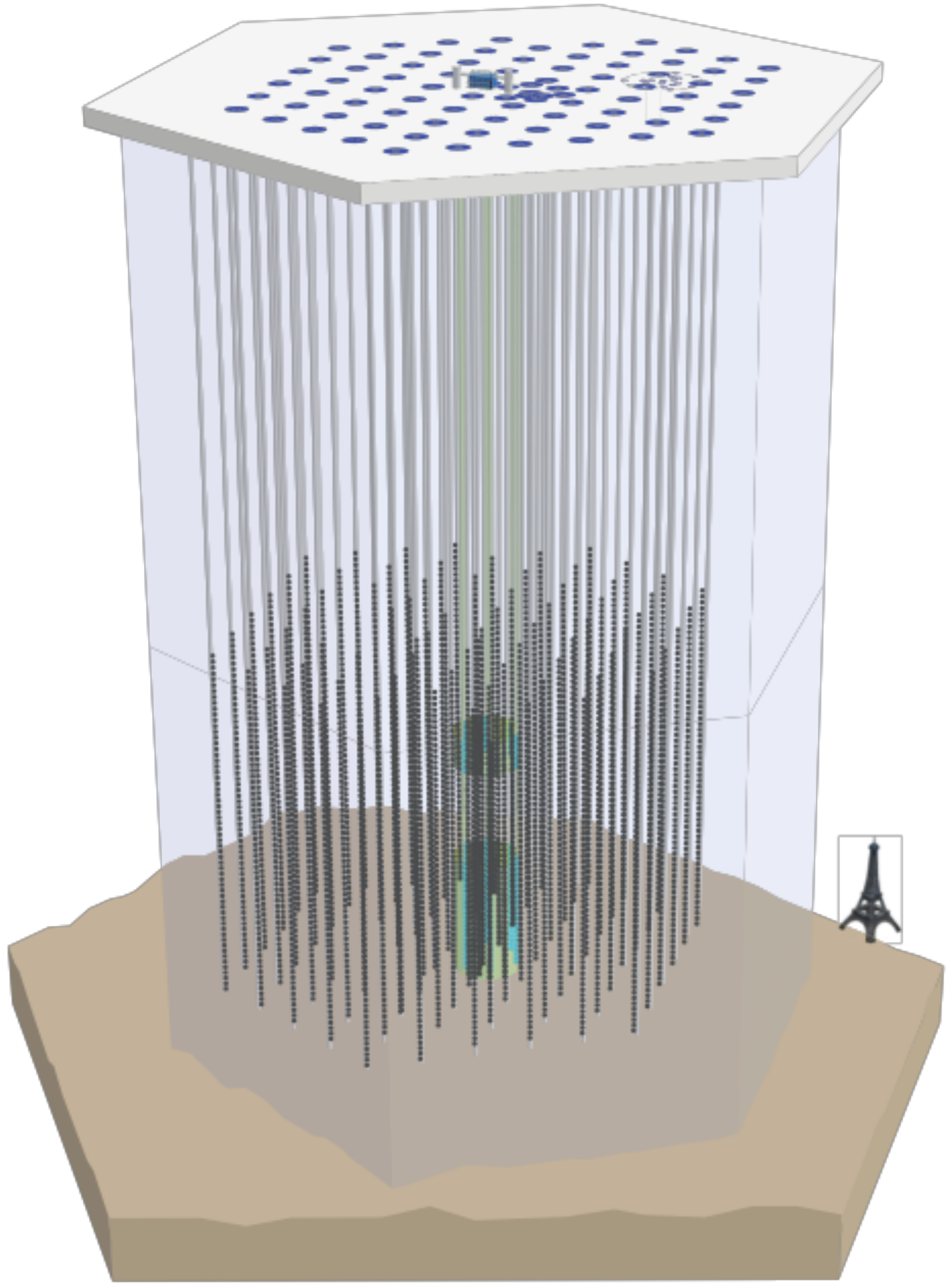
Technical progress
- detector performance, calibration, R&D efforts

Albrecht Karle

March 2019

The IceCube Neutrino Observatory



IceTop (surface array): 81 stations

IceCube: 86 strings

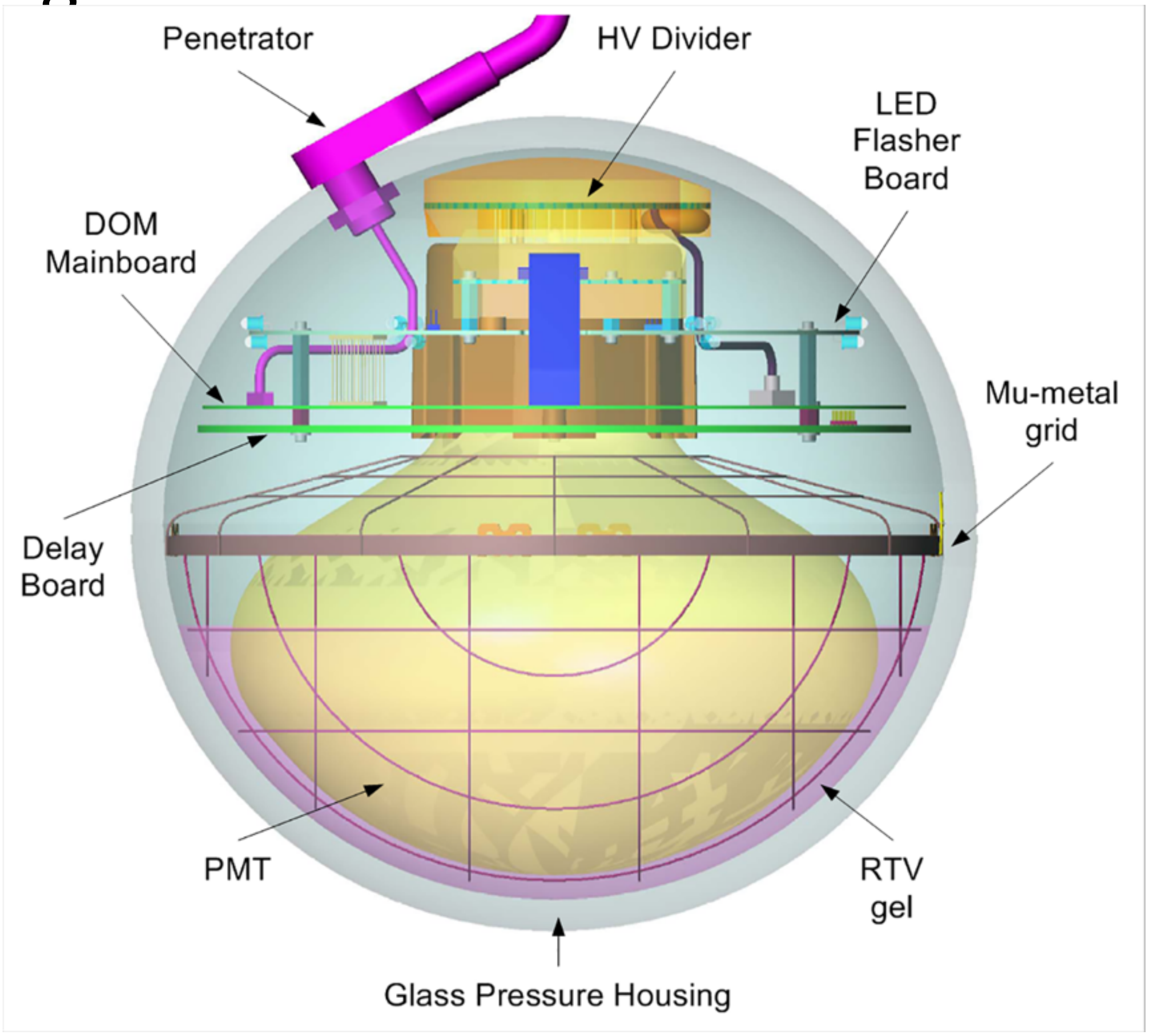
5160 optical sensors over 1 km^3 volume

17 m vertical spacing

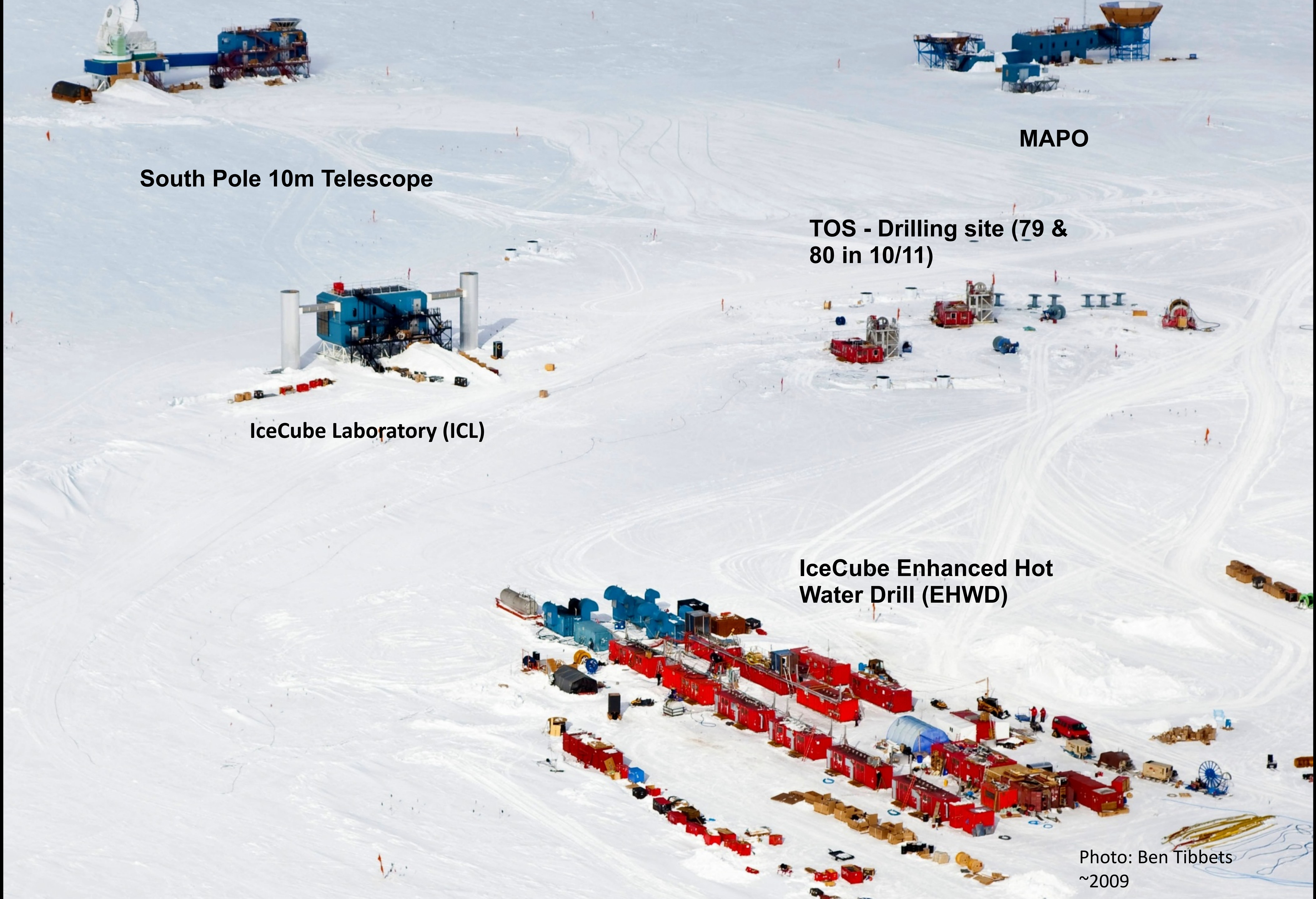
125 m horizontal spacing

Highly stable operation.

Since 2016: livetime > 99.5%

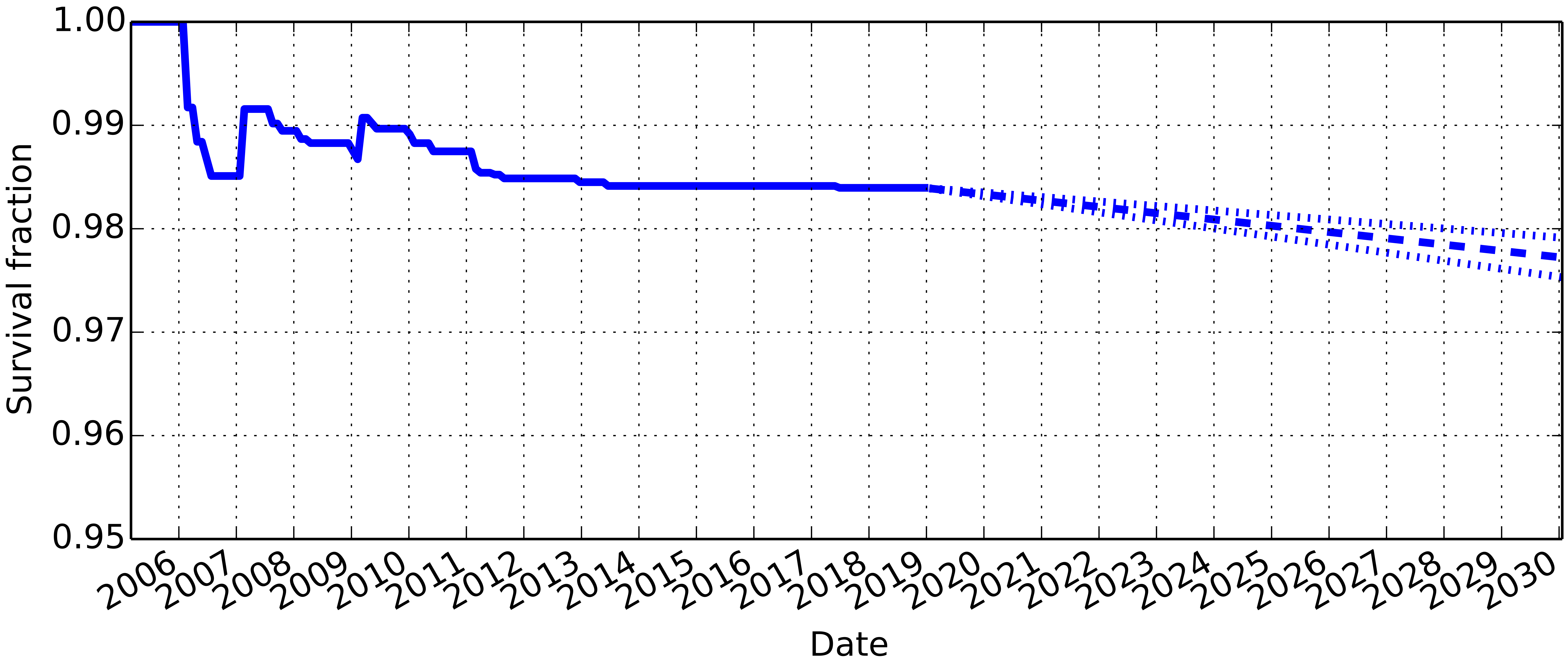


DeepCore (low energy threshold)


MAPO
South Pole 10m Telescope
TOS - Drilling site (79 & 80 in 10/11)
IceCube Laboratory (ICL)
IceCube Enhanced Hot Water Drill (EHWD)
Photo: Ben Tibbets ~2009


5160 sensors are deployed
to a depth between 1500
and 2500m.

DOM survival rate



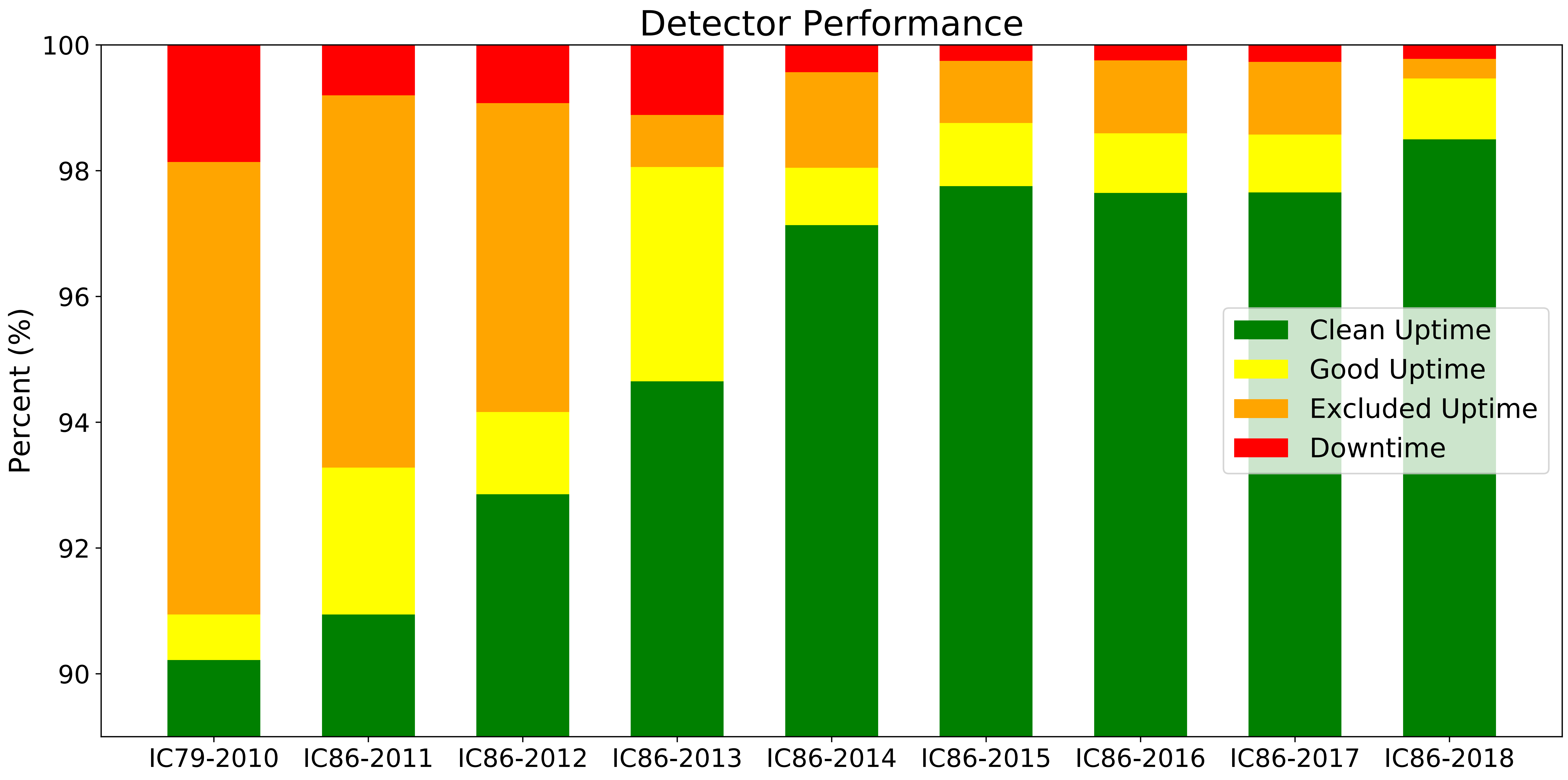
DOMs display very high reliability.

Only ~1 failure per year over the last 5 years.

Detector Uptime

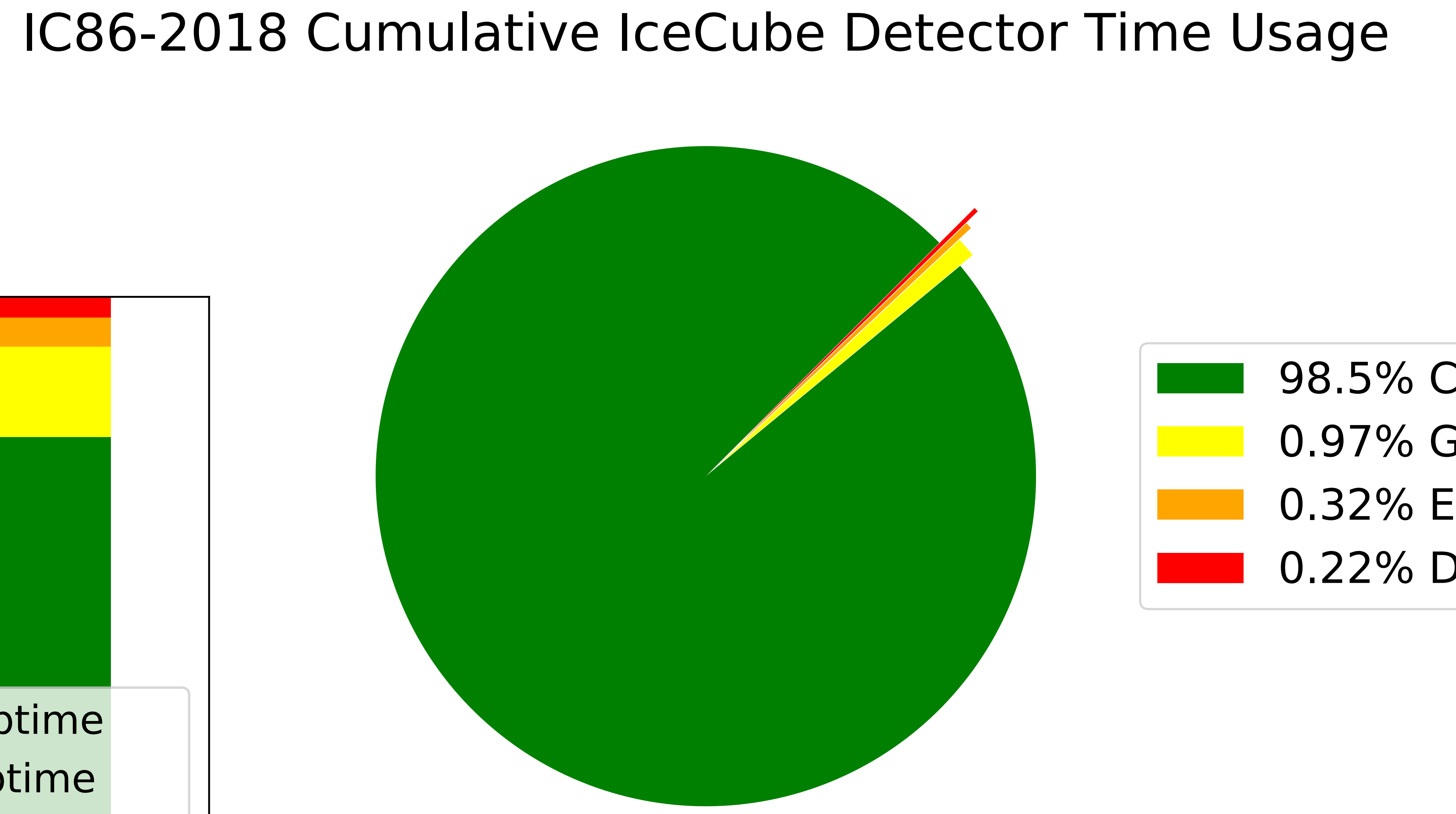
100%

90%



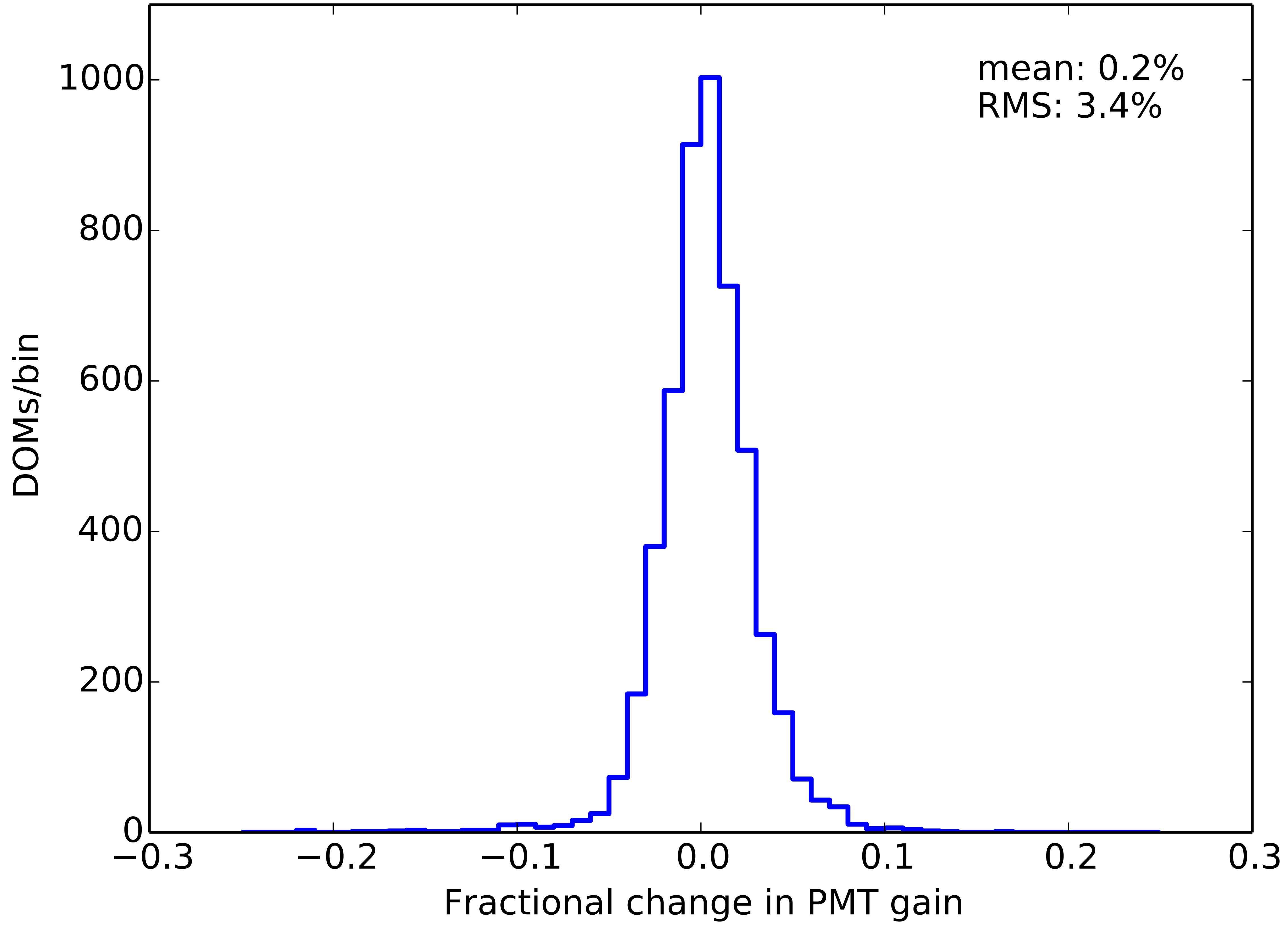
2010

2018



PMT gain stability 2011 - 2016

No indication for any changes since 2016.



