IceCube Upgrade and IceCube-Gen2:
The future of (Neutrino) Astronomy at the South Pole

Summer Blot
21.10.2022
Matter and the Universe 2022

DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE GEN2

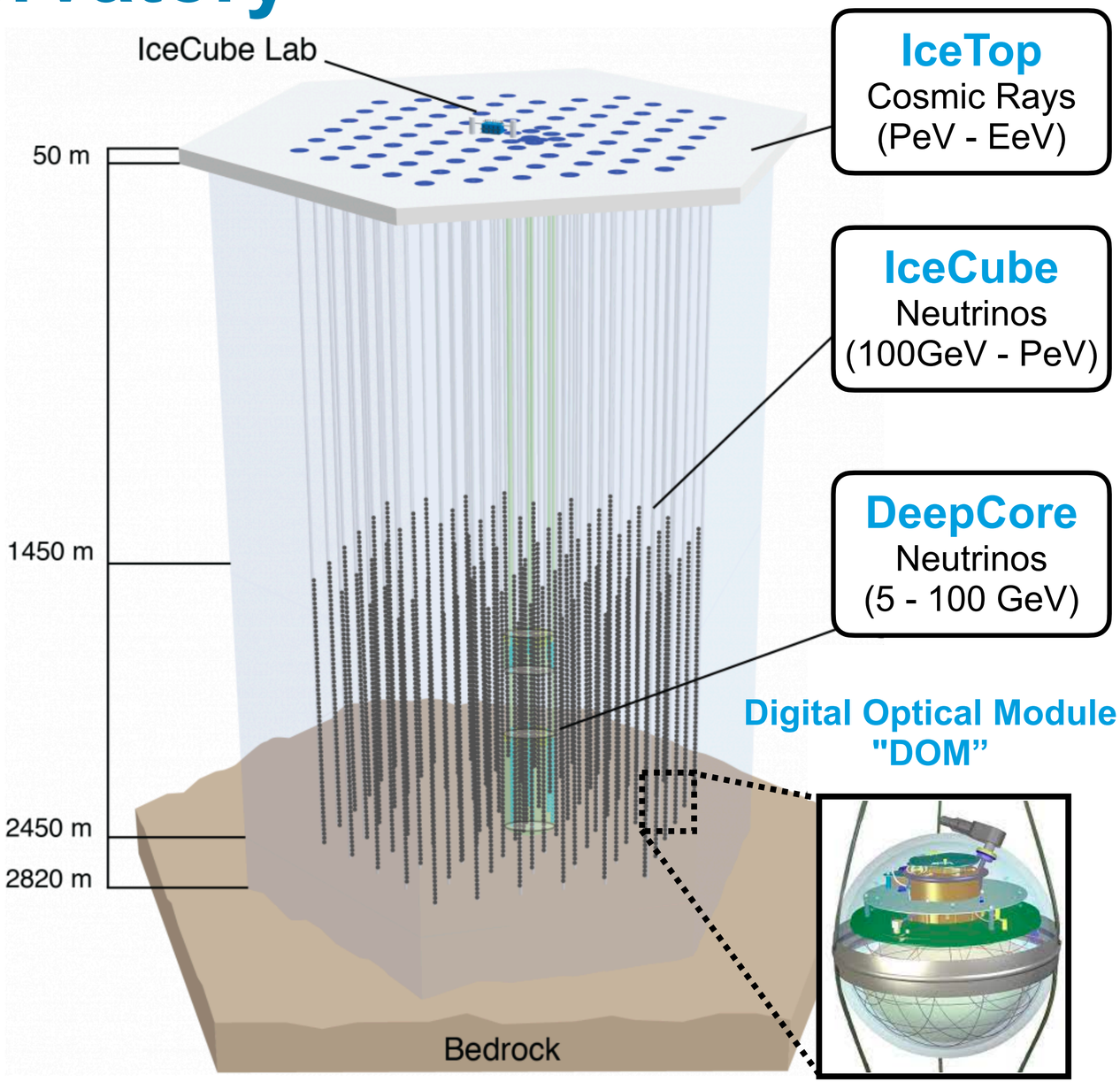
The IceCube Neutrino Observatory

Pioneering multipurpose detector

- 5160 Digital Optical Modules (DOMs) instrumenting ~1km^3 of ice
- Detect Cherenkov radiation produced via relativistic charged particles created in neutrino interactions

	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	~100
DeepCore	50	7	~5

- IceTop surface tanks ~125 apart contain 2 DOMs
- Completed in 2010:
  ~95% clean uptime, ~98% of DOMs surviving



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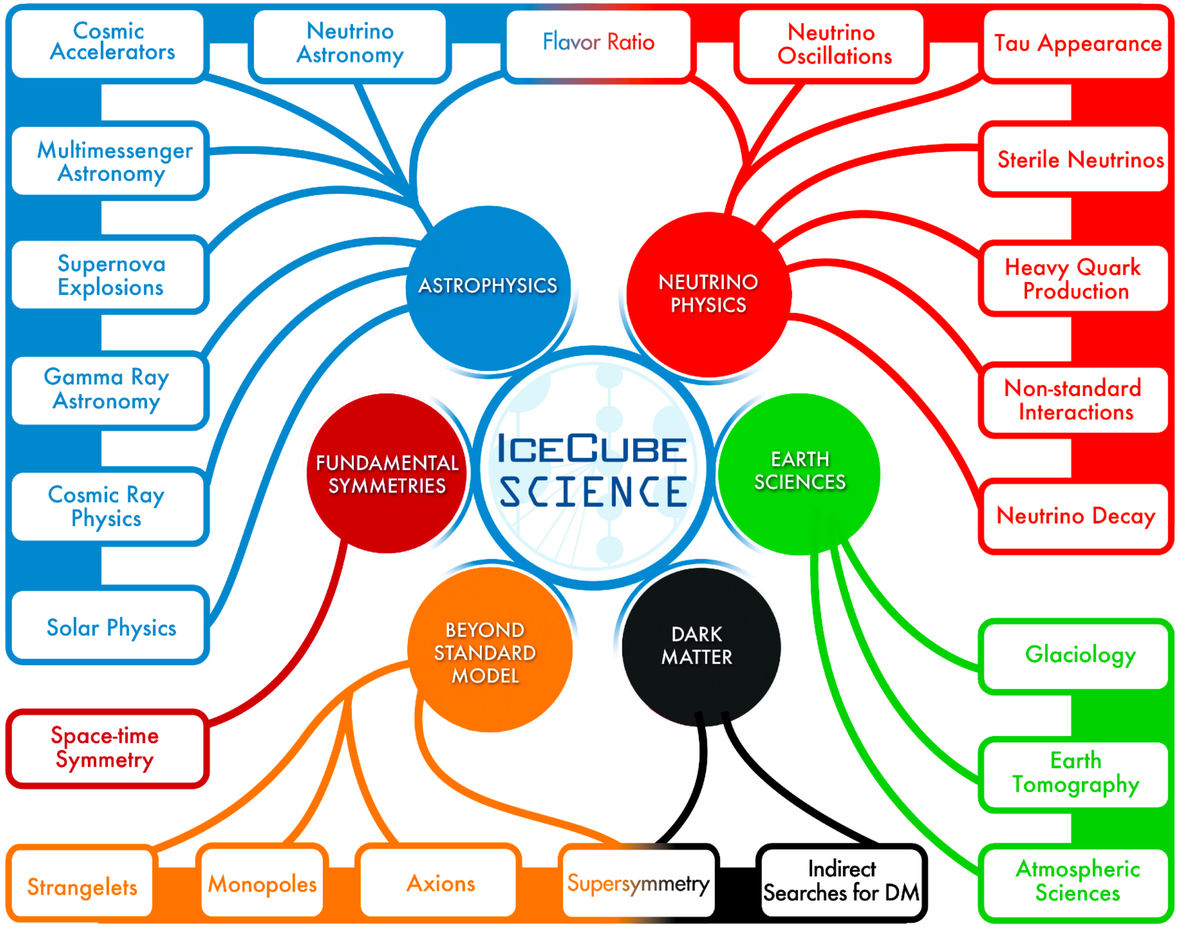
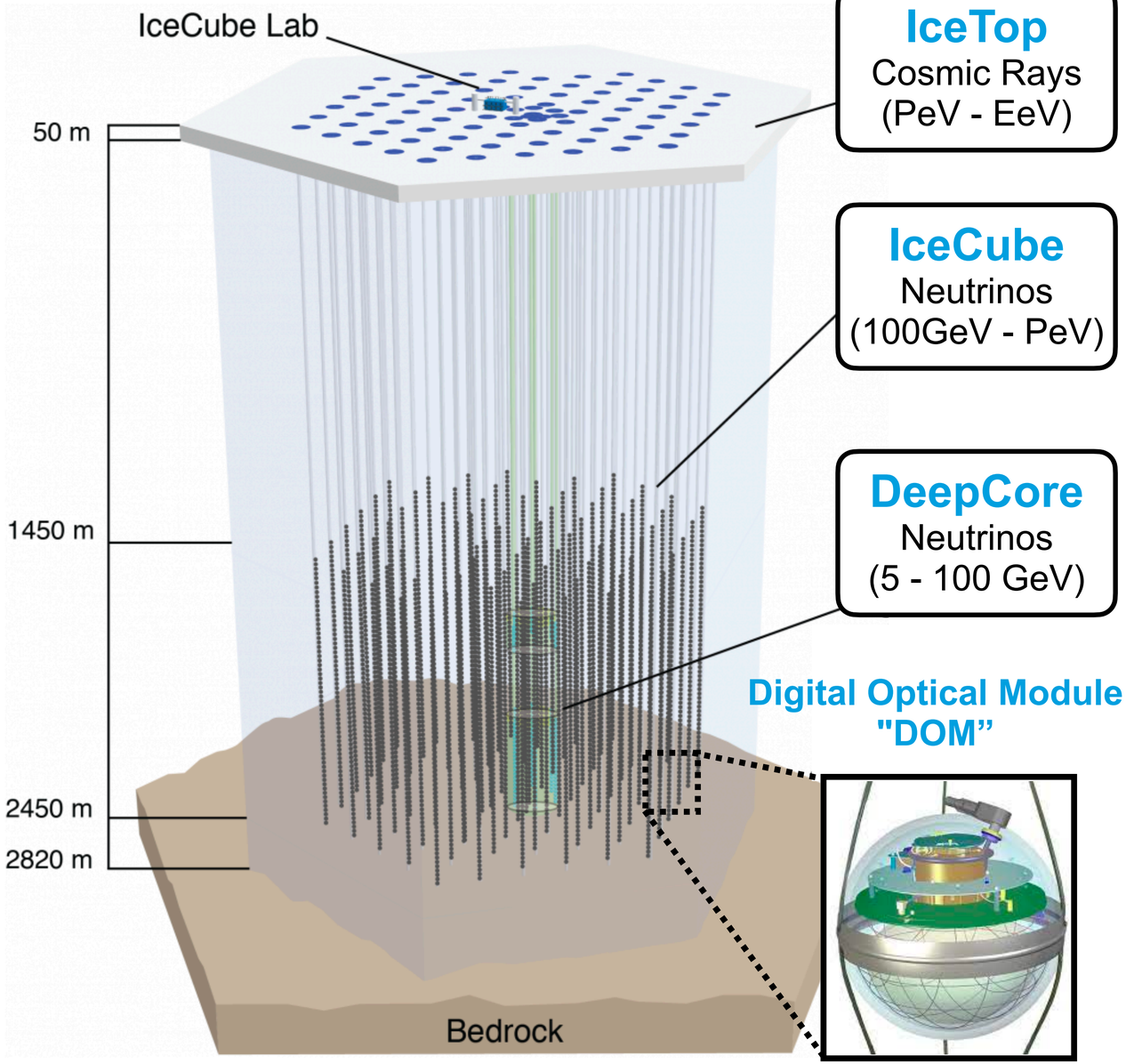
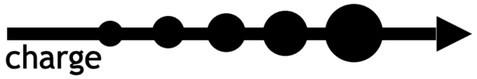




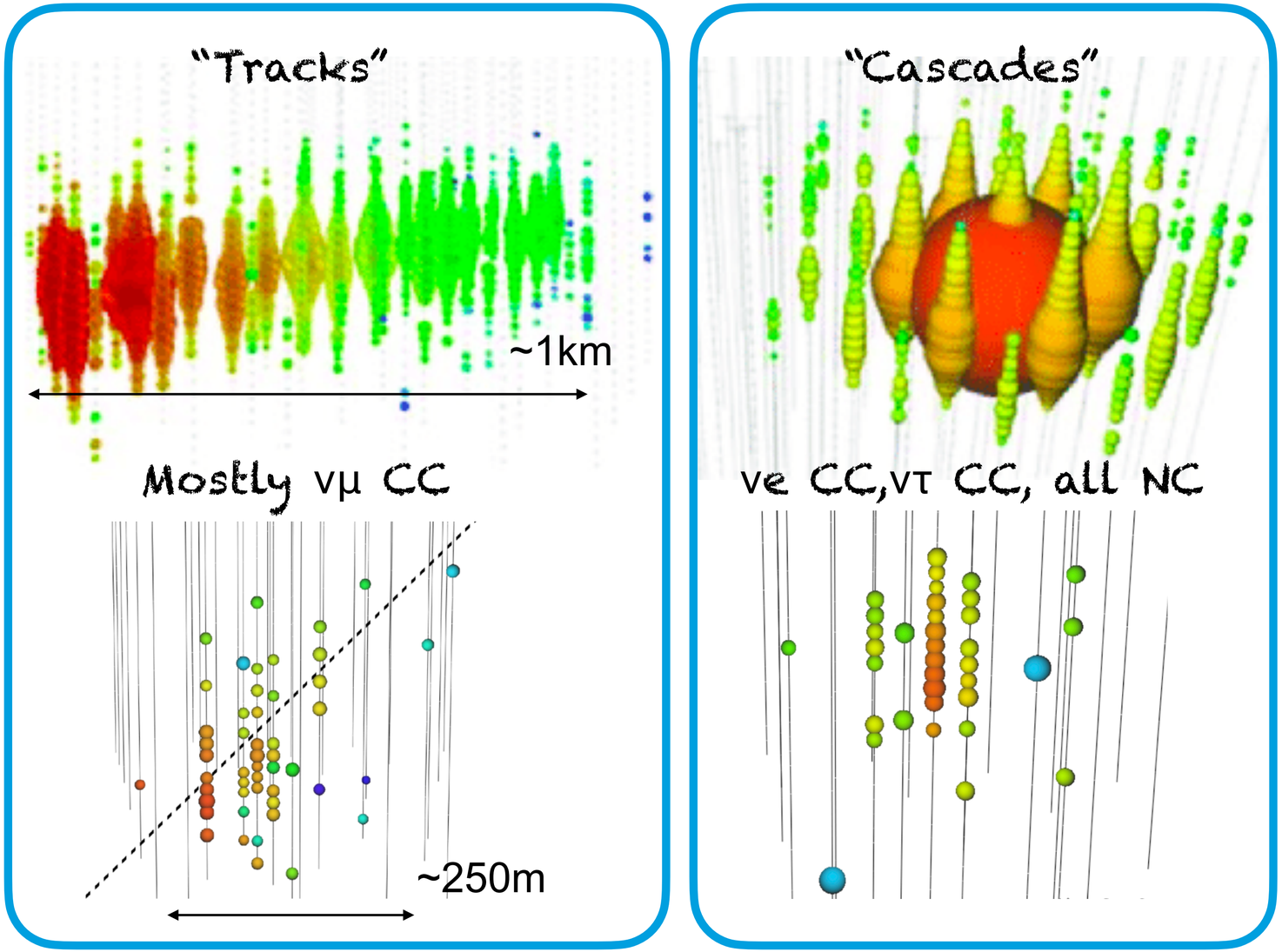
IceCube Events



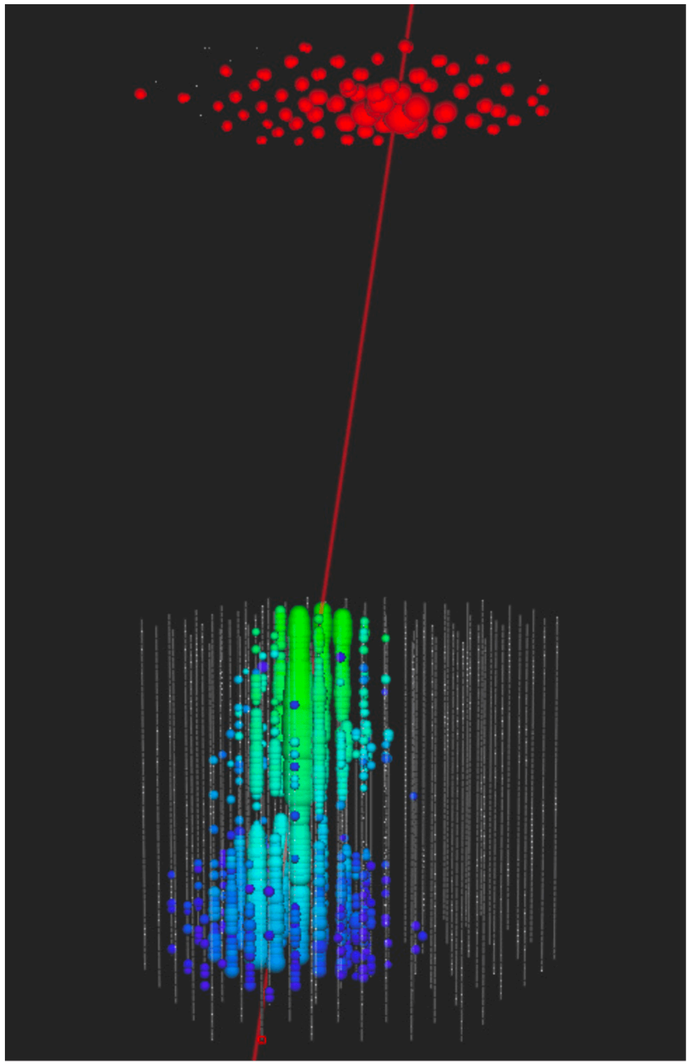
Deep Inelastic Scattering in the Ice

TeV-PeV

Few GeV



Air showers with IceTop



Atmospheric neutrino oscillations

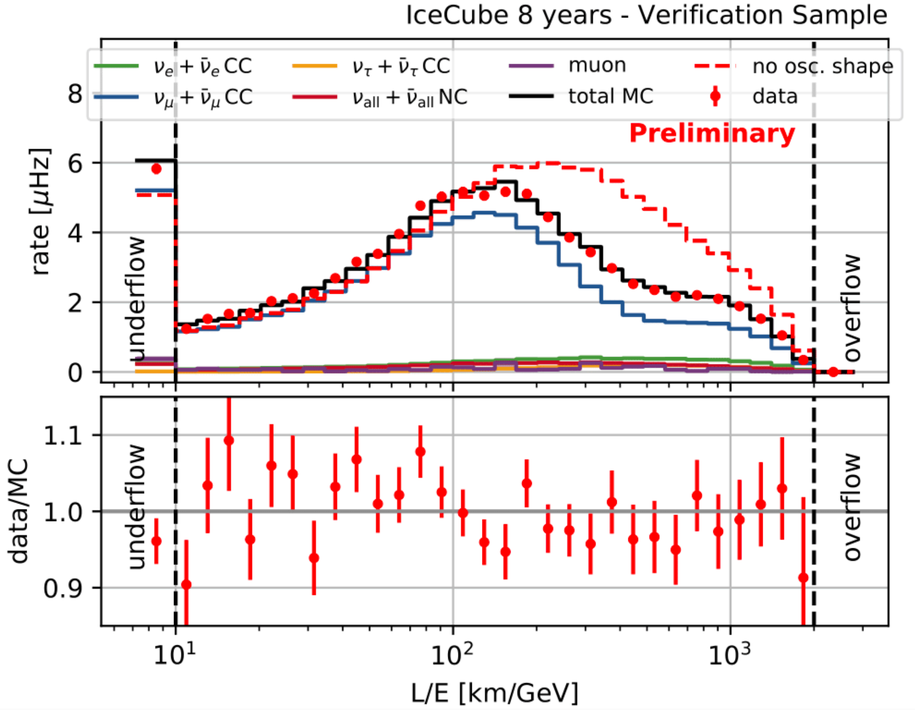
New 8 year sample of 5-100 GeV neutrinos

