The IceCube Neutrino Observatory.

Summer Blot
16.06.2021
IceDUNE Virtual Workshop

DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Happy Pride!

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Outline

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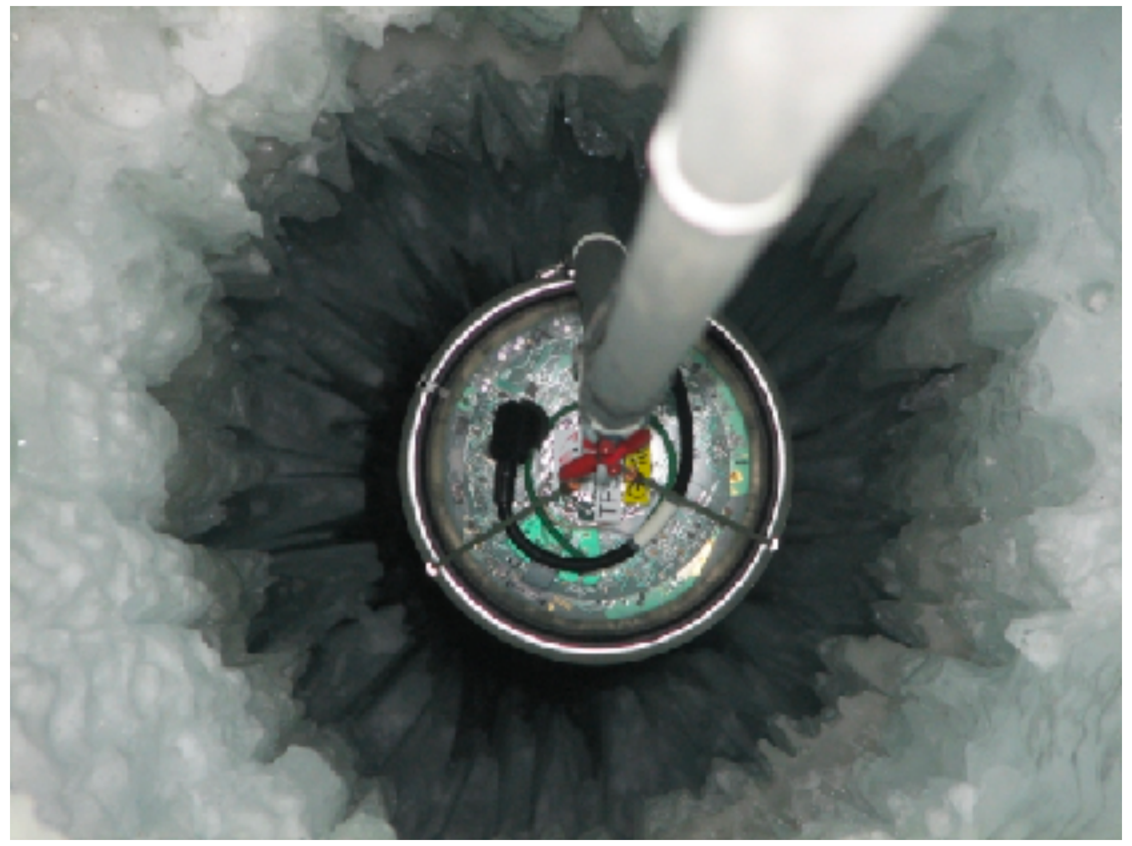
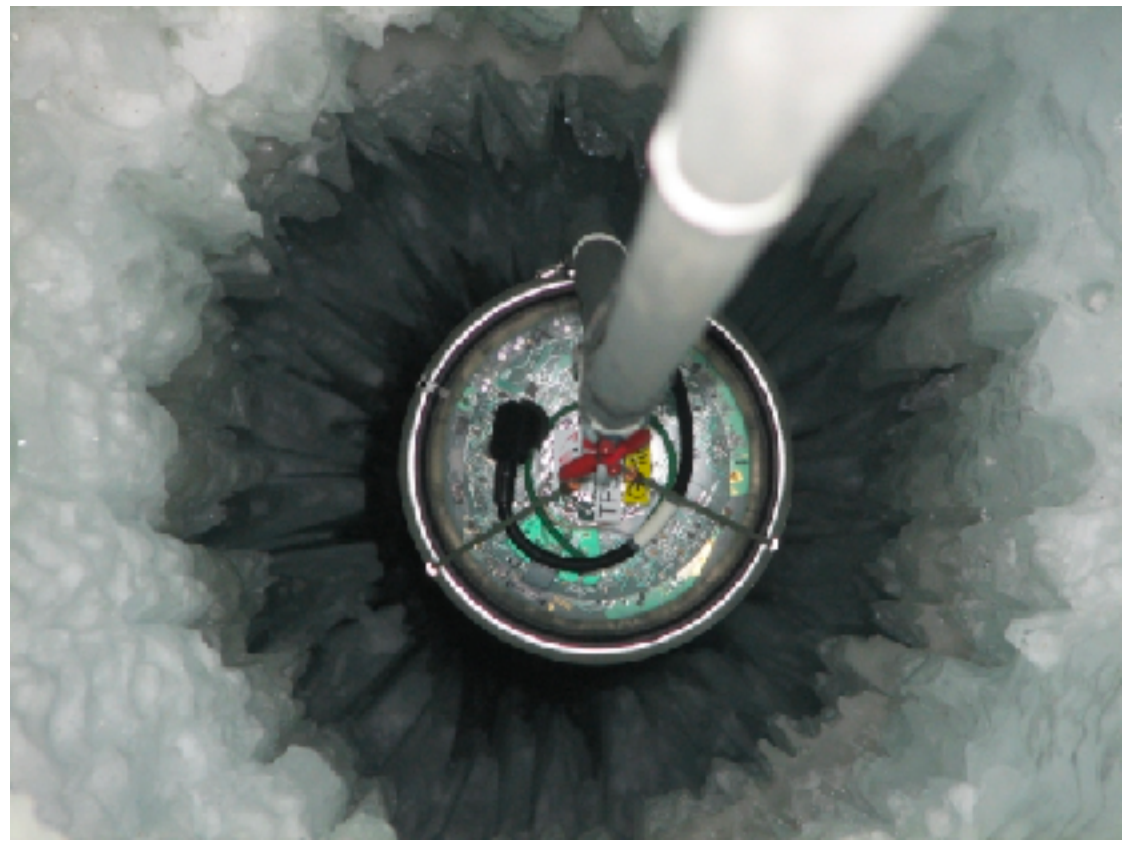
1. What we built

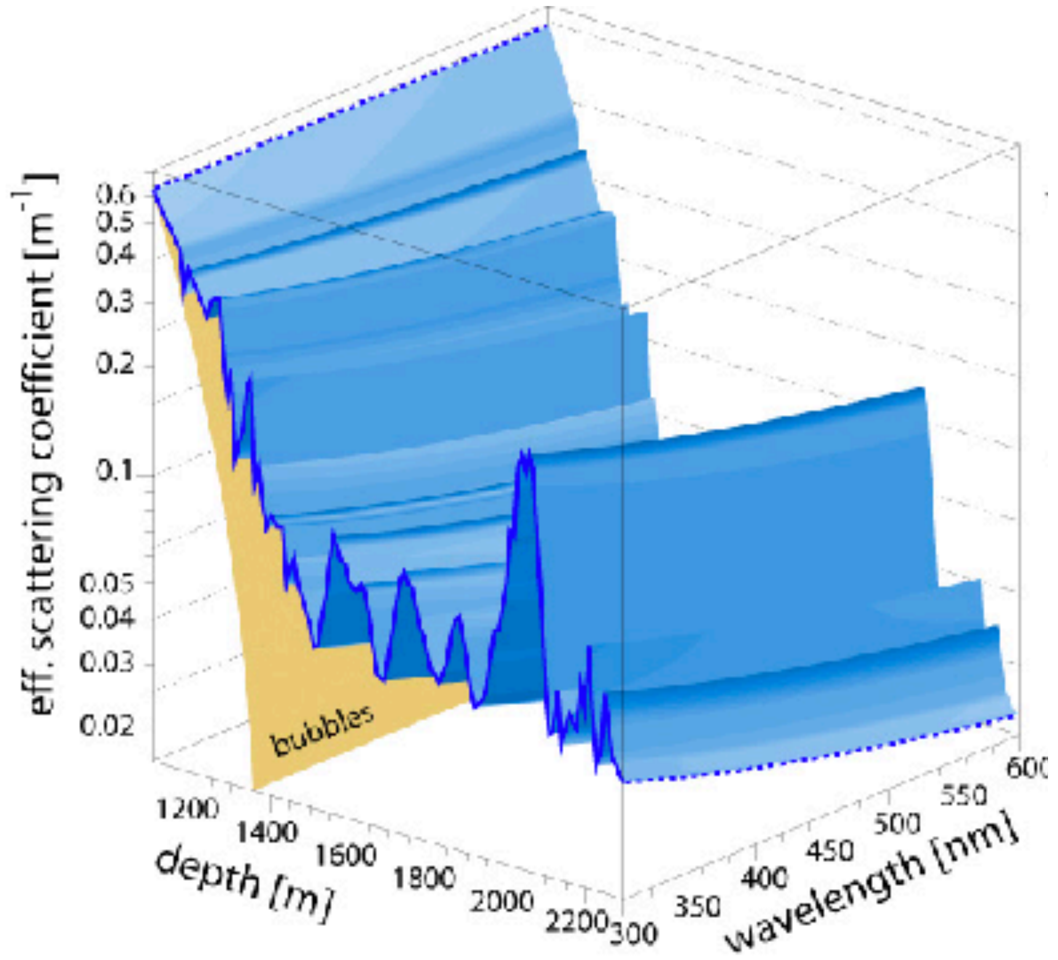


Outline

1. What we built

2. What nature built



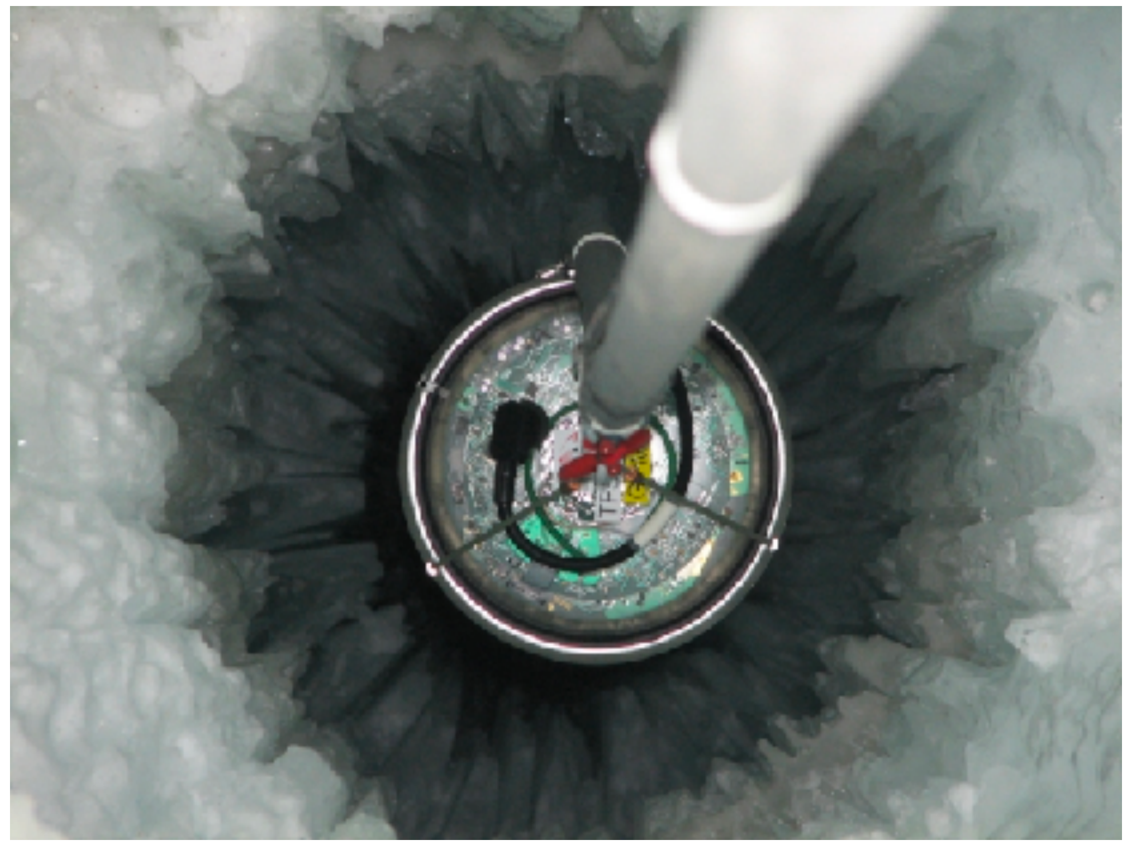


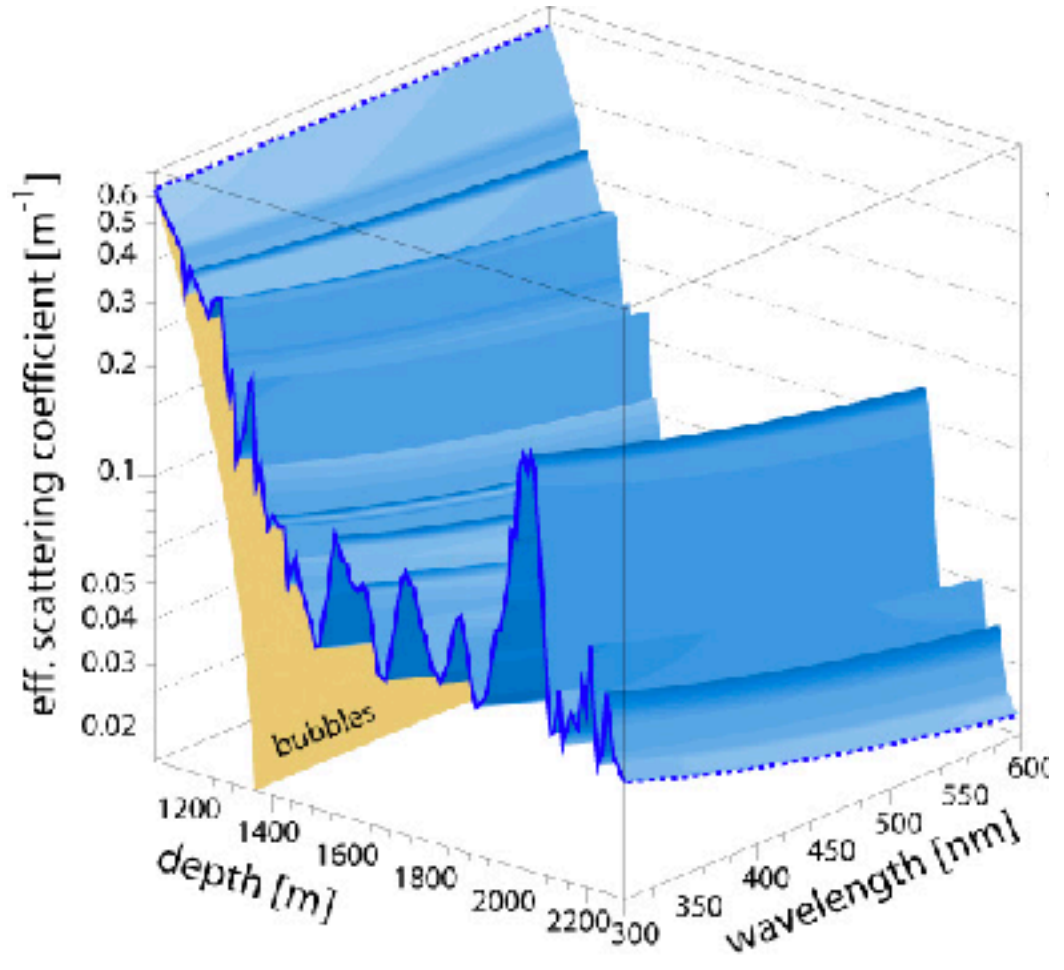
Outline

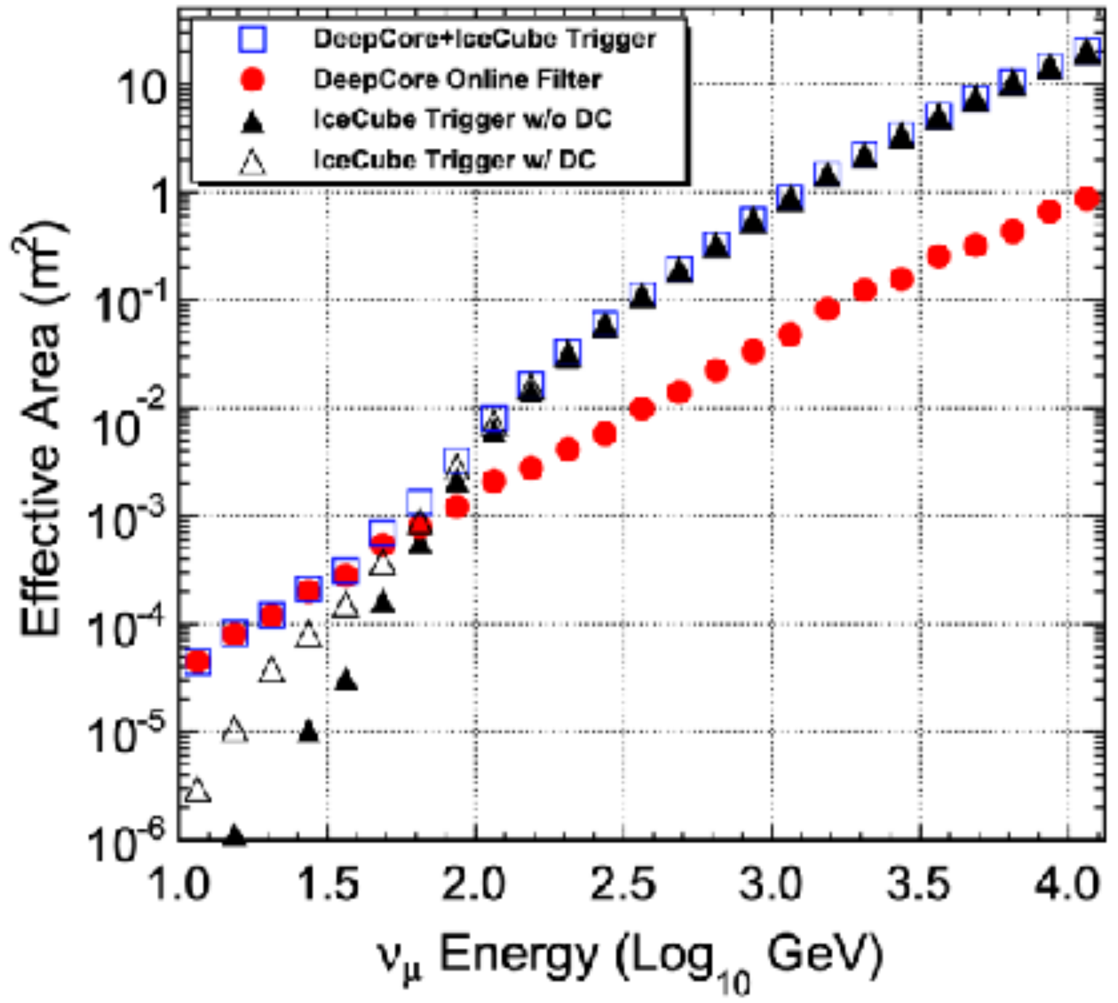
1. What we built

2. What nature built

3. Detector performance







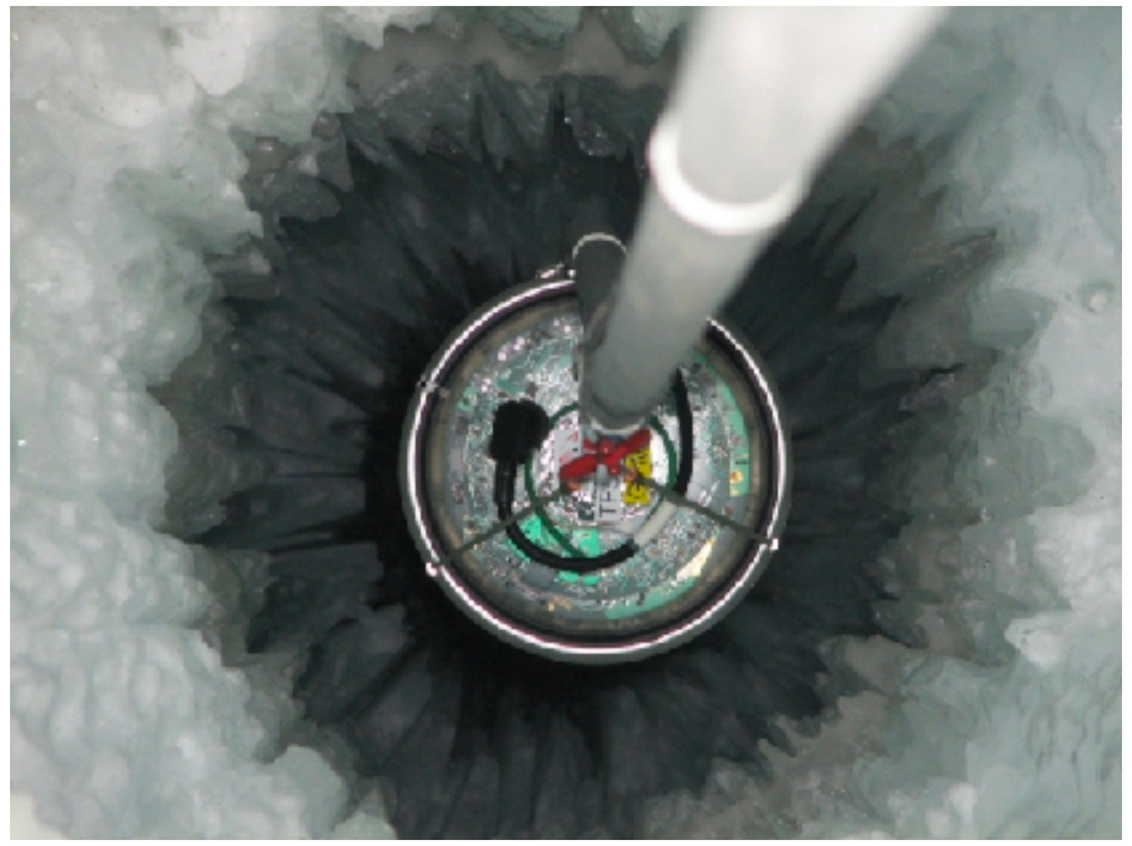
Outline

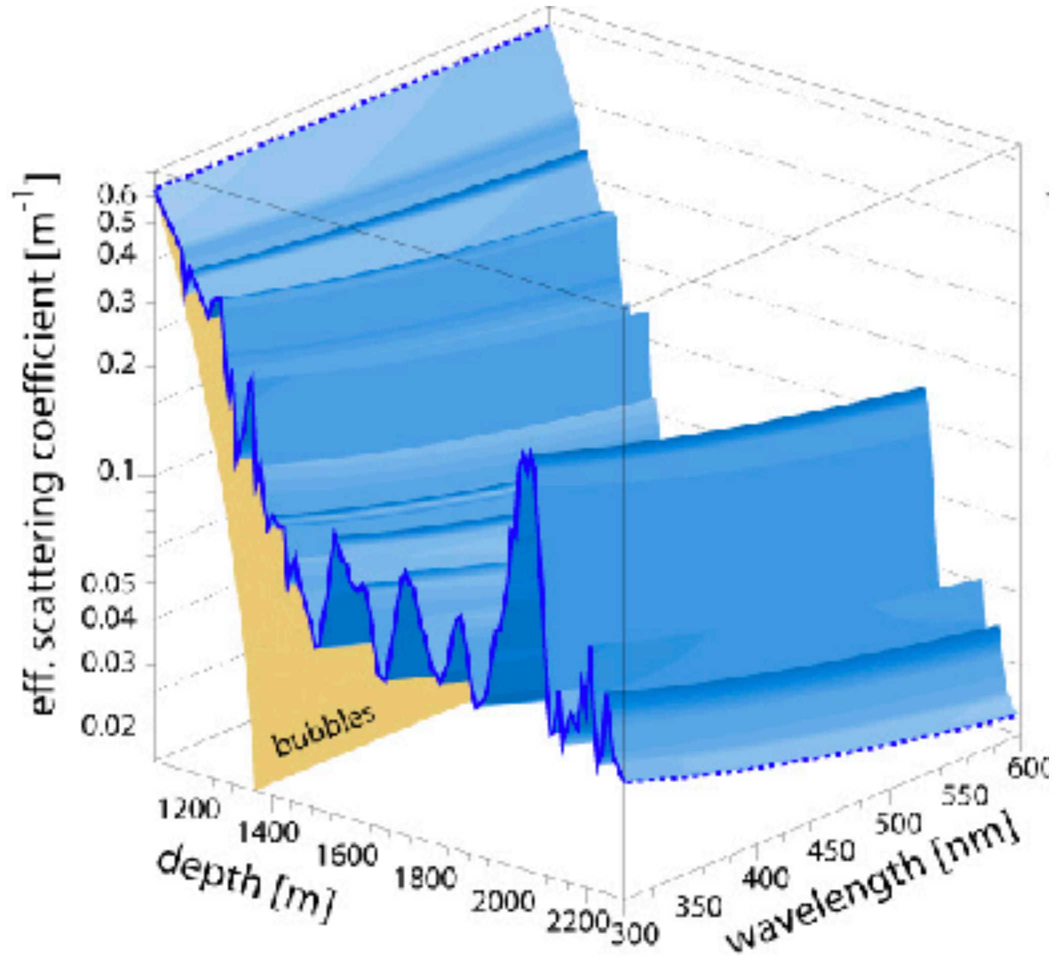
1. What we built

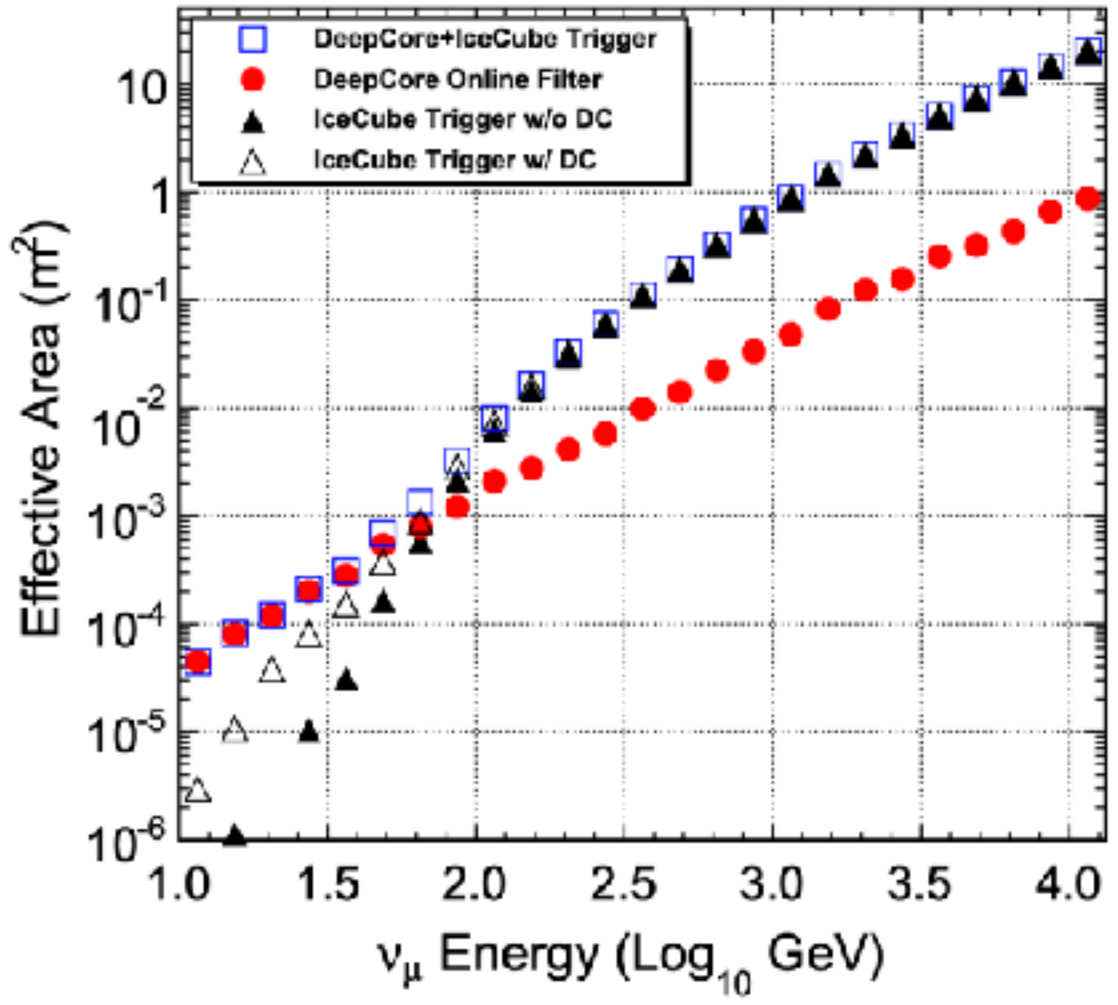
2. What nature built

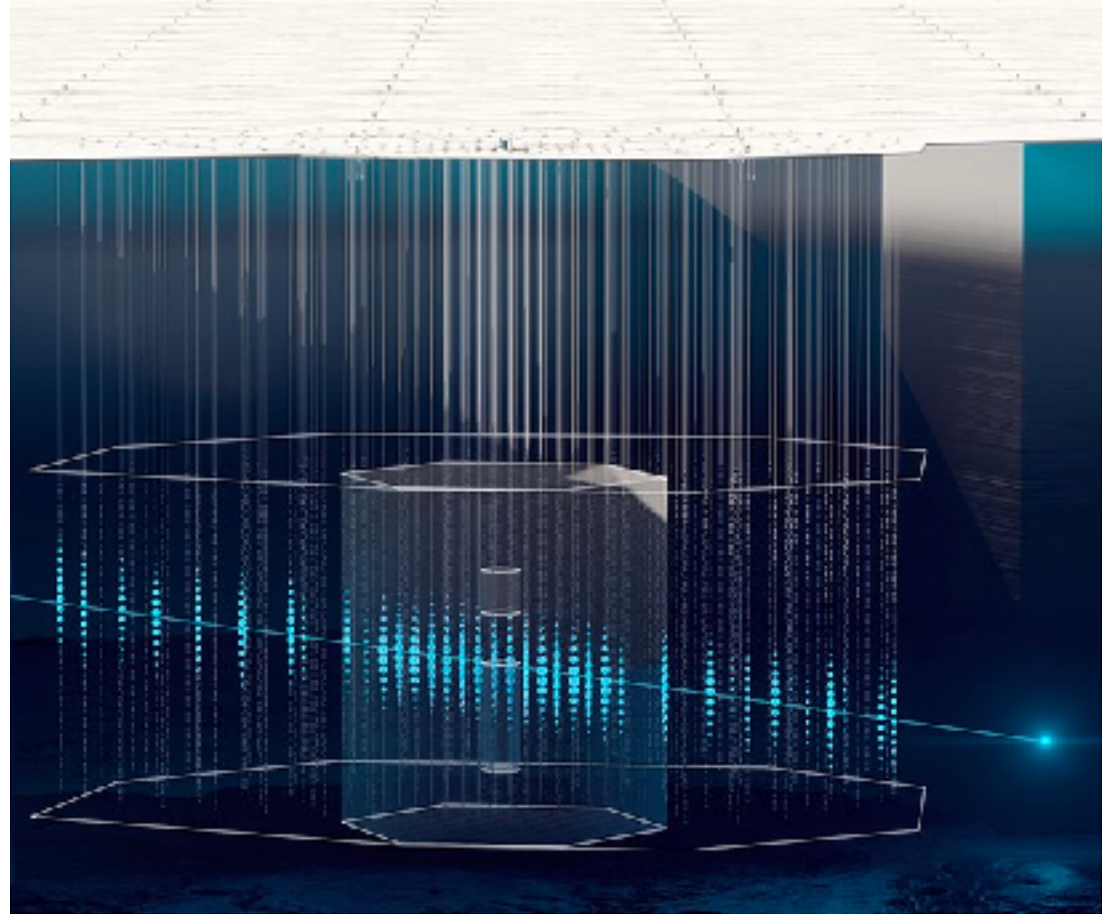
3. Detector performance

4. What’s next?









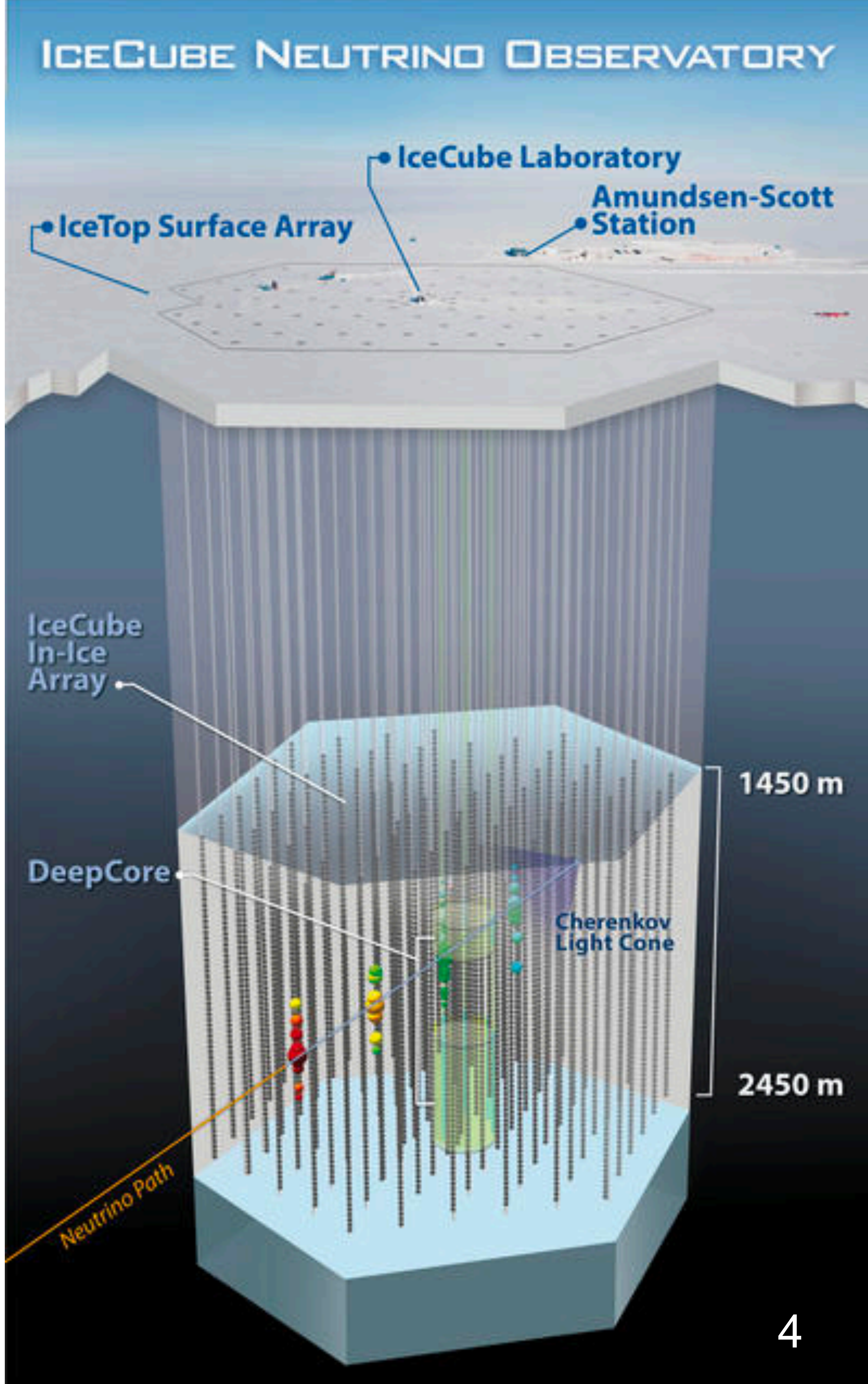
Part 1:
What we built

The IceCube Neutrino Observatory

Facility overview

- Ice Cherenkov detector at the South Pole
- Three components: IceTop, IceCube, DeepCore (This talk)
- In-ice detector layout
  - 86 vertical boreholes drilled with hot-water
  - Each hole instrumented with cable + 60 digital optical modules + refrozen ice → (a.k.a. "string")

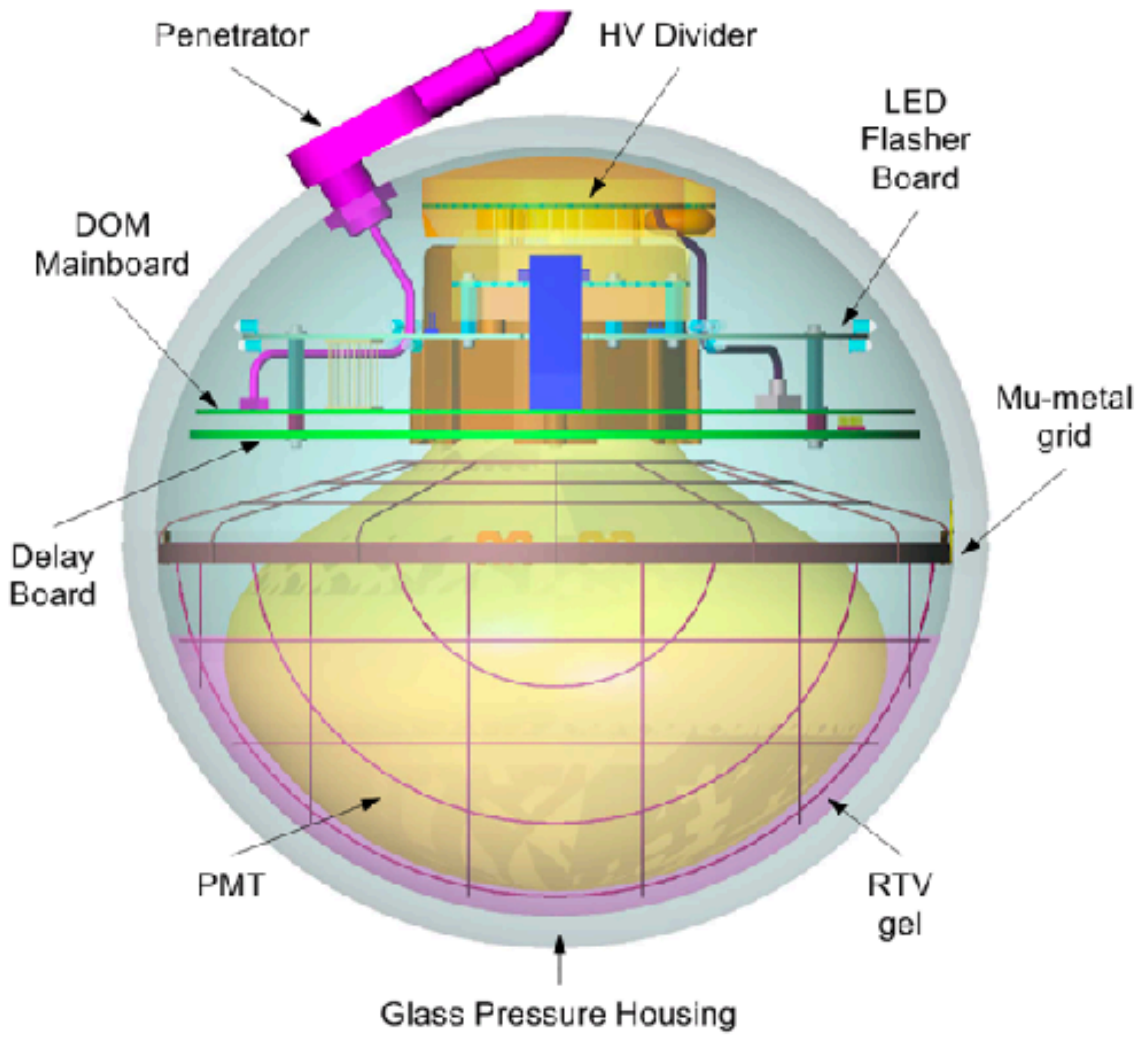
	String spacing [m]	
	Horizontal	Vertical
IceCube	125	17
DeepCore	42-72	7

