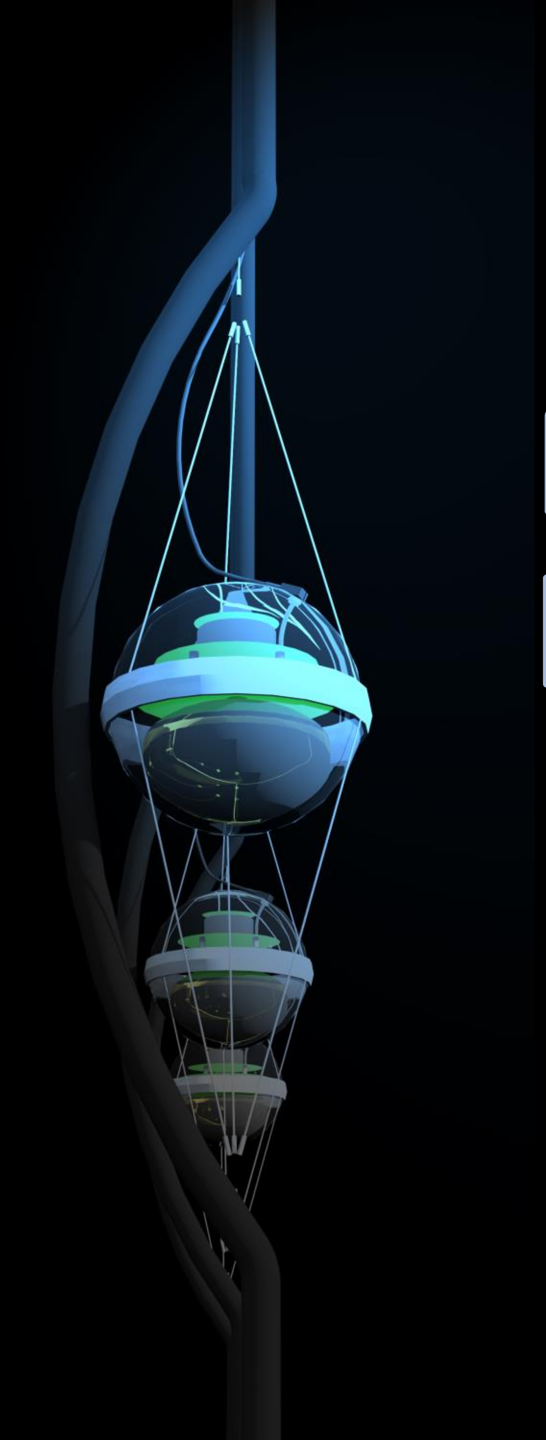

Neutrinos from heaven and hell in IceCube

Juan-Pablo Yáñez

j.p.yanez@ualberta.ca

LIP – May 29th, 2018

Note: All results shown are pre-Neutrino18. New results high-energy results were shown at the conference. See:

https://zenodo.org/record/1286852#.WzPG96dKhjE

https://zenodo.org/record/1286919#.WzPHBadKhjE

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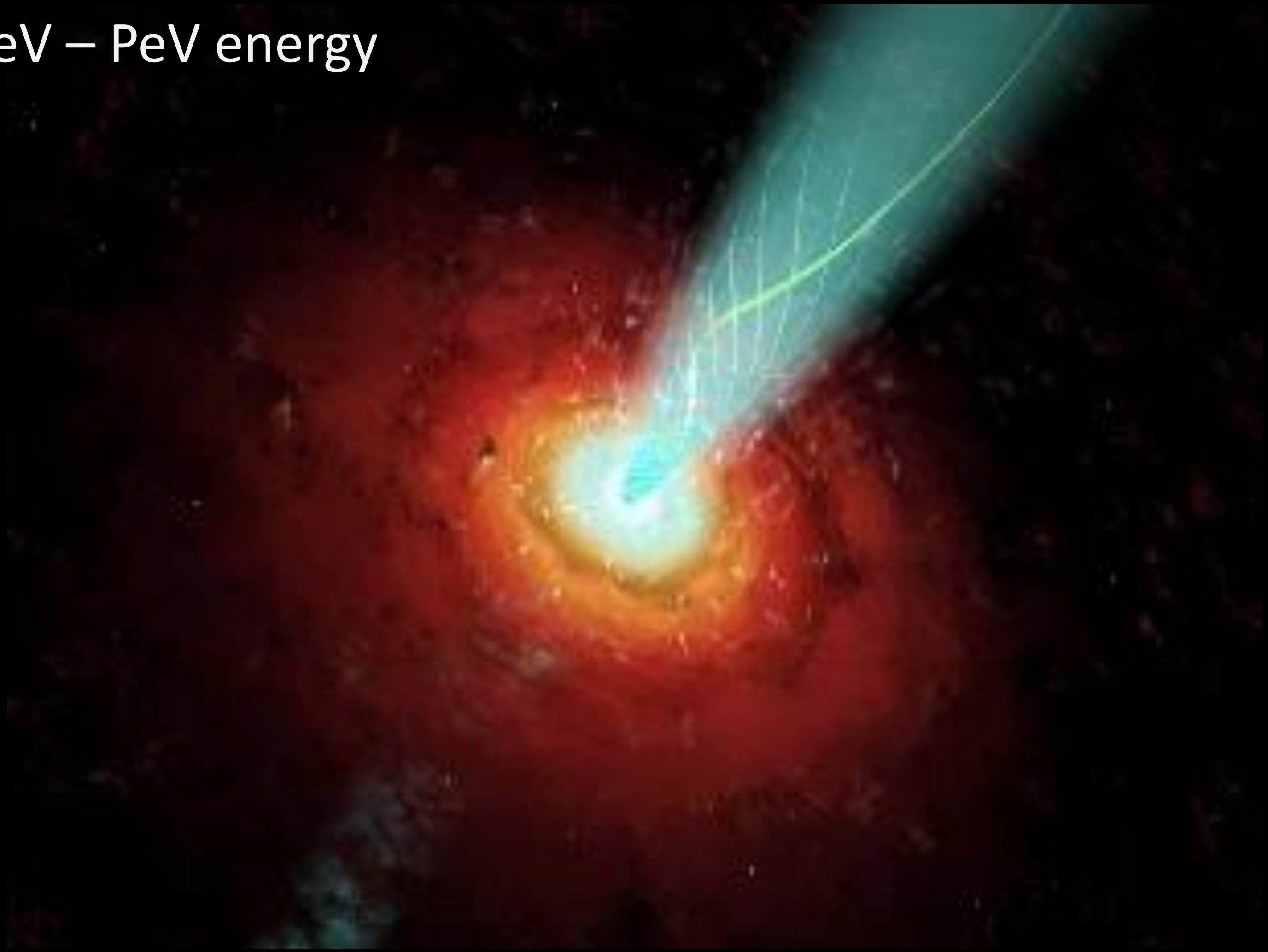
Neutrinos from Hell

TeV – PeV energy



The promise of HE neutrinos

A hundred year puzzle: the cosmic ray spectrum

- Where do they come from?

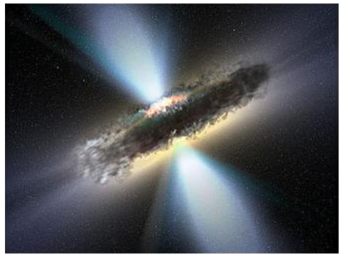
Victor Hess before his 1912 balloon flight in Austria, during which he discovered cosmic rays

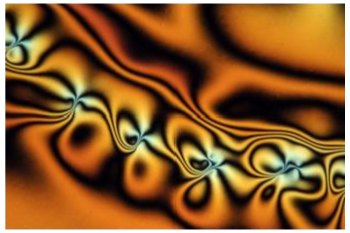
https://faculty.washington.edu/wilkes/salta/balloon/

The promise of HE neutrinos

A hundred year puzzle: the cosmic ray spectrum

- Where do they come from?
  - Cosmic accelerators? Exotics?

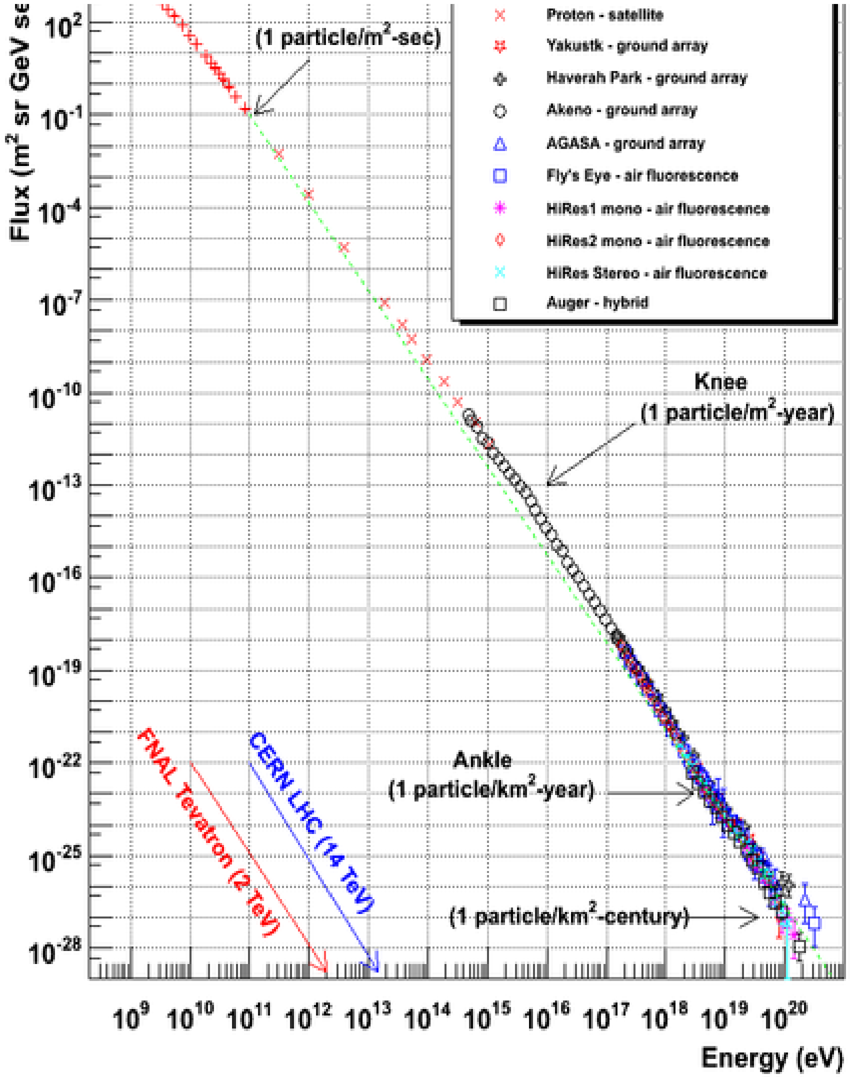




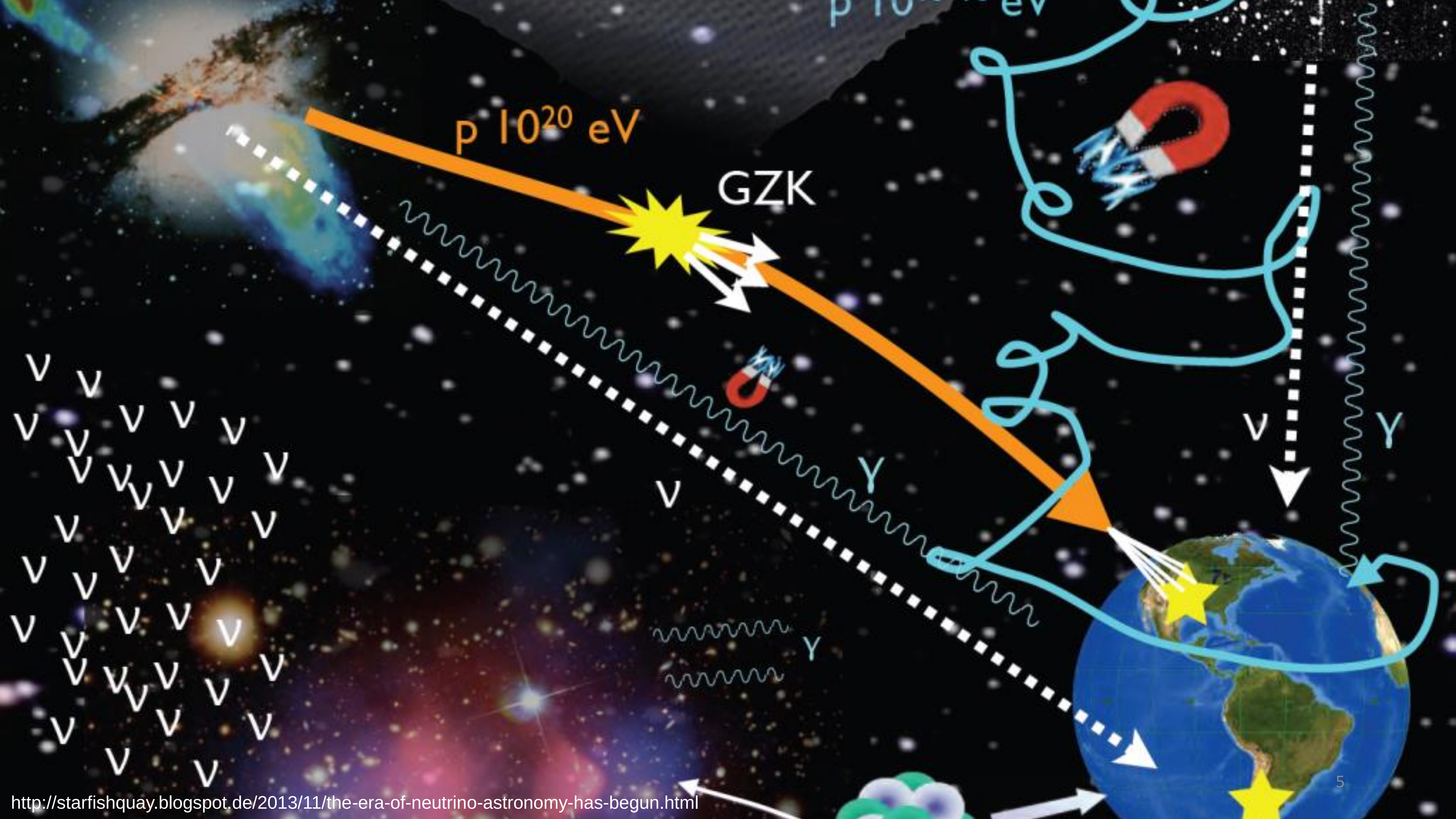
- ν's most likely involved

$$p + \gamma \to \Delta^+ \to n + \pi^+$$

→ E ~ [TeV, PeV]

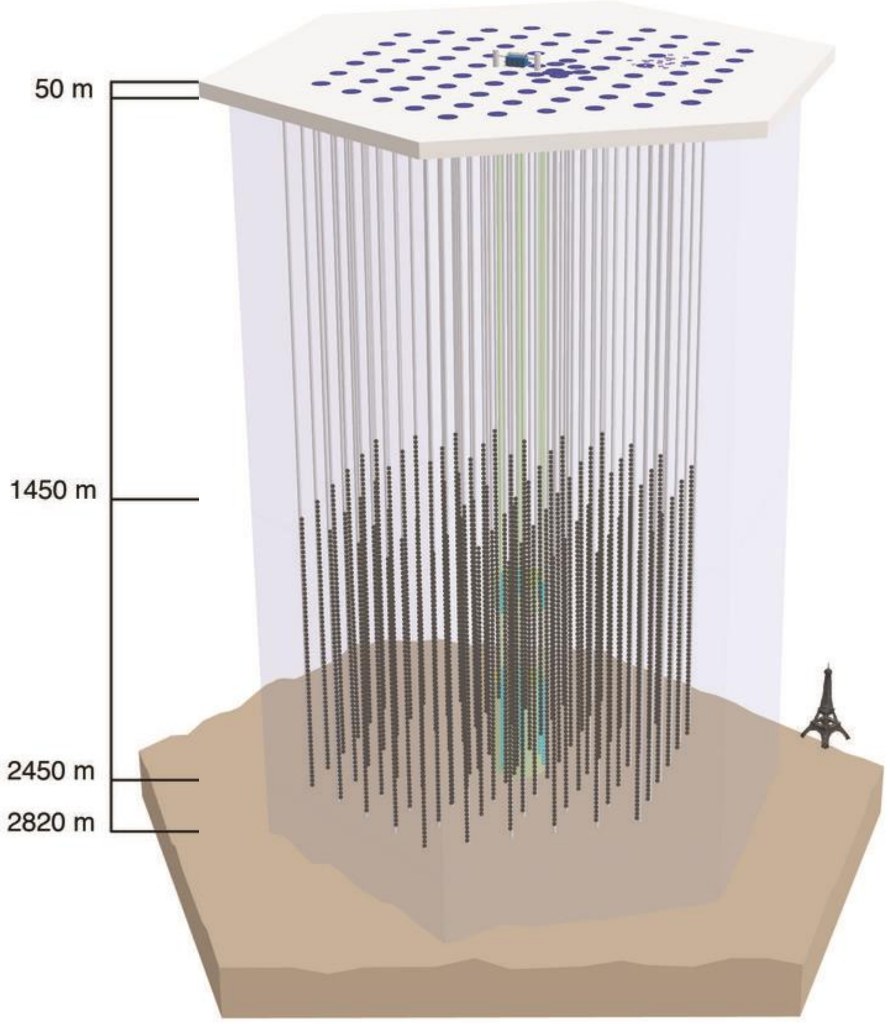


http://www.physics.utah.edu/~whanlon/spectrum.html



http://starfishquay.blogspot.de/2013/11/the-era-of-neutrino-astronomy-has-begun.html

IceCube:
An instrument for neutrino astronomy



- Ice Cherenkov neutrino detector
- 5,160 DOMs
- 86 strings
- Spacing: 17m in z, 125 in x-y
- 1 km3 volume
- 1.5 – 2.5 km under ice
- At the geographic South Pole

IceCube:
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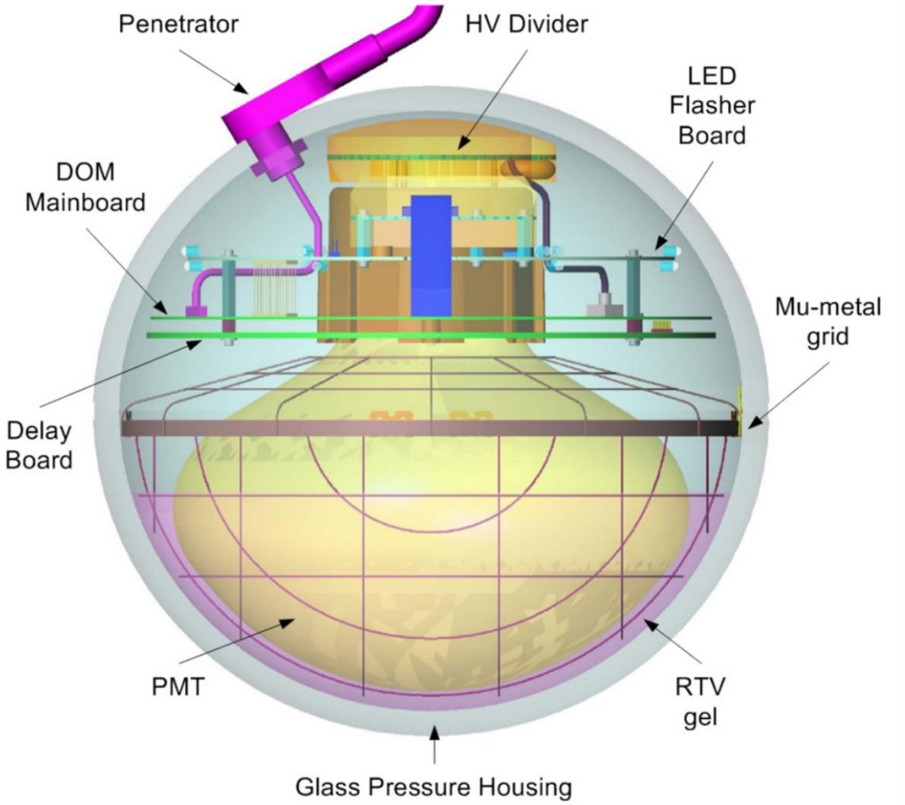

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- 5,160 DOMs
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- Spacing: 17m in z, 125 in x-y
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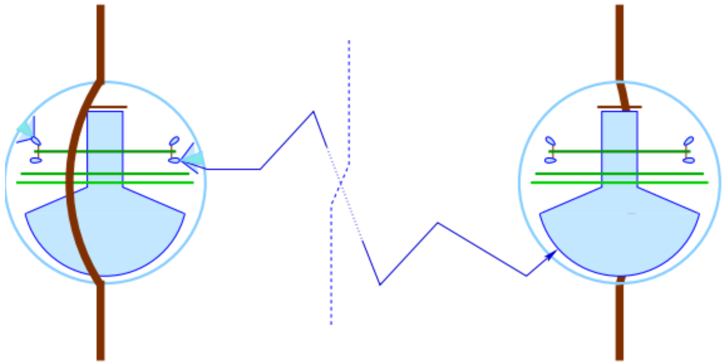
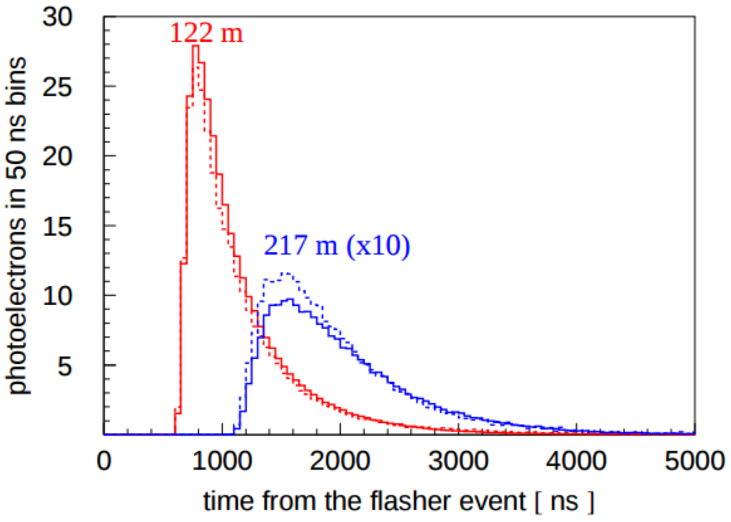
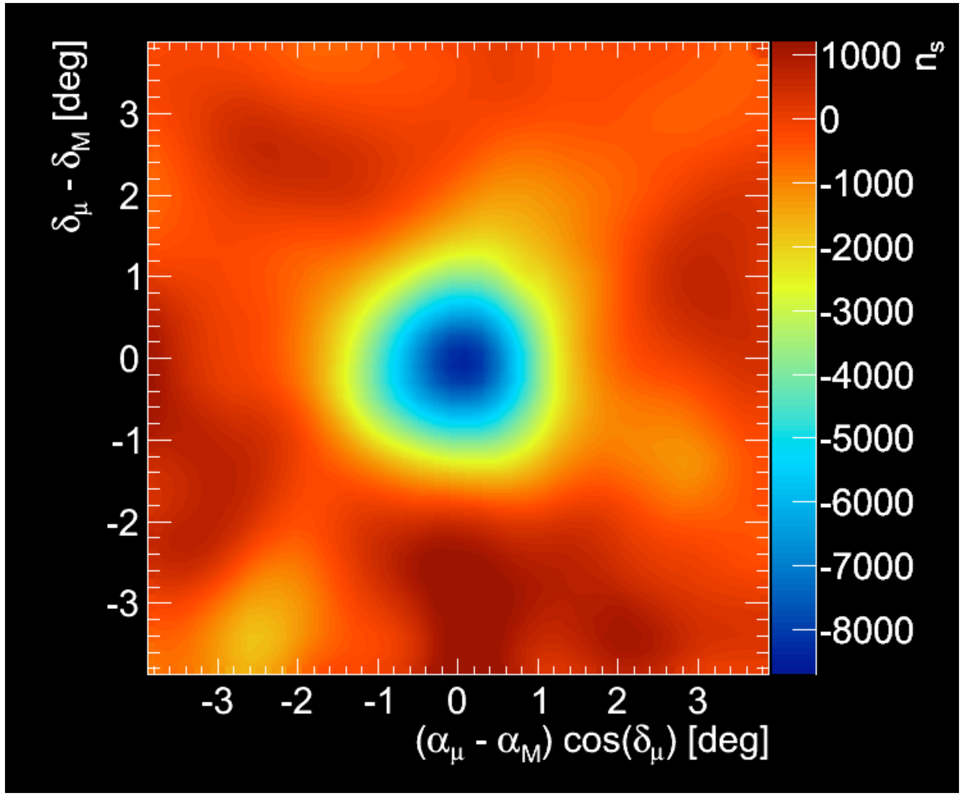
- At the geographic South Pole

Detector calibration

- LED flashers on each DOM
- In-ice calibration laser
- Minimum ionizing muons
- Moon shadow
- In-situ camera

