Atmospheric neutrino oscillations with Very Large Volume Neutrino Telescopes

AHEP "Neutrino masses and oscillations" (2015), ID 271968
arXiv:1509.08404

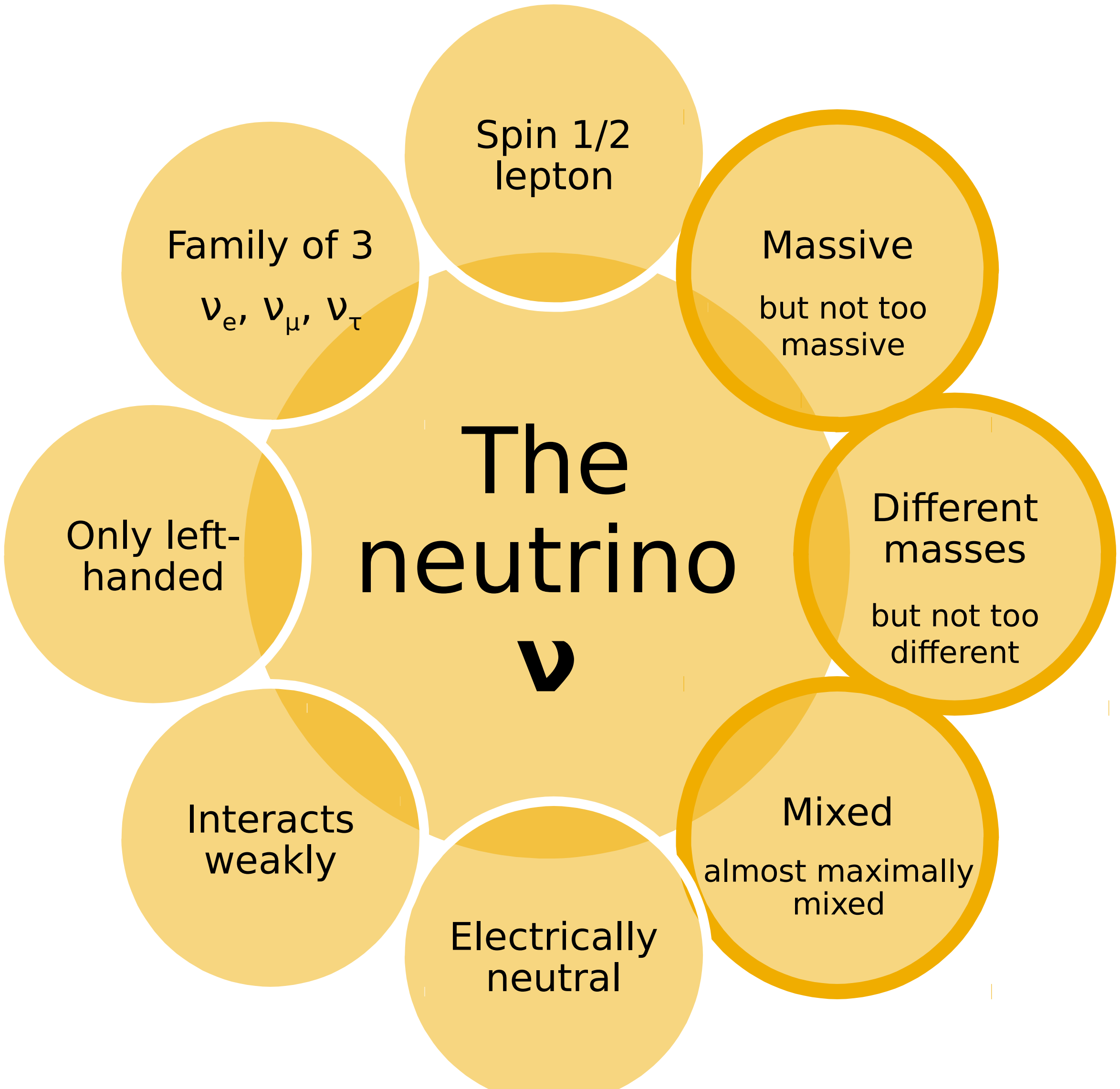
Juan Pablo Yáñez

Trends in Astroparticle Physics – Beyond the mainstream
January 2016

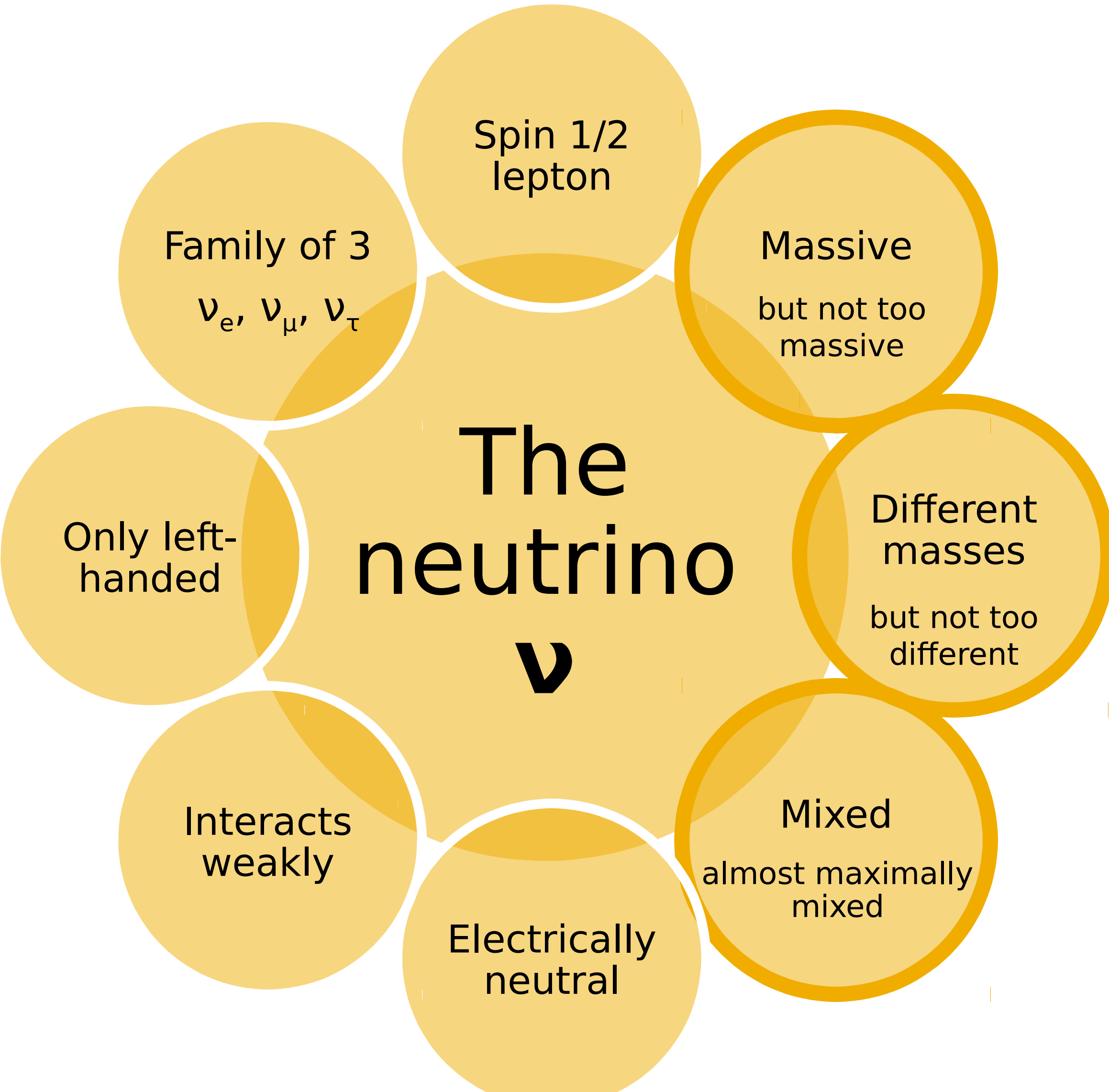
Bundesagentur für Arbeit

Atmospheric neutrino oscillations

The neutrino

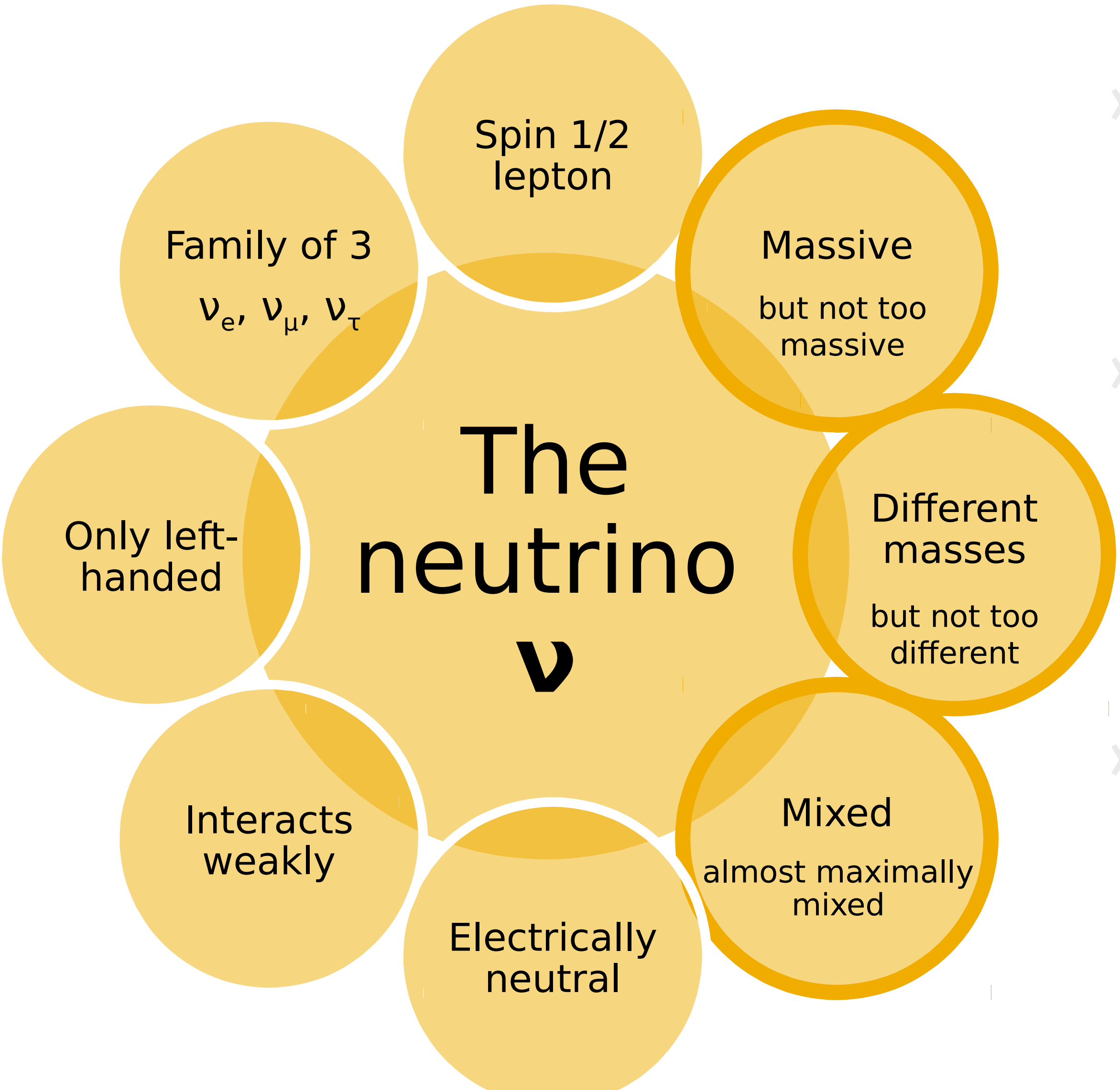


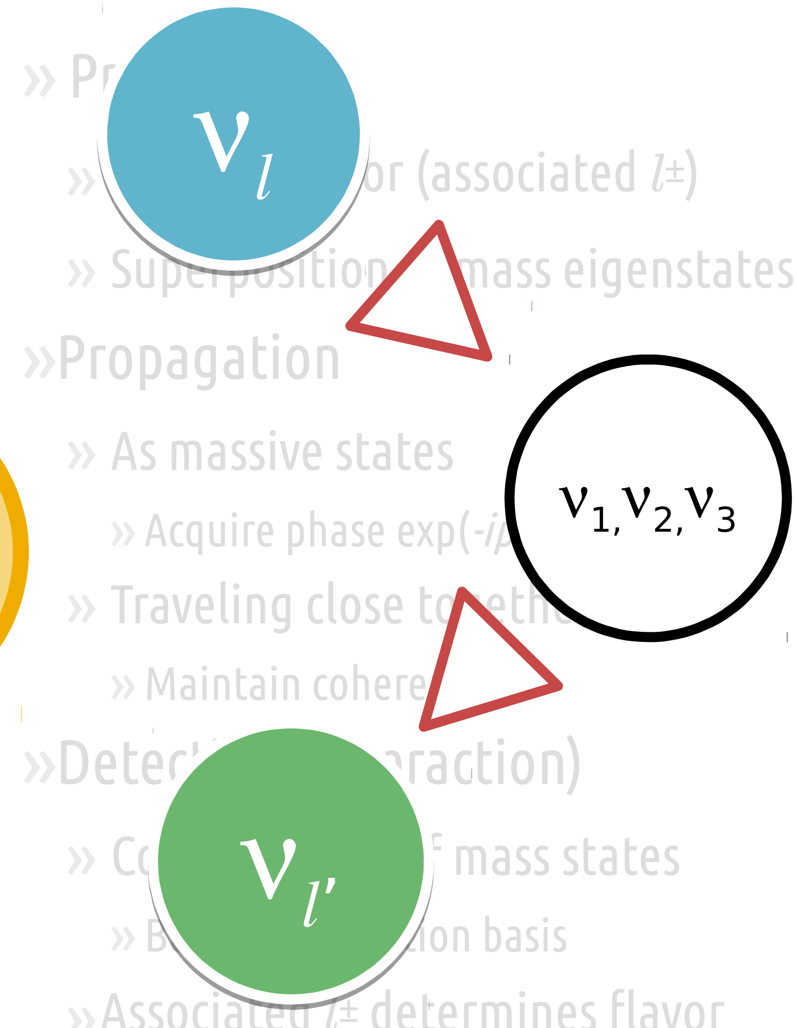
Neutrinos and oscillations



- Production
  - Definite flavor (associated $l^\pm$)
  - Superposition of mass eigenstates
- Propagation
  - As massive states
    - Acquire phase exp($-ipx$)
  - Traveling close together
    - Maintain coherence
- Detection (interaction)
  - Coherent sum of mass states
    - Back to interaction basis
  - Associated $l^\pm$ determines flavor

Neutrinos and oscillations





The math of oscillations

» The projection between bases $\nu_\alpha = \sum_{k=1..3} U^*_{\alpha k}\, \nu_k$

» The mixing matrix, function of 4 parameters: θ_{12}, θ_{13}, θ_{23}, δ

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

» The transition probability (in vacuum)

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta \,|\, \nu(t) \rangle = \langle \nu_\beta \,|\, e^{-i\mathcal{H}_0 t} \,|\, \nu_\alpha \rangle .$$

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) = \sum_k U^*_{\alpha k}\, e^{-iE_k t} \langle \nu_\beta \,|\, \nu_k \rangle ,$$

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)|^2 = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j} U^*_{\beta j}\, e^{-i(E_k - E_j)t} .$$

The math of oscillations

» The projection between bases $$\nu_\alpha = \sum_{k=1..3} U^*_{\alpha k}\, \nu_k$$

» The mixing matrix, function of 4 parameters: θ_{12}, θ_{13}, θ_{23}, δ

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

» The transition probability (in vacuum)

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\beta\alpha} - 4 \sum_{k>j} \Re[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{kj}}{4E} L\right)$$

$$\pm\, 2 \sum_{k>j} \Im[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}] \sin\left(\frac{\Delta m^2_{kj}}{2E} L\right)$$

Amplitude

Oscillations!

The math of oscillations

» The projection between bases $\nu_\alpha = \sum_{k=1..3} U^*_{\alpha k}\, \nu_k$

» The mixing matrix, function of 4 parameters: θ_{12}, θ_{13}, θ_{23}, δ

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

» The transition probability (in vacuum)

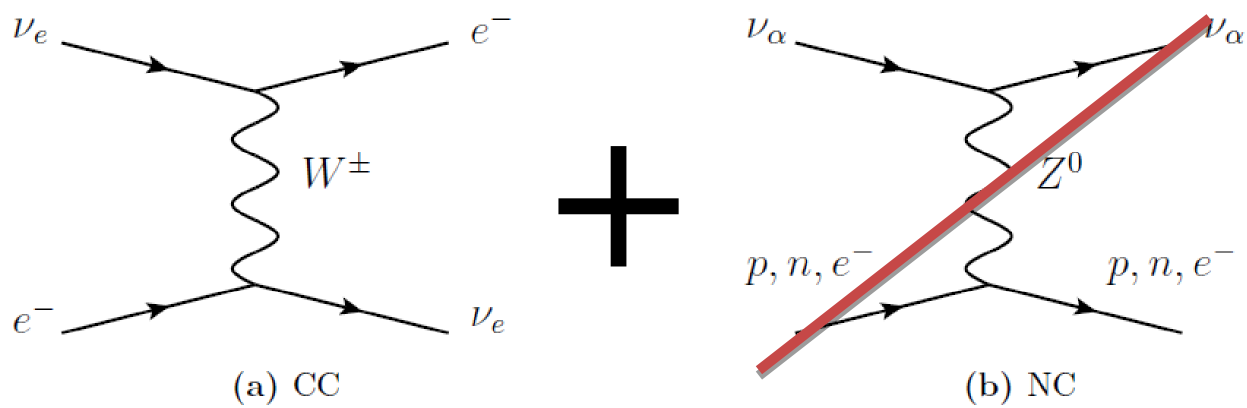
$$|\Delta m^2_{\mathrm{large}}| \gg |\Delta m^2_{\mathrm{small}}|$$

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

effective mixing angle

Neutrinos crossing matter

» Scattering processes in ordinary matter



$$\mathcal{H}_0 \to \mathcal{H} = \mathcal{H}_0 + V(n_e) \qquad V(n_e) = \pm\sqrt{2}\, G_F\, n_e(x)\, \beta,$$

» Recycling the formalism: effective parameters in matter

In constant electron density:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{\rm CC})^2 + (\Delta m^2 \sin 2\theta)^2}\,,$$

$$A = \pm 2\sqrt{2}\, E\, G_F\, n_e.$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \dfrac{A_{\rm CC}}{\Delta m^2 \cos 2\theta}}.$$

*See Phys.Rev.D64:053003,2001 for a full derivation

Matter effects in oscillations

» MSW resonance and saturation, a local effect

if $A_{\mathrm{R}} = \Delta m^2_{31}\cos(2\theta_{13}).$ ⇒ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ ⇒ $\theta^{\mathbf{M}}_{13} = \dfrac{\pi}{4}$

---

if $|A_{\mathrm{R}}| \gg \Delta m^2_{31}\cos(2\theta_{13}).$ ⇒ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ ⇒ $\theta^{\mathbf{M}}_{13} = \dfrac{\pi}{2}$

Matter effects in oscillations

» MSW resonance and saturation, a local effect

if $A_{\mathrm{R}} = \Delta m^2_{31}\cos(2\theta_{13}).$ ⇒ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (goes to zero) ⇒ $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{4}$ maximal (resonance)

---

if $|A_{\mathrm{R}}| \gg \Delta m^2_{31}\cos(2\theta_{13}).$ ⇒ $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (becomes large) ⇒ $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{2}$ no mixing (saturation)

Matter effects in oscillations

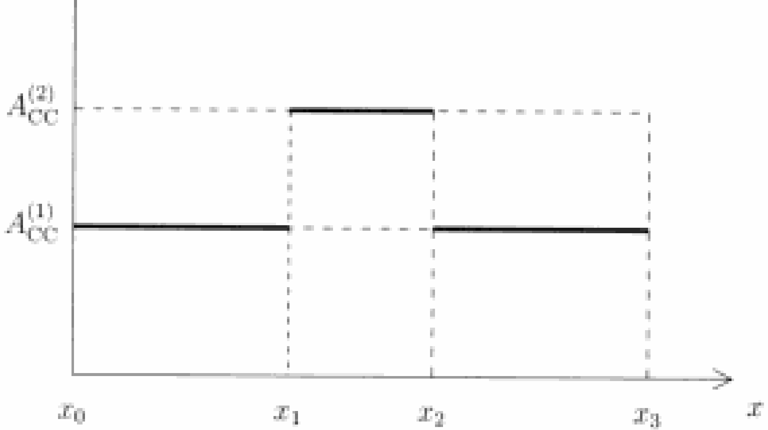
» MSW resonance and saturation, a local effect

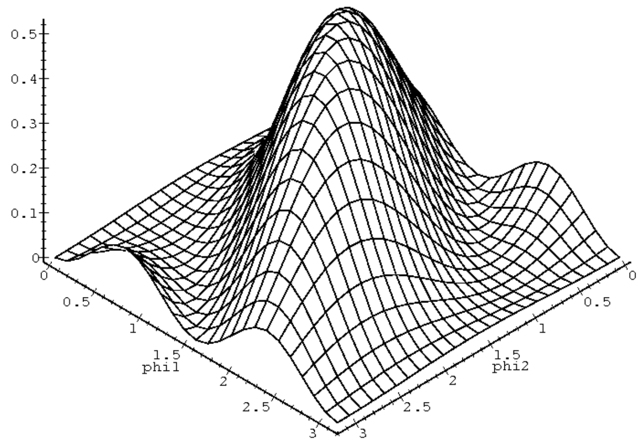
if $A_R = \Delta m^2_{31}\cos(2\theta_{13})$. → $\tan(2\theta^M_{13}) = \frac{\tan(2\theta_{13})}{1 - \frac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (goes to zero) → $\theta^M_{13} = \frac{\pi}{4}$ maximal (resonance)

if $|A_R| \gg \Delta m^2_{31}\cos(2\theta_{13})$. → $\tan(2\theta^M_{13}) = \frac{\tan(2\theta_{13})}{1 - \frac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (becomes large) → $\theta^M_{13} = \frac{\pi}{2}$ no mixing (saturation)

» Parametric resonance, a global effect

$$P_{\nu_e\to\nu_\mu} = [2s_1\sin 2\theta_{M1}(c_1c_2 - s_1s_2\cos 2(\theta_{M1}-\theta_{M2})) + s_2\sin(2\theta_{M2})]^2$$

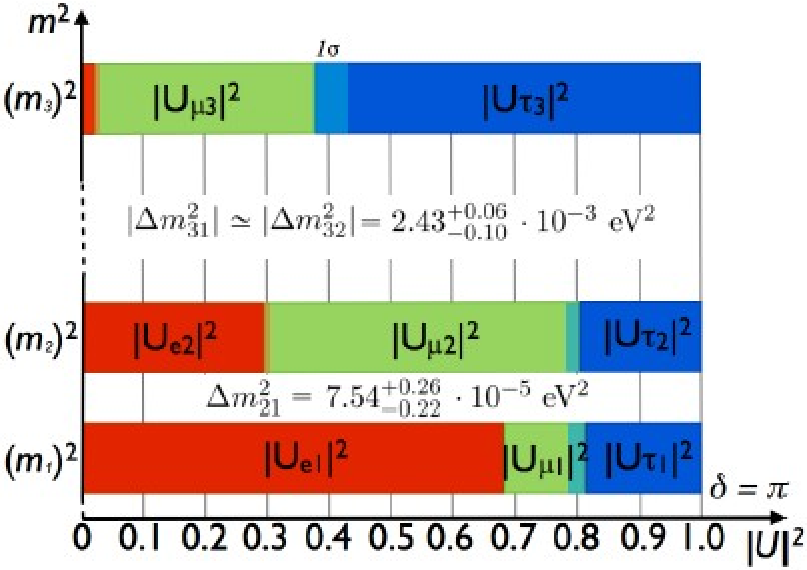




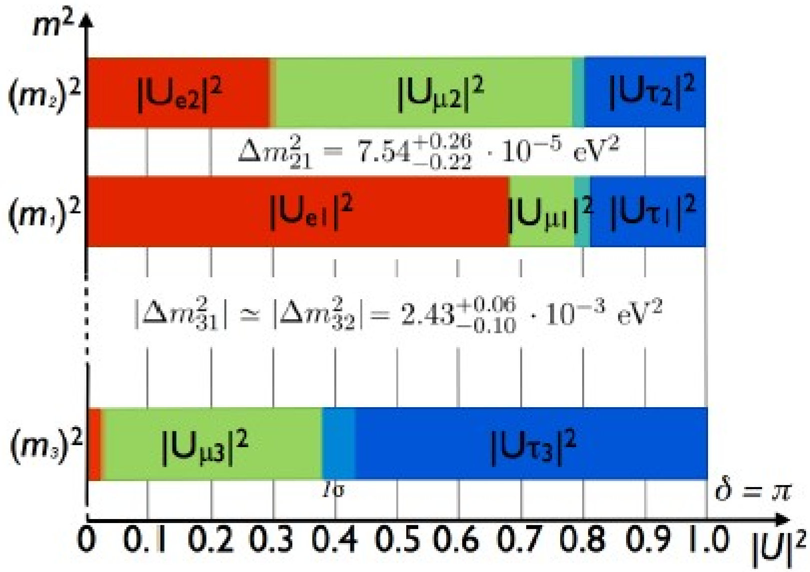
The experimental landscape

» Knowledge on oscillation parameters

θ_{12} is large	Δm^2_{21} ~ 10^{-5} eV^2
θ_{23} is almost maximal	$\|\Delta m^2_{31}\| \approx \|\Delta m^2_{32}\|$ ~ 10^{-3} eV^2
θ_{13} small but non-zero	δ_{cp} still no idea*