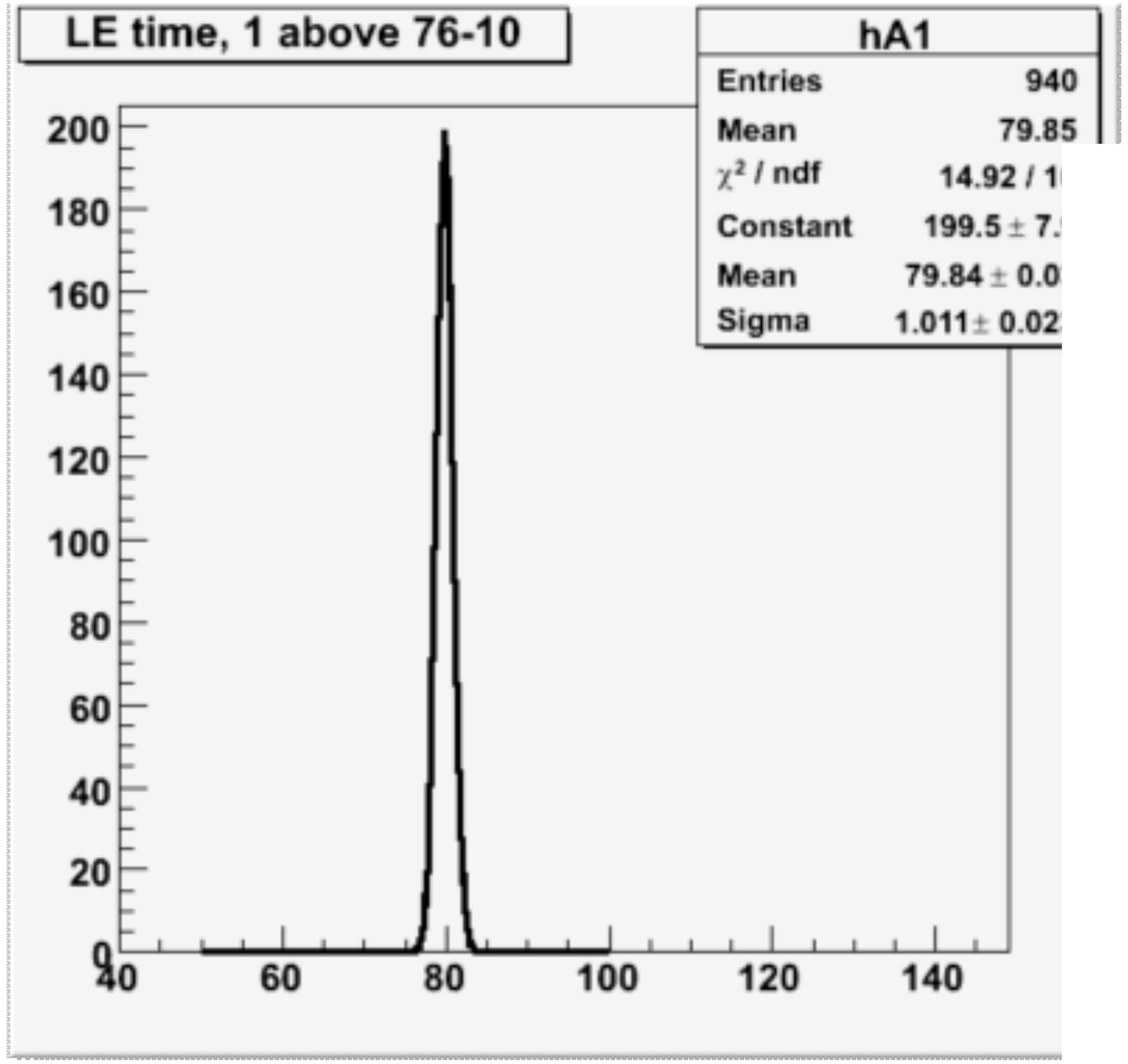
DOM gain appears stable!

(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

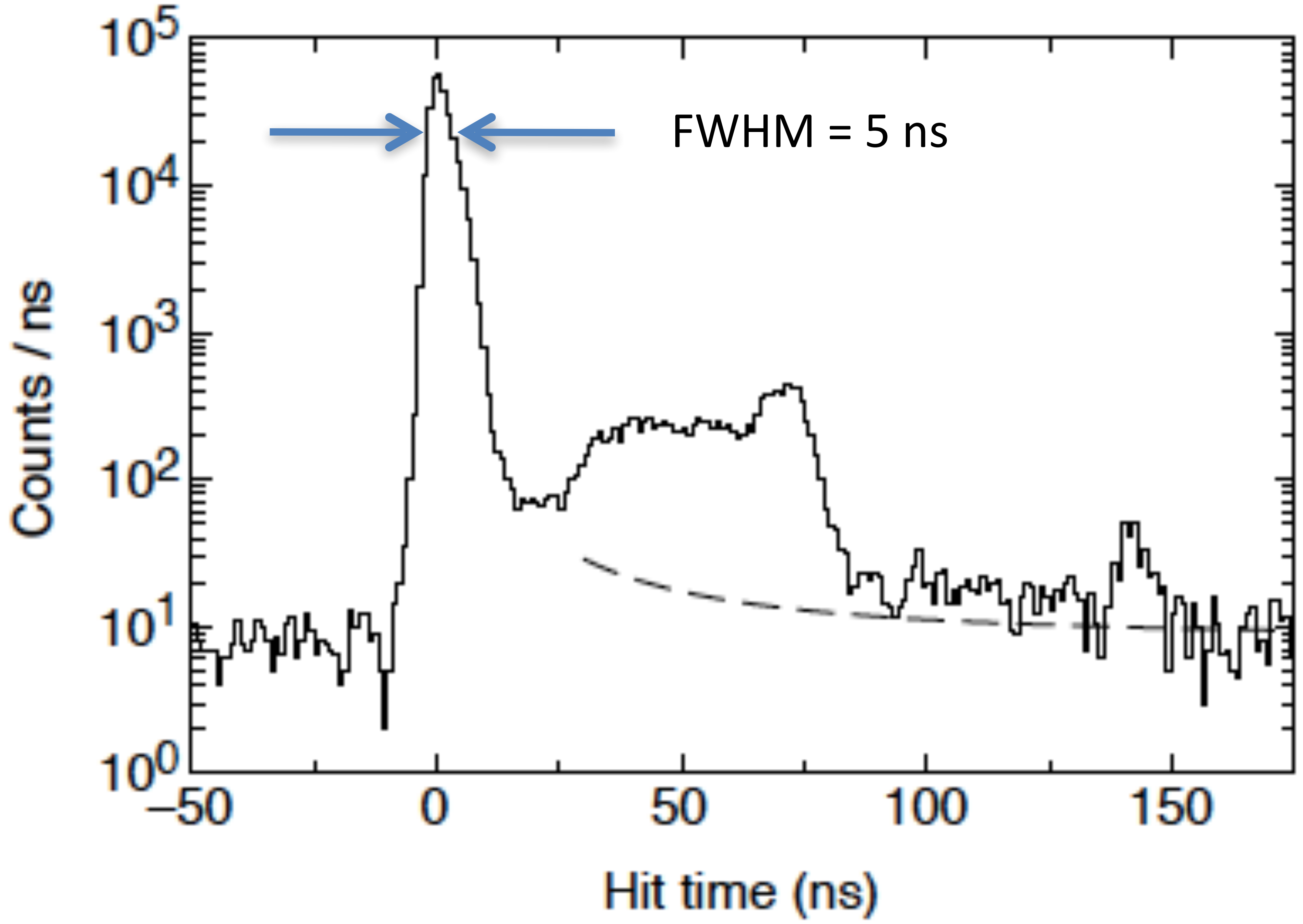
- Time difference between neighboring DOMs fired with (bright) flasher pulses: ~1 ns.

  (this includes clock timing)



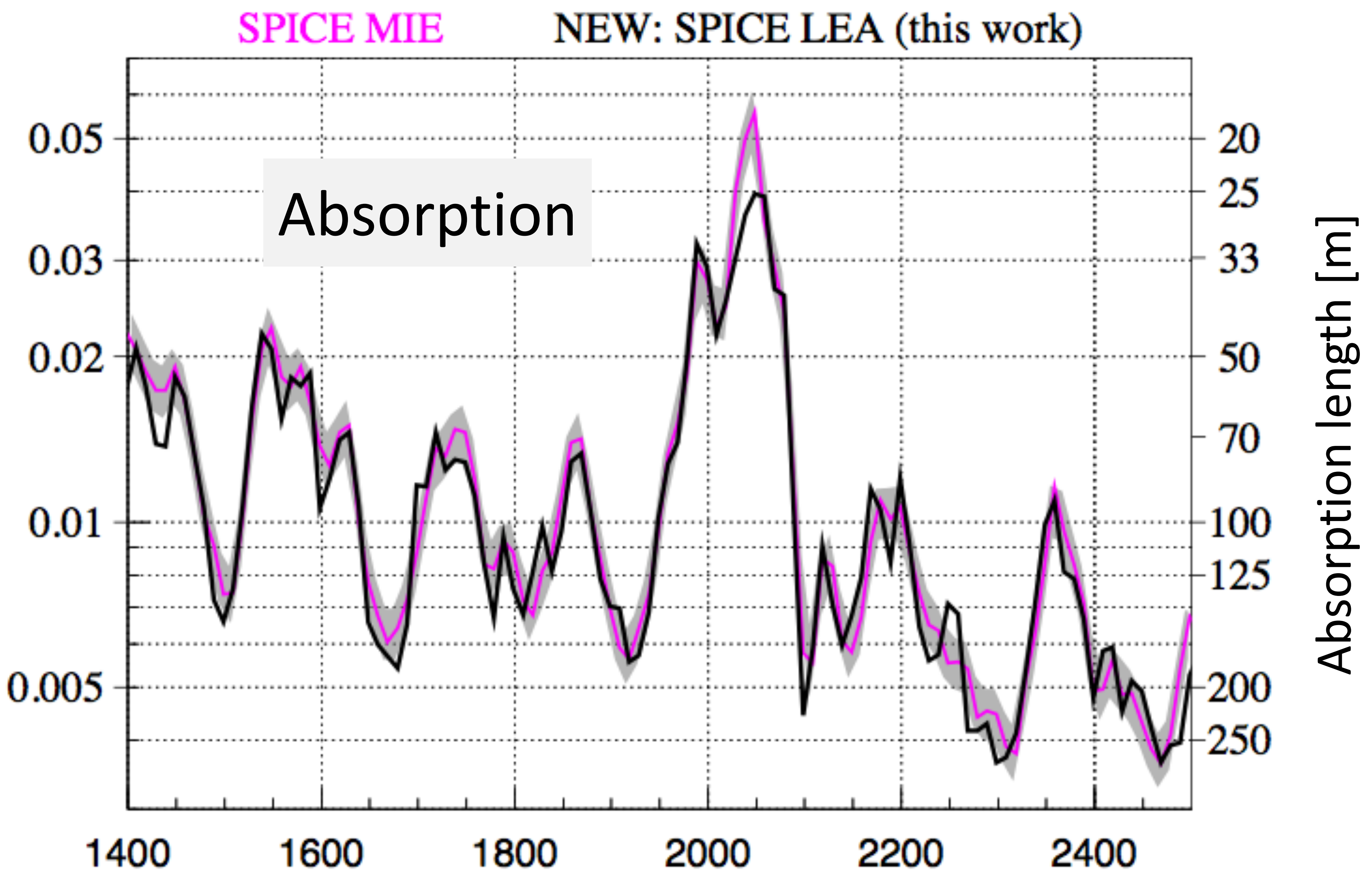
Single photoelectron pulse resolution limited by PMT. RMS in the peak: ~2ns

Lab measurement with laser.



Understanding the ice

1. Vertical structure of ice parameters



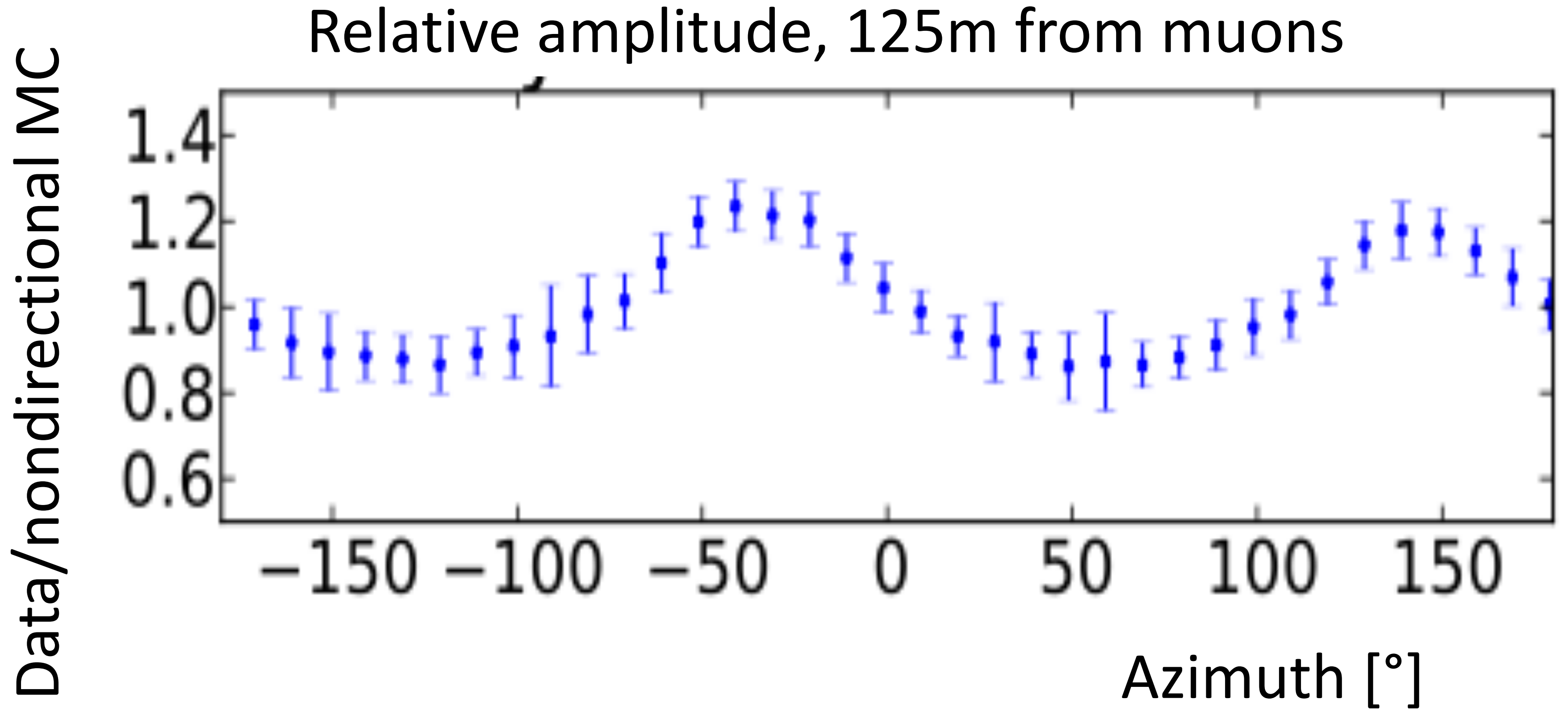
Scattering (eff.): 20 – 50 m
Absorption: 100 – 200 m

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

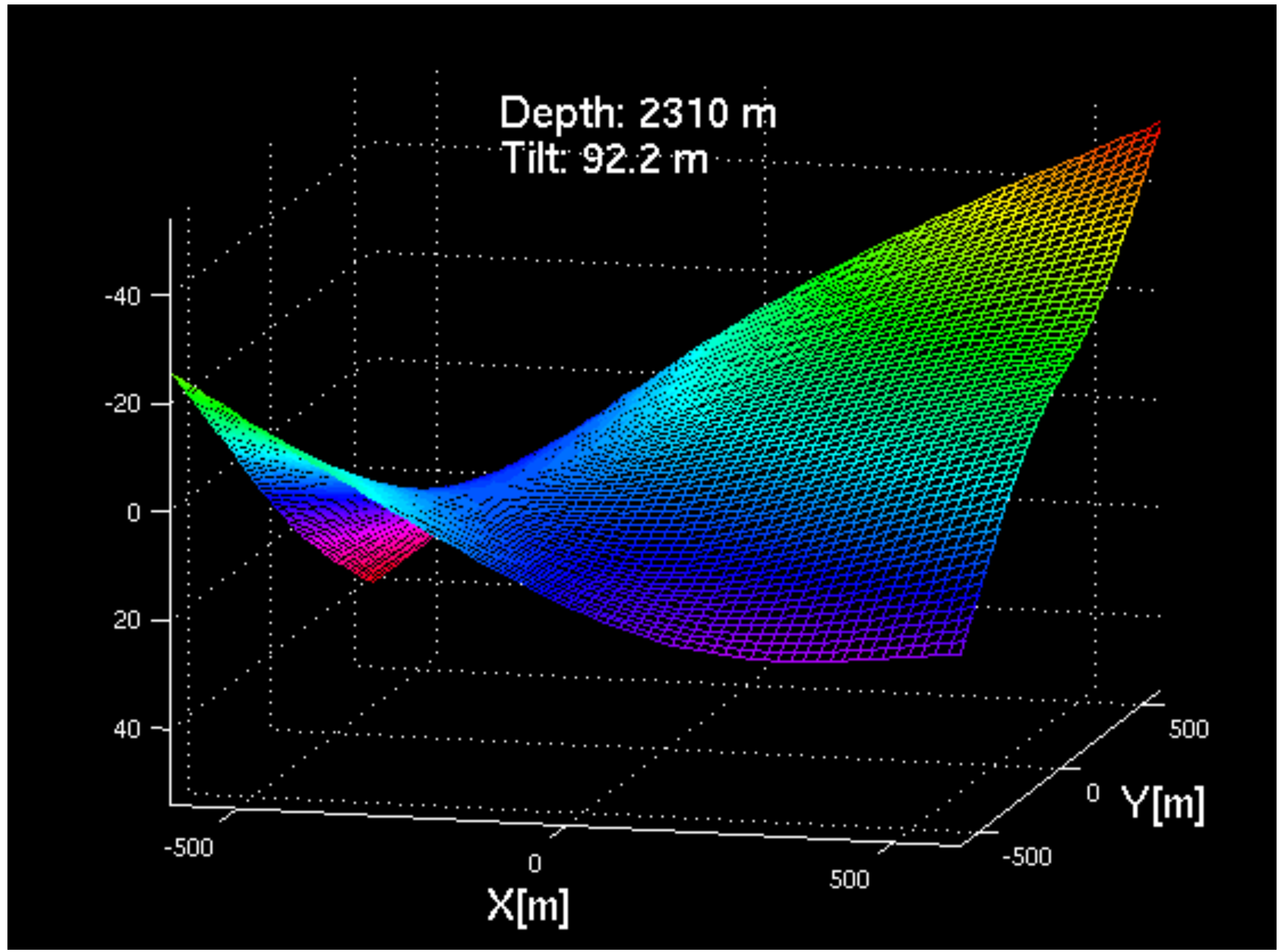
Aartsen et al., (IceCube Coll.), NIMA55353
http://arxiv.org/abs/1301.5361

2. Azimuthal variation in of scattering

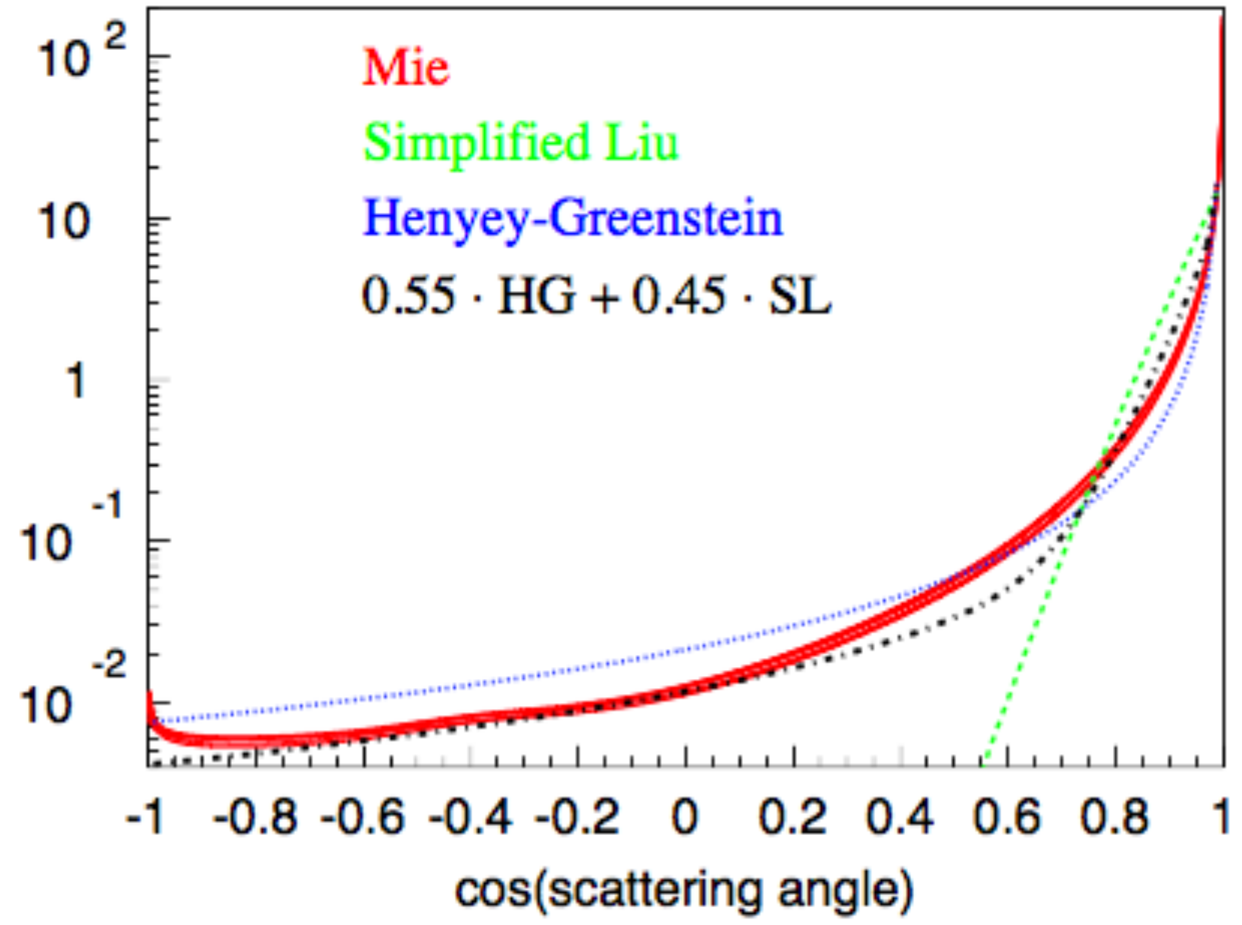
Less scattering in direction of ice flow:
→ up to ~10% /100m variation in amplitude



