Detecting the next Galactic SN with IceCube

Carsten Rott

(for the IceCube Collaboration)

Sungkyunkwan University, Korea

rott@skku.edu

Feb 12, 2017

1398

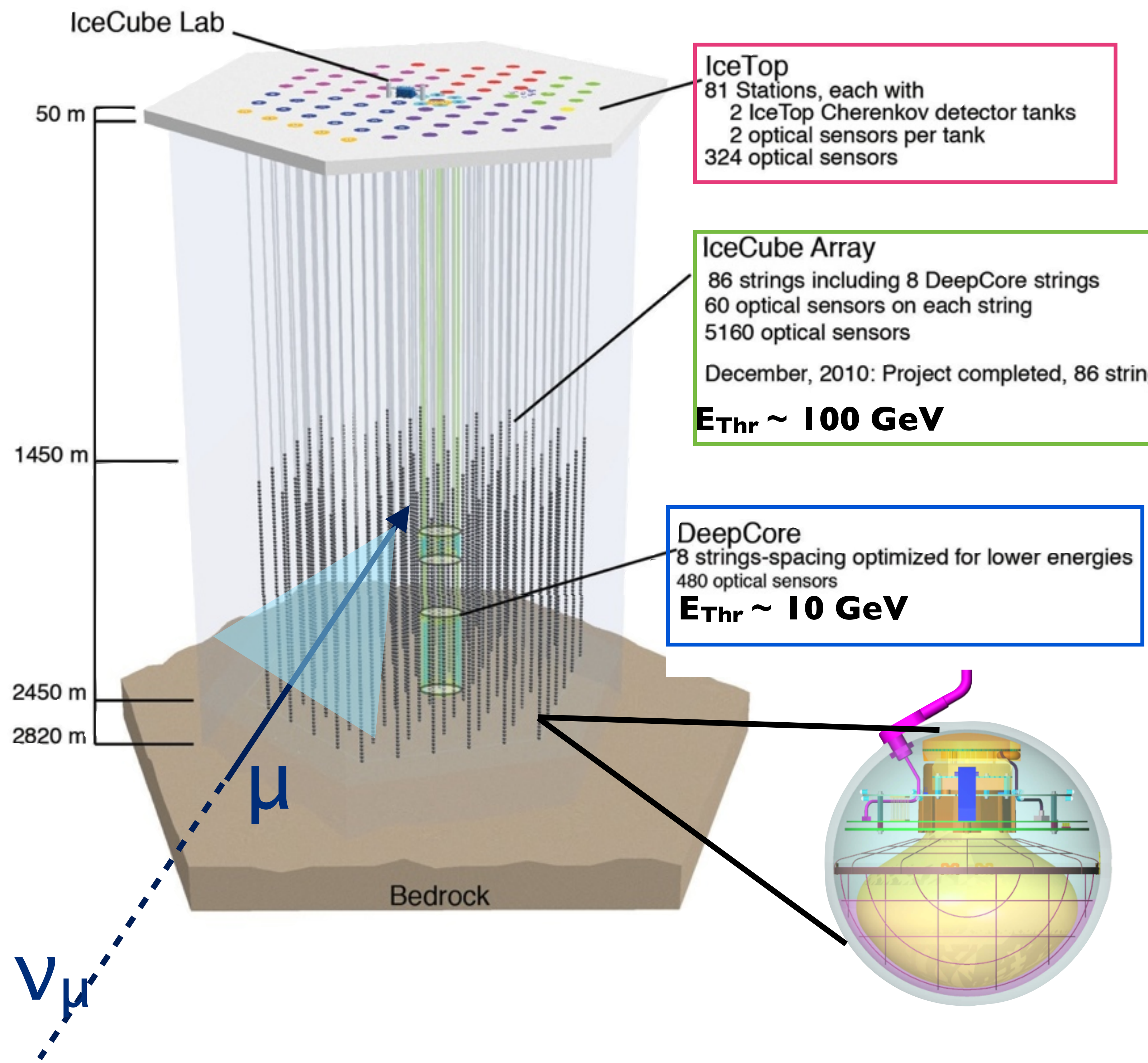
Workshop on Supernova at Hyper-Kamiokande @ University of Tokyo Feb 12 - 13, 2017

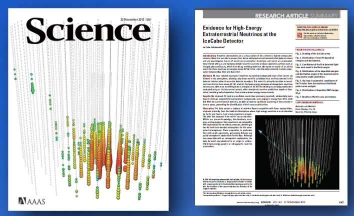
Outline

- The IceCube Neutrino Telescope and Science Highlights
- Supernova Neutrino Detection with IceCube
- IceCube Upgrade Plans
- Supernova sensitivity
- Conclusions

The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules (DOMs) distributed over 86 strings
  - incl. 6 strings with HQE DOMs
- Completed in December 2010, start of data taking with full detector May 2011
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice
- Supernova detection via collective noise rate increase



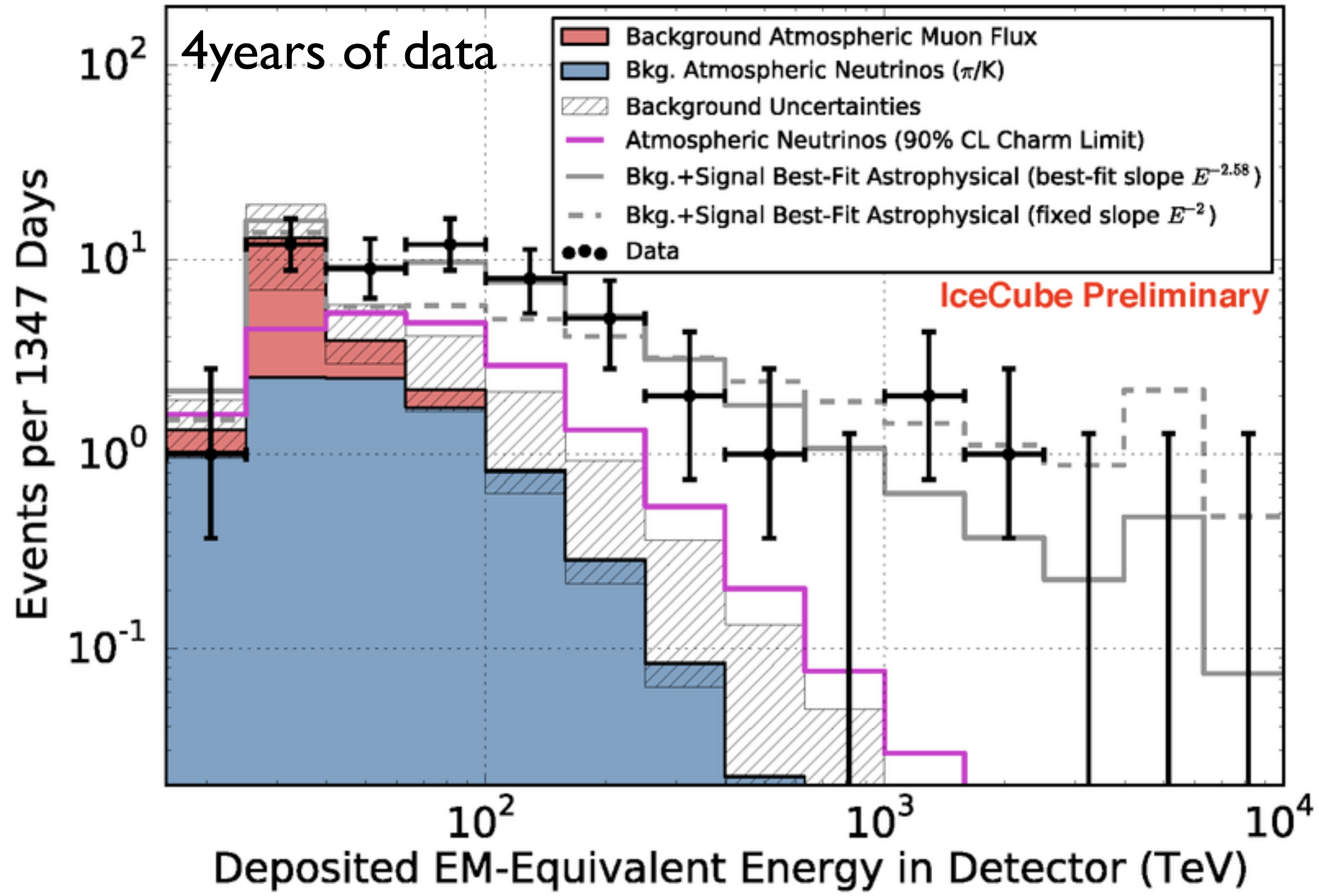


High Energy Astrophysical Neutrinos

High-energy starting events (HESE)

54 events (15 track-like, 39 showers)

Expectation from conventional atm. muons and neutrinos ~21.6

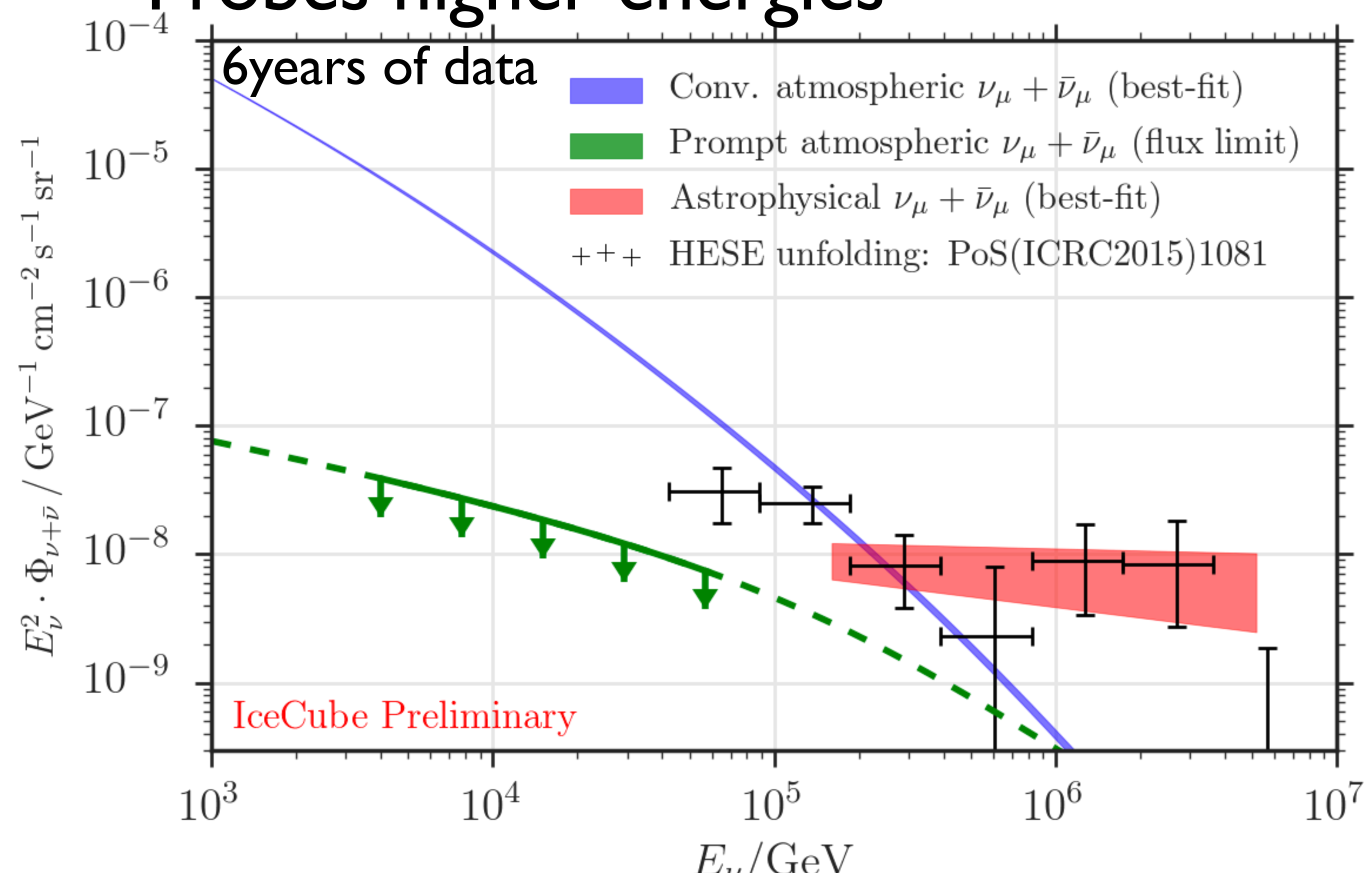


~7 sigma rejection of atmospheric-only hypothesis

ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

Up-going muon neutrino analysis

Incoming tracks →
- Larger effective area,
- Restricted to Northern Sky
- Probes higher energies



Best fit:

$$\Phi_\nu(E) = \Phi_0 \cdot (E/100\ \mathrm{TeV})^{-2.08\pm0.13}$$

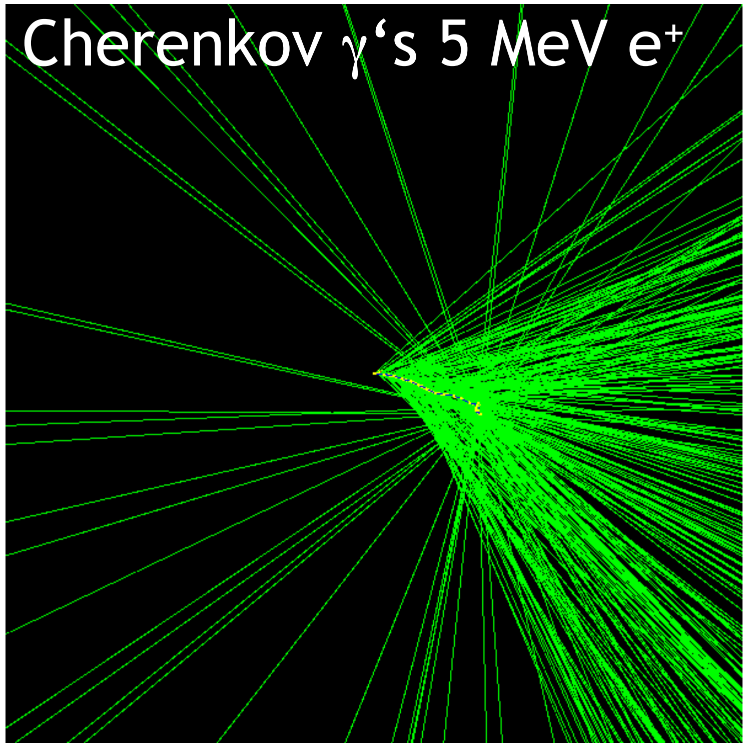
$$\Phi_0 = 0.82^{+0.30}_{-0.26} \times 10^{-18}/\mathrm{GeV/cm^2/s/sr}$$

