

Technical progress

- detector performance, calibration, R&D efforts

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March 2019

The IceCube Neutrino Observatory

IceTop (surface array): 81 stations

IceCube: 86 strings

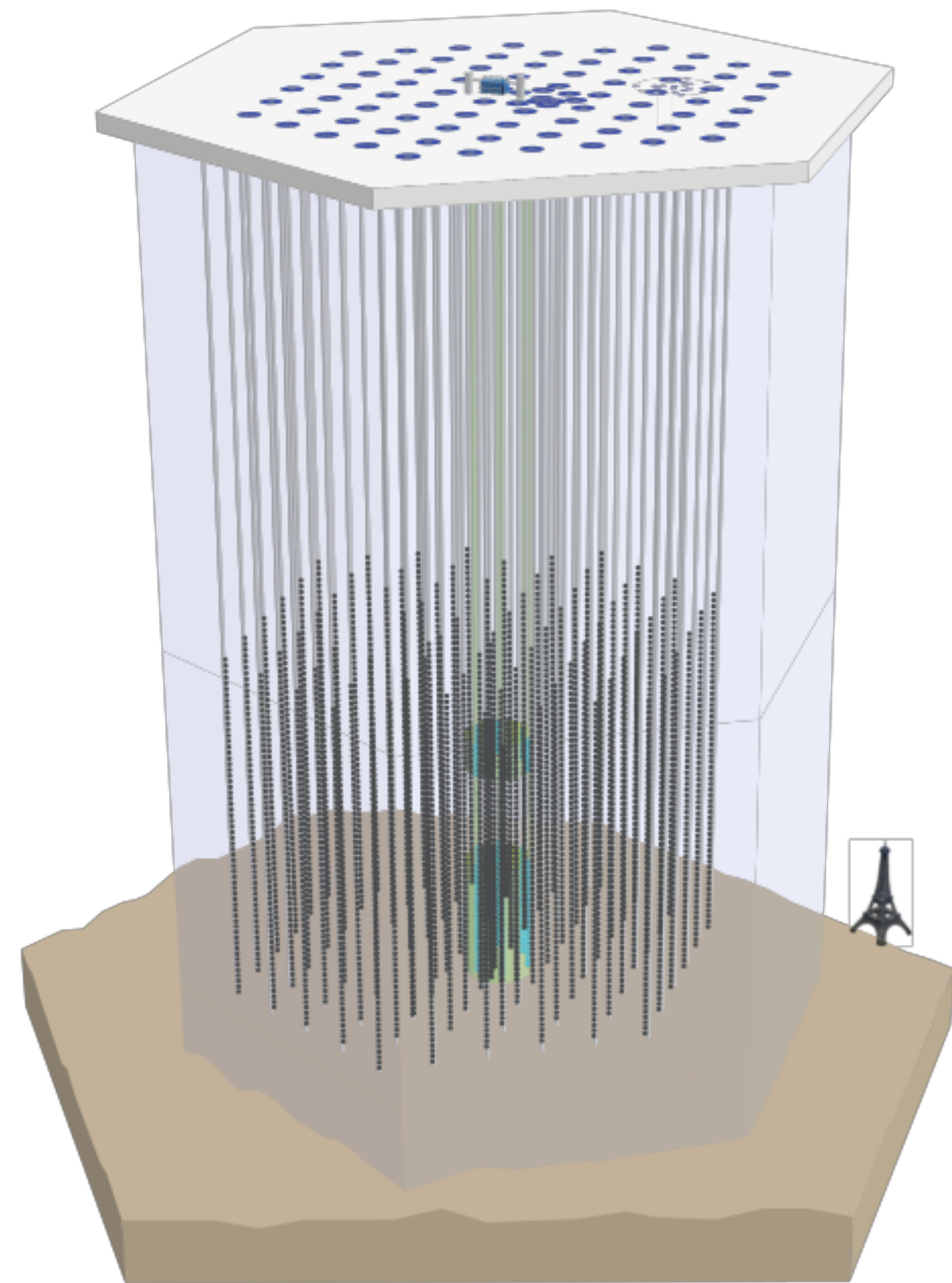
5160 optical sensors over 1 km³ volume

17 m vertical spacing

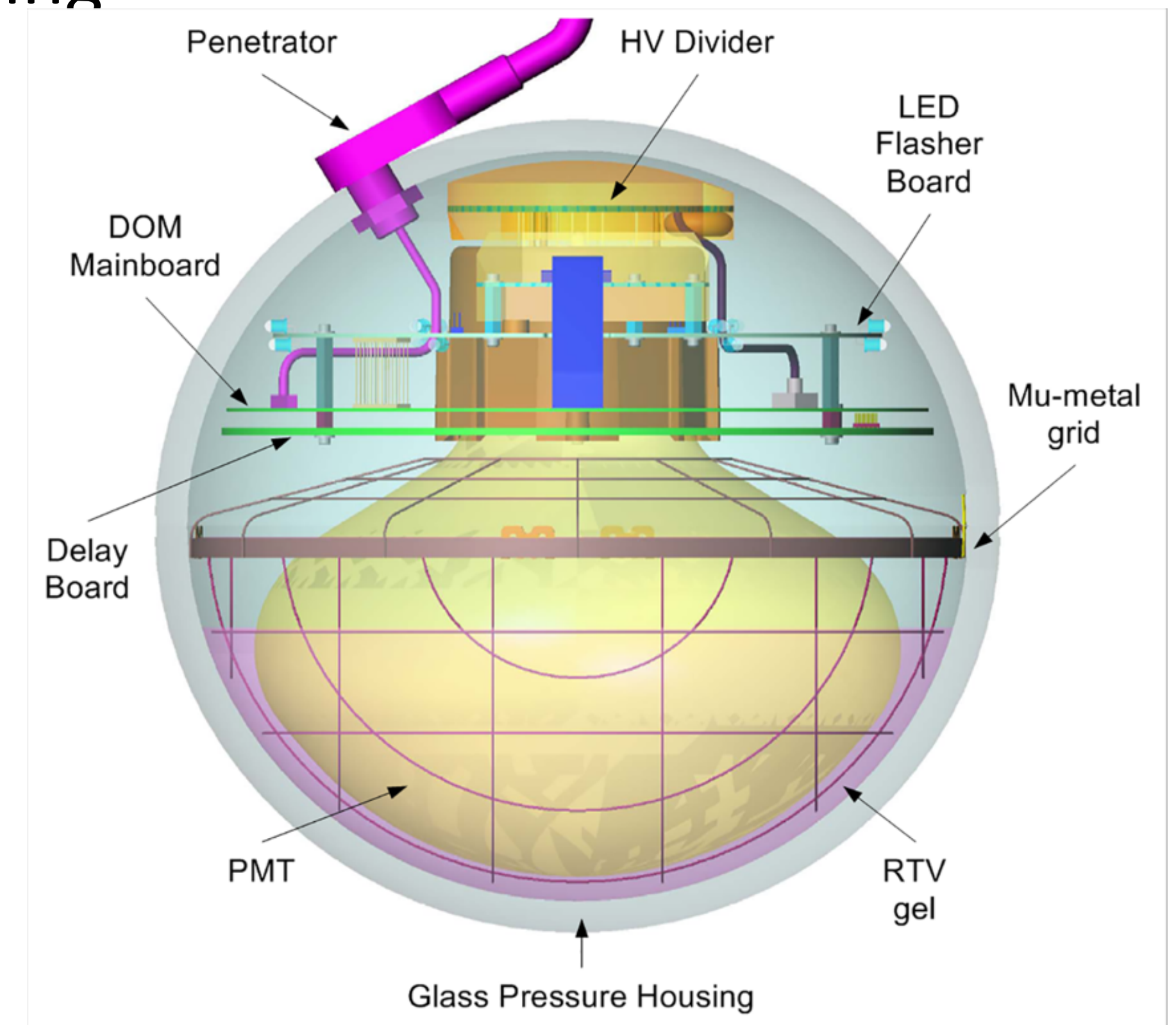
125 m horizontal spacing

Highly stable operation.

Since 2016: **livedtime** > 99.5%



DeepCore (low energy threshold)





South Pole 10m Telescope



MAPO

TOS - Drilling site (79 & 80 in 10/11)



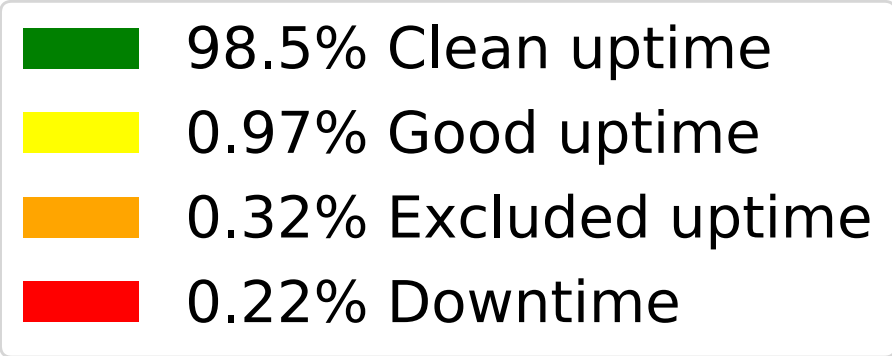
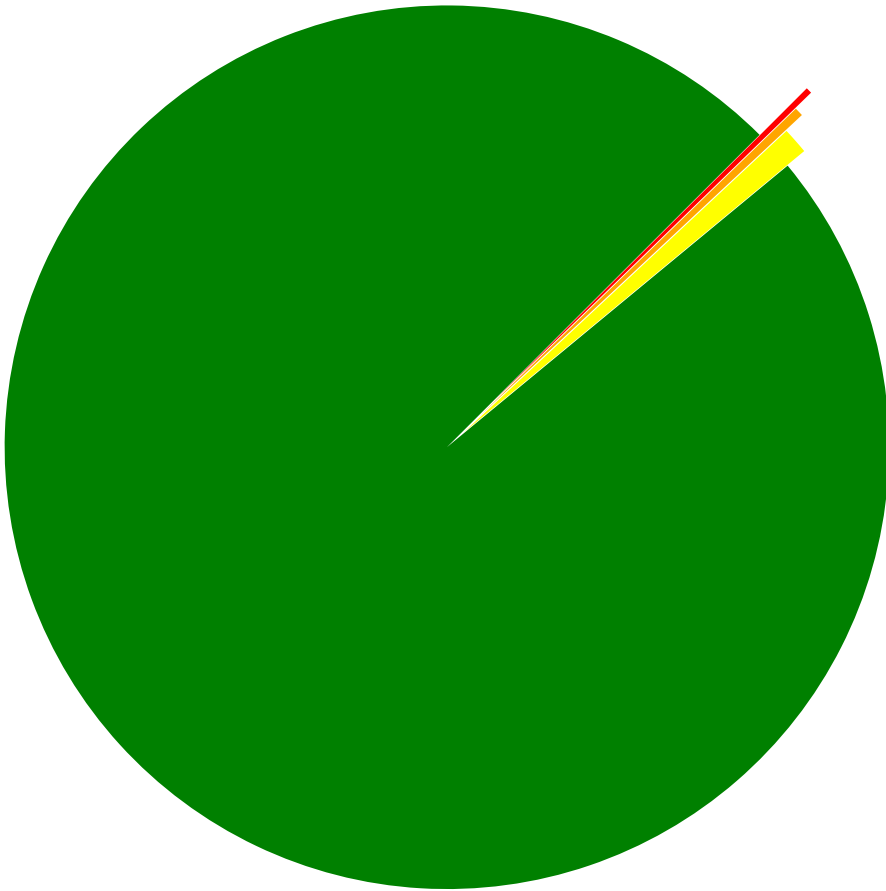
IceCube Laboratory (ICL)

IceCube Enhanced Hot Water Drill (EHWD)

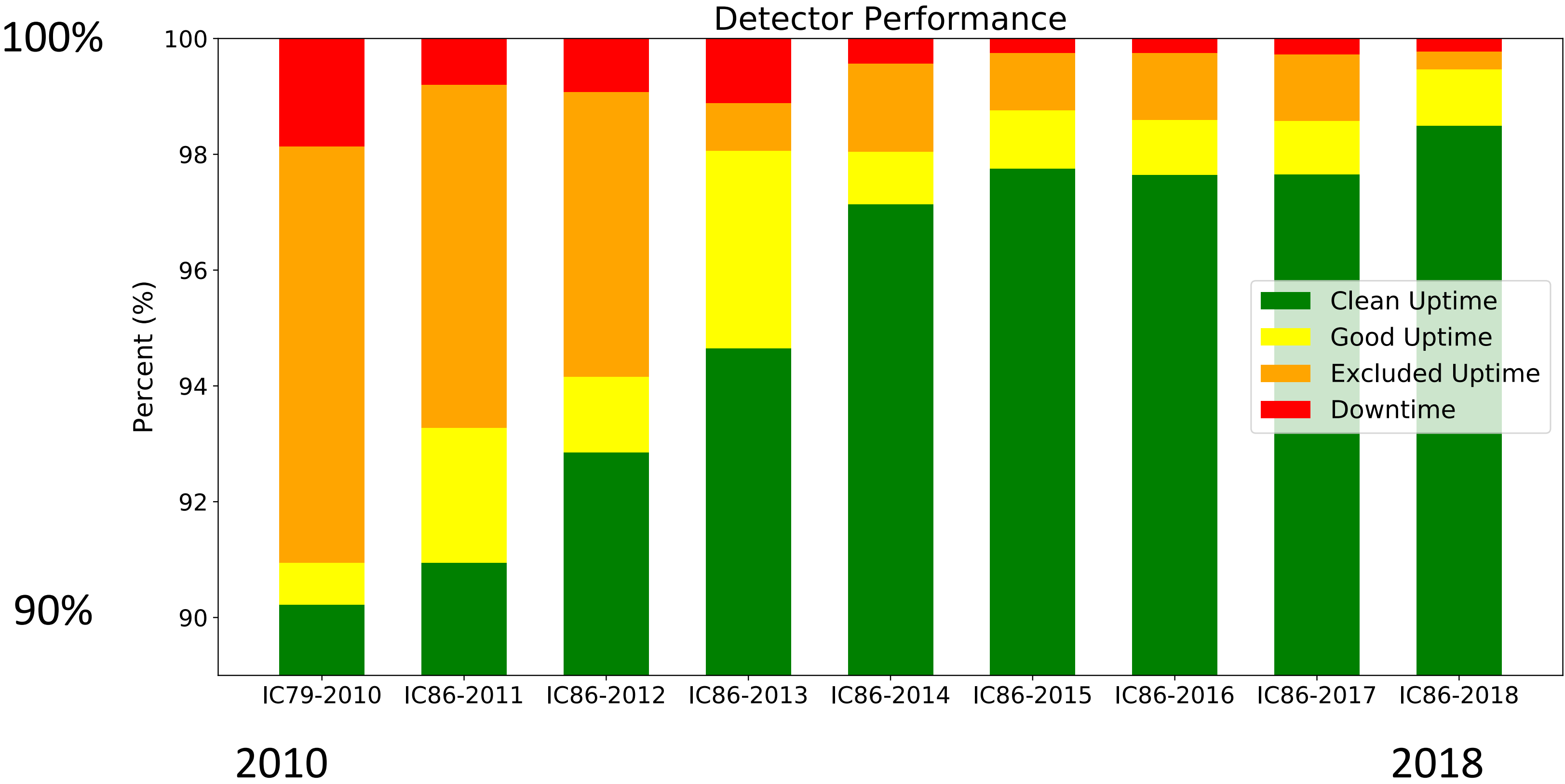


5100 sensors are deployed
to a depth between 1500
and 2500m.



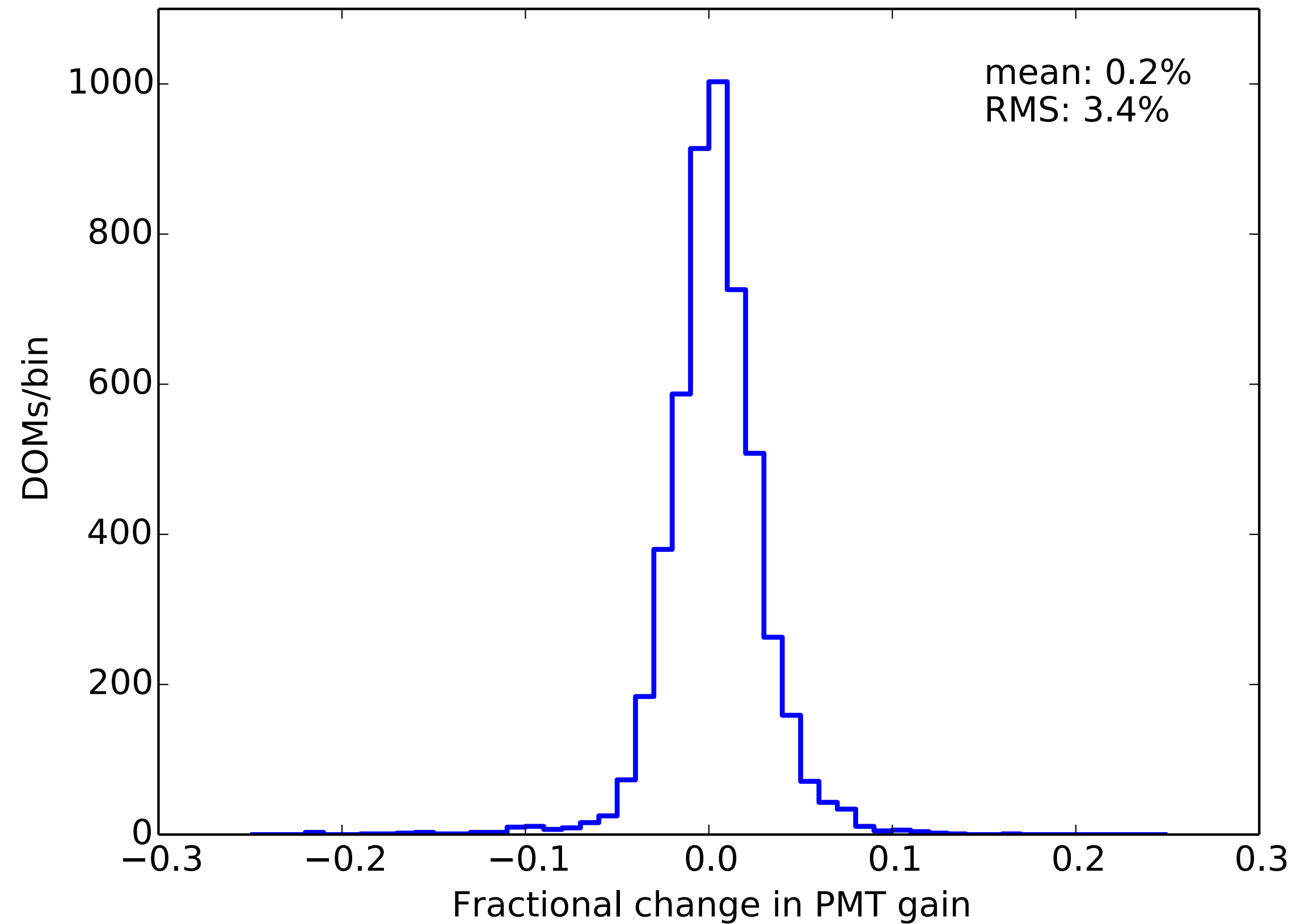


Detector Uptime



PMT gain stability 2011 - 2016

No indication for any changes since 2016.

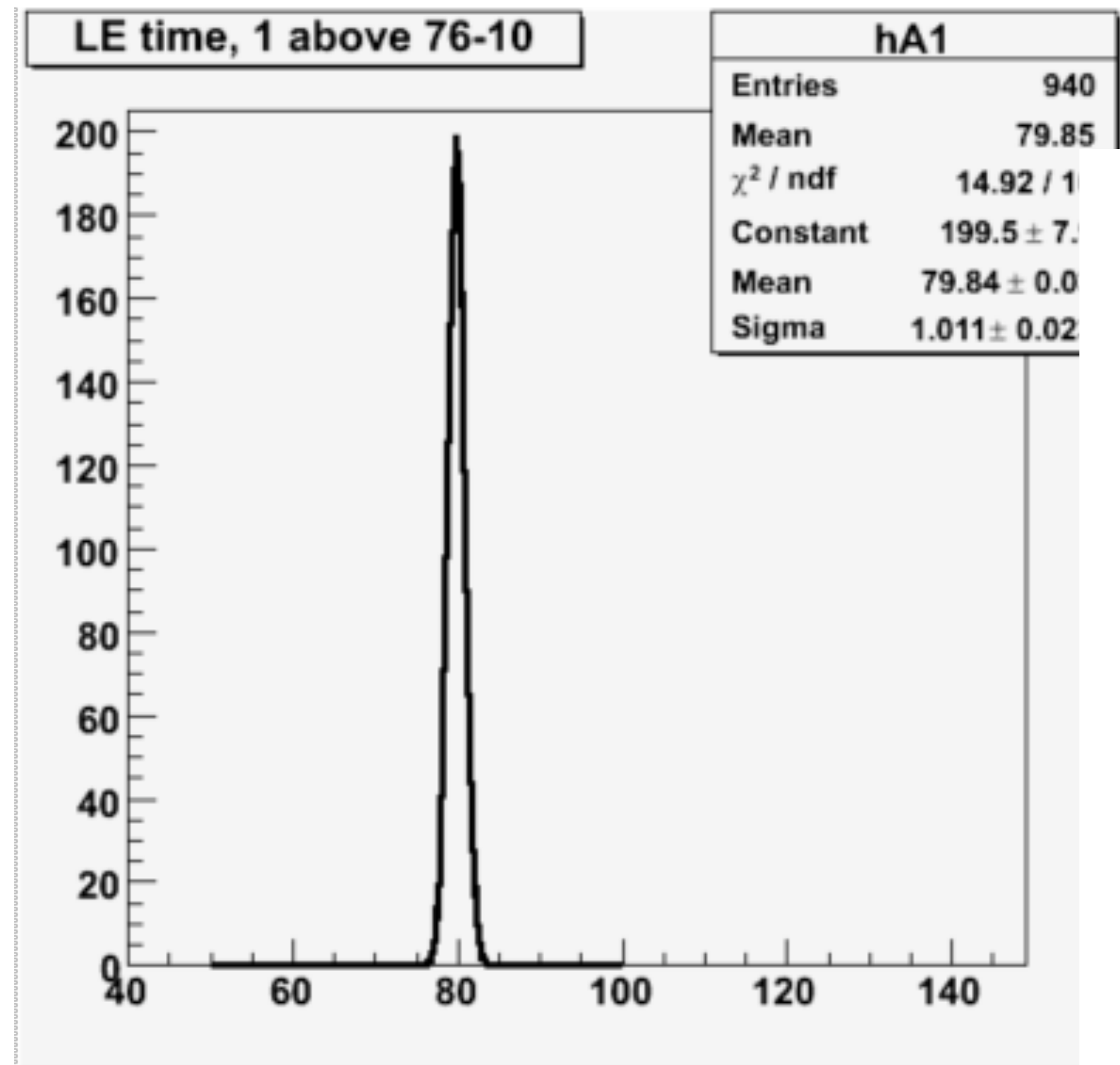


DOM gain appears stable!

(PMT gain of $1E7$ is small.
Noise rates are small.
→ Very small integrated current on anode.
→ No aging from that.