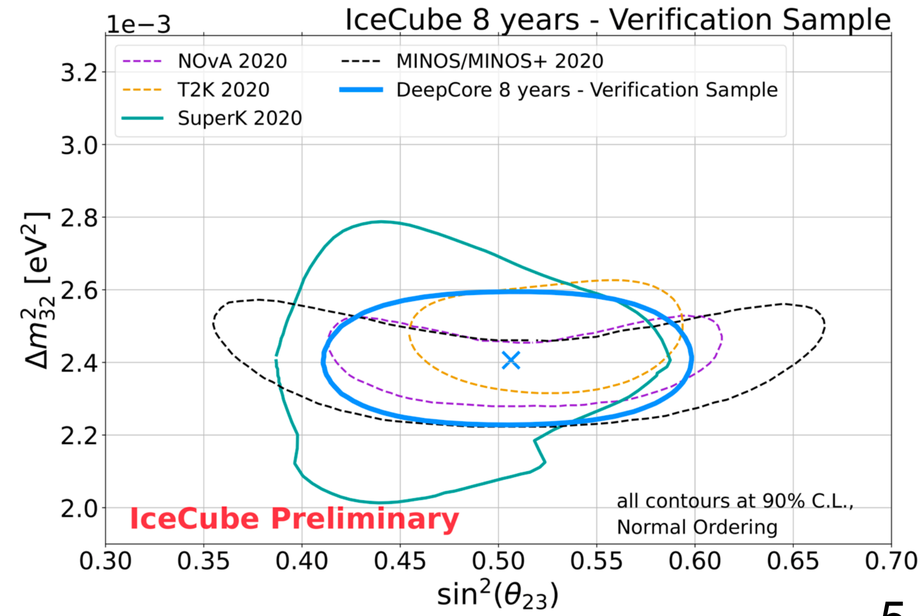
Highest energy probe of νμ → ντ mixing

- Compare tracks to cascades as function of energy and cos(zenith) (i.e. propagation length)
- New result analysing only 7% of available data

$\Delta m^2_{32} = 2.41 \times 10^{-3}\ eV^2$ $\sin^2\theta_{23} = 0.505$

- ~20% of error related to detector calibration





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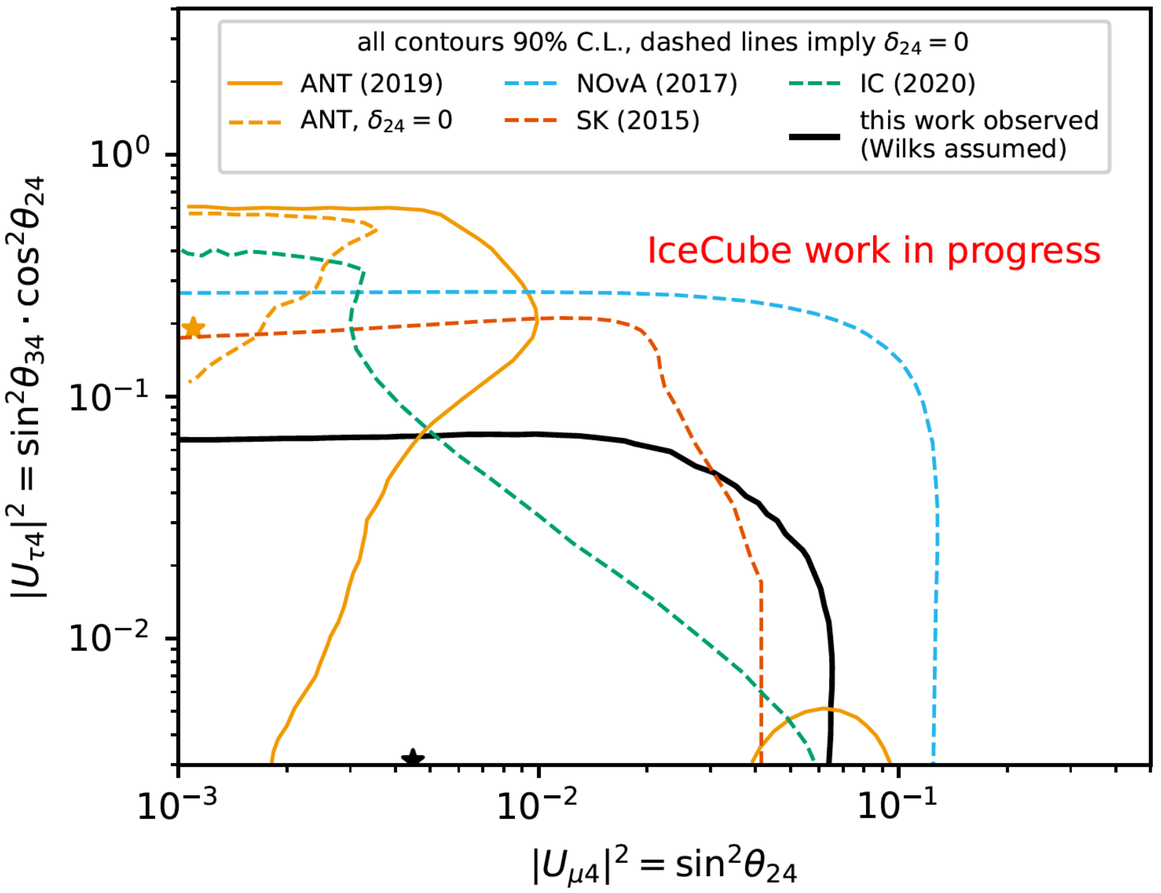
Search for eV-scale sterile neutrinos

- Exploit long neutrino baselines through variable matter profile of the Earth
  - Sterile neutrinos don't feel matter potential
- Results consistent with null hypothesis

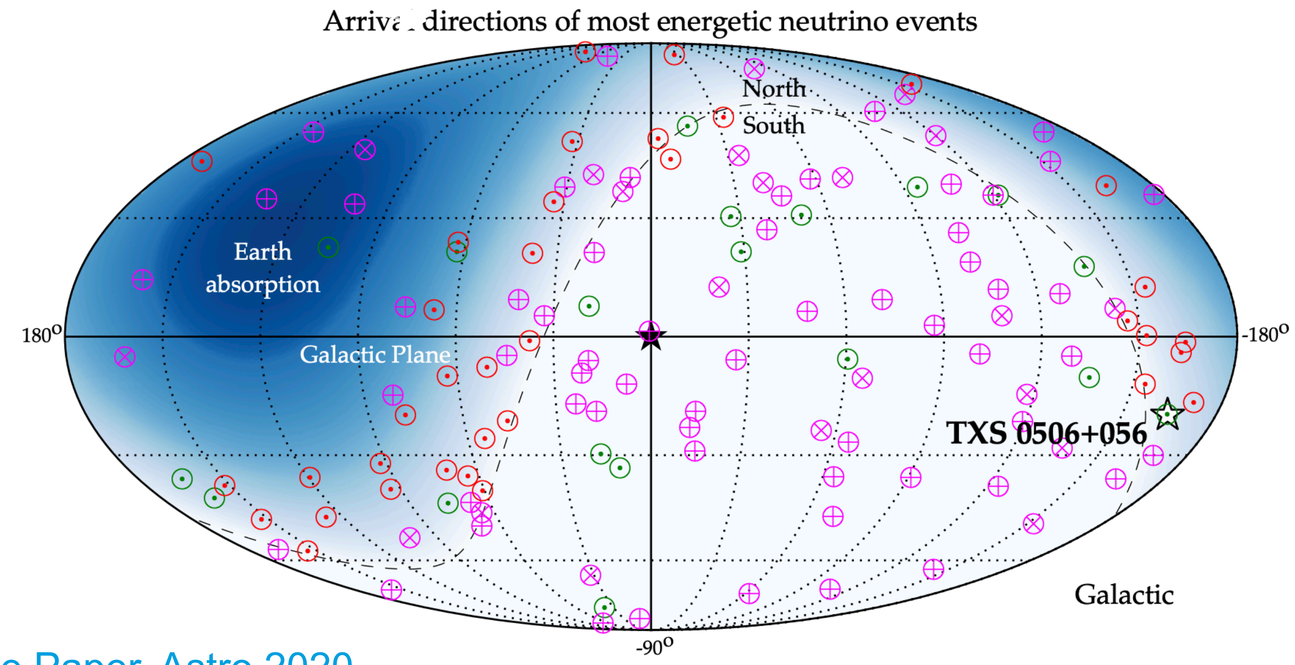
NEW! (Do not distribute)



Astrophysical neutrinos

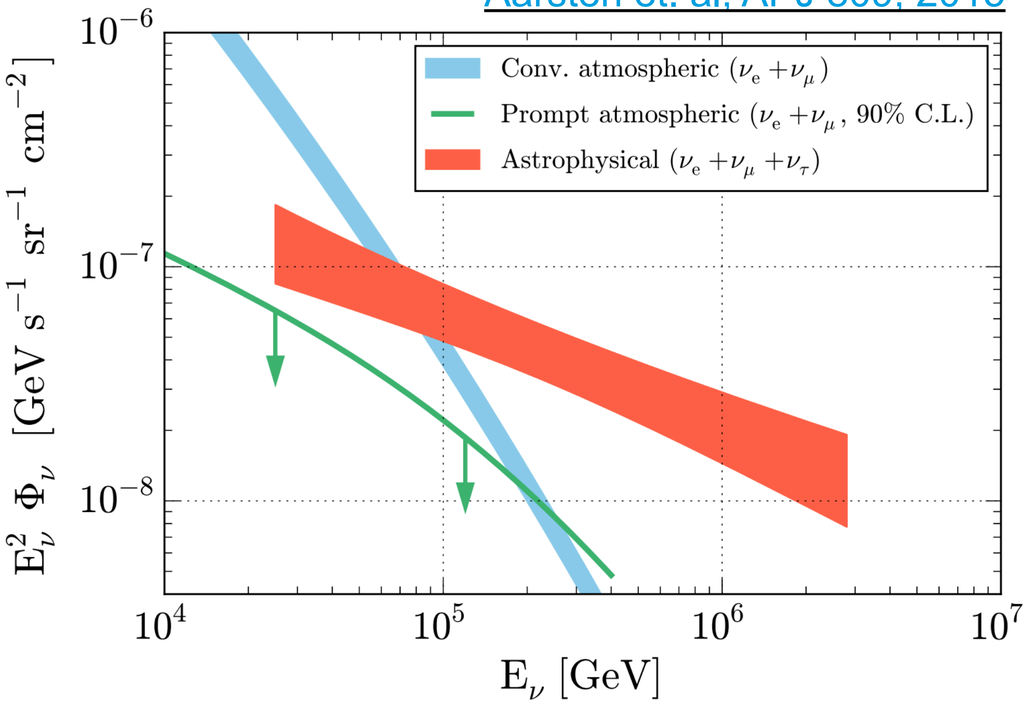
Discovered in 2013

Astrophysical neutrino flux now well established in many detection channels



White Paper, Astro 2020

Aarsten et. al, APJ 809, 2015



Signal appears to be mostly extragalactic and diffuse with a few notable exceptions…

Neutrino point sources

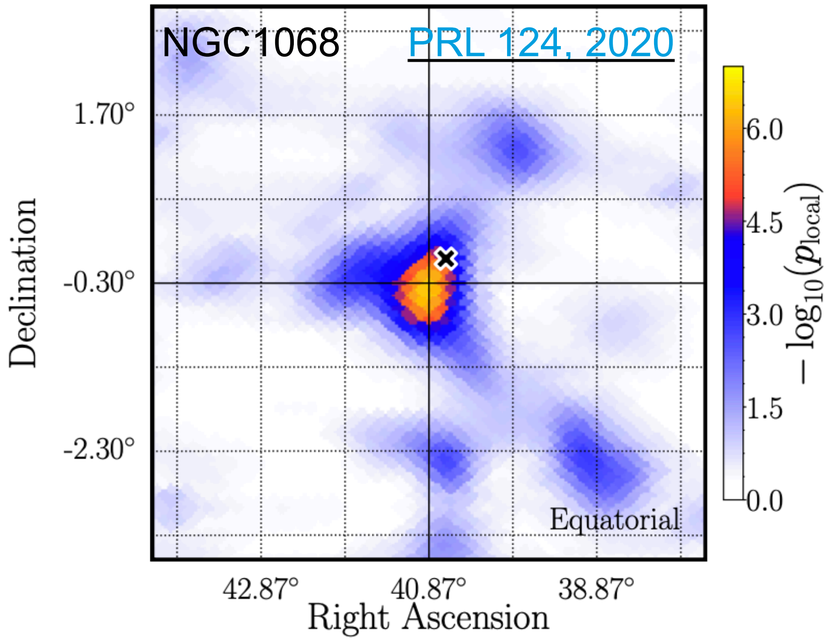
Hunting the origin of astrophysical neutrinos

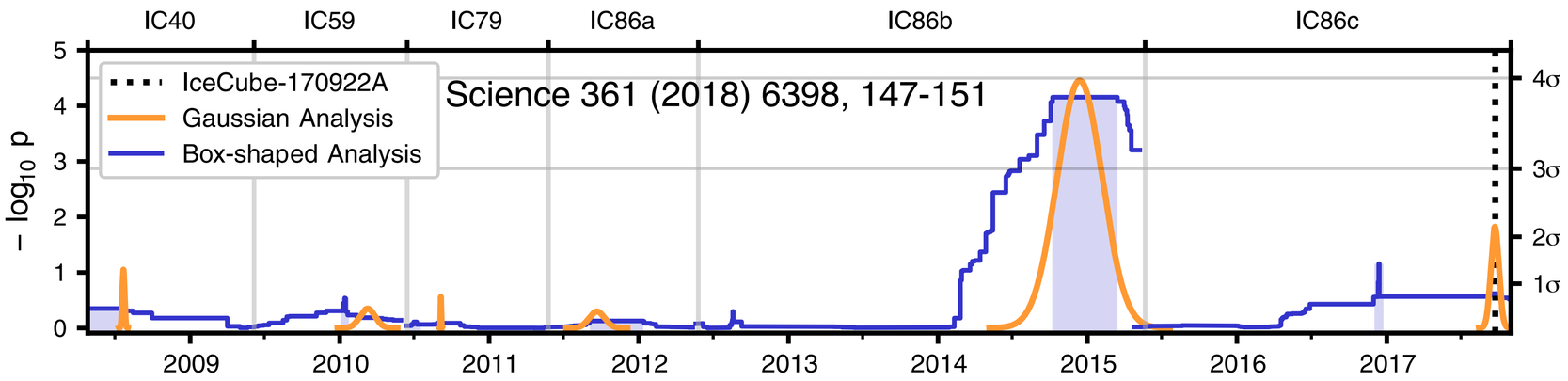
Time integrated searches - 10+ years of data

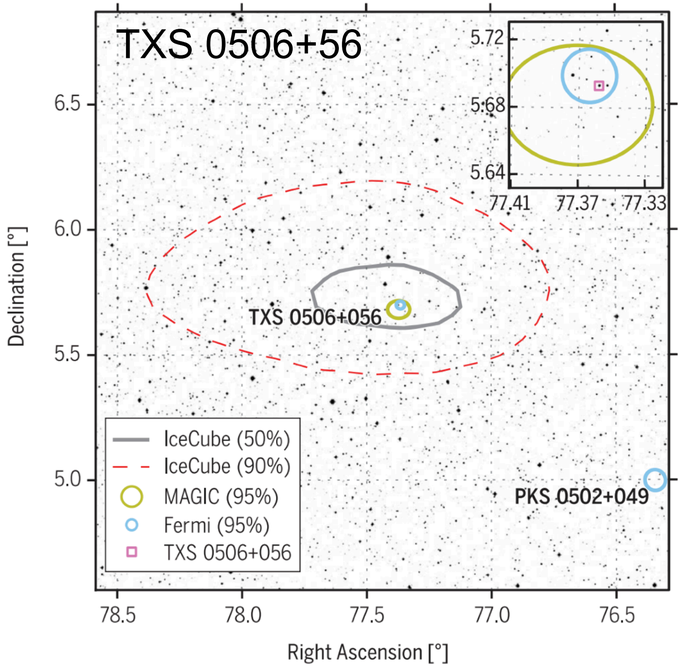
- Look for correlations with candidate sources using catalogs
- Most significant correlation: NGC1068 (3σ-post trial)

Transient searches

- Realtime program: astrophysical neutrino alerts sent <1 min from detection enabling multi-wavelength follow-up
- Time-dependent neutrino clustering around common sources



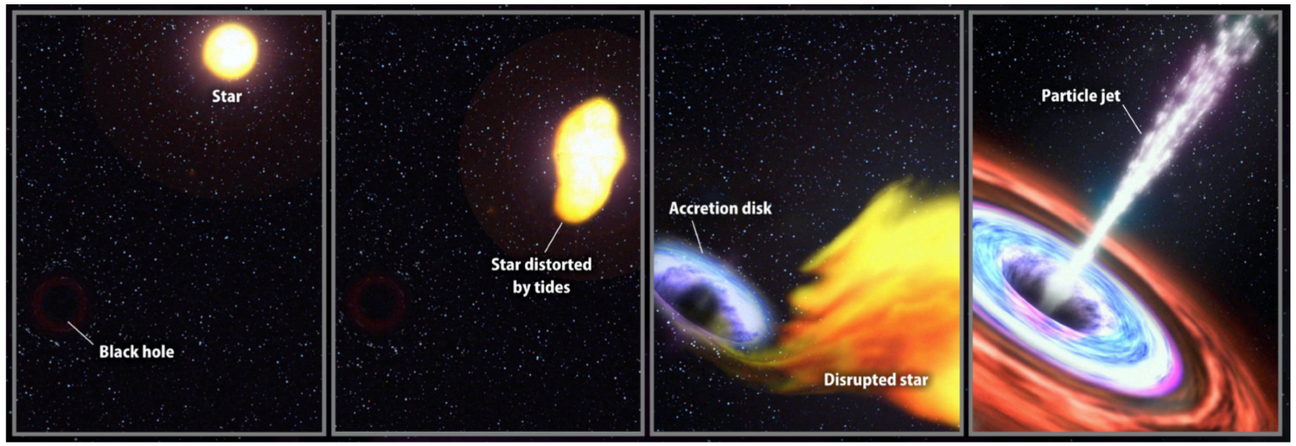


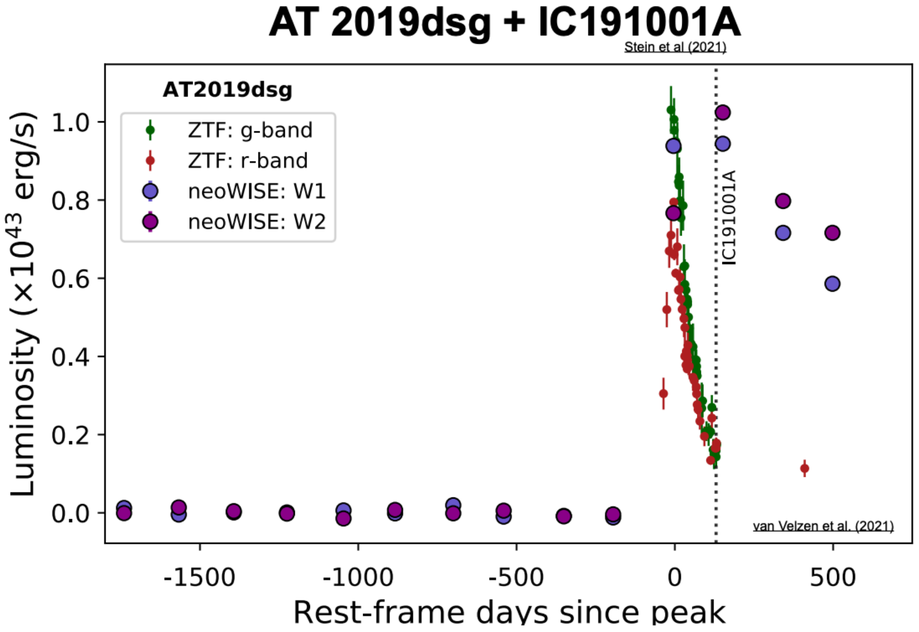


Tidal disruption events

Neutrinos from accretion flares?

