Status of IceCube-Gen2 Phase1 (aka IceCube Upgrade)

Construction:***2004-2011***

ICECUBE

Construction:***2021-2023***

ICECUBE UPGRADE

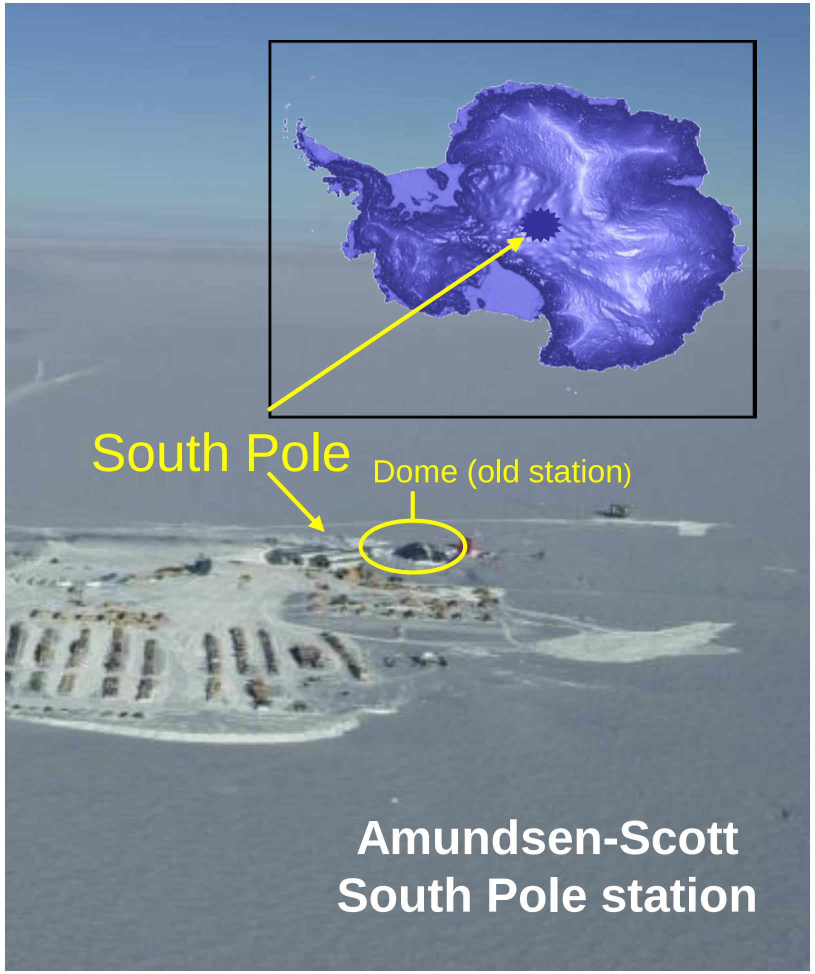
Construction:***2023-***

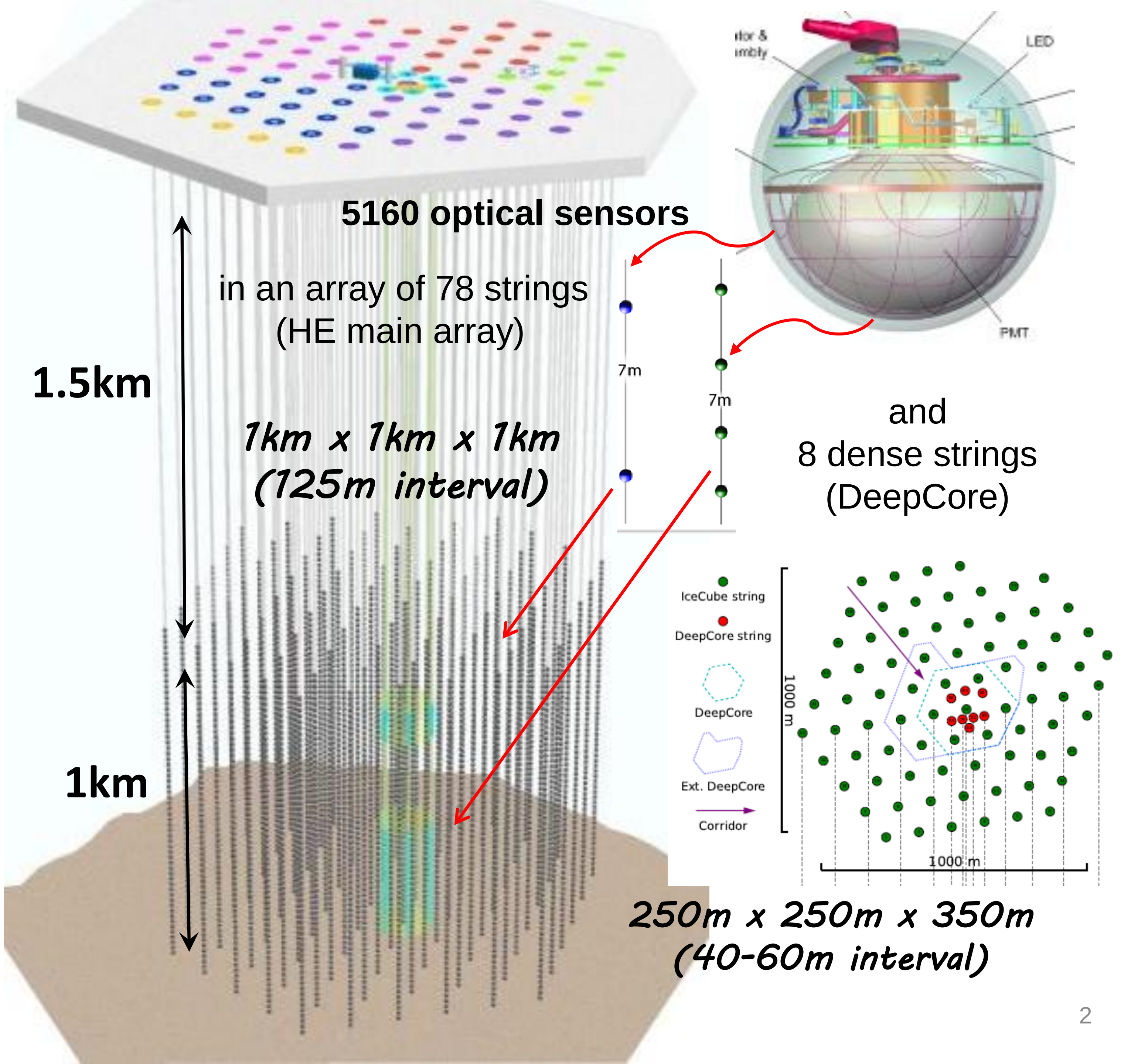
ICECUBE GEN2

Aya Ishihara (Chiba University)

Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2019 @ IGA, Mie

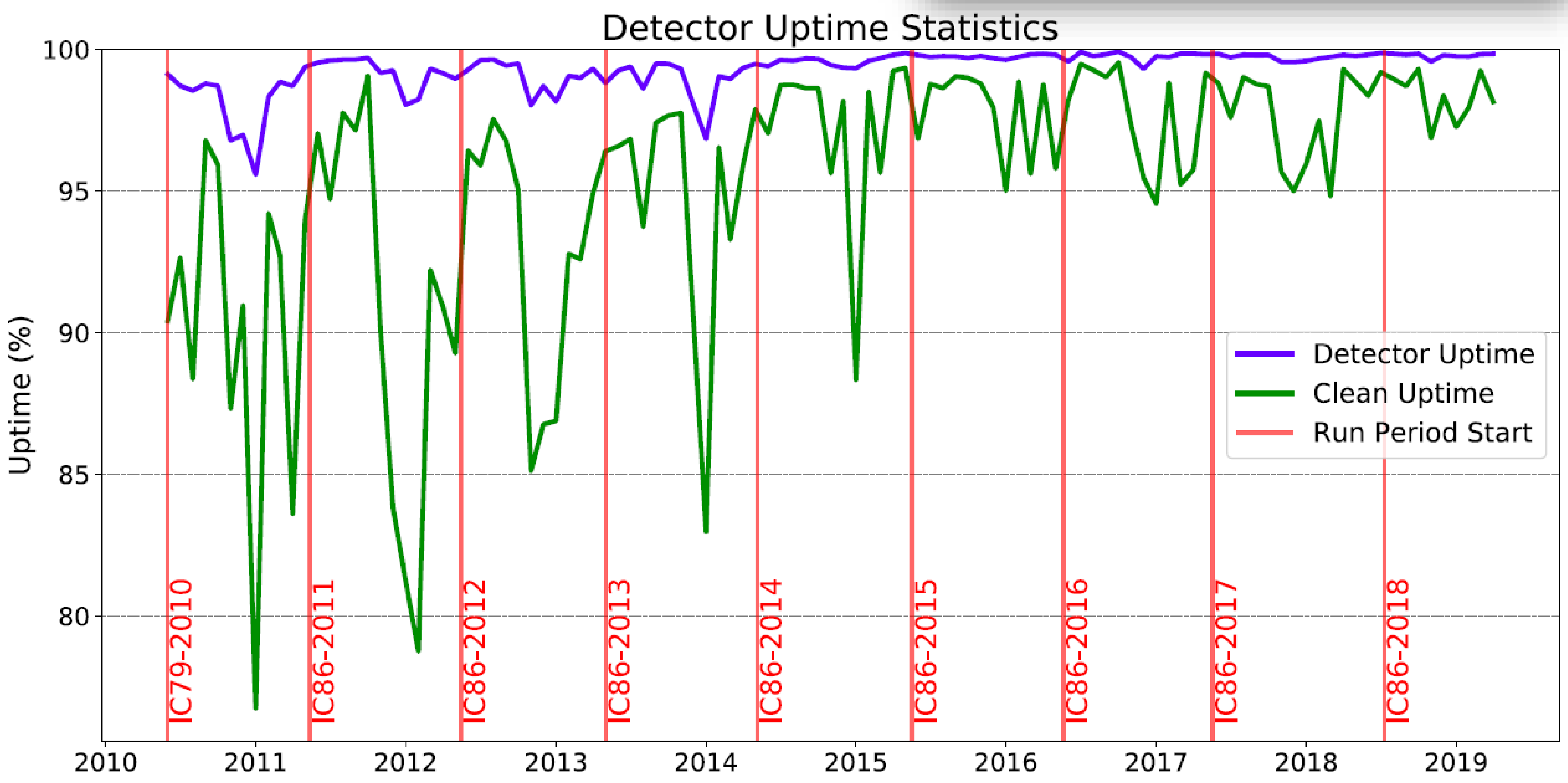
IceCube Detector



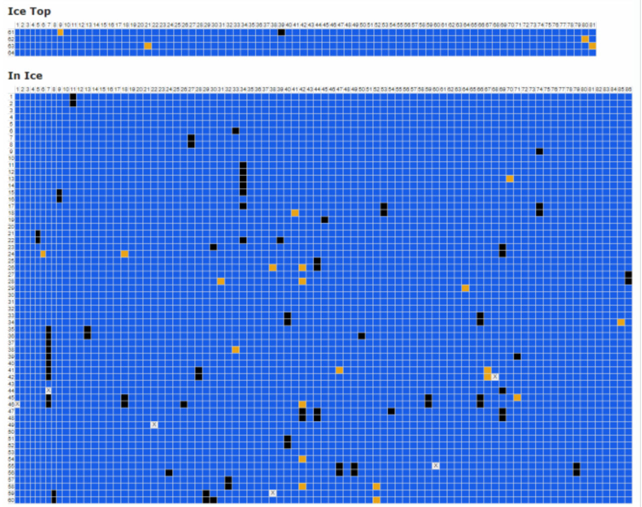


IceCube Uptime!

	Apr. 2017 – Sep. 2017	Oct. 2017 – Apr. 2018	May 2018 – Aug. 2018	Sep. 2018 – Apr. 2019
pDAQ	99.8%	99.7%	99.8%	**99.8%**
SNDAQ	99.8%	99.5%	99.8%	**99.7%**



- String 21 deployed January 2005 (the oldest 14.5 yrs of operation) no OM frailer, no degrading!
- (81+6)/5160 dropped from operations. <1.7% excluded in the recent runs
- Without any replacement
  - Harsh but highly protective environment for photosensors



IceCube's Highlights

- Discovery and characterization of high energy ***cosmic neutrinos***
  - Consistent observations with several ***independent*** detection channels
    - Through going muon tracks
    - Starting track and fully contained cascades
    - Partially contained cascades
    - tau neutrinos
- A timing and directional ***coincidence with light*** from blazer
  - Realtime analysis/alerts of cosmic neutrinos
    - Alerts to telescopes in the world within 1min or less
    - Multimessenger follow up system from radio to very high energy gamma-ray functional!
- Limits including those on the Beyond Standard Predictions
  - **Killed** many "thought to be promising" CR source models
  - Limits on the BSM models, e.g. cross-sections, monopoles, LV, etc and also WIMP

From DeepCore

- Muon neutrino disappearance and tau neutrino appearance analyses in 5.6GeV to 56 GeV
- Using 3 years of data (May 2012 and April 2014, ～1000days)
  - Two independently developed sets of event selections and analysis frameworks
  - 7 years data analysis are ongoing with new selection and analysis

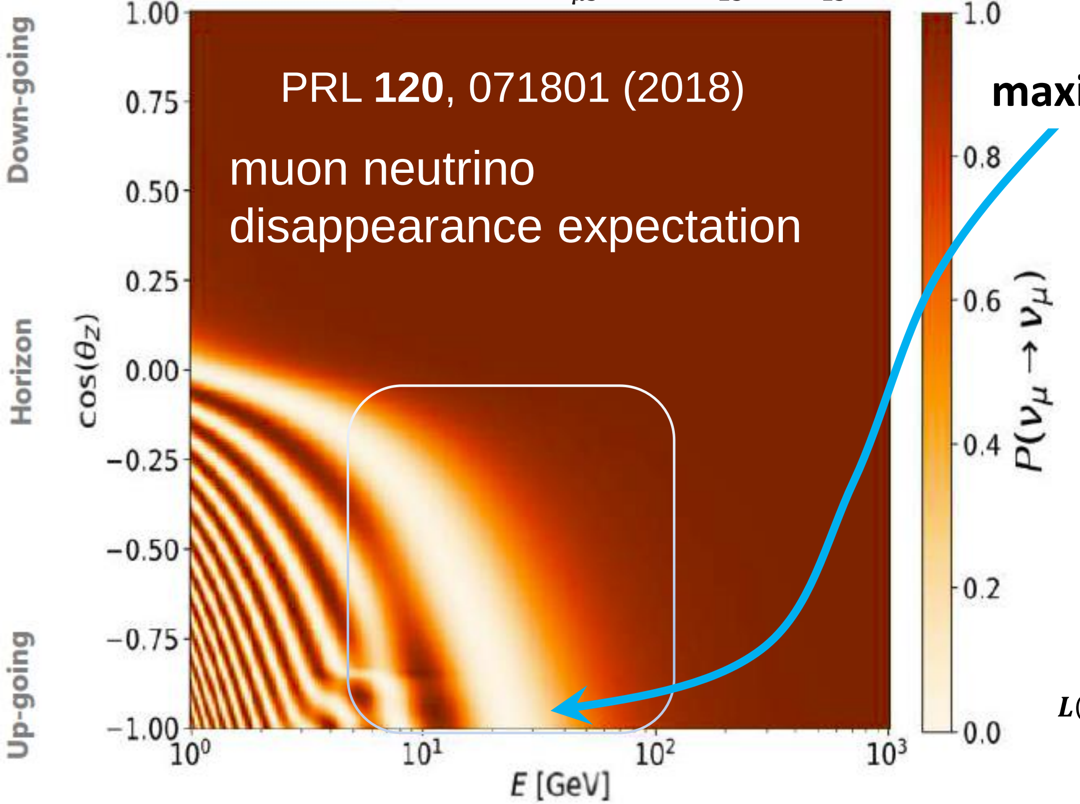
$$P(\nu_\mu \to \nu_\mu) \approx 1-4|U_{\mu3}|^2(1-|U_{\mu3}|^2)\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

$$U_{\mu3} = \sin\theta_{23}\cos\theta_{13}$$

$$P_{\nu_\mu\to\nu_\tau} = \sum_{j,k} U_{\mu j}U^*_{\tau j}U^*_{\mu k}U_{\tau k}\exp\left(i\frac{\Delta m^2_{jk}L}{2E_\nu}\right)$$

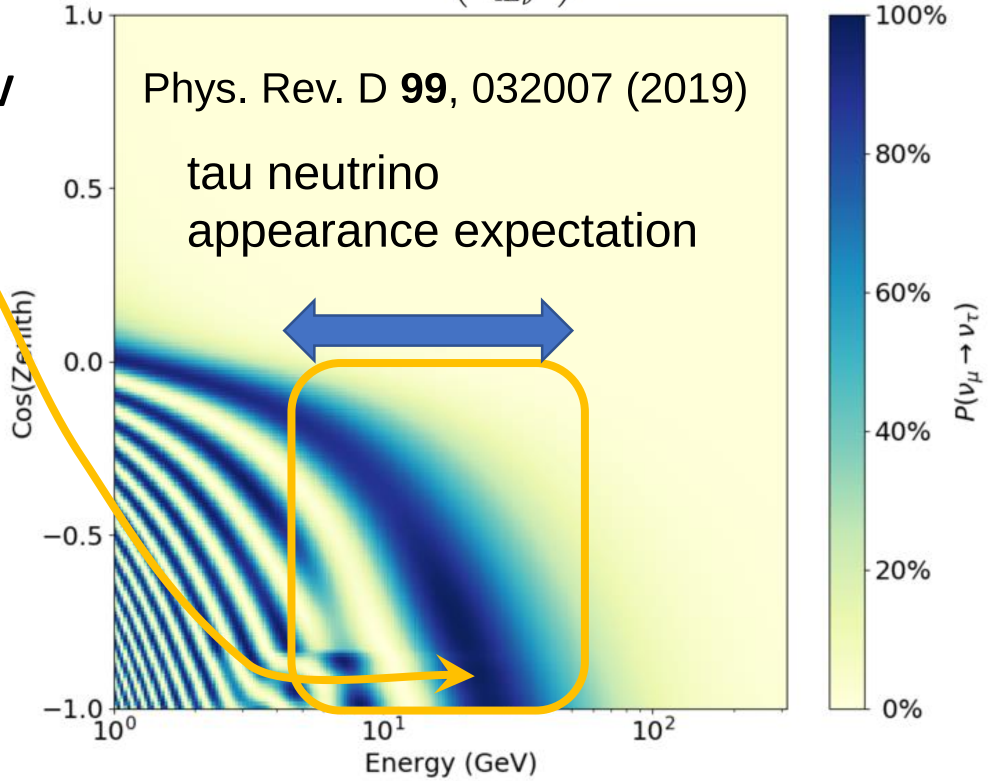
$$\approx \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$L = L(\theta)$



maximal at 25 GeV

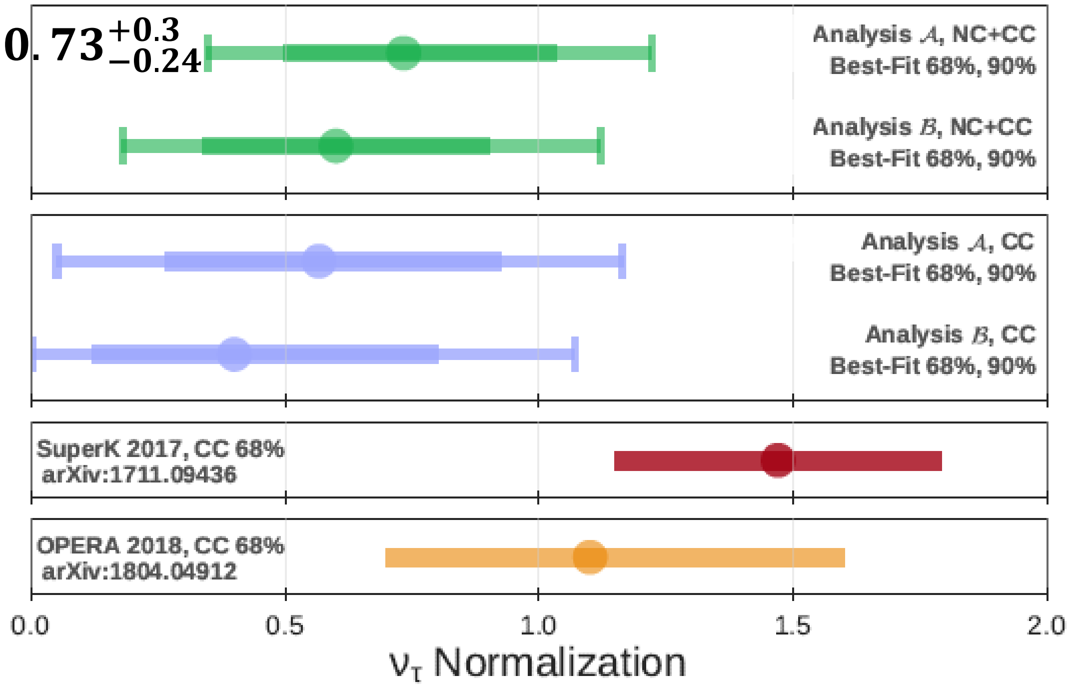
$L(\theta = 0) = 12700$ km

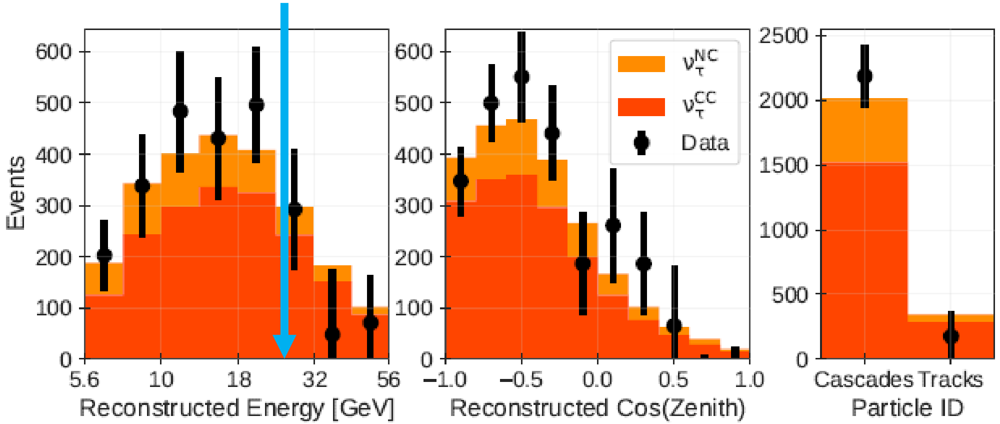


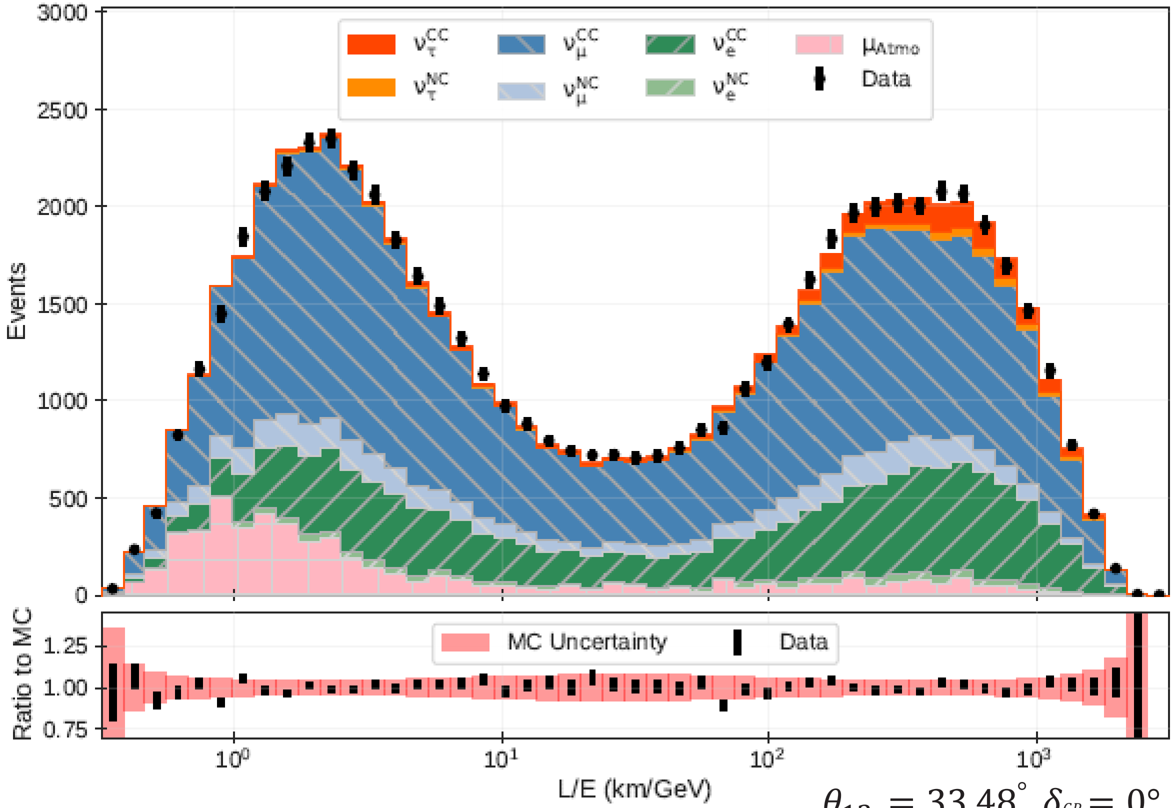
5.6-56 GeV tau neutrinos with DeepCore

Phys. Rev. D **99**, 032007 (2019)