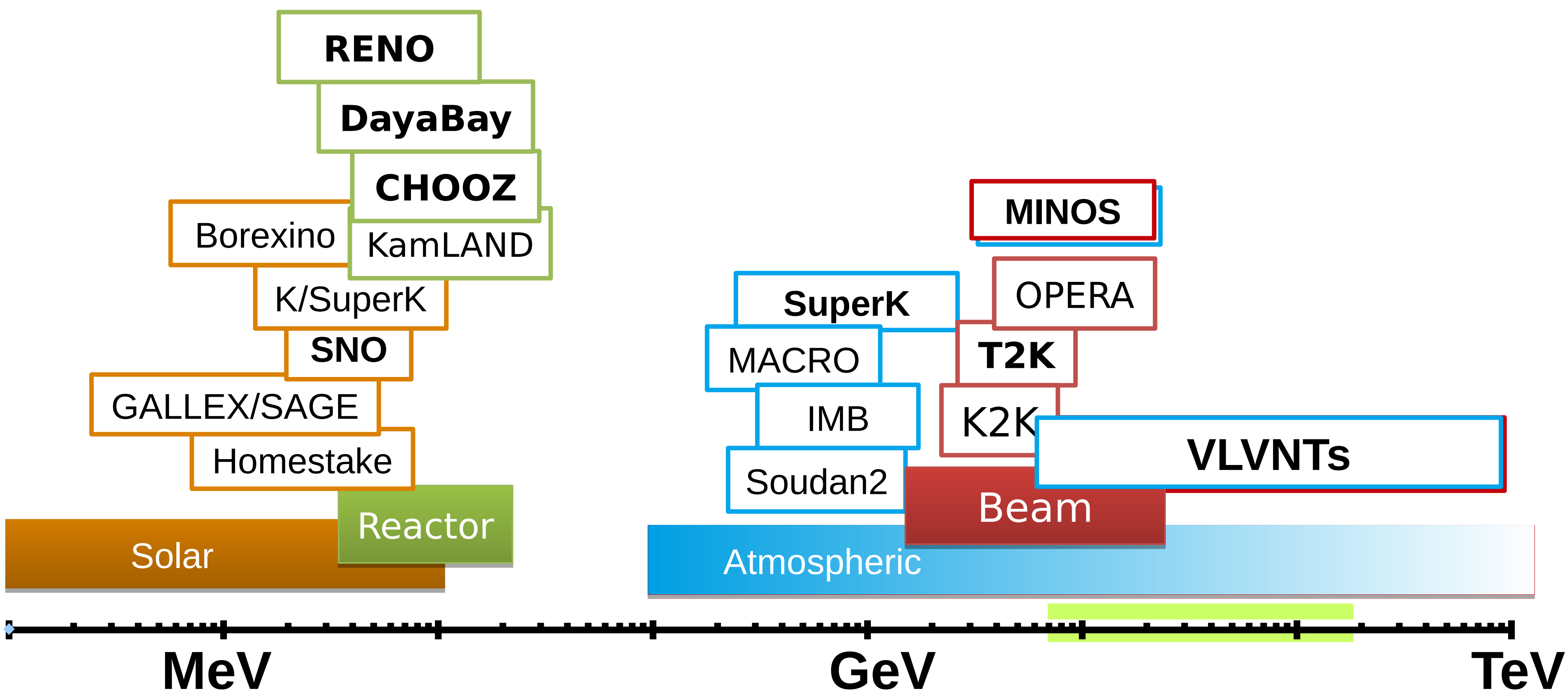
(a) Normal hierarchy



(b) Inverted hierarchy

The experimental landscape

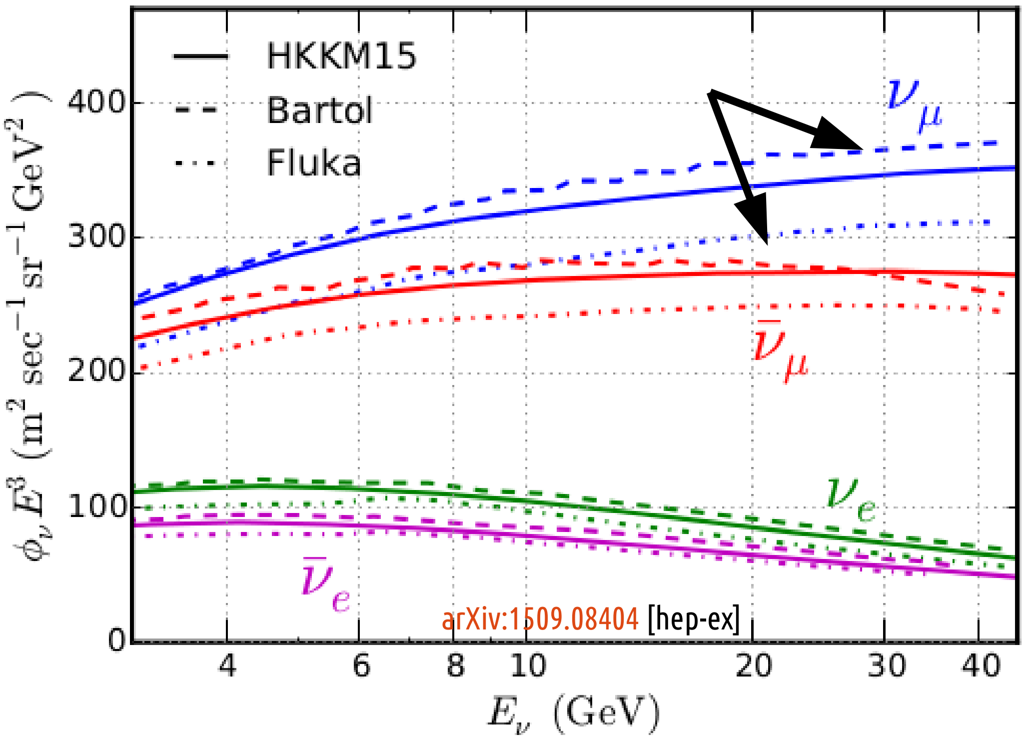
- (Incomplete) list of neutrino oscillation experiments
  - Using multiple sources, covering a wide E range



Atmospheric neutrino oscillations

- Cosmic rays interacting in the atmosphere produce neutrinos
  - Electron and muon (anti-)neutrinos
- Travel distances range from ~20 to 12,700 km

$$CR + N \to X + \pi^{\mp},\, K^{\mp}\,,$$
$$\pi^{-},\, K^{-} \to \mu^{-} + \bar{\nu}_{\mu}\,,$$
$$\pi^{+},\, K^{+} \to \mu^{+} + \nu_{\mu}\,,$$
$$\mu^{-} \to e^{-} + \bar{\nu}_{e} + \nu_{\mu}\,,$$
$$\mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}\,.$$

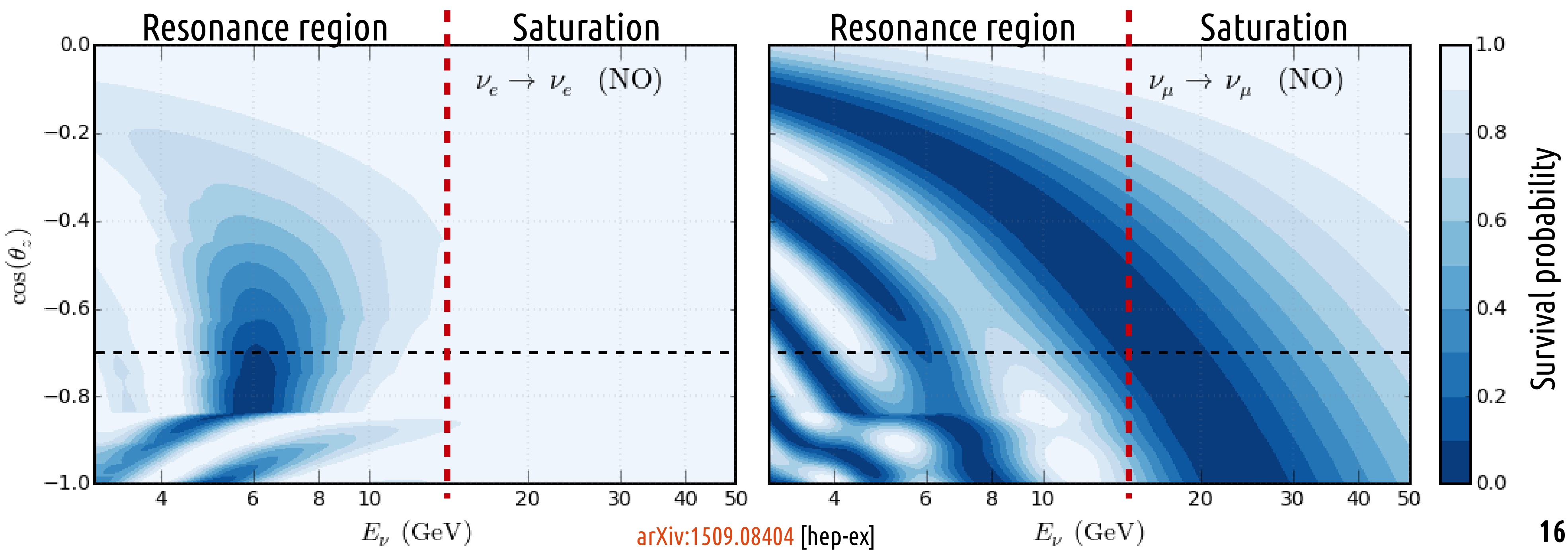


Atmospheric neutrino flux

Atmospheric neutrino oscillations

Earth's matter profile modifies expectation from vacuum oscillations

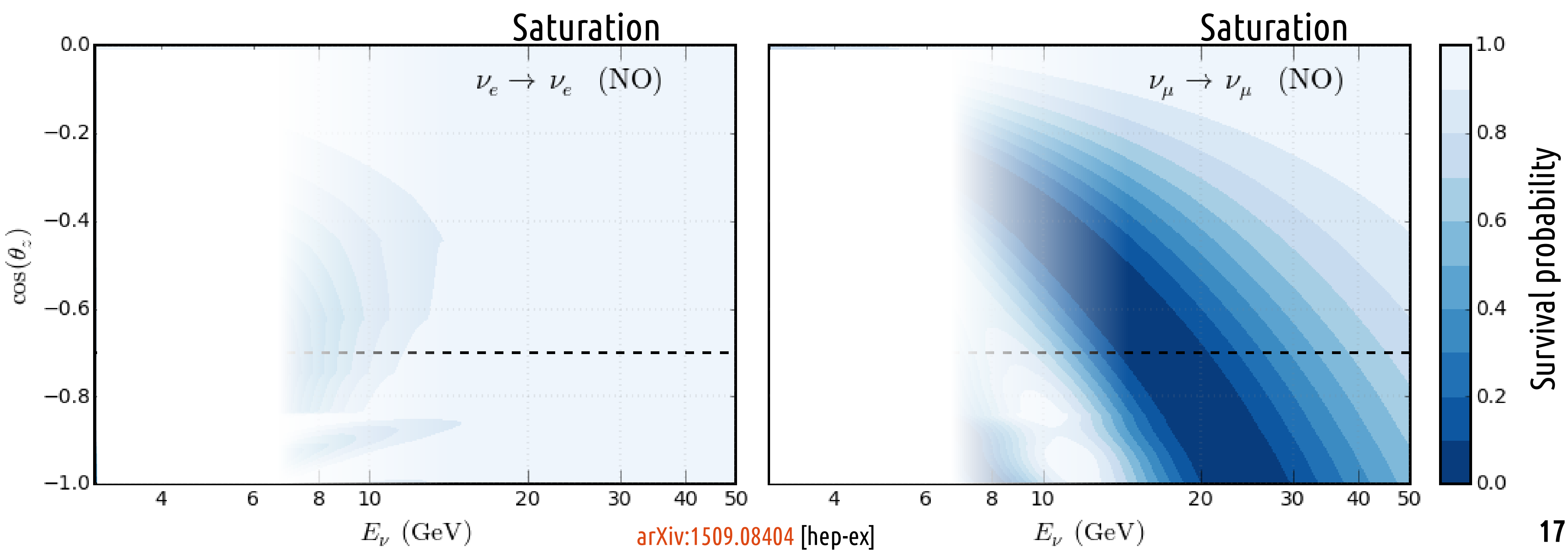
- Between E_ν = 2-15 GeV → resonances, transitions $\nu_e \leftrightarrow \nu_\mu$ take place
- For E_ν >15 GeV → saturation ($\theta_{13} \rightarrow \pi/2$), dominated by $\nu_\mu \leftrightarrow \nu_\tau$ transitions



arXiv:1509.08404 [hep-ex]

Atmospheric neutrino oscillations

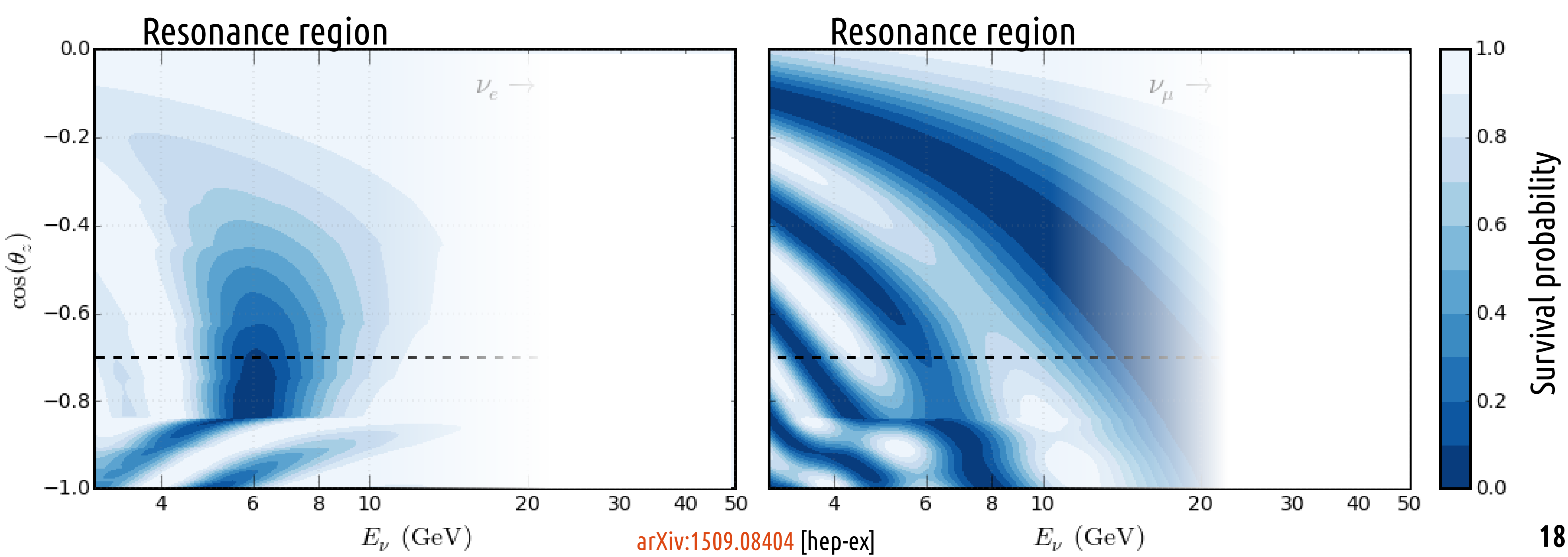
- Saturation region
  - Simple disappearance depends on θ_{23} and $|\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$
  - Largely insensitive to θ_{13}
  - Accessible with currently running VLVNTs



arXiv:1509.08404 [hep-ex]

Atmospheric neutrino oscillations

- Resonance region
  - Complicated disappearance pattern, different for neutrinos/antineutrinos
  - Oscillations depend on $\theta_{13,}$ θ_{23} and $\Delta m^2_{32}, \Delta m^2_{31}$ **including their sign**
  - At/Below the threshold of currently running VLVNTs

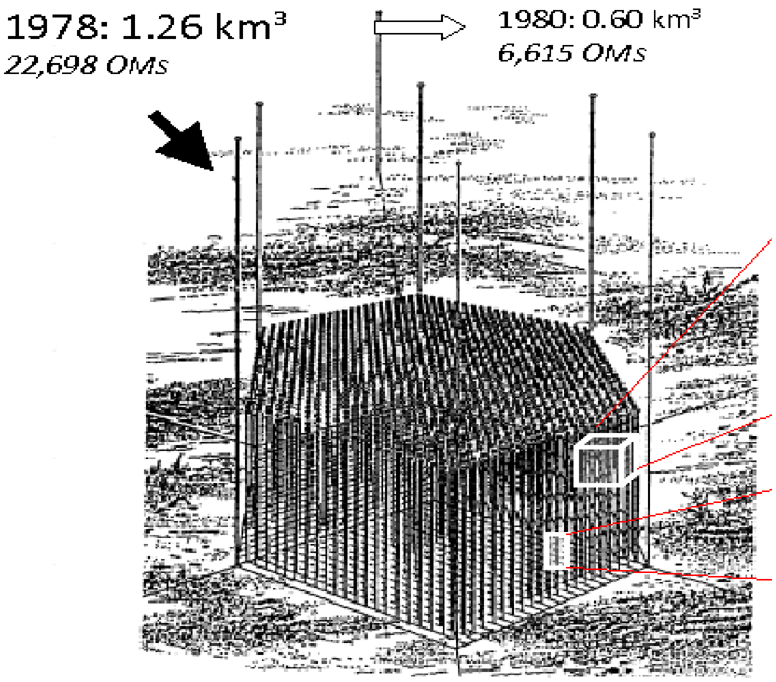


arXiv:1509.08404 [hep-ex]

VLVNTs at 10-100 GeV

VLVNT concept

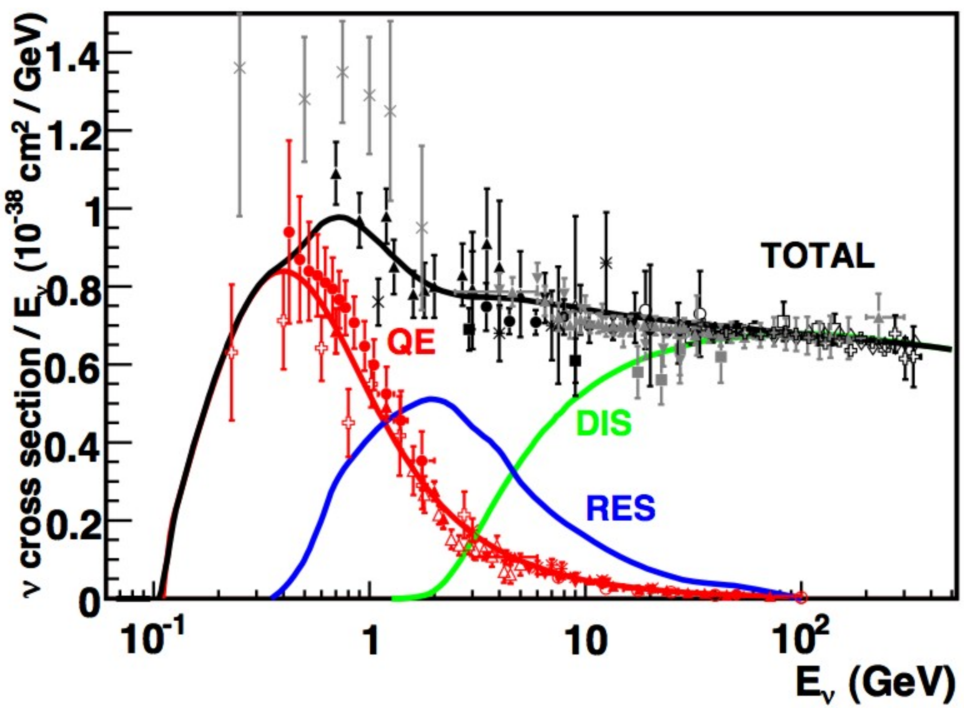
- Detect charged particles from nu interaction via Cherenkov light
- Medium: optically transparent, naturally occurring
- Layout: 3D array of photo-sensors
- Location: deep underground
- Spacing defines E threshold

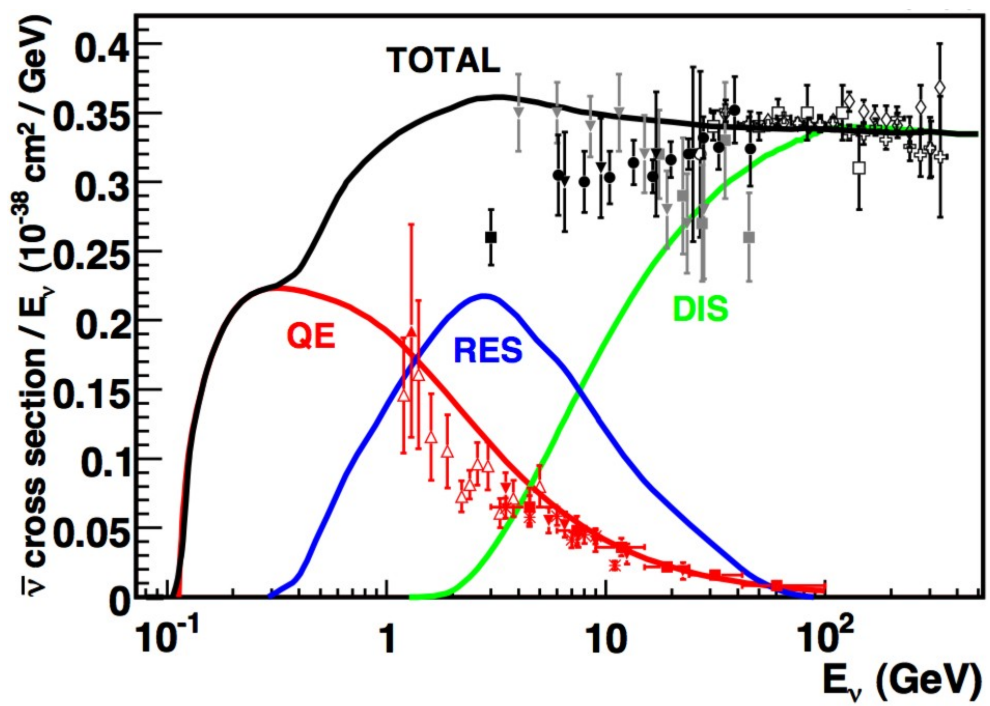


arXiv:1402.2096 [astro-ph.IM]

Neutrino interactions in VLVNTs

- Mainly deep inelastic scattering (DIS)
  - Well understood, calculated
- Production of resonances not negligible below ~20 GeV
  - Not that well understood or calculated

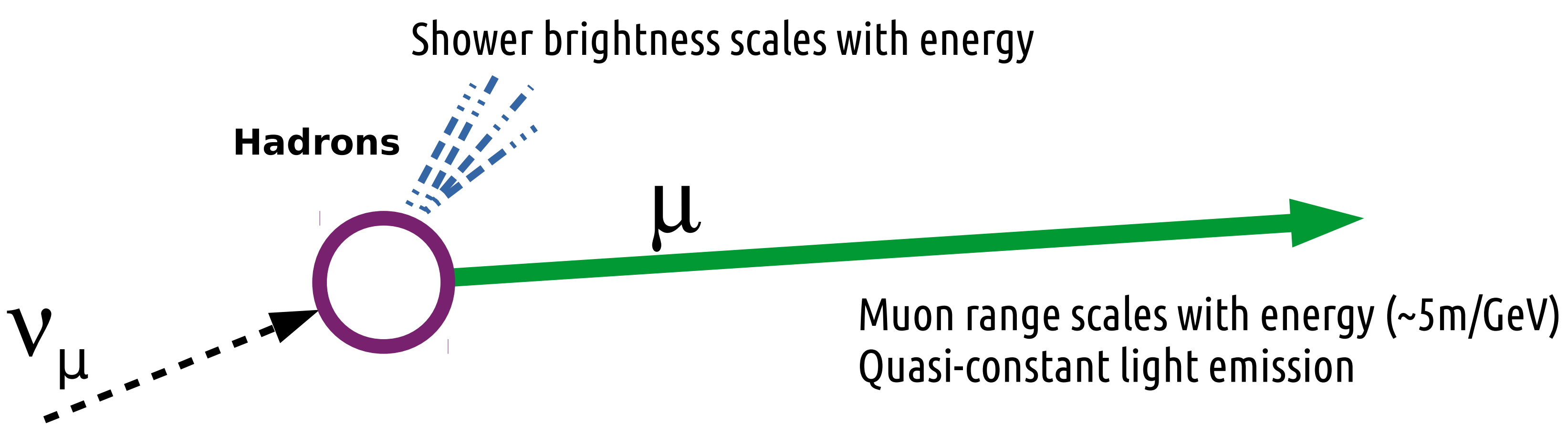




Rev. Mod. Phys. 84, 1307 (2012)

