



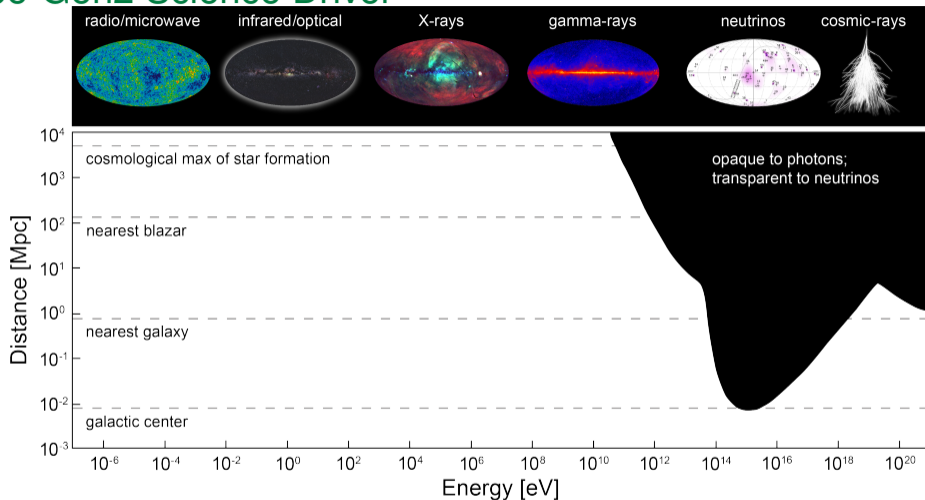
IceCube Gen2 and IceCube Upgrade

Joshua Hignight
for the IceCube-Gen2 Collaboration



November 3rd, 2018

IceCube-Gen2 Science Driver

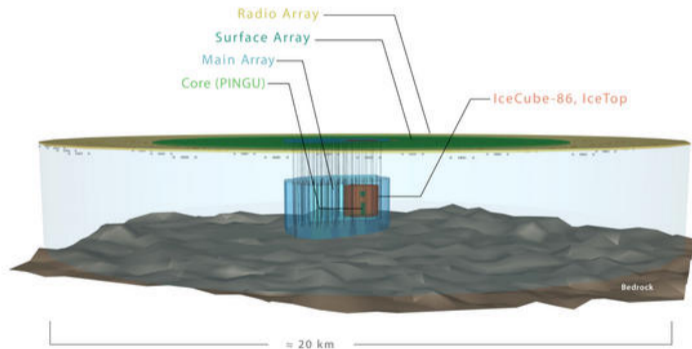


The Universe is opaque to EM radiation at high energies → explore this uncharted territory with IceCube-Gen2

IceCube-Gen2

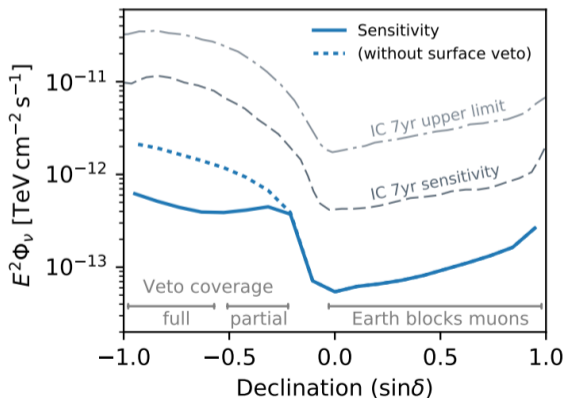
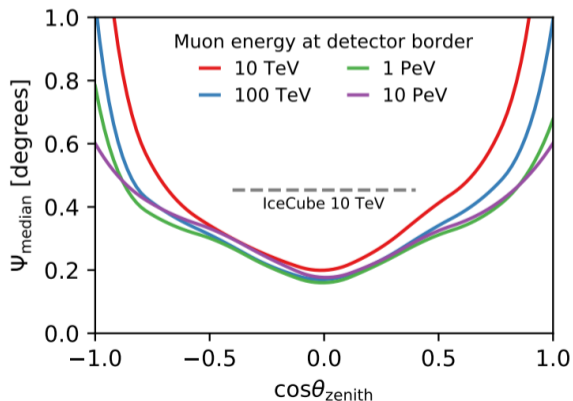
- IceCube-Gen2 is a versatile facility for future South Pole physics
- Radio Array
- Surface Array
- High Energy Array
 - ▶ 120 strings \times 90 sensors/string
 - ▶ $\sim 8 \text{ km}^2$ area with wider string spacing
- PINGU
 - ▶ Low energy infill

