Recent Progress in Neutrino Astroparticle Physics

Carsten Rott

Sungkyunkwan University, Korea

rott@skku.edu

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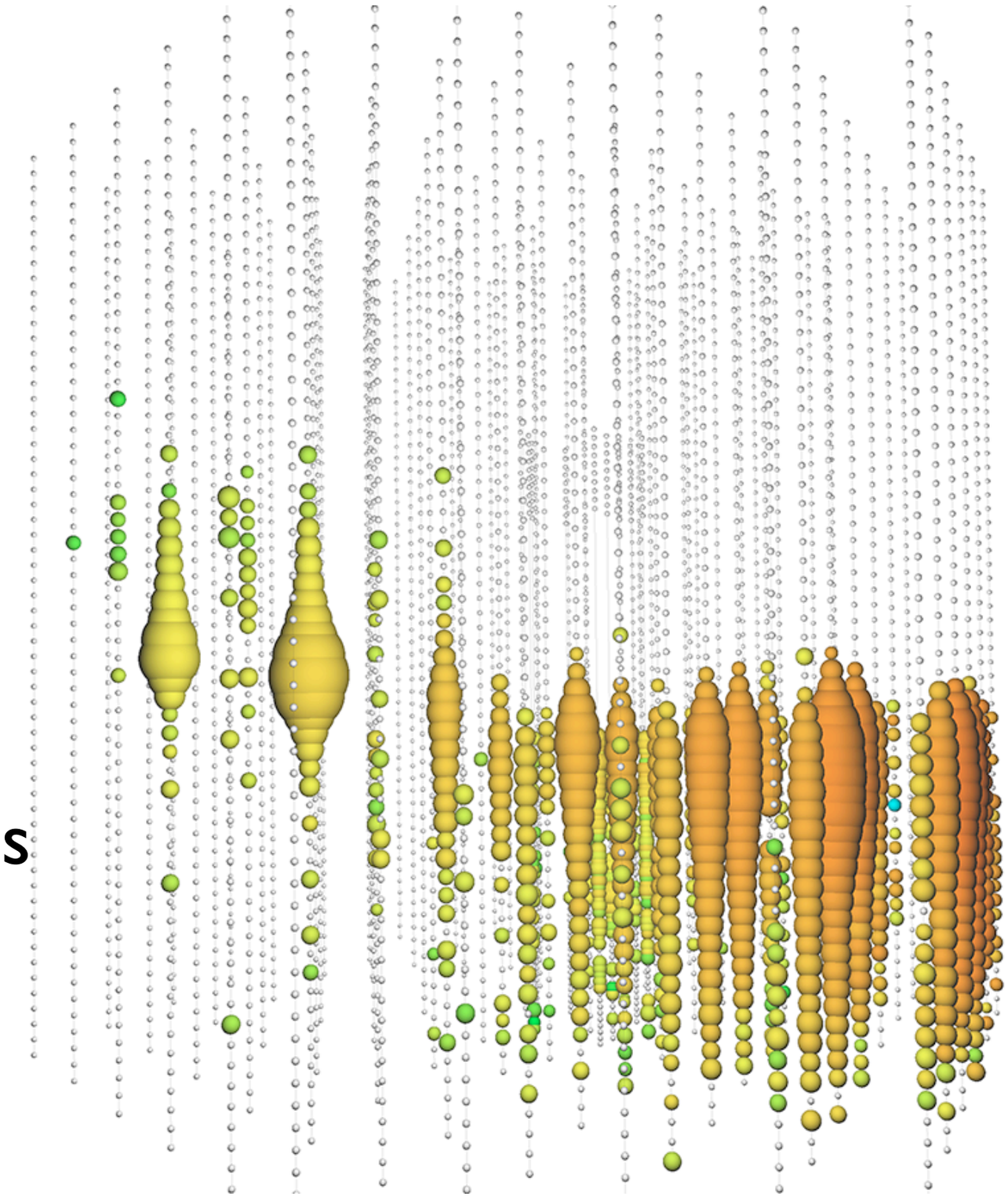
5th fl., Seminar Rm #1503, KIAS

Nov. 9 (Mon) – Nov. 13 (Fri), 2015

Outline

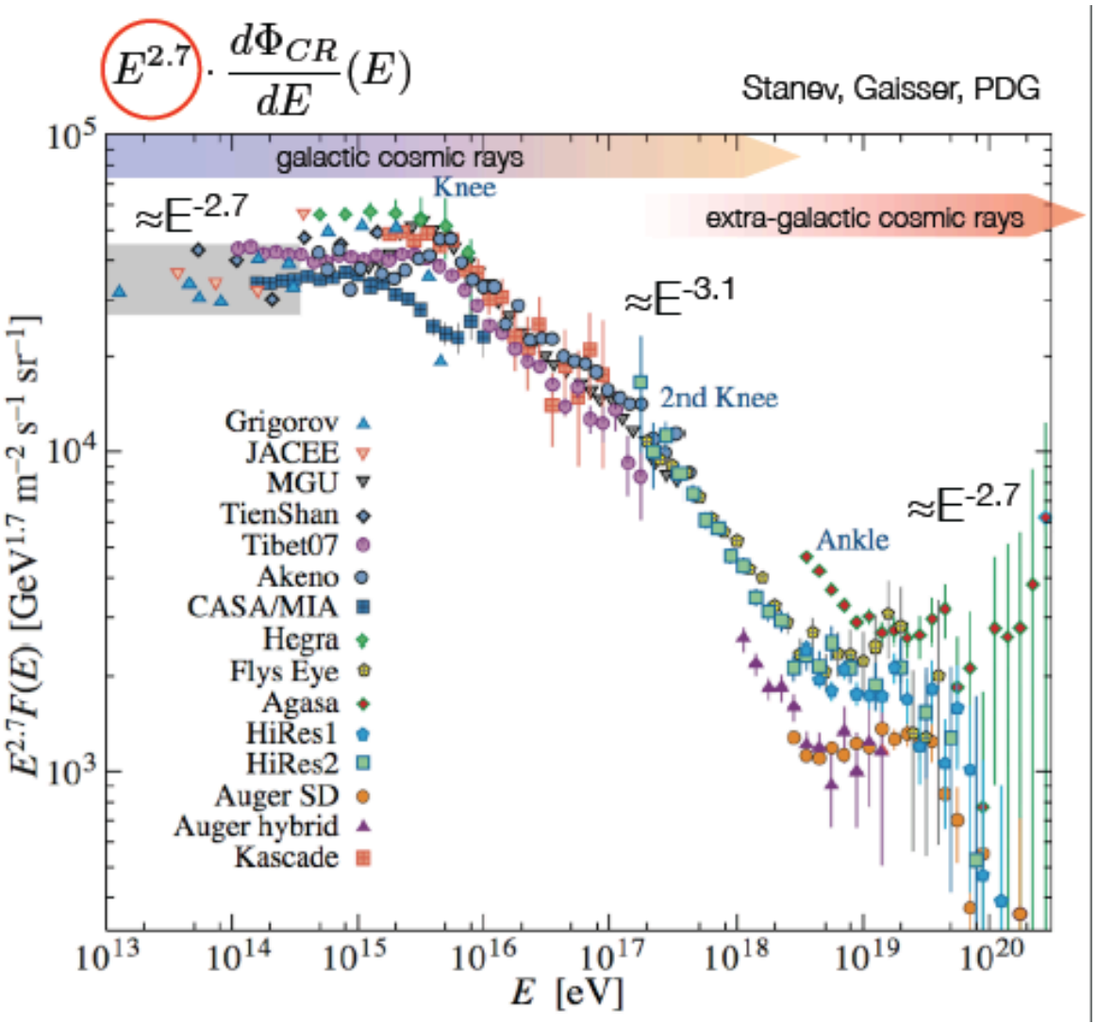
- Motivation
- Neutrino Telescopes
- Astrophysical Neutrinos
- Selected Results
- Outlook and Conclusions



High Energy Cosmic Ray Mystery

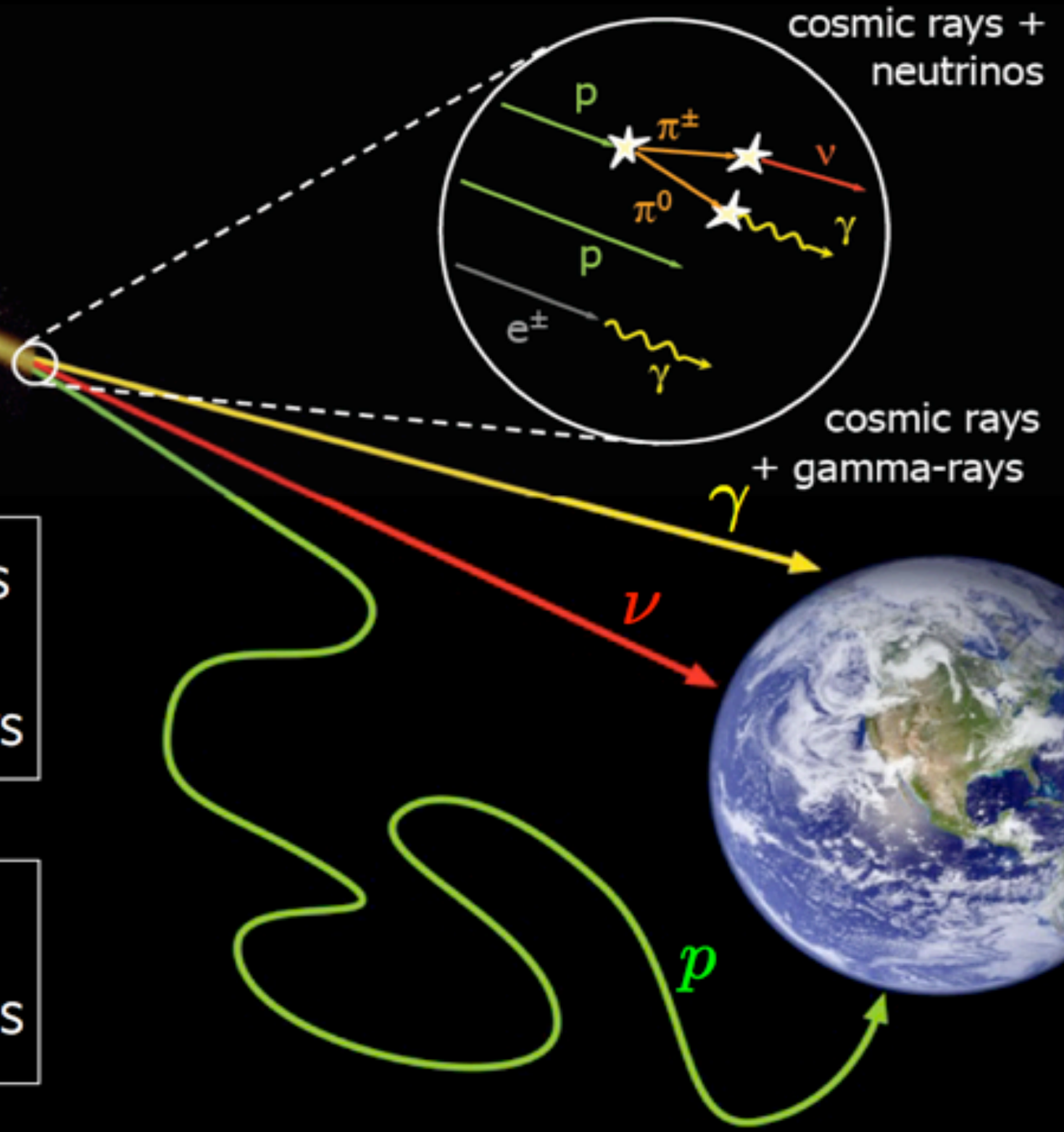
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

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

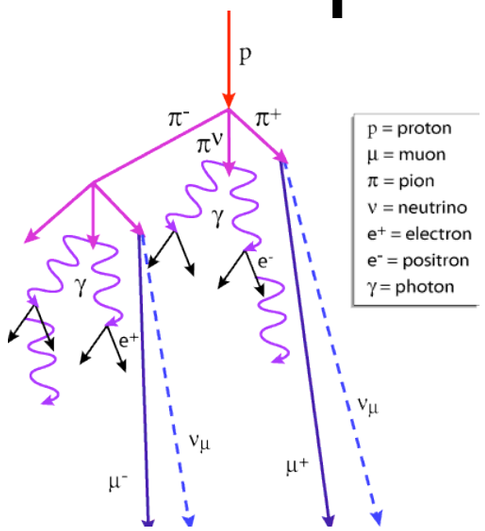


Hadrons *or* electrons can produce the observed gamma rays

Neutrinos only produced by hadrons

Sources of High Energy Neutrinos

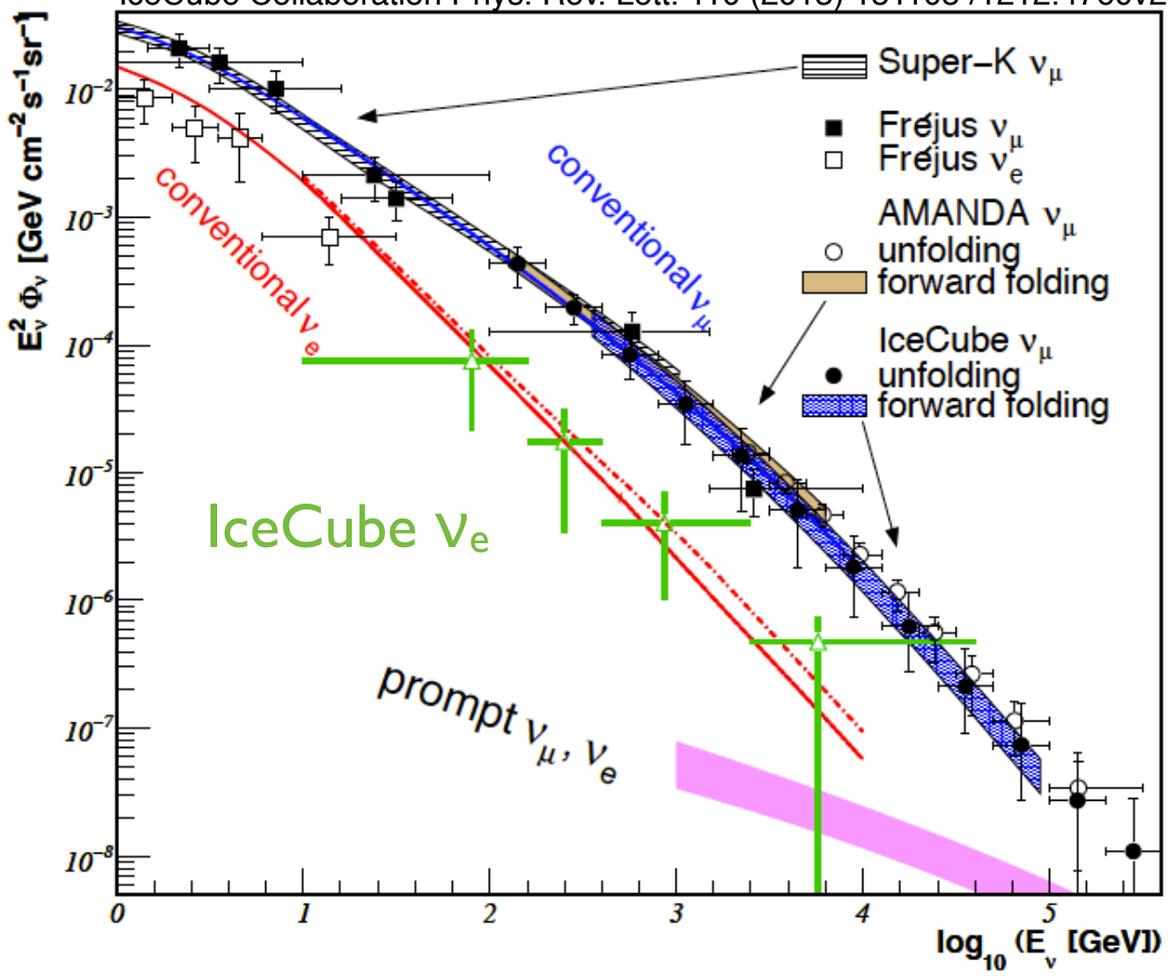
Atmospheric Neutrinos



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



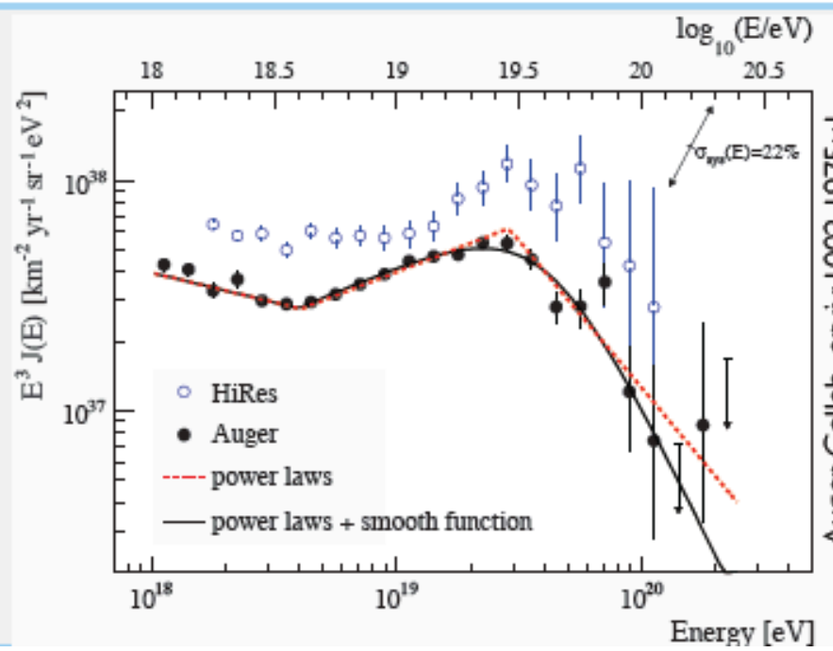
Astrophysical

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

Gamma-ray Bursts

Active Galactic Nuclei

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



Principle of an optical Neutrino Telescope

Array of optical sensors capture the light

41°

$\gamma_č$

Cherenkov Radiation

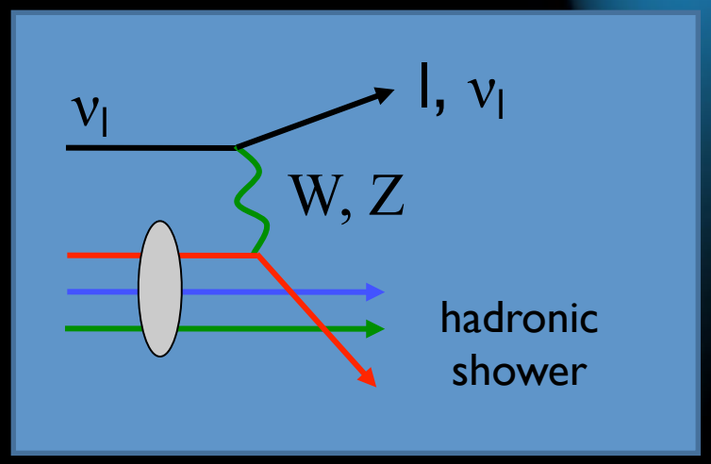
Muon

μ

Muon Neutrino

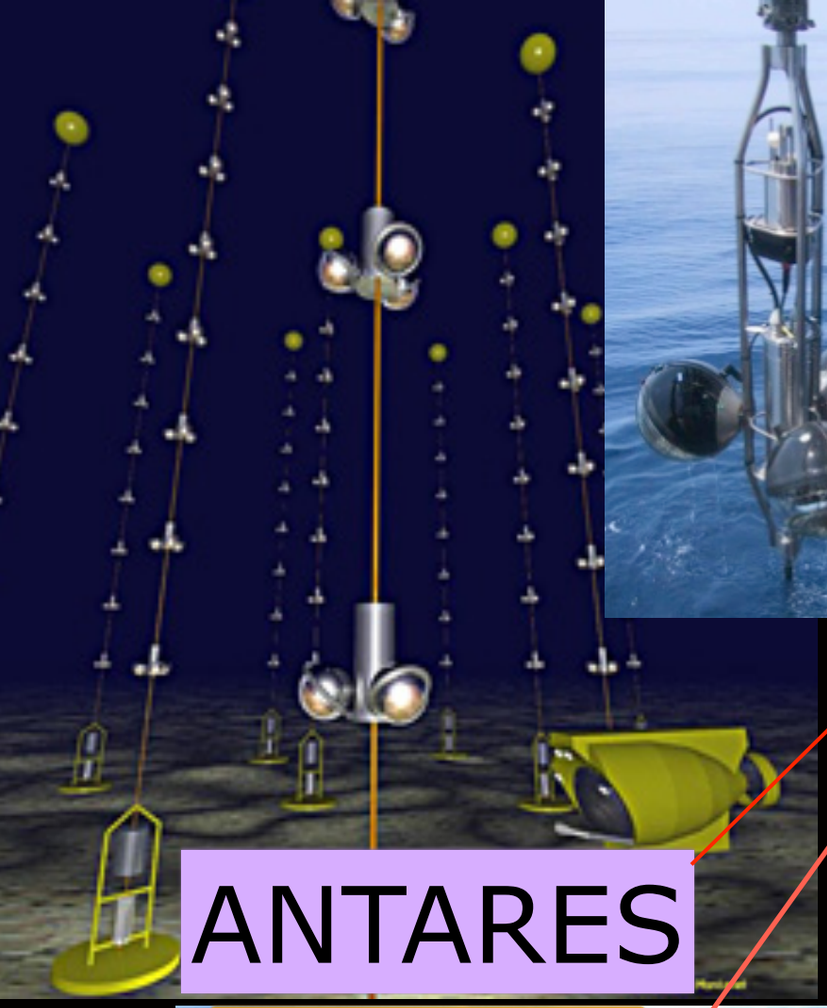
ν

interaction

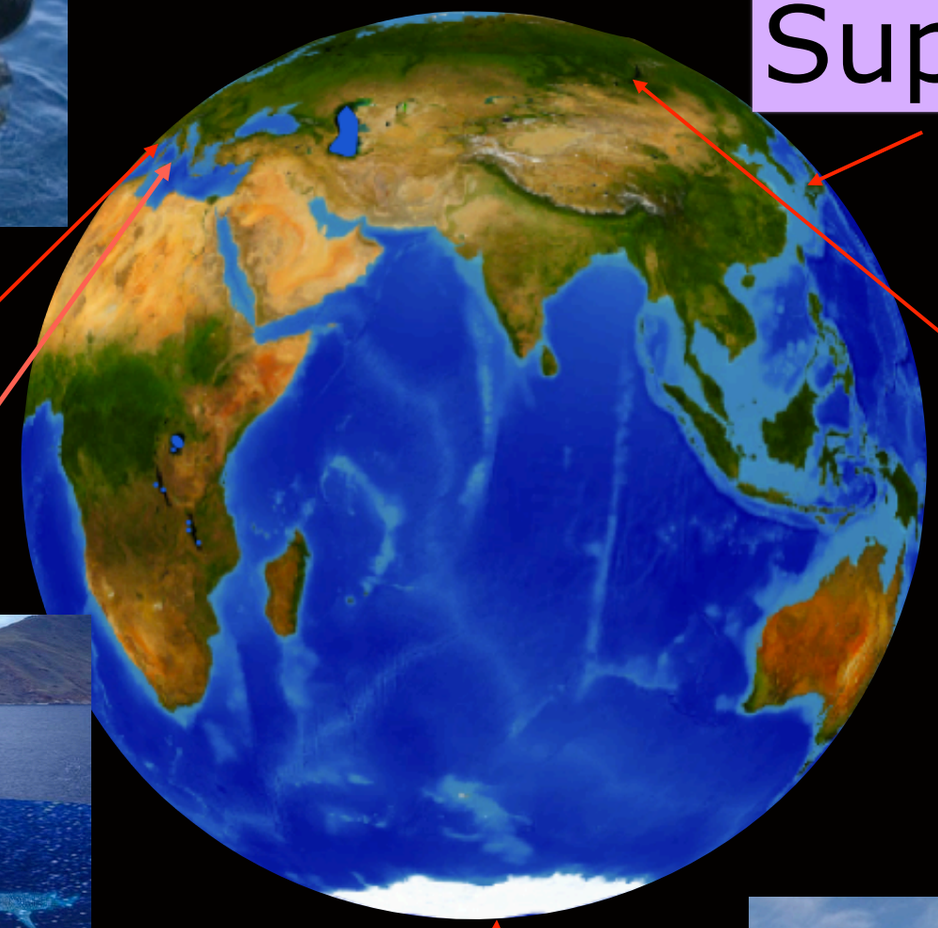


Neutrino Telescopes

Neutrino Telescopes & Detectors

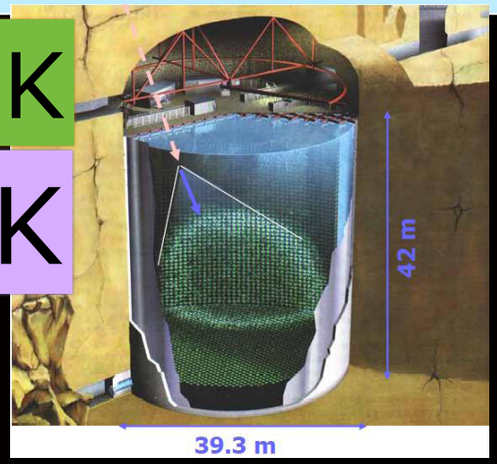


ANTARES



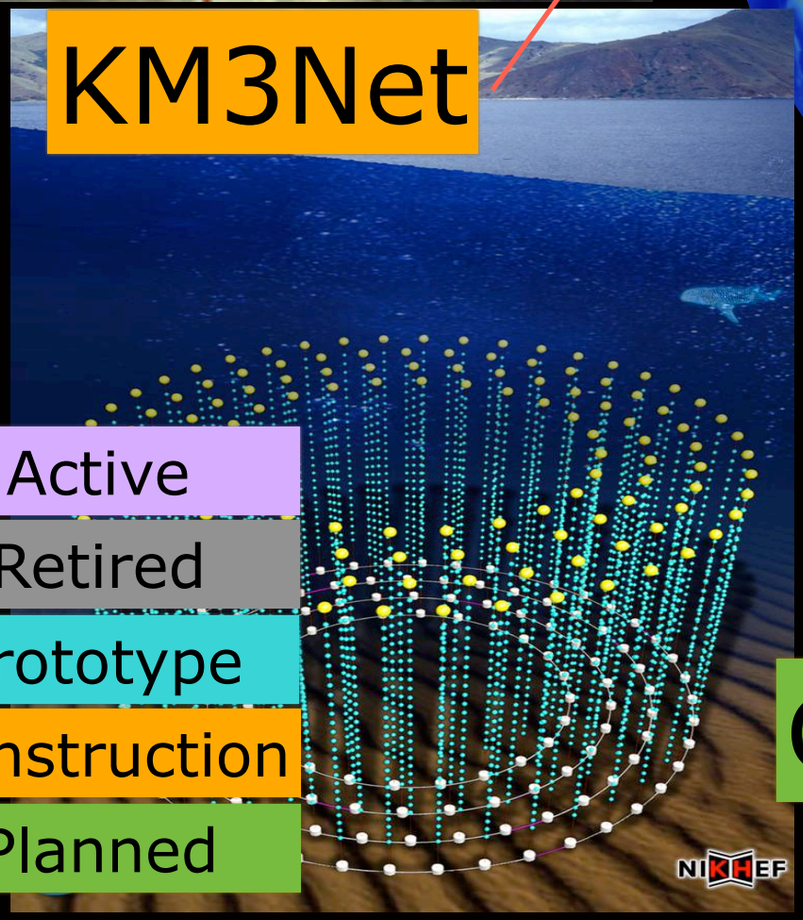
Hyper-K

Super-K



Lake Baikal

GVD



KM3Net

Active

Retired

Prototype

Construction

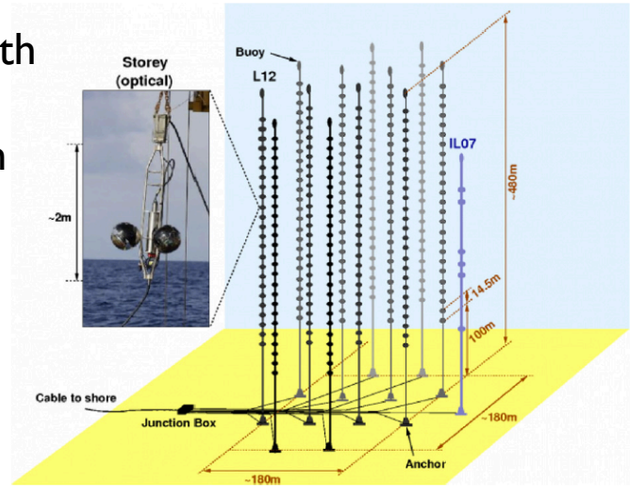
Planned

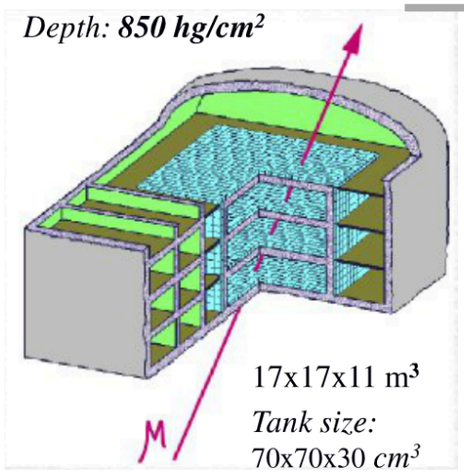
IceCube

Gen2/PINGU

Neutrino Telescopes / Detectors

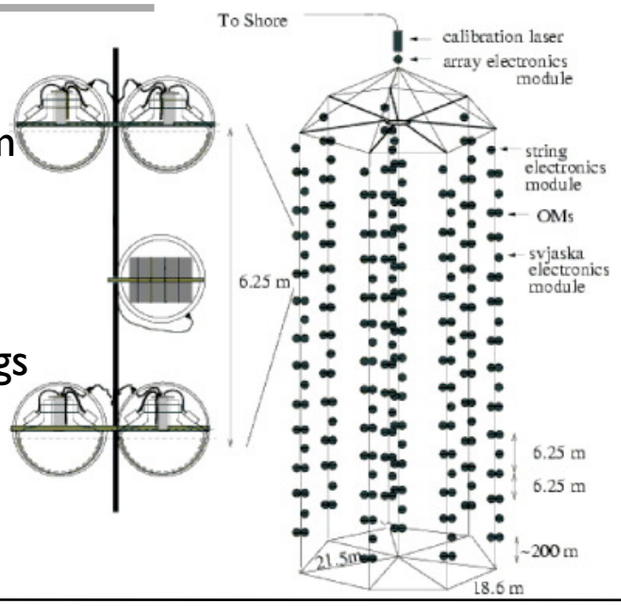
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



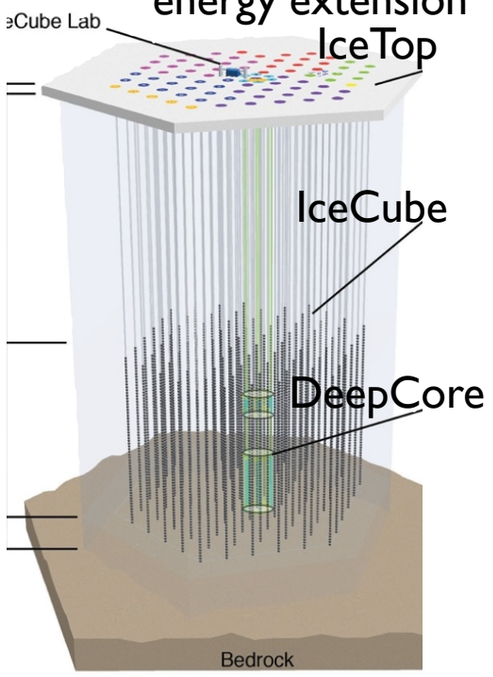


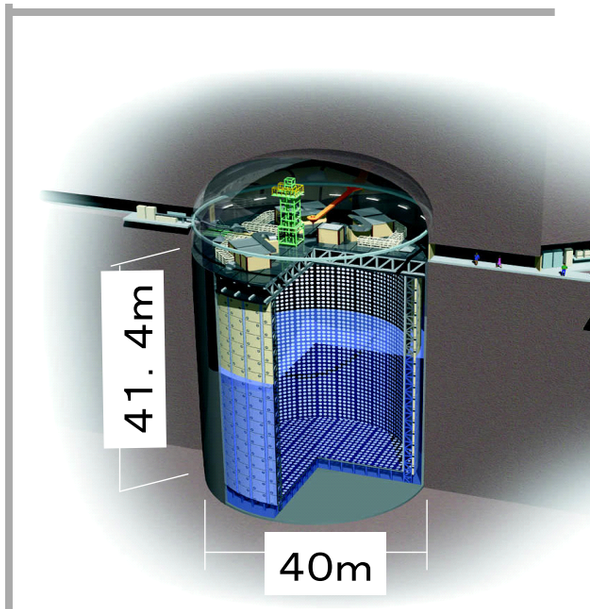
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km^3
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension



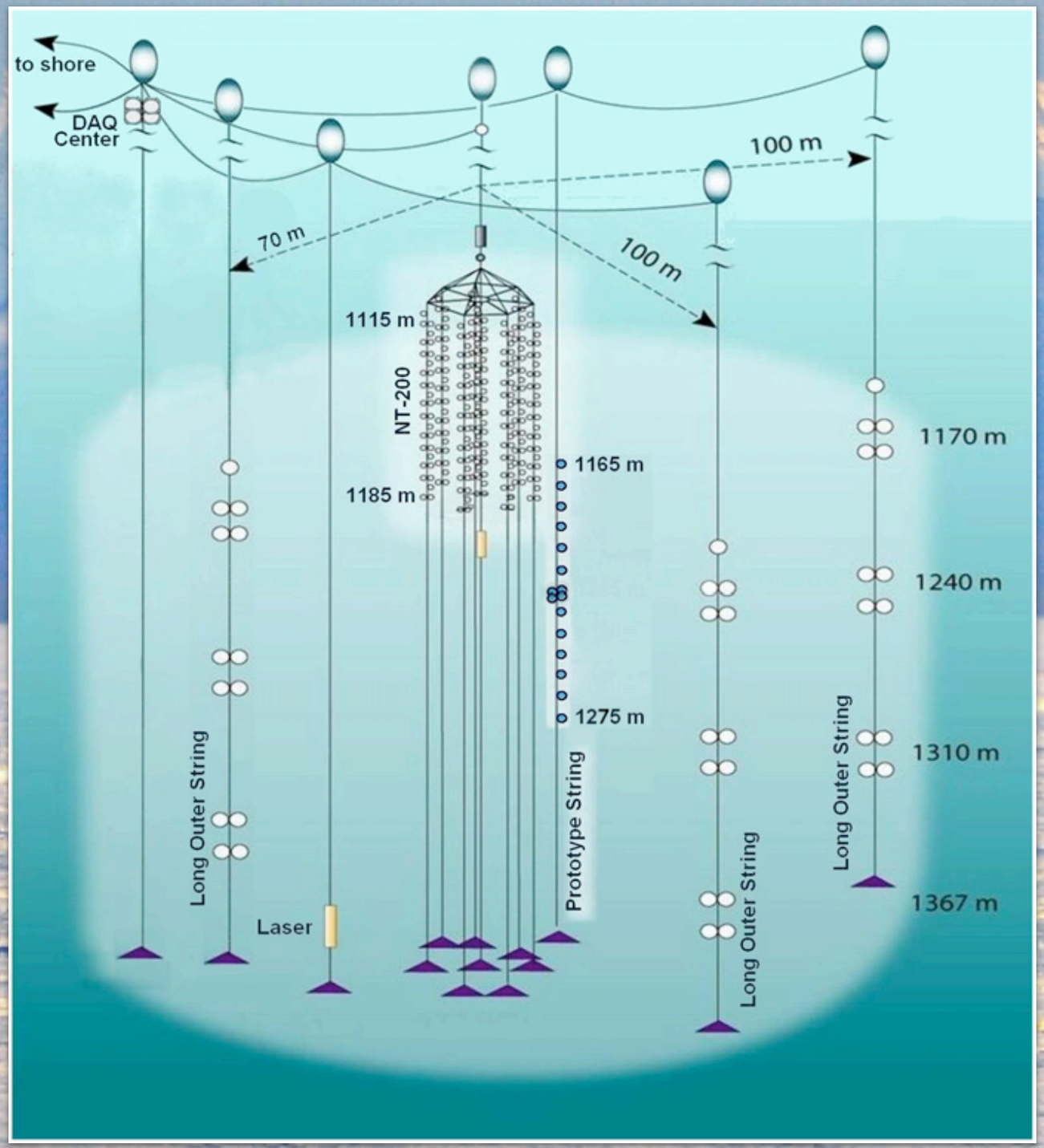


- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

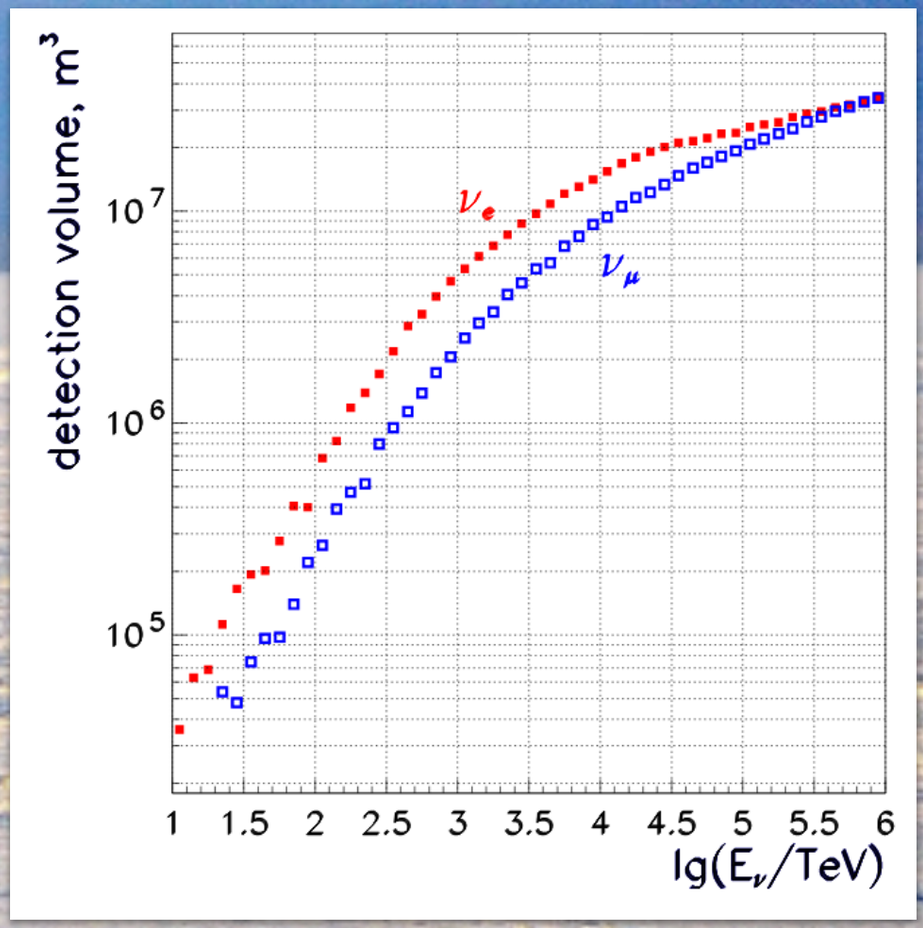
Lake Baikal

Lake Baikal

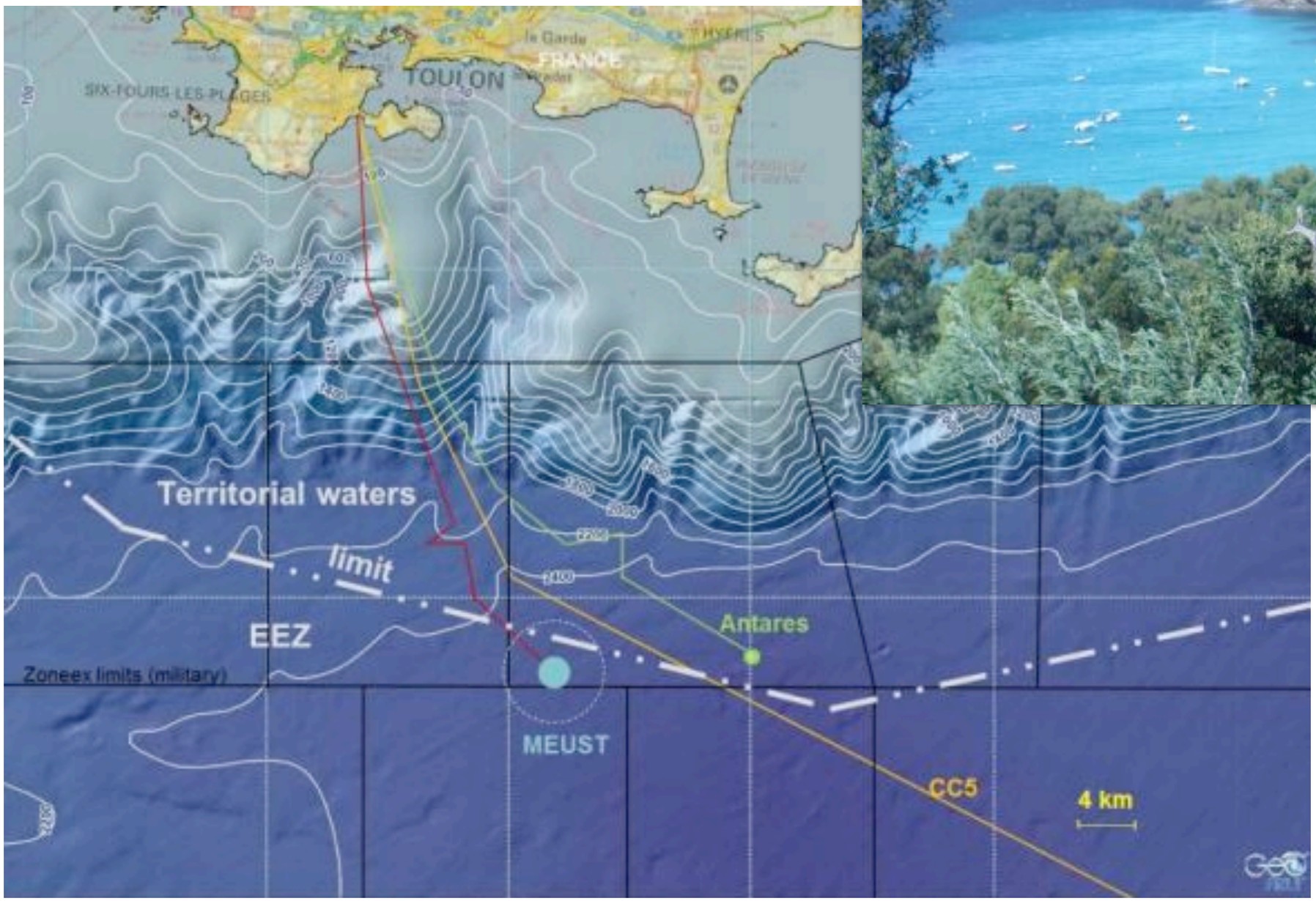
arXiv:astro-ph/0609743

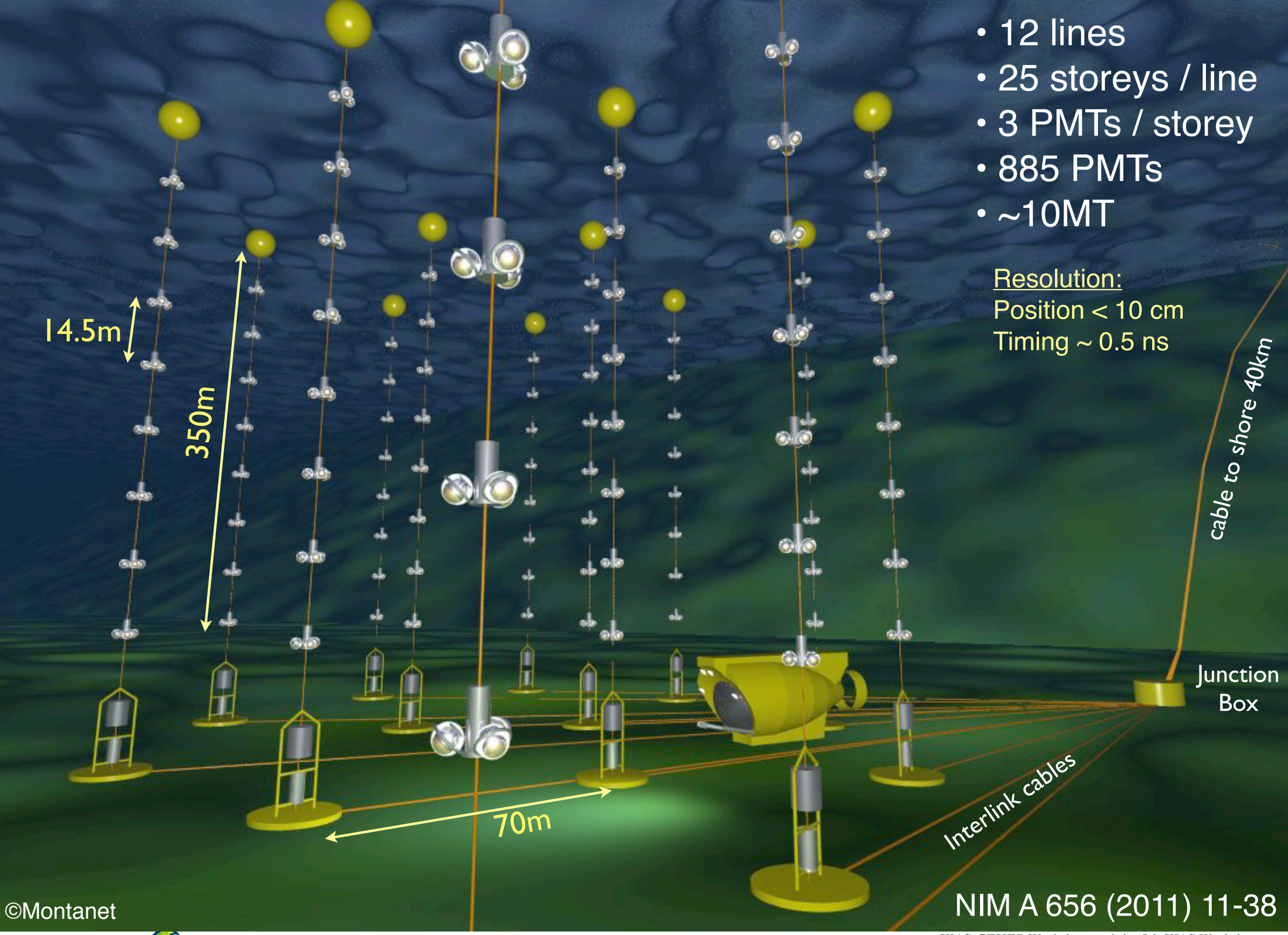


228 PMTs
~0.1 MT Volume

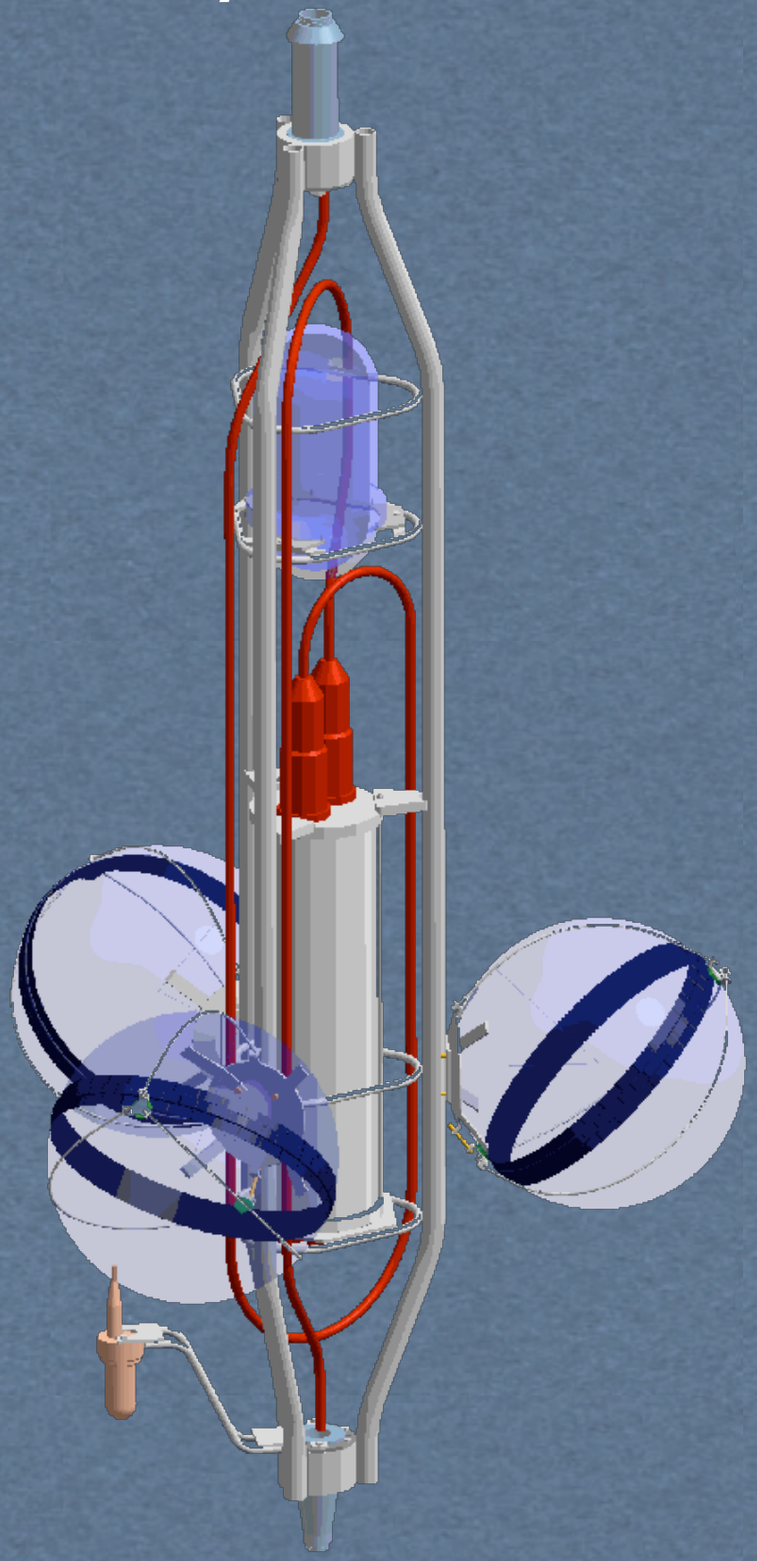


ANTARES


TOULON
SIX-FOURS-LES-PLAGES
Territorial waters
limit
EEZ
Zoneex limits (military)
Antares
MEUST
CC5
4 km


• 12 lines
• 25 storeys / line
• 3 PMTs / storey
• 885 PMTs
• ~10MT
Resolution:
Position < 10 cm
Timing ~ 0.5 ns
14.5m
350m
70m
cable to shore 40km
Junction Box
Interlink cables
©Montanet
NIM A 656 (2011) 11-38

