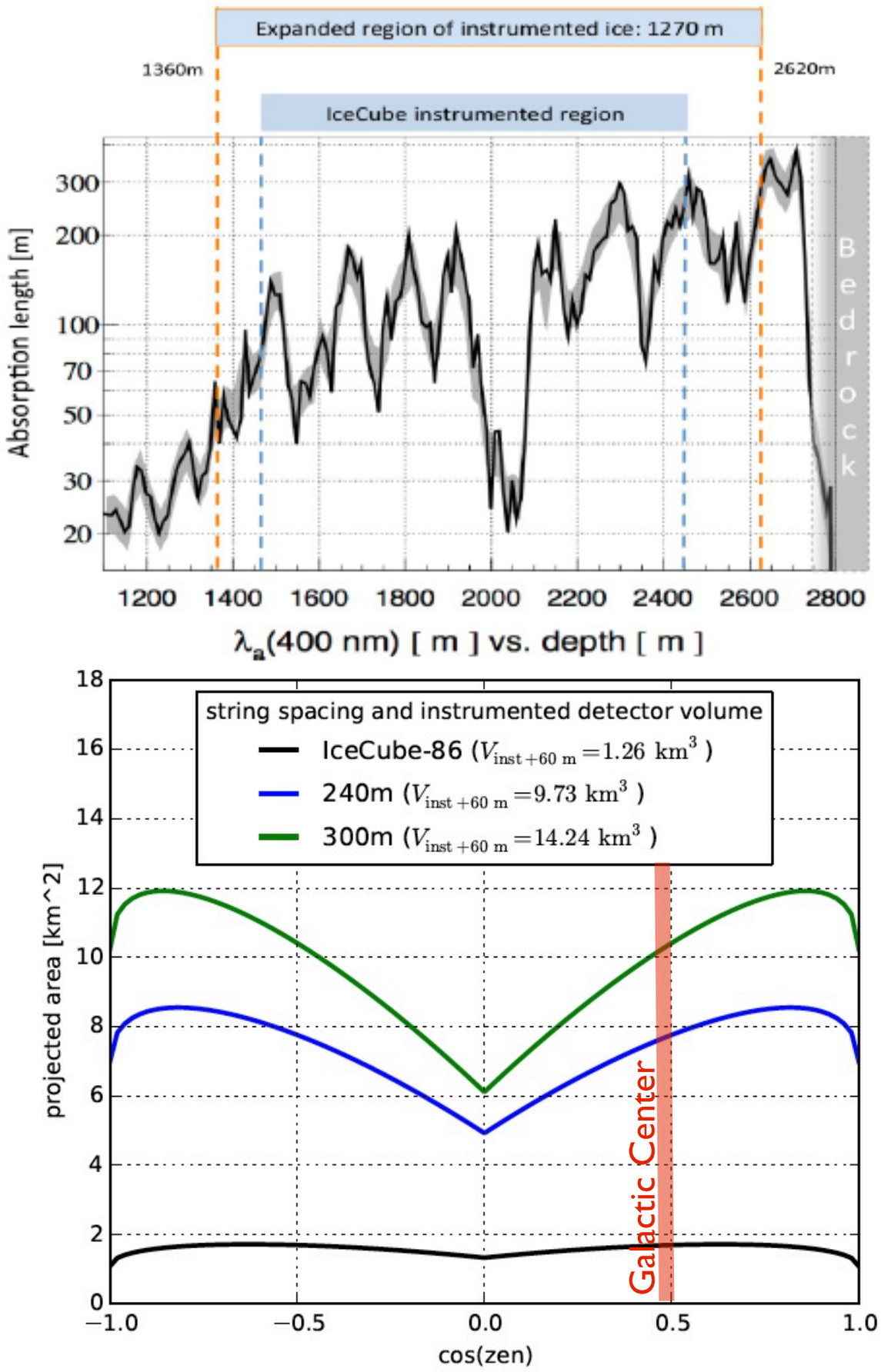
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...