The IceCube Gen2 Facility



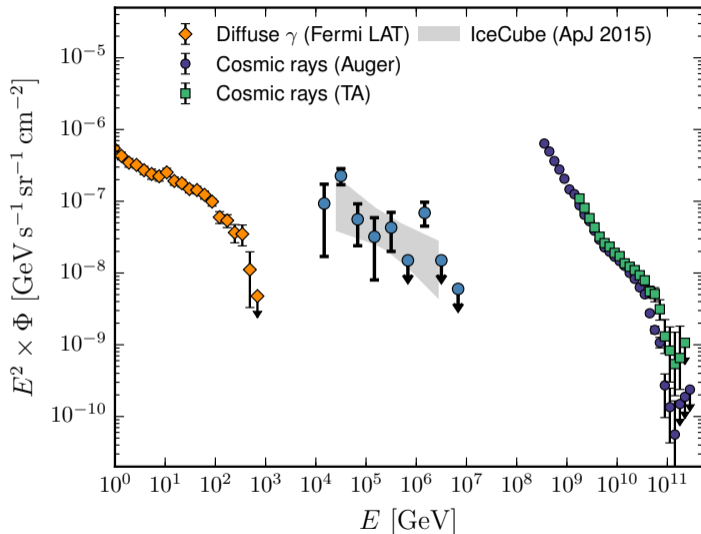
Point Source Sensitivity

- Improved angular resolution
- Order of magnitude better point sensitivity
- Order of magnitude increase in number of TXS0506+056-like flares observable with Gen2



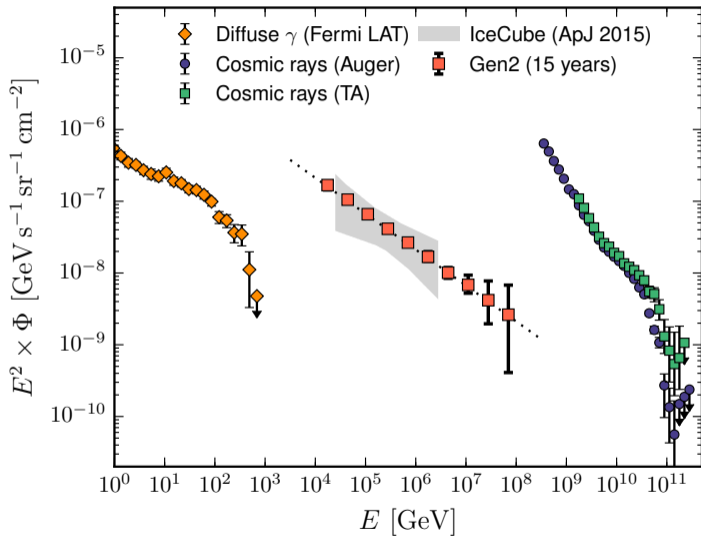
Measuring the EHE Spectrum

- Understand the evolution of the spectral index
 - ▶ Does it soften at low energies?
 - ▶ High energy cut-off?
- Connect the neutrino spectrum to the cosmic ray spectrum



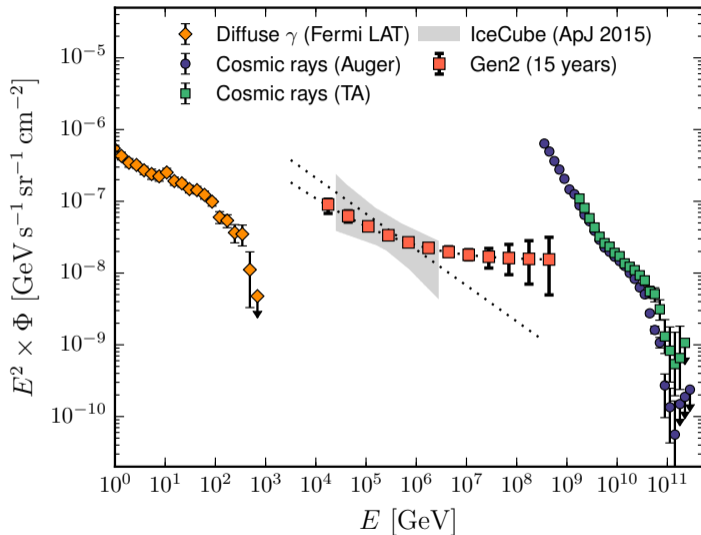
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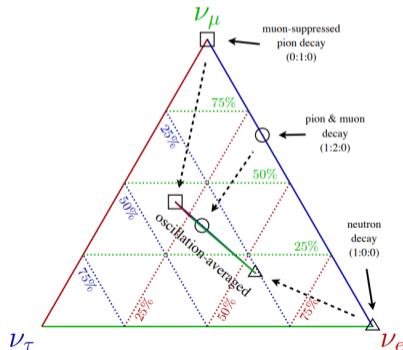
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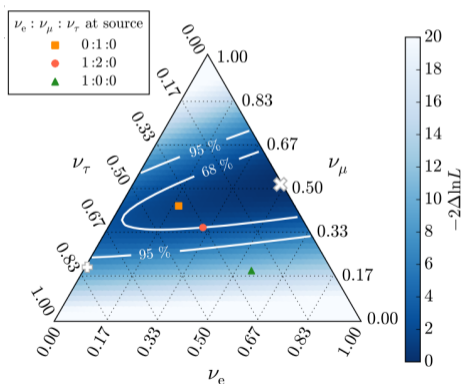
Flavor Ratio