Storey with 3OMs



- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs
- ~10MT

Resolution:
Position < 10 cm
Timing ~ 0.5 ns

70m

Junction Box

ble to shore 40km

Interlink

©Montanet

NIM A 656 (2011) 11-38

The IceCube Neutrino Telescope

IceCube

50 m

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

Detector Volume
~1000 MT

1450 m

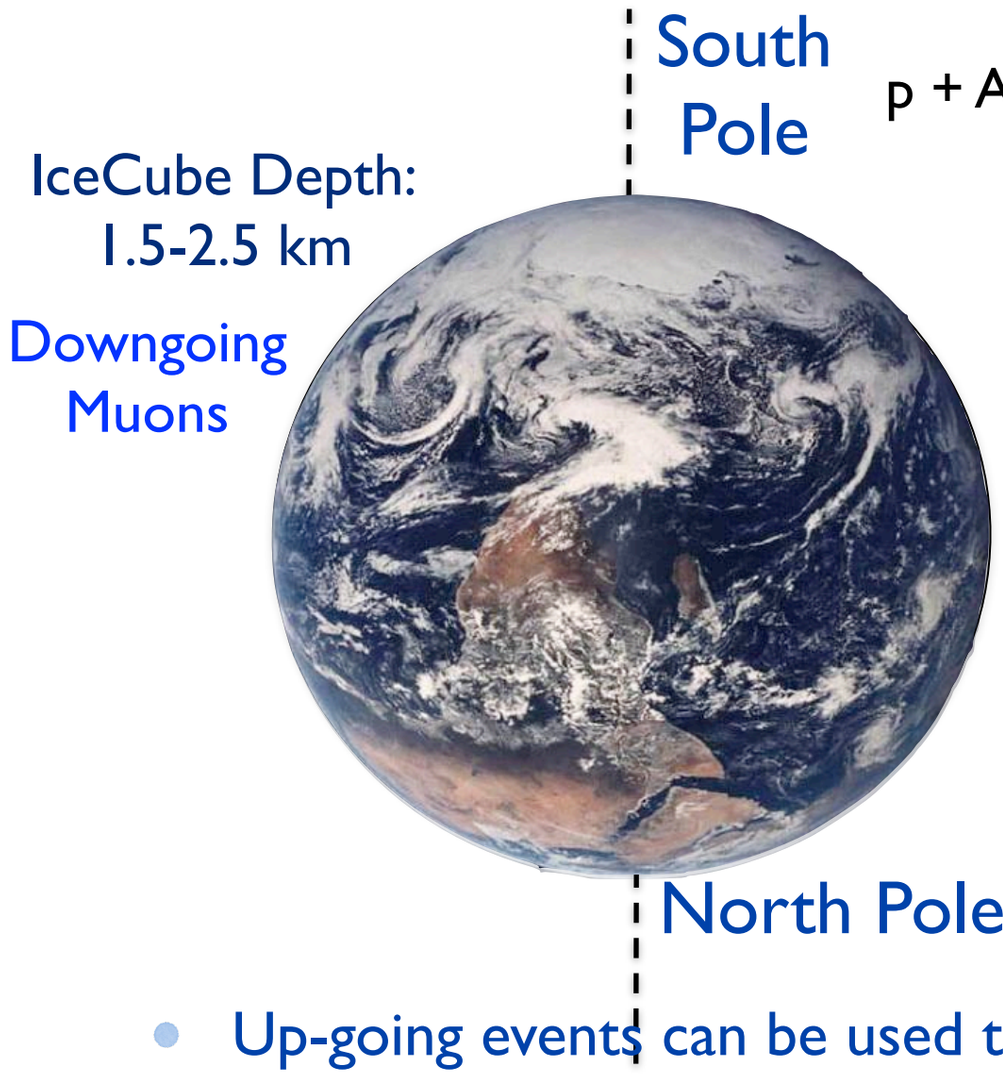
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

2450 m

2820 m

Eiffel Tower
324 m

Signals in IceCube



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

- 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

South Pole

IceCube Depth:
1.5-2.5 km

Downgoing Muons

North Pole

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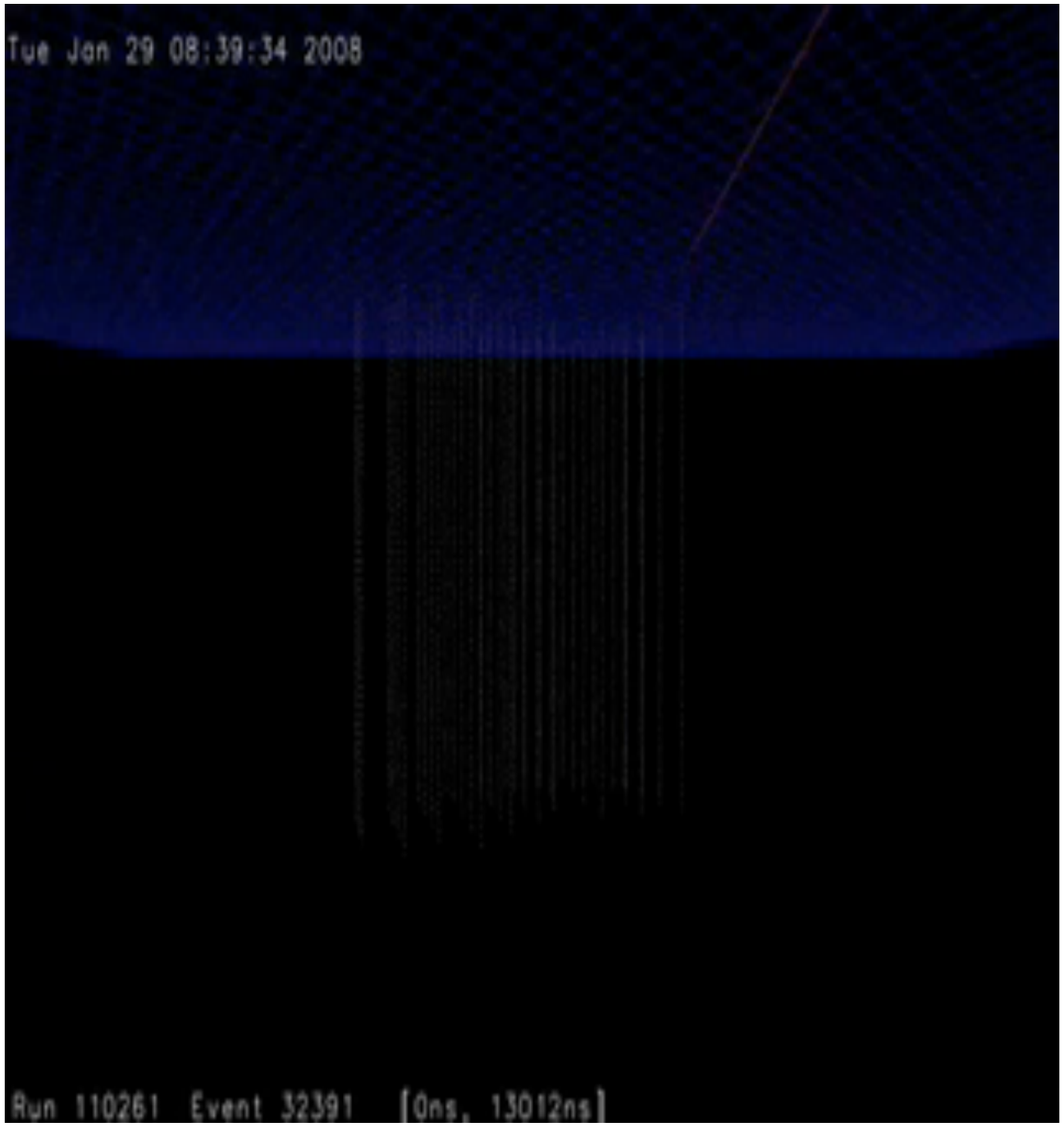

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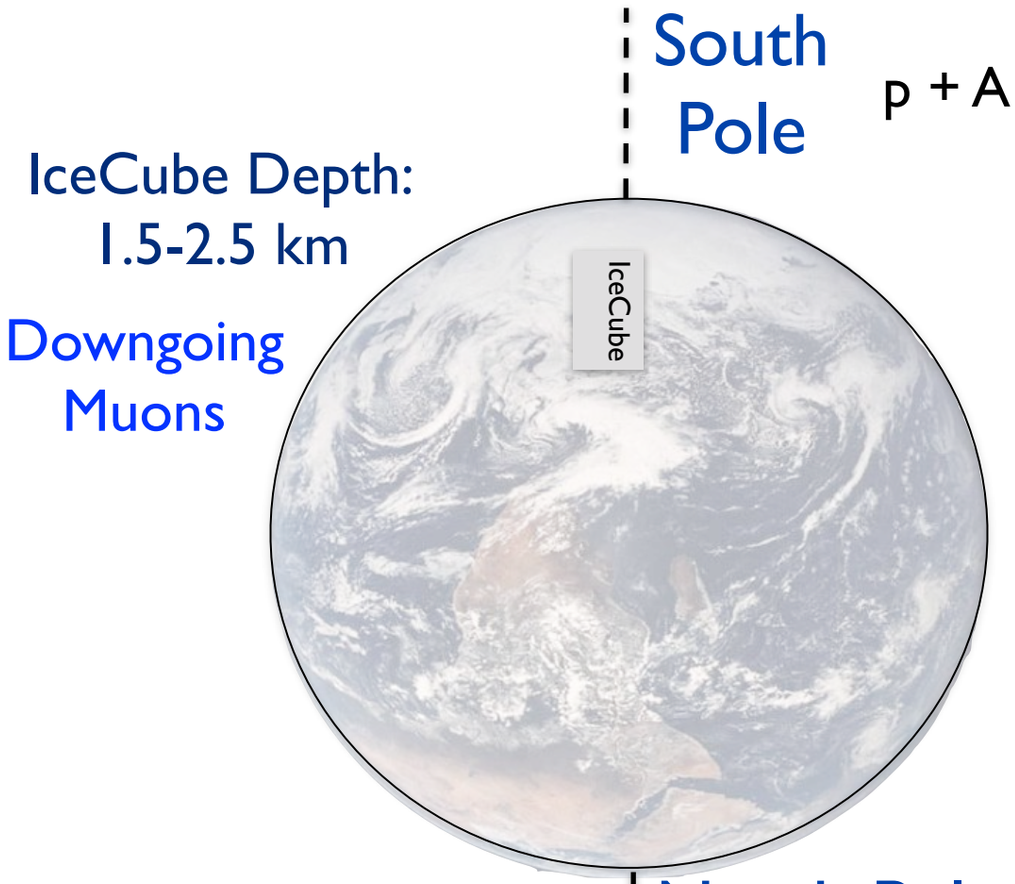

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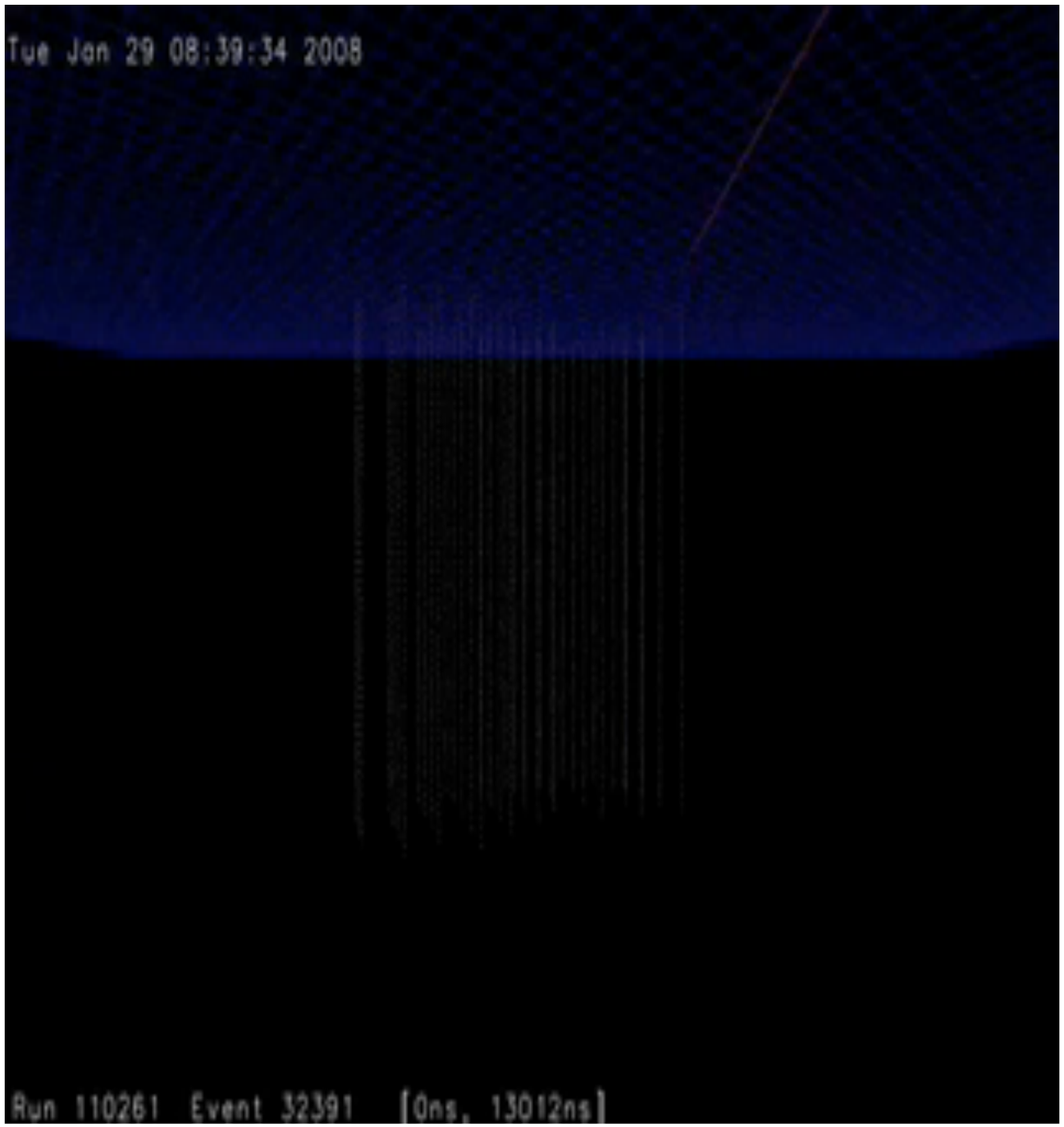

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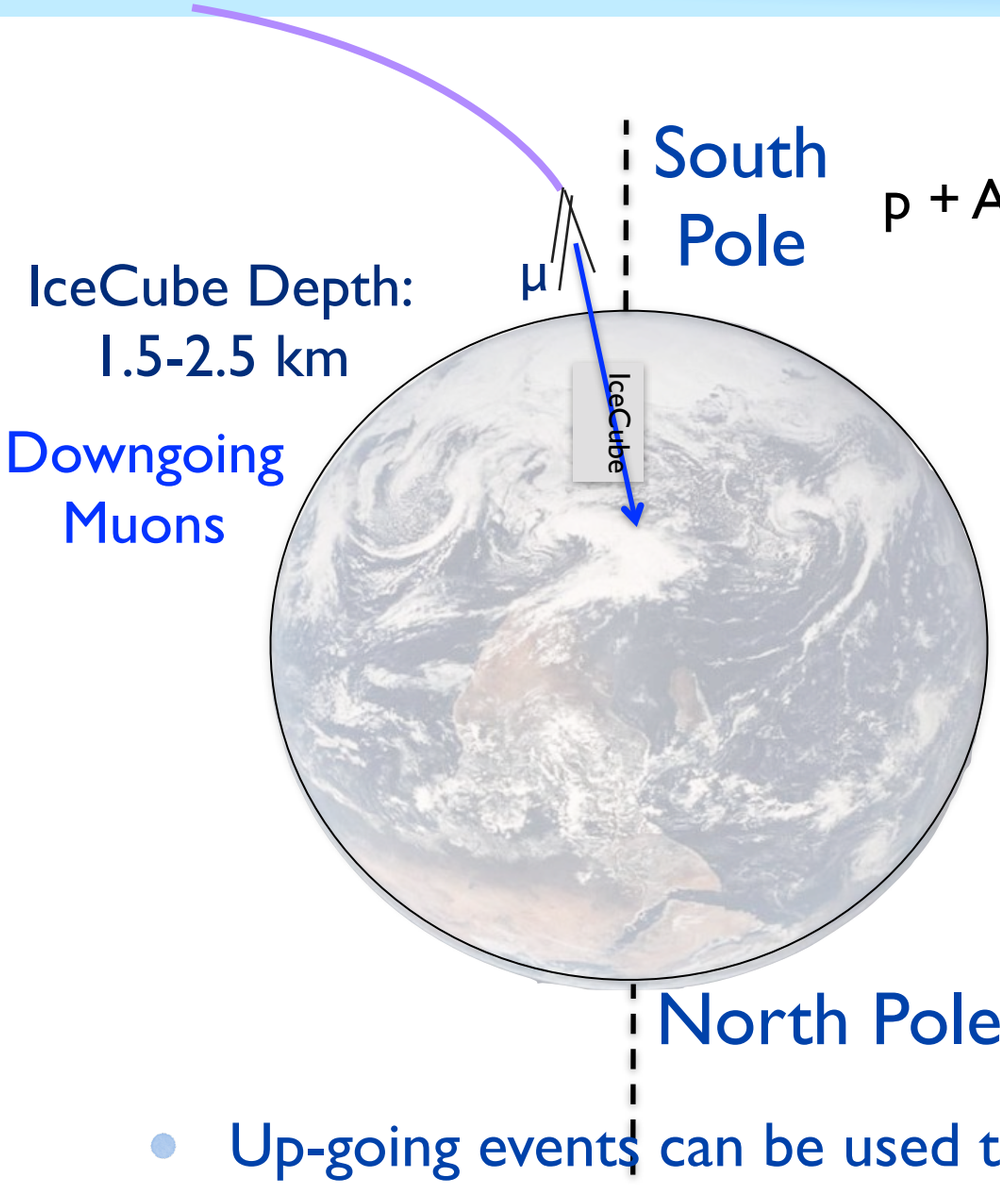

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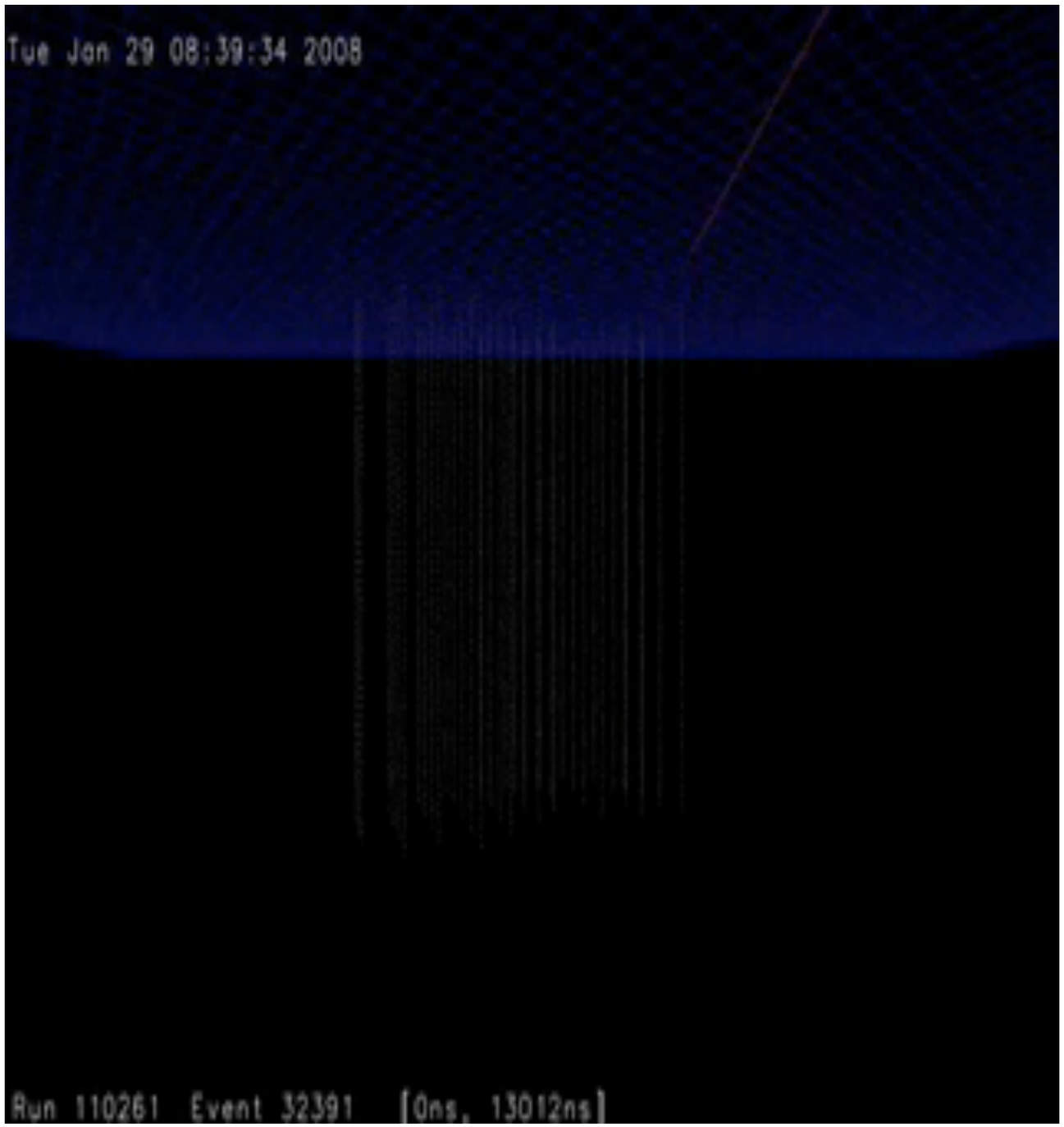

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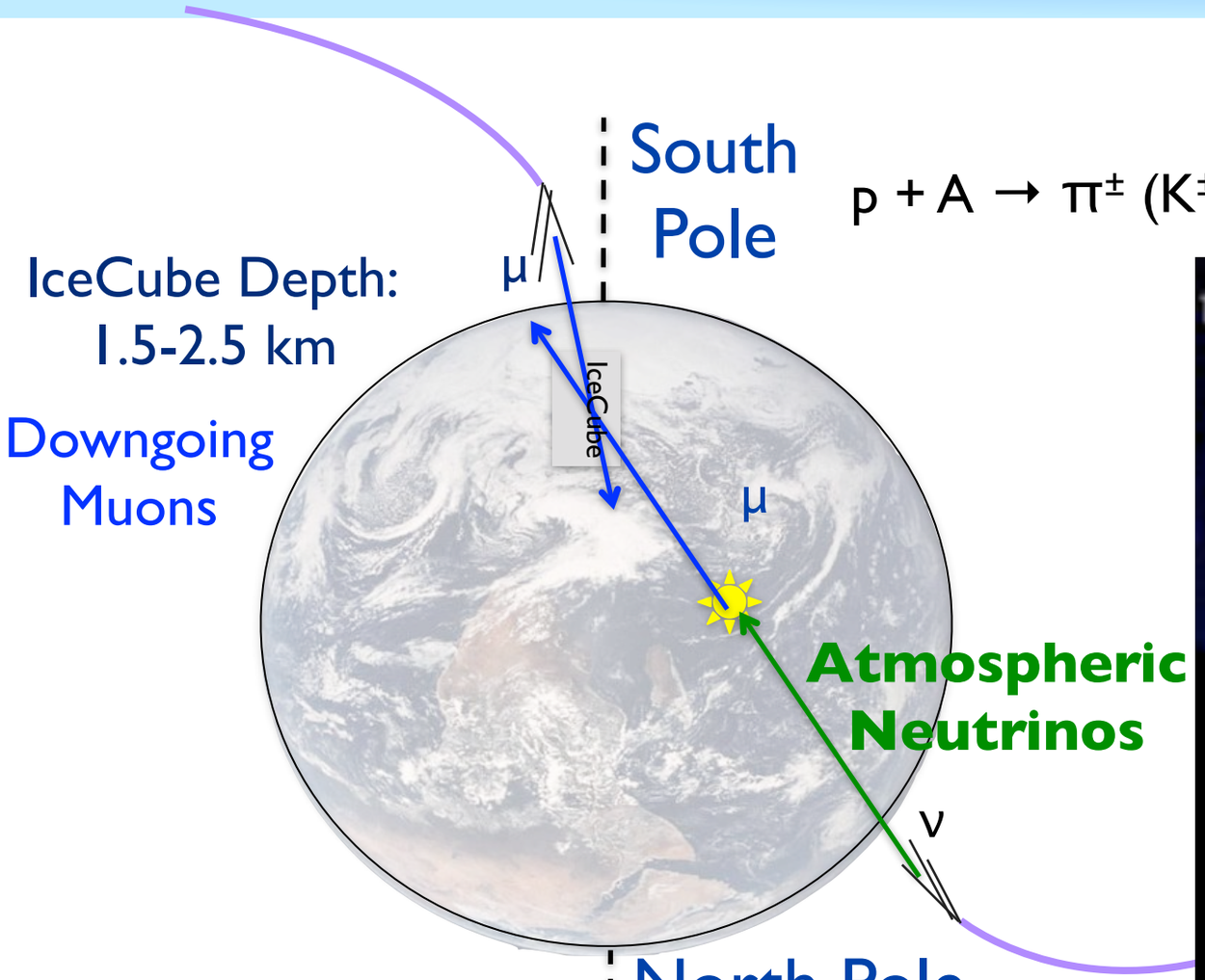

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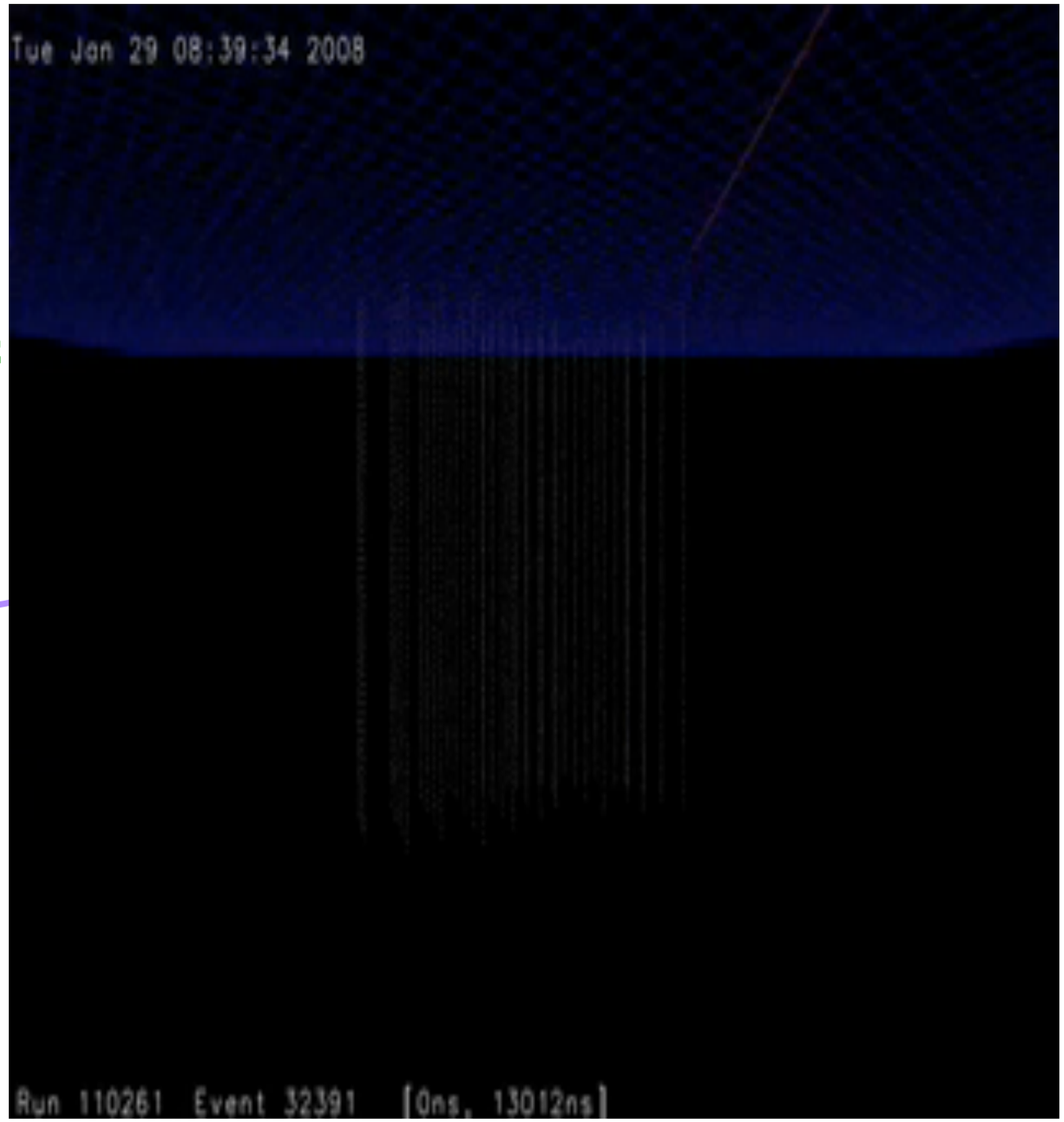

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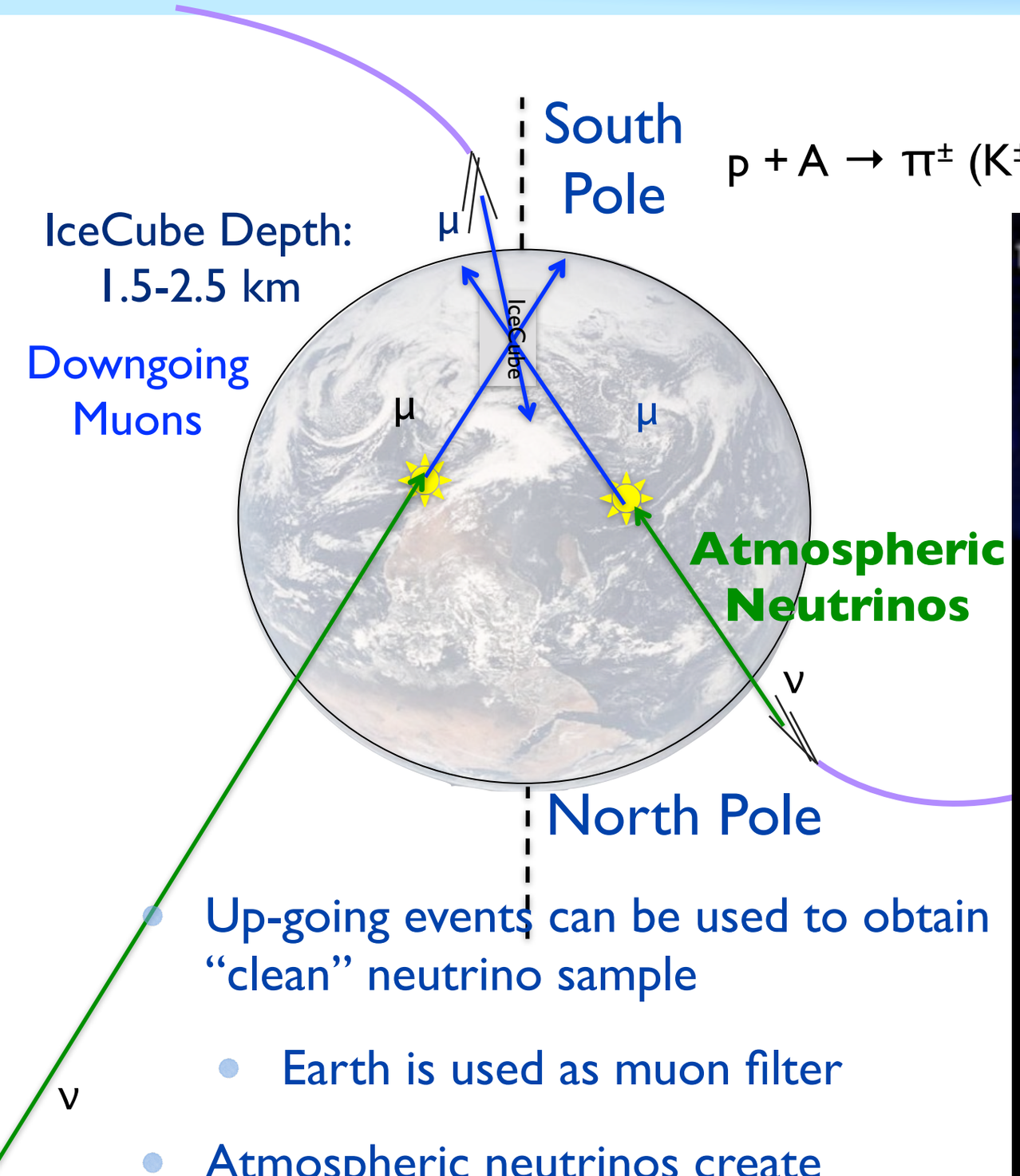

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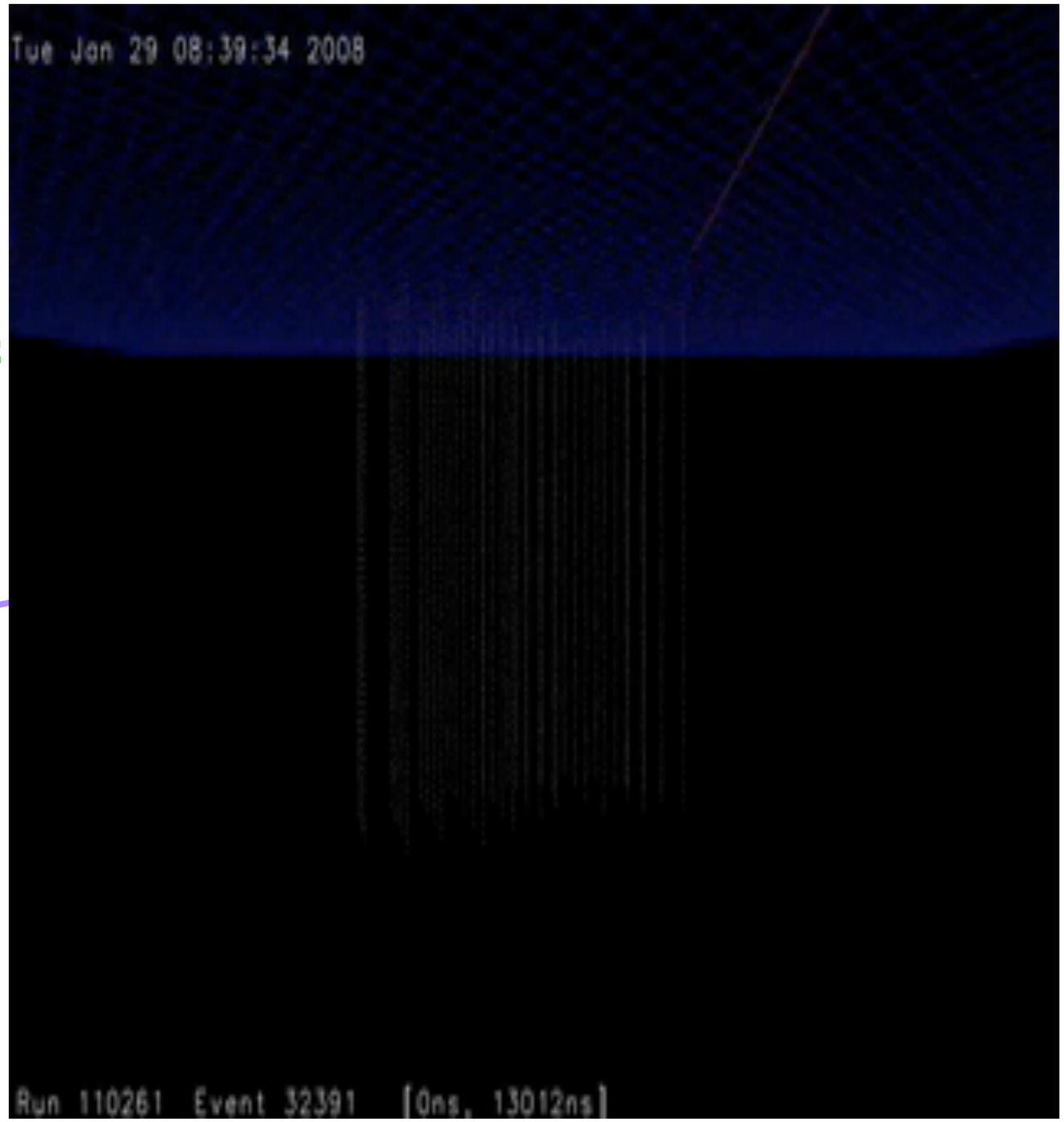

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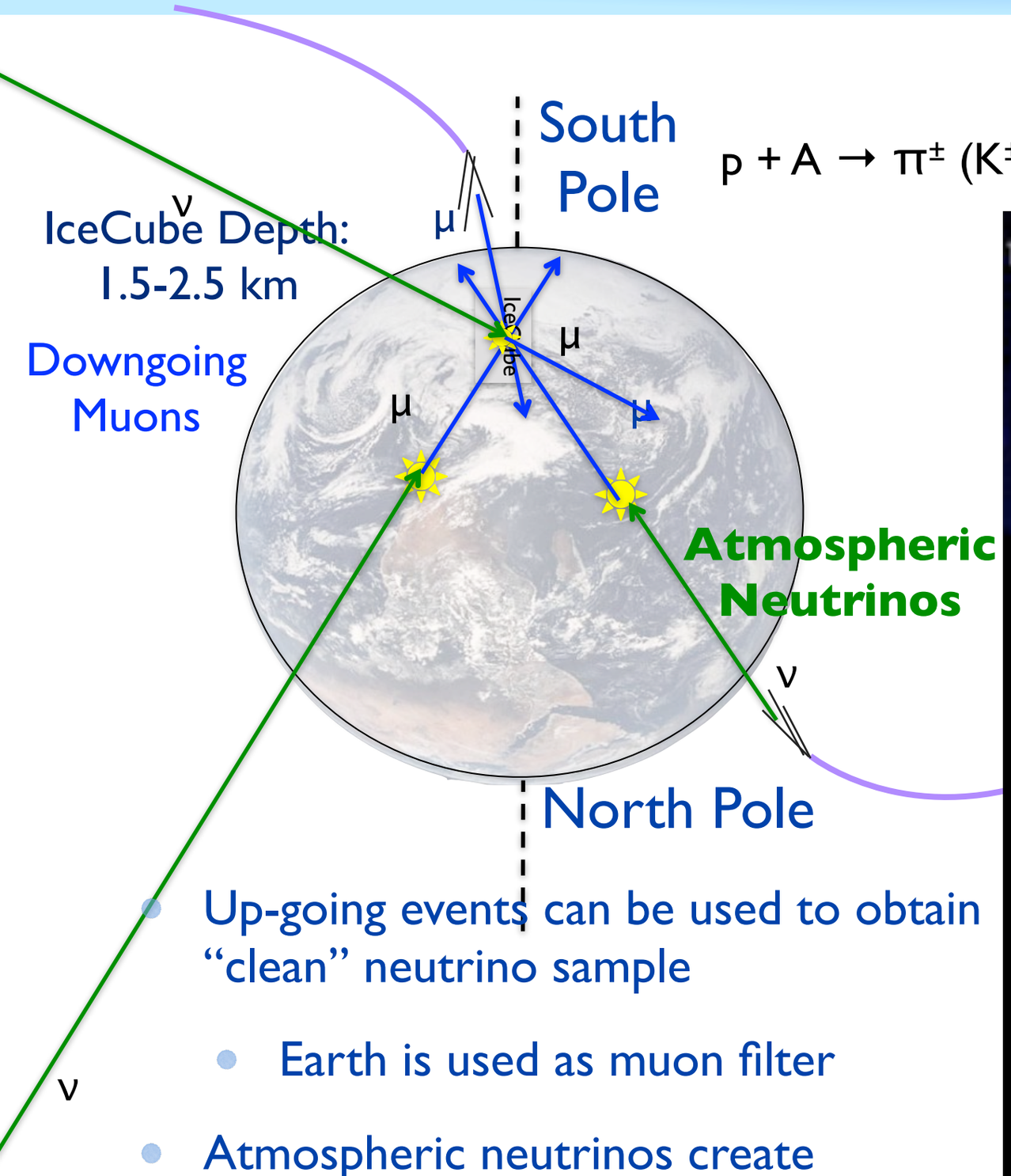

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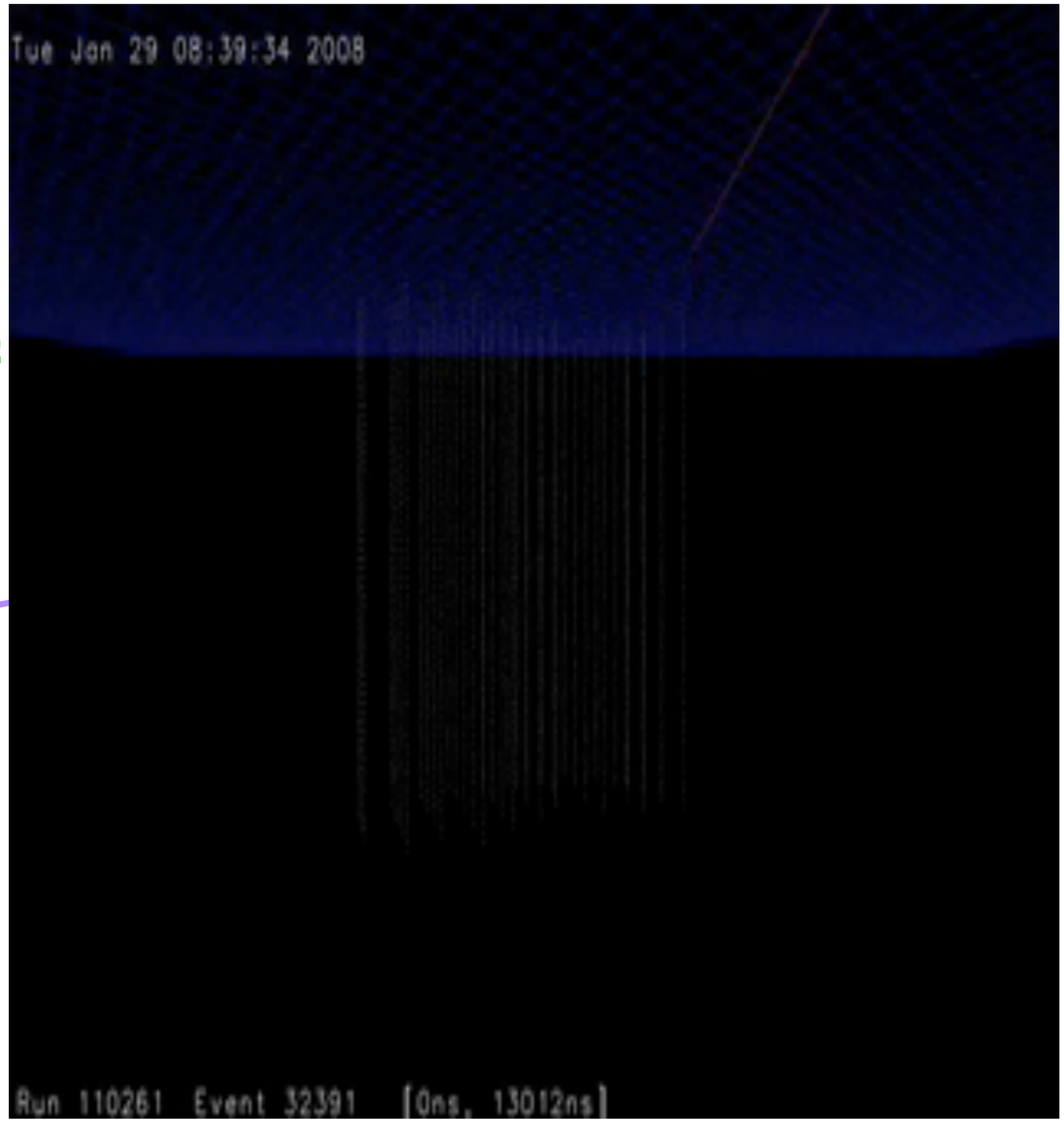

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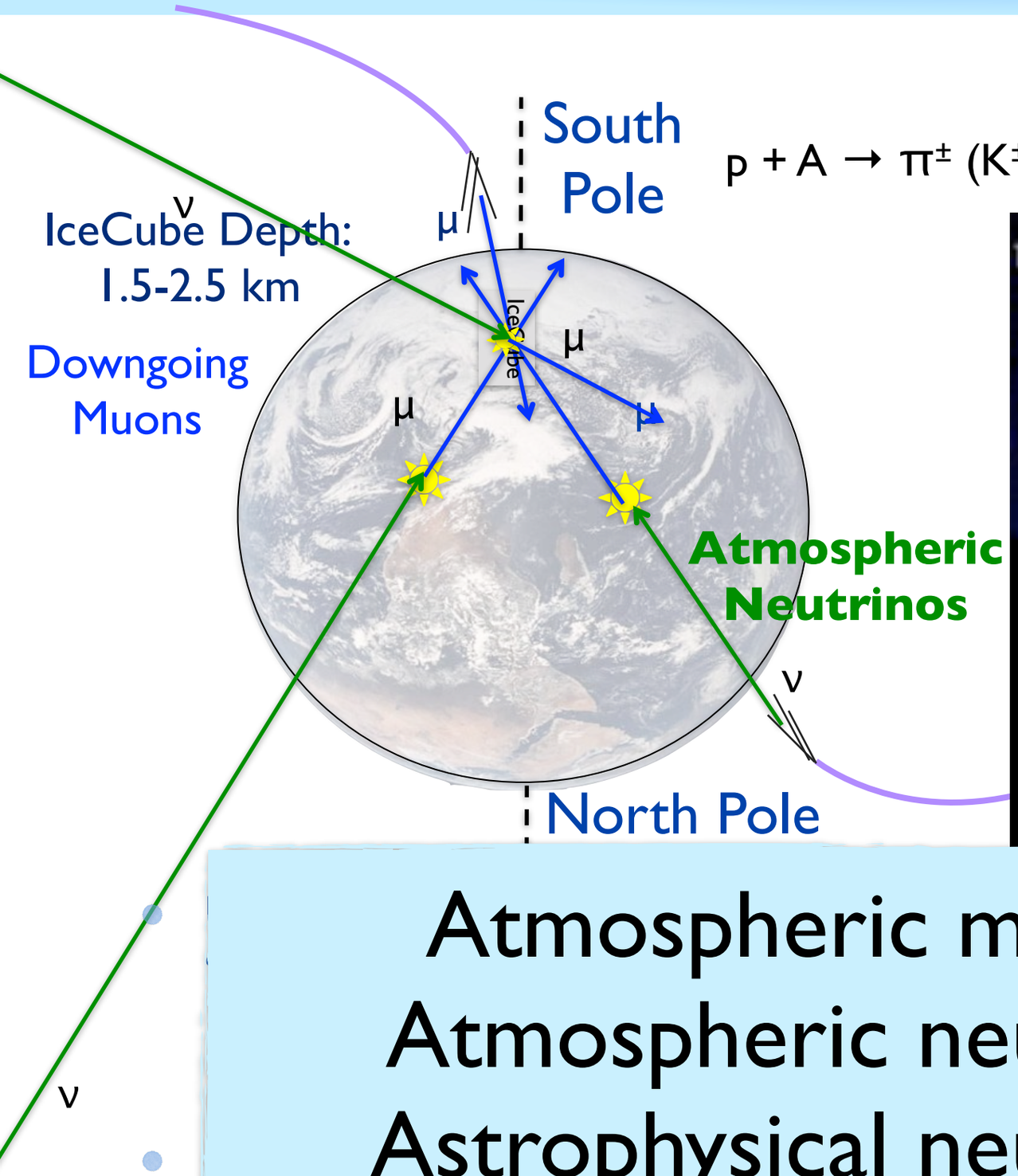

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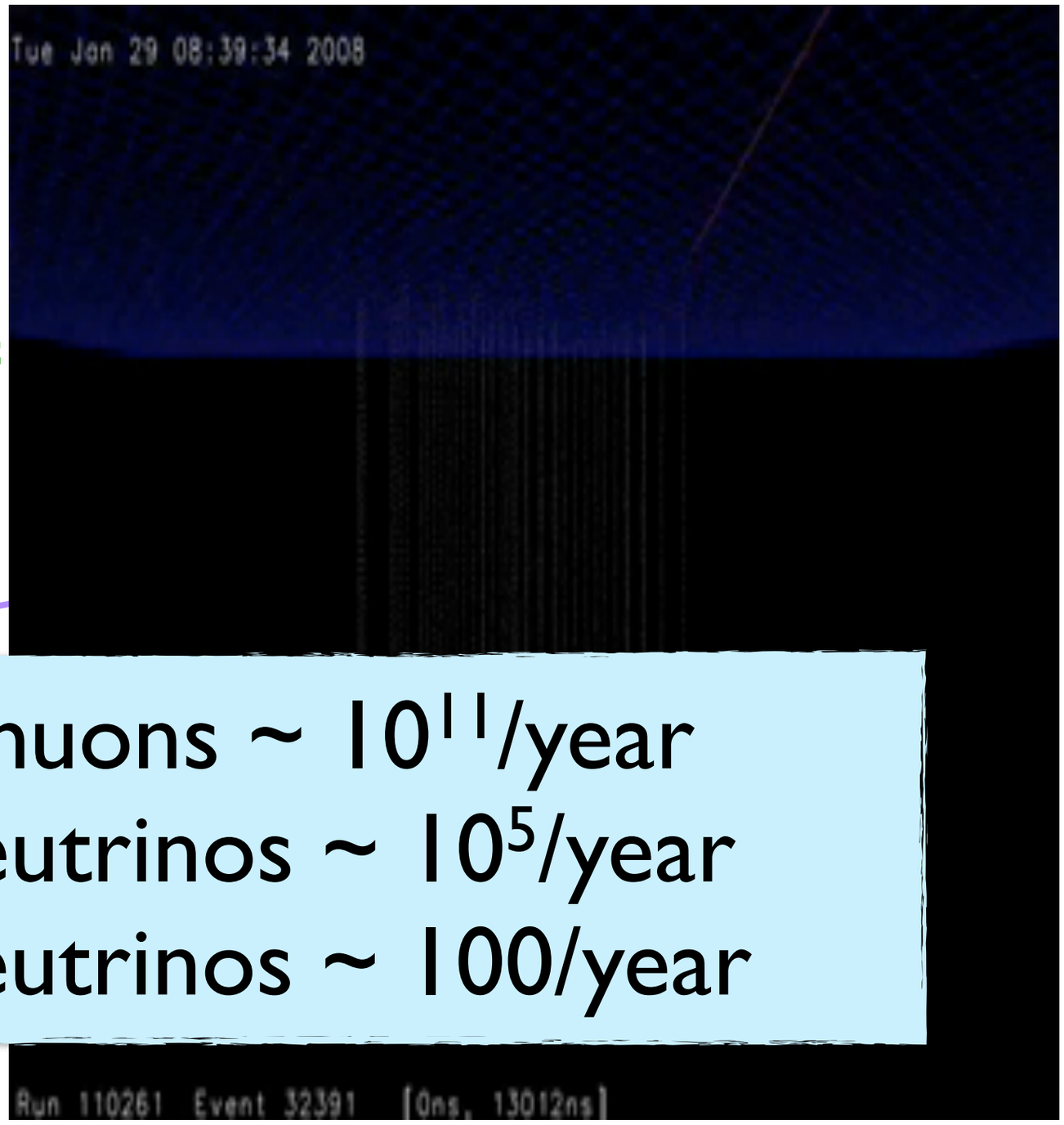
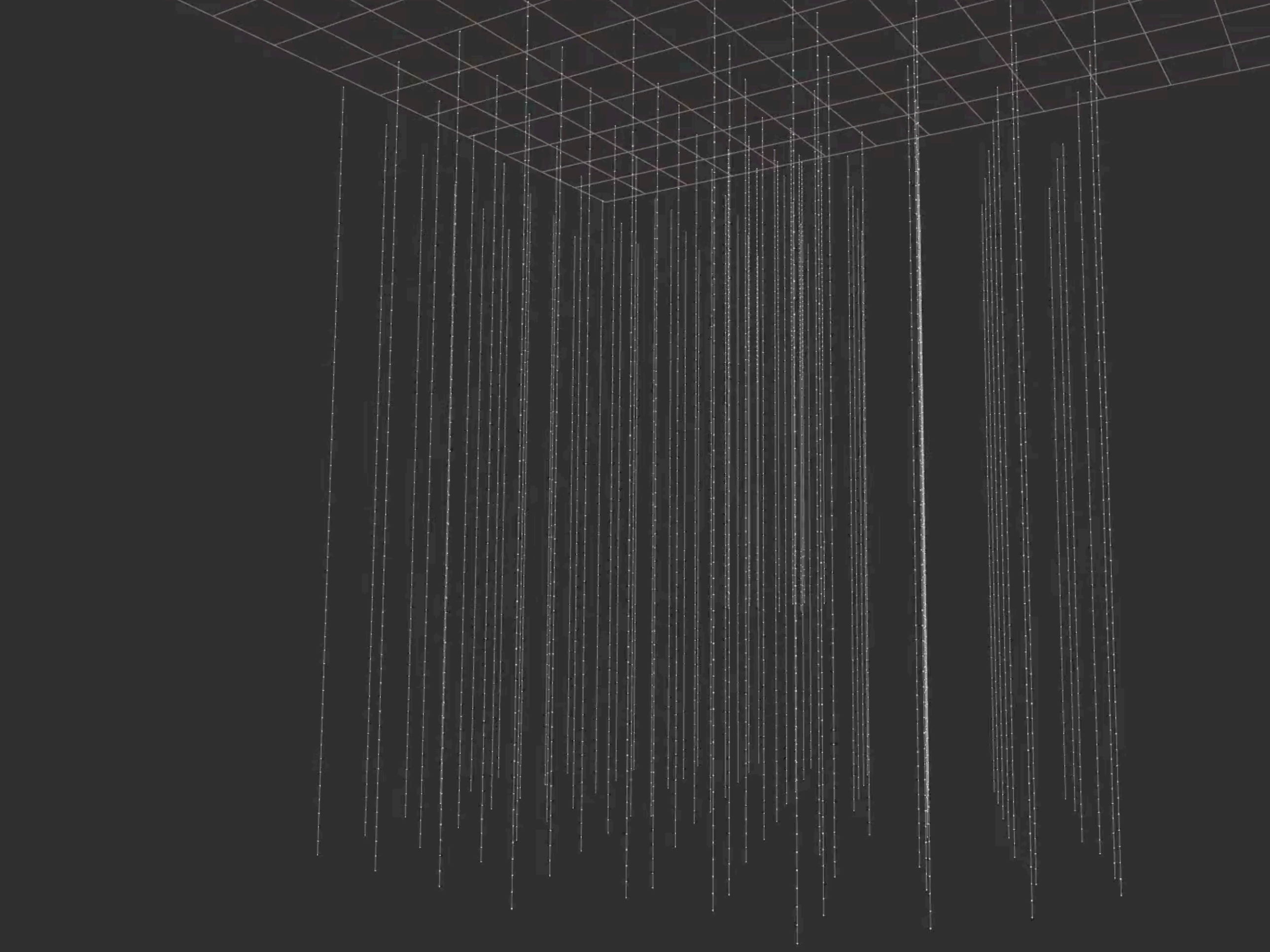


Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

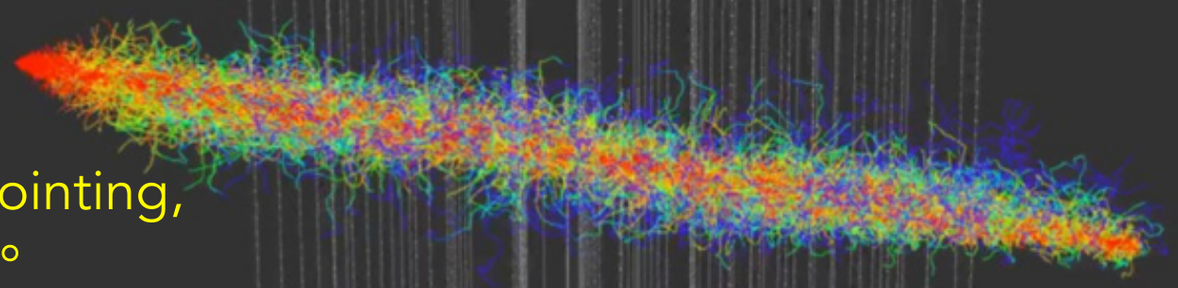
irreducible neutrino background to
extra terrestrial neutrino fluxes



Event Topologies in IceCube

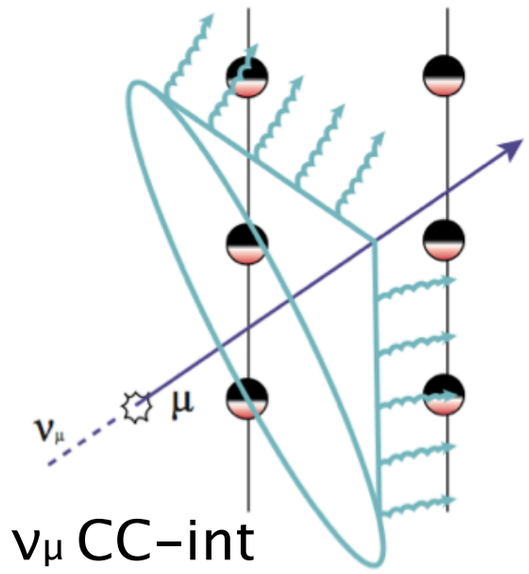
Track topology

(e.g. induced by muon neutrino)



Good pointing,
0.2° - 1°

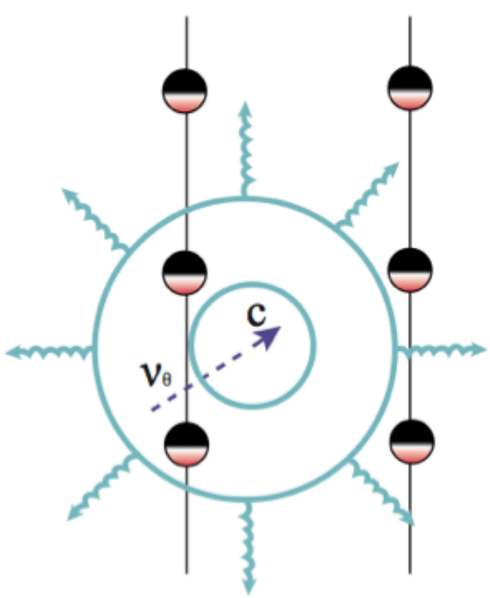
Lower bound on energy for through-going events



ν_μ CC–int

Cascade topology

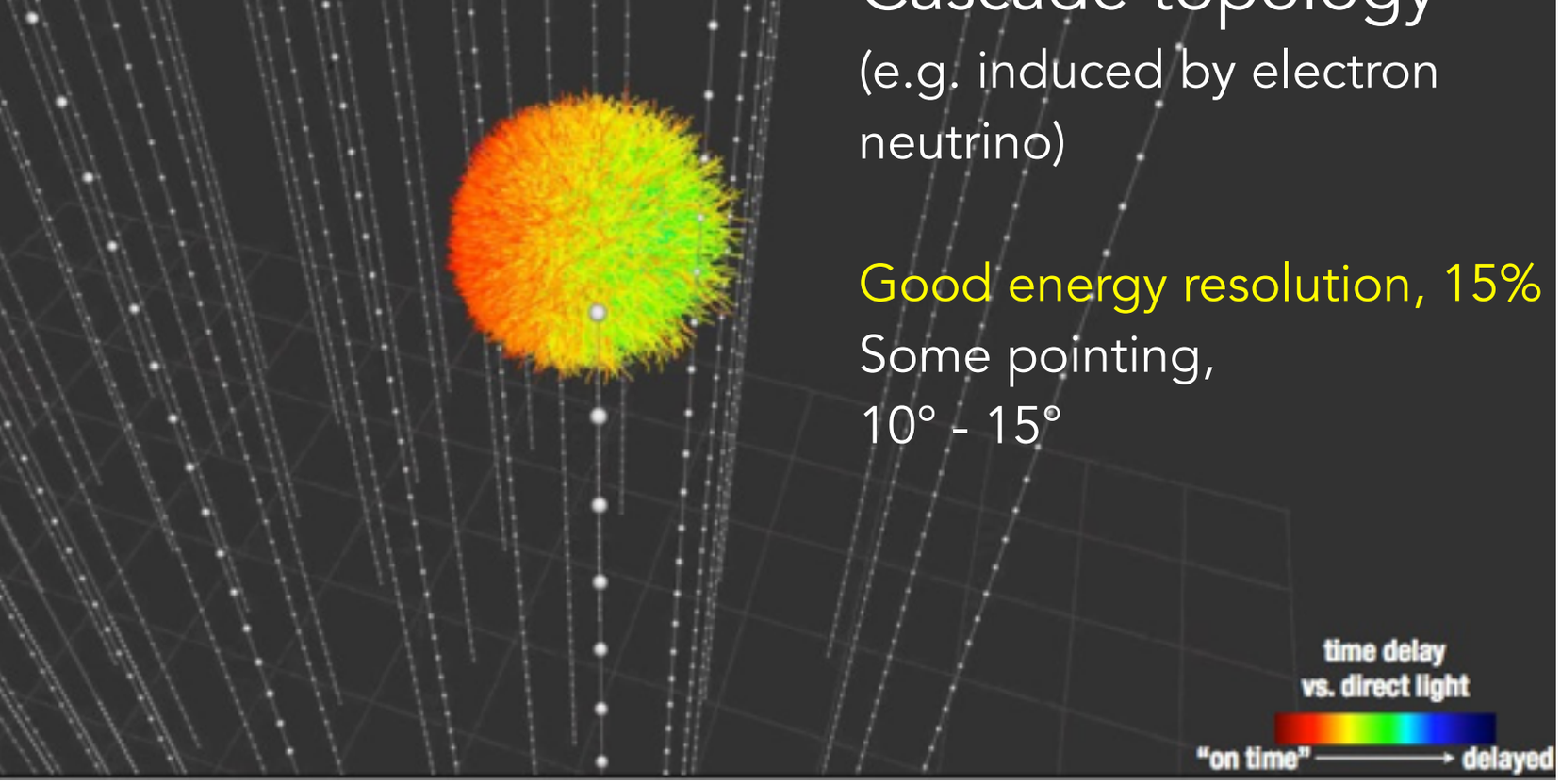
(e.g. induced by electron neutrino)



ν_e ν_τ CC–int & ν_i NC–int

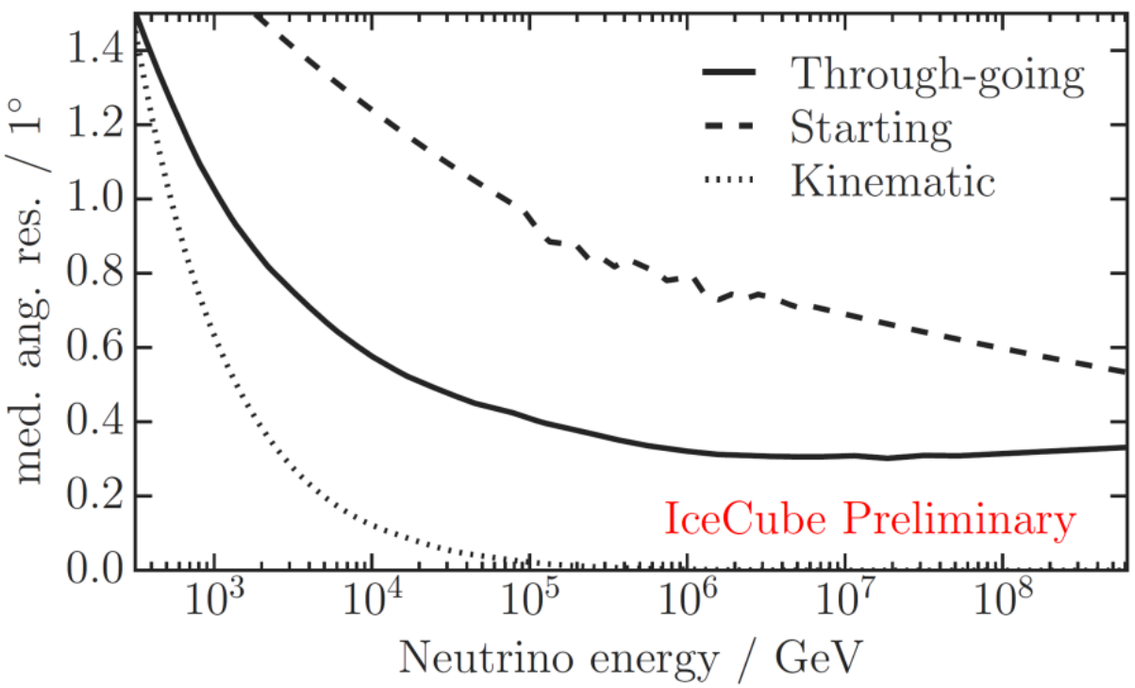
Good energy resolution, 15%

Some pointing,
10° - 15°

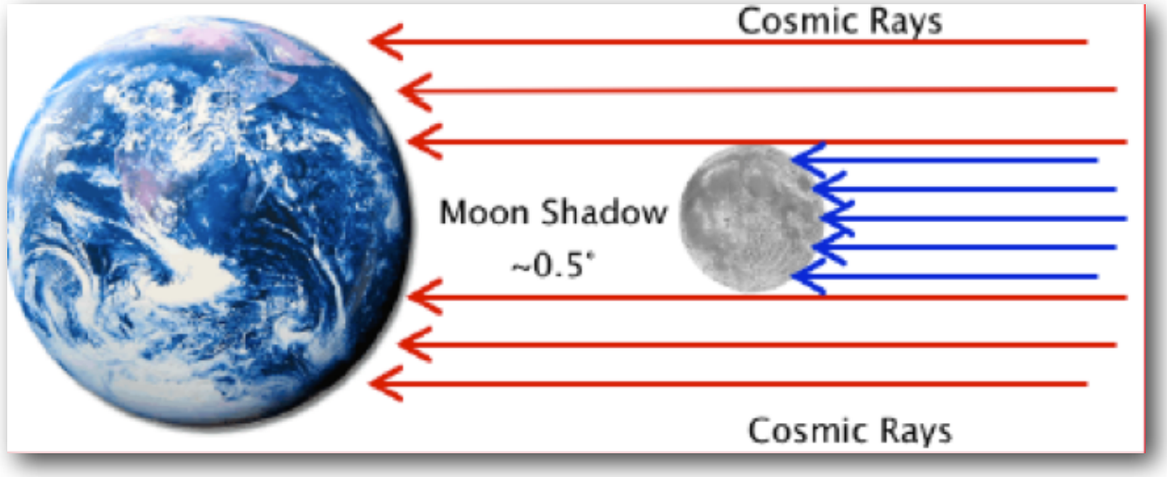


Calibration and Performance

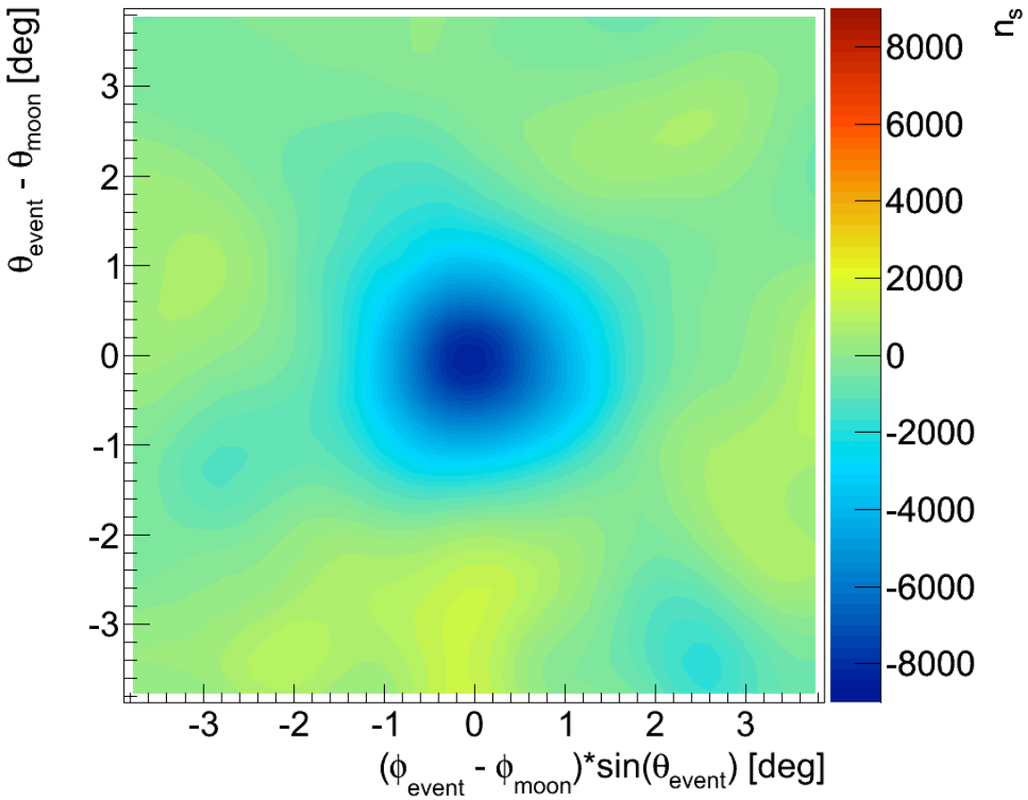
- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons



Physical Review D89 (2014) 102004



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
- systematic pointing error <0.1°



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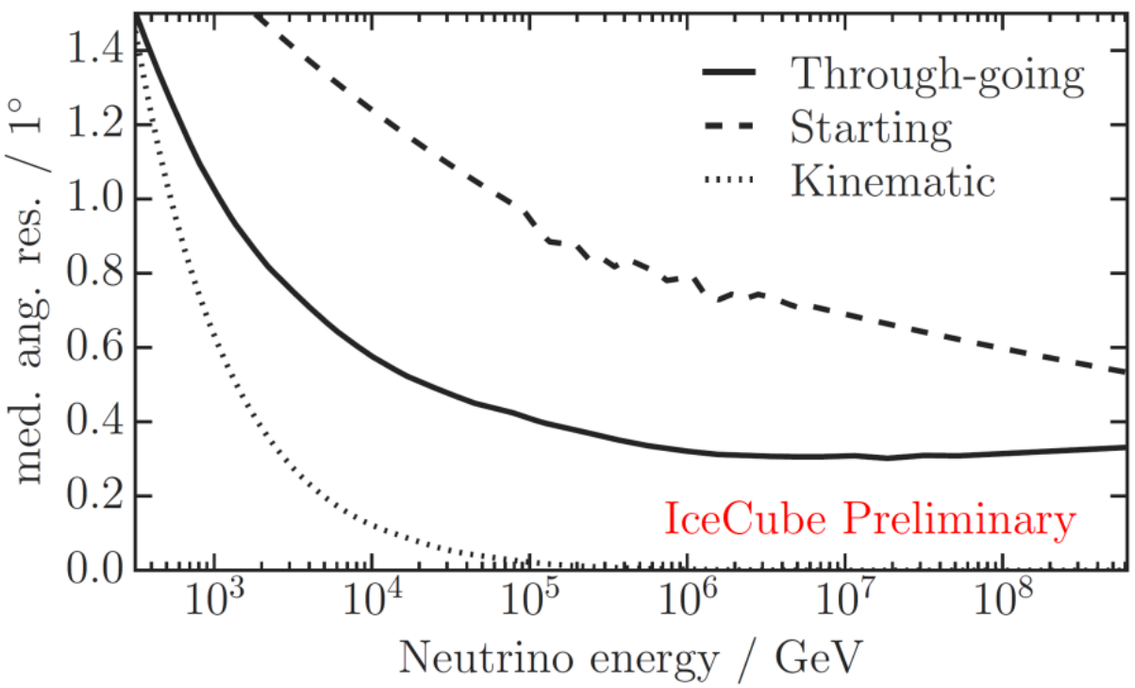
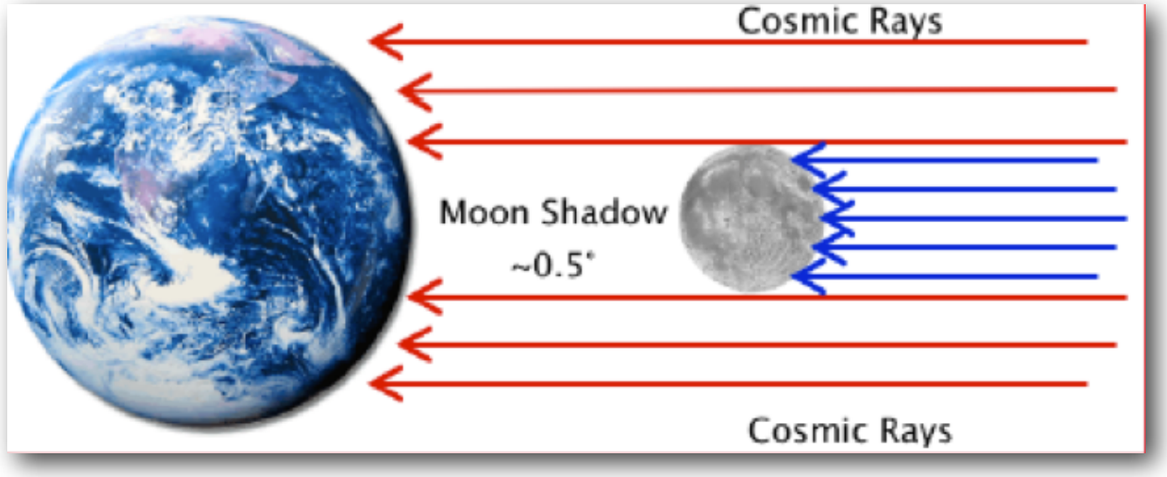
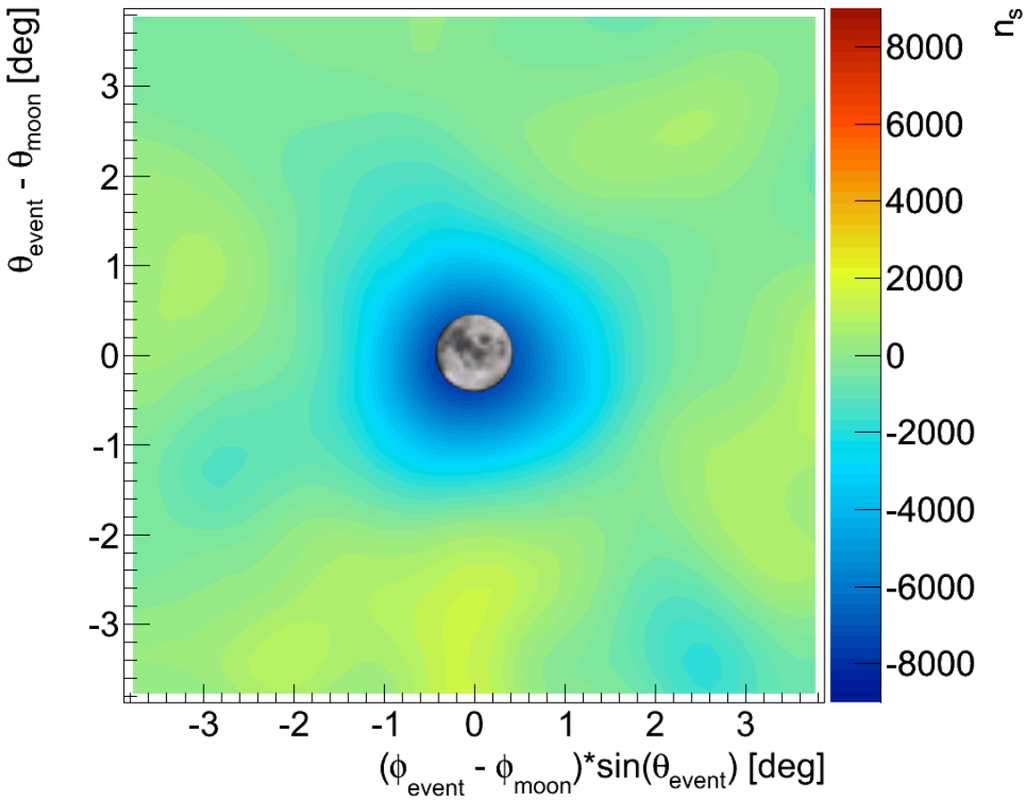
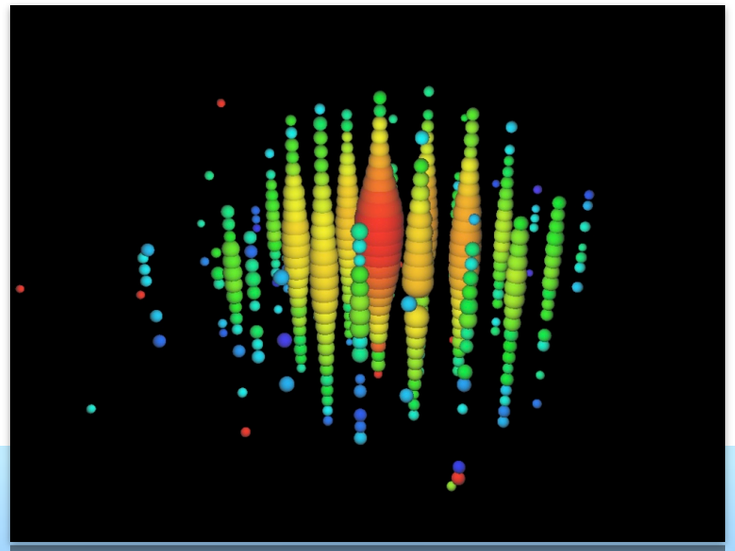


Physical Review D89 (2014) 102004



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
- systematic pointing error <0.1°





Astro-physical Neutrino Search

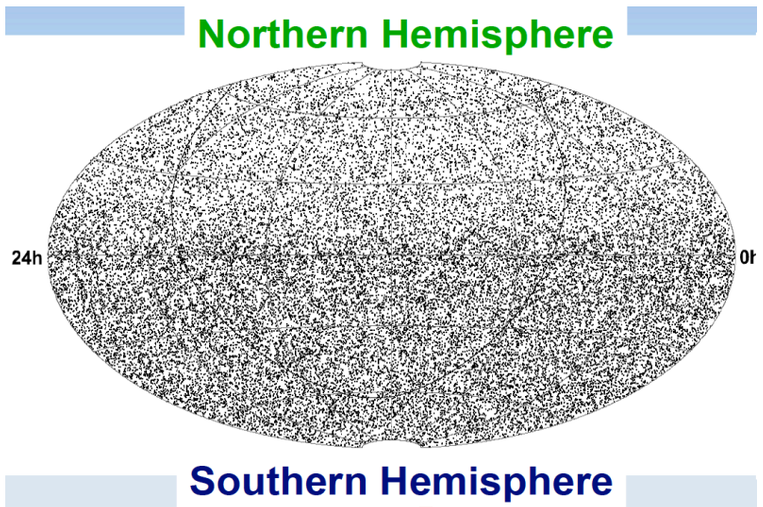
Finding Astrophysical Neutrinos

- 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 ?

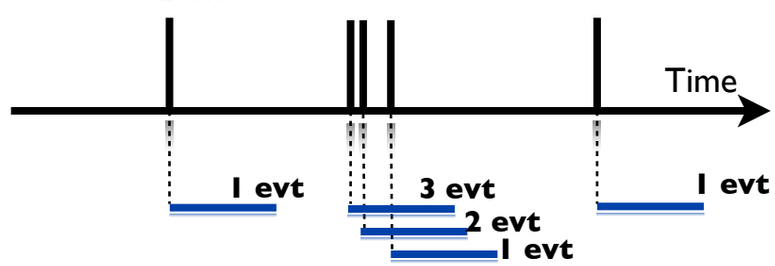
1. Point Source

single dominant source



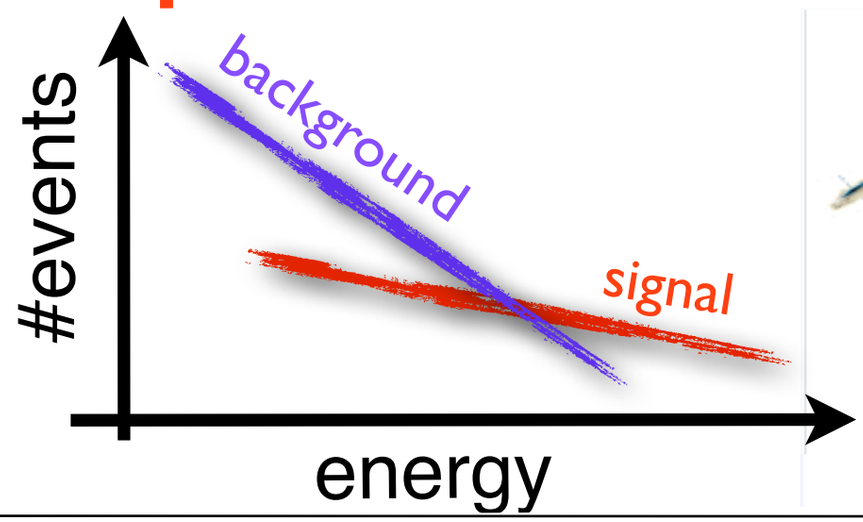
2. Time clustering

transient source



3. Spectral feature

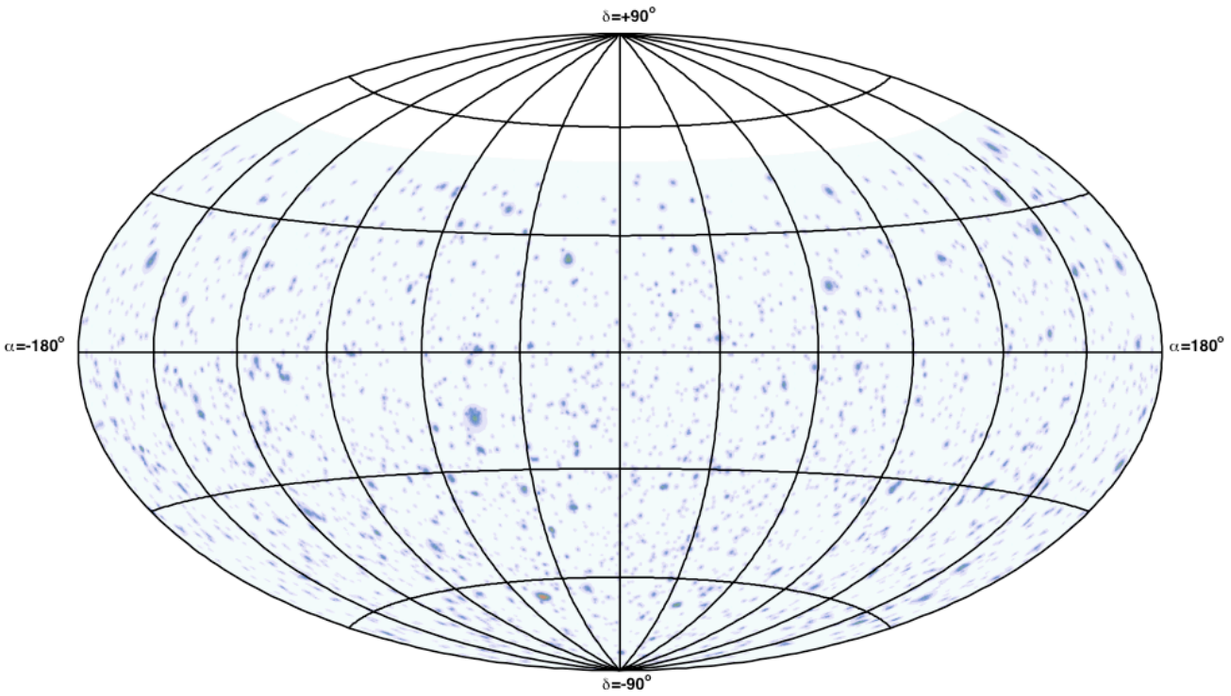
cumulative flux



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

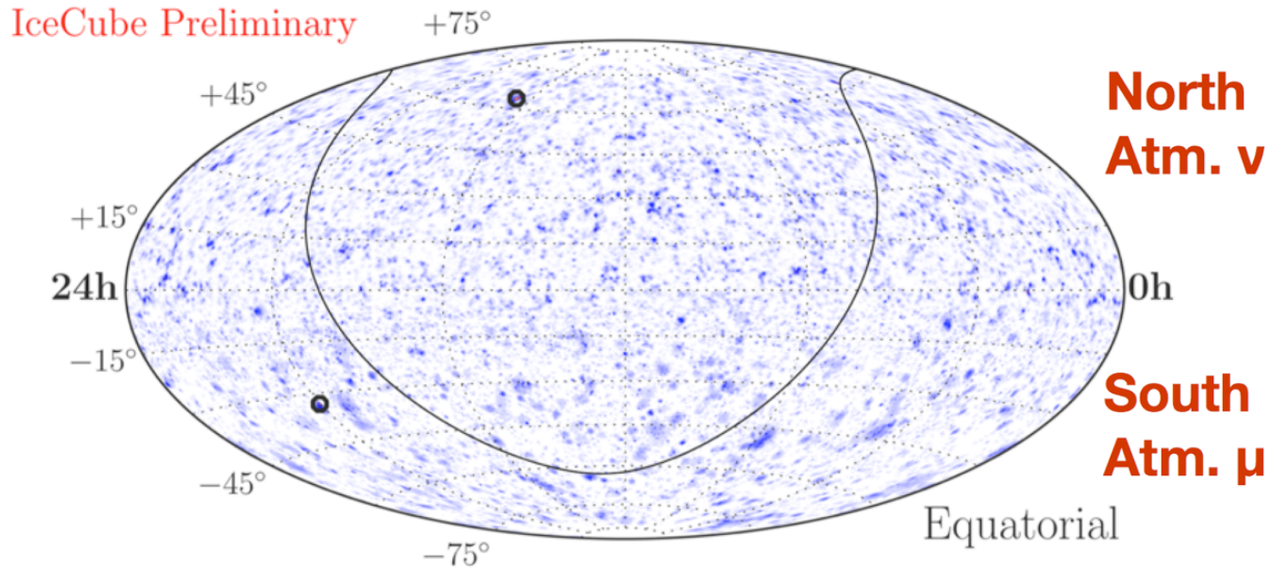
Point sources

ANTARES 4-year up-going muon point source search



2.6% change probability

IceCube 6-years up-going muons and down-going high energy muons



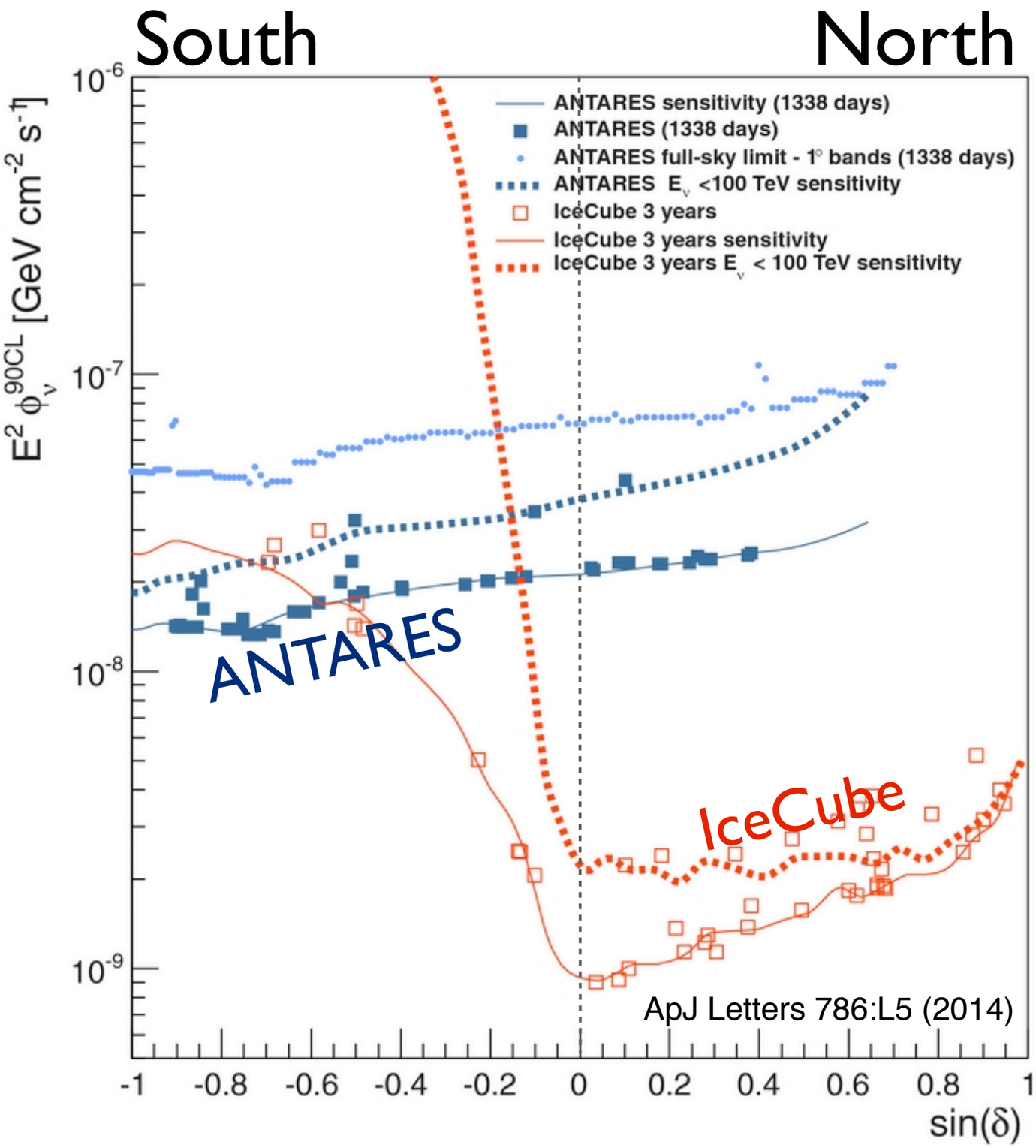
No significant clustering observed

35% change probability (up-going muons)

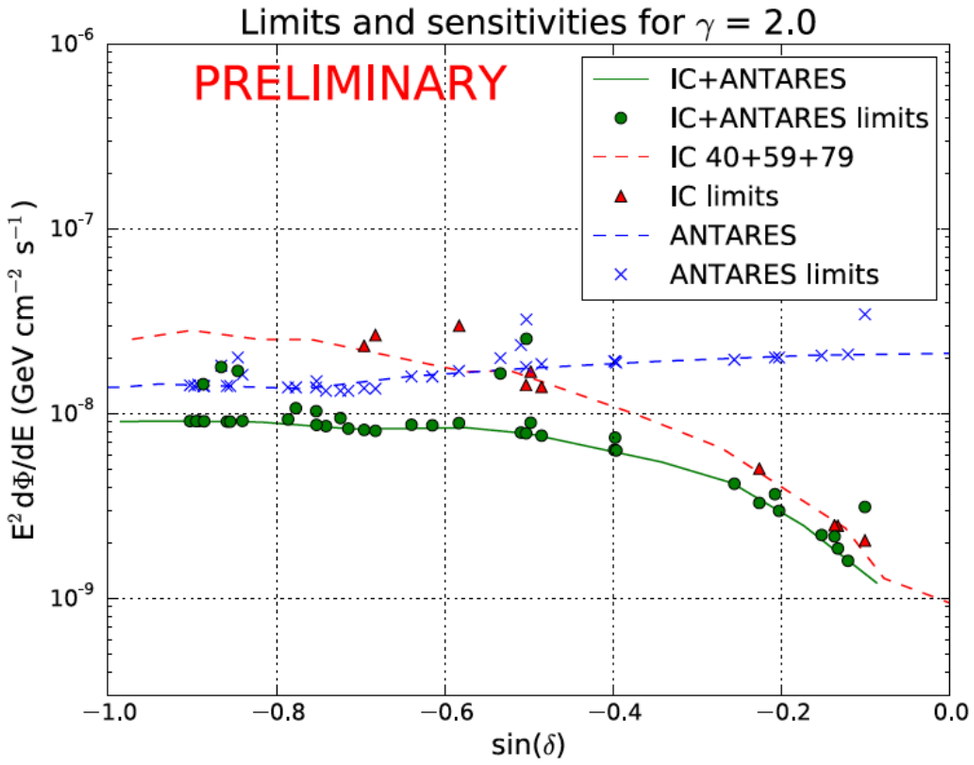
87% change probability (>PeV down-going muons)

arXiv:1511.02149

Point source sensitivity and constraints

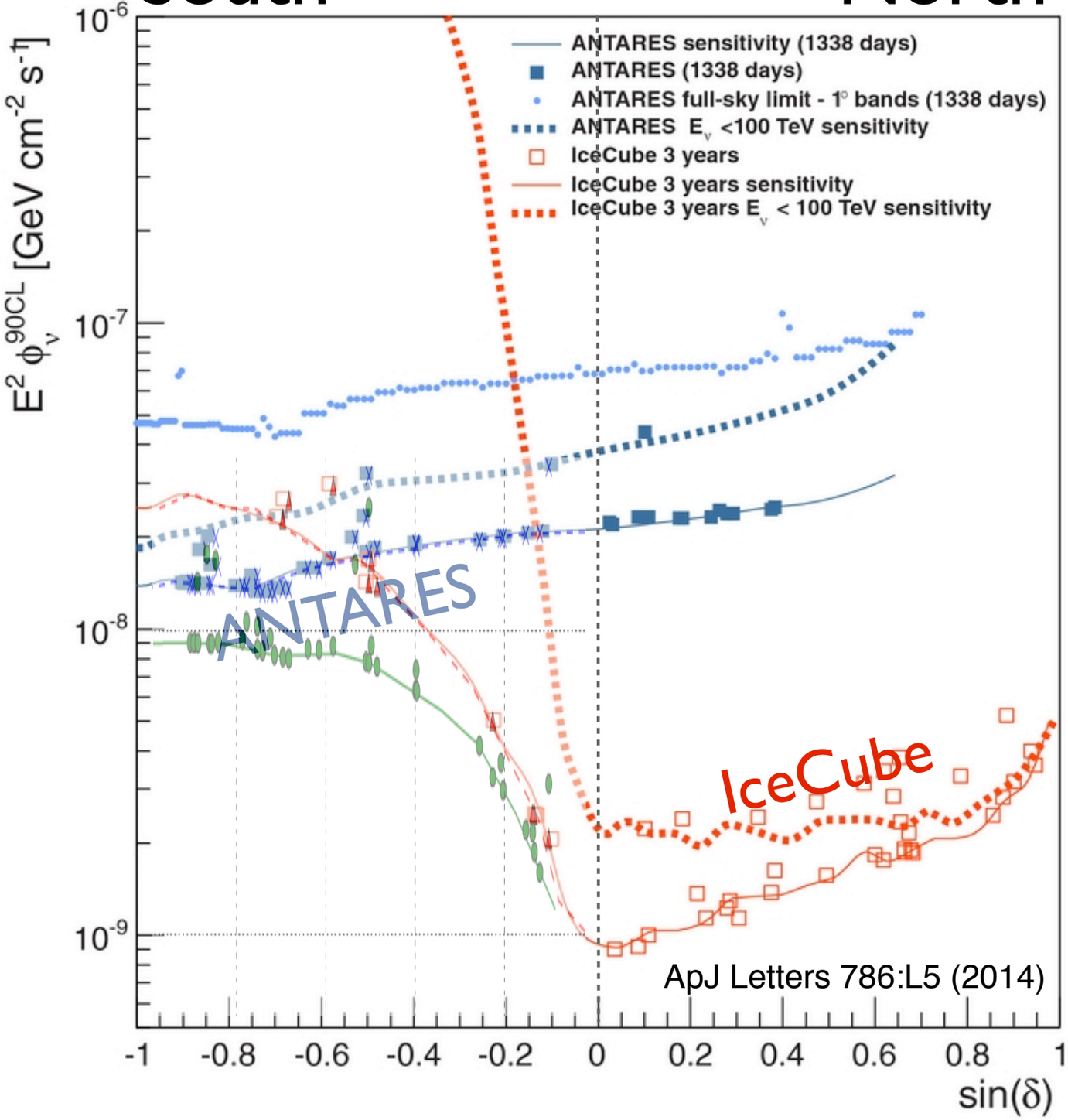


ANTARES can observe the southern sky through the Earth
→ lower threshold, better limits in the south
IceCube has a larger effective area
→ more events, better limits in the north
New: combined IceCube/ANTARES search



Point source sensitivity and constraints

South North



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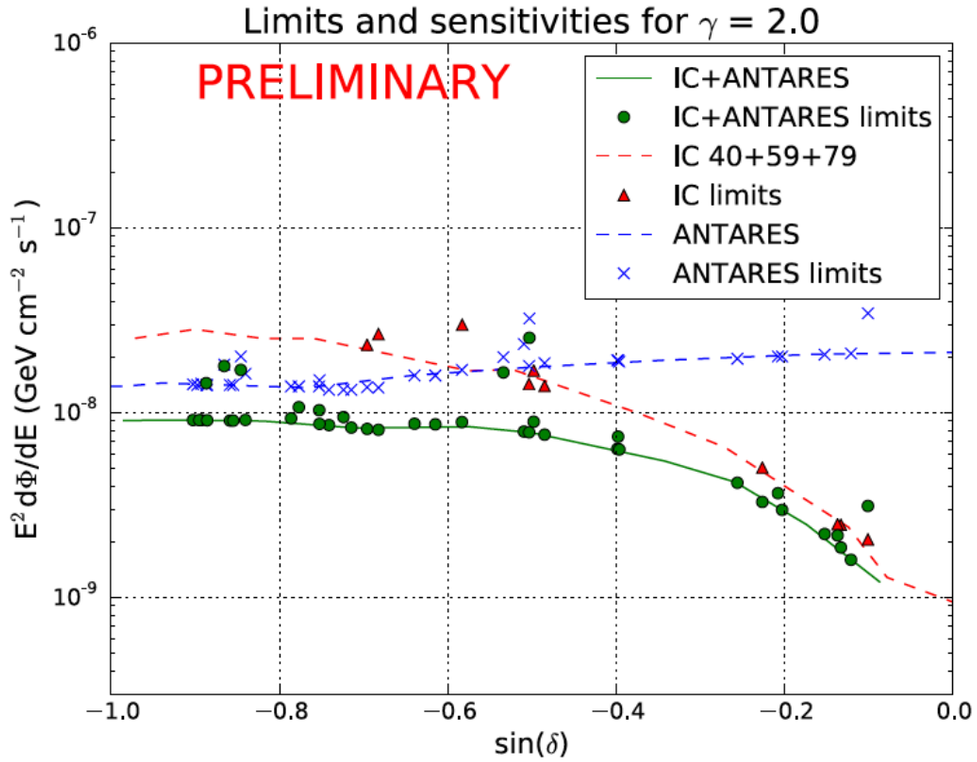
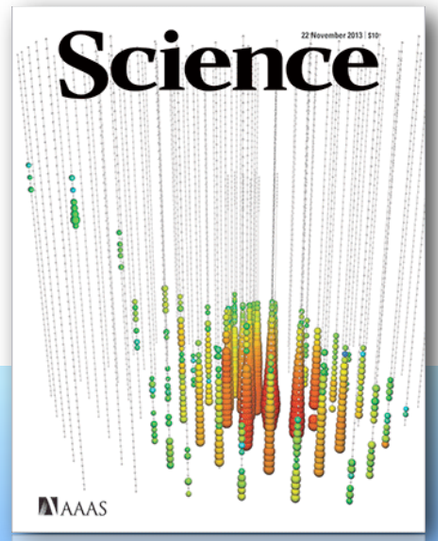
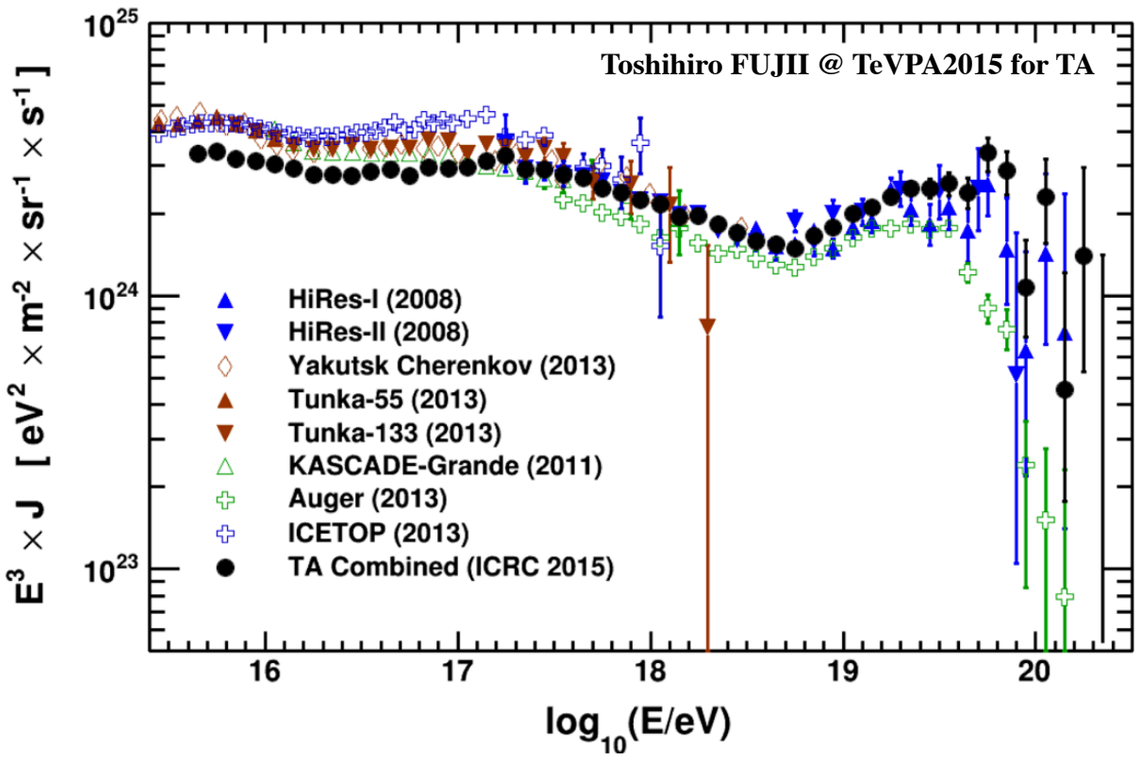
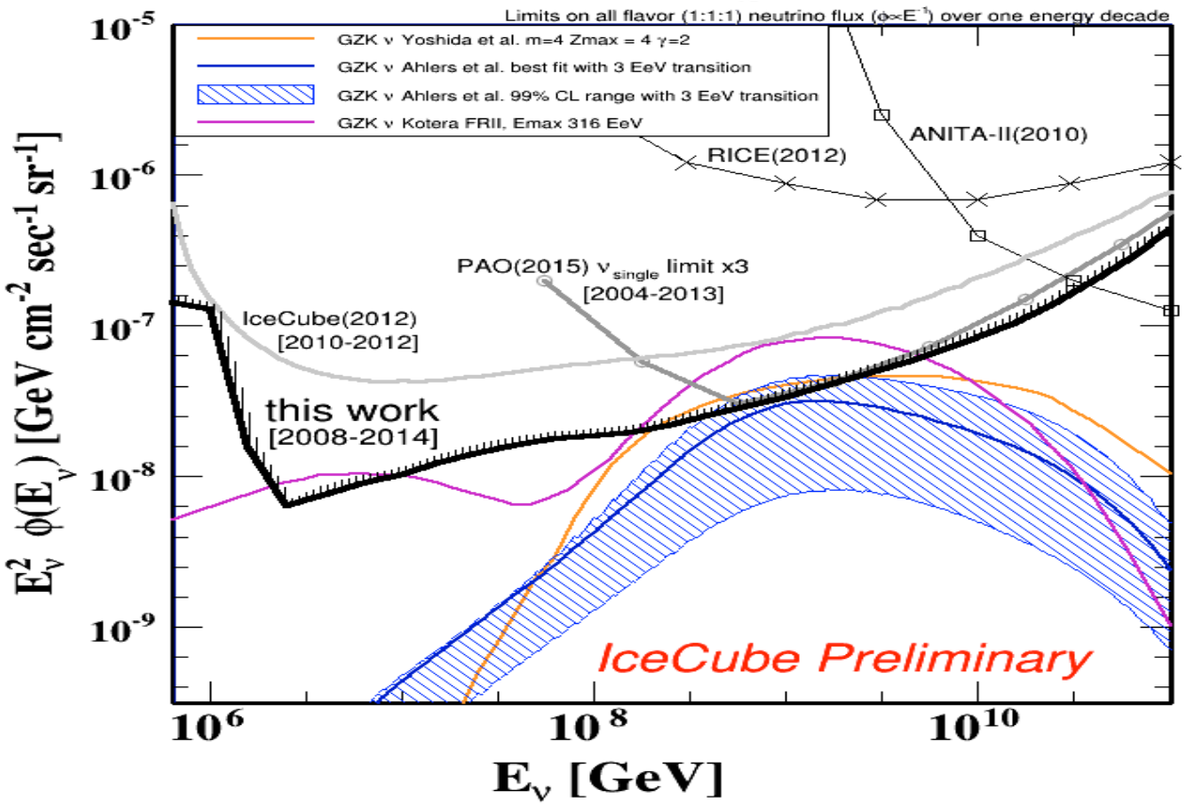