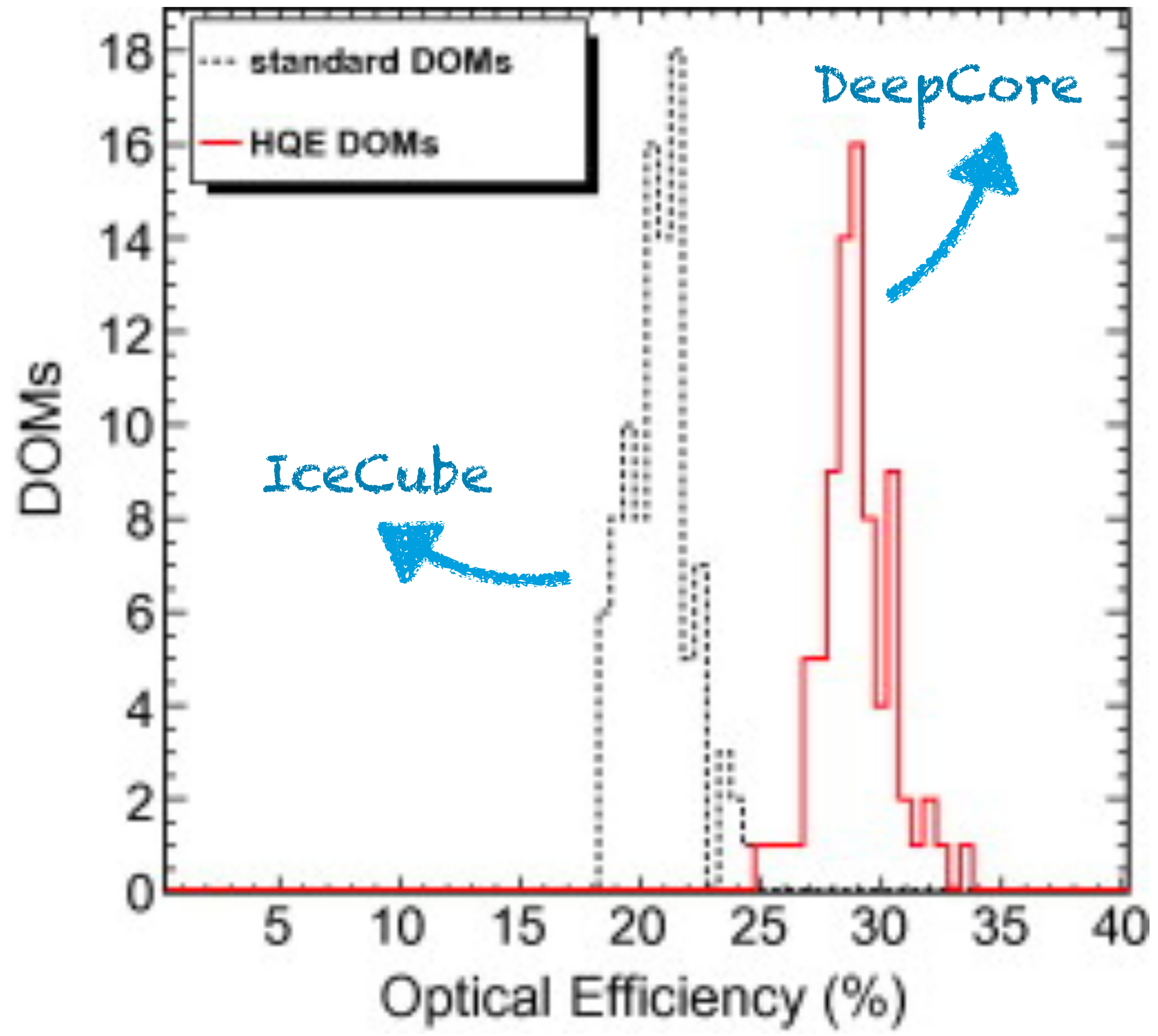


The Digital Optical Module (DOM)

The fundamental building block of IceCube

- **10” PMT from Hamamatsu**
  - sensitive in range ~300-650 nm
  - R7081-02 (QE ~25%) and R7081-02MOD (HQE ~34%)
- **On-board electronics**
  - HV supply/divider
  - Mainboard - communication/control, waveform readout/ digitization, storage, calibration…
- **Borosilicate glass pressure housing**
  - Protects from pressure (during freeze-in up to 690 bar!)
- **12 Calibration LEDs**
  - Mostly 405nm
  - Pulsed light emission





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DOM quick facts

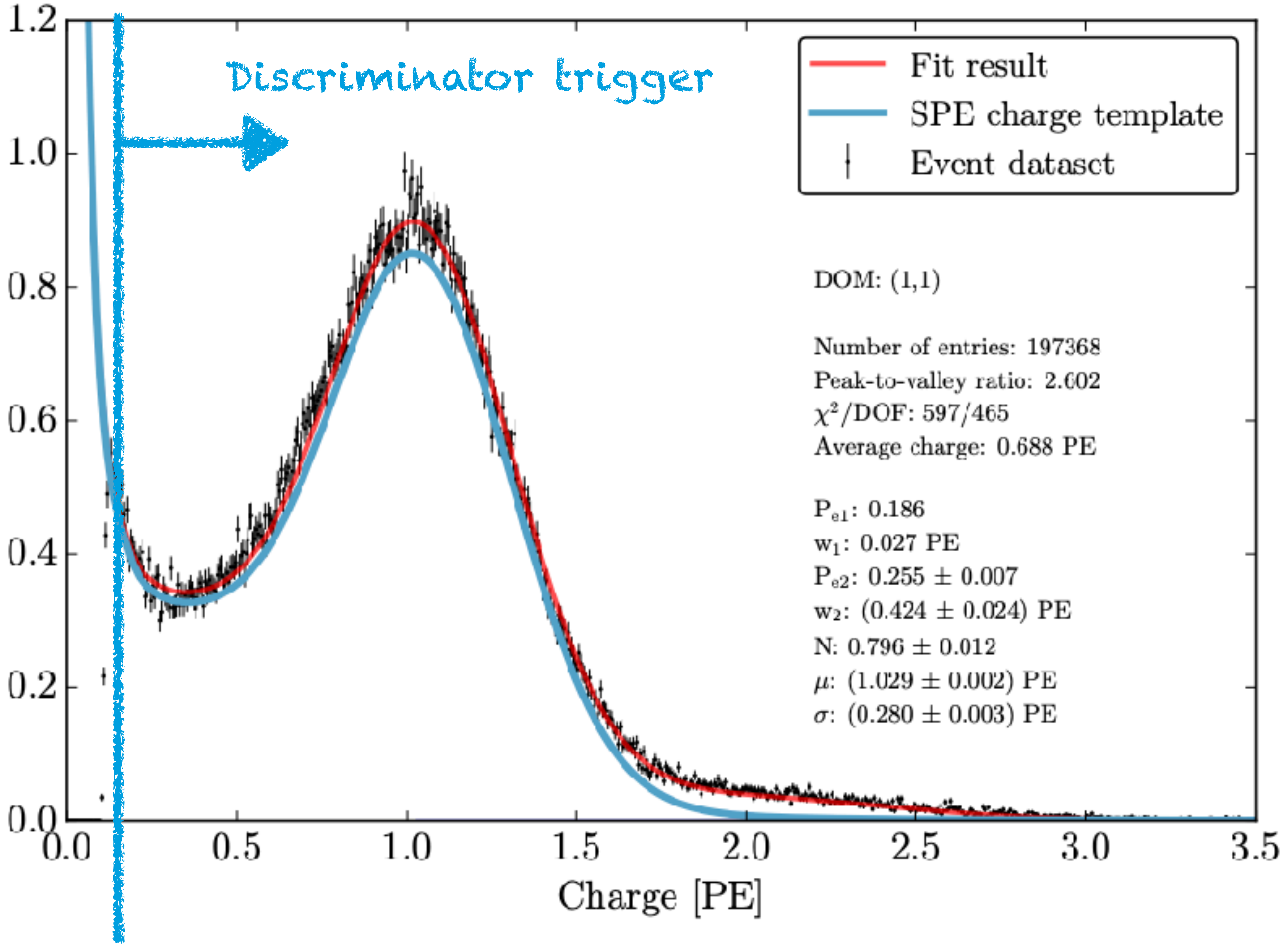
- ~98% of DOMs operational
- Calibrated once per year
- No signs of decreased performance (15 yrs)
- Energy scale calibrated to ~10%
- Timing precision ~2 ns

Signal readout and triggering

A deeper look at the detector threshold

- PMT signal monitored by discriminator at ~0.2 PE

M.G. Aartsen *et al* 2020 *JINST* **15** P06032



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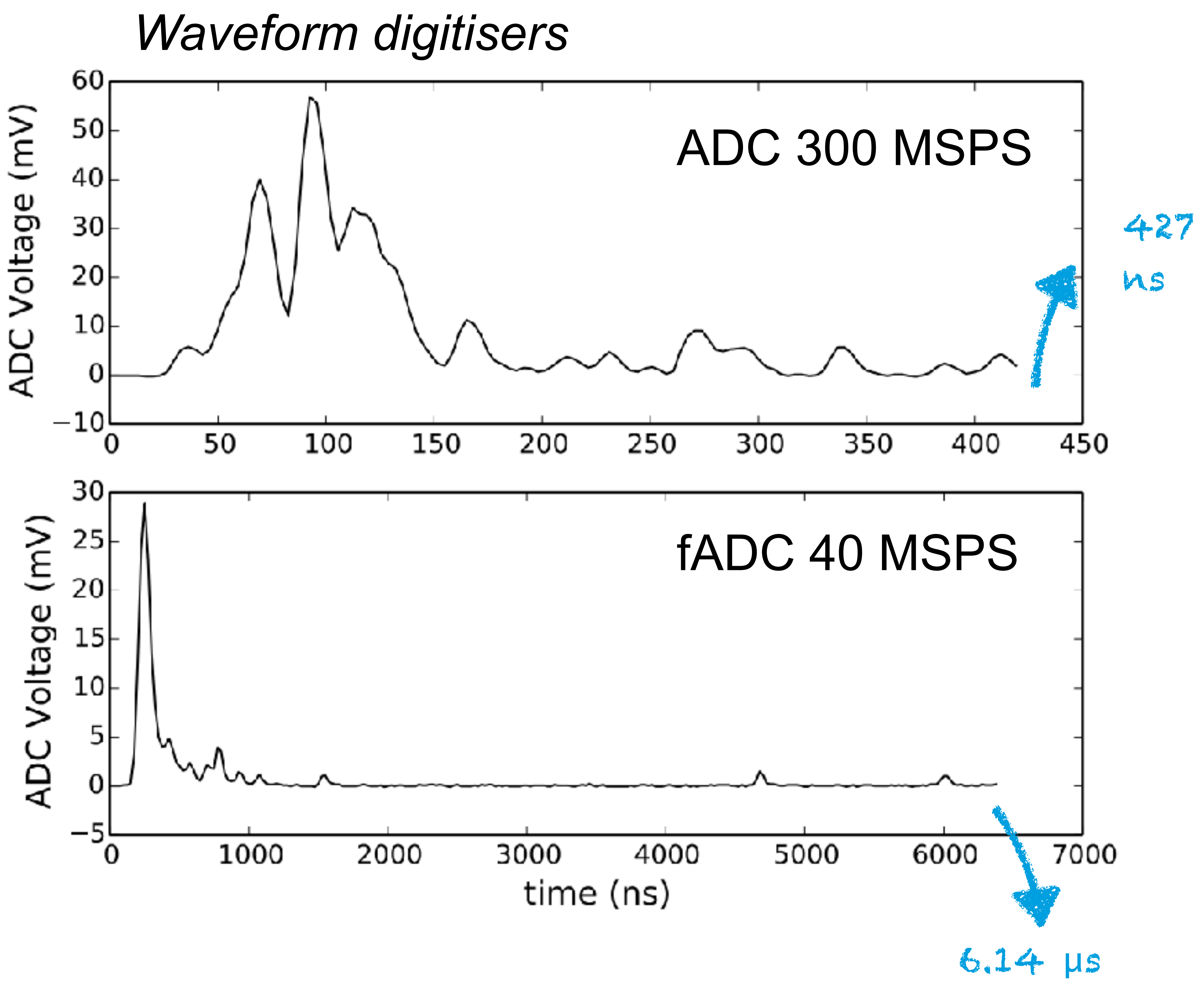
- **If single DOM triggered…**
  - PMT signal digitised by fast (300 MSPS) ADC and slow (40 MSPS) fADC
  - Trigger flags sent to nearest neighbour DOMs



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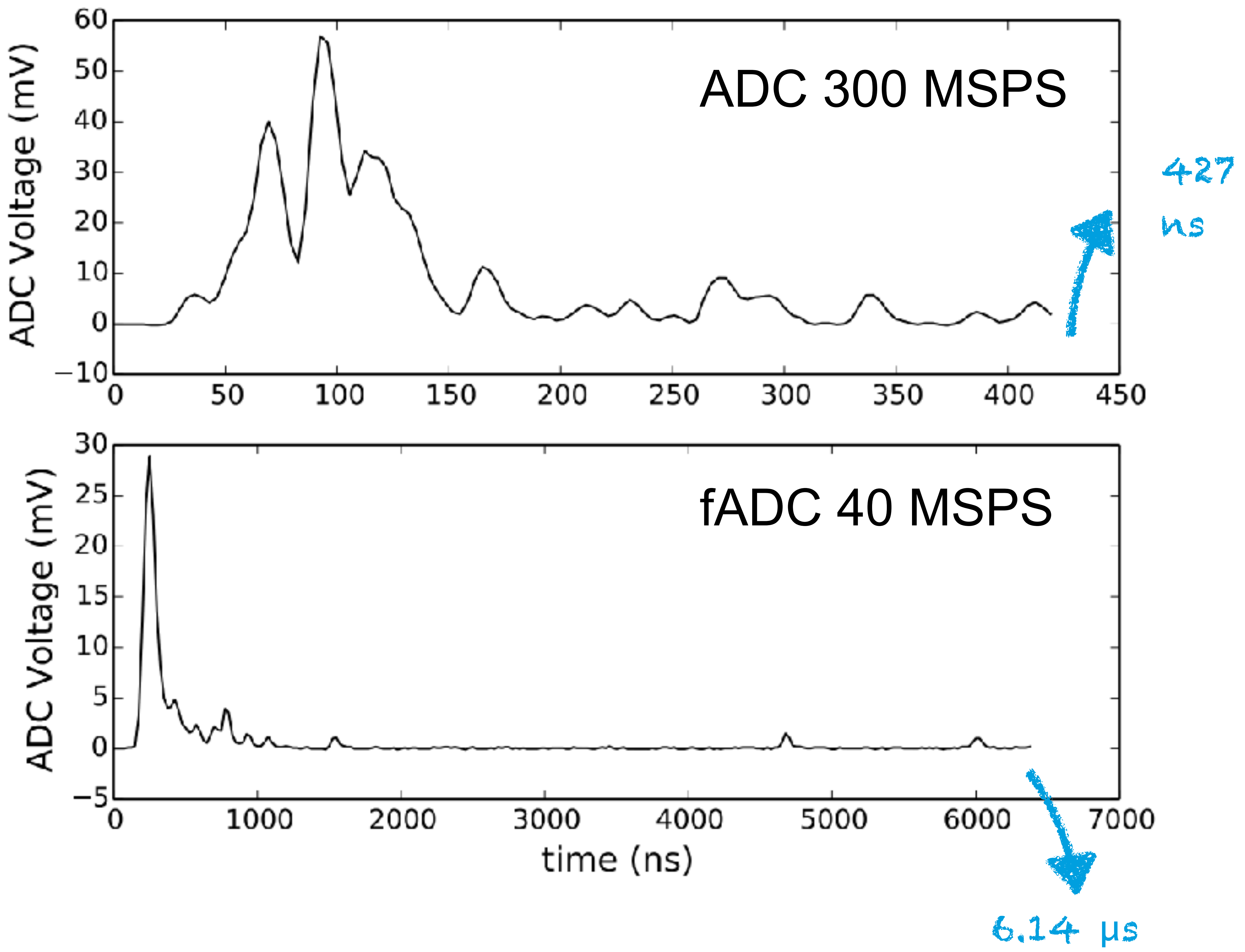
- If nearby* DOM *also* triggered, send full waveform information + timestamp to surface DAQ
- Otherwise, send only timestamp and charge summary

Waveform digitisers



***Nearby** = neighbour or next-to-nearest neighbour along string*

Signal readout and triggering

JINST 12 P03012 (2017)

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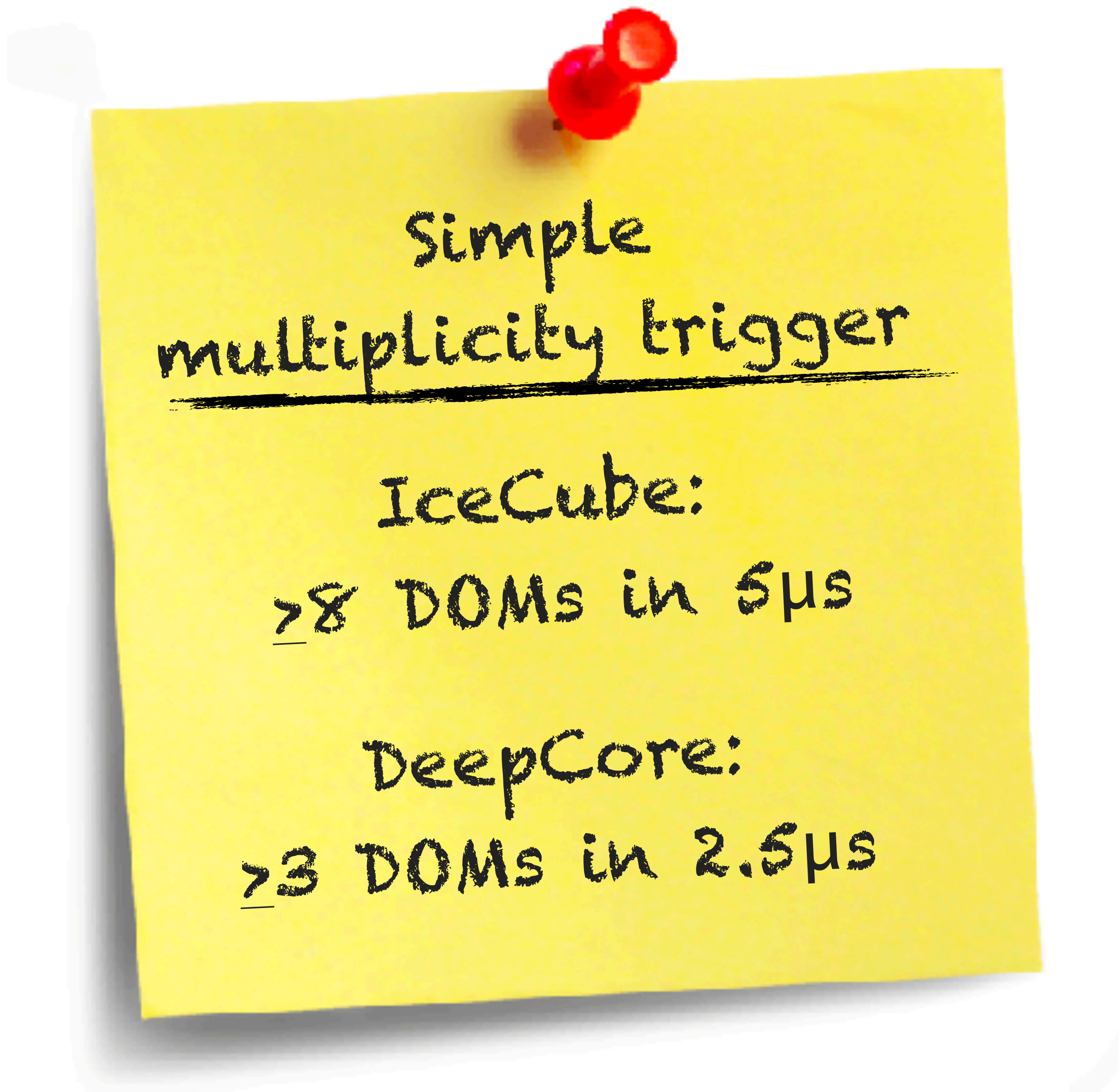
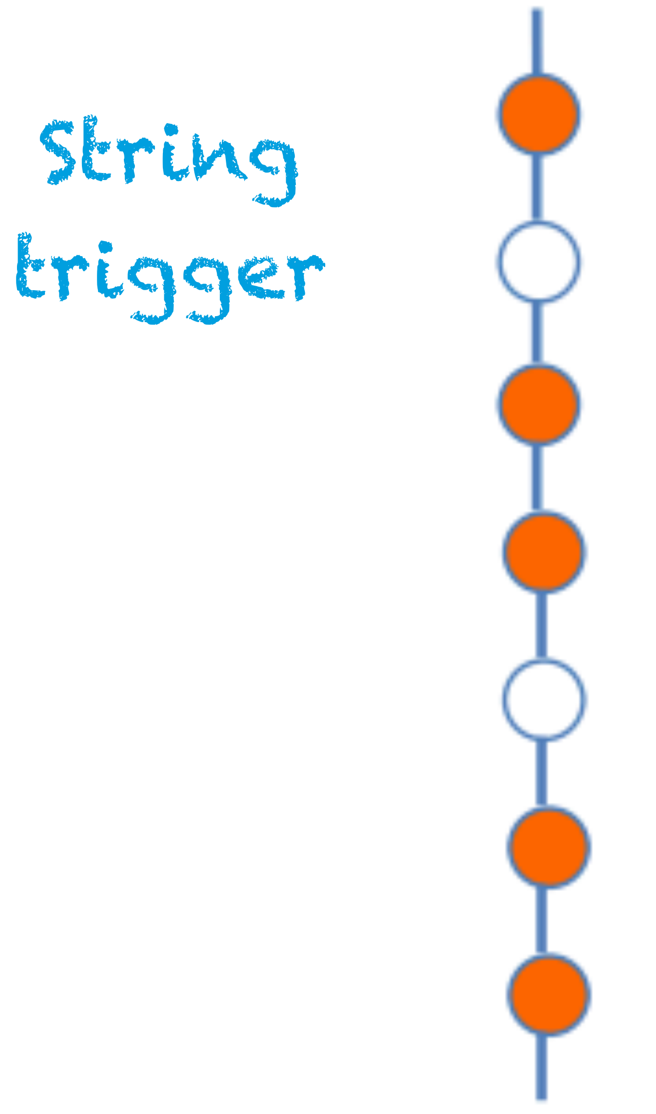
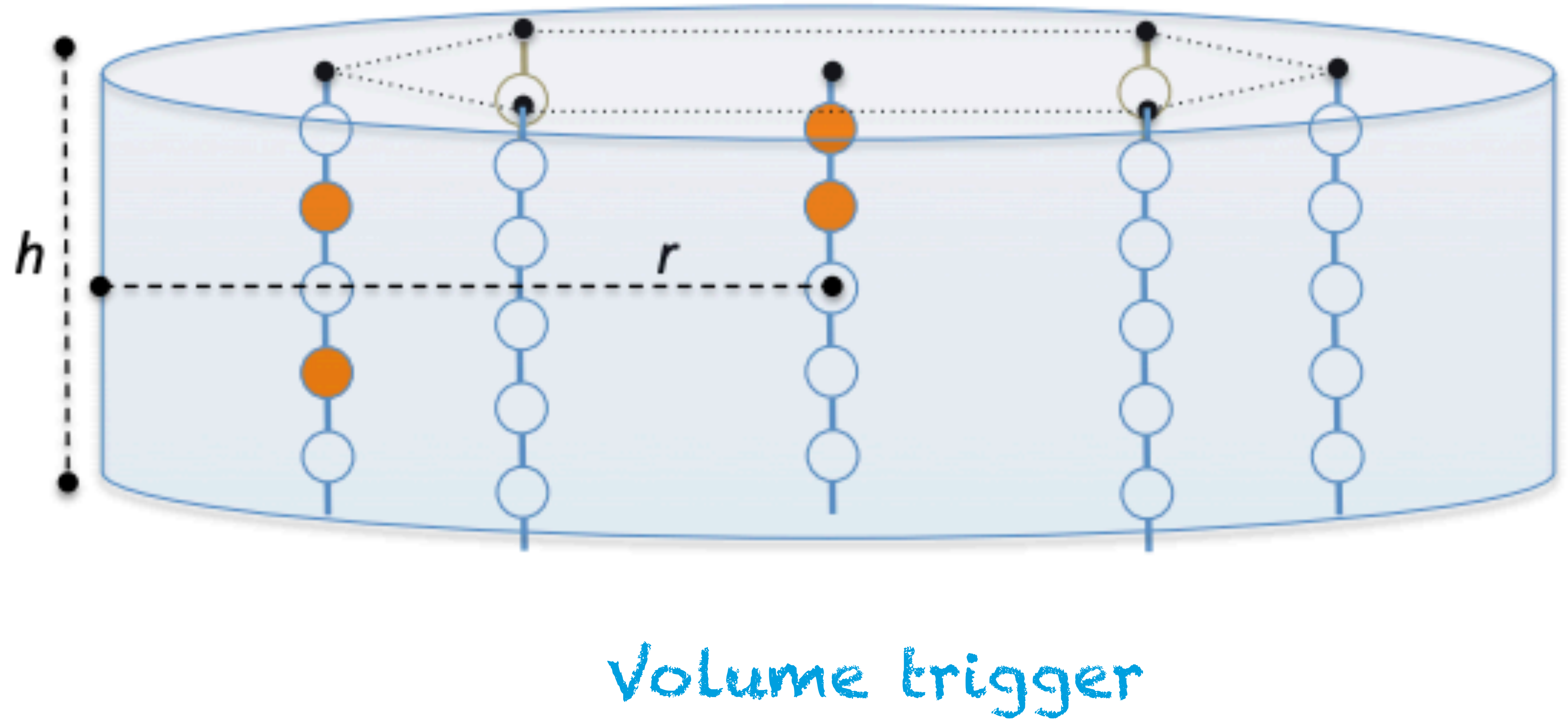
- If nearby* DOM *also* triggered, send full waveform information + timestamp to surface DAQ
- Otherwise, send only timestamp and charge summary
- **Event triggers** are built from multiple coincidences + volume (optional)

*Nearby*** = neighbour or next-to-nearest neighbour along string*



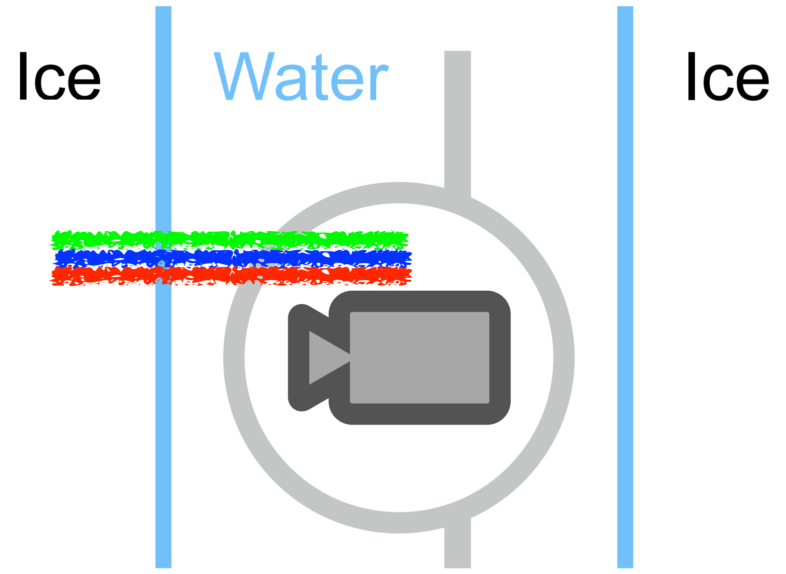




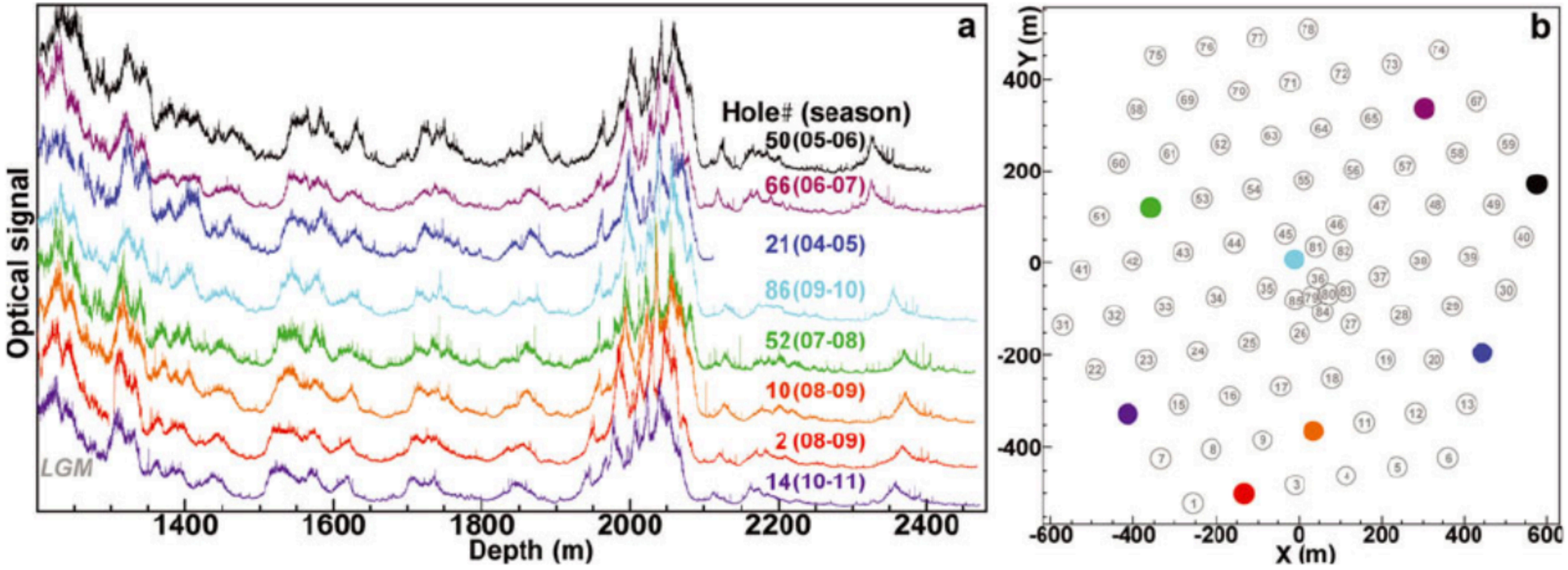
Part 2:
What *nature* built

Natural detection medium

The “Bulk” ice



- Ice layers serve as historical record of atmospheric conditions
- Photons experience variable scattering and absorption lengths as they travel from production to detection
  - Average effective scattering length ~30m
  - Average absorption length ~100m



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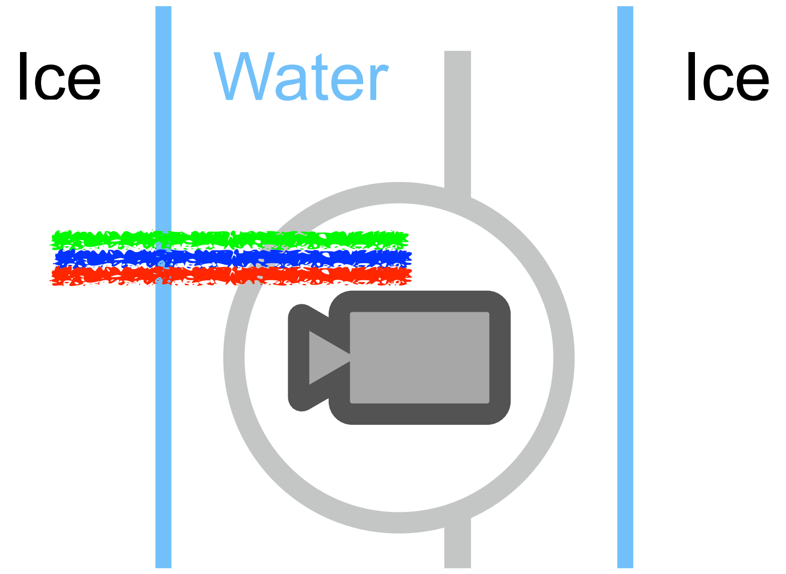

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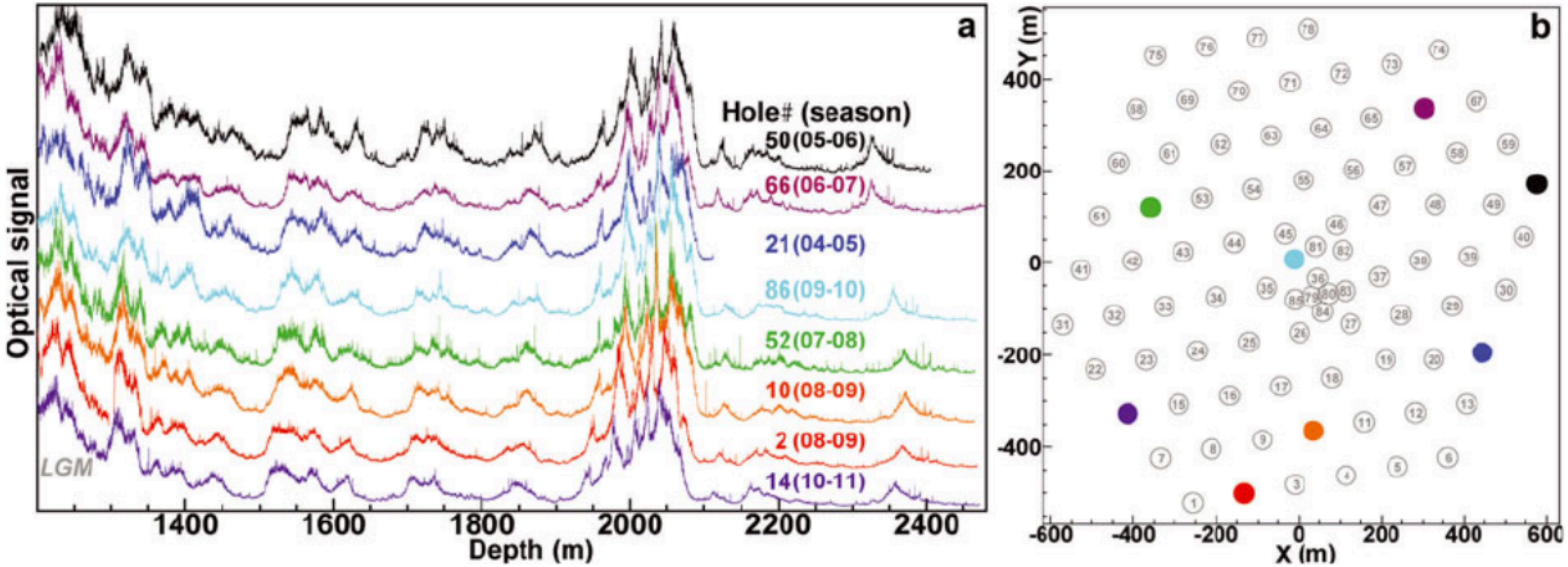

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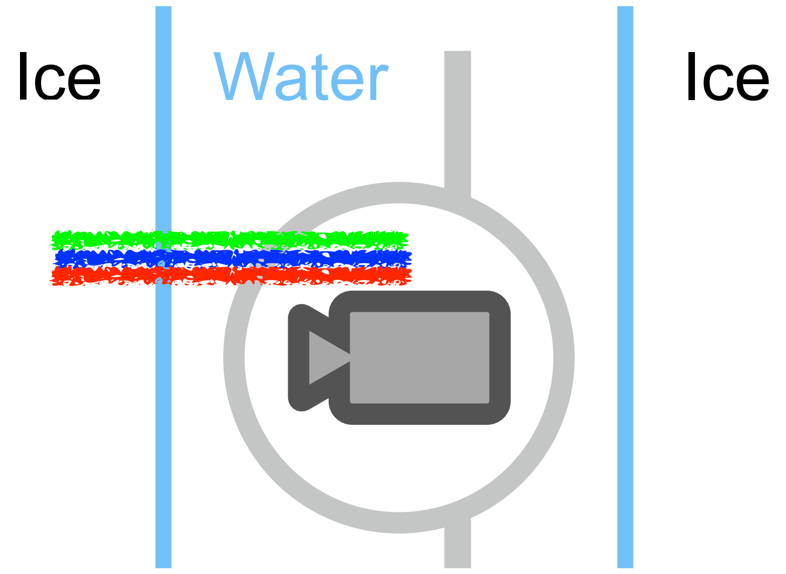

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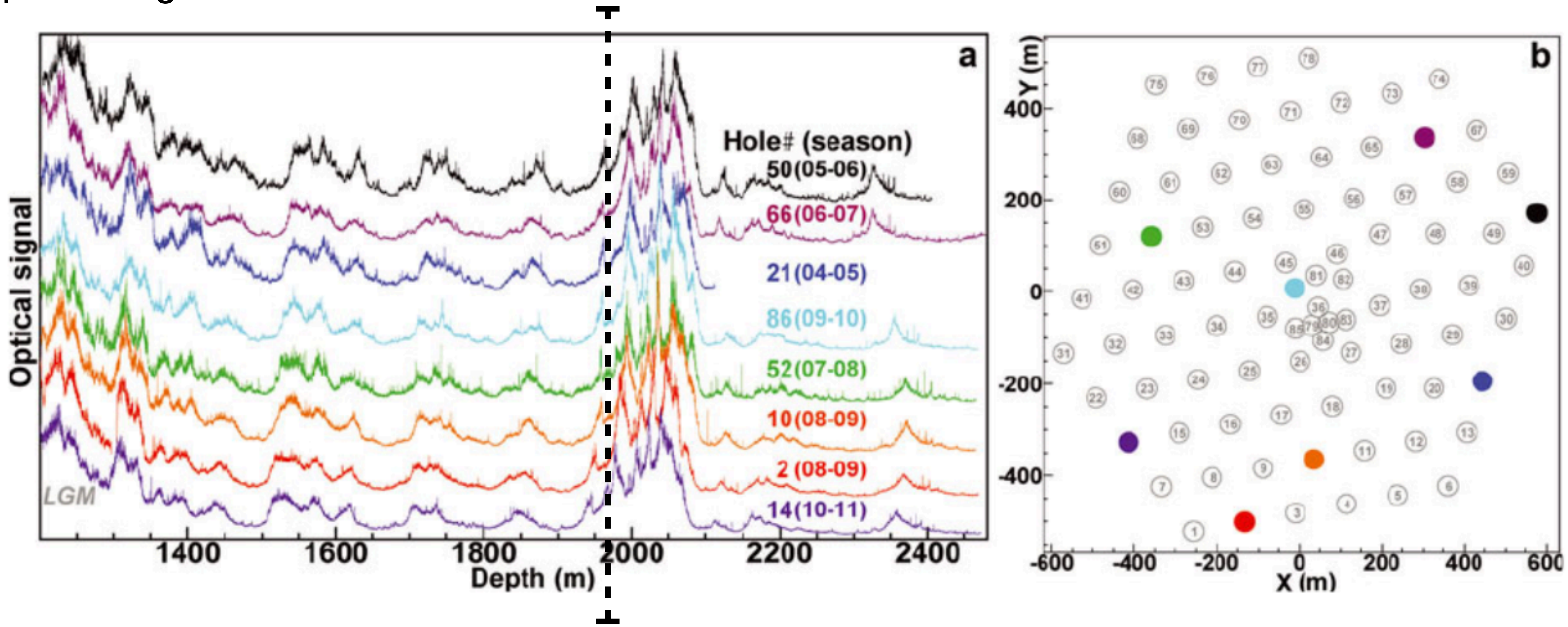

