XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

Sep. 16 to 21, 2013 Natal, Brazil

Determining the Neutrino Mass Hierarchy with PINGU

Alexander Kappes for the IceCube Collaboration

XXIV Workshop on Weak Interactions and Neutrinos

Natal, September 17, 2013

News from IceCube & Determining the Neutrino Mass Hierarchy with PINGU

Alexander Kappes for the IceCube Collaboration
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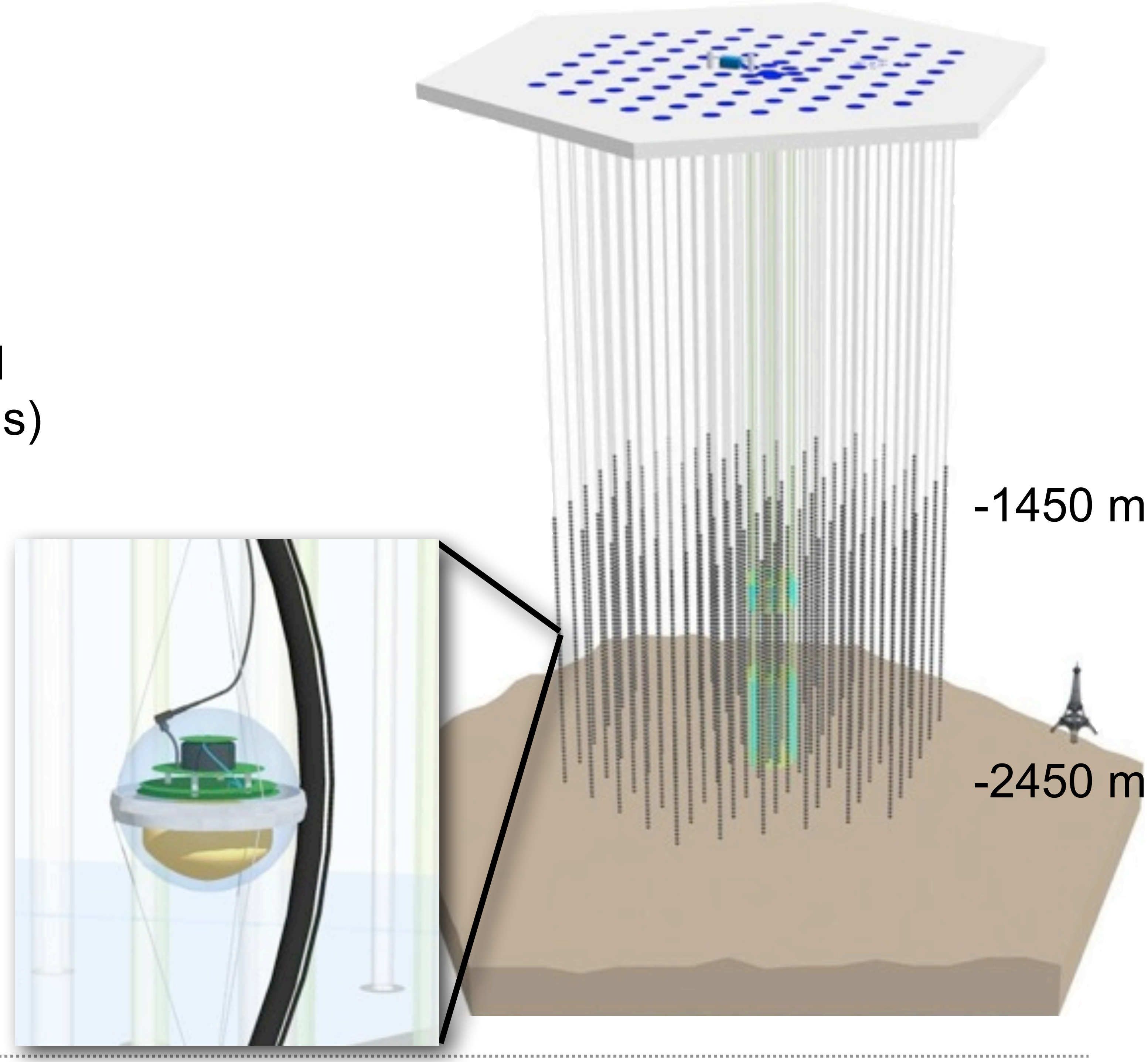
Outline

- The IceCube neutrino observatory
- Selected results from IceCube
  - high-energy neutrinos
  - search for Dark Matter in the Sun
  - atmospheric neutrino oscillation
- PINGU and the neutrino mass hierarchy
  - neutrino oscillation and mass hierarchy
  - current status of sensitivity studies to mass hierarchy

The IceCube Observatory

- IceTop: Air shower detector
- InIce: 86 strings (5160 PMTs)
  Instrumented volume: 1 km^3
- DeepCore: densely instrumented central region (8 dedicated strings)
- Optical sensor
  10” photomultiplier (PMT)
  + in situ signal digitization
  in pressure glass sphere
- Completed in Dec. 2010
  (data taking since 2005)



Detection of cosmic neutrinos

- Neutrinos only interact very weakly + low fluxes
  → huge detection volumes → natural abundances of ice or water
- Detection & reconstruction via Cherenkov light of secondary particles
  → transparent detection media

Time & position of hits

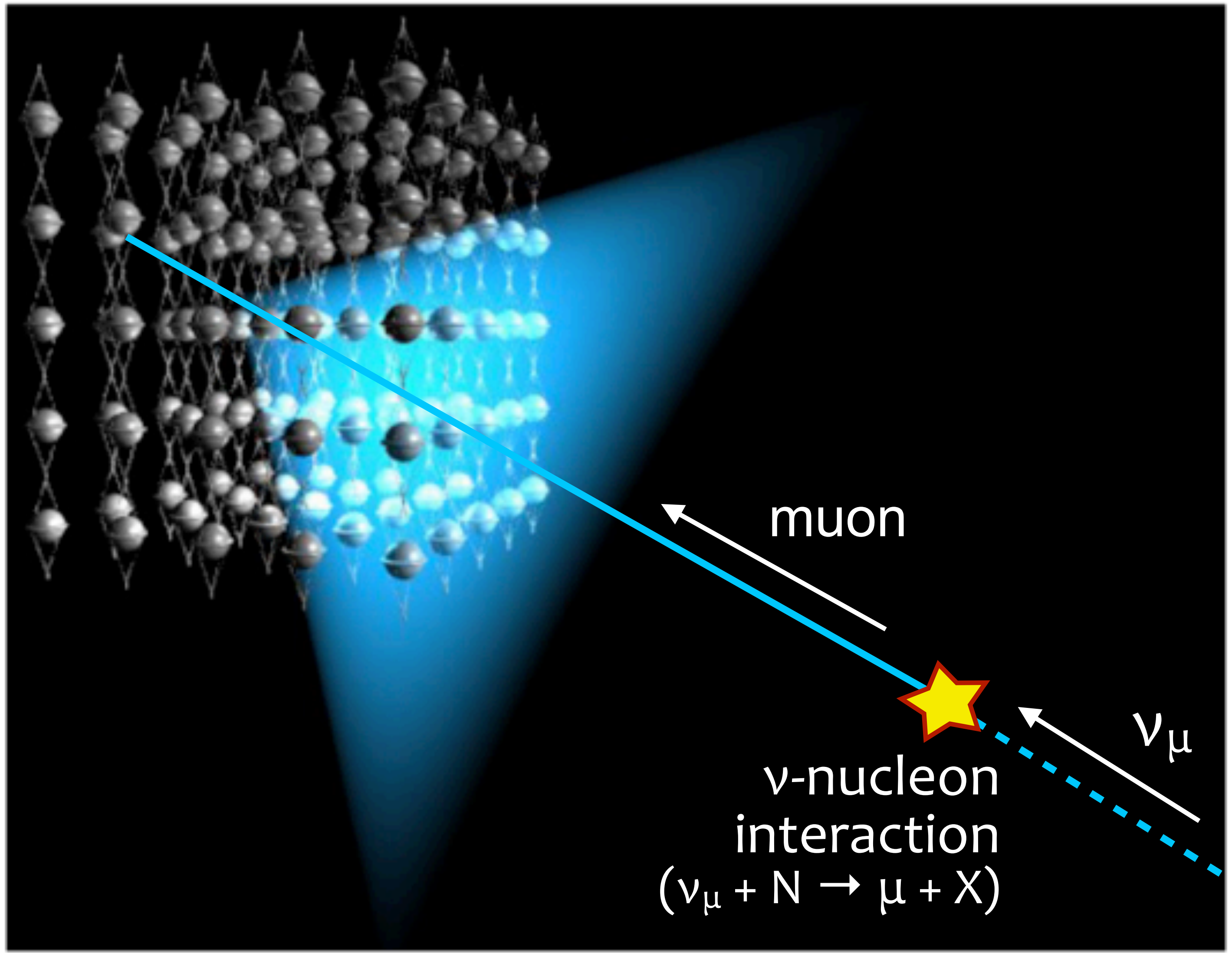
⬇

μ trajectory → ν trajectory

Light intensity

⬇

Energy

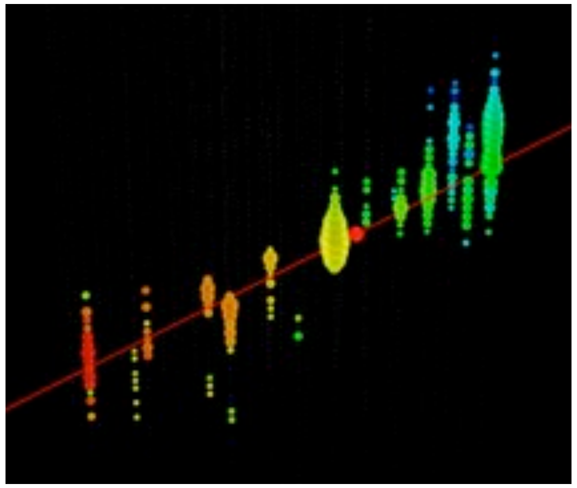


Event classes in neutrino telescopes

Tracks:

- Source: ν_μ CC interaction
- Good angular resolution (< 1°)
- Factor of 2 resolution in muon energy
- Sensitive volume ≫ instrumented volume

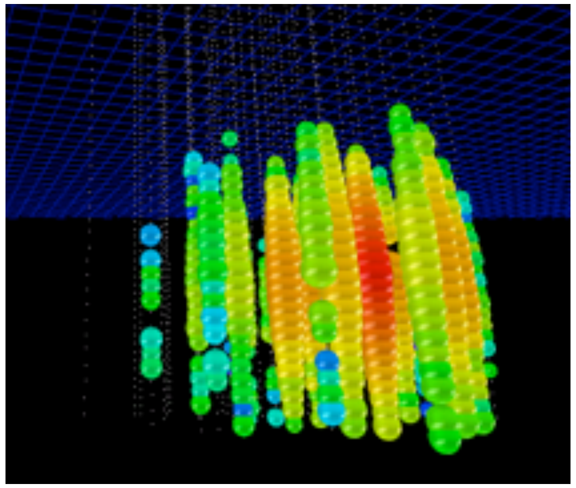
muon (IceCube data)



Cascades:

- Source: ν_e, ν_μ, ν_τ NC + ν_e CC interaction
- Good energy resolution (~10% at high energies)
- Limited angular resolution (≳ 10° in IceCube)
- Sensitive volume ≈ instrumented volume

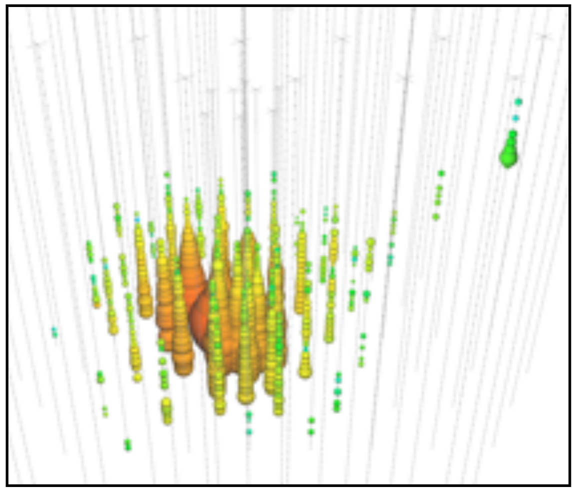
cascade (IceCube data)



Composites:

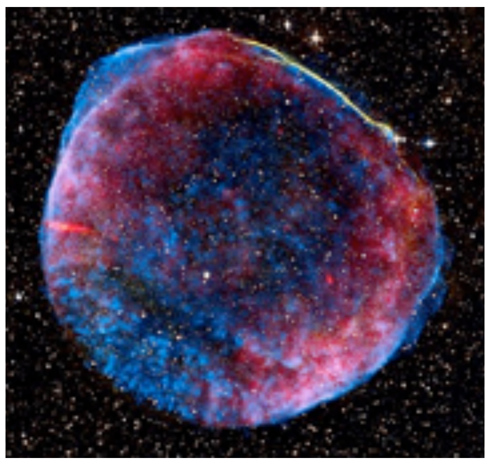
- Source: ν_μ CC (ν_τ CC) inside instrumented volume

starting muon (IceCube data)

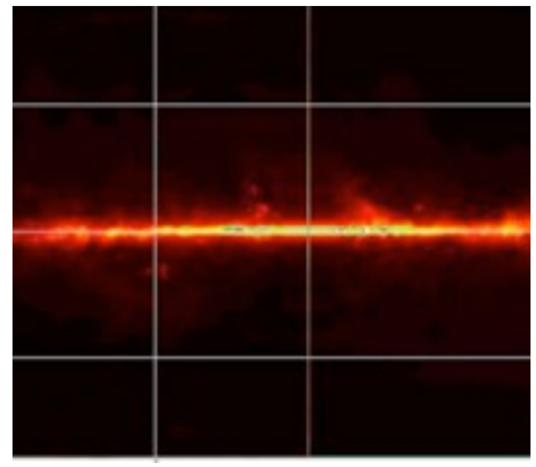


Physics with IceCube

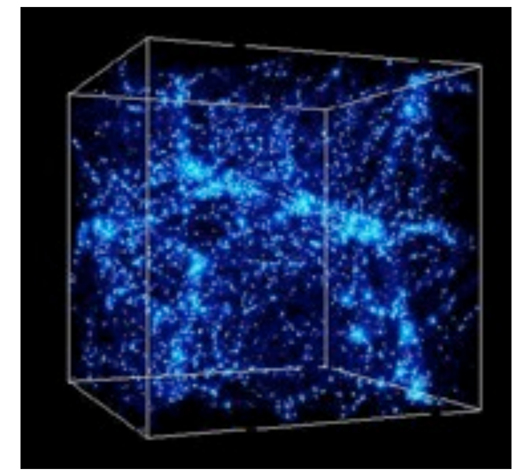
Cosmic accelerators



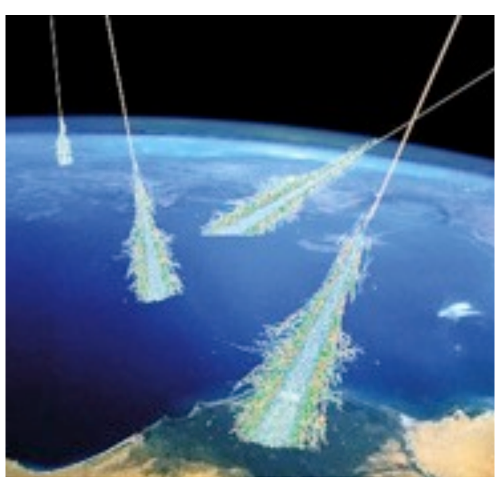
Diffuse fluxes



Dark Matter & Exotic Physics

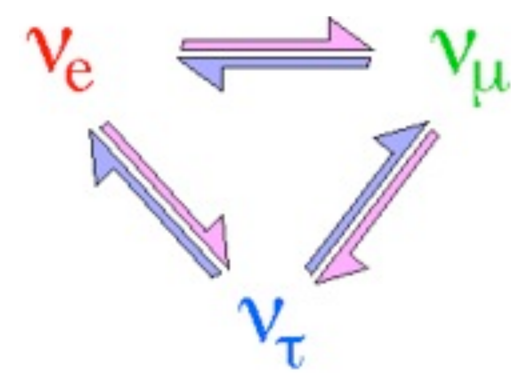


Cosmic rays



Supernovae

Neutrino Properties & Particle Physics



Physics with IceCube

Cosmic accelerators

- Point-like sources (SNRs, Binaries ...)
- Extended sources
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
- Galactic plane
- Extended structures (e.g. Fermi-Bubbles)

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls
- Lorentz invariance violation

Cosmic rays

- Spectrum around "knee" (10^{15}–10^{17} eV)
- Composition
- Anisotropy

Supernovae

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

Neutrino Properties & Particle Physics

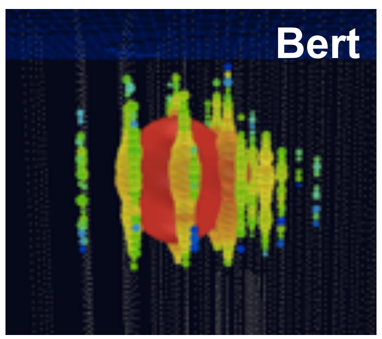
- Neutrino oscillations
- Charm in showers
- K/π ratio in showers
- Cross sections at very high energies

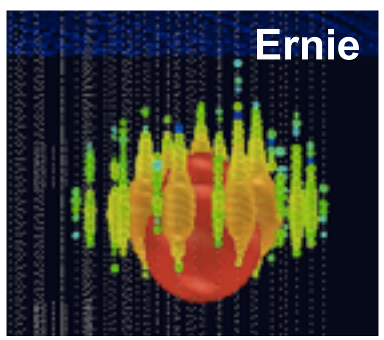
Selected results from IceCube

IceCube search for cosmogenic neutrinos in IC79+IC86

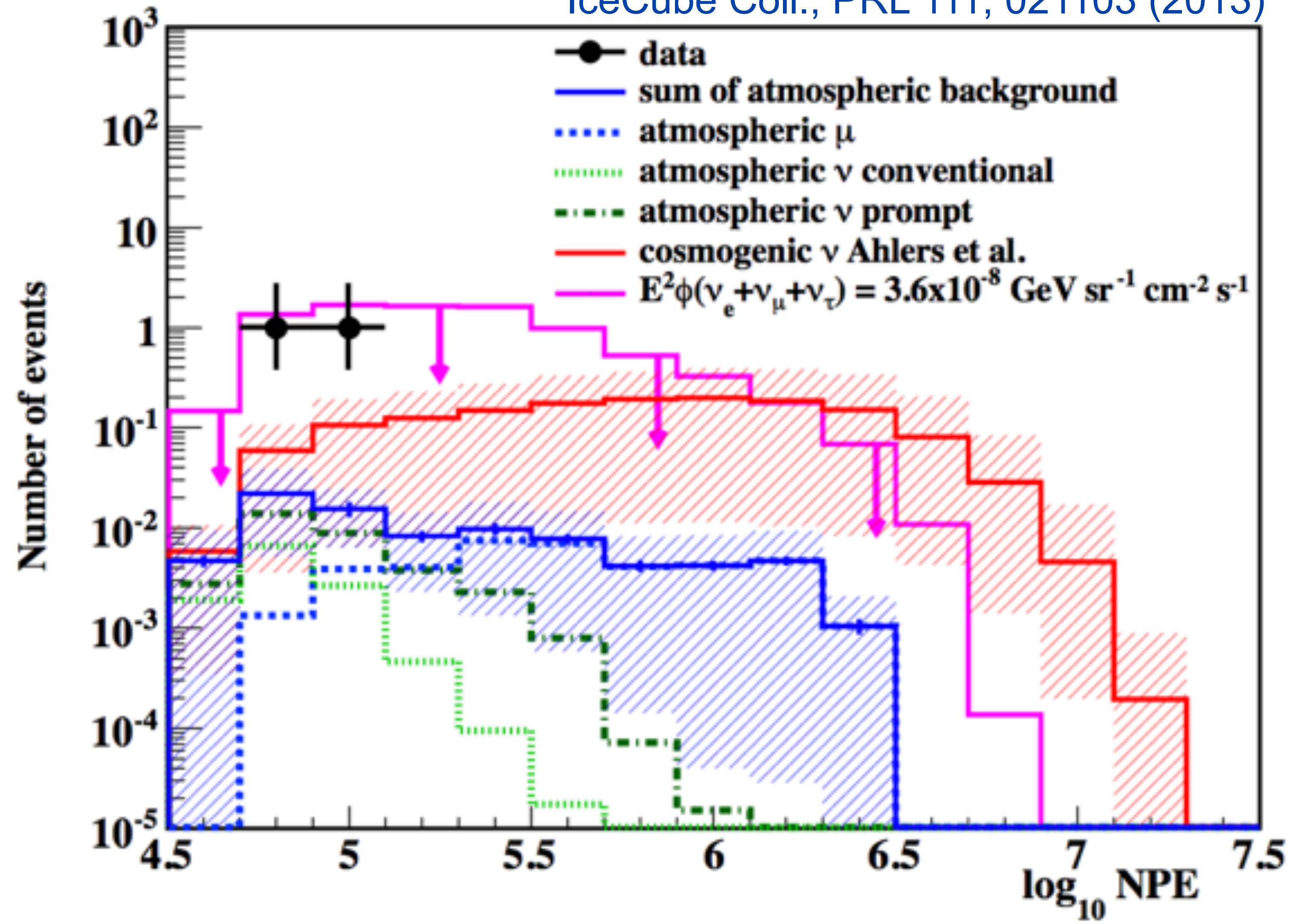
Two events with $E_{dep} \approx 1$ PeV

- Shown at Neutrino'12
- Both downgoing cascades
- Expected background: 0.082
  → 2.8σ excess





IceCube Coll., PRL 111, 021103 (2013)



Needed more statistics

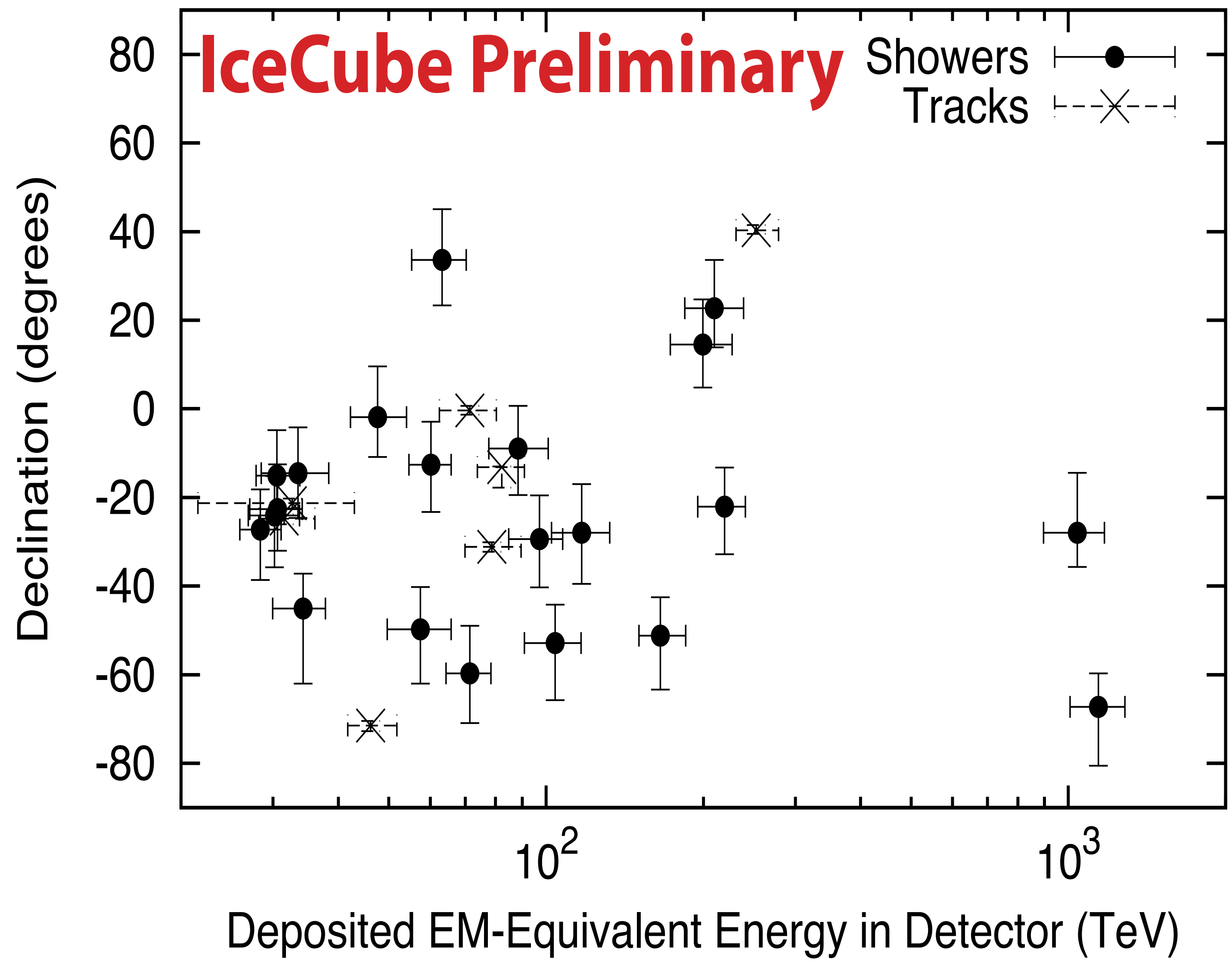
→ follow-up analysis:

- extends sensitivity to lower energies
- optimized on events starting inside detector

Results of follow-up search in same data (IC79+IC86)

- 28 events observed including the two PeV events
  (7 with visible muons, 21 without)
- Expected background 12.1±3.4
  (preliminary)
- Significance calculation
  - previous analysis (Ernie & Bert)
    → 2.8σ
  - follow-up analysis (PDF-based)
    (26 events, without Ernie & Bert)
    → 3.3σ (preliminary)

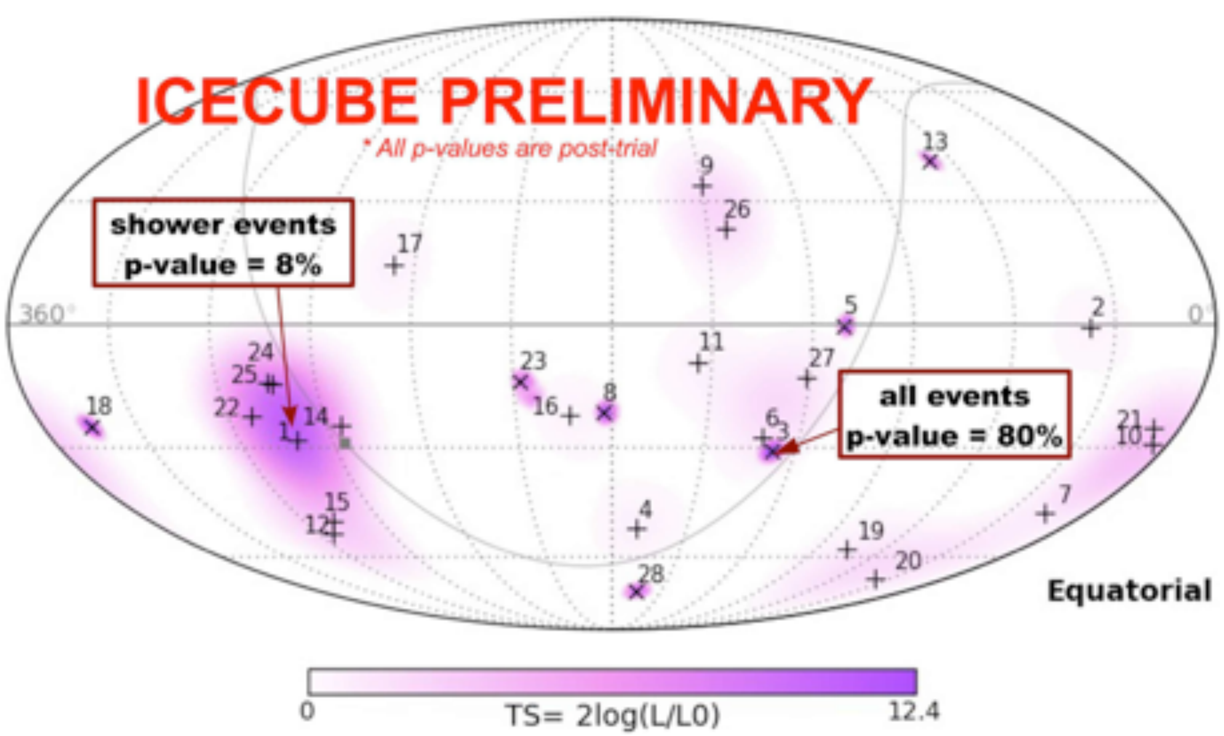
Combined 4.1σ
(preliminary)

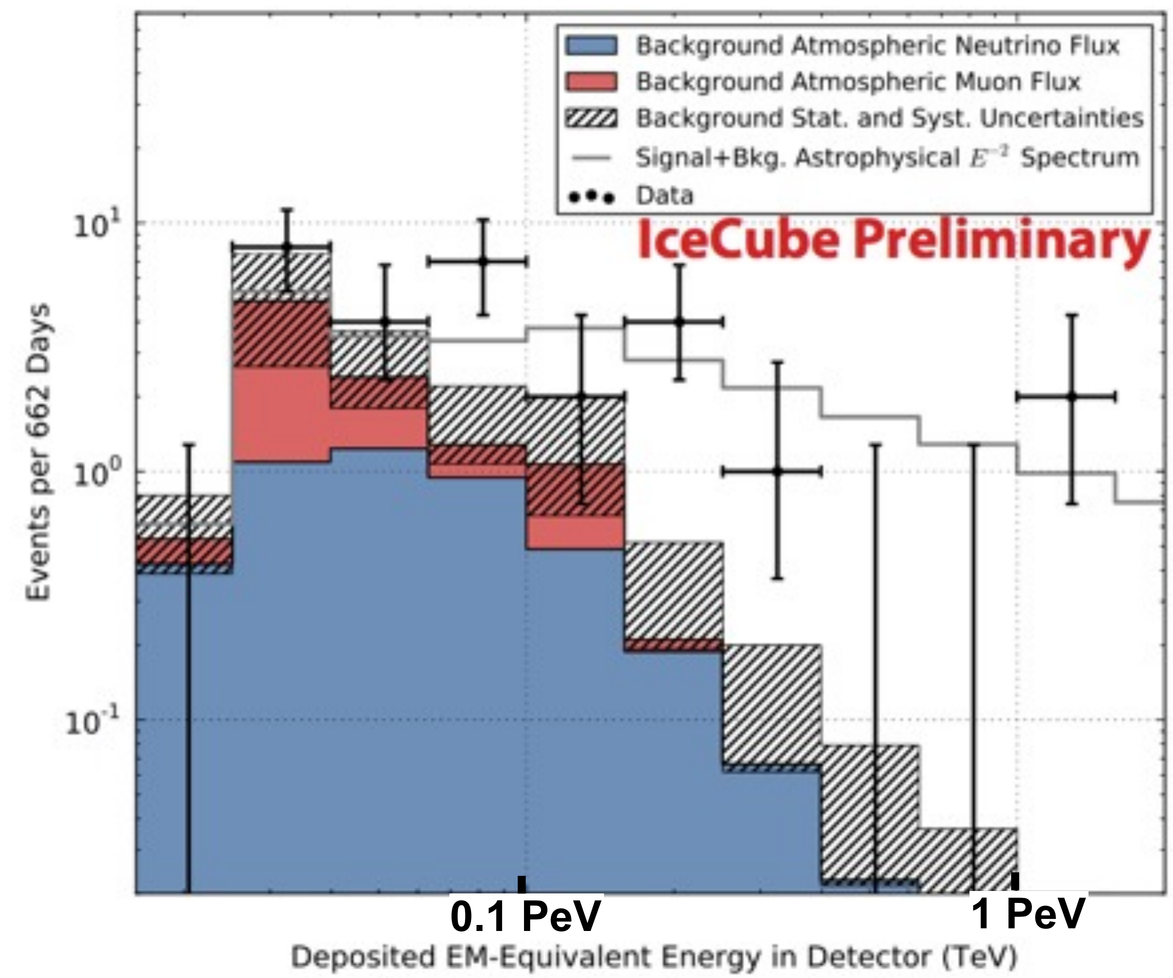


Track events (×) can have much higher neutrino energies

Energy and zenith distribution of events

- Harder than expected from atmospheric background
- Excess compatible with isotropic flux (1 : 1 : 1)
  (per flavor $E^2\,\Phi_\nu = 1.2\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1})
- Potential cutoff at $1.6^{+1.5}_{-0.4}$ PeV
  (otherwise 3−6 more events at 2−10 PeV)
- No clustering of events or significant correlation with Galactic plane