Neutrino interactions in VLVNTs

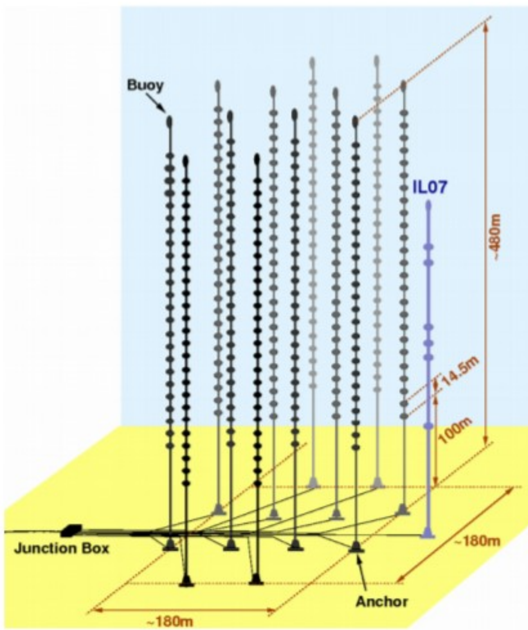
- Mainly deep inelastic scattering (DIS)
  - Well understood, calculated
- Production of resonances not negligible below ~20 GeV
  - Not that well understood or calculated
- **In the DIS case**

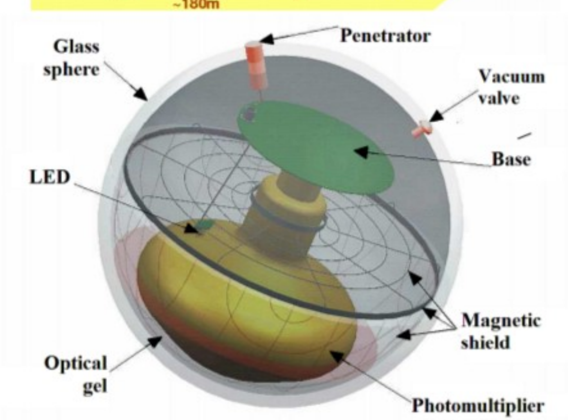


Energy distribution Had/Lepton different for neutrino/antineutrino
*Most other interactions will not produce a muon

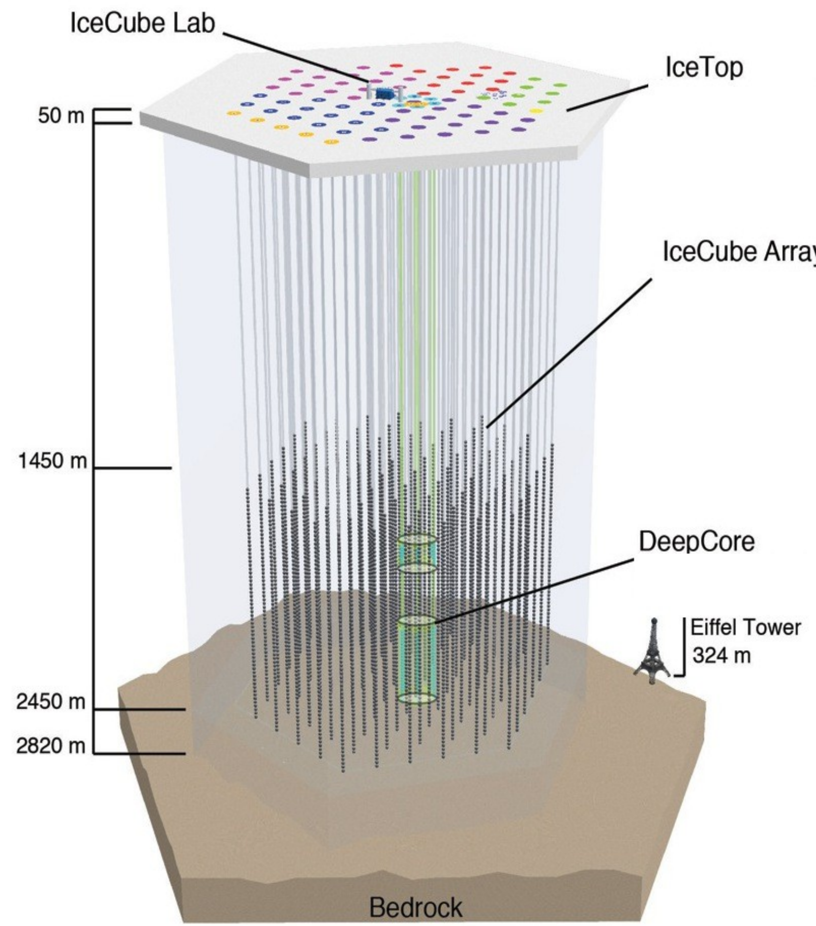
VLVNTs in operation
(and measuring oscillations)

» ANTARES

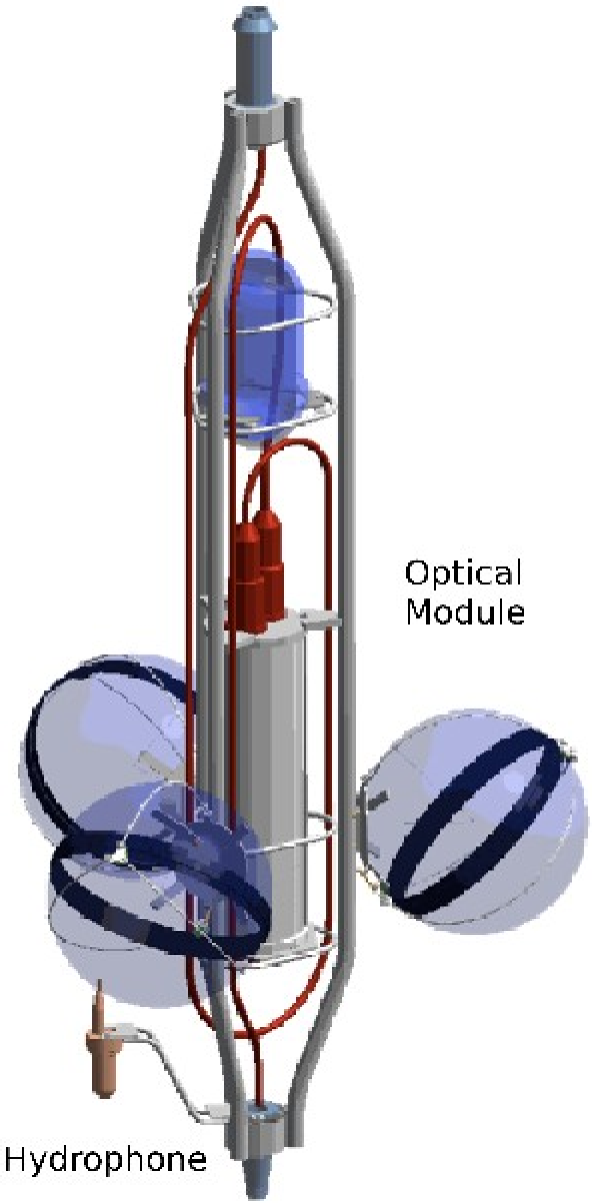




» IceCube DeepCore



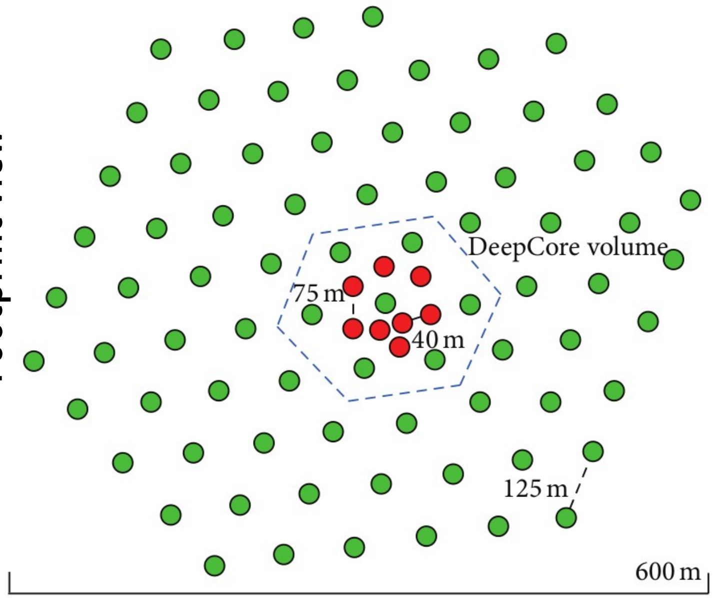
ANTARES



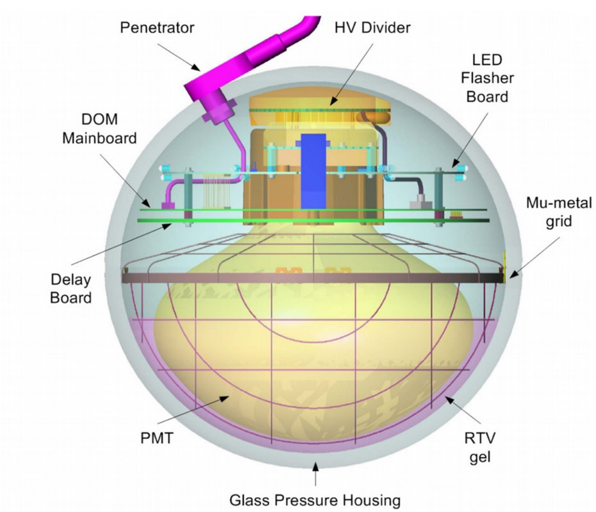
- At the Mediterranean Sea (salt water)
- Depth of 2025-2457 m
- 885 optical modules (in triplets)
- 12 lines, 25 triplets per line
- 14.5m distance between triplets
- 60-70m separation between lines
- Dimensions: 180x180x480m
- Energy threshold ~20 GeV

IceCube DeepCore

Footprint view



Digital optical module



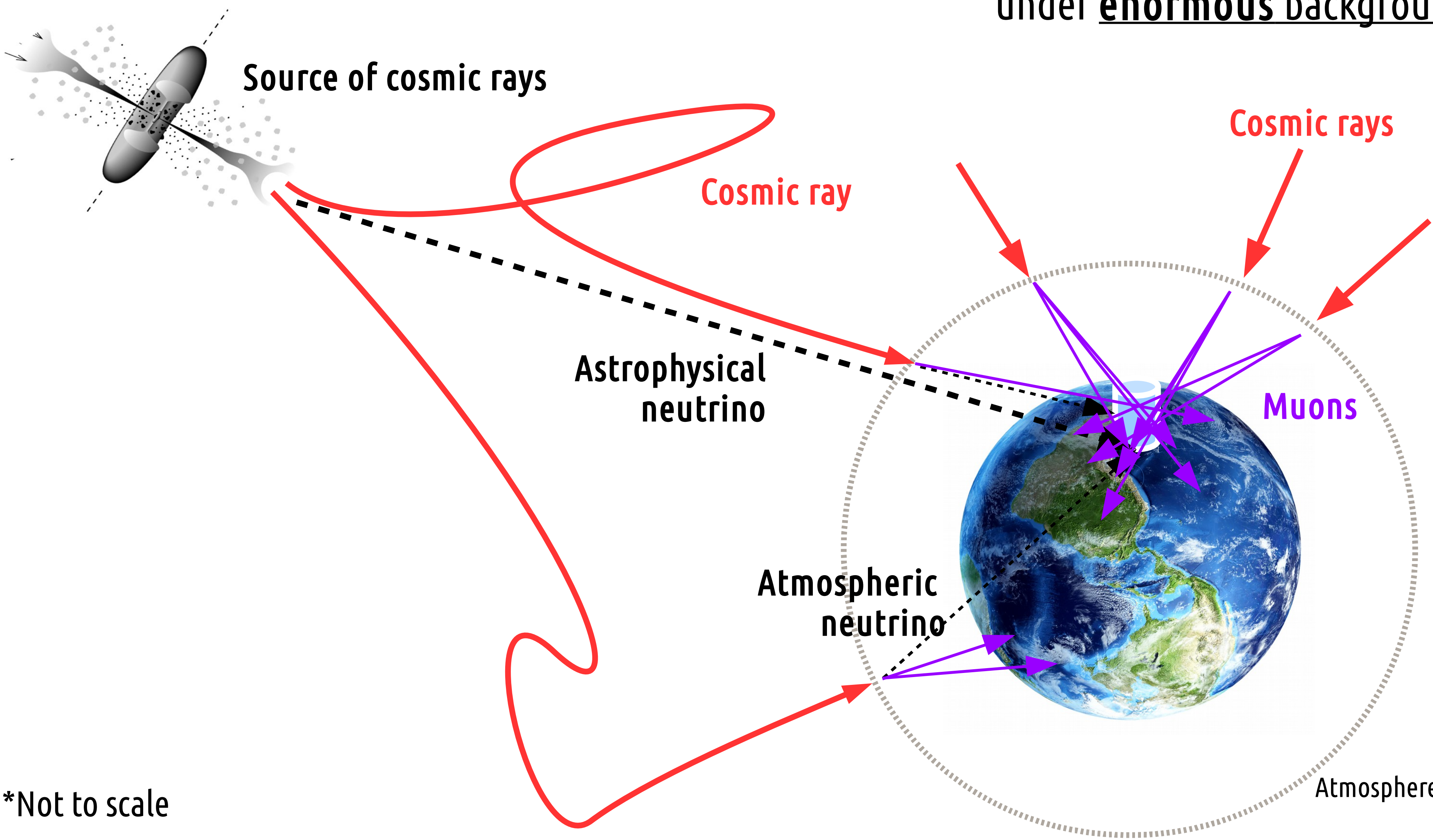
- » At the South Pole (ice)
- » Depth of 1450-2450 m
- » 5160 digital optical modules
- » 86 strings, 125m separation
- » 17m between DOMs in a string

<u>DeepCore volume</u>

- » ~ 500 DOMs, 7m apart
- » 40-70m between strings
- » Energy threshold ~ 10 GeV

Measuring atmospheric neutrino oscillations

where the signal is buried under **enormous** background

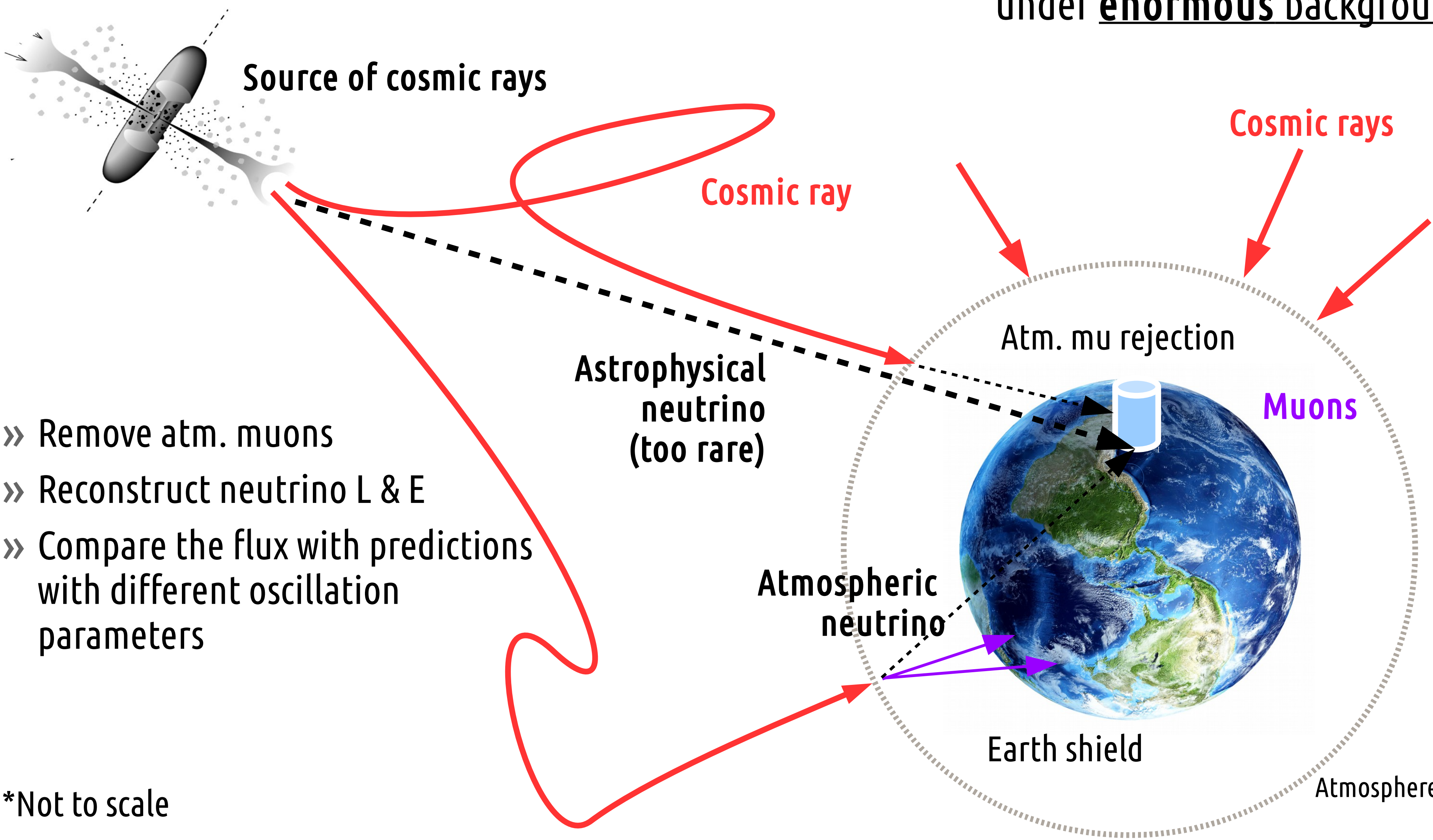


*Not to scale

Image: http://globe-views.com/dreams/earth.html

Measuring atmospheric neutrino oscillations

where the signal is buried
under **enormous** background



- Remove atm. muons
- Reconstruct neutrino L & E
- Compare the flux with predictions with different oscillation parameters

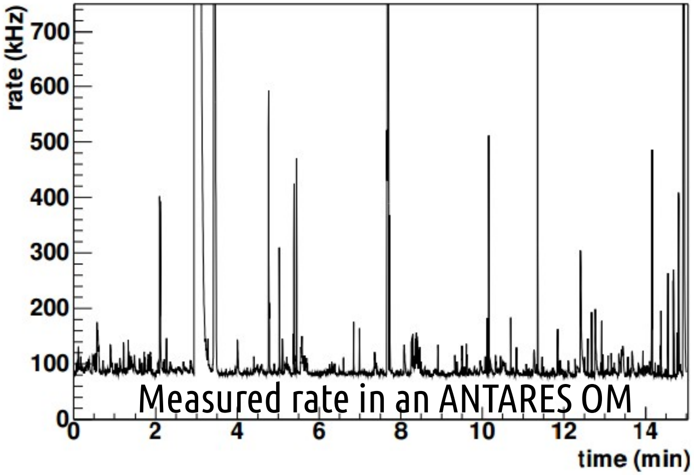
*Not to scale

Image: http://globe-views.com/dreams/earth.html

Measurement challenges

- » **Sparse detector**
  - » Sensors separation from 7m to 70m
  - » A few photons detected at threshold (E~10-20 GeV)
- » **Photons travel in a complex optical medium**
  - » Water: Very high noise rates (kHz) due to ^{40}K
  - » Ice: Layered structure, varying scattering and absorption
  - » Ice: Columns of newly formed ice at drilled holes
- » **Atmospheric muons detection rate is 10^5 that of neutrinos**
  - » Non-negligible probability of fake signals
  - » More misreconstructed muons than neutrinos at the beginning of data selection

Deployment of an IceCube DOM



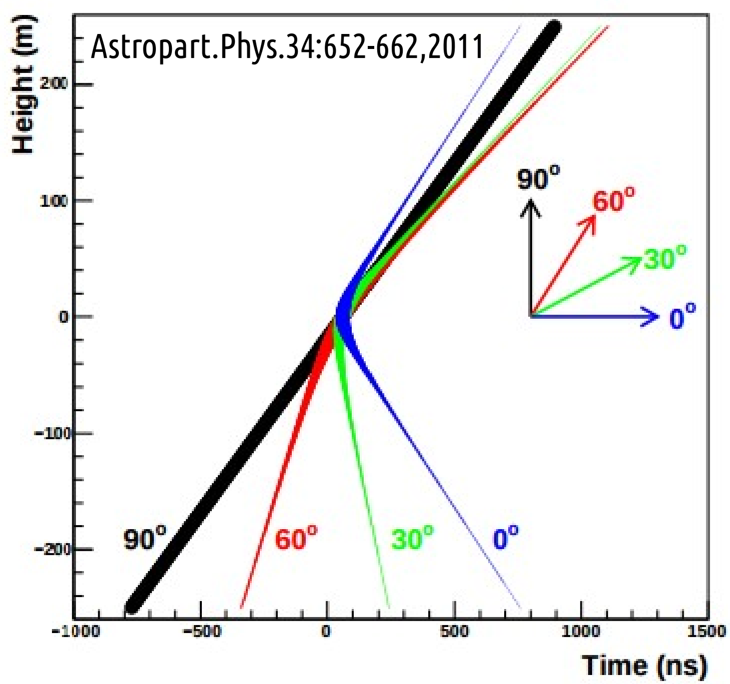
Measured rate in an ANTARES OM

Measurement strategy - background

ANTARES

Phys.Lett. B714 (2012) 224-230

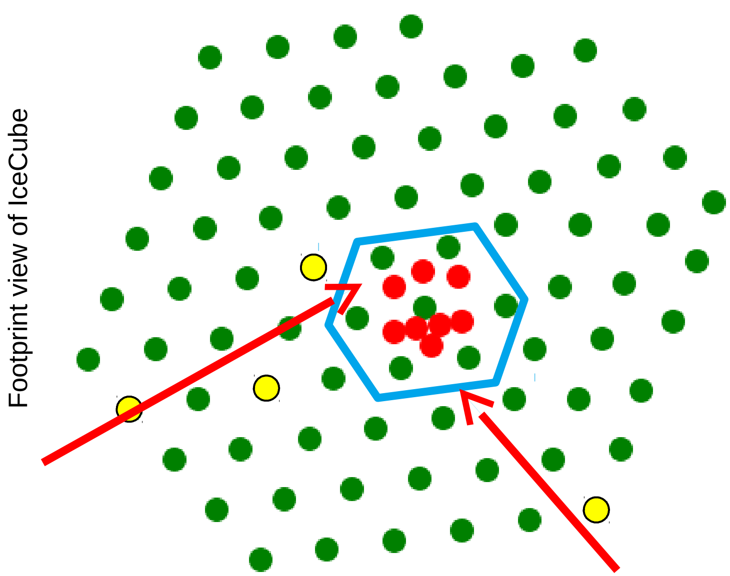
- Noise
  - Strict timing requirements
  - Use Cherenkov light cone



IceCube

Phys. Rev. D 91, 072004 (2015)

- Misidentified atm. μ
  - Heavy use of veto algorithms
  - Select starting events only

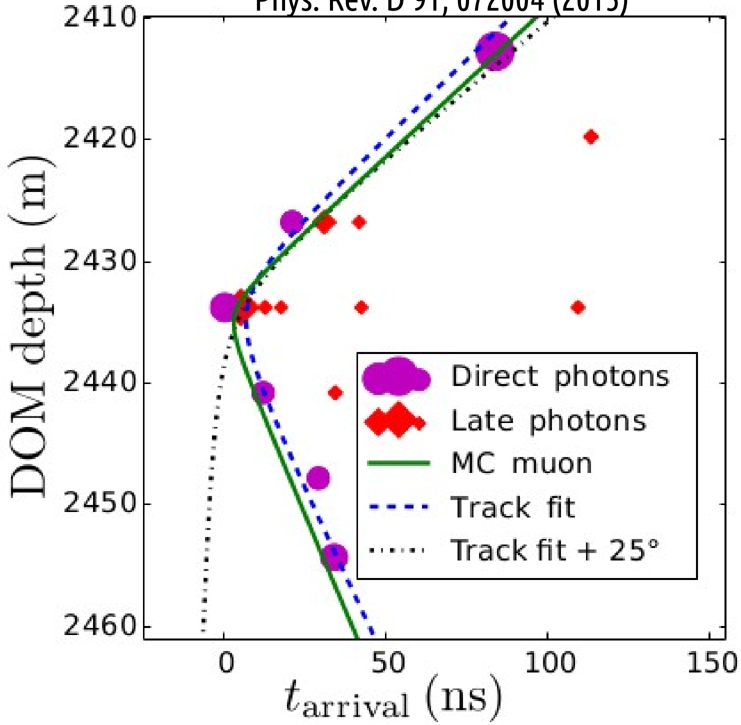


Measurement strategy – event reco

ANTARES & IceCube

- Cherenkov alignment fit
  - Assume no scattering (!)
  - Allow single string events