Production Mechanism	$f_e : f_\mu : f_\tau$ at source	$f_e : f_\mu : f_\tau$ at detector
π decay	1 : 2 : 0	0.93 : 1.05 : 1.02
μ cooling	0 : 1 : 0	0.6 : 1.3 : 1.1
n decay	1 : 0 : 0	1.6 : 0.6 : 0.8



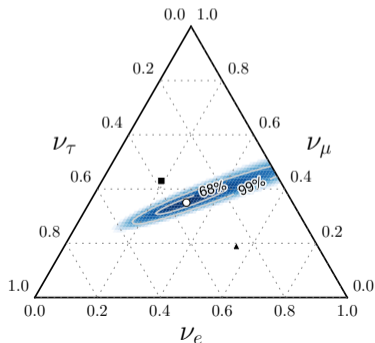
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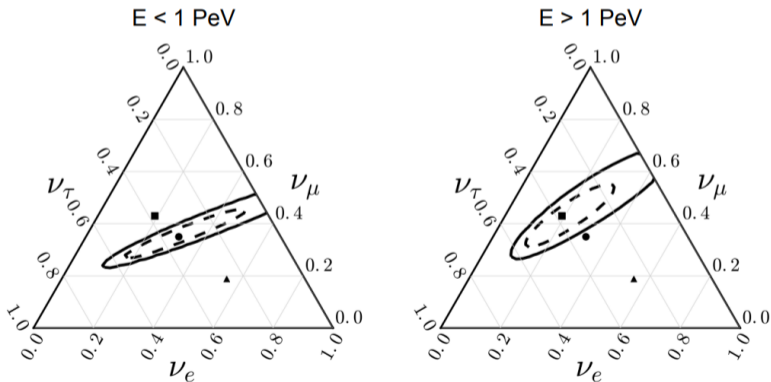
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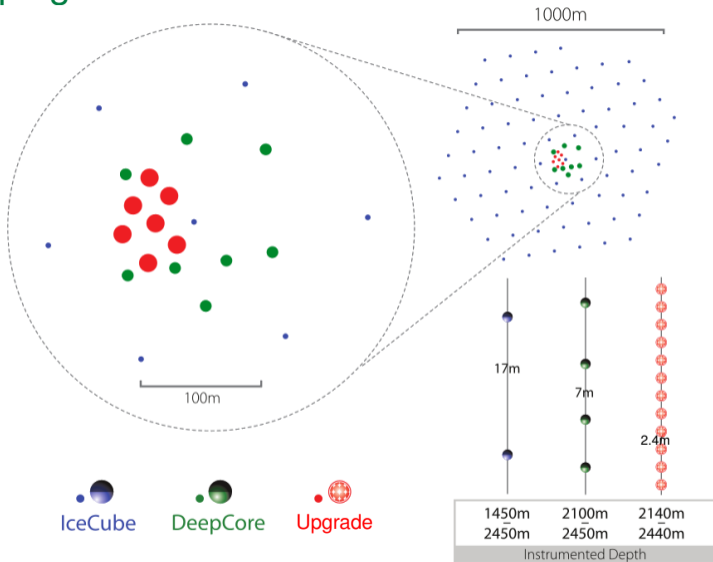
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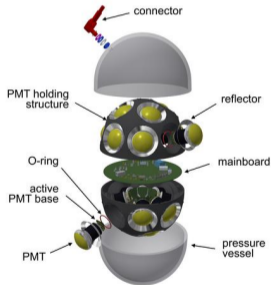
IceCube Upgrade: Stepping Stone to Gen2

- 7 new strings
- ~ 20m spacing between strings
- 125 modules/string
- 2.4m vertical module spacing
- Located inside IceCube-DeepCore

