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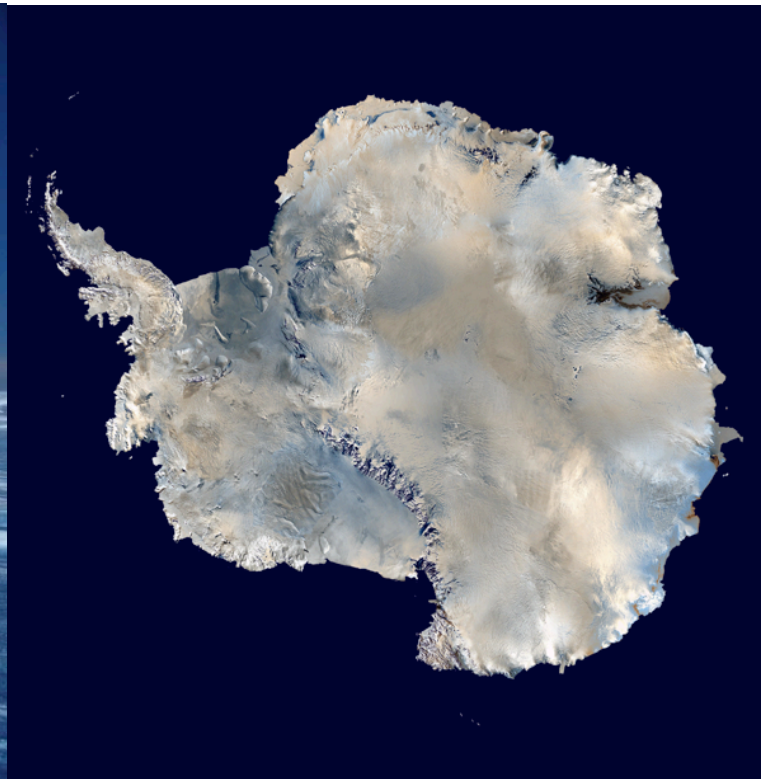
ICECUBE GEN2

IceCube and IceCube-Gen2

Justin Evans
University of Manchester



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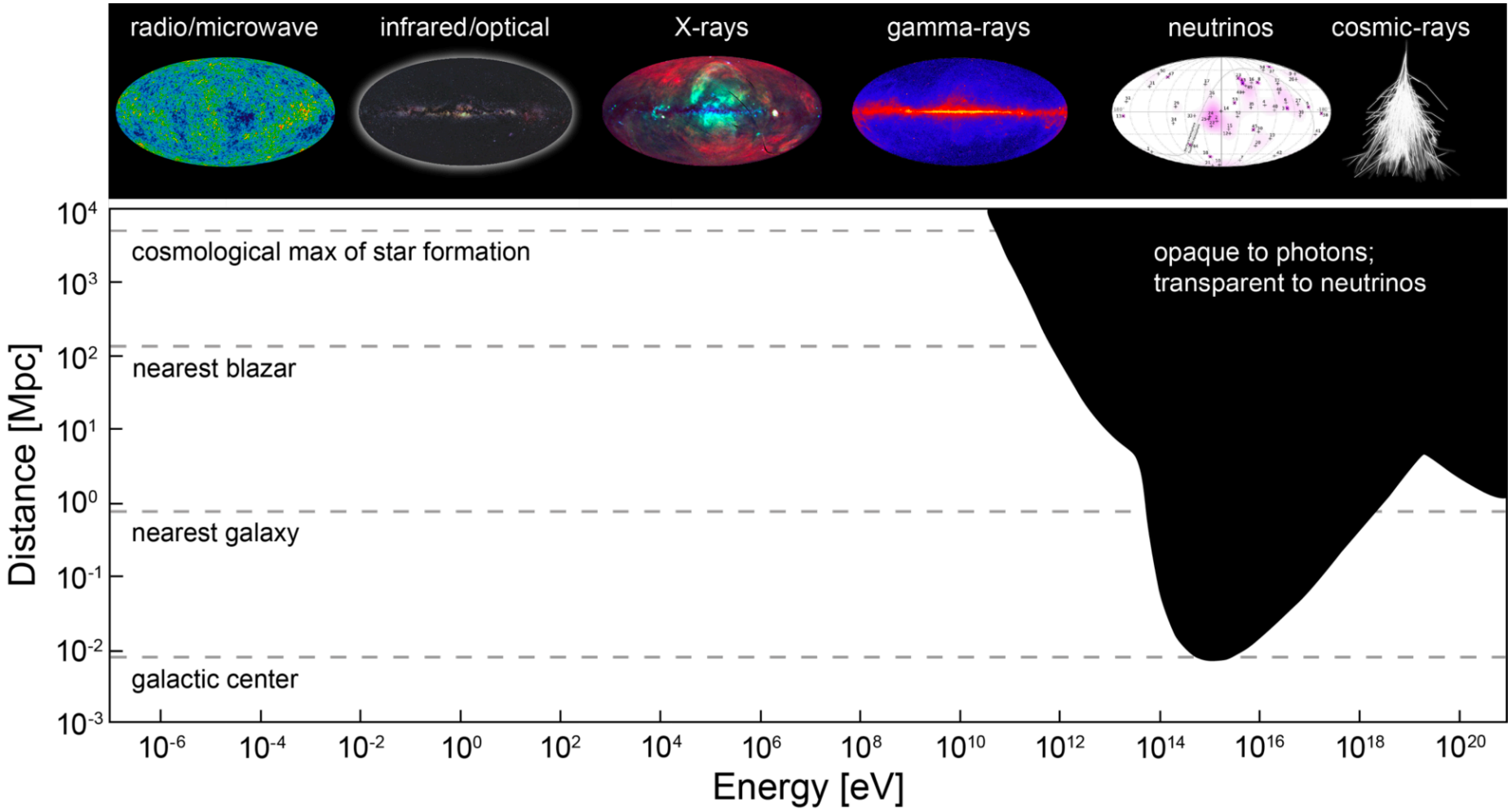
Where photons fear to tread

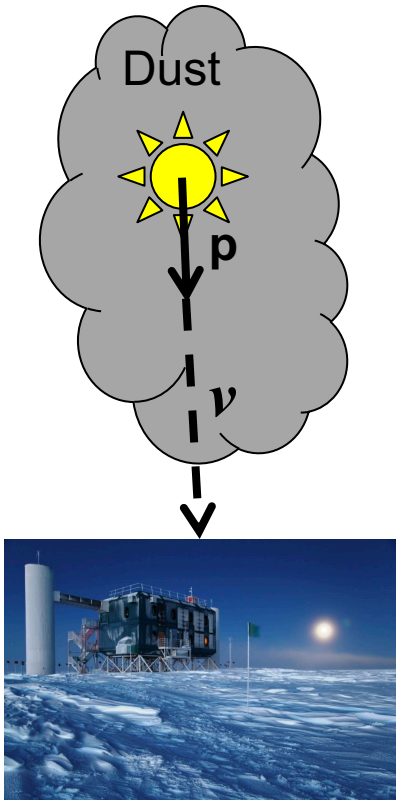


Finding the source

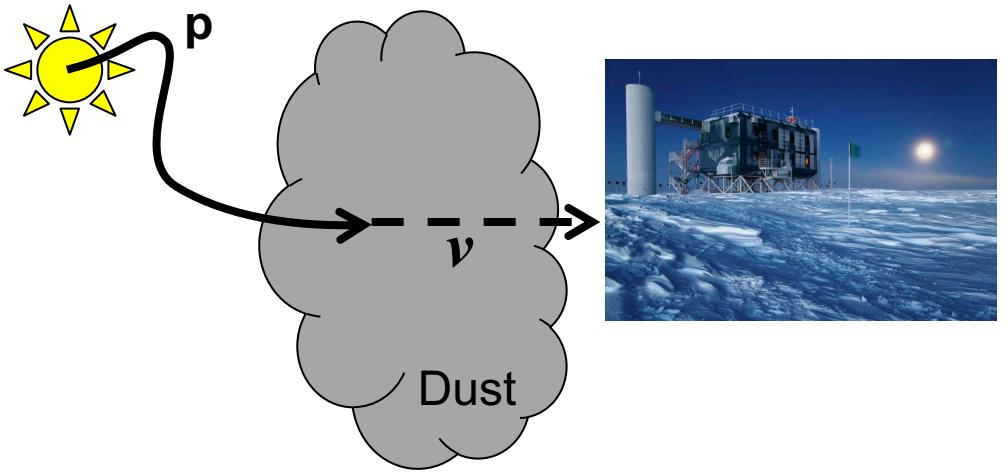
Neutrinos are not affected by interstellar magnetic fields

- But that doesn't mean they all point back to sources
- Galactic neutrinos: can be source-like or diffuse, and sources can be extended
- Extragalactic neutrino sources are unlikely to be resolved

A neutrino source



Diffuse neutrinos



IceCube

- 5160 PMTs
- 17 m vertical spacing
- 86 strings
- 125 m string spacing
- 1 km^3 volume

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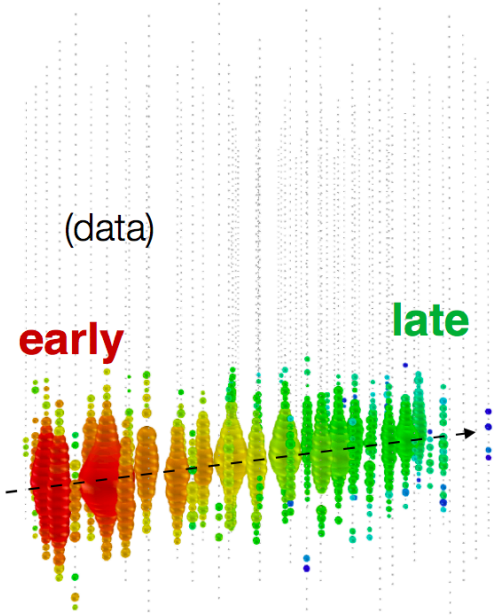
High-energy neutrinos

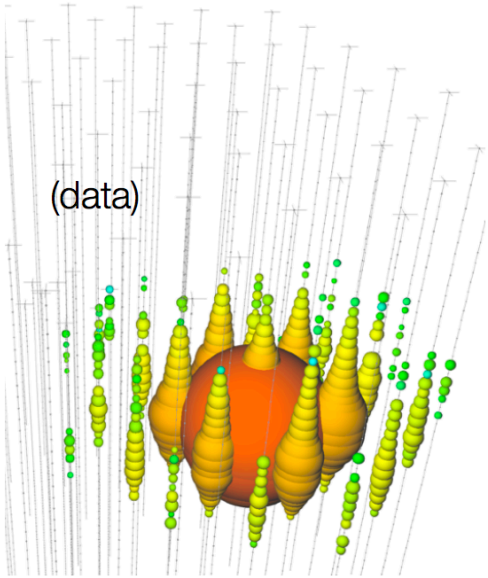
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

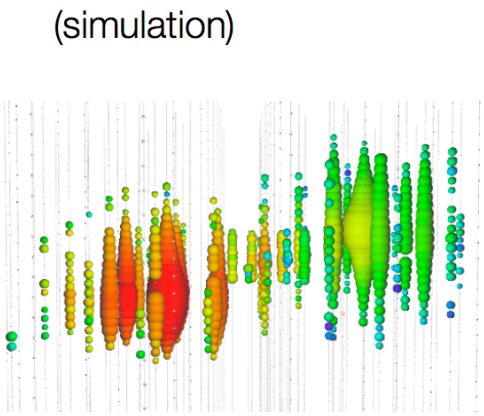
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ



Double cascade

(resolvable above O(100) TeV deposited energy, 20 m τ decay length)