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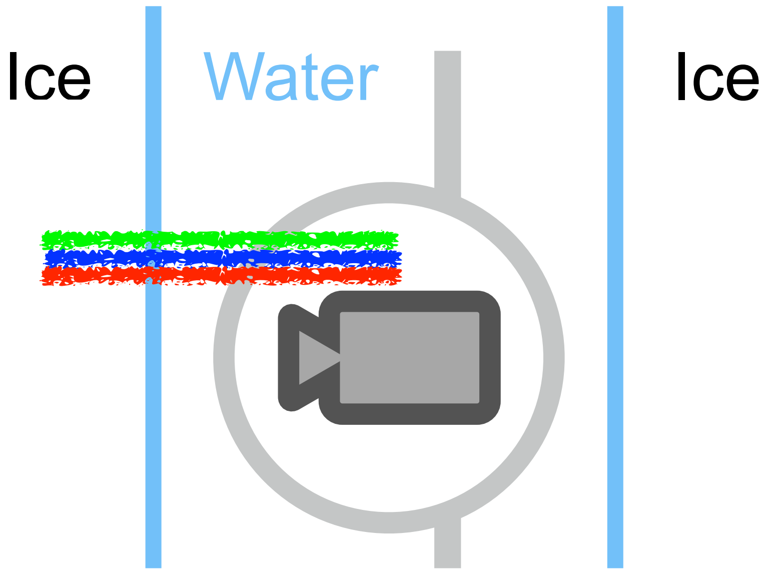

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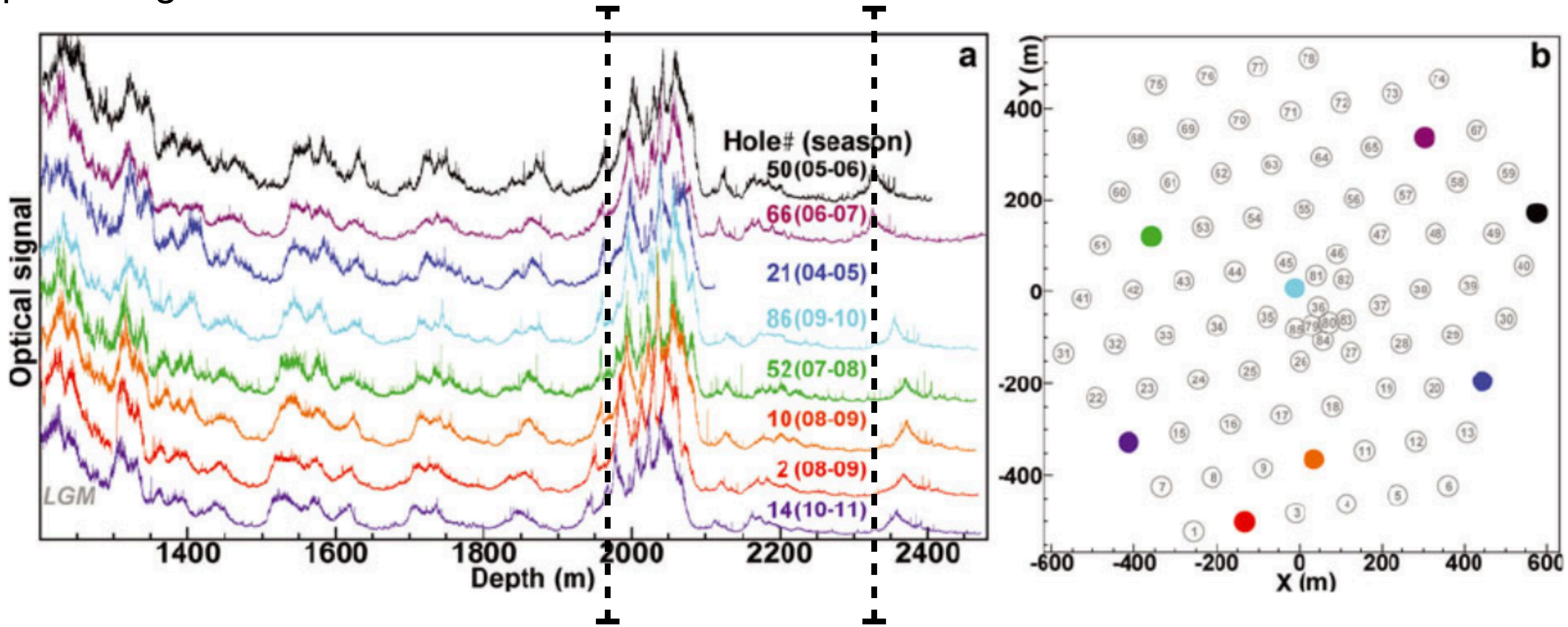
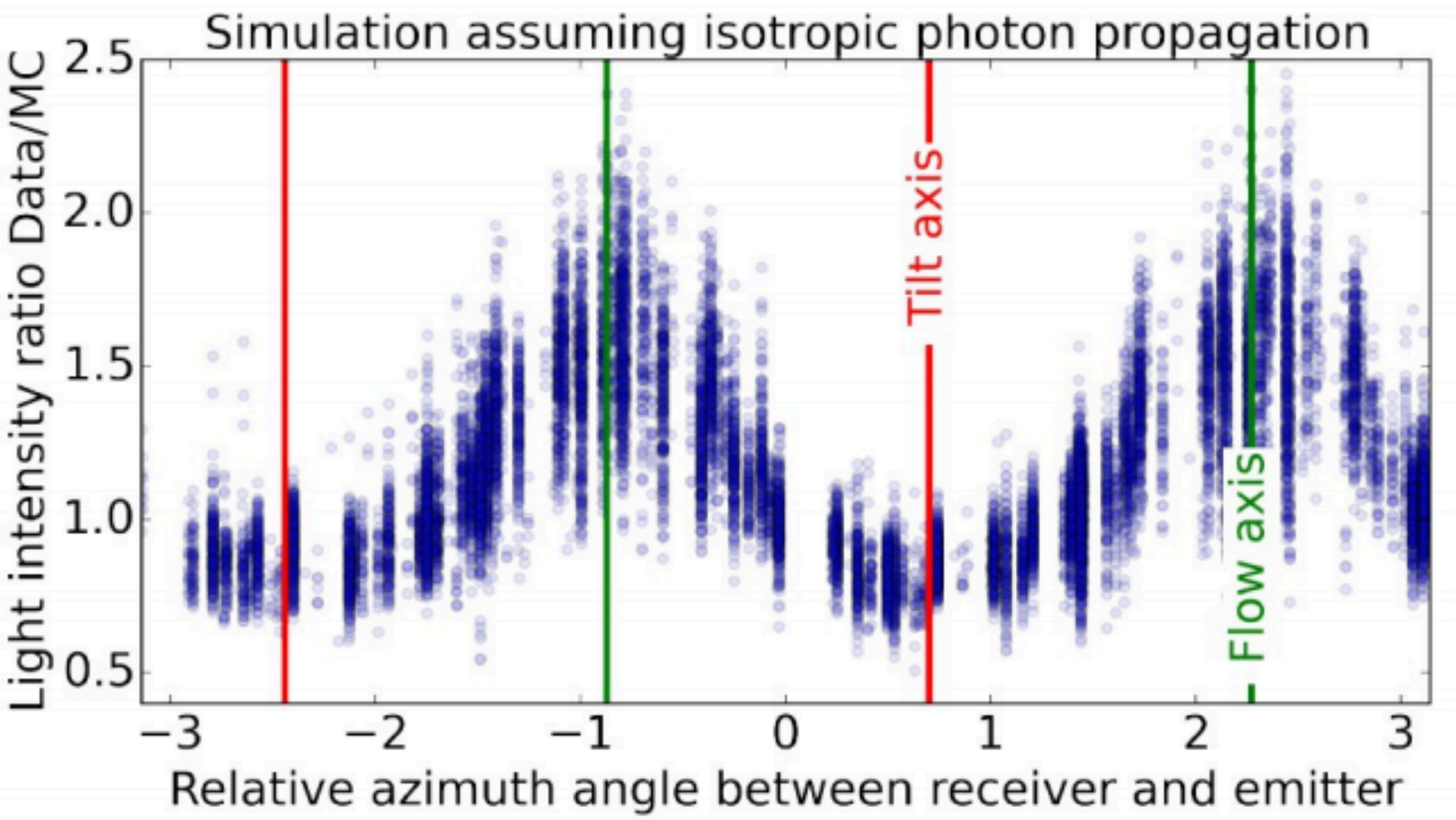


Anisotropic photon propagation

The need for glaciological insights

[1] Aarsten, et al, JINST (2017)
[2] Chirkin, ICRC 2013
[3] Chirkin, Rongen ICRC 2019
[4] Rongen, Bay, Blot The Cryosphere 2020

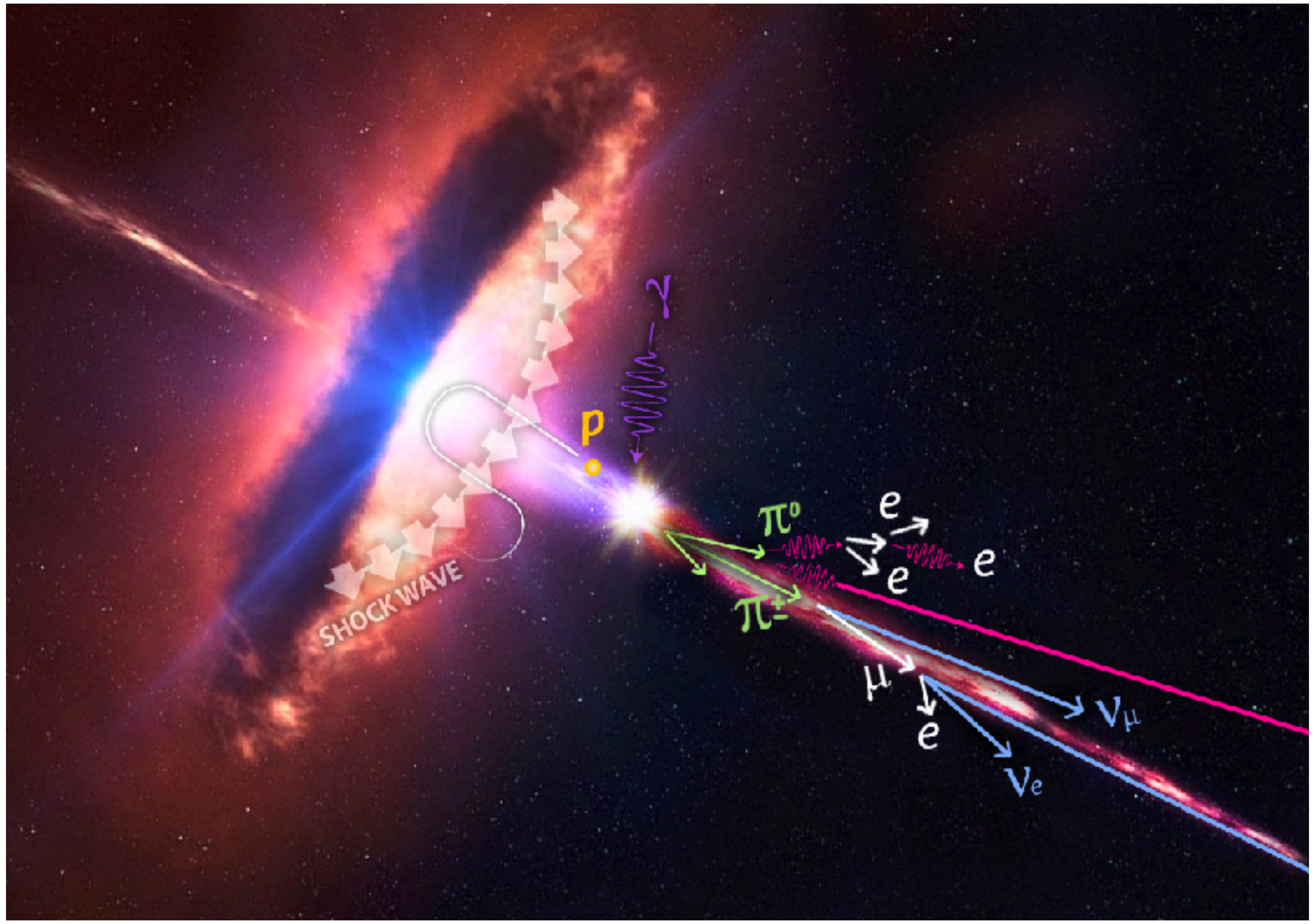
- Azimuthal anisotropy observed in photon propagation [1-4]
- Recent progress in understanding the cause & improving models
  - Birefringence of ice crystals is now the leading explanation
  - Depends on ice fabric properties and glacial flow
- Further developing collaboration between IceCube & glaciology community



Organic neutrino beams

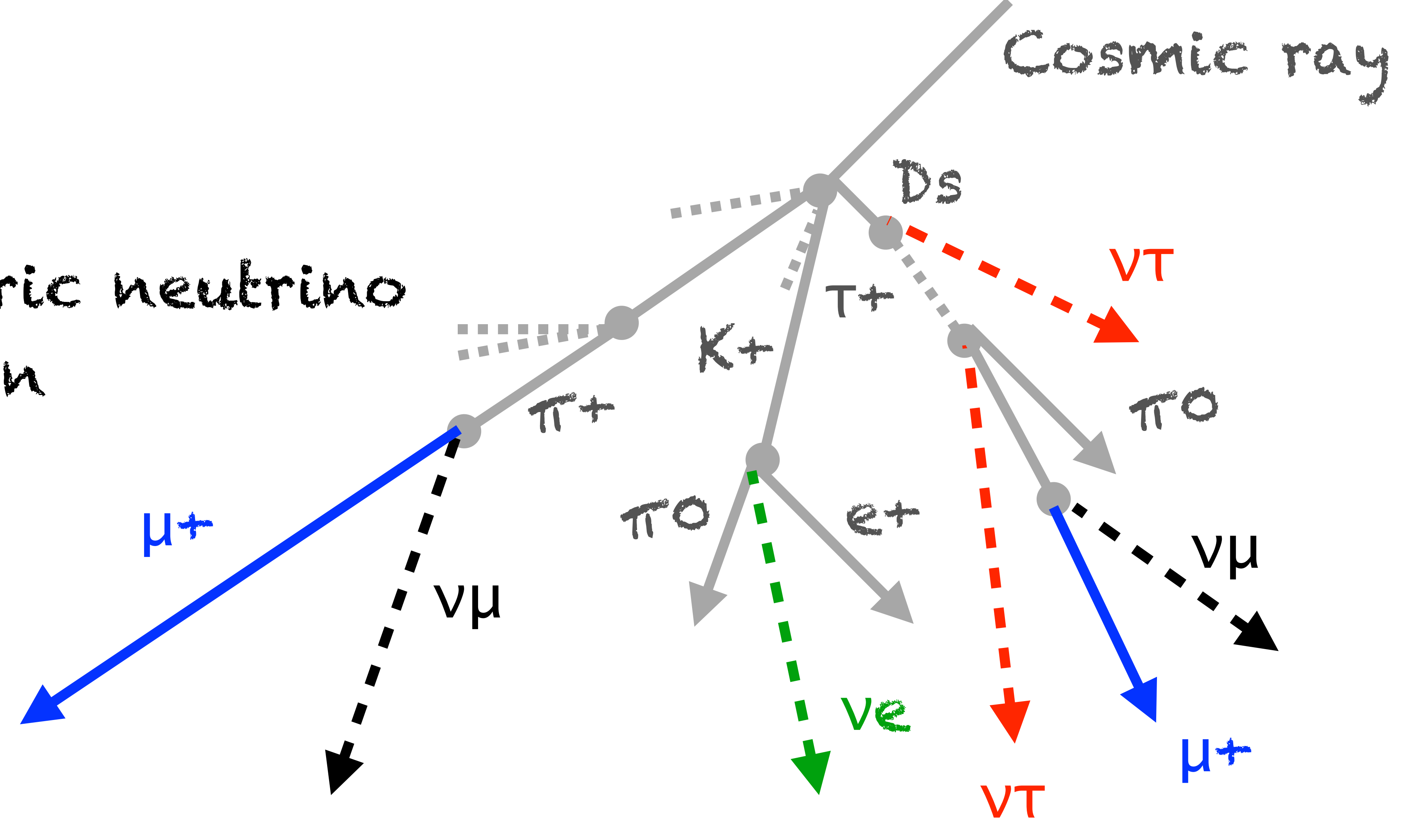
Beam dumps in the sky

Astrophysical neutrino production



Sources produce all flavours, nu + antinu, and IceCube is sensitive to them all!

Atmospheric neutrino production



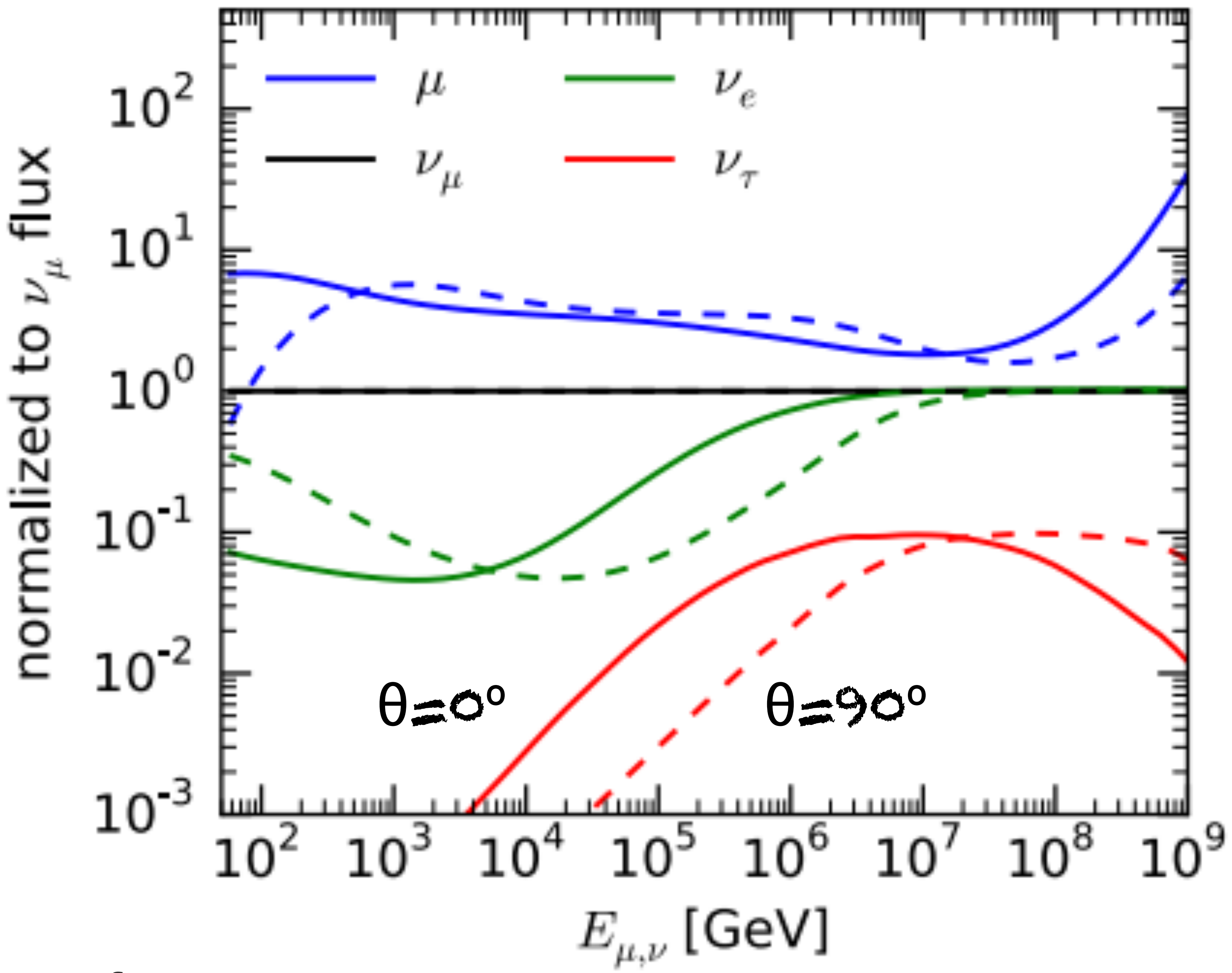


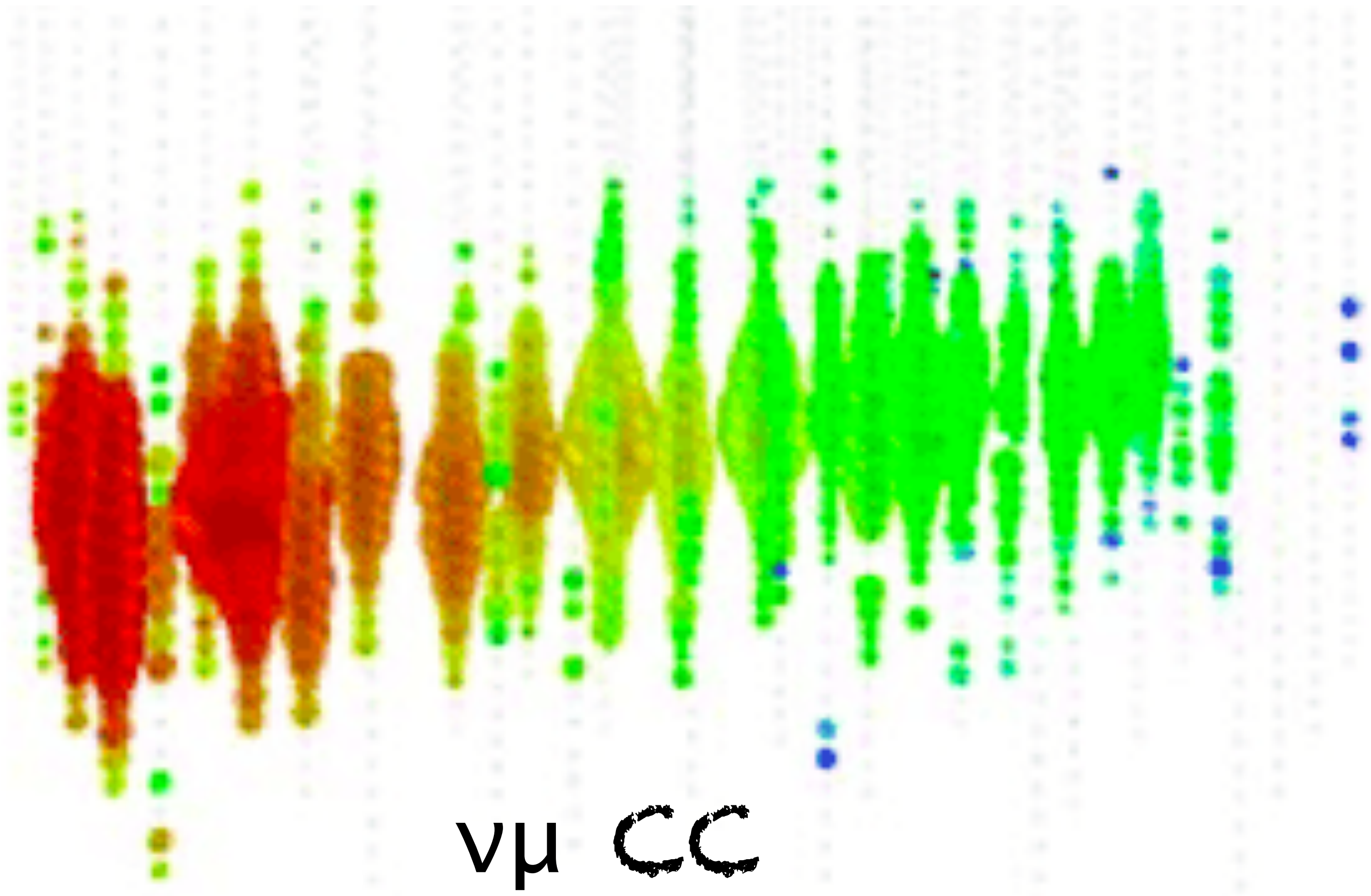
Figure from
Fedynitch *et al*, *EPJ Web Conf.* 99 (2015) 08001

Part 3:
What can we do?

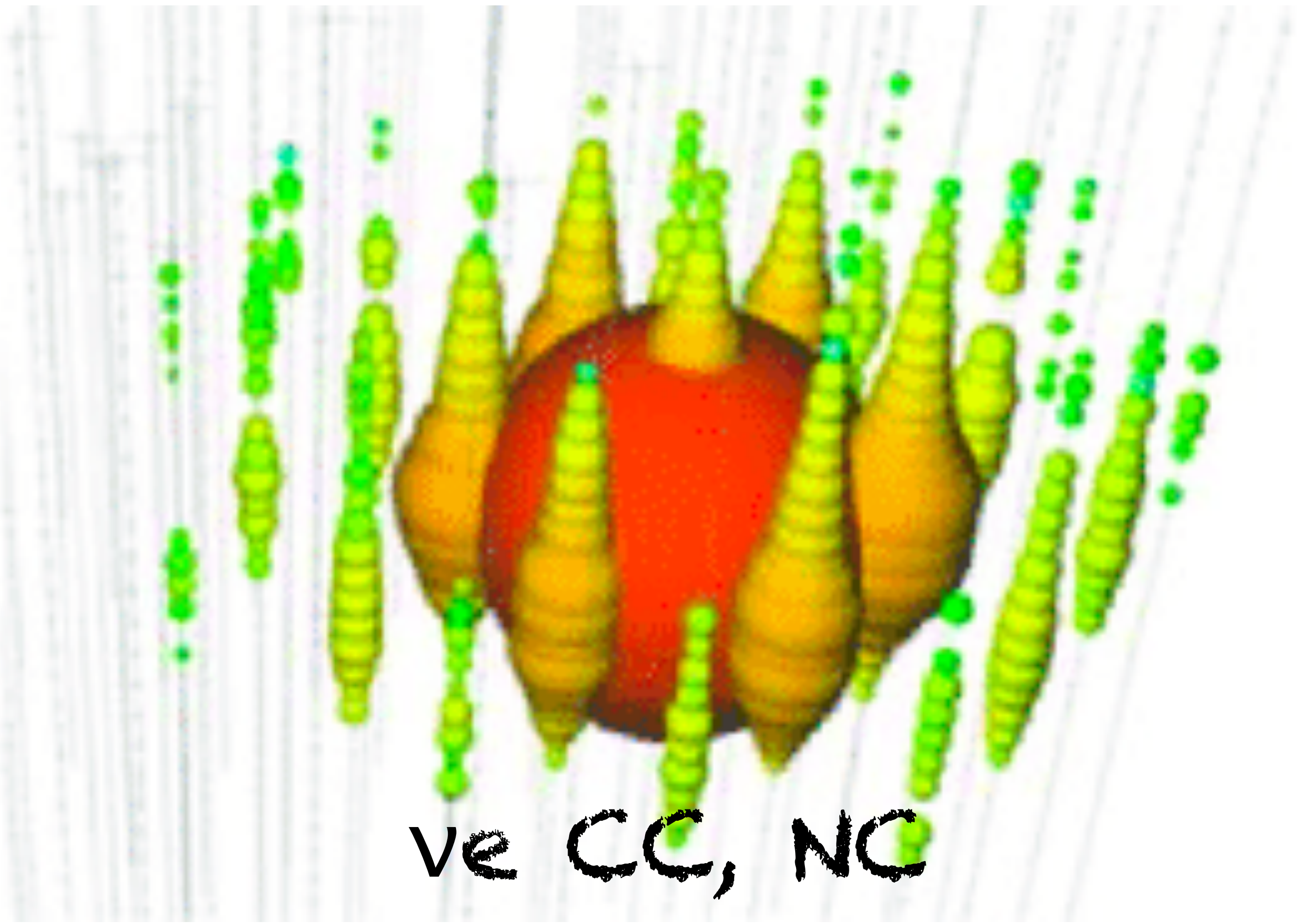
High energy interactions

Distinct event signatures at PeV-scale

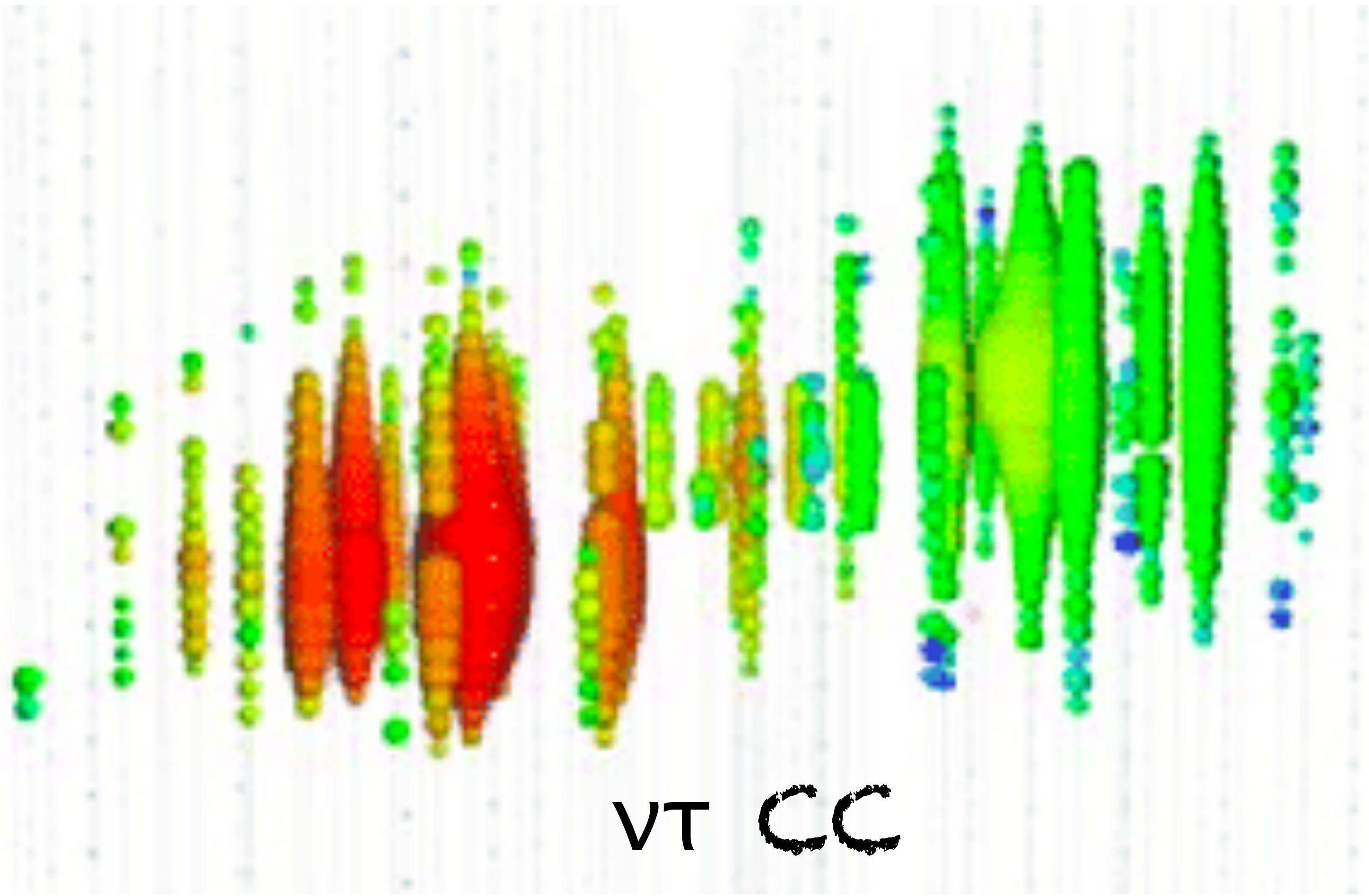
“Tracks”



“Cascades”



“Double cascades”



High energy interactions

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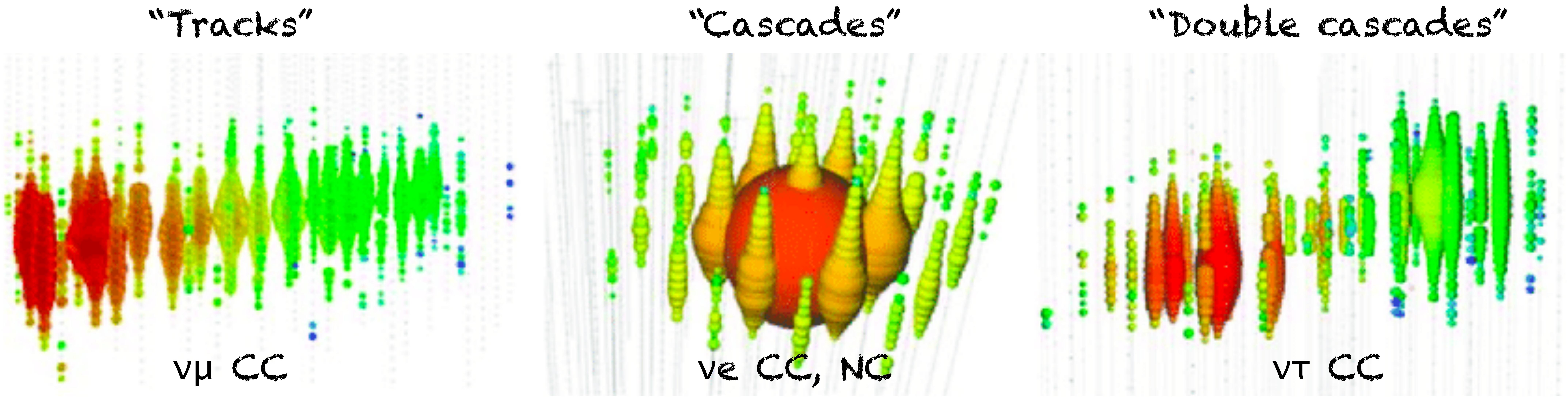
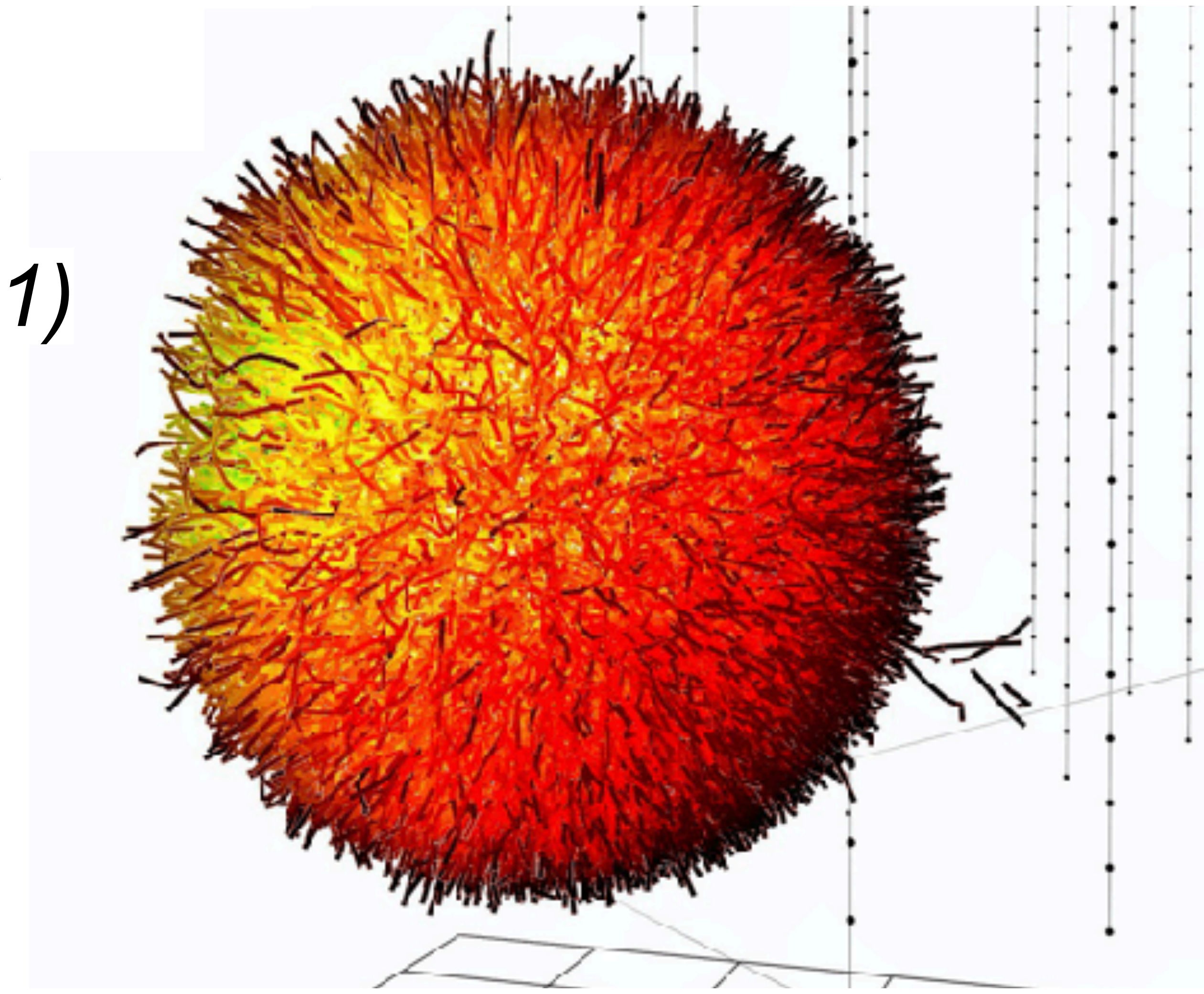


Glashow-like event:
Nature 591, p220–224 (2021)



Exciting new opportunities...