ICRC2015 / PoS(ICRC2015)1079

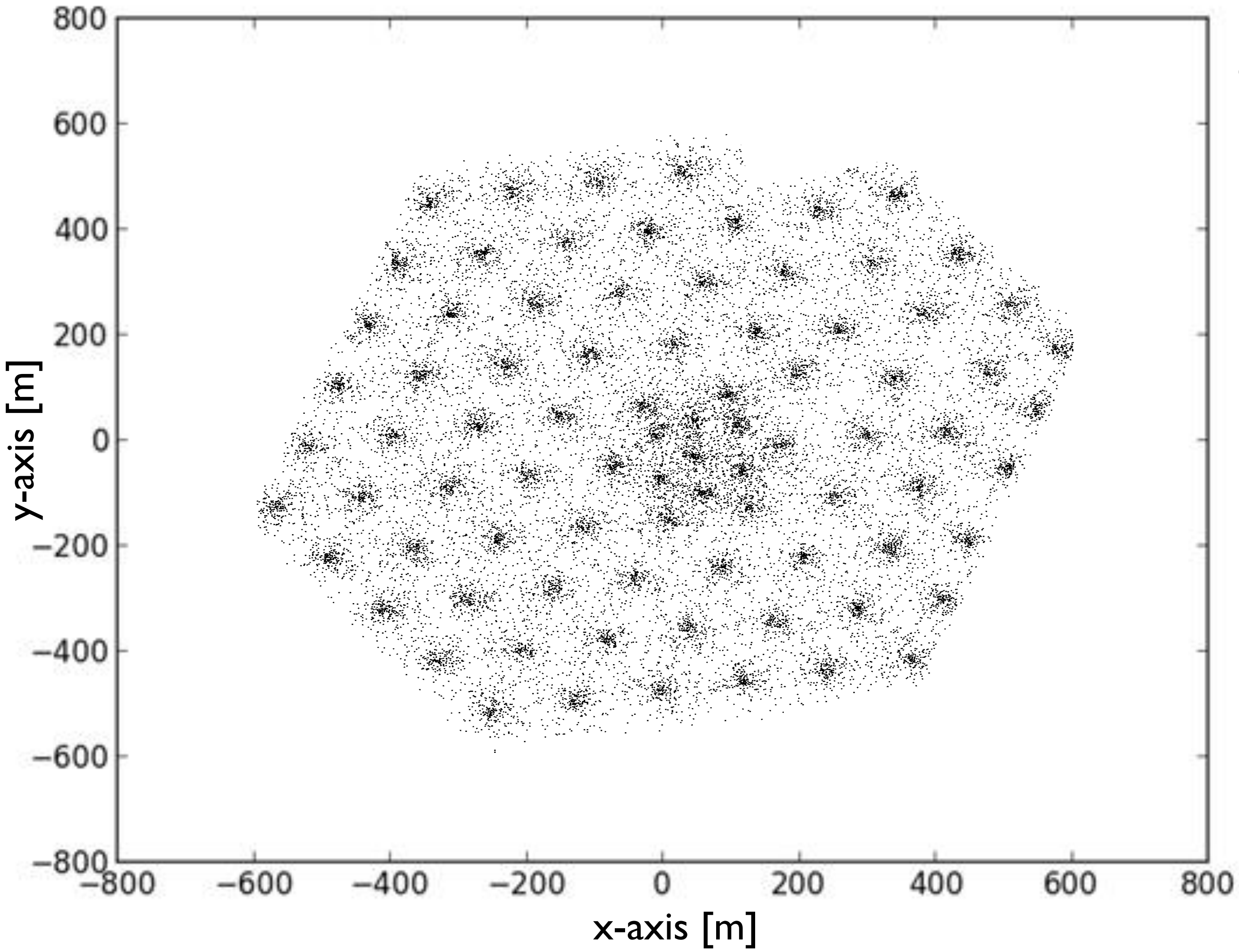
SN Detection in IceCube

Supernova Neutrinos on Ice

- Typical supernova neutrino energy ~ 10MeV and 30MeV
- Detection of Supernova neutrinos via inverse beta decay
  - Positrons produces Cherenkov light along a short track (roughly 0.6 cm/MeV and 325 photons/cm)
  - Individual neutrinos cannot be reconstructed

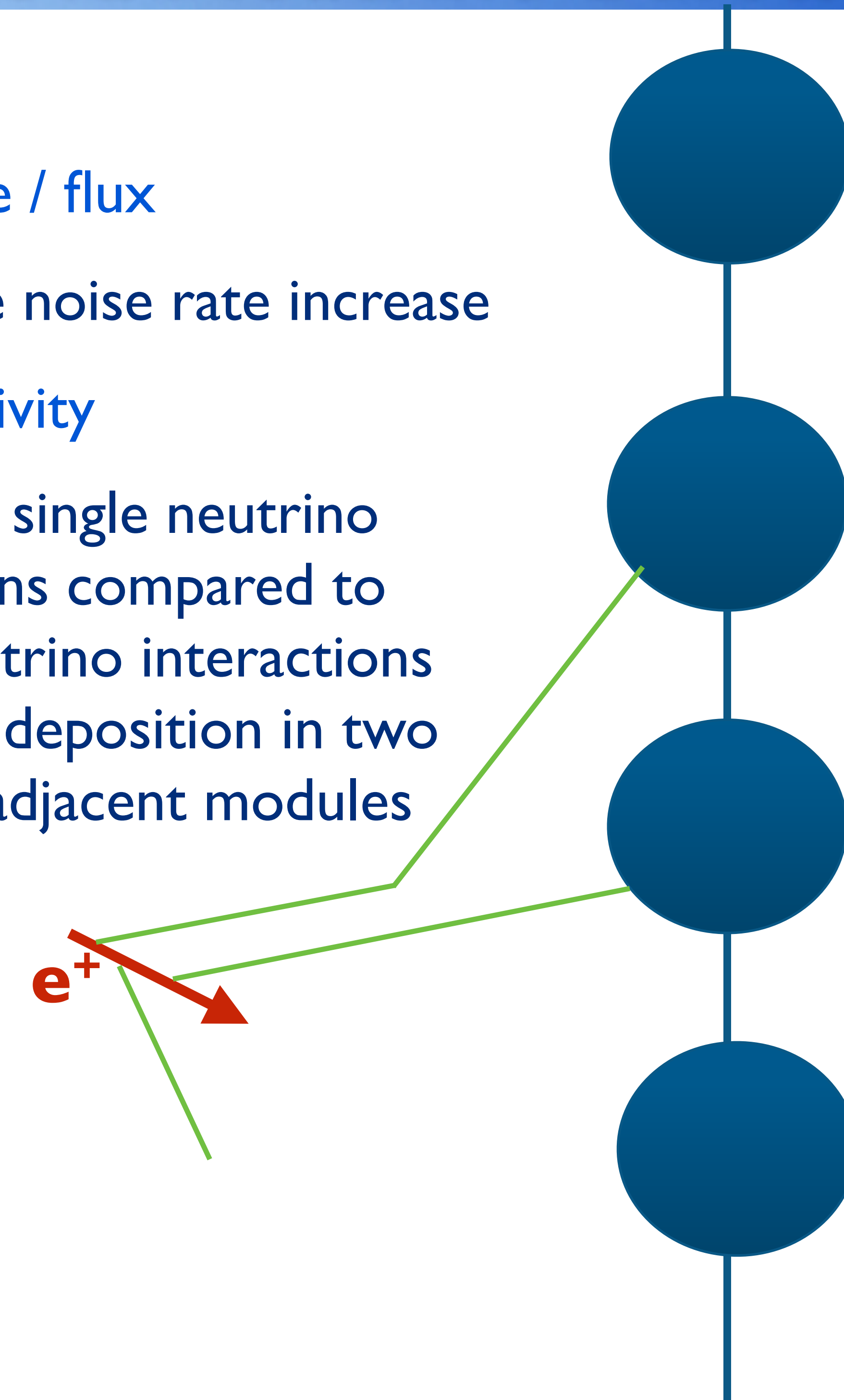


IceCube Sensitivity to Supernova Neutrino Bursts



Two methods:

- Timing profile / flux
  - Collective noise rate increase
- Energy sensitivity
  - Rate with single neutrino interactions compared to single neutrino interactions with light deposition in two or more adjacent modules

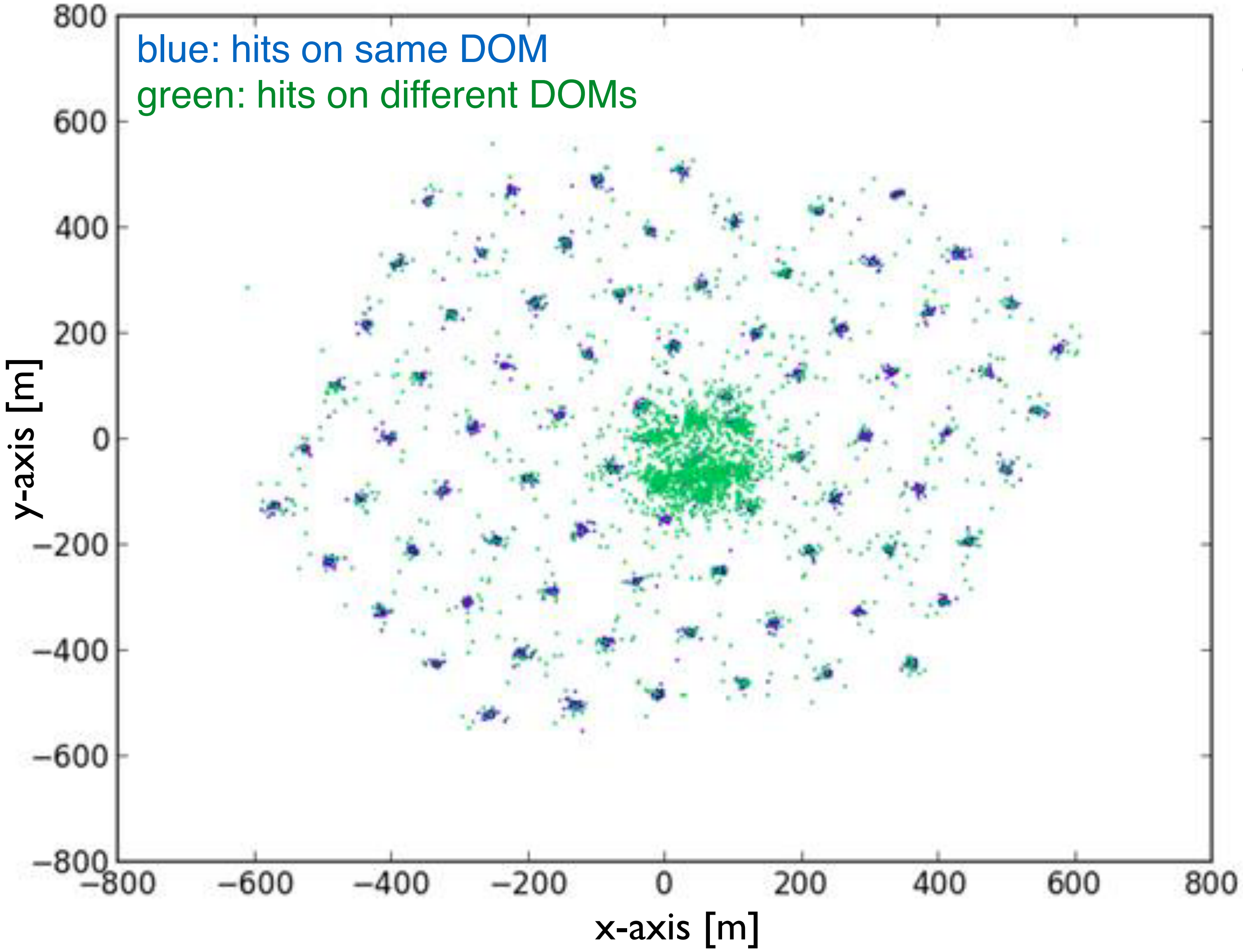


Detector	single hit	nearest neighbor	triple coincidence
IceCube	583 m^3	0.6 m^3	0.0002 m^3
DeepCore	767 m^3	2.7 m^3	0.03 m^3
PINGU (20 × 60)	912 m^3	4.4 m^3	0.11 m^3

SN burst effective volume

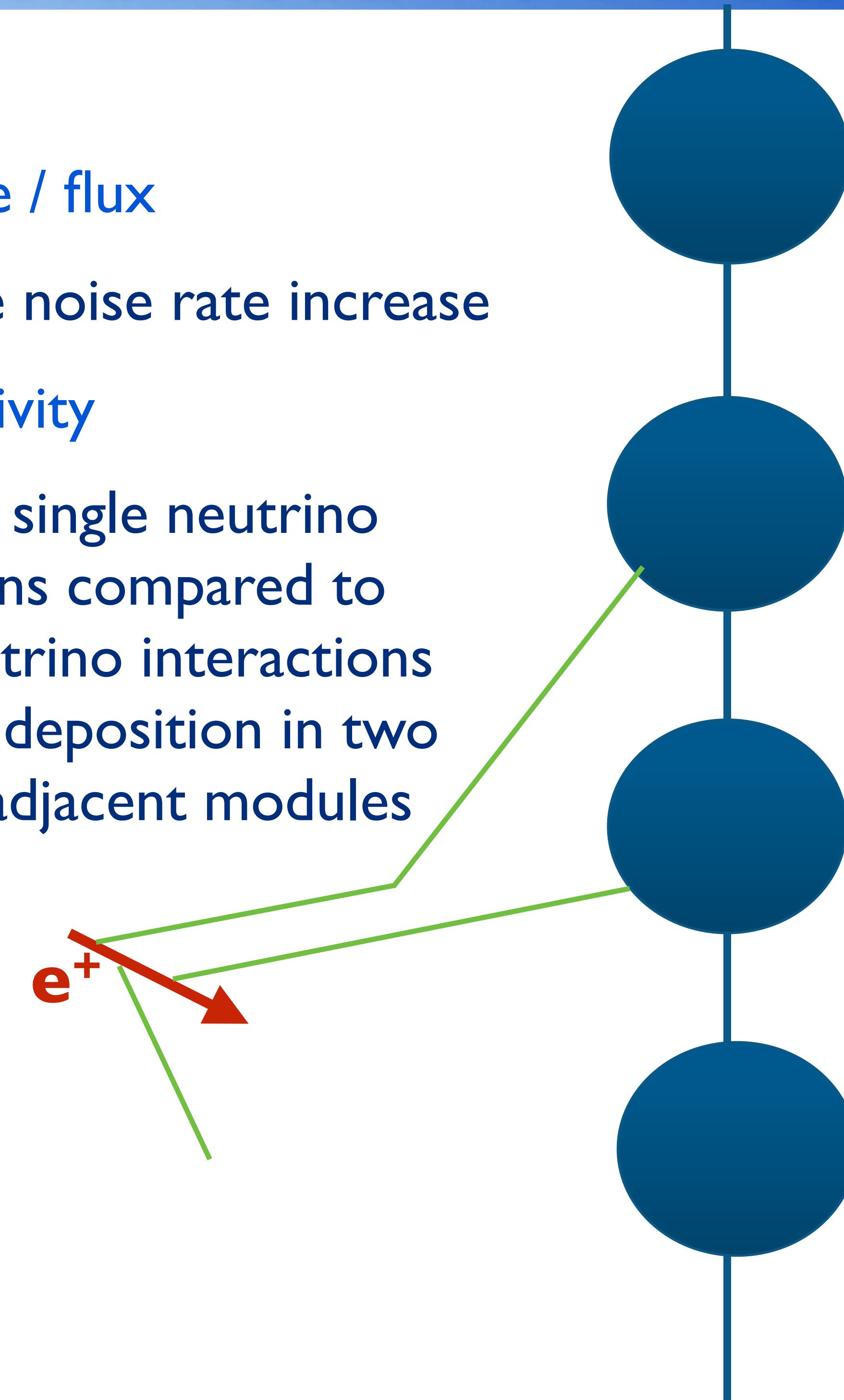
$V_{eff}\ (e^+) = N_{detected}\ /\ n(e^+)$

