ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

THE UNIVERSITY OF UTAH®

성균관대학교
1398
SUNG KYUN KWAN UNIVERSITY(SKKU)

IceCube-Gen2 Optical

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Community Summer Study
SNOWMASS
July 17-26 2022, Seattle

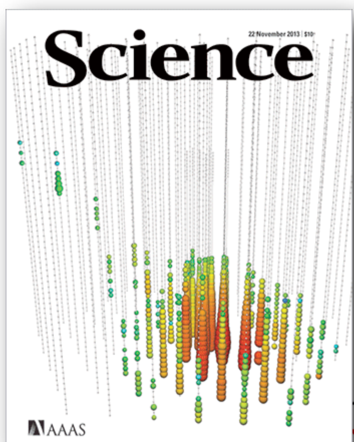
Motivation

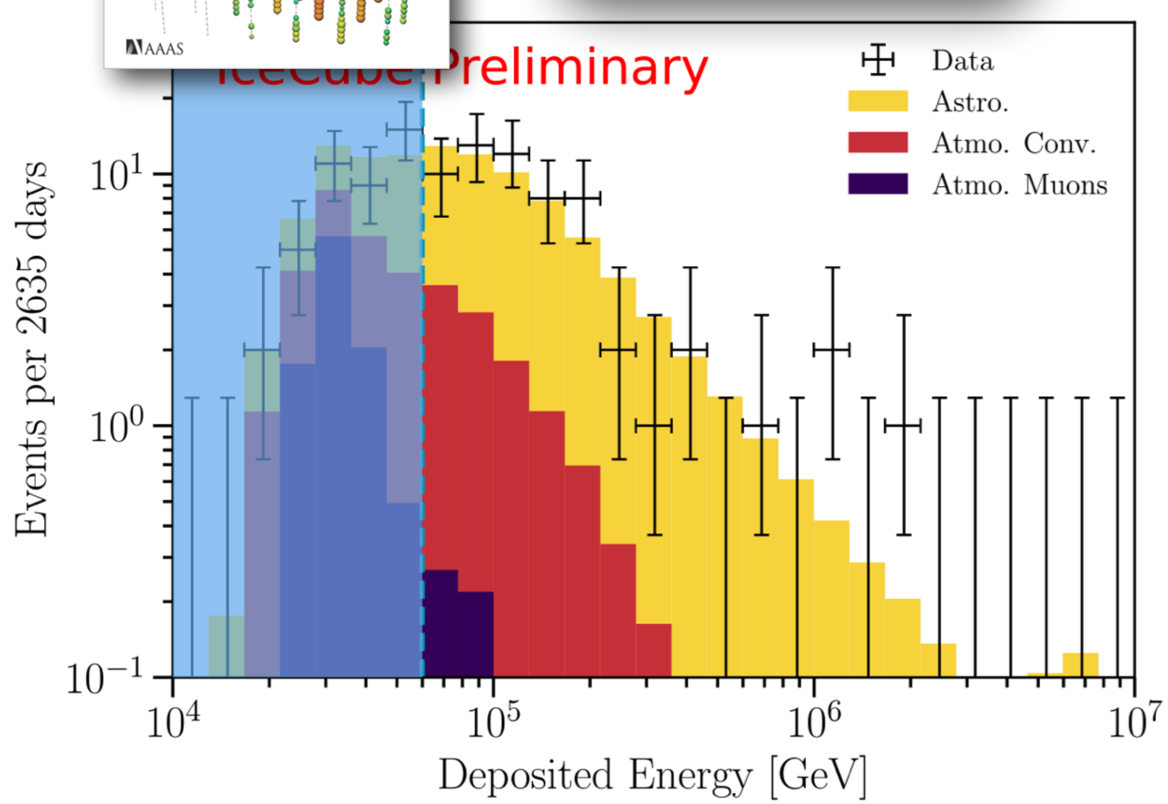
New Window to the Universe !