Absence of tau neutrino oscillation excluded at 3.2σ



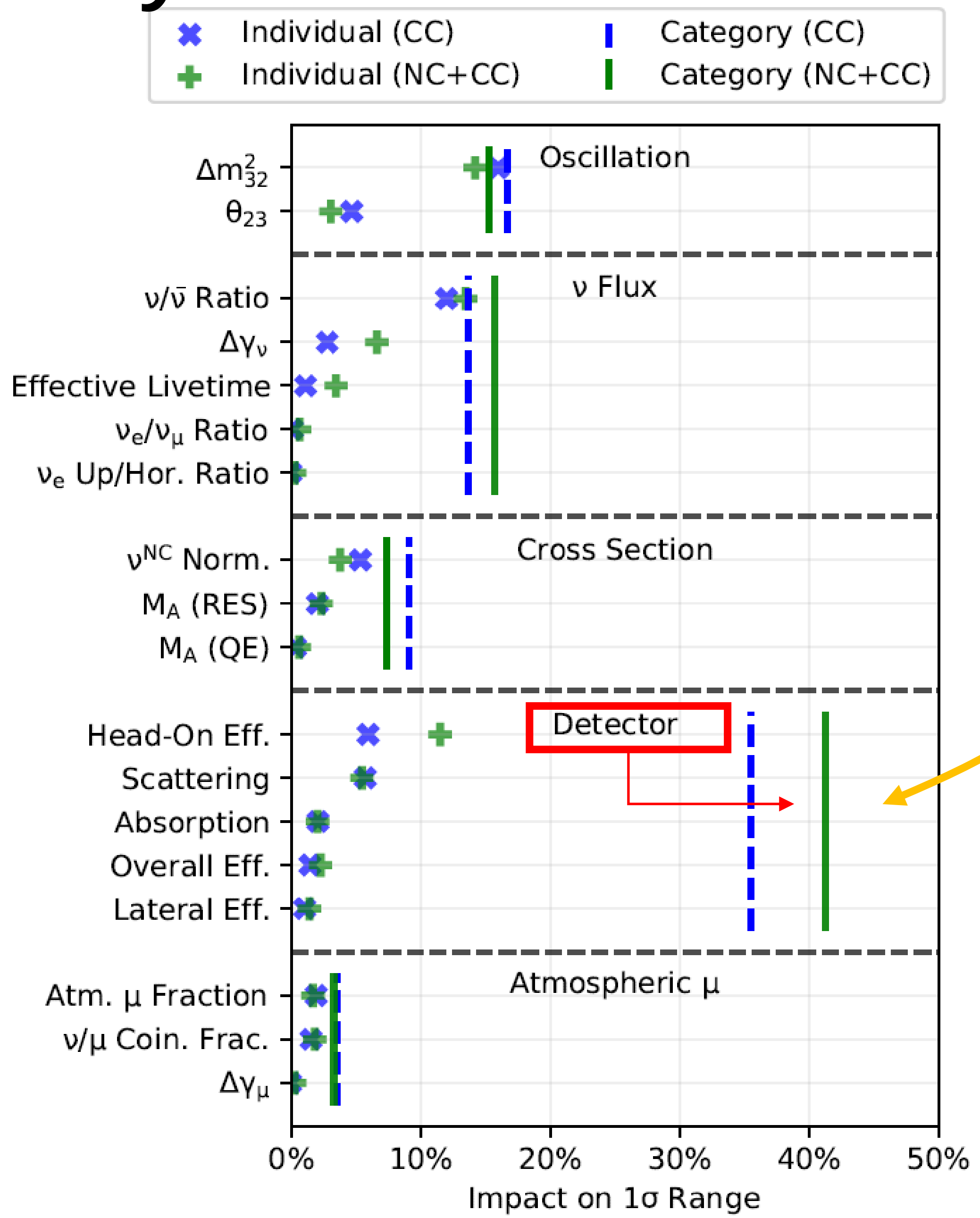




$\theta_{12} = 33.48^\circ, \delta_{CP} = 0°$
$\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2$
no assumption on $\Delta m^2_{32}, \theta_{23}$, mass ordering

Best fit signal rates: **1804 Charged Current** and **556 Neutral current ν_τ** events in 1000days (800evts/year)

Systematic Limitation



Phys. Rev. D **99**, 032007 (2019)

41% systematic uncertainty from detector calibration (detector parameters are correlated)

- ice absorption sets viewing distance
- ice scattering differs arrival direction of photons

Calibration of **refrozen-ice**

Major systematics for oscillation analysis

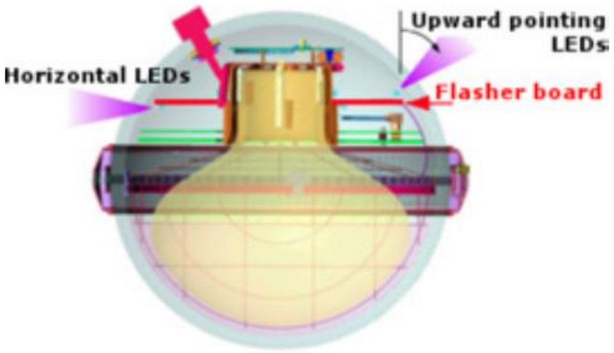
Calibration of **bulk ice**

- Anisotropy of photon propagation in ice along glacial flow

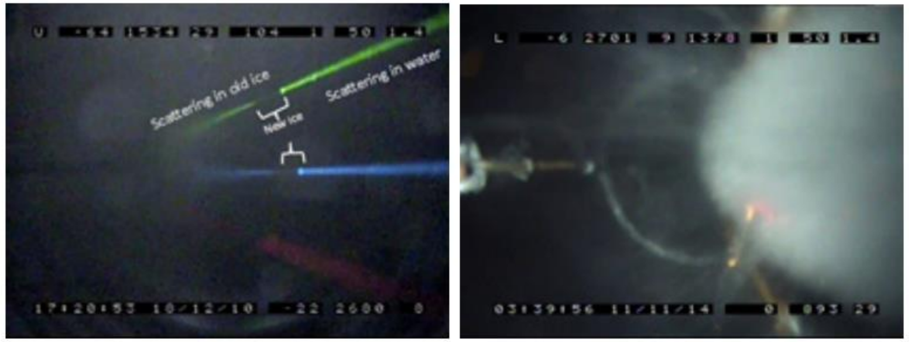
Major systematics for high energy cascade/tau analysis

Refrozen ice calibration in IceCube

(1) Every OM includes 12 LEDs

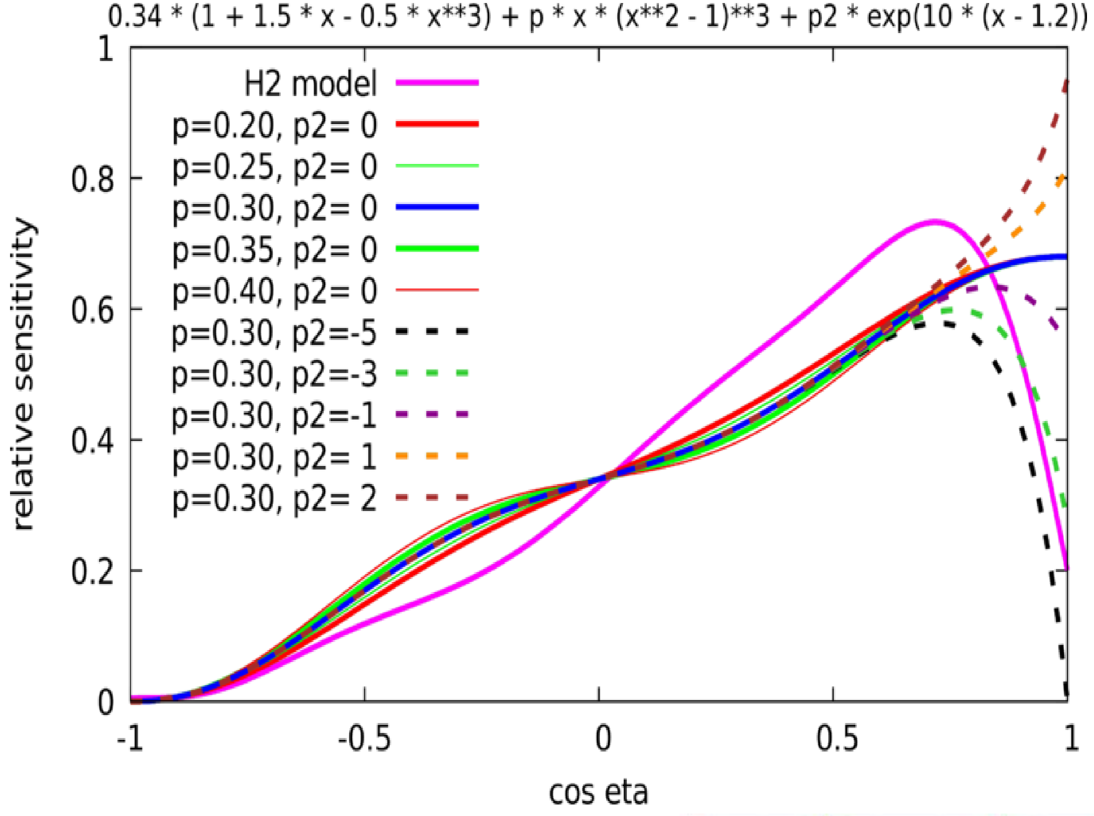


(2) Camera at one deep location

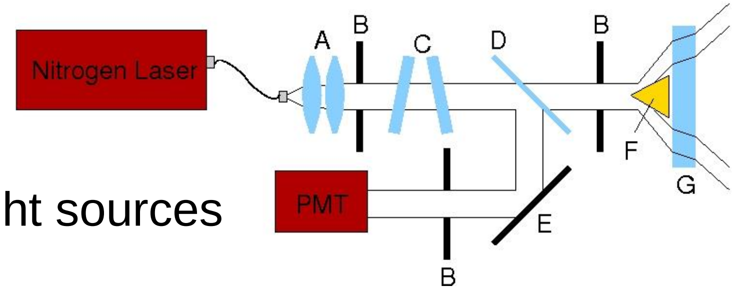


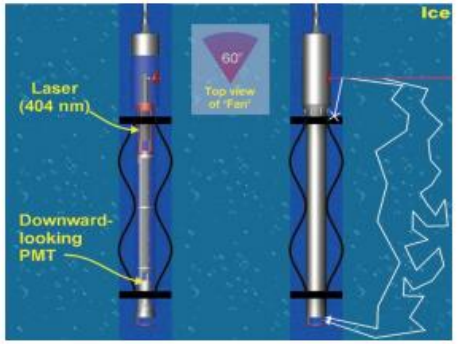
(a) Camera looking sideways into the bulk ice (b) Camera looking downward into the hole ice

Relative acceptance of photons versus photon arrival angle



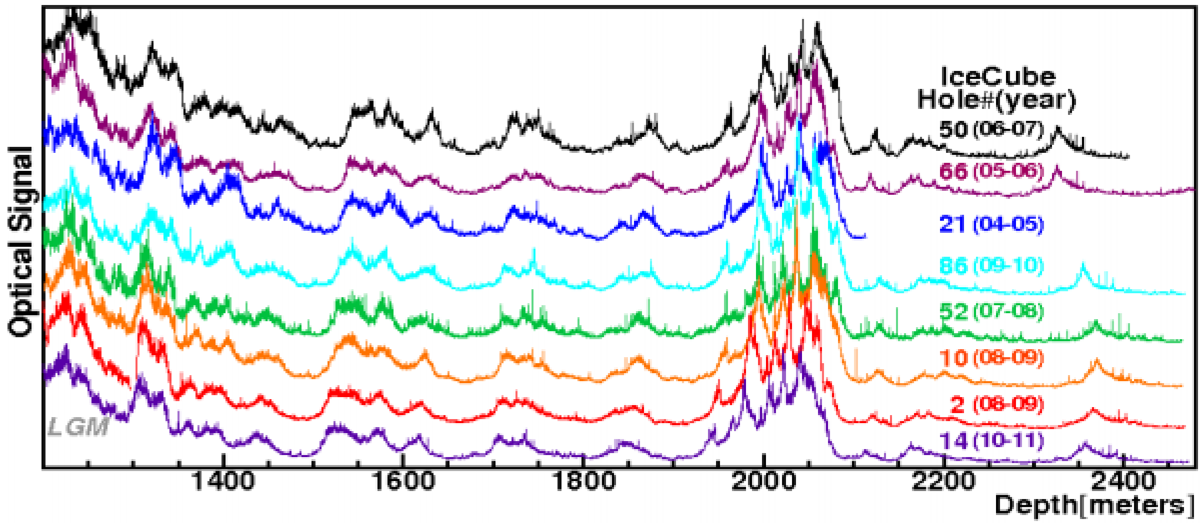
vertically down facing region unconstrained!

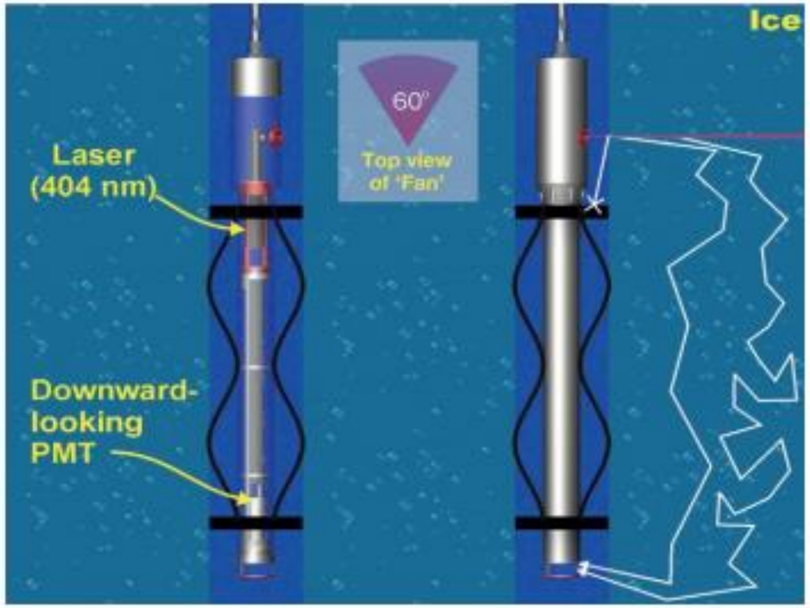


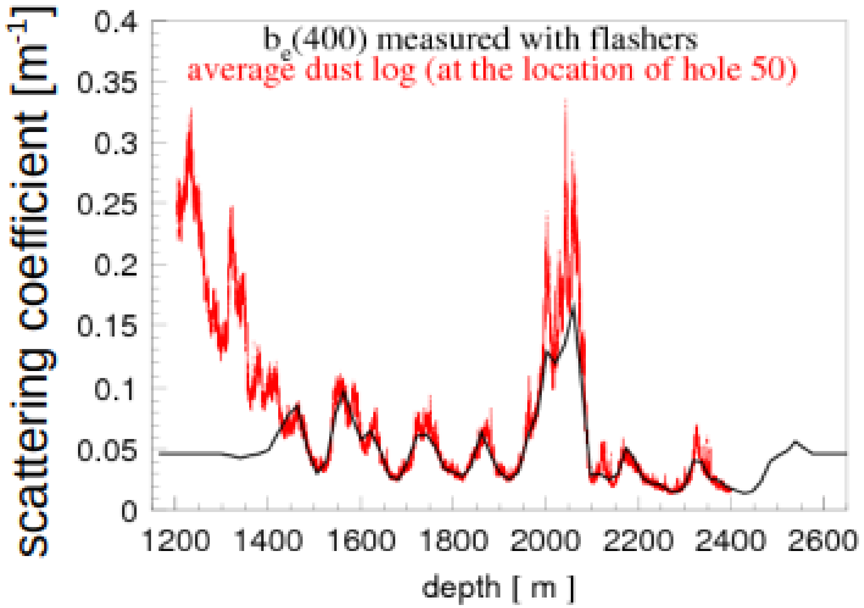


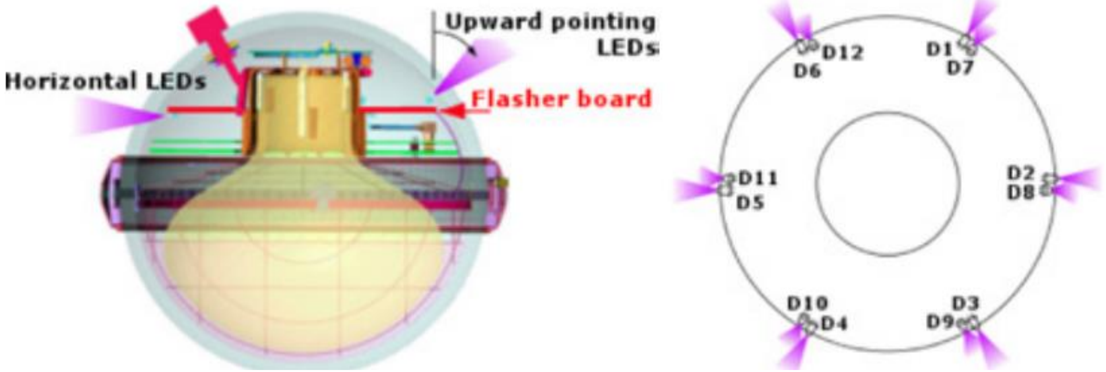
(3) Laser based calibration light sources

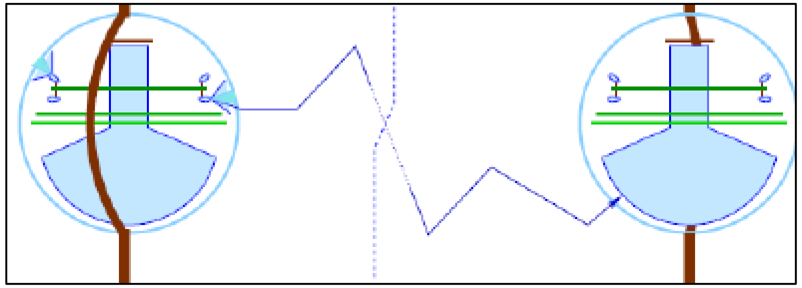
Bulk ice calibrations



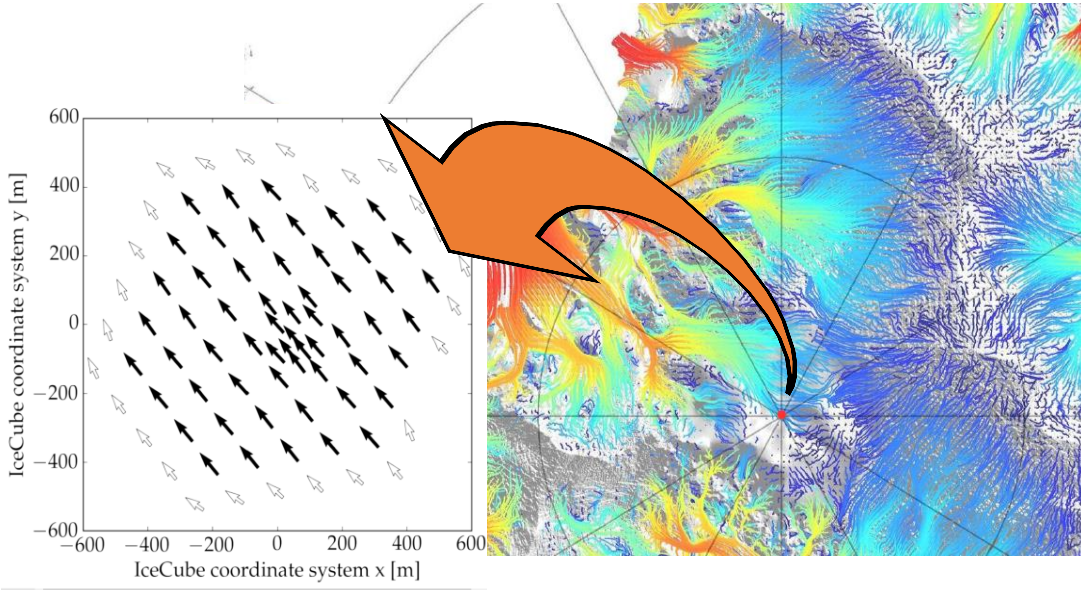




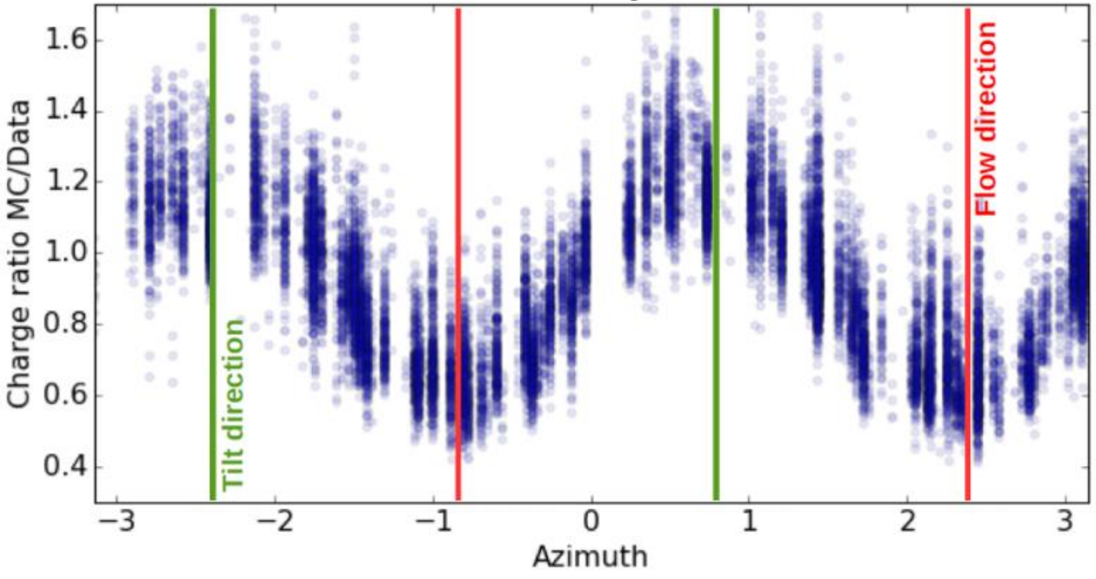




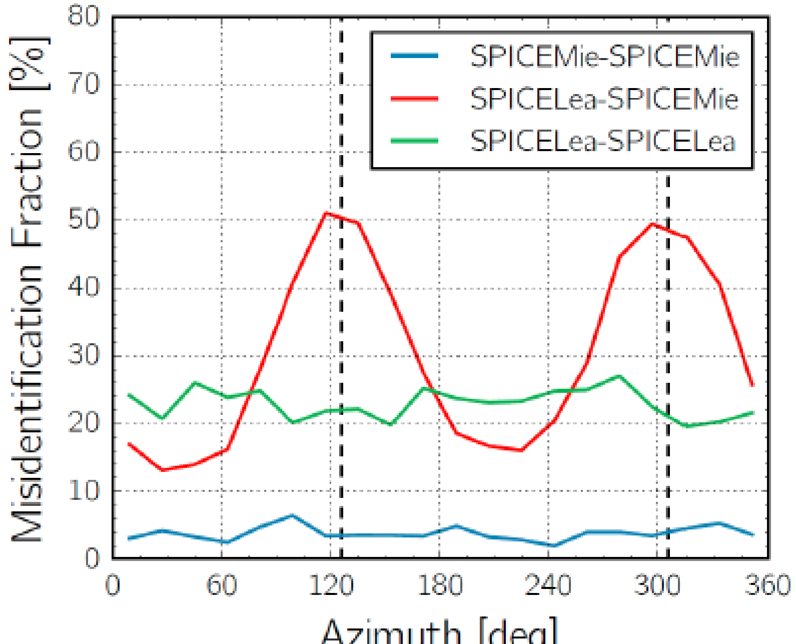
Anisotropy of ice



Flasher Charge Ratio



Cascade reconstruction



- Rivers over the Antarctica!   Anisotropy along the ice flow
  - ☞ Reconstruction bias likely due to the anisotropy
- Explanation based on birefringence of ice
  - Depth dependence of anisotropy factor
  - Flasher data strongly favors an absorption only anisotropy (timing is well matched)