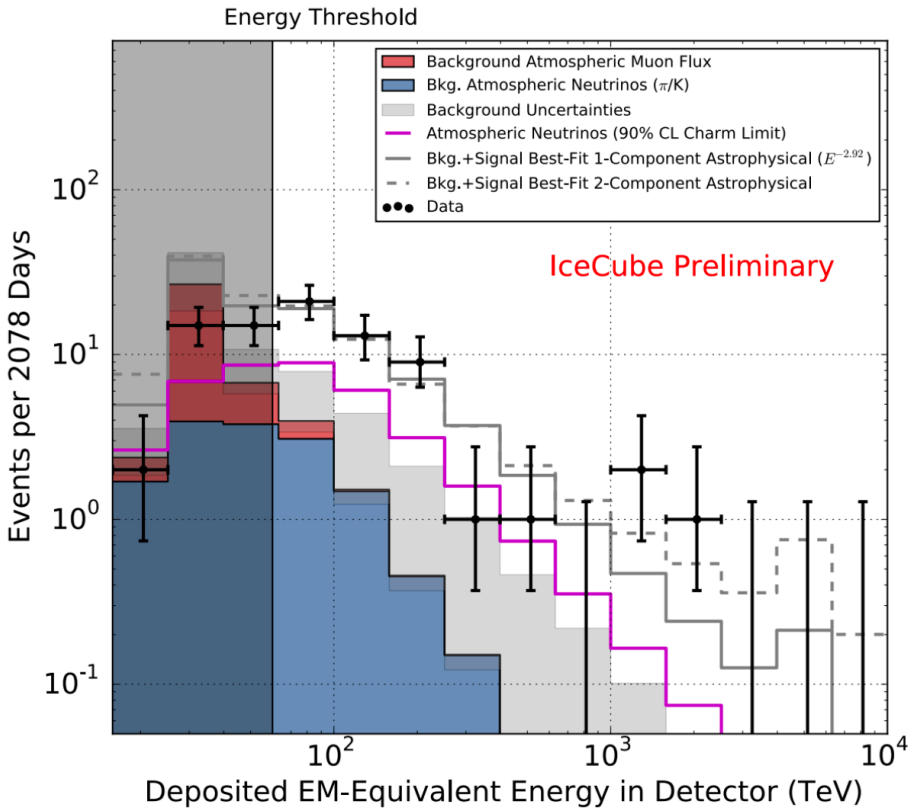
Interstellar neutrinos have been seen

82 events observed above 100 TeV after 6 years

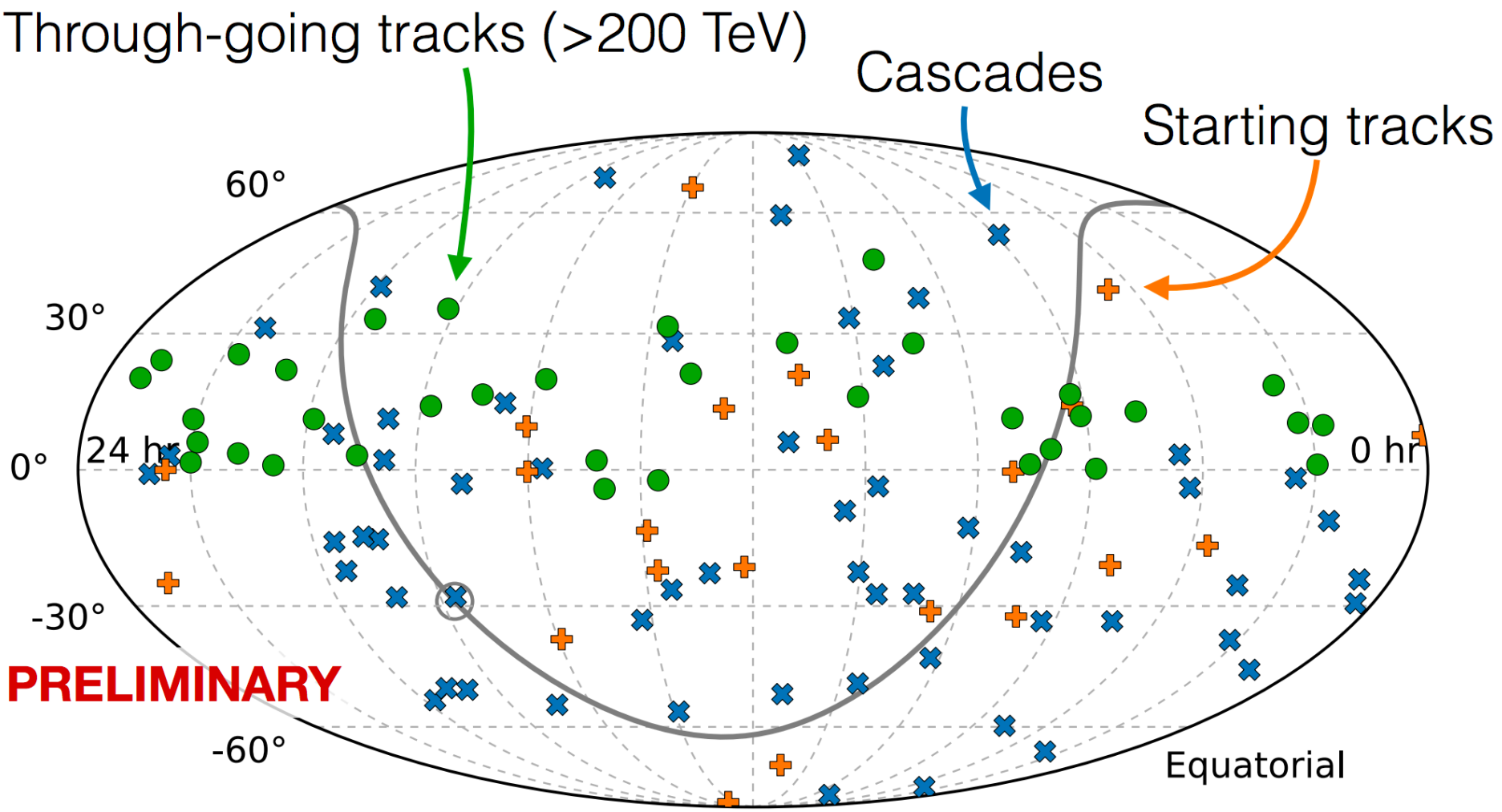
Expected backgrounds

- $15.6^{+11.4}_{-3.9}$ atmospheric neutrinos
- 25.2±7.3 atmospheric muons

Two of the events are coincident muons from cosmic ray air showers



No sources yet

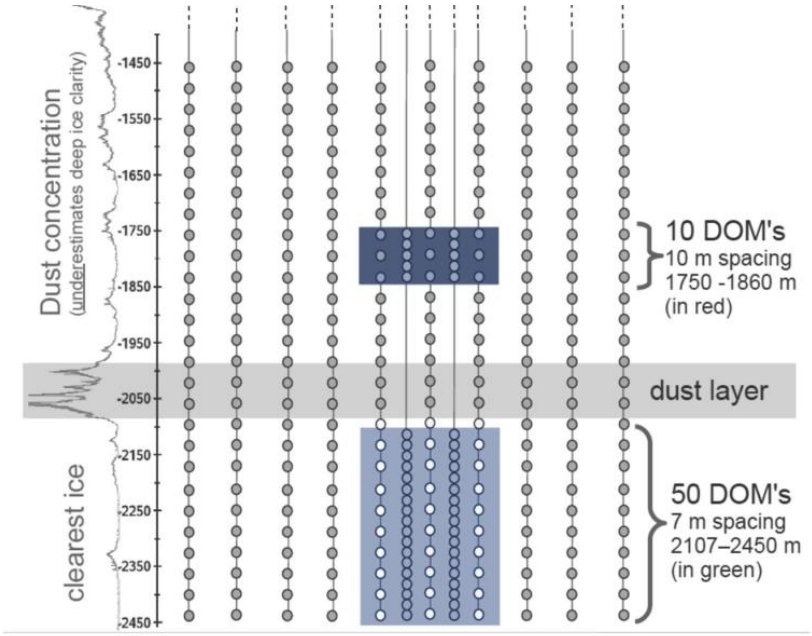


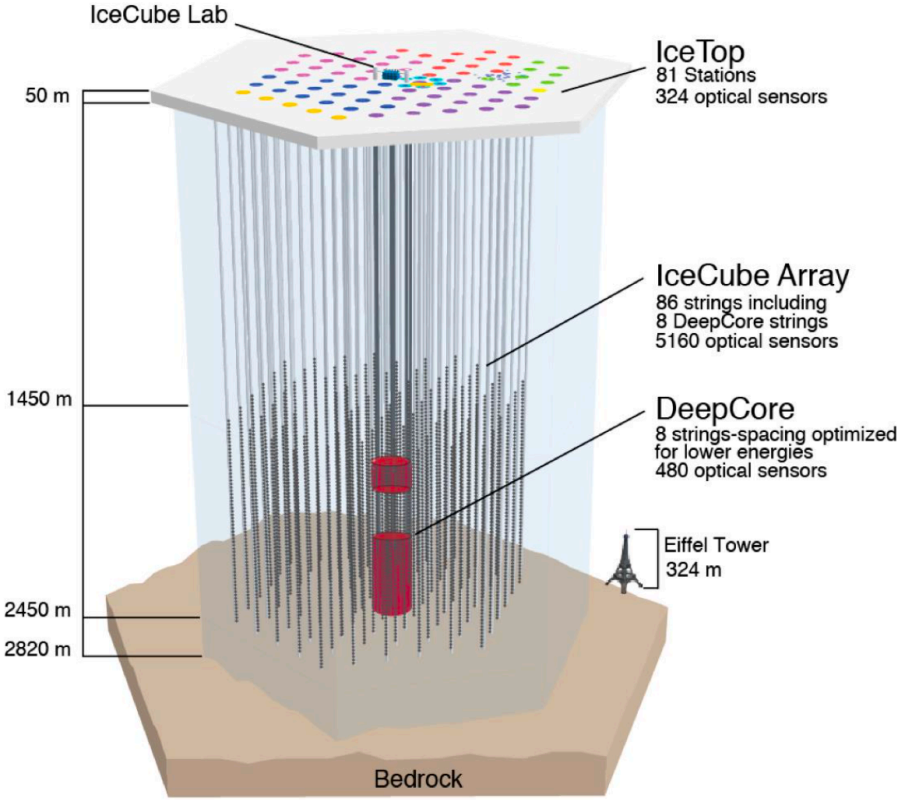
New 6-year data

DeepCore

8 densely-instrumented strings

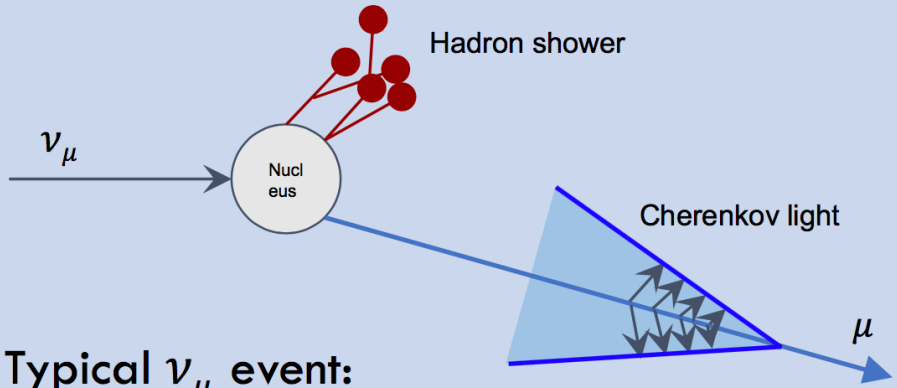
- In the clearest ice
- Surrounded by IceCube strings for active veto
- High-efficiency optical modules
- Neutrino energies down to 5 GeV



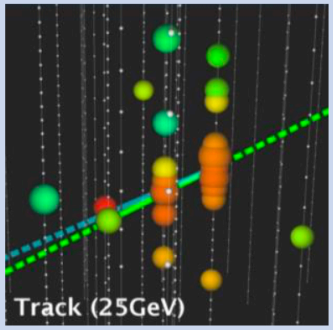


Low-energy neutrinos

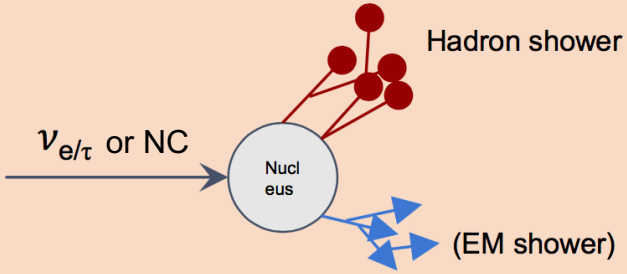
Track like



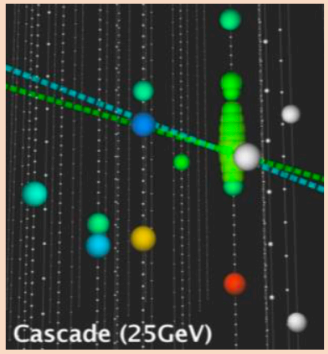
Typical ν_μ event:
Energy deposited in
- Extended muon track (E ~ length)
- Hadron shower from e.g. DIS