The Breakthrough

GZK Neutrino Search





Cosmogentic (GZK) neutrinos

GZK: Greisen–Zatsepin–Kuzmin

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

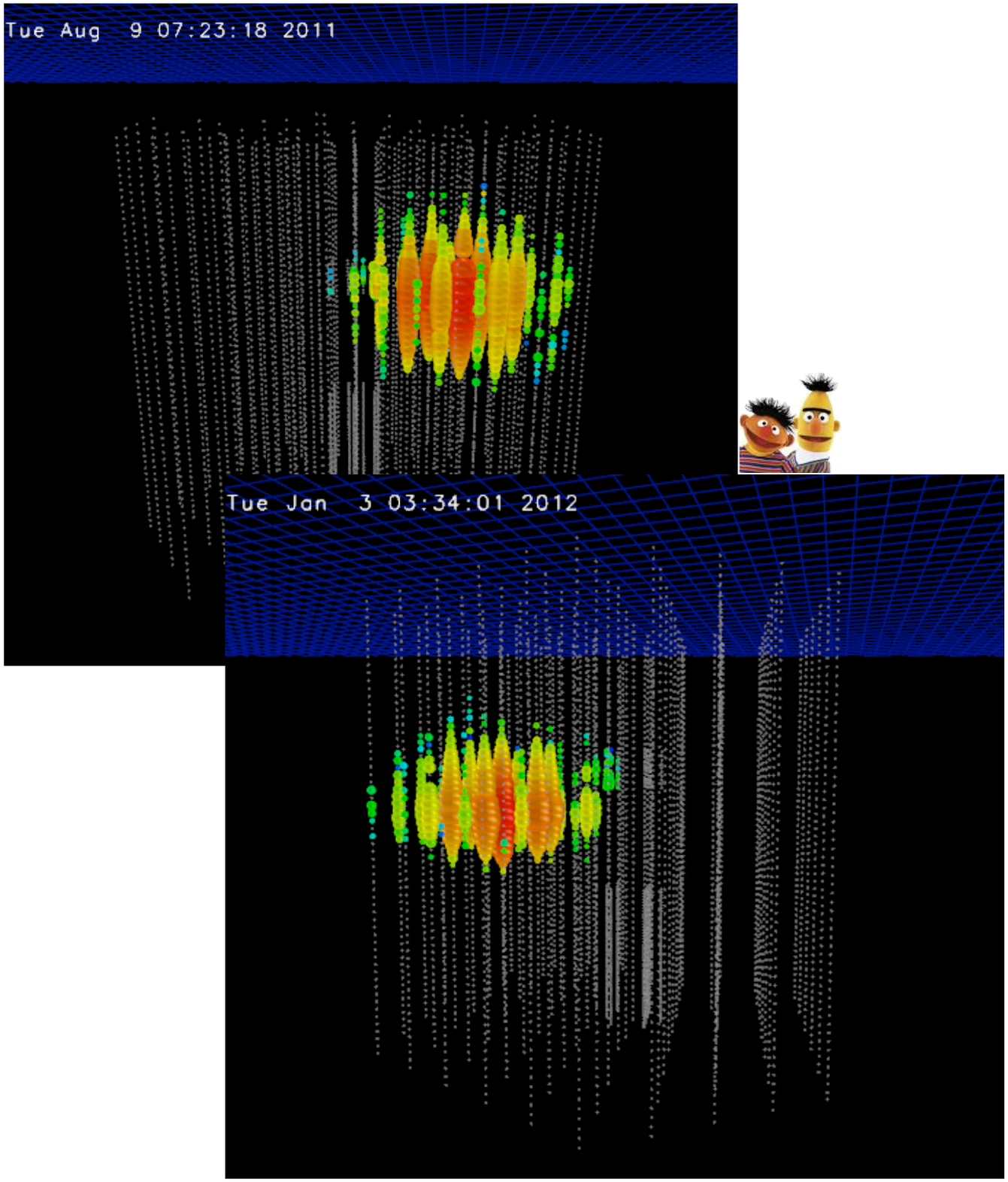
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- No evidence for GZK neutrinos, but 2012 IceCube analyses found two events in the signal region

Search for highest energy neutrinos

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



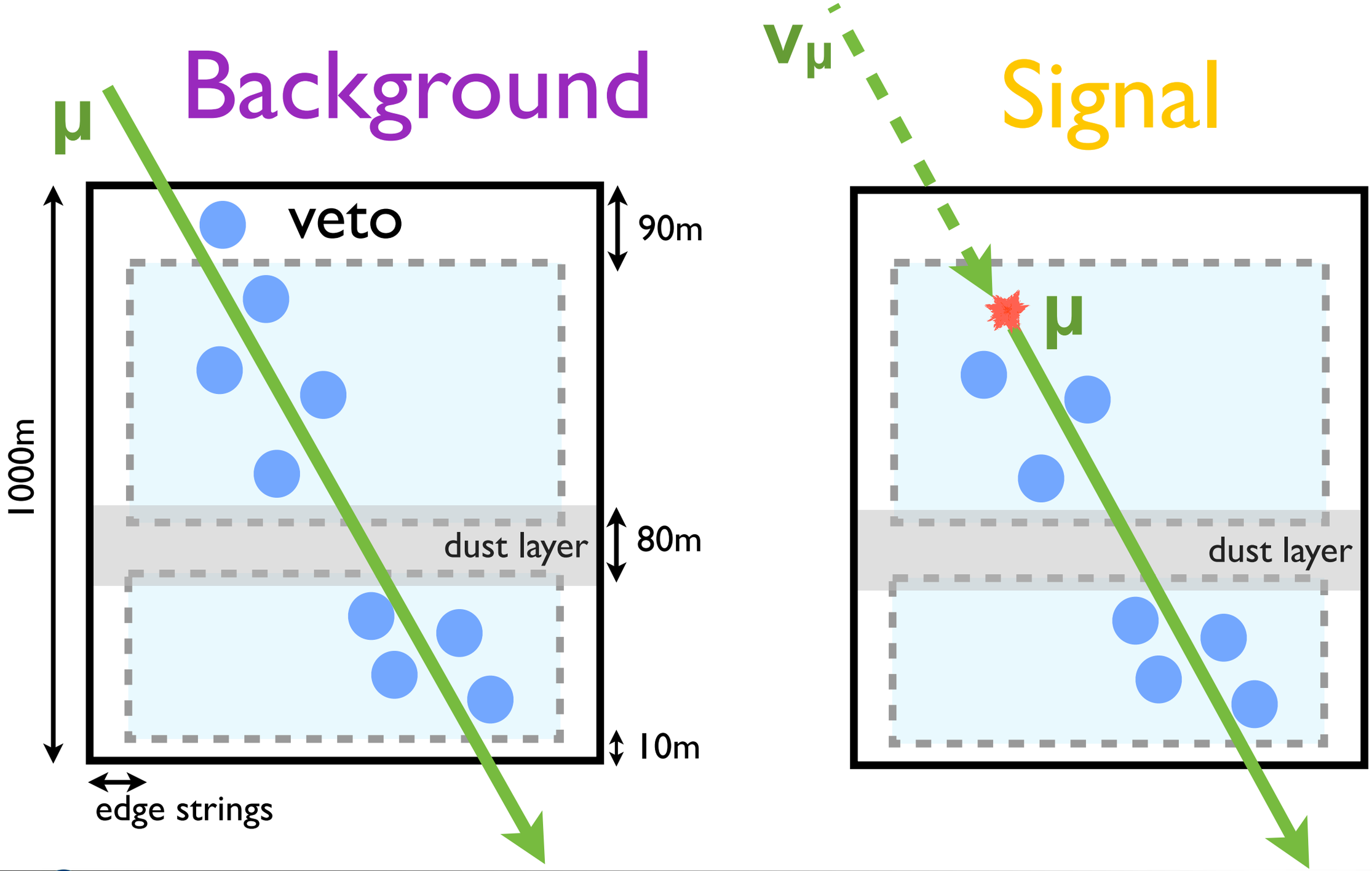
Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events (→ 2.7σ)

- 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

Ernie & Bert are not GZK, but ...

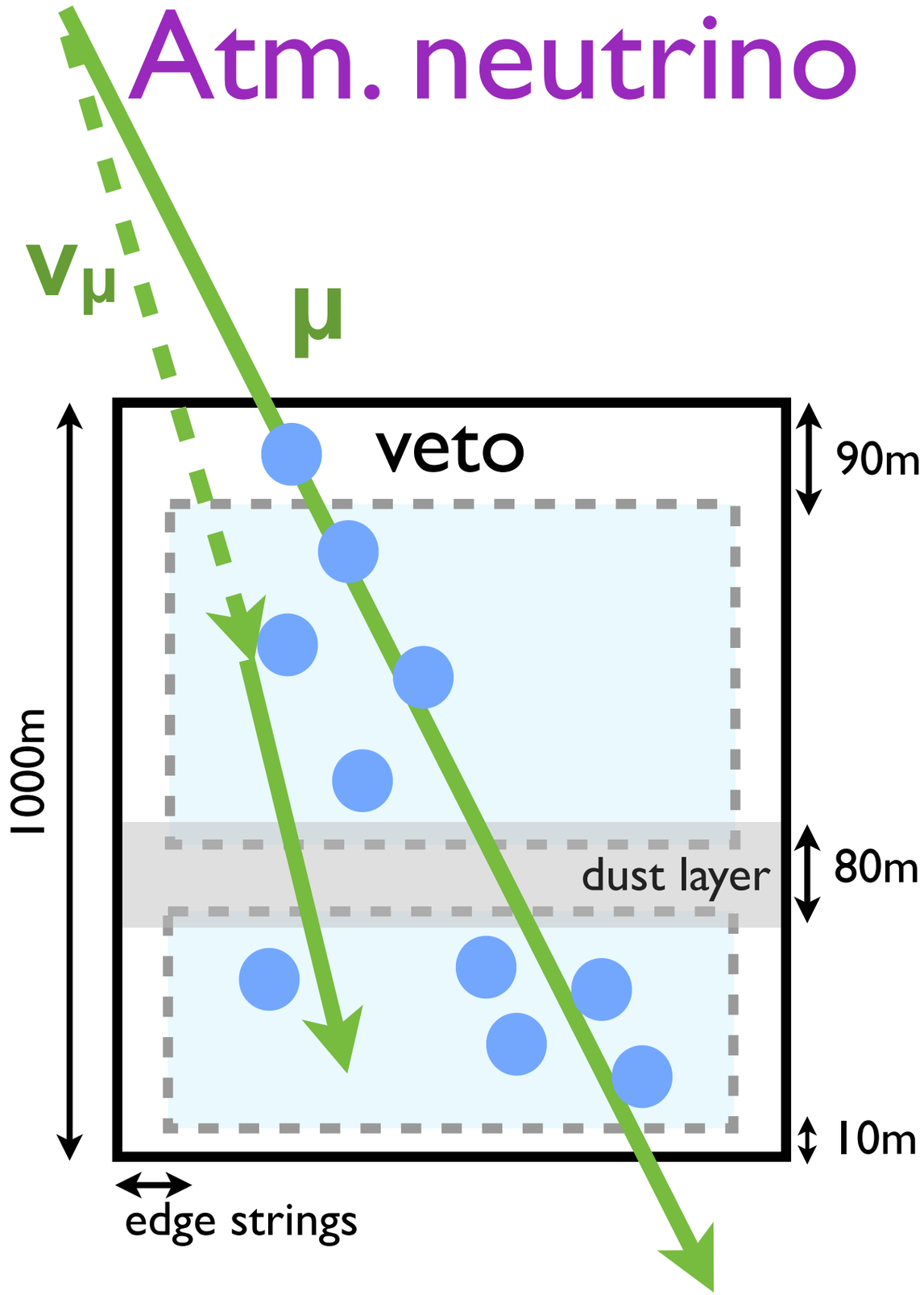
Follow up analysis to trace high-energy excess

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

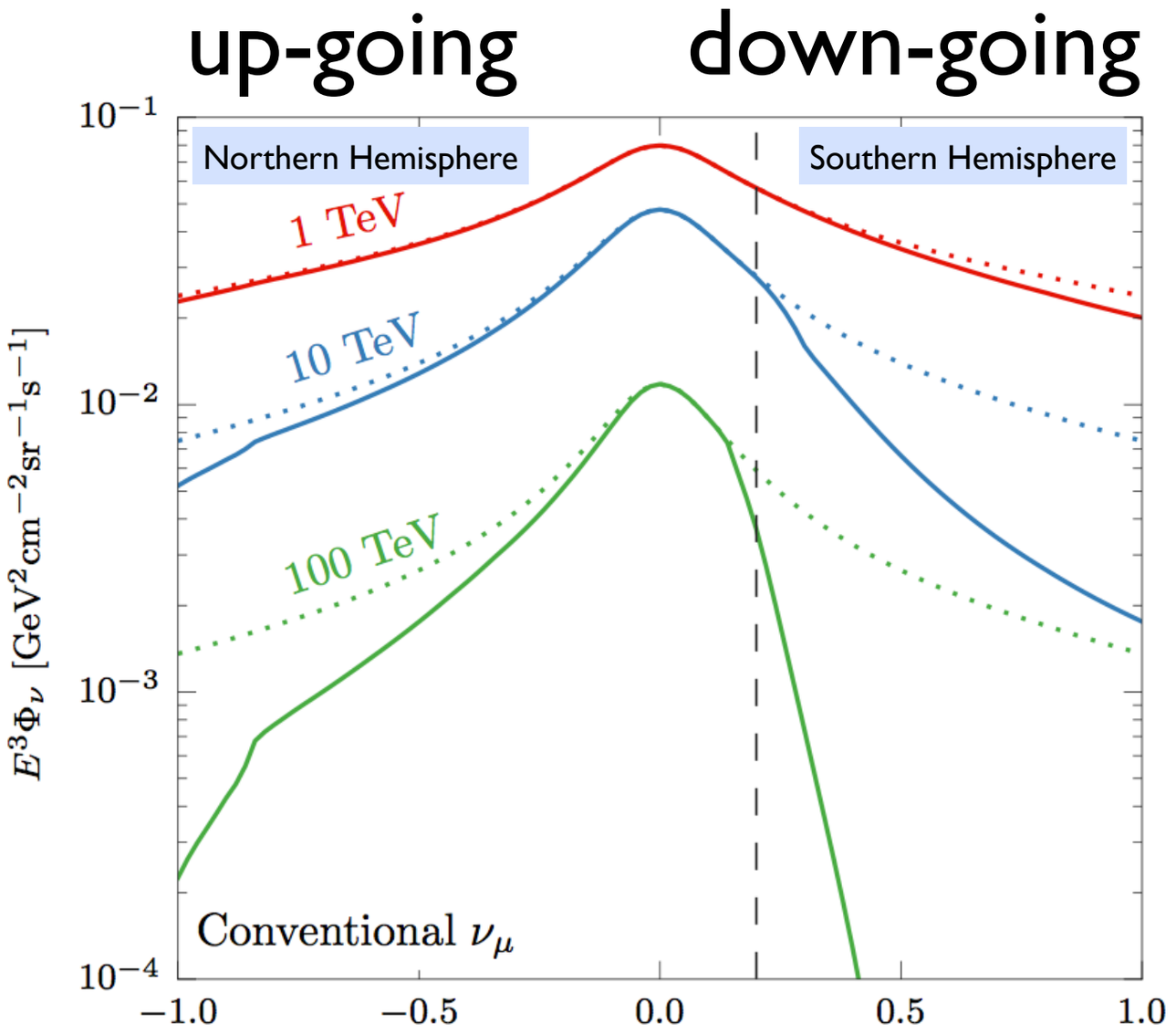


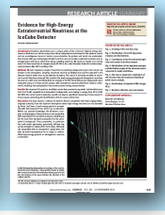
IceCube Collaboration
arxiv:1410.1749

Veto and Self-veto



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

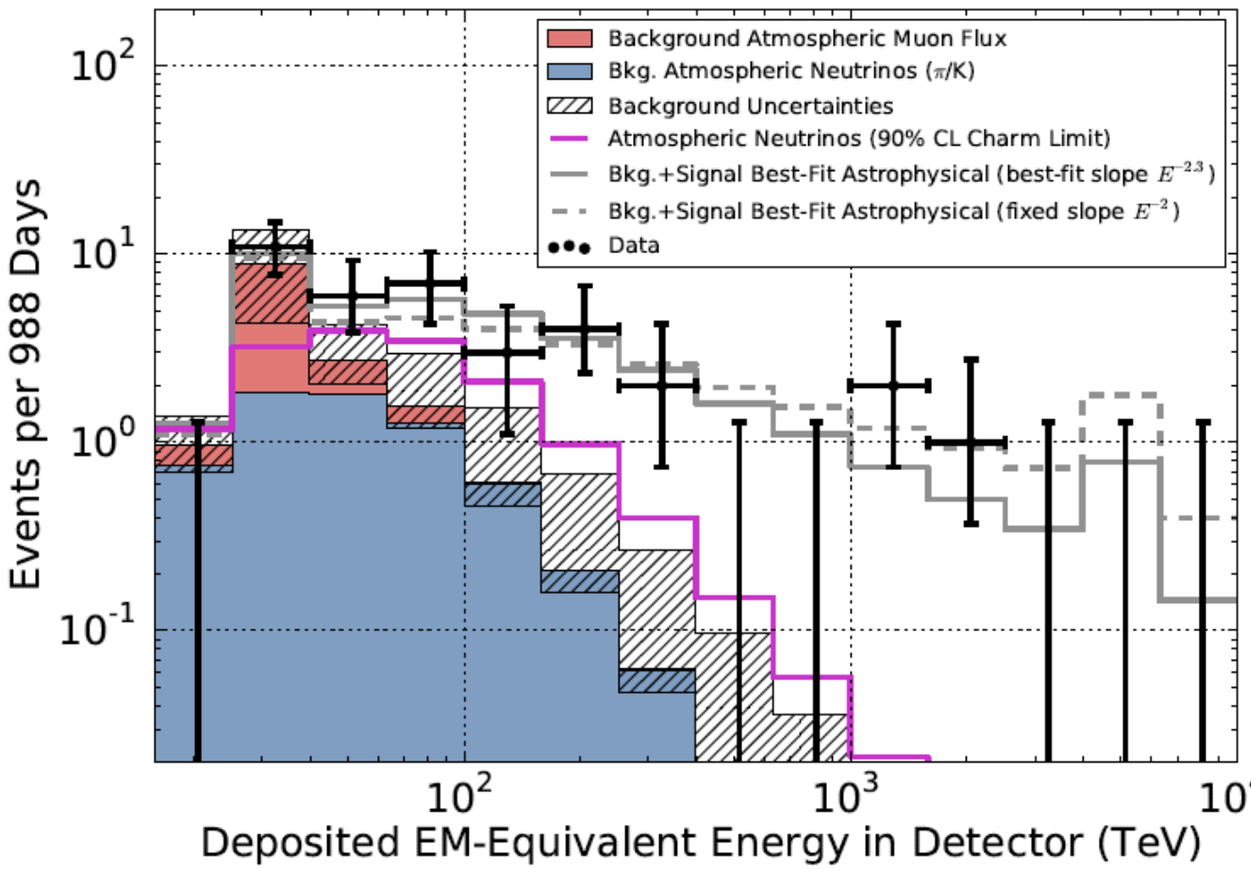


Starting event analysis

Glowing significance: 4.1σ(2y) → 5.7σ(3y) → 6.5σ(4y)

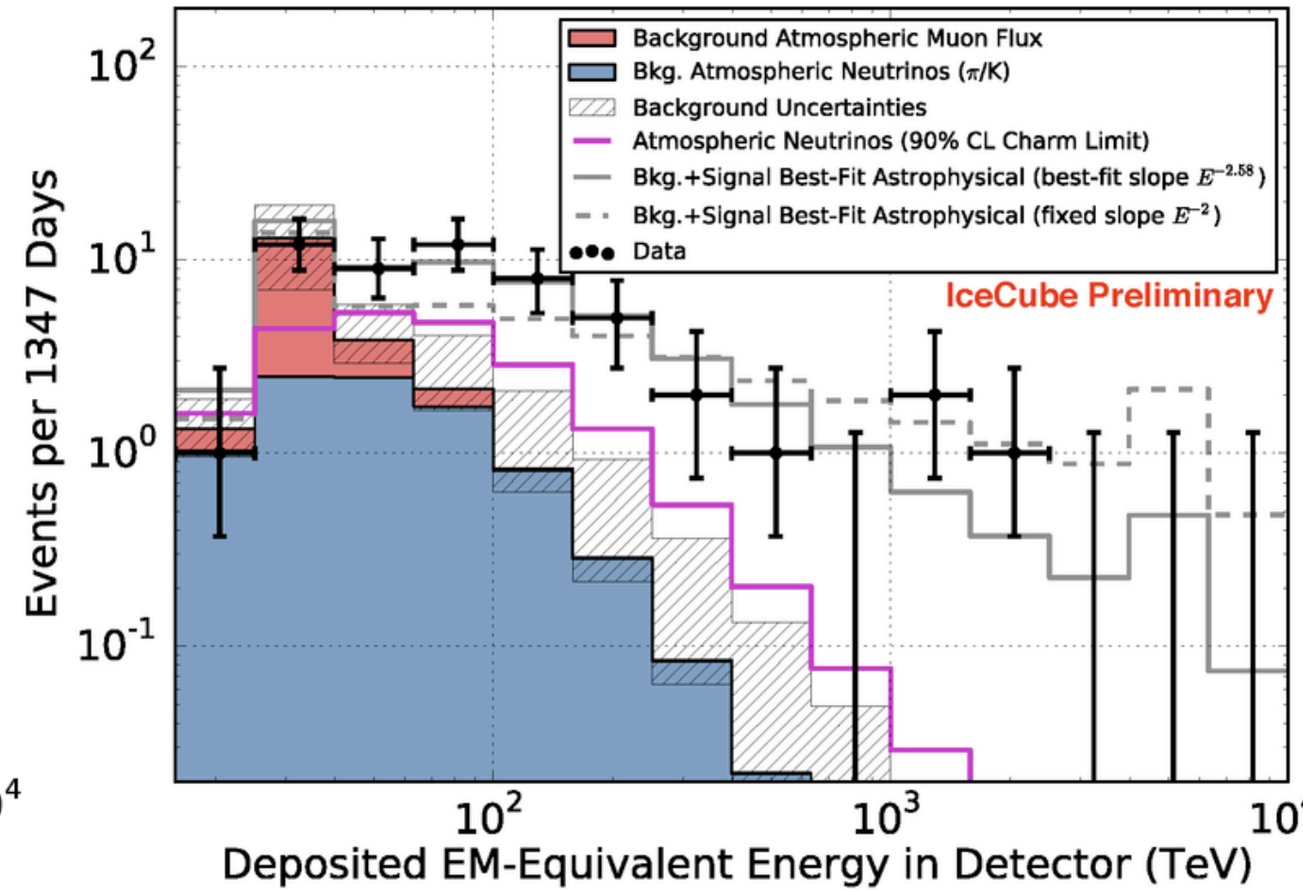
Increasing number of events: 28(2y) → 36+1(3y) → 53+1(4y)



37 events (9 track-like, 28 showers)

Expectation from conventional atm. muons and neutrinos ~15.0

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



54 events (15 track-like, 39 showers)

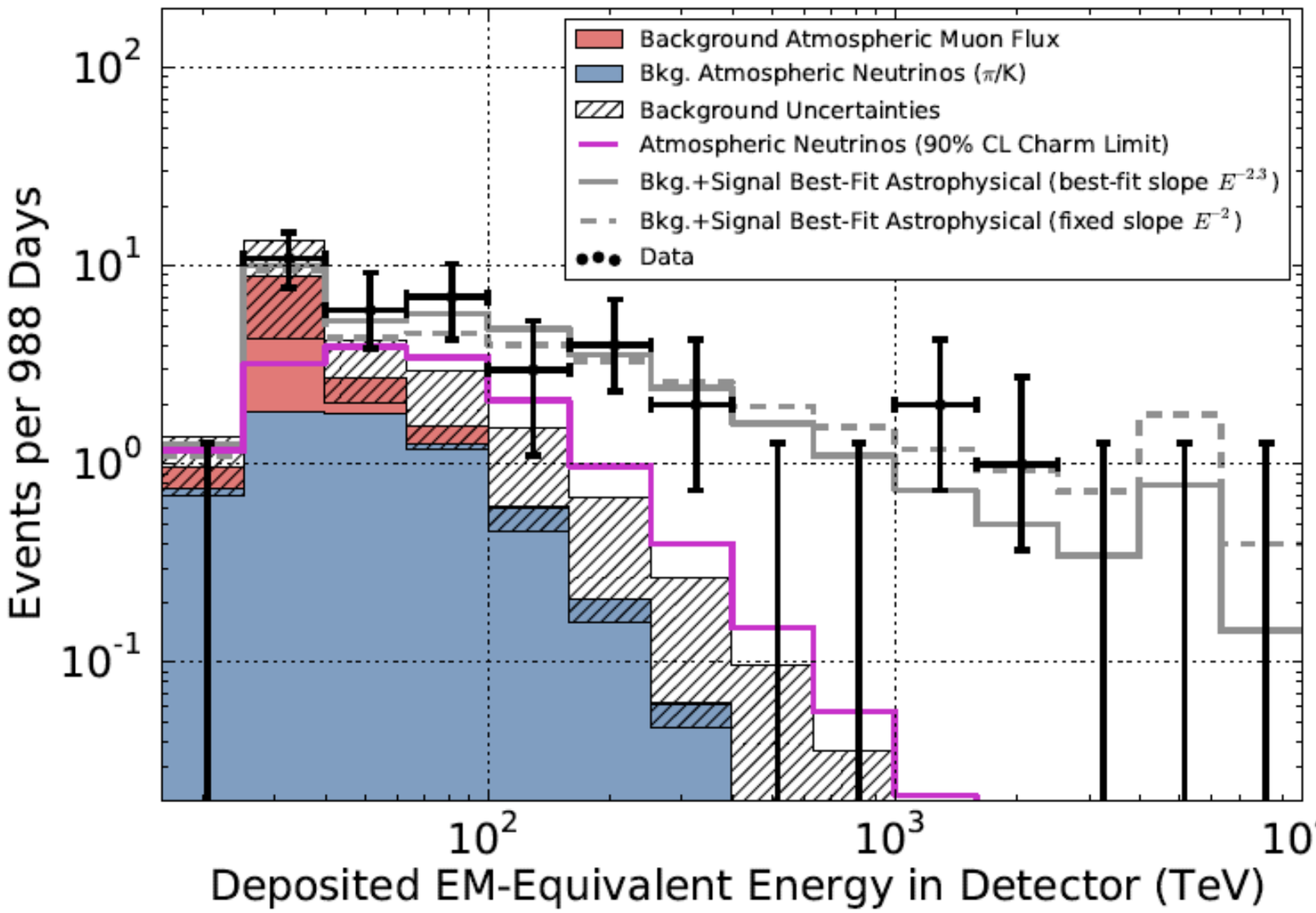
Expectation from conventional atm. muons and neutrinos ~21.6

IceCube coll. ICRC 2015 proceedings

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.

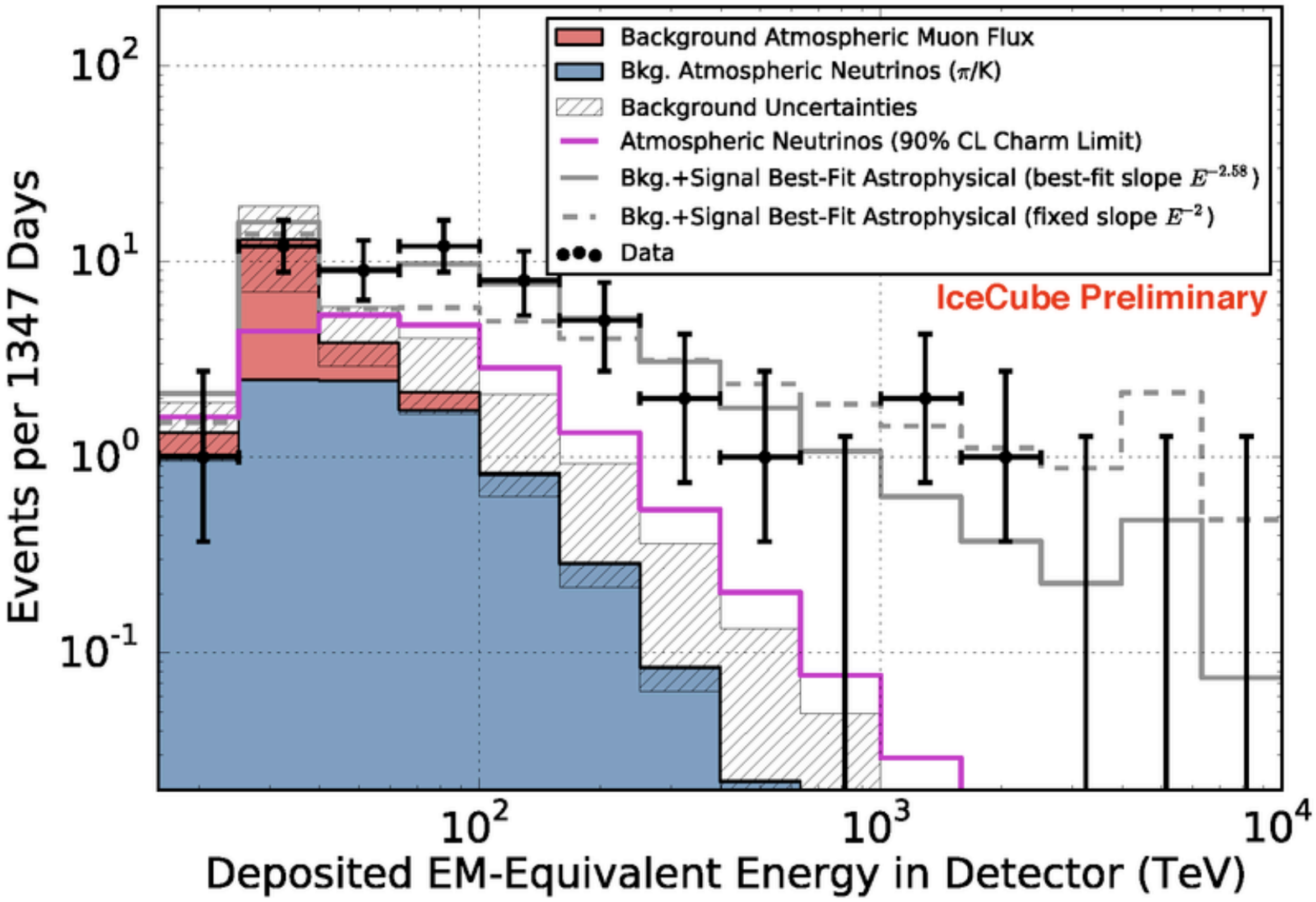
5.7 sigma rejection of atmospheric-only hypothesis

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

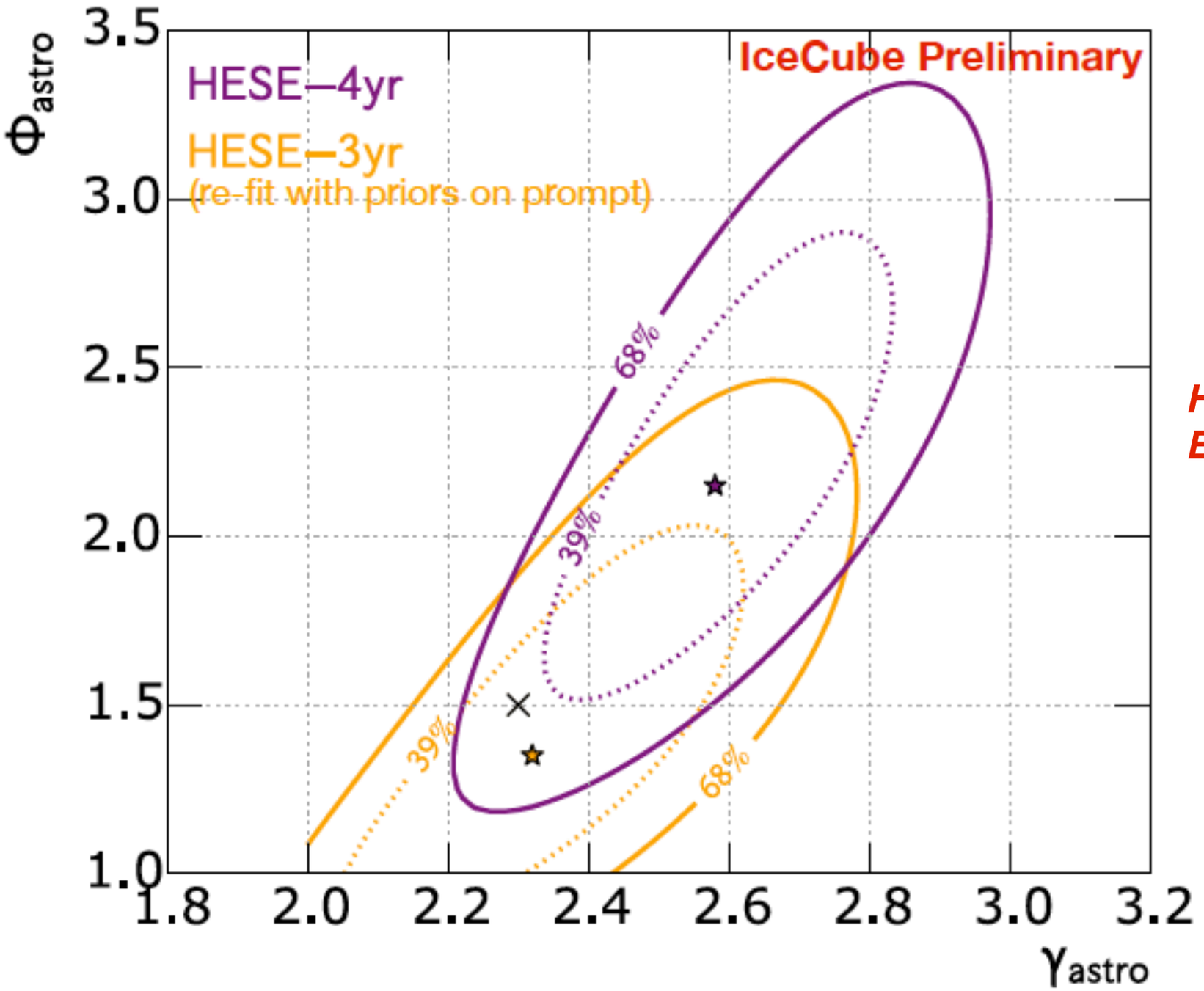


- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including 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

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

Spectral index and flux



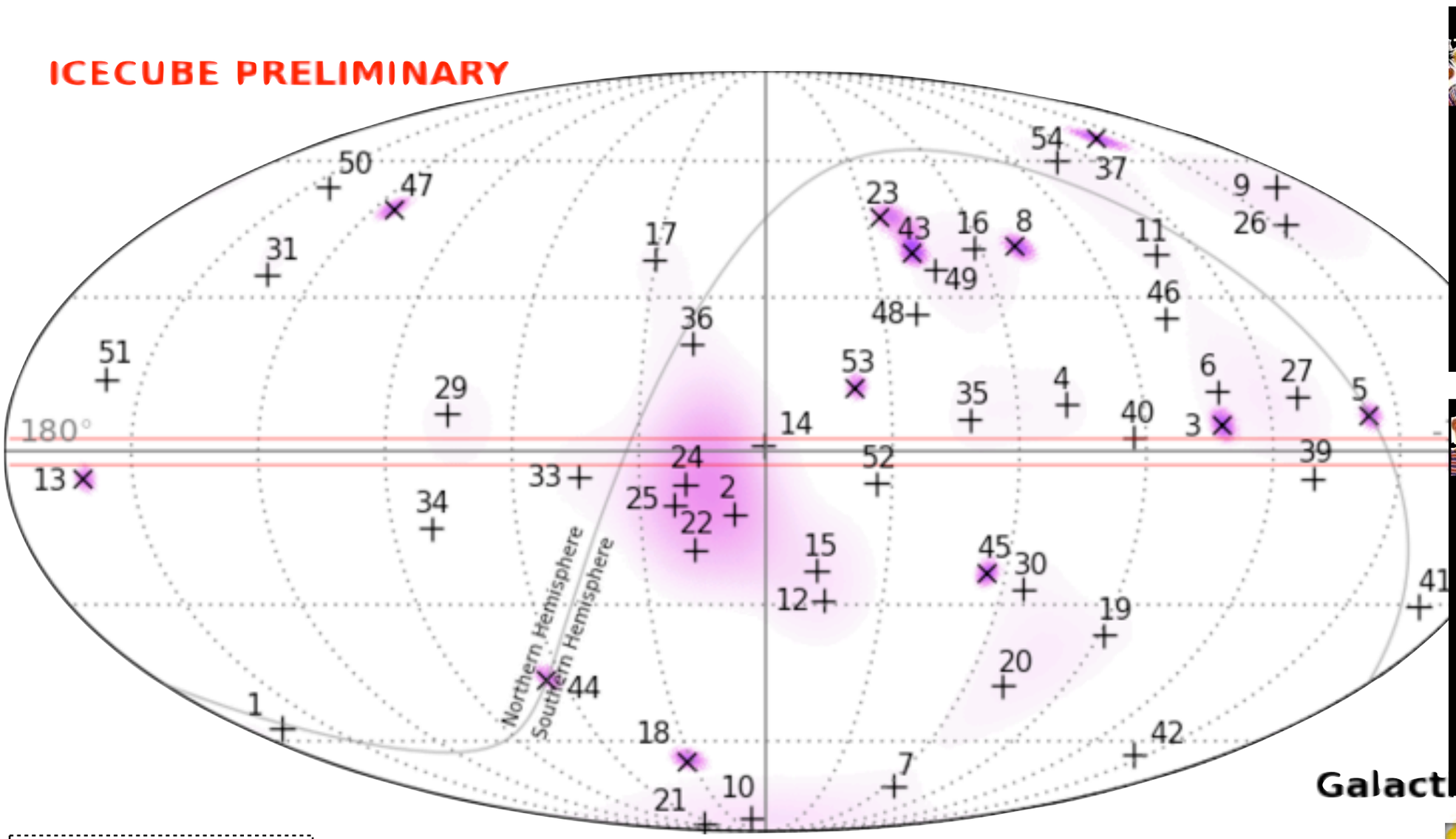
Contour plot in spectral index vs. normalization at 100TeV

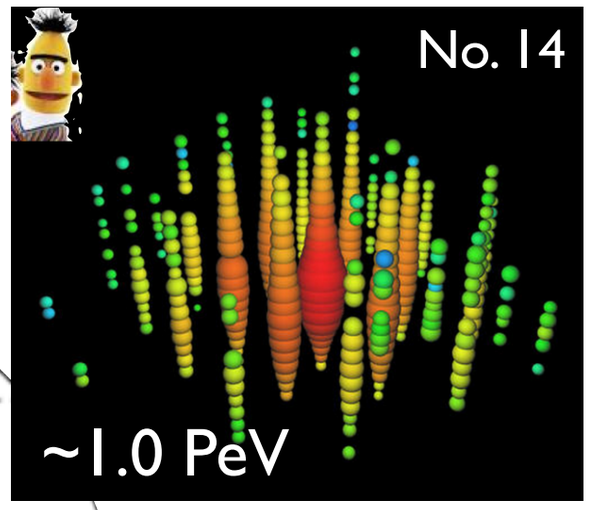
HESE-4yrs best fit flux:
$E^2\Phi$ = ~2.2 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

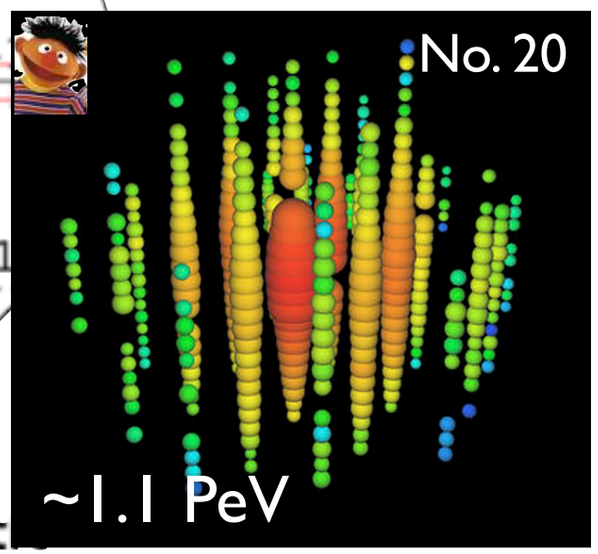
Spectral index has steepened
(no new PeV events but relatively large number in TeV)

Skymap HESE-4yrs

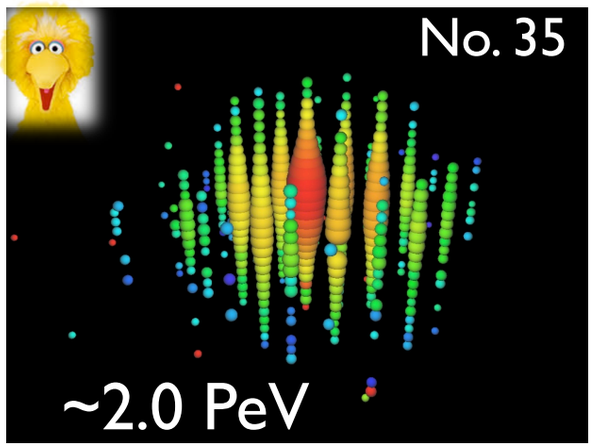
IceCube Collaboration, *Science* 342, 1242856 (2013)







Galact



no significant correlations -- spacial or temporal

p-value for cascade events "clustering" 18%

Can we make an independent confirmation of the "Observation of Astrophysical Neutrinos"

ANTARES Diffuse Search

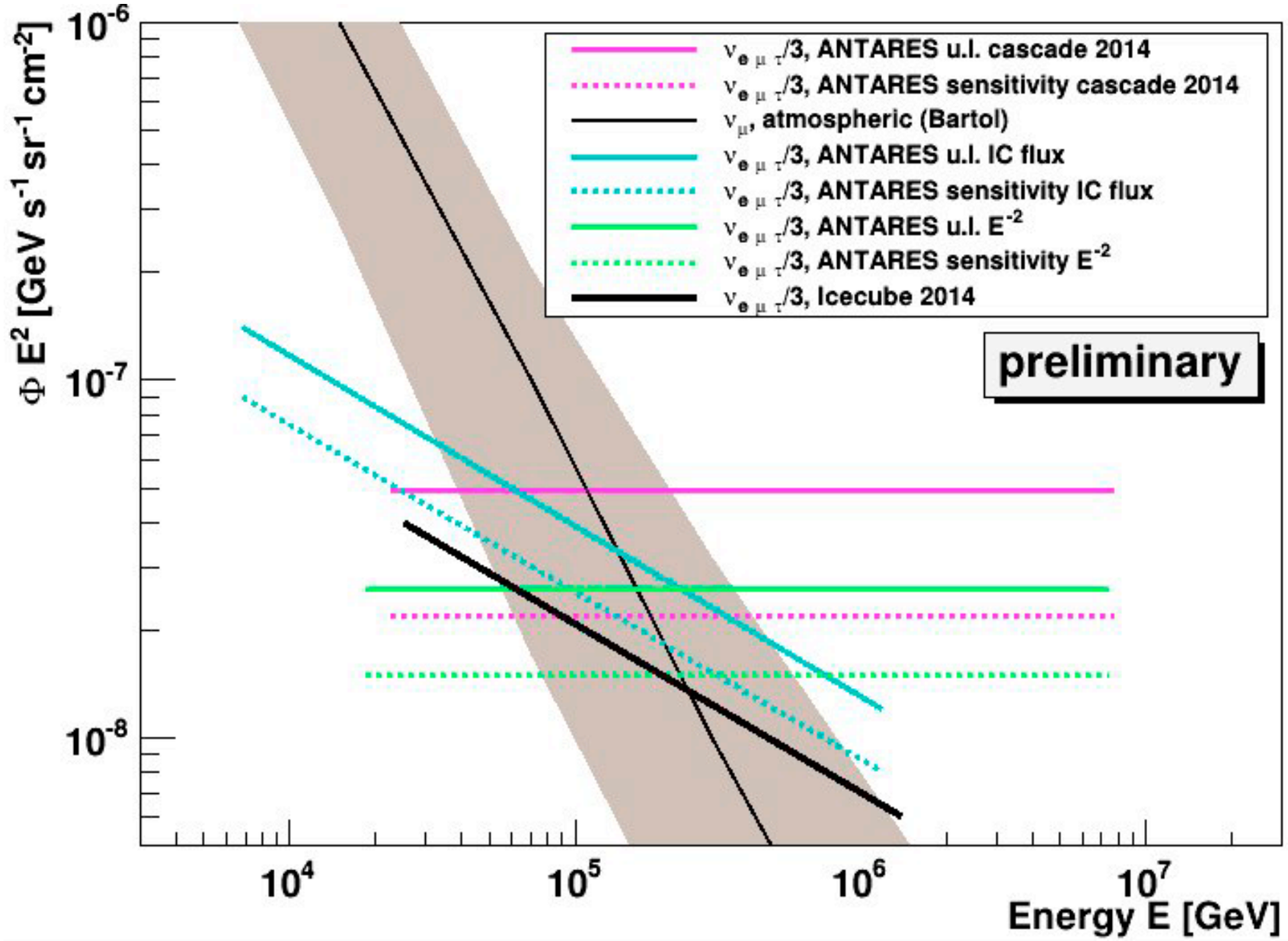
J. Schnabel ICRC2015

Expected events:

- Background: 9.5 ± 2.5
- Astrophysical: 5.0 ± 1.1

Observed:

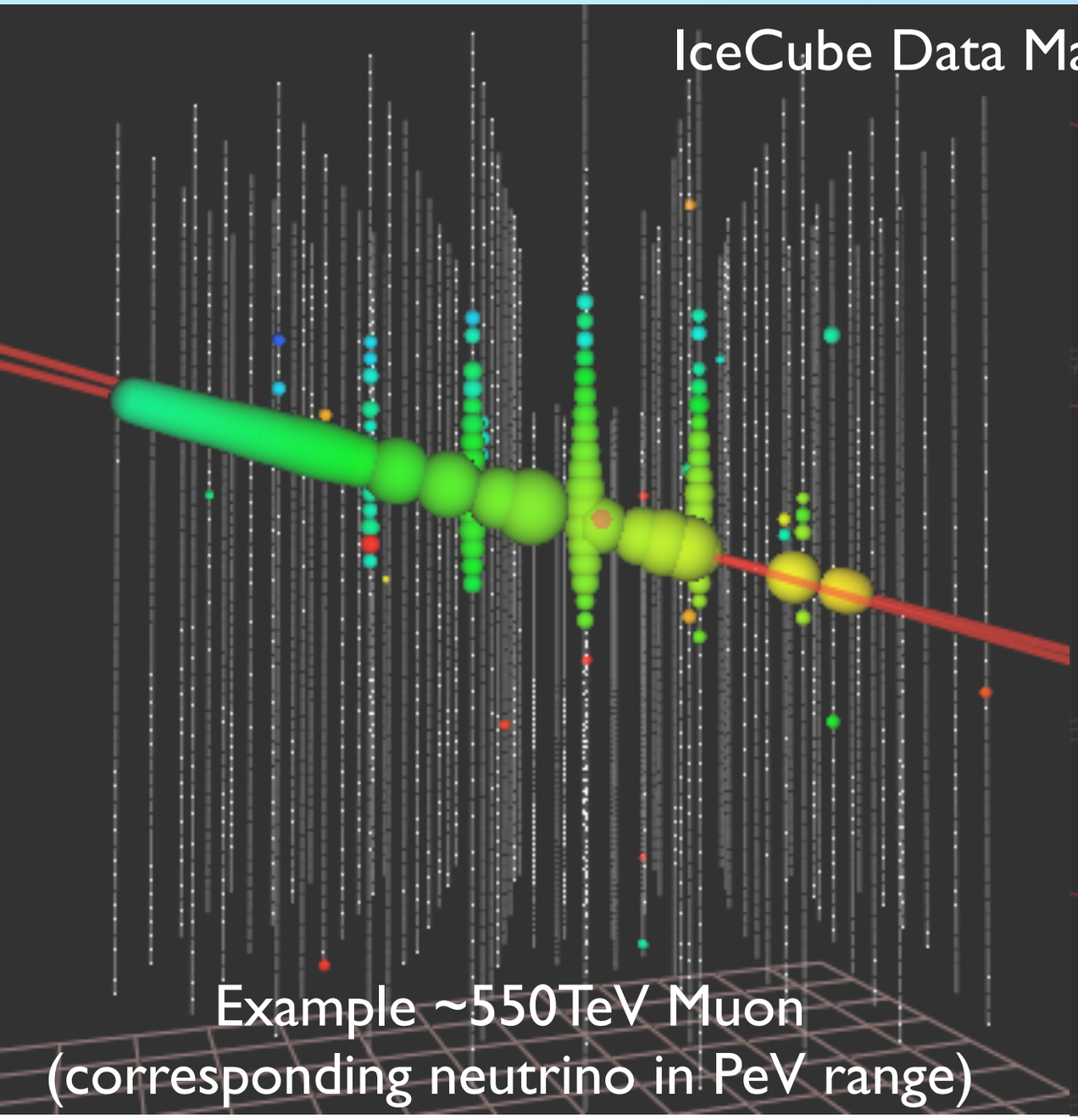
- 12 events



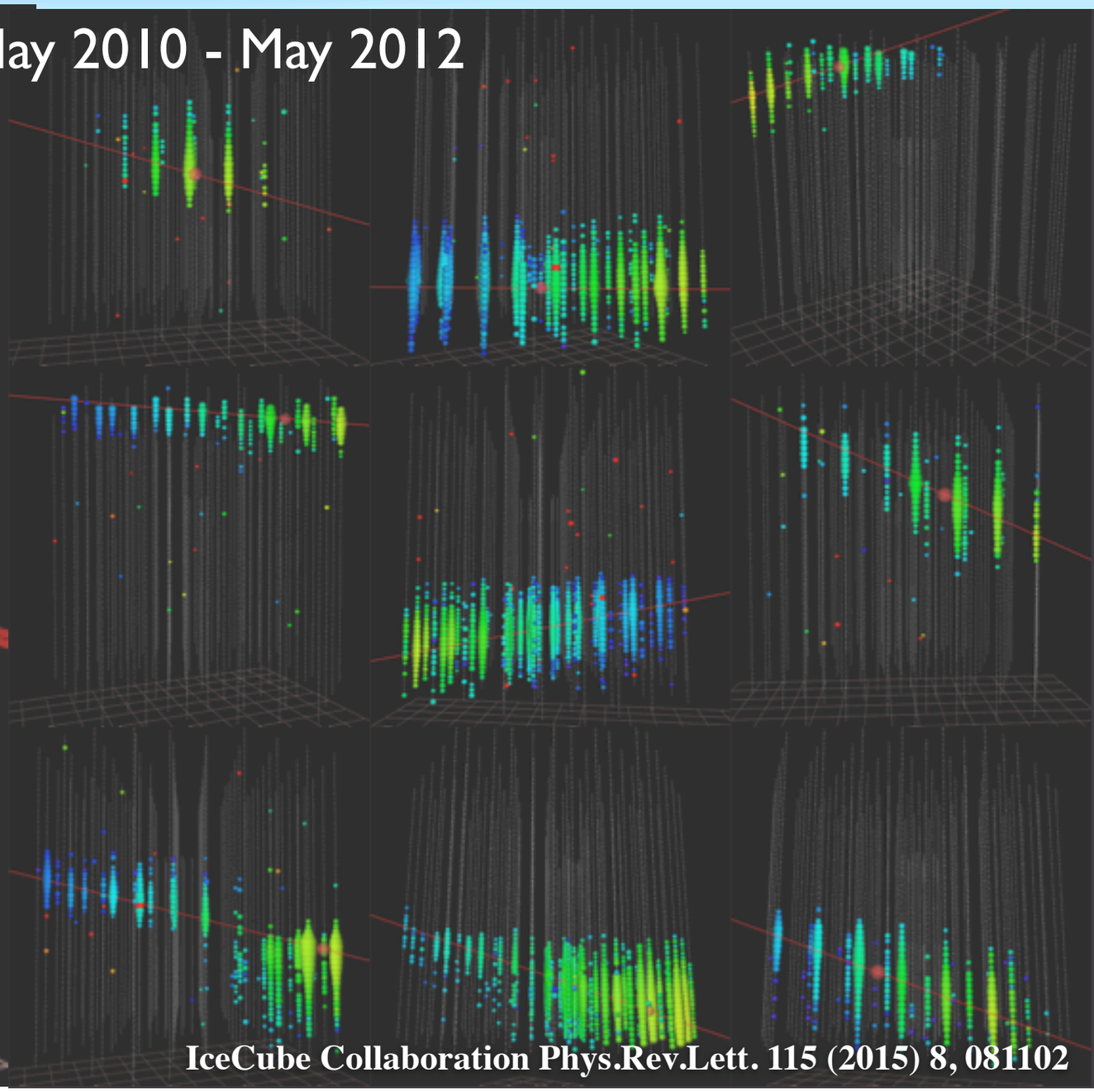
- Results:
  - Consistent with background
  - Consistent with IceCube

IceCube -- Through-going muons

IceCube Data May 2010 - May 2012



Example ~550TeV Muon
(corresponding neutrino in PeV range)



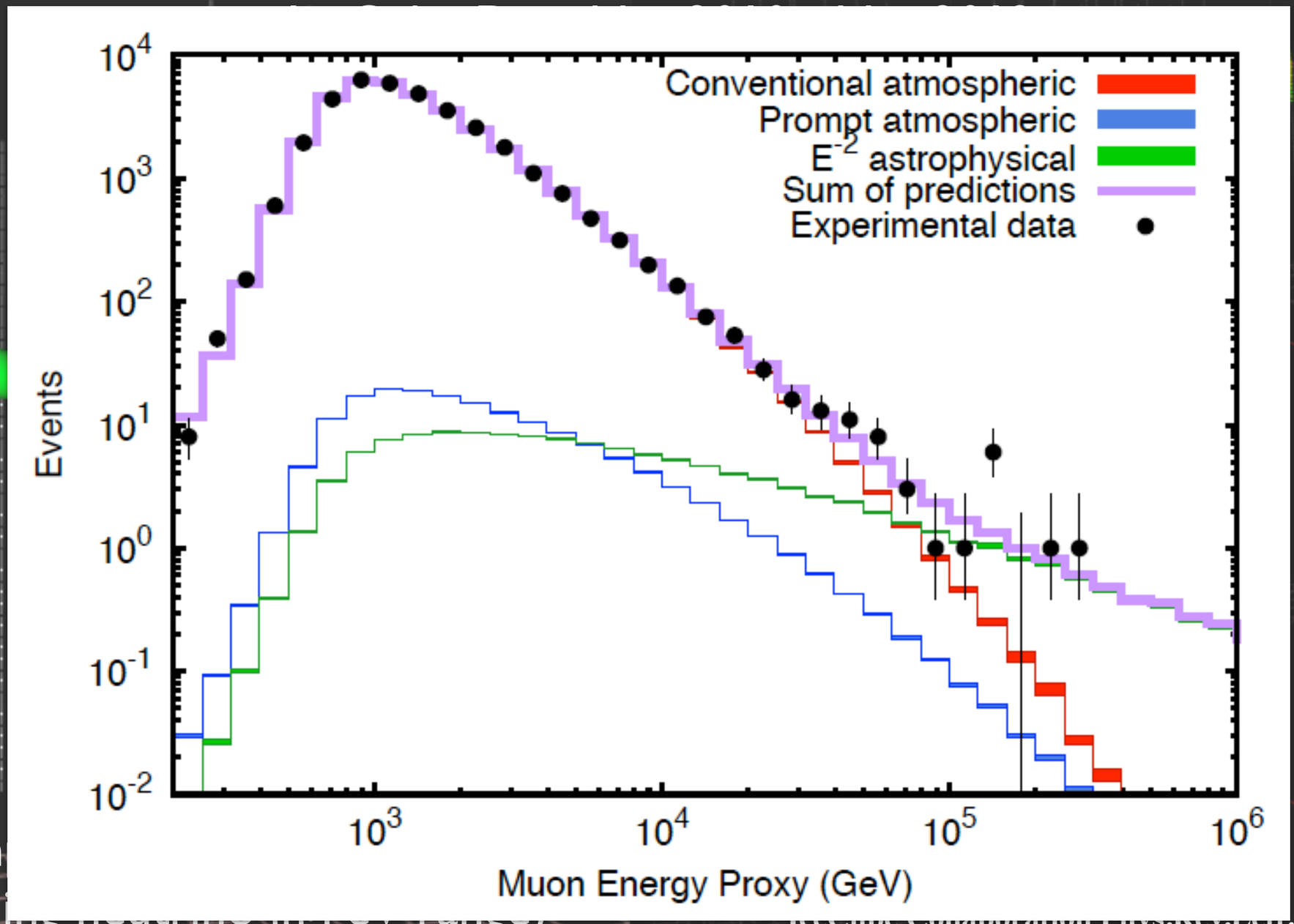
IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

Highest energy events are inconsistent with a hypothesis of solely terrestrial origin at **3.7σ**

Best fit astrophysical flux consistent with High-Energy Starting Events

Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}$ 10^{-8} E^{-2} GeV cm^{-2} s^{-1} sr^{-1}

Through-going muons



Exam
(correspondi

IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

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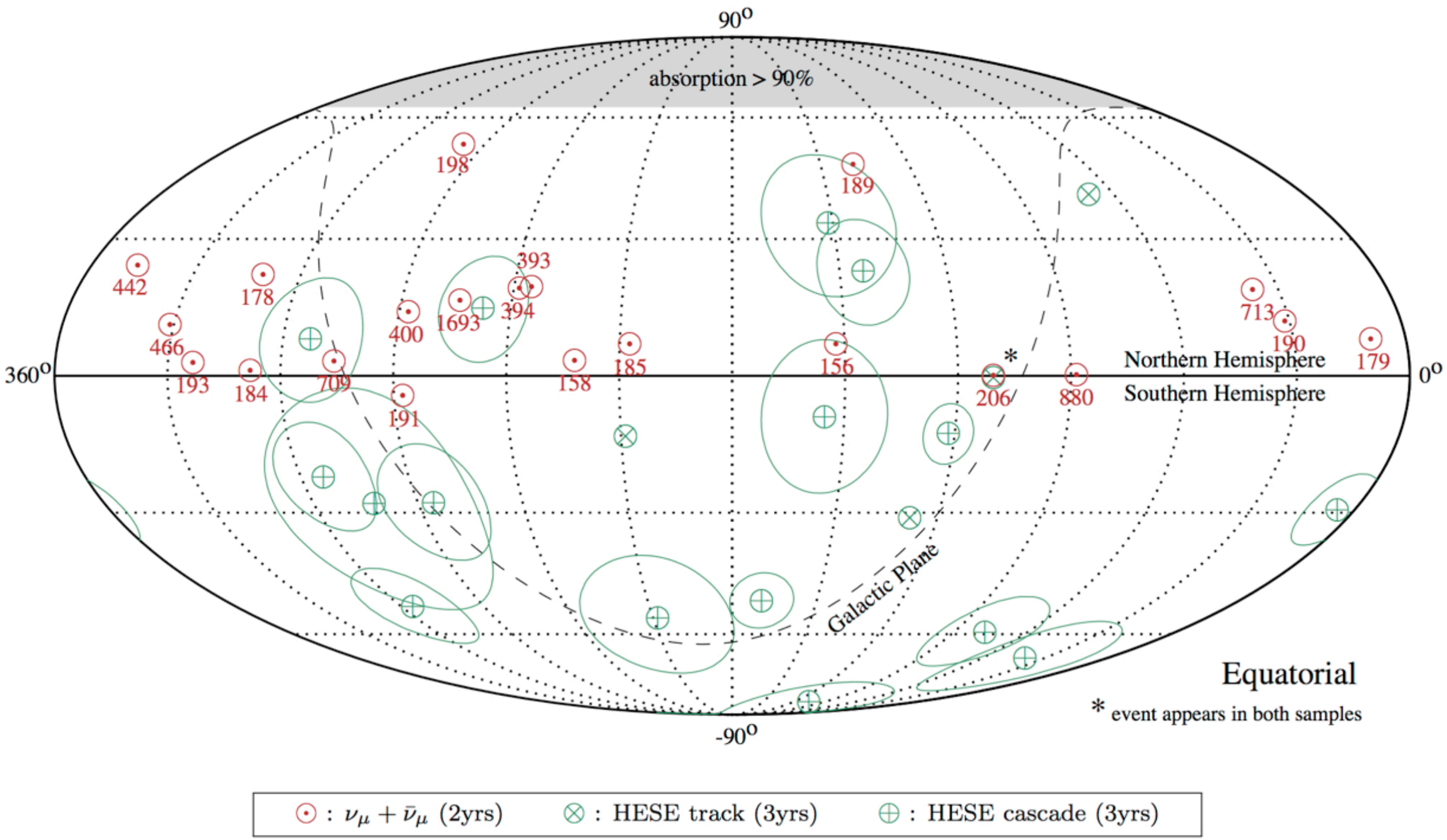
IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

Up-going muons + HESE

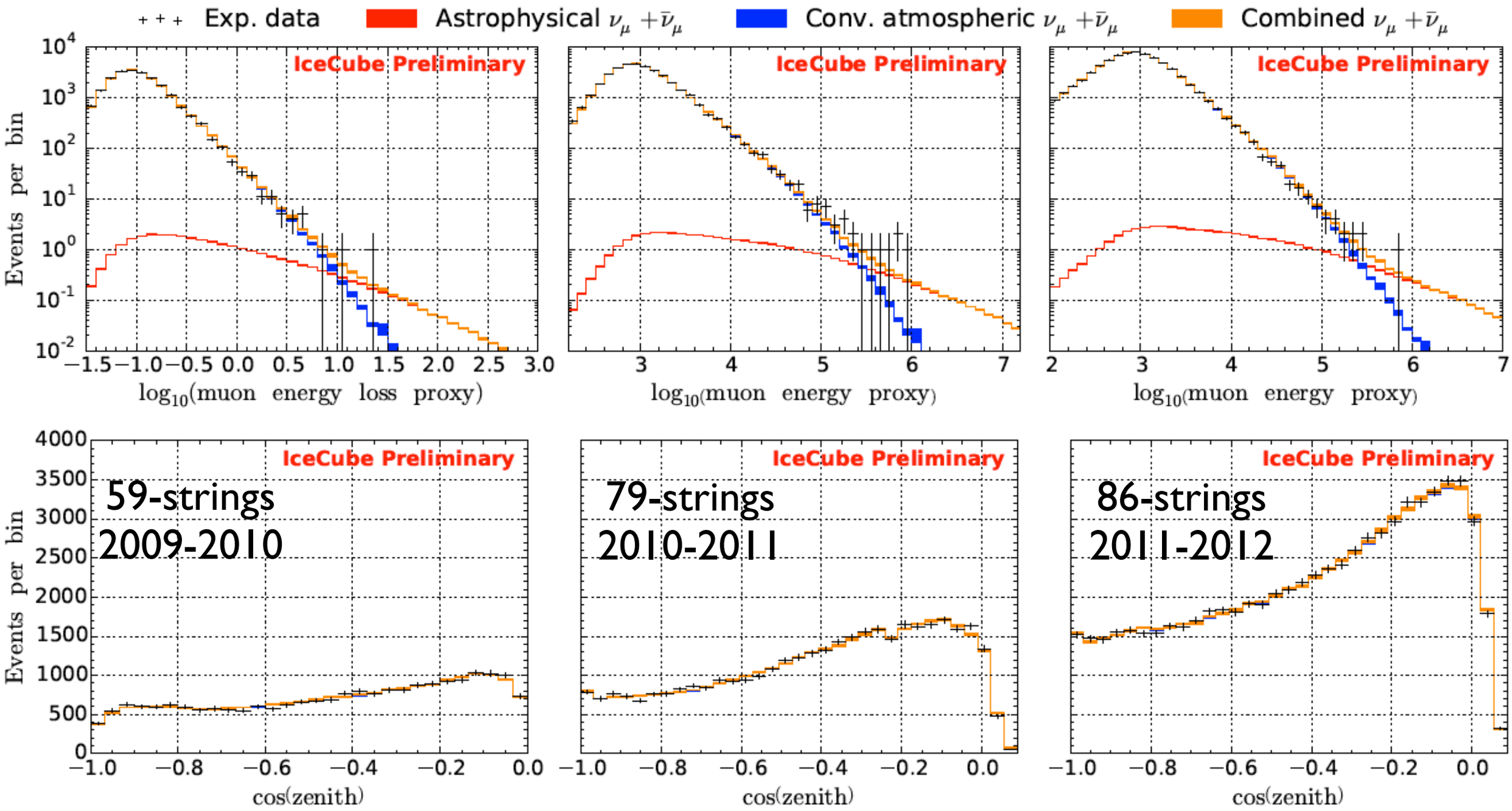
http://icecube.wisc.edu/news/view/348



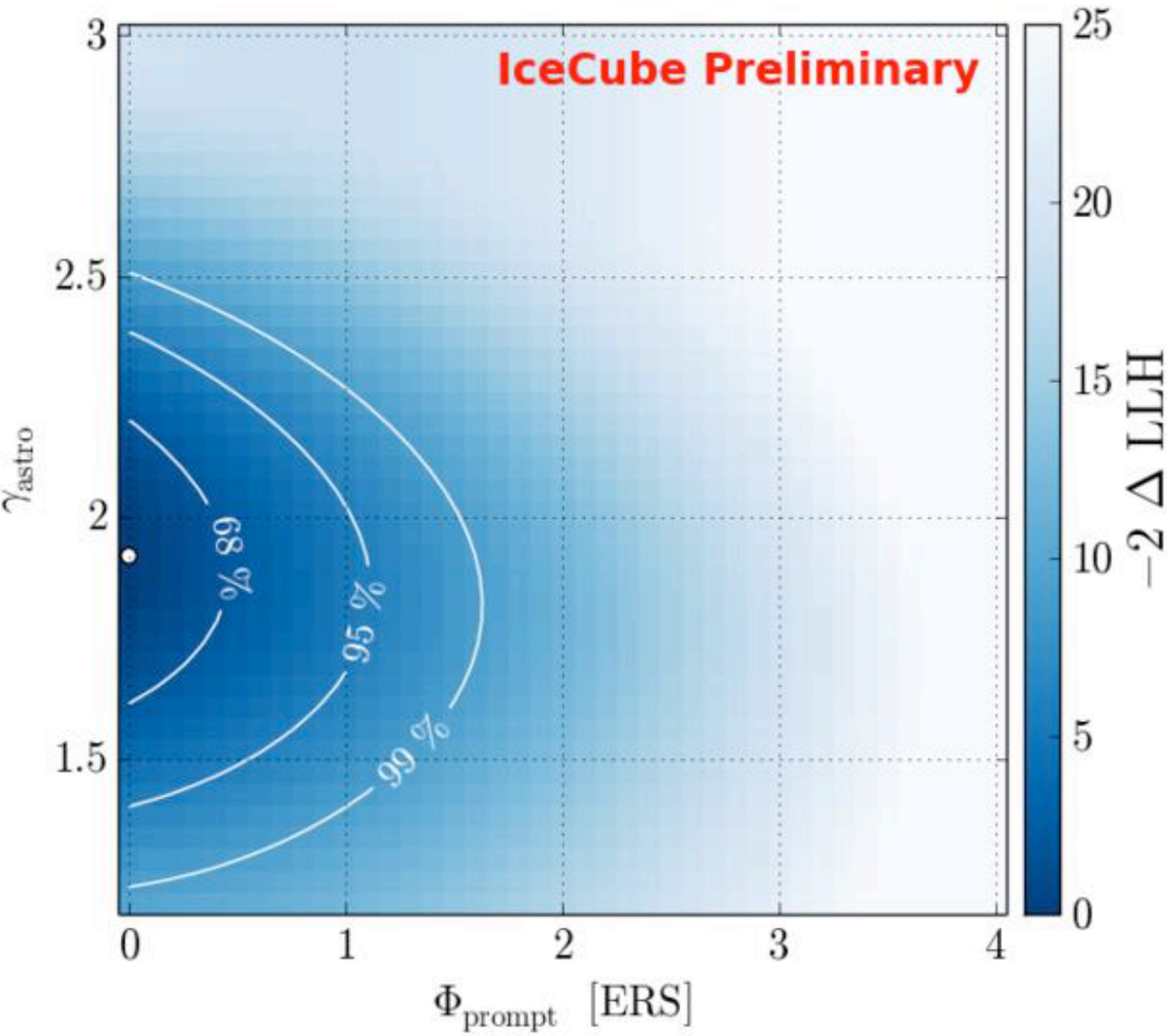
Sky map in equatorial coordinates of the arrival direction of the 21 highest-energy events of this analysis (red dotted circles). The most probable neutrino energy (in TeV) indicated for each event assumes the best-fit astrophysical flux of the analysis. For comparison, the events of the 3-year high-energy starting event (HESE) analysis with deposited energy larger than 60 TeV (tracks and cascades) are also shown. Cascade events are indicated together with their median angular uncertainty (thin circles). Image: IceCube Collaboration

Through-going muons

- Preliminary Results on 6years of IceCube muon data
  - 3 years reanalyzed and extending to 6 years



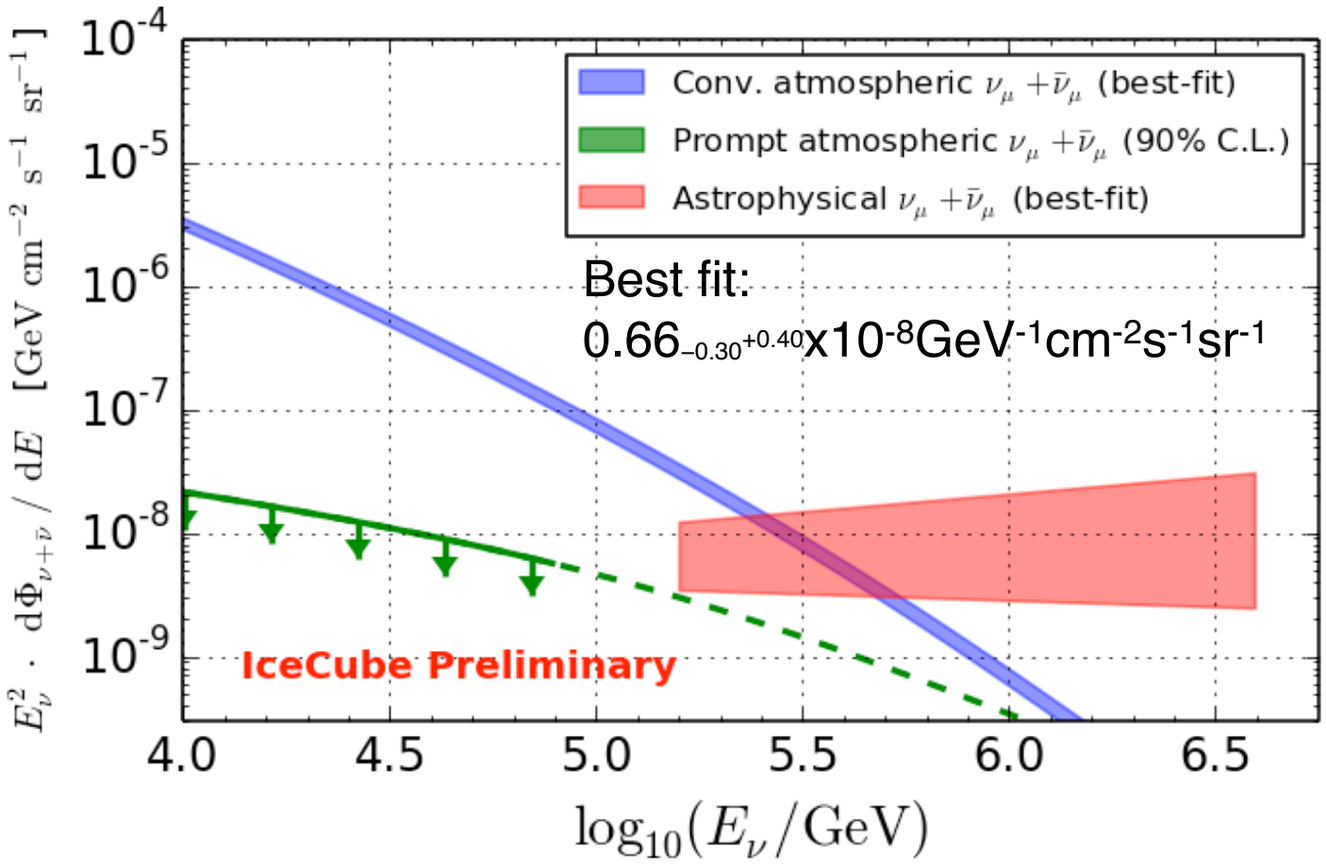
Astrophysical Spectral index and flux



Best-fit spectral index:

γ_{astro}=1.91±0.20

Measured astrophysical spectral index nearly independent of the prompt normalization



Energy region:

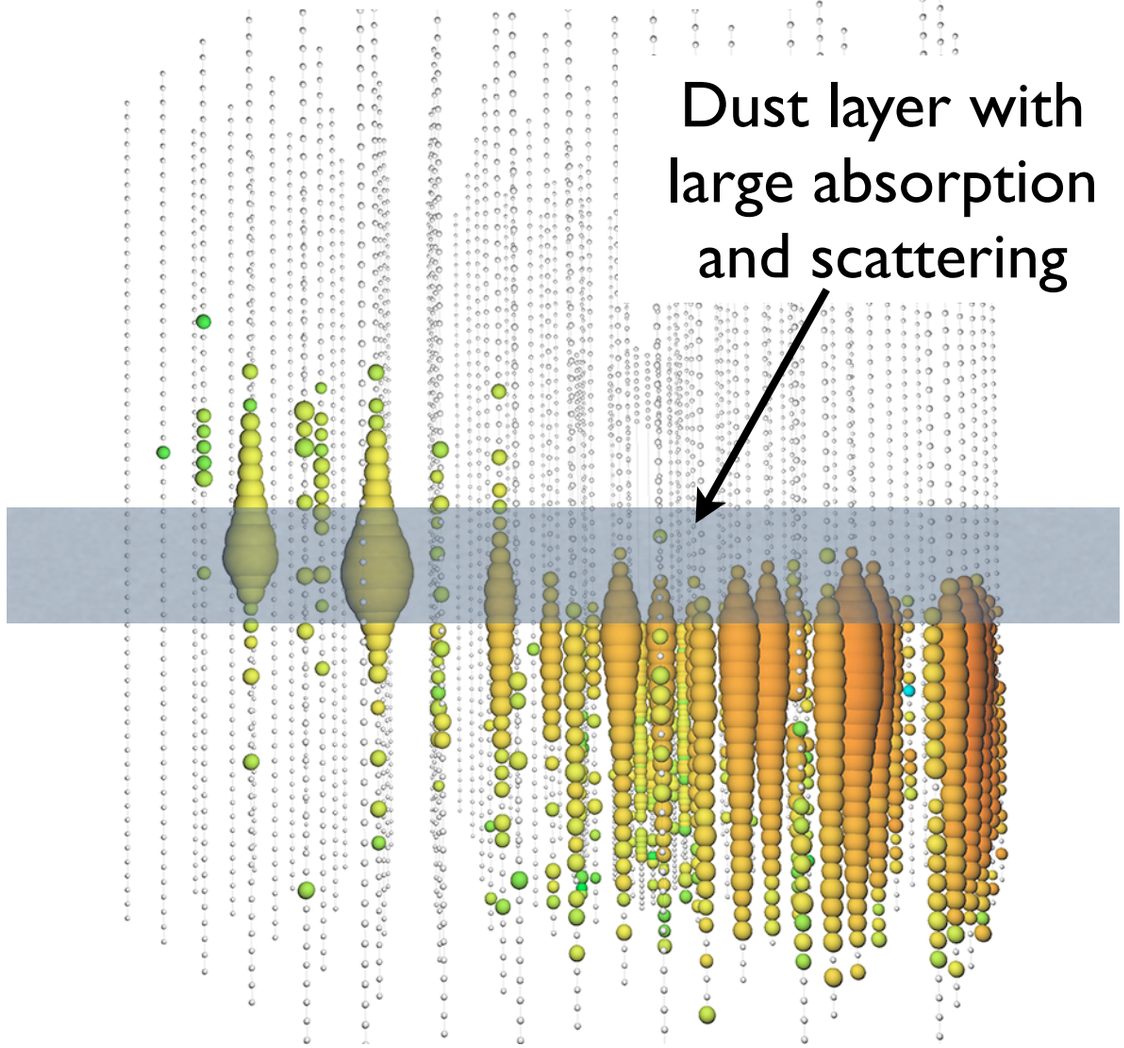
E_ν = 170TeV - 3.8PeV

Independent confirmation of astrophysical signal observed in IceCube HESE Analysis

Atmospheric-only hypothesis excluded by 4.3σ with three years

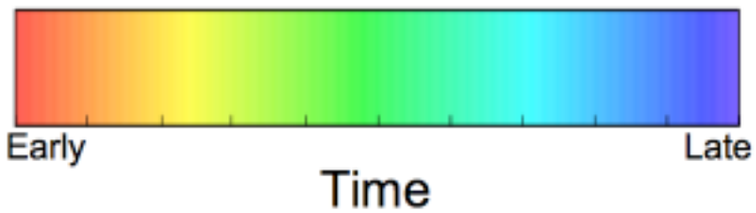
Multi-PeV Track Event

track-like neutrino event
E_{dep}= 2.6 ±0.3 PeV



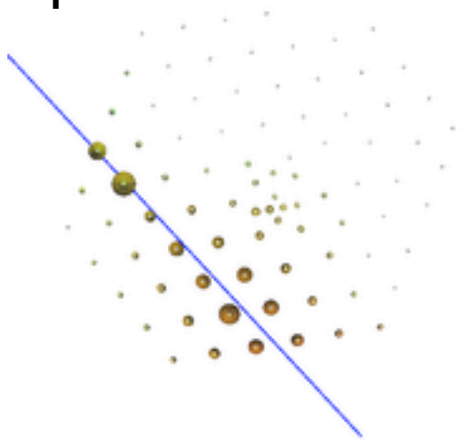
- Up-going (i.e. not a CR muon)
- Deposited energy: 2.6±0.3 PeV
  - Lower bound on the neutrino energy
  - Neutrino energy significantly higher
- Date: June 11, 2014
- Direction: 11.48° dec / 110.34° RA
- Angular resolution <1°

The event above was detected in IceCube on June 11, 2014. Image: IceCube Collaboration.

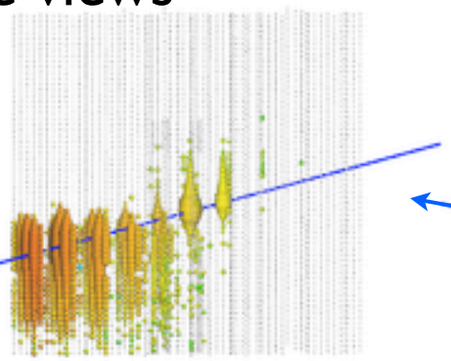


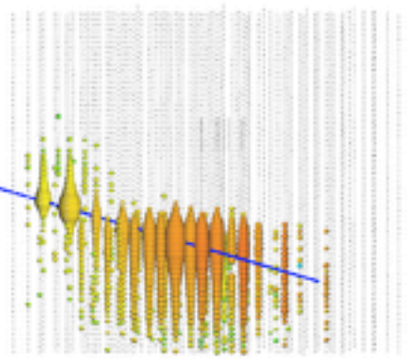
Multi-PeV Track Event

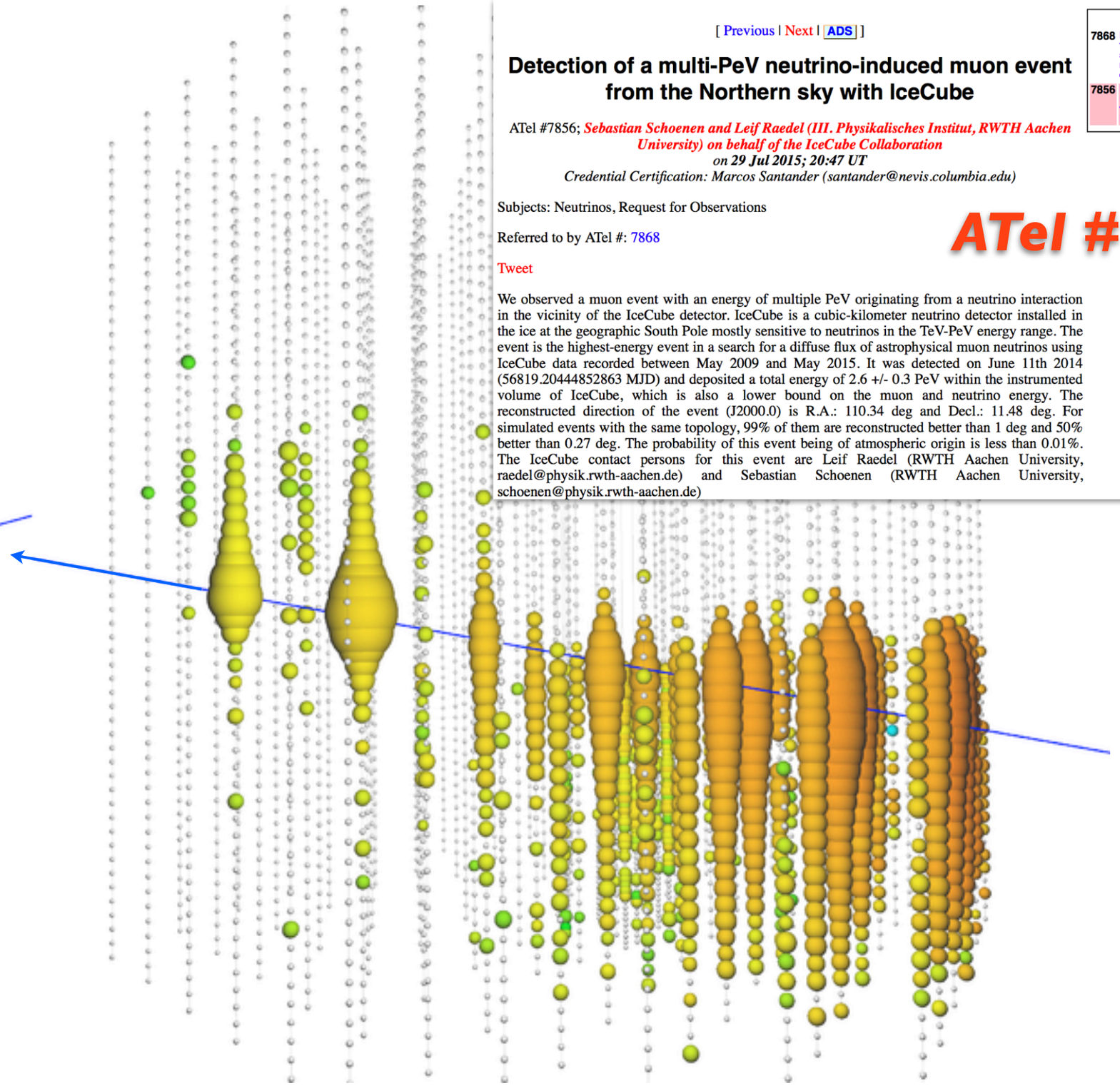
Top view



Side views







[Previous | Next | ADS]

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
on 29 Jul 2015; 20:47 UT
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

Tweet

We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)

Related

7868 HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event

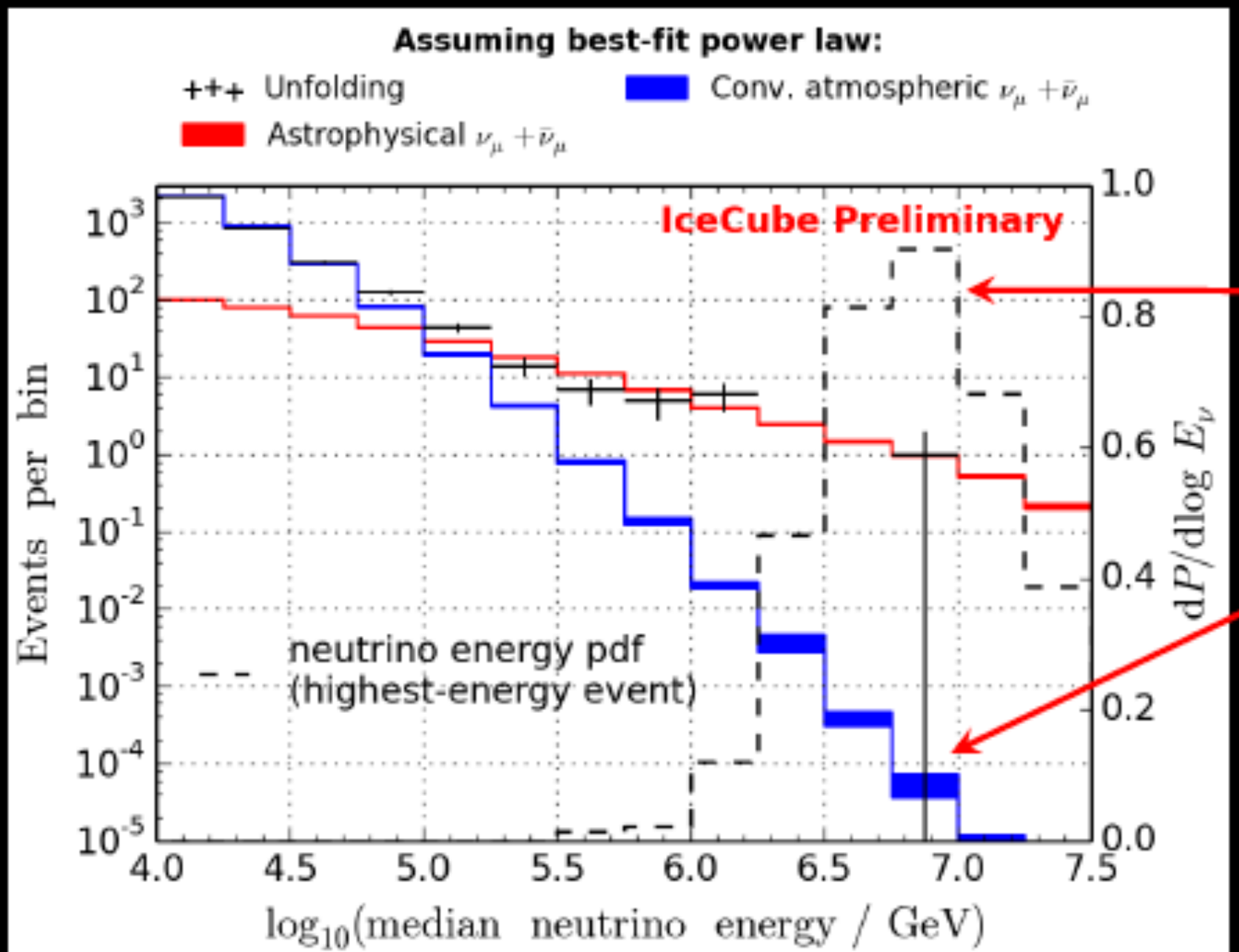
7856 Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856

Unfolded astrophysical muon neutrino spectrum

III. Physikalisches Institut

RWTH AACHEN IceCube



Multi-PeV track neutrino energy pdf

Multi-PeV track p-value < 0.01% to be of atmospheric origin

- Atmospheric-only hypothesis excluded by 5.9σ

[Previous | Next | ADS]

ANTARES neutrino detection and possible Swift X-ray counterpart

ATel #7987; *D. Dornic (CPPM), S. Basa (LAM), P. A. Evans (U. Leicester), J. A. Kennea (PSU), J. P. Osborne (U. Leicester) and V. Lipunov (MSU)*
on 3 Sep 2015; 12:18 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

Subjects: Optical, X-ray, Neutrinos, Request for Observations

Referred to by ATel #: 7992, 7993, 7994, 7995, 7996, 7998, 7999, 8000, 8002, 8003, 8006, 8027, 8034, 8097, 8124

Tweet

On September 1st, 2015, at 07:38:25 UT, ANTARES has detected a bright neutrino at a location of:

RA(J2000) = 16h 25m 42s
DEC (J2000) = -27d 23m 24s
with an uncertainty of 18 arcmin (radius, 50% containment)

A target of opportunity alert has been sent immediately to Swift. The XRT onboard Swift followed the ANTARES error box 10 hours after the neutrino detection. An uncatalogued X-ray source has been detected above the limit of RASS, with the flux varying between 5e-13 and 1.4e-12 erg cm^-2 s^-1 (0.3-10 keV), at location:

RA(J2000) = 16h 26m 2.12s
DEC (J2000) = -27d 18m 14.8s

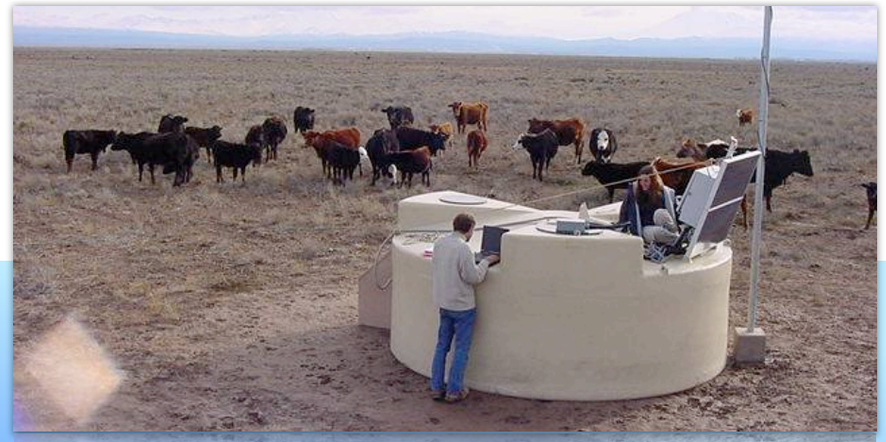
with an uncertainty of 2.4 arcsec (radius, 90% containment).

The detected X-ray source seems to be variable. By contrast no transient source in the visible domain with MASTER SAAO has been observed so far until the magnitude 18.5 with a galactic extinction of 2 (Schlegel et al). Further Swift observations have been planned.

We encourage strongly further multi-wavelength observations to identify this X-ray source.

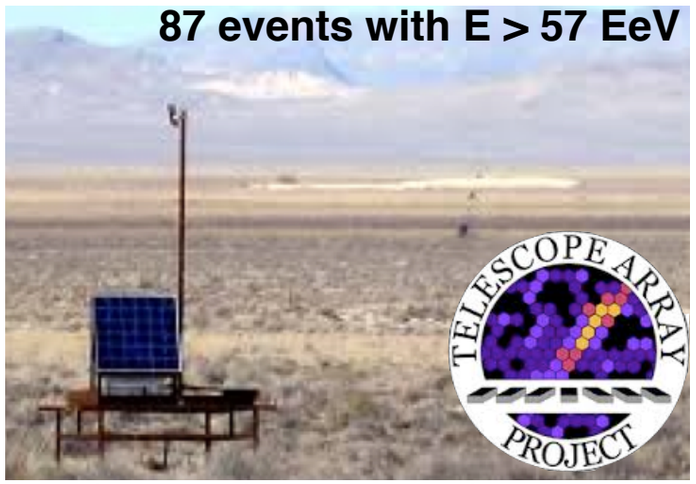
Related

8124 ANTARES neutrino detection: kinematic evidence that the Swift/XRT X-ray counterpart is a likely Upper Sco member
8097 Search for Counterpart to ANTARES Neutrino Detection with IceCube
8034 ANTARES neutrino detection: A preliminary VLA catalogue of radio source components and their variability levels in the field
8027 Pan-STARRS search for optical counterparts to the ANTARES neutrino detection
8006 ANTARES neutrino detection: Nishi-Harima NIR photometry
8003 MAXI/GSC upper limit for an X-ray counterpart of the ANTARES neutrino event detected on September 1.
8002 ANTARES neutrino detection: LSGT B, V, R optical observation
8000 ANTARES high energy neutrino Alert150901.32 Error-box X-ray, B, V, R optical observations and Possible Candidate to Neutrino Source
7999 Jansky VLA observation of the ANTARES neutrino detection region
7998 ANTARES neutrino detection: CAHA photometry & spectroscopy of the Swift source
7996 WiFeS and Kepler K2 Observations of the stellar x-ray source within the ANTARES neutrino detection region
7995 ANTARES neutrino detection: INTEGRAL upper limit on the hard X-ray counterpart
7994 ANTARES neutrino detection: Optical/NIR spectroscopy of the Swift/XRT counterpart candidate from NOT
7993 ANTARES neutrino detection: optical spectroscopy of X-ray counterpart candidate with SALT
7992 Pan-STARRS imaging of the x-ray source position within the ANTARES neutrino detection region
7987 ANTARES neutrino detection and possible Swift X-ray counterpart



Multimessenger

UHE Cosmic-Ray correlations with HE neutrinos



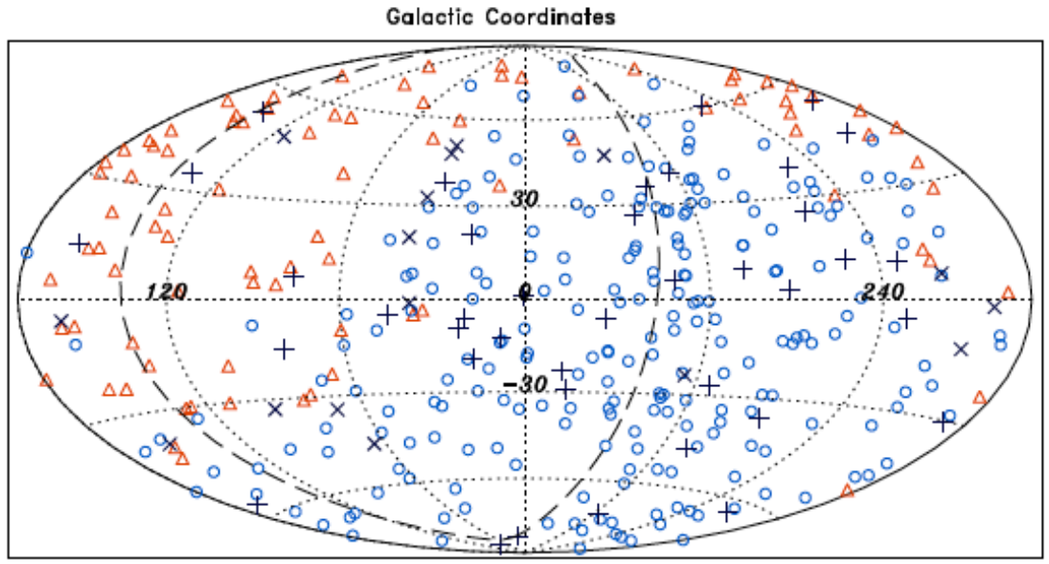
700 km² surface array of 507 plastic scintillation detectors
+ 3 fluorescence detector stations

Dataset: May 2008 - May 2014

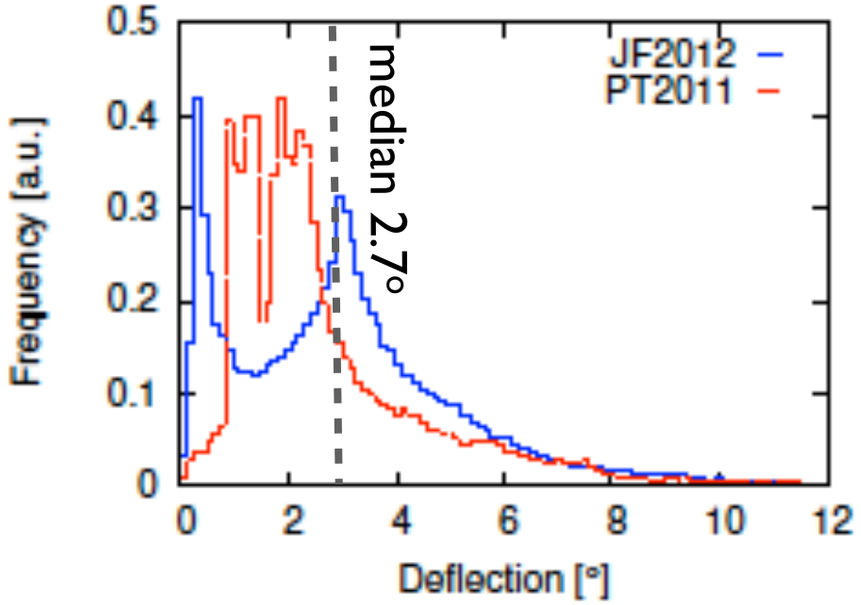
3000 km² surface array with 1660 water-Cherenkov detectors
+ 4 fluorescence detector stations

Dataset: Jan 2004 - March 2014

ICRC2015 IceCube + Auger + TA Collaborations arxiv1511.02109

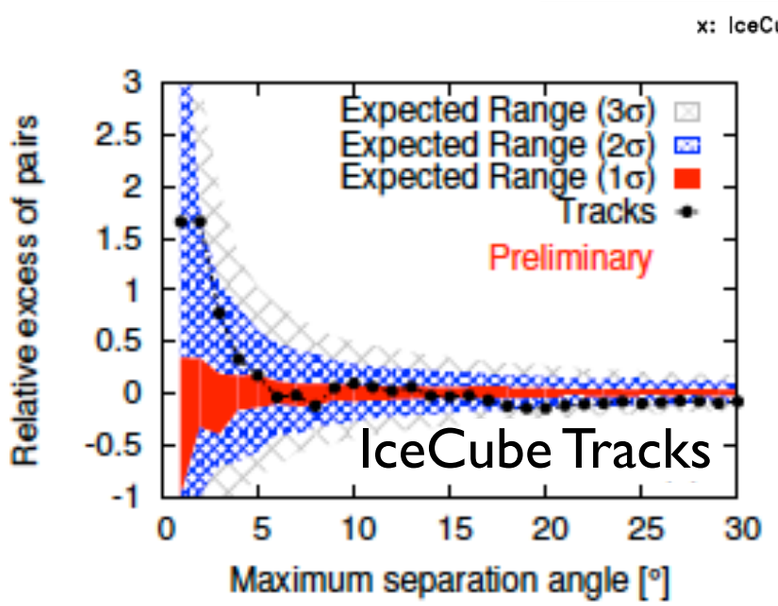


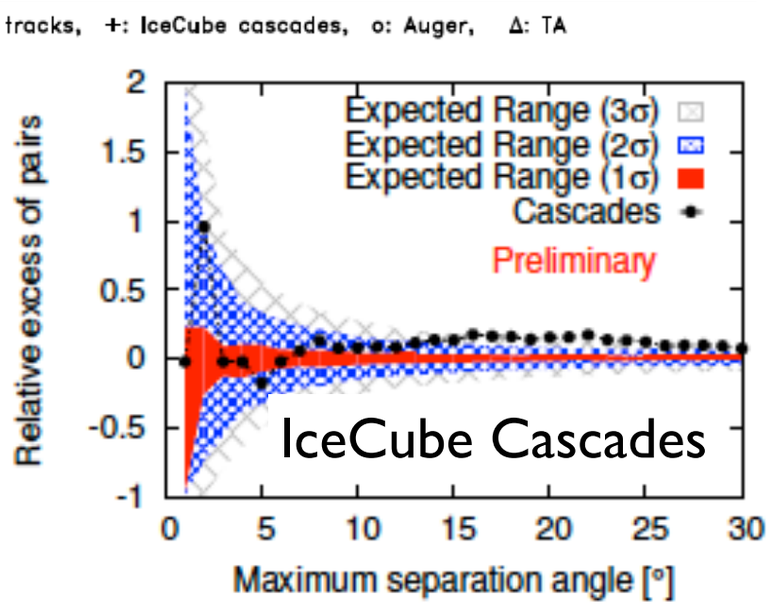
Distribution of UHECR deflections in Galactic magnetic fields for rigidity E/Z>100EeV



[PT2011] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, K. J. Newton-McGee, Astrophys. J. 738 (2011) 192.
[JF2012] R. Jansson & G. R. Farrar, Astrophys. J. 757 (2012) 14.

x: IceCube tracks, +: IceCube cascades, o: Auger, Δ: TA





Relative excess of pairs, $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$

- More statistics needed. All results below 3.3σ

Neutrinos in coincidence with gamma-ray bursts?

