



Results from IceCube

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for the IceCube Collaboration
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Berkeley
UNIVERSITY OF CALIFORNIA



The IceCube Collaboration & PINGU



International Funding Agencies

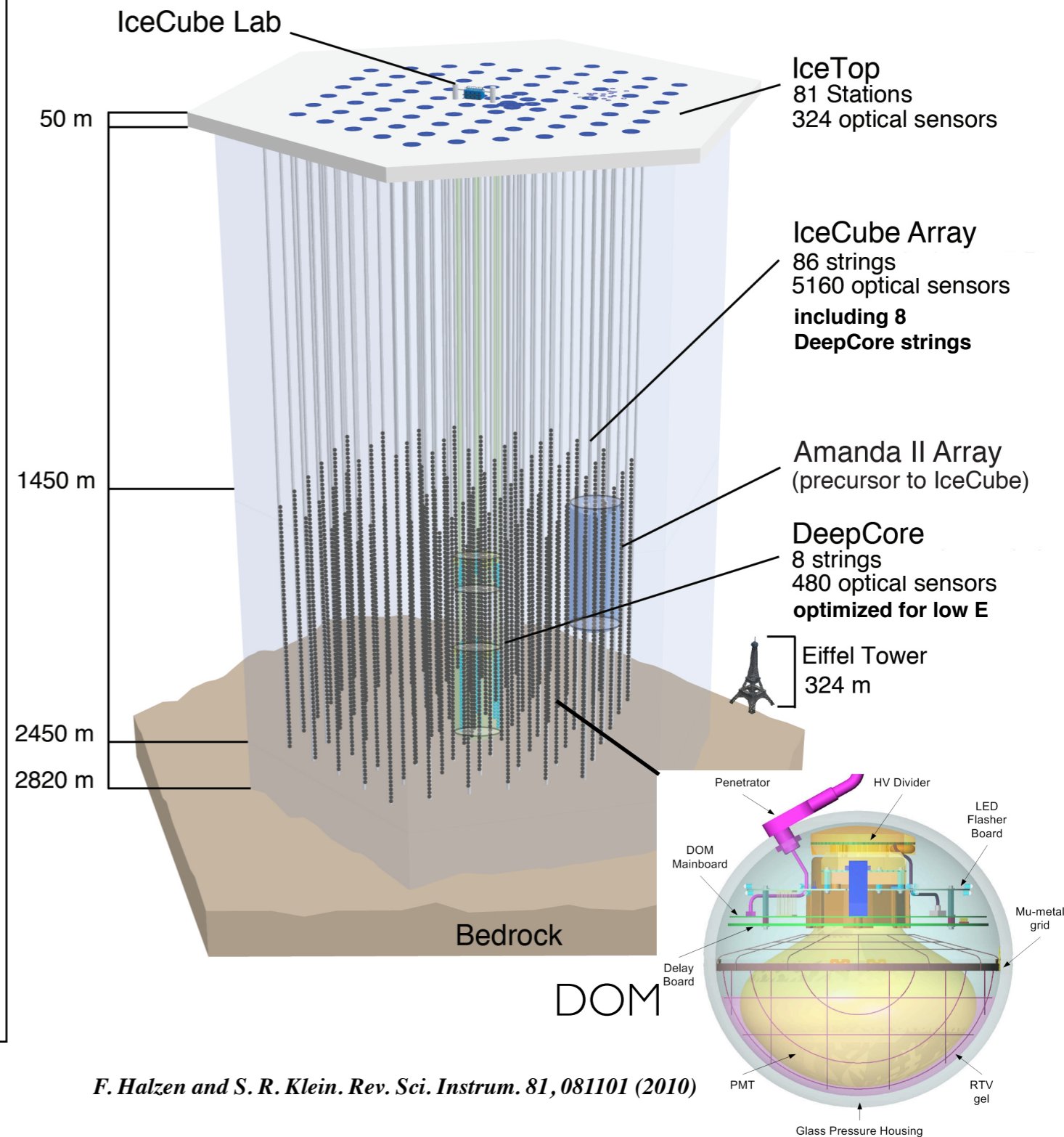
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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German Research Foundation (DFG)

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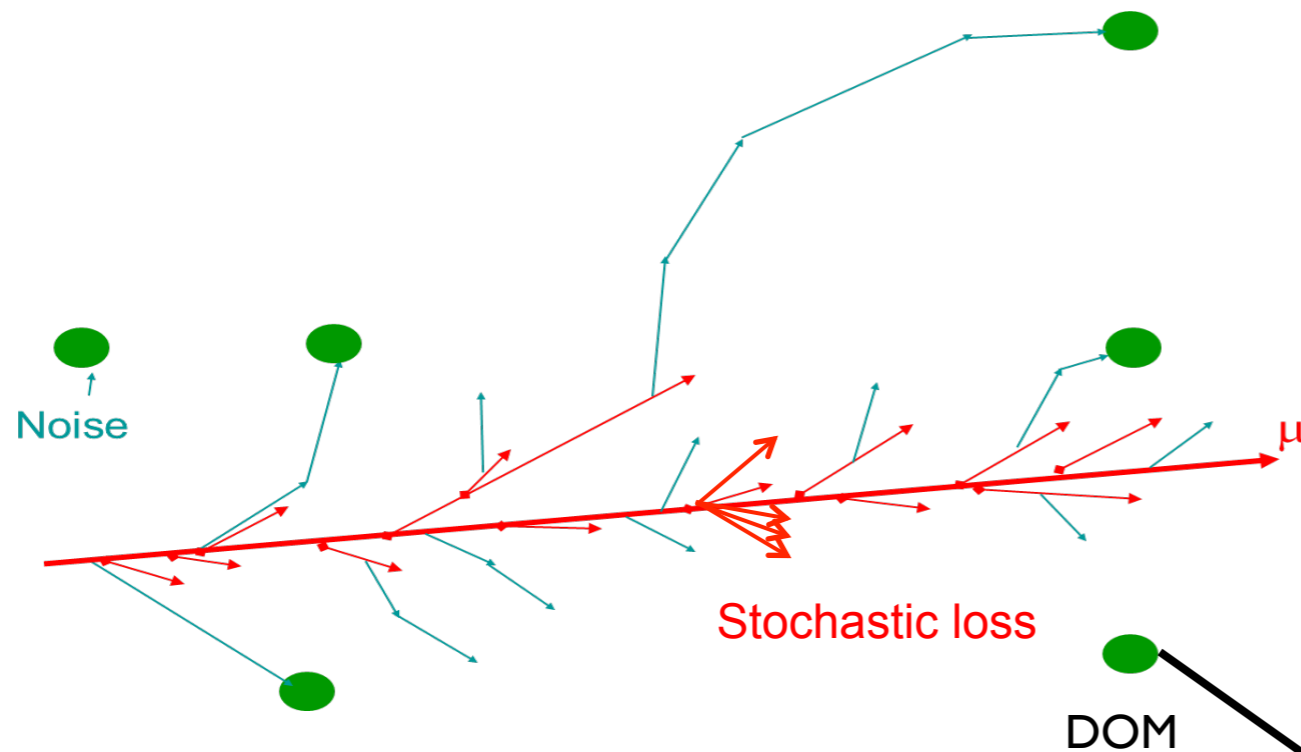
IceCube : 1 km³ Neutrino Telescope

- Detects Cherenkov photons in ice from charged particles created by high-E neutrino interactions
- 5160 Digital Optical Modules (DOMs) with a 10 inch PMT on 86 vertical strings
- IceTop air shower array
- 162 Tanks each with 2 DOMs
- Low-E ($E_{\text{threshold}} \sim 10 \text{ GeV}$) DeepCore array
- 8 strings include high quantum efficiency DOMs

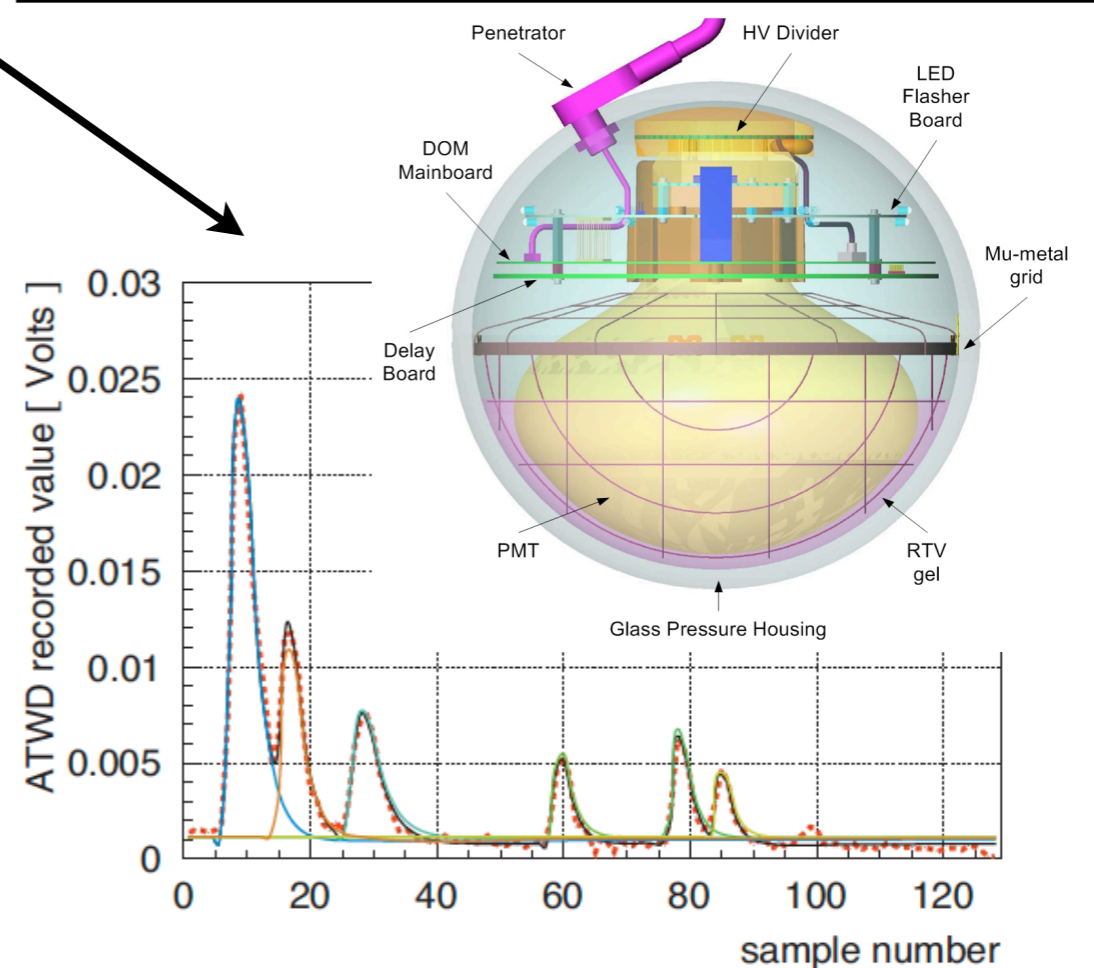
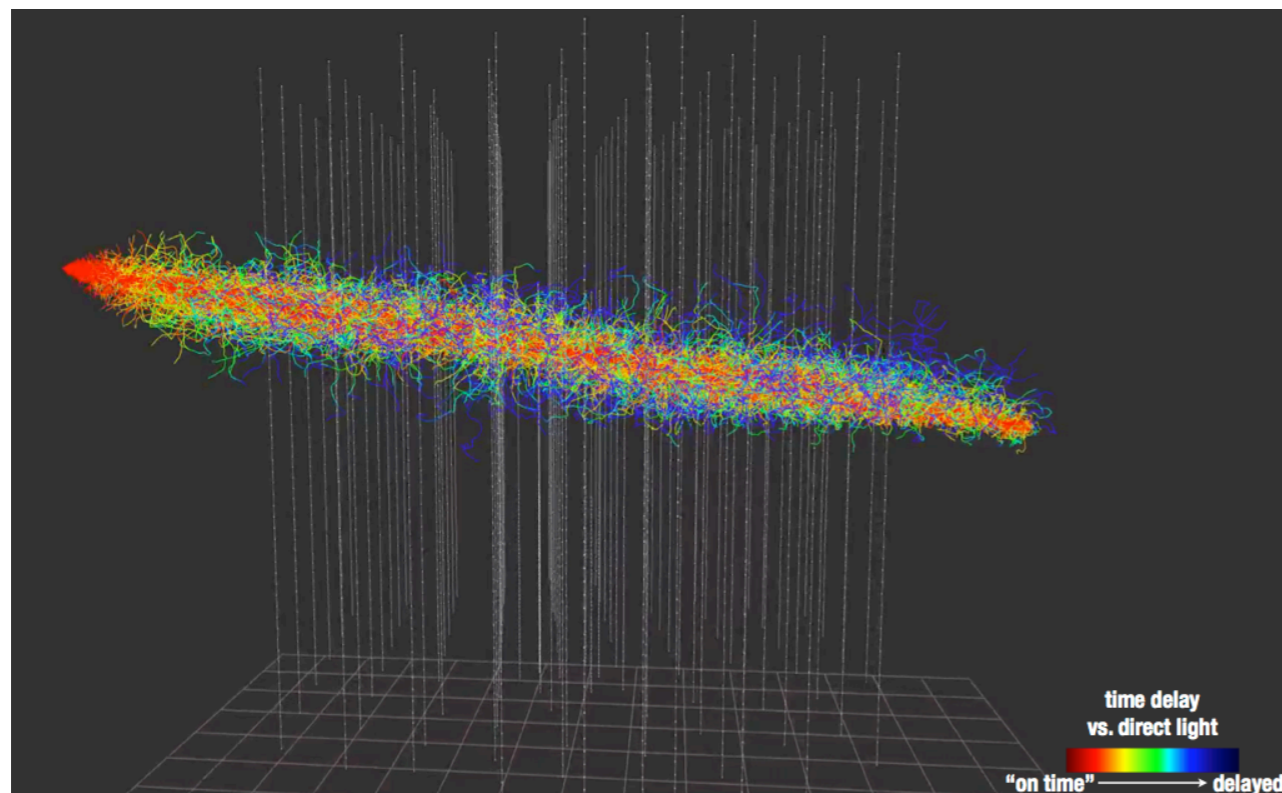