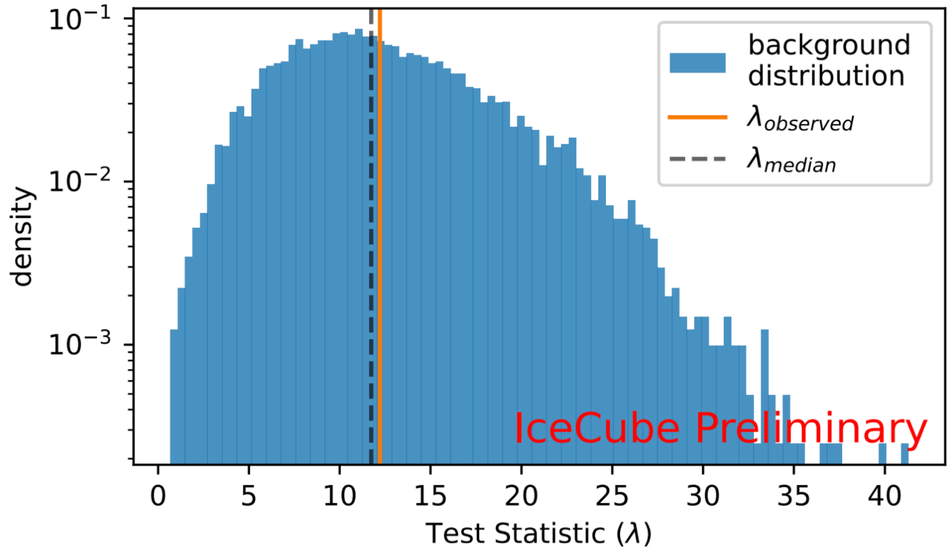
Credit: NASA





- Infrared data suggests neutrino emission from “dust echo” PRL 128, 221101 (2022), https://arxiv.org/pdf/2111.09391.pdf
- External analysis using 36 public alerts: 3.7σ correlation
- Internal IceCube analysis using larger neutrino dataset (extended energy range, offline reconstruction): p=0.45 (see talk by J. Necker, TeVPA 2022)

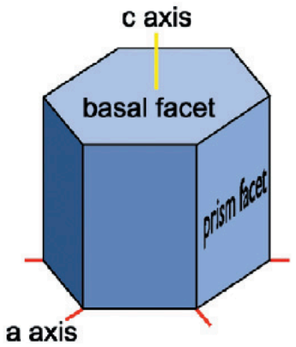
J. Necker, TeVPA 2022



Systematic uncertainties

The challenge of a natural detector medium

- Inhomogenous optical properties all the way down
- Need improved modelling of glacial properties, photon propagation and DOM response
- New: photon propagation from first principles
  - *Ice is a birefringent material and crystal axes are preferentially oriented along glacial flow*
  - Birefringence causes anisotropic light propagation seen in IceCube data - new systematics!



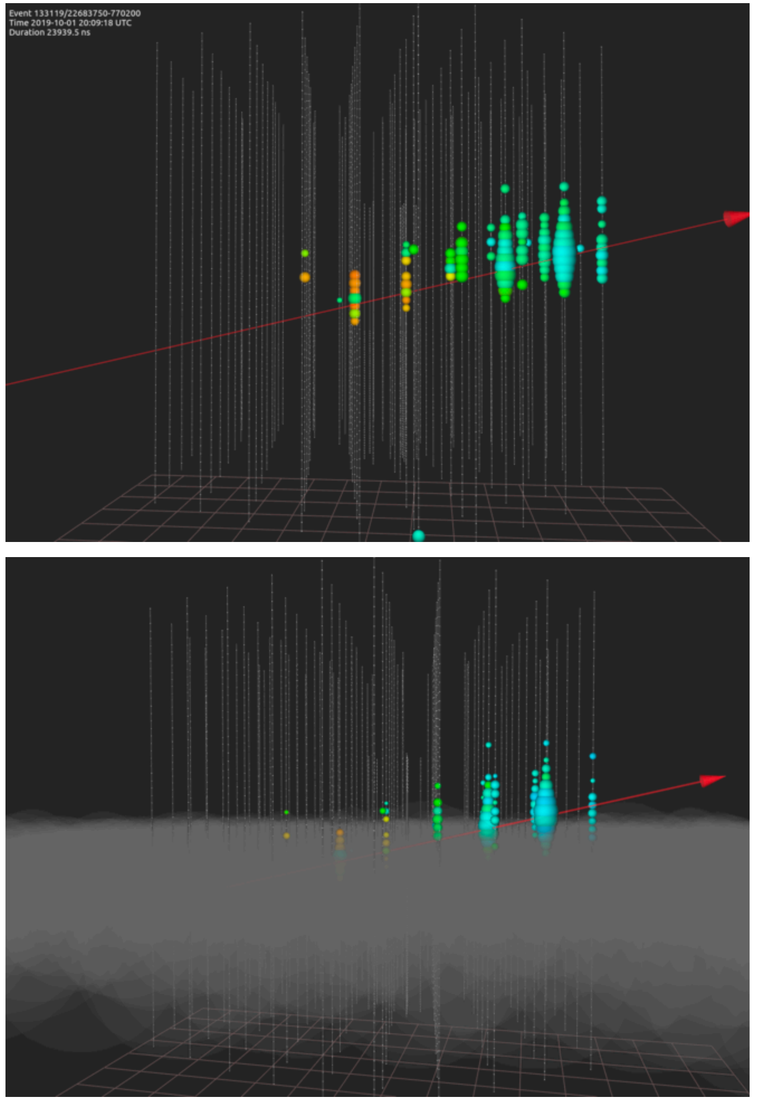
Credit: K. Libbrecht

[1] Aarsten, et al, JINST (2017)
[2] Chirkin, ICRC 2013
[3] Chirkin, Rongen ICRC 2019
[4] Rongen, Bay, Blot The Cryosphere 2020
[5] https://tc.copernicus.org/preprints/tc-2022-174/

Collaboration with glaciology community is key!

IC191001A (The Bran Stark neutrino)

GCN Notice



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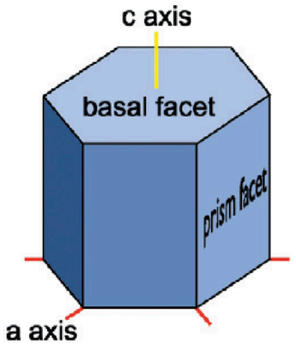

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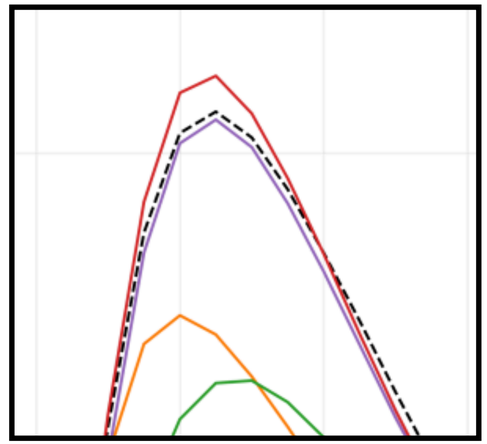
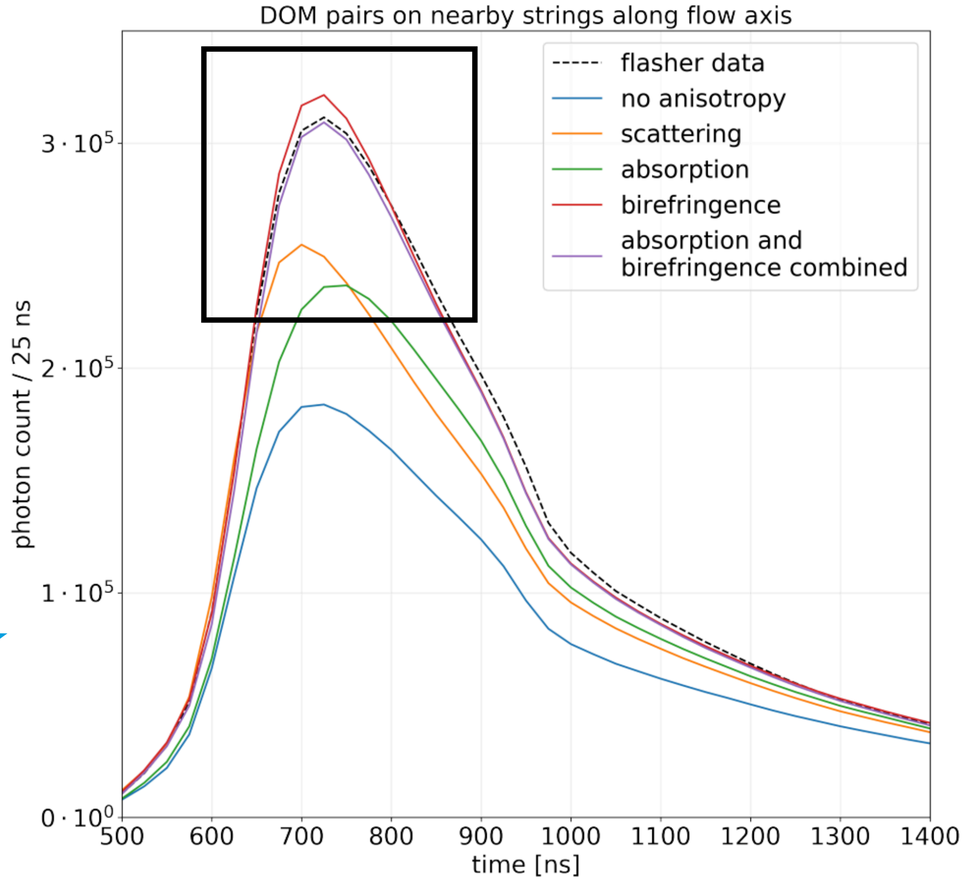


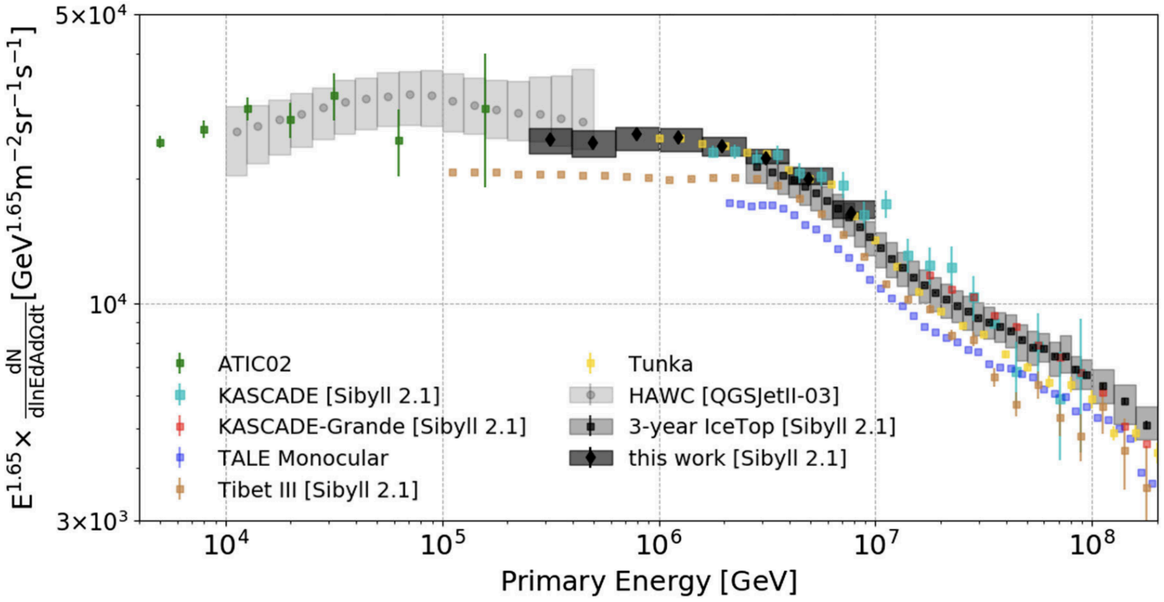
Unprecedented agreement in calibration data!



Cosmic Ray studies

With IceTop

Phys. Rev. D 102, 122001

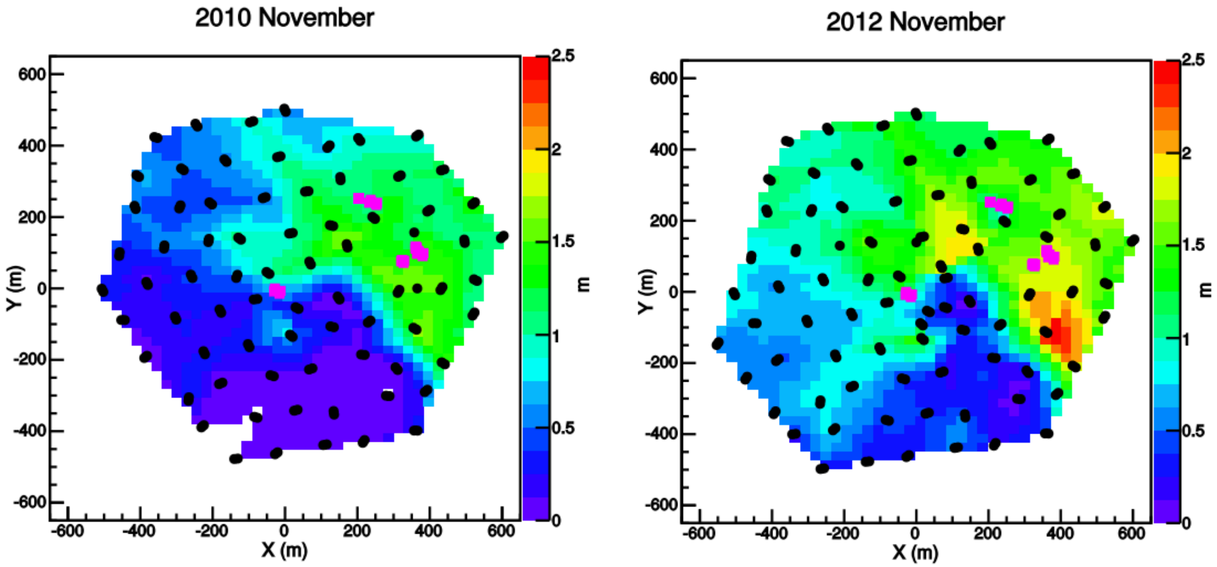


Key science drivers

- Study cosmic ray energy spectrum and mass composition
- Understand cosmic ray production and propagation
- Probe hadronic interaction models in forward region
- Serves as a surface veto for in-ice array

Current challenges

- Muon puzzle and impact on mass composition
  See MU Flash Talk by D. Soldin
- Snow piling up and other systematic uncertainties



Looking towards the future

How do we…..

Take neutrino oscillation measurements from **complementary to competitive**?

Stop swimming in a sea of **3σ detections** of astrophysical sources?

Move from **discovery to precision**?

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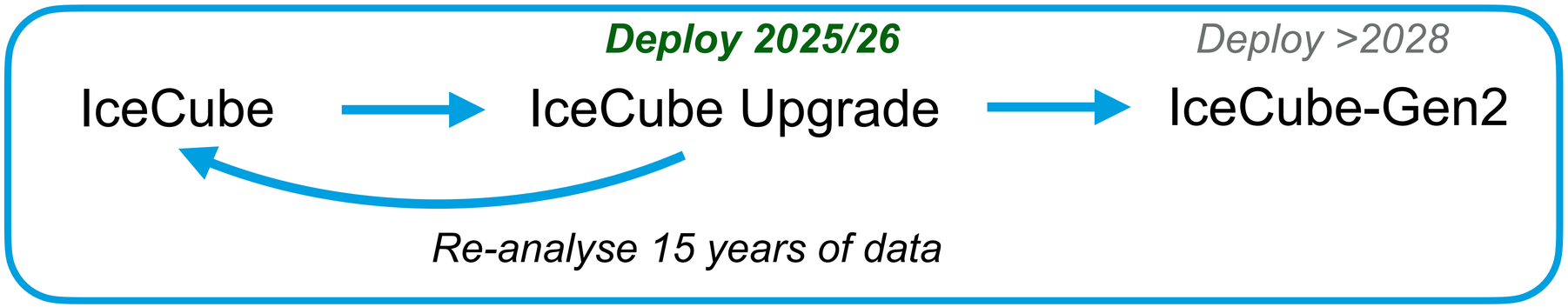
Stop swimming in a sea of **3σ detections** of astrophysical sources?

Move from **discovery to precision**?

We have a plan!



