Neutrino Flavor Physics with IceCube & PINGU

Chang Hyon Ha (LBNL & UC Berkeley)
for the IceCube Collaboration

The Rencontres du Vietnam Flavour Conference
July 31, 2014

The IceCube–PINGU Collaboration

47 institutions, ~300 members

http://icecube.wisc.edu/

International Funding Agencies

Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
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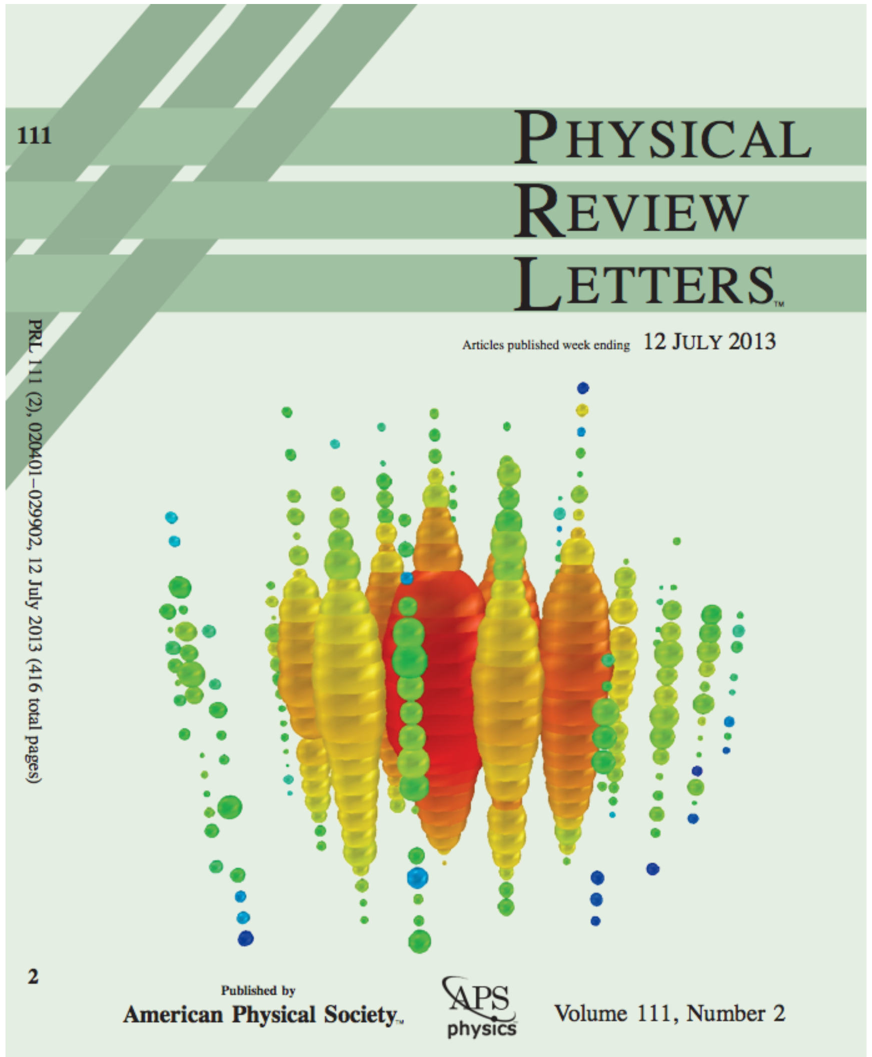
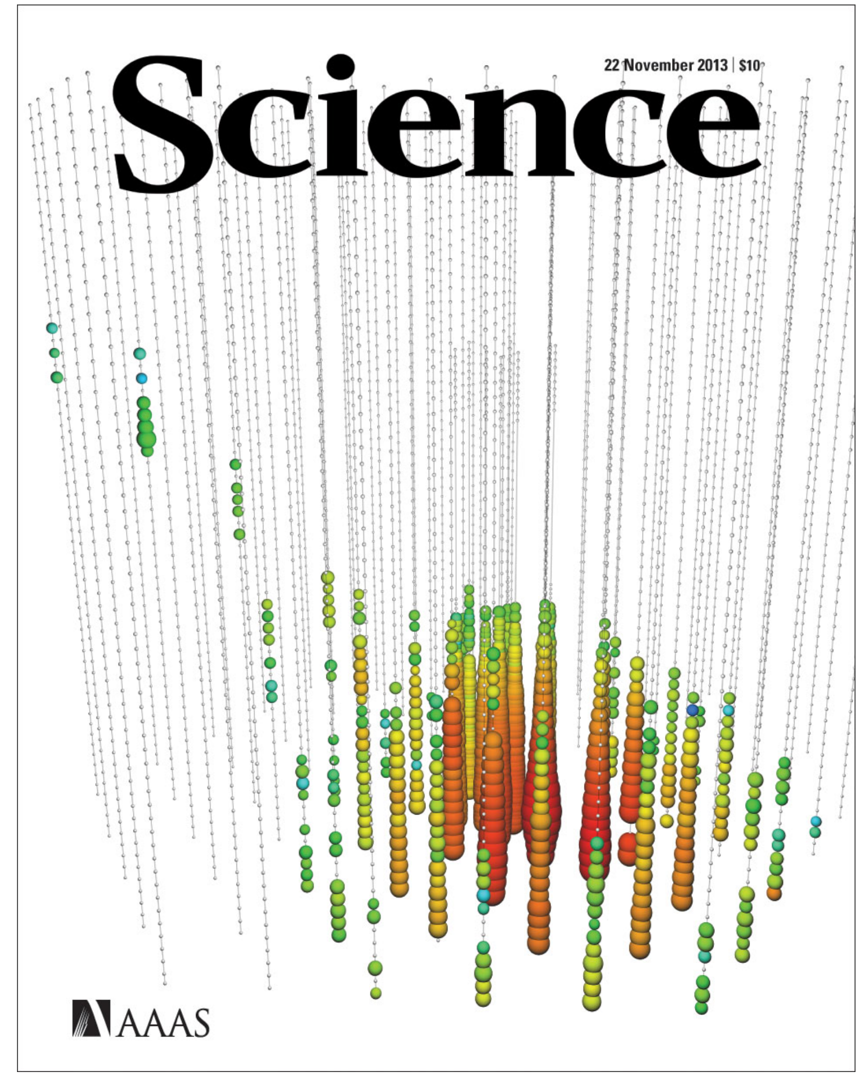
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Two Covers





Observation of PeV-Energy Neutrinos

Physical Review Letters 111 (2013) 021103 [arXiv:1304.5356]

Evidence for High-Energy Extraterrestrial Neutrinos

Science 342, 1242856 (2013) [arxiv:1311.5238]

Color : Time order, Size : Amplitude

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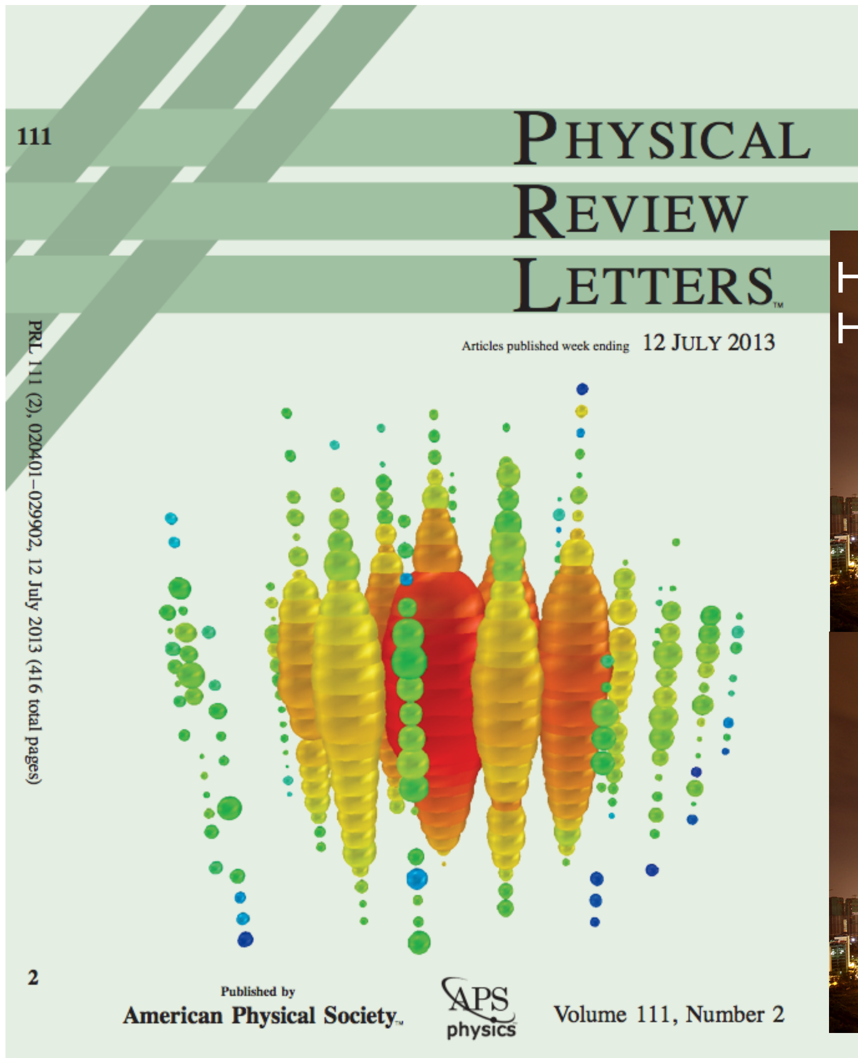

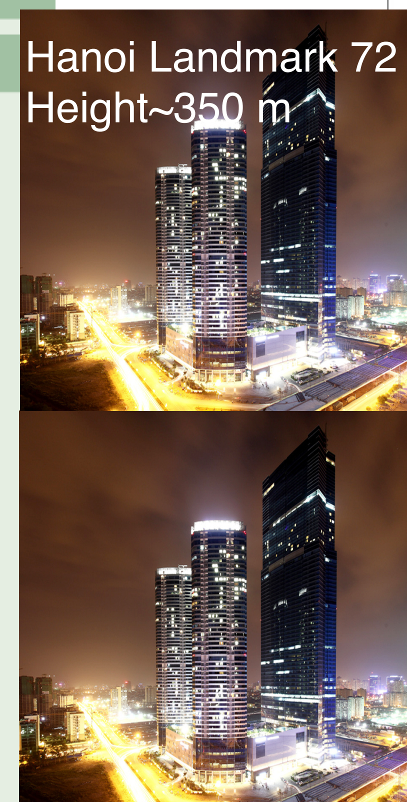

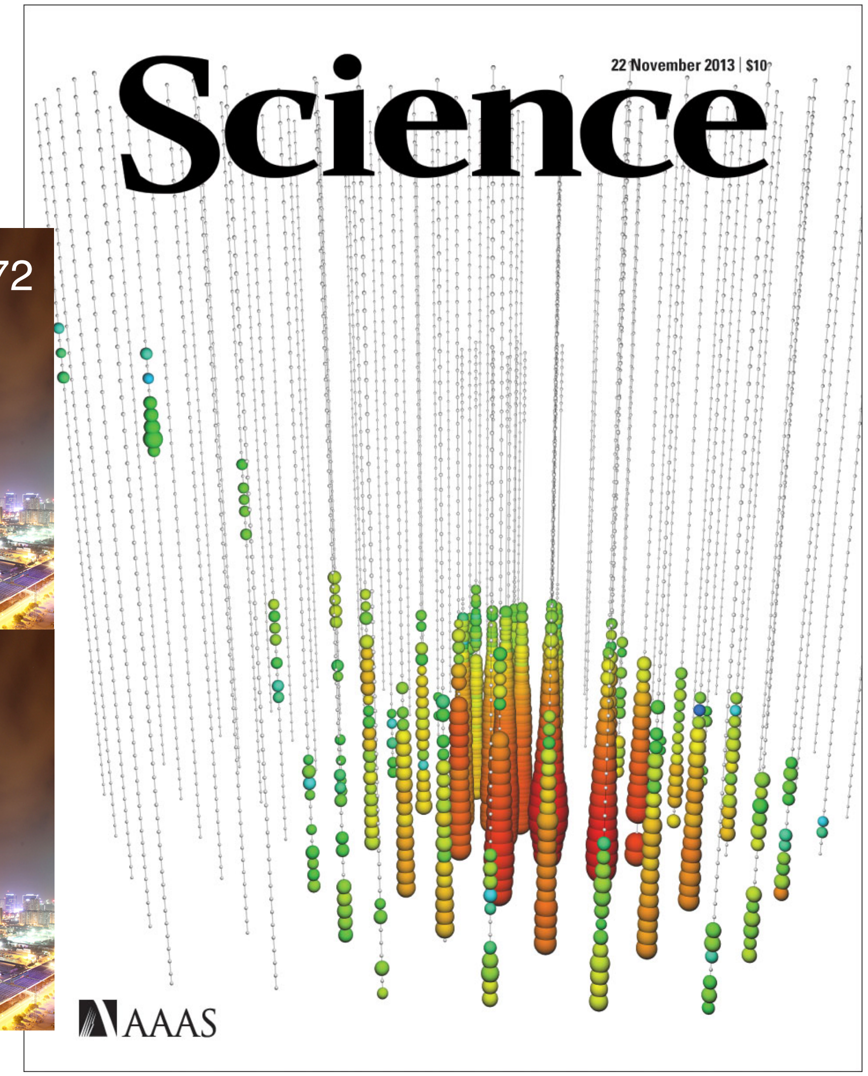

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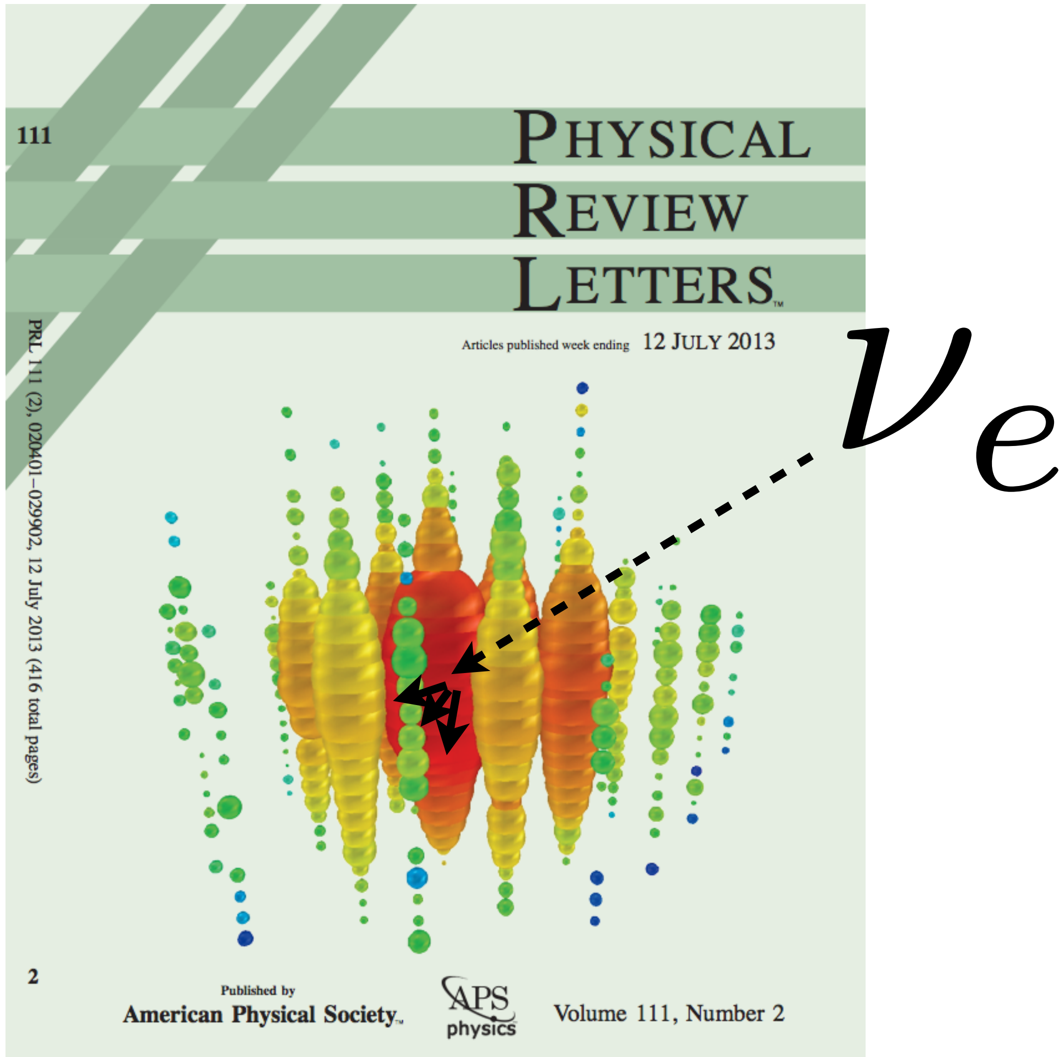