Phys. Rev. D 91, 072004 (2015)



ANTARES

- Muon projection onto string
  - Muon range is energy proxy

IceCube

- Fit track length + cascade E
  - Use all photons in detector
  - Include ice properties

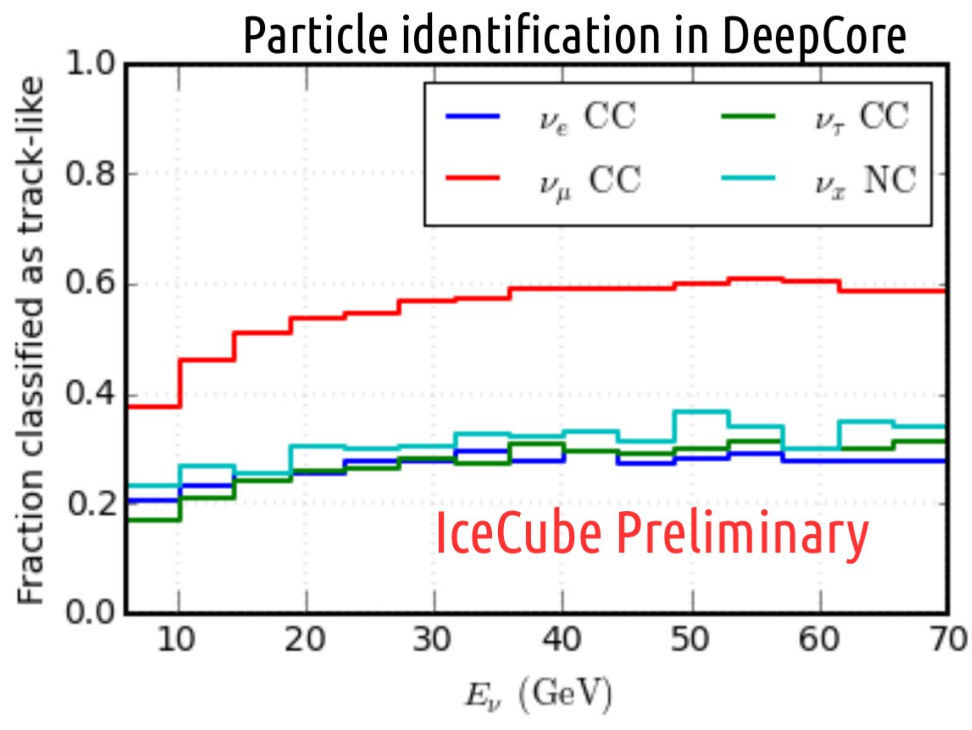
Measurement strategy – particle ID

ANTARES

- Require elongated events
  - Threshold of 100m
  - Translates to E > 20 GeV
- Keeping only NuMu CC
  - NC + NuE CC + NuTau CC are not elongated
  - They compose < 1% of sample

IceCube

- Fit track & cascade light
  - Ratio of fit qualities
  - Keep track-like events only



Measurement strategy – background

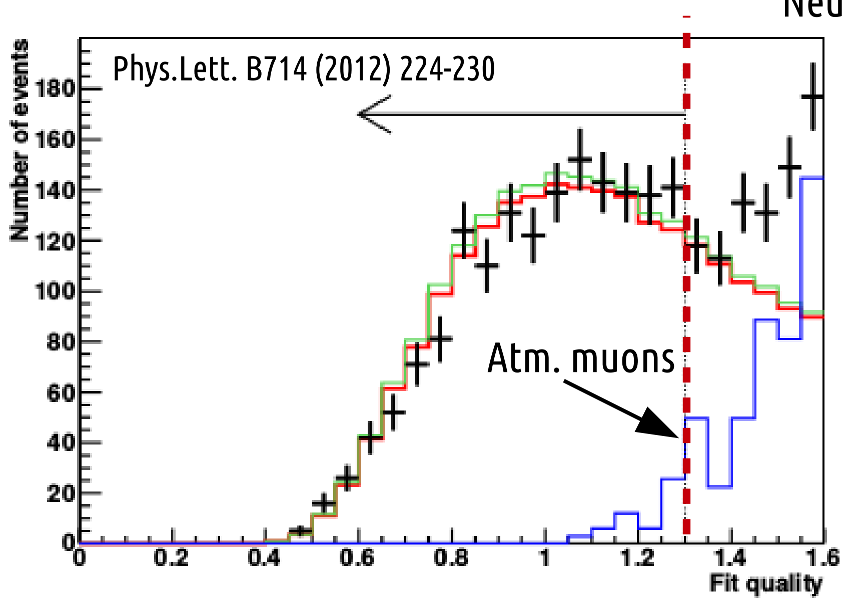
ANTARES

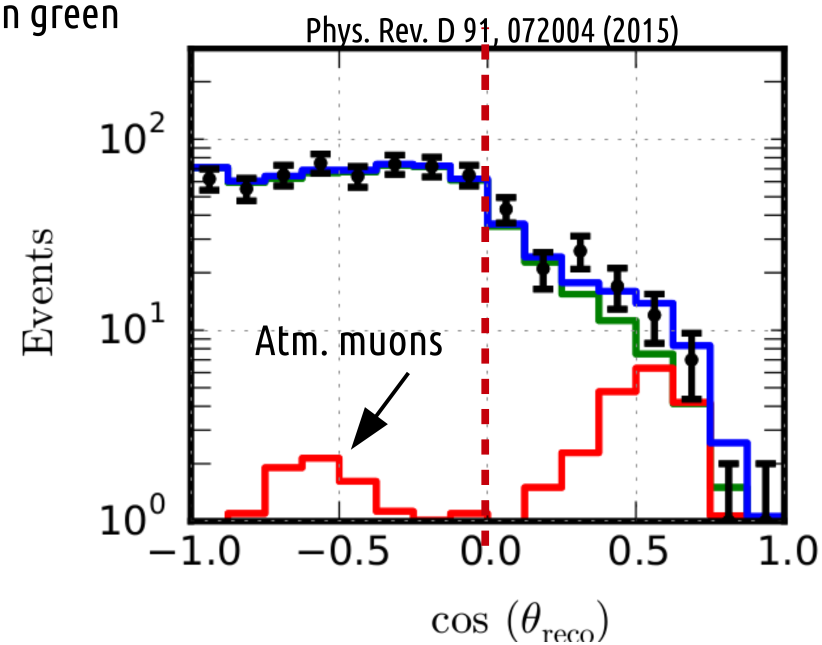
- Muons
  - Look only through Earth
  - Cut on fit quality

IceCube

- Muons
  - Get background PDF from data
  - Fit PDF together with osc.

Data points in black
Neutrino MC in green





VLVNTs vs established players

- Comparison of ANTARES & IceCube with experiments driving the field
  - Trade-off: single experiments over multiple L/E for event resolution

	Parameter	VLVNT ANTARES	VLVNT DeepCore	SK	MINOS, T2K, and NOvA
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% + 22%	25% at 20 GeV	3% at 1 GeV	10–15% at 10 GeV
	θ_ν resolution	3° at 20 GeV	8° at 20 GeV	2-3°	—
	Particle ID capabilities	Muon/no muon in interaction		e, μ, π (rings)	Individual particles, charge
Neutrino flux	Source of neutrinos	Atmosphere: mix of $\nu_e, \bar{\nu}_e, \nu_\mu$, and $\bar{\nu}_\mu$			Accelerator: $\nu_\mu/\bar{\nu}_\mu$ modes
	Baseline	10–12700 km			300–800 km
	Flux determination	Atm. ν models, self-fit		+top/down ratios	Near/far detector
	Energy range	10–100 GeV		Few MeV–few GeV	Few GeV
	Main interaction channel	DIS		QE	QE, RES, COH, and DIS
	ν events expected with osc.	530	1800	2000	30 (T2K), 900 (MINOS)
	and without osc. (per year)	660	2300	2300	120 (T2K), 1050 (MINOS)

arXiv:1509.08404 [hep-ex]

Data analysis – IceCube example

- Fit oscillation parameters by matching histograms (1D, 2D)
  - Systematic uncertainties included as nuisance parameters

Source of error		Nominal value from	Uncertainty
Neutrino interactions	Total cross-section scaling	GENIE model	Free
	Linear energy dependence		E^(+/-0.03)
	Axial mass of non-DIS events		~ +/-20%*
Atmospheric neutrino flux	Overall normalization	Honda 2015	Free
	Spectral index		E^(+/-0.04)
	NuE relative normalization		+/- 20%
Detection	Hadronic energy scaling	Geant4 (model)	+/- 5%
	DOM overall efficiency	Muons, flashers	+/- 10%
	DOM angular acceptance (scattering in hole-ice)	Fit to flasher data	As large as 50%‡
	Bulk-ice model		Two models

* Exact value depends on the individual process

‡ Largest deviation for photons perpendicular to PMT direction

Where are we now?

ANTARES – the first result

- Observation of oscillations (with ~2000 events)
  - Limited statistics, rejecting no oscillations on ~2-3σ
  - In agreement with measurements from other experiments

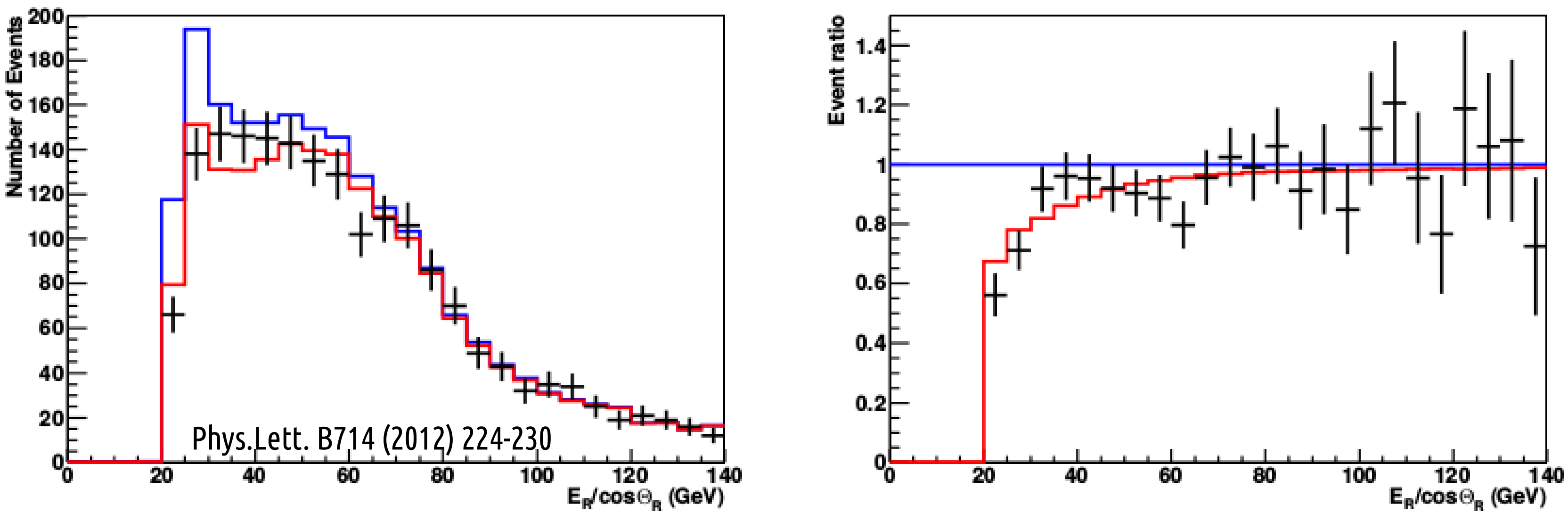
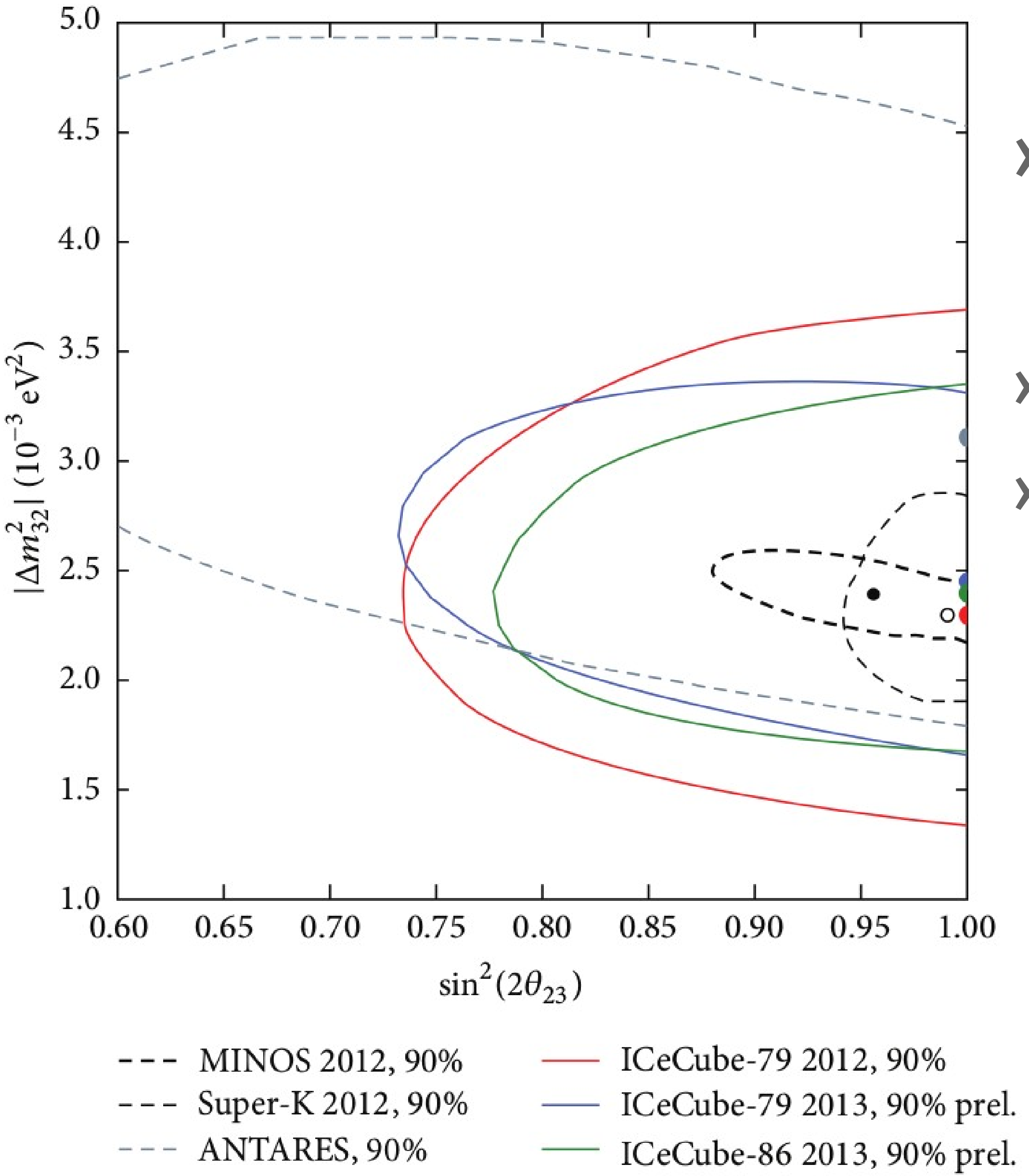


Figure 4: **Left**: Distribution of $E_R / \cos\Theta_R$ for selected events. Black crosses are data with statistical uncertainties, whereas the blue histogram shows simulations of atmospheric neutrinos without neutrino oscillations (scaled down by a factor 0.86) plus the residual background from atmospheric muons. The red histogram shows the result of the fit. **Right**: The fraction of events with respect to the non-oscillation hypothesis. Same color code as for the left figure.

ANTRES & IceCube – evolution



- Fits in 2 neutrino mode

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- ANTARES: published results
- IceCube: Multiple analysis strategies
  - Looking at one year of data
  - Using different event selections
  - Different reconstructions
  - In good agreement

IceCube – latest result

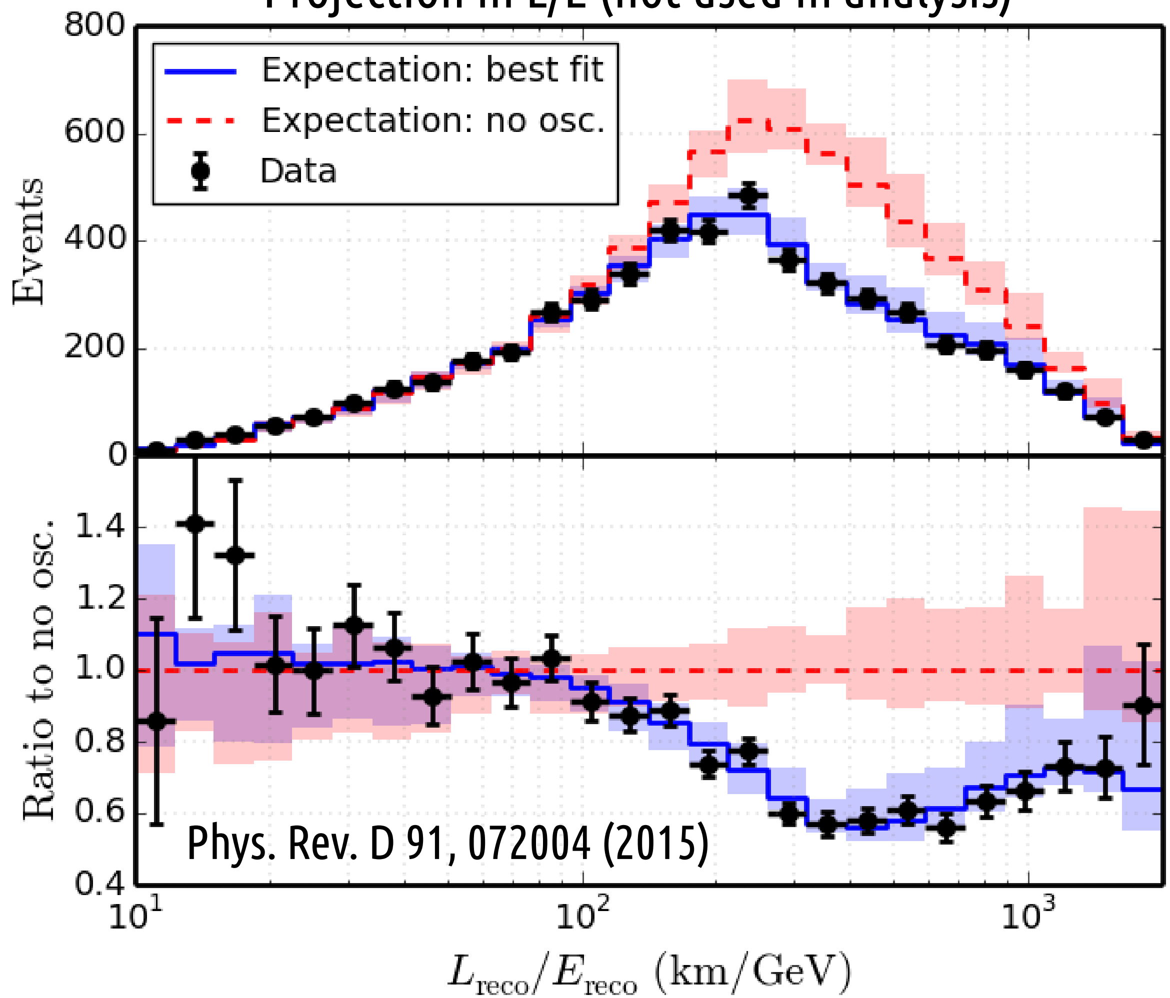
» Best fit to the data from a 2D analysis (E, θ)

» 5174 events in 3 years

» In 2D fit histogram

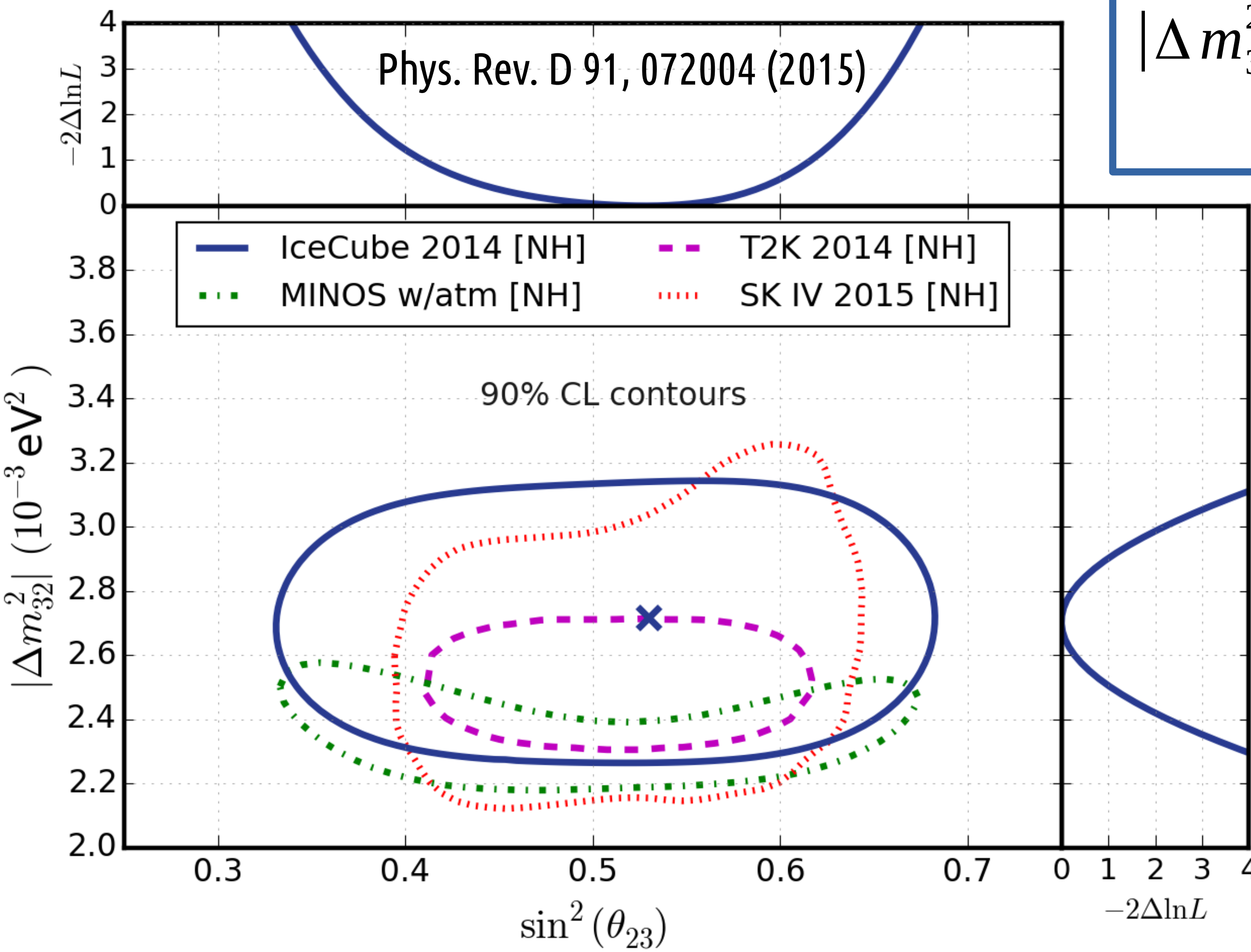
  » χ^2 = 54.9 / 56 d.o.f.