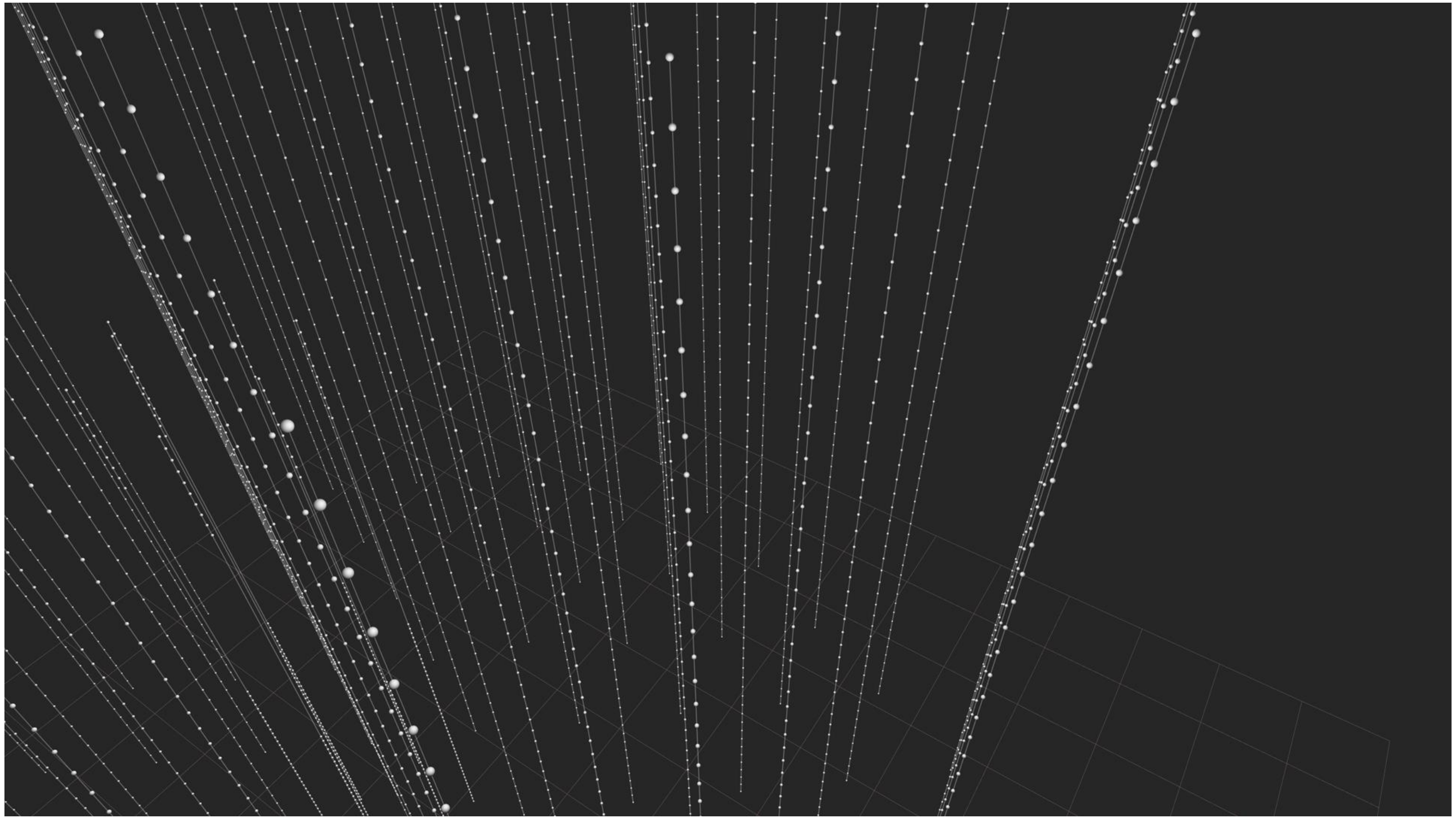




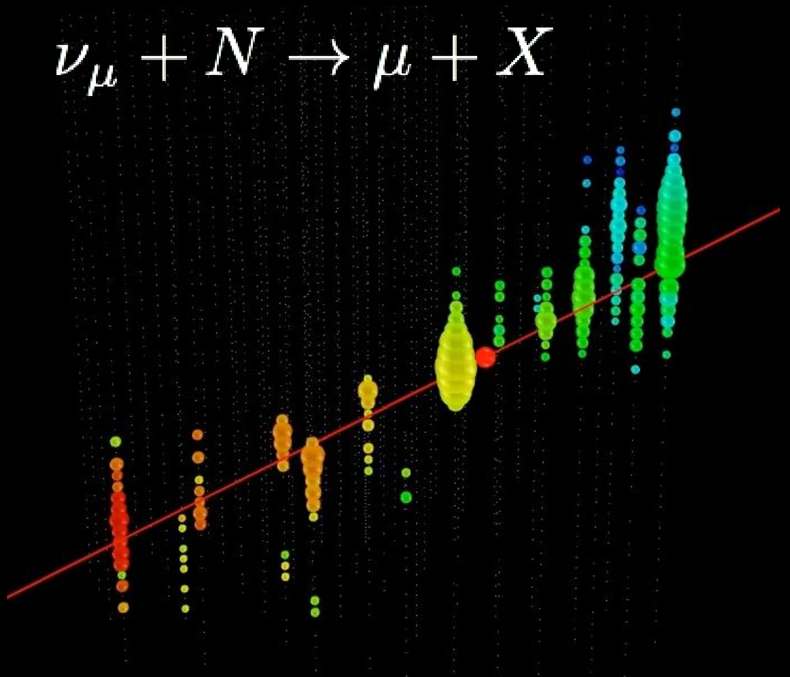


Moon shadow in cosmic rays in IC59

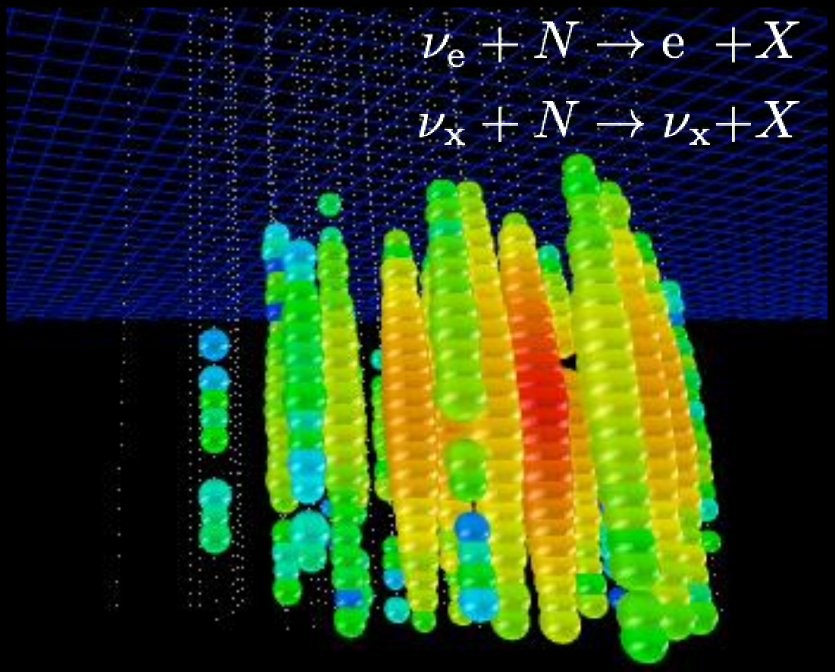
Neutrino detection in IceCube



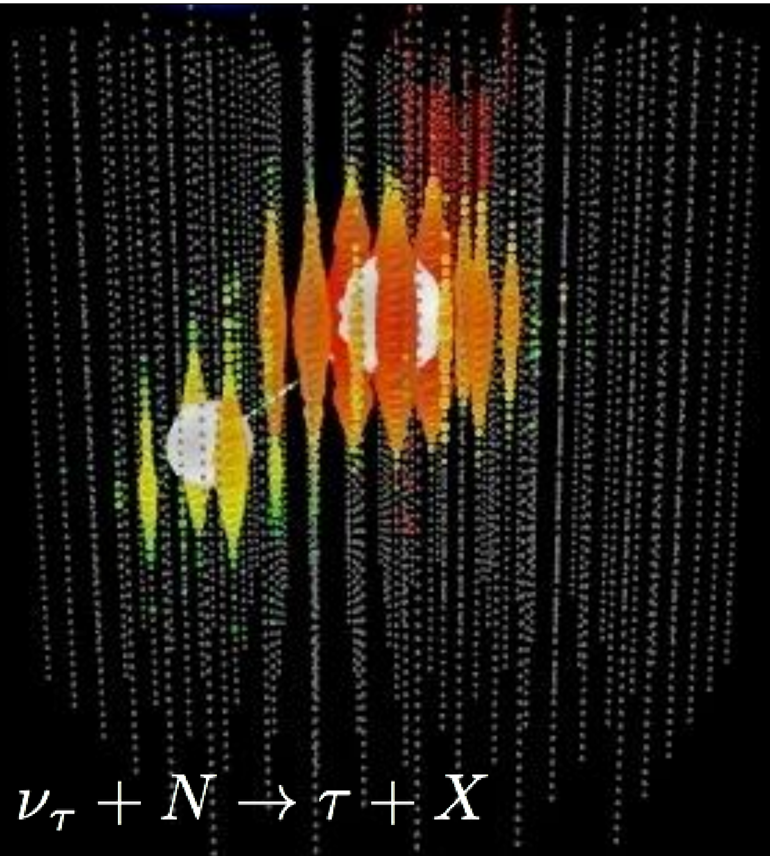
Neutrino event topologies



track (data)
factor of ≈ 2 energy resolution
Ang res. < 1° at high energies

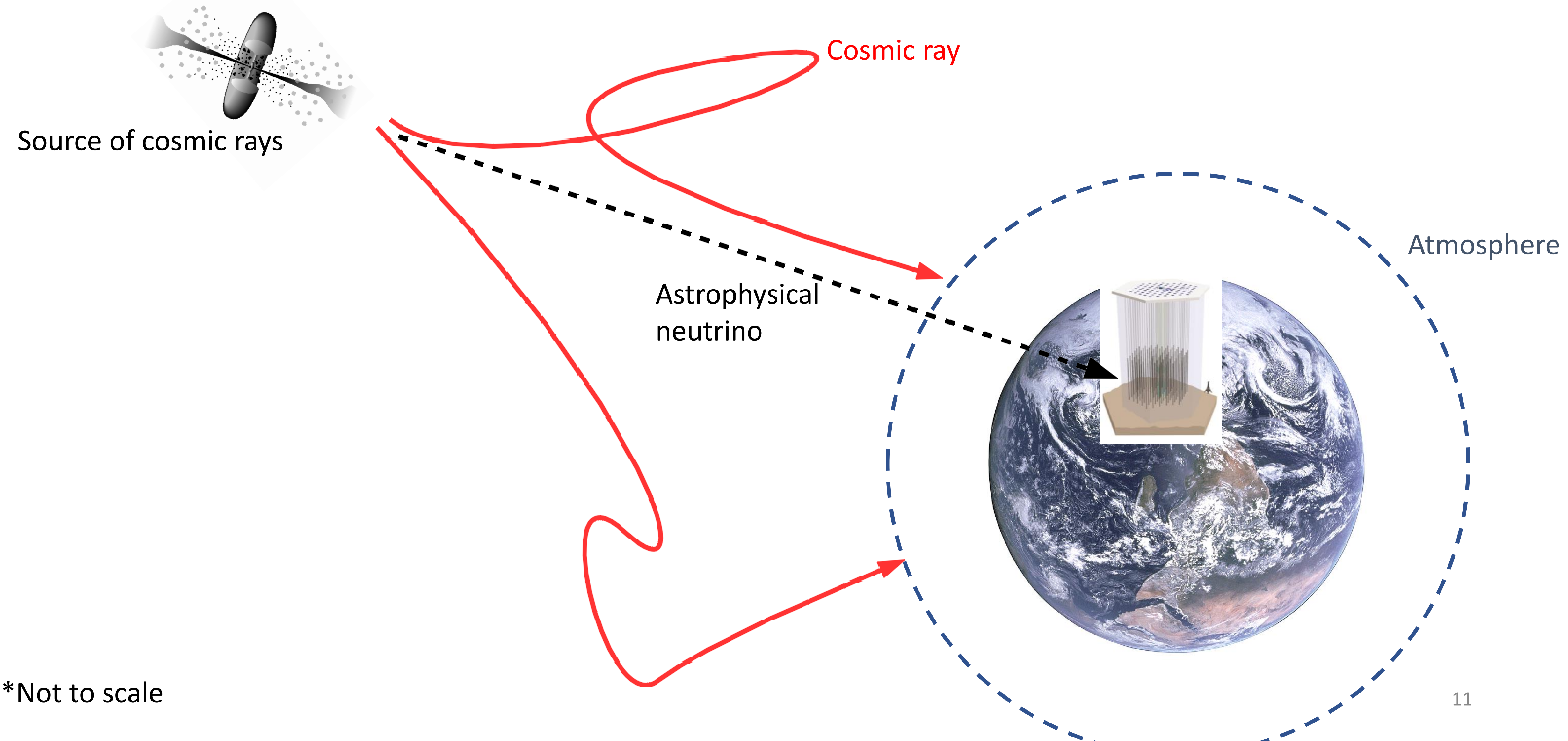


cascade (data)
≈ ±15% deposited energy resolution
≈ 10° angular resolution (E>= 100 TeV)



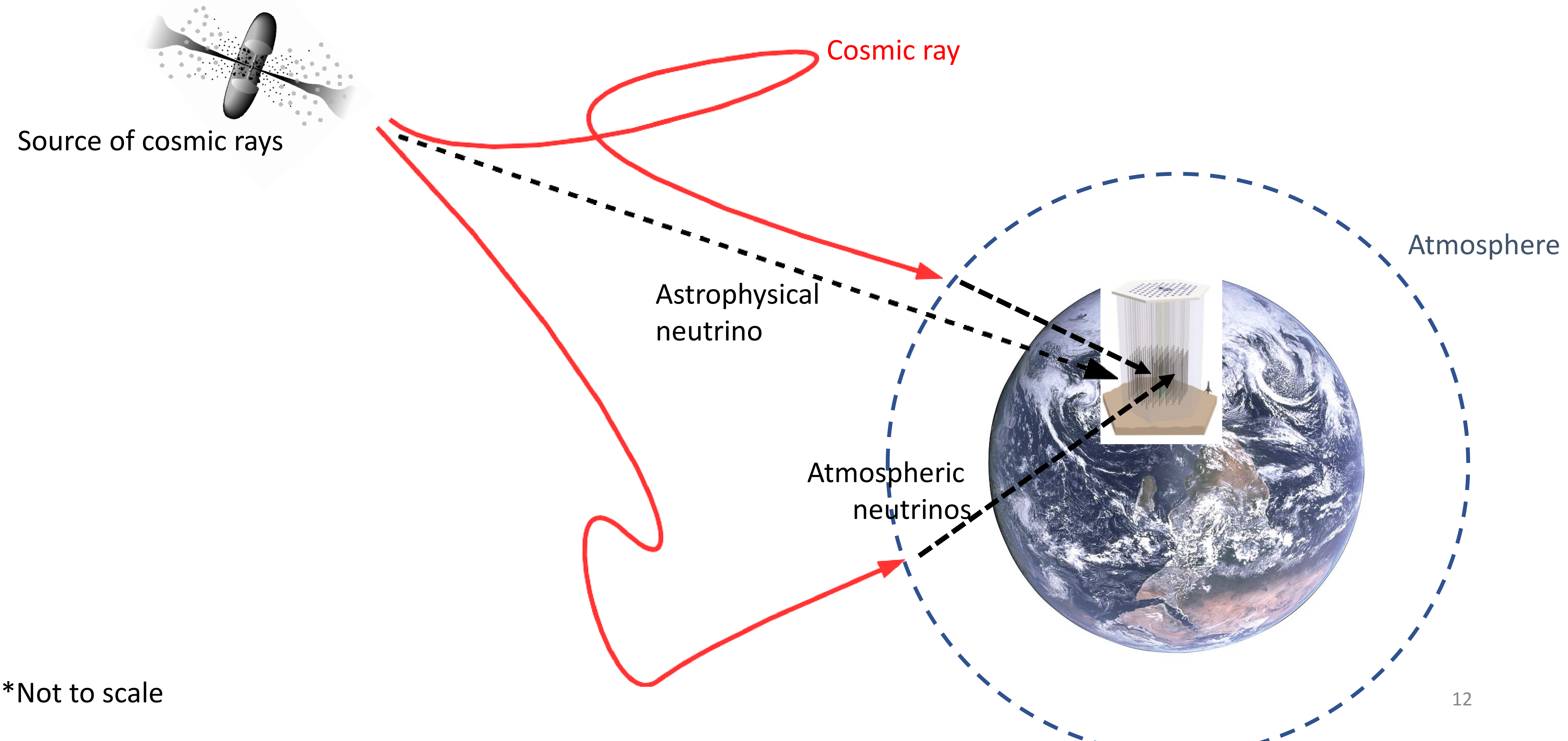
Two cascades (E>10 PeV)
Not observed yet: τ decay length is 50 m/PeV

Neutrinos in IceCube



*Not to scale

Neutrinos in IceCube



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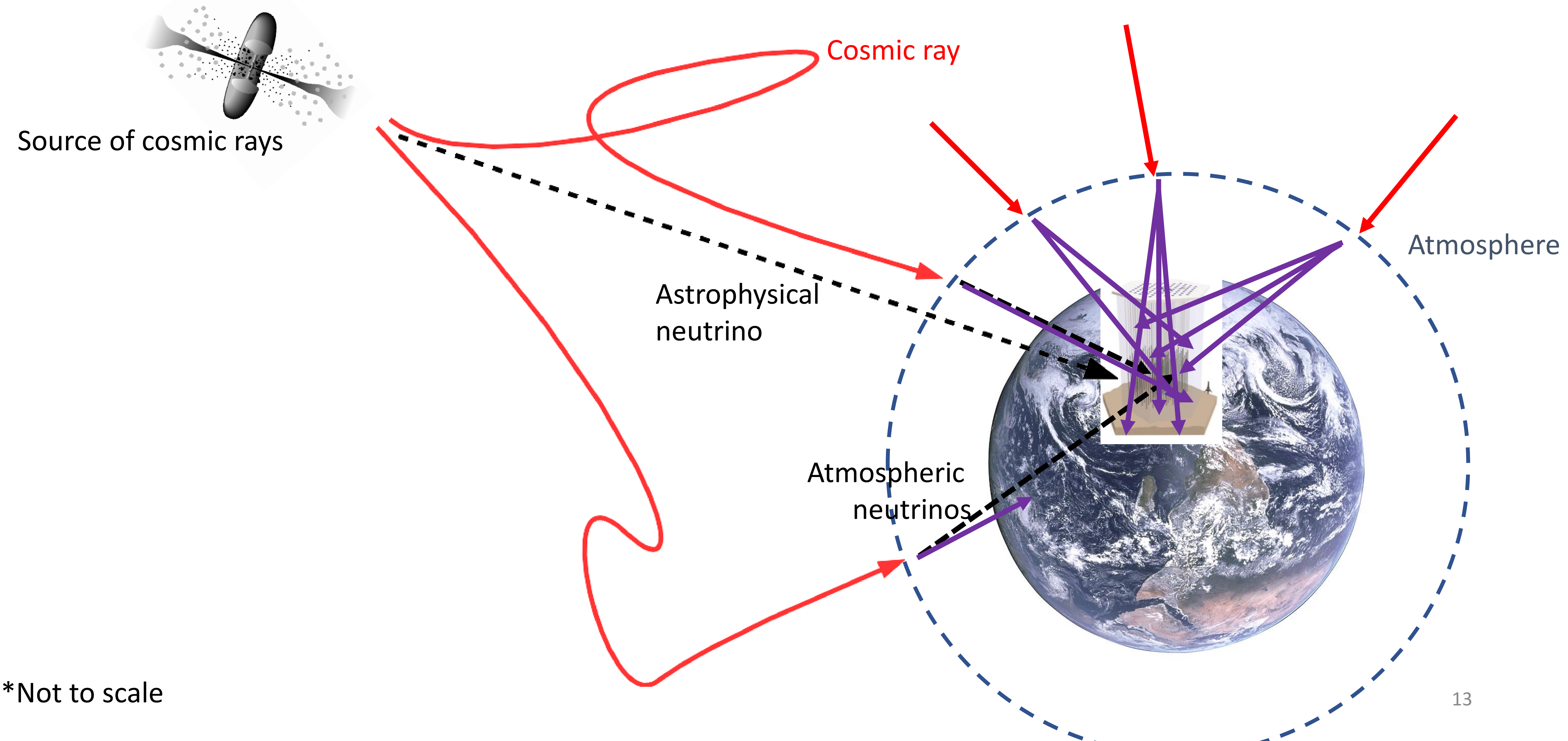
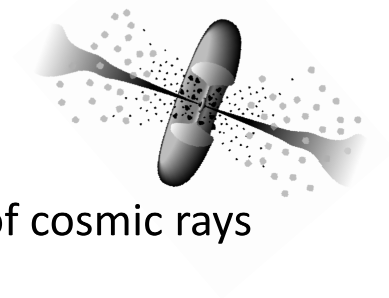
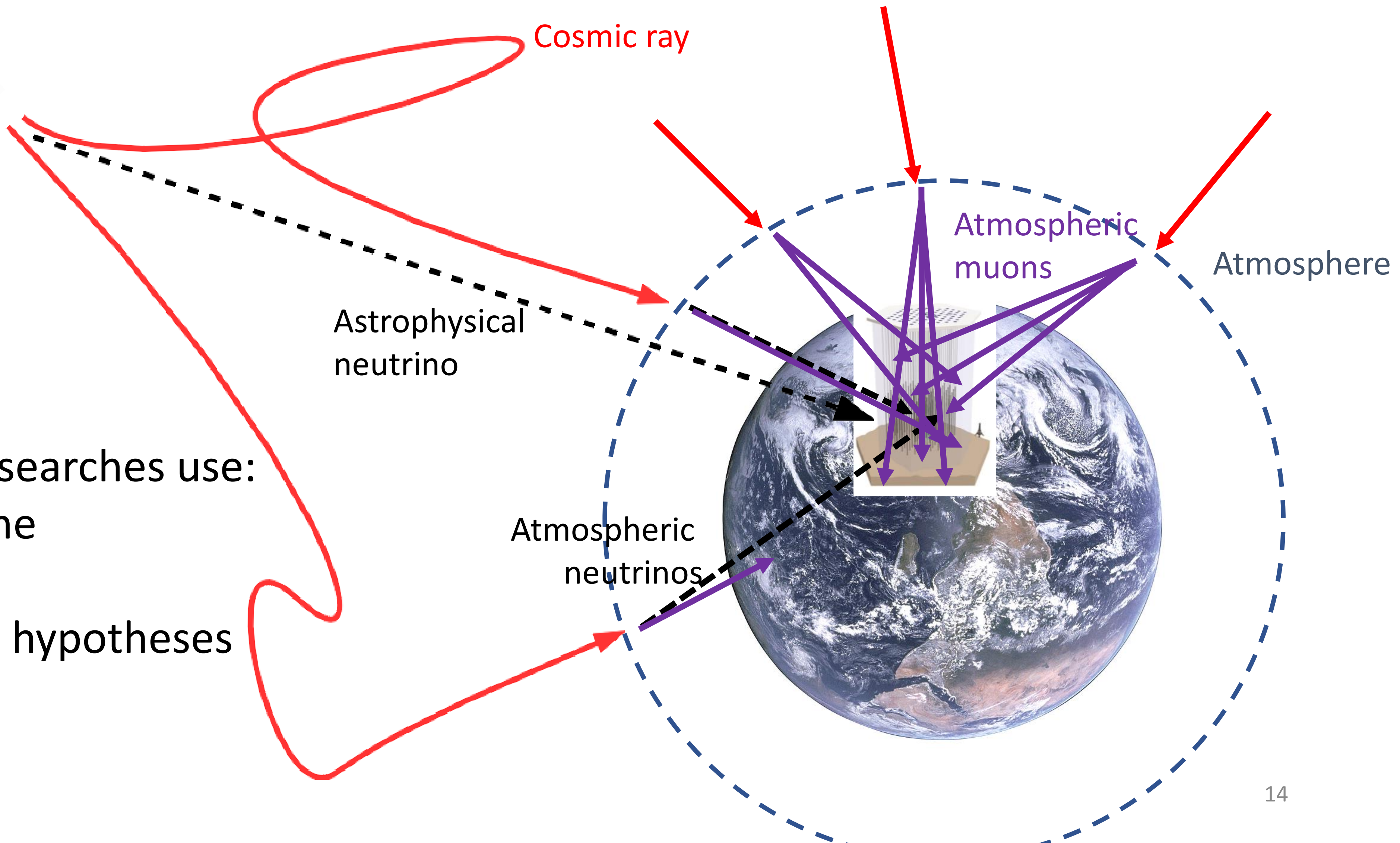
Neutrinos in IceCube



*Not to scale

Neutrinos in IceCube





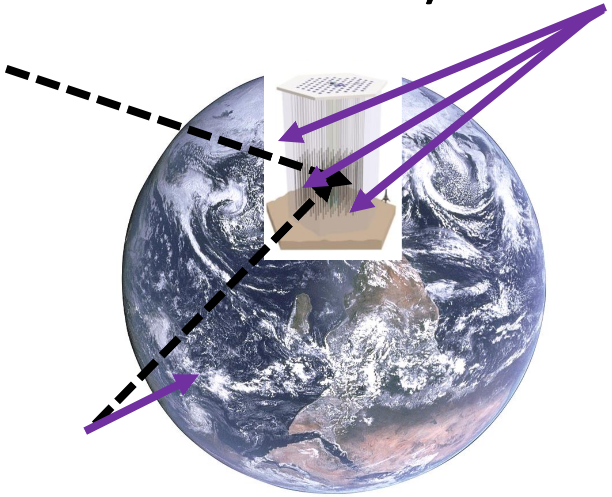
Astrophysical neutrino searches use:

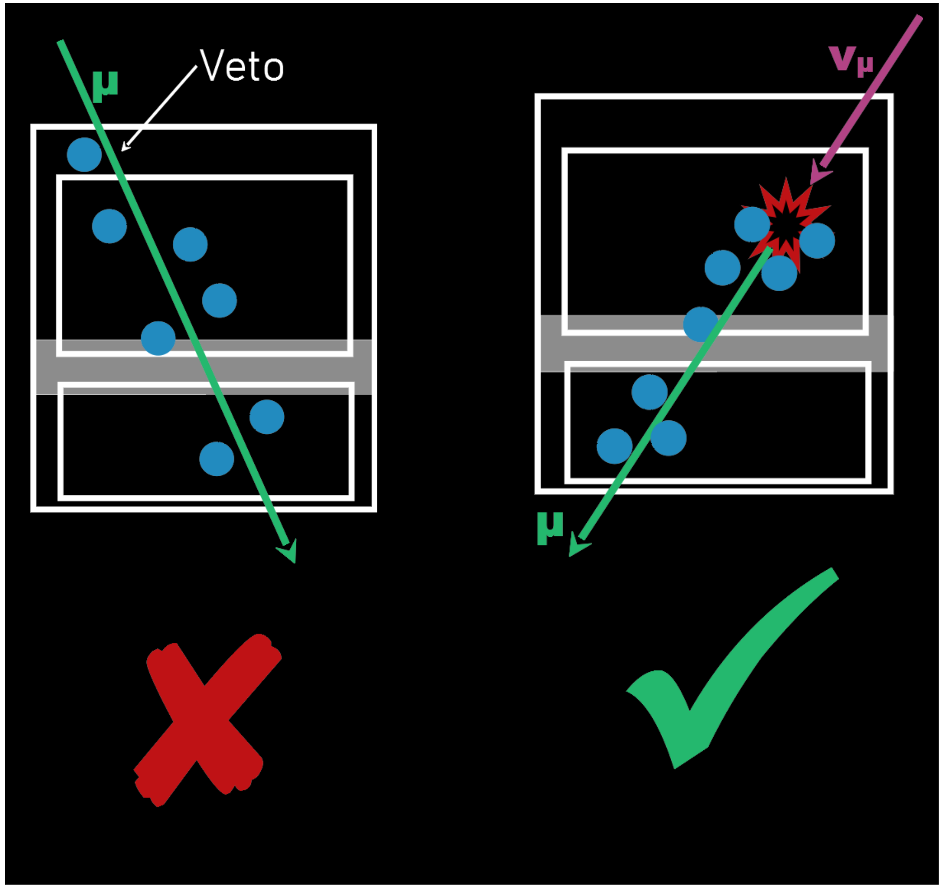
- Direction, energy, time
- Event topology
- Diffuse, point-source hypotheses

*Not to scale

Isolating neutrinos

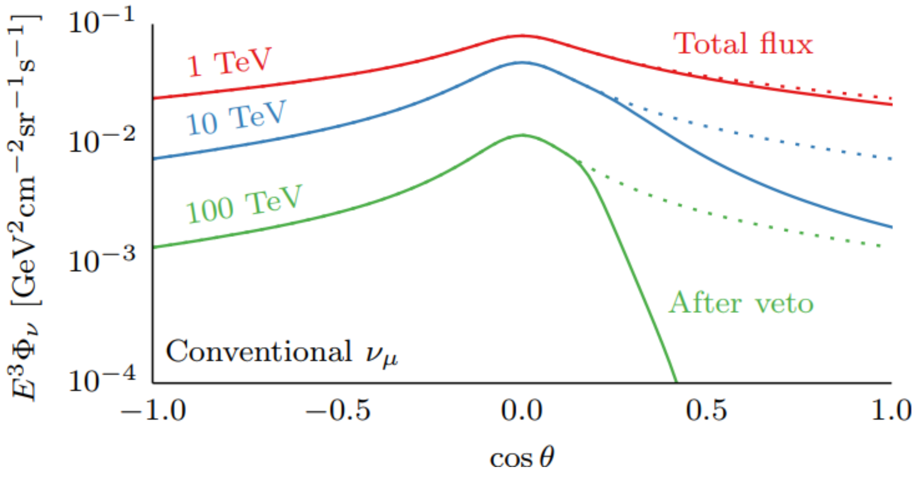
- Use the Earth as a shield
  - Only neutrinos can come from “below”
  - Look down, sacrifice half of the sky
- Use the detector to tag backgrounds
  - Only neutrinos can “start” inside
  - Sacrifice about half of your detector