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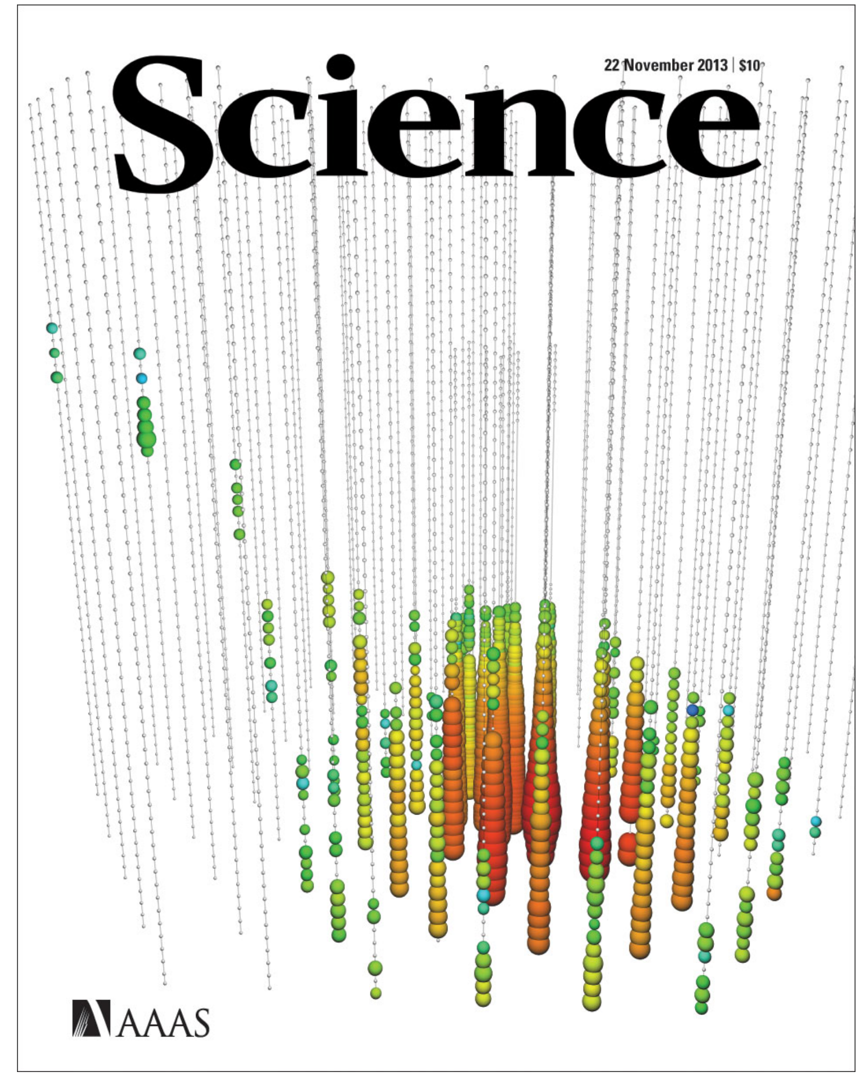

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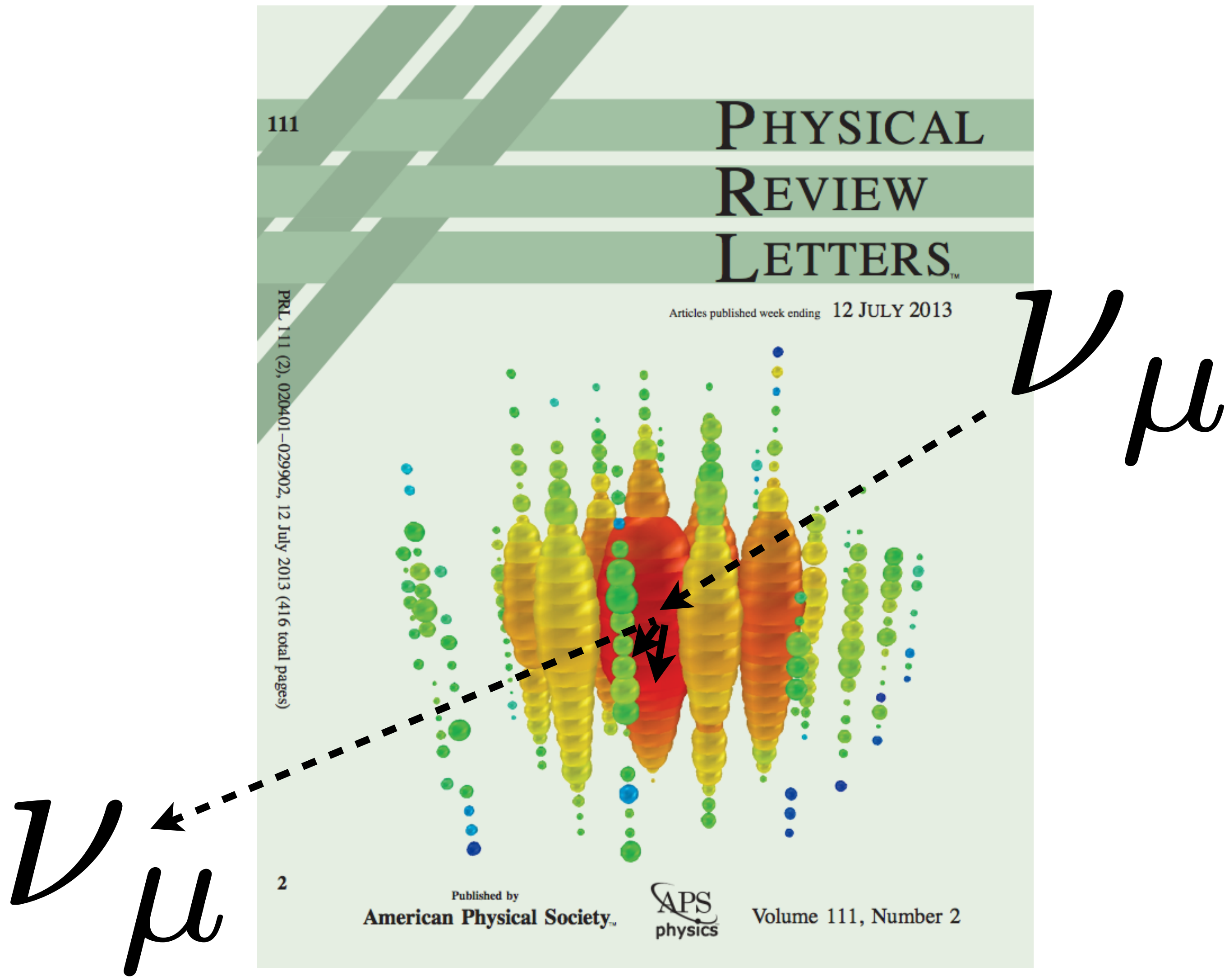

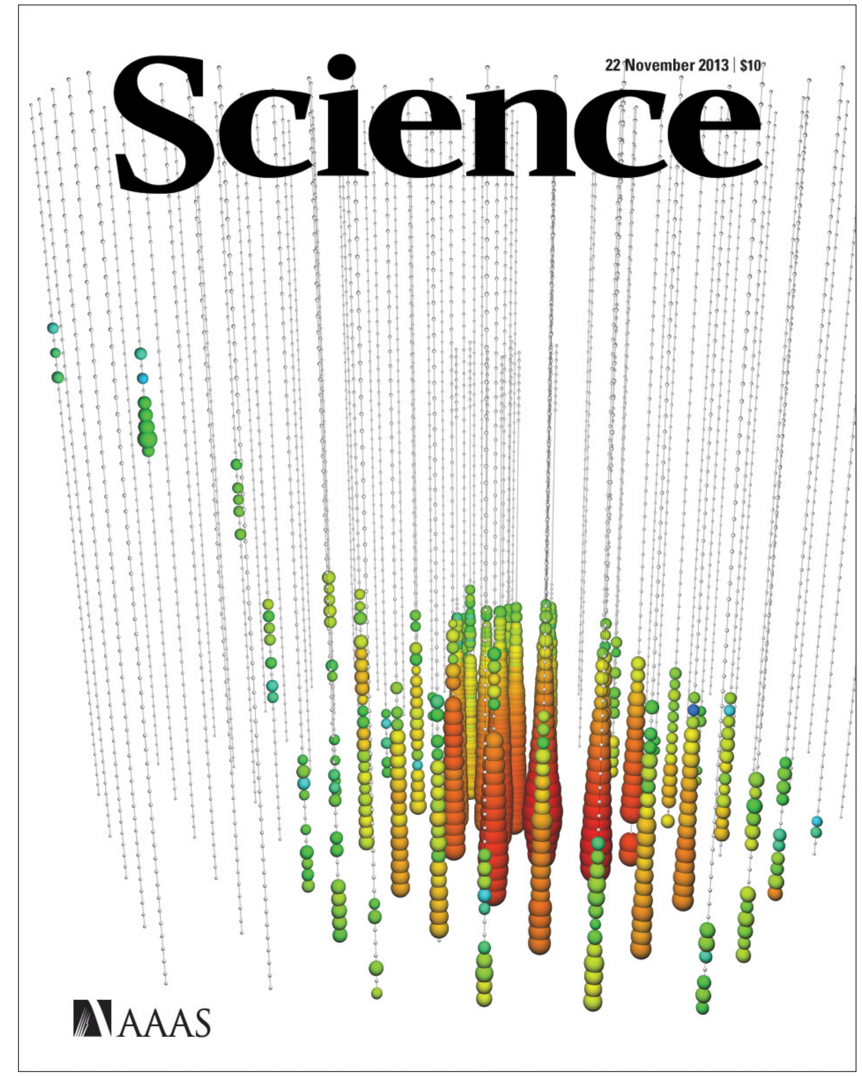

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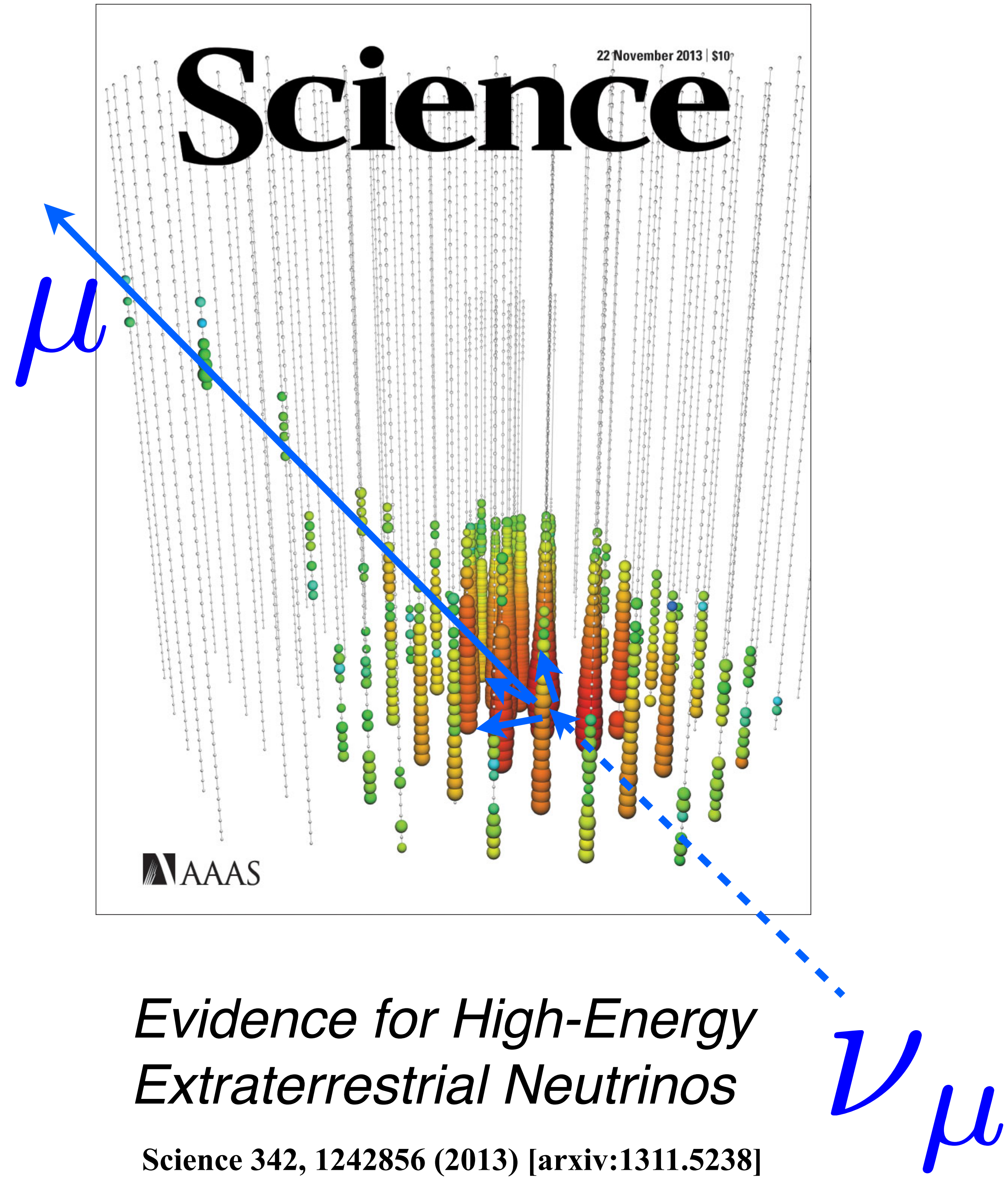

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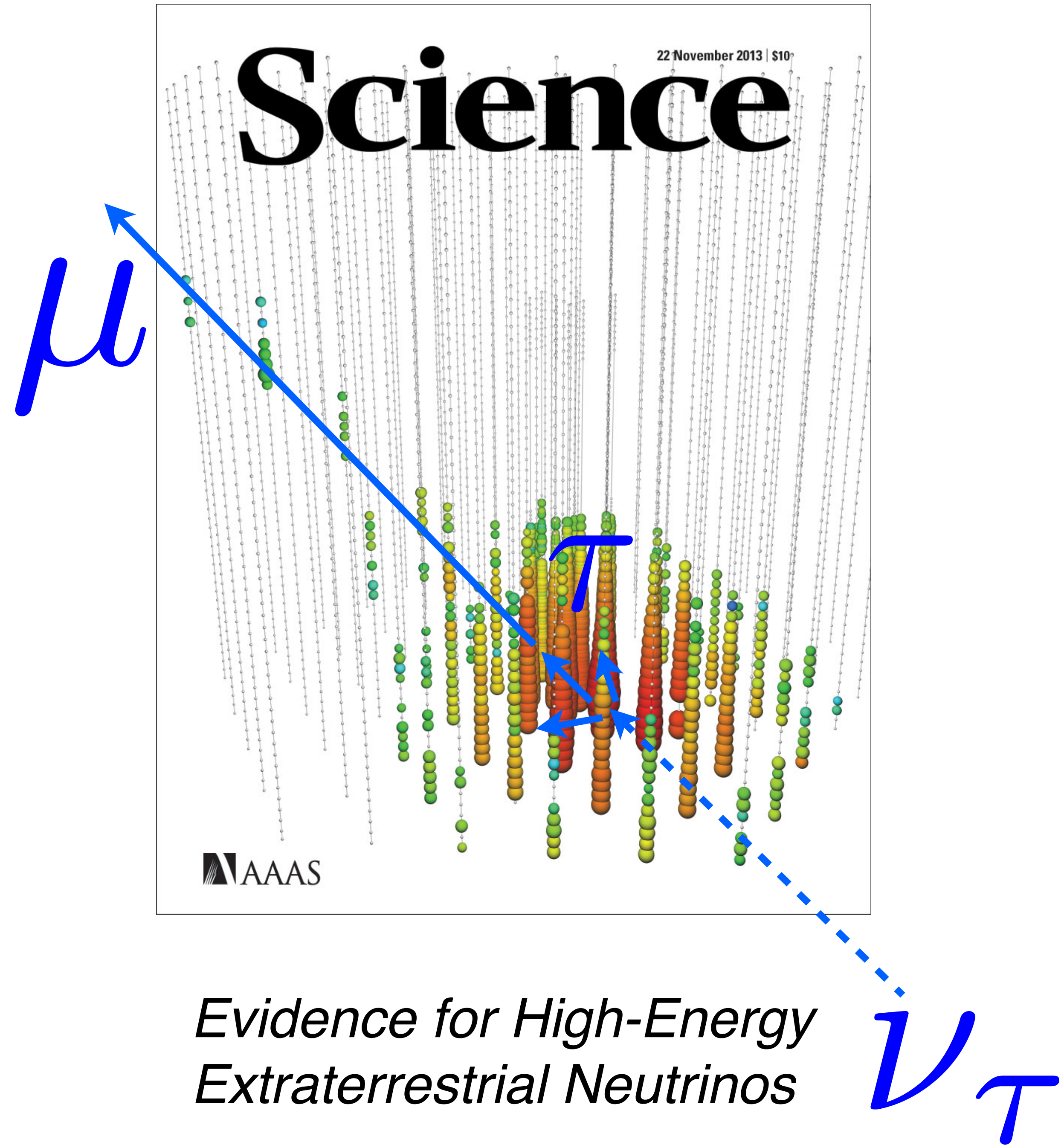