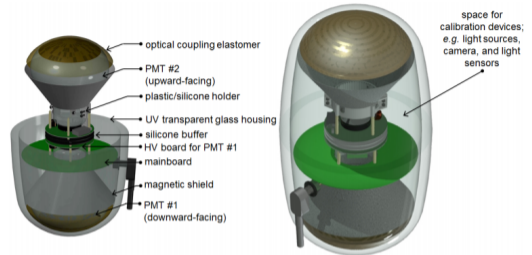


IceCube Upgrade: Modules

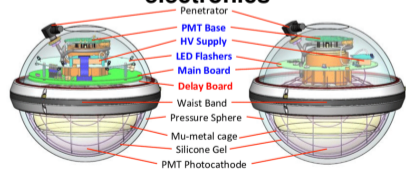
mDOM: 24x3-inch PMTs, better directional coverage



D-EGG: 2x8-inch PMTs, slimmer design, improved UV acceptance



pDOM: IceCube PMT and glass, improved electronics



IceCube
DOM

Gen2
DOM

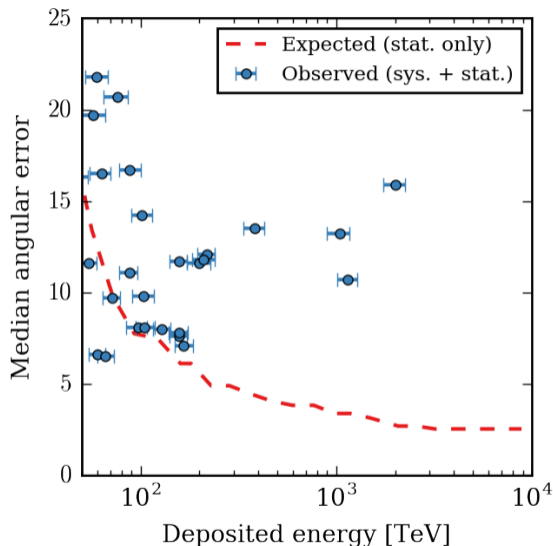
KEY:
 Component identical
 Component eliminated
 Component redesigned

IceCube Upgrade: Calibration

- Reduce primary systematic uncertainties
 - ▶ Better calibration of new and existing sensors
 - ▶ Improved knowledge of glacial ice
- Integrated devices
 - ▶ LED flashers
 - ▶ Acoustic sensors
 - ▶ Optical cameras
- Stand-alone light sources
 - ▶ Precision Optical Calibration Module (POCAM)
 - ▶ ns-pulse LEDs with small opening angle



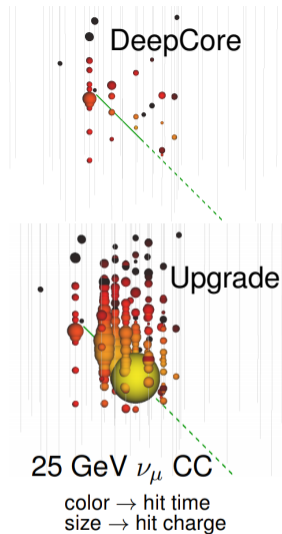
IceCube Upgrade: Calibration



- Will have better angular resolution
 - ▶ Median error not scaling with photon statistics in IceCube
- Will have better Ice modeling systematic uncertainties
 - ▶ Bubble column distorts angular acceptance
 - ▶ Anisotropy of photon scattering and/or absorption lengths in ice
- New calibrations will be applied to the entire accumulated IceCube data set

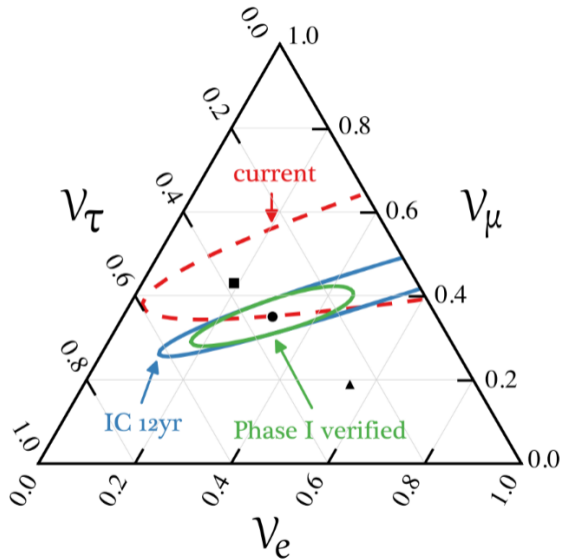
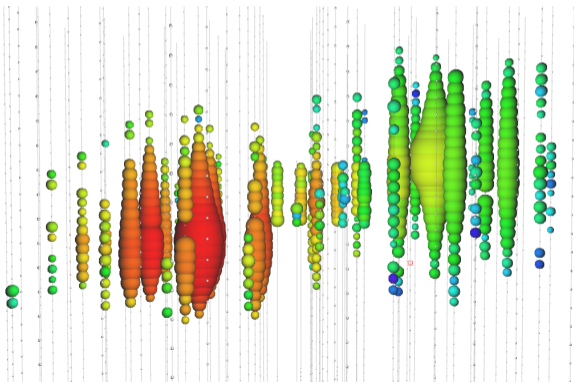
IceCube Upgrade: Science Goals

