High energy astrophysical neutrinos – observations and implications

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WIPAC
Wisconsin IceCube Particle Astrophysics Center

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

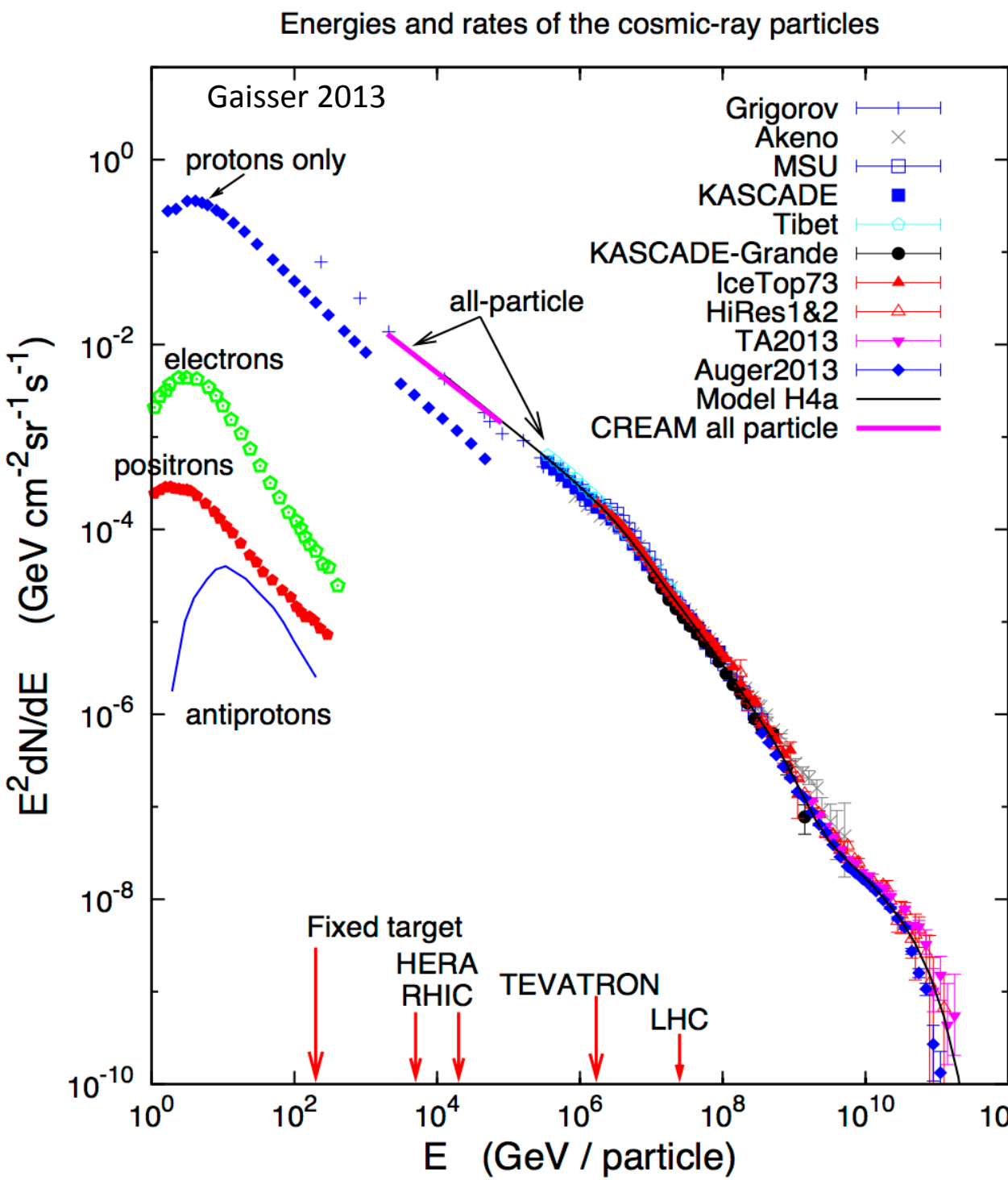
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts



Neutrino production from cosmic rays on known targets.

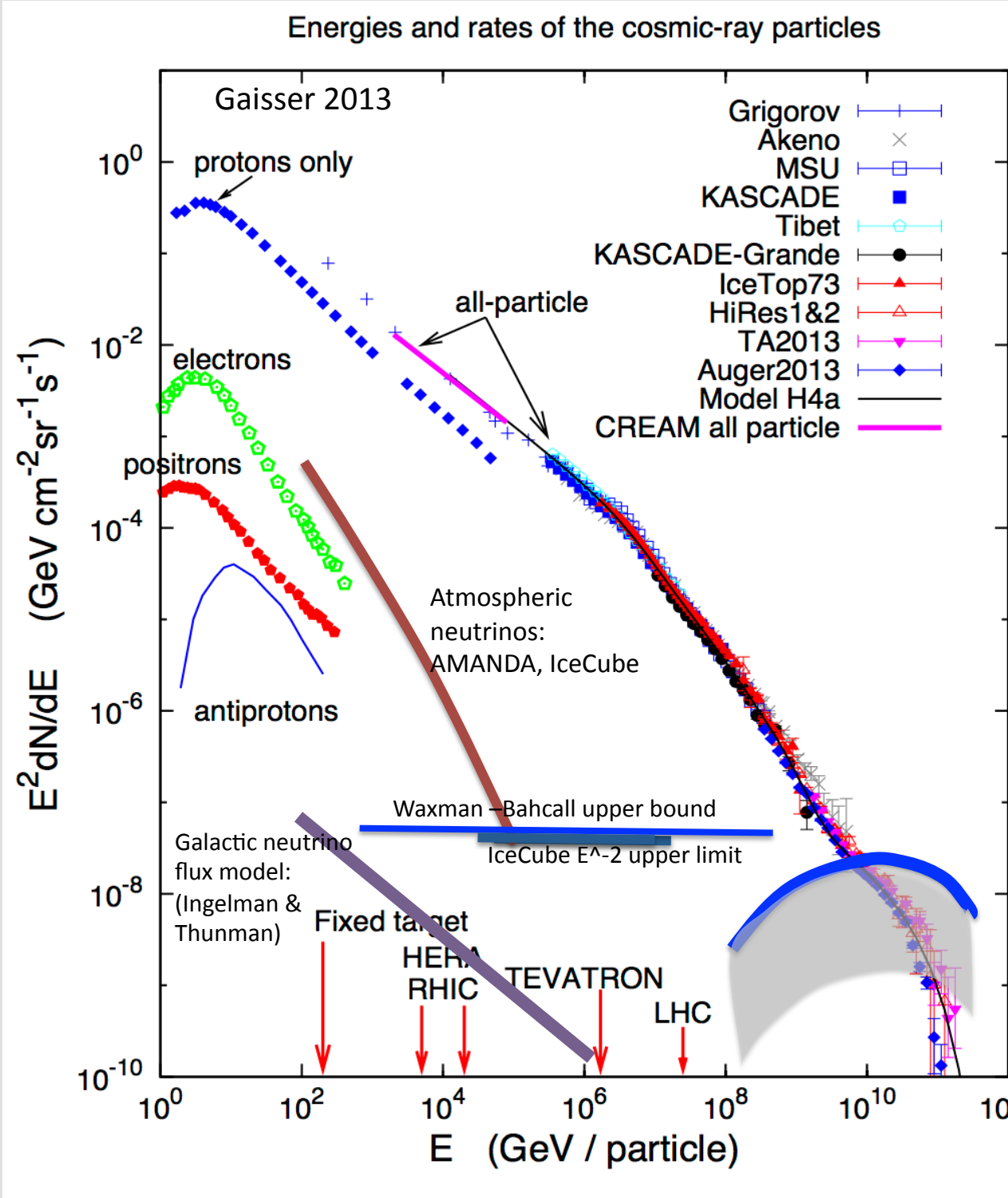
$$p\,p \rightarrow N\,N + p\,\dot{o}ns; \qquad p\gamma \rightarrow p\pi^0, m\pi^+$$

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

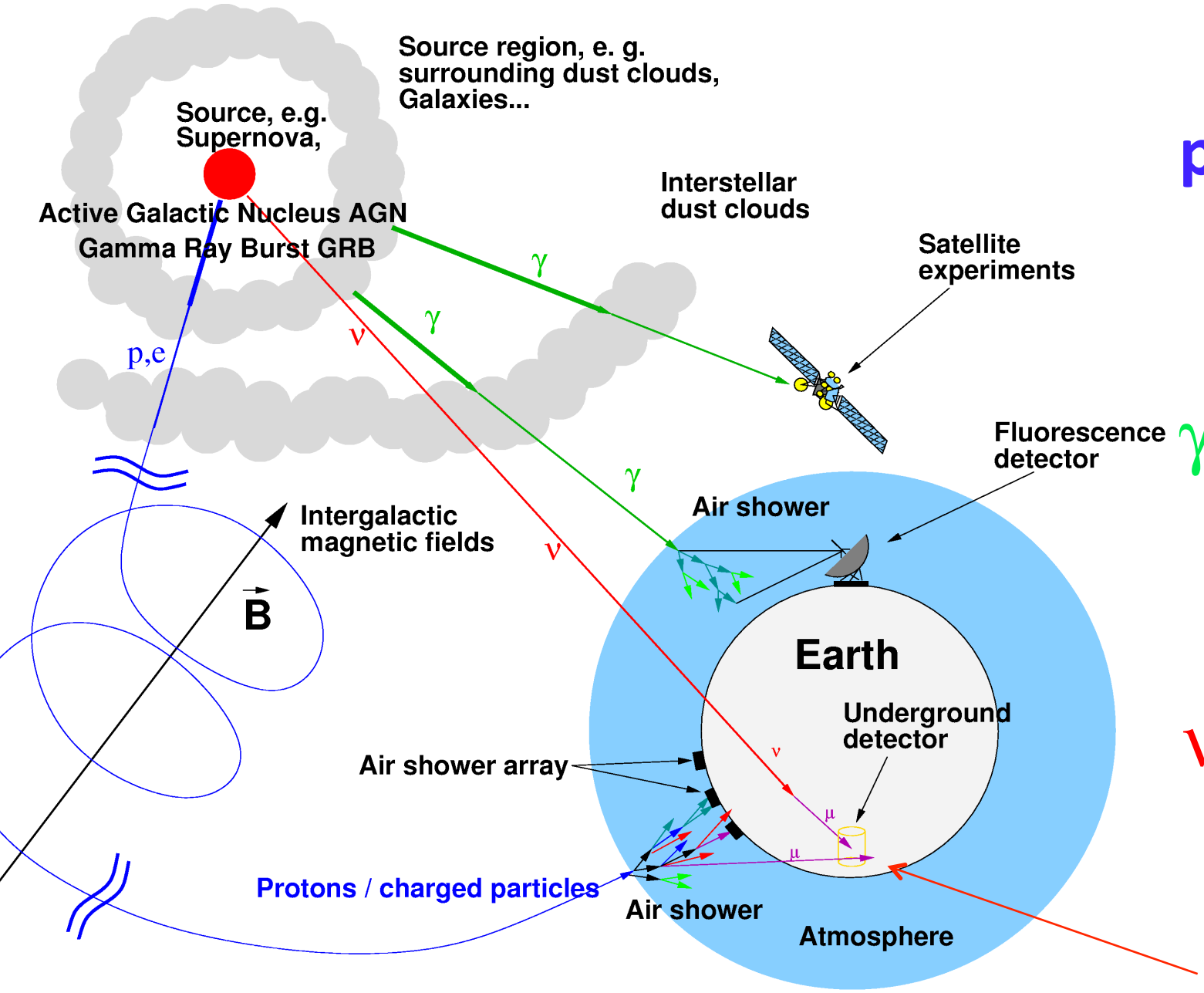
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

nown targets:

- Earth's atmosphere: Atmospheric eutrinos (from π and K decay)
- Interstellar matter in Galactic lane: Cosmic rays interacting with terstellar matter, concentrated in the sk
- Cosmic Microwave background: HE cosmic rays interact with hotons in intergalactic photon fields.



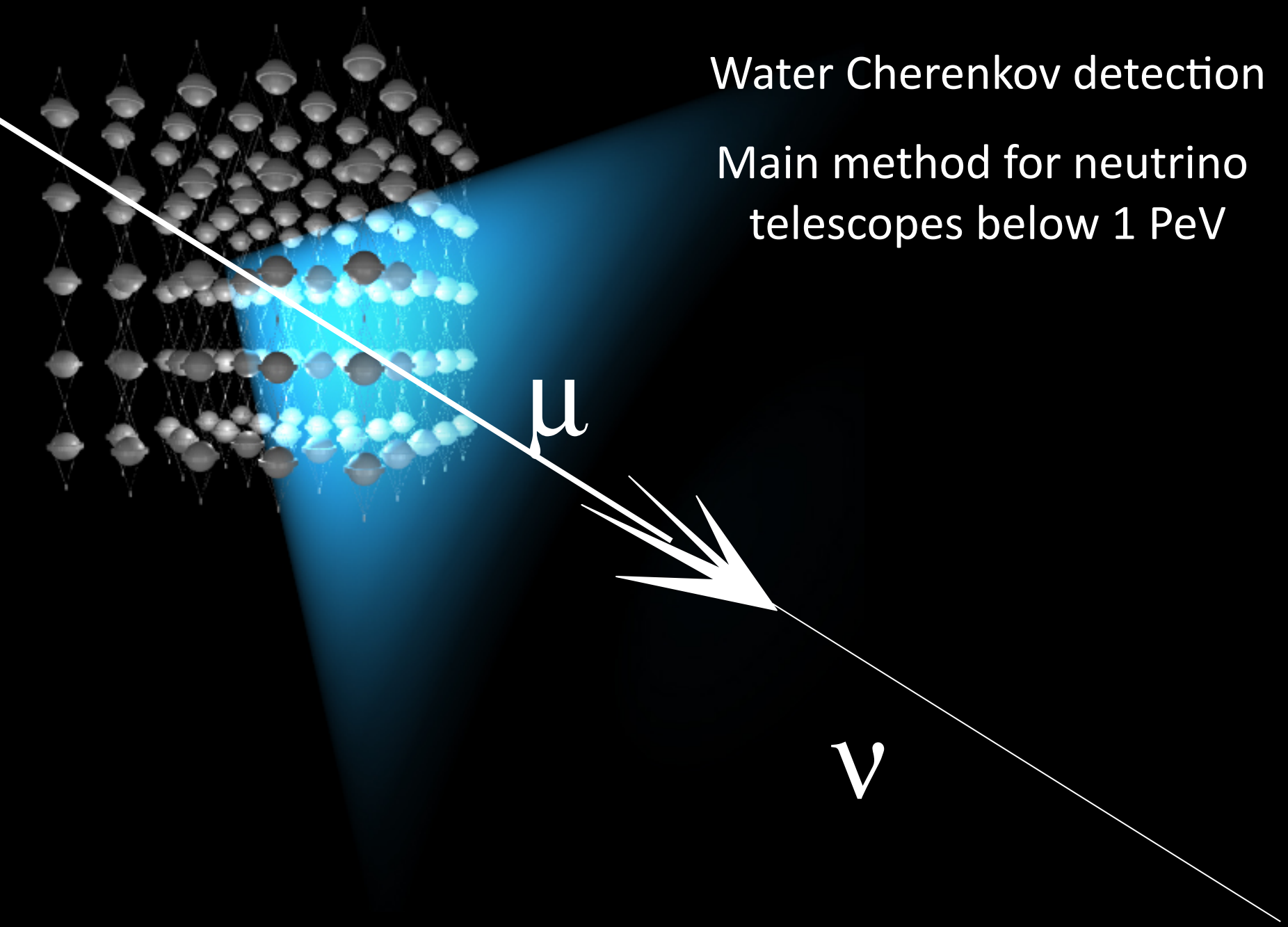
Neutrinos as Cosmic Messengers



p *Protons:* deflected by magnetic fields.

γ *Photons:* easily absorbe by CMB and IR backgrounds. EM/ Hadronic discrimination difficult

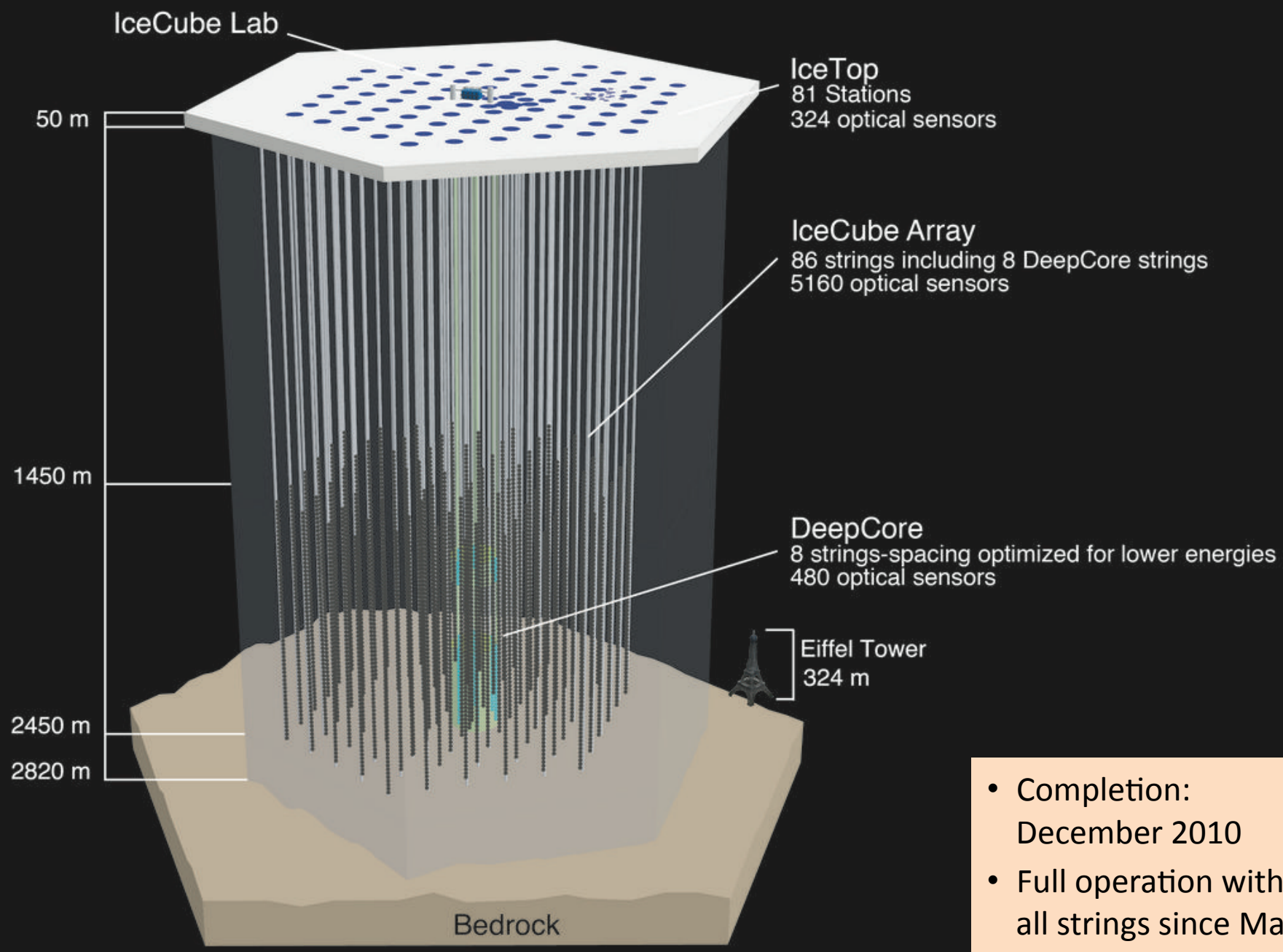
ν *Neutrinos:* not deflected by magnetic fields. Low interaction cross-section.



Water Cherenkov detection

Main method for neutrino telescopes below 1 PeV

IceCube



- Completion: December 2010
- Full operation with all strings since May 2011.

Digital Optical Module

DOM Low Noise rate
(300 Hz from radio activity in the glass, no noise from extremely pure ice.

High reliability, very few sensor issues per year.

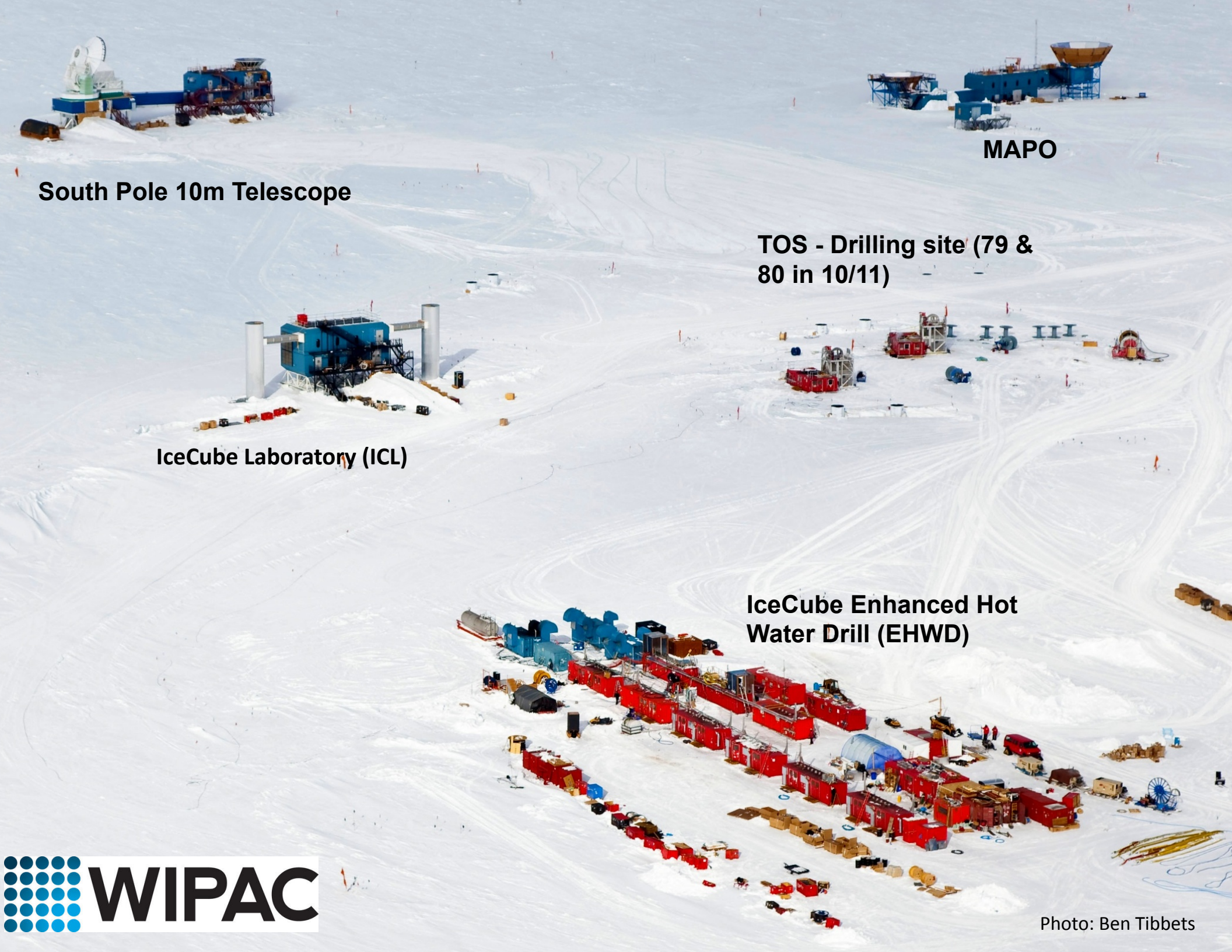


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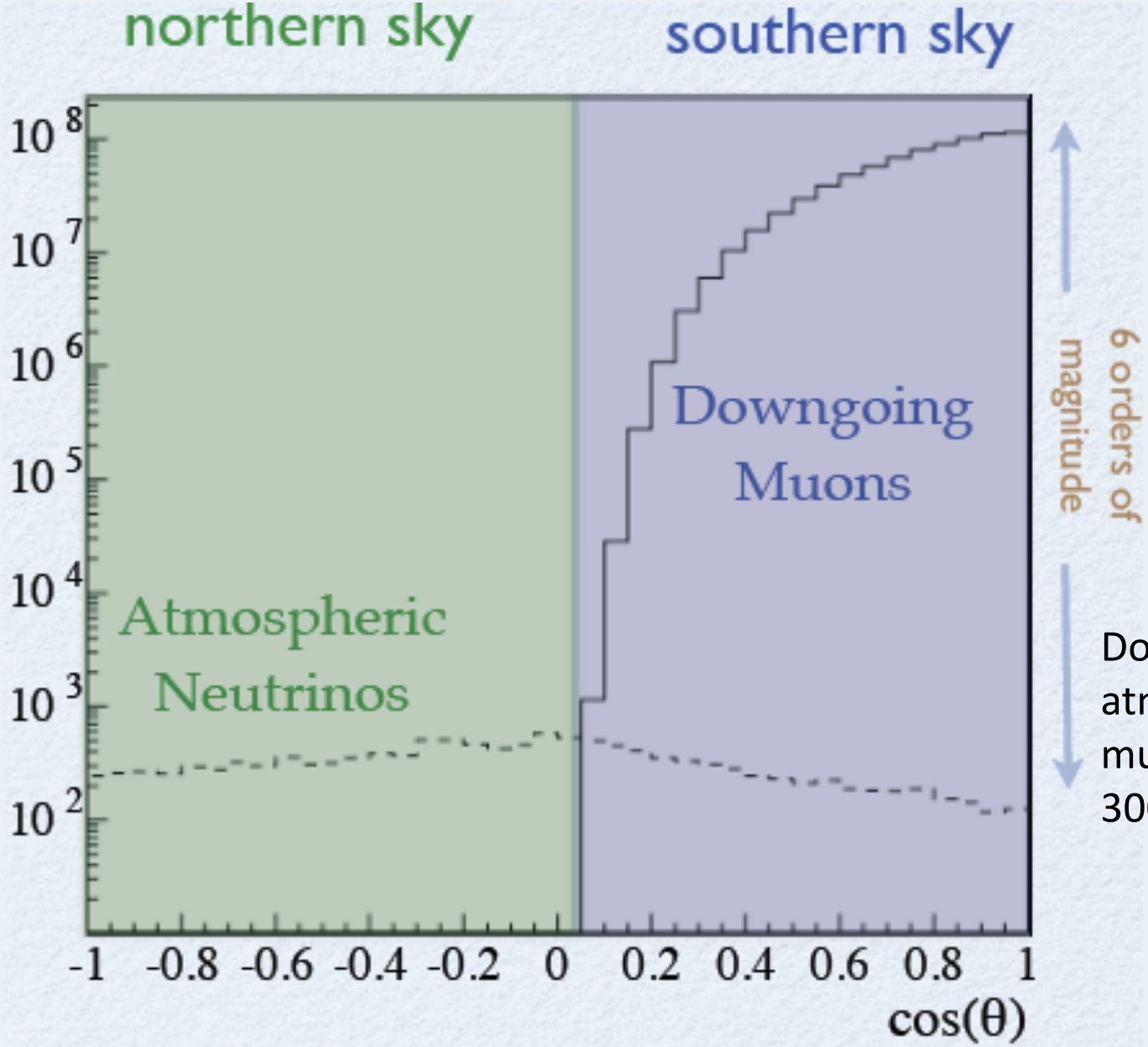
Photo: Ben Tibbets

Muons and neutrinos at depth



eutrino-induced
uons from all
irections
0000 / day

Downward atmospheric muons
300 million / day

→Neutrinos: Use Earth as filter; look for neutrinos from below (GeV to PeV), at high energies from above
→Cosmic ray muons:

15 years of neutrino skymaps

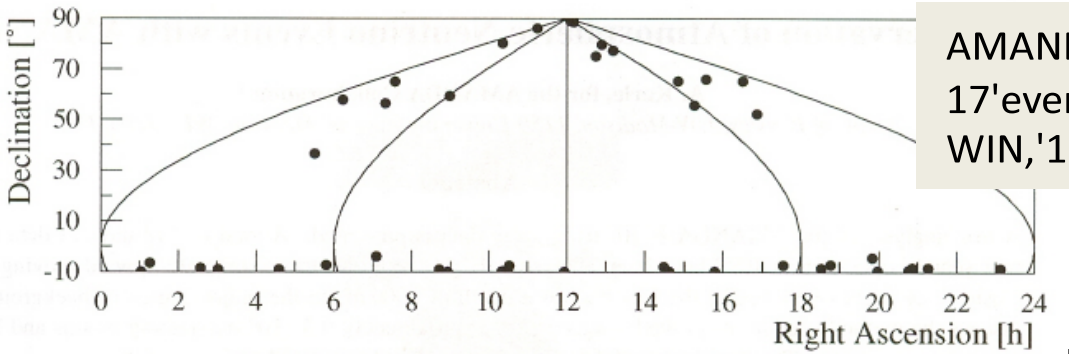
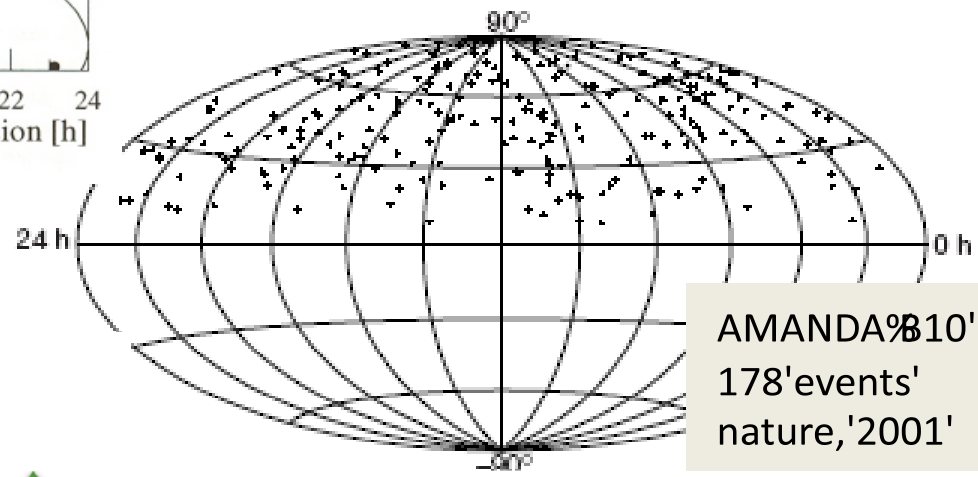
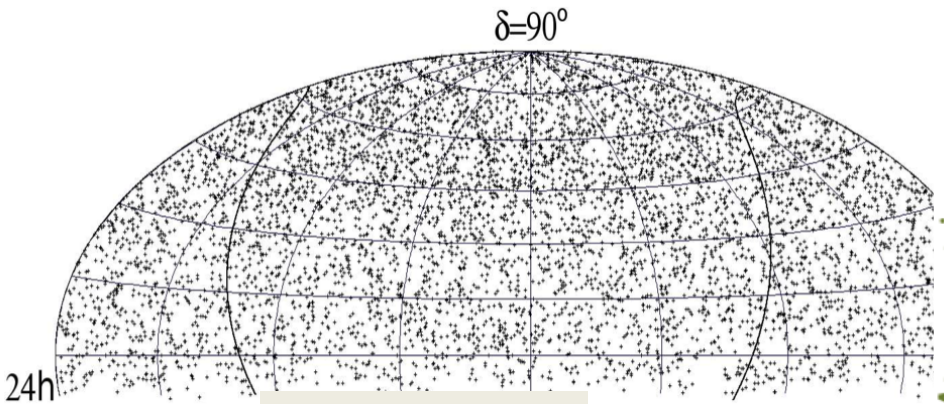


Figure 2: Sky plot of all events that pass level 4 quality cuts.

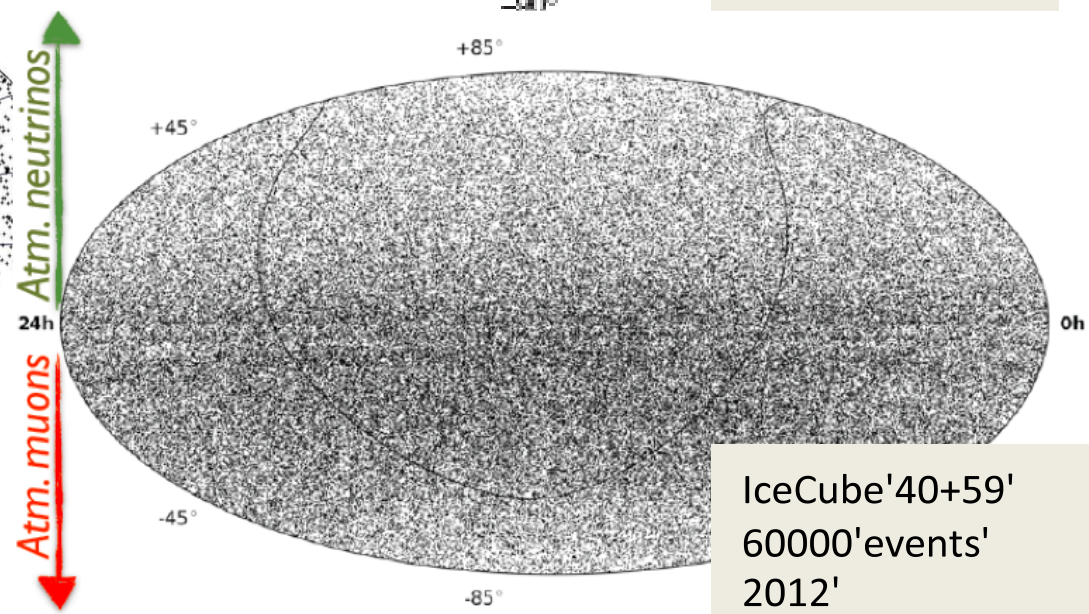
AMANDA%B10'
17'events'
WIN,'1999'



AMANDA%B10'
178'events'
nature,'2001'

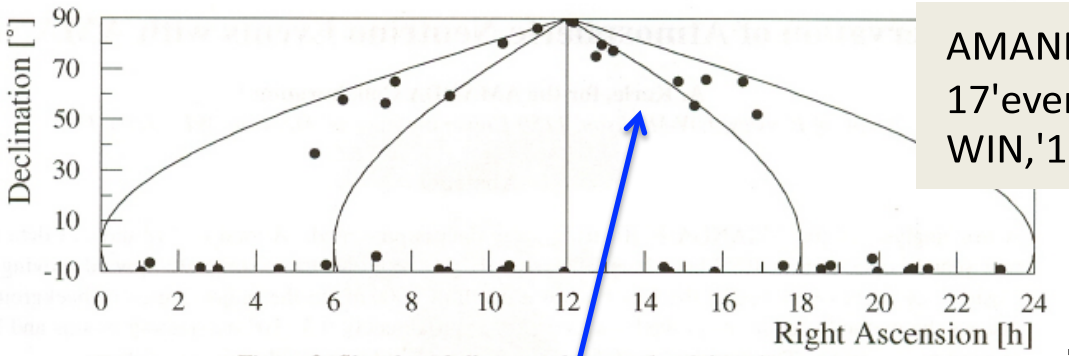


AMANDA%b'
7'years''
6995'events'
2006'



IceCube'40+59'
60000'events'
2012'

15 years of neutrino skymaps



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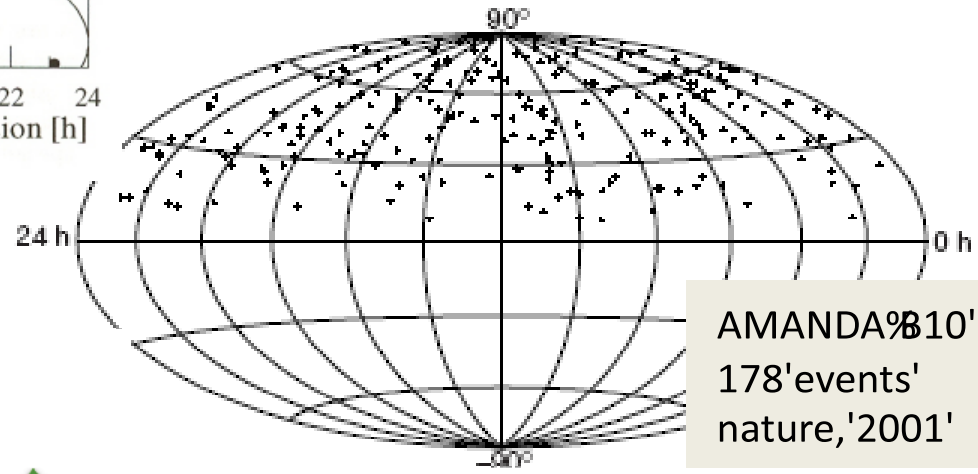
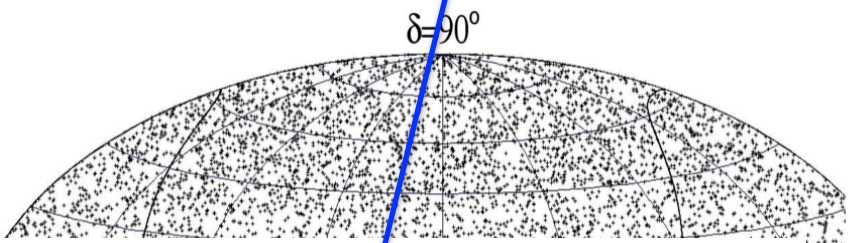
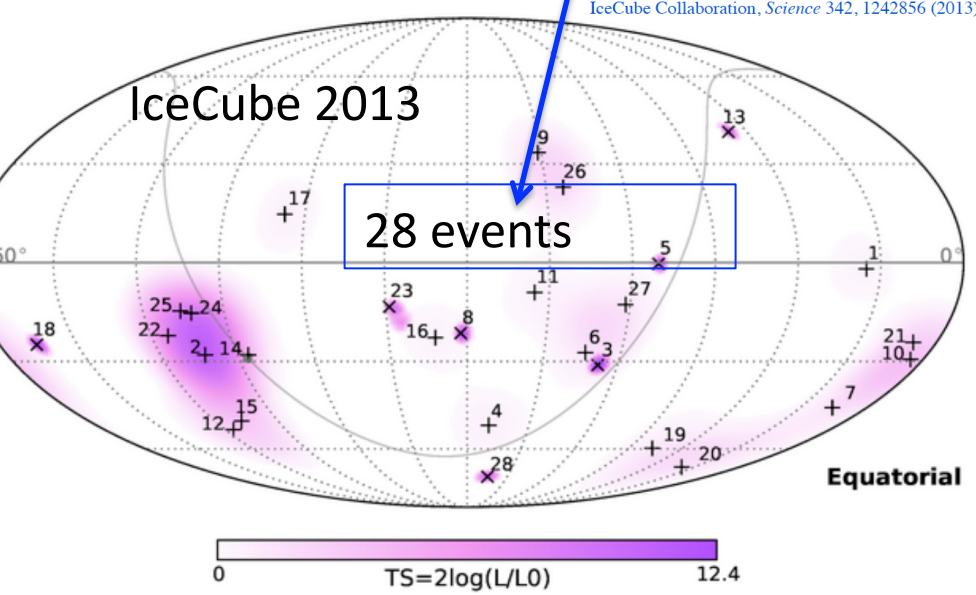


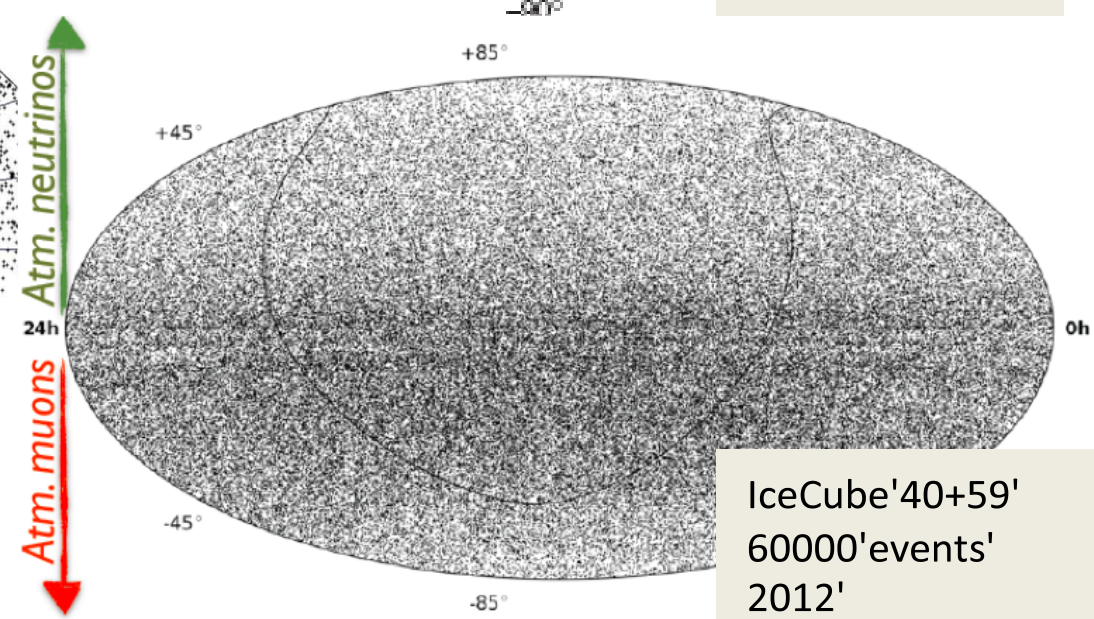
AMANDA%B10'
178'events'
nature,'2001'

?



