

DeepCore and PINGU

Studying Neutrinos in the Ice

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TORONTO

Neutrino Oscillations

- Already been introduced several times to oscillations
- Important part is that we need to know the energy (E) and the distance traveled (L)

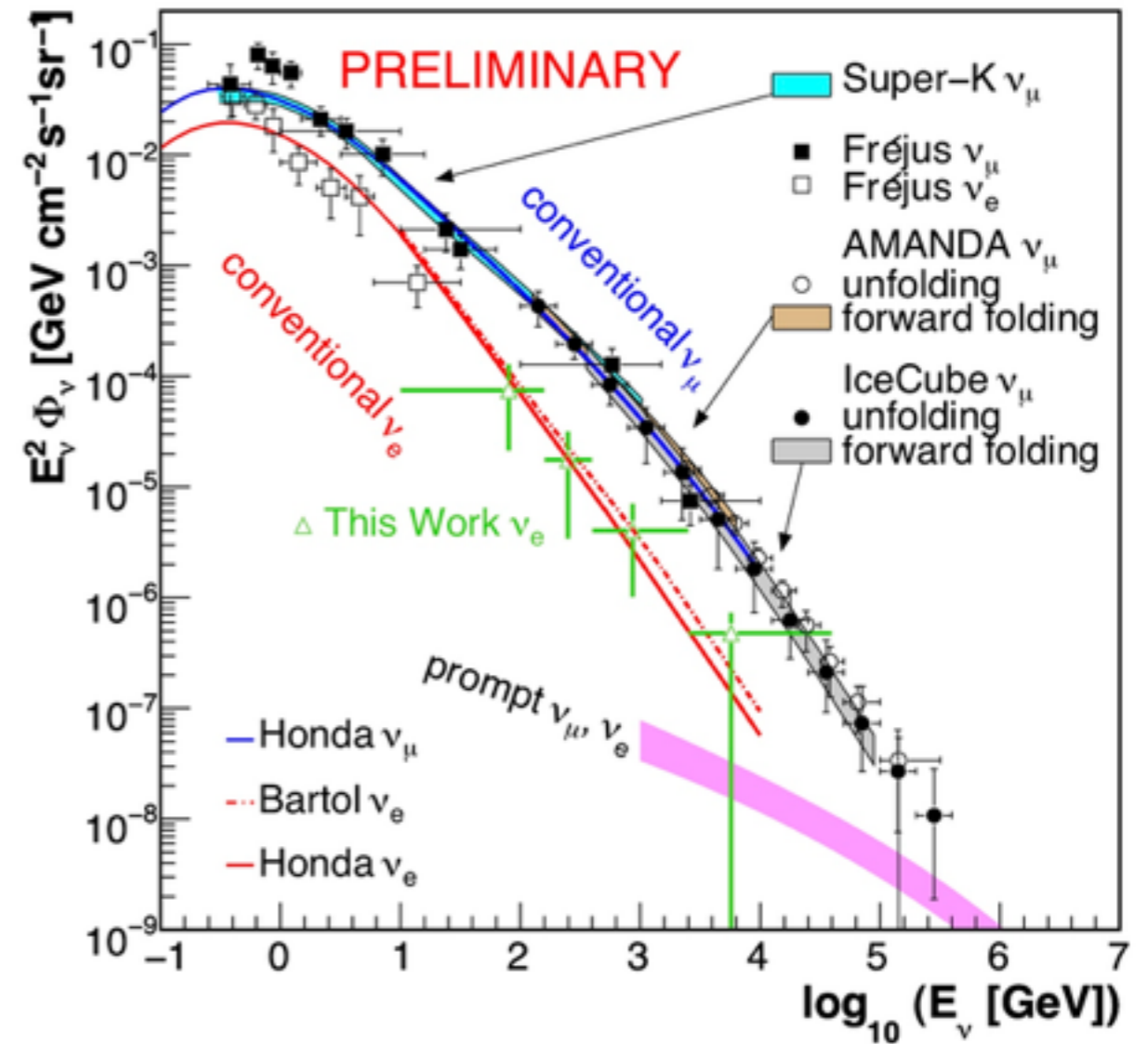
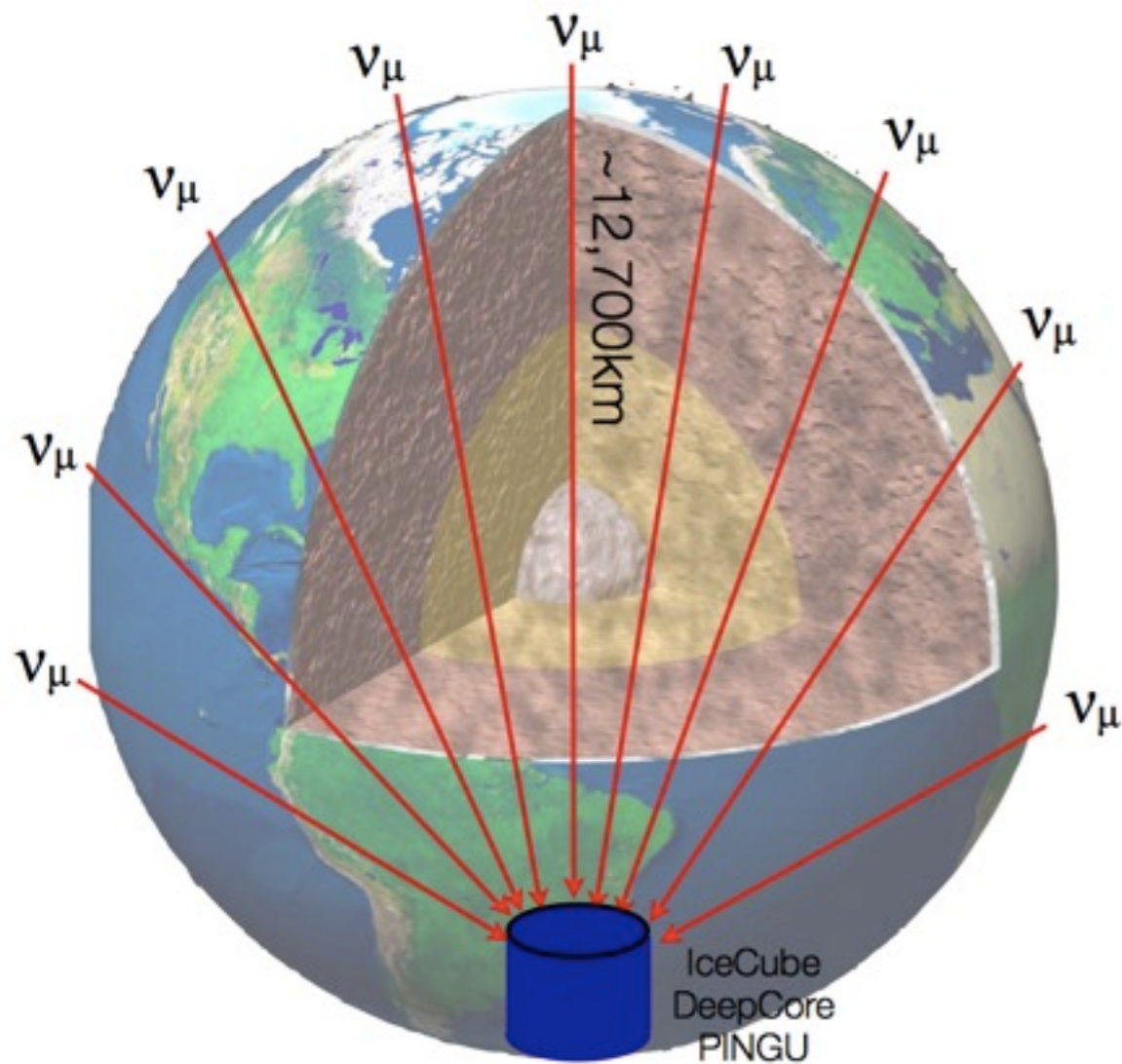
$$P(|\nu_\alpha\rangle \rightarrow |\nu_\beta\rangle) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$

Neutrino Oscillations

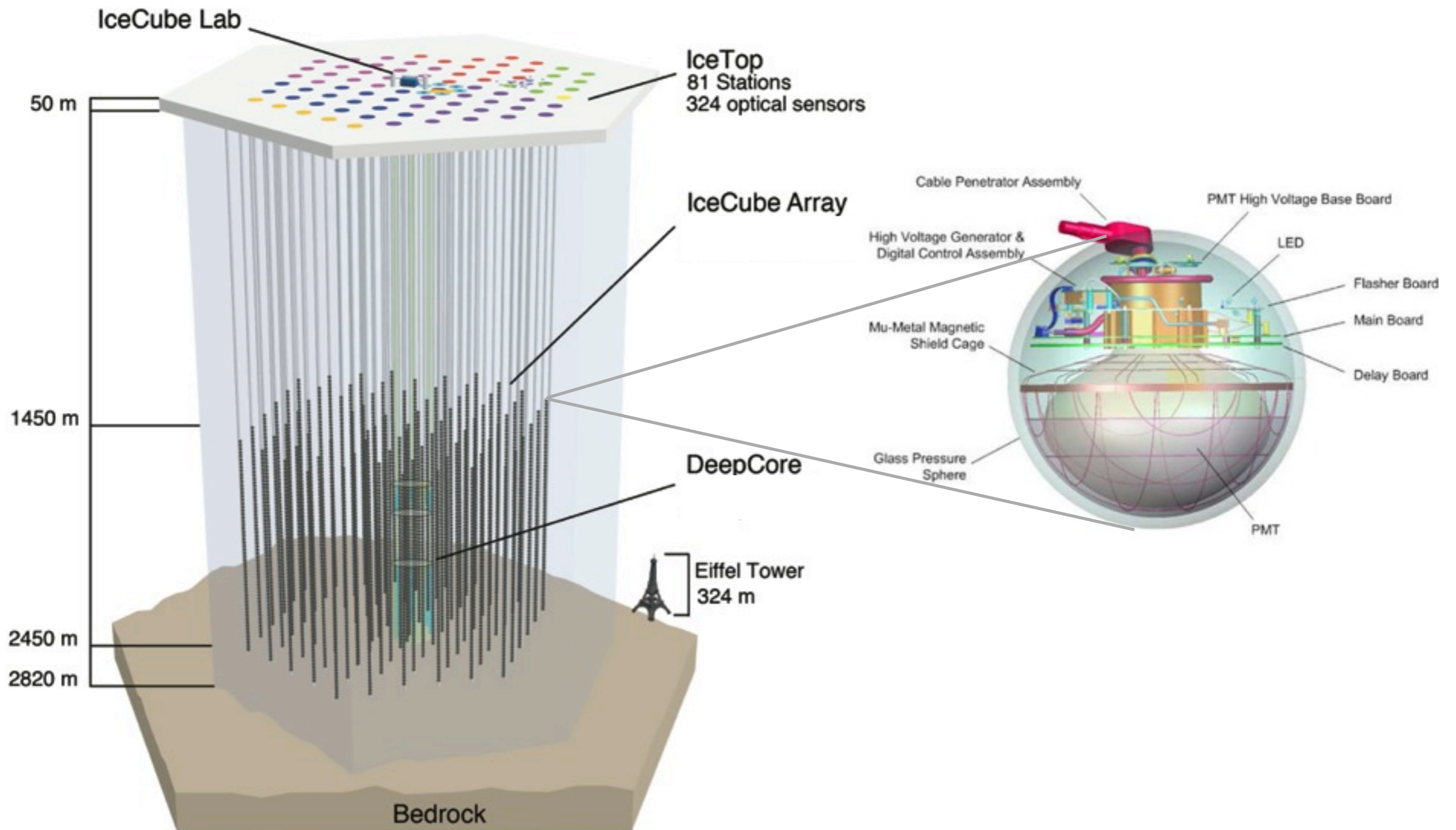
L

E

PRL 110, 151105 (2013)