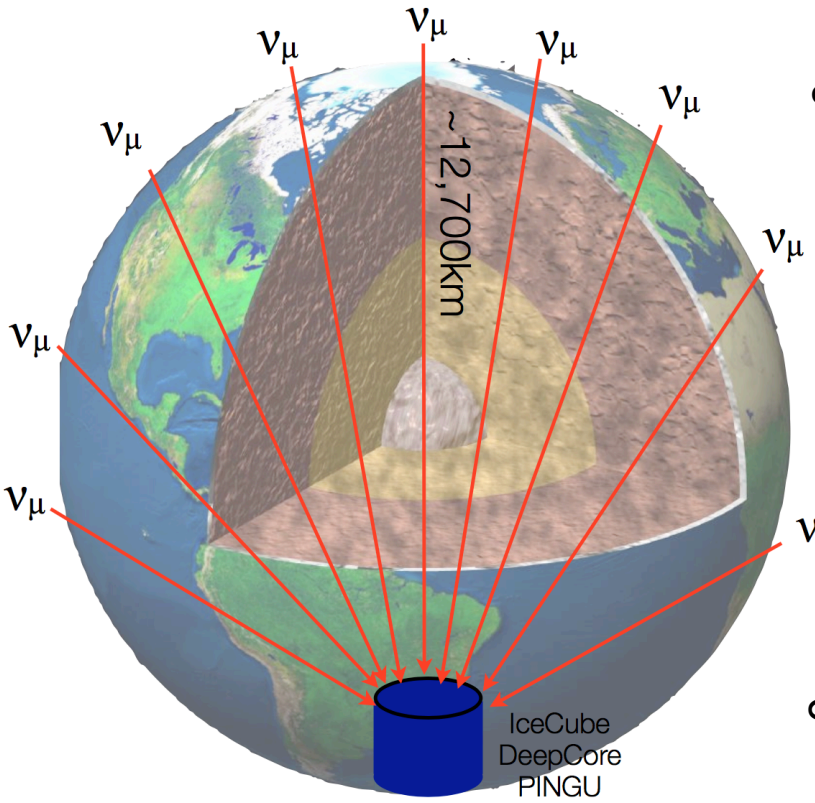
Cascade like

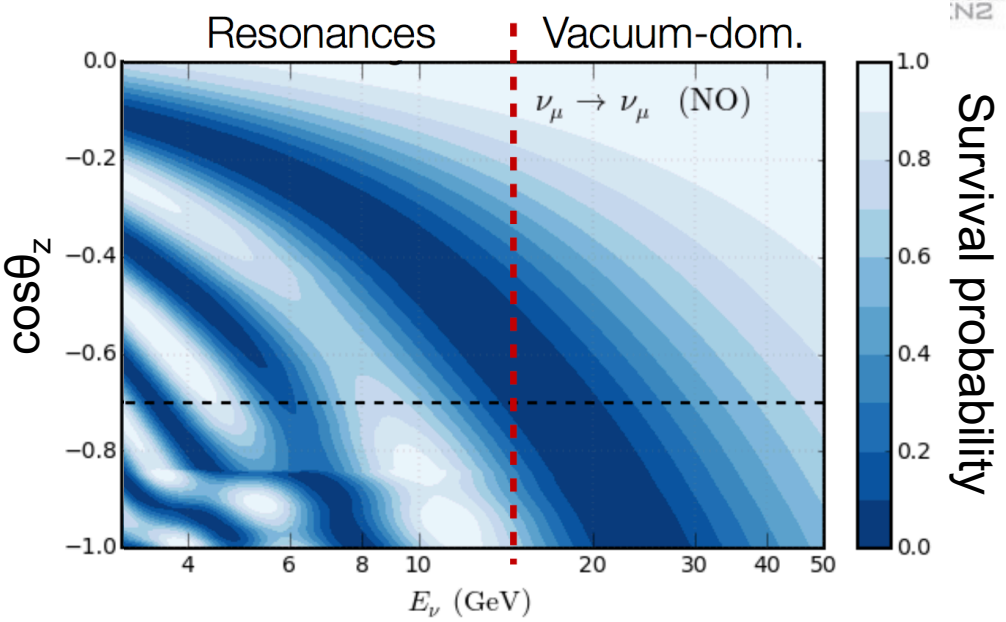


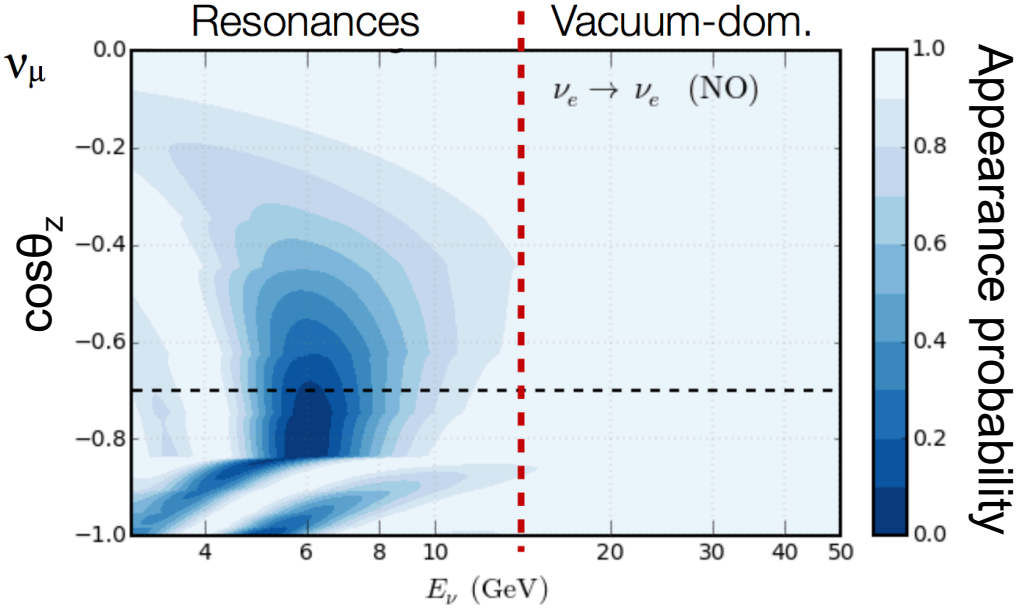
Typical $\nu_{e/\tau}$ event:
All energy deposited in form of showers (hadronic and electro-magnetic)
Spatially more compact (no track)