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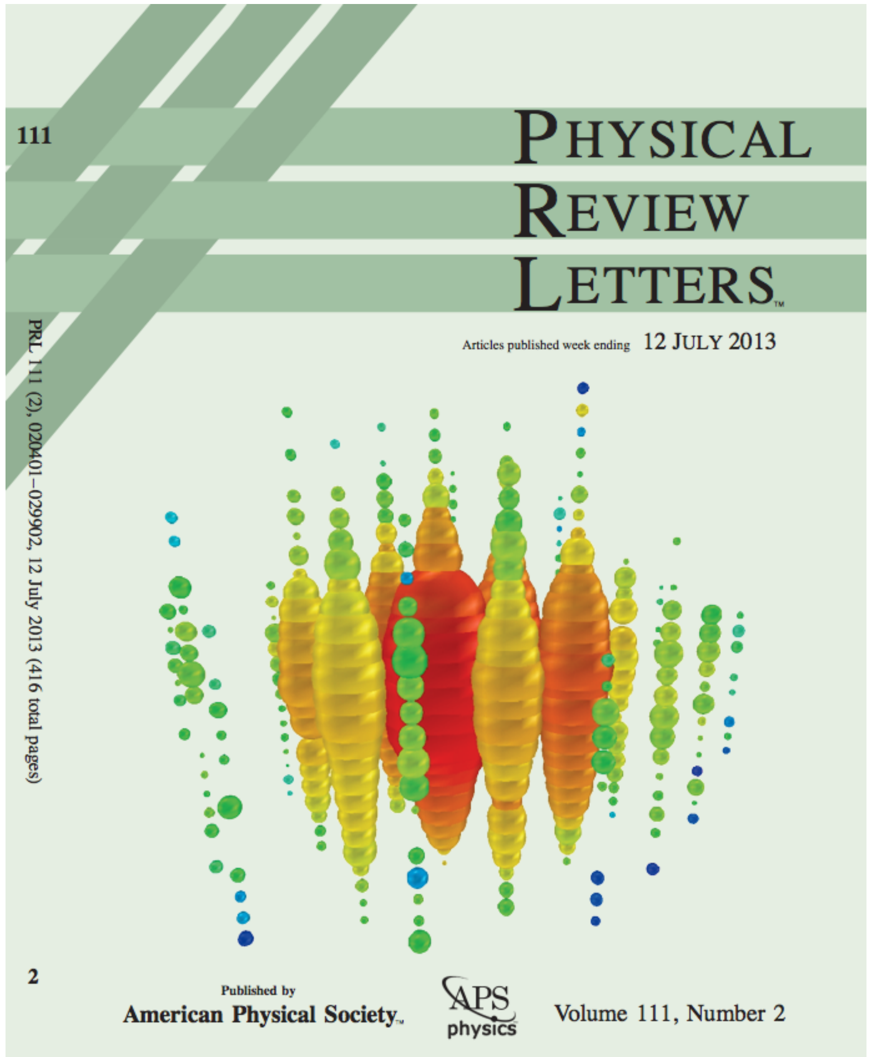

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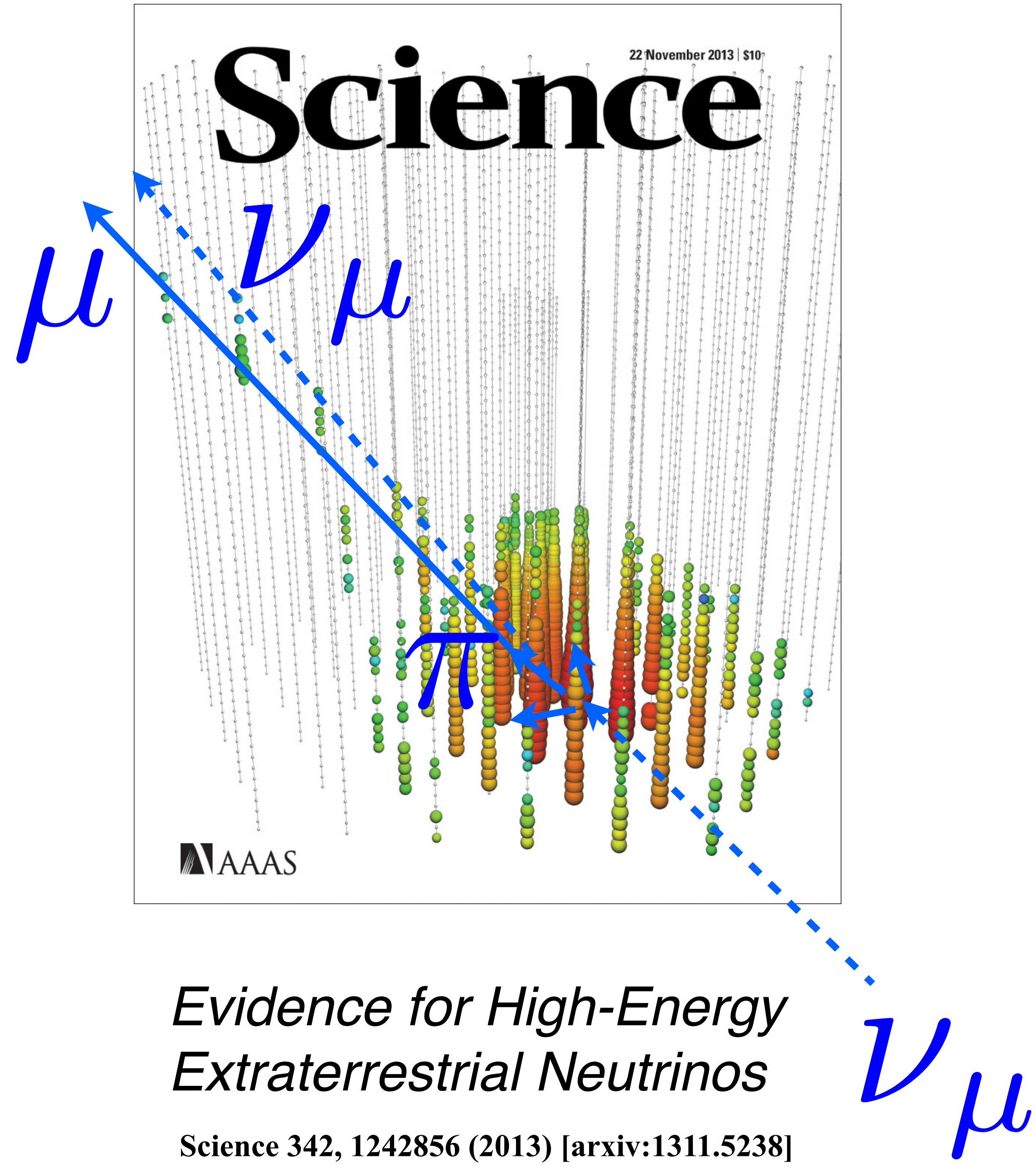

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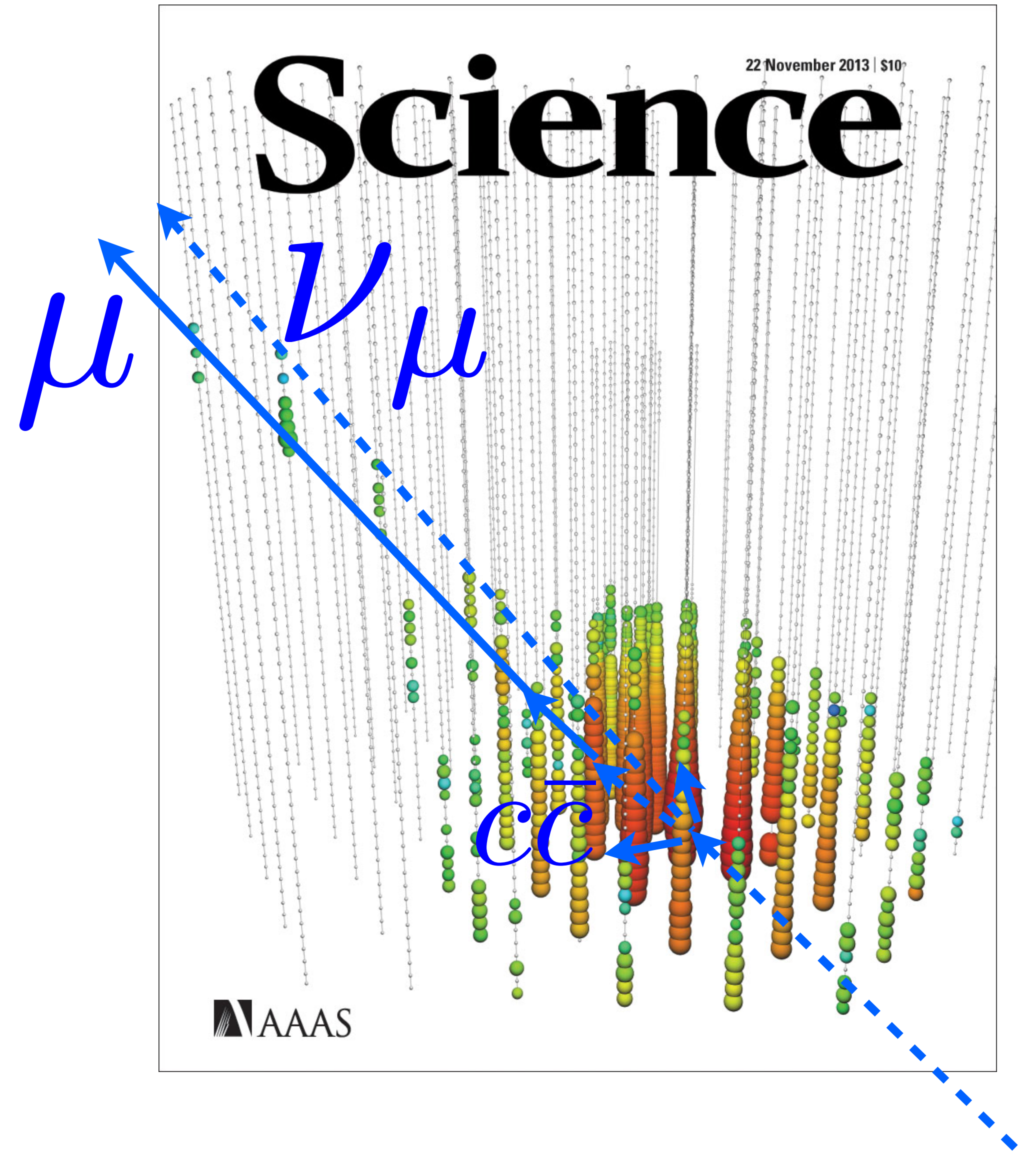

Evidence for High-Energy Extraterrestrial Neutrinos

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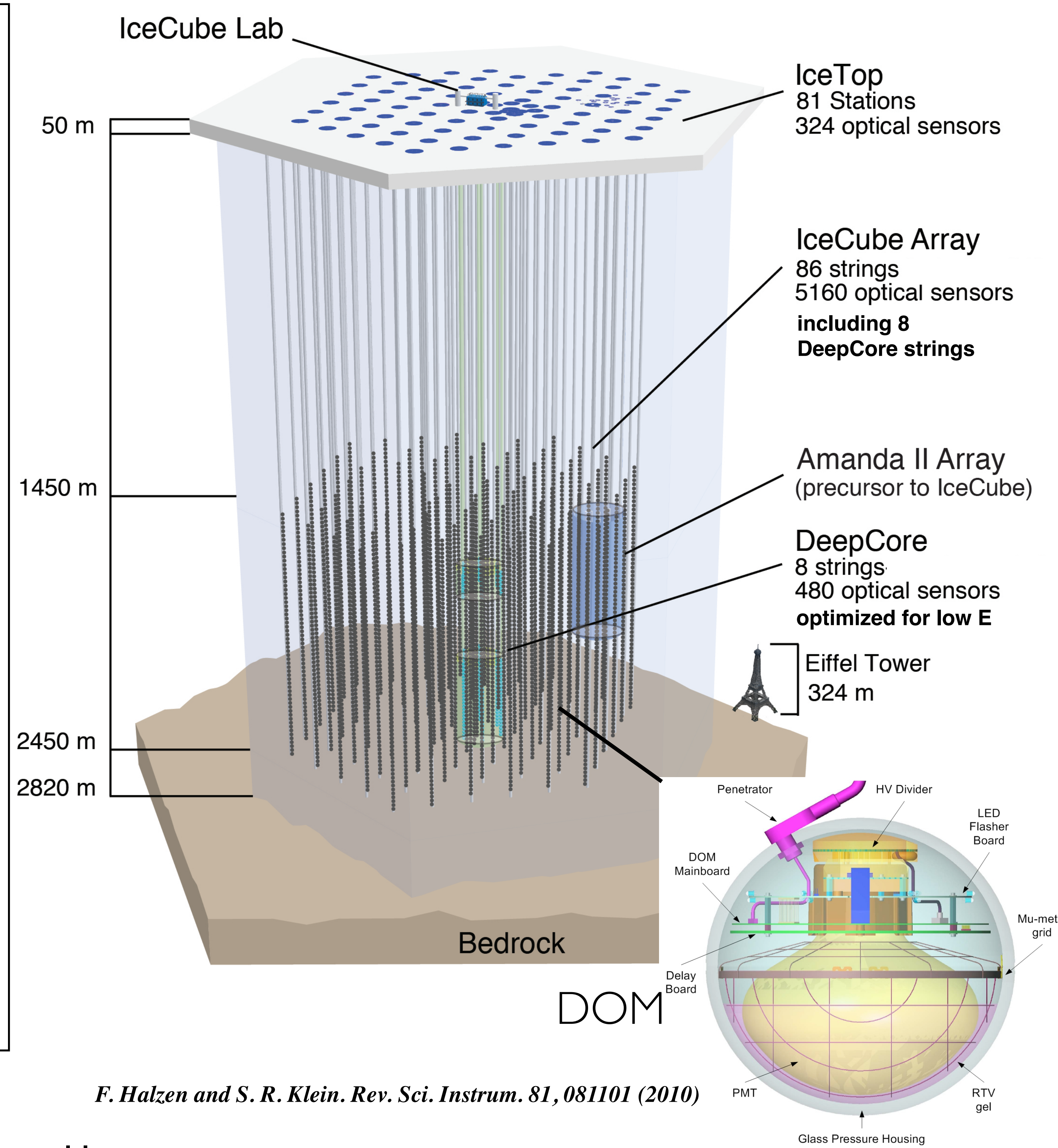
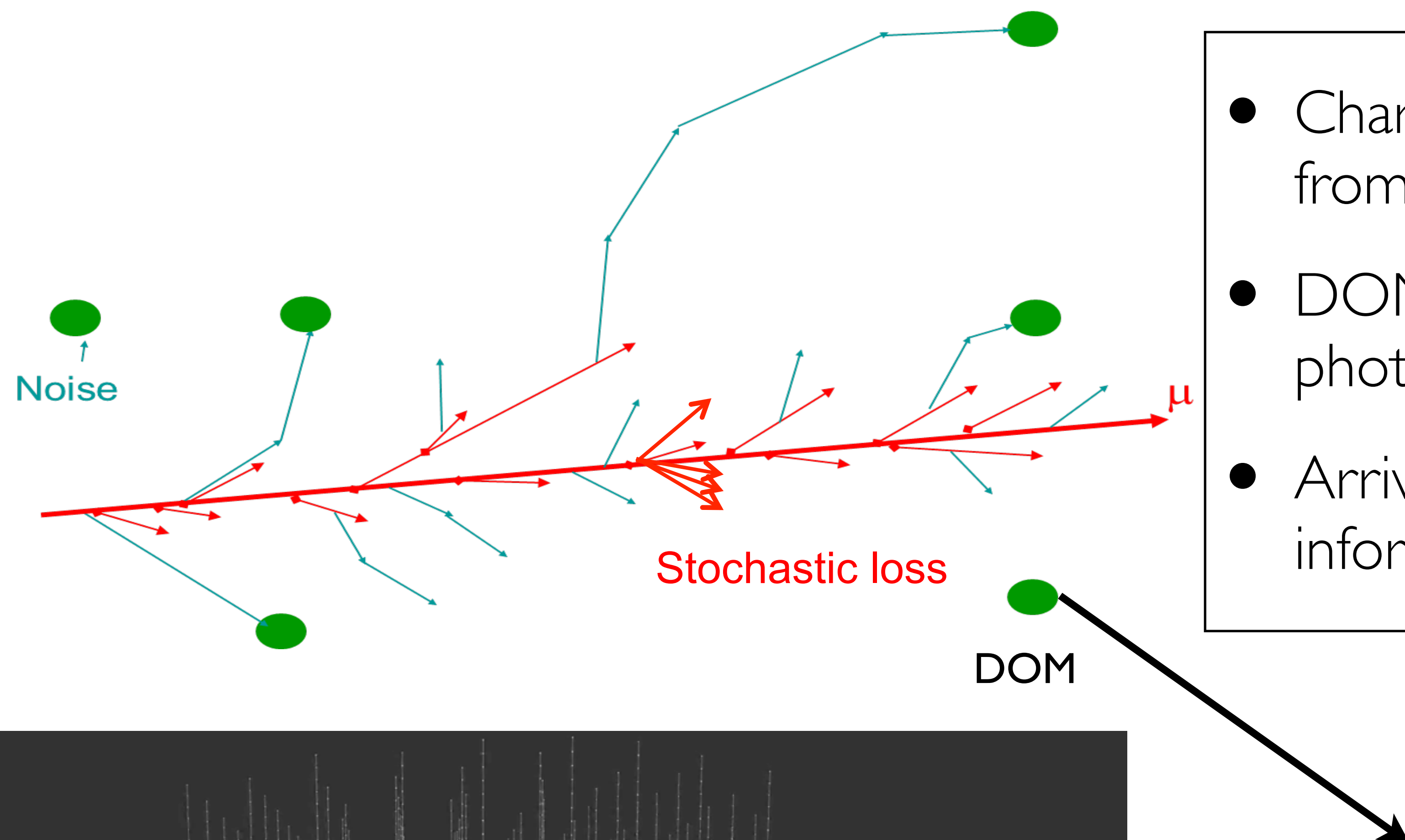
IceCube : 1 km^3 Neutrino Telescope