F. Halzen and S. R. Klein. Rev. Sci. Instrum. 81, 081101 (2010)

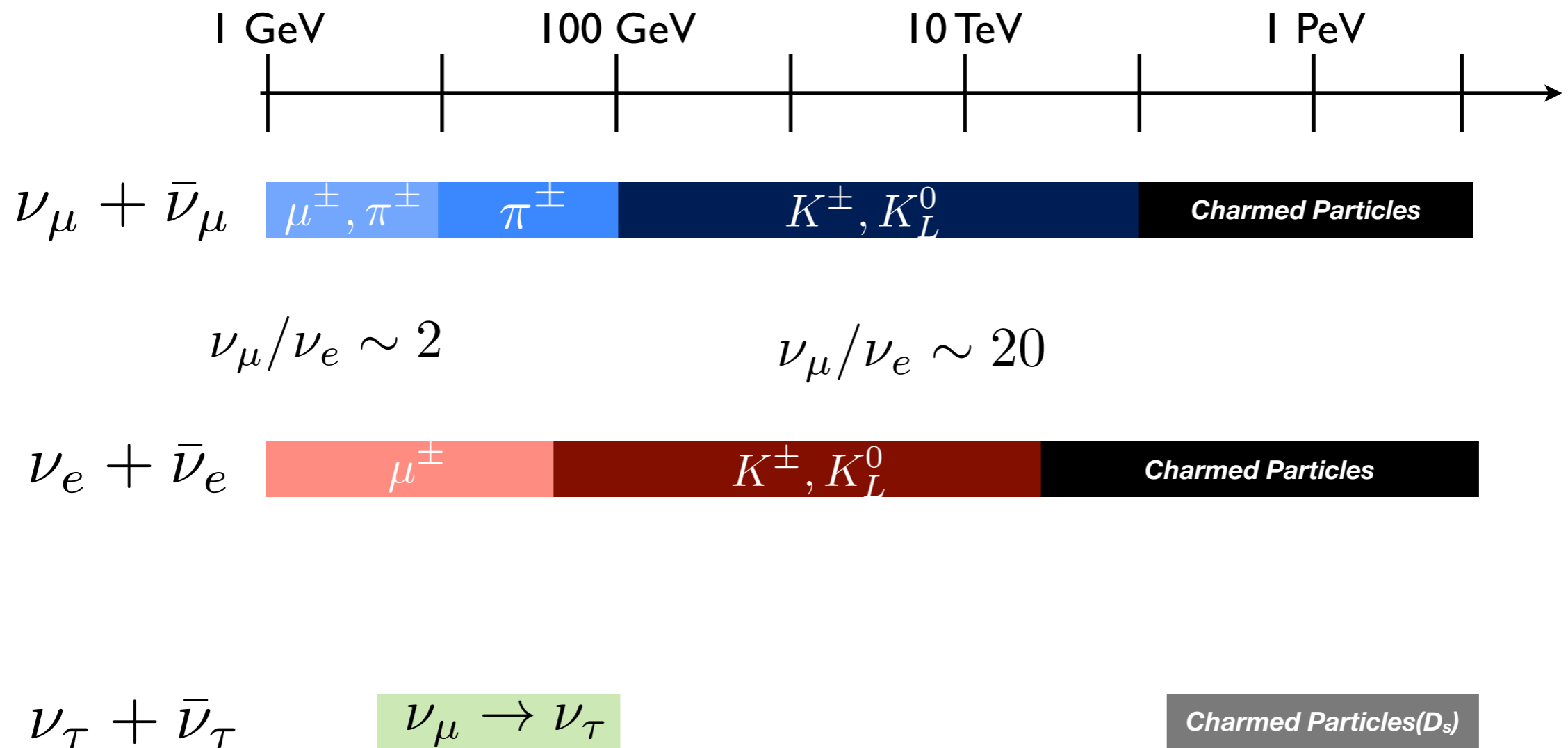
Waveforms from charged particles in ice



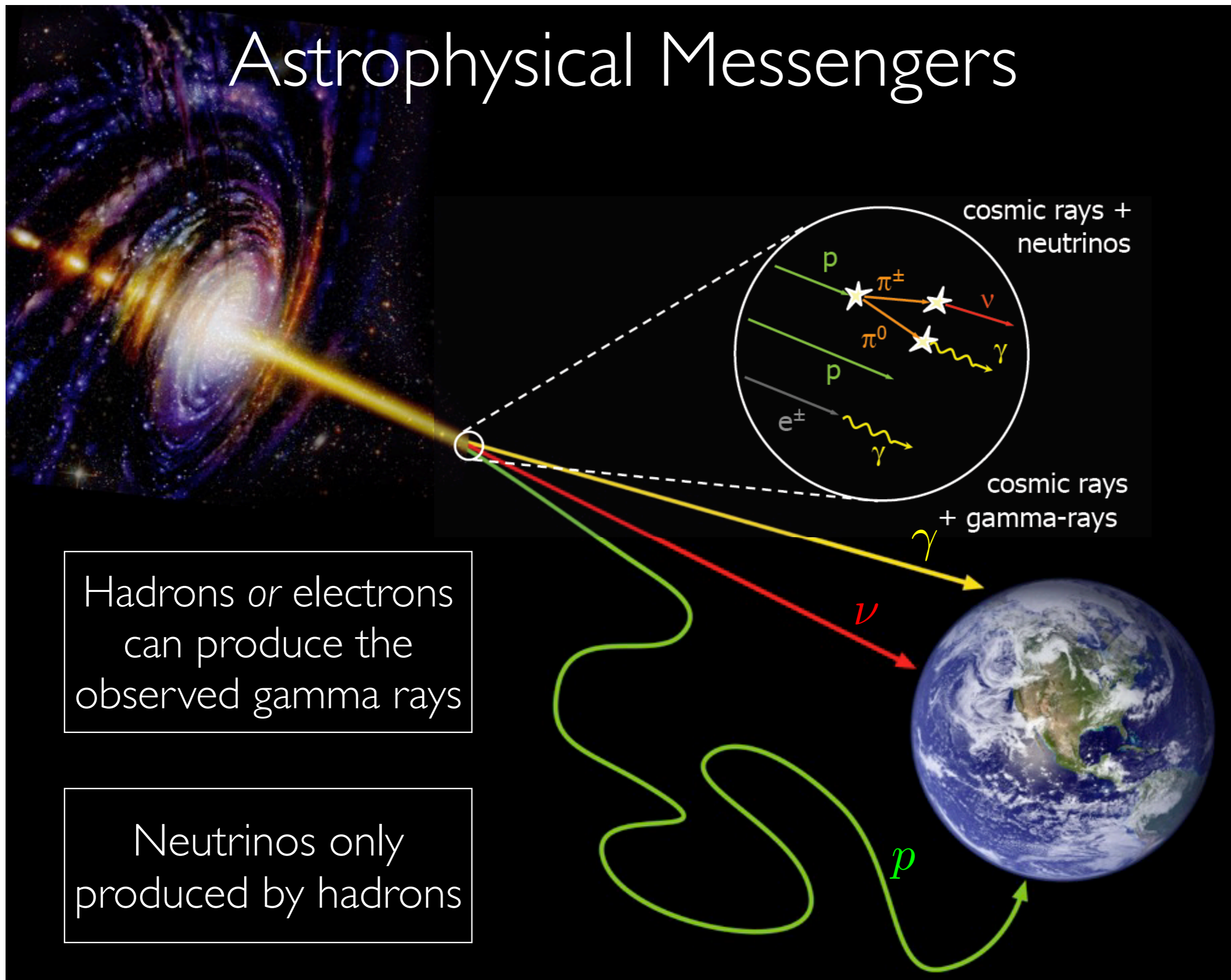
- Charged particles produce radiation from ionizations and stochastics in ice
- DOMs digitize the PMT waveforms of photoelectrons
- Arrival time and recorded charge information used to reconstruct events



Sources of Atmospheric Neutrinos



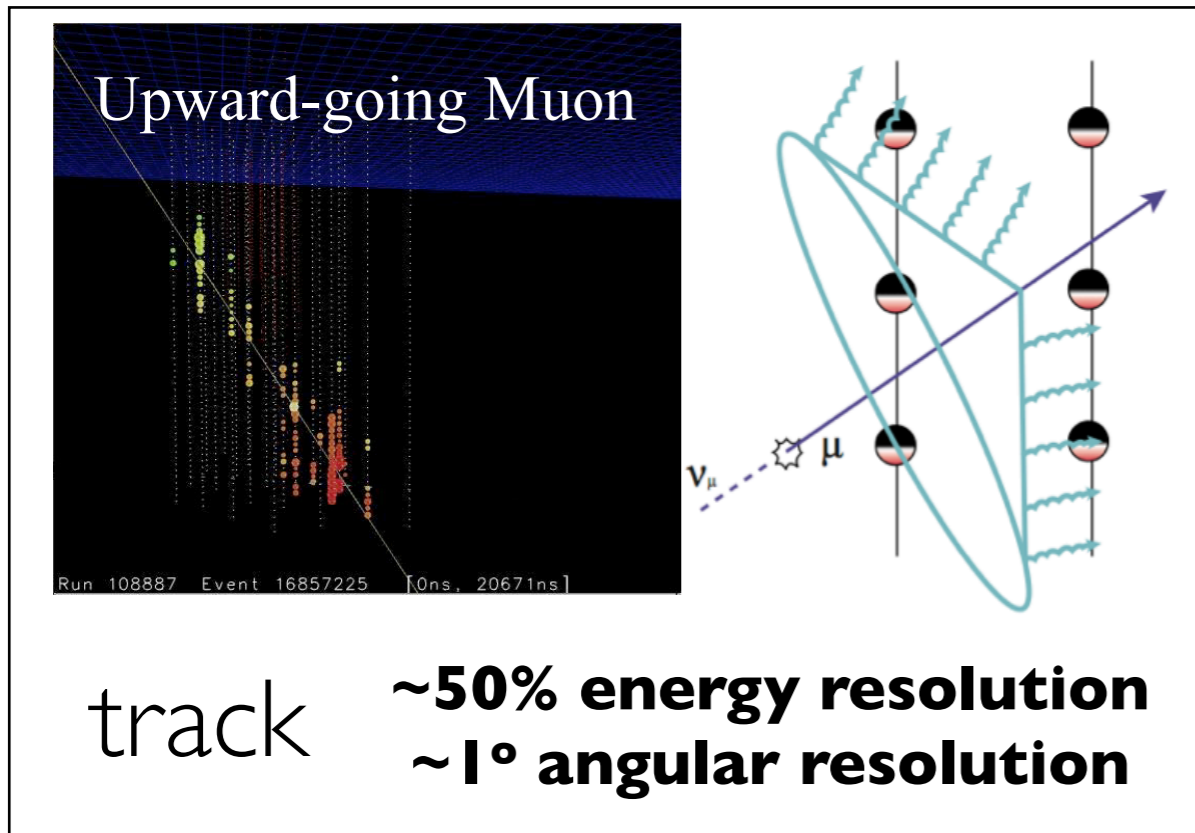
Astrophysical Messengers



Hadrons or electrons can produce the observed gamma rays

Neutrinos only produced by hadrons

Detection Methods : Cherenkov Radiation

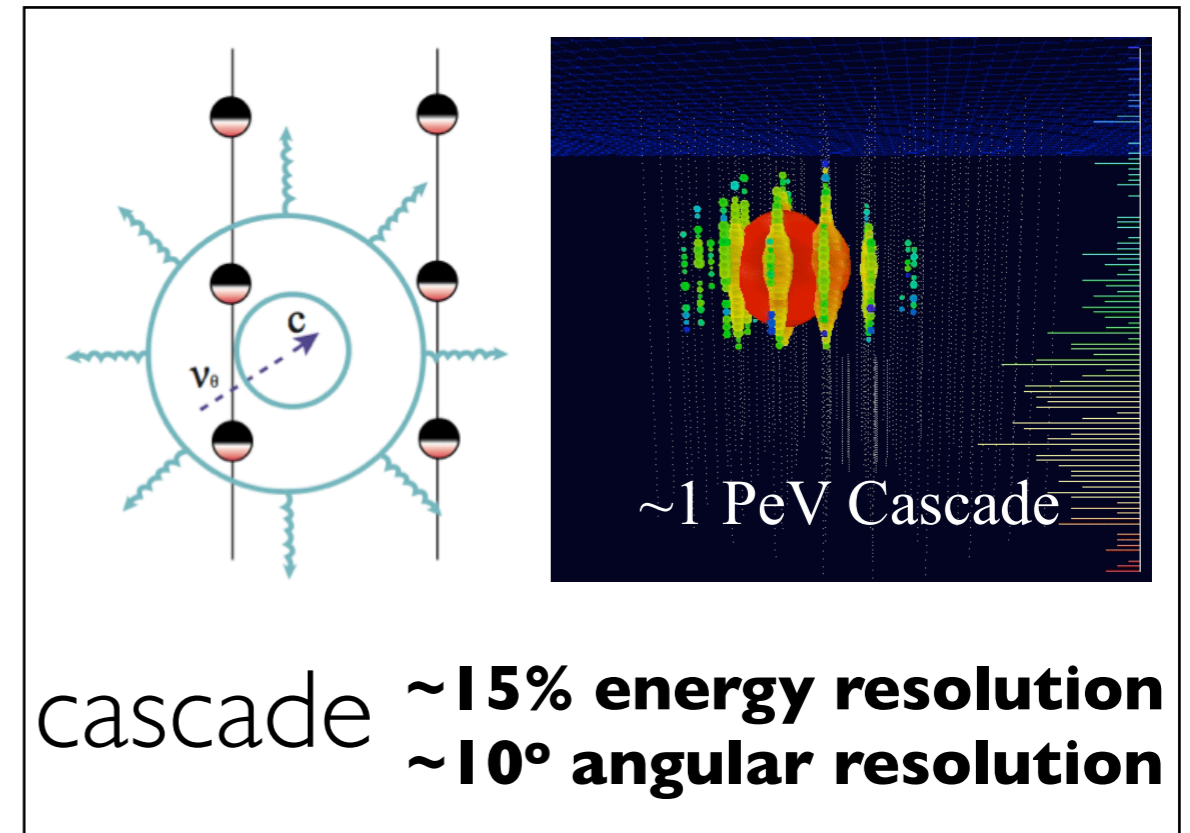


Upward-going Muon

Run 108887 Event 16857225 [0ns, 20671ns]

track **~50% energy resolution**
~1° angular resolution

The diagram shows a muon (μ) moving upwards through a medium, indicated by a dashed arrow labeled ν_μ . It produces a track of Cherenkov radiation, represented by a blue cone of light. The track is shown as a series of black and white spheres connected by a line, with wavy lines representing the radiation.



~1 PeV Cascade

cascade **~15% energy resolution**
~10° angular resolution

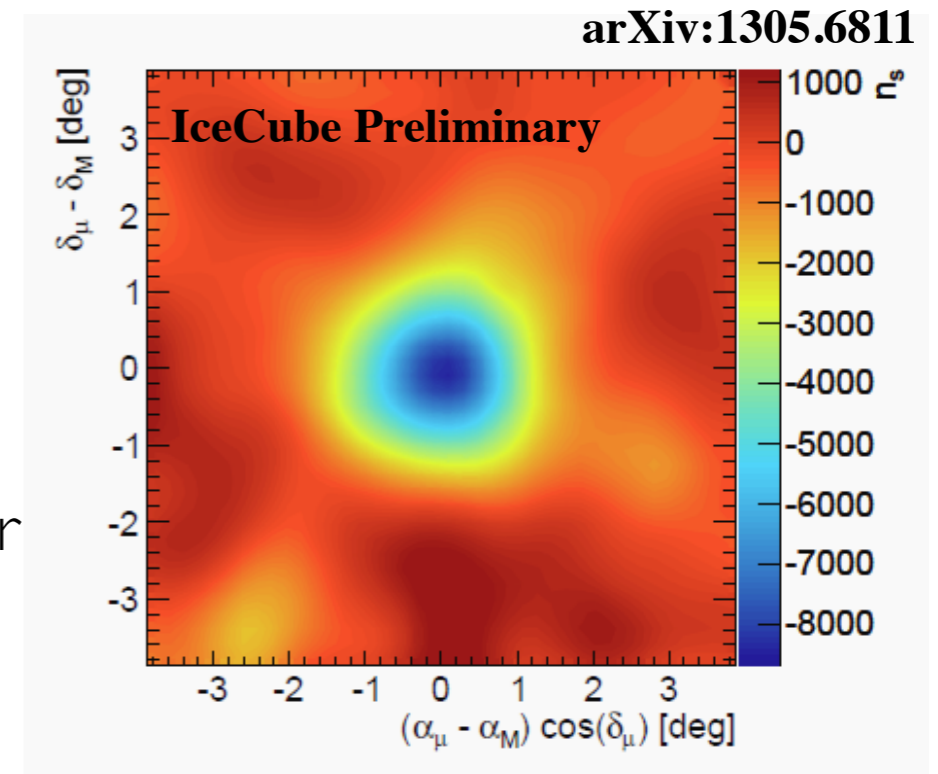
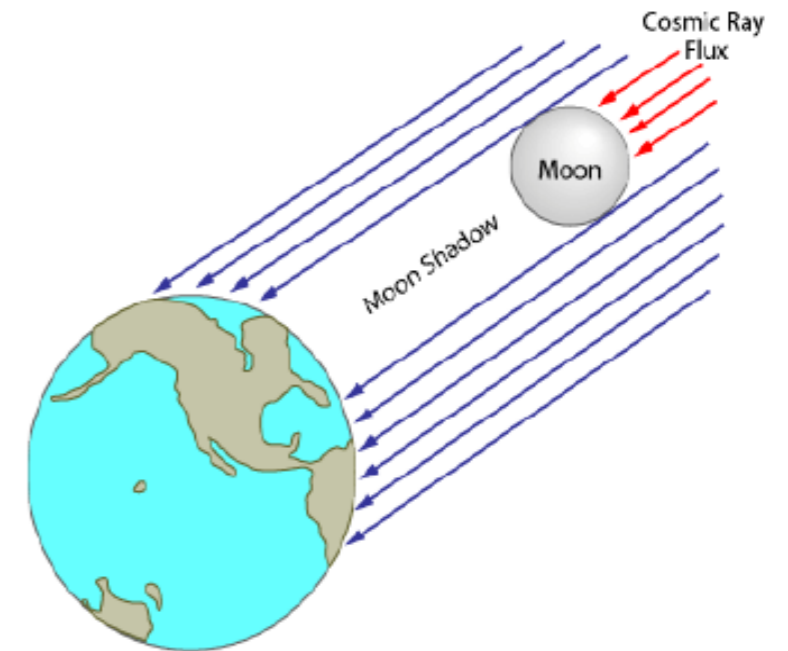
The diagram shows a cascade of particles, represented by a large blue circle with a smaller inner circle labeled 'c'. A dashed arrow labeled ν_θ points towards the center. The cascade is shown as a series of black and white spheres connected by a line, with wavy lines representing the radiation. To the right, a visualization of a cascade shows a central red and yellow core surrounded by a blue and green outer shell, with a histogram-like structure on the right side.