3. Ice layers are tilted – not planar



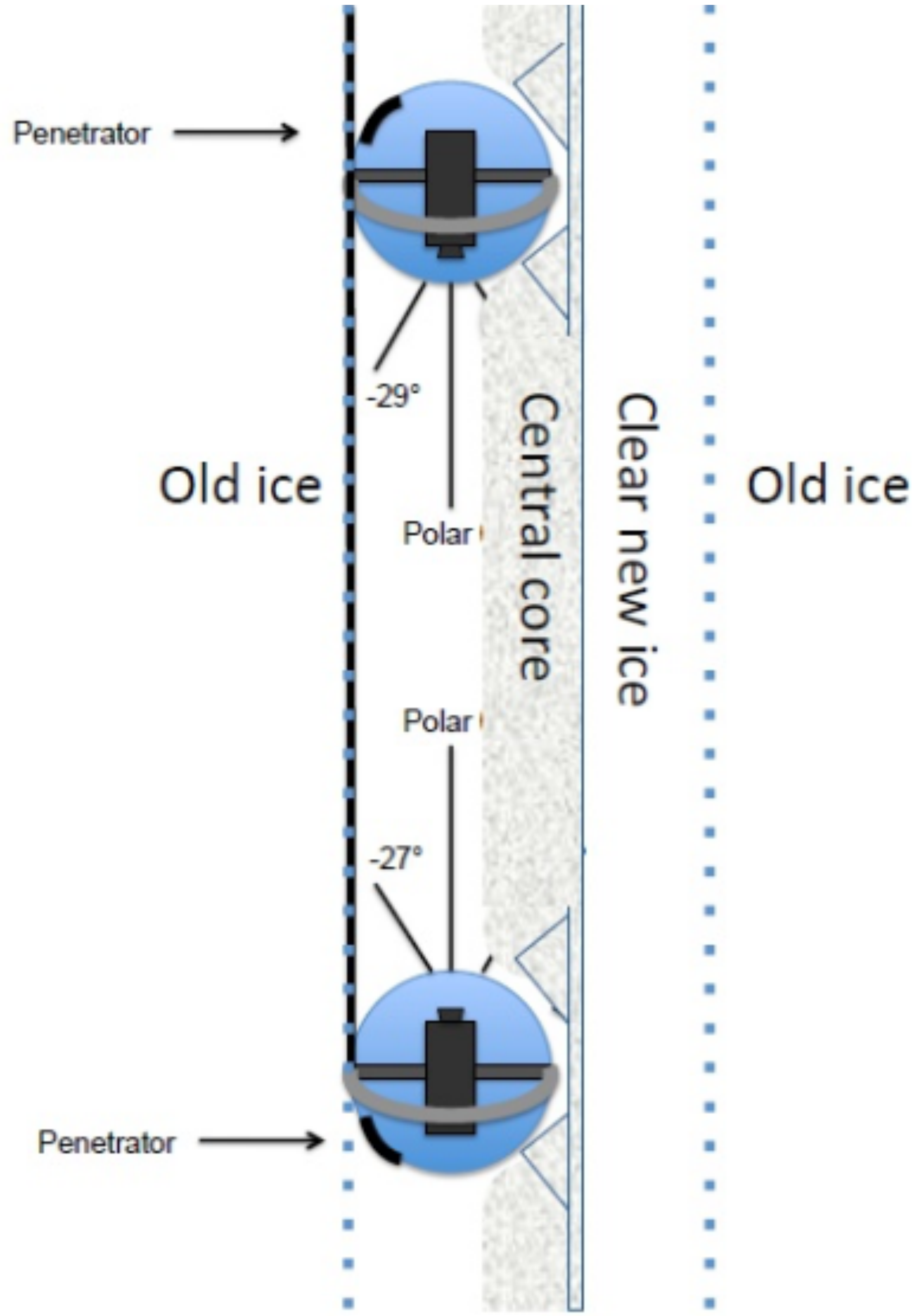
3. Scattering function

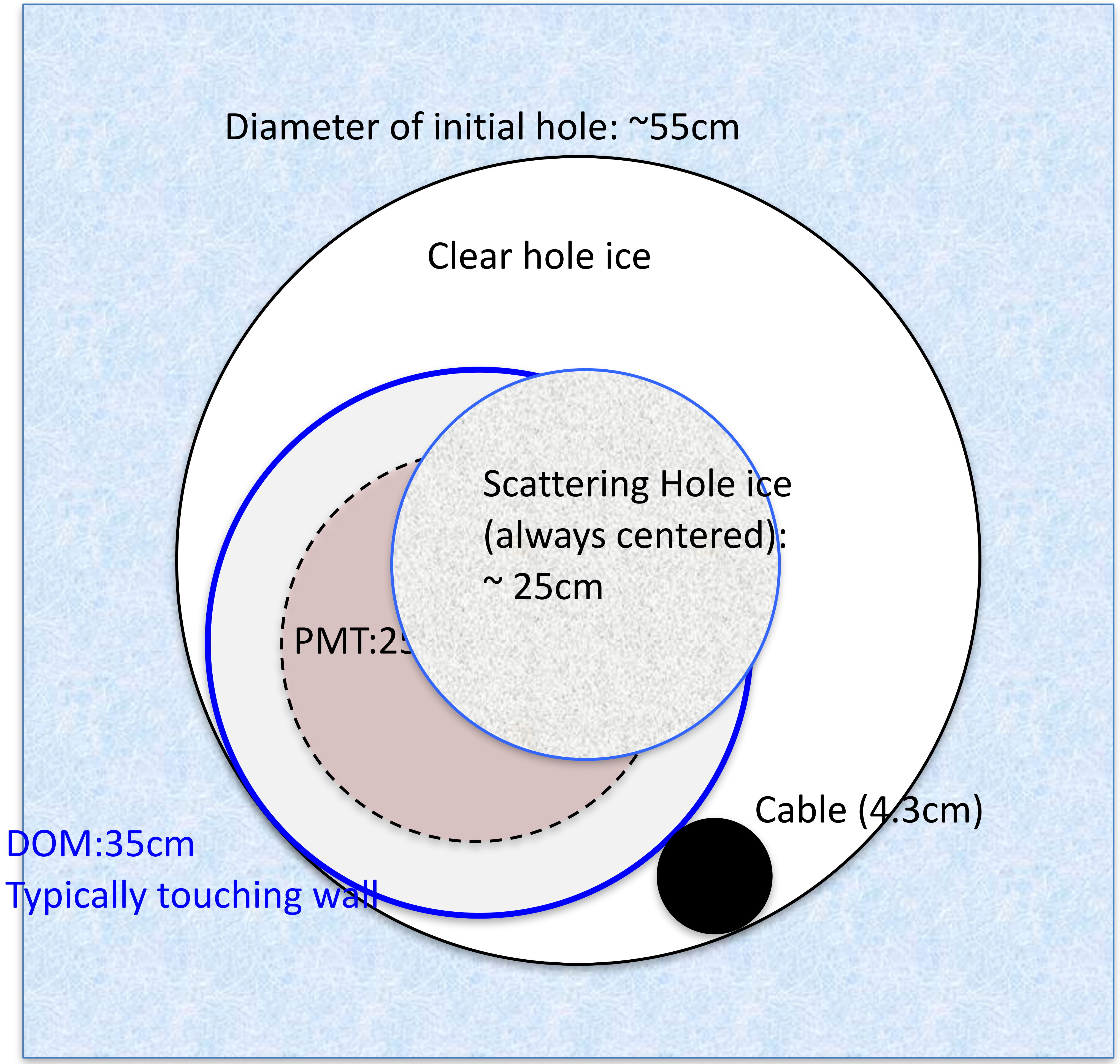


Systematic uncertainties: DOM and local ice

Current picture of hole ice

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





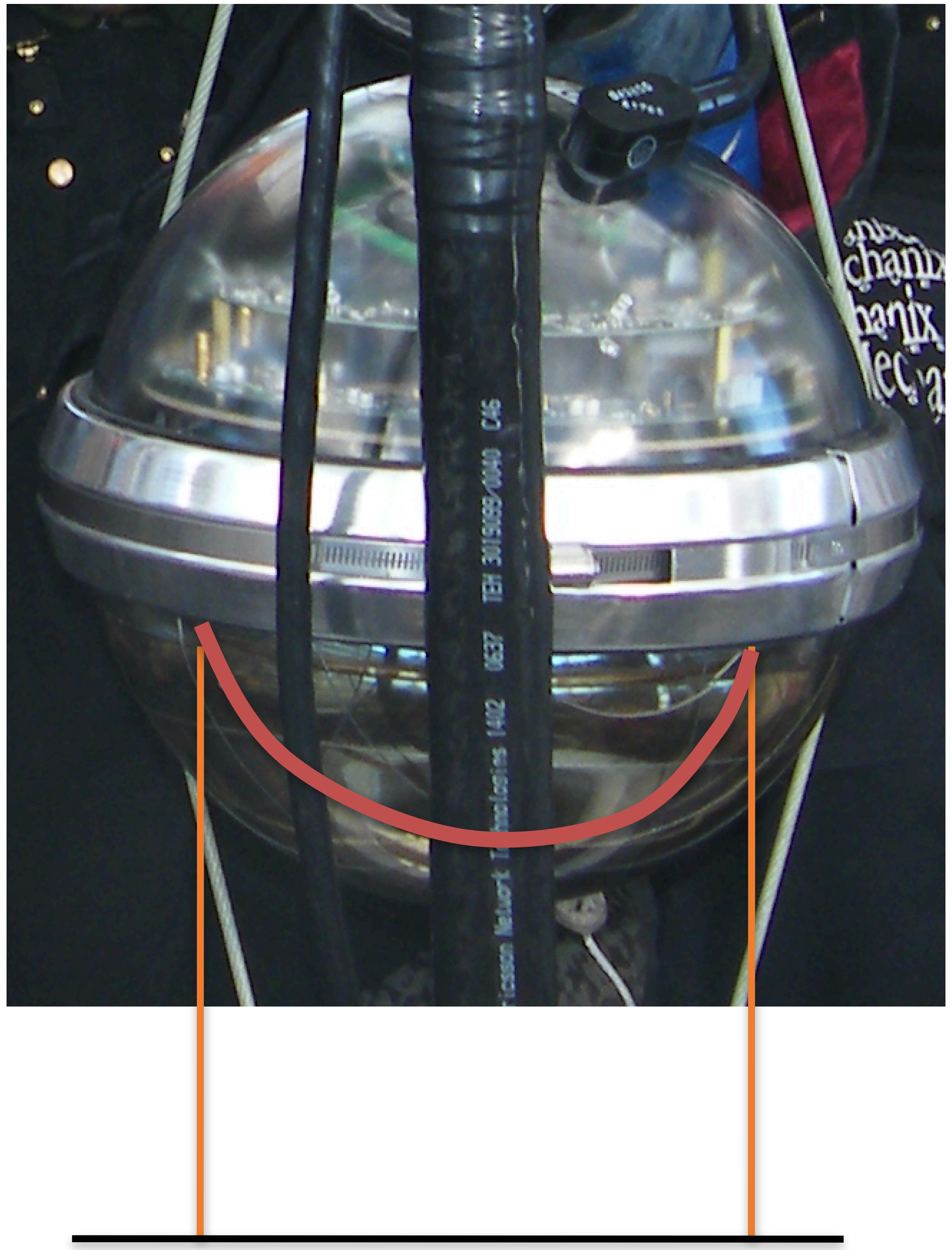
DOM and local ice

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

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

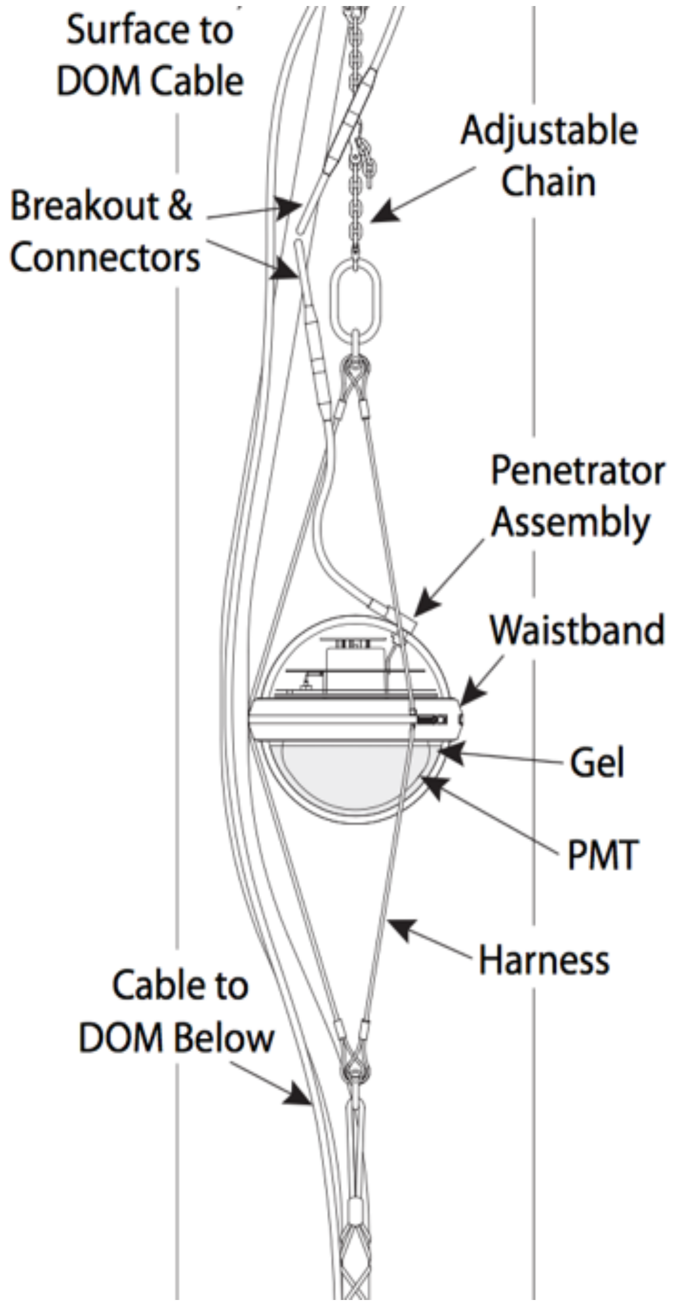
Cable shadow

Cable diameter: 4.5cm

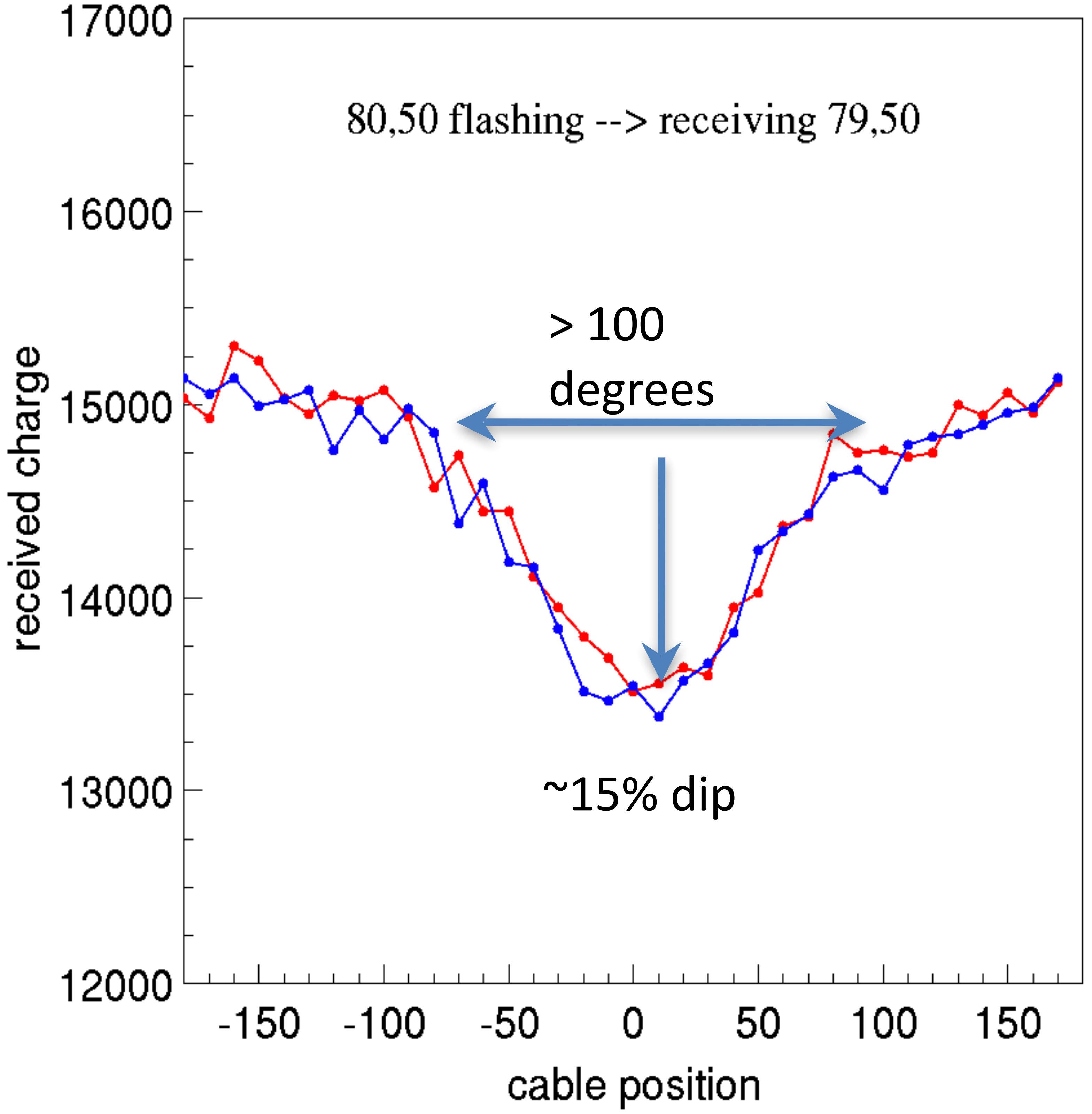


DOM sphere:32.5

PMT cathode diameter: 22 cm



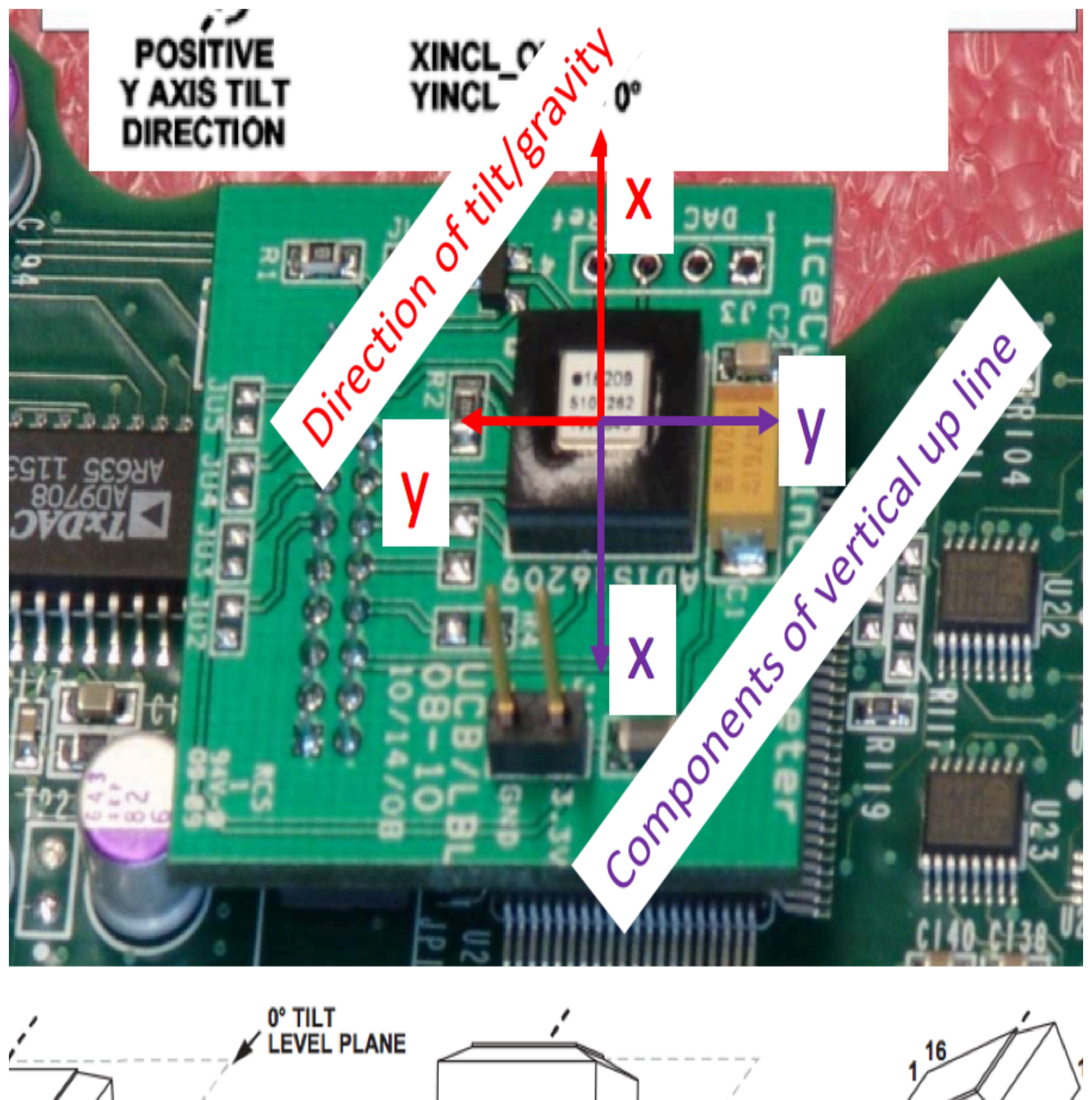
Azimuthal DOM response: Simulated effect on receiving DOM from flashers at close distance.

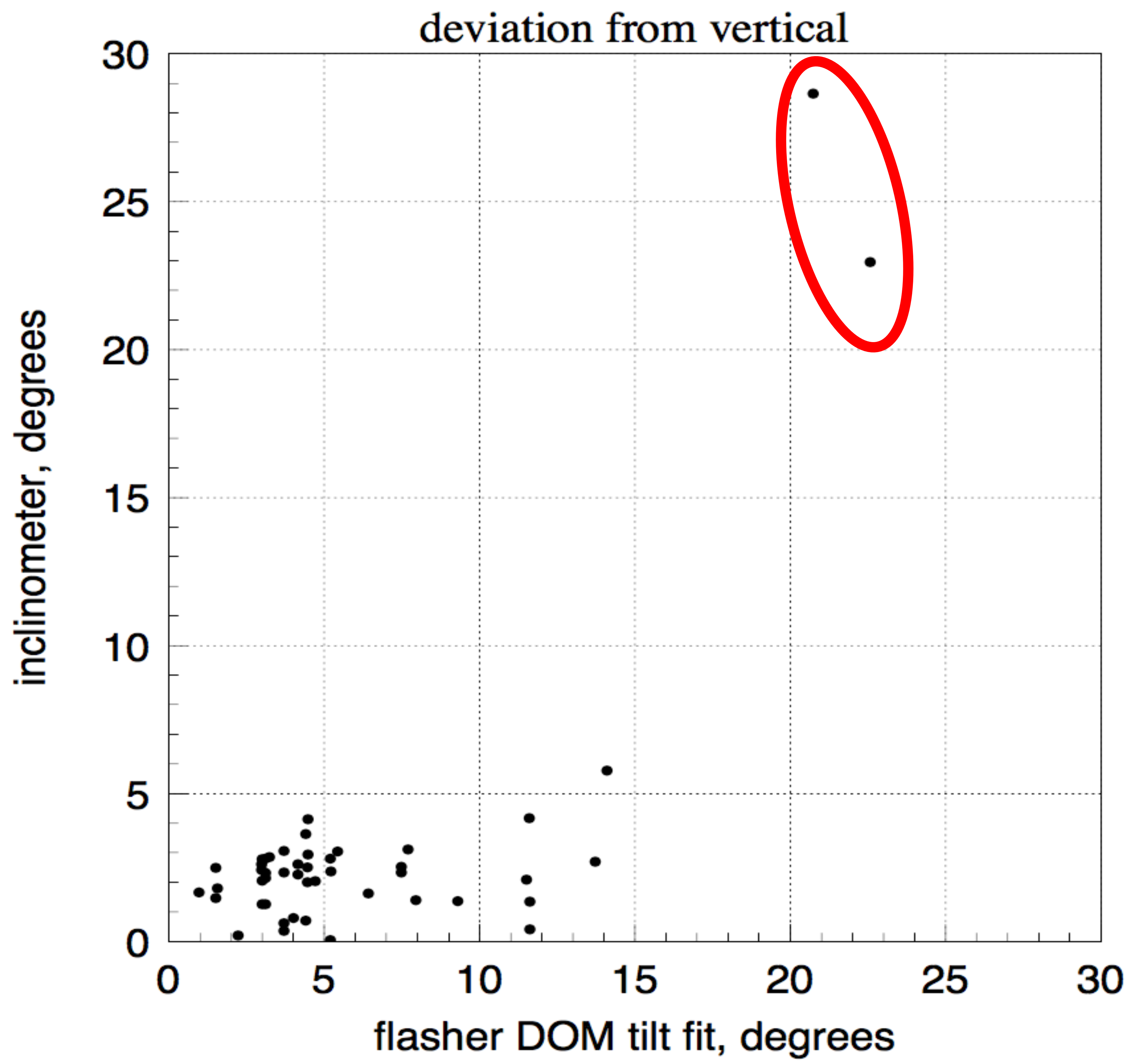


Built-in inclinometers vs DOM tilt fit

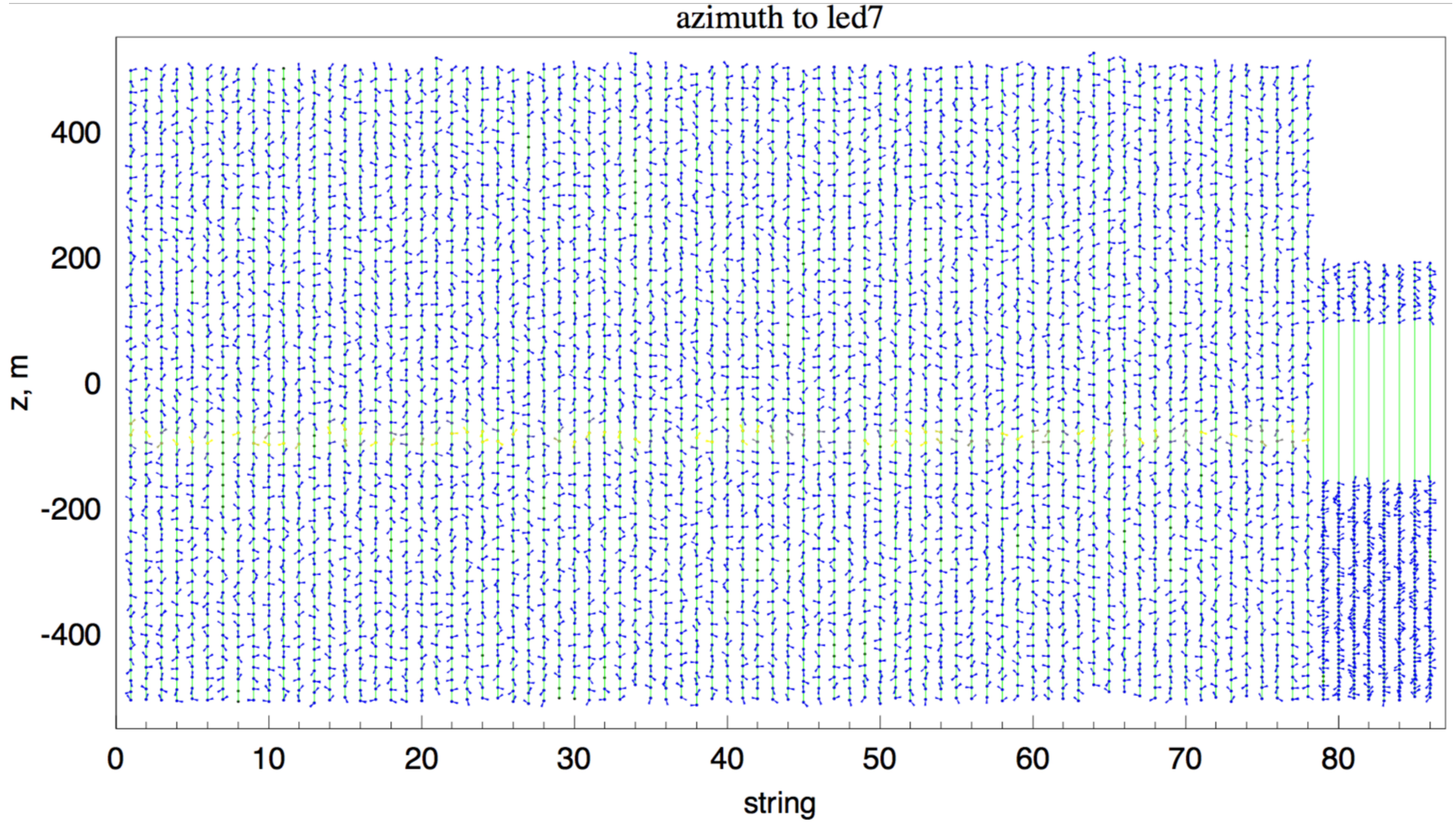
Indication of real tilt for 2 DOMs (out of 48)!

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.





