Recent results and new developments from the IceCube Neutrino Observatory

Stockholms universitet

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IceCube

Anna Obertacke

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IceCube

South Pole

IceTop Array
81 stations

IceCube Laboratory

Working principle

- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Fully operational since 2011

Geometry

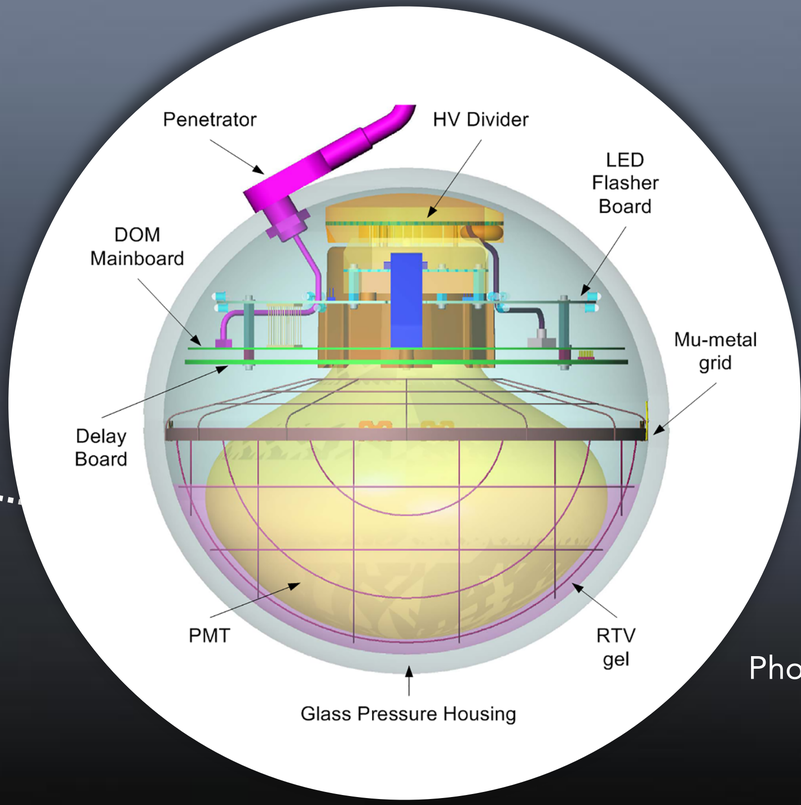
- volume 1 km^3
- vertical spacing 17 m
- horizontal spacing 125 m

1450m –

2450m –

InIce Array
86 strings,
each with 60 optical sensors

Digital Optical Module (DOM)



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News 2025

Astrophysical neutrinos

After IC analyses on different datasets showed different spectral indices for a single power law a dedicated analysis made a fit on a rather wide energy range and found that a broken power law describes the flux best.

Neutrino sources

Several hard X-ray sources start to cross 3 σ in neutrinos.

Highest energies

The standard scenario to explain the cutoff of cosmic rays at highest energies, GZK, predicts them to be protons that collide with photons from the cosmic microwave background producing extreme high energy neutrinos. In this new analysis, no neutrinos were found, which for the first time constrains the proton hypothesis to 70%

Neutrino flavors

The standard scenario for neutrino production by cosmic rays is delta resonances that would give a flavor ratio of (electron - muon - tau) 1:2:0. These and further scenarios were tested.

Galactic plane

With added data, the galactic plane passed 5 σ for being an astrophysical source of neutrinos. First analyses start to extract physical parameters from this flux, among them Ludwig's at SU.

KM3NeT neutrino

KM3NeT discovered a signature that could be a 220 PeV muon neutrino. This is difficult to bring into agreement with IceCube current limits.

Local highlights

Neutrino reconstruction

With its first 3 sources, IceCube can now really be used as a telescope. But traditional telescopes have much smaller angular resolution. In order to approach this, a new technique was developed using transformer encoded mapping of a normalizing flow on the 2-sphere . This improves resolution up to 300%.

Hunting exotic particles

With IceCube it is also possible to search for exotic particles which leave distinct signatures in the detector emitting unusual signatures of light.

Upgrade construction started this November

The low energy extension of IceCube, the Upgrade will be build this austral summer (this winter in Sweden). First IceCubers have arrived at Pole and start setting up the construction area. Swedish institutes were involved in several of the new devices that will be deployed: the Sweden Camera, the WOM. Additionally people in Sweden worked on the baseline sensors, the mDOM and D-Egg.

Preparations for Gen2

The high energy extension of IceCube, so-called IceCube Gen2, will increase the current volume by a factor of 8. The prototype of the future sensor is currently being developed. Soon the preparations for mass productions start.

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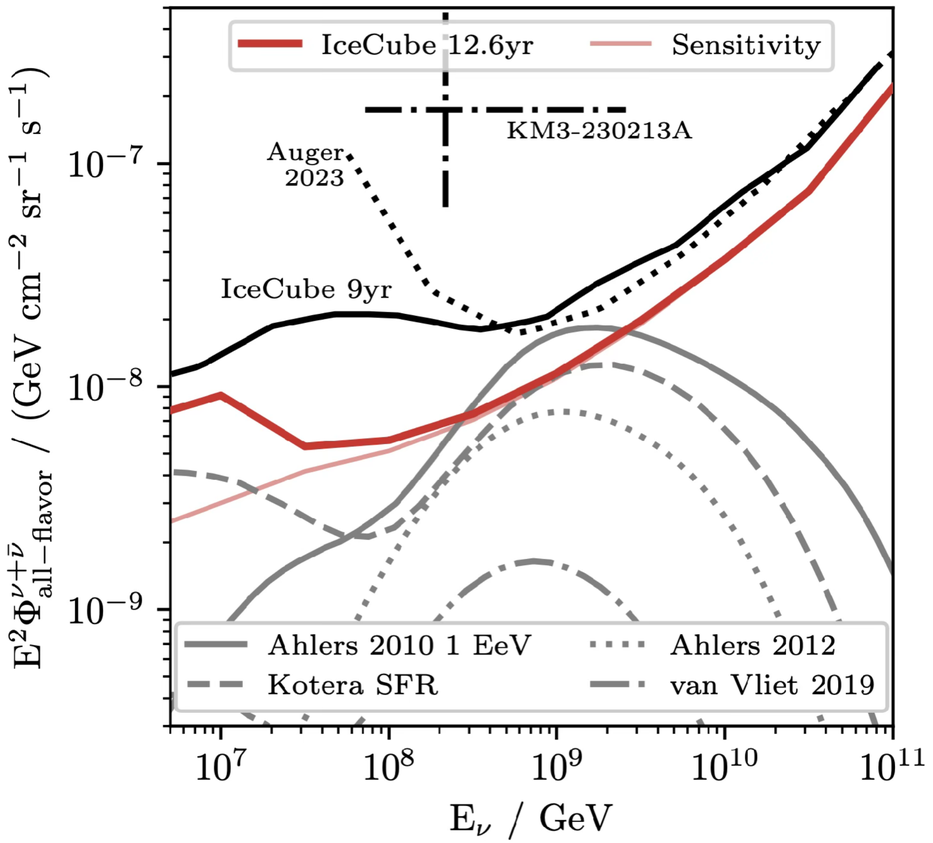
Extreme high energy neutrinos

- cosmic ray cutoff at > 10^{20} eV might be due to GZK effect, giving extreme high energy neutrinos

$$p_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Phys. Rev. Lett. 135, 031001 (2025)

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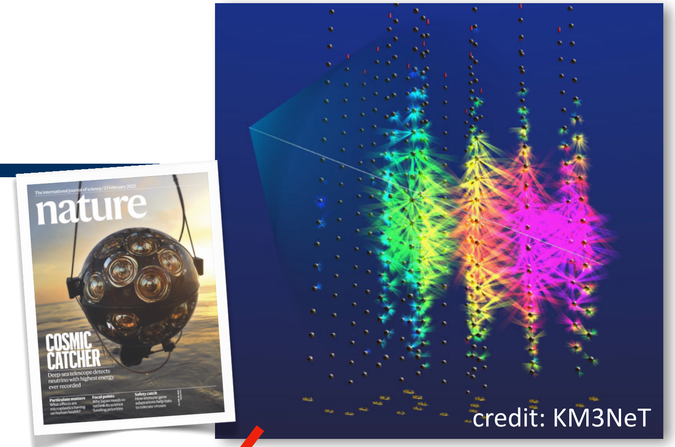
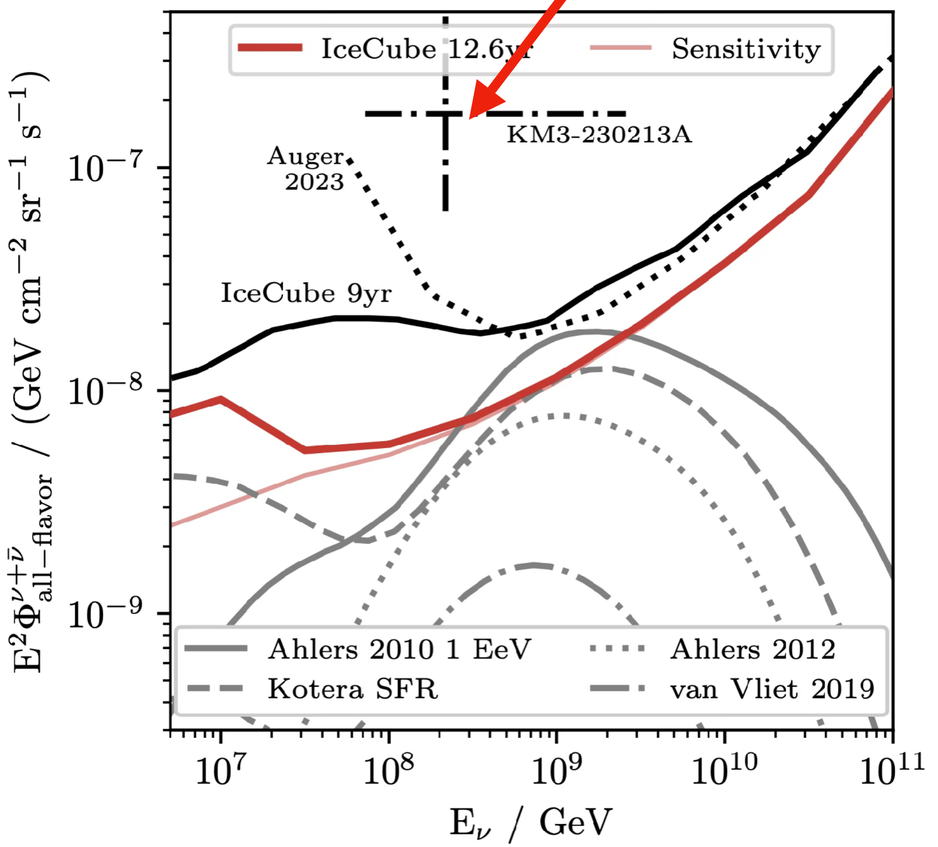
- derived diffuse neutrino flux would lead to 70 neutrinos expected within IceCube datasets (excluded by > 10 σ)





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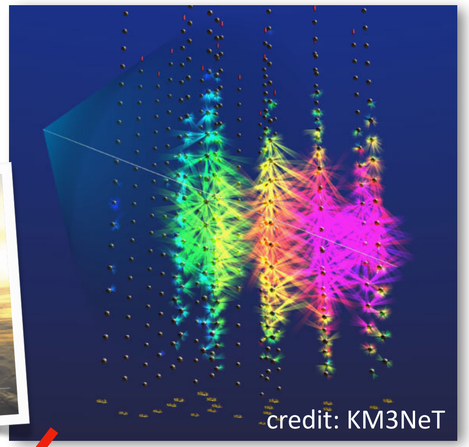

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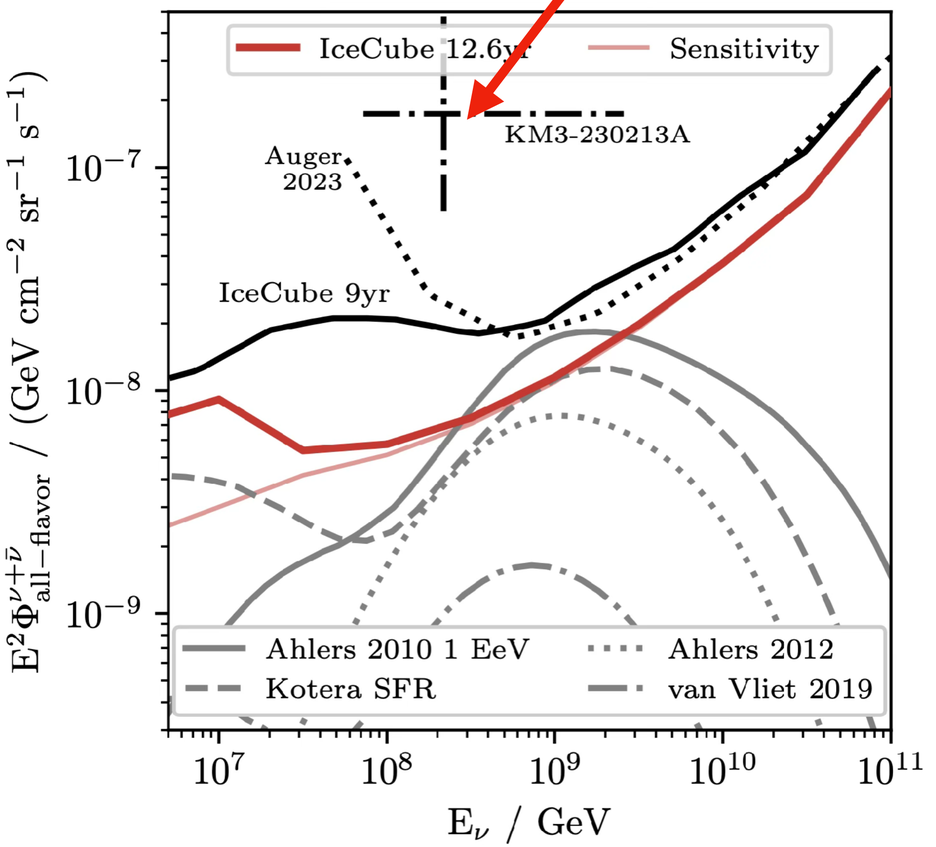
- derived diffuse neutrino flux would lead to 70 neutrinos expected within IceCube datasets (excluded by > 10 σ)
- joint fit with KM3NeT + Pierrer Auger + IceCube reduces tension to 2.9 σ:

$$E^2\phi_{all\text{-}flavor} = 1.7 \times 10^{-9}\ \text{GeV cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}$$

Phys. Rev. X 15, 031016 (2025)



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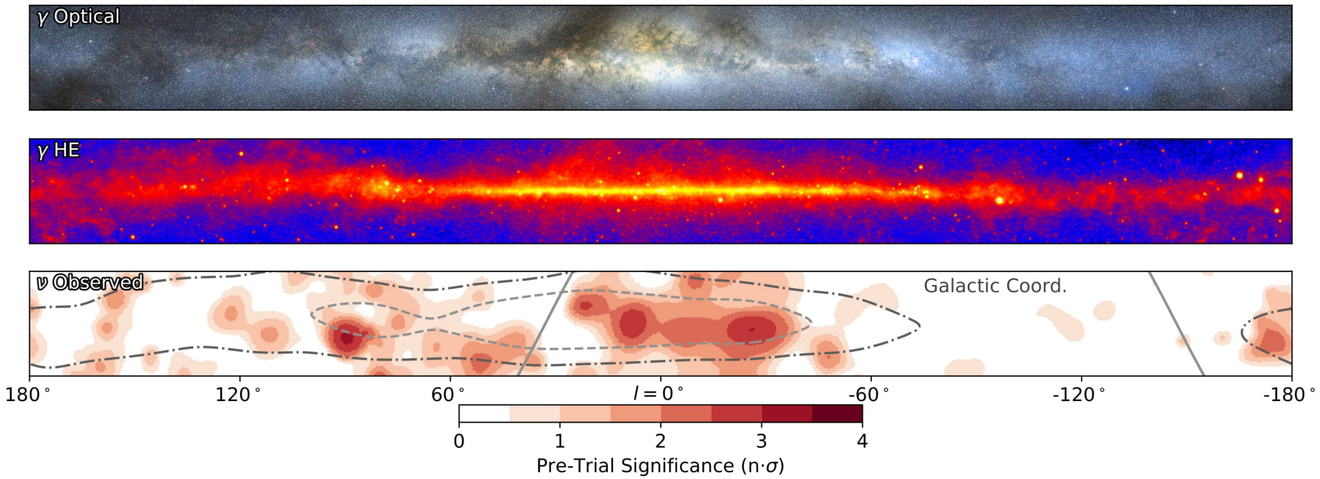
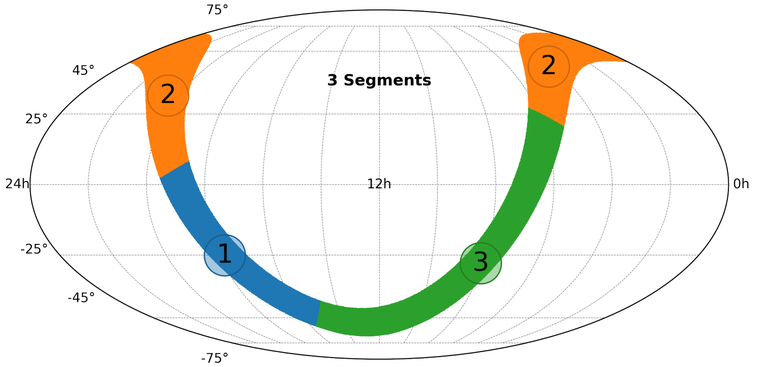
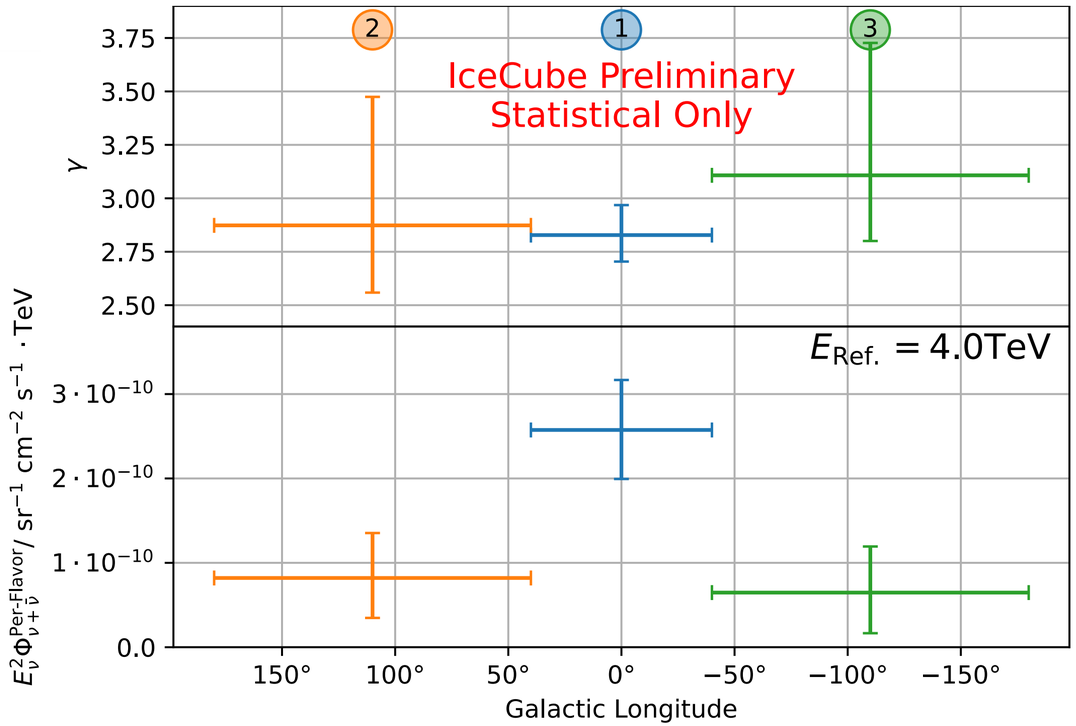
Measuring properties of the galactic plane neutrino flux