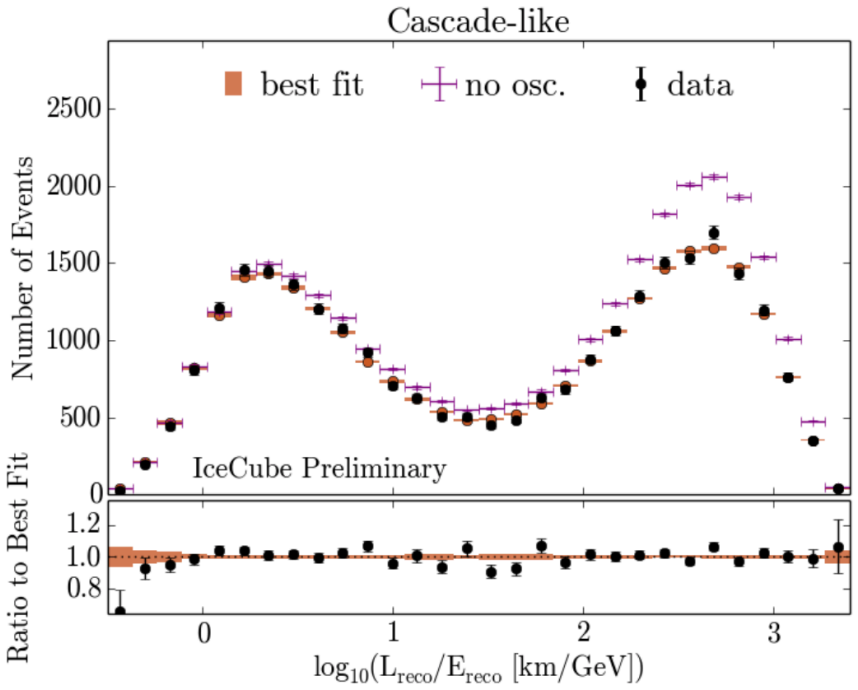
Atmospheric neutrino oscillations

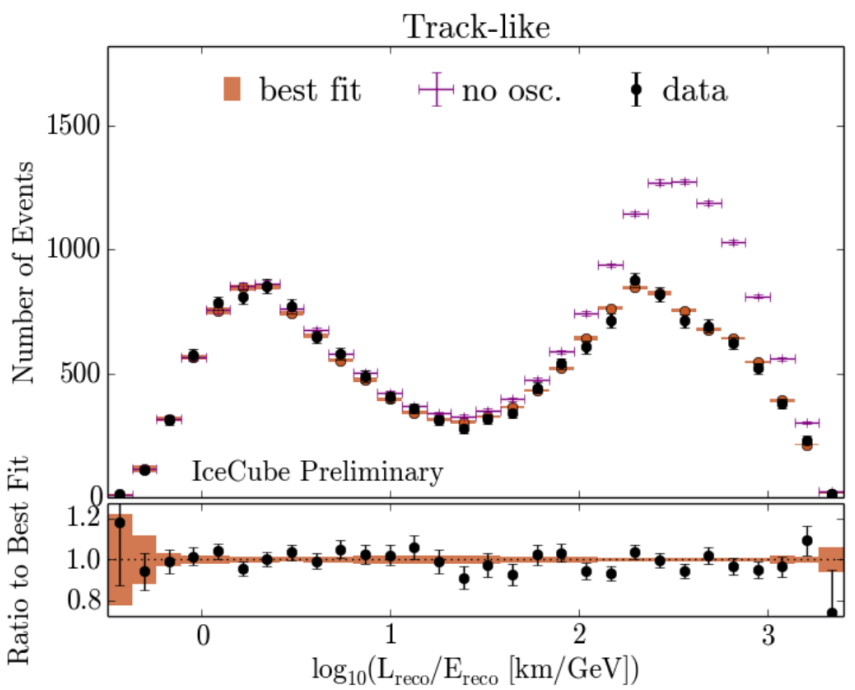






Neutrino oscillations



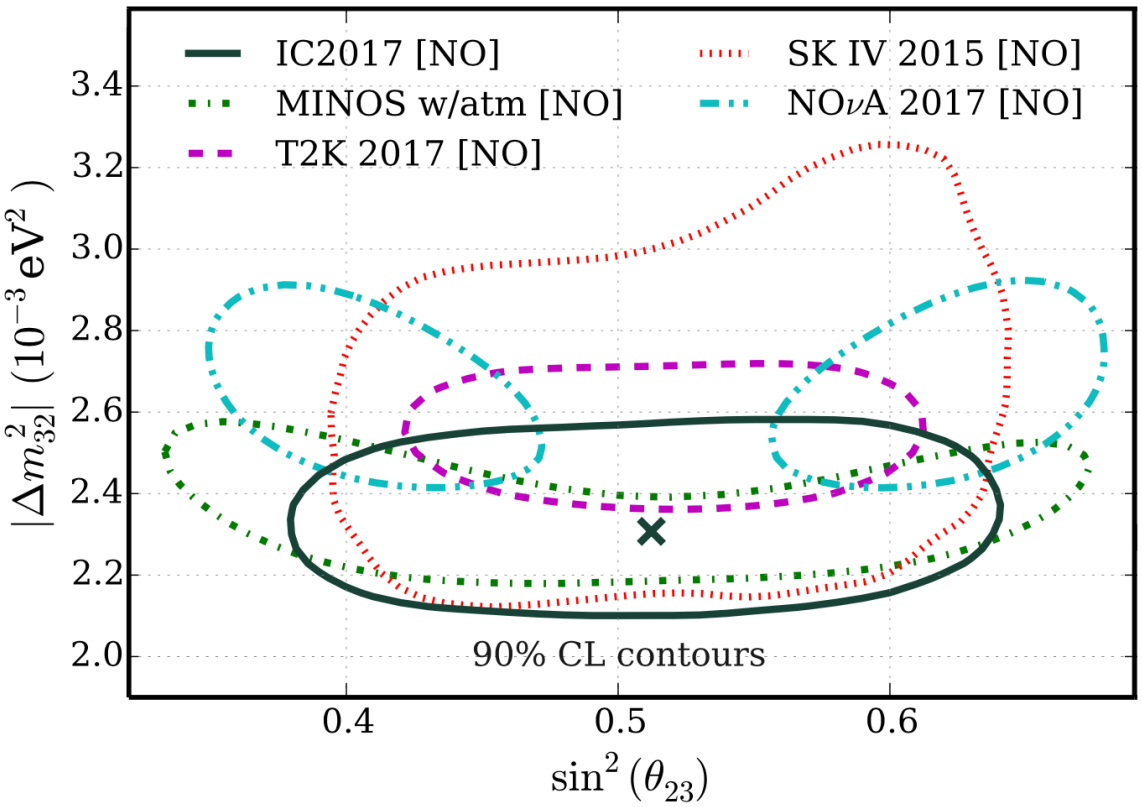


Full analysis uses a 2D spectrum of E_ν v $\cos\theta_z$

- Projected onto one L/E_ν axis here for illustration

Neutrino oscillations

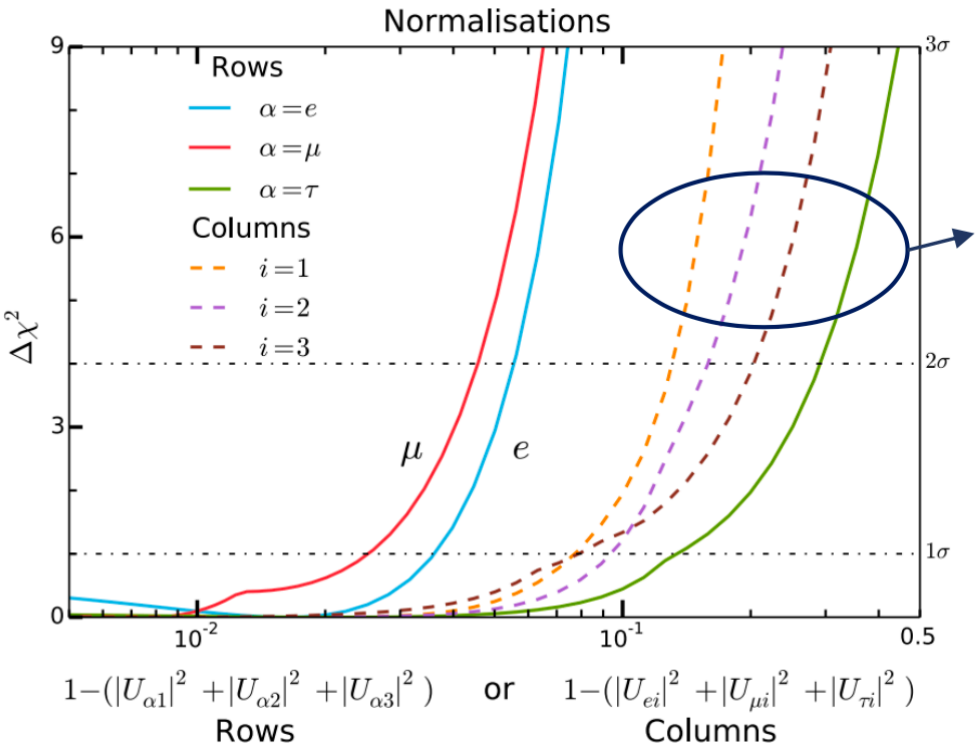
*arXiv:1707.07081



Best Fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \cdot 10^{-3}\mathrm{eV}^2$ & $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

41,599 total events from 2012-2014

Tau-neutrino appearance



All these contain one or more τ-elements

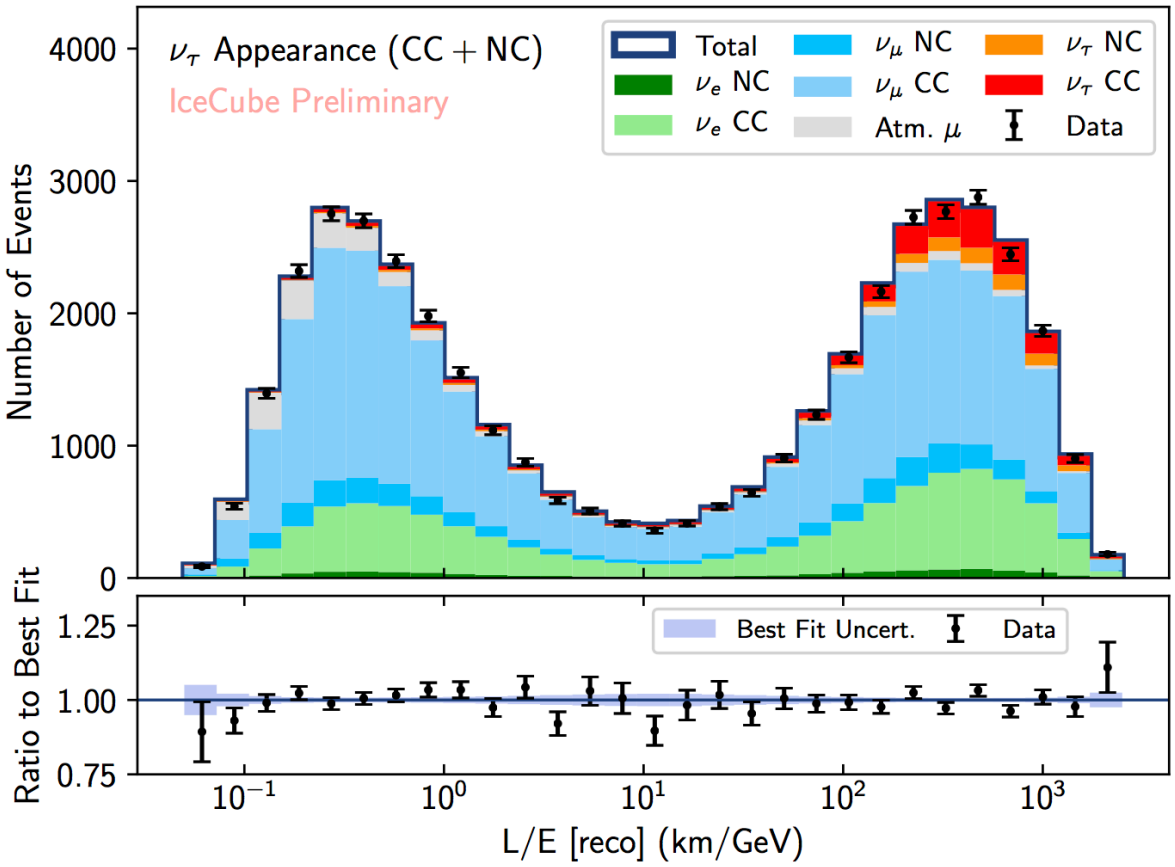
Parke & Ross-Lonergan Phys. Rev. **D93**, 113009 (2016)

τ sector is the least well-constrained

- An order of magnitude worse than the e and μ sectors

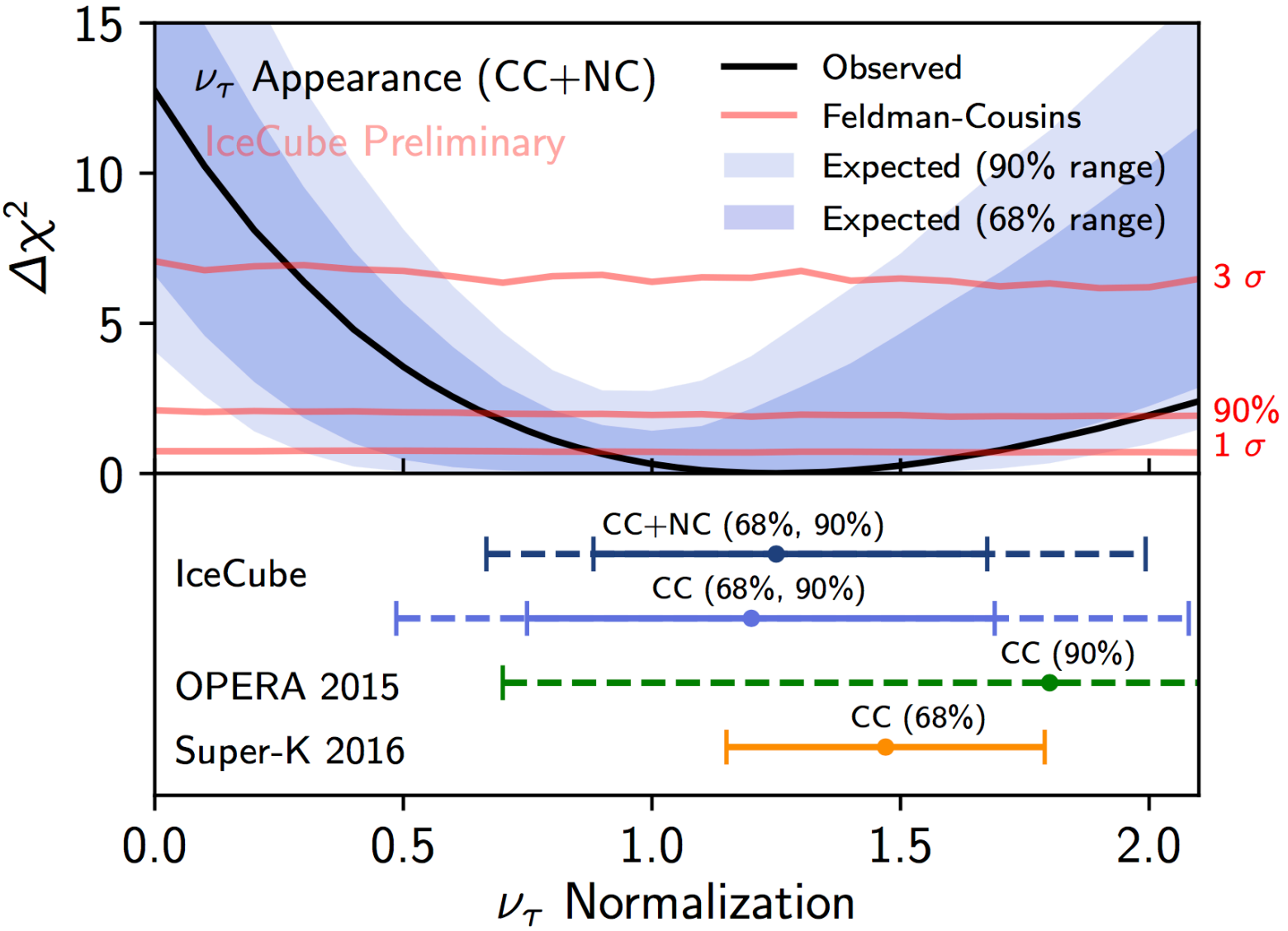
Important constraint on PMNS matrix unitarity