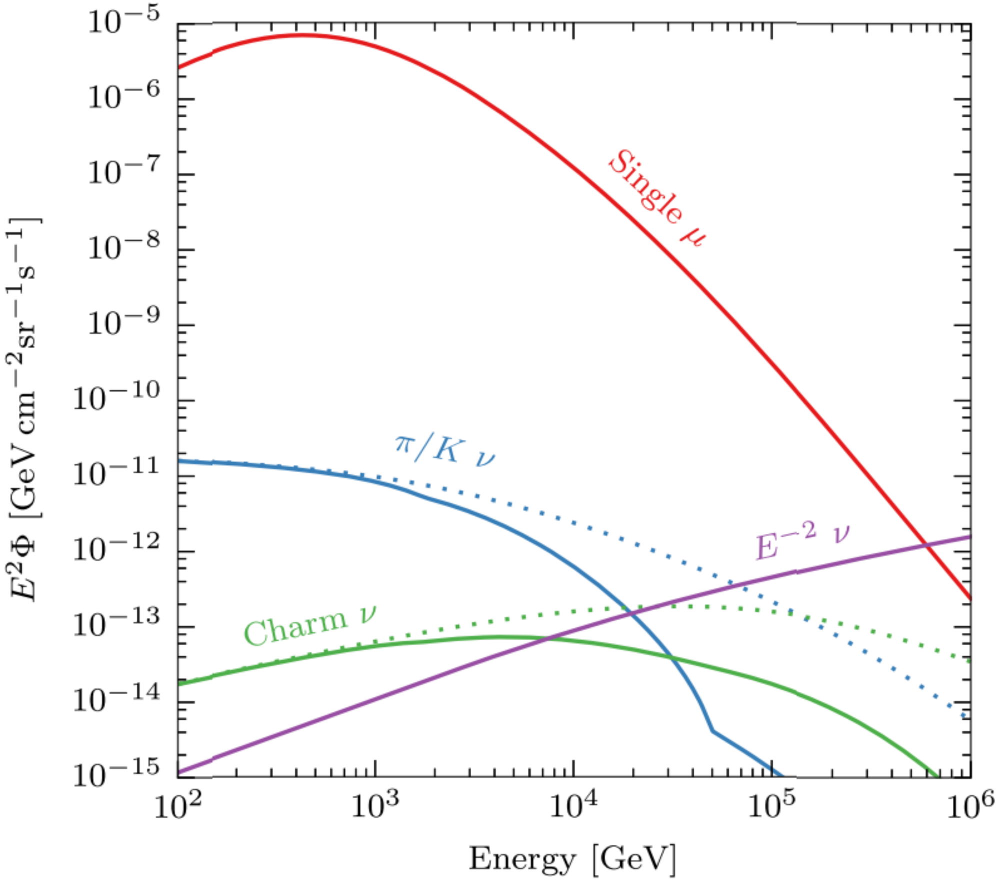




Diffuse, starting events

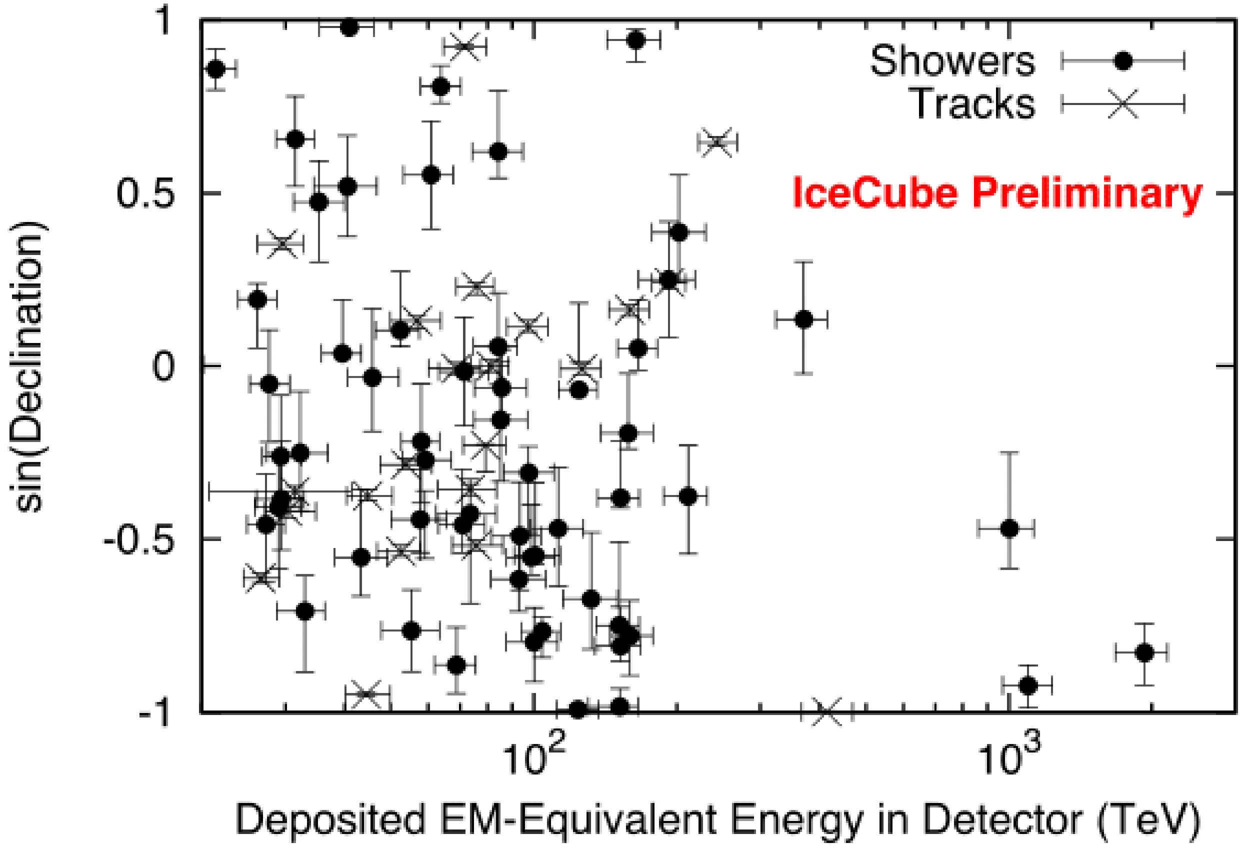
- Exploit different E spectra → focus on HE
- Use the detector as veto
  - Accompanying muons



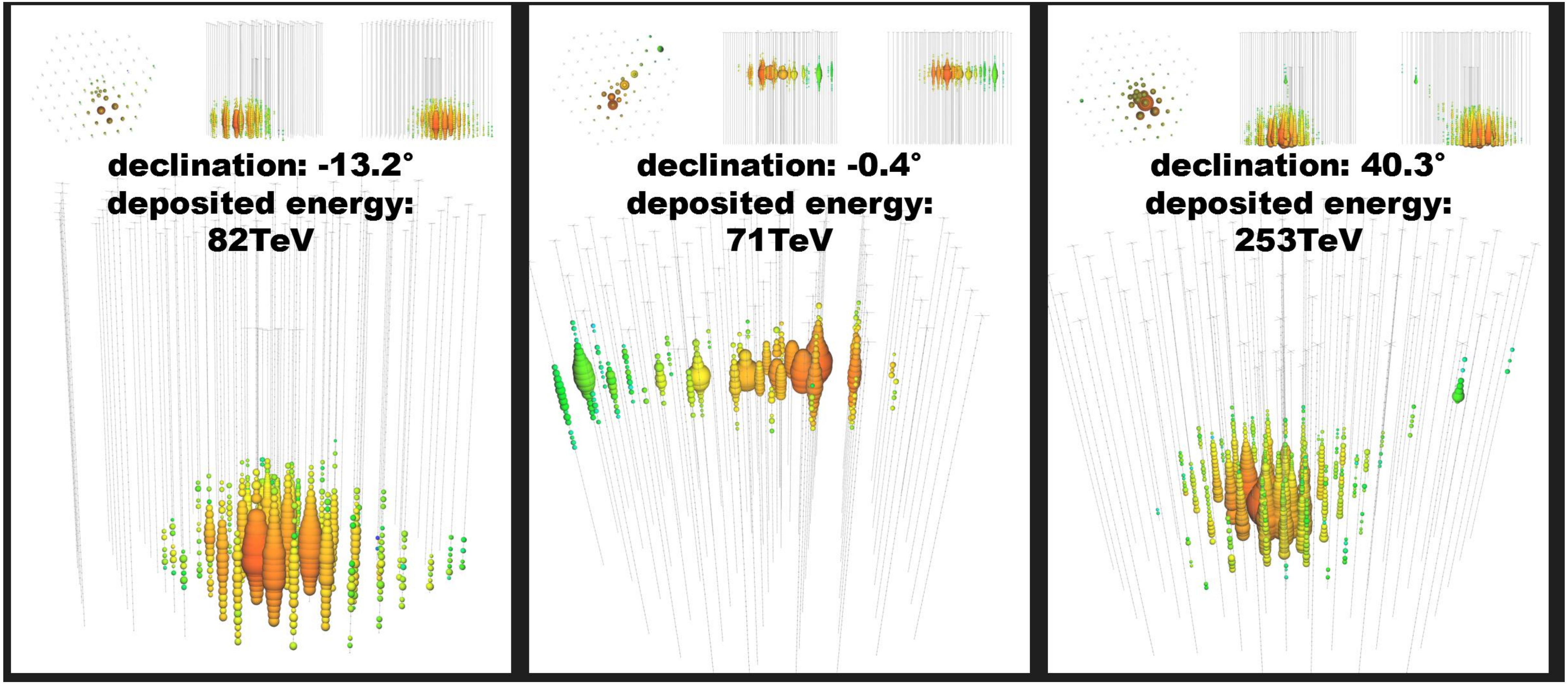


Starting events: Most recent results

- Using 6 years of data
- **80(+2)** events observed
- Estimated background:
- $15.6^{+11.4}_{-3.9}$ atm. neutrinos
- 25.2±7.3 atm. muons
- Two of them are an obvious (but expected) background:
- Coincident muons from two CR air showers



High energy events

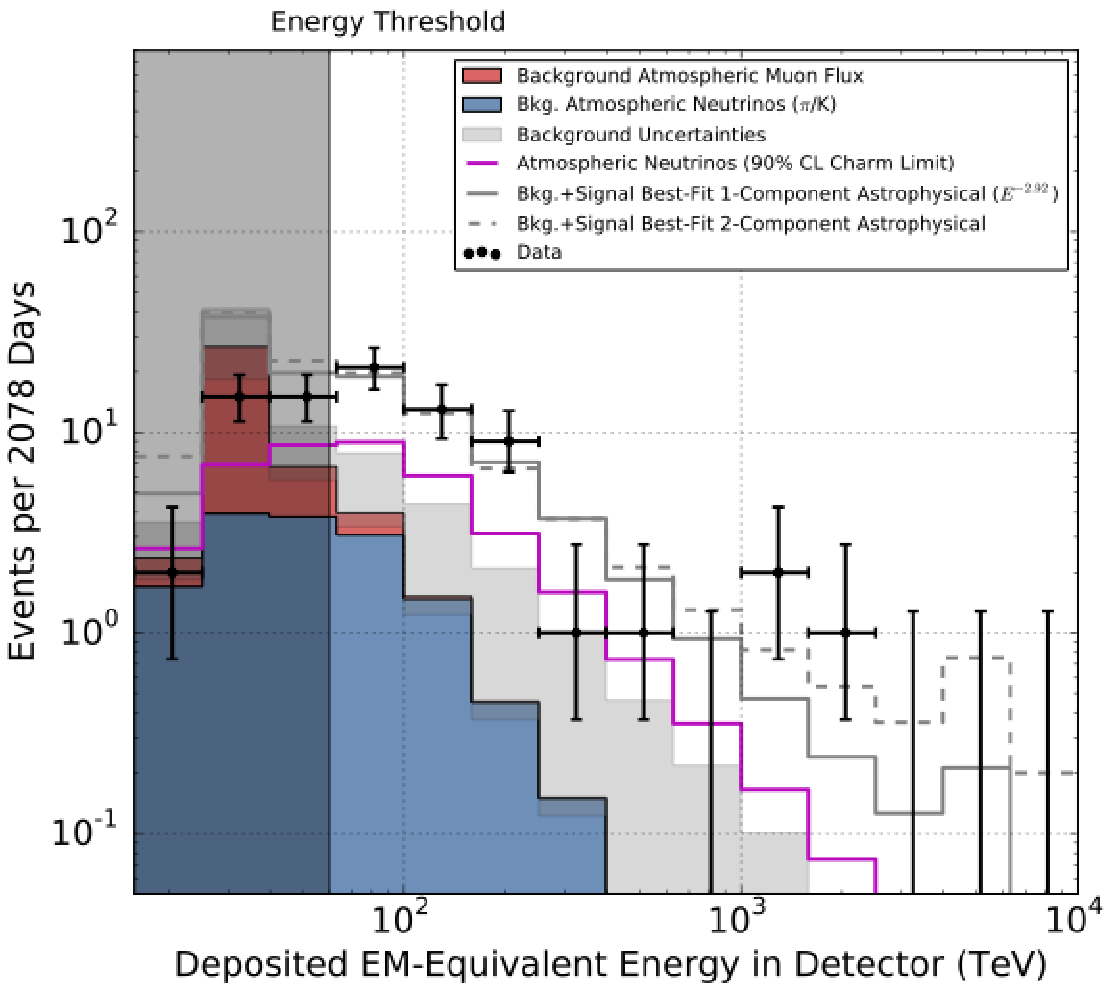


Starting events: Energy spectrum

- Compatible with benchmark single power-law model.
- Things might be more complicated, but this is not the analysis to decide that.
- Best fit spectral index

  $(E^{-\gamma})$: $\gamma=-2.92^{+0.33}_{-0.29}$
- $E^2\phi = 2.46 \pm 0.8 \times 10^{-8}$ x

  $(E / 100\text{TeV})^{-0.92}$ GeV cm^{-2} s^{-1} sr^{-1}

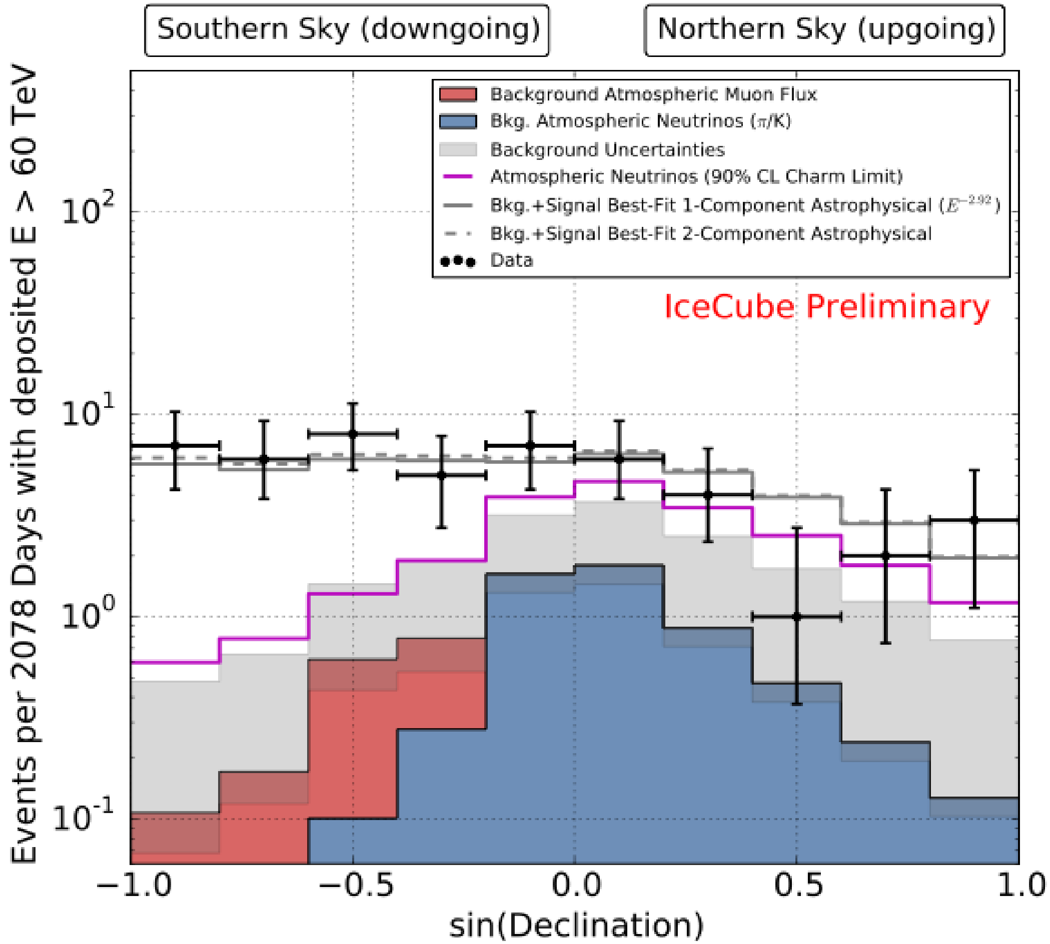


Starting events: Zenith distribution

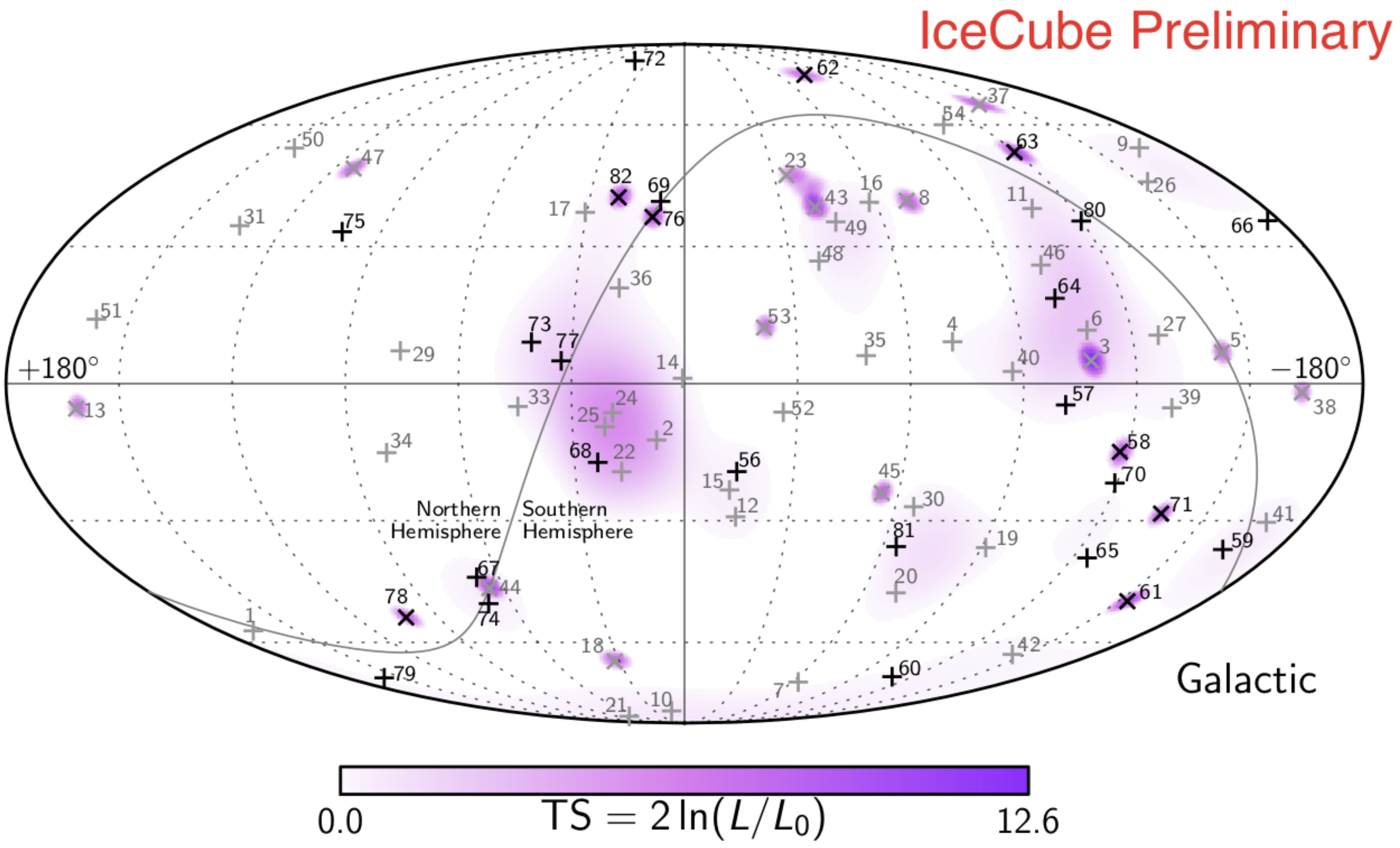
- Compatible with benchmark single power-law model.
- Things might be more complicated, but this is not the analysis to decide that.
- Best fit spectral index

  ($E^{-\gamma}$): γ=-2.92$^{+0.33}_{-0.29}$
- $E^2\phi$ = 2.46 ± 0.8 x 10^{-8} x

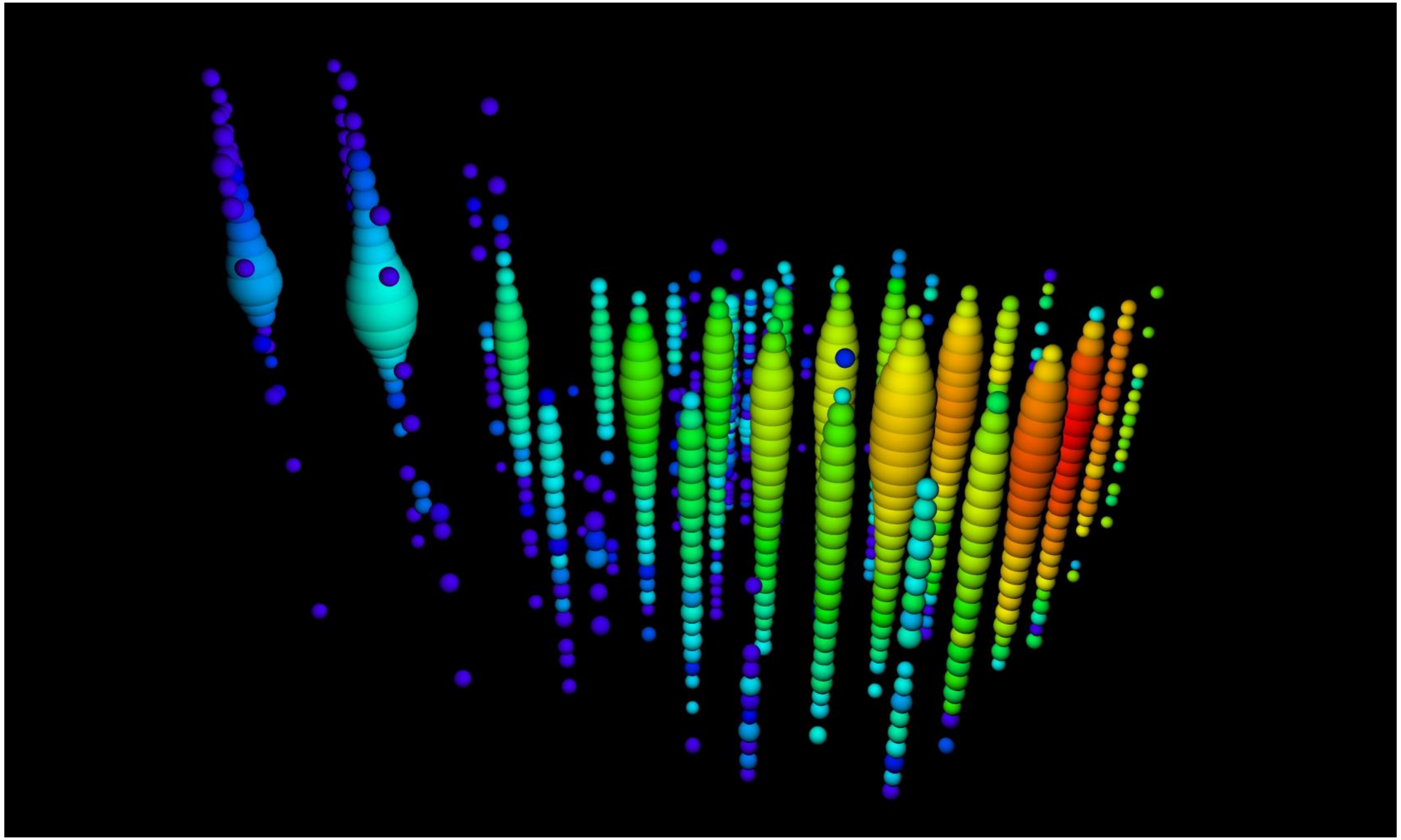
  (E / 100TeV)$^{-0.92}$ GeV cm^{-2} s^{-1} sr^{-1}



Starting events: clustering (or the lack-of)

