Testing the Neutrino Mass Ordering with Multiple Years of IceCube/DeepCore

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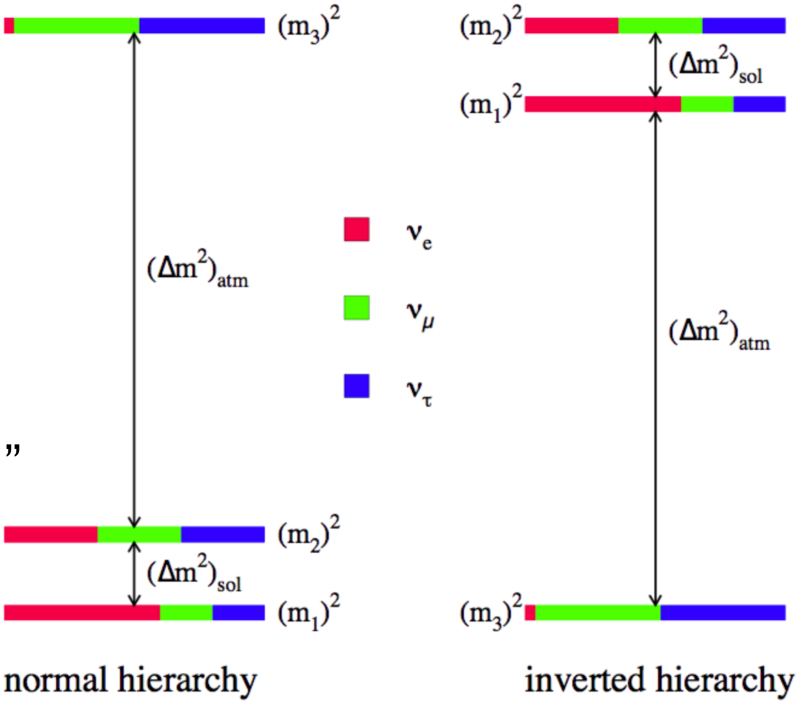
- IPA, May 2017 -

Neutrino Mass Ordering …

… what is it about and why should I care?

What is Neutrino Mass Ordering?

- Neutrinos are massive particles
- Masses are fundamental, unknown constants in SM
- NMO describes the ordering of these masses
- Only two possibilities remain: "Normal" or "Inverted"



(from: arXiv:1205.2671)

… and why should I care about it?

- Neutrino masses still not understood in SM (Nobel prize 2015)
- Ordering has impact on many fields of physics (cosmology, double-beta decay, absolute masses, CP violation…)
  - *W. Winter, Lake Louise Winter Institute, Feb. 2017*
- Many experiments (e.g. IceCube extension PINGU) aiming to measure NMO within next 5-10 years

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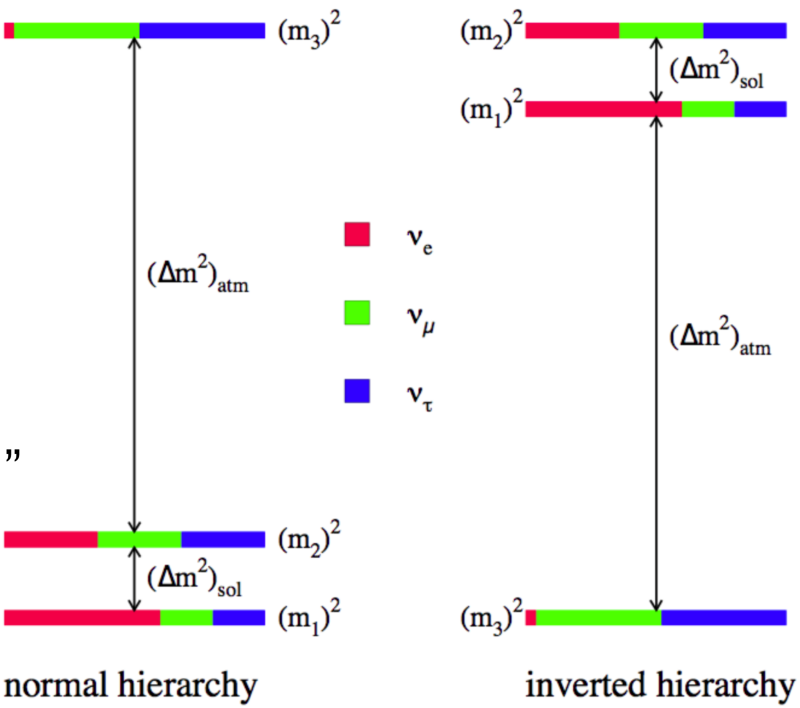

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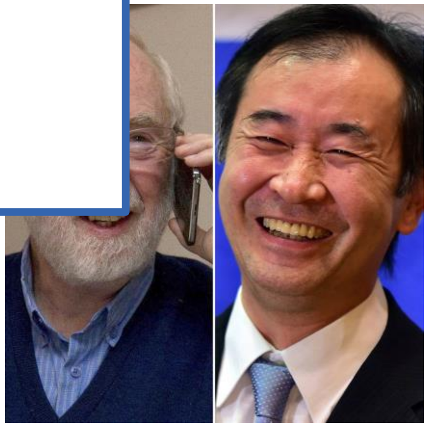
… and why should I care about it?

- Neutrin
- Orderir
(cosmo

Where can we get such neutrinos from to probe the NMO?

➤ *W. Winter, Lake Louise Winter Institute, Feb. 2017*

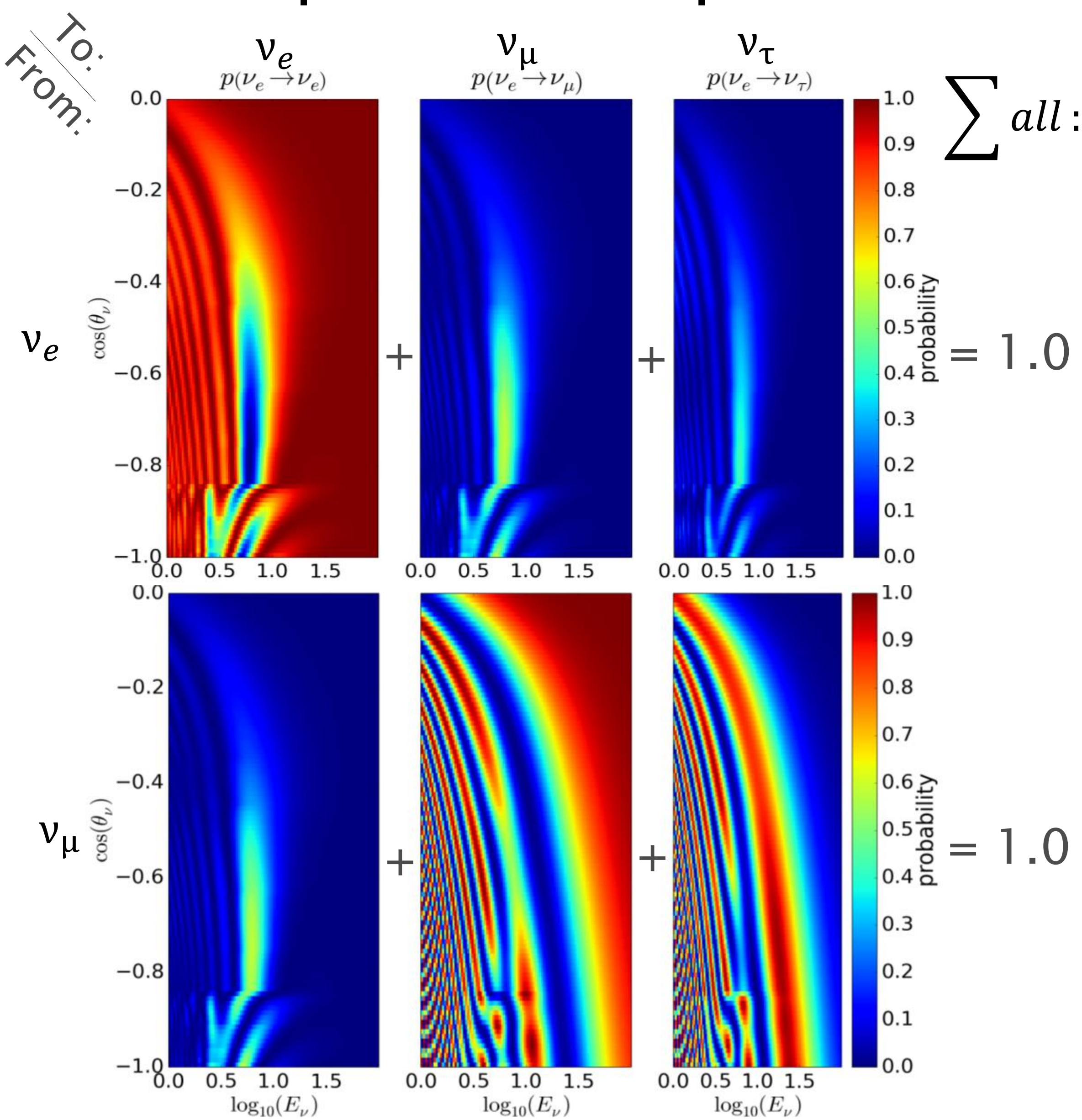
- Many experiments (e.g. IceCube extension PINGU) aiming to measure NMO within next 5-10 years

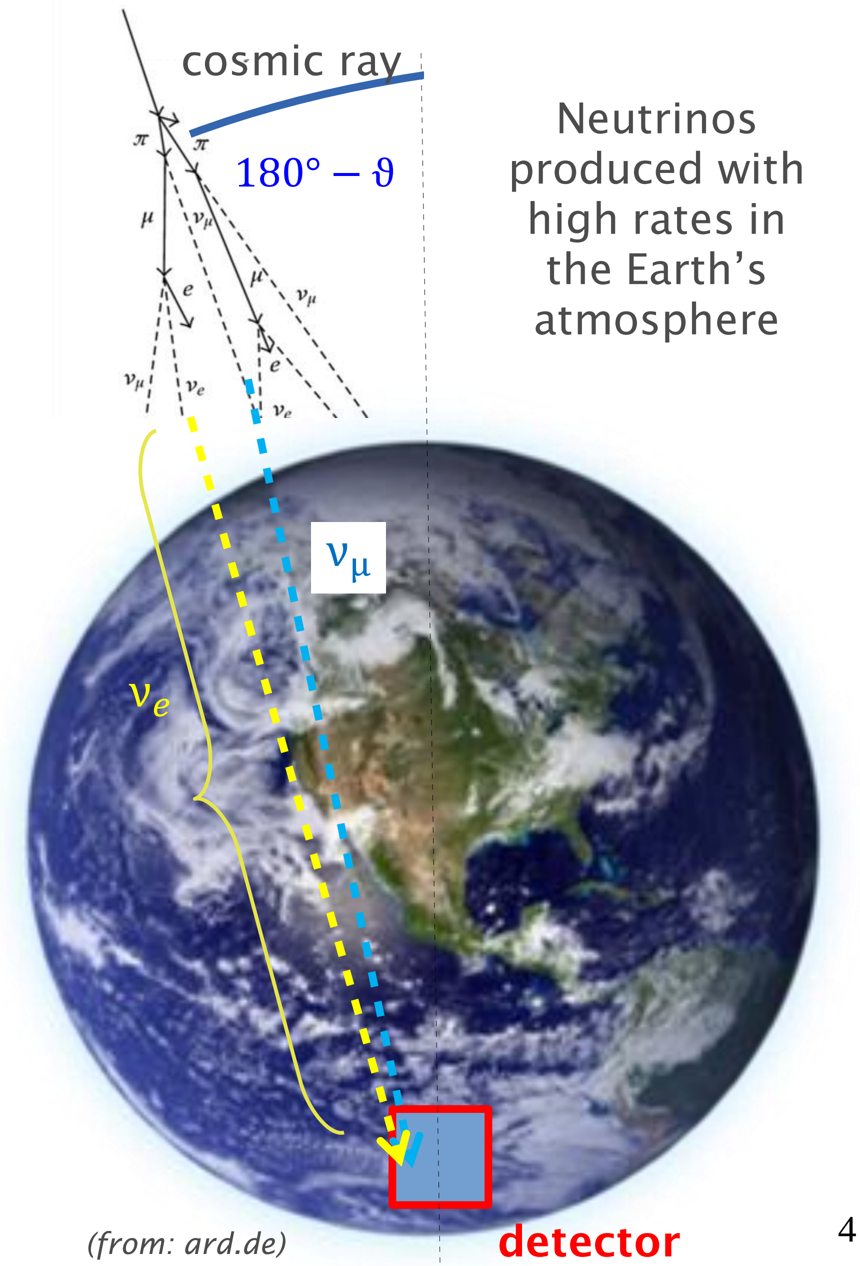


Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

Oscillation pattern for atmospheric neutrinos:





Neutrinos produced with high rates in the Earth's atmosphere

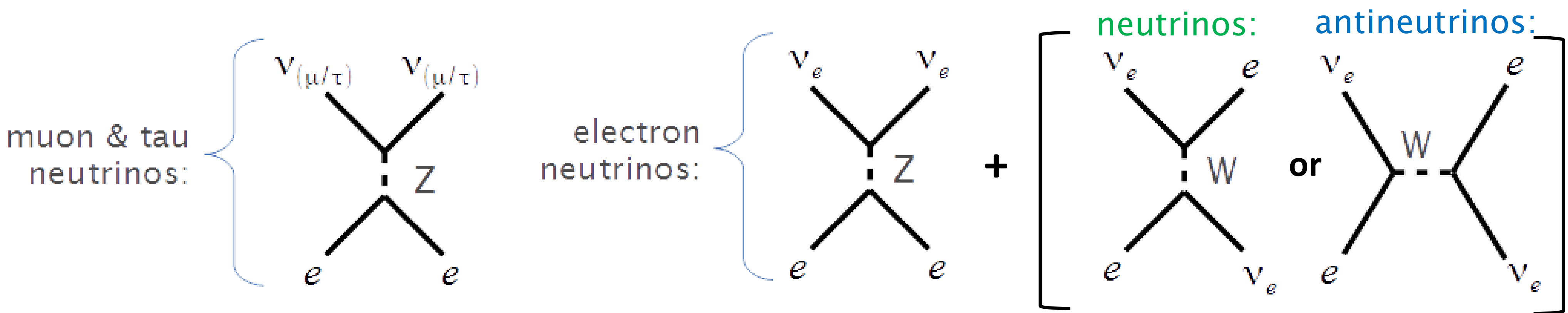
Matter Effects …

… as probe for the NMO

What does the ordering really change?