Tau-neutrino appearance

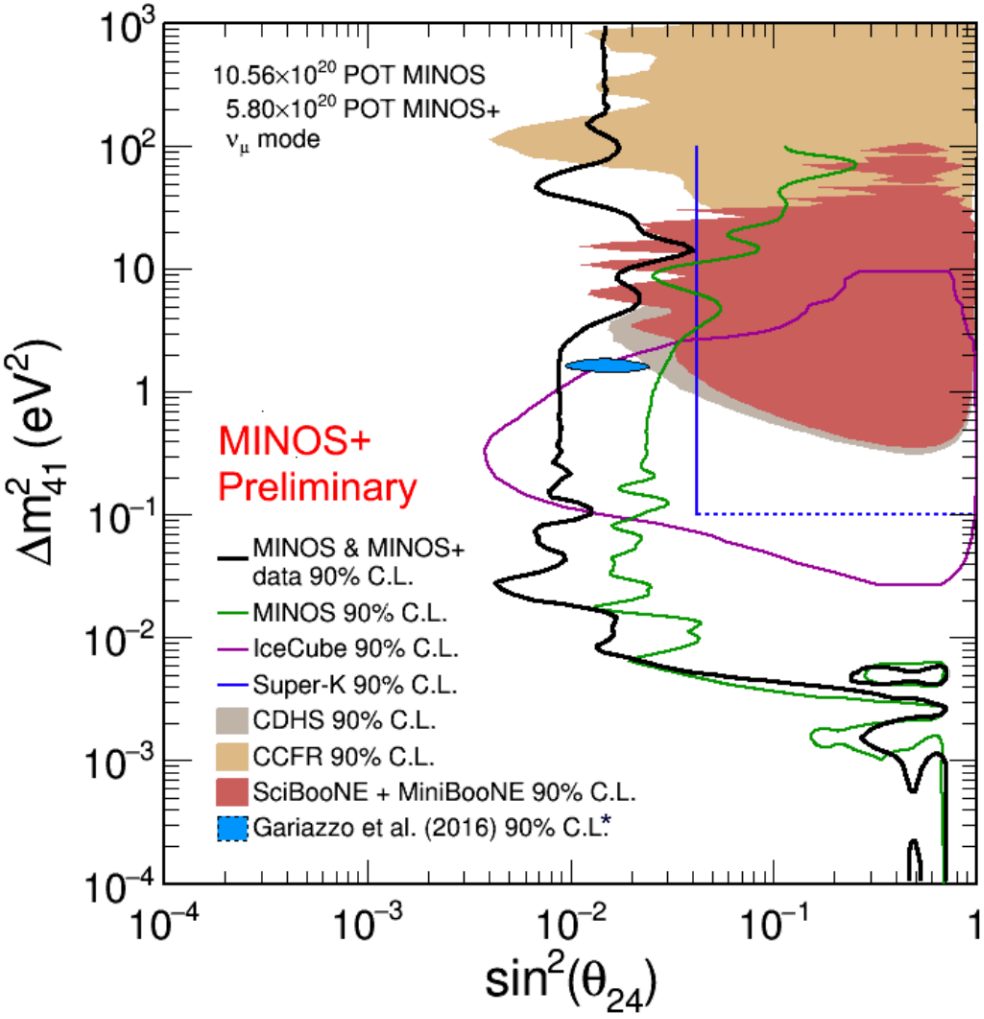


- Mainly in the up-going cascade sample

Tau-neutrino appearance



Sterile neutrinos



IceCube has used ν_μ dissapearance to set a limit on the mixing between sterile and muon neutrinos

- Taking advantage of high-energy matter effects

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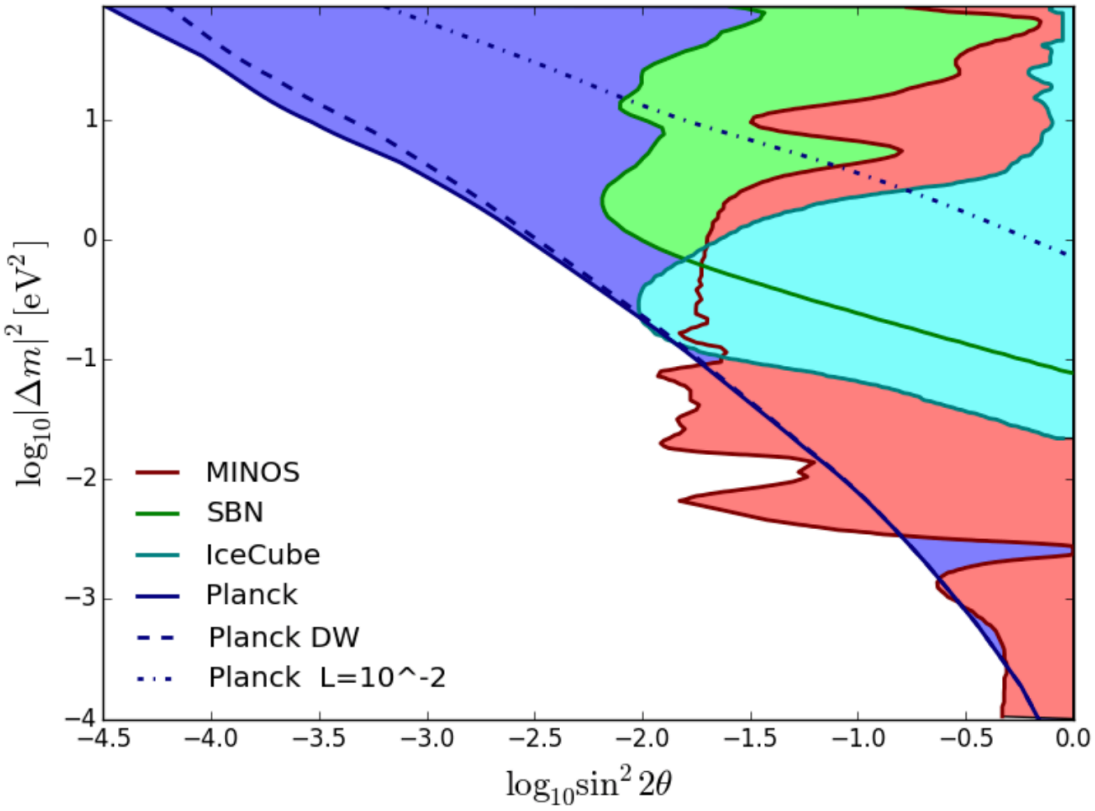
Sterile neutrinos – Comparison with cosmology

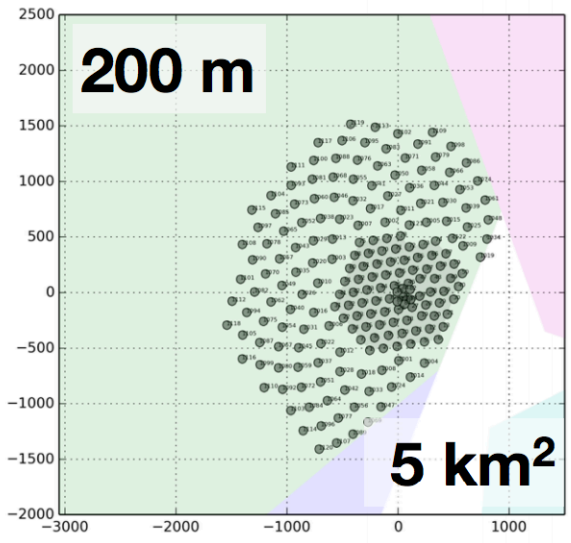


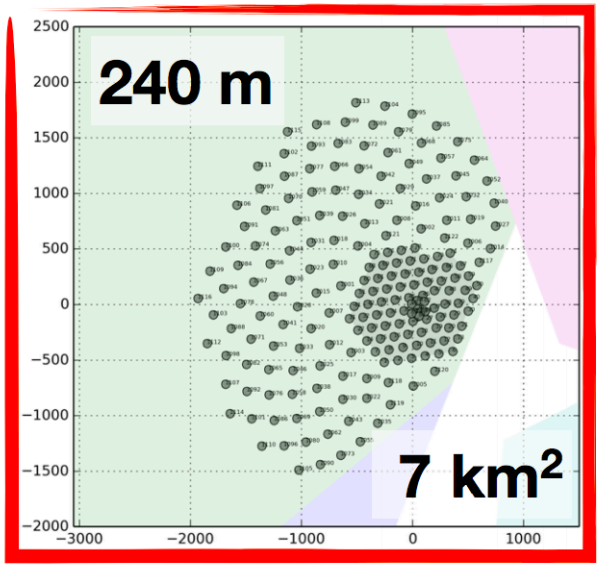
Planck CMB measurements set a limit on the effective number of neutrino flavours

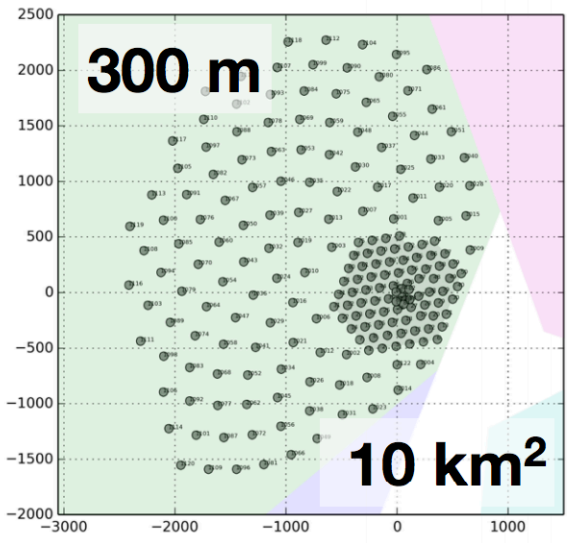
This can be converted into a limit on a mixing angle

- S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

IceCube Gen2: high energy







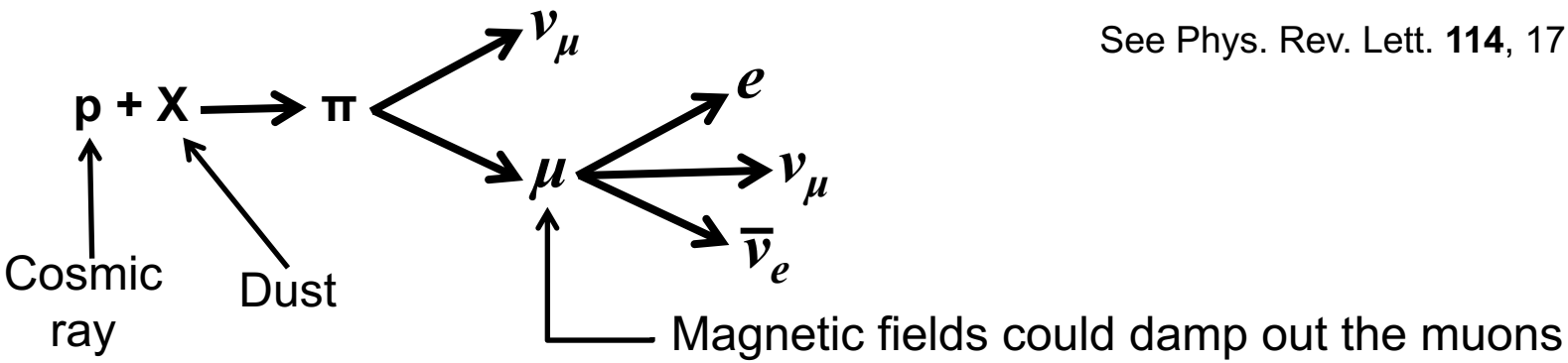
Moving from discovery to measurement and characterisation

Several layouts under consideration

- ~120 new strings, 80 DOMs per string
- ~10x IceCube volume for contained events above 100 TeV

New DOM technologies increase photocathode area and provide more directionality

Flavour ratio



See Phys. Rev. Lett. **114**, 171102 (2015)

Production mechanism	$f_e : f_\mu : f_\tau$ at source	$f_e : f_\mu : f_\tau$ at detector
Pion decay	1 : 2 : 0	0.93 : 1.05 : 1.02
Muon cooling	0 : 1 : 0	0.6 : 1.3 : 1.1
Neutron decay	1 : 0 : 0	1.6 : 0.6 : 0.8