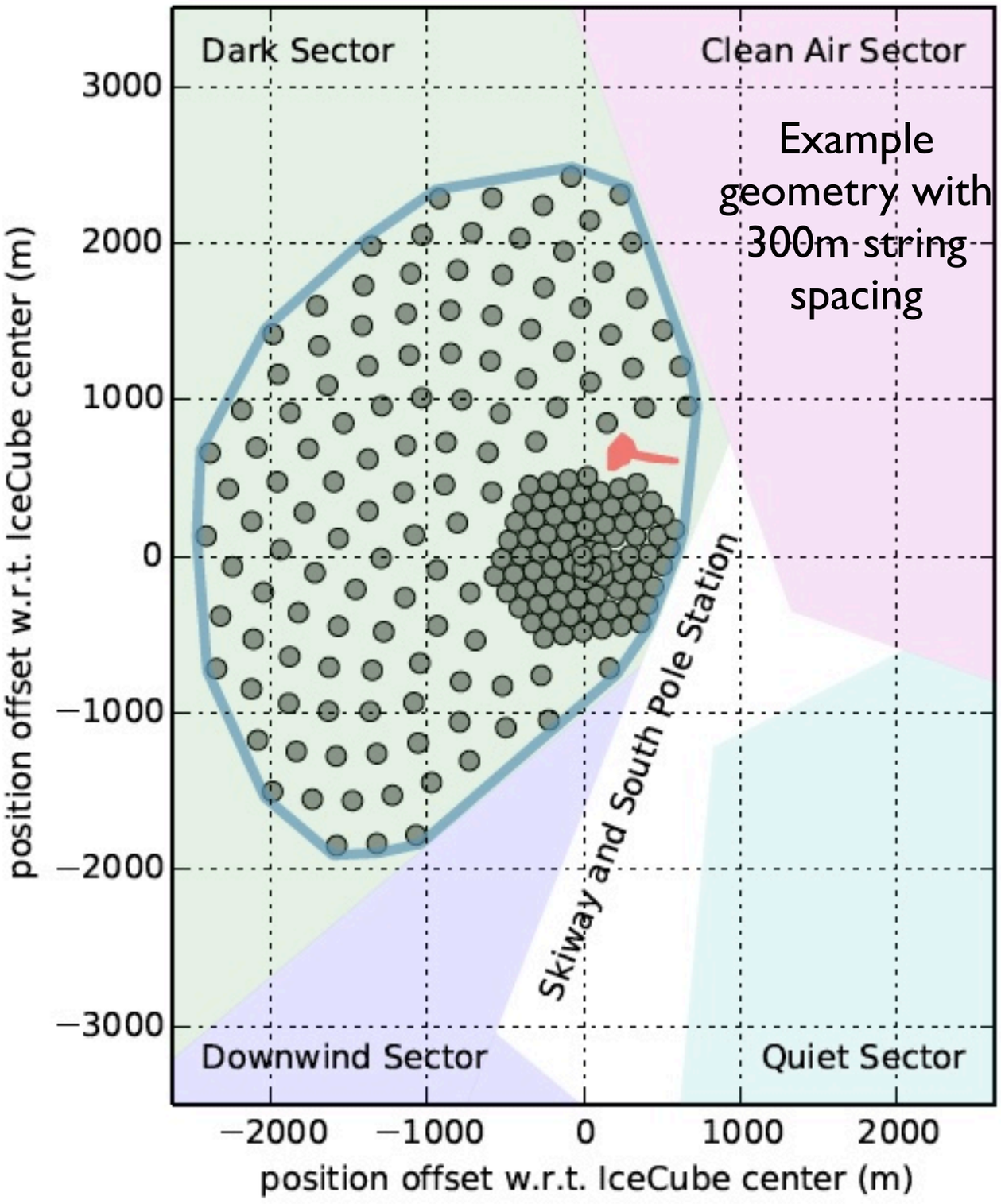




IceCube Gen 2

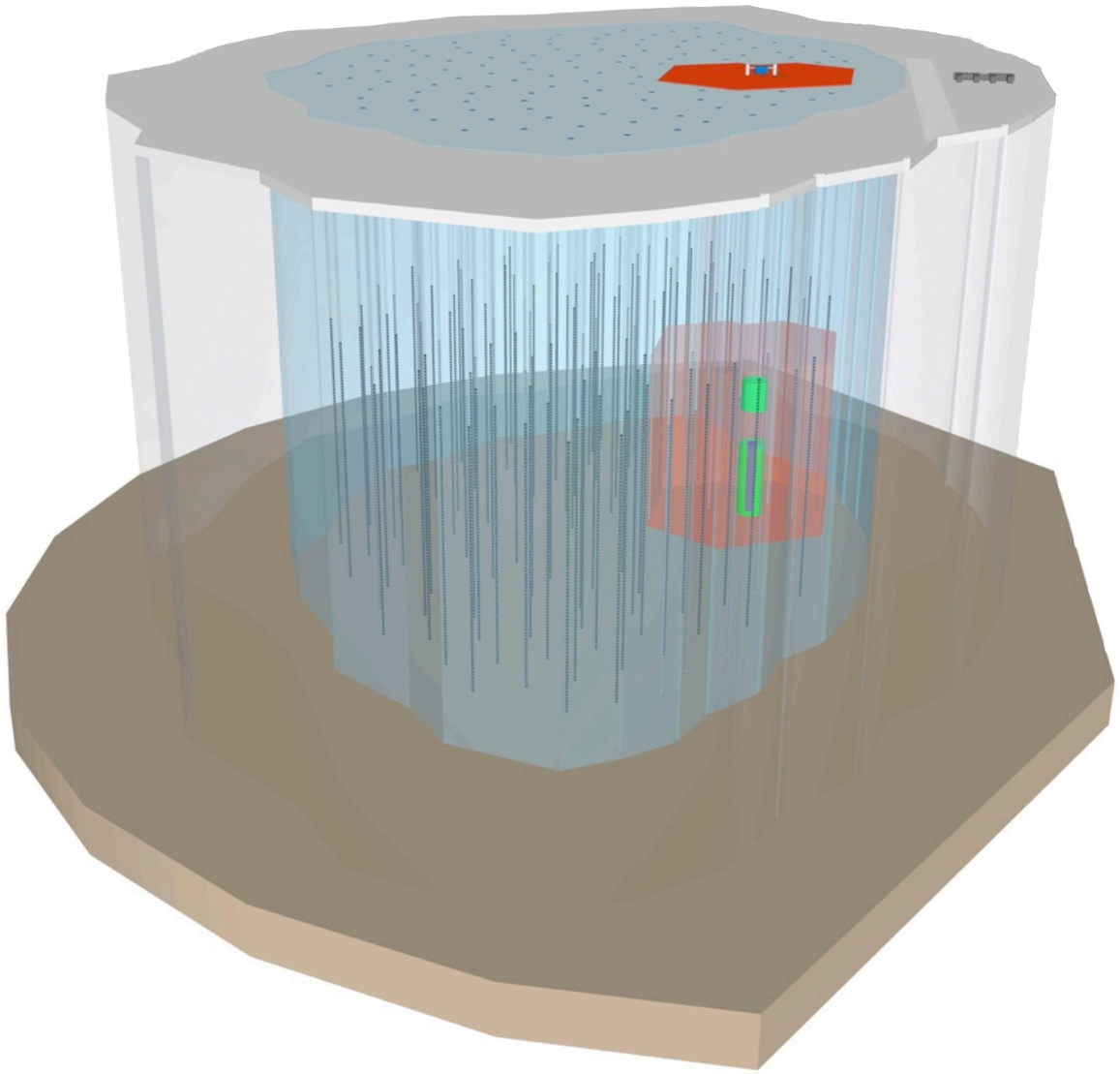


IceCube Coll. Gen2 LOI arXiv:1412.5106



Conclusions

- IceCube has reigned in a new era in astro-particle physics
  - What's the origin of the high-energy neutrino excess ?
  - Let's find out !
- Many more exciting physics topics: Galactic Supernovae, cosmic-rays, atmospheric neutrinos, exotics, ...
- Strong physics potential and prospects for IceCube upgrades
  - PINGU in-fill aims at creating a large volume detector with a threshold of few GeV and could be the first determine the neutrino mass hierarchy
  - High-energy extension could acquire high-statistics TeV and PeV neutrino sample