IceCube

ν

γ, ν

Gamma-ray satellites

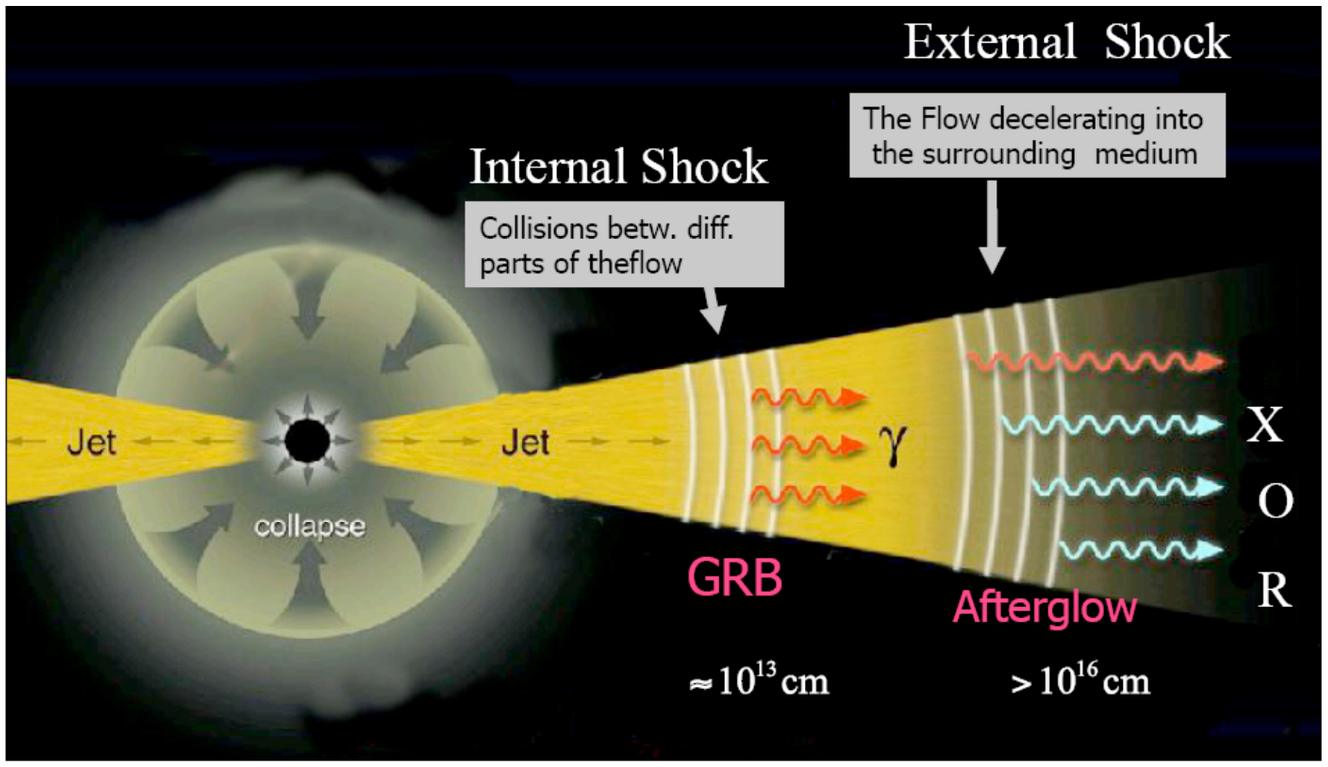
GRB timing/localization information from correlations among satellites

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

distant GRB

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

Transient Search GRBs



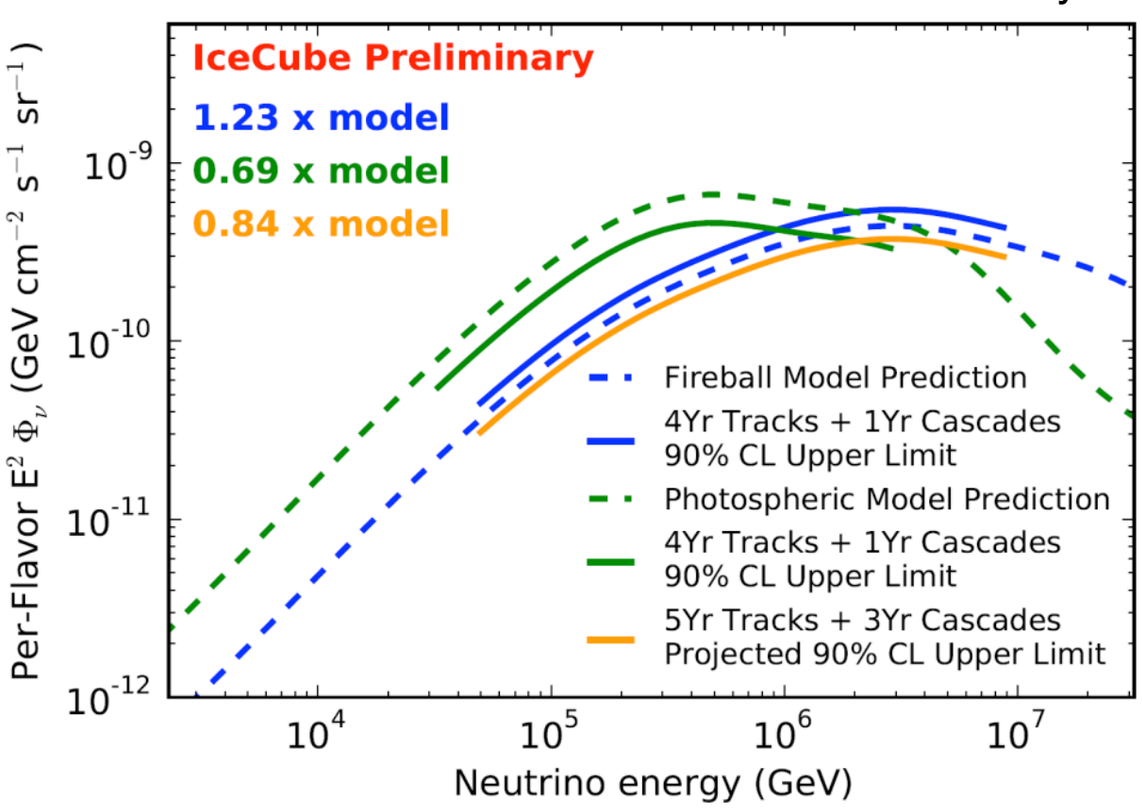
IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern and 85 from southern sky) analyzed. **No coincidence found**

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

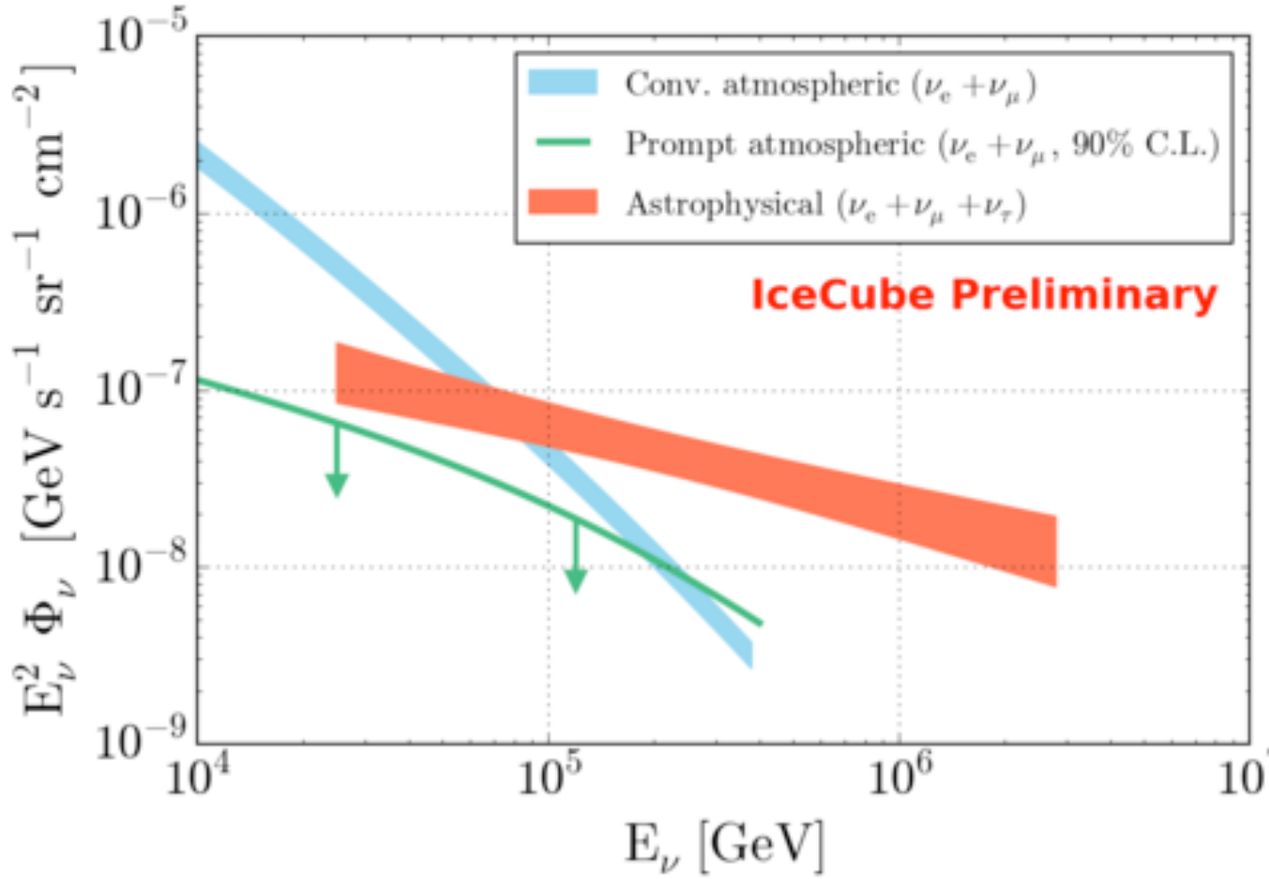


What have we learned so far ?

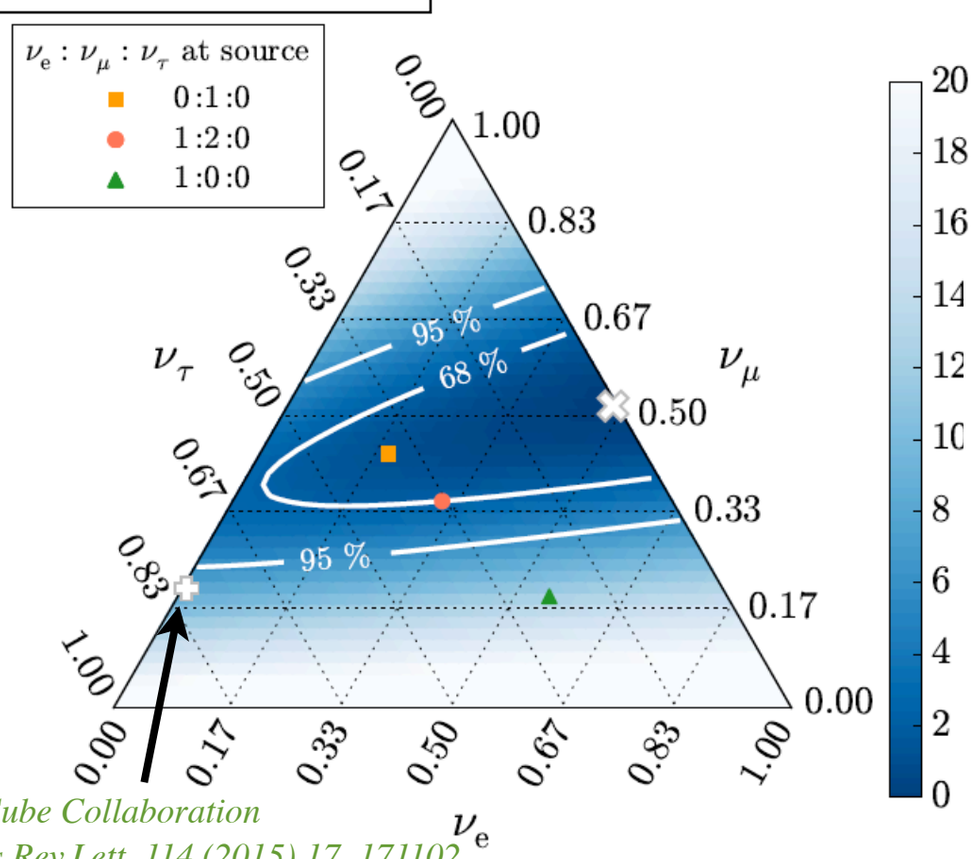
Global fit

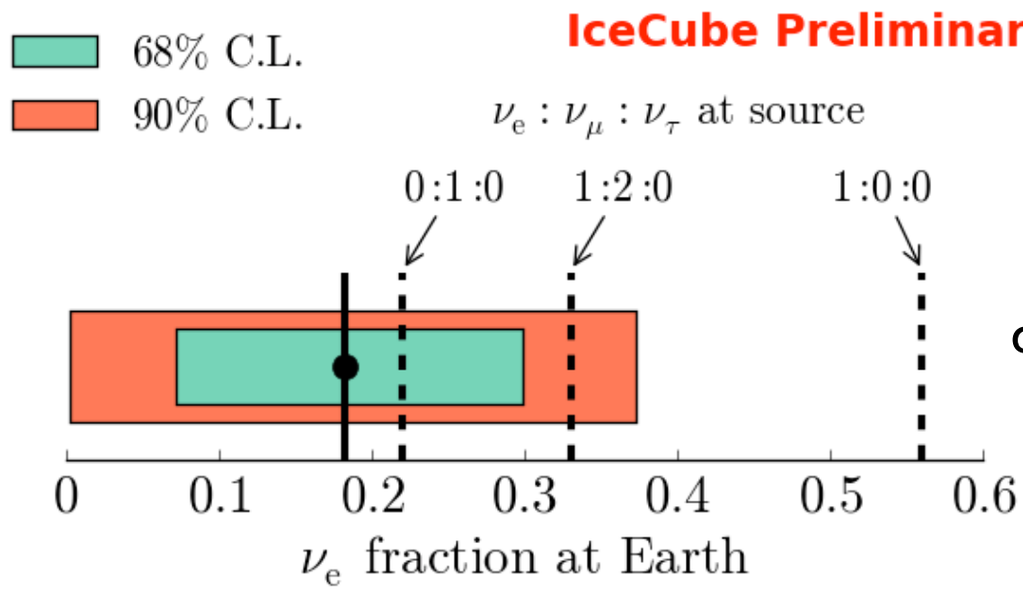
IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

- 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

Global fit

IceCube Collaboration Astrophys.J. 809 (2015) 1, 98

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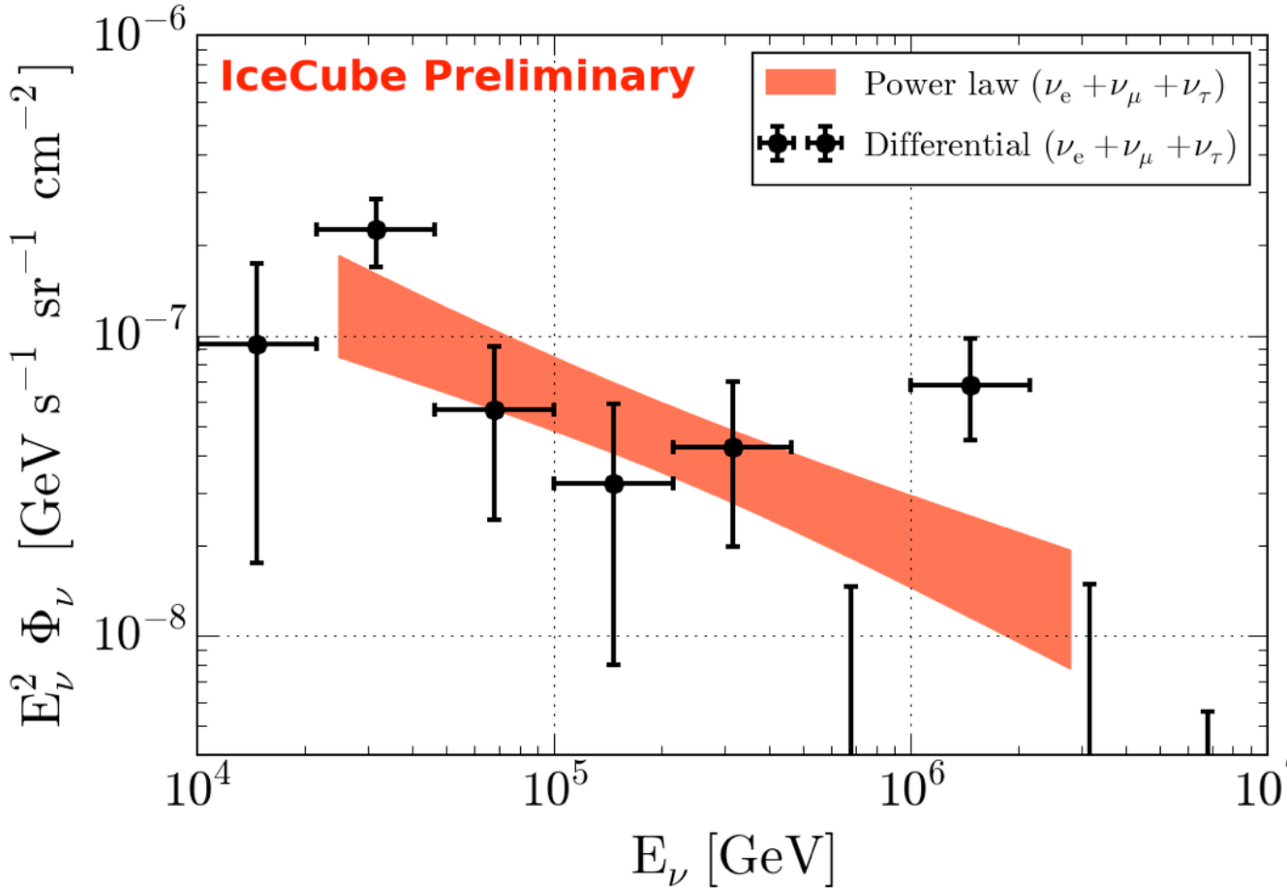
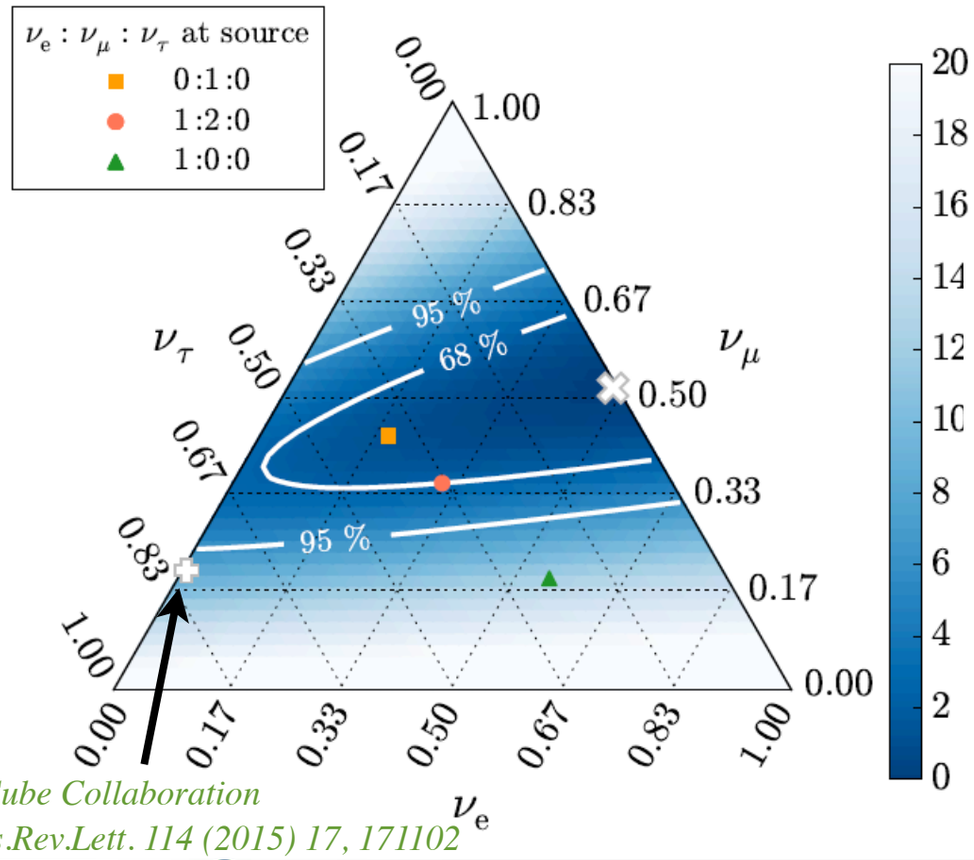
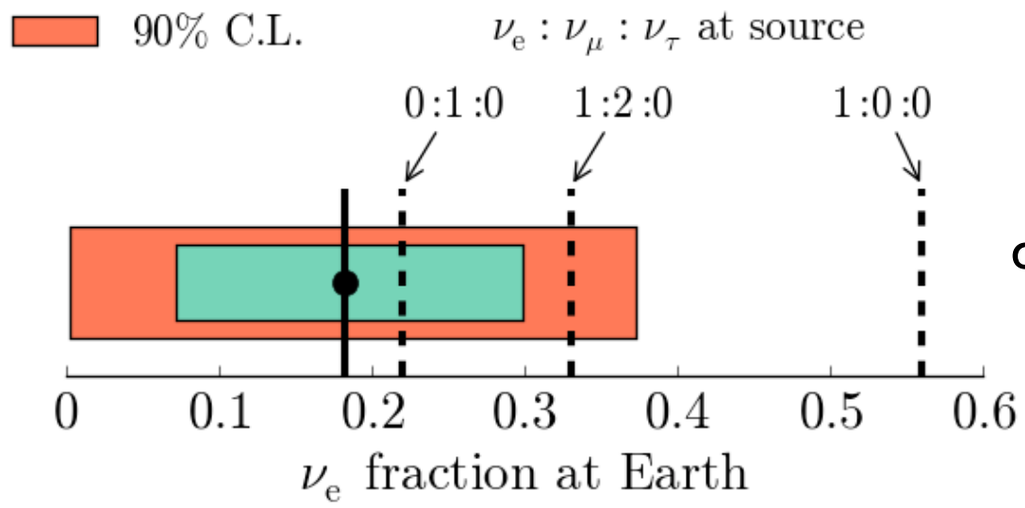


1:2:0 pion-decay
0:1:0 muon-damped
1:0:0 neutron-beam





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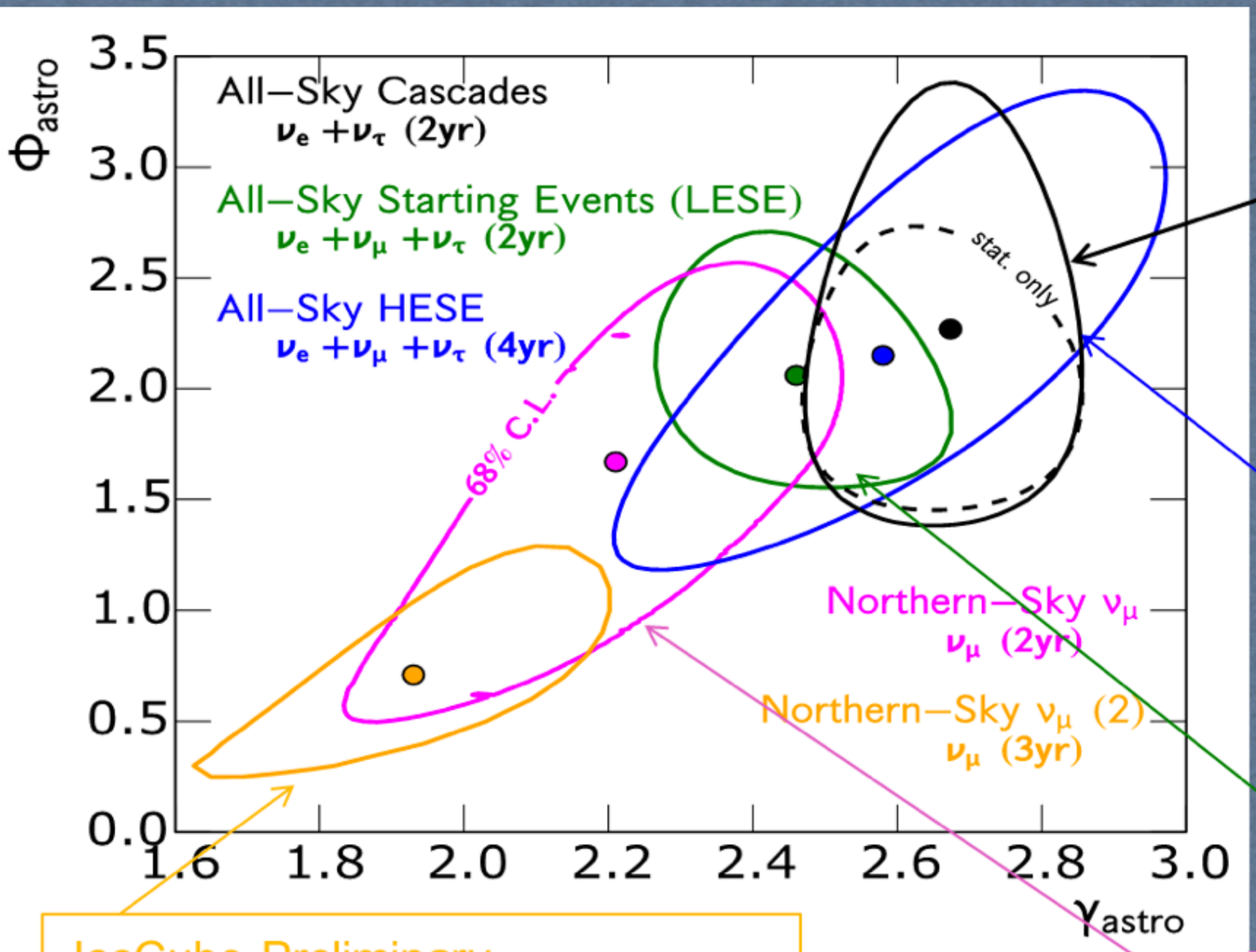
Phys.Rev.Lett. 114 (2015) 17, 171102



IceCube Preliminary
2y Cascades
ICRC2015

IceCube Preliminary
4 year HESE
All flavor ($\nu_e + \nu_\mu + \nu_\tau$)
ICRC2015

PRD 91, 022001 (2015)
($\nu_e + \nu_\mu + \nu_\tau$) 2year

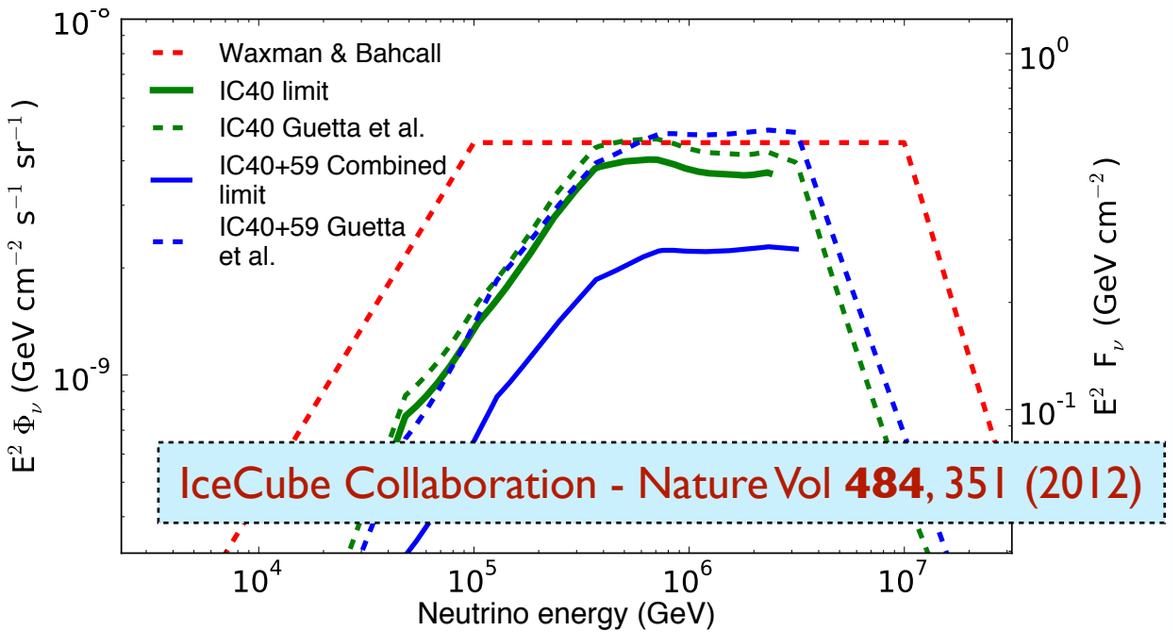
PRL 115 (2015) 8, 081102
ν_μ (Northern Sky only) 2year

IceCube Preliminary
ν_μ (Northern Sky only) 3year
ICRC2015 to be updated

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst



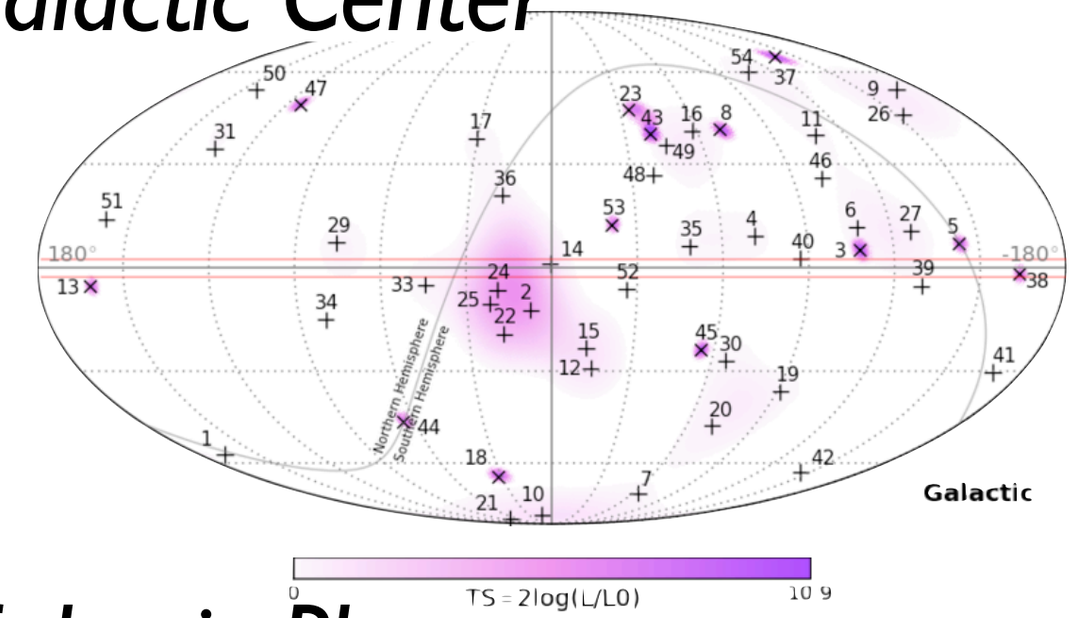
IceCube Collaboration - Nature Vol **484**, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

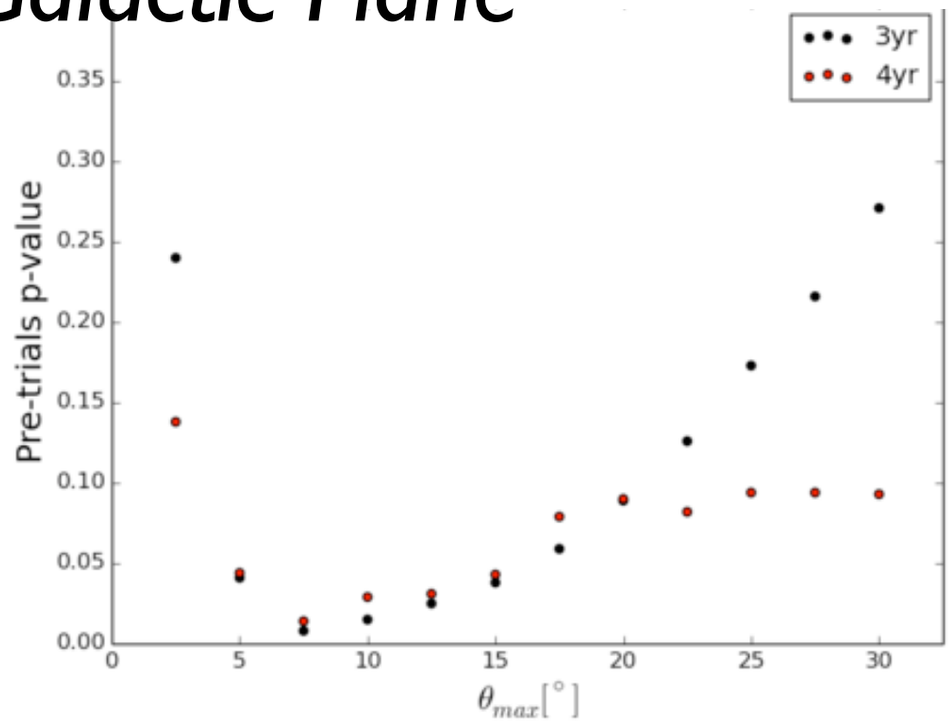
Starburst	M82	148.97	69.68	0.07	0.15
Radio Galaxies	NGC 1275	49.95	41.51	0.0	–
	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

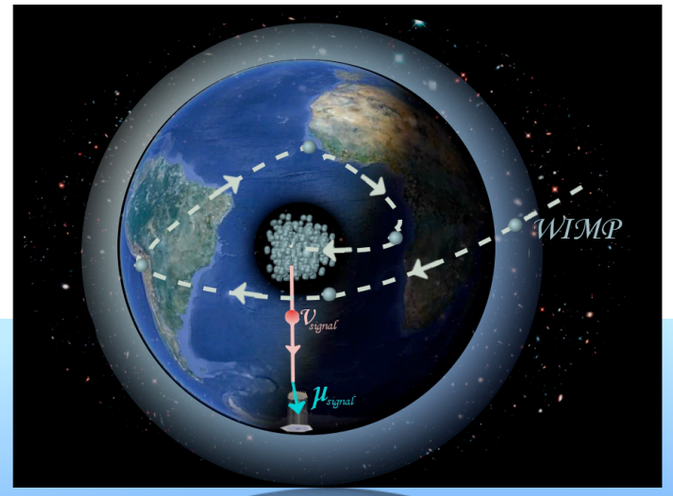
Galactic

Galactic Center



Galactic Plane





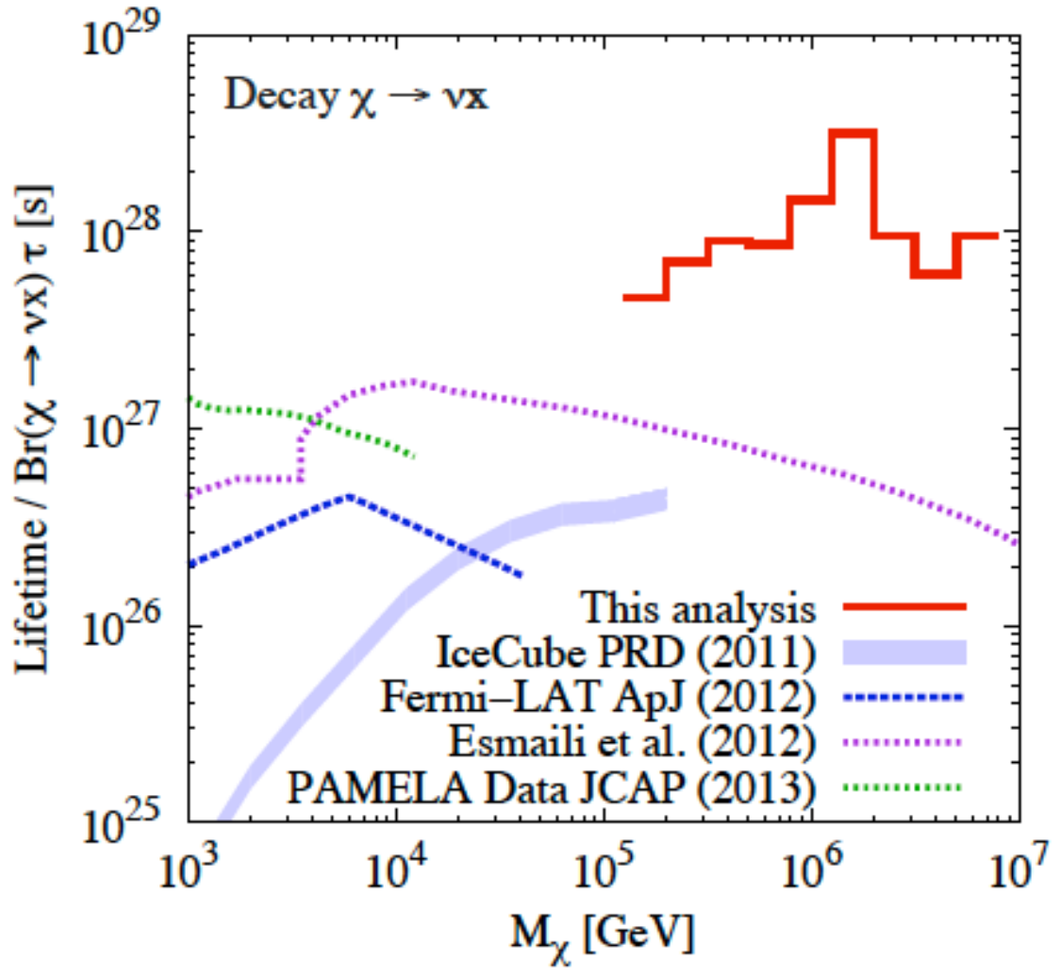
Exotic Discoveries ?

Heavy Dark Matter

- 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).

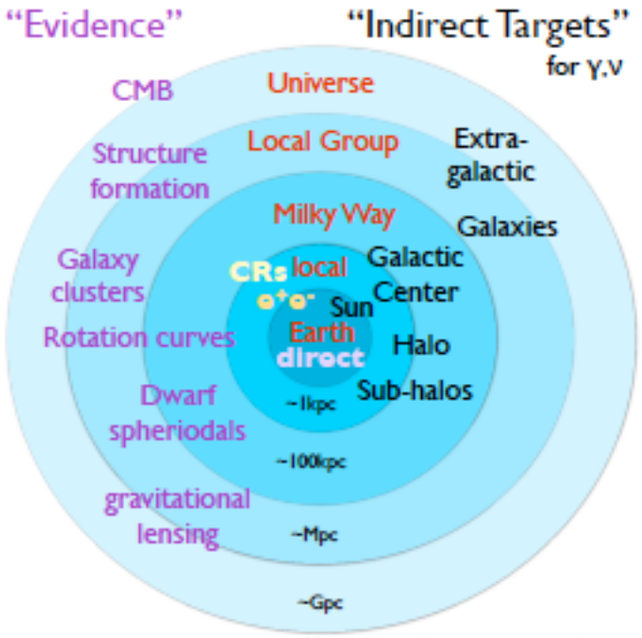
Bound on lifetime ~10^{28}s

Rott, Kohri, Park PHYS. REV. D 92, 023529 (2015)



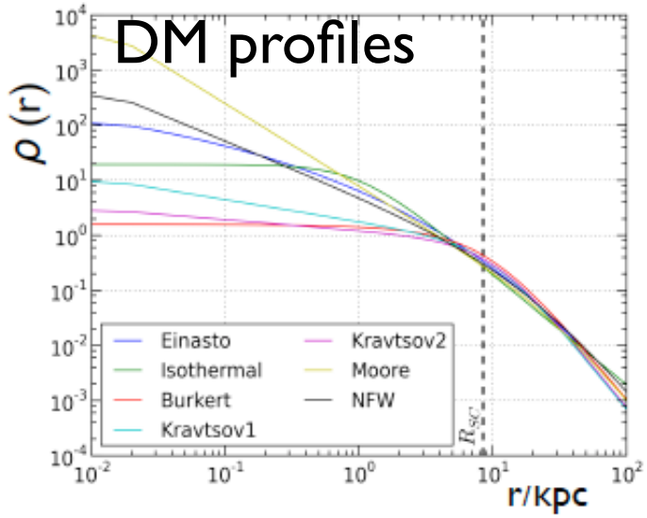
Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

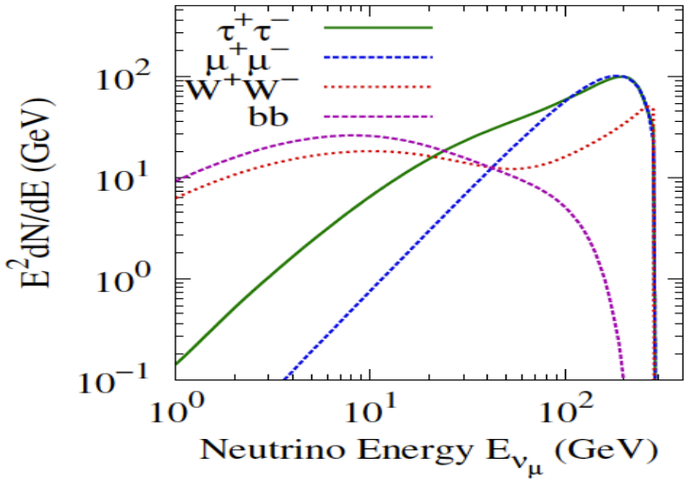
Dark Matter

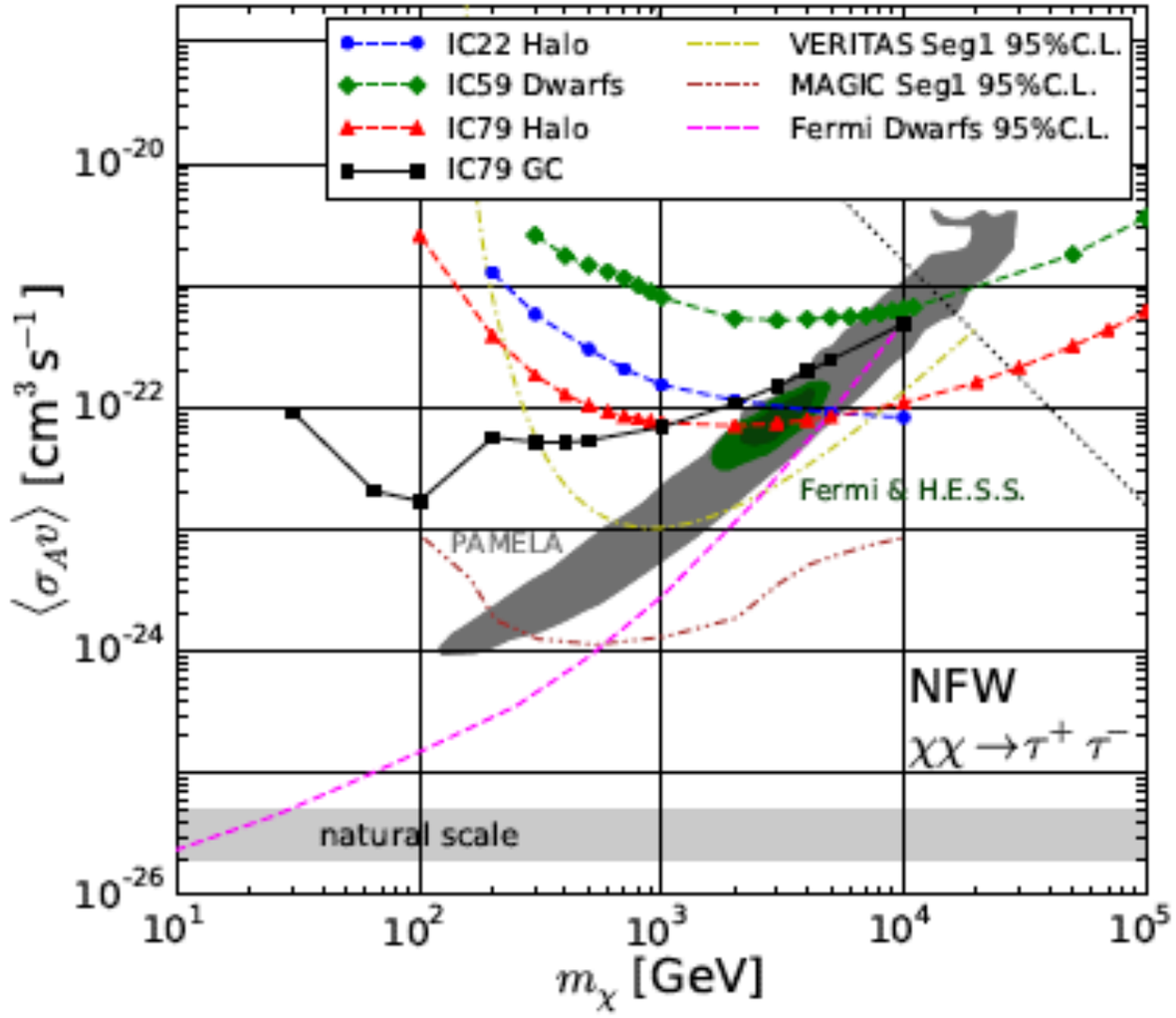


Nucl.Phys.Proc.Suppl. 235-236 (2013) 413-420

Figure 1. Observational evidence for dark matter and potential target that are expected contain significant amounts of dark matter.