2002

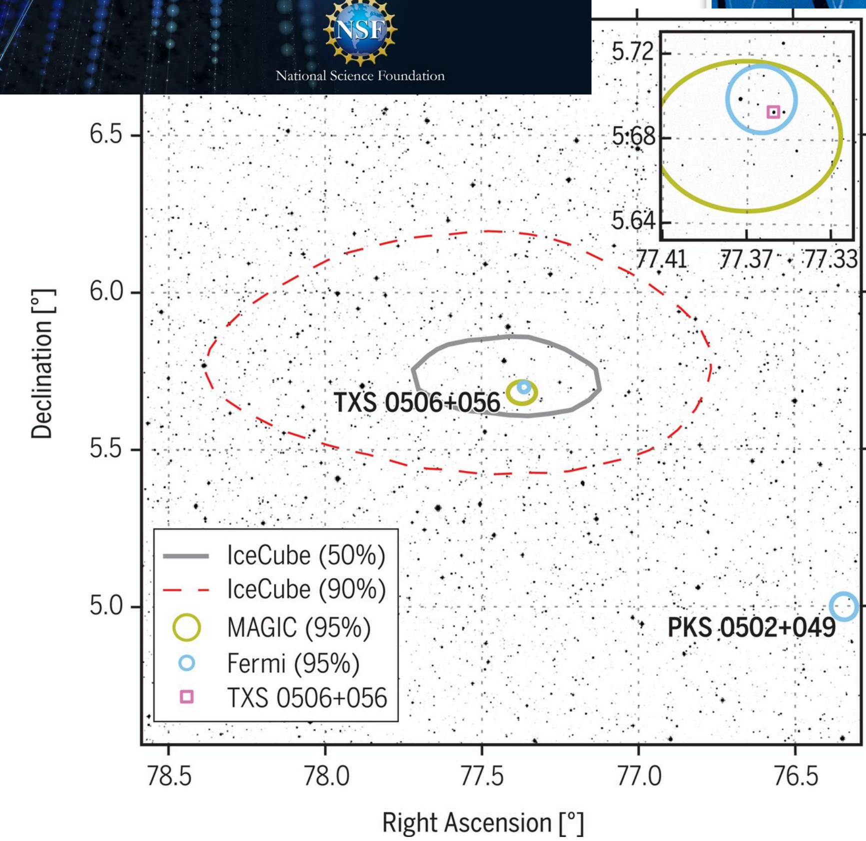
Following the observation of supernova burst neutrinos in 1987*, neutrino astronomy is becoming a reality quickly now …*