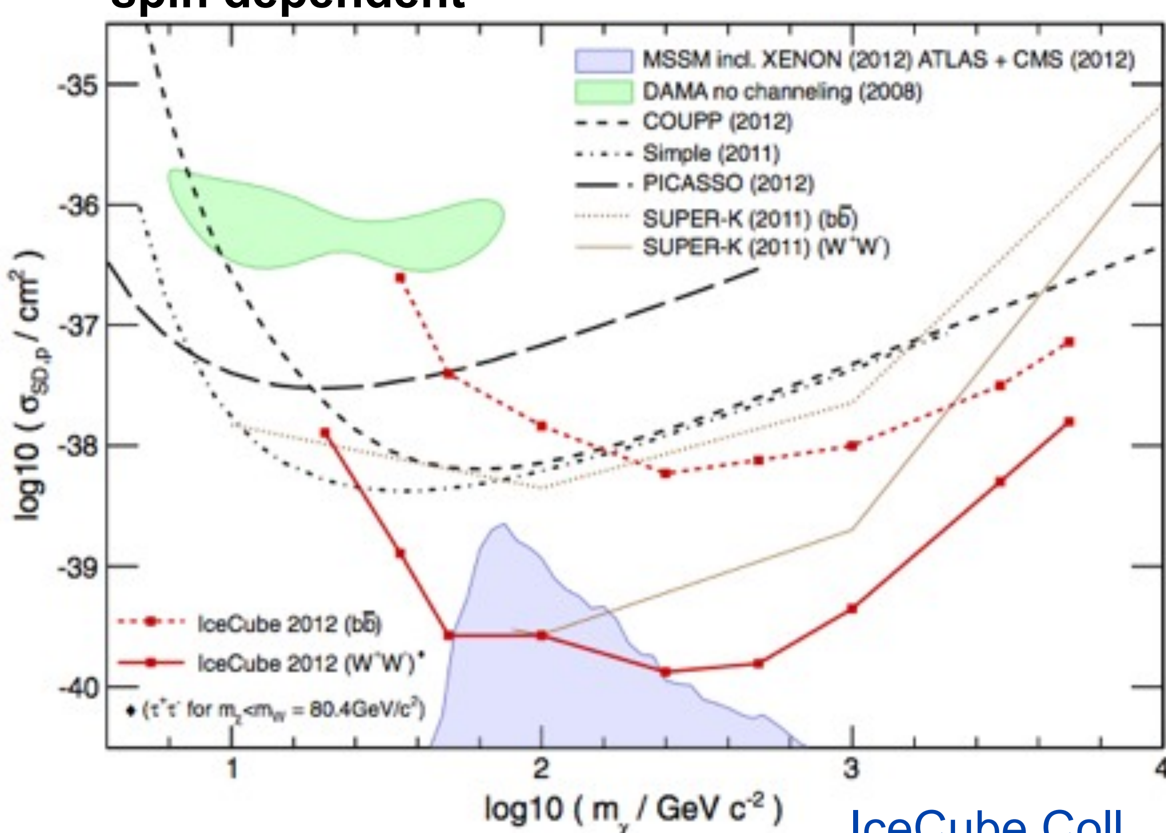




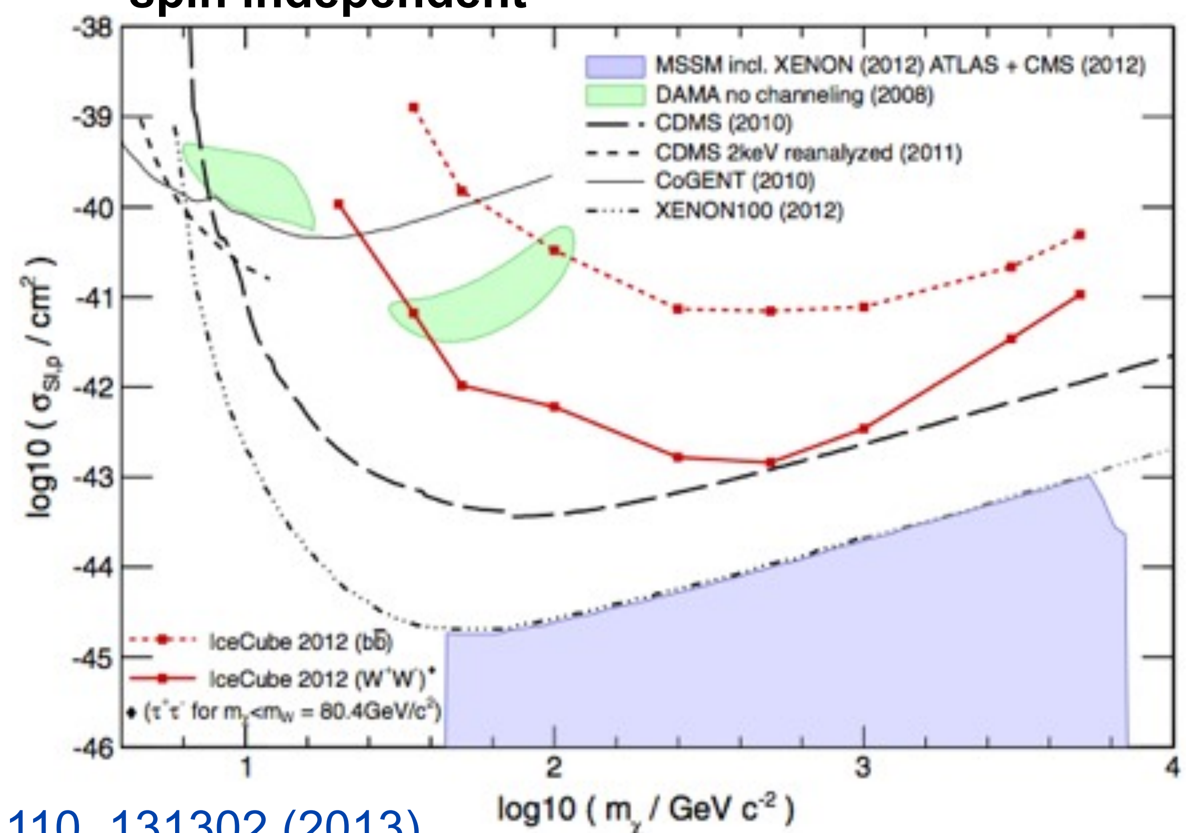
Search for Dark Matter accumulation in the Sun

- WIMPs (χ^0) captured by elastic scattering off nuclei in Sun
- Accumulation in center → annihilation to neutrinos
  (R parity conservation assumed)
- After some time: equilibrium between capture and annihilation
  → annihilation rate depends on WIMP scattering cross section
- Sun mainly protons → IceCube mostly sensitive to spin-dependent cross section

spin dependent



spin independent

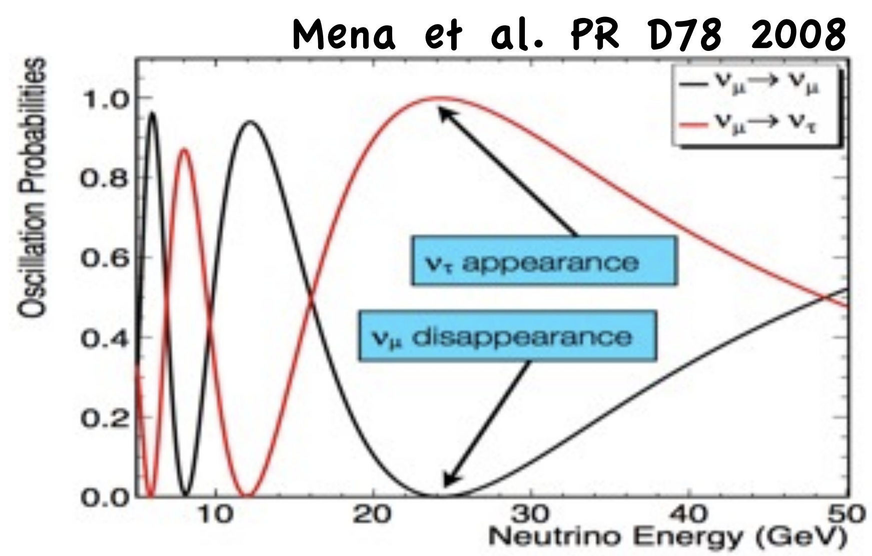


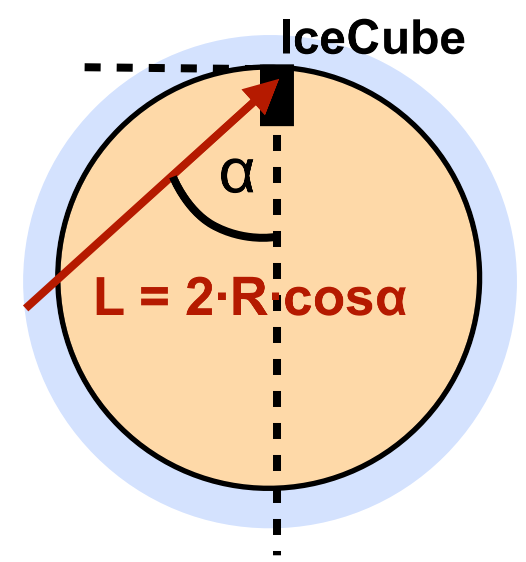
IceCube Coll., PRL 110, 131302 (2013)

Neutrino oscillations in IceCube

- **Goal:** measurement of atm. muon neutrino oscillations

  Minimum for P($\nu_\mu \rightarrow \nu_\mu$) at ~25 GeV (L = Earth diameter)

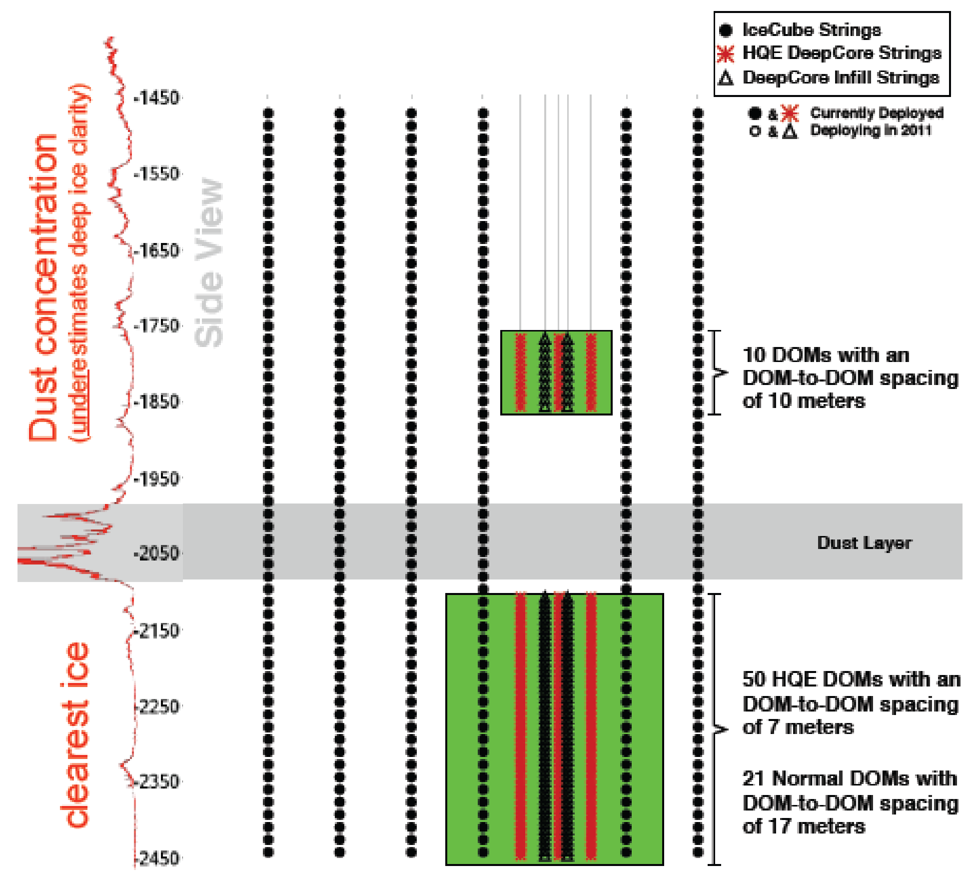




- **IceCube energy threshold ~100 GeV** (too few photons)

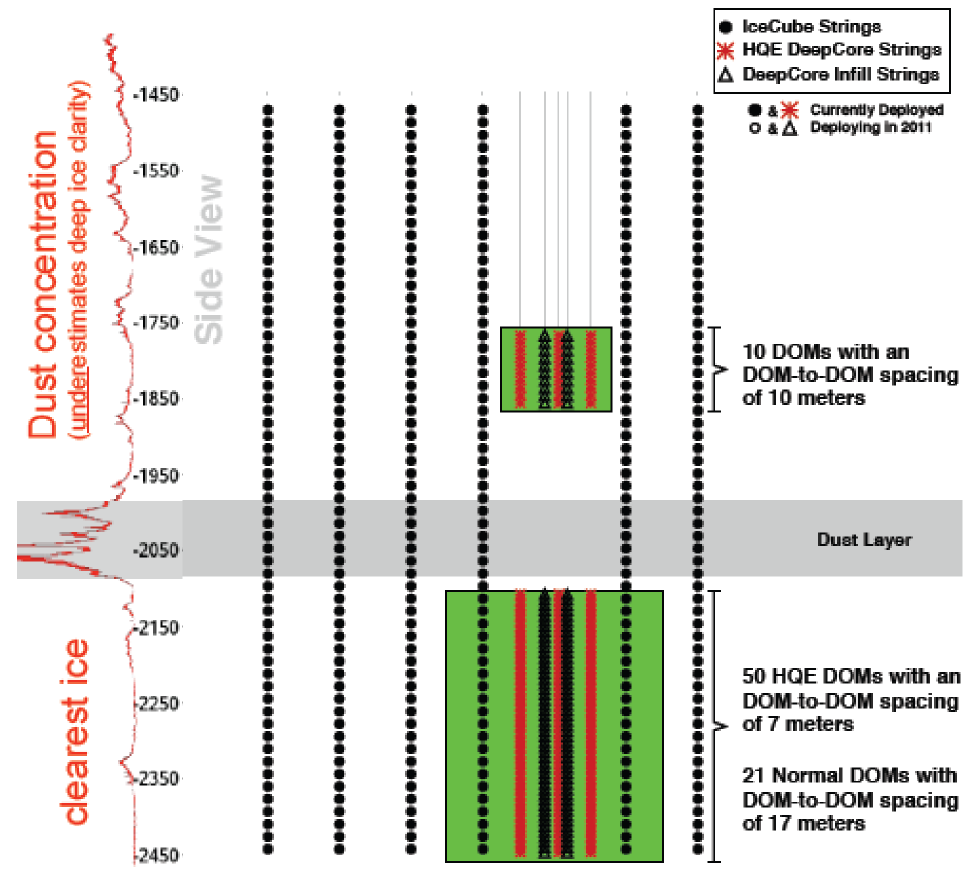
  → higher sensor density with DeepCore

  - Instrumented volume: 10−100 Mton
  - Average DOM density: 4× IceCube
  - Energy range: 10 GeV – 100 GeV



First oscillation analysis (IC79) − Event selection

- Selection of a low and high energy sample (only low-energy sample effected by oscillations)
- In particular, low-energy sample effected by mis-reconstructed atmospheric muons
  → suppression using IceCube veto and improved reconstruction (DeepCore)
- High purity muon neutrino samples
  - low energy sample ~85% (main contamination ν_e)
  - high-energy sample ~95% (main contamination muons)



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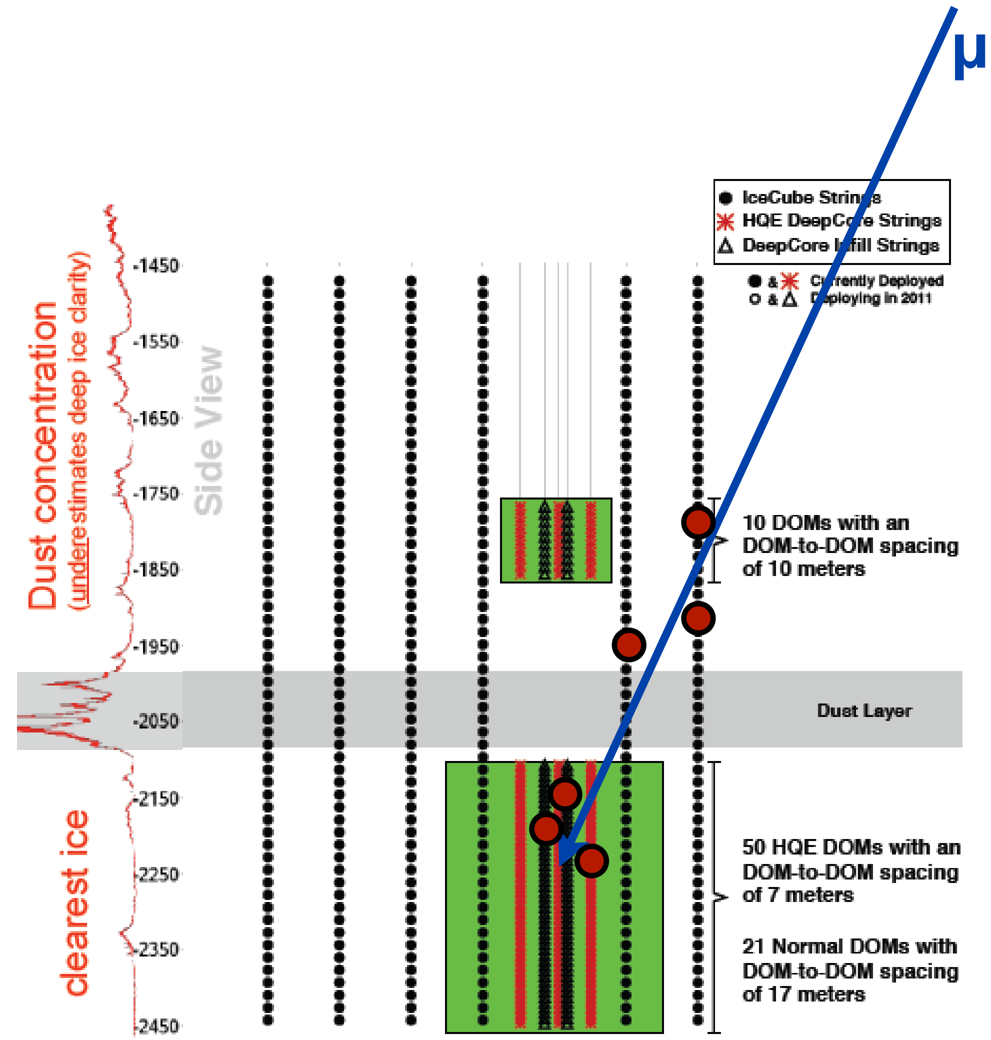

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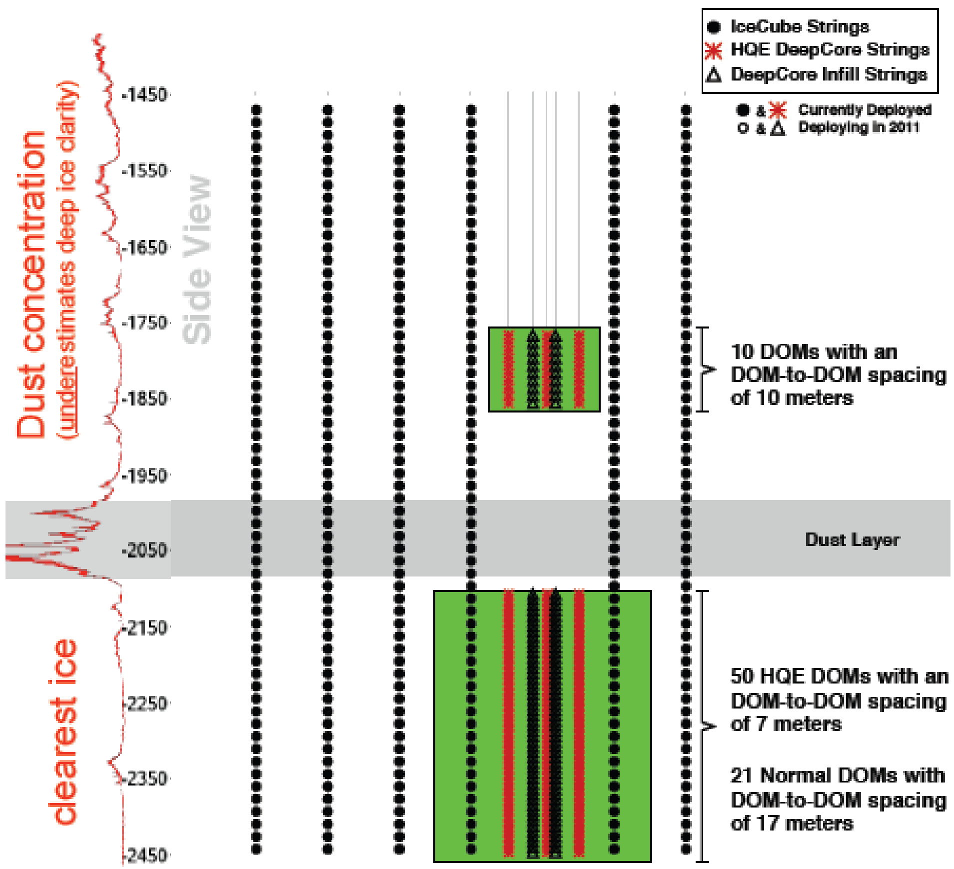

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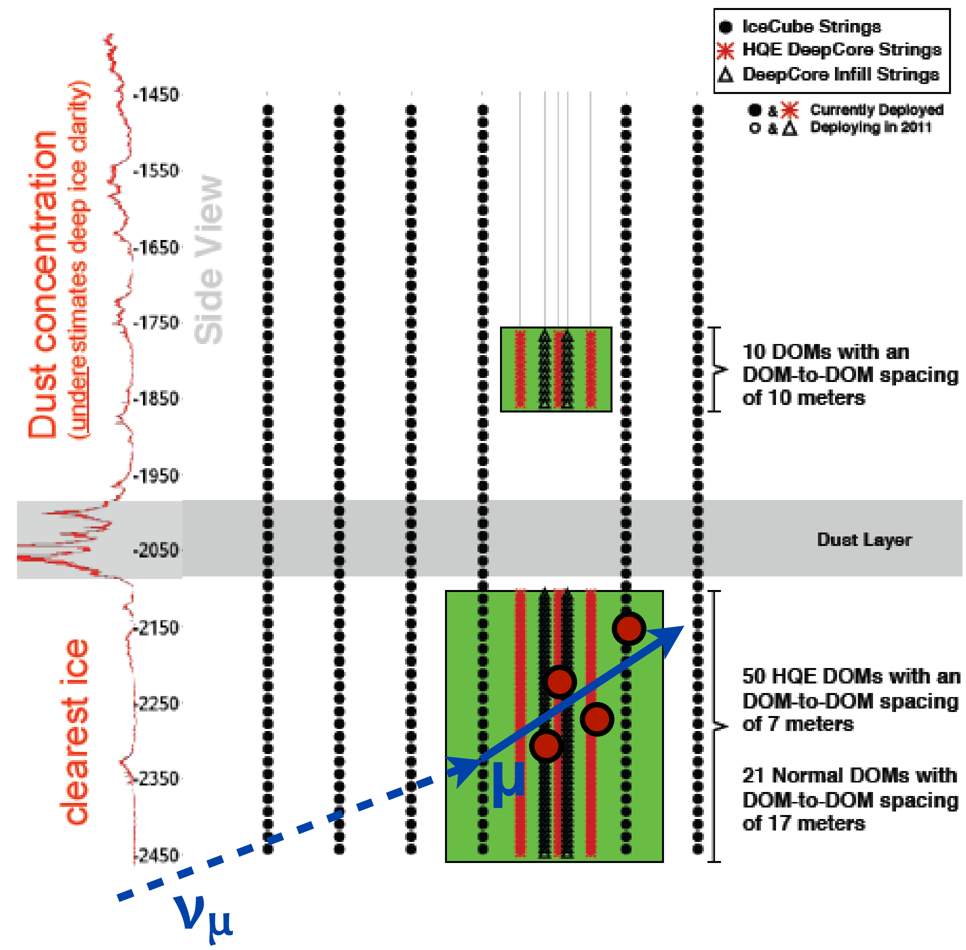

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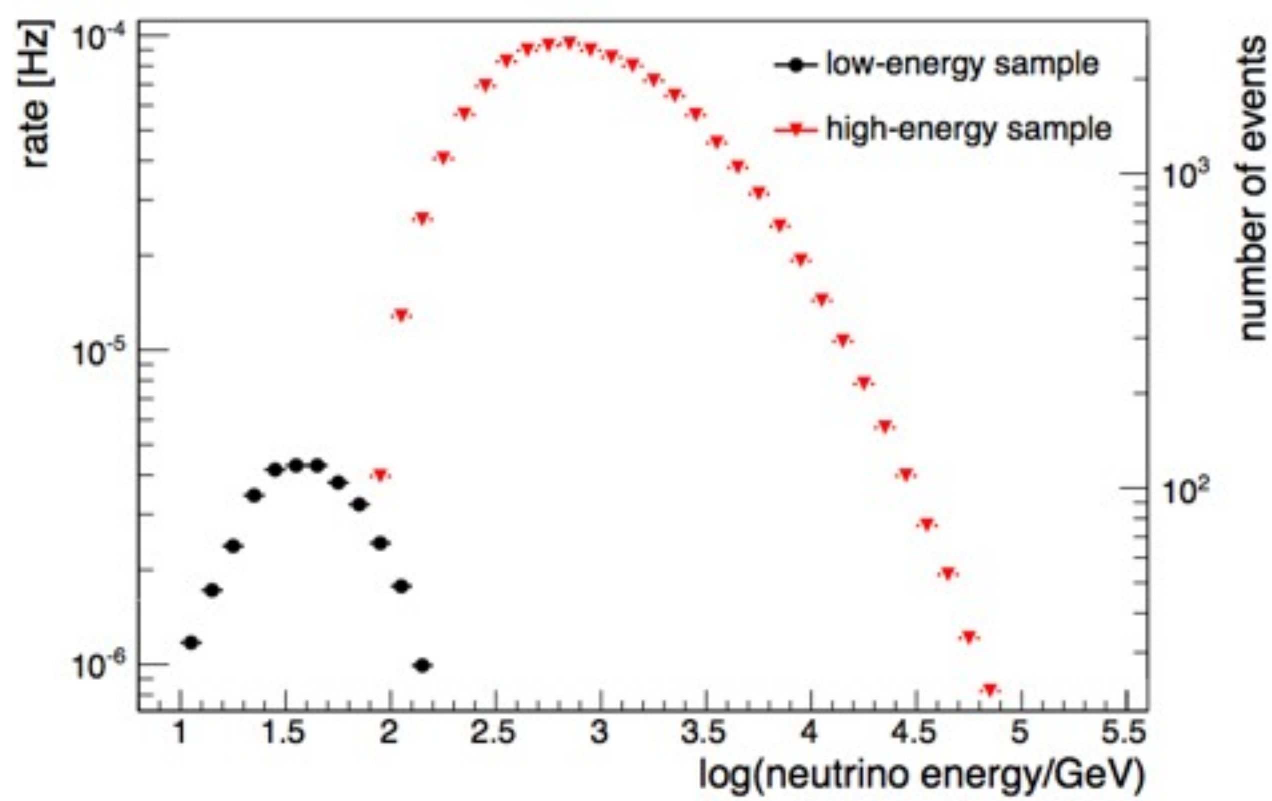


IceCube Coll., accepted by PRL

First oscillation analysis (IC79) – Results

- **Method:** Combined χ^2 of low- and high-energy sample in 2× 10 bins of cos θ

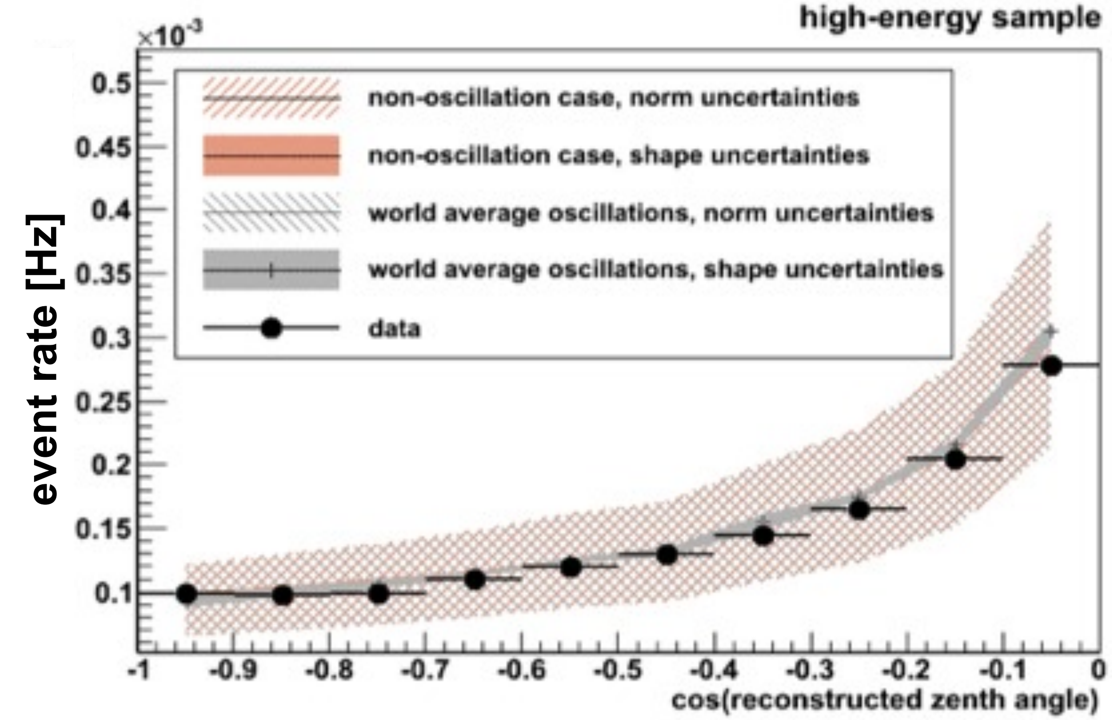
$$\chi^2 = \sum_{ij} (y_i - \bar{y}_i)(y_j - \bar{y}_j)\sigma_{ij}^{-2}$$

$$\sigma_{ij} = \delta_{ij} u_i u_j + \sum_k c_i^k c_j^k$$

stat. errors — k^{th} sys. uncertainty

Systematics: DOM eff., ice model, rate norm., atm. flux model, ν_e norm., ν xsec

- **Results:**
  - oscillations observed with more than 5σ
    $\Delta\chi^2 = 30 \triangleq 5.6\sigma$



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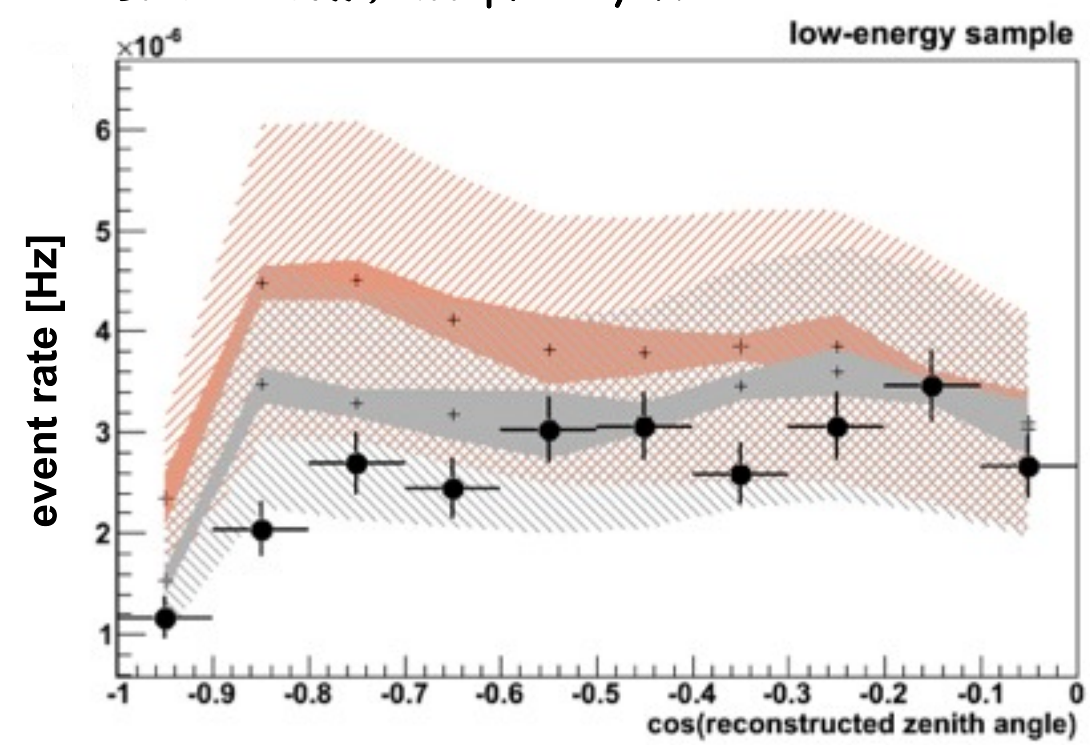