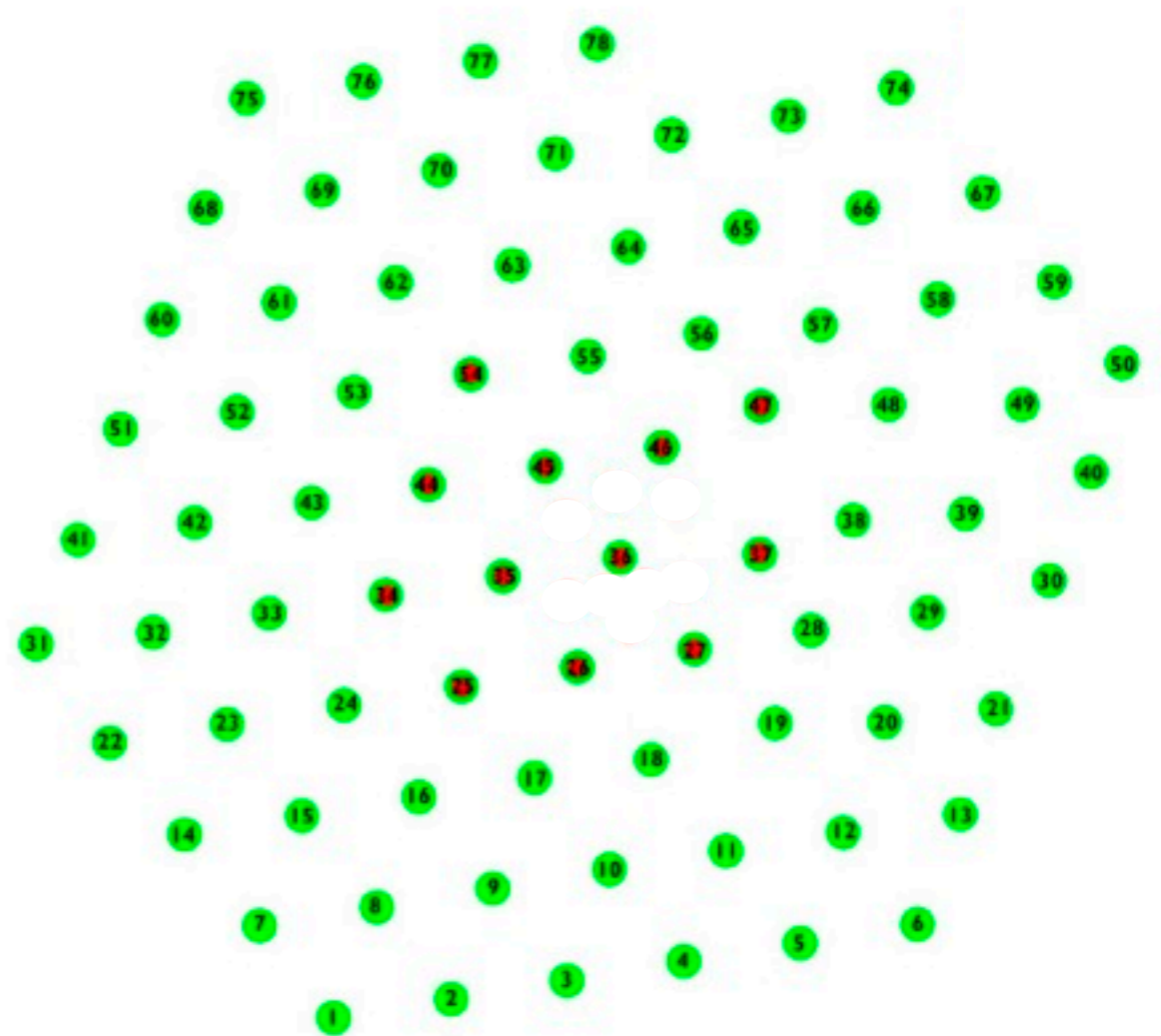


The IceCube Neutrino Telescope



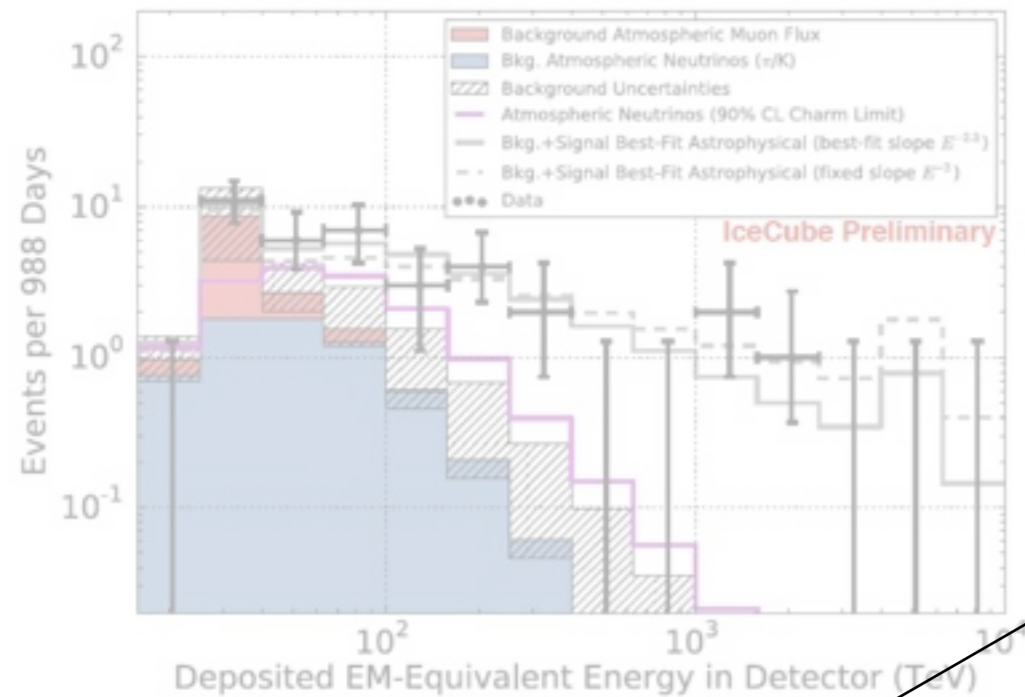
IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing

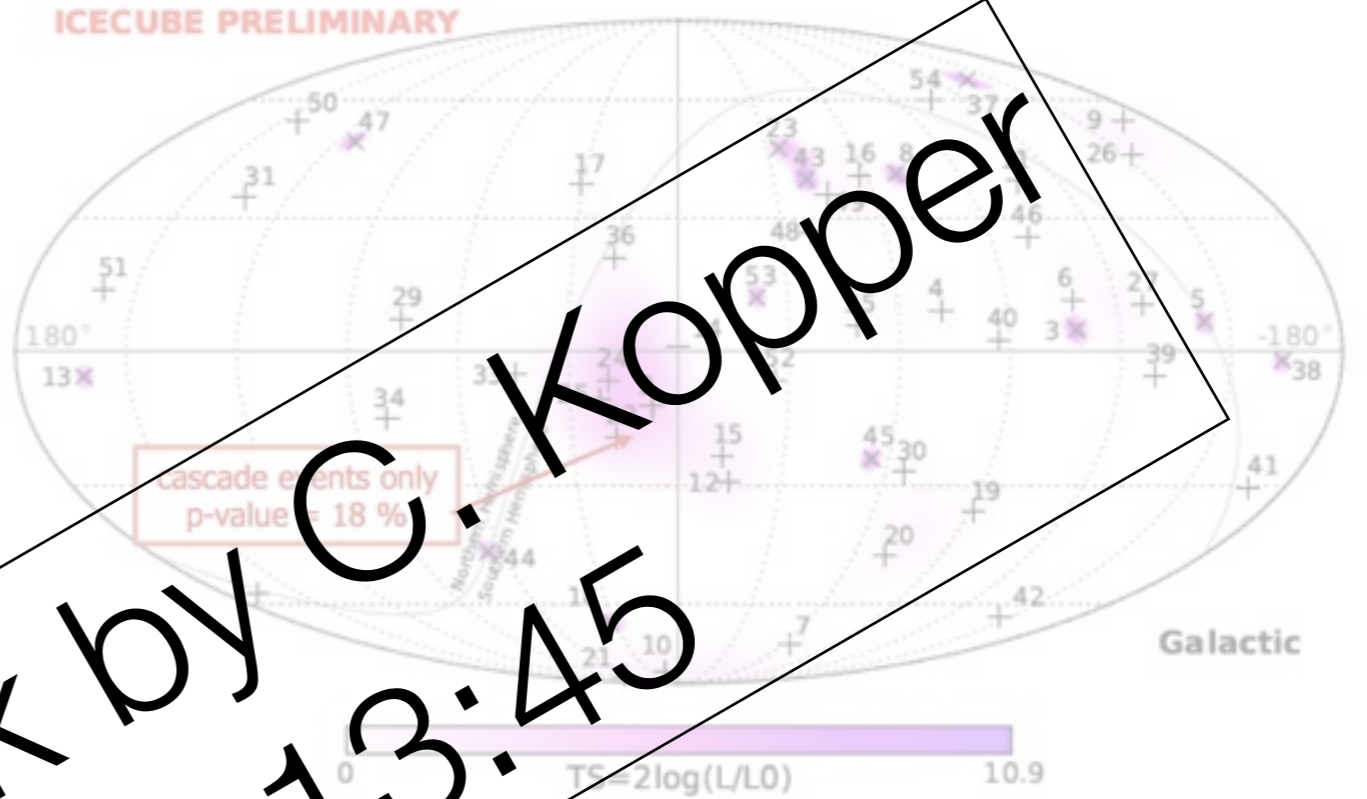


IceCube

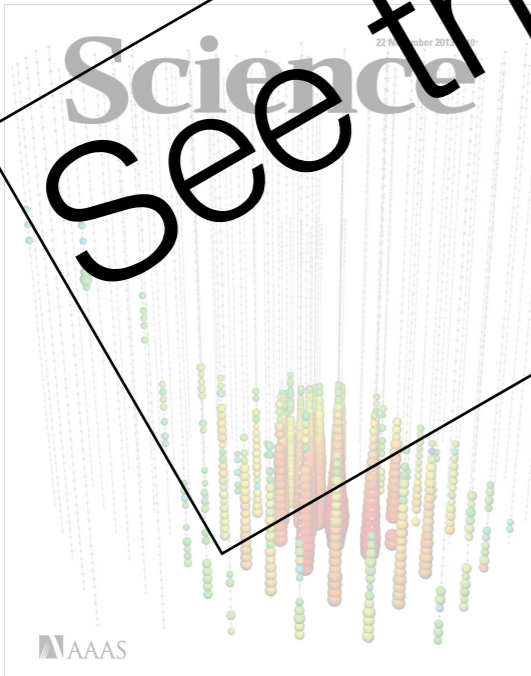
IceCube Results



ICECUBE PRELIMINARY

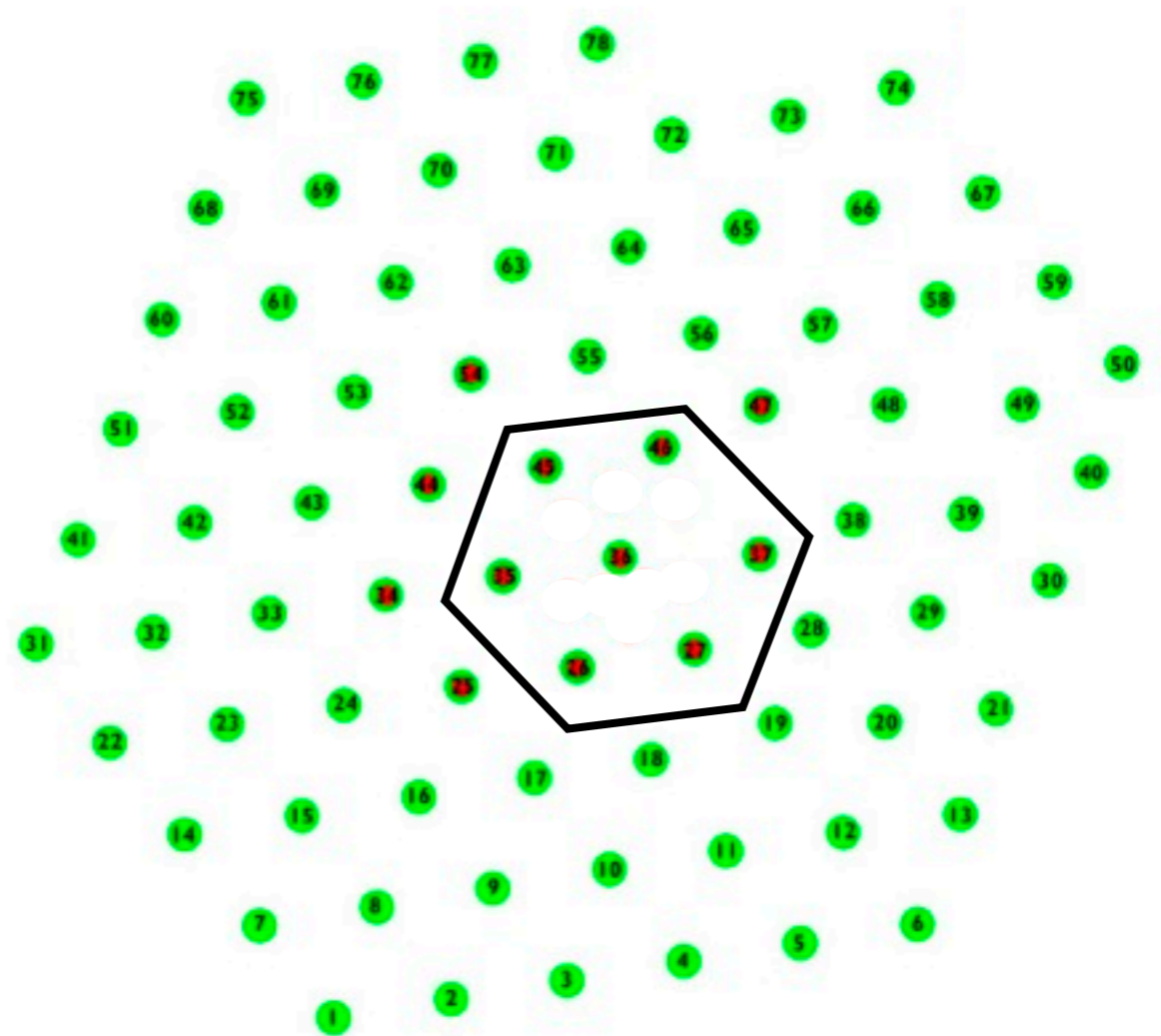


Science



IceCube

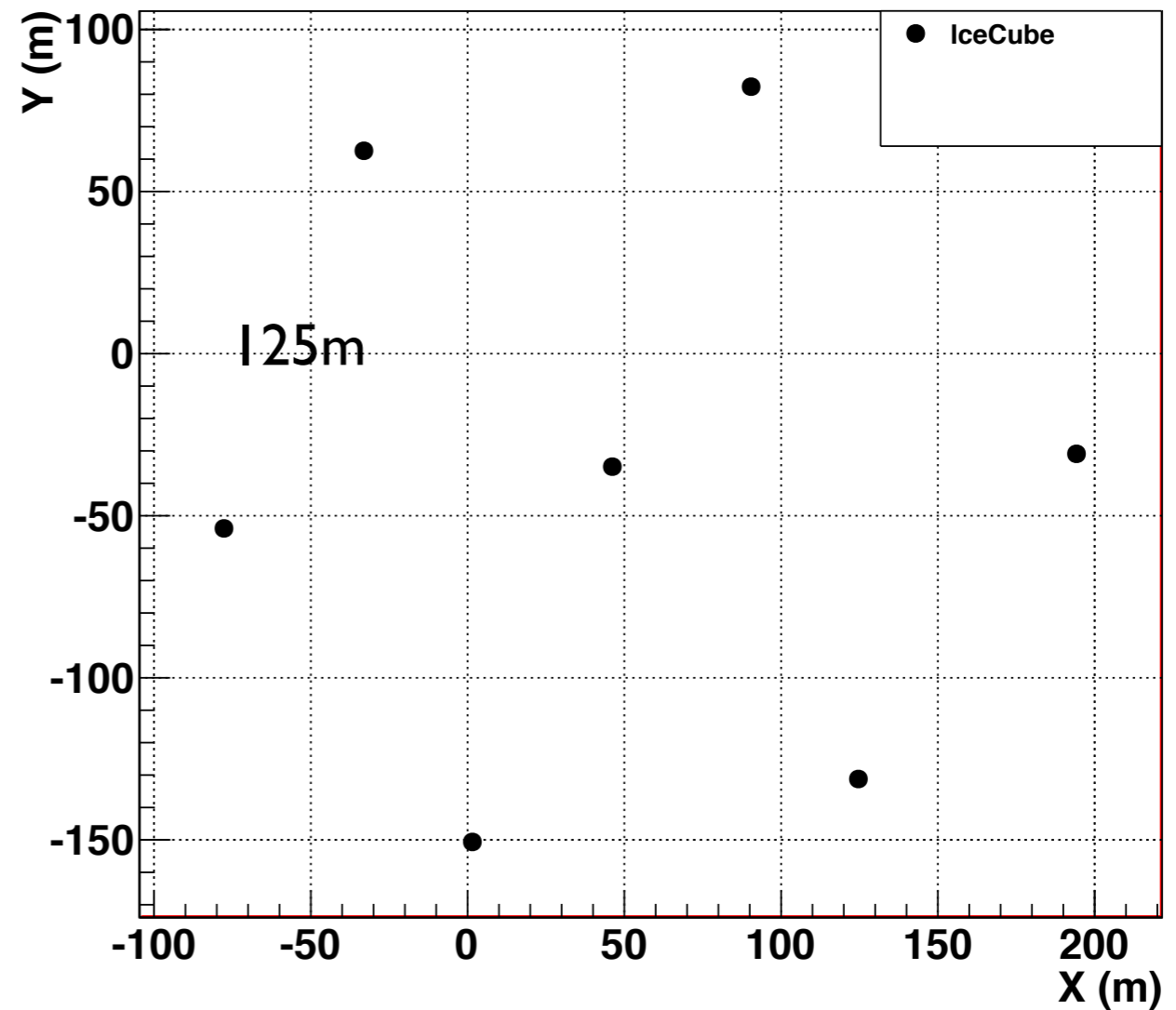
- 78 Strings
- 125m string spacing
- 17m DOM spacing