symbols	process	signature	note
ν_μ^{CC}	$\nu_\mu + N \rightarrow \mu + X$	track	cascade+track if contained
ν_e^{CC}	$\nu_e + N \rightarrow e + X$	cascade	
ν_τ^{CC}	$\nu_\tau + N \rightarrow \tau + X$	cascade	E.M. shower + Hadronic shower tau travels ~50 m at 1 PeV
ν_α^{NC}	$\nu_\alpha + N \rightarrow \nu_\alpha + X$	cascade	$\alpha = \mu, e, \tau$

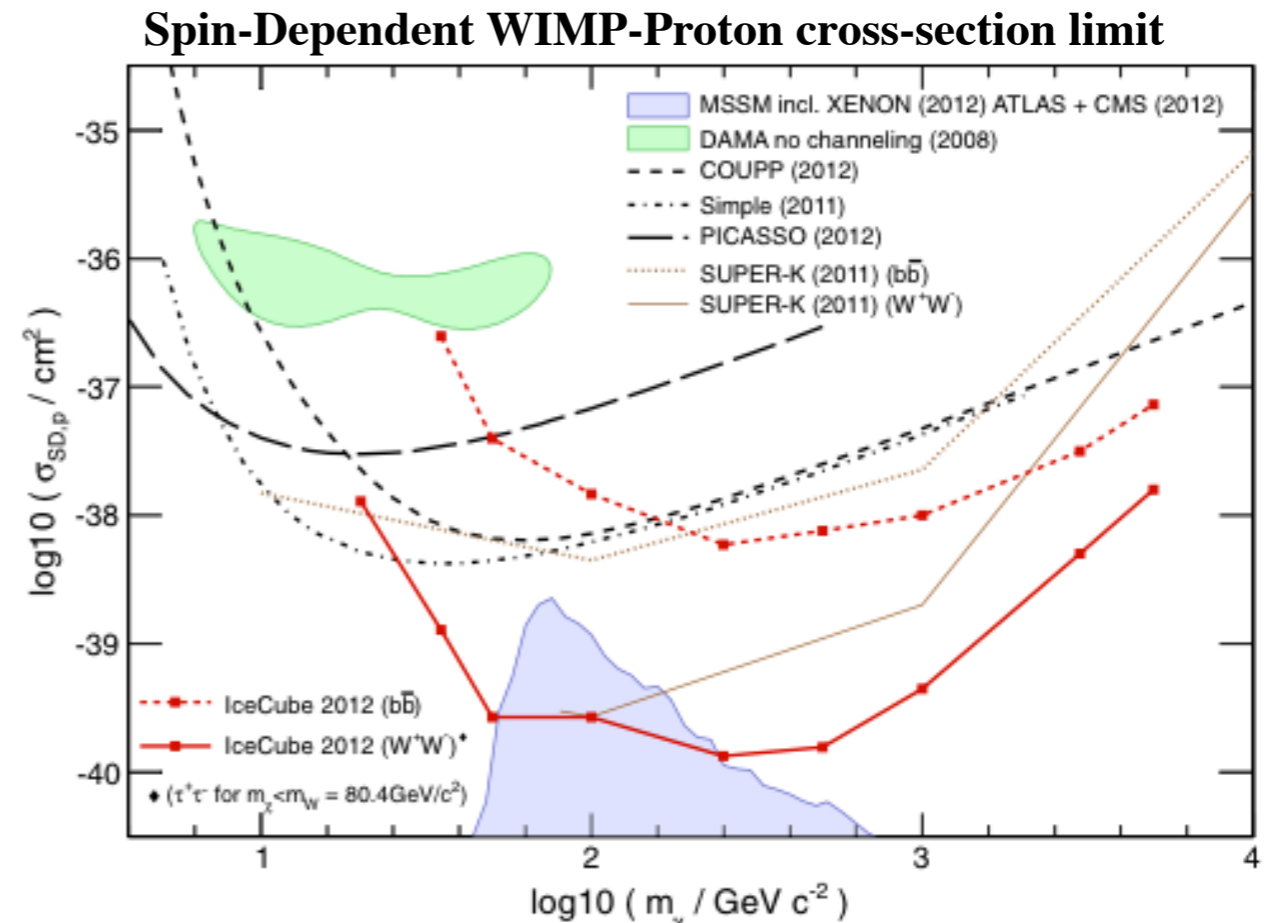
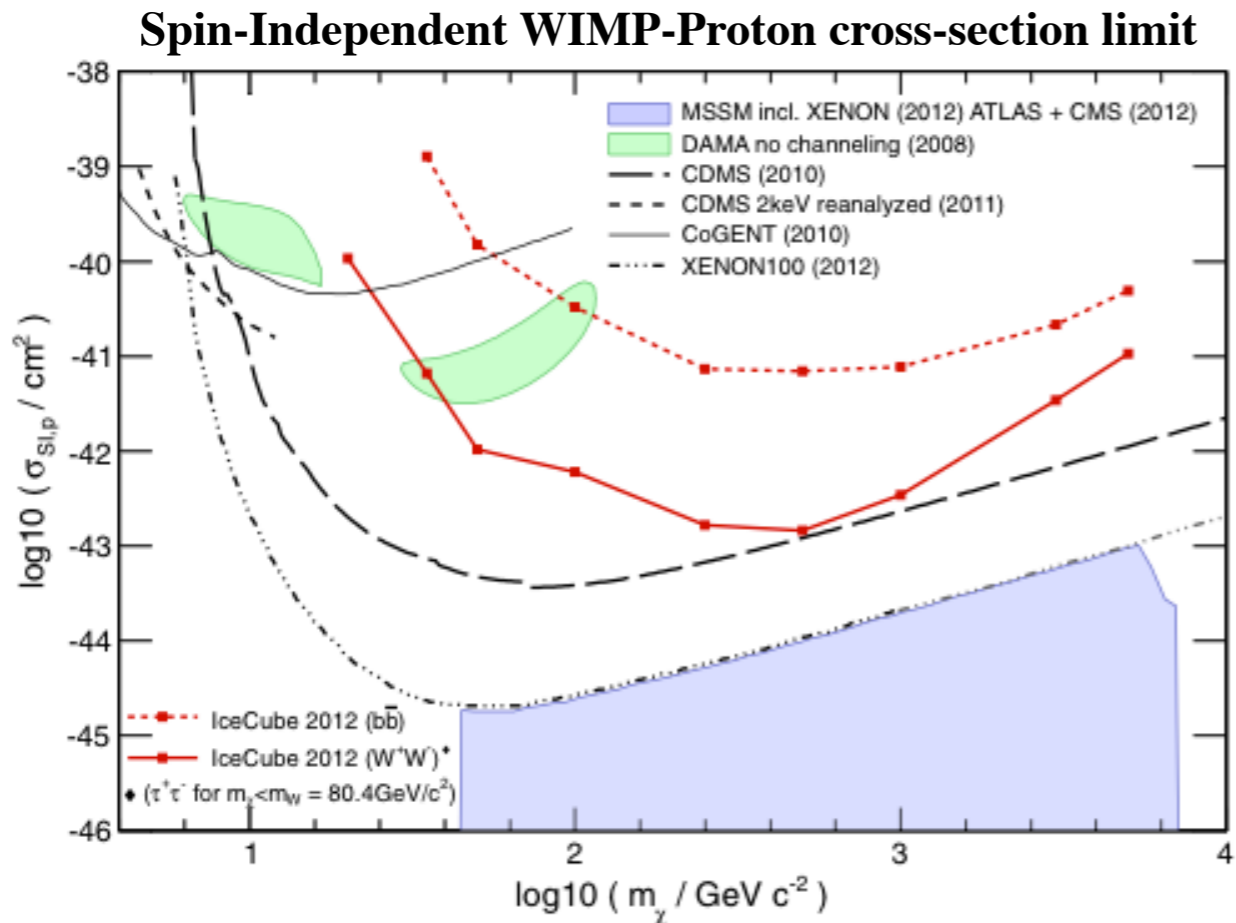
N= Target Nucleon and X = Hadronic Shower

IceCube Detector Performance

- The full detector (86 strings) has been running for 2 years (Currently taking the third year data)
- IceCube built on time, on budget, and exceeds design requirements
 - 5160 Sensors are deployed, only 1.5% not taking data
 - Only two sensors failed since 2012
 - 99% up-time
- Cosmic ray muon Moon shadow verifies $\sim 1^\circ$ pointing resolution
- Refining ice model is an ongoing calibration effort (arXiv:1301.5361, NIM.A711 (2013) 73)
- High-E sample $\sim 7 \times 10^4 \nu_\mu$ per year (1.3 event per 10 min) at final analysis level.
- Low-E sample (DeepCore) $\sim 10^4 \nu_\mu$ per year at final



Indirect search for the Dark Matter from the Sun

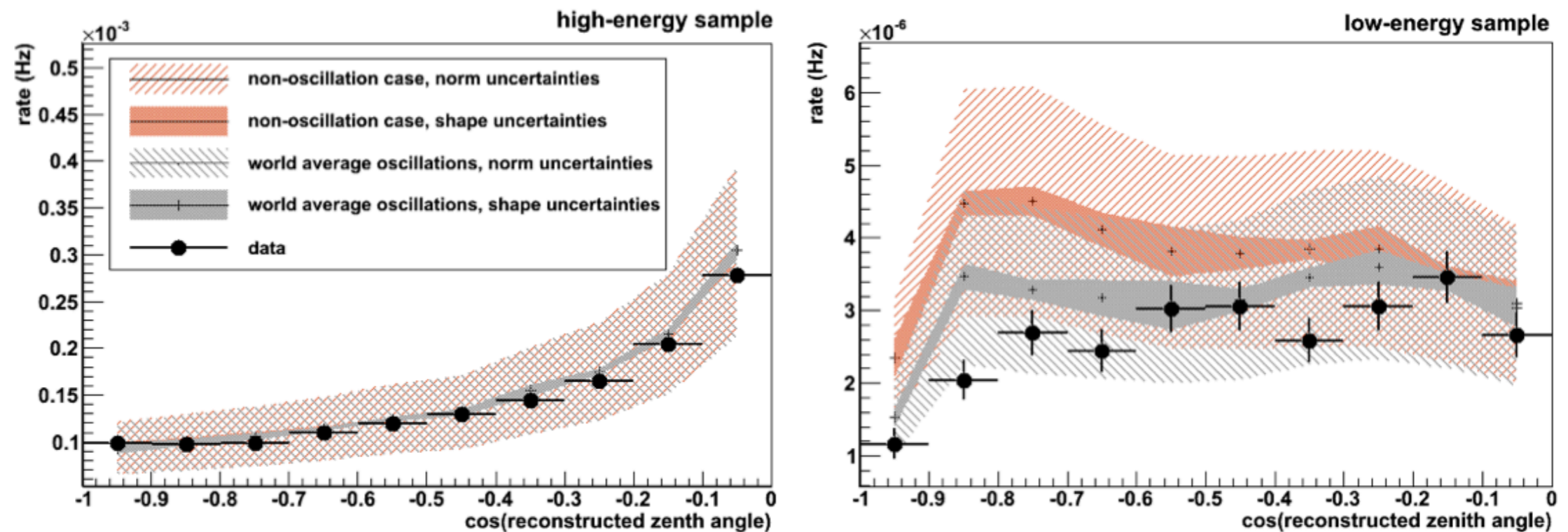


Phys. Rev. Lett. 110, 131302 (2013)

- Dark Matter trapped in the sun gravitationally.
- Reaches equilibrium, annihilating to produce neutrinos.
- Capture rate (\sim annihilation rate) is sensitive to scattering cross-section.
- Most stringent Spin-Dependent WIMP-Proton cross-section limit
- Complementary to direct searches

Neutrino Oscillations : ν_μ Disappearance

-First Analysis : Zenith Angle Only



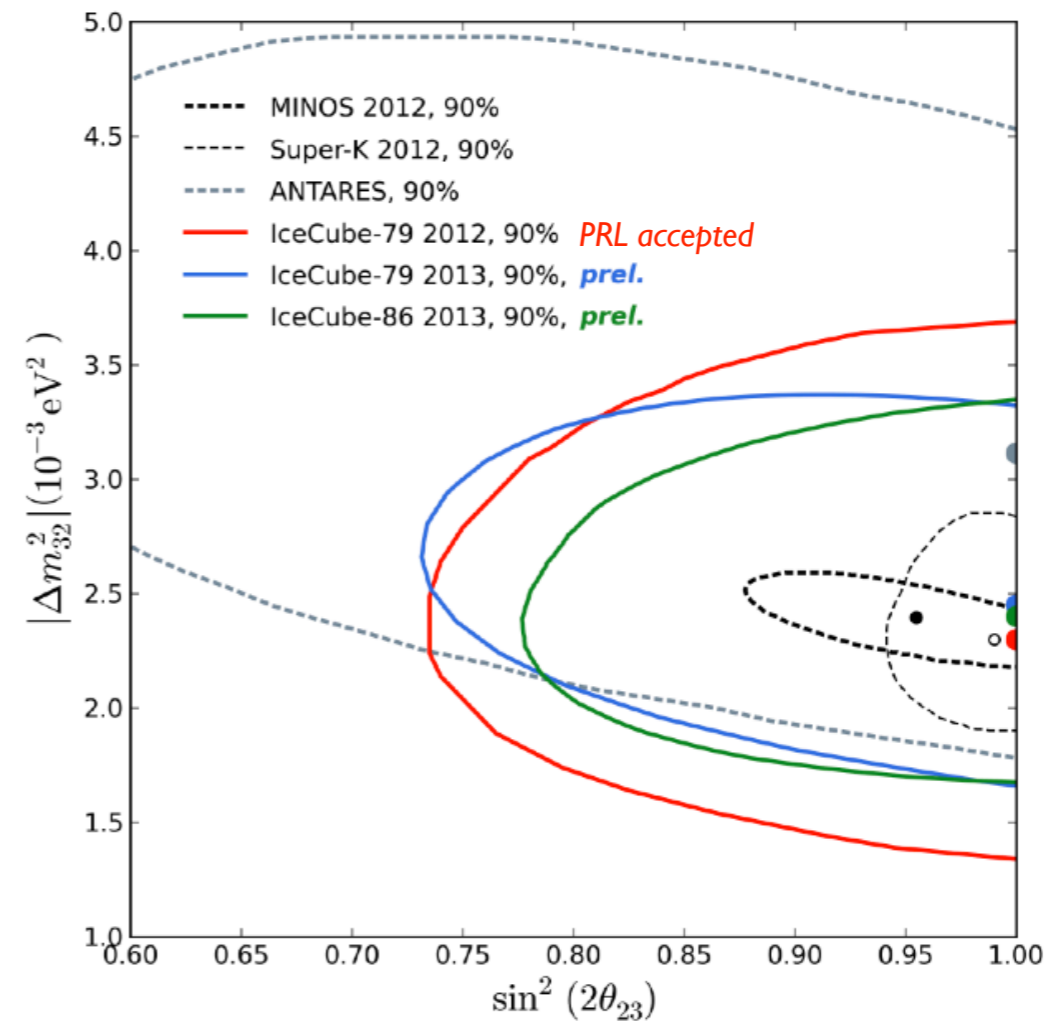
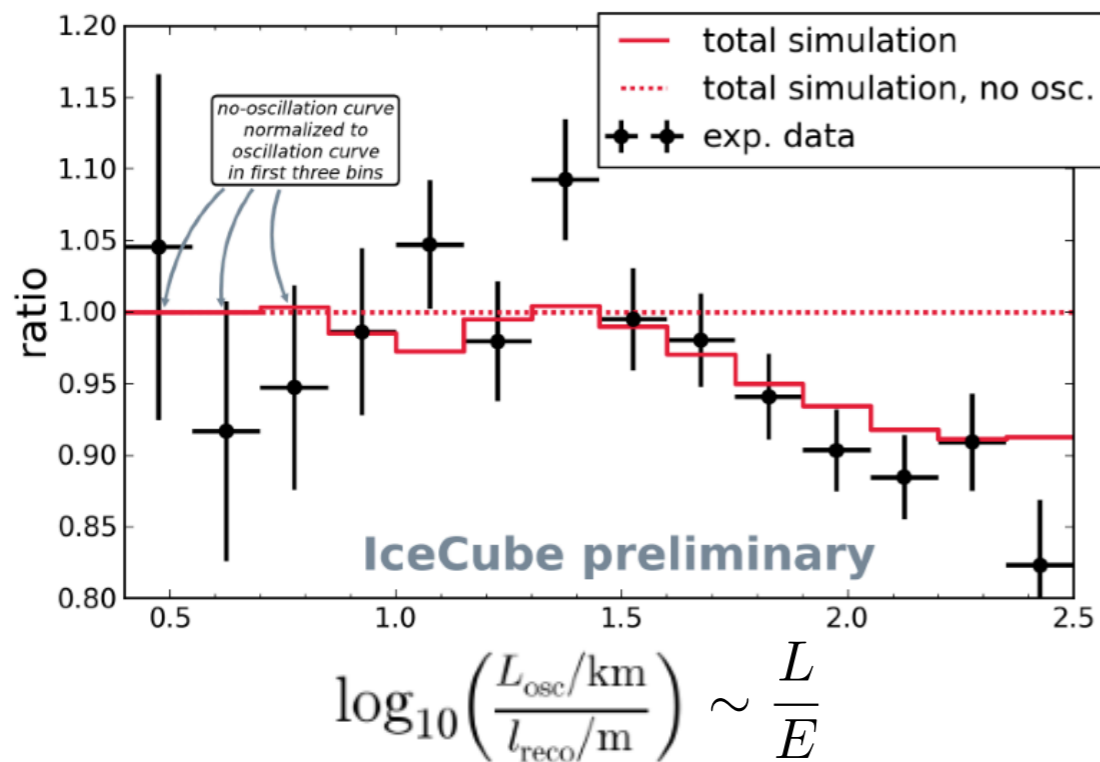
PRL accepted, arXiv:1305.3909