The IceCube Upgrade

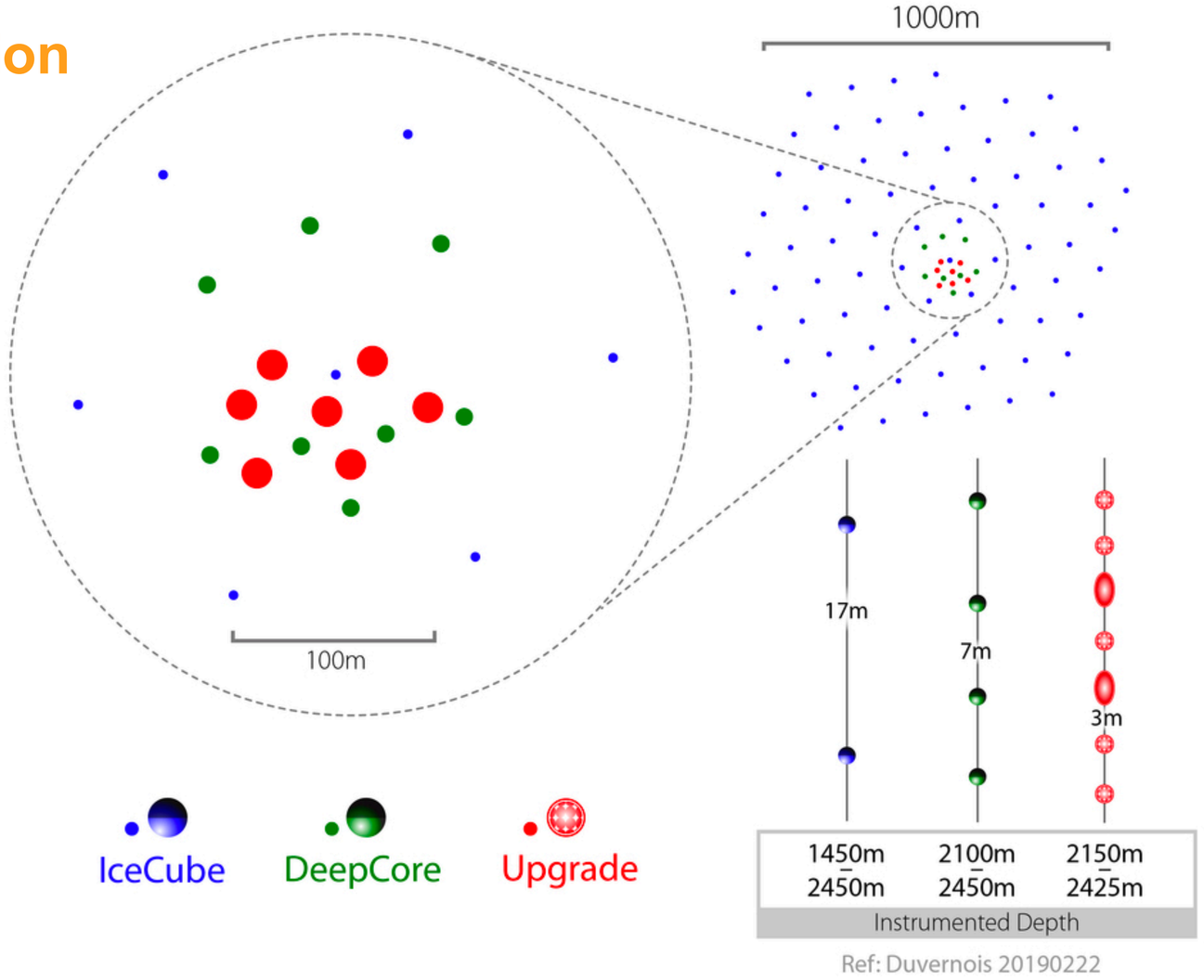
7 new strings packed with instrumentation

IceCube Upgrade goals:

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

Key features

- > 800 new devices
- Reduced spacing between devices
  - On par with average photon scattering length (~40m)
- Explore the deep ice down to 2600m



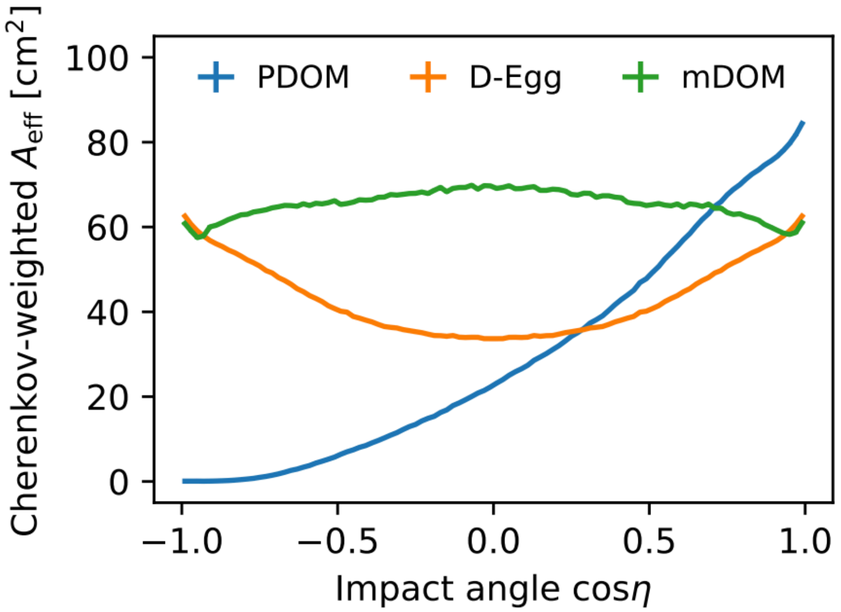
Delays due to COVID: re-baseline **APPROVED** by NSF in September 2022 - **Deployment scheduled 2025/26**

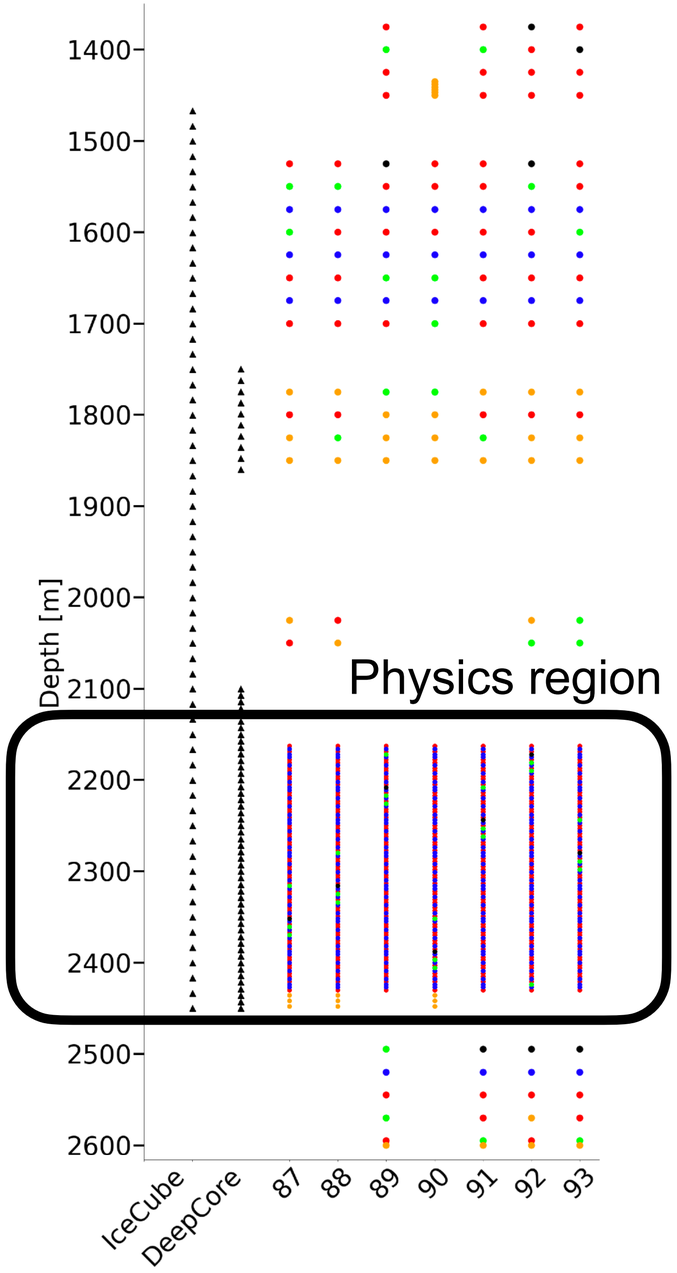
Physics region of the Upgrade

Enhanced sensitivity to GeV scale physics

Very dense instrumentation

- 3m vertical spacing
- Mostly comprised of DEggs and mDOMs
  - Increased sensitive area per module with ~4π acceptance

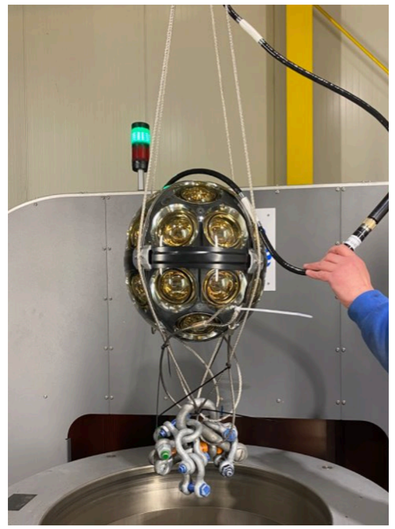




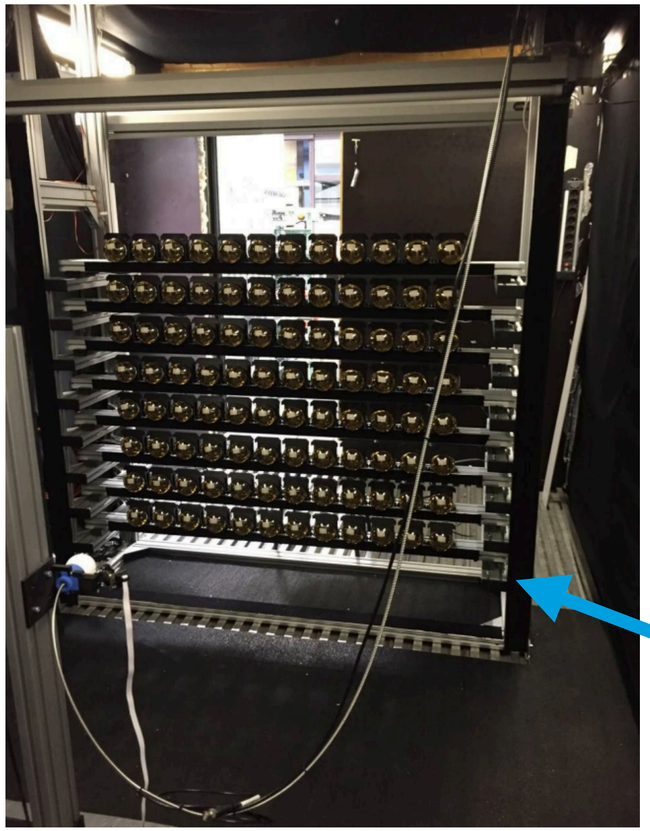
The multi-PMT Optical Module

Collaboration between German Universities and DESY/KIT

Harness
(Wuppertal)



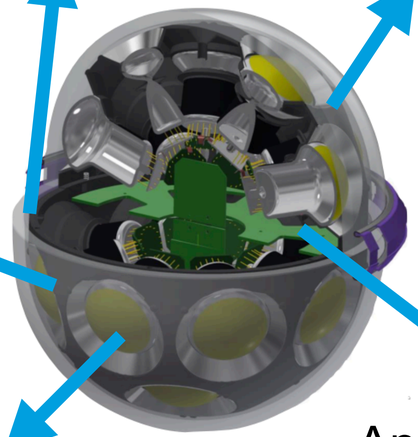
PMT testing in climate chambers
(Aachen and Dortmund)



Germany on track to deliver 225 mDOMs by 2024
+ knowledge transfer to MSU
(Responsible for remaining 200)

PMT support structure
(Münster)

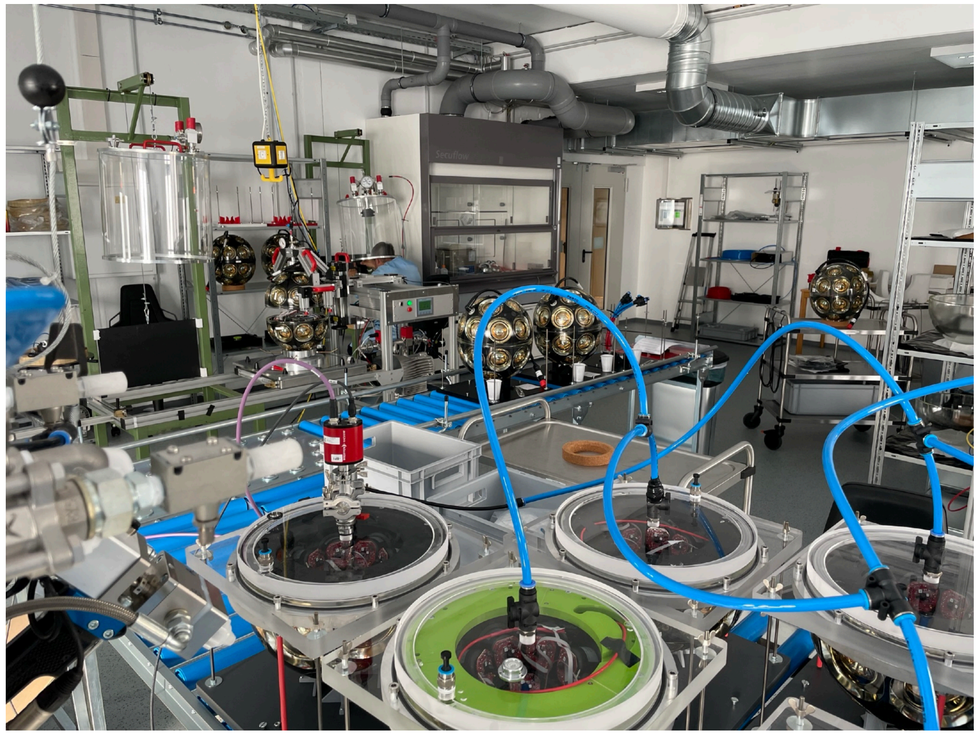
Calibration LEDs
(Mainz)



Laser calibration stand
(Erlangen)

PMTs **(KIT)**

Analog Front-End
(DESY)



Production started at DESY, Autumn 2022

IceCube Upgrade

Expected performance

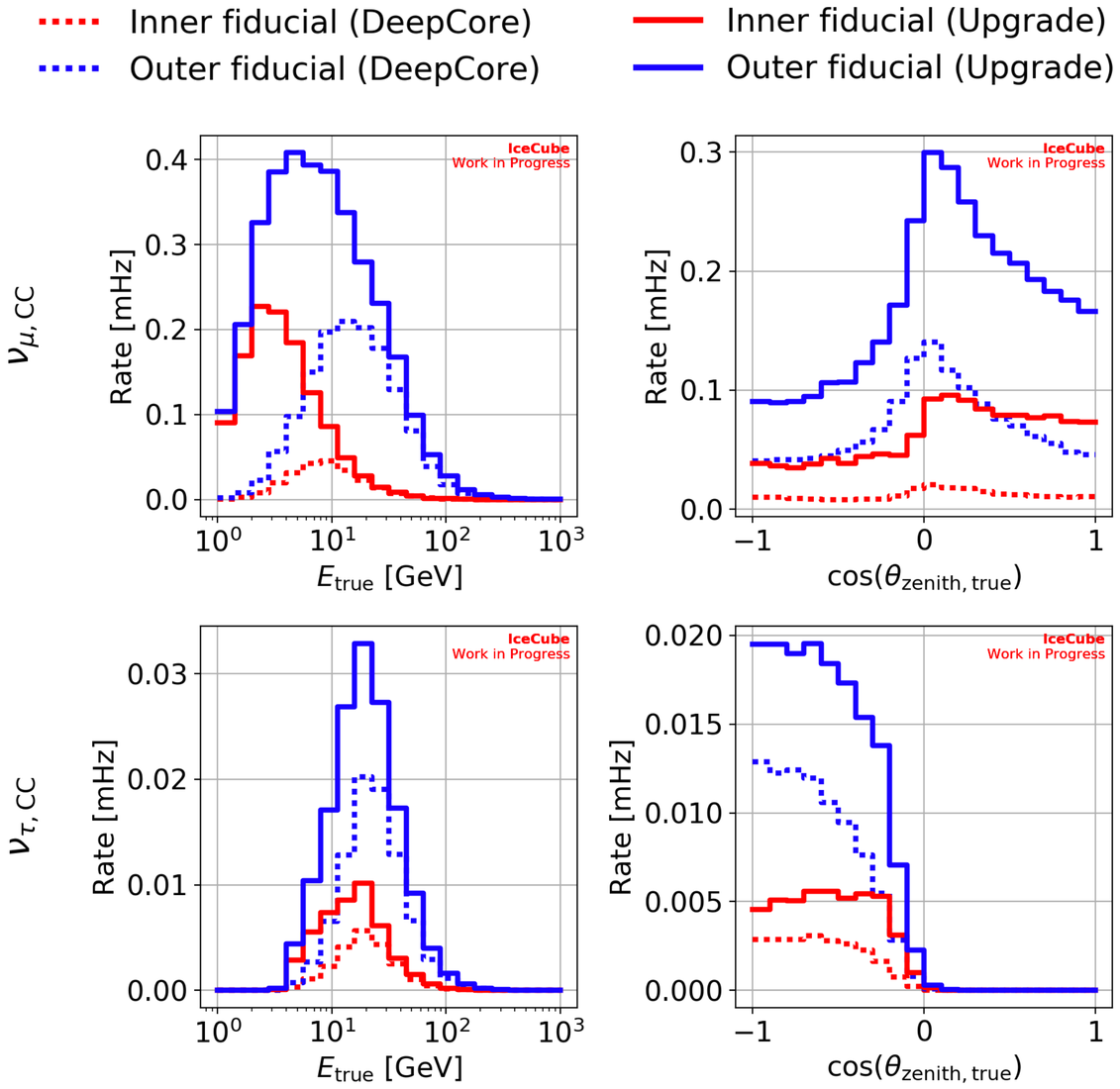
IceCube Upgrade Monte Carlo data release: click here!

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



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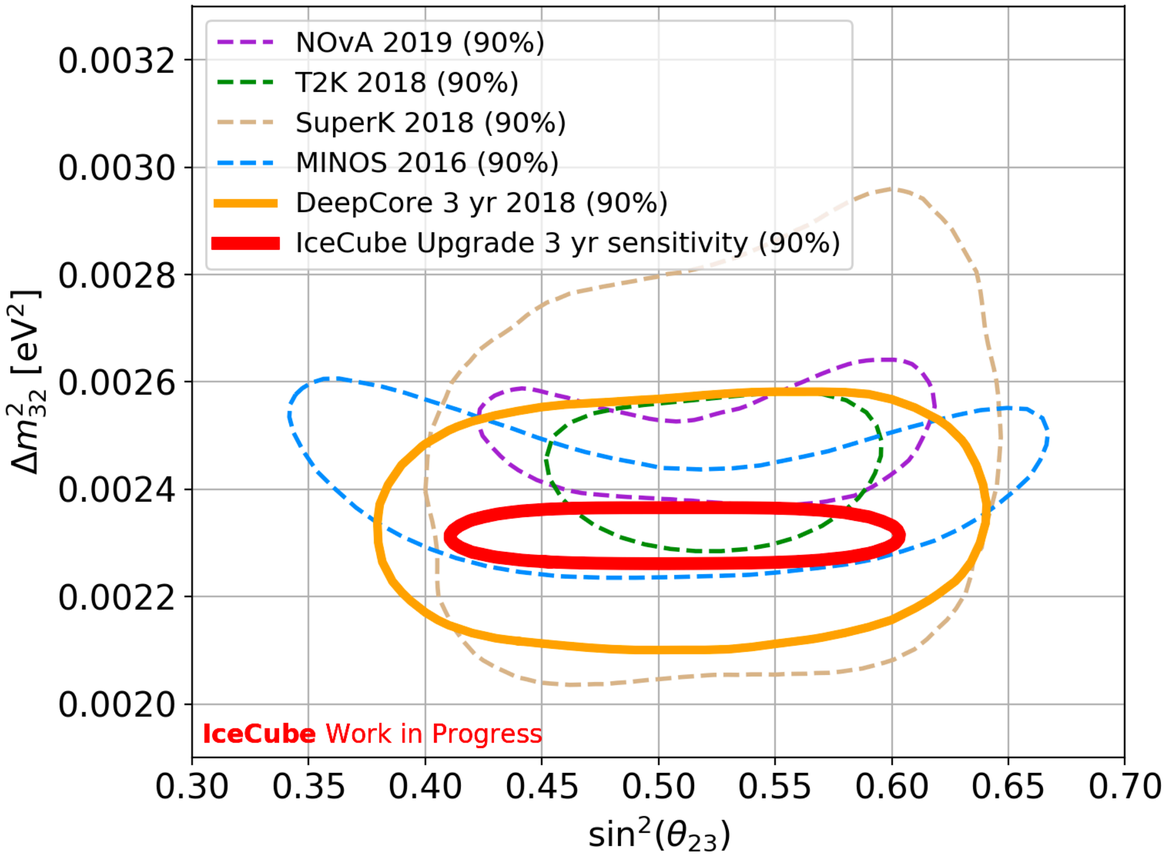
3 years of DeepCore vs. 3 years of Upgrade