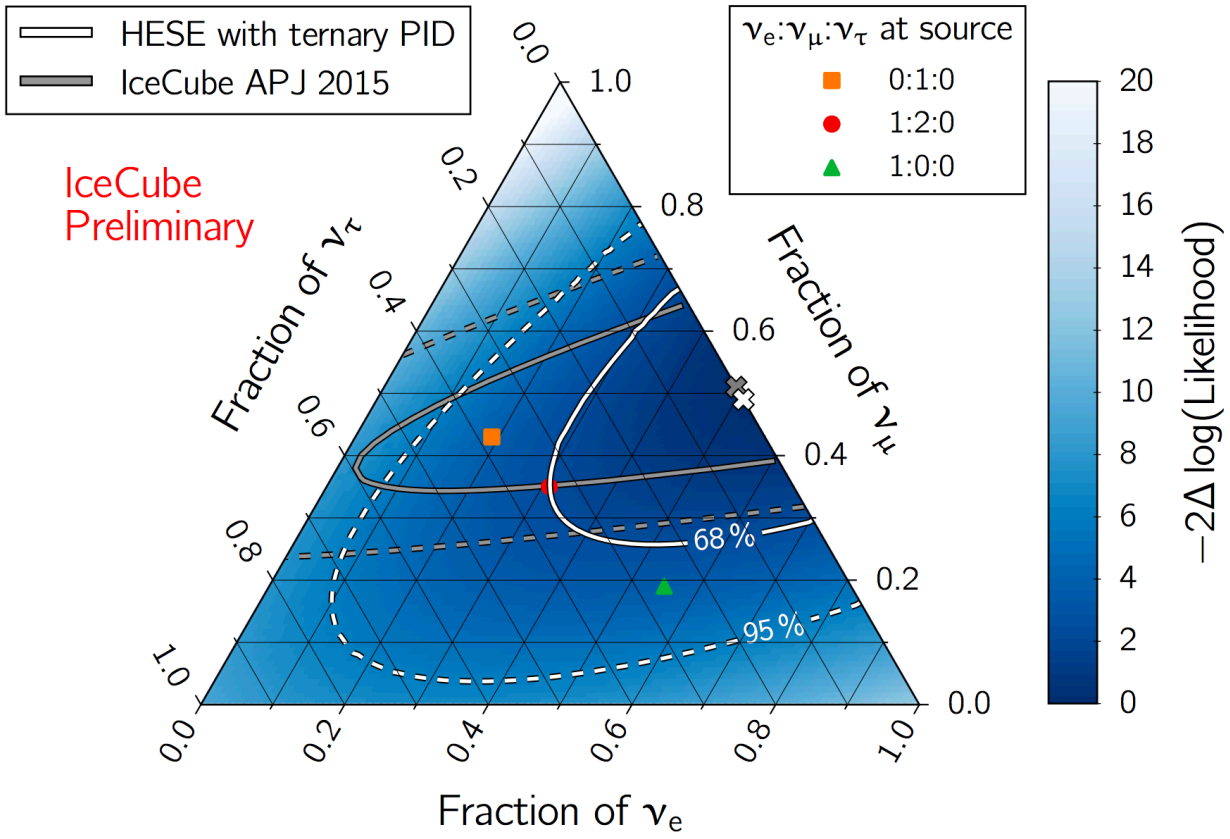
We can learn about neutrino physics

- A deviation from the expectation could indicate new physics as the neutrinos propagate

We can learn about neutrino production mechanisms

- Given present understanding of neutrino oscillations, we can infer the flavour ratio at the source

Flavour ratio



$$f_{\nu_e} = 0.51^{+0.12}_{-0.13}$$

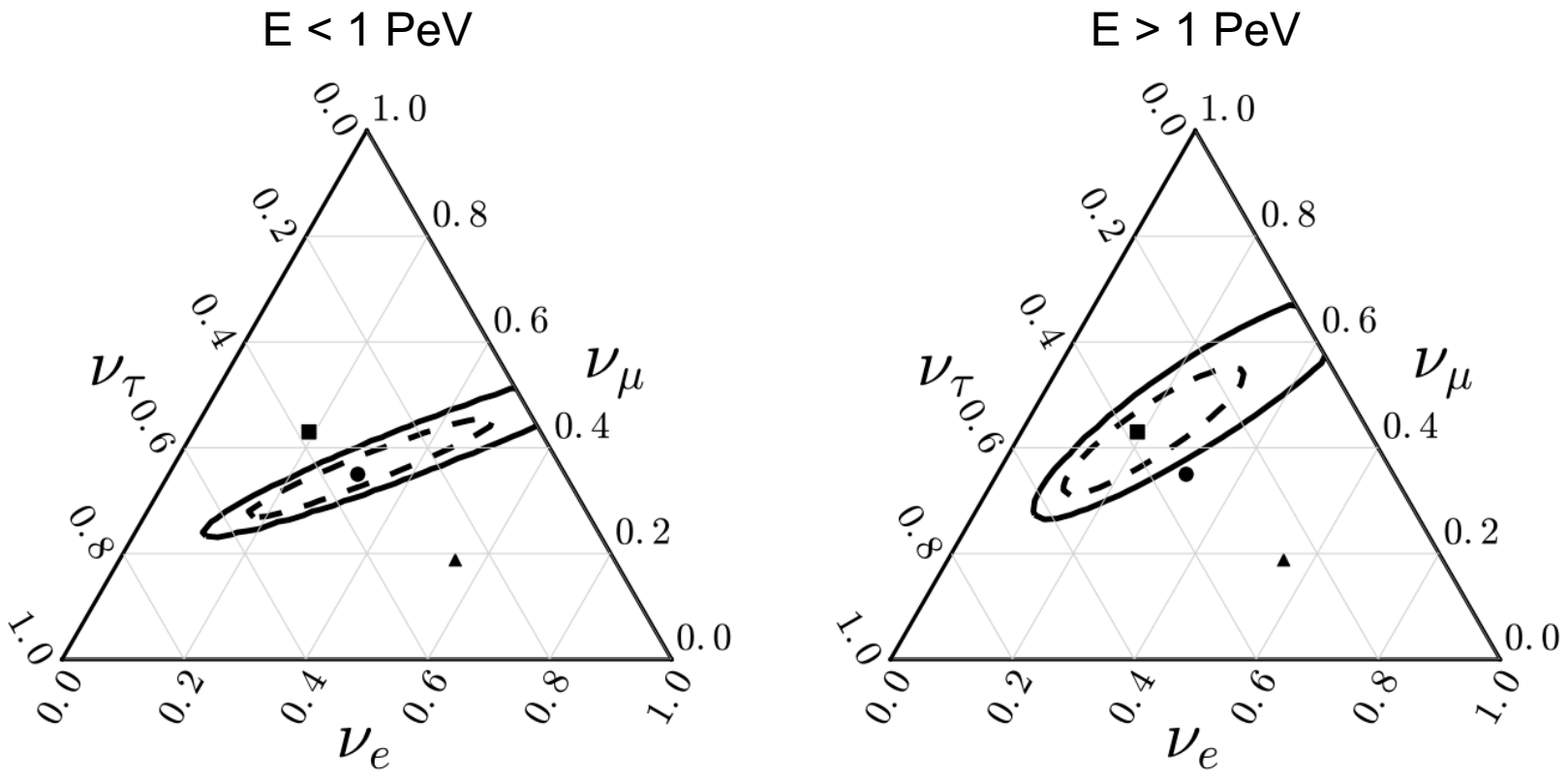
$$f_{\nu_\mu} = 0.49^{+0.12}_{-0.13}$$

$$f_{\nu_\tau} = 0.00^{+0.16}_{-0.00}$$

No tau neutrinos observed yet

- Consistent with the statistical expectation: 2.83 expected: 9.3% probability

Flavour ratio with IceCube Gen2



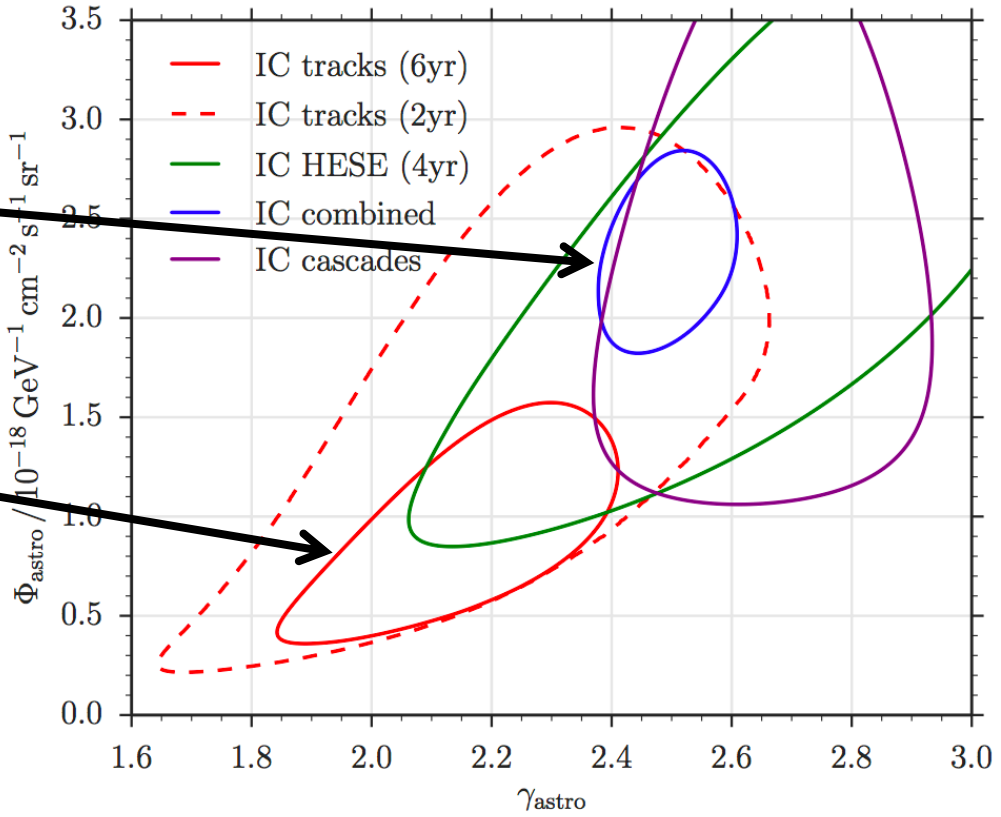
Energy-dependent flavour studies will be possible

- 15 years of data with Gen2

Spectral index

Lower energy threshold
Mainly sensitive to southern sky

Higher energy threshold
Mainly sensitive to northern sky



Astrophys. J **833**, 3 (2016)
arXiv:1607.08006

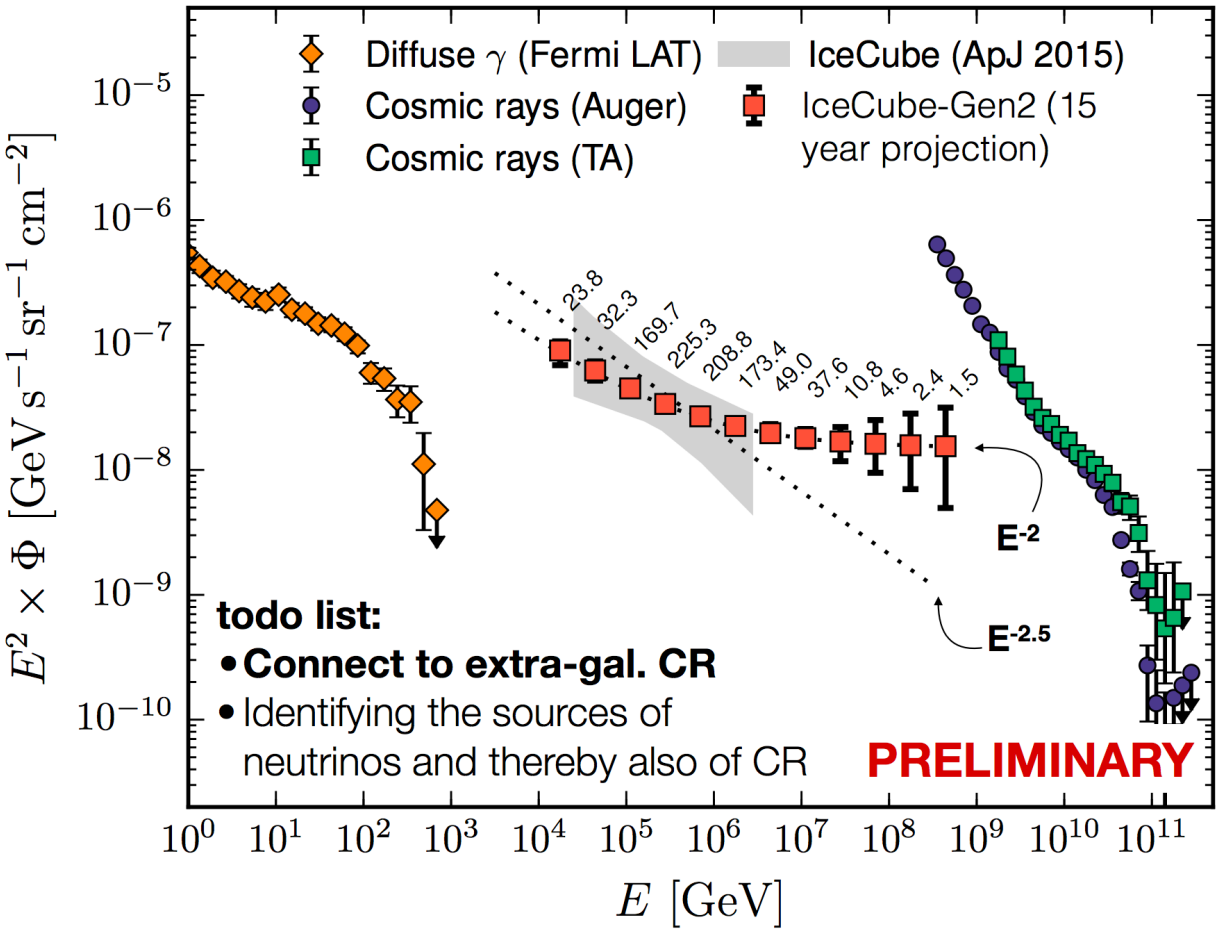
Incompatible at 3.3σ

A spectral break for some reason?