Significant zenith angle deviation in Low-energy sample
(Systematic uncertainties included)

Neutrino Oscillations : ν_μ Disappearance

-Next Analyses : Zenith Angle and Energy

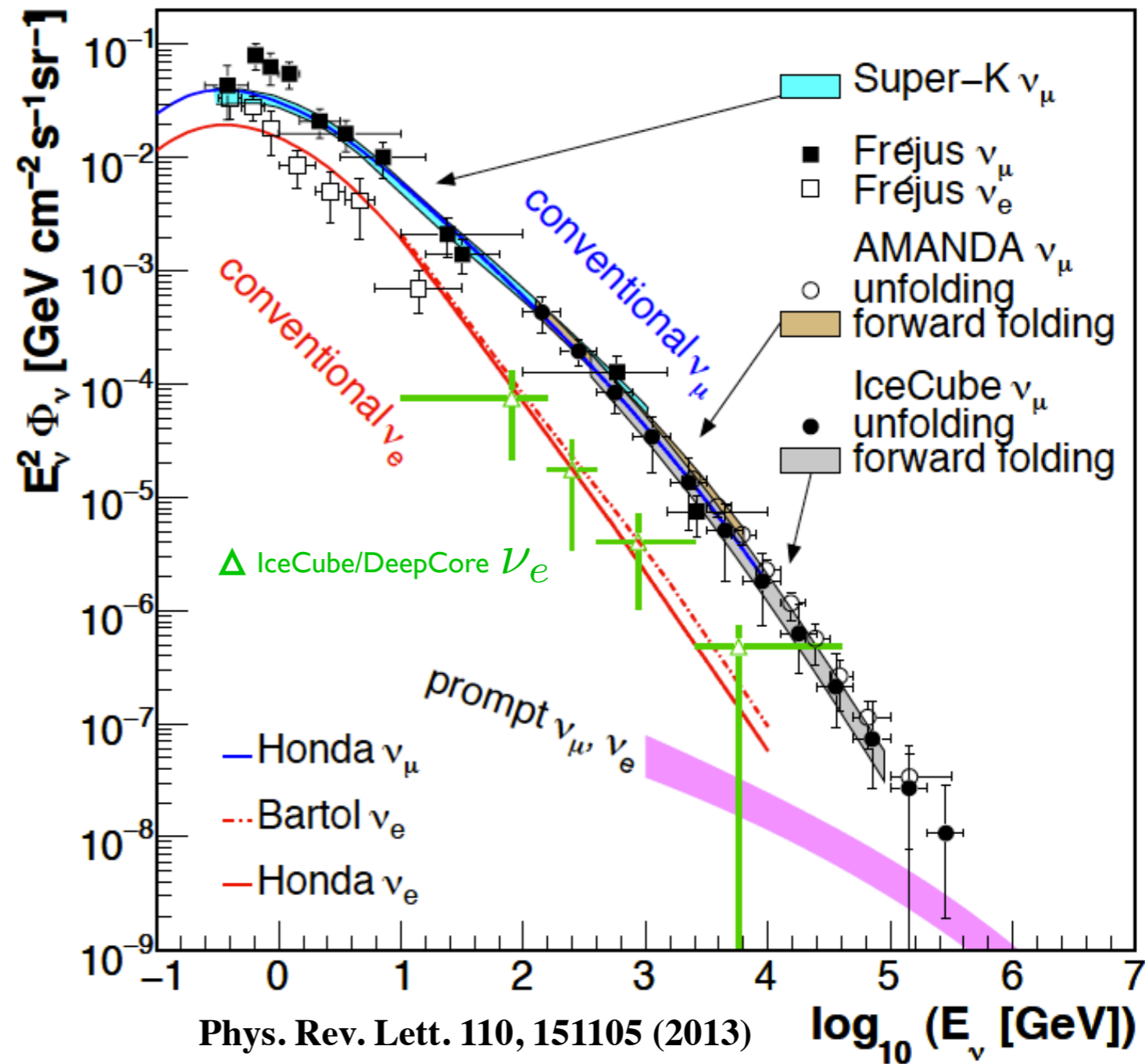
$$Ratio = \frac{N_{event}}{N_{event, no-oscillations}}$$



- Improved statistics $\times 10$
- Reduced systematic uncertainties
- Lower energy threshold
- Global 2-dim Likelihood Fit of Zenith & Energy

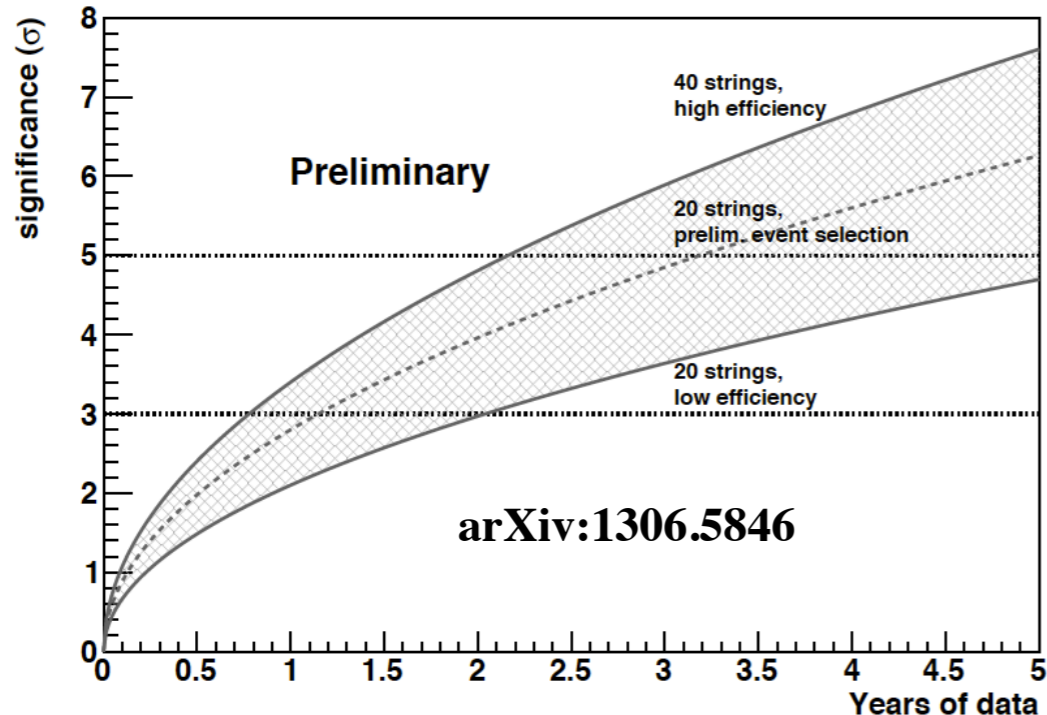
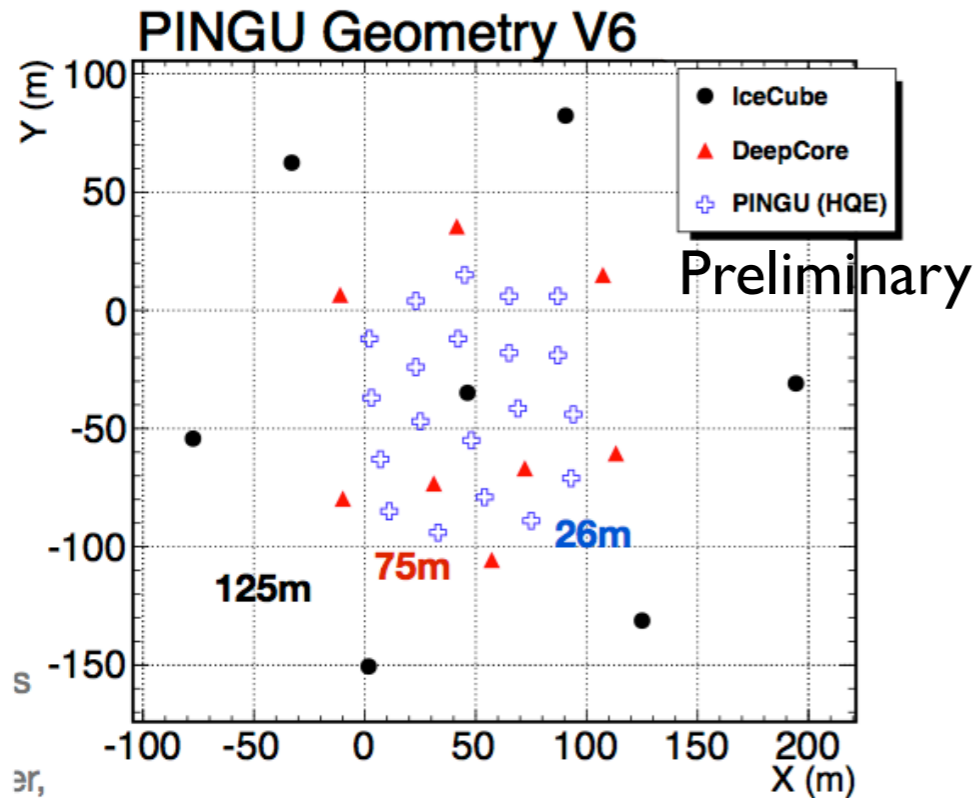
Atmospheric ν_e Flux Measurement

- Subtracted backgrounds statistically (atm. ν_μ & atm. μ)
- First measurement in the energy range 80 GeV - 6 TeV
- Agreement with the models of atmospheric neutrinos.



Future Direction : PINGU

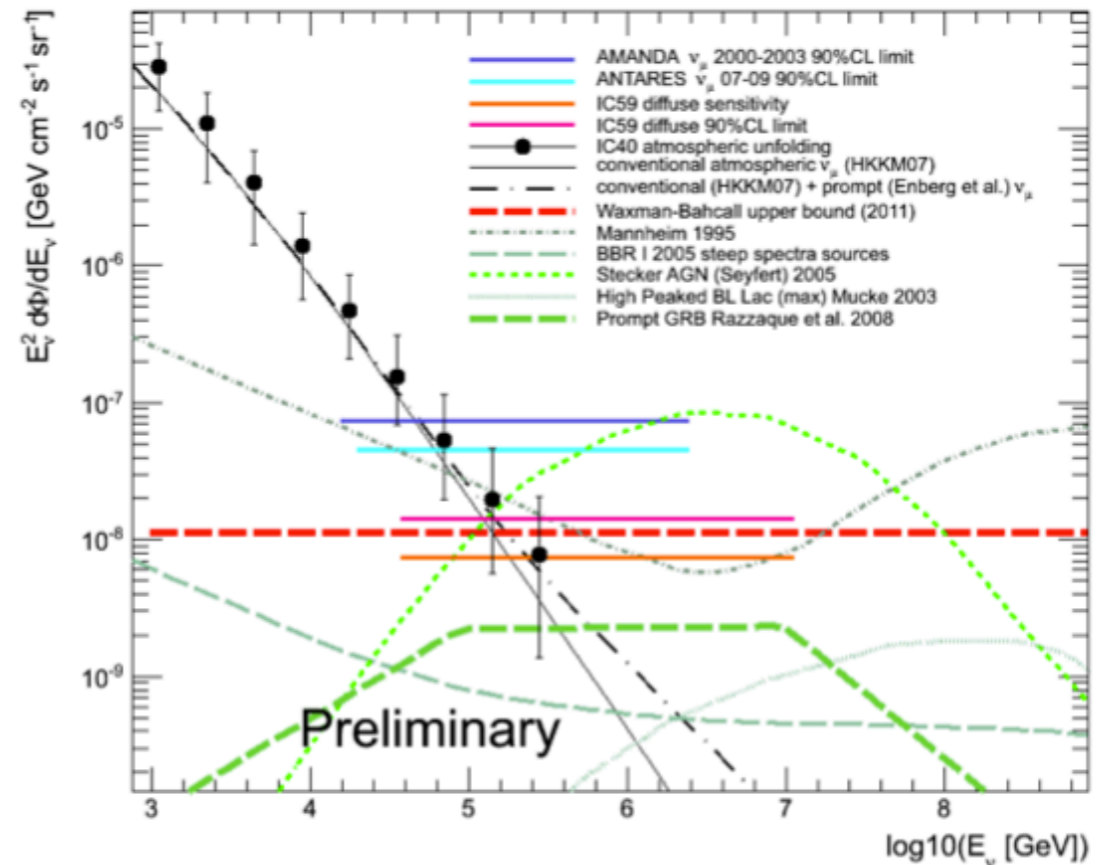
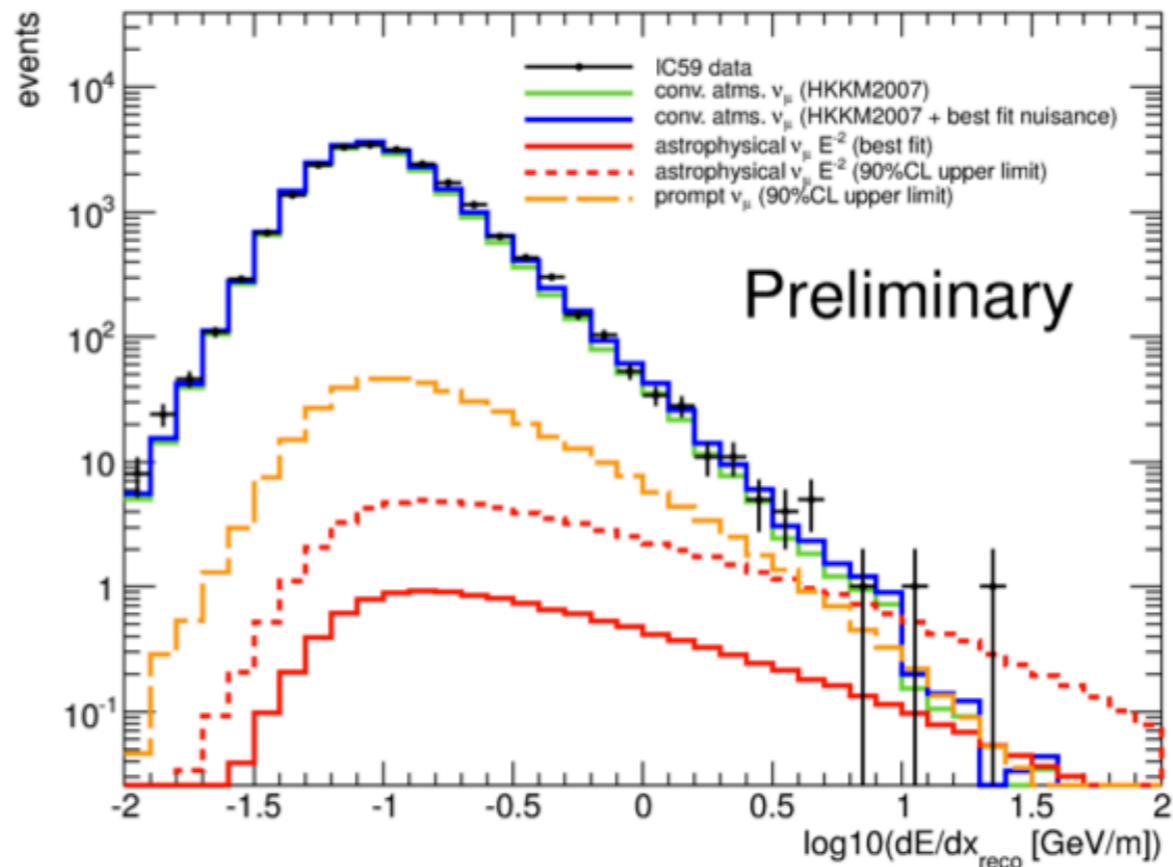
(Precision IceCube Next Generation Upgrade)