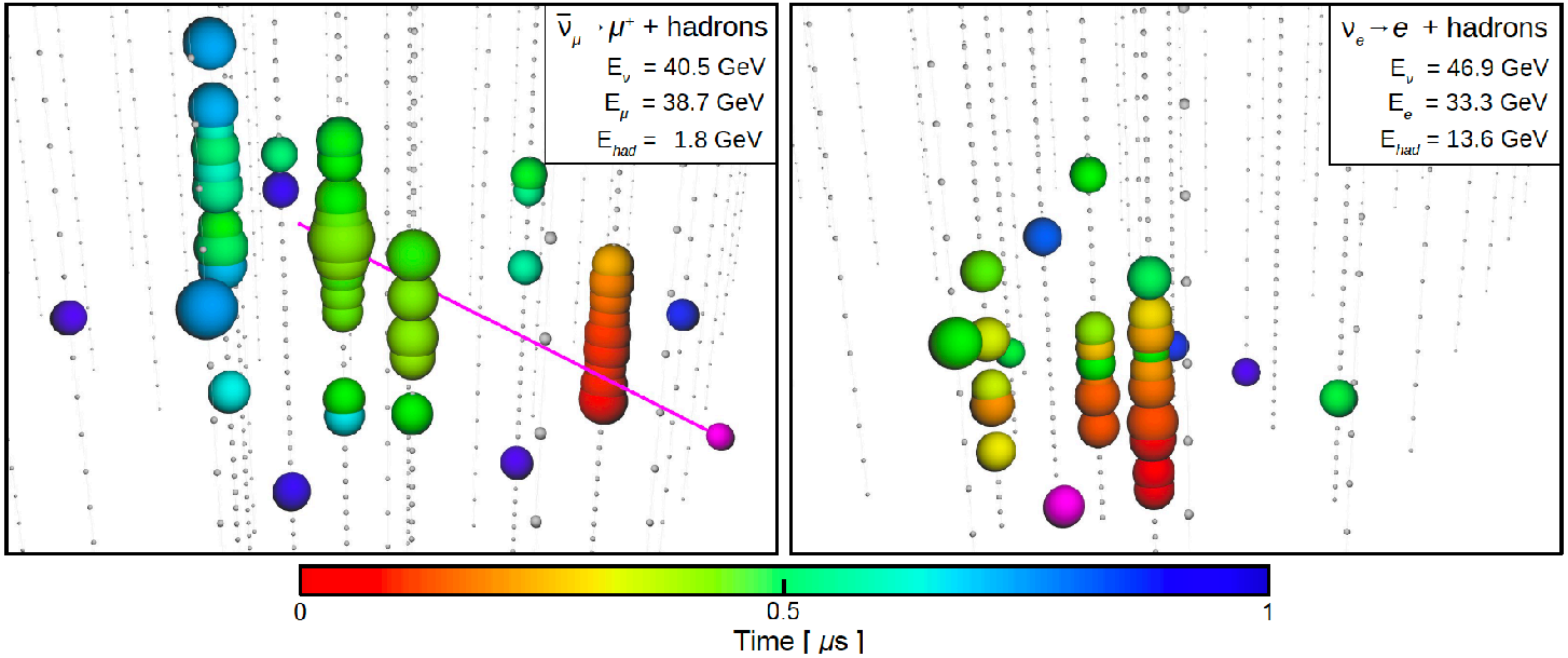
Leading muons can help tag hadronic shower

Low energy interactions

Distinguishable event signatures at GeV scale

"Tracks" νμ CC, few ντ CC

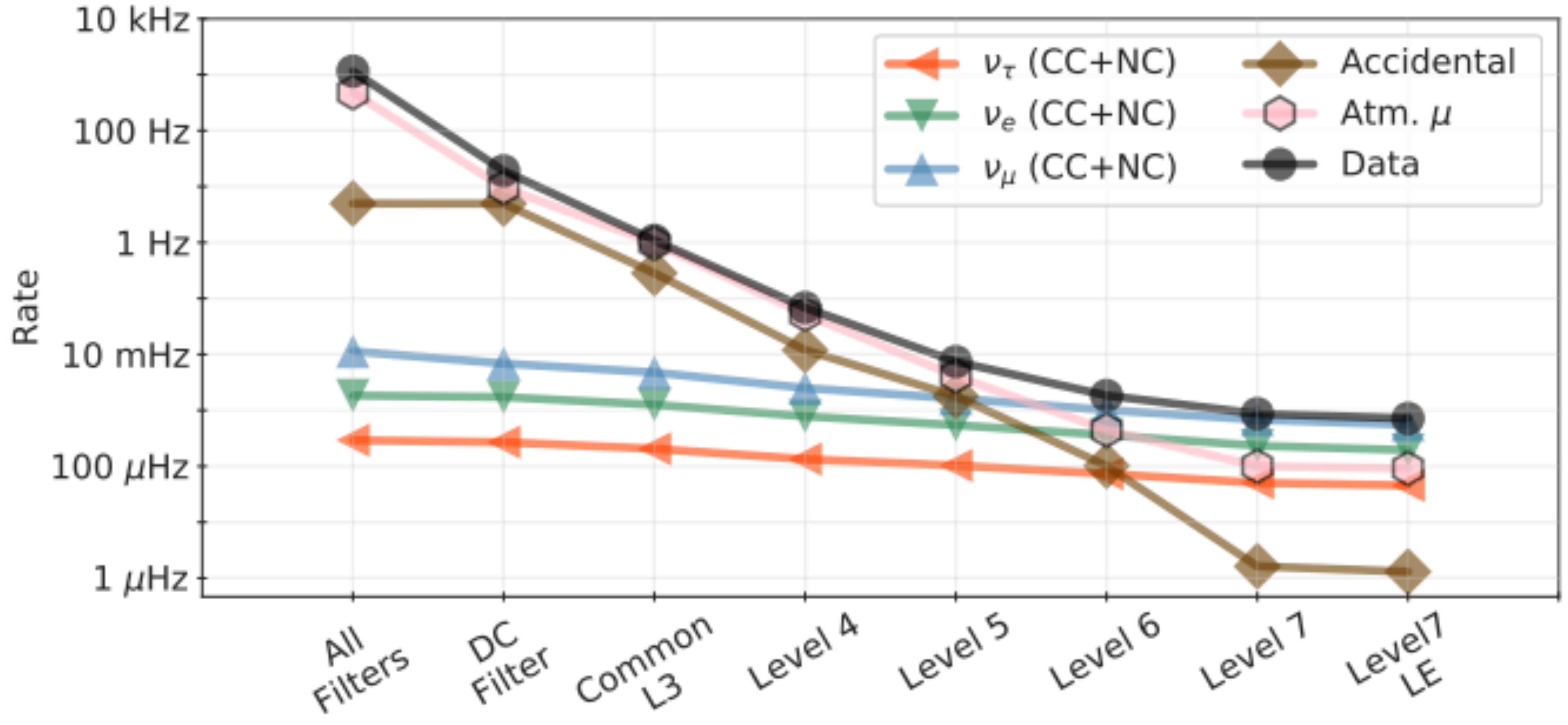
"Cascades" νe CC, most ντ CC, NC



**** Most DOMs register only ~1 photon, even for several 10's GeV!

DeepCore performance

- First challenge: reduction of atmospheric muon contamination
- Sparse instrumentation and complex detector medium limits resolution
- Where we lack in resolution, we make up for in statistics



3 year sample at analysis level

Type	Events	$\pm 1\sigma$
$\nu_e + \bar{\nu}_e$ CC	13462	29
$\nu_e + \bar{\nu}_e$ NC	1096	9
$\nu_\mu + \bar{\nu}_\mu$ CC	35706	48
$\nu_\mu + \bar{\nu}_\mu$ NC	4463	19
$\nu_\tau + \bar{\nu}_\tau$ CC	1804	9
$\nu_\tau + \bar{\nu}_\tau$ NC	556	3
Atmospheric μ	5022	167
Noise Triggers	93	27
total (best fit)	**62203**	**180**
observed	**62112**	**249**

Resolutions @20 GeV:

	Tracks	Cascades
Energy	24 %	29 %
Zenith	10º	16º

Track identification:

~50% accurate at 20 GeV
~80% accurate at 56 GeV

Phys. Rev. D 99, 032007 (2019)

DeepCore - moving to an 8 year sample

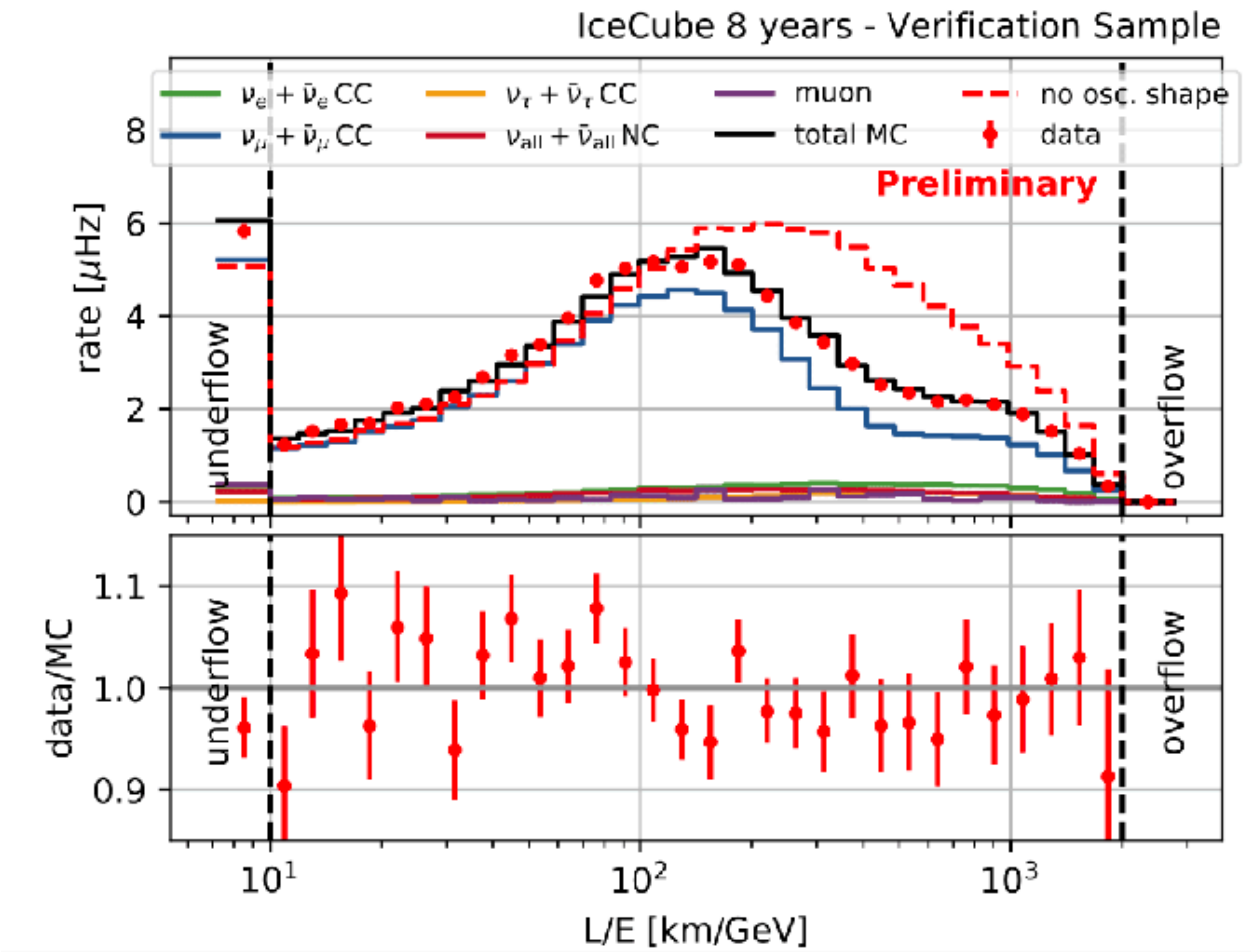
- New calibrations, event selection, MC simulation
- More detailed treatment of systematic uncertainties
- Carve out "golden events" with many unscattered photons
  - Only ~7% of full 8 year sample!
- Perform search for $\nu_\mu \to \nu_\tau$ oscillations to measure atmospheric mixing parameters

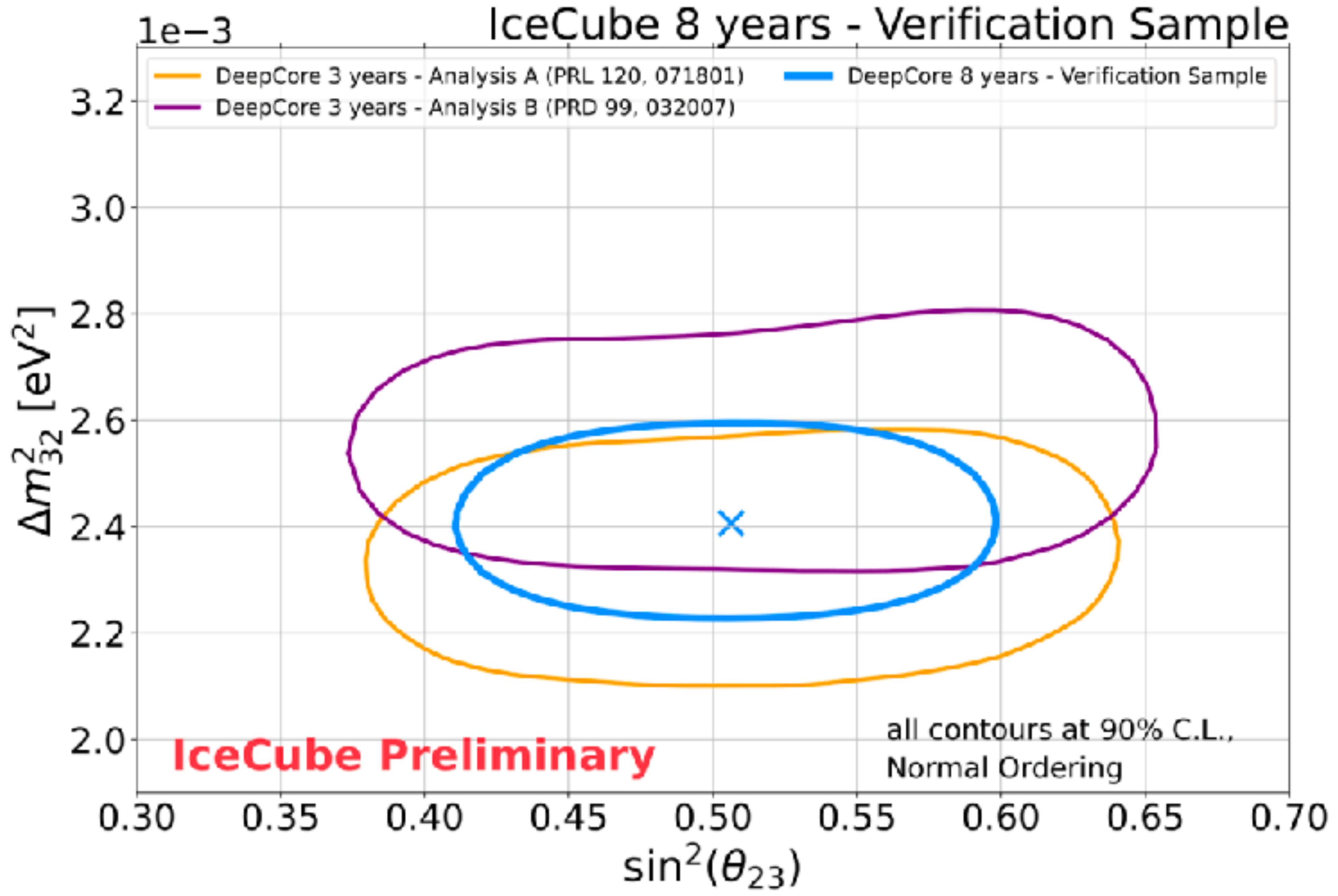
New result:

$\Delta m^2_{32} = (2.41 \pm 0.084) \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$

Good data/MC agreement!





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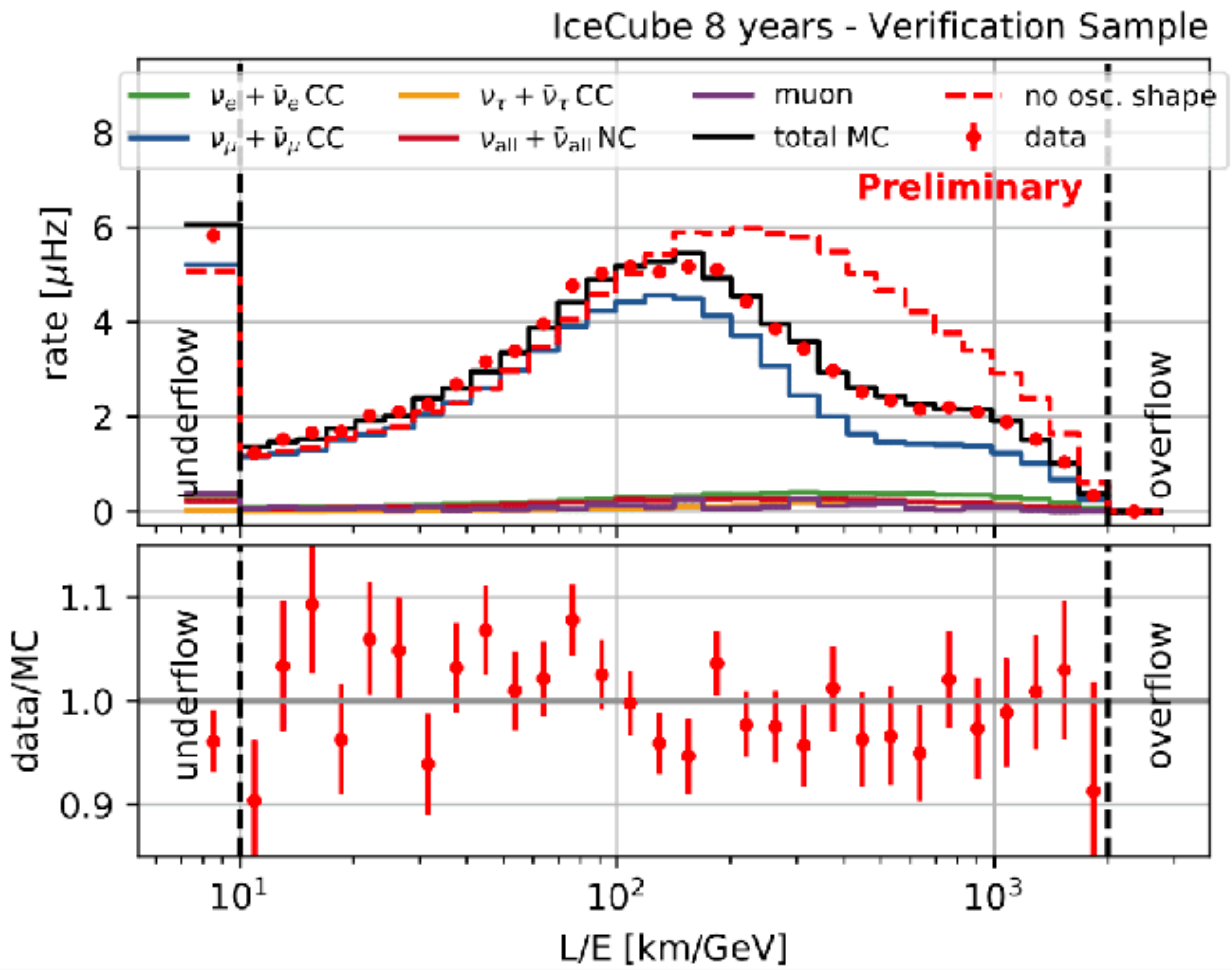
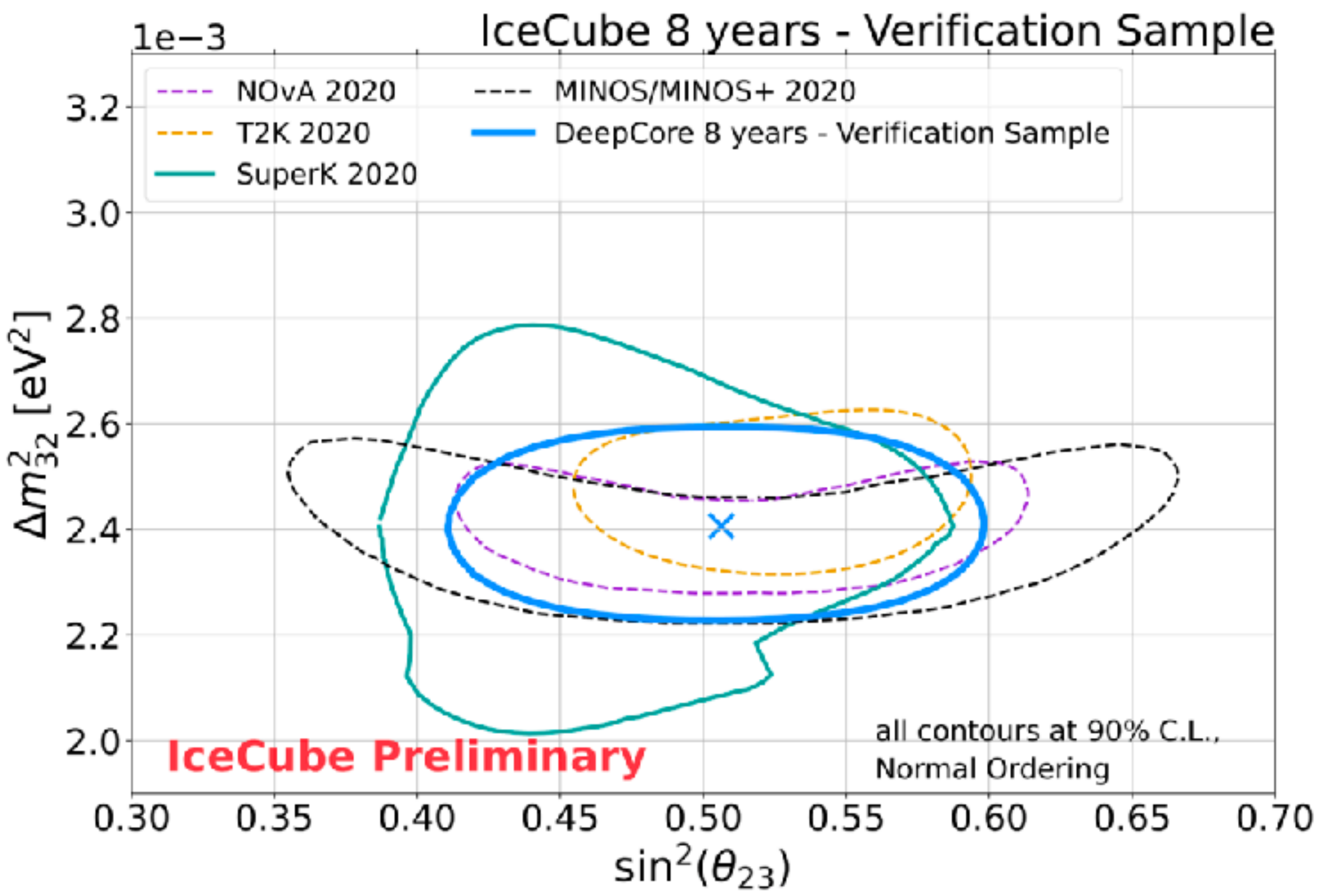


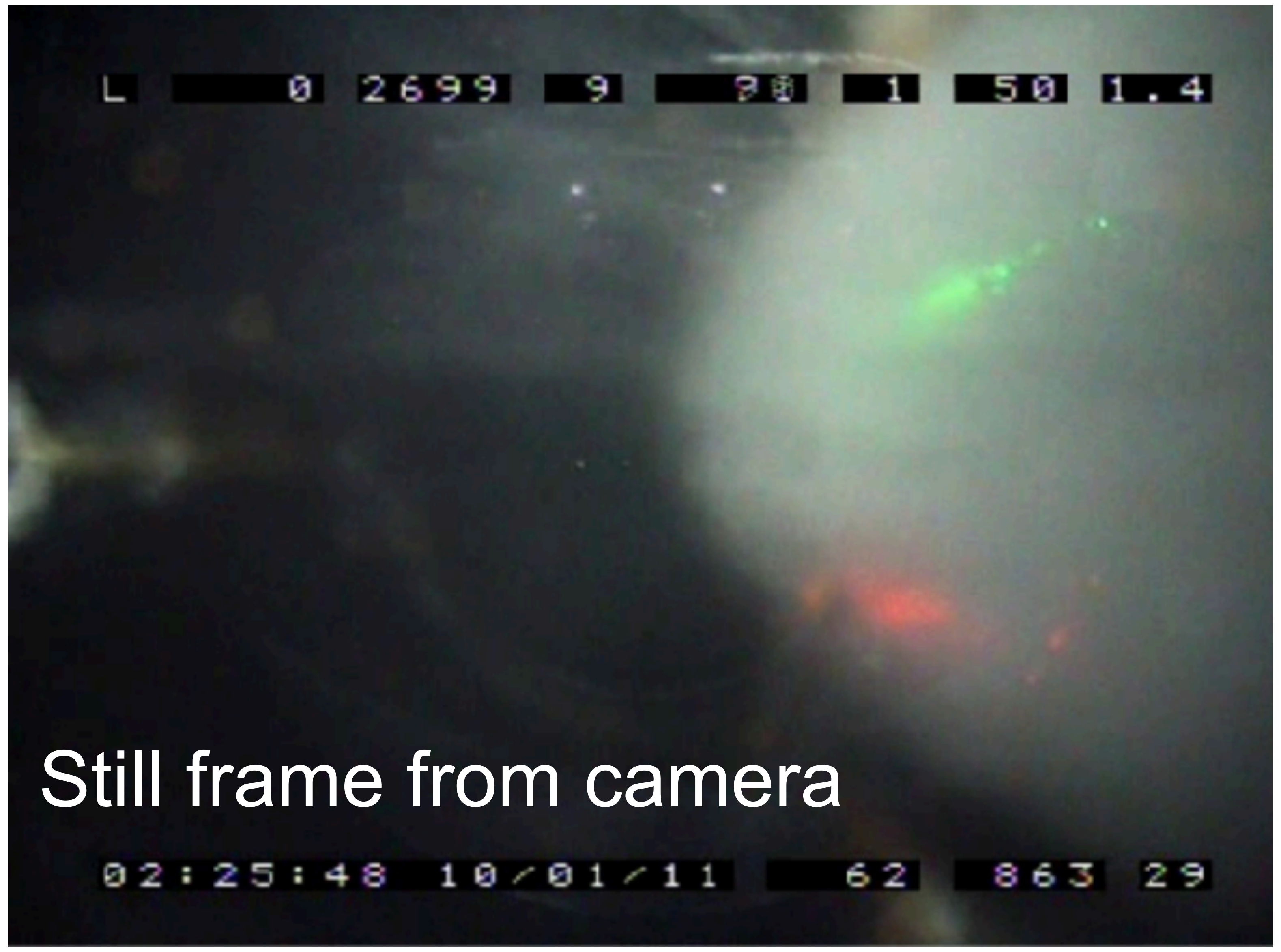


Other noteworthy features

A personal selection

[1] M. G. Aarsten et al, PRD 2014
[2] M. G. Aartsen et al, PRD 2021

- Bubble formation inside of refrozen boreholes continues to be a leading systematic for many analysis
- Dark rates from PMTs not typically an important background (analysis dependent), but critical for accurate energy estimation
- Absolute pointing calibration performed using cosmic ray moon shadow [1,2]



Still frame from camera

- Robust identification of EM vs hadronic interactions is hard
  - Leading muon reconstruction is promising avenue
  - Neutron echo search also in development
- Neutrino/anti-neutrino separation also very challenging

Better characterisation of PMT late/afterpulses is needed

Part 4:
What’s next?

The IceCube Upgrade

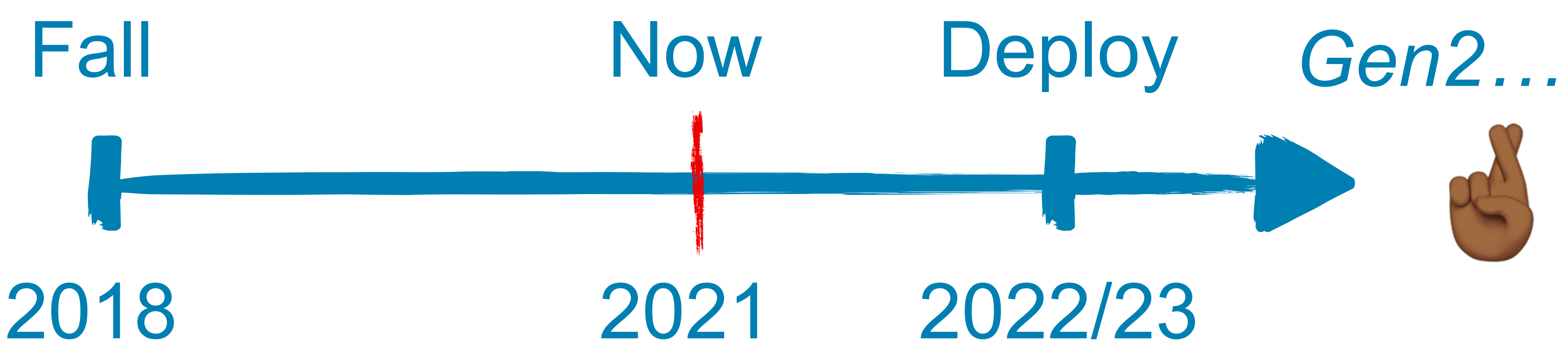
7 new strings in deep core of instrument

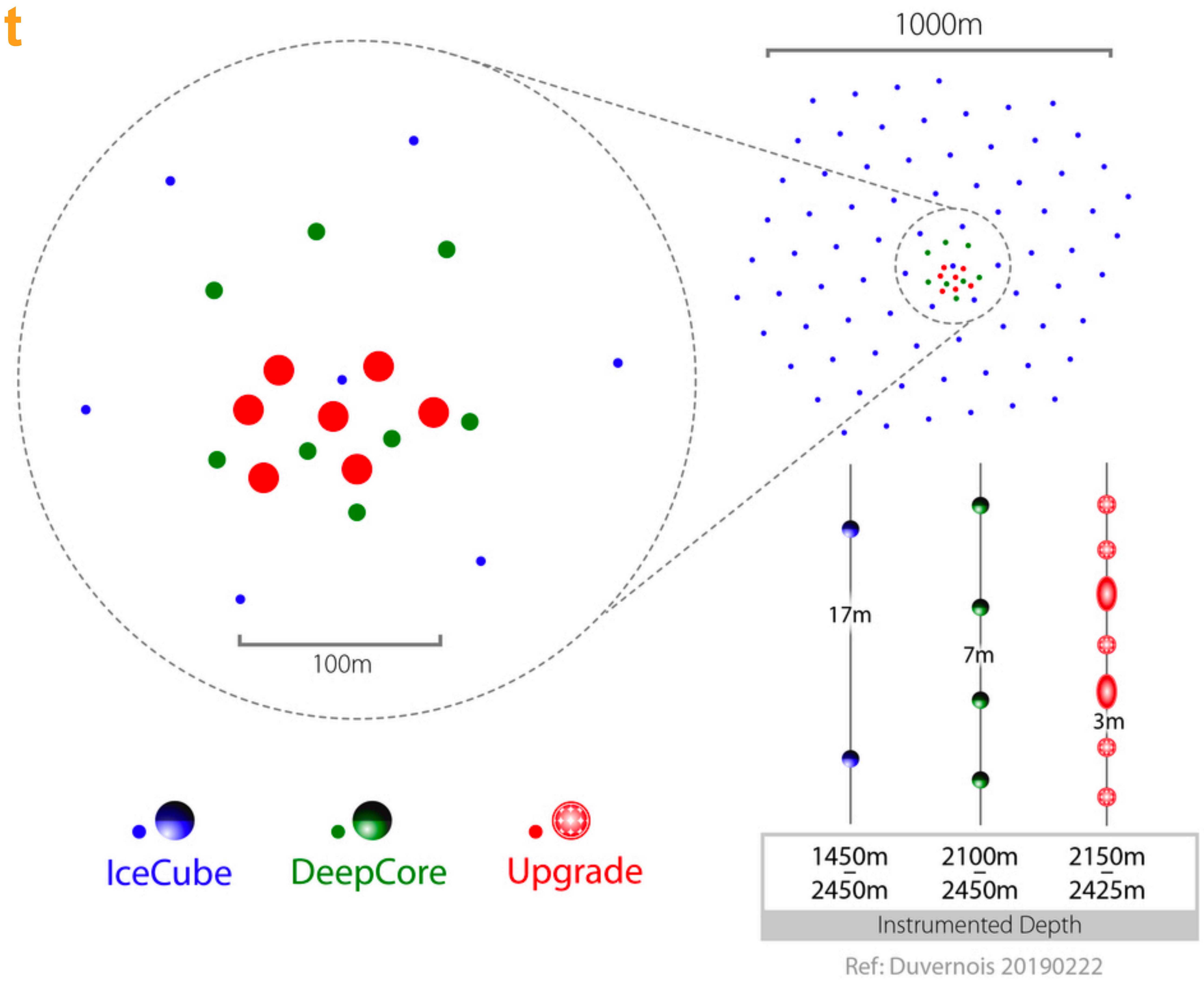
IceCube Upgrade goals:

- Precision oscillation measurements
- Improved detector calibrations
- R&D for IceCube-Gen2

Key features

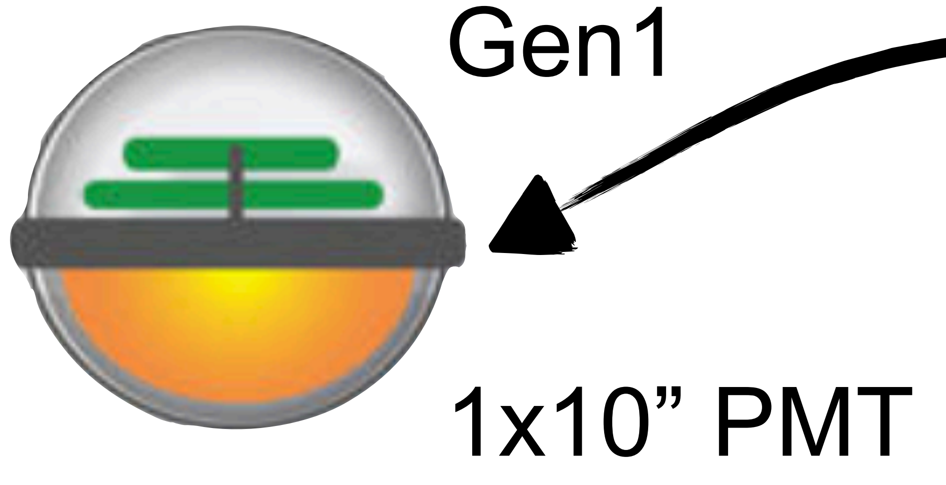
- > 800 new devices
- Reduced spacing between devices
- Explore the deep ice down to 2600 m