Projection in L/E (not used in analysis)



Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc

IceCube – latest result



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

- » First time a very large volume neutrino detector fits in this figure
- » Measuring large L/E range
- » Affected by different syst. than accelerator results
- » Stat. only errors

$$\sigma(|\Delta m^2_{32}|) = {}^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sigma(\sin^2\theta_{23}) = {}^{+0.06}_{-0.08}$$

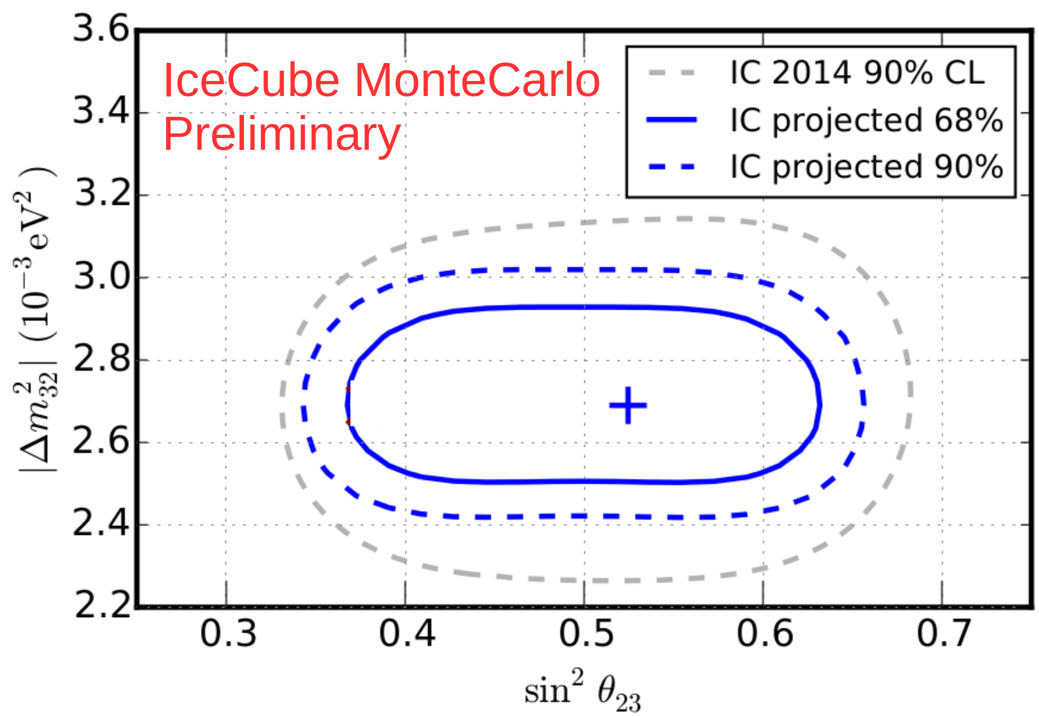
Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc

What comes next?

IceCube – potential

<u>Projected MC sensitivity from re-analysis of 3 years of DeepCore data</u>

- Classify interactions:
  - Use both tracks and cascades
  - Cascade-like events have worse angular resolution, similar energy resolution
- Renewed calibration efforts
  - Noise modeling, angular acceptance, individual DOM behavior



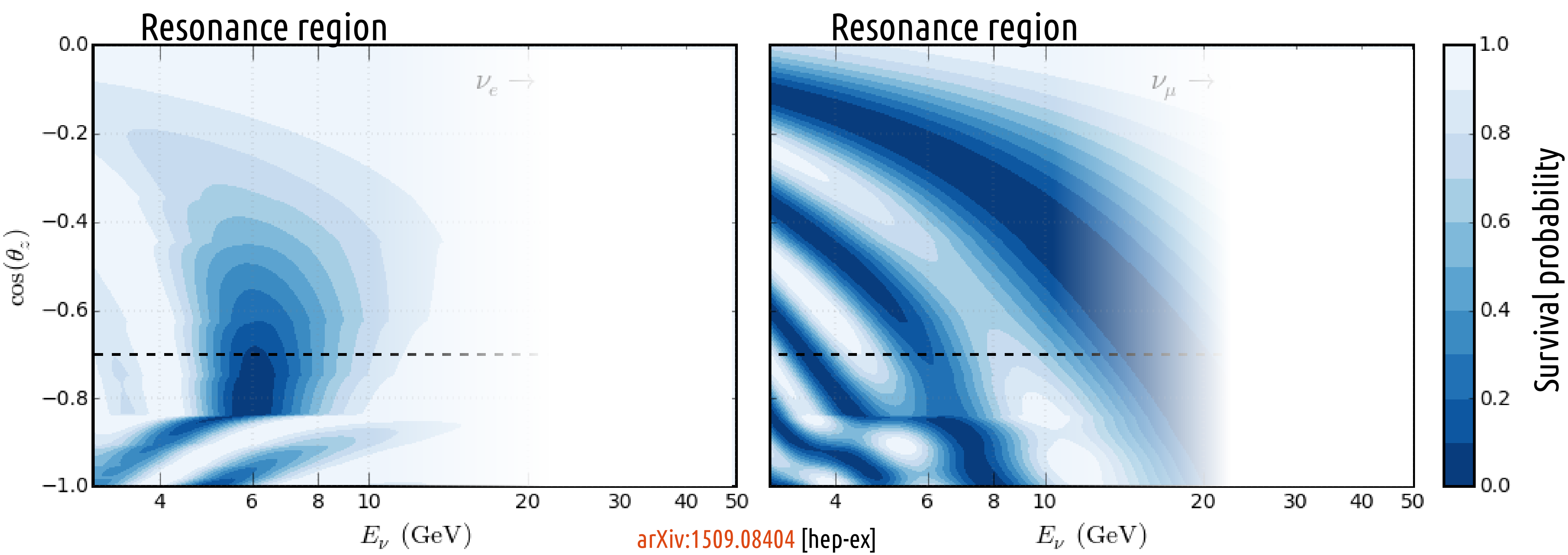
Other studies to be done

- Appearance of NuTau
  - Statistical identification of the need of NuTau cascades
- Atmospheric neutrino spectrum unfolding
- Sterile neutrinos – is there another family member?
- Non-standard interactions – another boson?
  - Introduce effective matter potentials
  - Modify oscillations pattern

Effects in the energy range of currently running VLVNTs

What about lower energies?

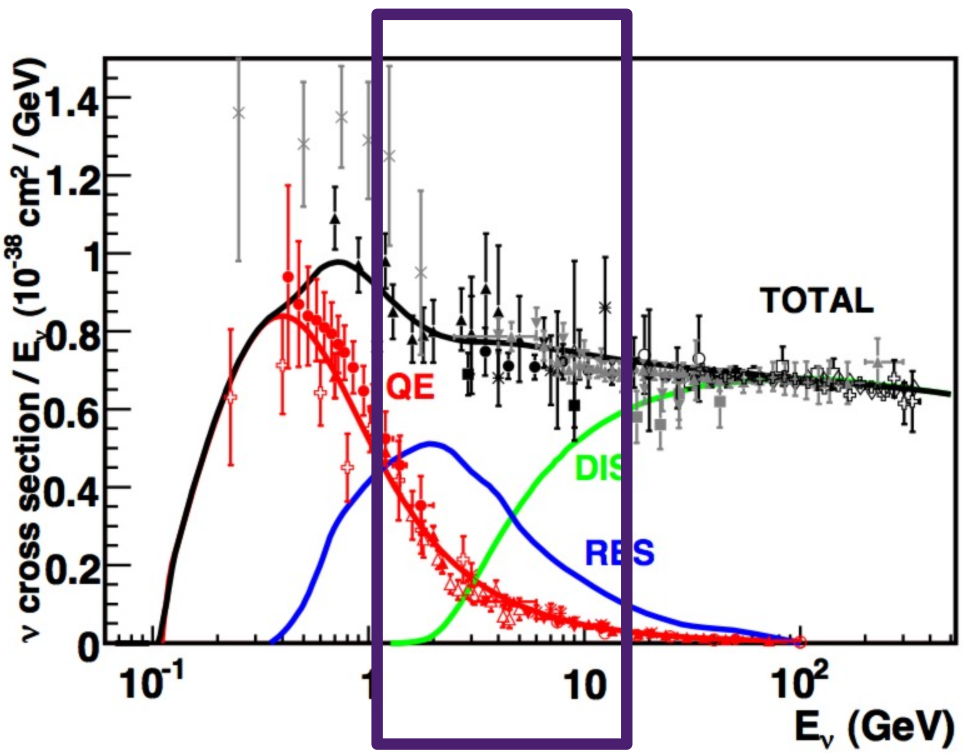
- » Possible to access effects of neutrino mass ordering!
- » A denser detector is required to lower threshold

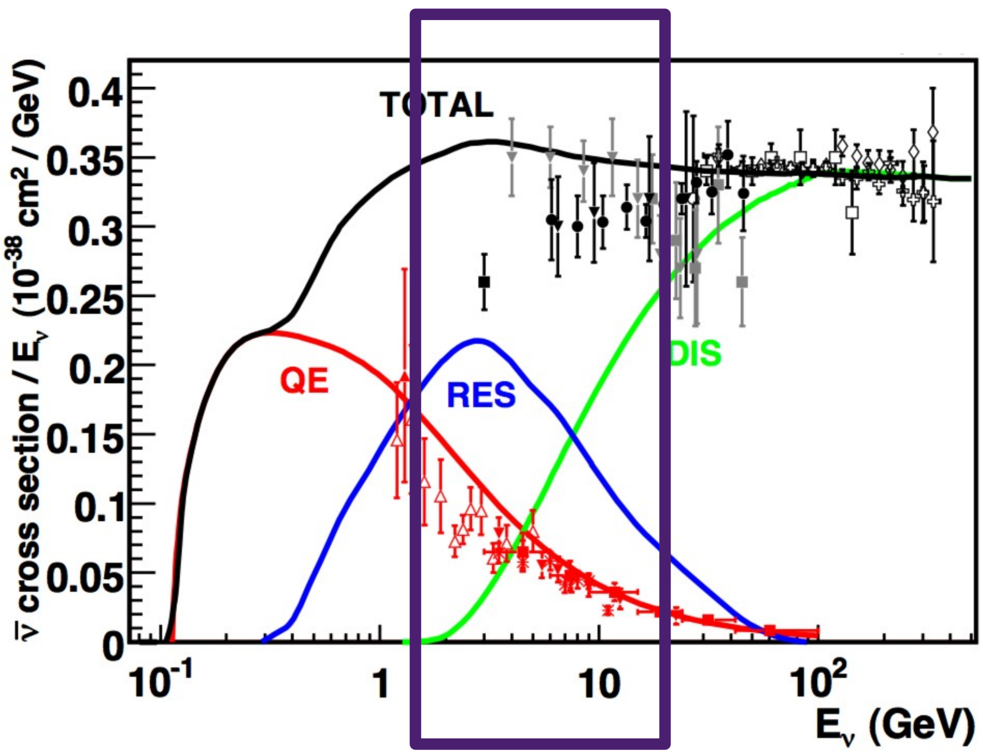


arXiv:1509.08404 [hep-ex]

What about lower energies?

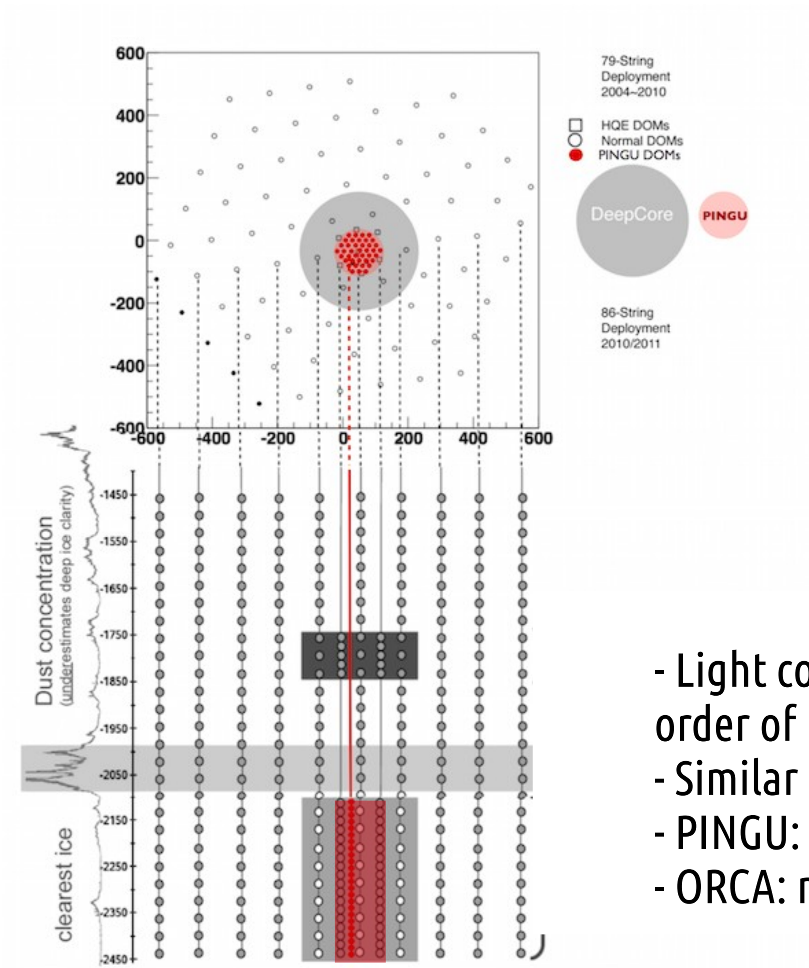
- Possible to access effects of neutrino mass ordering!
- Improved analysis to deal with this transition region



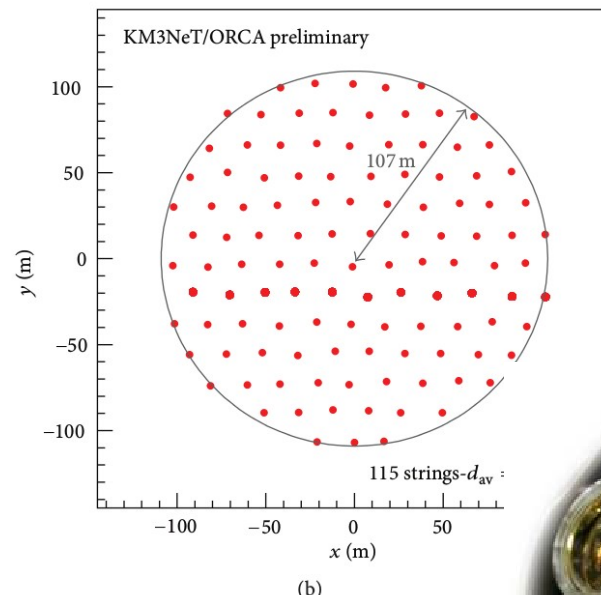


Proposals: PINGU and ORCA

- Precision IceCube Next Generation Upgrade (PINGU – IceCube Gen2)
  - Deploy additional 40x96 DOMs
  - Spacing 20x3m



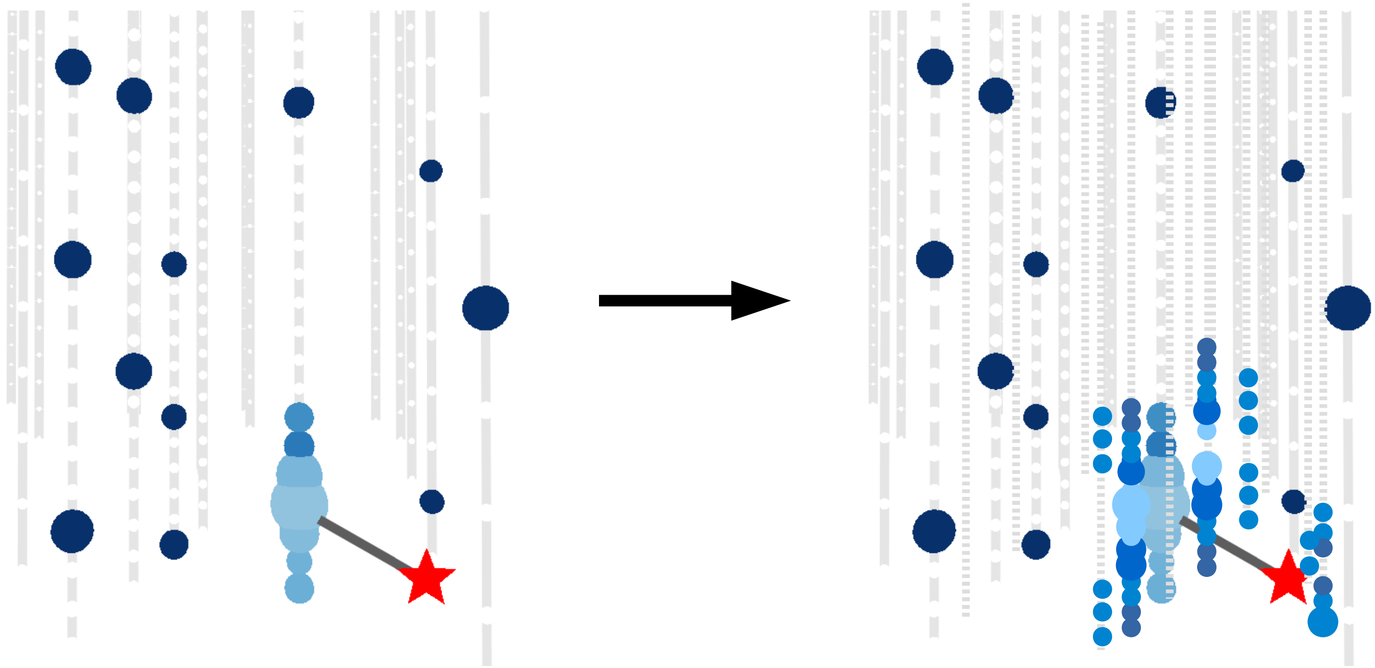
- Oscillations Research with Cosmics in the Abyss (ORCA – Km3NeT)
  - Deploy new 115x18 multiOMs
  - Spacing 20x6m



(b)

- Light collection increased by an order of magnitude
- Similar instrumented volume
- PINGU: relying on IC veto
- ORCA: not using a veto

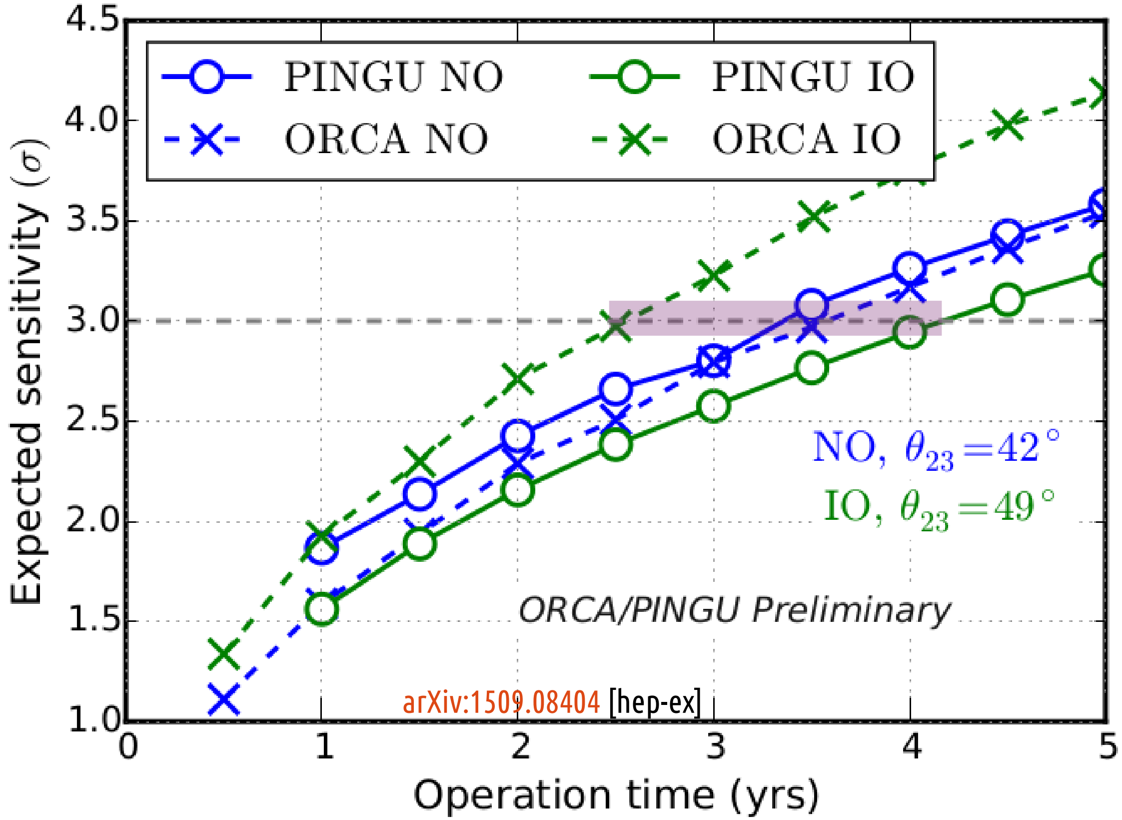
Proposals: PINGU and ORCA



Sketch: MC interaction in DeepCore and PINGU
12 GeV NuMu interaction
8 GeV track (R~40m) + 4 GeV cascade

Projections: PINGU and ORCA

- Main goal: determine the neutrino mass ordering
  - Reachable by both detectors in **2.5-4 years** of operation (depends on Nature)
  - Projections based on more sophisticated analyses than current results*
- Potential for other physics measurements (listed before)



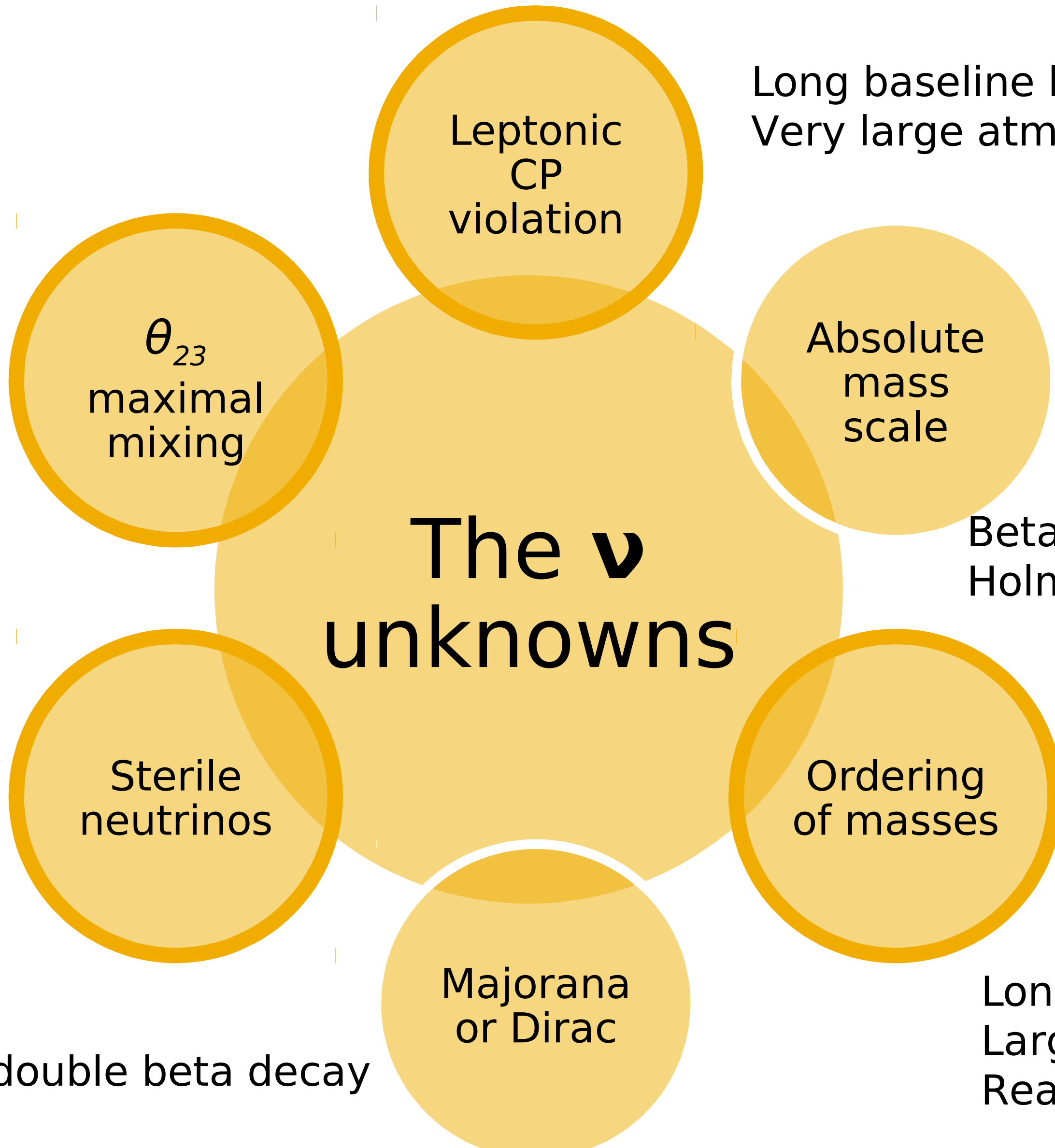
arXiv:1509.08404 [hep-ex]

Summary

» VLVNTs have started making meaningful contributions to the field of neutrino oscillations