- Tau appearance measurement with DeepCore is challenging
 - Need a low-energy cascade analysis with good angle & energy
 - Expect to have enough statistics $\sim \mathcal{O}(1000)$
 - Better reconstruction would help.
- Feasibility studies for Neutrino Mass Hierarchy measurement with PINGU
 - Muon neutrinos through Matter effect in varying baseline
 - Understanding the systematics is the key to the measurement
 - Additional calibration devices can be added
 - A Letter of Intent is forthcoming

Diffuse Muon Neutrino Search

arXiv:1302.0127

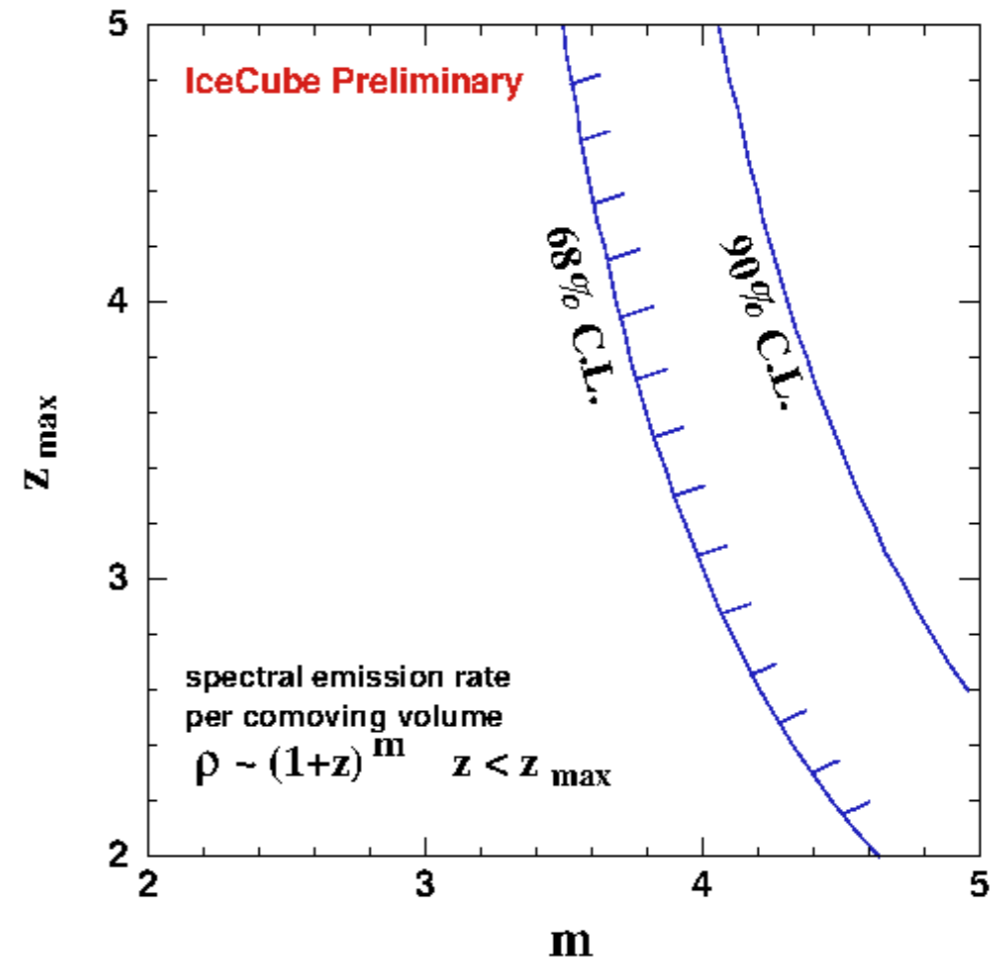
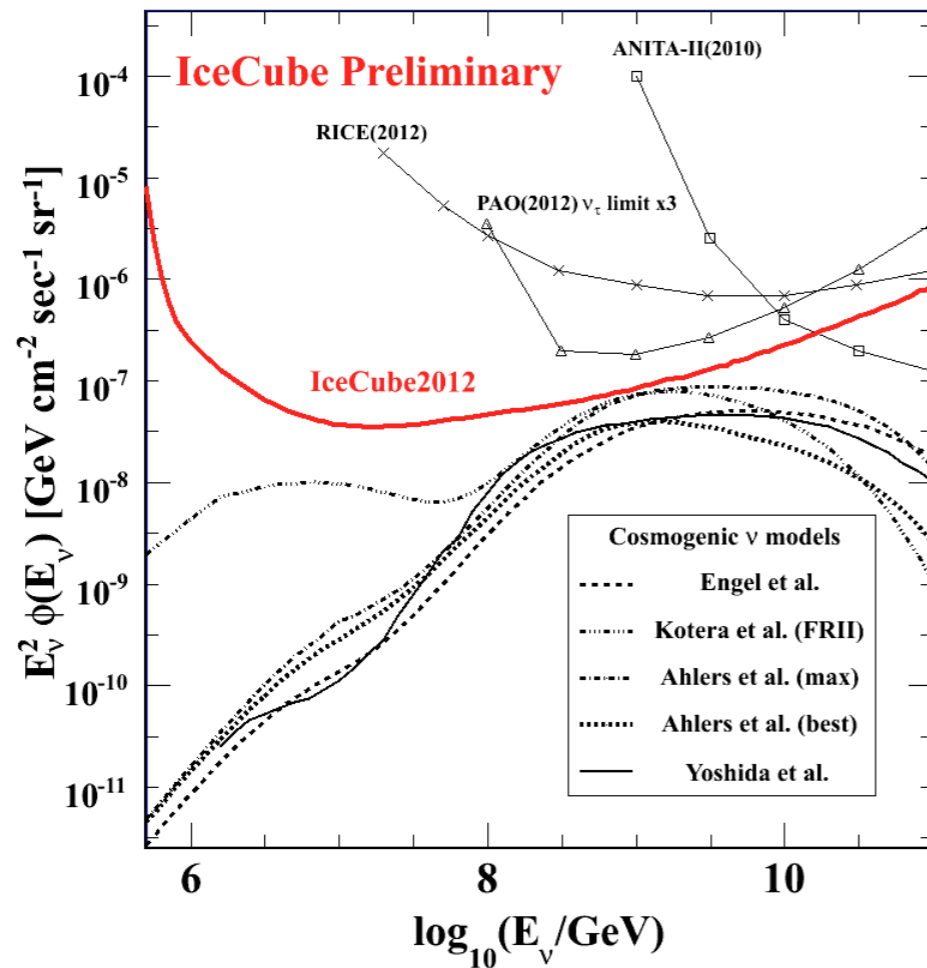
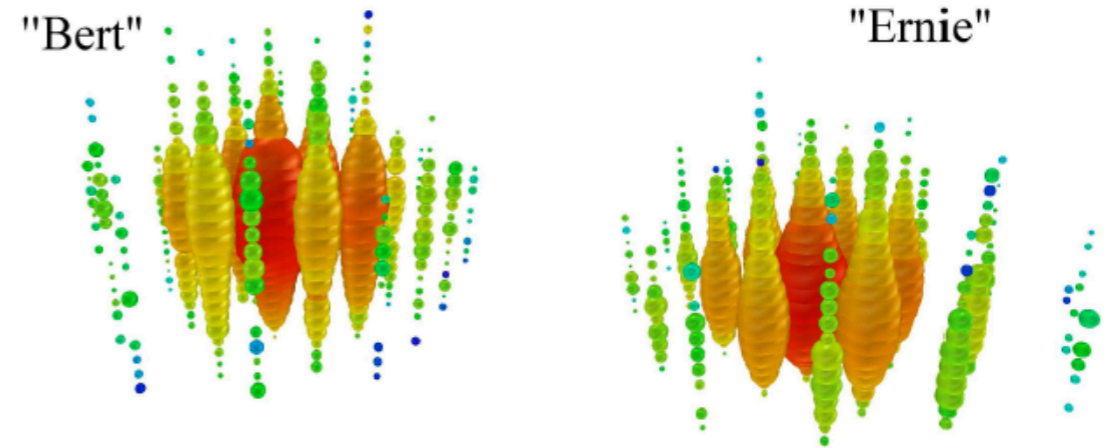


- The diffuse search sums up muon neutrino flux from all directions
- Fit three spectra (conventional $\sim E^{-3.7}$, prompt $\sim E^{-2.7}$, and astrophysical $\sim E^{-2.0}$) for both the shapes in zenith angle and the slopes in energy
- Muon neutrino flux measured up to 400 TeV

Cosmogenic (GZK) Neutrino Search

- IC79+86 2-year search found two previously reported PeV events (Bert & Ernie)
 - Too low to be cosmogenic neutrinos
- Set Limits on cosmogenic neutrinos
- Start to test some optimistic models
 - Evolution Parameters (Z_{max} & m)

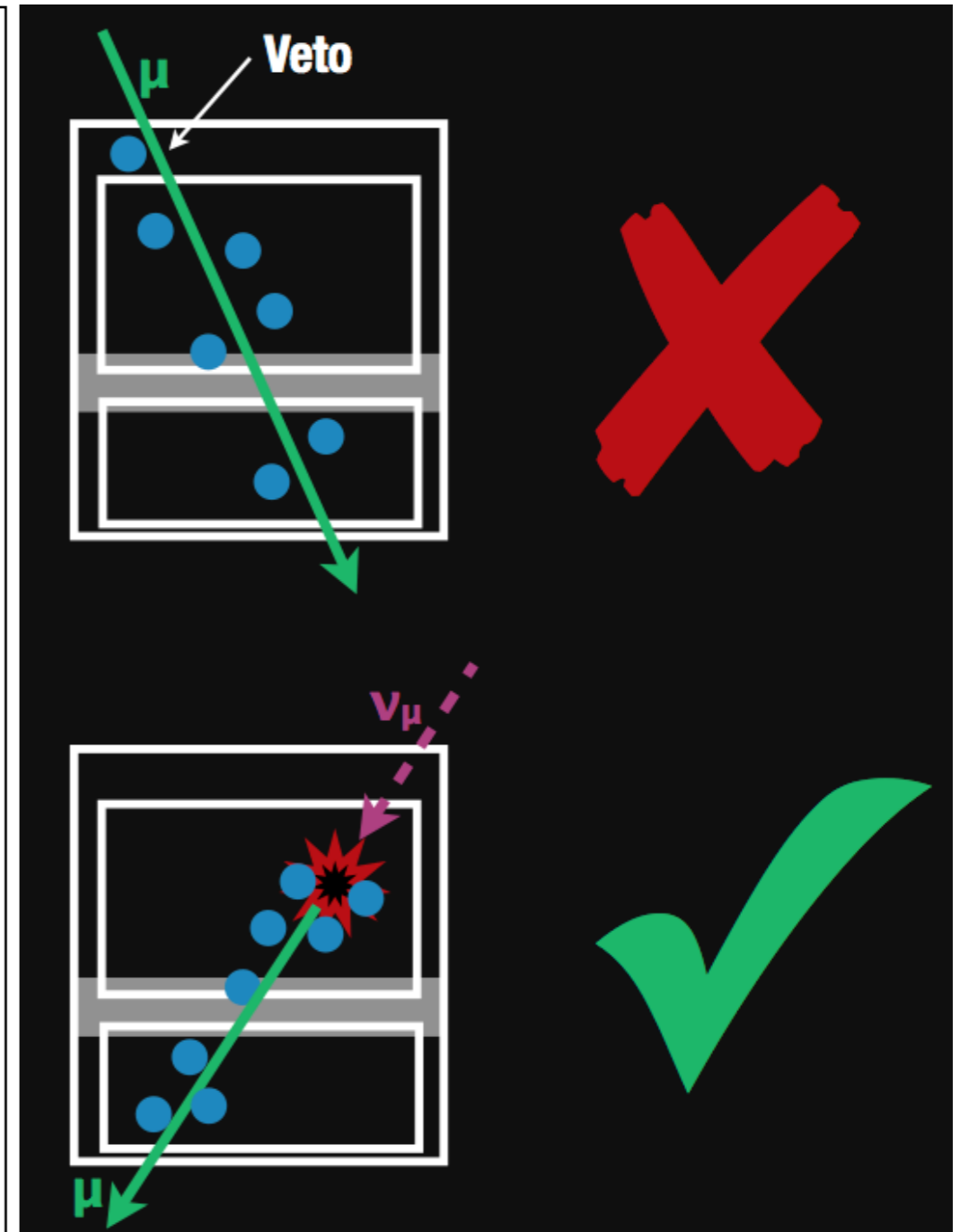
Phys. Rev. Lett. 111, 021103(2013)