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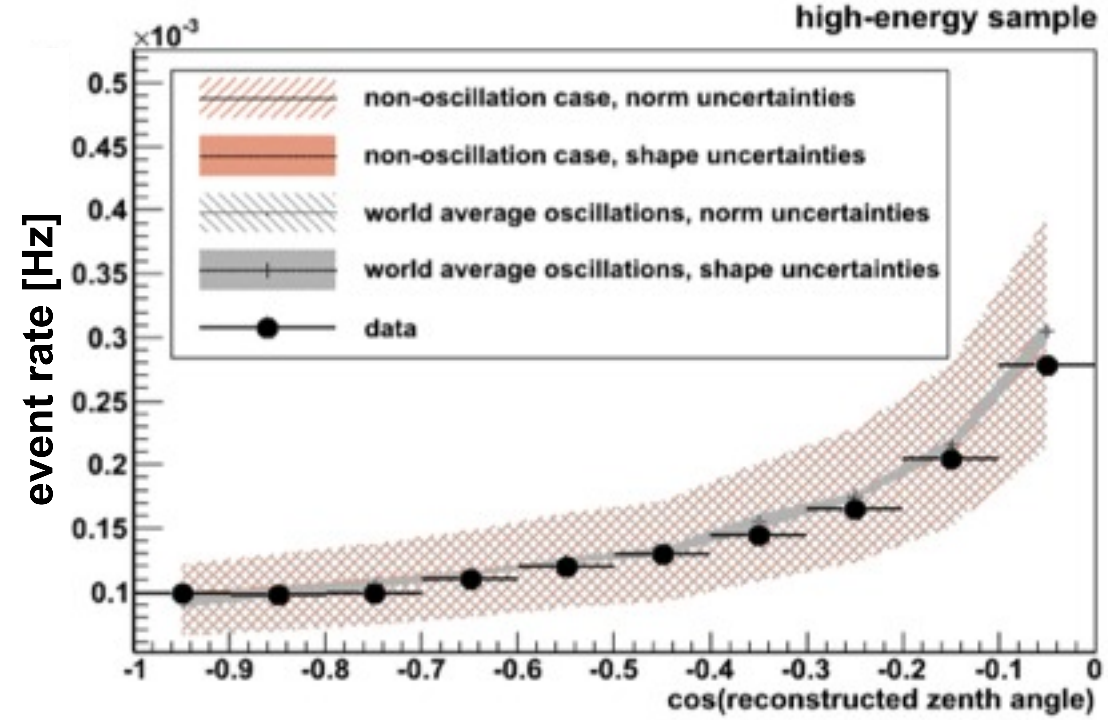

IceCube Coll., accepted by PRL

- **Results:**
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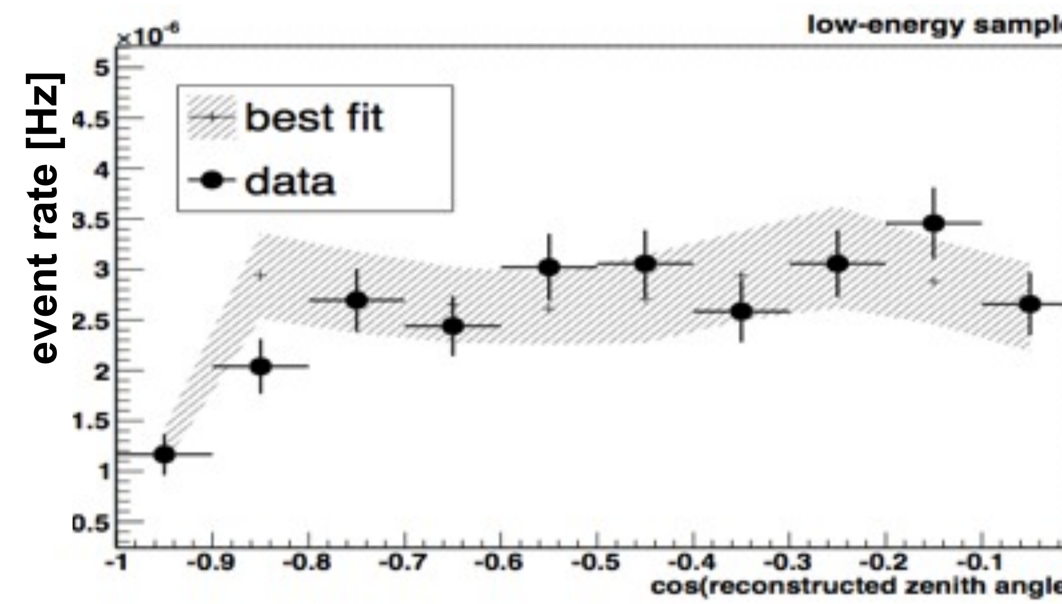
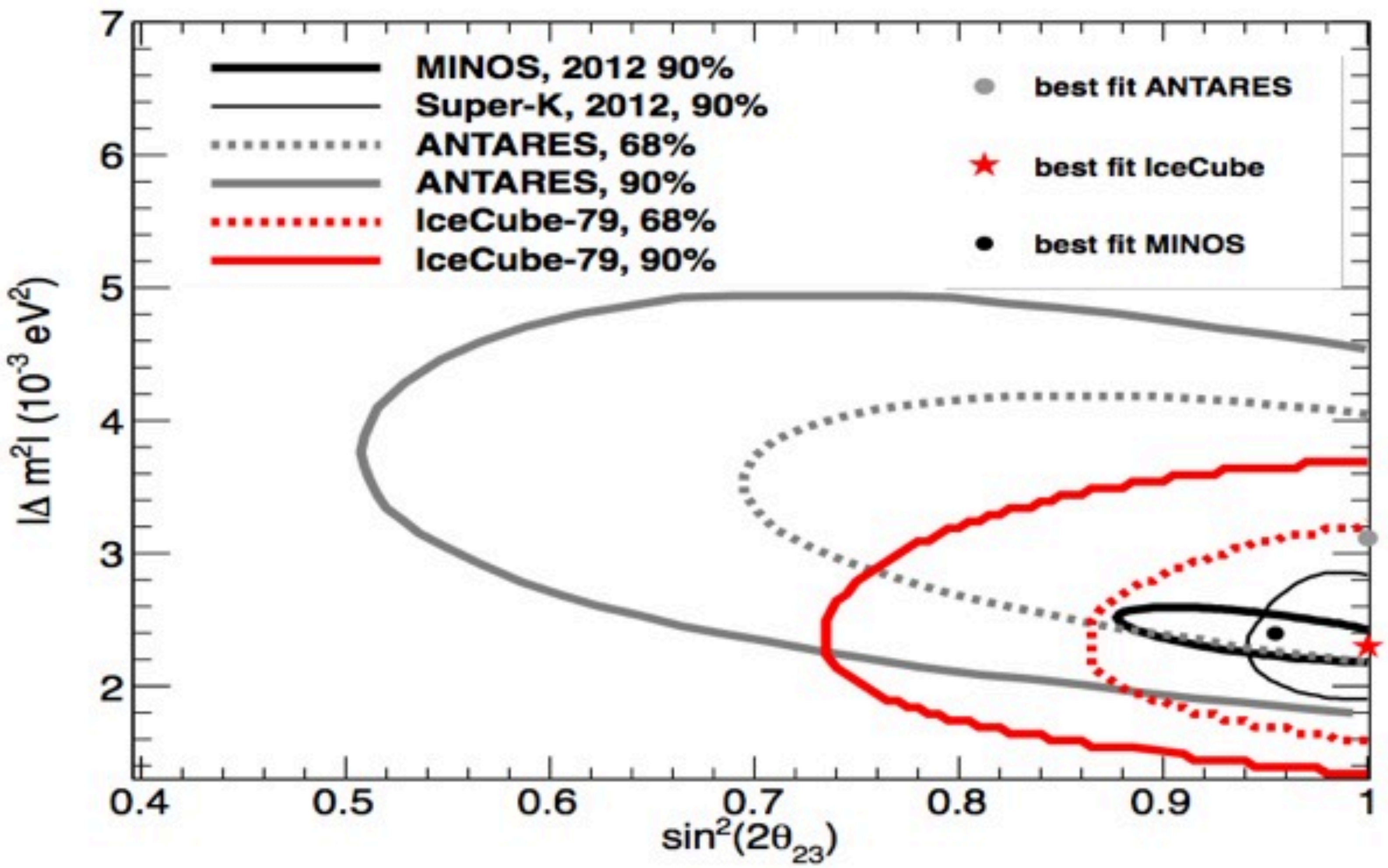
  - best-fit: χ^2 / n.d.f = 15.7 / 18



Constraints on oscillation parameters (IC79)



IceCube Coll., PRL 111, 081801 (2013)

IC86 data
→ talk J.P. Yanez

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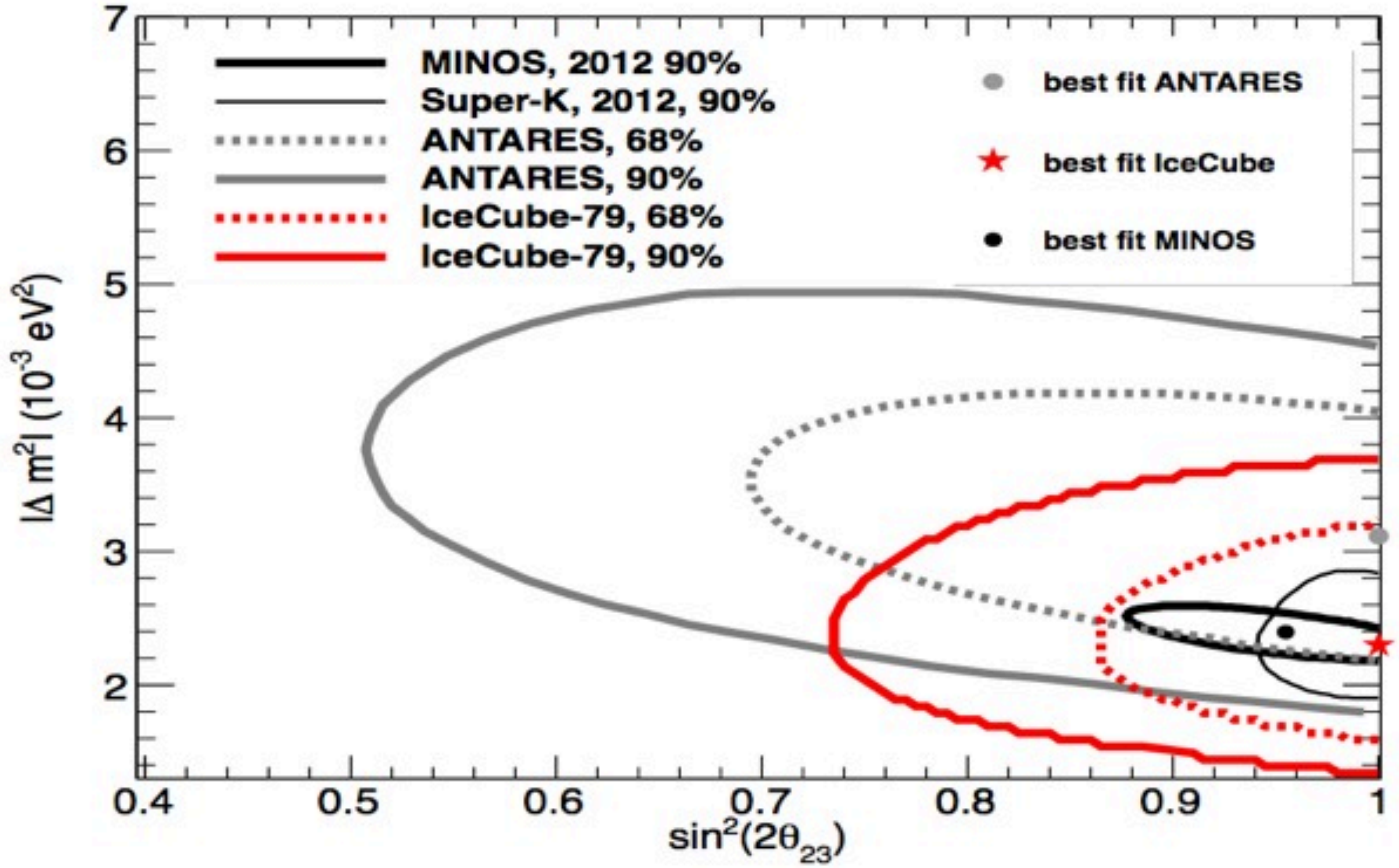

IceCube Coll., PRL 111, 081801 (2013)

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Neutrino oscillation with high significance but not high precision yet

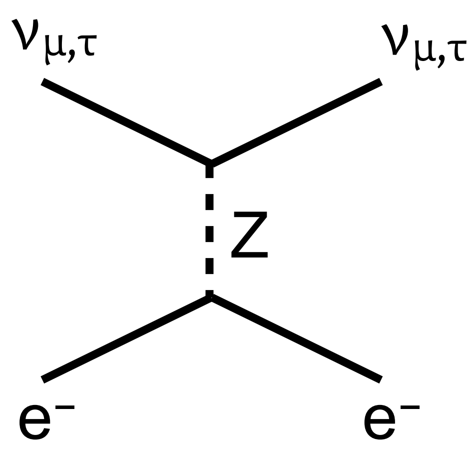
- $|\Delta m^2| = [2.5 \pm 0.5(\text{stat}) \pm 0.3(\text{sys})]\ 10^{-3}\ \text{eV}^2$
- $\sin^2(2\theta_{32}) > 0.92$ (68% CL)

PINGU and the Neutrino Mass Hierarchy

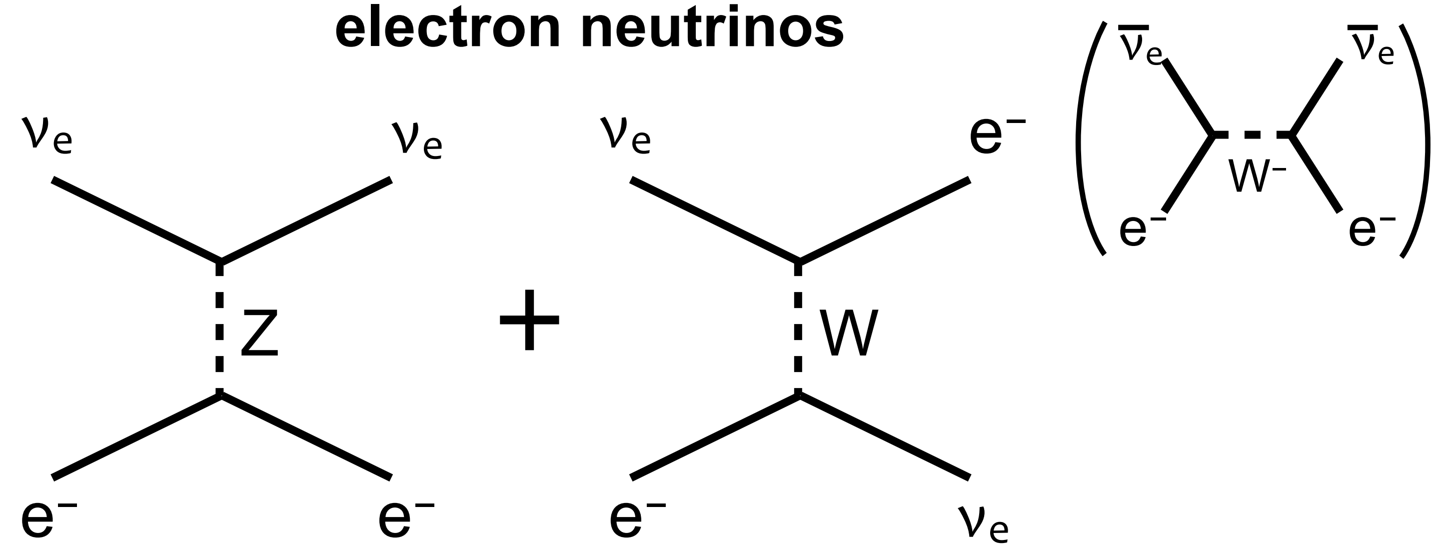
Matter effects

- Up to now, neutrino oscillation not affected by matter
- In matter particles can gain “effective mass” in presence of interactions (known from solid state physics)

muon, tau neutrinos



electron neutrinos



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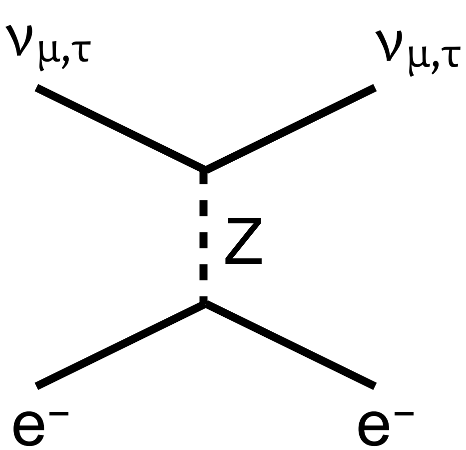

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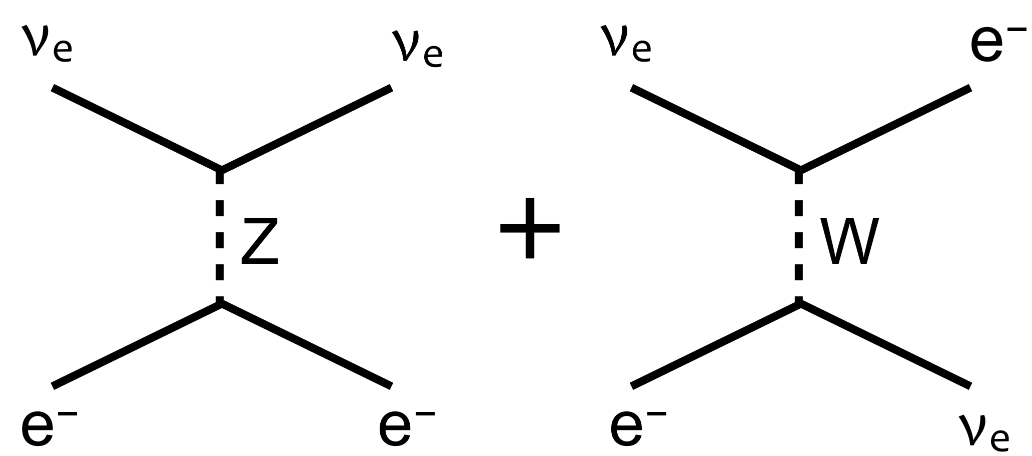

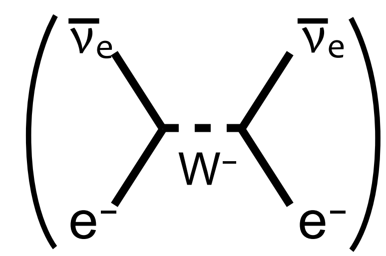

electron density N_e

$\rightarrow A_{CC} = \pm 2\sqrt{2}\, E_\nu\, G_F\, N_e$

(+) ν_e ; (−) $\bar{\nu}_e$

Effective parameters for 2-flavor mixing:

$$\Delta m_M^2 = \xi \times \Delta m^2 \qquad \sin 2\theta_M = \frac{\sin 2\theta}{\xi}$$

$$\xi = \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \frac{A_{CC}}{\Delta m^2}\right)^2}$$

Matter effects – the MSW effect

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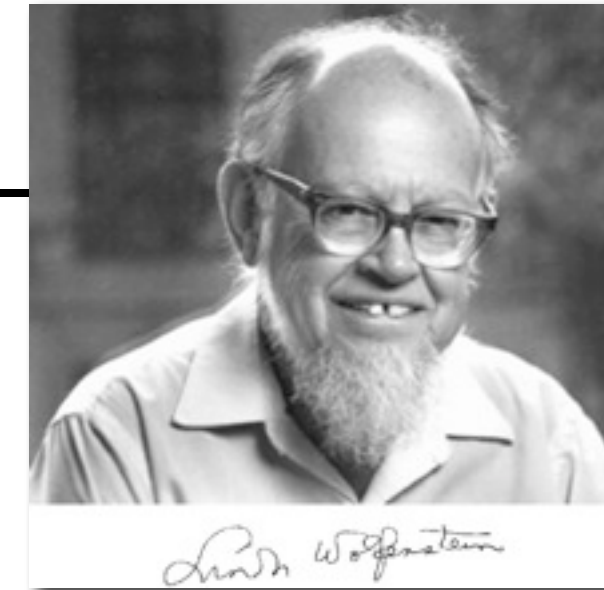
Mikheyev,
Smirnov,
Wolfenstein



Mixing becomes maximal ($\sin 2\theta_M = 1$) if $A_{\mathrm{CC}}^R = \Delta m^2 \cos 2\theta$ i.e. $N_e^R = \dfrac{\Delta m^2 \cos 2\theta}{2\sqrt{2}\, E\, G_F}$

→ complete transition from one to other flavor possible !

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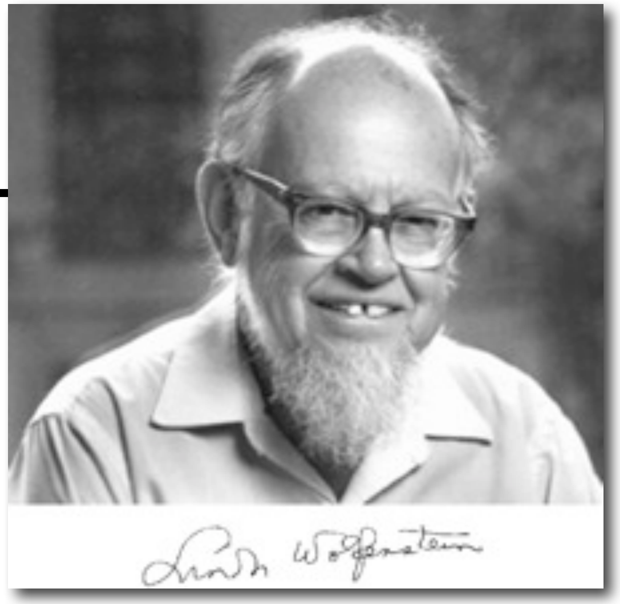

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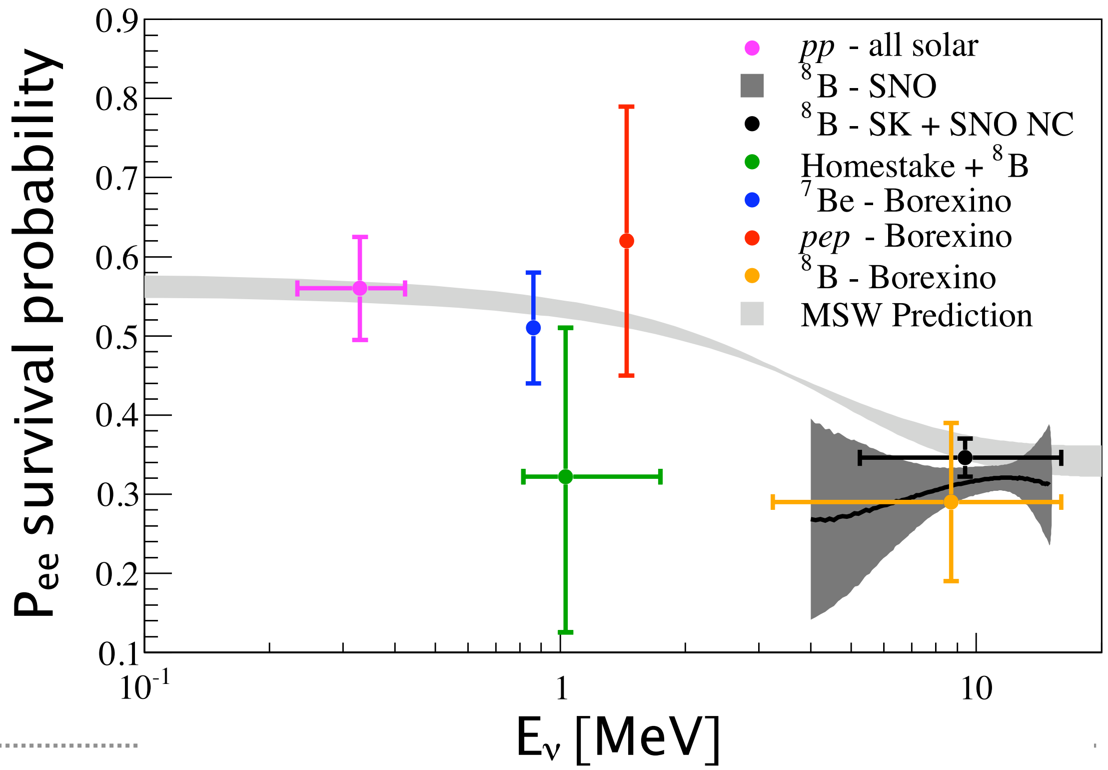
Example: Neutrinos from the Sun

- Propagation along smoothly decreasing density profile → at some point $N_e = N_e^R$
- Effect is energy dependent ...



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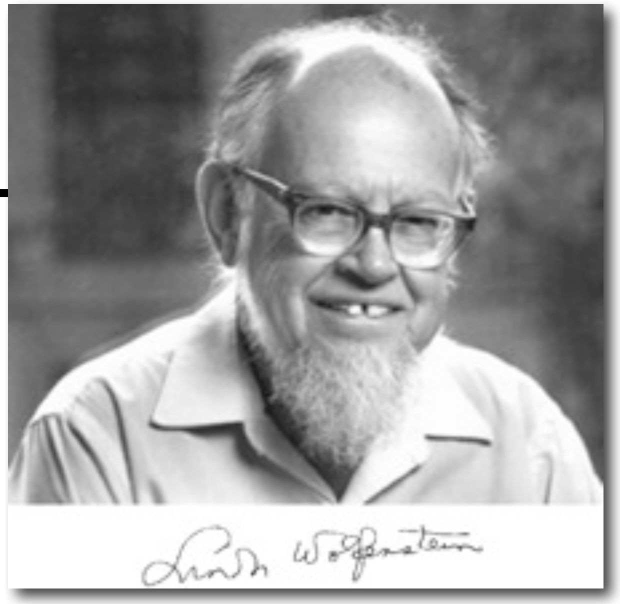
Mikheyev,
Smirnov,
Wolfenstein



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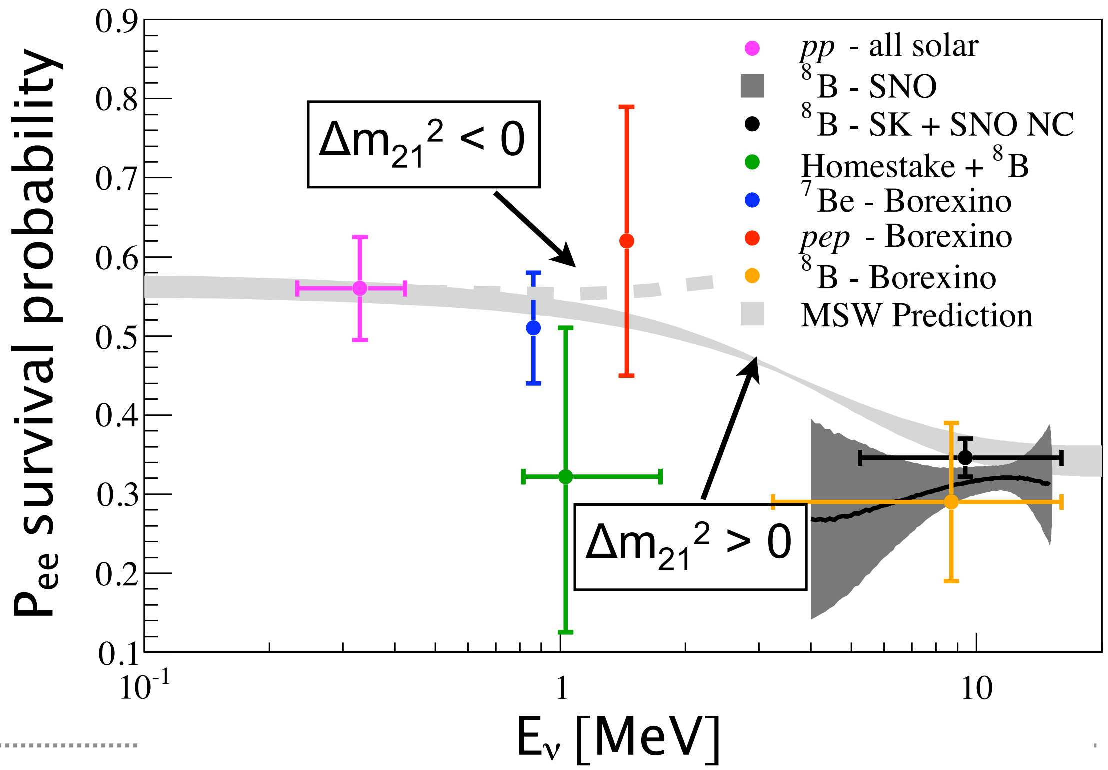
$\rightarrow$ complete transition from one to other flavor possible !