- 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 ($E_{threshold}$ ~ 10 GeV) DeepCore array
  - 8 strings include high quantum efficiency DOMs

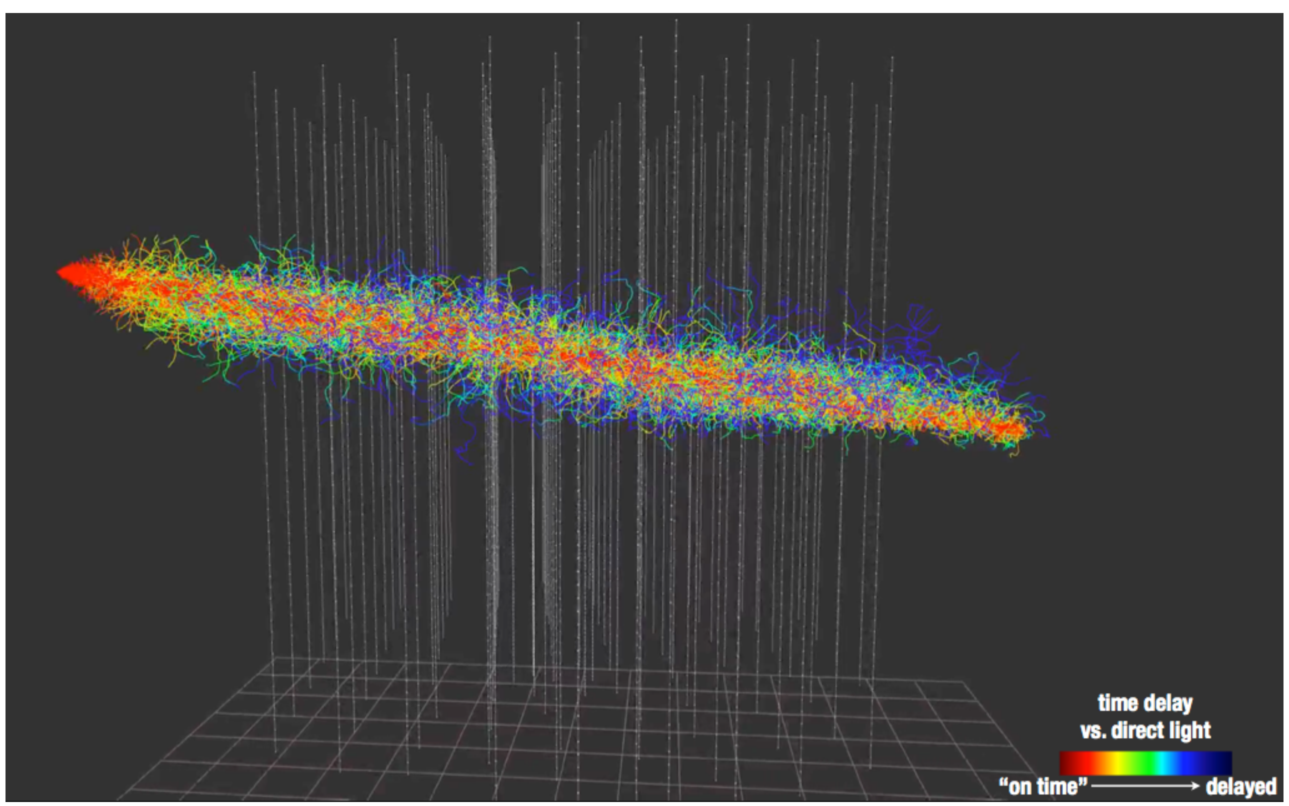


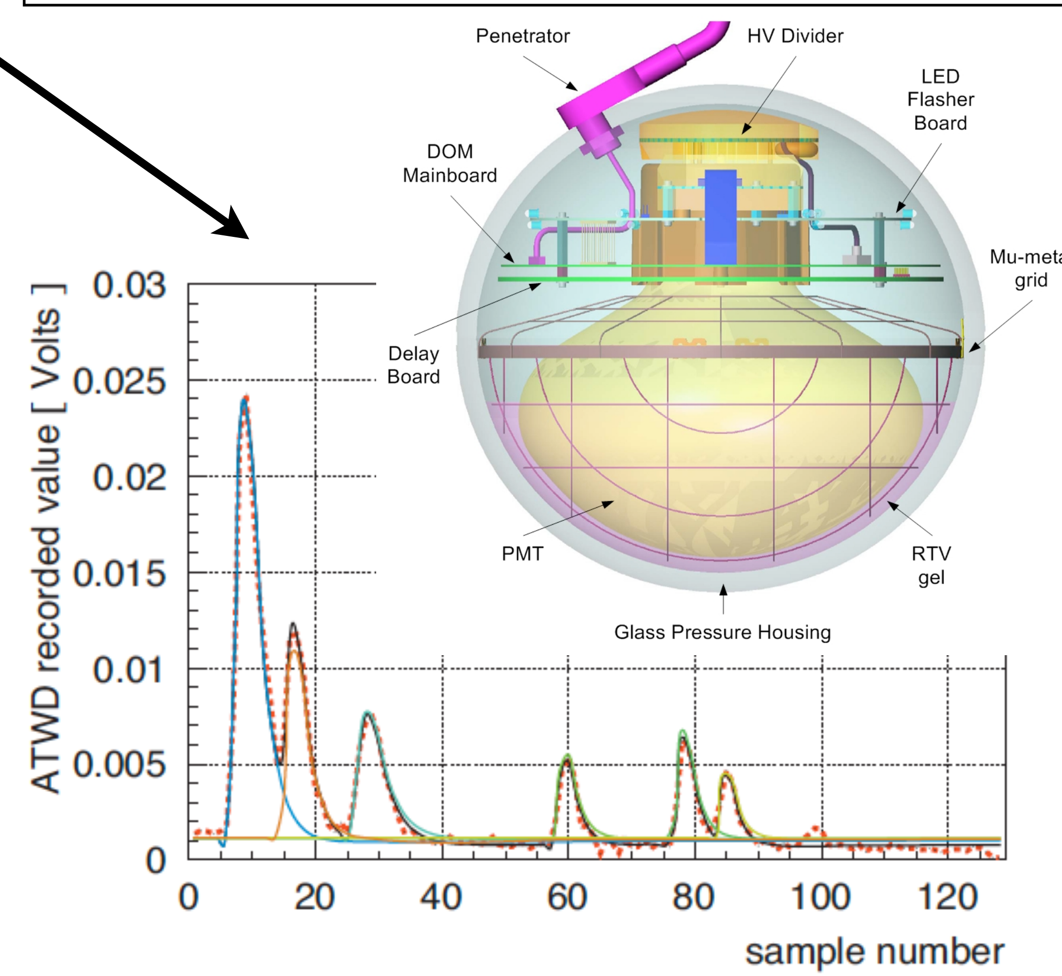
F. Halzen and S. R. Klein. Rev. Sci. Instrum. 81, 081101 (2010)

Waveforms from charged particles in ice

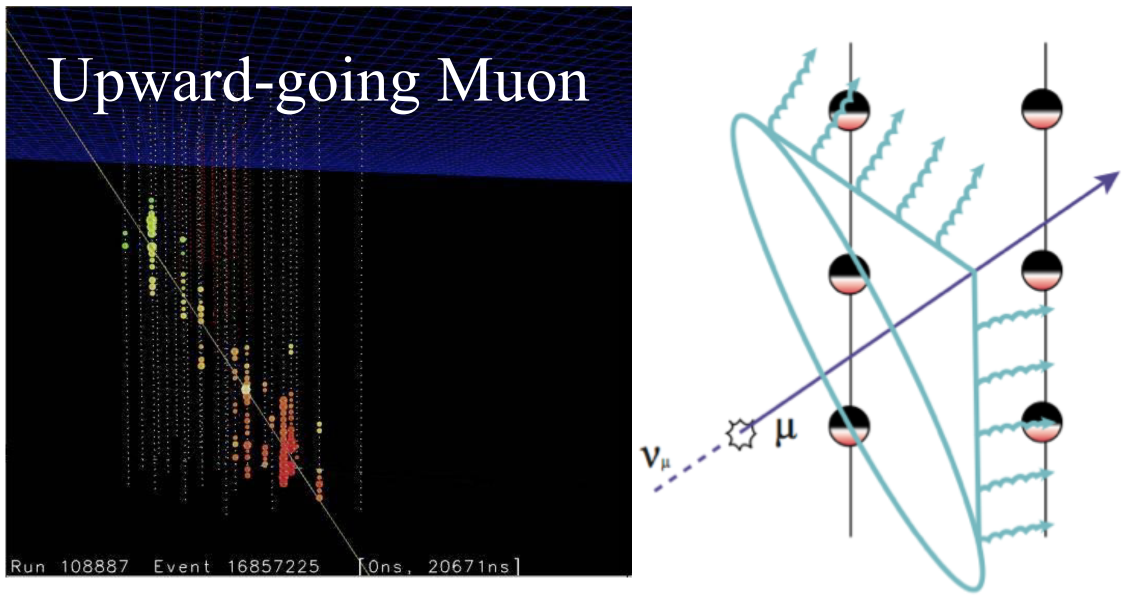


- Charged particles produce radiation from ionizations and stochastics in ice
- DOMs digitize the PMT waveforms of photoelectrons
- Arrival time and recorded charge information used to reconstruct events



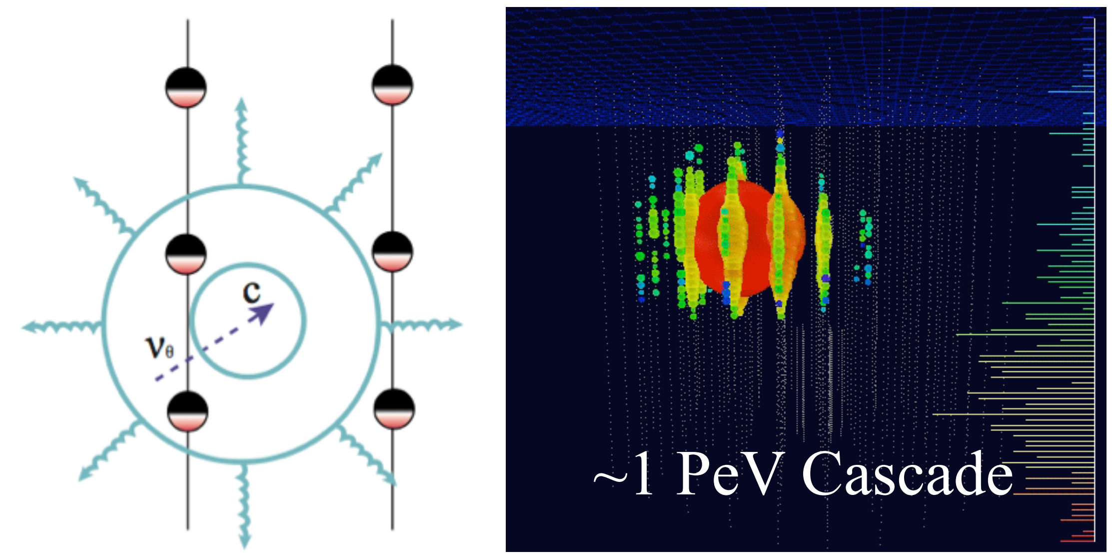


Detection Methods : Cherenkov Radiation



track

limited energy resolution
~1° angular resolution



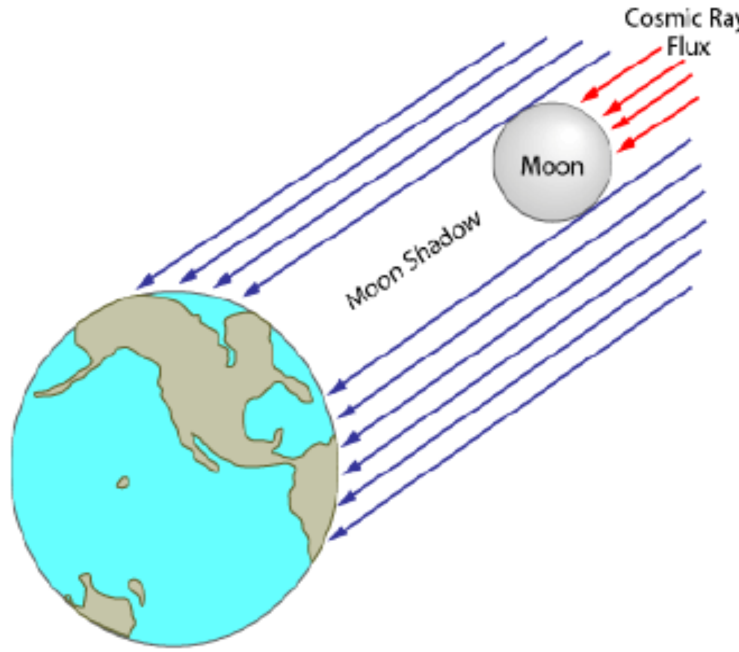
cascade

~15% energy resolution
~10° angular resolution

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	E.M. shower + Hadronic shower
ν_τ^{CC}	$\nu_\tau + N \rightarrow \tau + X$	cascade	tau travels ~50 m at 1 PeV
ν_α^{NC}	$\nu_\alpha + N \rightarrow \nu_\alpha + X$	cascade	$\alpha = \mu, e, \tau$

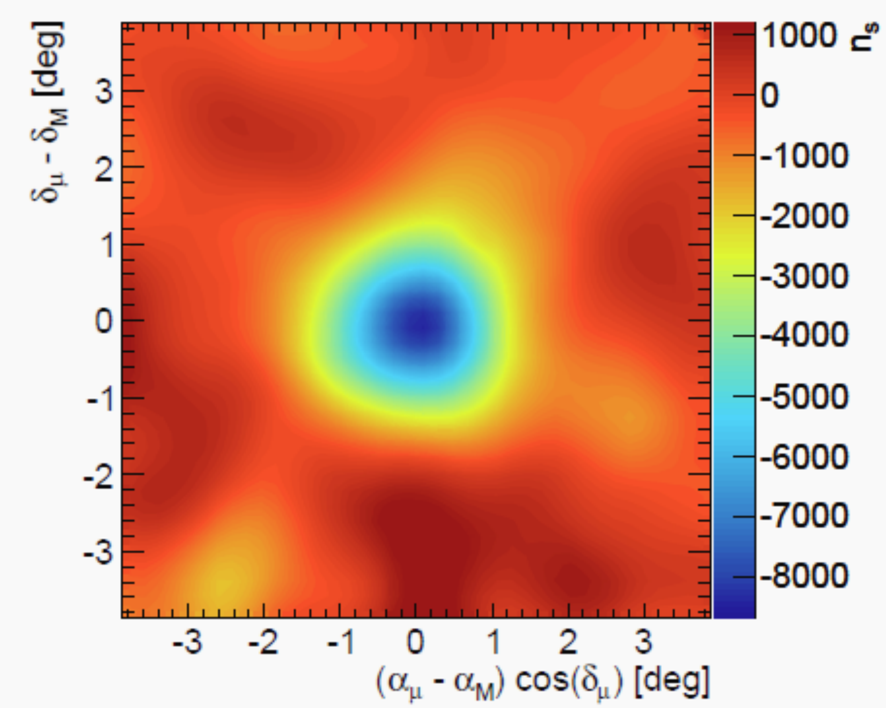
N= Target Nucleon and X = Hadronic Shower