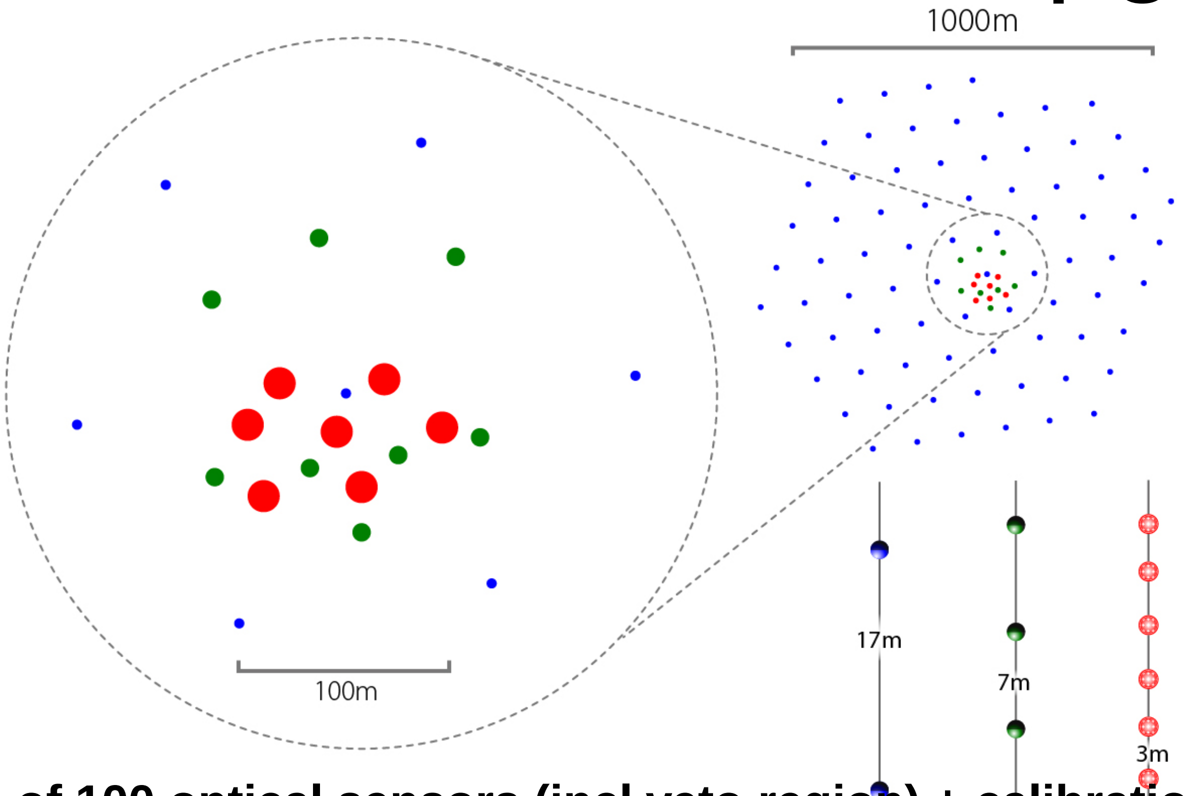
from wikipedia

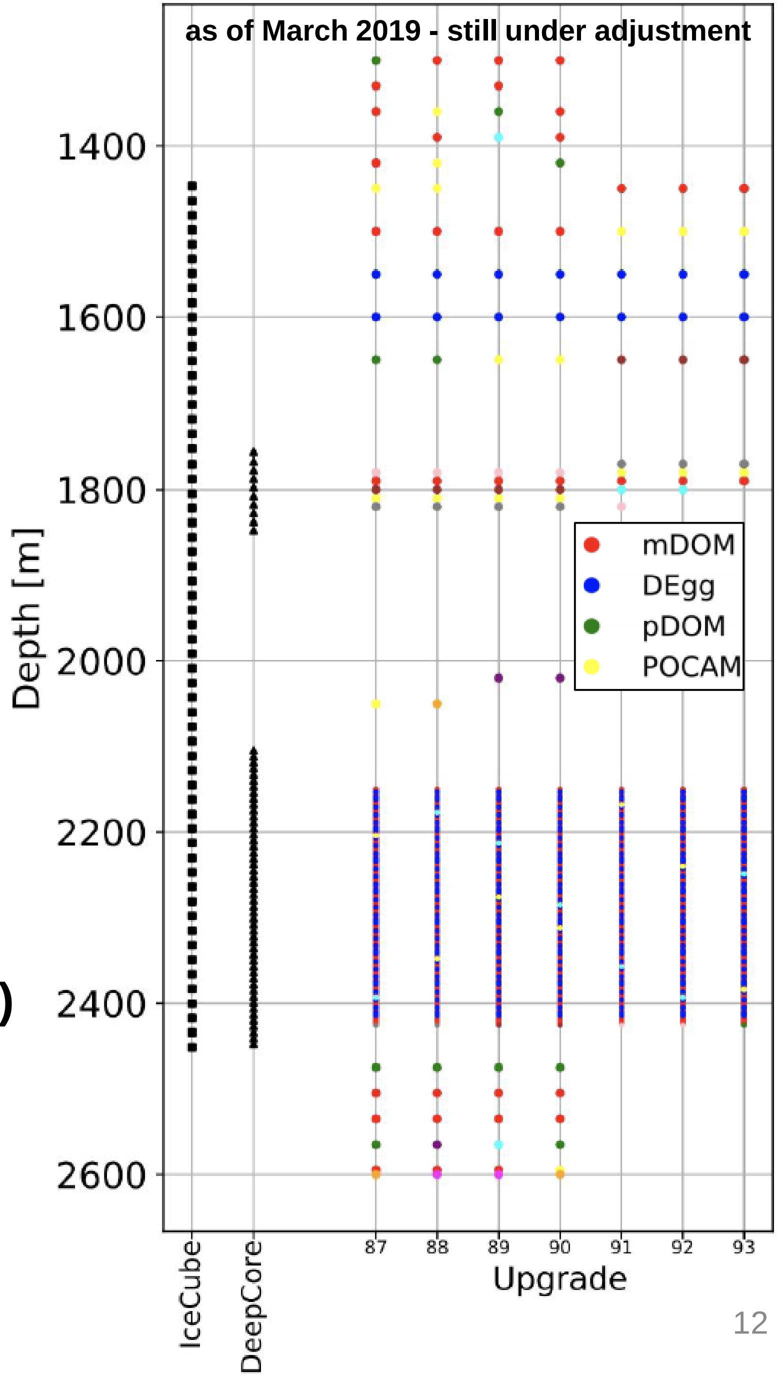
Identifications of multiple cosmic neutrino emitting objects!

while working on the large scale proposal, let's tackle the challenges of IceCube that **enhance the Gen2 science potential even more**

"Prove the improvements!"

Gen2-Phase1 aka IC-Upgrade





- **7 strings of 100 optical sensors (incl veto region) + calibration devices**
- **Total: ~300 D-Egg (Chiba) + ~400 D-Egg (Germany) + ~20 PDOM (Madison)**
- **Vertically 3m, horizontally 20m separations forms 2Mt volume array**
- **2021/22 Surface cable drag, 2022/23 make 7 holes and install 700 sensors**
- **15 long and narrow R&D Optical sensors for Gen2 (fits in 15cm holes)**
- **$23M (Drill, NSF, incl. Labor) + $10M (OMs, non-US, excl. Labor)**

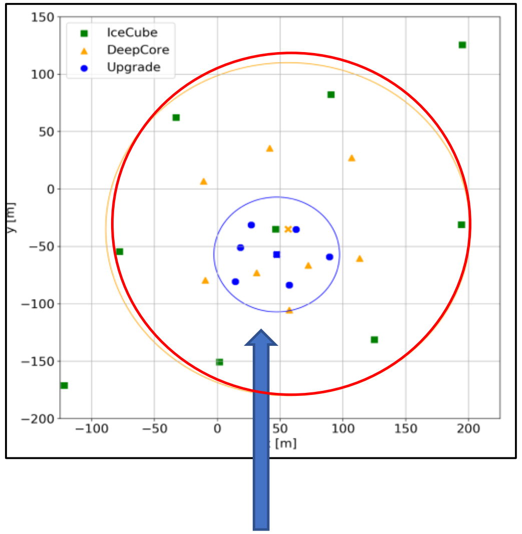
What we want to with Upgrade?

- Concrete understanding of glacial ice below 1300m
  - Do we really know 3000m deep ice?
    - Yes. we know quite well
    - but we are the first experiment reaches and uses that depth of ice. Can not be perfect
  - Ice is still the largest systematic – in high energy astrophysical neutrino analyses and in low energy neutrino physics
  - New understanding of ice is applicable to >10 years worth of archived IceCube data

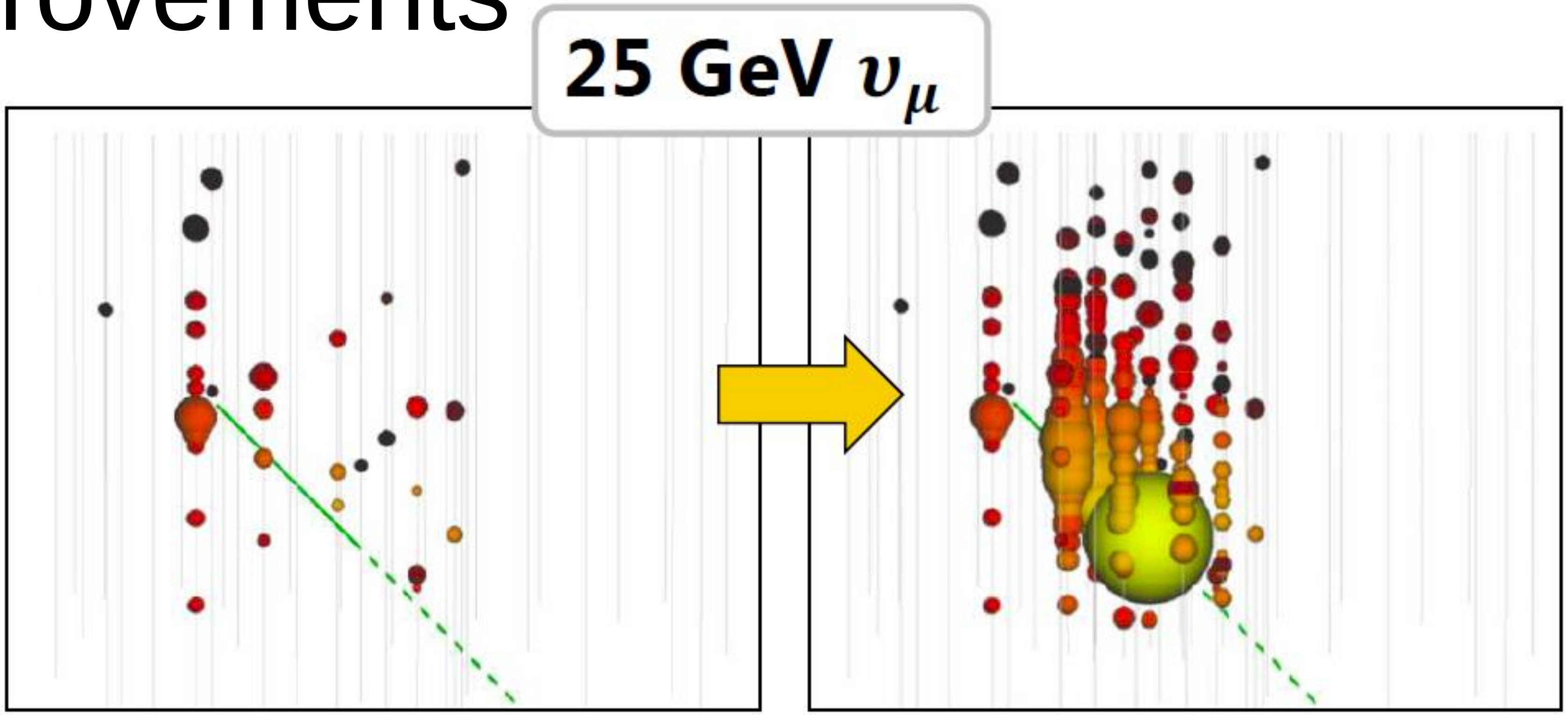
- Physics with 5-100 GeV neutrinos
  - Low energy / small volume compared to IceCube but high energy + **high statistics (large volume) opportunity** compared to the many other

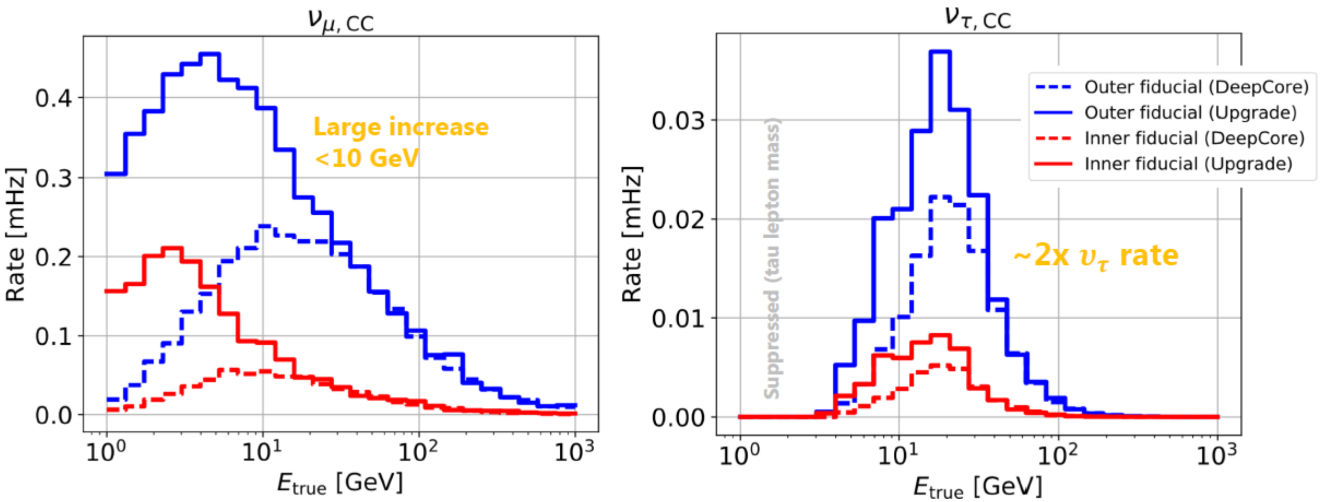
- Prove new techniques and improvements from the hardware side
  - **3 types of new optical sensors** (plus more R&D designs for Gen2)
  - Technical challenges: New drill, cleaner ice, controlling various calibration modules...