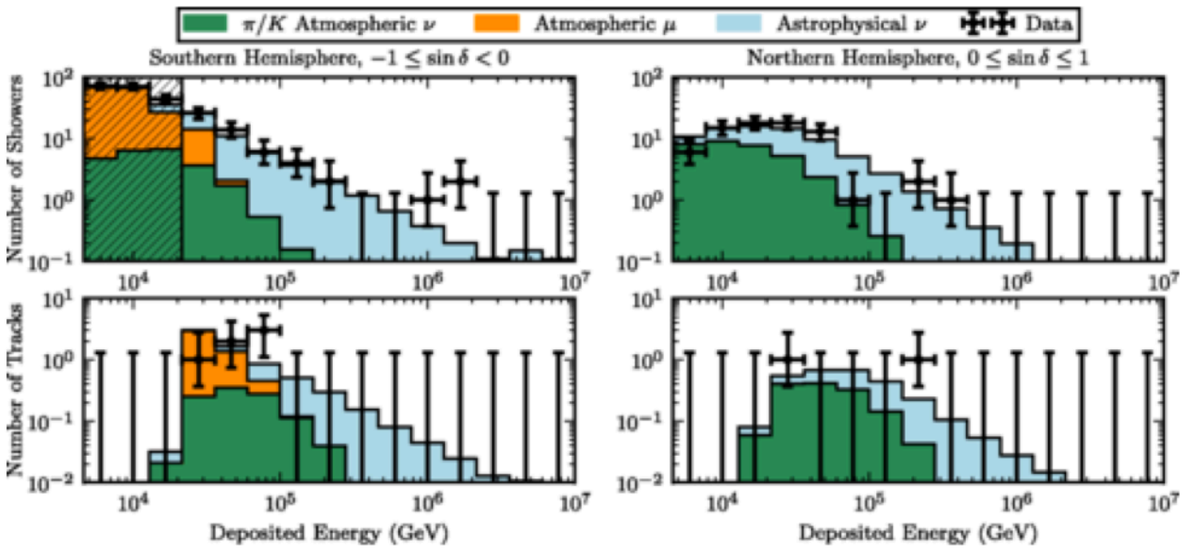


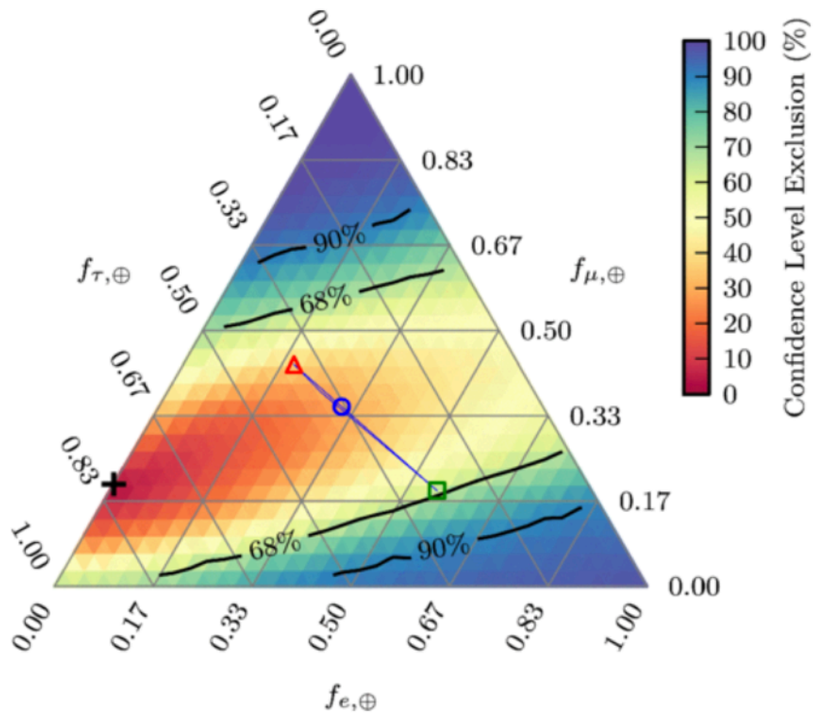
Thanks !