Two components?

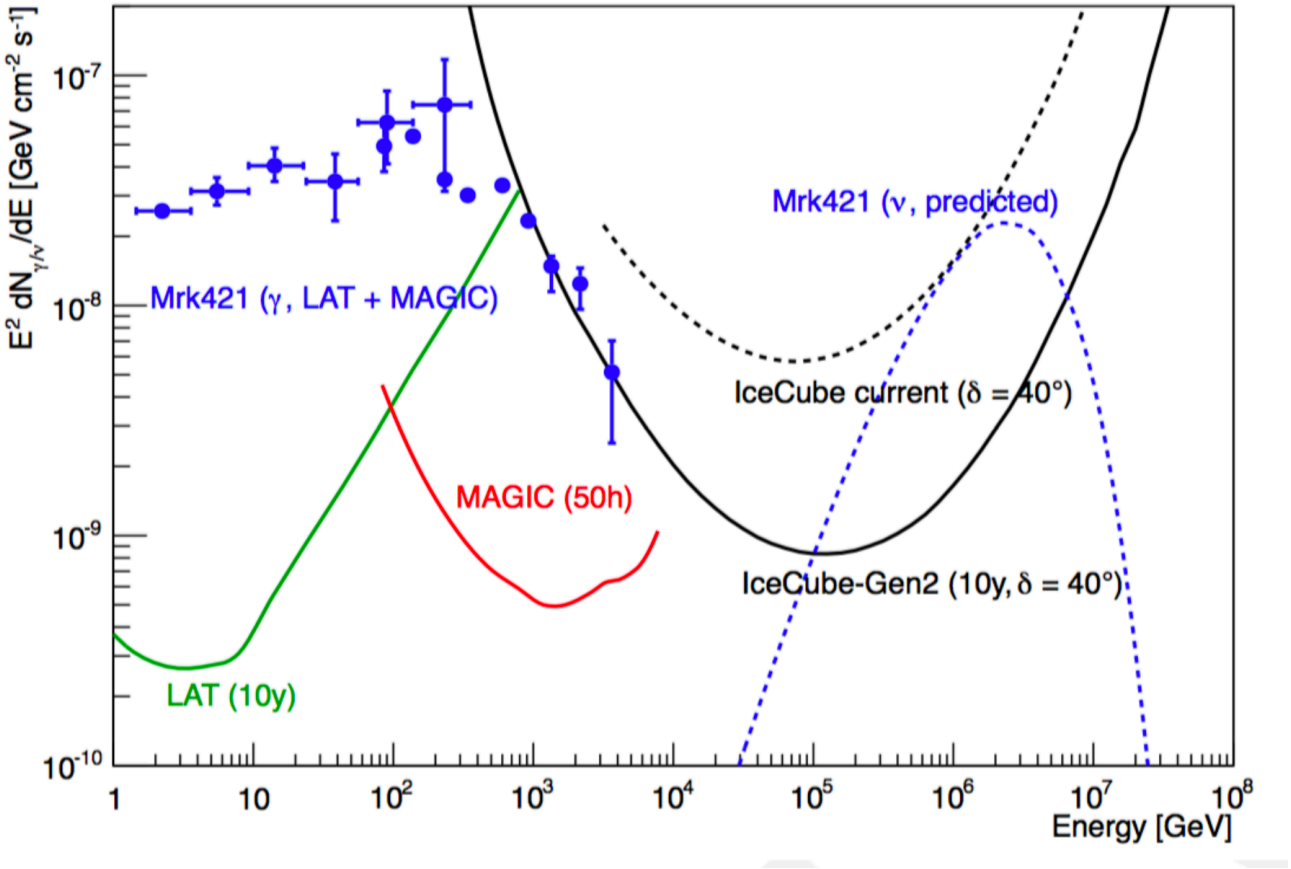
- Galactic (southern sky) and extra-galactic?

Spectral index with Gen2



- Understand the evolution of the spectral index
- Connect the neutrino spectrum to the cosmic ray spectrum

When will we see a point source?



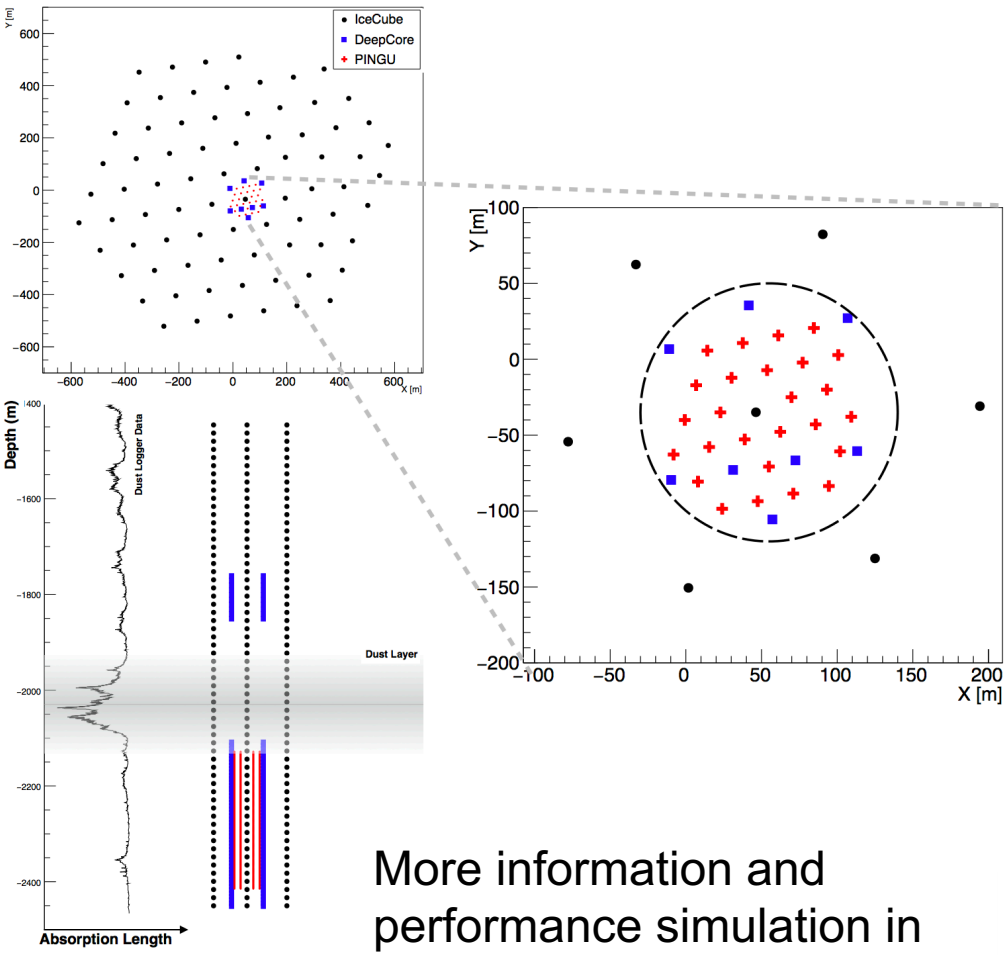
Markarian 421

One of the closest blazars to Earth

Many point sources are at the edge of IceCube's sensitivity

- But IceCube-Gen2 should start to see them

IceCube Gen2: low energy



26 additional, very densely instrumented strings embedded in DeepCore

- Additional calibration devices to better control detector systematics

6 Mton fiducial volume with few GeV energy threshold

Precision neutrino physics

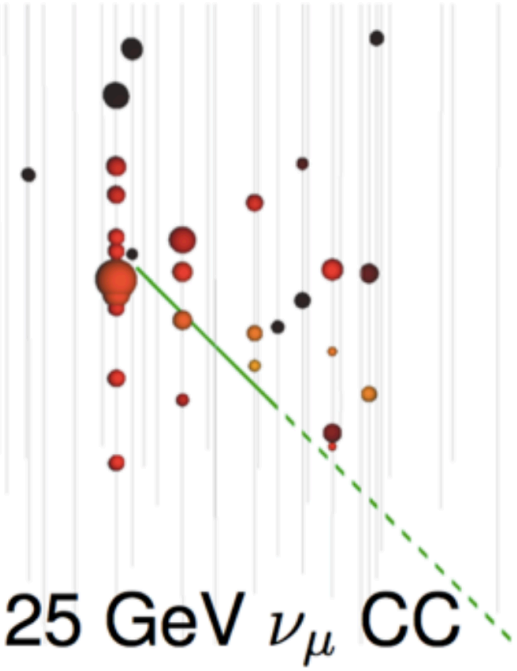
- Mass ordering
- Tau neutrino appearance
- Maximal mixing and octant

More information and performance simulation in updated Letter of Intent, **arXiv:1401.2046**