IceCube Sensitivity to Supernova Neutrino Bursts



<u>Two methods:</u>

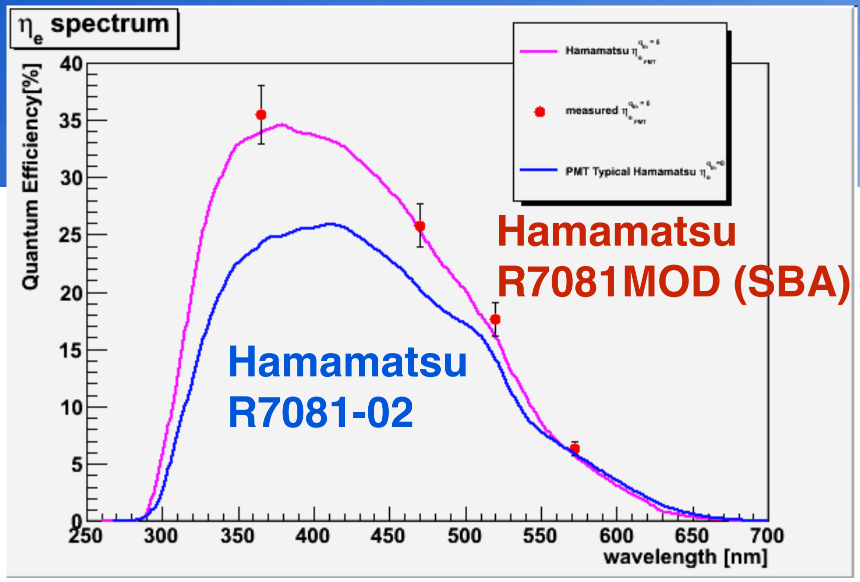
- Timing profile / flux
  - Collective noise rate increase
- Energy sensitivity
  - Rate with single neutrino interactions compared to single neutrino interactions with light deposition in two or more adjacent modules



Detector	single hit	nearest neighbor	triple coincidence
IceCube	583 m^3	0.6 m^3	0.0002 m^3
DeepCore	767 m^3	2.7 m^3	0.03 m^3
PINGU (20×60)	912 m^3	4.4 m^3	0.11 m^3

SN burst effective volume
$V_{eff}(e^+) = N_{detected} / n(e^+)$

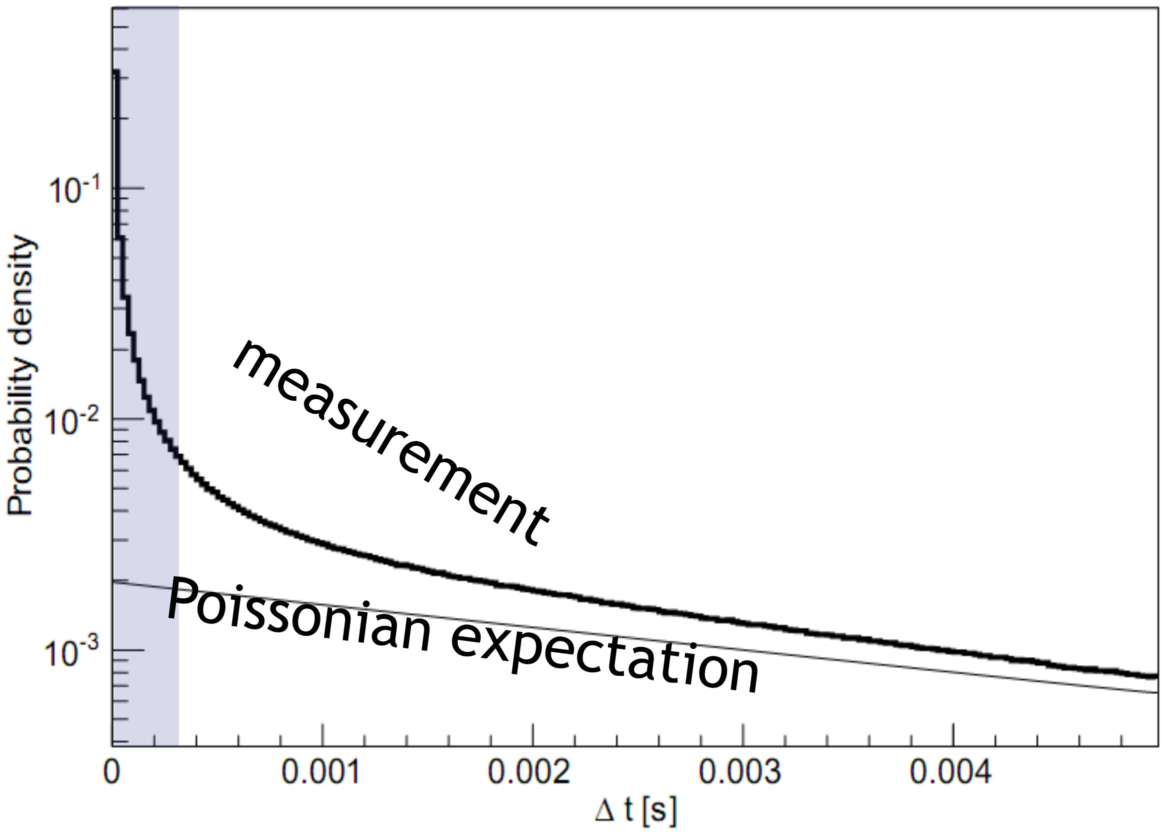
IceCube background noise



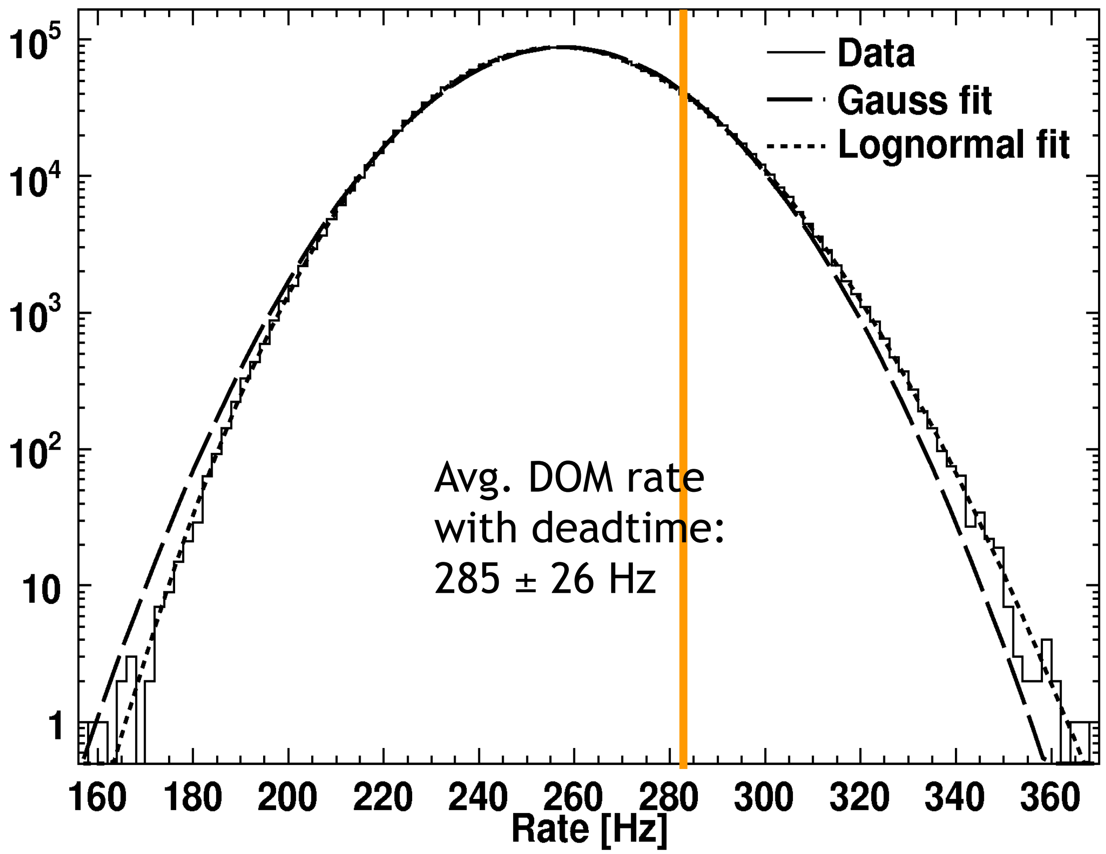
Standard DOMs (4800): 540 Hz
High quantum efficiency DOMs (360): 680 Hz

very stable rates, slight depth (-45C° → -17C°) dependence

time difference between pulses



single DOM rate distribution

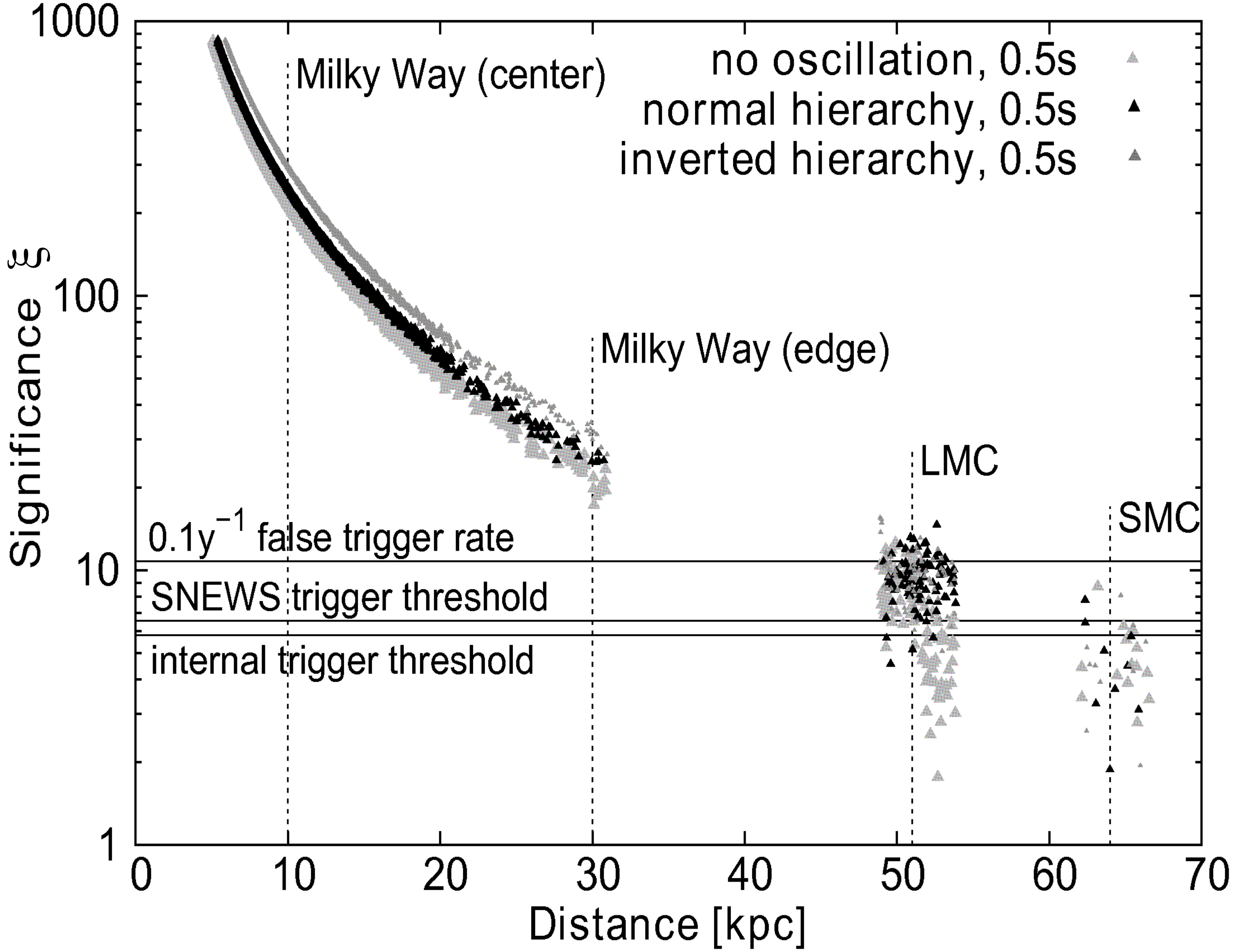


application of artificial deadtime (250 μs) to reduce correlated noise …

IceCube SN DAQ System

- The rate of each DOM is buffered in 1.6384ms bins and transferred to the IceCube Supernova DAQ (SNDAQ) system
- Data is synchronized and regrouped in 2ms bins for processing
- For satellite bandwidth constrains data are rebinned in 0.5s intervals, however if a SN trigger is issued data is kept in 2ms bins for a period of [-30s,60s]
- SNEWS alert time delay ~6min

Expected significance



Expected Significance ξ
ξ > 25 in the Milky Way
ξ ~ 3-10 in Magellanic clouds

$$\xi = \Delta\mu / \sigma_{\Delta\mu}$$

$$\Delta\mu = \sigma^2_{\Delta\mu} \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i \left(r_i - \mu_i\right)}{\sigma_i^2} \quad ,$$

$$\sigma^2_{\Delta\mu} = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\sigma_i^2} \right)^{-1} \quad .$$

±5minutes of background window to determine σ_i and μ_i

IceCube SN operations and improvements

- Fast analysis 2ms bins
  - close to real time analysis
- Cosmic ray muon subtraction
  - Lower trigger threshhold , reduced seasonal effects
- Bayesian Blocks - Data divided into piecewise constant bins with "changepoints" IDing changes in rate
  - Maximize sensitivity to unexpected transients
    - Details: J.D. Scargle et al., ApJ 764:167, 2013, arXiv:1207.5578
- Since 2015
  - stop-less runs
    - SN DAQ up-time increased to ~99.7%
  - Hitspooling
    - Buffering of all DOM hit data

SNDAQ hitspooling data

Hitspooling

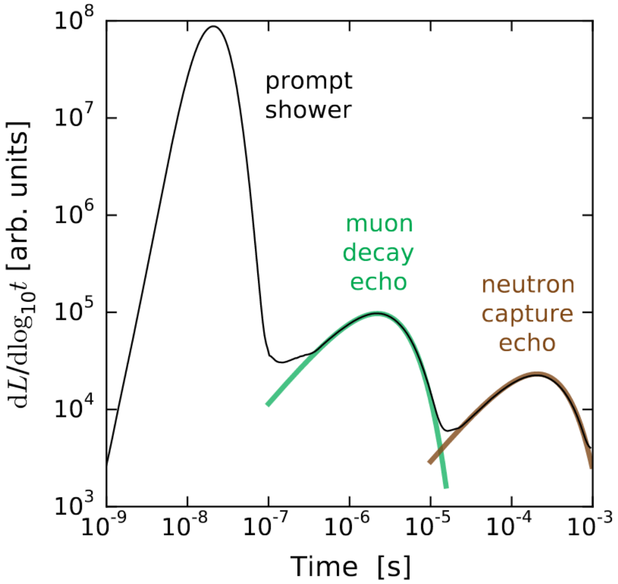
- Retrieval of all buffered hits for adjustable time span
  - Automatic data transfer (90s) and analysis
  - Up to 10minutes of hitspool data buffered and transferred depending on the significance of the alert
- Advantages of hitspooling for SN Search:
  - precision burst onset time
  - fine temporal structures
  - coincidences between modules
  - cosmic ray muon identification
  - burst dependent artificial deadtime optimization

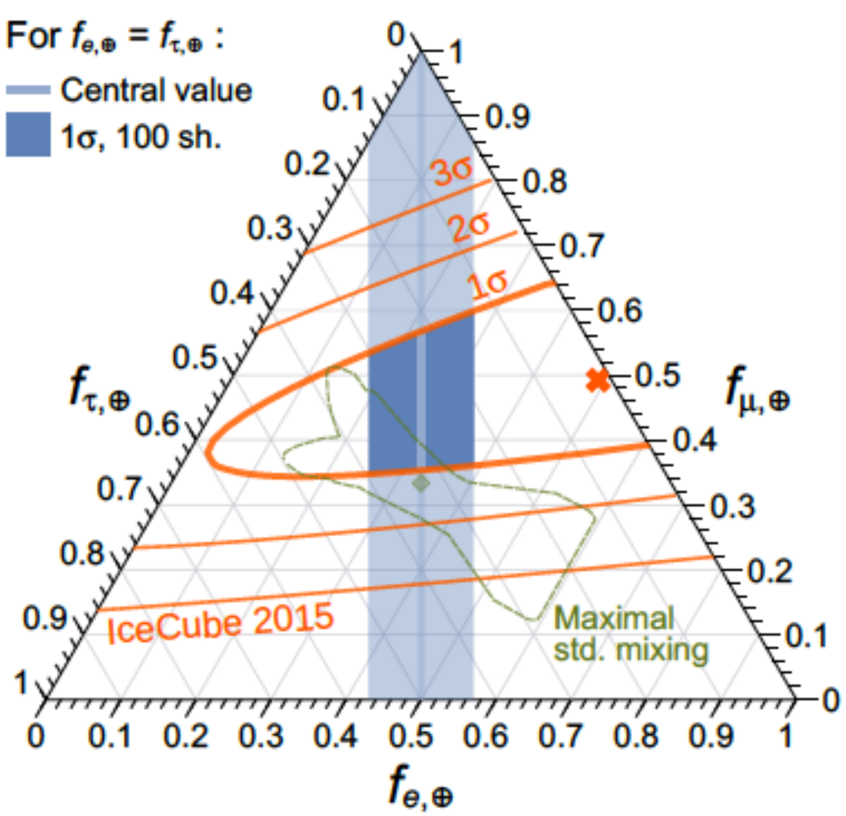
Applications of hitspooling goes beyond SN detection: HESE (1s), Solar flares (1h), Gravitational waves (~10m), …