IceCube

IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing



10 MeV

100 MeV

1 GeV

10 GeV

100 GeV

1 TeV

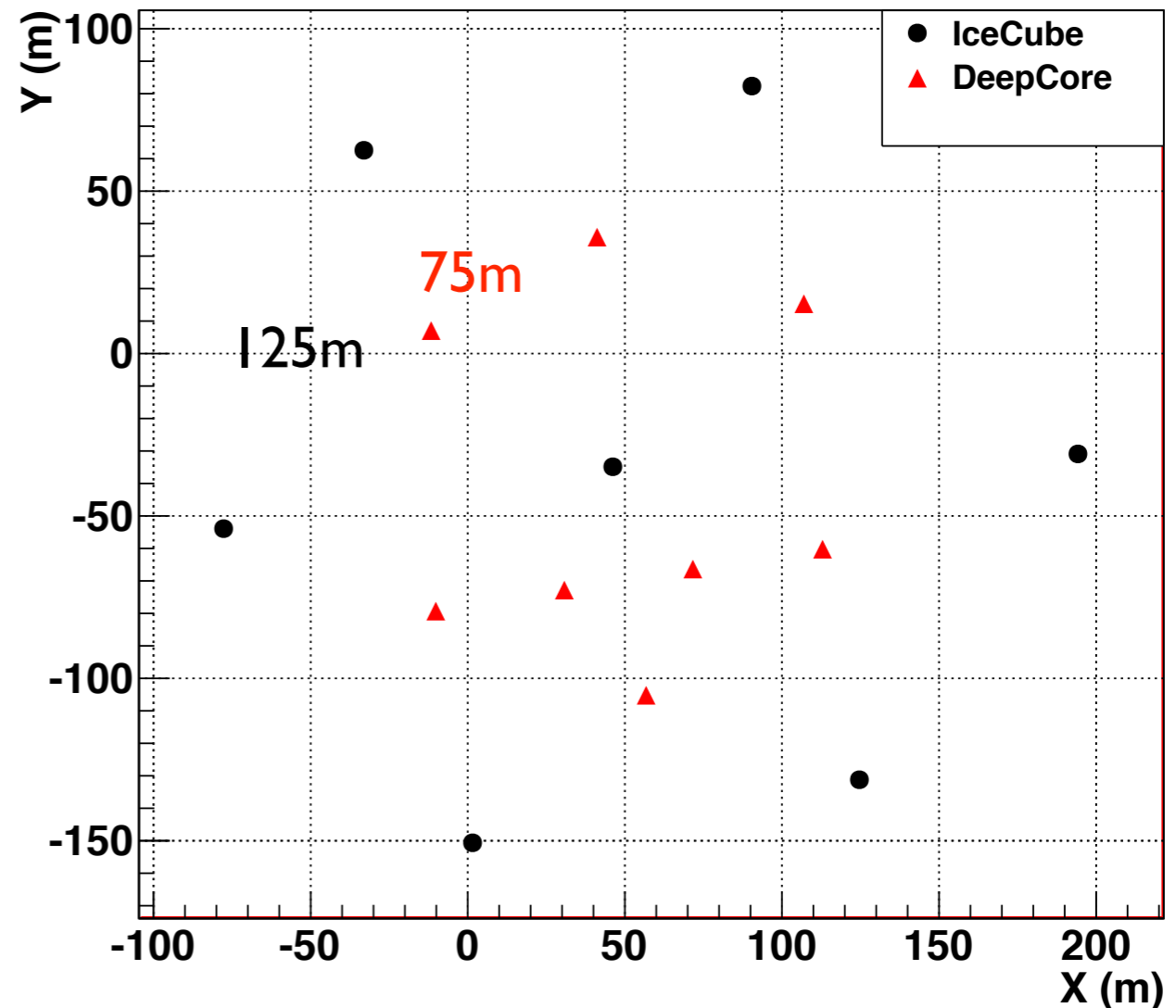
10 TeV

1 EeV

IceCube

IceCube + DeepCore

- 78 Strings
 - 125m string spacing
 - 17m DOM spacing
- Add 8 strings
 - 75m string spacing
 - 7m DOM spacing



10 MeV

100 MeV

1 GeV

10 GeV

100 GeV

1 TeV

10 TeV

1 EeV

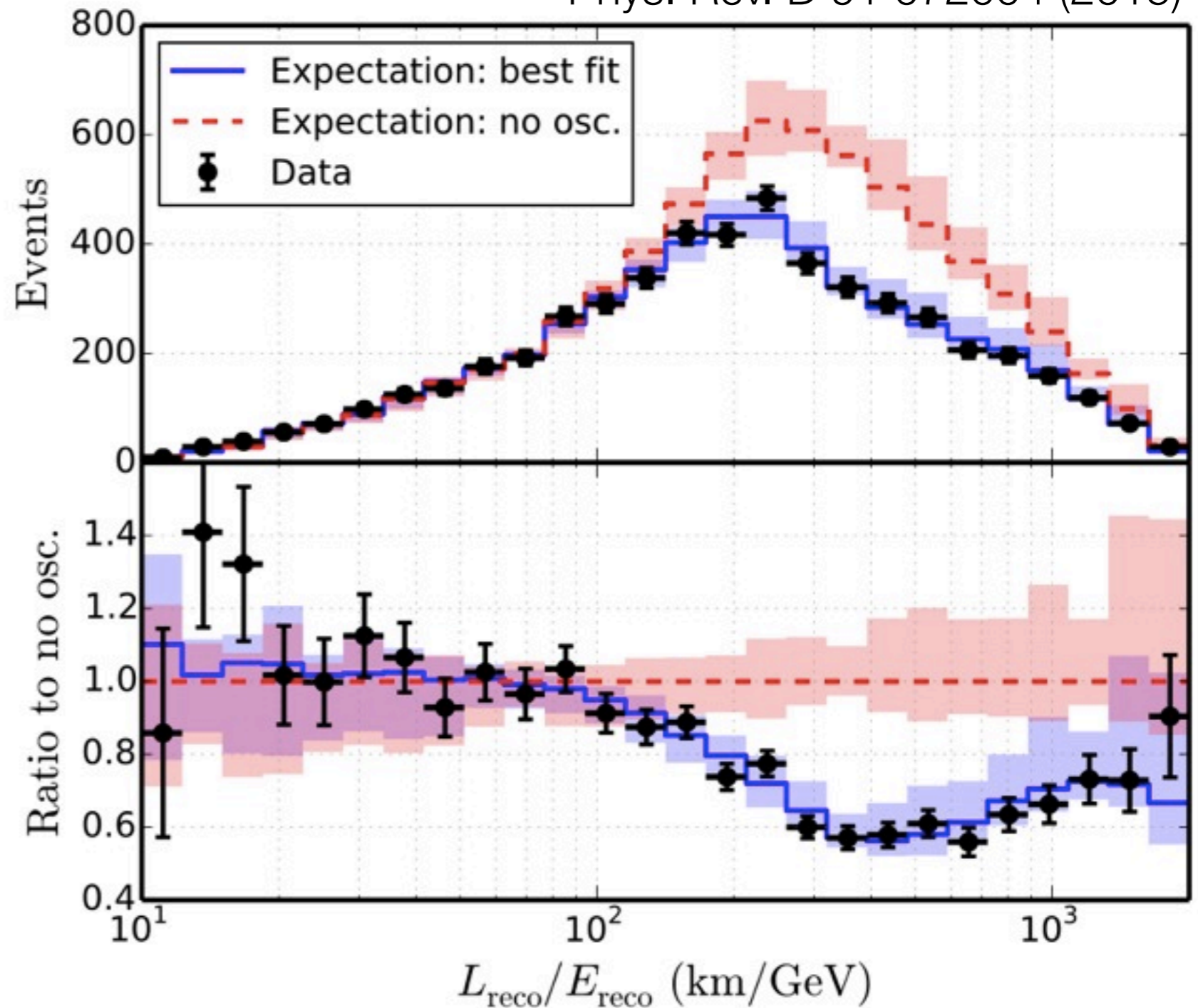
DeepCore

IceCube

DeepCore Results

Phys. Rev. D 91 072004 (2015)

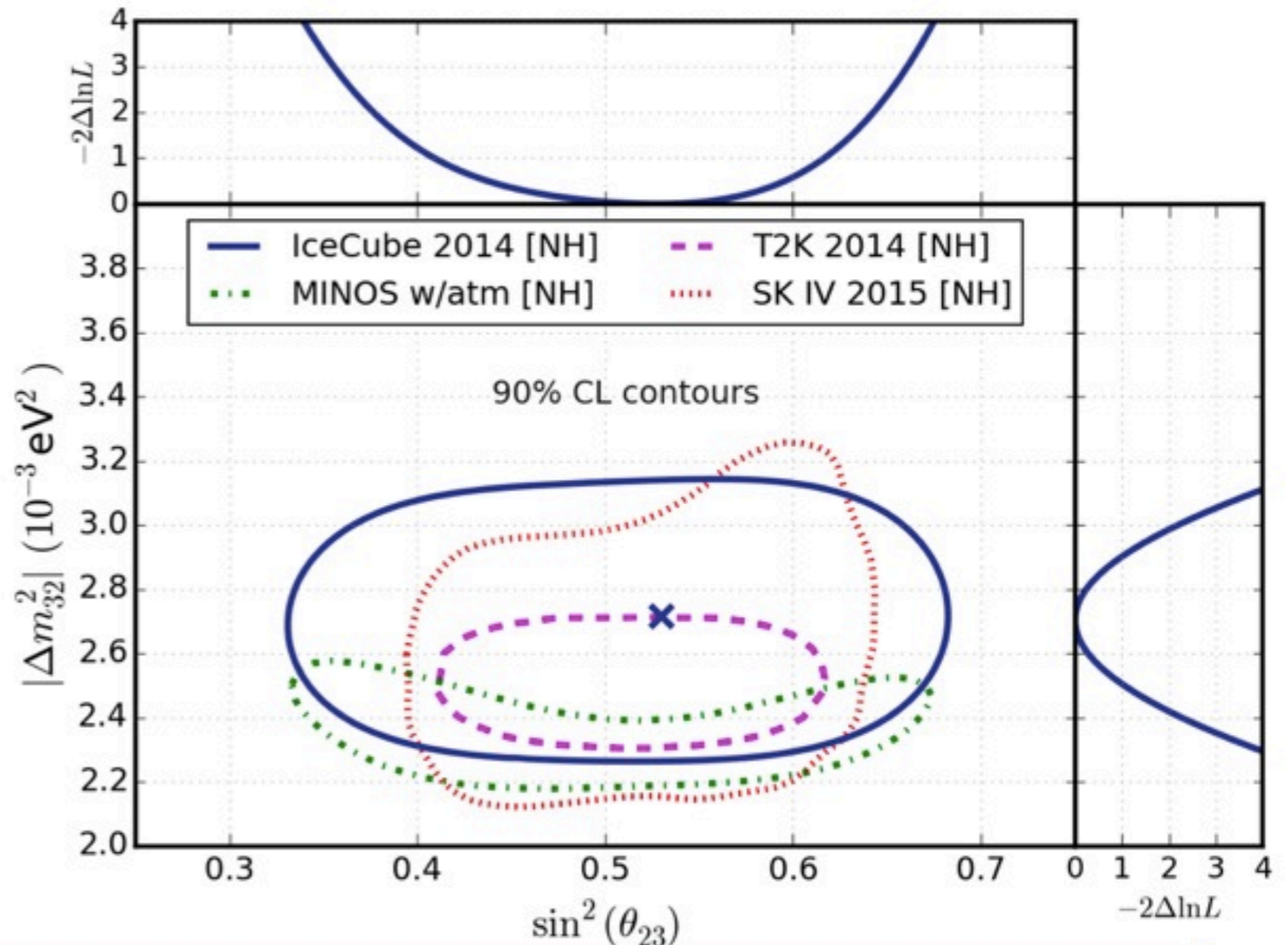
- Approximately 3 years of data analyzed
- High rate in detector provides large event sample