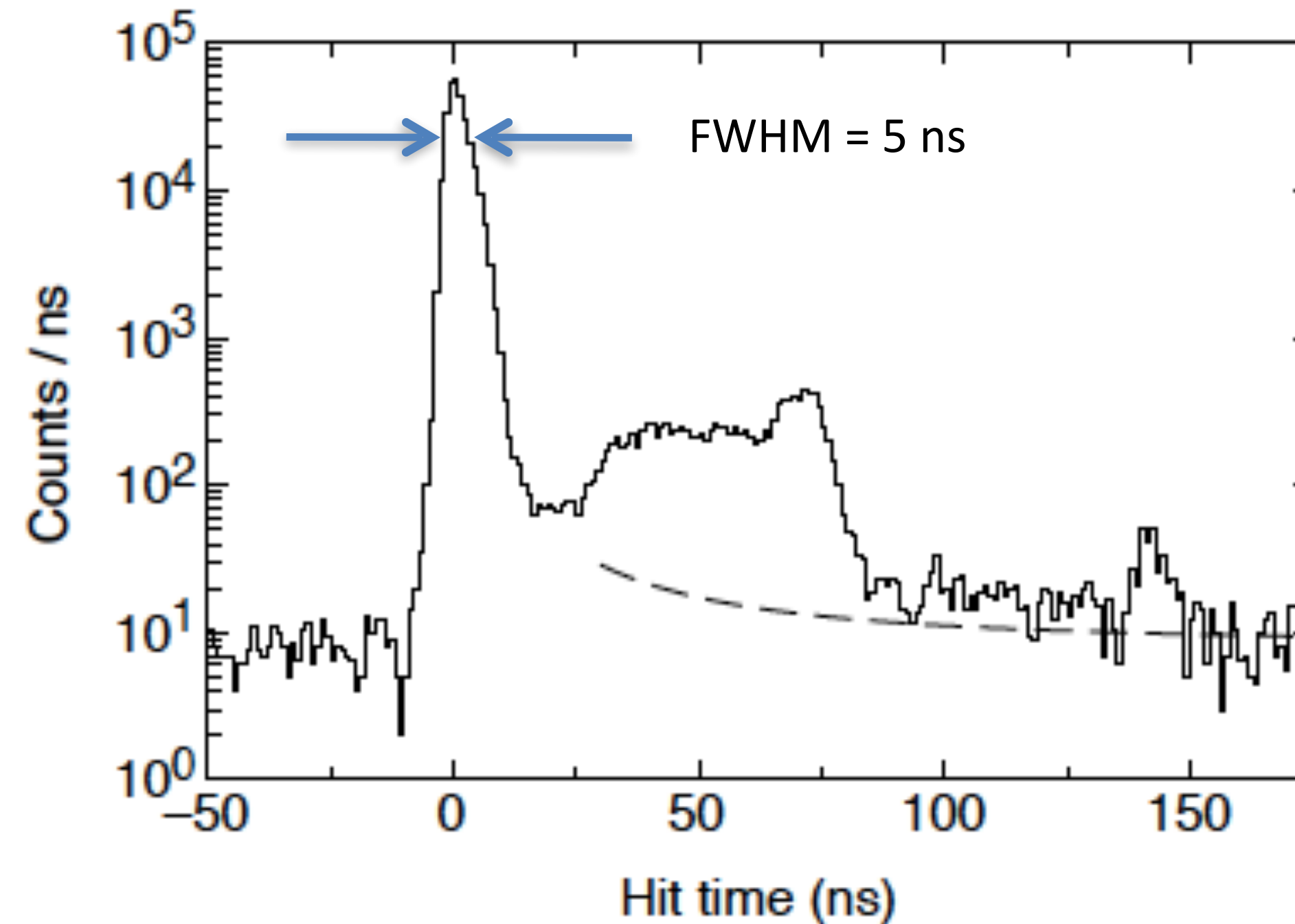
Time resolution: ~1ns for bright pulses

- Time difference between neighboring DOMs fired with (bright) flasher pulses: ~1 ns.
(this includes clock timing)



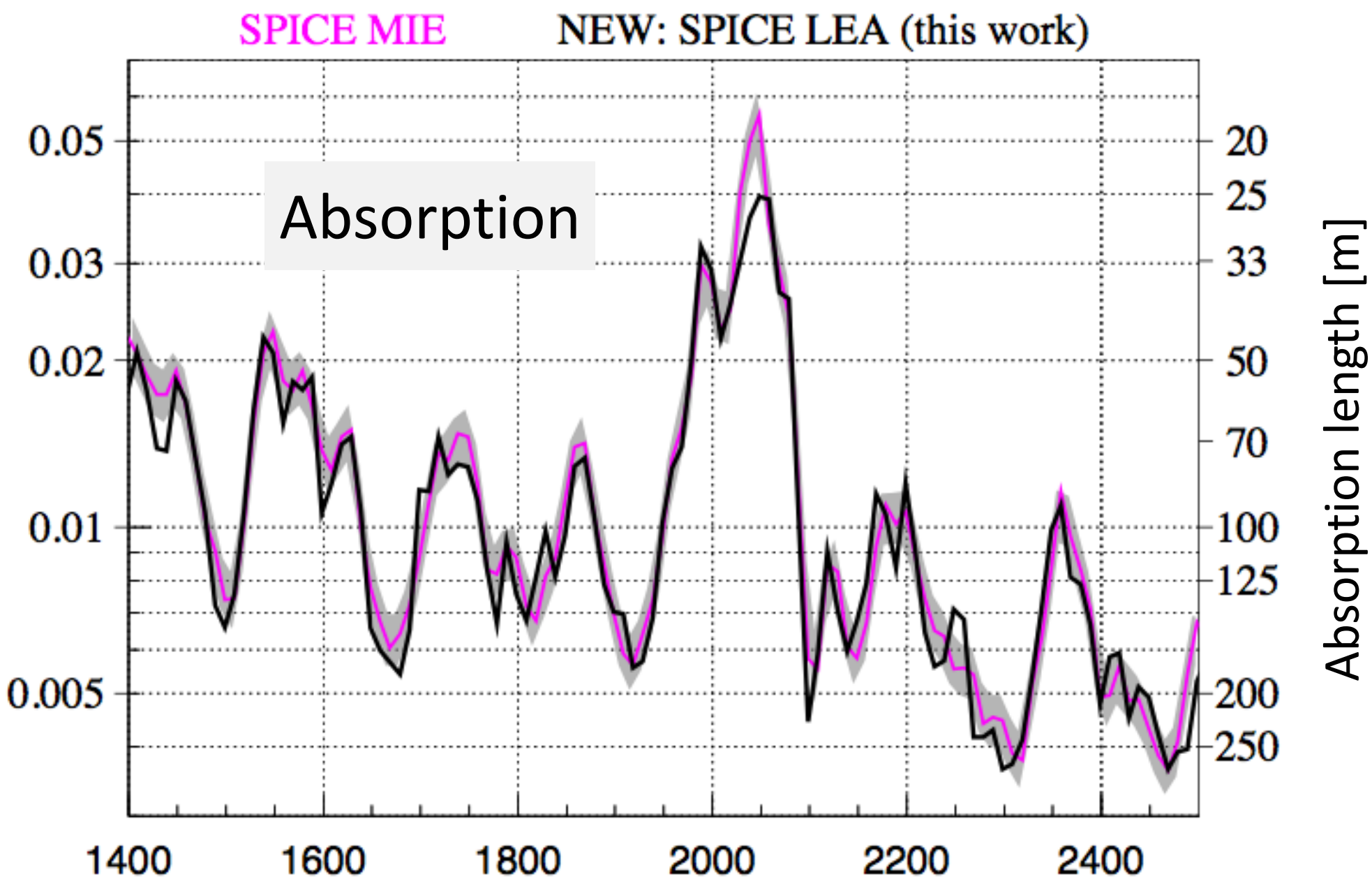
Single photoelectron pulse resolution limited by PMT.
RMS in the peak: ~2ns

Lab measurement with laser.



Understanding the ice

1. Vertical structure of ice parameters



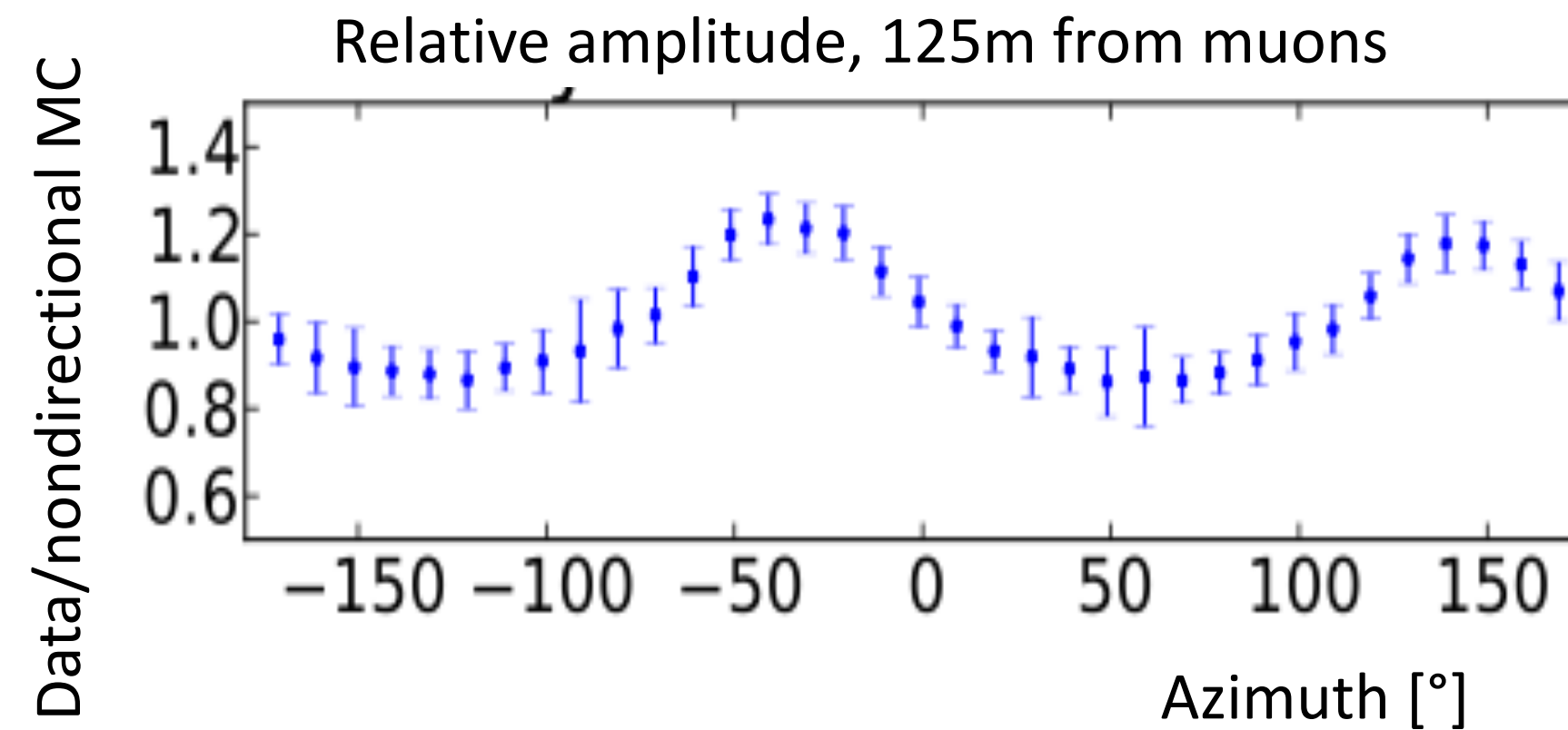
Scattering (eff.): 20 – 50 m
Absorption: 100 – 200 m

Measurement of South Pole ice transparency with the IceCube LED calibration system,

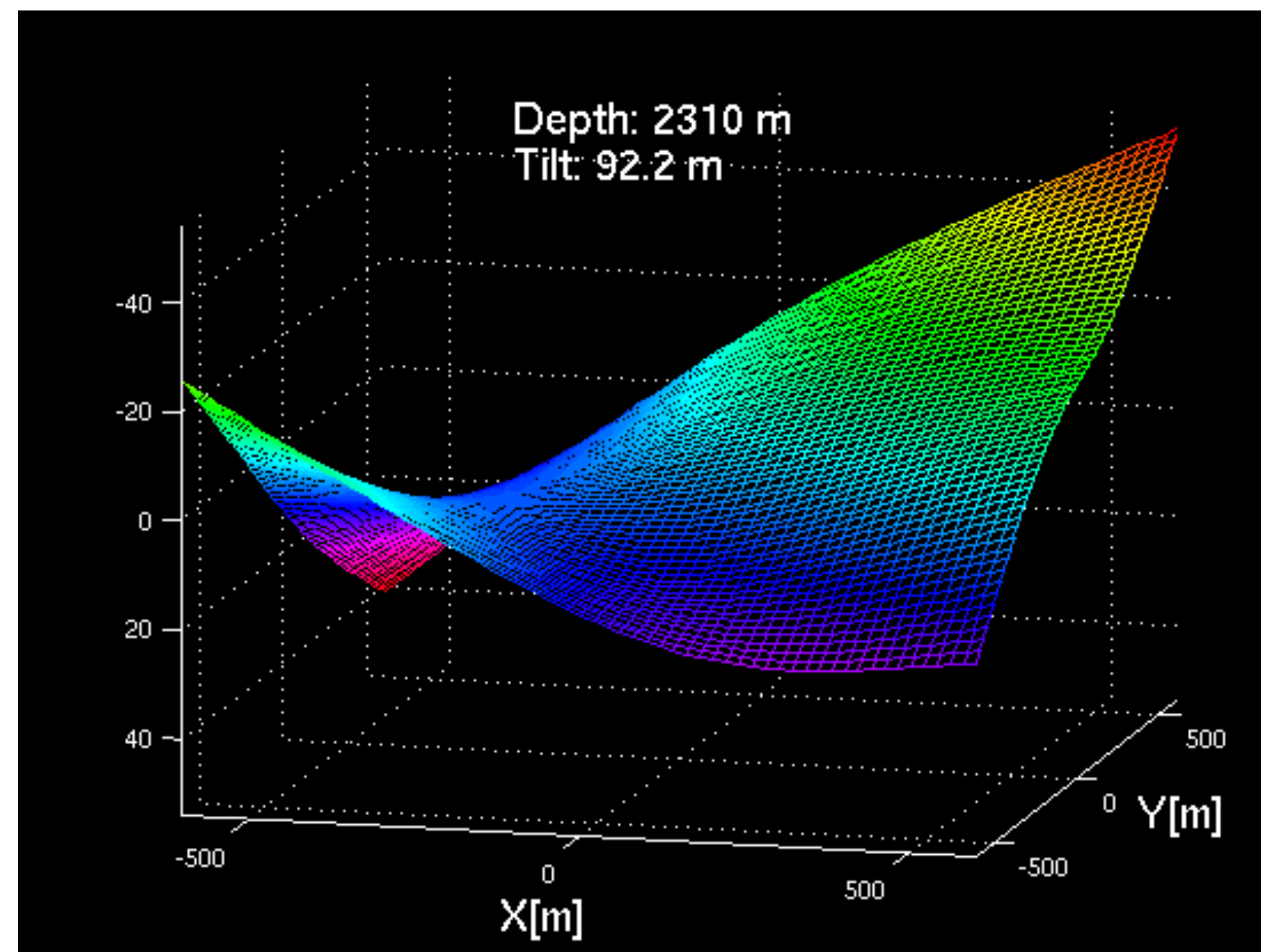
Aartsen et al., (IceCube Coll.), NIMA55353
<http://arxiv.org/abs/1301.5361>

2. Azimuthal variation in of scattering

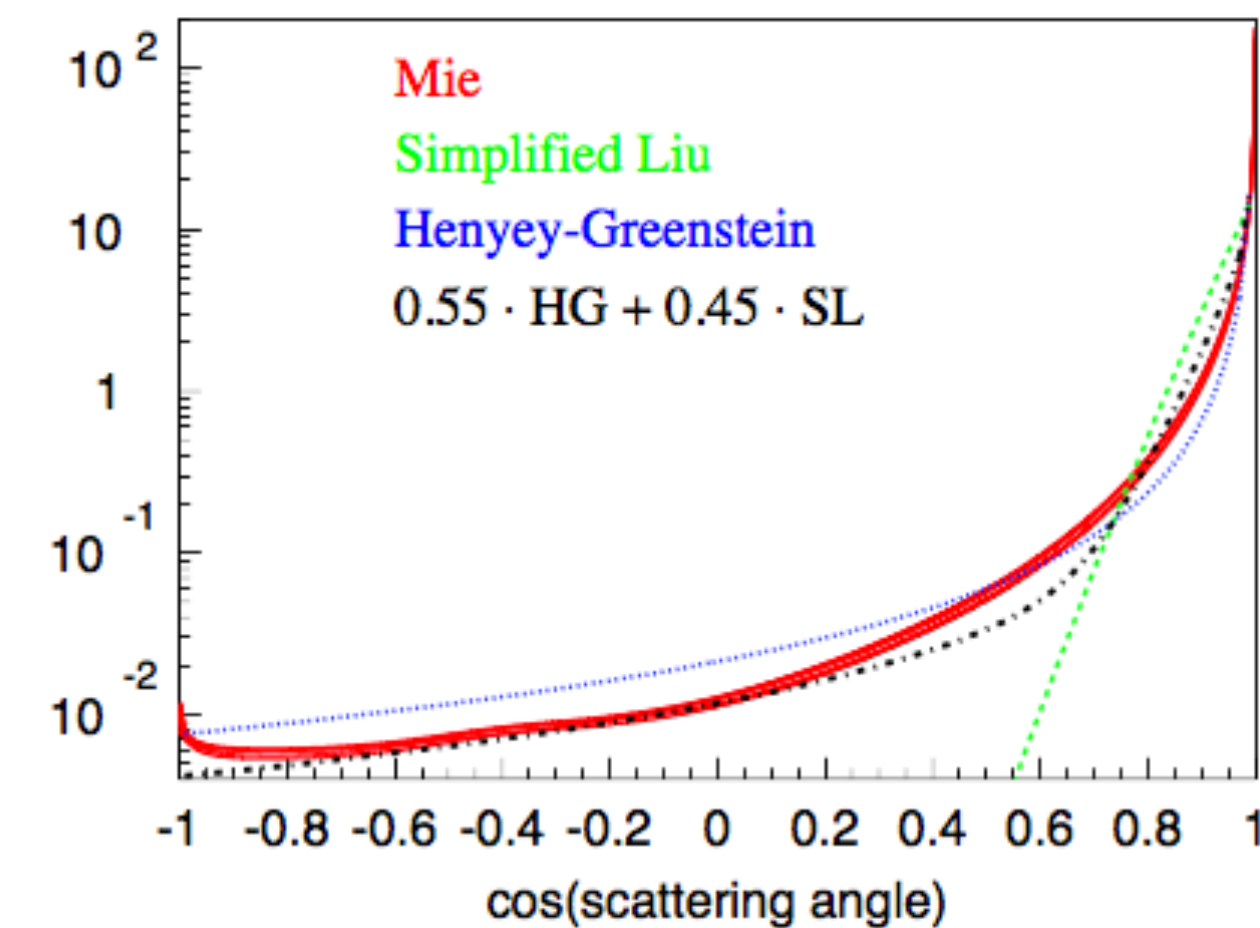
Less scattering in direction of ice flow:
→ up to ~10% /100m variation in amplitude



3. Ice layers are tilted – not planar



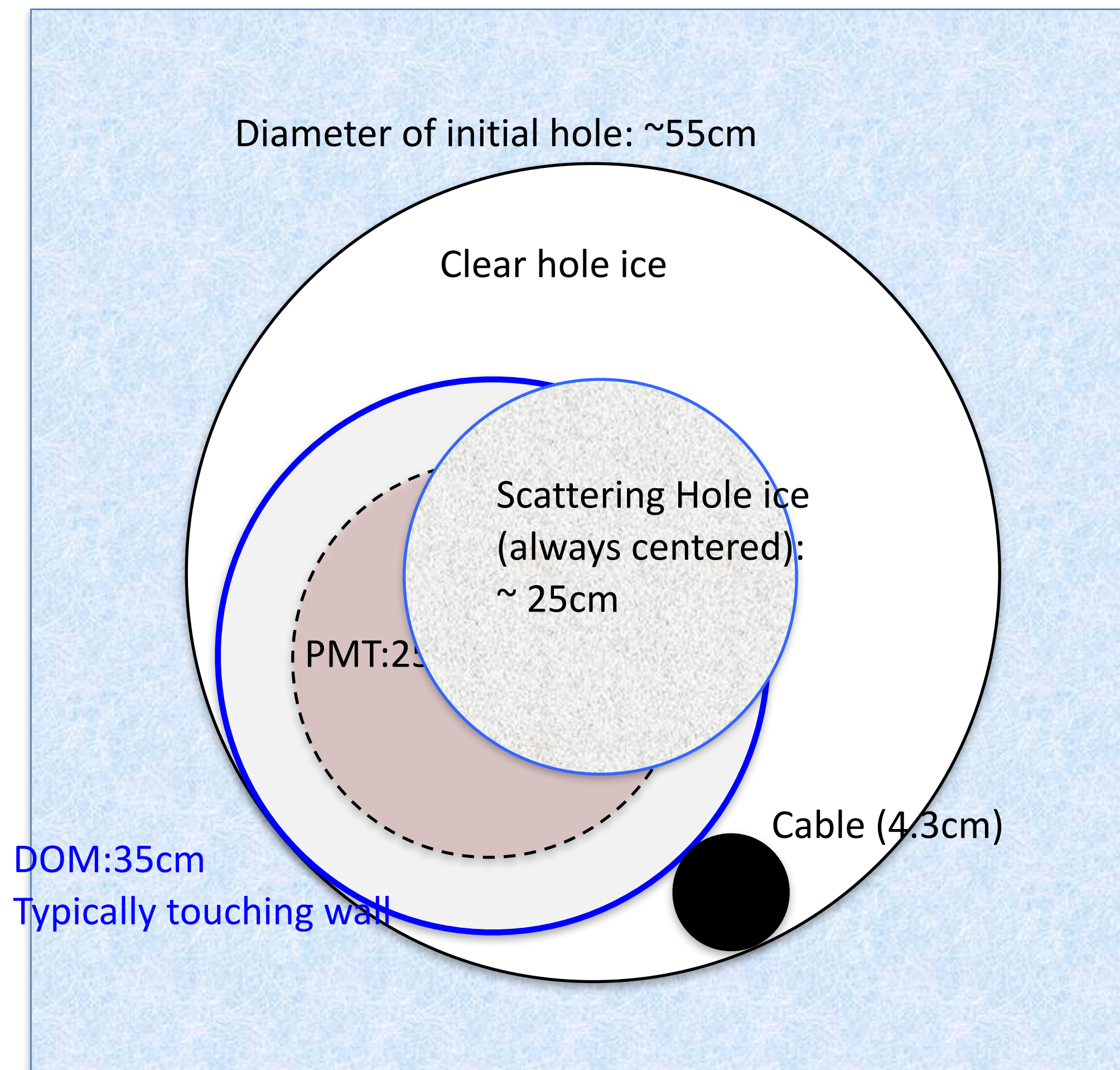
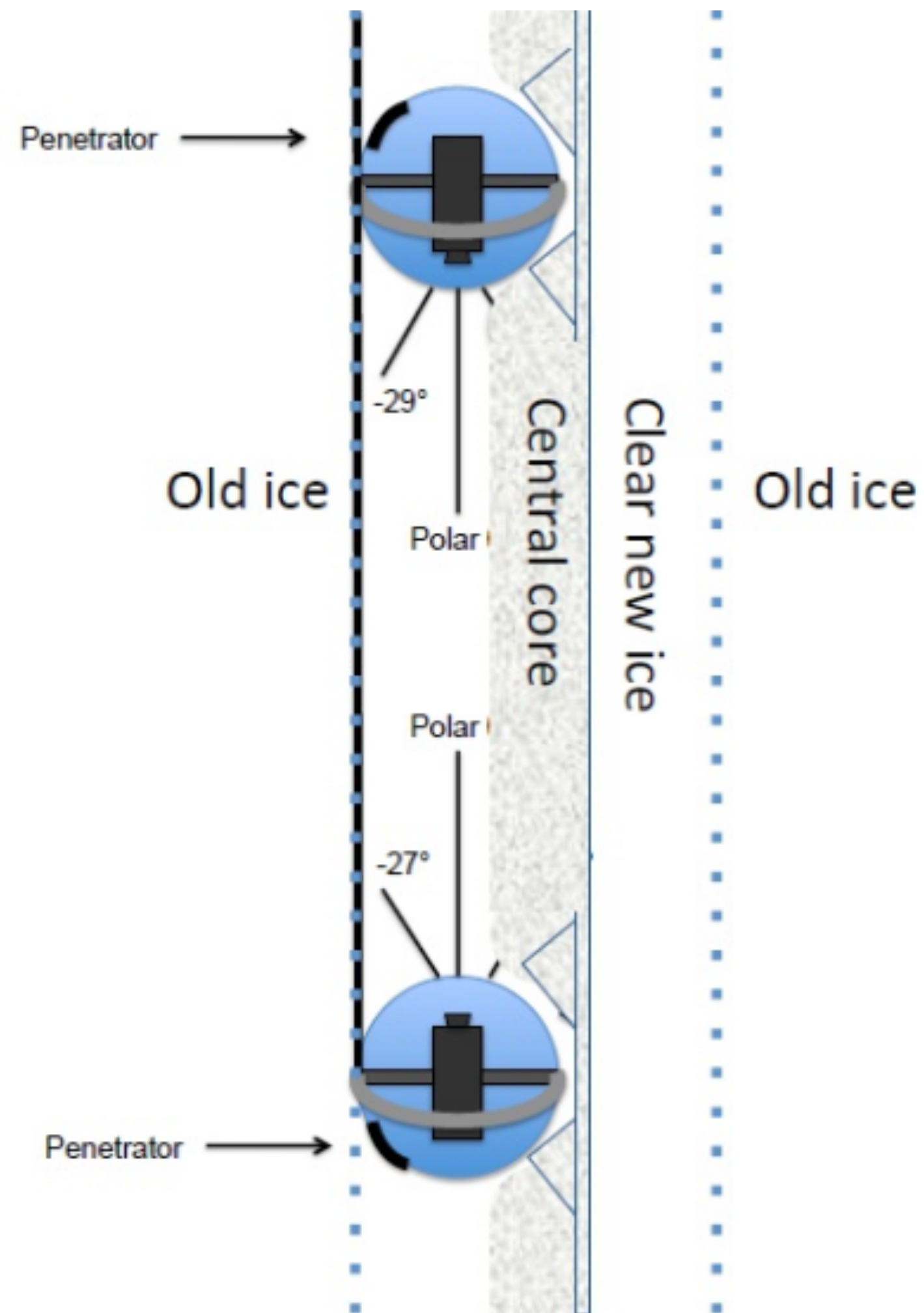
3. Scattering function



Systematic uncertainties: DOM and local ice

We plan to map the full surface sensitivity of every DOM precisely cable position to $<3^\circ$ (can be determined with local LEDs), then fit effect of hole ice.

Current picture of hole ice



DOM and local ice

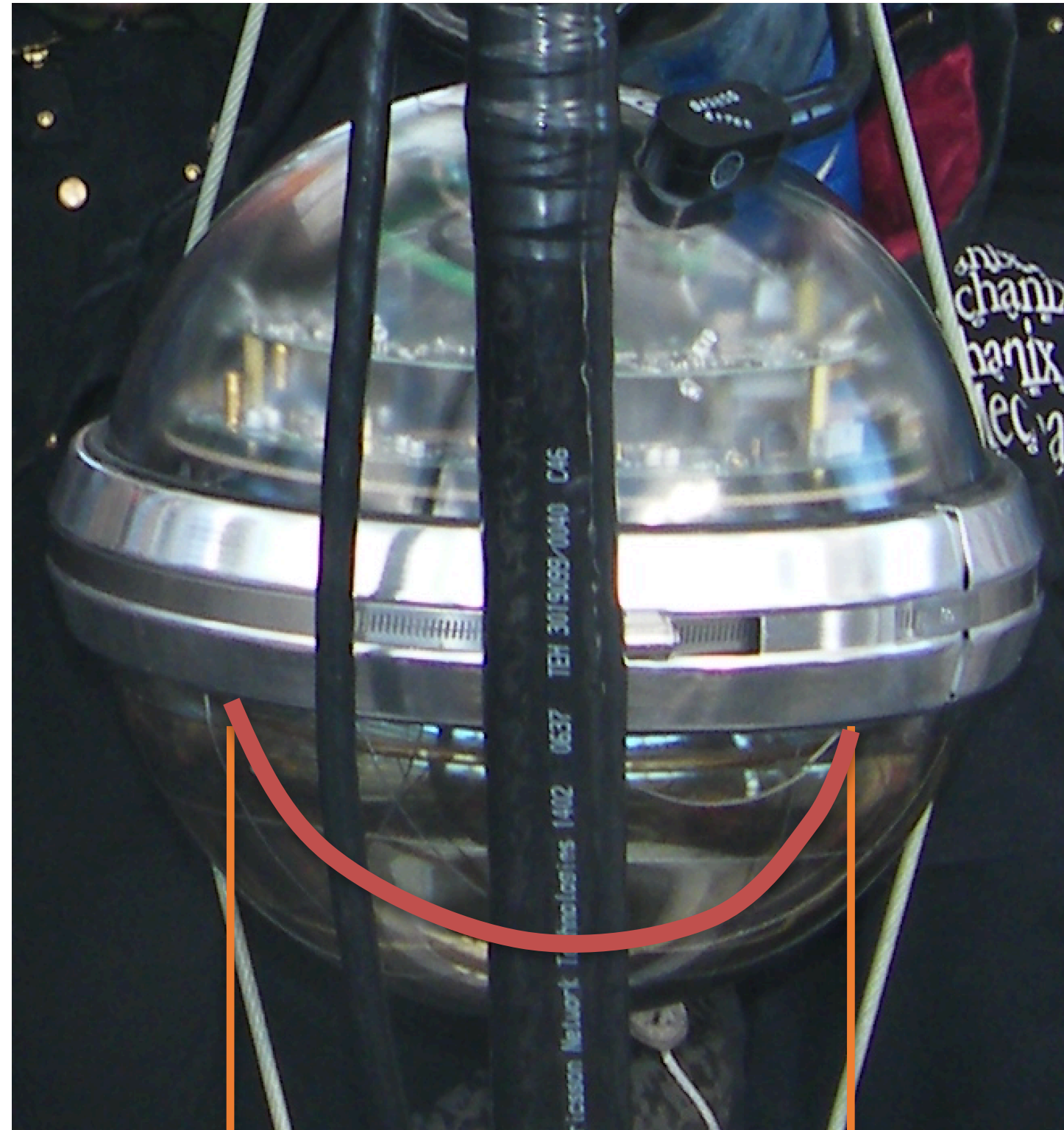
Images taken with camera ("Swedish Camera") during refreeze process:



Hole ice visible on the right.
Need to determine the effect
for every single DOM.