Example: Neutrinos from the Sun

- Propagation along smoothly decreasing density profile $\rightarrow$ at some point $N_e = N_e^R$
- Effect is energy dependent ...
- ... and differs for $\Delta m_{21}^2 > (<)\ 0$!
  $\rightarrow$ sign of Δm_{21}^2 known

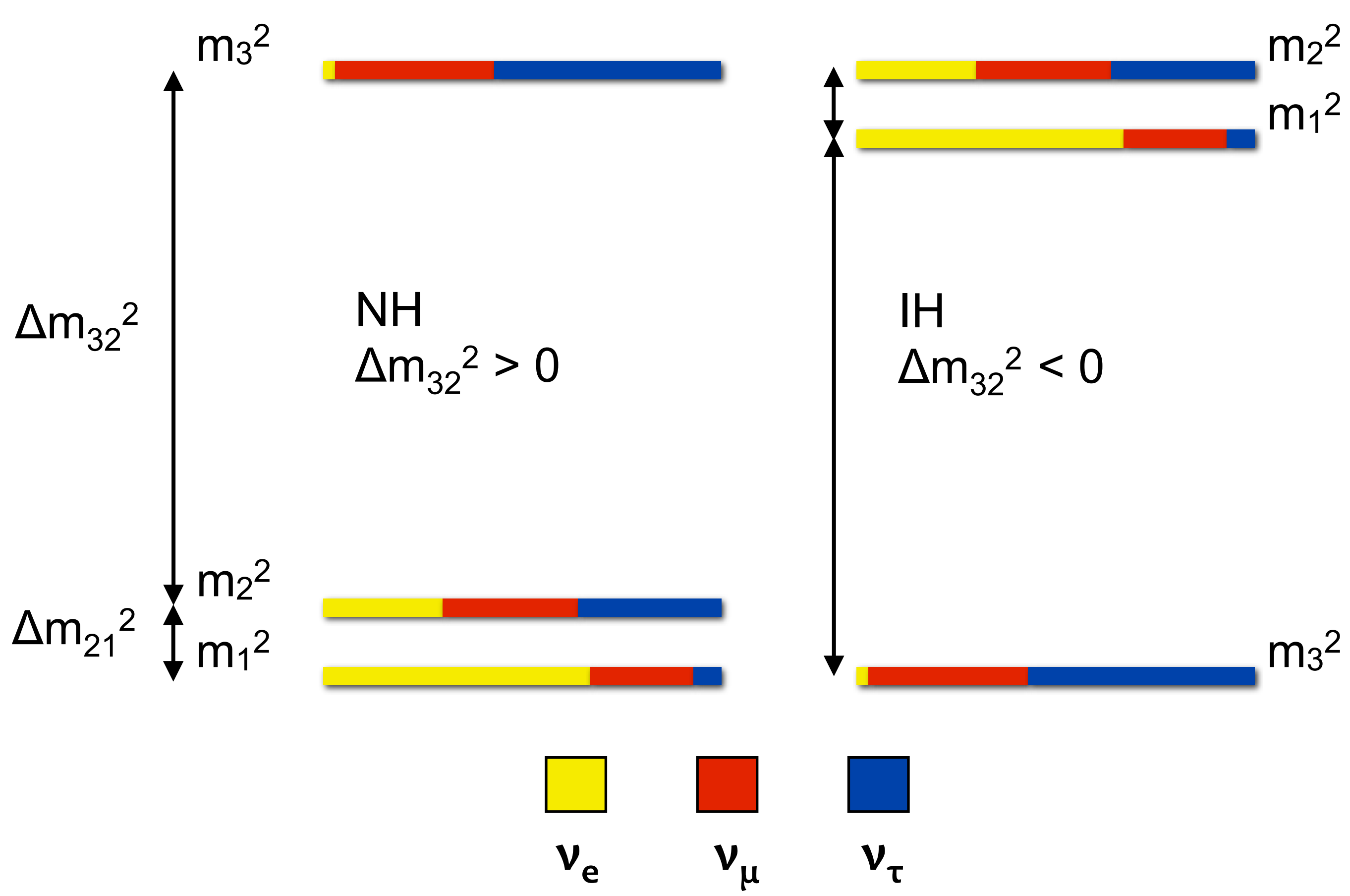


Neutrino mass hierarchy

- Sign Δm_{21}^2 known from MSW effect in Sun
- Sign of Δm_{32}^2 still unknown (atmospheric muon neutrino oscillation)

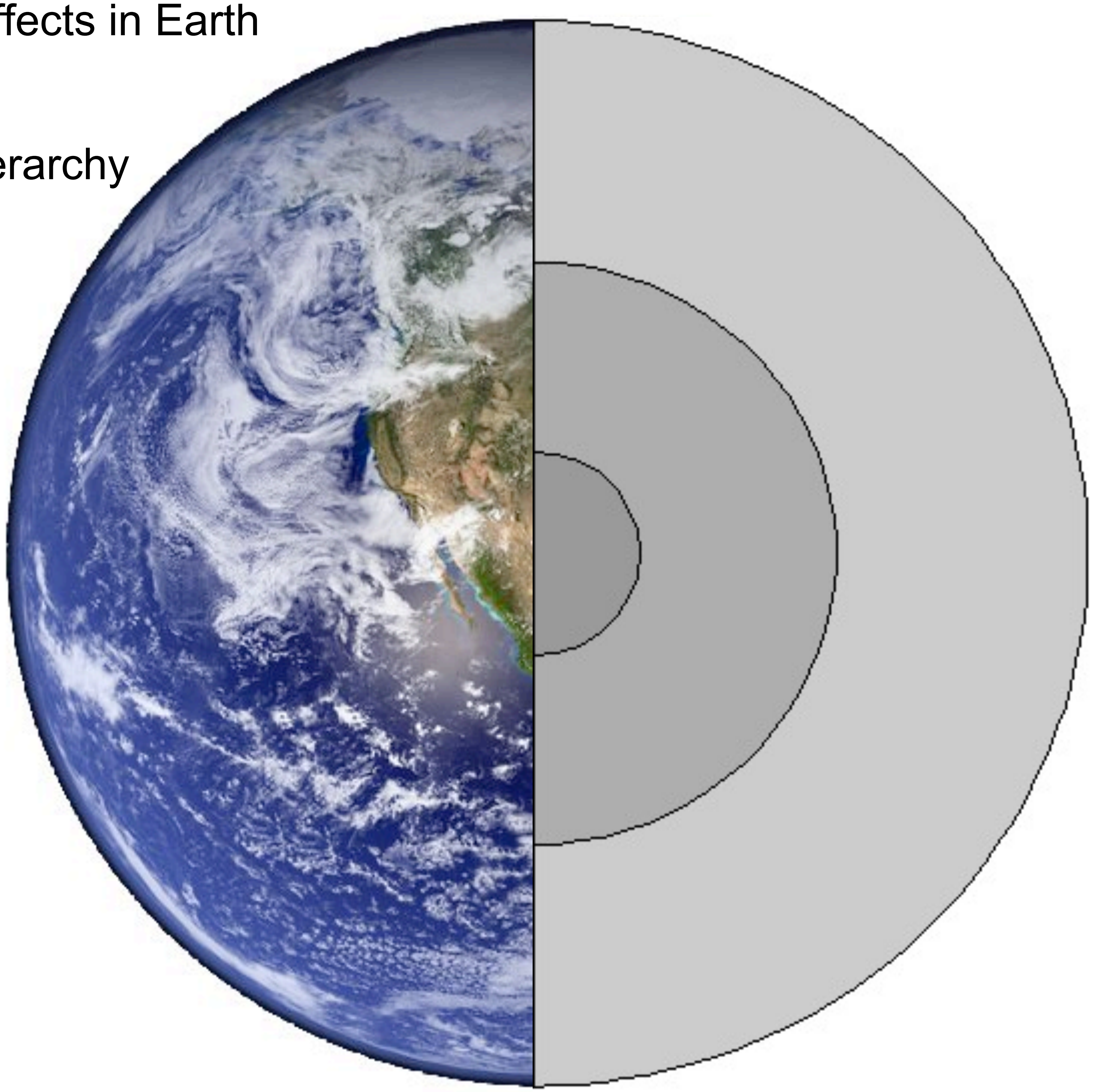
  $\Delta m_{32}^2 > 0 \rightarrow$ Normal hierarchy (NH)

  $\Delta m_{32}^2 < 0 \rightarrow$ Inverted hierarchy (IH)

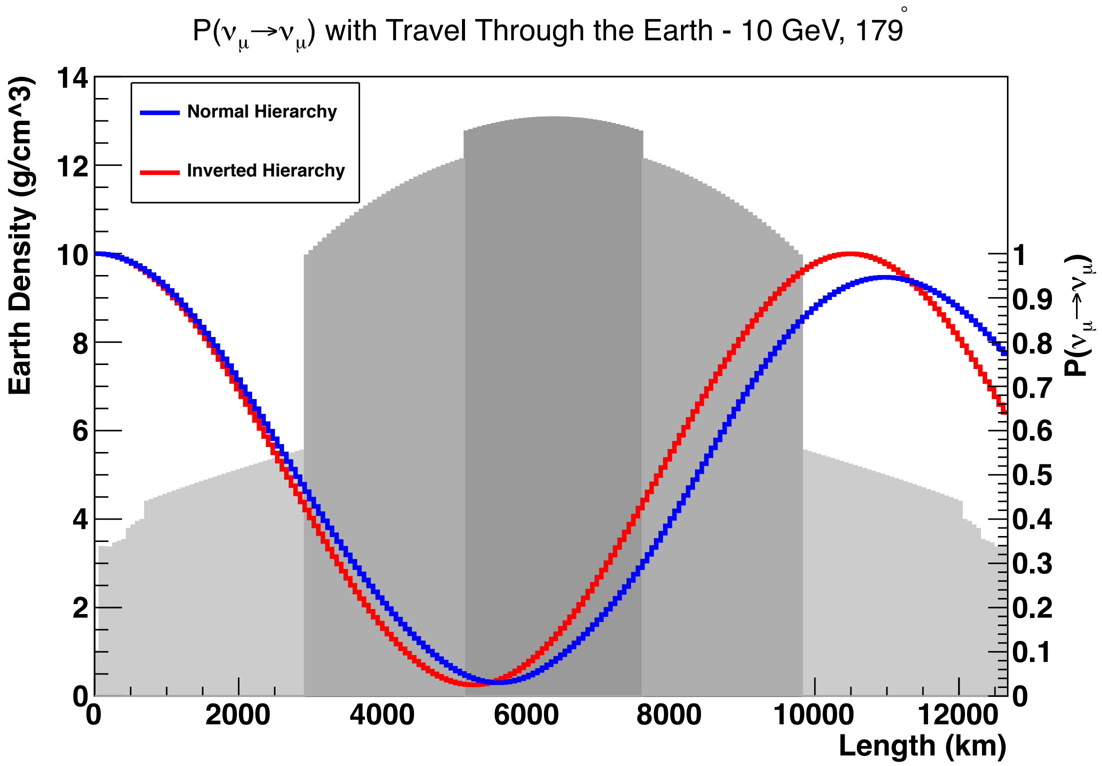


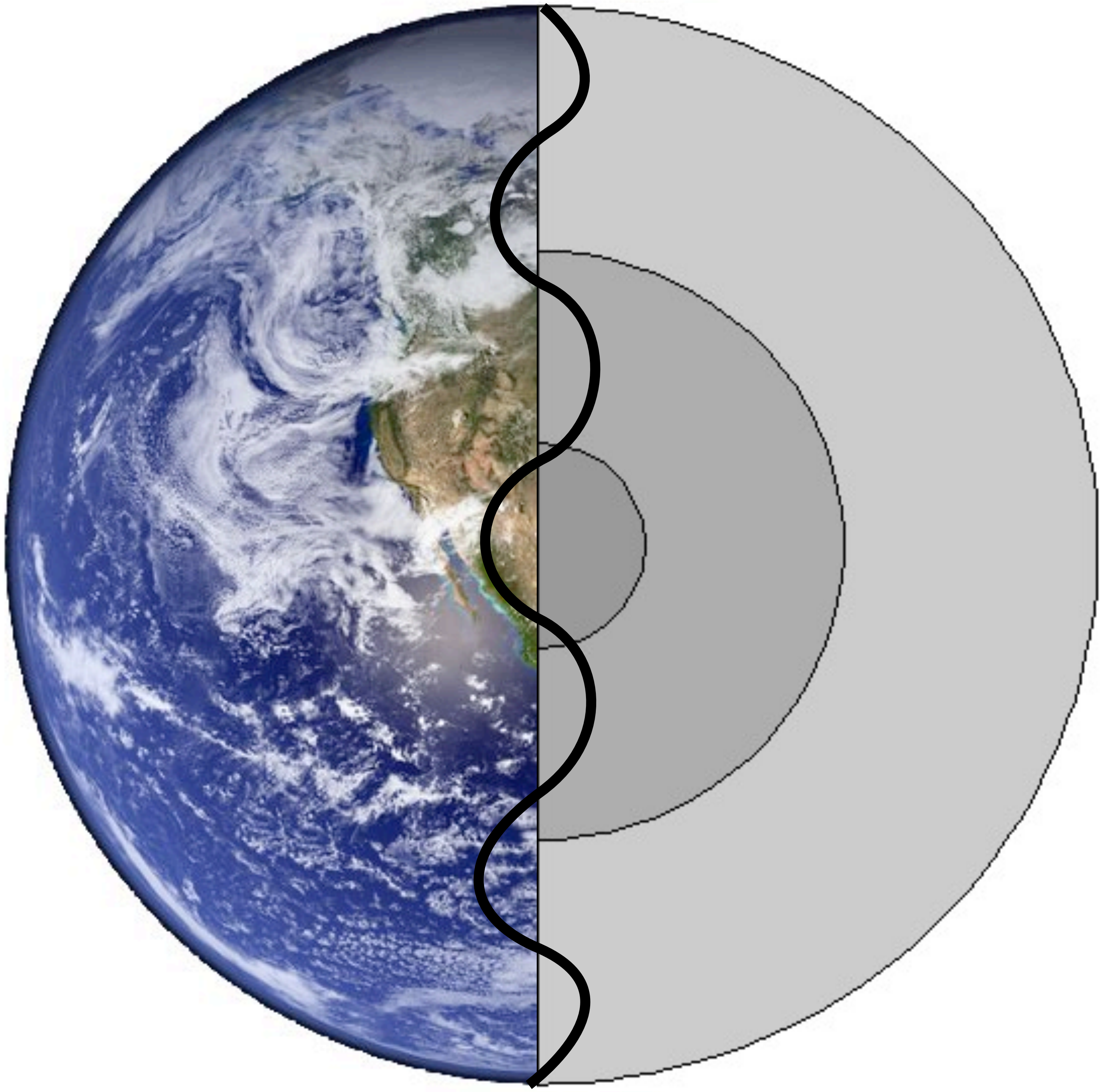
Neutrino mass hierarchy with neutrino telescopes

- Oscillation pattern modified by matter effects in Earth (MSW effect + parametric resonances)
- Effect differs for normal and inverted hierarchy (sign of Δm^2 changes)

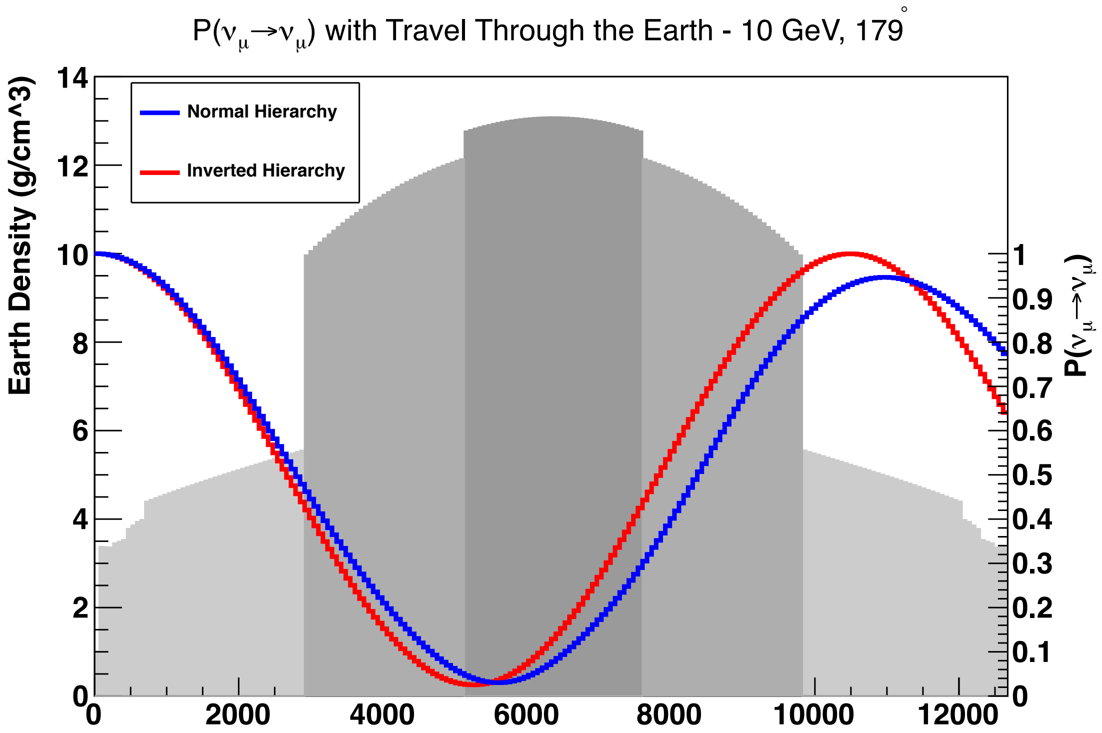


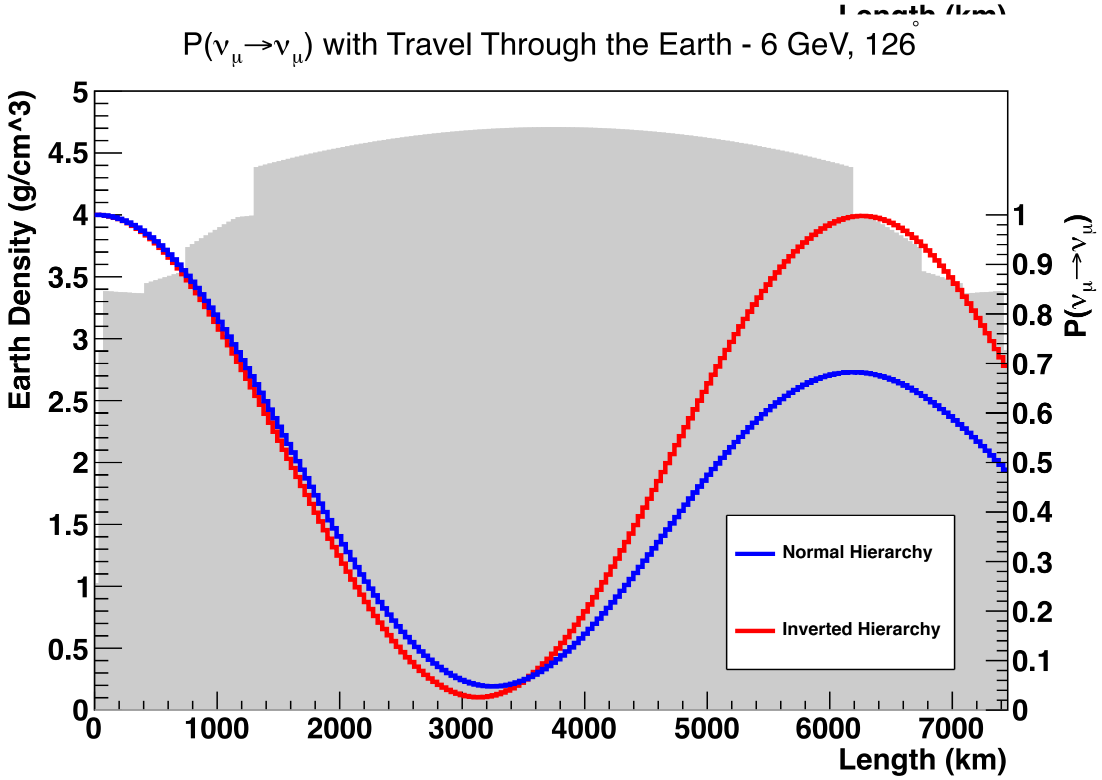
Neutrino mass hierarchy with neutrino telescopes

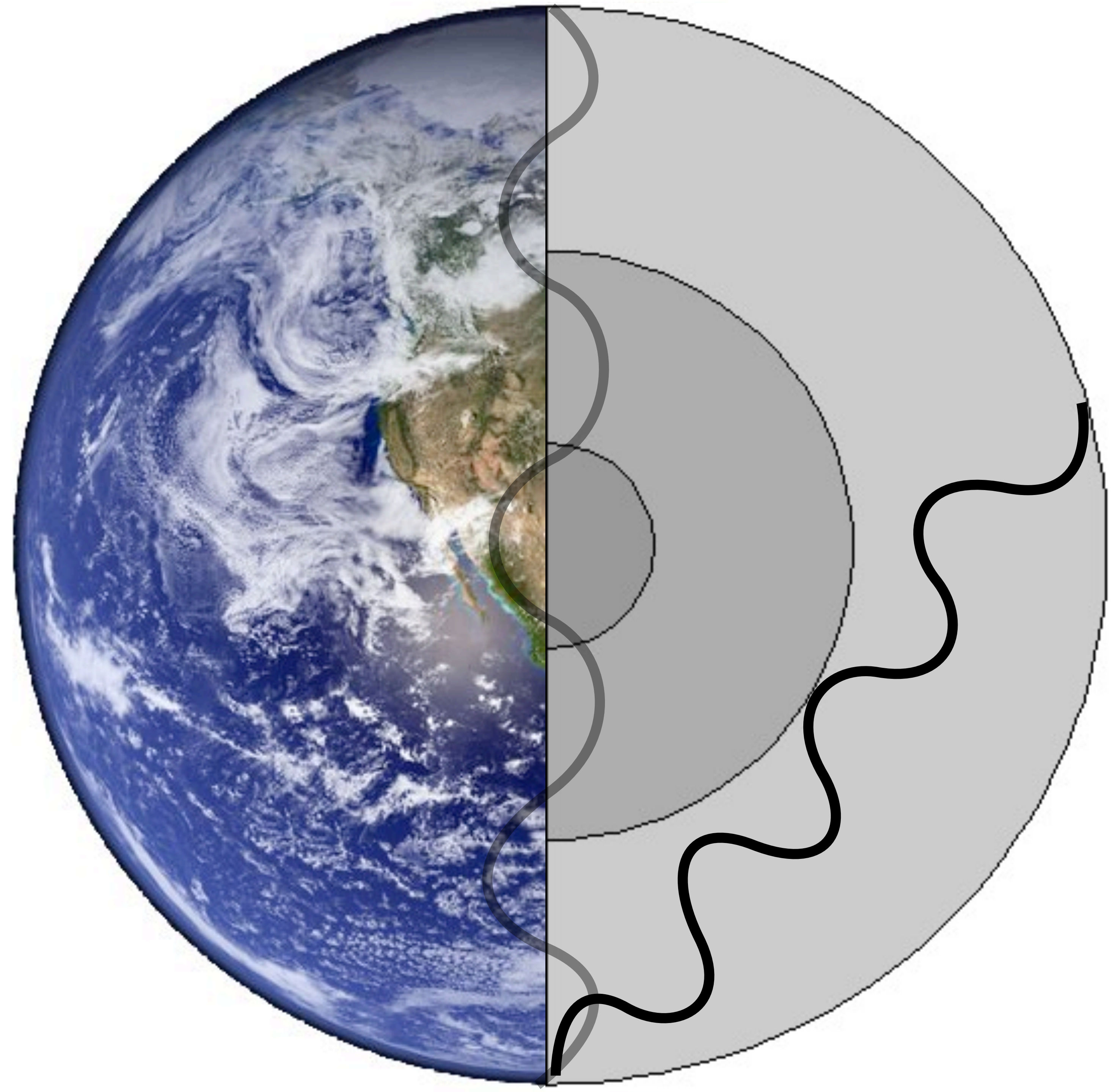




Neutrino mass hierarchy with neutrino telescopes



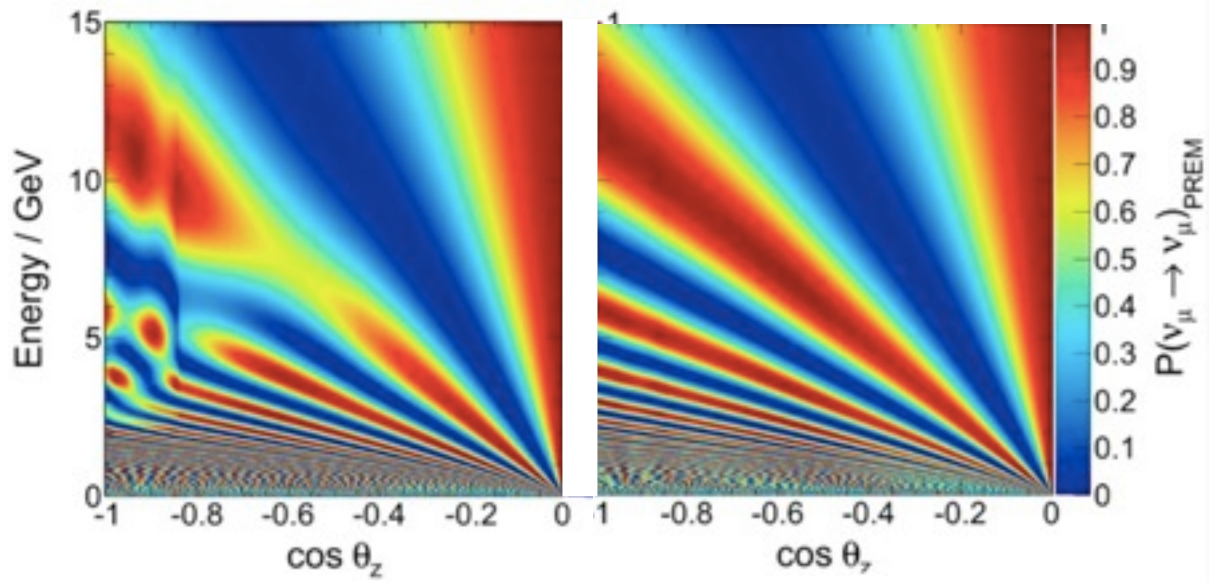




Neutrino mass hierarchy with neutrino telescopes

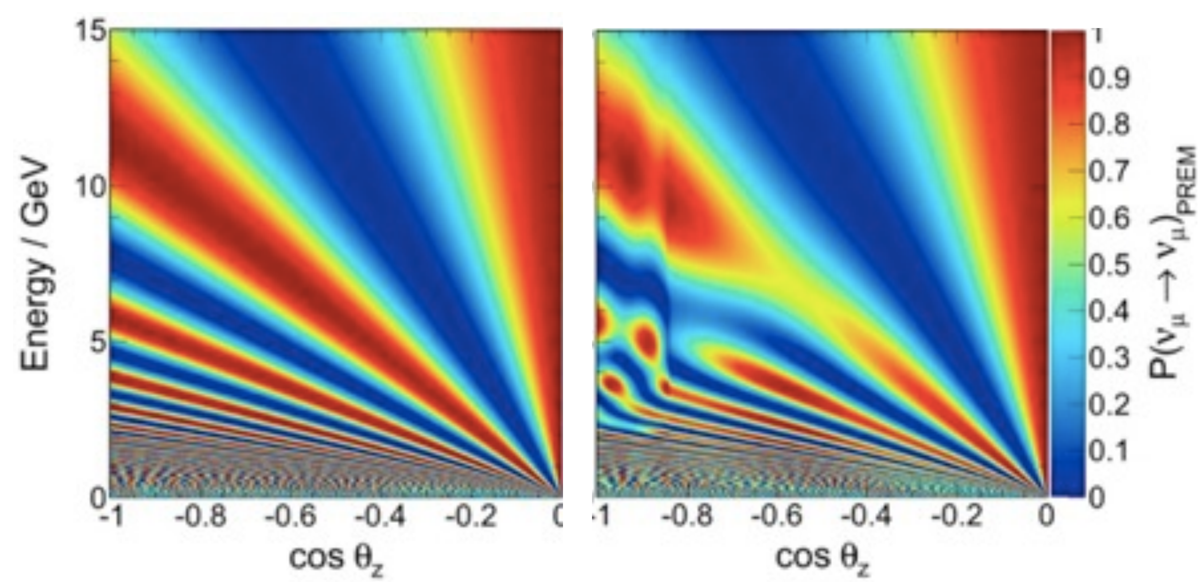
Normal hierarchy

neutrinos anti-neutrinos



Inverted hierarchy

neutrinos anti-neutrinos



- Maximum effect NH ↔ IH for θ=130° at 7 GeV
- For $\bar{\nu}$ NH and IH approximately swapped

Recap: $\xi = \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \frac{A_{CC}}{\Delta m^2}\right)^2}$ $A_{CC}(\bar{\nu}_e) = -A_{CC}(\nu_e)$

→ effect cancels if <u>detected</u> $N(\nu) = N(\bar{\nu})$

- Fortunately, flux(ν_{atm}) ≈ 1.3 × flux($\bar{\nu}_{atm}$)
  and xsec(ν) ≈ 2 × xsec($\bar{\nu}$)

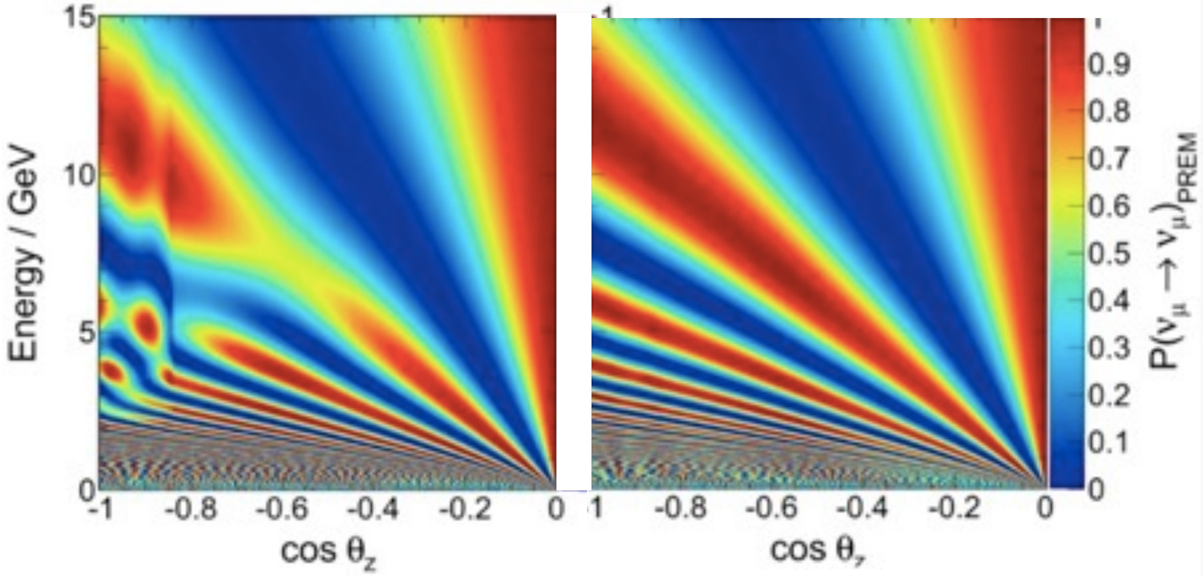
⟹ Count $N_\mu(E,\theta)$ from $\nu_\mu + N \rightarrow \mu + X$
and compare with NH / IH predictions

Remark:
neutrino telescopes inherently insensitive to $\nu \leftrightarrow \bar{\nu}$

