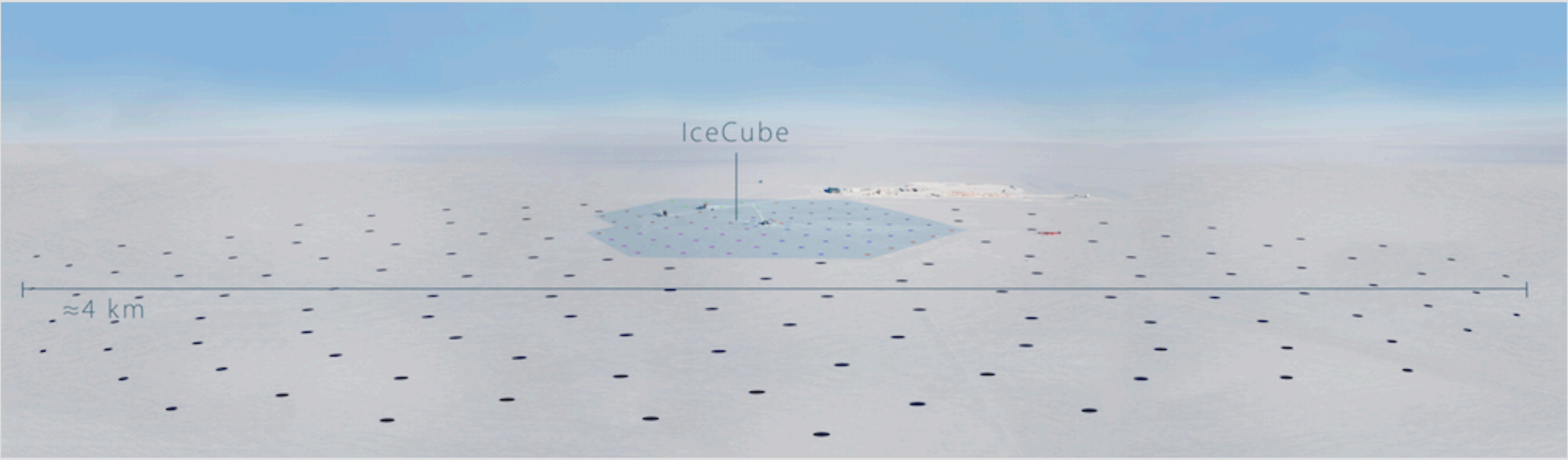
IceCube Upgrade and Gen-2



Summer Blot,
for the IceCube-Gen2 collaboration
06 September 2018
RICAP'18

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE GEN2 DESY

IceCube Neutrino Observatory

A pioneering multi-purpose detector

Astrophysics

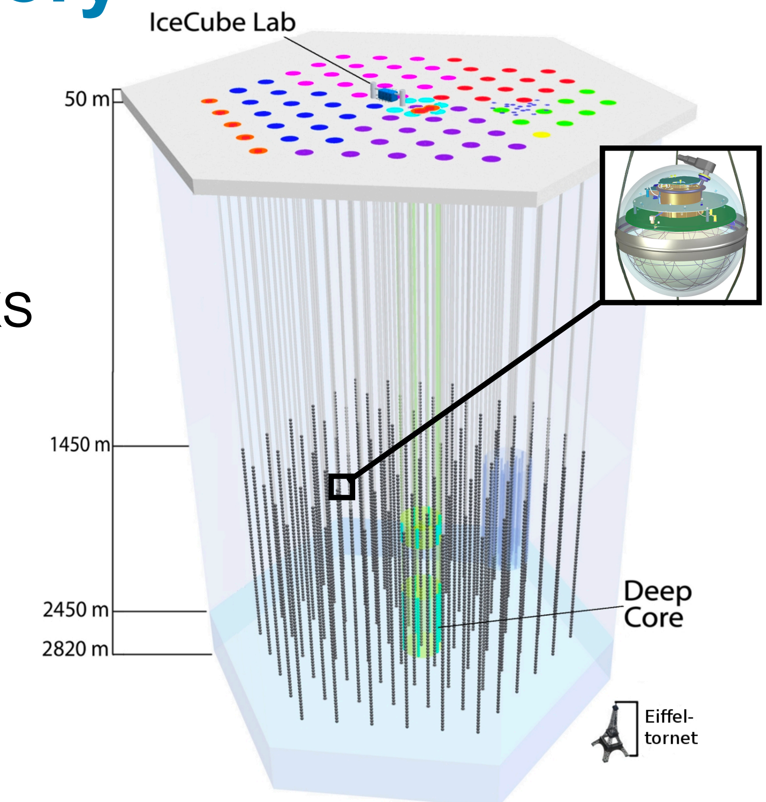
- Discovery of astrophysical neutrinos
- First evidence for neutrino point source with TXS
- Key partner in multi-messenger landscape
- Cosmic rays with IceCube including IceTop

Particle Physics

- Atmospheric neutrino oscillations
- Neutrino cross-sections at TeV-scale
- Exotic/BSM physics searches

Earth science

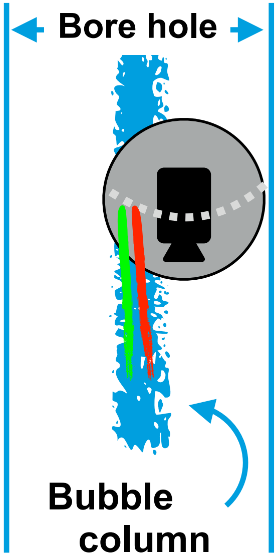
- Glaciology
- Earth tomography



	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	~100
DeepCore	50	7	~5

IceCube limitations

More potential to exploit!

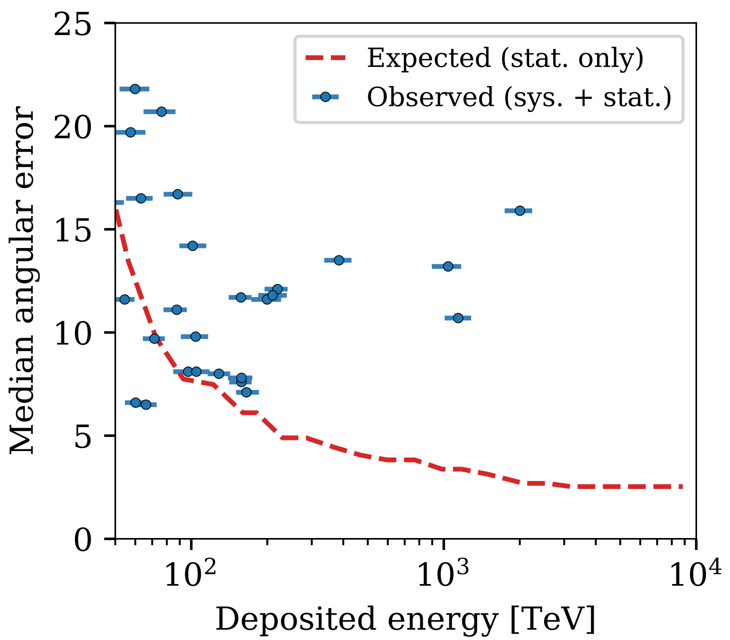


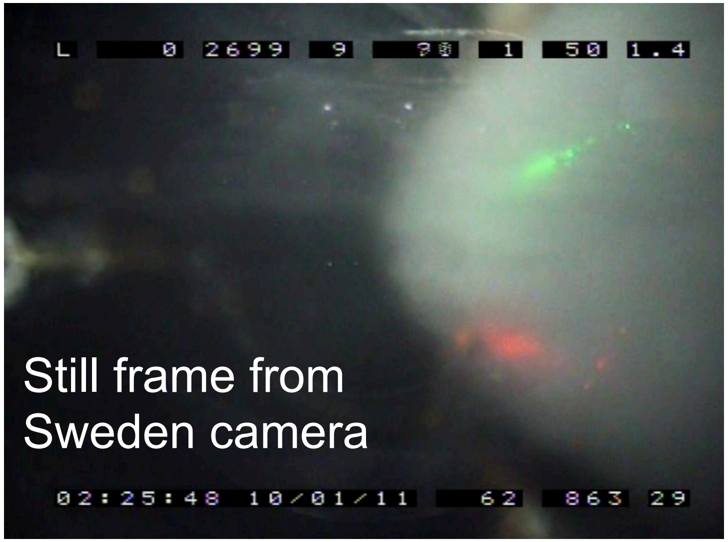
Angular resolution

- Median error not scaling with photon statistics

Ice modelling systematic uncertainties

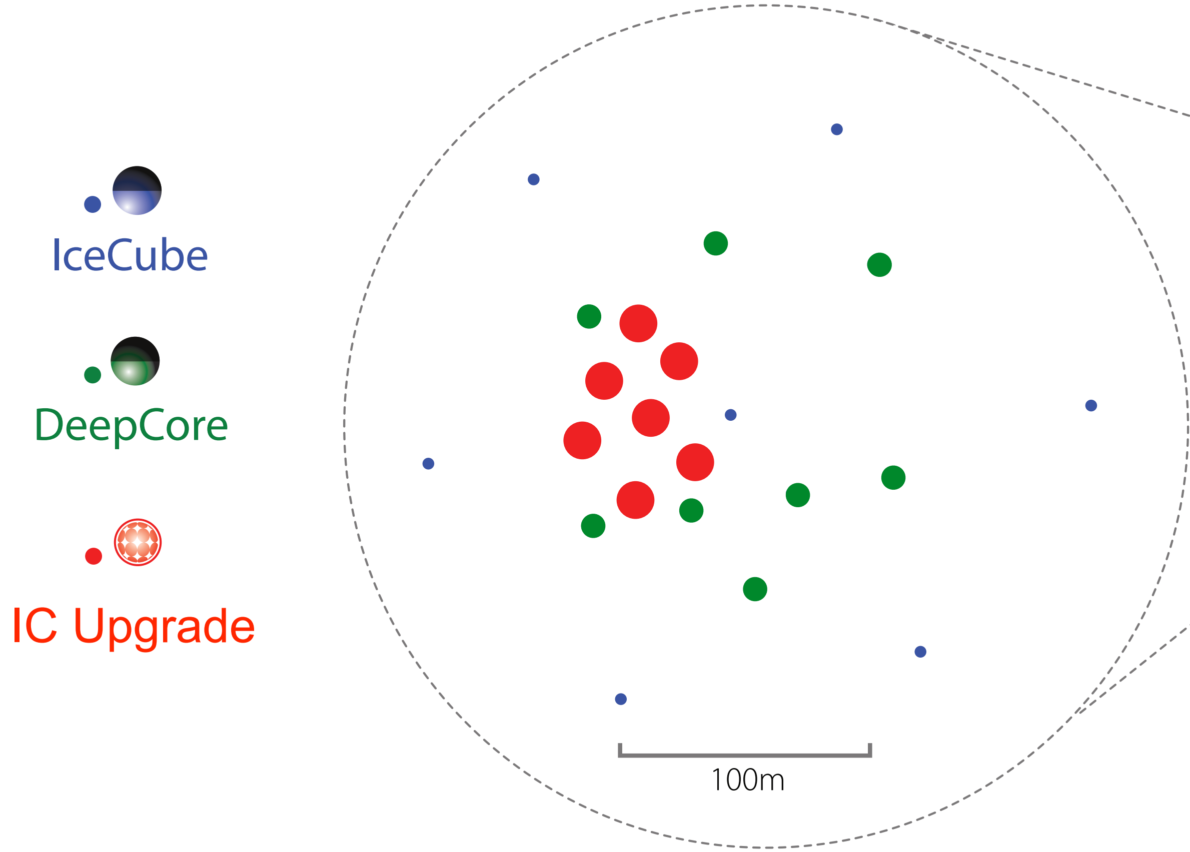
- Bubble column distorts angular acceptance
- Anisotropy of photon scattering and/or absorption lengths in ice

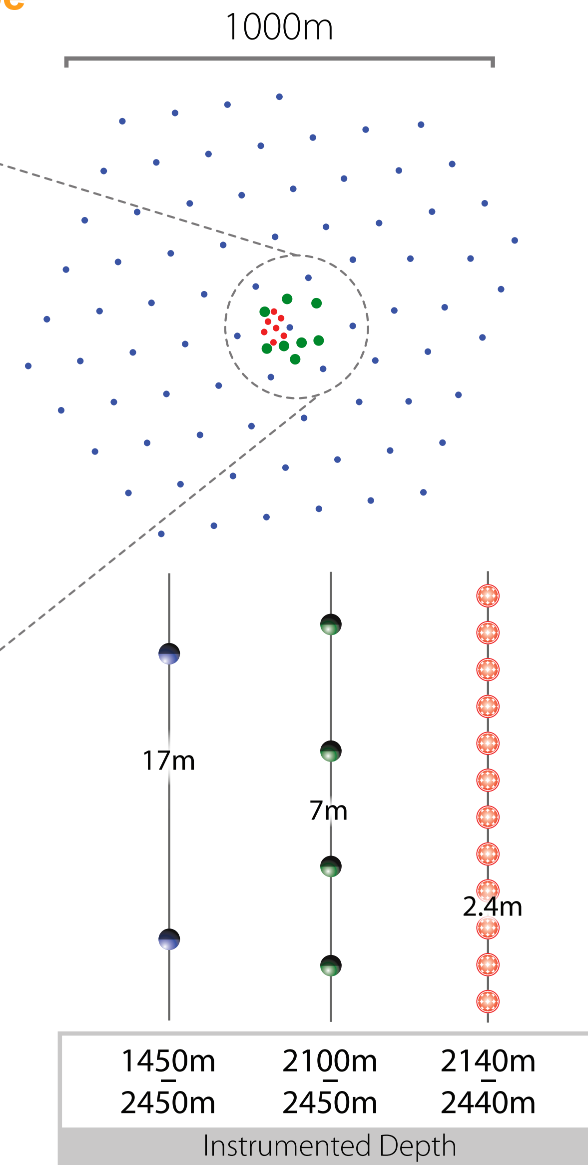




The IceCube Upgrade

The next step in precision astroparticle physics with IceCube





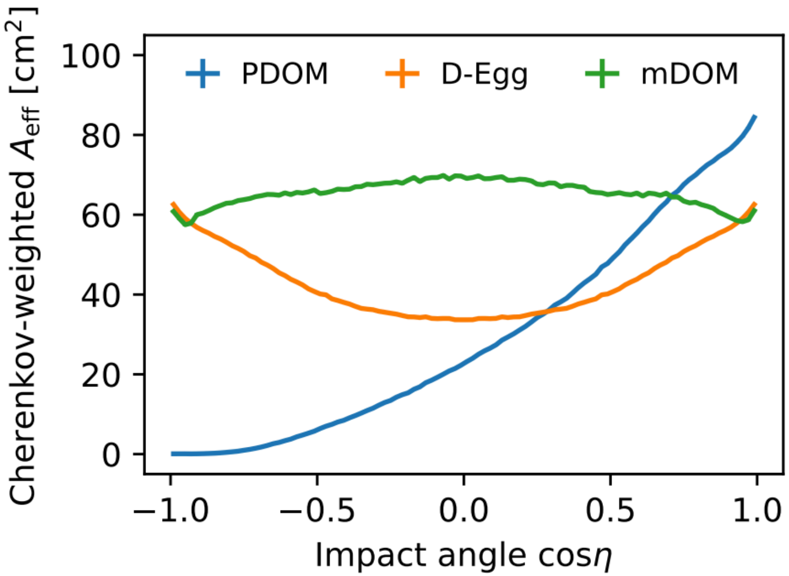
- 7 strings with ~20 m spacing
- 2 m vertical spacing of 125 modules / string
- Located inside of IceCube-DeepCore

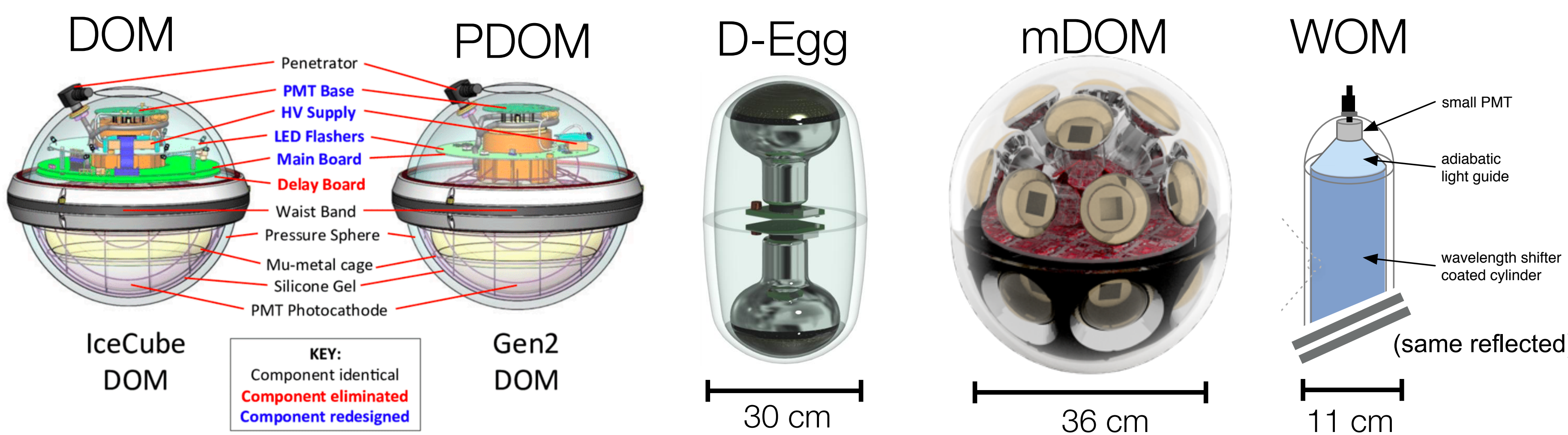
The IceCube Upgrade - R&D

In-situ testing of new optical modules

New sensor designs will incorporate one or more of the following:

- Upgraded electronics
- Smaller diameter
- Increased UV acceptance
- Larger and/or pixelated effective area





The IceCube Upgrade - Calibration

Deployment of new devices at better distances

Integrated devices

- LED flashers
- Acoustic sensors
- Optical cameras

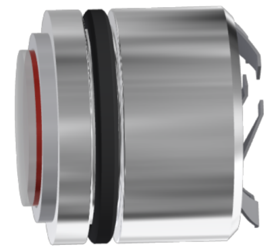
Stand-alone light sources

- Precision Optical Calibration Module (POCAM)
- “Movable” sub-ns pulsed LEDs with small opening angle

Reduce primary systematic uncertainties

- Better calibration of new and existing sensors
- Improved knowledge of glacial ice

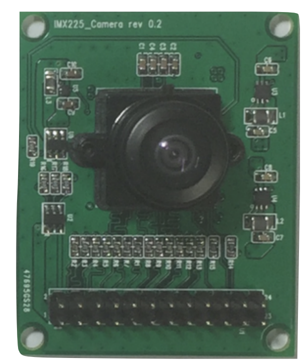
Piezo-module[1]



POCAM[3]

CCD[2]

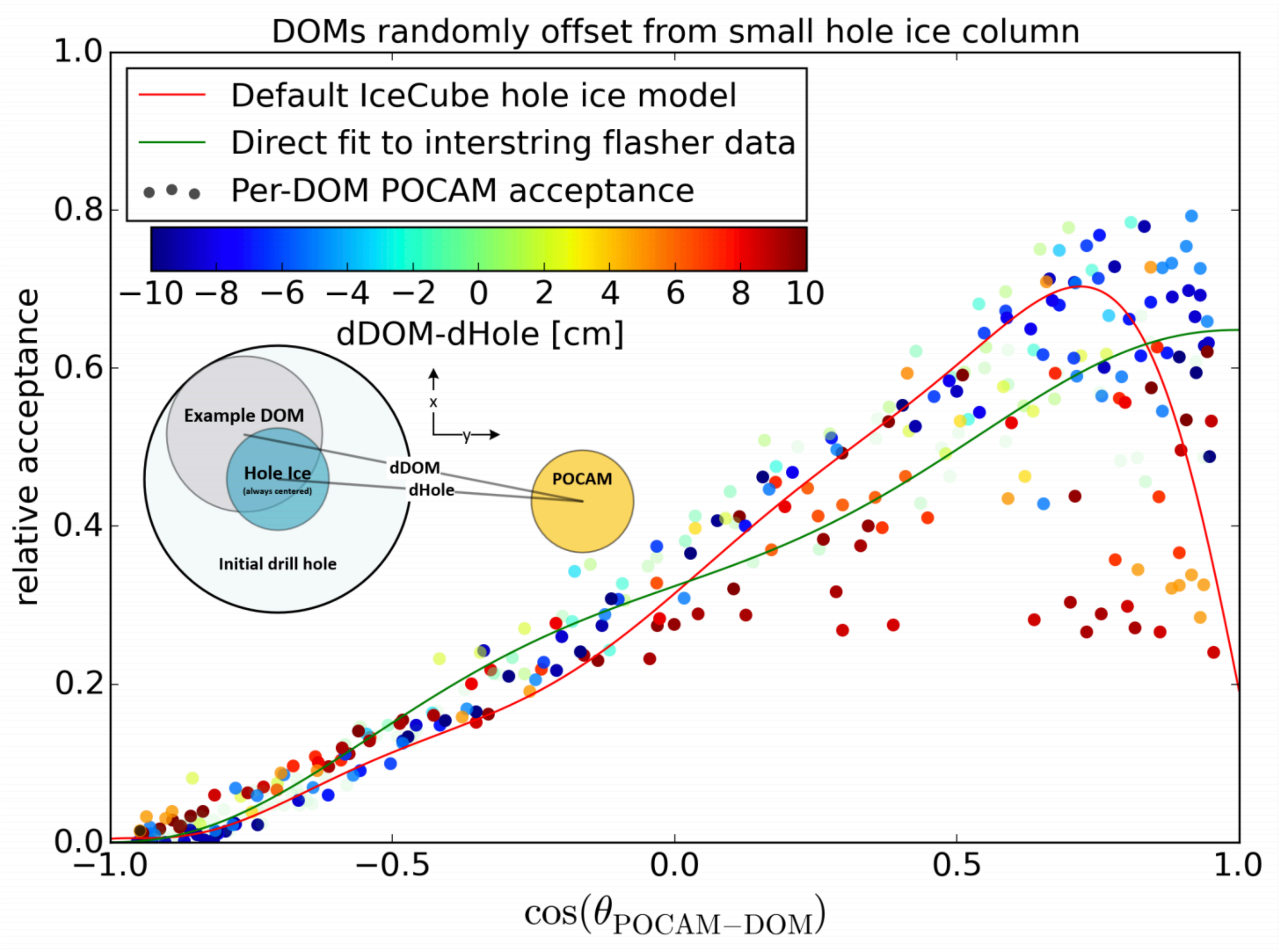
CMOS[2]



[1] https://doi.org/10.1051/epjconf/201713506003
[2] https://doi.org/10.22323/1.301.1040
[3] https://doi.org/10.22323/1.301.0934

The IceCube Upgrade - Calibration

Example: POCAM triangulation and characterisation of bubble column

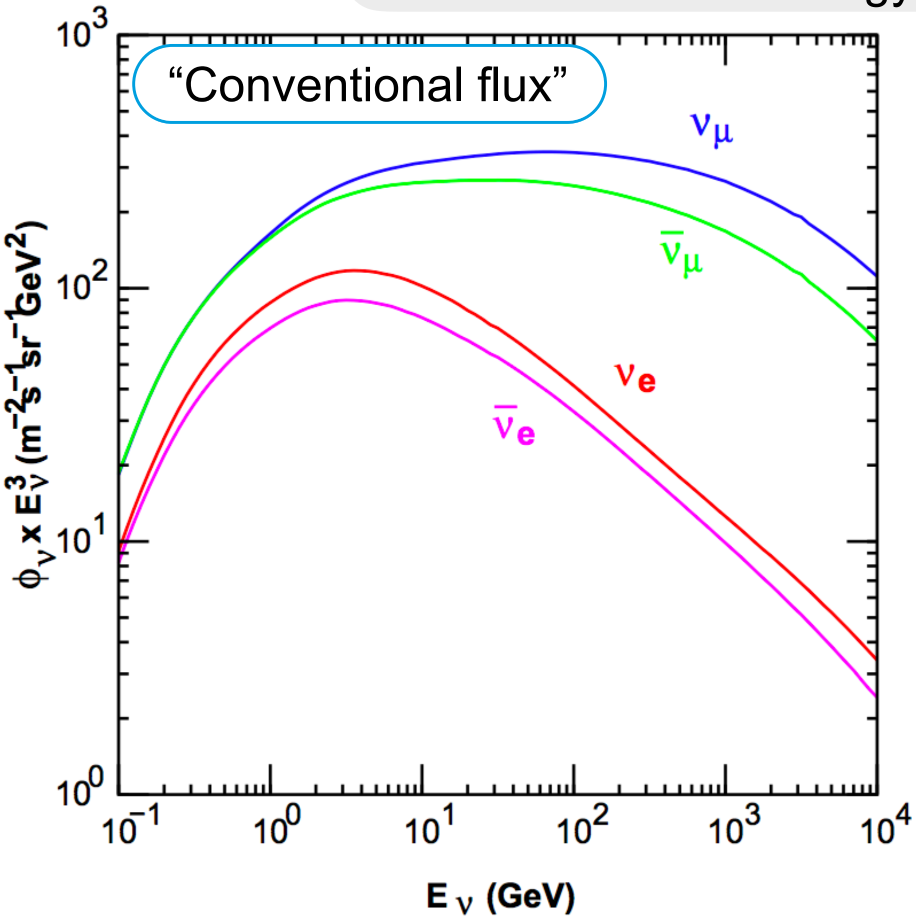


https://doi.org/10.22323/1.301.0934

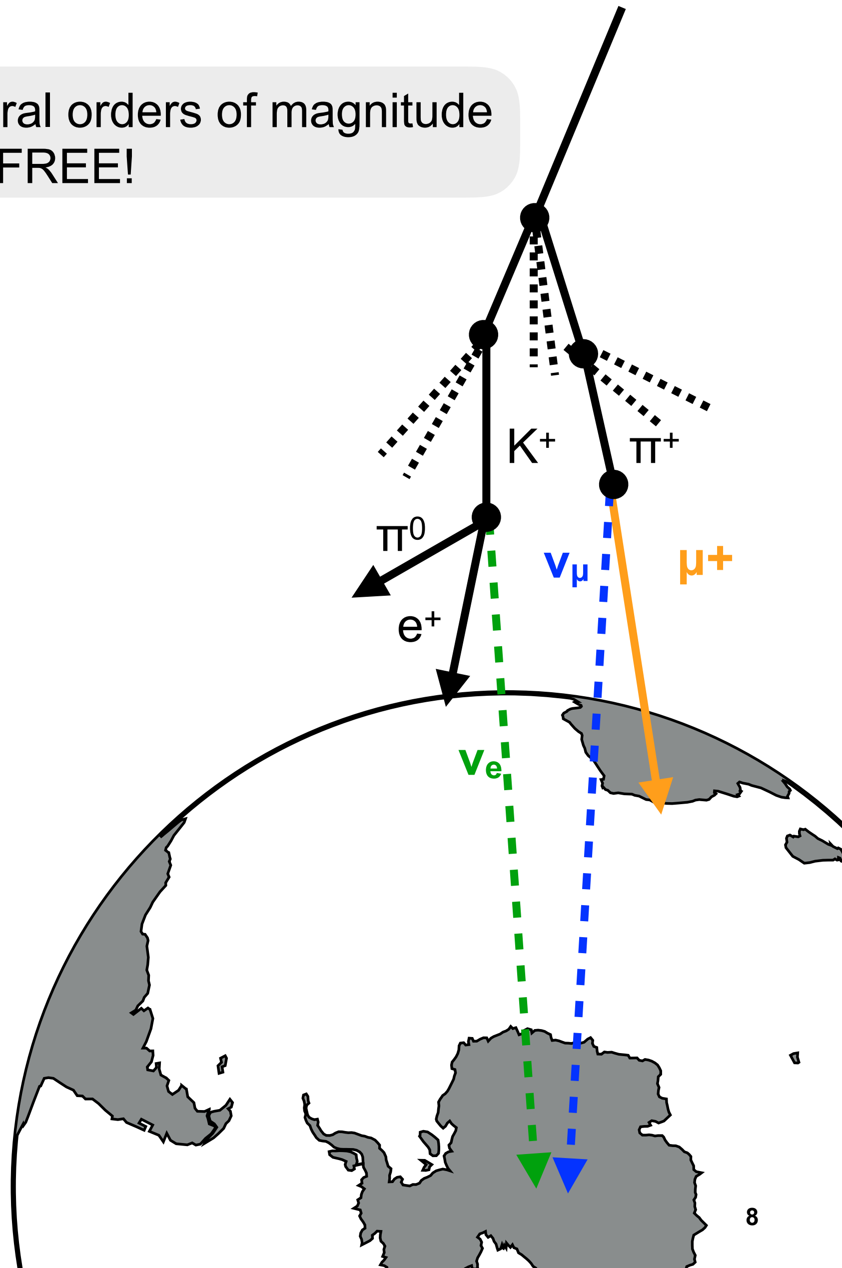
The IceCube Upgrade - Science

Not just for calibration and R&D!

High statistics sample over several orders of magnitude in energy FOR FREE!



Honda, et. al: https://arxiv.org/abs/1502.03916

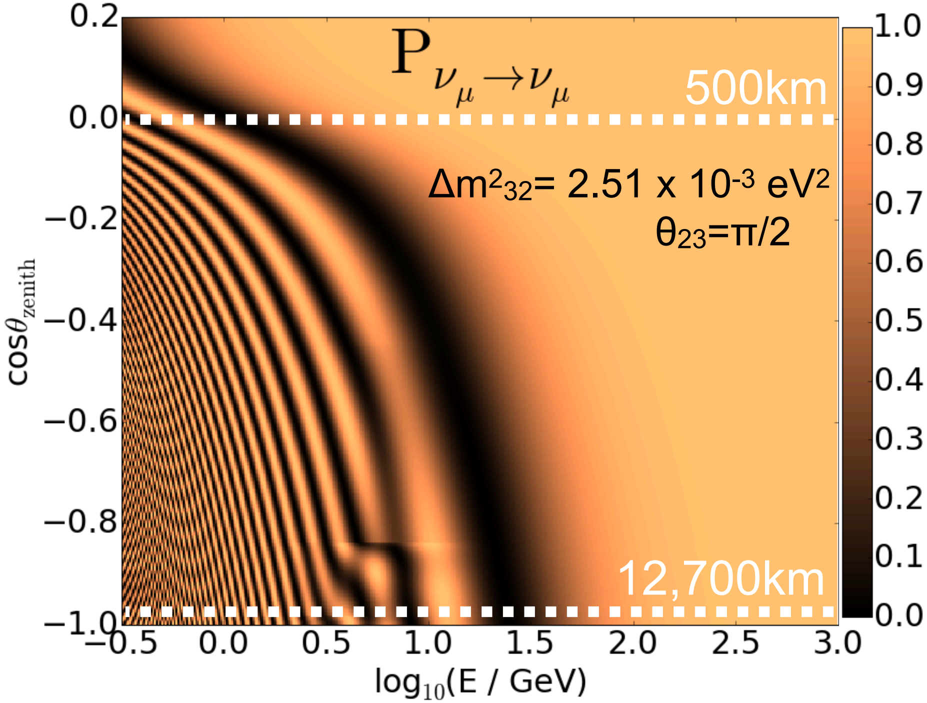


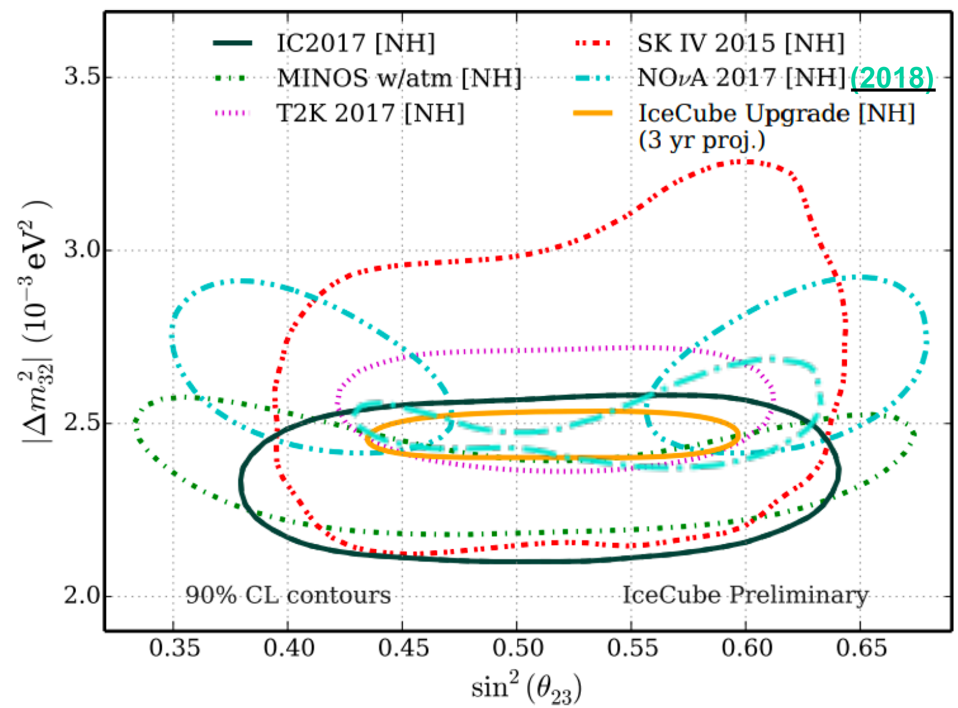
The IceCube Upgrade - Science

Precision atmospheric oscillation measurements

Similar physics program to DeepCore, just better!