- Better neutrino astronomy at high energies
 - ▶ Improved angular resolution and veto performance
 - ▶ ν_τ identification
 - ▶ Multi-messenger astronomy
- ν_τ appearance analysis
 - ▶ PMNS unitarity tests
- Precision measurements of $\sin^2(\theta_{23})$ and Δm_{32}^2
 - ▶ Octant/Maximal mixing
 - ▶ Complementary to LBL experiments
- Neutrino mass ordering at $1.5\text{-}2\sigma$ in 3 years
- Improvement on eV sterile ν searches, NSI, solar dark matter searches, and other BSM searches



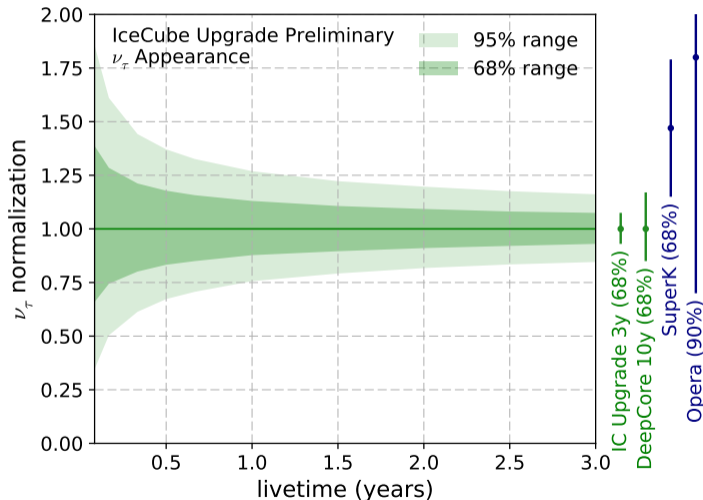
IceCube Upgrade: HE Science

- New calibration devices inside IceCube enhance HE science
- Can simulate tau neutrino “double bang” events with baselines of 20m

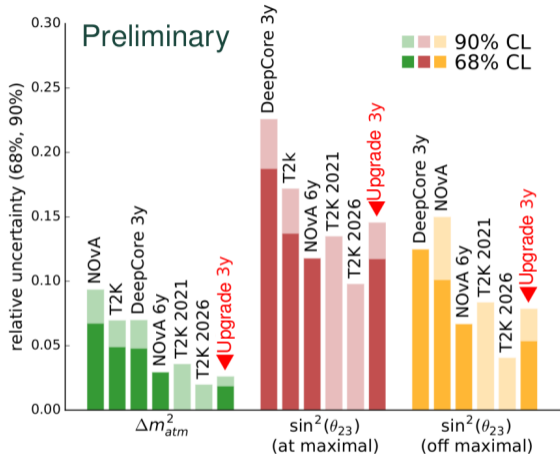


IceCube Upgrade: ν_τ Appearance

- $< 7\%$ precision on the ν_τ normalization after 3 years of data.
- $\sim 10\%$ precision needed for real tests of the unitarity of the PMNS mixing matrix.
- Very few experiments can do this measurement!



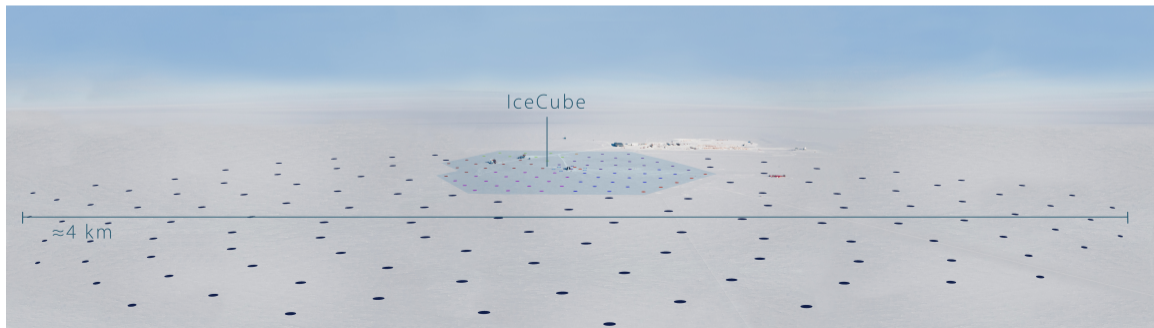
IceCube Upgrade: ν_μ Disappearance



Projected limits on $\sin^2(\theta_{23})$ and Δm_{32}^2 competitive with dedicated LBL experiments.