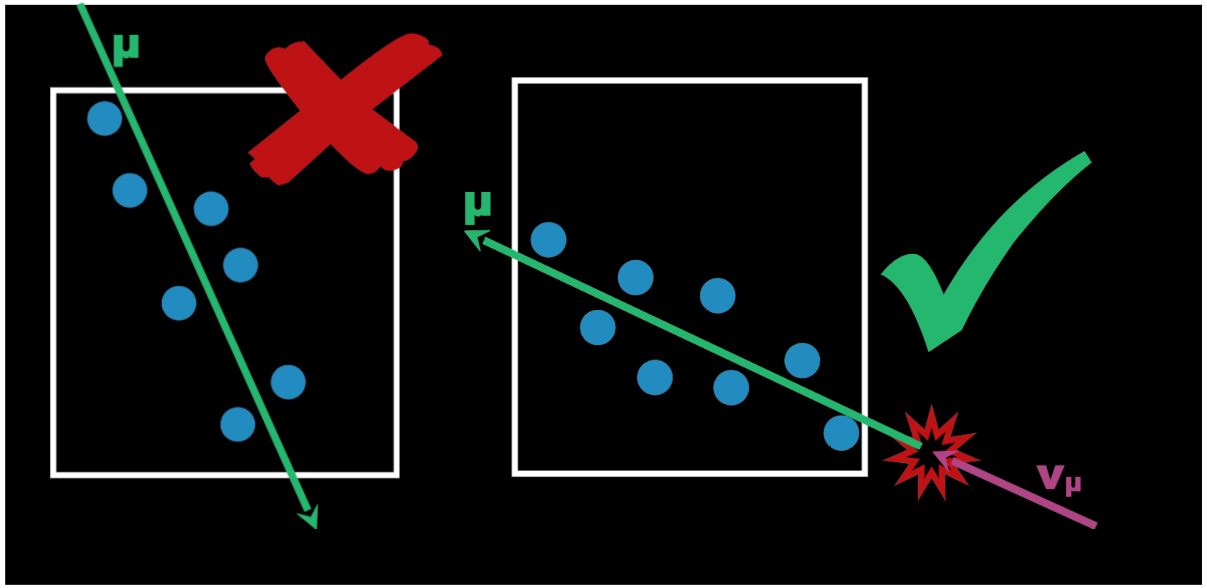


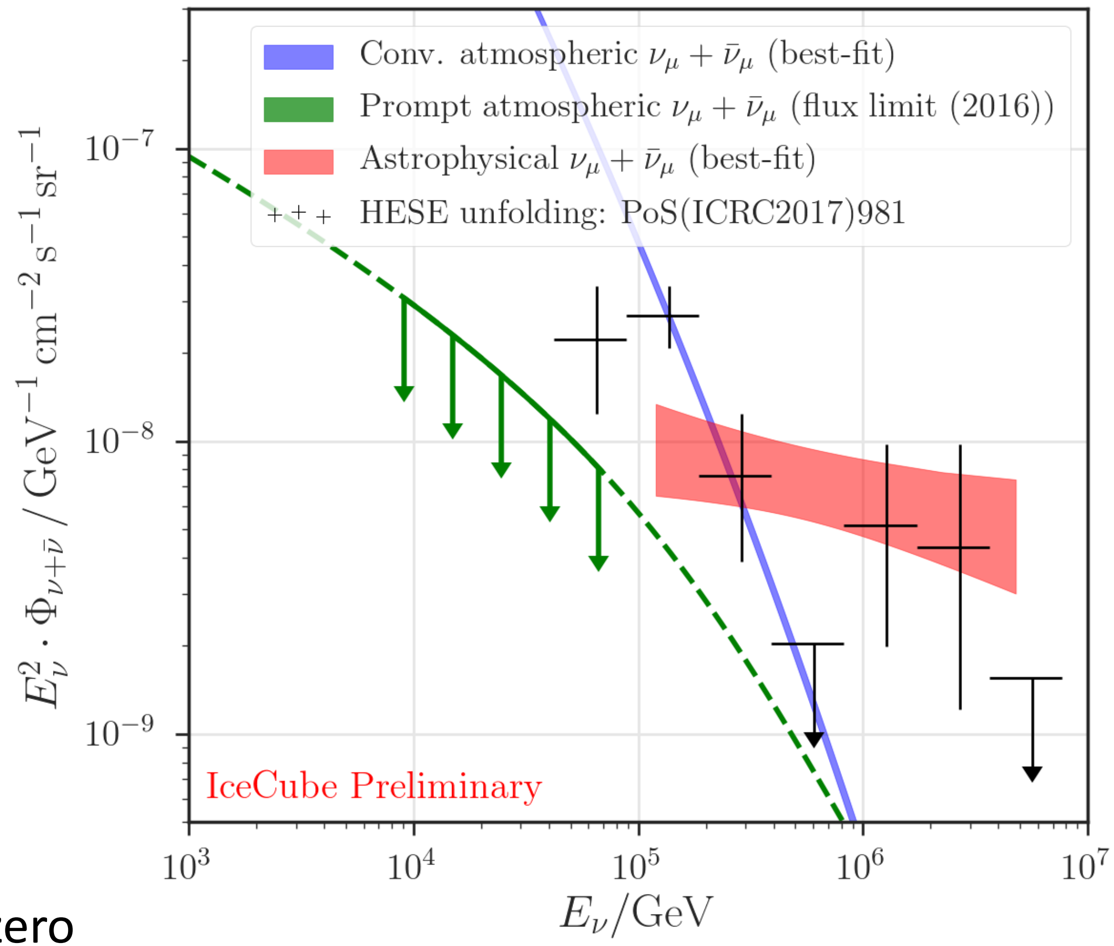
Through-going muons



- up-going (i.e. not a CR muon)
- deposited energy:2.6±0.3 PeV
- neutrino energy: 8.7 PeV (median)
- date: June 11, 2014
- direction: 11.48° dec / 110.34° RA
- ApJ 833 (2016) no.1, 3

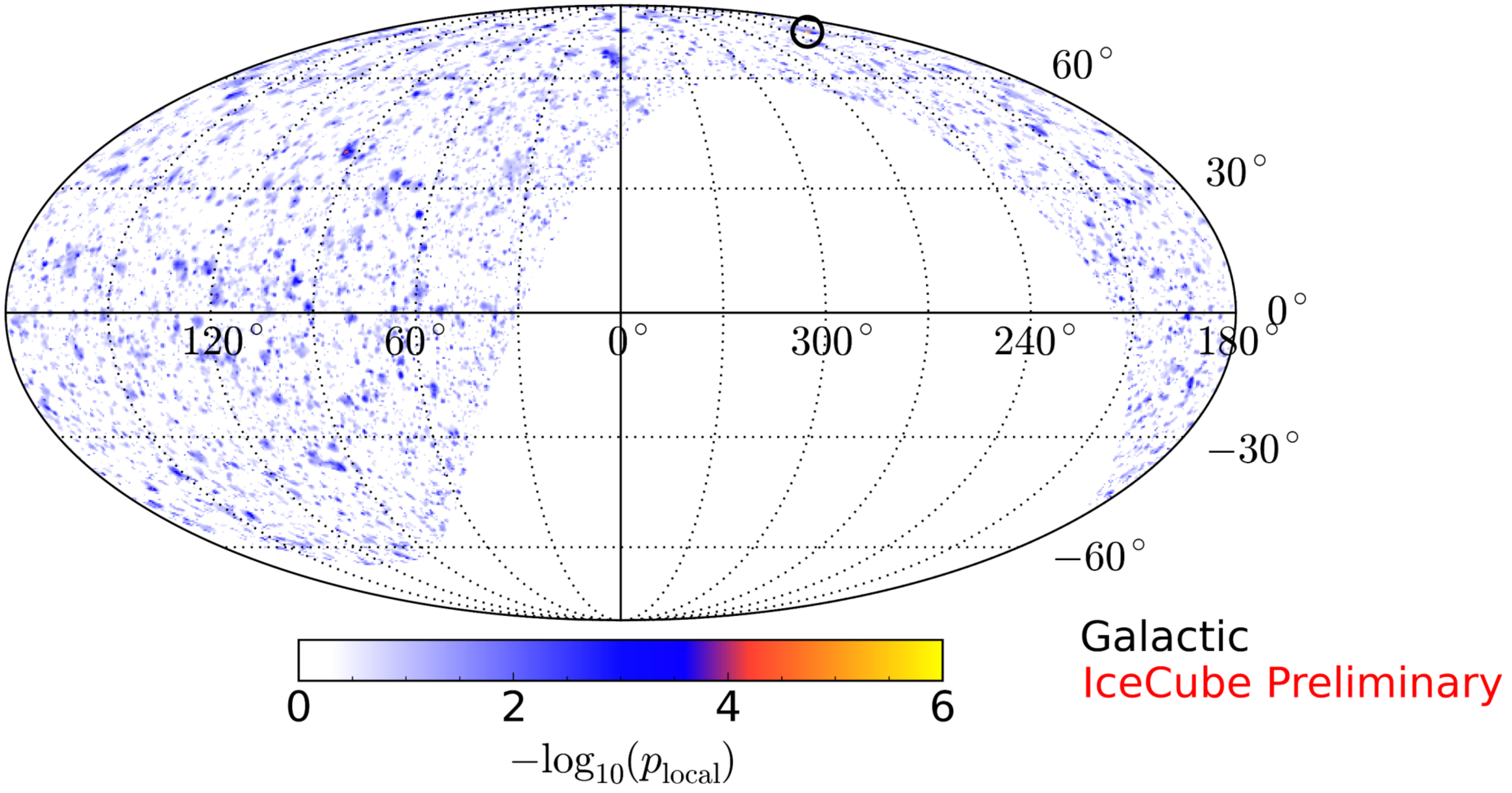
Through-going muons





- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~120 TeV
- power-law index: 2.19±0.10prompt component fits to zero

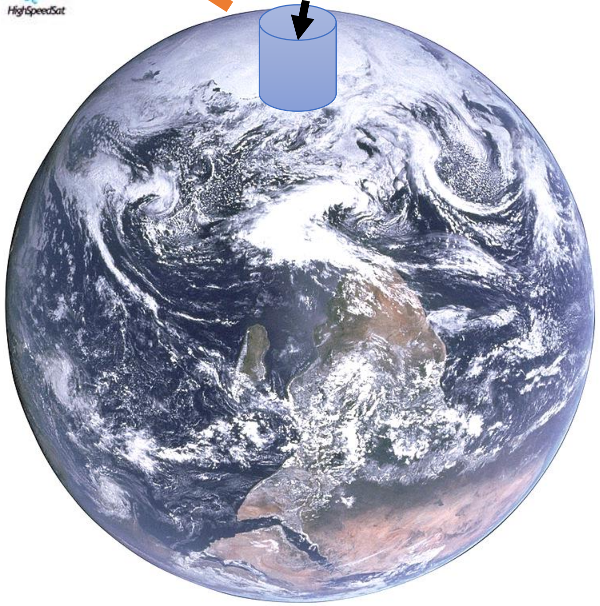
Through-going muons: lack of clustering



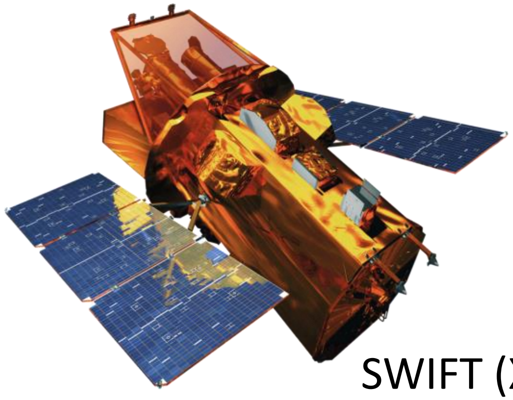
Alerts & follow-ups

PTF (optical)

"The North"



Gamma ray telescopes
(Veritas, HESS, MAGIC)



SWIFT (X-ray)

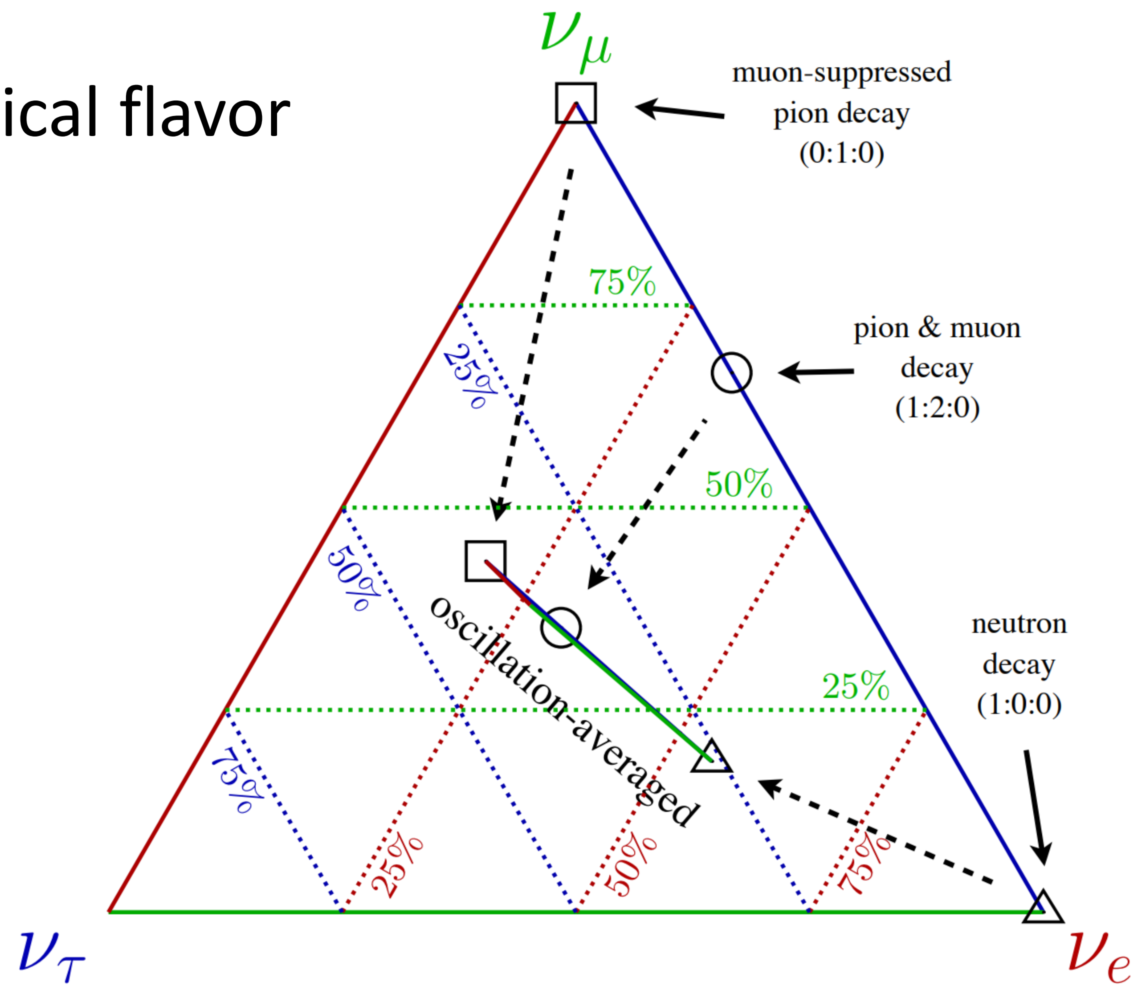
Astrophysical flux flavor composition

- Multiple predictions for astrophysical flavor

  $(\nu_e:\nu_\mu:\nu_\tau)$
  - Standard pion+muon decay (1:2:0)
  - Muon damped (0:1:0)
  - Neutron decay (1:0:0)

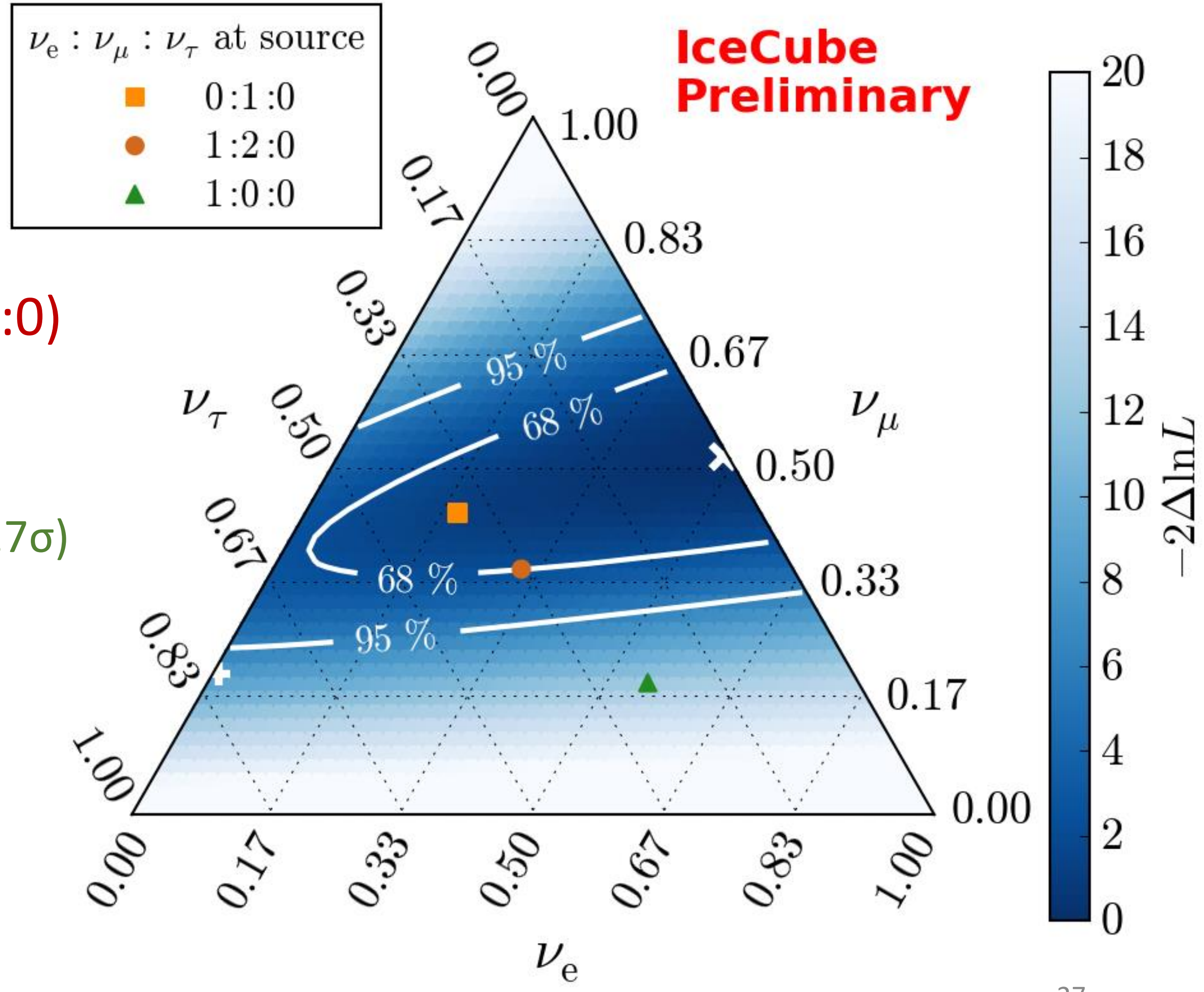
Oscillations

- Detection flavor close to (1:1:1)



Astrophysical flux flavor composition

- Simultaneous spectrum fit
  (ν_e:ν_μ:ν_τ)
  - Standard pion+muon decay (1:2:0)
  - Muon damped (0:1:0)
  - Neutron decay (1:0:0)
    - Only one significantly excluded (3.7σ)
- No tau-neutrino signals yet
  - Hard to identify
  - Compatible with statistics



ApJ 809, 98 (2015)/PoS(ICRC2015)1066

Summary from hell

- Well established diffuse **astrophysical neutrino flux** observed
- Neutrinos found up to **a few PeV**
- Sources **not yet** identified
- Multi-messenger program in place looking for **coincidences**
- Identification of **neutrino flavor** ongoing – no HE tau neutrino yet

All studies are limited by **statistics**

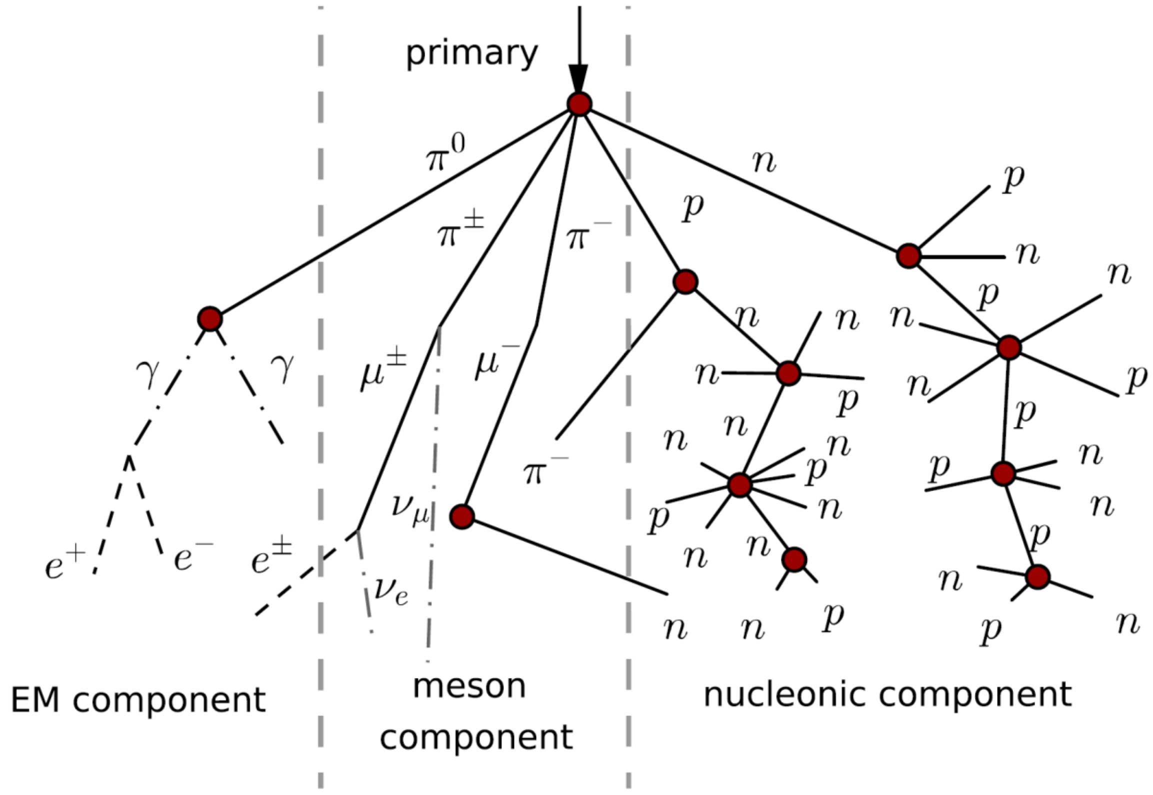
we need more events

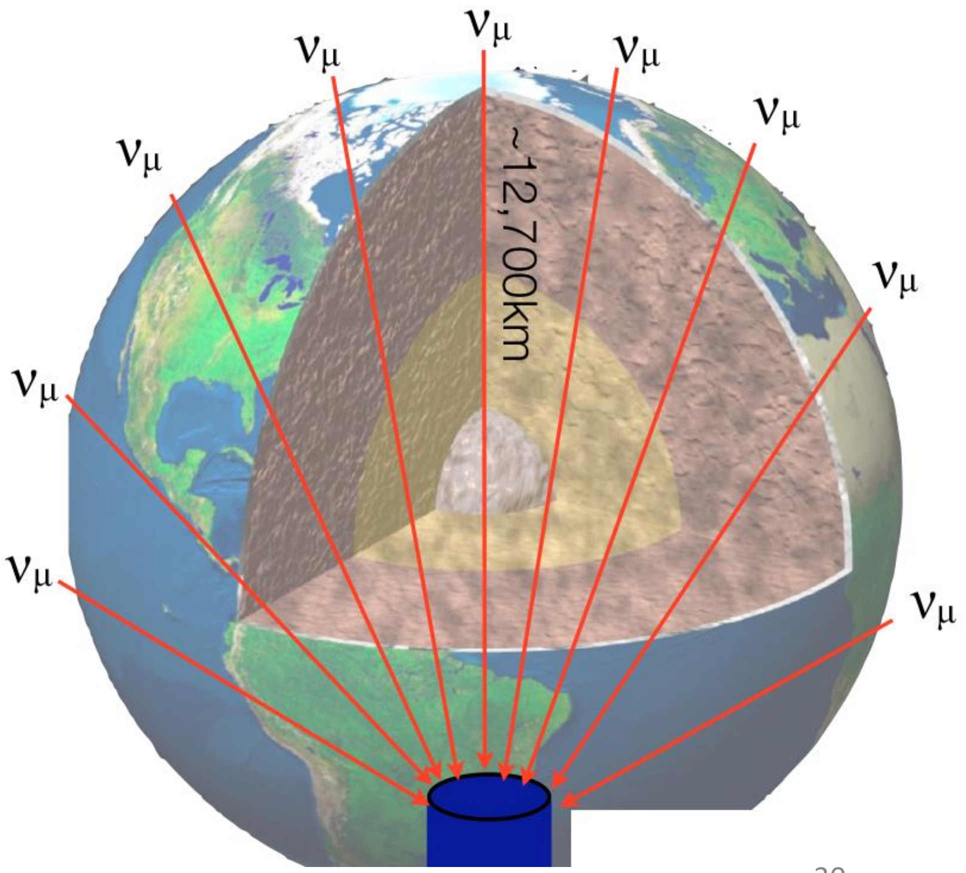
Neutrinos from heaven

10-100 GeV

Atmospheric neutrinos

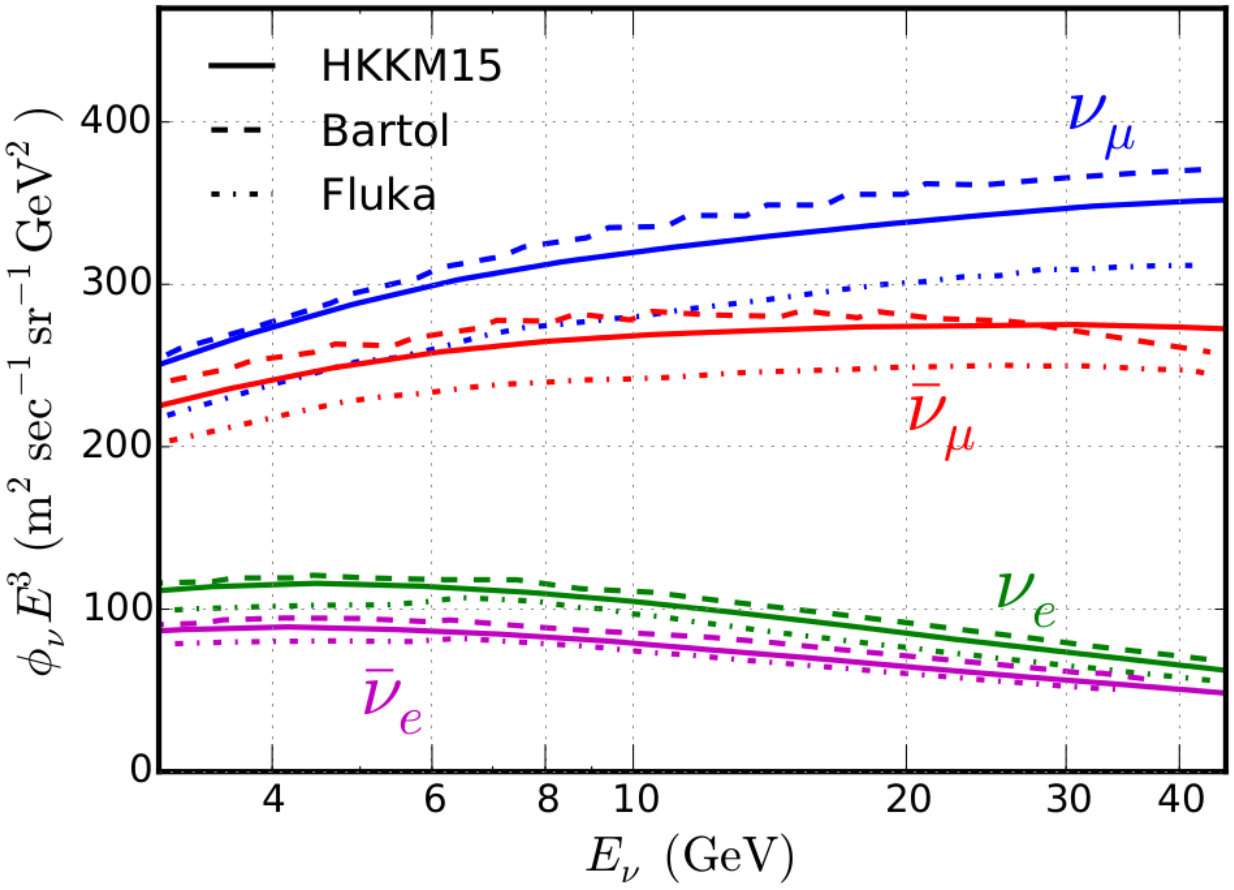
- Some people's background is another people's signal

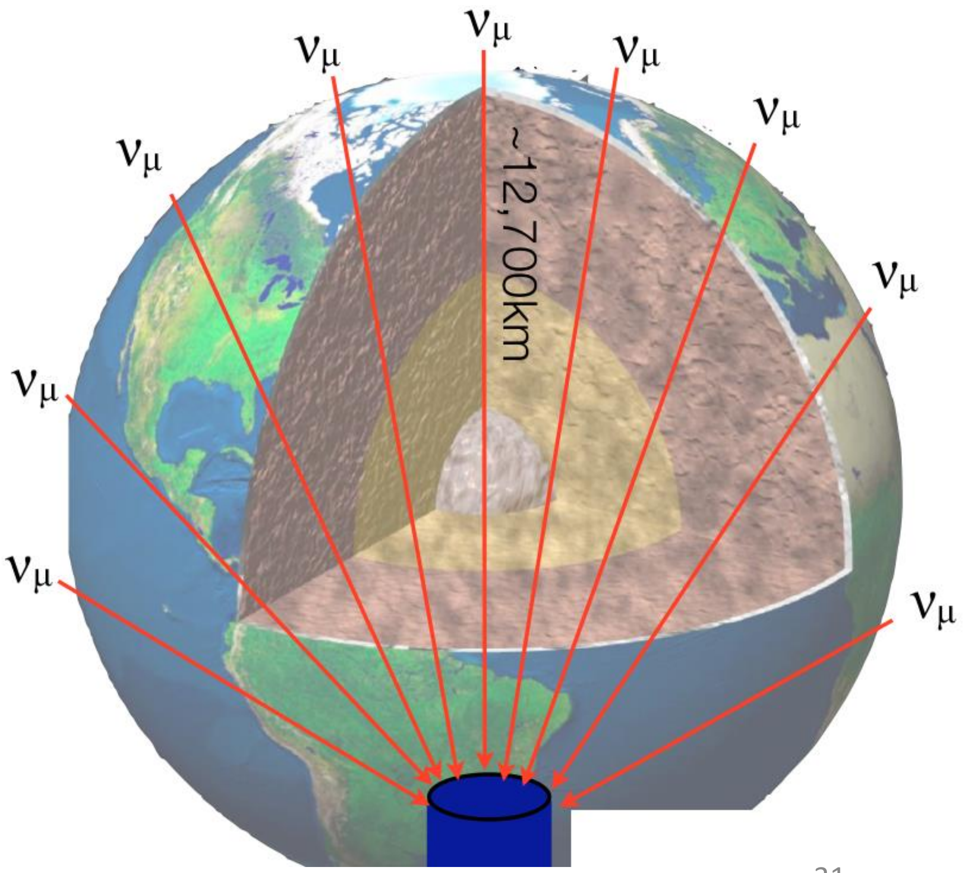




Atmospheric neutrinos

- Free beam of neutrinos. Wide E range, varying travel distance.