- Oscillations, non-standard interactions, sterile neutrinos, dark matter…





First order effect for atmospheric neutrinos:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\Delta m^2_{32}\frac{L}{4E_\nu}\right)$$

The IceCube Upgrade - Science

Precision atmospheric oscillation measurements

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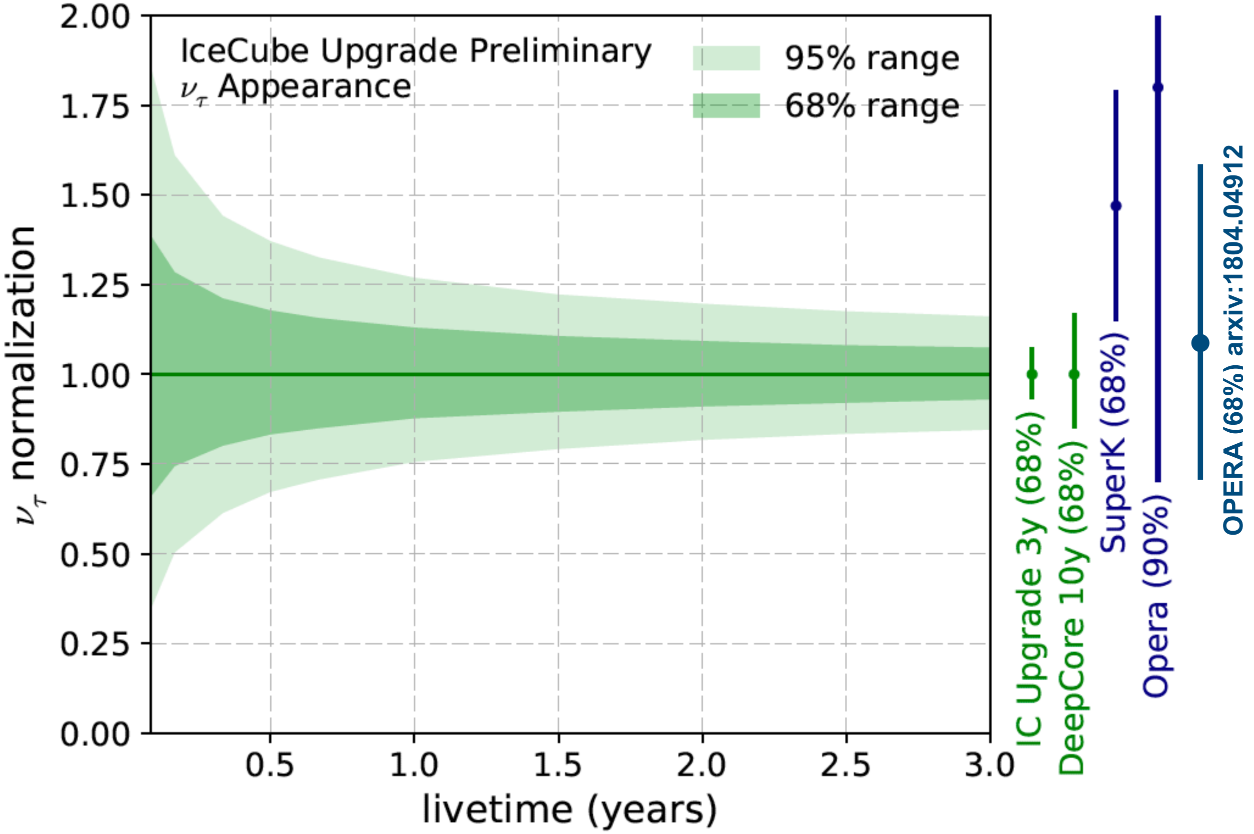


Projected sensitivities ***do not*** include reduced ice/OM systematics

IceCube-Gen2

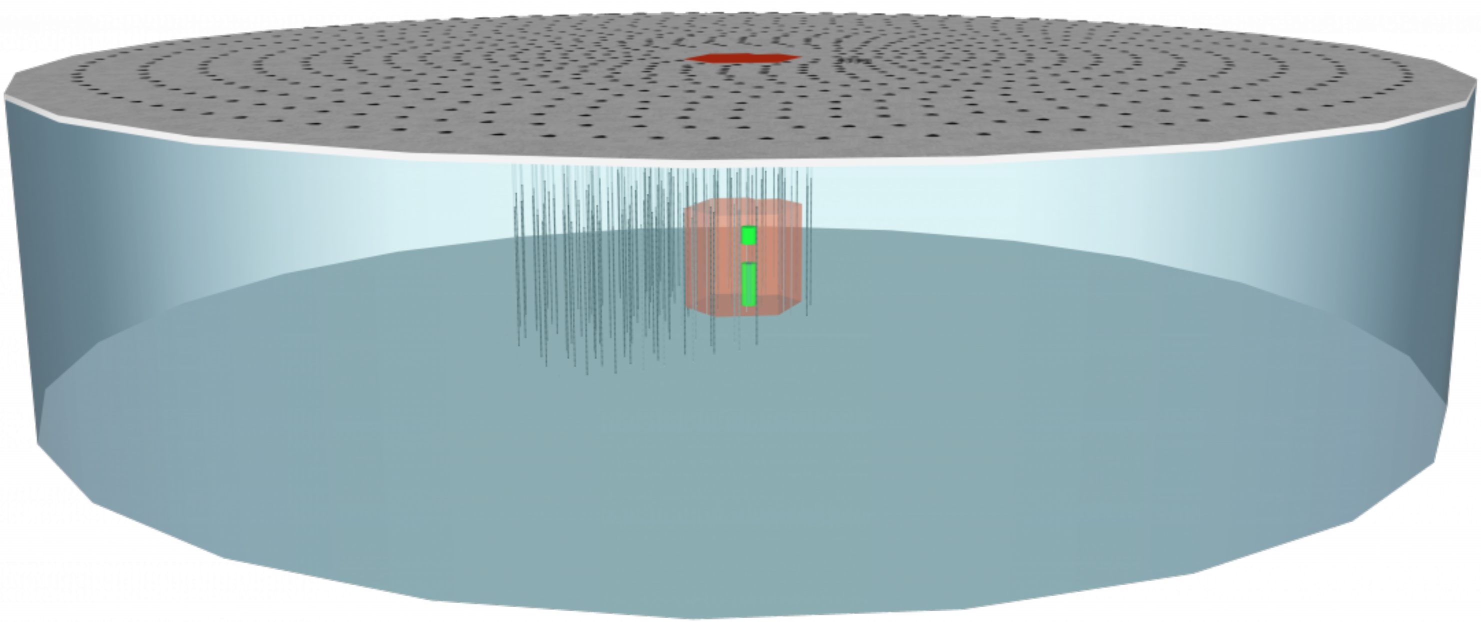
A vision for the future of neutrino astroparticle physics at the South Pole

High energy

- Find (more) neutrino point sources
- Characterise spectrum, flux, and flavour composition of astrophysical neutrinos with higher precision
- GZK neutrinos
- Continue search for BSM physics

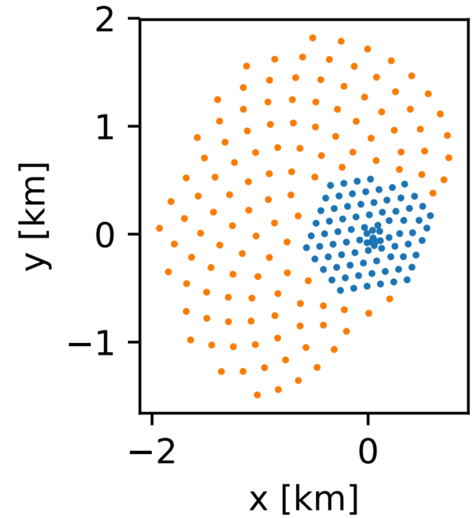
Low energy

- Precision measurements of atmospheric neutrino oscillations:
  - $\nu_\mu \rightarrow \nu_\tau$
  - Neutrino mass ordering
- Characterise atmospheric flux (hadronic interactions)
- Also continue search for BSM physics



IceCube-Gen2

High energy facility

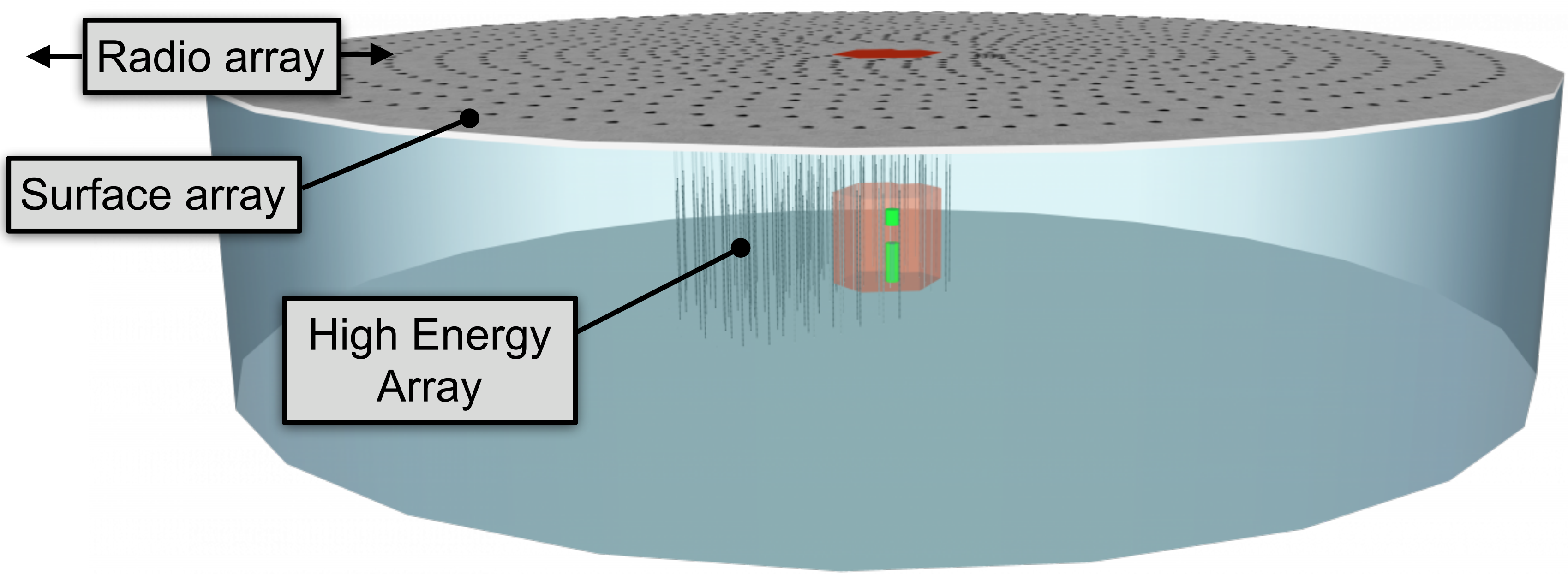


In-Ice High Energy Array (HEA)

- 120 strings with ~240 m spacing and 80 OMs each
- 6.2 - 9.5 km³ instrumented volume (not yet fixed)

Surface array

- Under investigation: Air Cherenkov Telescope (IceAct) vs scintillator panels
- Prototypes of both systems deployed and operating at the South Pole

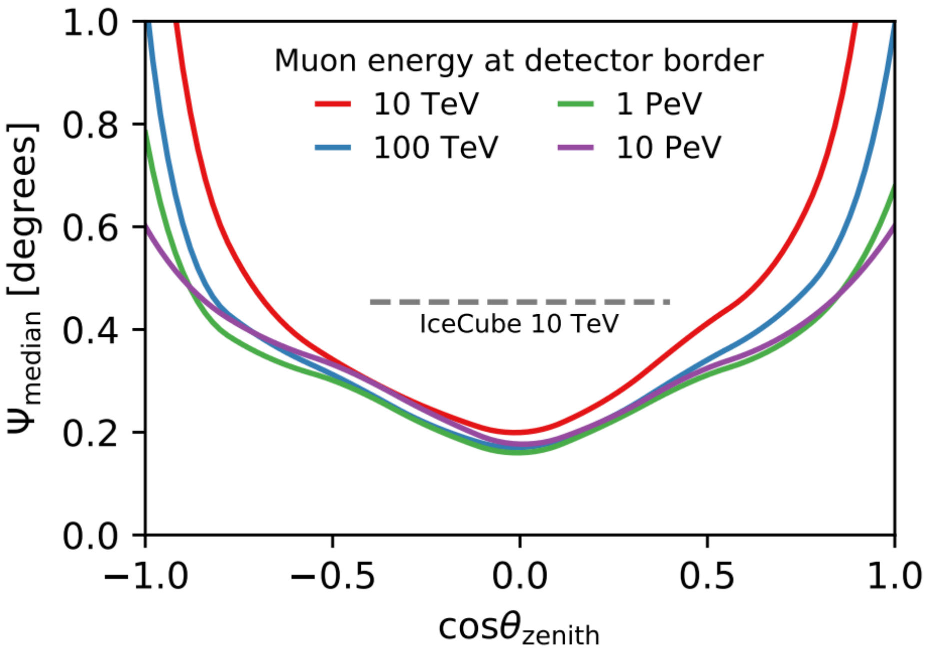


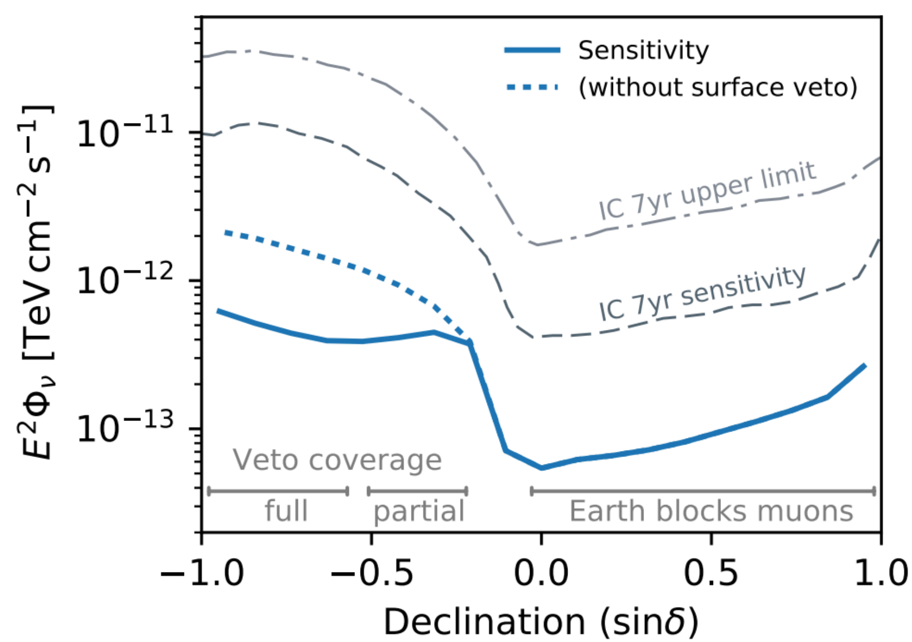
PoS (ICRC2017) 991

High Energy Array

Projected sensitivity

- Improved angular resolution
- Better point sensitivity, here shown for 15 y IC86 + 15 y IC-Gen2
  - Discovery potential ~2.5x better than sensitivity
- Surface veto (assumed 75 km²) improves sensitivity (discovery potential) by factor ~3