Statistical Improvements



upgrade volume 2Mt, 2.5x denser than DC

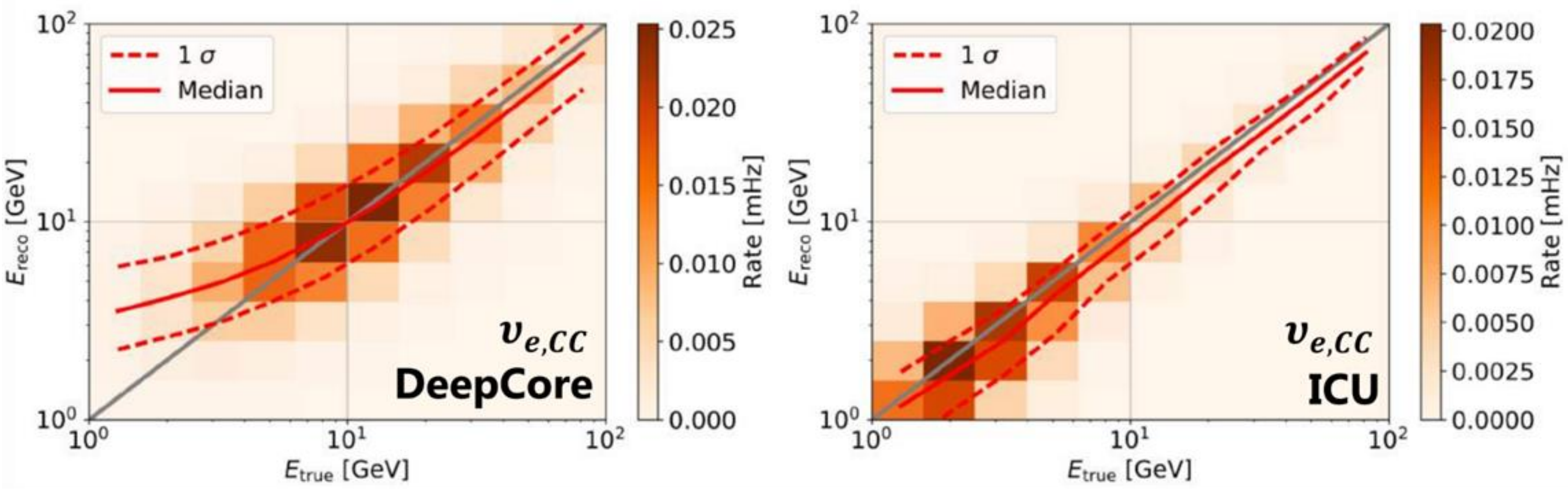




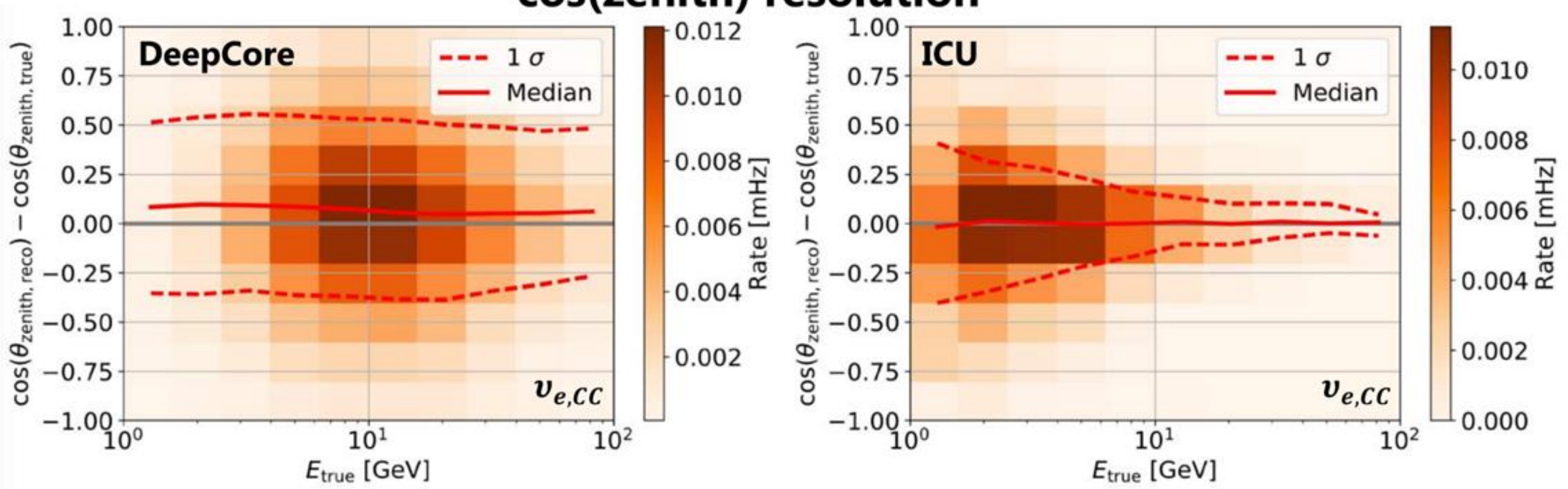
with improved event selections

Low Energy Event Reconstruction

Energy resolution

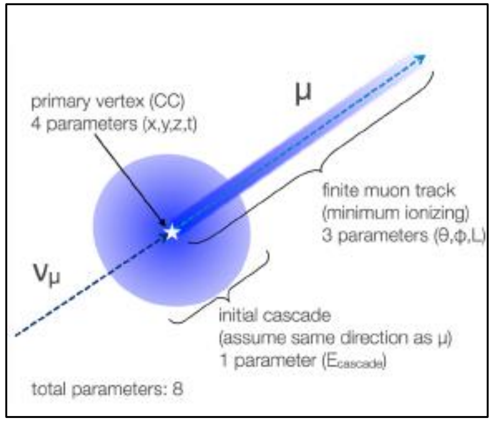


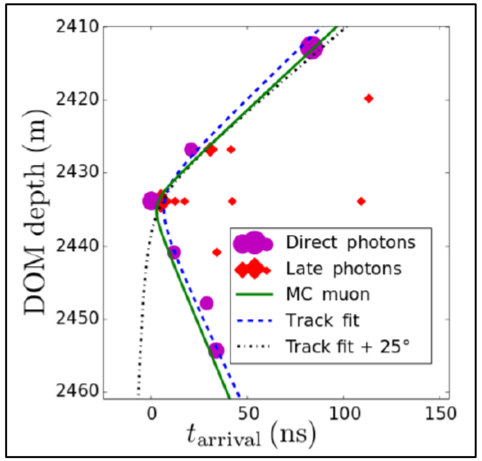
cos(zenith) resolution



- systematics not included

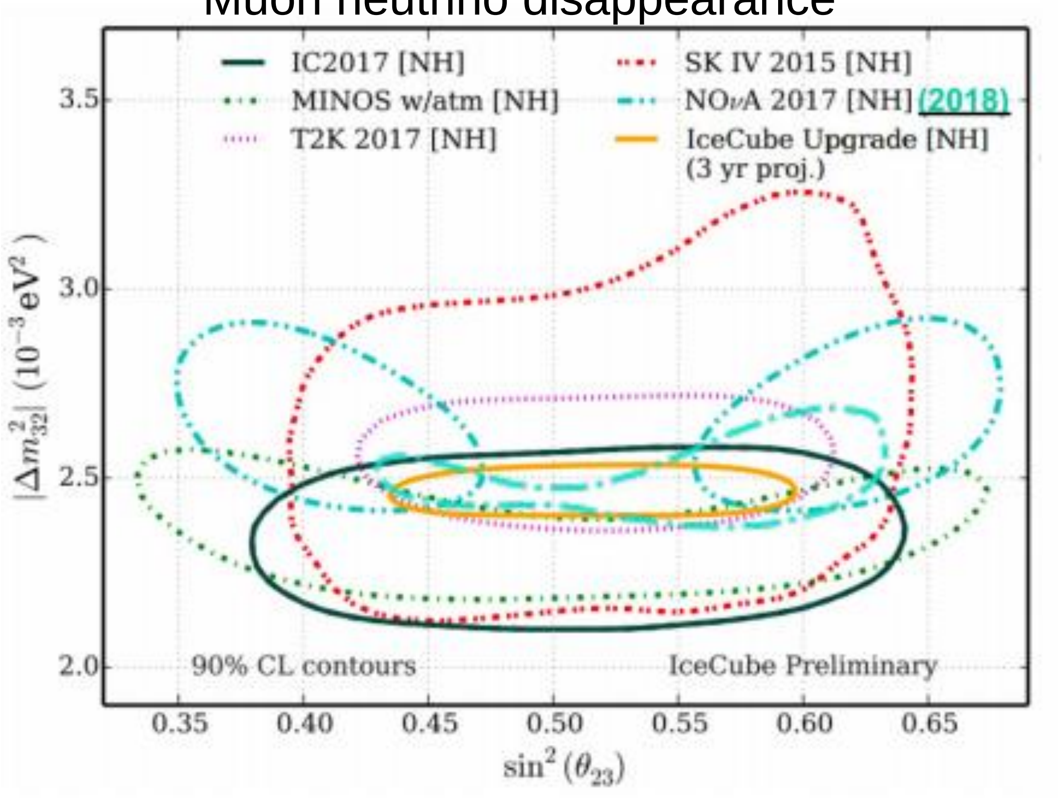
reco methods



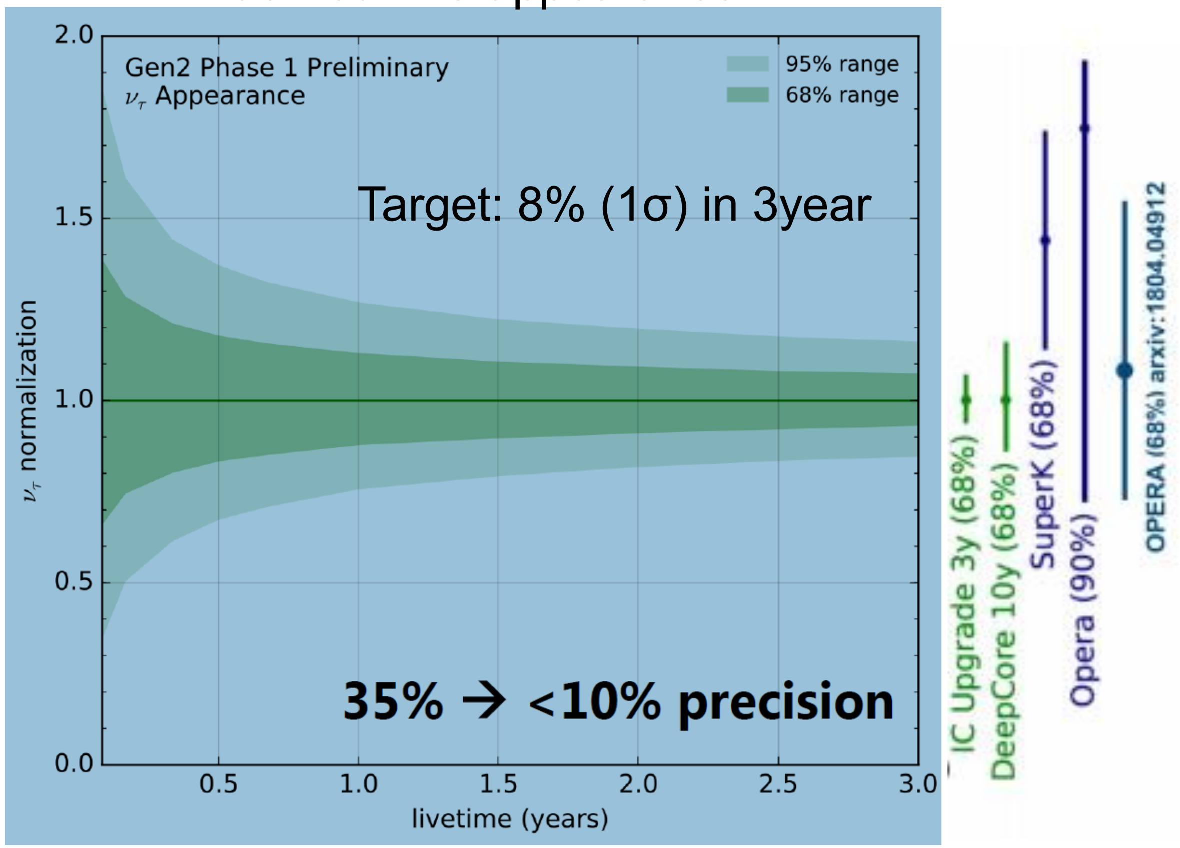


Expected Sensitivities

Muon neutrino disappearance



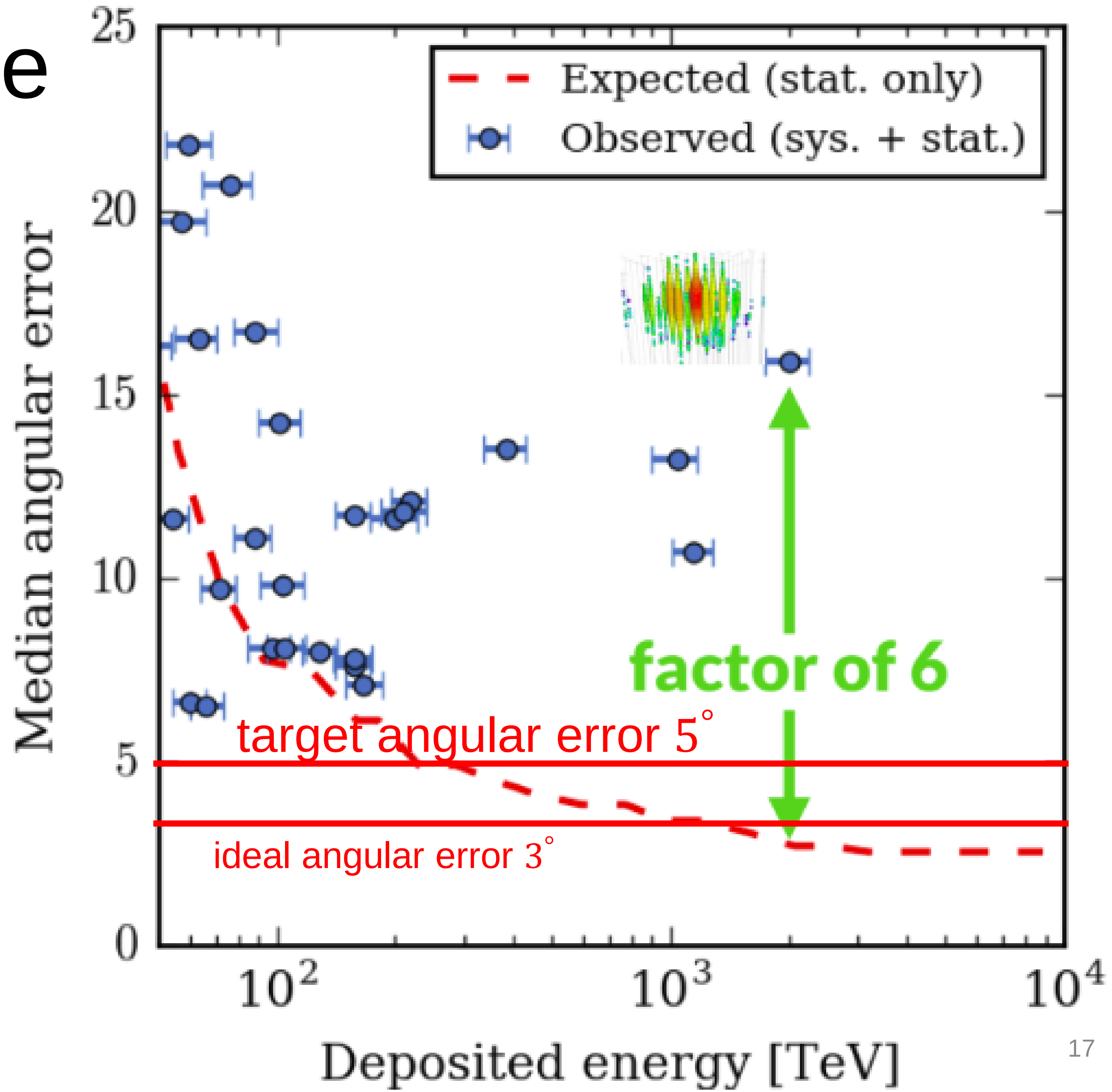
Tau neutrino appearance

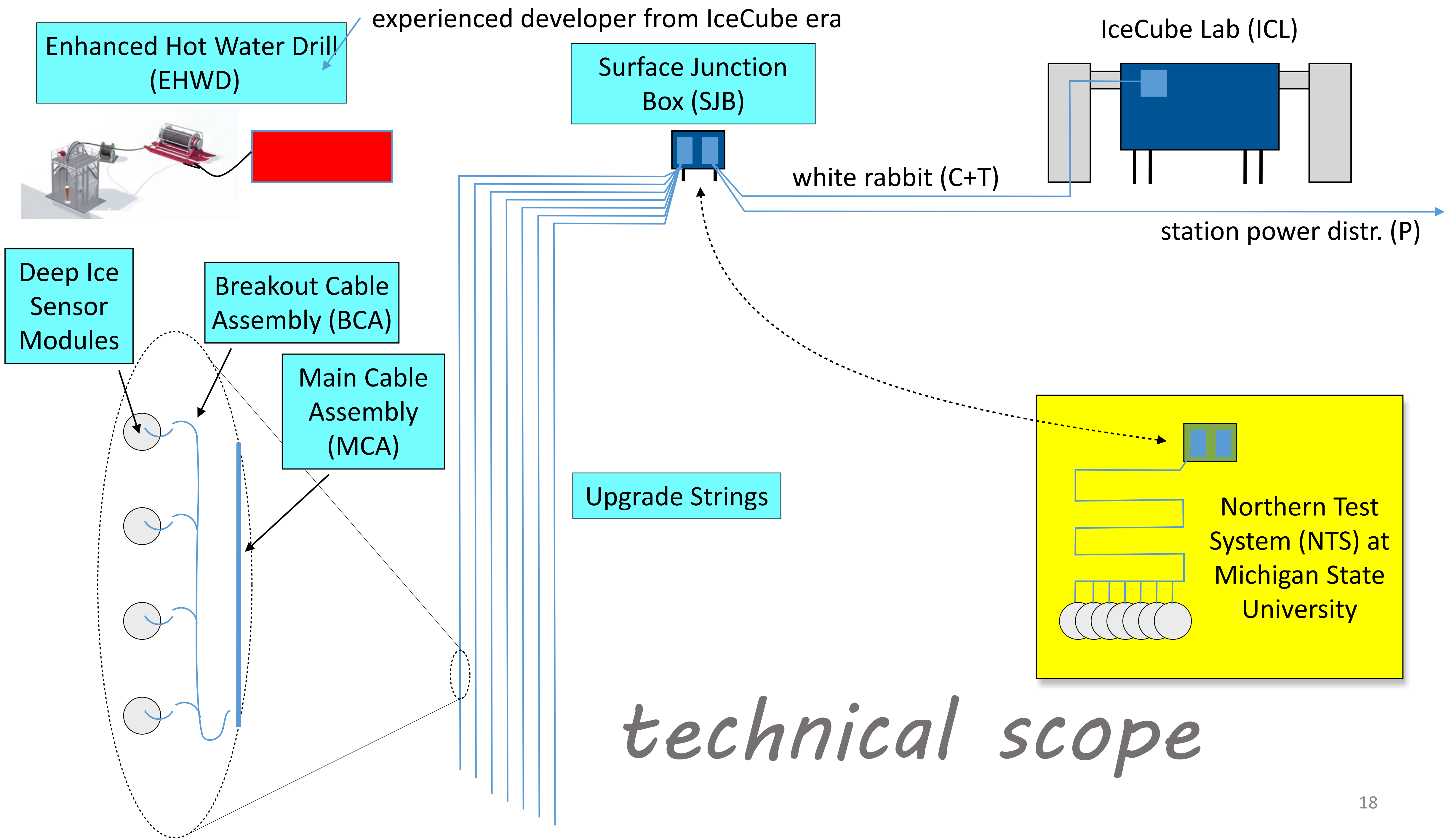


With improved new event selection
10% (1σ) in 1year foreseen

High energy cascade reconstruction

- Full calibration of ice properties allows us to calibrate and re-analyze of 10 years of IceCube data
- More efficient cascade point source analysis possible
- Better reconstructed track and cascade sample using future and past IceCube data





experienced developer from IceCube era
Enhanced Hot Water Drill (EHWD)
Surface Junction Box (SJB)
IceCube Lab (ICL)
white rabbit (C+T)
station power distr. (P)
Deep Ice Sensor Modules
Breakout Cable Assembly (BCA)
Main Cable Assembly (MCA)
Upgrade Strings
Northern Test System (NTS) at Michigan State University
technical scope

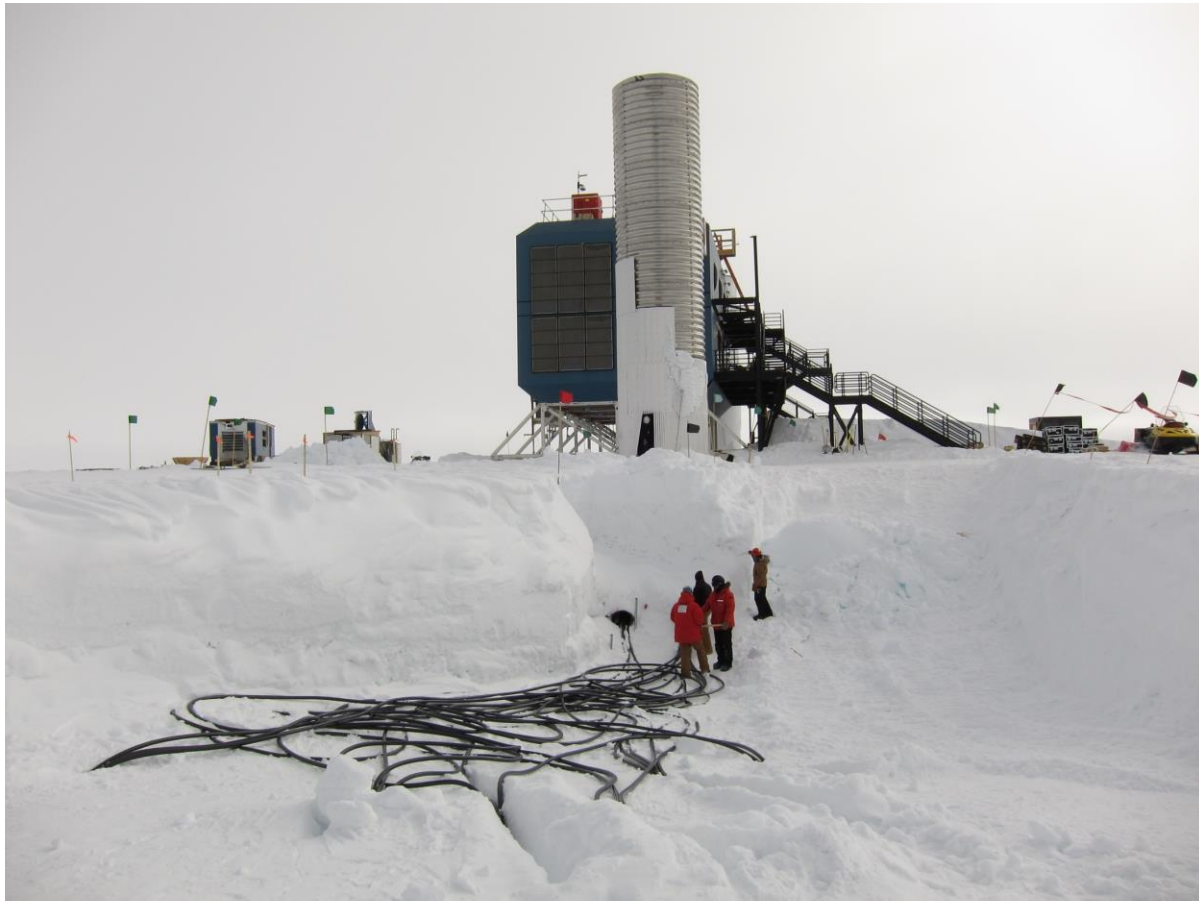
Limited Power, Bandwidth and Wires and more

Working environment -40C~-20C

Construction environment

Temperature shock from air -40C to water +20C

Pressure shock upto 70MPa

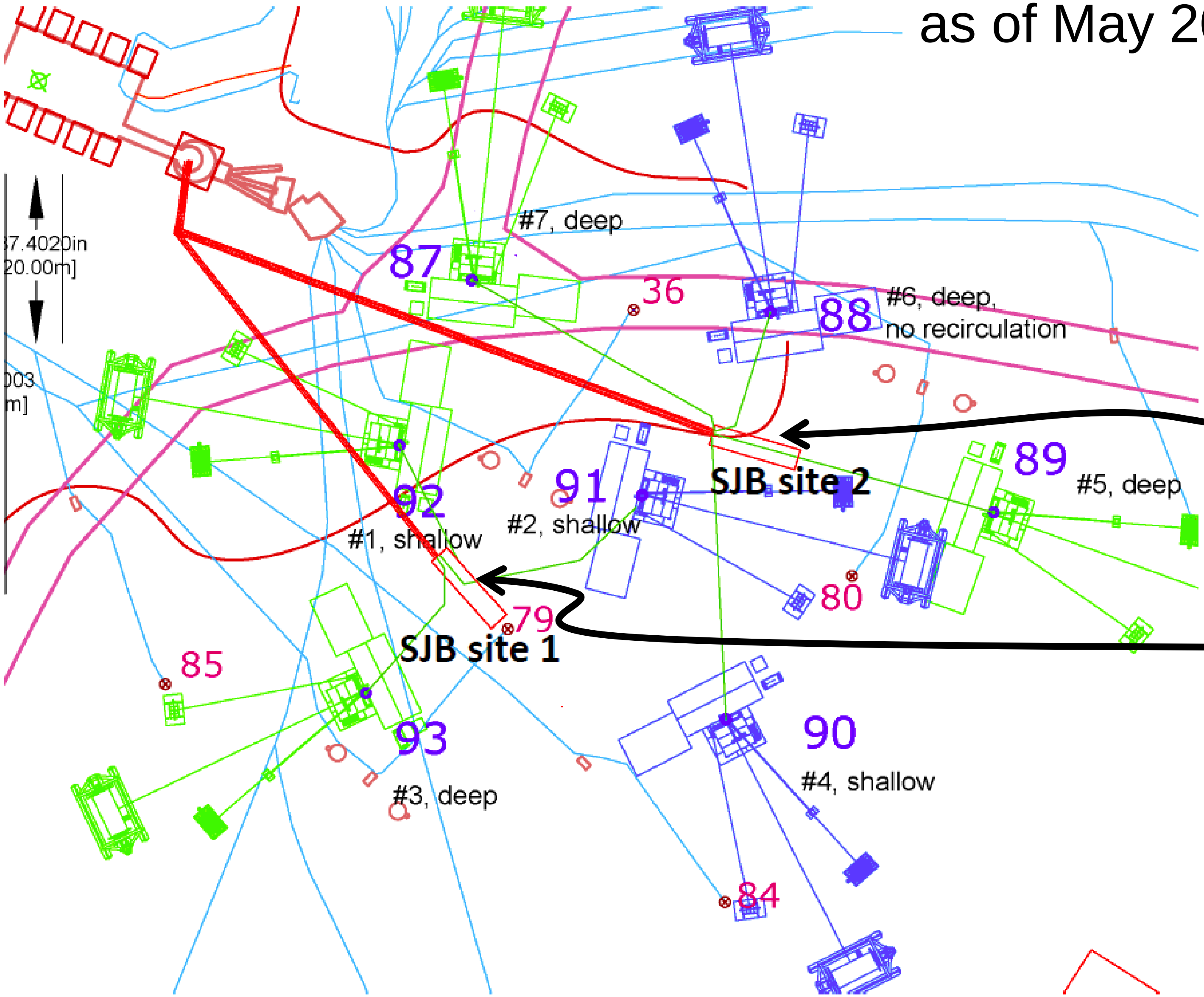


South Pole rated copper wires are very expensive

- One OM has only a wire pair lines. Communication over input power ±48 V
- Maximum available bandwidth is ***1.2 Mbit/sec/pair***. A wire pair is shared with several modules. Design target <= 4 devices / wire pair
- ***~18W per wire*** pair given +/-48V distribution, including nominal surface cable lengths. Design target <= 4 devices / wire pair
- For upgrade 3 x DOMs / pair, and max 2 mDOMs / pair

String 87 to 93

as of May 2019 - still under adjustment

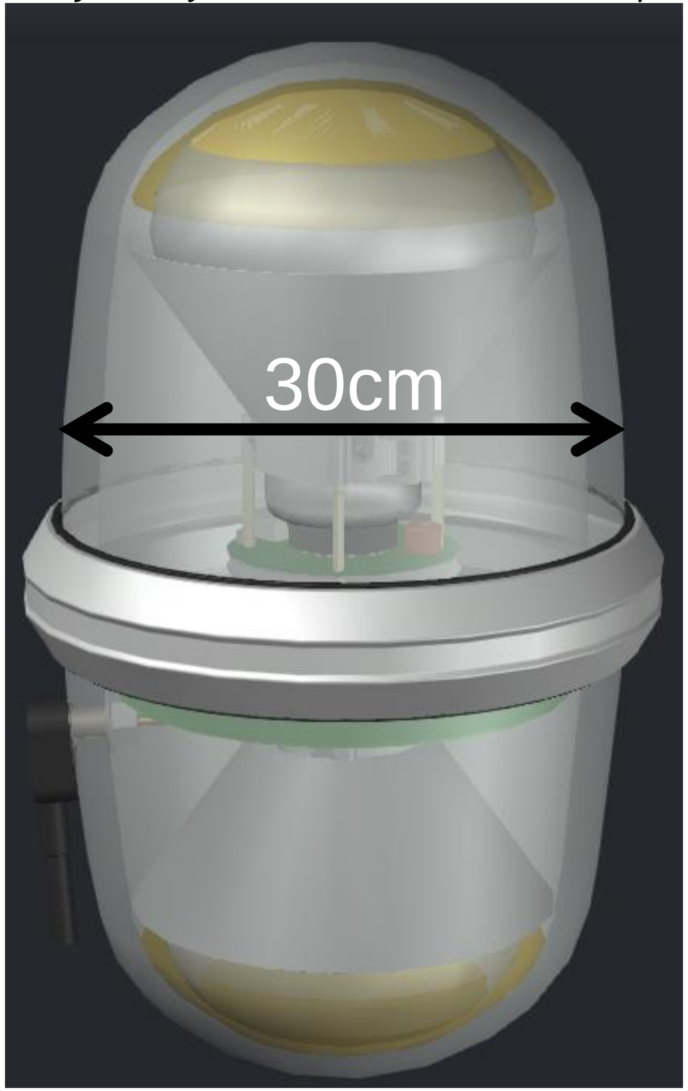


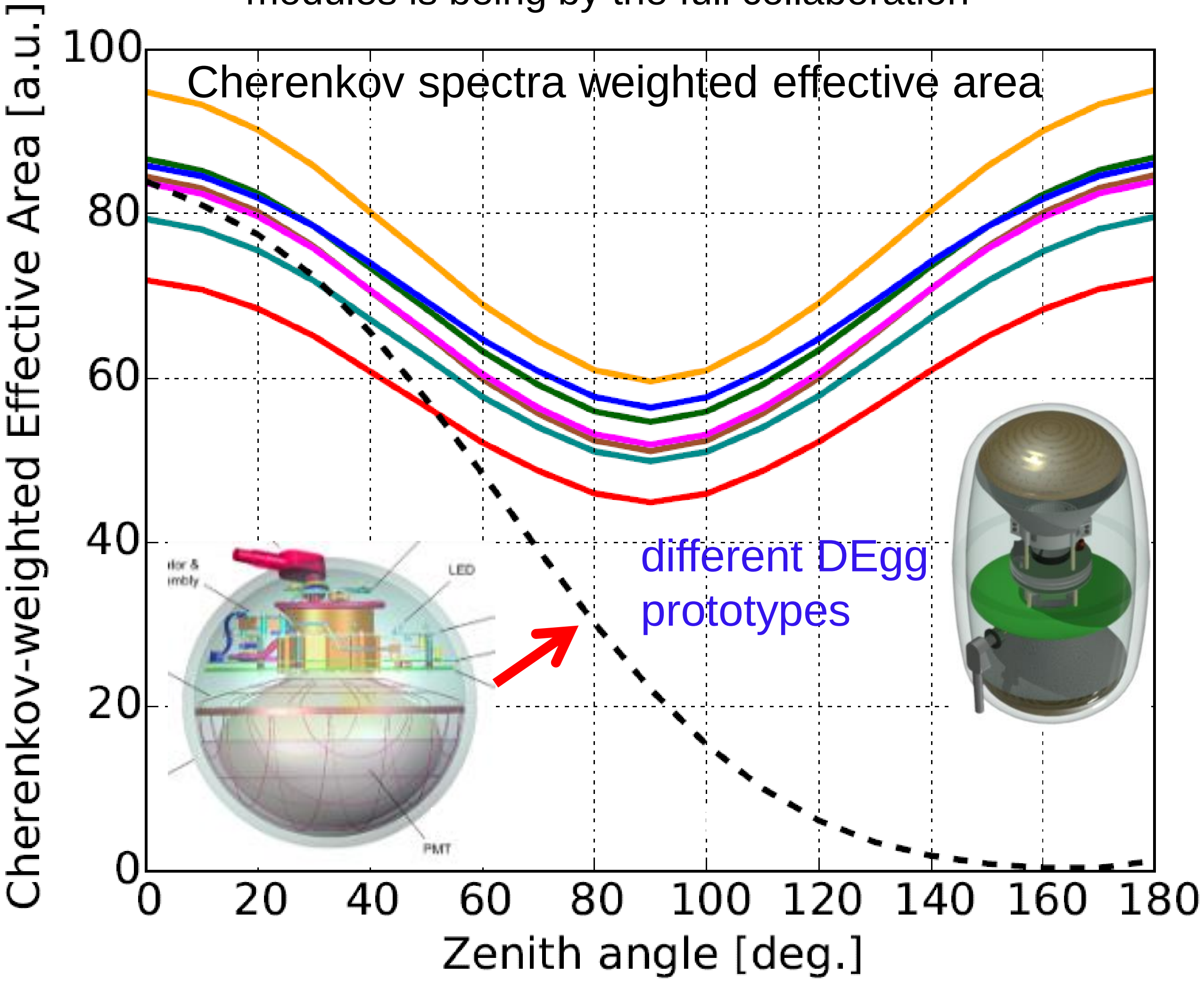

passive junction boxes

New Optical Module: DEgg

Full review process has started since the last September. Each components as well as integrated modules is being by the full collaboration