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

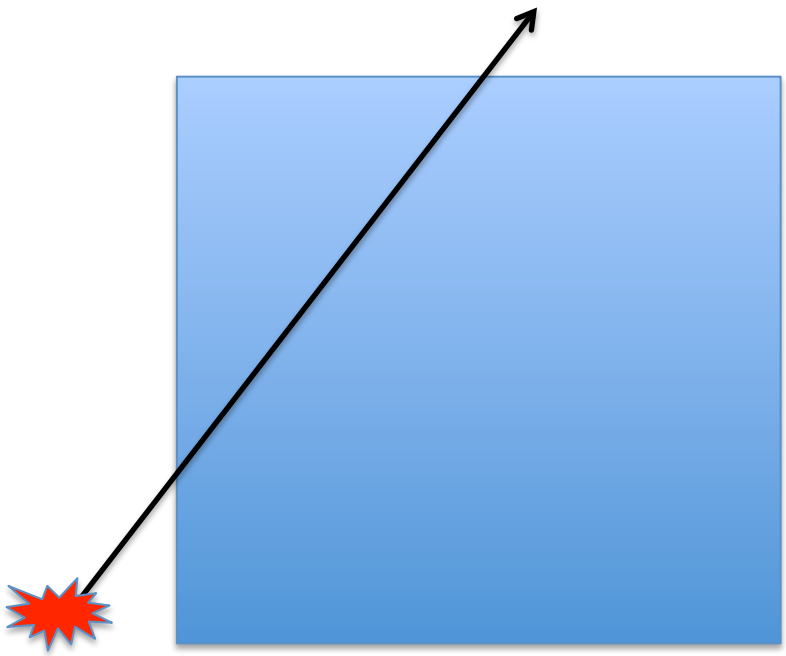




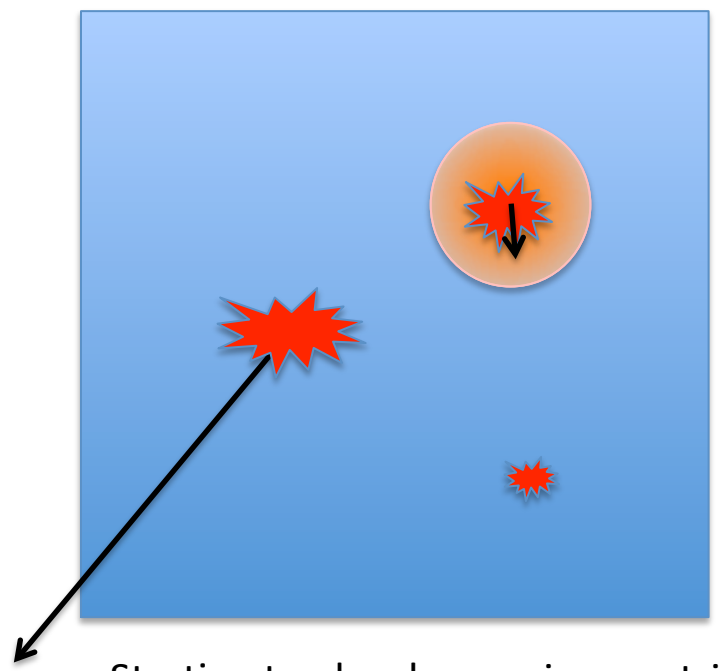
IceCube'40+59'
60000'events'
2012'

Diffuse search strategies – event types

- **Throughgoing muons** –
  - the workhorse for neutrino astronomy, good angular resolution
  - Vertex can be far outside the detector. Increased effective volume!

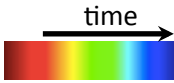


- **Events with contained vertex:**
  - **Neutrinos of all flavors, CC and NC**
  - High energy resolution for cascades (fully active calorimeter, all energy gets deposited in the detection volume)
  - Angular reconstruction above ~50TeV

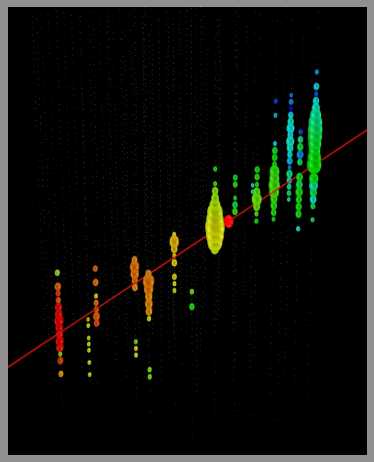


  - Starting tracks: downgoing neutrino astronomy (reject background of throughgoing cosmic ray muons AND possibly atmospheric neutrinos)

Can detect all neutrino flavors



CC Muon Neutrino

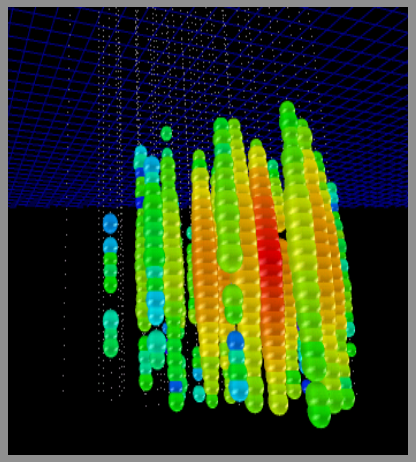


$$\nu_\mu + N \rightarrow \mu + X$$

ack (data)

ctor of ≈ 2 energy resolution
0.5° angular resolution

Neutral Current /Electron Neutrino



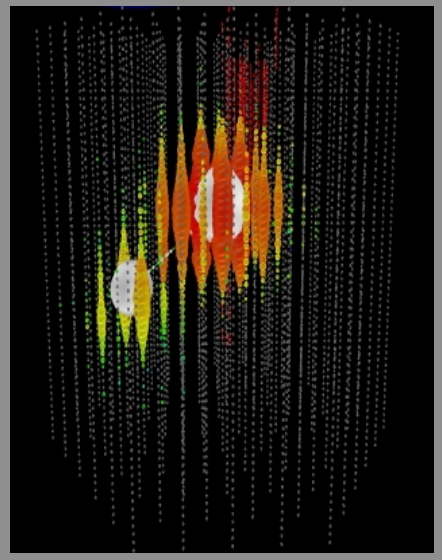
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino



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

"double-bang" and other signatures (simulation)

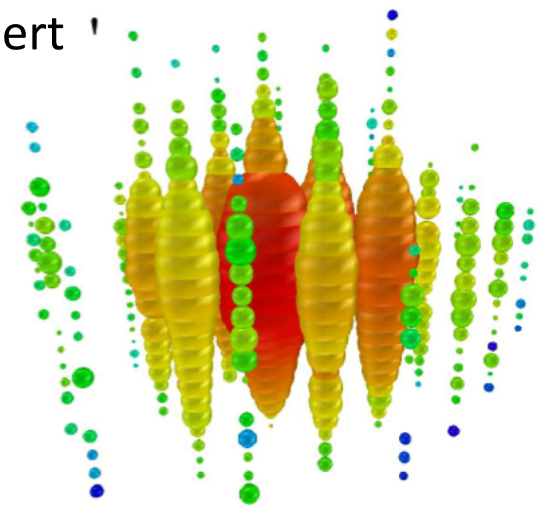
(not observed yet)

Search for highest energy events

Phys. Rev. Let. 111, 021103 (2013)

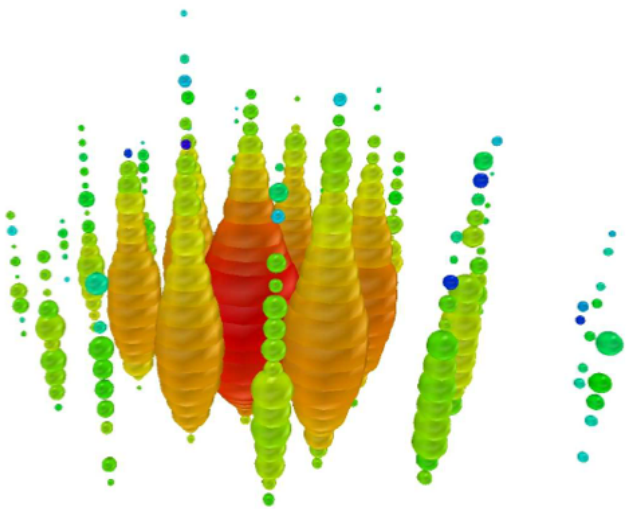
arXiv:1304.5356

' Bert '



Energy: ~1.05 PeV

' Ernie "

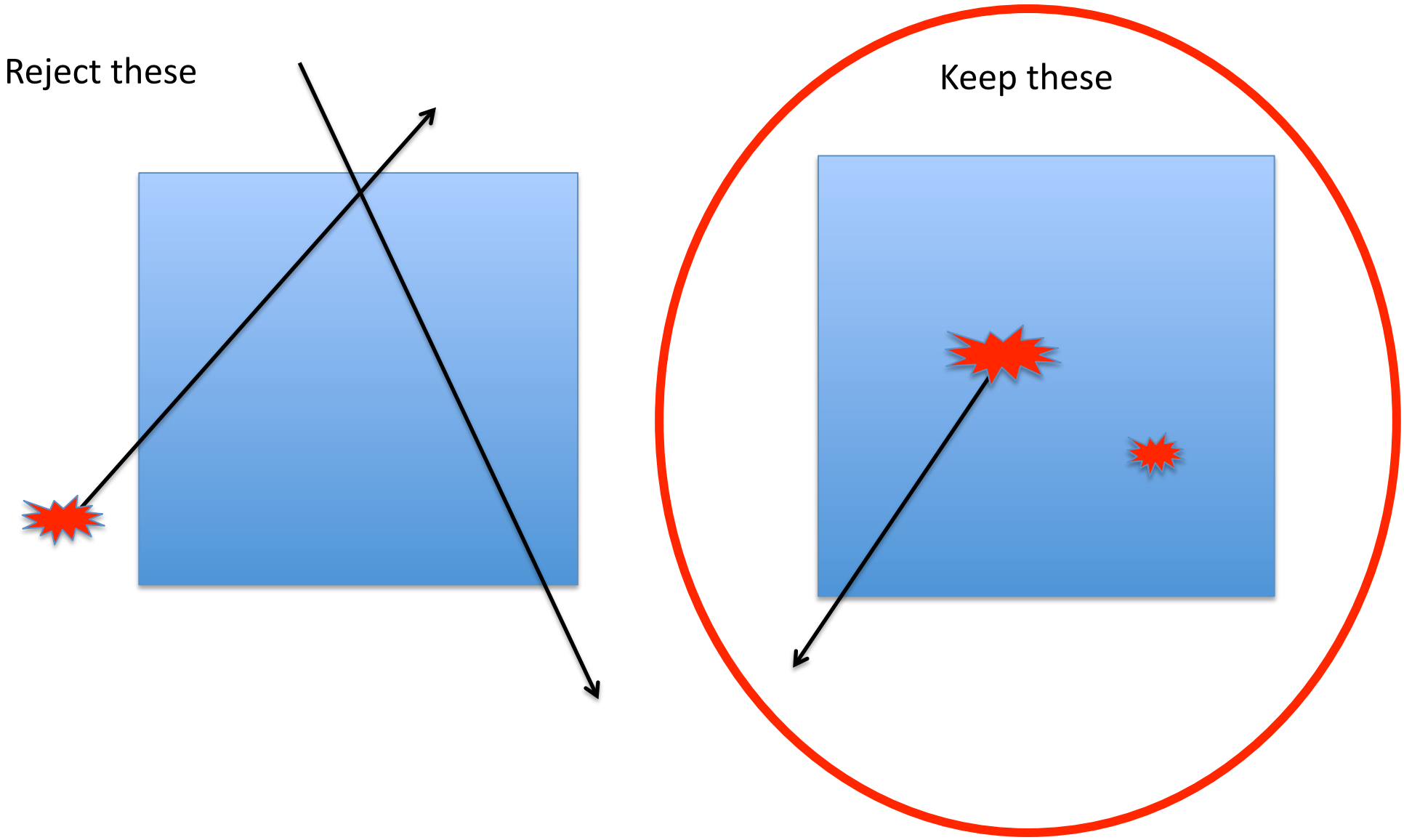


Energy: ~1.15 PeV

Both are cascade events, very good quality, energy resolution ~10%, electron neutrino (or tau or neutral current).

2.8 sigma excess over terrestrial (atmospheric) backgrounds

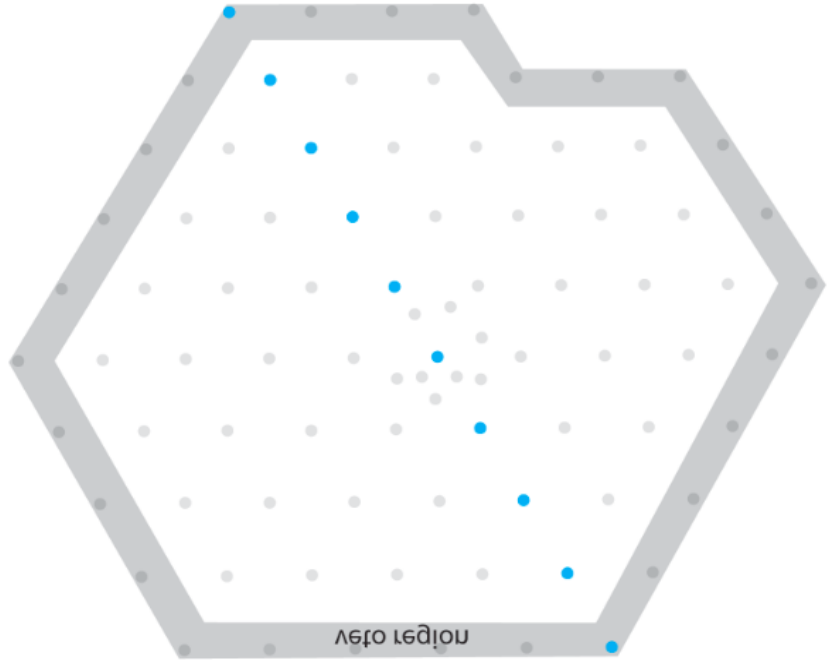
Refined search:
look for events of high energy, extend energy range to below 100 TeV
&& require that the interaction vertex be well contained

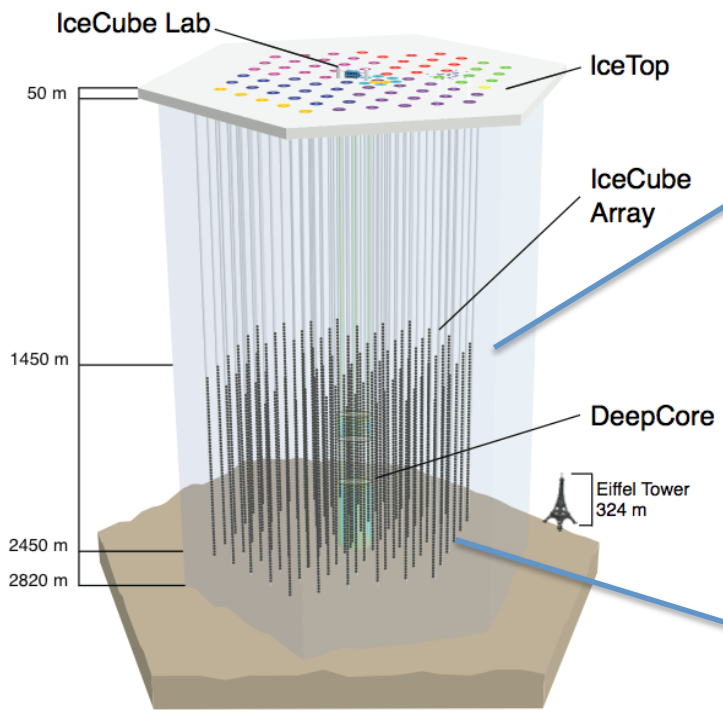


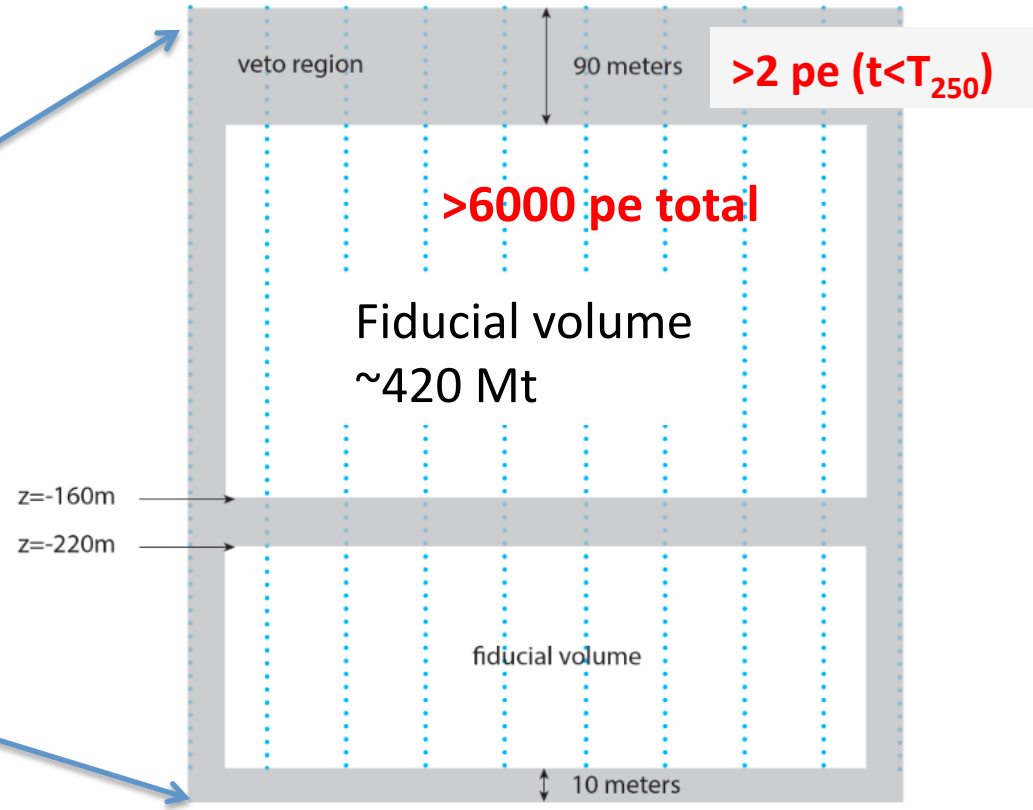
Veto region

The PMT signals of all PMTs
in the veto region are treated as Veto signals:
~2400 DOMs
Contained vertex events: "First light is in fiducial region"

Amongst the first 250 photoelectrons of an event, not more than 3.0 photoelectrons are allowed in the veto region.