Two matter effects during propagation through Earth:

- Interactions with electrons in the Earth (**MSW-Effekt**):



$$\sin(2\theta_M) = \frac{\sin(2\theta)}{\xi}$$

$$\Delta m_M^2 = \Delta m_{\text{atm}}^2 \cdot \xi$$

with:

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

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

+: neutrino
-: antineutrino

neutrino energy

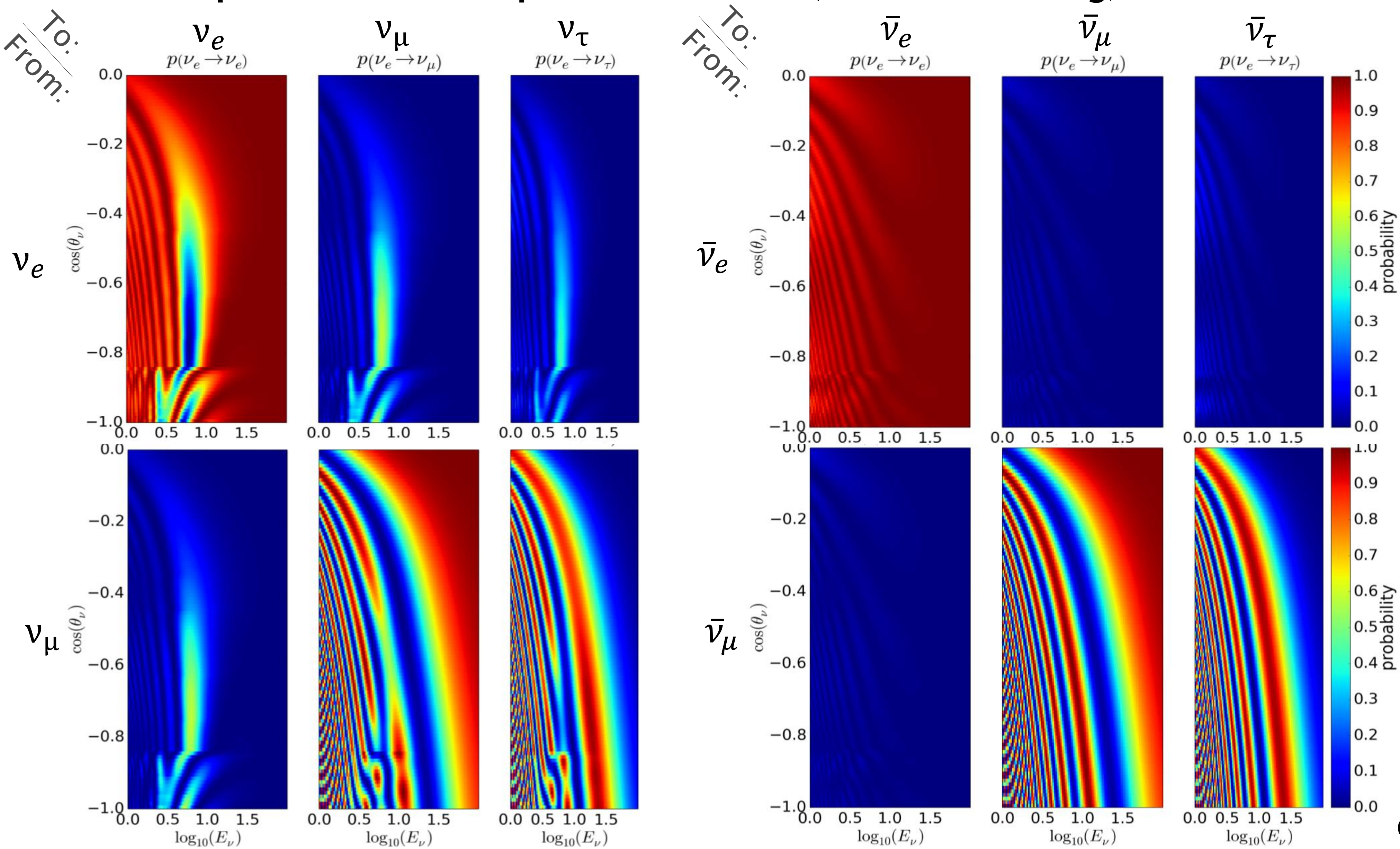
electron density

- **Parametric enhancement** due to non-homogeneous matter distribution:
  - Earth's core and mantle differ in matter density by a factor of ~2
  - Resonance occurring from periodicity of matter profile

Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

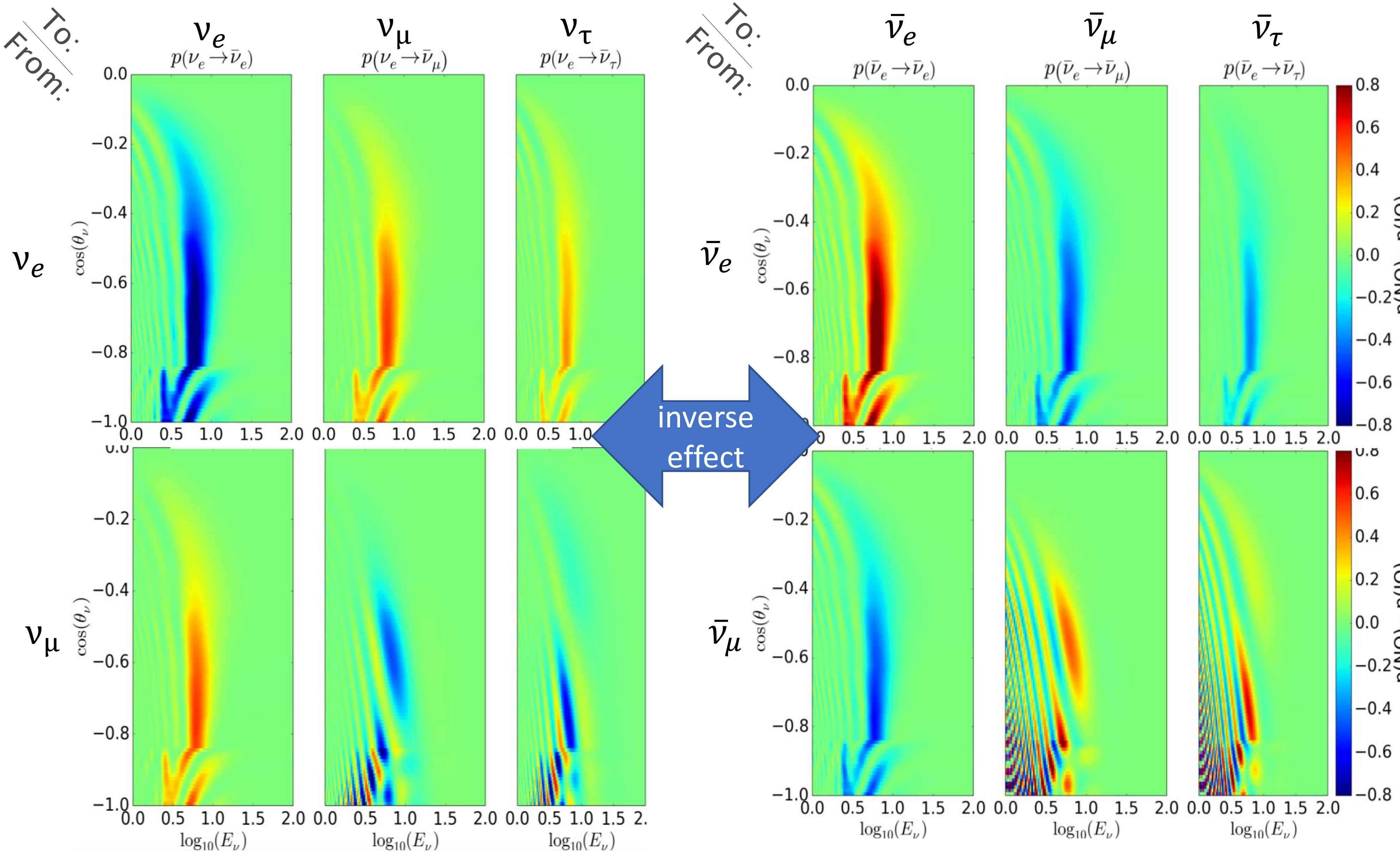
Oscillation pattern for atmospheric neutrinos (Normal Ordering):



Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

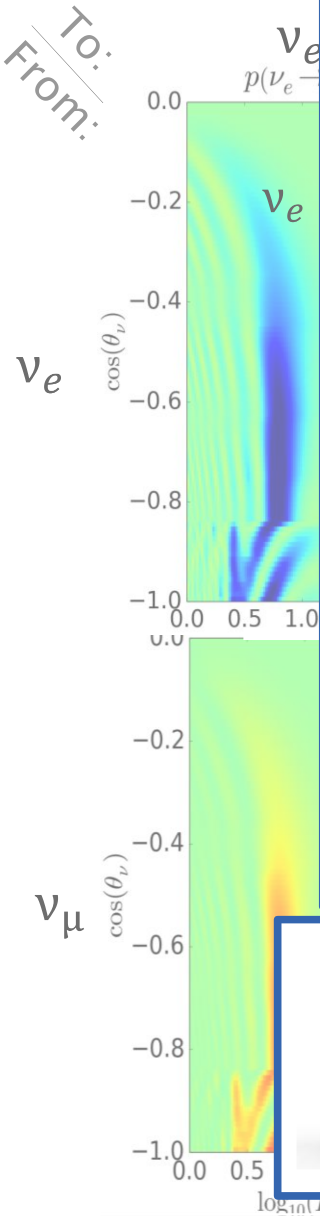
Differences between NO and IO for (anti-)neutrinos:

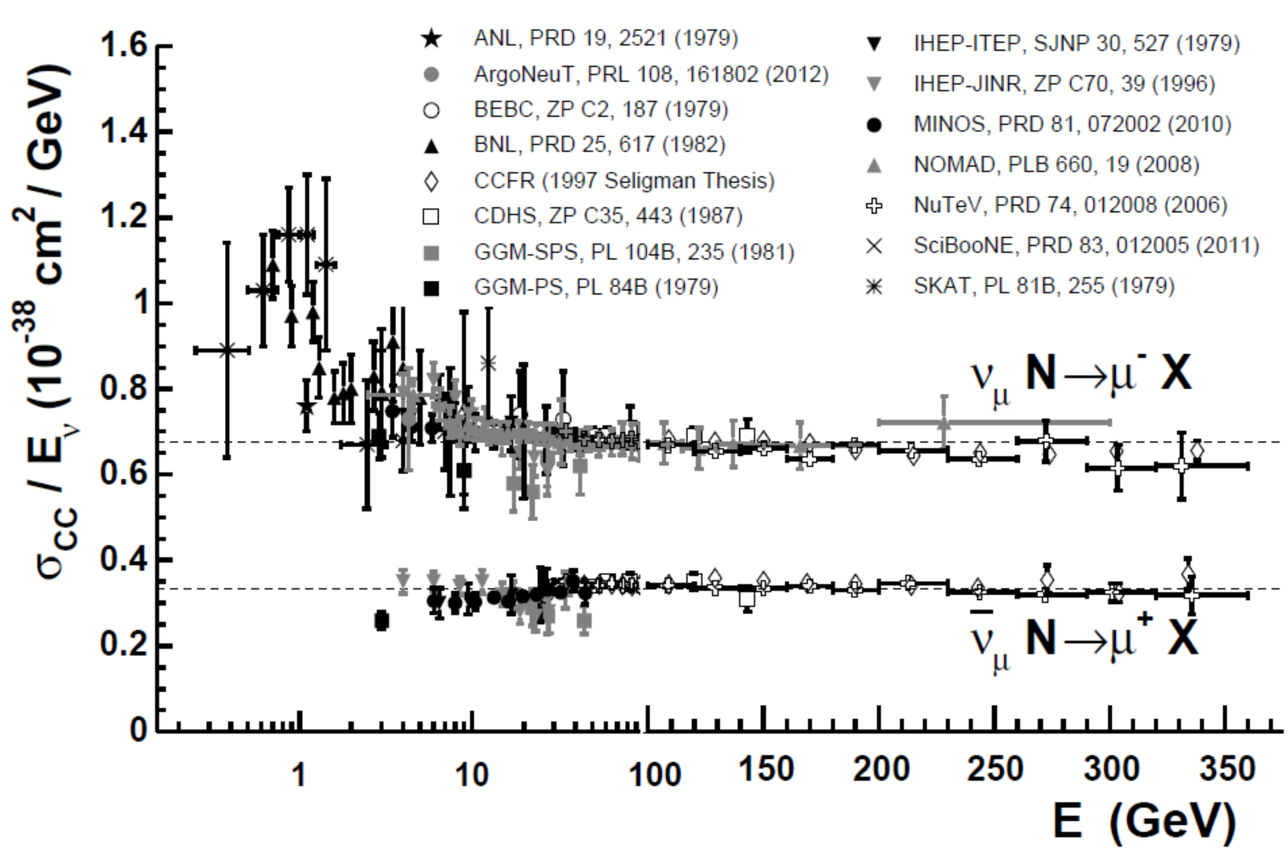


Atmospheric Neutrinos…

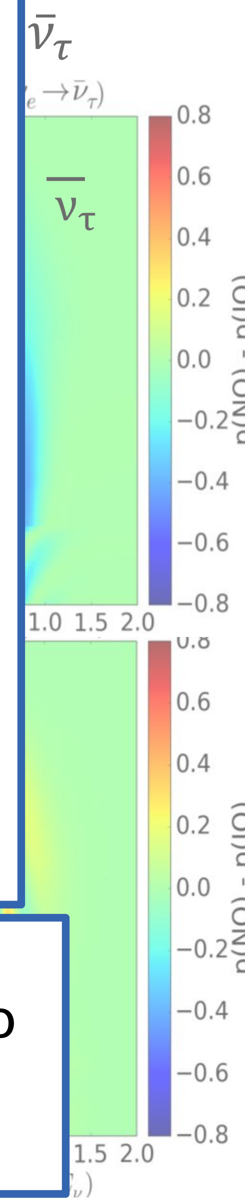
… as a source for neutrino oscillation measurements