D-Egg





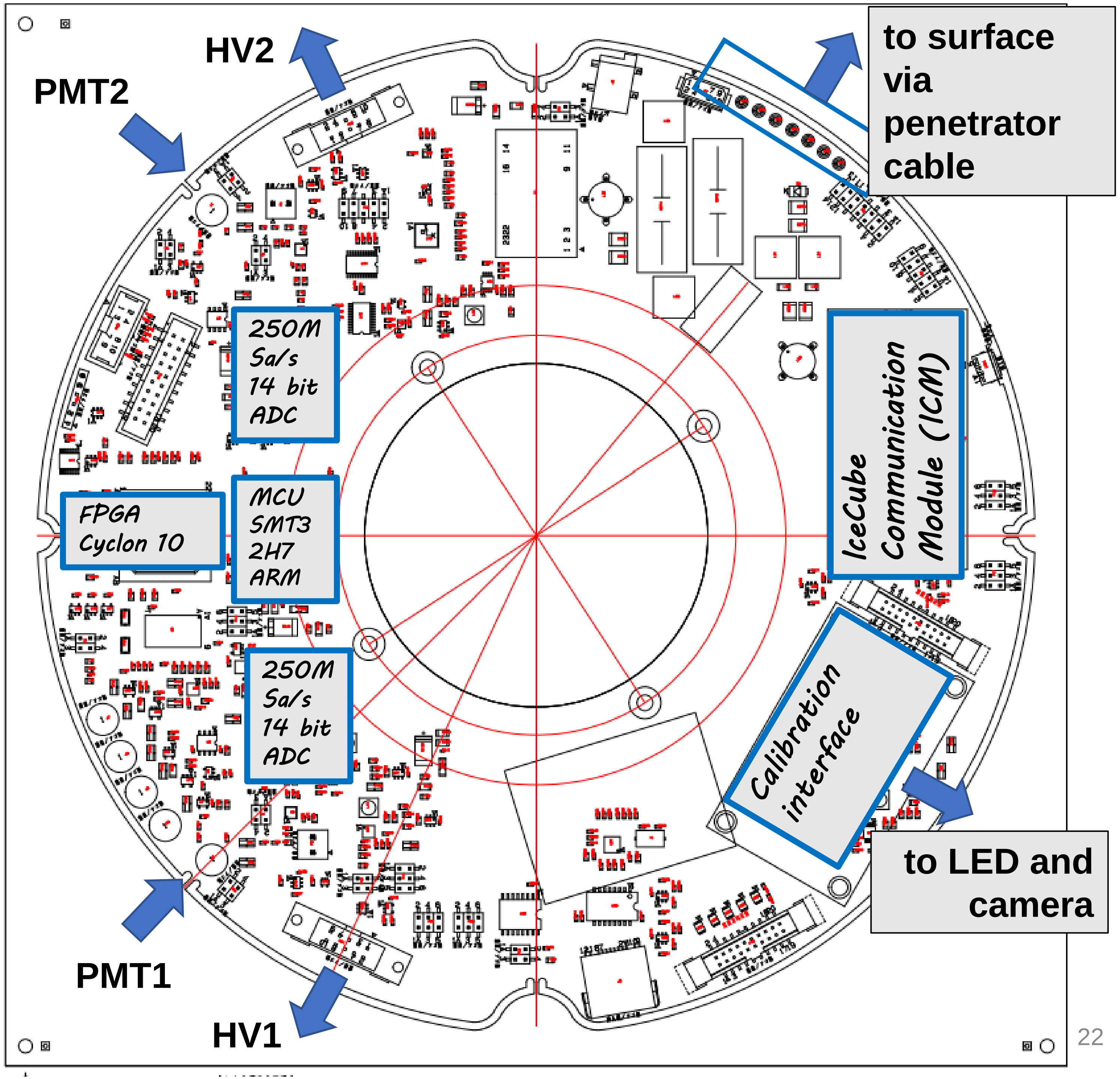
Final verification of Design in Sept to December, 2019
300 DEgg production starts in January 2020

DEgg Readout

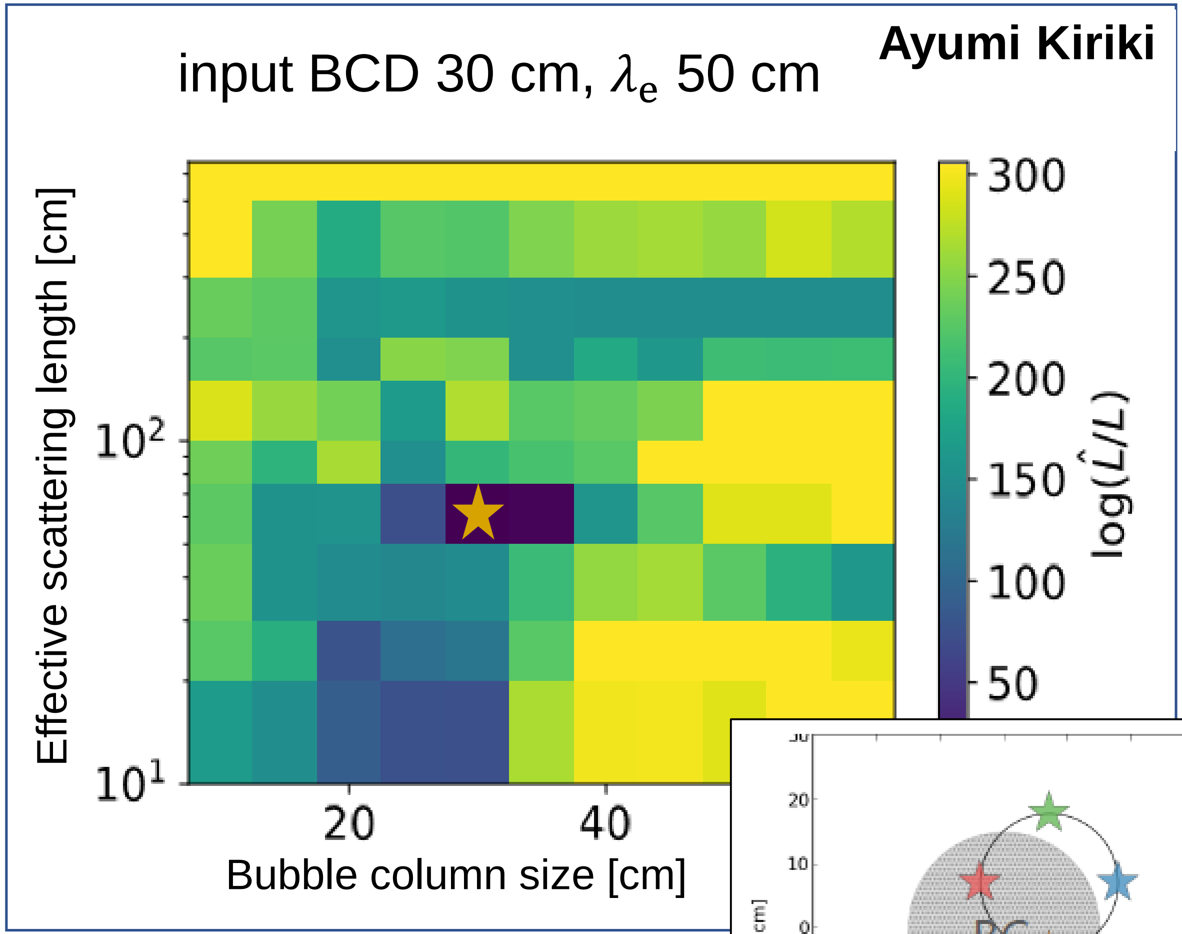
- Each PMT signals are continuously sampled with two separate 250-MSa/S 14 bit **ADC**s
- **FPGA** takes the digital output of the ADC
- **ICM** (common to all Oms) communication between readout board and surface DAQ
- **Microcontroller unit** common to all OMs serves
  - Configuration/monitoring/readout of hardware
  - Reading and processing hits/waveforms in memory buffer; feature extraction
  - Exchanging data with the surface client
  - Loading the DOM FPGA
  - Data reduction and analysis for testing/calibration, e.g. calibration

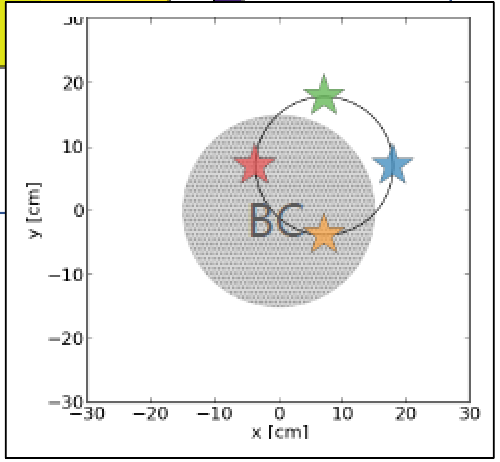
Expected power consumption:
- 240mW(ADC) x 2ch + 100mW(HV) x 2ch +1000mW(FPGA) + 250mW(MCU) = **1.93W**

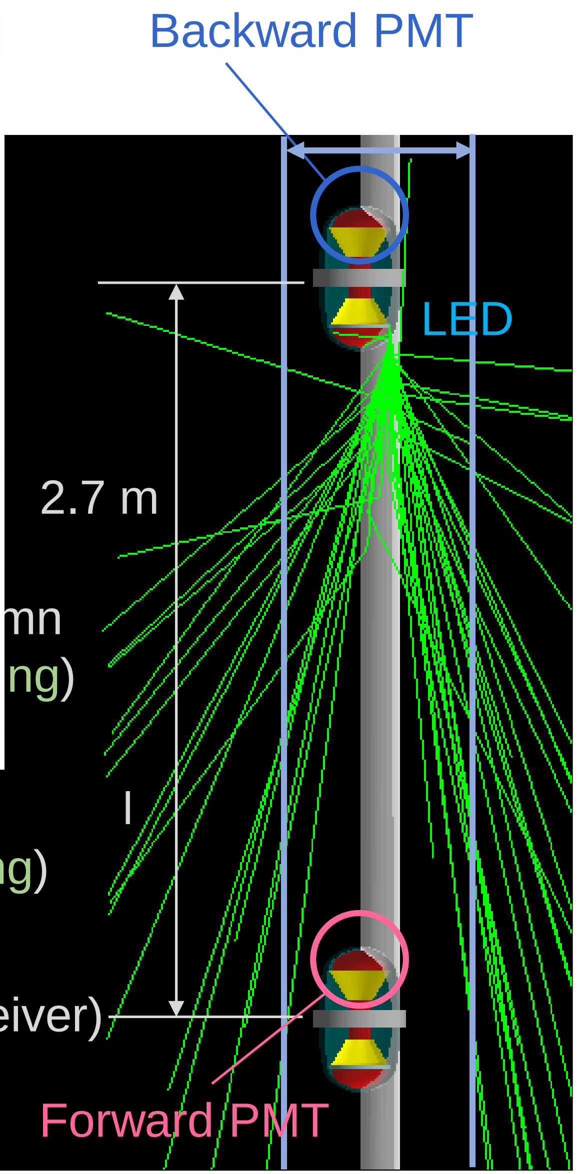
Expected bandwidth:
- **360 kbps** without pulse extraction
- 120kbps with pulse extraction



Measurements of refrozen ice properties with DEgg







Refrozen ice bubble column properties can be resolved even they are not in the center of the hole

mDOM

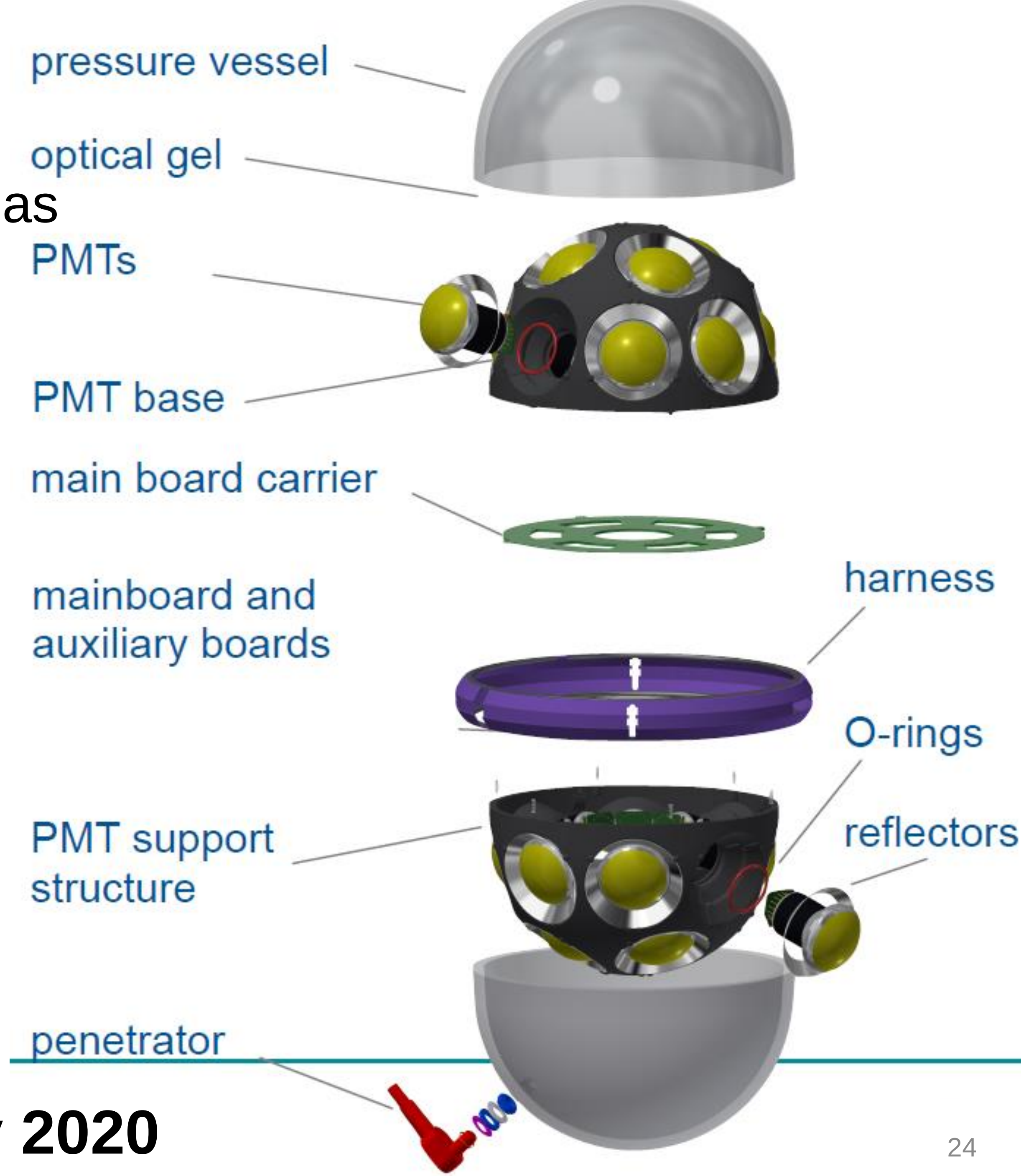
Pros: Large detection area, 24 segmented areas

Cons: Large

challenges on

- power consumption
- negative cathode
- bandwidth (noise)
- readout

	Noise rate [Hz]	
	Per PMT	Per OM
IceCube	569	569
DEgg	891	1782
mDOM	385	9240
pDOM	622	622



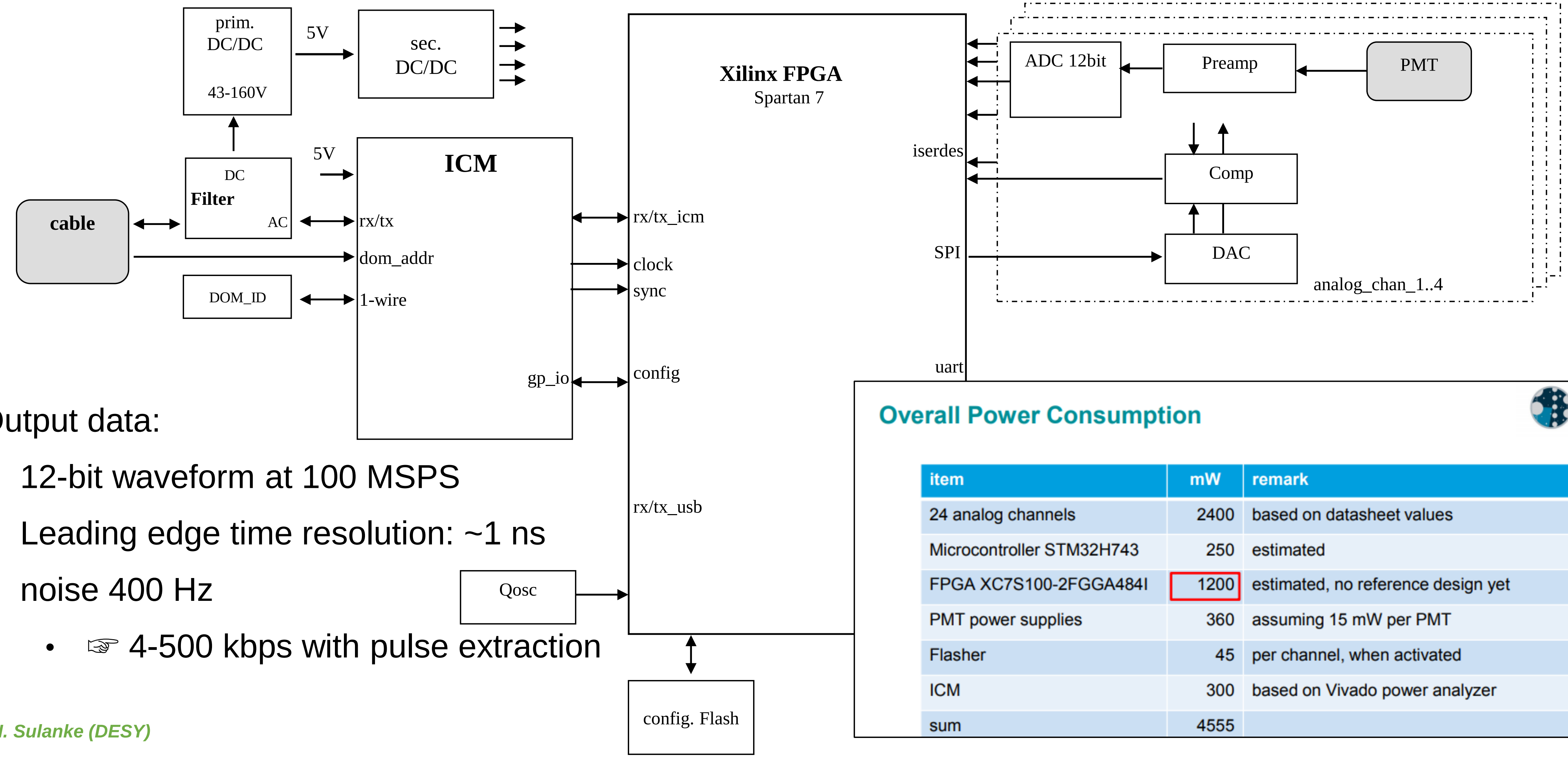
400 mDOM production starts in July 2020

mDOM Readout

Quad-Channel, 12-bit, 125 MSPS ADC
Ultra-Low Power Consumption: 98 mW / Ch

ADC3432
Sampling @ 100 MHz
(can switch to 125 MHz in FW if needed)

ADCMP600
Combined 24 channels to measure TOT @ ~1 GHz



Output data:

- 12-bit waveform at 100 MSPS
- Leading edge time resolution: ~1 ns
- noise 400 Hz
  - ☞ 4-500 kbps with pulse extraction

Overall Power Consumption

ICECUBE GEN2

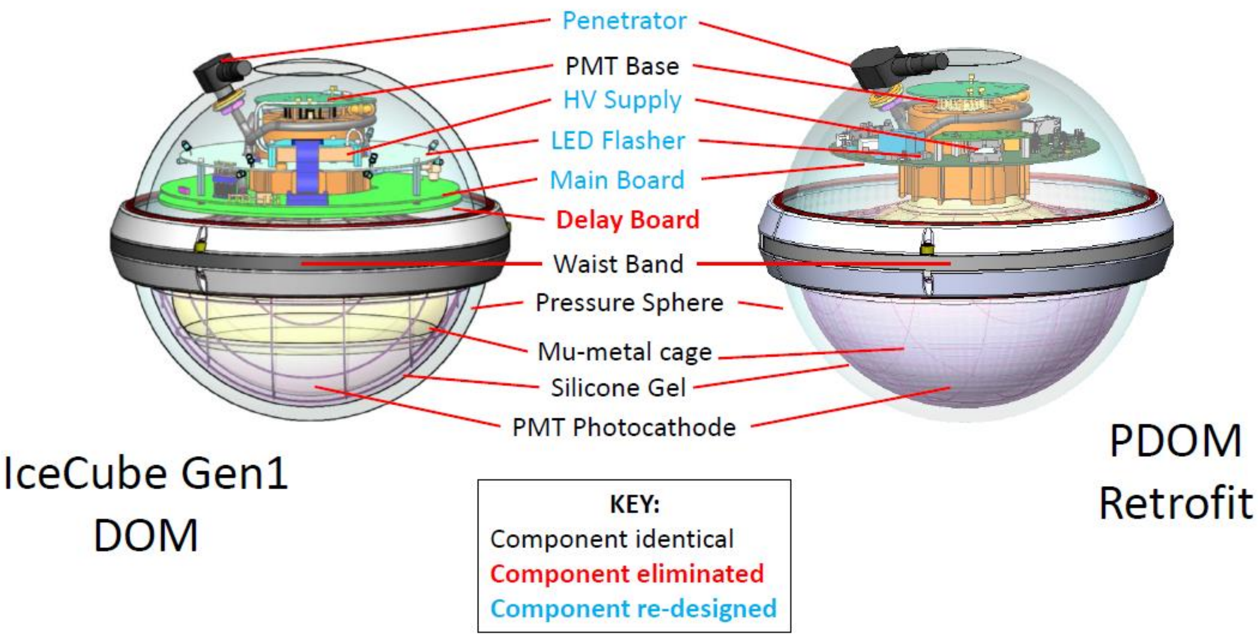
item	mW	remark
24 analog channels	2400	based on datasheet values
Microcontroller STM32H743	250	estimated
FPGA XC7S100-2FGGA484I	1200	estimated, no reference design yet
PMT power supplies	360	assuming 15 mW per PMT
Flasher	45	per channel, when activated
ICM	300	based on Vivado power analyzer
sum	4555	