Neutrino flavour ratio

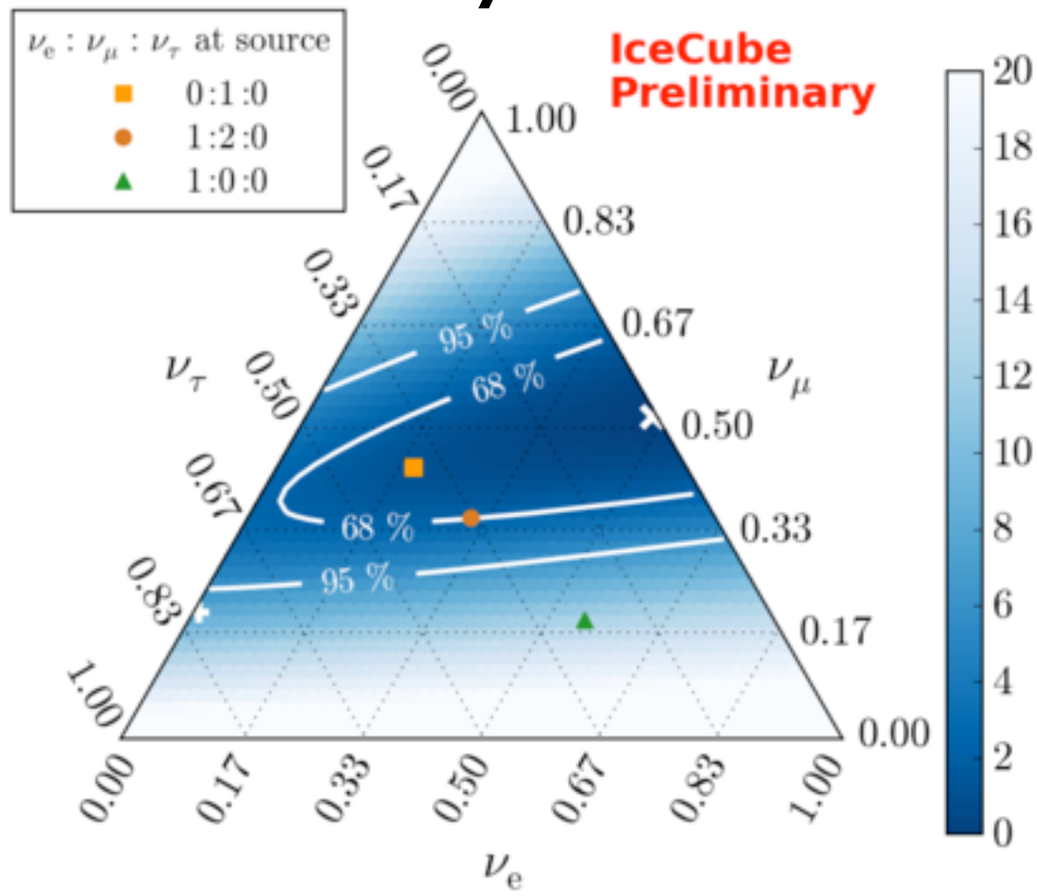
Phys.Rev.Lett. 114 (2015) 17, 171102

3yrs of IC86



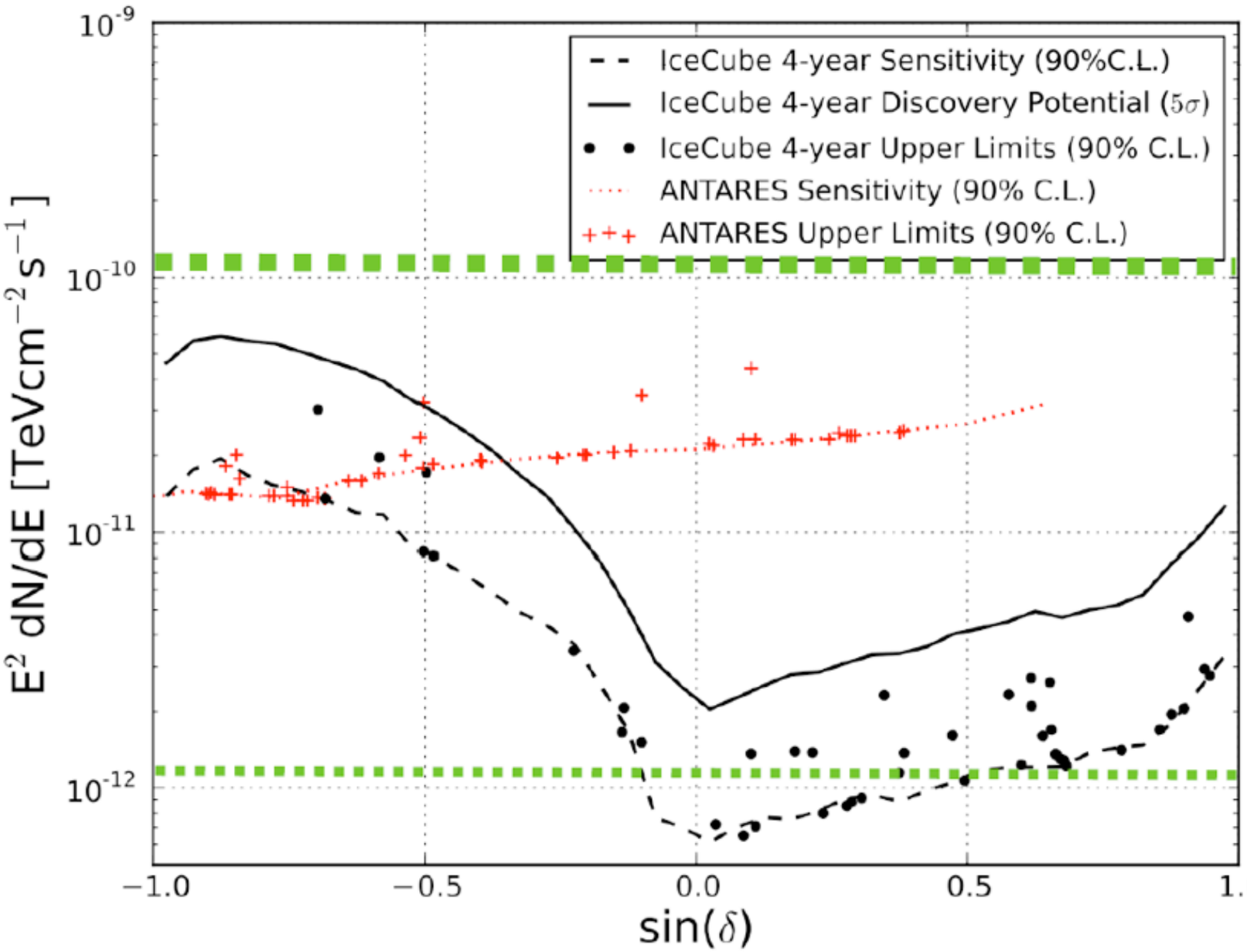


Global analysis



Flux limits

slide from Chad Finley @ RICAP 2014



Point-source equivalent flux if the diffuse flux came from:

one point in the sky

100 points in the sky

1000 points in the sky

Principle of an optical Neutrino Telescope

Array of optical sensors capture the light

$\gamma_č$

Cherenkov Radiation

41°

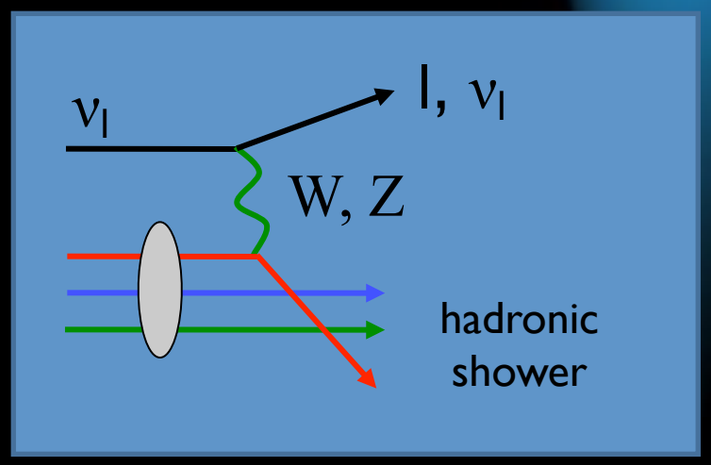
Muon

μ

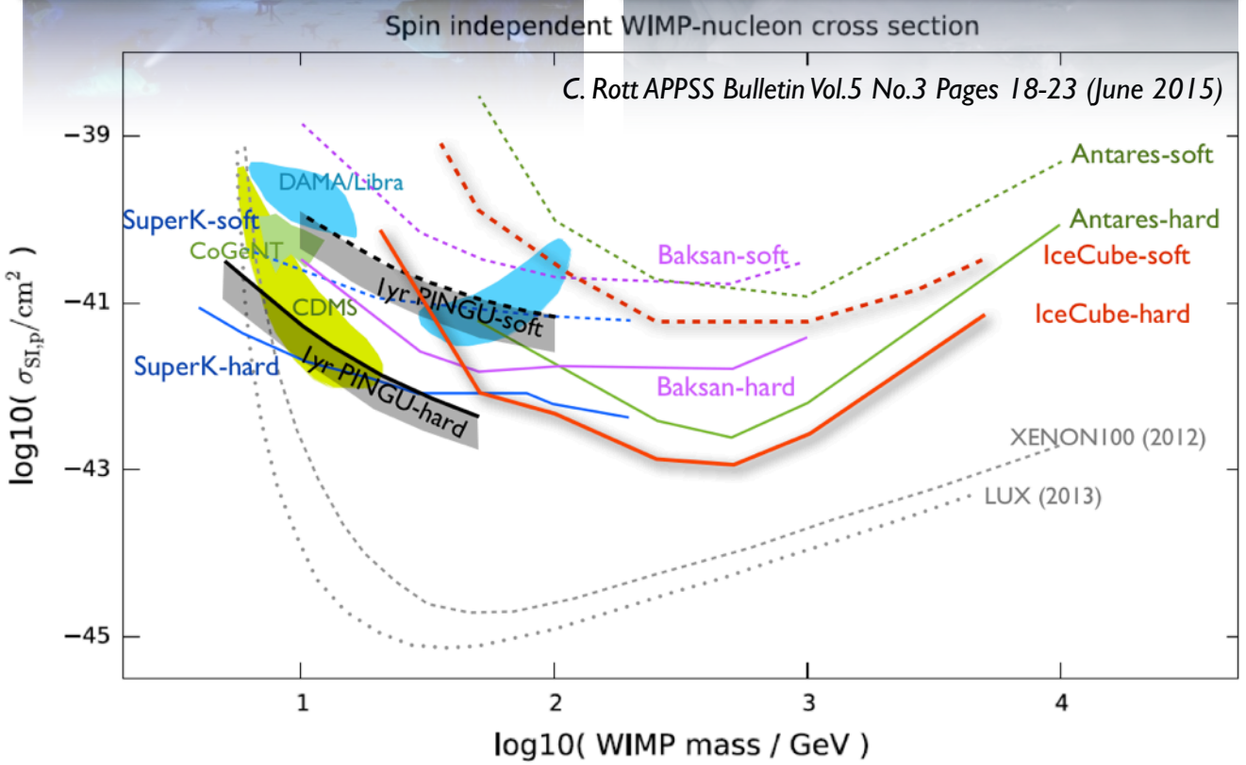
Muon Neutrino

ν

interaction



Current indirect bounds