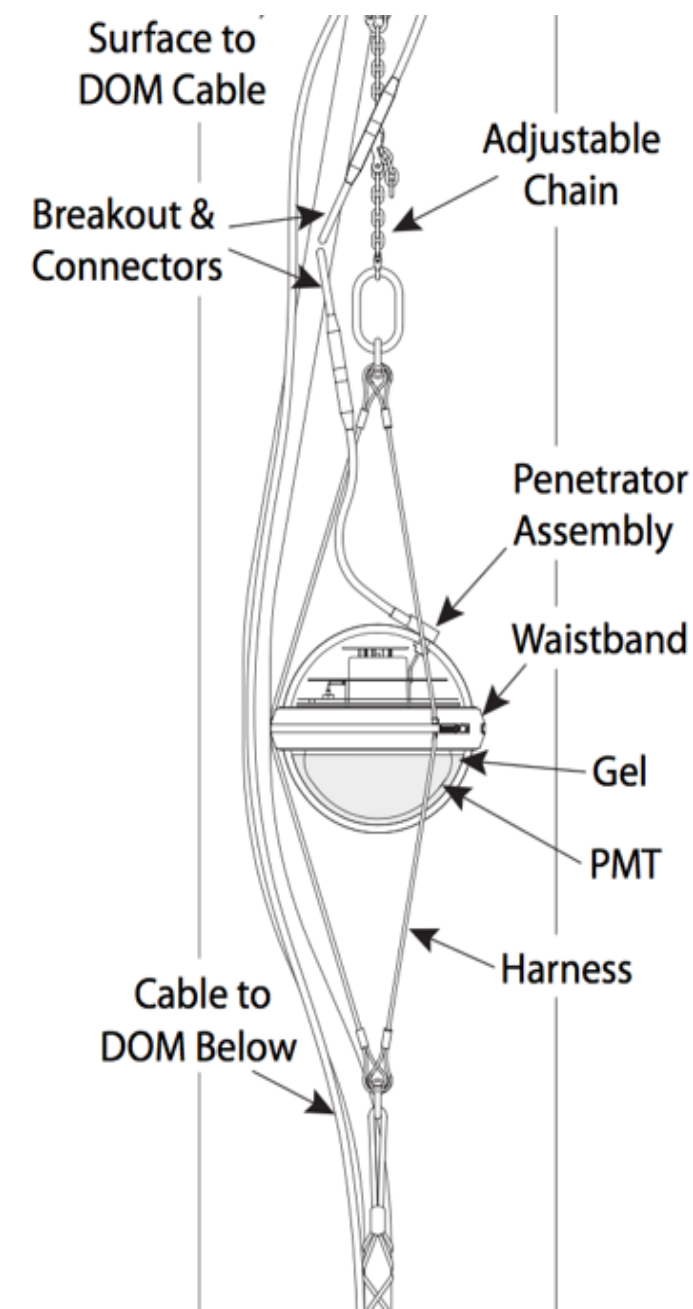
Cable shadow

Cable diameter: 4.5cm

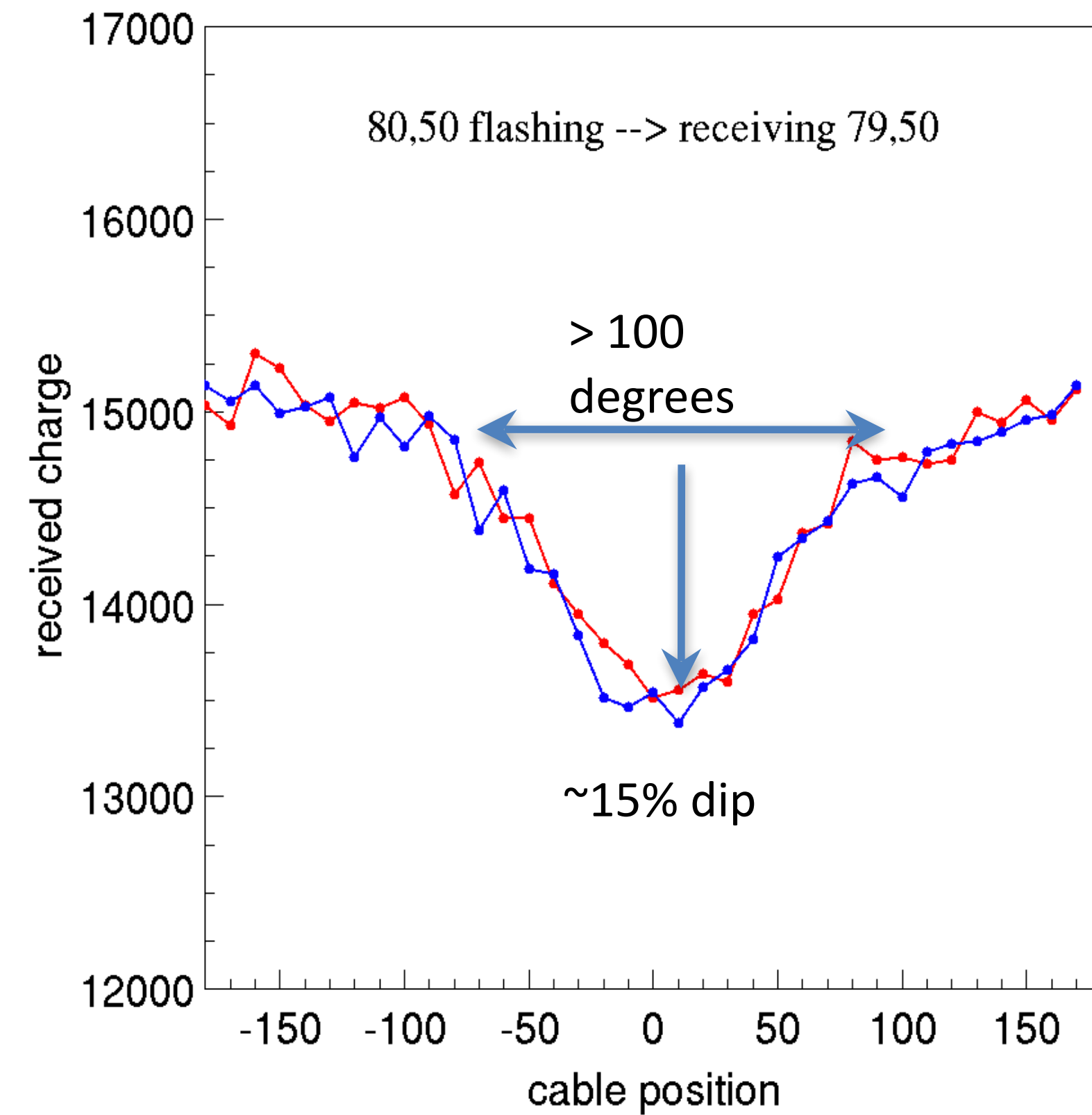


DOM sphere: 32.5

PMT cathode diameter: 22 cm



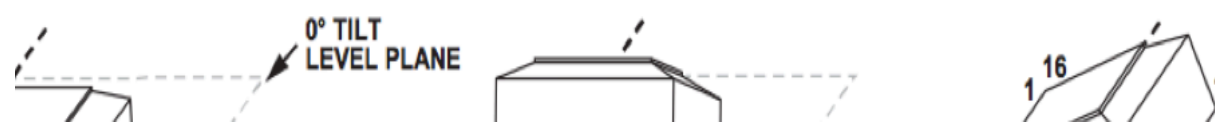
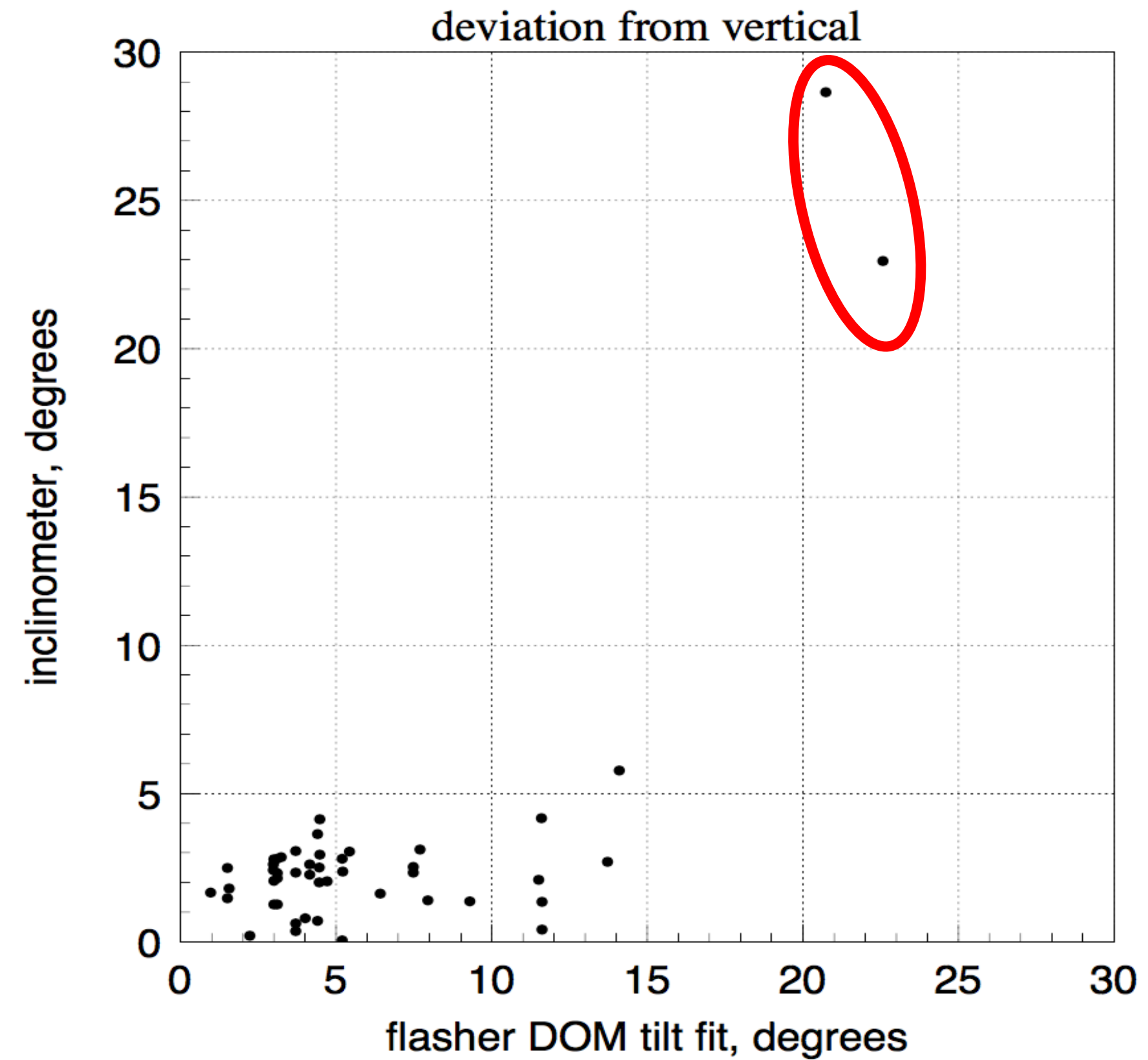
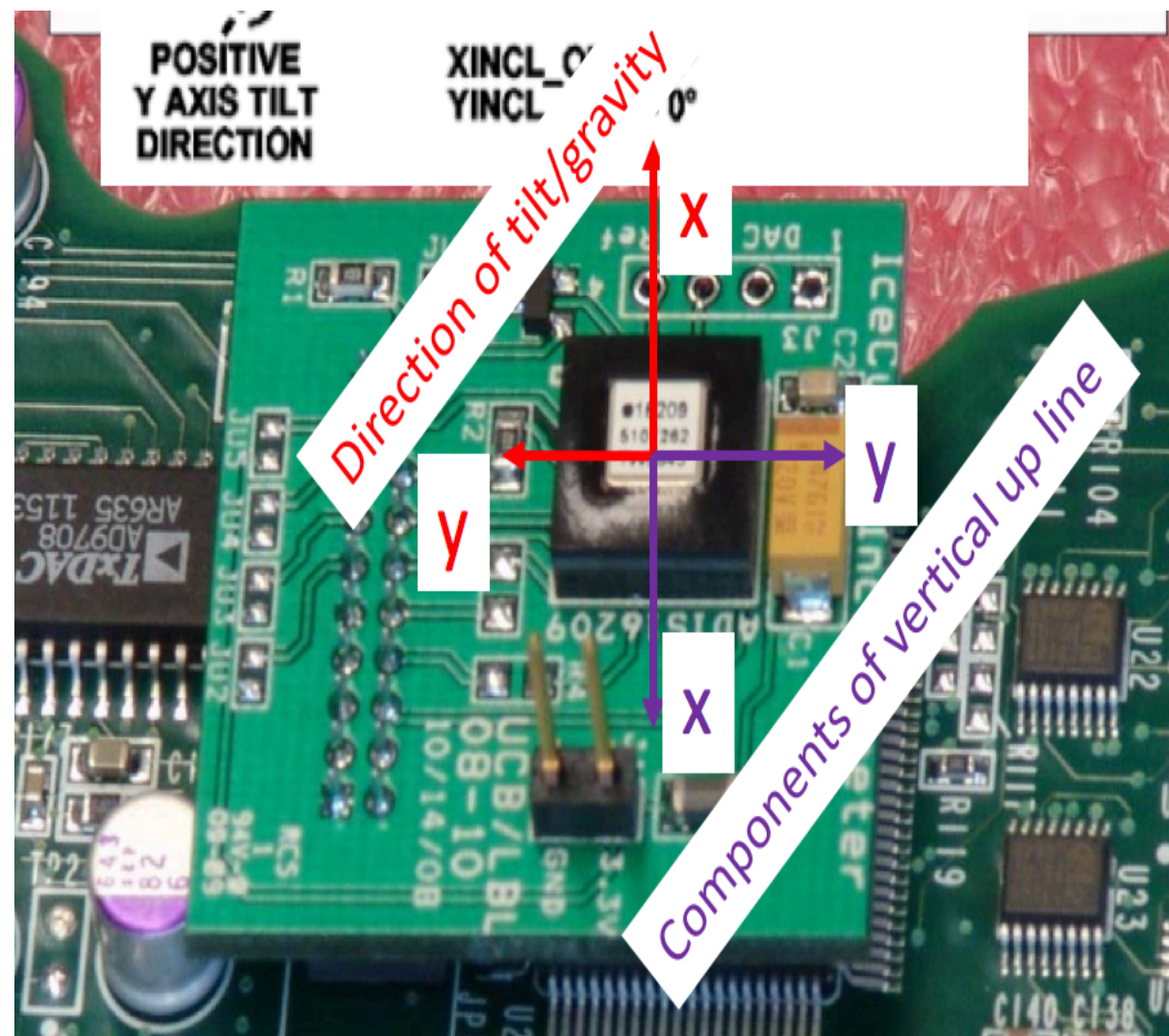
Azimuthal DOM response:
Simulated effect on receiving
DOM from flashers at close
distance.



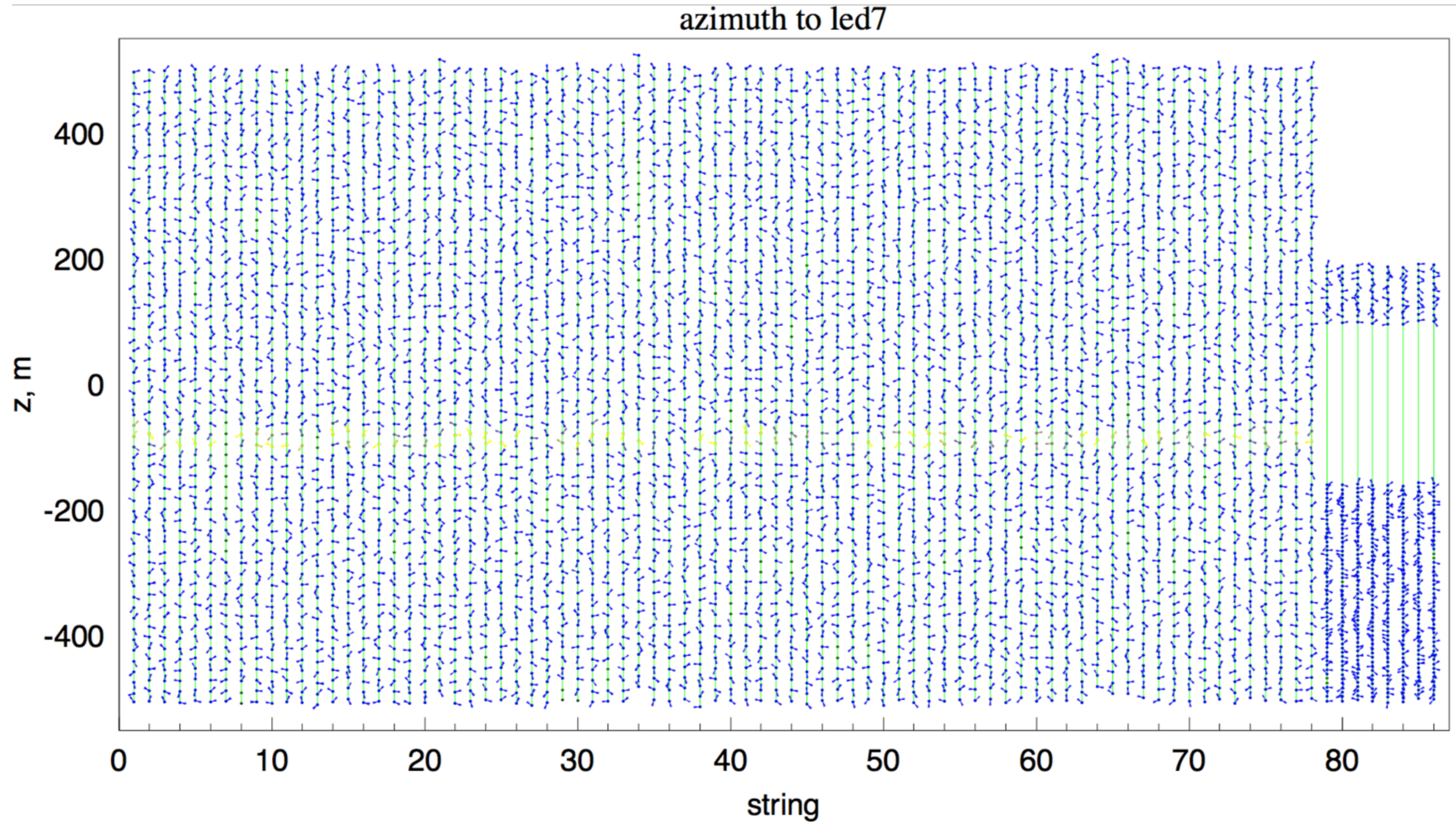
Built-in inclinometers vs DOM tilt fit

Indication of real tilt for 2 DOMs (out of 48)!

4 dozen DOMs have a built-in inclinometer, mounted on the mainboard, most of them have measured very small tilts, while 2 have tilts in excess of 20 degrees.

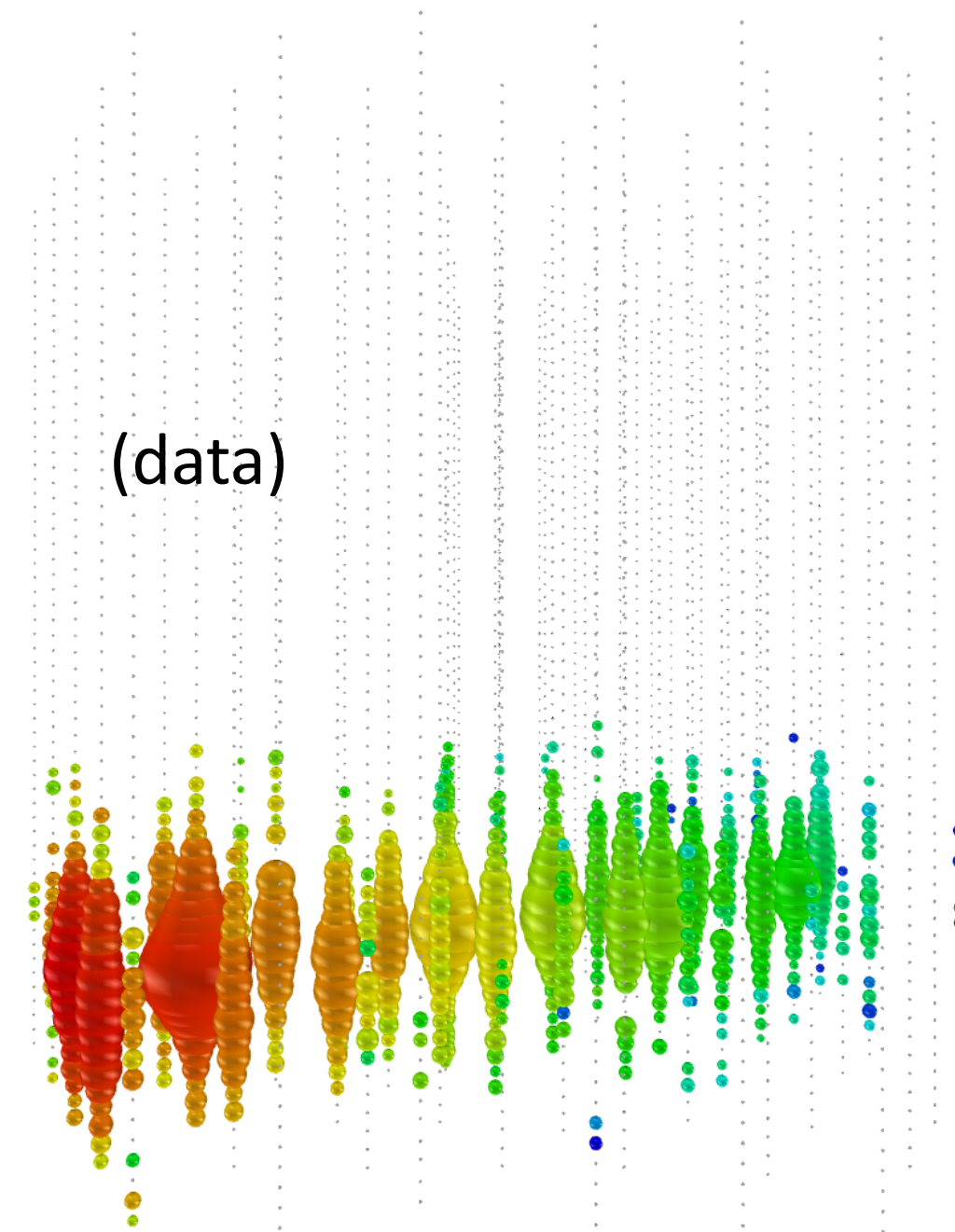


Example of DOM level calibration work:
determined position of individual cables near DOM to few degree
precision



Types of events and interactions

Charged-current ν_μ



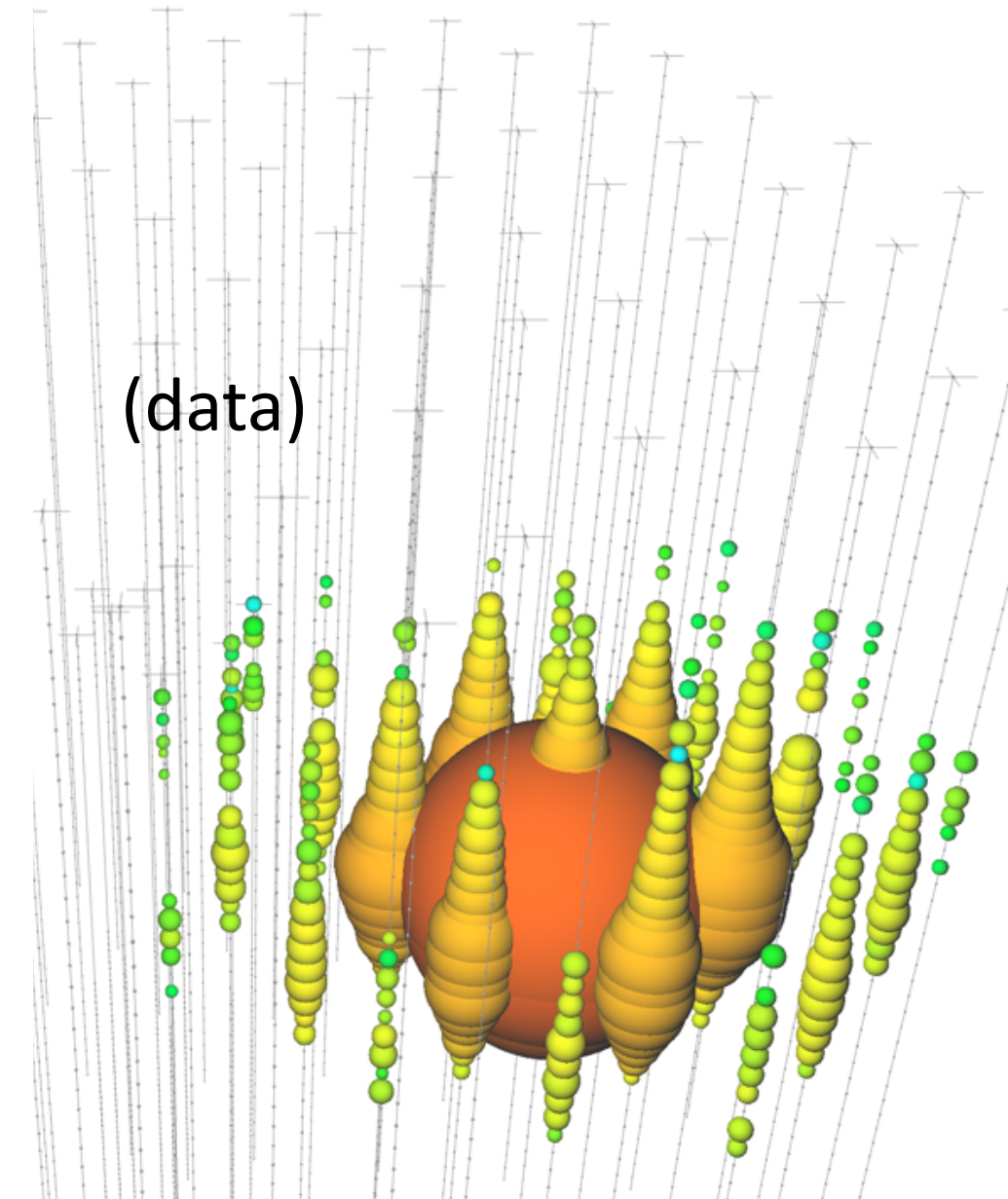
(data)