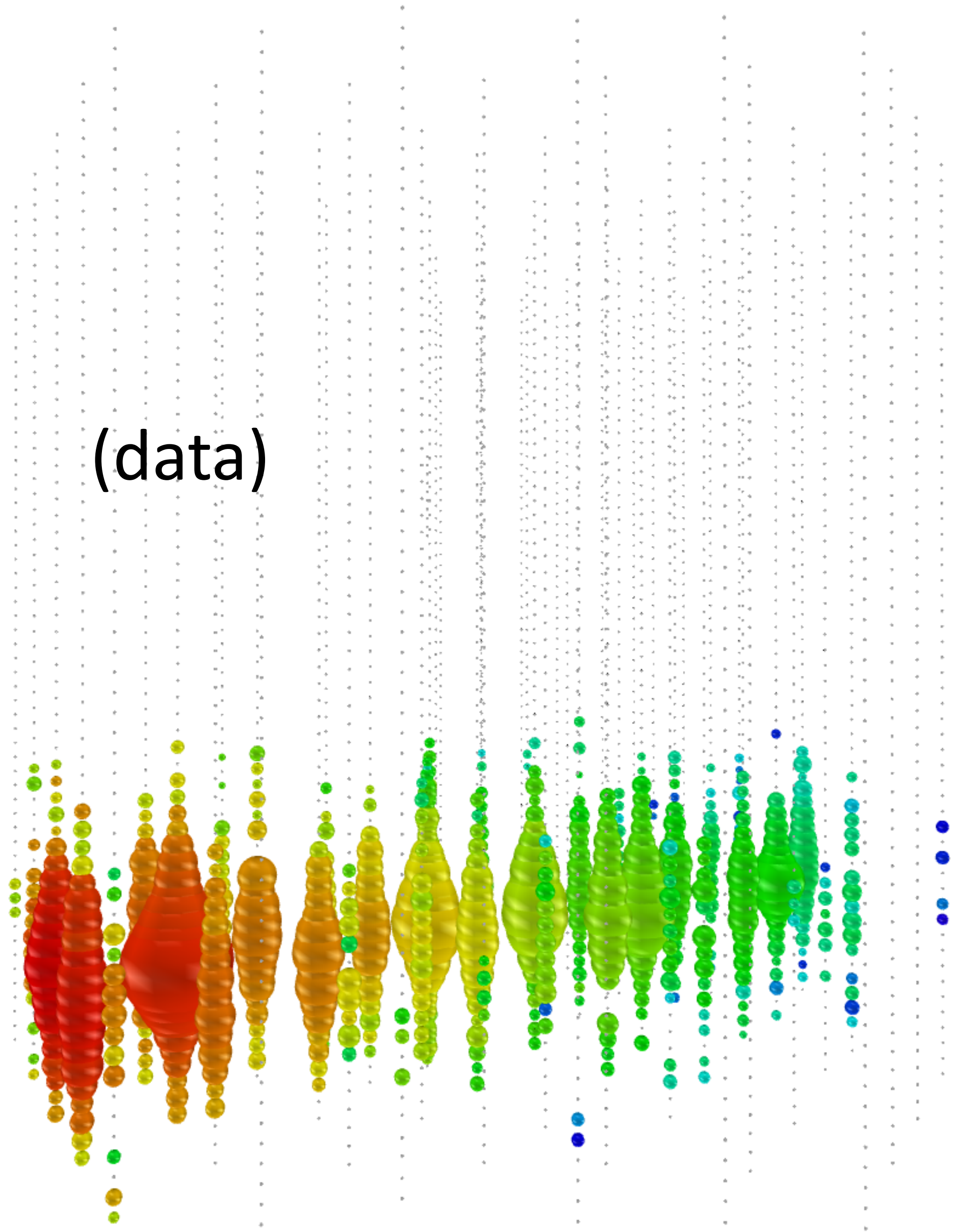
Example of DOM level calibration work: determined position of individual cables near DOM to few degree precision



Types of events and interactions

Charged-current ν_μ

(data)



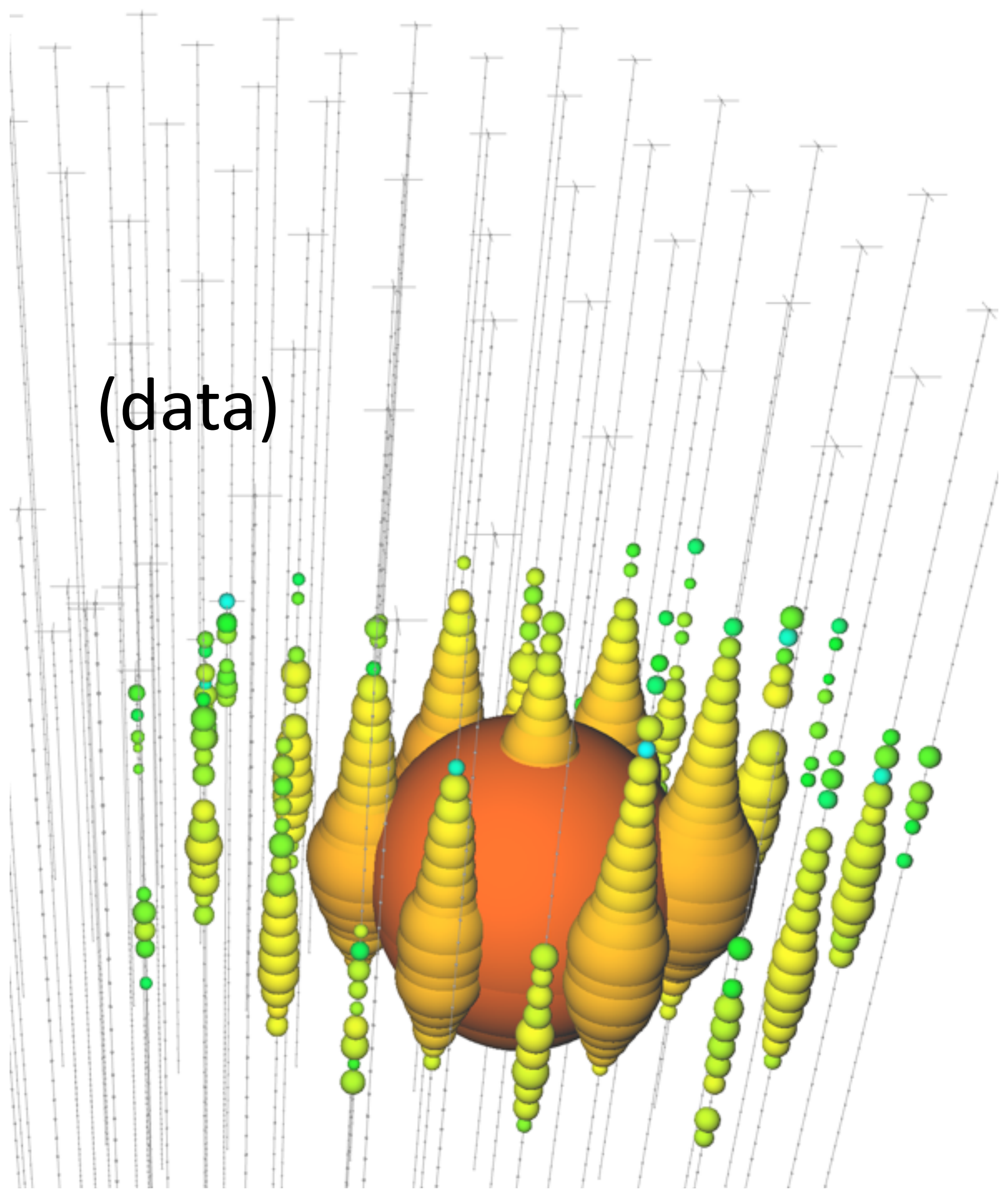
Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

Neutral-current / ν_e

(data)

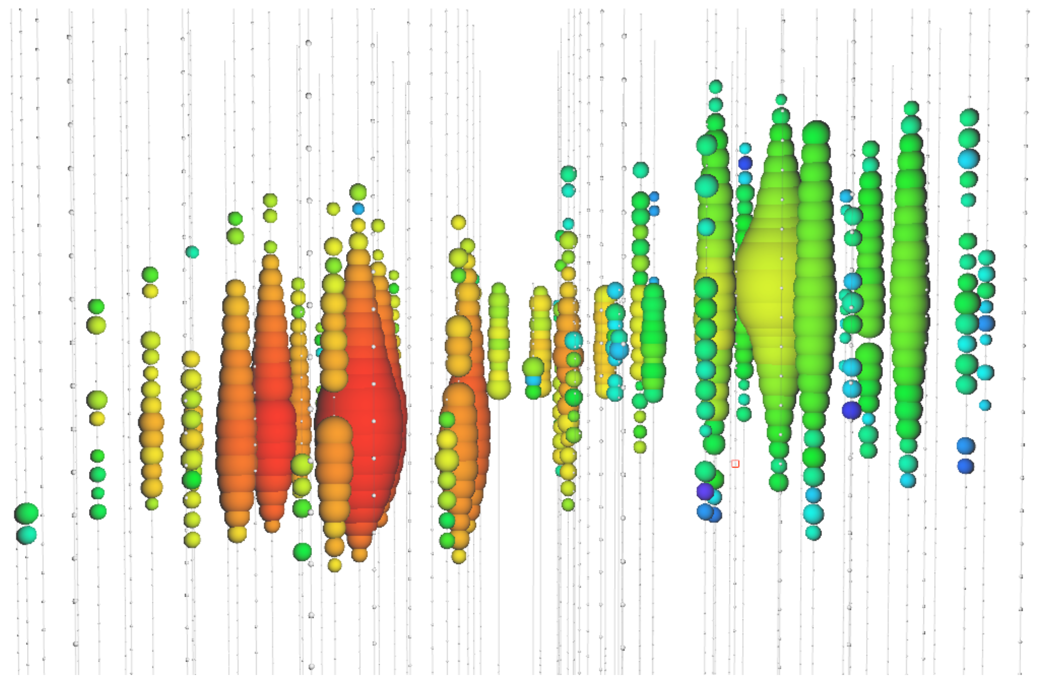


Isolated energy deposition (cascade) with no track

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

Charged-current ν_τ

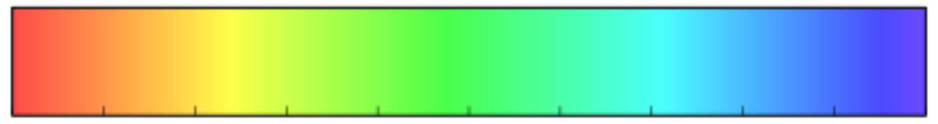
(simulation)



"Double-bang"

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

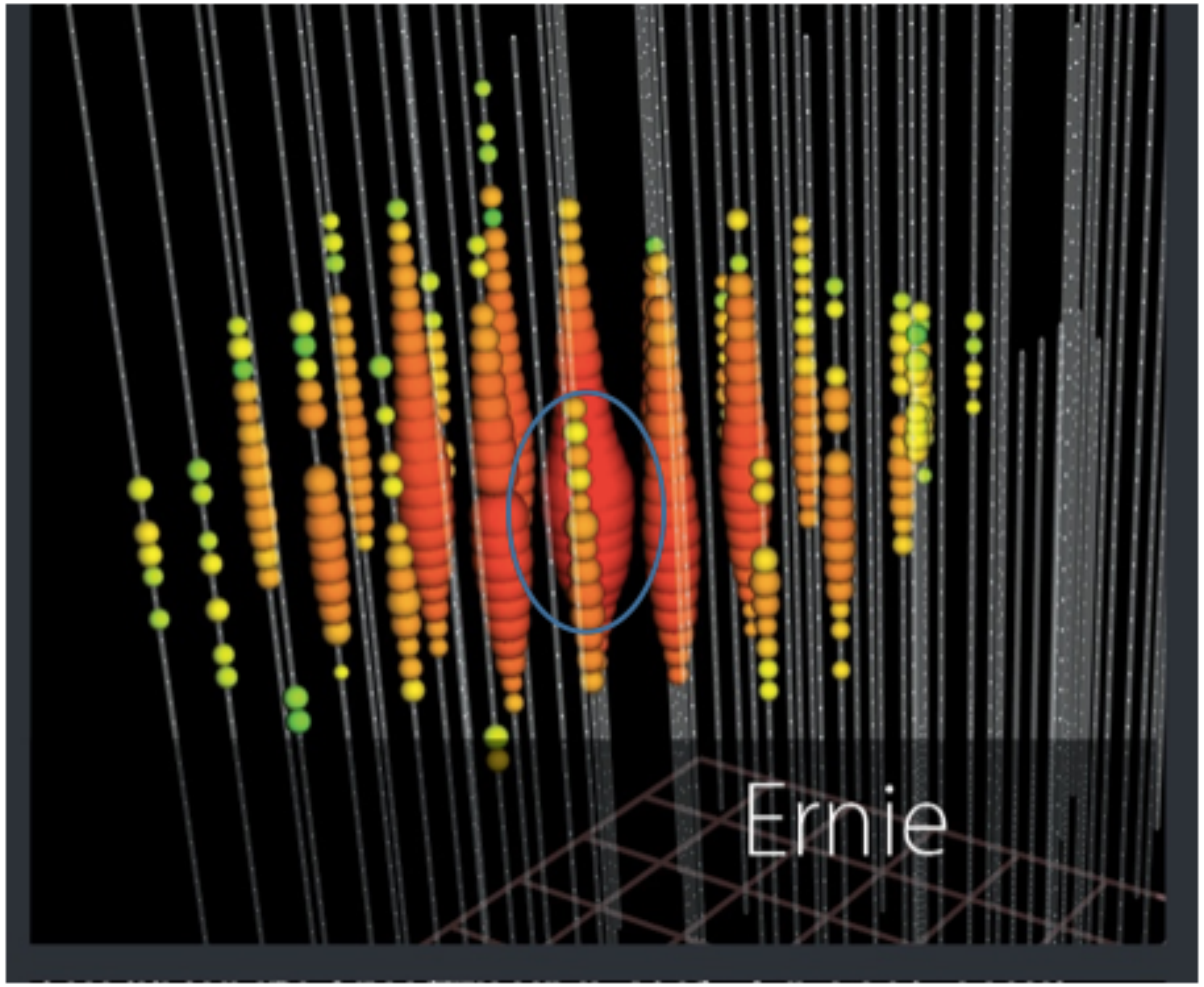
ID: above~ 100 TeV (two methods)

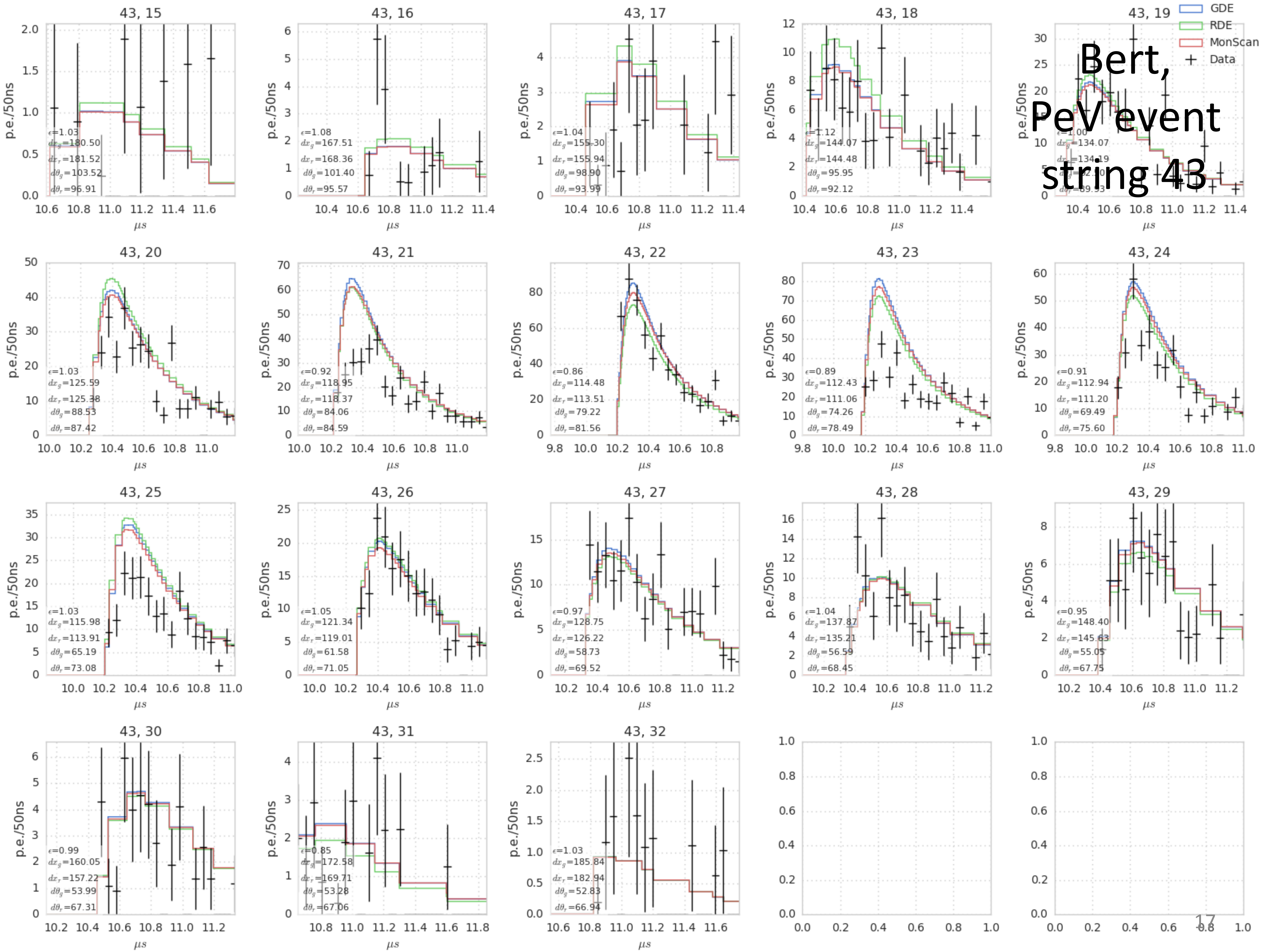
Early  Late

Bright DOMs

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

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



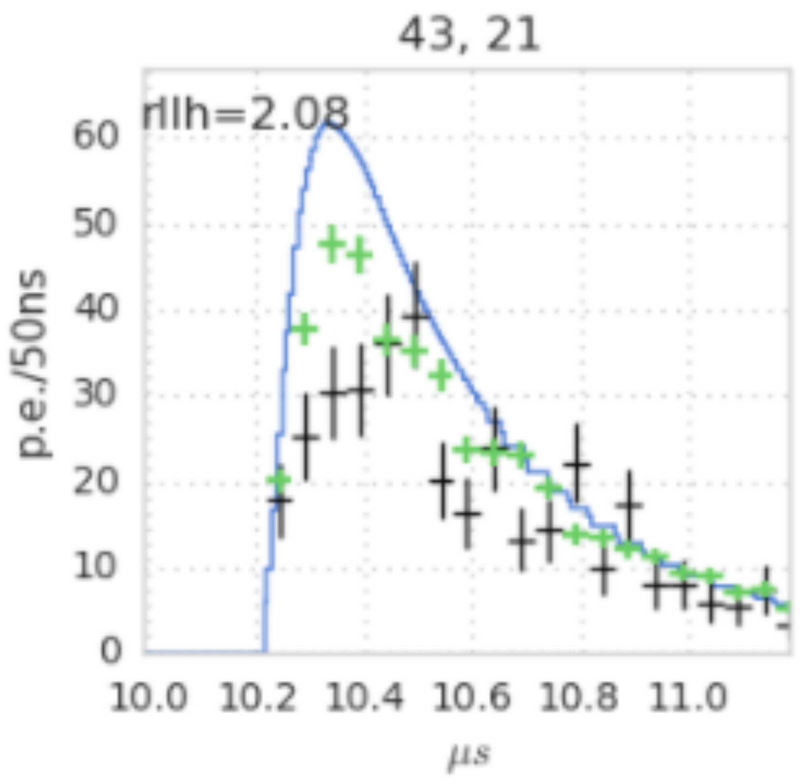

Bert,
PeV event
string 43
GDE
RDE
MonScan
Data
43, 15
43, 16
43, 17
43, 18
43, 19
43, 20
43, 21
43, 22
43, 23
43, 24
43, 25
43, 26
43, 27
43, 28
43, 29
43, 30
43, 31
43, 32
p.e./50ns
μs

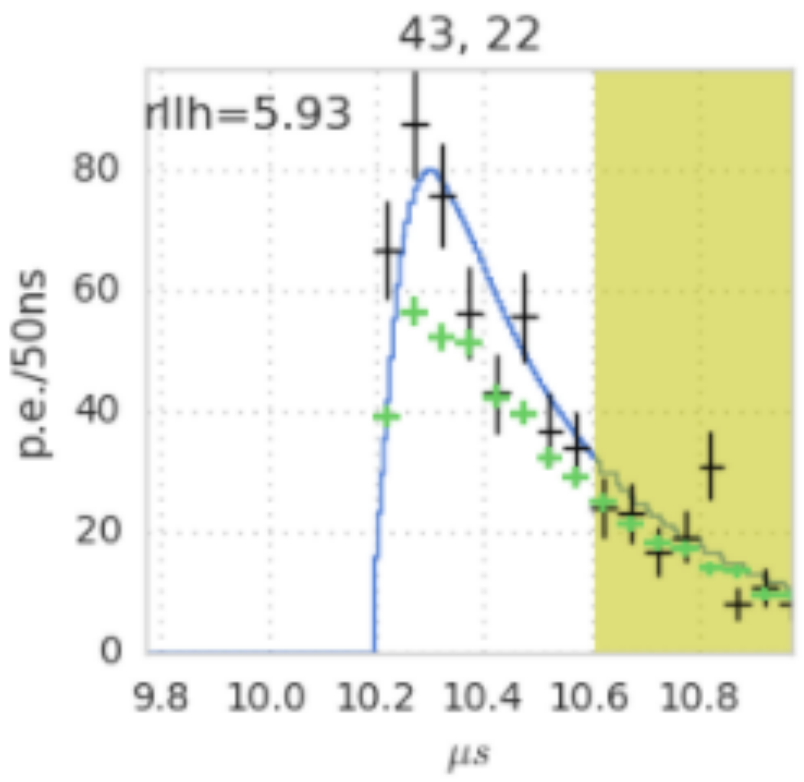
Local effects: DOM orientation and cable position

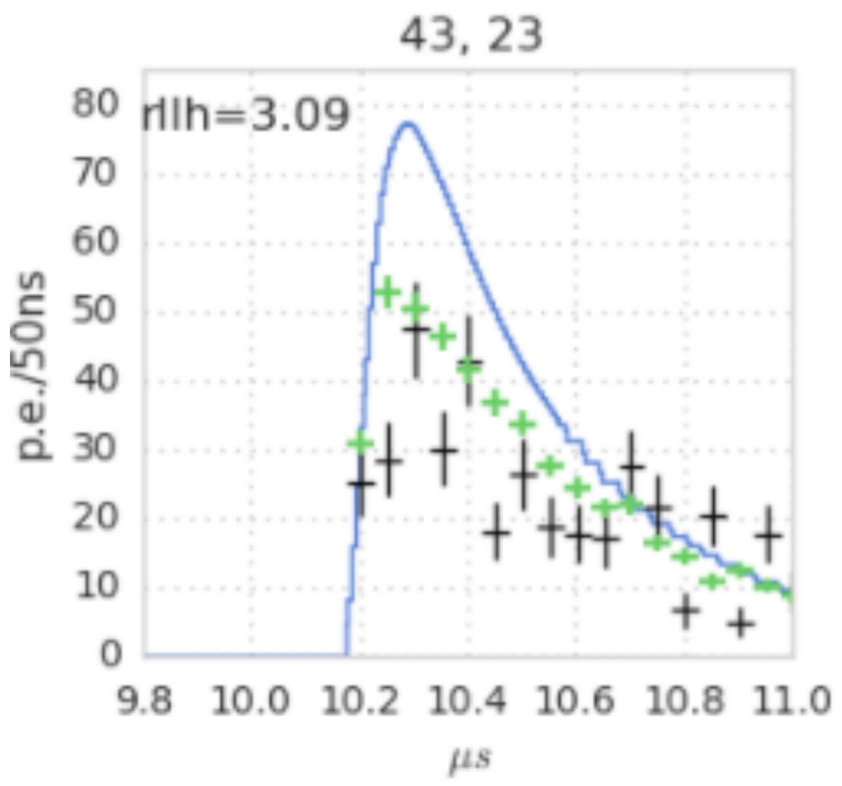
Without local effects

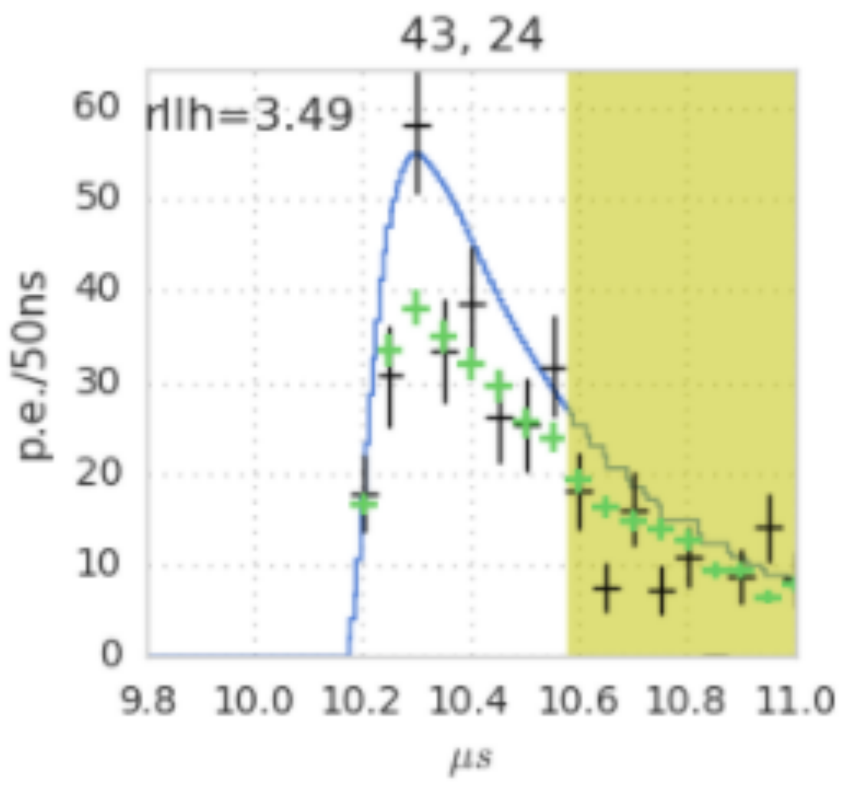
With local effects

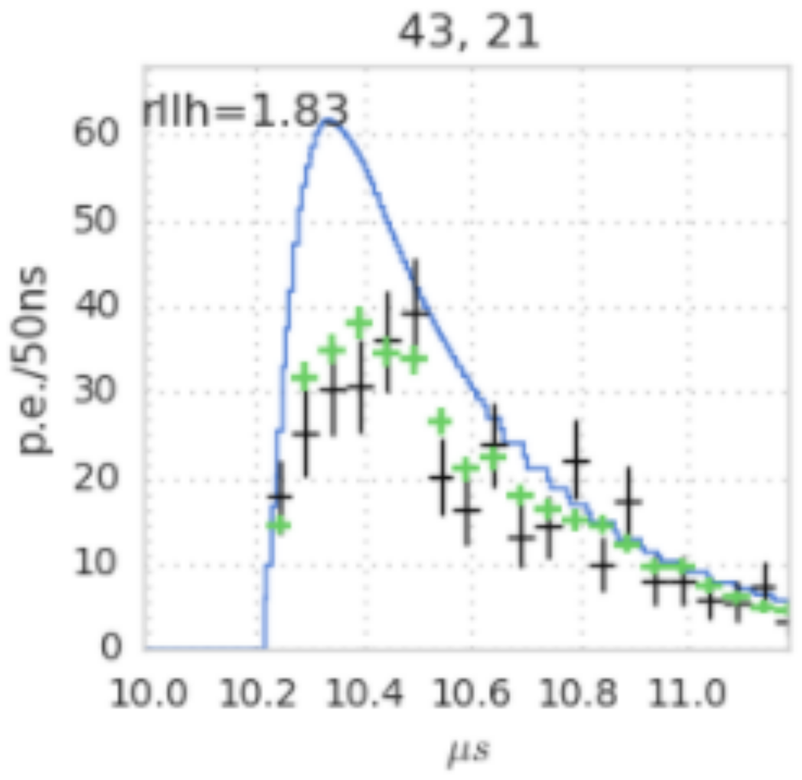
Bert data
Direct photon MC
Effective photon MC