Conclusion

- IceCube-Gen2 is a versatile facility for future South Pole physics.
 - ▶ Has many components including a radio array and surface array.
 - ▶ Better sensitivity to find more point sources!
 - ▶ Will help us better understand HE neutrinos origin and production mechanism.
- IceCube Upgrade now funded and should be completed by 2023!
 - ▶ Stepping stone towards full IceCube-Gen2 program.
 - ▶ Compelling science case on its own.



The IceCube-Gen2 Collaboration



Funding Agencies

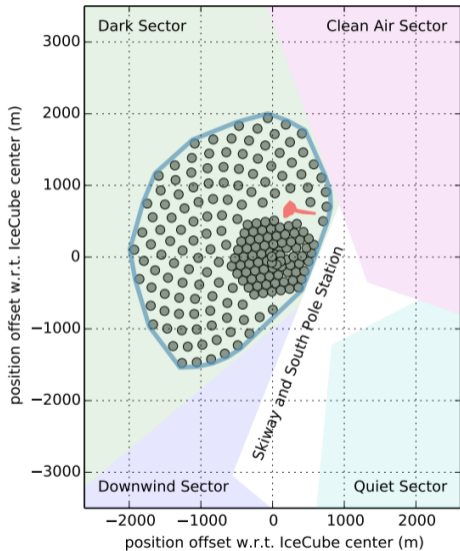
Fonds de la Recherche Scientifique (FRS-FNRS)
 Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
 Federal Ministry of Education & Research (BMBF)
 German Research Foundation (DFG)

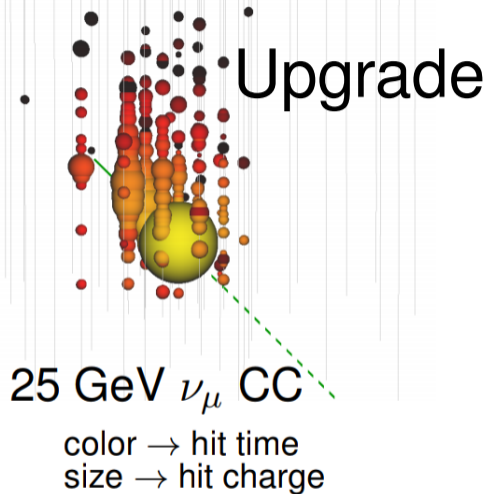
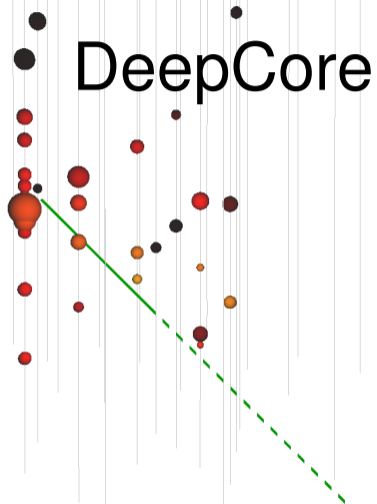
Deutsches Elektronen-Synchrotron (DESY)
 Japan Society for the Promotion of Science (JSPS)
 Knut and Alice Wallenberg Foundation
 Swedish Polar Research Secretariat
 The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
 US National Science Foundation (NSF)