Up-going (throughgoing) track

Factor of ~ 2 energy resolution
 $\sim 0.5^\circ$ angular resolution

0.3° above 100 TeV

Neutral-current / ν_e



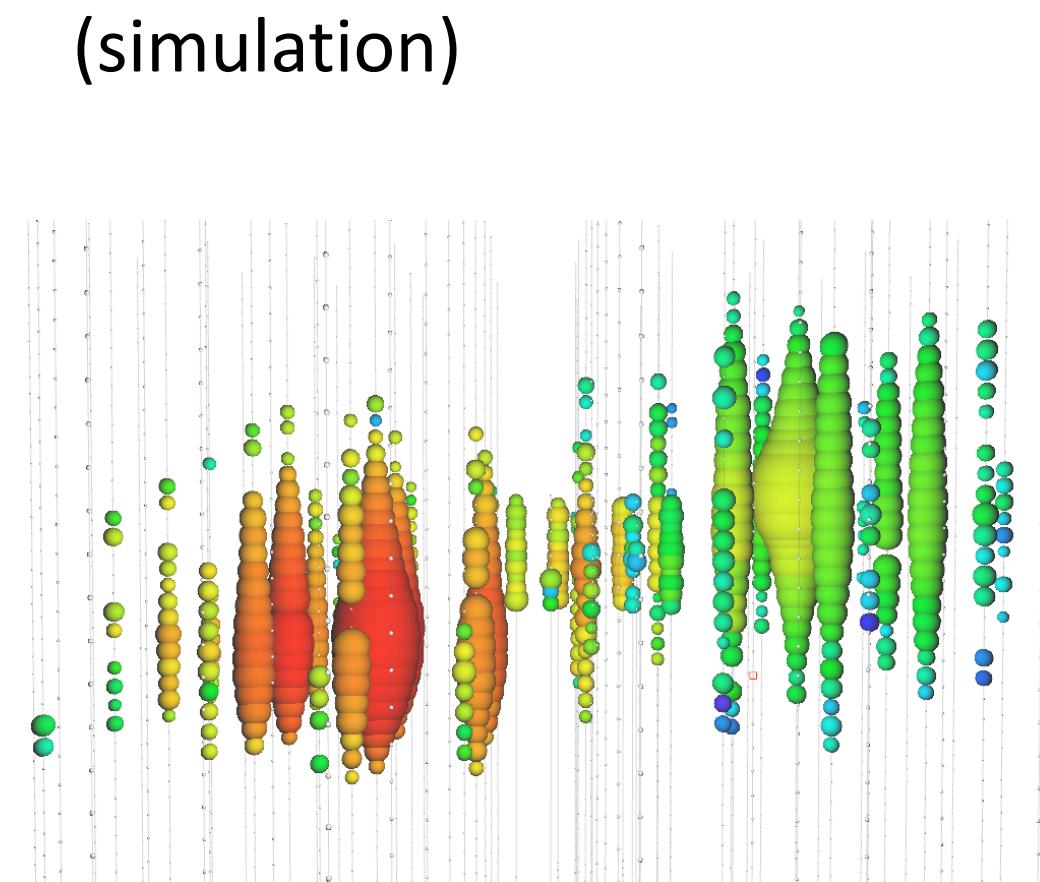
(data)

Isolated energy deposition
 (cascade) with no track

15% deposited energy resolution
 10-15° angular resolution (above 100 TeV)
 Working on improving that.



Charged-current ν_τ



(simulation)

“Double-bang”

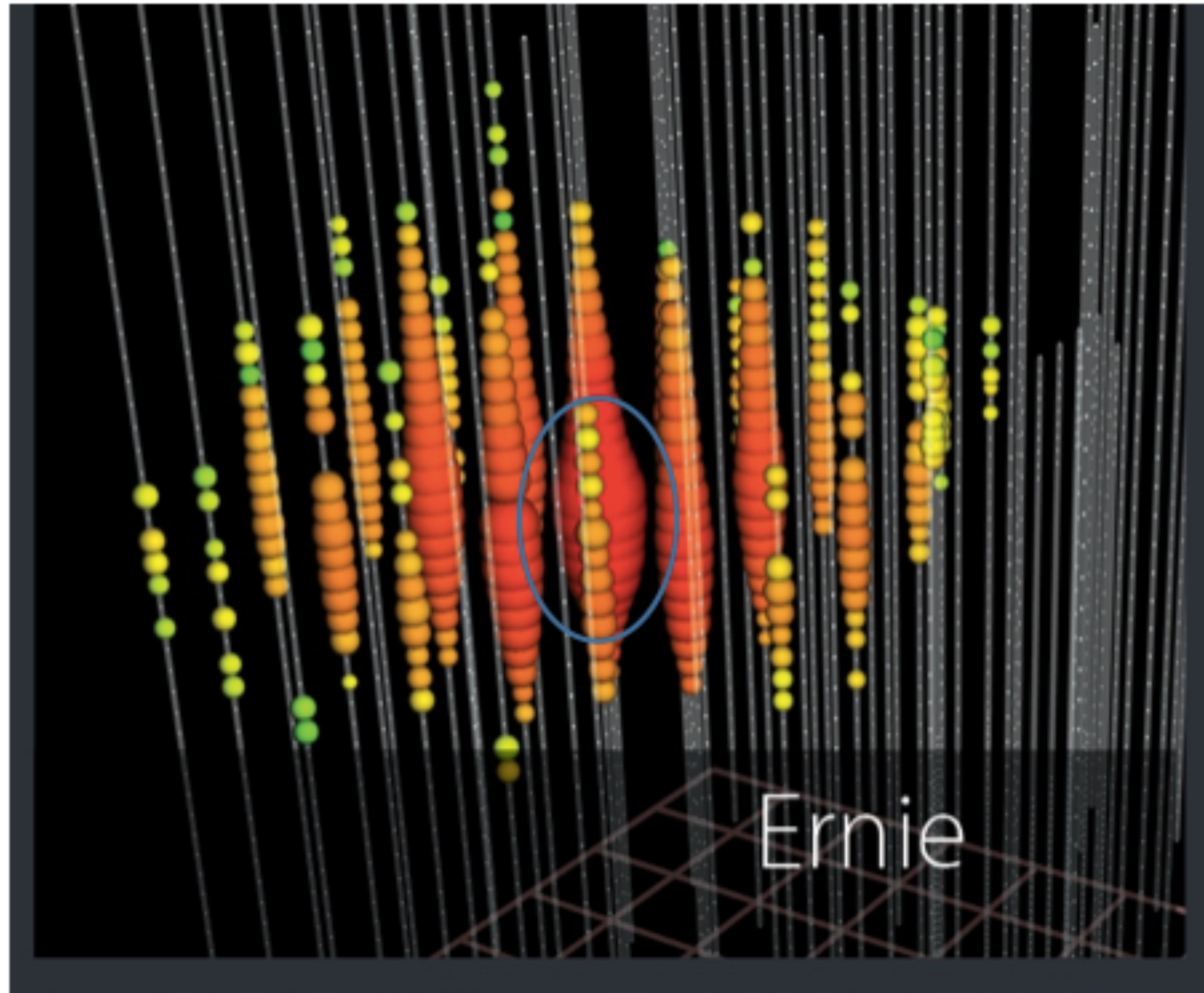
(none observed yet: τ
 decay length is 50 m/
 PeV)

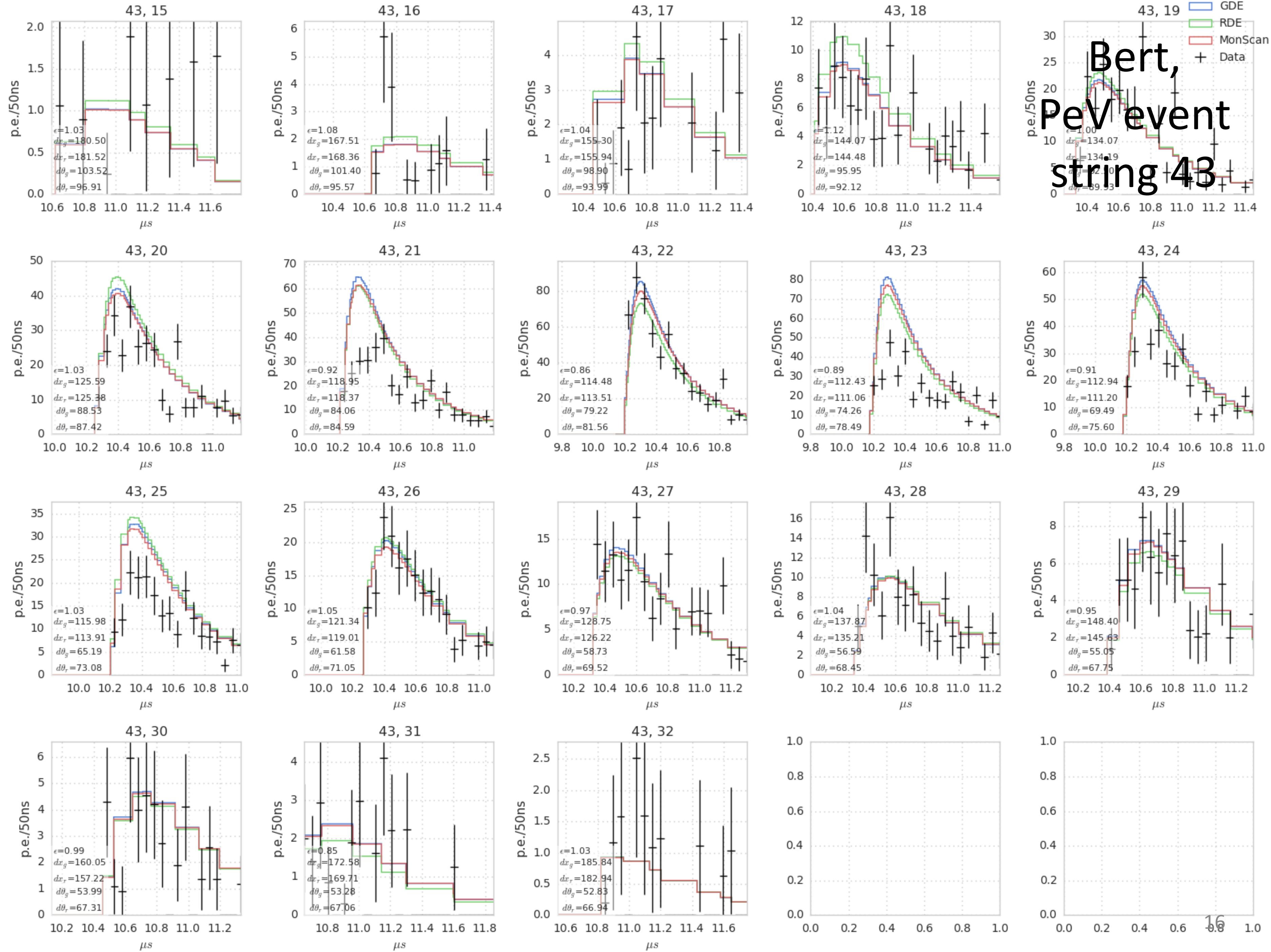
ID: above ~ 100 TeV
 (two methods)

Bright DOMs

DOMs with $Q_{\text{bright}} > 10 * Q_{\text{avg}}$ are classified as “Bright”

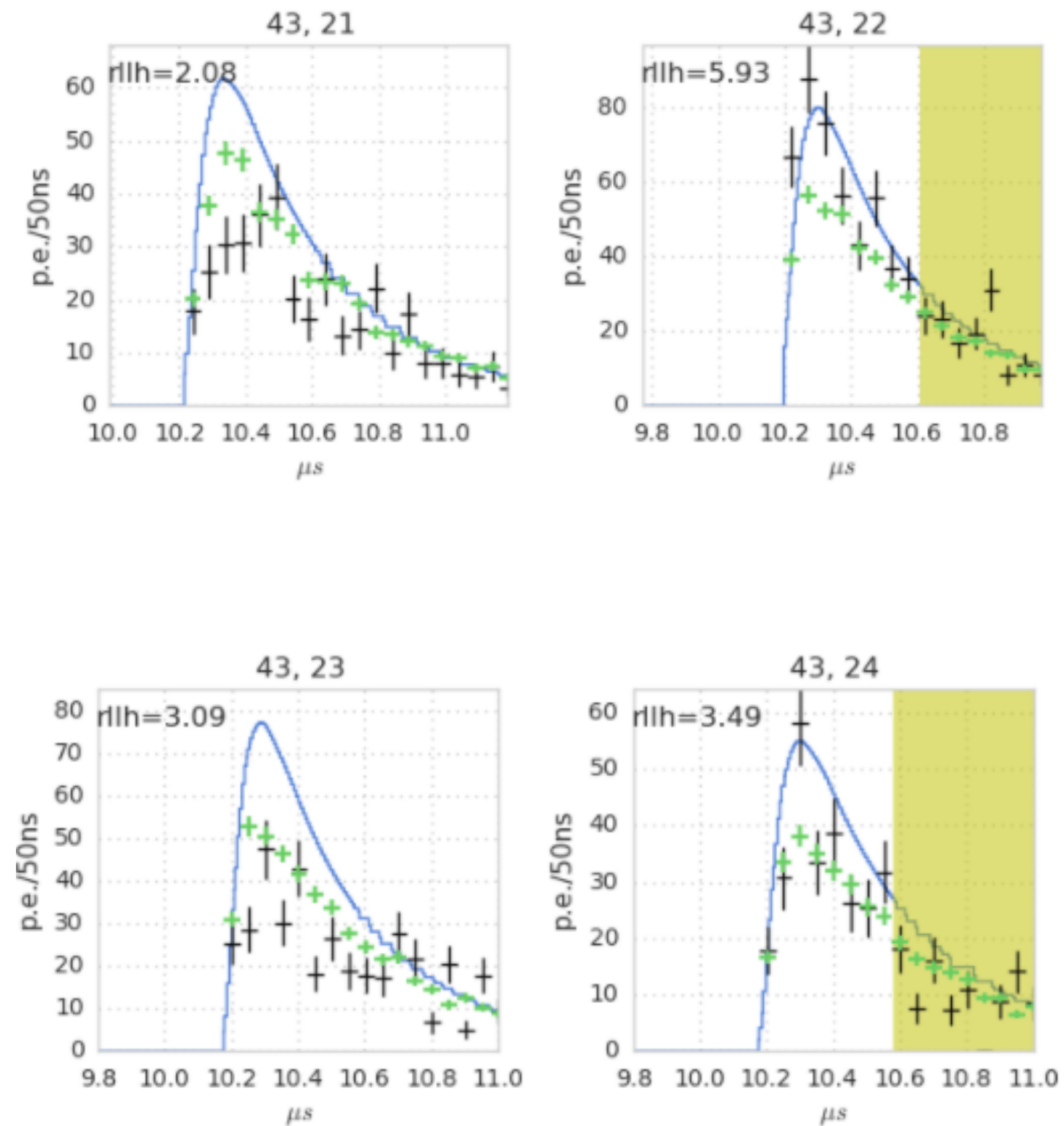
PMT not necessarily saturated, but excluded because unmodeled systematic uncertainties start to dominate at high photon statistics