» **More is yet to come**

Outlook: known unknowns



Long baseline beam
Very large atm. ν detectors

Beta decay spectrometry
Holmium detectors

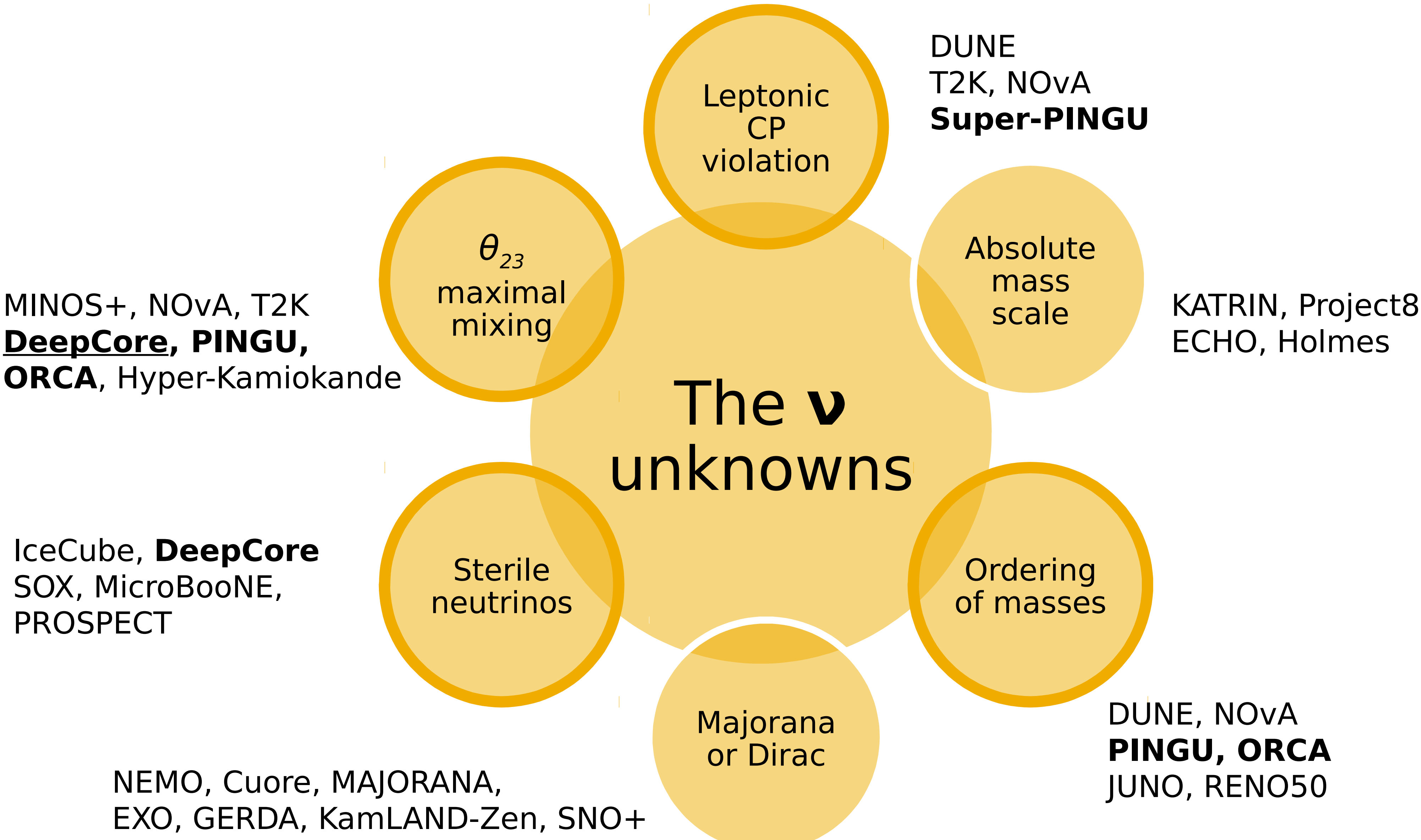
Long baseline beam
Large atm. ν detectors
Reactor-ν detectors

Neutrinoless double beta decay

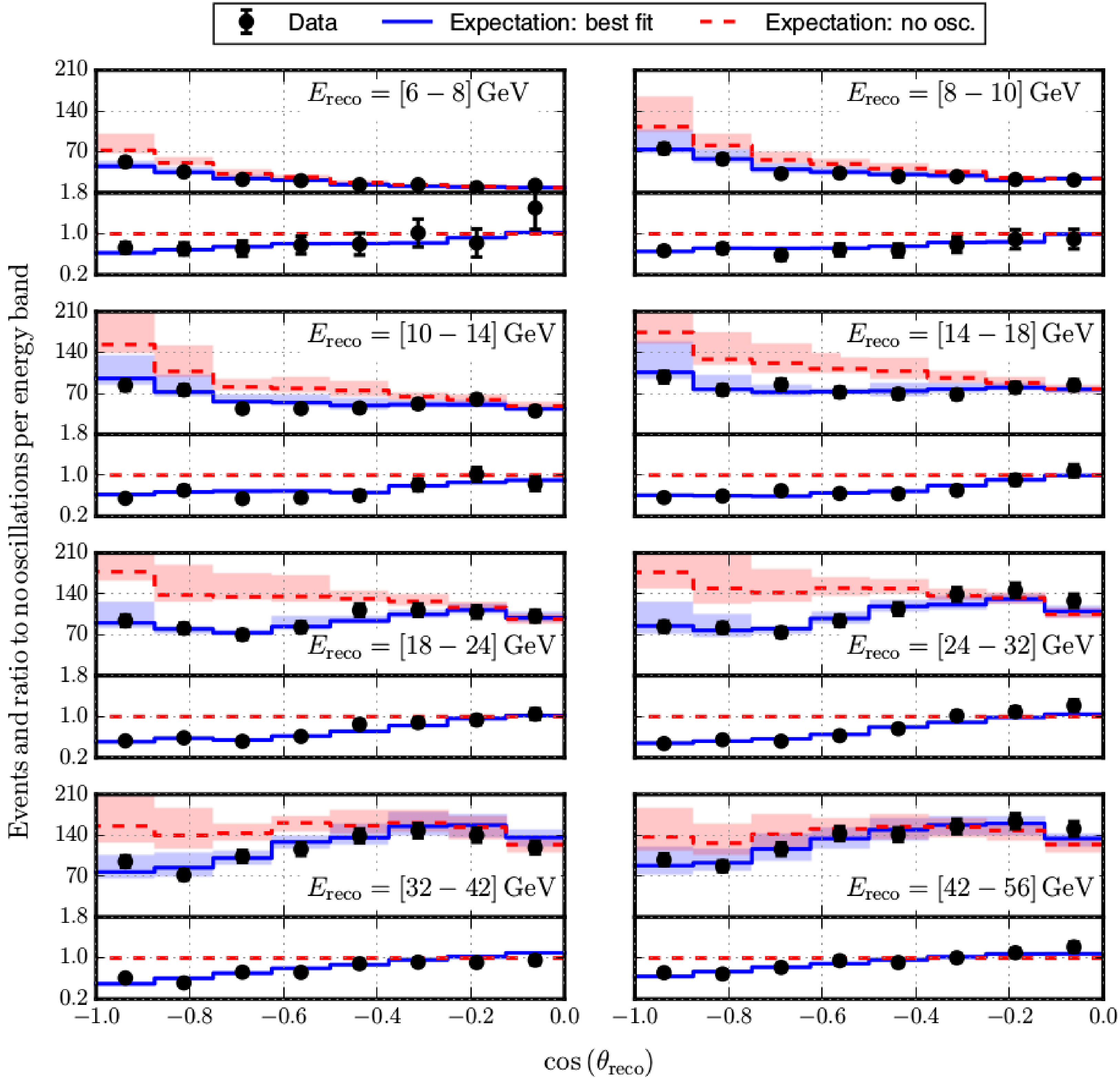
Reactor-ν detectors
Short baseline beam
Large atm. ν detectors

Long baseline beam
Large atm. ν detectors

Outlook: searching for answers



Backup slides



Data
Expectation: best fit
Expectation: no osc.
$E_{\mathrm{reco}} = [6-8]$ GeV
$E_{\mathrm{reco}} = [8-10]$ GeV
$E_{\mathrm{reco}} = [10-14]$ GeV
$E_{\mathrm{reco}} = [14-18]$ GeV
$E_{\mathrm{reco}} = [18-24]$ GeV
$E_{\mathrm{reco}} = [24-32]$ GeV
$E_{\mathrm{reco}} = [32-42]$ GeV
$E_{\mathrm{reco}} = [42-56]$ GeV
Events and ratio to no oscillations per energy band
$\cos(\theta_{\mathrm{reco}})$

III. Analysis of the data

Updated list of uncertainties considered

Source of error		Nominal value from	Uncertainty
Neutrino interactions	Total cross-section scaling	GENIE model	Free
	Linear energy dependence		E^(+/-0.03)
	DIS cross section		From models
	Axial mass of non-DIS events		~ +/-20%*
Atmospheric neutrino flux	Overall normalization	Honda 2015	Free
	Spectral index		E^(+/-0.04)
	Up/Horizontal ratio		E dependent (+/- 8%)
	Nu/NuBar ratio		E dependent (+/- 25%)
	NuE relative normalization		+/- 3%
Detection	Hadronic energy scaling	Geant4 (model)	+/- 5%
	Hadronization/propagation		From models
	DOM overall efficiency	Muons, flashers	+/- 10%
	DOM angular acceptance* (scattering in hole-ice)	Fit to flasher data	As large as 50%‡
	Bulk-ice model		Two models

* Exact value depends on the individual process

‡ Largest deviation for photons perpendicular to PMT direction

$$U'_{li} = e^{-i\beta_l} \; U_{li} \; e^{i\alpha_l}, \tag{6.118}$$

where α_i and β_l are arbitrary constant phases. In fact, we have

$$\mathrm{J}^{ik}_{l'l} = \mathrm{Im}(U_{l'i} \; U^*_{l'k} \; U^*_{li} \; U_{lk}) = \mathrm{Im}(U'_{l'i} \; U'^*_{l'k} \; U'^*_{li} \; U'_{lk}) = (\mathrm{J}^{ik}_{l'l})' \tag{6.119}$$

It is easy to see that (for Dirac neutrinos) the mixing matrices U and U' are equivalent. In fact, let us consider the lepton charged current. We have

$$j^{\mathrm{CC}}_{\alpha} = 2 \sum_{l,i} \bar{\nu}_{iL} U^*_{li} \gamma_\alpha l_L = 2 \sum_{l,i} \bar{\nu}'_{iL} U'^*_{li} \gamma_\alpha l'_L, \tag{6.120}$$

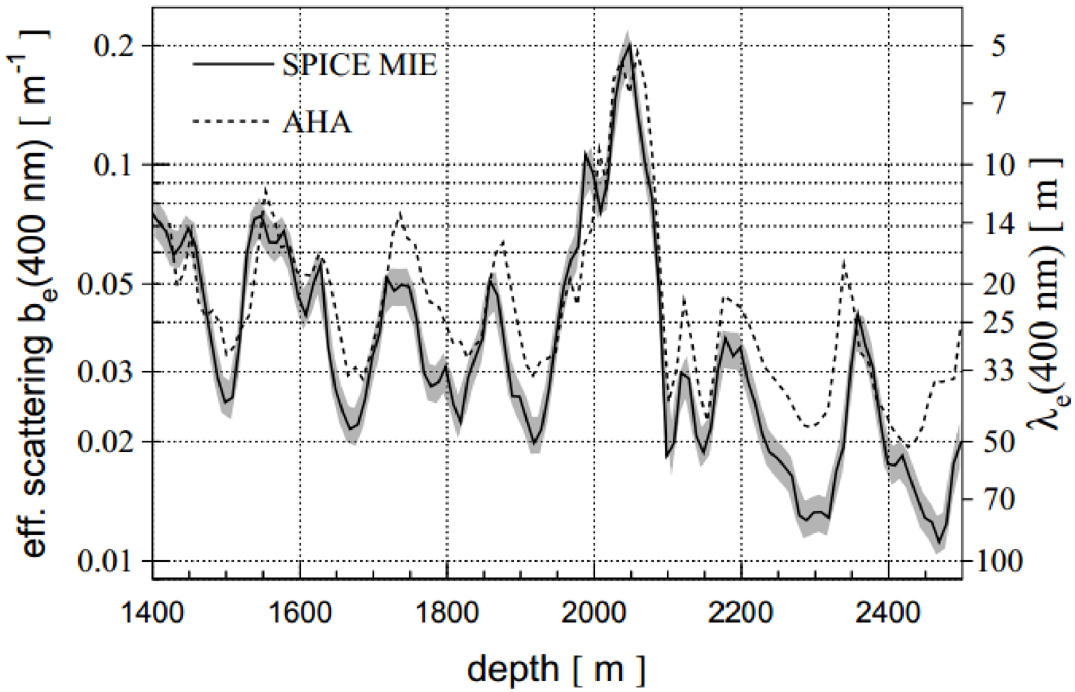
where the primed fields are determined as follows

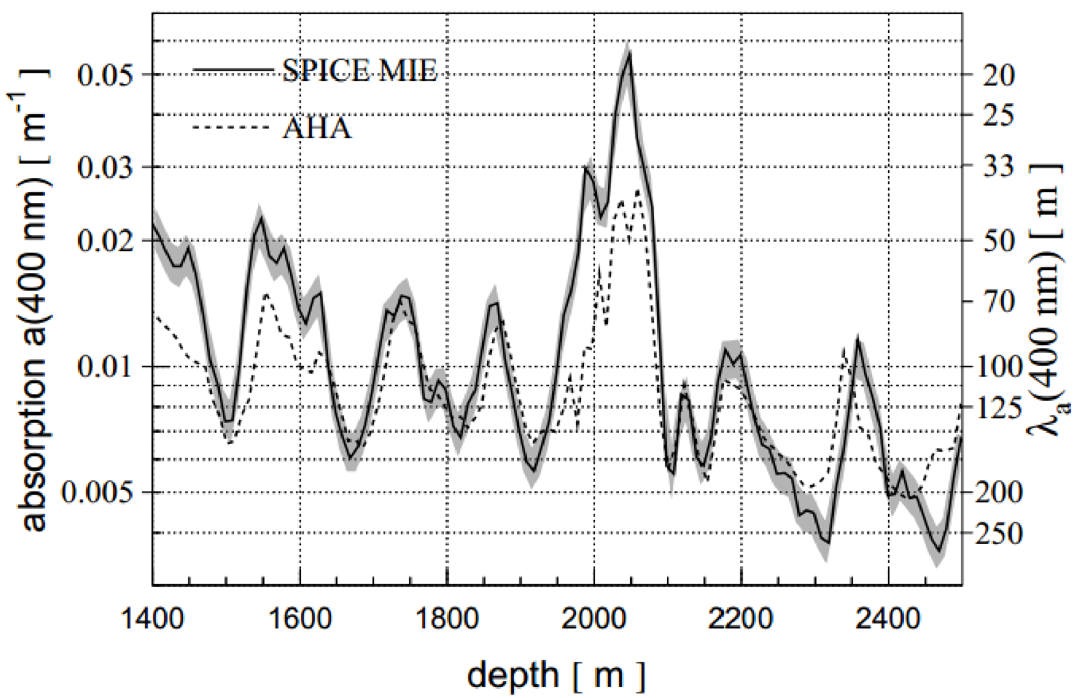
$$\nu'_i(x) = e^{-i\alpha_i} \nu_i(x), \quad l'(x) = e^{-i\beta_l} l(x) \tag{6.121}$$

The fields $\nu'_i(x)$ and $l'(x)$ cannot be distinguished from $\nu_i(x)$ and $l(x)$. Thus, the mixing matrix (in the Dirac case) is determined up to the phase transformation (6.118) and the transition probabilities must be invariant under this transformation.

In the standard parametrization of the mixing matrix U (see previous chapter) for the Jarlskog invariant we obtain the following expression

$$J = -c_{12} c_{23} c^2_{13} s_{12} s_{23} s_{13} \sin \delta. \tag{6.122}$$



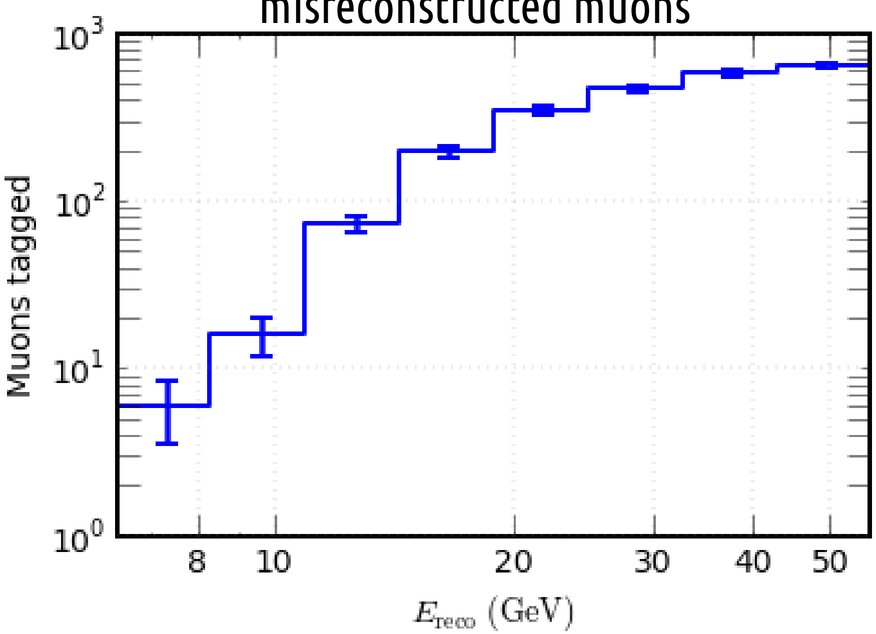


Nucl. Instr. Meth. A711 (2013) 73

I. Background

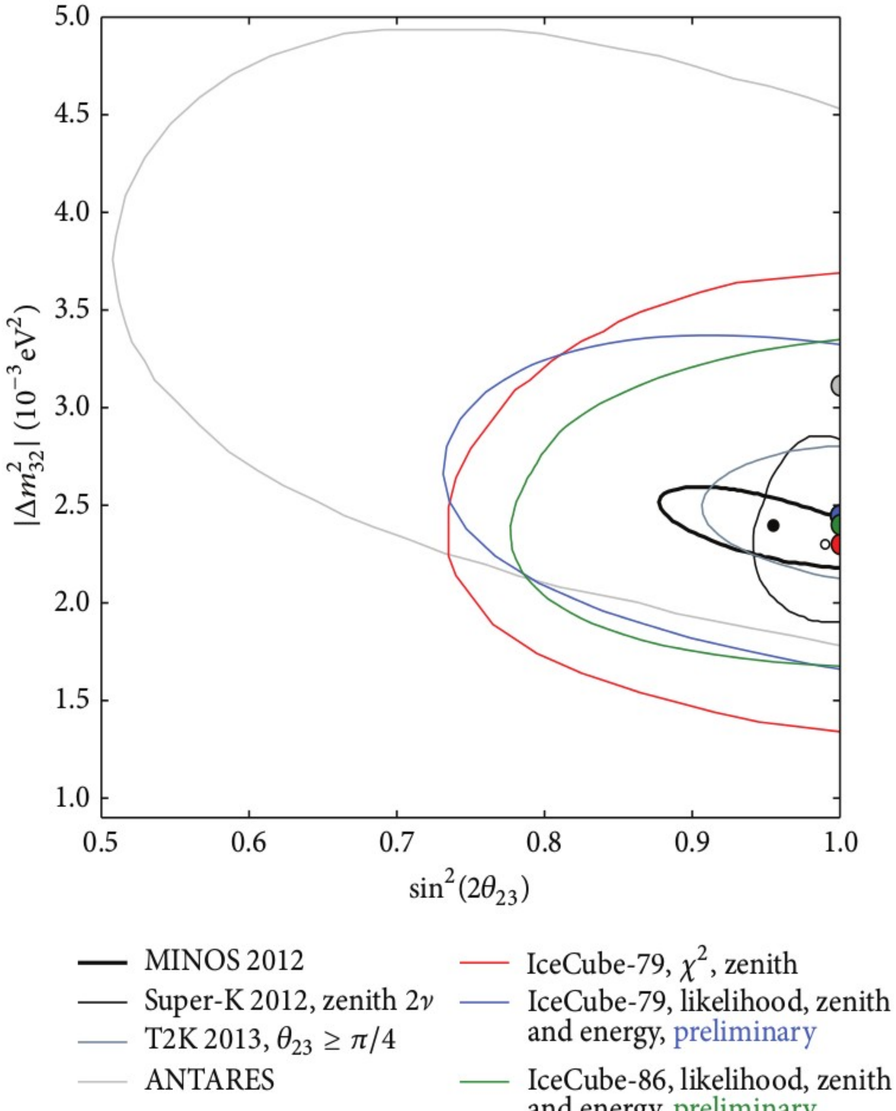
- Muons from air showers
  - Starting events → IceCube as veto for DeepCore
  - Tag muons directly from data
  - Use “event quality” to remove misreconstructions

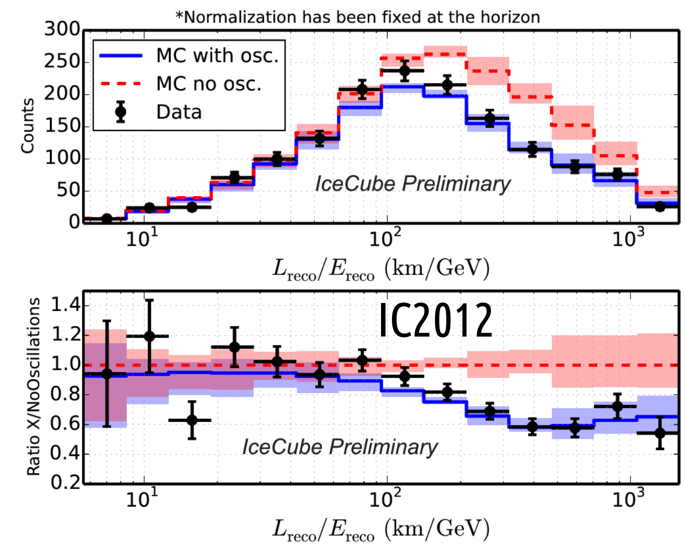
Analysis of **DeepCore data**
misreconstructed muons

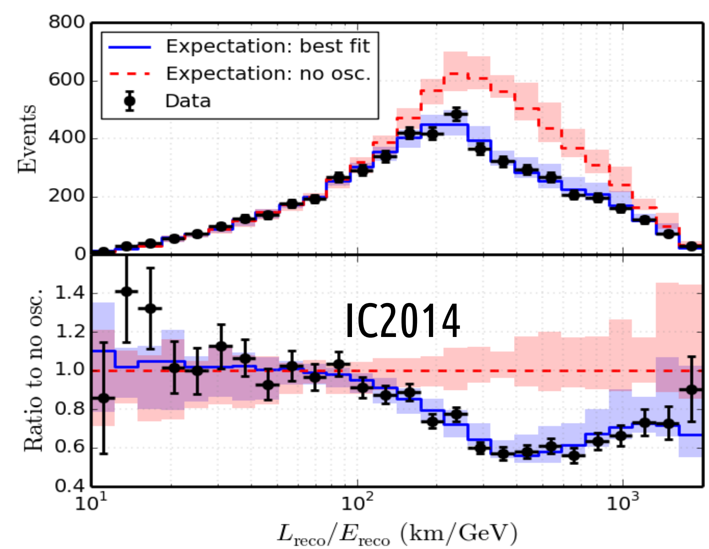


- IceCube veto useful for DC
- Background muon rate α Ereco
- **Results use only up-going events**
  - Down-going region under study

Evolution of oscillation analysis in IceCube DeepCore

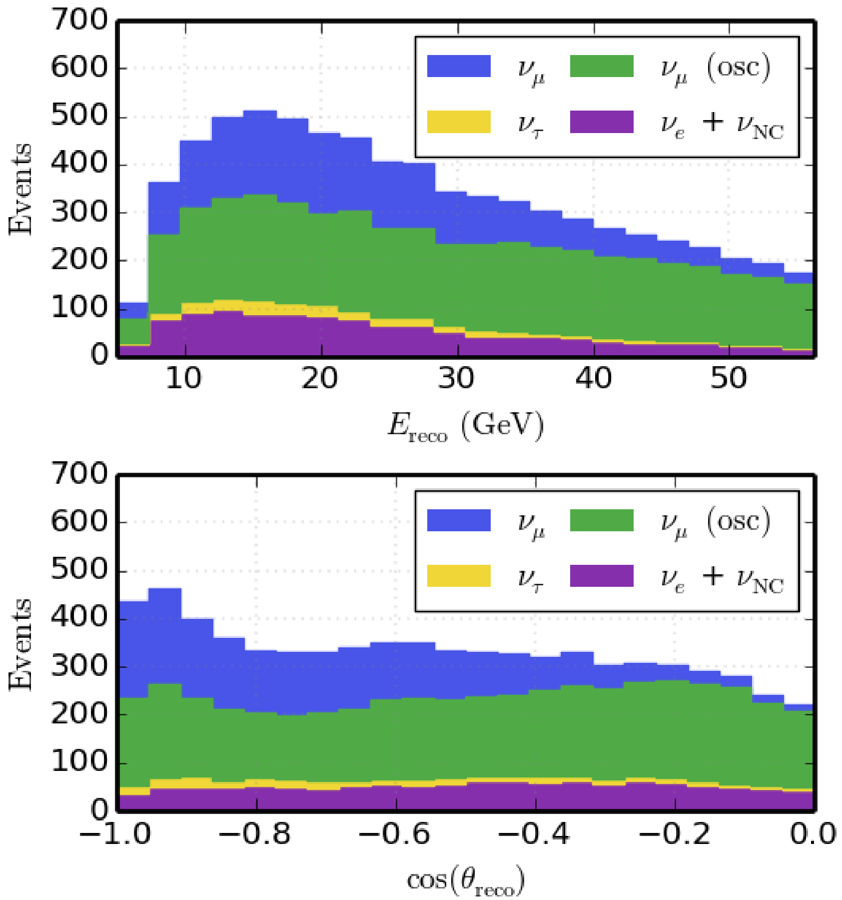






Sample breakdown

Component	Events in sample	
	Osc.	No osc.
ν_μ	3755	5900
ν_τ	273	-
ν_e	678	650
ν_{NC}	418	
Atm. μ	54	