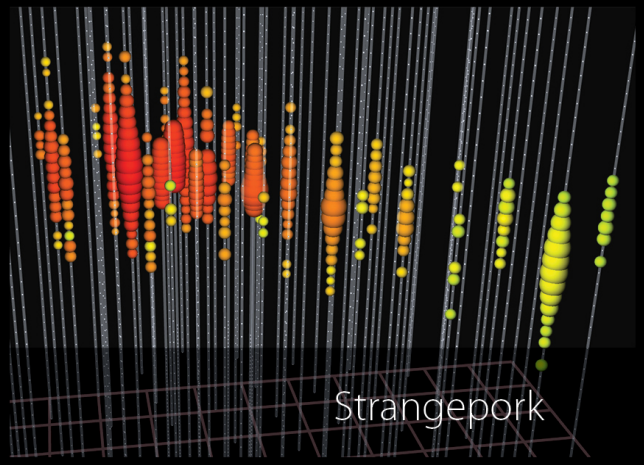


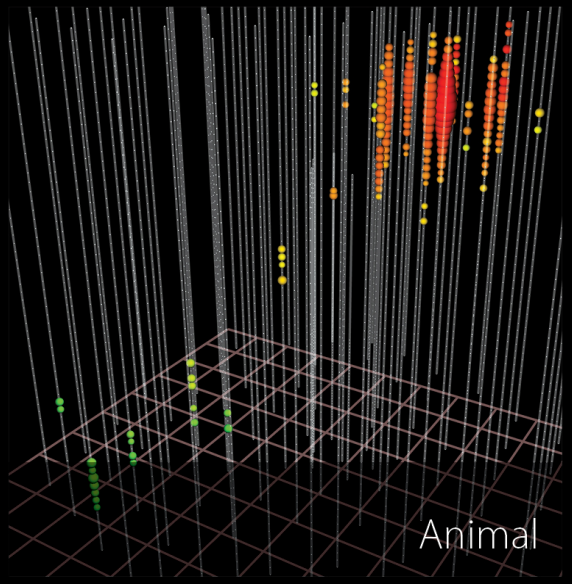


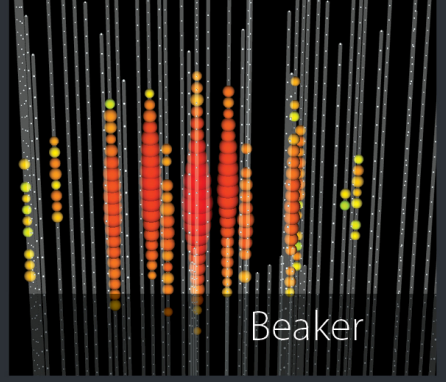


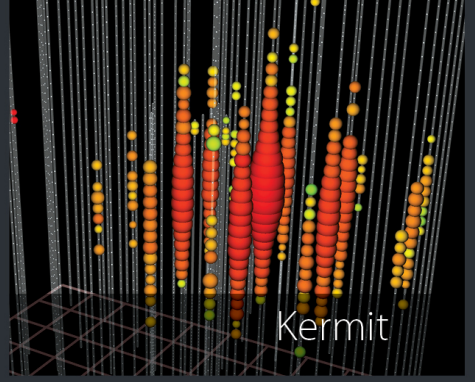
Examples of the

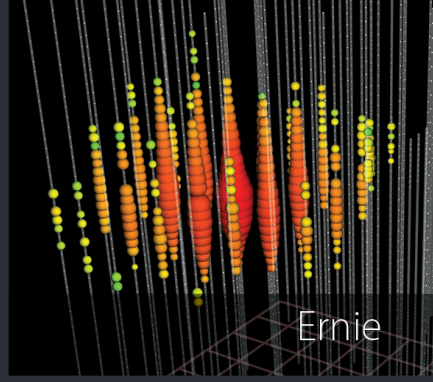
28 High Energy Events

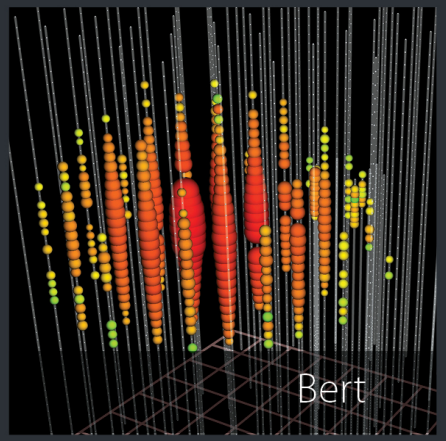


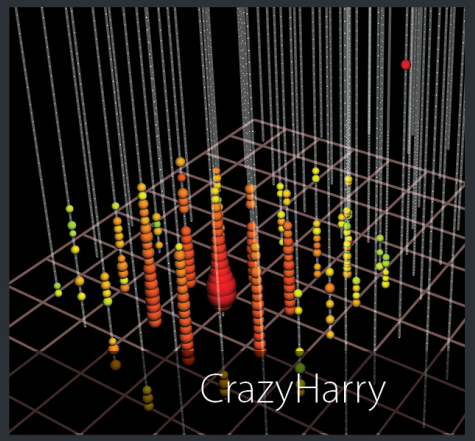


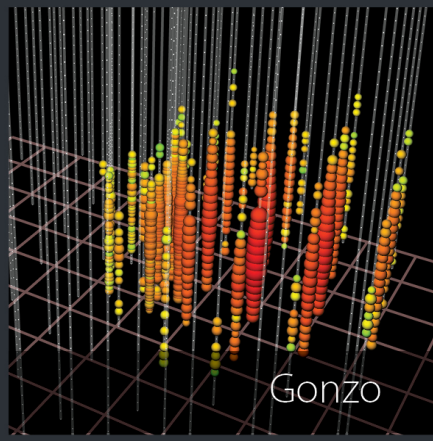


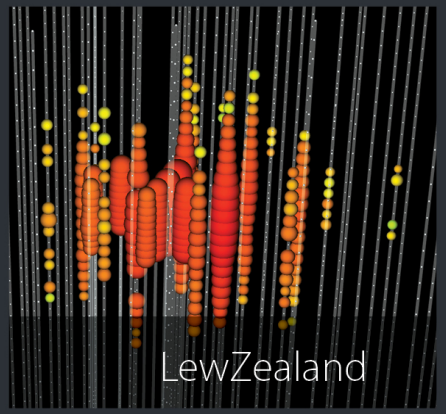


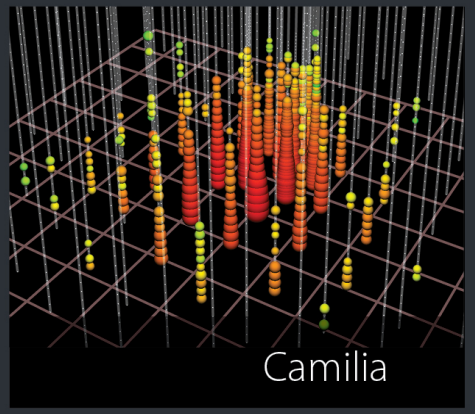


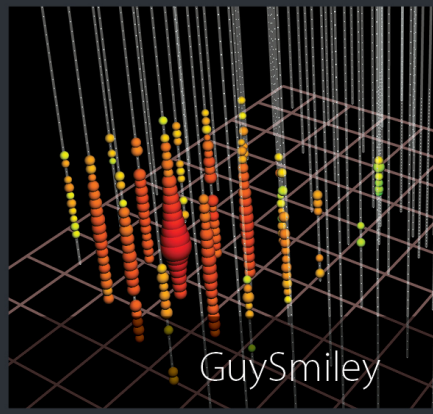


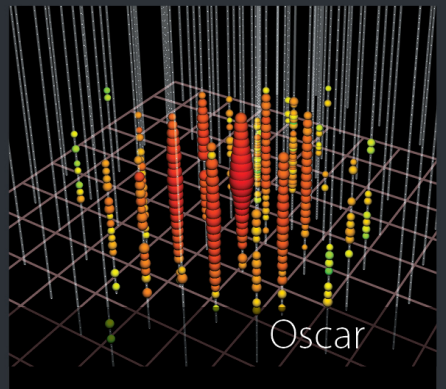


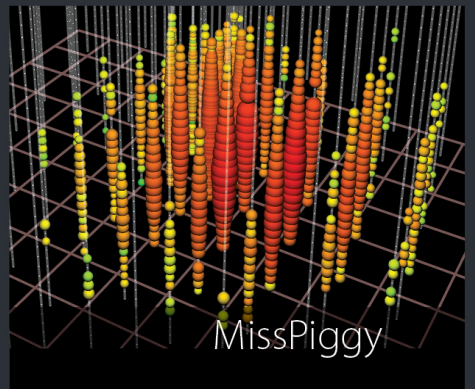


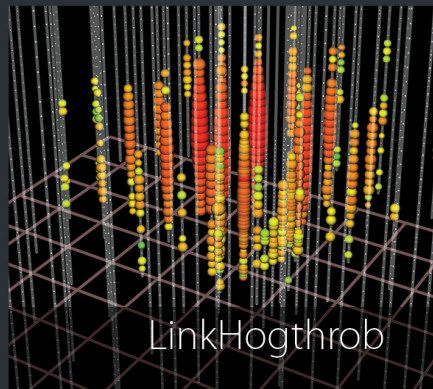


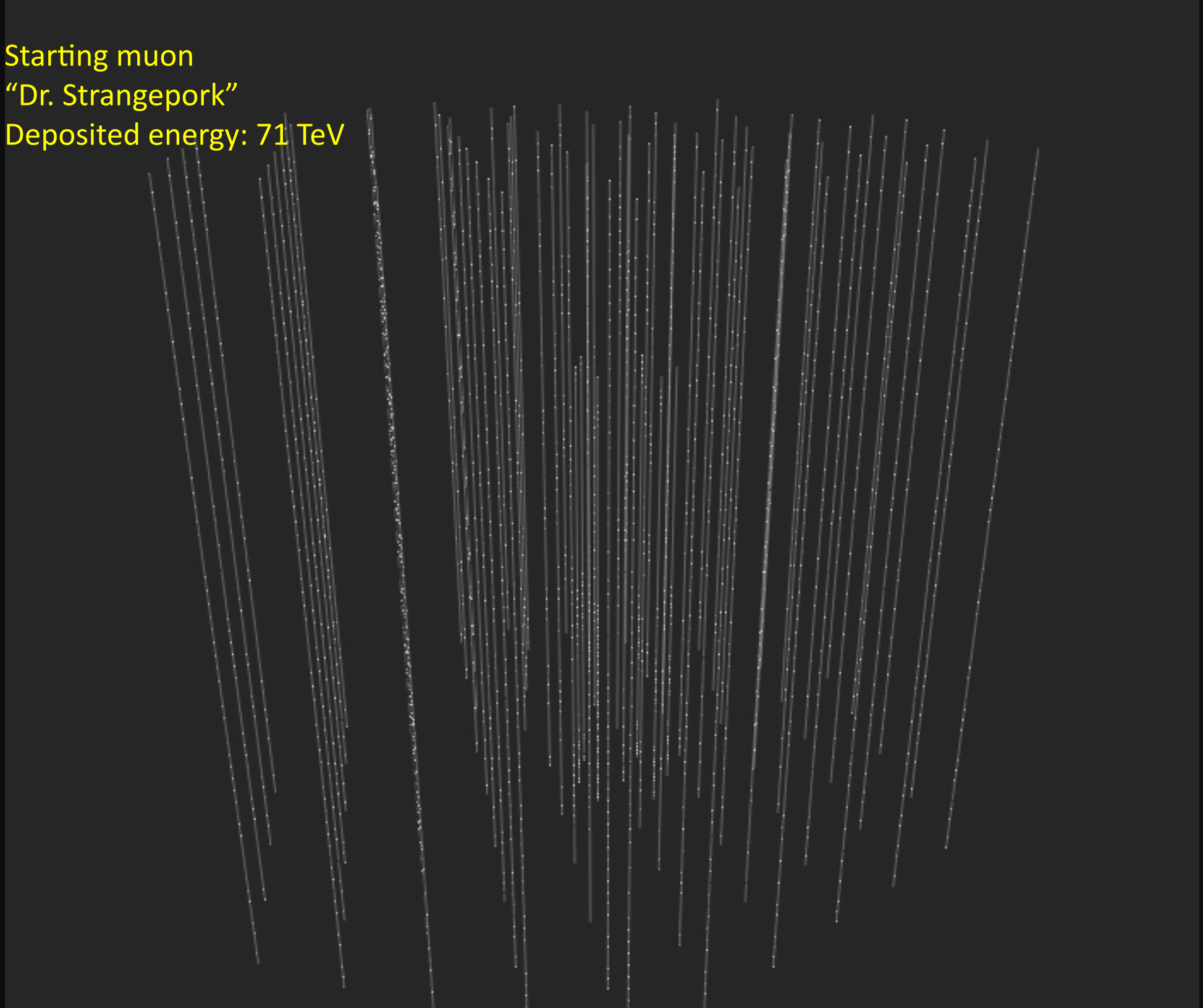




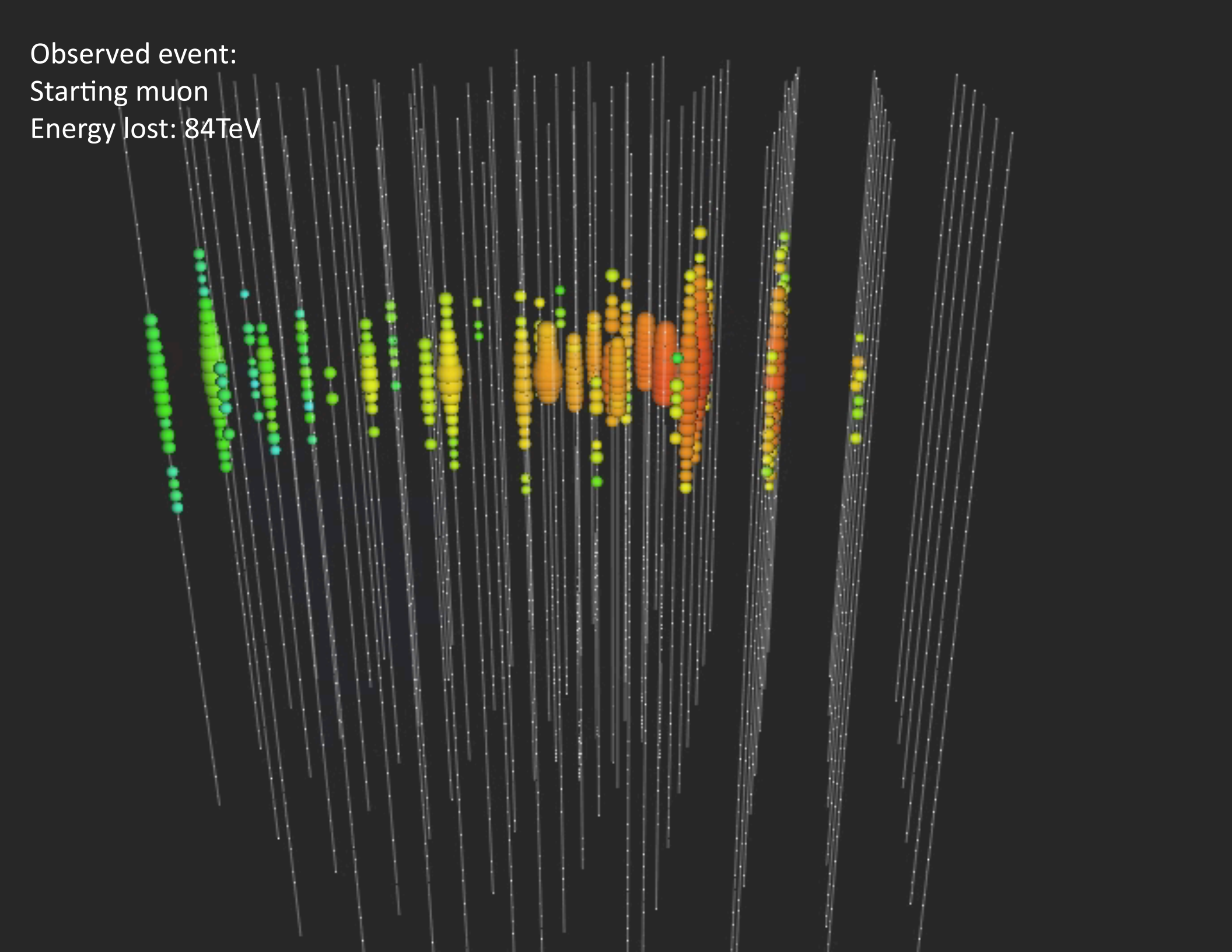


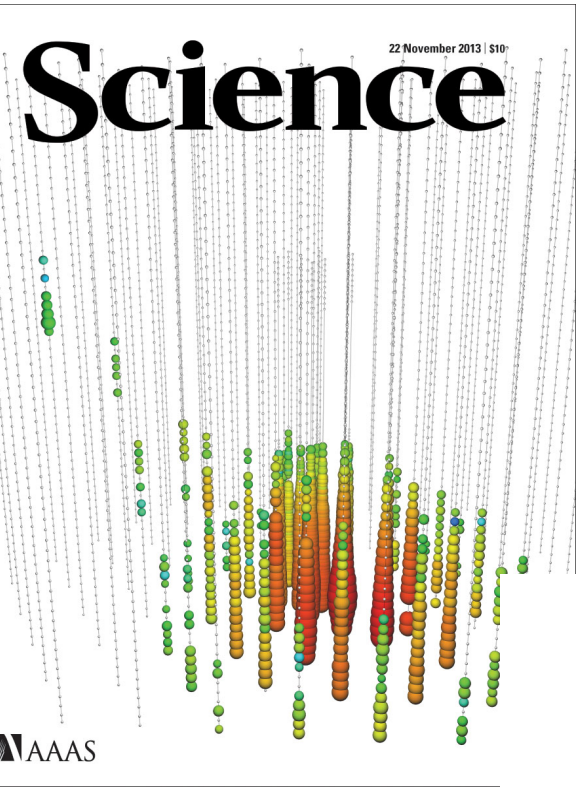





Starting muon
“Dr. Strangepork”
Deposited energy: 71 TeV

Observed event:
Starting muon
Energy lost: 84TeV

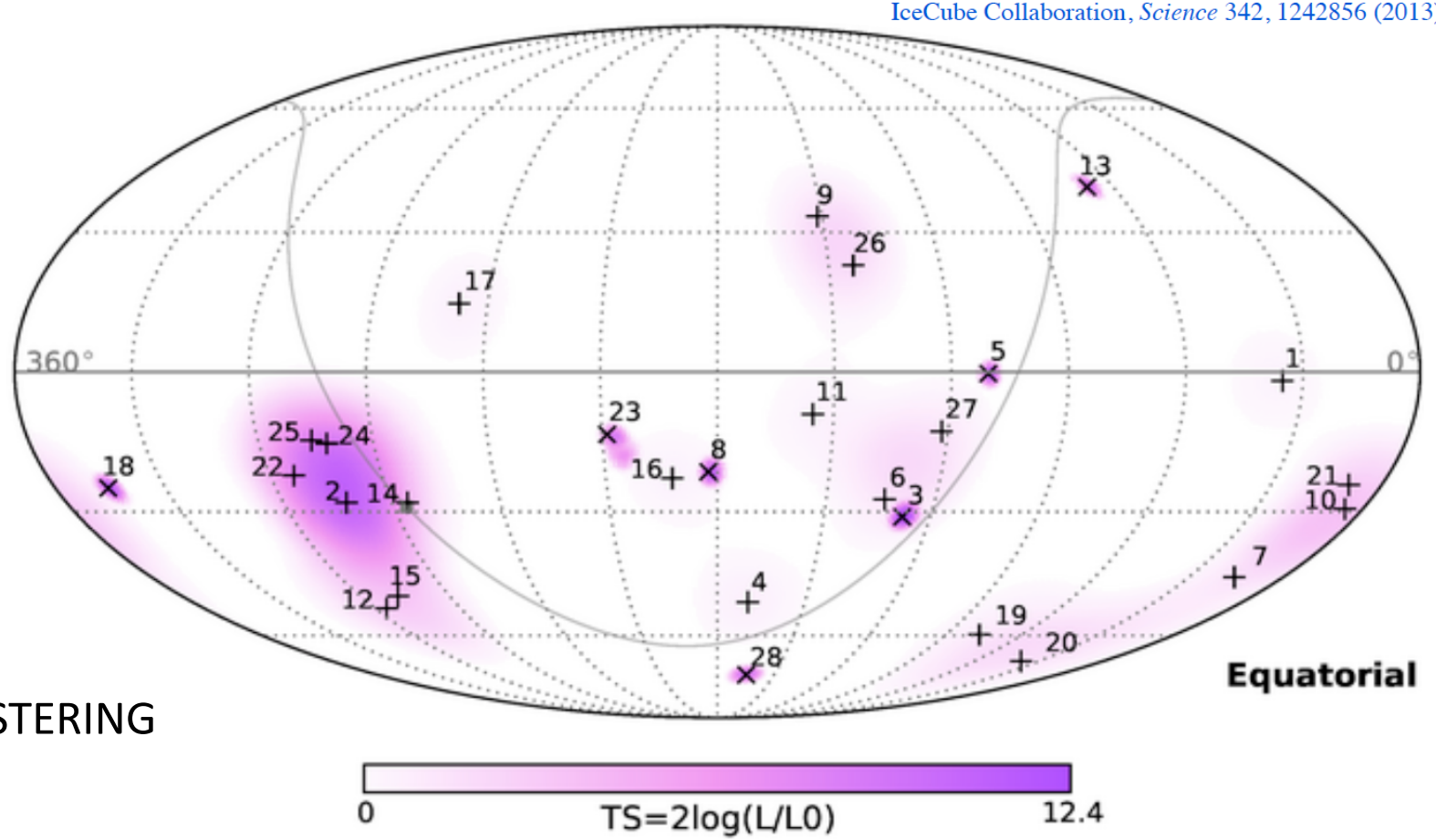




Evidence for astrophysical neutrinos of very high energy.

28 events,
Including two events with energies of more than 10^15 eV

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



NO SIGNIFICANT CLUSTERING OBSERVED.

One more year of data have been inspected with the same method

Additional data confirm the reported results:

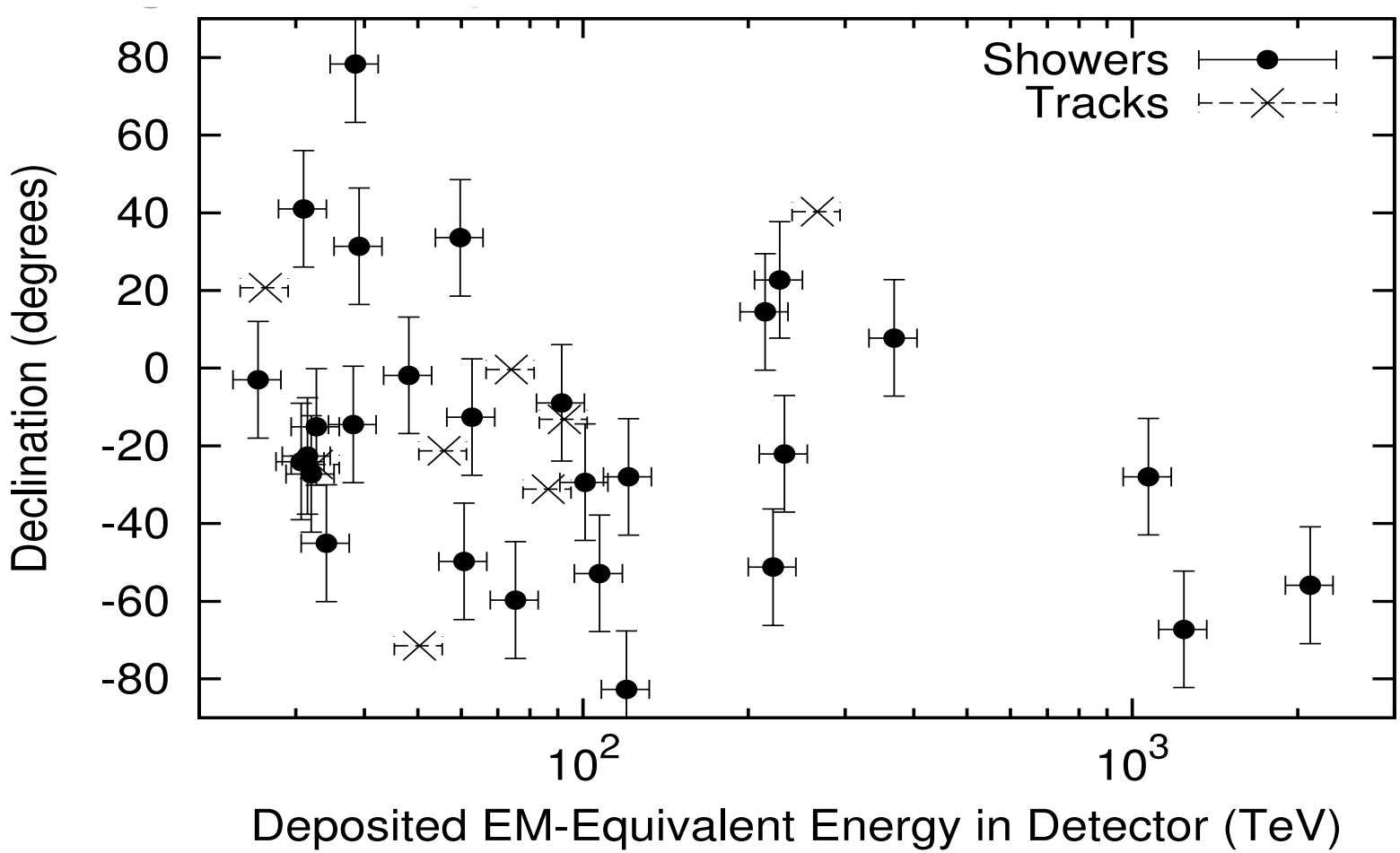
- 8 more events (37)
- One event at 2 PeV
- Same characteristics

IceCube reported new results since

- One more year (IC86-2, May 2012 to May 2013) of data analyzed
  - Consistent with results in Science paper
    - 8 more events, one with energy 2 PeV
    - Same characteristics

- Two years (IC79 +IC86-1) of upgoing muon neutrinos
  - Flux appears also present at the same level in the Northern hemisphere and in muon neutrinos?

HESE: From 2 to 3 years
Declination vs energy



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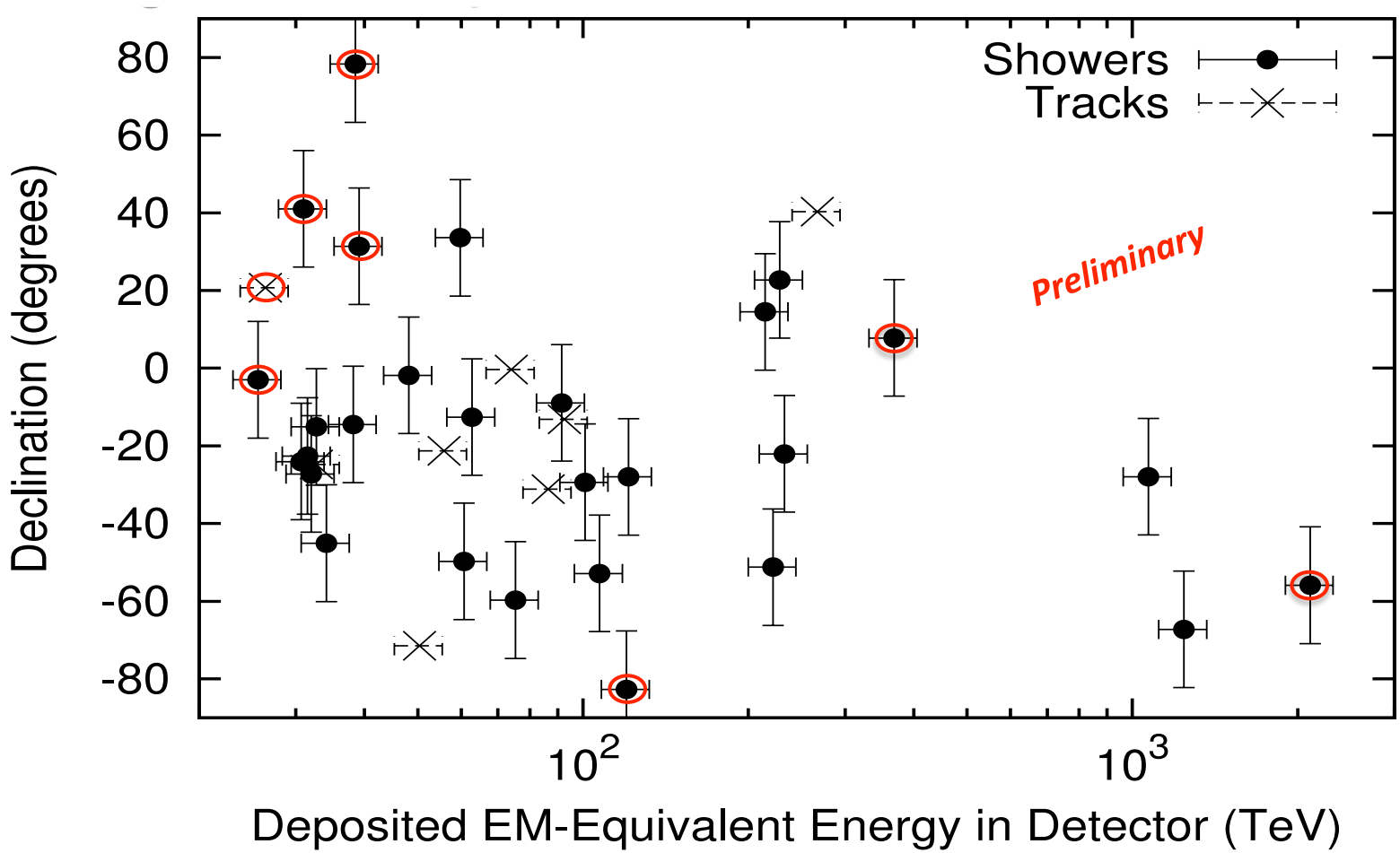
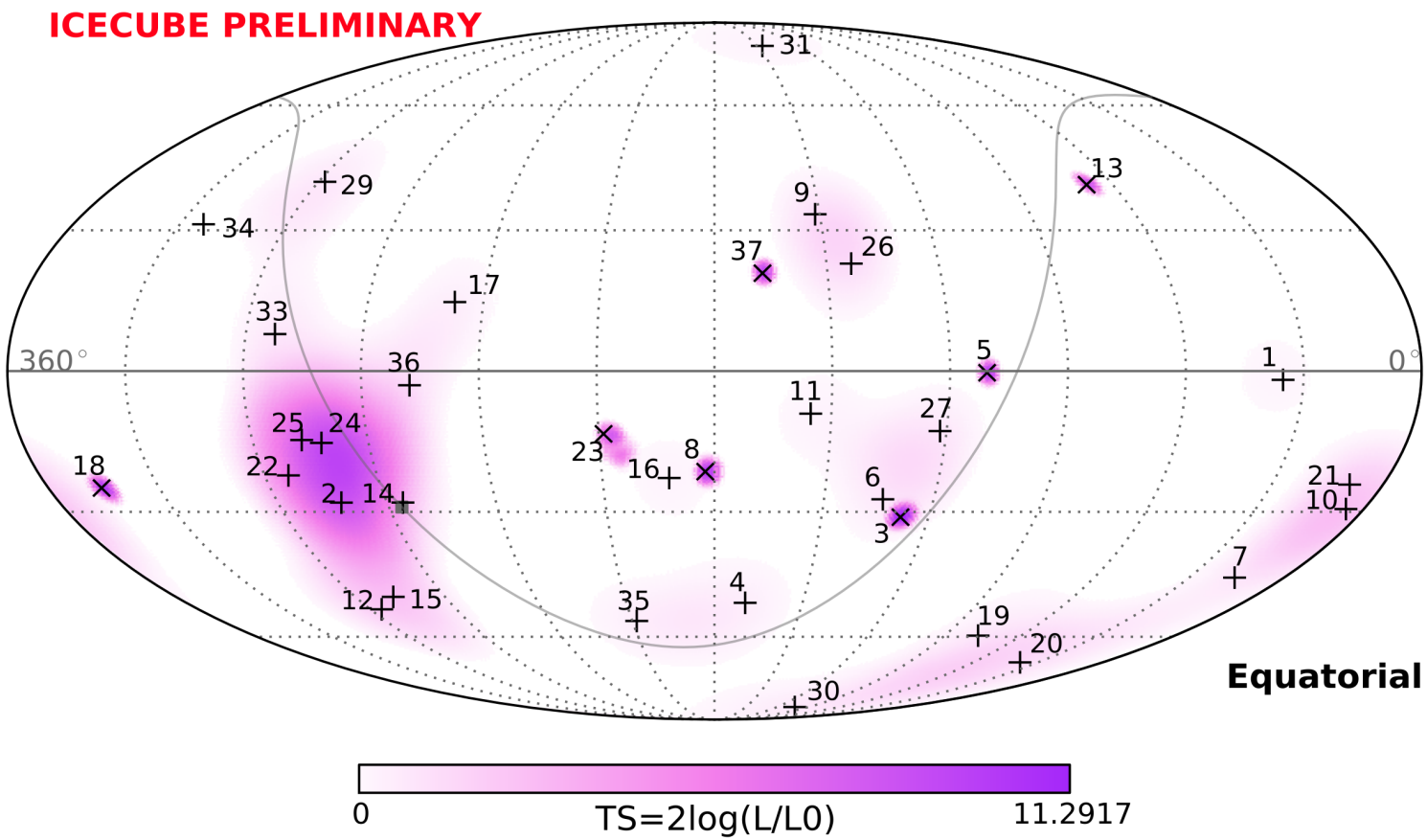


988 day sample
detected 37 events
expected background of 8.4 ± 4.2 cosmic ray muon events and
6.6+5.9 atmospheric neutrinos.

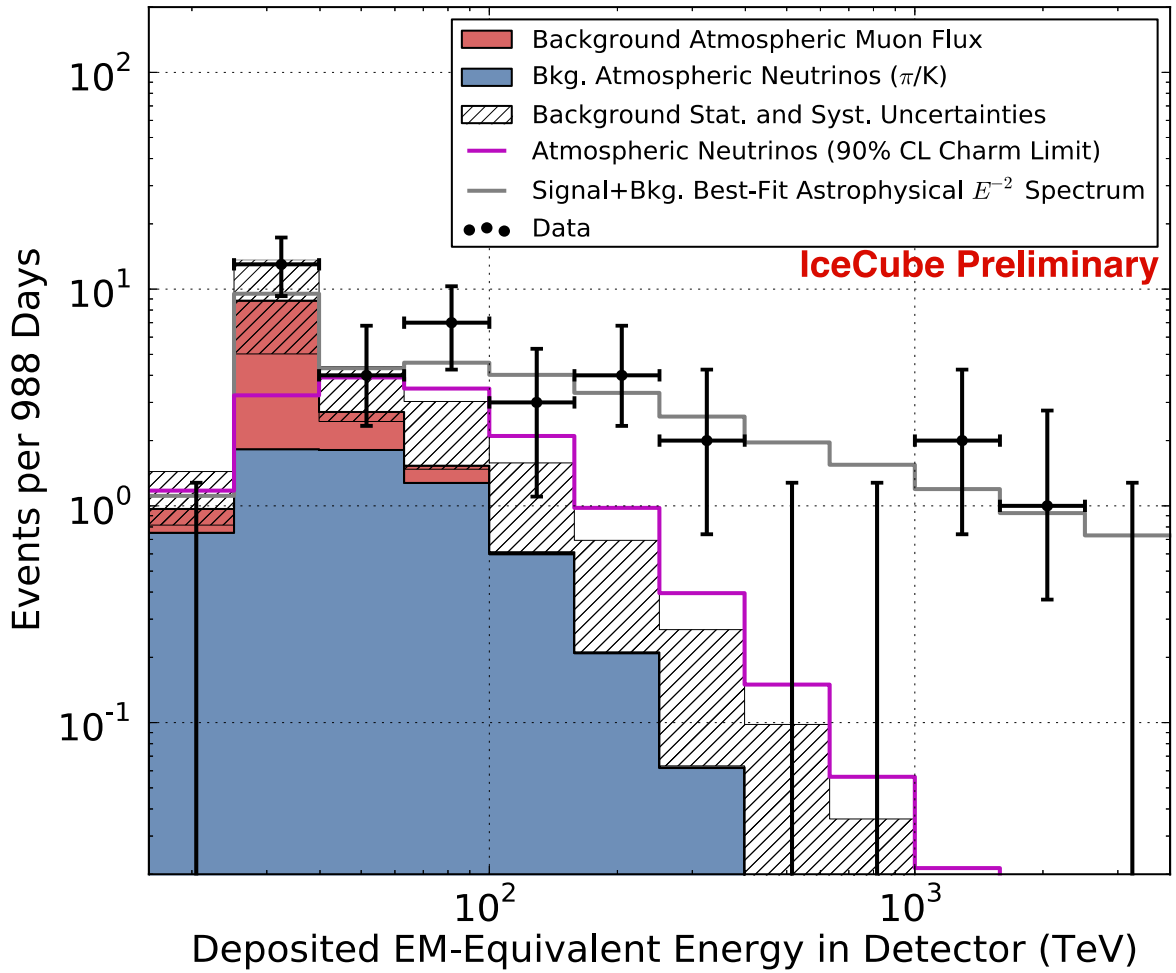
Clustering search using 3 year skymap



No significant clustering, post trial p-value:
Showers only: 7.2%
All events: 84%

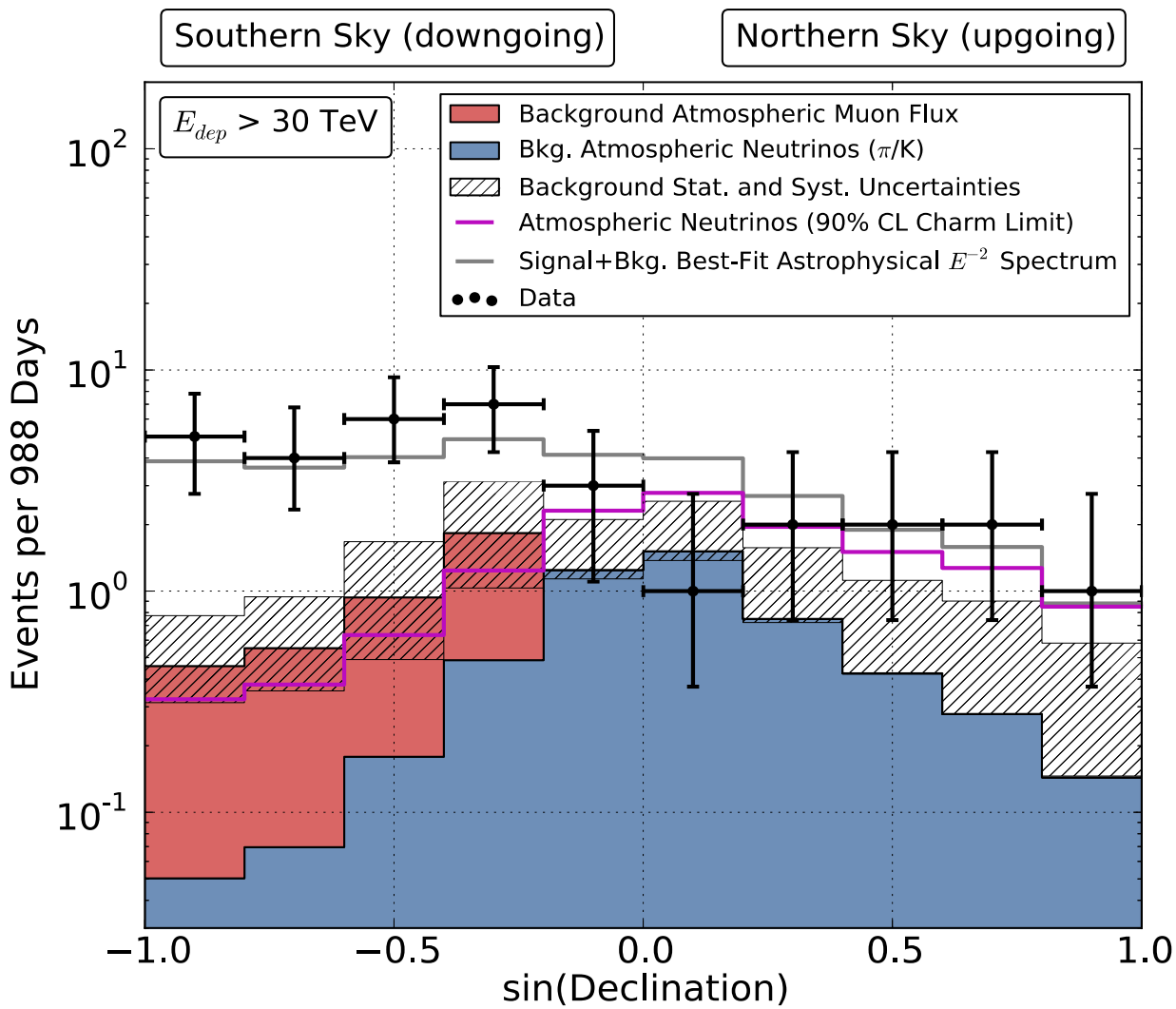
Updated results from 3 year data

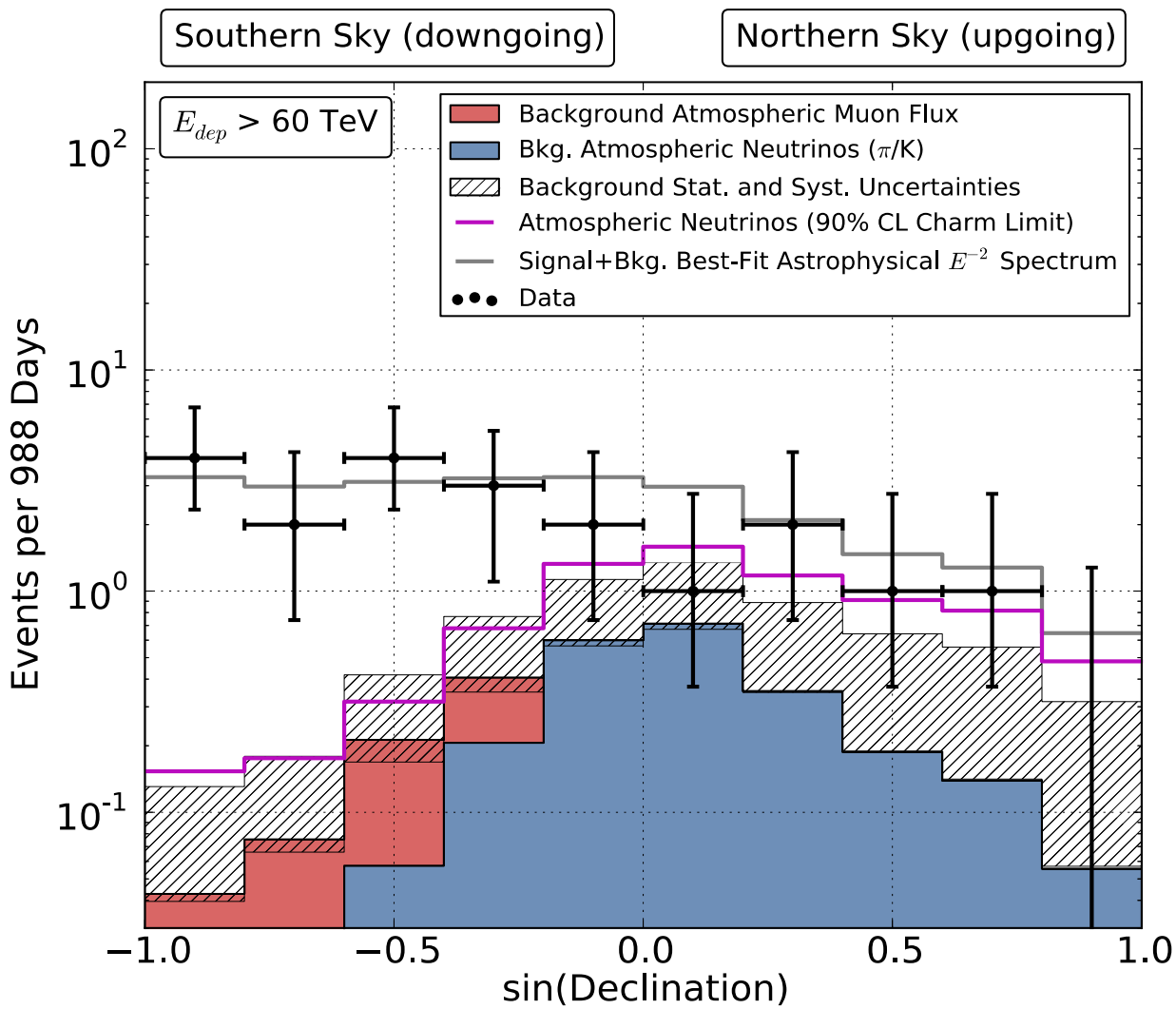
Energy distribution

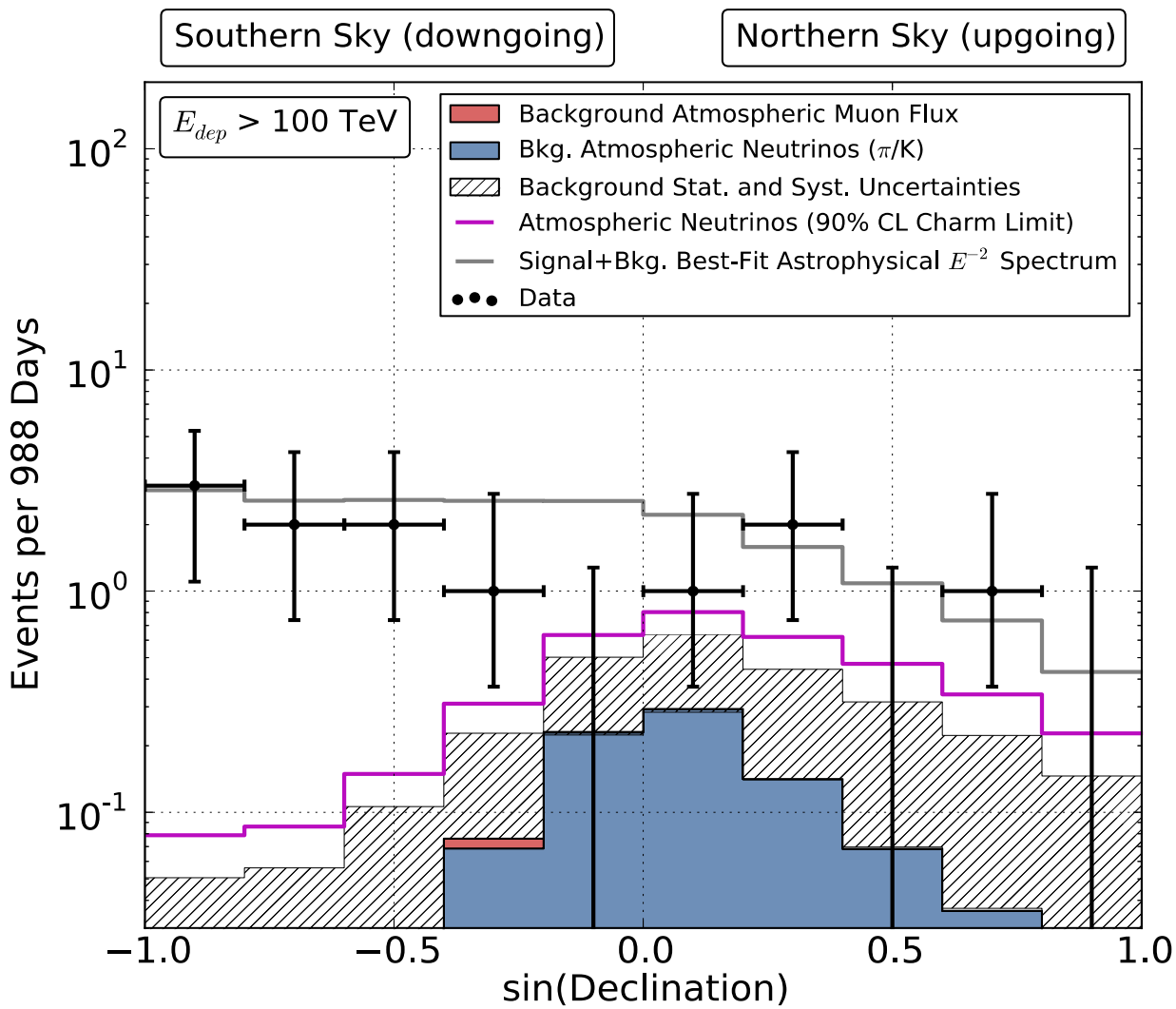


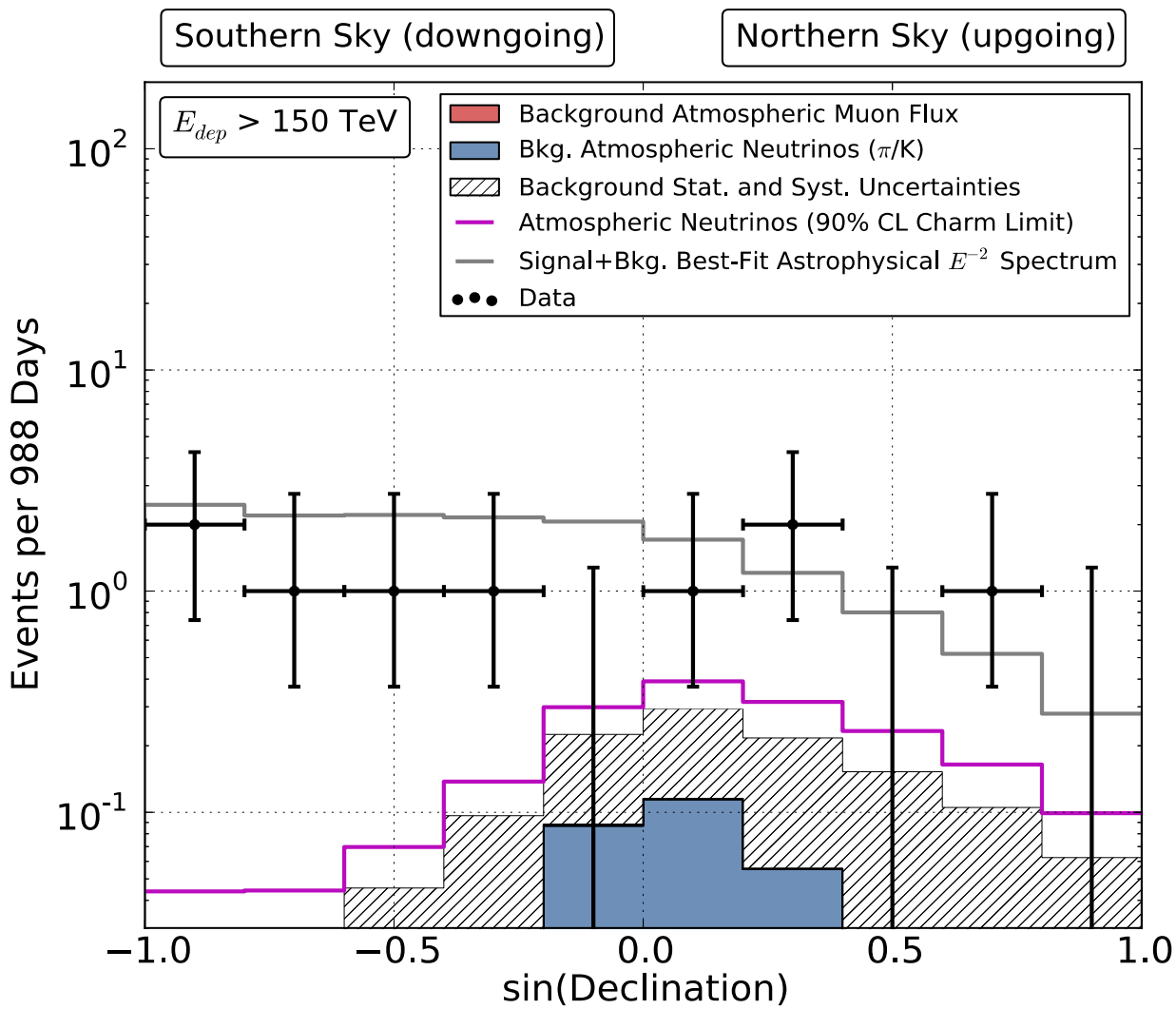
best-fit per-flavor astrophysical (E^{-2}) flux in the energy range of 60 TeV – 3 PeV:

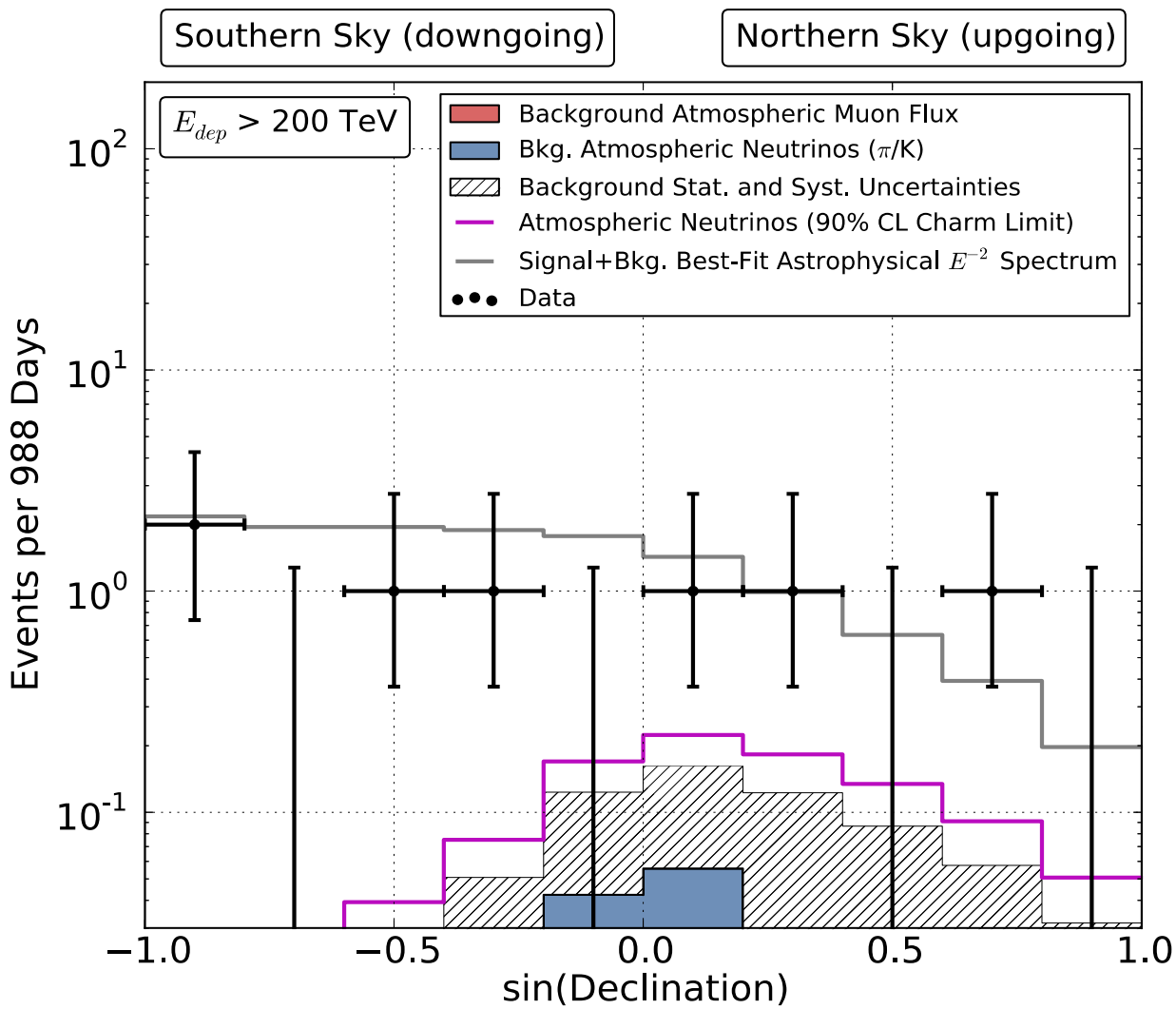
$$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$


Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 30 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)


Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 60 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

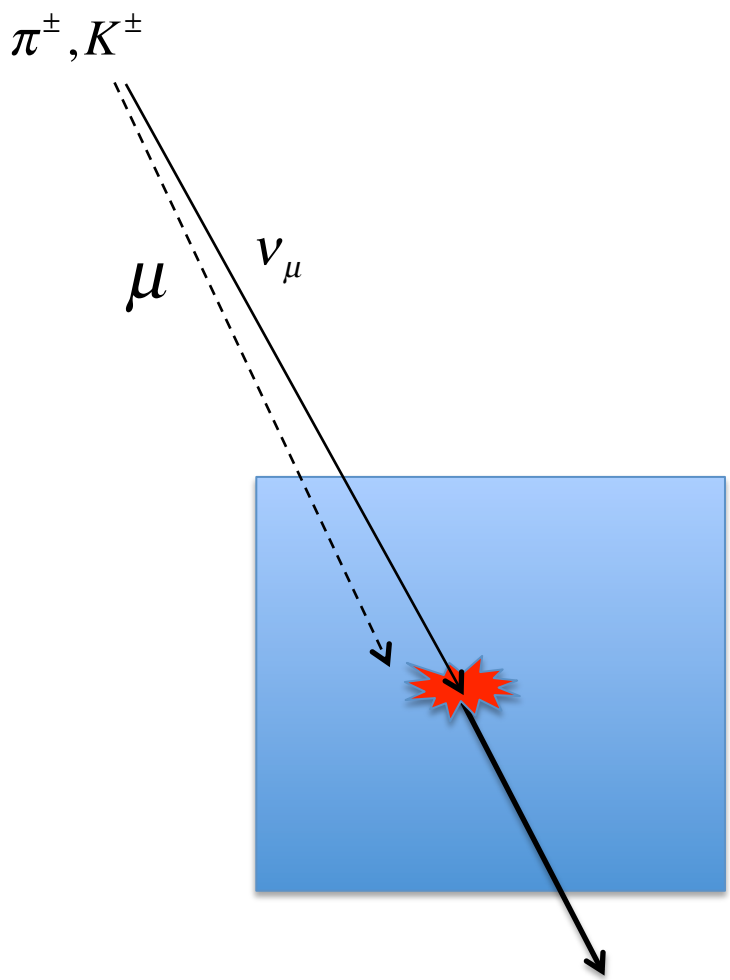

Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 100 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)


Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 150 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)


Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 200 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

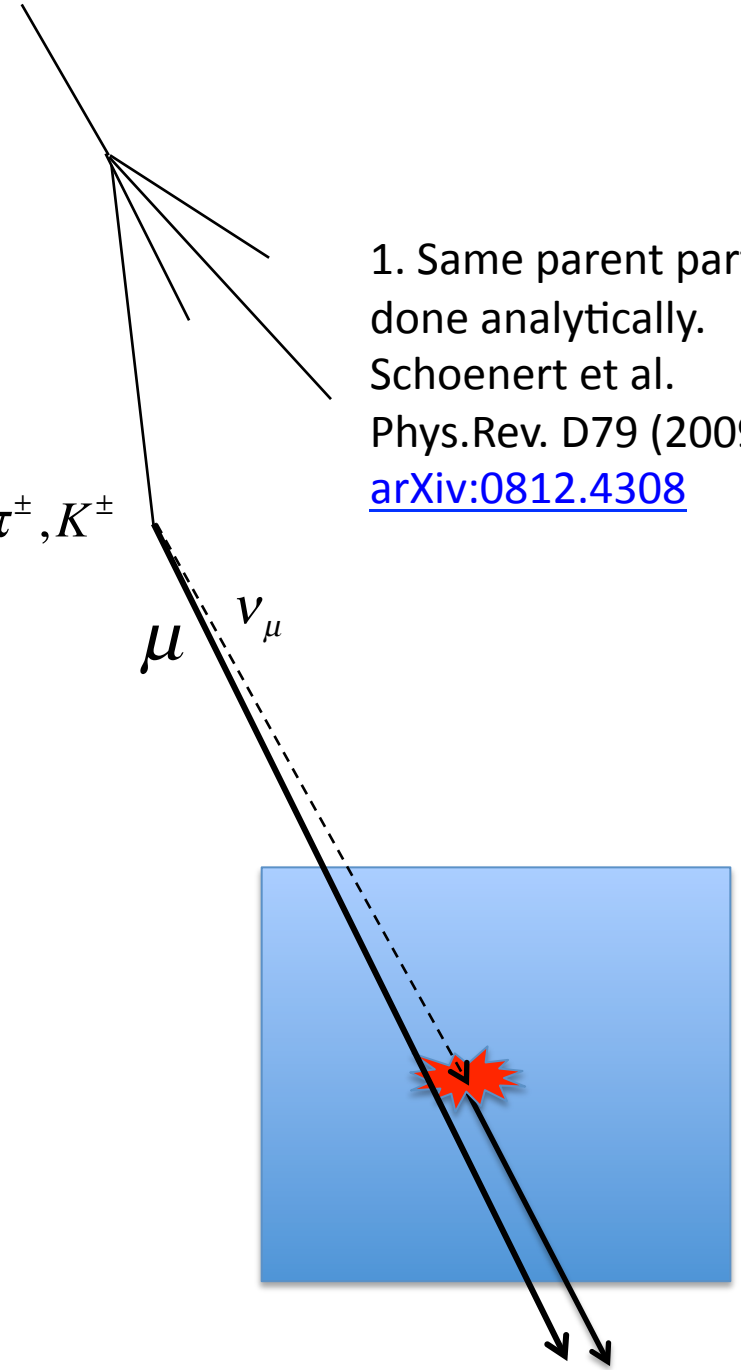
Excursion: Neutrino self veto – Background free neutrino astronomy?

- "Atmospheric neutrinos" are generated in cosmic ray air showers.
- Above some neutrino energy, ~100 TeV, these neutrinos will likely be accompanied by one or more muons from parent air shower.
- Those muons can be used to veto atmospheric neutrino background.

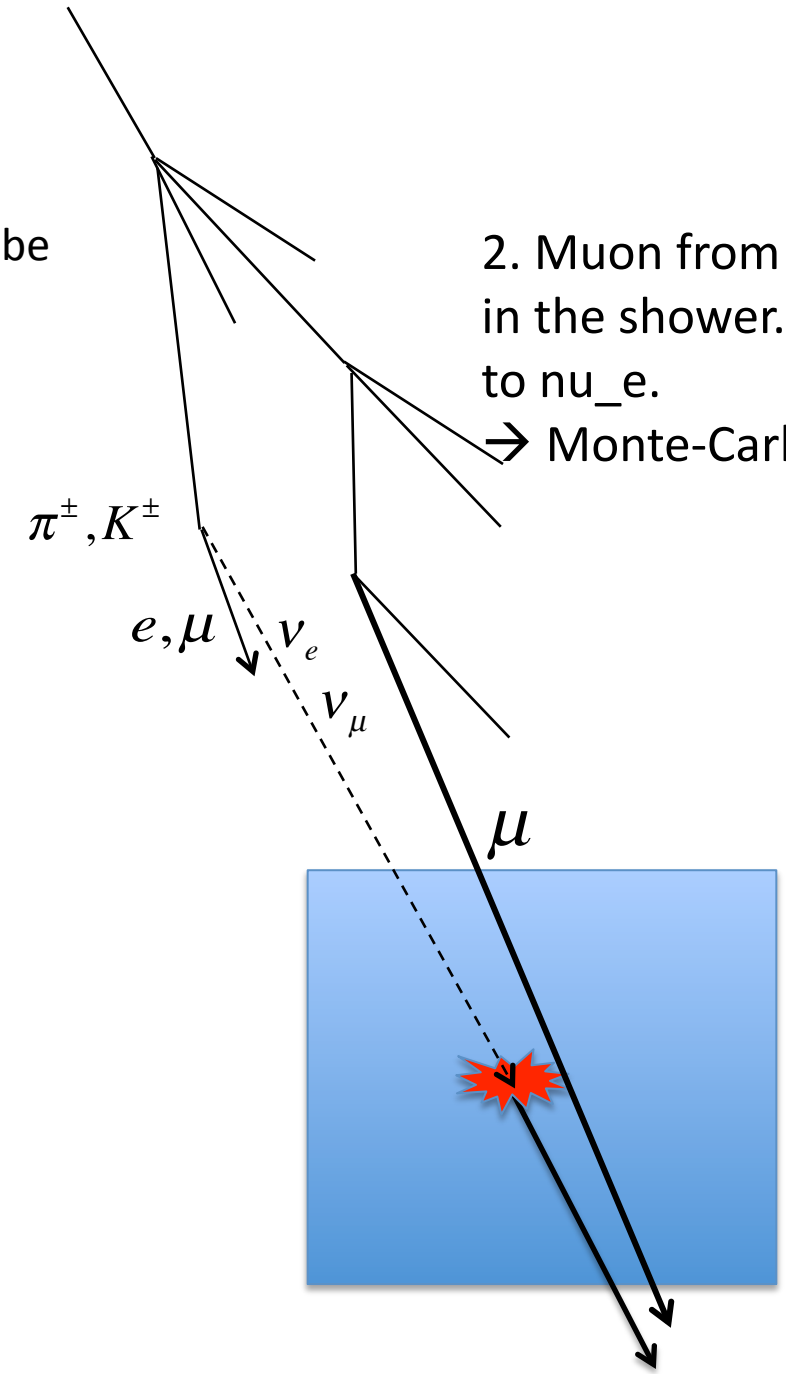


Schoenert et al.
Phys.Rev. D79 (2009) 043009
arXiv:0812.4308

Two cases



1. Same parent particle, could be done analytically.
Schoenert et al.
Phys.Rev. D79 (2009) 043009
arXiv:0812.4308



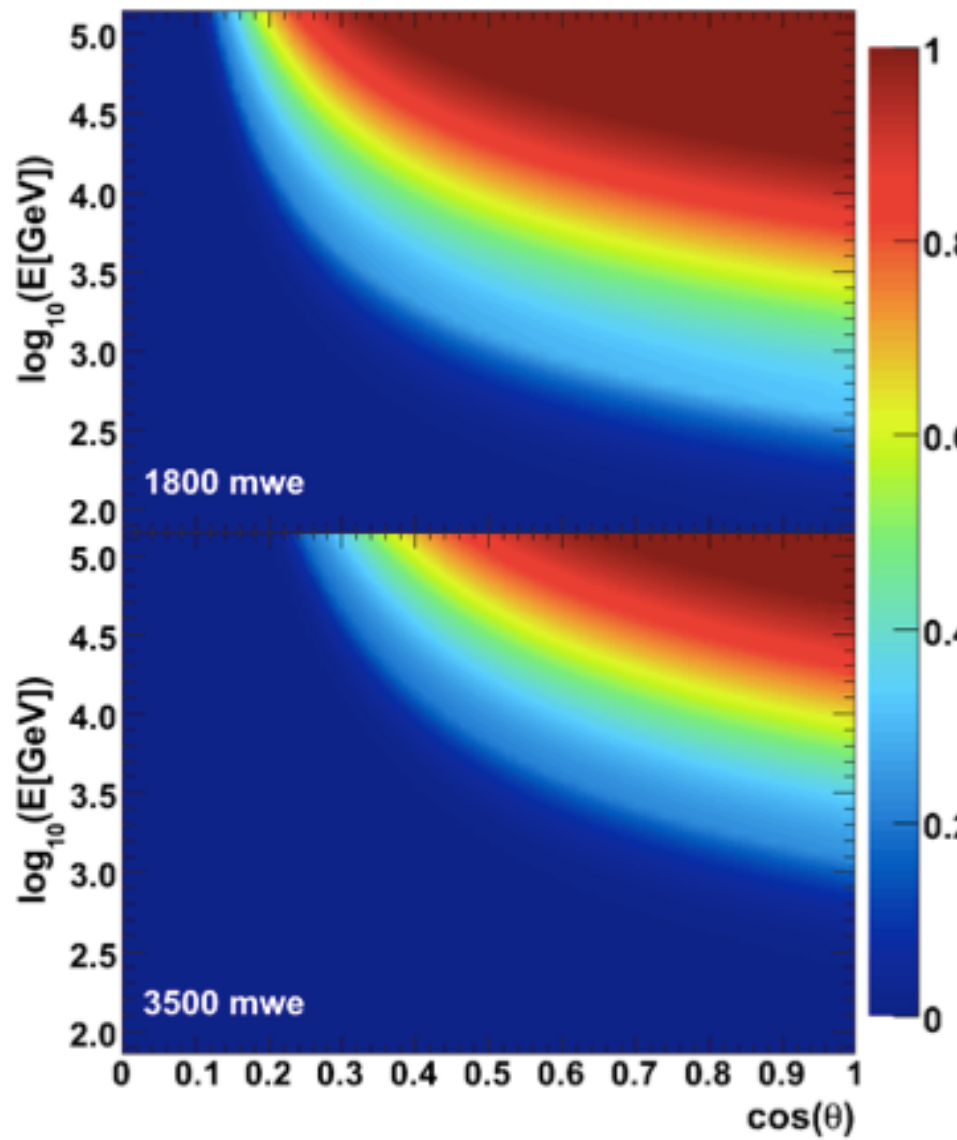
2. Muon from elsewhere in the shower. Applies also to nu_e.
→ Monte-Carlo

Zenith angle/energy dependence

Analytic calculation

- Applies to nu_mu only
- For E_{nu} > 100 TeV, cos(zenith angle)>0.3:

  Passing rate <10%
- 70% of downward solid angle
- Even better at higher energies
- Works best at modest depth



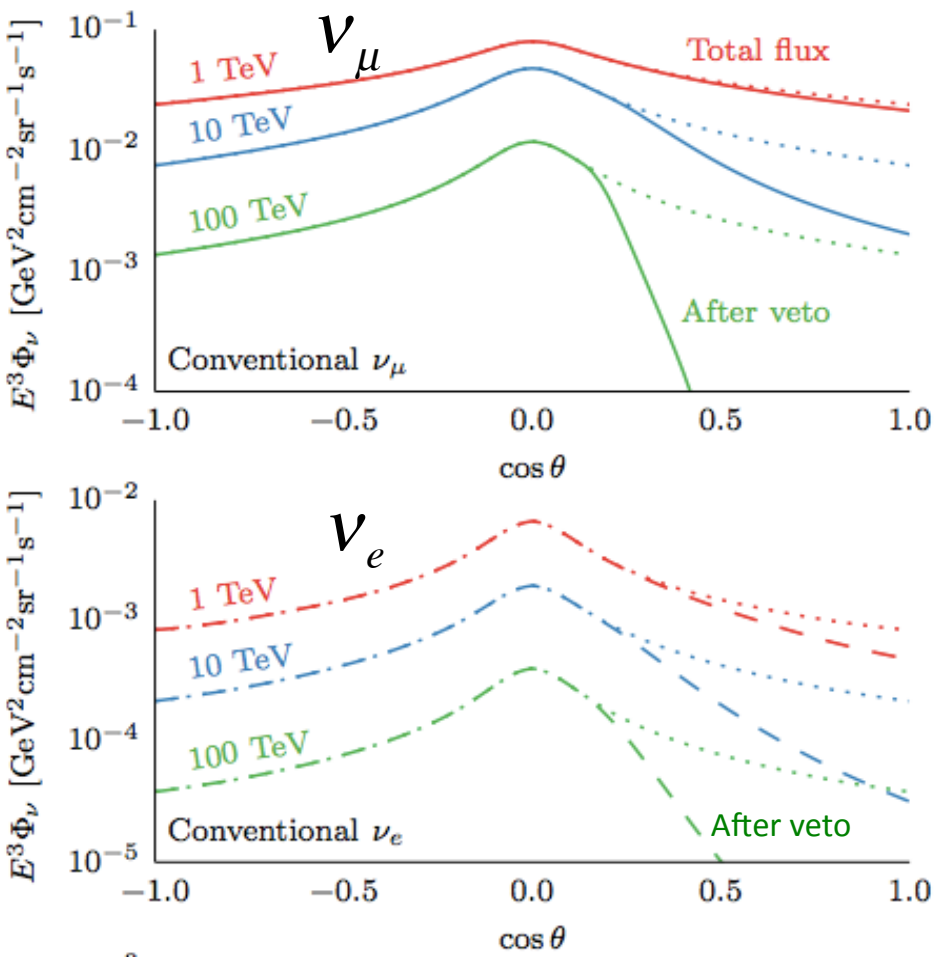
Schönert et al. PR D79 (2009) 043009

Neutrino self-veto

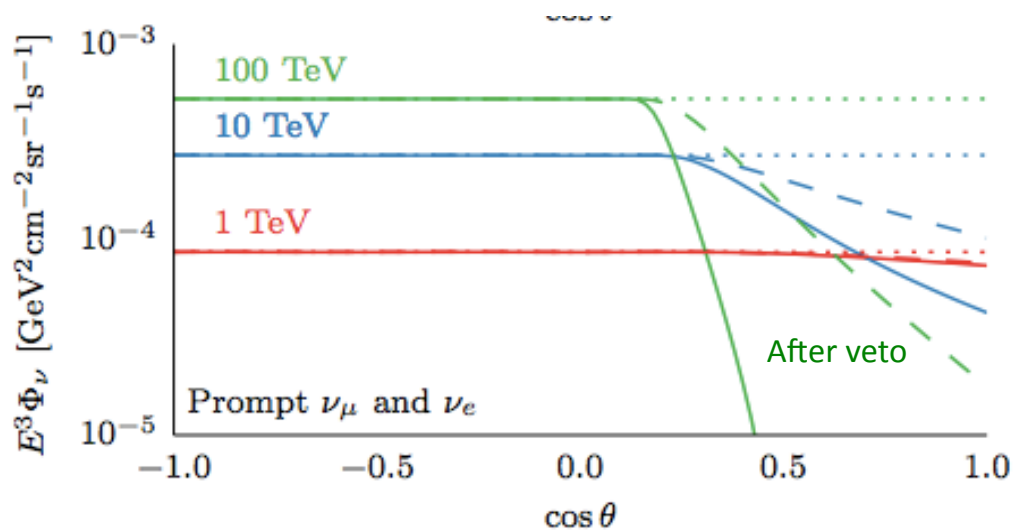
Based on full simulation

T. Gaisser, K. Jero, AK and J. v. Santen
arXiv:1405.0525

Conventional



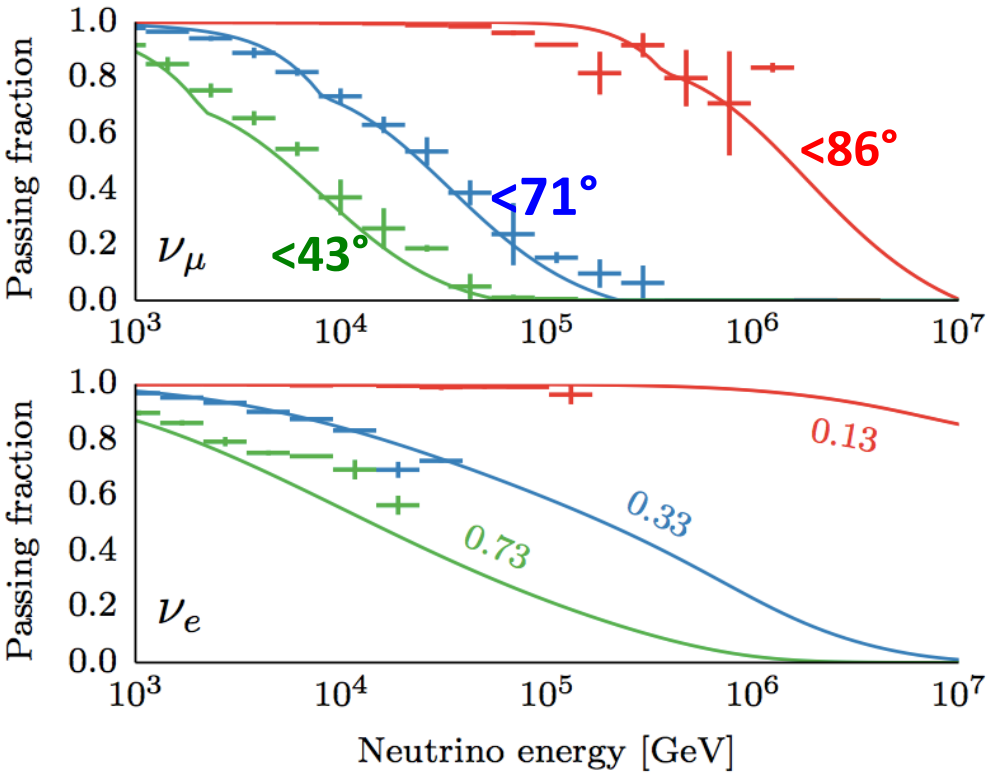
Prompt ν_μ and ν_e



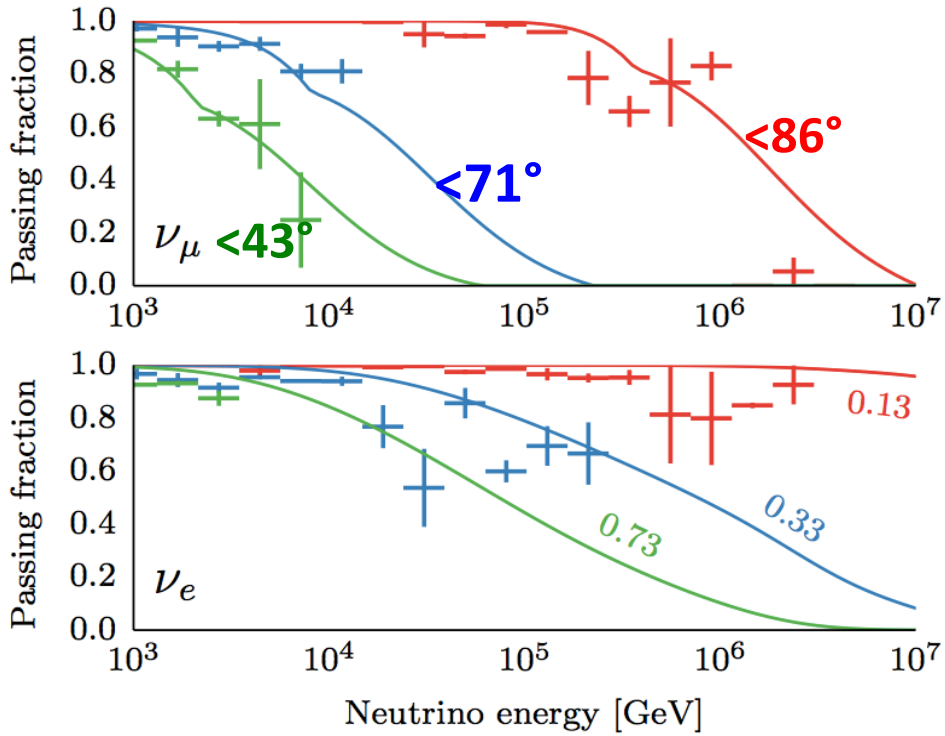
Atmospheric neutrino flux obtained by applying full atmospheric veto to the atmospheric neutrino flux.
(Earth attenuation above 100 TeV is not shown)

Comparison with full simulation

Conventional neutrinos

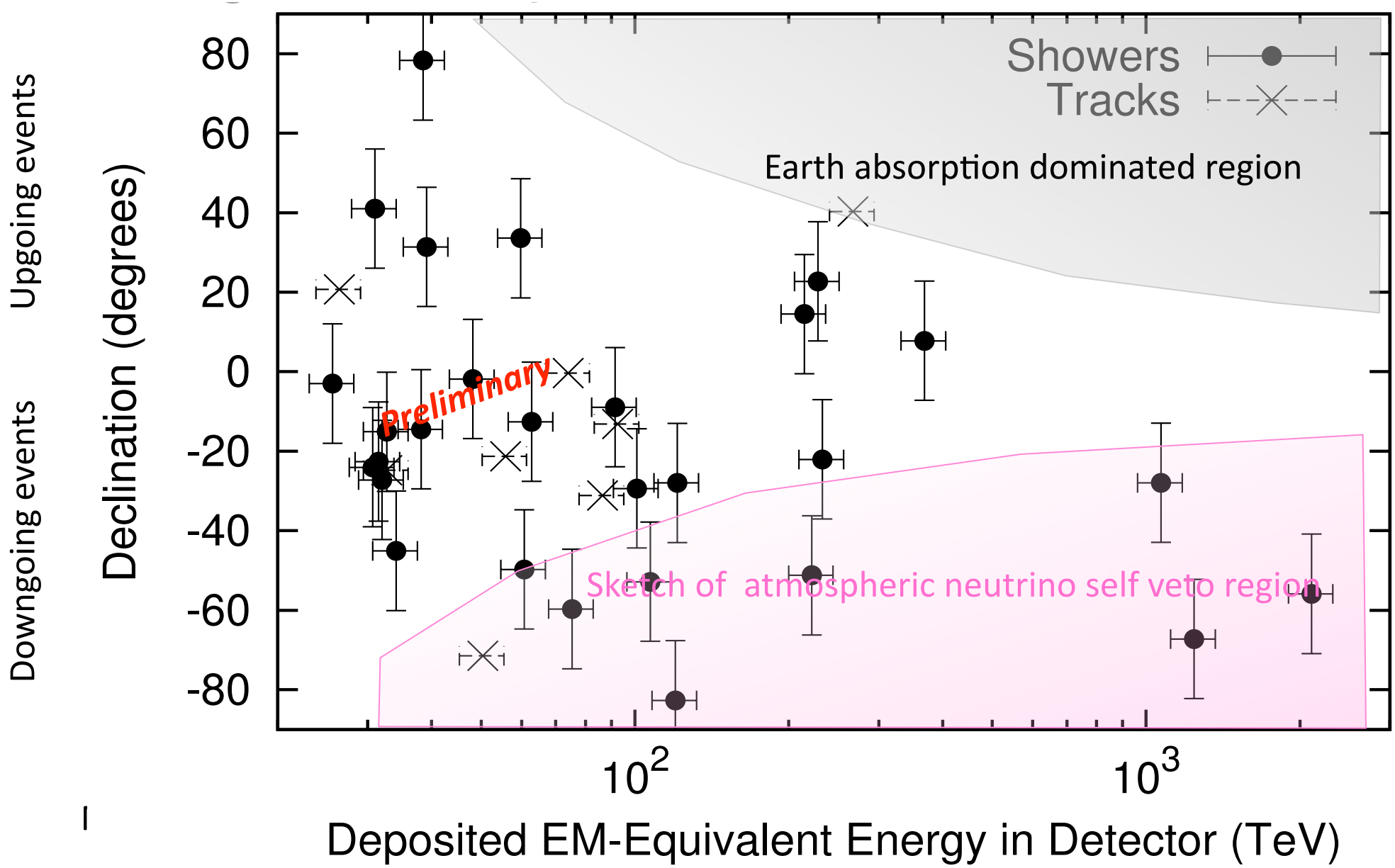


Prompt neutrinos



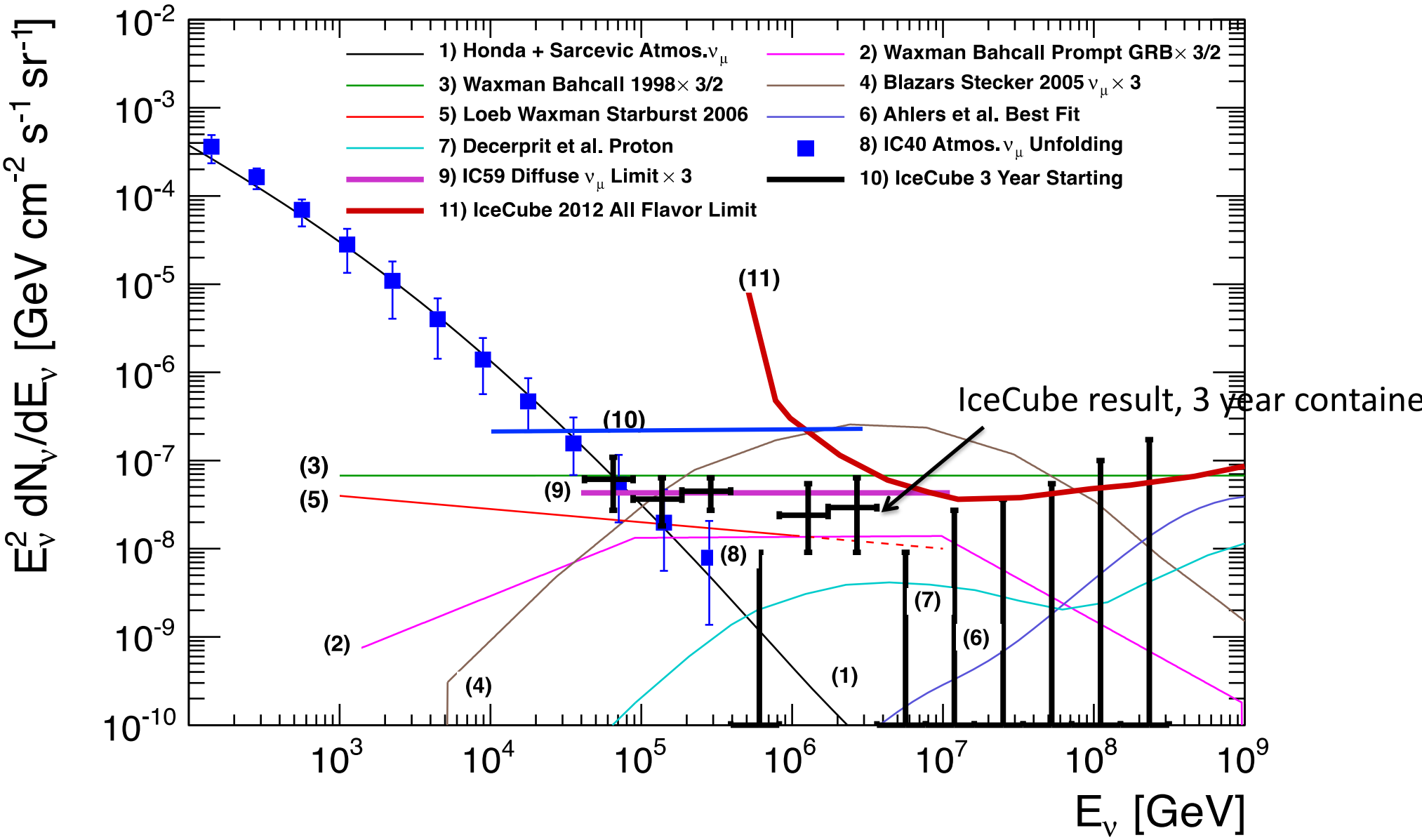
Good suppression up to 70 degrees

Back to IceCube HESE (High enrgy starting events): Declination vs energy

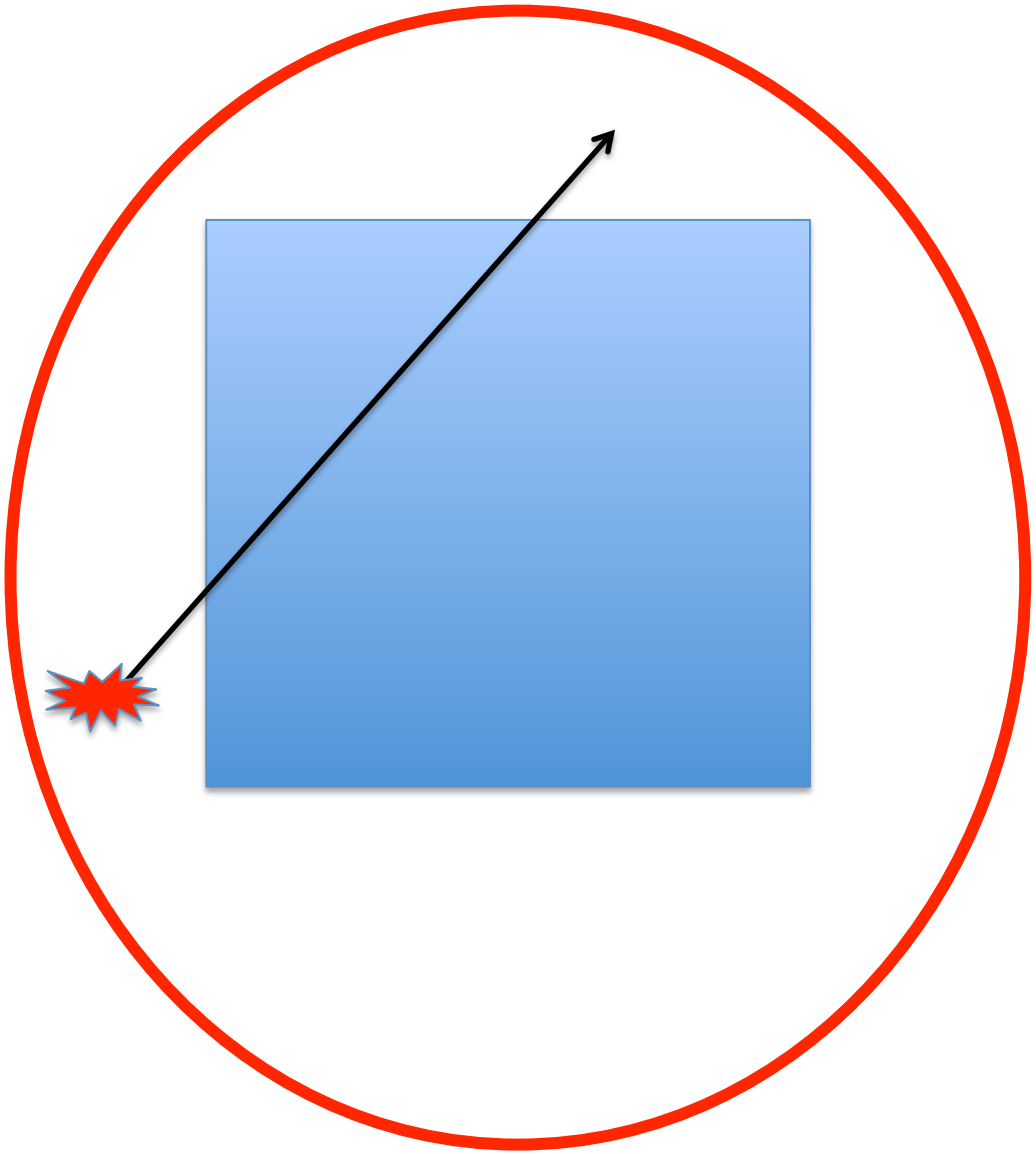


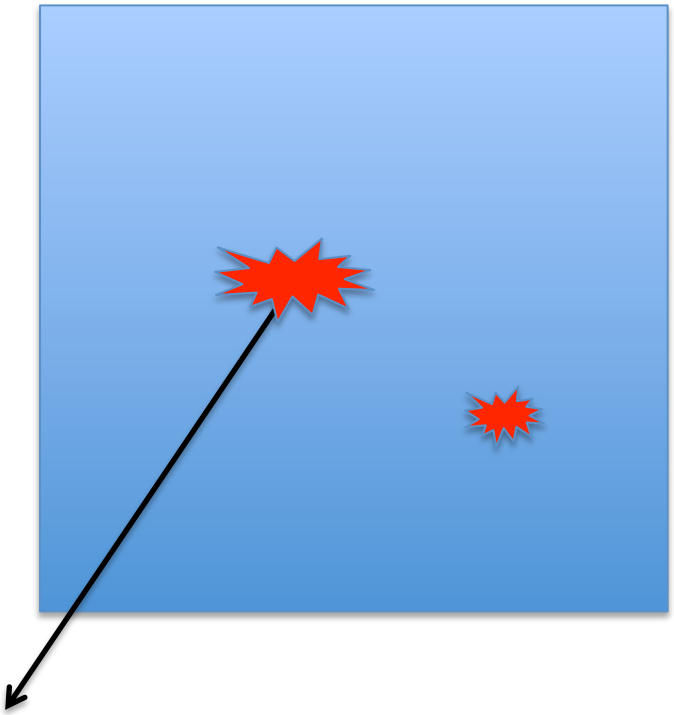
Most events in Southern hemisphere (downgoing).