Neutrino mass hierarchy with neutrino telescopes

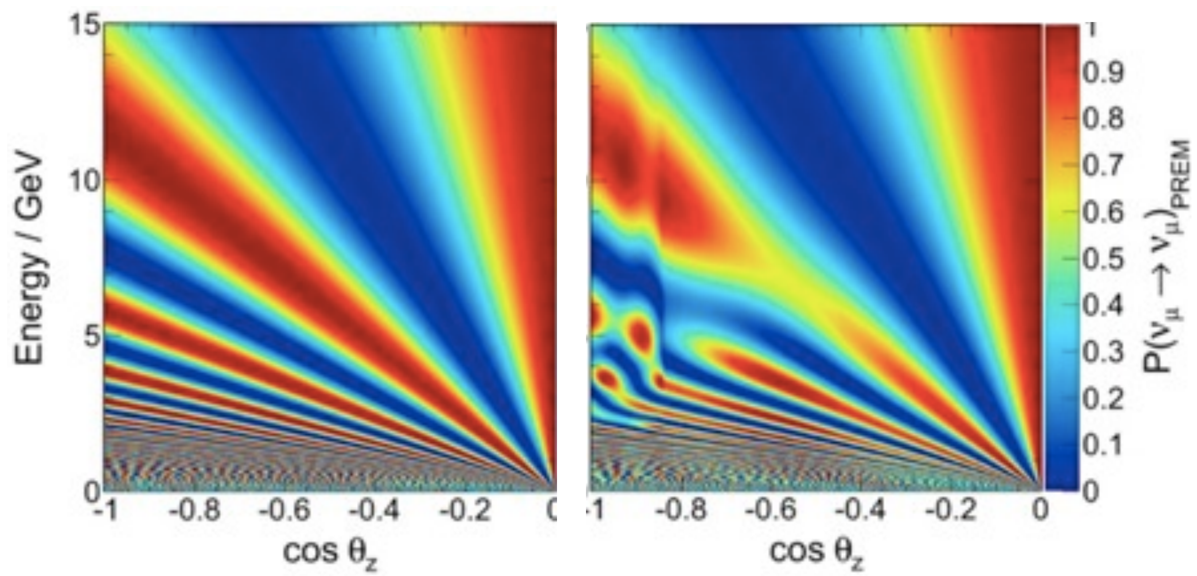
Normal hierarchy

neutrinos | anti-neutrinos

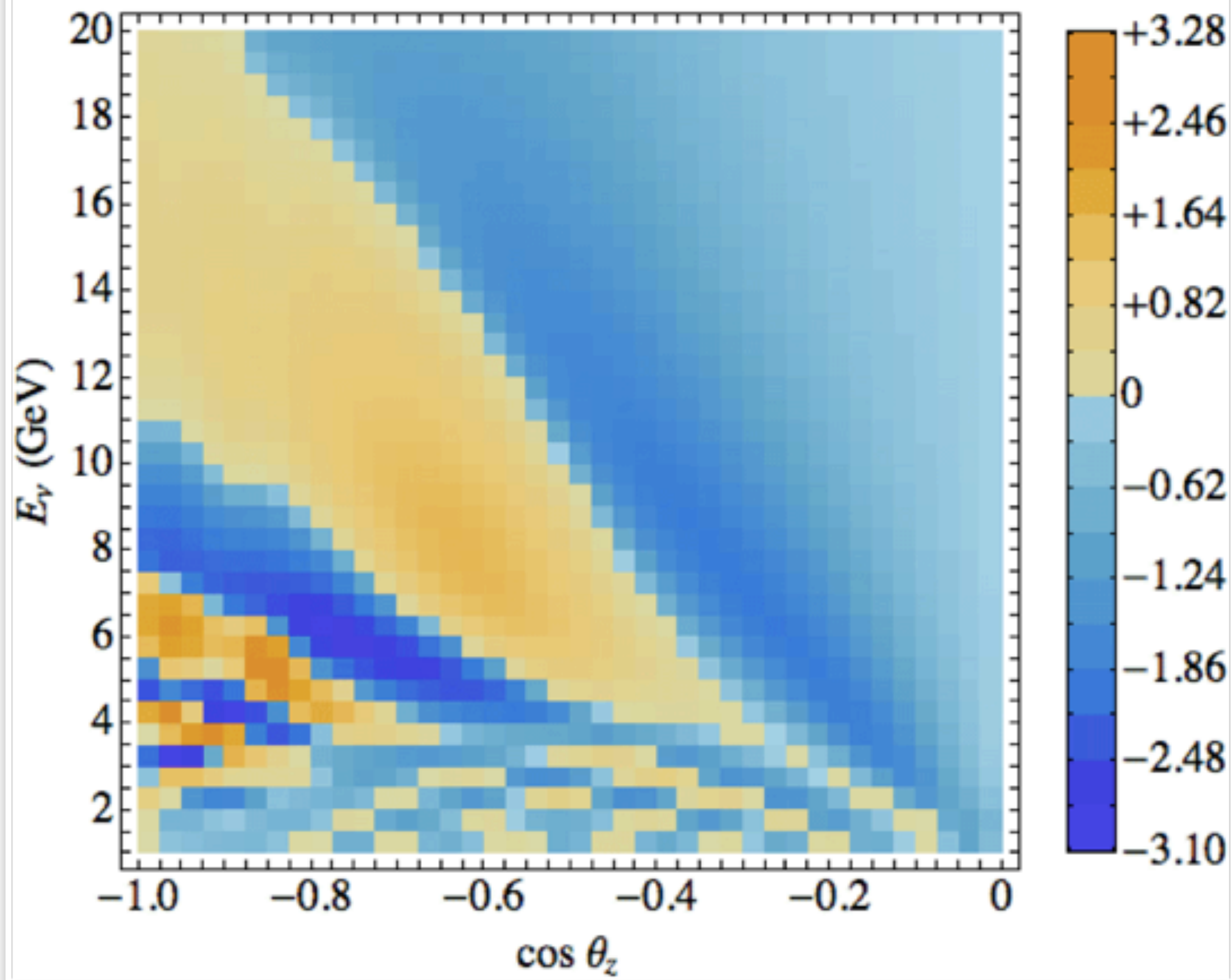


Inverted hierarchy

neutrinos | anti-neutrinos



Difference between NH and IH for atmospheric $\nu_\mu+\bar{\nu}_\mu$ flux

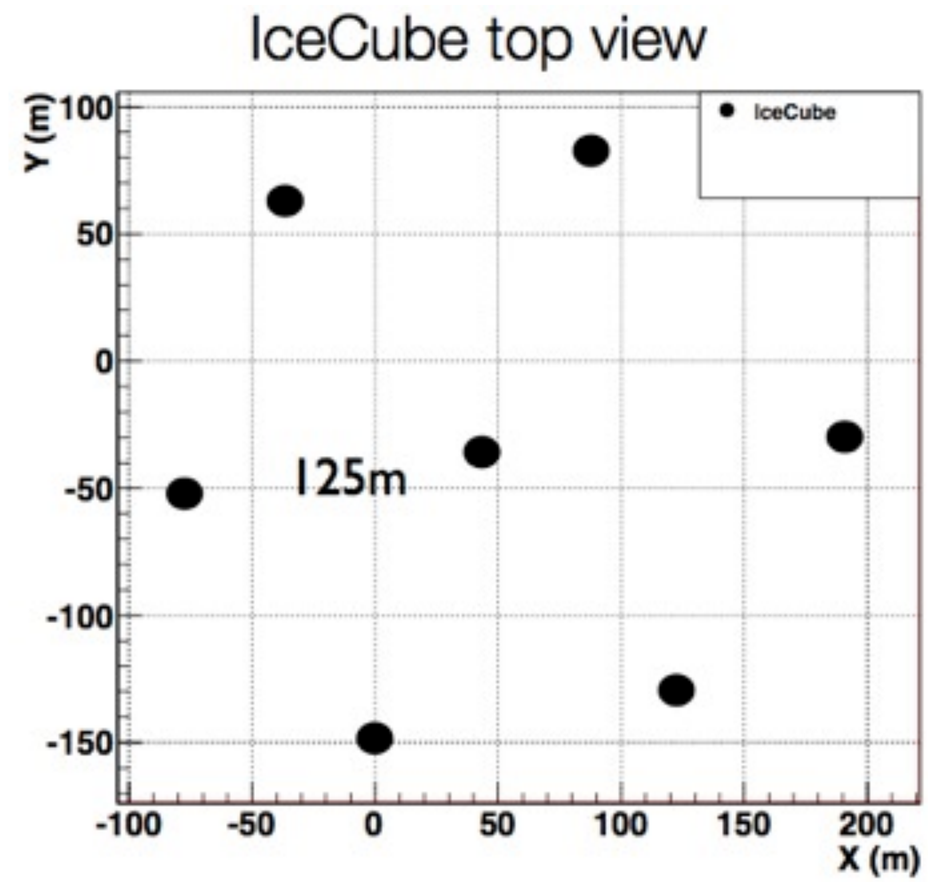


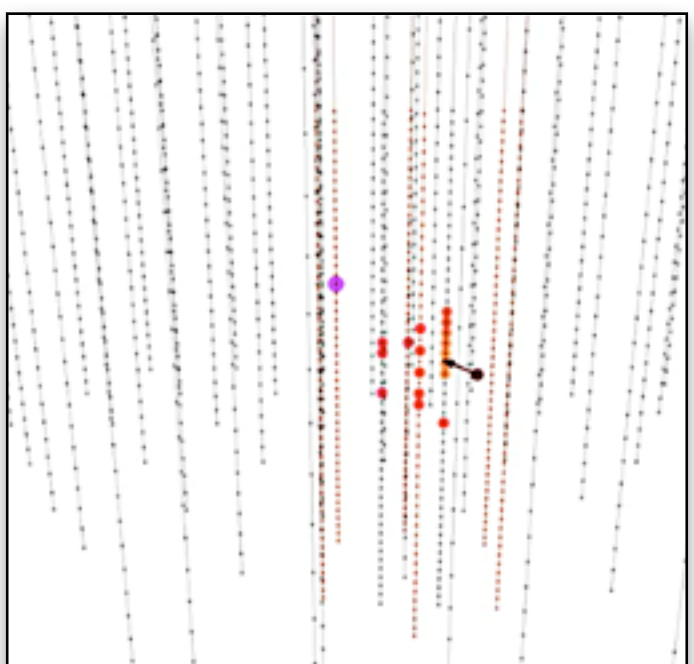
Akhmedov et al., arXiv:1205.7071

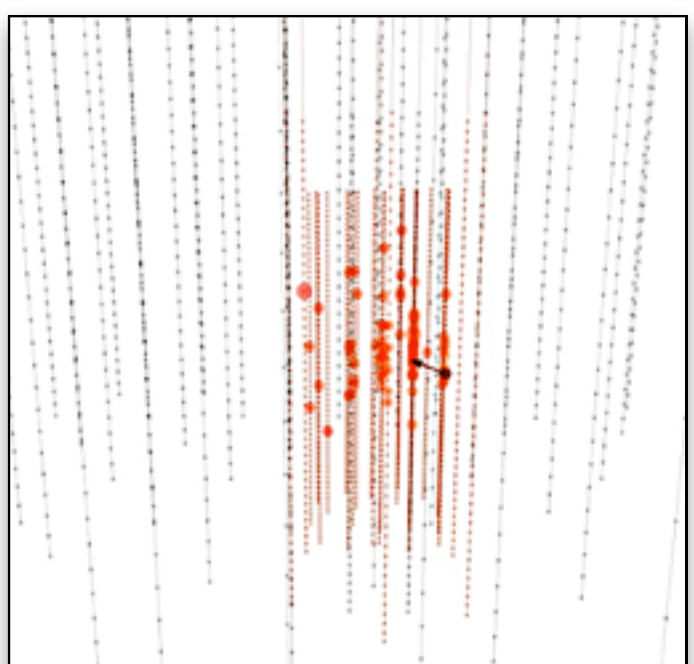
From IceCube via DeepCore to PINGU

IceCube

78 strings, 125 m string spacing, 17 m DOM spacing
→ energy range: ≳ 100 GeV







Number of hit optical modules
(PINGU 20 strings)

- Neutrino energy: 9.3 GeV
  Muon energy: 4.8 GeV
  Cascade energy: 4.5 GeV
- Hit modules:
  20 (DC) → ~50 (DC + PINGU)

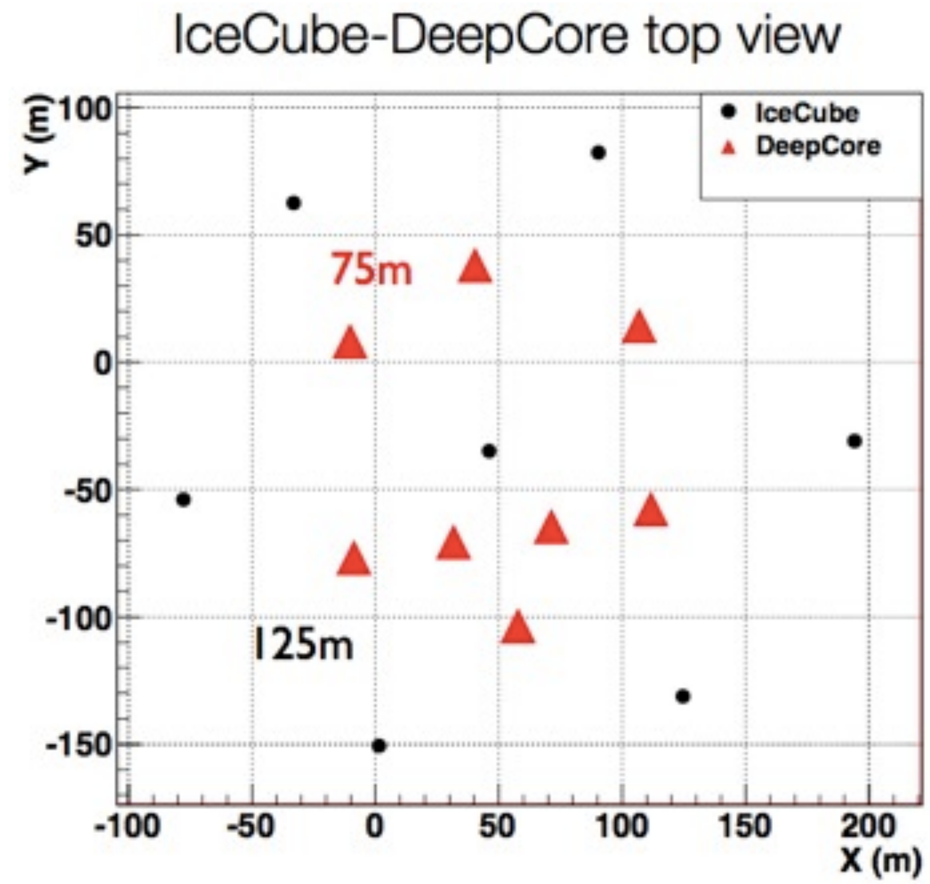
From IceCube via DeepCore to PINGU

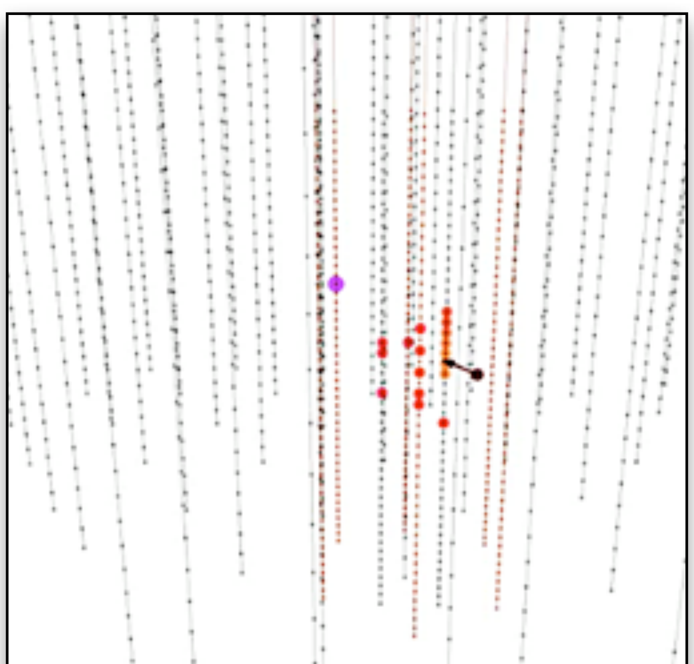
IceCube

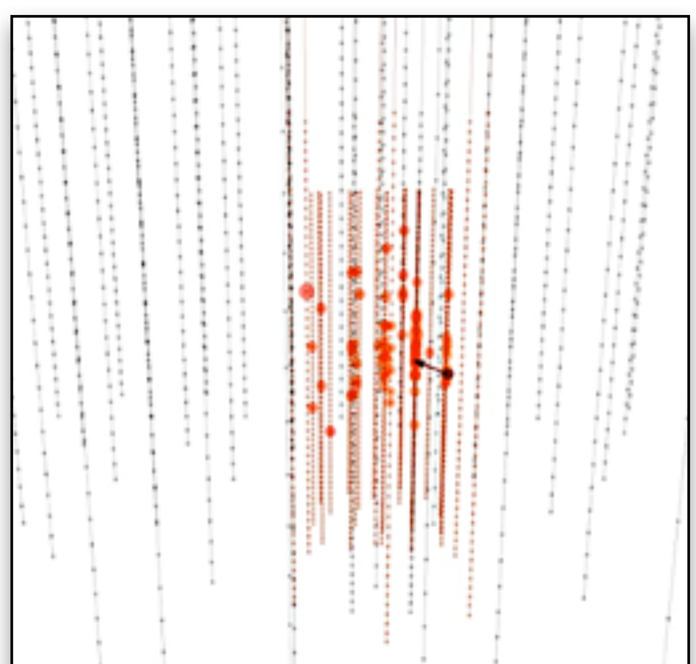
78 strings, 125 m string spacing, 17 m DOM spacing
→ energy range: ≳ 100 GeV

DeepCore

+8 strings, 75 m string spacing, 7 m DOM spacing
→ energy range: 10 GeV – 100 GeV







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From IceCube via DeepCore to PINGU

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78 strings, 125 m string spacing, 17 m DOM spacing
→ energy range: ≳ 100 GeV

DeepCore

+8 strings, 75 m string spacing, 7 m DOM spacing
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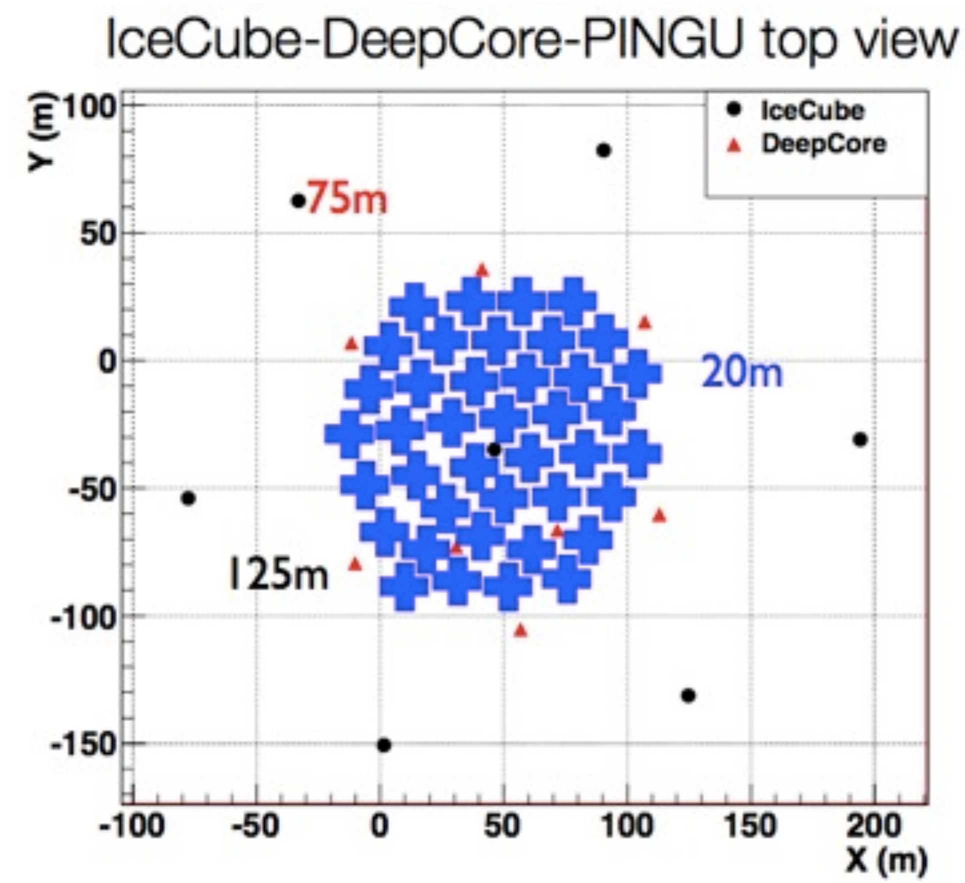
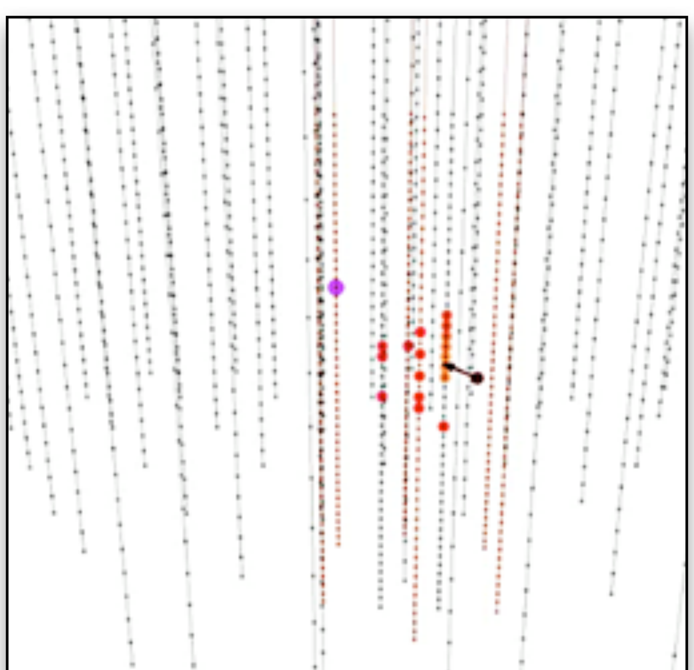
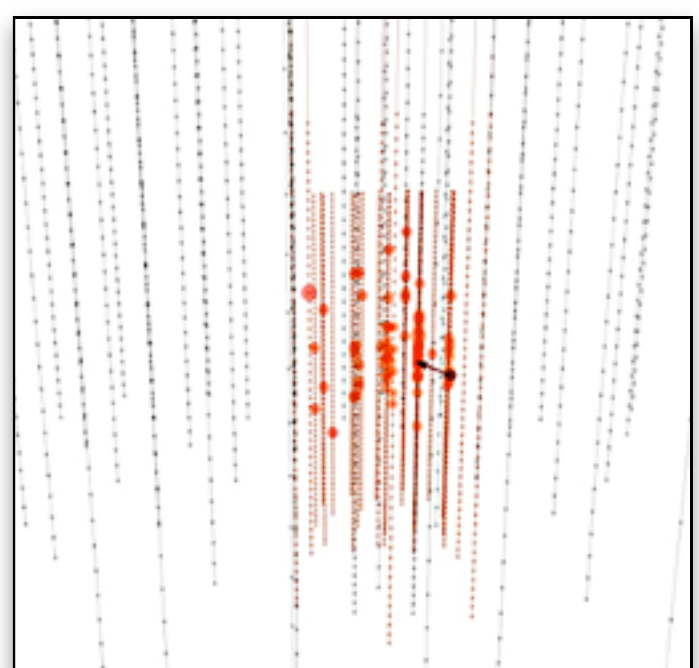
PINGU

+40 strings (baseline), ~20 m string spacing, 5 m DOM spacing
→ energy range: 1 GeV – 20 GeV







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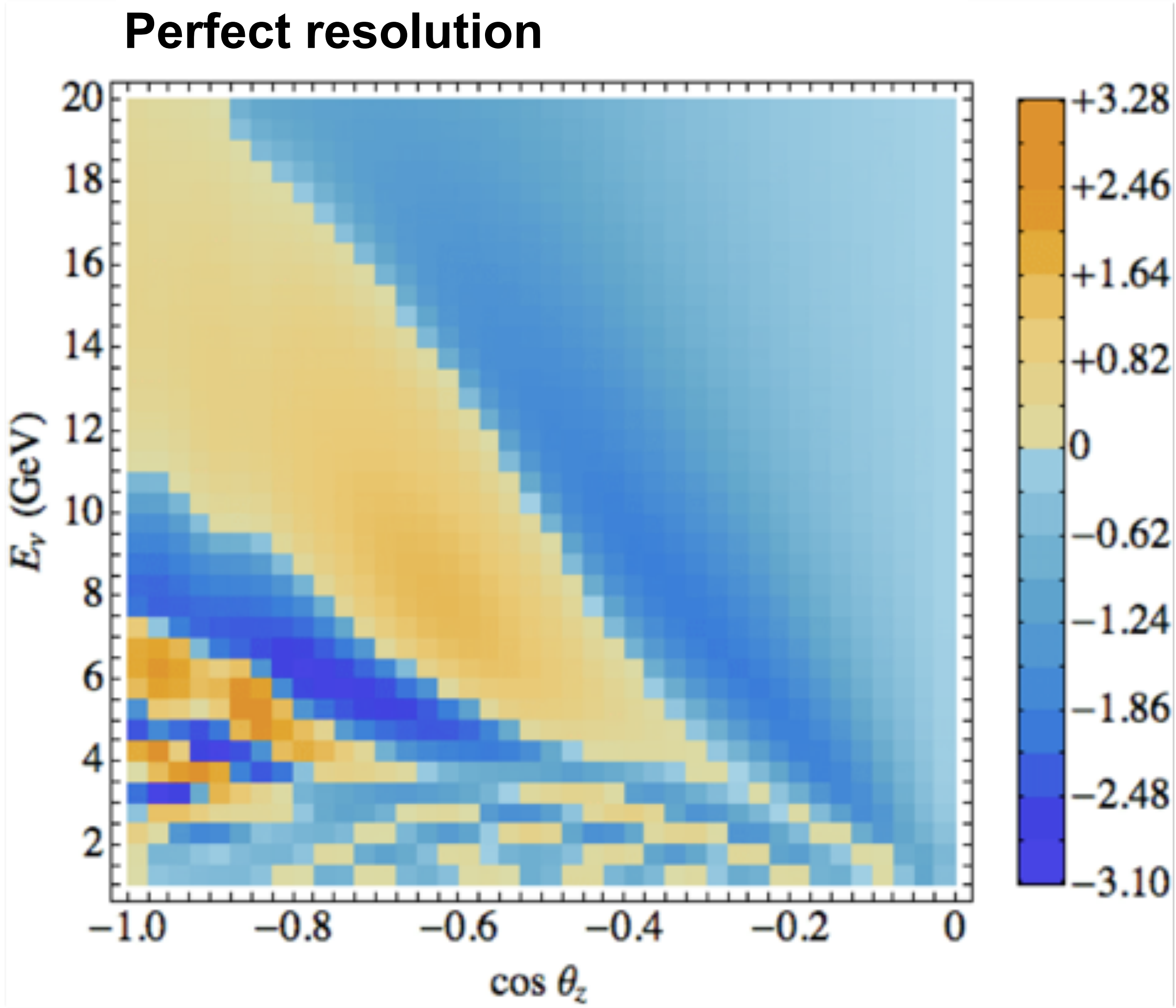
Neutrino mass hierarchy with neutrino telescopes

- For illustrative purpose use metric from Akhmedov et al:

  ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]
  - idealized case (for a 20-string PINGU) (perfect flavor-ID, no quality cuts)
  - no correlation with oscillation parameters taken into account
  - NOT used for actual sensitivity estimates

- Angular / energy resolution and muon identification crucial
  Relevant energy range: 5−10 (20) GeV

ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]



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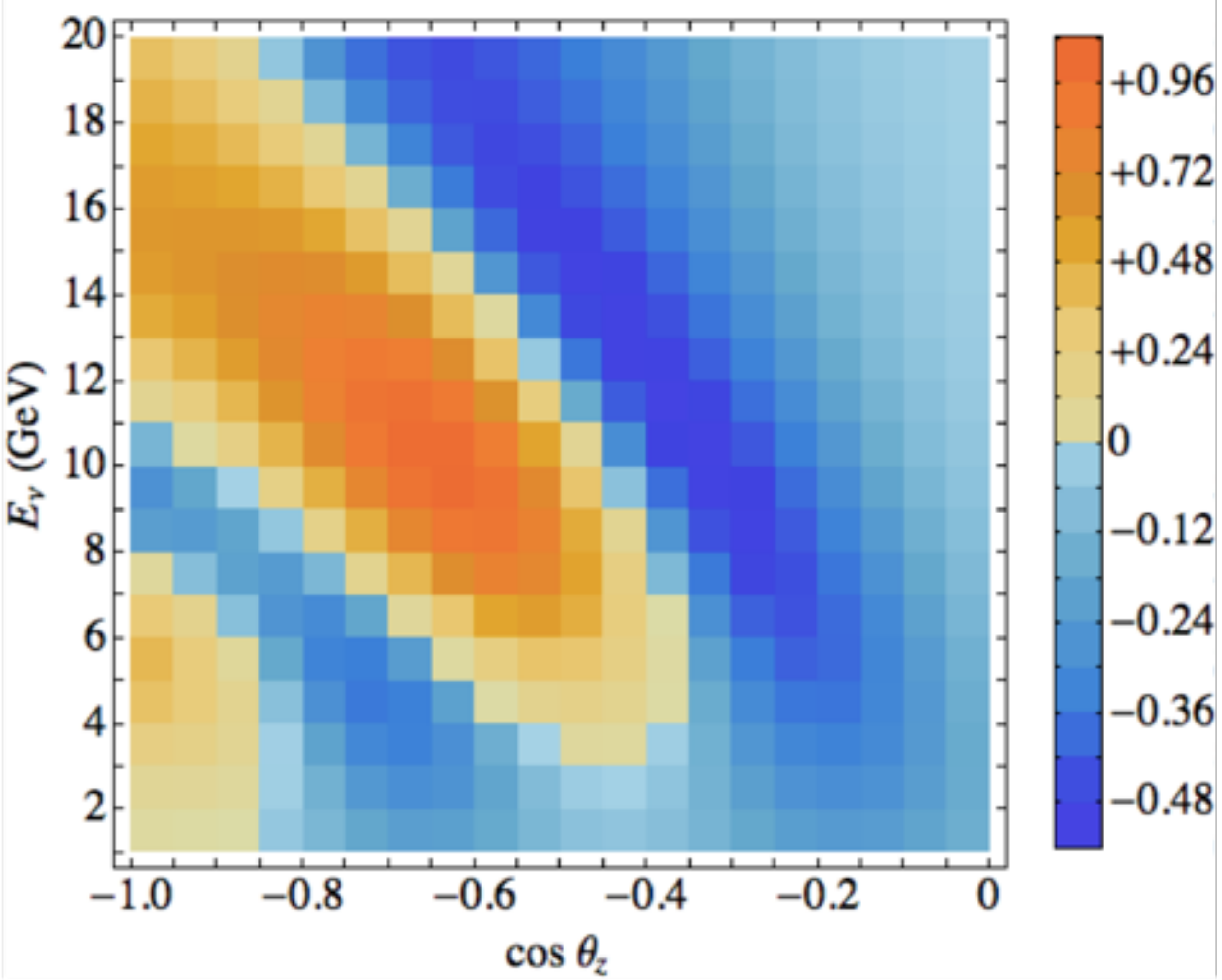
ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]

σ_θ = 11° σ_E = 2 GeV



Akhmedov et al., arXiv:1205.7071

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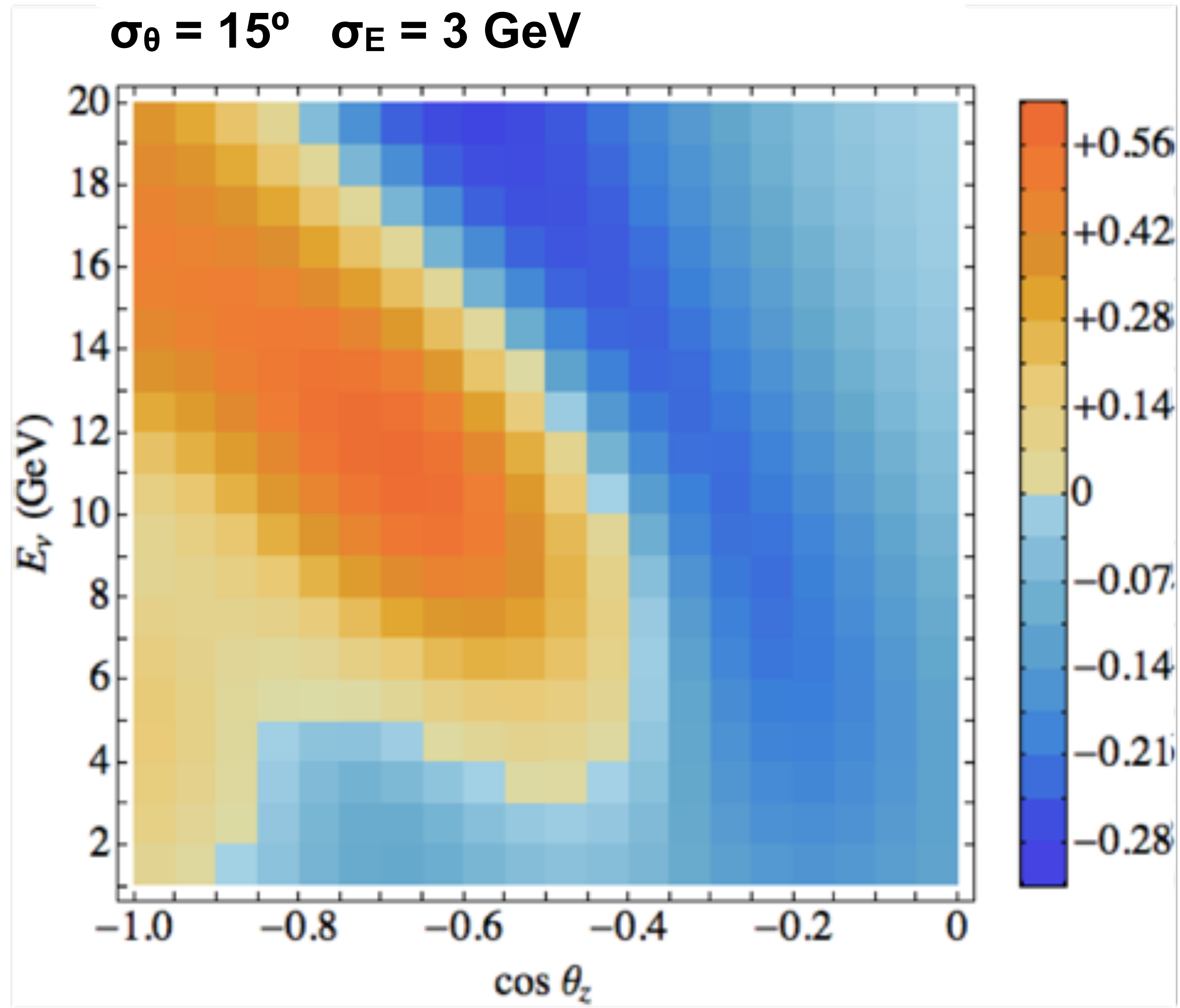

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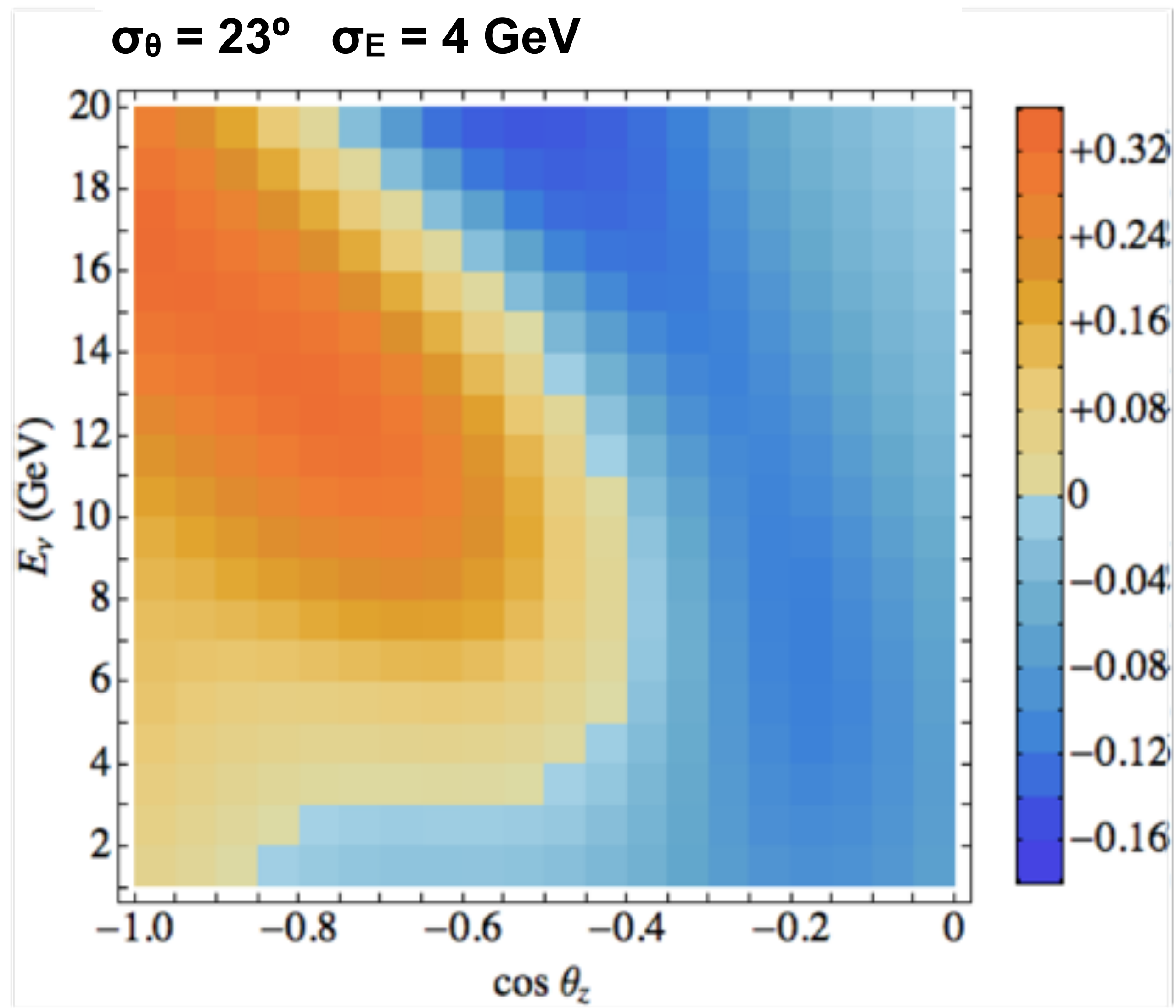
  Relevant energy range: 5−10 (20) GeV

- Required minimum resolutions:
  ΔE/E < 40%, Δθ < 15º

ΔN(IH−NH) / √N(NH) [PINGU 1 yr, 10% sys.]