K.-H. Sulanke (DESY)

PDOM

Gen1 DOM + Electronics the same as D-Egg

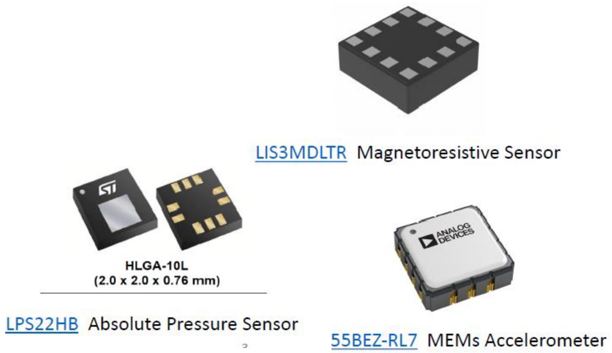
100+ retrofit candidates "ready to ship" or with various FAT faults

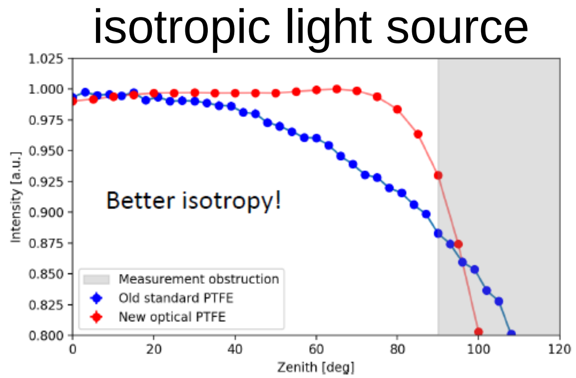


Calibration devices

All optical sensors contain the same

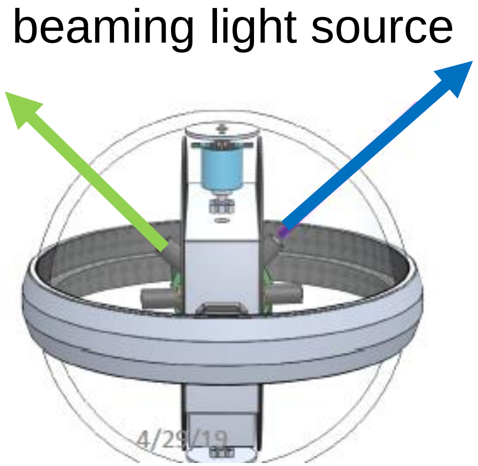
- Cameras (3)
- LEDs in each optical sensors (12 LEDs for DEgg and min 9 for mDOM)
- magnetometer, inclinometer, pressure, temperature sensors
- Acoustic sensors only in mDOM





Standalone lights sources

- PCAM
  - Absolutely calibrated light source, Intensity: 10^6 - 10^{10} p.e., Pulse length: 1 - 70 ns, working prototype
- Pencil Beam
  - points 4π anywhere 12 LED wavelengths. Mechanical prototype built, electronics and collimator design in progress



Schedule

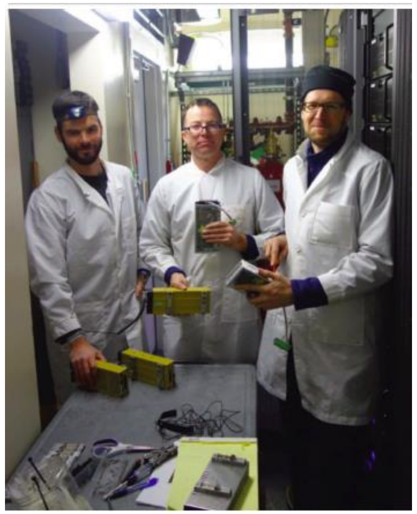
- DEgg design fix in September, verification of 10 fully integrated modules from Oct to Dec 2019
- 300++ DEgg production January 2020 – March 2021
- mDOM design fix in April 2020, verification of 10 fully integrated modules from May to July, 2020
- 400++ mDOM production July 2020 – Aug 2021
- All optical modules have to pass 20days +25C to -50C temperature cycling electric readout test
- Drill development has started! Many members from IceCube development team re-joined
- Drill shipping in 2021-2022 season
- Shipping of all OMs to US in September 2021 traverse to SP by Feb 2022
- Installation of junction boxes and surface cables in 2021-2022 season
- 7 holes in 2022-2023, commissioning and calibration of detector will follow

Summary

- The IceCube experiment has made a significant progress on the HE neutrino astronomy
- The next definite target is to discover more neutrino emitting sources with multimessenger technique!
- While moving in the direction, a test bed for Gen2 and also upgrade of IceCube are being projectized, called Gen2-Phase 1 or IceCube Upgrade, as it acts both roles (and funded)
- Much smaller project compared to Gen2 but significant challenges, need to move forward in timely manner, construction season is 2022/2023!
- Can expect significant improvements on the understanding of the IceCube detector, including optical properties of glacial ice, and tau appearance analysis

Power requirements

Acopian Power Supply Model W48NT600



S. Axani, T. Bendfelt, and P. Eller swapping power supplies

- 3 xDOMs / pair, and max 2 mDOMs / pair
- Target power consumption DEgg/PDOM 4W
- Total DOM power: 4.7–9.4 kW
  - Loss (heat) from DOM power supplies: 0.6–1.4 kW
  - Other electronics: 0.7–2.0 kW
- Peak power capacity excluding heating 13kW
- Limited power consumption (<4W per DOM, measu 5.7W/OM including power supply efficiency and tra losses)

Mean Well MSP-200-48

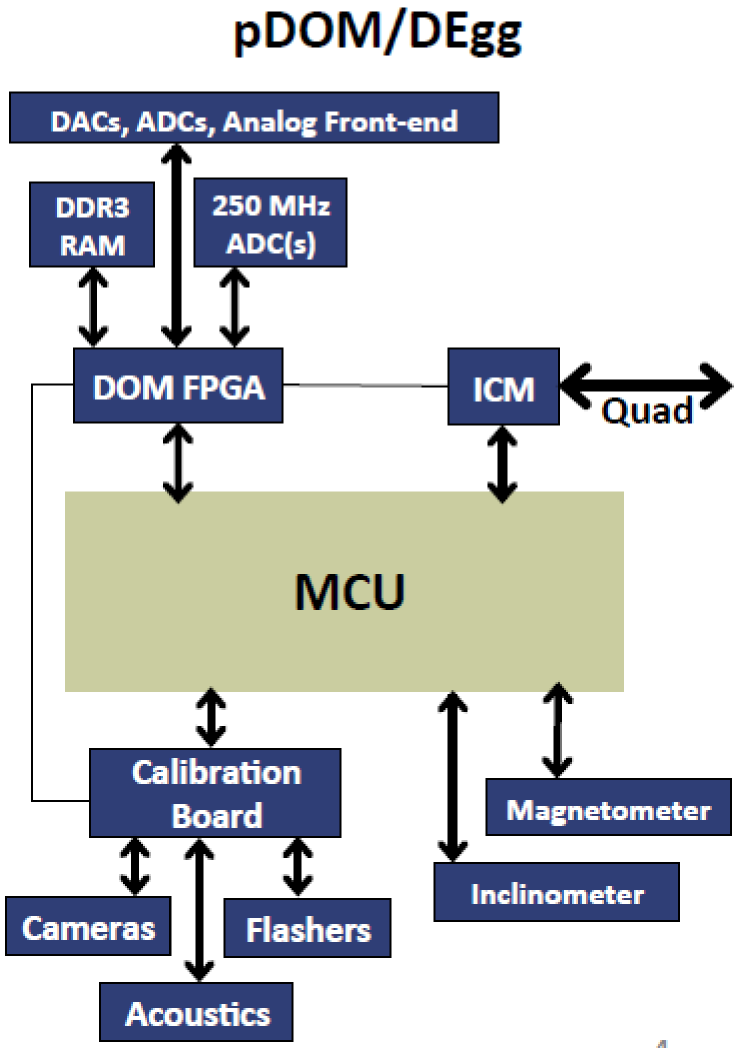
Data transfer

- Total data rate per module 371 kb/s this is the required data bandwidth per module if no signal processing on FPGA takes place
- Solution: Main Cable Assemblies connect into the ICL
- via new Surface Cable Assemblies and passive Surface
- Junction Boxes
- • proven strategy from IceCube–Gen1
- • SCAs and SJBs to be deployed in 21–22 season
- • reduce risk to drill / deployment schedule
- • quick string connection for commissioning, calibration runs

microcontroller

MCU responsibilities

- – Configuration/monitoring/readout of hardware
- – Reading and processing hits/waveforms in memory buffer; feature extraction
- – Exchanging data with the surface client
- – Loading the DOM FPGA
- – Data reduction and analysis for testing/ calibration
- STM32 ARM Flash memory (via ICM)



Overall Power Consumption

Power budgent

item	mW	remark
24 analog channels	2400	based on datasheet values
Microcontroller STM32H743	250	estimated
FPGA XC7S100-2FGGA484I	1200	estimated, no reference design yet
PMT power supplies	360	assuming 15 mW per PMT
Flasher	45	per channel, when activated
ICM	300	based on Vivado power analyzer
sum	4555	

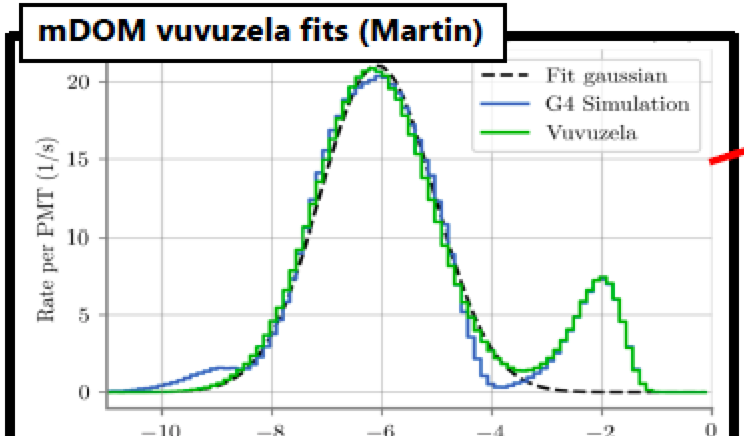
item	mw	comments
high speed ADC	240x2=480	
microcontroller STM32H743	250	estimated
FPGA Cyclone 10	1000	estimated no reference yet
PMT power supplies	100mW (SVM)x1	estimated need to be evaluated
	300mW (Matsusada)	estimated need to be evaluated

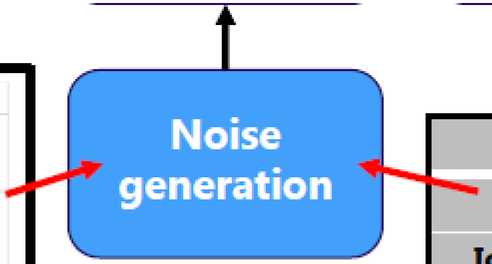
ICM

- MB readout
- HV slow control (monitor)
- MB boot control
- MB sensor monitor

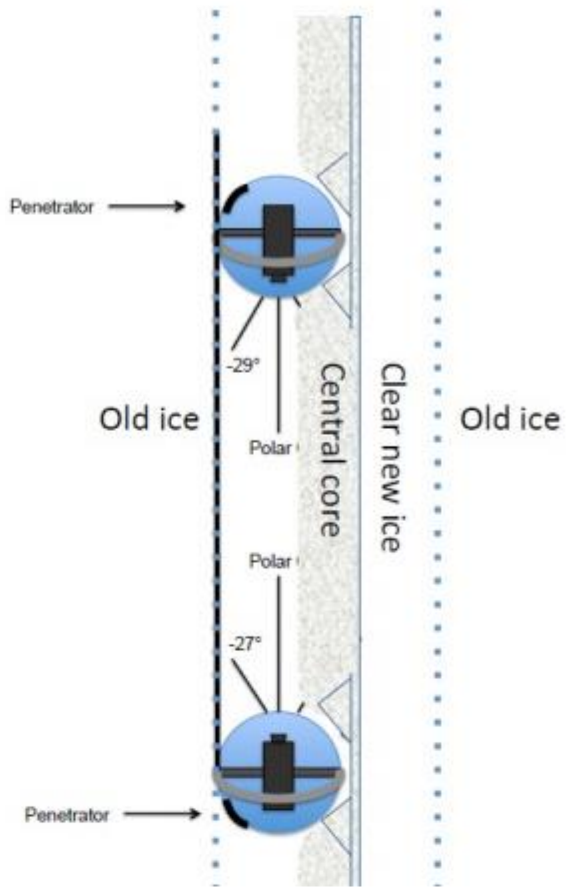
Limiting number of xDOMs

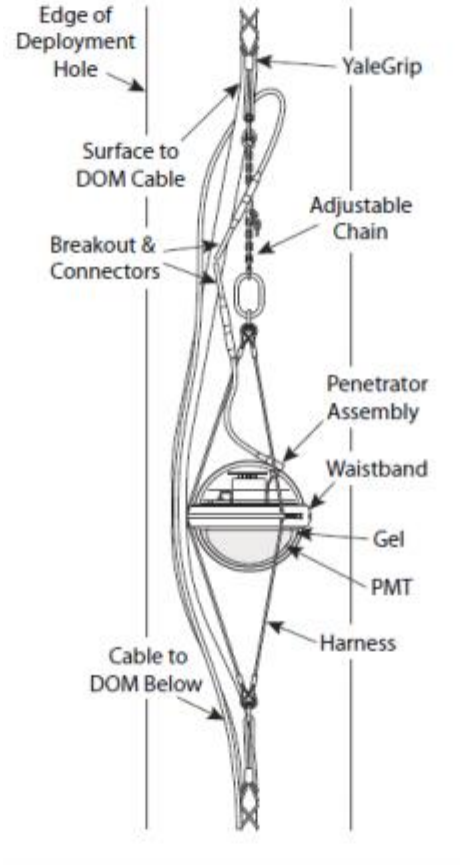
- <= 2 mDOMs / wire pair
  - Conservative for bandwidth
- 300 DEggs 400 mDOMs 12 pDOMs
- 15 Long and narrow R&D Optical sensors for Gen2 (fits in 15cm holes)



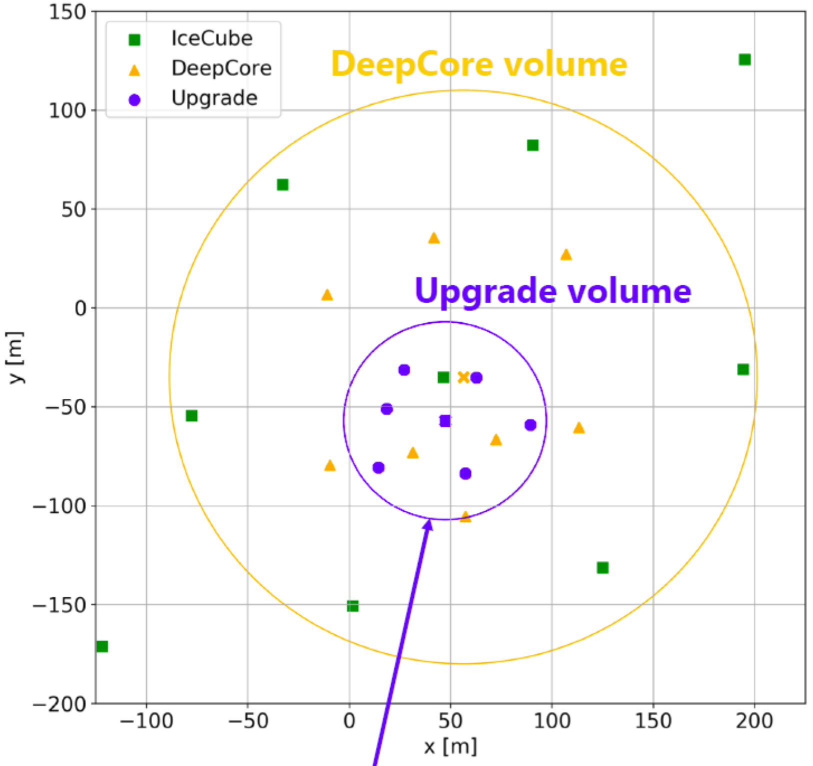


	Noise rate [Hz]	
	Per PMT	Per OM
IceCube	569	569
DEgg	891	1782
mDOM	385	9240
pDOM	622	622

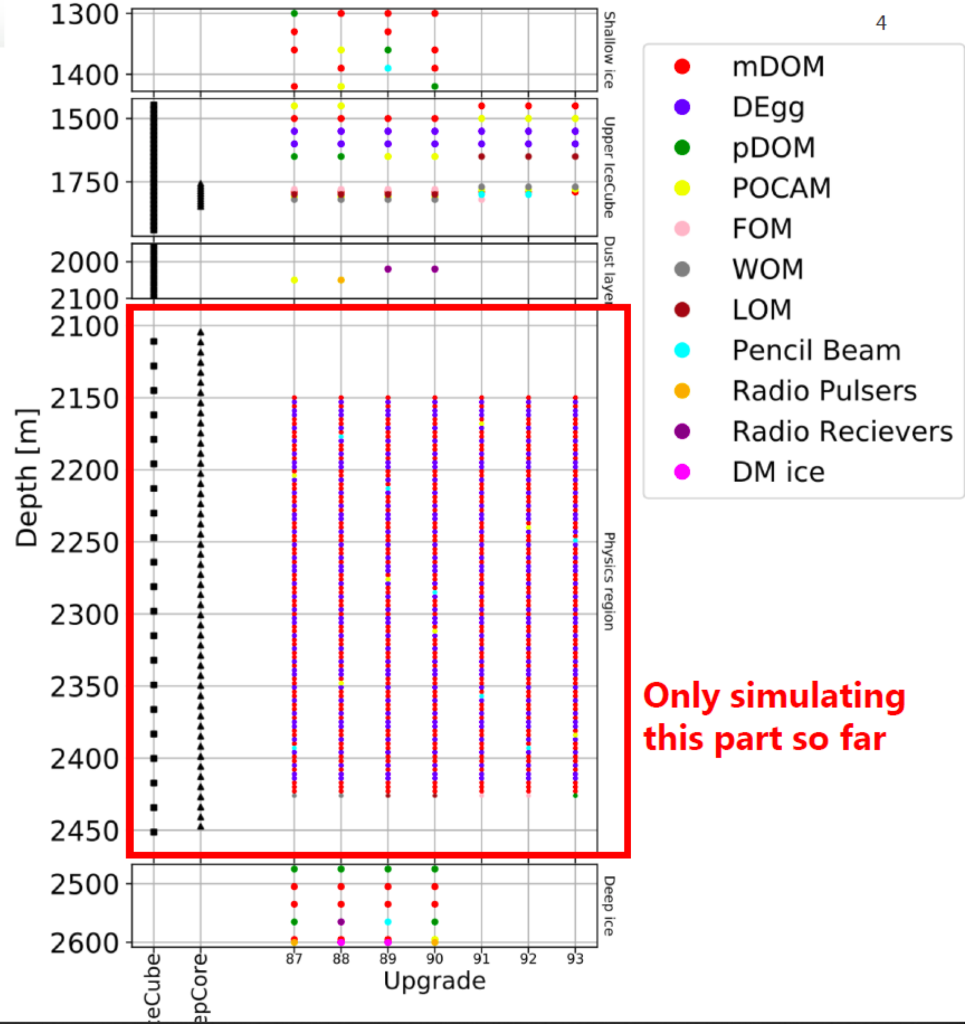

Penetrator
Penetrator
-29°
-27°
Polar
Polar
Old ice
Central core
Clear new ice
Old ice


Edge of Deployment Hole
YaleGrip
Surface to DOM Cable
Adjustable Chain
Breakout & Connectors
Penetrator Assembly
Waistband
Gel
PMT
Harness
Cable to DOM Below

Geometry



Only using Upgrade volume for analysis so far (2 Mton)



Construction

passive junction boxes

#1 **DeepCoreFilter**

- 12 IceCube strings 8 DC strings
- uses a fiducial volume based on all strings with a 3-layer veto
  - seededRT cleaned SLC hits + HLC
  - SMT3 ⇒reject down-going atmospheric muons with 3 veto layer ⇒
  - Time corrected COG in the fiducial volume
  - Exclude events with one or more time (speed of light) correlated hits in the veto region

Transport Summary by Method by Season					
Method of Transport	**2019/20**	**2020/21**	**2021/22**	**2022/23**	**TOTAL**
Vessel to McMurdo	49,172	33,200	147,600	-	**229,972**
ComSur to CHC	24,400	24,400	88,550	42,600	**179,950**
ComAir to CHC	-	-	2,000	3,600	**5,600**
C-17 to McMurdo	24,400	24,400	90,550	46,200	**185,550**
Traverse ZCM to NPX	61,000	104,372	-	-	**165,372**
Fly LC-130 ZCM to NPX	24,400	39,600	123,750	193,800	**381,550**
Estimated Flights (23,800/ea)	**1**	**2**	**5**	**8**	**16**

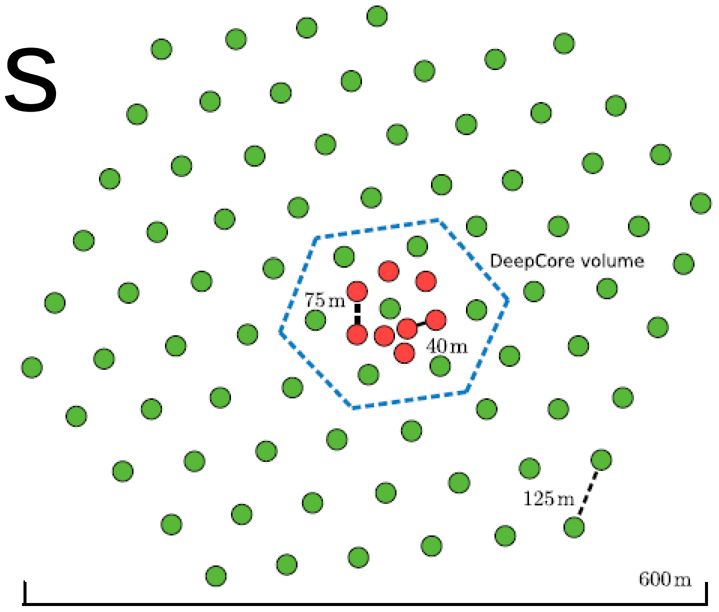
* All weight in pounds

- Traverse consists only of EHWD Generator modules and over-sized SALSA equipment
- Does NOT include fuel (cargo only)

D-Egg

- Toward 10 DVT DEgg testing

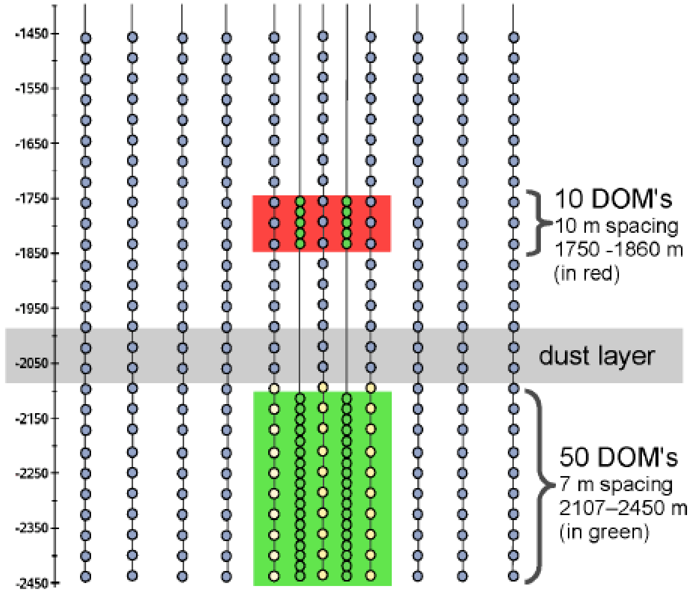
DeepCore oscillation analysis



8-DC strings and 7-IC strings forms a DC low E neutrino array

- Sample: nu mu CC interaction induced ***contained*** muon track
  - Use an active veto
  - Reconstruct neutrino zenith angle as proxy for L & E

- Analyses: To measure $\nu_\mu \rightarrow \nu_\mu$ survival pattern (absorption, but not due to νN interactions)
  - The pattern is convoluted with initial ν_μ flux, interaction probability, and detection probability in 15GeV-50GeV
  - Compare the flux with predictions with different oscillation parameters

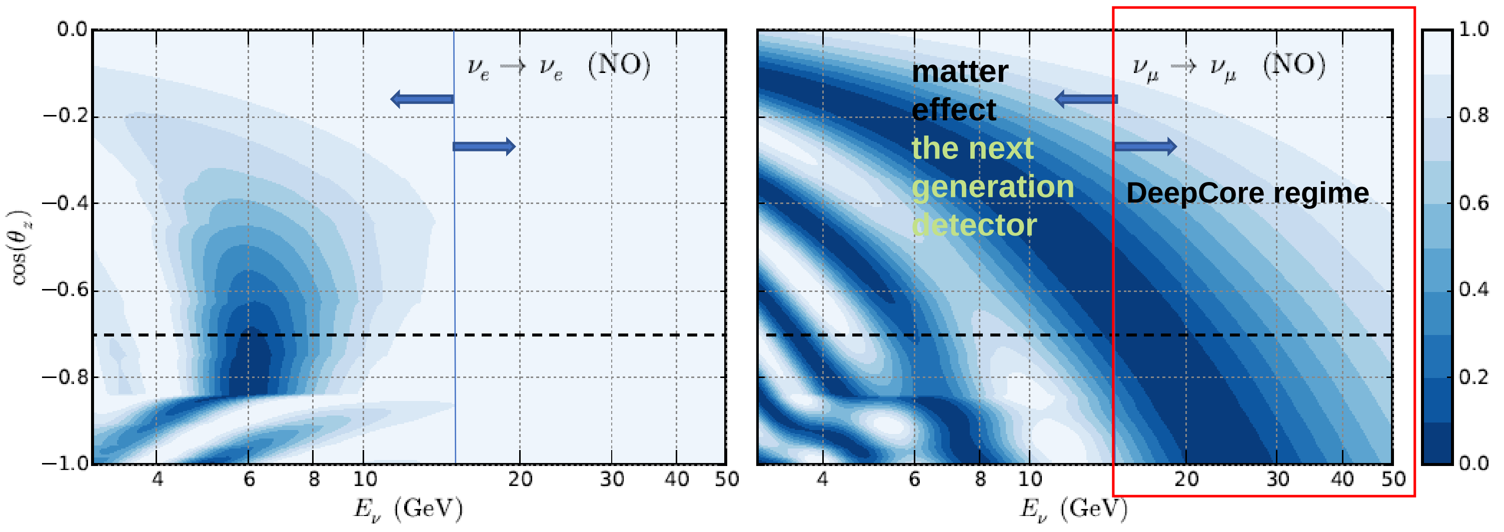


PHYSICAL REVIEW D 91, 072004 (2015)

What we want to measure?