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

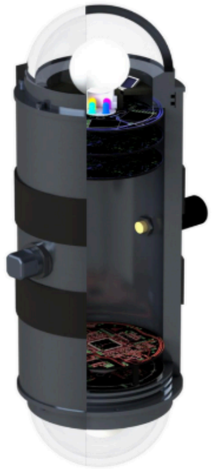
Current projections are conservative

The IceCube Upgrade

A goldmine for calibration lovers

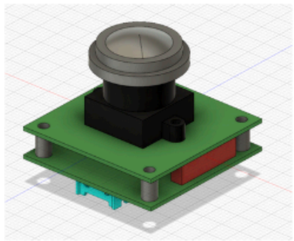
Stationary devices

Precision Optical Calibration Module (POCAM)



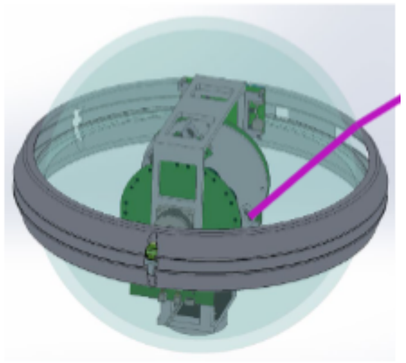
Acoustic modules for geometry

Fixed focus cameras

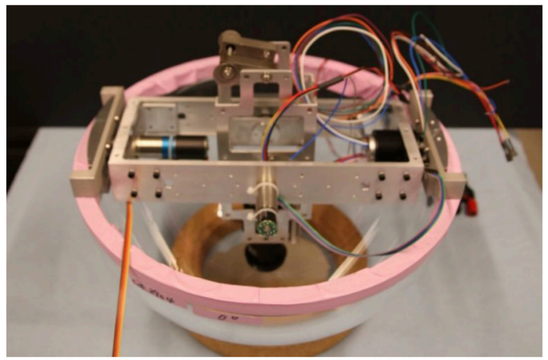


3 per DEgg/mDOM

Rotating devices

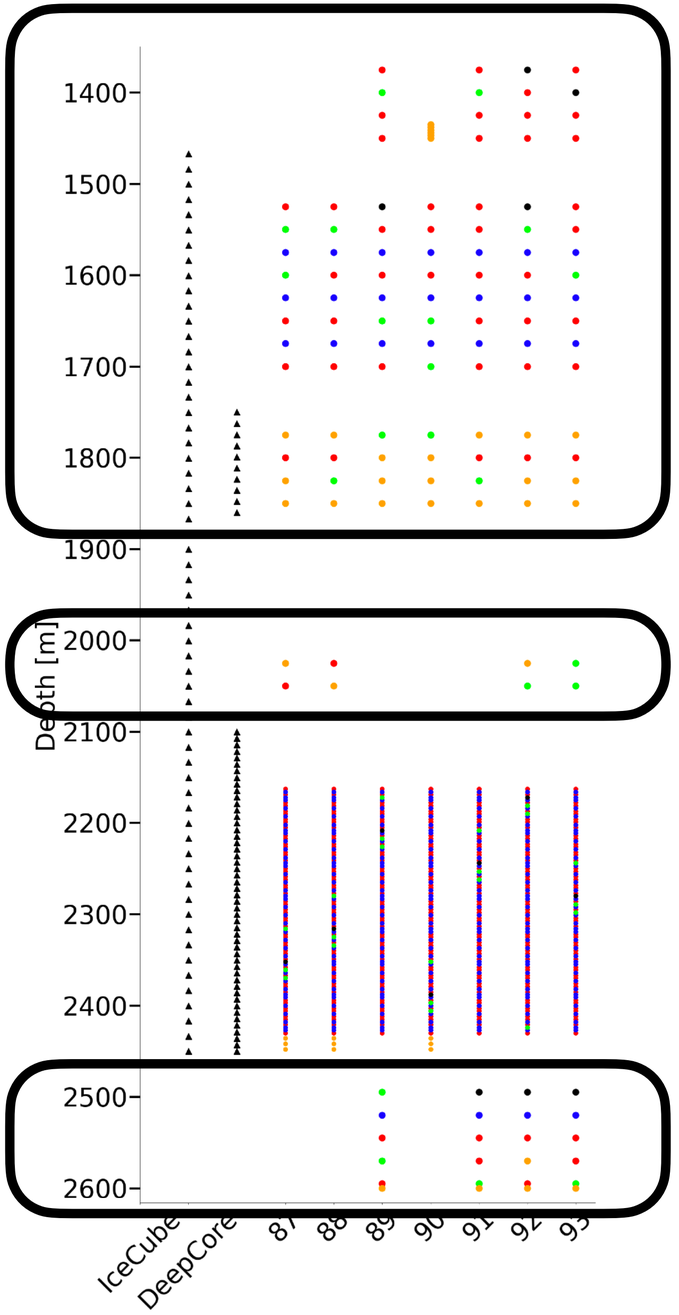


Pencil beam



Video camera

Calibration regions



IceCube-Gen2

The next generation facility

In-ice

- 12,000 new sensors for 8 km^3 effective volume

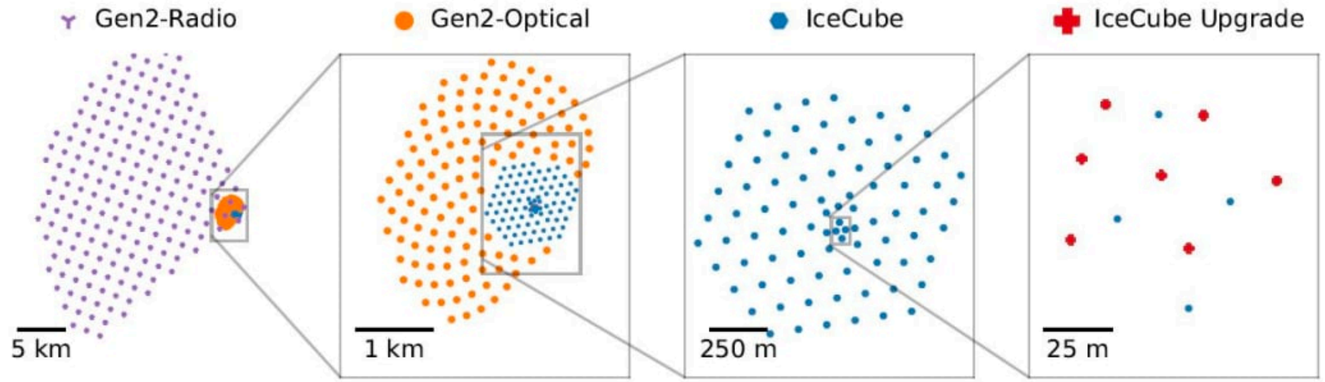
Surface array

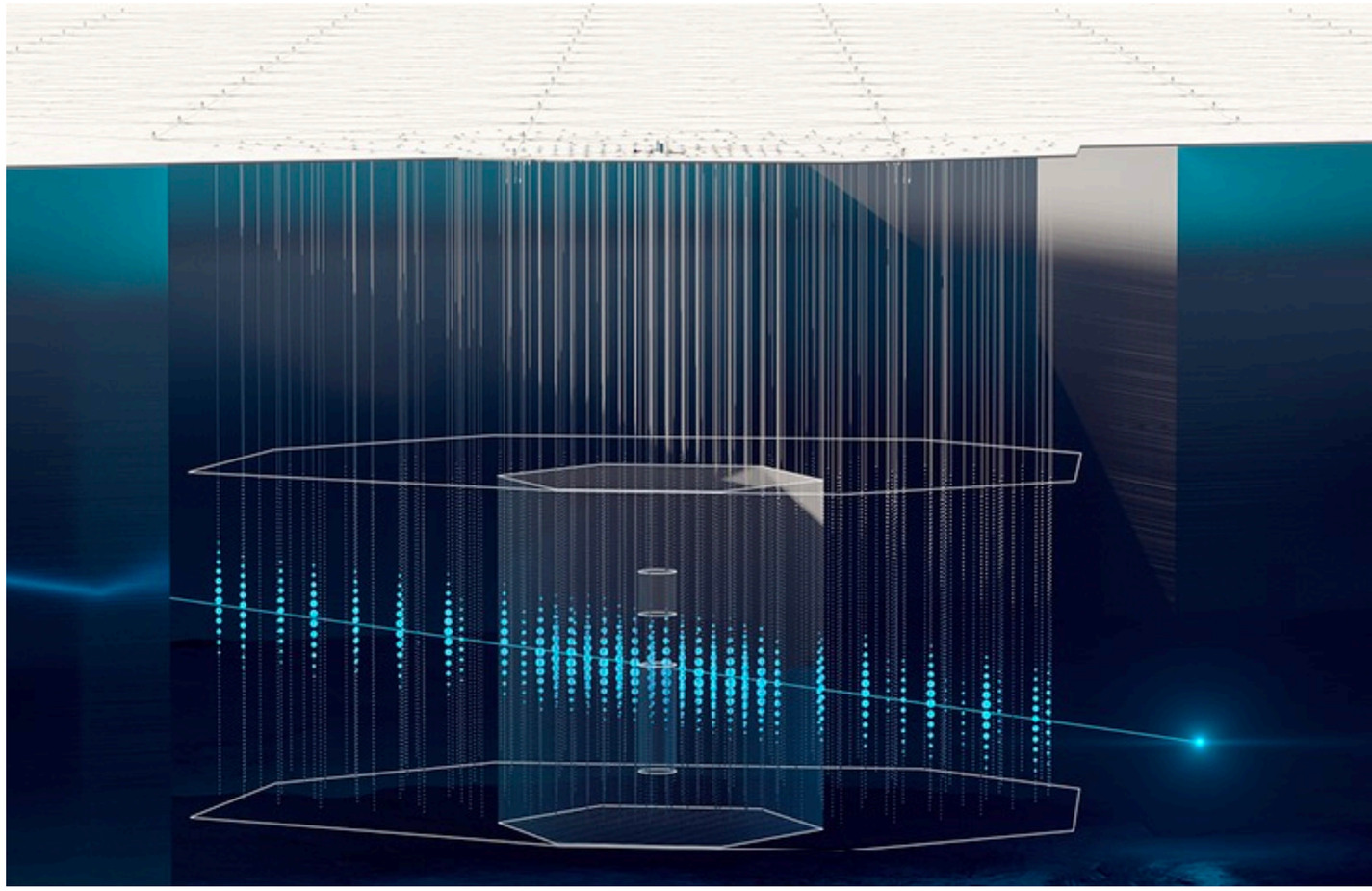
- 140 stations covering Gen2 in-ice footprint

Radio array

- 361 stations, footprint ~500 km^2

Learn more at https://www.icecube-gen2.de/



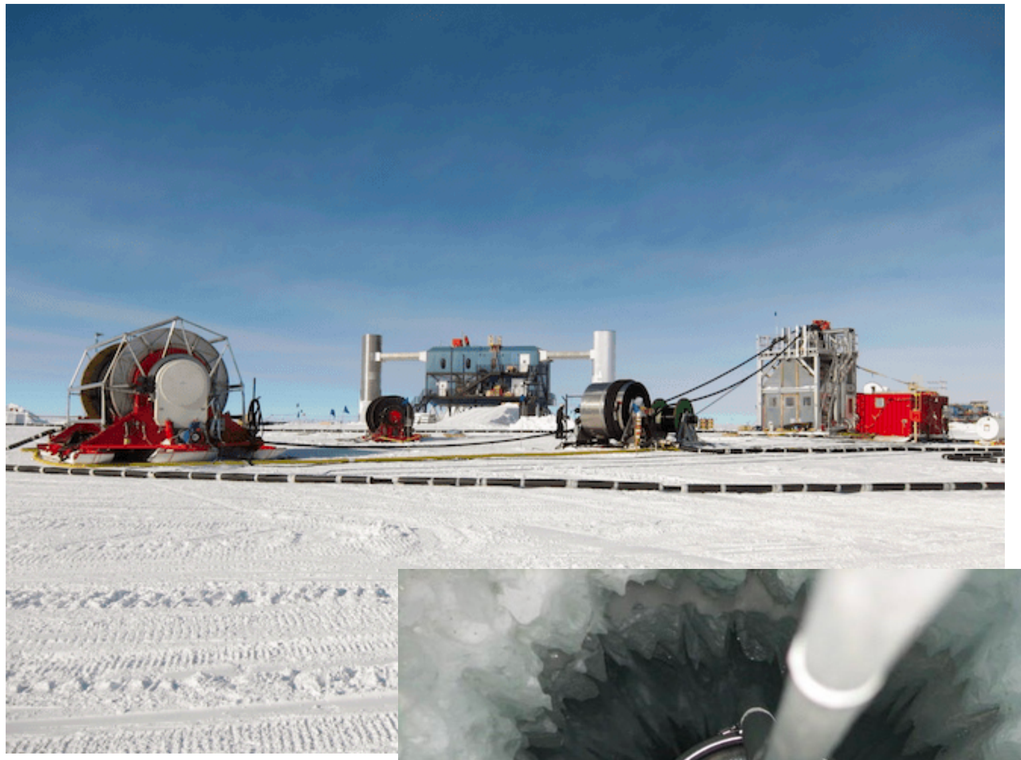


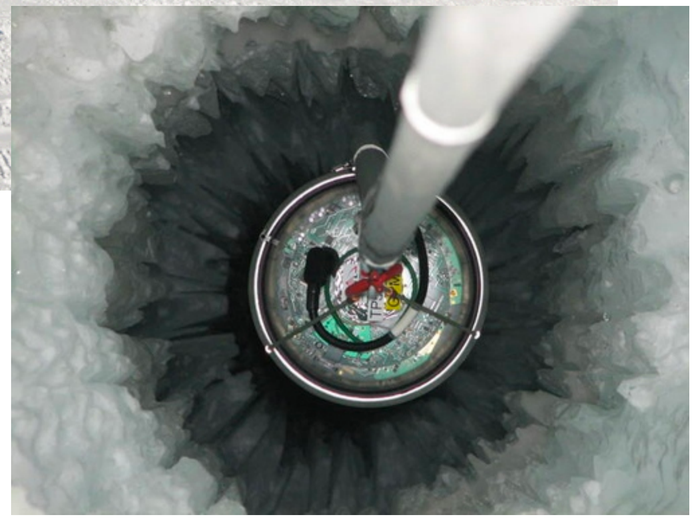
From the Upgrade to IceCube Gen2

- IceCube Upgrade originally approved as a $30 million project over 5 years (rebaselined to 7 yr)
- Original proposals called it **Gen2-Phase1**
- 20 million invested in drill refurbishment
  - **Critical investment for IceCube-Gen2**, which plans for a second drill

Gen2 sensor design:
merger of Upgrade technologies

Hot water drill equipment



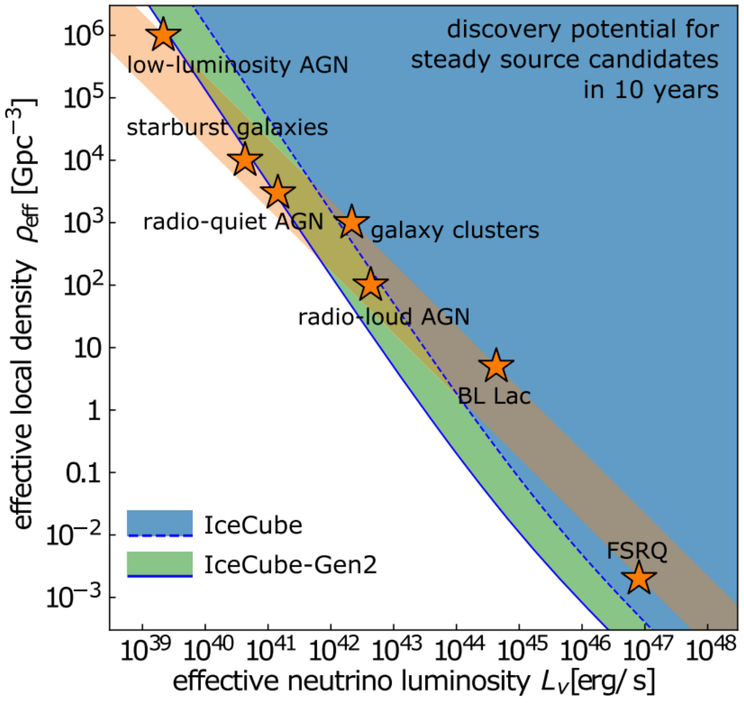


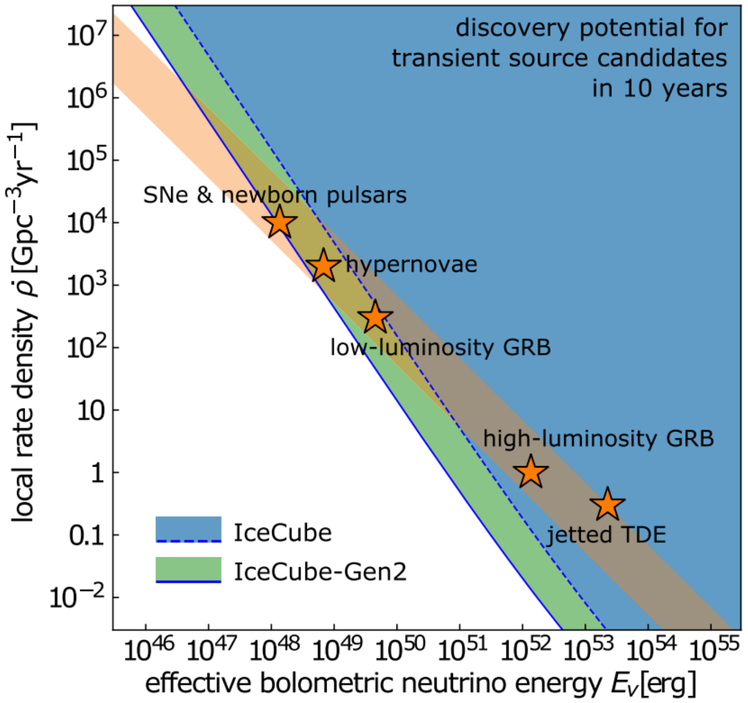
IceCube DOM deployment

IceCube-Gen2

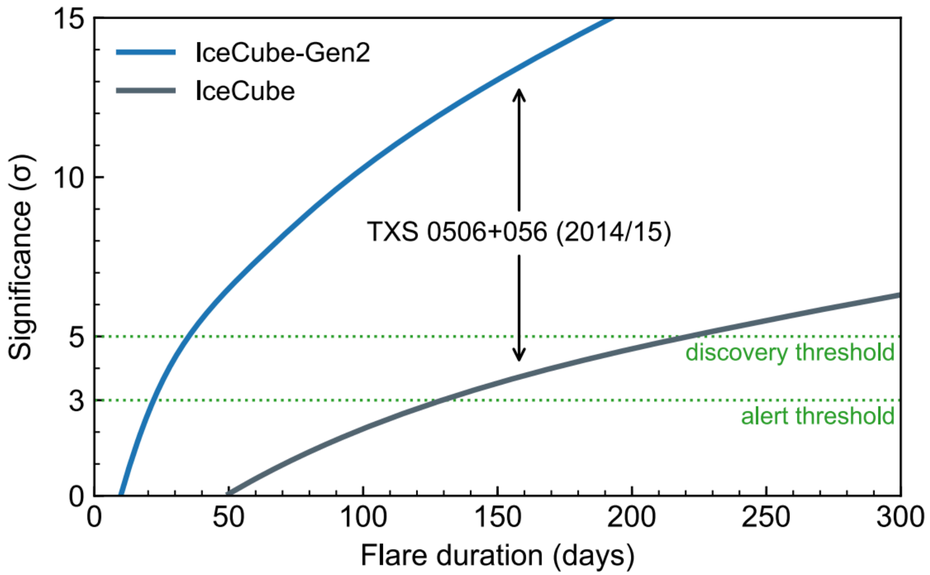
In-ice array

Improved angular resolution and larger effective volume increase sensitivity to new source classes