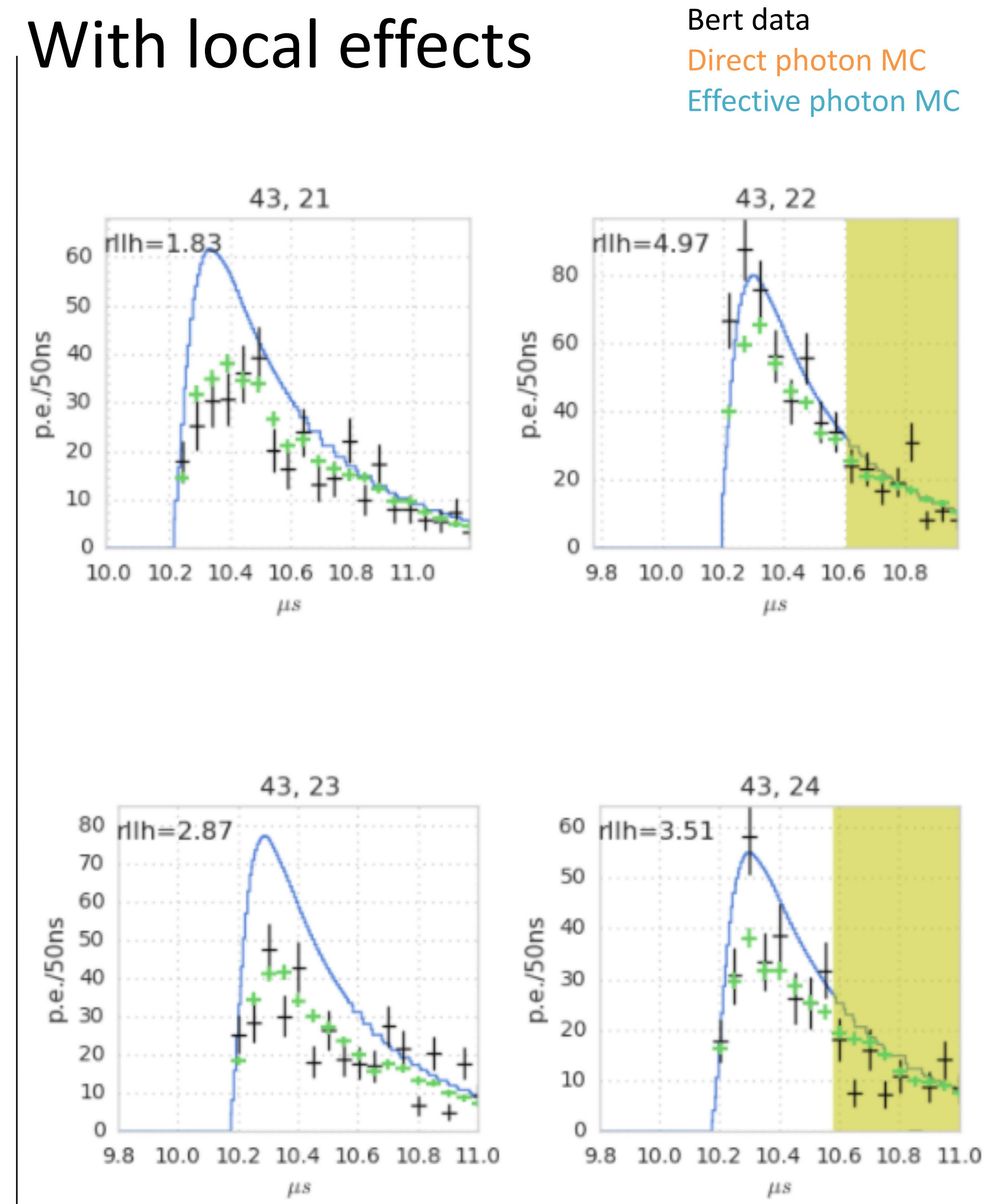


Local effects: DOM orientation and cable position

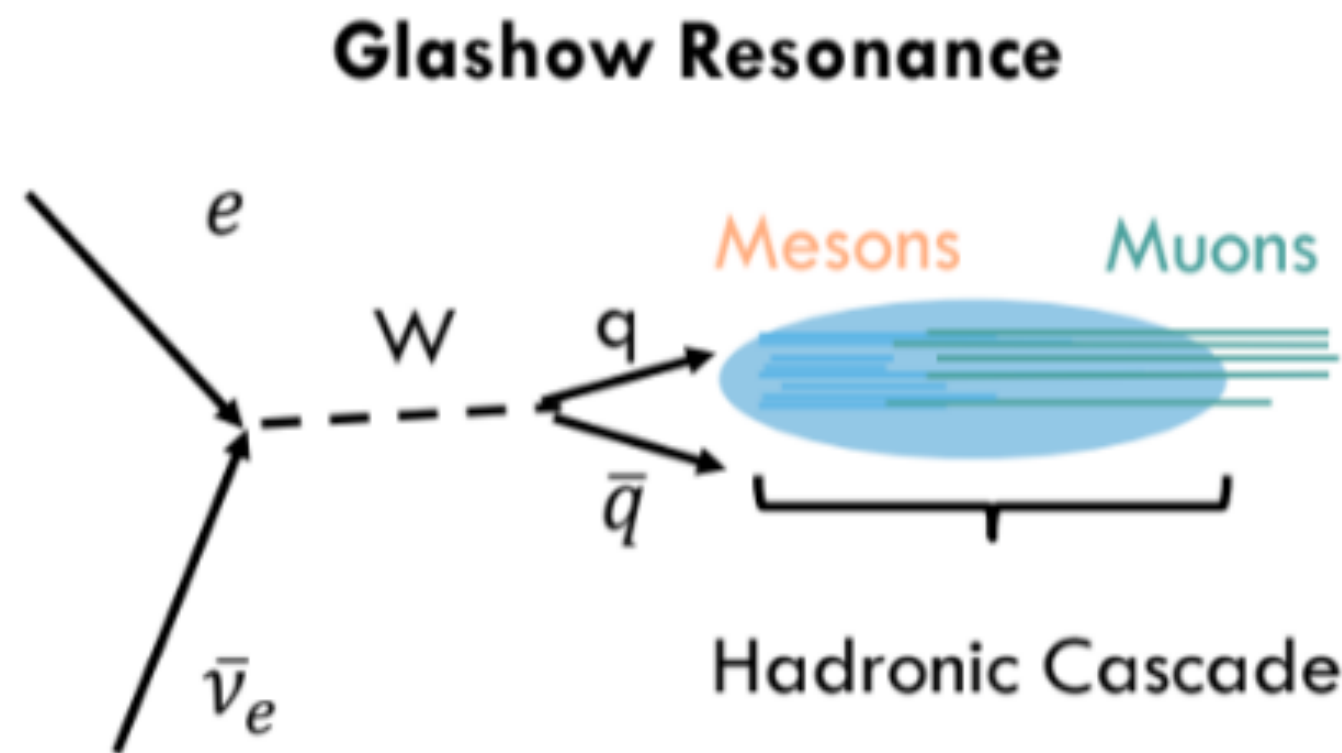
Without local effects



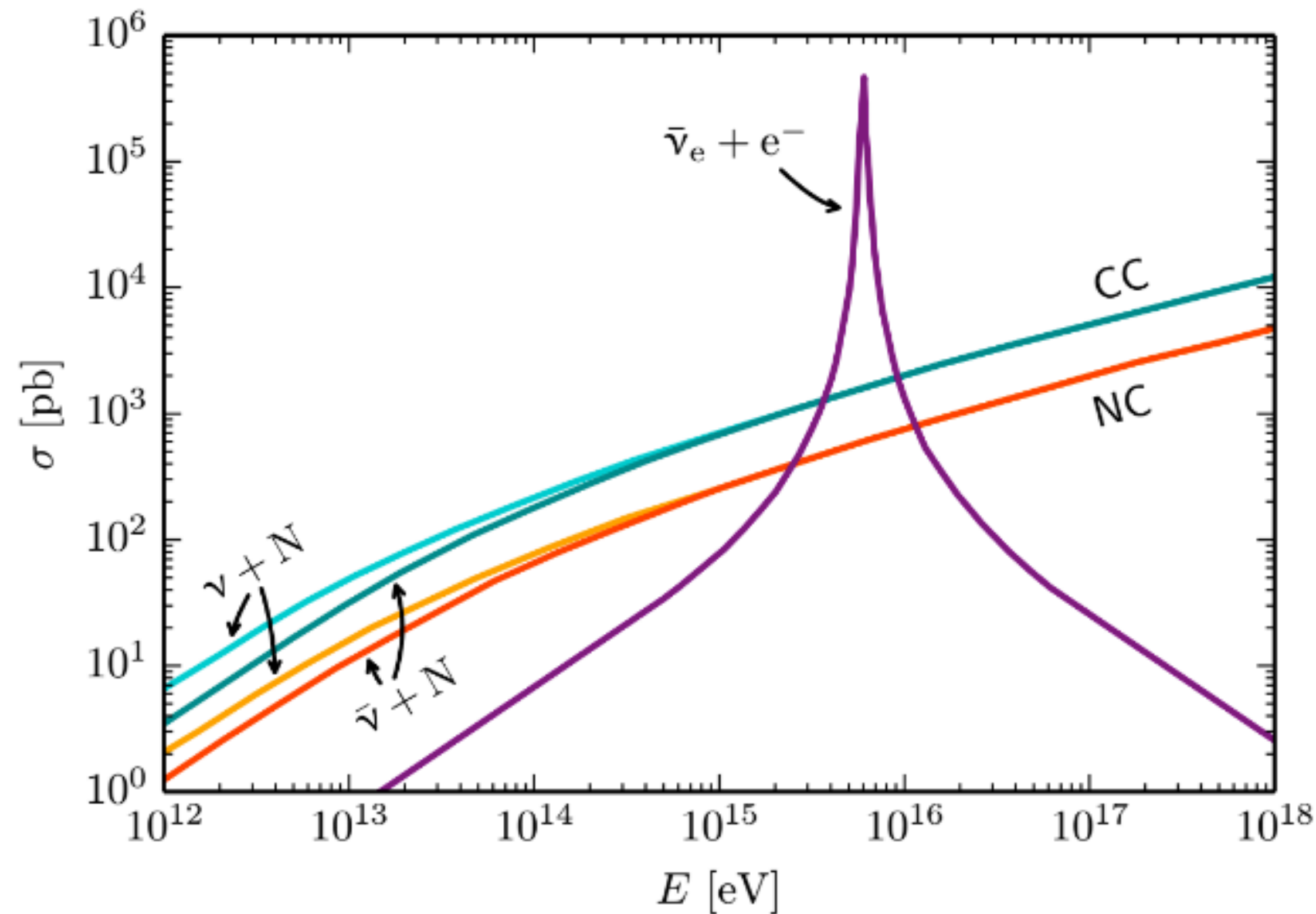
With local effects



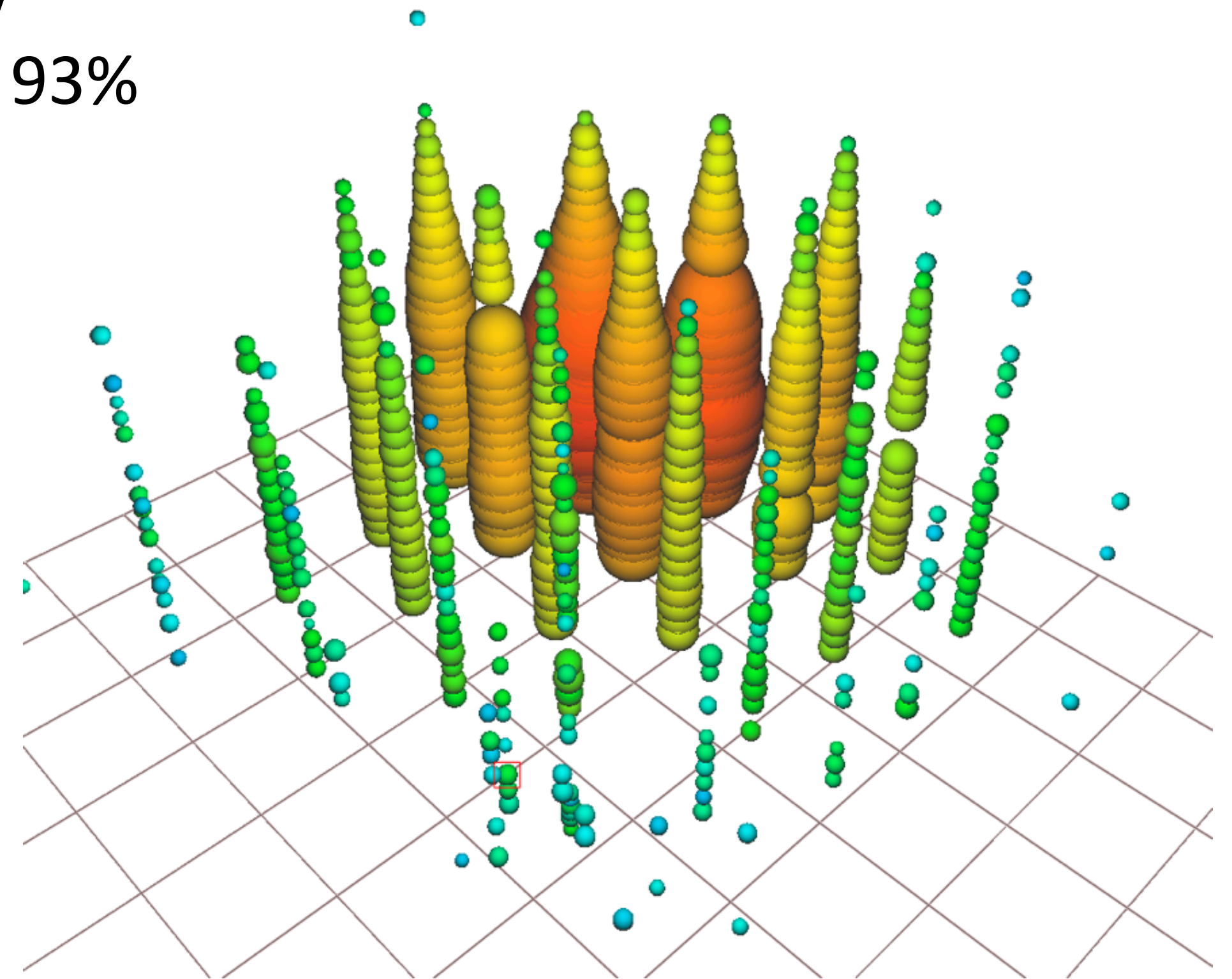
Observation of a 6 PeV neutrino of special interest



Resonance: $E_\nu = 6.3$ PeV
Typical visible energy is 93%



Work in progress



Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9 ± 0.18 PeV (stat only)

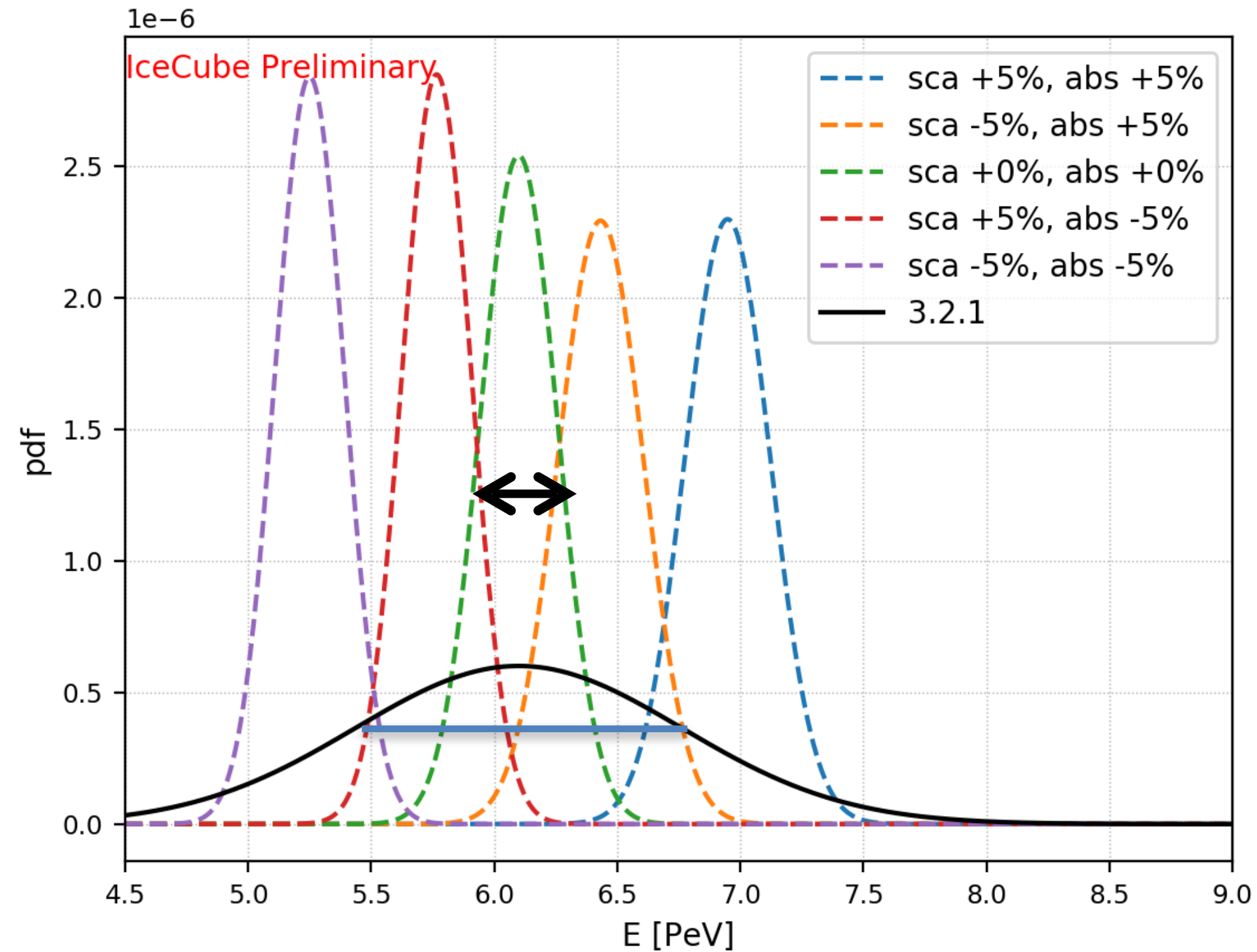
ICRC 2017 [arXiv:1710.01191](https://arxiv.org/abs/1710.01191)

Energy resolution limited by systematic errors: Impact on science

More precise energy reconstruction → reduces backgrounds for GR

Reconstructed width of resonance (and thus background) increases by factor 4 due to sys. errors

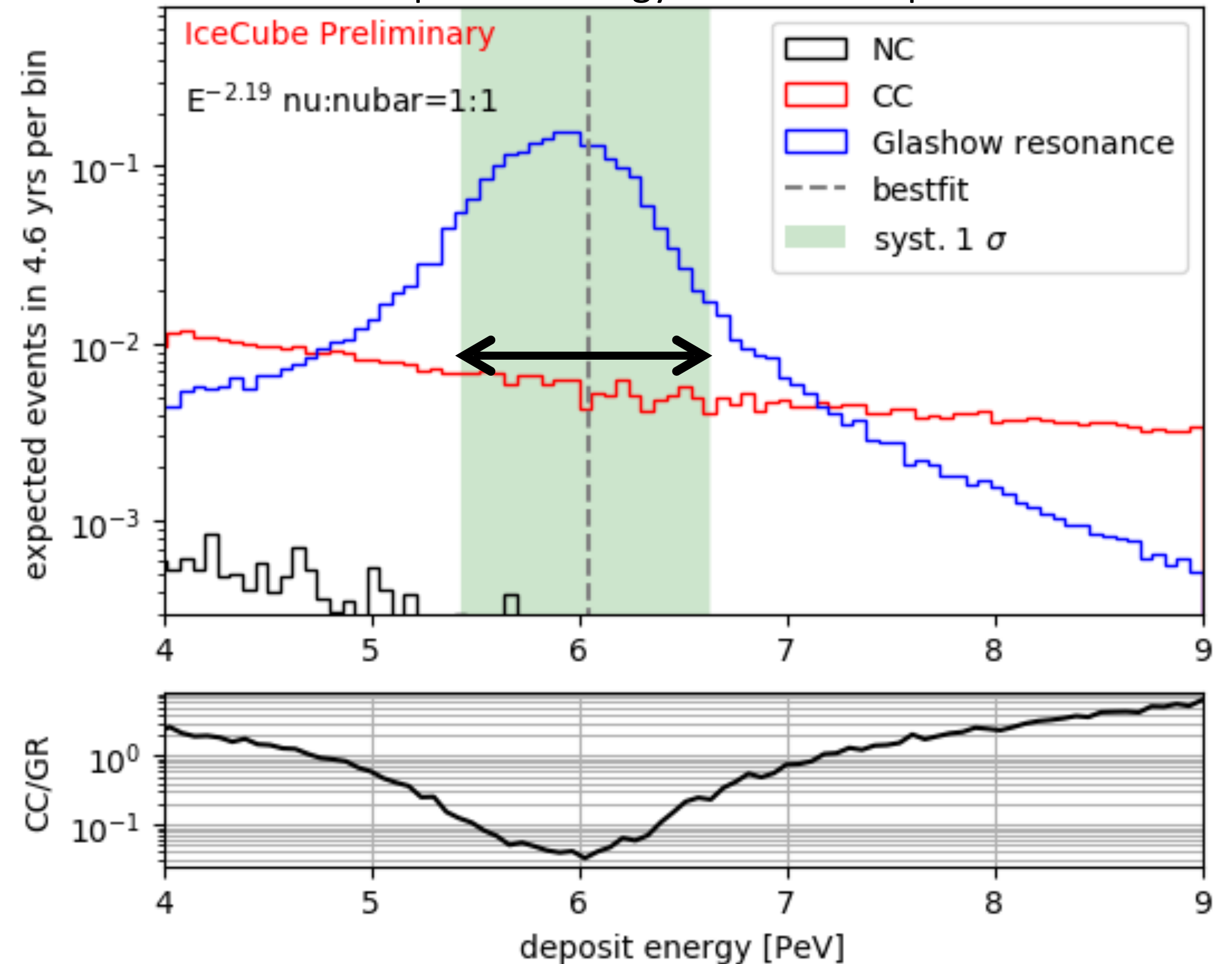
Energy depends on ice parameters



resolution on deposited energy

Statistical error: ~ 0.18 PeV
Systematic error: ~ 0.7 PeV

True deposited energy event rate expectation

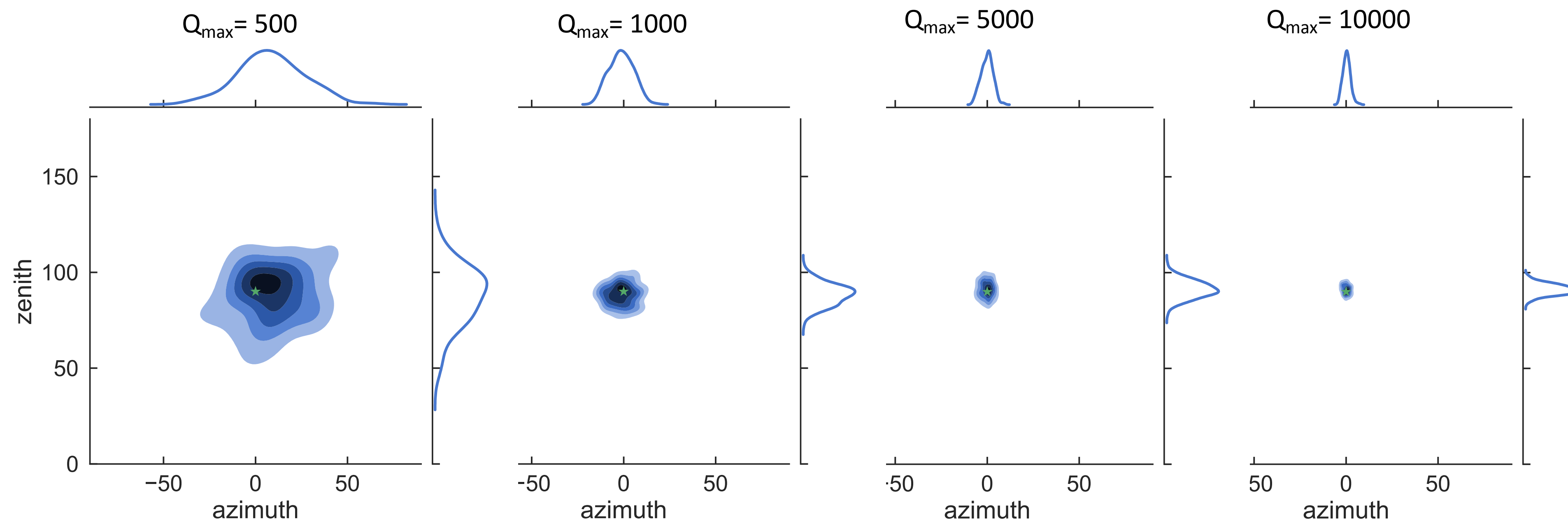


Angular resolution of cascades: limited by systematics

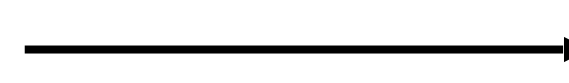
Currently, reconstruction does not use the most nearby sensors in construction.

Bright signals don't help because of systematic errors.