- ➢Survival probability of muon neutrinos

Advances in High Energy Physics (2015) Article ID 271968 arXiv:1509.08404



Energy region 15GeV-50GeV

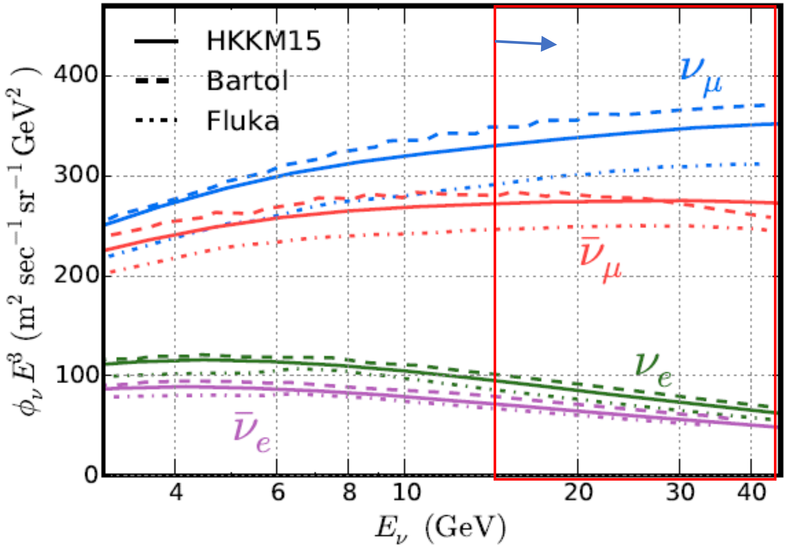
- Smooth disappearance pattern
- Independent of mass ordering
- Dominated by $\nu_\mu \to \nu_\tau$ transitions

Measureable pattern

- These oscillation patterns are convoluted with ***initial atmospheric neutrino fluxes*** and ***interaction***

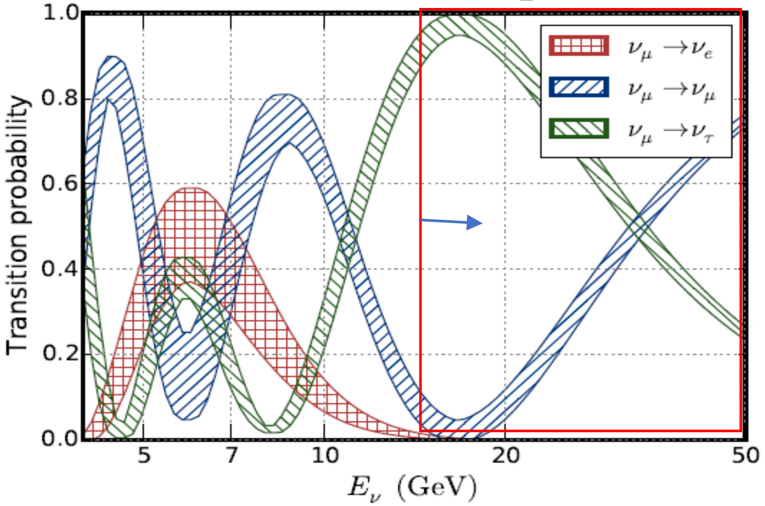
neutrino-nucleon
DIS dominant

$$CR + N \to X + \pi^{\mp}, K^{\mp},$$
$$\pi^-, K^- \to \mu^- + \bar{\nu}_\mu,$$
$$\pi^+, K^+ \to \mu^+ + \nu_\mu,$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



$\otimes$

Slice at $\cos(\theta_z)$=-0.7



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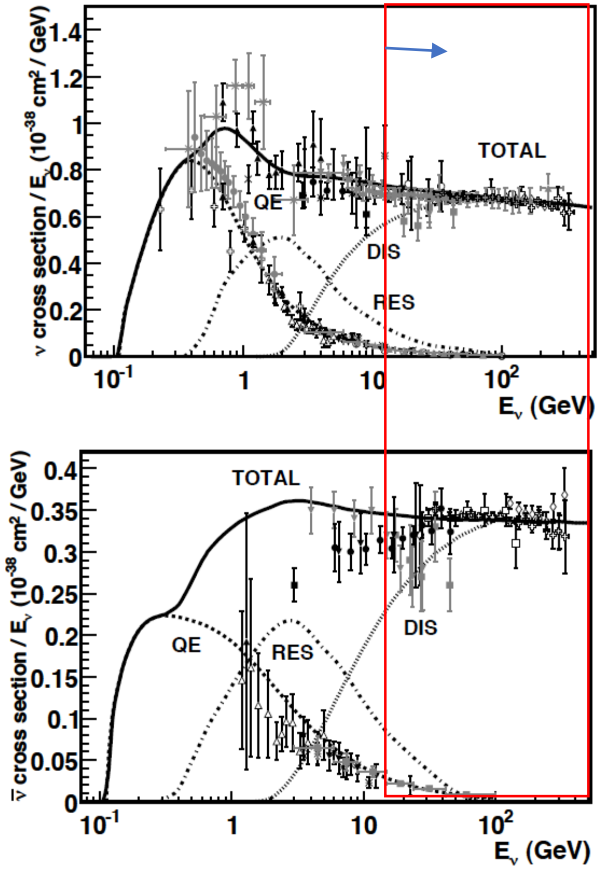
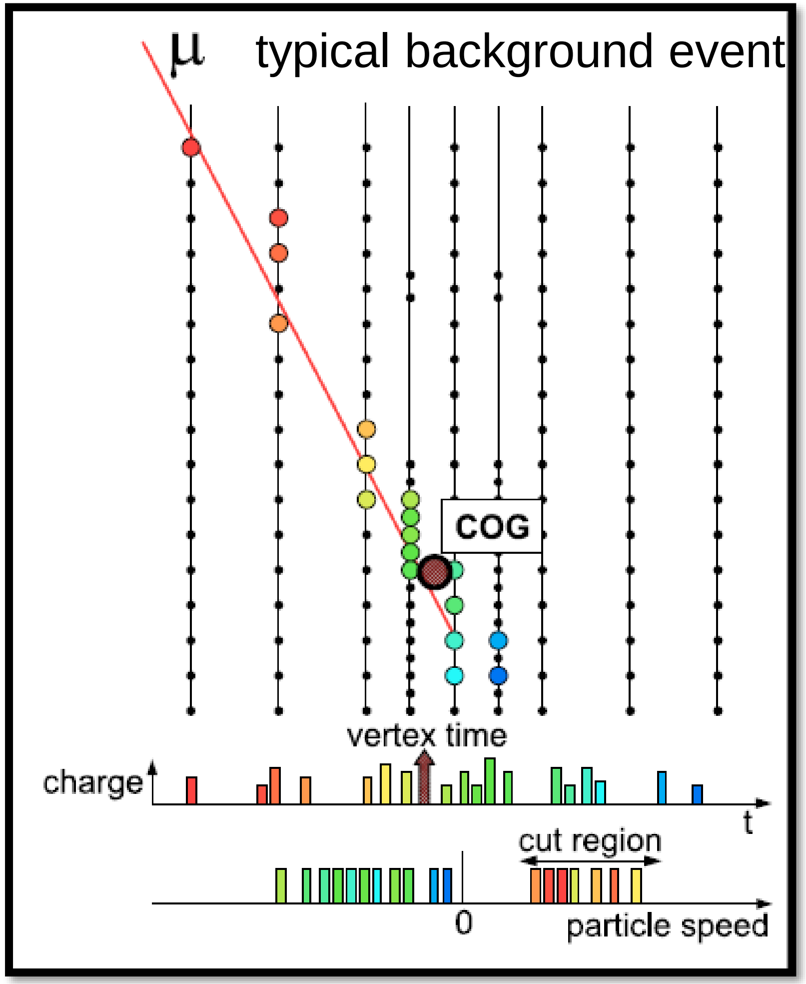
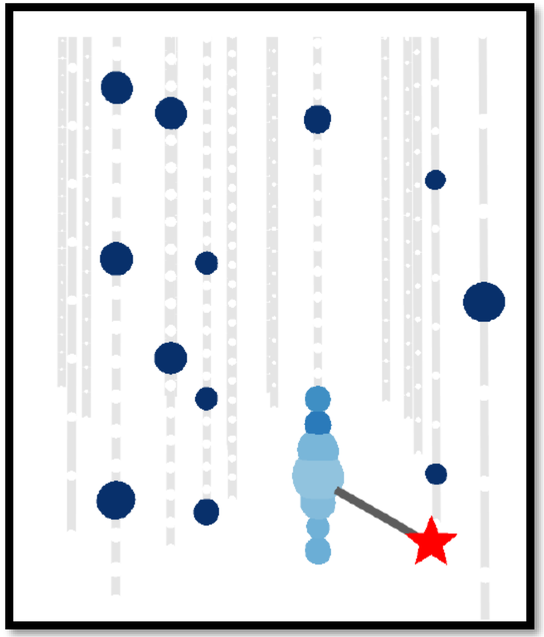


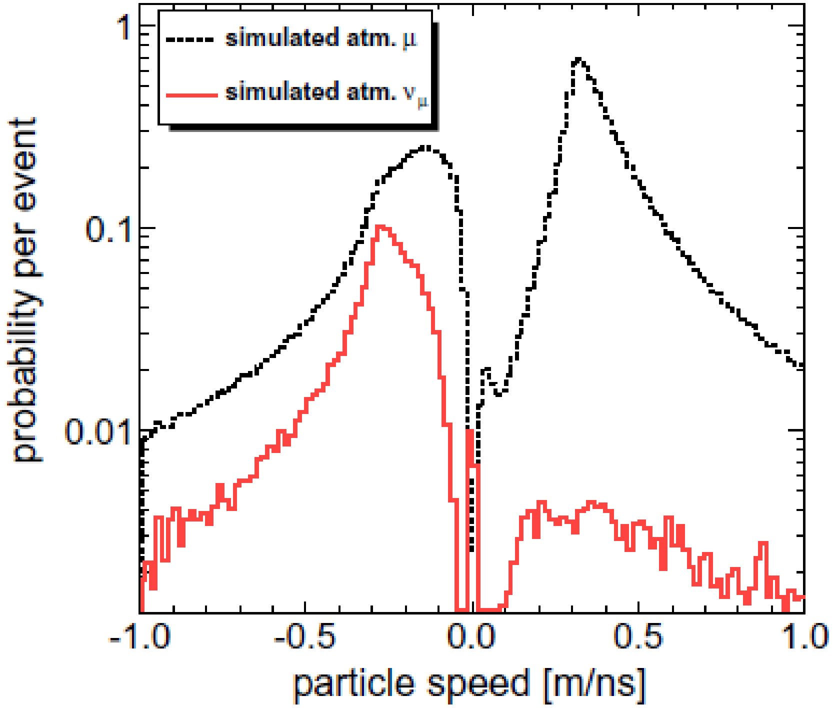
Event selection :veto

- Triggered by DeepCore DOM hits
- Large portion of background events are removed by IceCube array as an active muon veto



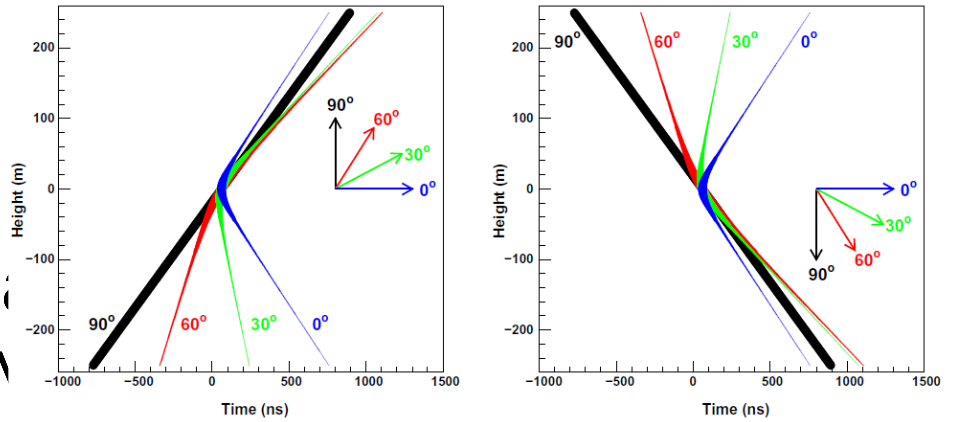
typical signal event
12 GeV muon neutrino

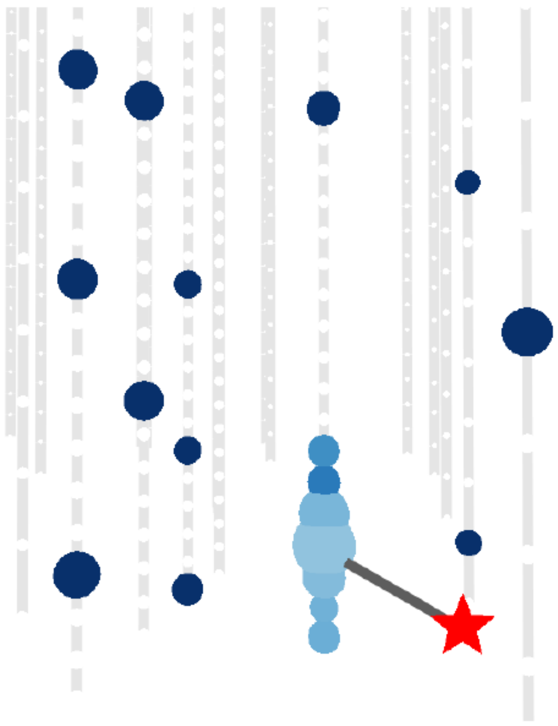


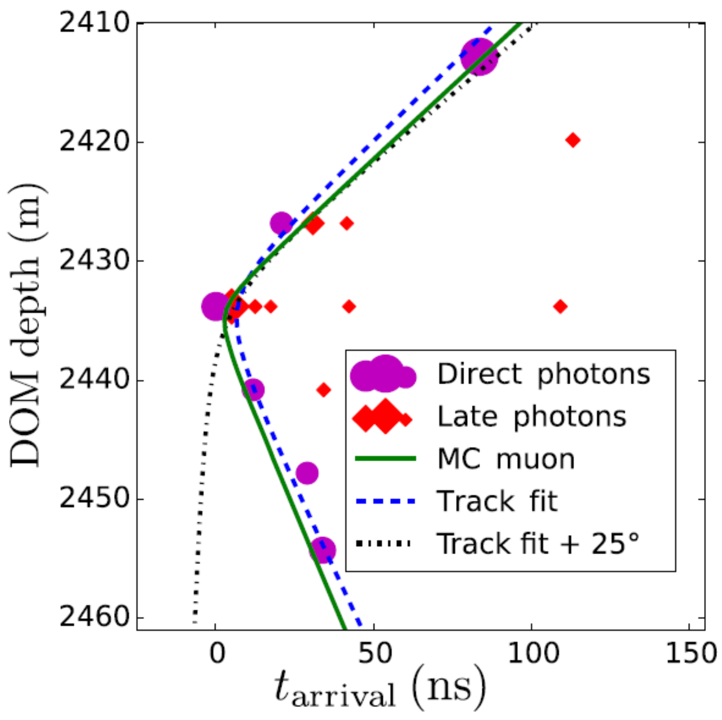


Reconstruction

- A simulated 12 GeV muon neutrino intera
  - producing an 8GeV muon (42m) and a 4GeV
  - 7 signal induced photon hit DOMs







- Preferentially selects events that occur close to a string which reduces the impact of optical scattering in the ice using unscattered photon (30% of events)
- Directional reconstruction is based on chi2 fit with a hyperbolic function (assuming cascade / track+cascade) by only using unscattered (direct) photon's arrival time and recorded charge
- Retain only consistent with track hypothesis

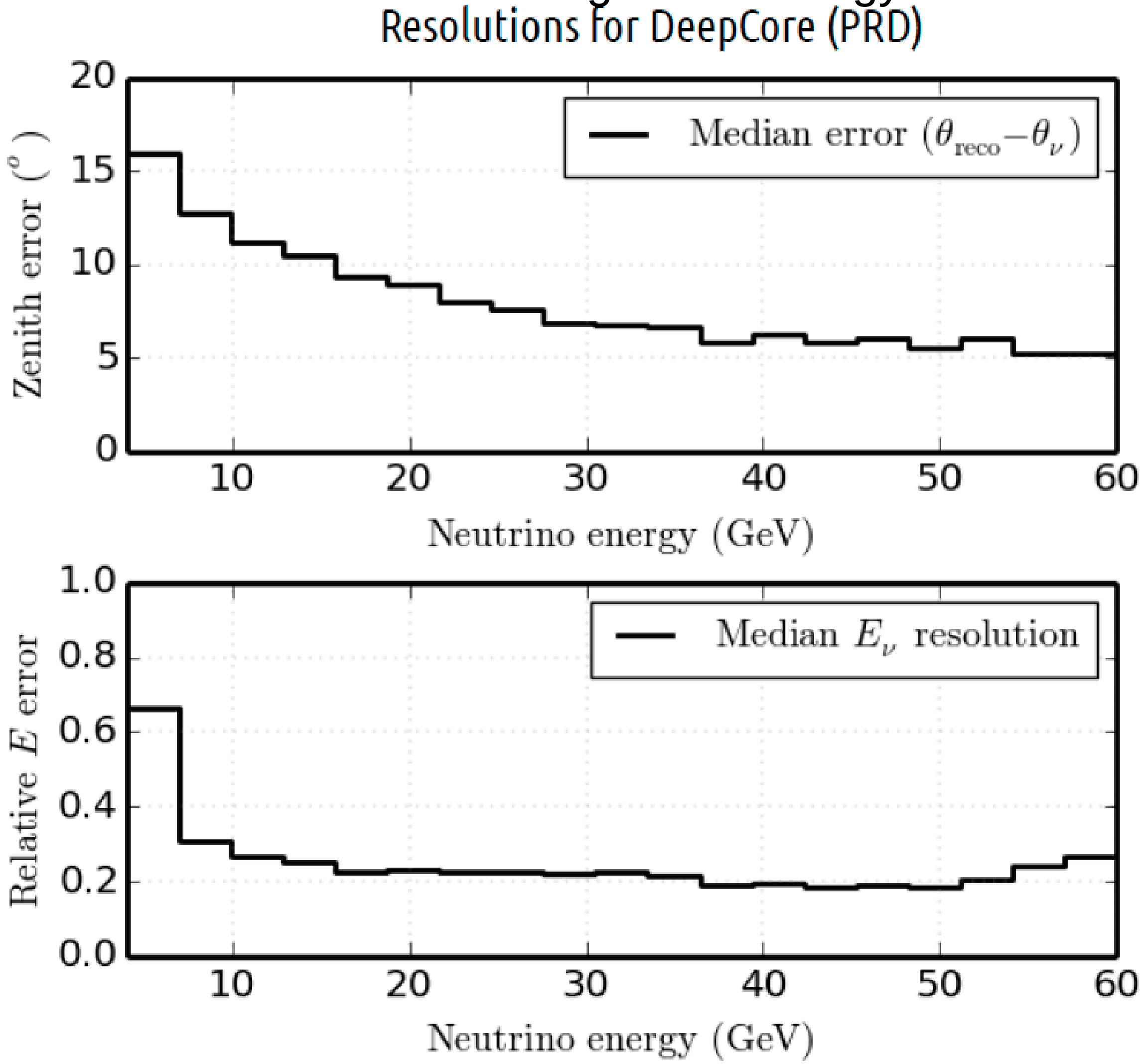
Reconstruction

- Energy reconstruction is performed using all connected hits

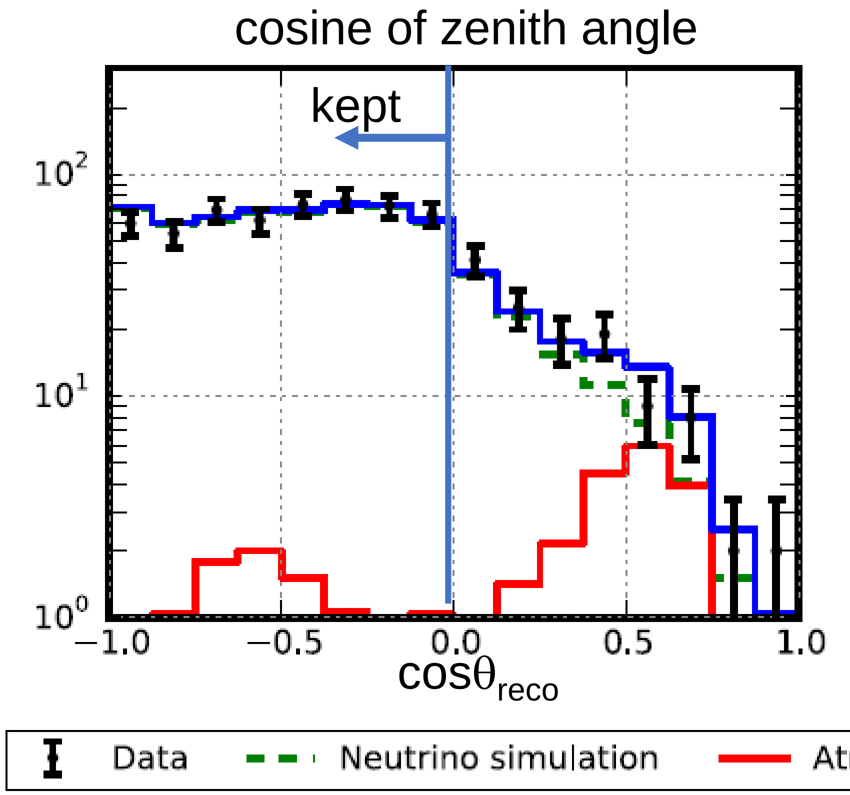
1. estimate range of muon track
   - LLH fit varying track length and vertex position with the given direction
2. add shower at the vertex