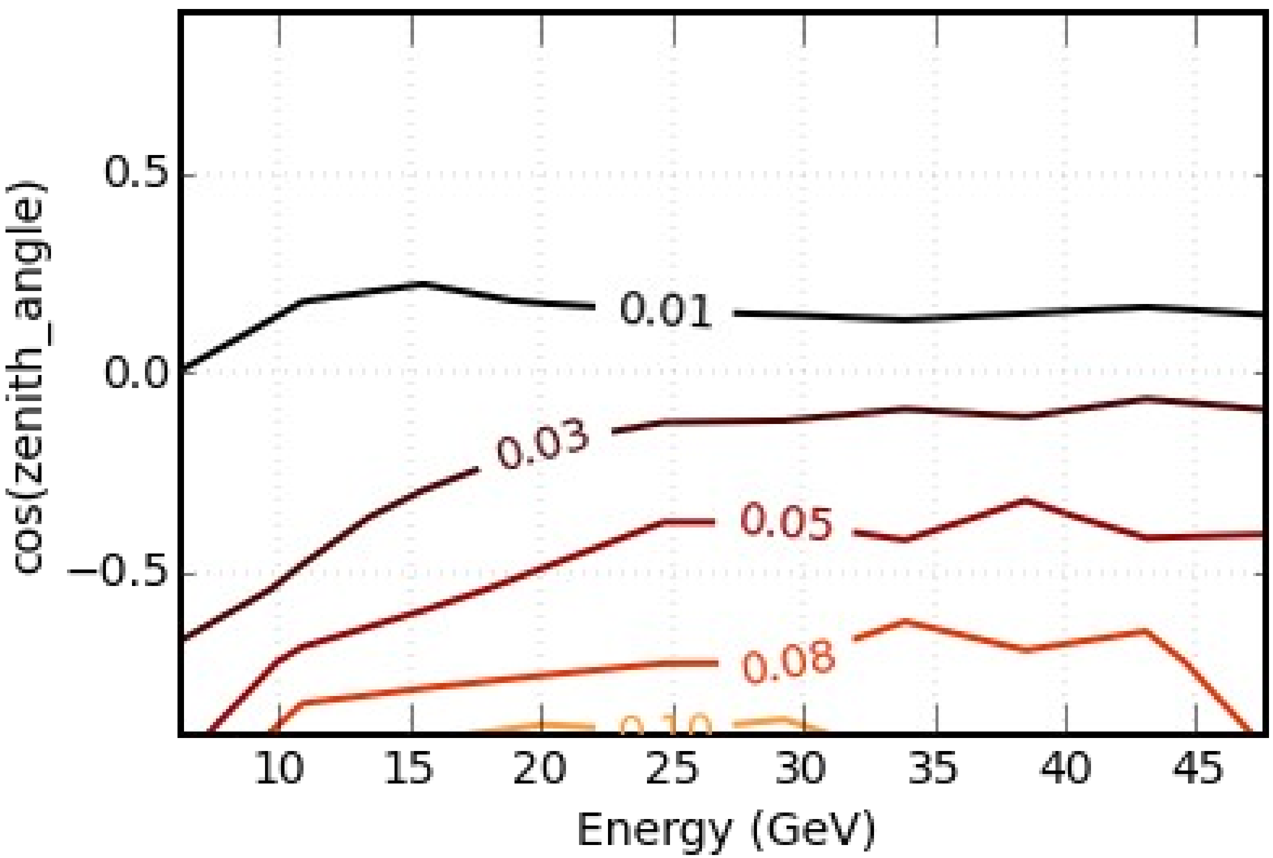
Impact of errors

» Expected reduction of error by removing individual sources of uncertainty

	sin(theta23)^2	DM31 (10^3 eV^2)
PRD errors	0.1	0.2
Hole ice	29.88%	2.34%
DOM eff	0.73%	19.06%
Gamma	0.13%	8.67%
NuE	0.05%	0.94%
Atm Mu	0.00%	0.72%

DeepCore selection efficiency

» Efficiency vs zenith angle

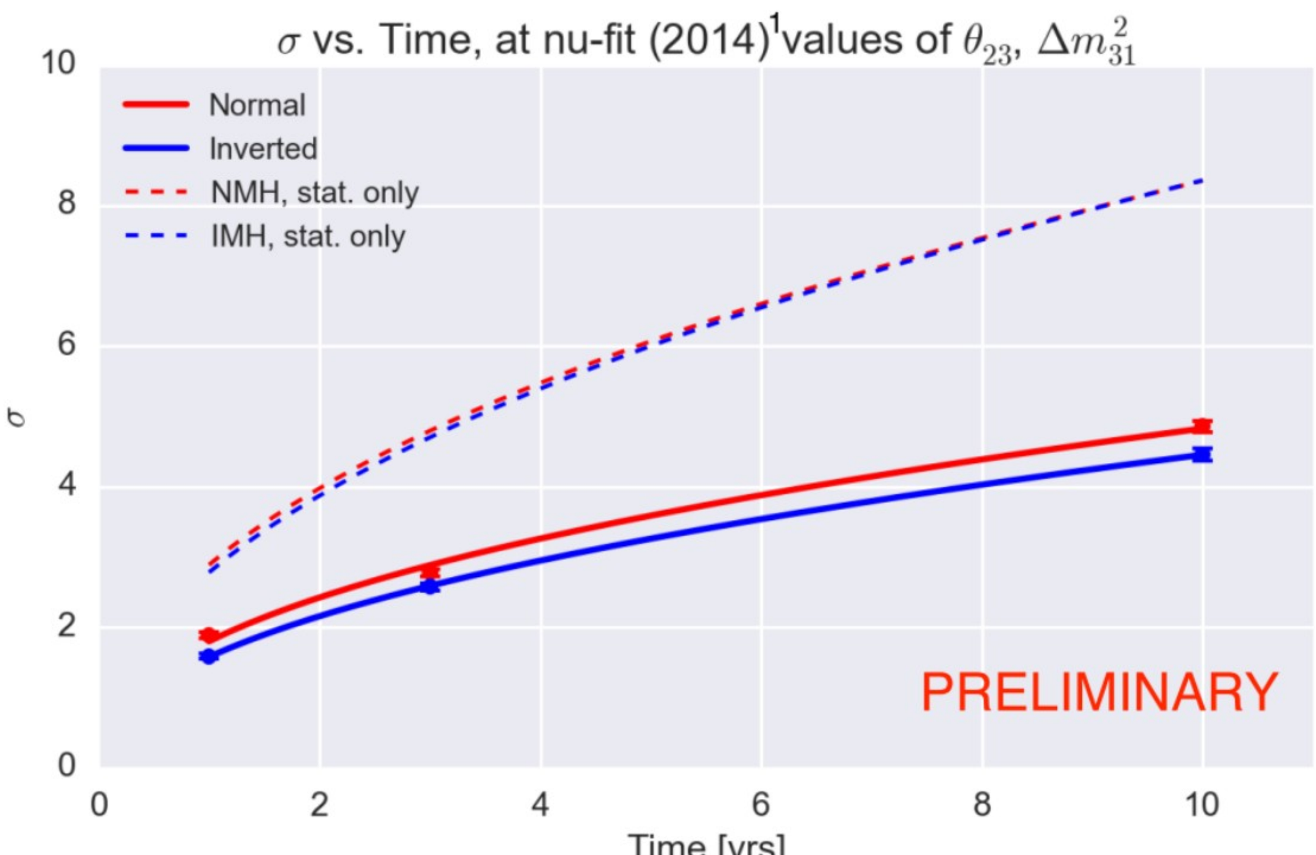


VLVLNT in context

	Parameter	VLVNT ANTARES	VLVNT DeepCore	SK	MINOS, T2K, NOvA
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% ± 22%	25% at 20 GeV	3% at 1 GeV	10-15% at 10 GeV
	θ_ν resolution	3° at 20 GeV	8 ° at 20 GeV	2-3°	–
	Particle ID capabilities	Muon/no muon in interaction		e, μ, π (rings)	Individual particles, charge
Neutrino flux	Source of neutrinos	Atmosphere: mix of ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$			Accelerator: $\nu_\mu/\bar{\nu}_\mu$ modes
	Baseline	10-12700 km			300-800 km
	Flux determination	Atm. ν models, self fit		+ top/down ratios	Near/Far detector
	Energy range	10−100 GeV		few MeV−few GeV	few GeV
	Main interaction channel	DIS		QE	QE, RES, COH, DIS
	ν events expected with osc.	530	1800	2000	30 (T2K), 900 (MINOS)
	and without osc. (per year)	660	2300	2300	120 (T2K), 1050 (MINOS)

PINGU – sensitivity vs time

- 3σ identification with 3-4 years of data
  - Oscillation parameters are most important source of error
  - Slightly better sensitivity to normal hierarchy



Significance including only one set of uncertainties

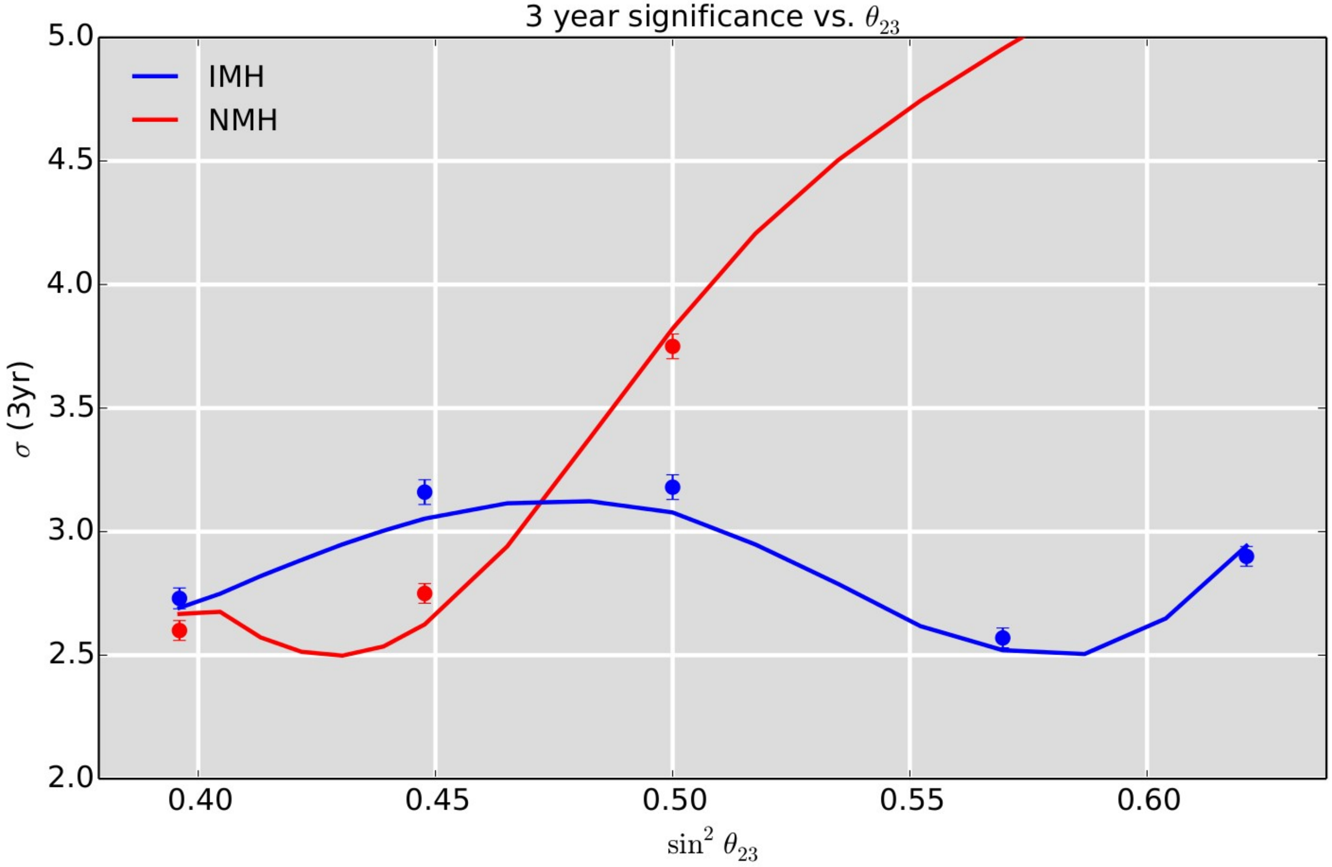
Type	3yr σ (NMH)	3yr σ (IMH)
stat. only	4.84	4.82
flux only	4.55	4.56
det. only	4.06	3.99
θ_{23} only	3.52	3.26
osc. only	2.96	2.53
All	2.90	2.51

Preliminary

*delta-cp kept fixed at 0 (injected)

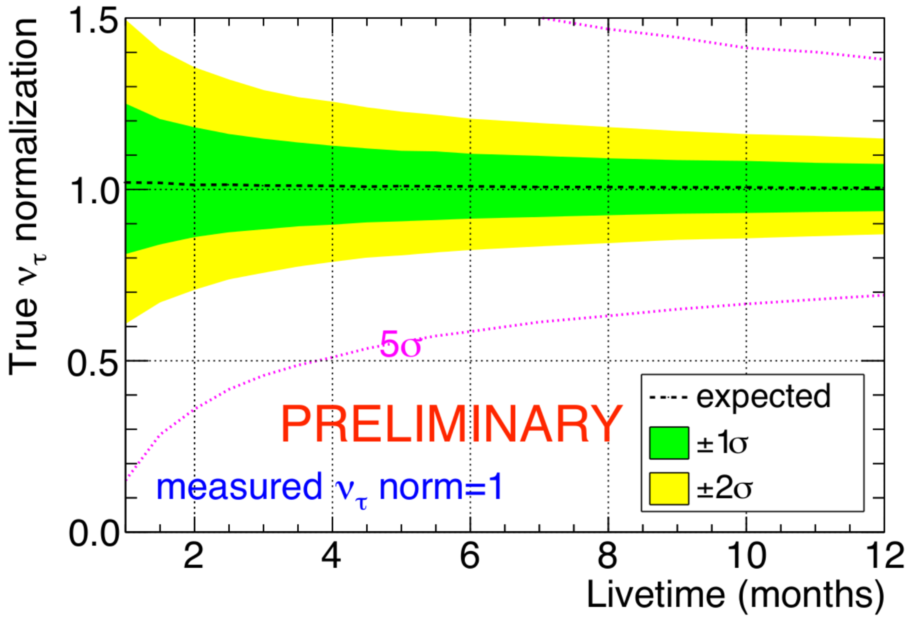
PINGU – sensitivity vs θ_{23}

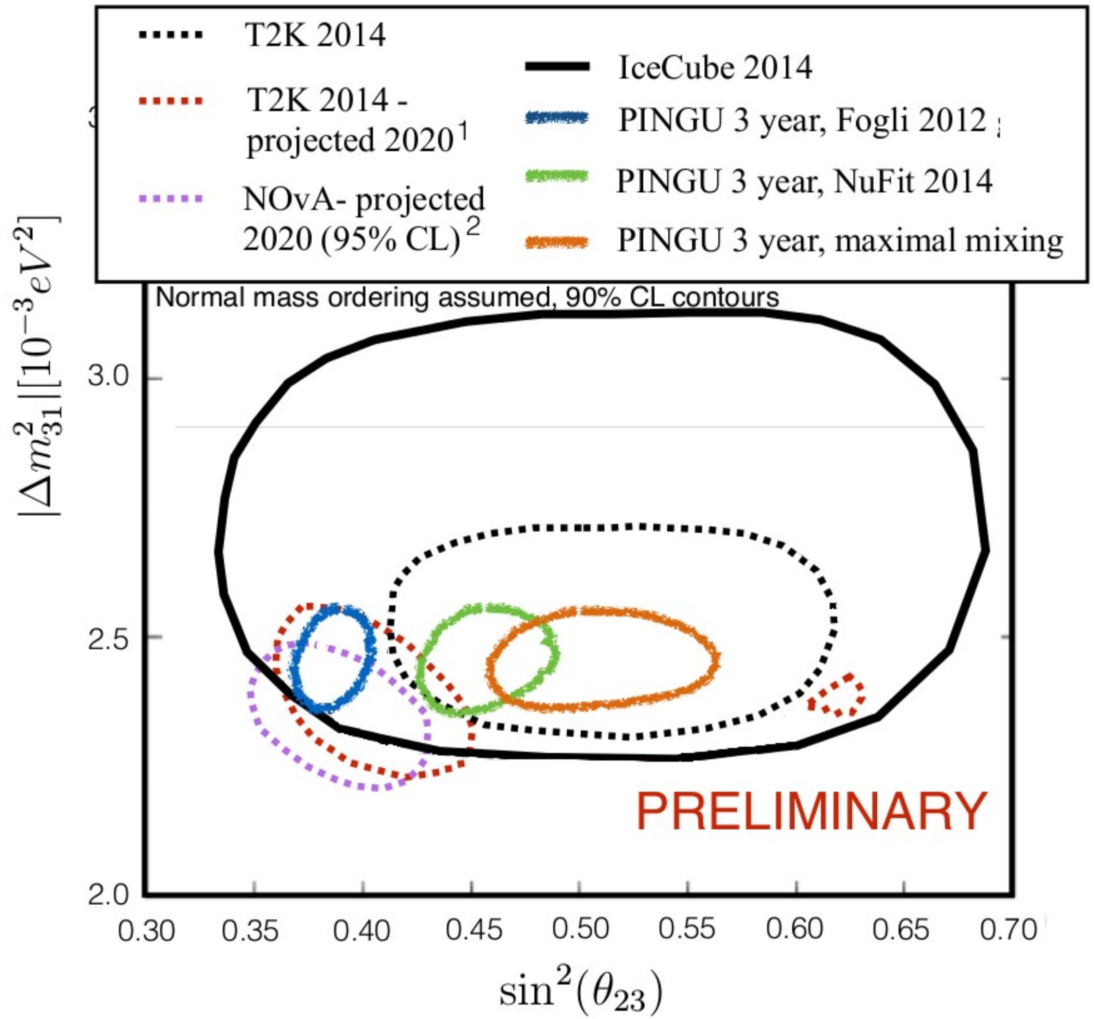
- Mass ordering sensitivity dependence on θ_{23}
  - Lines from $\Delta\chi^2$ based analysis
  - Points from likelihood ratio studies



PINGU – atm. params. sensitivity

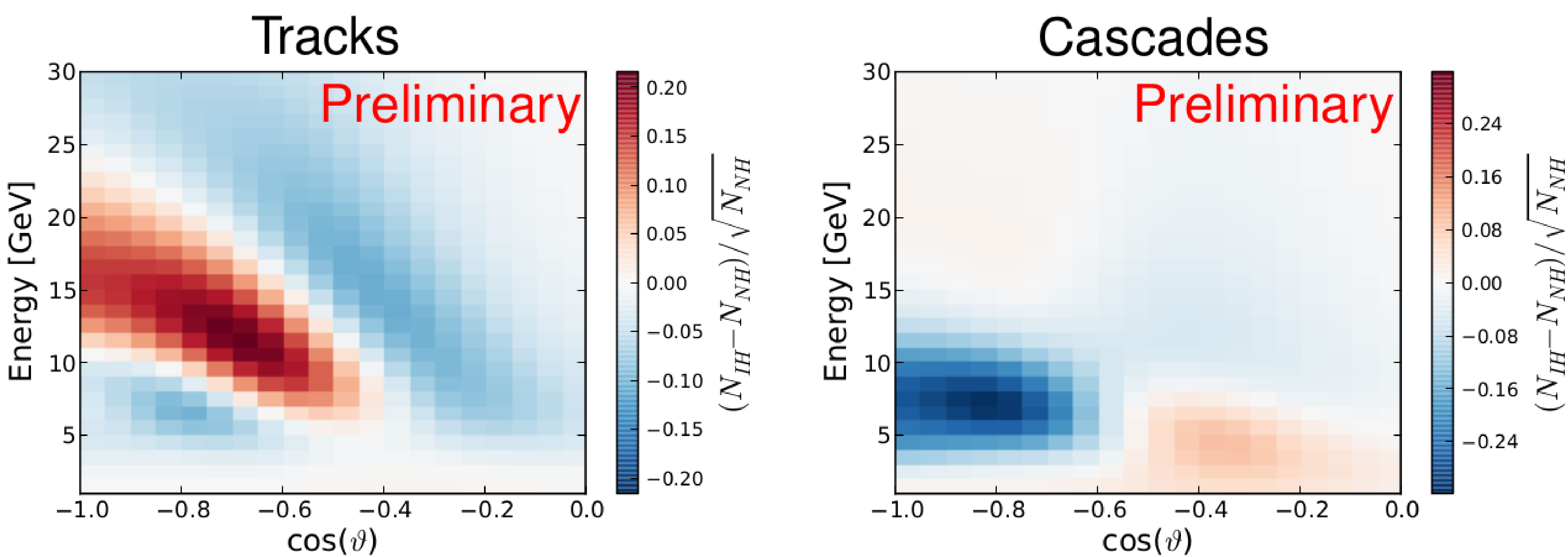
- Competitive sensitivity to oscillation parameters expected
- Appearance of tau neutrinos at 5σ within a month of operation





PINGU – mass ordering signature

- Bin-wise significance for one year of data
- Tracks are mostly muon neutrinos
- Cascades are mostly electron neutrinos



III. Analysis – syst. uncertainties

Being studied in **PINGU simulation/analyses**

- Uncertainties on oscillation parameters included (atmospheric parameters dominant)
  - Using priors from nu-fit.org on solar parameters and θ_{13} (delta-cp fixed at 0)
- Detailed studies of **cross sections (6 parameters)** and **flux uncertainties (18 parameters)**
- The most relevant (non-oscillation) uncertainties are listed

Source of error		Nominal value	Uncertainty
Neutrino interactions and effective area (7+ parameters)	Total cross-section scaling	GENIE model	Free
	DIS cross section (4 parameters)		From models
	Axial mass of non-DIS events (2 parameters)		~ +/-20%*
Atmospheric neutrino flux (18+ parametes)	Overall normalization (Aeff scaling)	Honda 2015	Free
	Spectral index		E^(+/-0.05)
	π & κ production and decays		From models
	Neutrino/Antineutrino ratio		10%
	NuE relative normalization		+/- 3%
Detection	Energy scale	Muons, flashers	+/- 10%

Atmospheric neutrino uncertainties from Phys.Rev.D74:094009,2006

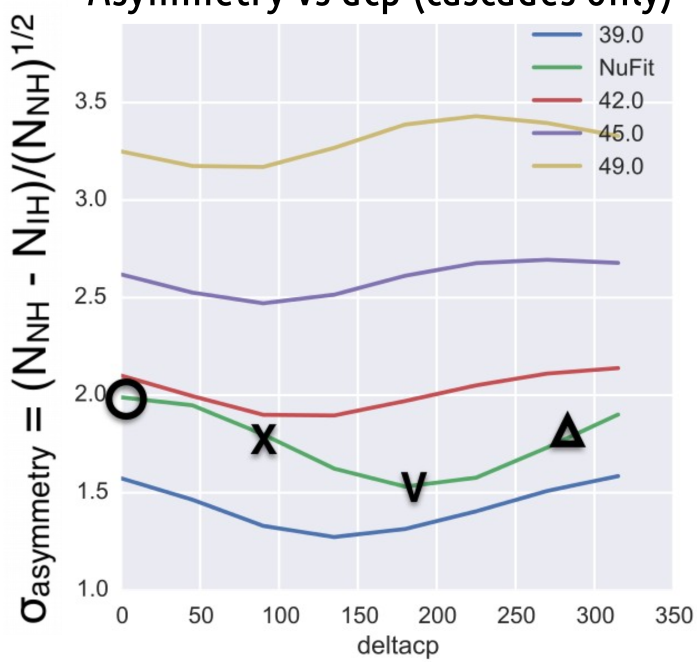
PINGU – sensitivity vs δ_{CP}

- Impact of the imaginary phase on sensitivity
  - Projections shown for the <u>3-year benchmark</u>
  - Sensitivity changes by ½σ depending on true δ_{CP} value