IceCube Detector Performance

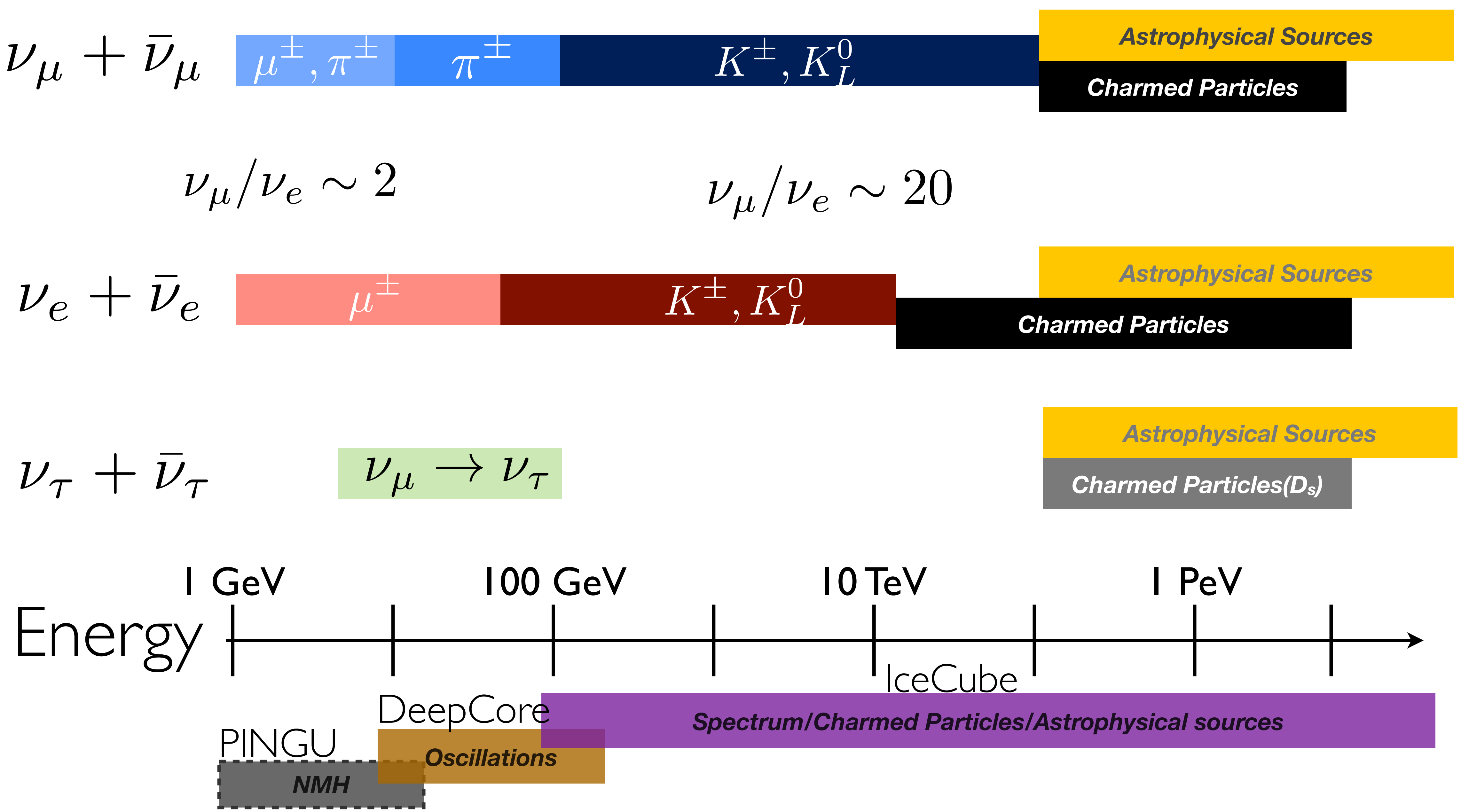


- The full detector (86 strings) has been running for 3 years (Currently taking the fourth year data)
- IceCube built on time, on budget, and exceeds design requirements
  - 5160 Sensors are deployed, only 1.5% not taking data
  - 99% up-time
- Cosmic ray Moon shadow verifies better than 1° angular resolution and correct pointing.
- Understanding optical properties in ice is an ongoing calibration effort (NIM. A711 (2013) 73)
- High-E sample ~7 X 10^{4} ν_μ per year (1.3 event per 10 min) at final analysis level (<E>~1TeV).
- Low-E sample (DeepCore) ~10^{4} ν_μ per year at final (<E>~30 GeV)

arXiv:1305.6811

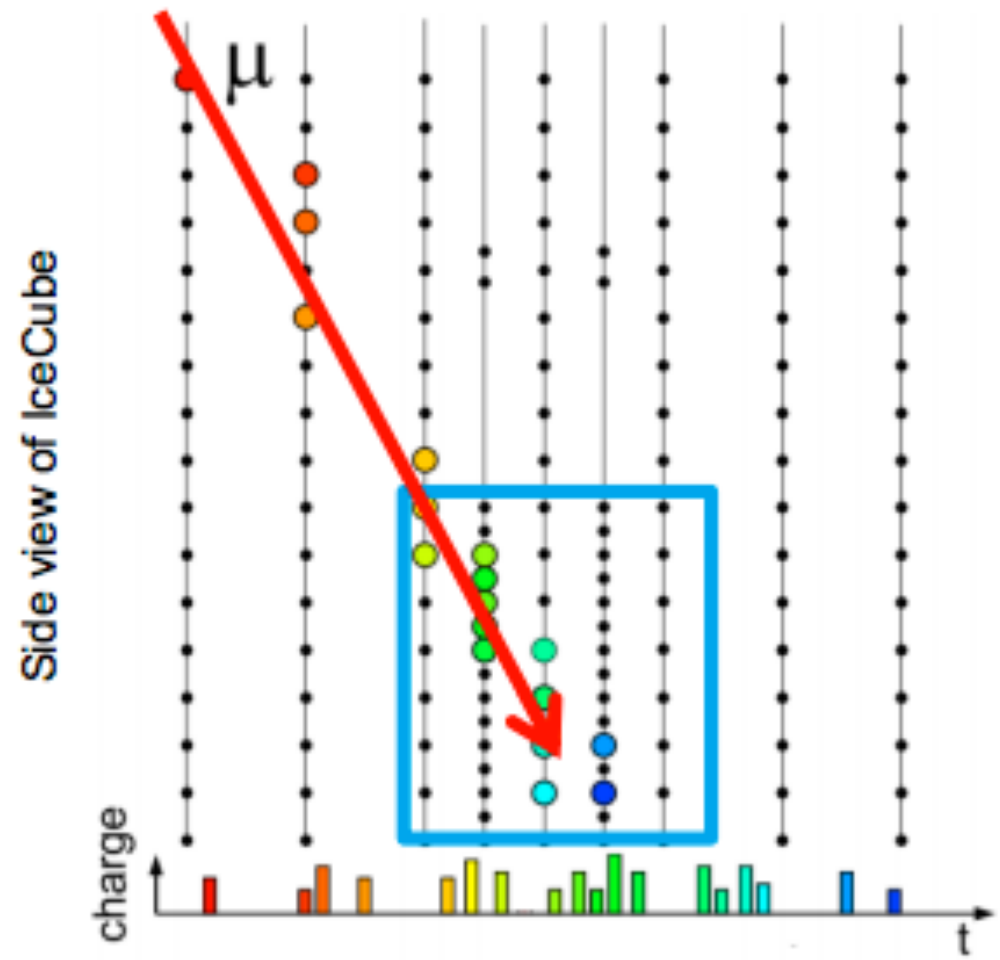


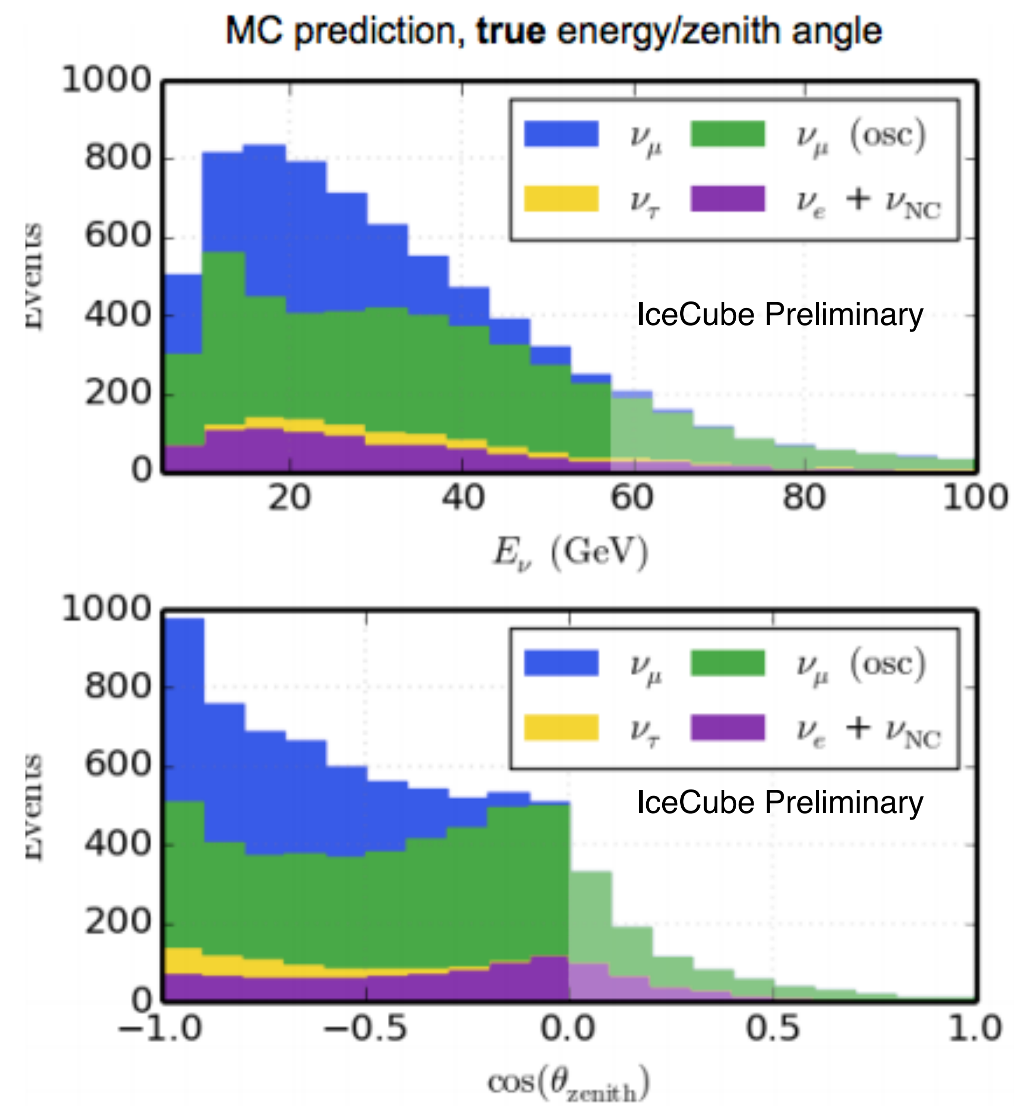
Sources of Neutrinos (Atmospheric/Astrophysical)



Neutrino Oscillations : ν_μ Disappearance

Zenith Angle and Energy with 3 year DeepCore (953 days)





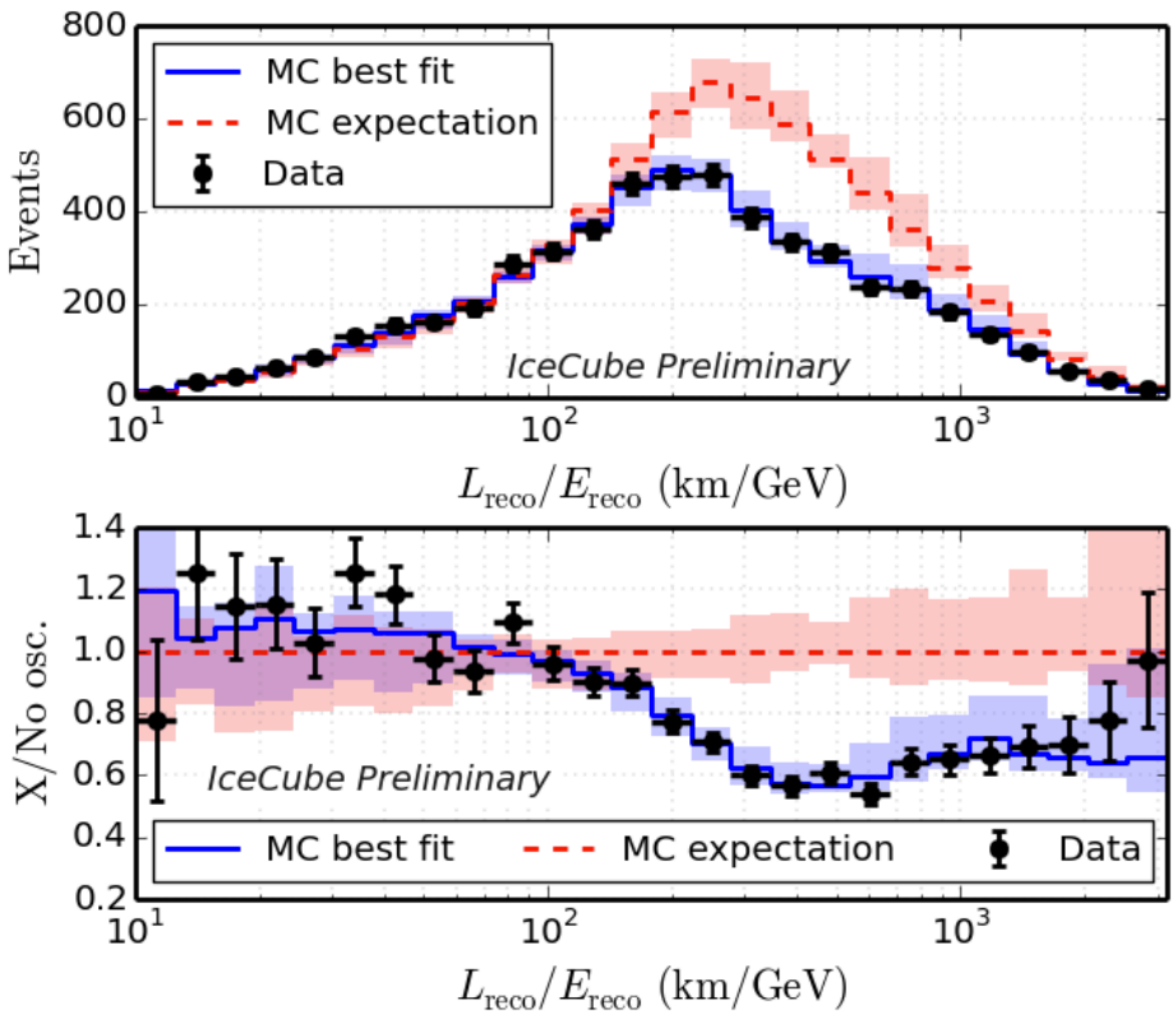
-Veto bkg. events that originate outside of the fiducial volume
-Analysis optimized for the lowest energy upward neutrino events

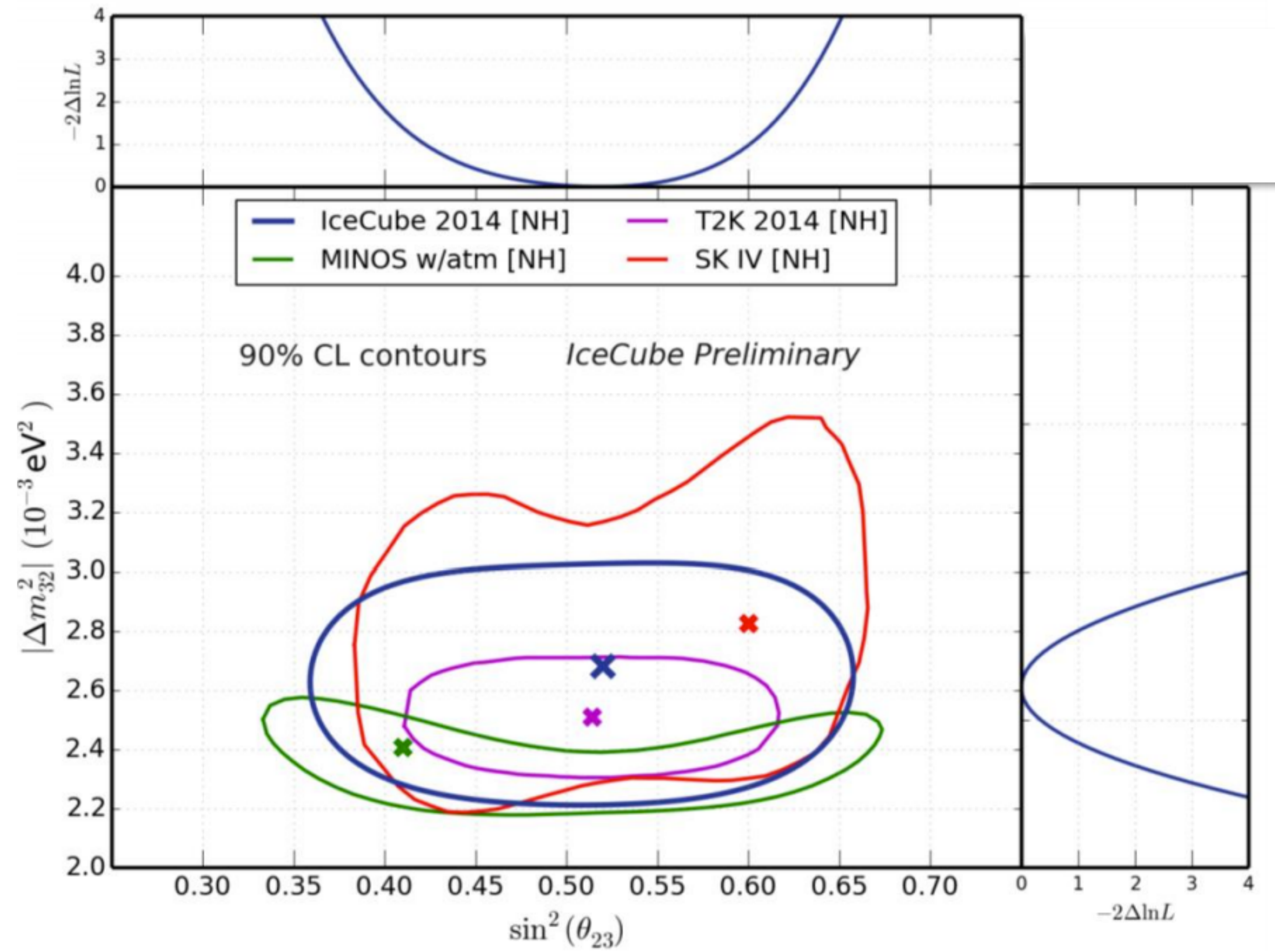
-No osc. prediction: 7000 events total (~30% disappeared)
-Energy Resolution : 30% at 10 GeV
-Zenith Resolution : 12 deg. at 10 GeV