High Energy Starting Event Search

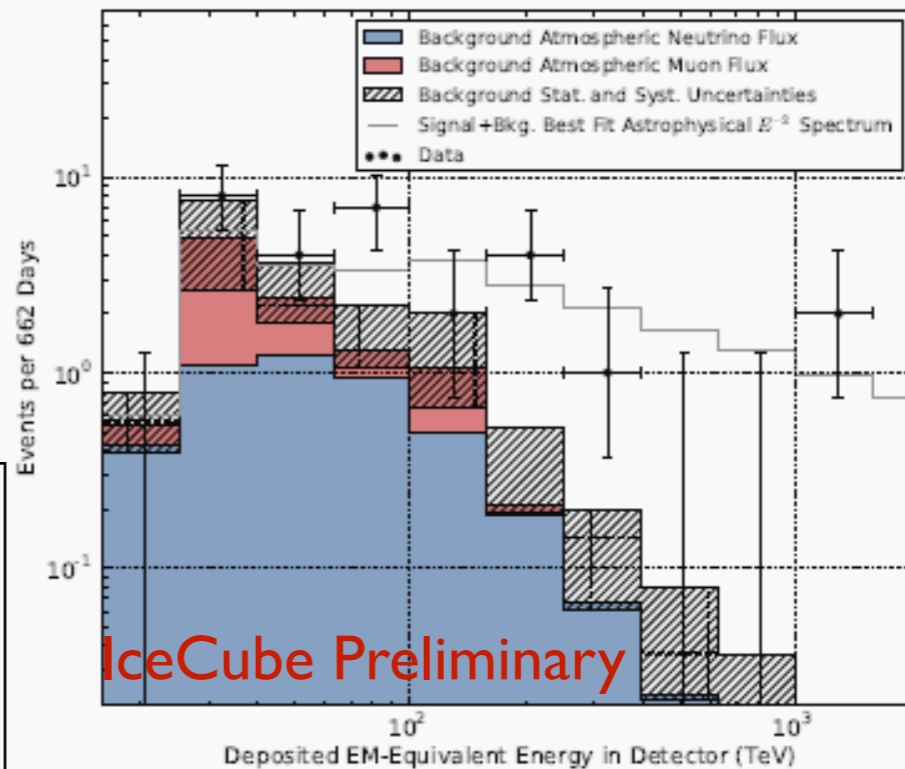
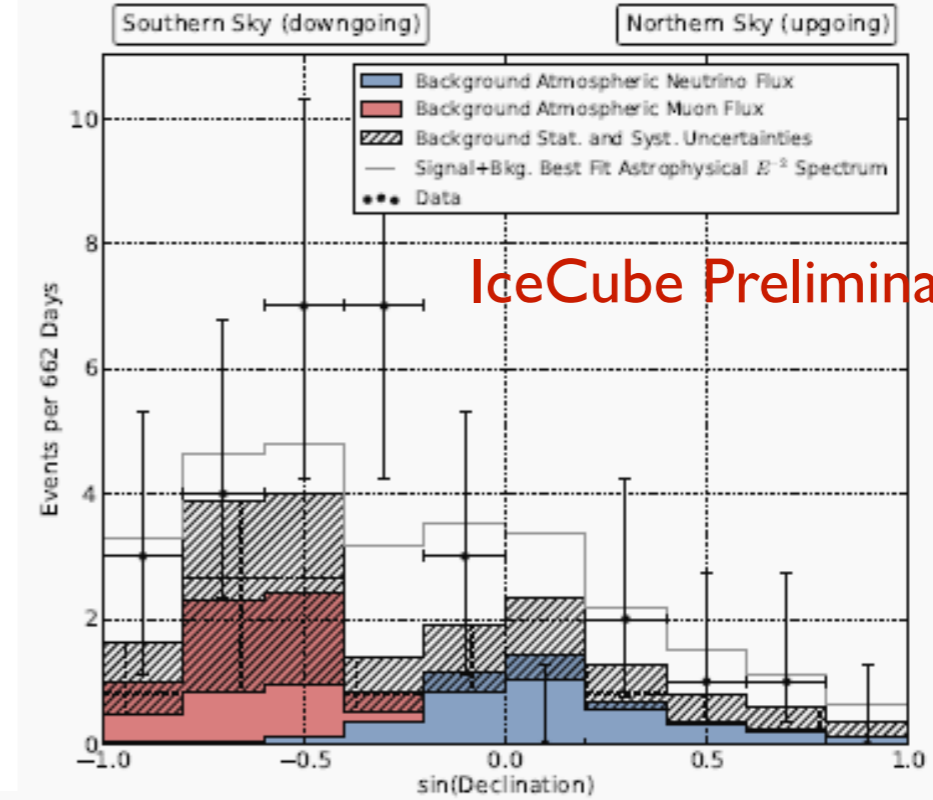
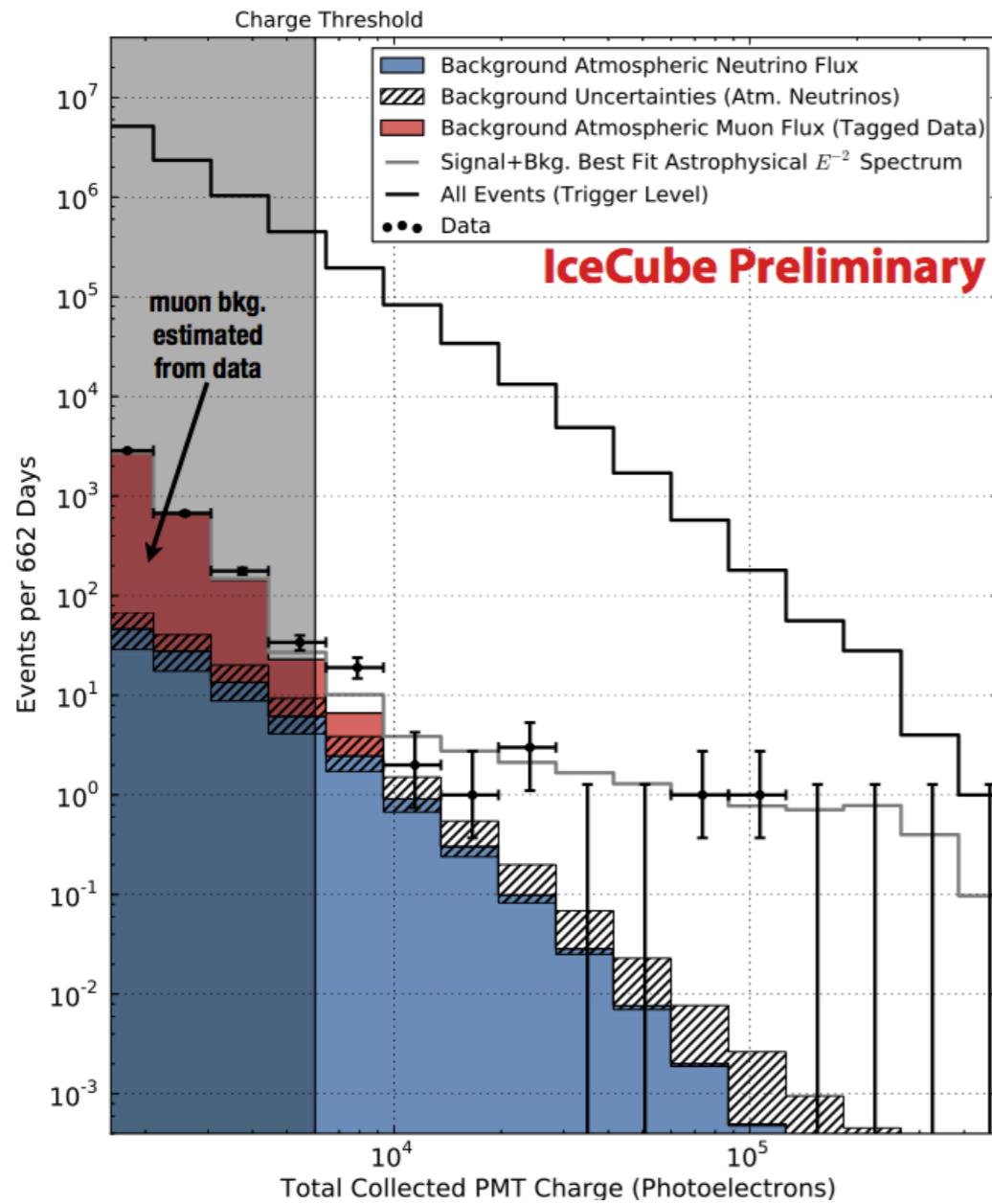
Follow-up Analysis to GZK event search

- Search for starting events at high energy
- Total charge > 6000 photoelectrons
- Require early charge to be relatively high
- ~ 400 Megaton effective volume
- Sensitive to all flavors above 60 TeV
- Backgrounds
 - Atmospheric muons : estimation from data (tagged muons)
 - Atmospheric neutrinos : very low but large uncertainty



High Energy Starting Event Search

26 additional events to the reported two ~ 1 PeV events



- Large uncertainty in the higher energy region of atmo. background is due to poor understanding of the current charmed meson production (i.e. charm pair x-section) in the atmosphere

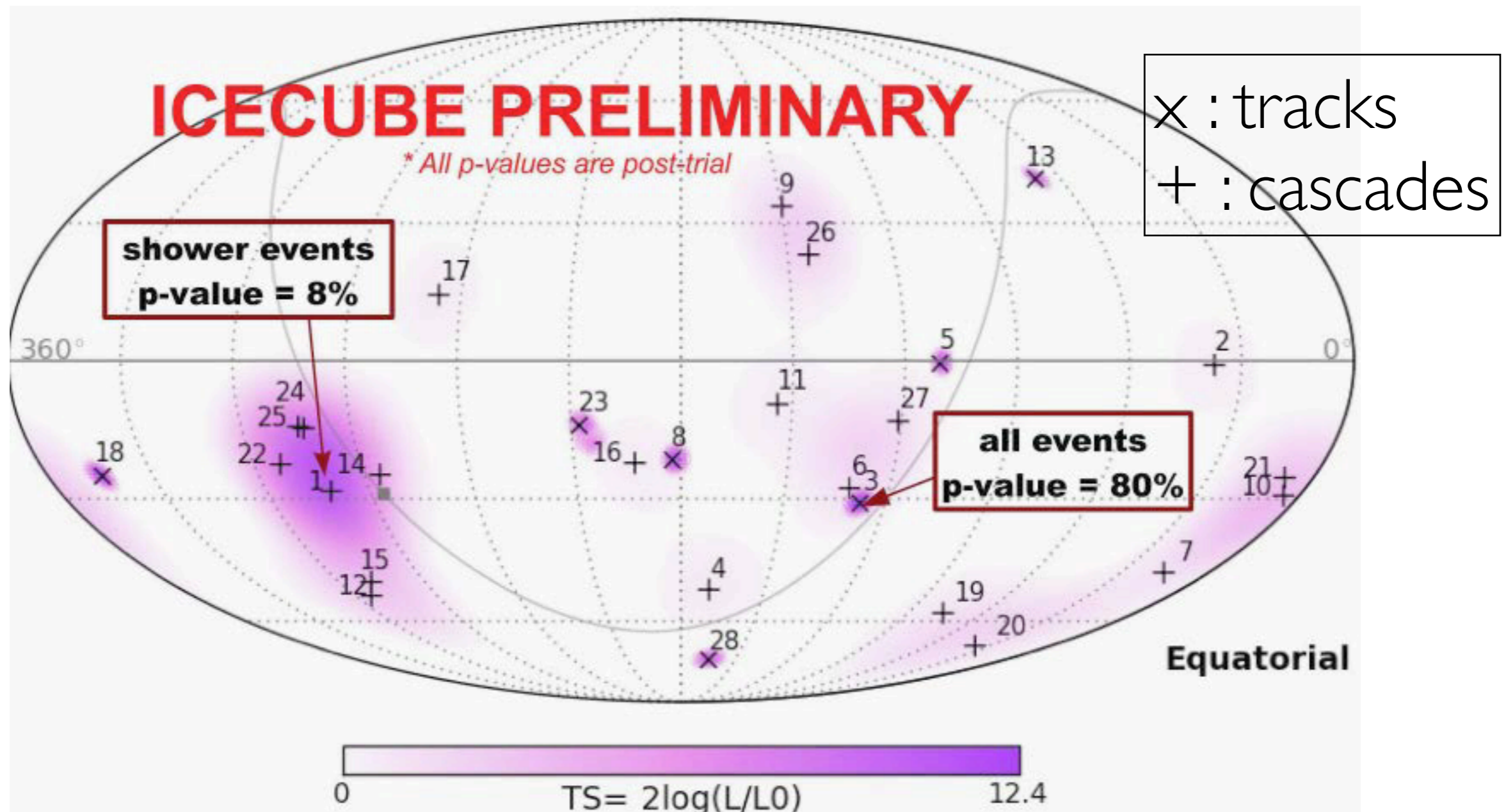
High Energy Starting Event Search : Significance

Assume 1xERS for charm

No Bert & Ernie (26 events)	With Bert & Ernie (28 events)
3.3σ	4.1σ

- 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 here.
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (6 ± 3.4), Conv. Neutrino (4.6 ± 1.2), and Prompt Neutrino (1.5 event for standard ERS)
- 24 of 28 events are downward-going and 21 of 28 are cascade events.
- Over $60 \text{ TeV} < E < 2000 \text{ TeV}$, the spectrum consistent with E^{-2} .
- E^{-2} spectrum predicts too many neutrinos above $\sim 2 \text{ PeV}$. So, a cutoff or steeper spectrum needed.

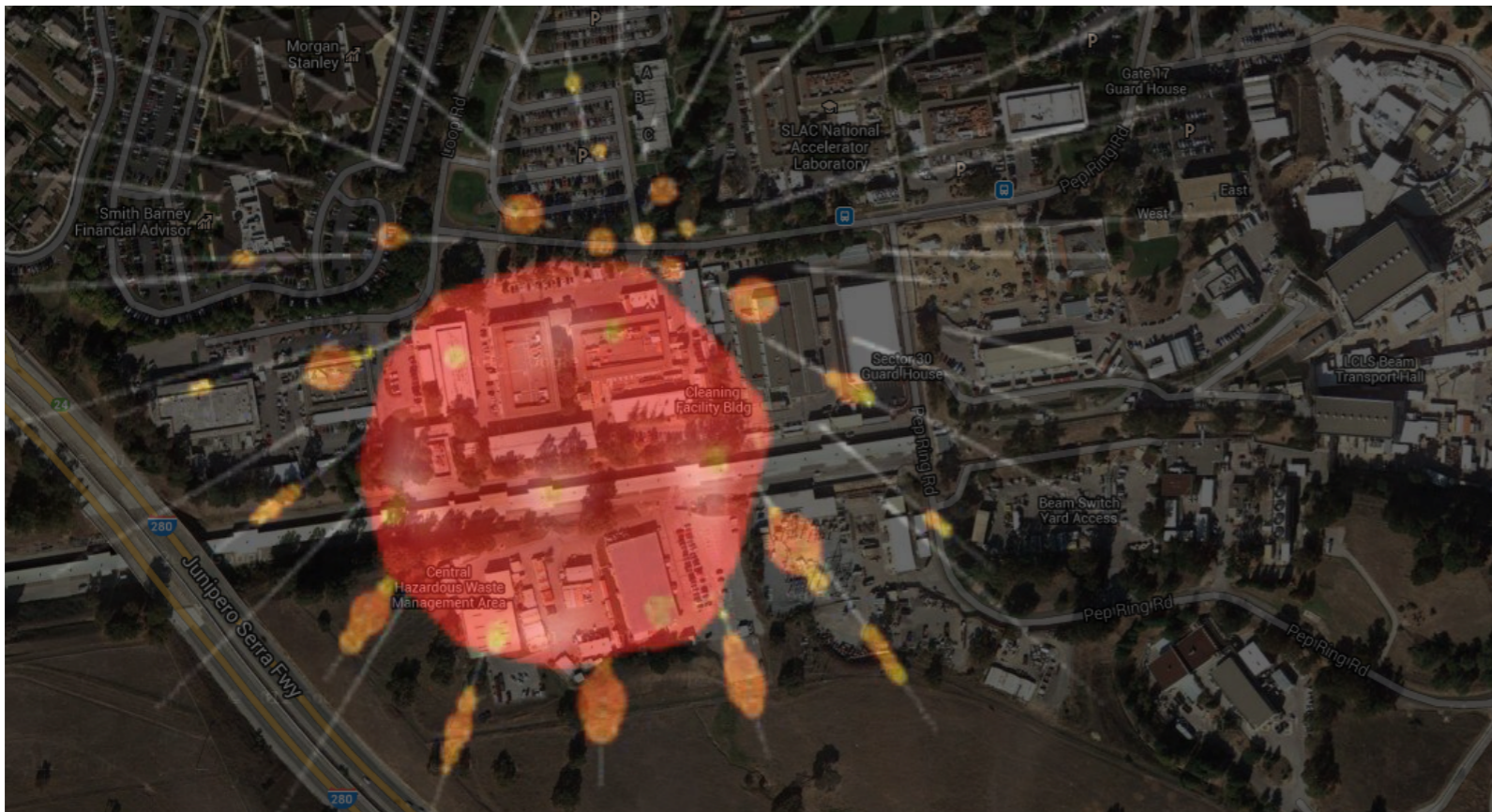
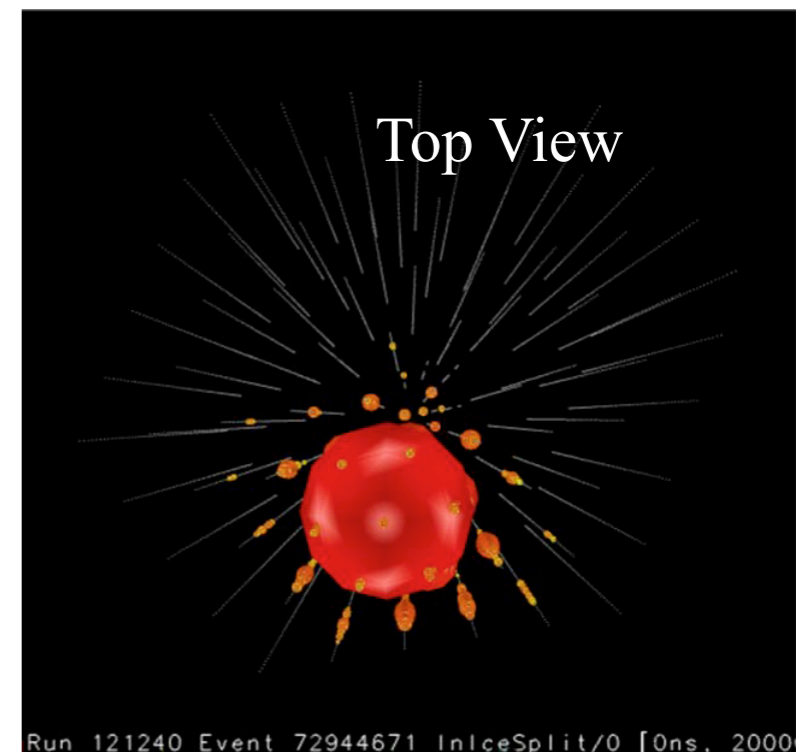
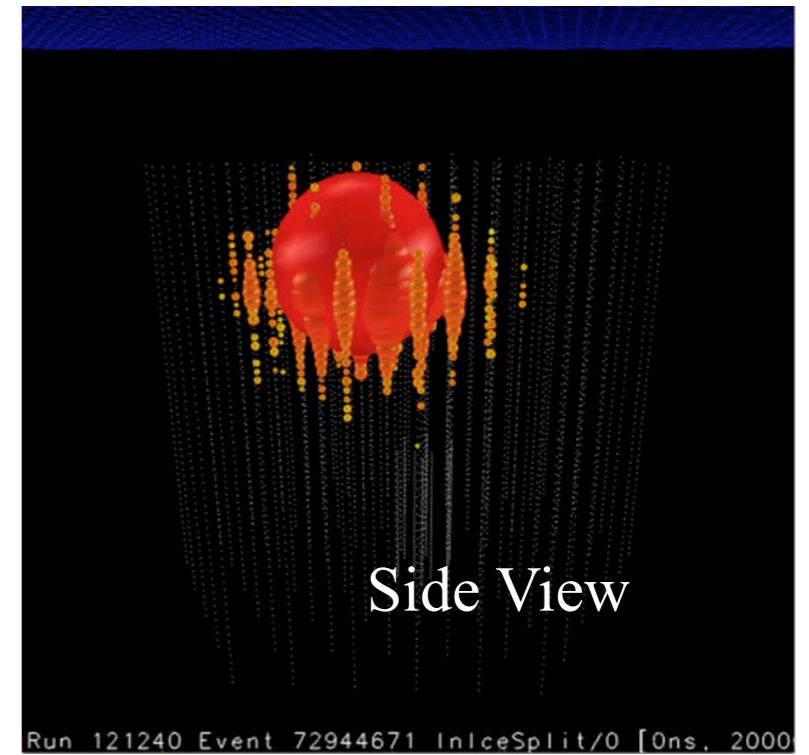
High Energy Starting Event Search : Sky map