Hitspool data uses

"Echo Technique"

Li, Bustamante, Beacom (2016)



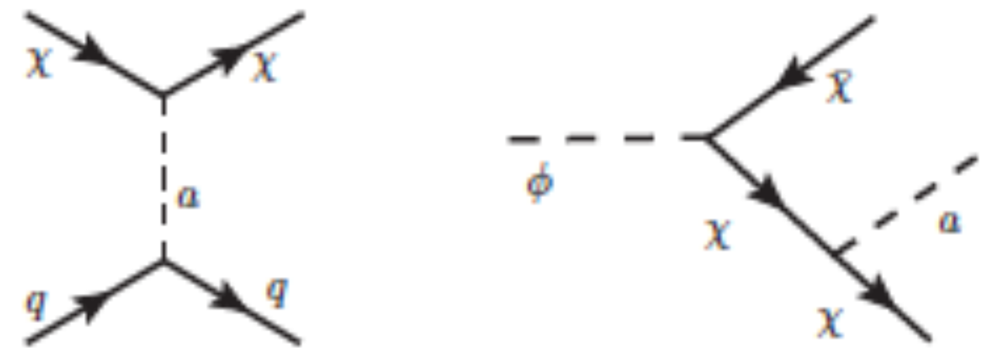


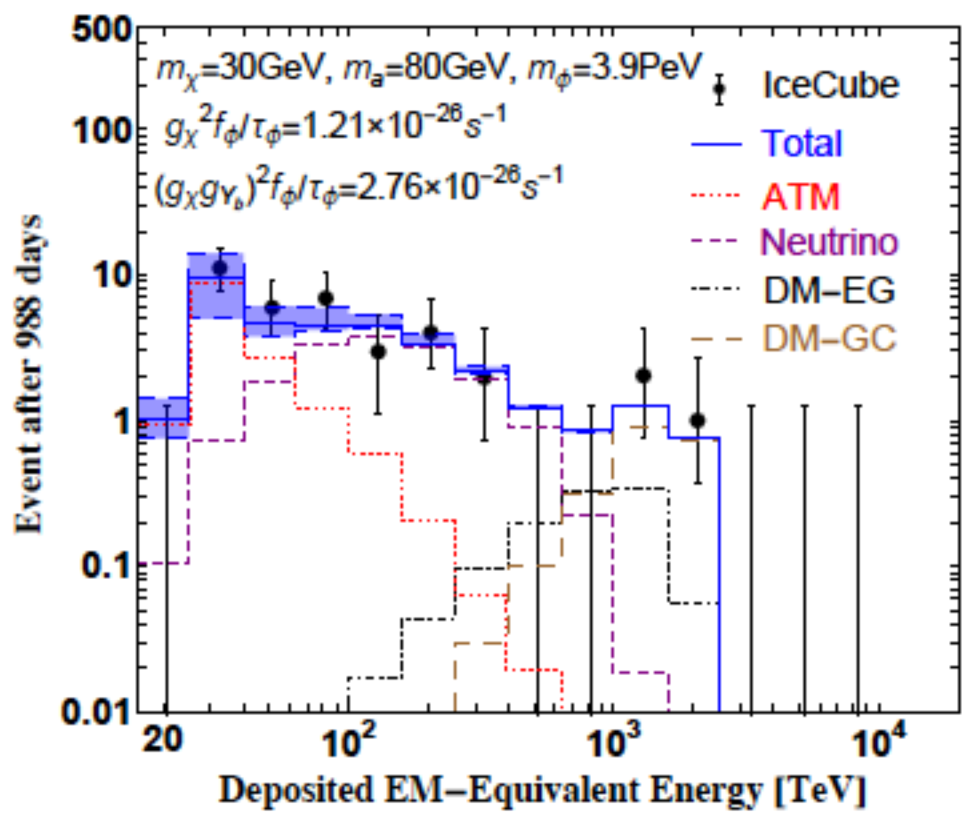
"Boosted Dark Matter Search"

Kopp, Liu, Wan (2015)

scattering of light DM particle χ on nucleons (hadronic cascade)

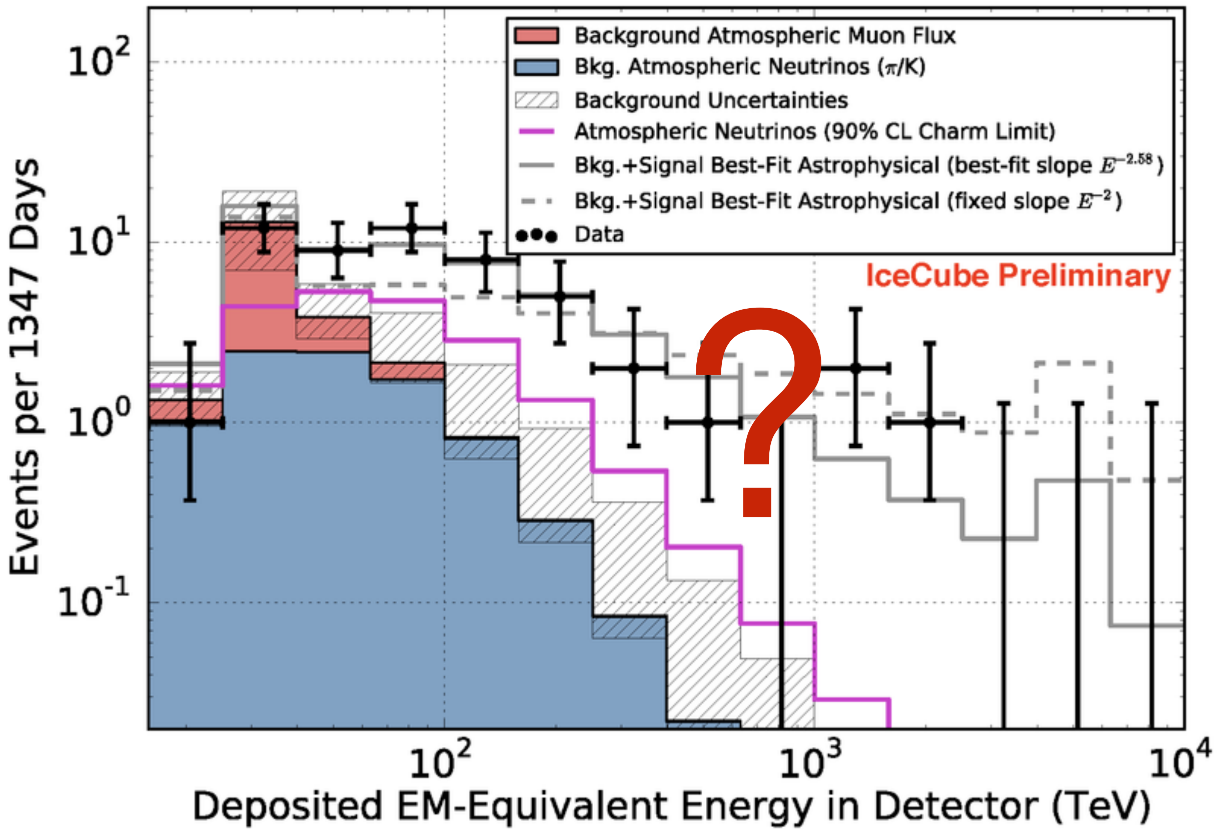
3-body decay φ→χχa additional neutrino flux from a decays (a→bb,…)



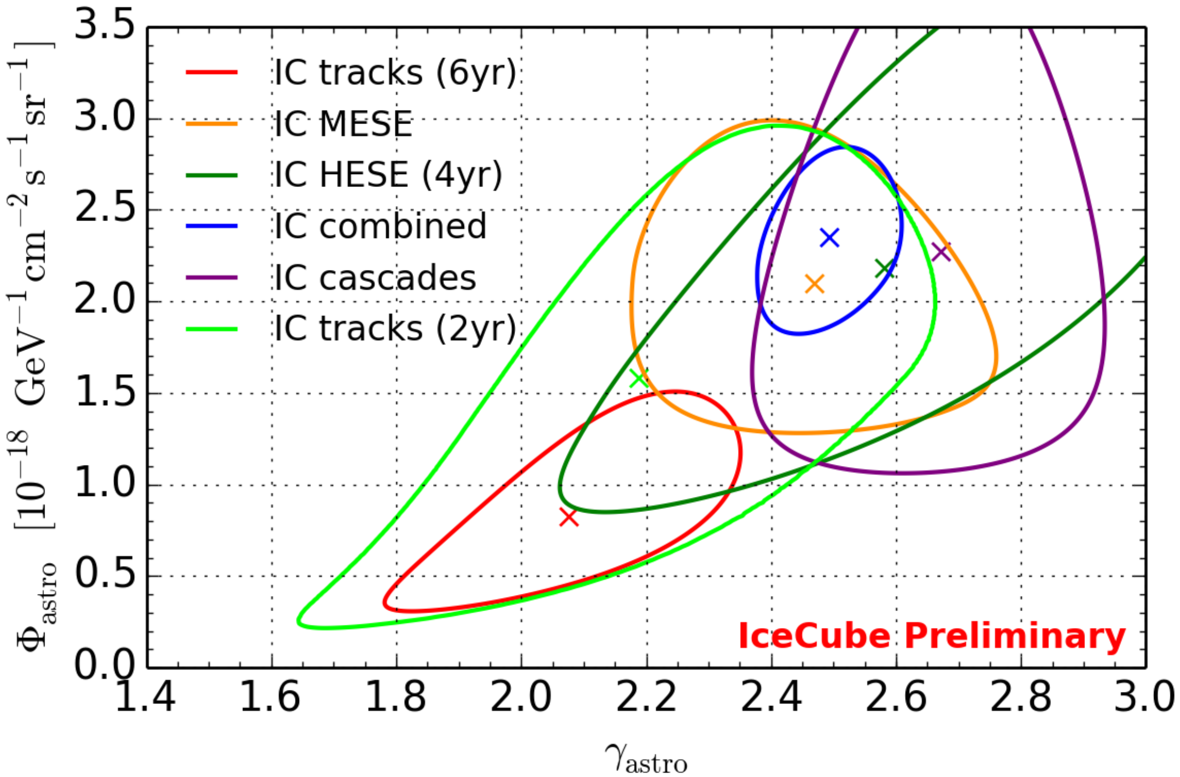


IceCube Upgrades

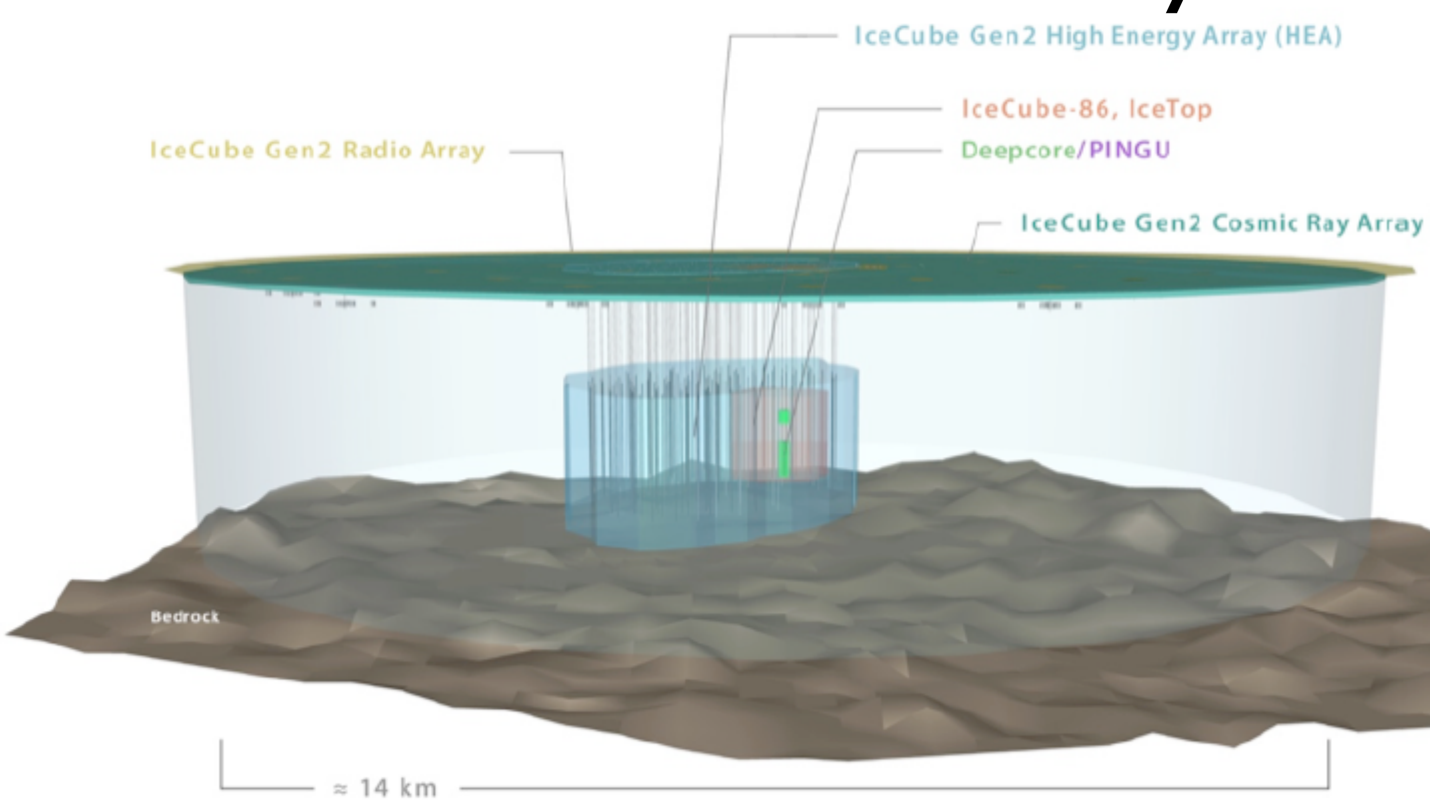
The case for Gen2



- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?