Example: TXS 0506+056



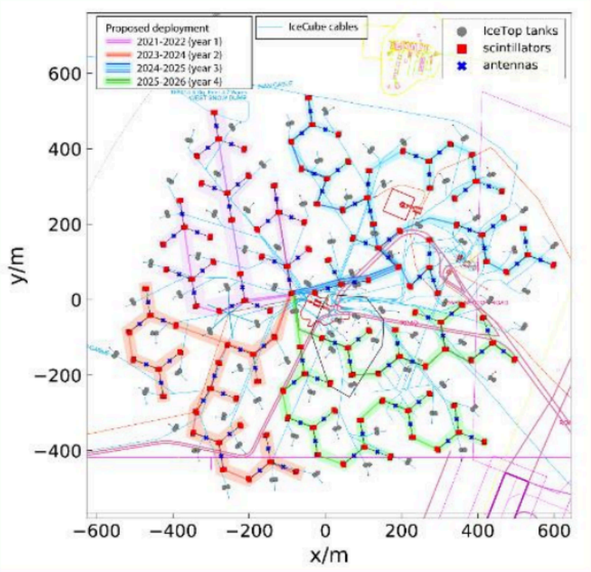
M G Aartsen *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 060501

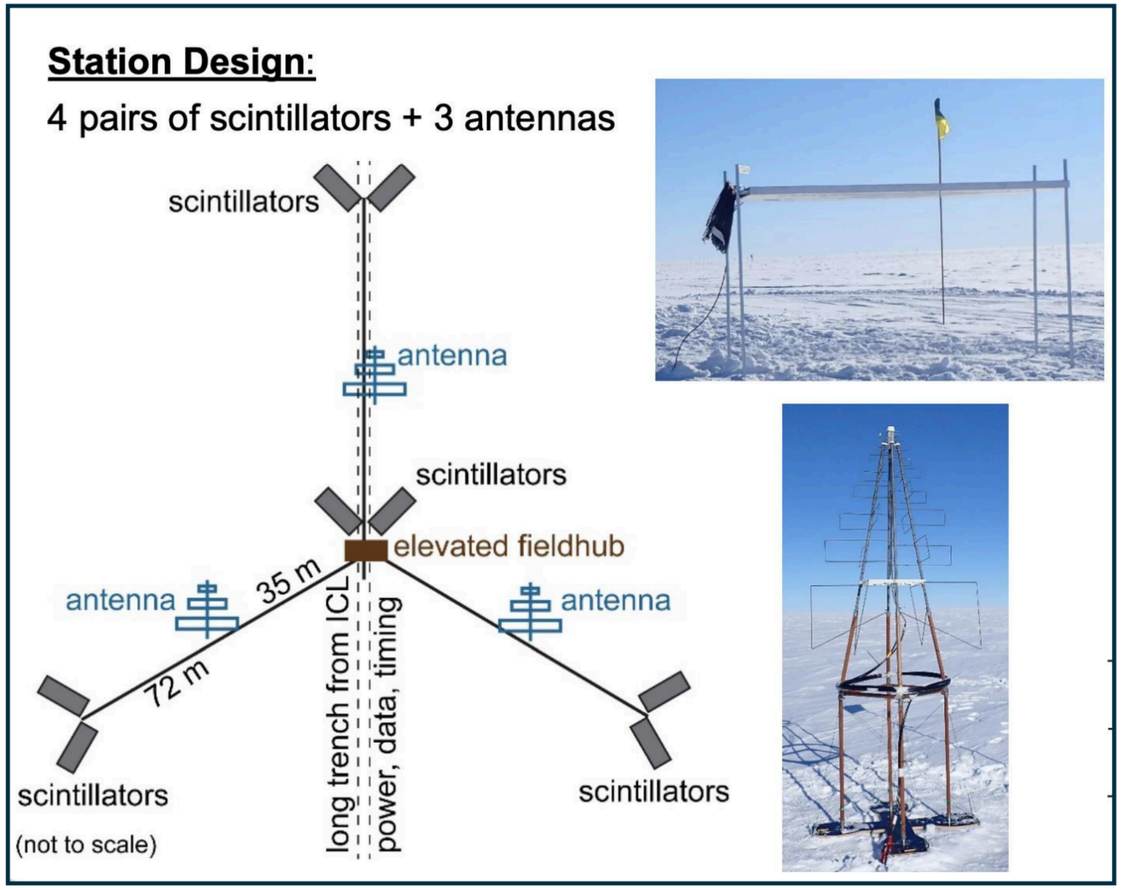
IceCube-Gen2

Surface array

A. Haungs

- Hybrid station design: raised scintillator panels + radio antennas
- Lowers primary energy threshold
- Reduced systematic errors
- Prototype at Pole operating well, with more on the way (IceTop Surface Enhancement)

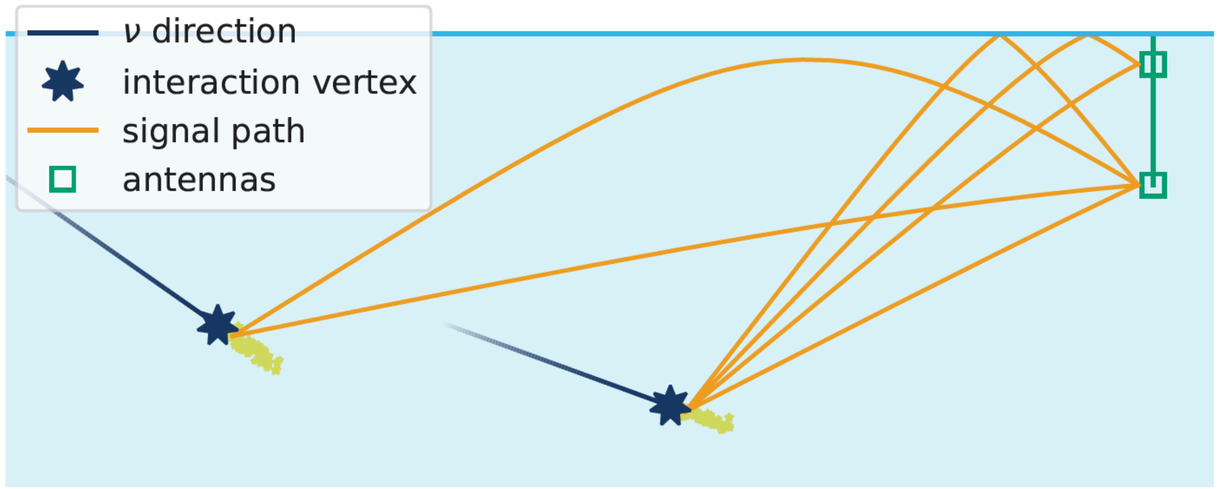




IceCube-Gen2

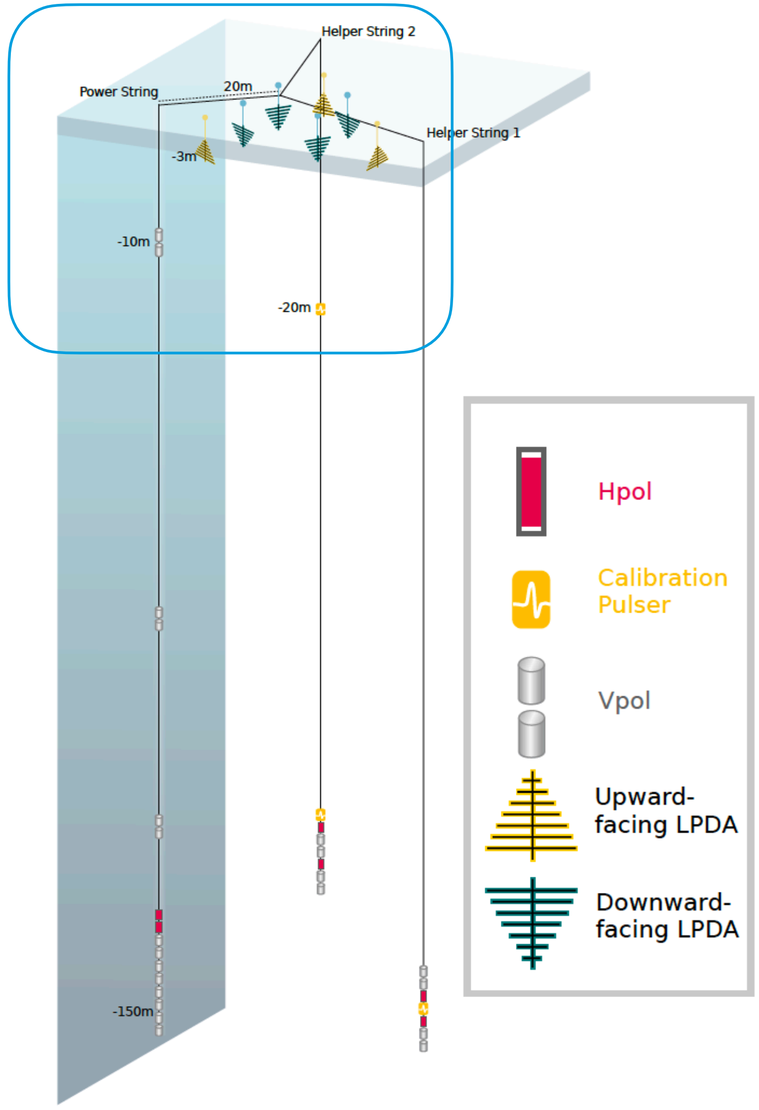
Radio neutrino detection

- New technology for EeV neutrino detection
- Design informed by predecessors (ANITA, ARA, ARIANNA…)
- Consists of both shallow and hybrid stations to optimise science, risk and cost



Shallow stations (20m)

Hybrid stations (150m)



IceCube-Gen2

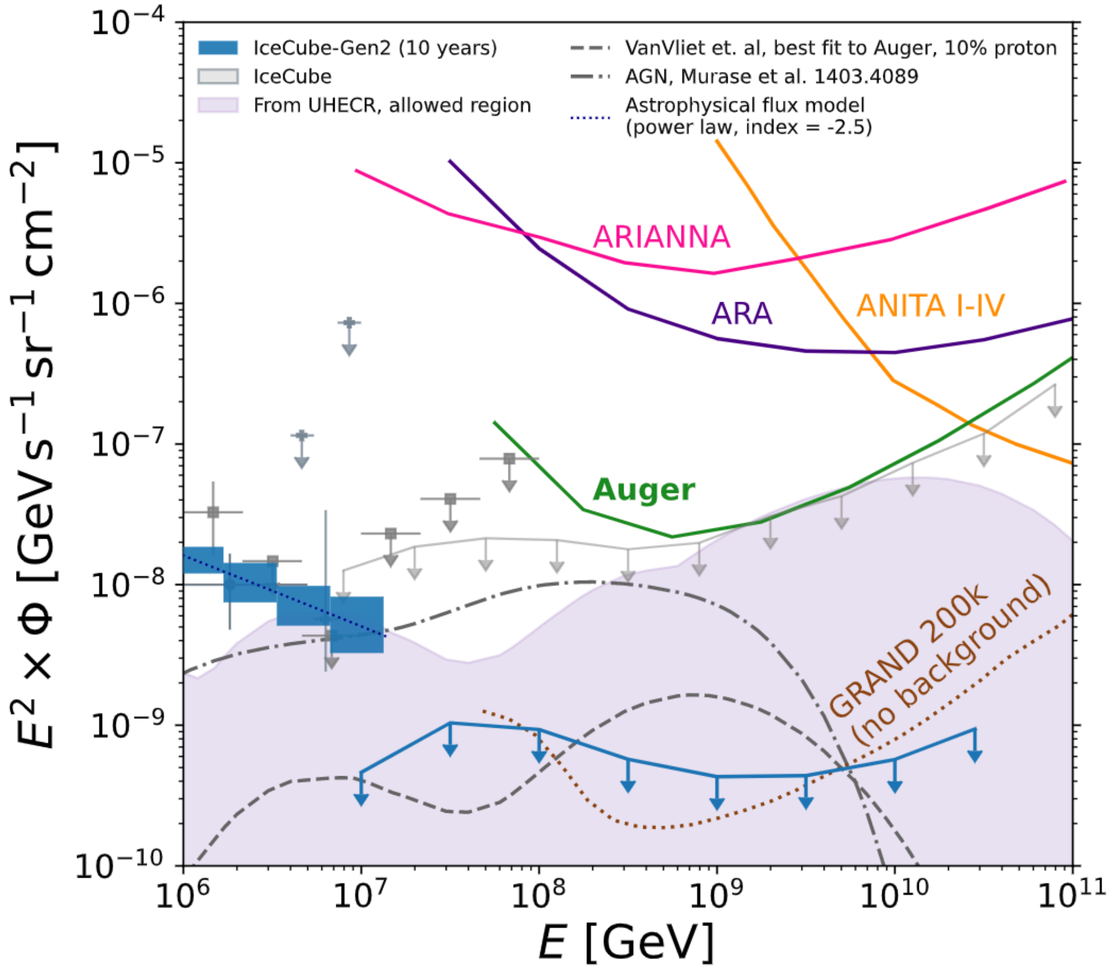
Radio neutrino detection

- New technology for EeV neutrino detection
- Design informed by predecessors (ANITA, ARA, ARIANNA…)
- Consists of both shallow and hybrid stations to optimise science, risk and cost

Science goals:

- Discovery of >PeV neutrino flux
- Reveal the sources of UHECR
- Cosmogenic neutrino detection

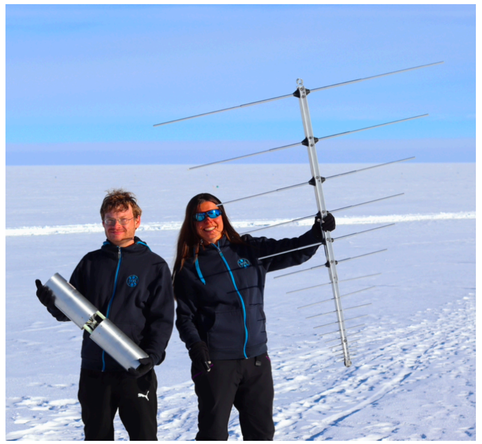
Energy threshold: >10 PeV

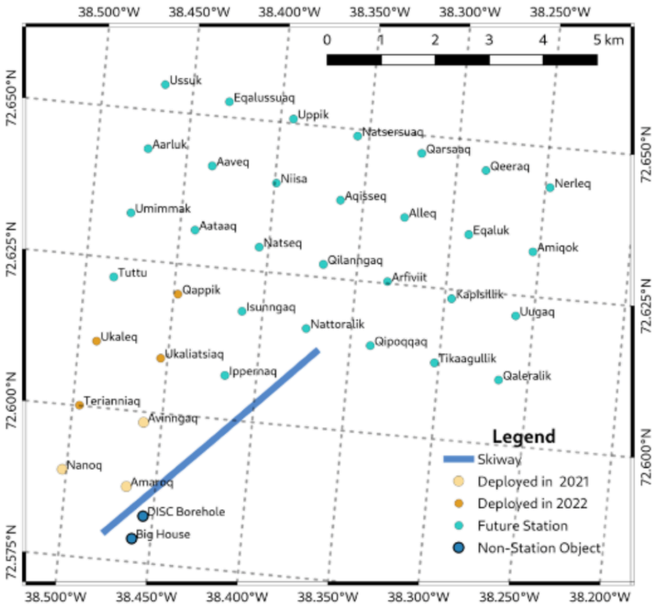


RNO-G

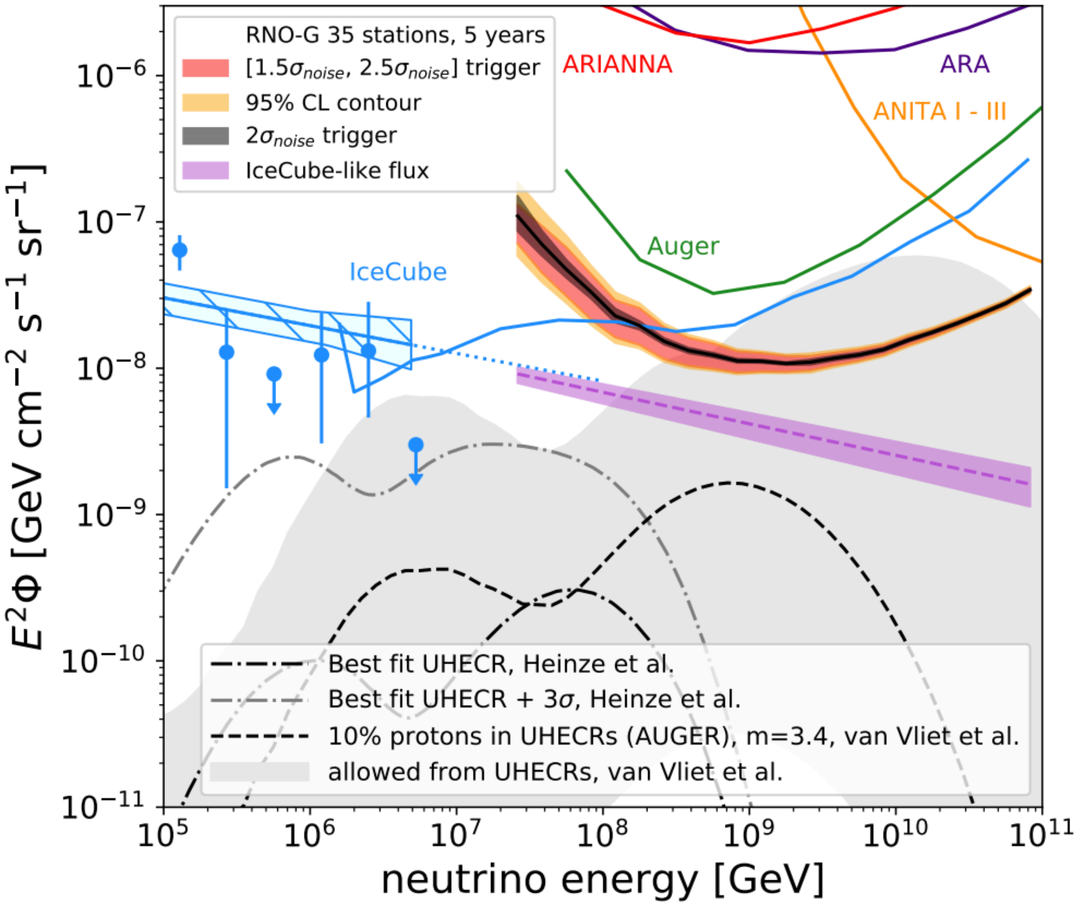
Field testing technology for Gen2 Radio

- 7 of 35 (total) stations deployed in Greenland
- 2 stations equipped with novel wind turbines
- Station deployment limited by hardware availability and drill speed
- Largest volume (potential) neutrino detector