Observed Neutrino Flux
HESE (starting events, 3 years)

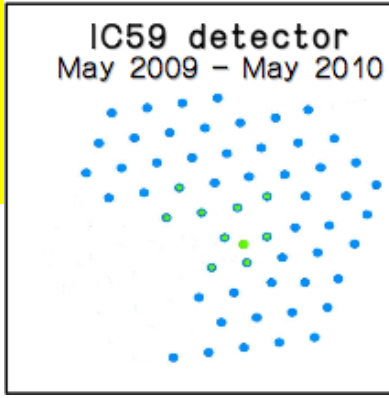


Diffuse analysis of upward throughgoing muon neutrinos

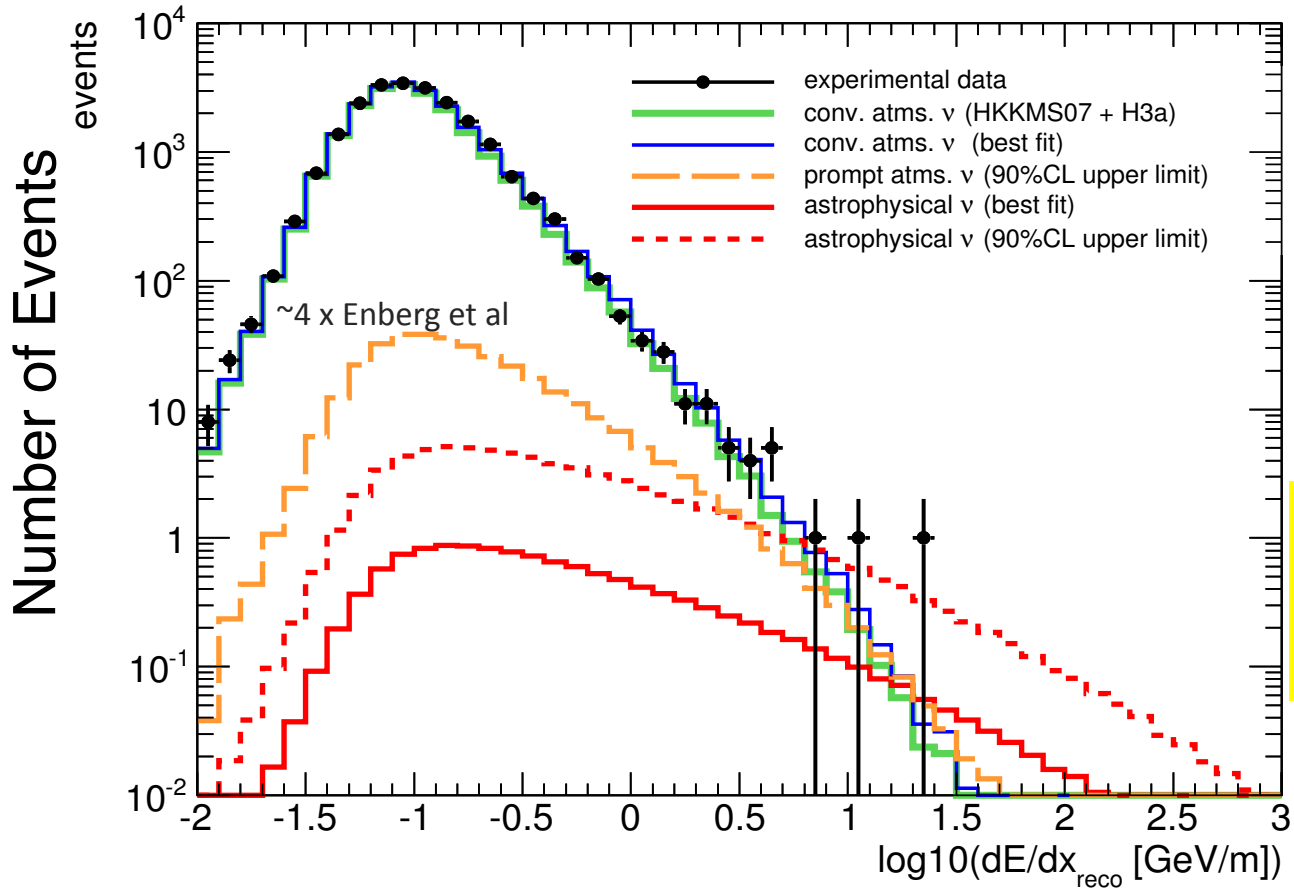




IC 59 diffuse ν_μ flux



(IceCube Coll.) Phys. Rev. D 89, 062007 (2014)

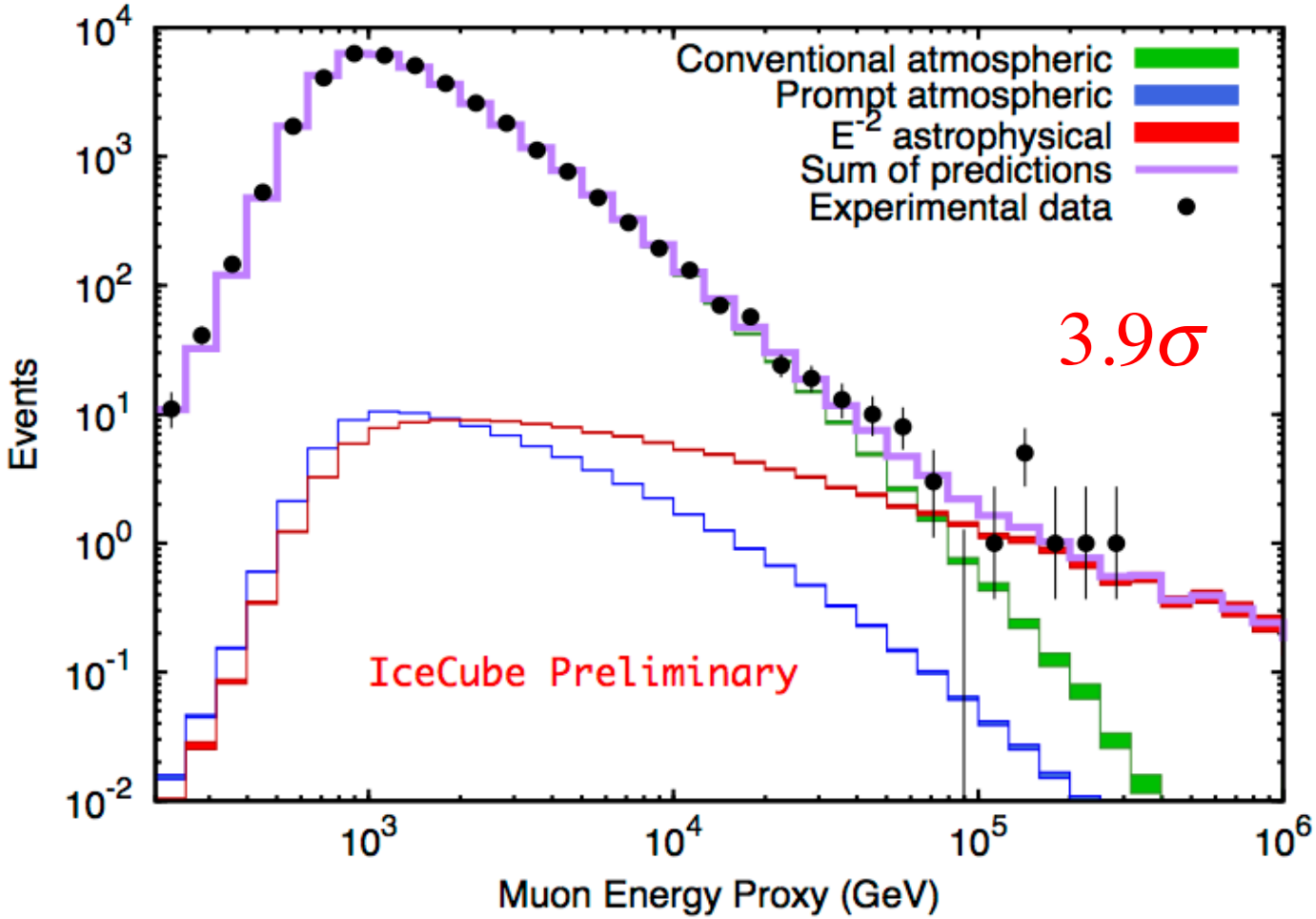


Data consistent with 0 astrophysical events at 2.1 sigma

Data from 2009-2010: 348 days of livetime with ~75% complete detector

Analysis looks for deviation from the expected atmospheric neutrino flux → slight tension.

IC79, 86-1 diffuse ν_μ neutrinos



Data set:
2 years of IceCube
(5-2010 to 5-2012)

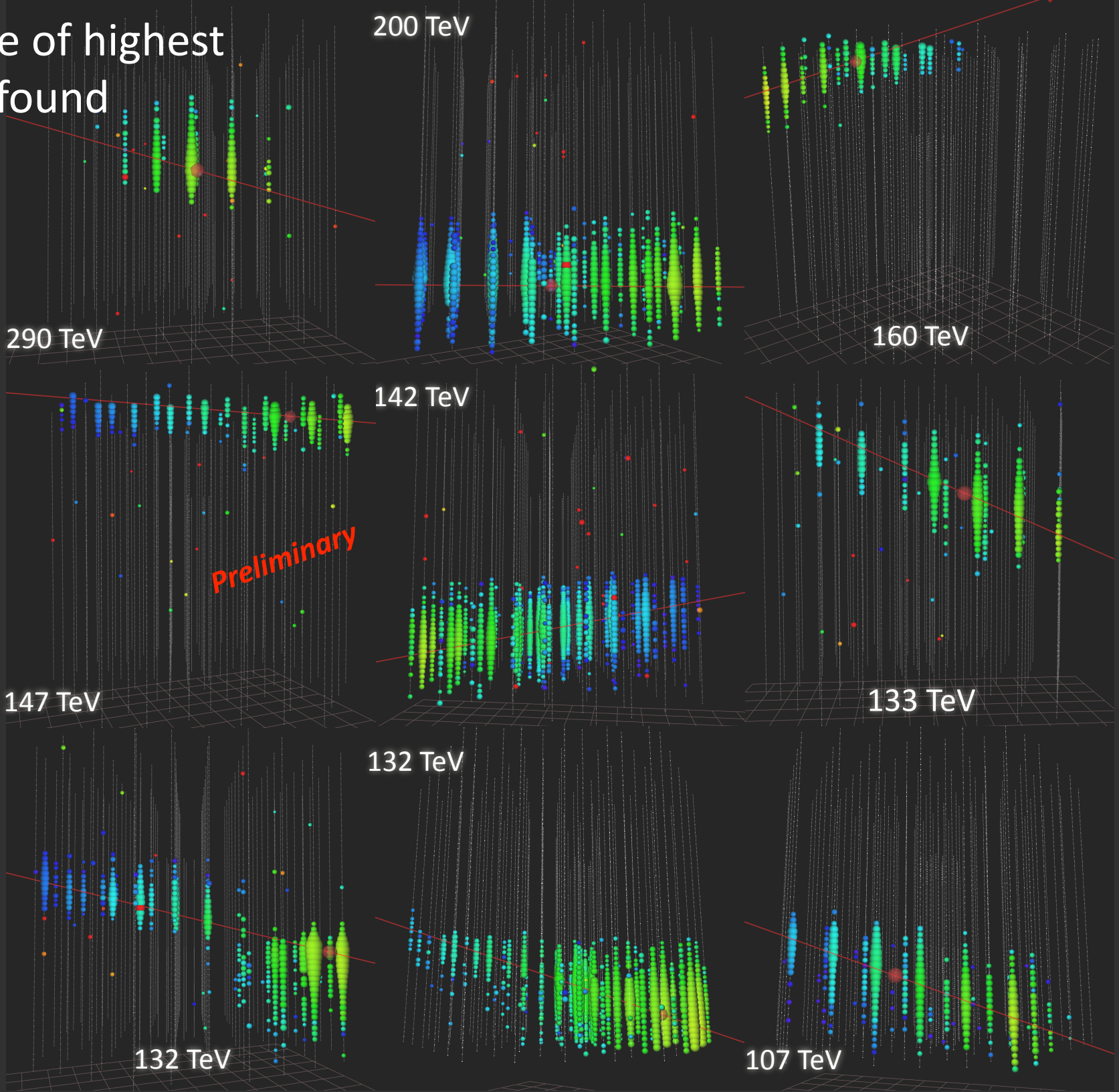
~20000 events

Results presented recently at APS spring meeting in talks by C. Weaver and N. Kurahashi

Method: Try to treat diffuse neutrino data as a superposition of three components:

- **Background 1: Conventional atmospheric neutrinos (HKKMS 2007)**
- **Background 2: Prompt atmospheric neutrinos (ERS 2008)**
- **Signal: Astrophysical neutrinos (isotropic with a spectrum of E^{-2})**

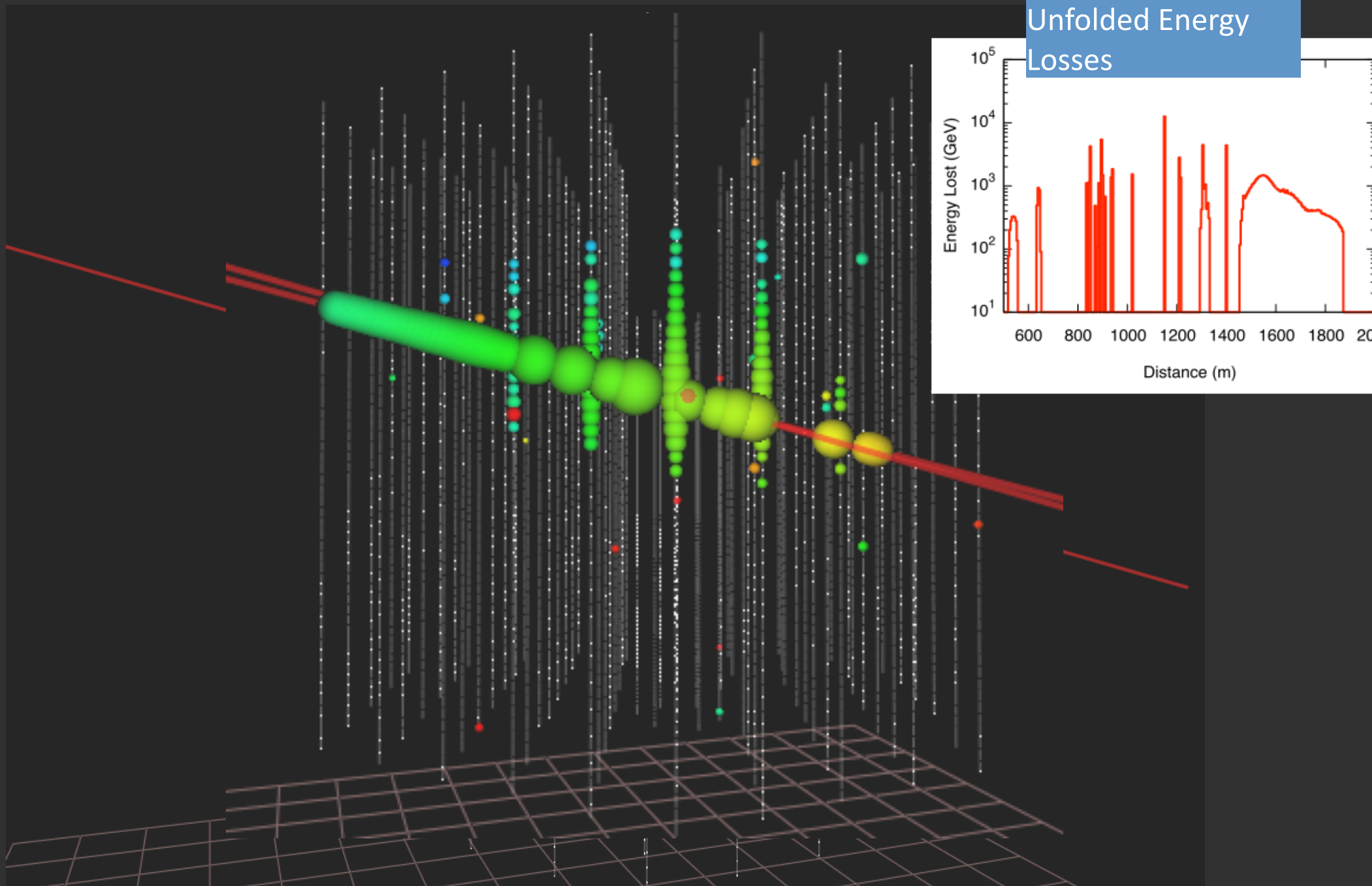
Example of highest events found



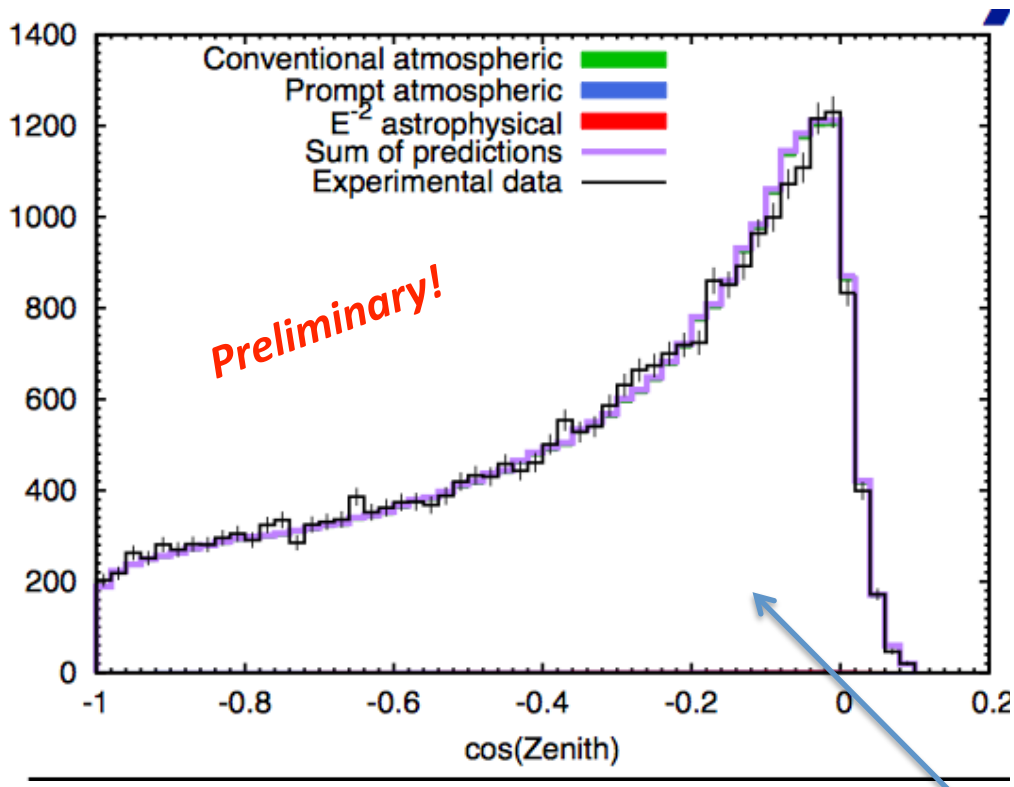
The highest energy event: ~0.5 PeV

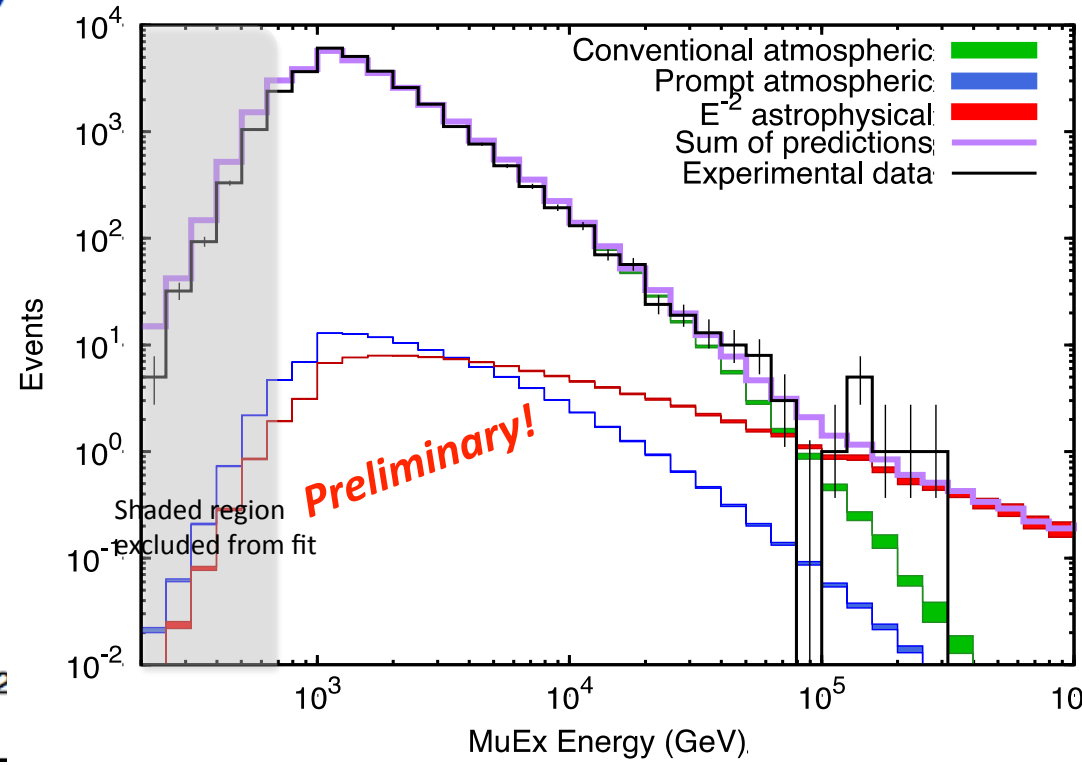
(Muon energy)

The neutrino energy is estimated in the PeV energy range



Two year diffuse ν_μ -preliminary

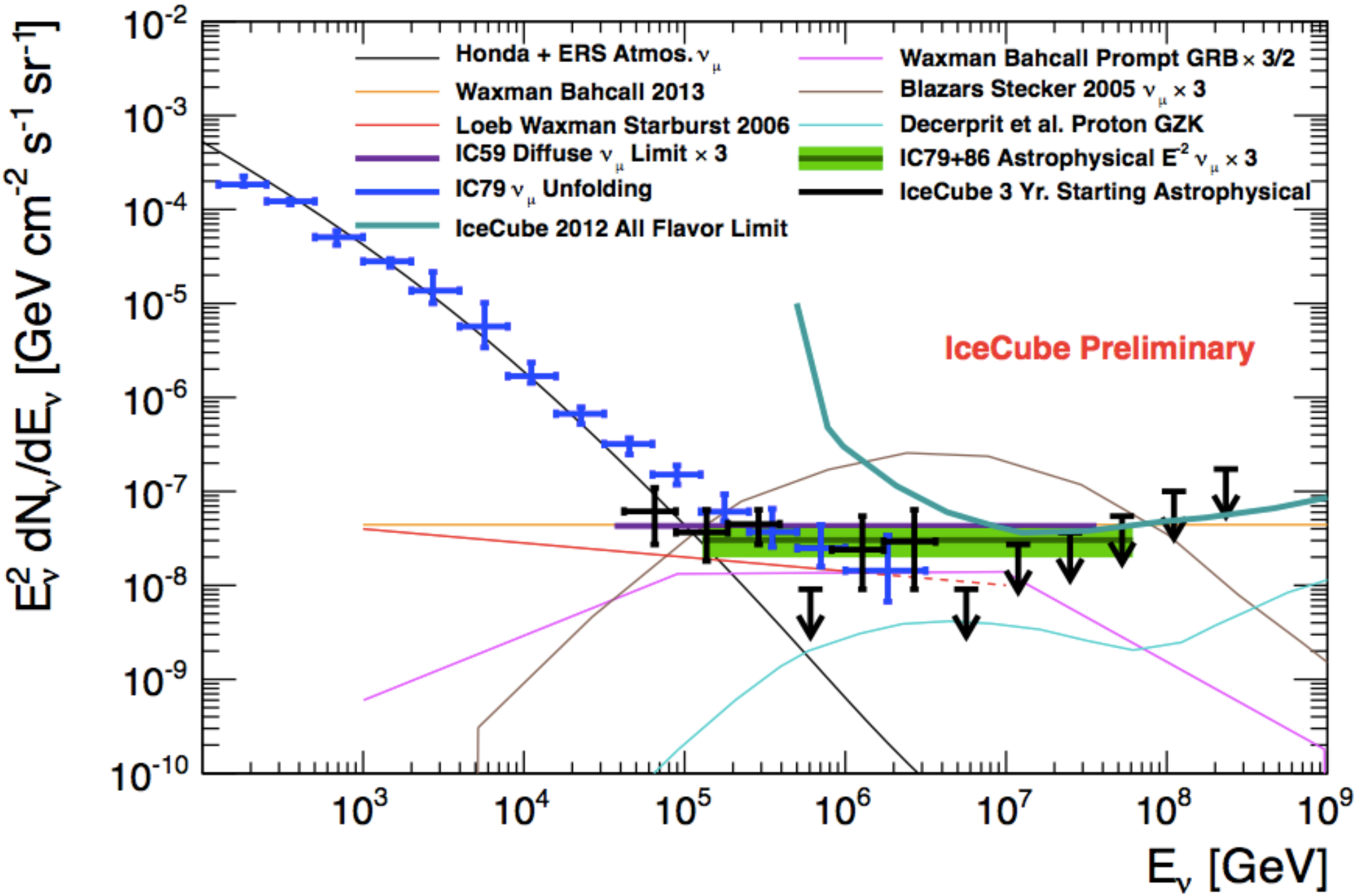




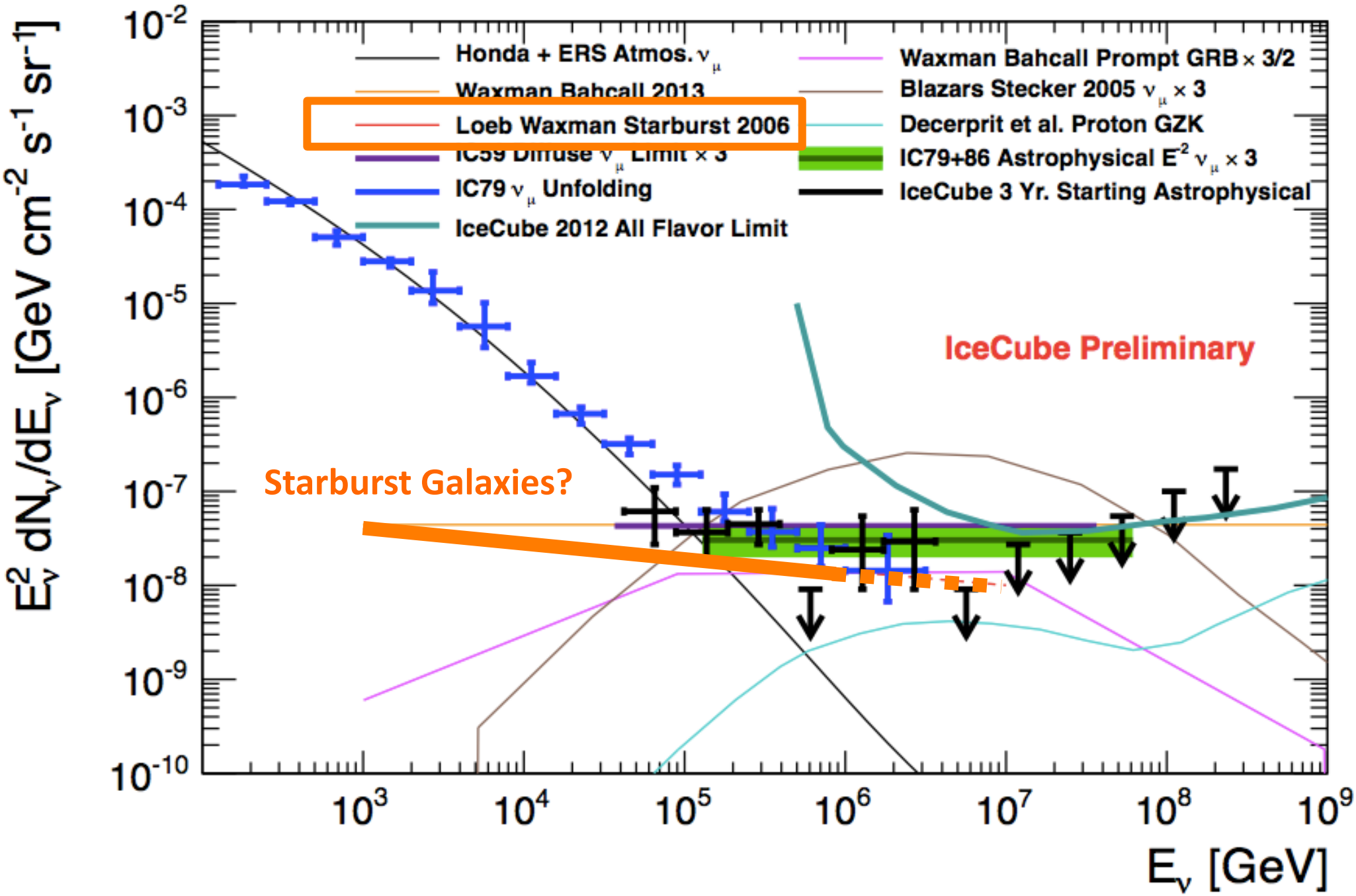
Excess in muon channel
At a level of ~3.9 sigma

Can also do sterile neutrinos,
But must be careful with systematic errors,
affecting zenith distribution.