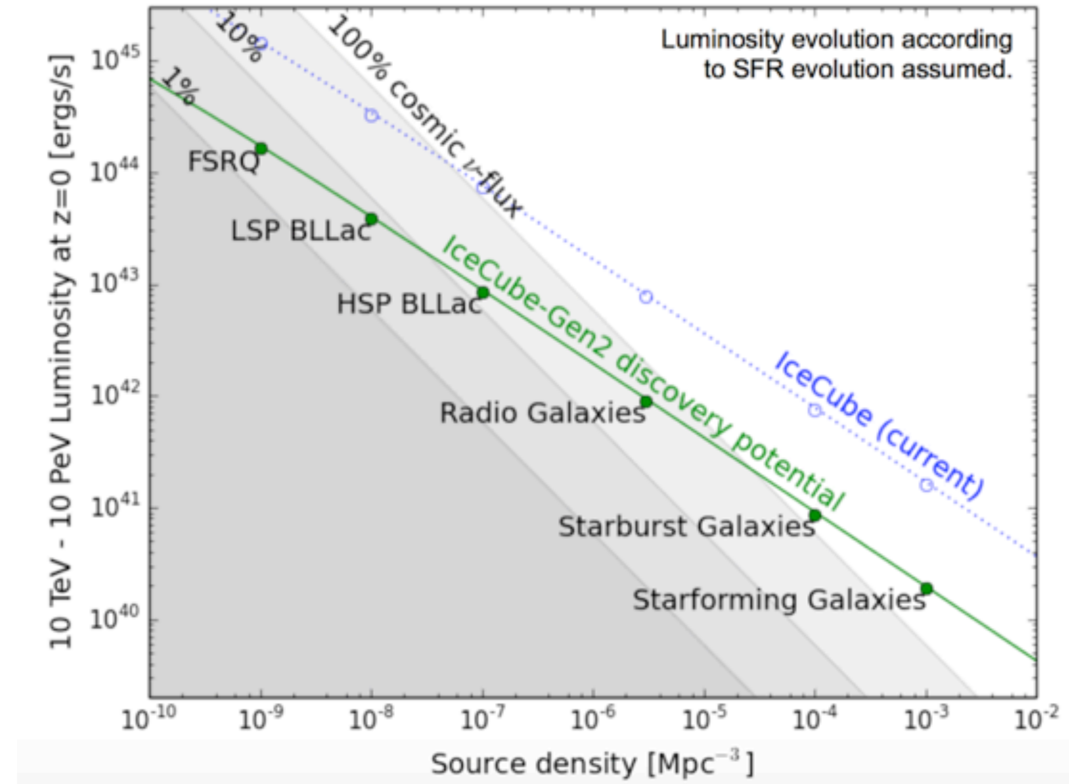
IceCube Gen2 Facility

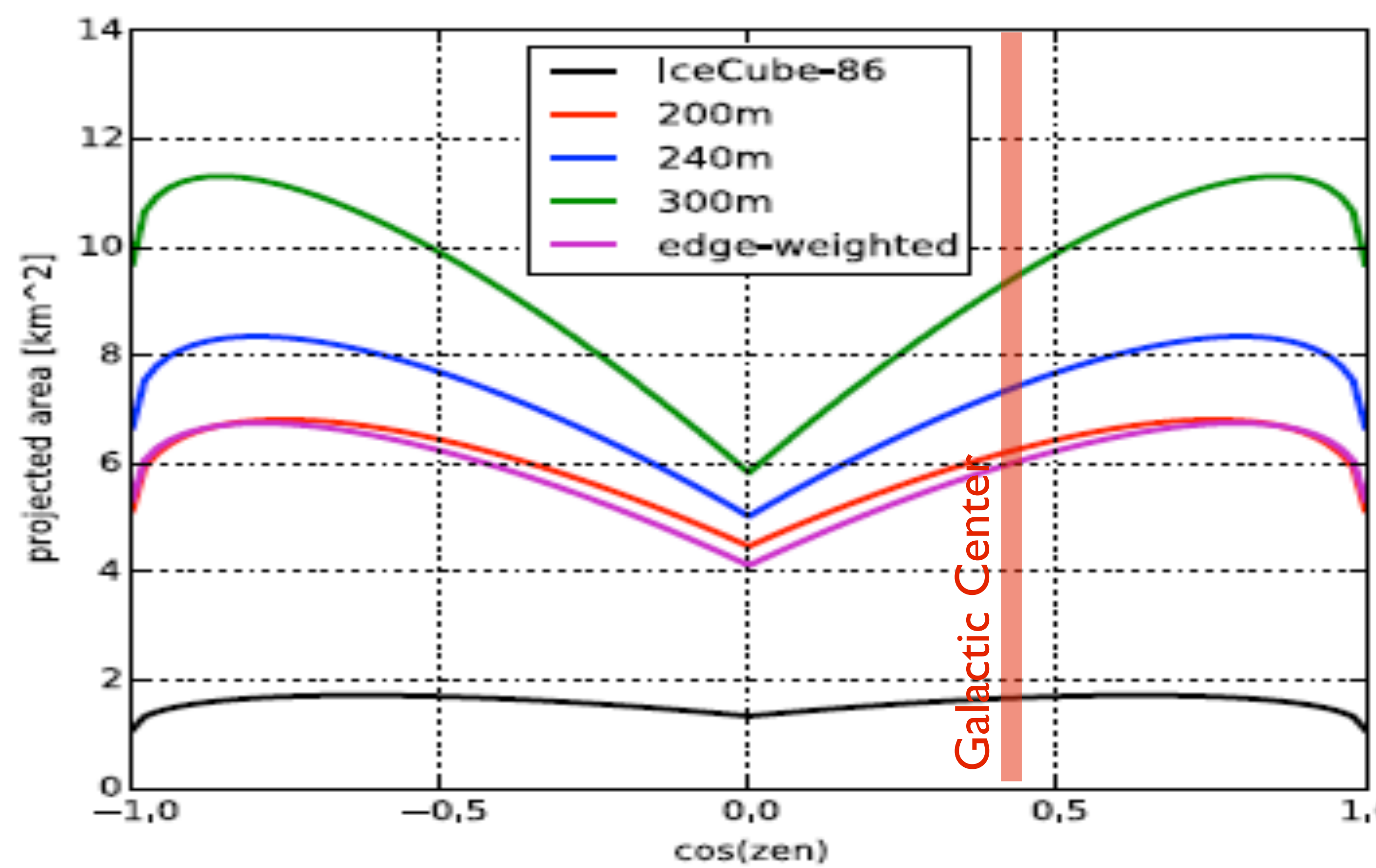


Next generation - IceCube Gen2 Facility

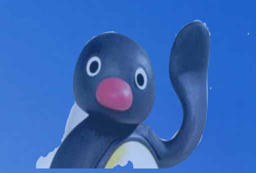
IceCube Gen2 arXiv:1412.5106

- IceCube has provided an amazing sample of events, but is still limited by the small number of events
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
  - So far non of the analyses has shown any evidence for point sources
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- ....





PINGU - Precision IceCube Next Generation Upgrade - First phase of "Gen2"

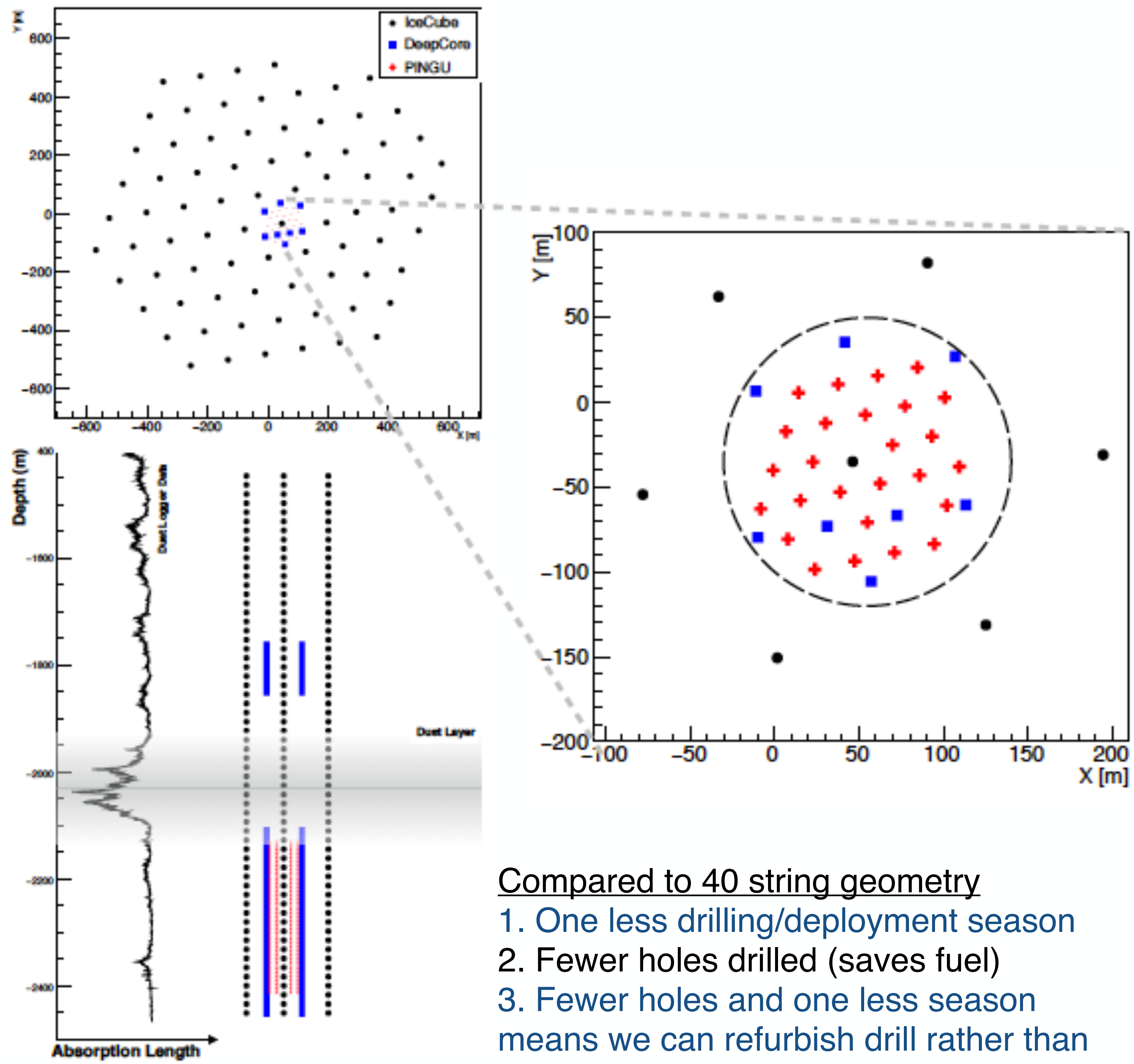


- PINGU upgrade plan
  - Instrument a volume of about 5MT with 20-26 strings
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, …)
    - Unitarity of the PMNS Matrix with first few strings
  - Test low mass dark matter models

PINGU LOI to be updated shortly

Short version https://arxiv.org/pdf/1607.02671.pdf

New PINGU Geometry



Compared to 40 string geometry
1. One less drilling/deployment season
2. Fewer holes drilled (saves fuel)
3. Fewer holes and one less season means we can refurbish drill rather than build a new one.

IceCube-Gen2 Phase 1

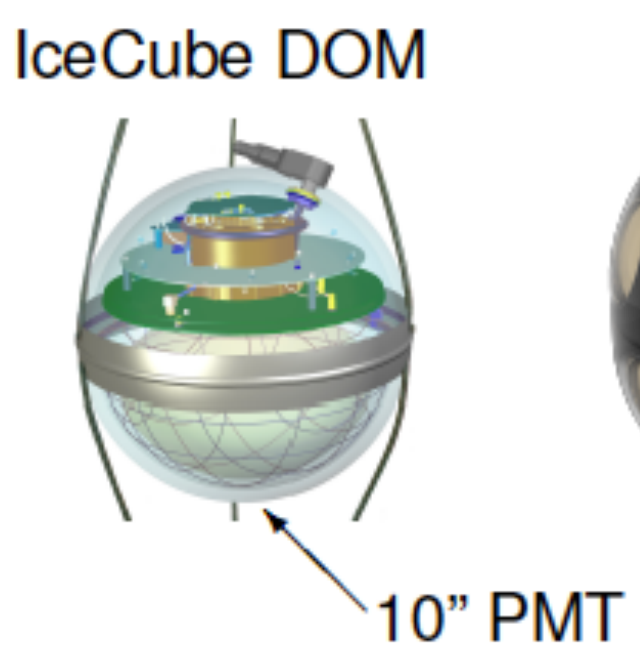
IceCube-Gen2 Phase1

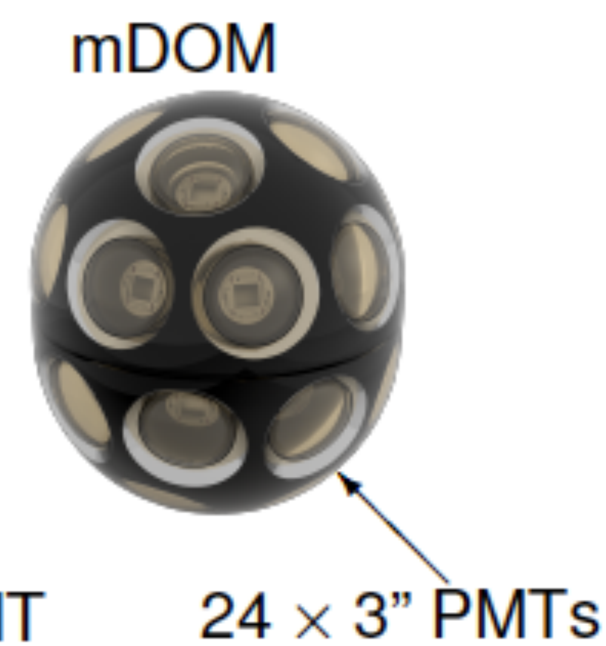
DeepCore

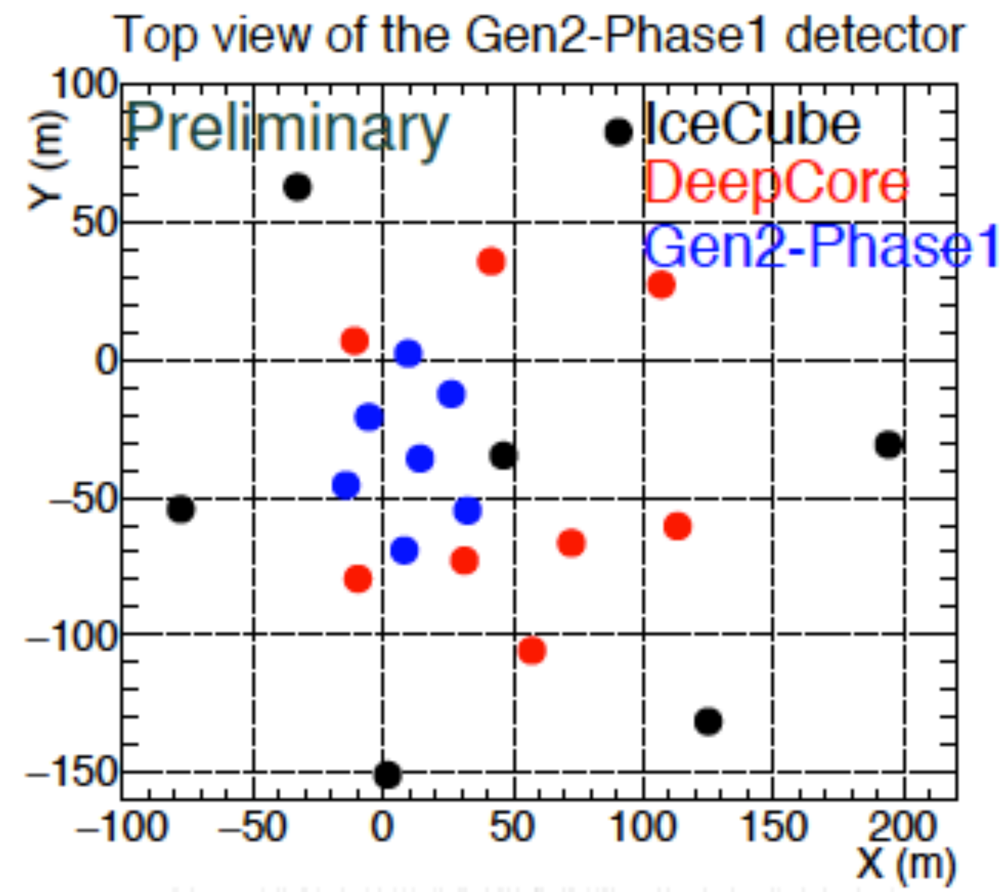
- 8 strings 40-75m horizontal spacing
- 60 DOMs/string, 7m vertical spacing