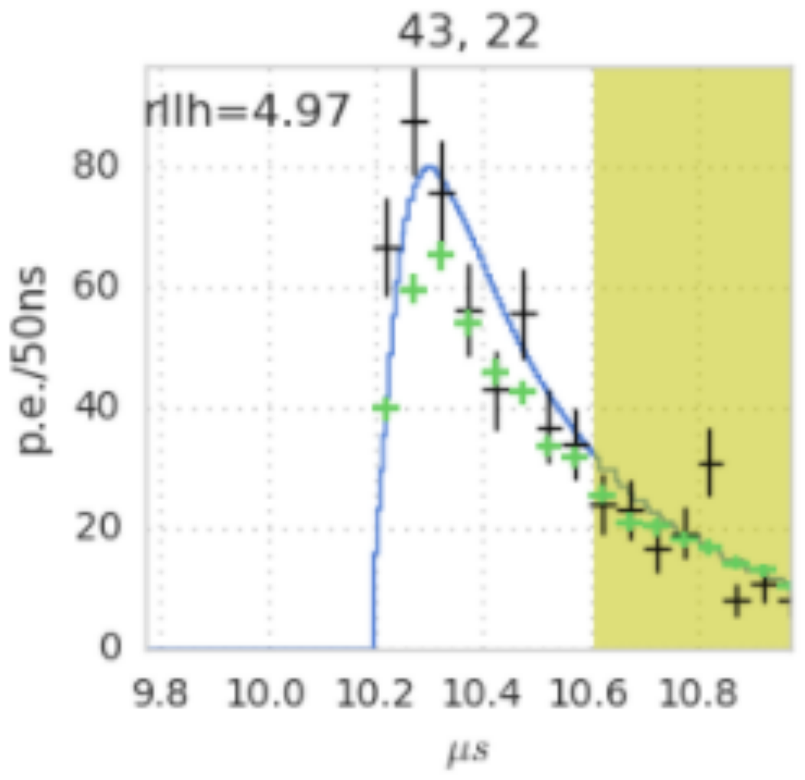


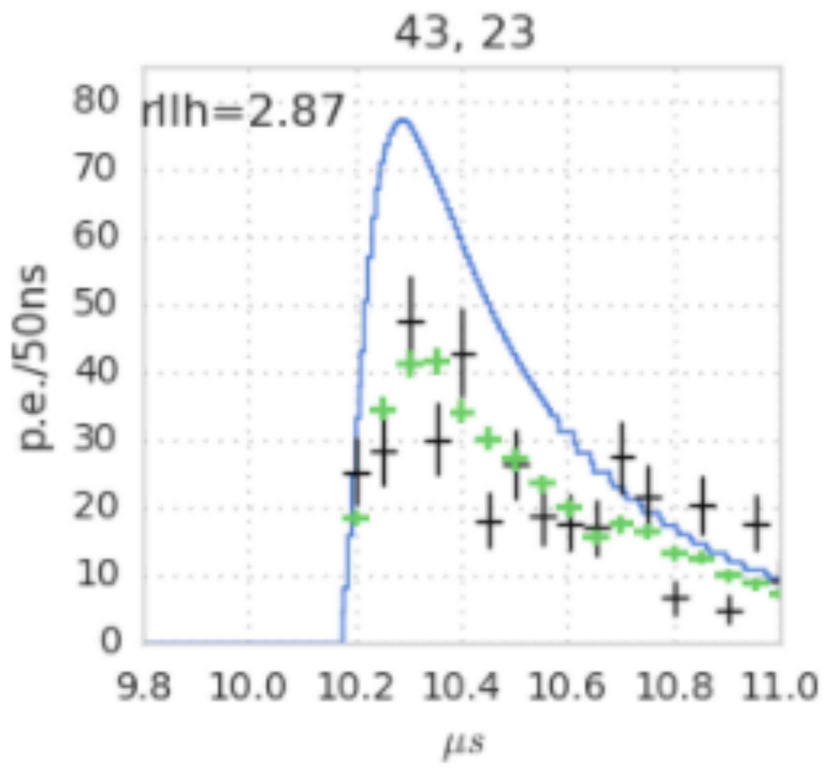


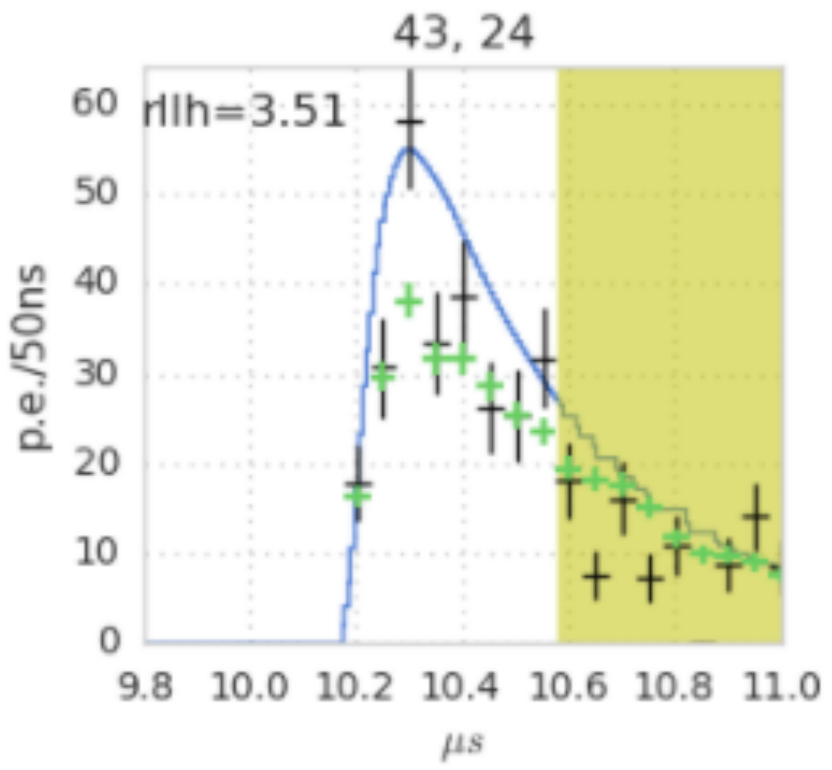




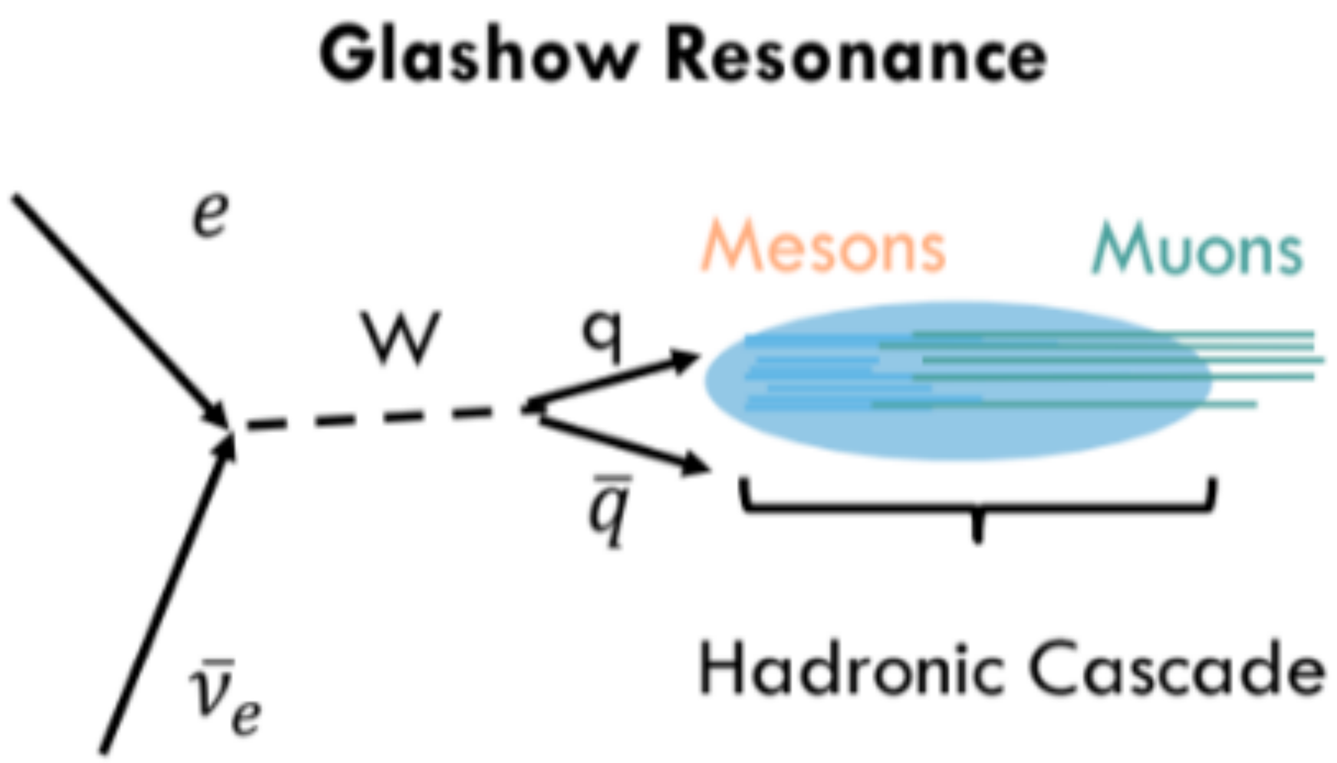






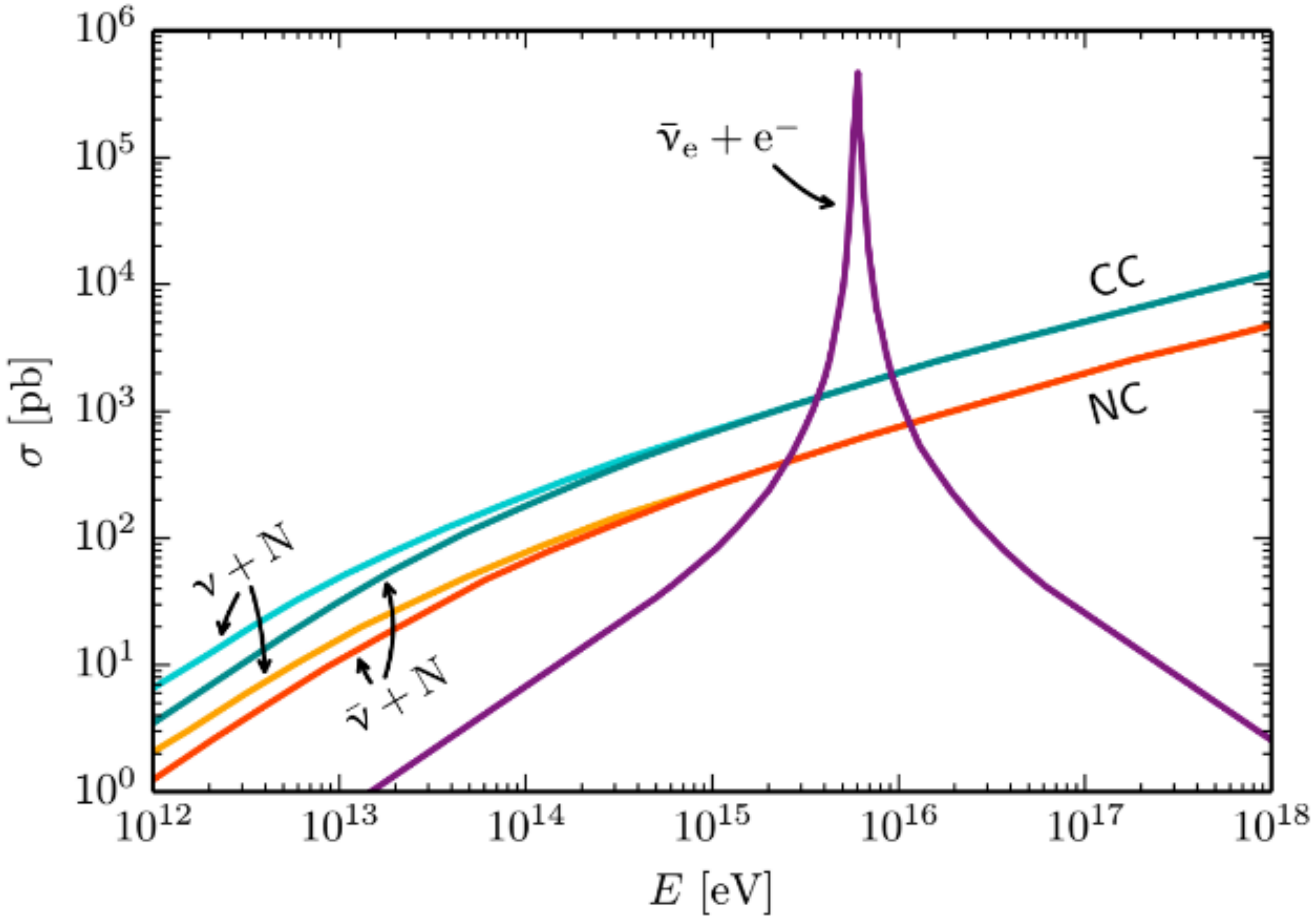


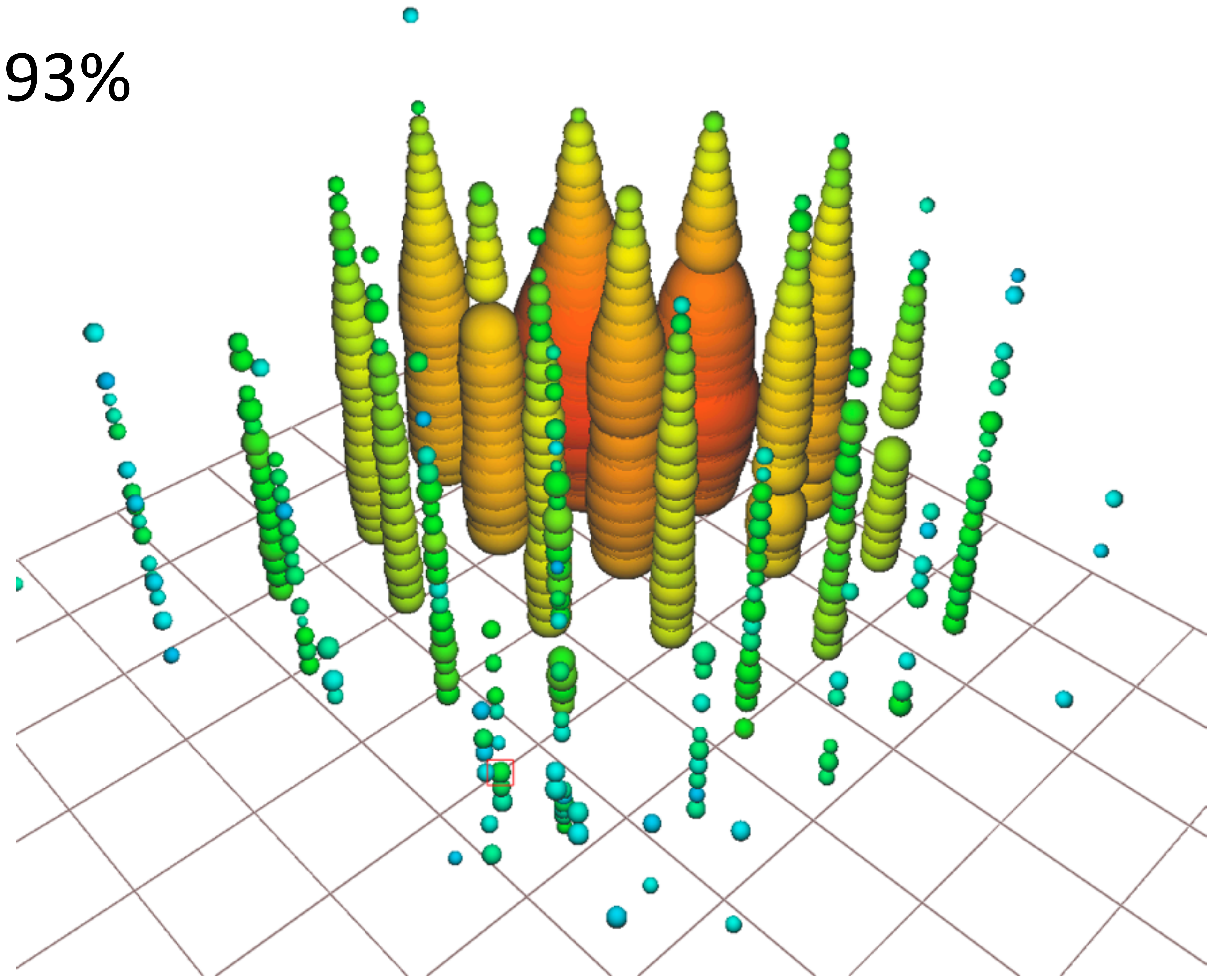
Observation of a 6 PeV neutrino of special interest



Resonance: E_ν = 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)

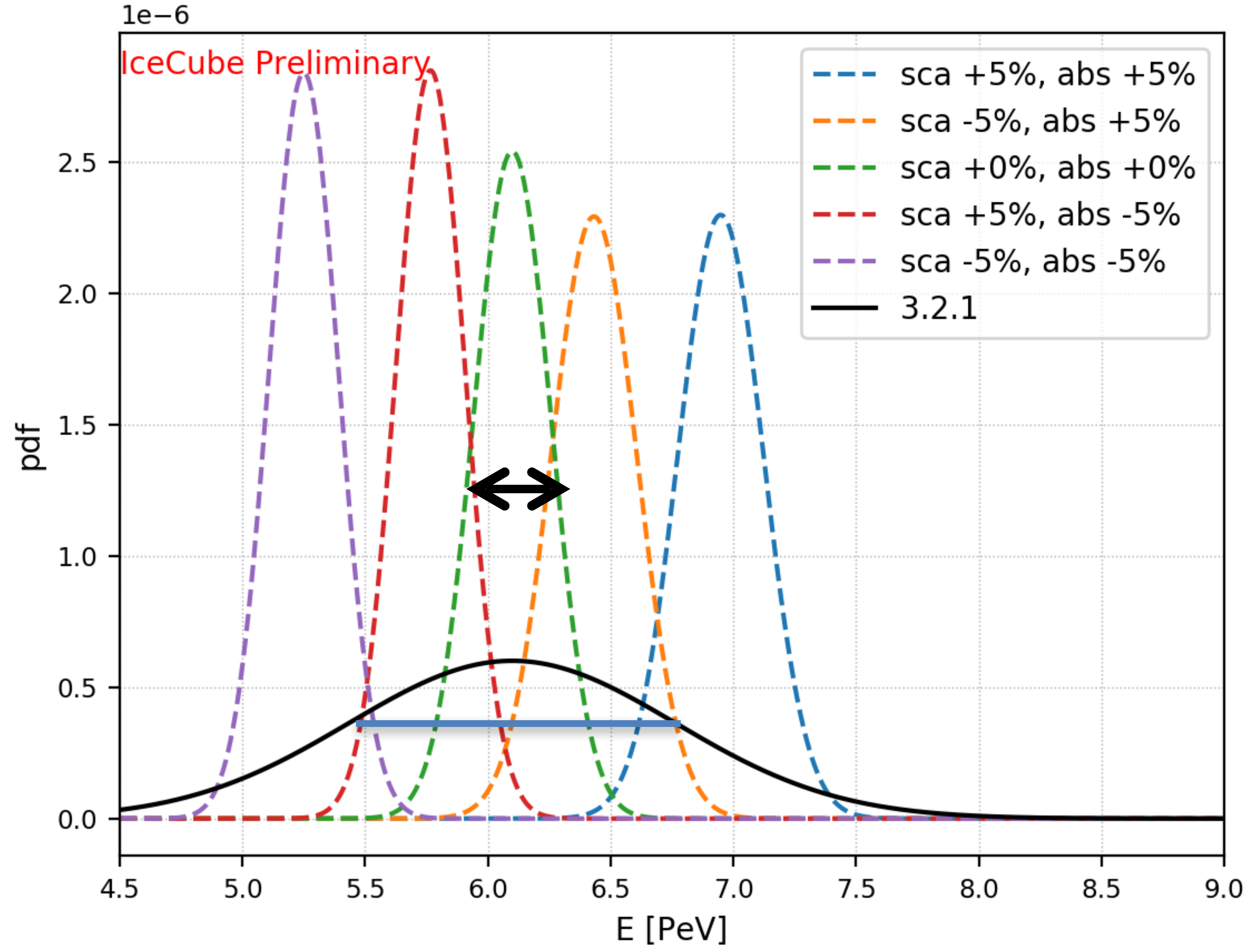
ICRC 2017 arXiv:1710.01191

Energy resolution limited by systematic errors: Impact on science

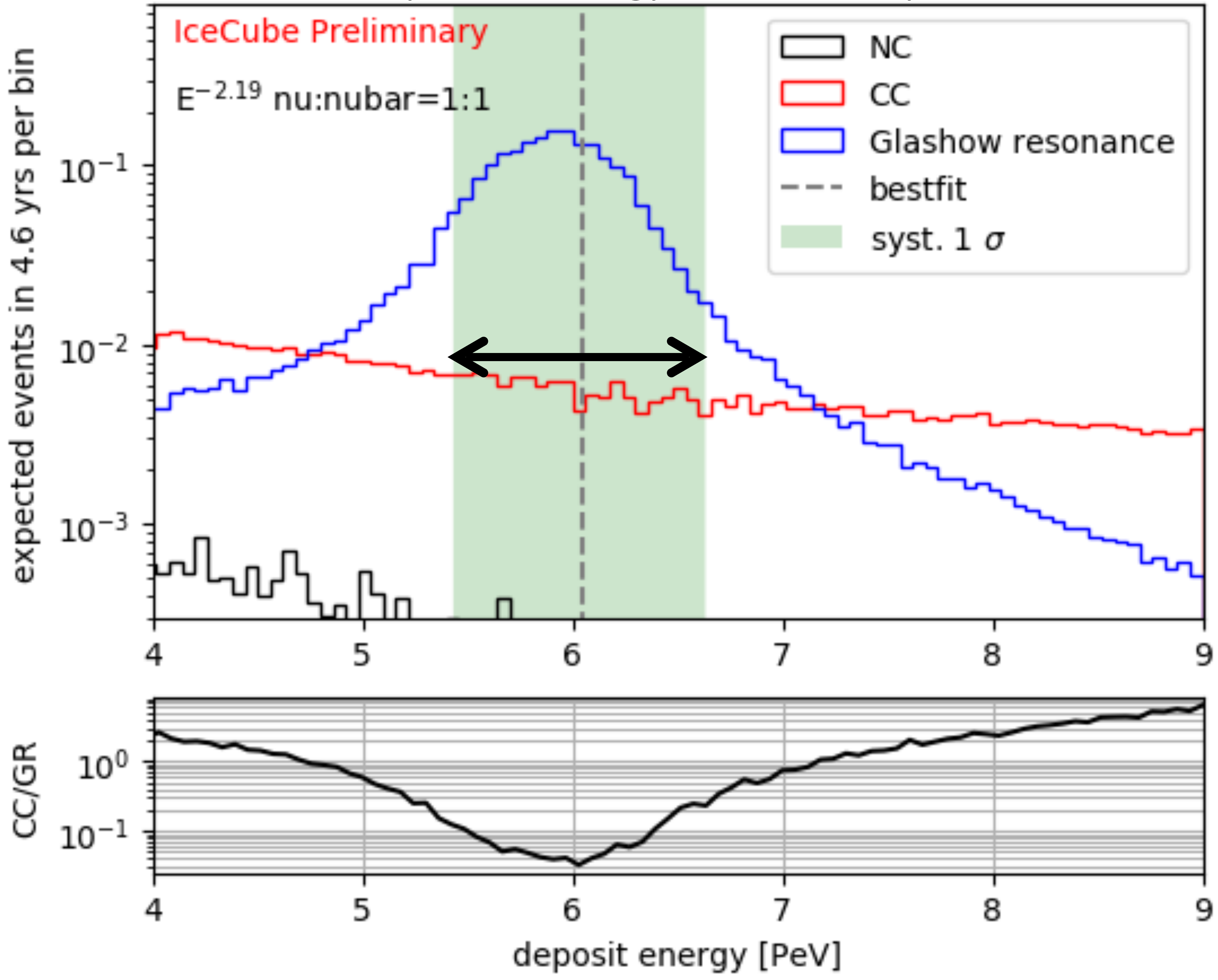
More precise energy reconstruction → reduces backgrounds for GR