POS 1130, ICRC 2025

- model independent analysis
- first measurement of the energy spectrum slope of the neutrino flux along the galactic plane



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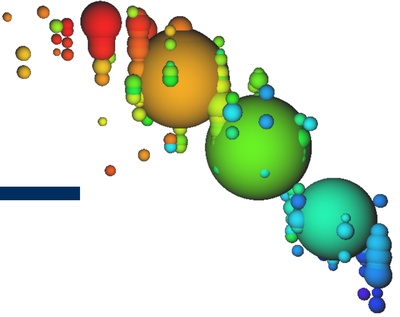
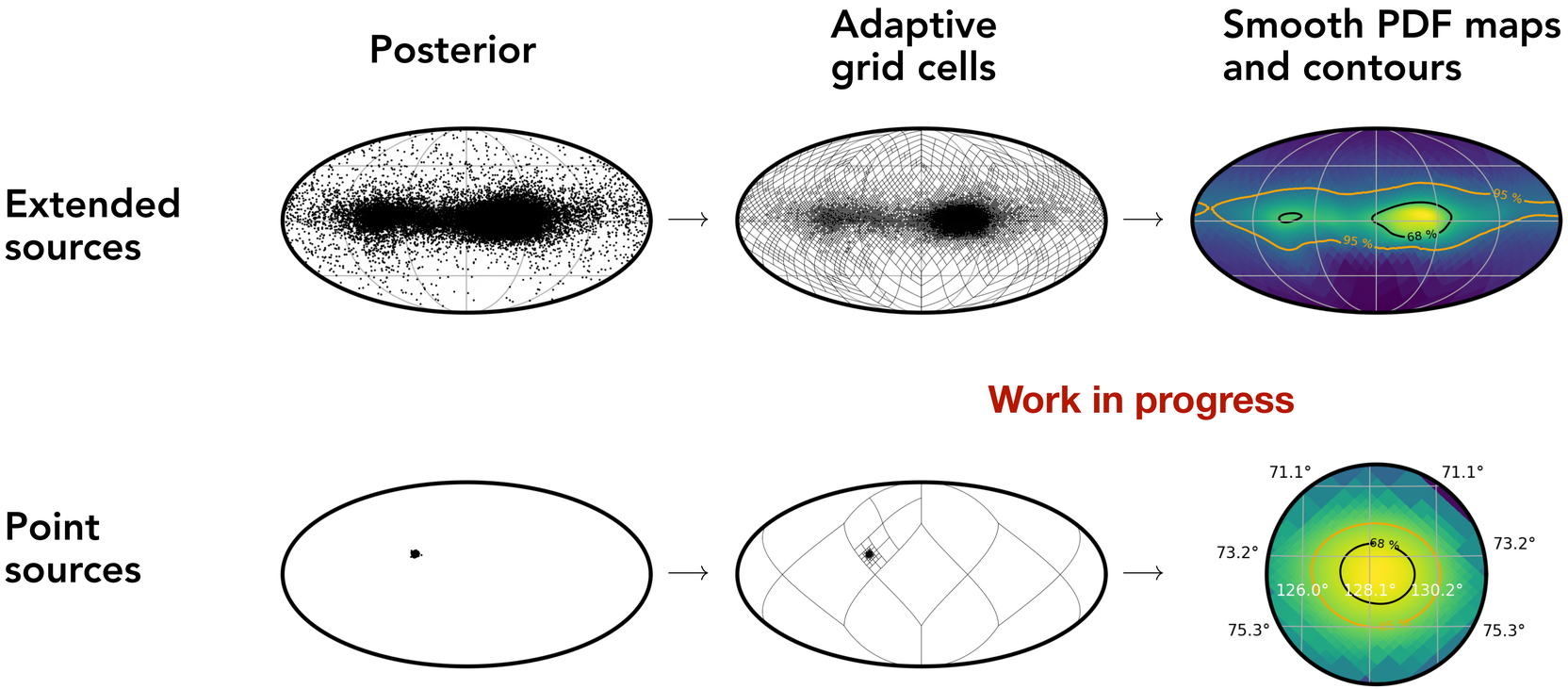
Neutrino reconstruction with transformers



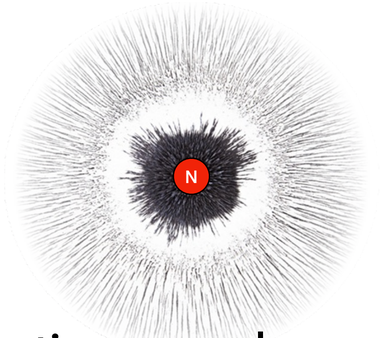
- IceCube entered astronomy, but directional reconstruction is challenging esp. for cascades
- transformer encoded mapping of a normalizing flow on the 2-sphere
- faster and significantly outperforming traditional LLH based B-splines

UU/SU

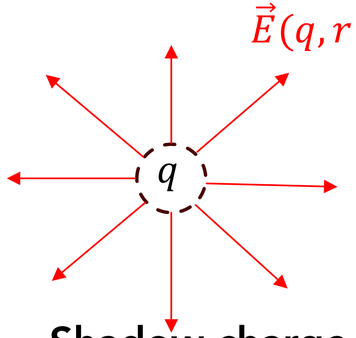


Slow exotic particles

- large volume -> large sensitivity
- direct detection "only" needs light emission
- extremely heavy would be slow (< 0.1 c)
- light emission process might be exotic, too 🇸🇪 $\mathcal{SU}$



Magnetic monopole
- single magnetic charge
- well motivated as its existence is tied to quantized electric charge



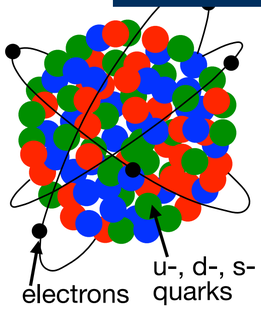
Shadow charge
- DM candidate
- doesn't respond to EM fields but is electrically charged
- follows geodesics

model dependent!

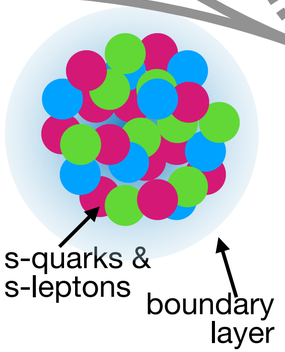
Proton decay

Lumine-scence

Thermal shock



Nuclearites
- stable states in SM!
- equal amounts of u-, d-, s-quarks
- produced after BB or as lumps of neutron stars



Q-balls
- predicted by super-symmetry
- coherent states of squarks, sleptons and the Higgs field
- charged or neutral

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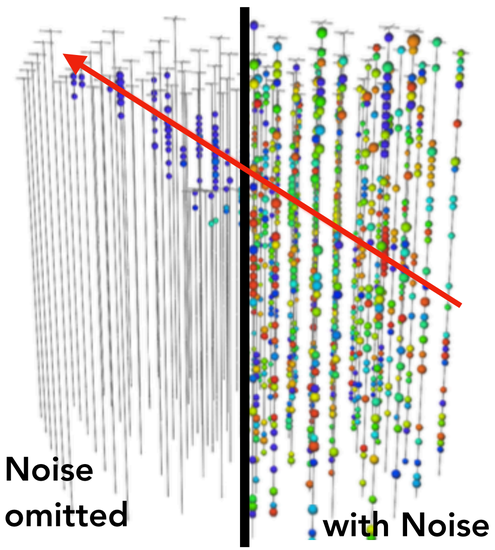

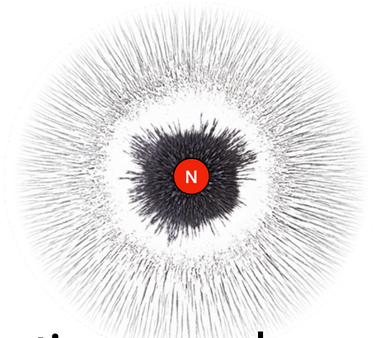

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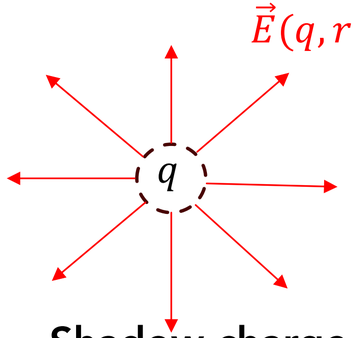

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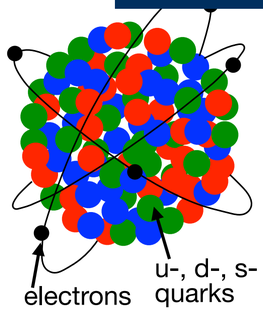

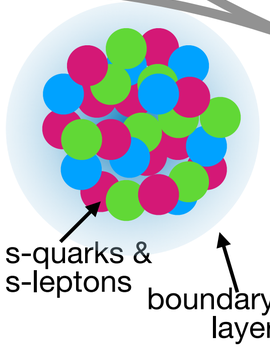

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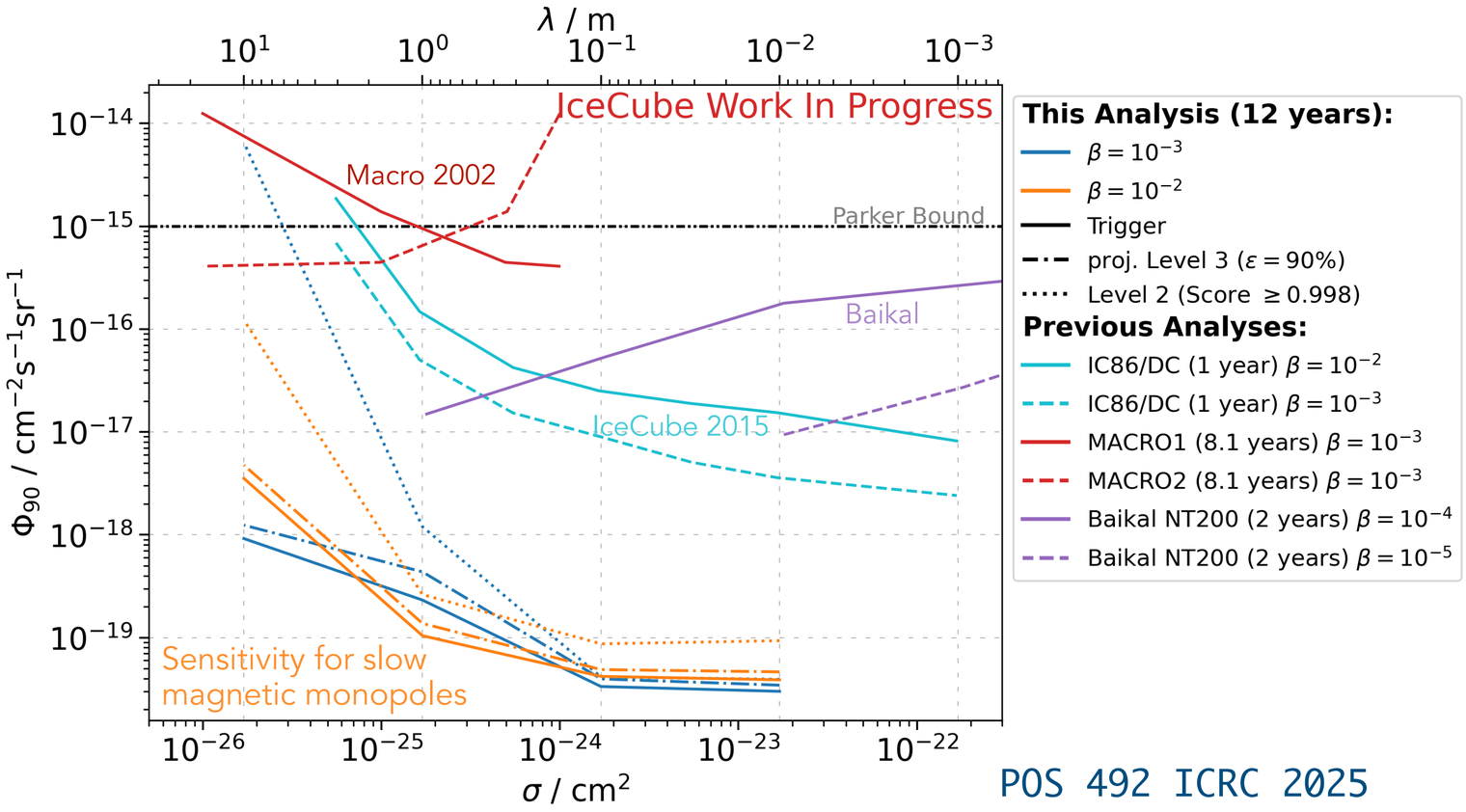
Slow exotic particles

New analyses significantly improved

- phenomenology
- sensitivity
- knowledge of light yields
  - luminescence
  - thermal shock 🇸🇪 *SU*



POS 492 ICRC 2025

Many other possibilities for BSM with IceCube
see long lived particles in the next talk! 🇸🇪 *UU*

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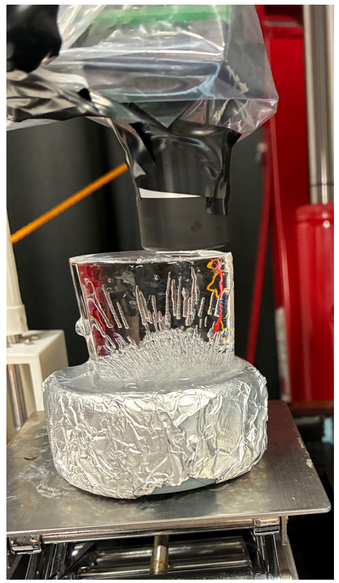
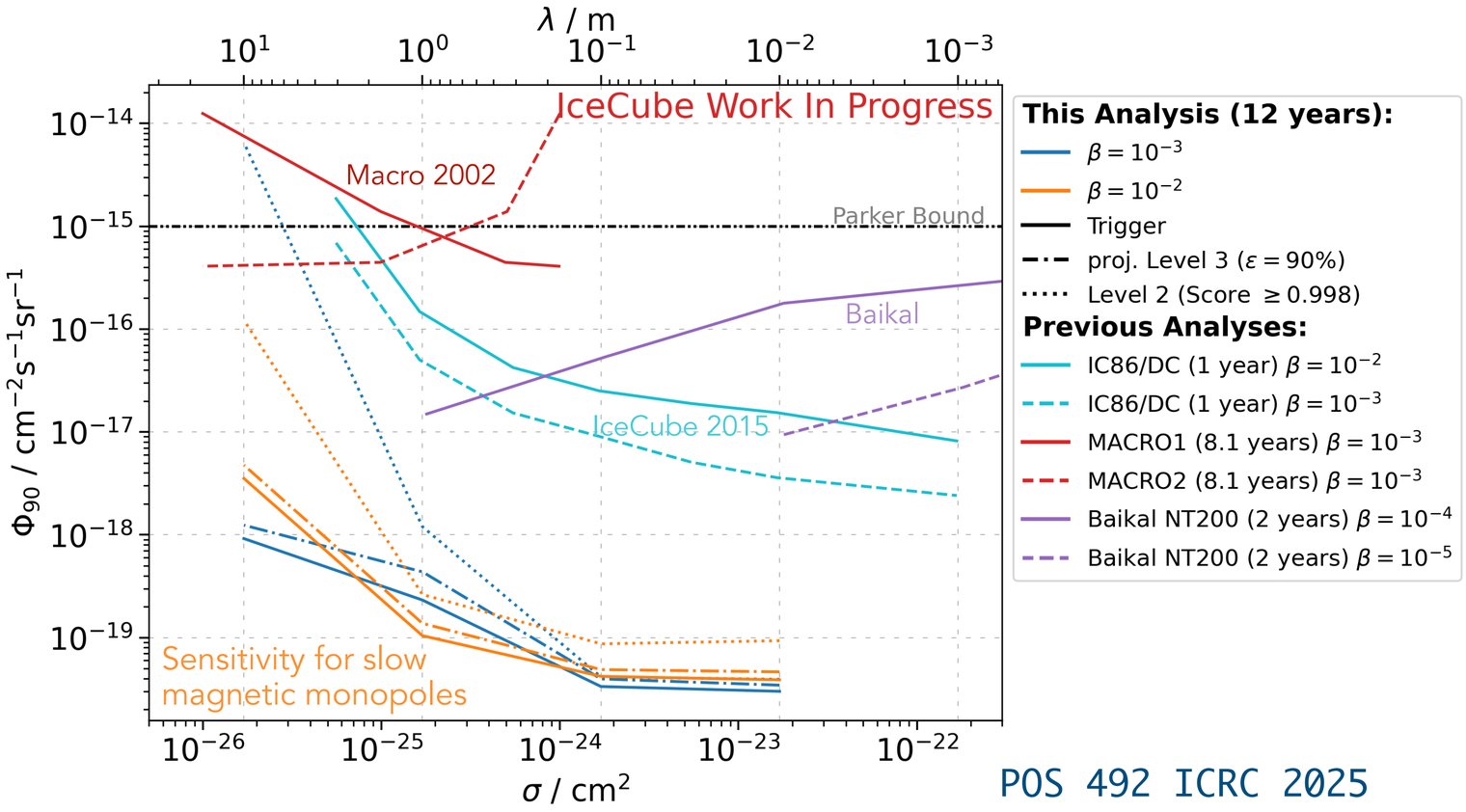


Visible damage of ice from thermal shock in prototype experiment



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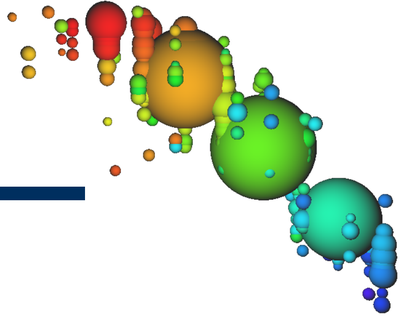
Detector extensions



Construction from ≳ 2030

IceCube-Gen2 Radio

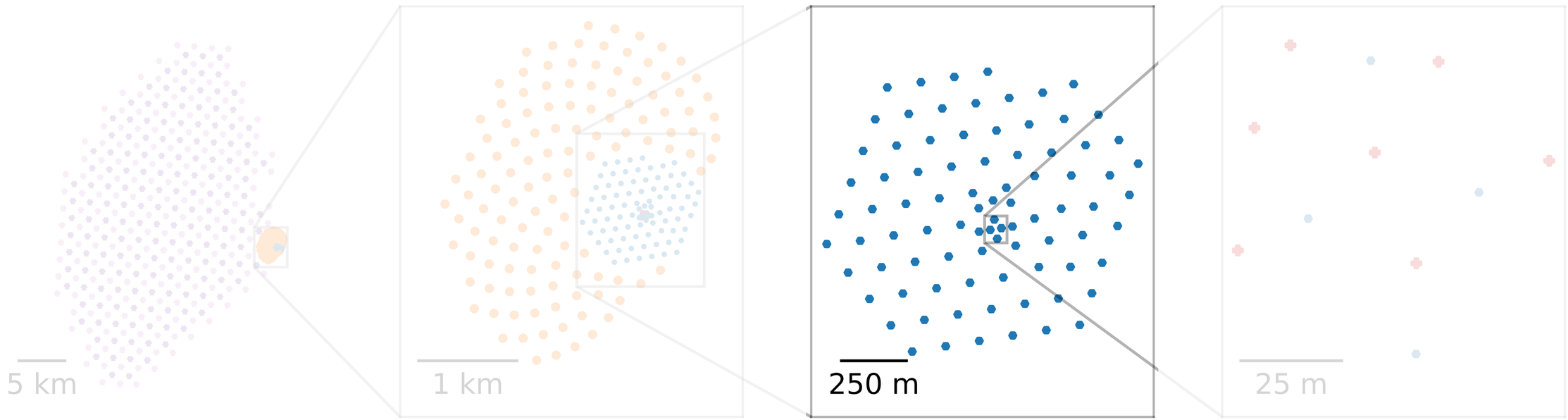
IceCube-Gen2 Optical

Construction 2004-2011

IceCube

Construction from this month!