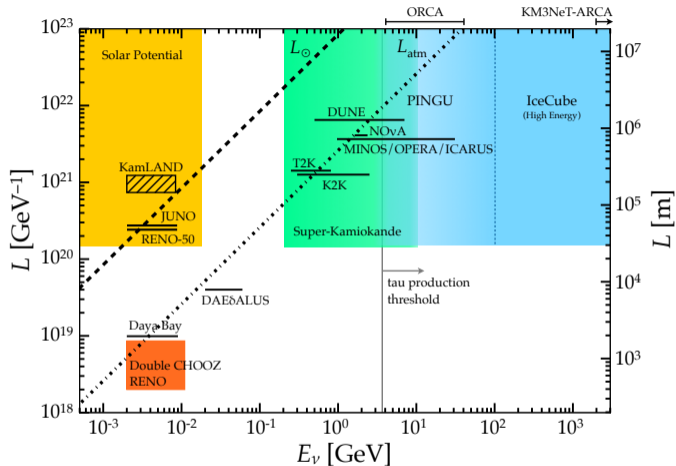
Backup

IceCube Gen2: Sunflower 240m



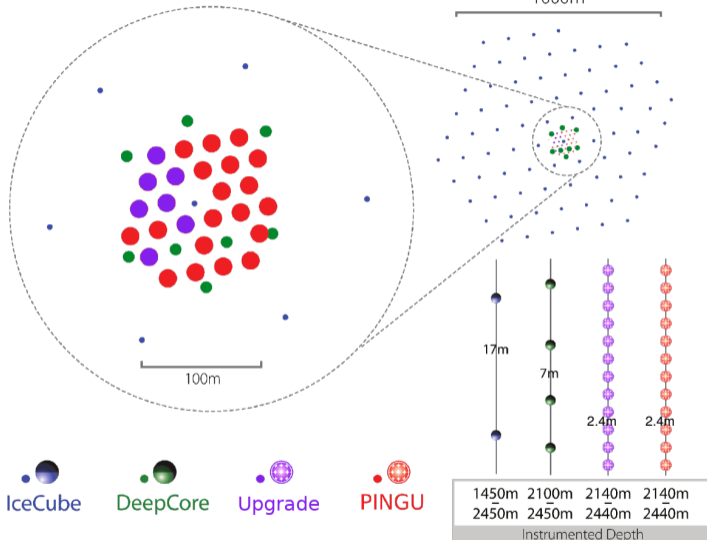
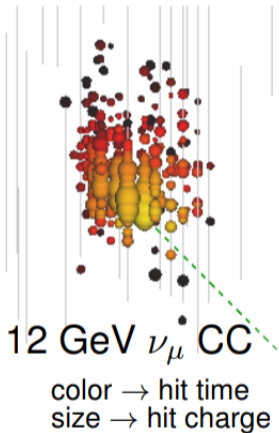


IceCube Upgrade: Oscillation Physics



IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments.

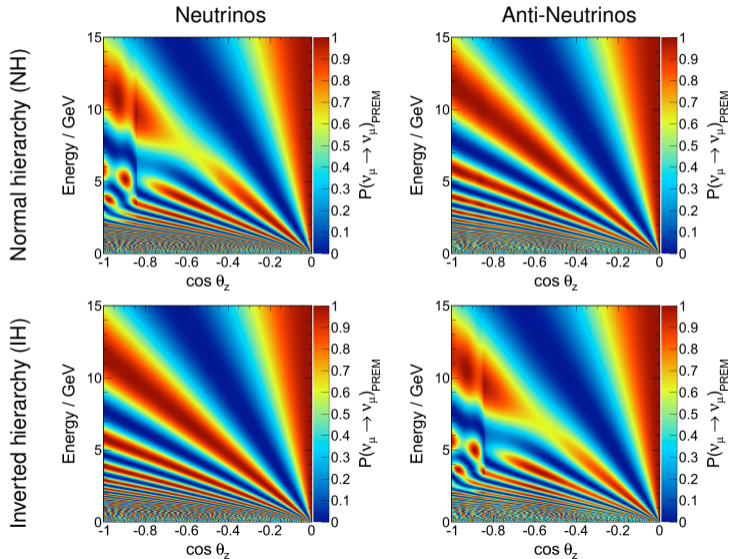
PINGU



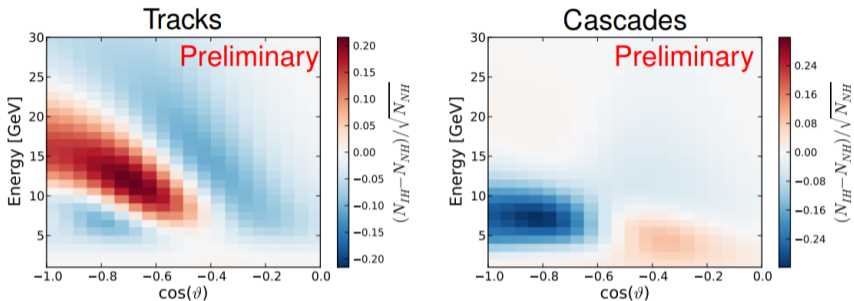
PINGU: Science Goals

- Augmenting the low-energy program of the upgrade.
 - ▶ $\sim 70\text{k}$ up-going atmospheric neutrinos per year
- Neutrino mass ordering
- ν_τ appearance
- $\sin^2(\theta_{23})$ octant sensitivity
- Wide breadth of other science:
 - ▶ Dark matter searches
 - ▶ Earth tomography
 - ▶ SN
 - ▶ ...