Akhmedov et al., arXiv:1205.7071

PINGU performance and systematics

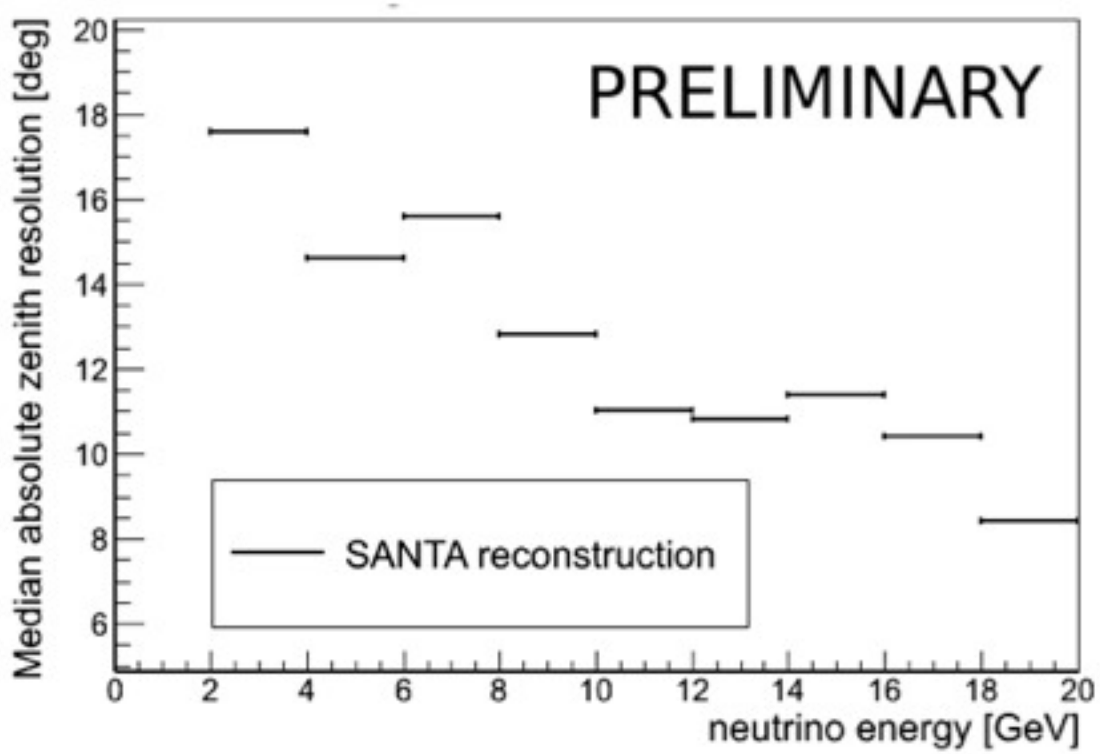
Performance

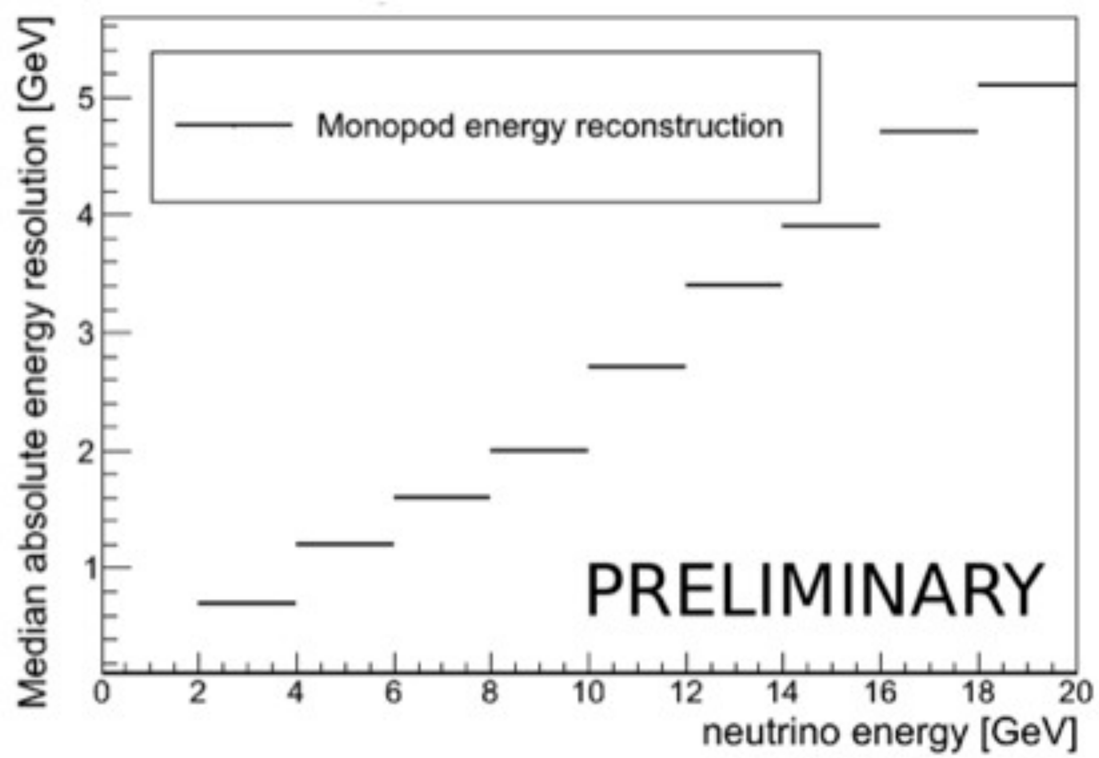
- Currently using adapted (fast) IceCube/DeepCore algorithms
- Meet minimum requirements but more elaborate (CPU intensive) algorithms promise improved resolutions

Systematics studied so far

- θ_{23},θ_{13}, Δm^2_{atm}, δ_{CP} within known uncertainties
- Efficiency (30%)
- Atmospheric ν spectral index (±0.05)
- Energy calibration (10%)
- Pointing accuracy (10%)
- Energy resolution (10%)
- Zenith resolution (10%)
- Earth density profile

→ Further systematics under study





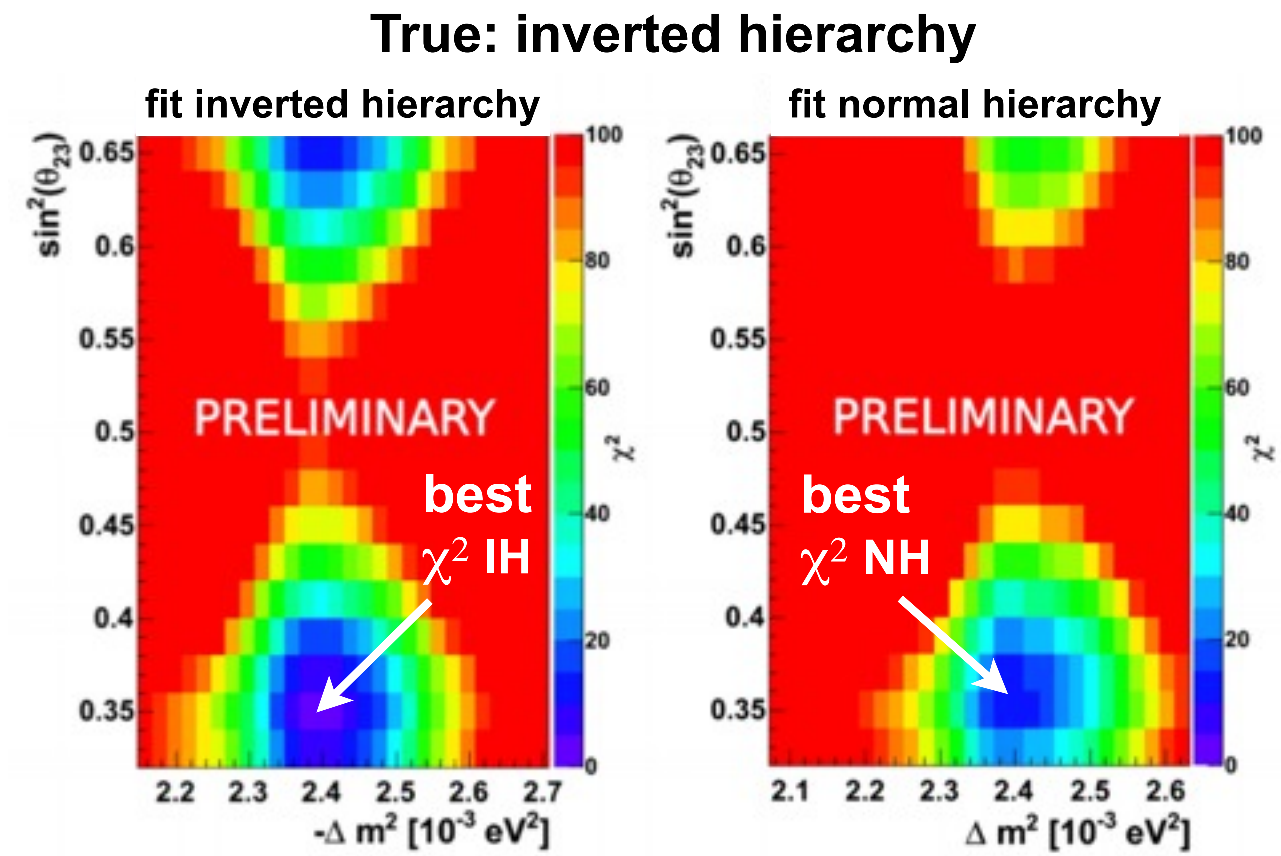
Preliminary sensitivity predictions for mass hierarchy

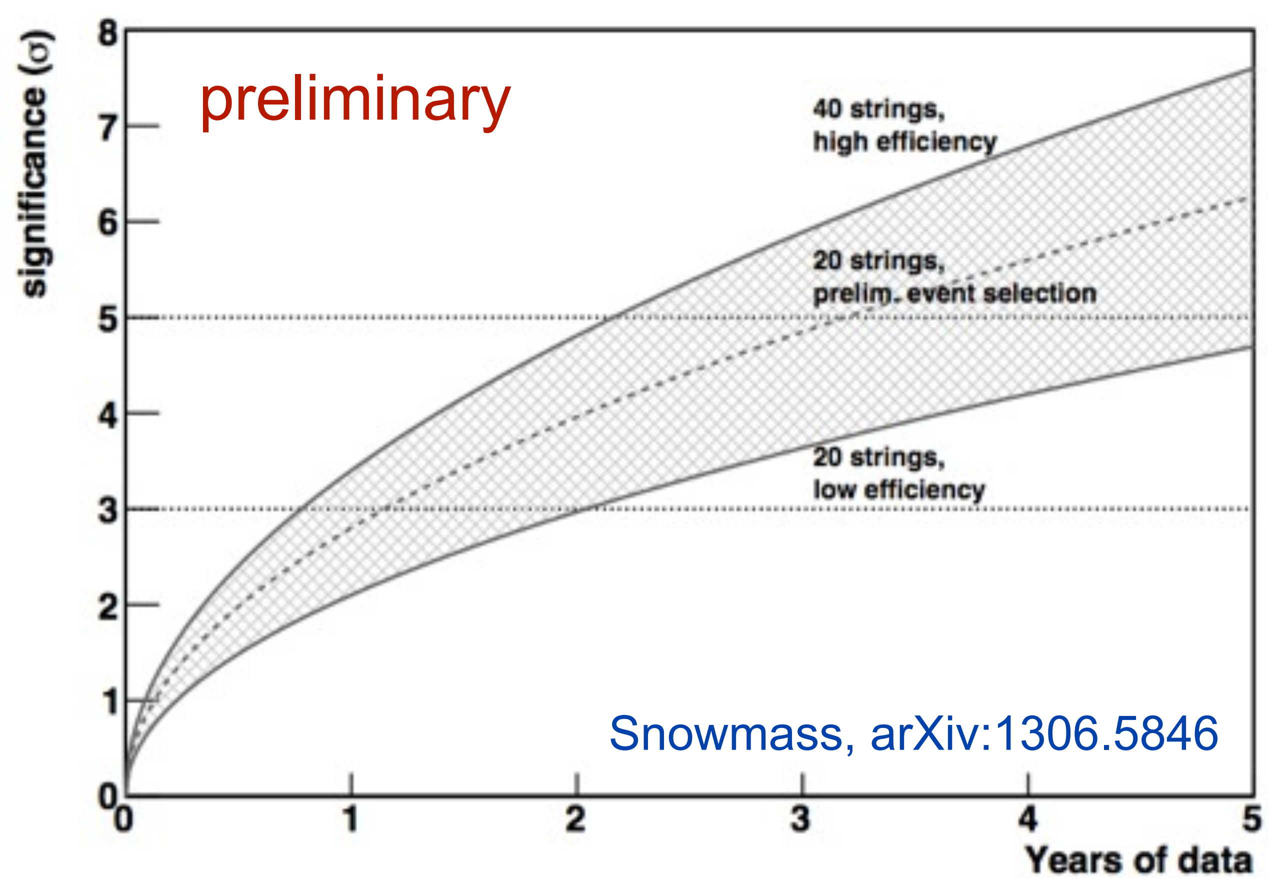
Expect ~20,000 ν_μ events/year < 30 GeV (preliminary selection based on DeepCore)

Several approaches with different focuses under investigations

- One of them: $\Delta\chi^2$ approach (includes systematics but no explicit background rejection)
  - calculate χ^2 between pseudo data and NH and IH hypothesis
  - $\Delta\chi^2$ between best fit for NH and IH yields significance for rejection (here $\Delta\chi^2 \approx 12$)
- Other approaches use a.o.
  - different event selections
  - efficiencies
  - detector geometries

  (not all systematics have been included here)

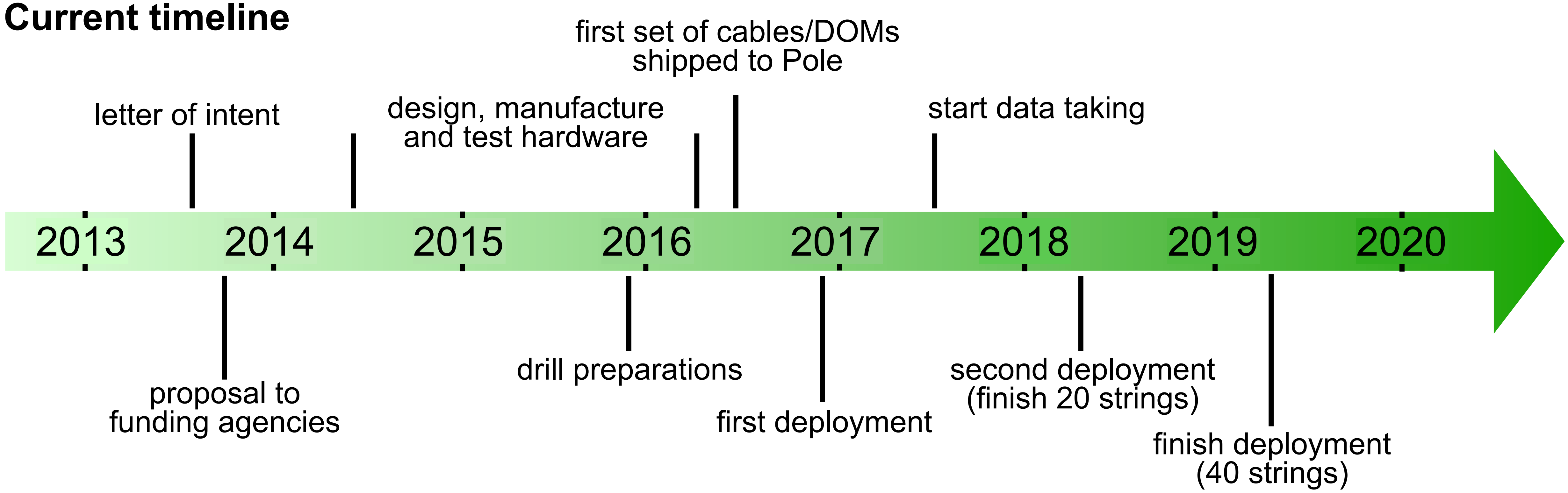




PINGU timeline

- Moderate timeline of ~10 years (data taking could start in 2017)
- Overall low risk for construction and operation (IceCube experience)
- Costs: ~10 M$ for startup (includes drill reactivation) + 1.25 M$ per string

Current timeline



Summary

- Neutrino telescopes cover a wide range of topics in astrophysical and particle physics with growing impact

- DeepCore has demonstrated the viability of low-energy neutrino physics in the Antarctic ice
  - enables atmospheric neutrino oscillation measurements
  - augments indirect Dark Matter searches at low energies

- PINGU aims at further expanding IceCube's low-energy capabilities
  - primary goal: first measurement of neutrino mass hierarchy
  - sensitivity studies advancing with high pressure; detailed Letter of Intend planned for this year
  - advantage: could be build and run on relative short time scales

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The IceCube Collaboration & PINGU

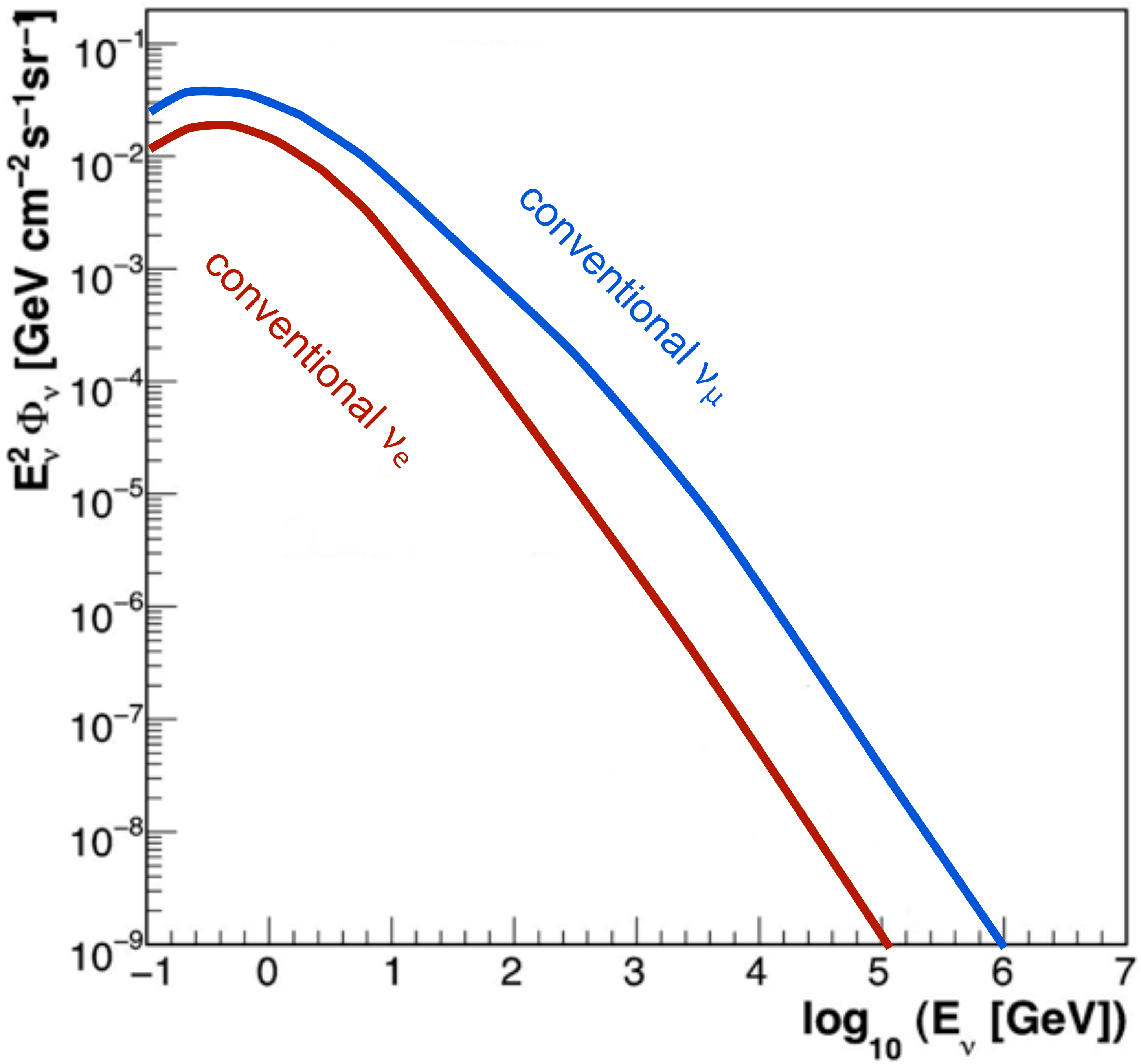
~250 authors from 44 institutes in 10 countries

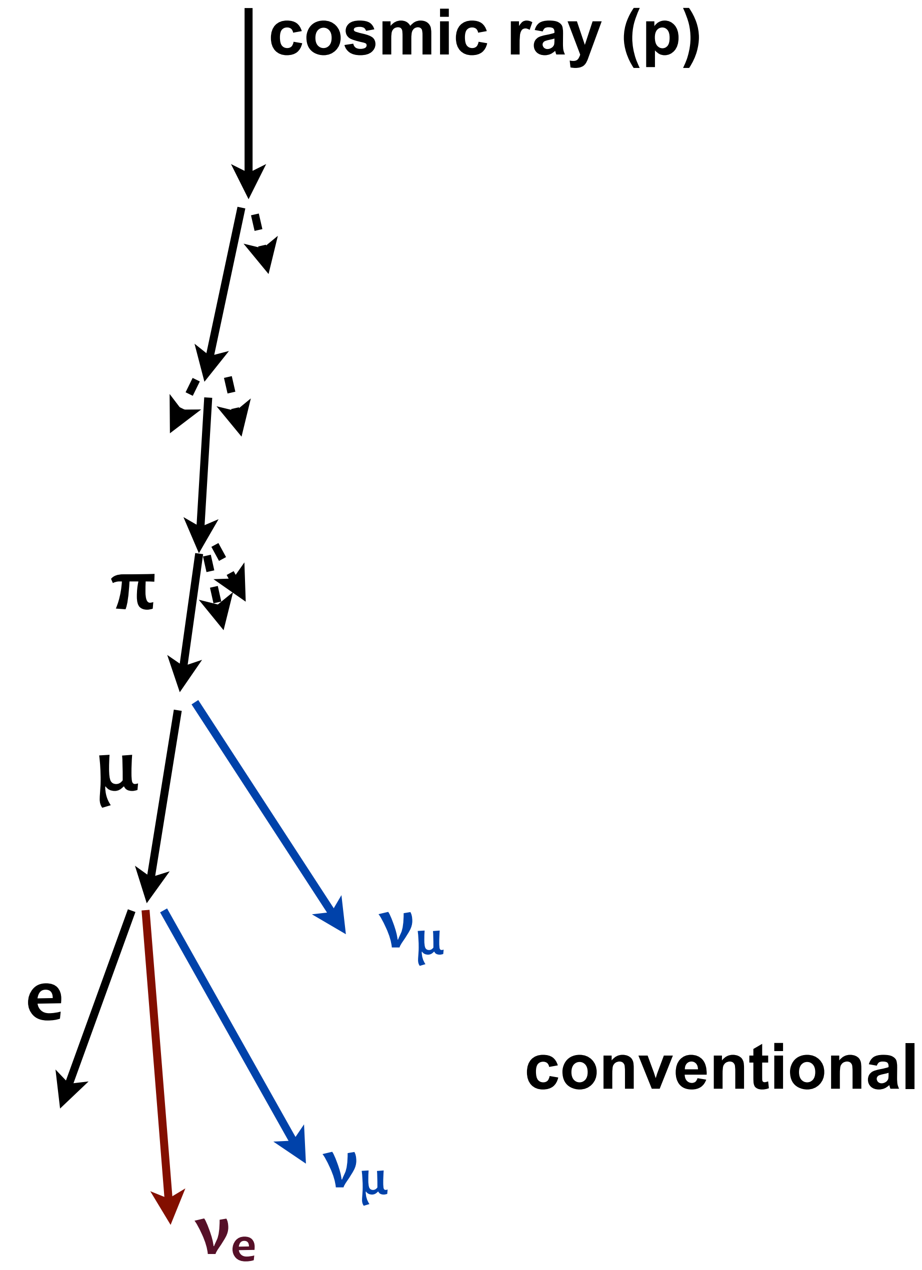
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