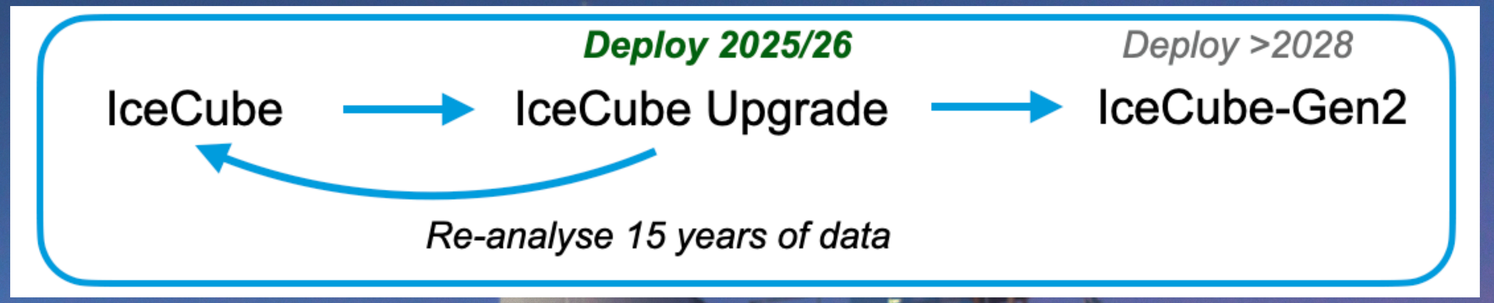




RNO-G design and sensitivity:
JINST 16 P03025 2021



Summary



IceCube operating stably for over a decade to deliver high impact results across an extremely wide range in energy (GeV-EeV) with diverse physics program

IceCube Upgrade (2025/26) will enable more precise measurements of low energy neutrino properties, and better calibrations will benefit entire IceCube science program

Longer term, IceCube-Gen2 will provide a unique facility for precision neutrino astronomy and cosmic ray physics

DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE GEN2

Backup

New sensor designs

Increased effective area

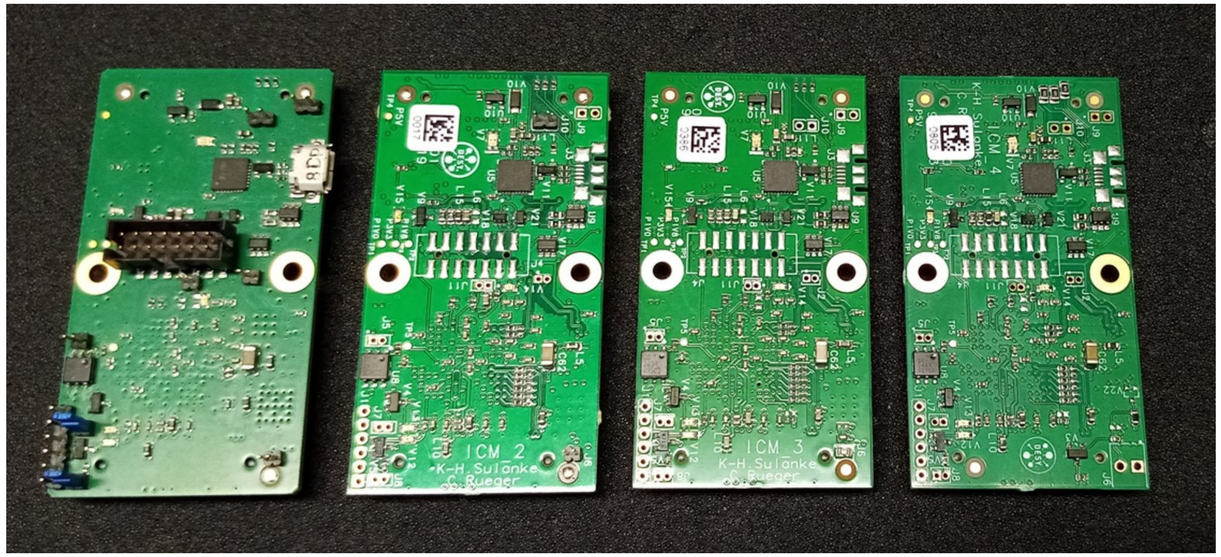
Module	PMTs	Diameter [cm]	N
IceCube-Gen1 DOM	1 x 10”	35	5160 deployed Produced at UW Madison, DESY and U. Stockholm
DEgg	2 x 8”	30	Deploy ~300 Produced at Chiba University
mDOM	24 x 3”	36	Deploy ~400 Produced at DESY and MSU

The Ice Comms Module (ICM)

Bringing order to chaos

- Many different types of modules with wide range of requirements
- The ICM goes inside every module
- Standardised communication interface to surface DAQ (simplifies firmware development)
- Inter-module timing synchronisation
- Set interlocks for light emitting devices
- “All modules speak DOM”
- DESY engineers playing a central role through design, production and testing of hardware
- Firmware developed by colleagues at WIPAC

ICM prototypes 1 - 4



Neutrino oscillations

The experimental landscape

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

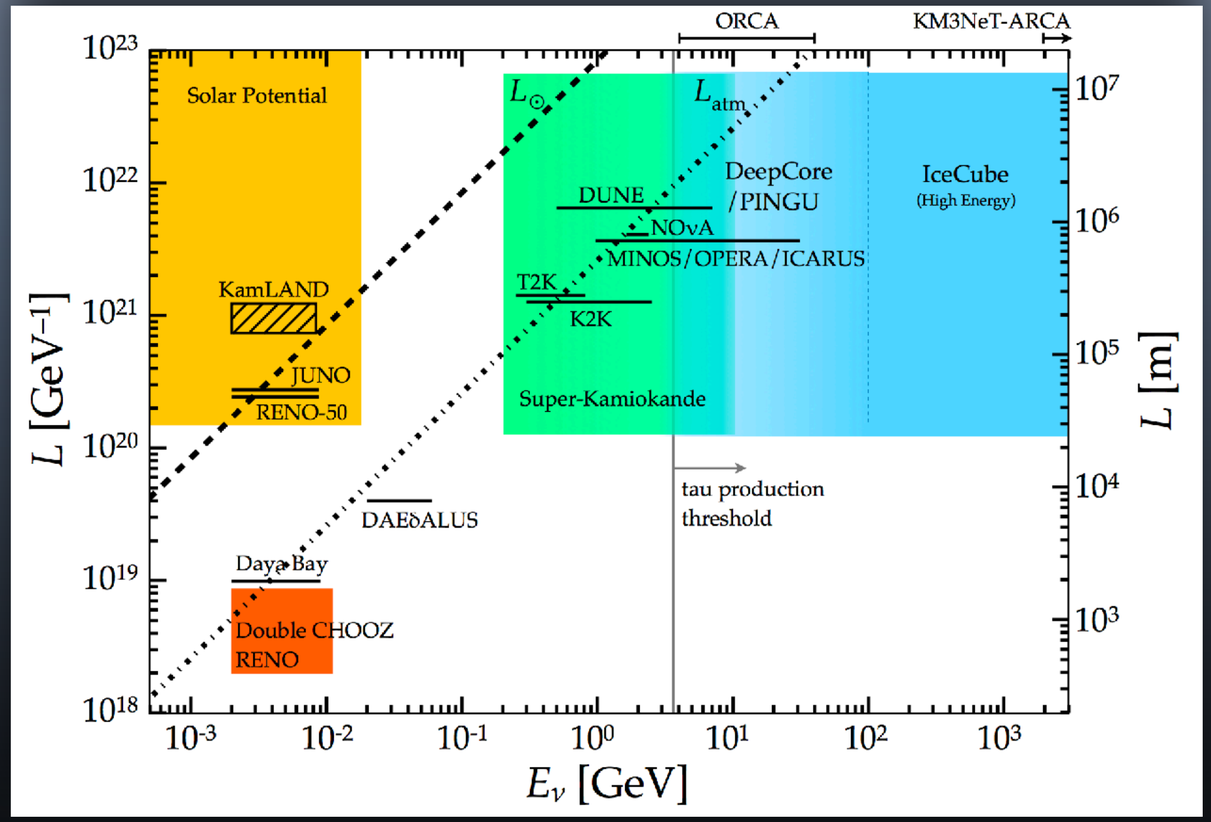
Well above the tau production threshold

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

DeepCore

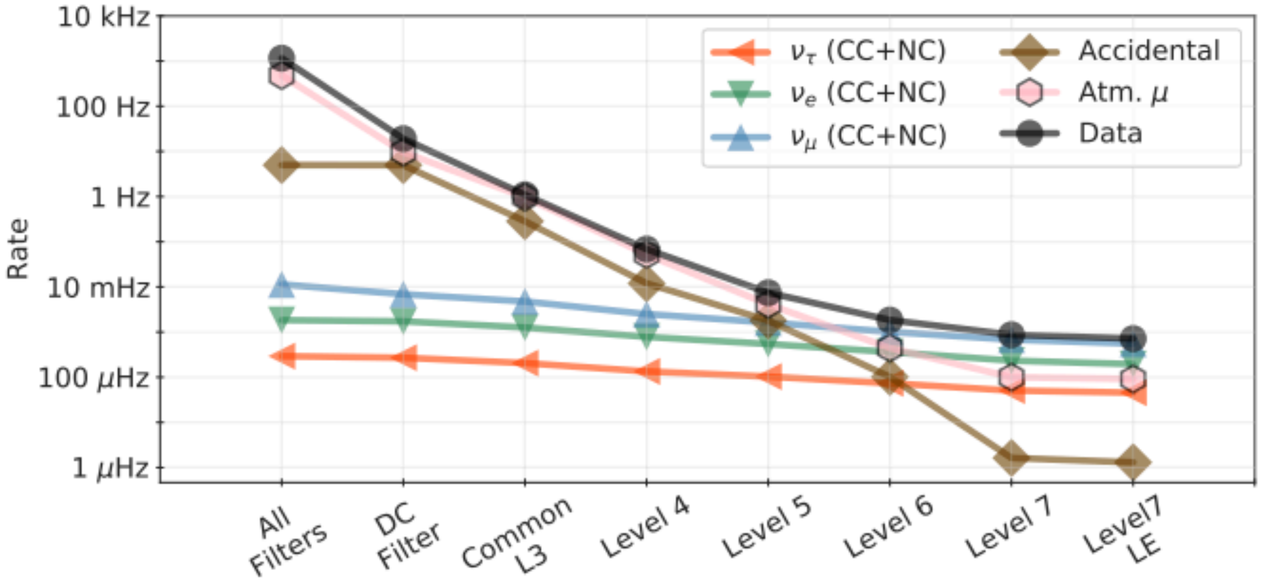
U_{PMNS} unitarity implies, e.g.:

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



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

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Searching beyond the νSM

Non-standard oscillation patterns

Favourable phase space

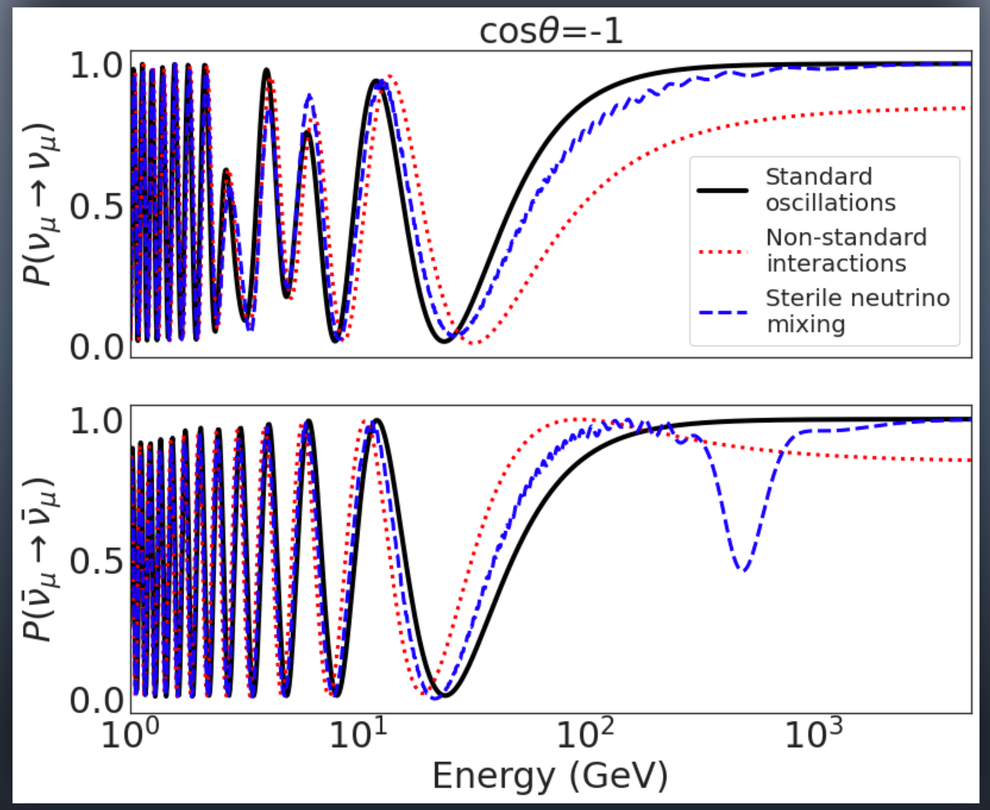
- High energies: access new physics coupling to τ-sector
- Long trajectories: exposure to new fields/interactions

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

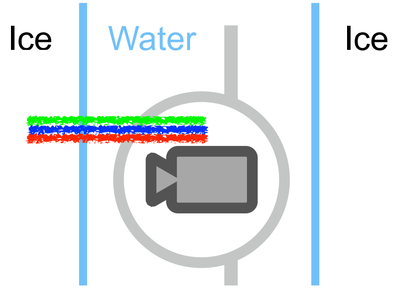
$$\hat{H} = \frac{1}{2E} U \hat{M}^2 U^\dagger + \hat{V}_{int}$$



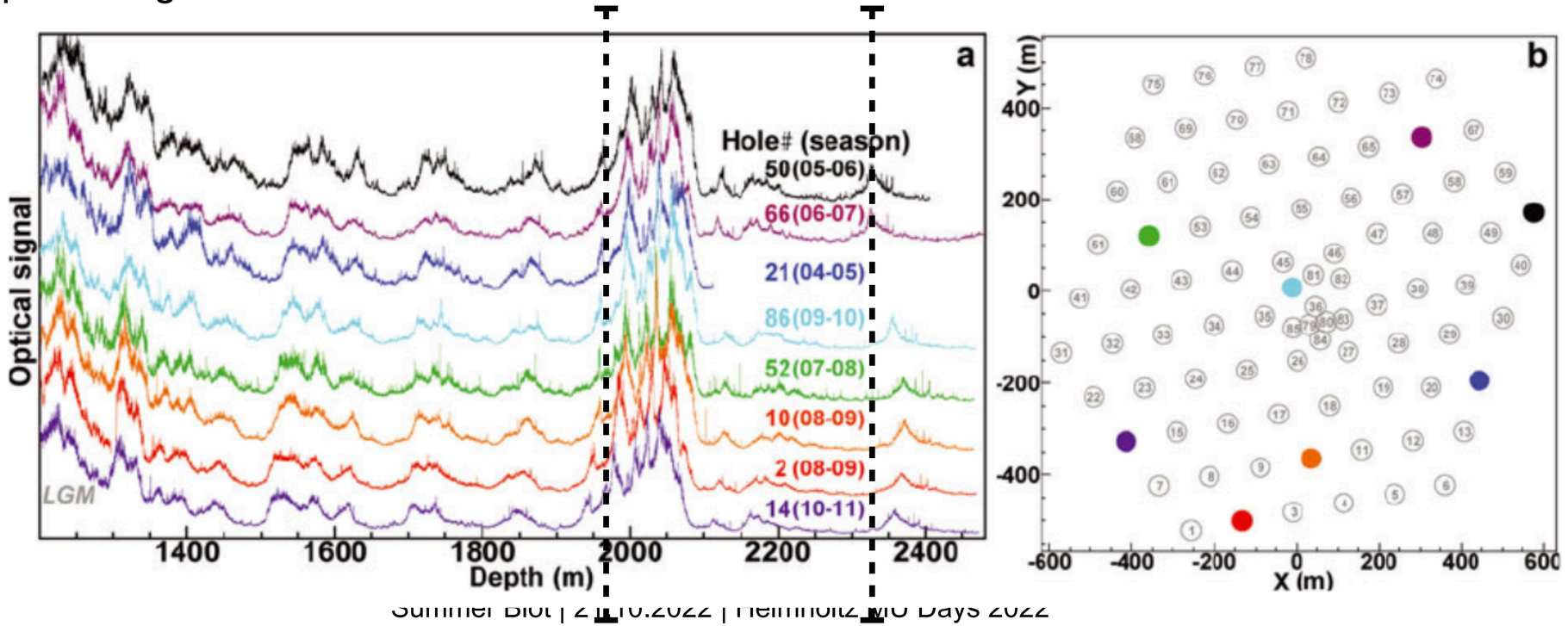
For particular realisations of non-standard physics

Natural detection medium

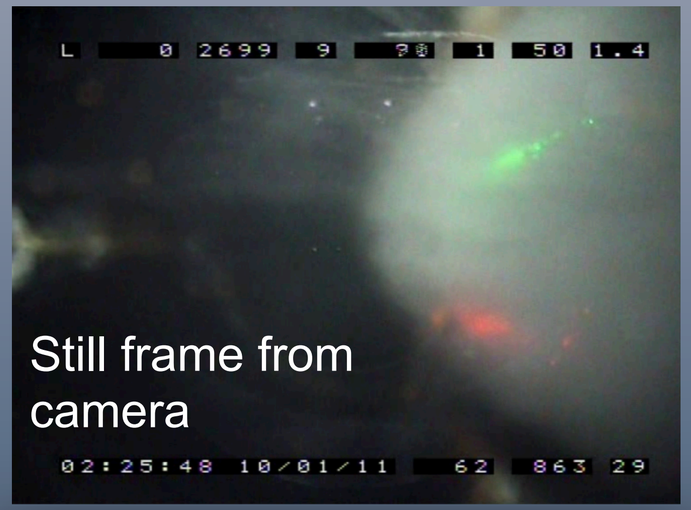
The “Bulk” ice

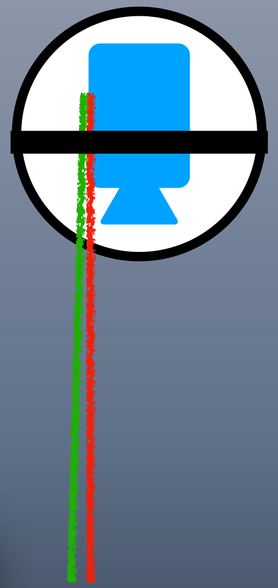


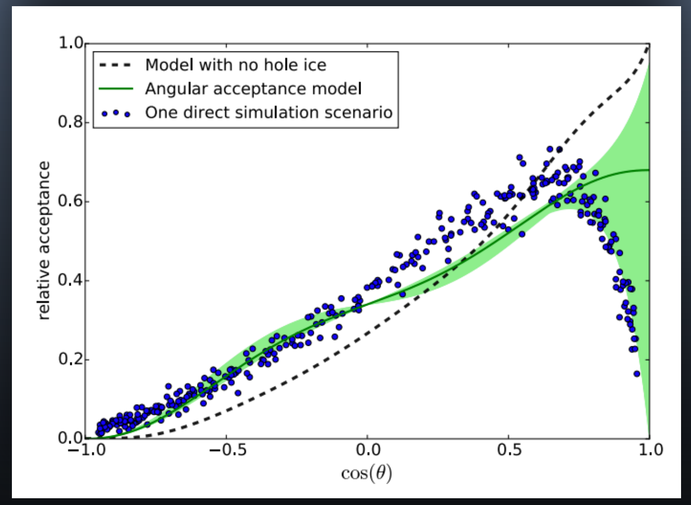
- Ice layers serve as historical record of atmospheric conditions
- Photons experience variable scattering and absorption lengths as they travel from production to detection
  - Average effective scattering length ~30m
  - Average absorption length ~100m