DeepCore Results

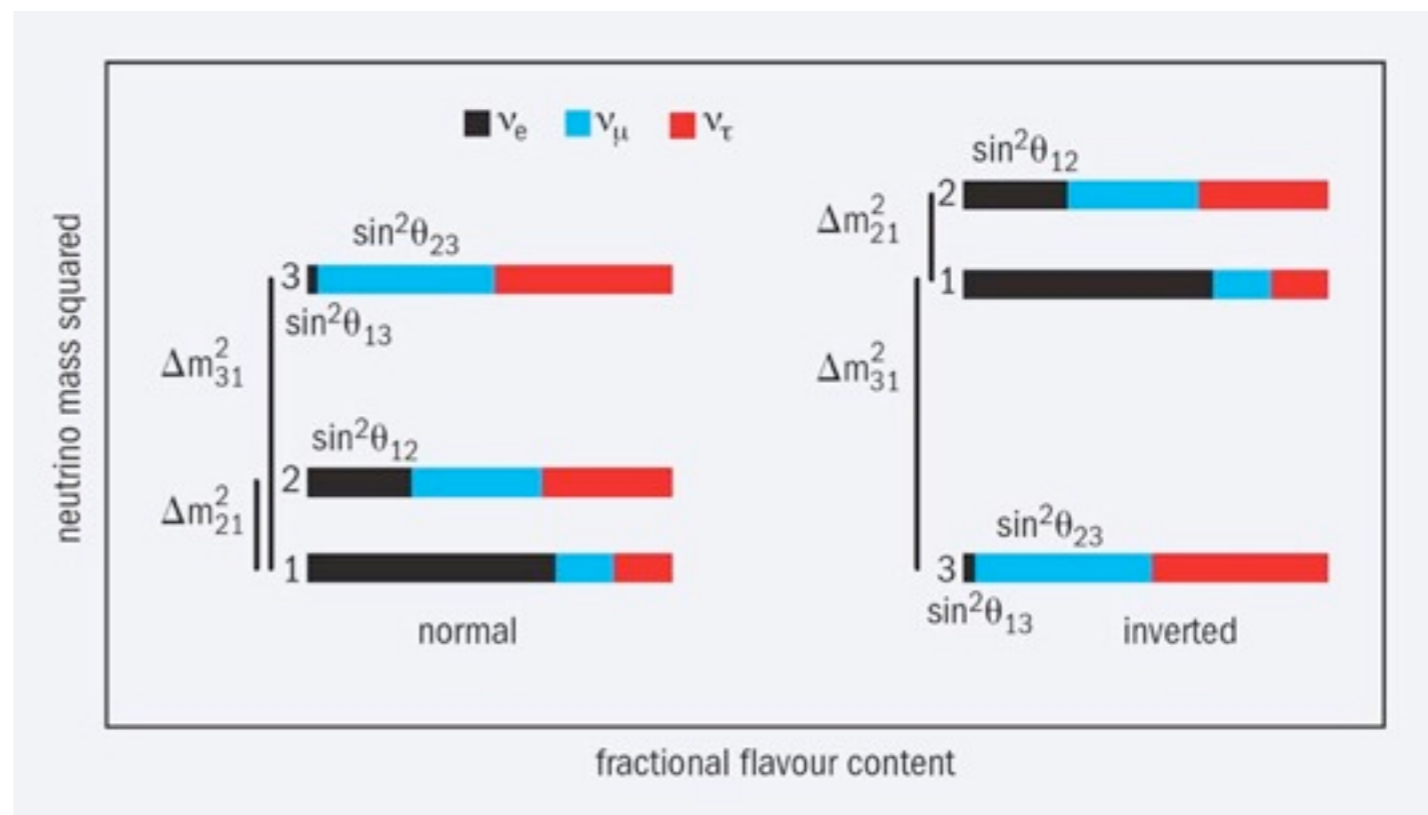
- Approximately 3 years of data analyzed
- High rate in detector provides large event sample
- Oscillation parameter constraints approaching those of dedicated experiments

Phys. Rev. D 91 072004 (2015)



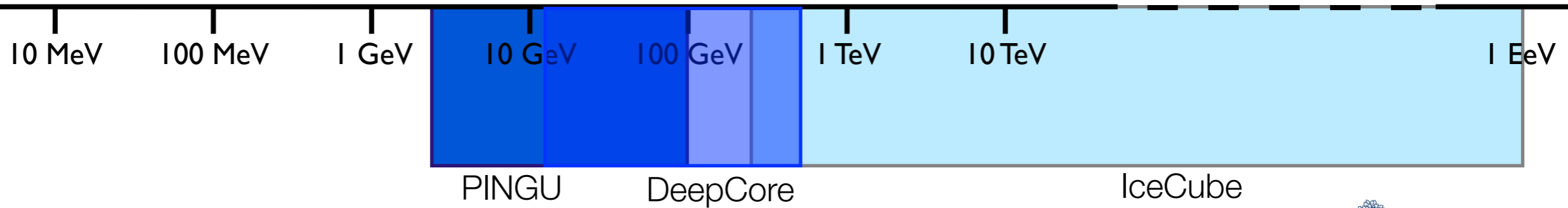
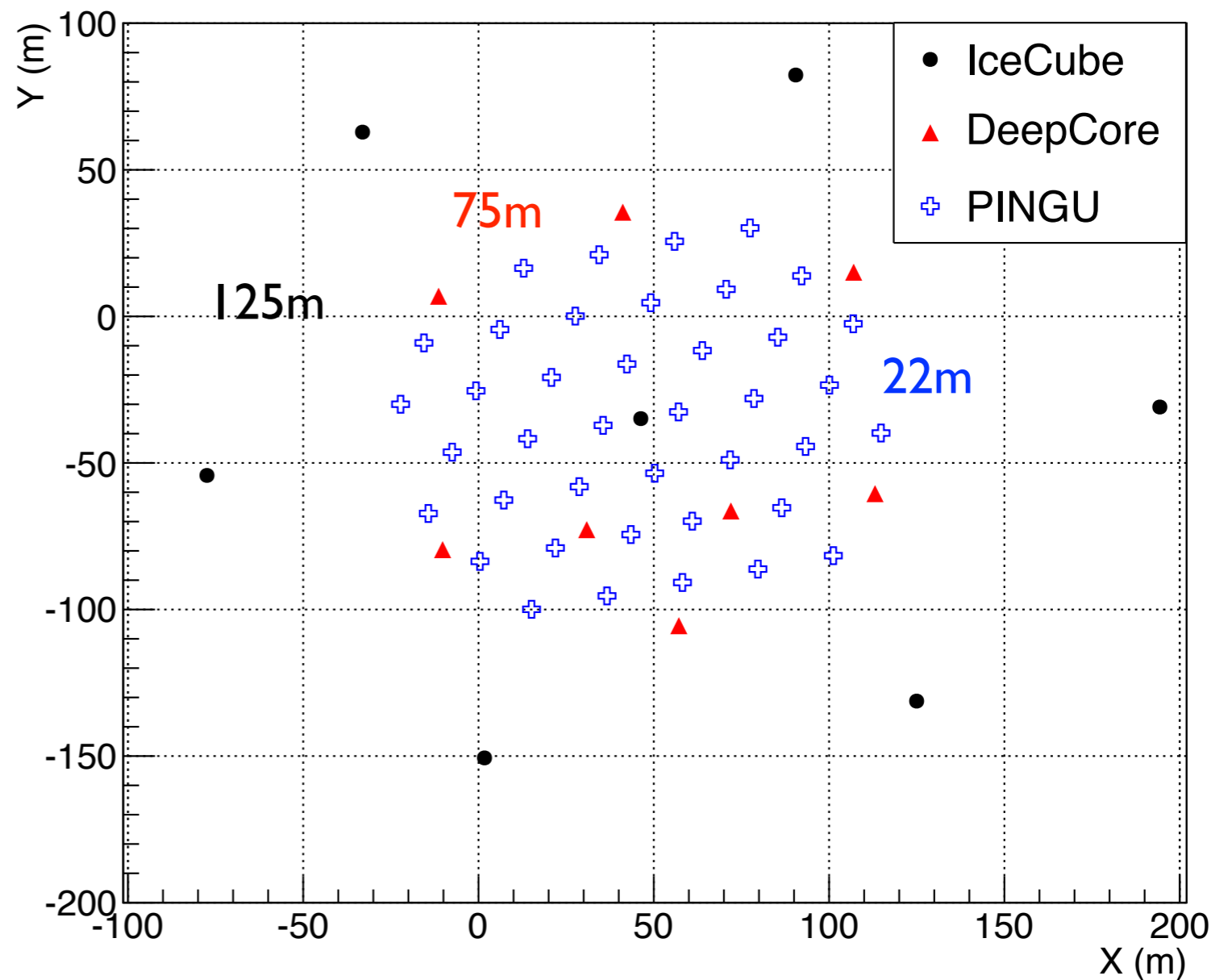
Even Lower Energies

- Deep Core is a success, but we get access to more physics with a lower threshold
- muon neutrino disappearance
- maximal θ_{23} measurement
- lower energy dark matter
- neutrino mass hierarchy

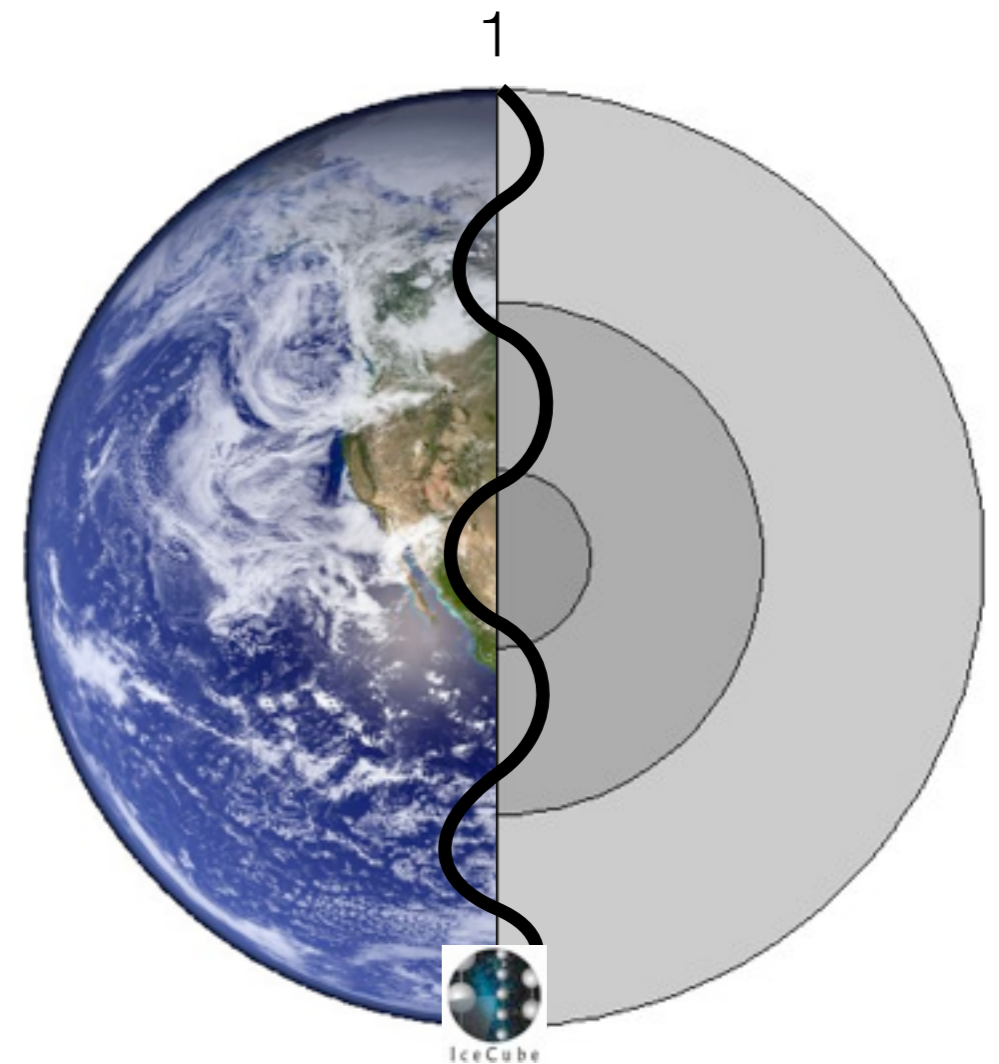
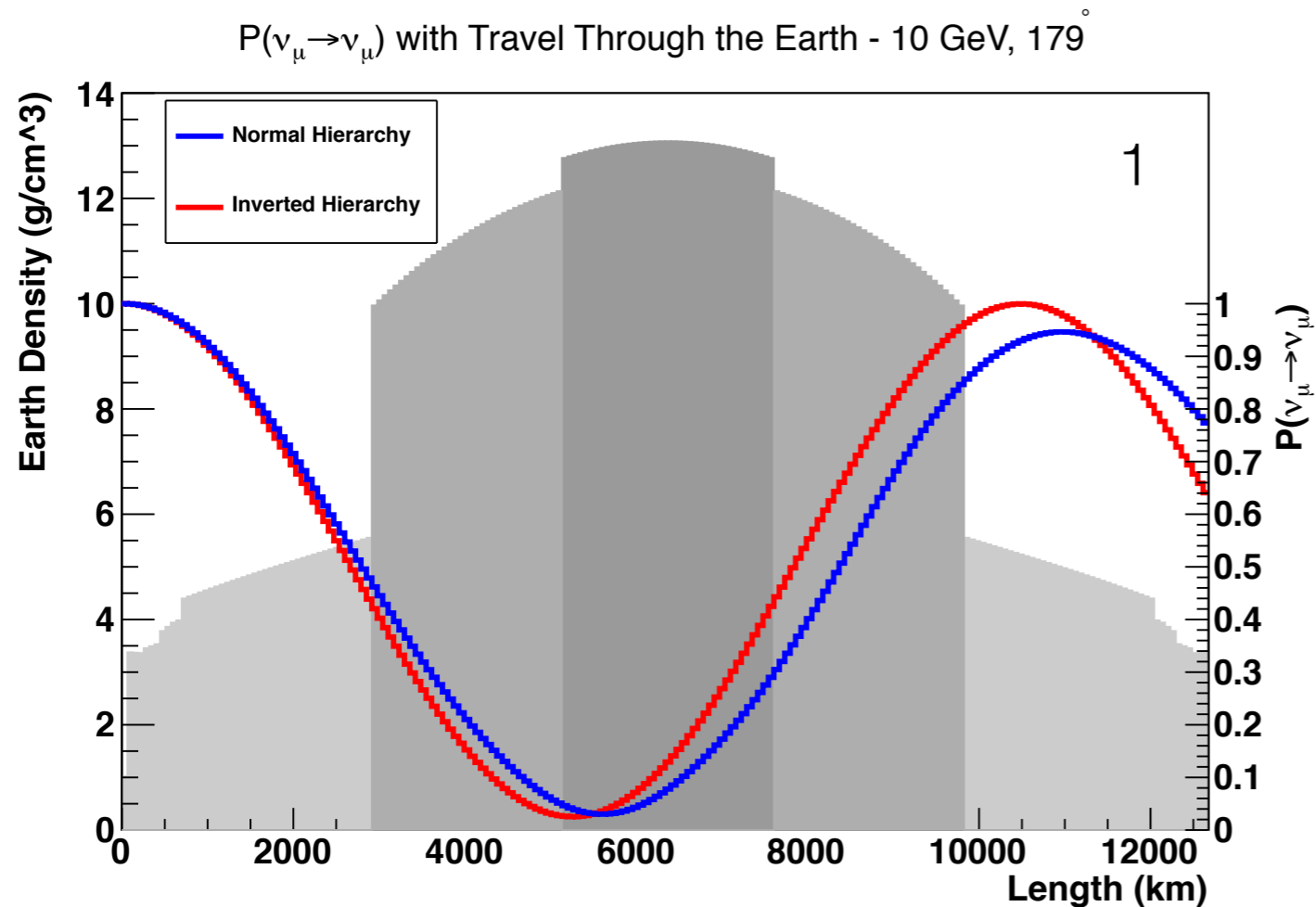