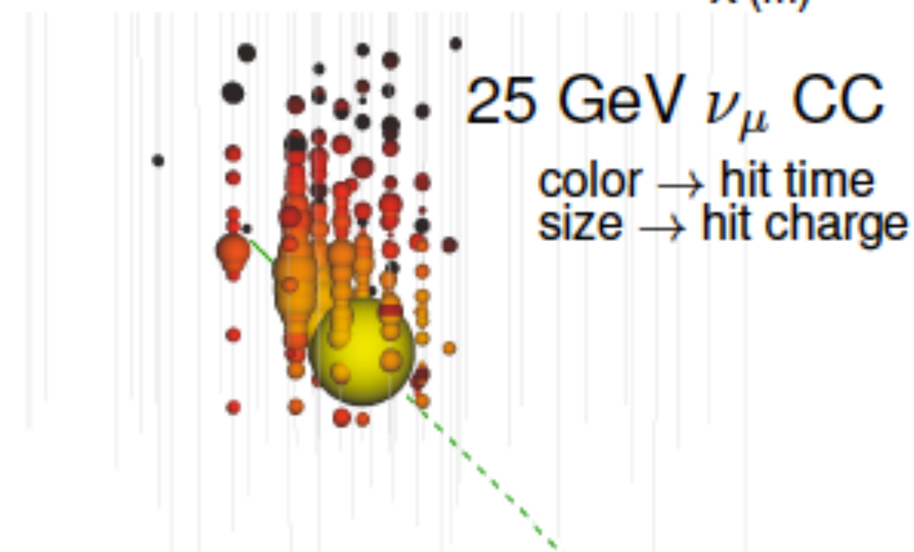
Gen2-Phase 1

- 7 strings 22m horizontal spacing
- 125 DOMs/string, 2.4m vertical spacing
- Located in clearest ice