Neutrino Oscillations : ν_μ Disappearance

Zenith Angle and Energy with 3 year DeepCore (953 days)

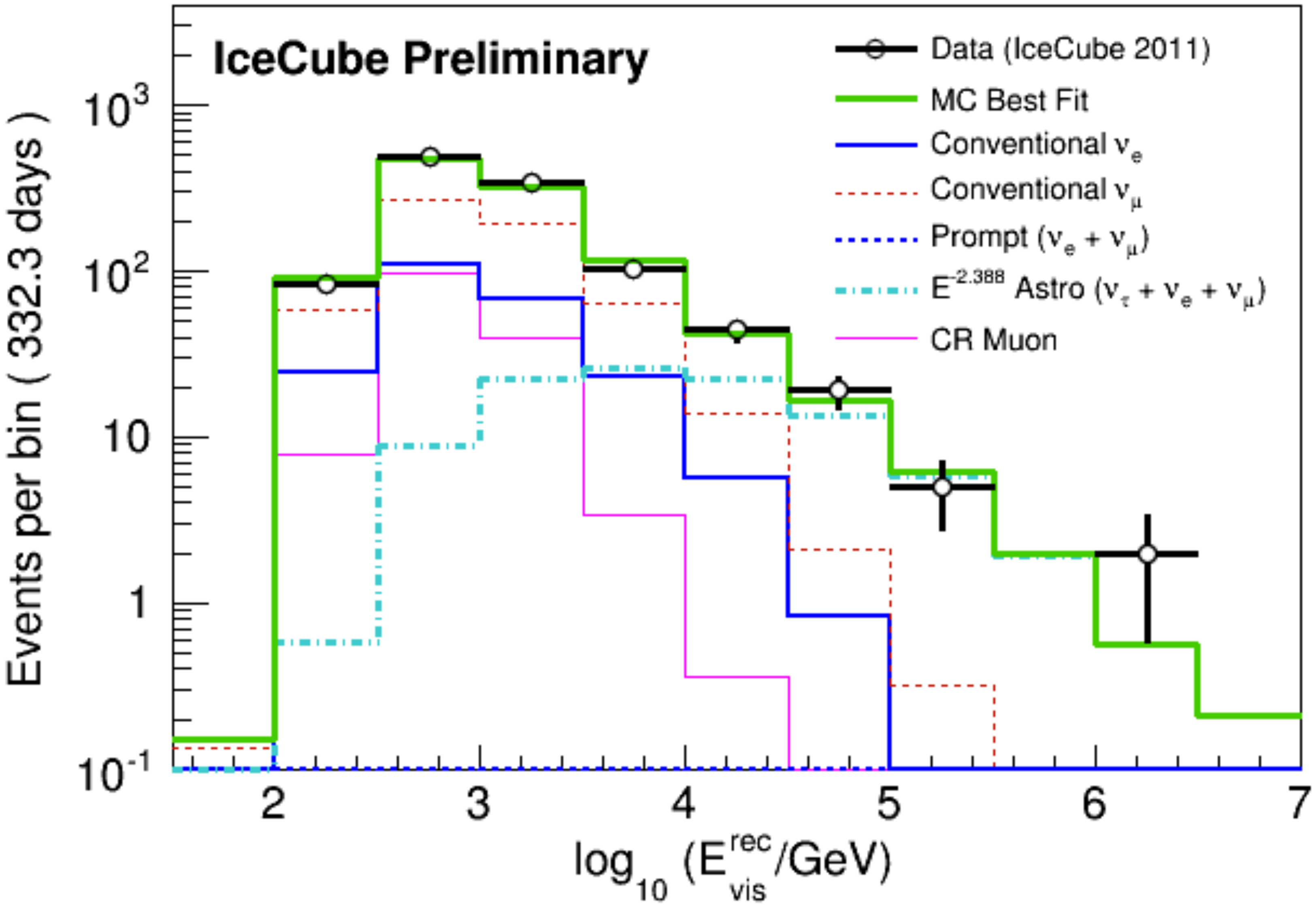
Bands: variations allowed by the systematic uncertainties ***assumed***

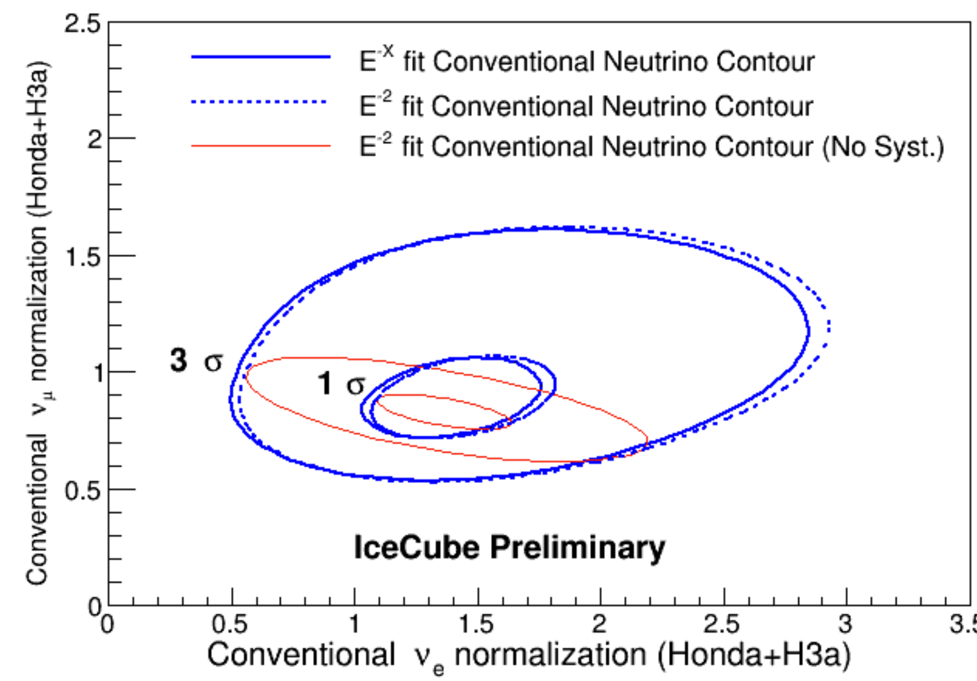




3-flavor oscillations measured with the high energy atmospheric neutrinos
Measurements are consistent with other results
We continue to improve the systematic uncertainties.

Atmospheric Spectrum Analysis (Cascades) Observables : Energy, Zenith angle, and PID

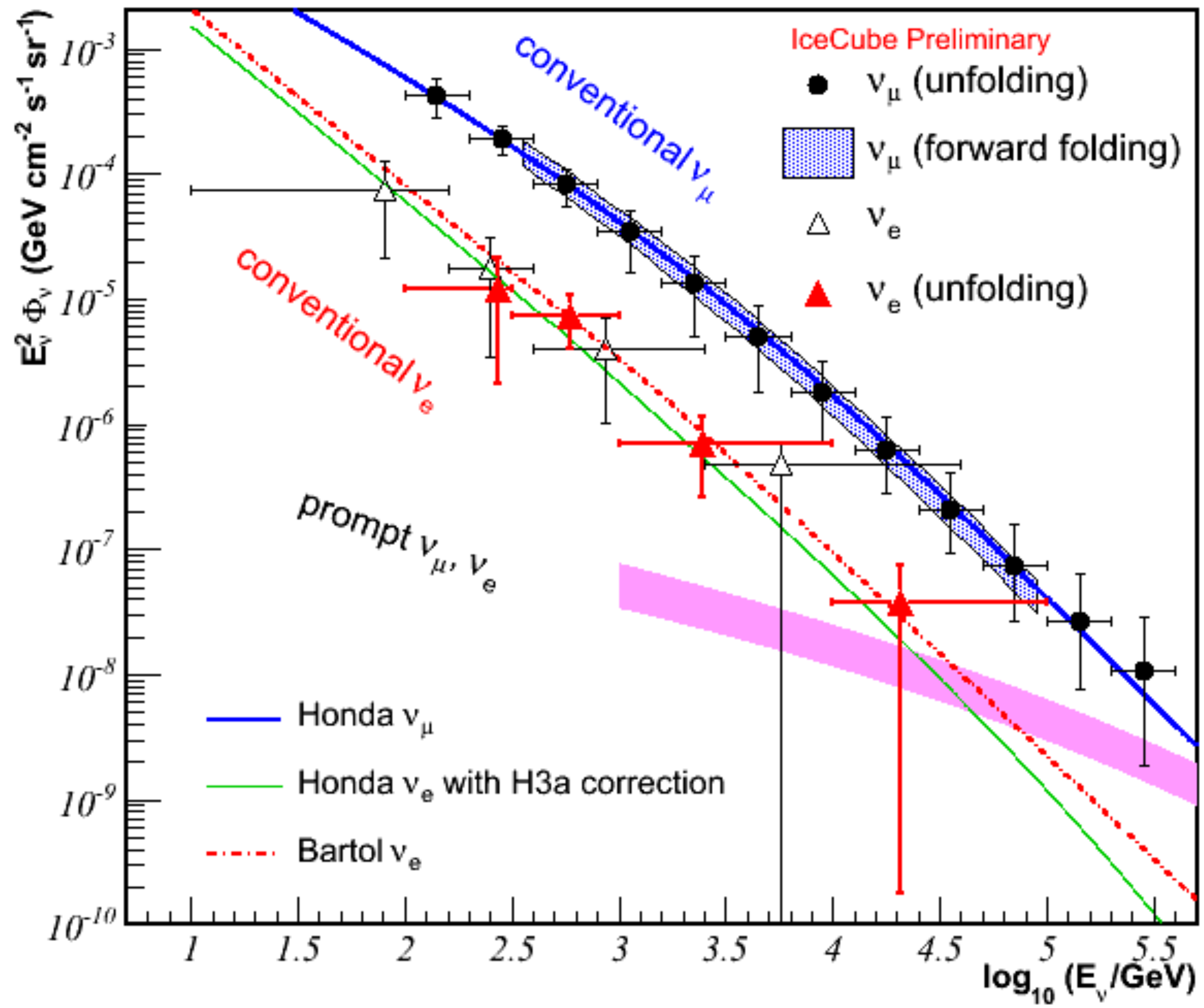




3-D Likelihood Fit with systematics as nuisance parameters to disentangle atmospheric components from astrophysical components

Atmospheric Neutrino Flux

- Conventional Neutrino flux (pi/K) follows a steep spectrum $\sim E^{-3.7}$
- NuE components are obtained from unfolding
- Measurements agree with models
- Prompt neutrino flux follows a spectrum $\sim E^{-2.7}$ (not measured yet)



ERS : Baseline Prompt Model

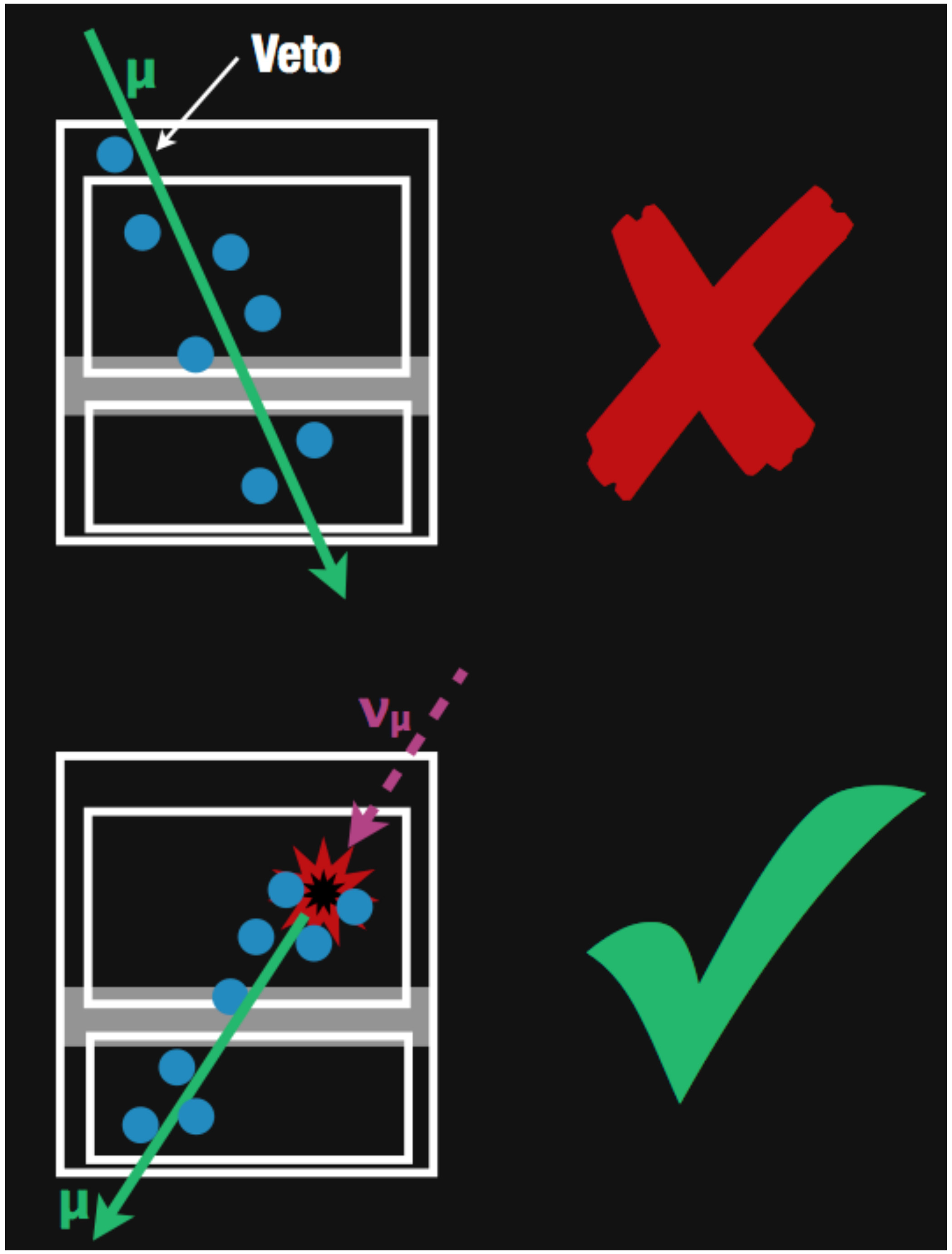
PHYSICAL REVIEW D **78,** 043005 (2008)

Atmospheric Neutrino Veto

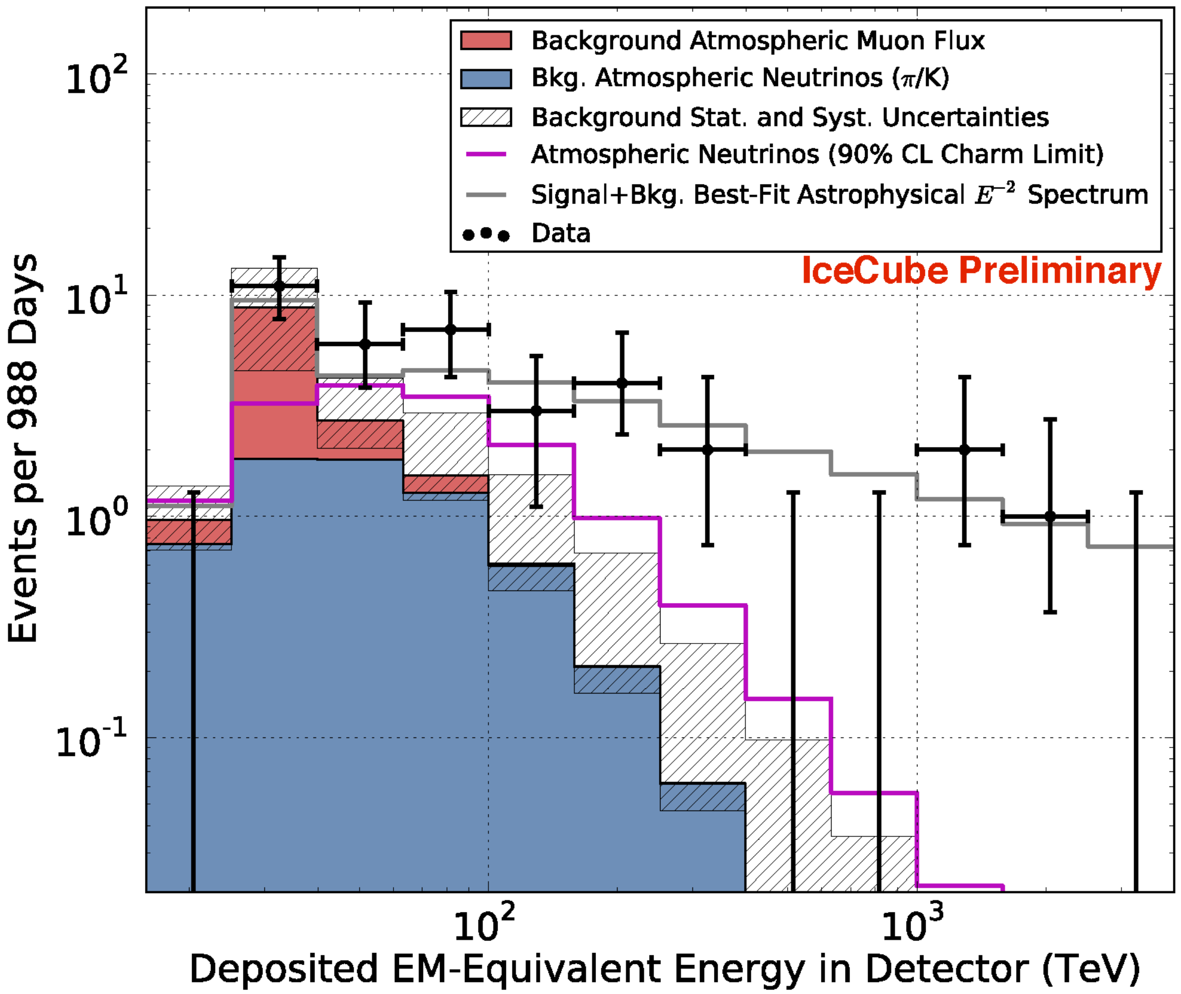
PHYSICAL REVIEW D **90,** 023009 (2014)