IceCube Upgrade



- ultra-high-energy neutrinos
- neutrino astronomy (sensitivity to 10x fainter sources than IC)
- astrophysical neutrino flux
- neutrino oscillation properties
- ice calibration
- detector R&D

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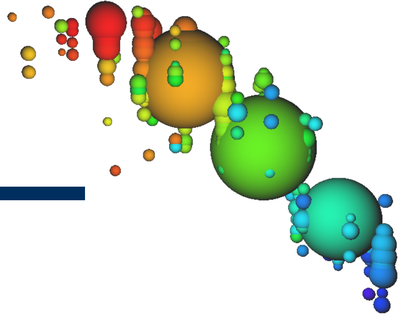

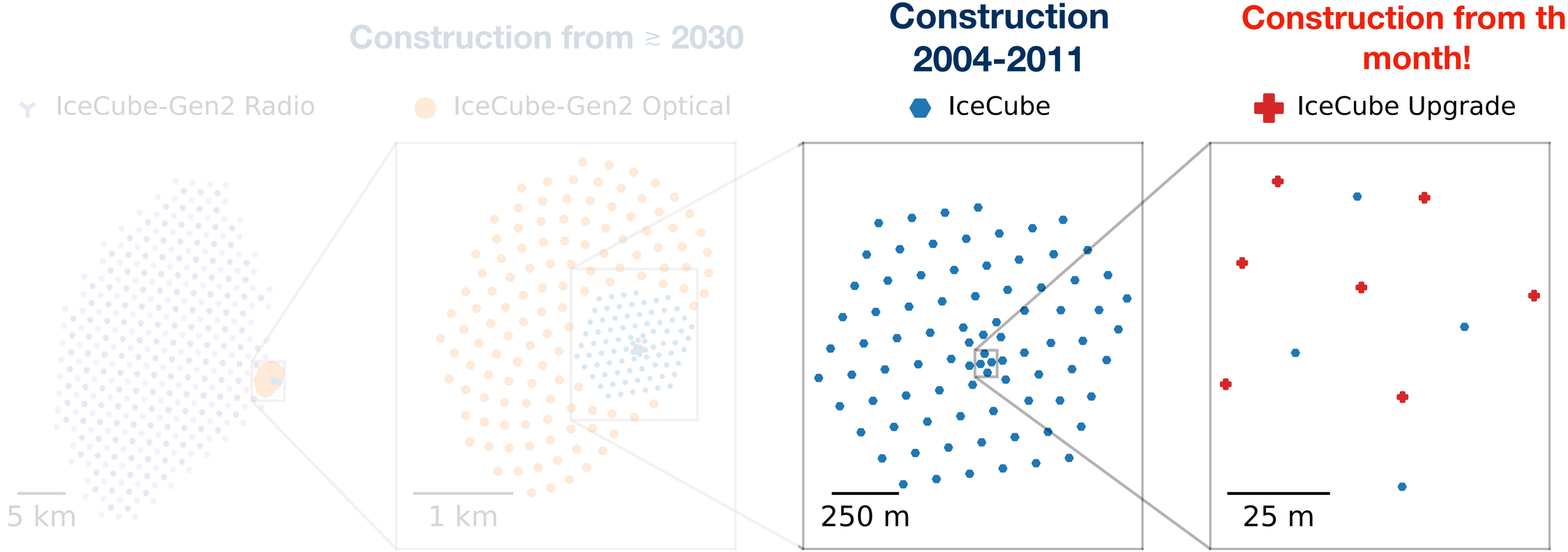

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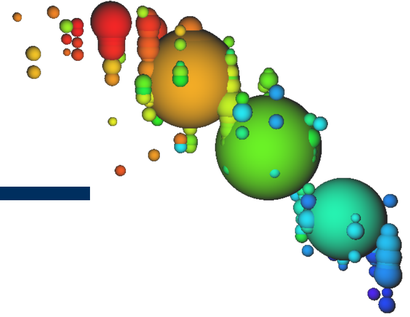

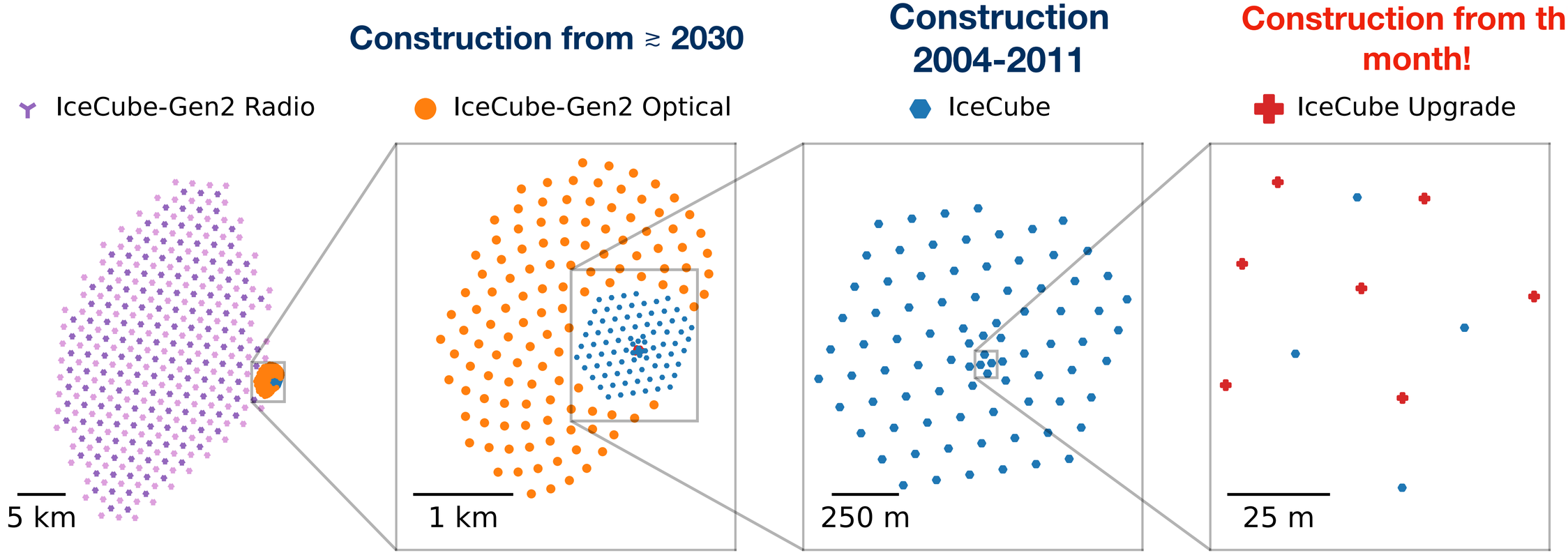

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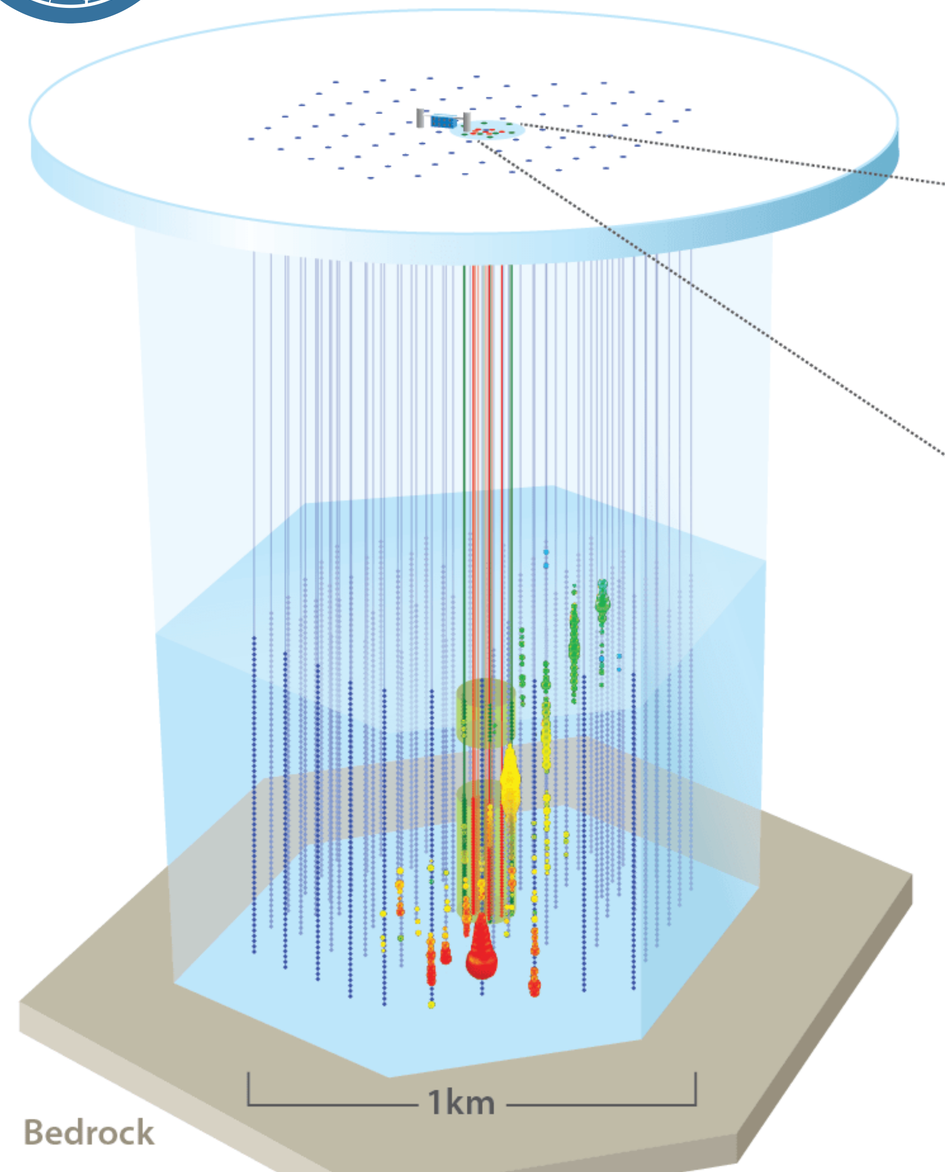
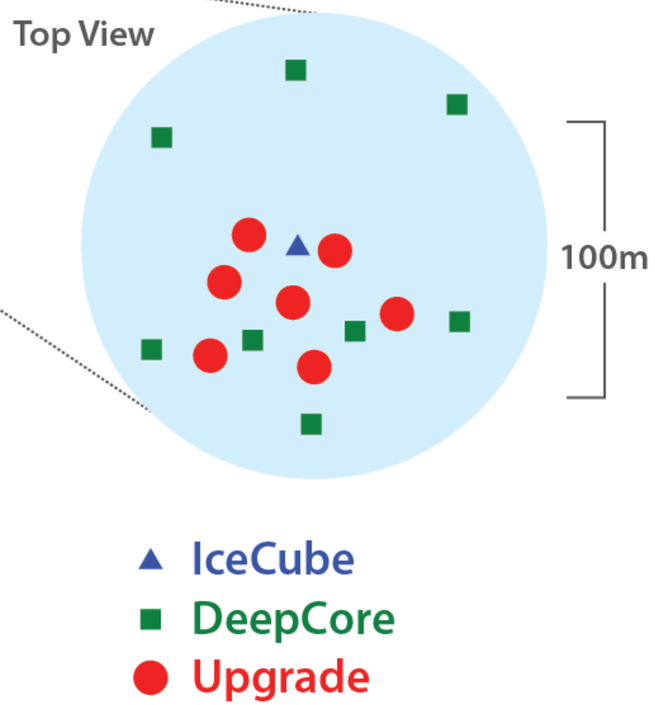
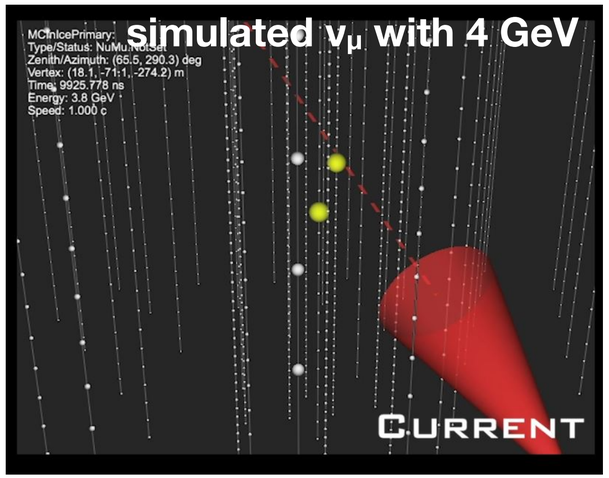
IceCube Upgrade

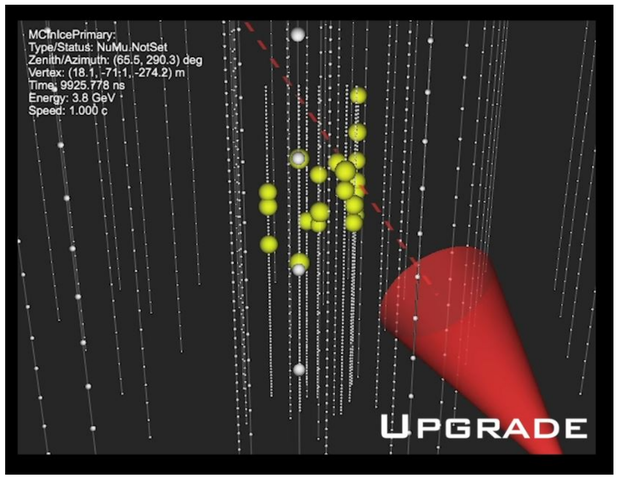
Low energy extension for IceCube

- 7 new holes with ~100 sensors each
- construction this austral summer!









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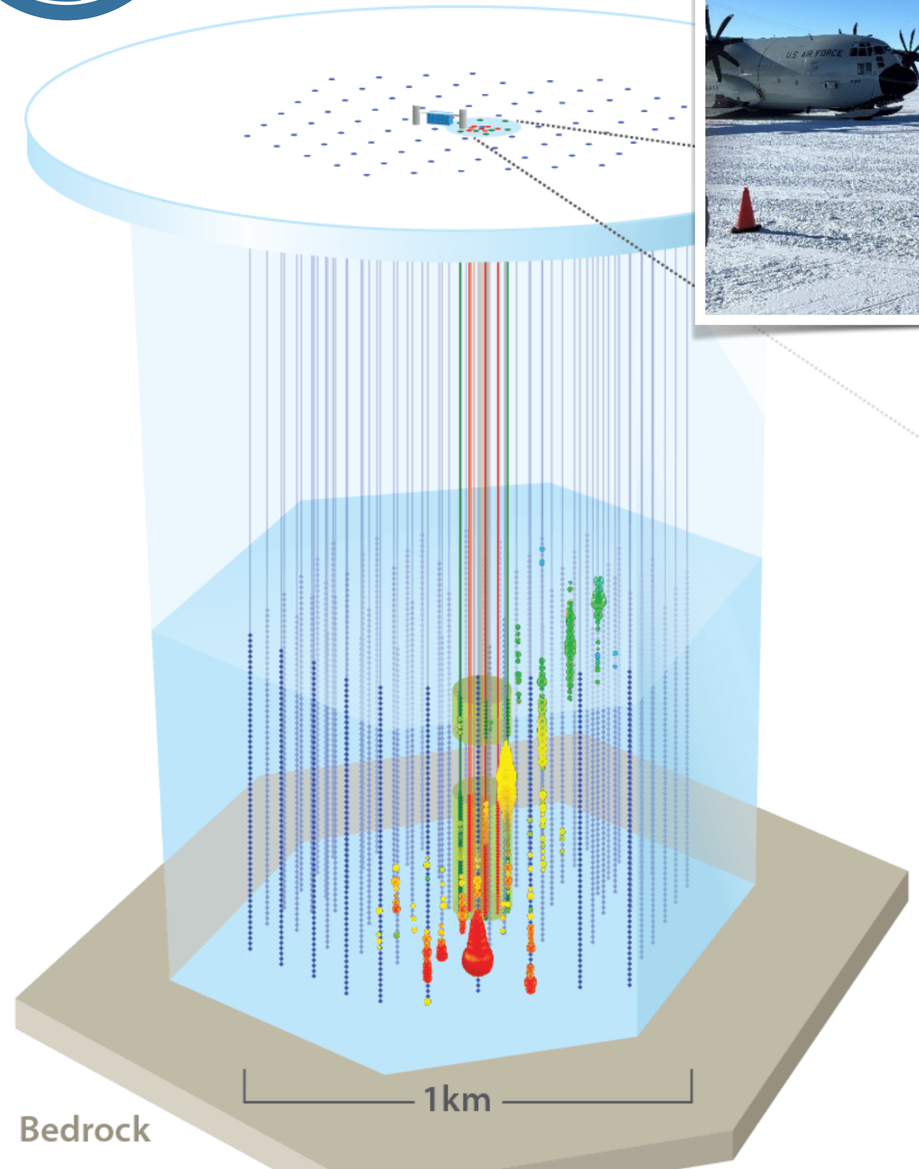
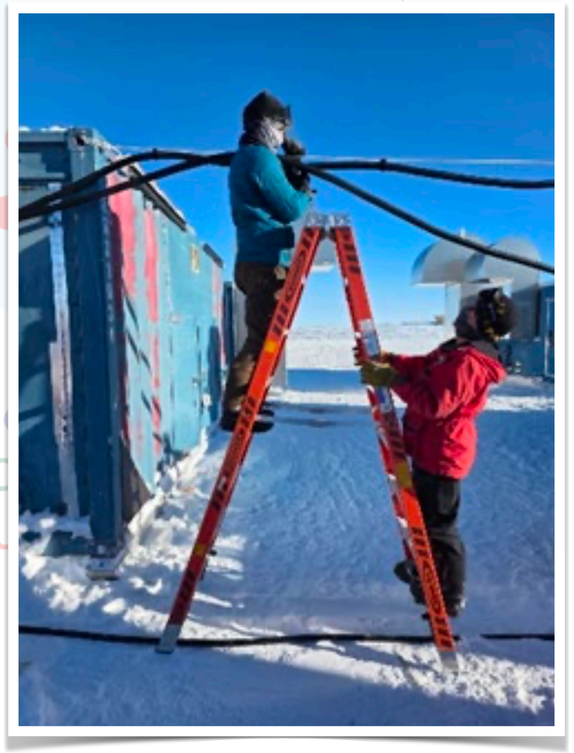
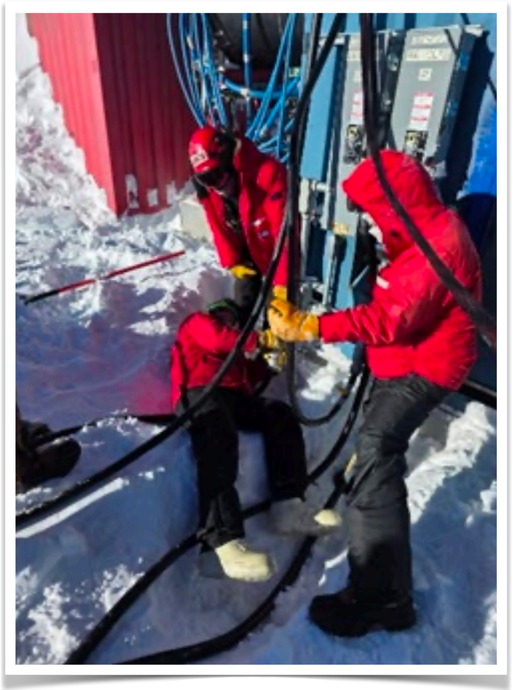
Swedish members of the IceCube drill team:

Jonas Kalin, Åse Torgilsson,
Erik Ejdepalm, Sven Lidström







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IceCube Upgrade

450 mDOM

290 D-Egg

New sensor generation

- large, isotropic sensitivity
- directional information / noise suppression
- integrated calibration systems

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IceCube Upgrade

10 WOM

Prototype: Wavelength-shifting optical module

- exploits UV part of Cherenkov spectrum
- significantly improved signal to noise ratio
- detection significance for MeV supernova neutrinos significantly enhanced 🇸🇪 *uu*

Sensors 2022, 22(4), 1385

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IceCube Upgrade

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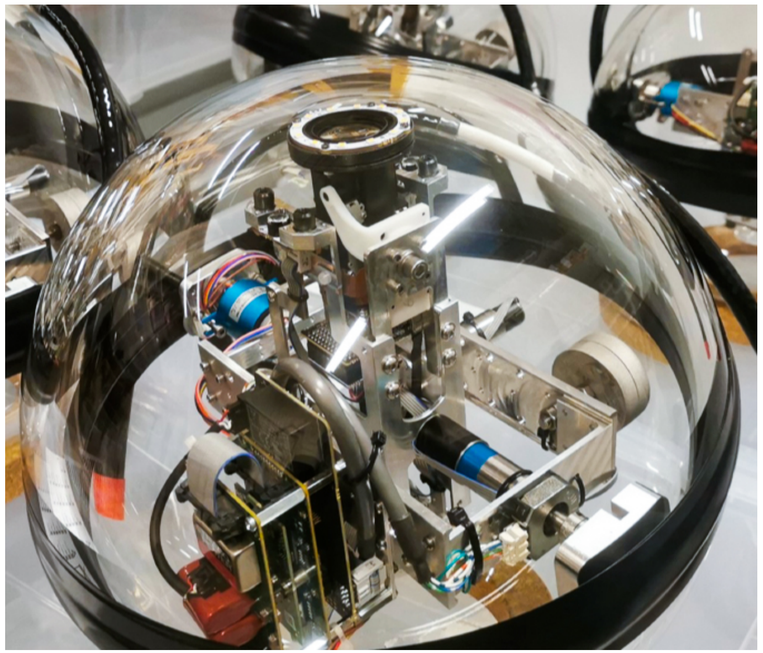
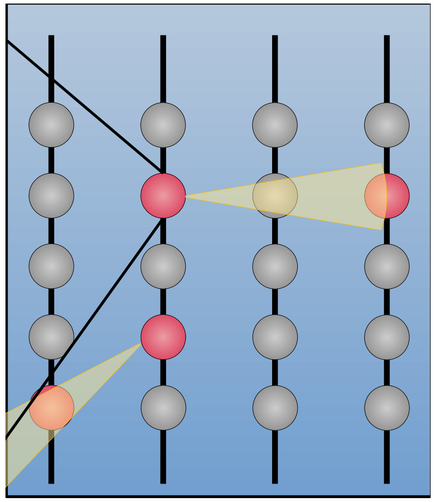
7 Sweden Cameras 2.0



joint SU & UU



Calibration

- steerable camera and laser
- observe the ice layers
- watch the freezing process
- visually measure light propagation in ice

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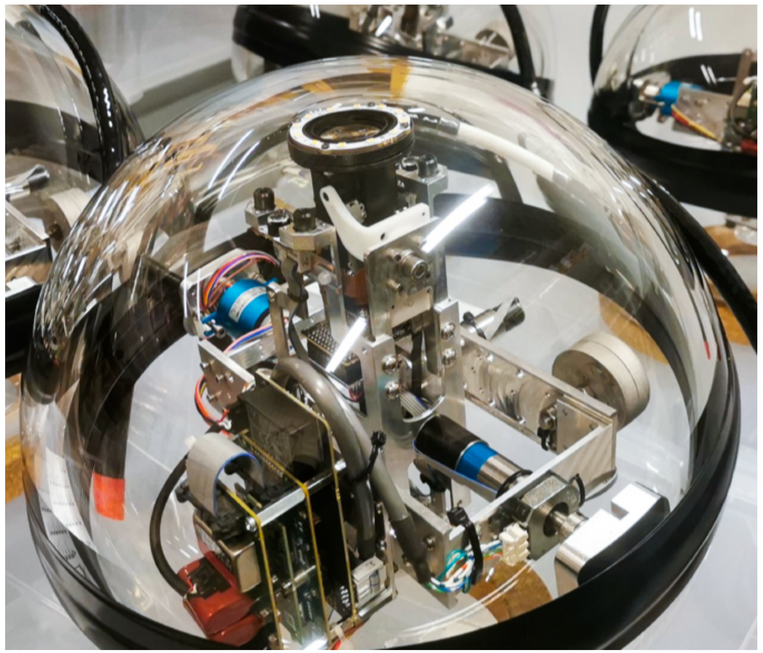

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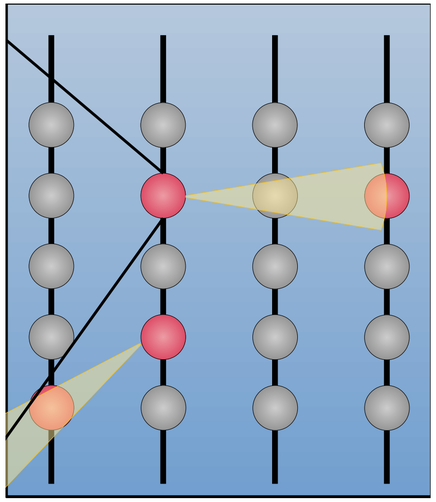

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UU

Main cable of strings manufactured in Sweden!

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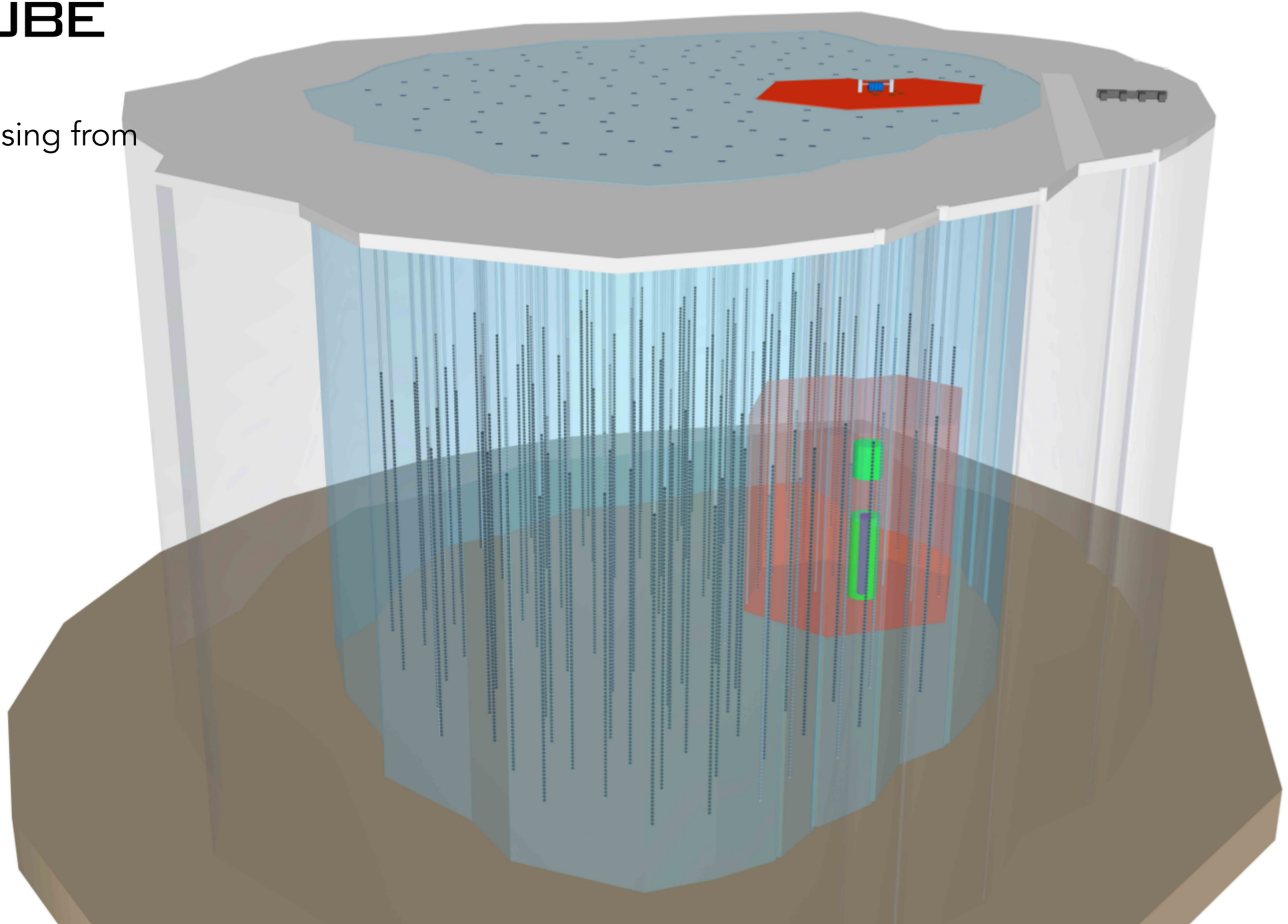
IceCube GEN2

Optical array: increasing from 1km^3 to ~8km^3



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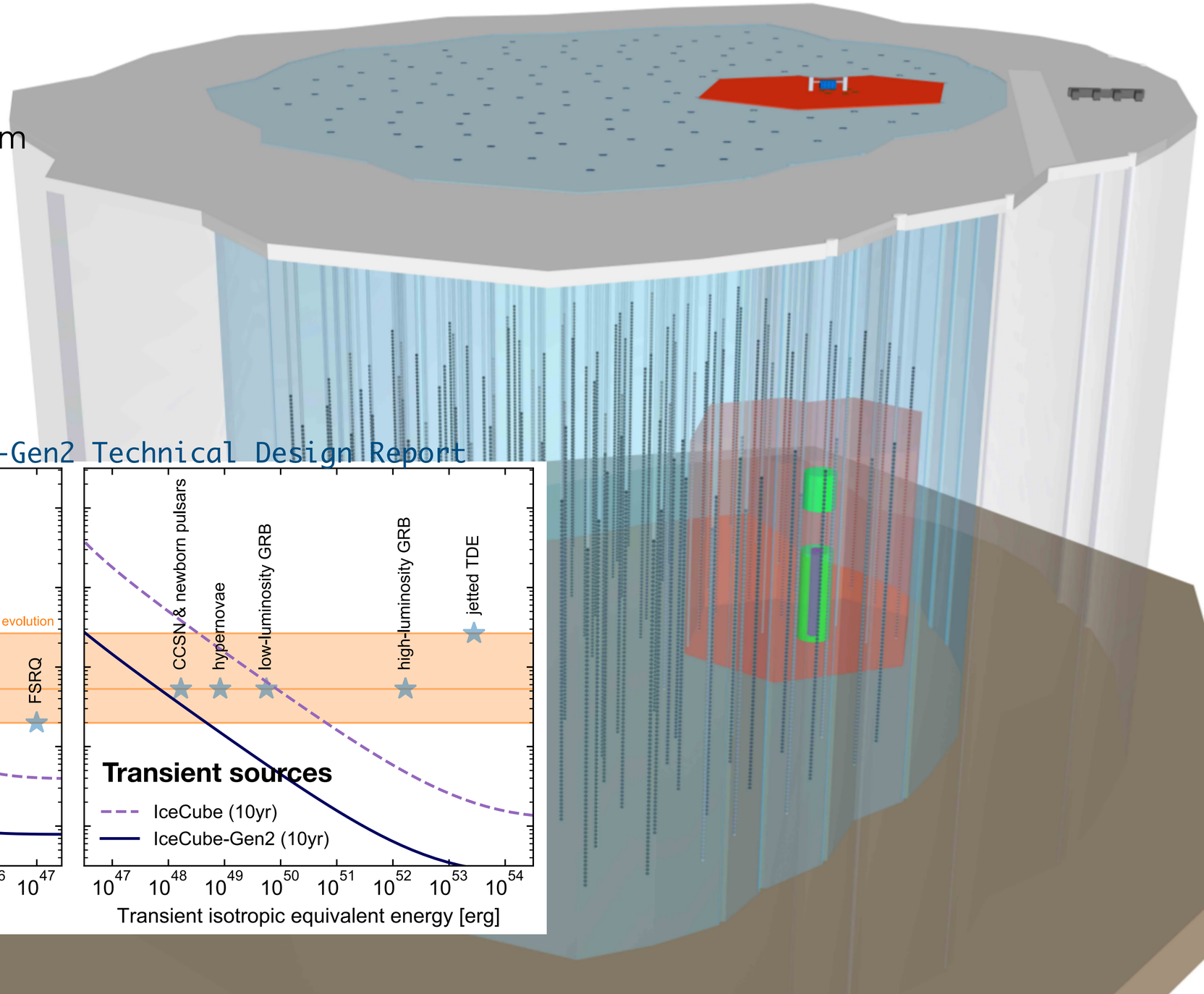
IceCube GEN2

Optical array: increasing from 1km^3 to ~8km^3



IceCube-Gen2 Technical Design Report

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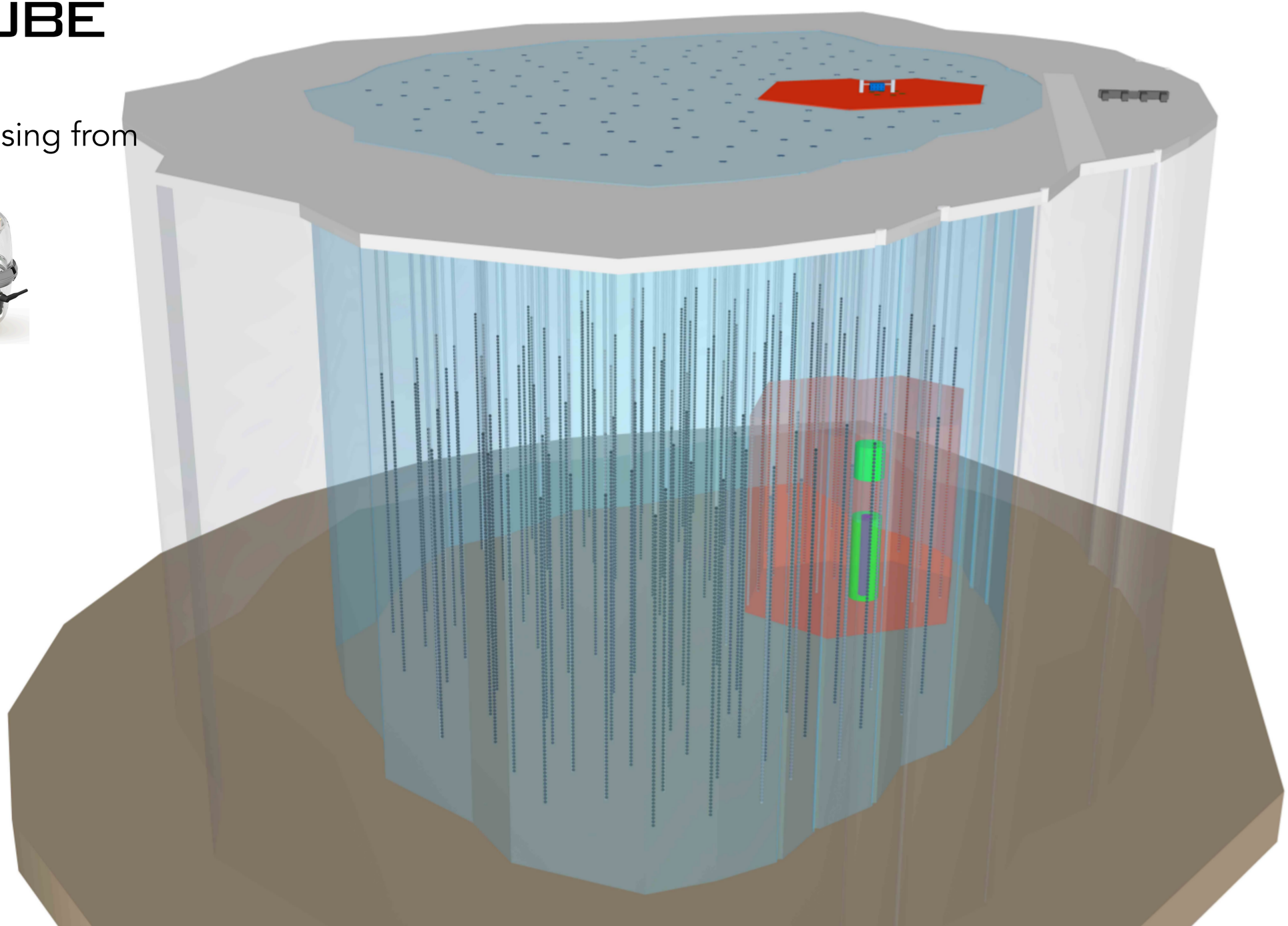