IceCube + DeepCore + PINGU

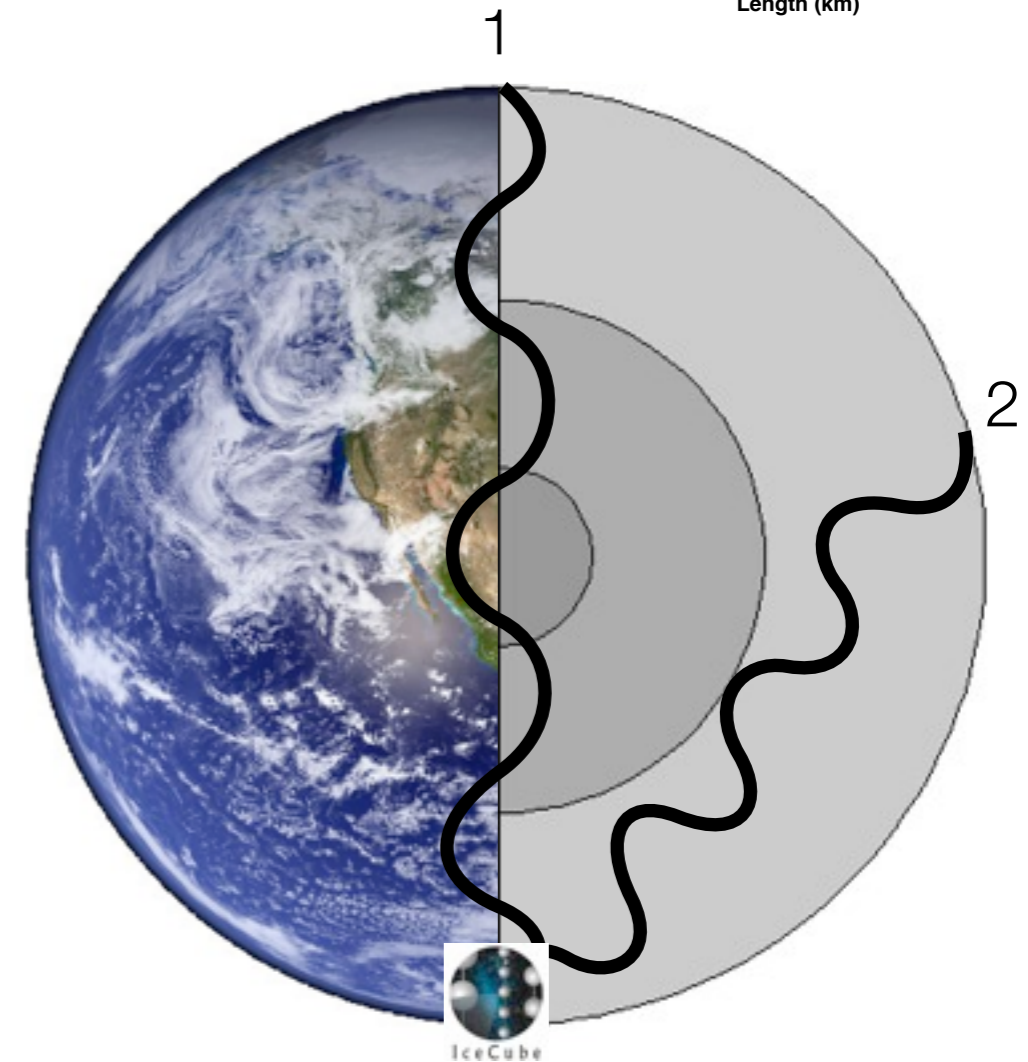
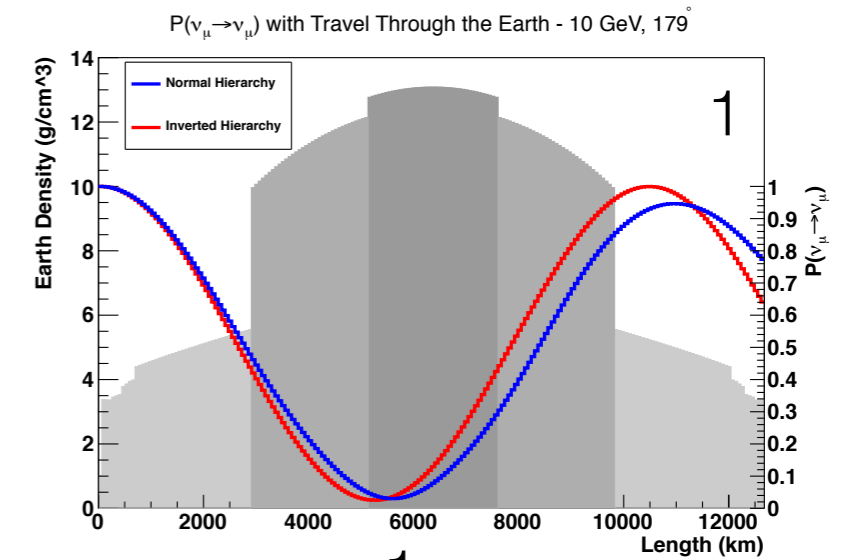
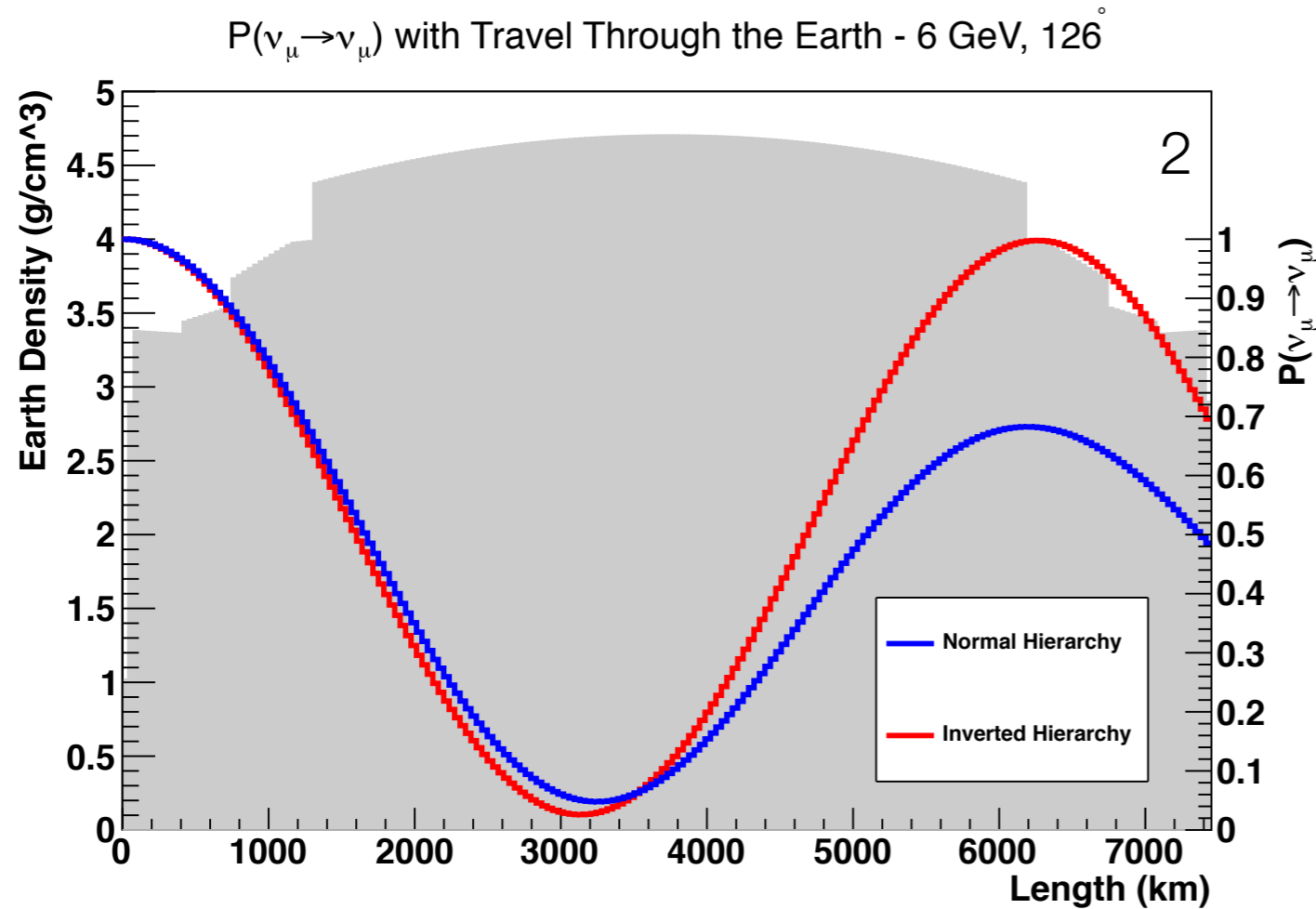
- 78 Strings
- 125m string spacing
- 17m DOM spacing
- Add 8 strings
- 75m string spacing
- 7m DOM spacing
- Add 40 strings
- 22m string spacing
- 3m DOM spacing