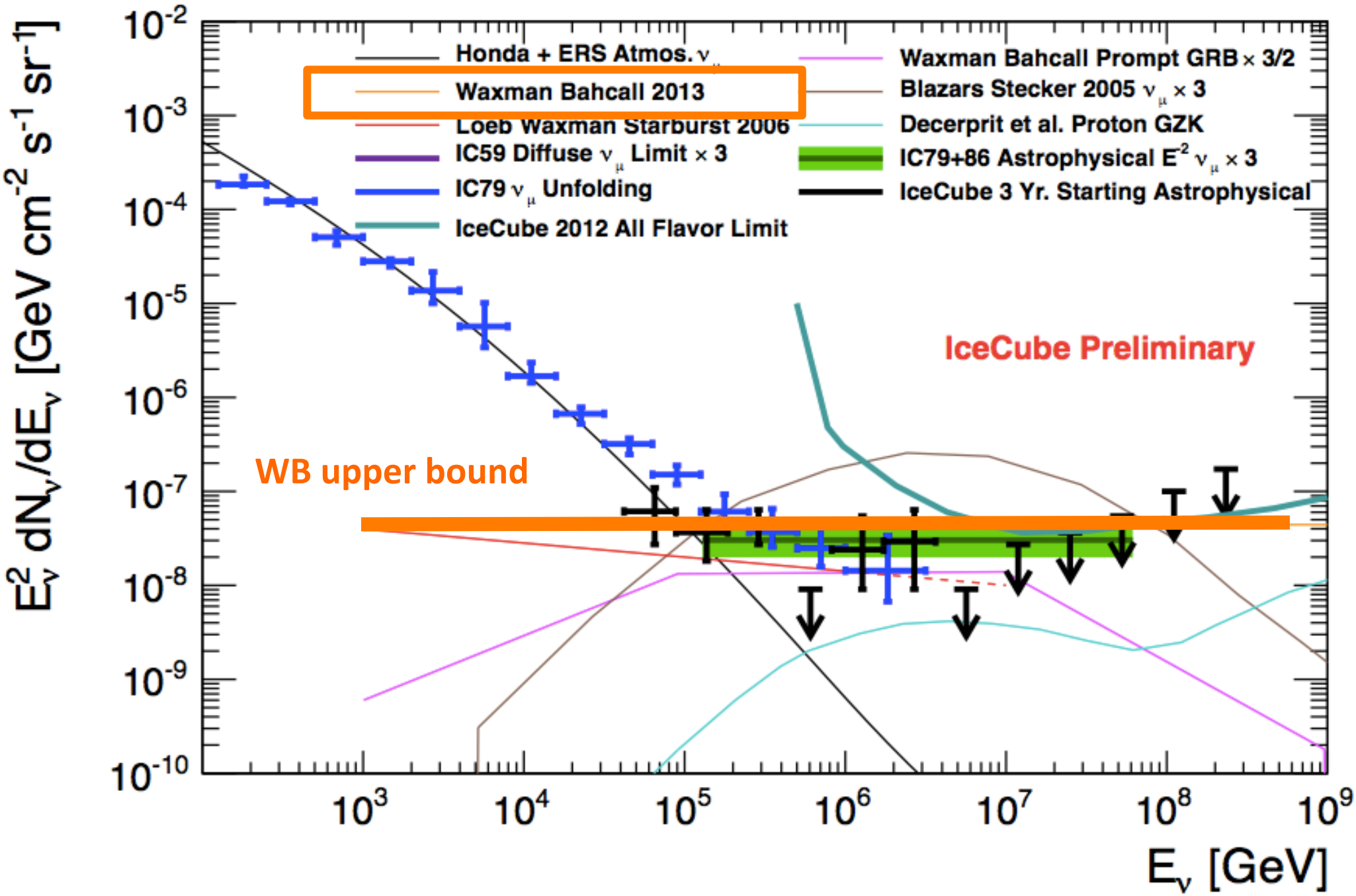
Diffuse flux data



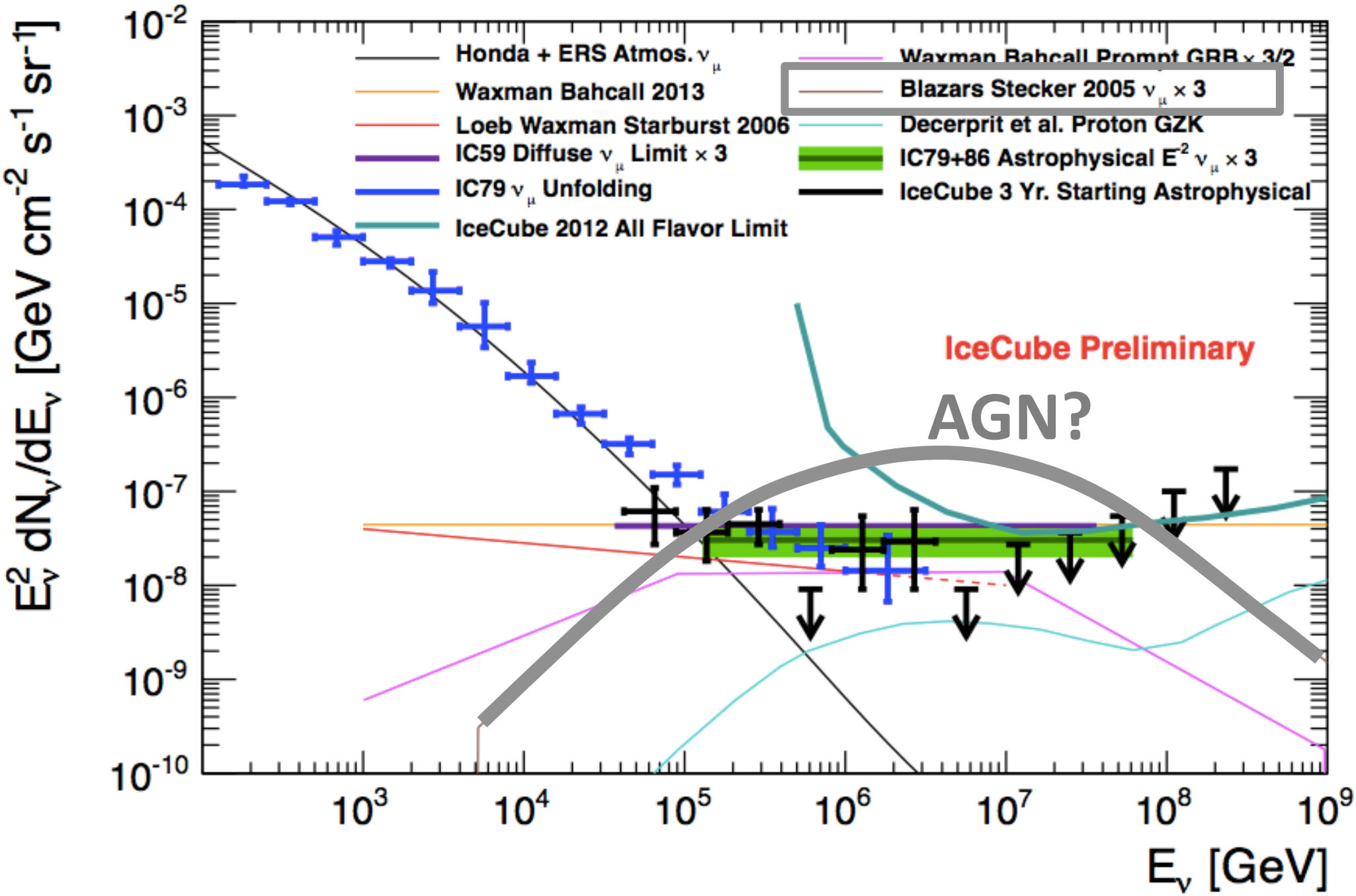
Diffuse flux data



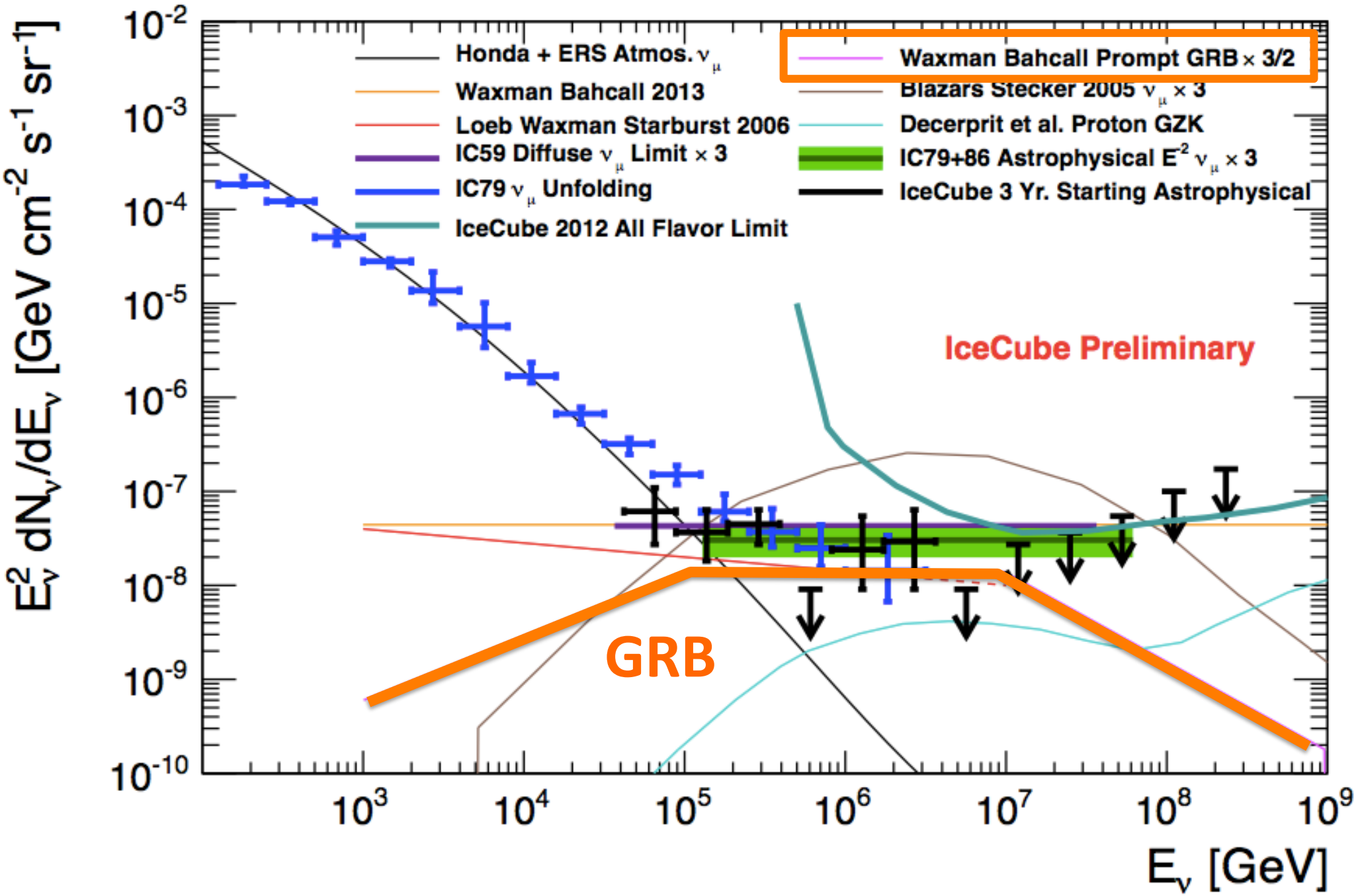
Diffuse flux data



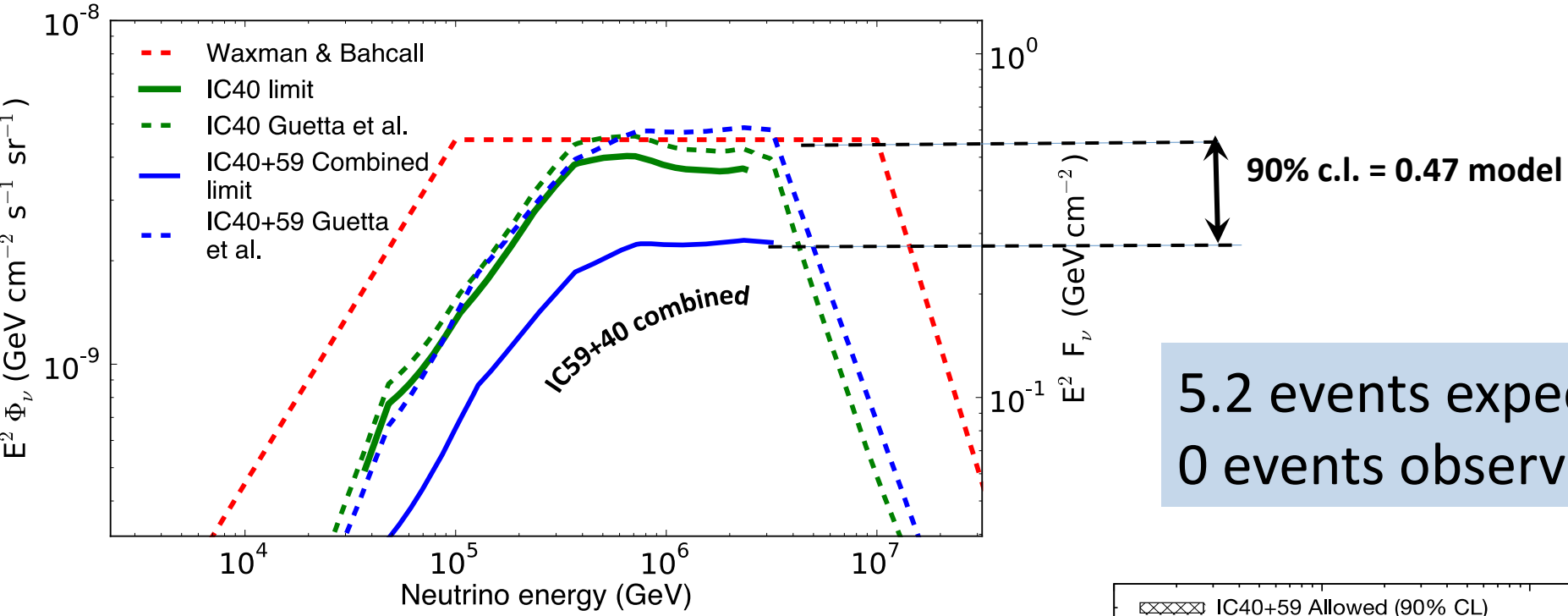
Diffuse flux data



Diffuse flux data

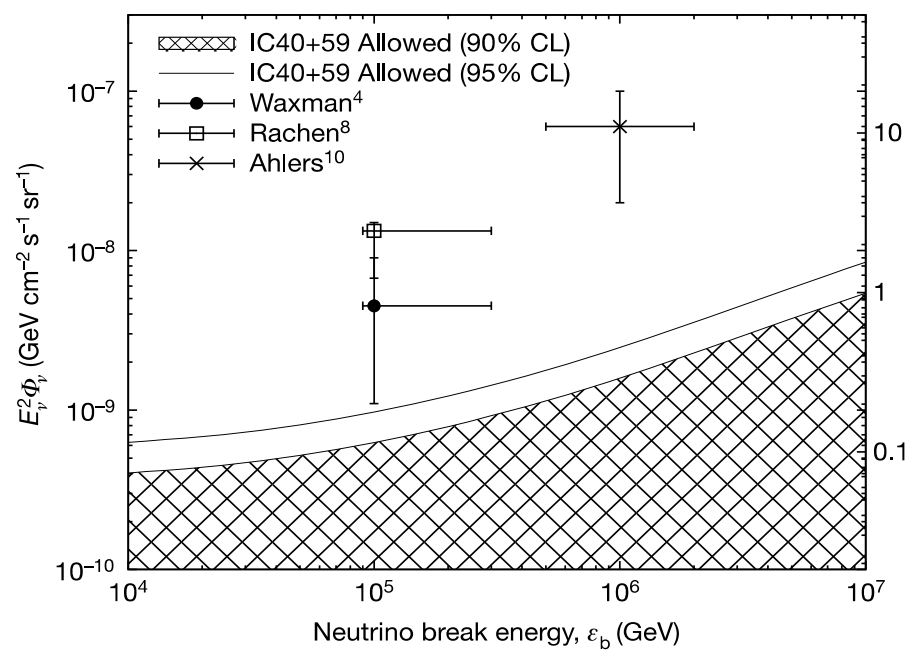


(No) neutrinos in coincidence with gamma ray bursts



5.2 events expected
0 events observed

Nature Vol **484**, 351 (2012)

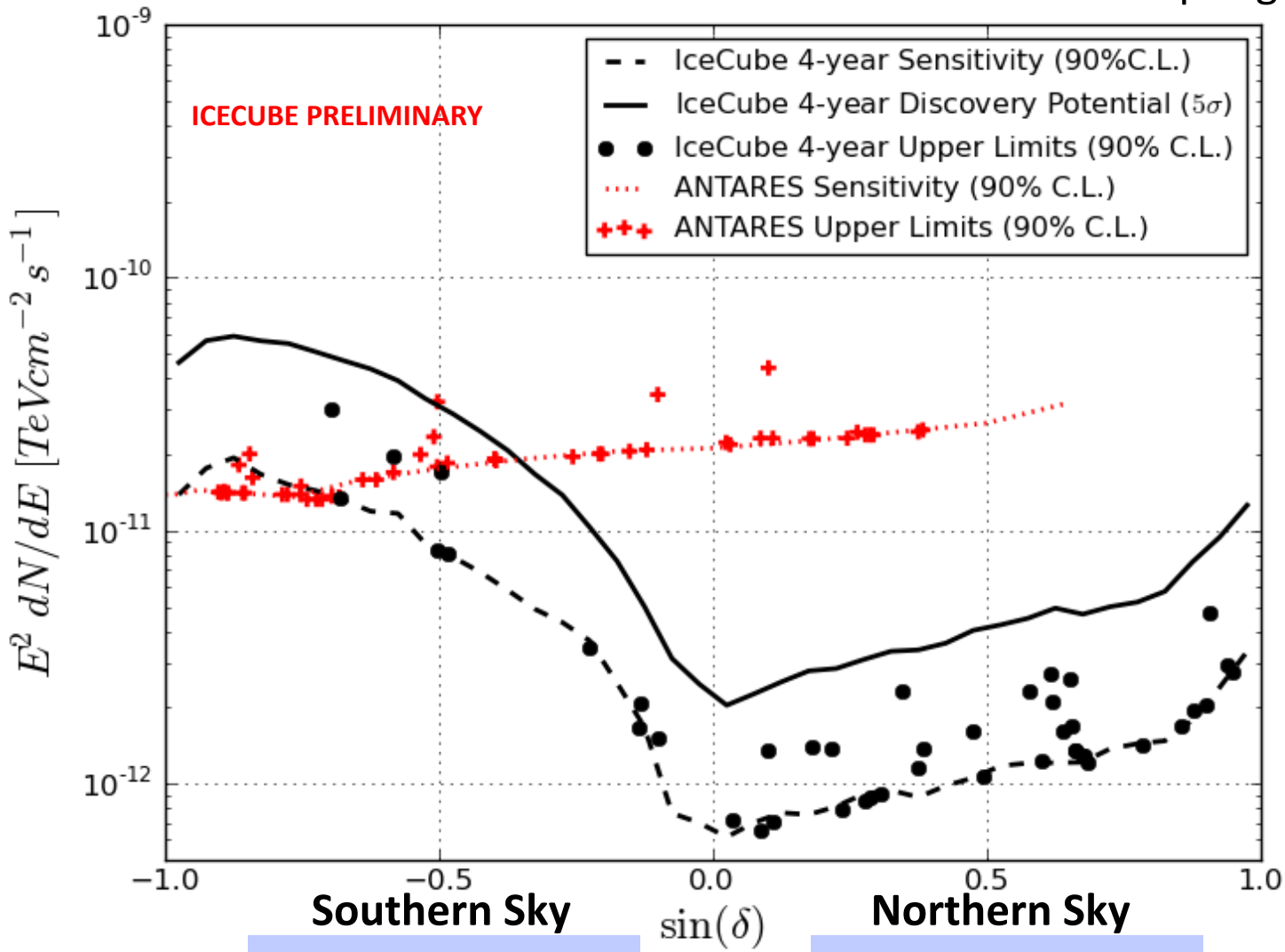


GRB fireball neutrino models tested.

GRBs as THE primary source of highest energy CR strongly disfavored for classes of models (neutron escape)

Combining point source limits with flux measurement constrains source population

J. Feintzeig,
APS spring meeting 2014



Southern Sky

PeV - EeV

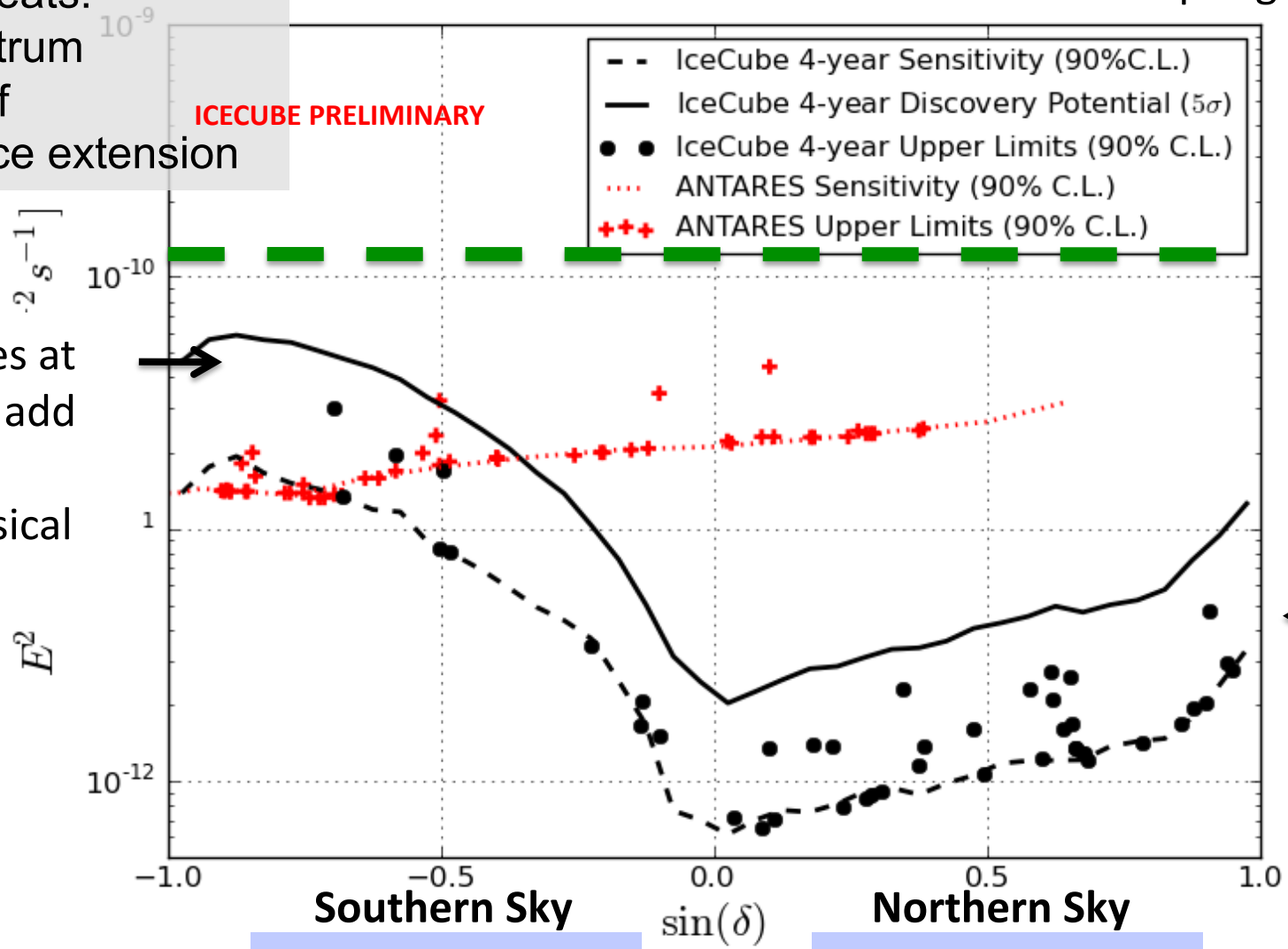
Northern Sky

TeV - PeV

Combining point source limits with flux measurement constrains source population

J. Feintzeig,
APS spring meeting 2014

Many caveats:
- E^{-2} spectrum
- No cutoff
- No source extension



Astrophysical flux (high-energy contained events)

~2 sources at this level add up to the astrophysical flux

~20 sources at this level add up to the astrophysical flux

Southern Sky

PeV - EeV

Northern Sky

TeV - PeV

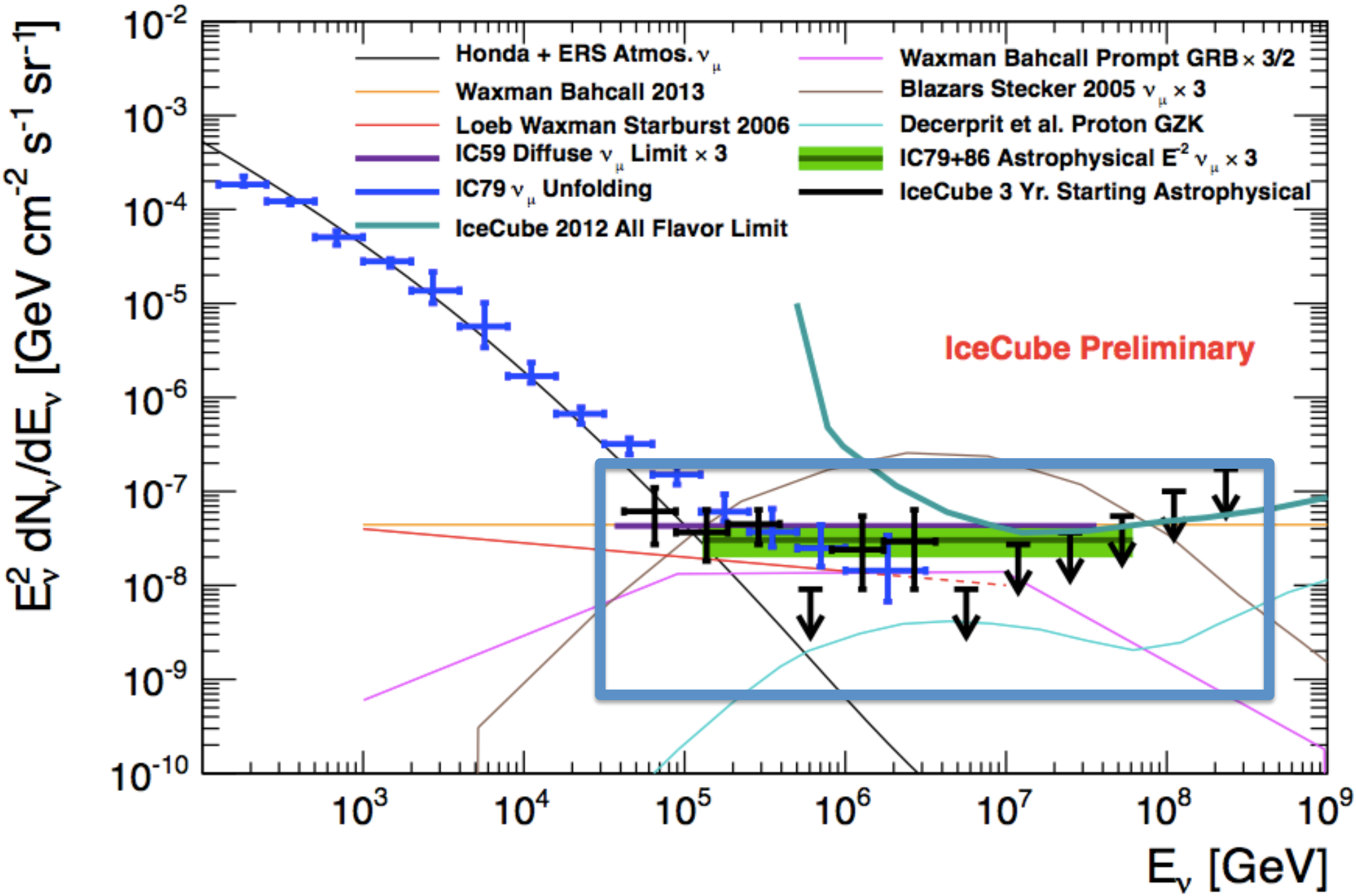
Observations and implications

- IceCube reports strong evidence for high energy neutrino flux in excess of terrestrial backgrounds
- Characteristics:
  - 30 TeV to several PeV
  - Flavor ratio appears consistent with 1:1:1
  - No clustering observed
  - Northern hemisphere nu_mu flux
  - Within statistics in good agreement with HESE flux (cascade dominated and more southern hemisphere)
  - No time structure
  - No statistically significant association with galactic plane or center.
  - Events up to 2 PeV, HESE spectrum consistent with E^-2.3+-0.3

- Consistent with astrophysical flux
- Suggestive of extragalactic at least in part (or need more out of the box models, eg DM)

Need more data to close in on sources.

Outlook, Future stratgies

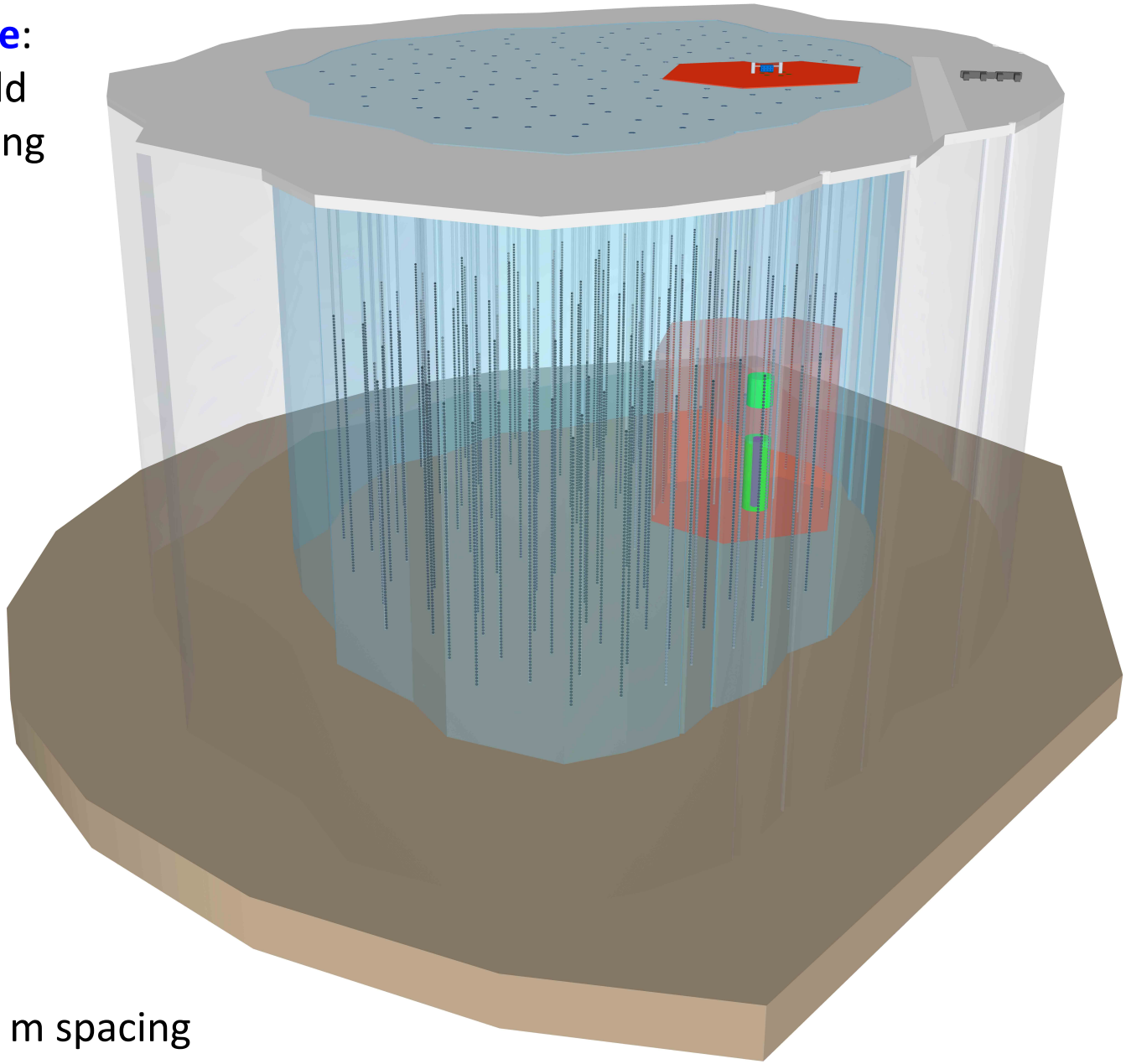


Outlook, Future strategies

- More statistics.
- Continue searches for association with sources
- Increase multi-messenger strategies with other telescopes, including transient sources.

- Consider experimental upgrades.
  - For 0.1 PeV to 10 PeV (1000 PeV) upgrade of IceCube
  - For GZK energies, pursue other radio detection techniques (eg. ARA at South Pole, ARIANNA)

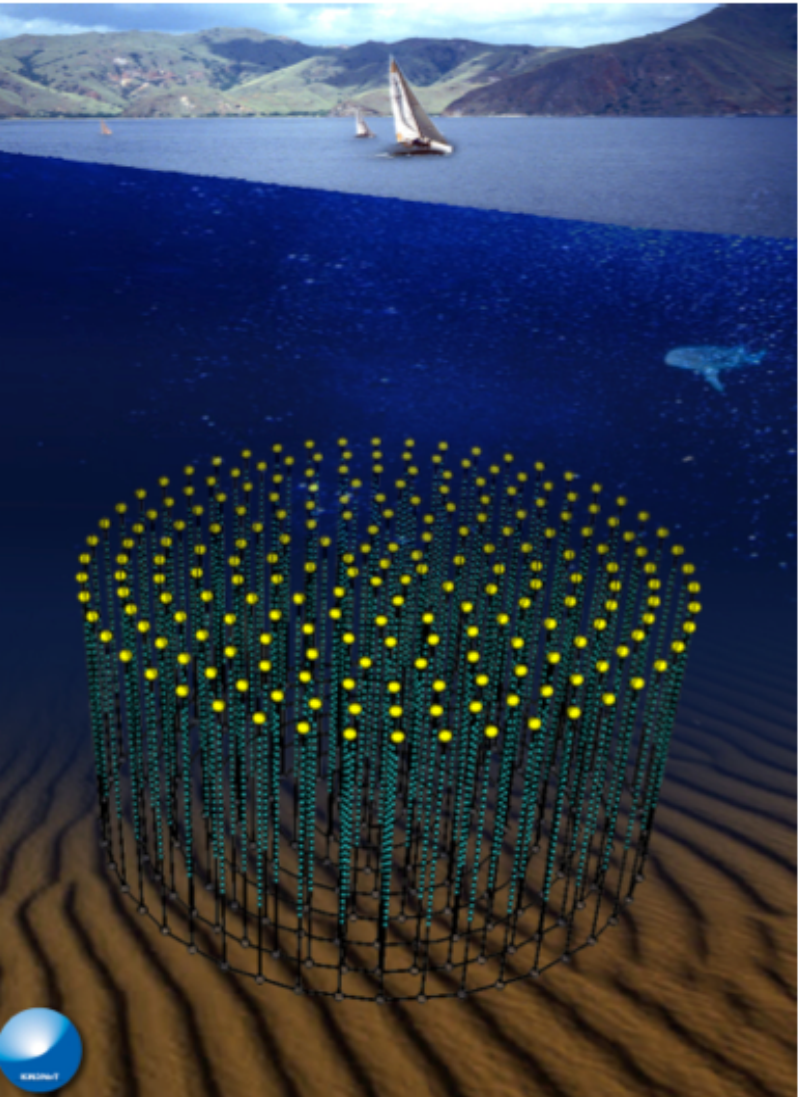
Possible strategy for a
Next Generation IceCube:
Increase energy threshold
allows larger string spacing



Artist conception
Here: 120 strings at 300 m spacing

Future plans for a large Mediterranean neutrino telescope

Scale: ~12000 optical modules
of 3xIceCube DOM optical sensitivity at three sites
(photo detection area: equivalent to 36000 IceCube DOMs)



Th

Status:
Phase 1 funded ((40M Euro) for stage 1 detectors at 2 sites.
Construction activities for phase 1 in preparation.
Estimated total cost: ~Euro 220M
(Mostly capital equipment)

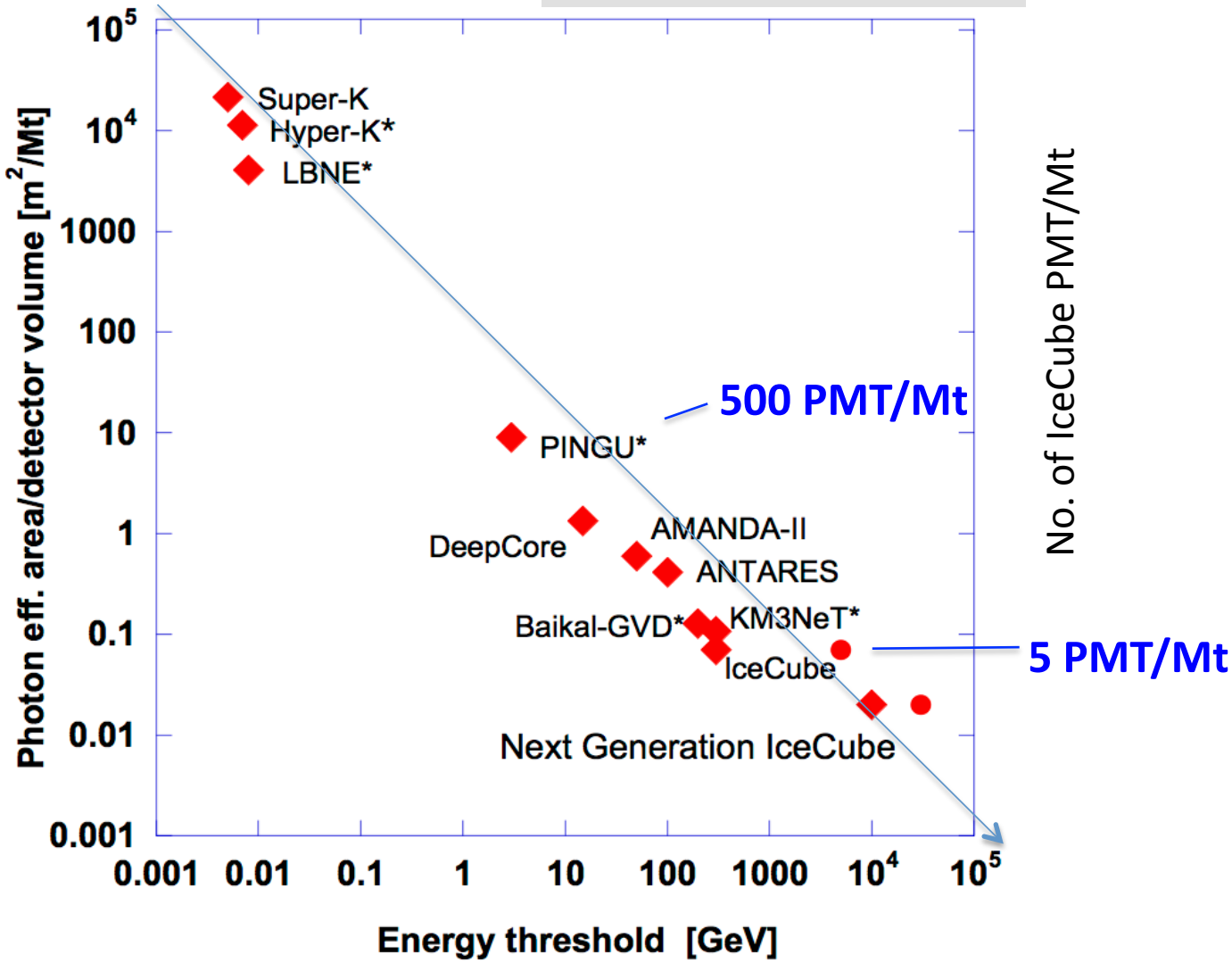
KM3NeT

Water Cherenkov detectors: PMT coverage vs energy threshold

New evidence at higher energy → science requirement: focus on higher energy
We can reduce the PMT coverage (string density) by increasing the energy threshold.