Differences



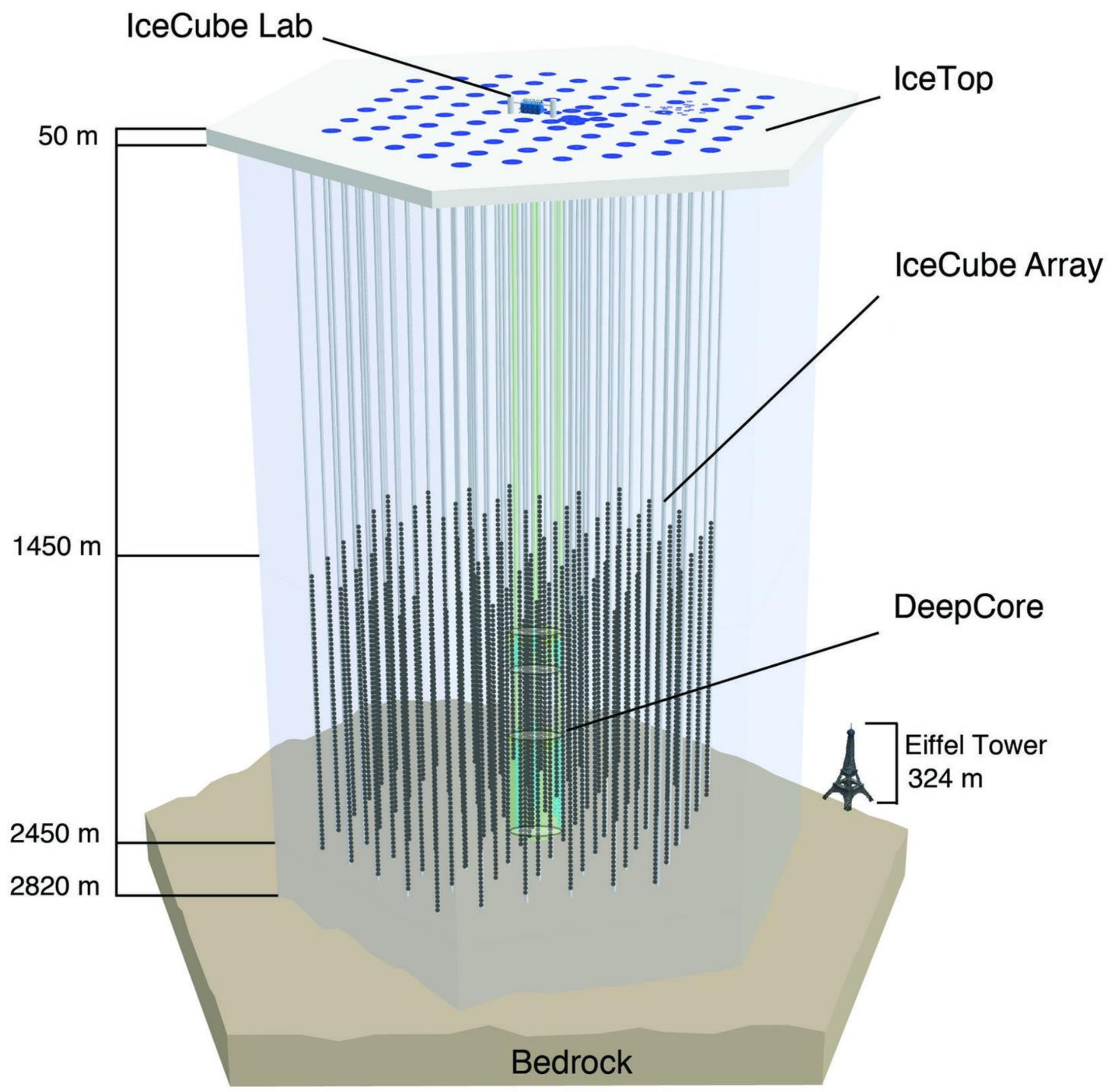


(from: : J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).)



Does that mean, the effect is invisible, if neutrino and anti-neutrino are not distinguishable?

The IceCube Neutrino Observatory…
… construction and setting of the experiment



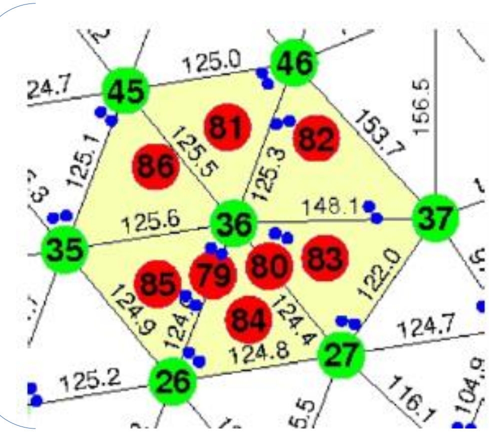
The IceCube Detector

- At Geographic South Pole
- Construction completed in 2010
- $\sim 1\ km^3$ size neutrino detector
- $1.5 - 2.5\ km$ depth
- 5160 DOMs at 86 strings
- Sees $E_\nu > 100\ GeV$

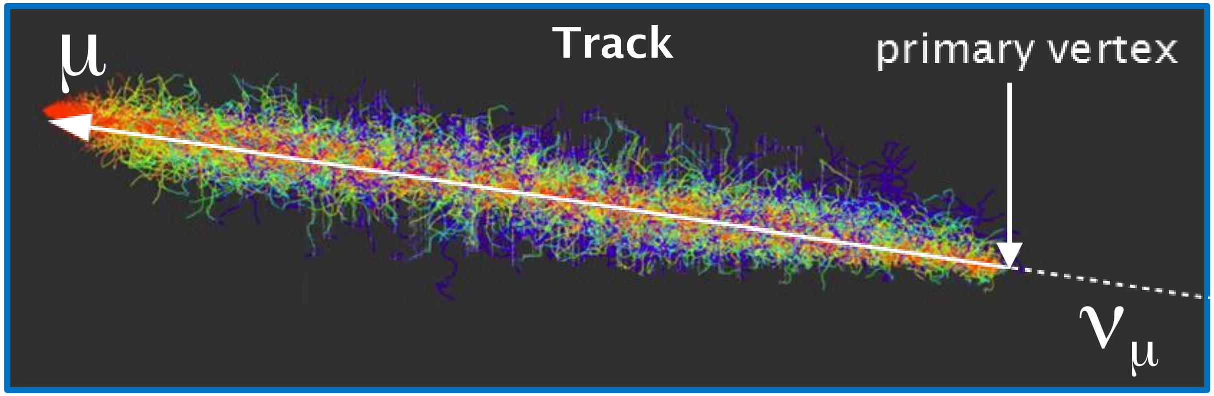
The DeepCore Extension

- 8 additional strings
- 460 high-QE DOMs (+35%)
- Sees $E_\nu > 5\ GeV$

DeepCore, on-top view / string locations

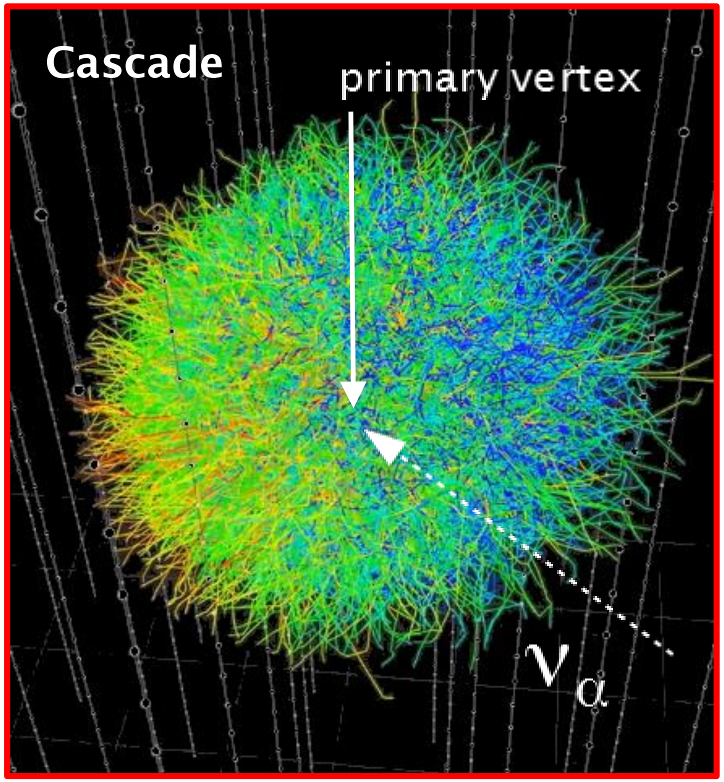


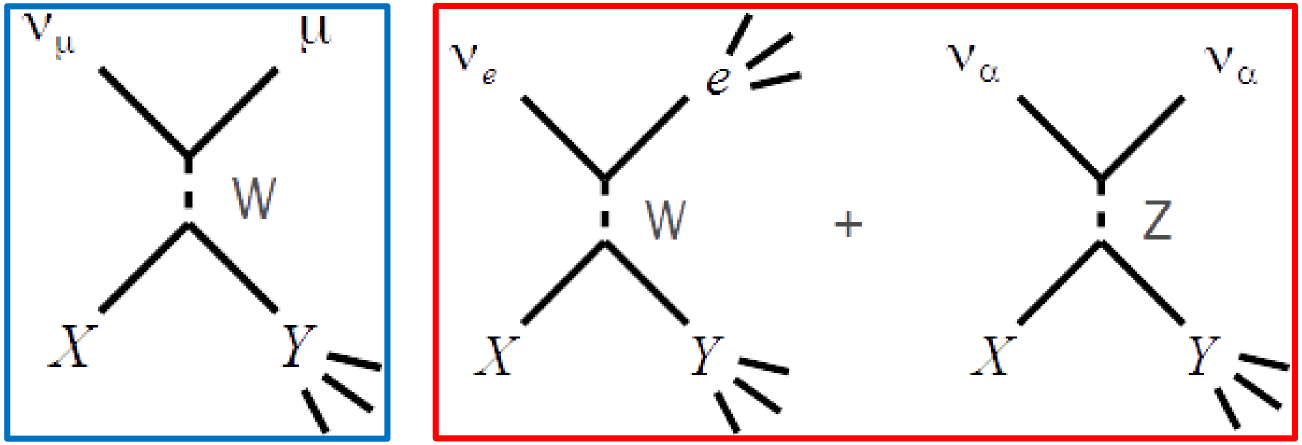
Flavor Separation in IceCube…
… using event topologies



Two Event Topologies:

- Tracks and Cascades
- Physics behind tracks:
  - CC muon neutrinos
  - Atmospheric muons
- Physics behind Cascades:
  - CC electron /tau neutrinos
  - NC interactions
- Left: Cherenkov Photon propagation
- Easy to separate at >100GeV





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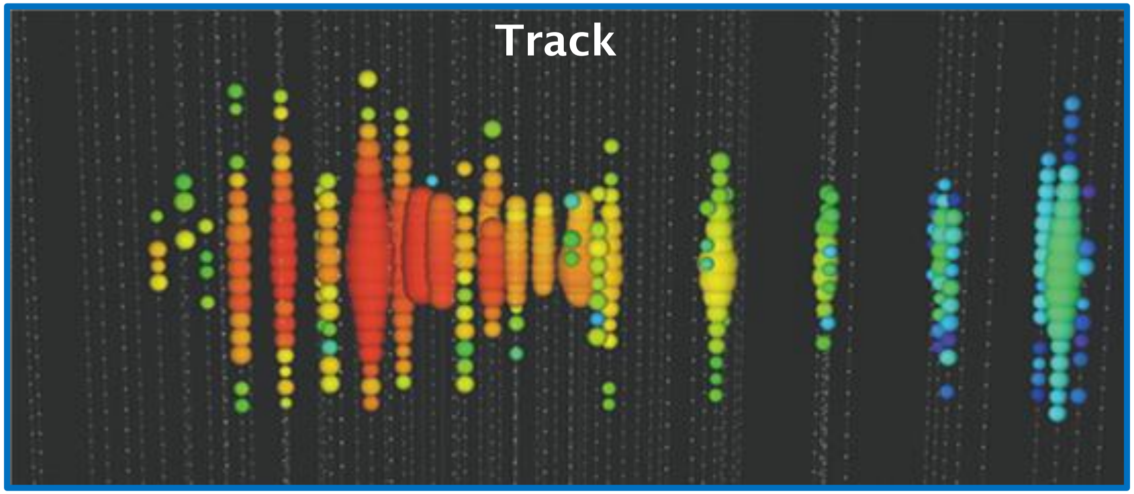