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

Energy depends on ice parameters



True deposited energy event rate expectation



resolution on deposited energy

Statistical error: ~0.18 PeV

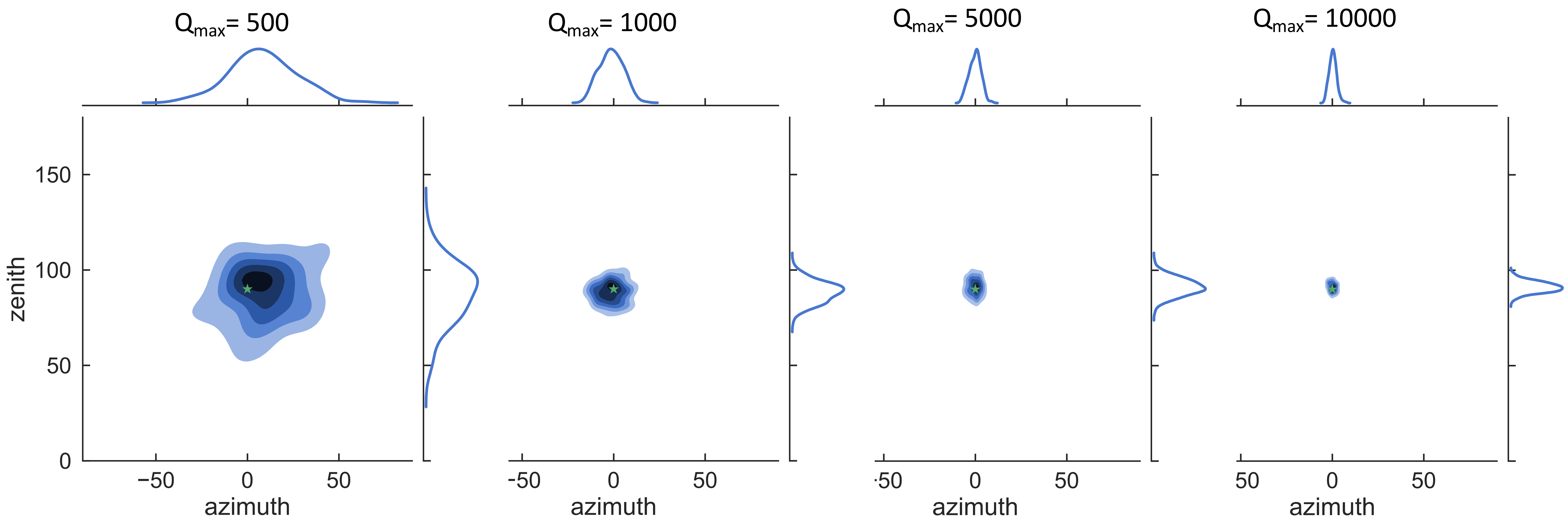
Systematic error: ~0.7 PeV

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



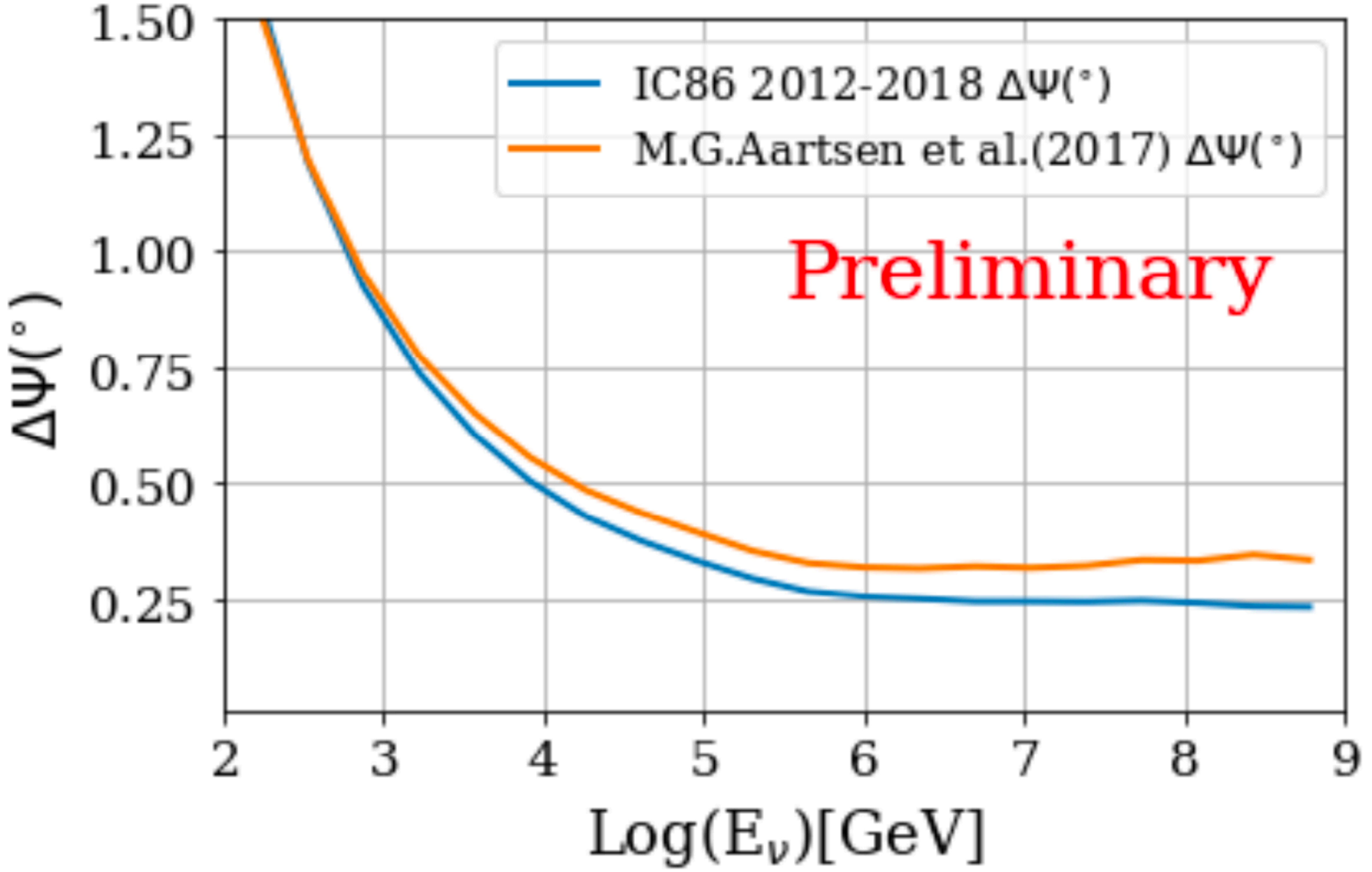
Less charge used → More charge used

Identical ice model for simulation and reconstruction

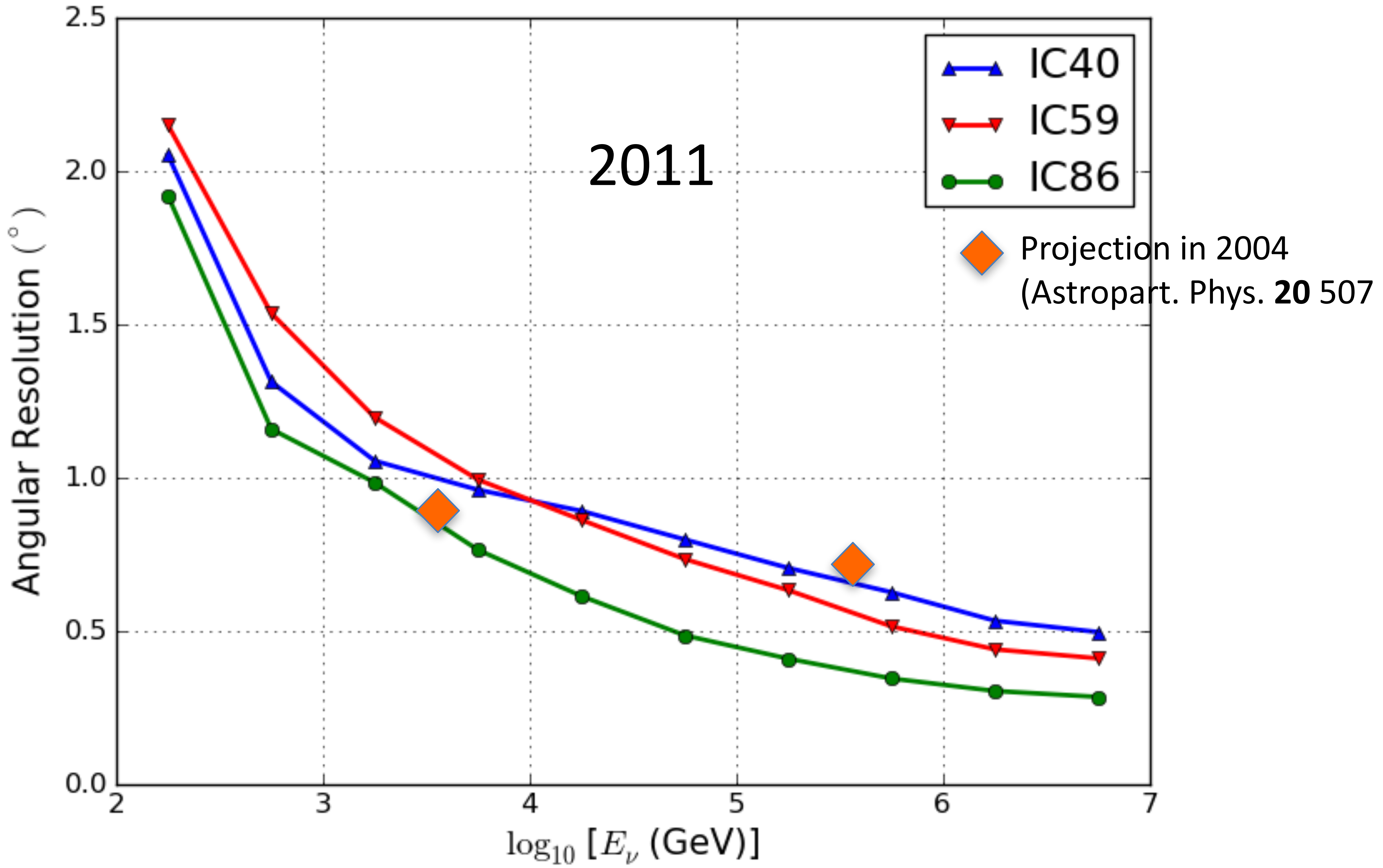
Higher level performance parameters

Angular resolution for muon neutrinos

2019

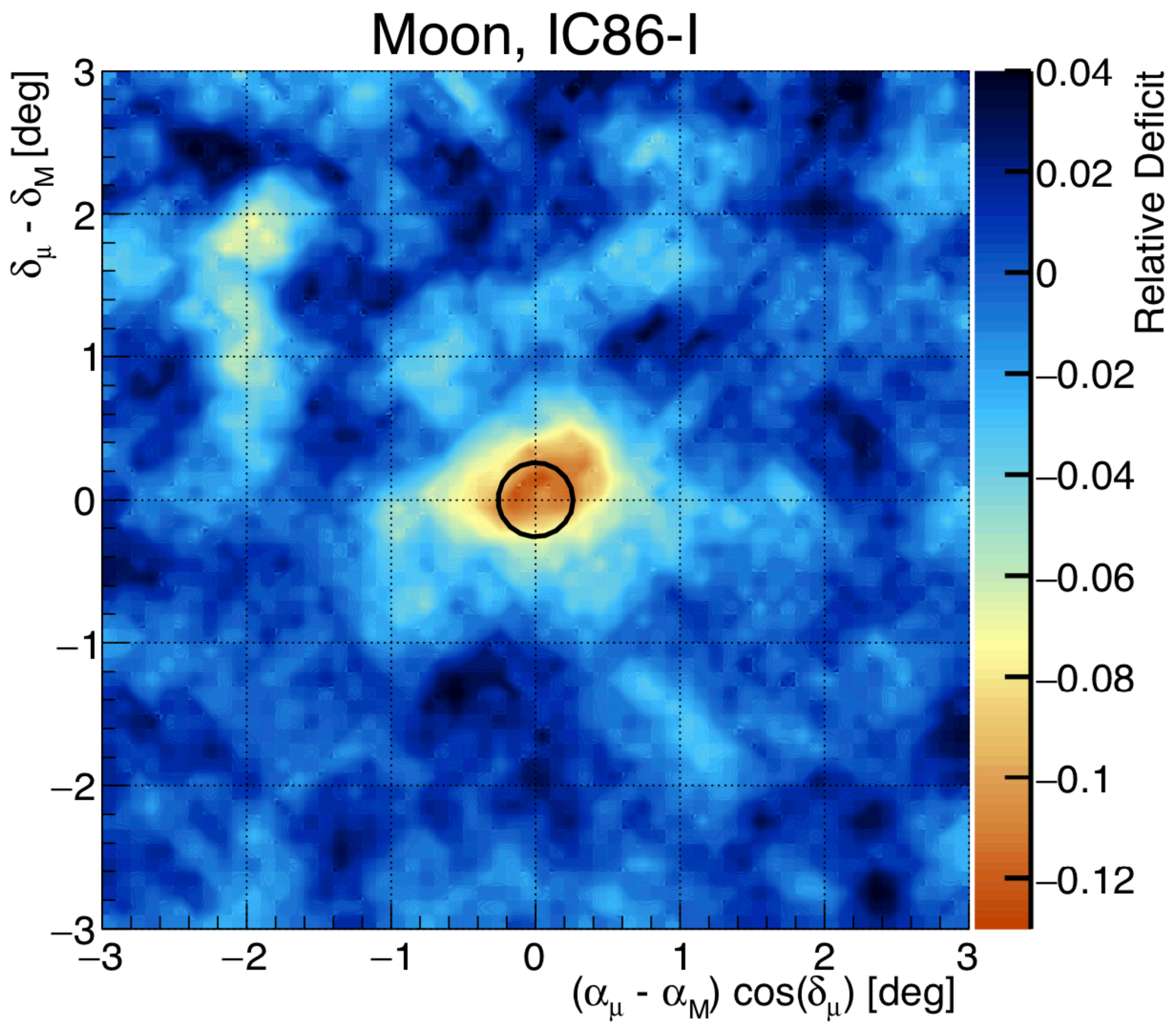


Continued improvement of reconstruction

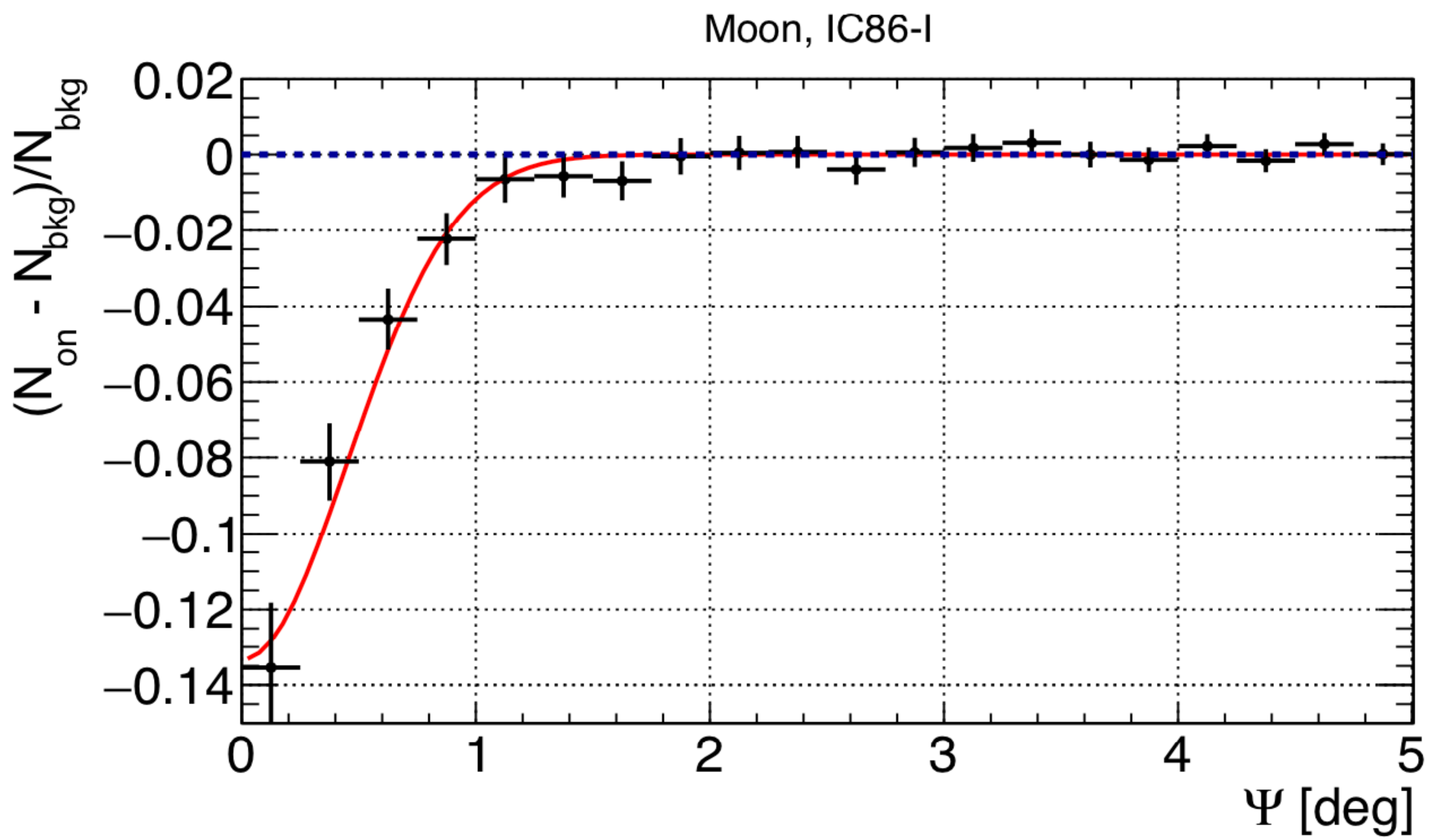


Moon shadow

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



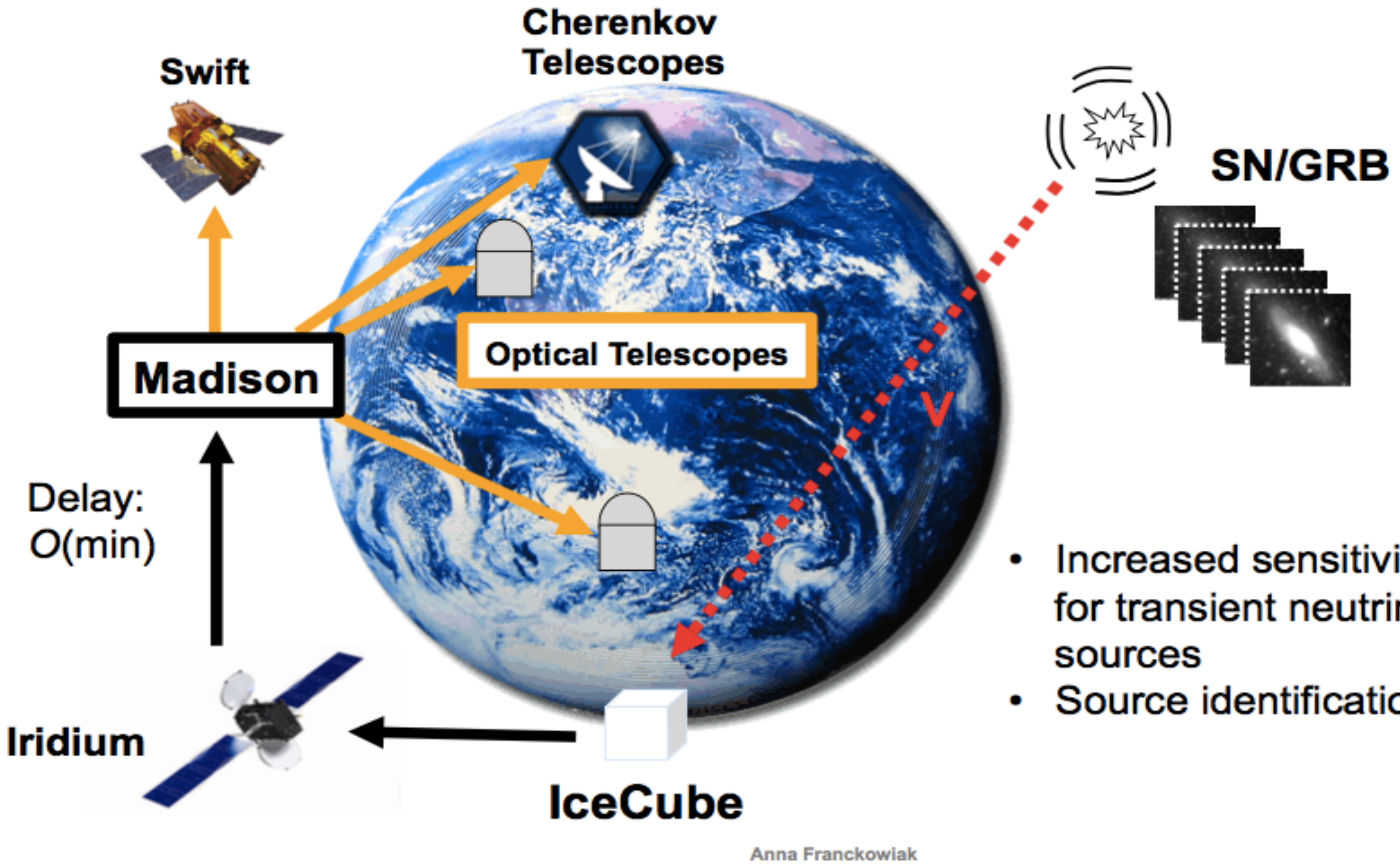
Absolute pointing verified to 0.1 °
Median resolution for low energy muons: 0.7°



Detection of the Temporal Variation of the Sun's Cosmic Ray Shadow with the IceCube Detector
ApJ, 872, (2019) 133

Multimessenger astronomy in real time - flares
Implementation of efficient realtime system online

Technical progress:
TXS alert published 43 seconds after interaction.

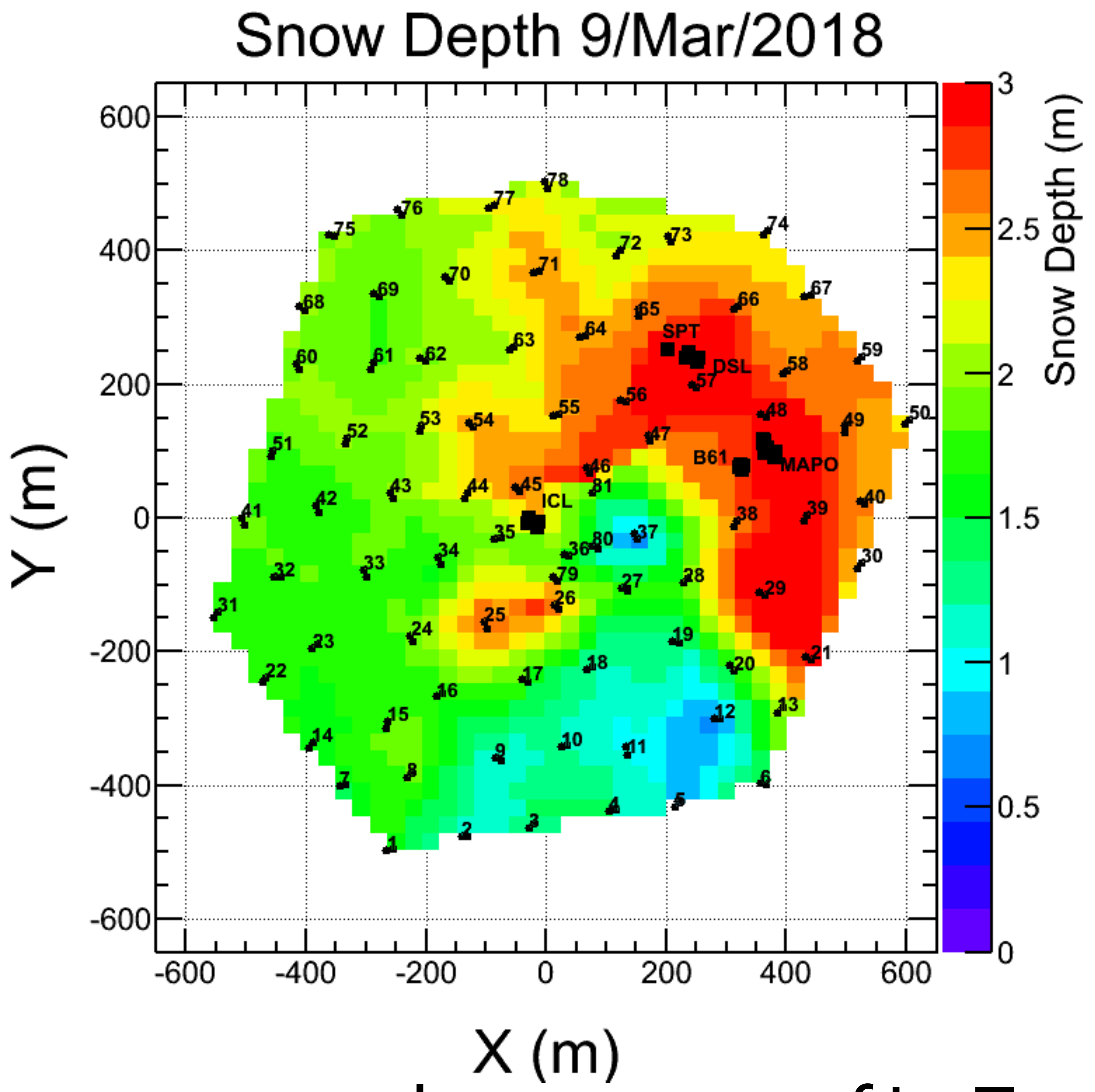


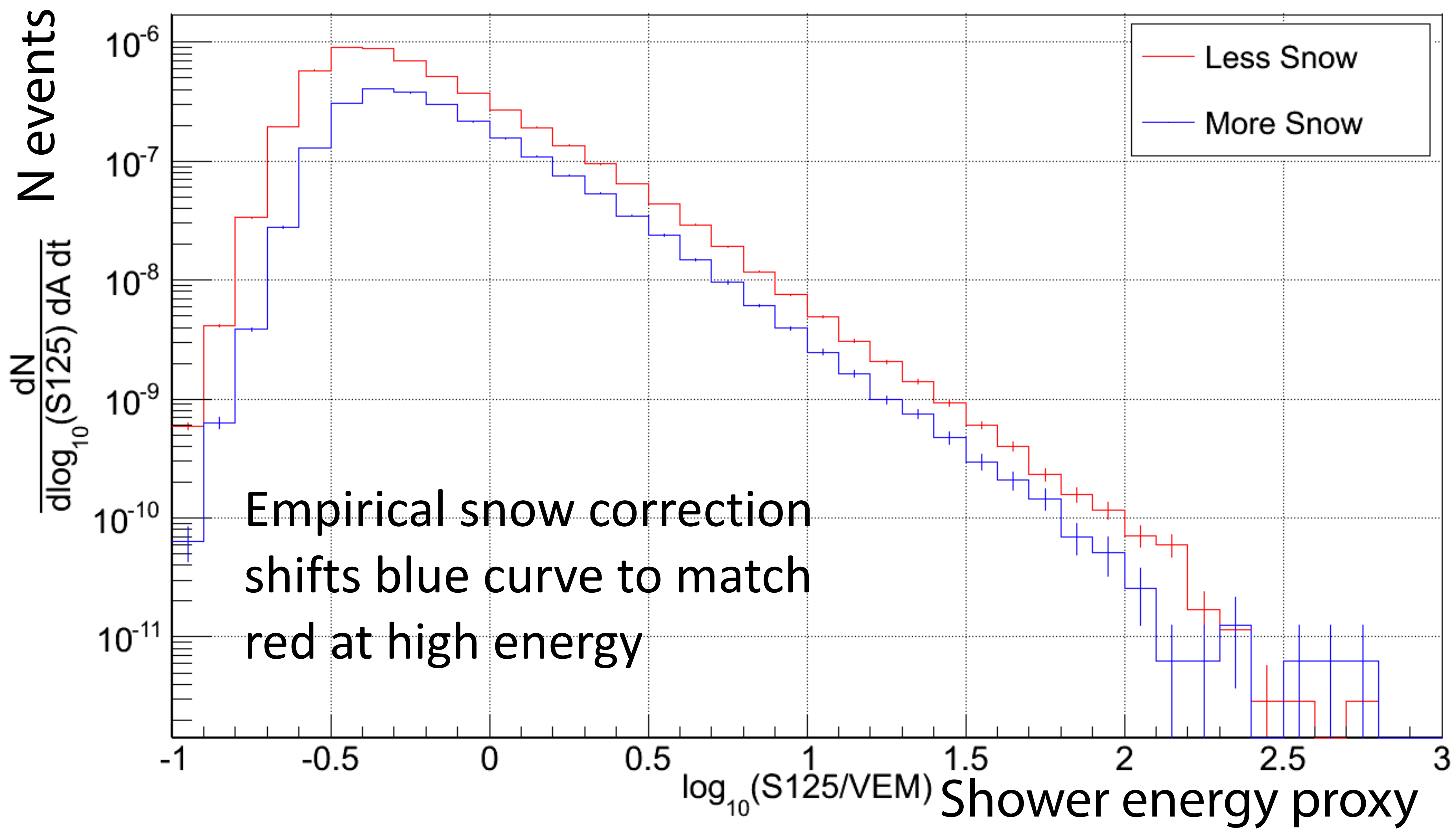
- Increased sensitivity for transient neutrino sources
- Source identification

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 from cosmic rays.
- 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.