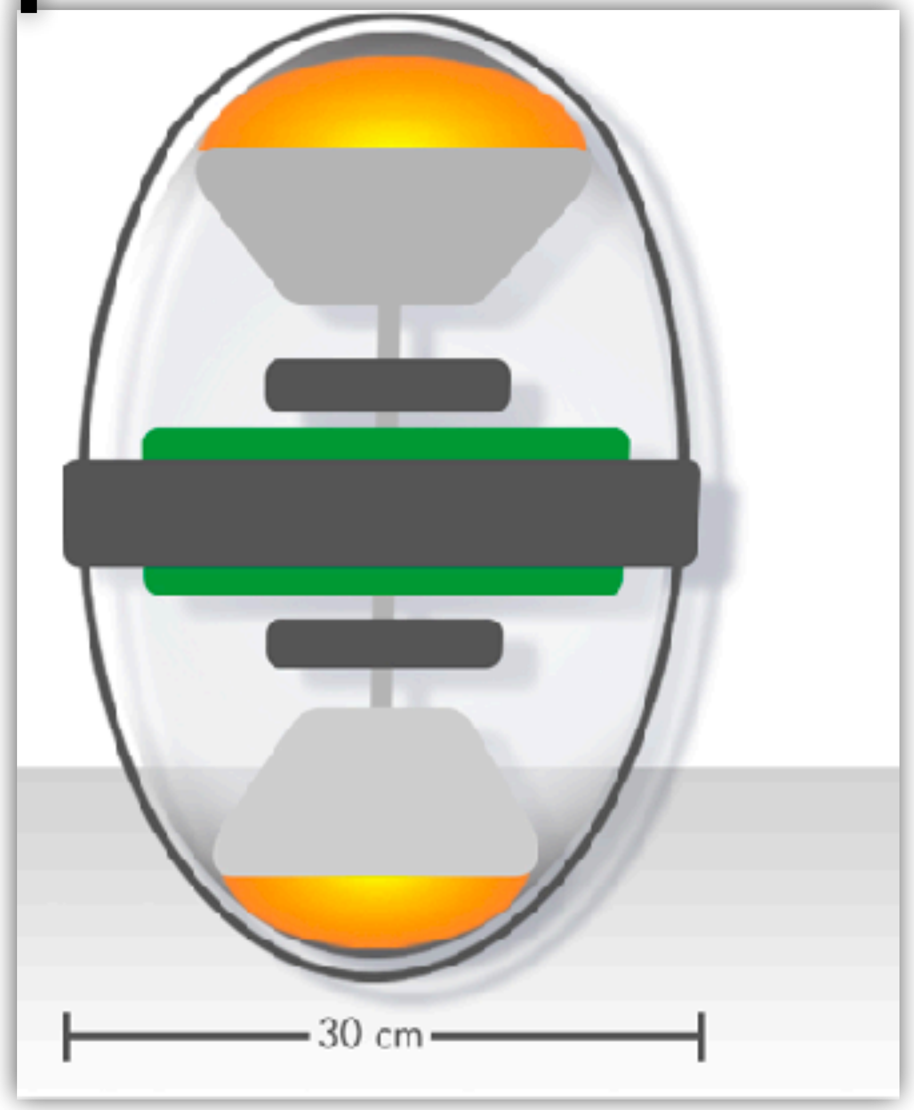
New sensor designs

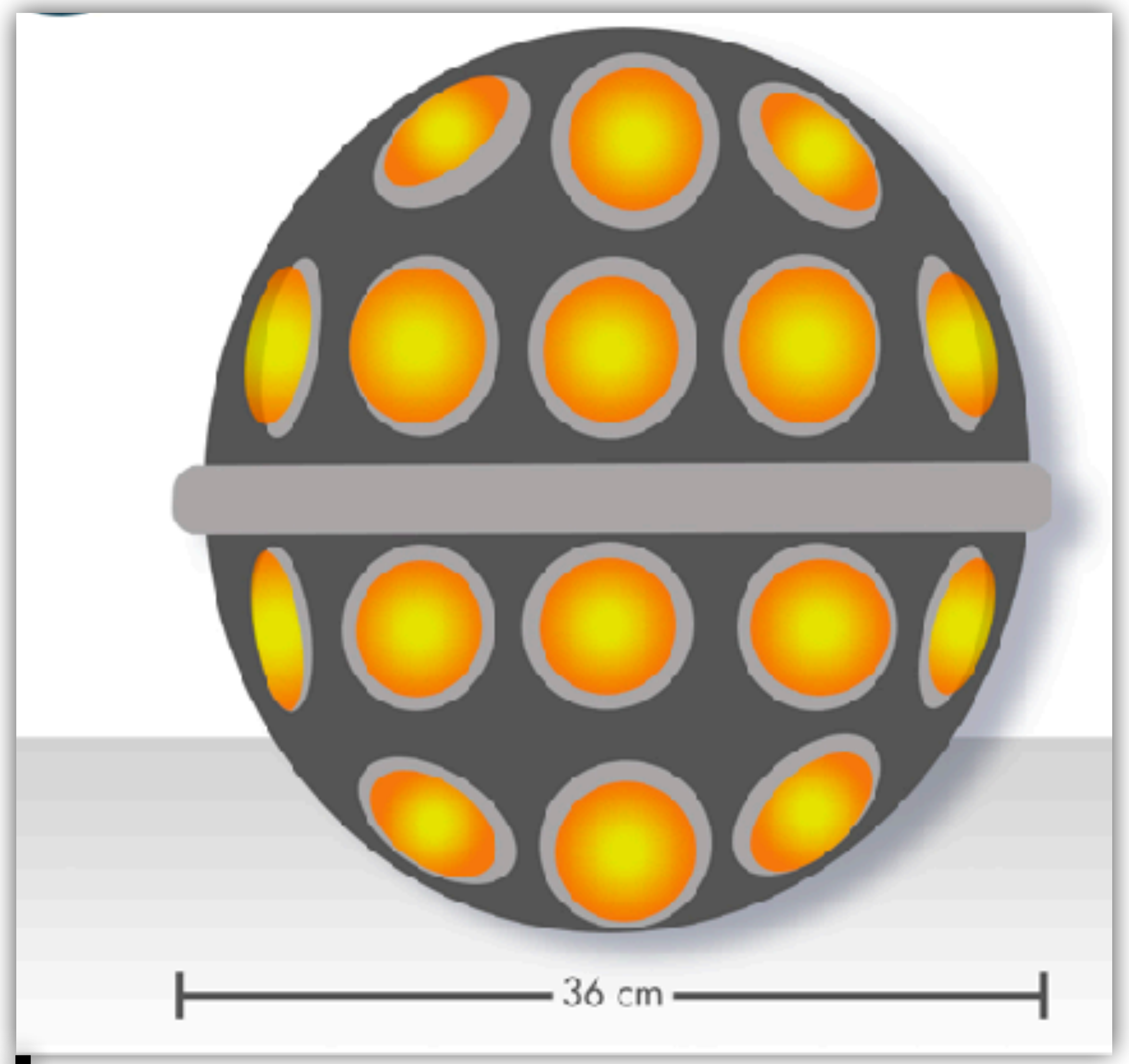
Increased effective area



DEgg

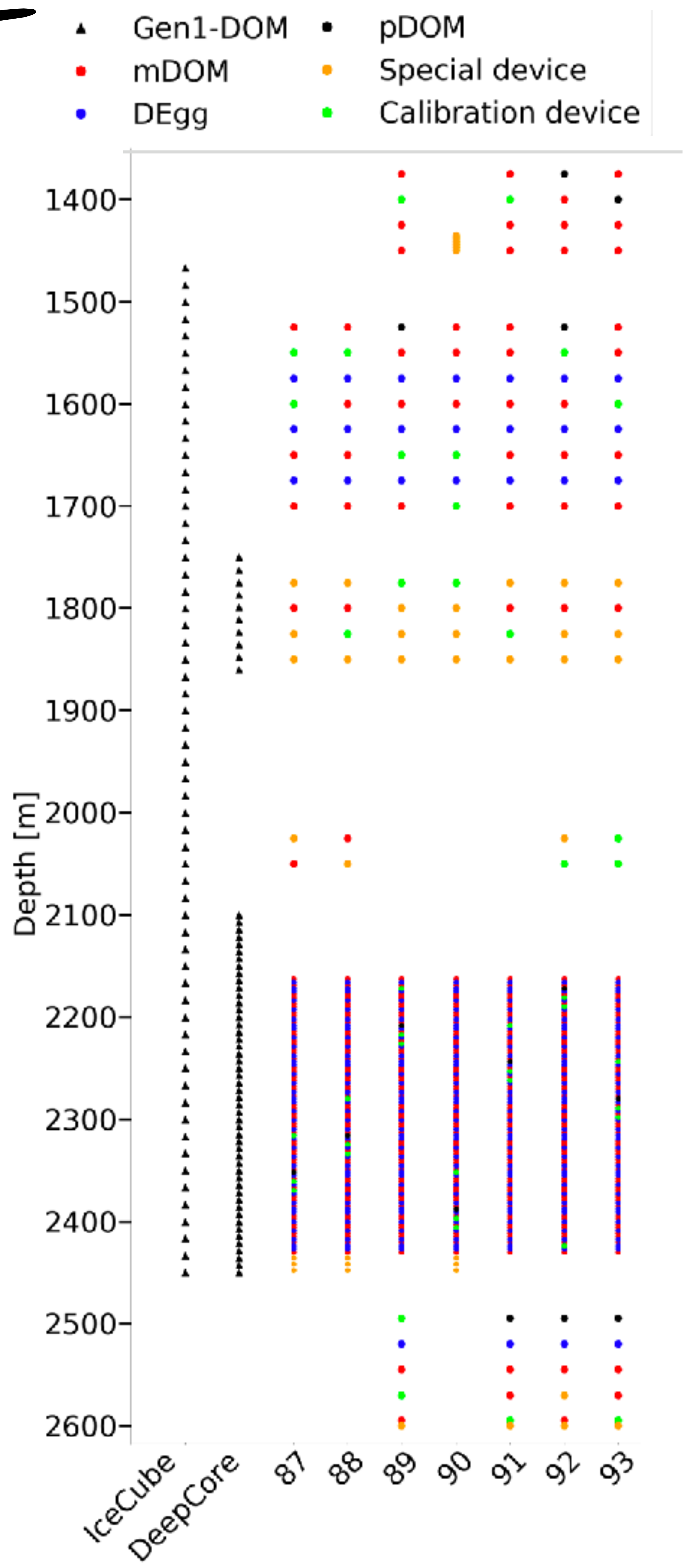
2x8" PMT
Produced at Chiba
Deploy ~300





24x3" PMT
Produced at DESY&MSU
Deploy ~400

mDOM

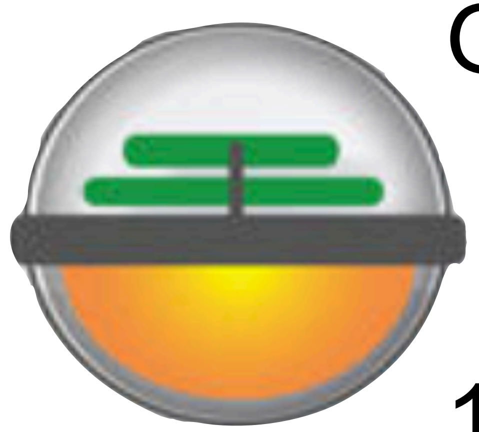


More total photocathode area, increased wavelength and angular acceptance

New sensor designs

Increased effective area

Gen1



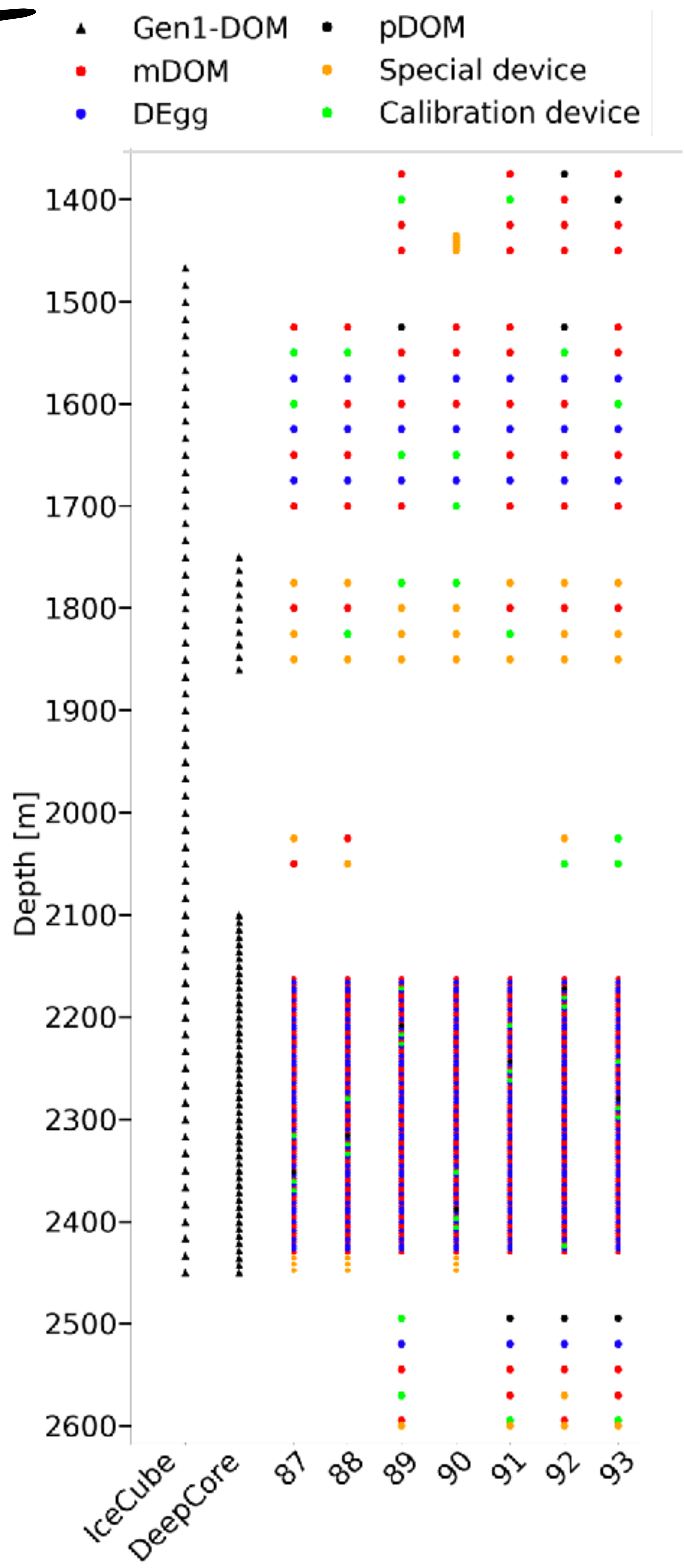
1x10” PMT

DEgg

2x8” PMT
Produced at Chiba
Deploy ~300

24x3” PMT
Produced at DESY&MSU
Deploy ~400

mDOM

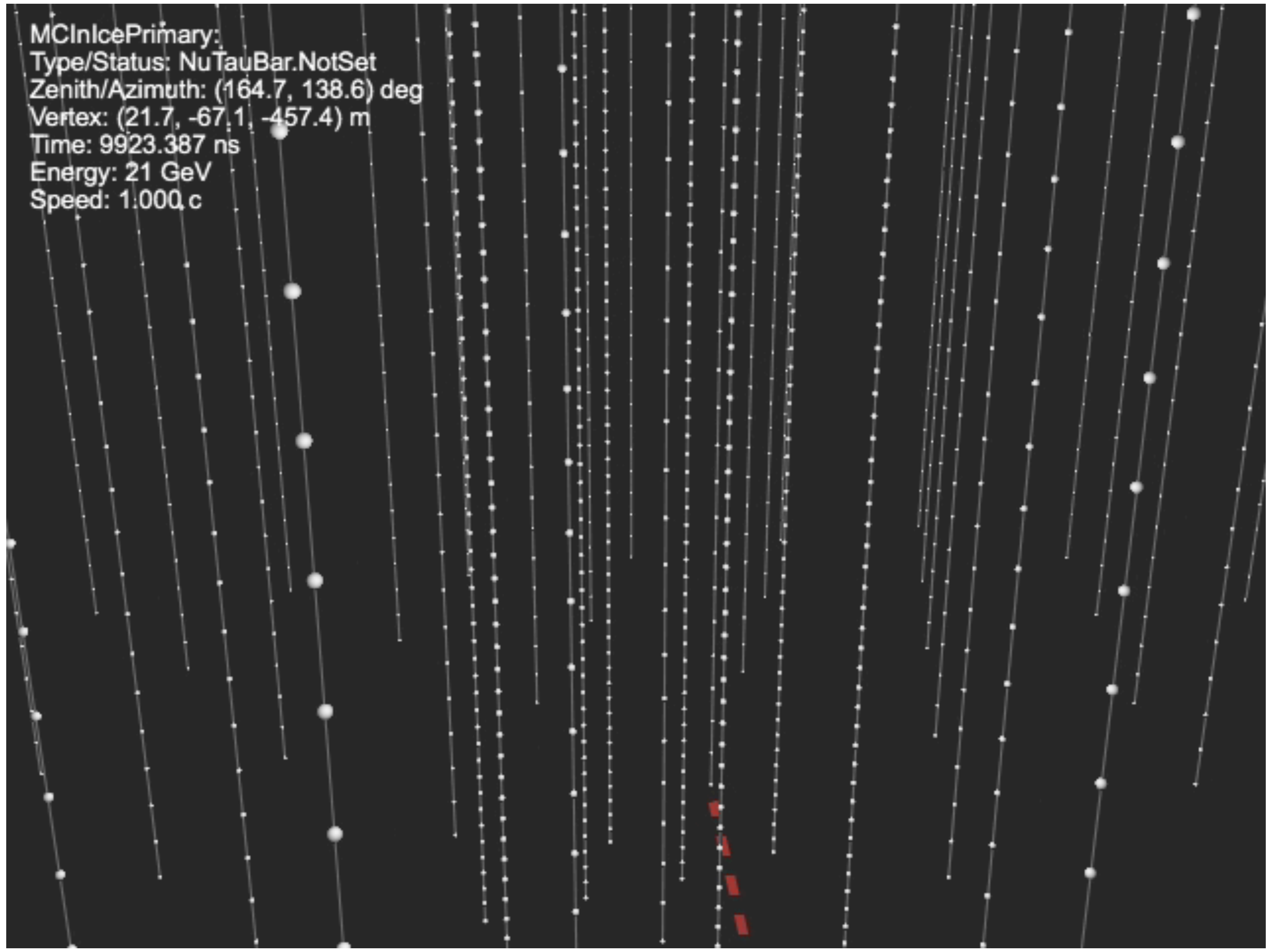


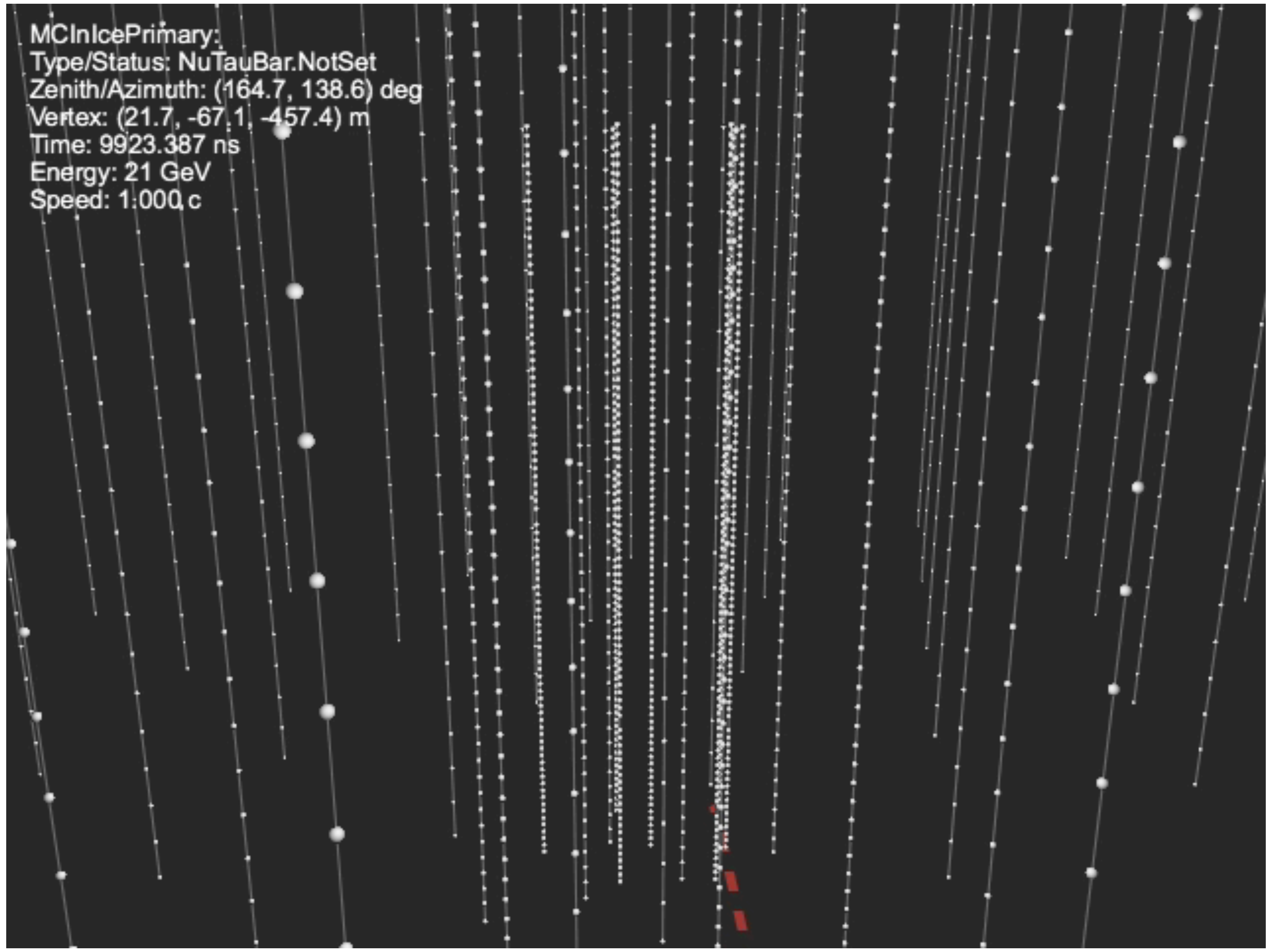
More total photocathode area, increased wavelength and angular acceptance

IceCube Upgrade Events

More detail in every event

DeepCore | 21 GeV ν_τ interaction | Upgrade



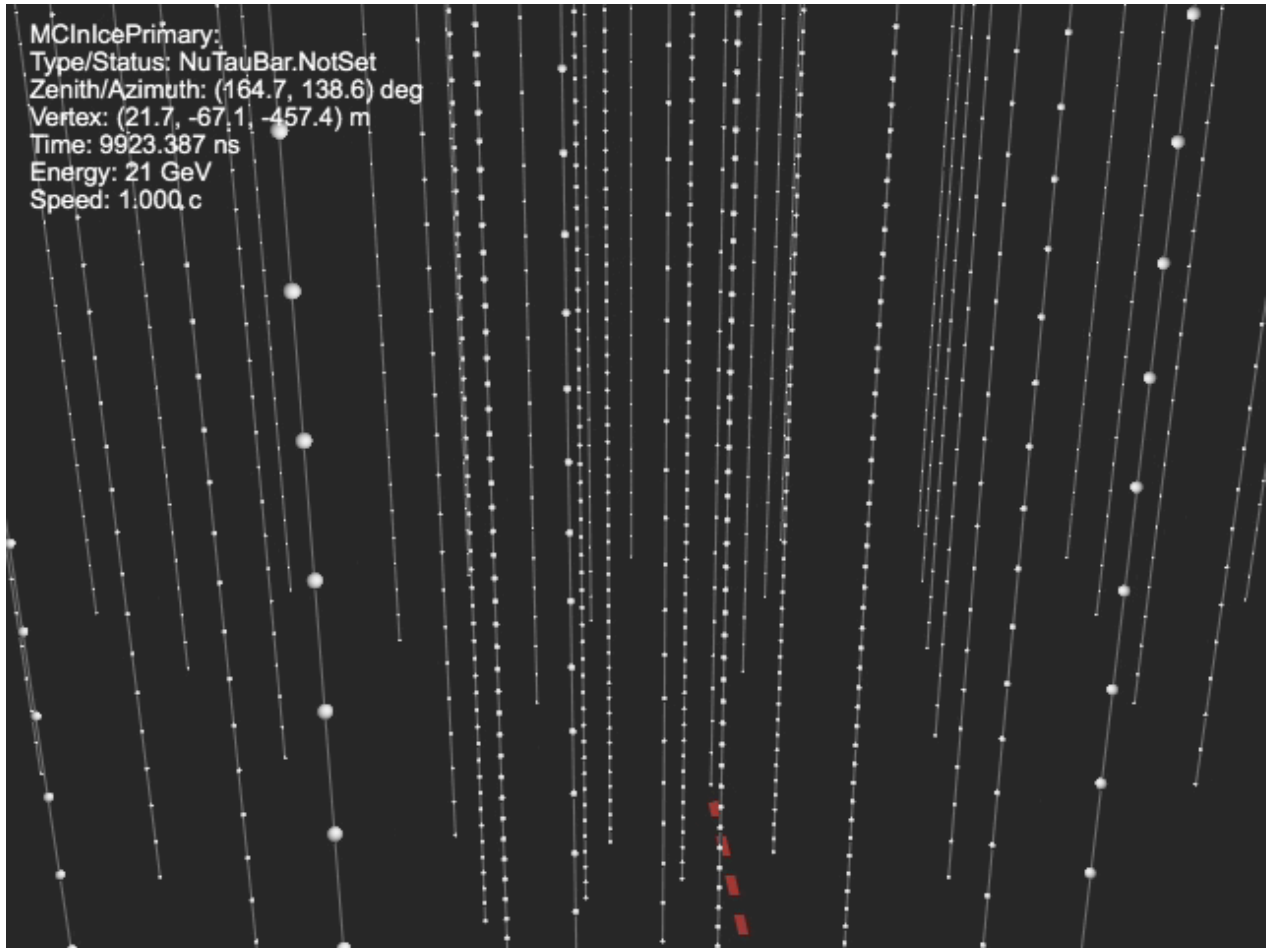


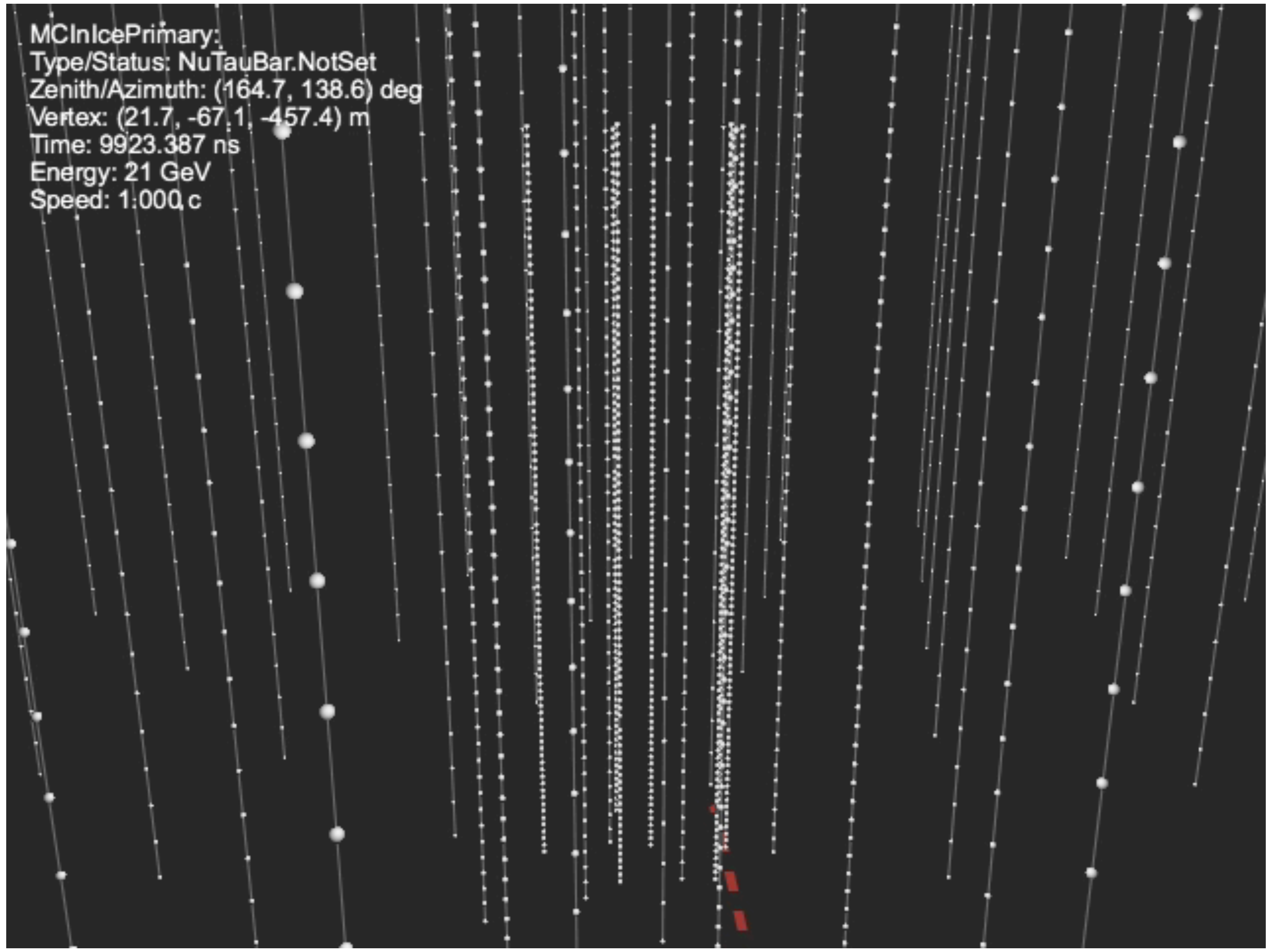
+ factor 2-4 increase in rates over DeepCore (depending on energy/interaction type)

IceCube Upgrade Events

More detail in every event

DeepCore — 21 GeV ν_τ interaction — Upgrade





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IceCube Upgrade

Expeced performance

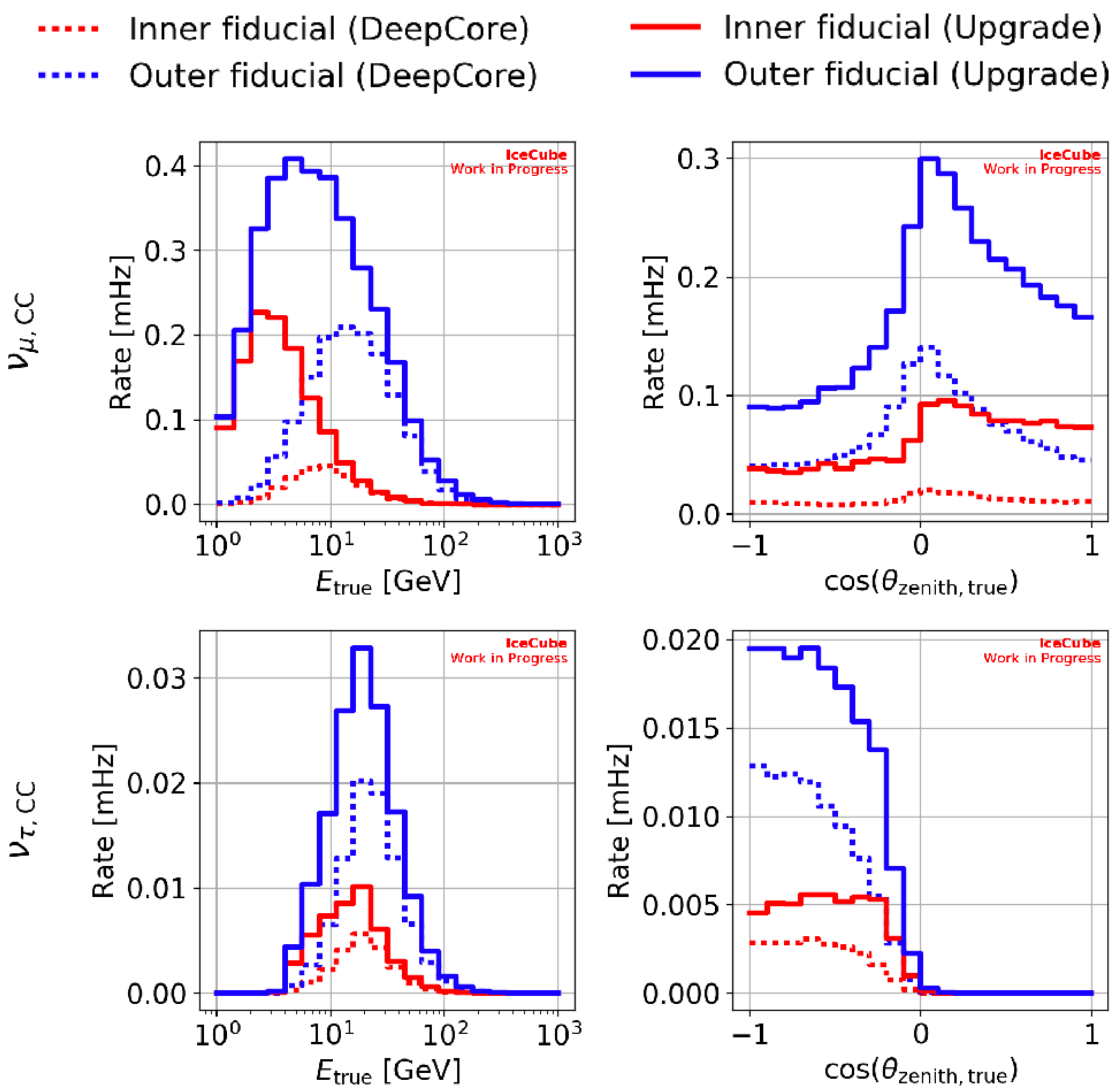
IceCube Upgrade Monte Carlo data release: click here!

What to look forward to

- Reduced energy threshold ~1 GeV
- Factor 2-4 more events
  - Depends on energy and interaction type
- Improved resolutions

Challenges ahead

- Higher noise rates with more complex timing & correlations in multi-PMT modules
- Reconstruction with very inhomogeneous detector
- Lower energy brings new systematic challenges e.g. flux, cross section



IceCube Upgrade

Expeced performance

IceCube Upgrade Monte Carlo data release: click here!

Current projections are conservative

What to look forward to

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  - Depends on energy and interaction type
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Challenges ahead

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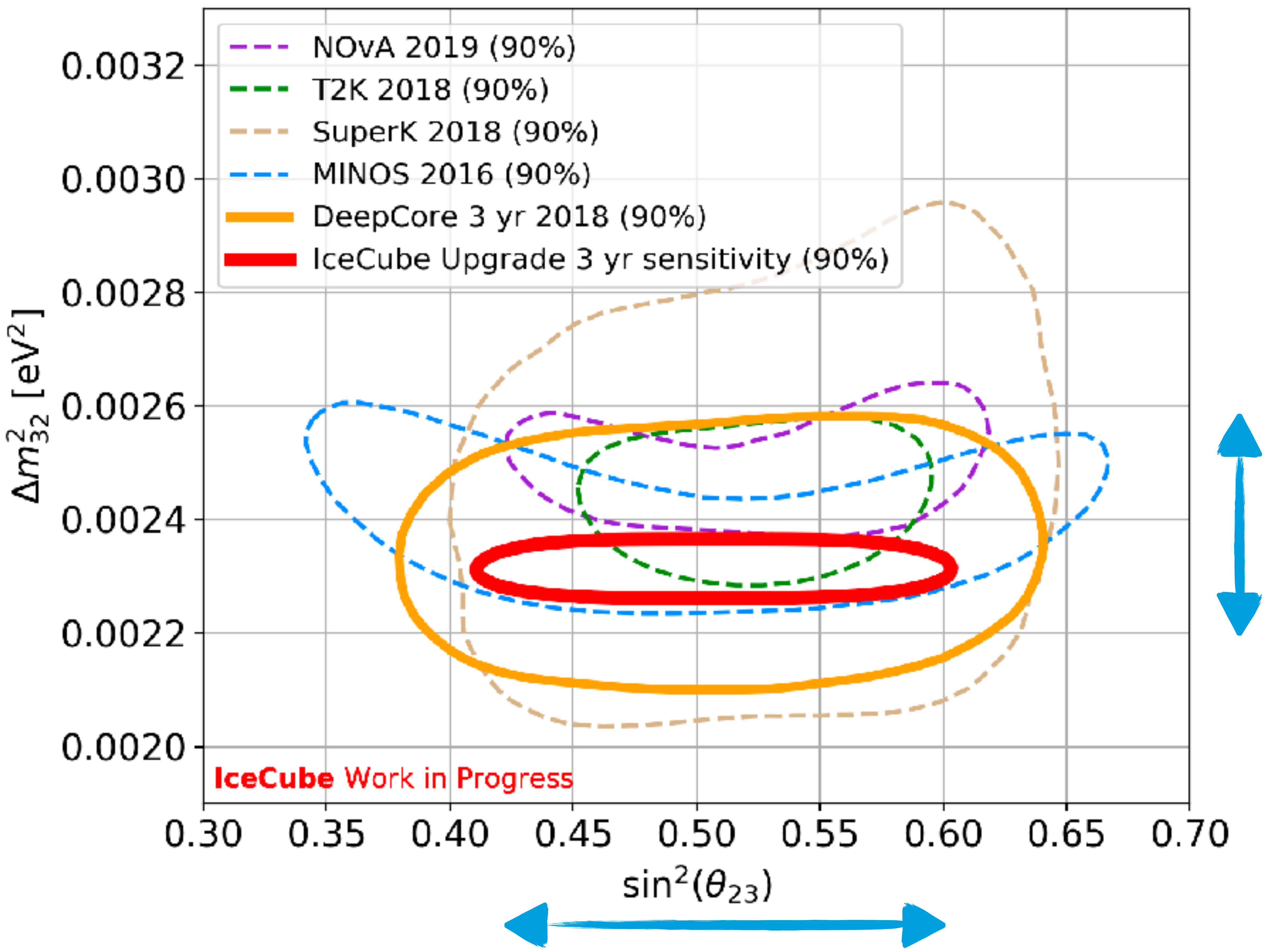
+++ Improved sensitivity to NMO, sterile nus, NSI, DM...



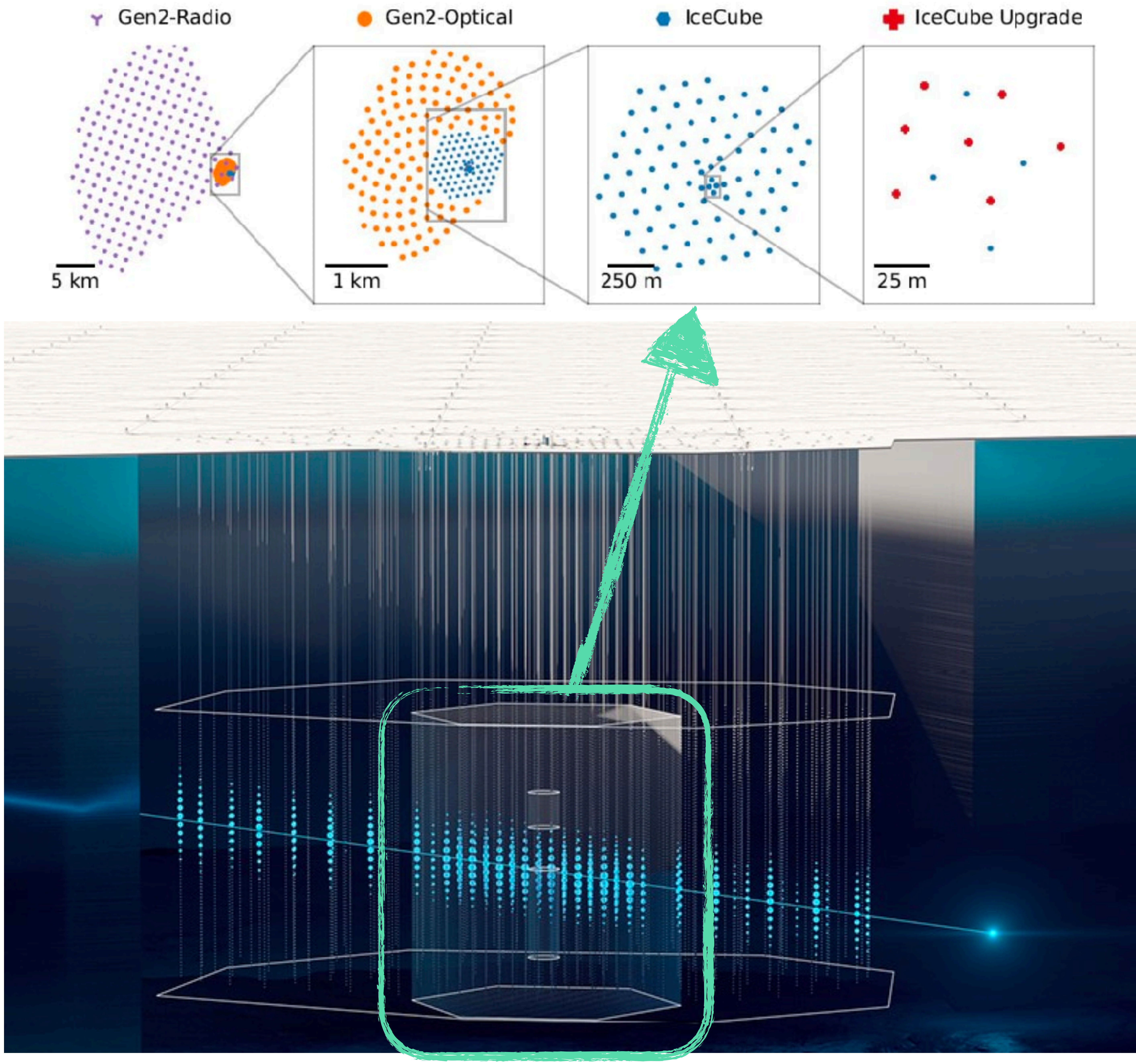
Approx. error on new 8 yr verification sample result

IceCube-Gen2

The next generation facility

- 8 km^3
- 12,000 new sensors
- Radio array for ultra-high energies
- Optical array 5x more sensitive

- ETA: 2032



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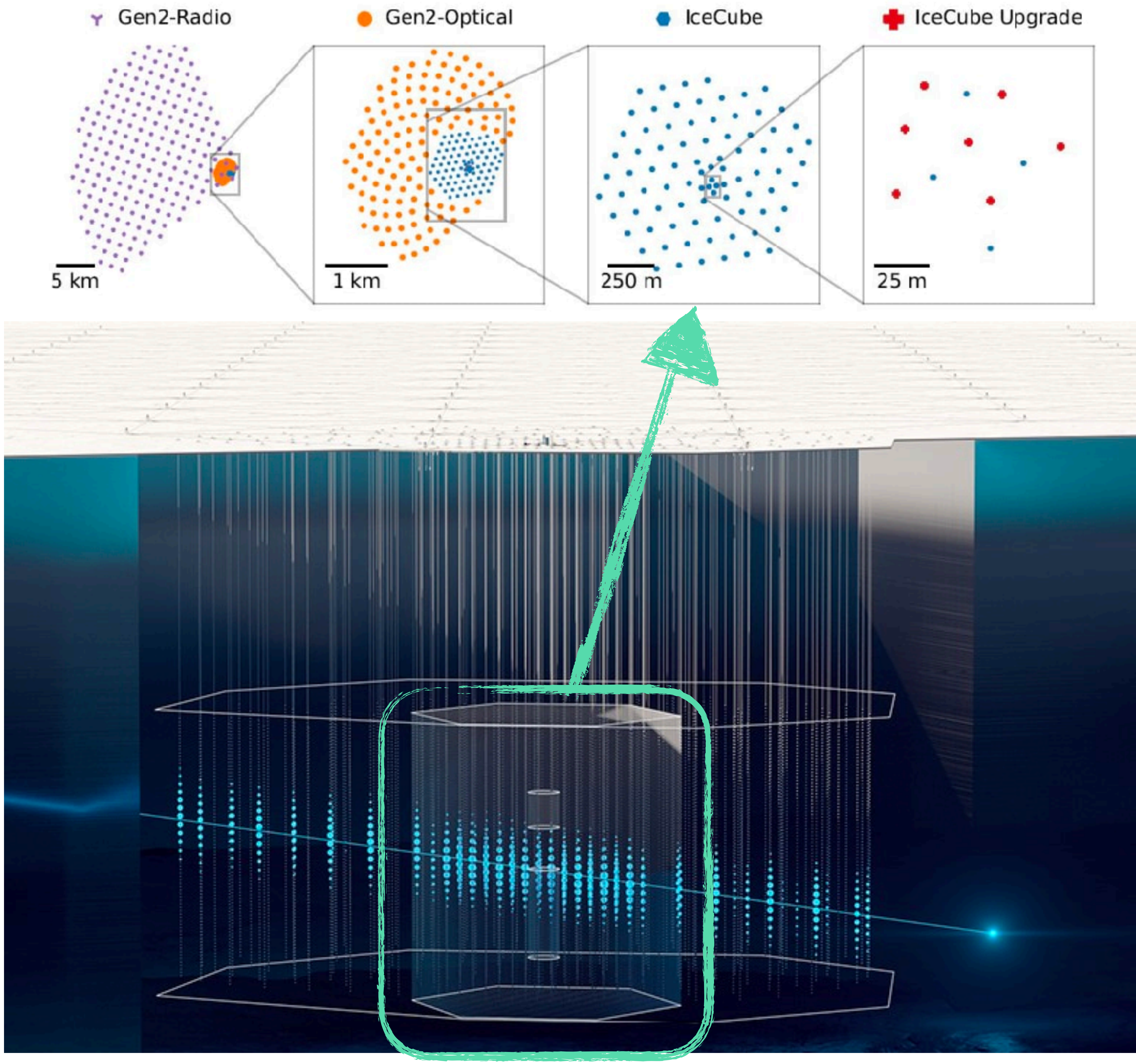
More details @ icecube-gen2.de



Summary

IceCube operating stably for over a decade, with GeV-scale physics enabled with DeepCore

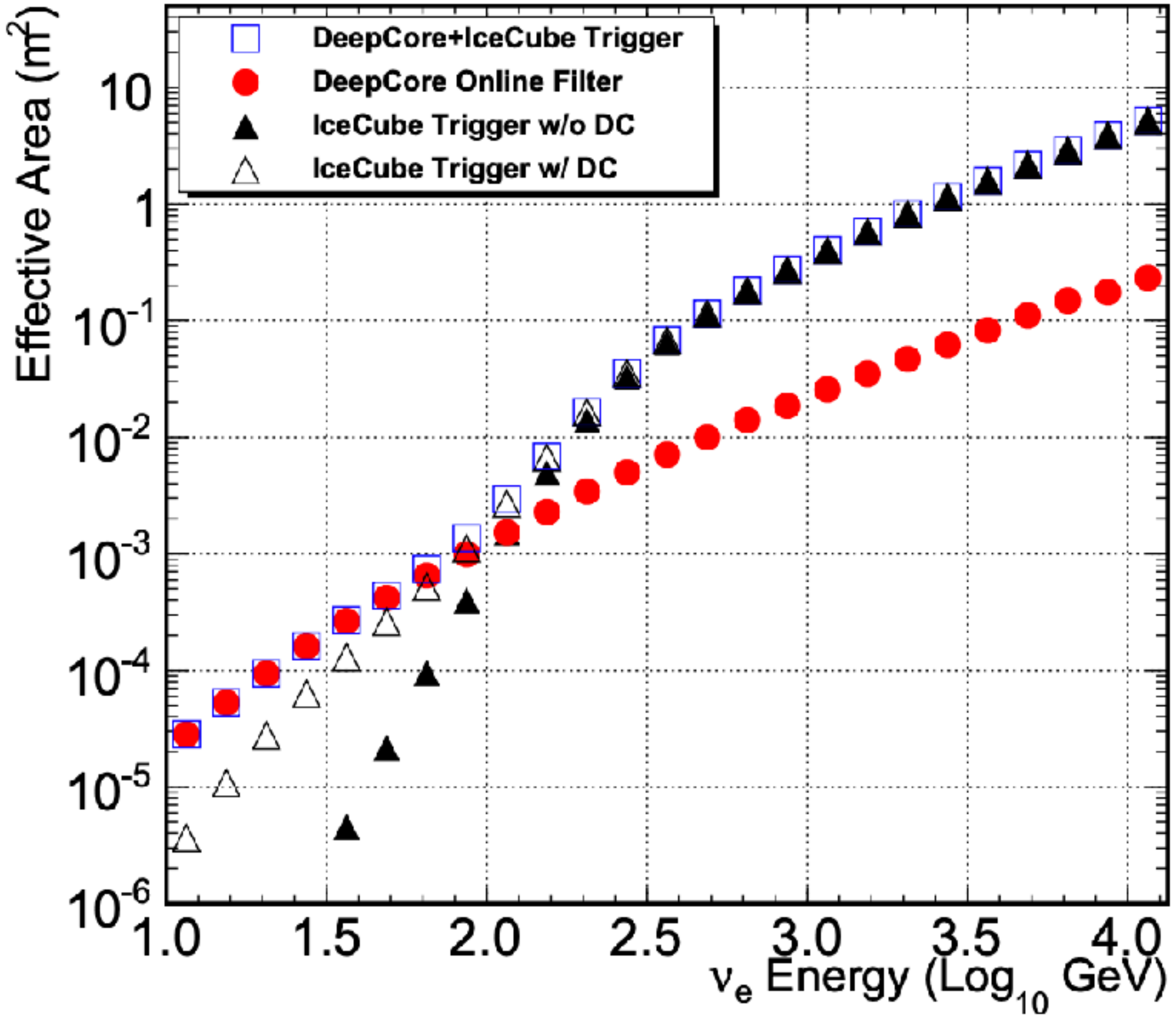
Natural detection medium is challenging to work with, but continued improvements in calibration lead to new and improved scientific results