For simulated 1 PeV cascade → Room to improve if local-ice is well-modeled



Less charge used



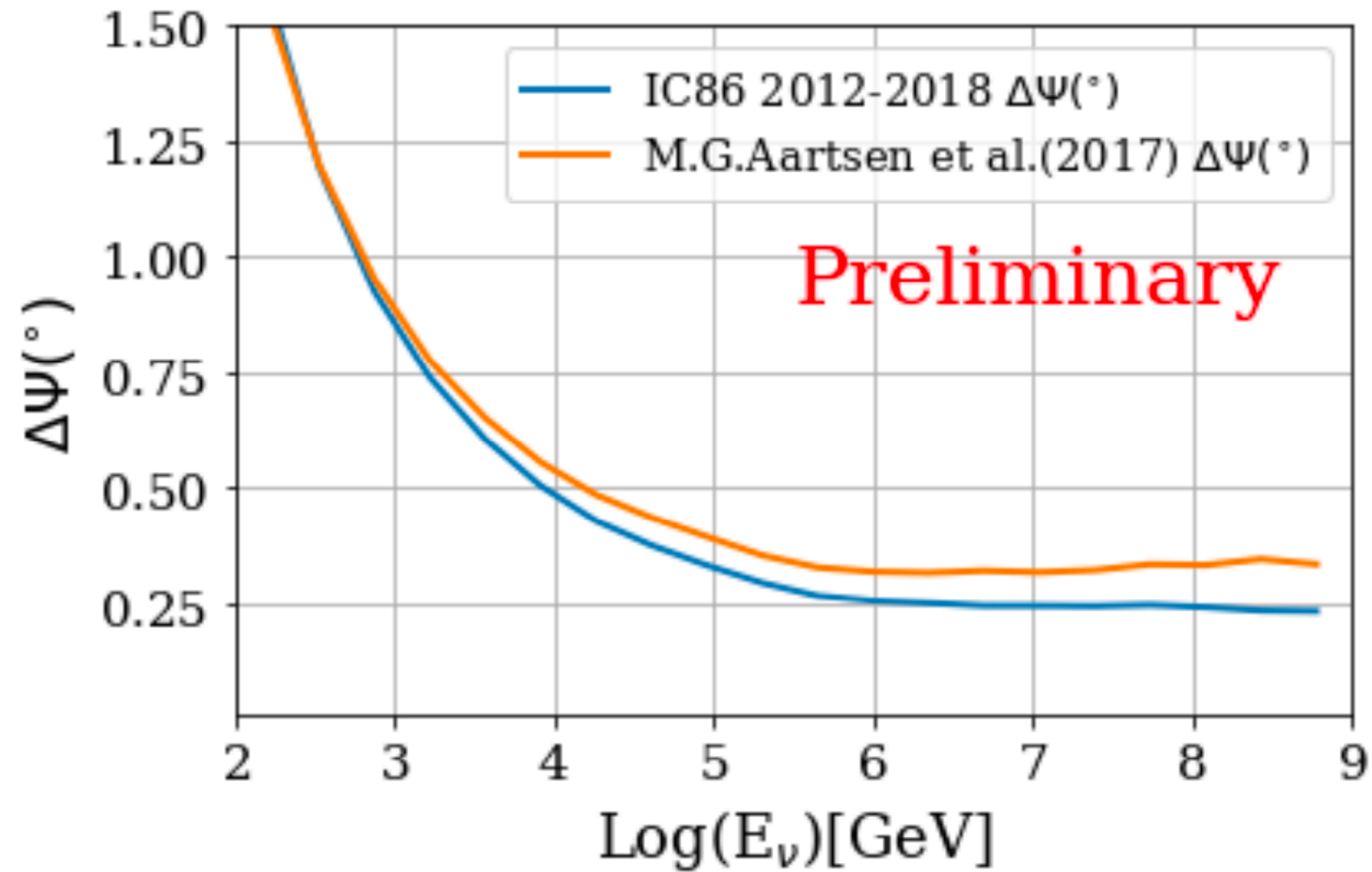
More charge used

Identical ice model for simulation and reconstruction

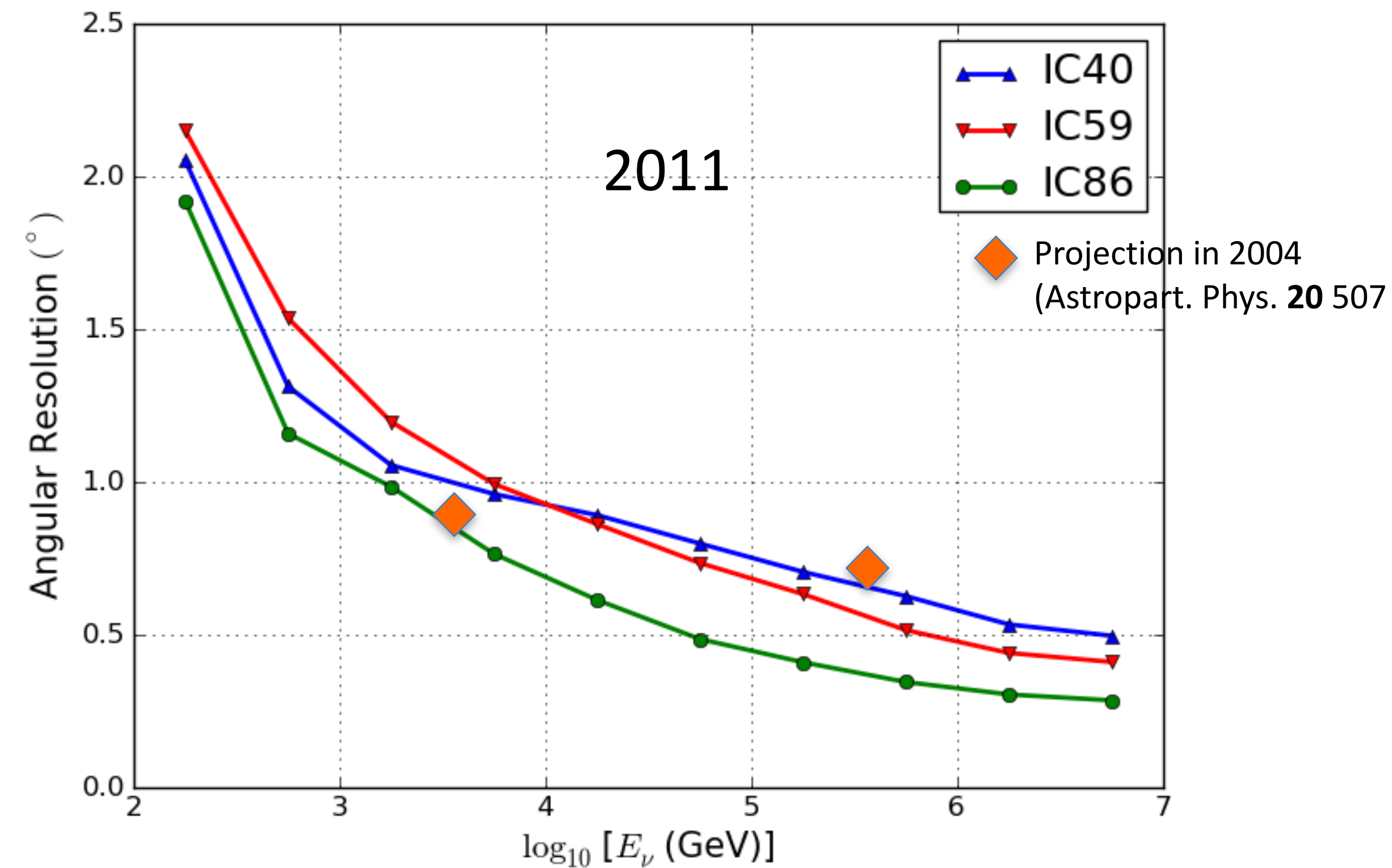
Higher level performance parameters

Angular resolution for muon neutrinos

2019

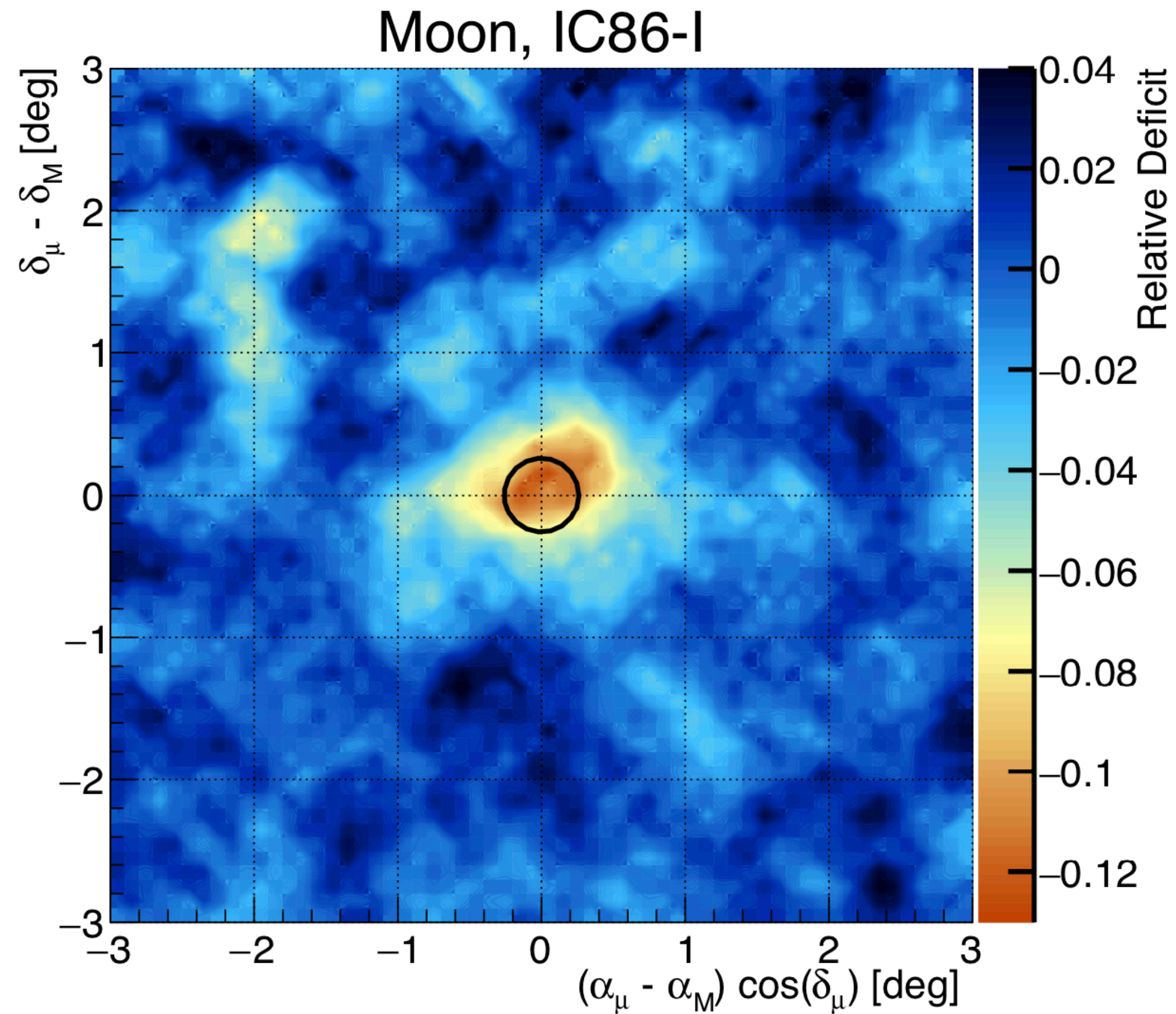


Continued improvement of reconstruction

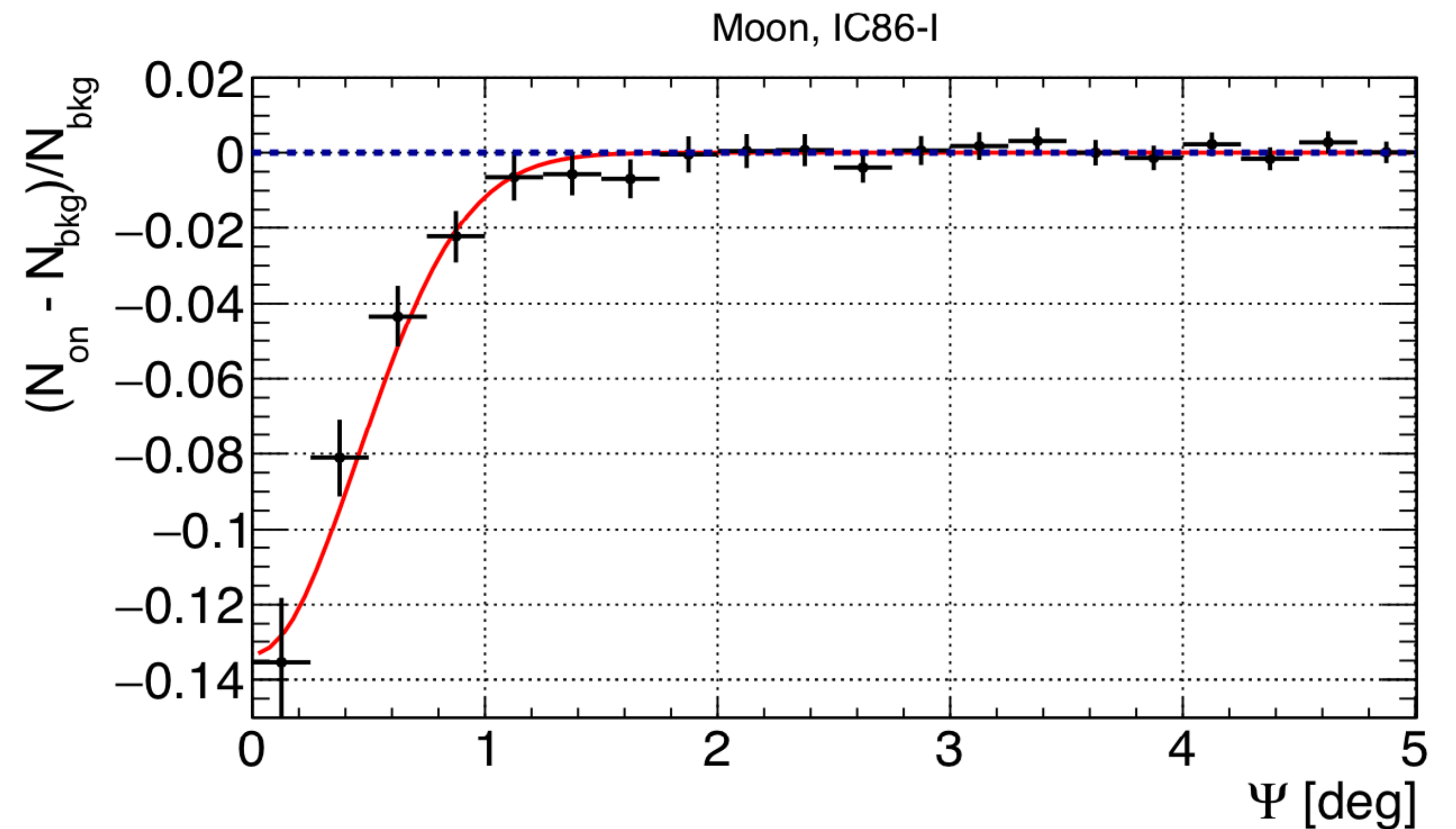


Moon shadow

Cosmic rays absorbed by the moon result in a deficit of muons in IceCube



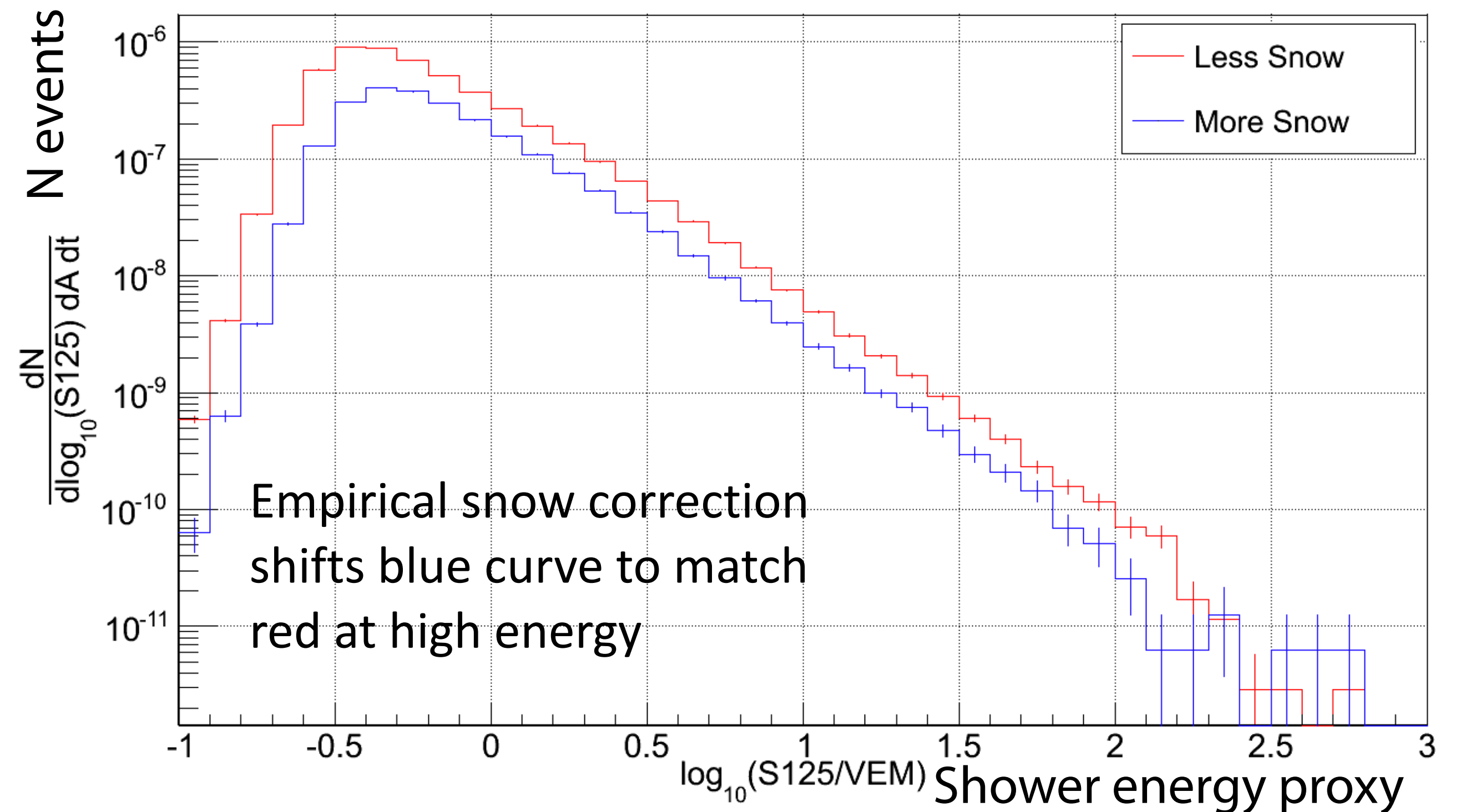
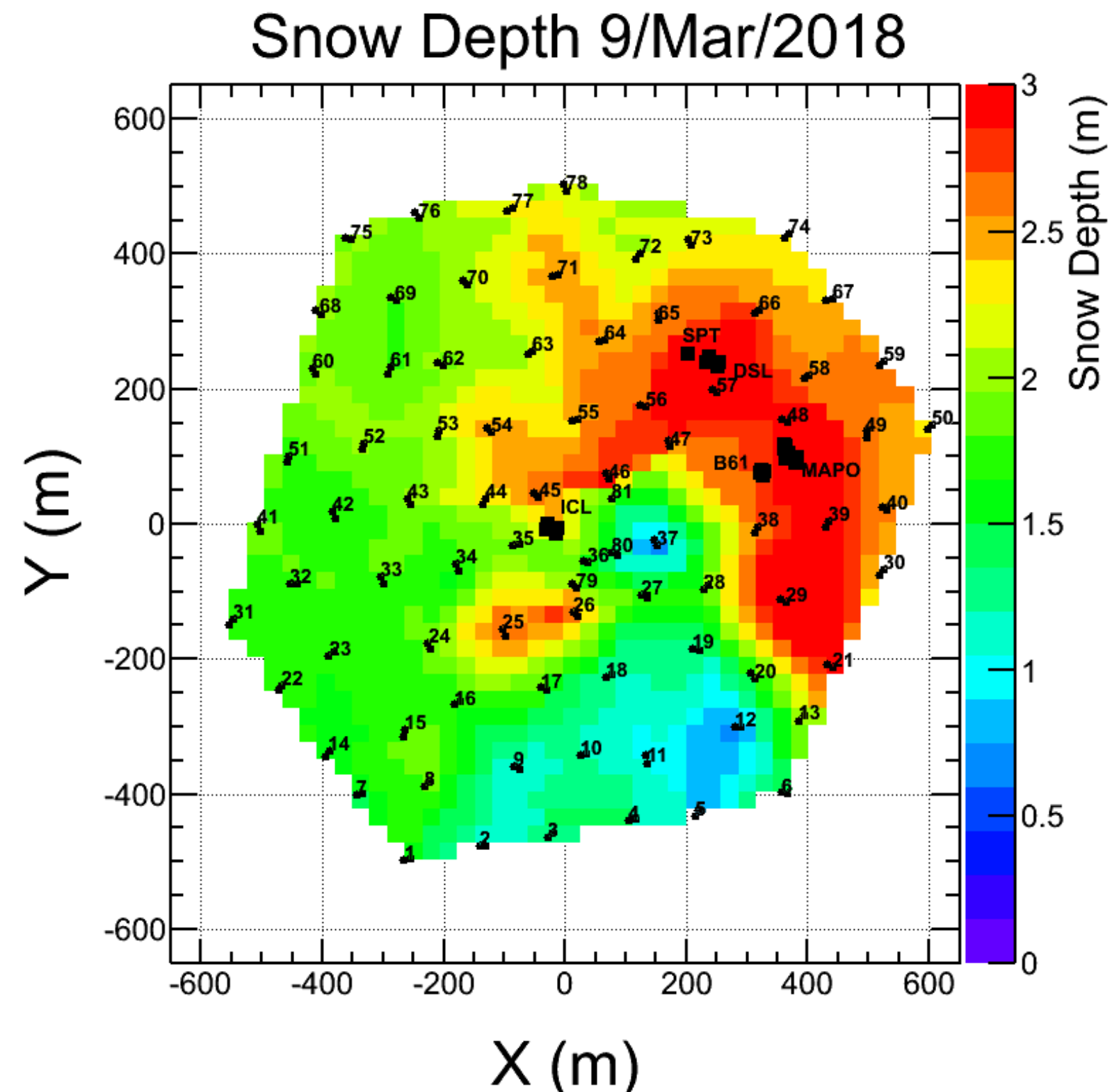
Absolute pointing verified to 0.1°
Median resolution for low energy muons: 0.7°



ICNO R&D

- R&D related to M&O and continued optimization of IceCube:
 - Surface instrumentation
 - SpiceCore
- R&D geared towards the future: Upgrade and Gen2
 - Detector R&D, new optical modules

Snow depth of IceTop & effects on physics analysis



Snow accumulates on top of IceTop tanks at an average rate of 20 cm/year.

- >70% tanks are under 2 meters of snow or more.
- Sensitivity to low energy showers is reduced
- Uncertainty affects a number of physics analyses

Science case for scintillator deployment

Enhance IceCube's neutrino measurements:

- Better understanding of atmospheric backgrounds due to more accurate measurements of the cosmic rays mass composition and energy spectrum, and interaction models.
- Improved calibration of in-ice detectors.
- More efficient veto of cosmic ray backgrounds - verification of crucial self veto method in energy range 10 to 100 TeV. The energy threshold at which the veto becomes efficient is estimated to be lower by a factor of two.

Cosmic Ray and other science

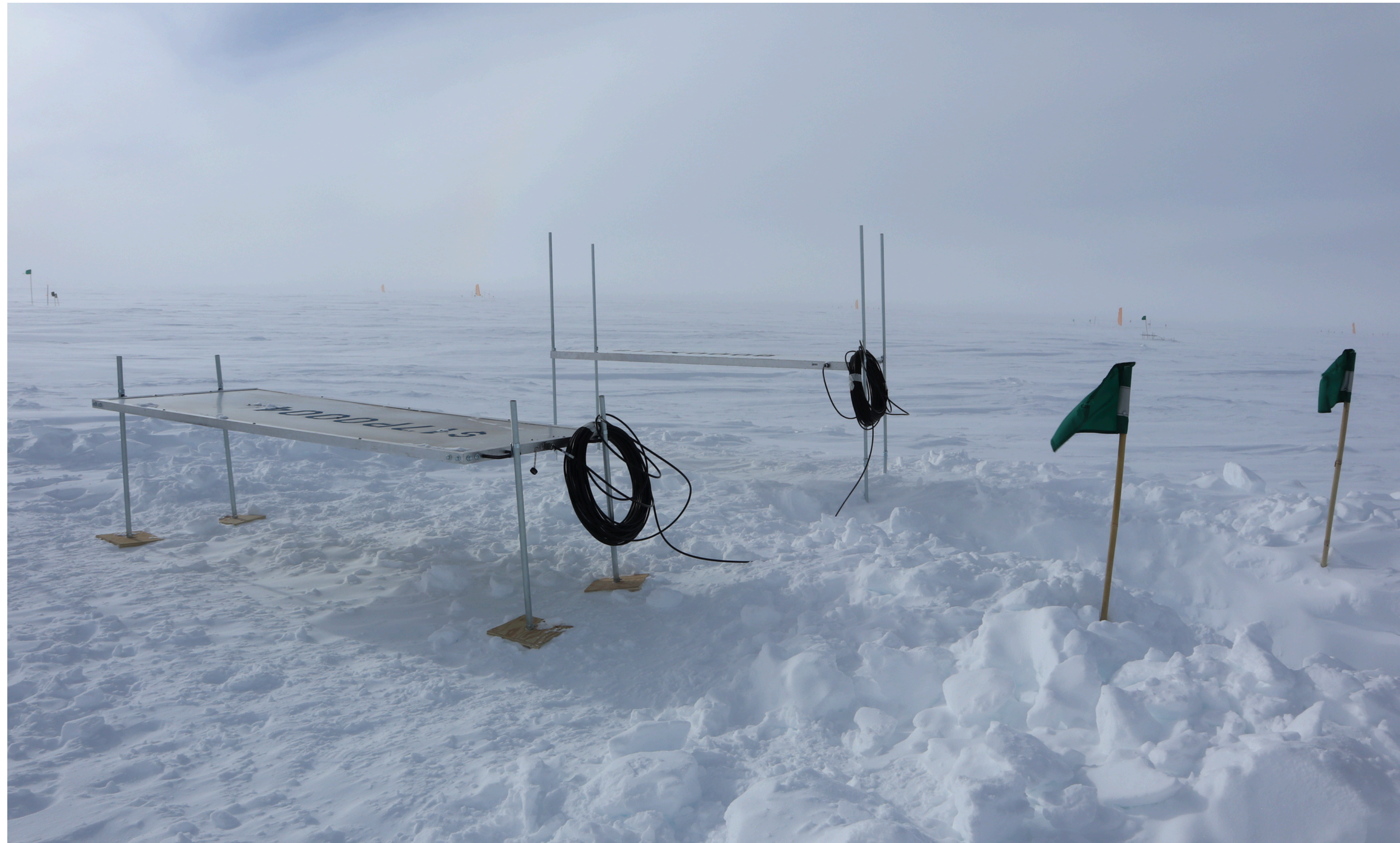
- By adding scintillators with a similar coverage as IceTop, the energy threshold at which the veto becomes efficient is estimated to be lower by a factor of two.

Other benefits: R&D for future detector upgrades

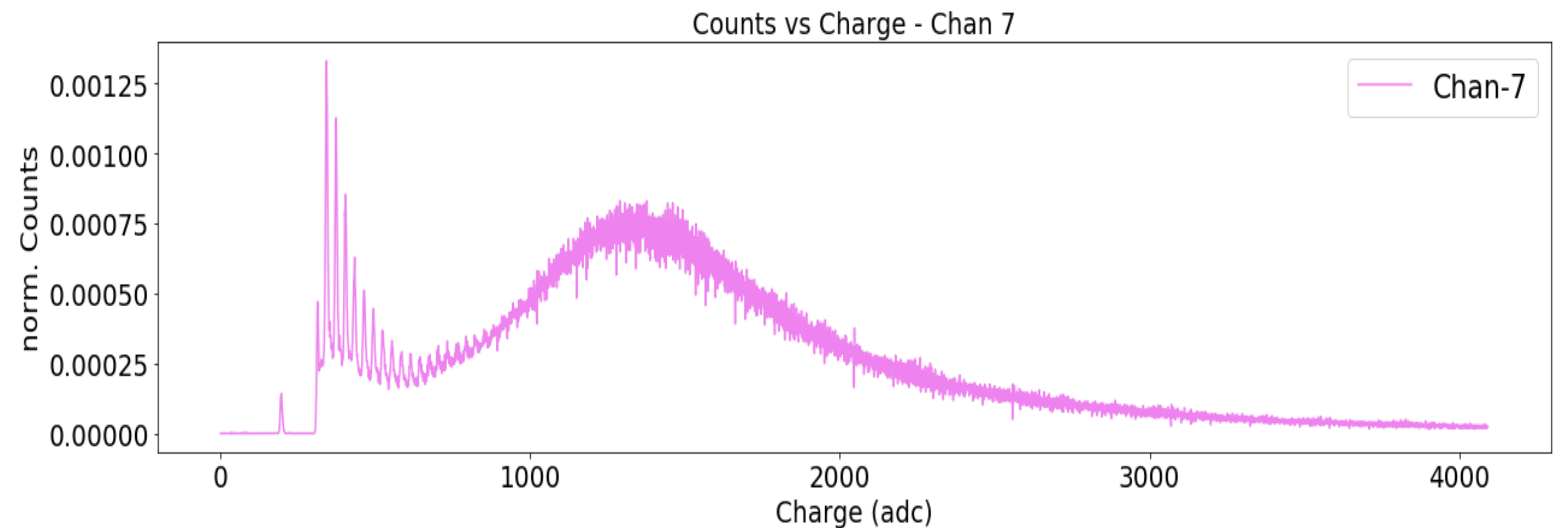
- A new, scalable precision timing and high-speed communications scheme for IceCube M&O and possible future projects.
- Efficient trenching procedures for instrumentation installation.
- Mechanical solutions to raise scintillator panels above the snow during the period of array deployment.

Performance

- Two stations (with different designs, each offering unique advantages) were installed in pole season 2018/19 and have been taking data since May 2018.



- Excellent performance of both stations



Radio component

2-4 radio antennas per scintillator station will help reconstructing gamma ray showers (which are particle-poor at surface) also from larger zenith angles (including the galactic center) and allow for:

- improving accuracy in the cosmic rays mass composition analysis
- searching for PeV photons from the Galactic Center
- testing hadronic interaction models

Science case backed up by simulation

Air Cherenkov R&D



Measure directly the CR showers electromagnetic component down to 20 TeV will:

- improve calibration of the in-ice detector and IceTop
- Lower veto threshold for IceCube
- Improve mass composition analysis

Some challenges to be overcome (duty cycle, snow drift, electronics)

- 2 more IceAct telescopes at the South Pole are being installed in 2018/19 season
 - One will replace current telescope on ICL roof
 - One will be installed next to Scintillator Station, using connections at the scintillators Field Hub

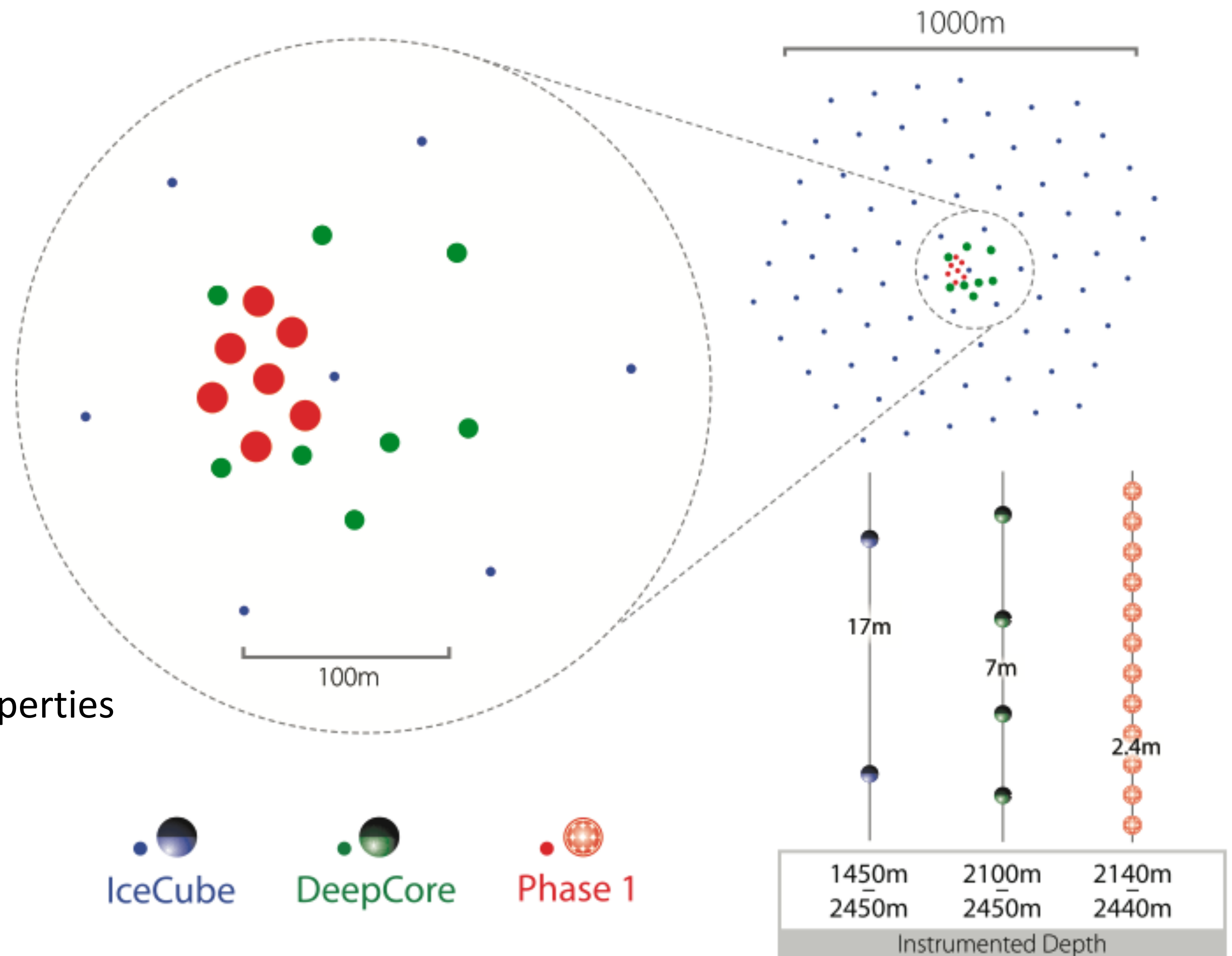
IceCube Upgrade (a step towards Gen2)

Funded.