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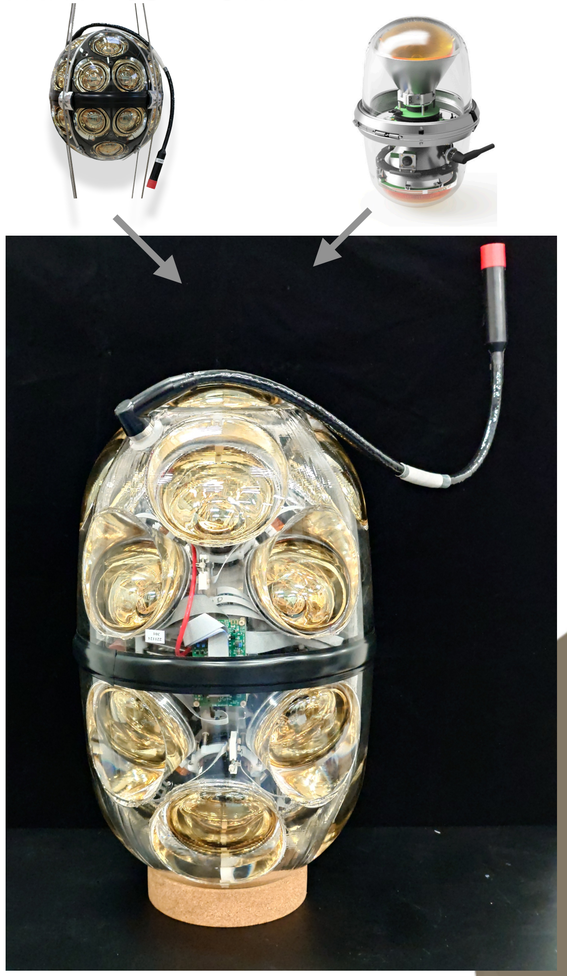

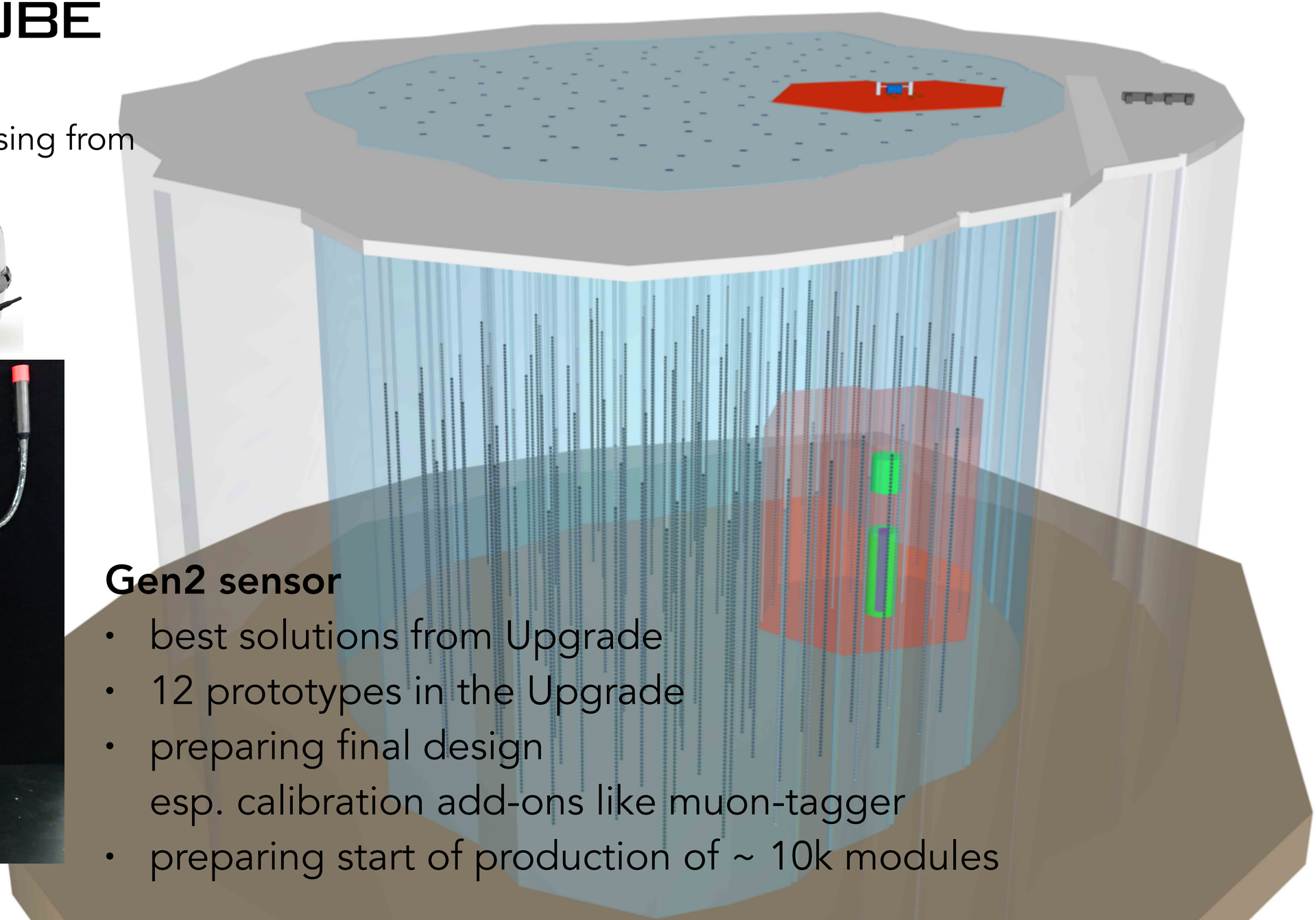

Gen2 sensor

- best solutions from Upgrade
- 12 prototypes in the Upgrade
- preparing final design
  esp. calibration add-ons like muon-tagger
- preparing start of production of ~ 10k modules

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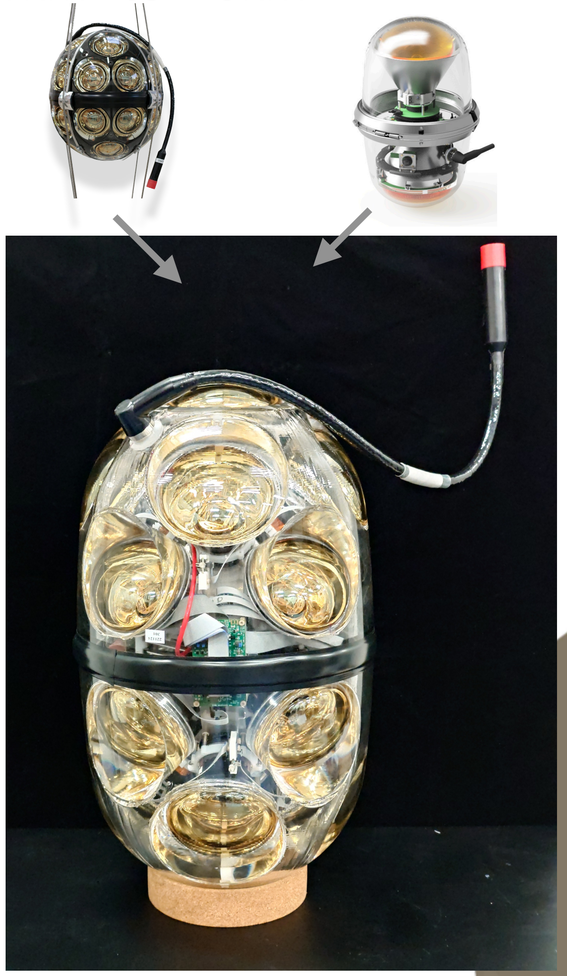
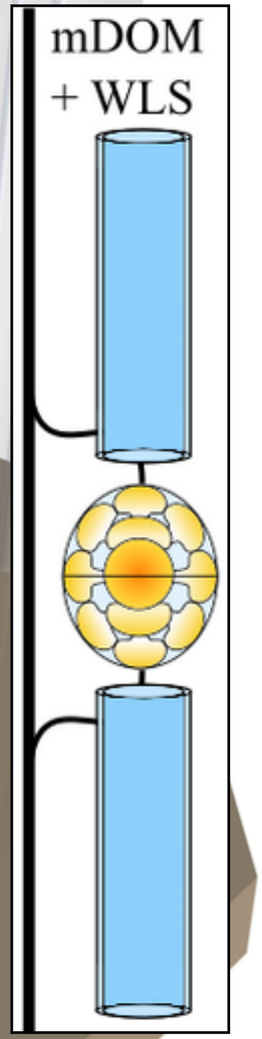


Gen2 sensor + wavelength shifter

- enhanced light collection at low noise
- from supernova detection to measurement of fast features in SN 🇸🇪 UU

Phys. Rev. D 112, 043011



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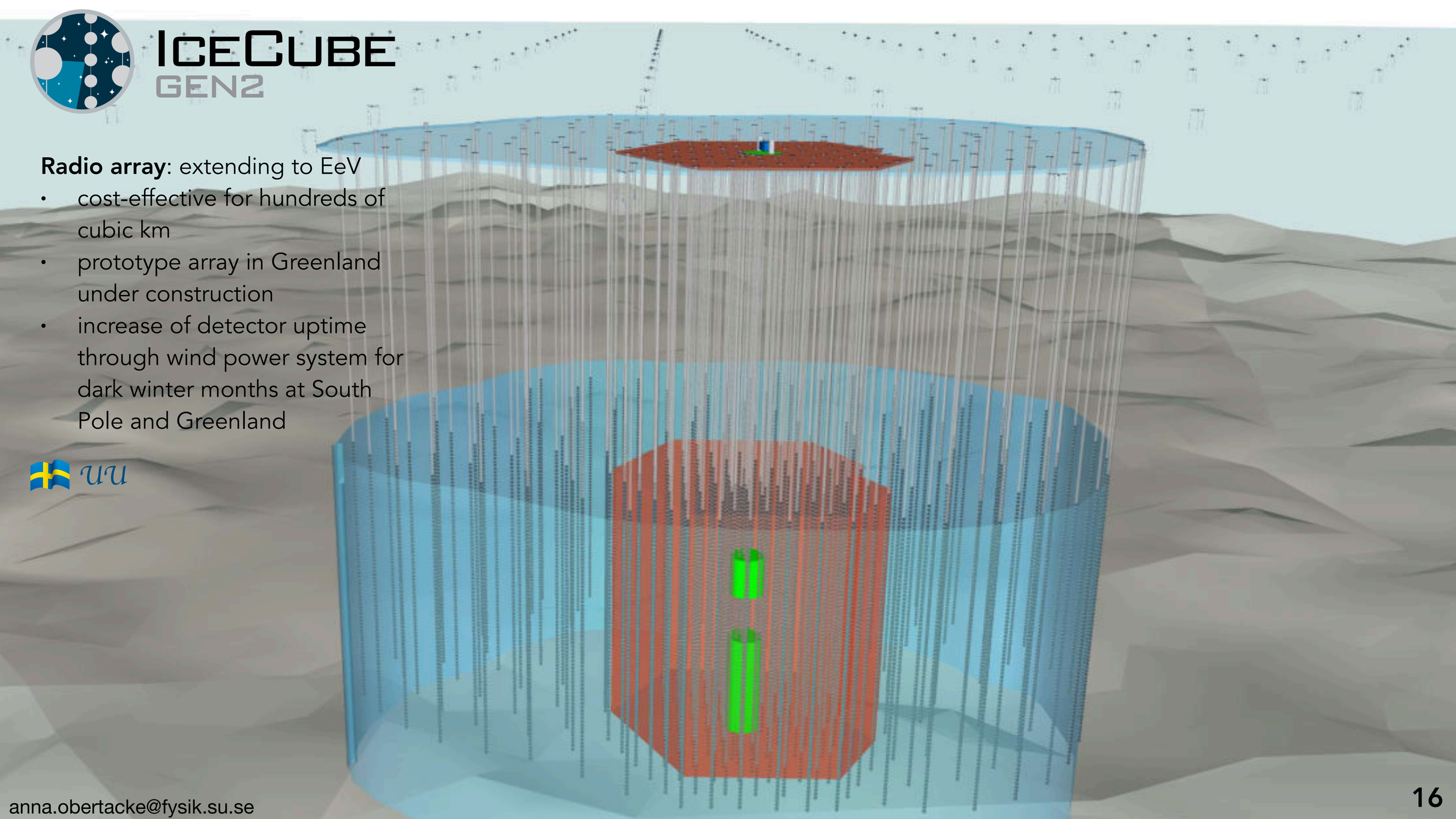

Radio array: extending to EeV

- cost-effective for hundreds of cubic km
- prototype array in Greenland under construction
- increase of detector uptime through wind power system for dark winter months at South Pole and Greenland

UU

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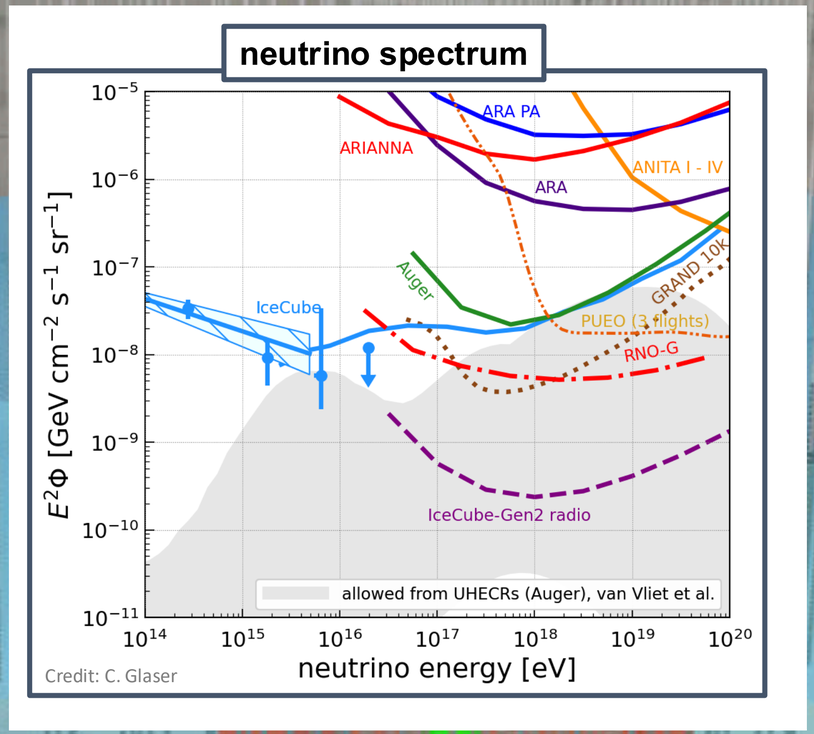

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IceCube Gen2

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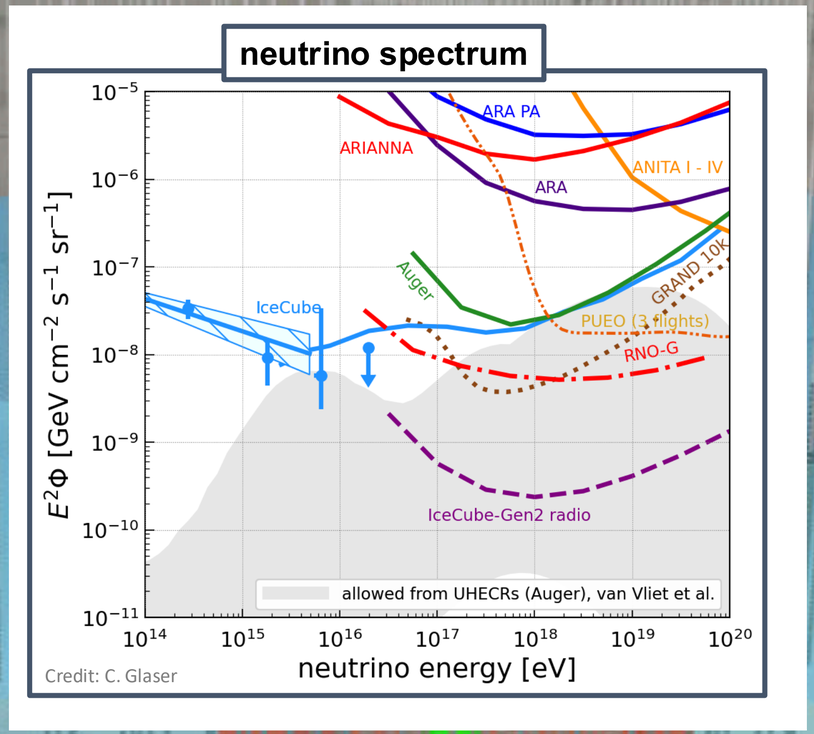

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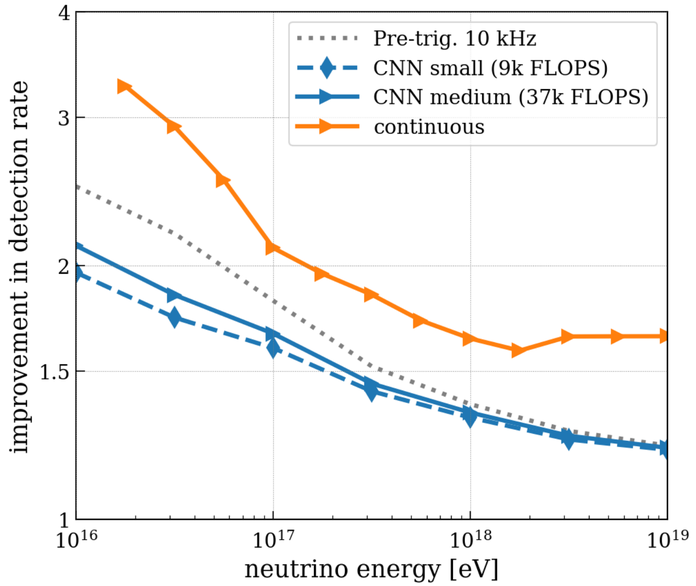
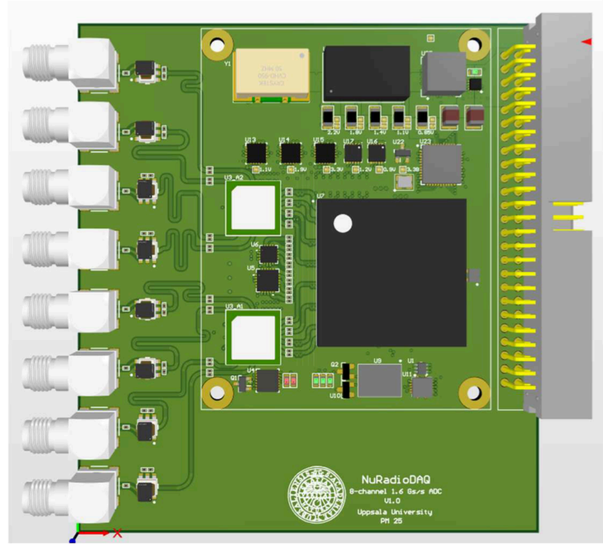
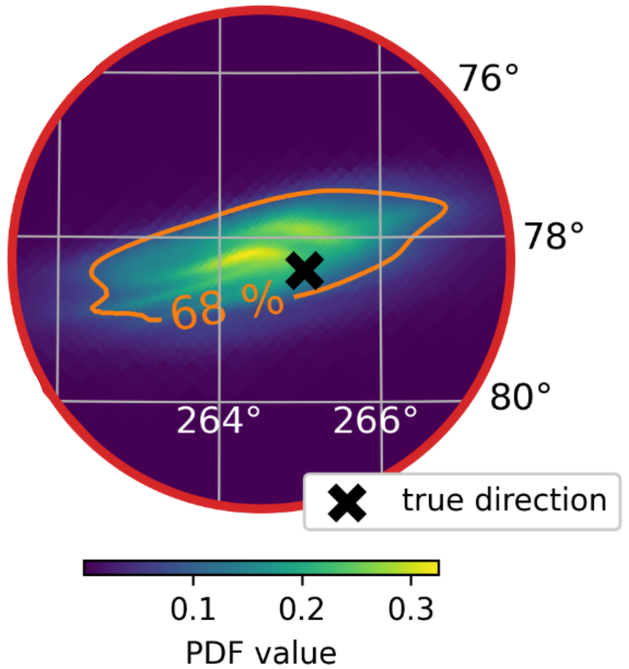
IceCube GEN2