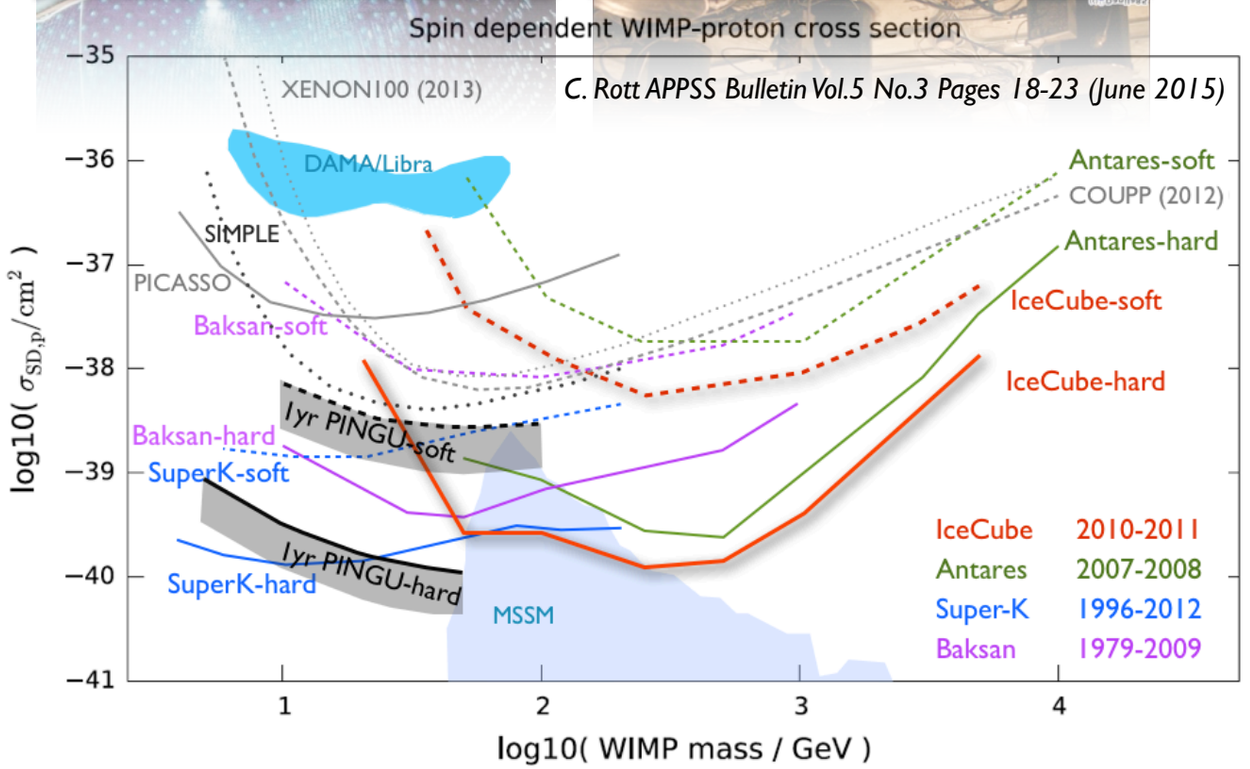


Table 1: Rough comparison of neutrino telescope characteristics relevant for current Solar DM searches. The median angular resolution (Θ) is quoted for different representative neutrino energies (E_ν), where applicable. More details in Refs. [35, 34] (IceCube), [39, 50] (ANTARES), [38, 51] (SK), and [40] (Baksan).