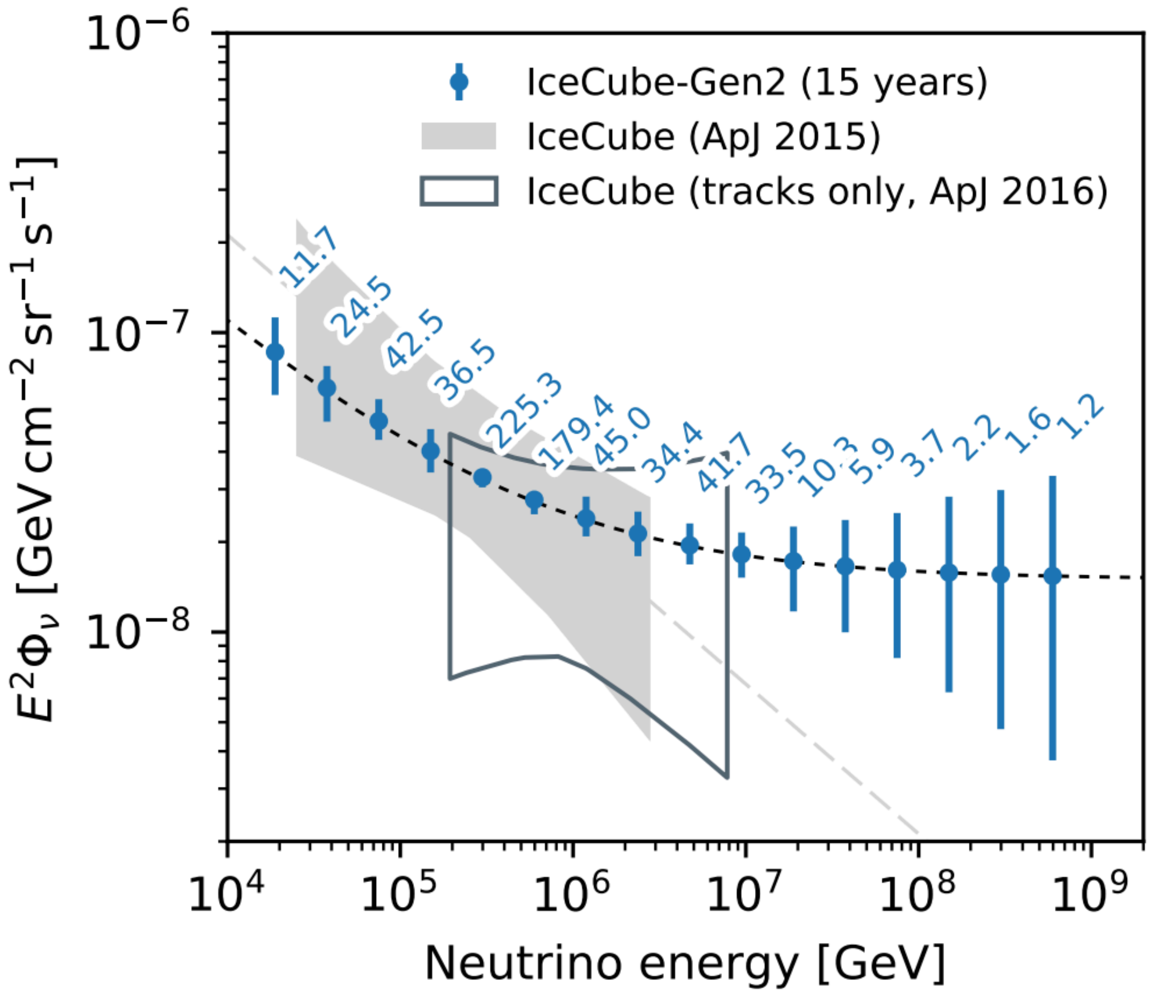




PoS (ICRC2017) 991

High Energy Array

Precise measurement of diffuse flux



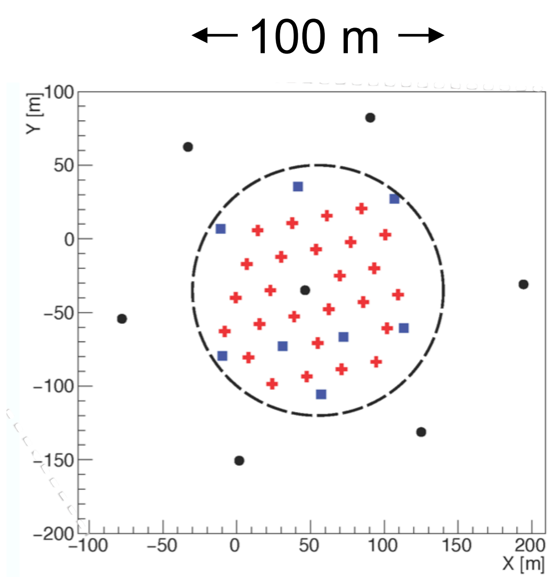
PoS (ICRC2017) 991

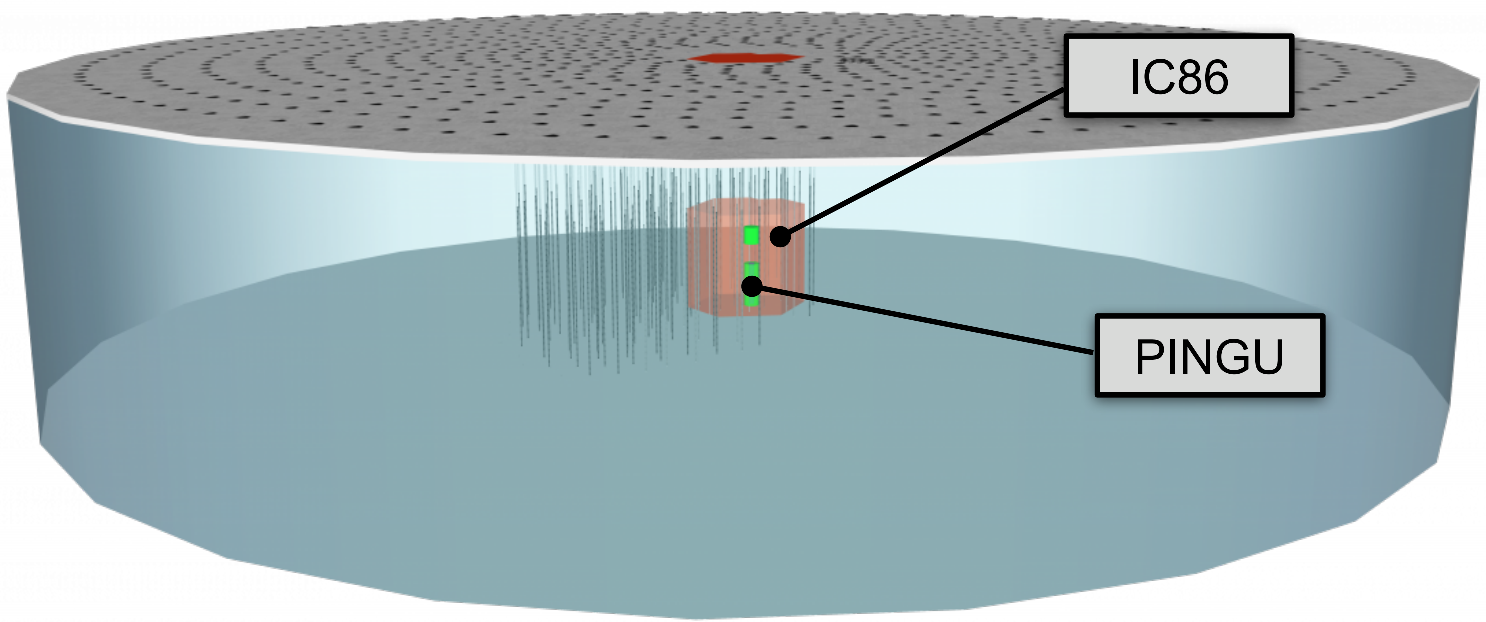
IceCube-Gen2

Low energy facility

Precision IceCube Next Generation Upgrade (PINGU)

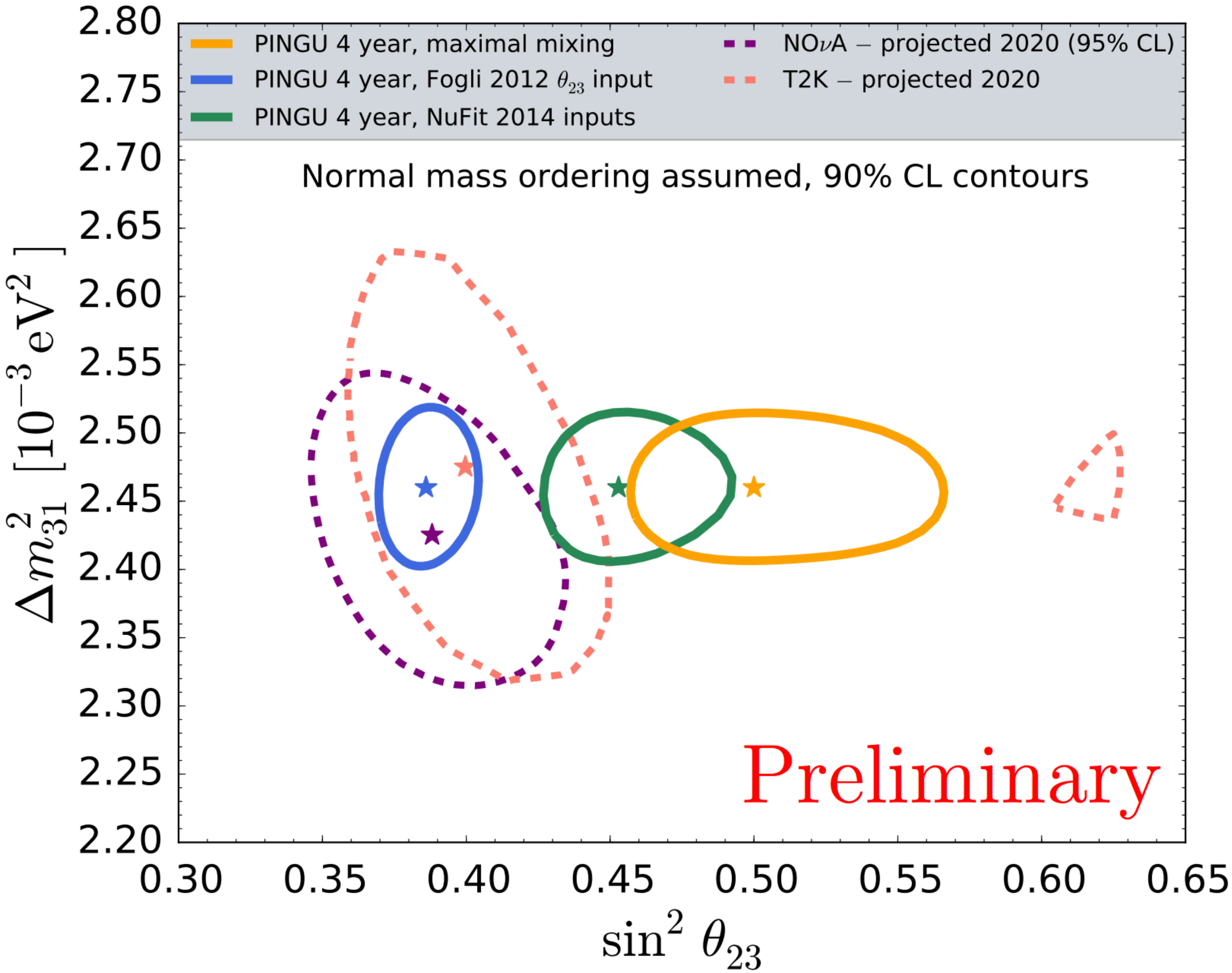
- 26 strings with ~20-30 m spacing and 125 OMs each
- Profit from surrounding 86-strings of IceCube-DeepCore as cosmic muon veto
- Lower energy threshold to ~100 MeV





Neutrino oscillations

Highest energy probe of atmospheric $\nu_\mu \rightarrow \nu_\tau$ mixing



Expected precision:

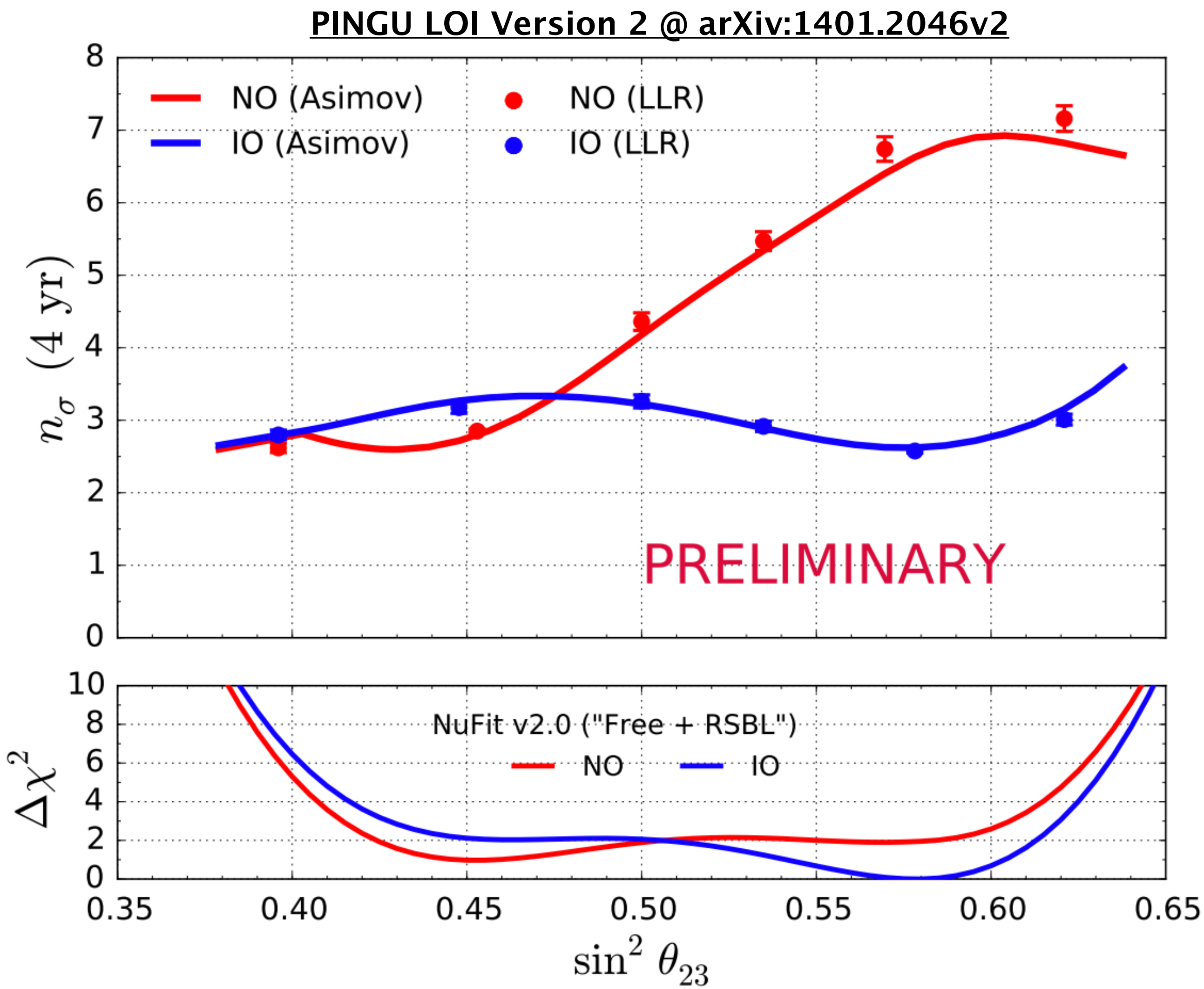
Δm^2_{32} ~ 1% (1σ)

θ_{23} ~ 4% (1σ)

depends on NMO and true θ_{23}

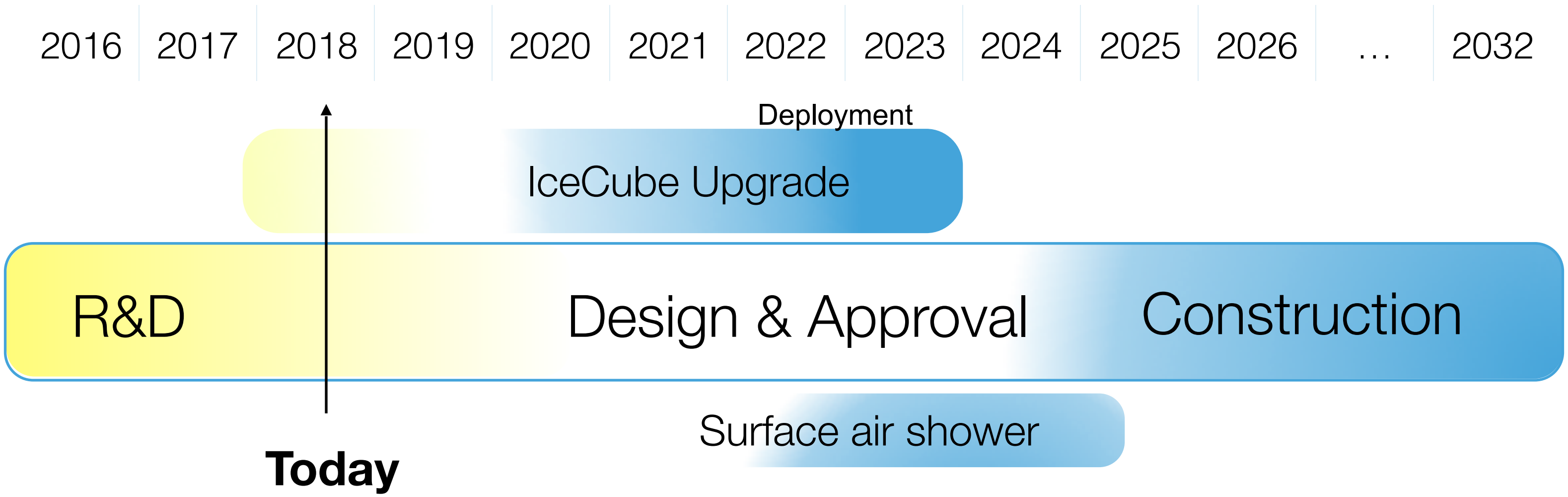
Neutrino oscillations

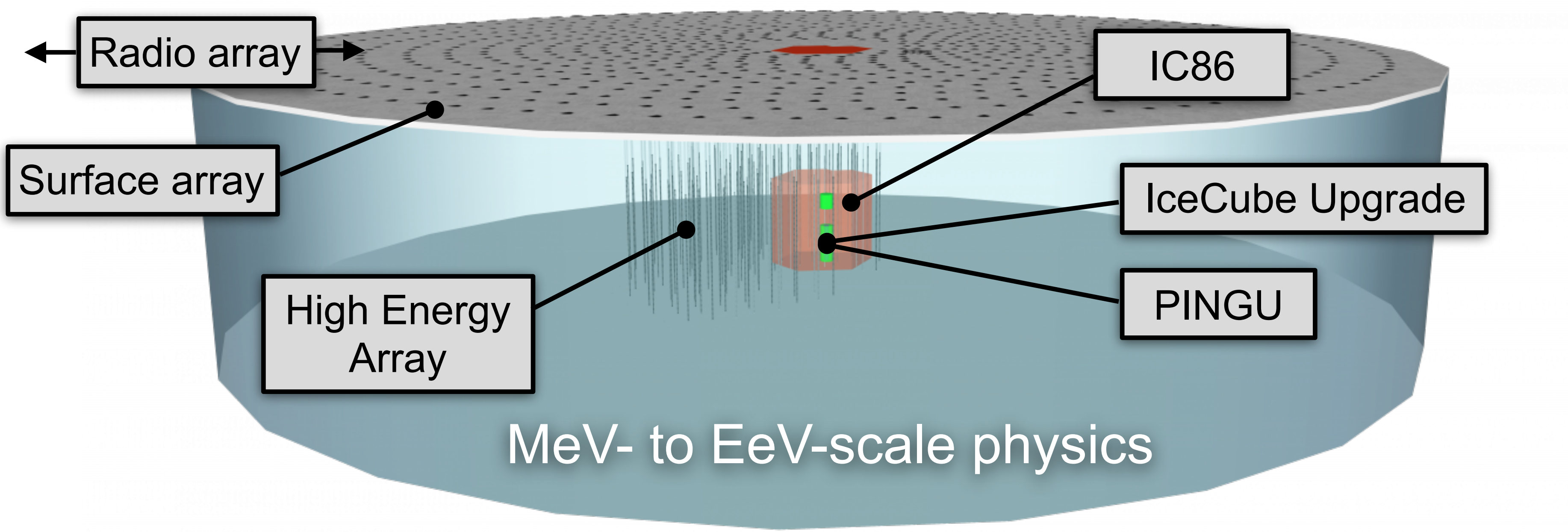
Neutrino Mass Ordering



The IceCube-Gen2 Facility

Preliminary timeline





Summary

Short term: IceCube 7-string Upgrade

- Deploy new optical sensors for testing
- Re-calibration of existing array for improved measurements at all energy scales
- Precision measurements of atmospheric neutrino oscillations