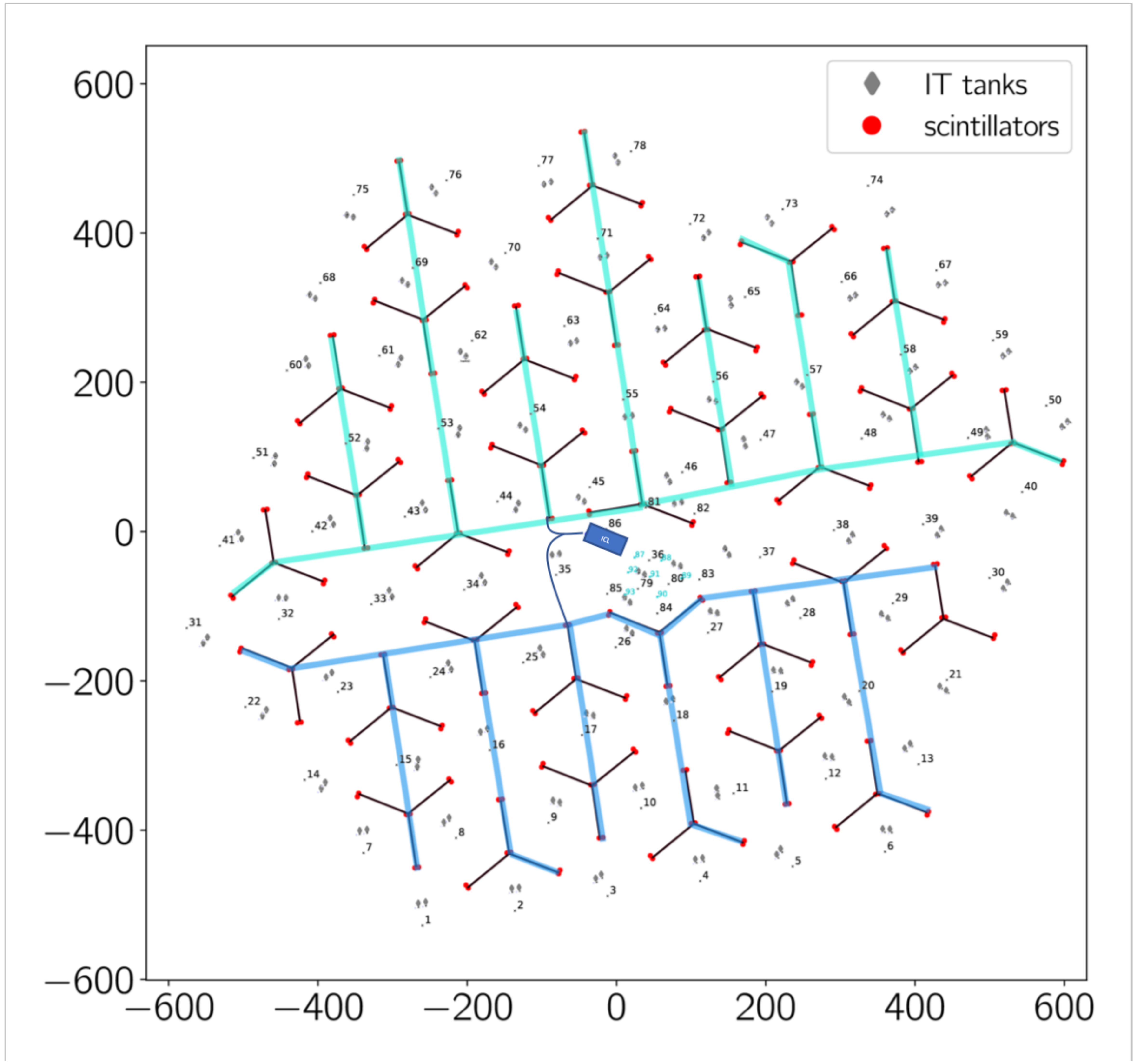
Cosmic Ray science

- More accurate measurements of the cosmic rays mass composition and energy spectrum above 1 PeV.

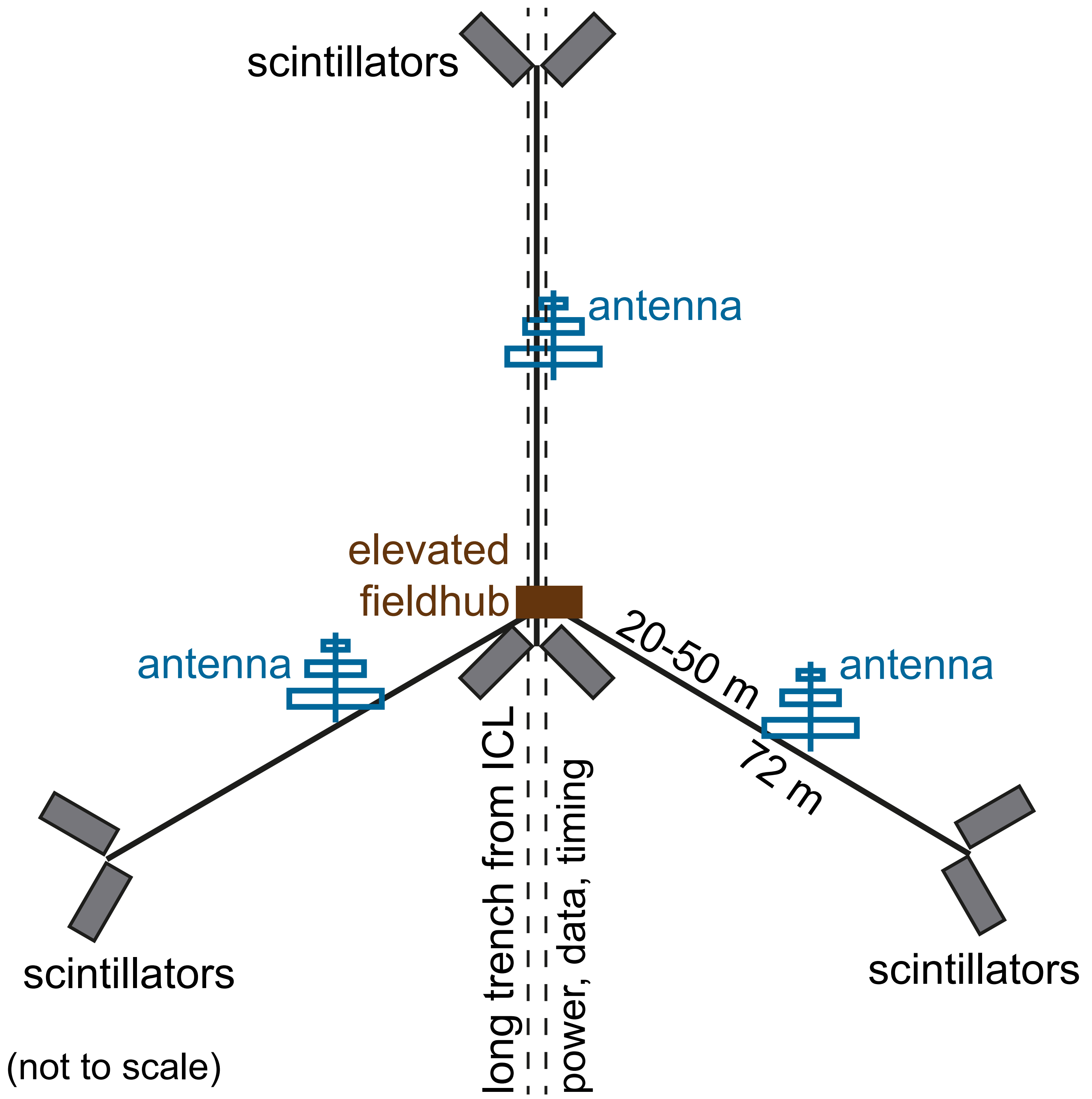
Other benefits: R&D for future detector upgrades

- 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.

Scintillator deployment



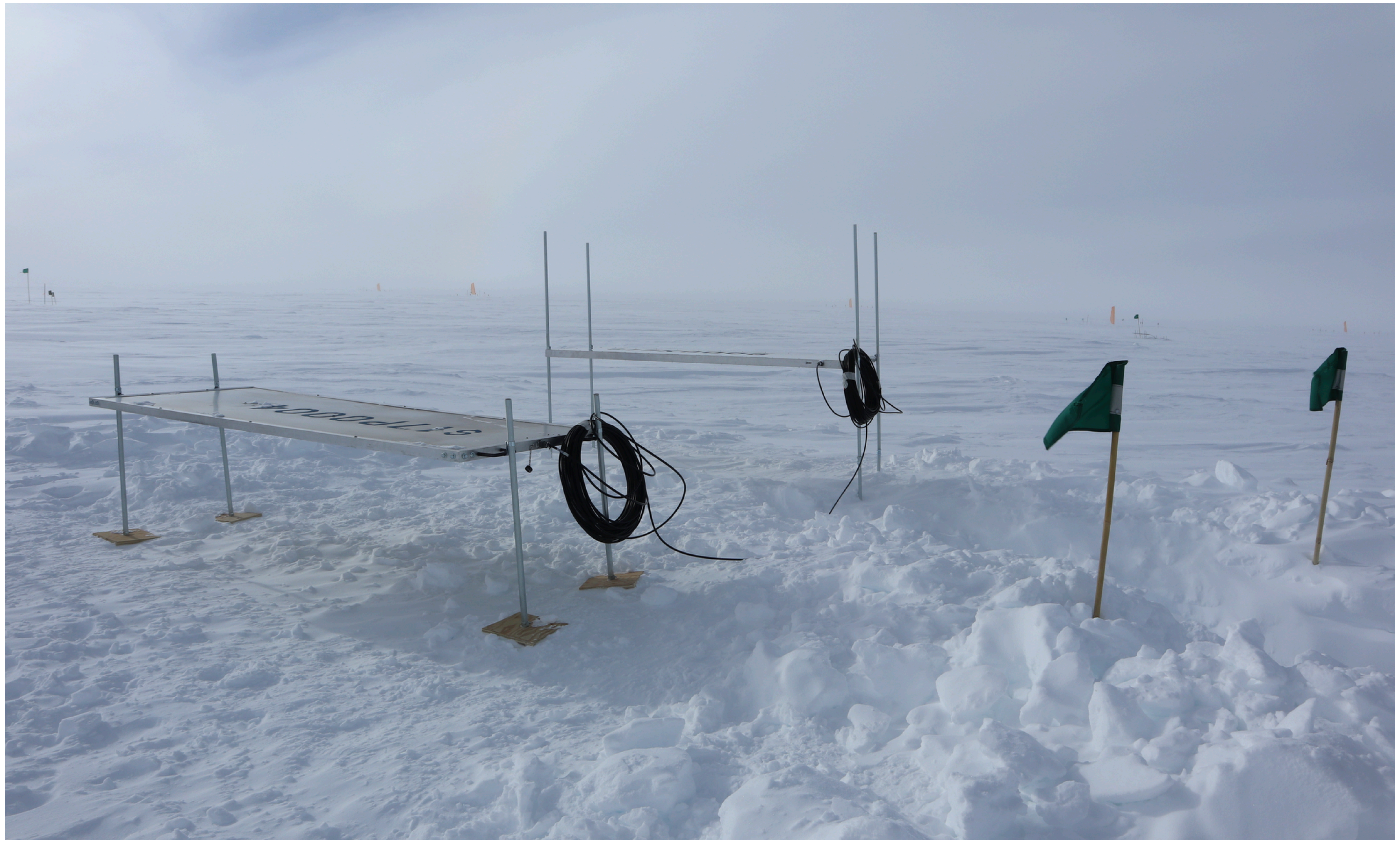
Layout is optimized both for science and ease of deployment

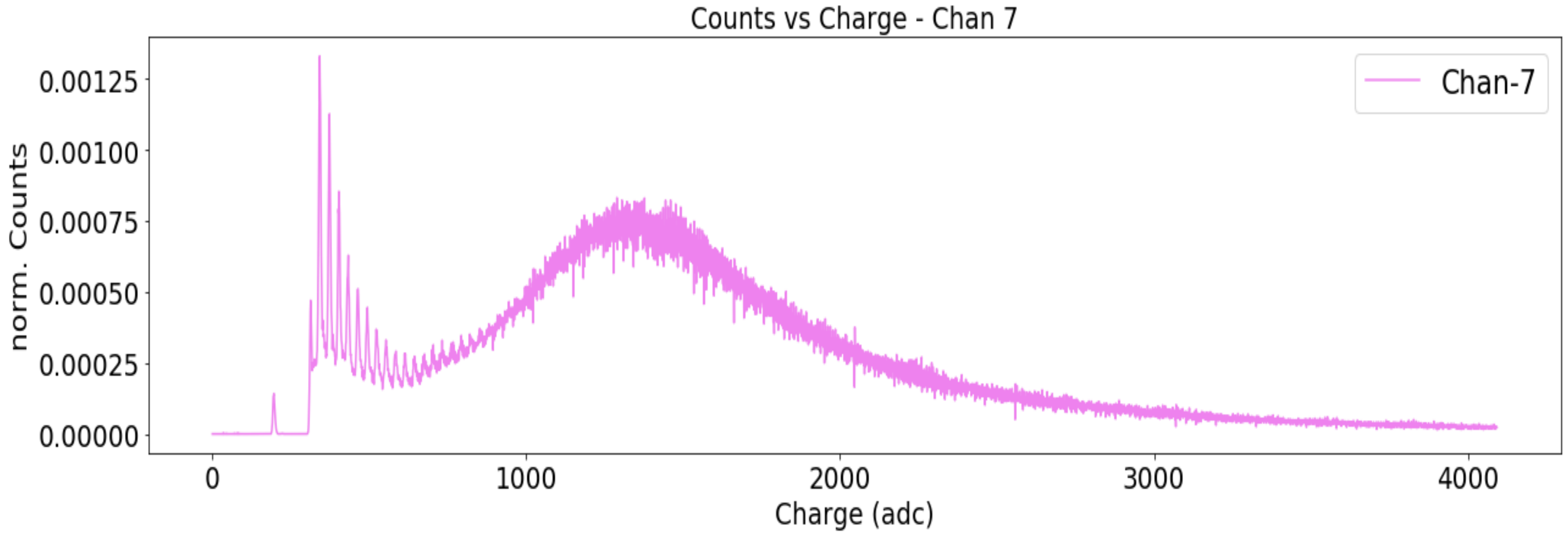


Performance

- Two stations (with different designs, each offering unique advantages) were installed in pole season 2017/18 and have been taking data since May 2018.

- Excellent performance of both stations





15 months later
(last week)

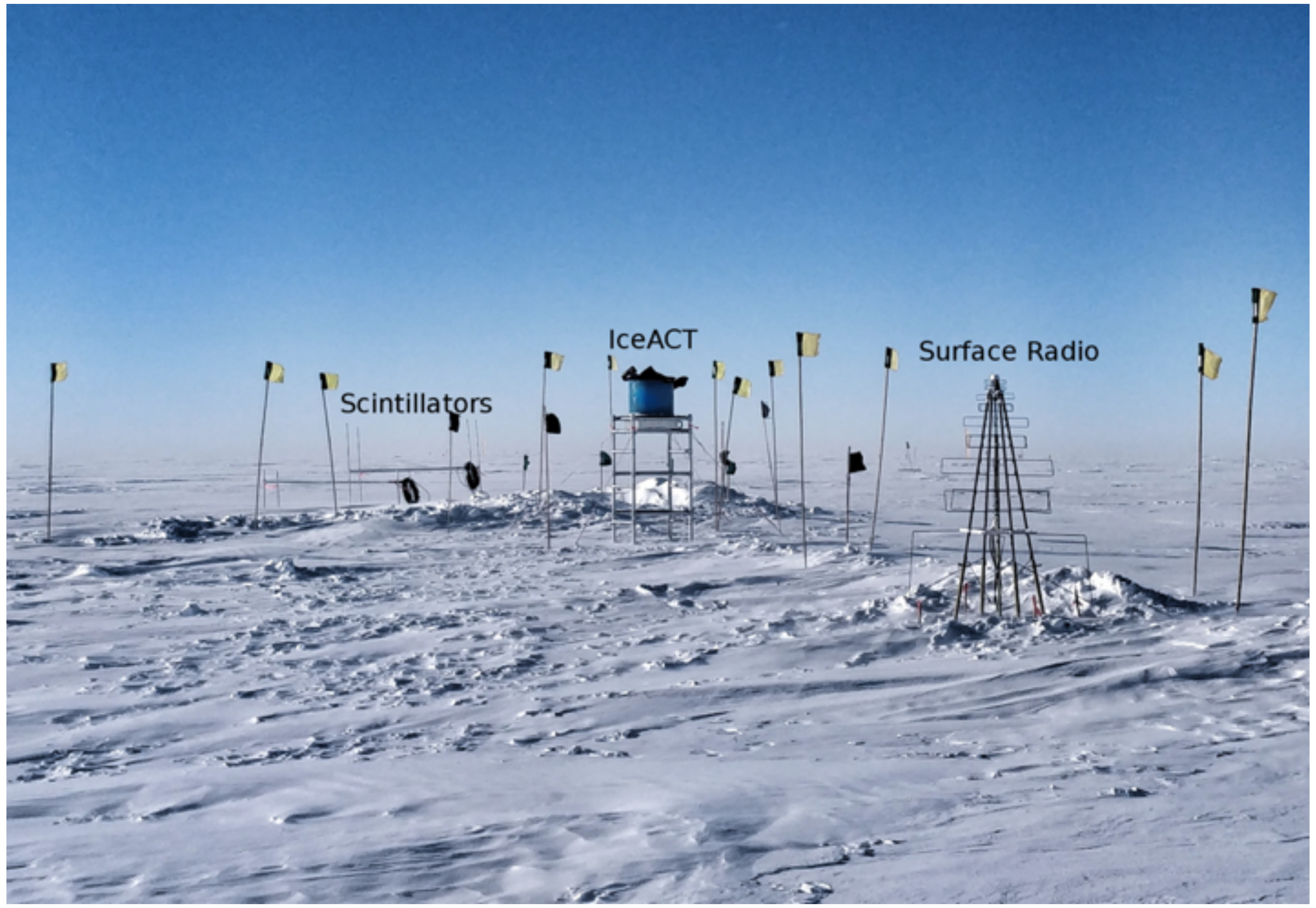
Radio component

3 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
- discovery potential for PeV photons in a scenario, where the HESS source of the Galactic Center would be the source of the most energetic CR in the Milky Way
- testing hadronic interaction models

Science case backed up by simulation

Photo:
Surface detector R&D
January 2019



Air Cherenkov R&D

Measuring directly the CR showers electromagnetic component down to 20 TeV would:

→support calibration of the in-ice detector and IceTop

→Lower veto threshold for IceCube for the area covered.

→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

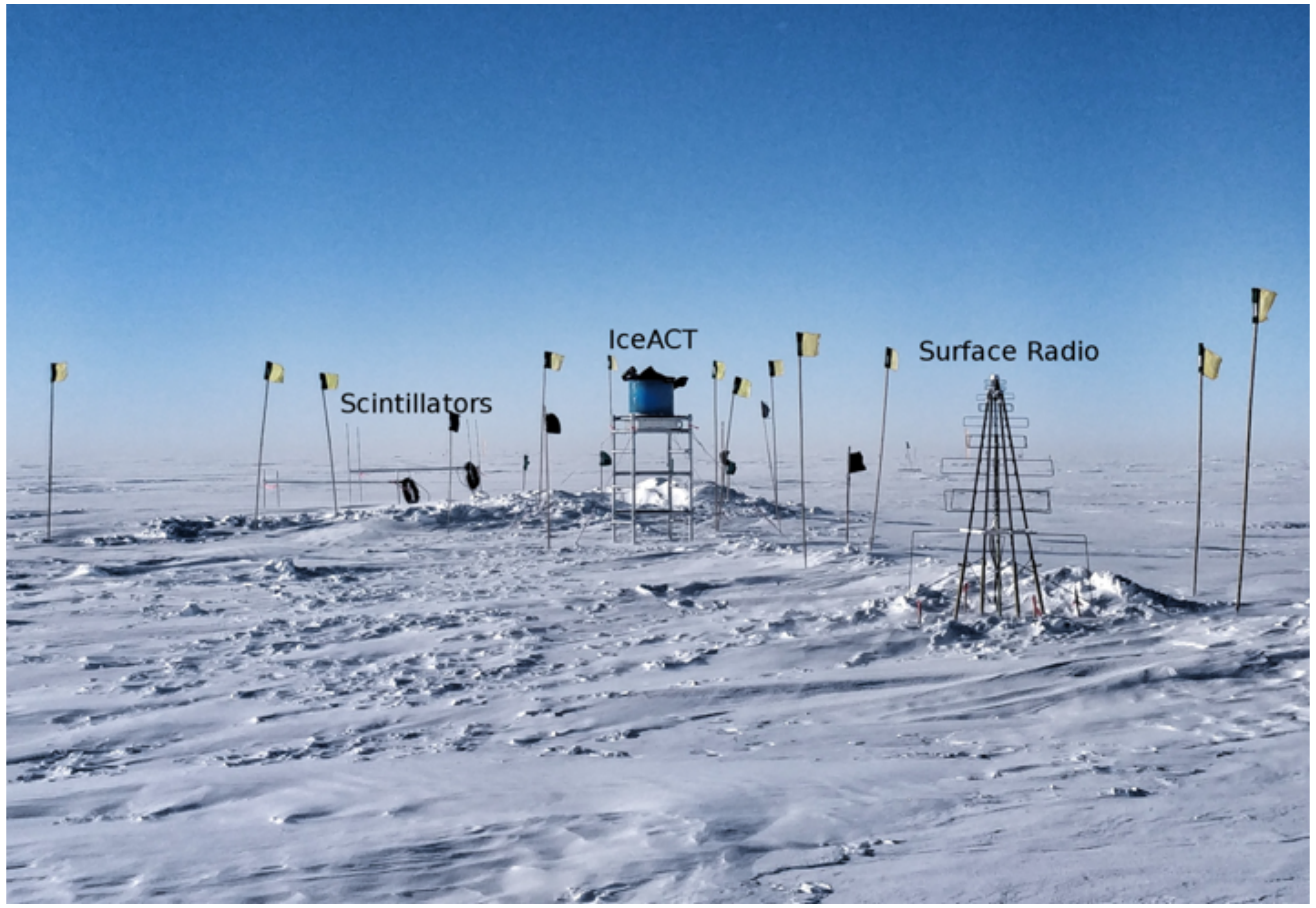


Photo:
Surface detector R&D
January 2019

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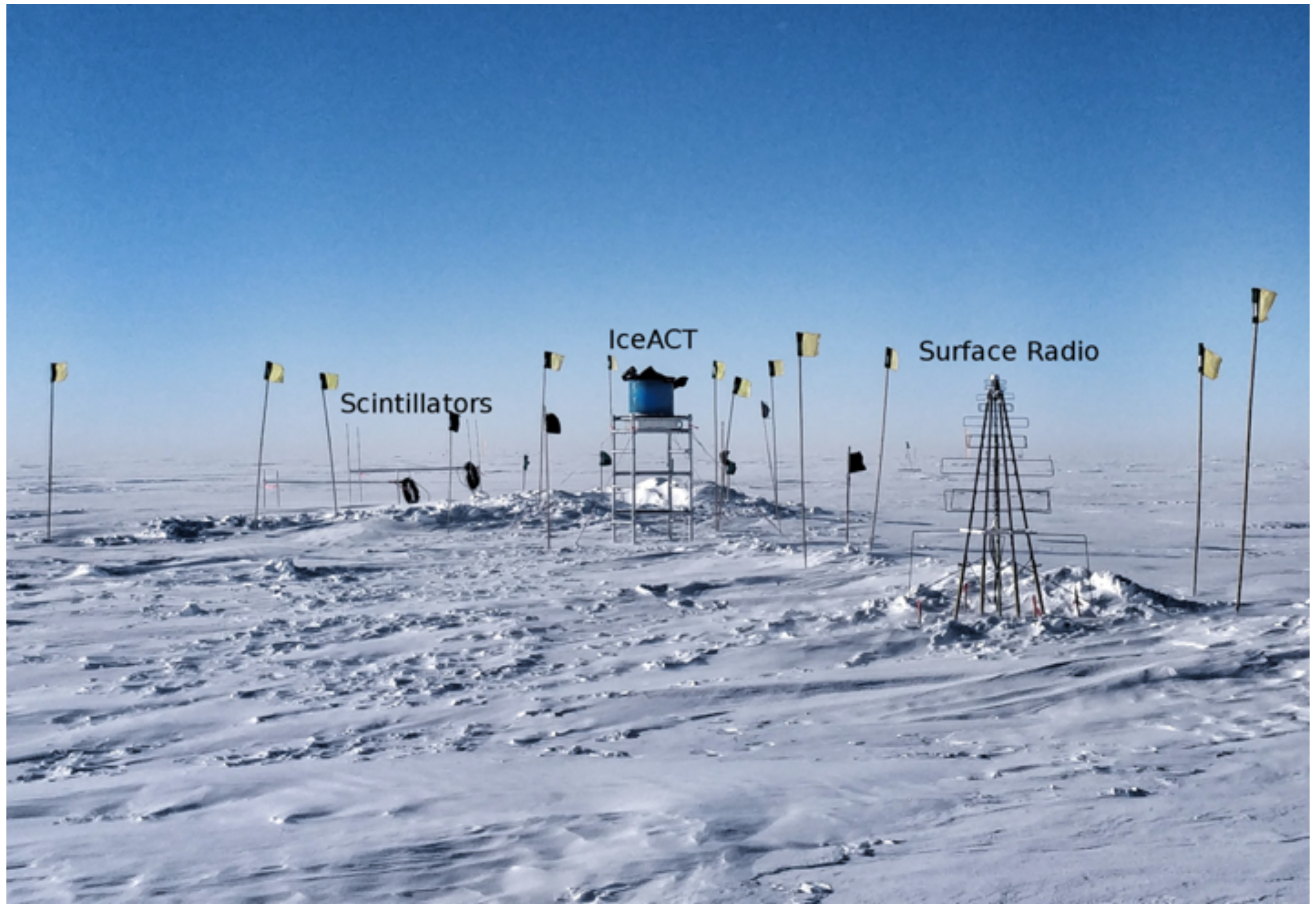
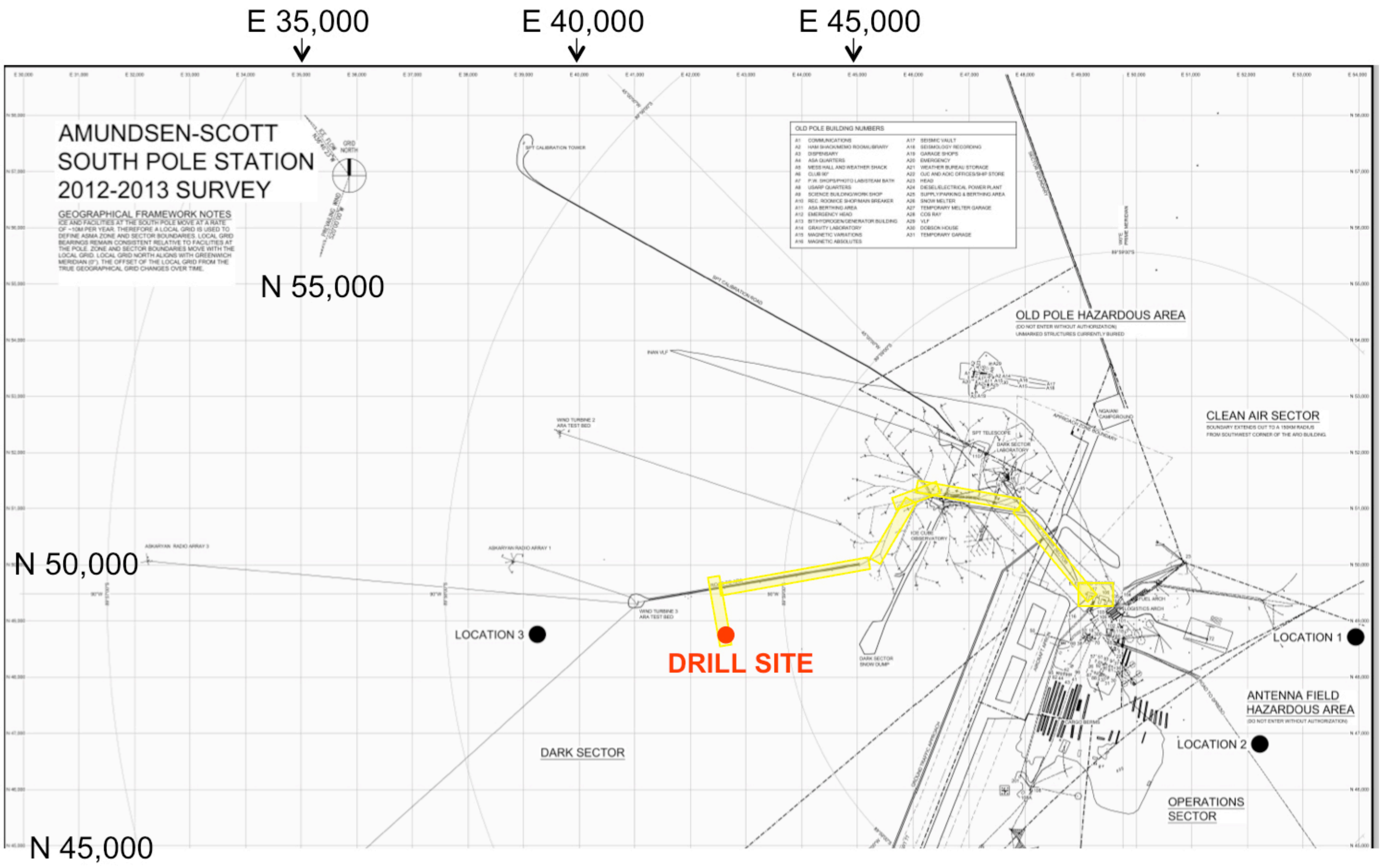