No significant source found

Another Event in test sample of new data

10% of the 2012 data have been looked at and found another big cascade-like event



Joins to Bert & Ernie.
NOT allow to discuss Energy & Direction

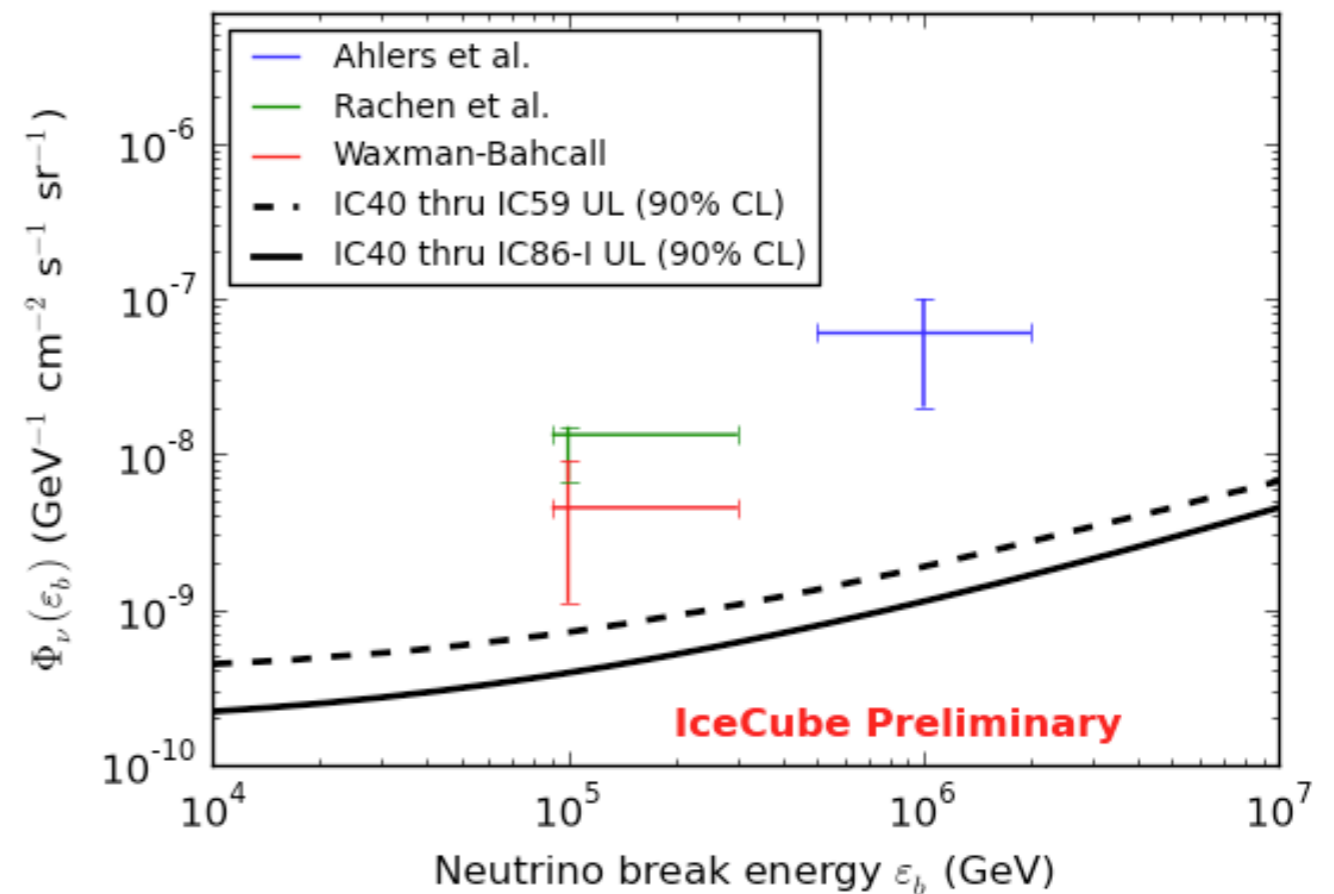
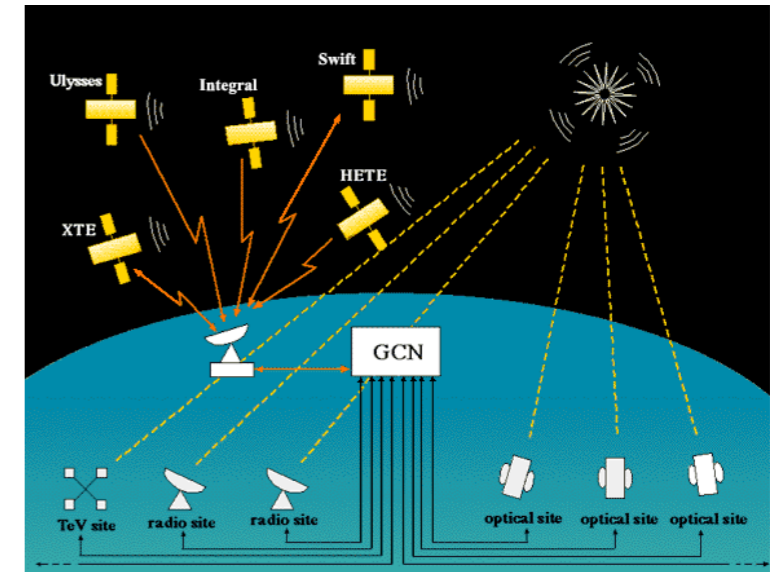
Conclusion

- The IceCube detector is running at full strength
 - Two years of 86-string data ready for analyses and taking the third year of 86-string data
 - The detector runs very smoothly
- IceCube is a multi-purpose detector
 - Indirect Searches for Dark Matter annihilations.
 - Searches for Astrophysical neutrino sources, including diffuse and point sources
 - Particle physics with DeepCore low energy extension, or possibly with PINGU
 - Not discussed : Exotic particle searches, Follow-up programs, Air shower physics, and so on.
- Highlights from Recent Results
 - Atmospheric neutrino oscillations & neutrino flux measurements (ν_μ and ν_e), which agree well with models of atmospheric neutrinos and world average.
 - The High Energy Starting Event search found 28 events (including previously reported two highest energy events, $E \sim 1$ PeV) inconsistent with atmospheric backgrounds at $\sim 4 \sigma$ level.
 - More data with improved analyses coming soon and stay tuned!

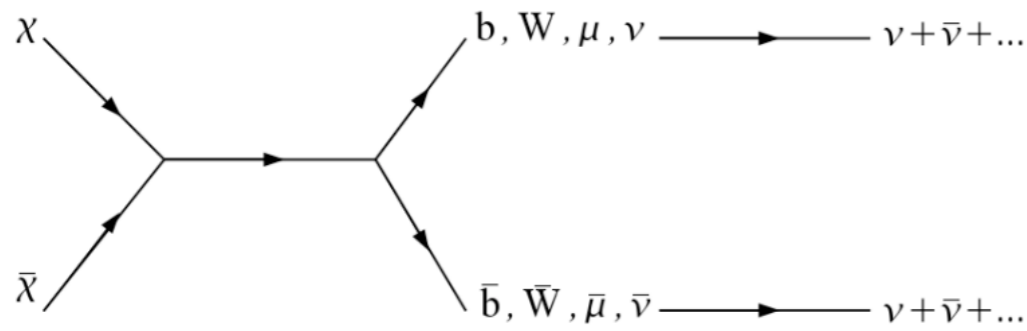
Back-up

Gamma-Ray Burst (GRB) Searches with Gamma-ray Coordinates Network (GCN)

- Looking for neutrino events in time & spatial correlations with GCN GRB reports
- 4-year search saw no significant correlations
- Limits have been improved by a factor of two with latest two year data



Other searches for the Dark Matter

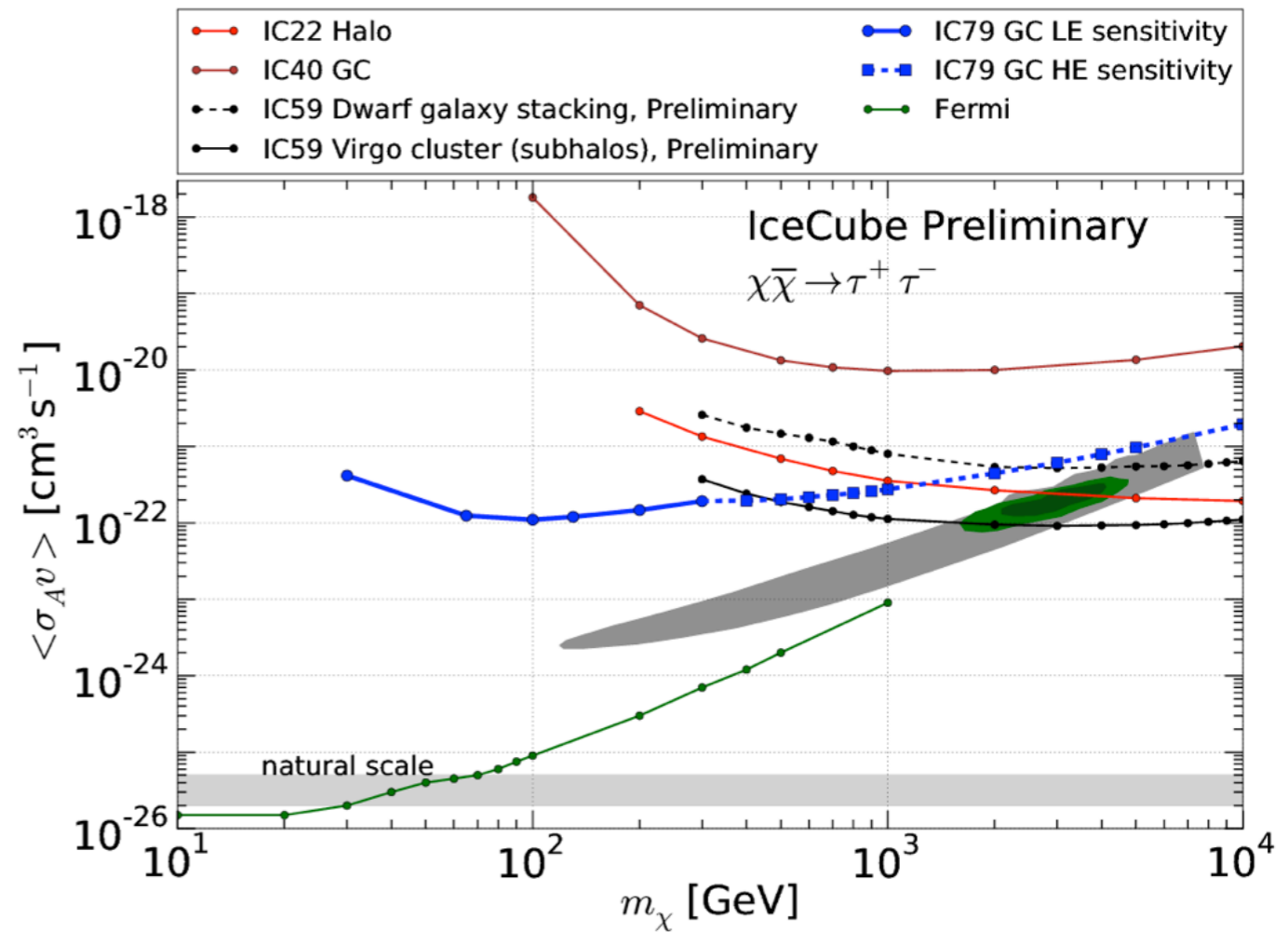
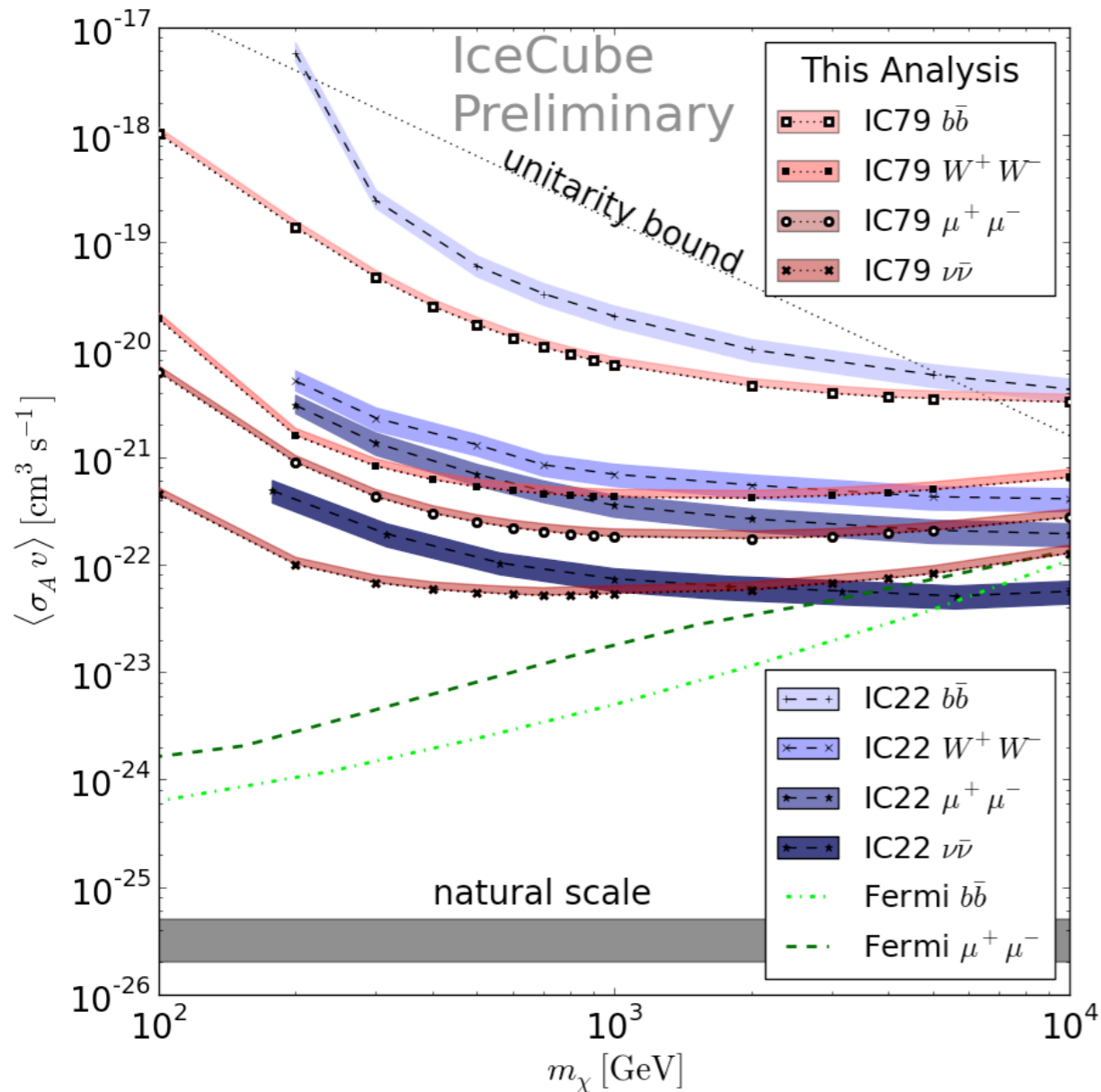