Neutrino oscillations in 2 minutes or less

Neutrino production

- definite flavor (associated $l^{+/-}$)
- superposition of mass eigenstates

Propagation

- as massive states → phase exp(-*ipx*)
- traveling close together, maintain coherence

Ddetection (interaction)

- coherent sum of mass states
- associated $l^{+/-}$ determines flavor

Neutrino oscillations in 2 minutes or less

$$\nu_\alpha = \sum_{k=1..3} U^*_{\alpha k}\, \nu_k$$

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

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Propagation

- as massive states → phase exp(-*ipx*)
- traveling close together, maintain coherence

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- associated *l* $^{+/-}$ determines flavor

Oscillations!

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

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

Neutrino oscillations in 2 minutes or less

$$\nu_\alpha = \sum_{k=1..3} U^*_{\alpha k}\, \nu_k$$

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

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- definite flavor (associated *l* $^{+/-}$)
- superposition of mass eigenstates

Propagation

- as massive states → phase exp(-*ipx*)
- traveling close together, maintain coherence

Ddetection (interaction)

- coherent sum of mass states
- associated *l* $^{+/-}$ determines flavor

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

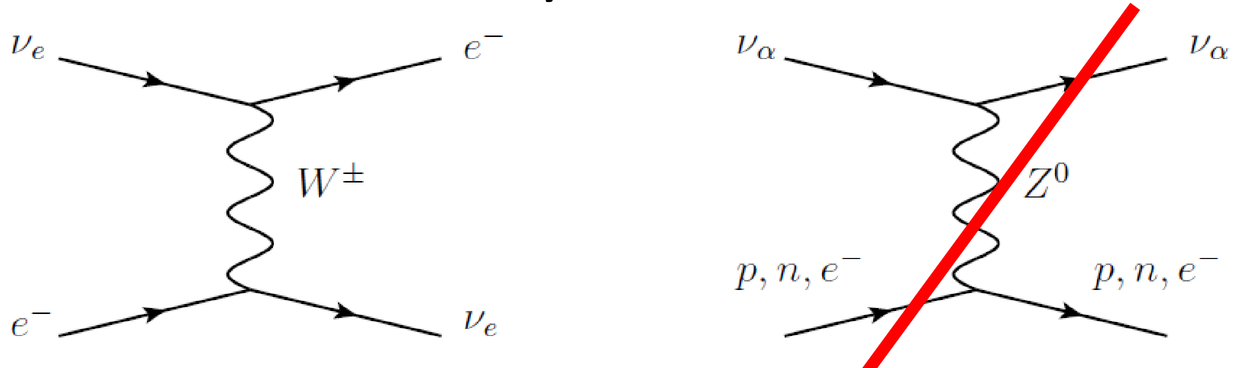
Relevant mass-splitting

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

effective mixing angle

Caveat: influence of matter

- Scattering processes in ordinary matter



(a) CC (b) NC

- In constant electron density

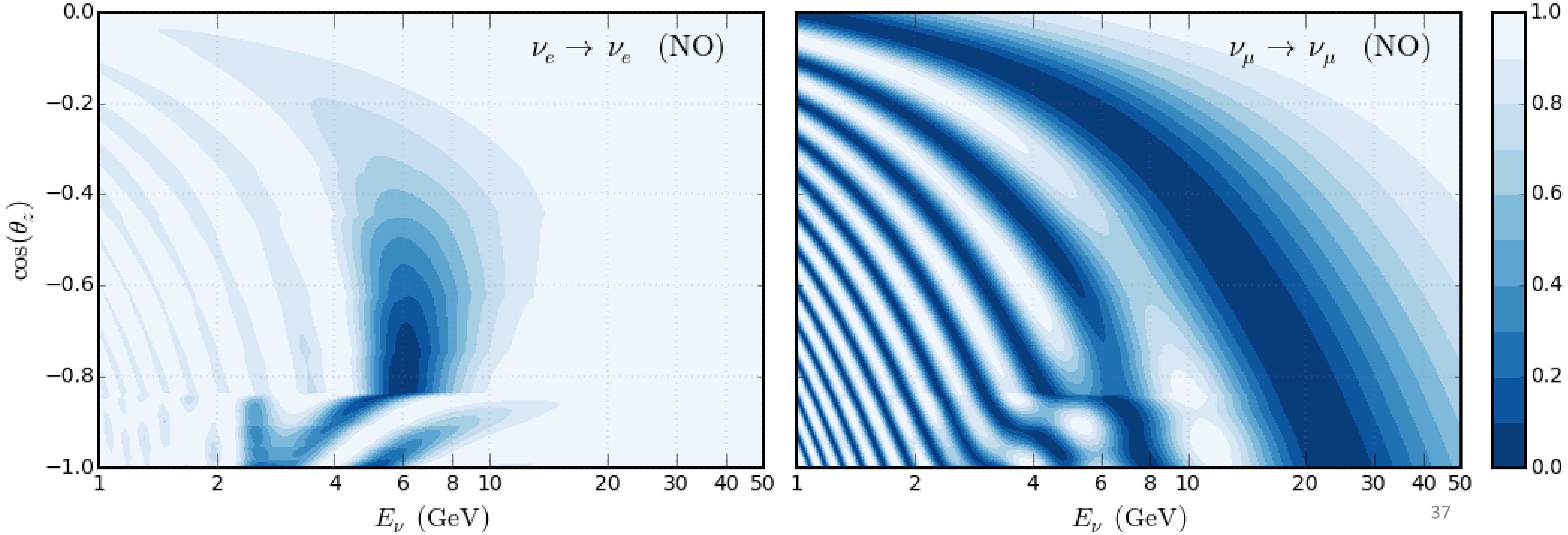
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{\mathrm{CC}})^2 + (\Delta m^2 \sin 2\theta)^2}\,,$$

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

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

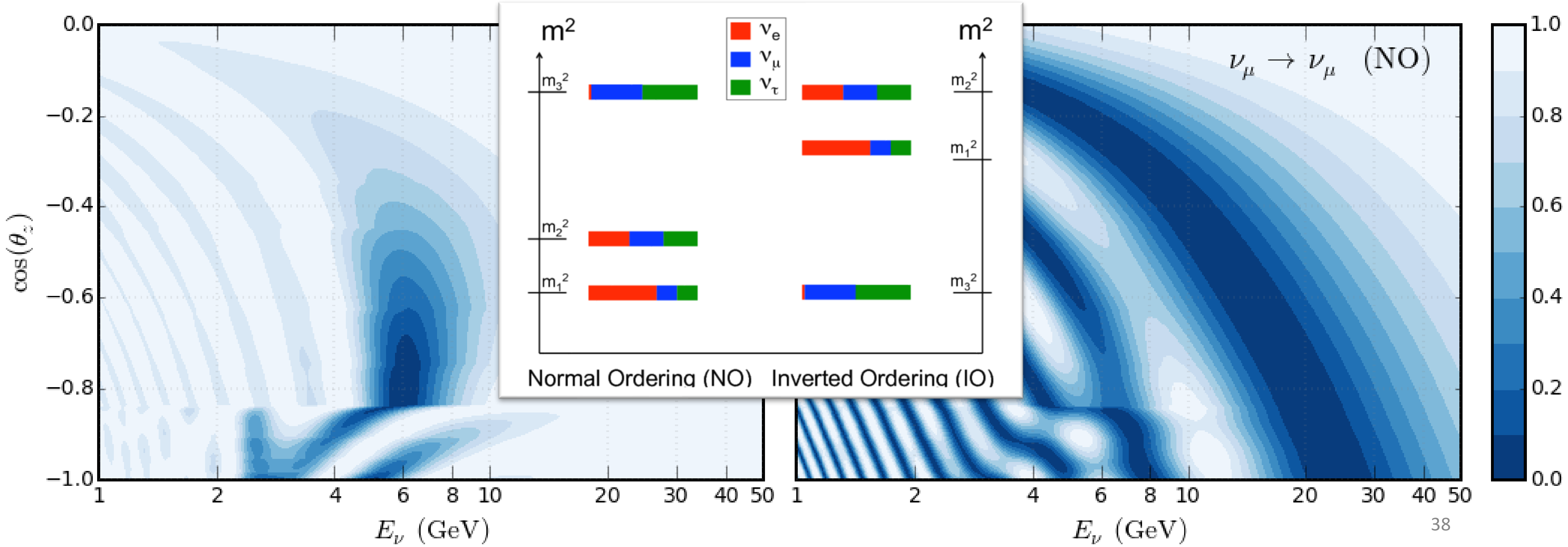
Standard oscillations in matter

Survival probabilities for atmospheric neutrinos (no approximations)



Standard oscillations in matter

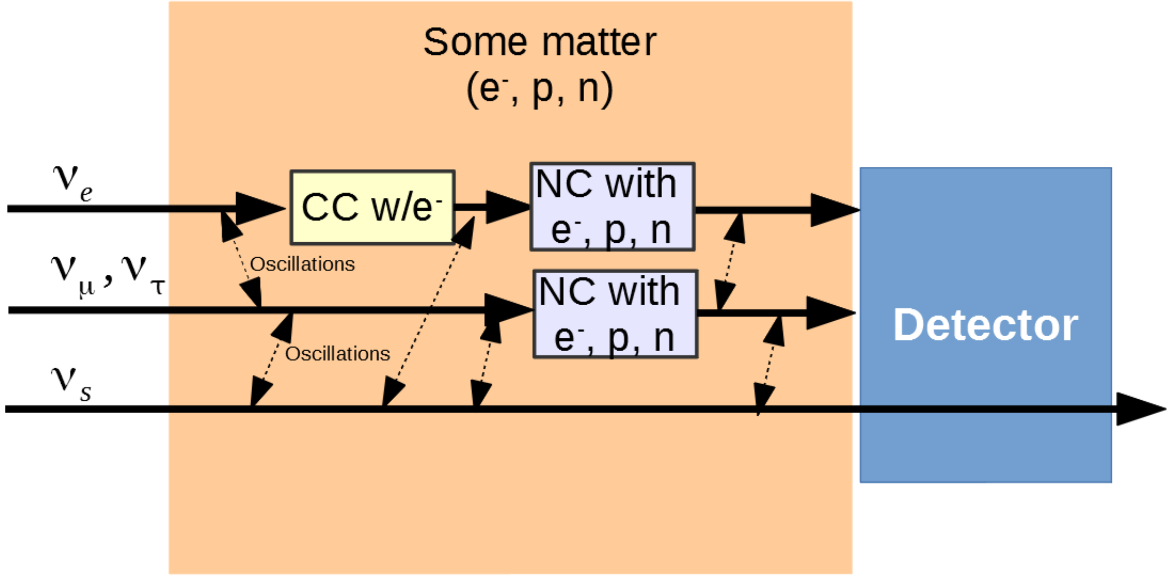
Survival probabilities for atmospheric neutrinos (no approximations)



And sterile neutrinos? They also fit

- Possibility: Additional neutrino state that doesn't couple to W/Z
  - New state mixes with known ones
  - Ex: 3+1 → +3 mixing angles +1 phase

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$



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

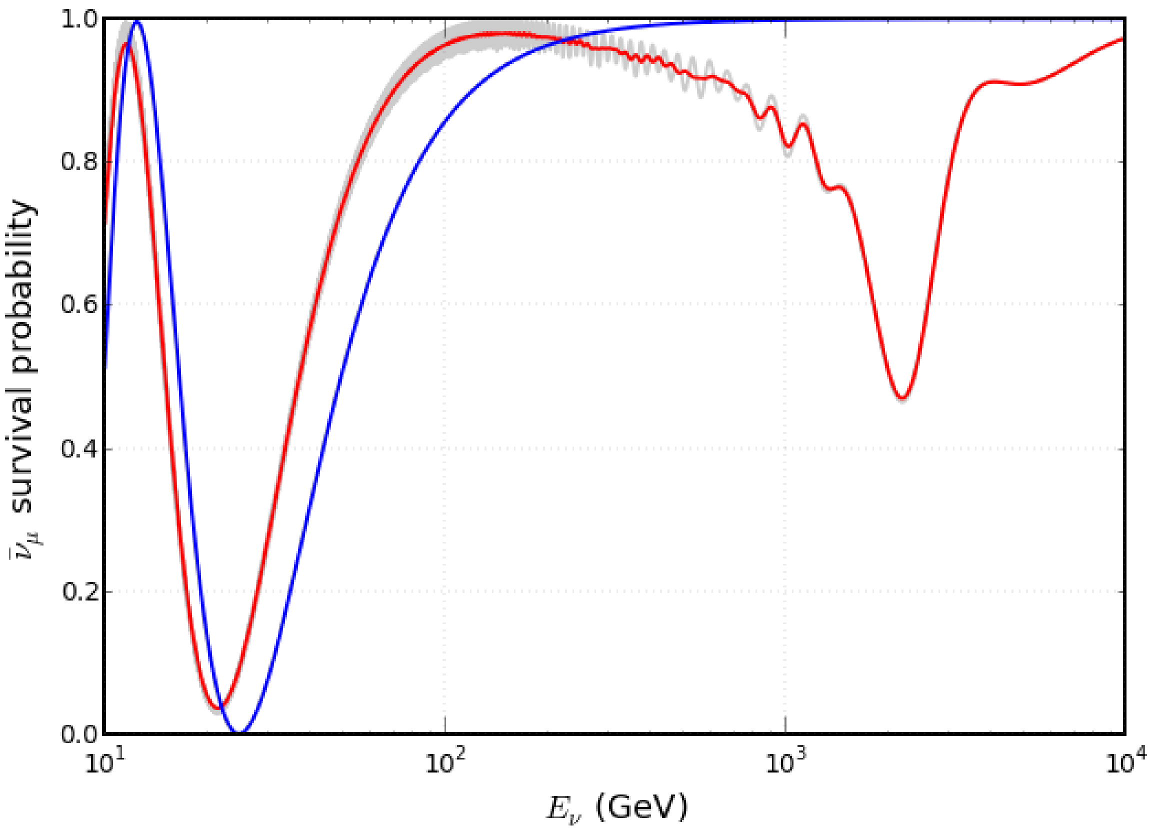
Sterile neutrino flux modifications

- For a higher mass difference

  → higher E

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

- Additional sterile mixing + matter enhancements changes oscillation amplitudes also at low energies



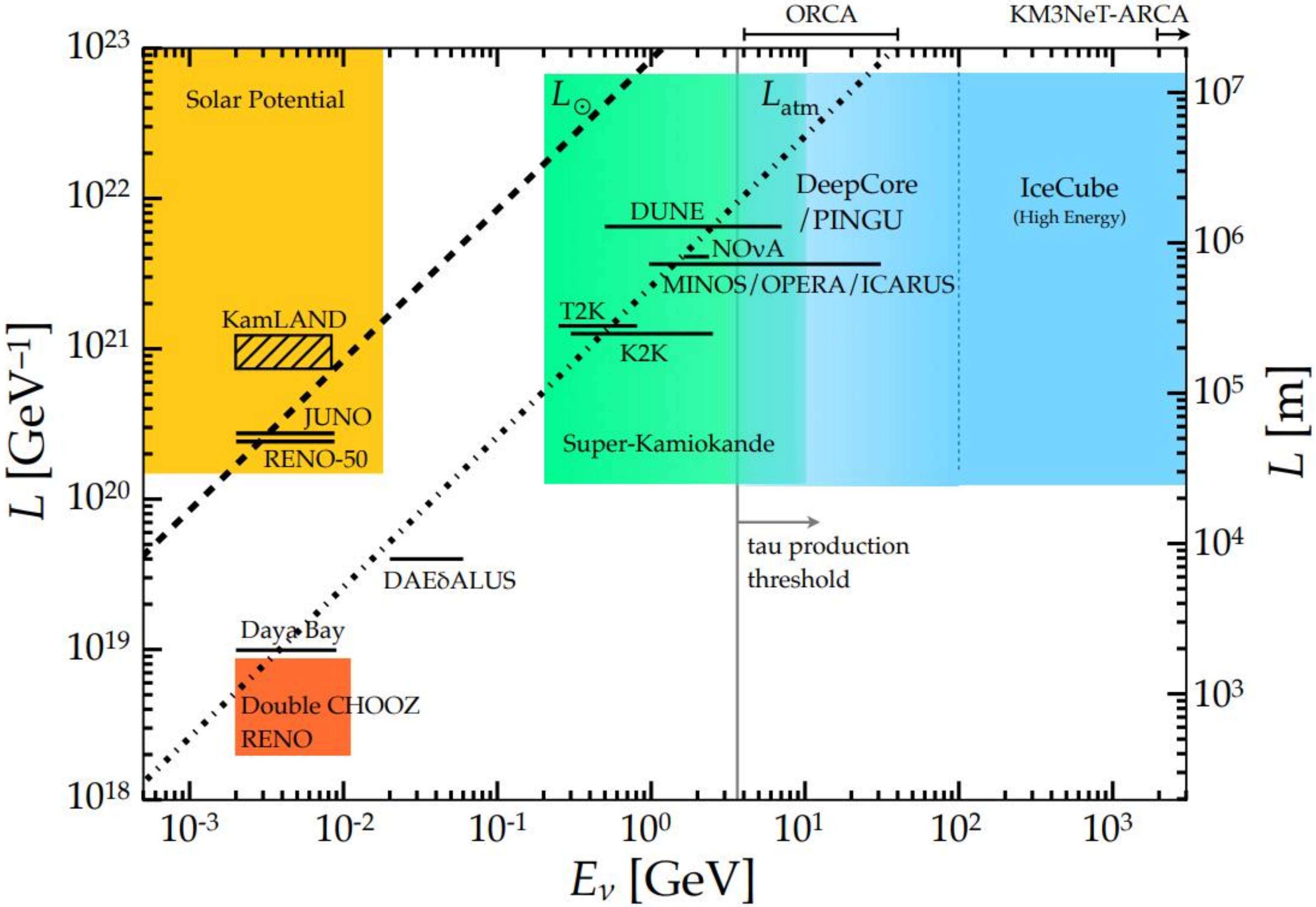
Probing oscillations

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

Relevant mass-splitting

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

effective mixing angle

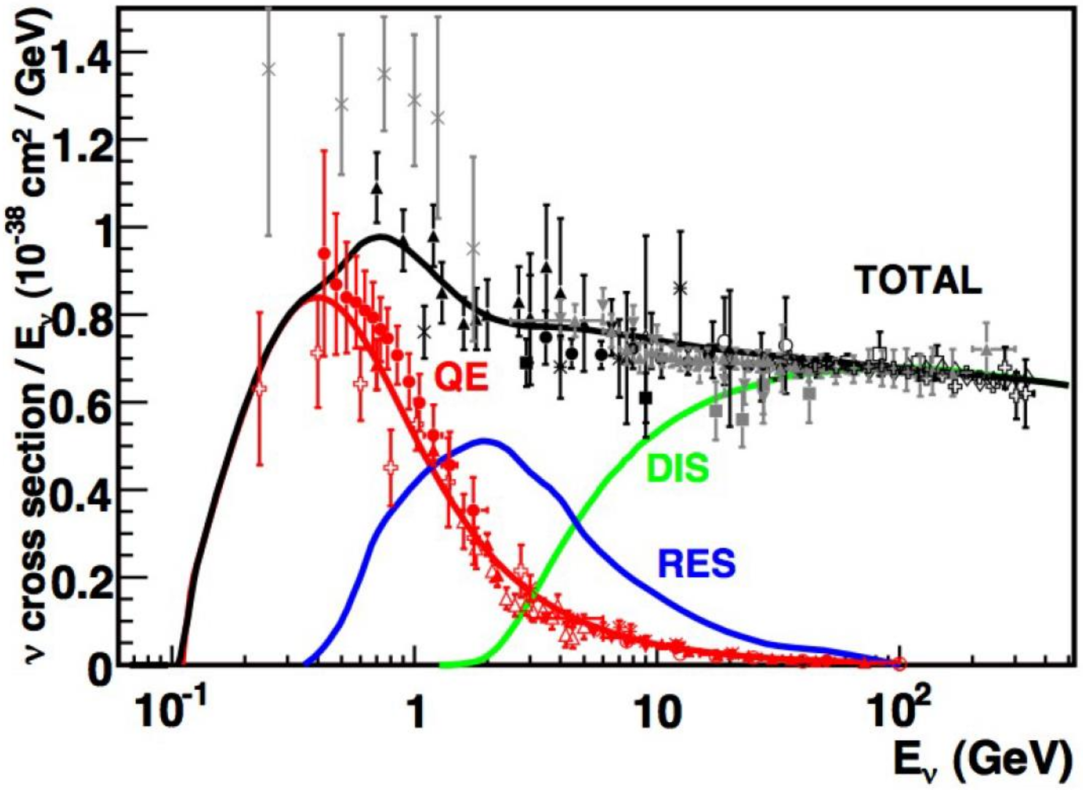


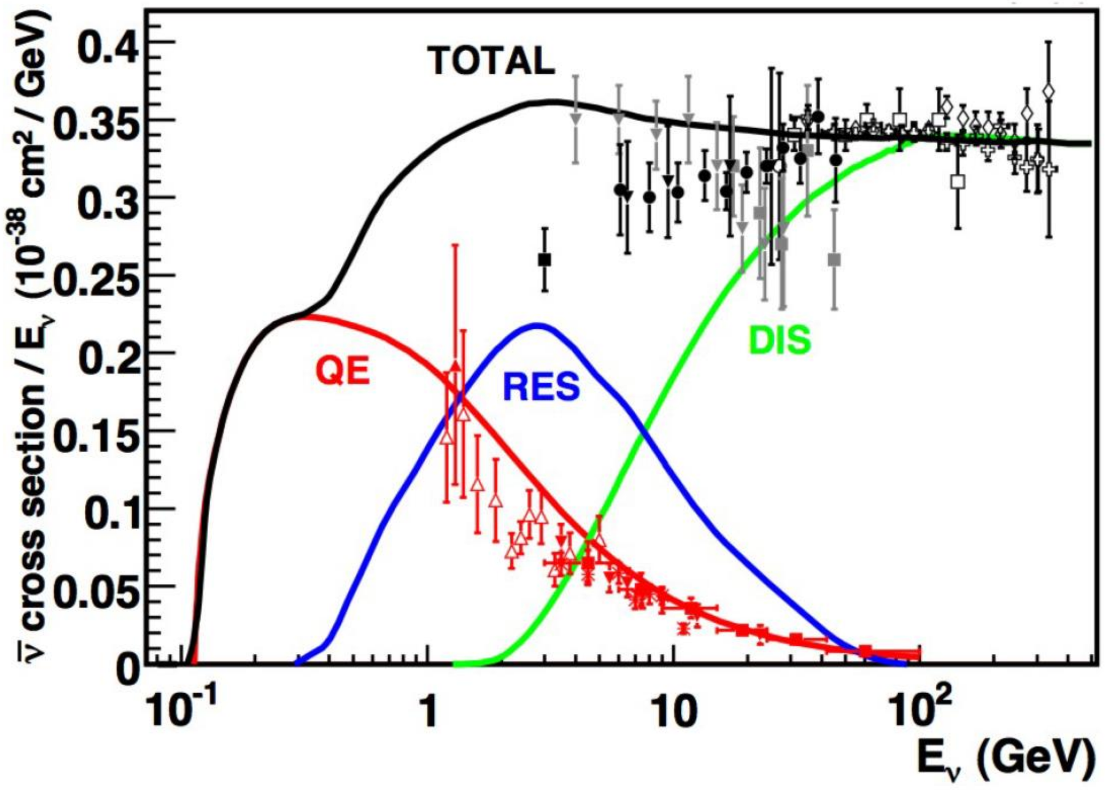
With atm. nu:

- large L&E regions of phase space
- 2 ν, anti-ν flavors in "beam"
- on/off signal regions
- E > τ threshold