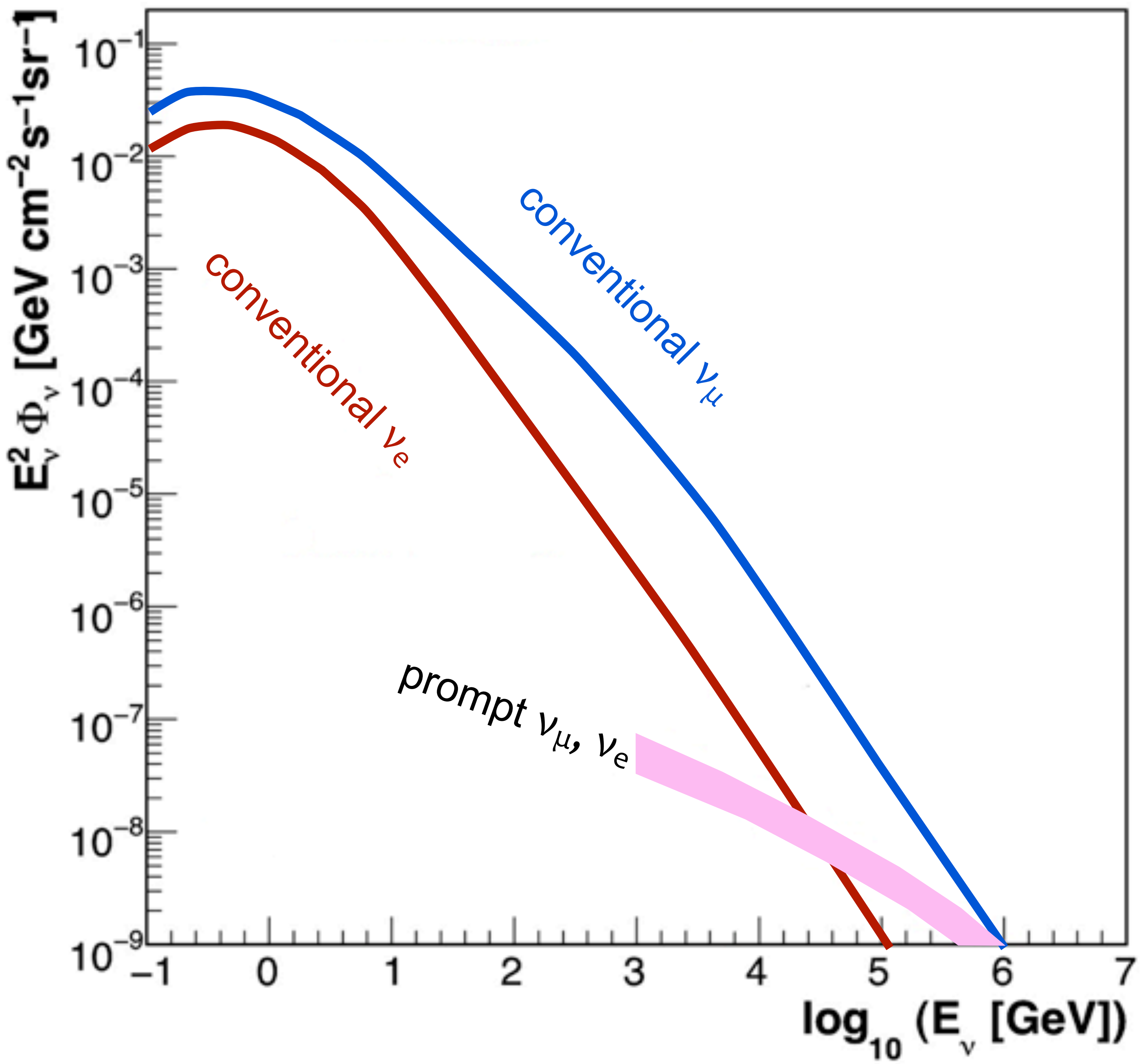
Backup

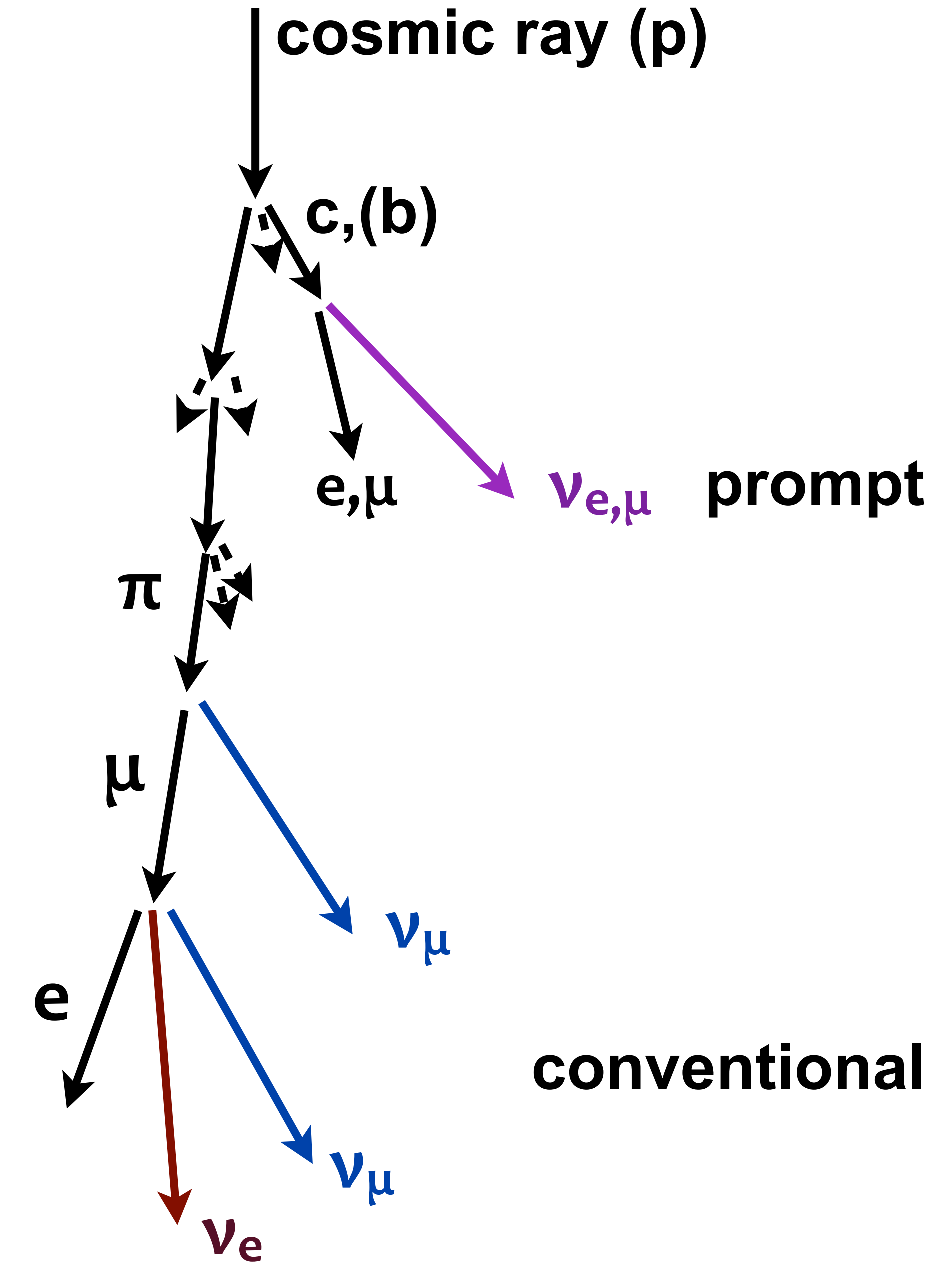
Atmospheric neutrino spectra





Atmospheric neutrino spectra





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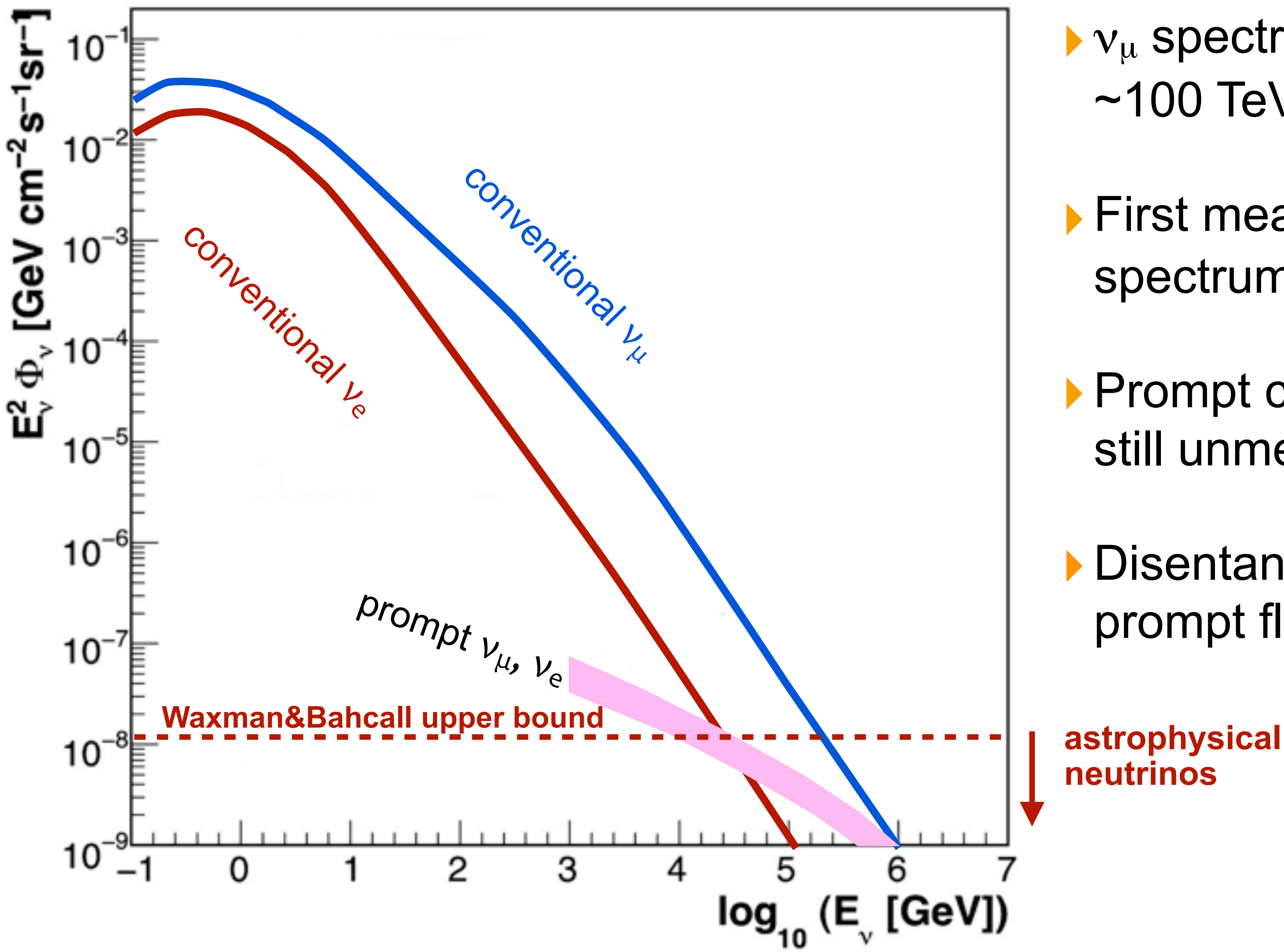
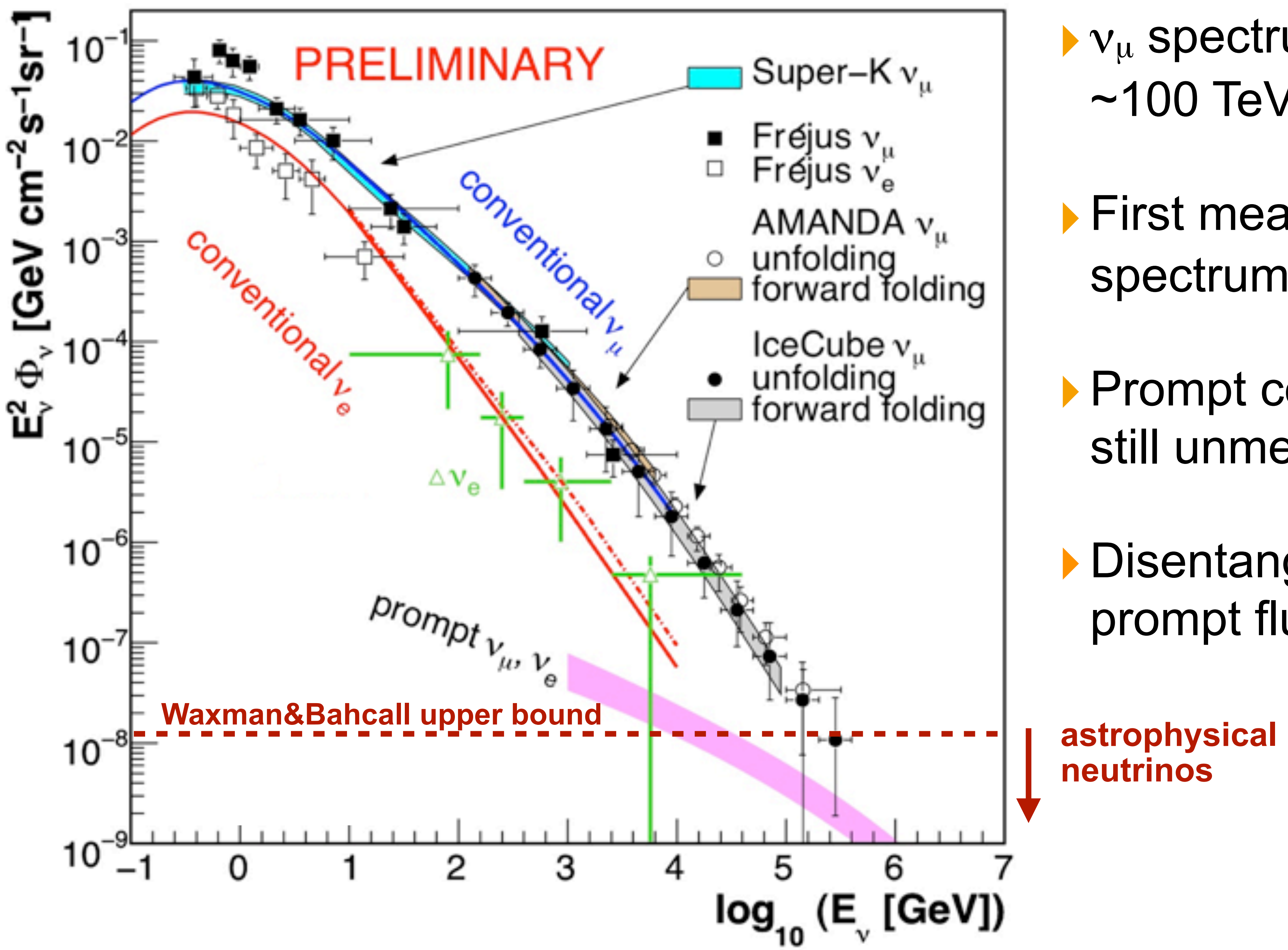


- ν_μ spectrum measured to ~100 TeV with high accuracy
- First measurement of ν_e spectrum at TeV energies
- Prompt components still unmeasured
- Disentangling cosmic and prompt fluxes challenging

Atmospheric neutrino spectra



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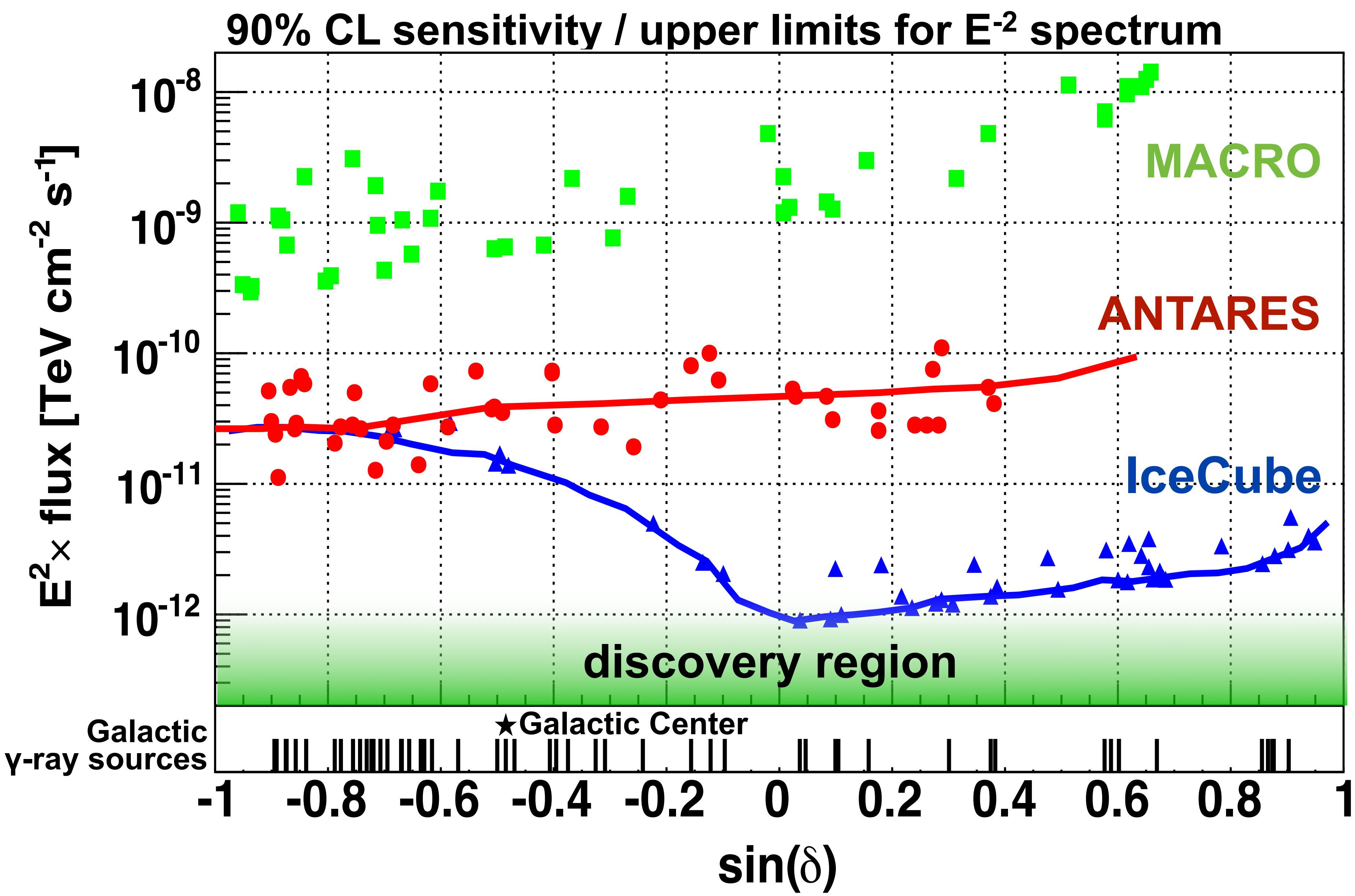
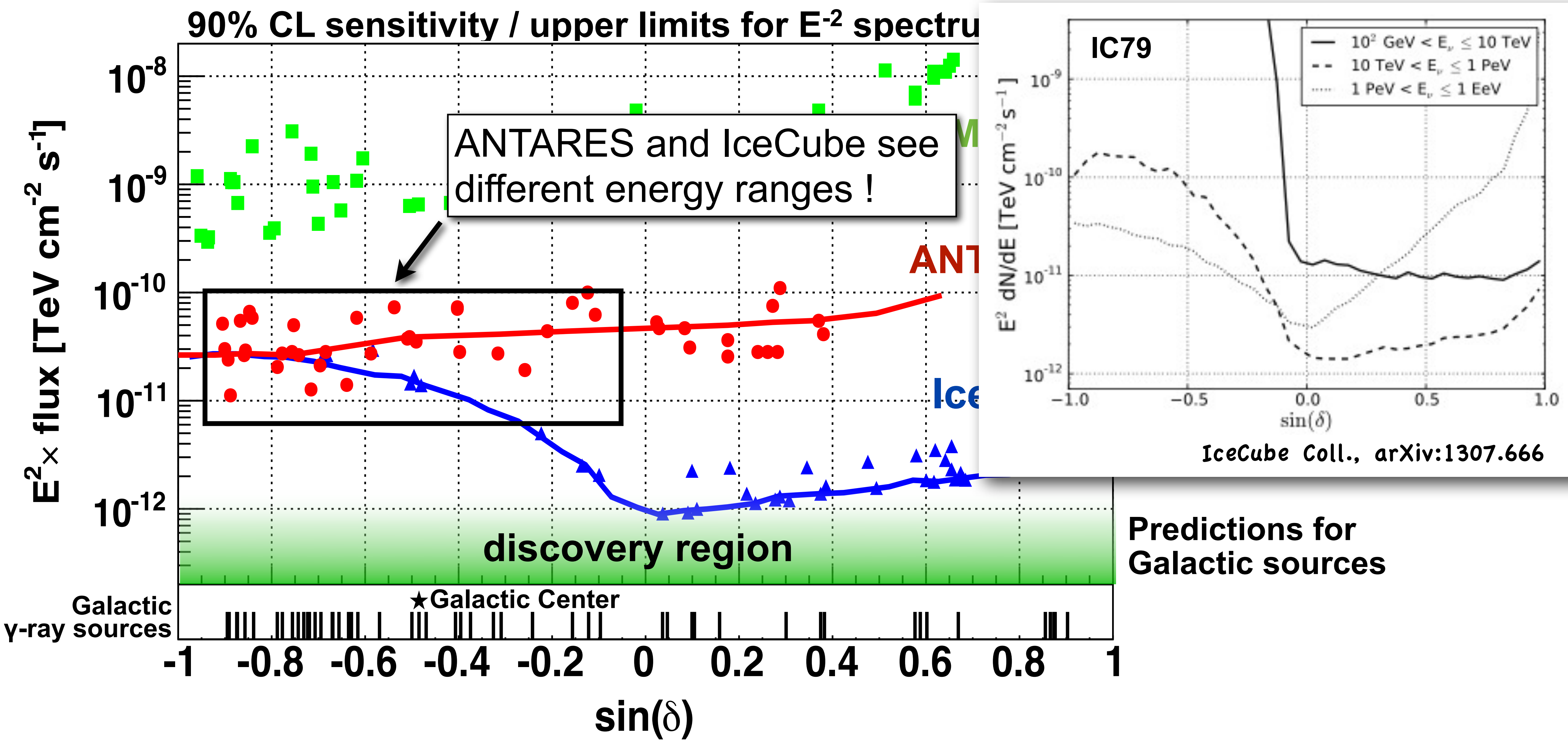
Point sources: Sensitivities & upper limits (IC40+59+79)



Predictions for Galactic sources

- Accumulation of data + improved reconstruction
  → further significant sensitivity improvement in next years

Point sources: Sensitivities & upper limits (IC40+59+79)



Predictions for Galactic sources

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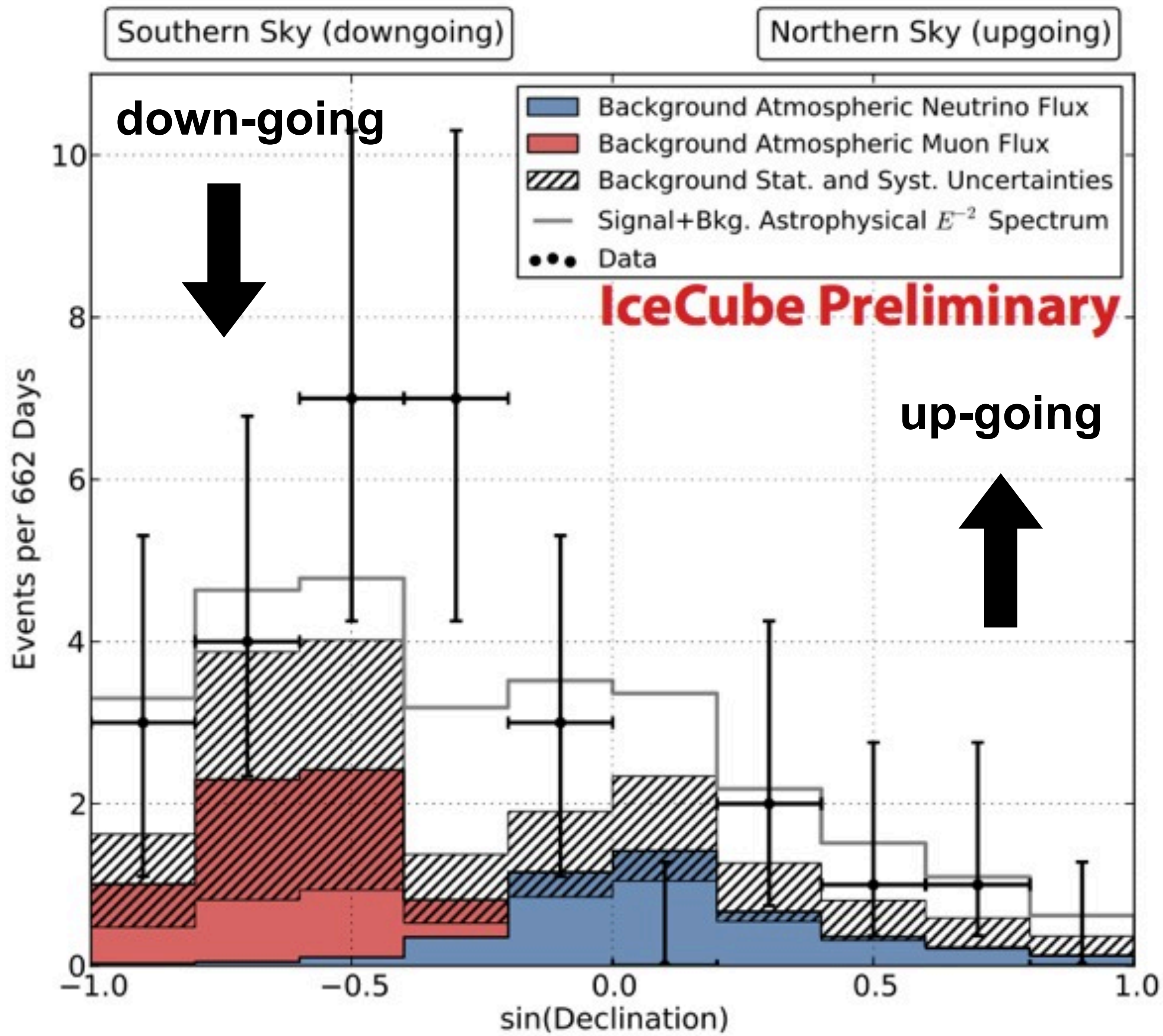
Starting event analysis − zenith distribution



What is neutrino oscillation?

If neutrinos have small and different masses

→ flavor eigenstates of weak interactions $\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$

≠ propagation mass eigenstates $\nu_i = \nu_1, \nu_2, \nu_3$

Connected by unitary matrix (Pontecorvo-Maki-Nakagawa-Saka PMNS)

$$U = \begin{pmatrix} U_{\alpha 1} & U_{\alpha 2} & U_{\alpha 3} \\ U_{\beta 1} & U_{\beta 2} & U_{\beta 3} \\ U_{\gamma 1} & U_{\gamma 2} & U_{\gamma 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, δ = CP-violating phase

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

… nothing special, typical quantum mechanical effect relating orthonormal vectors

Transition probability

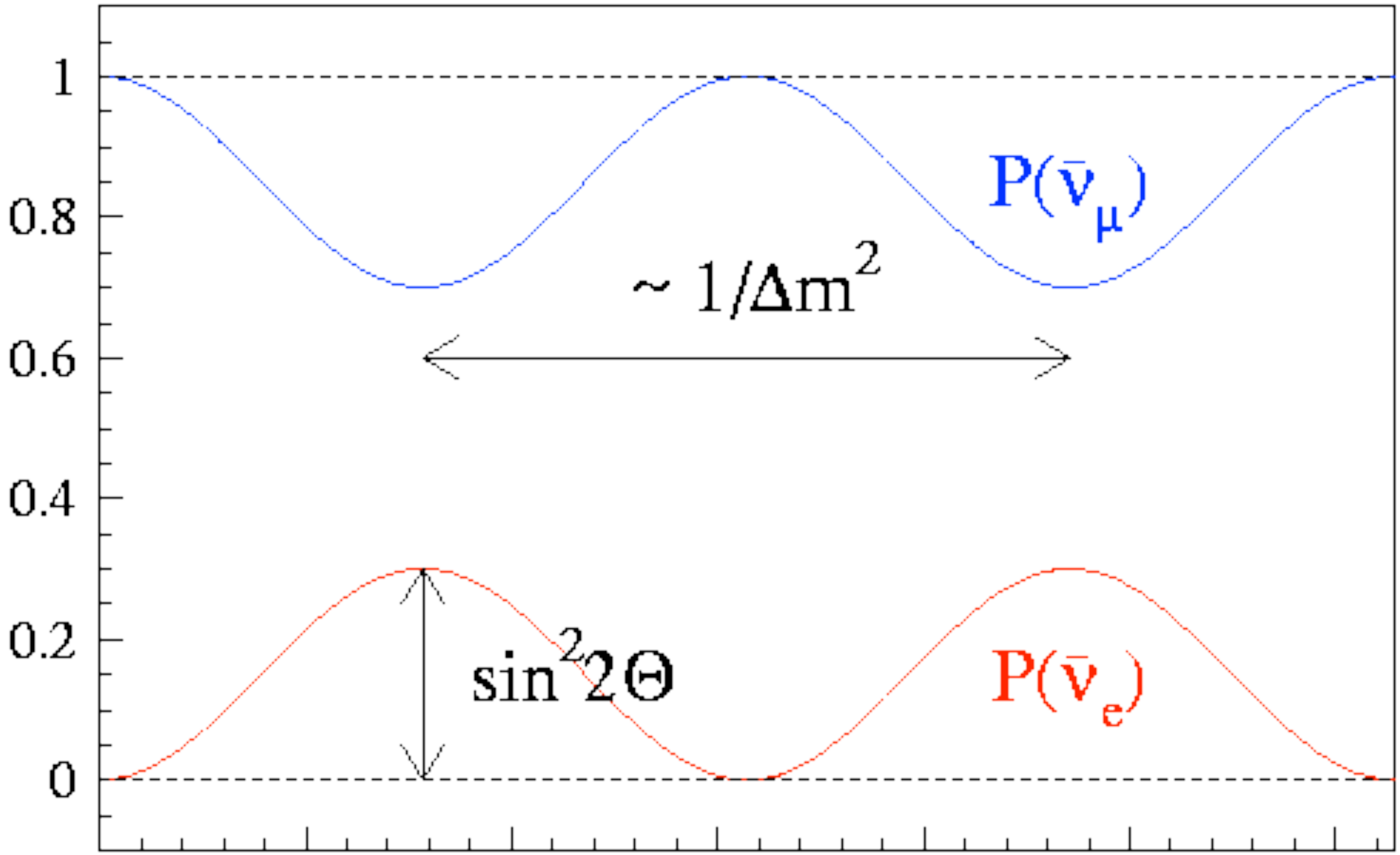
$$P_{\nu_\alpha \to \nu_\beta} = |\langle \nu_\beta(t)|\nu_\alpha(t=0)\rangle|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j} sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E_n u} \right)$$

(*U* only real components; no CP violation; neutrinos Dirac type)

Simple 2-flavor oscillation

Production of a ν_μ at t=0: $P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.267\times\Delta m^2\frac{L}{E_\nu}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$



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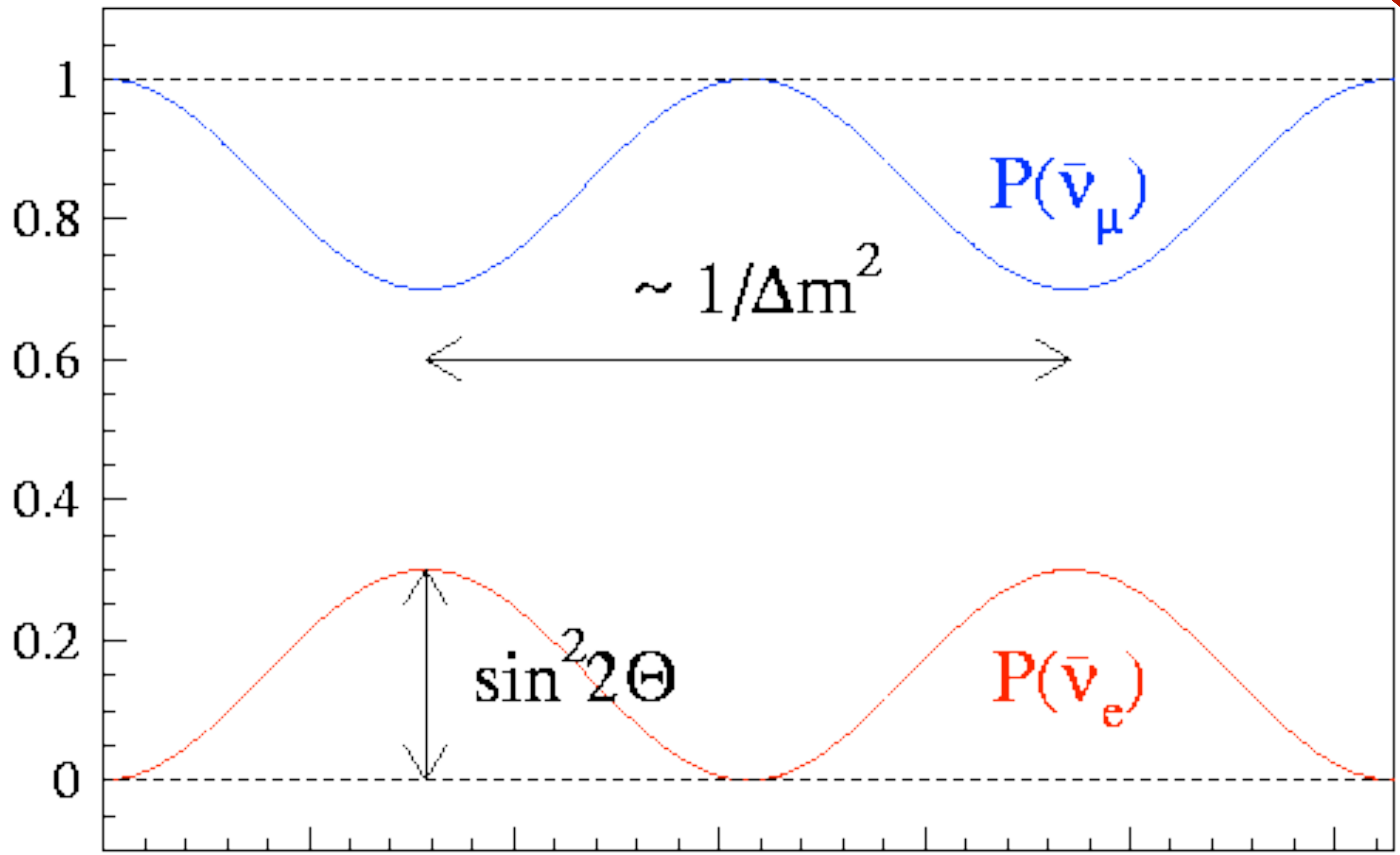
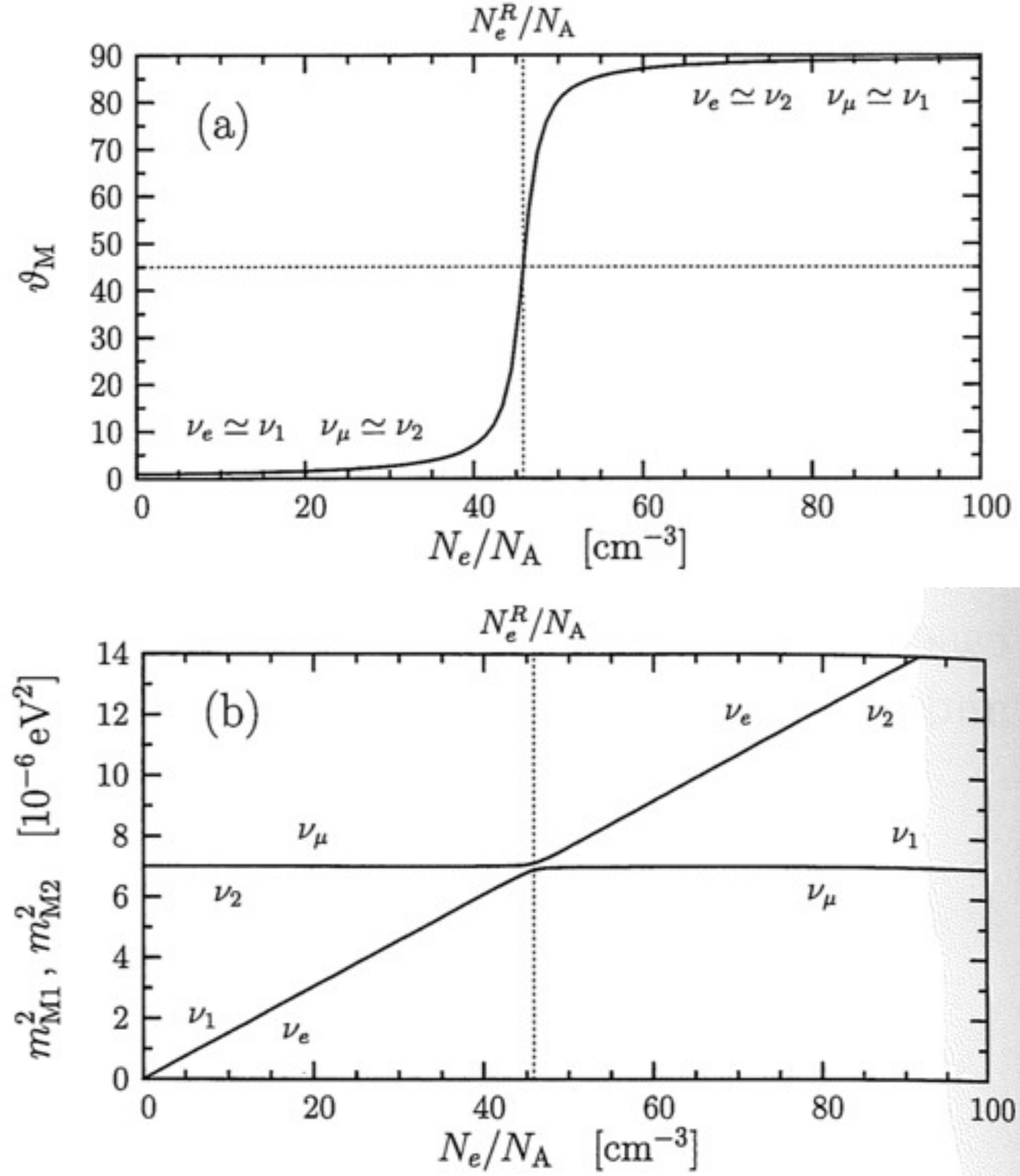
P independent of sign of Δm^2 !