$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_{A\nu} \rangle}{2} \frac{1}{4\pi} J(\Phi) \frac{R_{SC} \rho_{SC}^2}{m_\chi^2} \frac{dN_\nu}{dE}$$

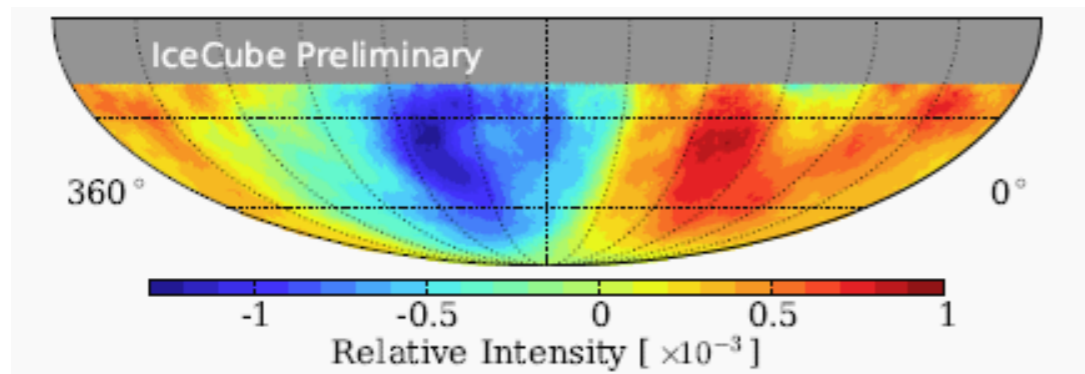
Limits Astrophysics

Detector Response

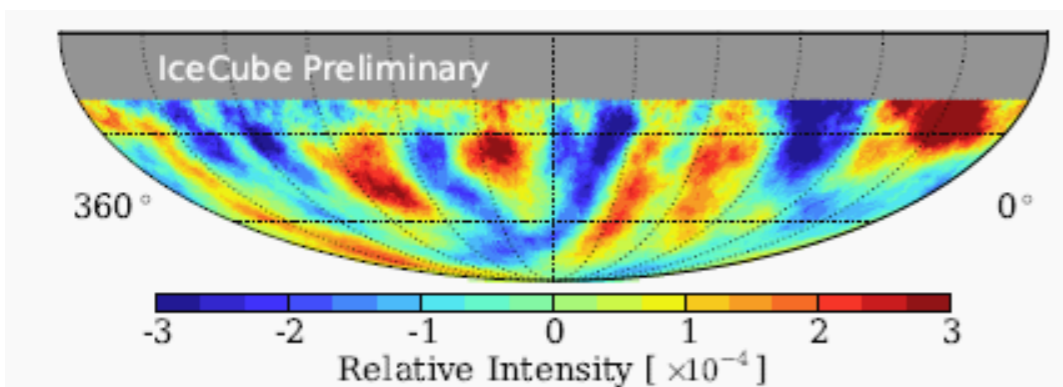
SUSY



Cosmic Ray Anisotropy



Cosmic Ray Anisotropy

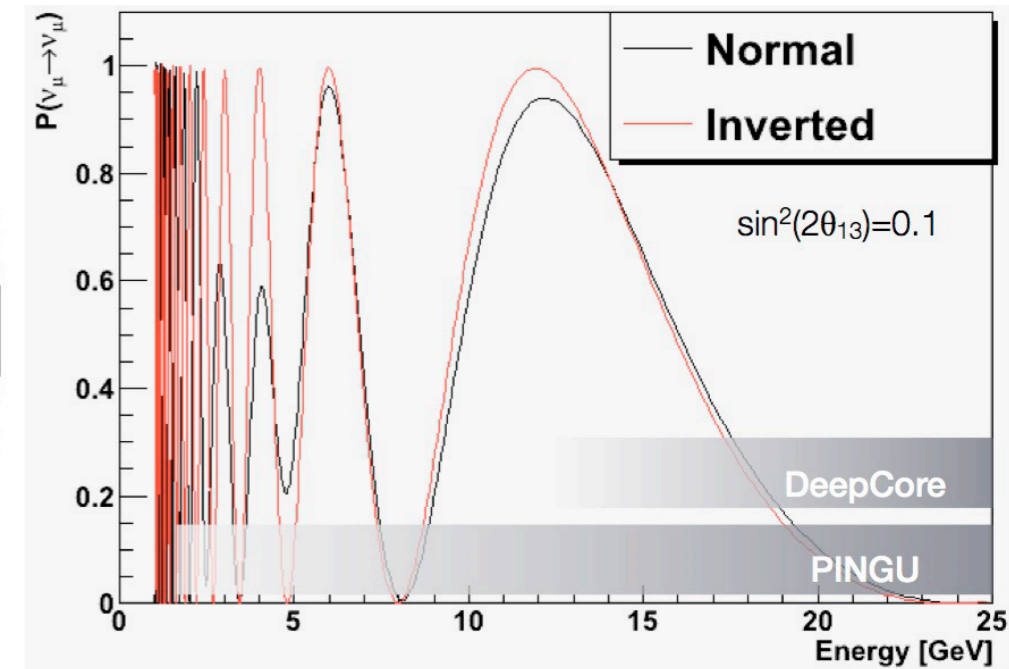
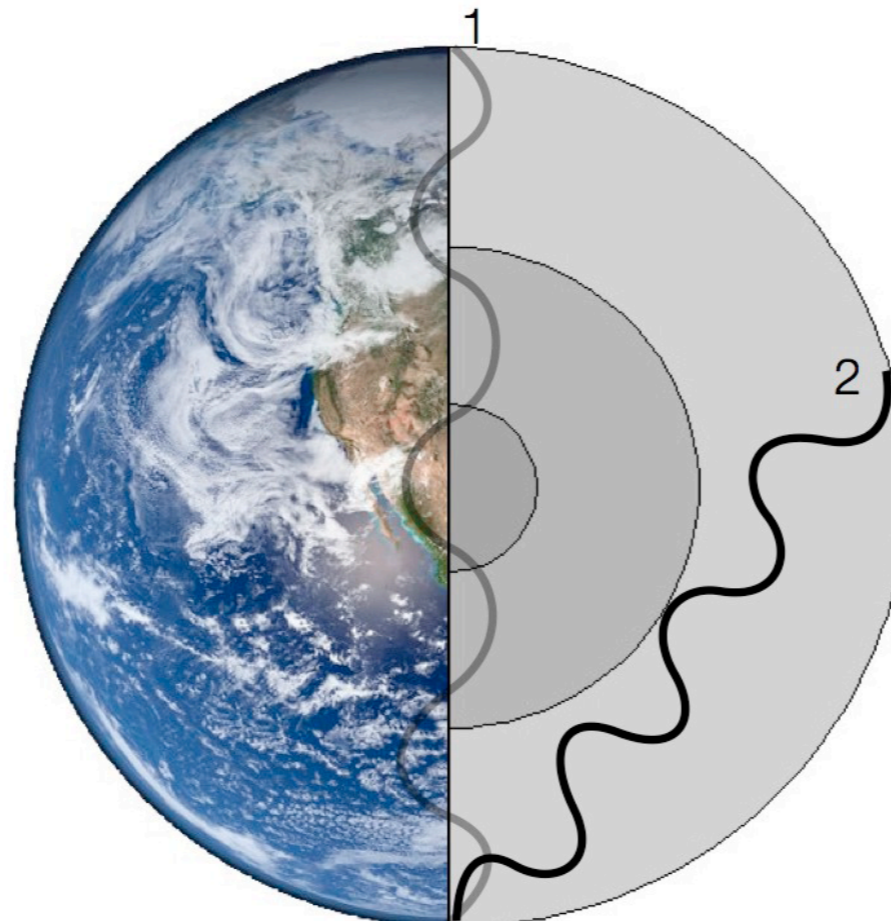
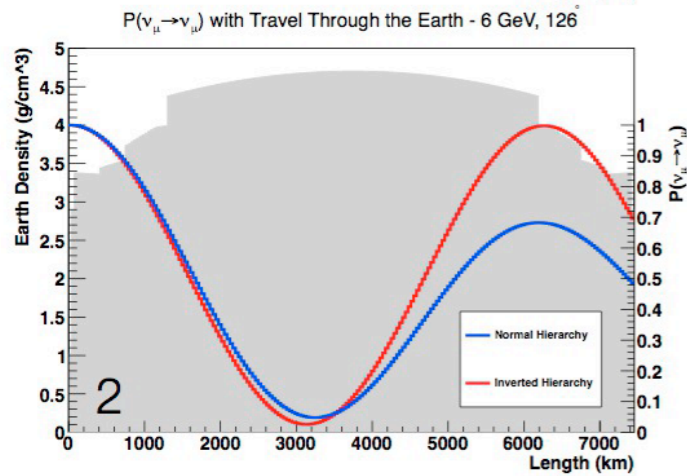
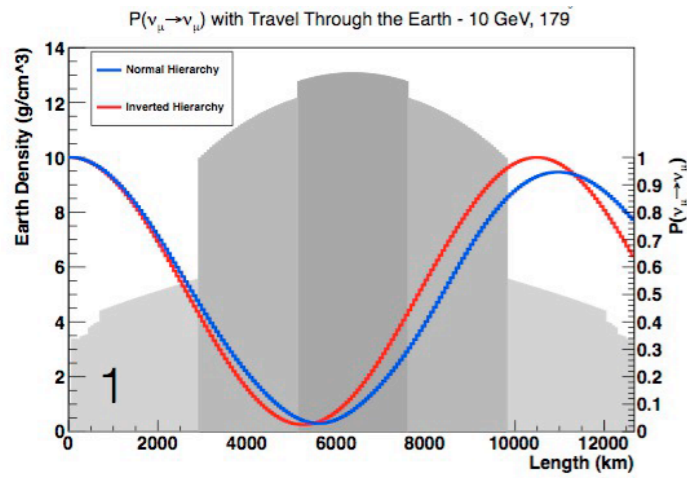


After dipole, quadrupole
subtraction

- 150 Billion CR muon events (>5 year data) are analyzed.
- Anisotropies at 10^{-3} amplitude at multiple angular scales.
- Matches well with other air shower experiments at Northern sites

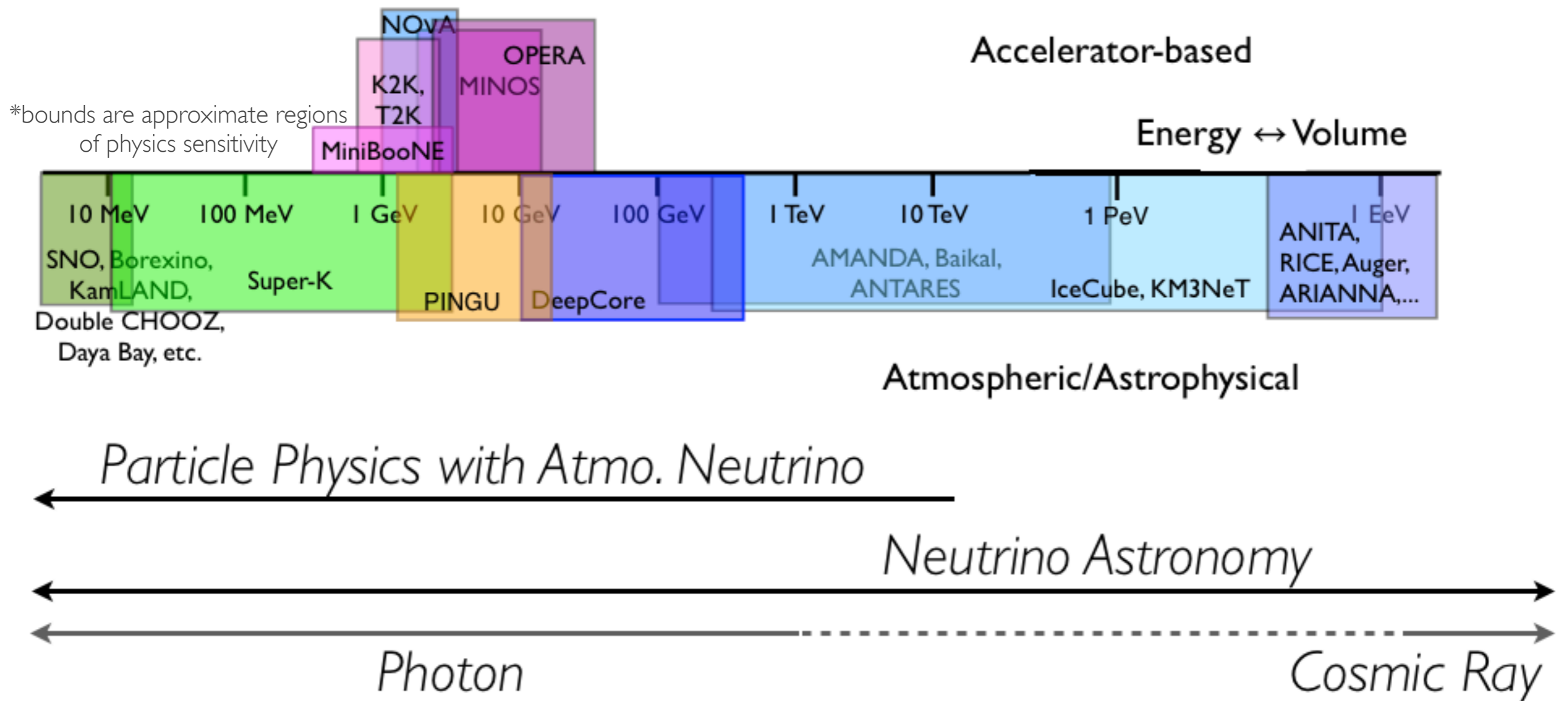
PINGU

(Precision IceCube Next Generation Upgrade)



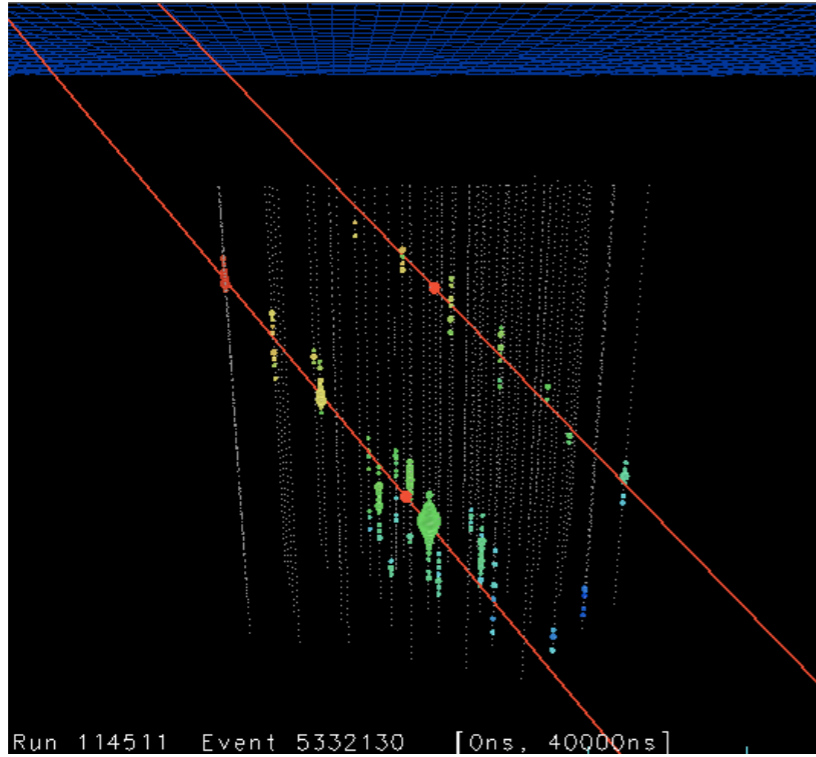
High Energy Neutrinos

from cosmic ray interaction in the atmosphere
& from astrophysical sources



Cosmic Ray Physics

-Lateral Muon Analysis



- Study of laterally separated muons
- Probes high transverse momenta
- The separation spectrum fits with steep component (exponential) and moderate component (power law;pQCD)
- Hadronic interaction models with charm components fit better with data