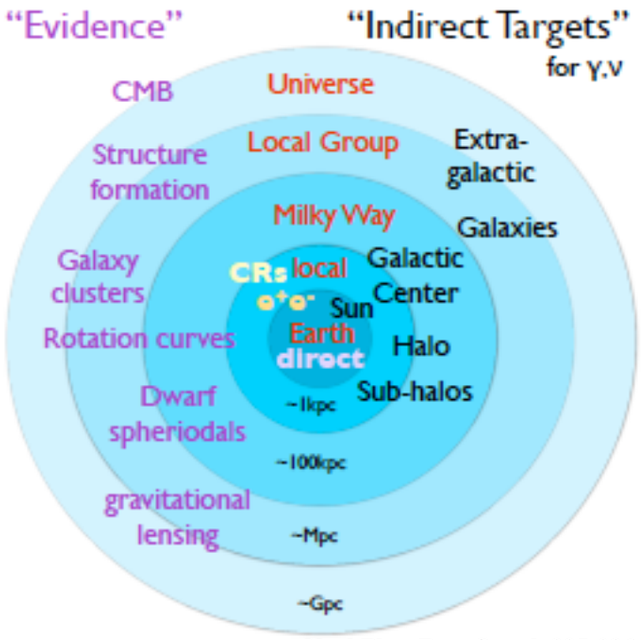






Various models motivated by increase in positron fraction can be excluded with neutrinos

Dark Matter



Nucl.Phys.Proc.Suppl. 235-236 (2013) 413-420

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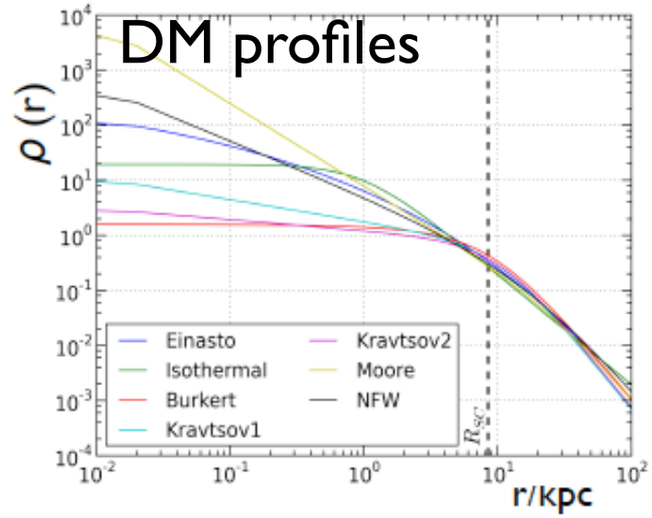
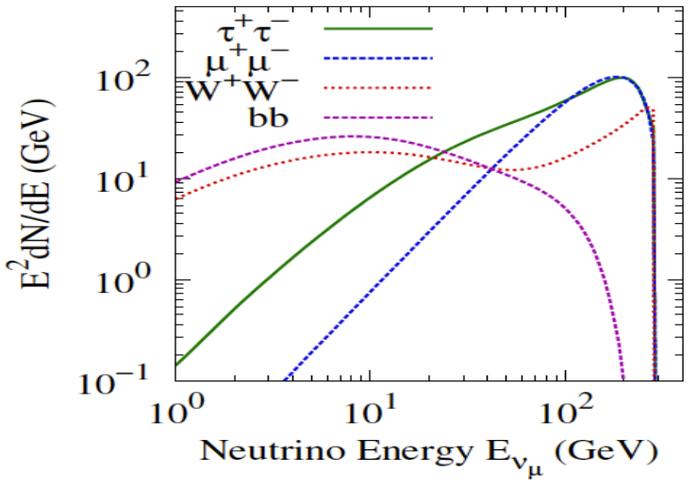
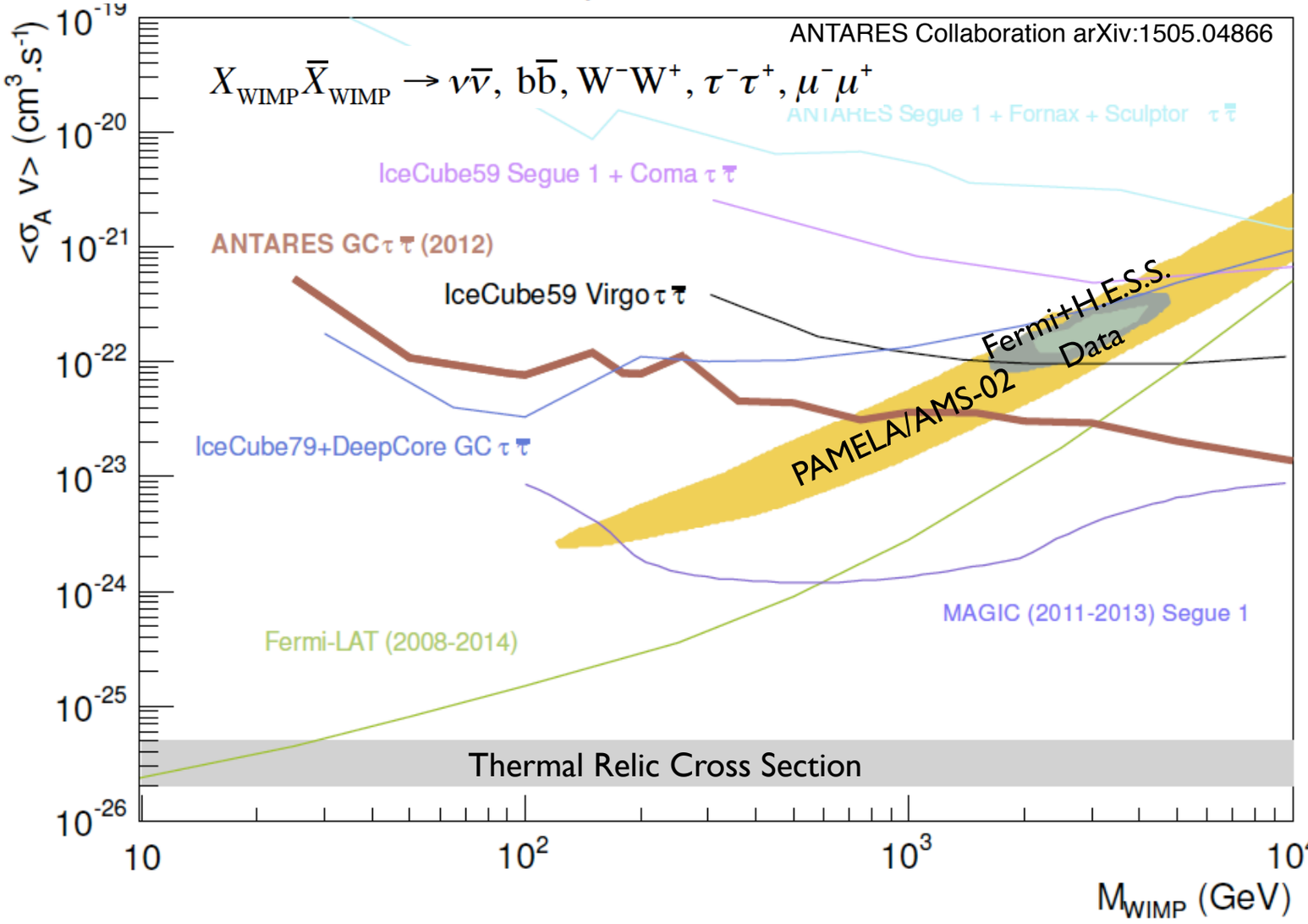
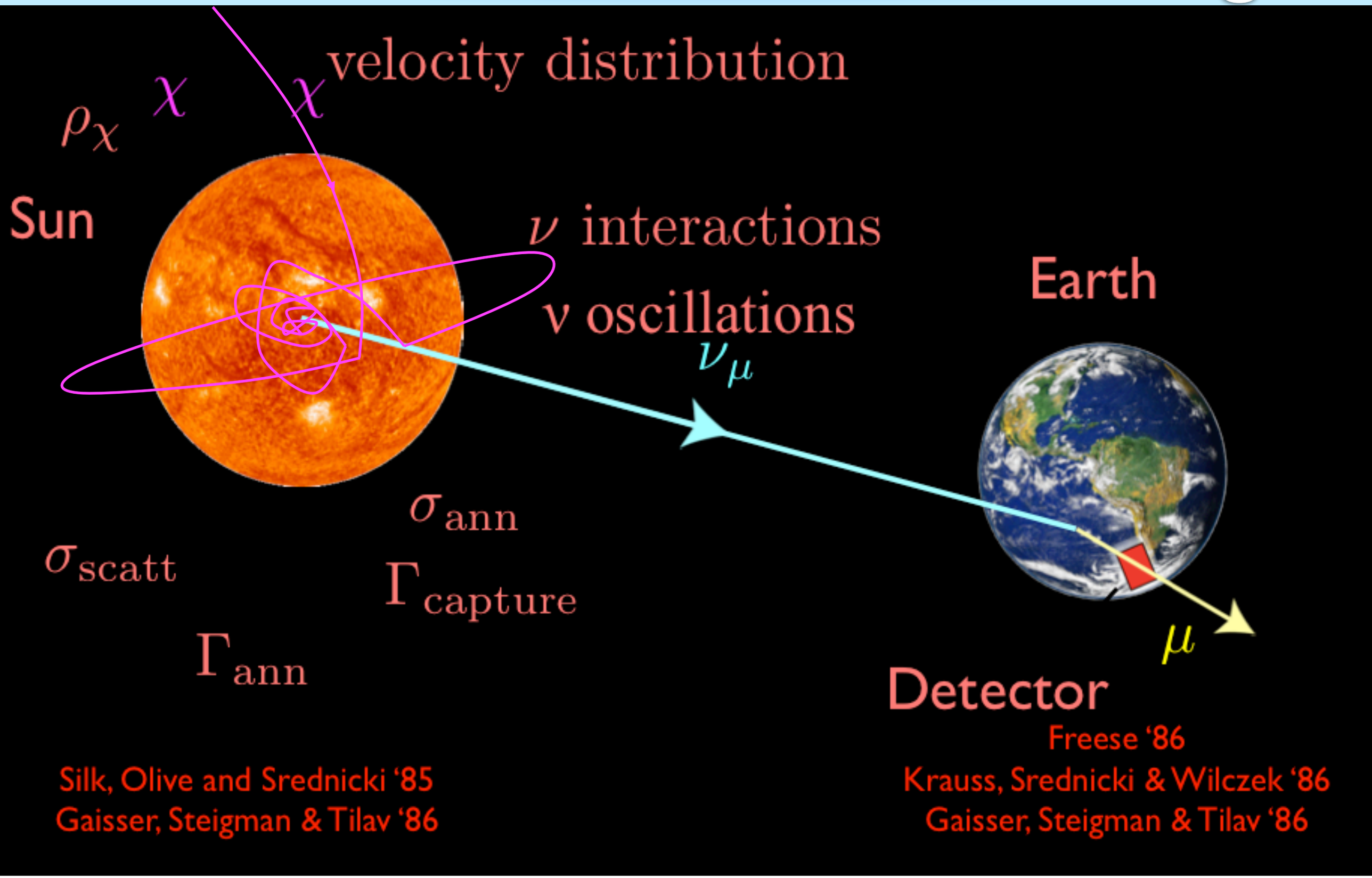






Various models motivated by increase in positron fraction can be excluded with neutrinos

Solar WIMP Signal

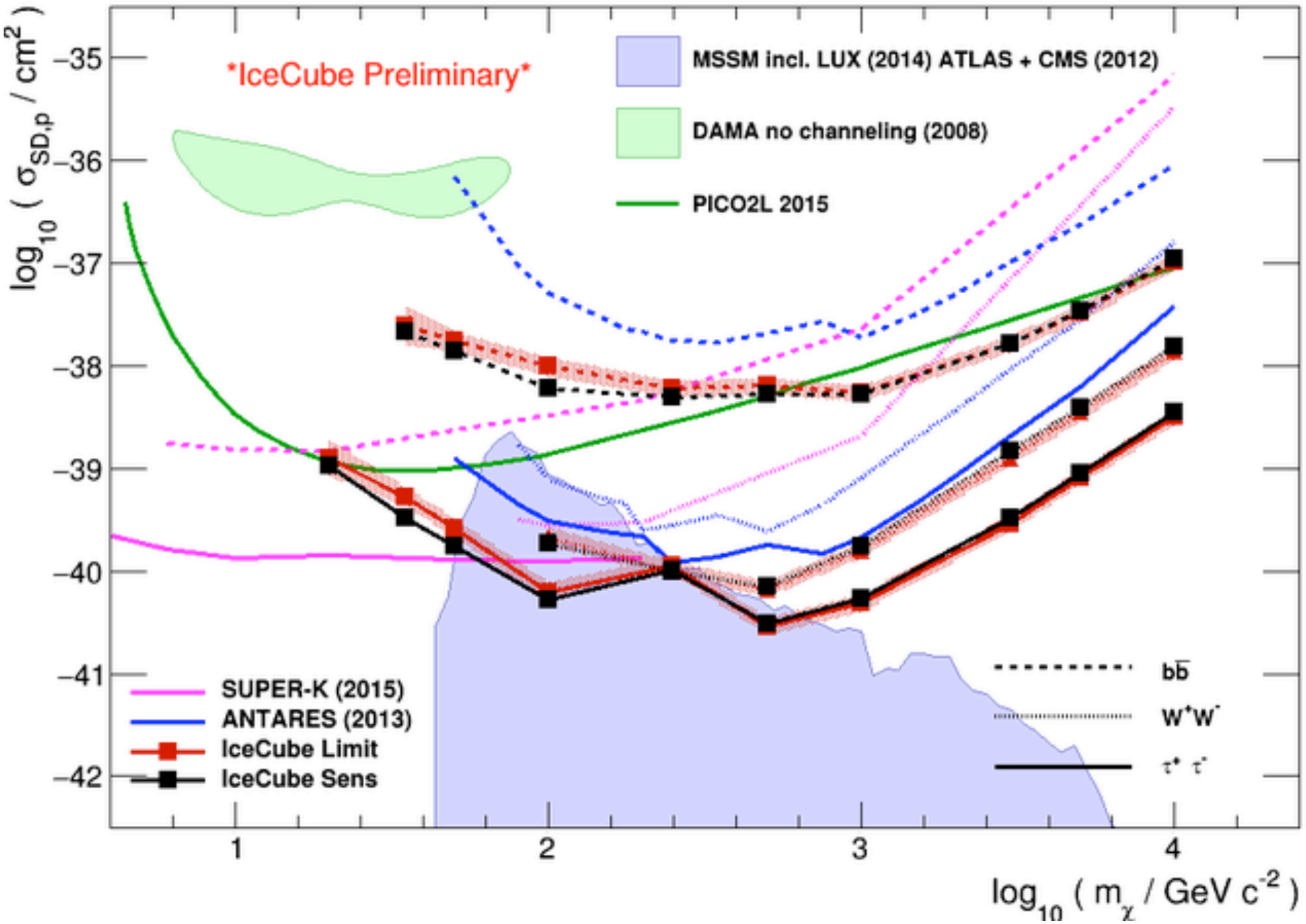


Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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

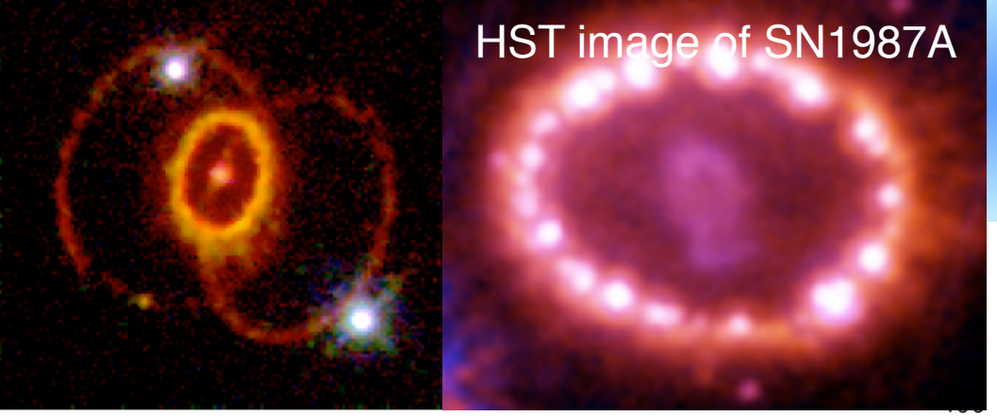
Solar WIMPs

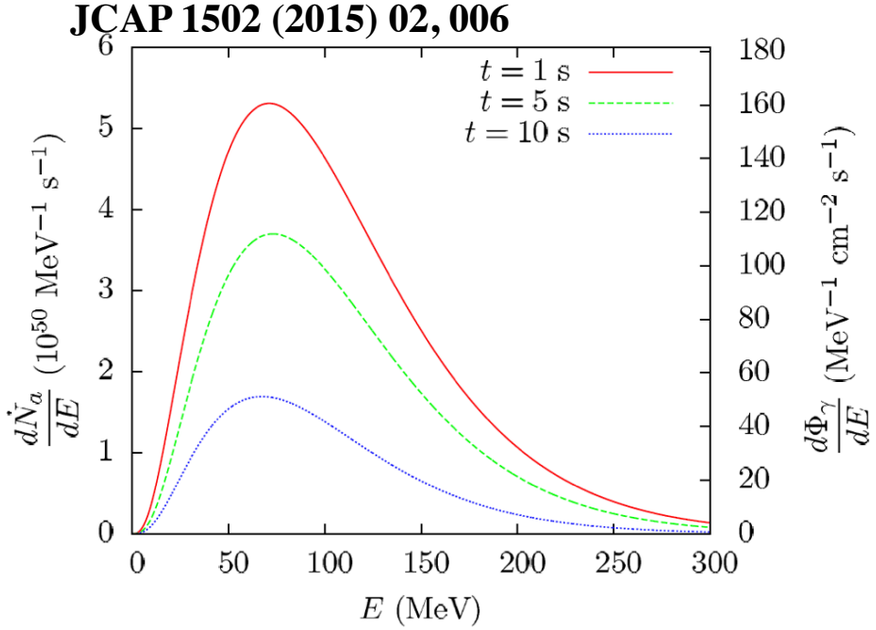
IceCubeColl., PoS(ICRC2015) 1099

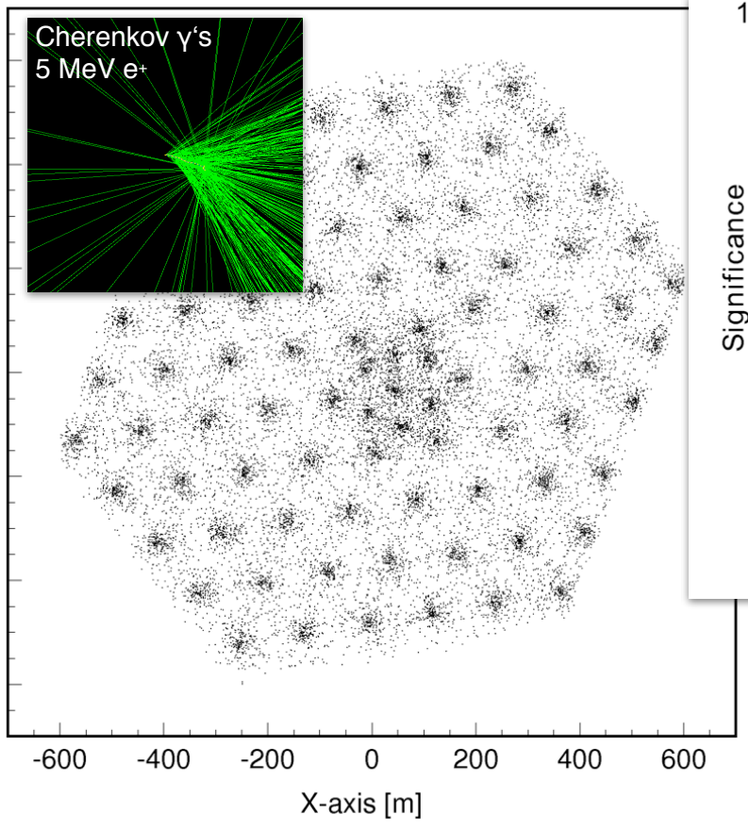


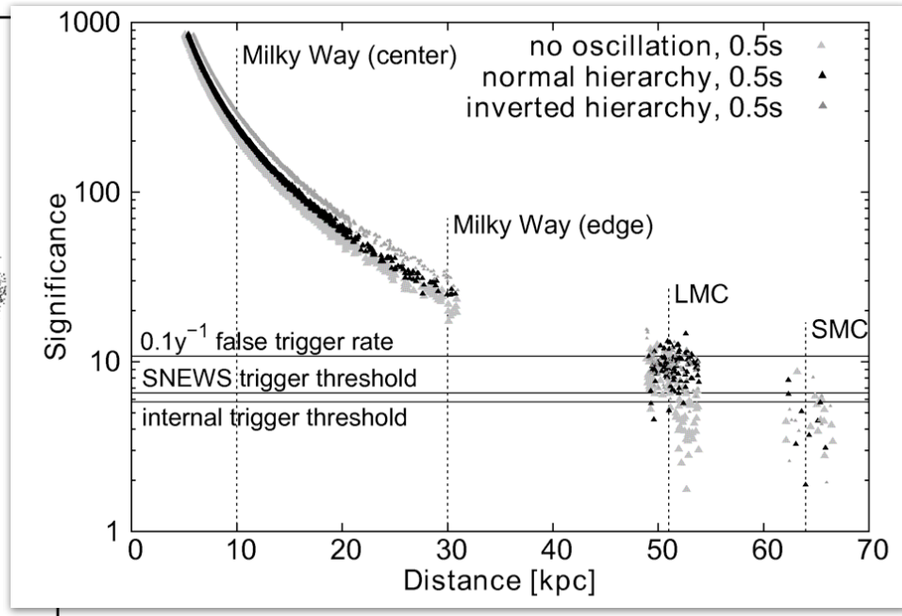
Neutrino bounds extremely competitive with Dark Matter direct detection
&
Can test models beyond the reach of LHC

Axion Dark Matter









IceCube SN Sensitivity

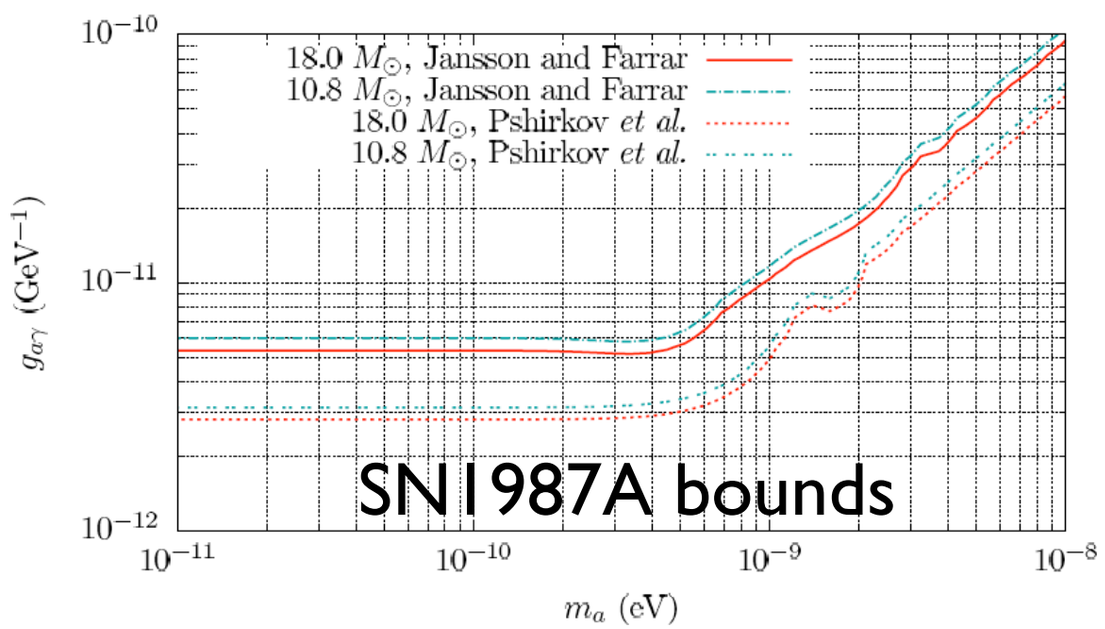


Figure 9. Upper limit obtained for the 10.8 $M_\odot$ and the 18 $M_\odot$ progenitors, using either the model of Jansson and Farrar or the one of Pshirkov *et al.* for the Galactic magnetic field.

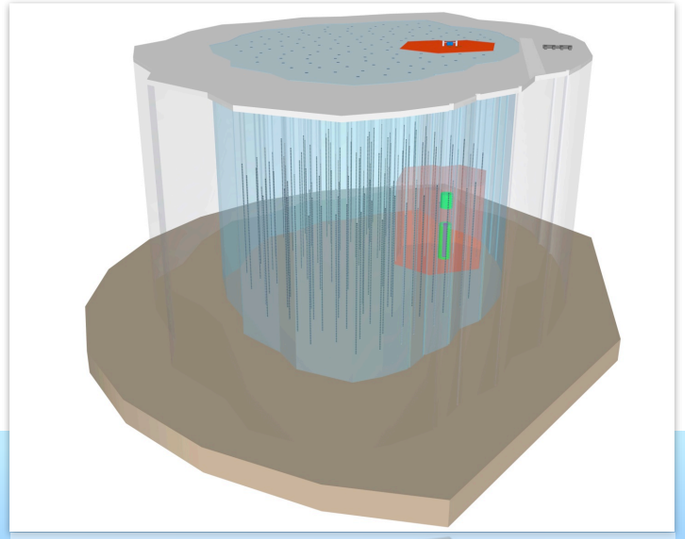
Axions generated in Supernovae burst

Dominant energy released in neutrinos (3×10^{53}erg)... can provide precise time stamp (~ms)

Axions convert to Gamma-rays in the Galactic magnetic fields (~1μG)

Precise time stamp + detection of gamma-rays from SN can discover Axions !

Nearby SN $g_{a\gamma}$ sensitivity ~10^{-13}GeV^{-1}

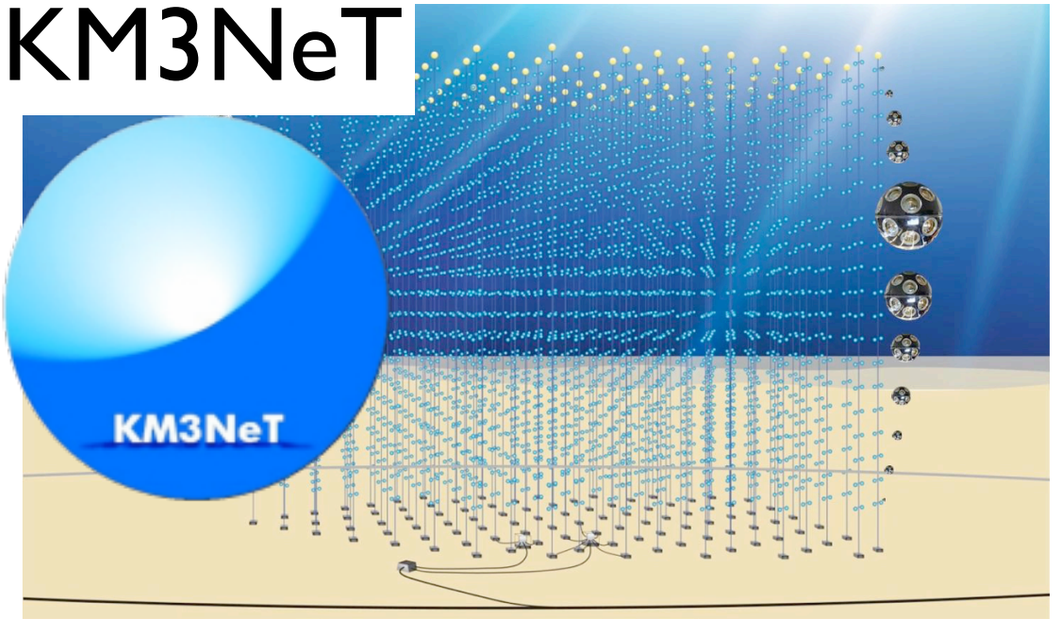


Future Plans

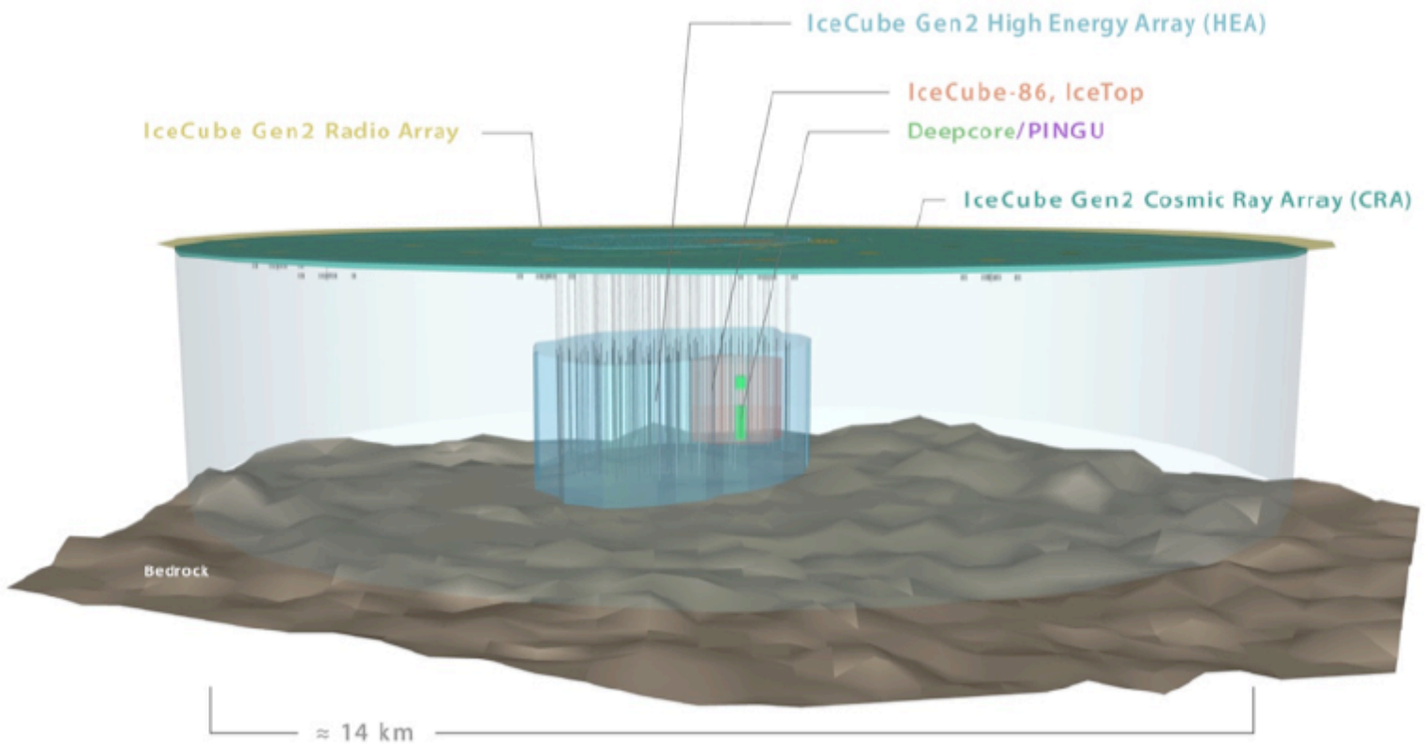
Next generation

- IceCube has provided an amazing sample of events, but is still limited by the small number of events
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
  - So far non of the analyses has shown any evidence for point sources
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- ....

KM3NeT

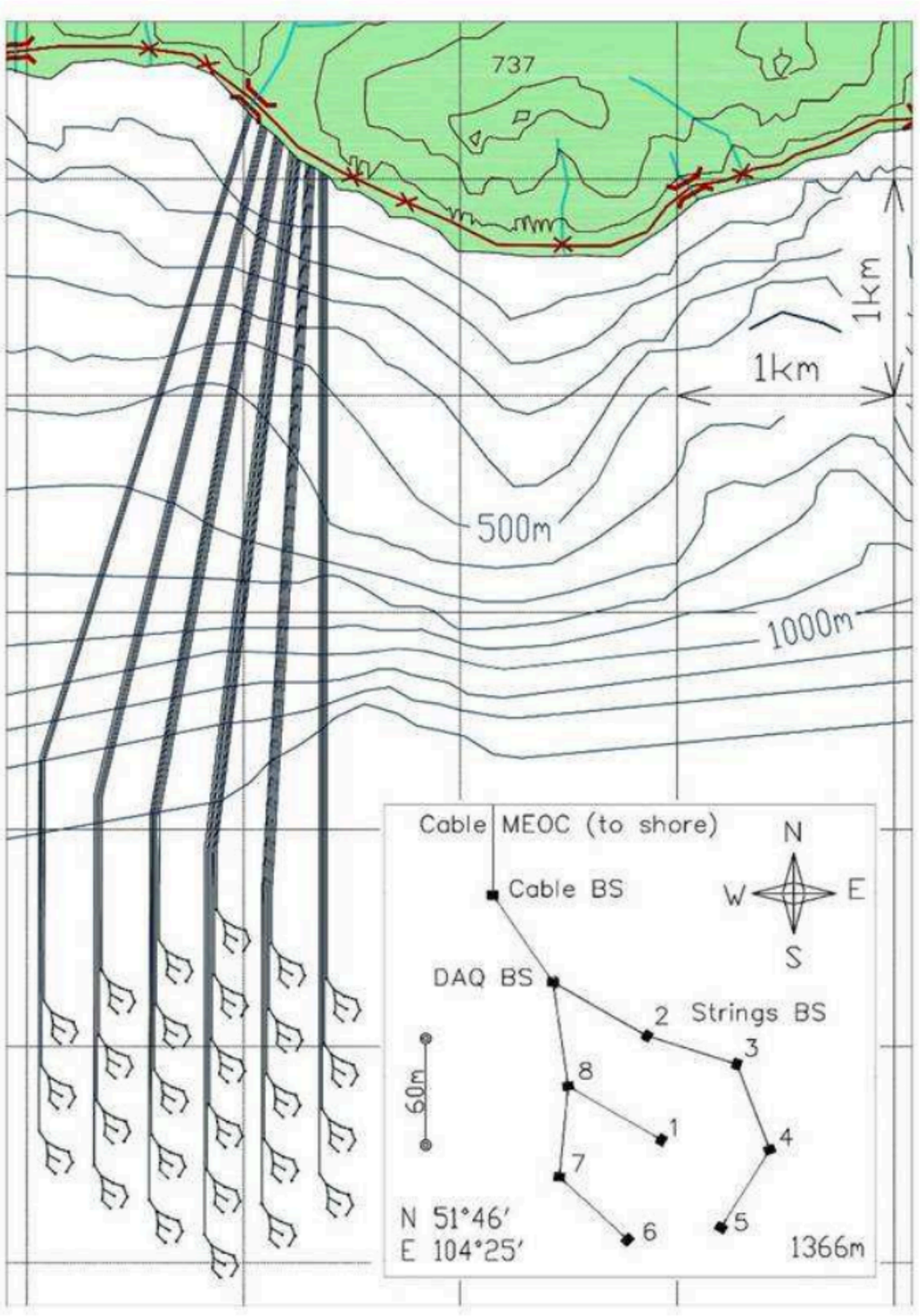


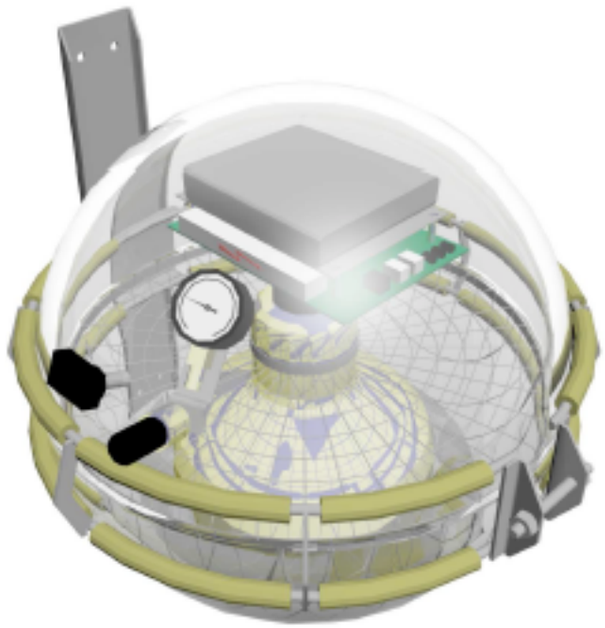
IceCube Gen2 Facility

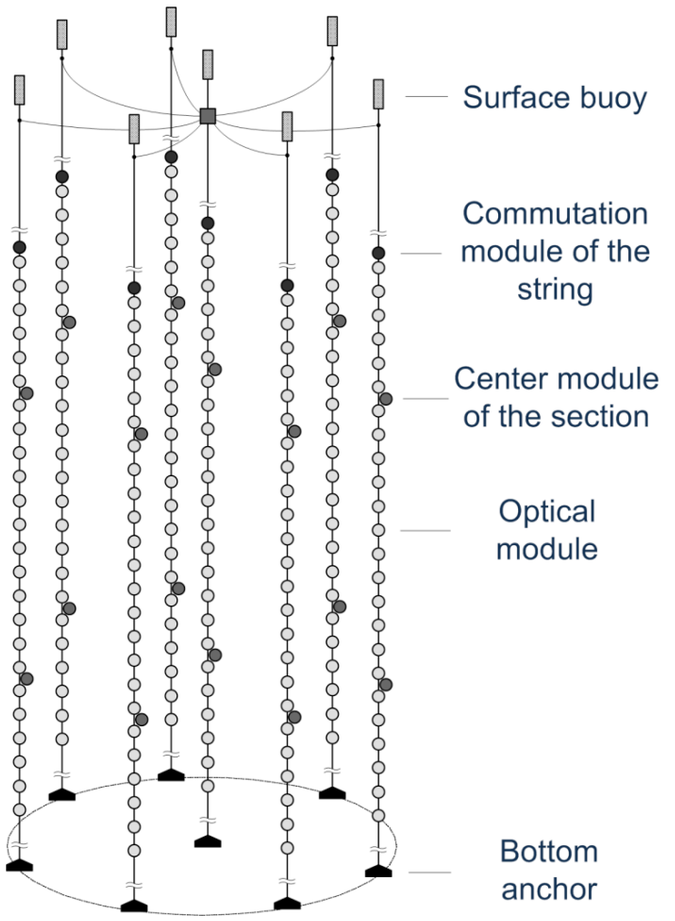


Baikal/Baikal-GVD

arXiv:1308.1833





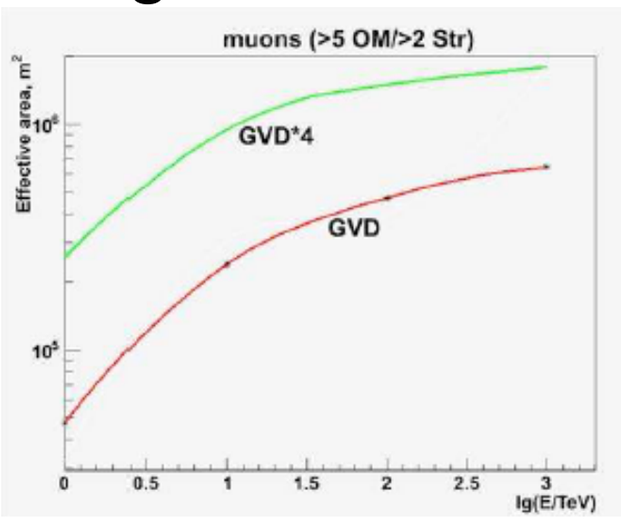


27 clusters of strings

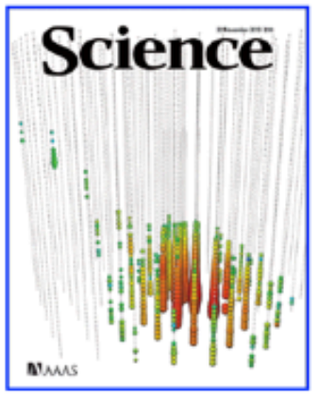
8 strings per cluster

Depth 600m - 1300m

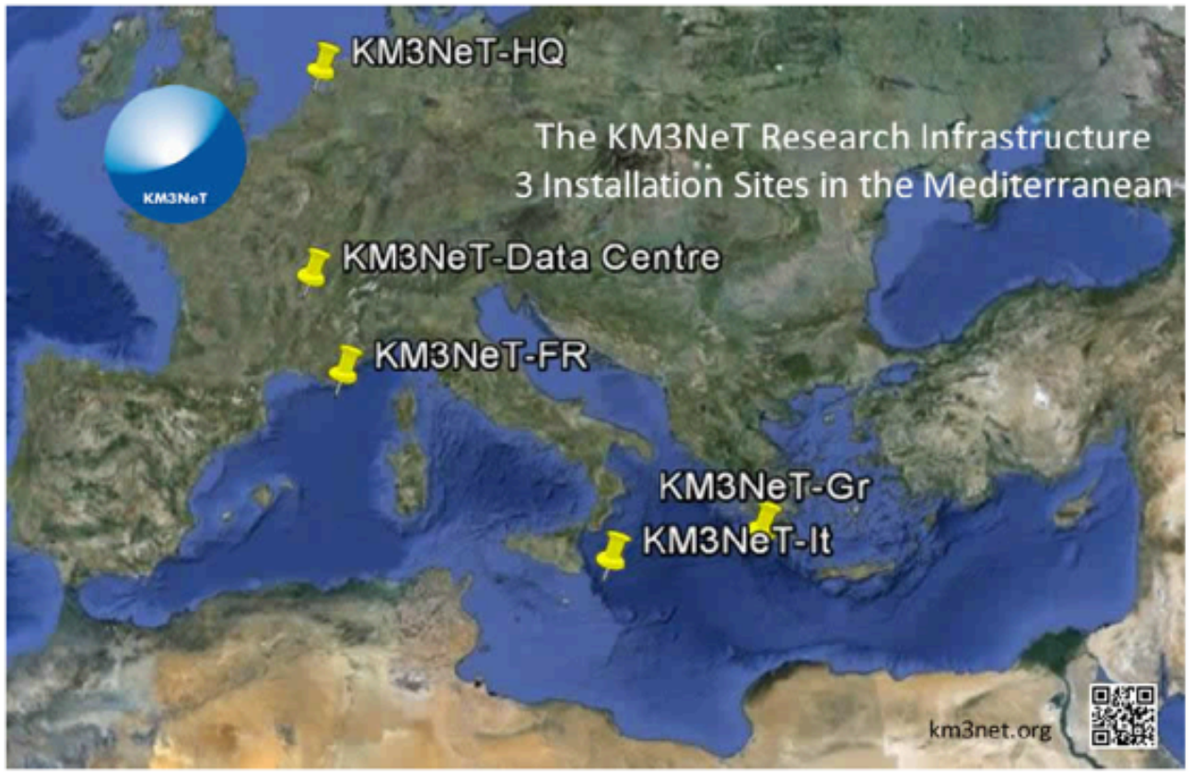
String: 705m / 48 OMs



KM3NeT sites and deployment



- ARCA: Astrophysical Research with Cosmic in the Abyss
  - Study astrophysical neutrino fluxes at E > 100 GeV
  - 2 'blocks' at KM3NeT-It
- ORCA: Oscillations Research with Cosmics in the Abyss
  - Resolve the neutrino mass hierarchy (1 GeV < E < 100 GeV)
  - 1 block at KM3NeT-Fr
- Phase 1:
  - ~10% ARCA, ~5% ORCA
  - Funded! Construction begun
  - 2017 completion
- Phase 2:
  - 100% ARCA and ORCA
  - Completion as soon as 2020



C.W. James, ANTARES highlights and KM3NeT prospects, ICRC 2015

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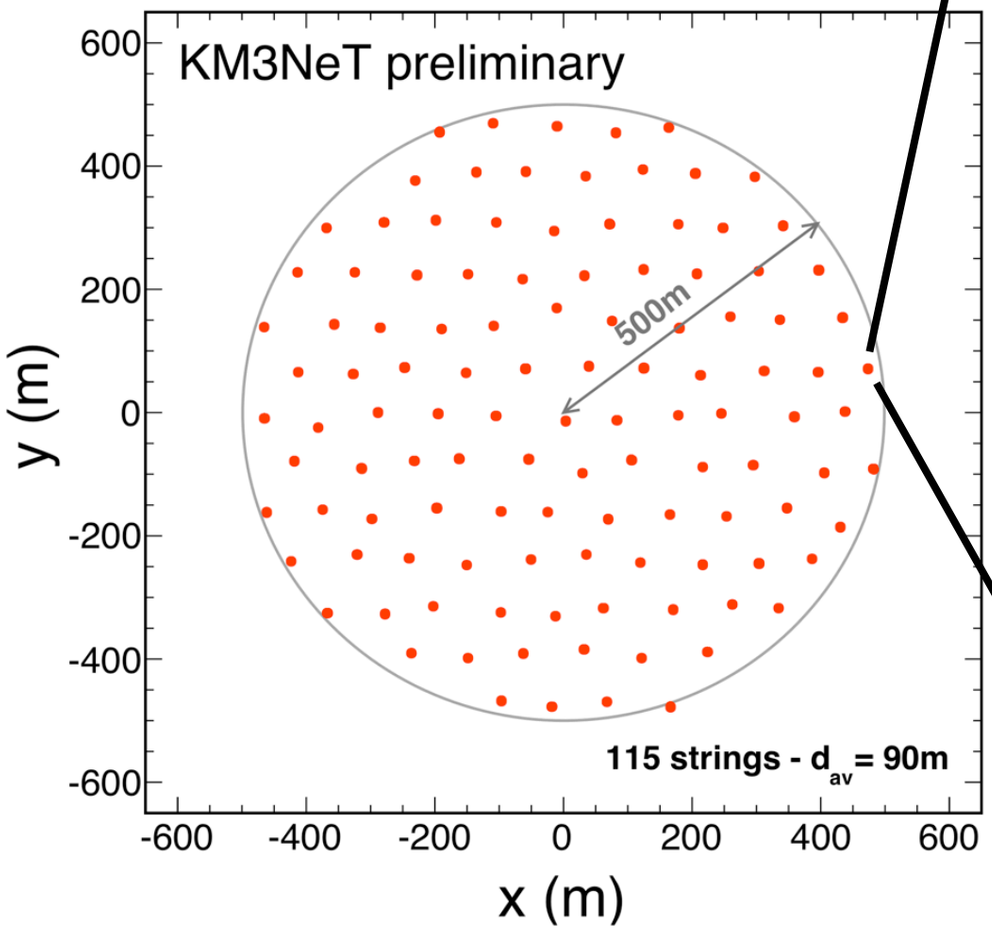
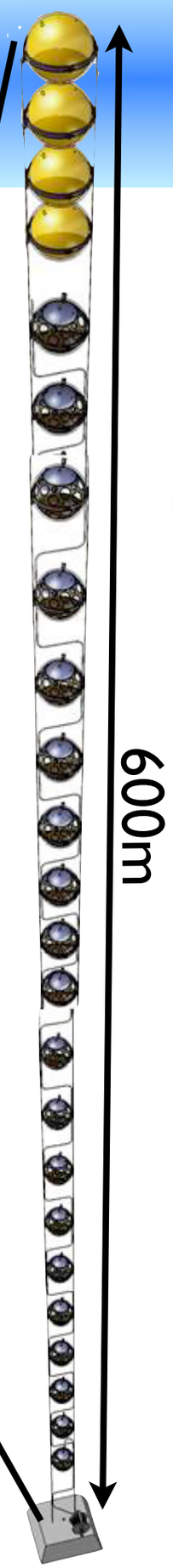
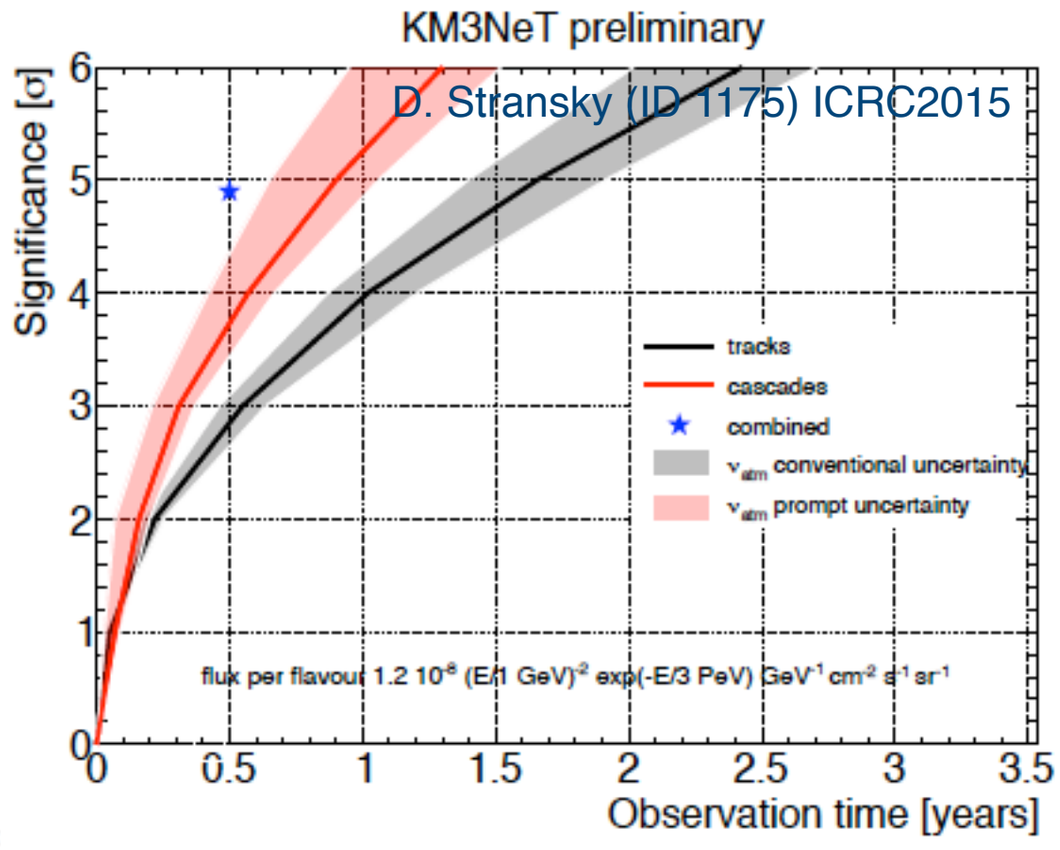
KM3NeT- ARCA

www.km3net.org

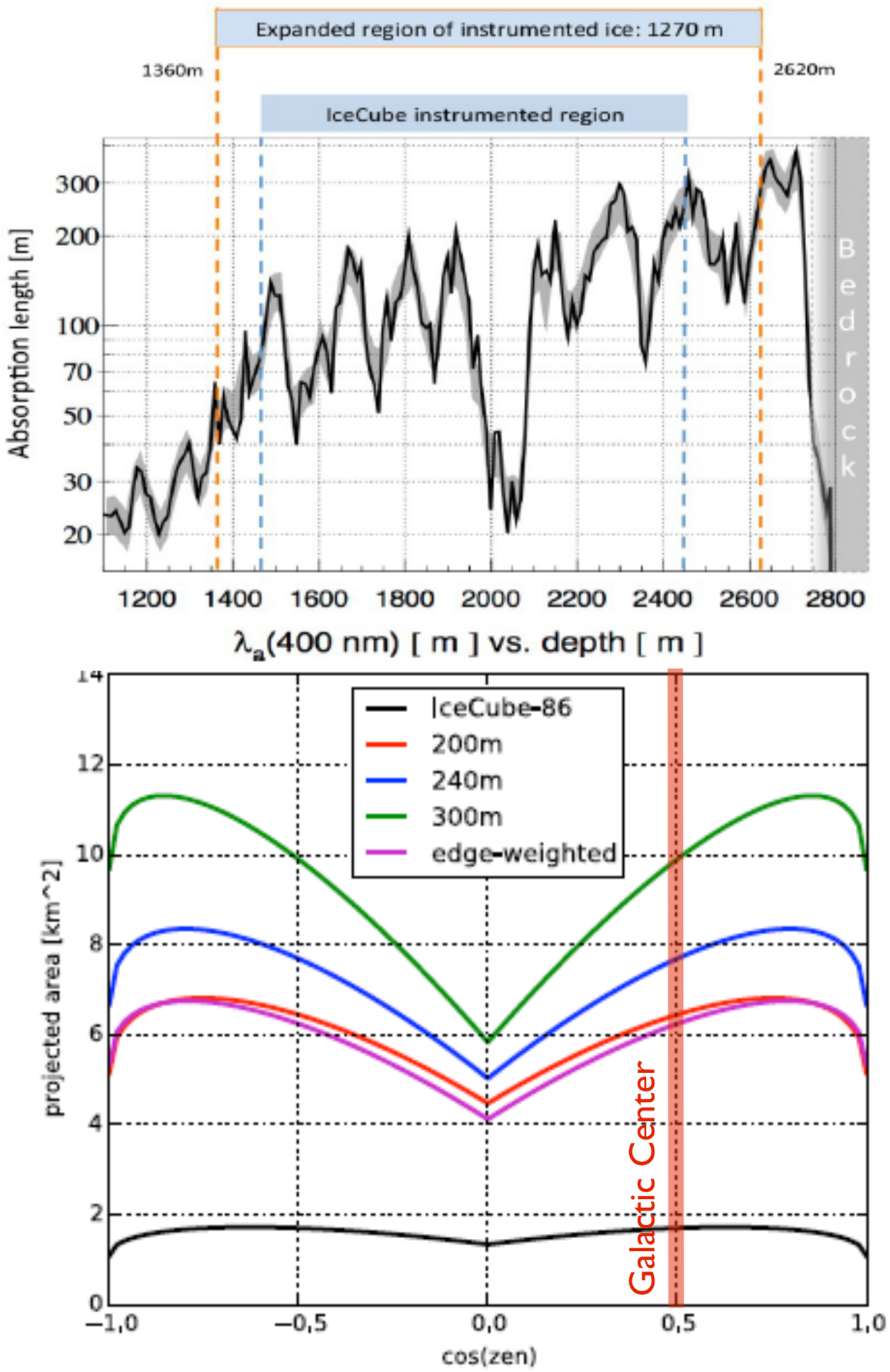
- ARCA blocks:
  - 115 lines
  - 90m horizontal
  - 36m vertical