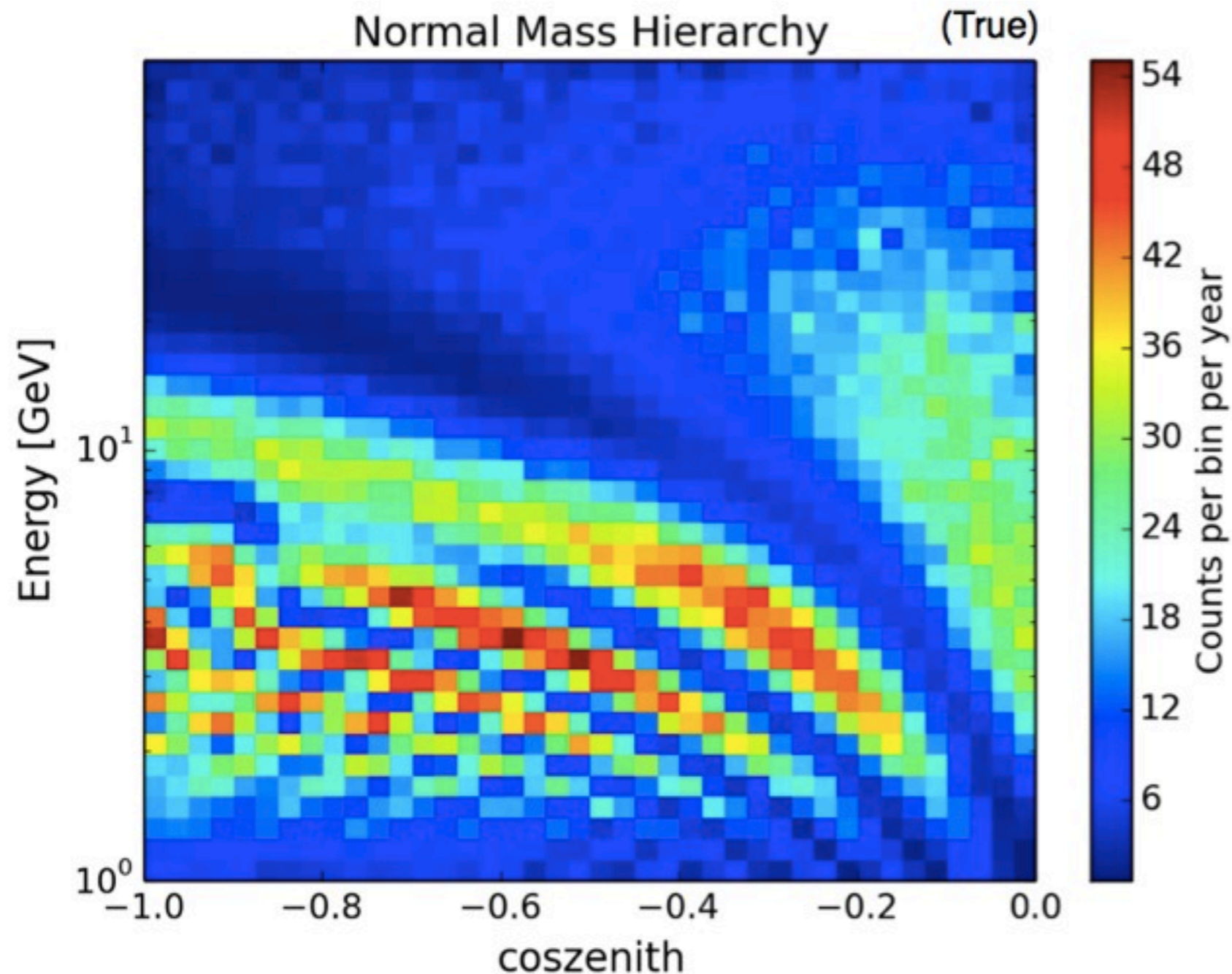
Mass Hierarchy Determination



Mass Hierarchy Determination

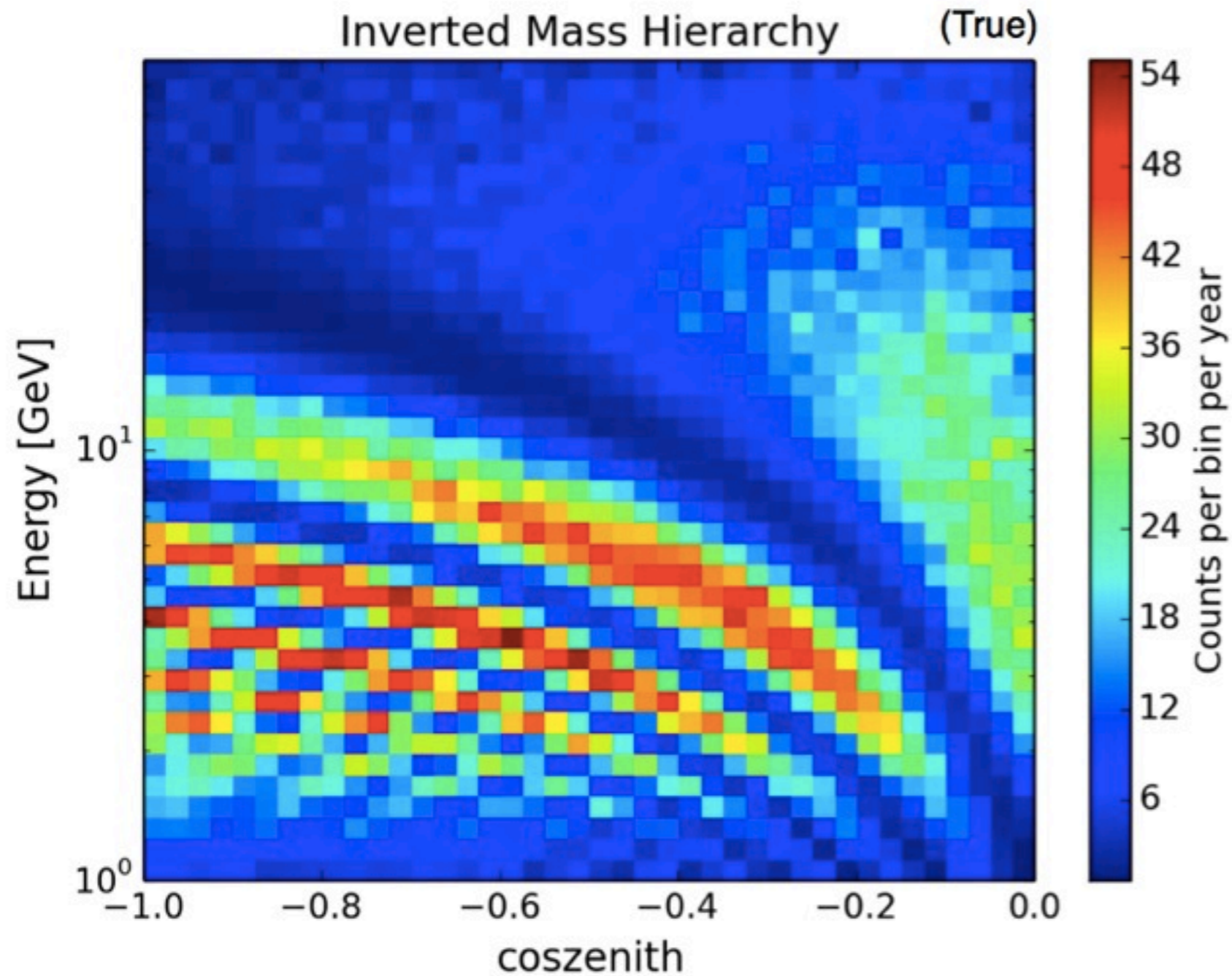


Neutrino Oscillograms



- Sum of ν_μ and $\bar{\nu}_\mu$
- Reconstruction and PID not included here

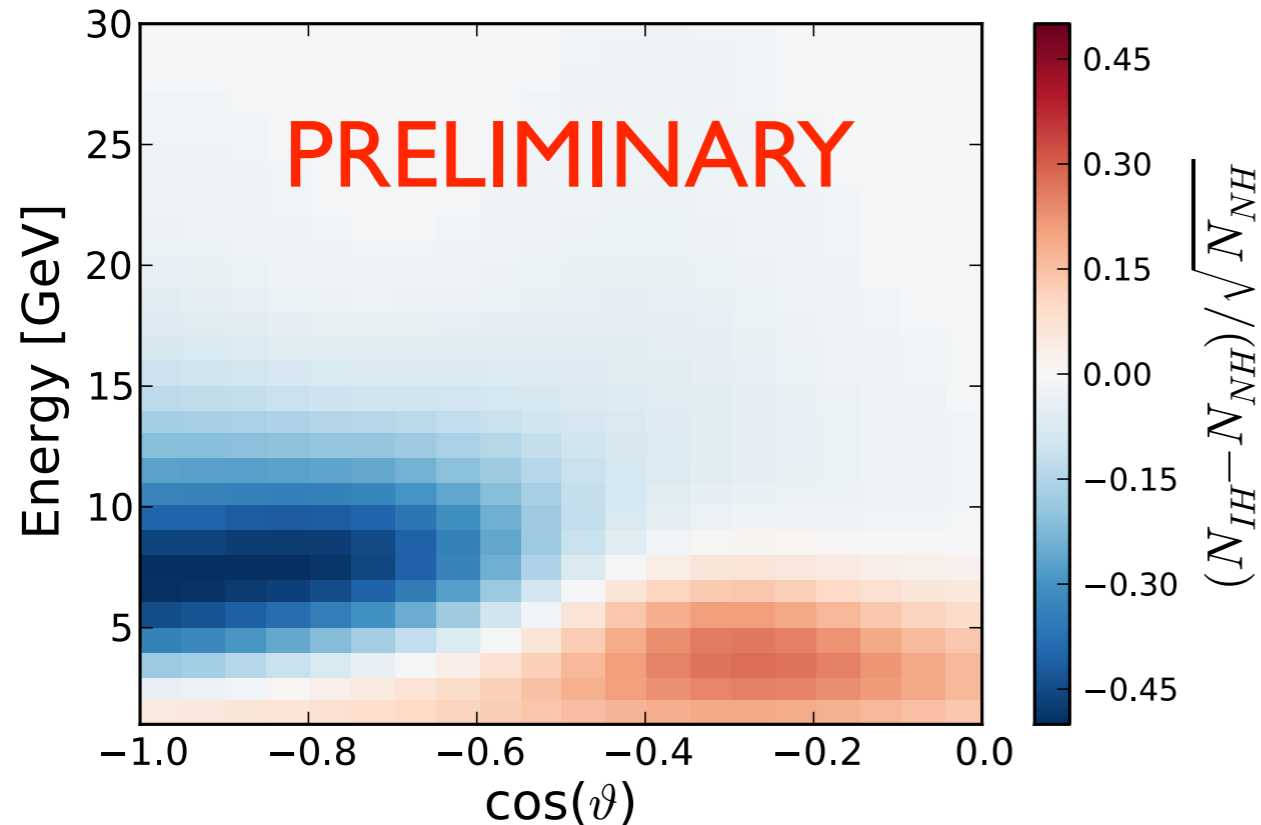
Neutrino Oscillograms



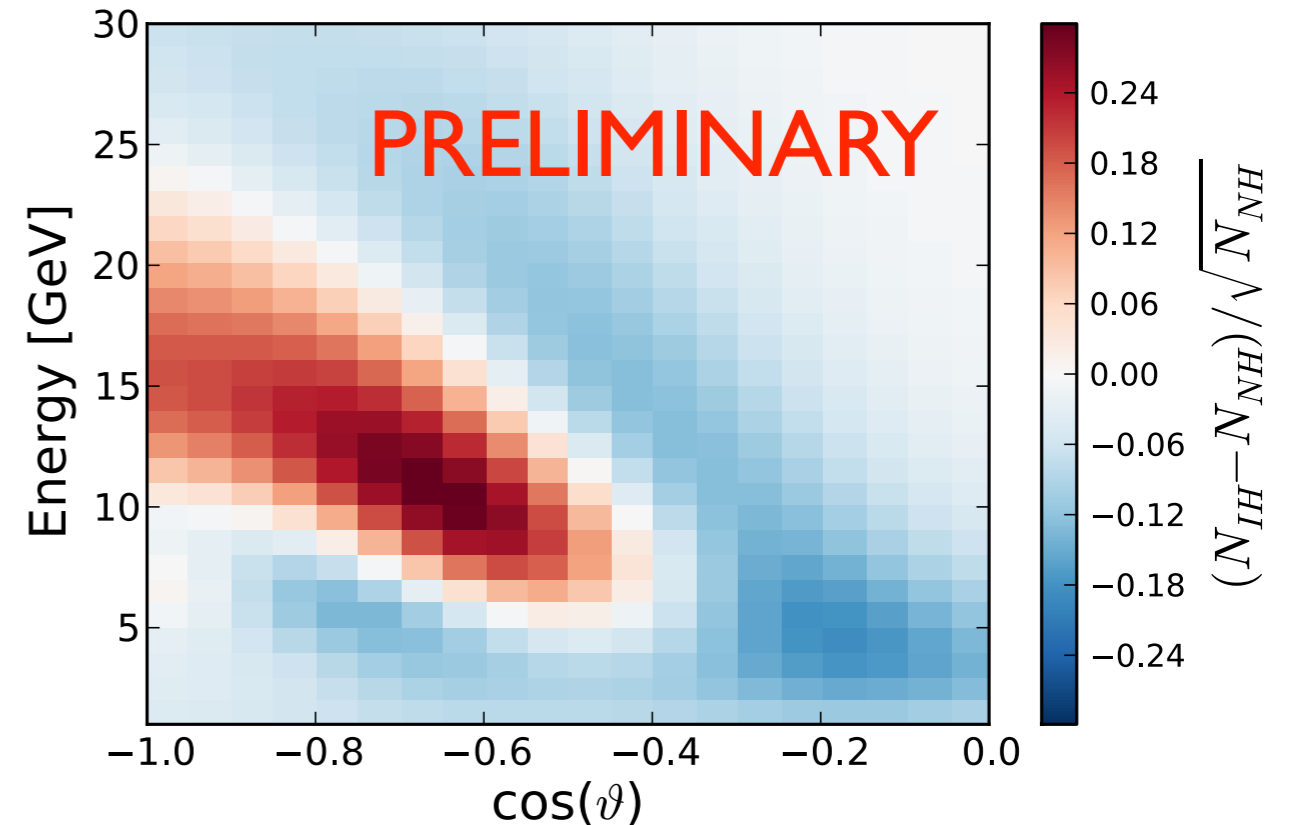
- Sum of ν_μ and $\bar{\nu}_\mu$
- Reconstruction and PID not included here

Mass Hierarchy Determination

Cascade-Like Events



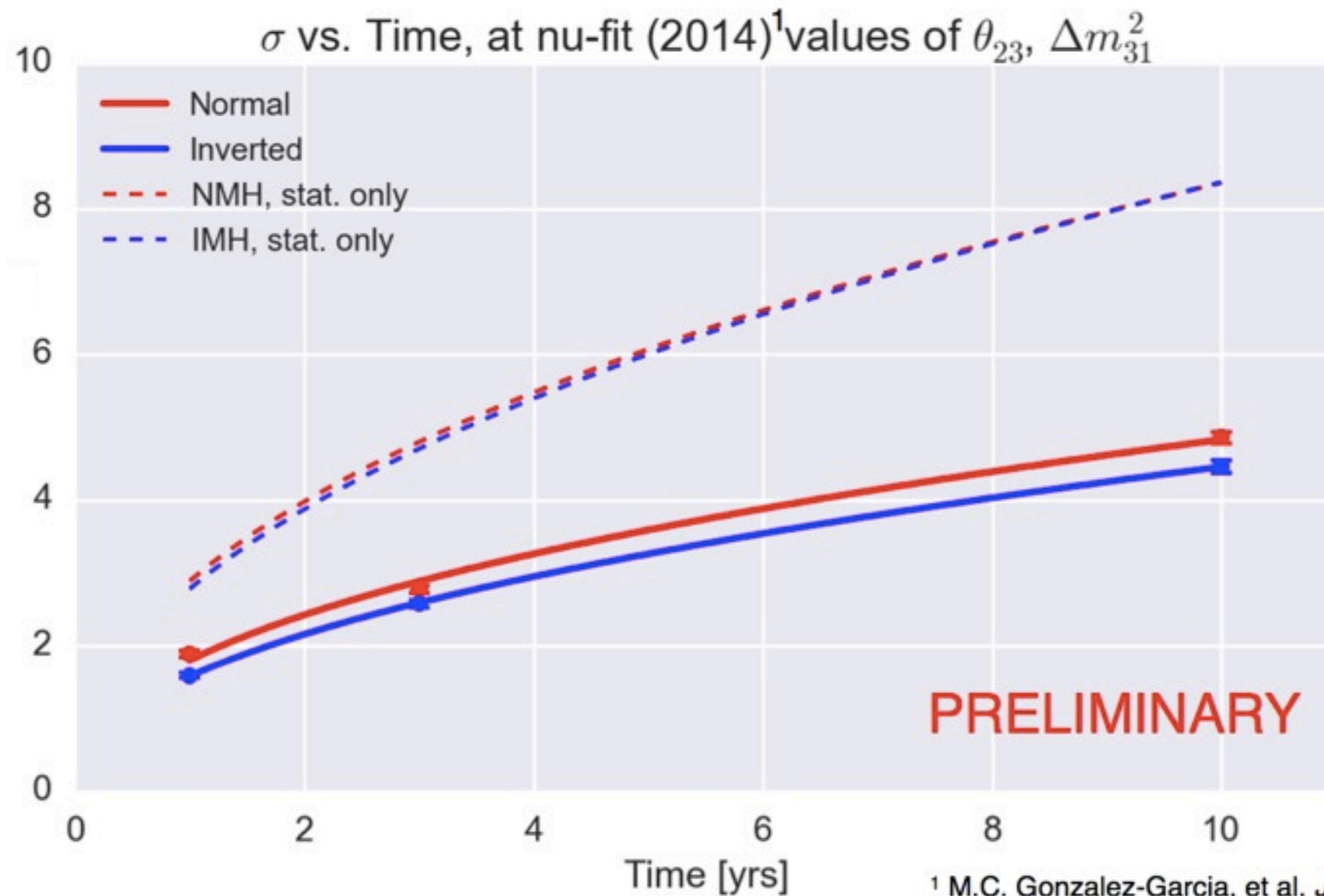
Track-Like Events



- Difference in counts between hierarchies illustrates distinguishability
- Background rejection cuts not included here

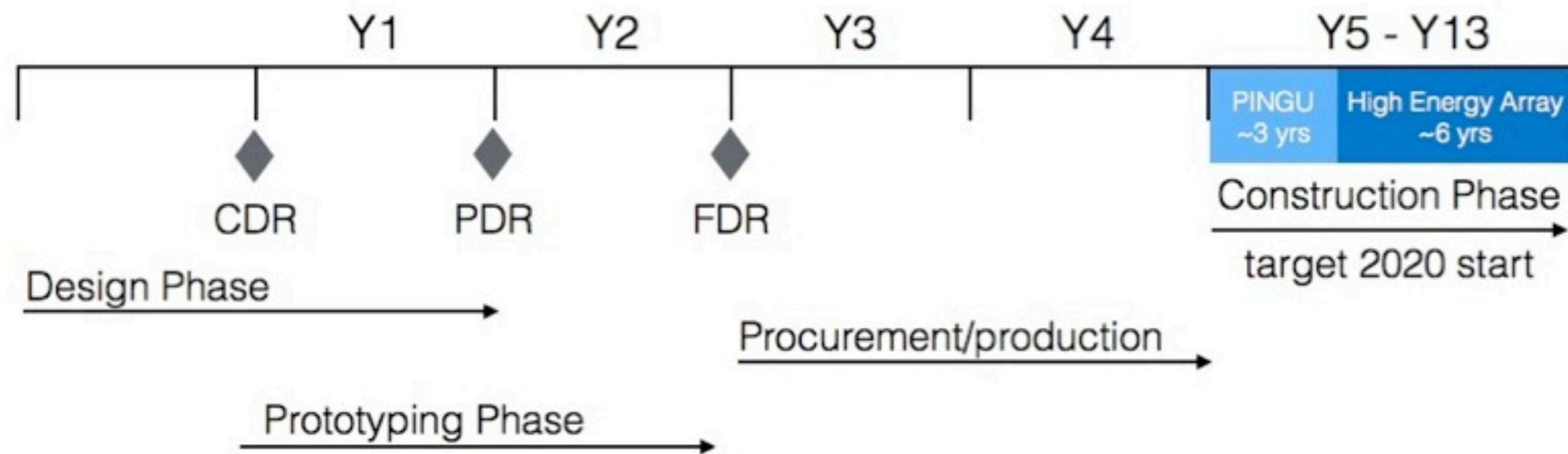
The Bottom Line

- Most important question is how long does it take to make a measurement?