IceCube Upgrade will enable more precise measurements of low energy neutrino properties, and better calibrations will benefit entire IceCube science program

Backup

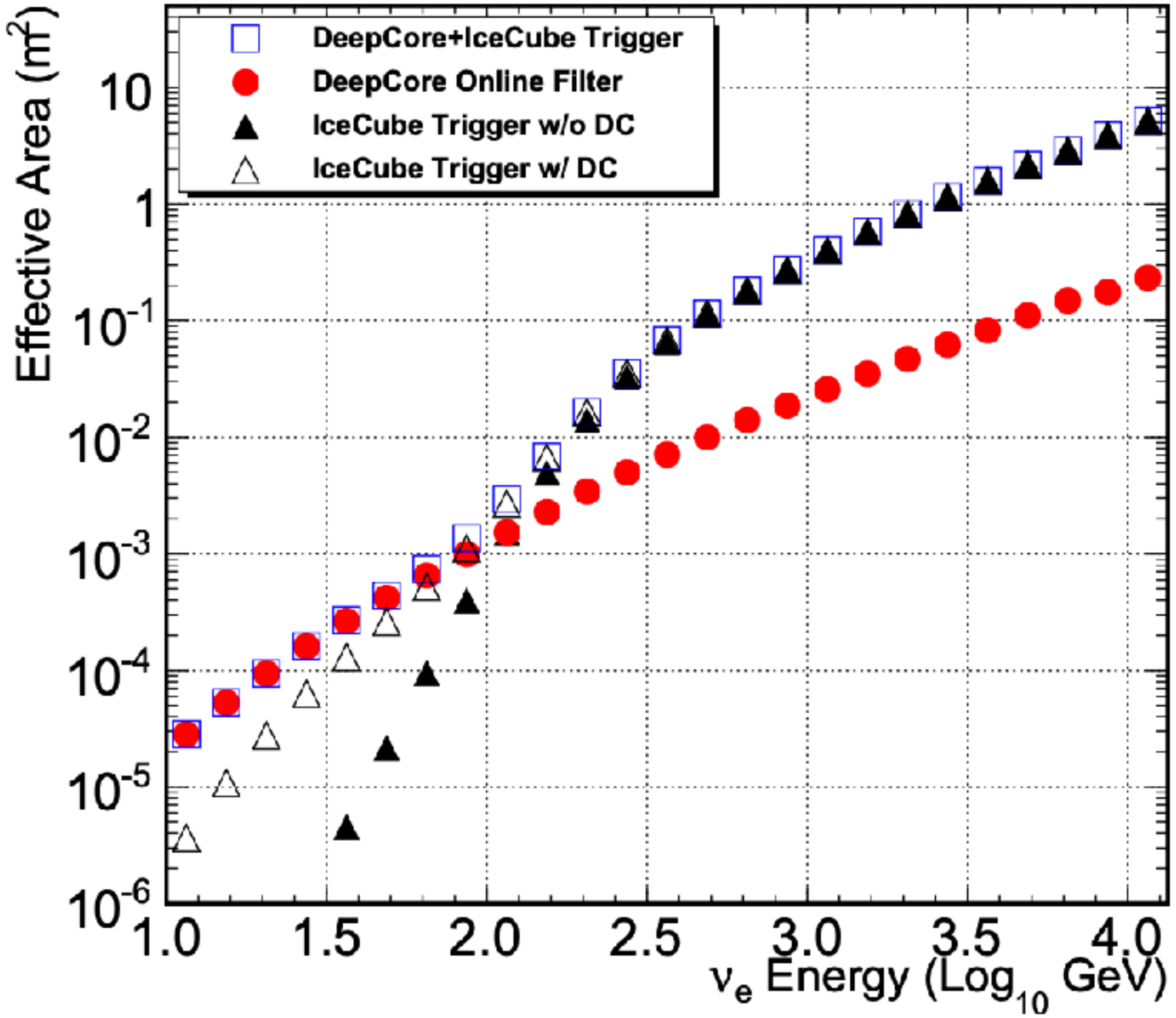
DeepCore

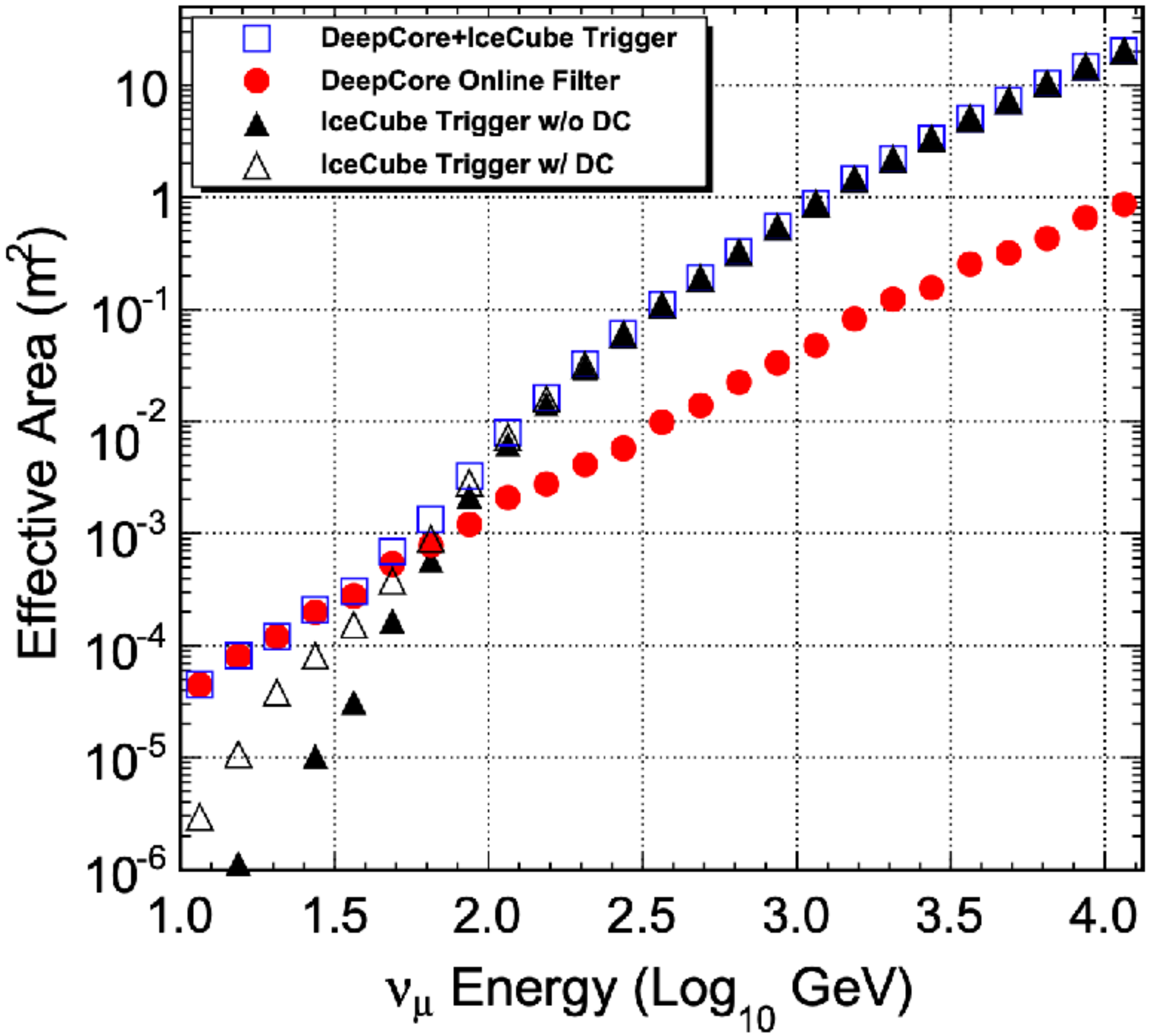
Effective Areas



DeepCore

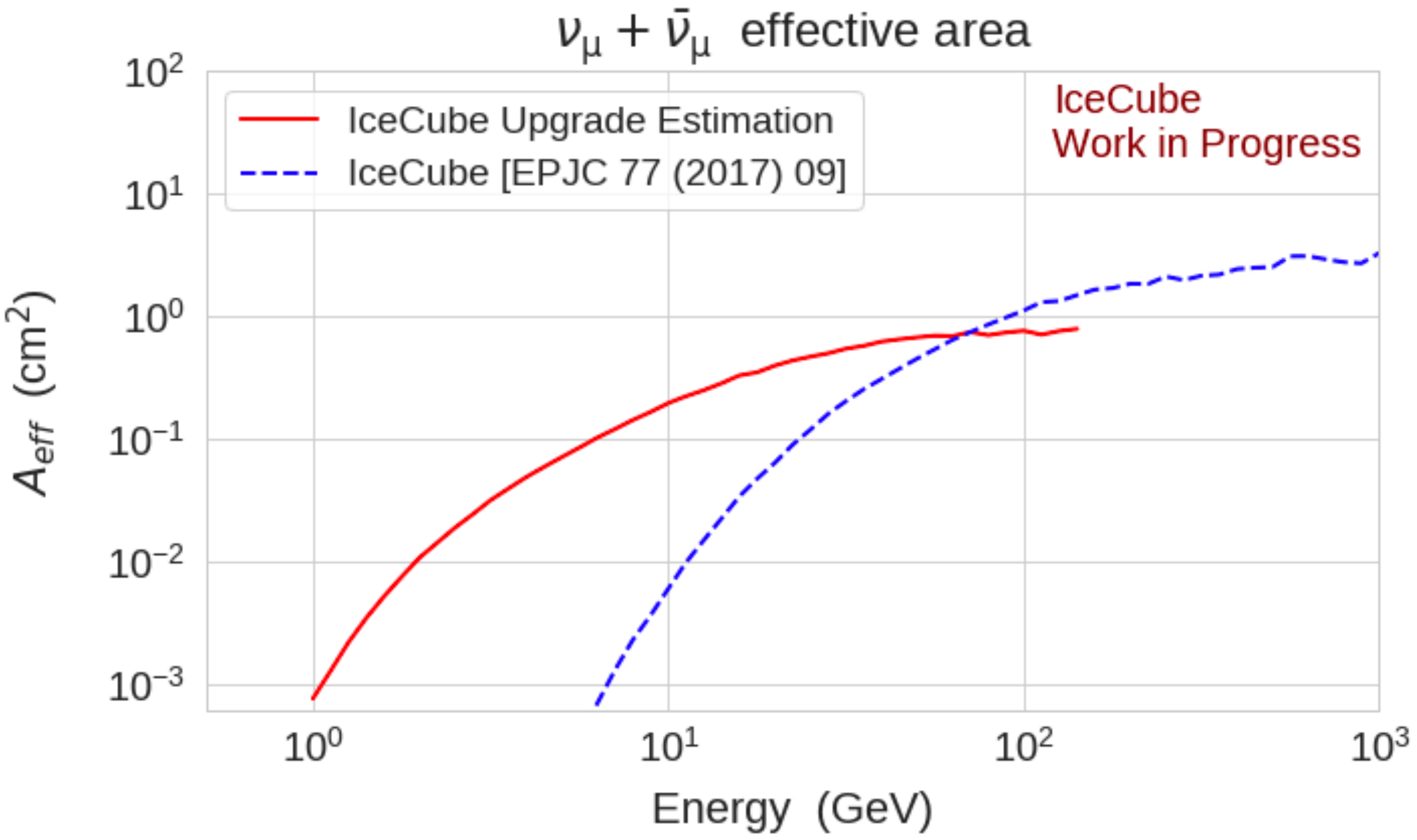
Effective Areas





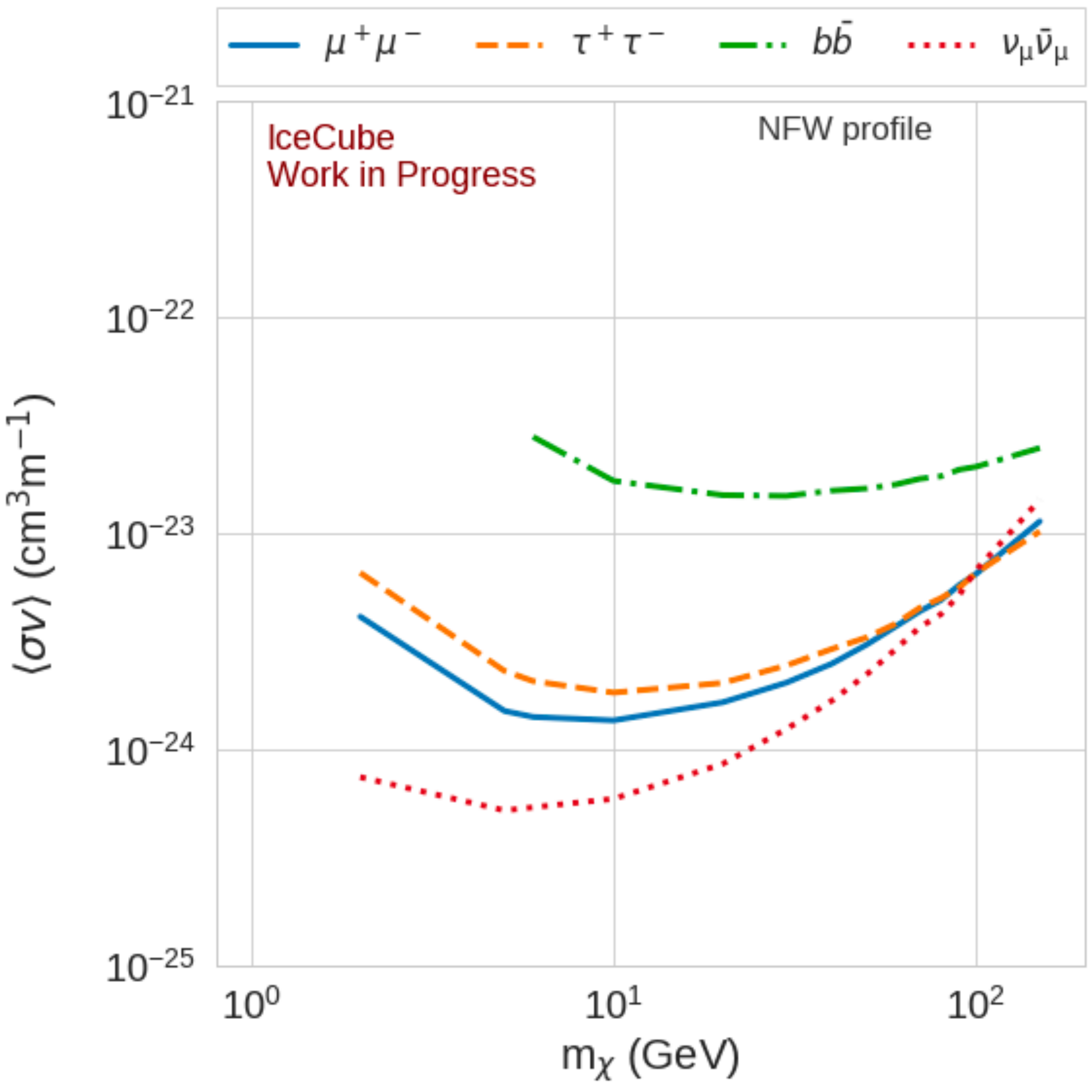
Upgrade

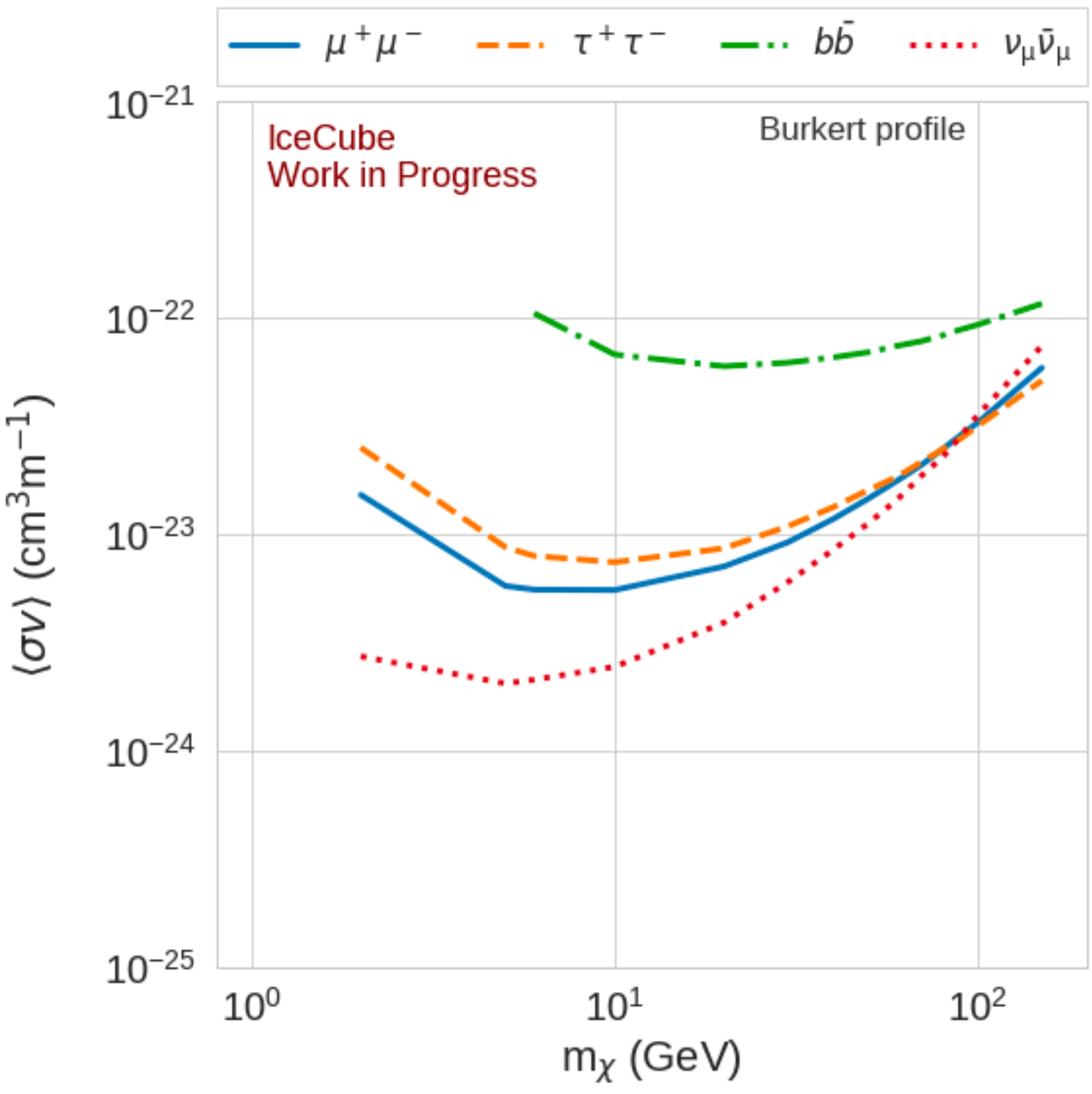
Effective Area



Upgrade

Effective Area





Neutrino oscillations

The experimental landscape

DeepCore measures oscillations at higher energies and over longer baselines (with differing matter profile) than accelerator experiments

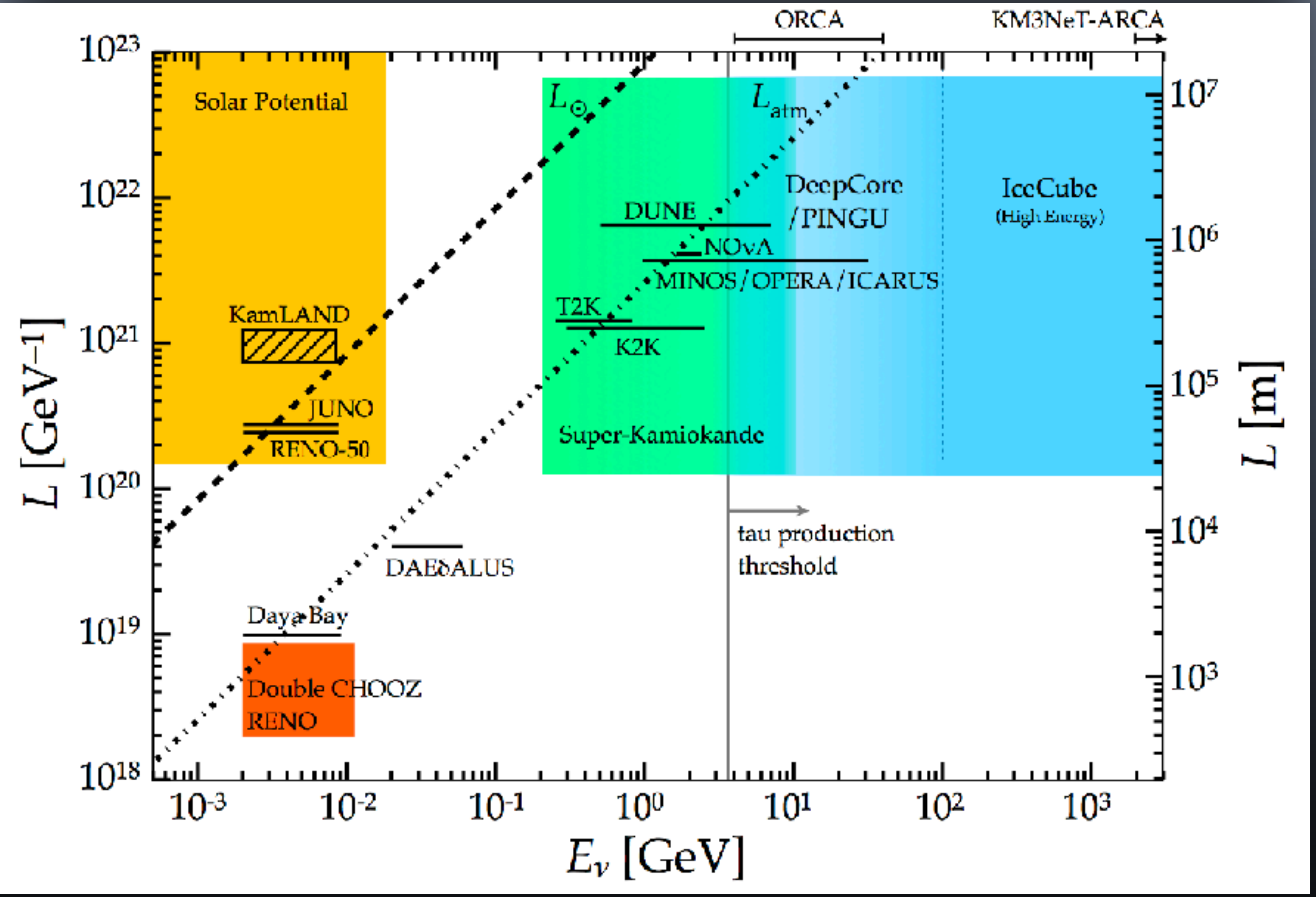
Well above the tau production threshold

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

DeepCore

U_{PMNS} unitarity implies, e.g.:

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$



Searching beyond the νSM

Non-standard oscillation patterns

Favourable phase space

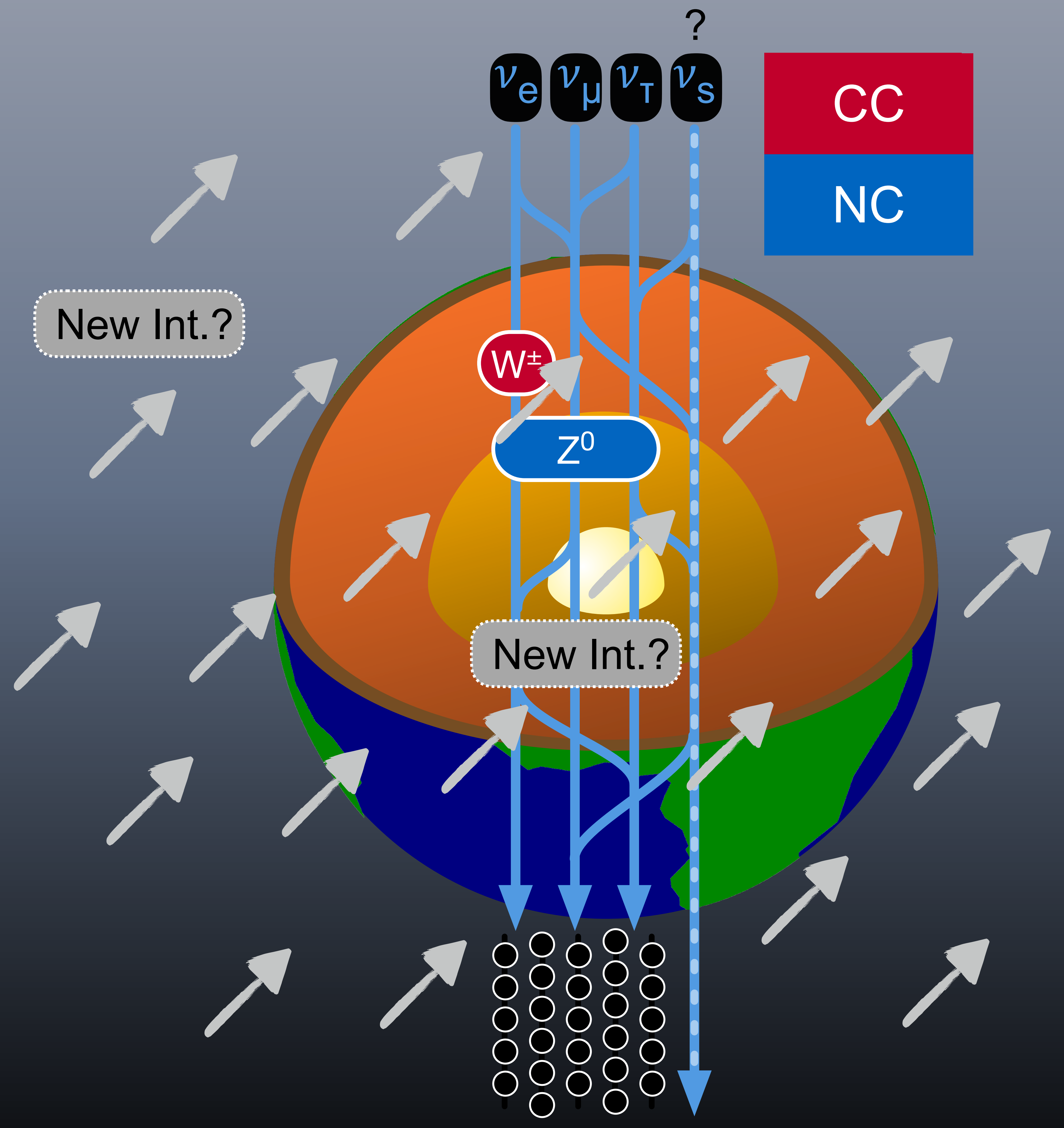
- High energies: access new physics coupling to τ-sector
- Long trajectories: exposure to new fields/interactions

Model dependent searches for new physics, e.g.:

- eV-scale sterile neutrinos
- Non-standard interactions
- ….+ much more!

Expected signatures are assessed by modifying neutrino mixing matrix and potential

$$\hat{H} = \frac{1}{2E} U\hat{M}^2U^\dagger + \hat{V}_{int}$$



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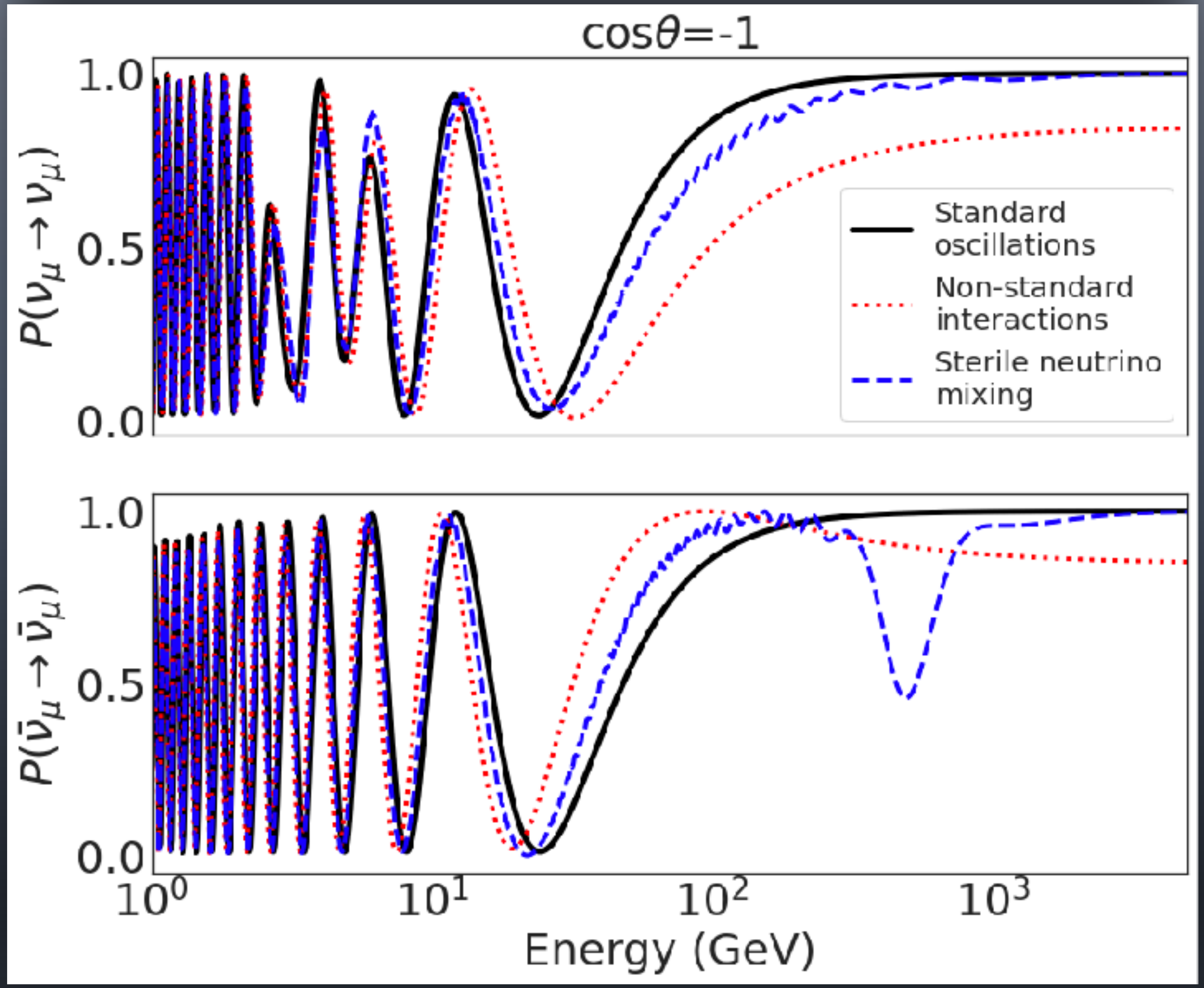
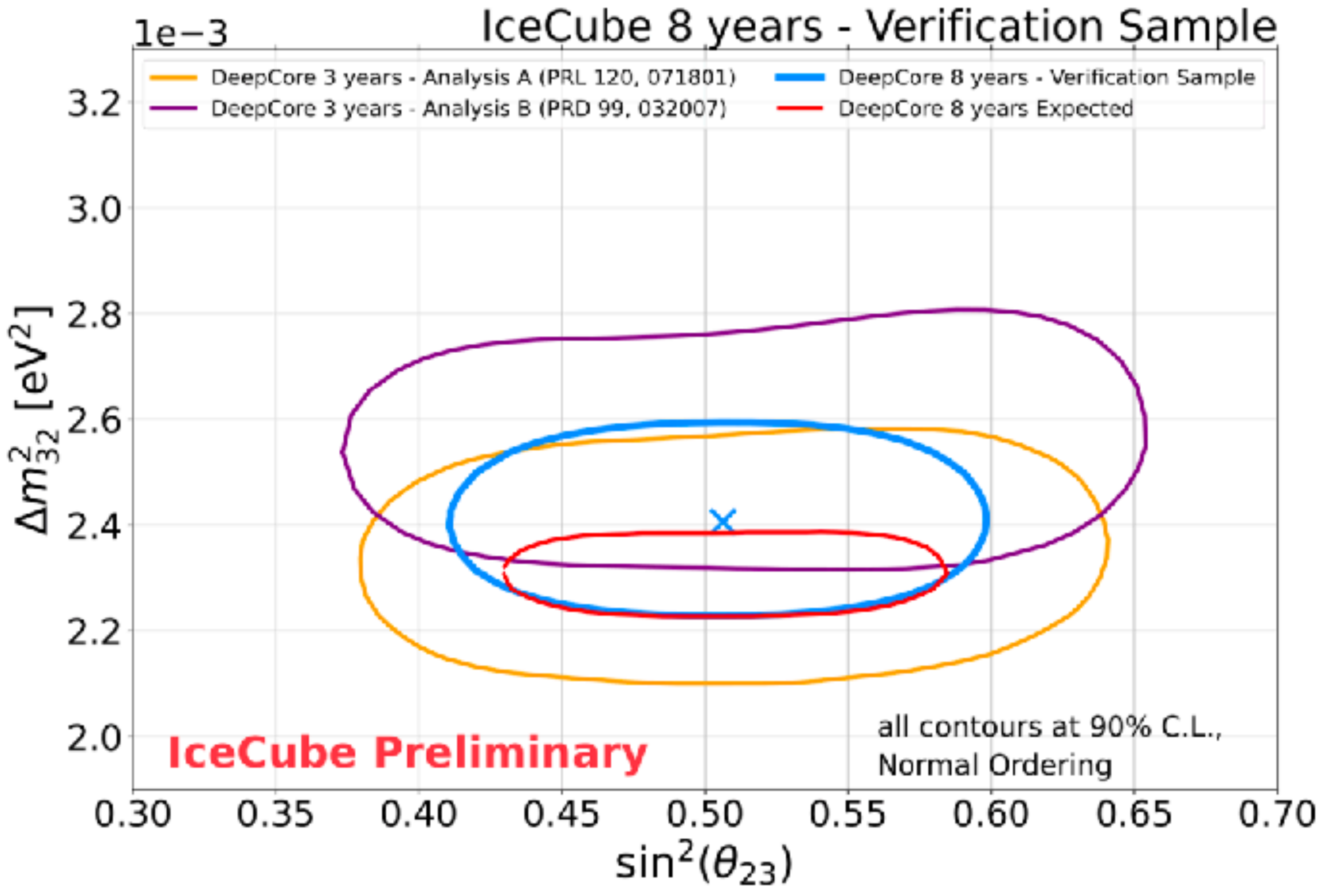
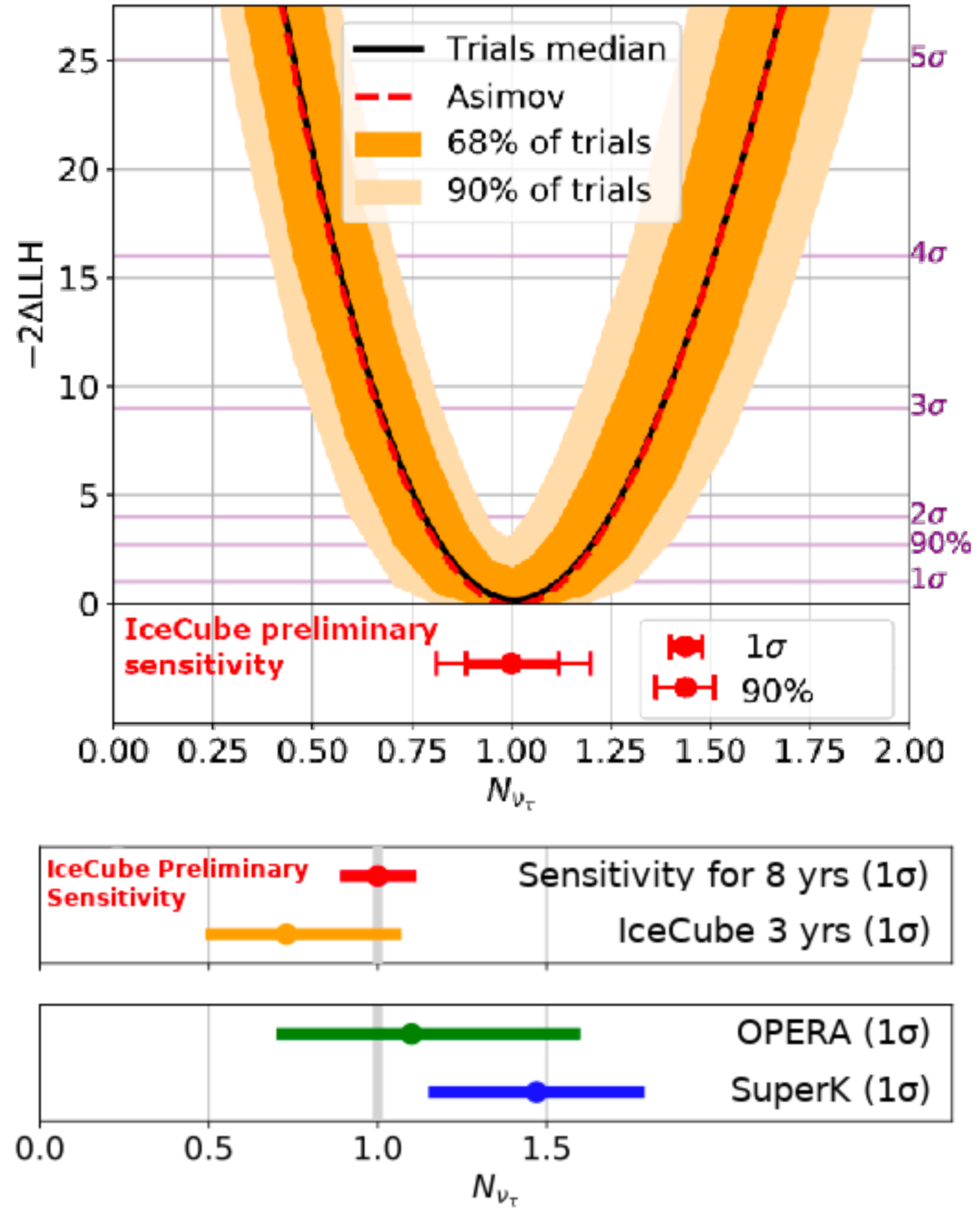