MSW effect in smoothly varying electron densities

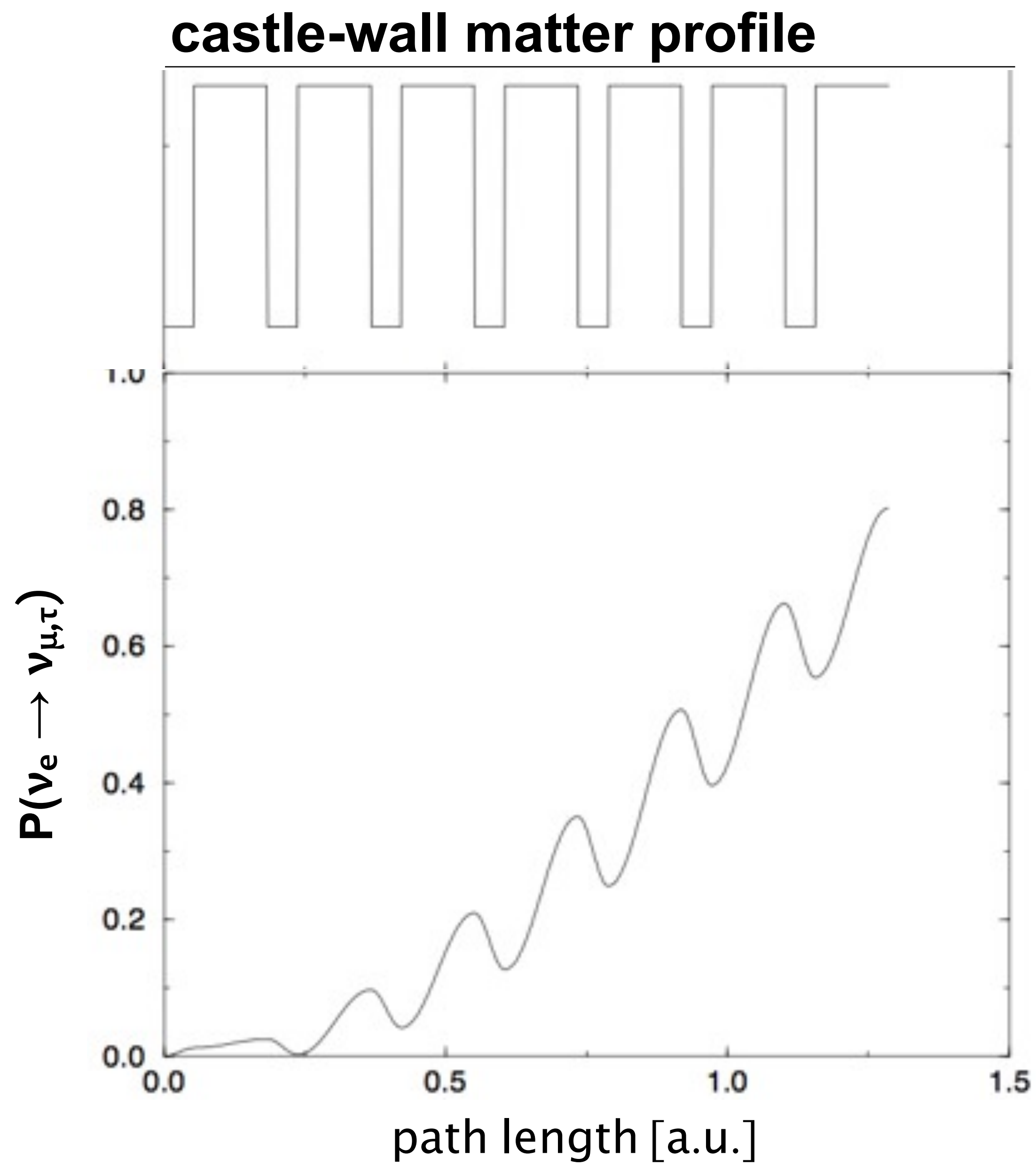
- Start with pure ν_e
- Parameters (fictional)

$$m_1 = 0$$
$$\Delta m^2 = 7 \times 10^{-6}\,\mathrm{eV}^2$$
$$\sin^2 2\theta = 10^{-3}$$
$$E_\nu = 1\,\mathrm{MeV}$$



Matter effects – parametric resonances

- Occur in systems with periodically varying density profile
- In contrast to MSW effect, mixing NEVER has to become large along path !
- Periodic density change leads to continuous increase of *P*

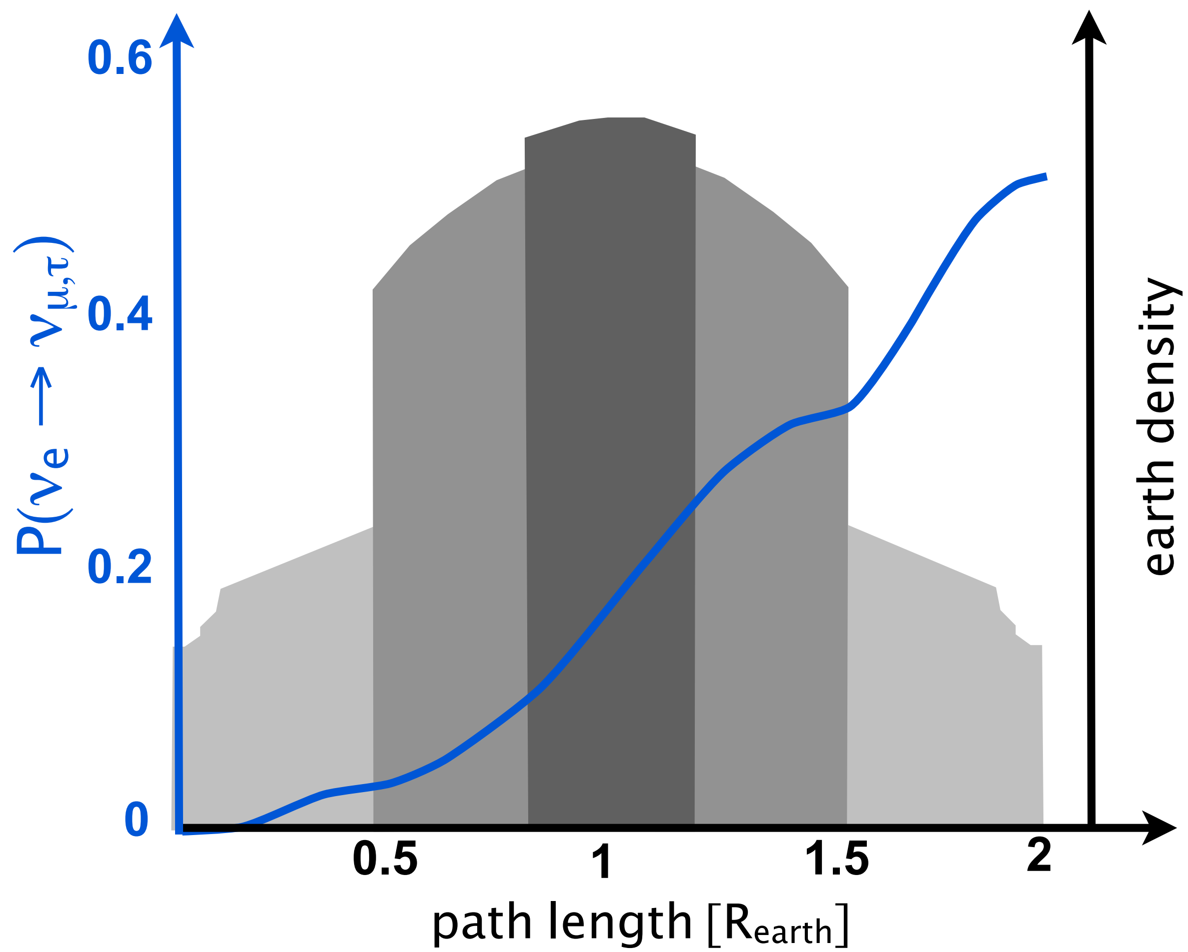


Akhmedov (2000), hep-ph/9907435

Matter effects – parametric resonances

- Occur in systems with periodically varying density profile
- In contrast to MSW effect, mixing NEVER has to become large along path !
- Periodic density change leads to continuous increase of *P*
- Works also for "truncated" periodic profiles like Earth mantel−core−mantel transition

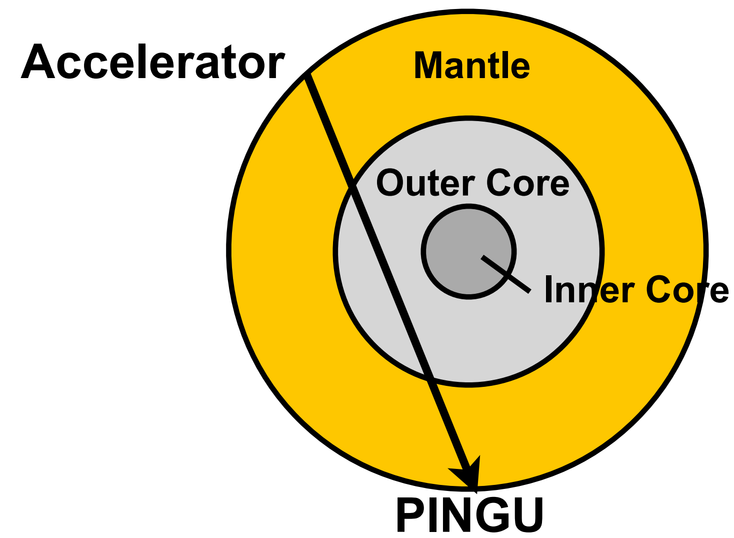
Neutrino traversing the Earth
($\Delta m^2/4E = 1.8 \times 10^{-13}$ eV, $\sin^2 2\theta_0 = 0.01$, $\Theta_n = 11.5^o$)



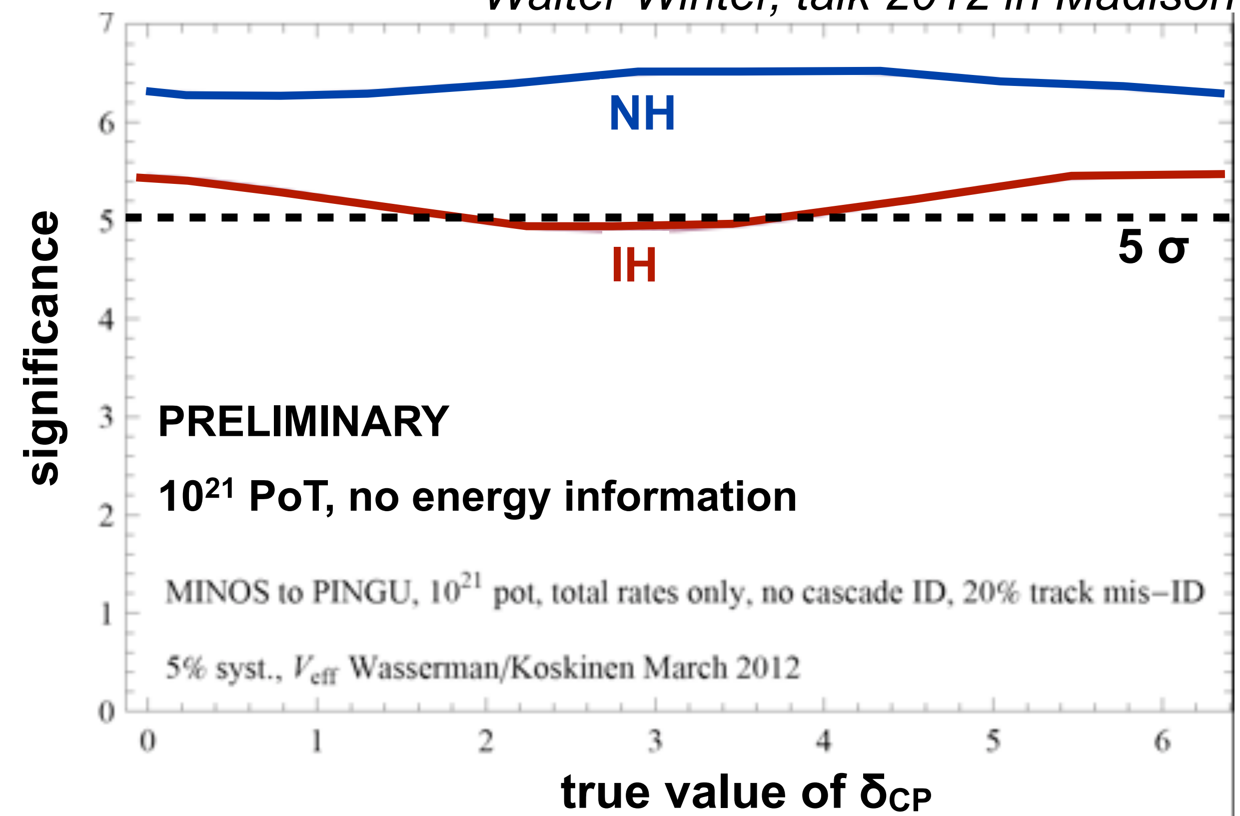
Akhmedov (2000), hep-ph/9907435

Neutrino mass hierarchy with an accelerator beam to PINGU

- Idea by Walter Winter
  (*Tang & Winter arXiv:1110.5908*)
- Accelerator beam: $\nu_\mu \rightarrow \nu_e$ appearance
- Advantages: very long baseline (~12000 km)
  + strong matter effects in dense core
- Capabilities w.r.t. δ_{CP} unclear yet
- Would require
  - cascade identification
  - limited energy resolution, no directional information
  - limited beam power
    (current neutrino beams sufficient, e.g. NuMI)
  - **but** dedicated (steeply inclined) beam line



Walter Winter, talk 2012 in Madison

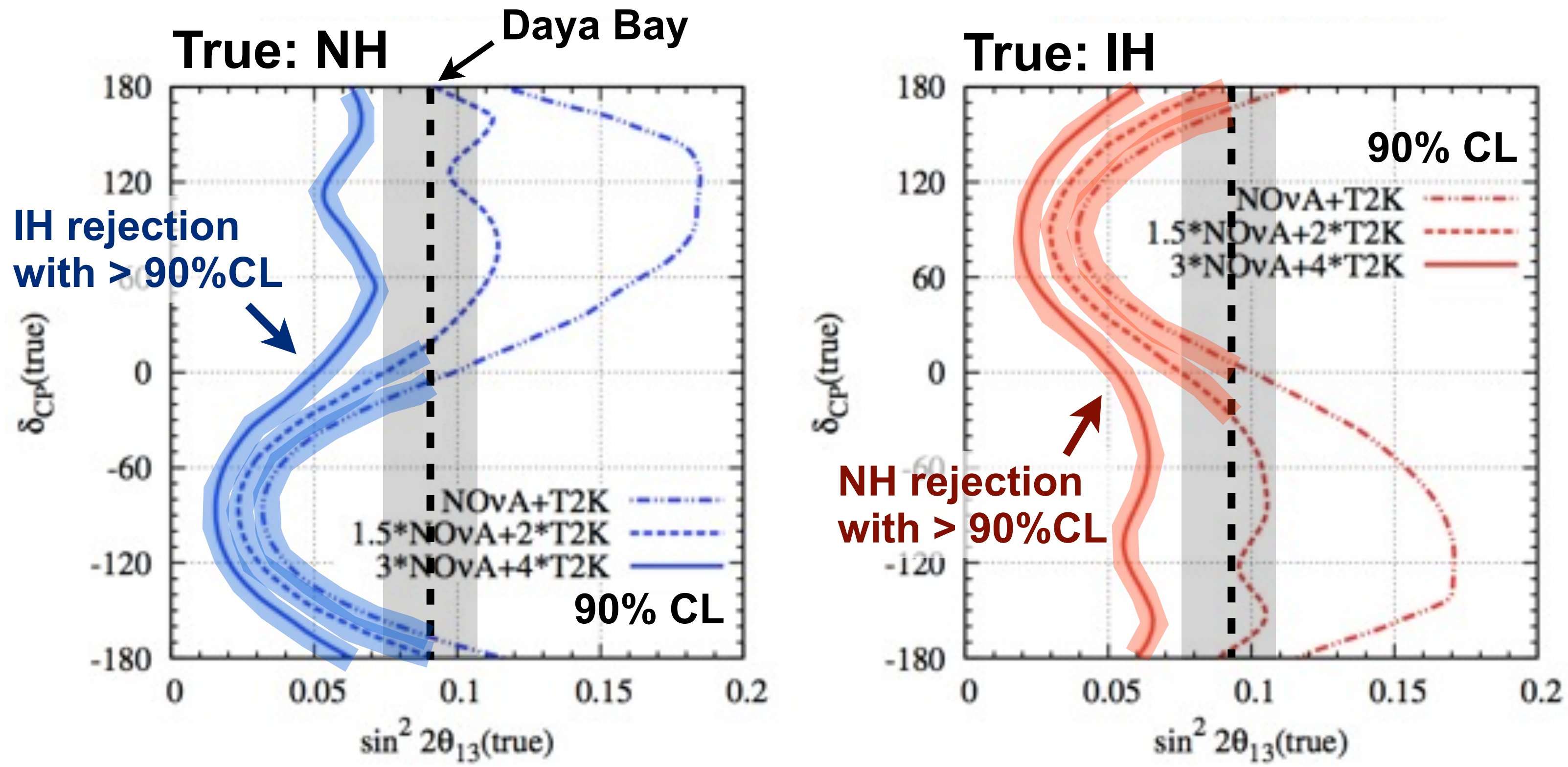


Neutrino mass hierarchy – experiments of the next decade

Current experiments:

NOvA and T2K

- $\nu_\mu \rightarrow \nu_e$ appearance
- Discrimination power depends on true value of δ_{CP}
- Complete δ_{CP} coverage (90% CL) needs ≳ (10 yr T2K + 9 yr NOvA)

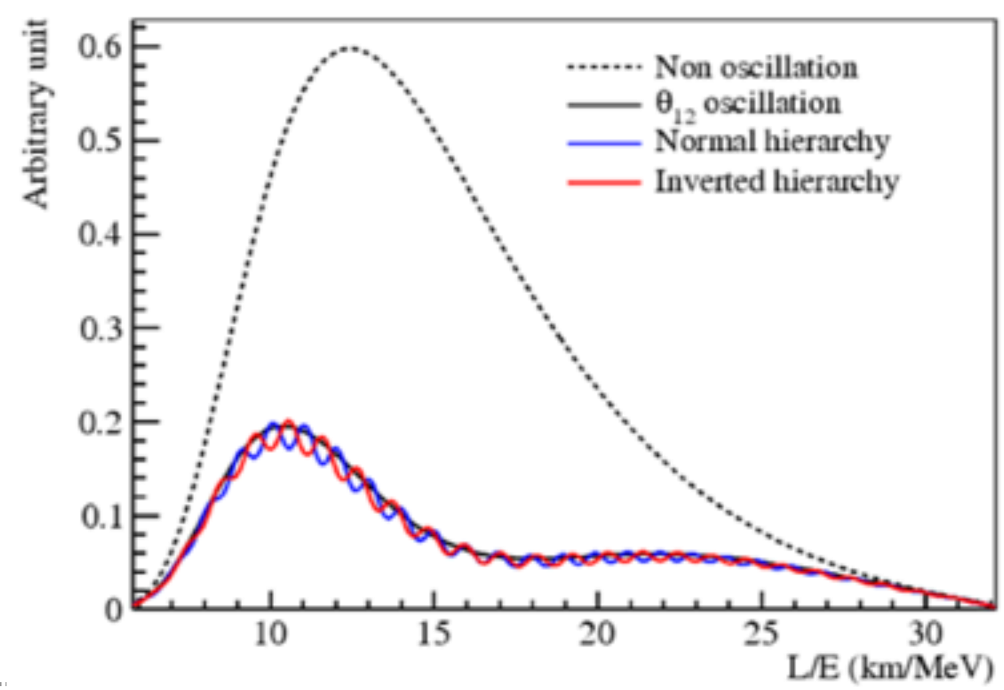


Prakash, Raut & Sankar, arXiv:1201.6485

Future experiments:

Daya Bay II

- Reactor experiment: $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$
- Requires $\Delta E/E = 3\%/\sqrt{E}$ (3σ after ~6 yr)

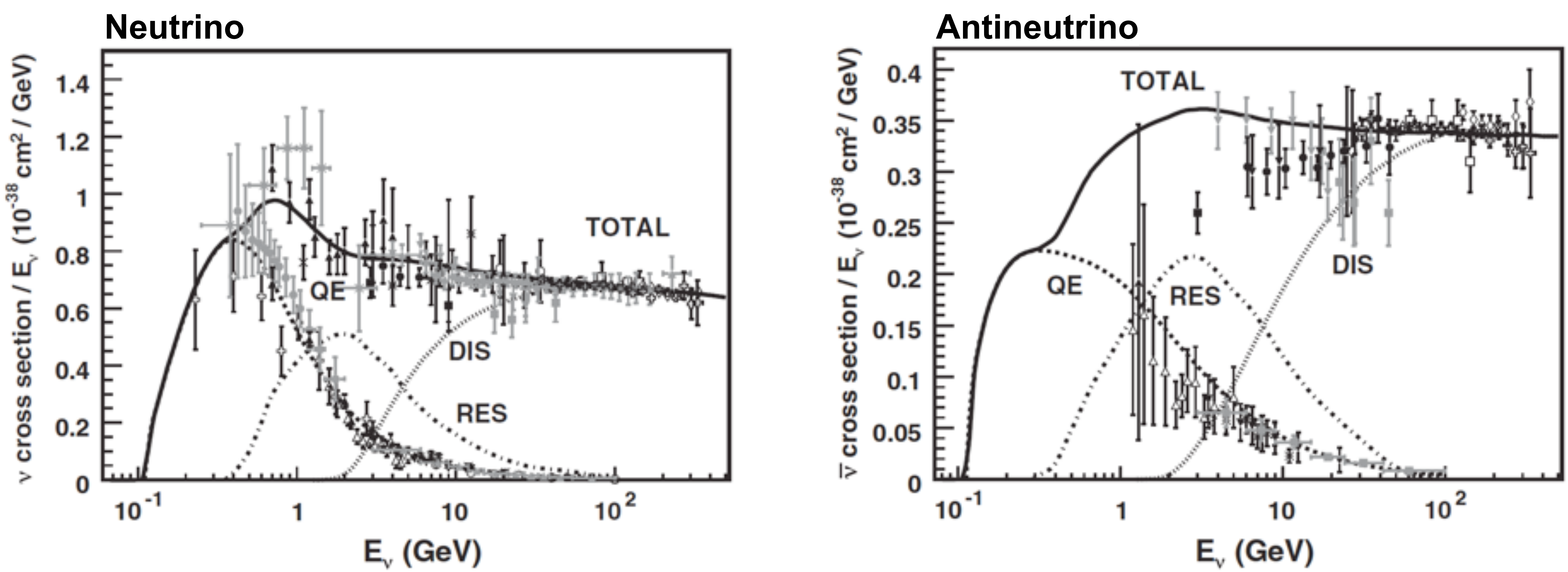


Changgen Yang, NuMass 2013

Simulations in PINGU

PINGU simulation chain

- Simulation of all neutrino flavors
- Neutrino interaction with GENIE
- Muon propagation with GEANT4
- Single Cherenkov photon tracking in ice (GPU based)



J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84(2012) , 1307

PINGU: channel separation

y distribution in Neutrino CC DIS

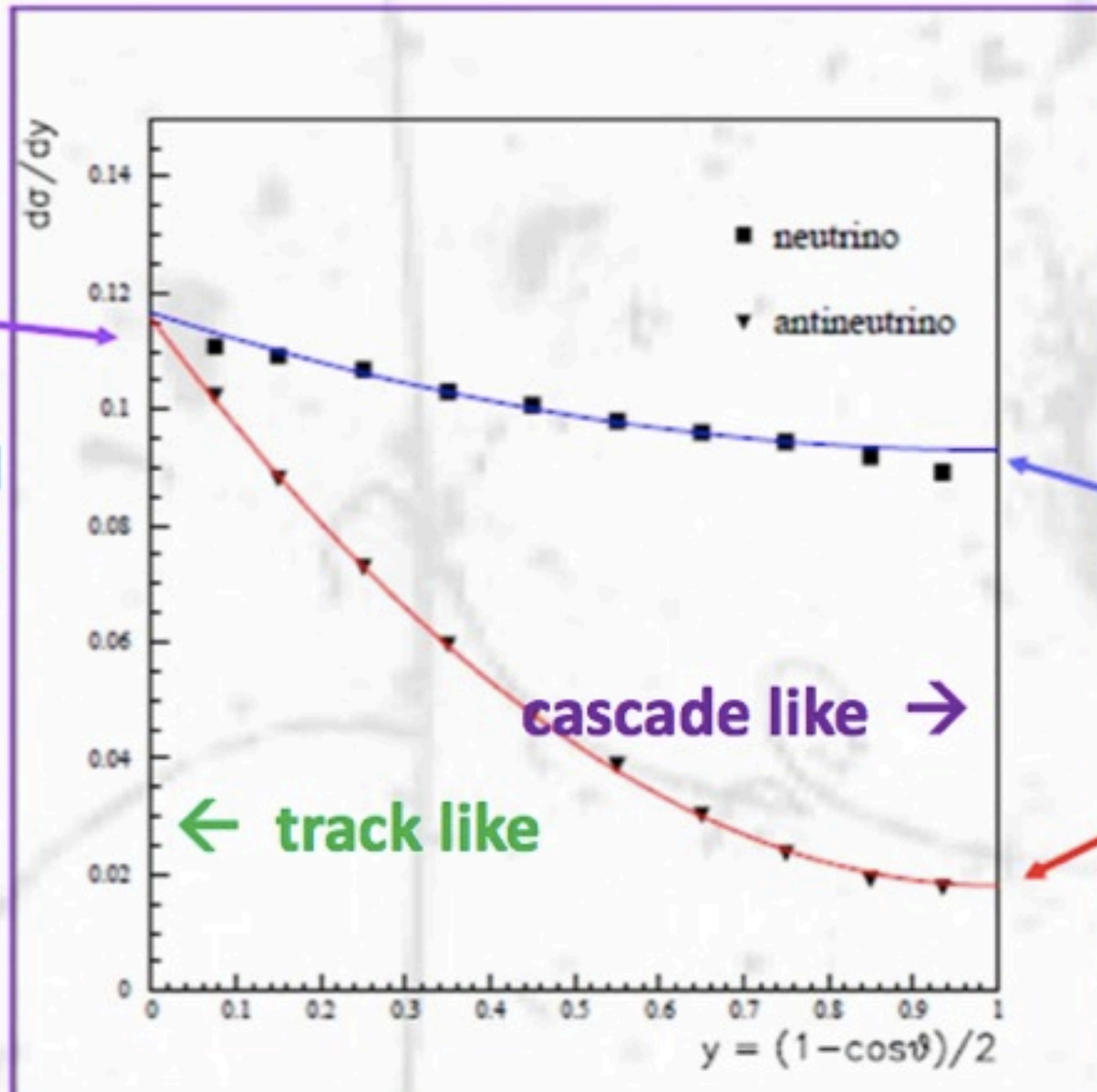
$$\frac{d\sigma(\nu q)}{dxdy} = \frac{d\sigma(\overline{\nu}\,\overline{q})}{dxdy} \propto 1$$

$$\frac{d\sigma(\nu \overline{q})}{dxdy} = \frac{d\sigma(\overline{\nu} q)}{dxdy} \propto (1-y)$$

y=0:

Quarks & anti-quarks

Neutrino and anti-neutrino identical



y=1:

Neutrinos see only quarks.

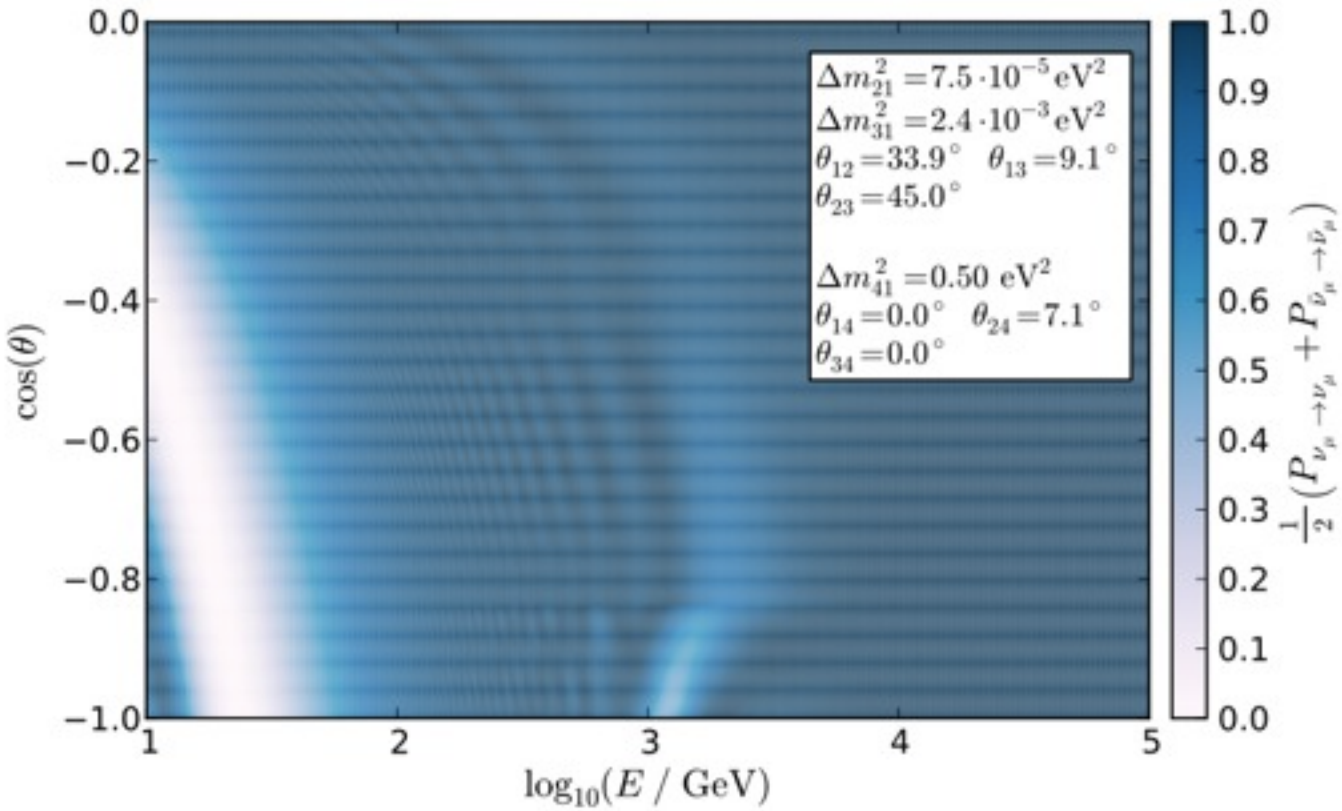
Anti-neutrinos see only anti-quarks

$$\sigma^{\overline{\nu}} \approx \frac{1}{2}\sigma^{\nu}$$

12-15 August 2006 Kevin McFarland: Interactions of Neutrinos 58

IceCube and sterile neutrinos

ν_μ survival probability



Sensitivity to sterile neutrinos