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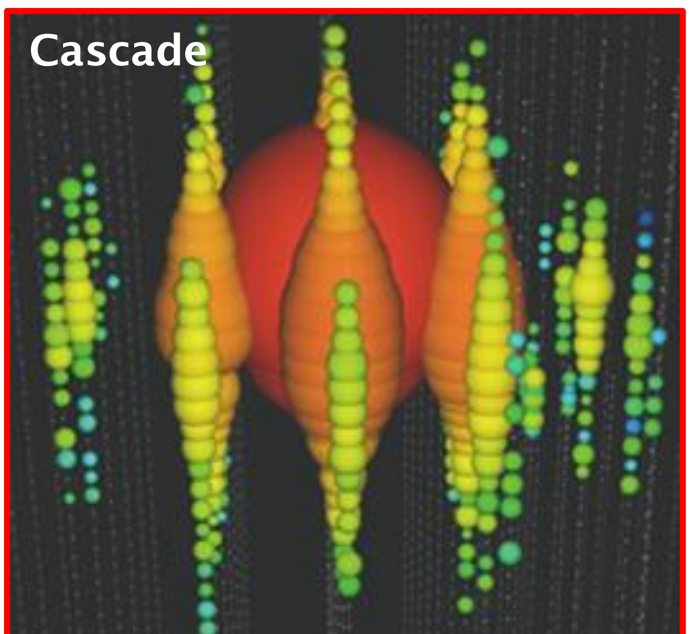

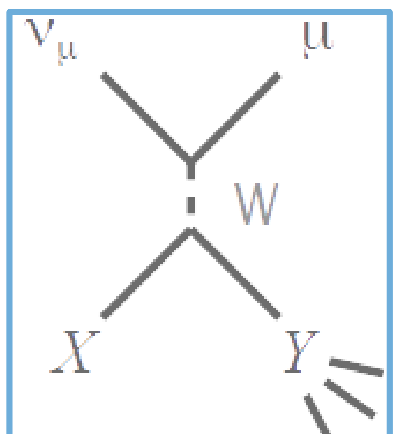

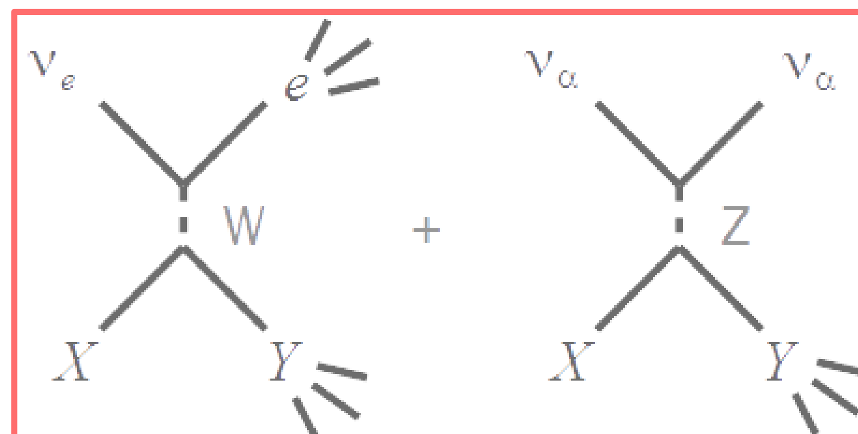

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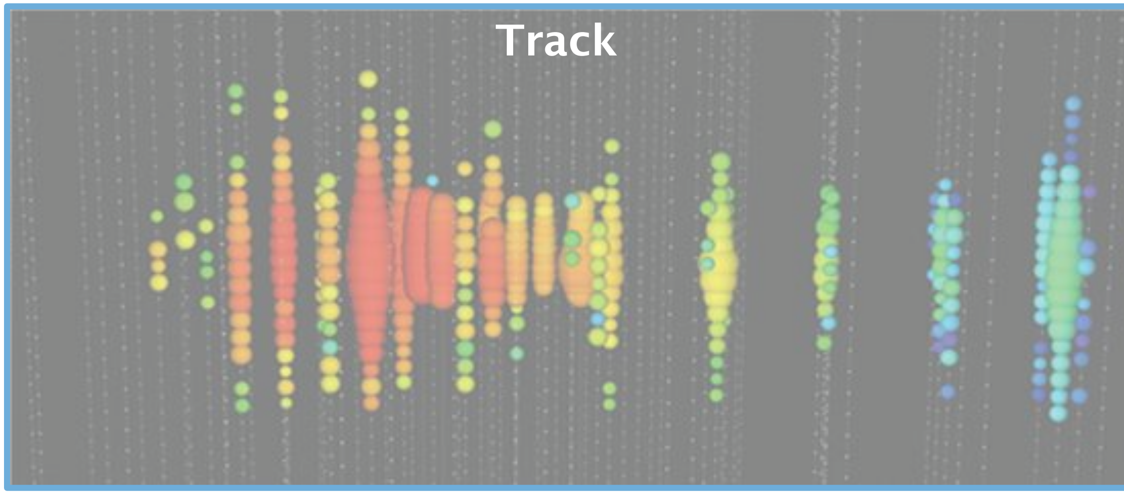
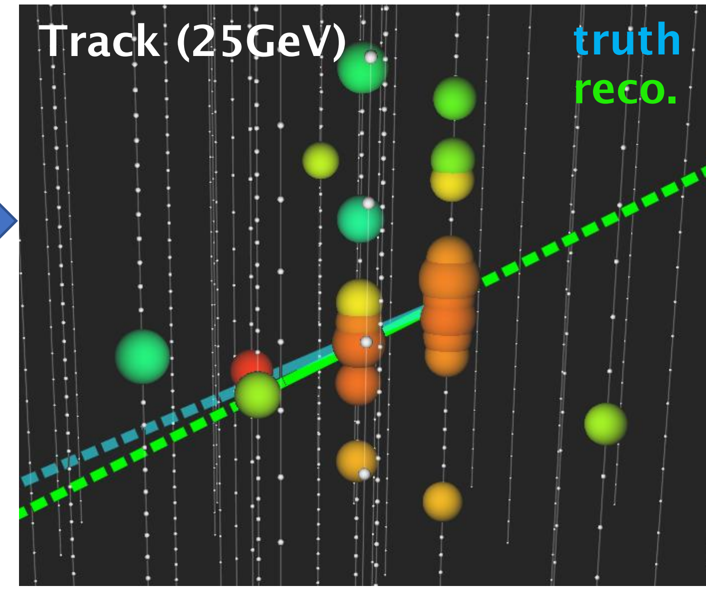
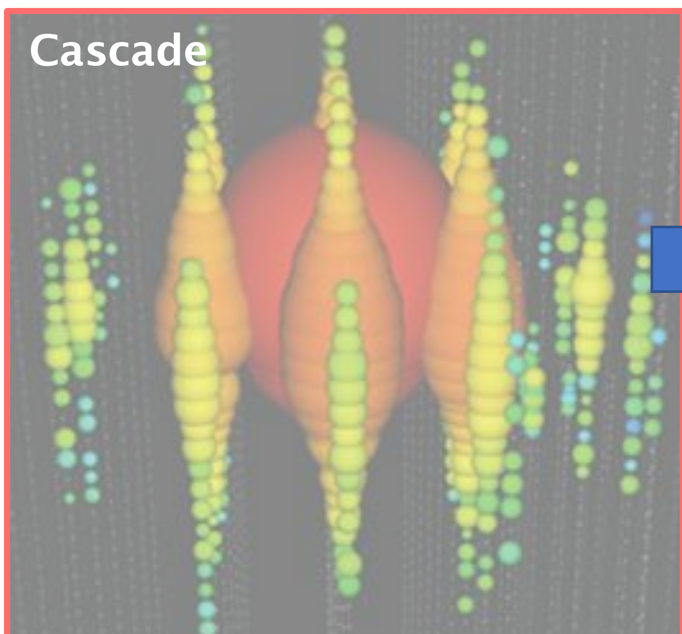
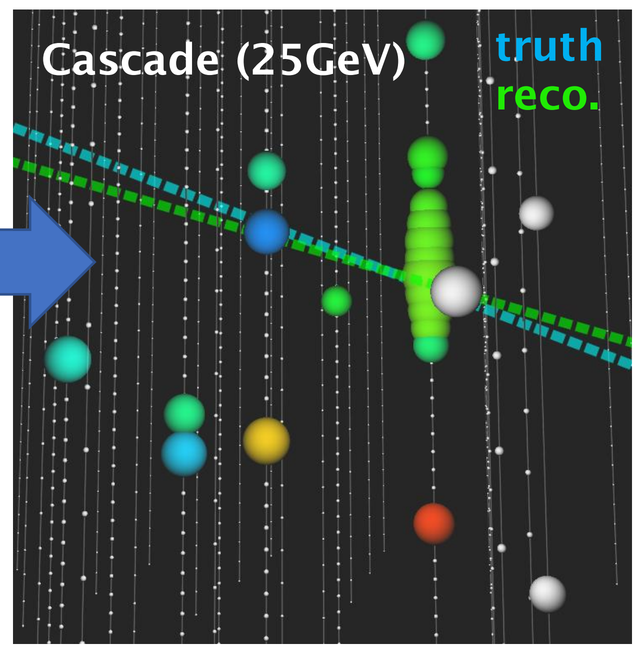








Separation at low energies:

- Only very little energy deposited in detector
- Weak separation power
- Separation of tracks and cascades statistical process
- Separation done using likelihood method testing track and cascade hypo.

Idea of Mass Ordering Measurement…

… with the IceCube/DeepCore detector

So, what do we need to measure for NMO?

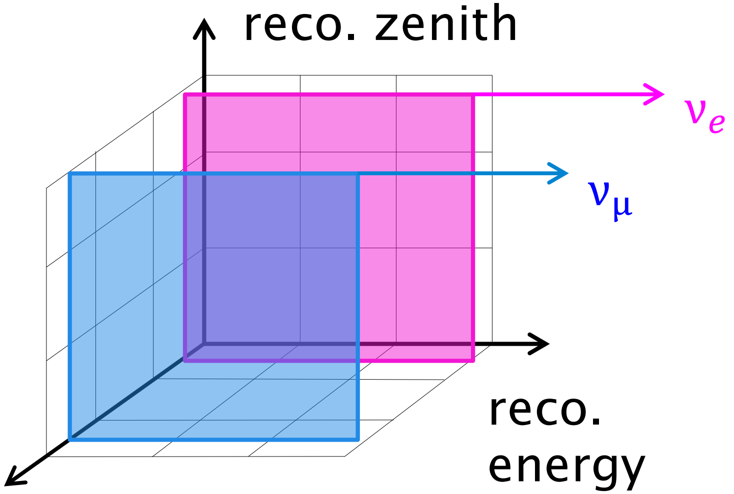
1) Neutrino Energy

2) Direction (zenith angle)

3) Flavor separator (PID)

need to reconstruct these 3 quantities at extreme low energies (<10GeV)

(challenging energy regime for data selection and reconstruction)



Analysis Method: 3D LLH Analysis

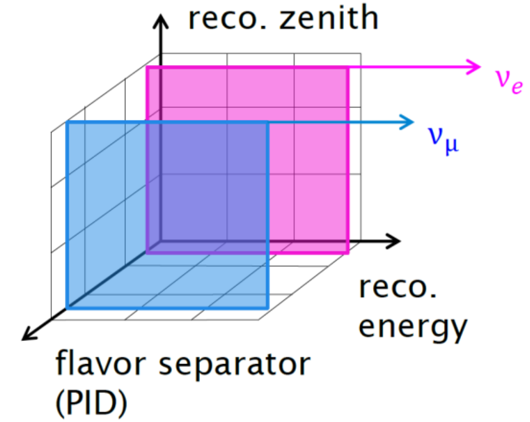
- Separate flavors within fitted diagram
- Fit oscillations for all flavors simultaneously
- Multiple years, high statistics, low-E sample
- Optimize Likelihood function:

$$LLH = -\sum_{i=1}^{N_{bins}} \log\left(p\left(obs_i \mid pred_i(\theta_{jk}, \Delta m_l^2, \boldsymbol{NMO}, \{p_k\})\right)\right)$$

Idea of Mass Ordering Measurement…
… with the IceCube/DeepCore detector

How do we do this analysis?