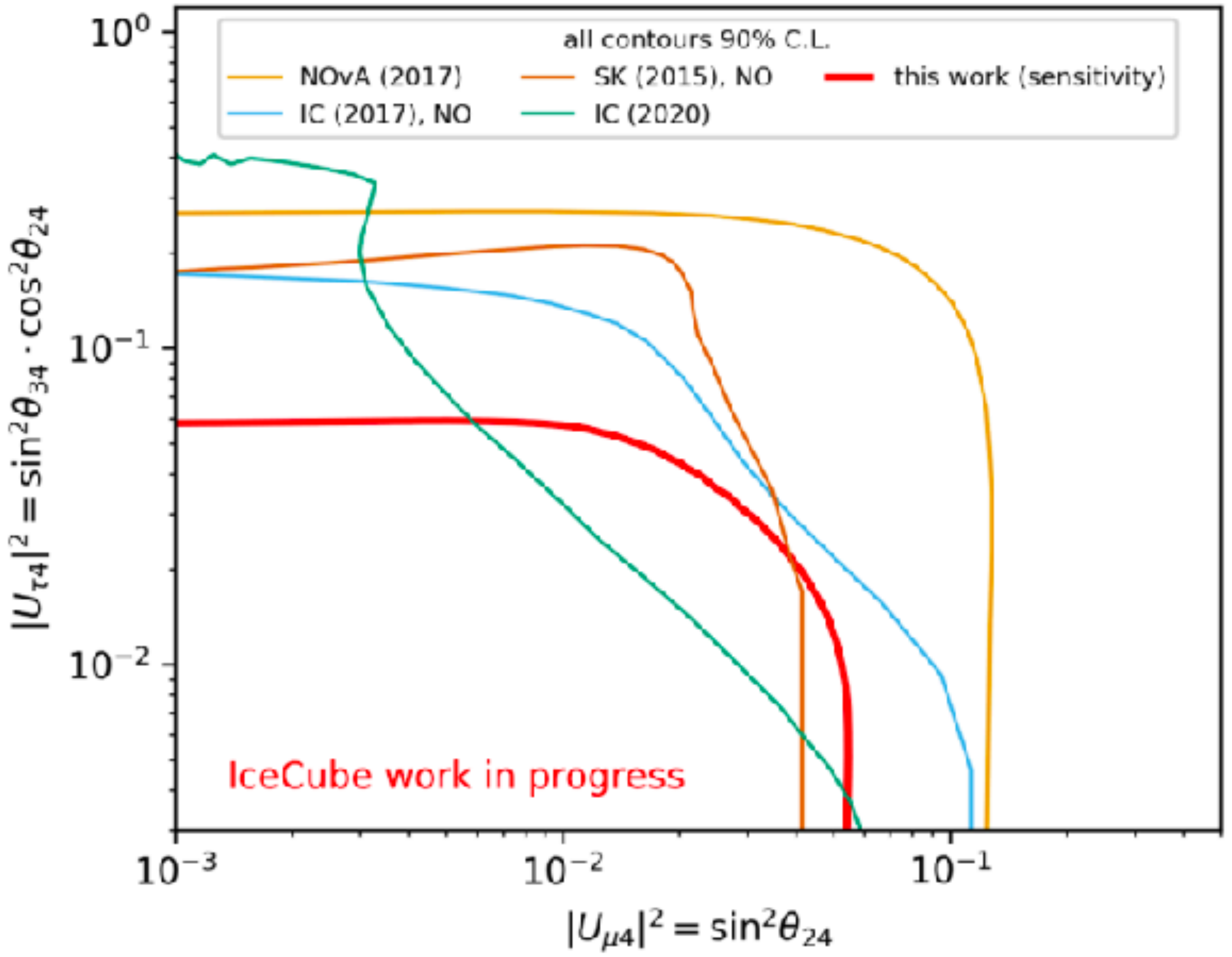
For particular realisations of non-standard physics

Full 8 year DeepCore sample

Expected sensitivities







Standard atmospheric oscillations

(Assume PMNS unitarity)

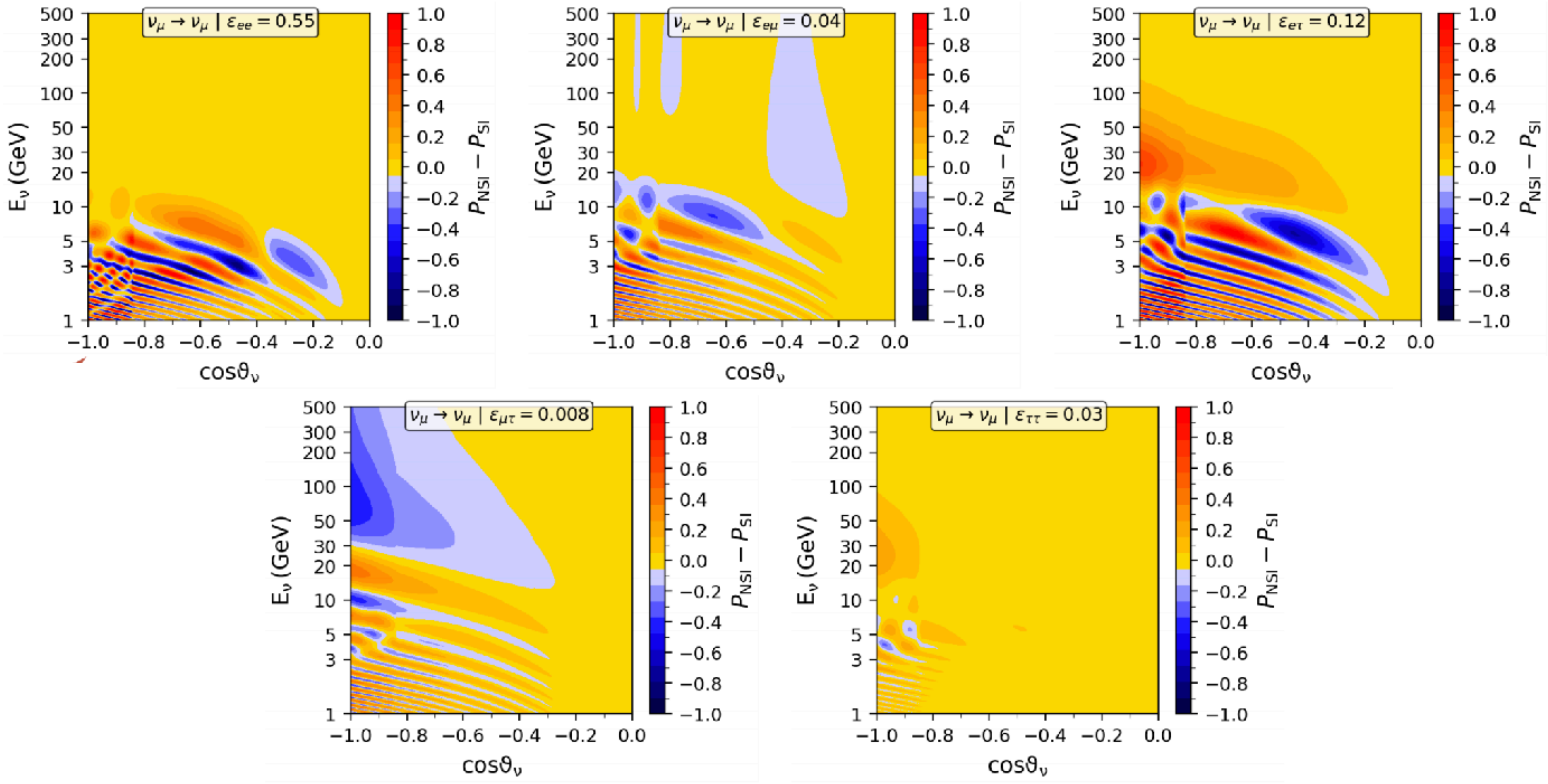
Model independent test of PMNS unitarity

eV sterile neutrino mixing

(Assume 4x4 unitarity)

NSI

Effect of different NSI couplings



Non-standard disappearance at high energy due to $\varepsilon_{e\mu}$ & $\varepsilon_{\mu\tau}$

Less disappearance at high energy due to $\varepsilon_{e\tau}$ & $\varepsilon_{\tau\tau}$

See poster #364 for more details

Non-standard interactions

New constraints from 3-year DeepCore sample

New mediators, e.g. Z'

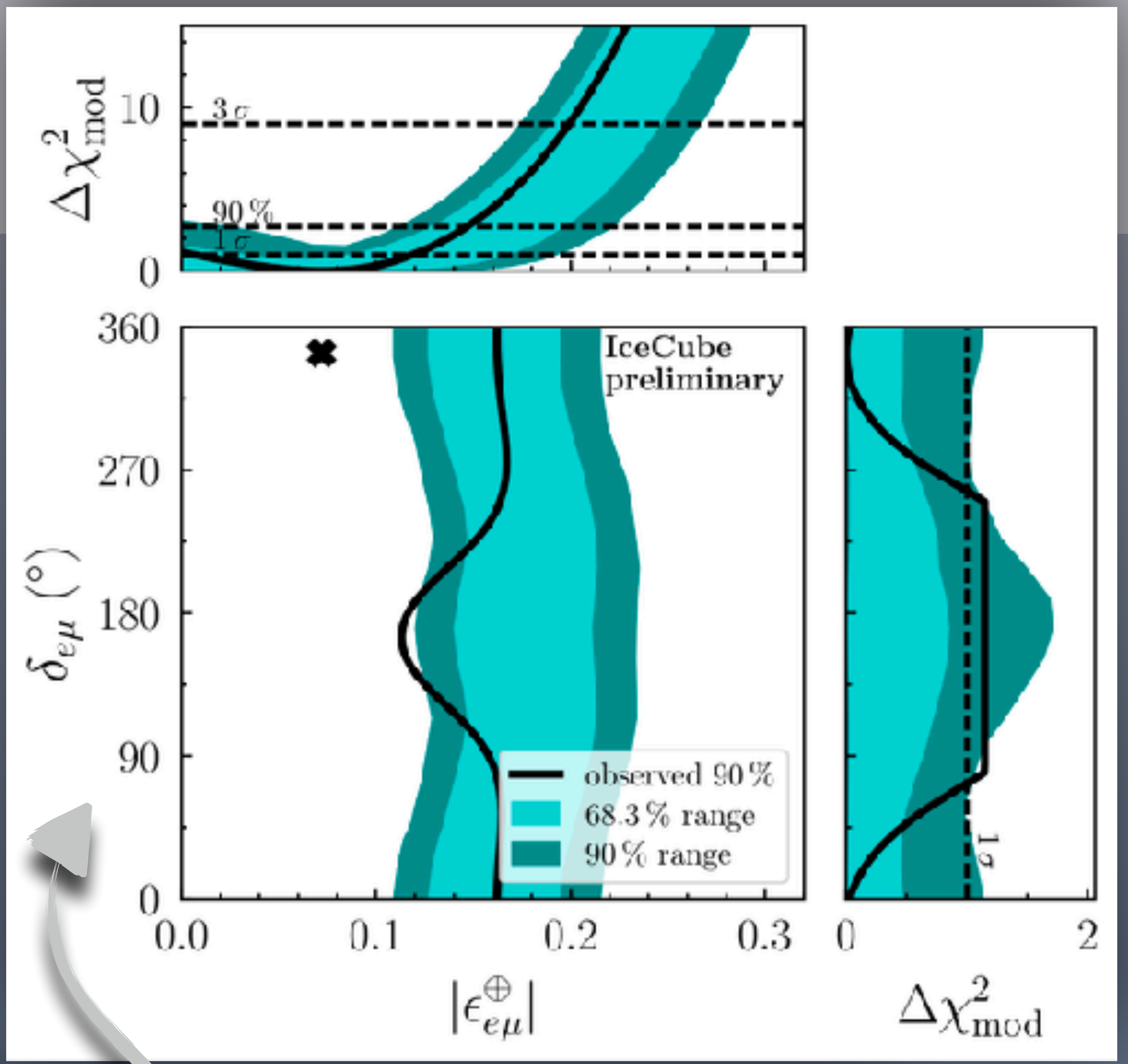
- Creates non-standard flavour changes
- Modifies effective matter potential experienced by neutrinos in transit through the Earth

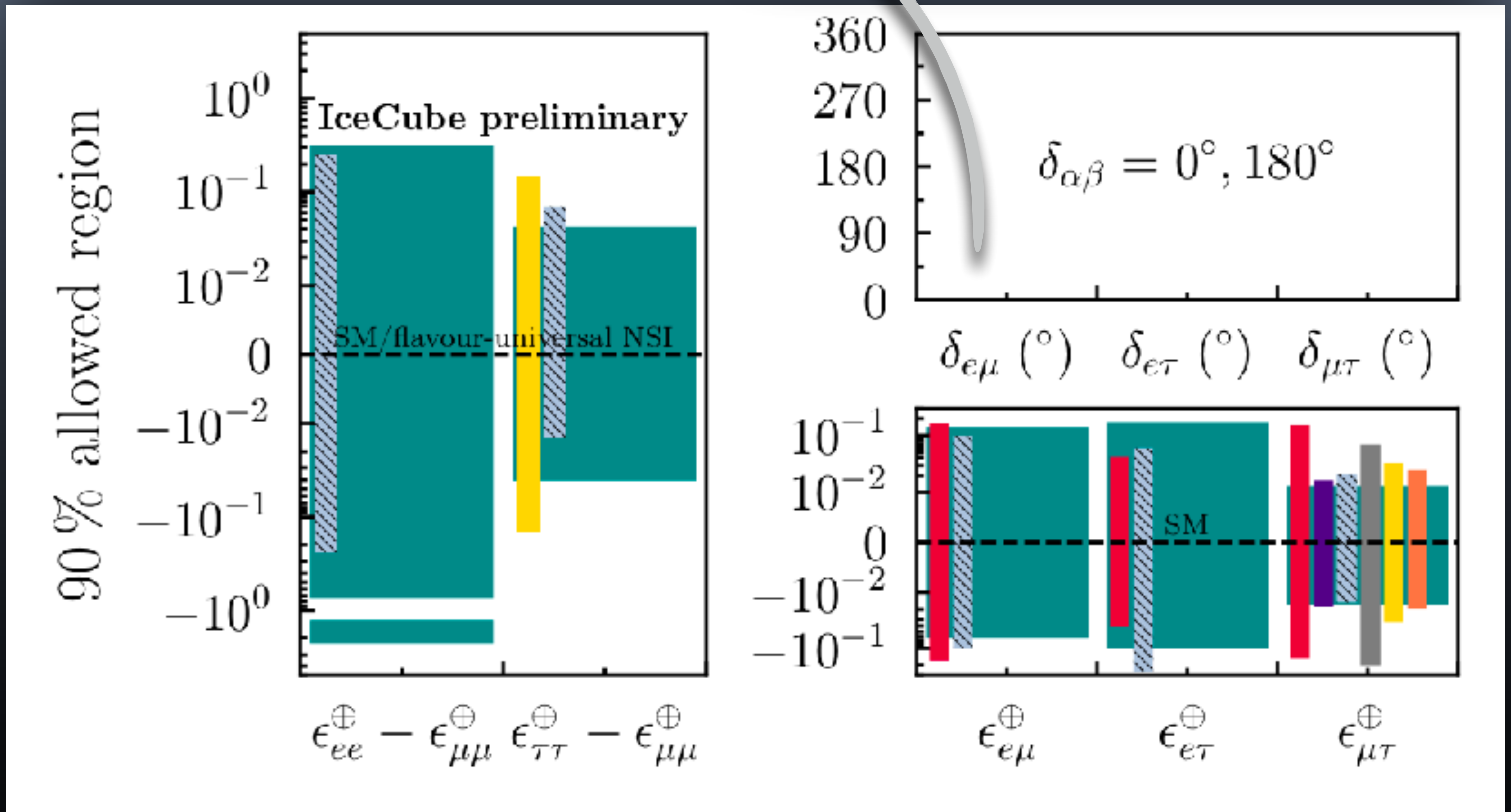
$$H_{\mathrm{mat}}(x) = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + (\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu})(x) & \epsilon^{\oplus}_{e\mu}(x) & \epsilon^{\oplus}_{e\tau}(x) \\ \epsilon^{\oplus *}_{e\mu}(x) & 0 & \epsilon^{\oplus}_{\mu\tau}(x) \\ \epsilon^{\oplus *}_{e\tau}(x) & \epsilon^{\oplus *}_{\mu\tau}(x) & (\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu})(x) \end{pmatrix}$$

for Earth: $\epsilon^{\oplus}_{\alpha\beta}(x) \approx \epsilon^{\oplus}_{\alpha\beta} = \epsilon^{e}_{\alpha\beta} + \epsilon^{p}_{\alpha\beta} + 1.051\epsilon^{n}_{\alpha\beta}$

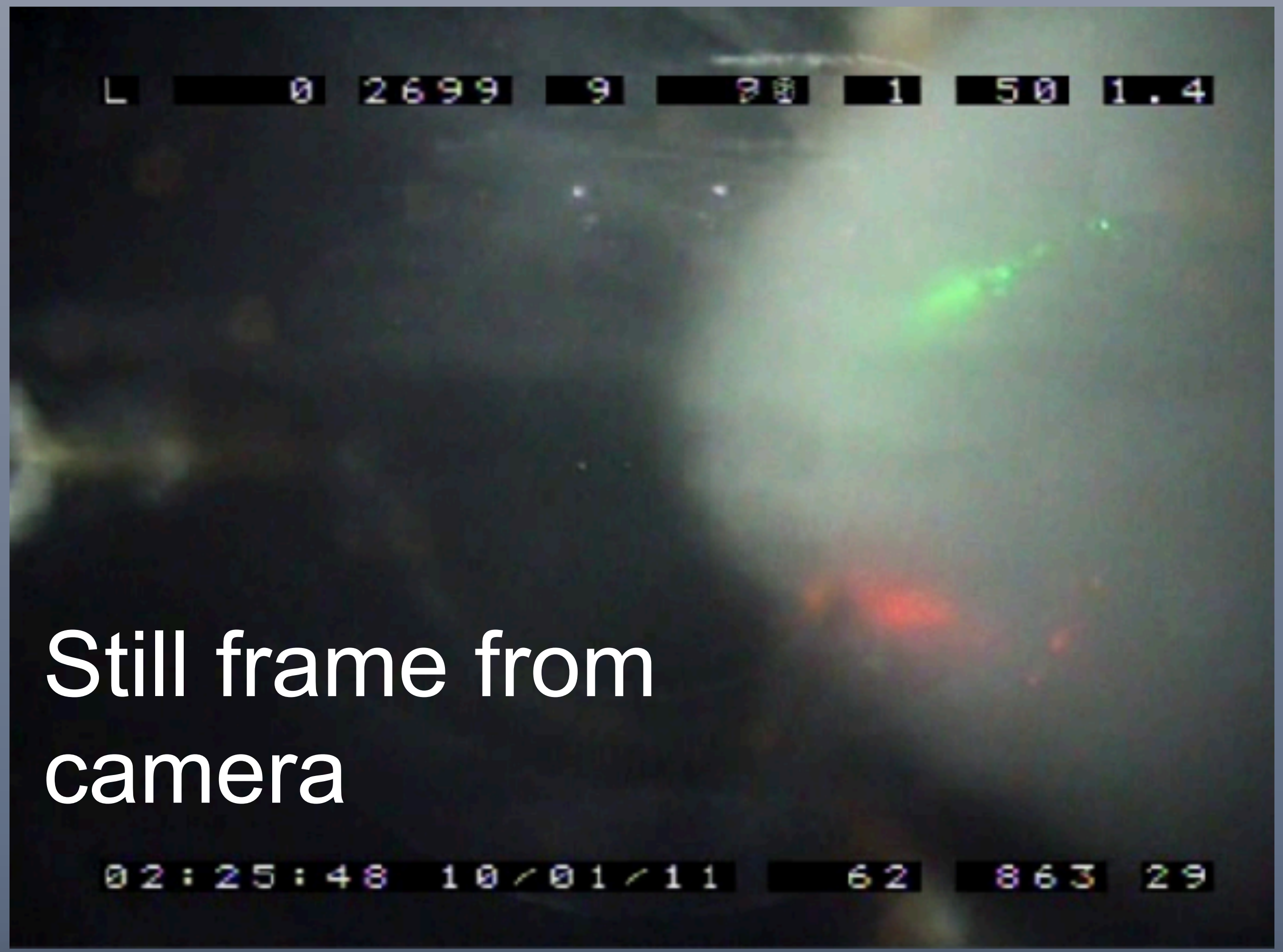
Results are consistent with the null hypothesis

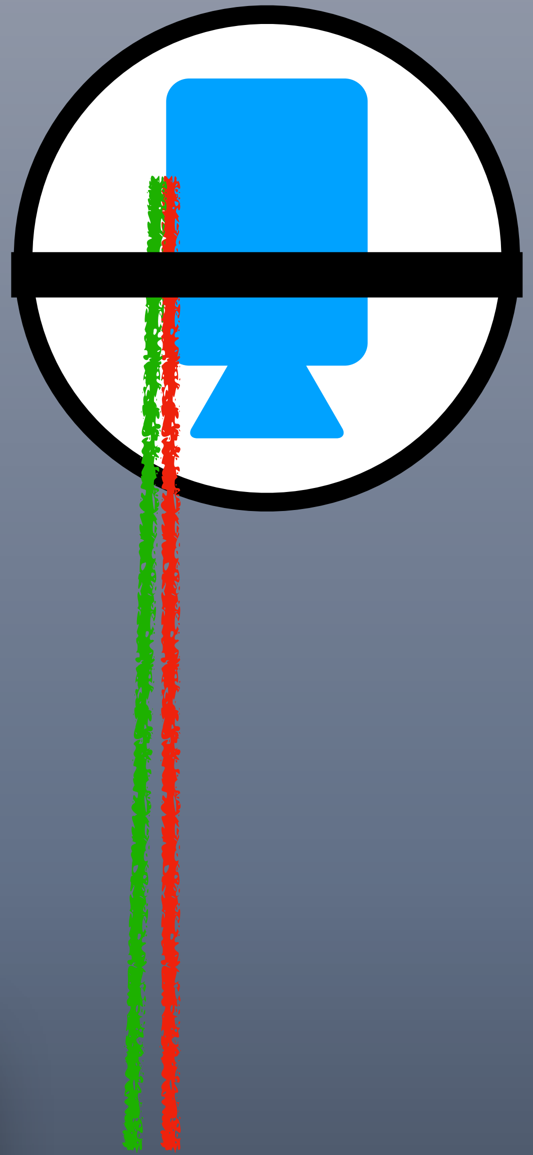
- Constrain real couplings with phases fixed to 0
- *New* - full parameter fit includes complex phases

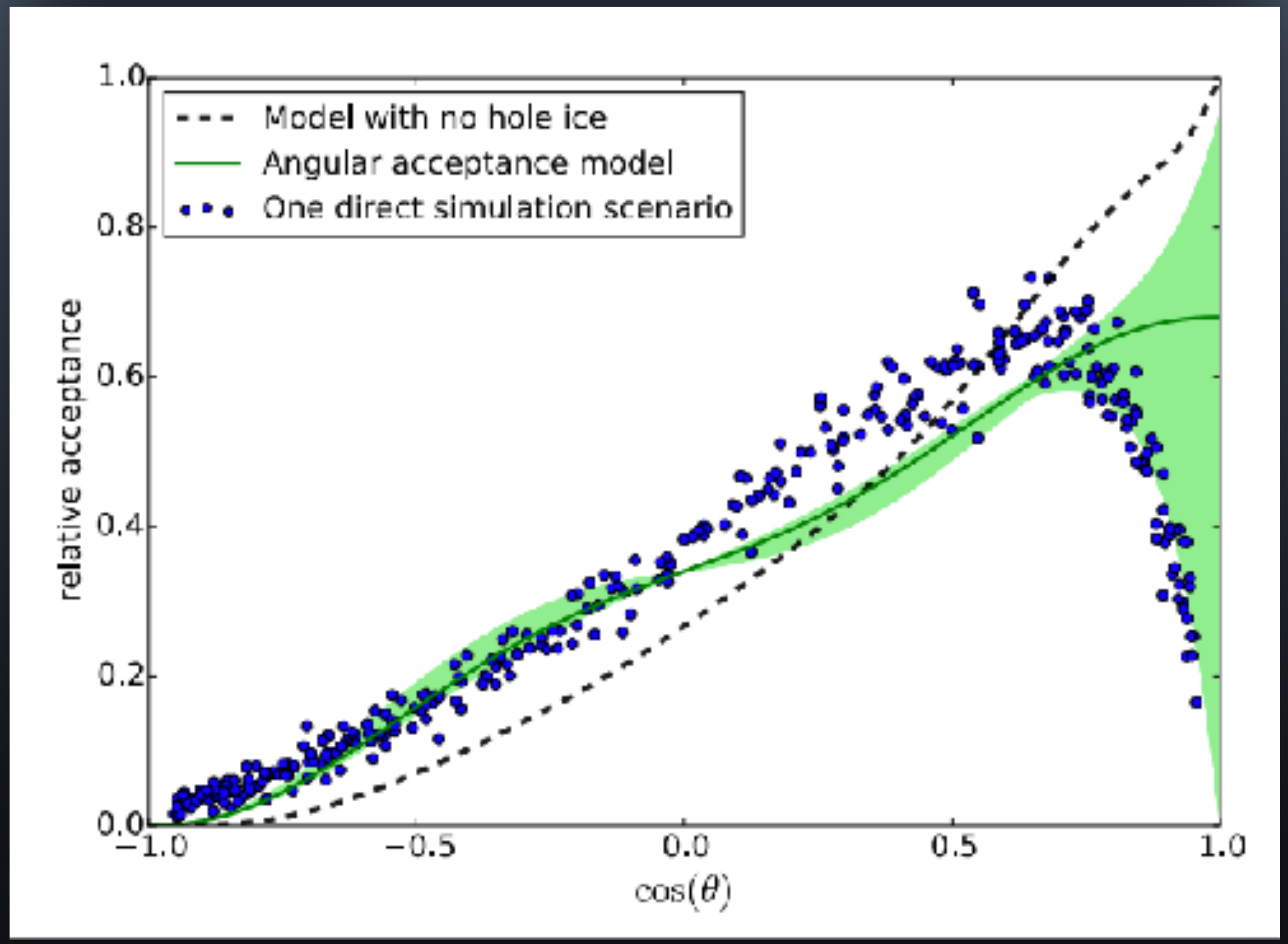


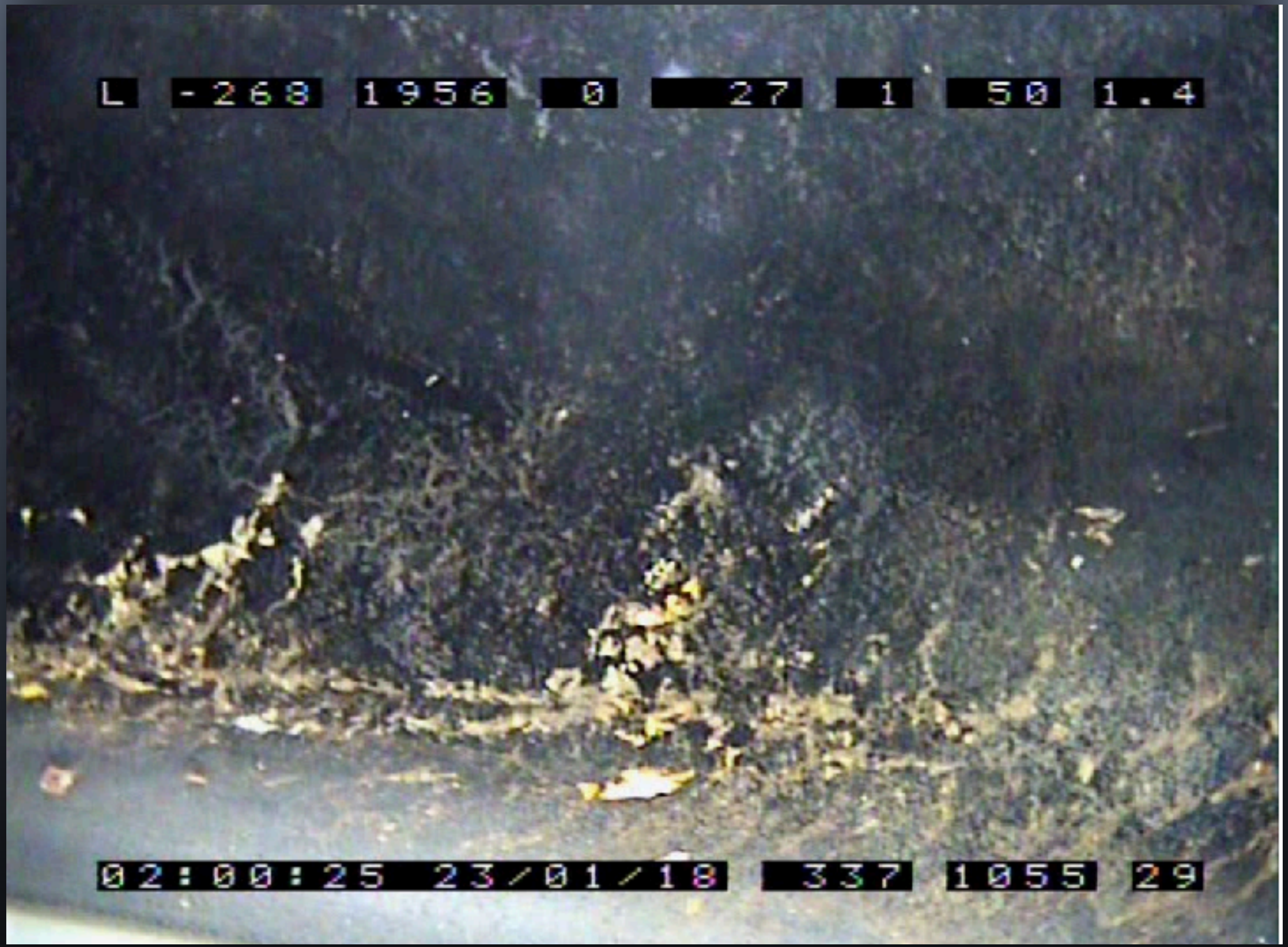


Local ice/DOM features





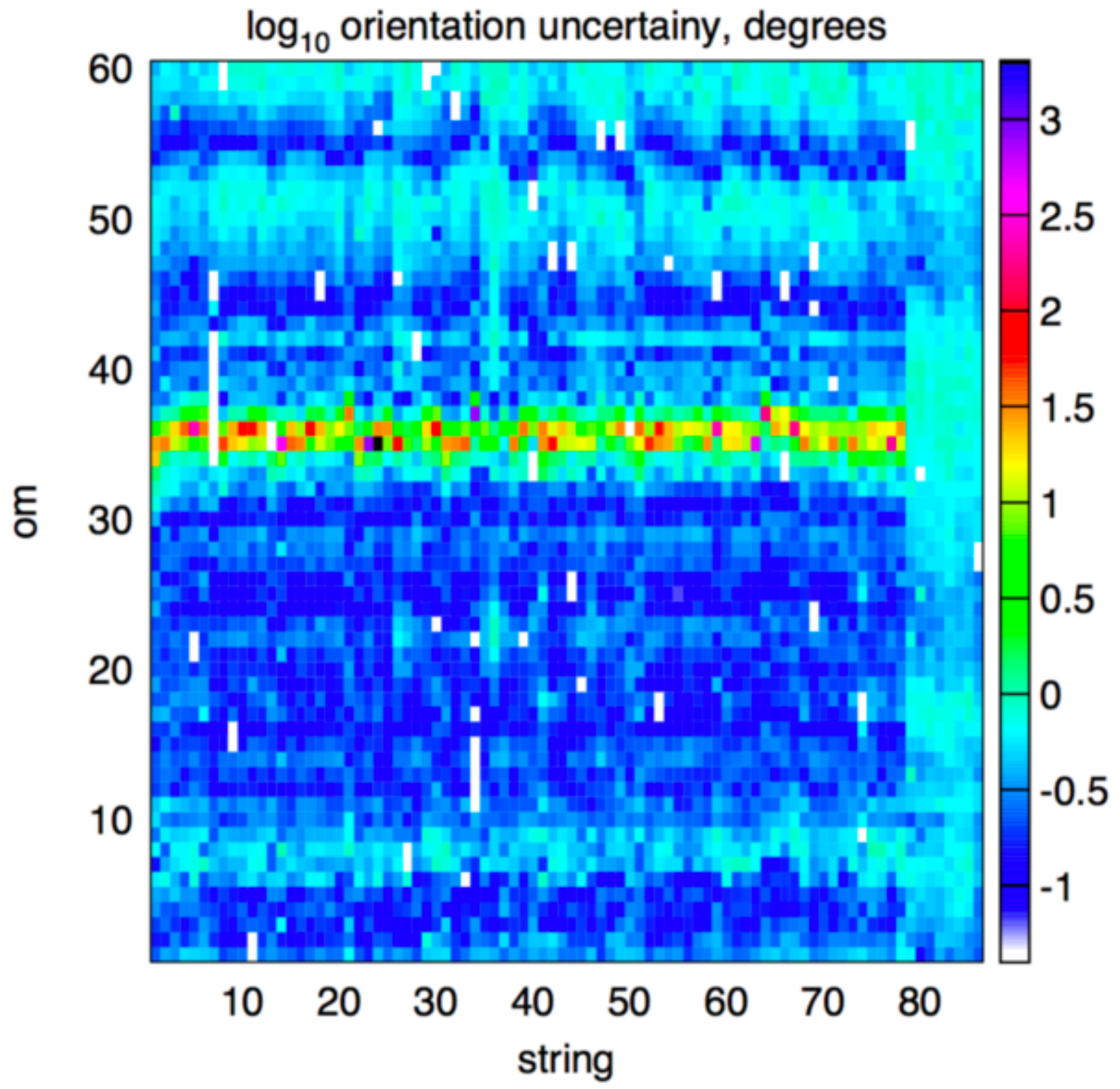


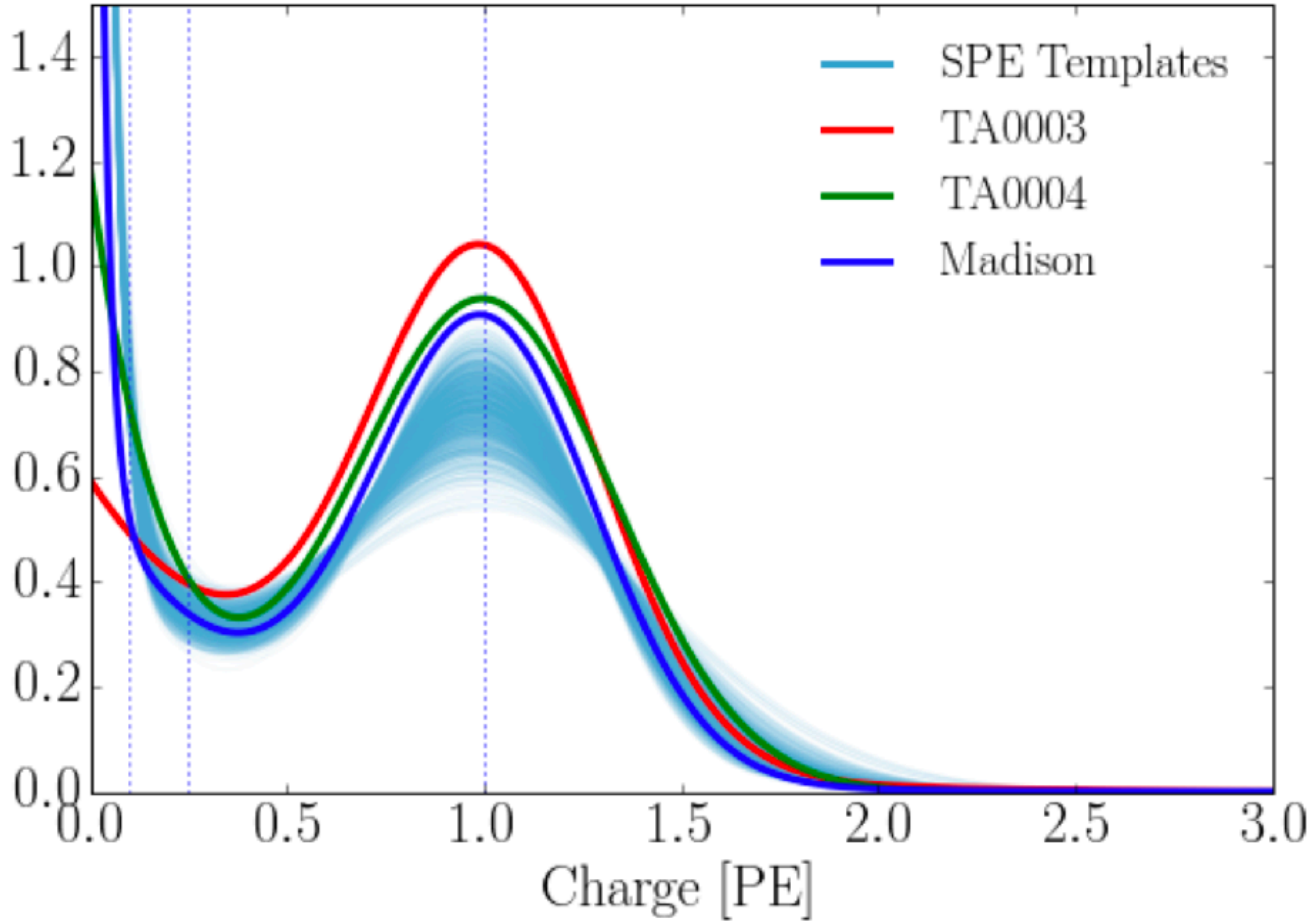


Detector recalibration

“With great statistics comes great responsibility”