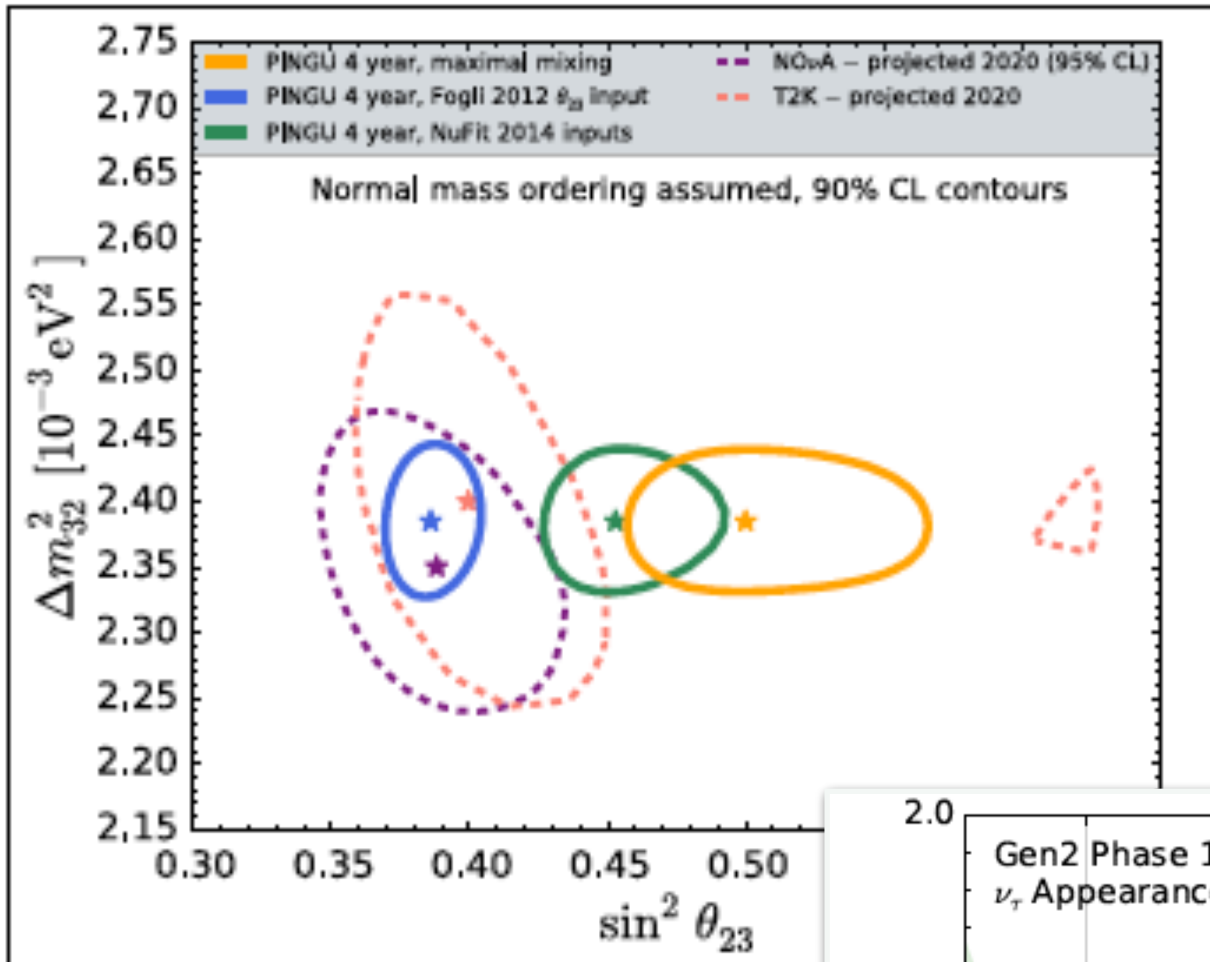






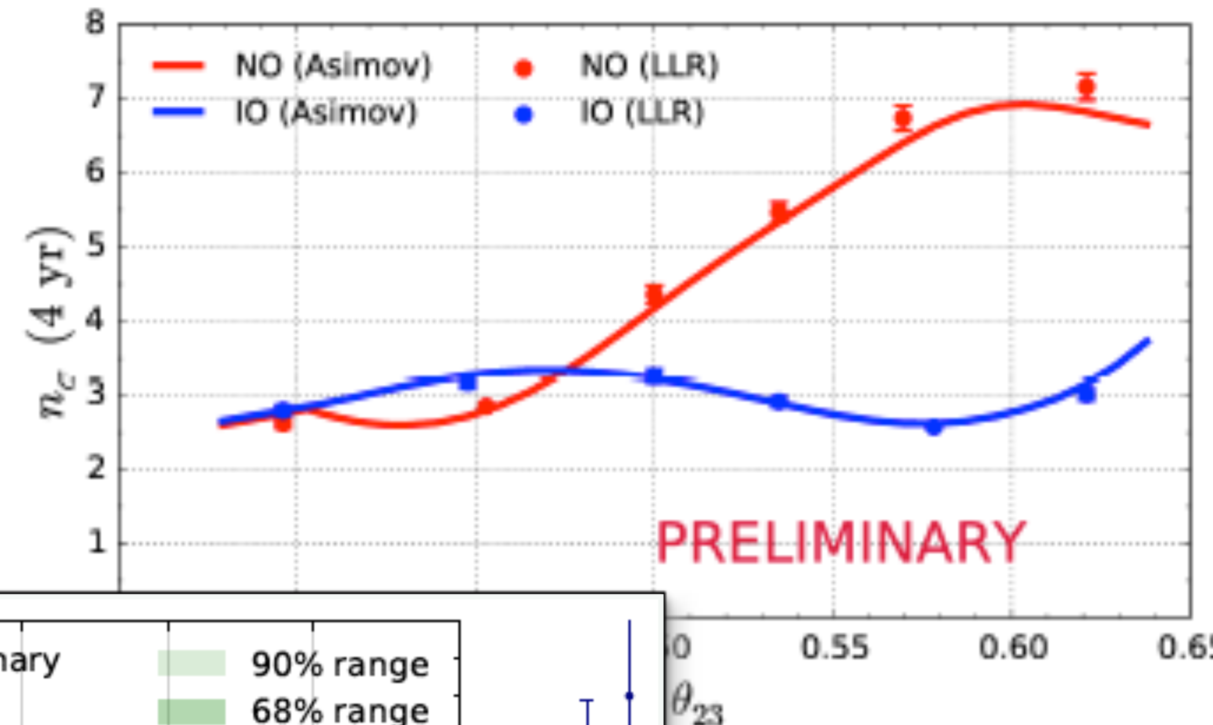


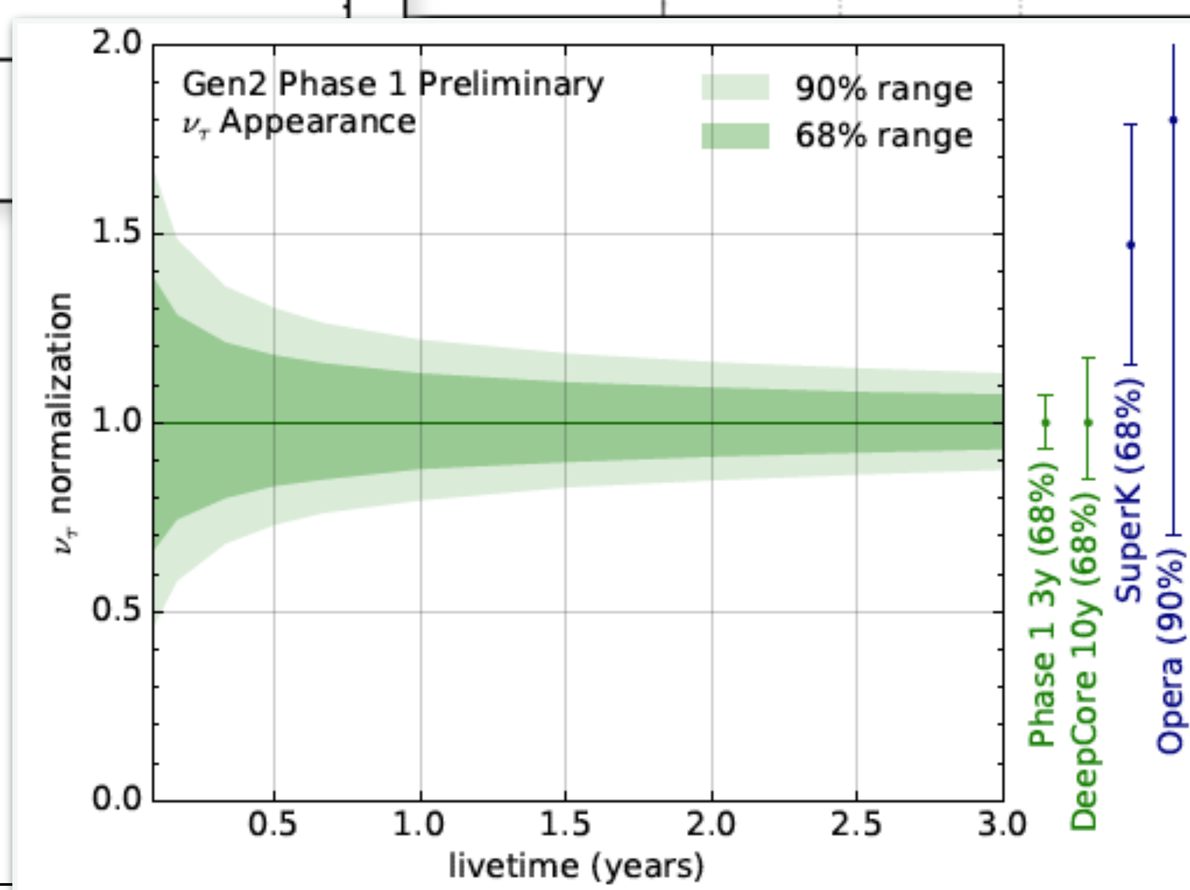
Neutrino Physics with PINGU



Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}

Determination of the neutrino mass ordering

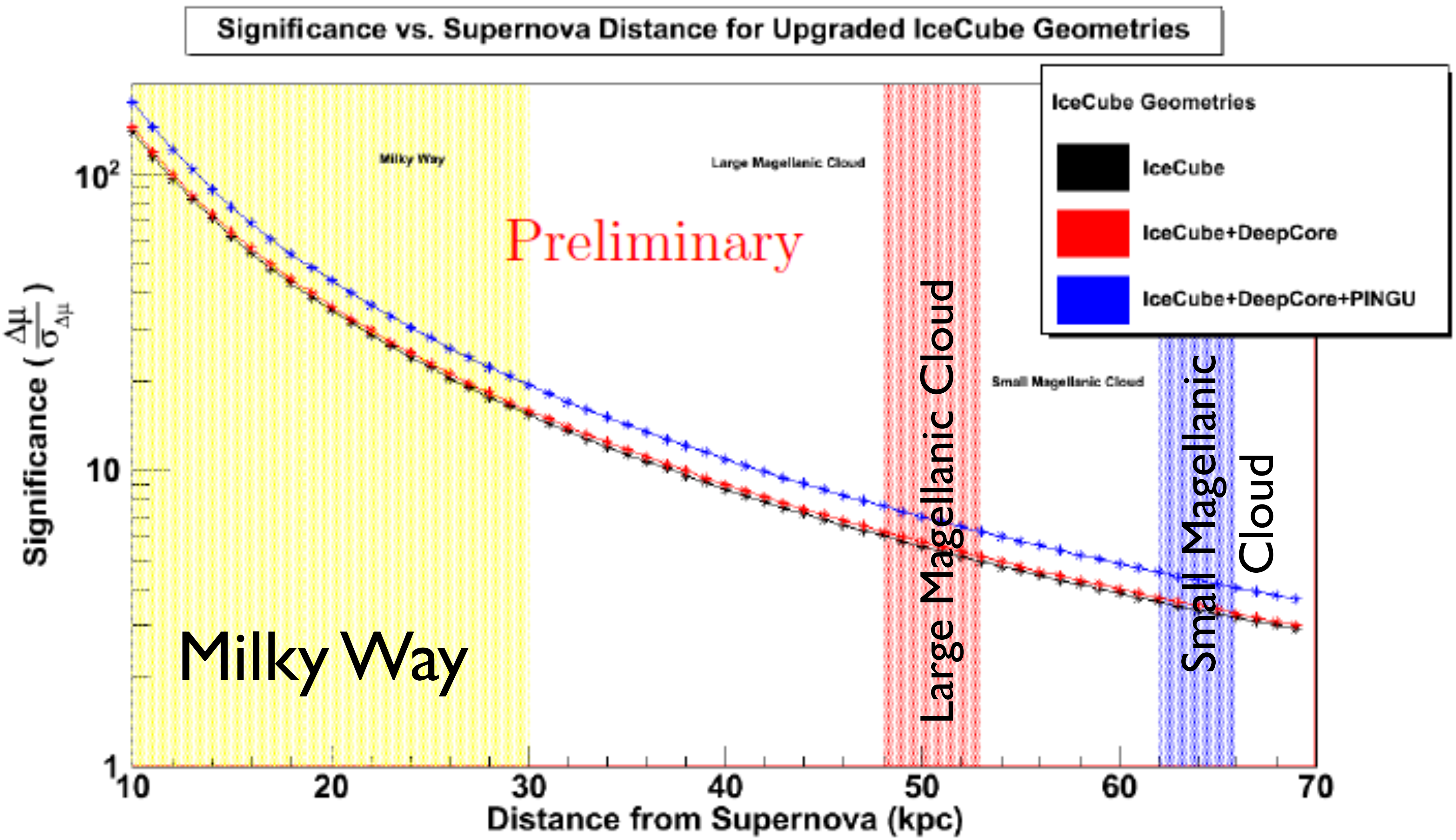




Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

SN Physics Sensitivity

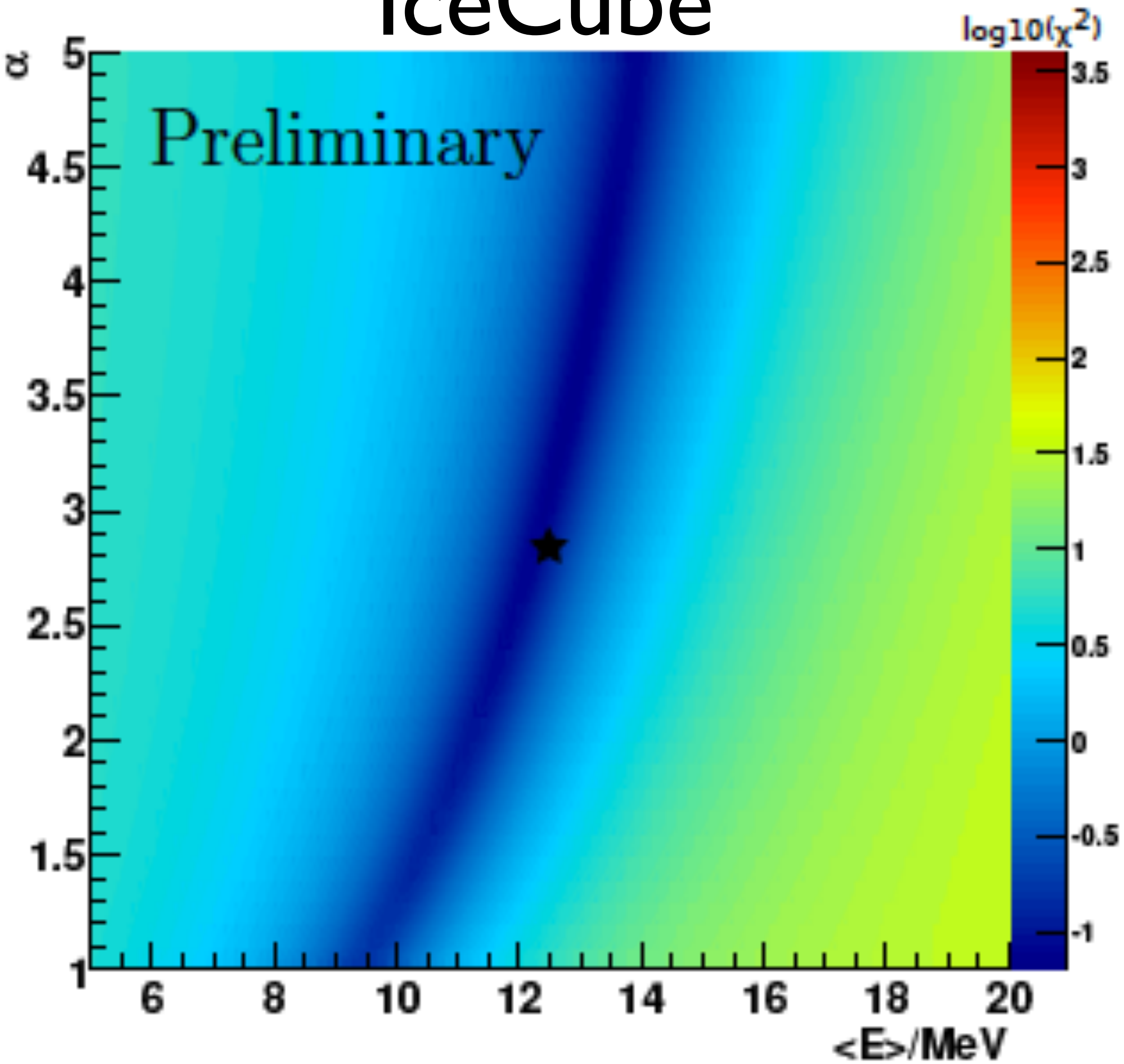
IceCube / PINGU Reach



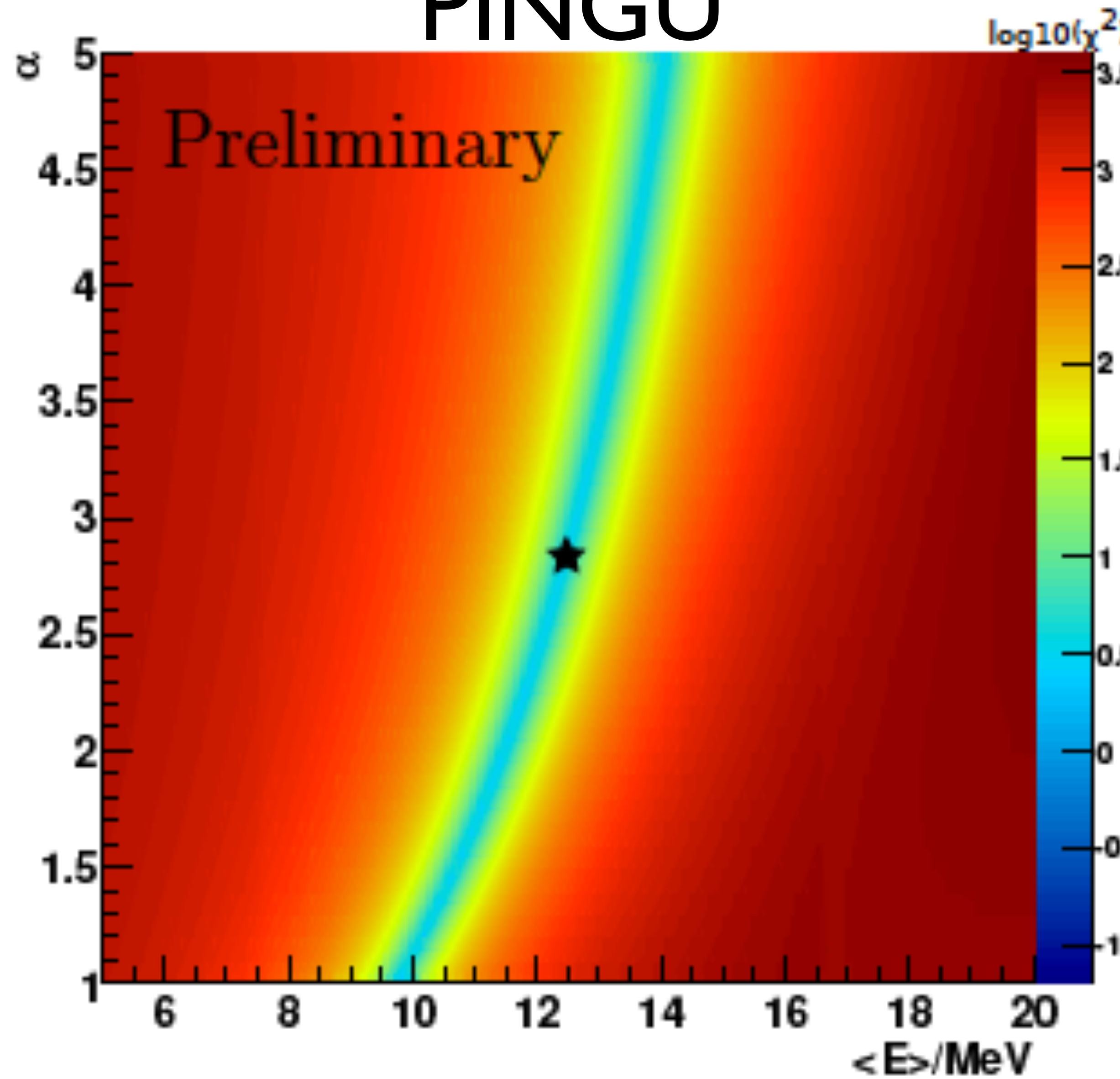
Significance as a function of distance for an O-Ne-Mg, 8.8M(Sun) supernova. The sensitivity of the 40x96 PINGU geometry is compared to the standard IceCube geometries.

- Precision on determining the average energy and shape parameter α for SN at 10kpc

IceCube



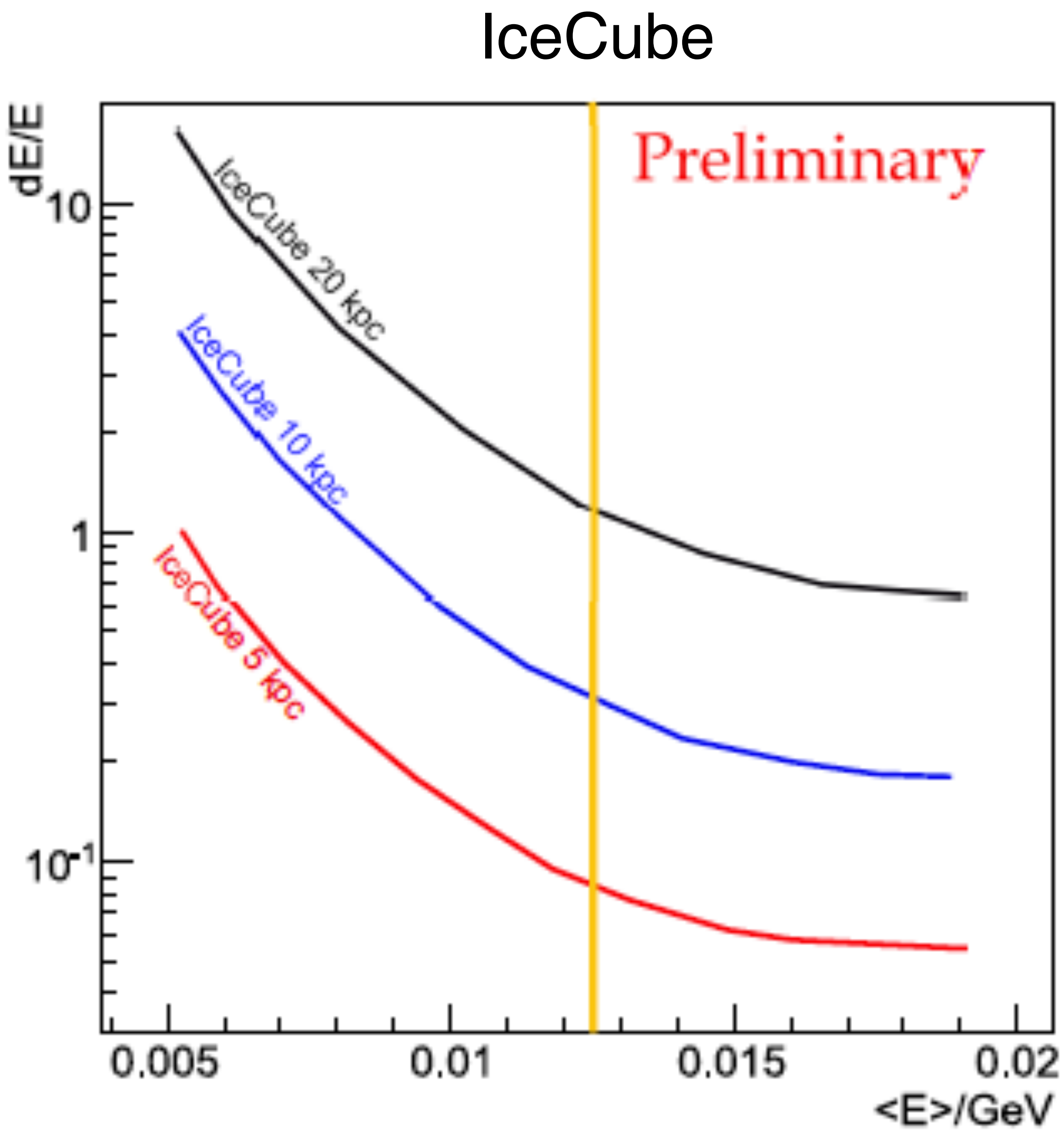
PINGU

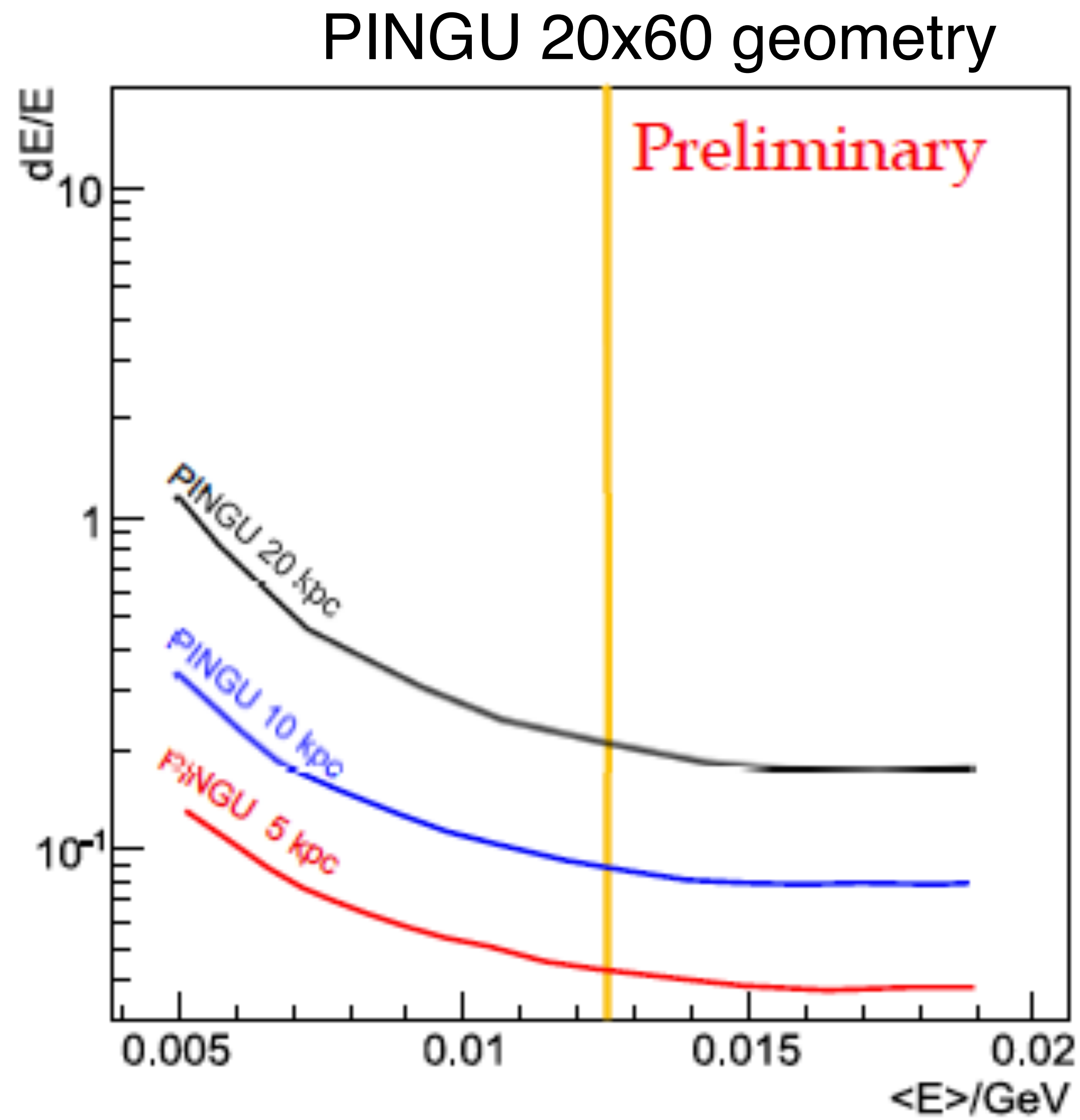


Input value
$(\langle E_{\bar{\nu}_e}\rangle = 12.6 \text{ MeV}, \alpha = 2.84)$

Shape parameter defined by M. T. Keil, G. G. Raffelt, and H.-T. Janka, Astrophys. J. 590 (2003) 971.