PRECISION ICECUBE NEXT GENERATION UPGRADE

Low-energy neutrinos with Gen2

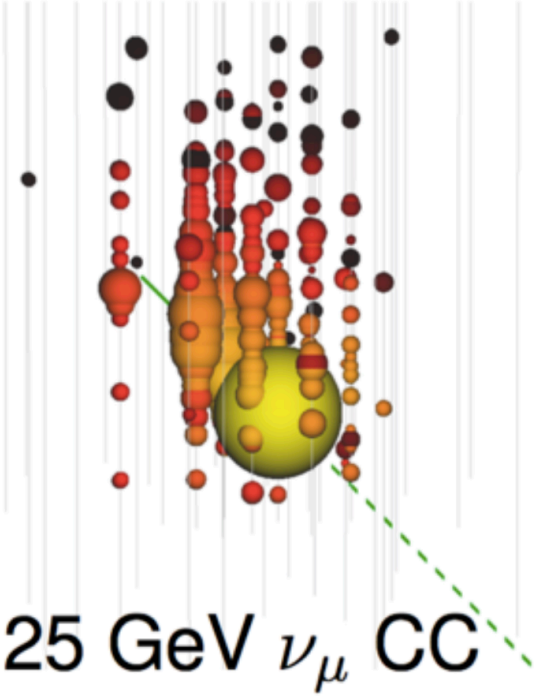
DeepCore



25 GeV ν_μ CC

color → hit time
size → hit charge

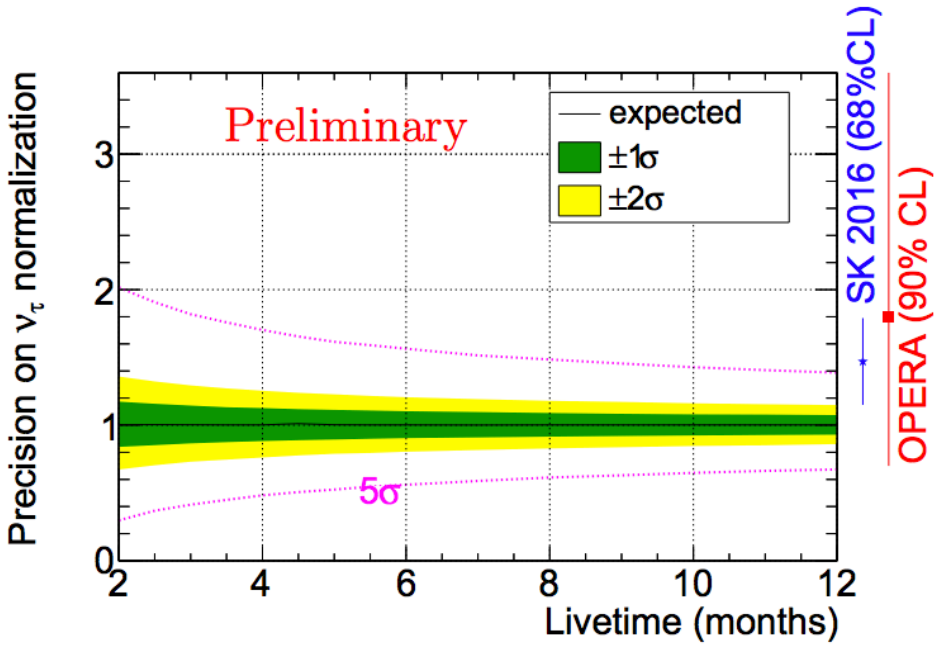
Gen2-PINGU

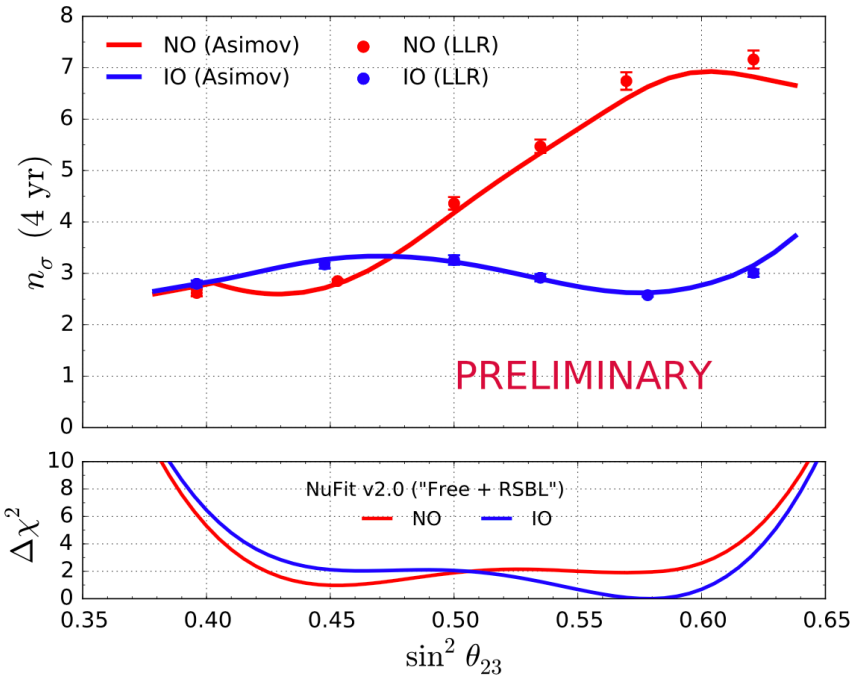


25 GeV ν_μ CC

color → hit time
size → hit charge

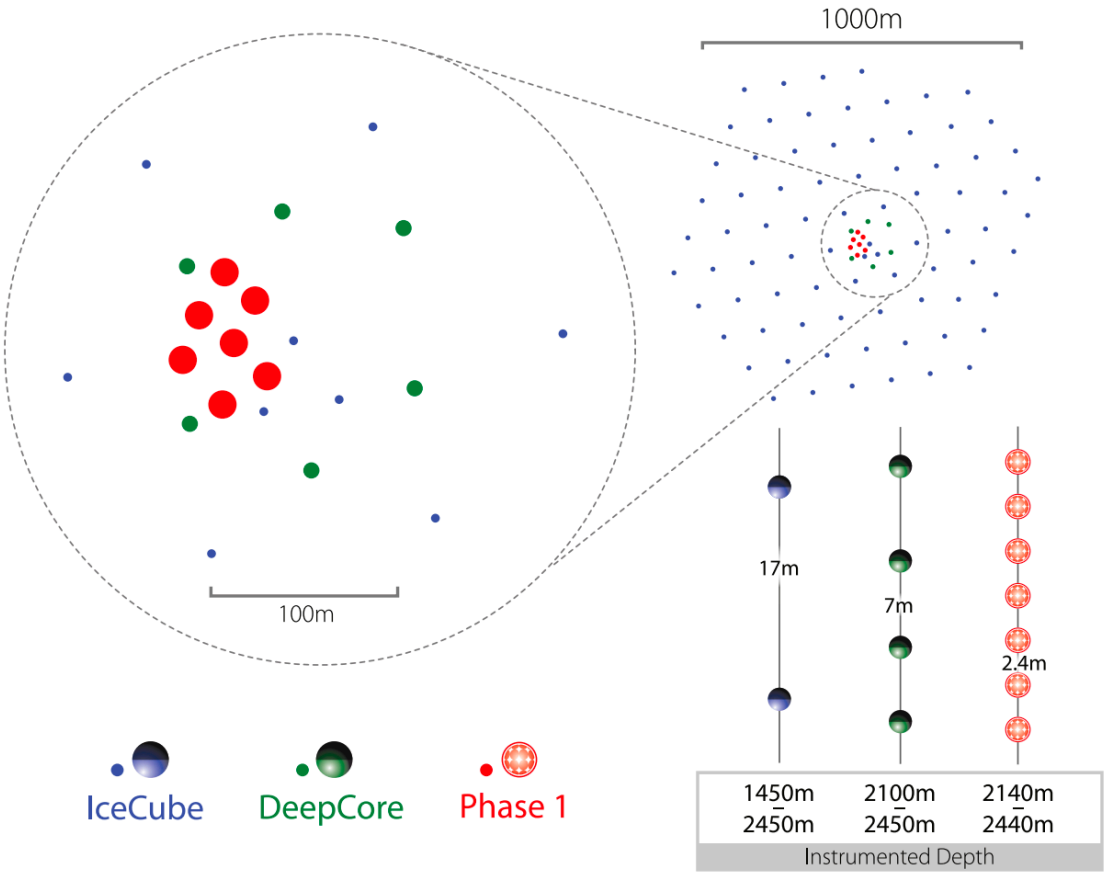
Gen2-PINGU physics





- Tau neutrino appearance on the timescale of months
- Neutrino mass hierarchy determination

Near-term IceCube upgrade



A proposal has been submitted to NSF to install 7 new strings

- In a 'low-energy' (PINGU-like) configuration
- Includes a suite of calibration devices to improve IceCube scientific capabilities at both low and high energies

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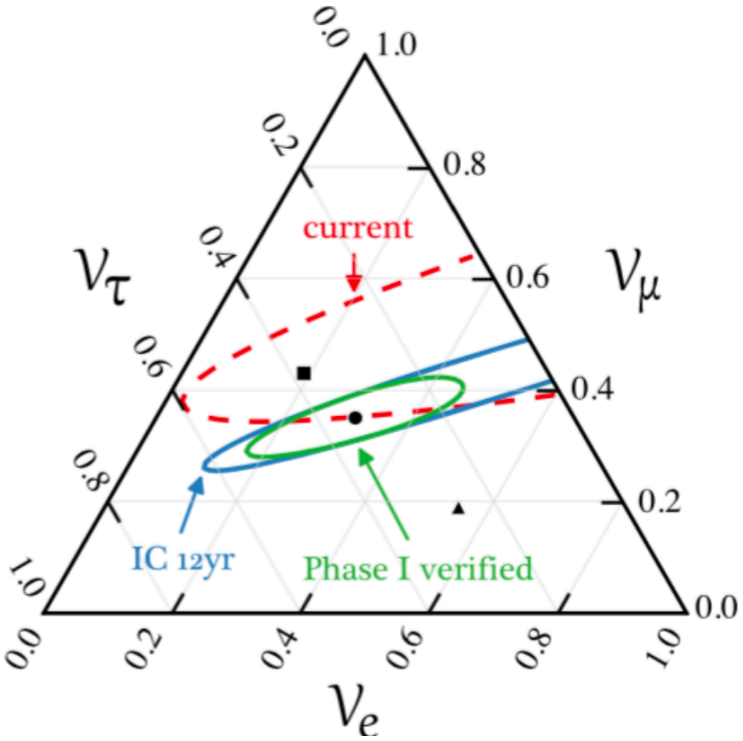
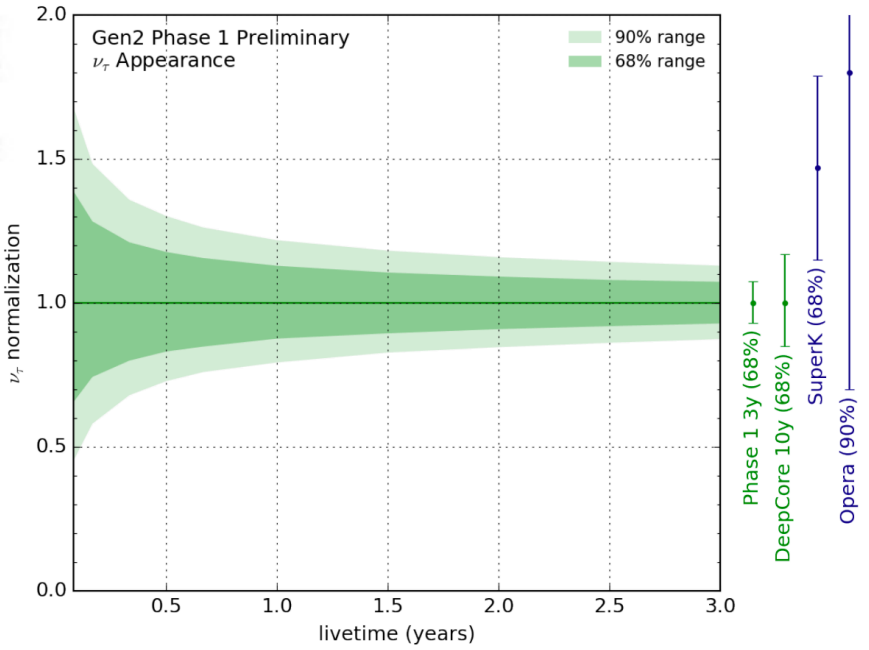
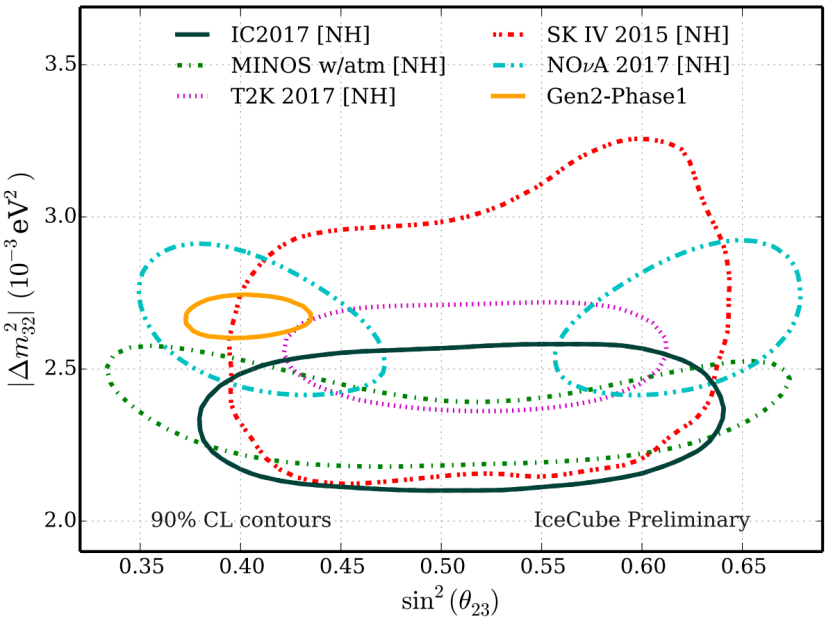
Physics with the 7-string upgrade







3σ discovery of cosmic tau neutrinos in 12 years of IceCube data, using the new calibration devices

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Summary

IceCube has discovered high-energy astrophysical neutrinos

And we are starting to quantify their properties

- Spectral indices
- Flavour composition

IceCube-Gen2 will take us from discovery to precision measurement

- We should see sources
- We will be able to distinguish between production models with our measurements of the flavour composition and spectral distributions

IceCube-DeepCore has an exciting neutrino oscillation physics programme

- Competitive oscillation parameter measurements
- Tau-neutrino appearance

IceCube-Gen2 will be a game-changer for the oscillation programme

- Unprecedented tau-neutrino statistics
- Mass hierarchy determination

A seven-string upgrade is the first step on the road to Gen2