7 strings in center of IceCube,
densely instrumented

Science goals:

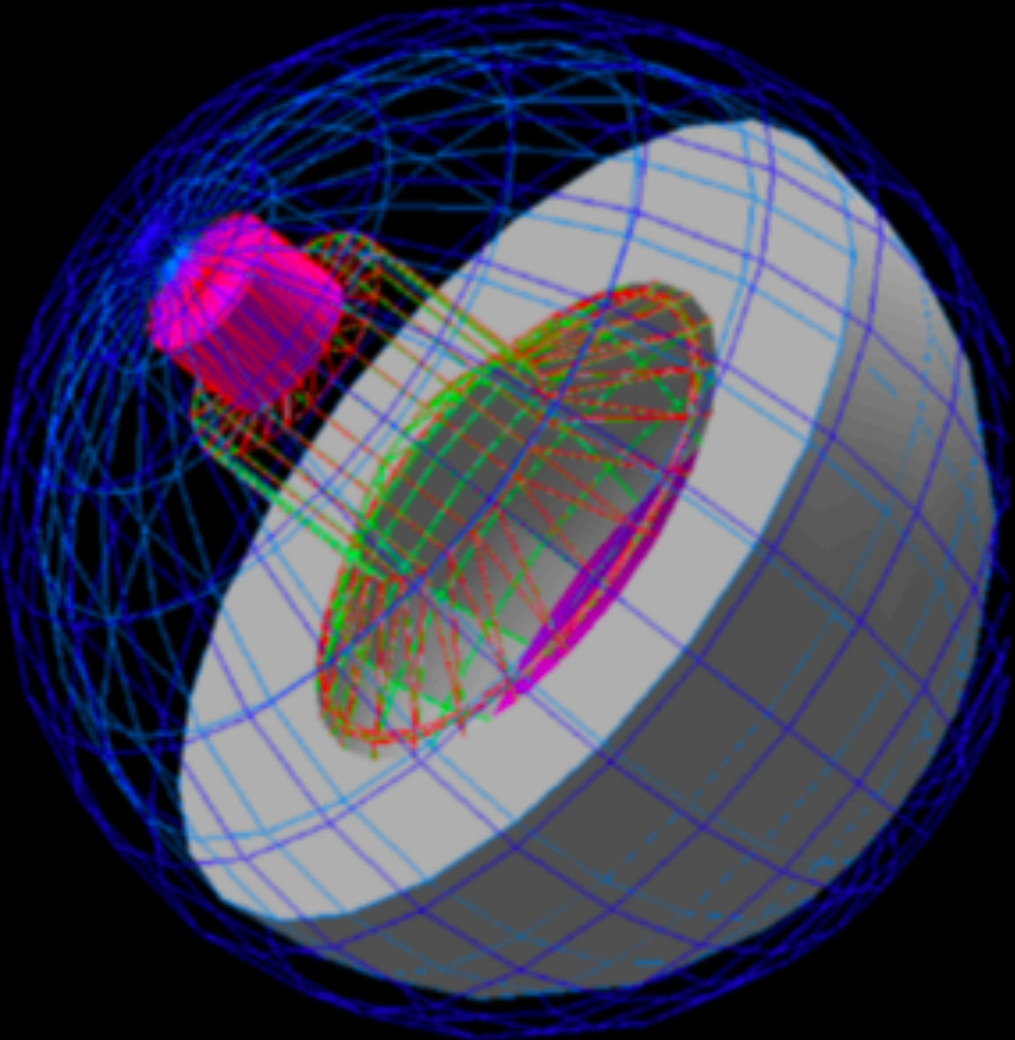
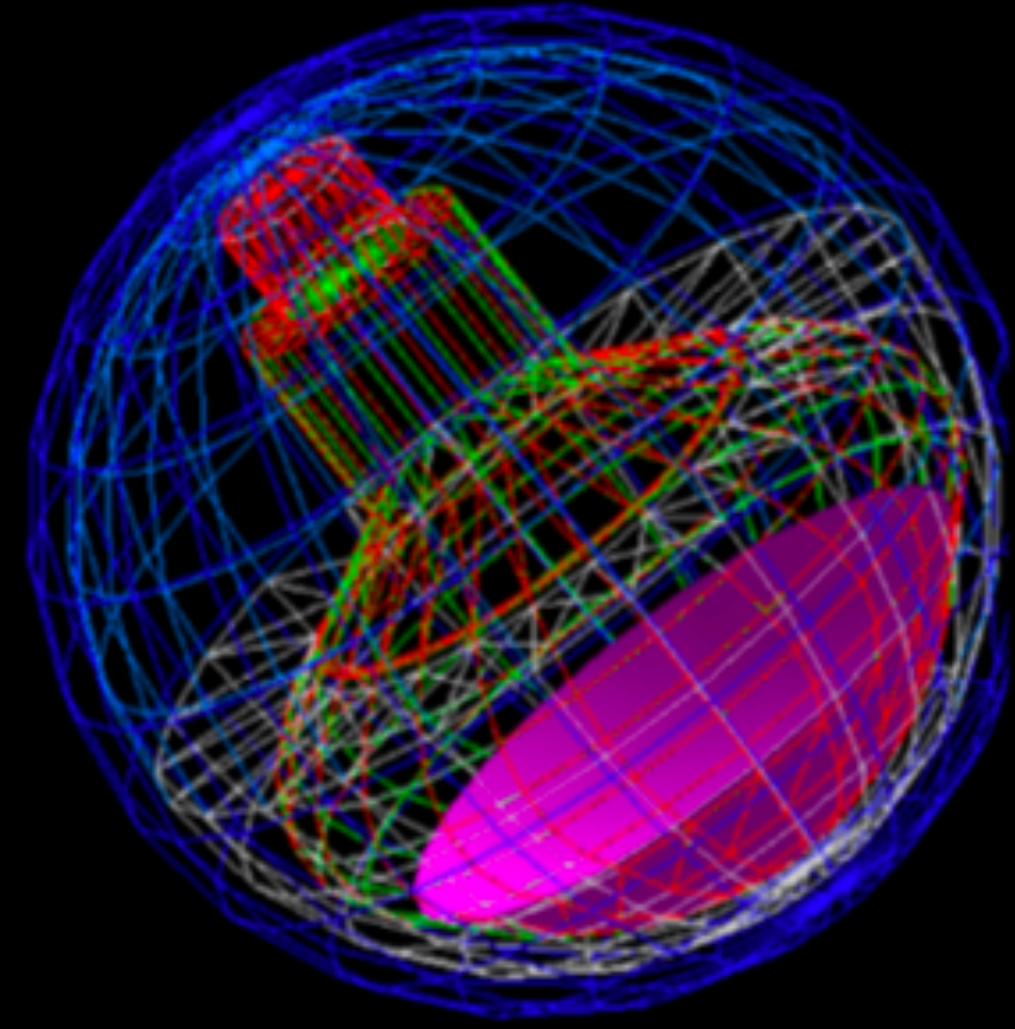
- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response



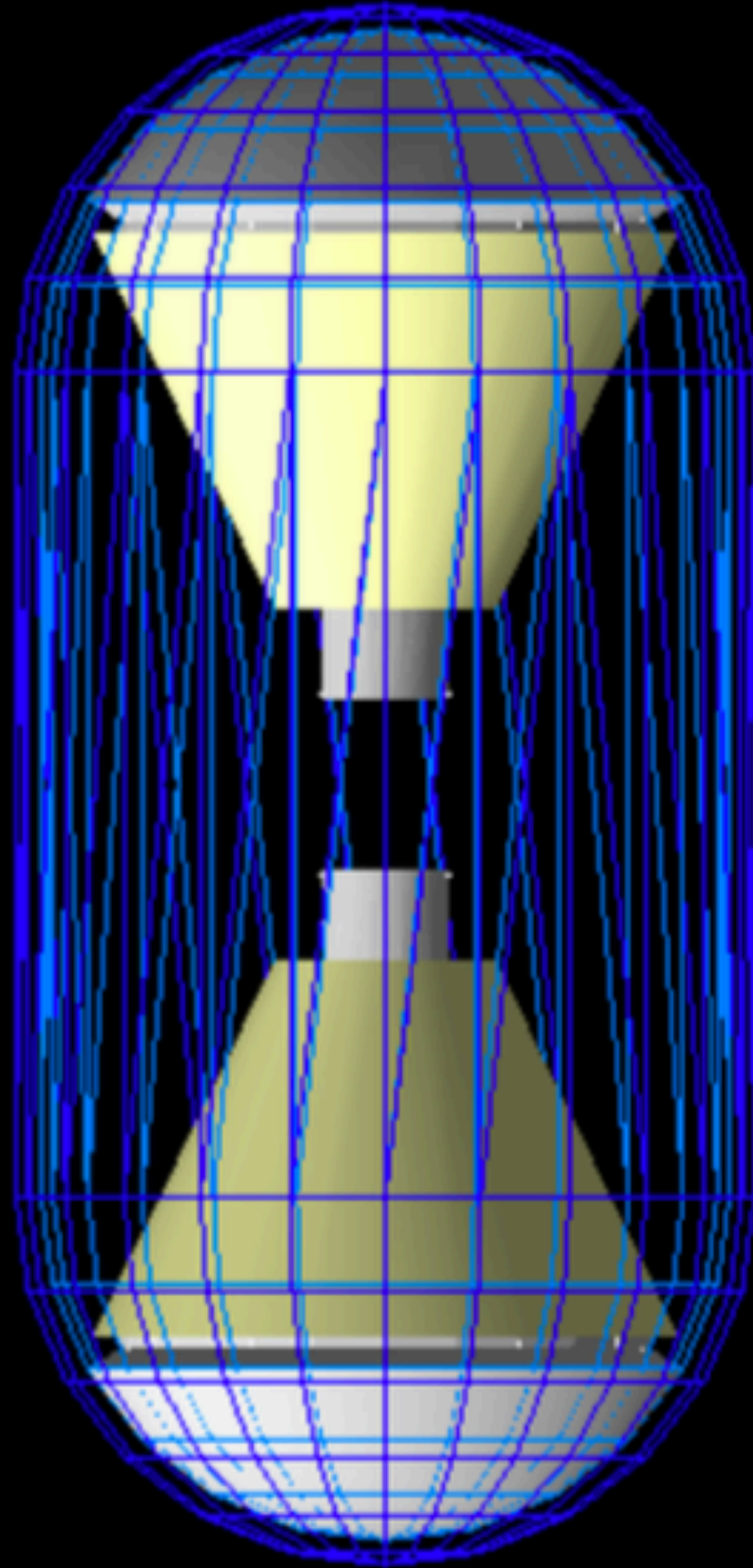
A big step towards IceCube-Gen2

Optical sensor R&D for IceCube-Gen2

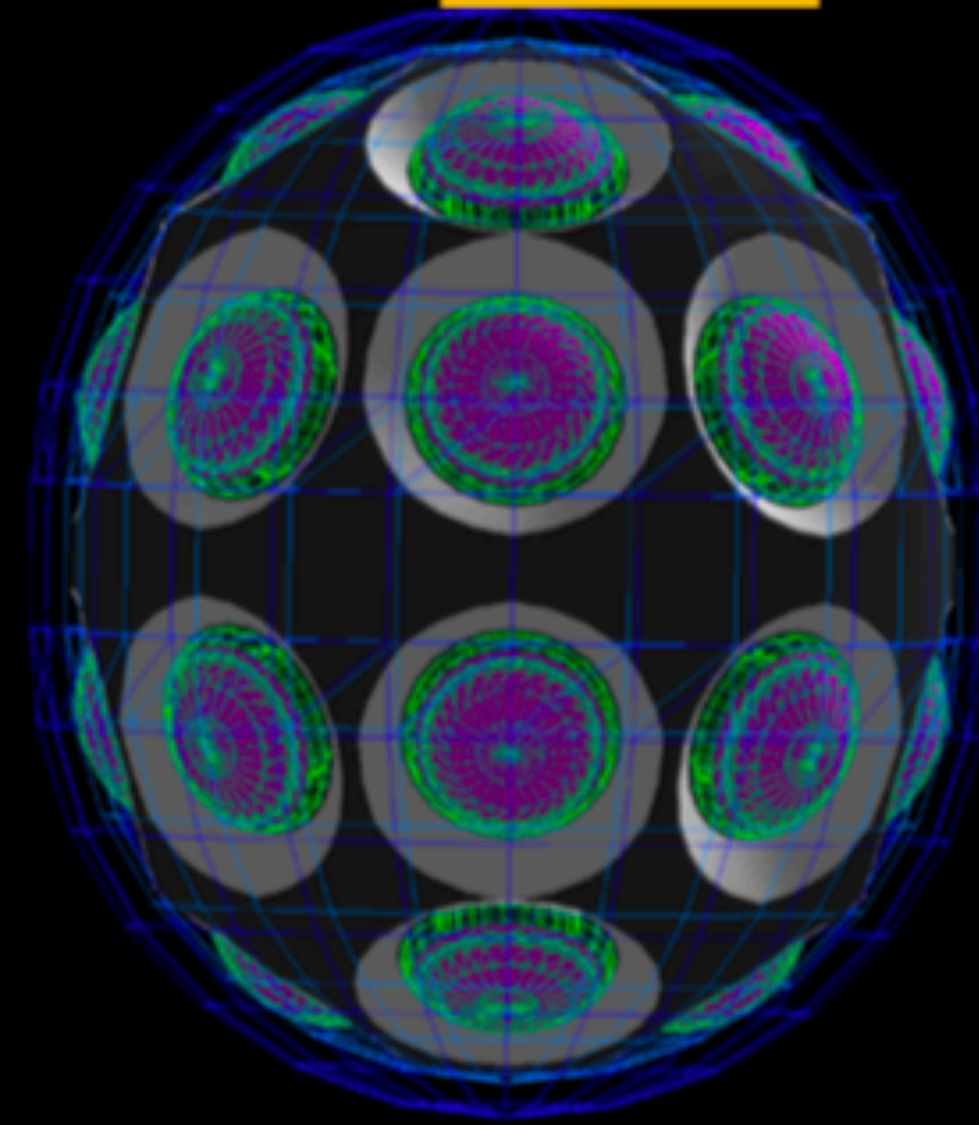
pDOM



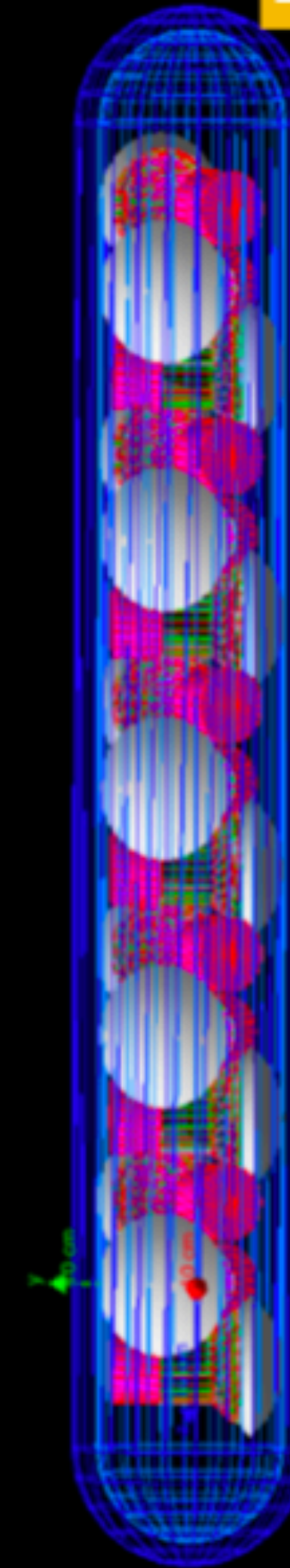
D-egg



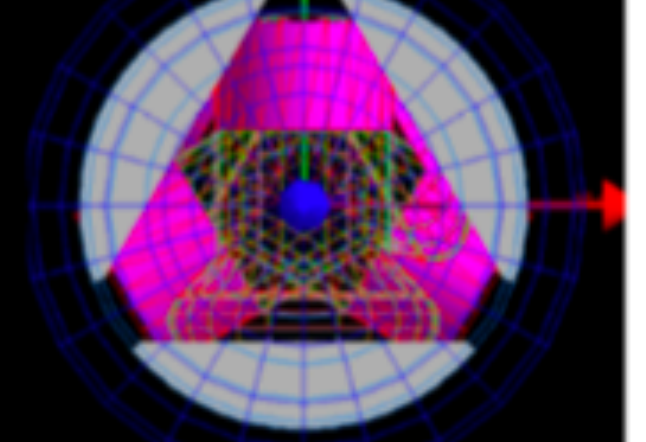
mDOM



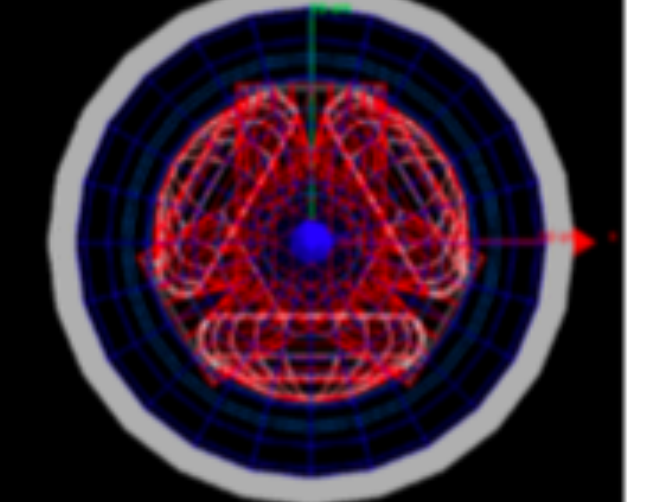
LOM



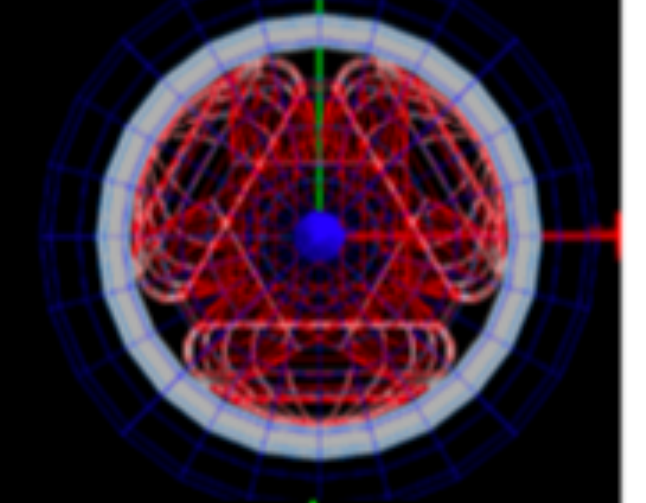
Gel option1



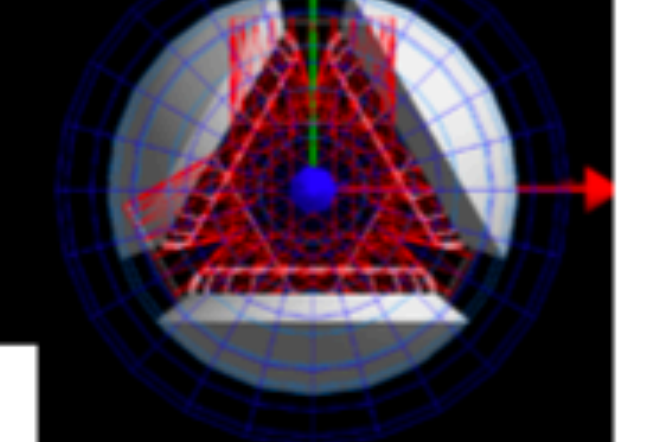
Gel option2



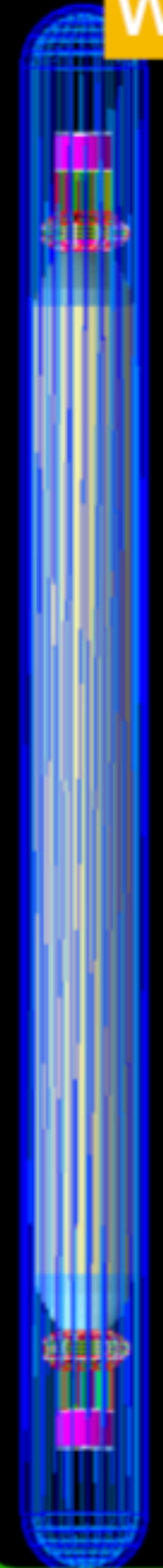
Gel option3



Gel option4



W



IceCube-Gen2

The next Generation IceCube: from discovery to astronomy

Multi-component observatory:

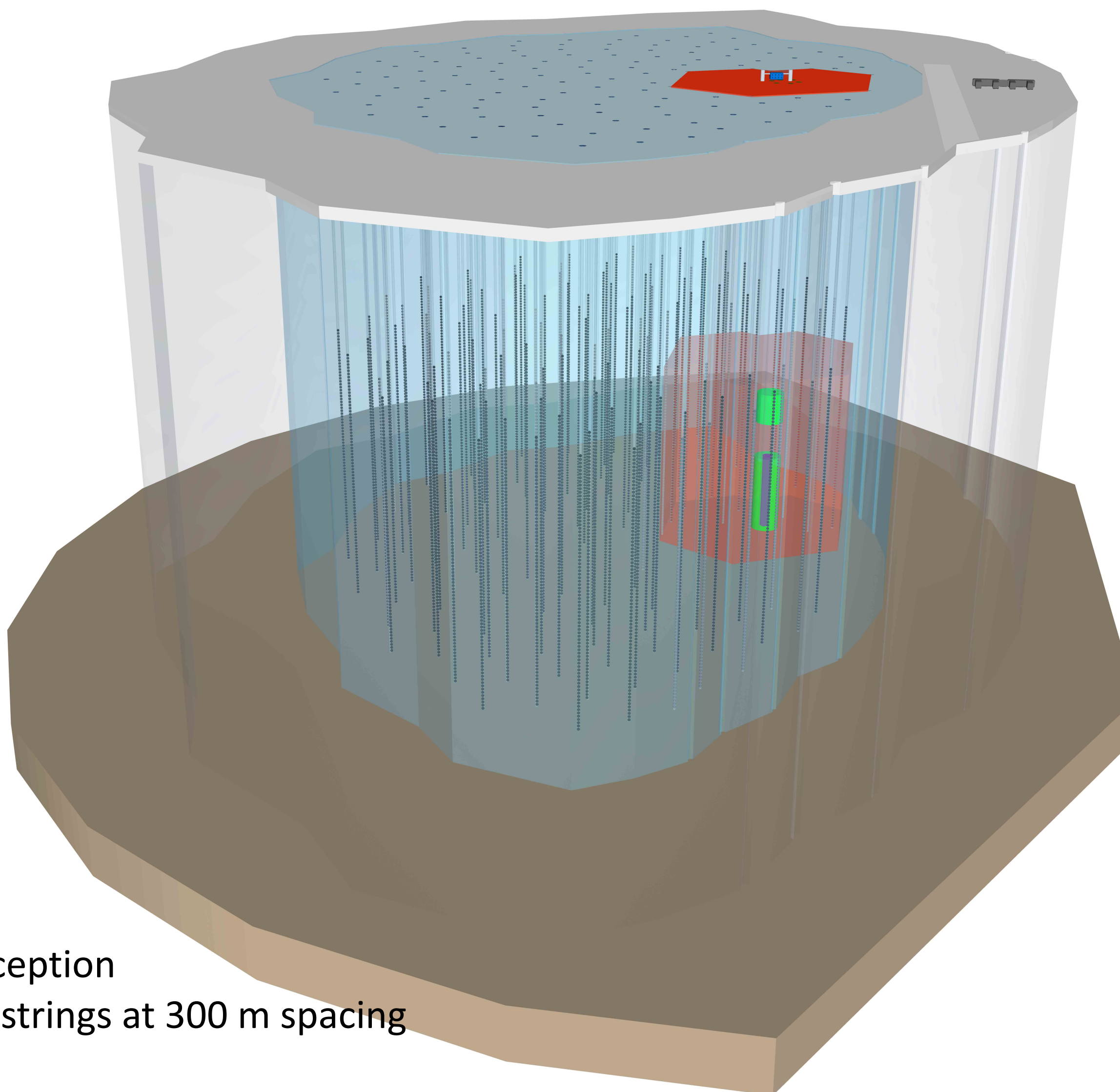
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector

Surface Area: $\sim 6.5 \text{ km}^2$ (0.9)

Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

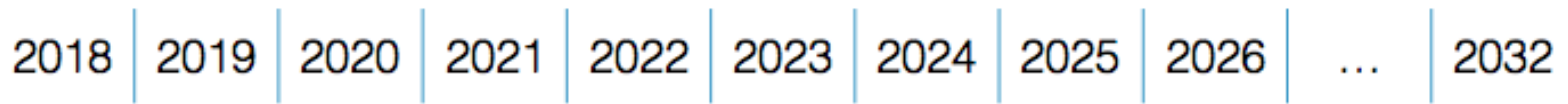
Order of magnitude increase
of contained event rate at high
energies.