PINGU: Neutrino Mass Ordering

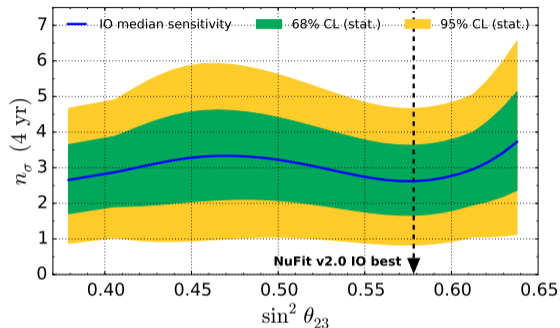
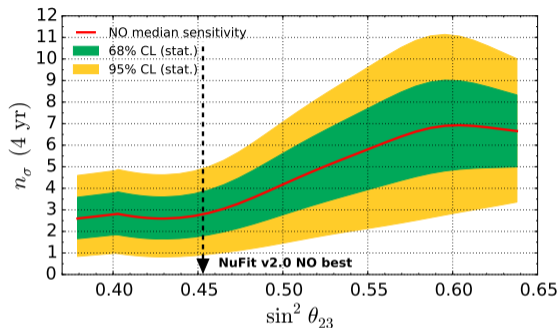


PINGU: Neutrino Mass Ordering



- PINGU cannot differentiate ν and $\bar{\nu}$: rely on difference in flux and cross-section
 - ▶ Large statistical samples: $\sim 33\text{k } \nu_{\mu} + \bar{\nu}_{\mu}$ CC per year, $\sim 25\text{k } \nu_e + \bar{\nu}_e$ CC per year
- Distinct ordering dependent signatures for tracks (mostly ν_{μ} CC) and cascades
 - ▶ Intensity is statistical significance of each bin with 1 year data
 - ▶ Particular expected “distortion pattern” helps mitigate impact of systematics

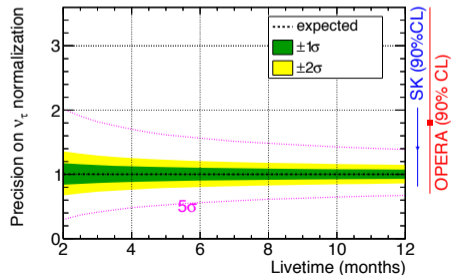
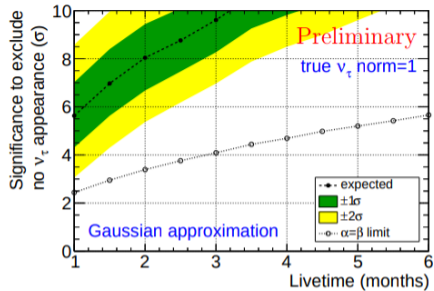
PINGU: Neutrino Mass Ordering



- Sensitivities calculated with 2 different methods (LLR and $\Delta\chi^2$) in agreement
- NMO sensitivity strongly depends on true $\sin^2(\theta_{23})$
- Median sensitivity of $\sim 3\sigma$ with 4 years of data for current best-fit values
 - ▶ Current global best fit close to sensitivity minimum for both orderings!

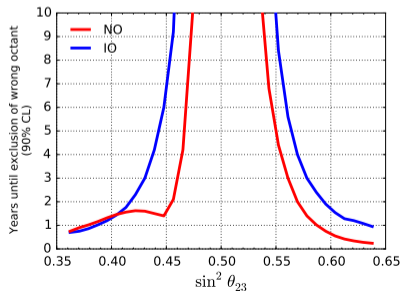
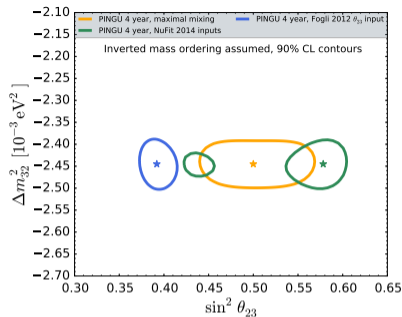
PINGU: ν_τ Appearance

- Expected to reach 5σ exclusion of no ν_τ appearance with a month of data
 - Can even reach 5σ exclusion of no ν_τ appearance within a year if ν_τ normalization is 0.6.
- Can reach Upgrade precision with less than 1 year of data.



PINGU: ν_μ Disappearance

- Precision of $\sin^2(\theta_{32})$ and Δm_{32}^2 measurement is as good as LBL experiments
- 4 year octant sensitivity $\gtrsim 3\sigma$ if:
 - ▶ NO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.62$
 - ▶ IO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.58$



IceCube Upgrade: Sterile Neutrinos

- Higher precision event reconstructions increase sensitivity considerably.
- Upgrade should produce similar improvements in searches for non-standard neutrino interactions (NSI), dark matter, and other BSM physics - under current investigation.