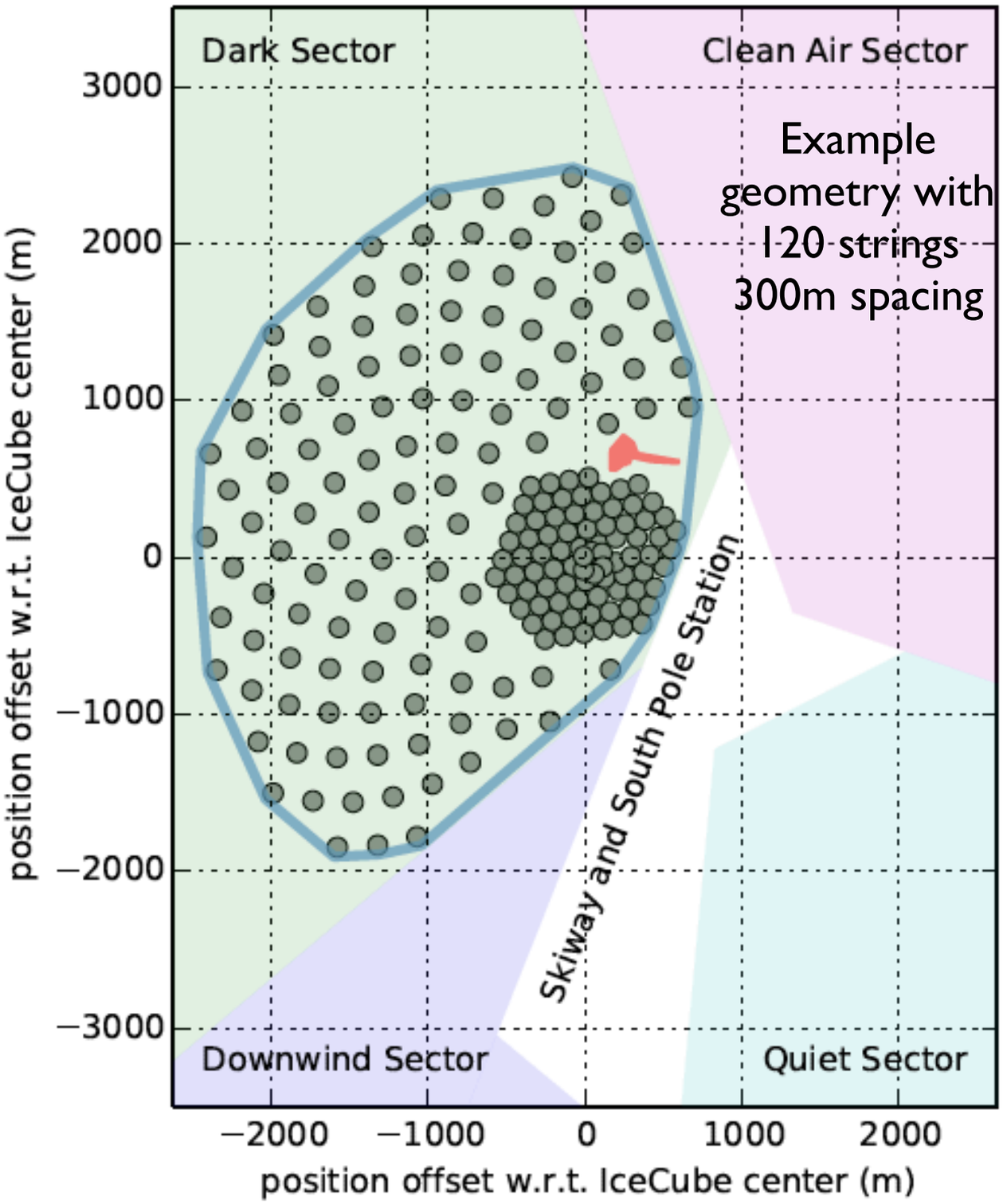


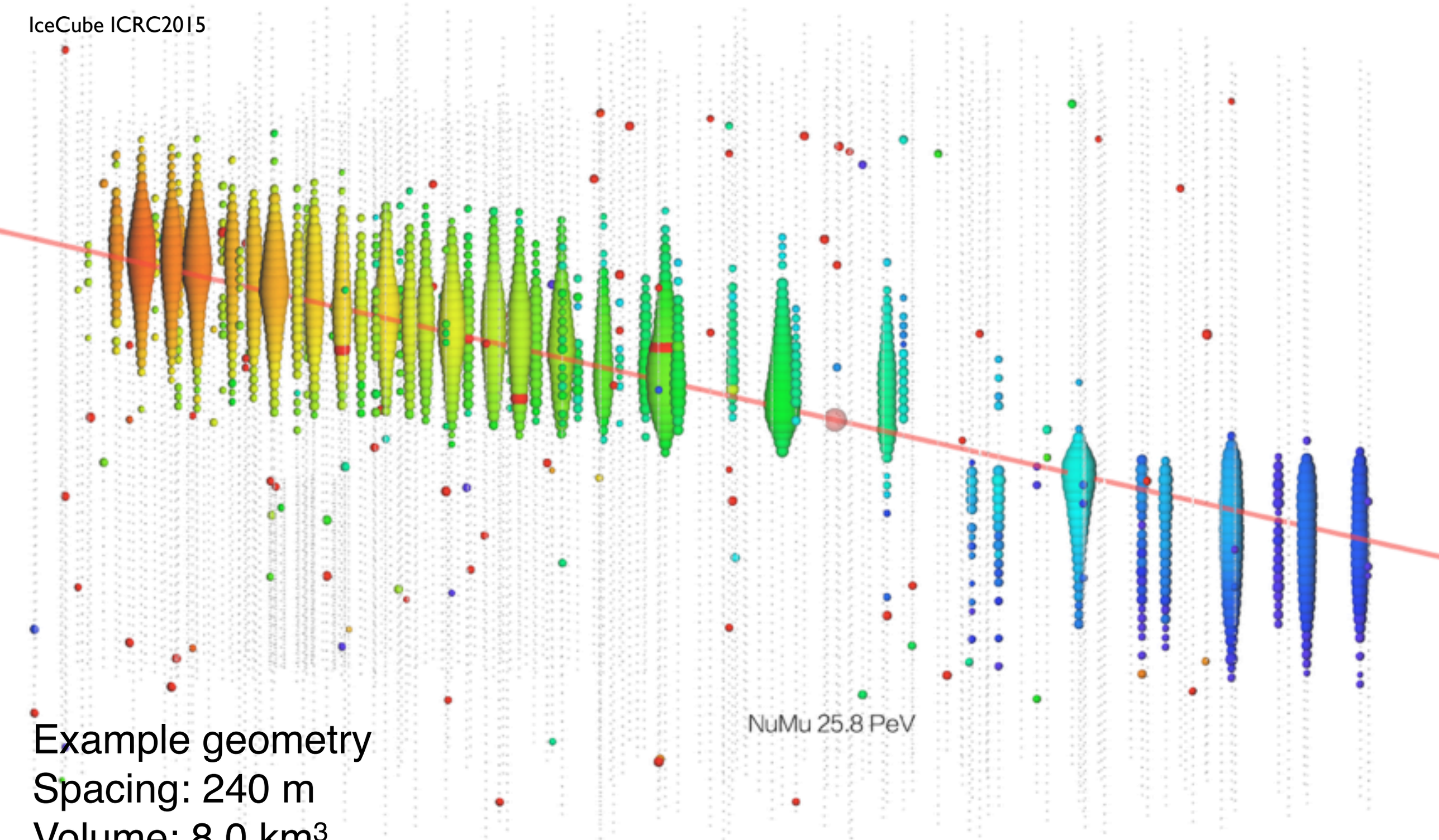


IceCube Gen 2



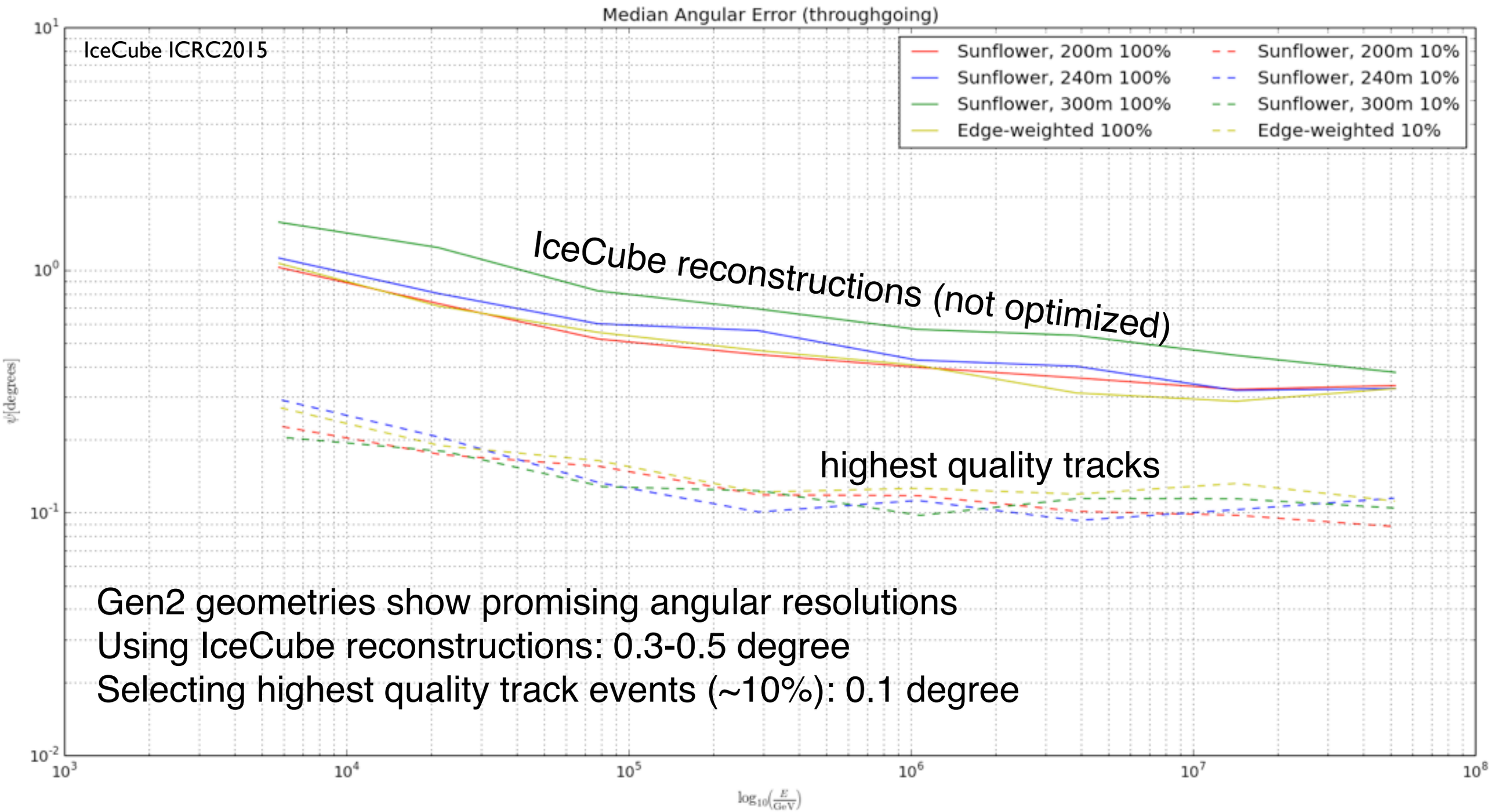
IceCube Coll. Gen2 LOI arXiv:1412.5106





Example geometry
Spacing: 240 m
Volume: 8.0 km^3

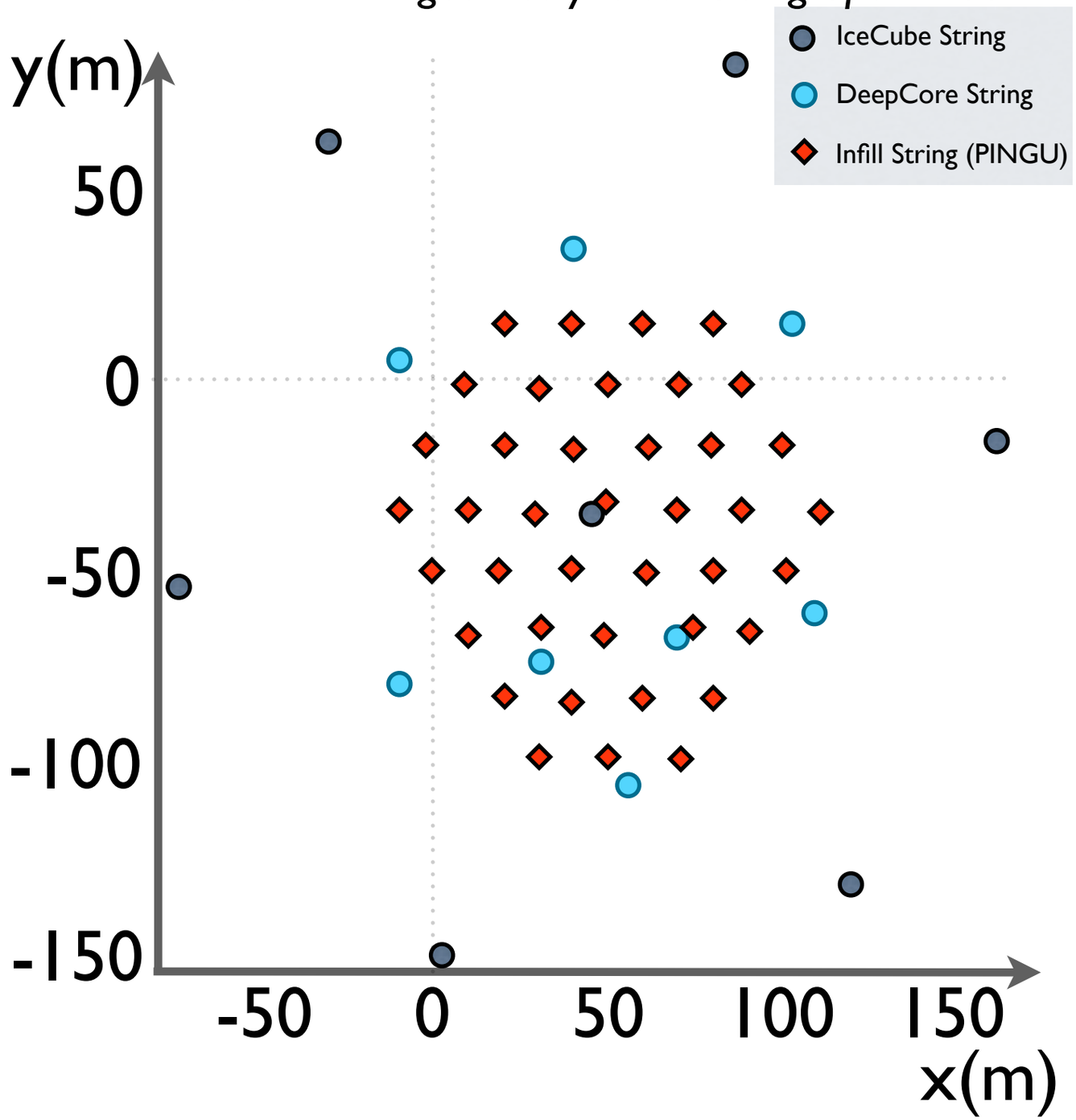
IceCube Gen 2 Angular Resolution



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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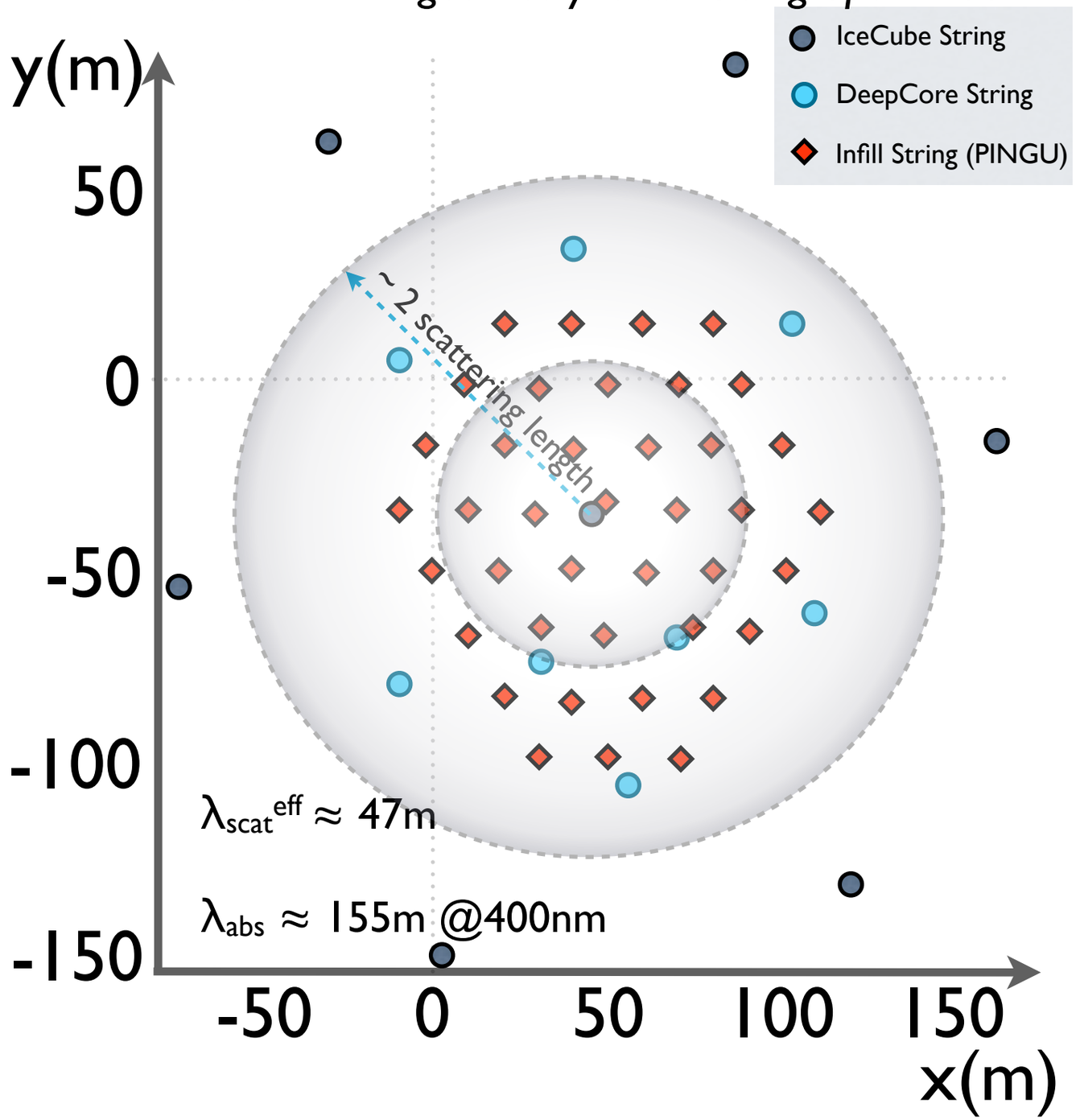
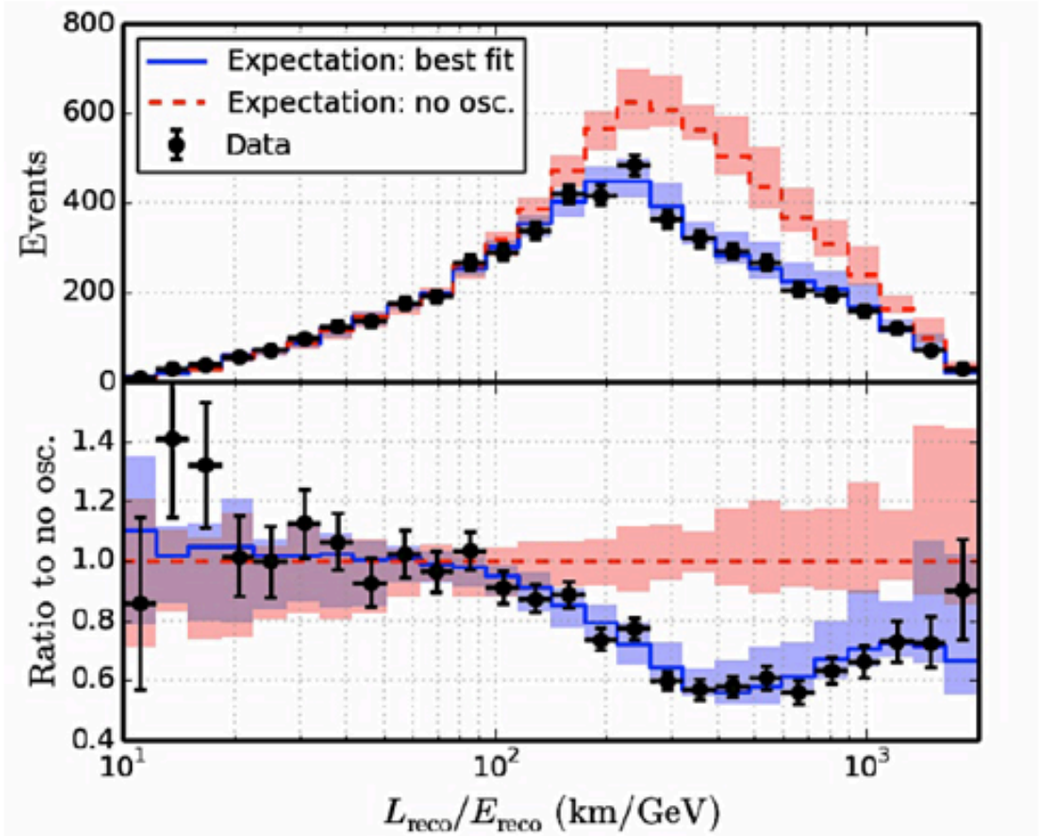


IceCube Neutrino Oscillations

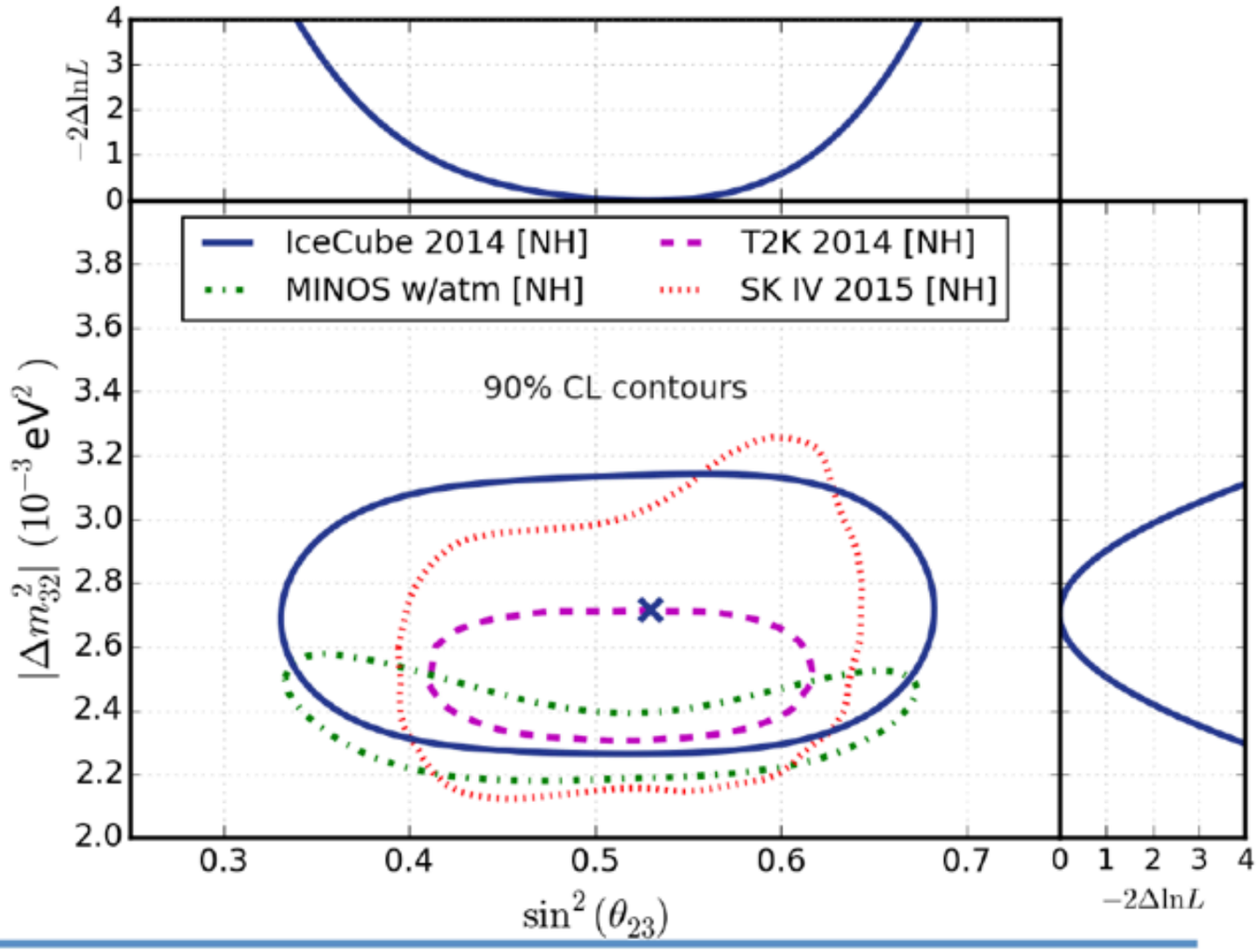


- select
  - starting events
  - clear μ tracks
  - rely on direct photons
- 5174 events observed cf. 6830 expected if no oscillation
- perform 2D fit in *E* and *cos(θ)*

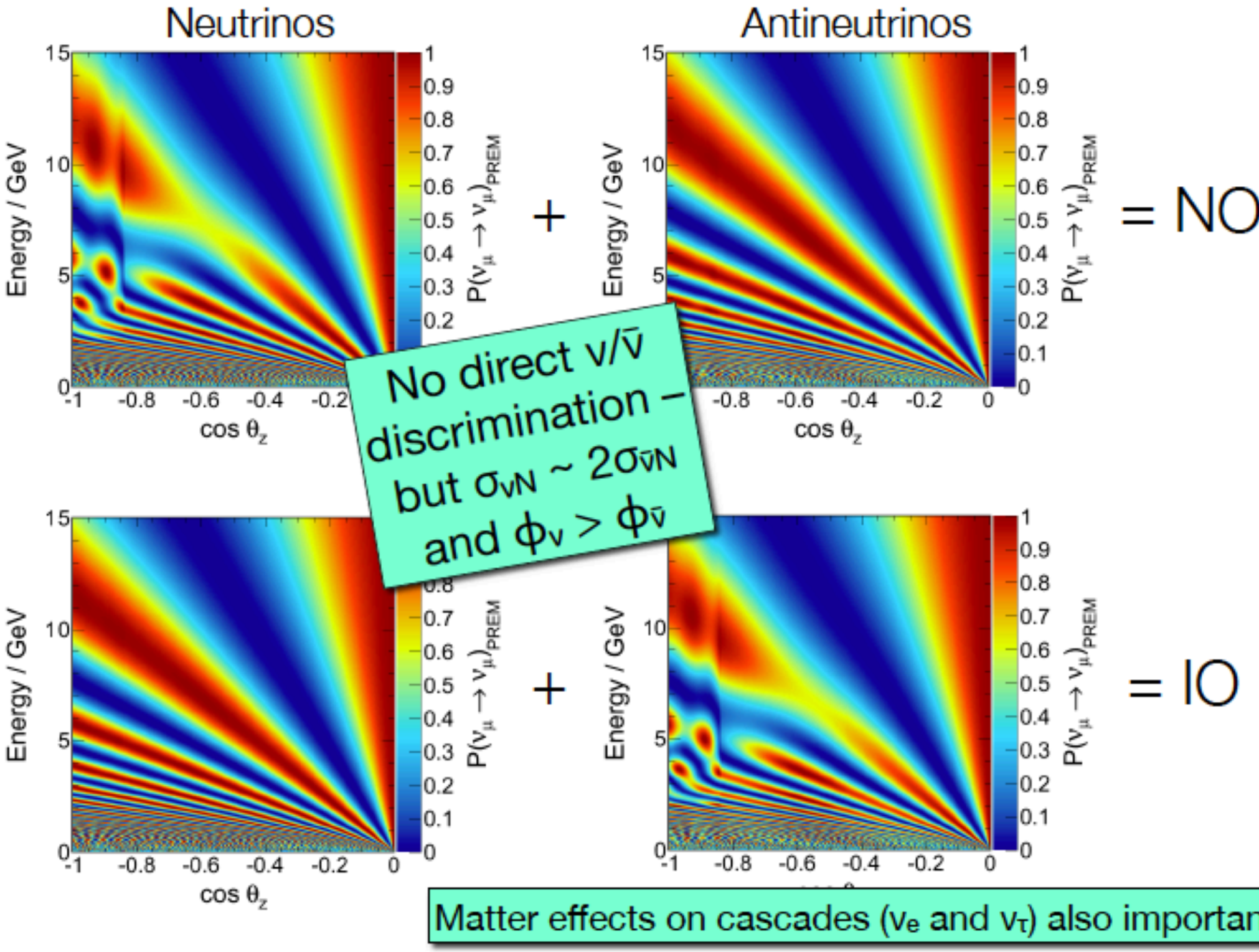
[*IceCube, Phys.Rev.D91:072004 (2015)*]

- competitive result (3 years)
- will improve further

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

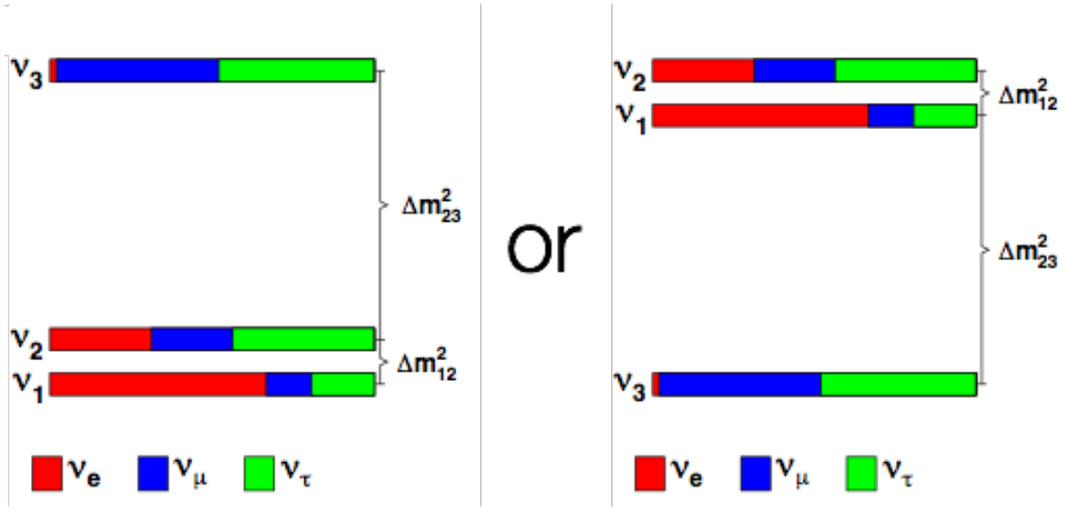


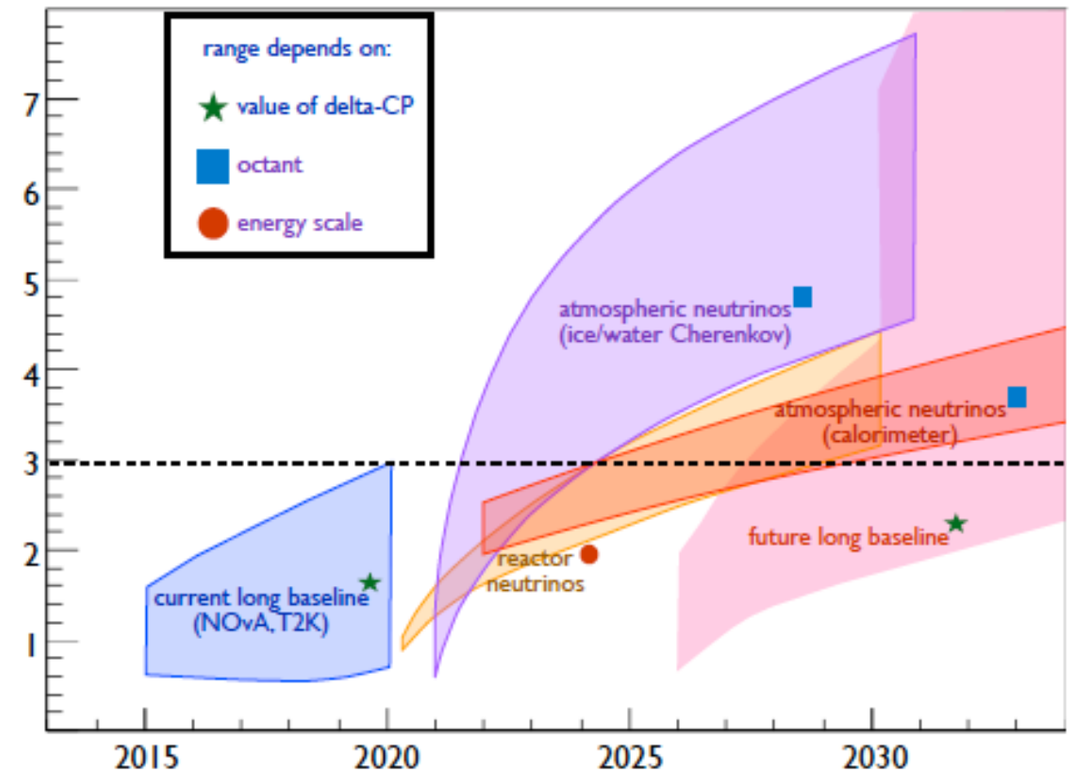
Neutrino Mass Hierarchy



Science Potential of PINGU and ORCA

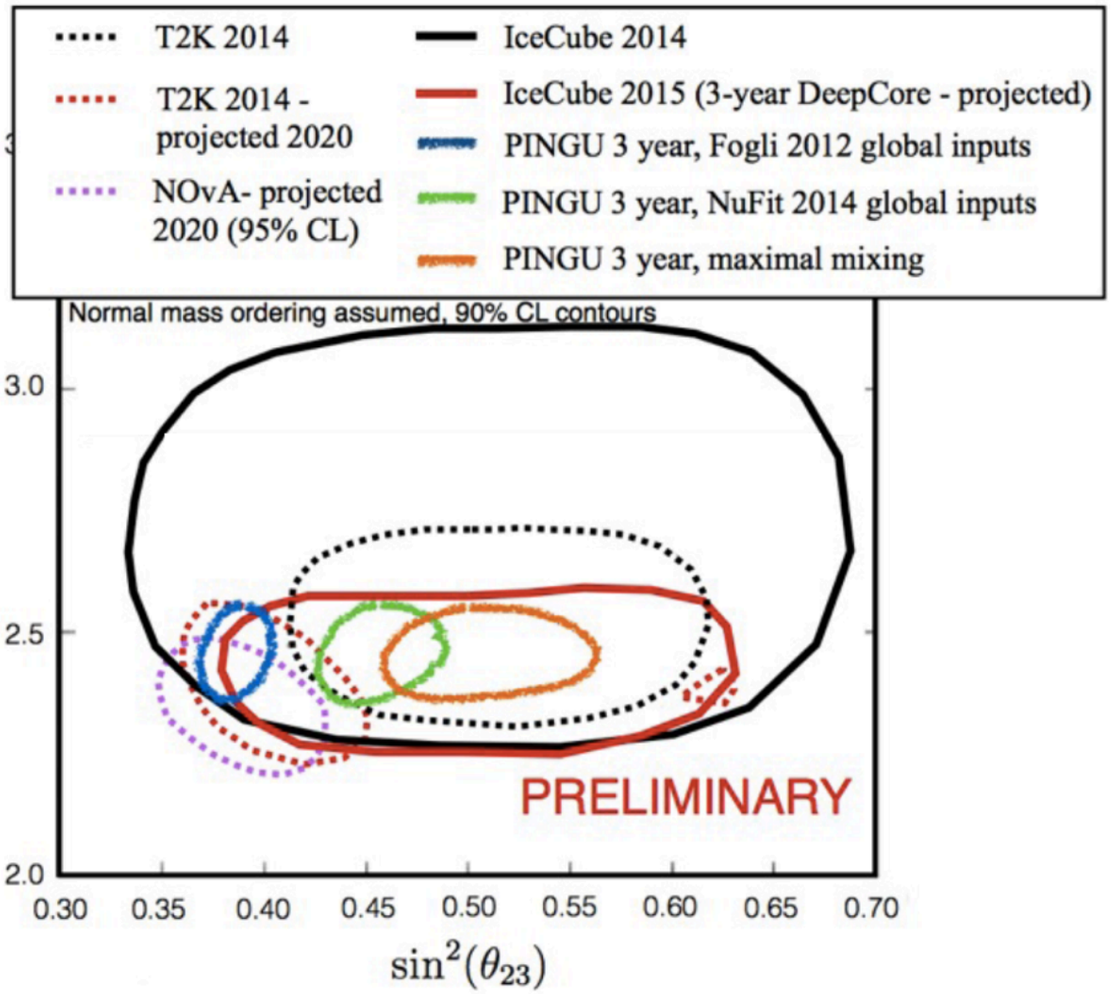
- Well-established detector and construction technology (low risk)
- Rapid schedule
  - PINGU: 3 seasons (first deployments in 2018/2019 ?)
  - ORCA: 5% till 2017 (100% by 2020 ?)
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors
- PINGU LOI released *arXiv:1401.2046* update later this year
- ORCA see www.km3net.org/

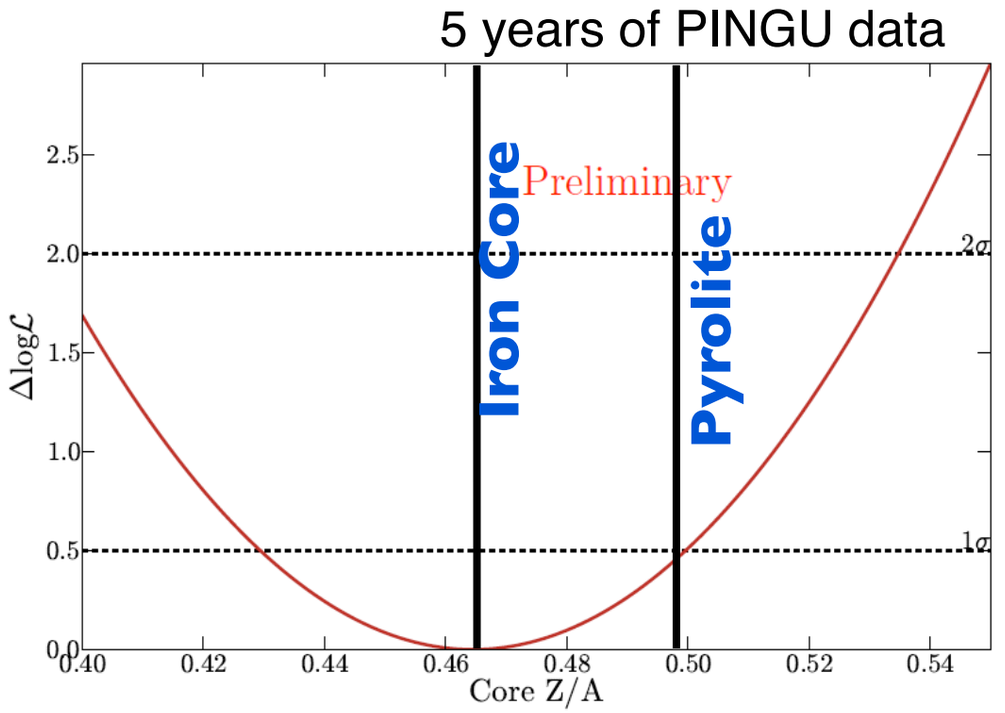


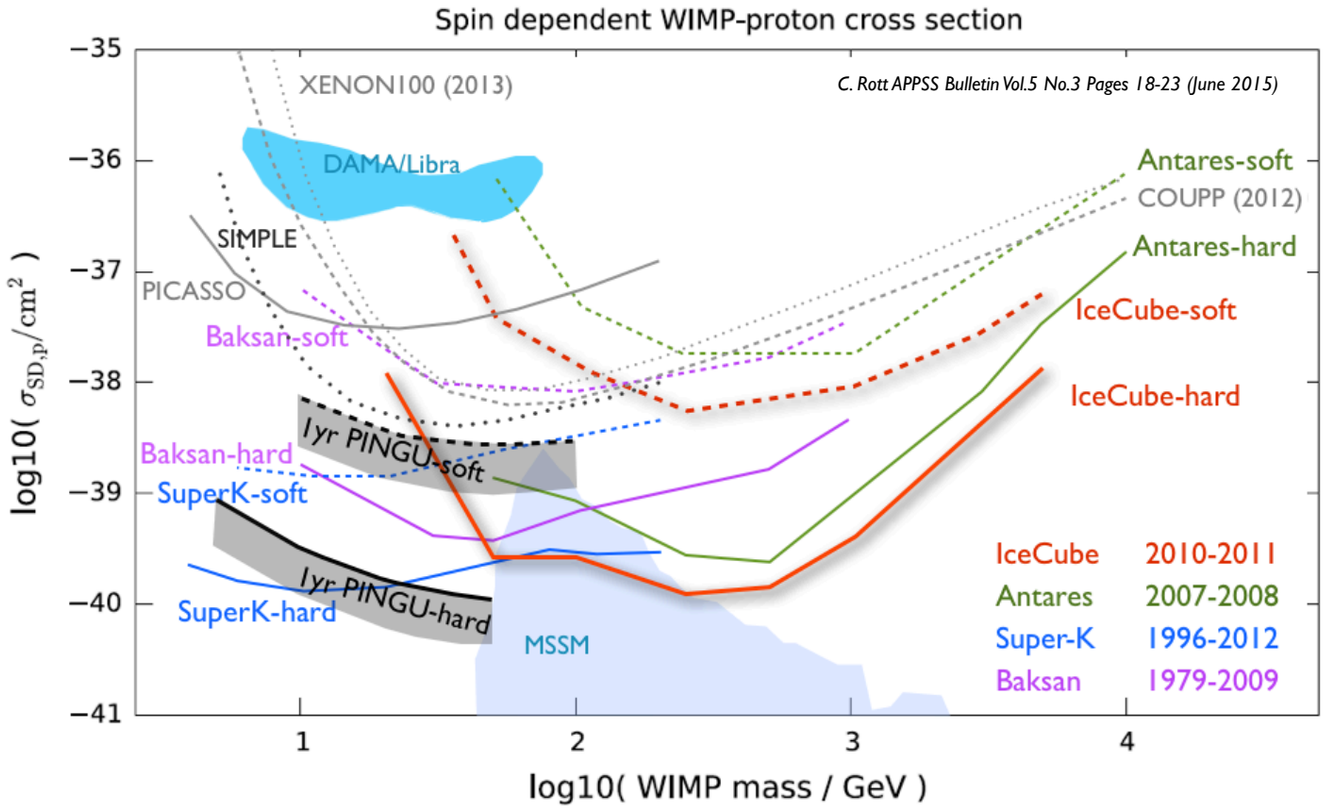


PINGU Multi-purpose experiment

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

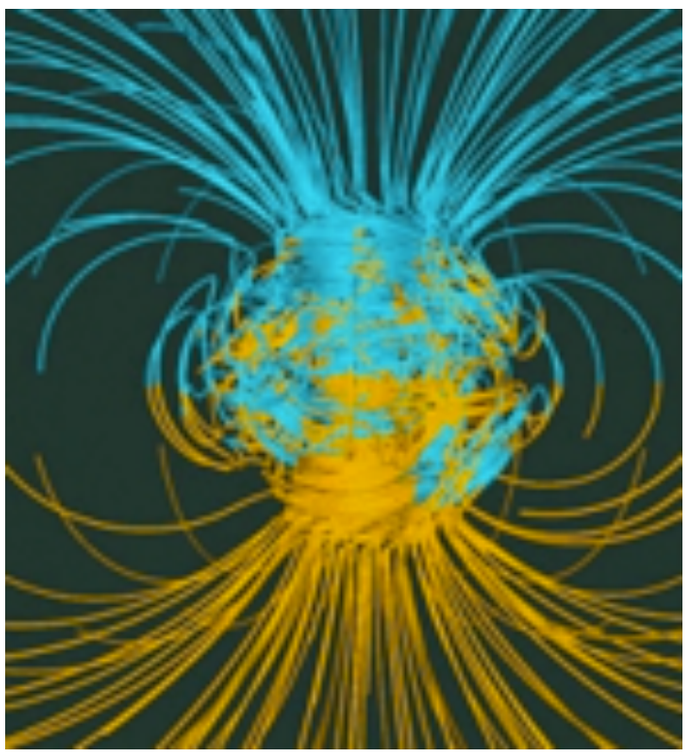


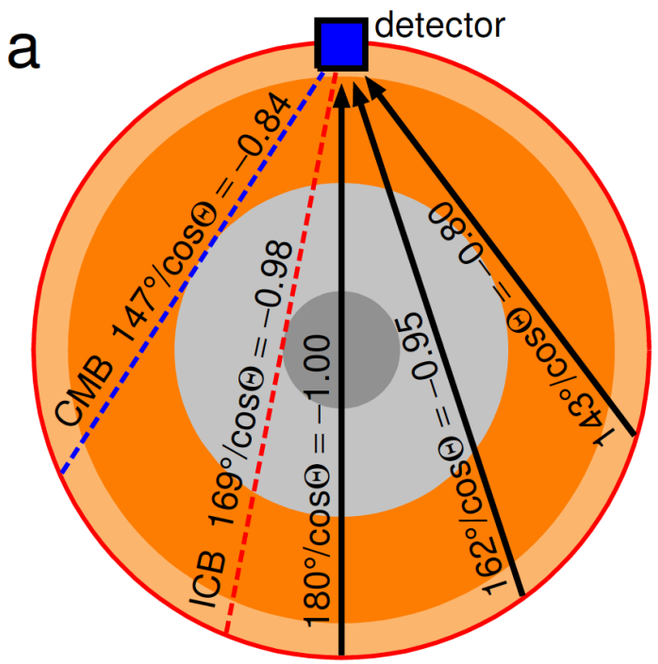


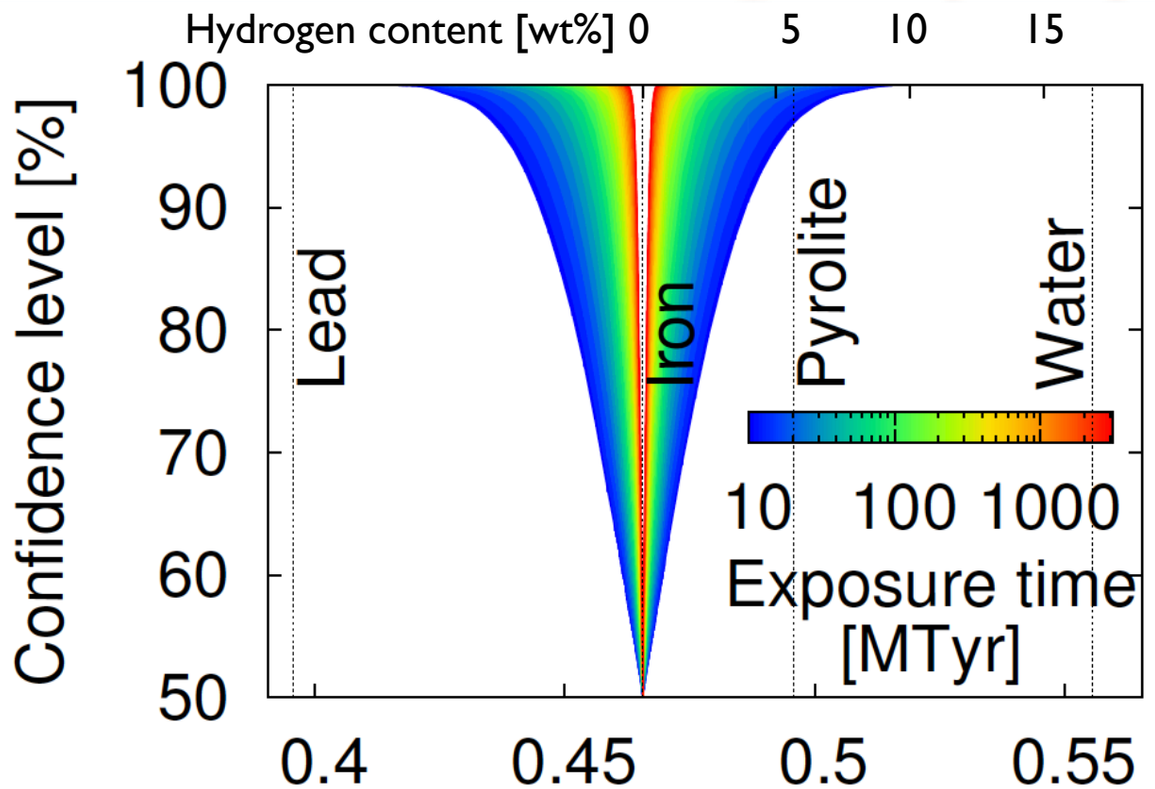


Rott & Taketa et al. Scientific Reports 5,
Article number: 15225 (2015) arxiv:1502.04930)

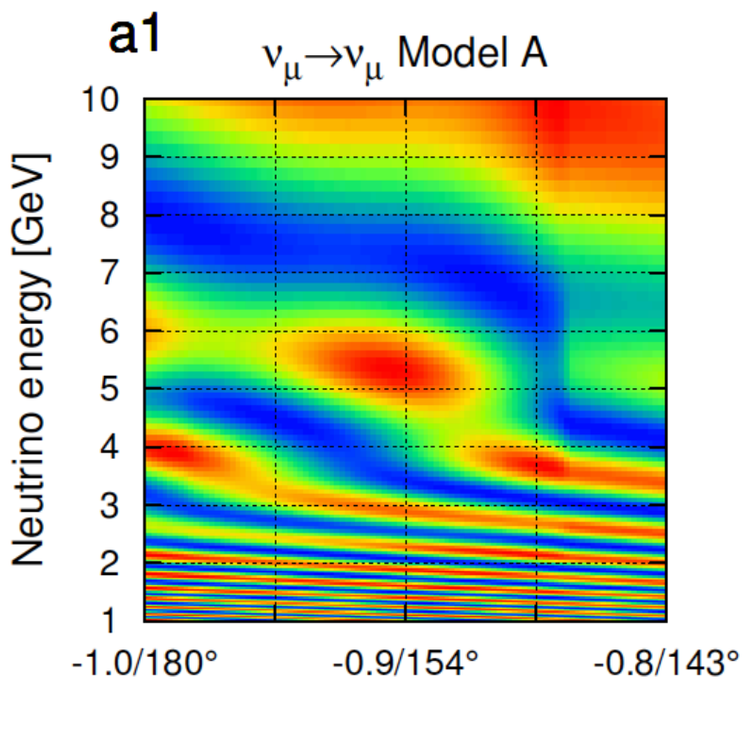
Neutrino Tomography

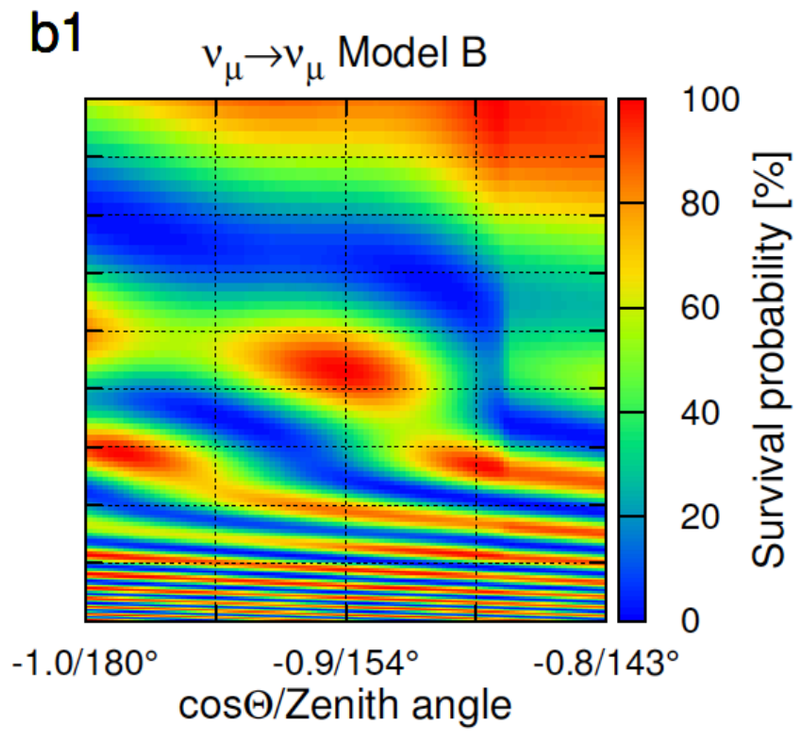


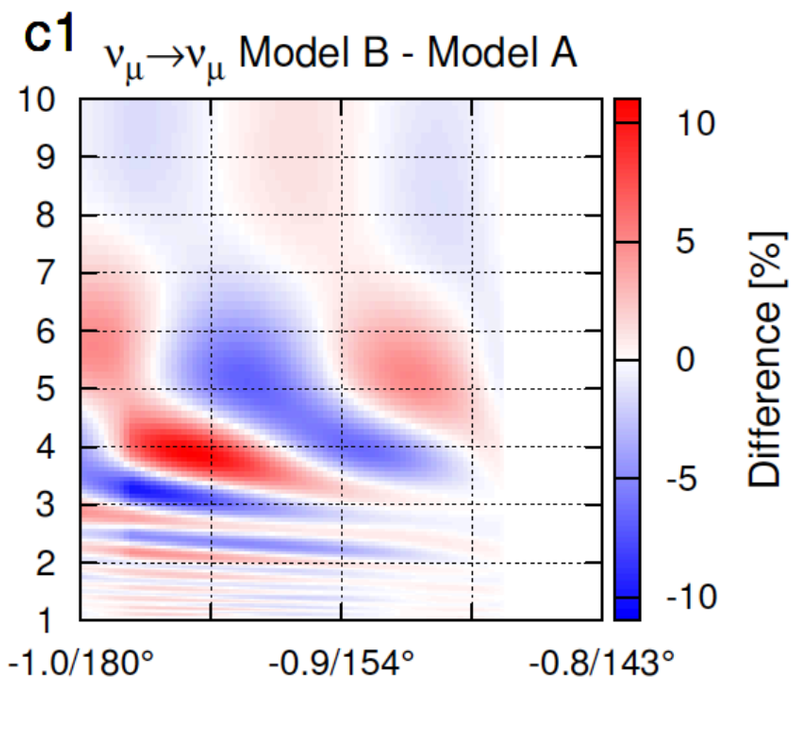




Z/A ratio







- 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 !
- Great prospect for future upgrades
  - Gen2 / ARCA for high statistics PeV neutrinos
  - PINGU/ORCA for Neutrino Mass Hierarchy and more
- Opportunity for unexpected discoveries !
  - Dark Matter, Galactic Supernova, ...

Image:Stephan Richter, IceCube/NSF