Perform 2 parallel analyses on IceCube/DeepCore …



Analysis A
(similar to std. oscillations)

- 3 years of IceCube/DeepCore data
- Event-containment and quality cuts
- Focuses on:
  - energy range 5-80GeV
  - upgoing events only
  - 2 PID bins (tracks and cascades)
  - coarse binning
- Expect ~9k events per year

Analysis B
(high statistics, low energy tuned)

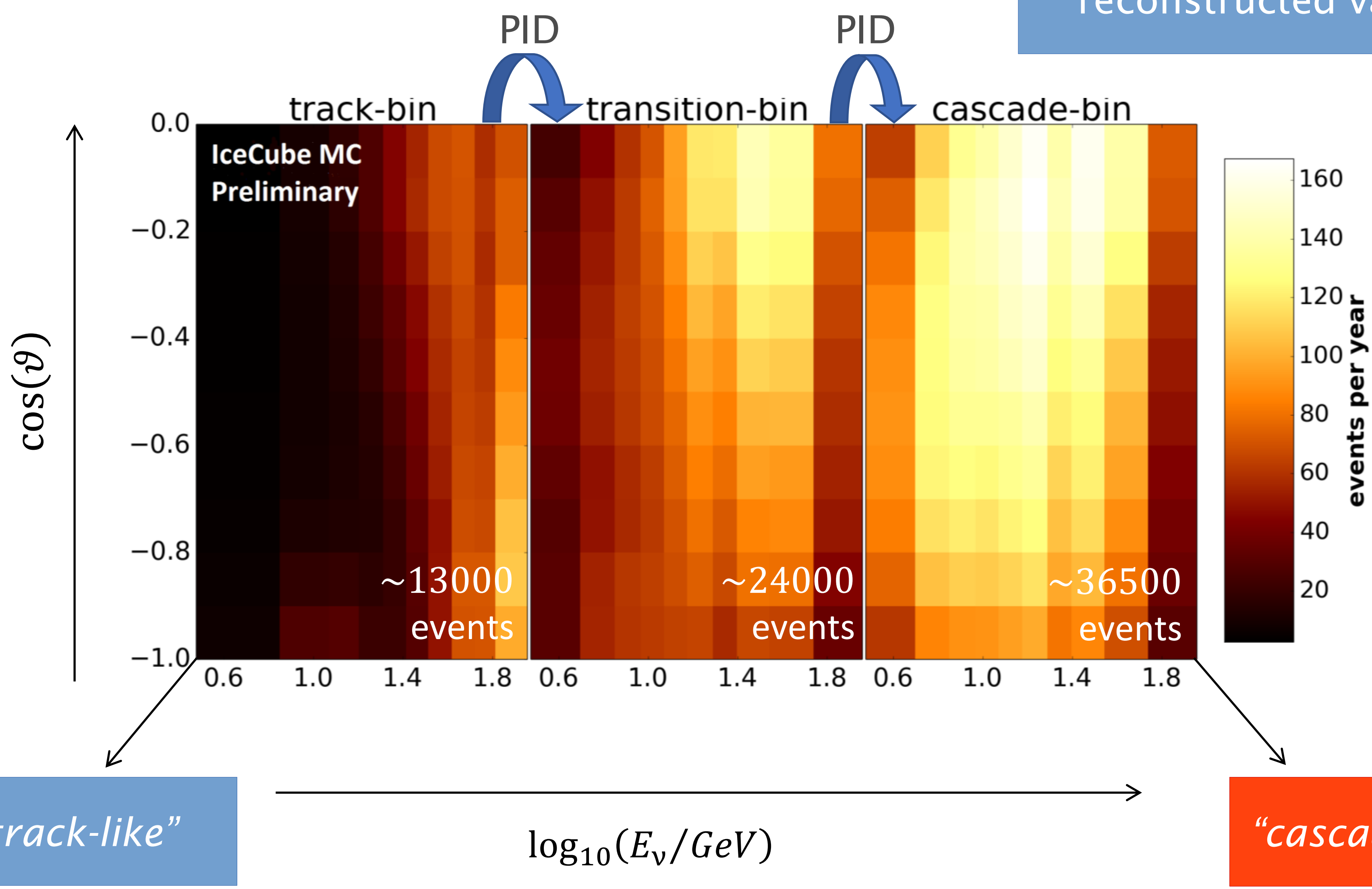
- 4 years of IceCube/DeepCore data
- Aiming to maximize statistics
- Focuses on:
  - energy range 4-90GeV
  - upgoing events only
  - 3 PID bins (+transition bin)
  - small, non-linear binning
- Expect ~22k events per year
- Focus on this in this talk!

Reconstructed Observables …

… inserting the NMO Likelihood

What do these 3D histograms look like?

shown for Analysis B in reconstructed variables



Reconstructed Observables …
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What do these 3D histograms look like?

shown for Analysis B in reconstructed variables

PID PID

$\cos(\vartheta)$

Signal:
- CC muon neutrinos (~55%)
- CC electron neutrinos (~20%)
- CC tau neutrinos (~5%)

Background:
- NC neutrinos (all flavors) (~10%)
- Atmospheric muons (~10%)
- Triggered detector noise (~0.1%)

Also, all components differ in (ϑ_ν, E_ν)–region they are showing up in.

0.6 1.0 1.4 1.8 0.6 1.0 1.4 1.8 0.6 1.0 1.4 1.8

"track-like"

$\log_{10}(E_\nu/GeV)$

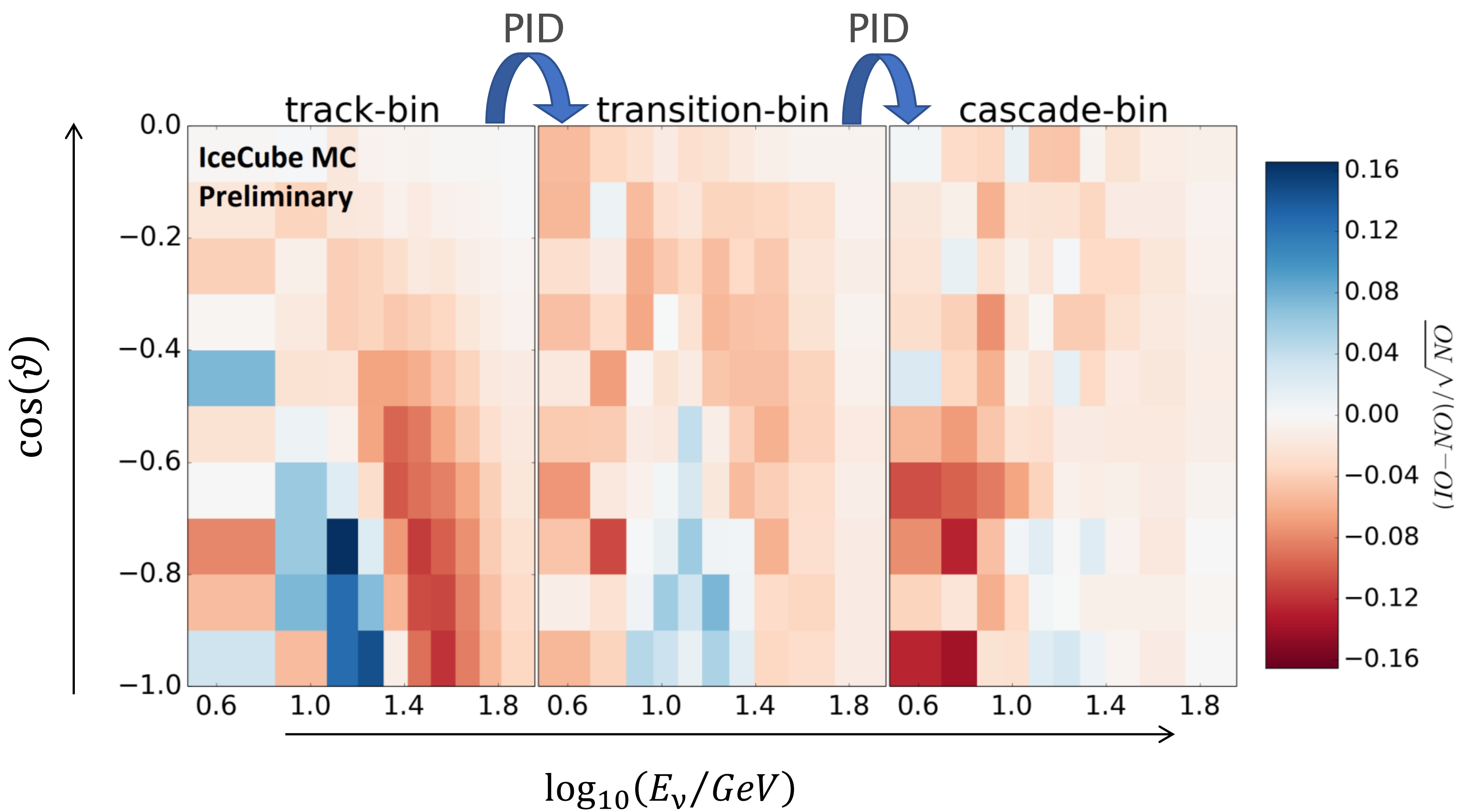
"cascade-like"

Reconstructed Observables …

… inserting the NMO Likelihood

What is the signature we expect in these 3D histograms?

shown for Analysis B in reconstructed variables



Reconstructed Observables …

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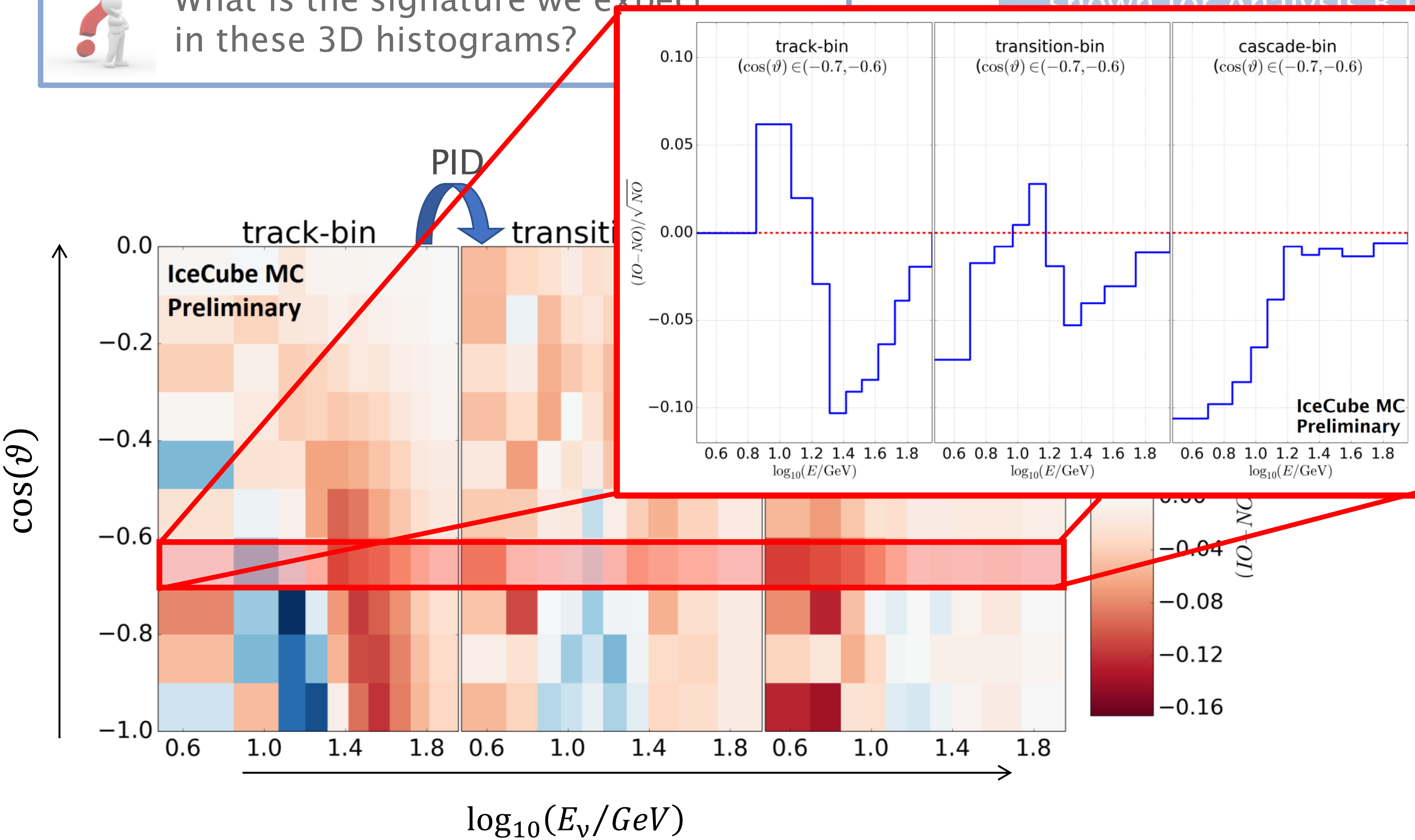
What is the signature we expect in these 3D histograms?

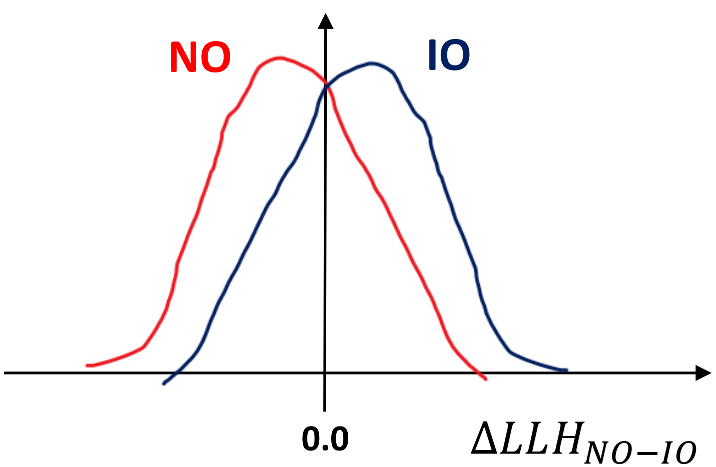
shown for Analysis B in … s

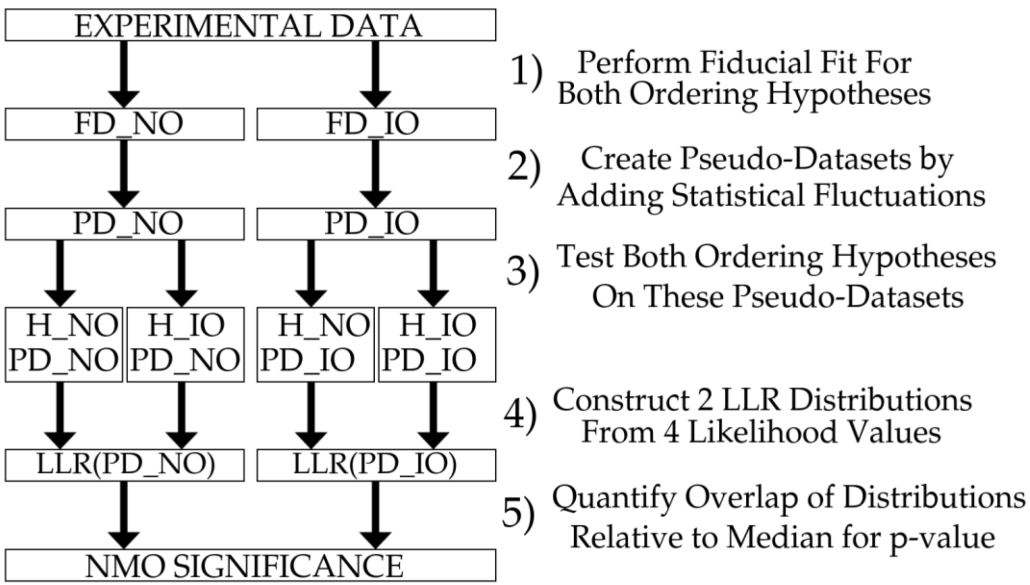


Performance Estimation

… calculation of sensitivity and significance

Final experimental result – estimate significance from pseudo experiments:





Fast estimation of sensitivity based on NMO-specific χ^2 -method:

- Method proposed by: DOI: 10.1007/JHEP01(2014)095
- Uses $\chi^2 \approx \Delta\mathrm{LLH}$ between several hypothesis:
  - Inject true hypothesis → fit NO and IO
  - Inject wrong hypothesis → fit NO and IO
- Results in estimate from 4 LLH values
- for each ordering for each estimate of sensitivity

$$\Sigma_{NH}[\sigma] = \frac{2 \cdot (\Delta LLH_{NH} - \Delta LLH_{NRH})}{2 \cdot \sqrt{2 \cdot \Delta LLH_{NRH}}}$$

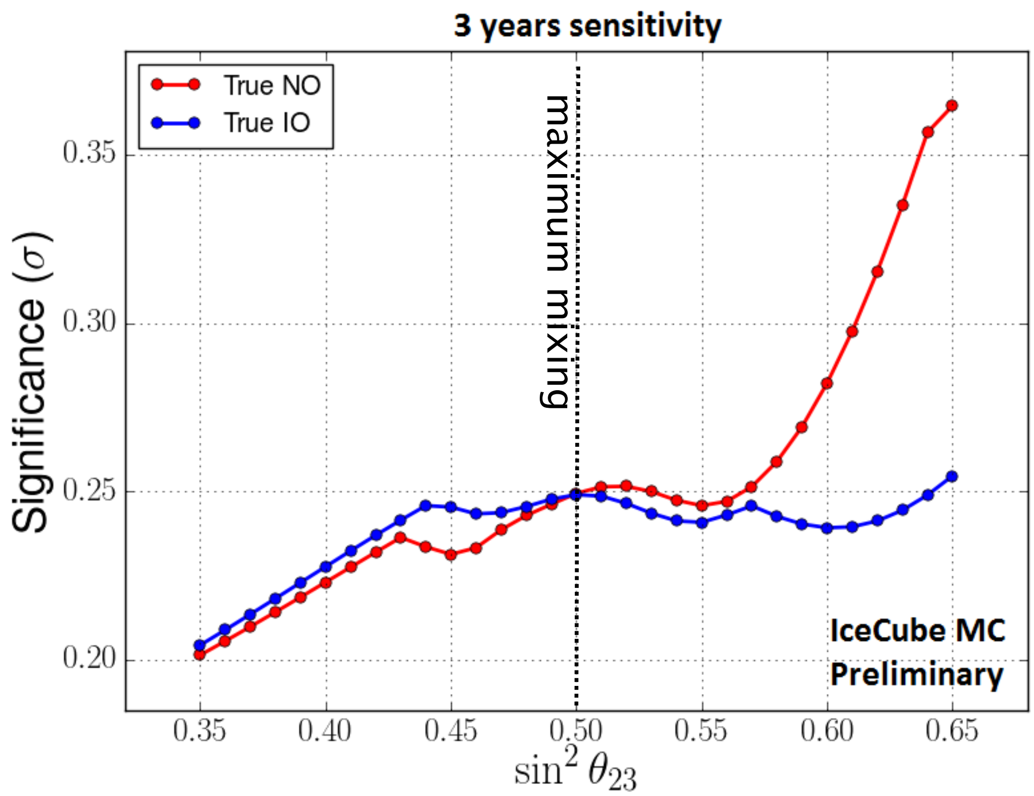
$$\Sigma_{IH}[\sigma] = \frac{2 \cdot (\Delta LLH_{IRH} - \Delta LLH_{IH})}{2 \cdot \sqrt{2 \cdot \Delta LLH_{IRH}}}$$

Sensitivity …

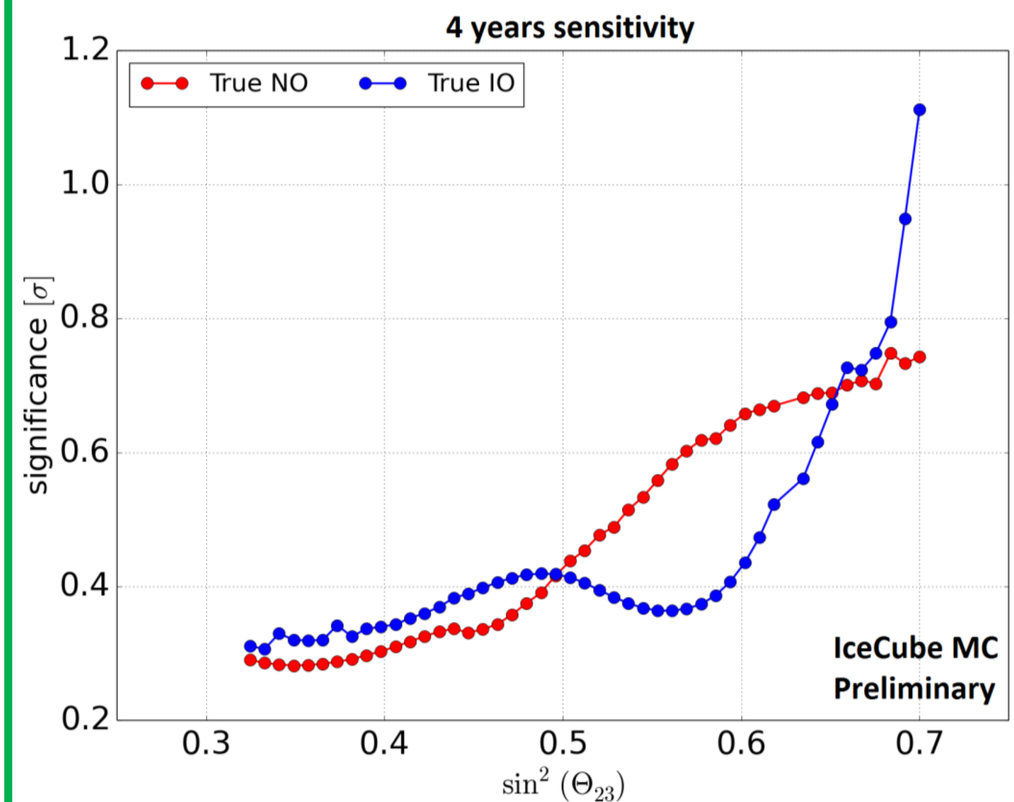
… of the 3 Observables inserting the oscillation LLH

How sensitive is DeepCore to NMO using multiple years of data?

Analysis A



Analysis B



regarding strong θ_{23} dependence of sensitivity

Systematic Influences …

… understanding detector and physics

How are systematic uncertainties treated in these fits?

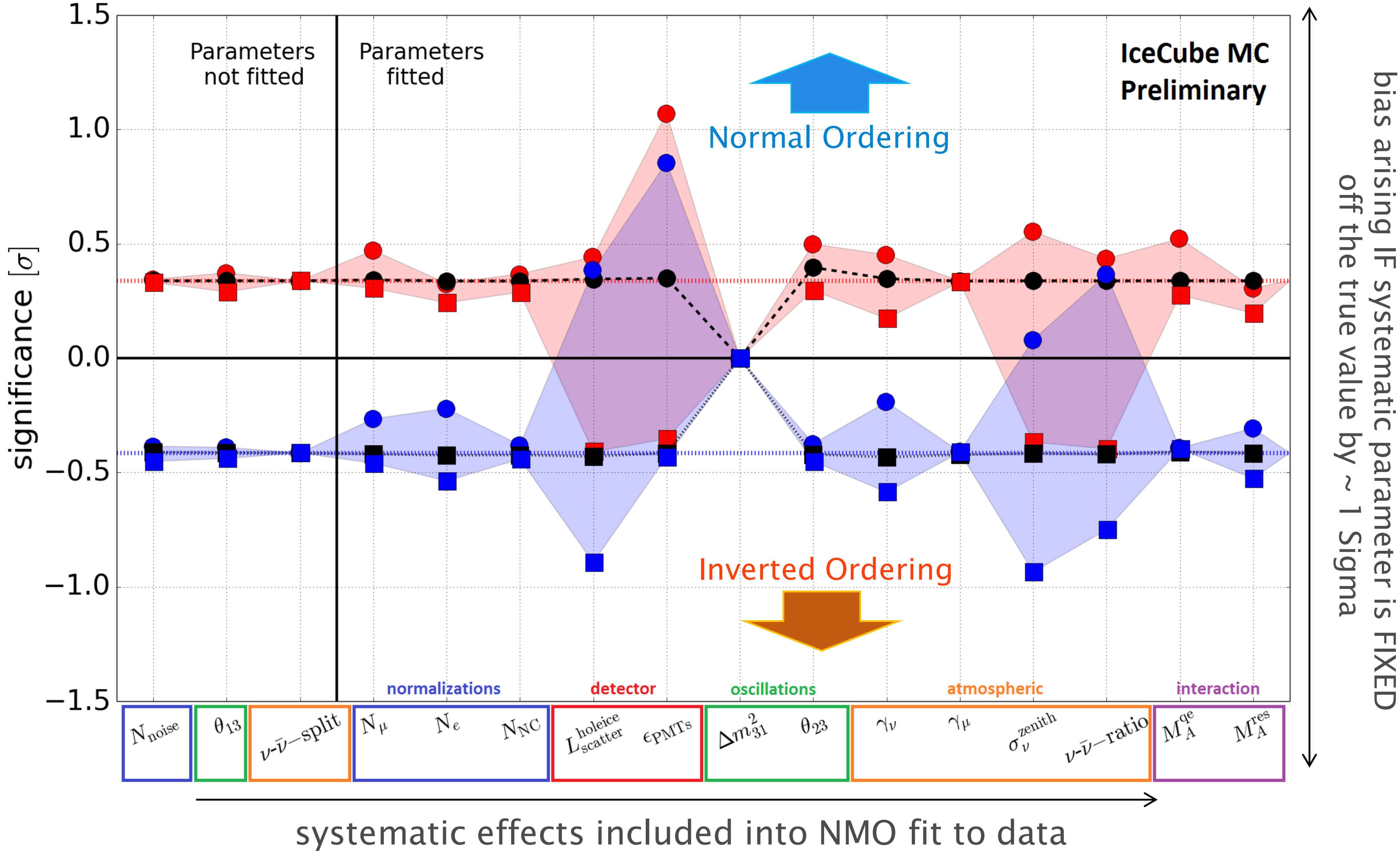
Systematic Uncertainties included in fit of signal parameters

- Parametrize impact of systematic uncertainty on 3D histogram:
  - **Normalizations**
  - **Detector uncertainties**
  - **Oscillation parameters**
  - **Atmospheric flux uncertainties**
  - **Interaction uncertainties**
- Fit all uncertainties simultaneously with fit of NMO
- Reduces significance for NMO by inclusion of systematics

Name:	Explanation:
N_{μ}	Normalization of atmospheric muons
N_e	Normalization of electron neutrinos
N_{NC}	Normalization of NC interactions
$L_{scatter}^{holeice}$	Scattering length in re-frozen ice
ϵ_{PMTs}	Efficiency of photomultipliers
Δm_{23}^2	Atmospheric neutrino mass difference
θ_{23}	Atmospheric mixing parameter
γ_{ν}	Neutrino energy spectrum uncertainty
γ_{μ}	Muon energy spectrum uncertainty
σ_{ν}^{zenith}	Atmospheric zenith spectrum uncertainty
ν-$\bar{\nu}$-ratio	Neutrino-antineutrino ratio
M_A^{res}	Resonant interaction uncertainty
M_A^{qe}	Quasi-elastic interaction uncertainty

Systematic Influences …

… understanding detector and physics



Summary & Outlook …
… and a short discussion

Summary

- NMO measurement is key goal of many future neutrino experiments (e.g. PINGU)
- Already currently running IceCube/DeepCore detector can explore this type of measurement
  - Extreme low-energy, $(E_\nu > 5\ GeV)$, high-statistics data samples
  - Challenging energy regime for data selection and reconstruction
  - Test NMO with 2 independent analyses with different focuses
- Stand-alone sensitivity of $\sim 0.3 - 0.7\sigma$ (depending on value of θ_{23})
- Explore this type of measurement for future PINGU extension

Outlook

- Experimental DeepCore result on NMO in near future
- Potential boost from inclusion of external oscillation measurements
- Also, sensitivity to testing matter effects vs. vacuum oscillations

from: http://www.capteurdereve.fr/

Summary & Outlook …
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  - C
  - T
- Stand
- Explo

Thank you!
… any questions?