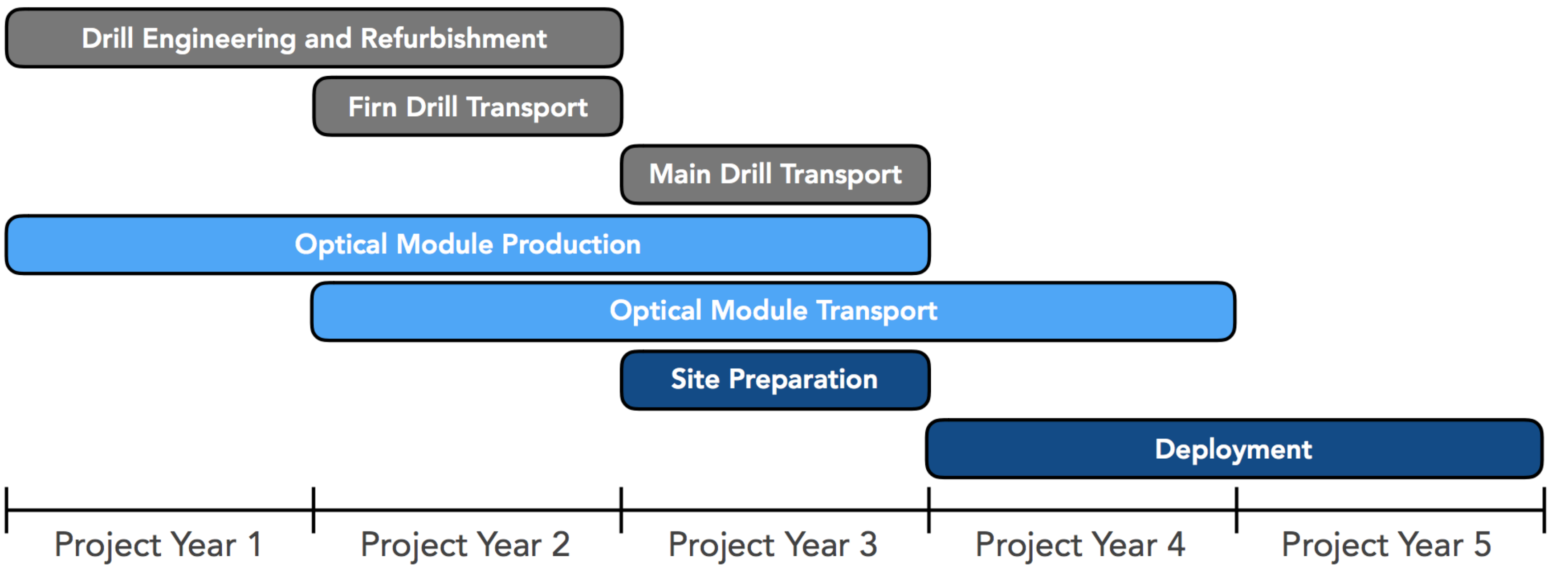
Longer term: IceCube Gen2 facility

- High energy array:
  - ~ 3.5x improved sensitivity to point sources
  - ~ 2x more PeV neutrinos compared to IceCube rate
- PINGU:
  - Precision measurements of oscillations, including NMO and tests of unitary
  - Complementary L/E to future accelerator projects
- Both high and low energies sensitive to many BSM processes (e.g. sterile neutrinos, dark matter (WIMPs), magnetic monopoles…)


Thank you for your attention!

Backup

Timeline in project years



Atmospheric neutrino physics

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle$$

Flavour states

Mass states (not equal)

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

Atmospheric
Accelerator

Reactor
Accelerator

Solar
Reactor

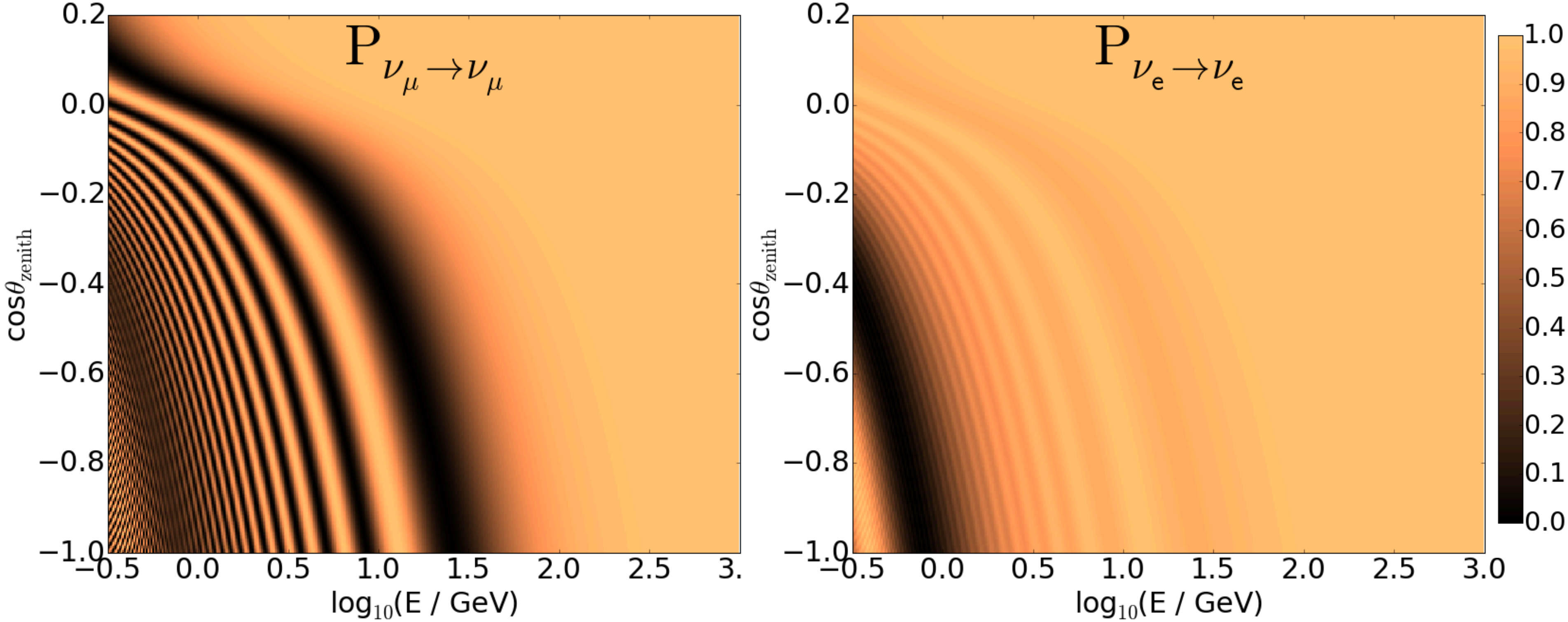
First order effect for atmospheric neutrinos:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\Delta m^2_{32} \frac{L}{4E_\nu}\right)$$

Neutrino oscillations

Vacuum oscillations

*Normal mass ordering assumed



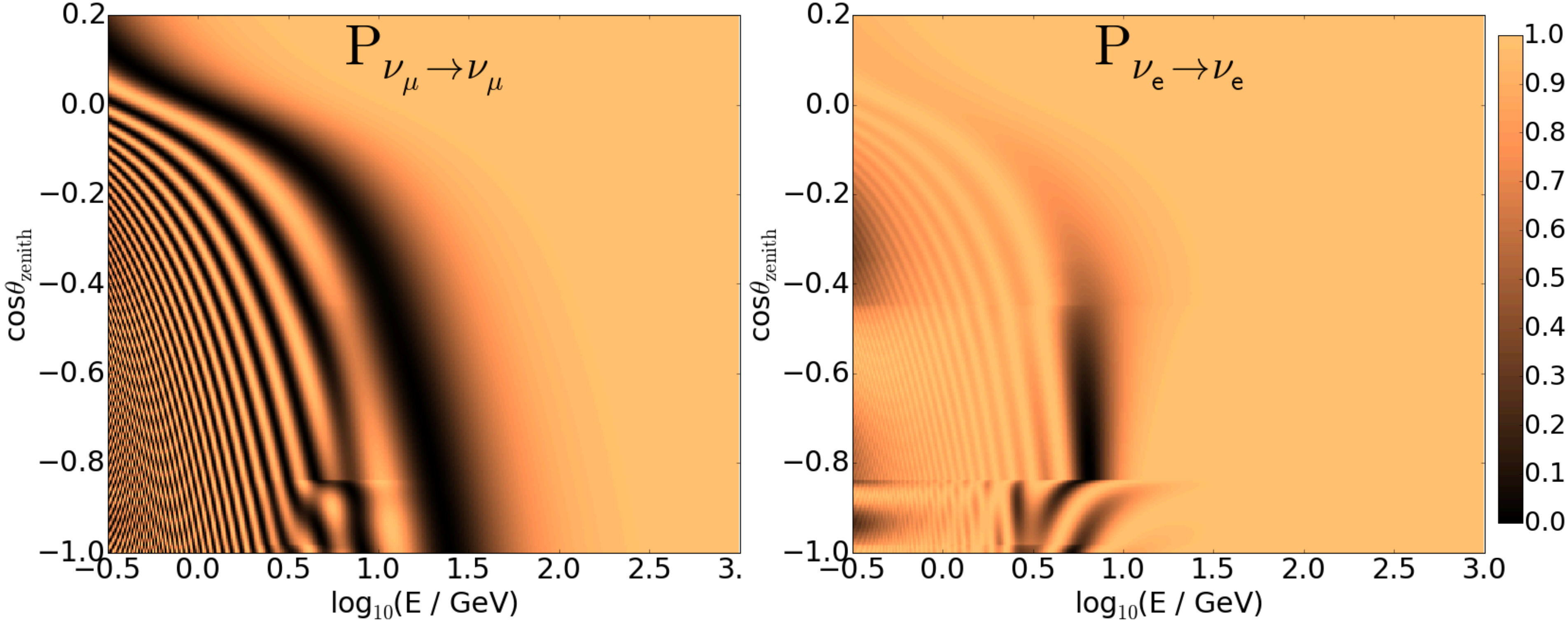
$\theta_{23}=\pi/2$

$\Delta m^2_{32}= 2.51 \times 10^{-3}\ eV^2$

Neutrino oscillations

Including matter effects

*Normal mass ordering assumed



$\theta_{23}=\pi/2$

$\Delta m^2_{32} = 2.51 \times 10^{-3}\ eV^2$

$$\hat{H}_F = \frac{1}{2E_\nu}\mathbf{U}\hat{M}^2\mathbf{U}^\dagger + \hat{V}_{int}$$

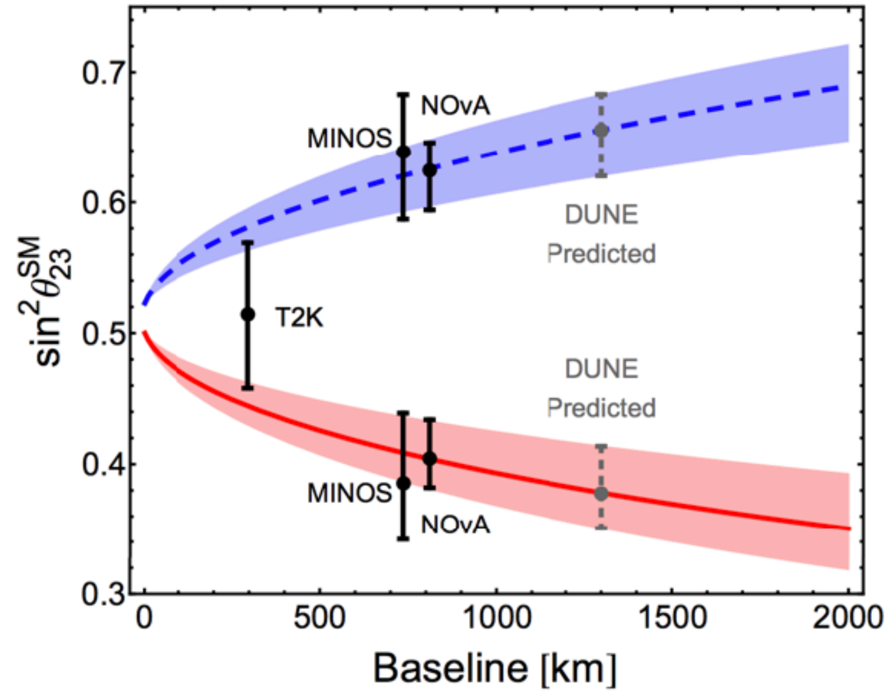
A probe for new physics

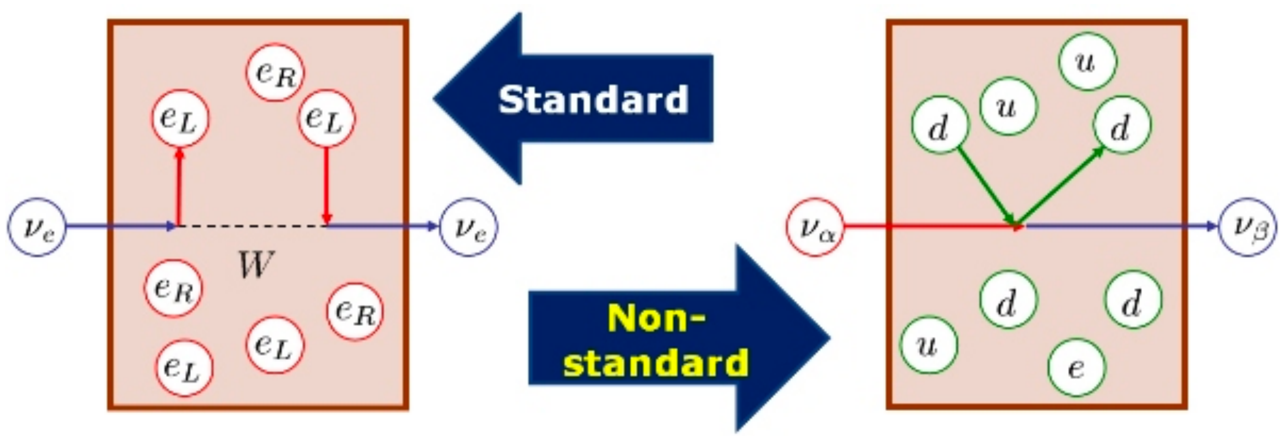
The matter matters!