¹ M.C. Gonzalez-Garcia, et al. *JHEP* 11 052, 2014

Timeline



Conclusion

- IceCube and DeepCore have been very successful and have shown that particle physics is possible in ice
- PINGU will provide insight into the nature of the NMH as well as the oscillation parameters



The IceCube-PINGU Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
 Fonds Wetenschappelijk Onderzoek-Vlaanderen
 (FWO-Vlaanderen)
 Federal Ministry of Education & Research (BMBF)
 German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
 Inoue Foundation for Science, Japan
 Knut and Alice Wallenberg Foundation
 NSF-Office of Polar Programs
 NSF-Physics Division

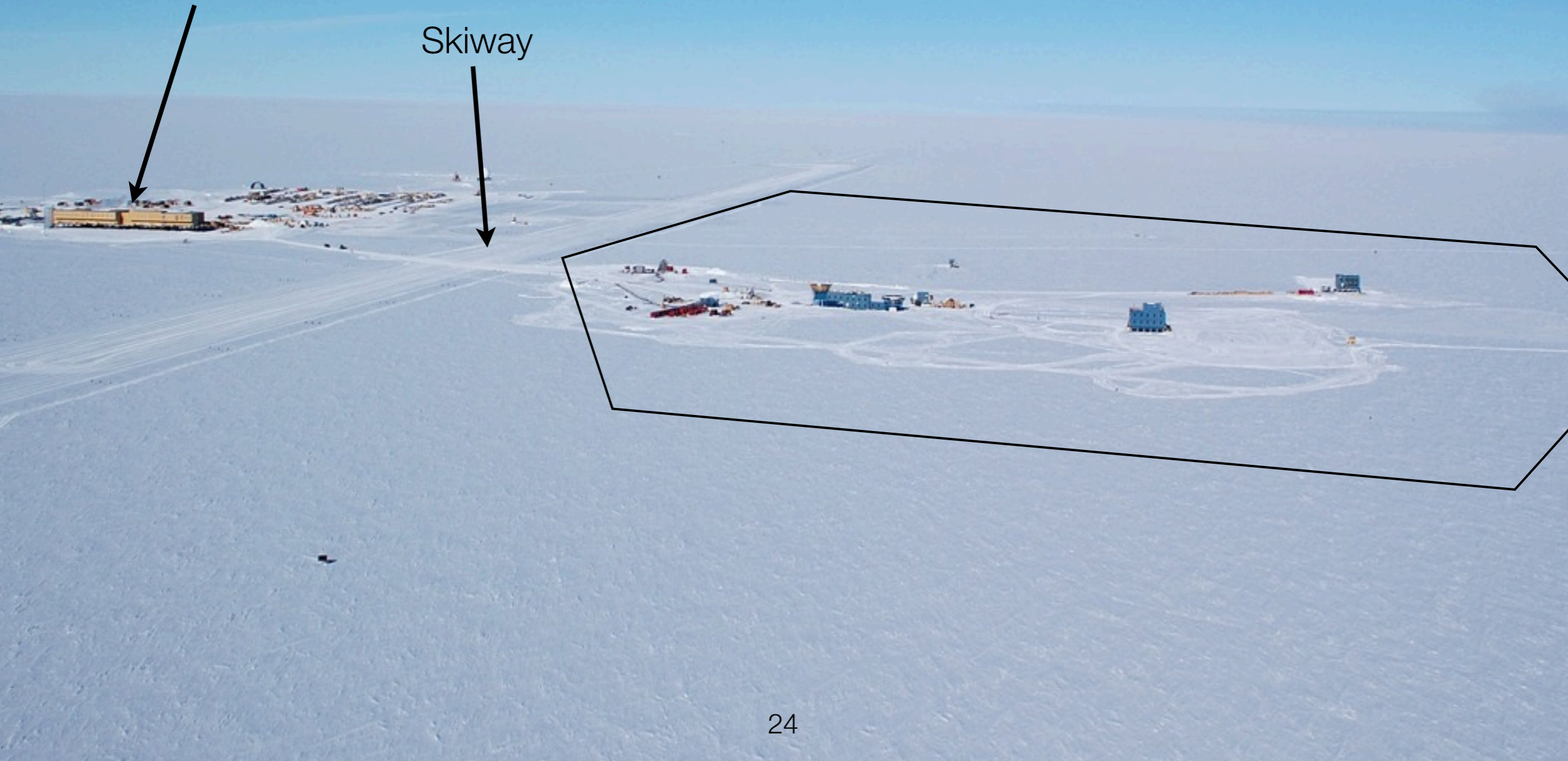
Swedish Polar Research Secretariat
 The Swedish Research Council (VR)
 University of Wisconsin Alumni Research
 Foundation (WARF)
 US National Science Foundation (NSF)