Outlook

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from: http://www.capteurdereve.fr/

BACKUP

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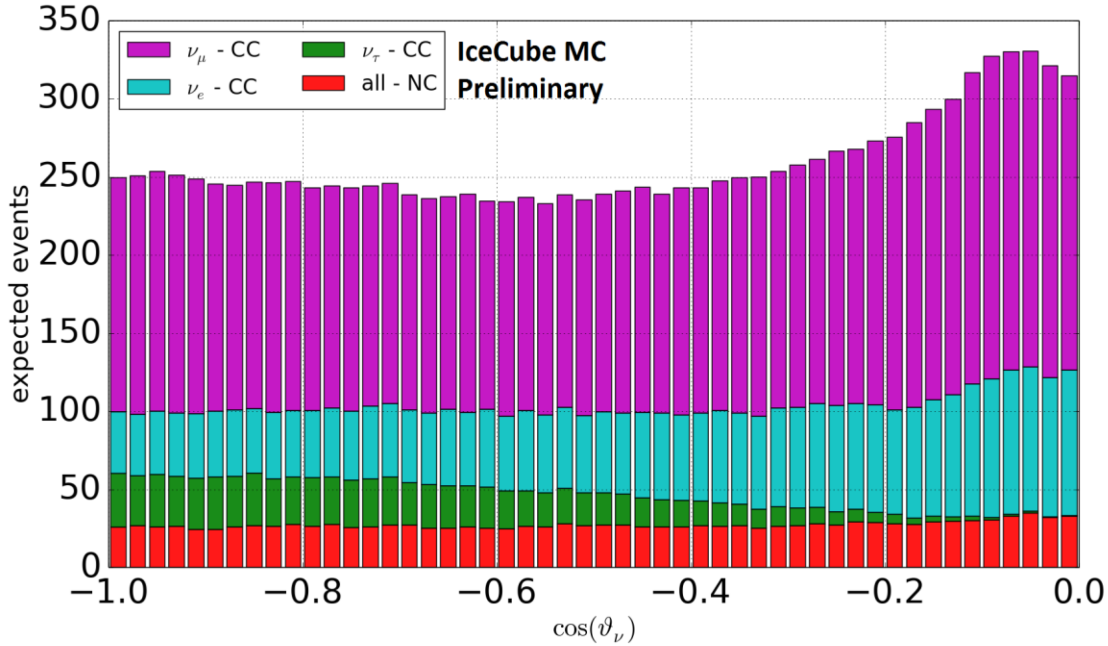
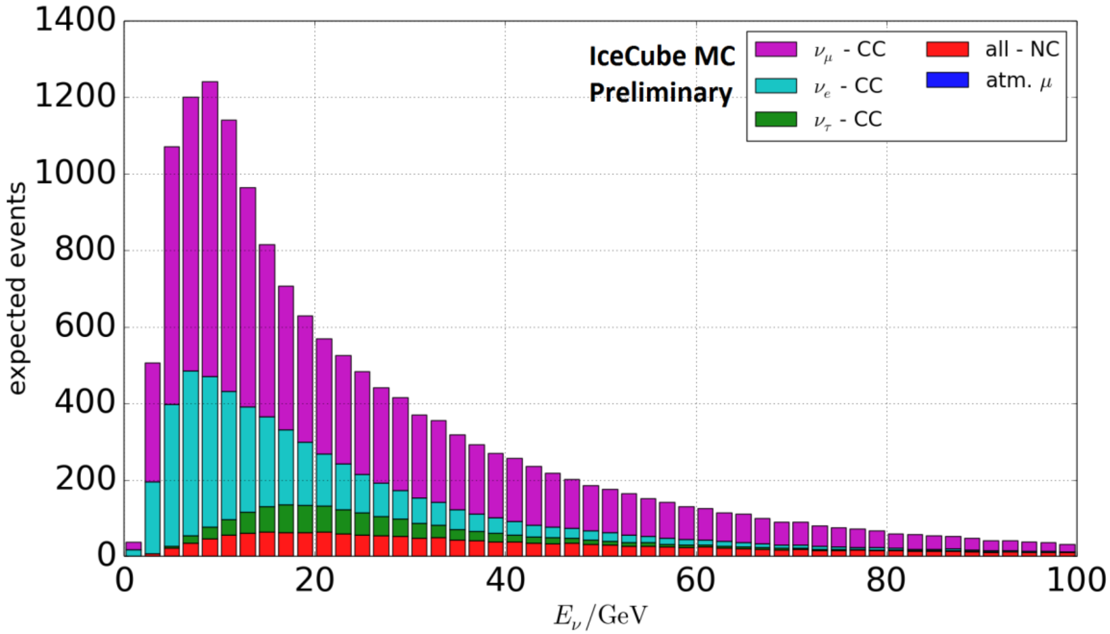


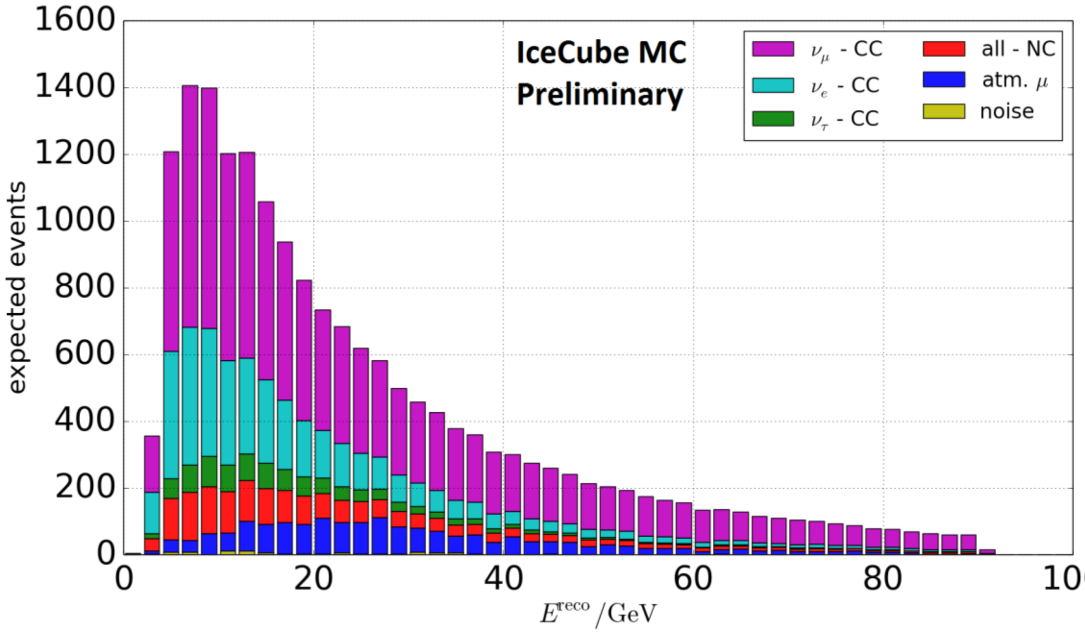


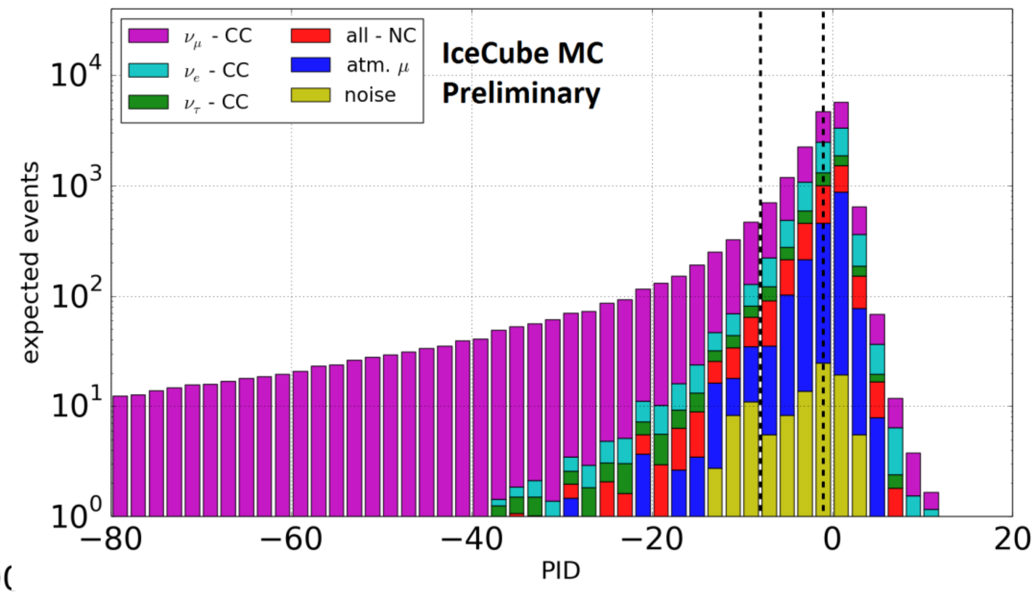
Distribution of …

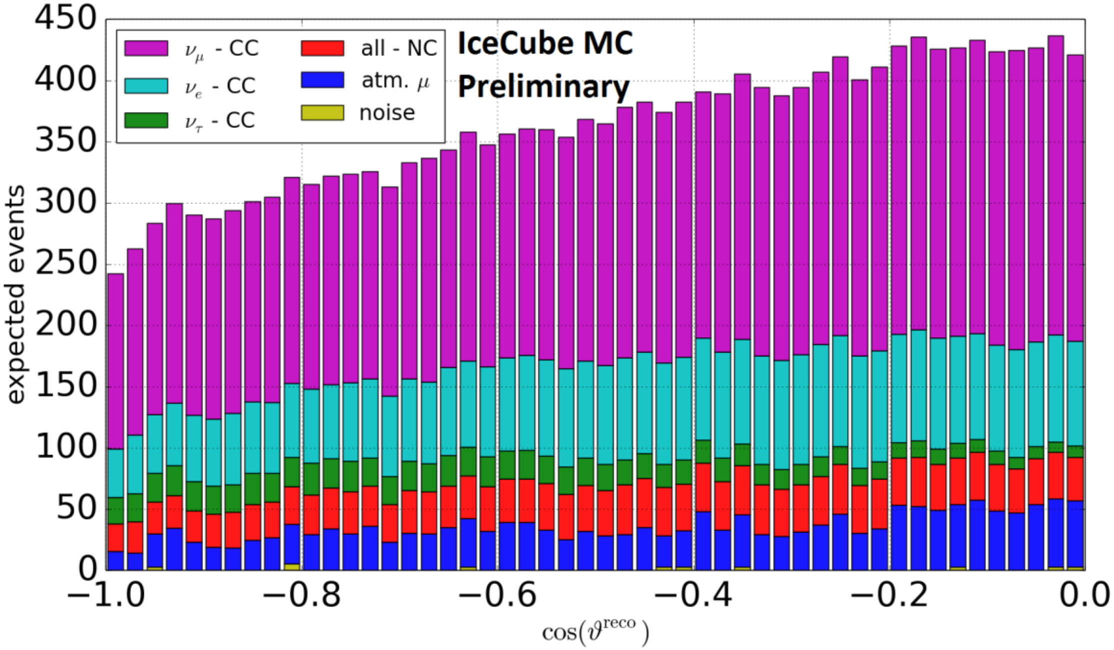
- true energy
- true zenith

… as predicted by IceCube Monte Carlo

BACKUP







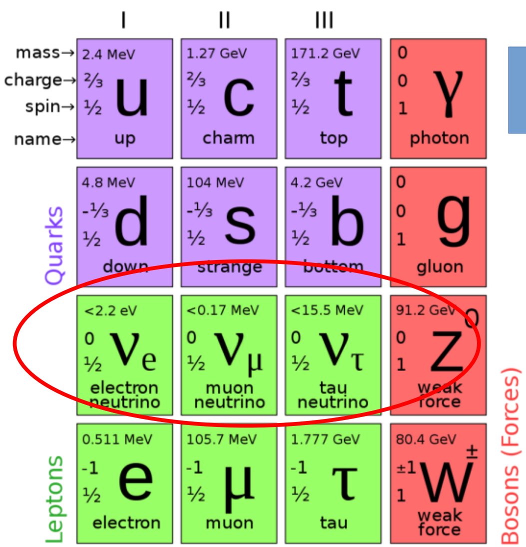
Distribution of …

- reconstructed energy
- reconstructed zenith
- flavor separator (PID)

… as predicted by
IceCube Monte Carlo

Neutrino Oscillations …

… as probe for the NMO



Transition probability of neutrino:

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha,k} U_{\beta,k} U_{\alpha,j} U^*_{\beta,j} \exp\left(-i \frac{\Delta m^2_{k,j} L}{2E_\nu}\right)$$

Described by PMNS-Matrix:

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

$$s_{ij} = \sin(\theta_{ij})$$

$$c_{ij} = cos(\theta_{ij})$$

$$(\delta \equiv 0)$$

Many measurements on oscillation parameters:

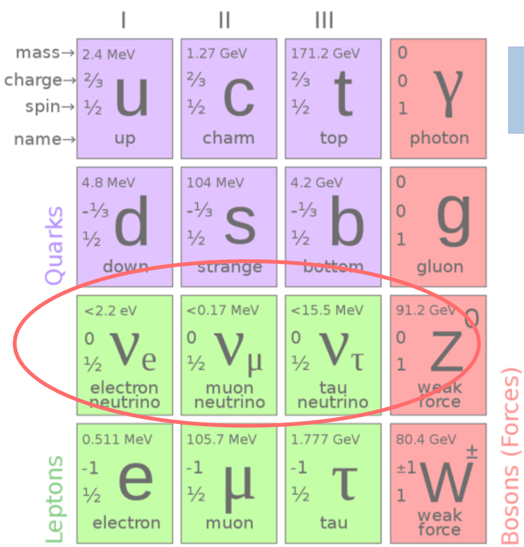
Parameter	Hierarchy	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}\ \mathrm{eV}^2$	NH or IH	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.97
$\sin^2\theta_{12}/10^{-1}$	NH or IH	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$	NH	2.50	2.46 – 2.54	2.41 – 2.58	2.37 – 2.63
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$	IH	2.46	2.42 – 2.51	2.38 – 2.55	2.33 – 2.60
$\sin^2\theta_{13}/10^{-2}$	NH	2.14	2.05 – 2.25	1.95 – 2.36	1.85 – 2.46
$\sin^2\theta_{13}/10^{-2}$	IH	2.18	2.06 – 2.27	1.96 – 2.38	1.86 – 2.48
$\sin^2\theta_{23}/10^{-1}$	NH	4.37	4.17 – 4.70	3.97 – 5.63	3.79 – 6.16
$\sin^2\theta_{23}/10^{-1}$	IH	5.69	4.28 – 4.91 ⊕ 5.18 – 5.97	4.04 – 6.18	3.83 – 6.37
δ/π	NH	1.35	1.13 – 1.64	0.92 – 1.99	0 – 2
δ/π	IH	1.32	1.07 – 1.67	0.83 – 1.99	0 – 2
$\Delta\chi^2_{\mathrm{I-N}}$	IH–NH	+0.98			