Added bonus: neutrino-nucleon xs

- High energy atmospherics: deep inelastic scattering regime





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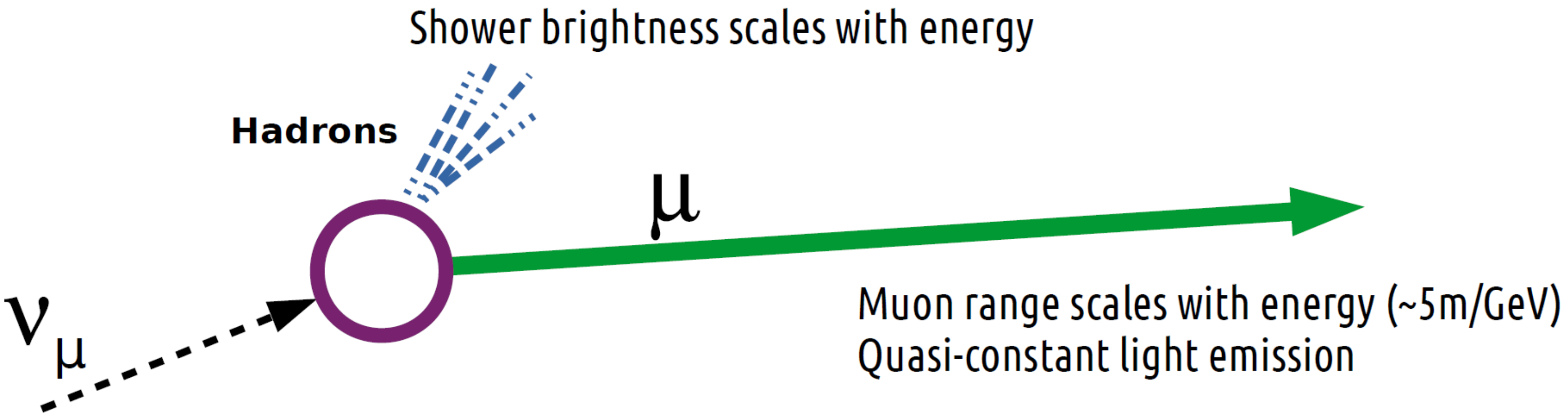
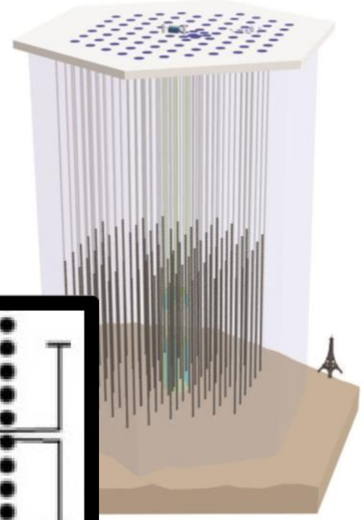
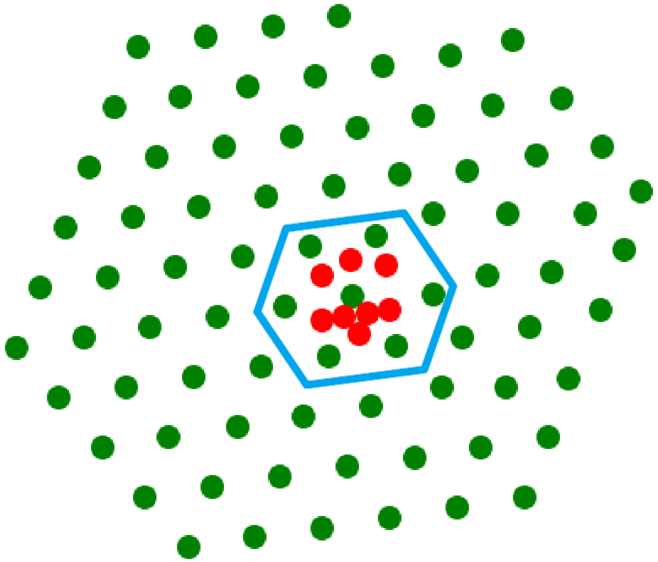
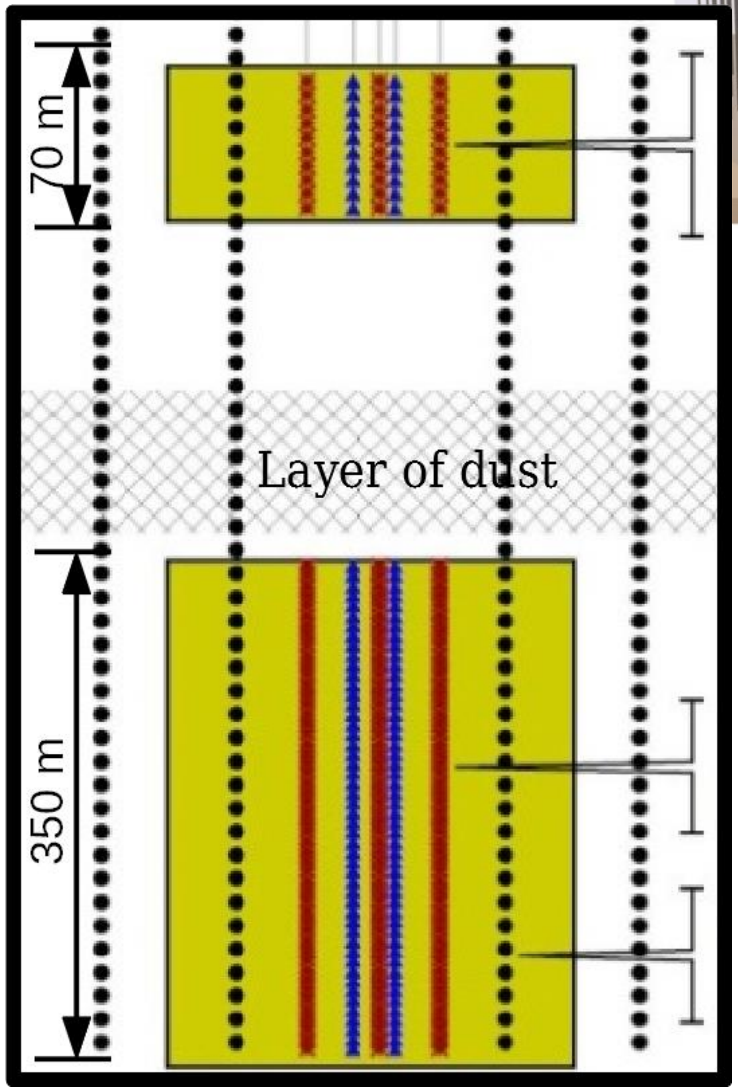


IceCube DeepCore

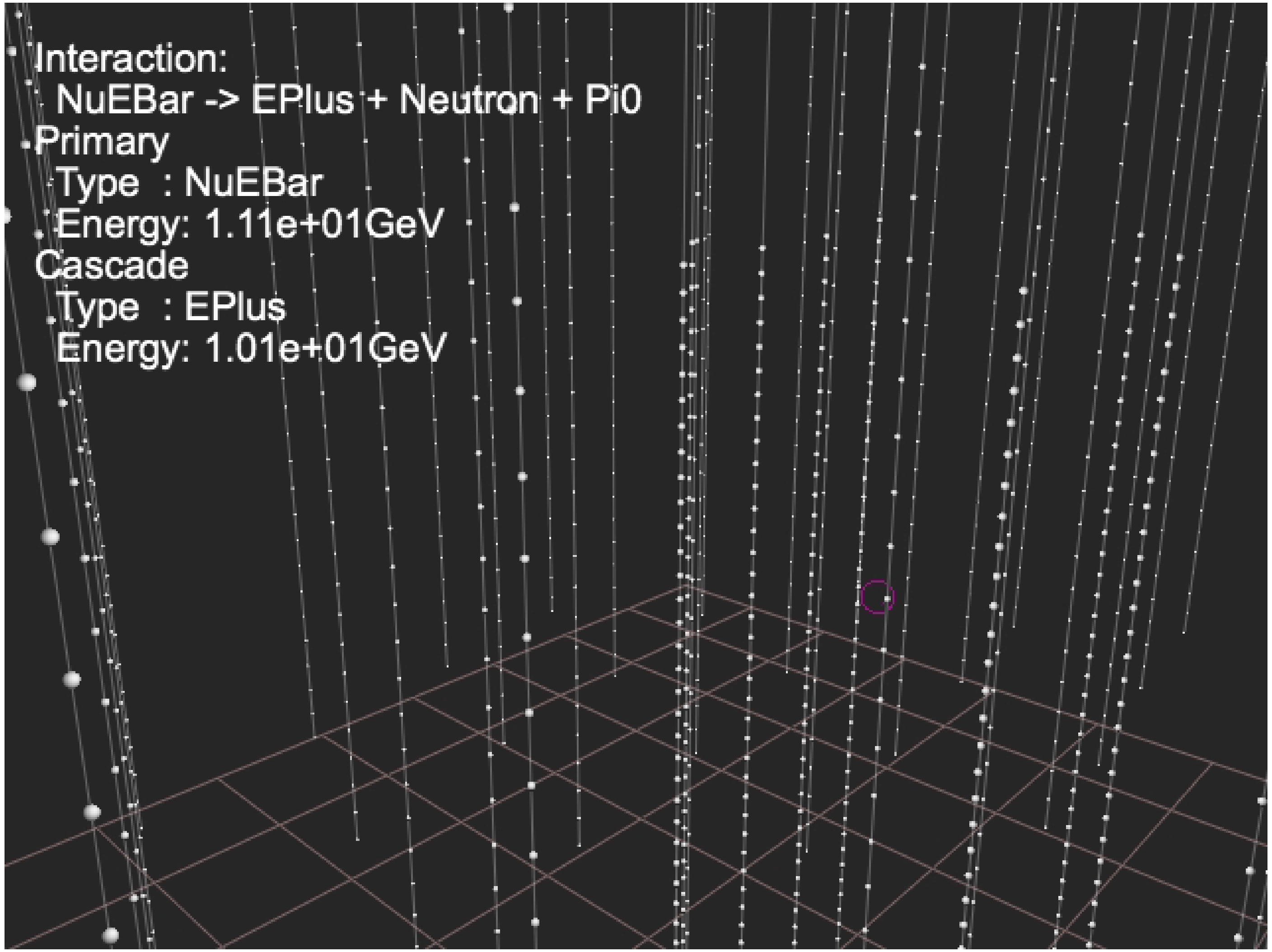
- 8 + 7 strings (DC + IC)
- About 500 DOMs in fid. vol.
- Spacing: 7m in z, 40-70m in x-y
- Neutrino energy threshold: 10 GeV



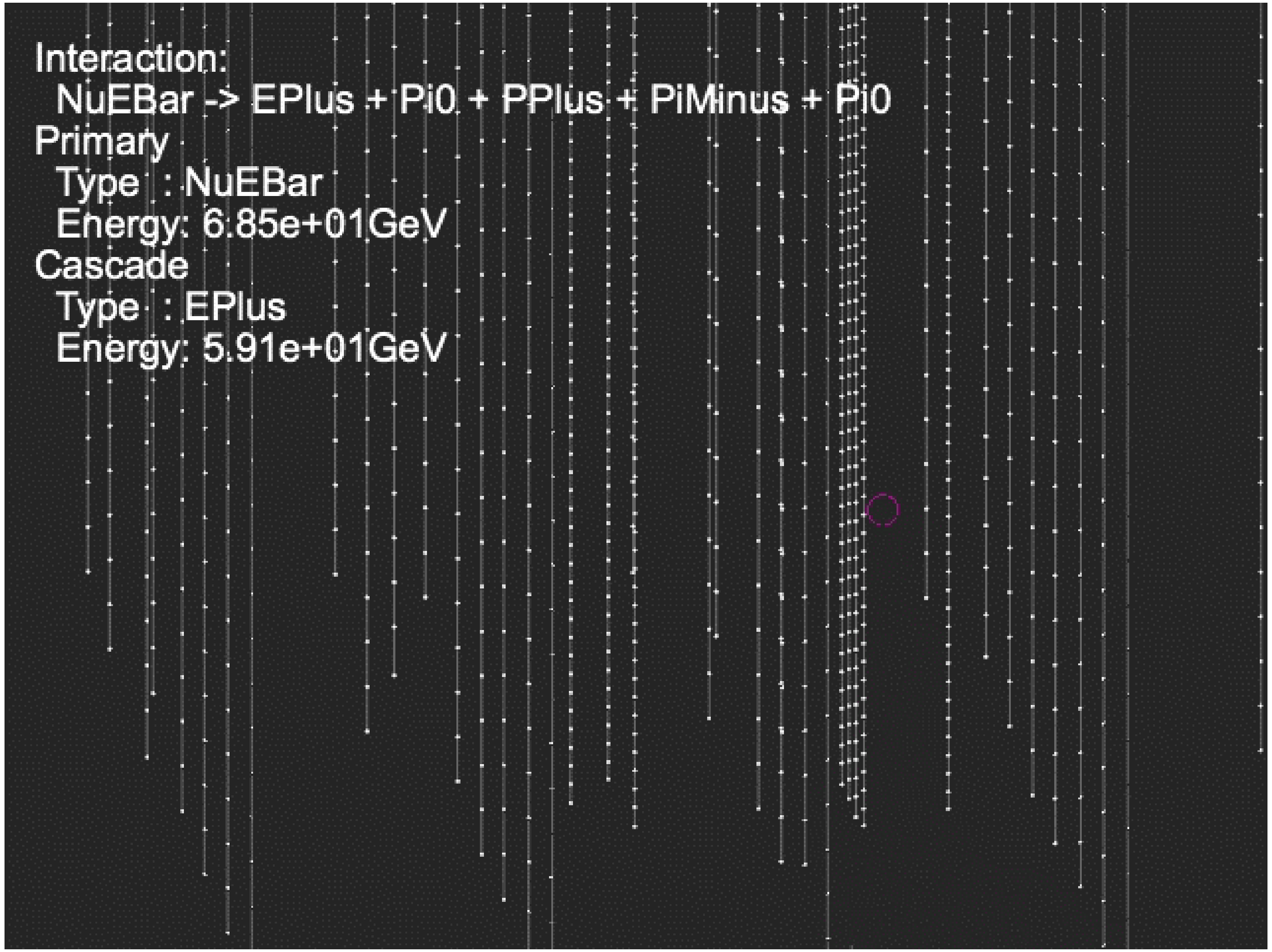




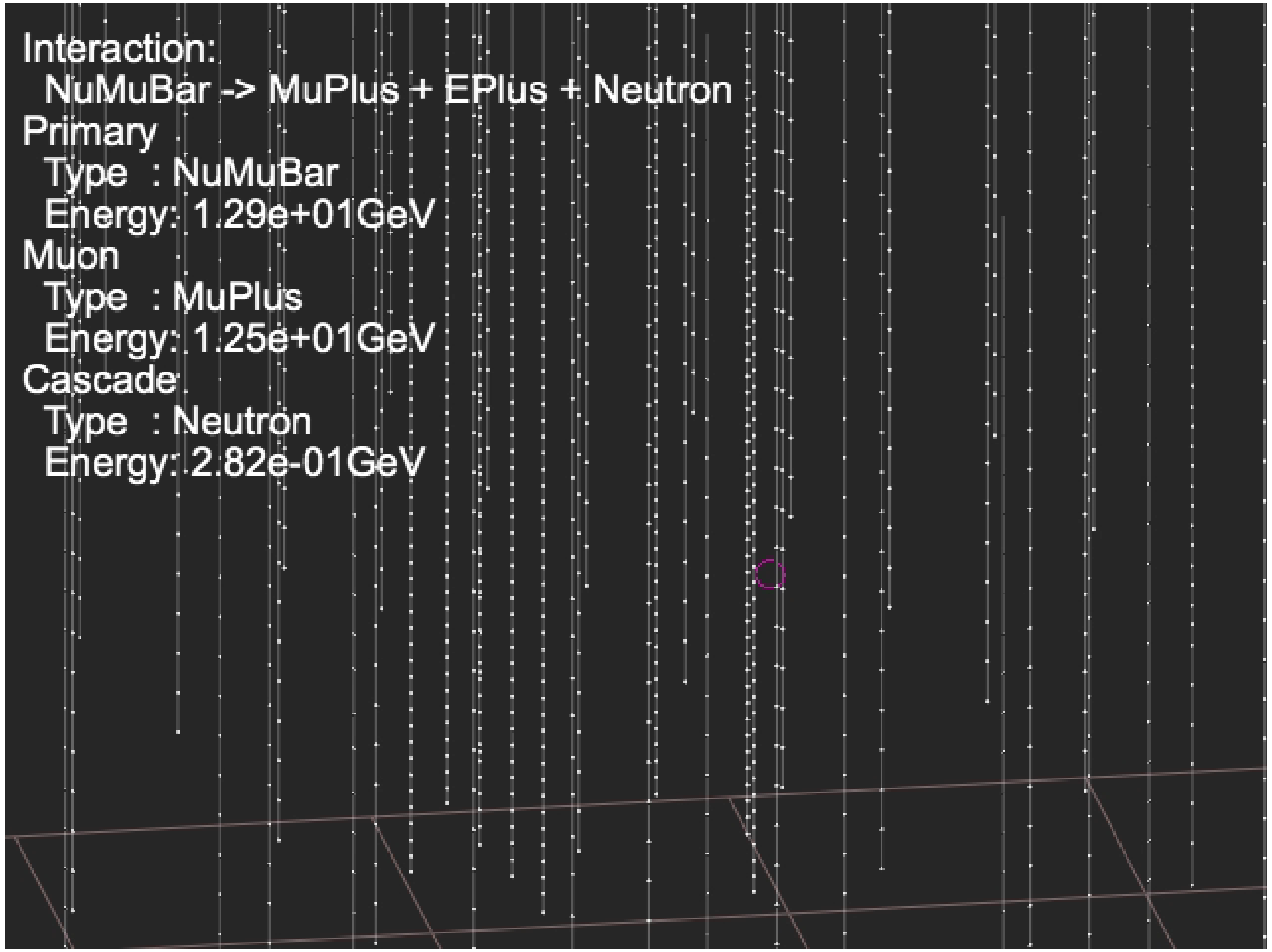
DeepCore events



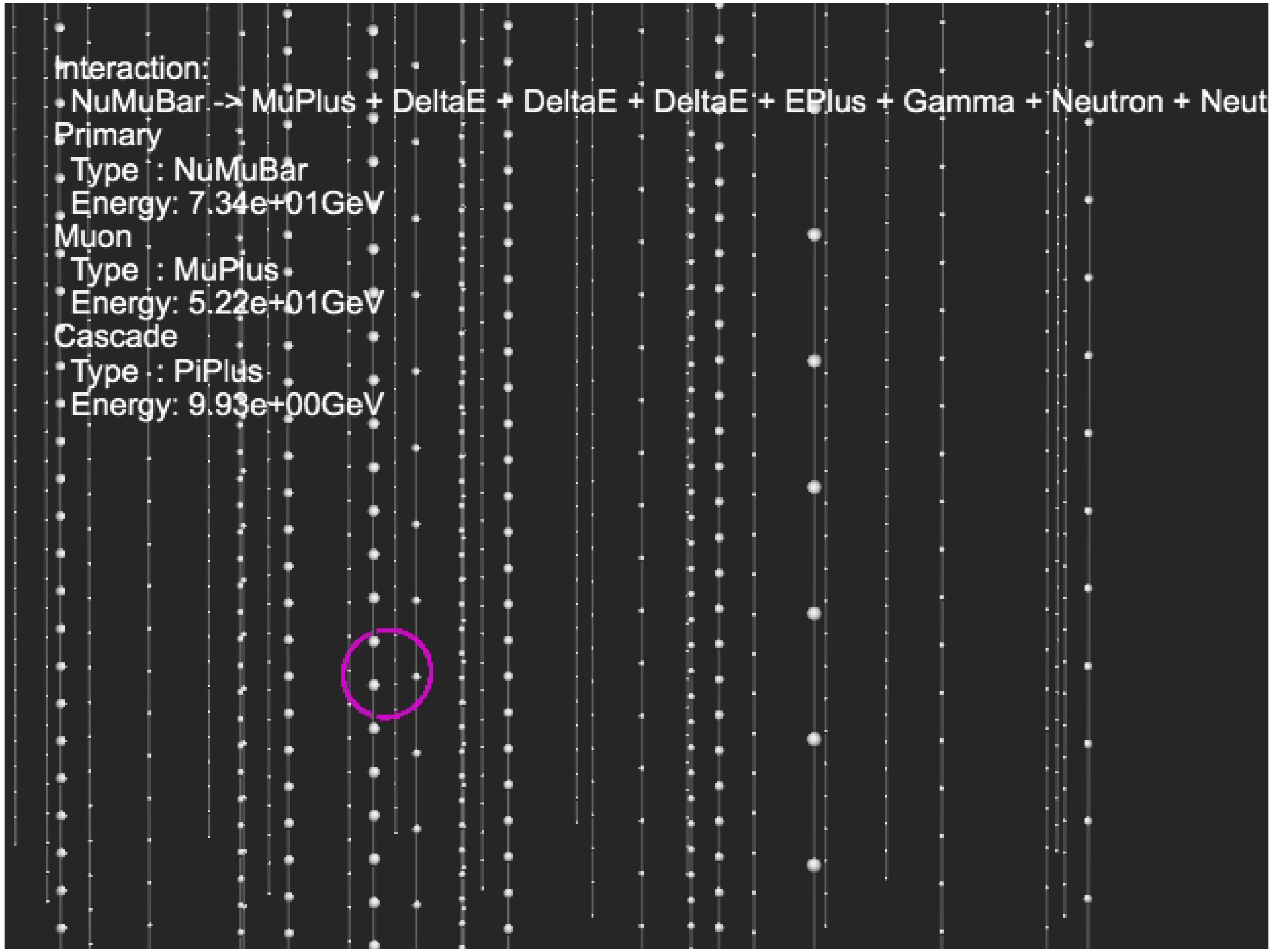
DeepCore events



DeepCore events

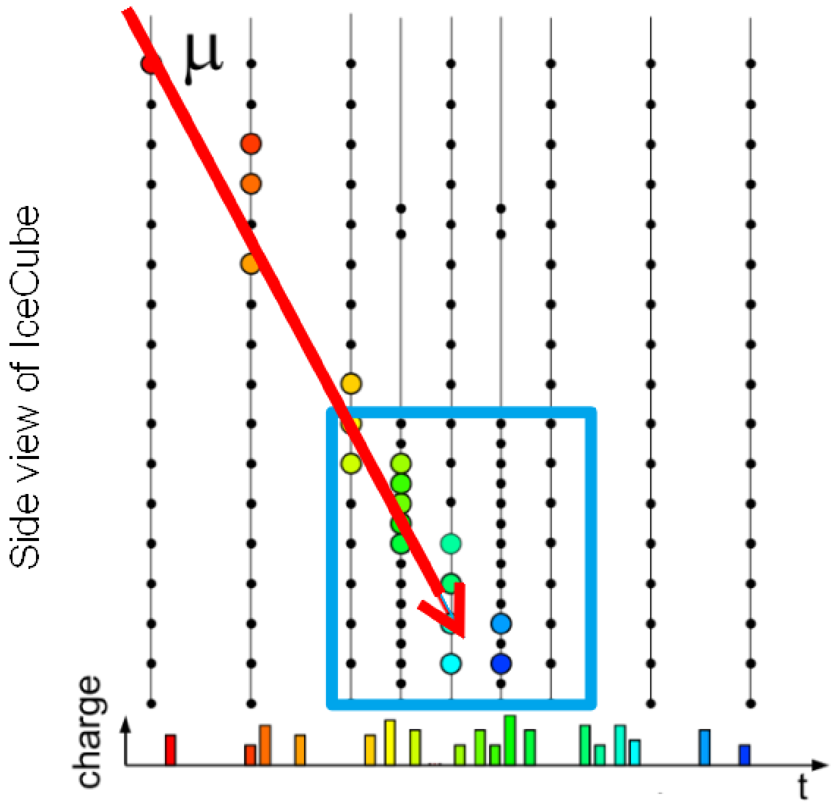


DeepCore events

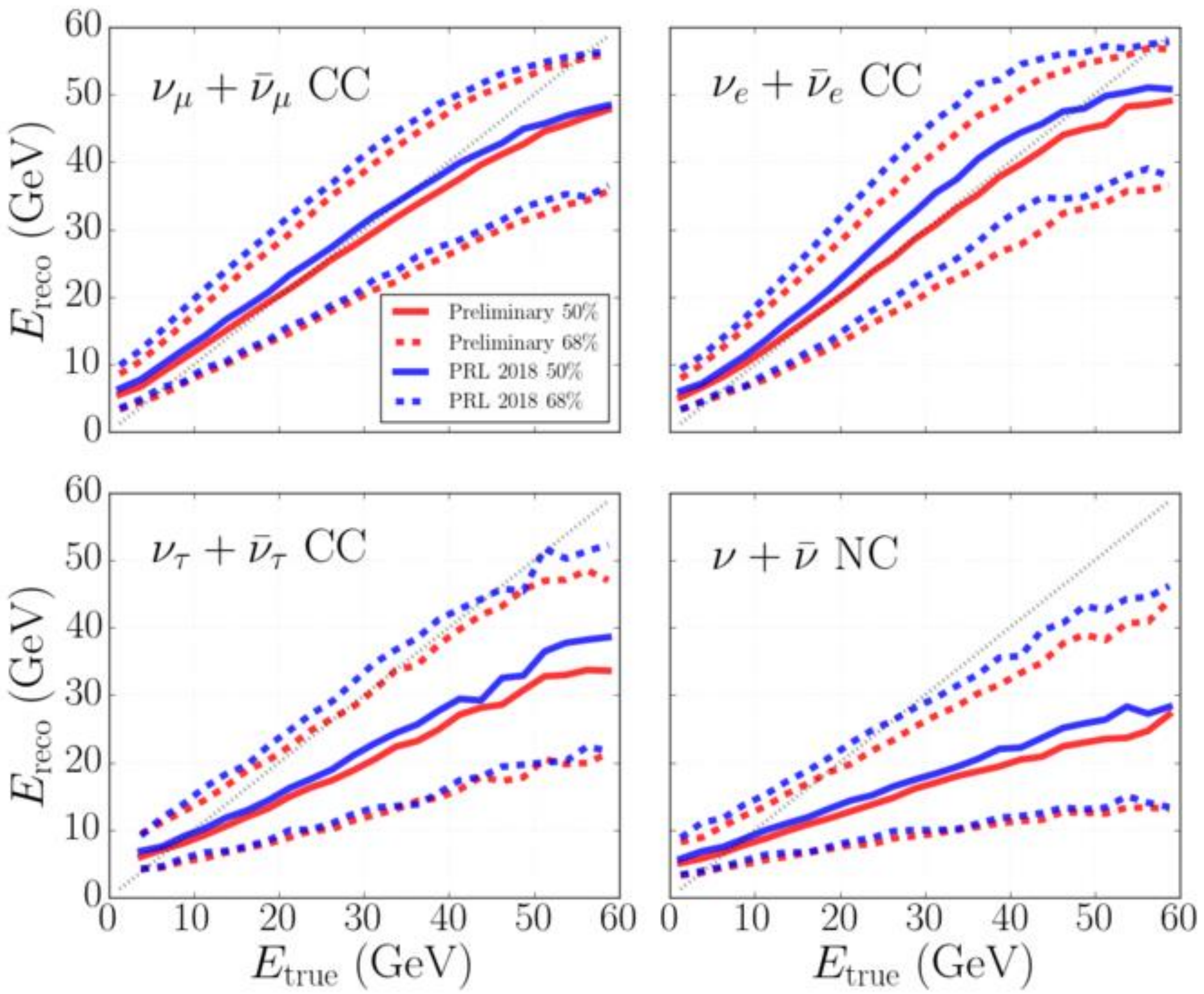


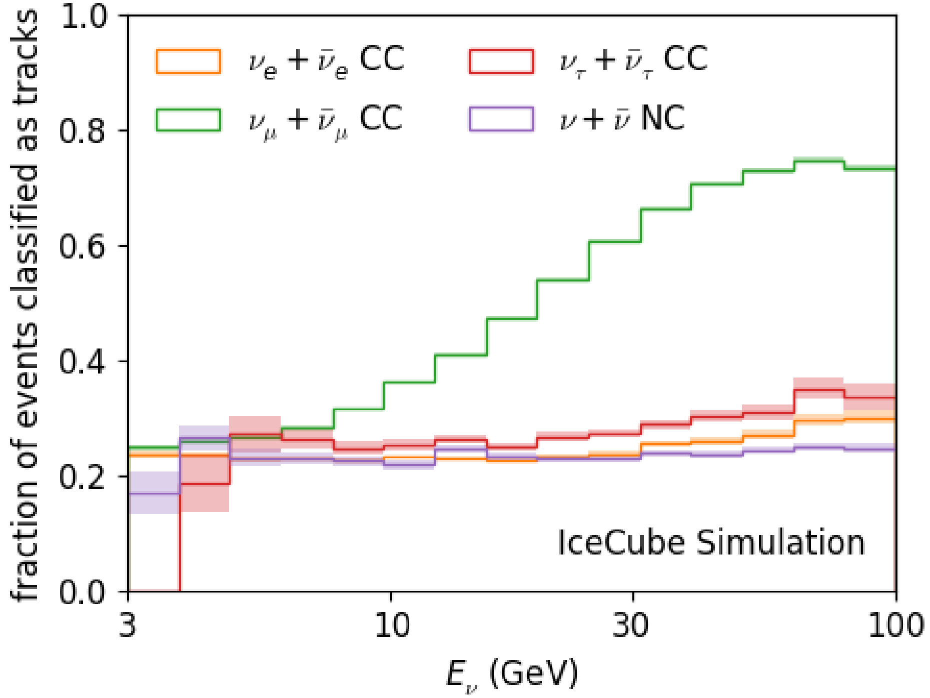
Analysis strategy

- Background
  - Aggressive vetoing to reject muons
  - Select starting events only
- Reconstruction
  - 8D likelihood w/track+cascade
  - Using detailed ice description
- Particle identification
  - Ratio of track+cascade/cascade only fit
- Parameterize systematic effects
  - Fit together with physics parameters