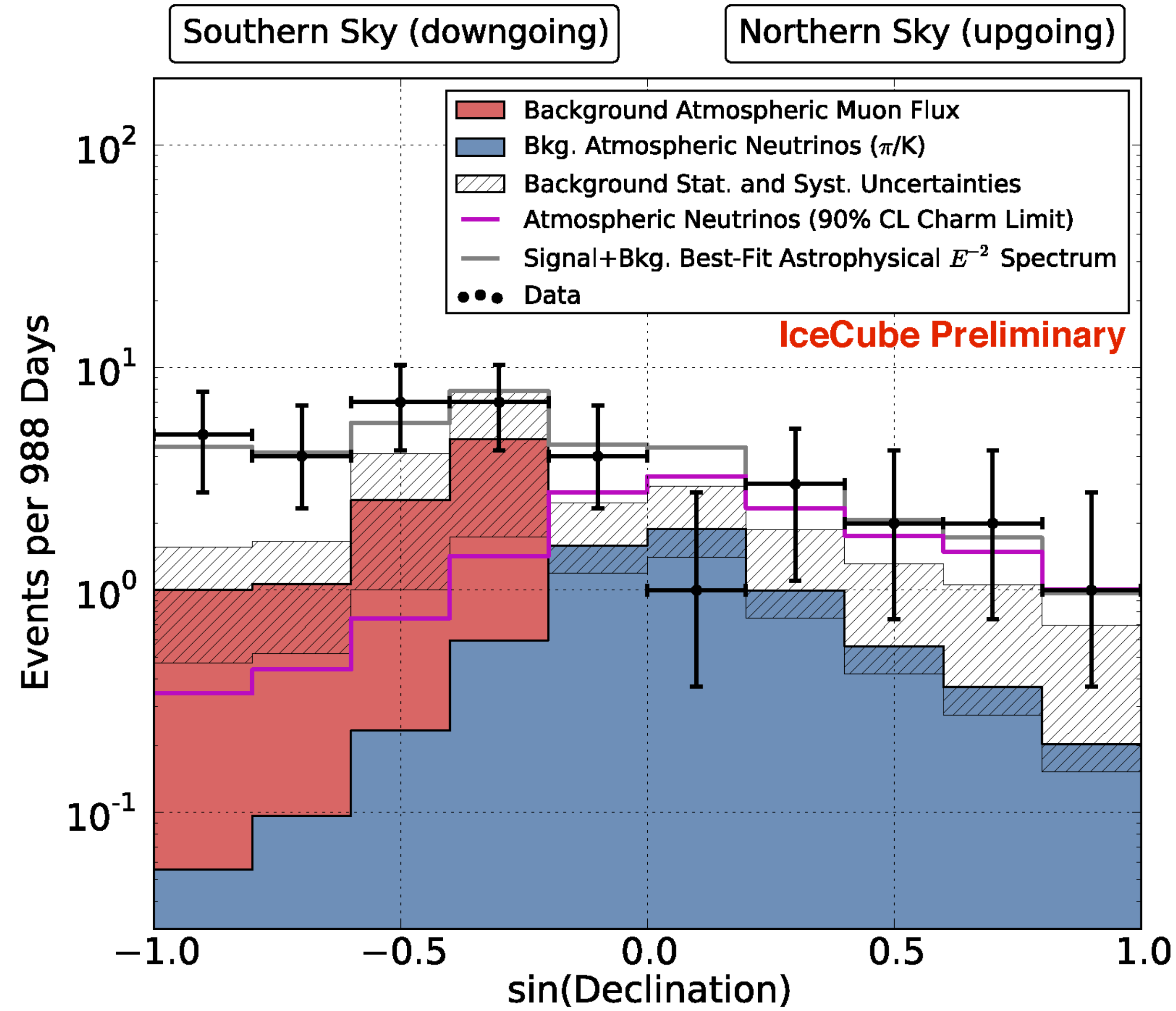
High Energy Starting Event Search

- 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



Astrophysical Neutrinos





Arxiv:1405.5305

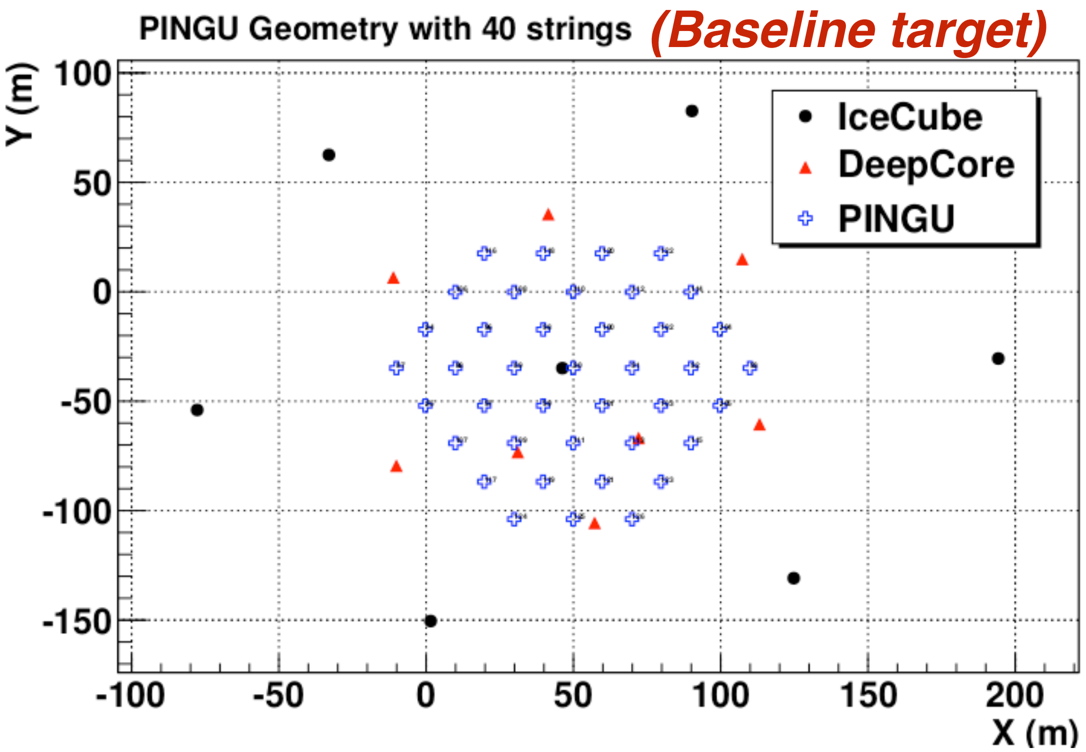
37 events in three years of data

- 8.4 +/- 4.2 atmospheric muons (background)
- 6.6+5.9-1.6 atmospheric neutrinos (background)

High confidence of non-atmospheric source of neutrinos
(5.7 sigma rejection of atmospheric-only hypothesis)

Future Direction : PINGU

(Precision IceCube Next Generation Upgrade)



- Instrument additional 40 strings
  - 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Low risk, Quick deployment

- Neutrino Mass Hierarchy measurement with PINGU
  - Neutrinos with Earth matter and density effect in varying baseline
  - Understanding the systematics is the key to the measurement
  - Additional calibration devices can be added

Oscillation Probability x Cross-section x Flux = Event Rate(N)

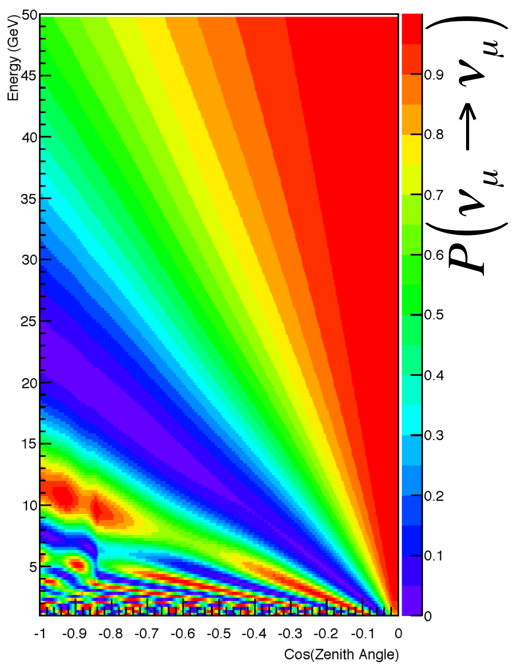
NH: Normal Hierarchy

IH : Inverted Hierarchy

ν_μ anti-ν_μ

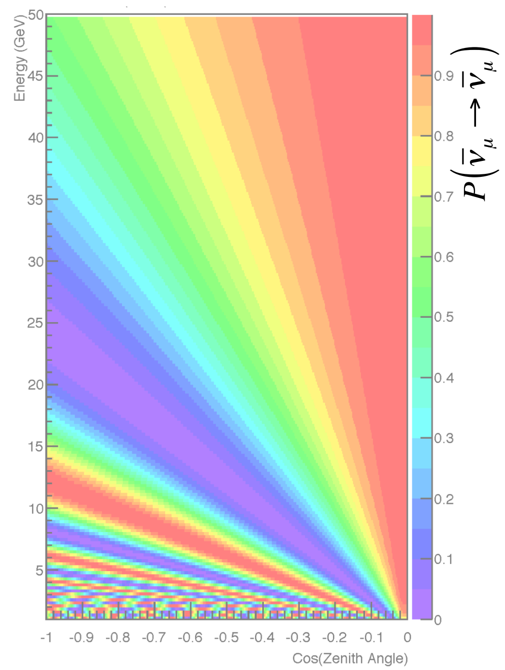
Energy

NH



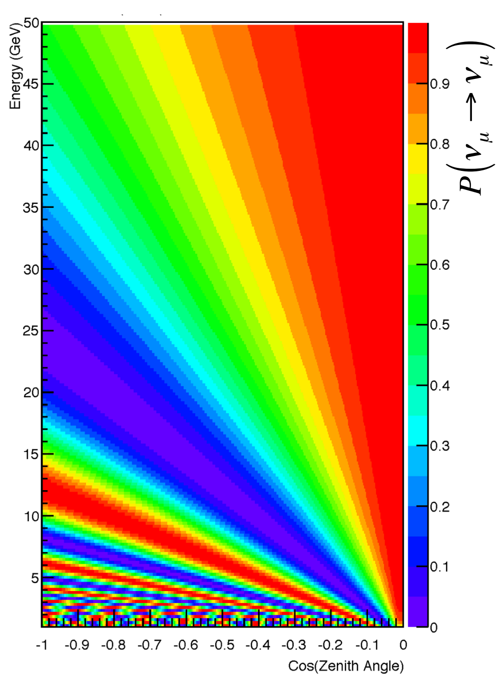
cos(θ)

+



$= N_{NH}$

IH



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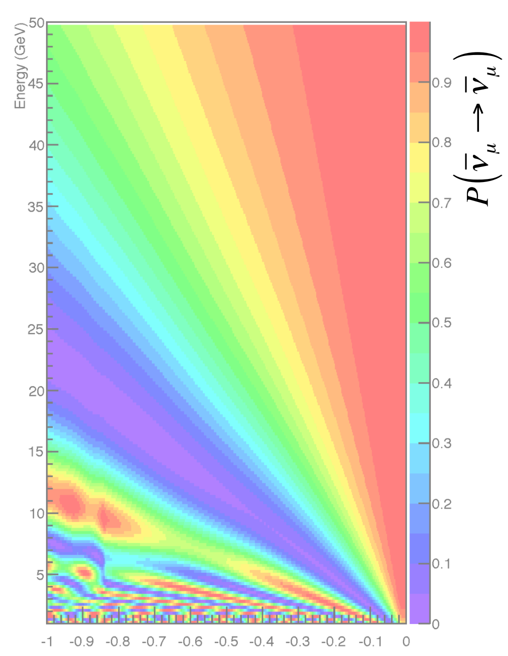


$= N_{IH}$

$\sigma(\nu)\sim 2\sigma(\text{anti-}\nu)$,
$\varphi(\nu_{atm}) > \varphi(\text{anti-}\nu_{atm})$
$\therefore N_{NH} \neq N_{IH}$!
(True for ν_e, too)

Distinguishability Plot

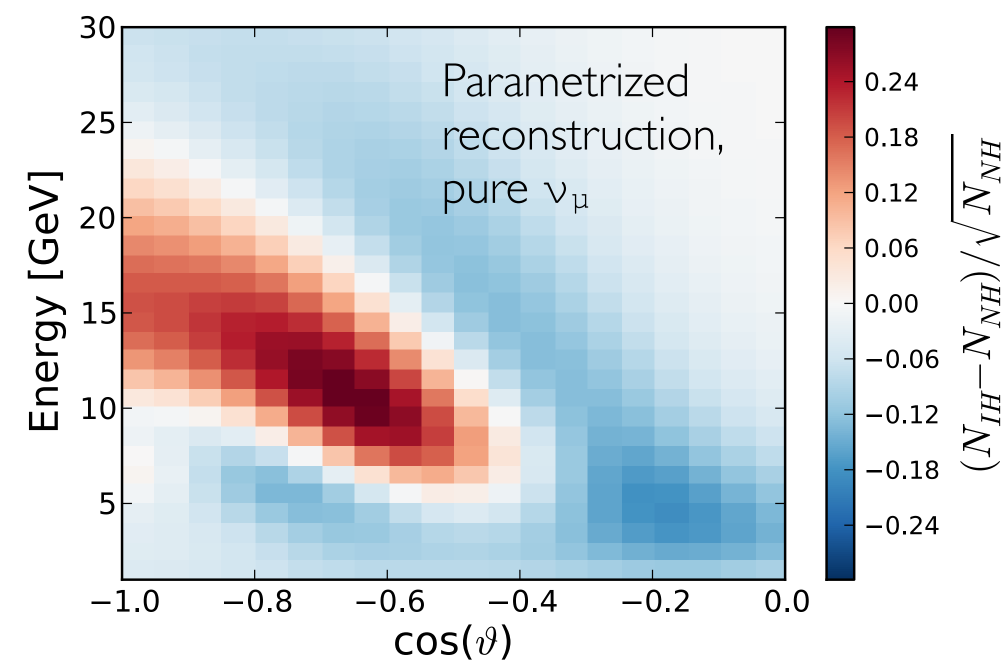
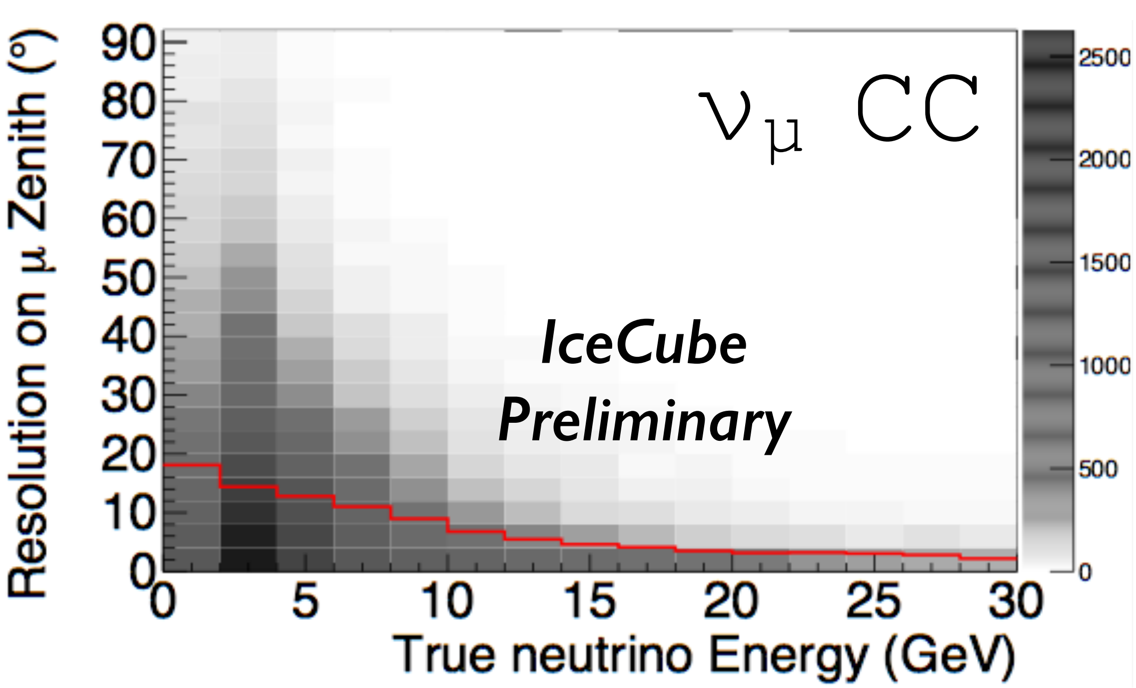
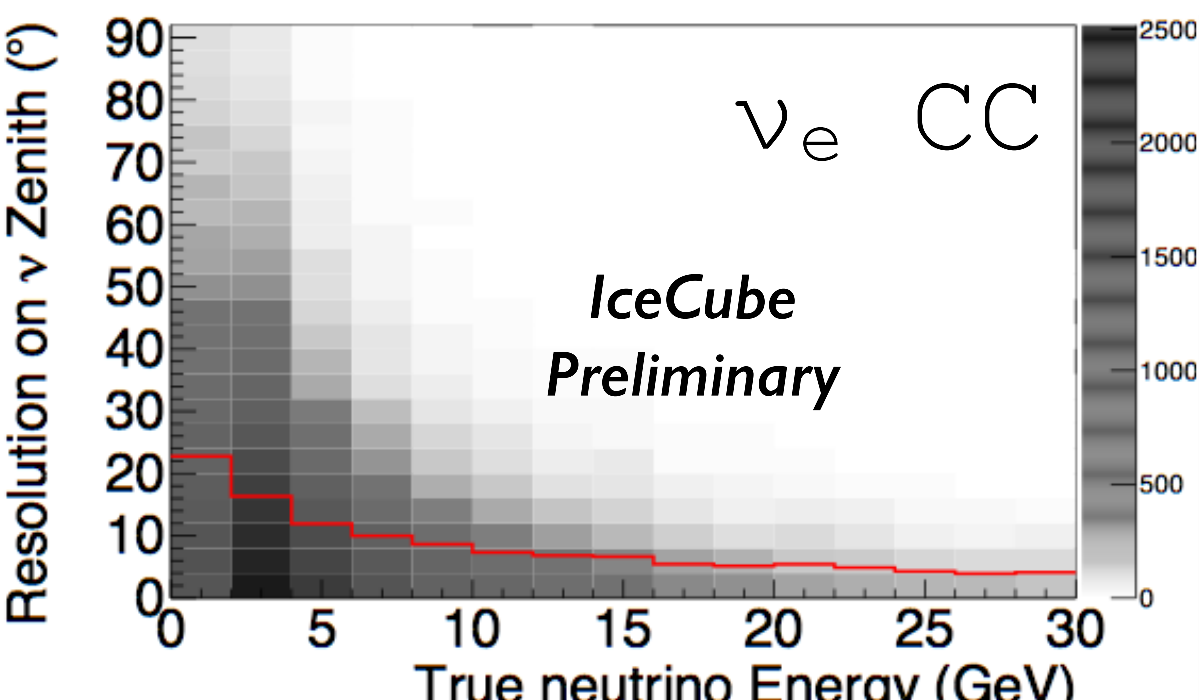