Full LLR analysis

	δ_{cp}(deg)	σ_{NH}	σ_{IH}
○	0	2.80	2.53
X	90	2.49	2.32
V	180	2.32	2.01
△	270	2.40	2.21

Asymmetry vs dcp (cascades only)

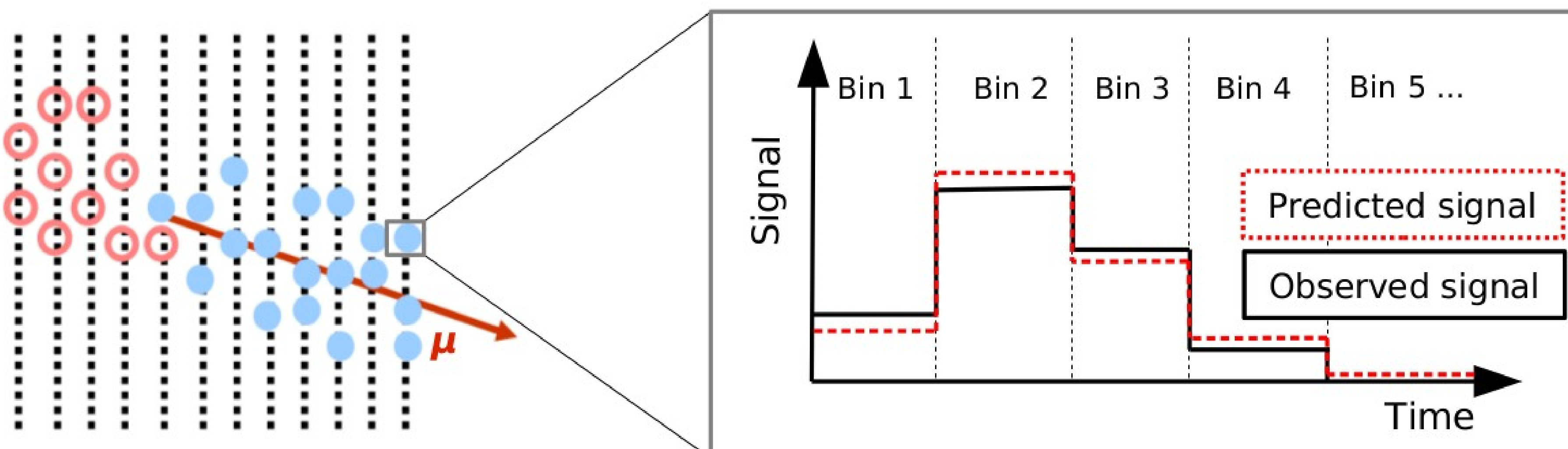


DeepCore improvements

<u>**More sophisticated reconstruction**</u>

- » Use arrival time of individual photons
- » Fit energy + direction simultaneously
- » <u>No need for direct photons, use all events</u>
- » Include ice properties (from ice models)
- » Assume track and cascade are collinear

- » **Similar resolutions in DeepCore**
- » **Higher efficiency (x 3-4)**
- » Working in **DeepCore**, testing vs data
- » Used in **PINGU** analyses

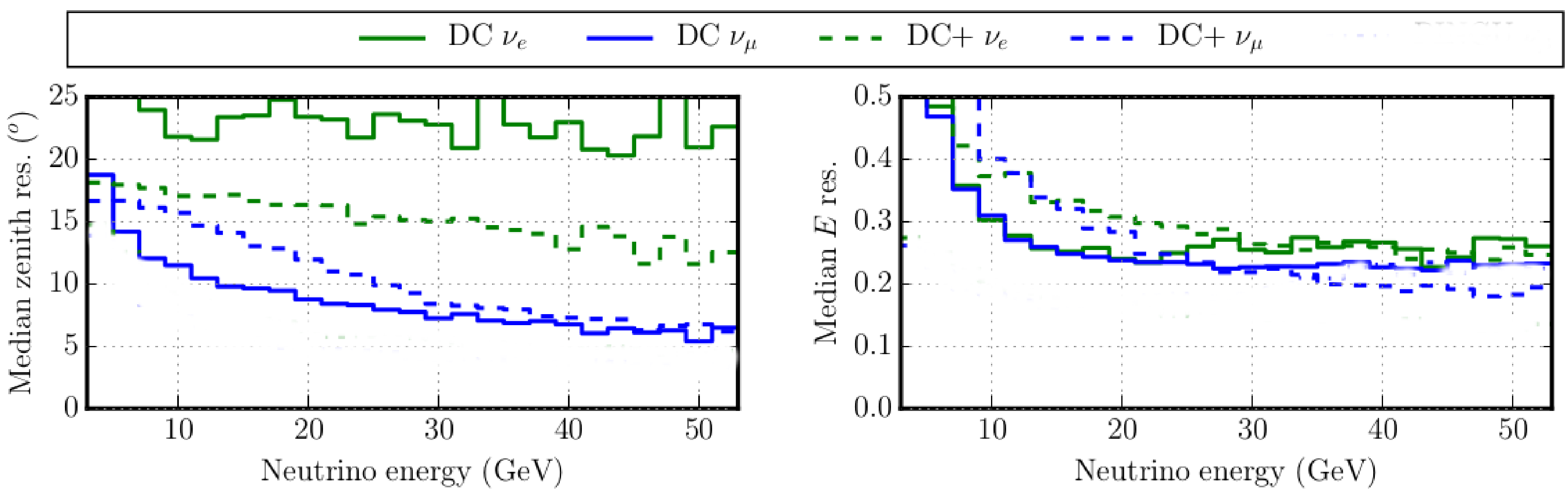


DeepCore improvements

<u>More sophisticated reconstruction</u>

- » Use arrival time of individual photons
- » Fit energy + direction simultaneously
- » <u>No need for direct photons, use all events</u>
- » Include ice properties (from ice models)

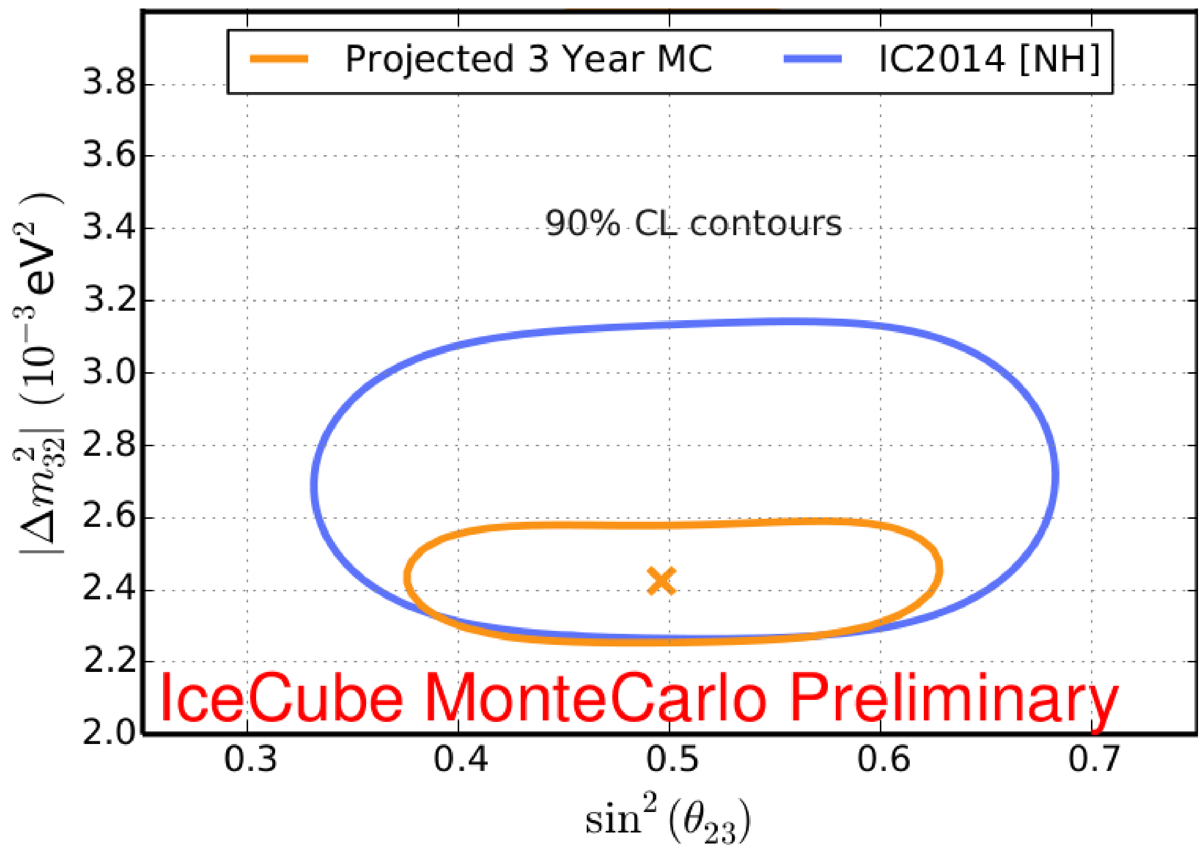
- » **Similar resolutions in DeepCore**
- » **Higher efficiency (x 3-4)**
- » Working in **DeepCore**, testing vs data
- » Used in **PINGU** analyses



DeepCore – projected sensitivity II

Projected MC sensitivity from re-analysis of 3 years of DeepCore data*

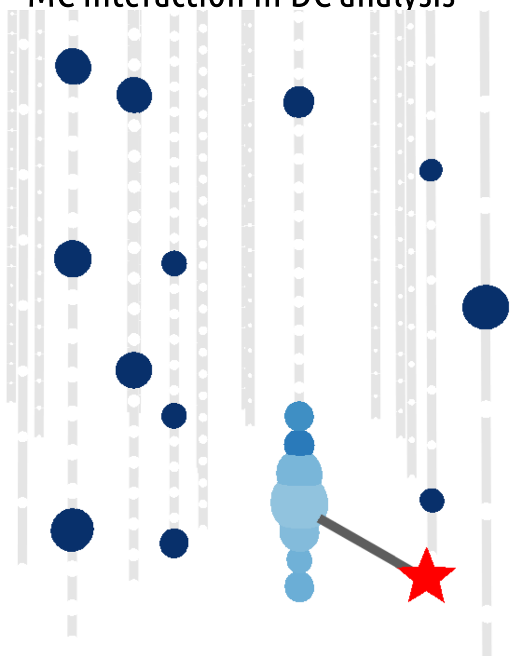
- Classify interactions:
  - Between track- and cascade-like
- Inclusive selection:
  - Direct hits required (5 → 3)
- Sophisticated reconstruction
  - Global fit of all parameters
- Including events from all directions
  - Also down-going (atm. Muons)
- Renewed calibration efforts
  - Noise modeling, angular acceptance, individual DOM behavior

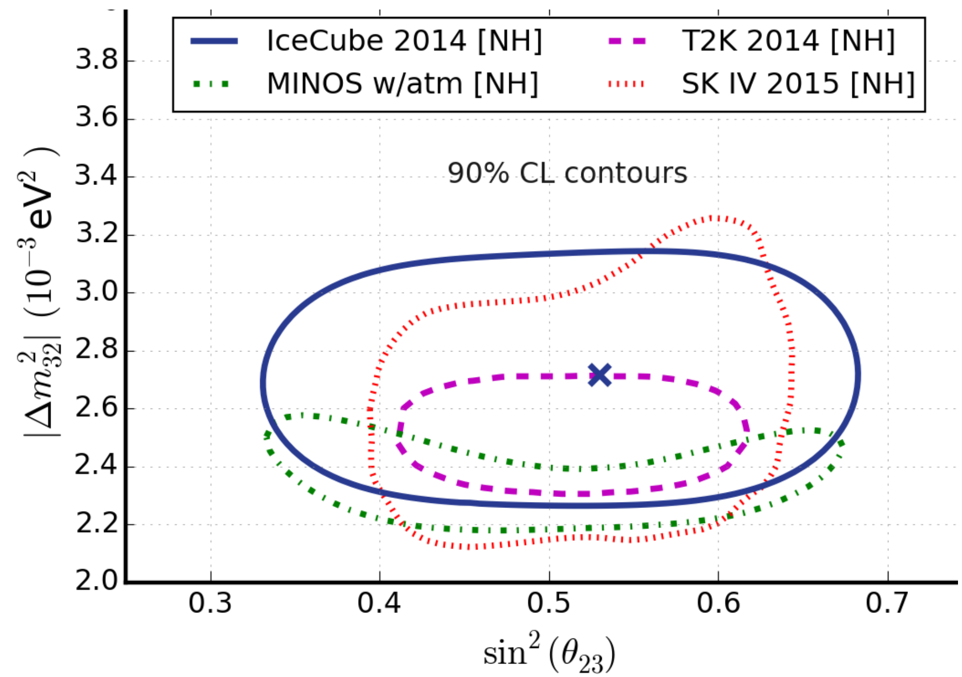


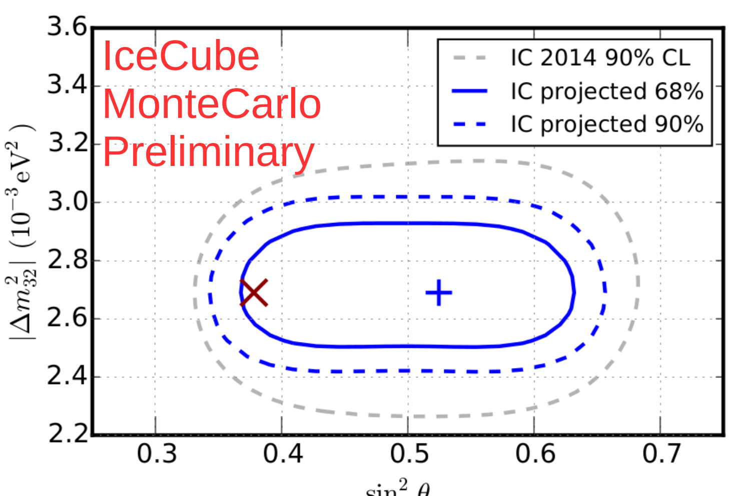
*Projections produced assuming current knowledge. Can change if newer information is available.

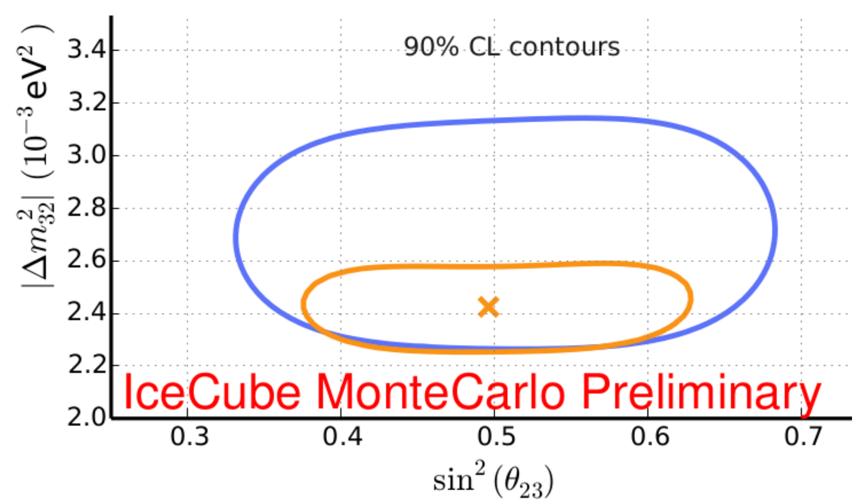
What comes next?

MC interaction in DC analysis

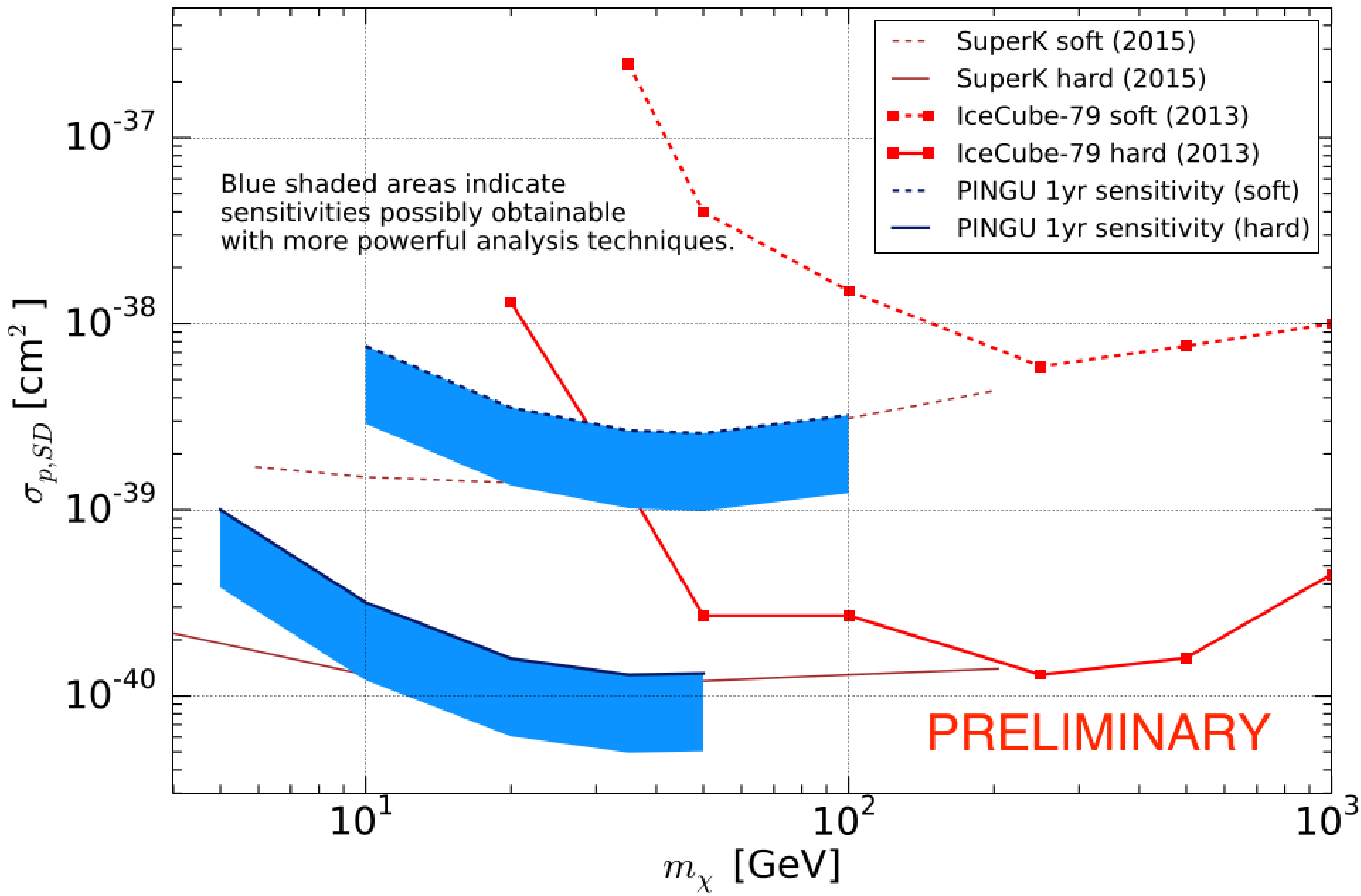




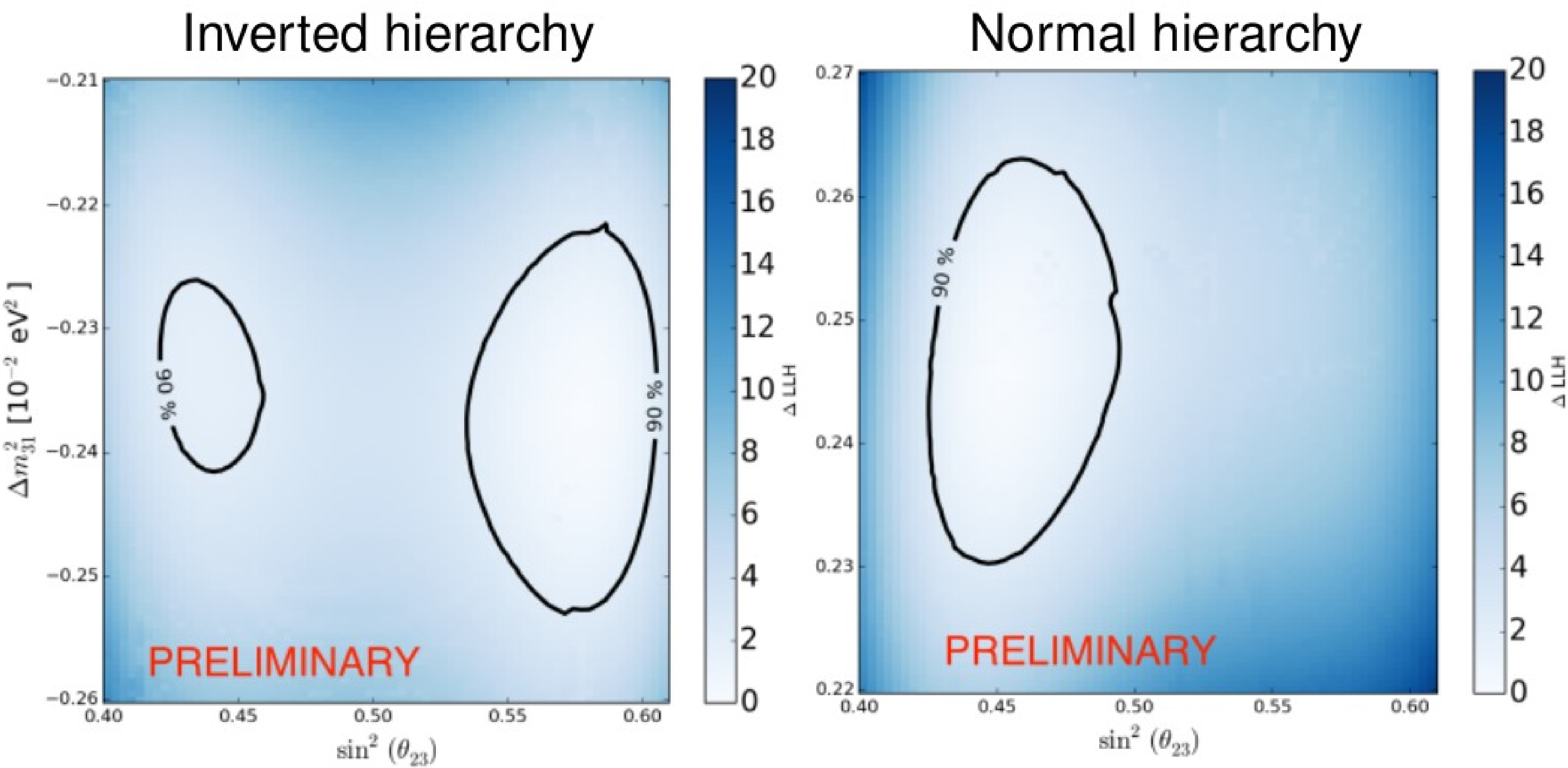




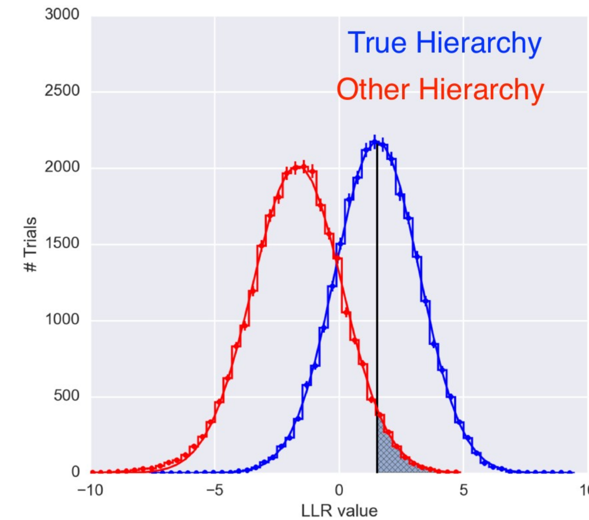
PINGU – Dark matter searches



PINGU - Atmospheric mixing



III. Analysis – methods



» **DeepCore**

Likelihood ratio with high stats. MC

- » Data and full MC sets selected, reconstructed
- » Detector systematics simulated in full → parameterized

» **PINGU**

- » Detector response from MC (created, selected, reconstructed and parameterized)

a) Likelihood ratio

- » Draw and fit pseudo-experiments

Good agreement between methods

b) $\Delta\chi^2$ based analysis

- » Gradients in parameter space to get covariance matrix
- » Angle θ_{23} covariance matrix calculated directly (no gradients)
- » Fast, well suited for optimization