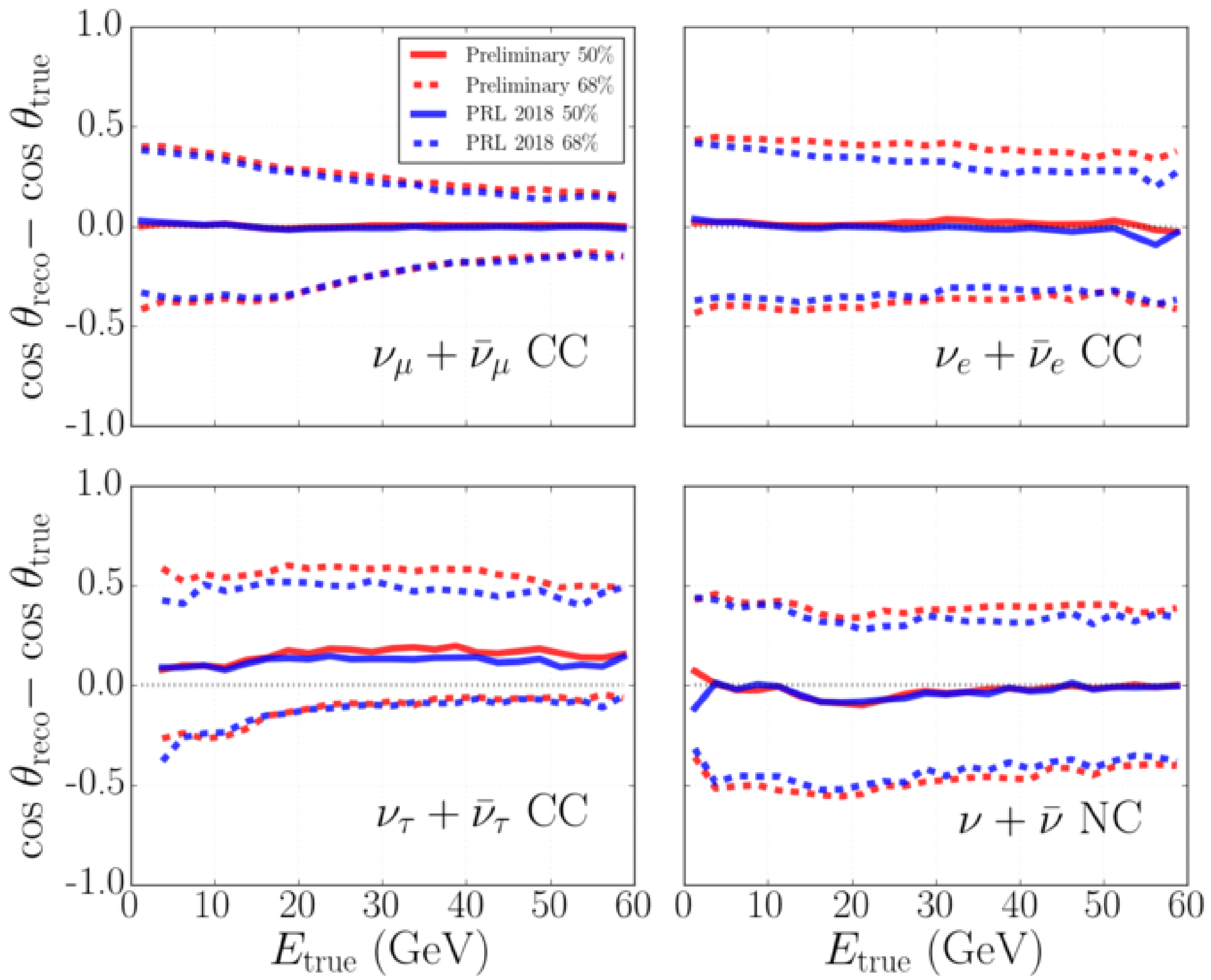


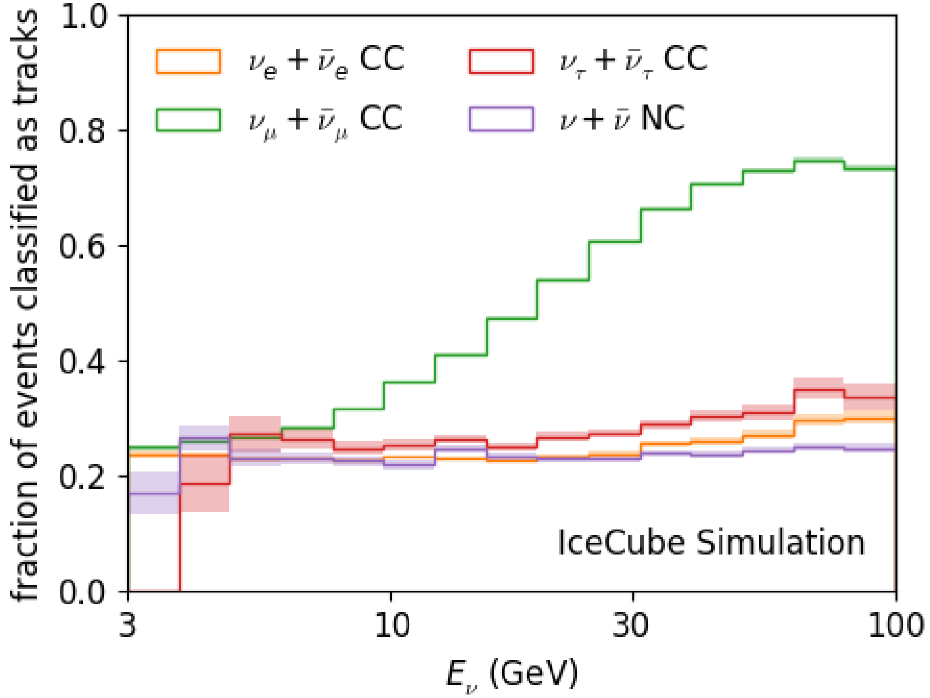
Reconstruction resolutions





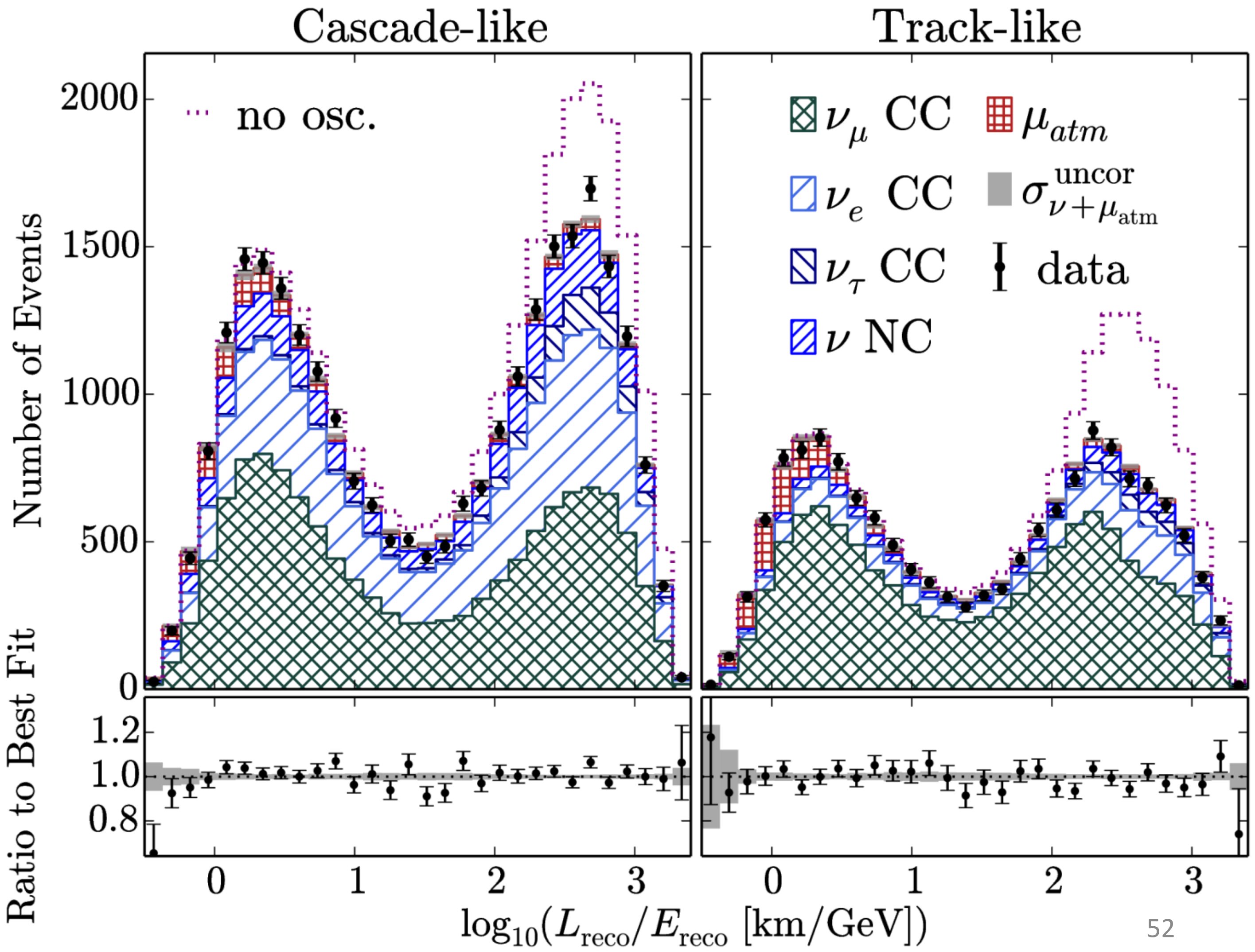
Reconstruction resolutions





Results: NuMu disappearance

- Analysis in L vs E space
- 48k events in 3 years
- χ^2 = 117.4/119 dof
- Data driven background



Phys. Rev. Lett. 120, 071801 (2018)

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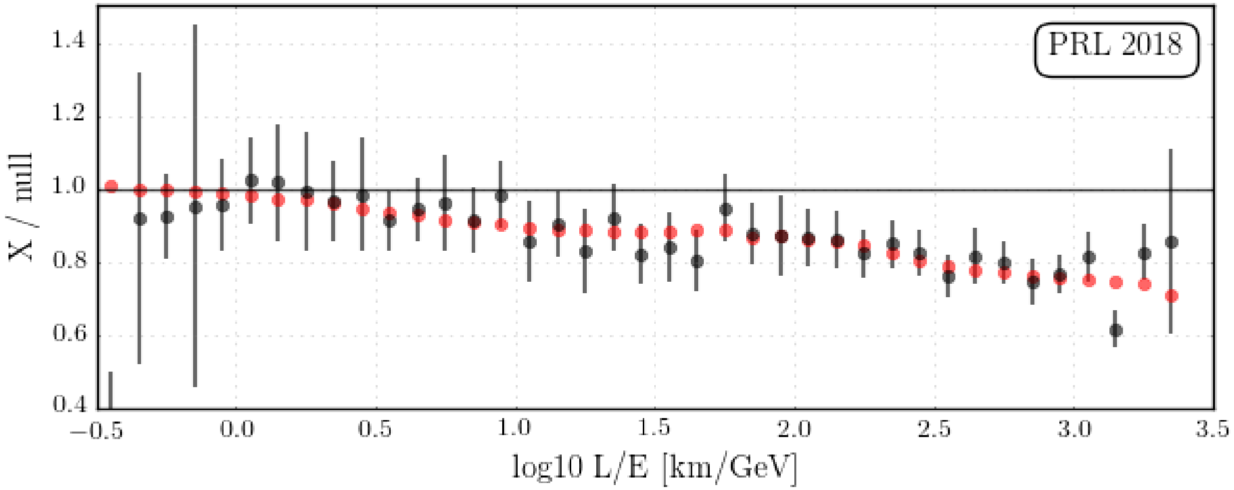
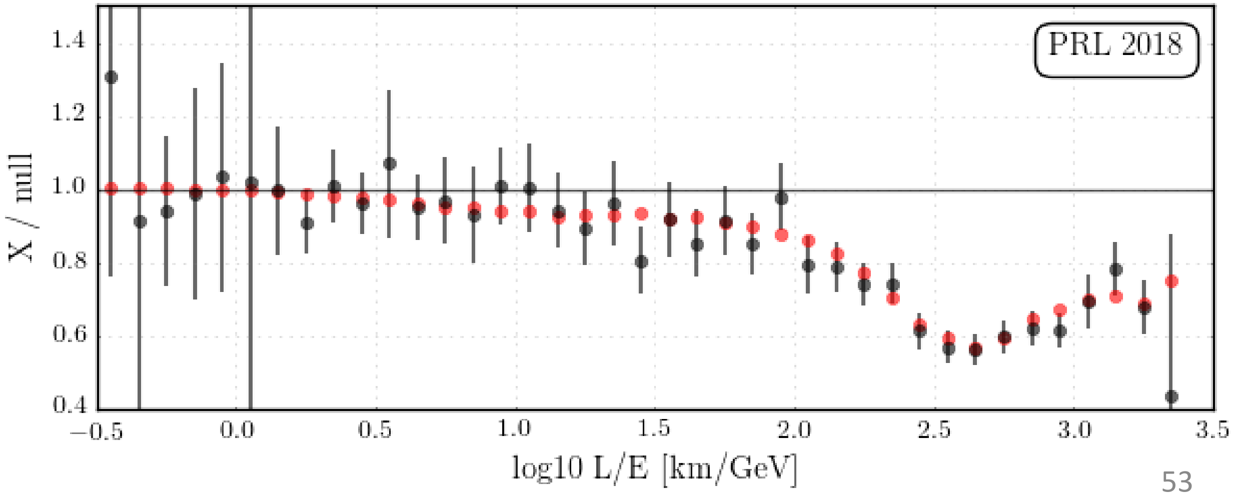
Phys. Rev. Lett. 120, 071801 (2018)

Cascade-like



Track-like



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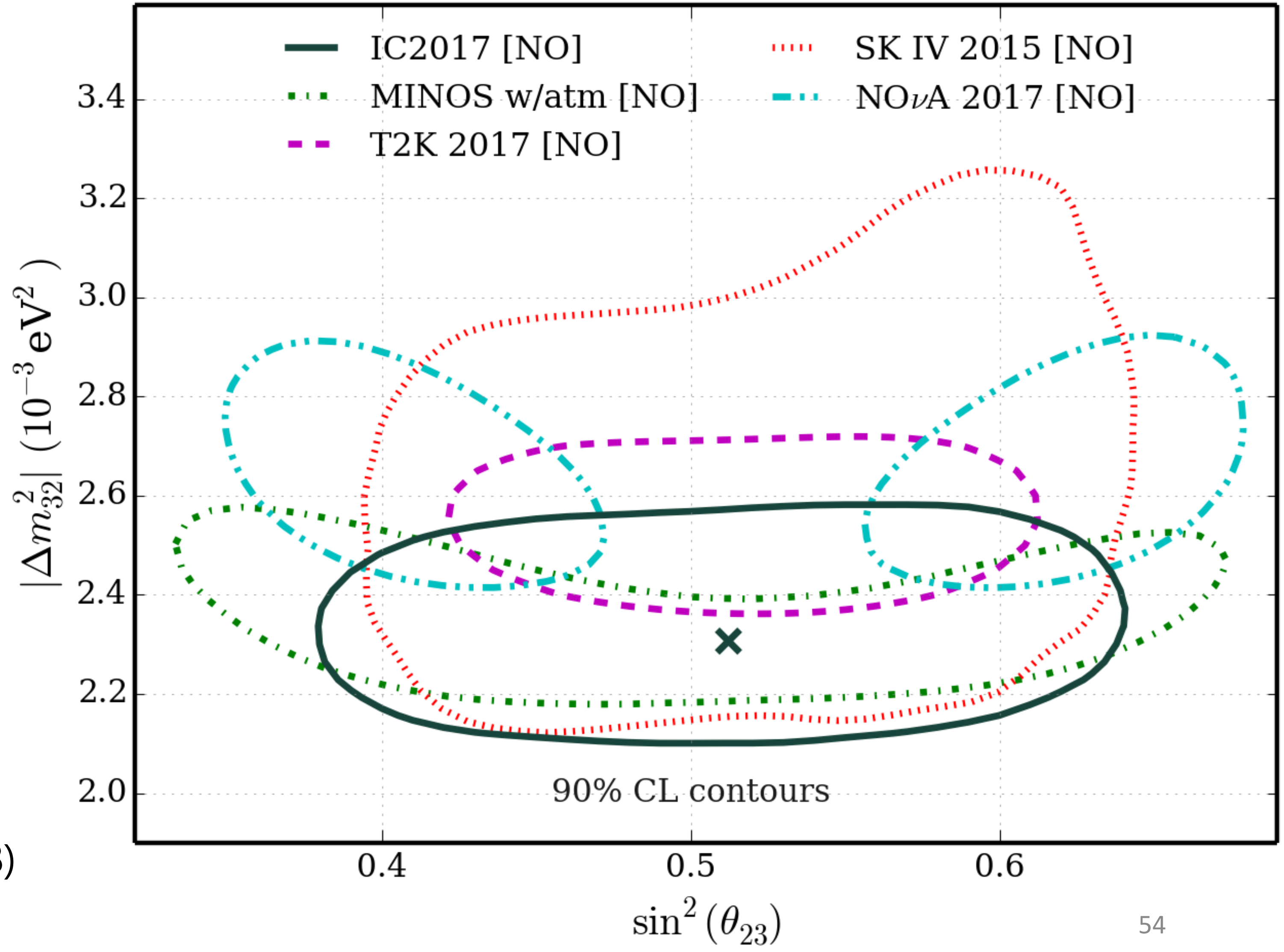

Phys. Rev. Lett. 120, 071801 (2018)

Results: NuMu disappearance

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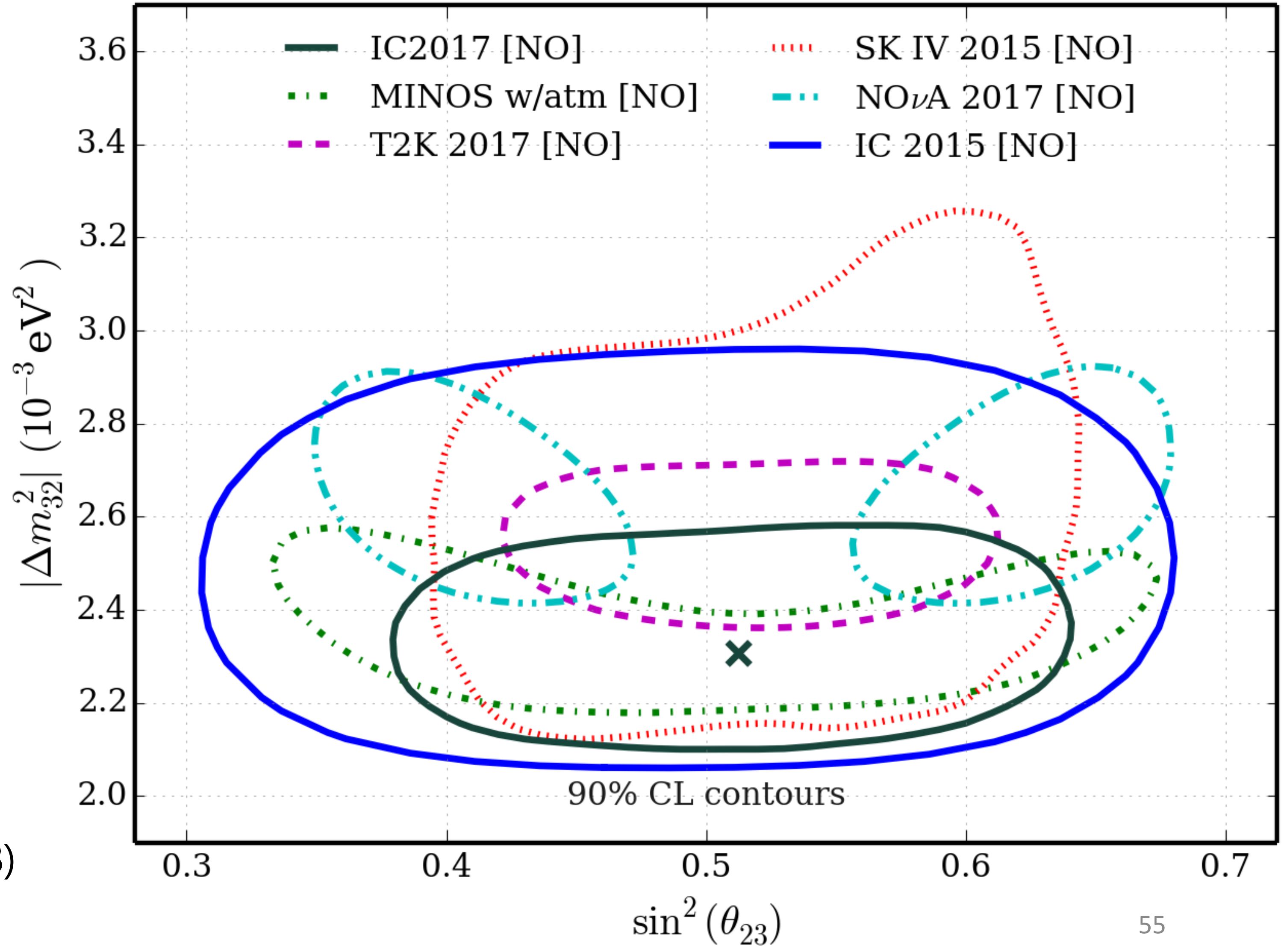
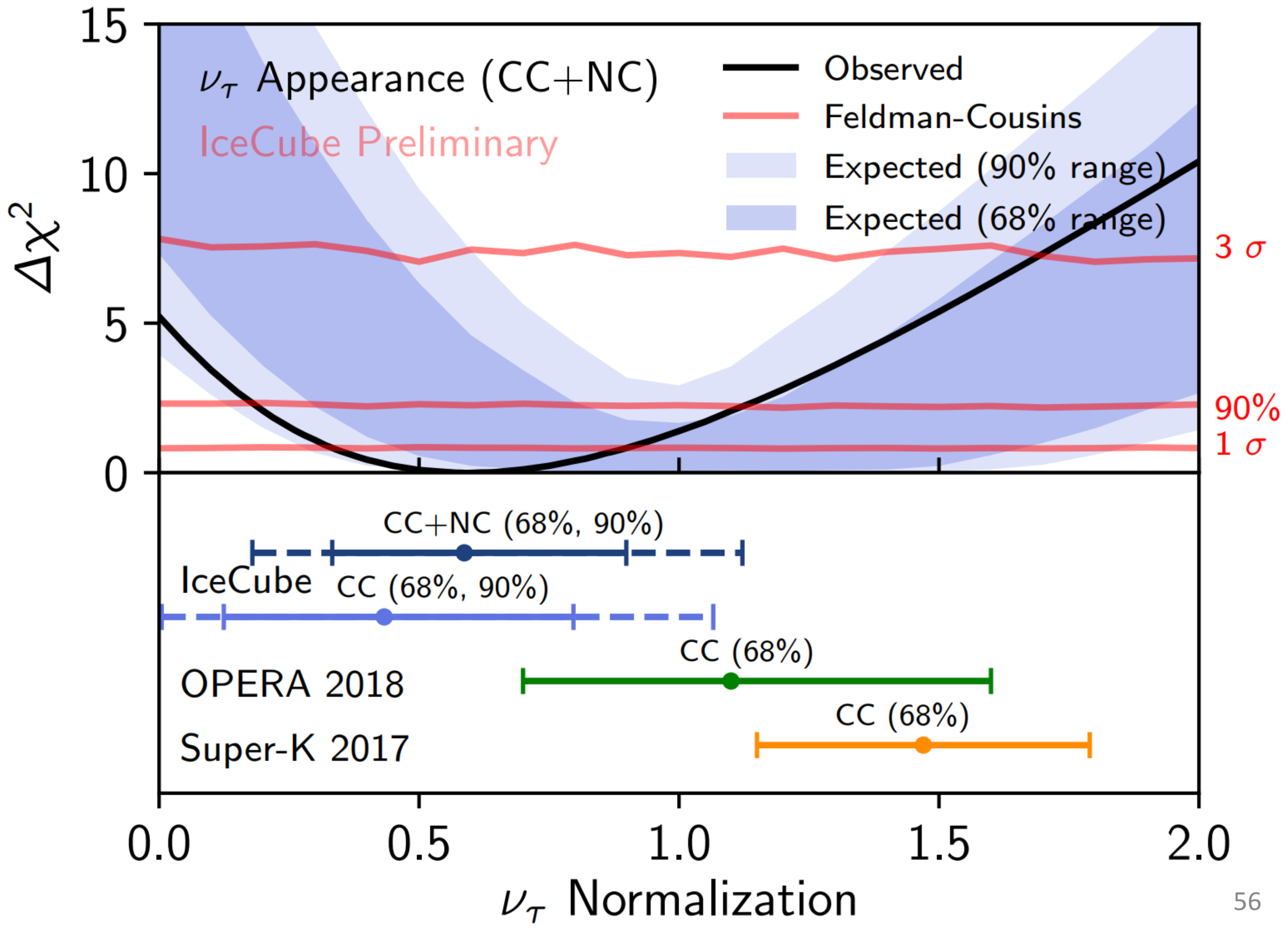
Phys. Rev. Lett. 120, 071801 (2018)