PRL 118, 221801 (2017)

New Physics

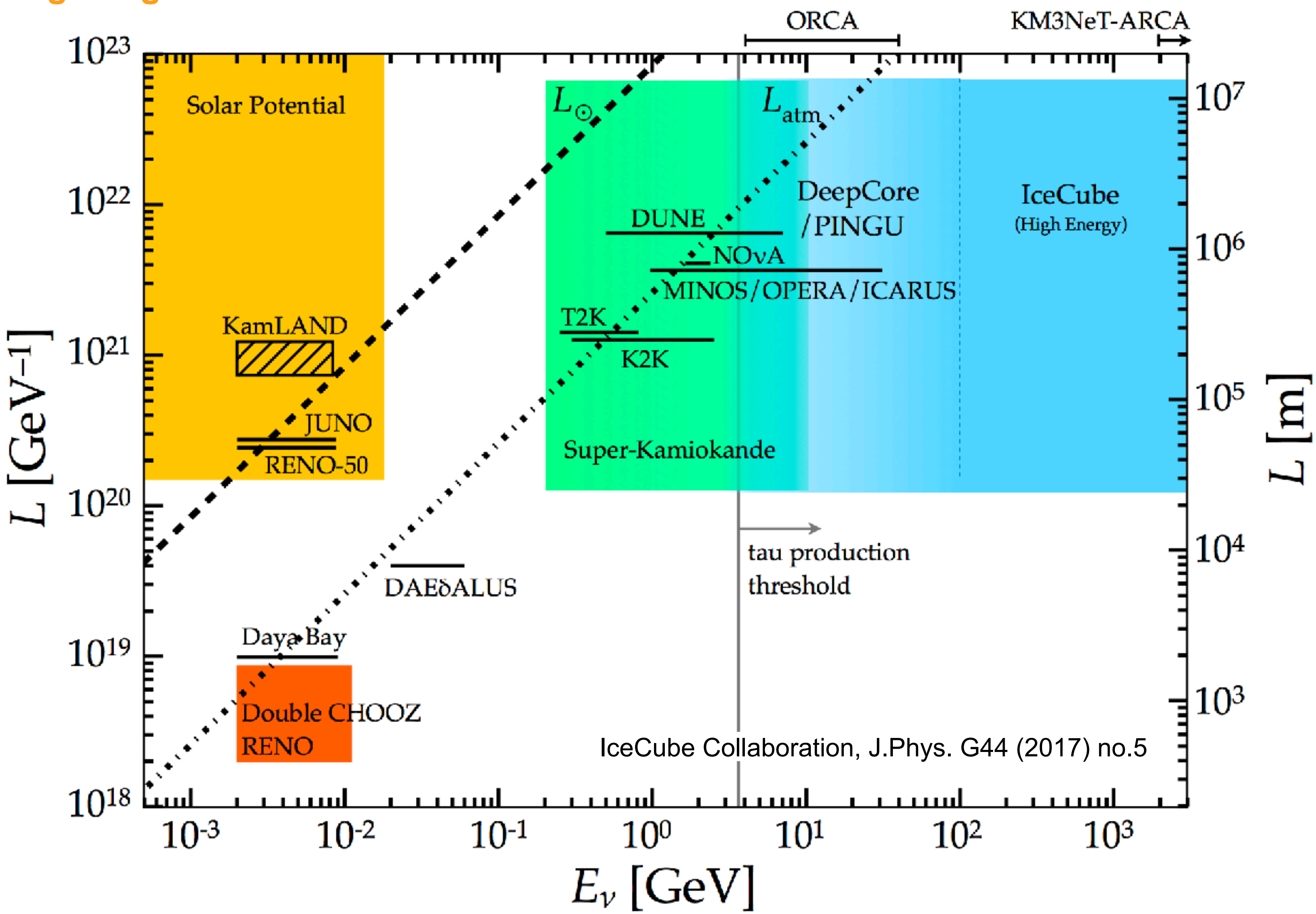
- Unitarity of PMNS matrix
- Non-standard interactions
  - Flavour changing
  - Cross-section enhancement
- Environmental decoherence





The global picture

Putting things in context



Neutrino oscillations

Testing unitary

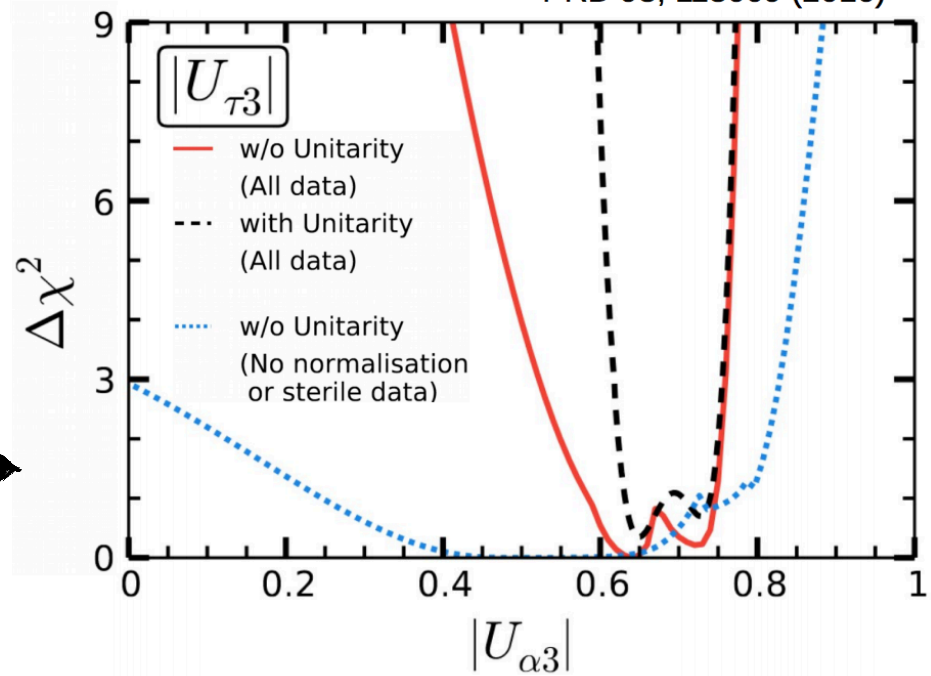
Standard mixing

$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\mathrm{PMNS}}^{3\mathrm{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

New physics

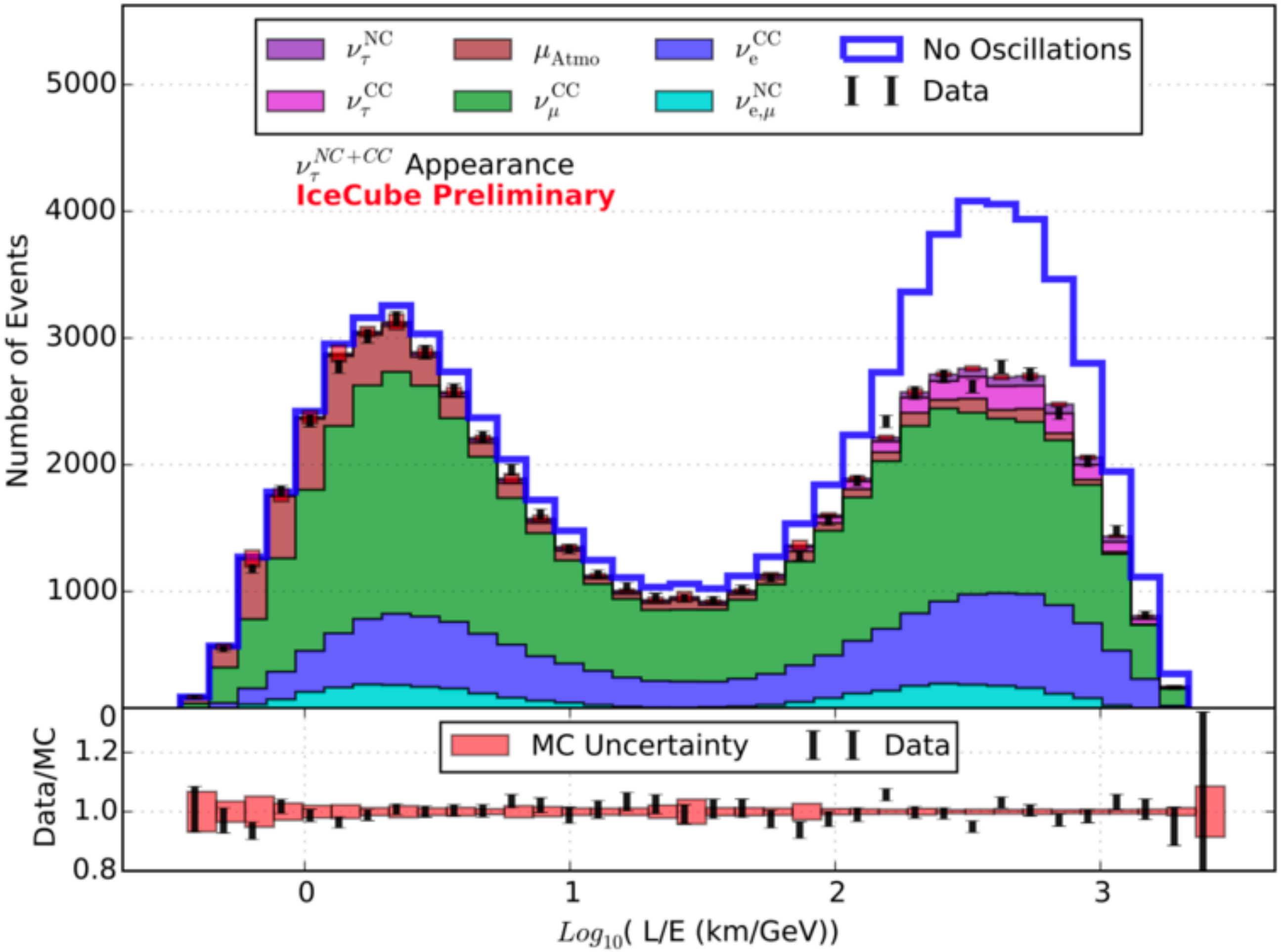
NuTau normalisation as model-independent way to test 3x3 unitarity

PRD 93, 113009 (2016)