Radio array

- NuRadioOpt: real-time NN-based trigger with end-to-end optimization of station layout
  - ➡ improvement equivalent to building a 3x larger detector
    - prototype of new DAQ system soon completed
- improved reconstruction methods
  - deep learning based
  - likelihood based







Outlook

- new analyses transition from detecting sources of high-energy neutrinos to measuring detailed properties of their fluxes
- leading sensitivities for exotic physics offer significant discovery potential
- a lot of new data incoming from the IceCube Upgrade
- work on IceCube-Gen2 to push the frontiers of neutrino astrophysics and particle physics

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IceCube in Sweden

Uppsala University

Faculty
- Erin O´Sullivan
- Christian Glaser
- Carlos Perez de los Heros
- Olga Botner
- Allan Hallgren

PhD students
- Jakob Beise
- Nils Heyer
- Martin Ravn
- Axel Pontén

Technical staff
- Nils Bingefors
- Pawel Marciniewski

Instrument makers
- Dan Cajander
- Tarek Altaiyan
- Samuel Hollman

Stockholm University

Faculty
- Chad Finley
- Klas Hultqvist
- Anna Obertacke

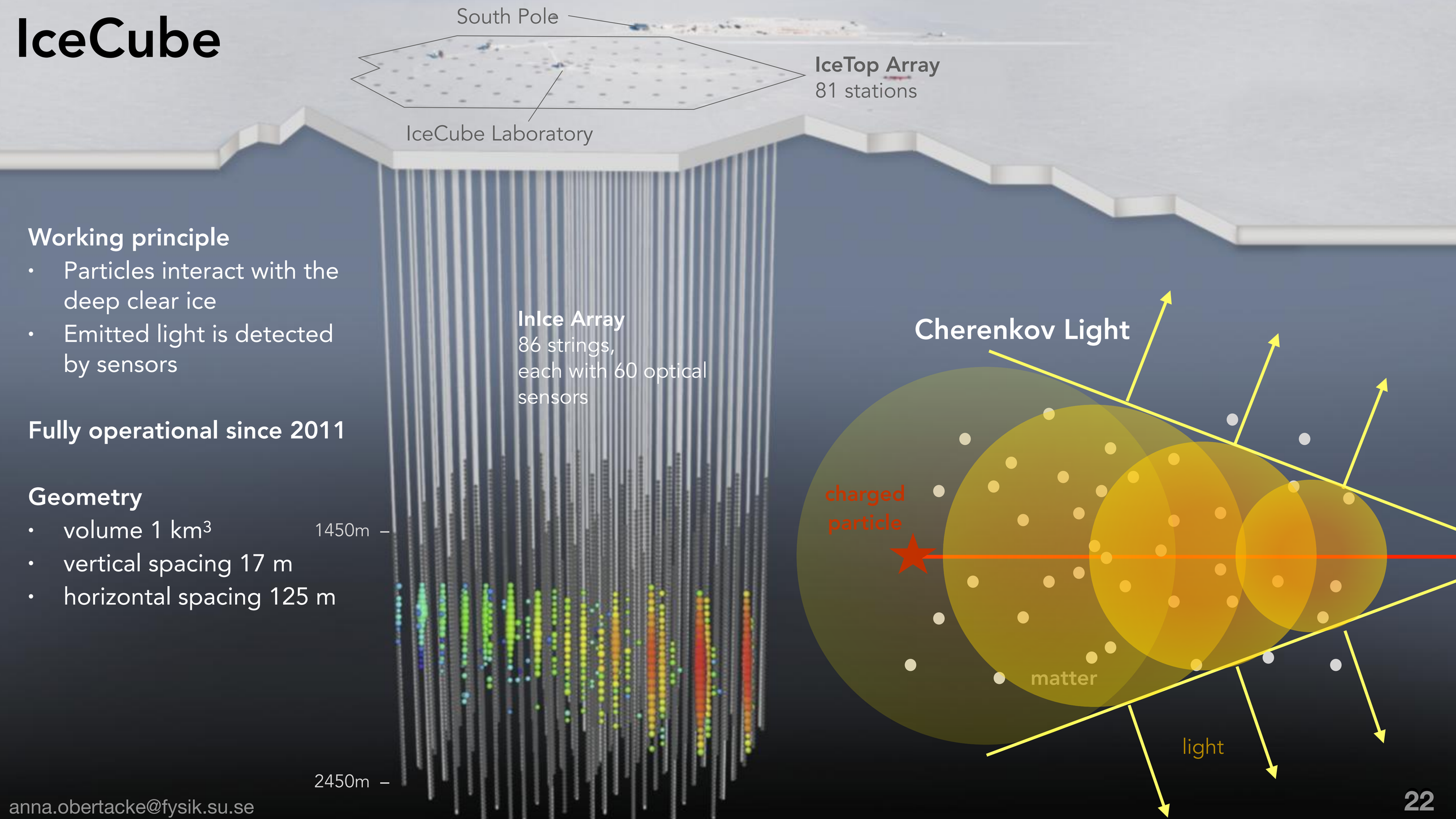
Postdoc
- Thorsten Glüsenkamp

PhD students
- Ludwig Neste
- Michael Hrywniak

Technical staff
- Attila Hidvegi
- Alex Kastanas
- Muhammad Sadiq
- Mikael Blom

Backup

IceCube



Working principle

- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Fully operational since 2011

Geometry

- volume 1 km^3
- vertical spacing 17 m
- horizontal spacing 125 m

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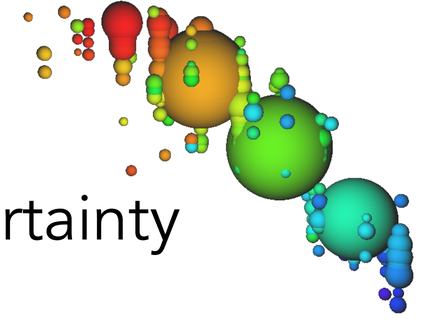
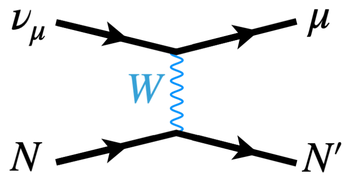
Neutrino signatures

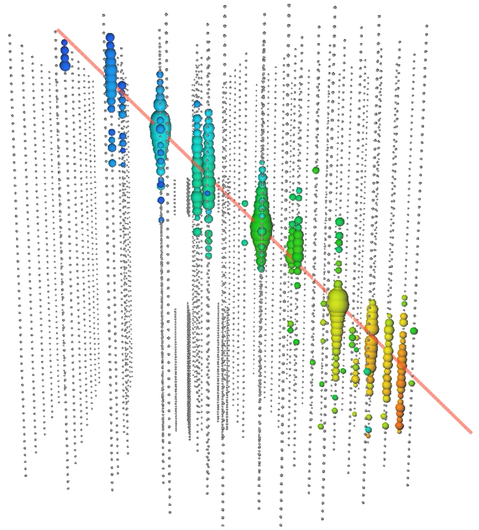
Characterised by reconstructed quantities: direction, energy, angular uncertainty

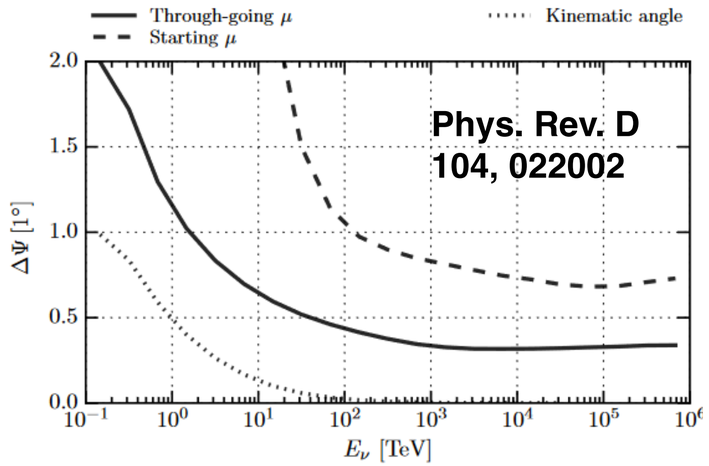


Track like topology

- good angular resolution 0.1° - 1°
- increased effective volume (vertex outside volume)
- challenging energy resolution

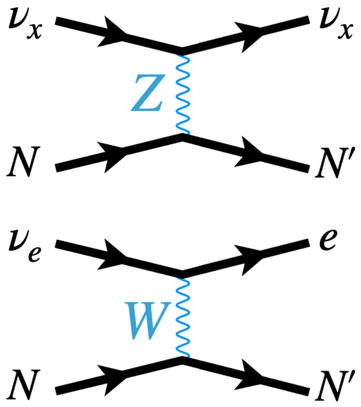


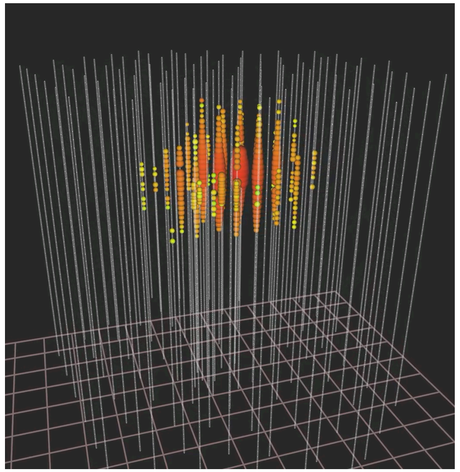


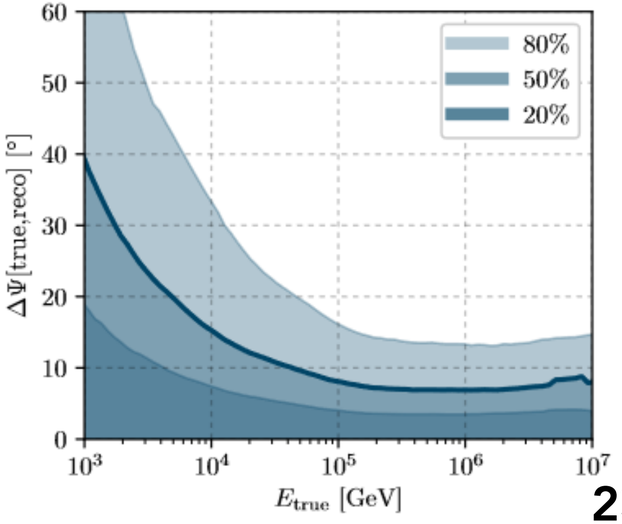


Cascade like topology

- all flavours
- calometric measurement of energy resolution ~15%
- angular resolution around 10° > 100 TeV







Messengers in detectors deep underground

Atmospheric Muons

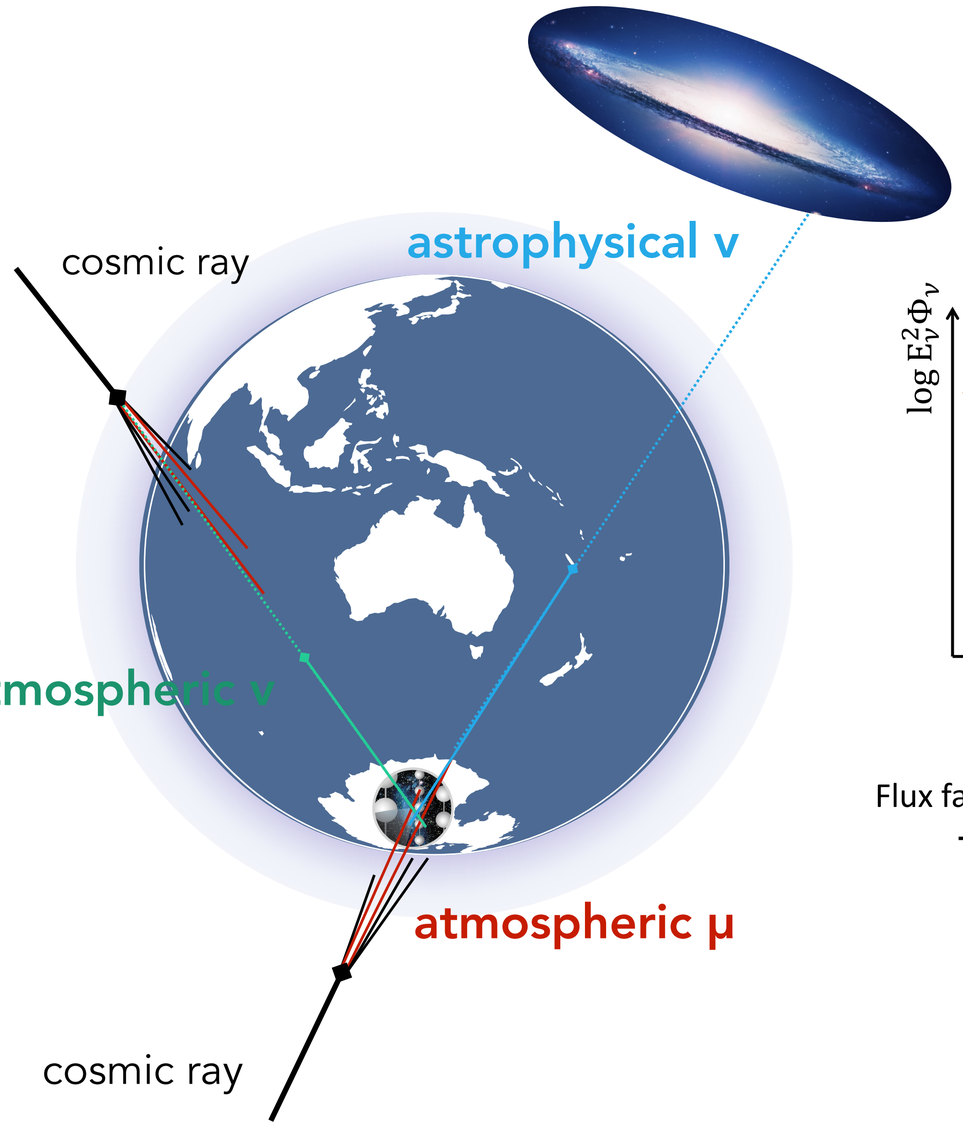
- charged energetic particles interact with atmosphere **(cosmic ray)**
- a particle shower develops through the atmosphere **(air shower)**
- **muons** reach the detector

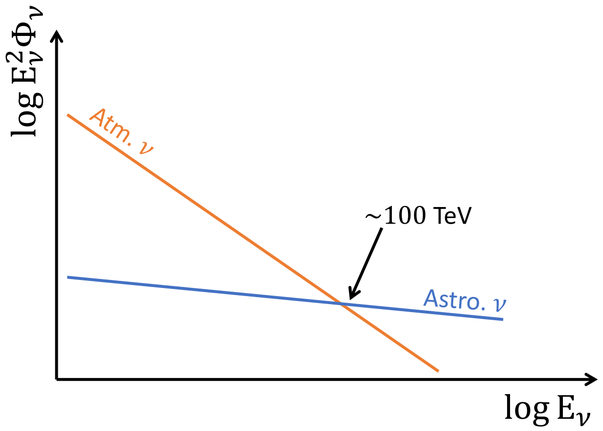
Atmospheric Neutrinos

- cosmic ray induces air shower
- neutrino is created in shower
- neutrino interacts in Earth or ice
- visible muon or shower in the detector

Astrophysical Neutrinos

- neutrino from outer space passes through Earth
- neutrino interacts in Earth or ice
- visible muon or shower in the detector