Results: NuTau appearance

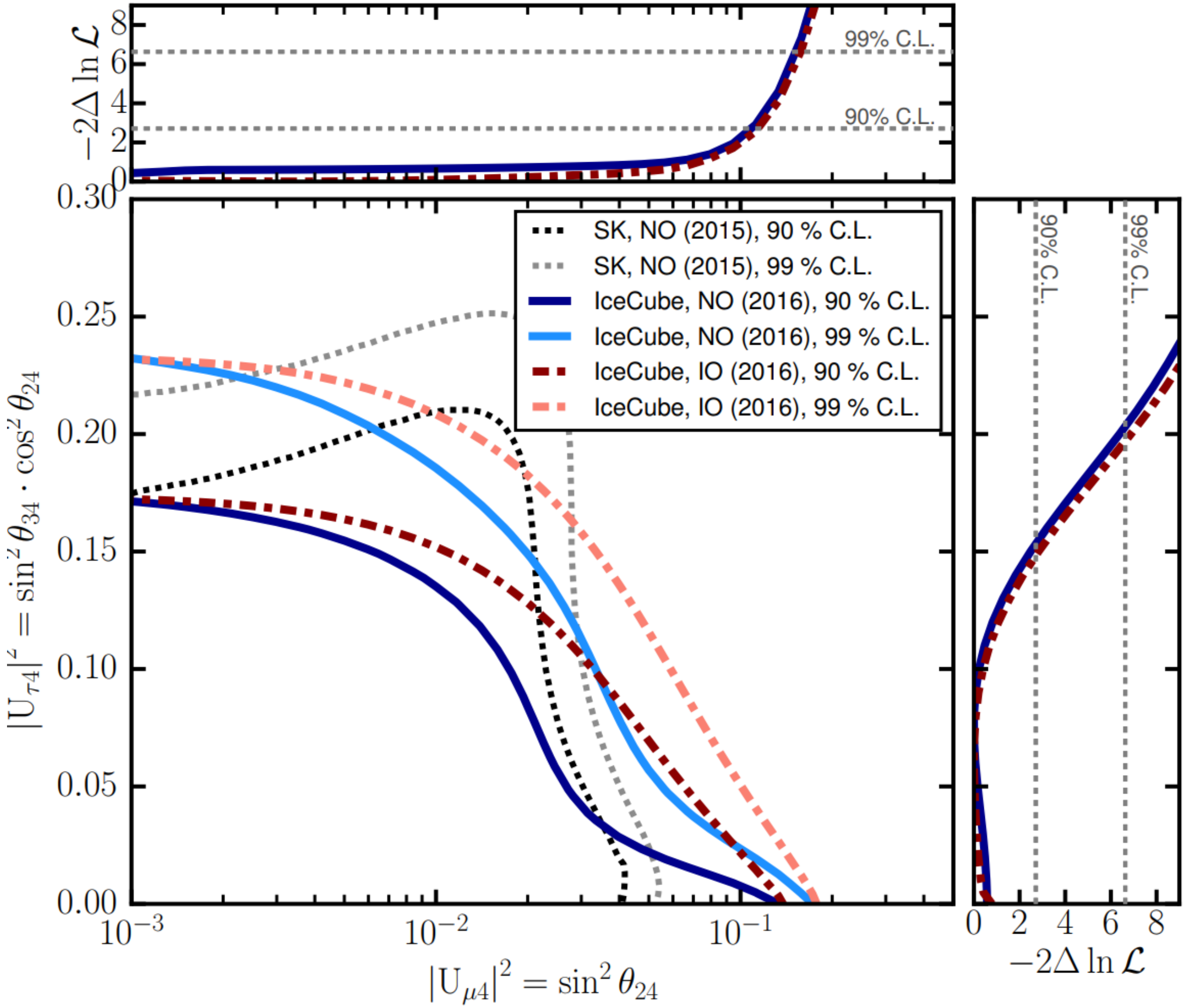
- Let tau neutrino component float
- Slightly below expected value (1.0)
- Not significant yet



Results: Sterile neutrinos - LE

- How would a sterile neutrino affect the sample?

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$



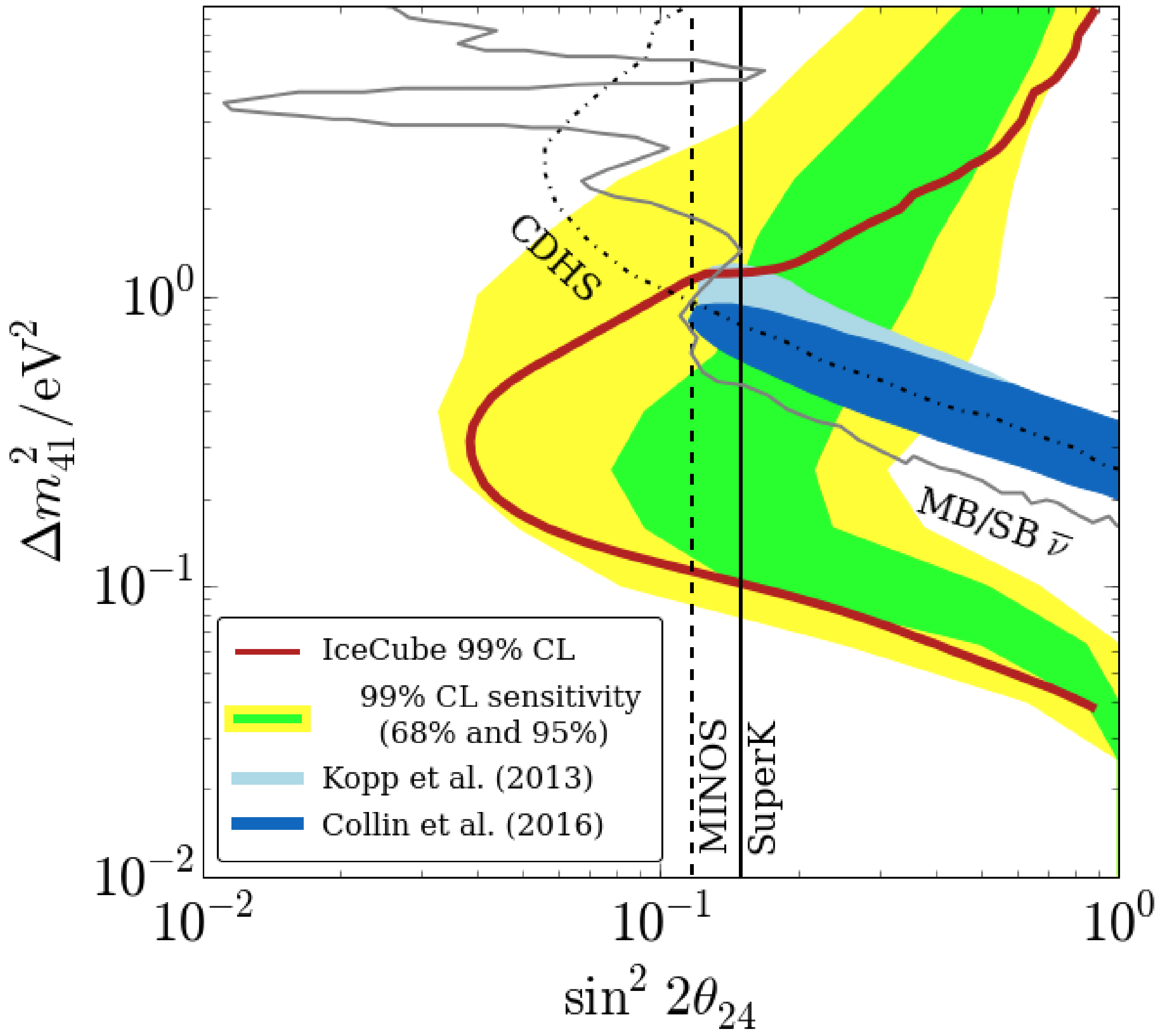
Phys. Rev. D 95, 112002 (2017)

Results: Sterile neutrinos - HE

- How would a sterile neutrino affect the **high energy** sample?

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

Phys. Rev. Lett. 117, 071801 (2016)



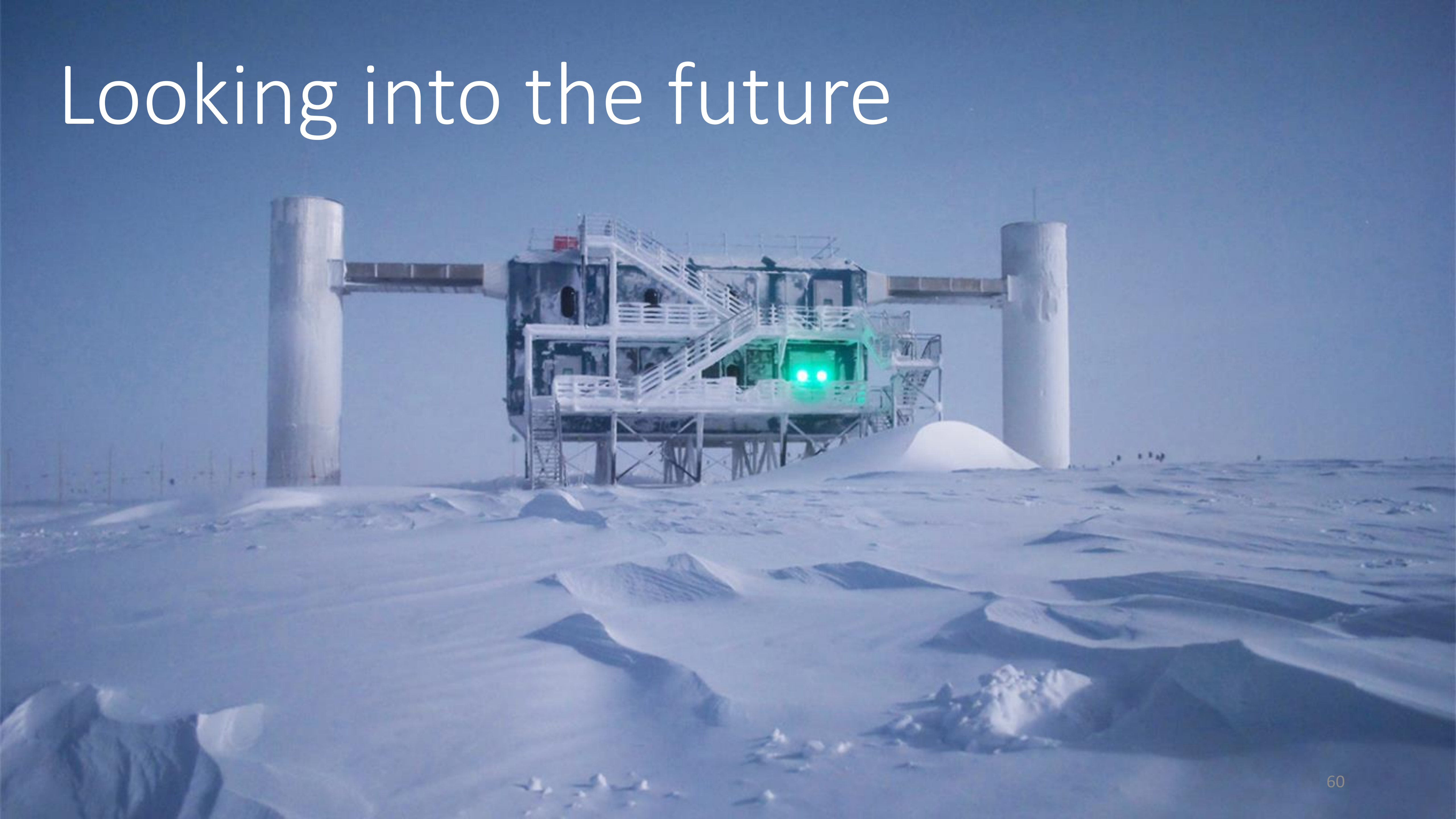
Summary from heaven

- Atmospheric neutrinos used for **particle physics** studies
- Events are hard to reconstruct, but we have **thousands per year**
- Measurements of **standard oscillations** improving rapidly
- **Tau neutrinos** from oscillations beginning to appear
- Exotic BSM ongoing: **steriles**, non-standard interaction, decoherence

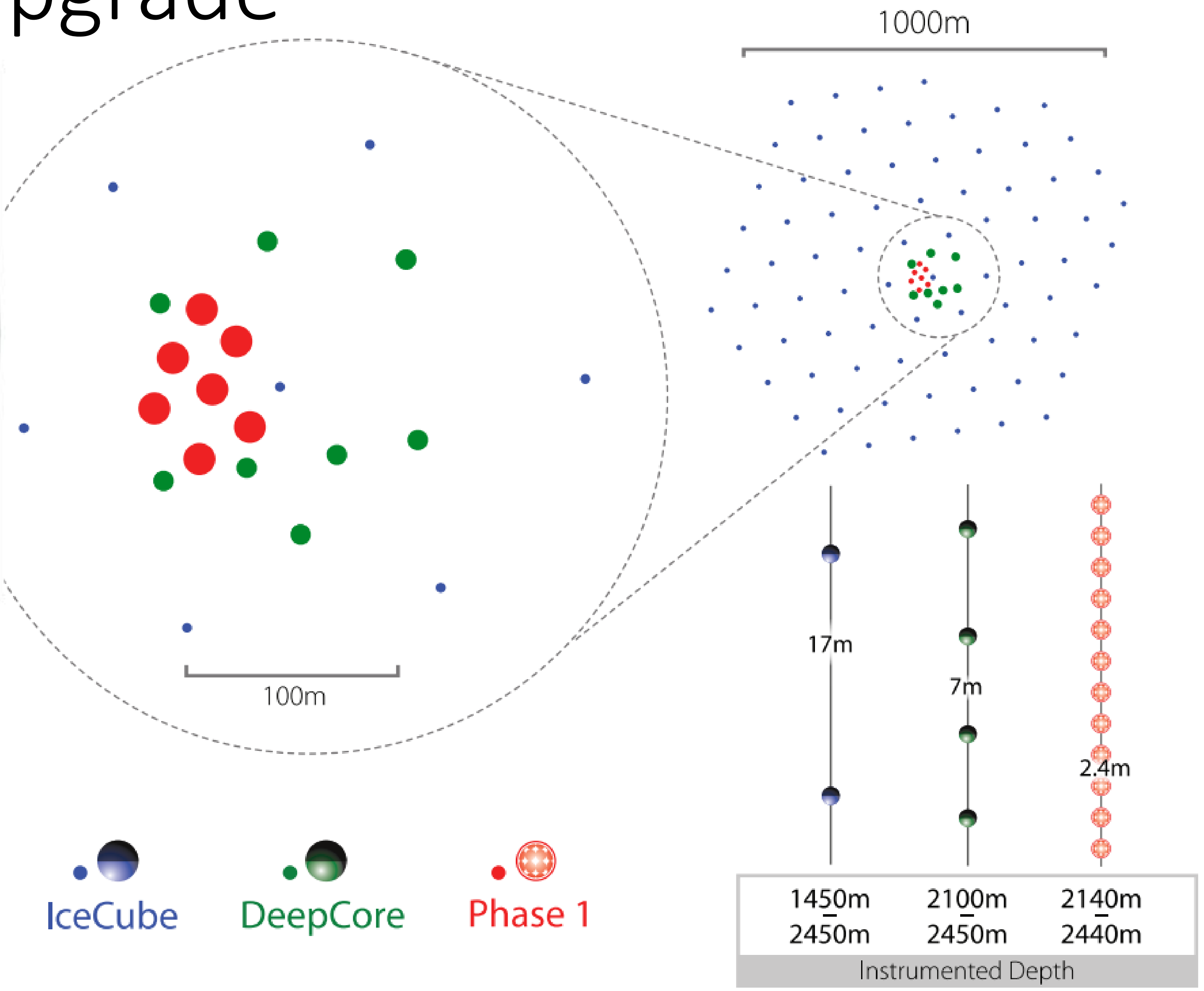
Studies start to be limited by **systematics**

we need more calibration sources

Looking into the future



The IceCube Upgrade

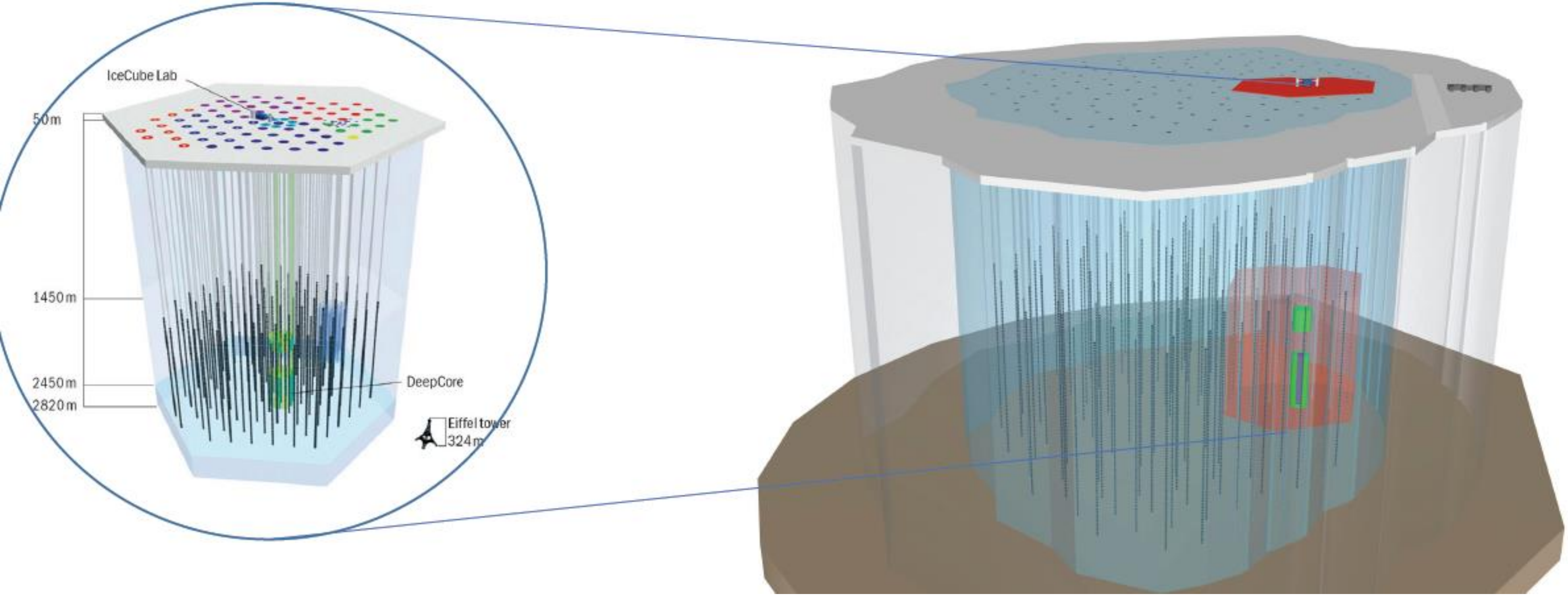


The IceCube Upgrade

- More sensors in same volume
  - Lower DeepCore E threshold
  - Better oscillation physics

- New calibration sources
  - Controlled light emission
  - Improved ice description
  - Better pointing at HE by factor 2
  - Re-analysis of current HE data

A step further: IceCube Gen-2



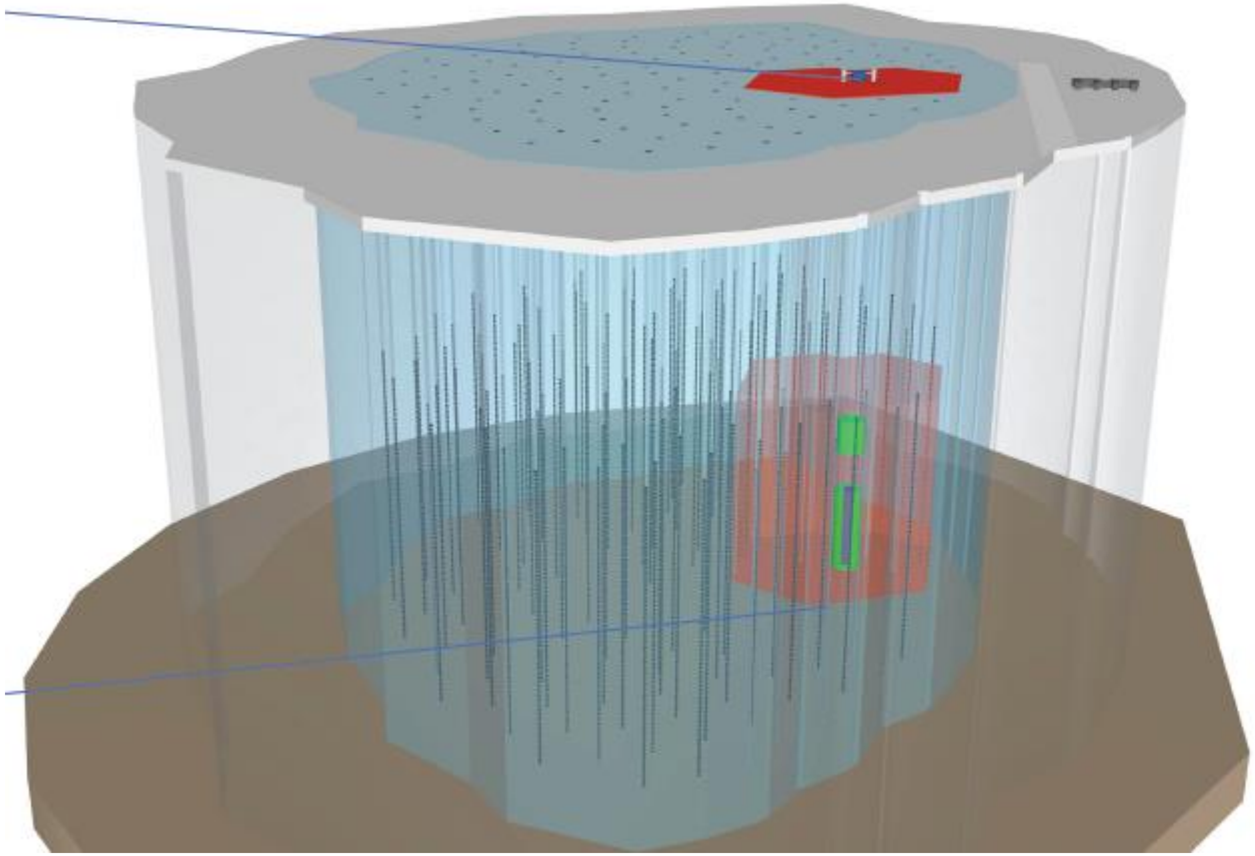
A step further: IceCube Gen-2

Main detector

- +120 strings
- 240m inter-string distance
- 80 Oms per string
- 8 km^3 volume

Extensions

- Surface array (CR and veto)
- Radio array (EHE neutrinos)



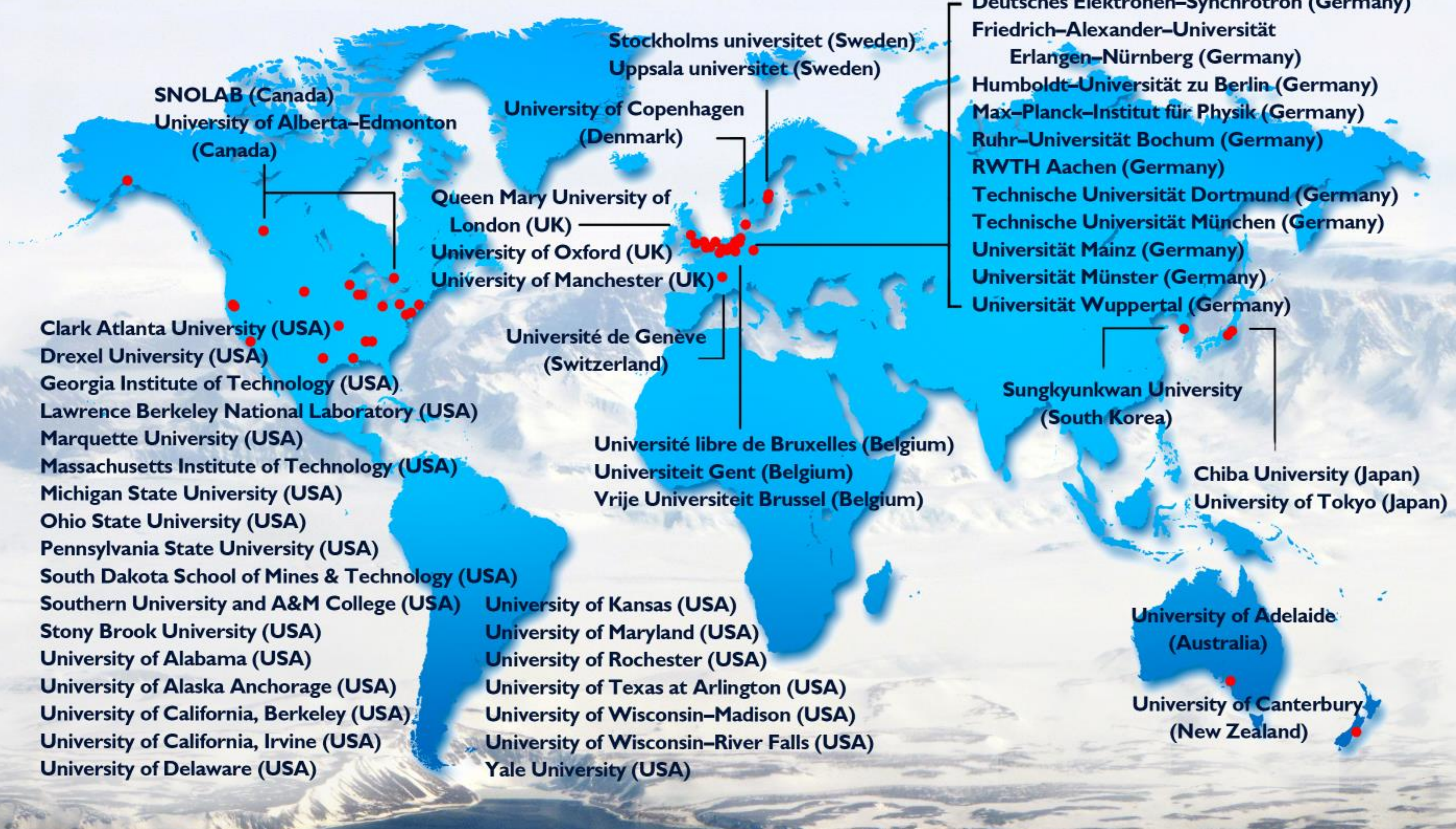
Final words

IceCube: a neutrino observatory from GeV to PeV energies

- Astrophysical neutrinos
- Neutrino oscillations
- Dark matter
- Cosmic ray physics
- …

More data and better calibration → constantly improving results

Upgrades proposed: maximize the science output at all energies



International Funding Agencies