Still open question

(from: Nuclear Physics B 908 (2016) 199–217)

Neutrino Oscillations …

… as probe for the NMO



Transition probability of neutrino:

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha,k} U_{\beta,k} U_{\alpha,j} U^*_{\beta,j} \exp\left(-i\frac{\Delta m^2_{k,j} L}{2E_\nu}\right)$$

Described by PMNS-Matrix:

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

$$s_{ij} = \sin(\theta_{ij})$$
$$c_{ij} = cos(\theta_{ij})$$
$$(\delta \equiv 0)$$

Many measurements on oscillation parameters:

Parameter	Hierarchy	Best fit	1σ range	2σ range	3σ range
$\sin^2\theta_{23}/10^{-1}$	IH	5.69	4.28 – 4.91 ⊕ 5.18 – 5.97	4.04 – 6.18	3.83 – 6.37
δ/π	NH	1.35	1.13 – 1.64	0.92 – 1.99	0 – 2
δ/π	IH	1.32	1.07 – 1.67	0.83 – 1.99	0 – 2
$\Delta\chi^2_{\mathrm{I-N}}$	IH–NH	+0.98			

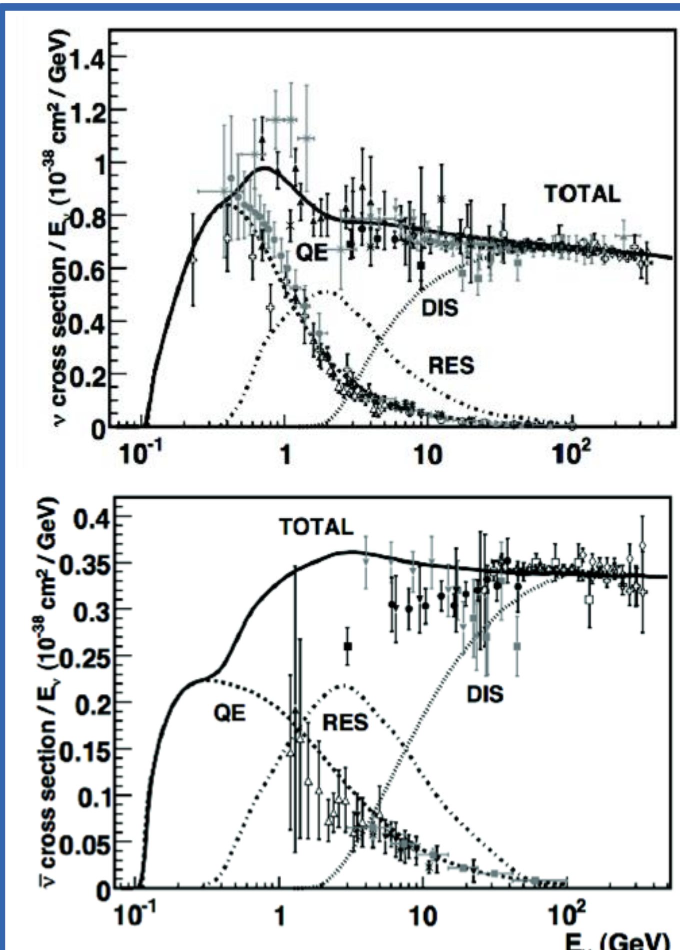
Where can we get such neutrinos from to probe the NMO?

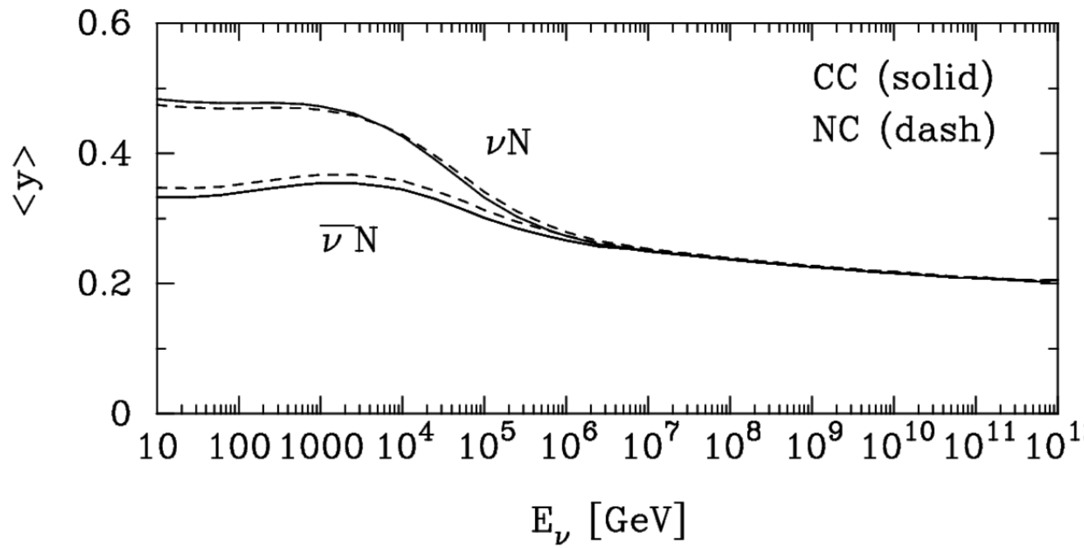
Still open question

(from: Nuclear Physics B 908 (2016) 199–217)

Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements





Still, differences in:
→ cross-sections, thus event rates
→ shape of events (inelasticity)

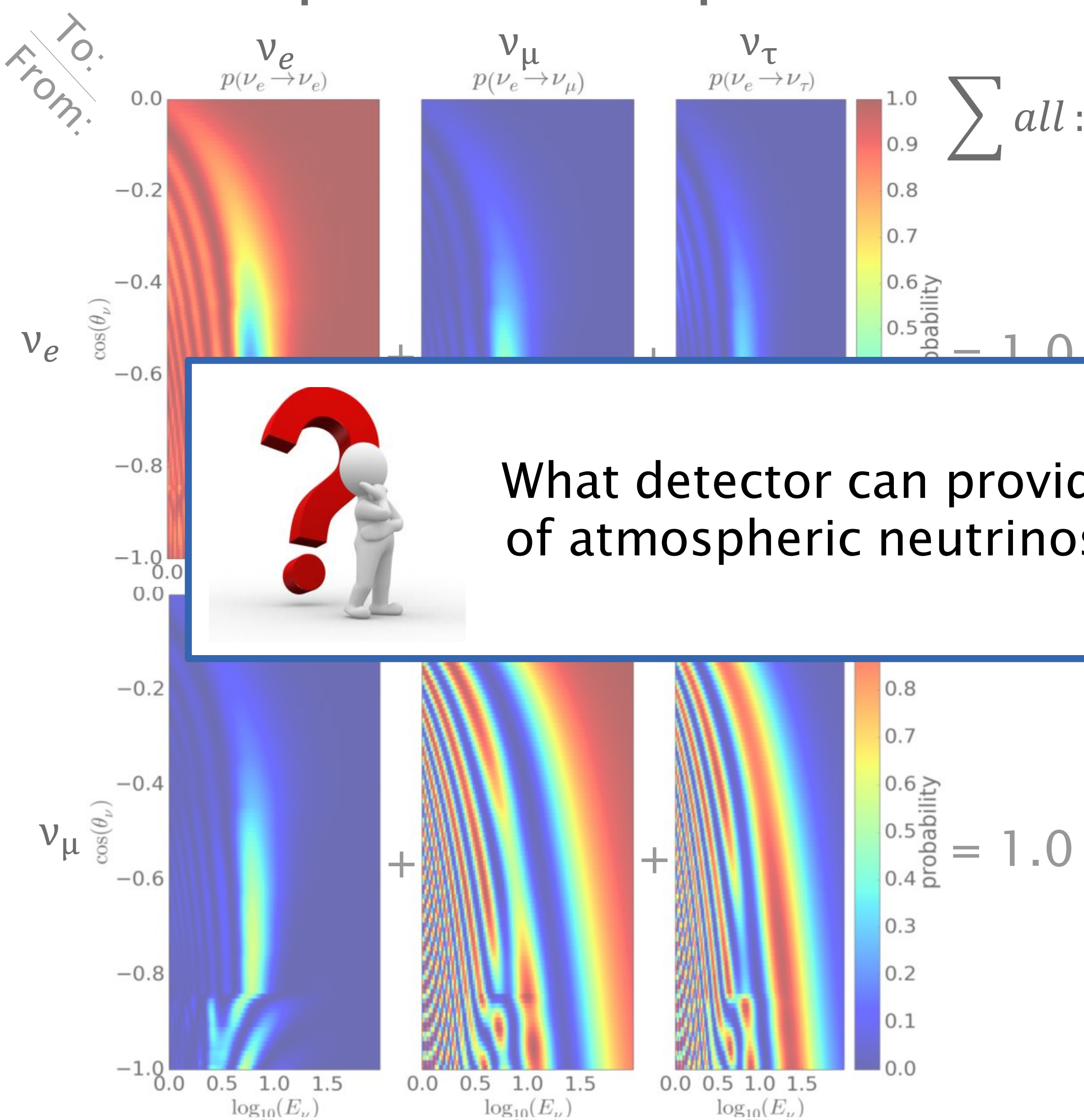
(from: Rev.Mod. Phys. 84 (2012), p. 1307, arXiv: 1305.7513.)

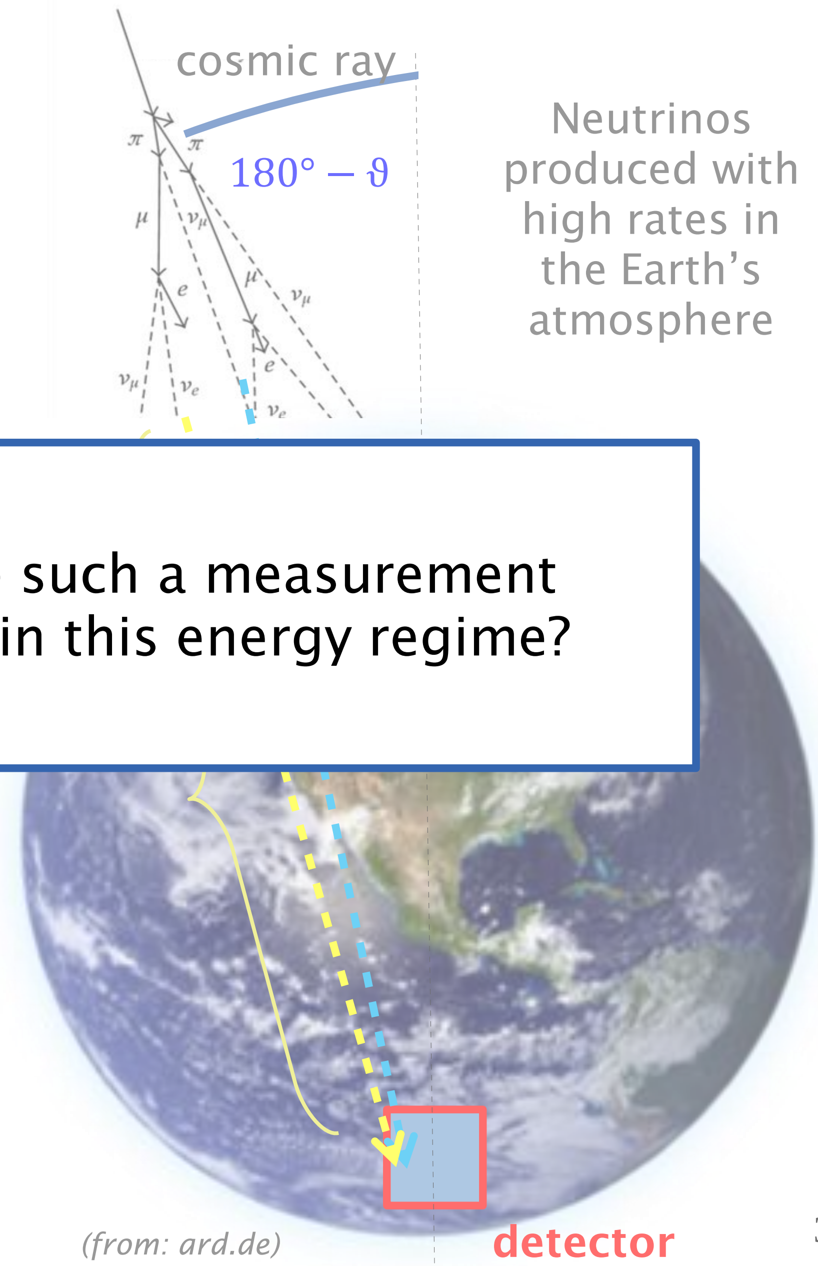
Does that mean, the effect is invisible, if neutrino and anti-neutrino are not distinguishable?

Atmospheric Neutrinos…

… as a source for neutrino oscillation measurements

Oscillation pattern for atmospheric neutrinos:





Neutrinos produced with high rates in the Earth's atmosphere

What detector can provide such a measurement of atmospheric neutrinos in this energy regime?