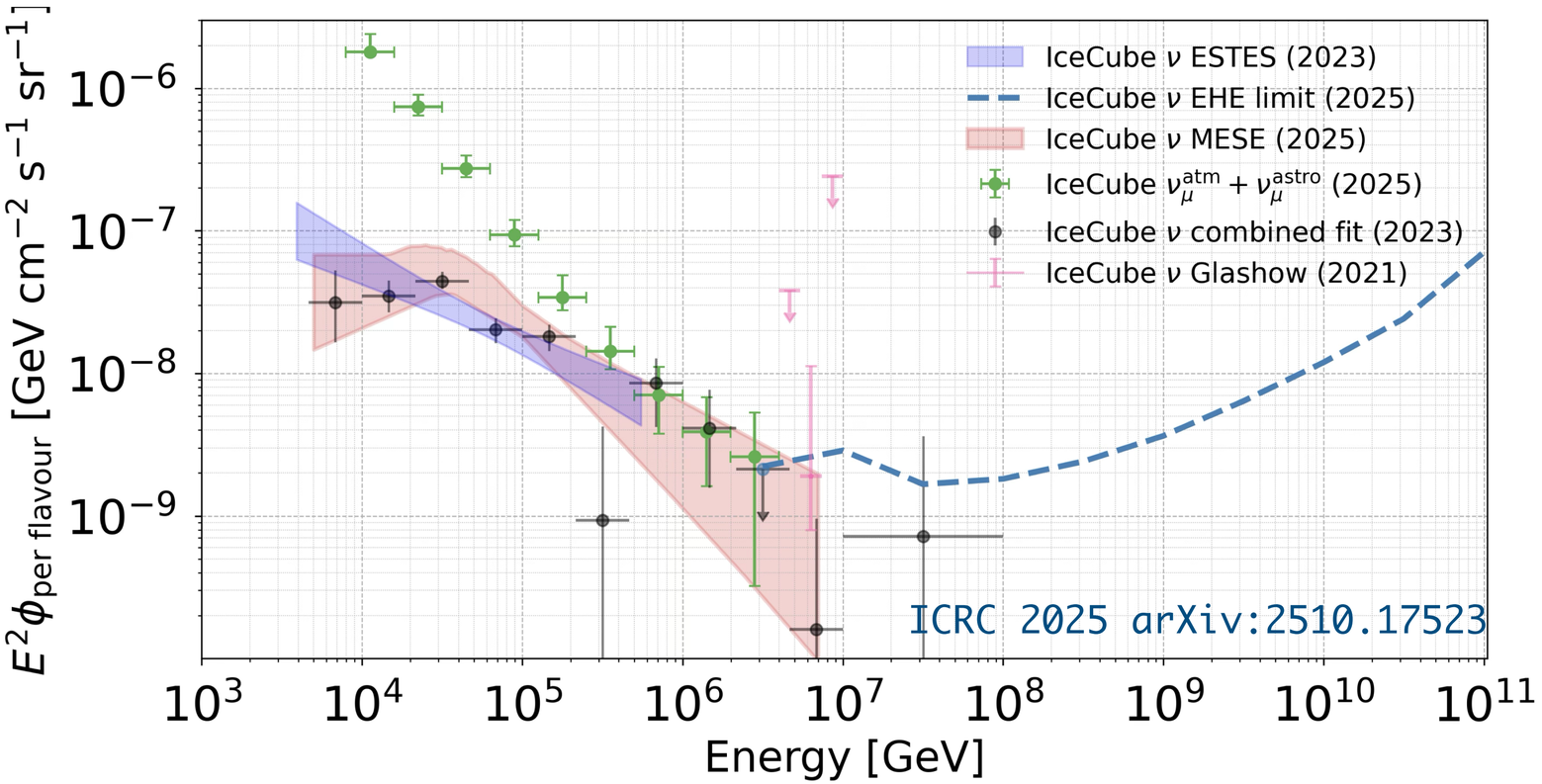
Power-law flux $\Phi_\nu = \Phi_0 E^{-\gamma}$
Flux falls off faster than cross section increases
→ Large statistics at lower energies

https://cdn.allwallpaper.in/

Diffuse neutrino flux

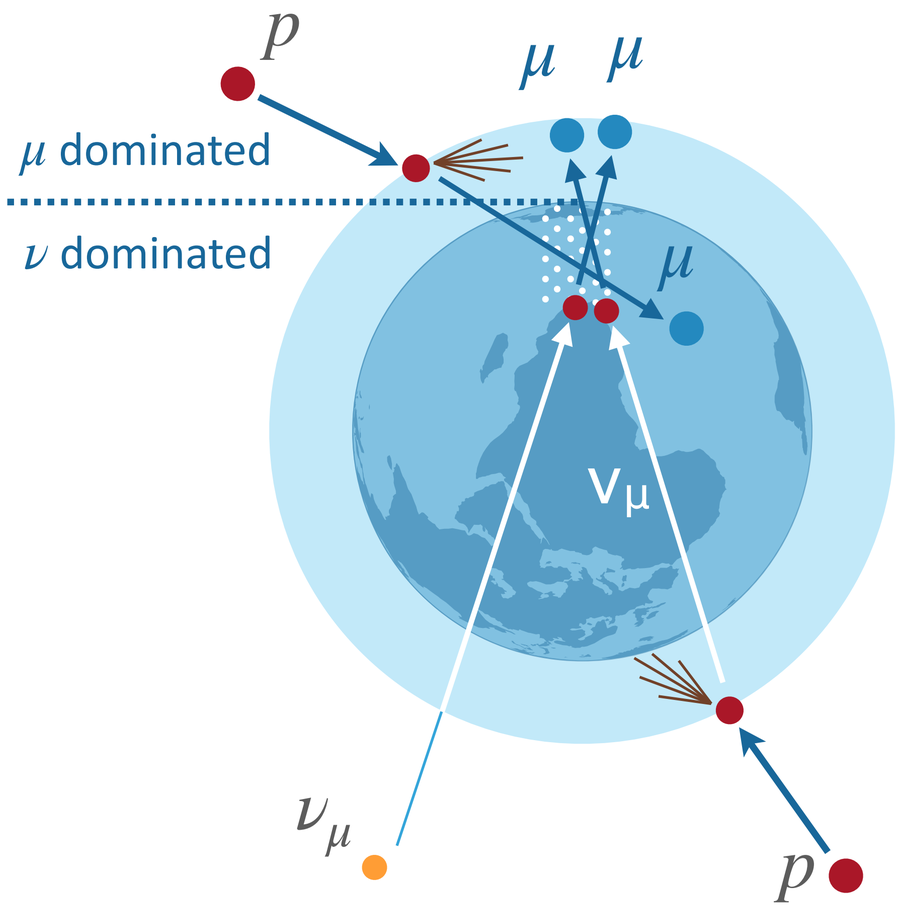
- different event selections lead to different spectral indices
- new analysis
  - more data
  - full energy range [1 TeV, 10 PeV]

➡ broken power law with 4.7 σ

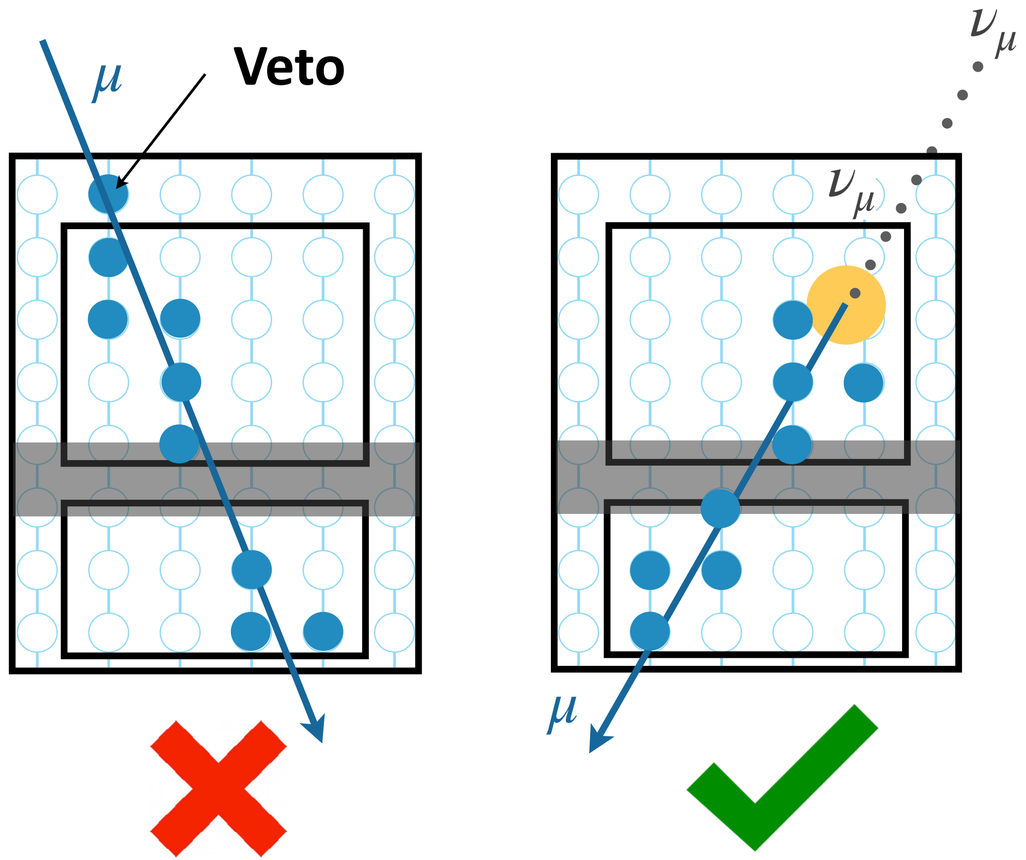


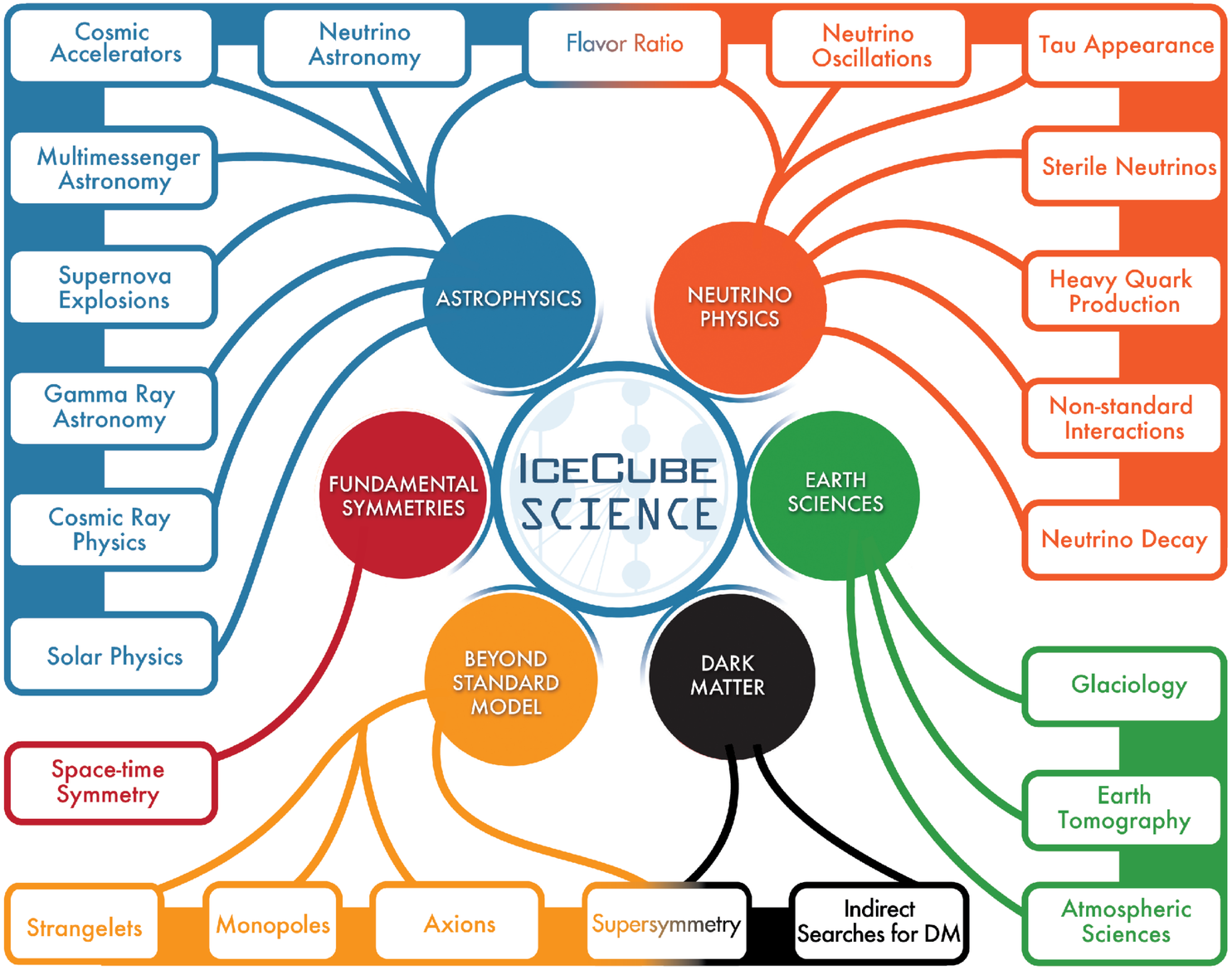
Background rejection

1 Using up-going **through-going muon** events using Earth as a shield against atmospheric muons.

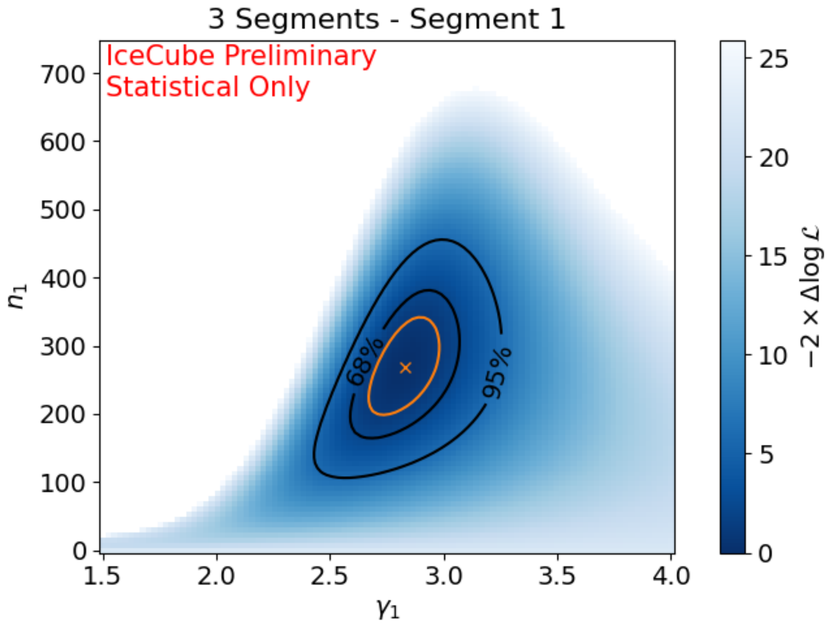


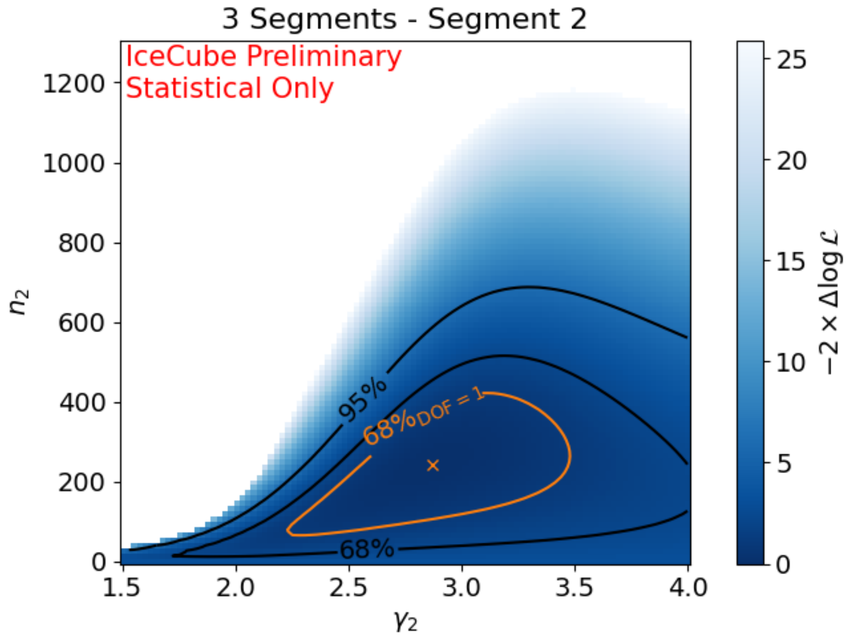
2 Using the outer layers as an active veto to select **starting events**.

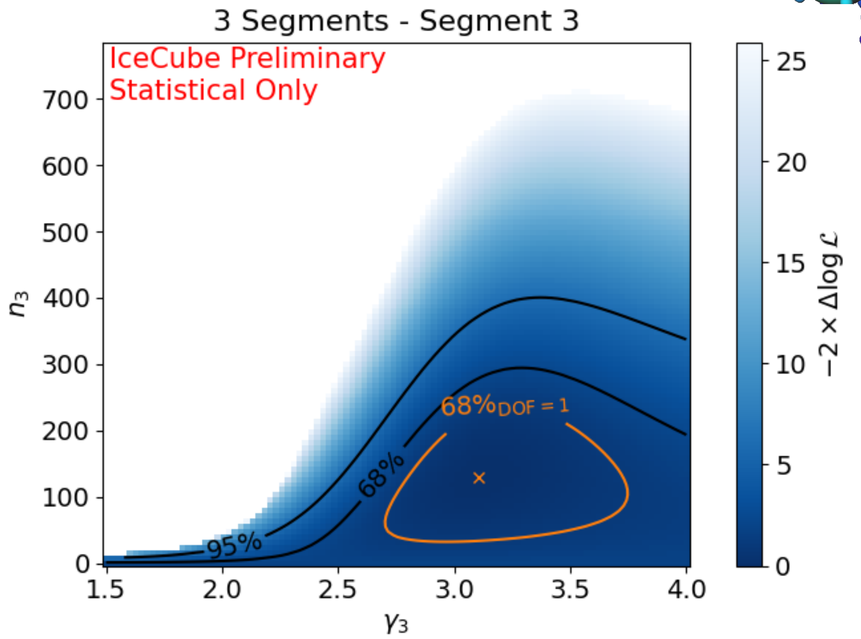



Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
ASTROPHYSICS
NEUTRINO PHYSICS
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
Cosmic Ray Physics
Neutrino Decay
Solar Physics
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences

Segmented galactic plane

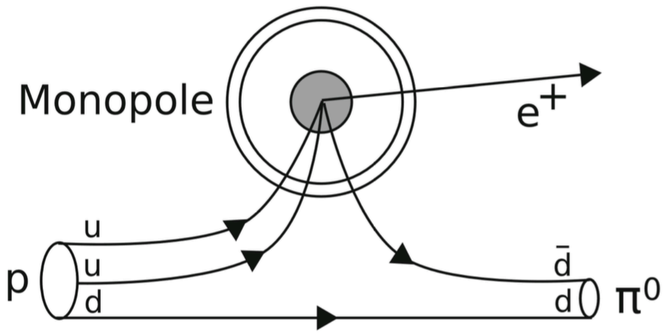


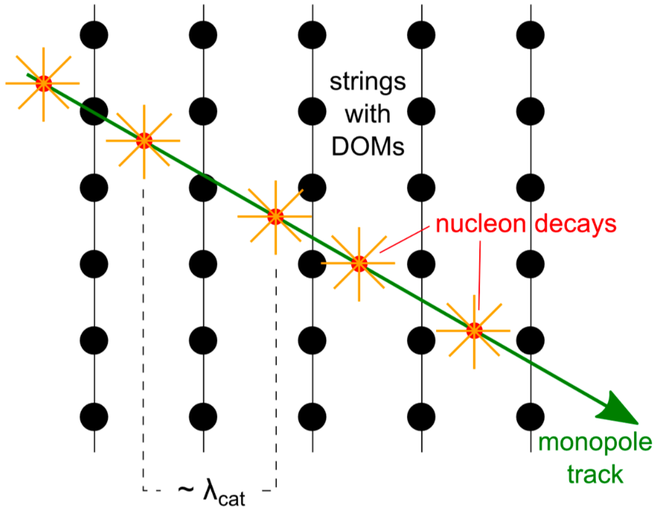


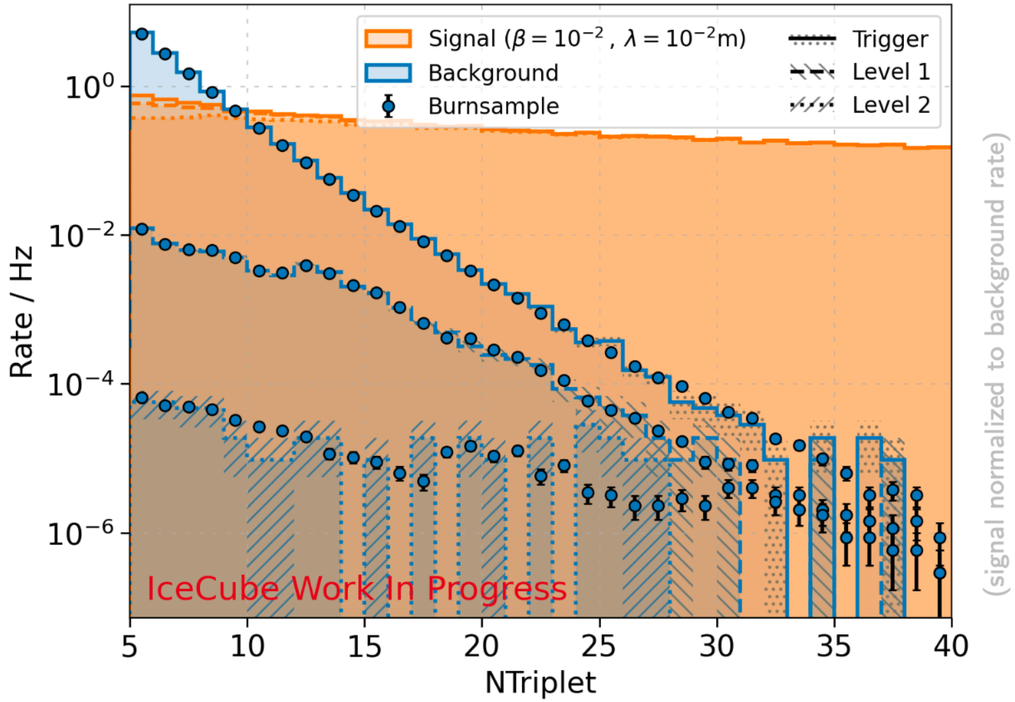


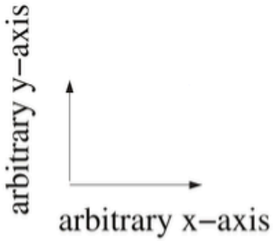
Magnetic monopoles

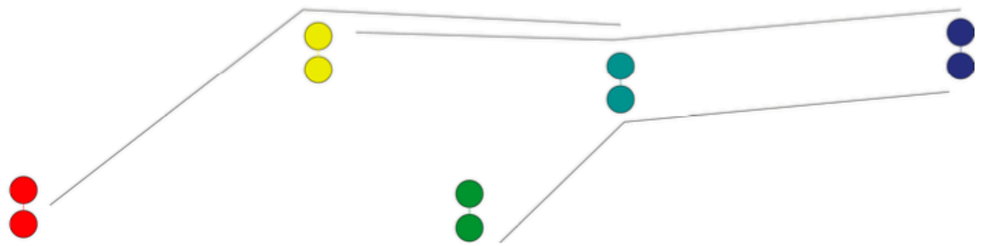
Rubakov-Callan effect
Catalysis of proton decay