Photo:
Surface detector R&D
January 2019

Spice-Core: measuring ice in a borehole at the Pole

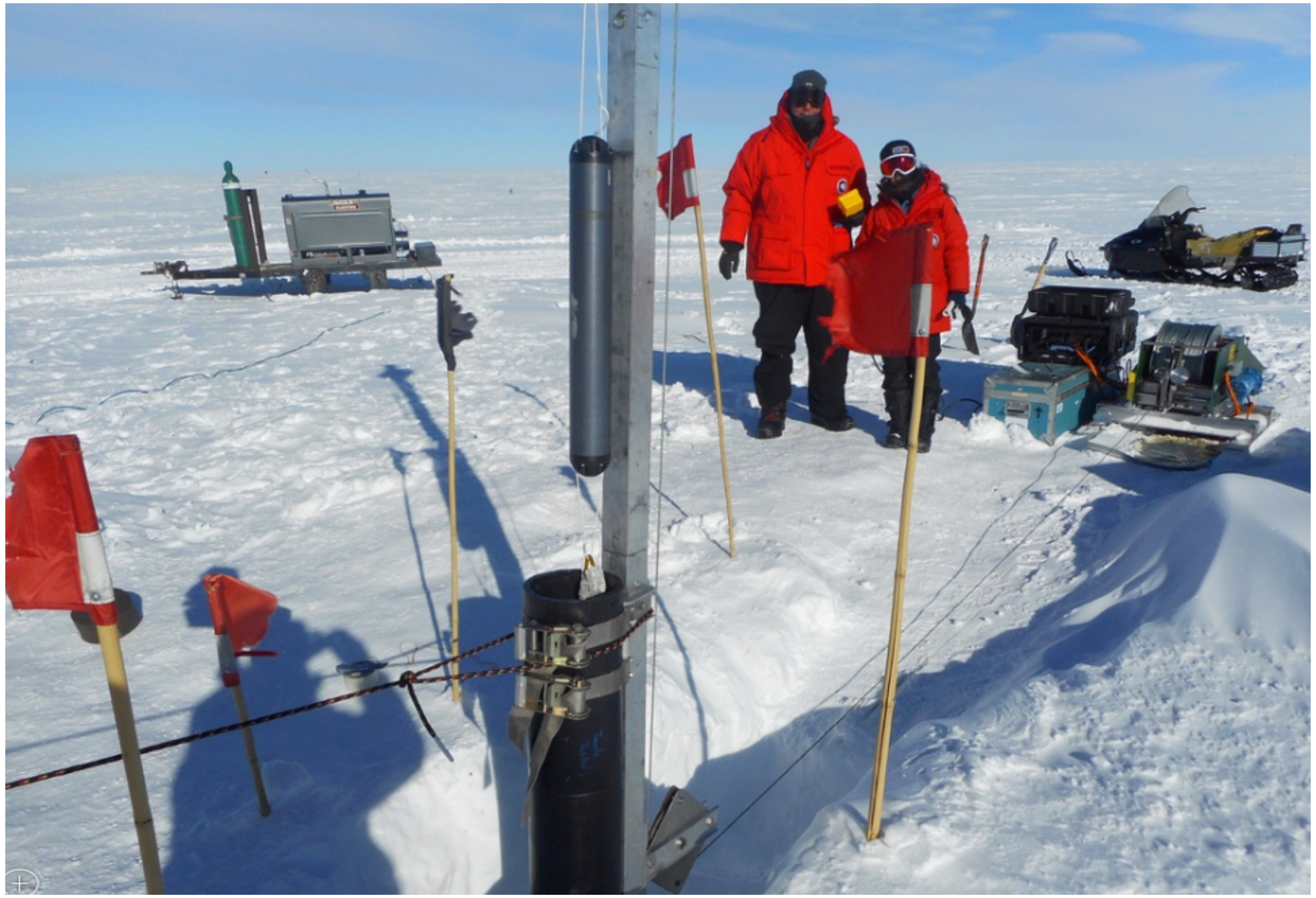
SpiceCore is a 4 inch bore hole left from an earlier ice-coring program:
depth ~1700m
distance: 2 km

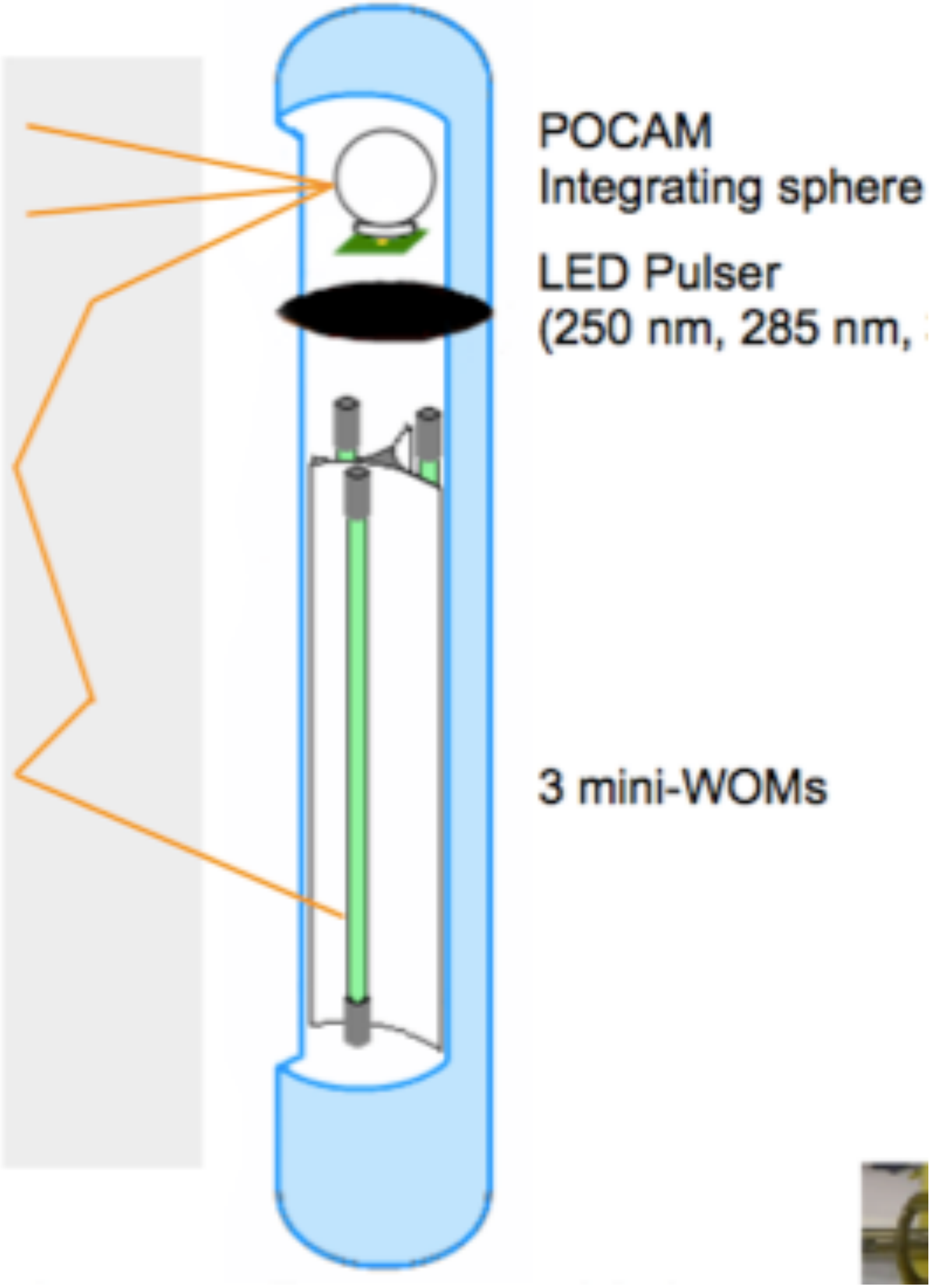
ICNO:
Use this hole to deploy sensors and measure properties of the ice, such as:
absorption in UV,
radio propagation parameters



Spice-Core: measuring ice in a borehole at the Pole

Measurements yielded useful results and experience.
Another measurement is planned for 2017/18





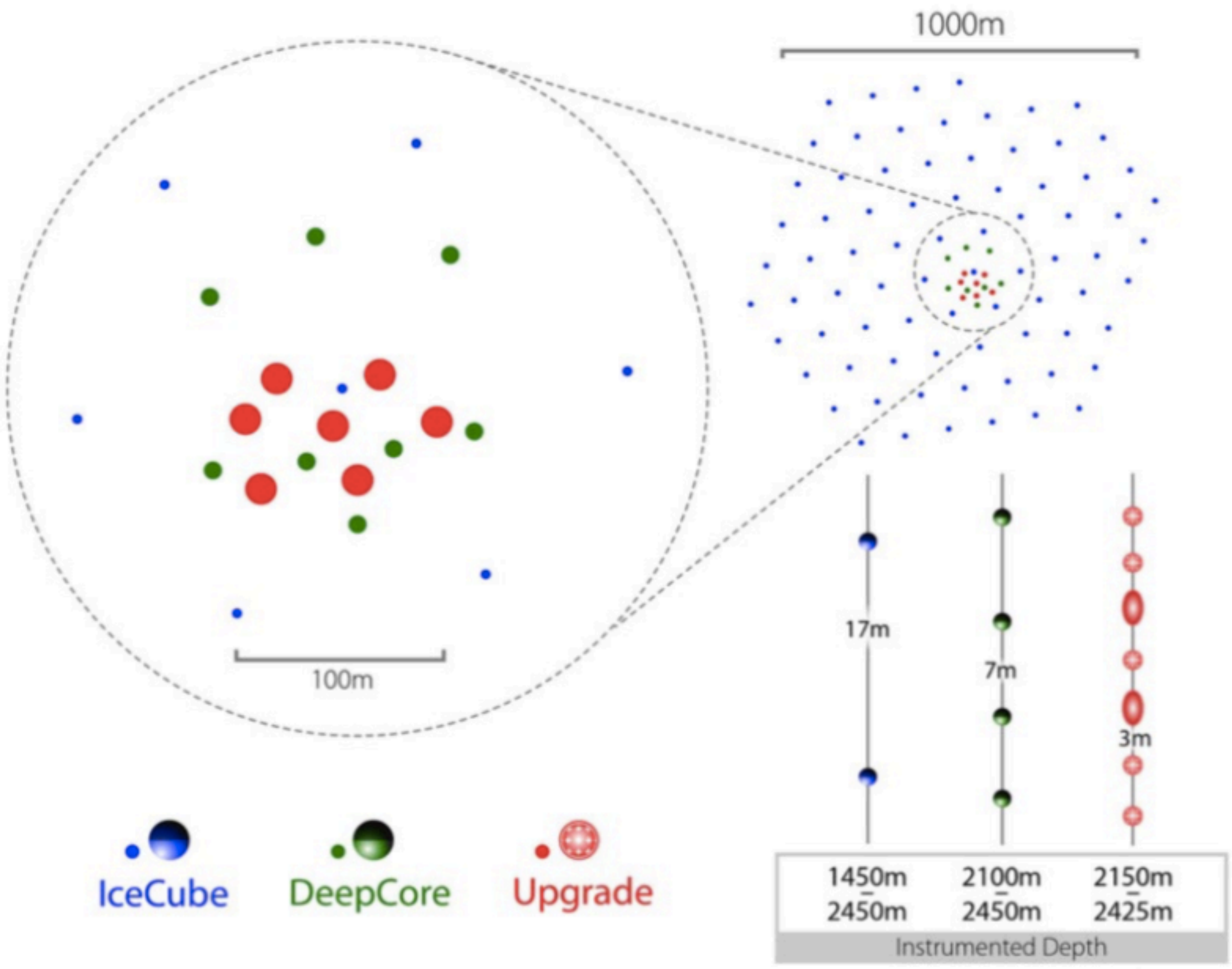
IceCube Upgrade (a step towards Gen2)

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



IceCube-Gen2

The next Generation IceCube: from discovery to astronomy

Multi-component observatory:

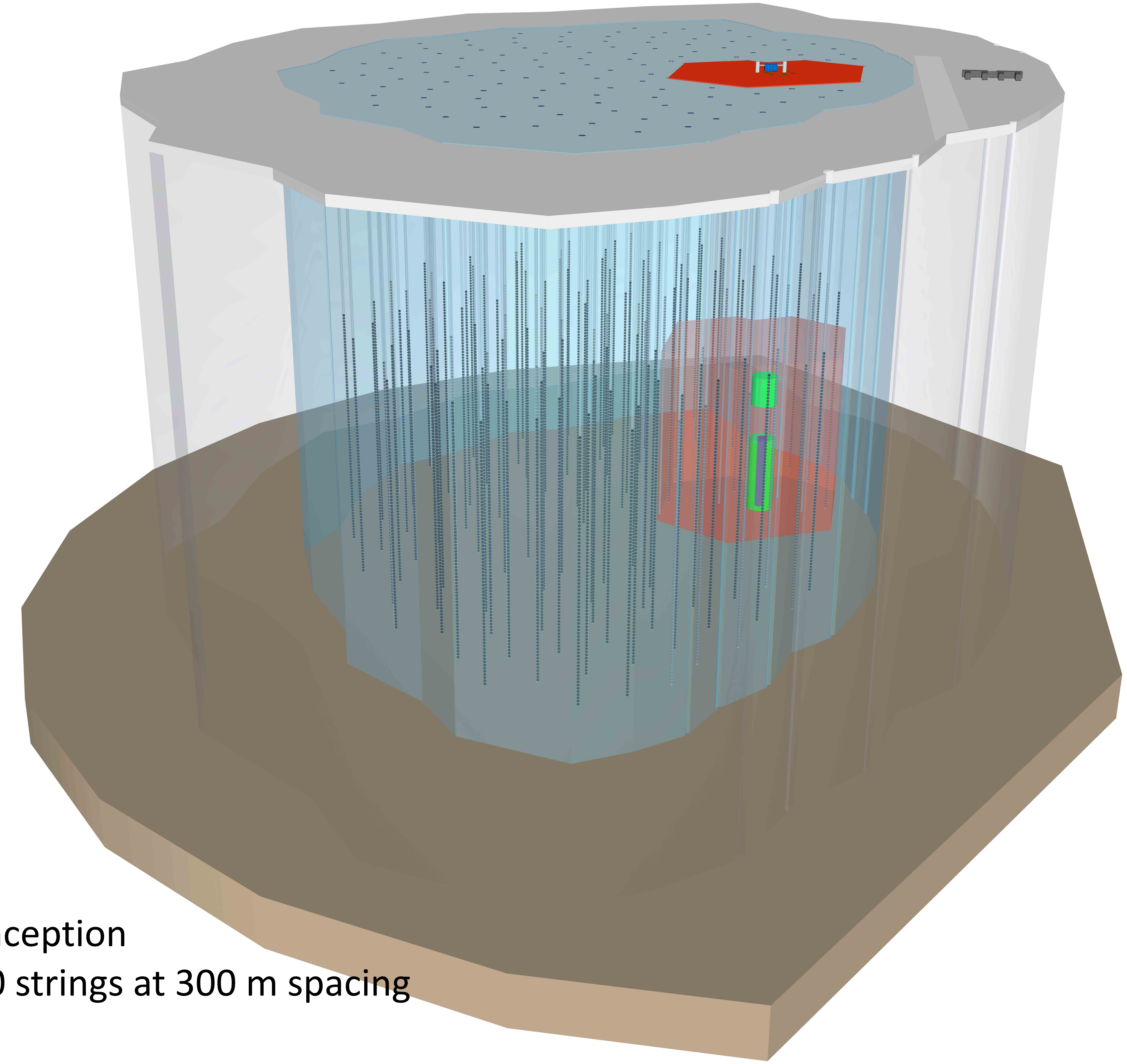
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector

Surface Area: ~6.5km^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

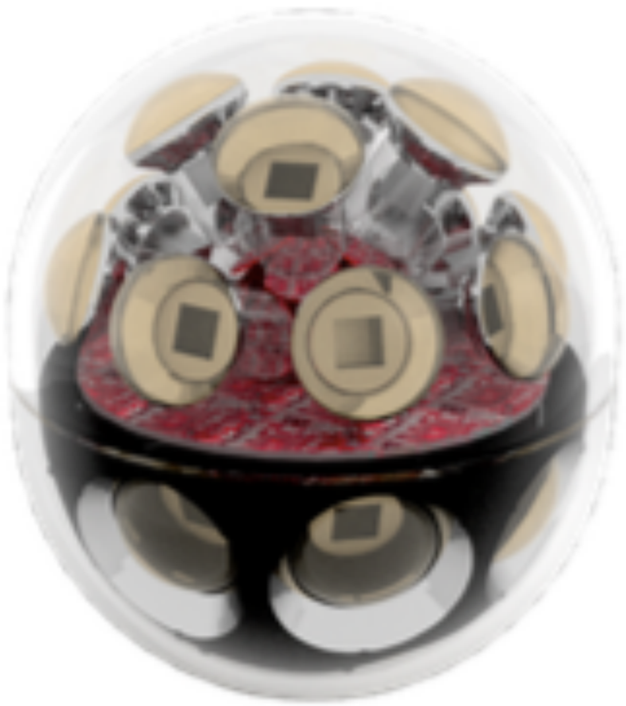
Here: 120 strings at 300 m spacing

Sensor design R&D for improved performance

IceCube DOM

33 cm

mDOM



36

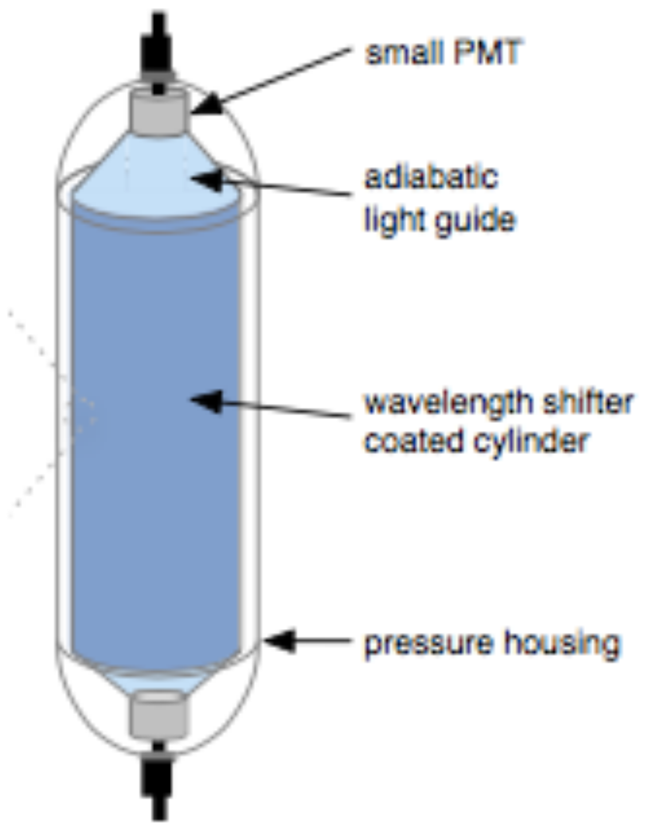
- Directional information
- More sensitive area per module

D-Egg

30

- Directional information
- More sensitive area per module
- Smaller geometry

WOM



11

- more sensitive area per $
- Small diameter
- Lower noise rate

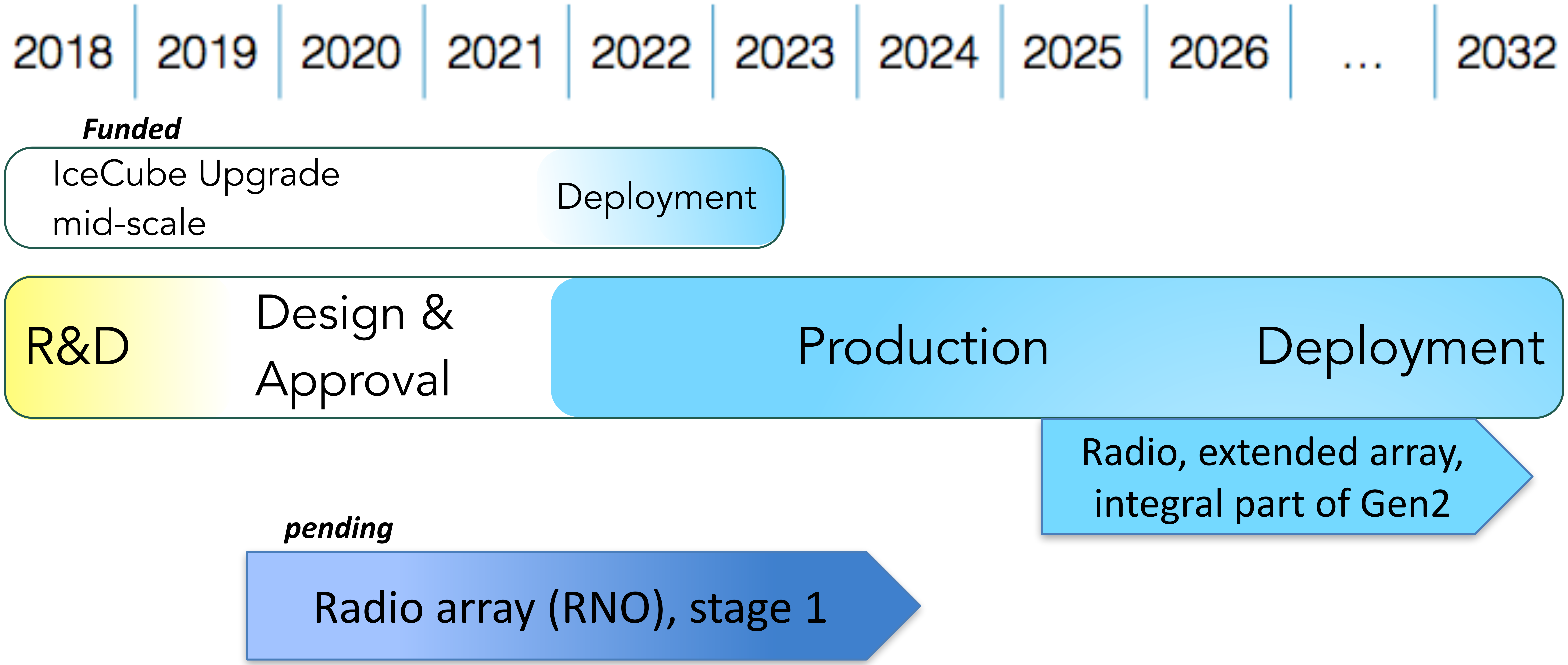
LOM

27

- Small diameter
- Directional info.
- More area per module

FOM

IceCube Gen2 schedule



Take away messages

- IceCube continues to evolve through improvements in understanding of ice, sensors and backgrounds that far exceed those anticipated in 2004.
- This knowledge results in improvements in performance, such as angular resolution that directly affects the results of multiple analyses.
- Systematic errors at all levels are increasingly important and vigorous efforts are underway to reduce them.
- Maintenance and R&D efforts such as surface instrumentation and measurements with in the SpiceCore will produce useful information.
- Detector R&D, sensor development, interface support is also happening to support the IceCube upgrade and maintain the ICNO facility as a support infrastructure for the future.

Thank you!