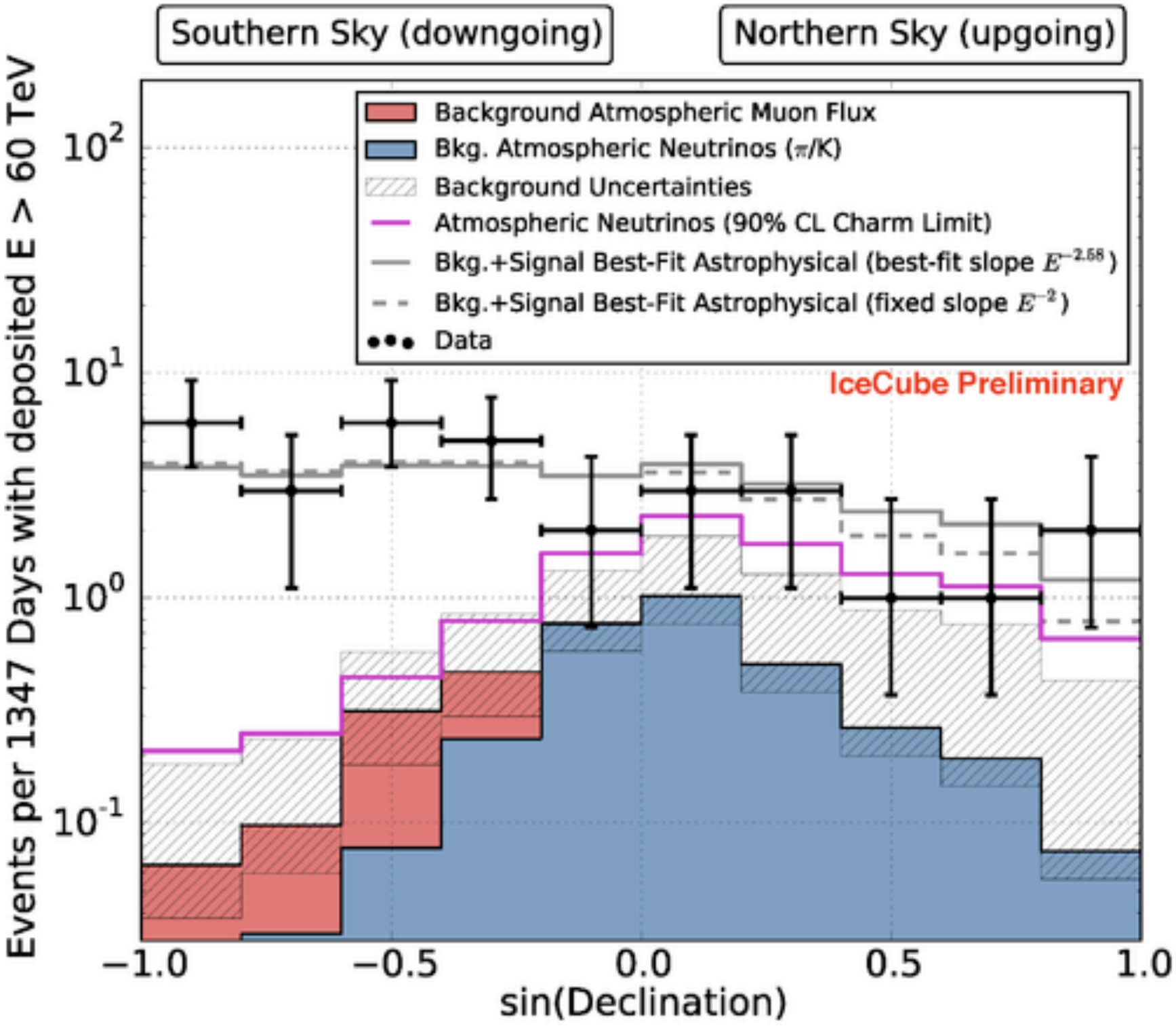
	Datasets with completed analyses	Livetime (days)	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	2010-2011	317	$\gtrsim 10$	~1 Gton	13 / 3.2 / 1.3
ANTARES†	2007-2008	295	$\gtrsim 10$	~20 Mton	6 / 3.5 / 1.6
SK	1996-2012	3903	$\gtrsim 0.1$	~50 kton	1-1.4‡
Baksan	1979-2009	8803	$\gtrsim 1$‡	~3 kton	1.5‡ (tracks > 7 m)

† Preliminary 2007-2012 results correspond to 1321 days livetime

‡ Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kinematic scattering angle.

M. Danninger & C. Rott "Solar WIMPs Unraveled" – Physics of the Dark Universe (Nov 2014)

HESE-4yrs


Southern Sky (downgoing)
Northern Sky (upgoing)
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
Data
IceCube Preliminary
Events per 1347 Days with deposited E > 60 TeV
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)