BACK UP

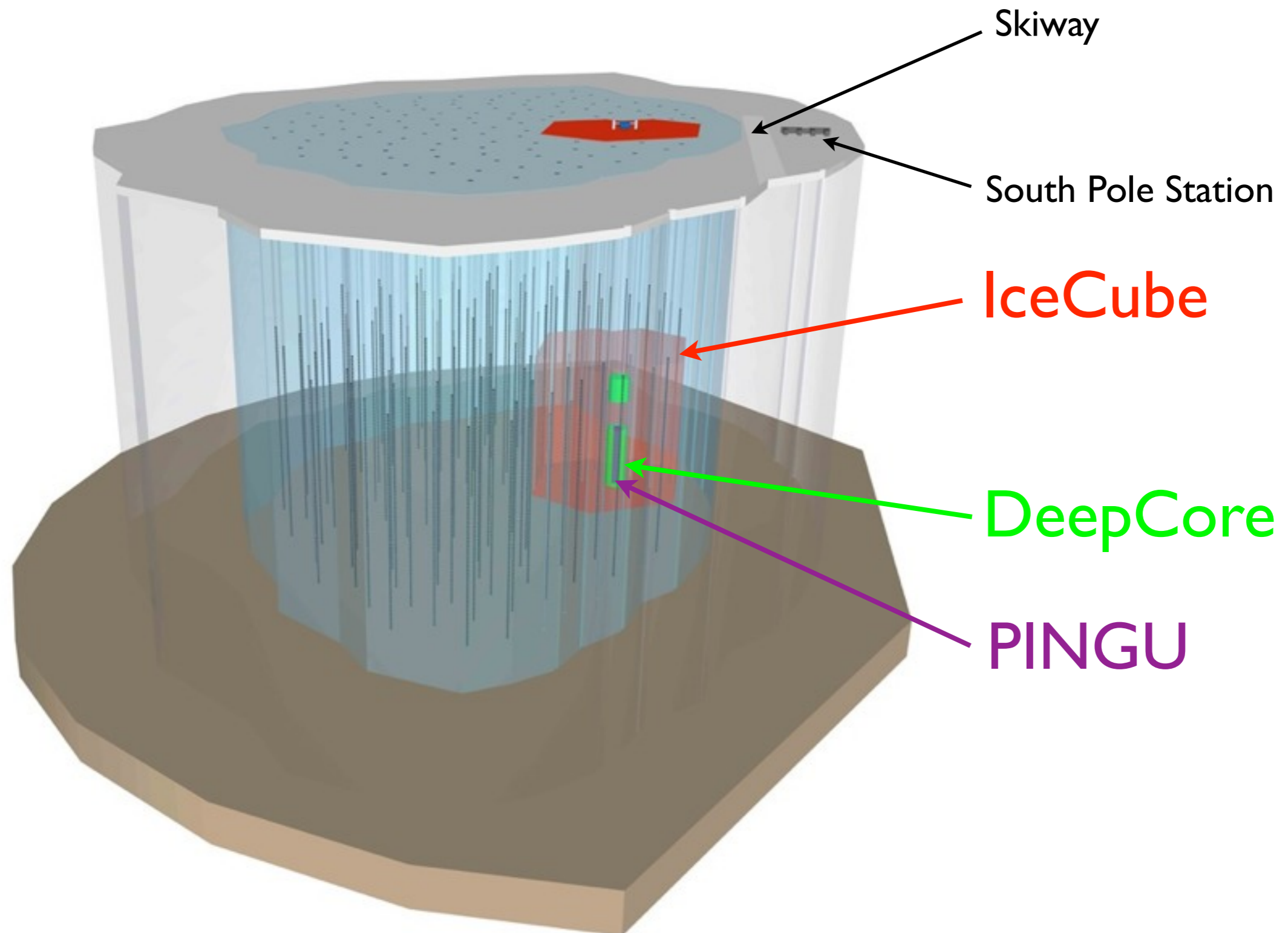
IceCube/DeepCore

South Pole Station

Skiway

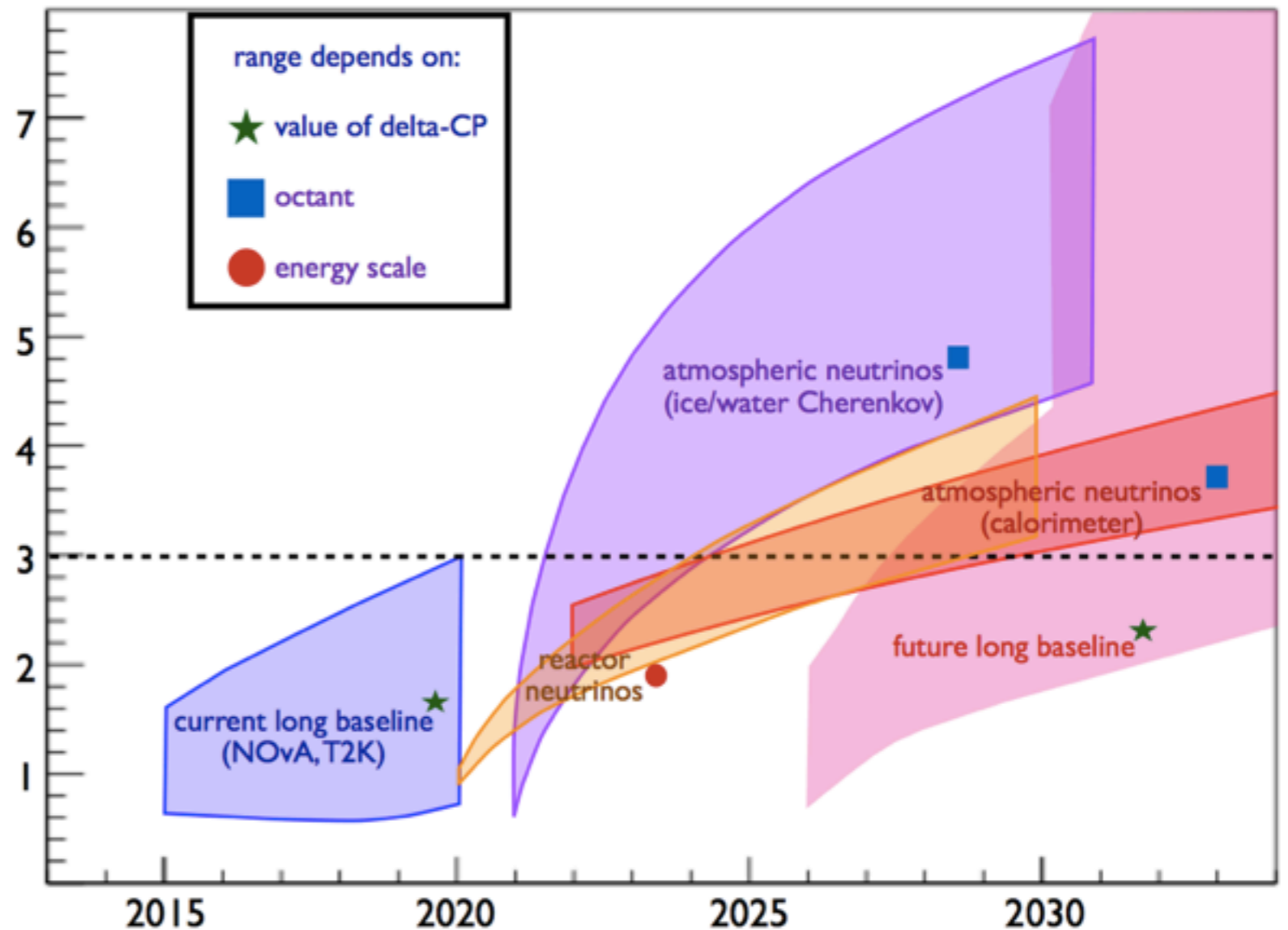


The IceCube Neutrino Telescope

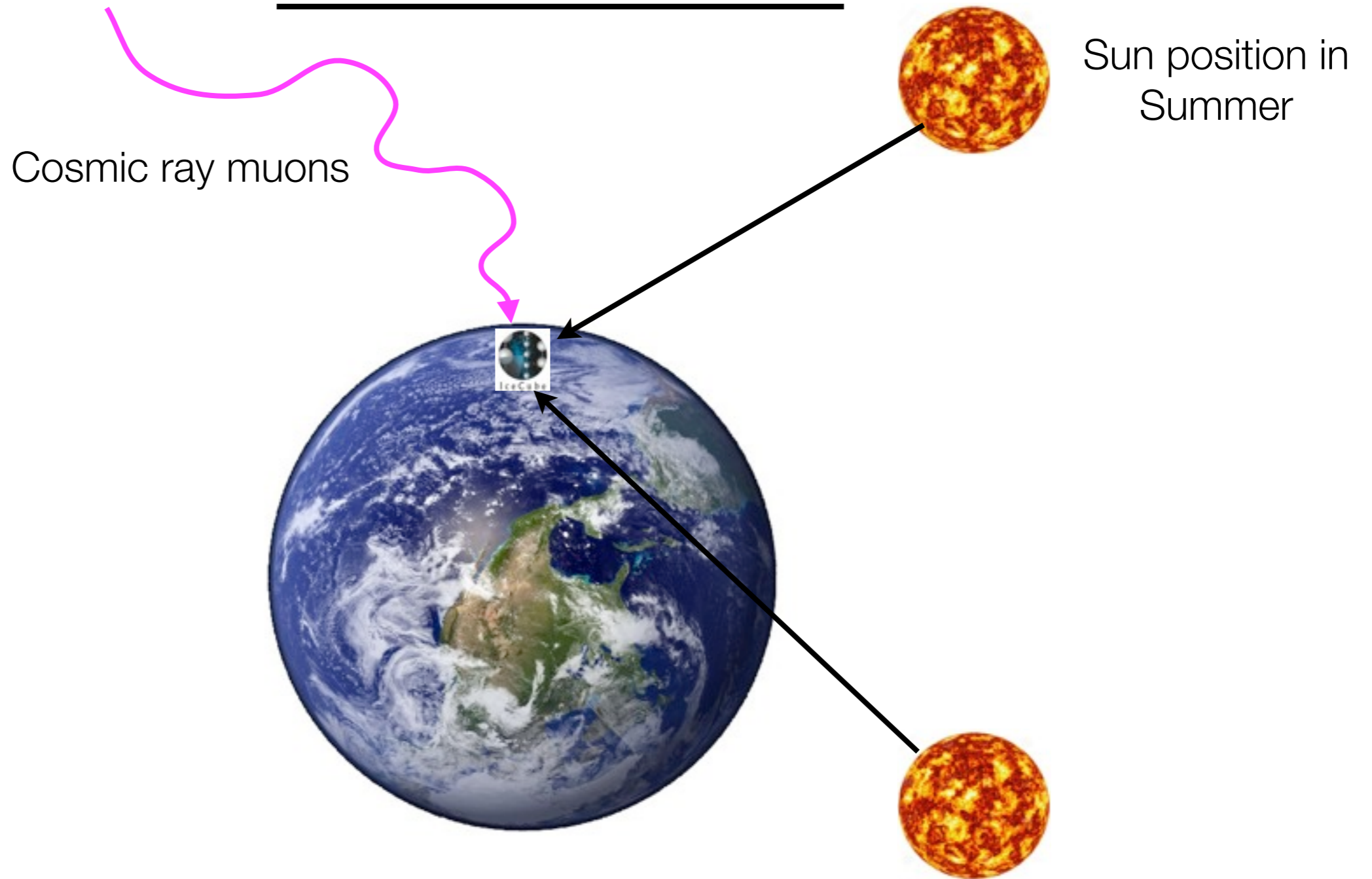


Future of the NMH Measurement

- **MANY** caveats
 - median outcome shown
 - width indicates effect of main uncertainty (δ_{CP} , θ_{23})
 - dates are also bound to change as time goes on



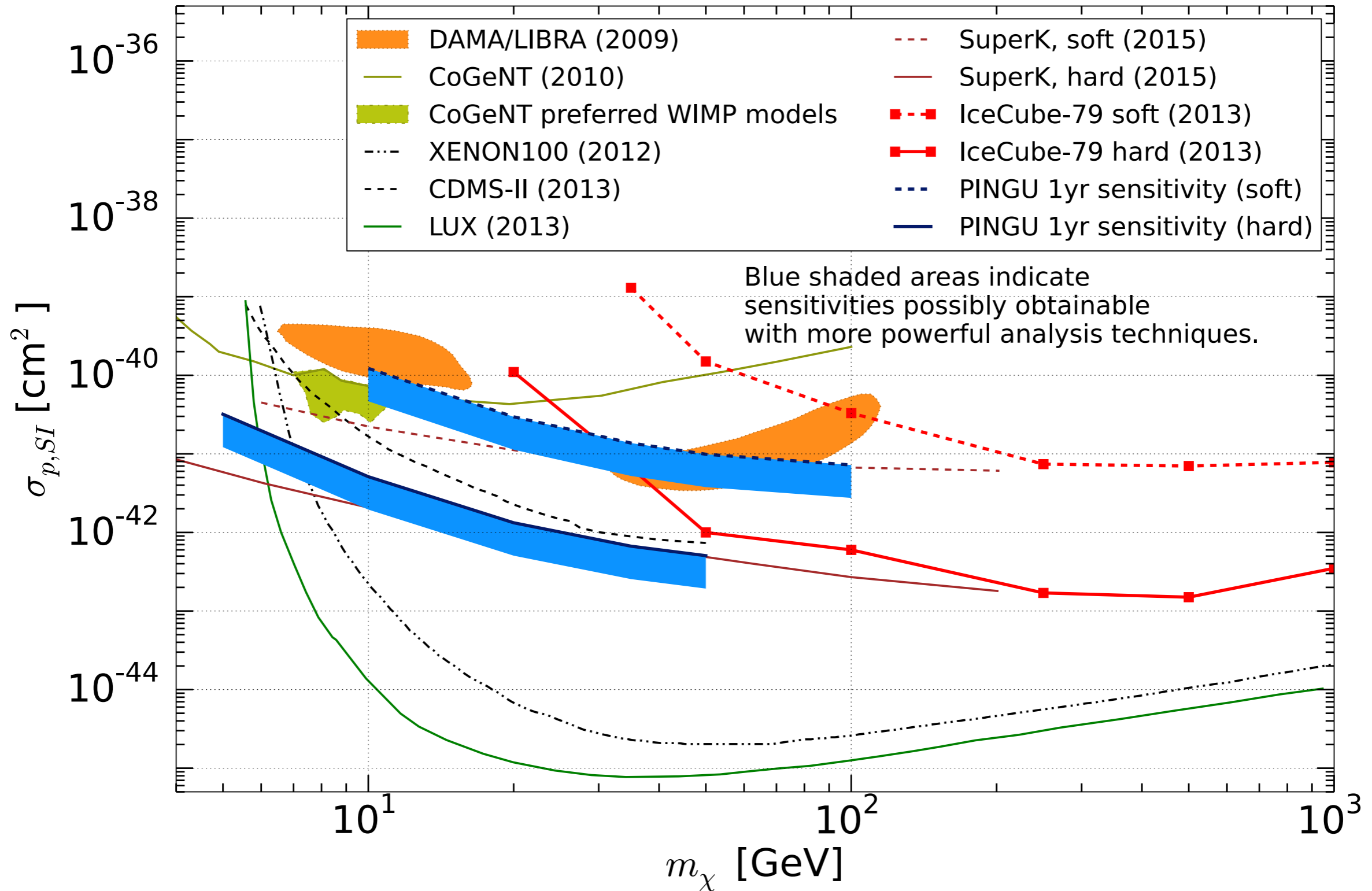
Dark Matter



Note: Not to scale

Sun position in Winter

Dark Matter



Systematic Effects

PRELIMINARY

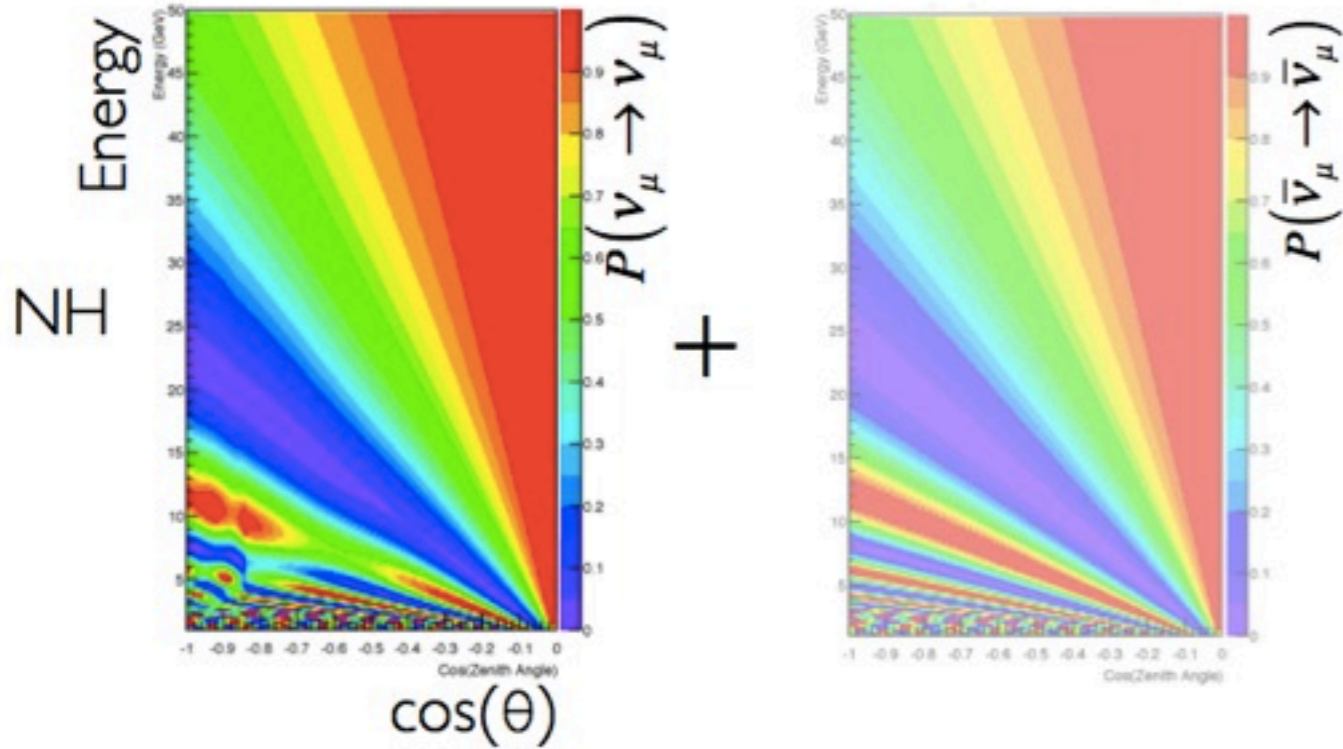
- Investigate the most significant systematics
- Right now θ_{23} has the largest effect

Type	3yr σ (NMH)	3 yr σ (IMH)
stat only	4.84	4.82
osc only	2.96	2.53
flux only	4.55	4.56
detector only	4.06	3.99
All	2.90	2.51

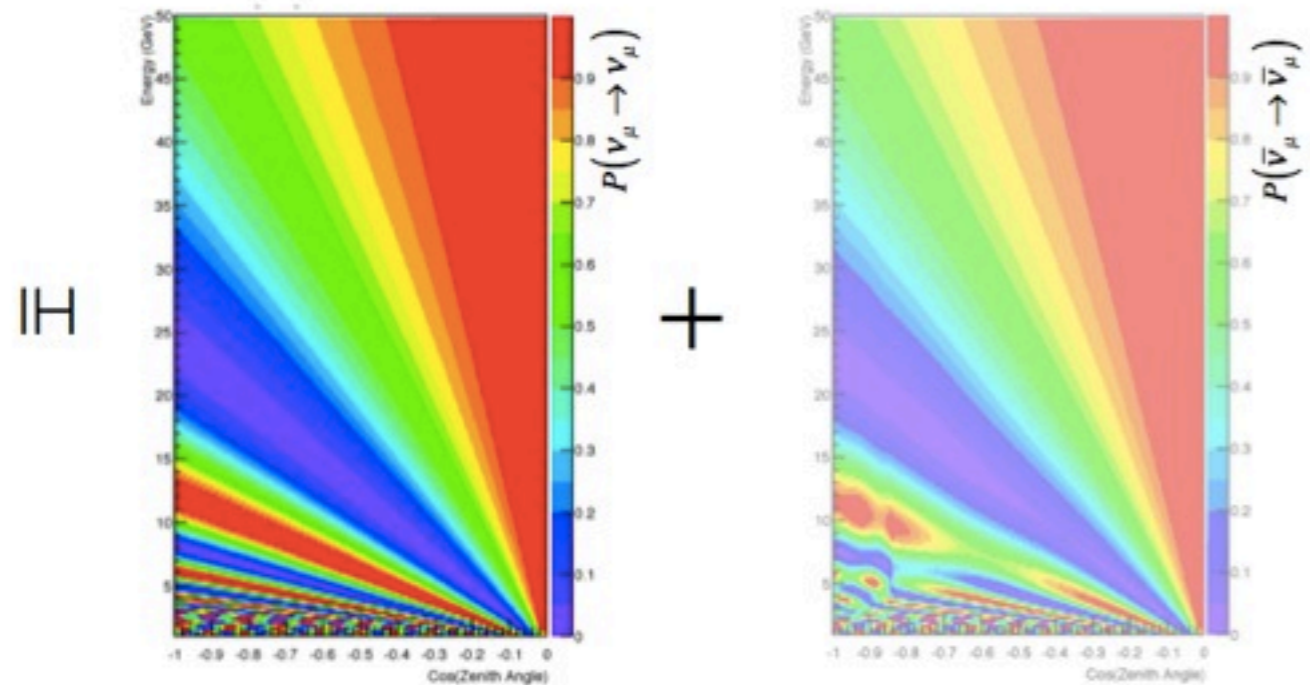
Neutrino Oscillograms

ν_μ

anti- ν_μ



+



+

- The cross-section and flux are different for ν_μ and $\bar{\nu}_\mu$
- The patterns are therefore different!

Oscillation Parameters