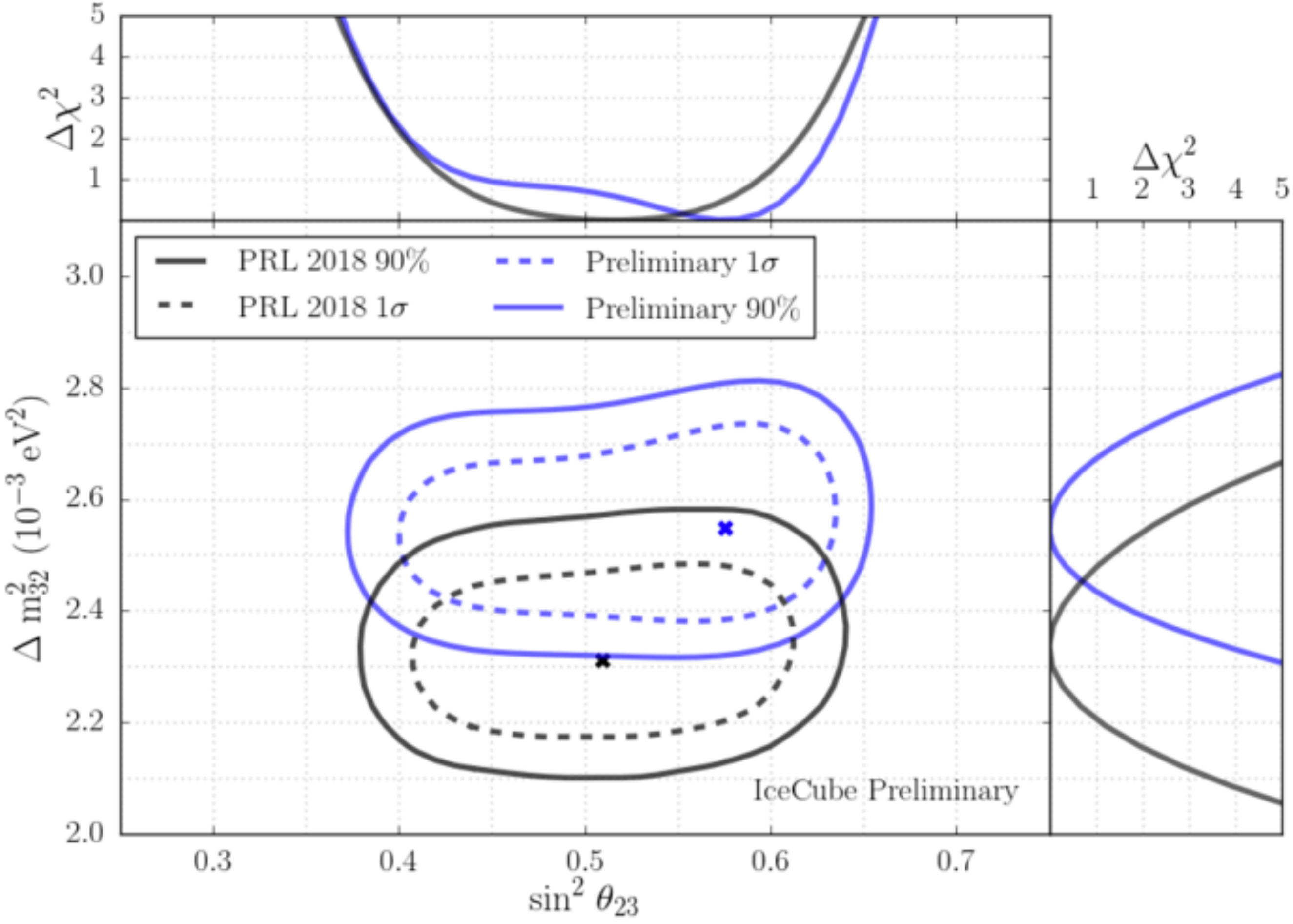
Neutrino oscillations

DeepCore NuMu Disappearance



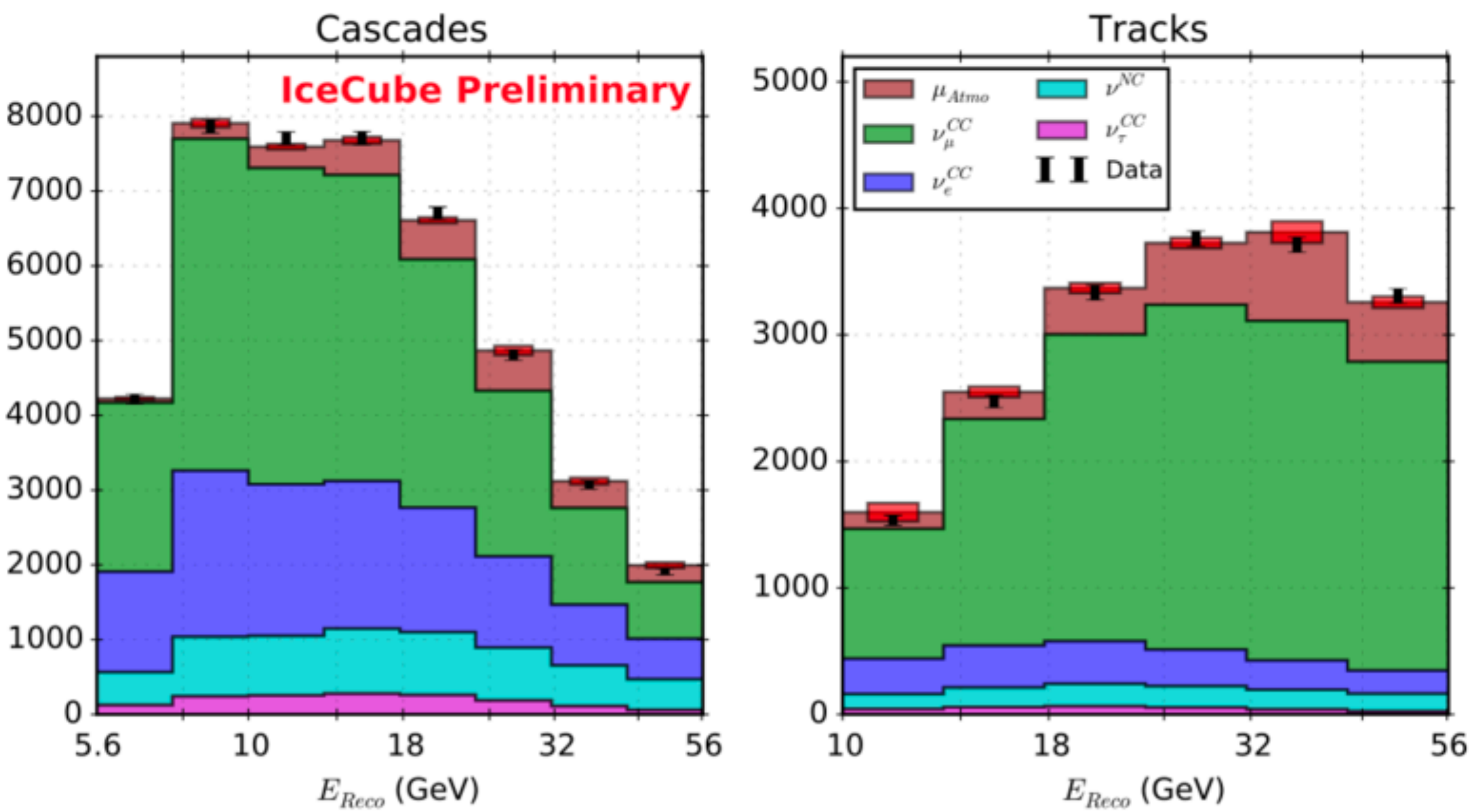
Neutrino oscillations

DeepCore NuMu Disappearance



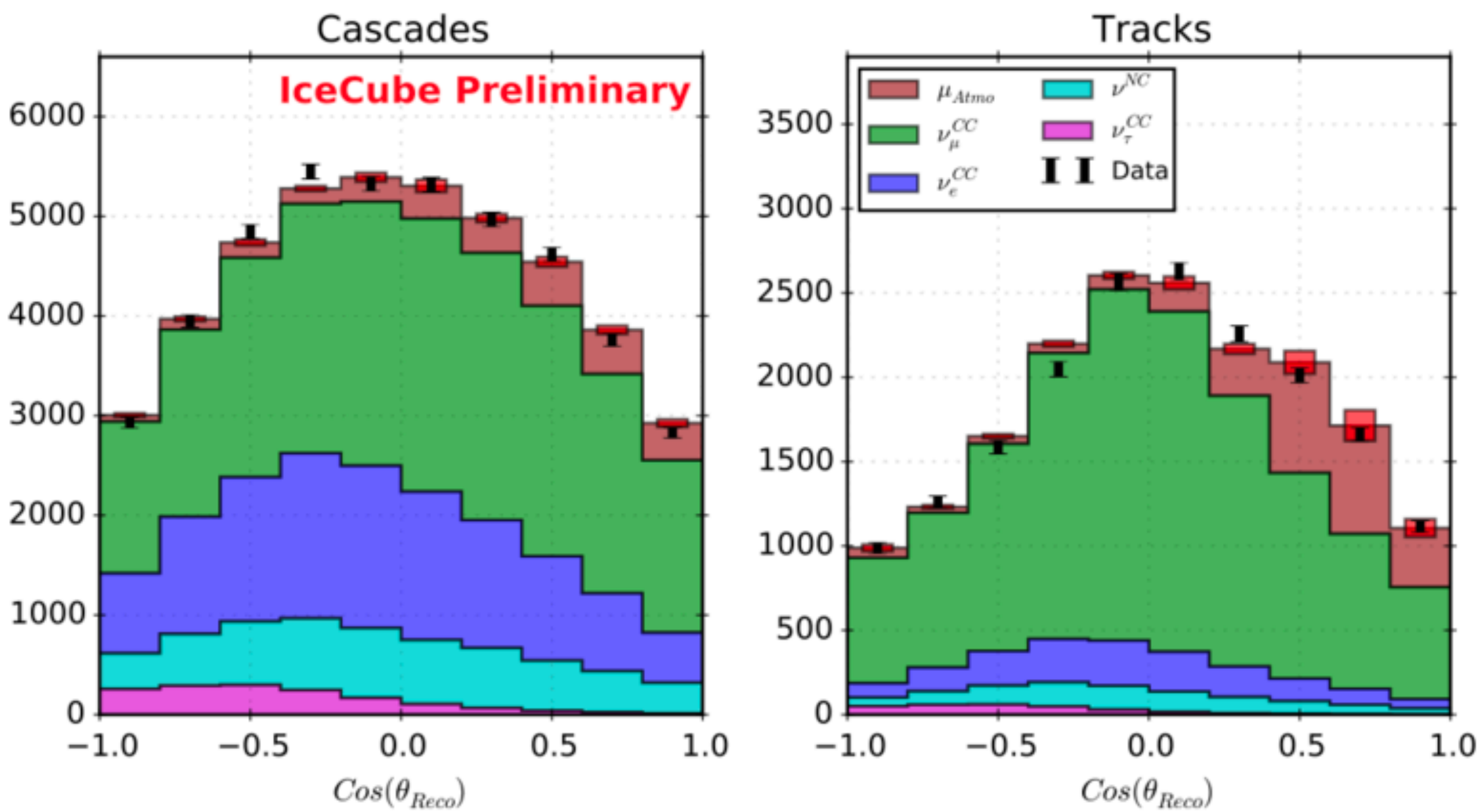
Neutrino oscillations

NuTau Appearance - energy signature



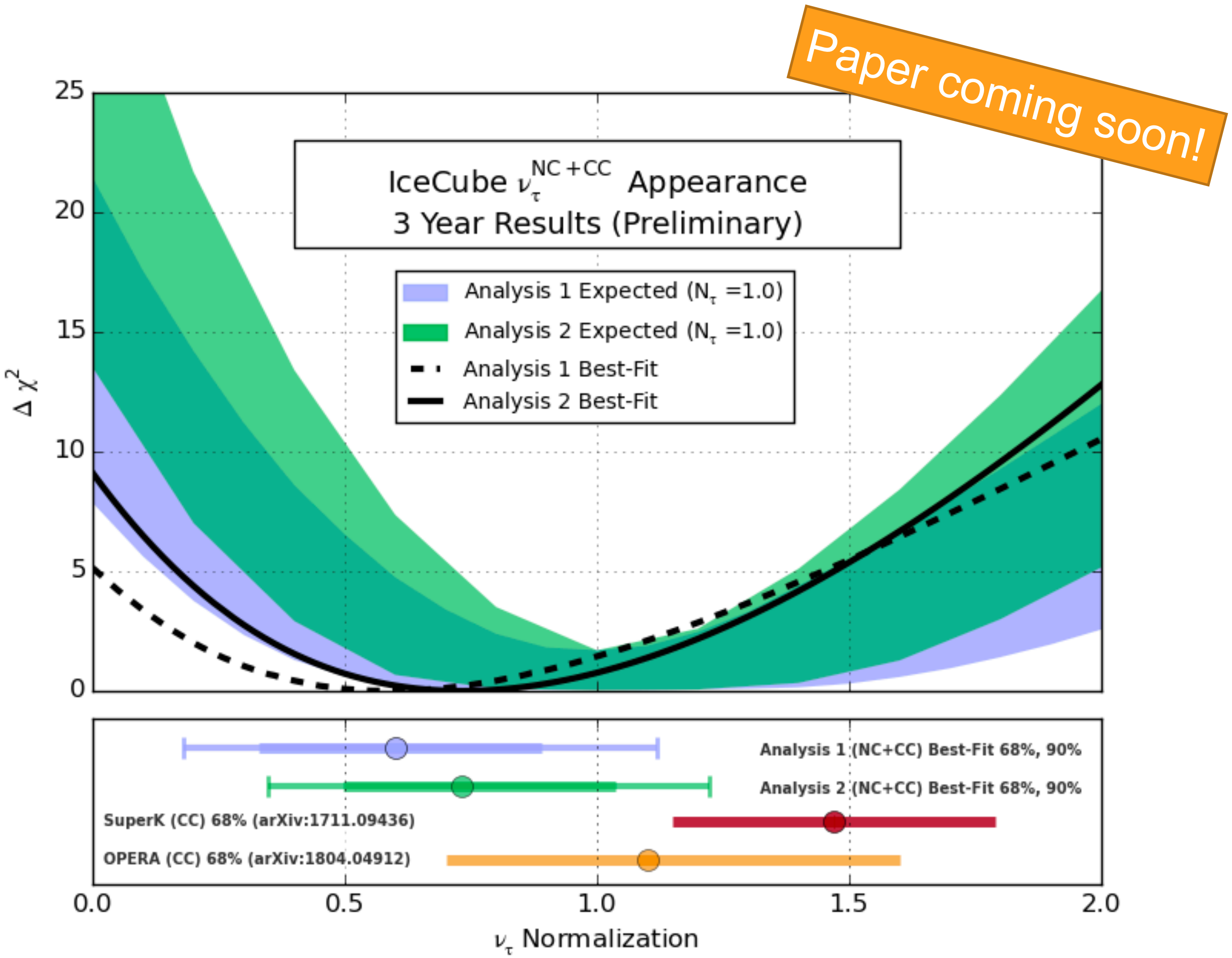
Neutrino oscillations

NuTau Appearance - zenith signature

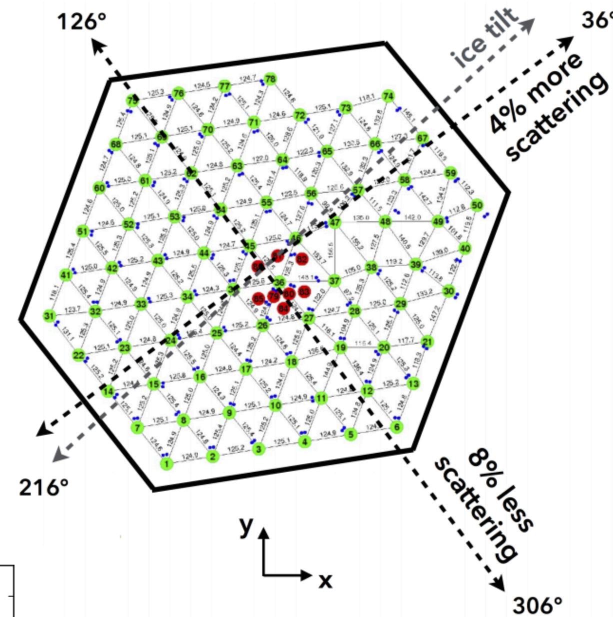


Neutrino oscillations

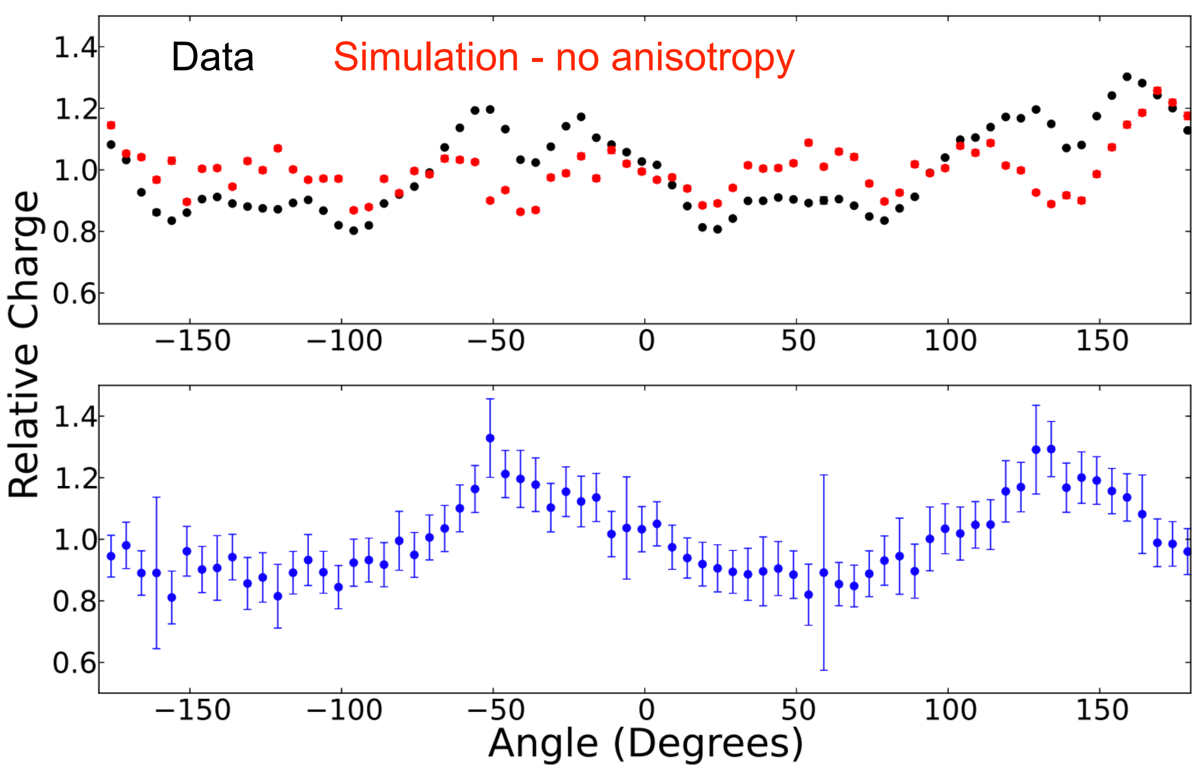
DeepCore NuTau Appearance



Ice anisotropy



South Pole ice anisotropy: Proceedings of ICRC2013 0580, 2014



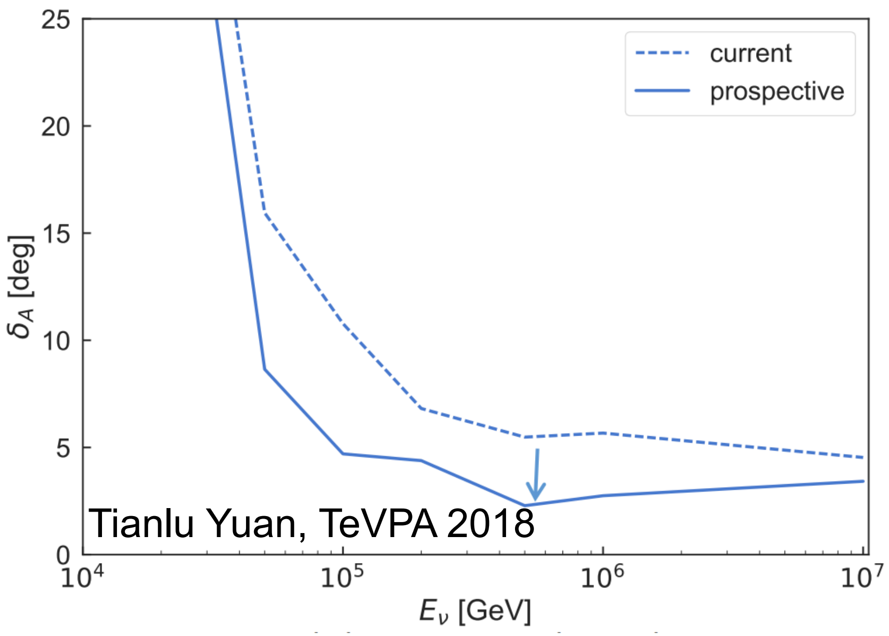
The IceCube Upgrade - Science

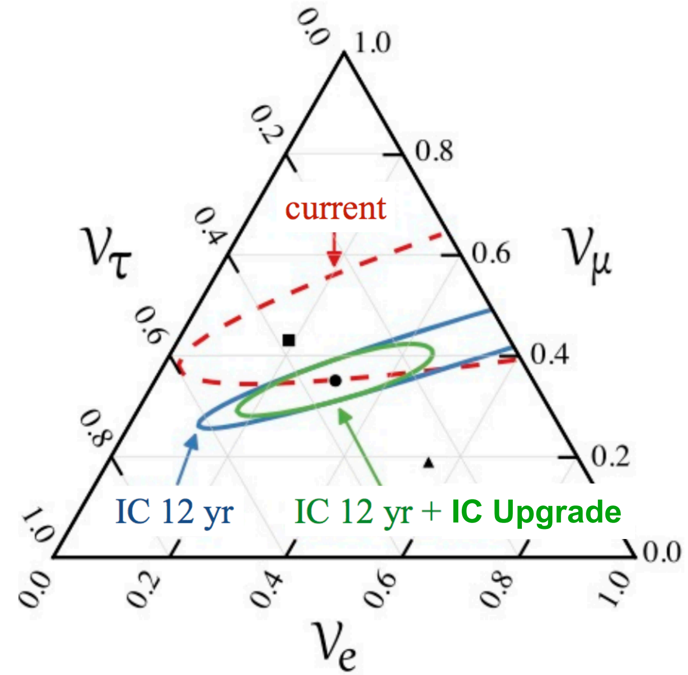
Improved reconstruction of high energy interactions

Improved cascade angular resolution

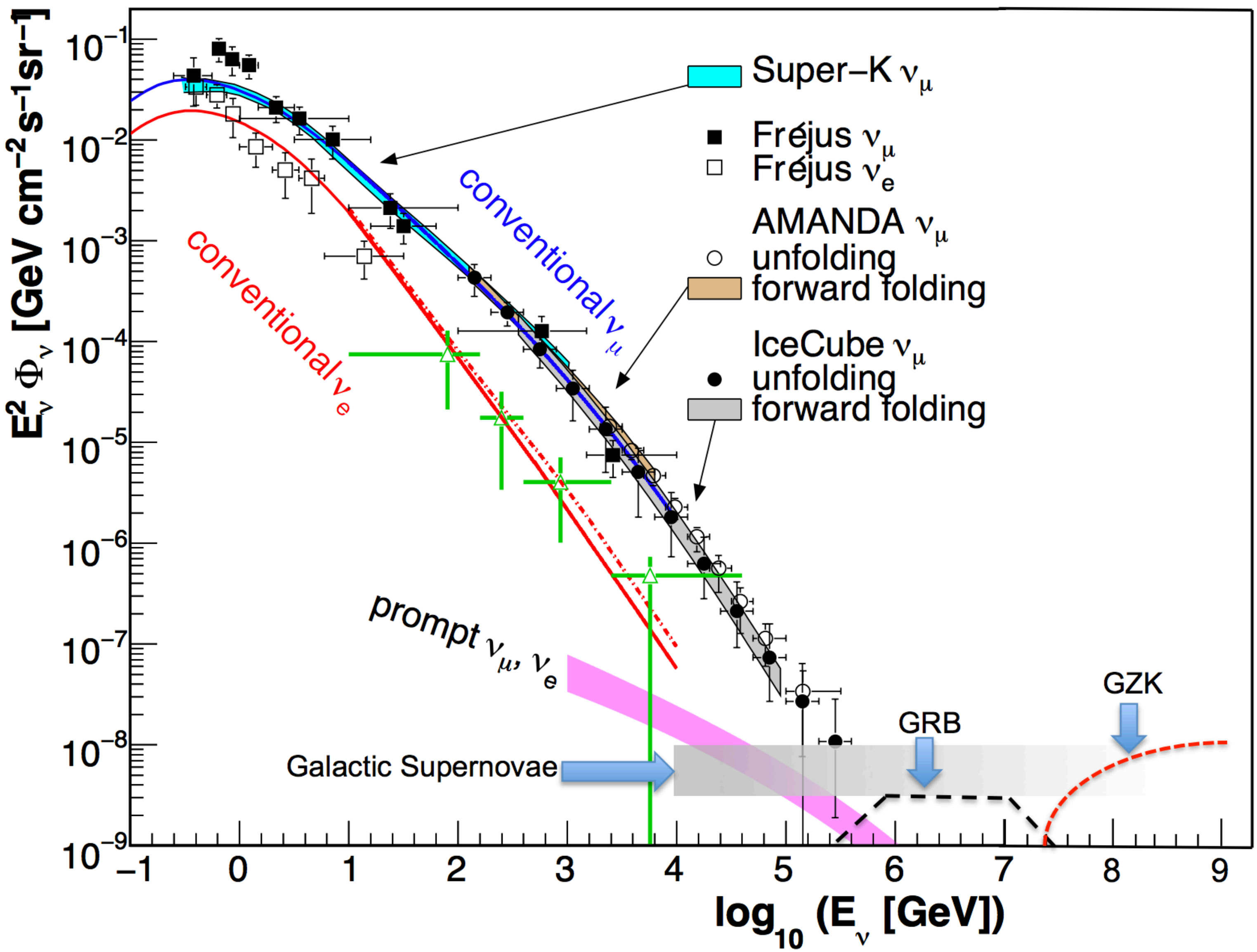
Improved identification of astrophysical ν_τ