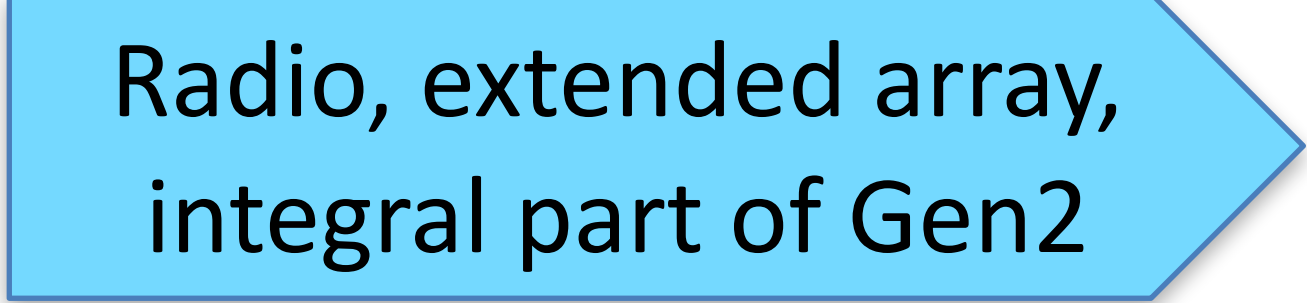
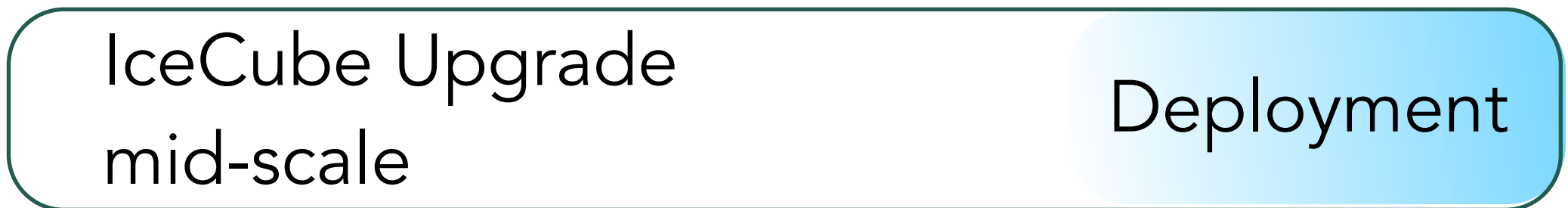
Artist conception
Here: 120 strings at 300 m spacing

summary slide on Gen 2 sensitivity

IceCube Gen2 schedule

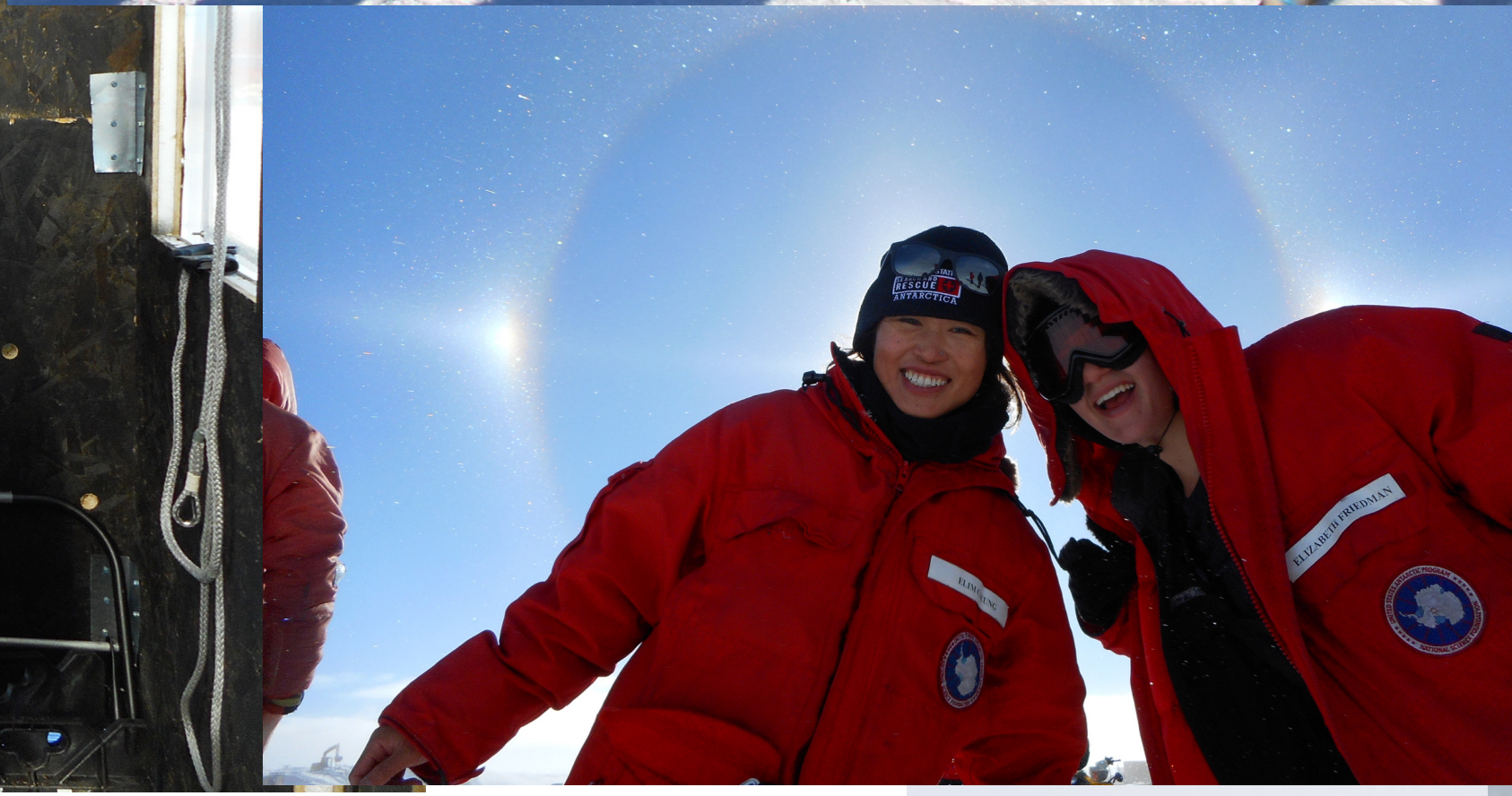
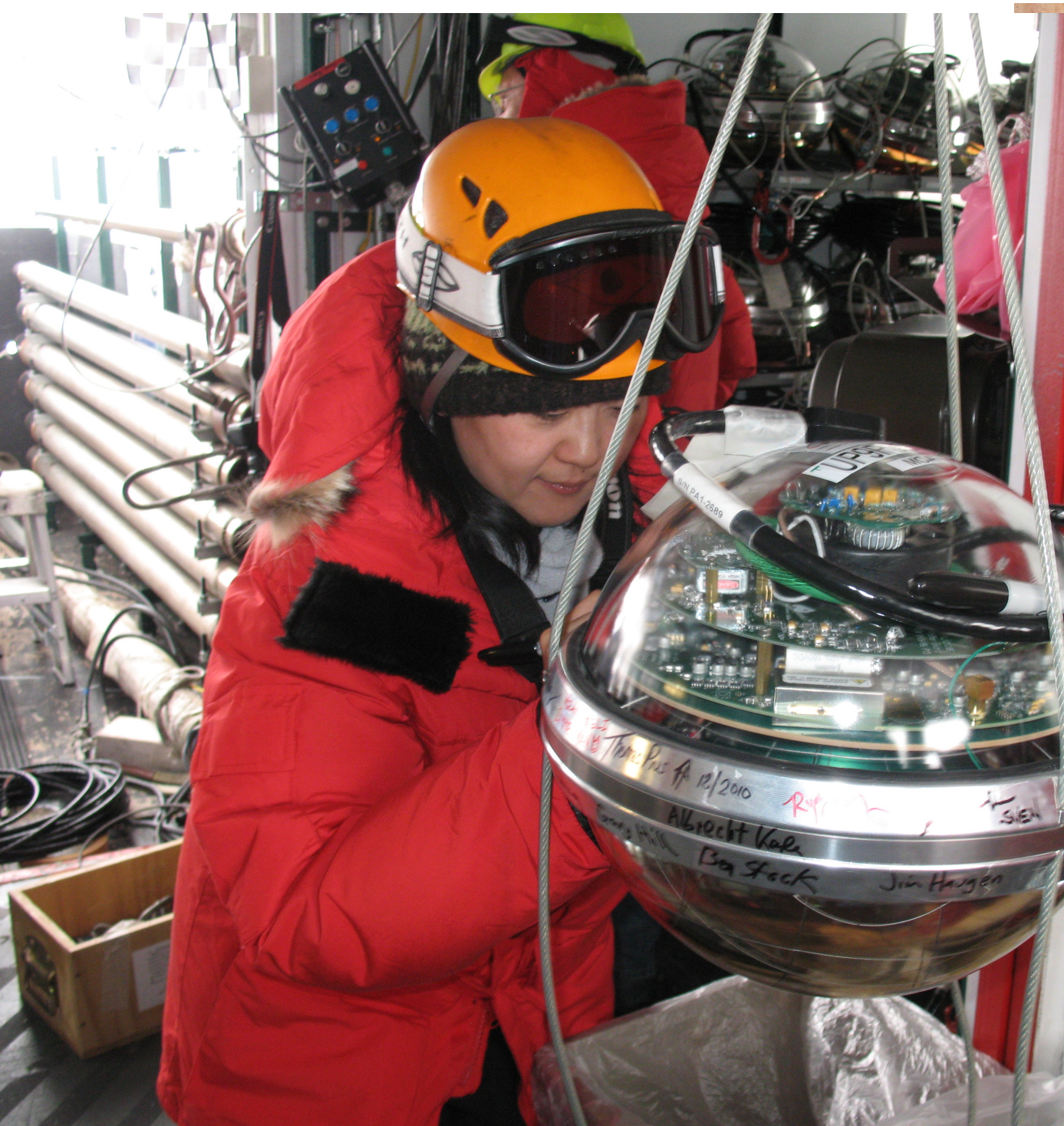


Funded



pending



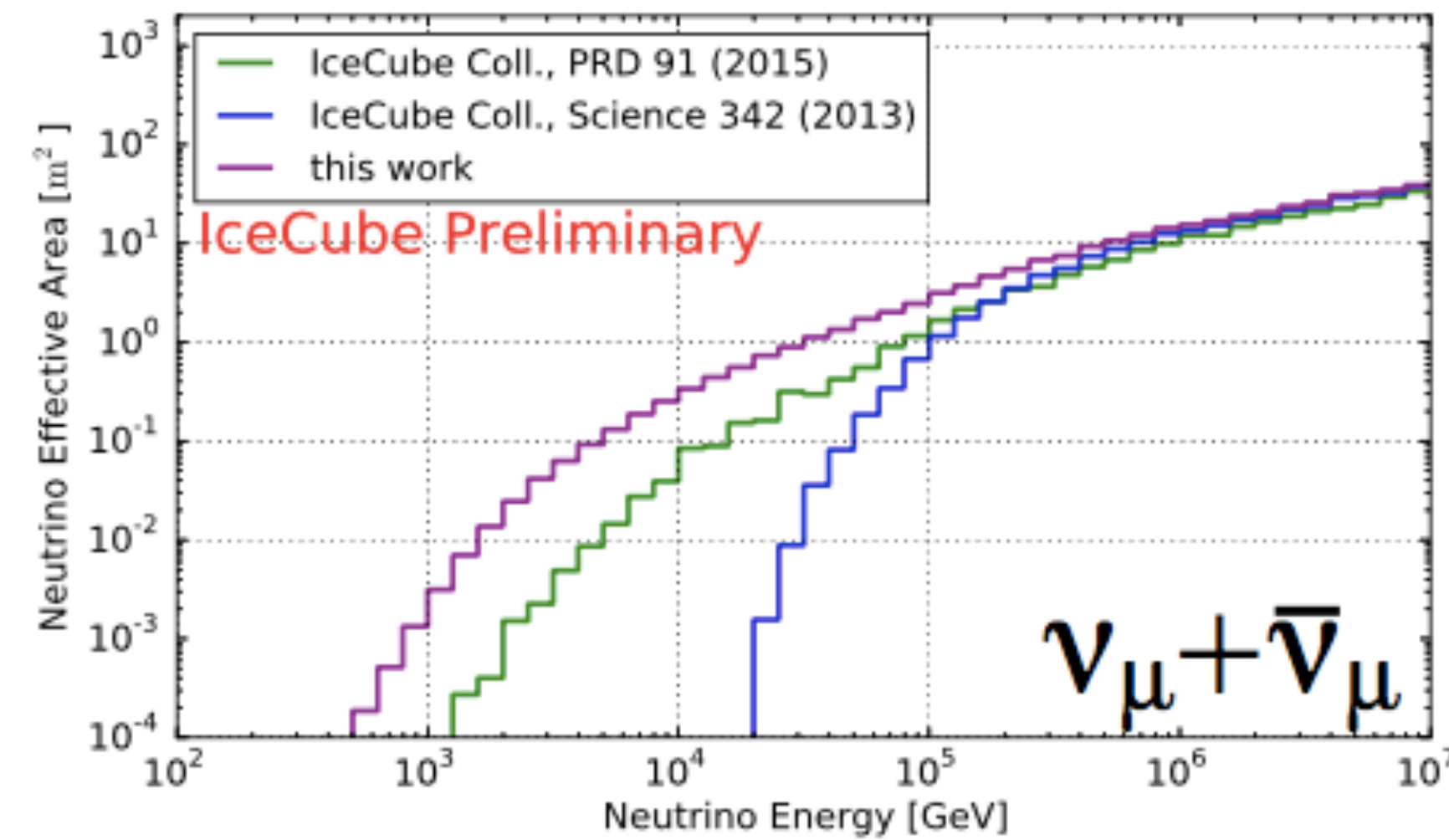
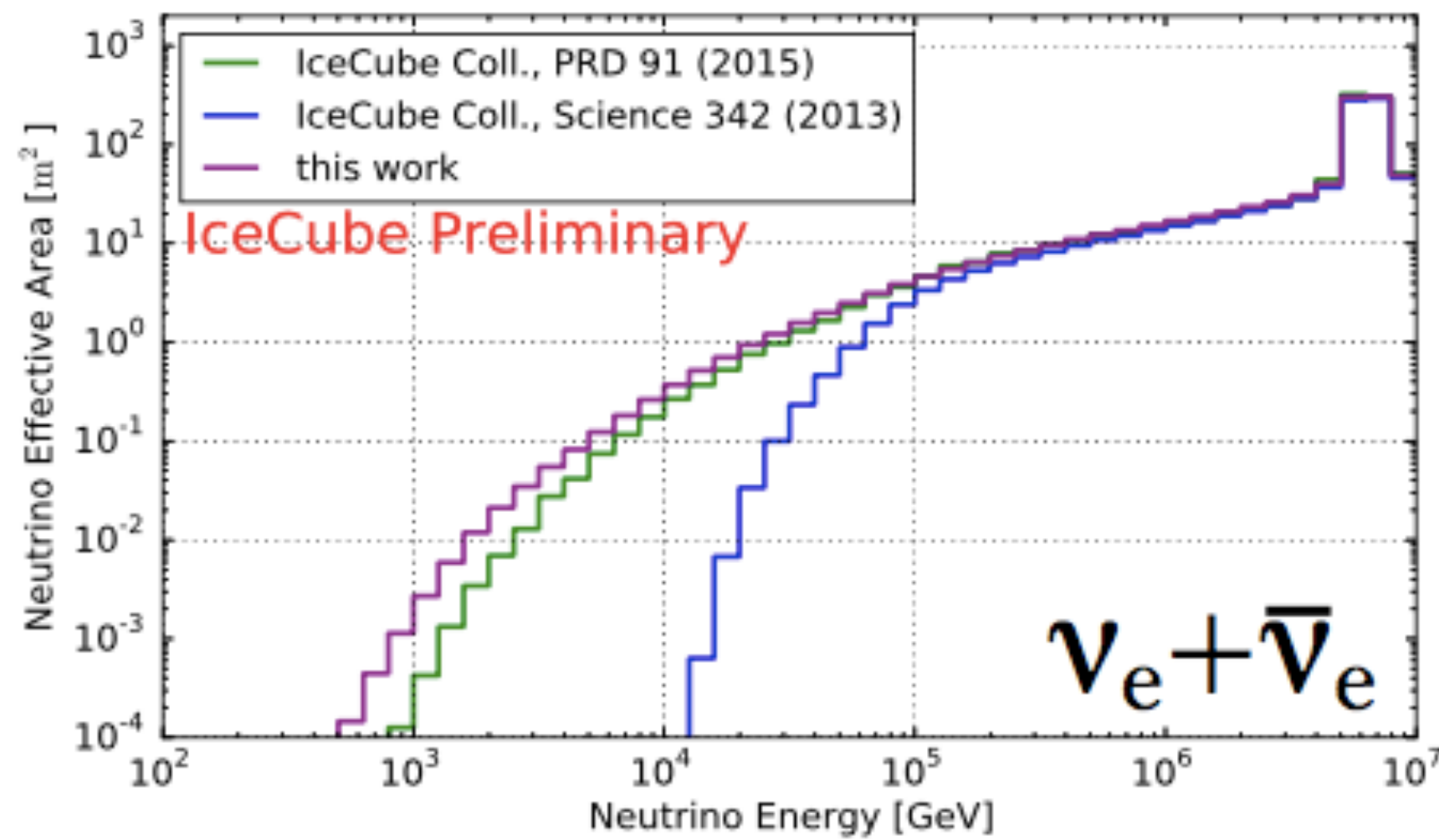
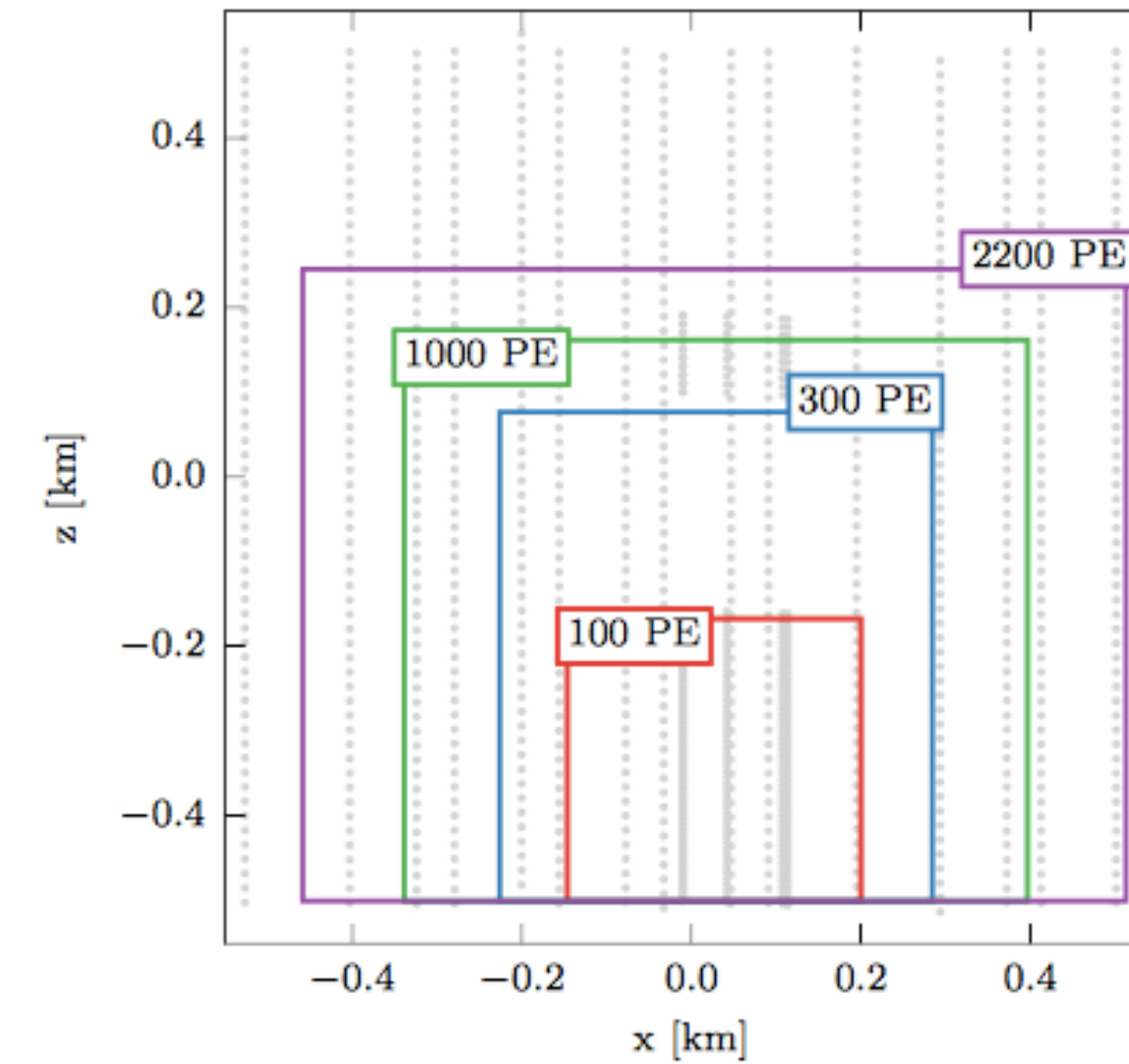


New event selections “below”
HESE and throughgoing muons...

From High to Medium energy: Part 1 - MESE

Follow-up analysis to [arxiv.org/1410.1749](https://arxiv.org/abs/1410.1749)

- 2 years \rightarrow 7 years
- and optimized

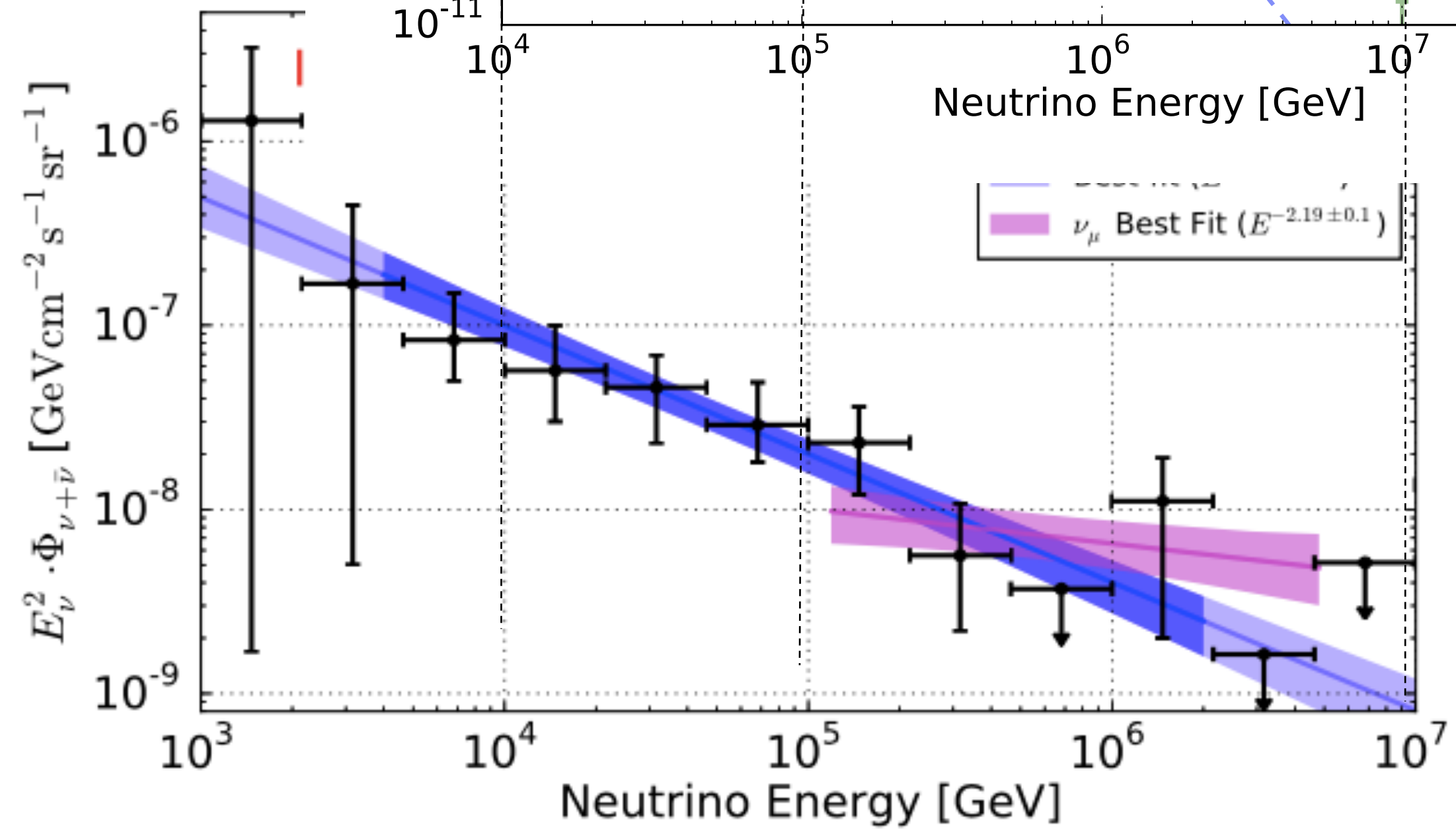
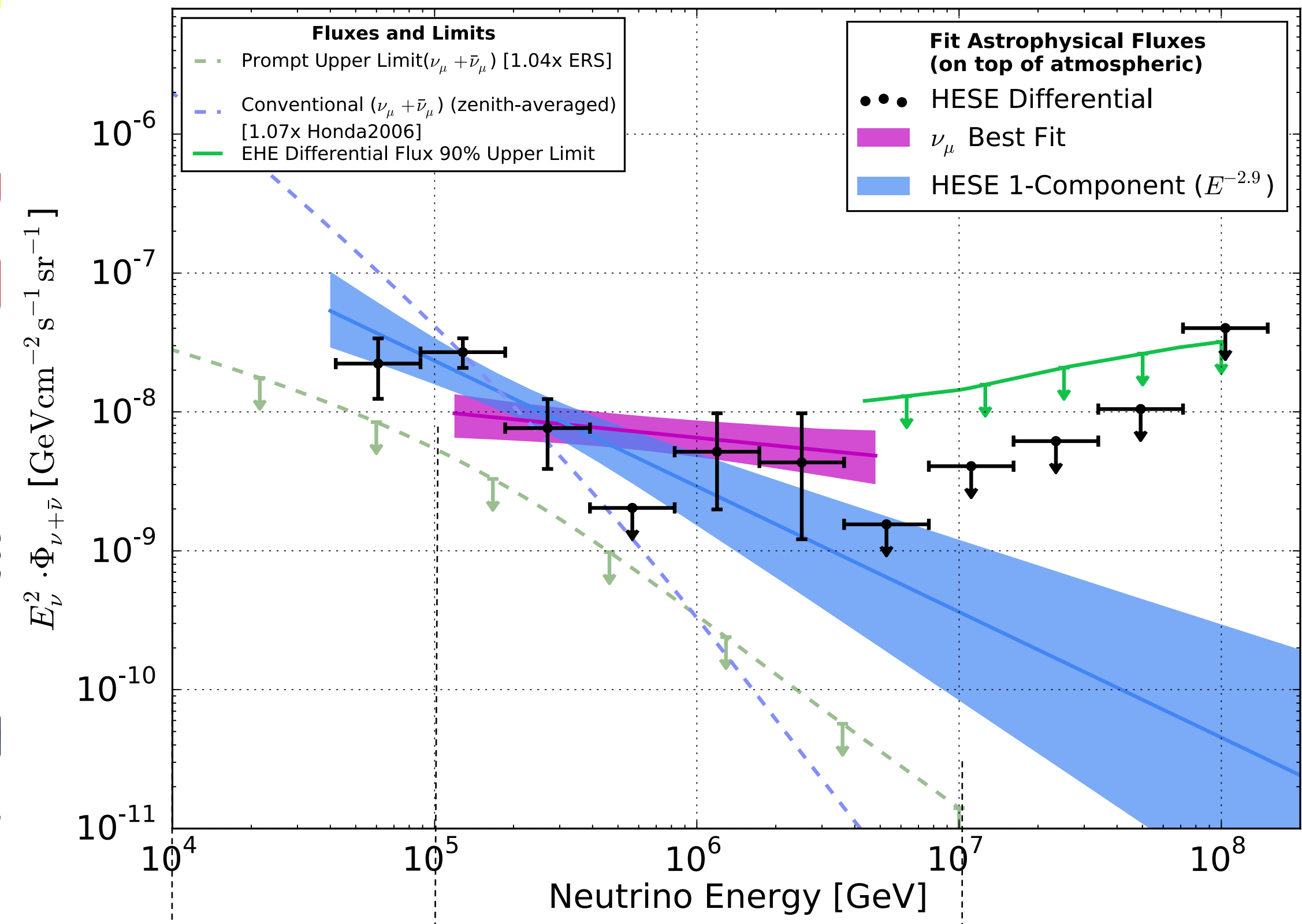


From High to Medium energy:

Low-threshold

7-yr unfolding

- Unfolding to ν_e
 - assume isotropic
 - compatible with tl



14

et!