Can we increase detection volume by an order of magnitude for similar cost?

This chart suggest yes.



Define:

Photon effective area =

Number of PMT
x Cathode area
x Quantum efficiency

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

For highest energies, need other detector: Radio detection of neutrinos

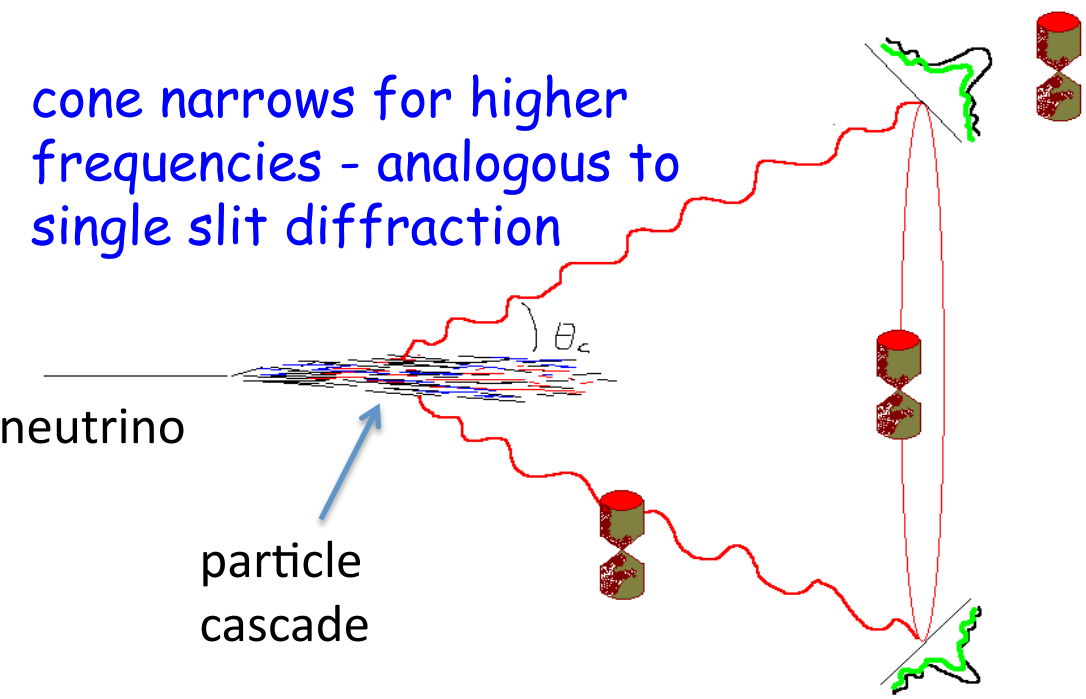
Coherent radio emission from e.m. cascade

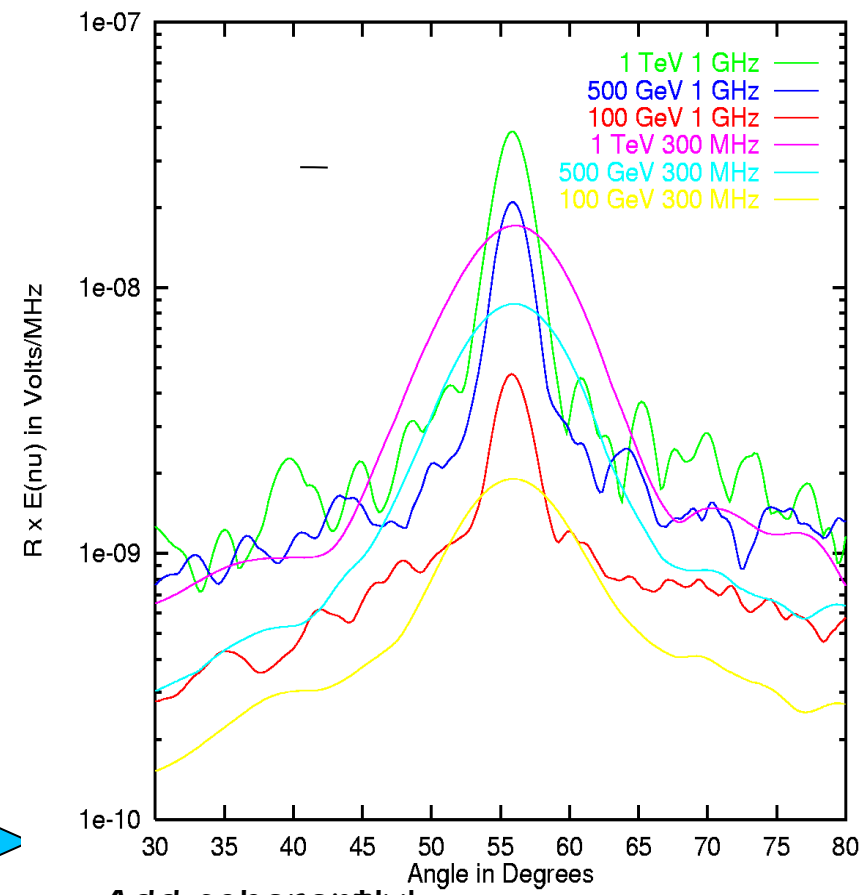
Gurgen Askaryan, 1960ies

charge asymmetry in particle shower development produces a net charge of cm extension.

→ coherent radio emission from c > c_medium moving charge

cone narrows for higher frequencies - analogous to single slit diffraction



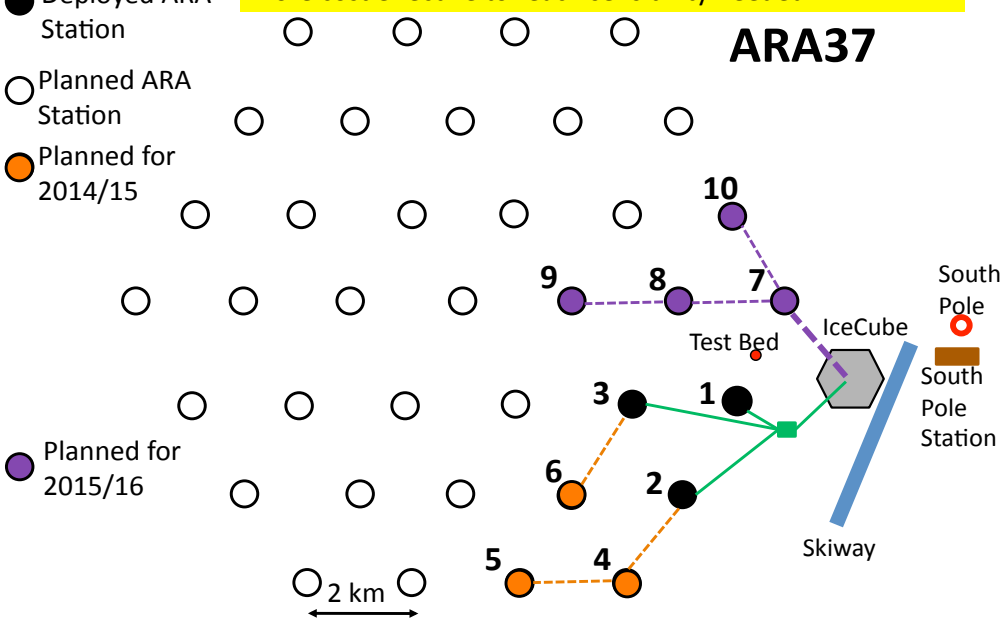


Add coherently!

Some experimental efforts based on radio detection.

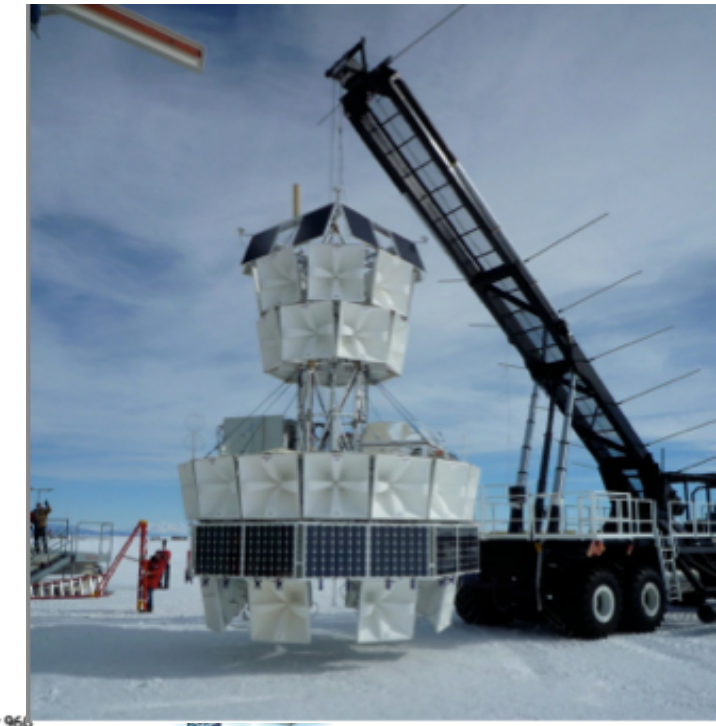
ARA (South Pole)

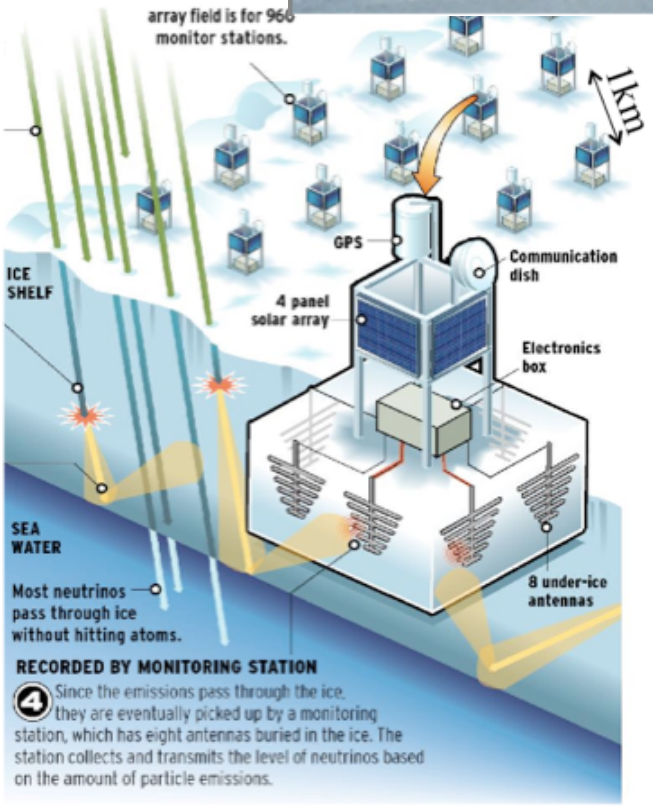
For energies > 100 PeV, Radio detectors are more scalable, more cost effective to reach sensitivity needed



ANITA

(ANTARCTICA, Balloon borne)





From OC Register 2012

ARIANNA

(ANTARCTICA)

At low energies

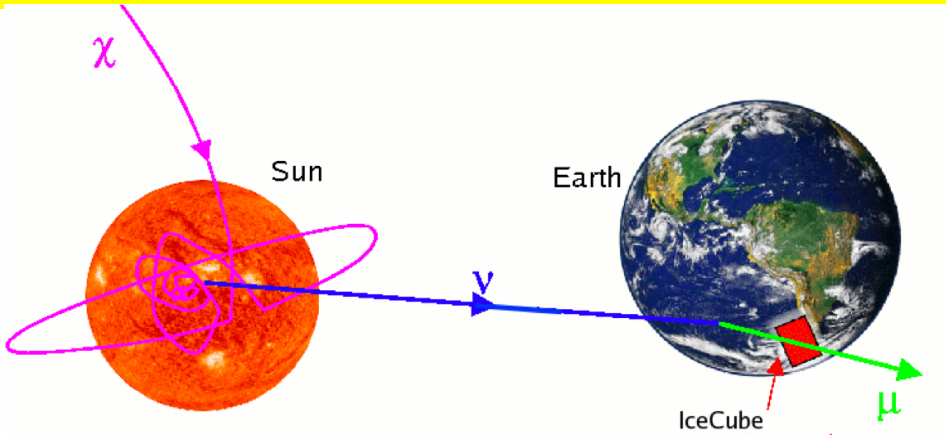
IceCube/DeepCore

Dark matter searches

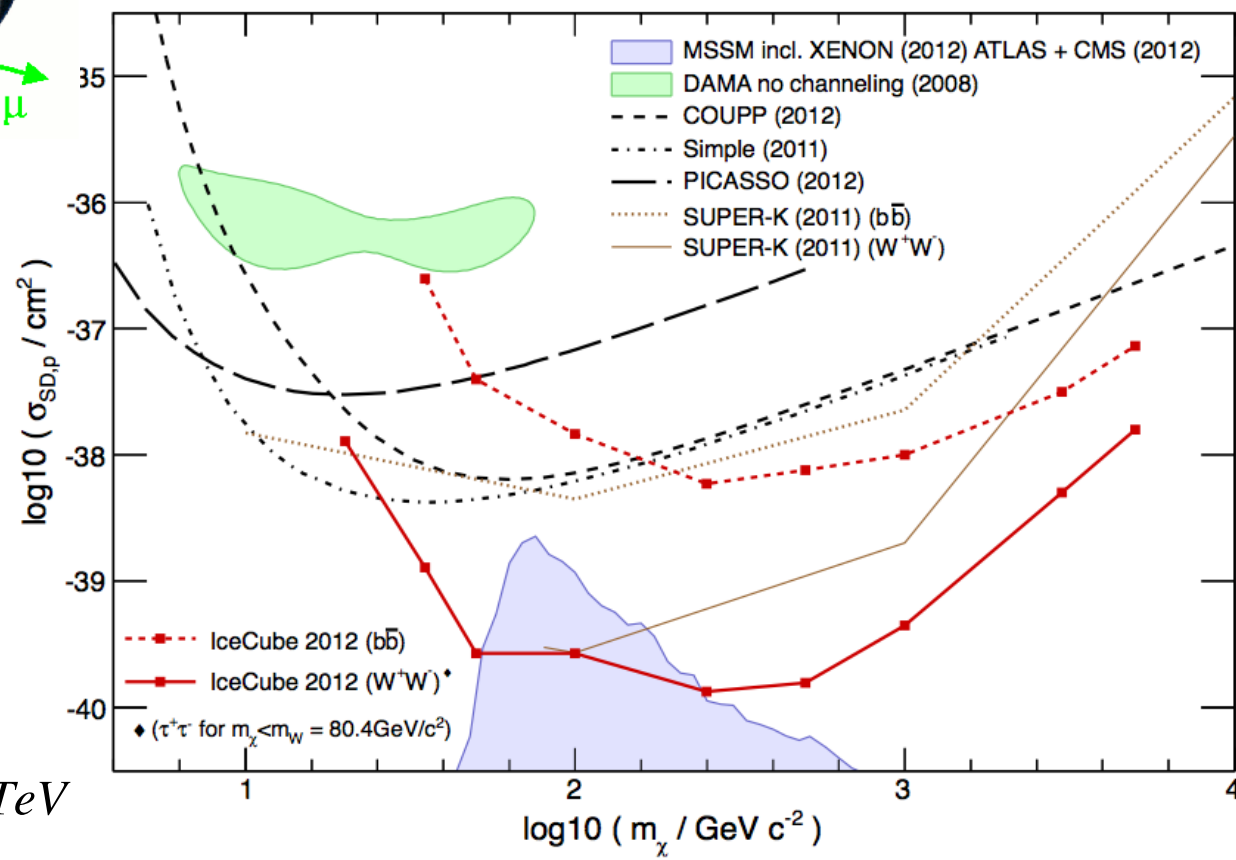
Oscillation physics

Outlook to PINGU

Dark matter: Indirect search, WIMPs in sun, galactic center, ….
Using IceCube-DeepCore (low energy subdetector)



arXiv:1212.4097,
accepted PRL



Dark matter accumulates in the sun, annihilating to high energy neutrinos

Equilibrium annihilation related to solar capture rate

→ probes scattering cross-section

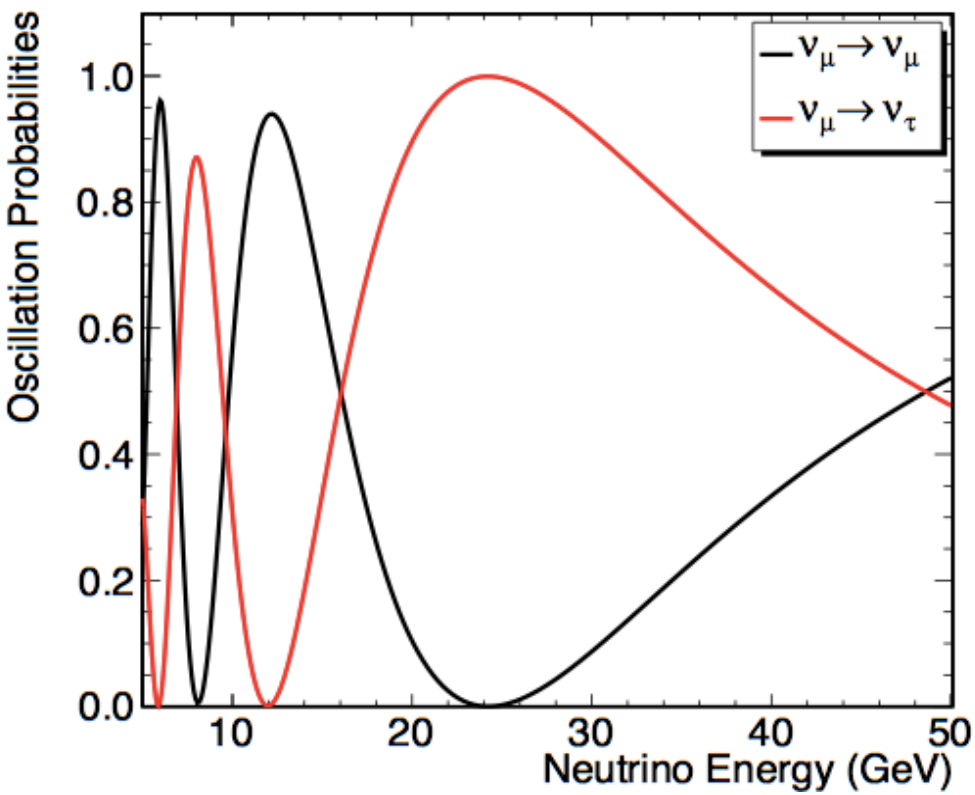
Sensitivity from

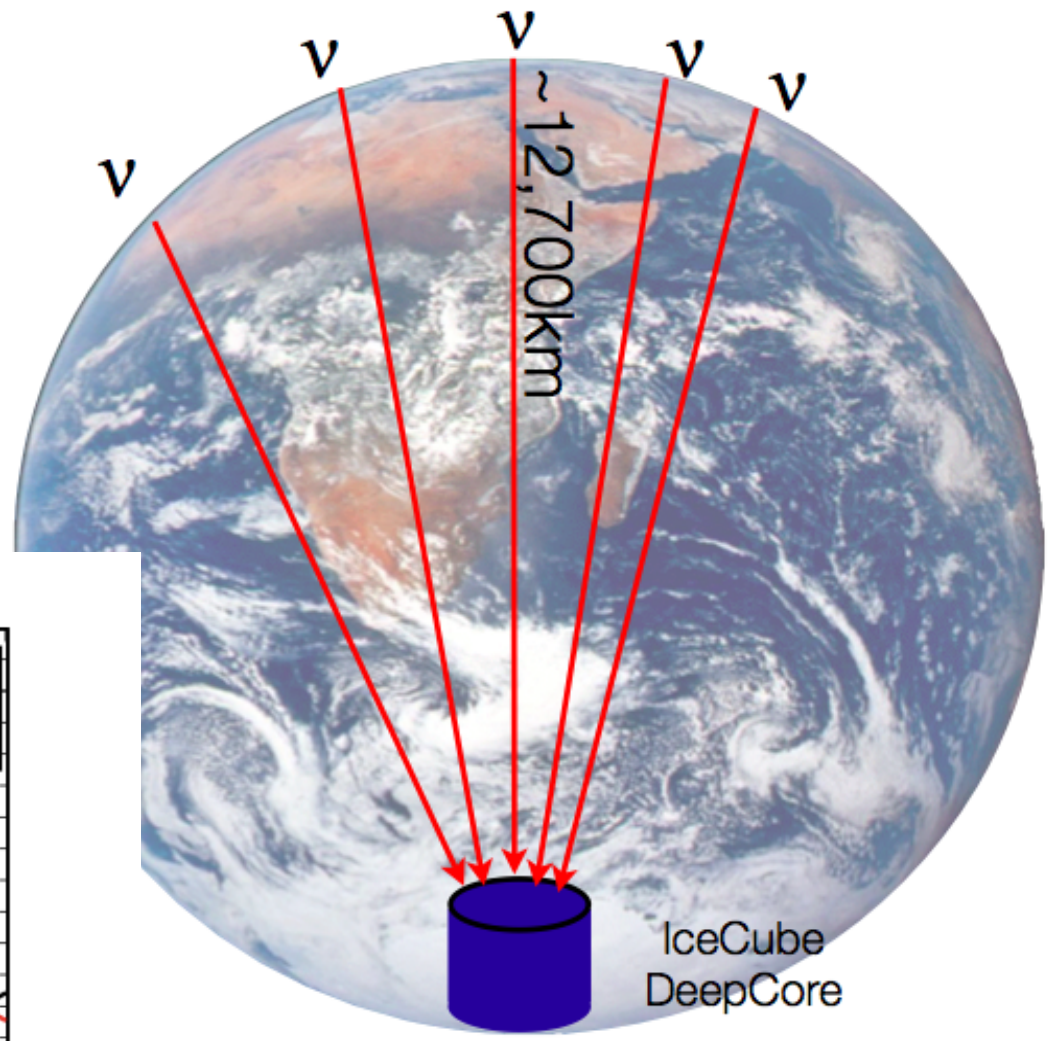
High sensitivity to spin-dependent cross section due to proton target

$20GeV \leq m_\chi \leq 10TeV$

Neutrino oscillation analysis with IceCube-DeepCore

- First oscillation maximum around 24 GeV, i.e. DeepCore energies
- Hierarchy-dependent matter effects below 10 GeV – too low for DeepCore





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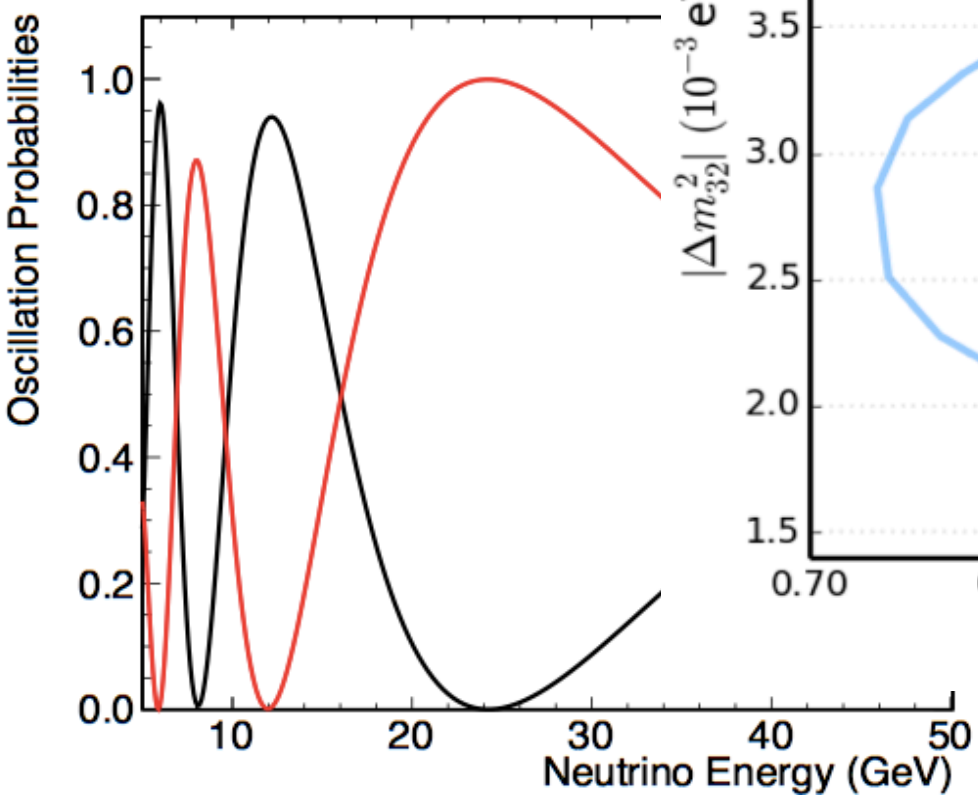
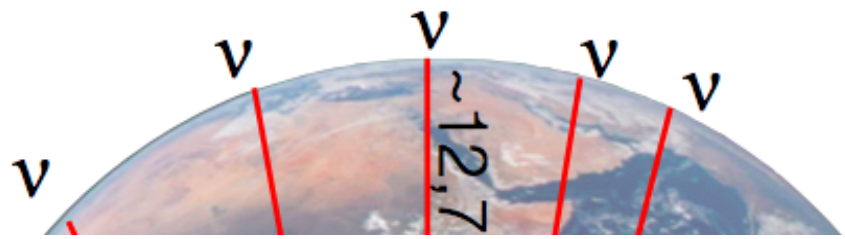
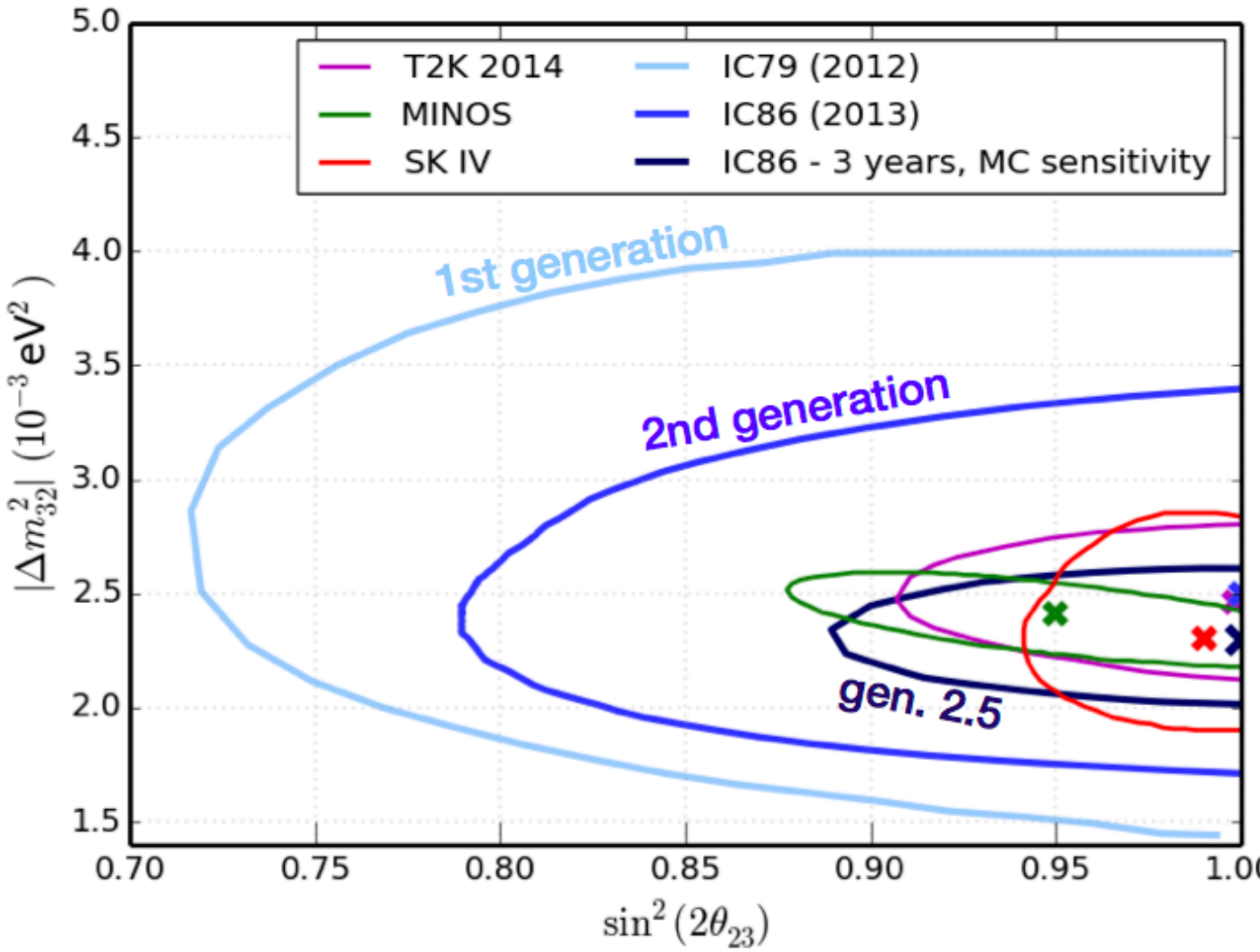




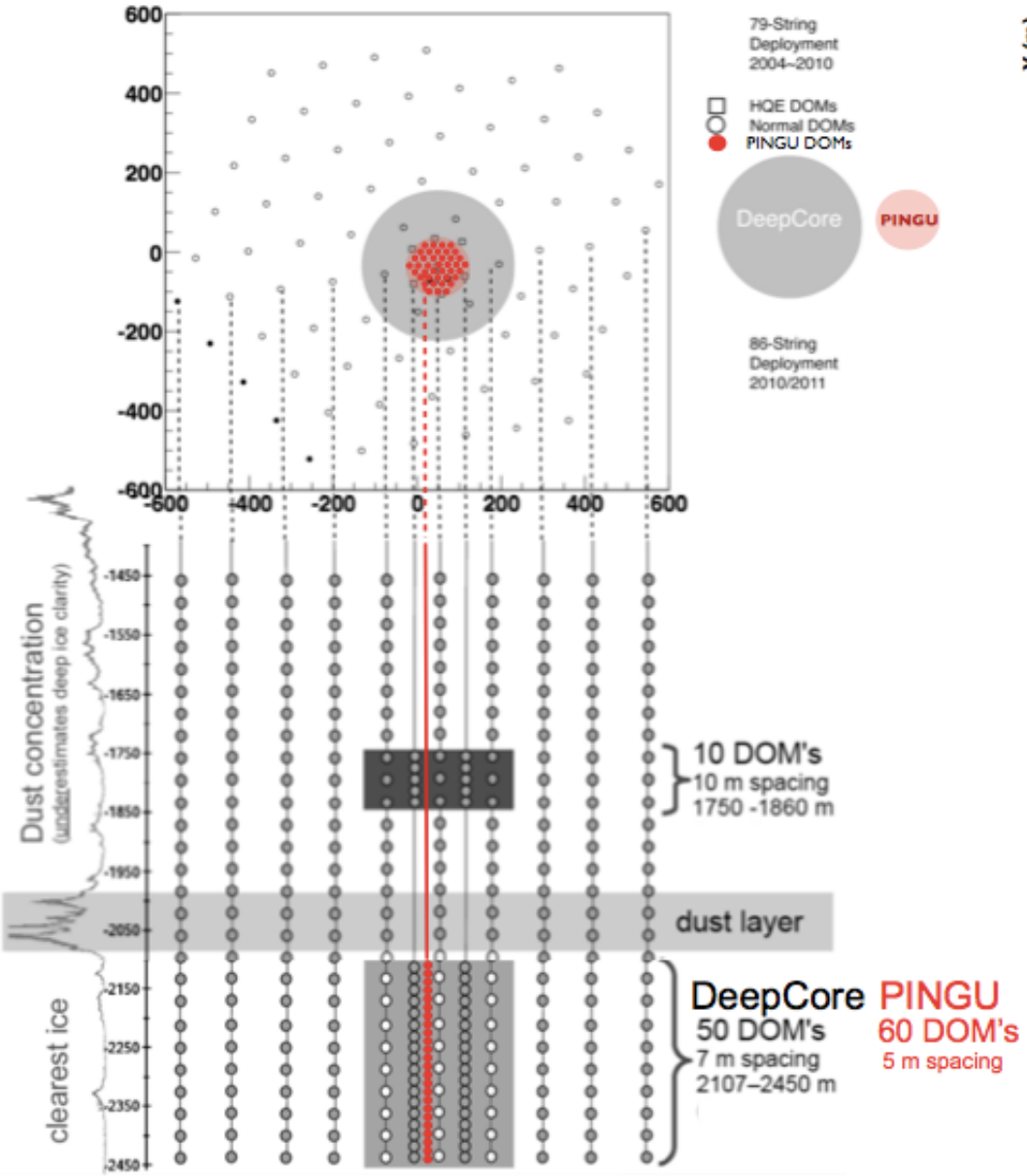


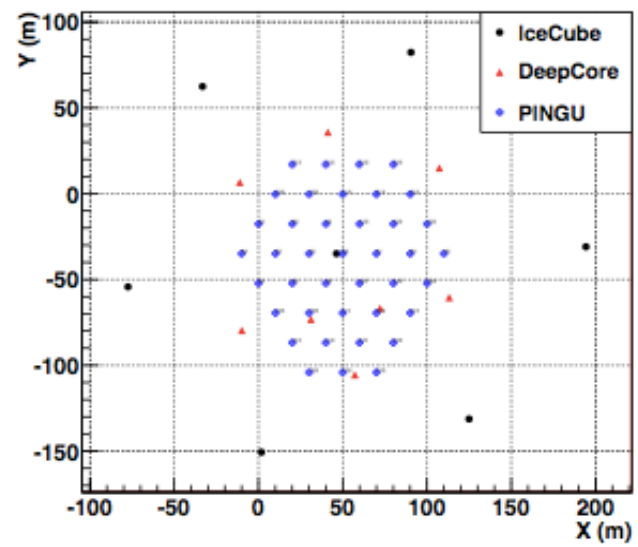
Earlier: arXiv:1305.3909 (accepted PRL)

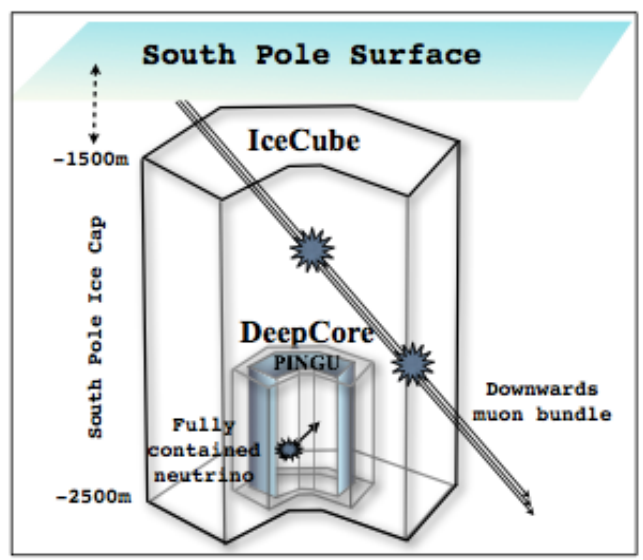
DeepCore and PINGU

DeepCore is part of the running IceCube,
8 additional in fill strings
Energy threshold ~ 10 GeV

PINGU is possible future denser infill array,
40 strings, 60 – 100 PMTs,



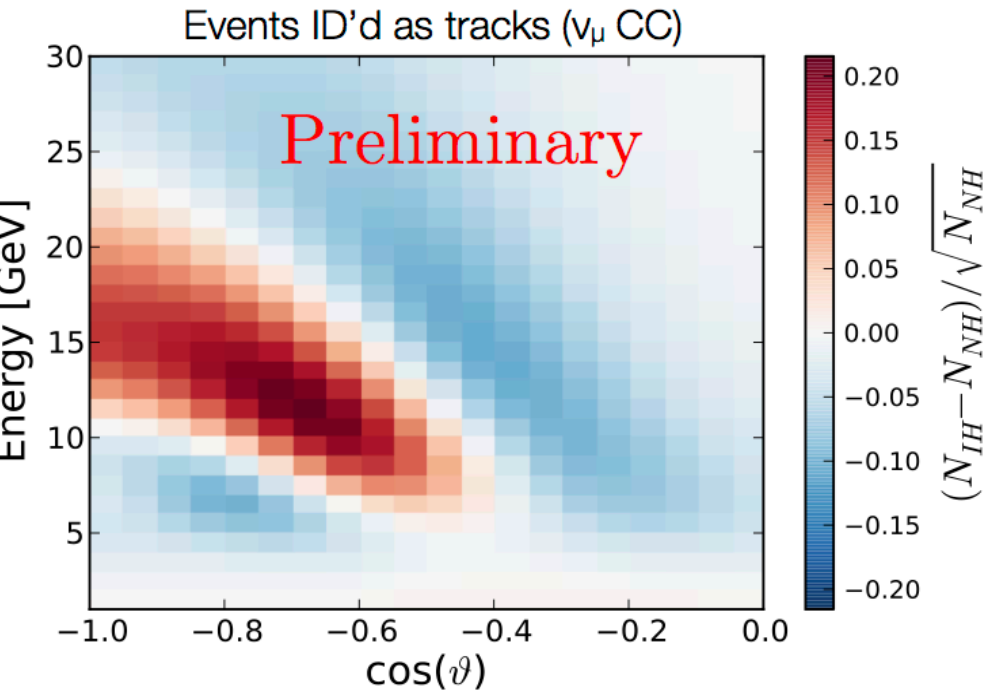


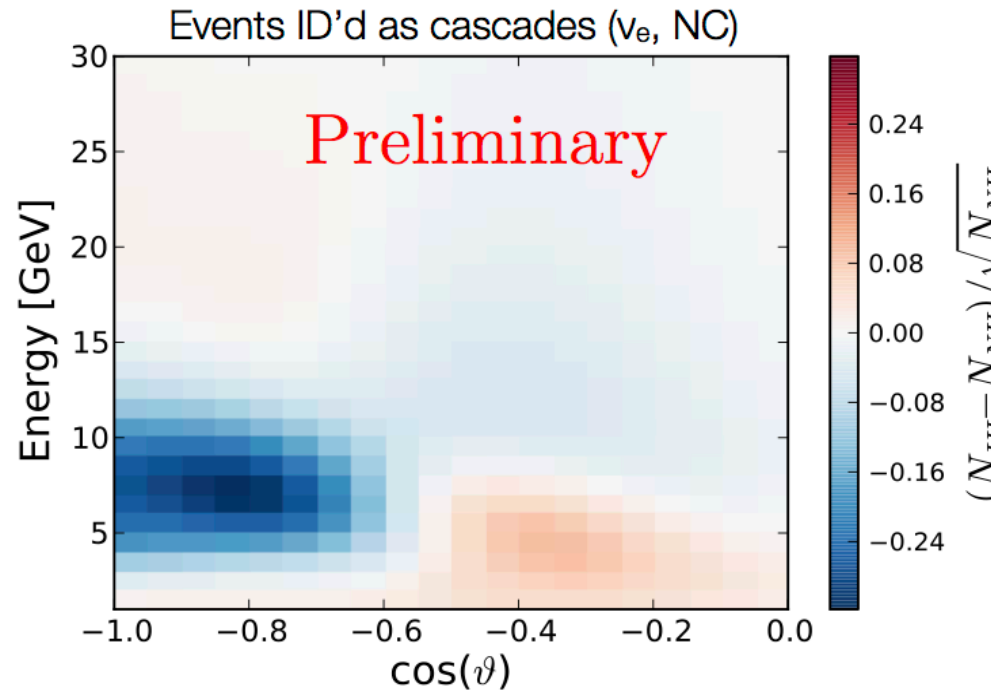


INGU goals:
eutrino mass hierarchy, oscillation physics, dark matter searches

Experimental Signatures of Mass Hierarchy

Ref: Letter of Intent, arXiv:1401.2046v1





- Hierarchy signature is a distinctive structure in energy-angle plane
  - Key to our approach to controlling systematics
- Experimental resolution and track ID efficiency smear the signature out, but do not eliminate it

With current techniques, a determination of the mass hierarchy with 3σ significance appears possible with 3.5 years of data.