- Precision on determining the average energy



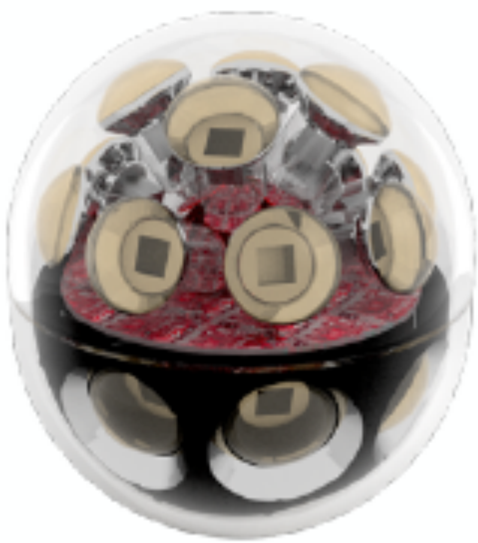


PINGU SN benefits:

- Galactic SN sensitivity improves by 40%
- Energy resolution by factor 5 improvement

New Sensor Designs for Gen2

mDOM



36cm

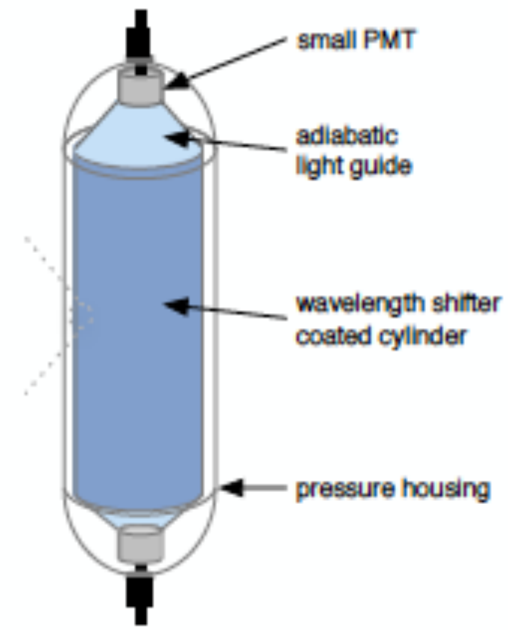
- Directional information (ϕ,θ)
- Large sensitive area per module
- SN multi-hit events
- SN directionality ?

D-Egg

30cm

- Directional information (θ)
- Large sensitive area per module
- Smaller geometry

WOM



11cm

- More sensitive area per $
- Large sensitive area per module
- Small diameter
- Very low noise rate

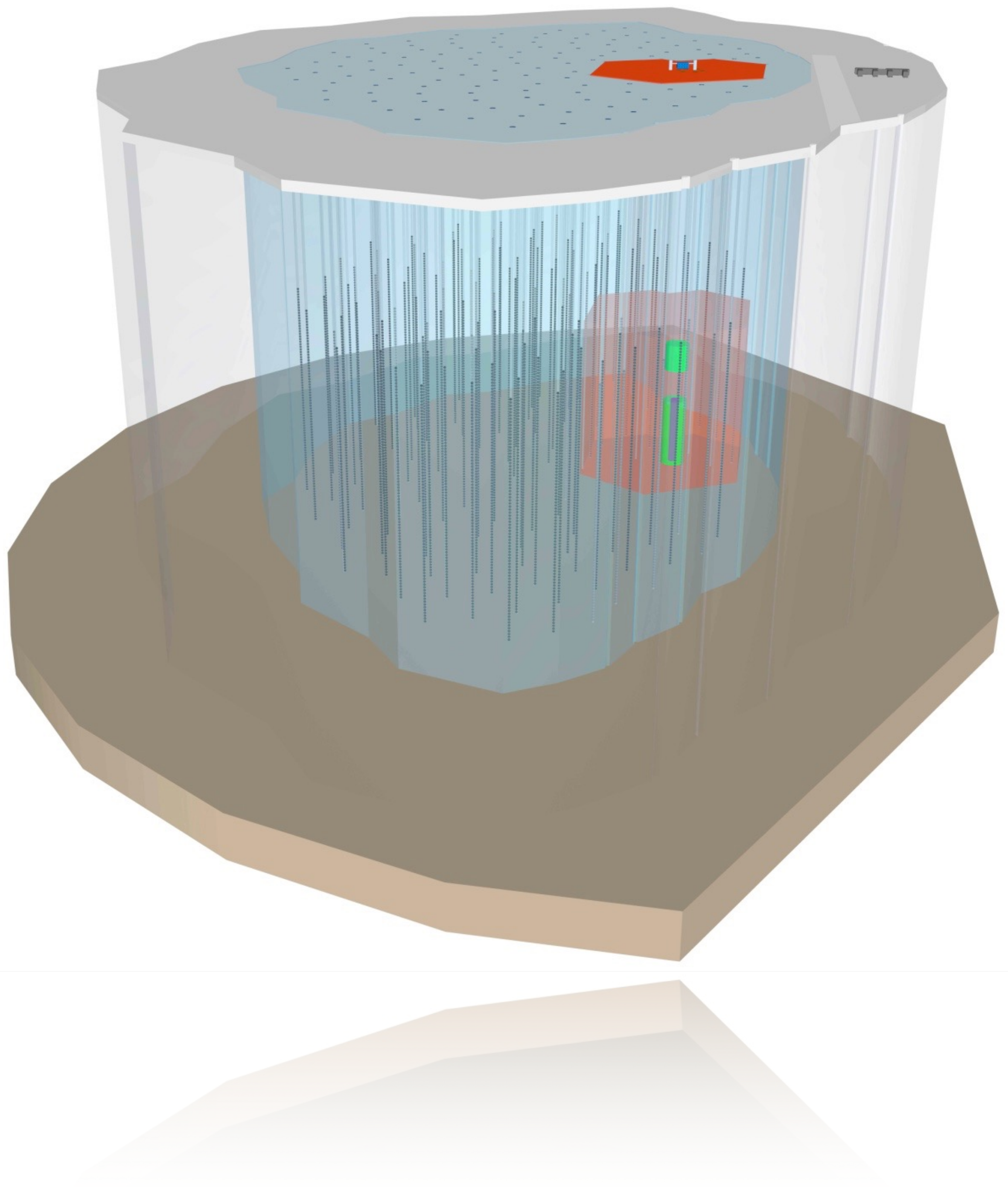
LOM

13cm

- Directional information (ϕ,θ?)
- Large sensitive area per module
- Small diameter
- SN multi-hit events

Conclusions

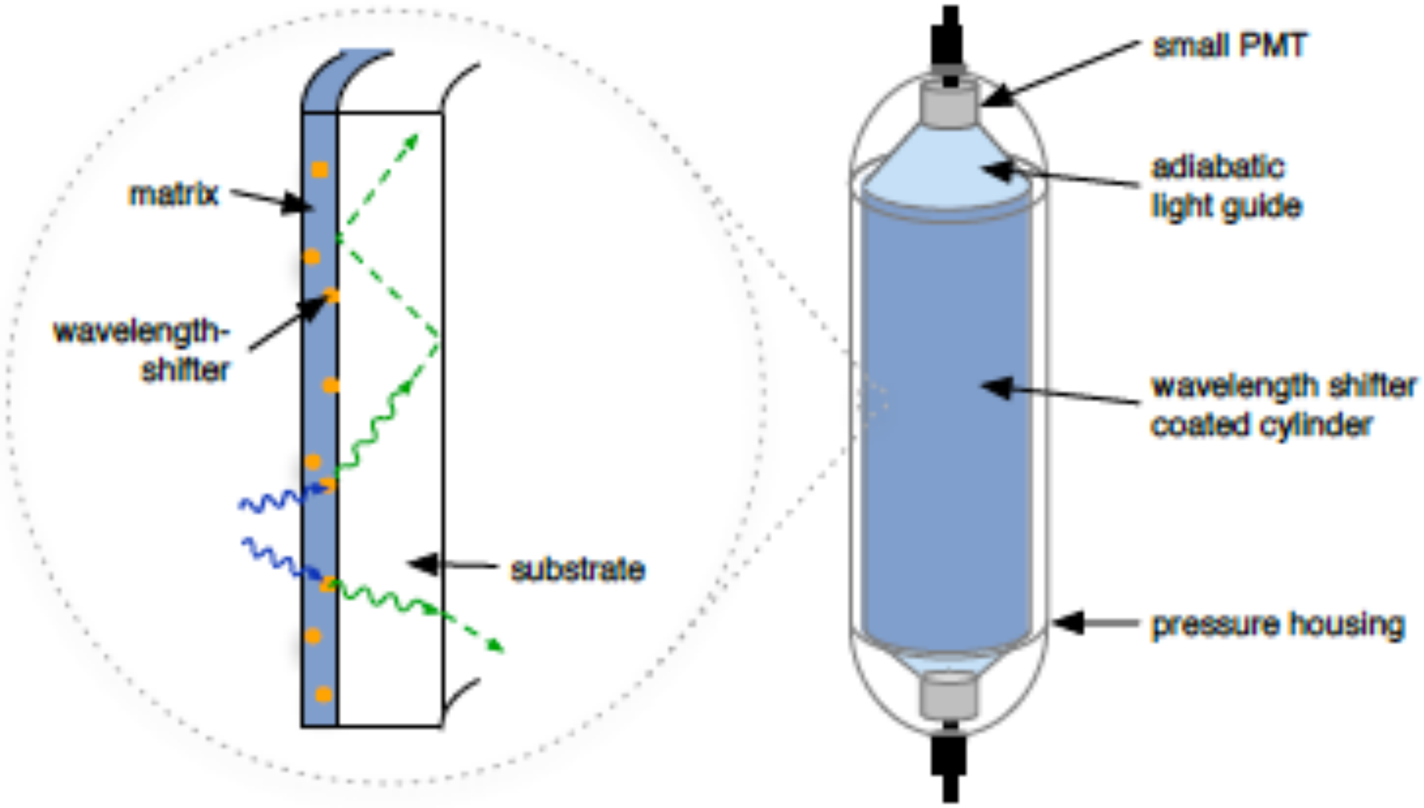
- IceCube is ready for the next Galactic Supernova
  - >99.5% uptime of SNDAQ
  - Resolve fine timing structure
- Follow up programs in place with GW, etc
- Discovery of high-energy astrophysical neutrinos
  - New era in astroparticle physics
    - Rich science potential with next-generation neutrino telescopes
- Great prospects for future upgrades
  - Improved SN sensitivity correlated hits and opportunity for new sensor modules

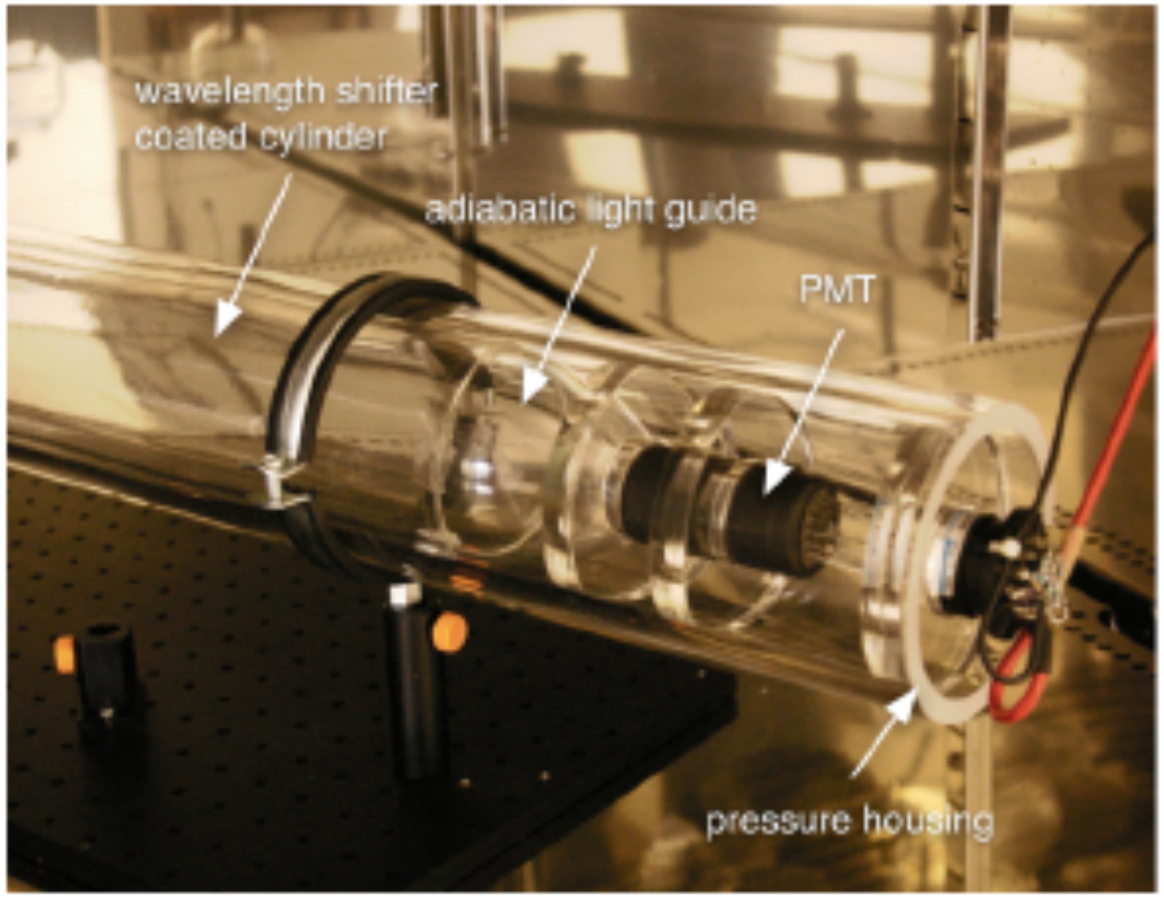


Thanks !


The IceCube–Gen2 Collaboration
SNOLAB (Canada)
University of Alberta–Edmonton (Canada)
Stockholms universitet (Sweden)
Uppsala universitet (Sweden)
University of Copenhagen (Denmark)
Queen Mary University of London (UK)
University of Oxford (UK)
University of Manchester (UK)
Deutsches Elektronen–Synchrotron (Germany)
Friedrich–Alexander–Universität Erlangen–Nürnberg (Germany)
Humboldt–Universität zu Berlin (Germany)
Max–Planck–Institut für Physik (Germany)
Ruhr–Universität Bochum (Germany)
RWTH Aachen (Germany)
Technische Universität Dortmund (Germany)
Technische Universität München (Germany)
Universität Mainz (Germany)
Universität Münster (Germany)
Universität Wuppertal (Germany)
Université de Genève (Switzerland)
Sungkyunkwan University (South Korea)
Université libre de Bruxelles (Belgium)
Universiteit Gent (Belgium)
Vrije Universiteit Brussel (Belgium)
Chiba University (Japan)
University of Tokyo (Japan)
Clark Atlanta University (USA)
Drexel University (USA)
Georgia Institute of Technology (USA)
Lawrence Berkeley National Laboratory (USA)
Marquette University (USA)
Massachusetts Institute of Technology (USA)
Michigan State University (USA)
Ohio State University (USA)
Pennsylvania State University (USA)
South Dakota School of Mines & Technology (USA)
Southern University and A&M College (USA)
Stony Brook University (USA)
University of Alabama (USA)
University of Alaska Anchorage (USA)
University of California, Berkeley (USA)
University of California, Irvine (USA)
University of Delaware (USA)
University of Kansas (USA)
University of Maryland (USA)
University of Rochester (USA)
University of Texas at Arlington (USA)
University of Wisconsin–Madison (USA)
University of Wisconsin–River Falls (USA)
Yale University (USA)
University of Adelaide (Australia)
University of Canterbury (New Zealand)
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)

Wavelength Shifting Optical Module





- very low noise rates on the order of ~20 Hz or below,
- UV sensitivity,
- large geometric acceptance and module sensitivity,
- long term stability,
- no necessity for magnetic shielding, and
- adequate timing resolution.