Illustration only

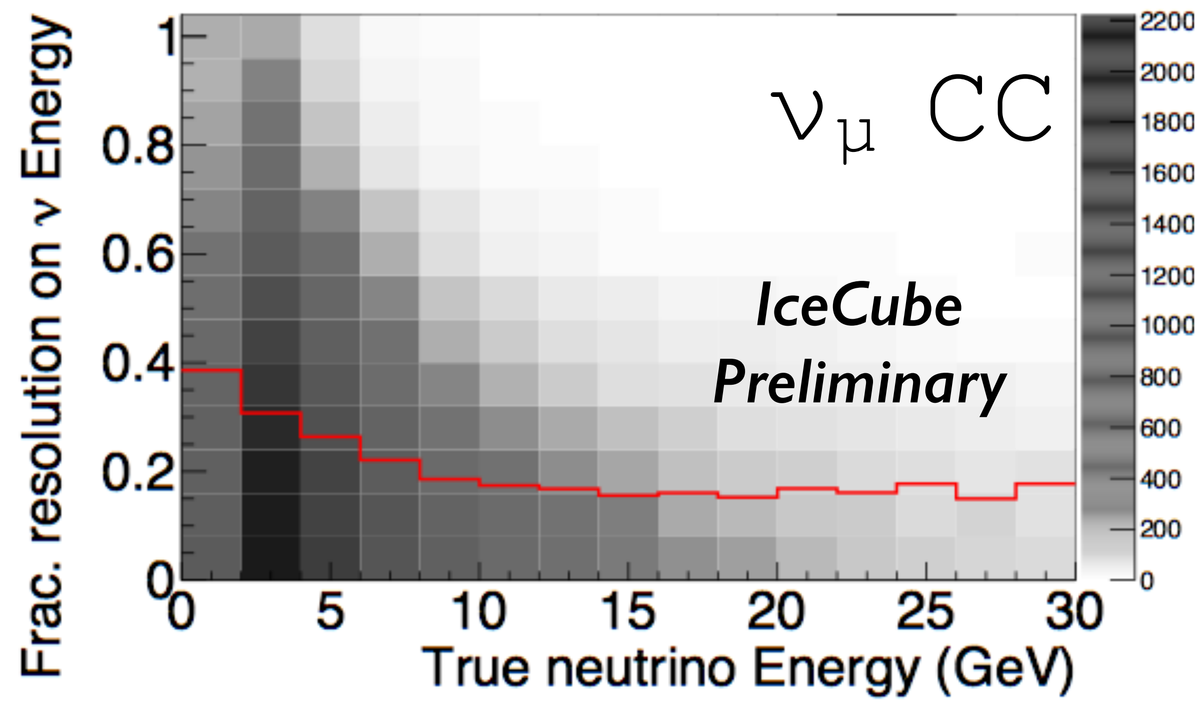
Event Reconstruction Status

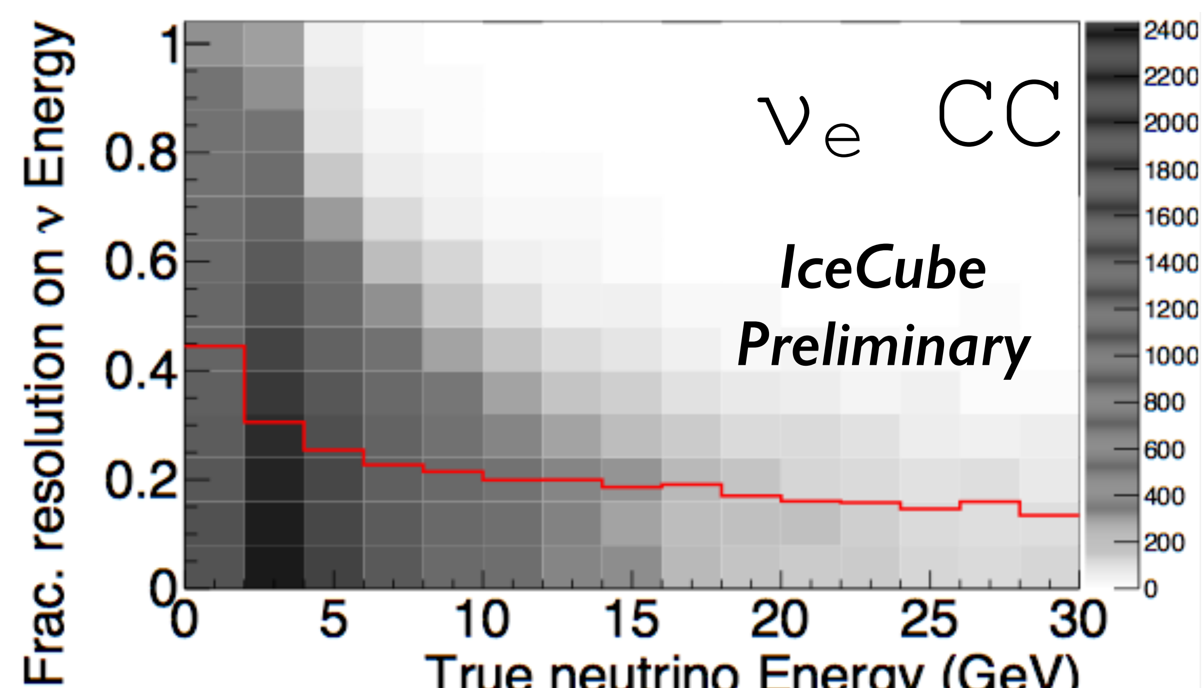
Zenith Angle Resolutions



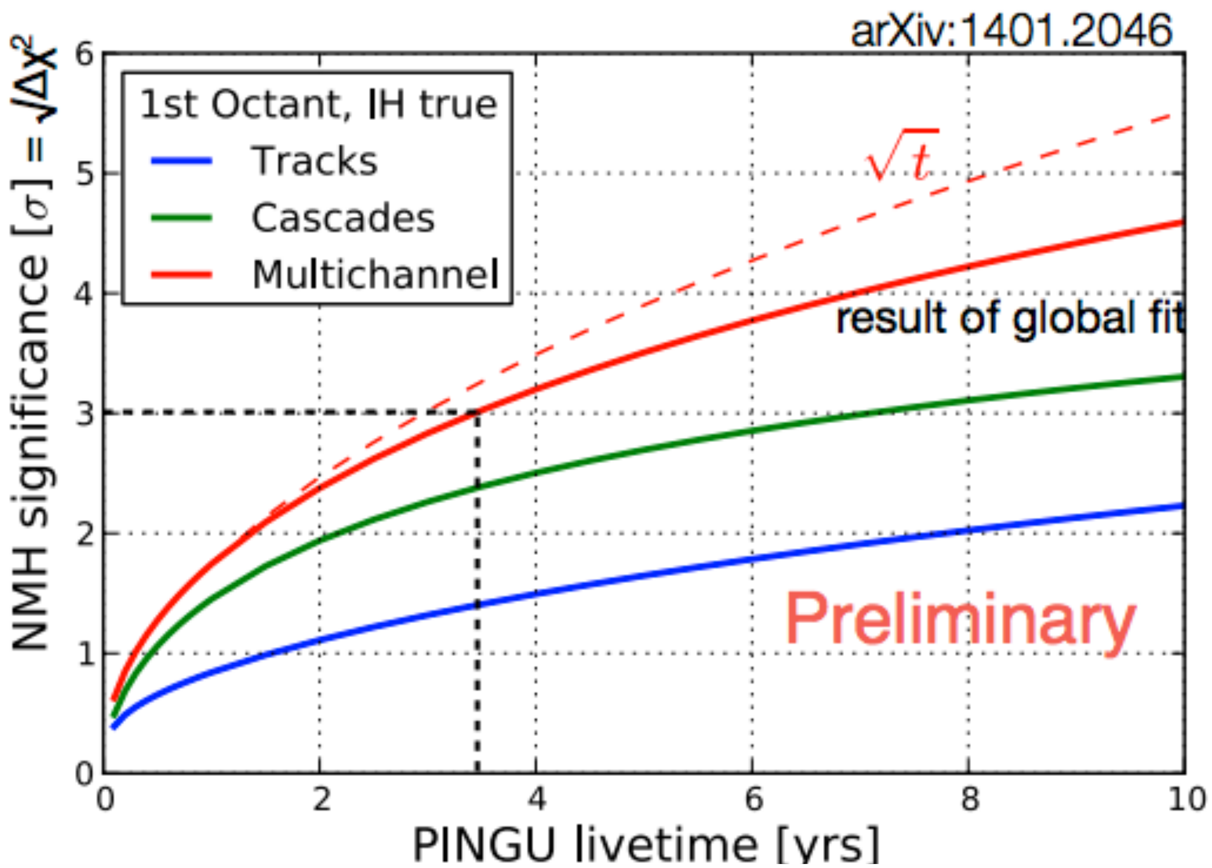


Fractional Energy Resolutions

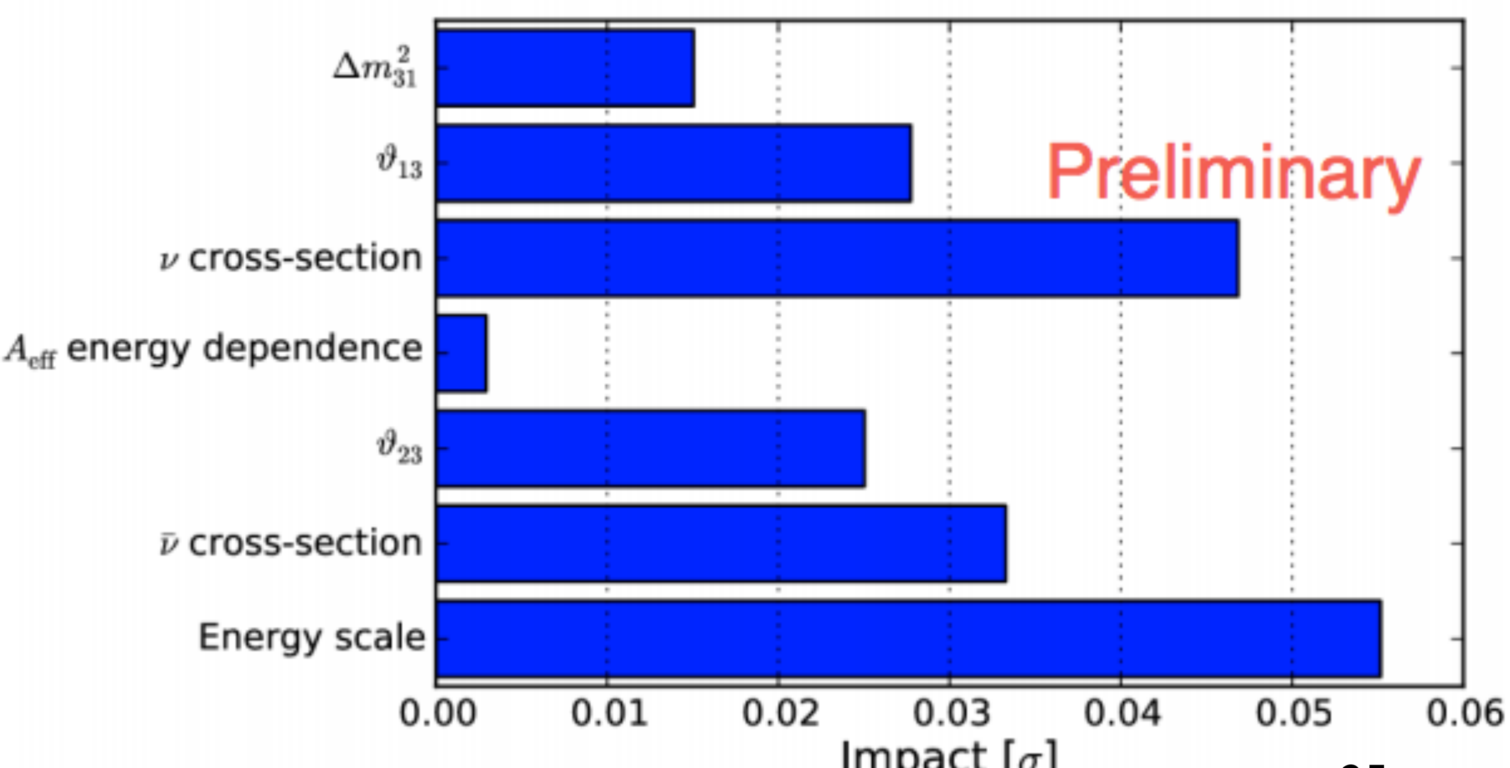




NMH Sensitivity



- 3 sigma result of neutrino mass hierarchy in 3.5 years of data
- Energy Scale & Neutrino Cross section are key systematics



Parameter	Description
Δm^2_{31}, ϑ_{23}, ϑ_{13}	Oscillation parameters
ν / $\bar{\nu}$ cross-section	Cross-section/flux normalization (fully degenerate)
A_{eff} energy dependence	Degenerate with spectral index of atmospheric flux
Energy scale	E_{reco}/E_{true}

Summary

- The IceCube detector is running at full strength
  - Three years of 86-string data are being analyzed while taking the fourth year of 86-string data
  - The detector runs very smoothly (~99% uptime)
- IceCube is a multi-purpose detector
  - Measurement of Atmospheric neutrino flux
  - Observation of astrophysical neutrinos and active prompt neutrino search program
  - Particle physics with DeepCore low energy extension, or possibly with PINGU
  - Other projects : Indirect Dark Matter searches, Exotic particle searches, Follow-up programs, Air shower physics, and so on.
- Highlights from Recent Results
  - The High Energy Starting Event search found 37 events (3 events above PeV) inconsistent with atmospheric backgrounds at ~5.7 σ.
  - Atmospheric neutrino oscillations & neutrino flux measurements (ν_μ and ν_e) agree well with models of atmospheric neutrinos and world average.
  - More data with improved analyses coming soon and PINGU can help determine NMH.