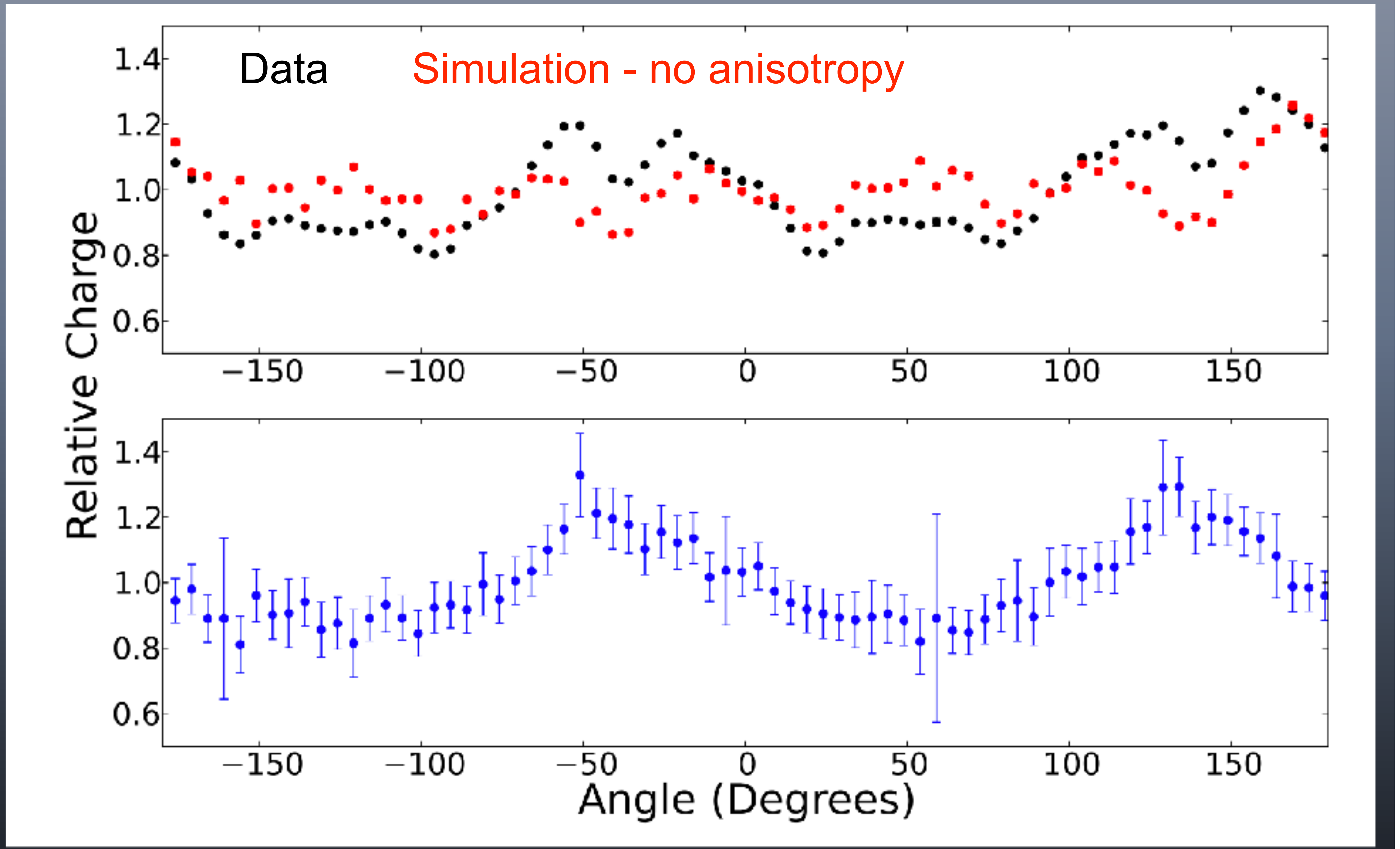
https://arxiv.org/abs/2002.00997

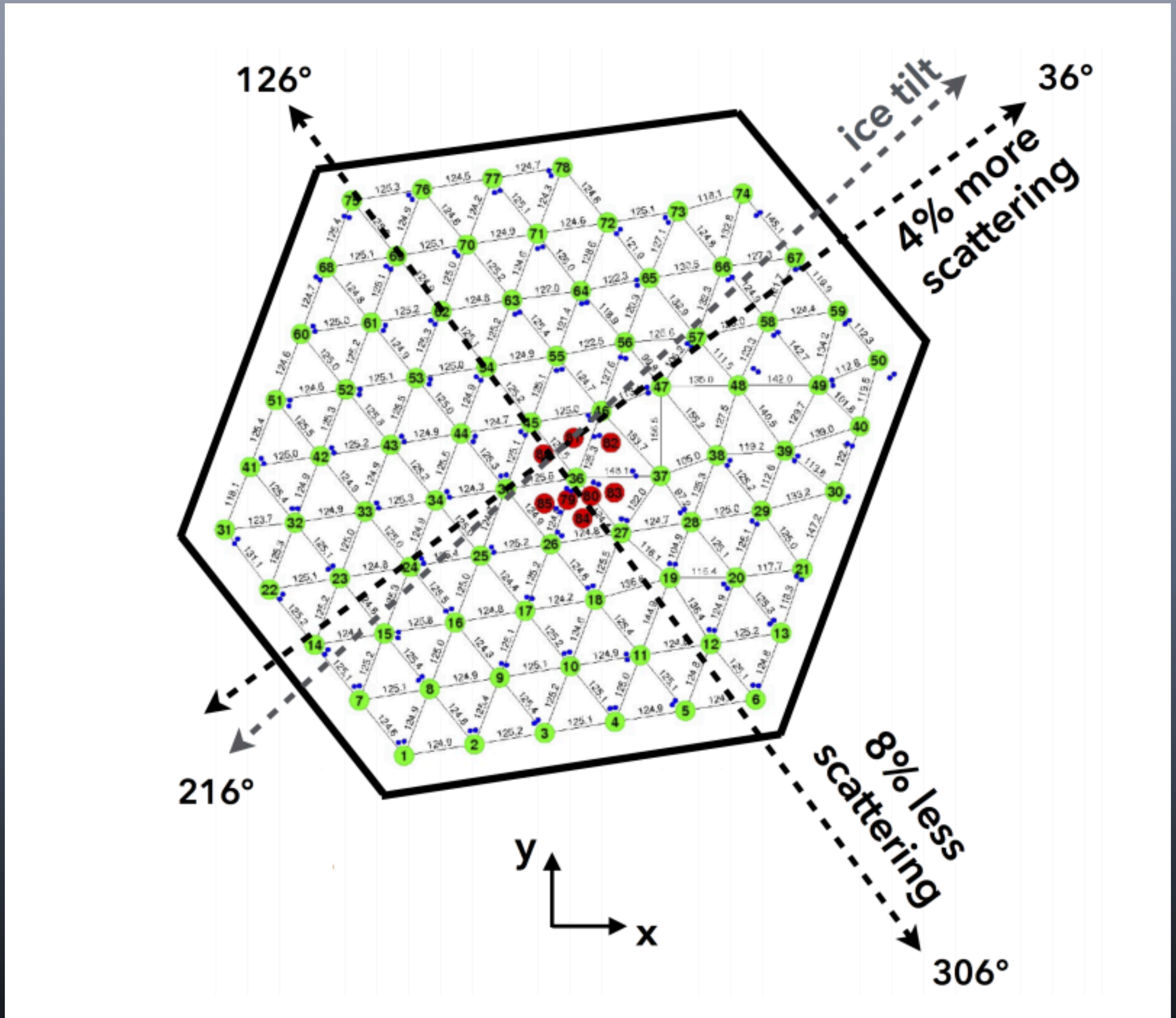




Ice anisotropy

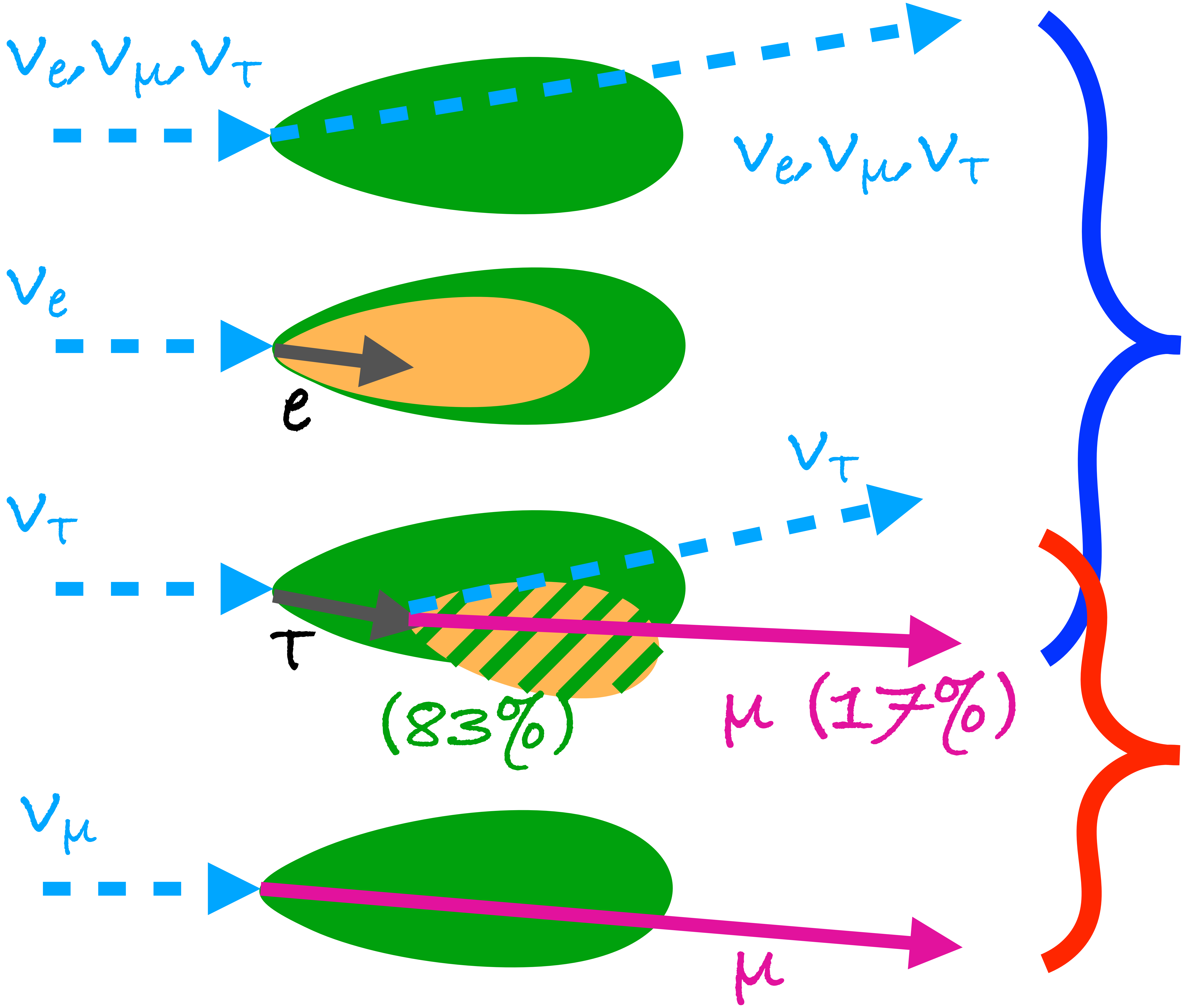
South Pole ice anisotropy: Proceedings of ICRC2013 0580, 2014

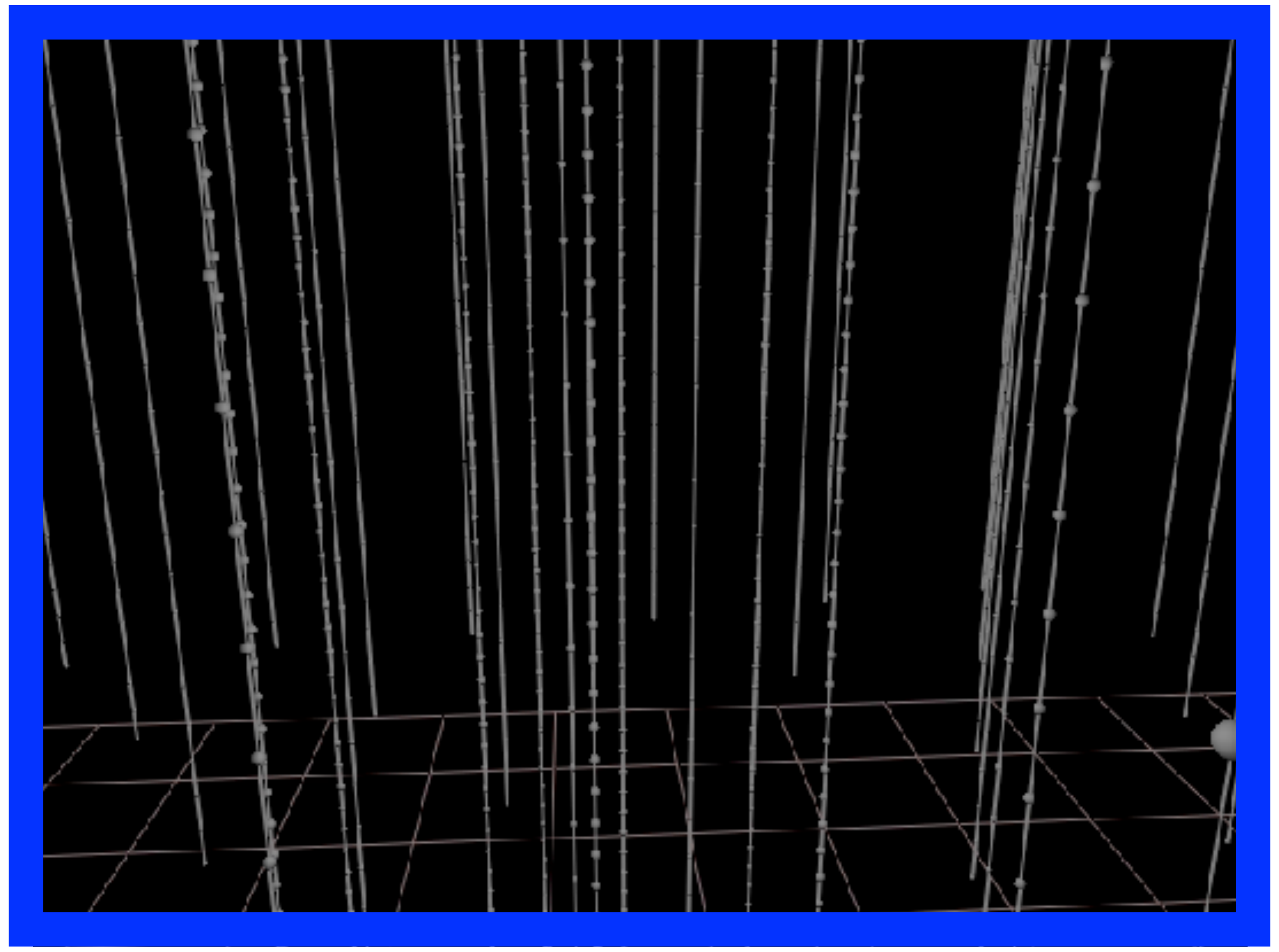


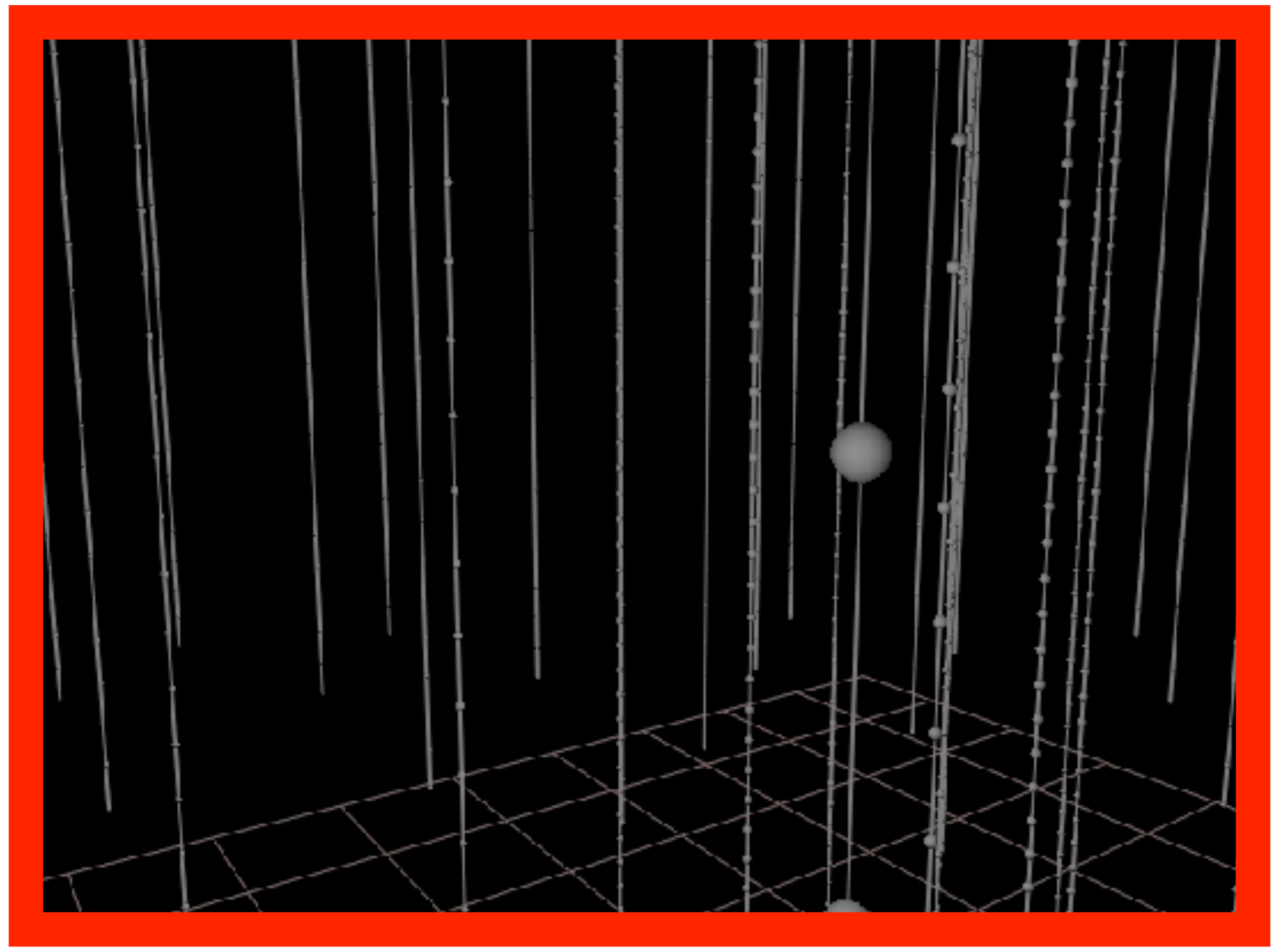


Neutrino interactions in IceCube

Event signatures







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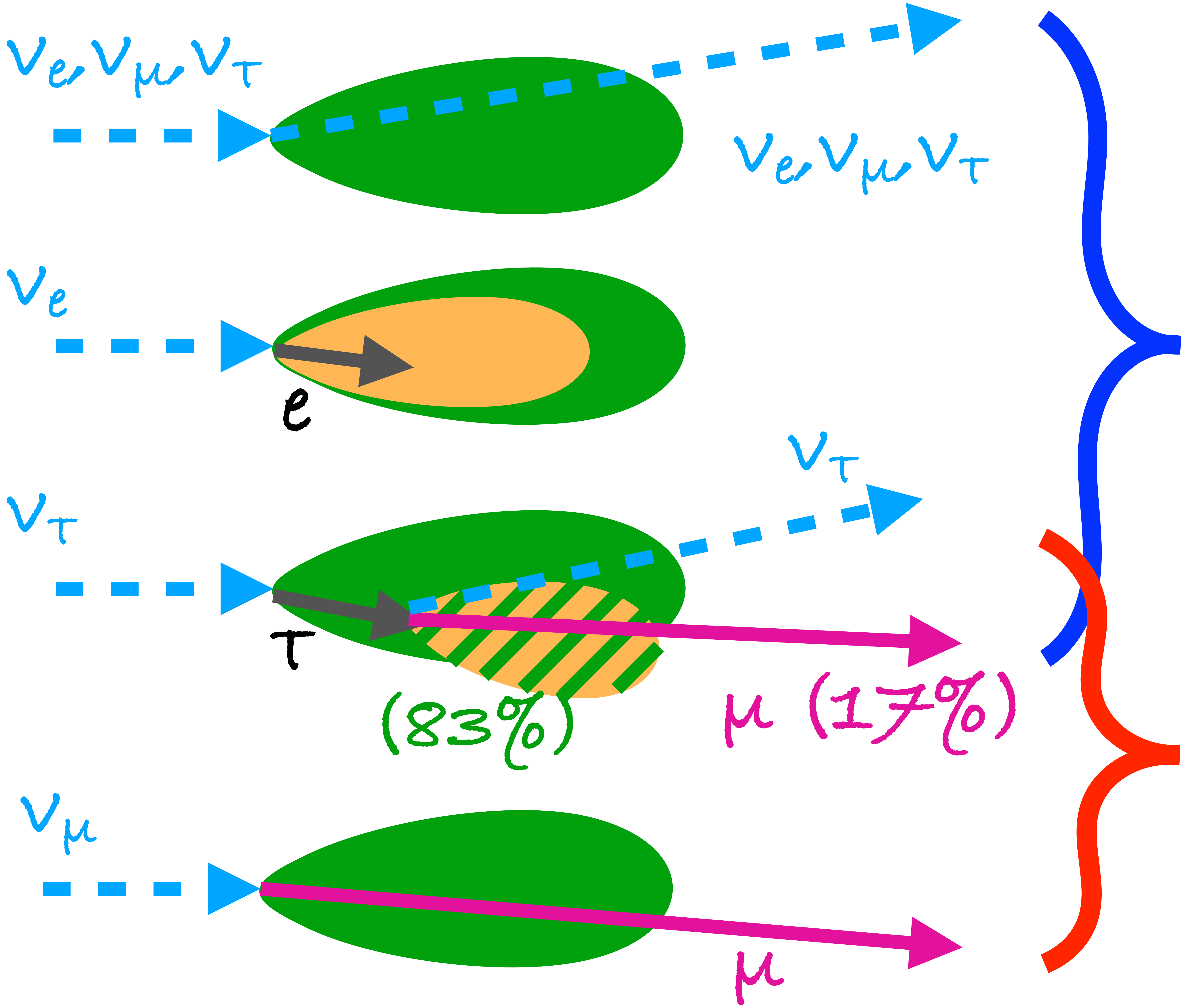
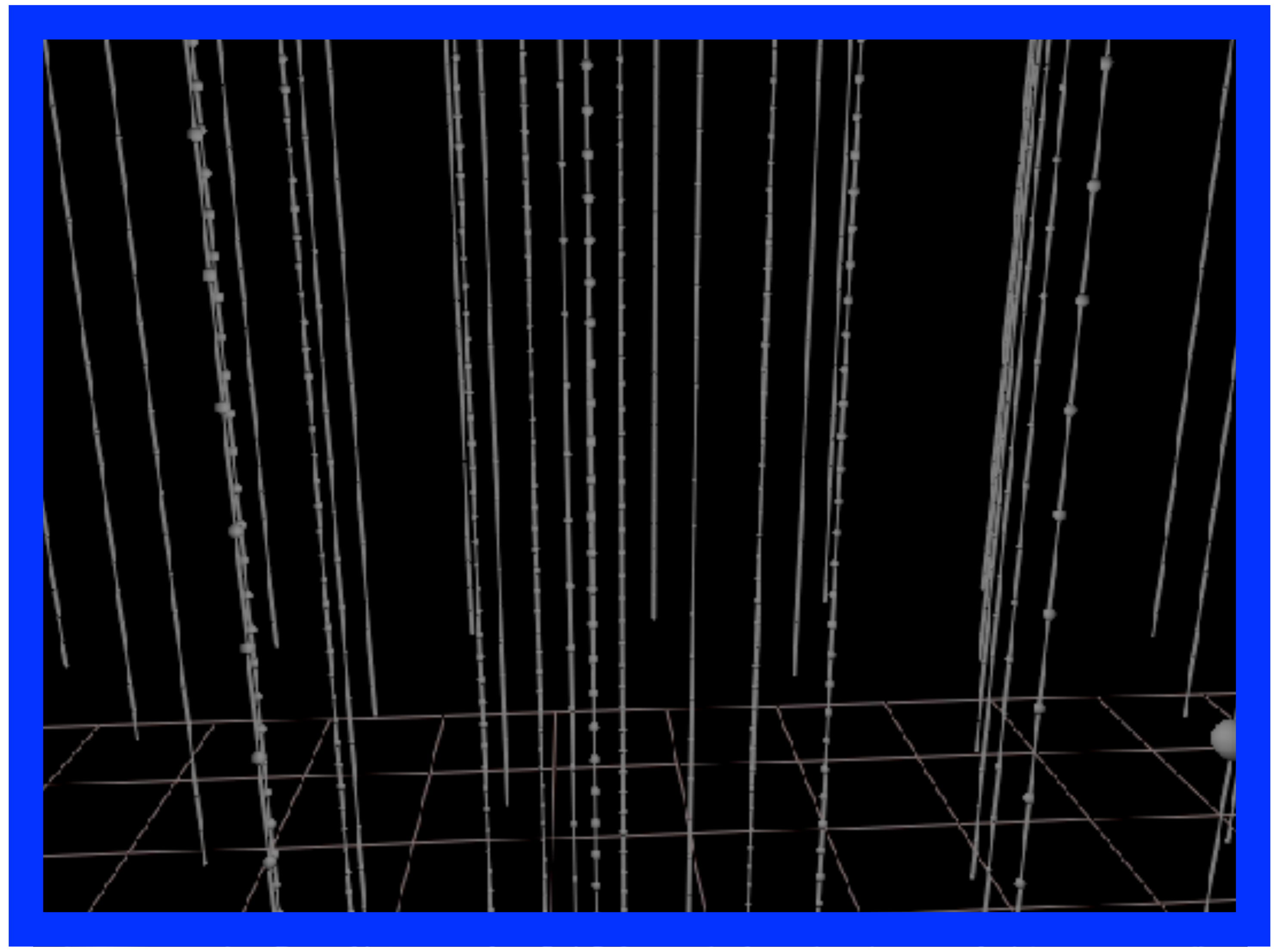
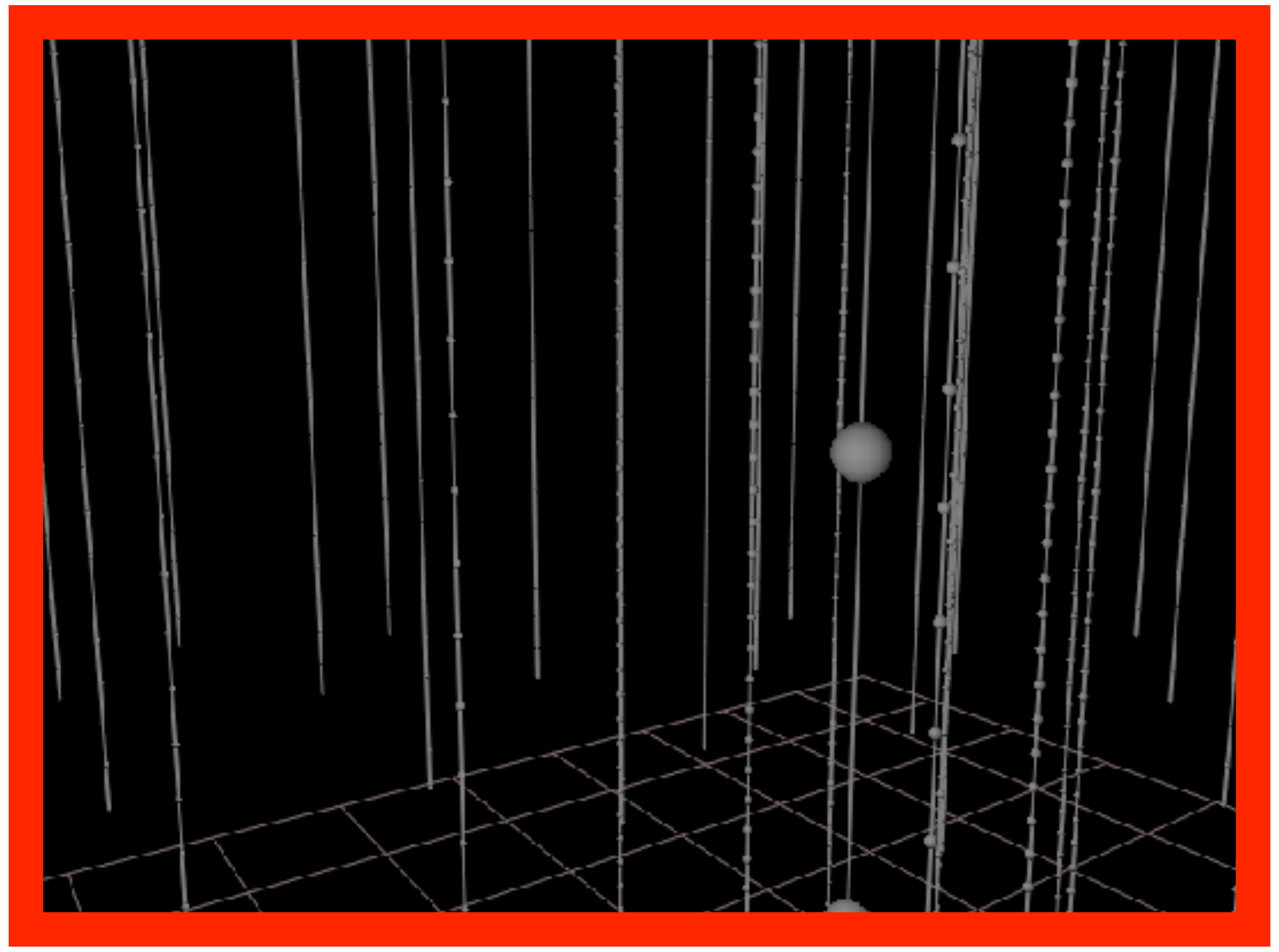






The IceCube Upgrade

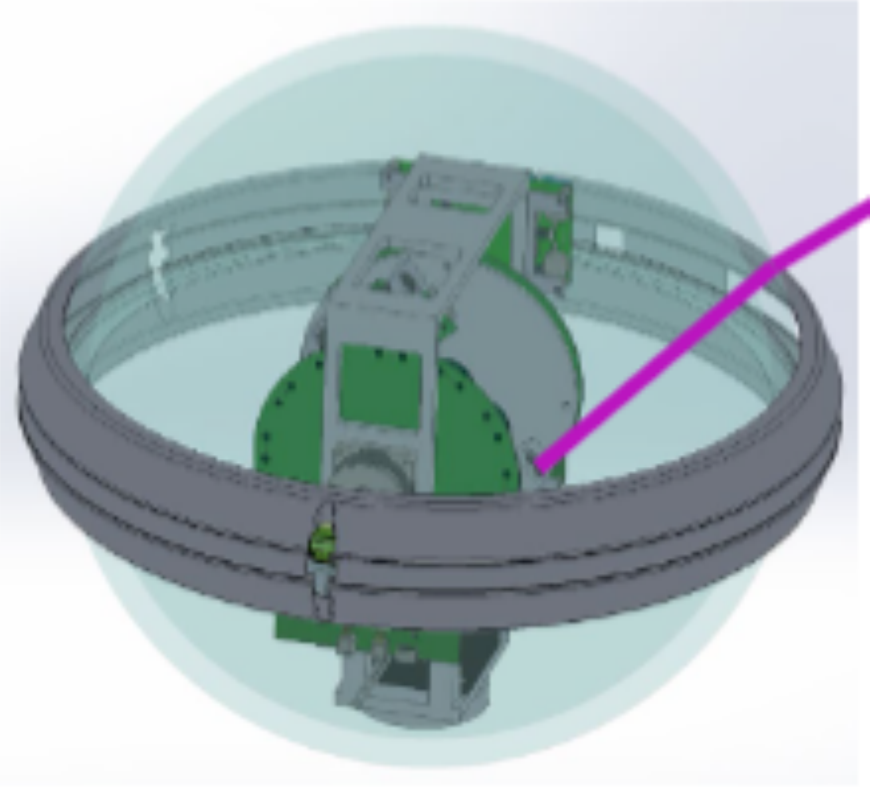
New opportunities for improved calibrations

Energy scale

- Precision Optical Calibration Module (POCAM)
- R&D for IceCube-Gen2

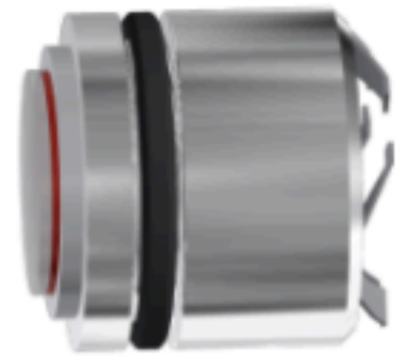
Bubble column

- Air bubbles released during drilling & trapped in centre of refrozen borehole
- New drilling technique will be tested to reduce bubble density
- Many new devices deployed to test results & calibrate older borehole bubble columns

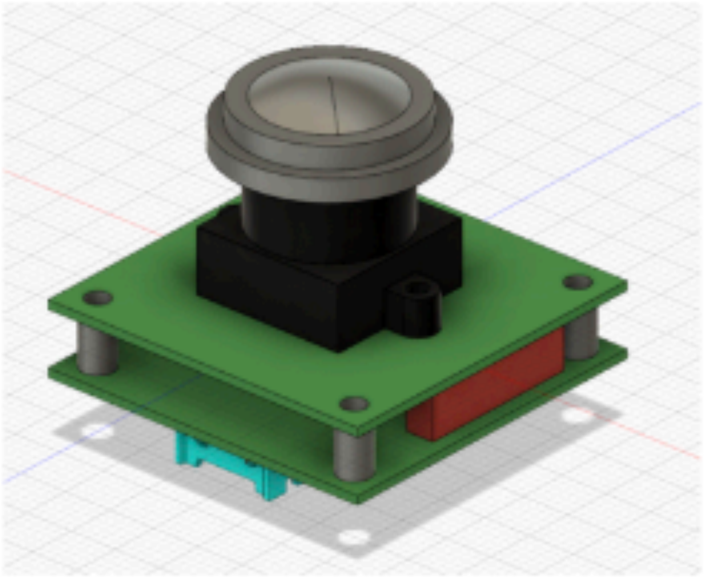


Pencil beam

POCAM



Acoustic sensors



Cameras

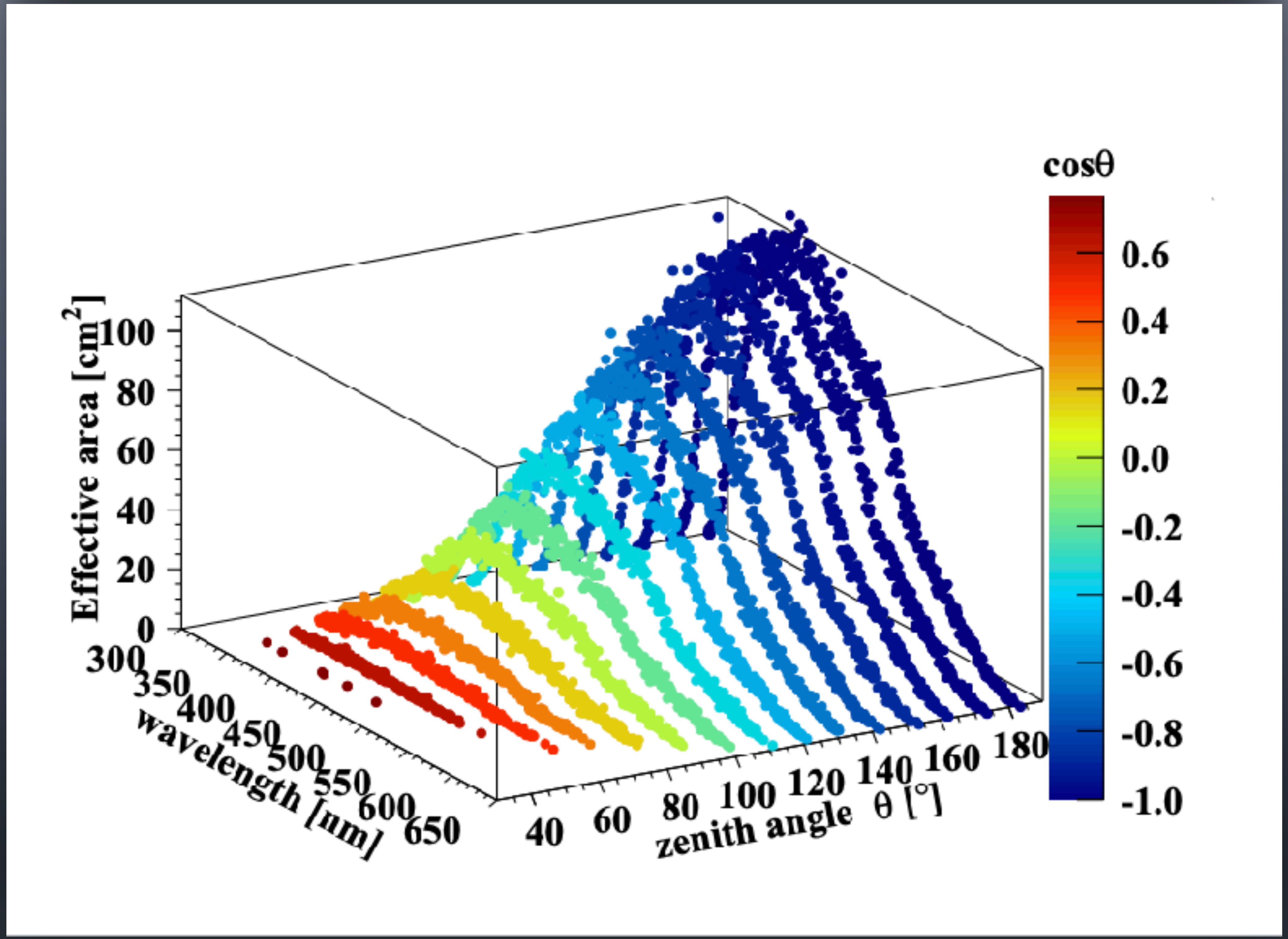
Not enough time to discuss all!

POCAM: https://arxiv.org/pdf/2005.00778.pdf (ADD proper REF)
Cameras: https://arxiv.org/pdf/1908.07734.pdf (ICRC 2019)
Acoustic: https://arxiv.org/pdf/1909.02047.pdf (ICRC 2019)

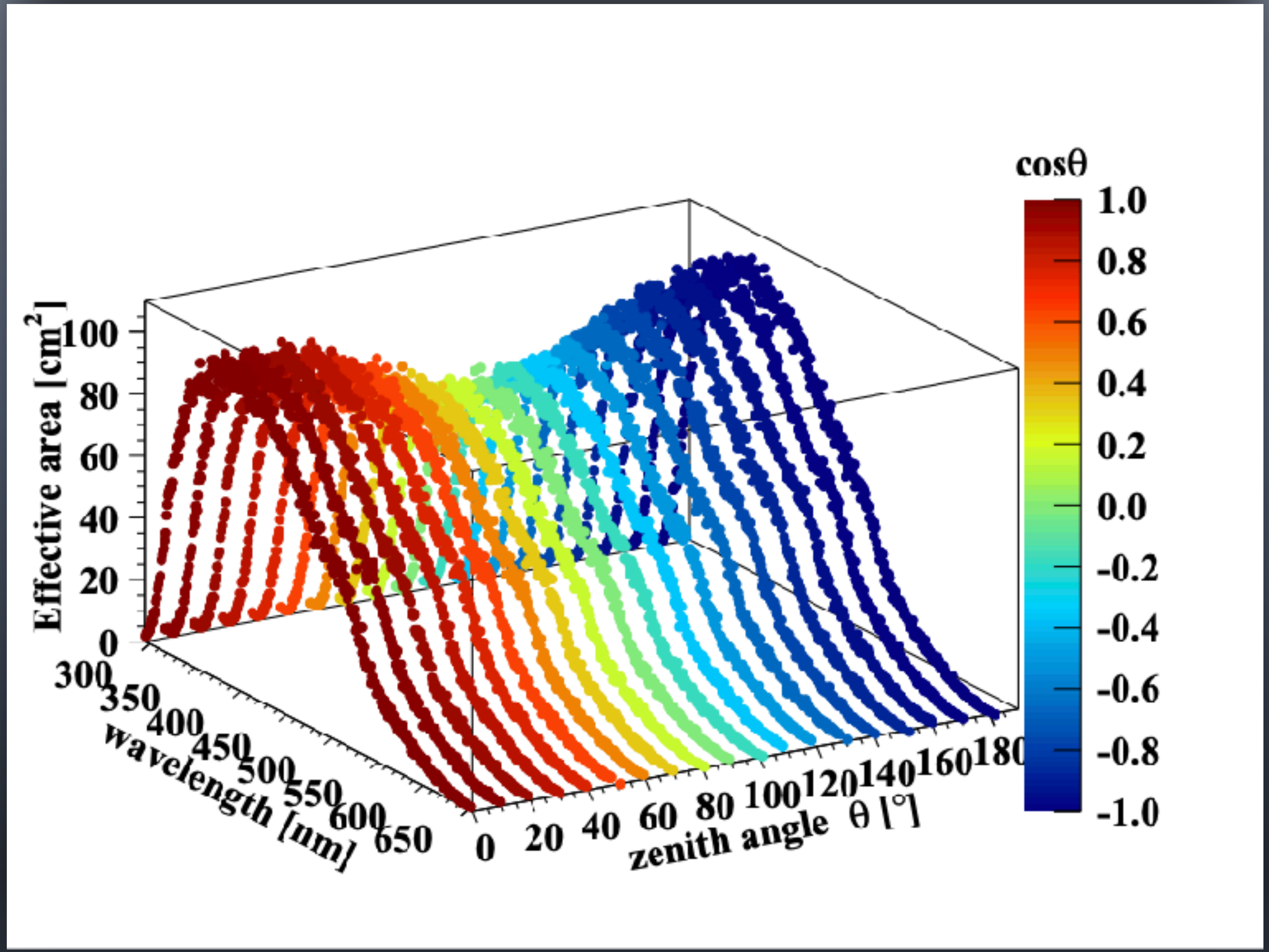
The IceCube Upgrade

New technology

IceCube Gen1 DOM



Upgrade module: DEgg



PINGU LOI v2: https://arxiv.org/pdf/1401.2046.pdf

NMO

Exploit synergy between JUNO and IceCube Upgrade

Phys. Rev. D 101, 032006 (2020)