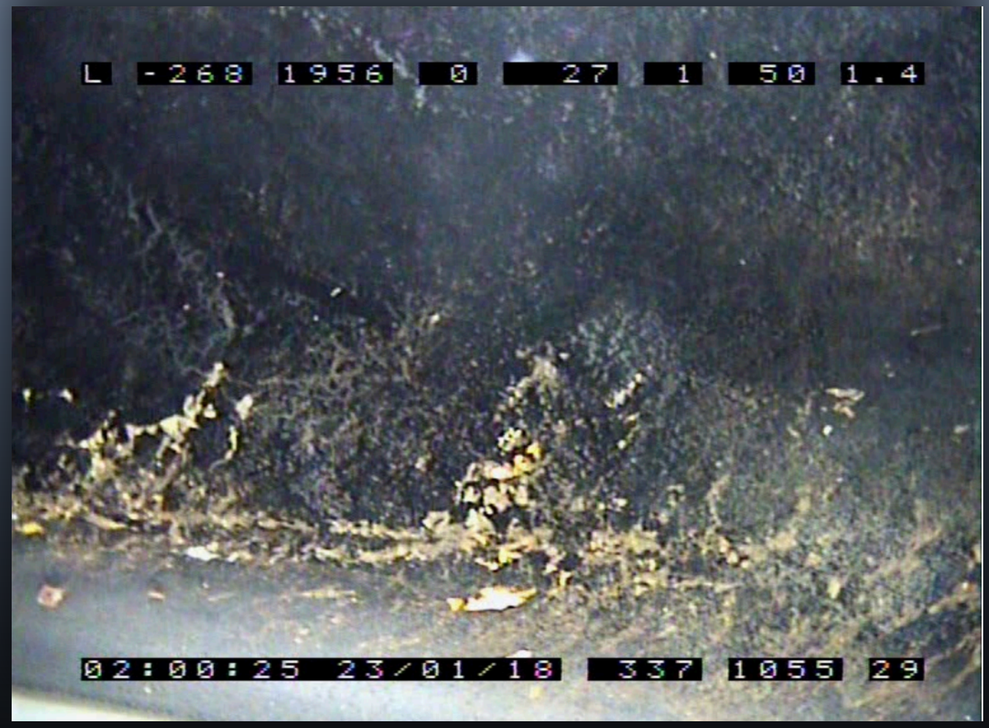


Local ice/DOM features



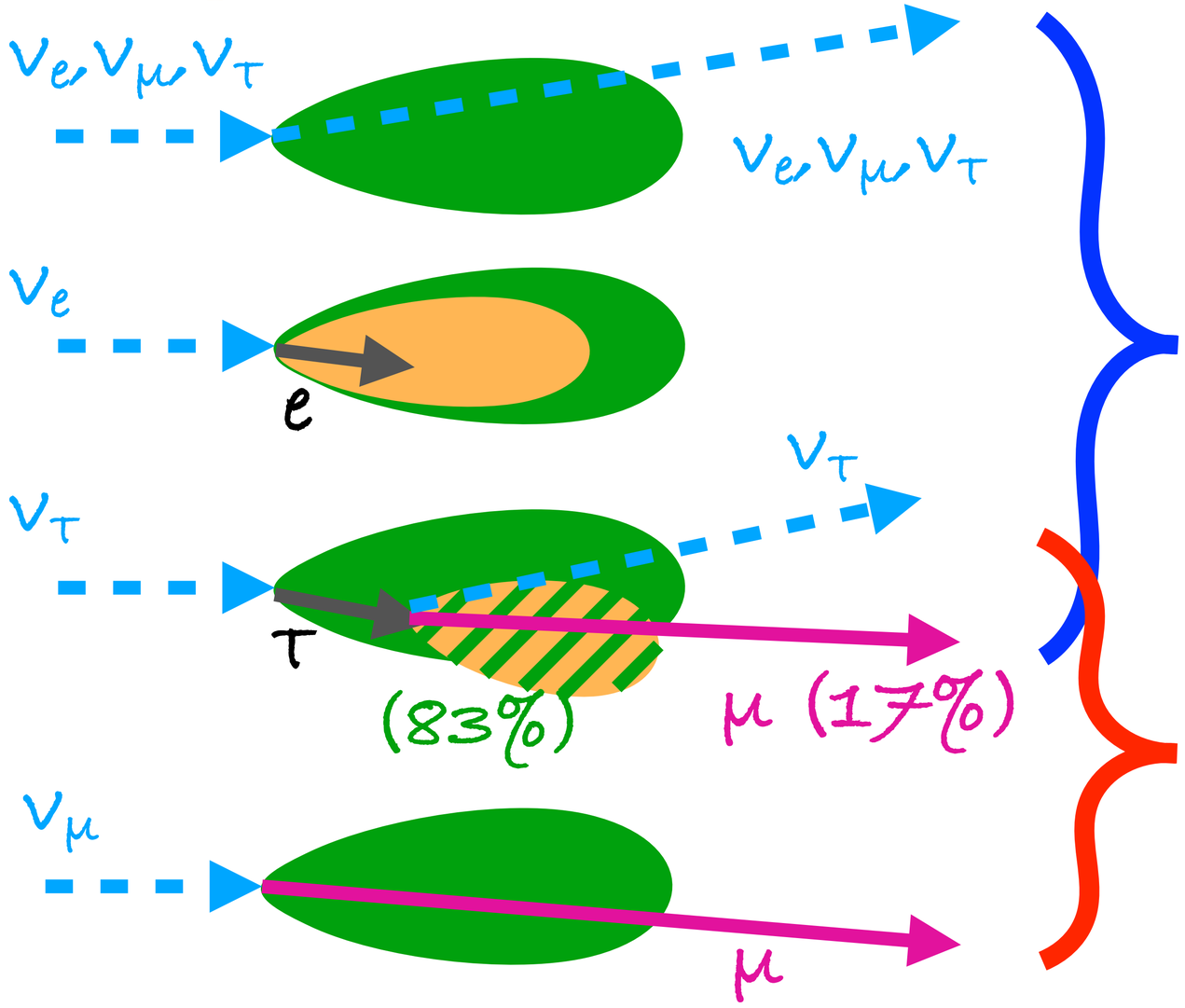


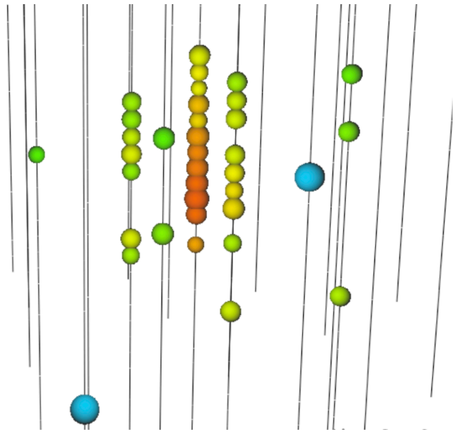


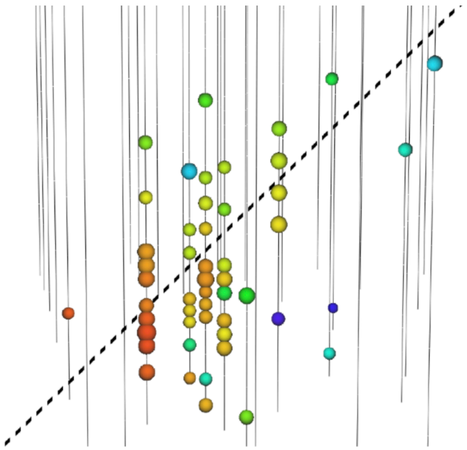


Neutrino interactions in IceCube

Event signatures



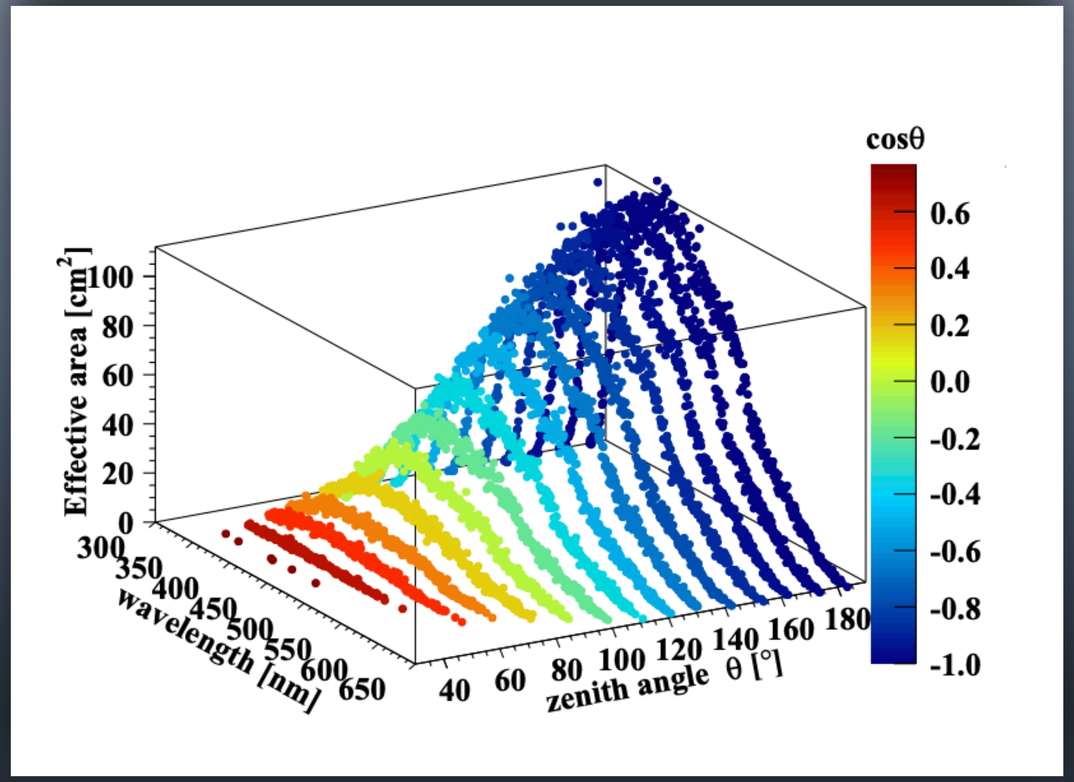




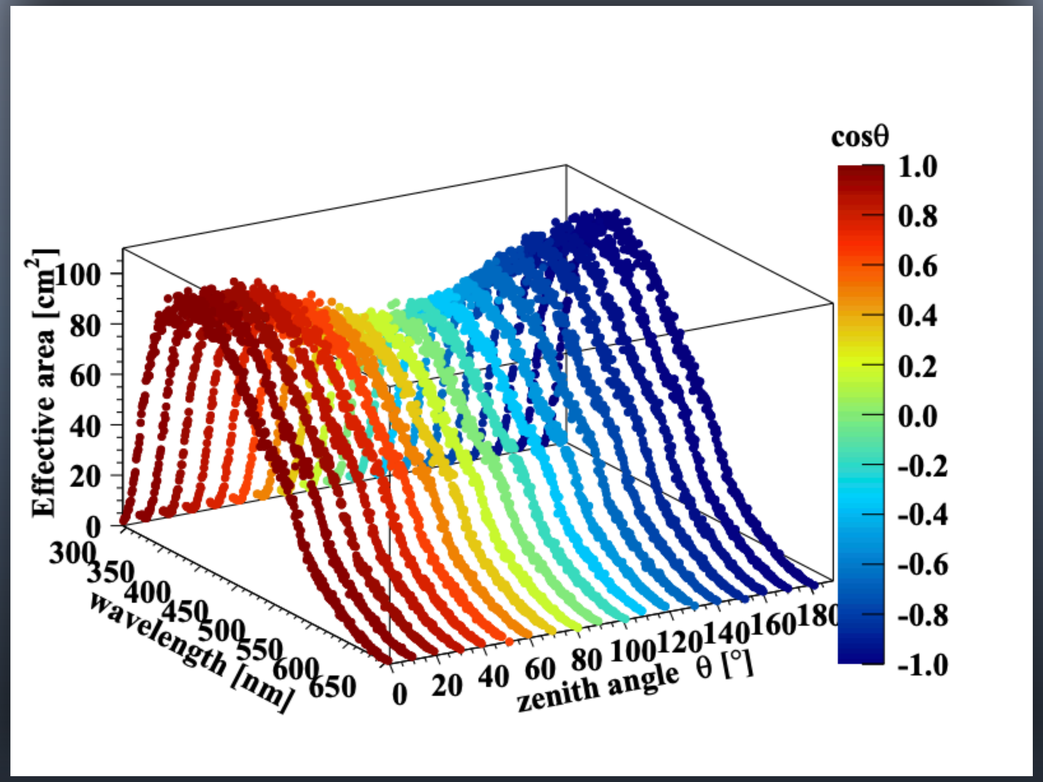
The IceCube Upgrade

New technology

IceCube Gen1 DOM



Upgrade module: DEgg



NMO

Exploit synergy between JUNO and IceCube Upgrade

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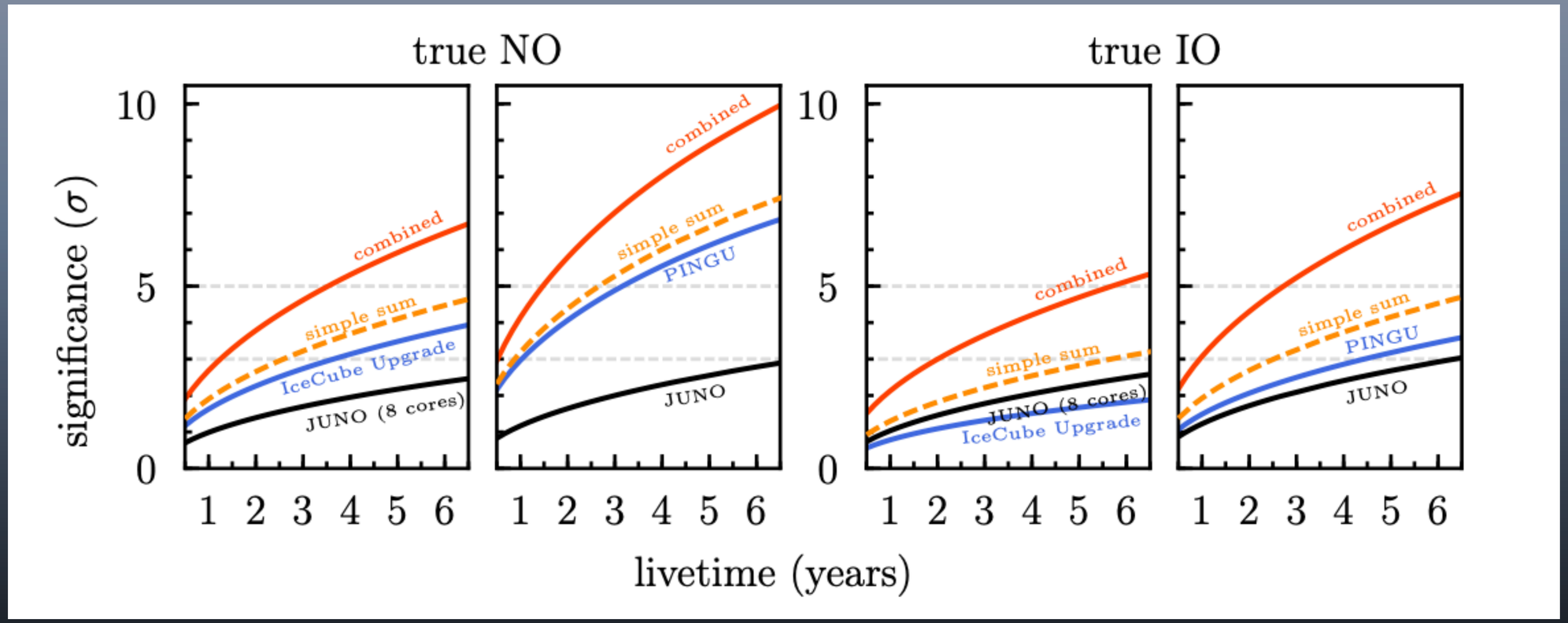

Particle physics with Astrophysical Neutrinos

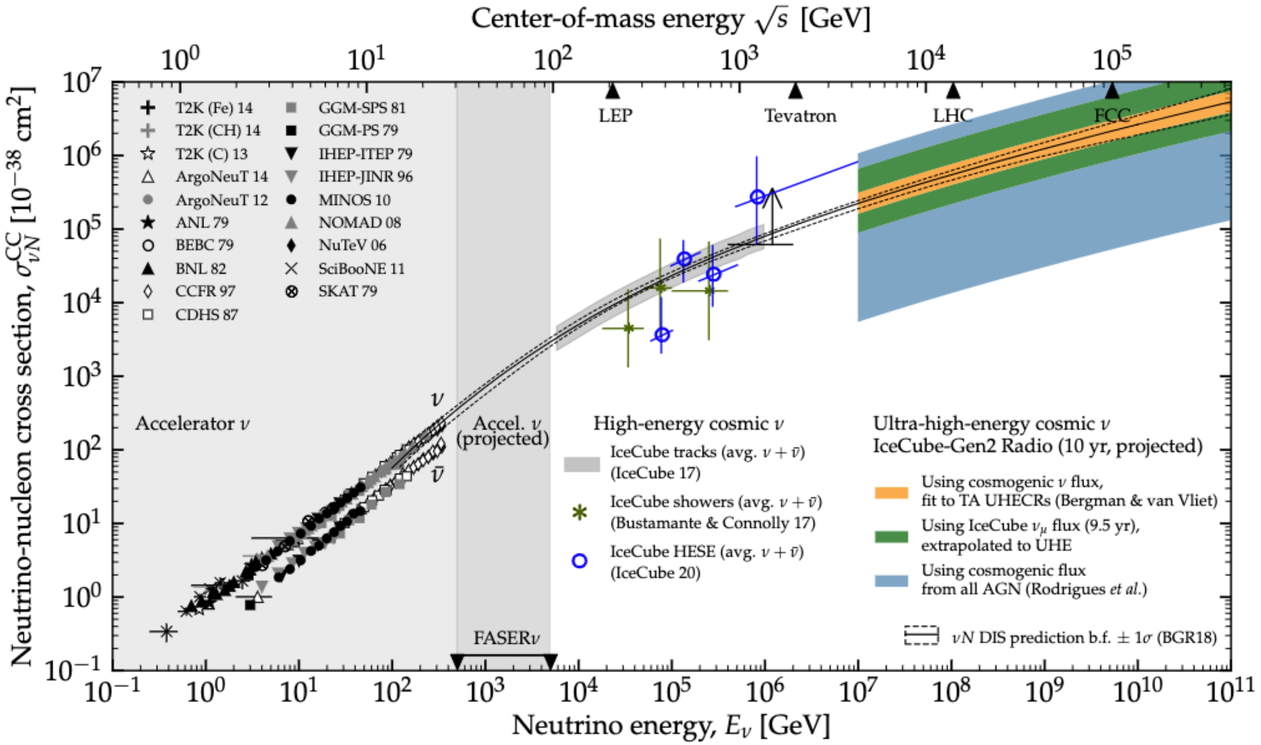

Figure 31: Neutrino-nucleon cross section measurements, compared to deep-inelastic-scattering (DIS) cross section prediction from Ref. [387] (BGR18). The forecasts at ultra-high energies are for the radio component of IceCube-Gen2 only, and for three different assumptions of the UHE neutrino flux. For each choice of flux, the cross-section sensitivity forecast accounts generously for the uncertain normalization of the flux prediction. The resolution in shower energy is 10% and the resolution in zenith angle is 2°. Forecasts are for a radio-array design consisting of 313 shallow radio stations and 144 deep ratio stations (200 m depth). Figure adapted from Ref. [390].