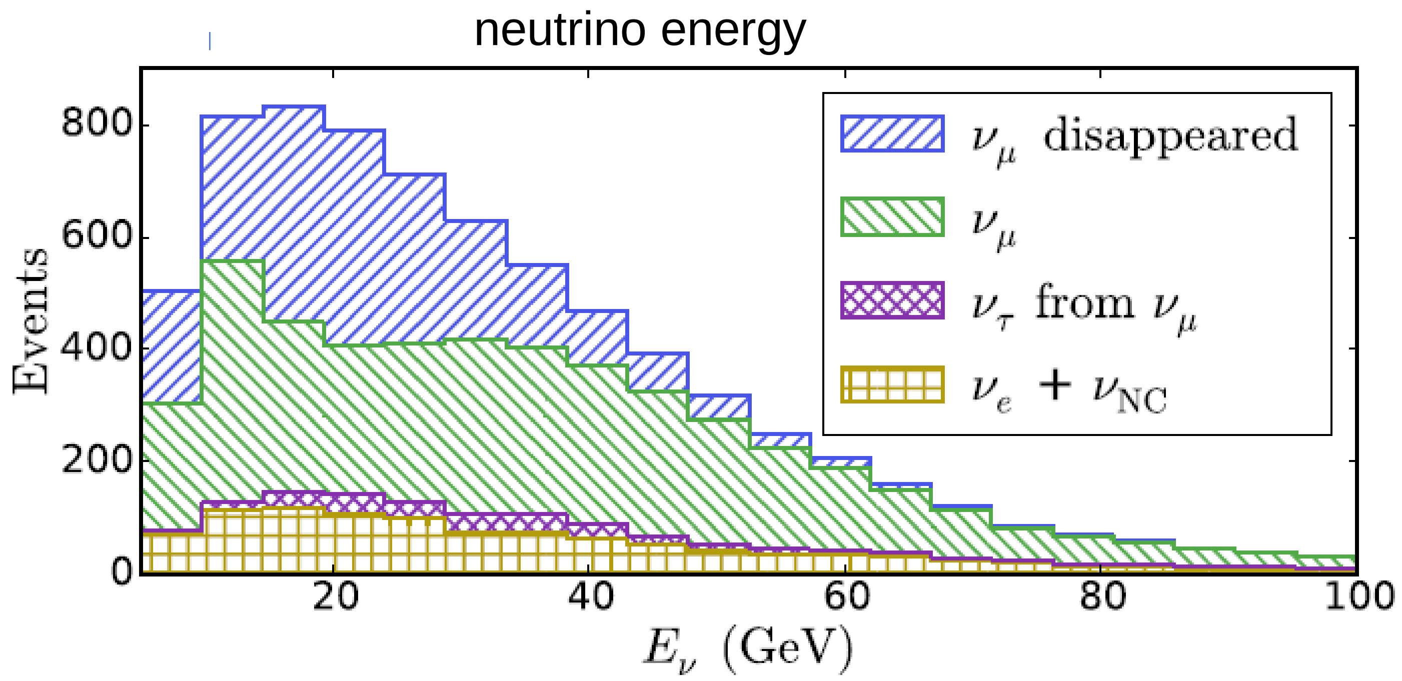
- $E_\nu = E_{shower} + aR_{muon}$ a = 0.226GeV/m

Median zenith angle and energy resolution



Event distributions





74% νμ CC, 13% νe CC, 8% neutral current interactions and 5% ντ CC, μ<5%: 80% DIS

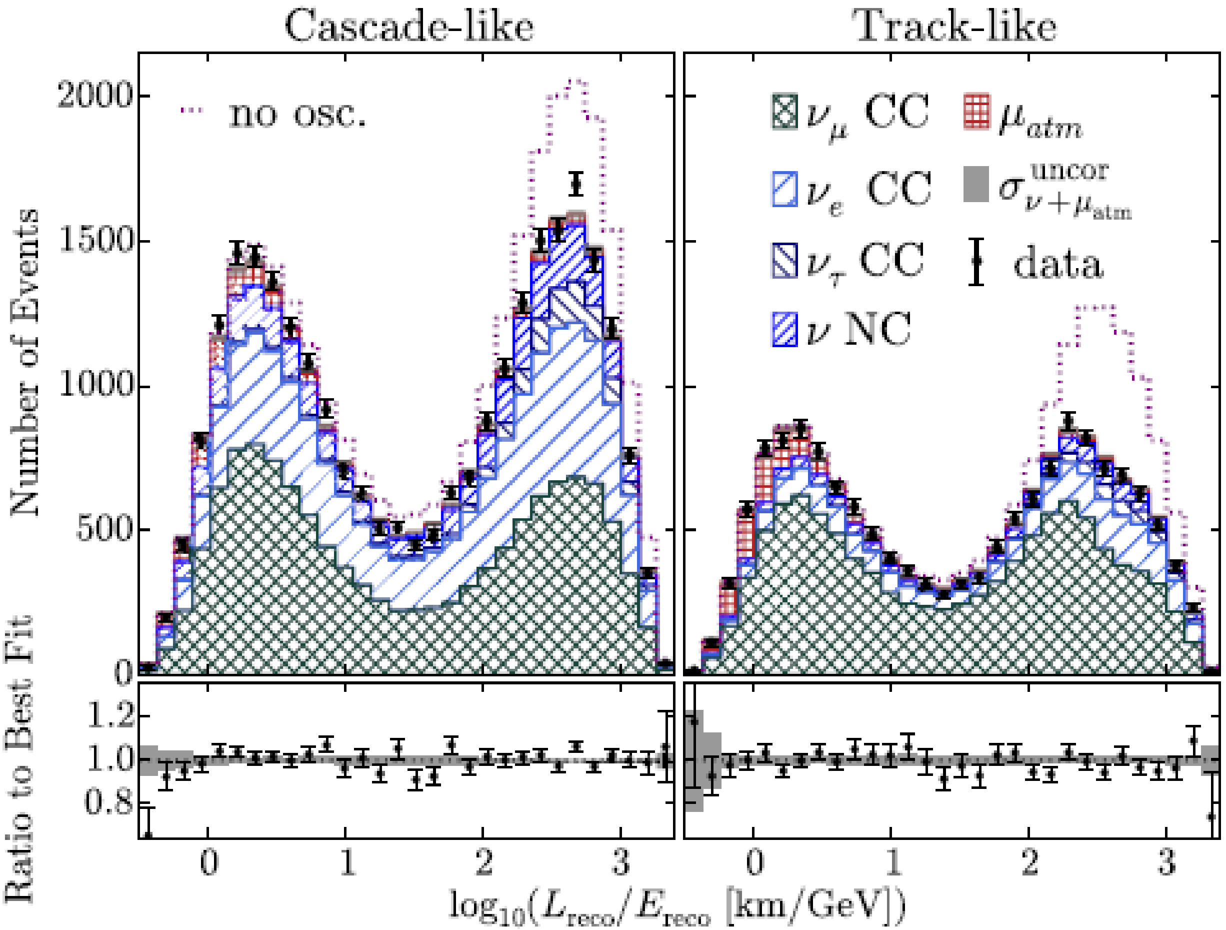
Fit parameter estimation

A binned (8x8, $\log E_{reco}$ and $\cos\theta$) maximum likelihood is used that includes nuisance parameters for systematic uncertainties: The physics parameters of the fit are the mixing angle θ_{23} and mass splitting Δm^2_{32}

- 3 year data from May 2011 to April 2014, 953 days
- A total of 5174 events compared to an expectation of 6830 events assuming no oscillations
- E_{reco} between 6 to 56GeV and $\cos\theta$ between -1.0 to 0
- θ_{13} is treated as a nuisance parameter
- The remaining oscillation parameters are fixed to the values given in Phys. Rev. D 86, 013012

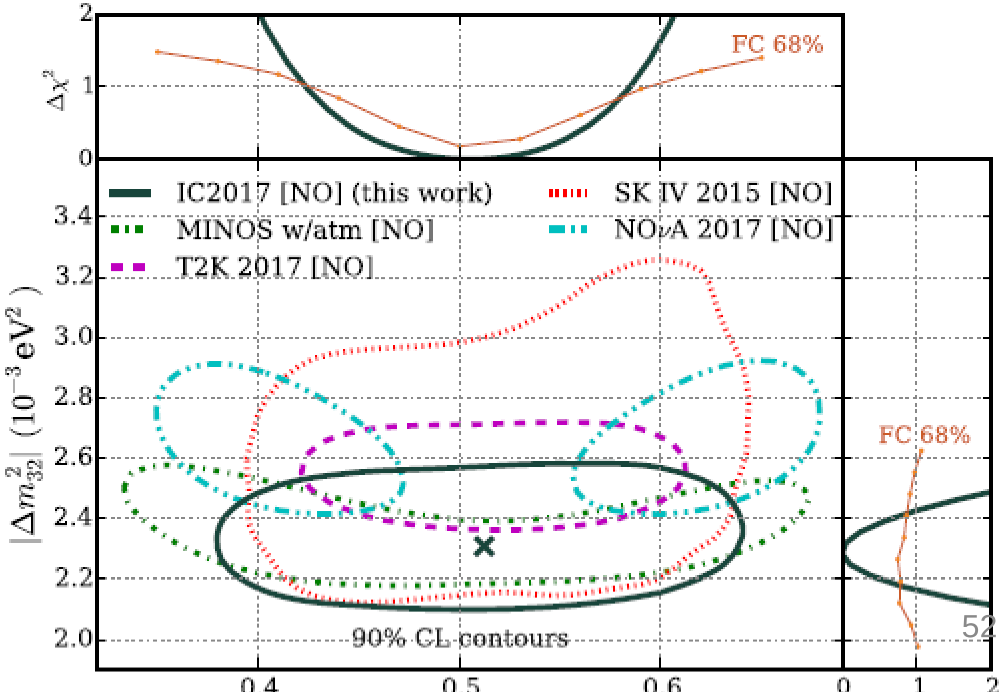
muon neutrino disappearance

L/E Projections

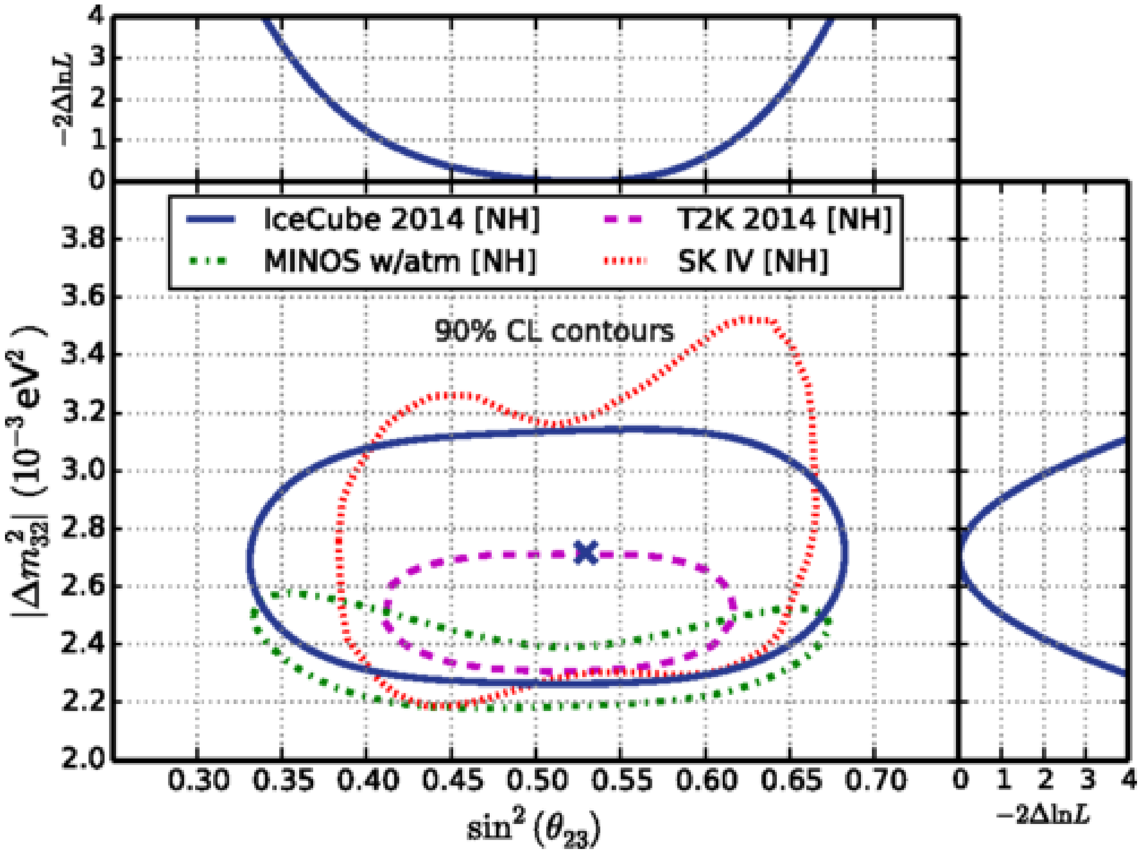


Assumes three-flavor oscillations

- $\Delta m_{21} = 7.53 \times 10^{-5}\,\mathrm{eV}^2$
- $\sin^2\theta_{12} = 0.304,$
- $\sin^2\theta_{13} = 2.17 \times 10^{-2}$
- $\delta_{CP} = 0°$



Fit results



- Best fit parameters

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

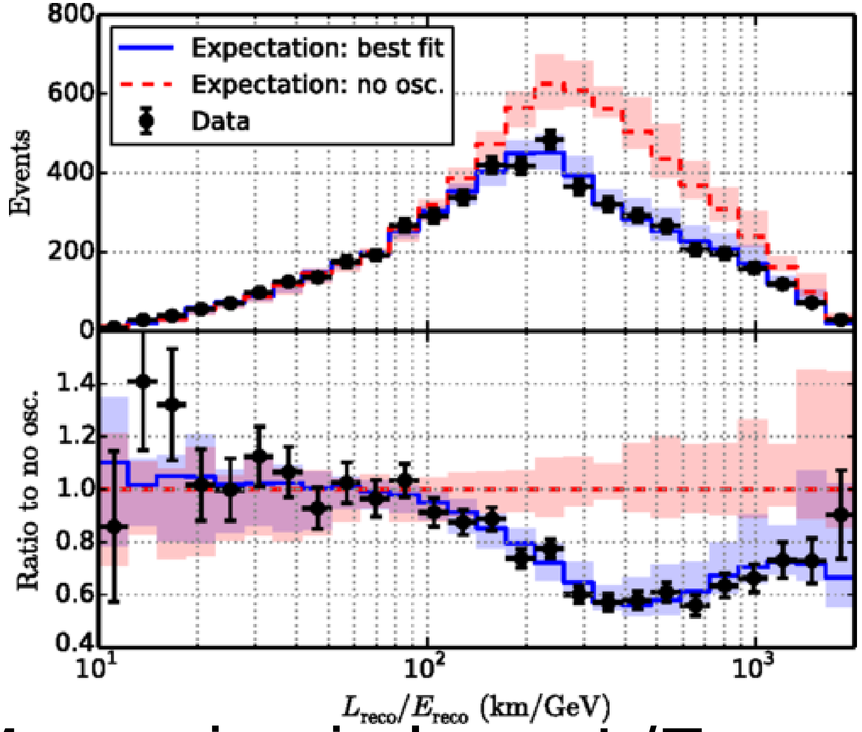
in 2D fit, chi2 = 54.9/56 dof

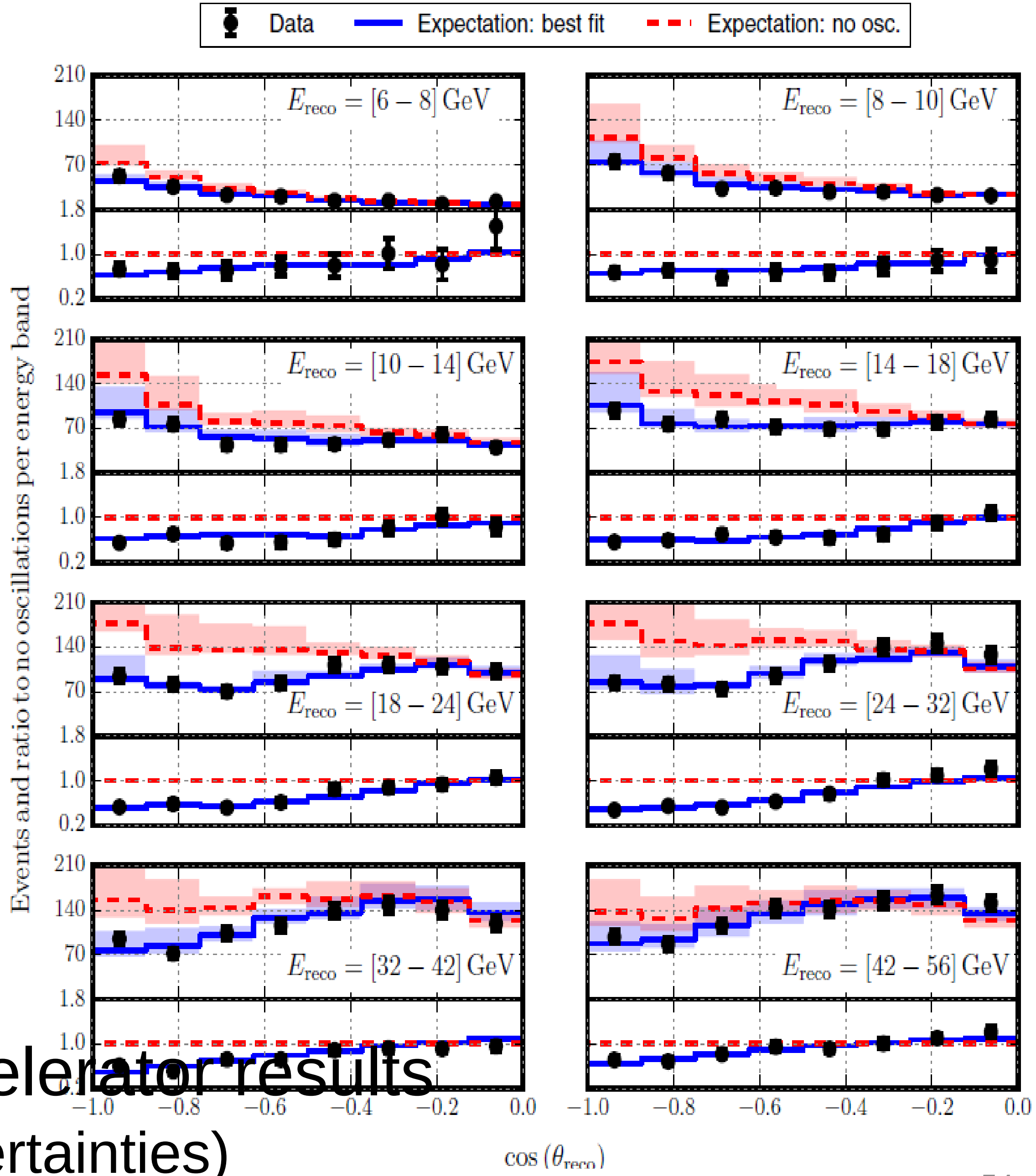
Size of statistical error only

$$\sigma(|\Delta m^2_{32}|) = ^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sigma(\sin^2\theta_{23}) = ^{+0.06}_{-0.08}$$

stat and syst similar sizes

Data/MC comparisons



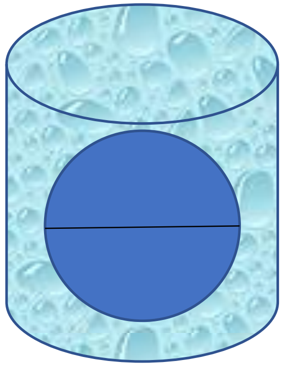


- Measuring in large L/E range
- Affected by different sys error than accelerator results
  - (Bands indicate estimated systematic uncertainties)

Uncertainties

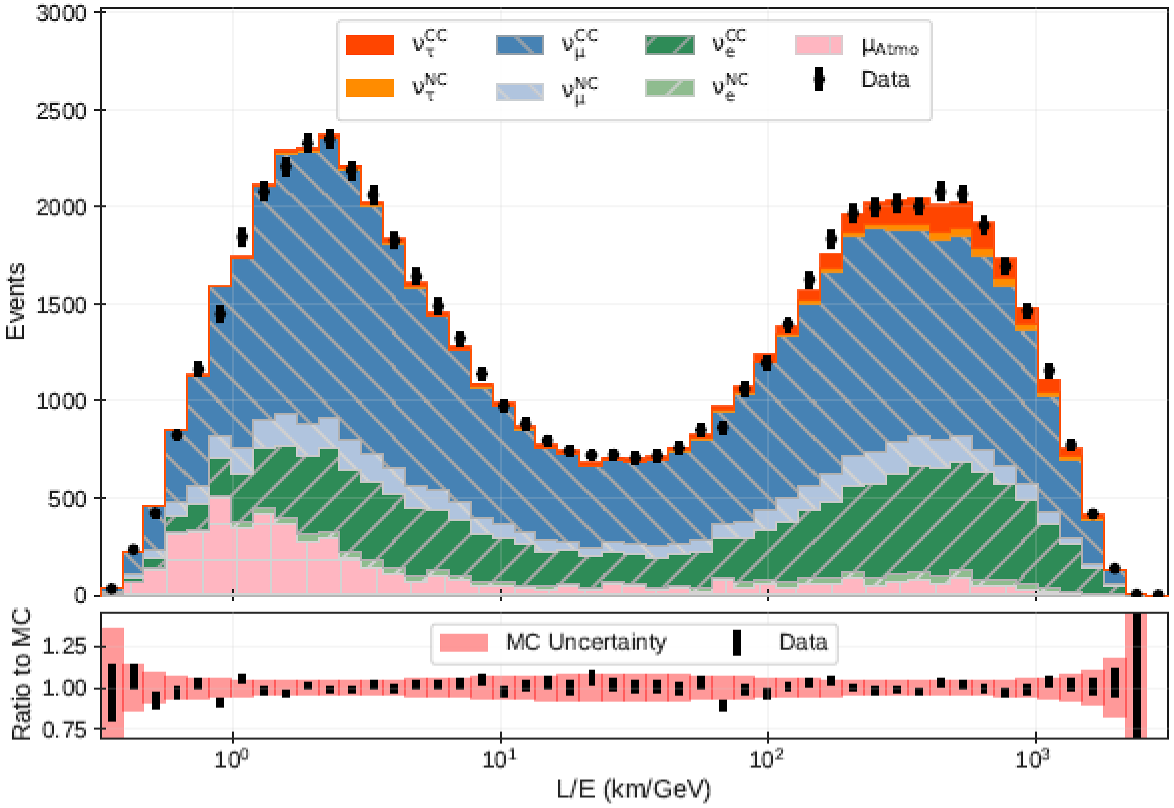
	$\sin^2(\theta_{23})$	Δm^2_{31} (10^3 eV^2)
PRD errors	~ 0.1	~ 0.2
Hole ice (angular acceptance)	29.88%	2.34%
DOM eff	0.73%	19.06%
Gamma	0.13%	8.67%
NuE	0.05%	0.94%
Atm Mu	0.00%	0.72%
Hadronic energy scale	< 1 %	< 1 %
Axial mass (non-DIS events)	< 1 %	< 1 %

Preliminary



Next steps with DeepCore

- Inclusion of cascade events
- Improve event selection and analysis of more data sample (currently 3 years, until April 2014)
- ...



ν_τ^{CC}
ν_μ^{CC}
ν_e^{CC}
μ_{Atmo}
ν_τ^{NC}
ν_μ^{NC}
ν_e^{NC}
Data
Events
Ratio to MC
MC Uncertainty
Data
L/E (km/GeV)

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