Exciting times!

Did not talk about many other science topics:
Cosmic rays,
Neutrino physics,
Supernova detection

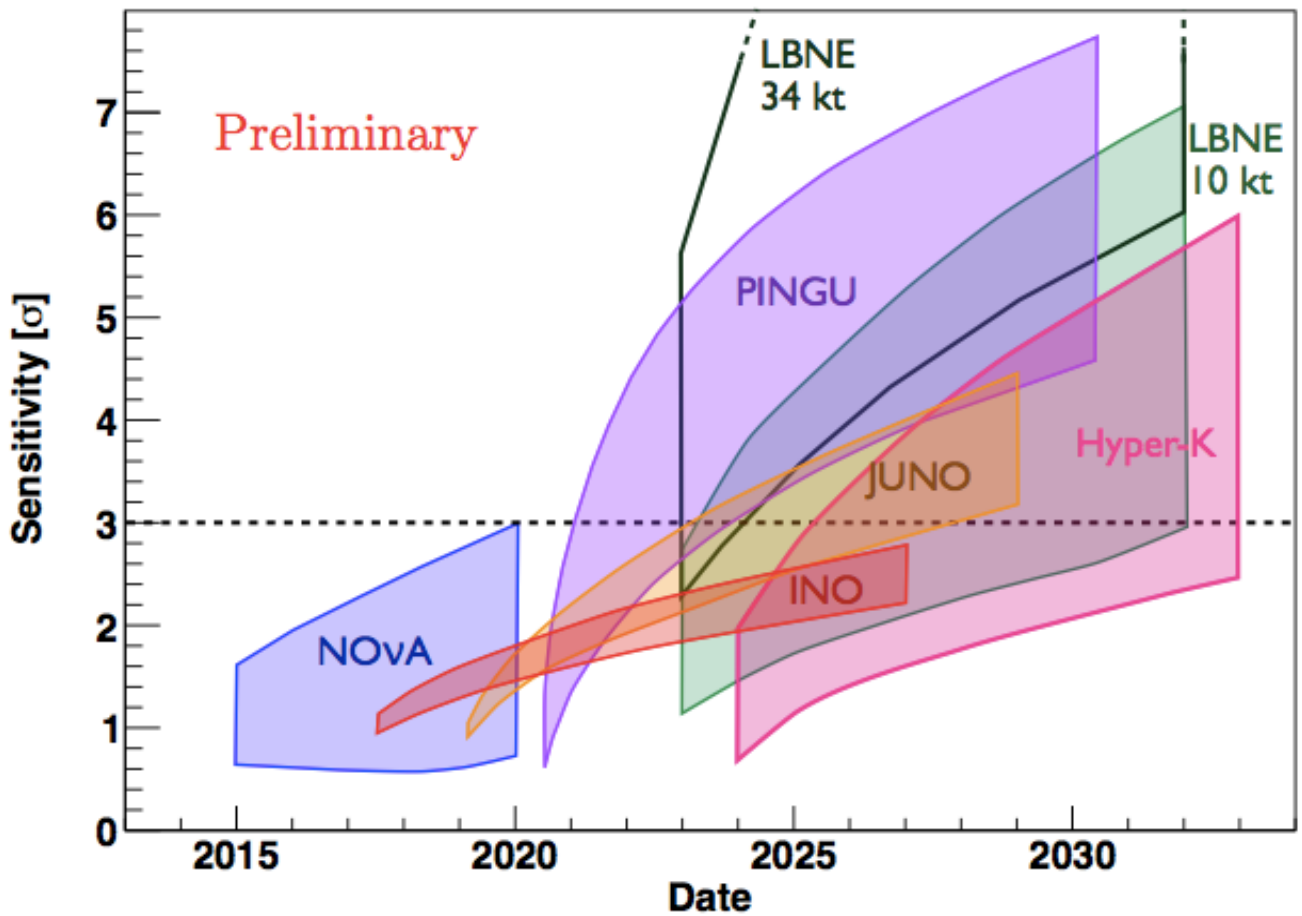
Thank you!

Experimental Probes of the Mass Hierarchy

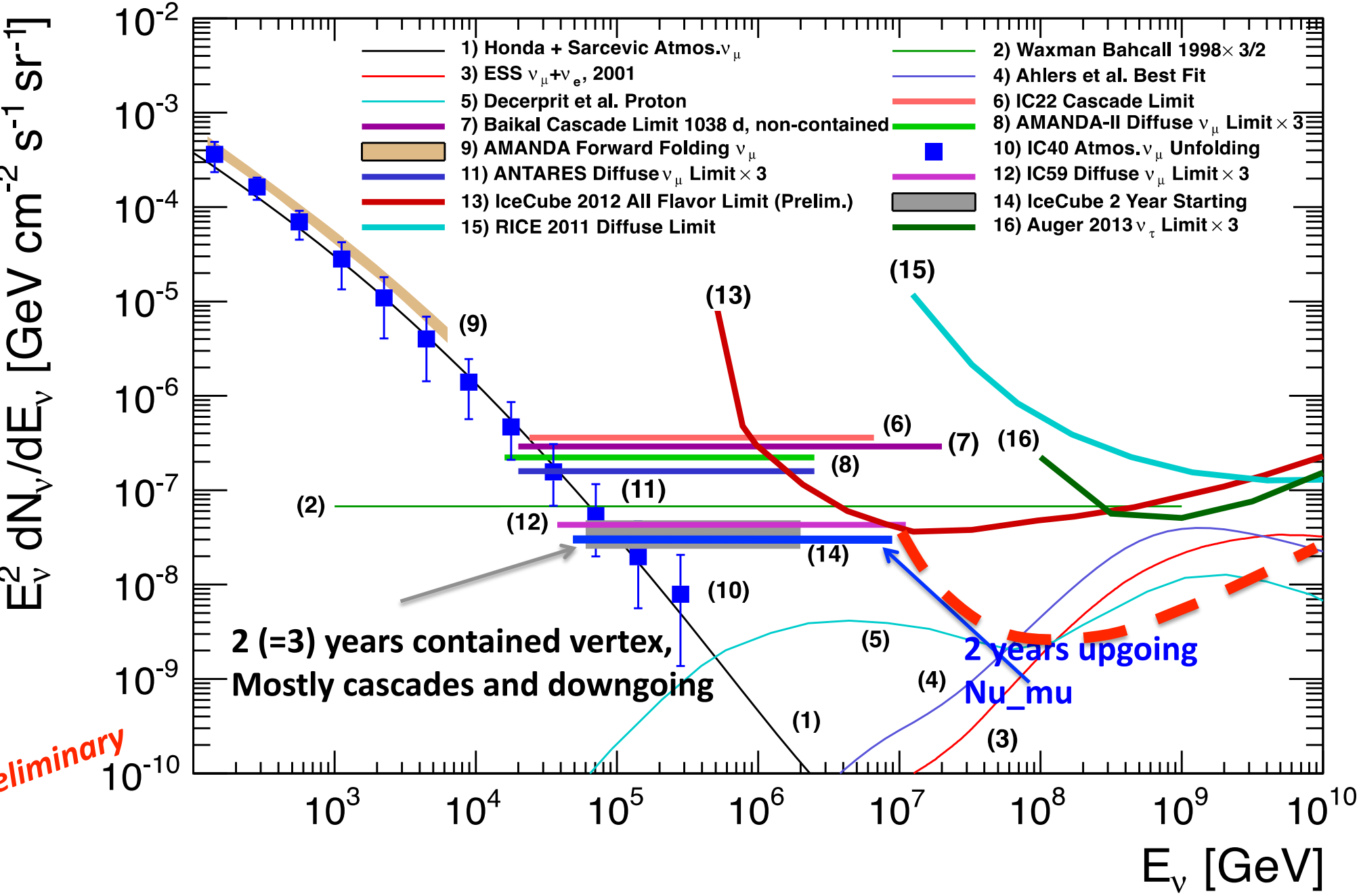
- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy
  - NB: *median* outcomes shown – there is a substantial risk of an inconclusive result from any single expt.
- Widths indicate main uncertainty
  - LBNE/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)

Ref: Letter of Intent, **arXiv:1401.2046v1**

after Blennow et al., arXiv:1311.1822



How do the searches for a diffuse muon neutrino flux fit in?

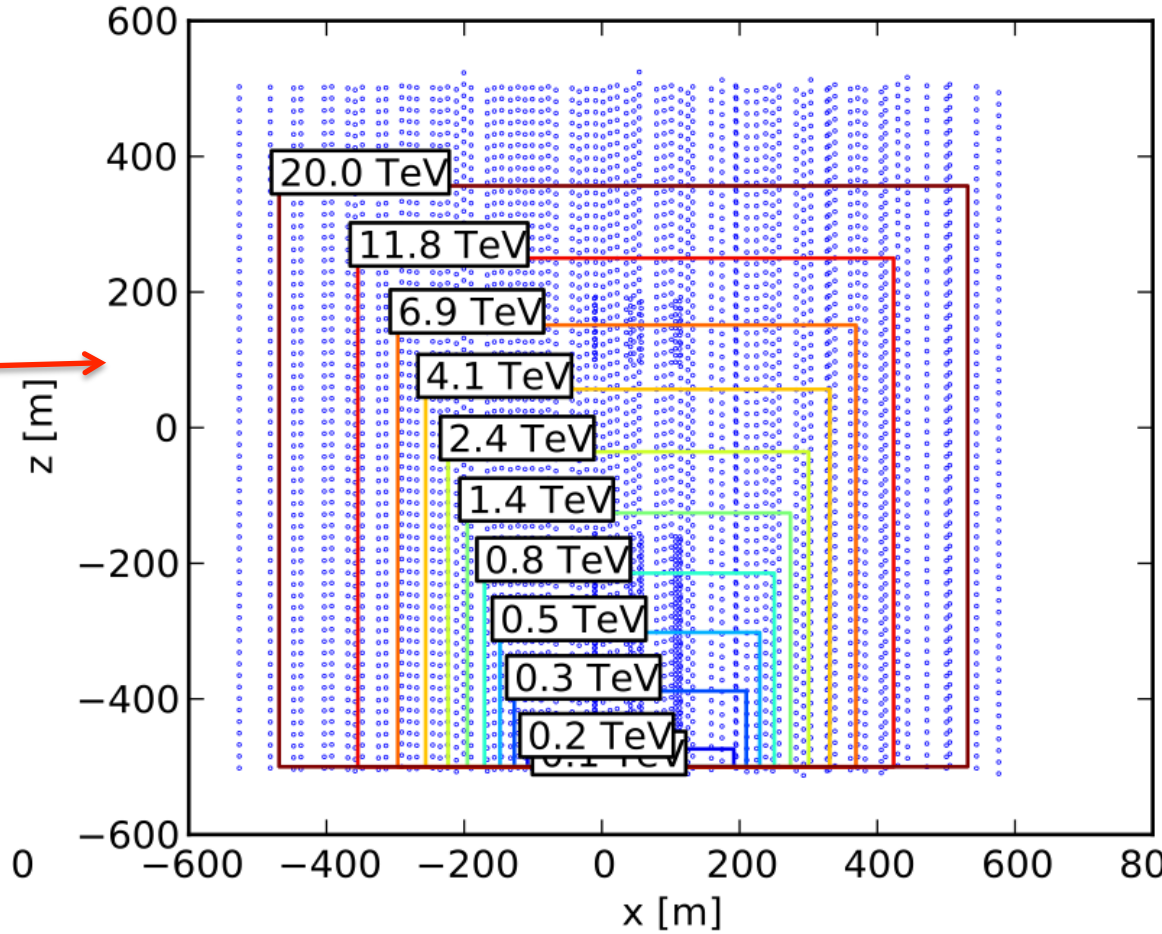


eliminary

Future of veto strategies for contained vertex analyses

- Veto application for contained vertex are becoming powerful at
  - high energies (>100 TeV)
  - Low energies 10 – 100 GeV (Deep Core)

  Goal: close gap!
- IceCube has significant zenith angle and energy space for complete (including atmospheric neutrino) background rejection
- Is it time to think about a serious veto extensions of IceTop (simple ice tanks, air Cherenkov detectors)?



Preliminary estimates for energy dependent contained cascade Searches based on veto techniques.

Tau neutrinos

Charged Current tau neutrino:

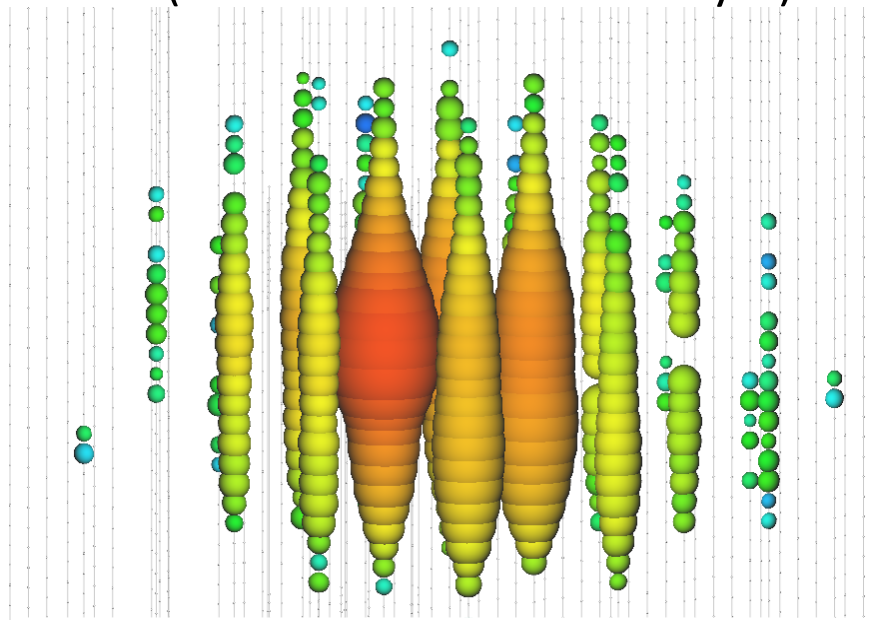
$$\nu_\tau + N \rightarrow \tau + X$$

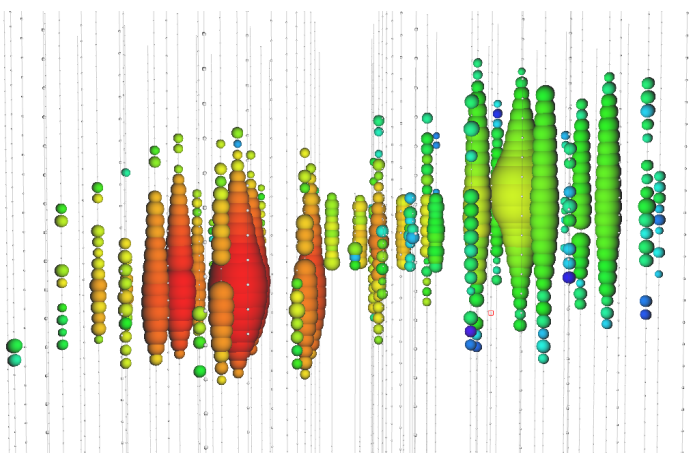
Double-bang signature from decaying tau, $l_\tau = \gamma c t_\tau \sim 50\,(E_\tau\,/\mathrm{PeV})\,\mathrm{m}$

Can identify double bang above ~ PeV

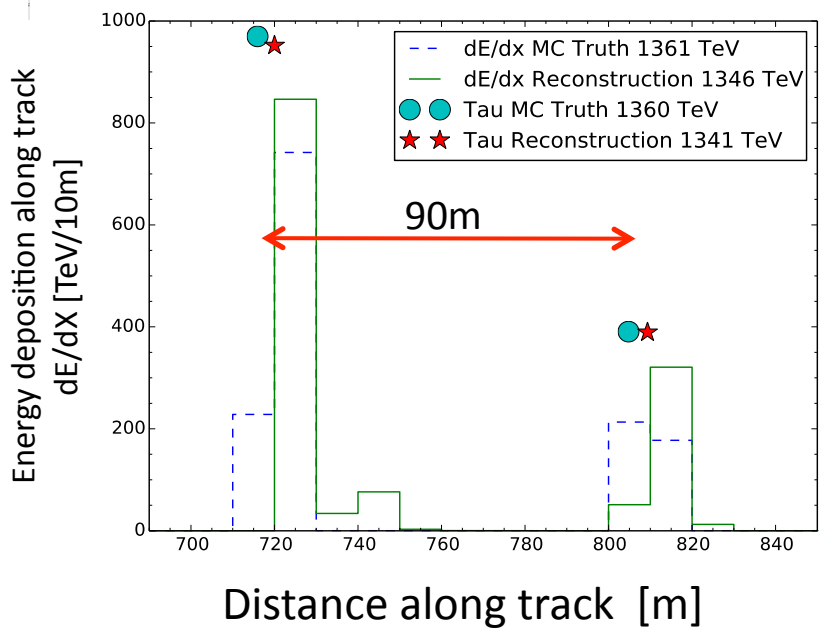
Lower energy id more limited possibilities.

Simulated event: 1.36 PeV
(no data event identified yet)

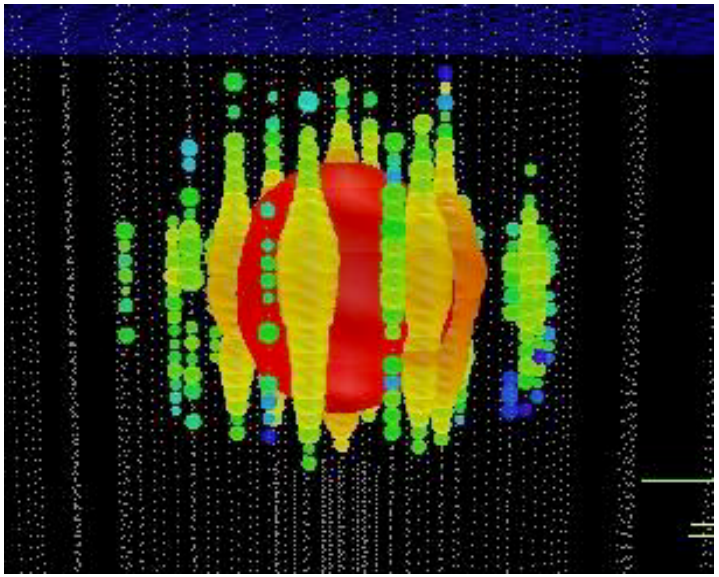




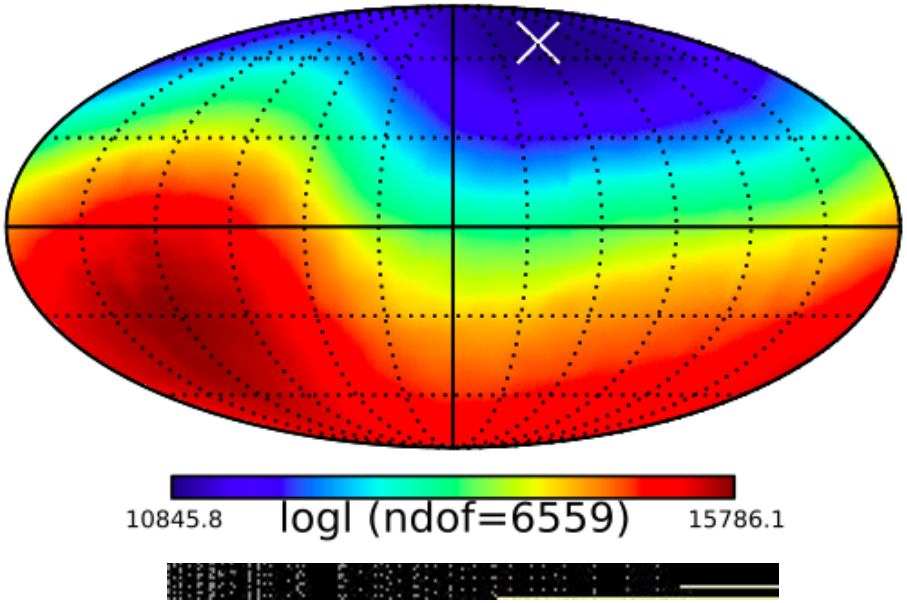
Event with longer decay length



Reconstruction of one PeV event



Directional reconstruction: blue is central region



Preliminary

Energy: 1.1 PeV +- 0.1

Zenith angle: 23° +- 10° +- non-gaussian tails + systematics

Independent method based on Markov chain approach,

event is resimulated 100s of times with full photon propagation

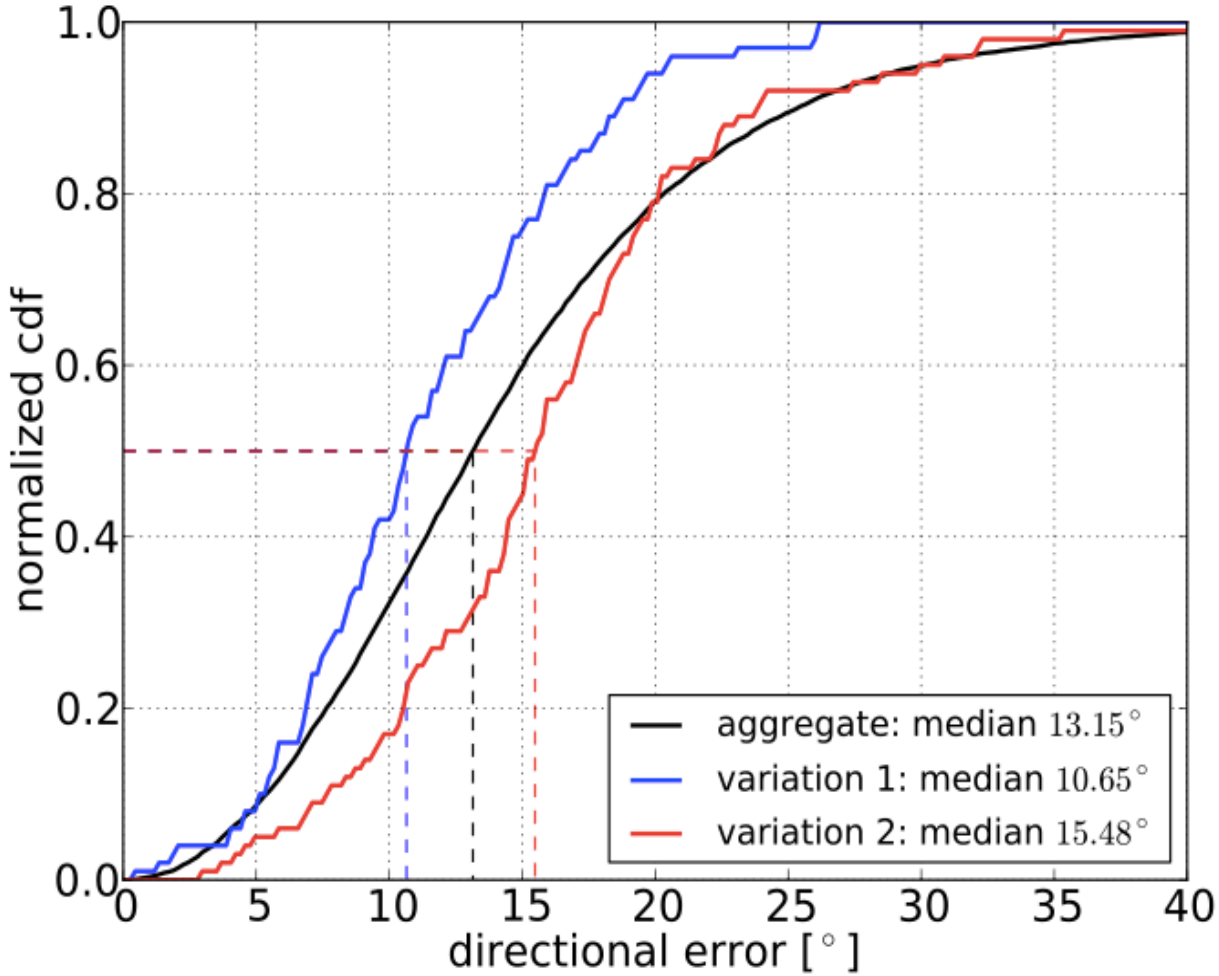
data are compared to simulation each time

Result within error bars both in energy and zenith angle.

Directional Resolution for Showers

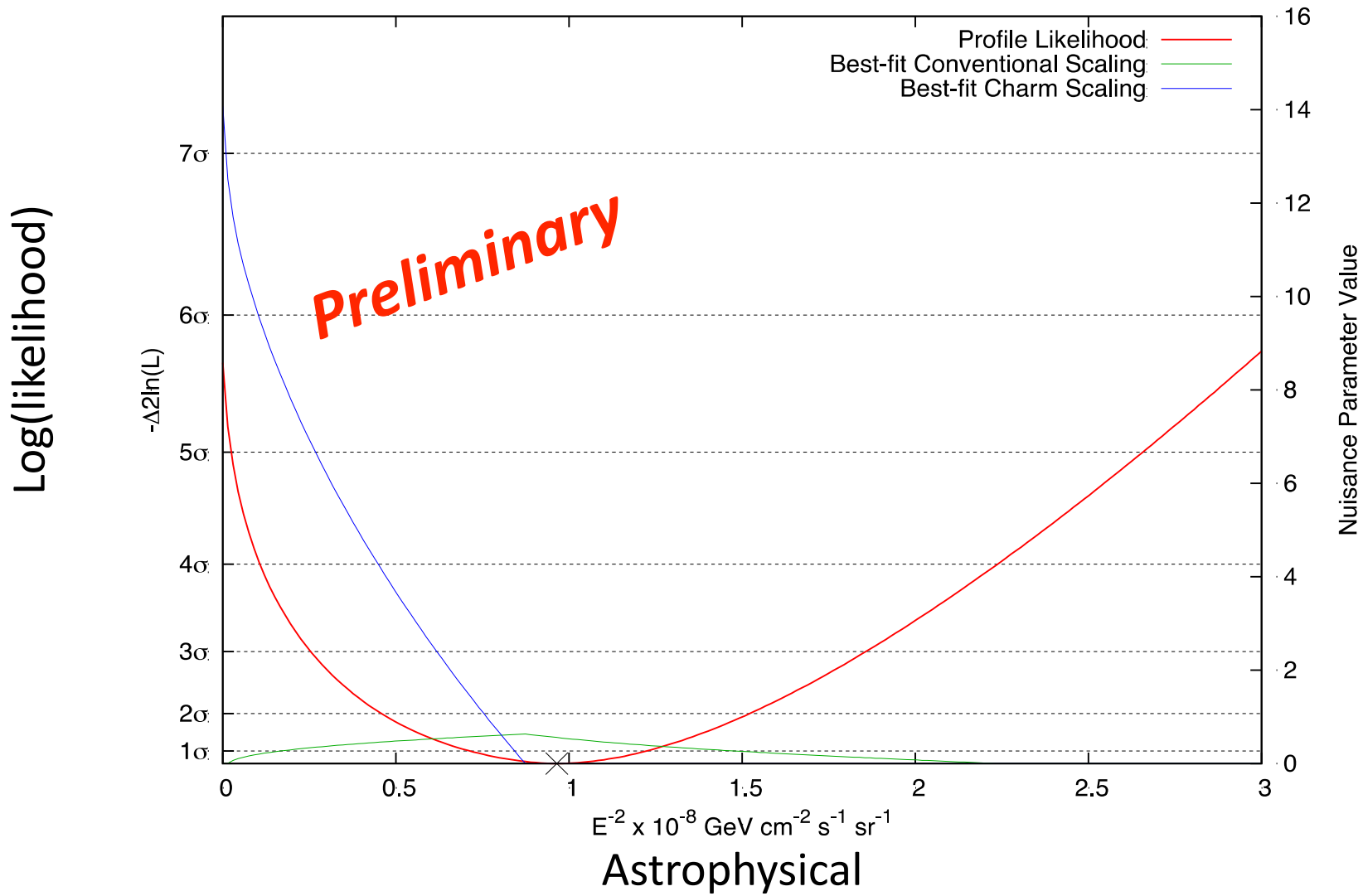
resolution for an individual example event from re-simulation

- Angular error distributions on the order of 10°-15° depending on the ice model assumption
  - two ice examples are shown
  - aggregate resolution in black



Best fit - charm background is nuisance parameter in fit

A zero astrophysical signal is disfavored in by more than 5 sigma,
Even if the normalization of the background from prompt atmospheric neutrinos is allowed to float freely.



Event reconstruction of cascade events

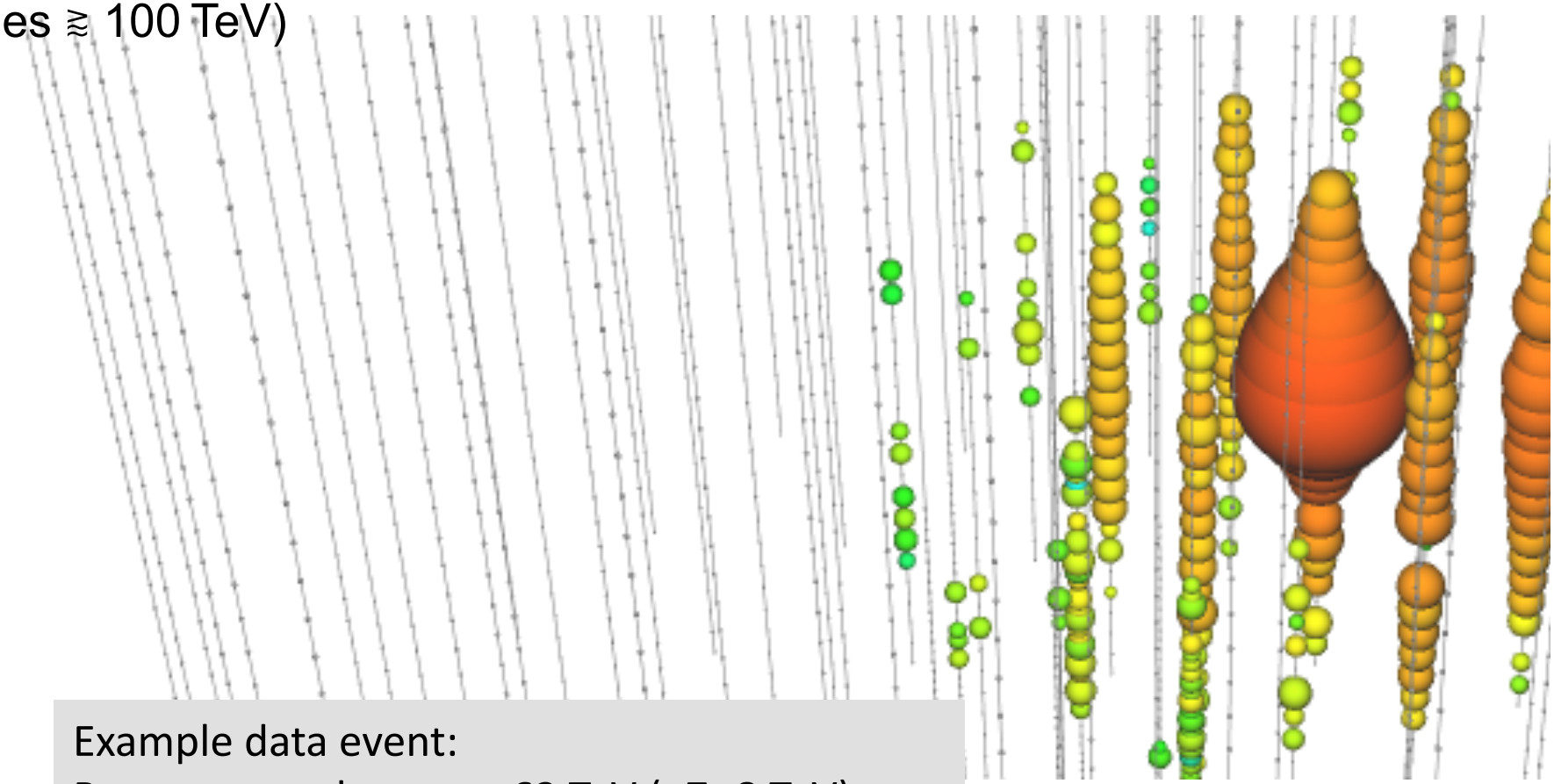
Resolution:

≈ ±15% deposited energy
(incl. all sys. errors)
≈ 10° angular resolution
(at energies ≳ 100 TeV)

Charged Current: $\nu_e + N \rightarrow e + X$

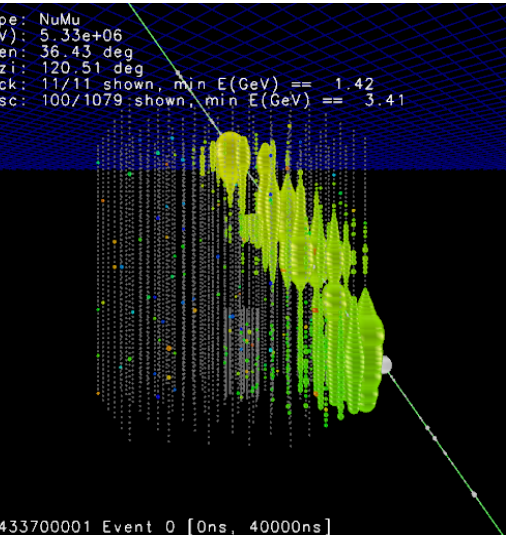
$\nu_\tau + N \rightarrow \tau + X$ *(Energy <~few PeV)*

Neutral Current: $\nu_x + N \rightarrow \nu_x + X$



Example data event:
Reconstructed energy: 63 TeV (+7,-8 TeV)
Zenith angle: ~54°

Improving event reconstruction, energy resolution



Simulated Muon of 5 PeV energy

Improved tools allow to resolve stochastic energy losses along the km long tracks

Muon energy resolution:
rms of log(E): ~0.3 - 0.25 for E>100 TeV

Limited by fluctuations in energy deposition.