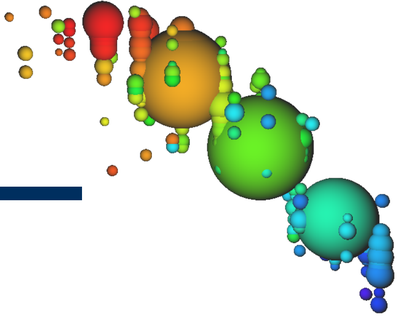






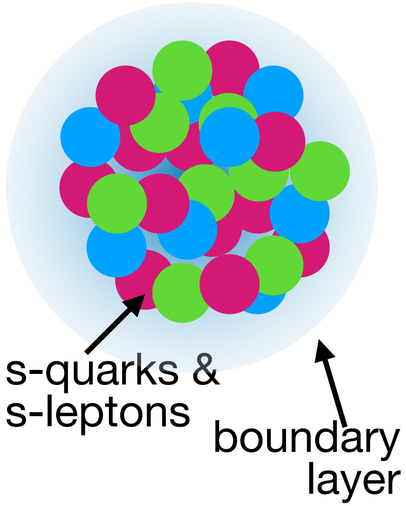
Credit: Jonas Häußler, Aachen

Heavy exotic particles



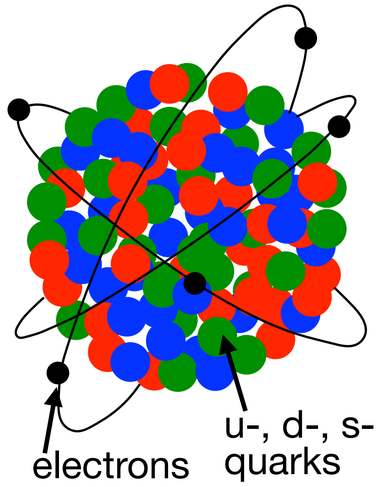
Q-balls

- predicted by super-symmetry
- coherent states of squarks, sleptons and the Higgs field
- created shortly after Big Bang with $m > 10^{11}$ GeV
- can be charged or neutral



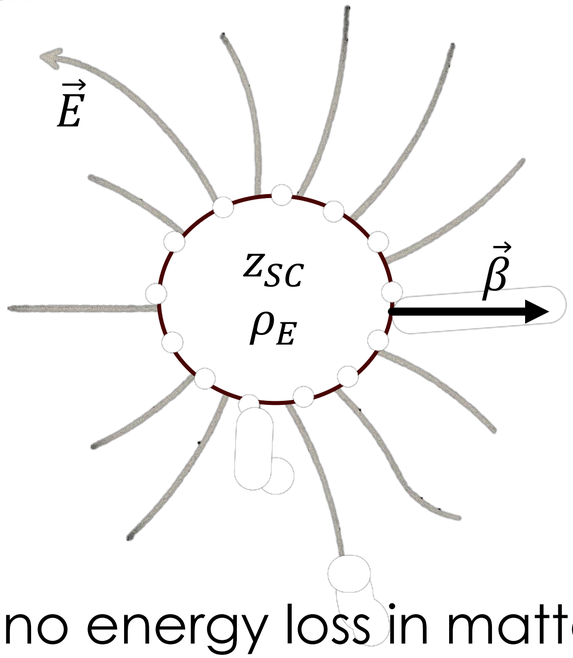
Nuclearites

- stable states in SM in thermodynamic processes
- heavy stable object of u-, d-, s-quarks
- almost neutral
- produced after Big Bang or as lumps of neutron stars



What is a shadow charge?

- Recently predicted "*particle*":
  - arXiv:2307.09475v1 [hep-th] 18 Jul **2023**
  - arXiv:2405.06374v1 [hep-ph] 9 May **2024**
- Moving electric field centered around a virtual charge
- No mass, but an energy density ρ_E
- Charge restricted to $z_{SC} < \frac{1}{\alpha} = 137$ (Schwinger limit)
- Doesn't react to microscopic forces (not a real particle) ⇒ no energy loss in matter
- Only follows geodesics ⇒ Behaves like dark matter ⇒ $\beta \approx 10^{-3}$



- Similar to an infinitely massive slow ion

Credit: Nicolas Møller, Chiba

Where do they come from?

Classical laws (Maxwell eq.) — Quantum EM

Dynamical equations

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right)$$

⟸ $i \frac{\partial}{\partial t} |\psi\rangle = H|\psi\rangle$ (Schrödinger)

Constraint equations†

$$\vec{\nabla}\, \vec{E} - j_0 = 0 \quad \text{(Gauss law)}$$

$$\vec{\nabla}\, \vec{B} = 0$$

⟸ + initial condition $|\psi(0)\rangle$

Historically: we impose the initial condition of the quantum theory (state of lowest energy) to recover the observed classical laws
BUT in the quantum theory (better theory of nature), the initial condition is a free parameter

$$\vec{\nabla}\, \vec{E} - j_0 = j_0^d \quad \text{(broken Gauss law)}$$

⟸ arbitrary initial condition

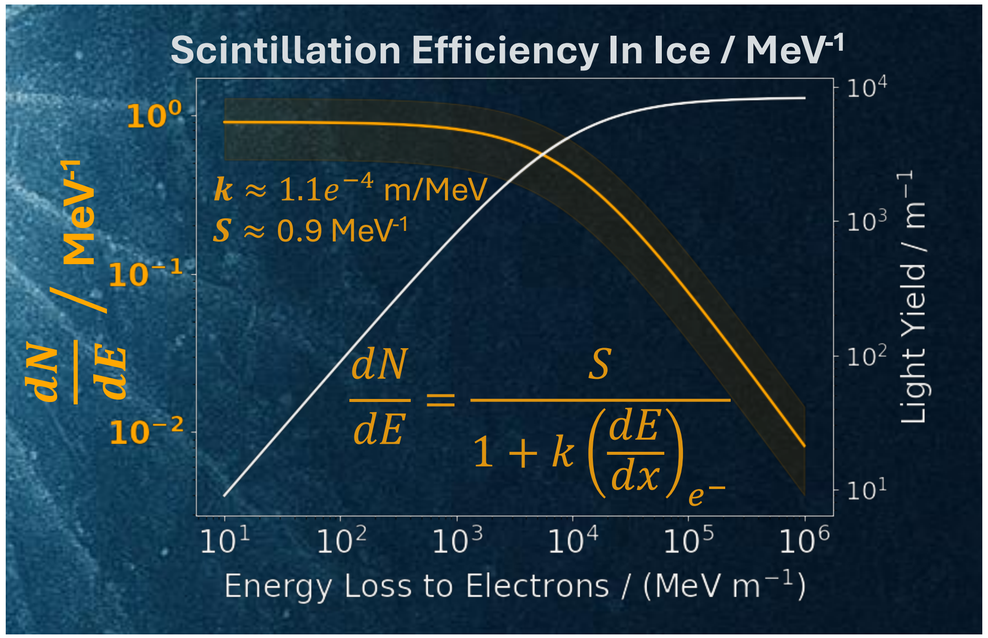
$$\nabla_\mu F^{\mu\vartheta} = \left(J^\vartheta + J^\vartheta_{aux} \right) \quad \text{(Maxwell eqs. + gravity)}$$

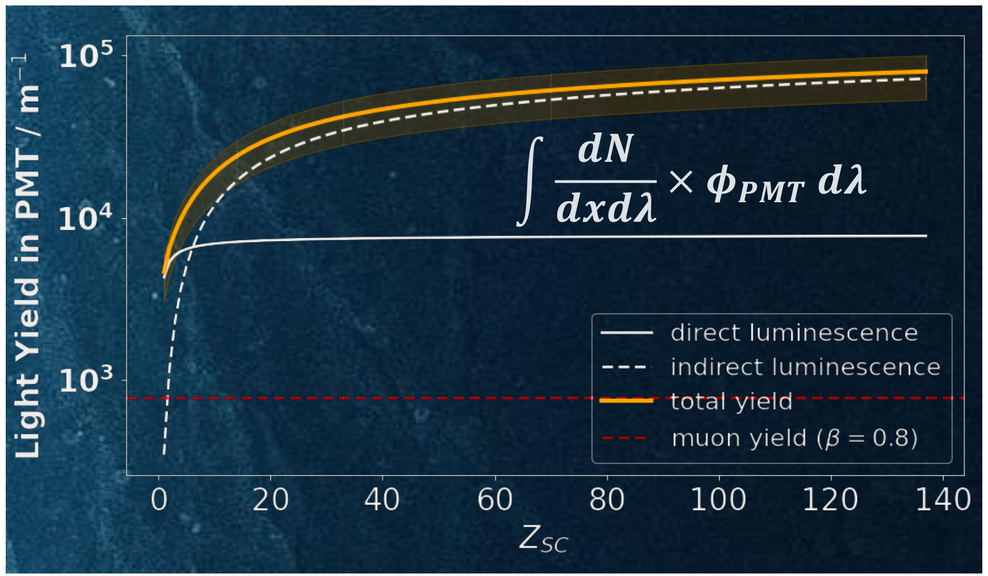
J^ϑ_{aux} : Background charge density with no time evolution (constant value)

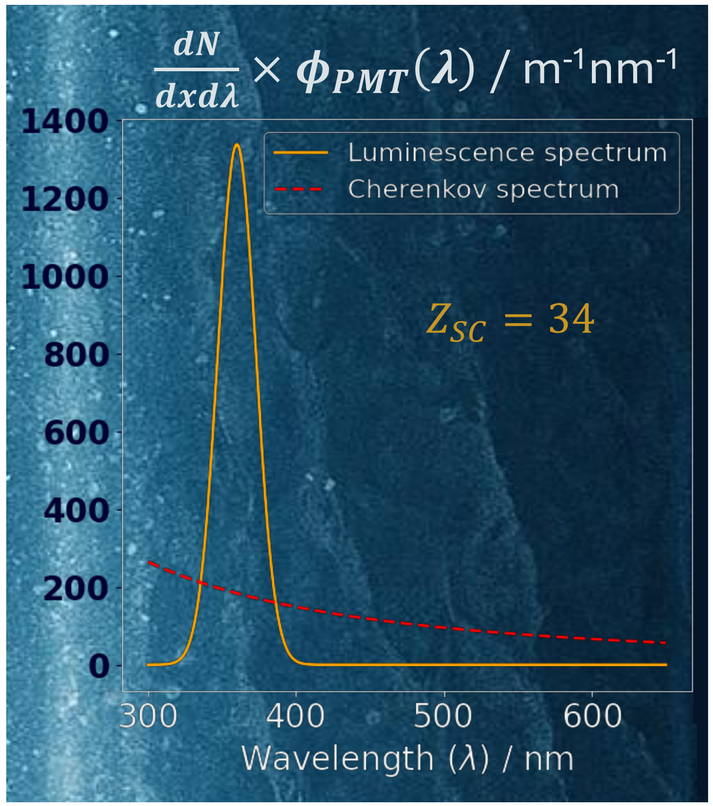
† Non-dynamical equations obtained by varying the action of a gauge theory on the non-physical fields

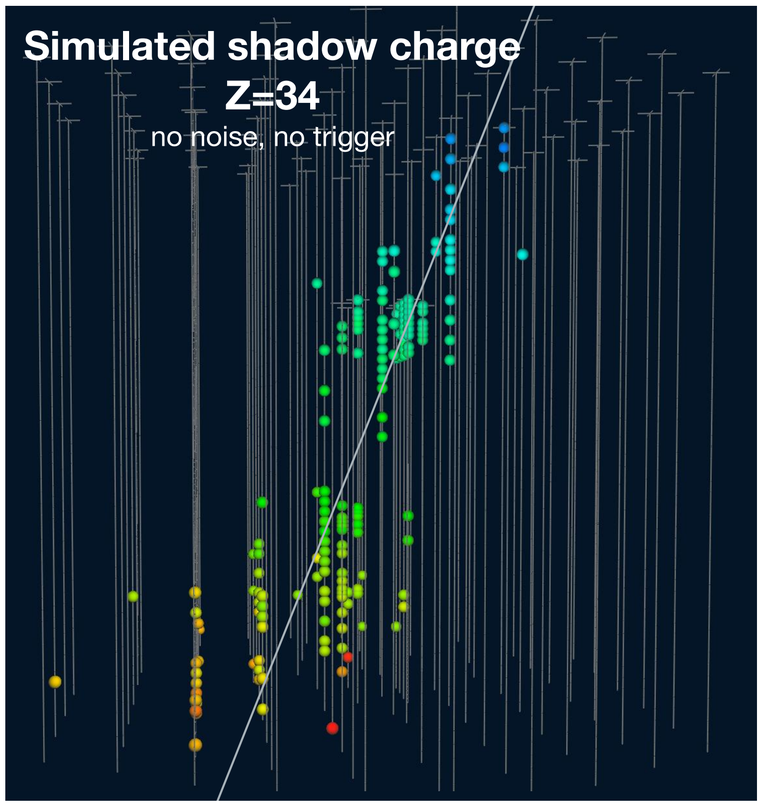
Credit: Nicolas Møller, Chiba

Shadow charges and luminescence light



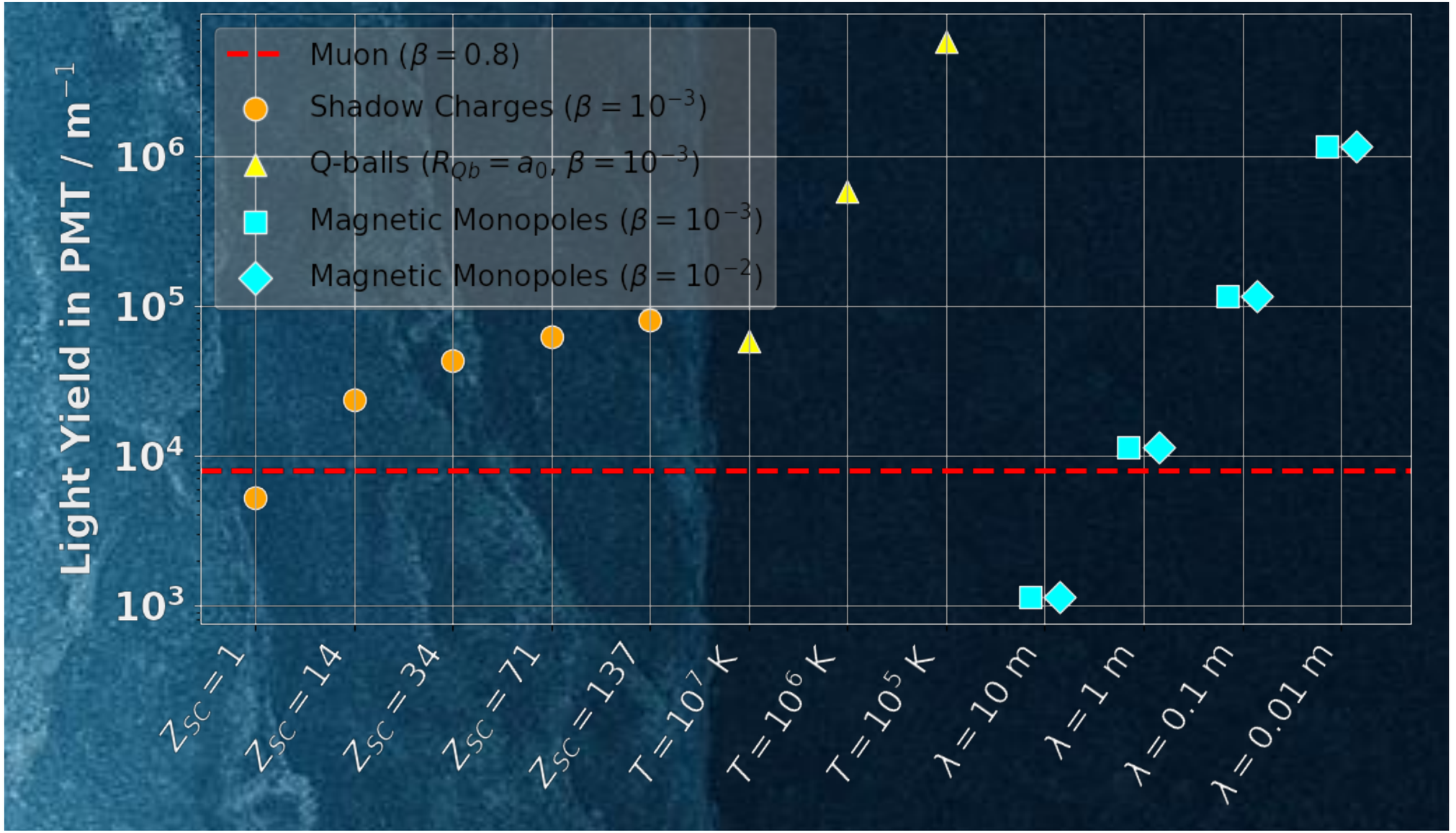






Credit: Nicolas Møller, Chiba

Slow particles in IceCube



Credit: Nicolas Møller, Chiba