- Use POCAMs to mimic double-bang with 20m spacing
- Reduced uncertainty on ice anisotropy



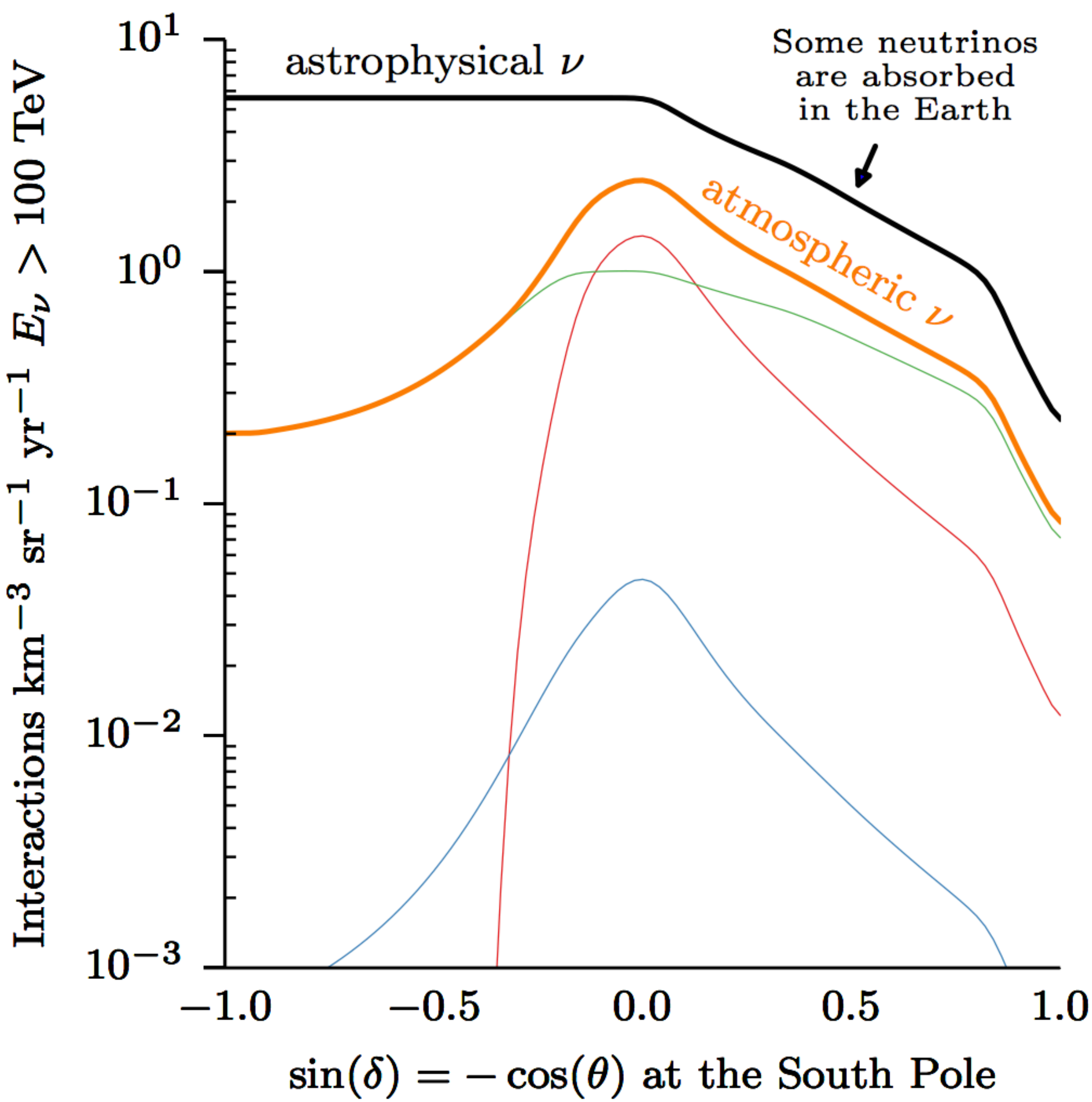


https://arxiv.org/pdf/1412.5106.pdf



DESY.

Zenith distribution of astrophysical neutrinos



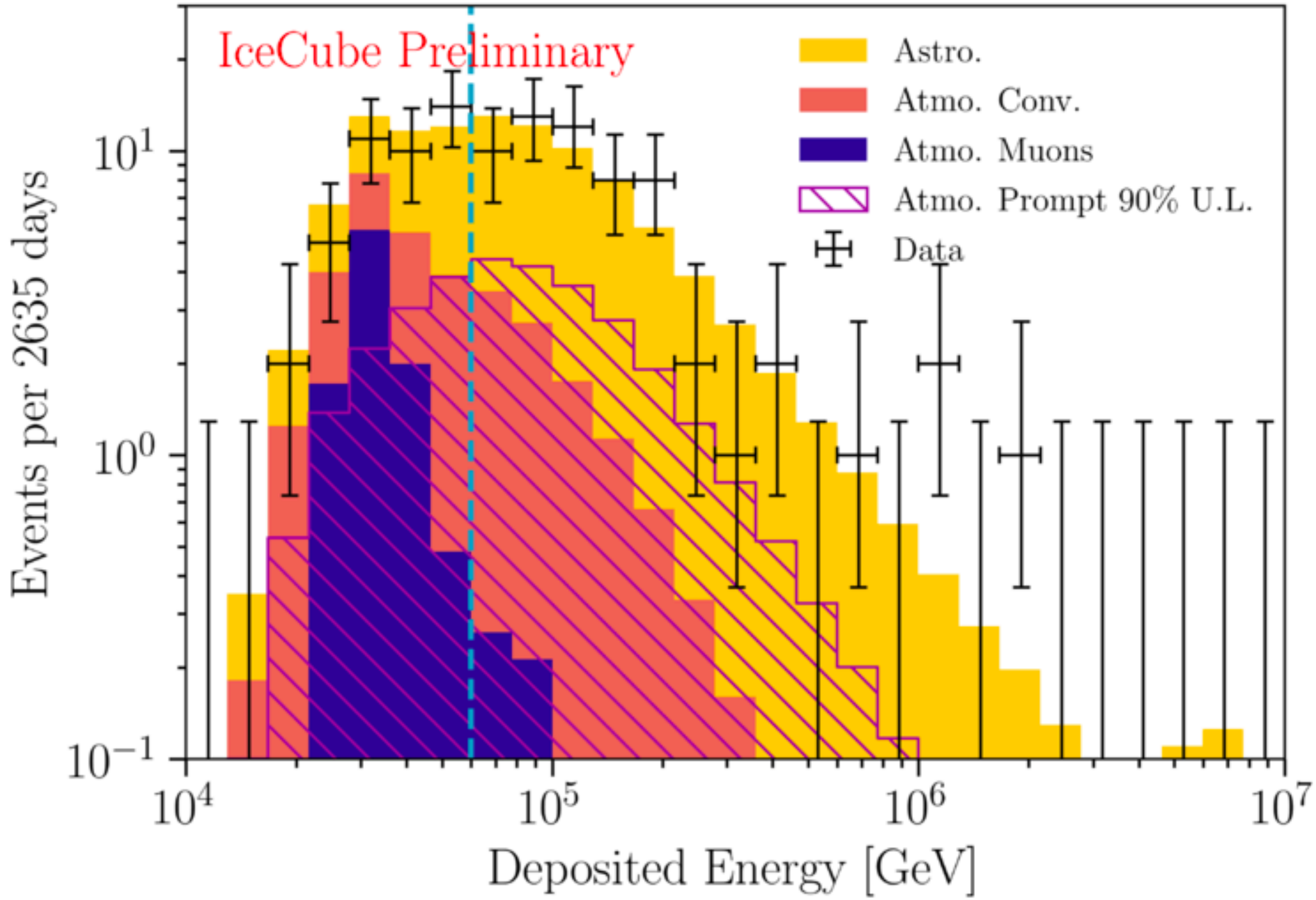
The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

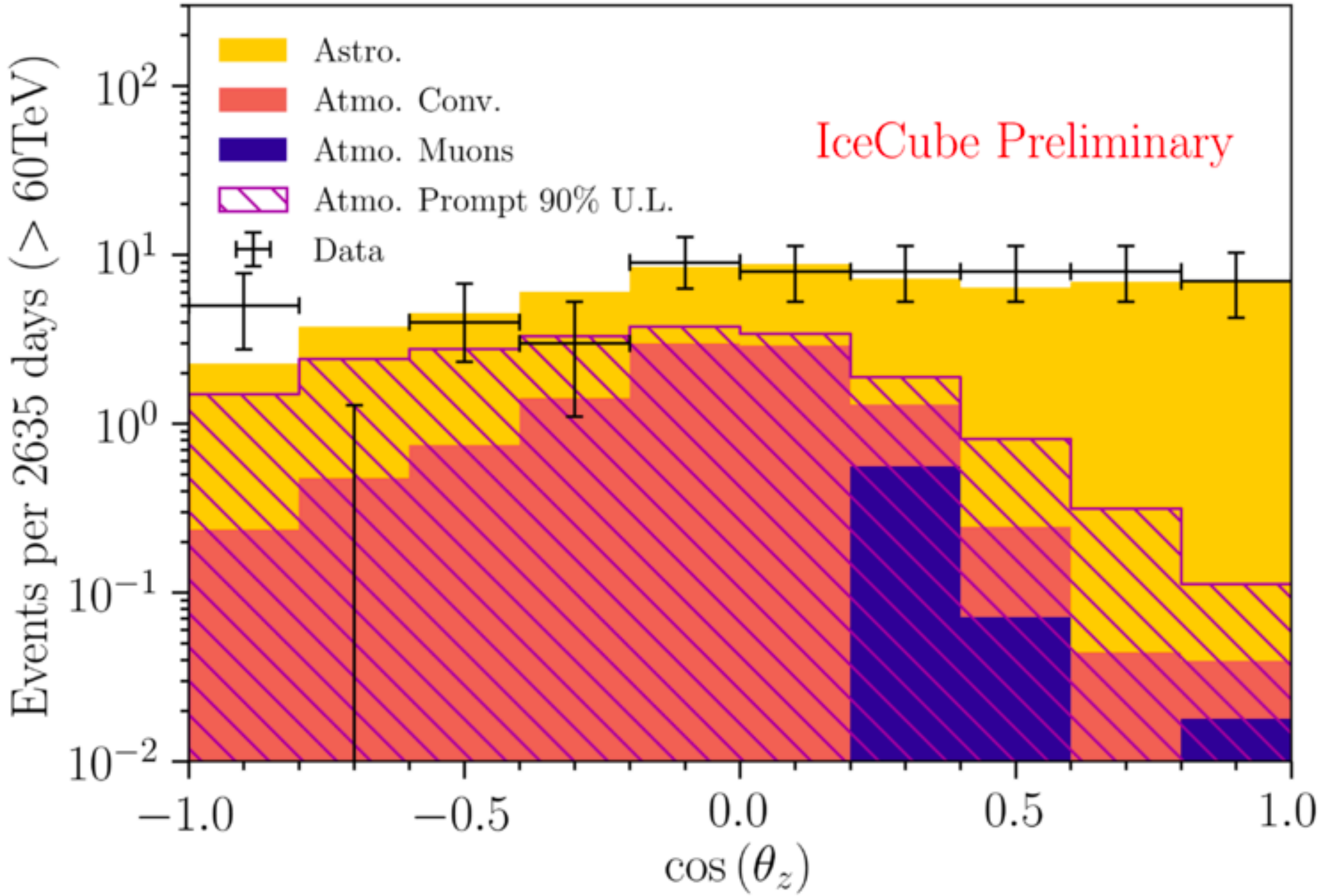
Astrophysical Neutrinos

HESE 7 yr - Energy



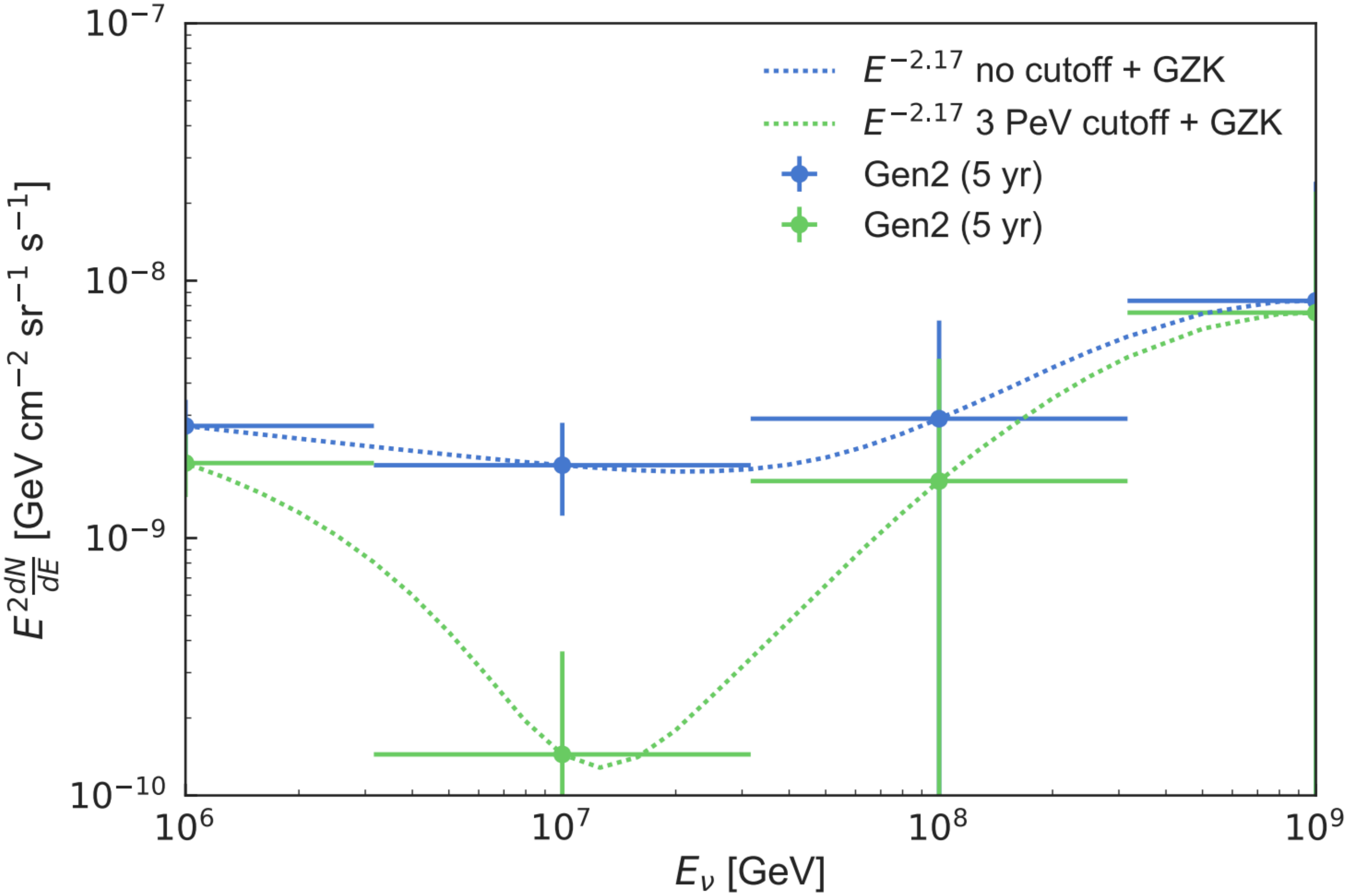
Astrophysical Neutrinos

HESE 7 yr - Direction



IceCube Gen2

PeV cut-off sensitivity



IceCube Gen2

PINGU Dark Matter

Solar WIMPs