2013 Discovery of diffuse astrophysical neutrino flux

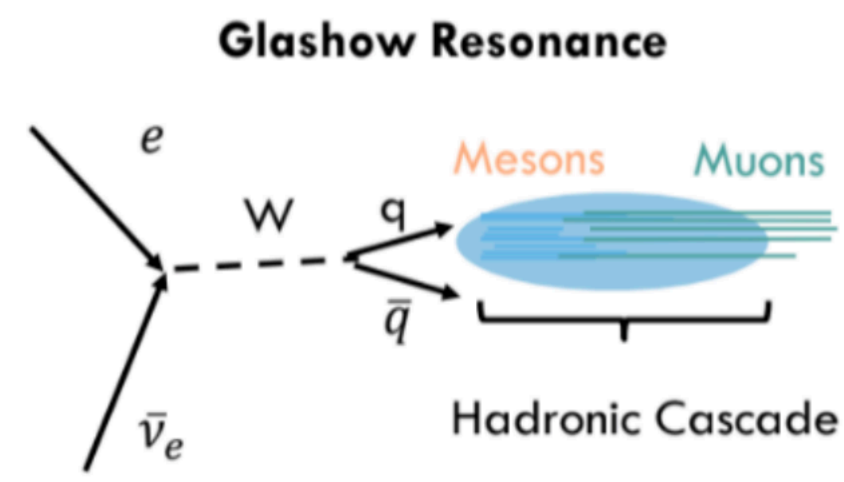




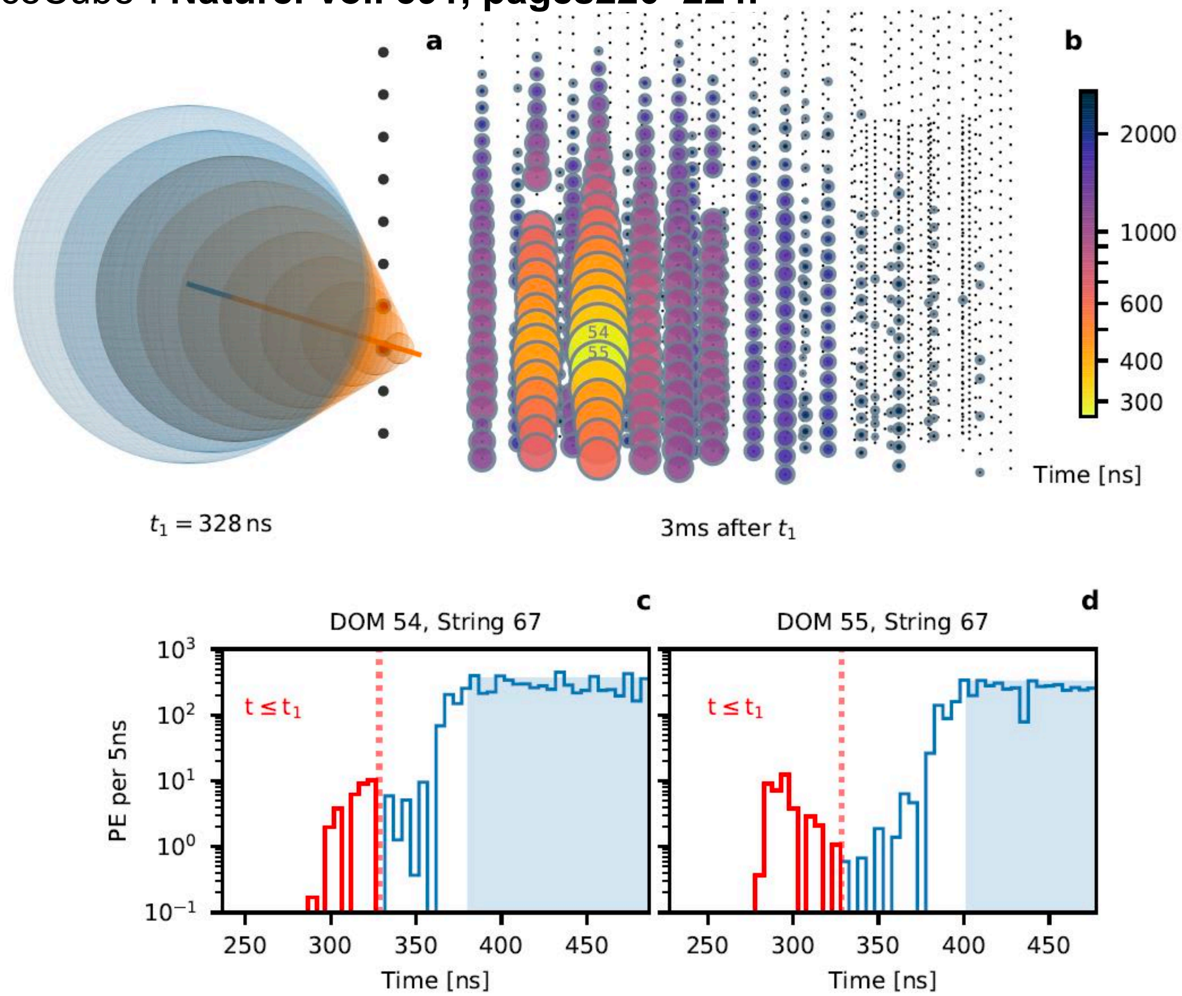
2018 Neutrino multi-messenger astroparticle physics

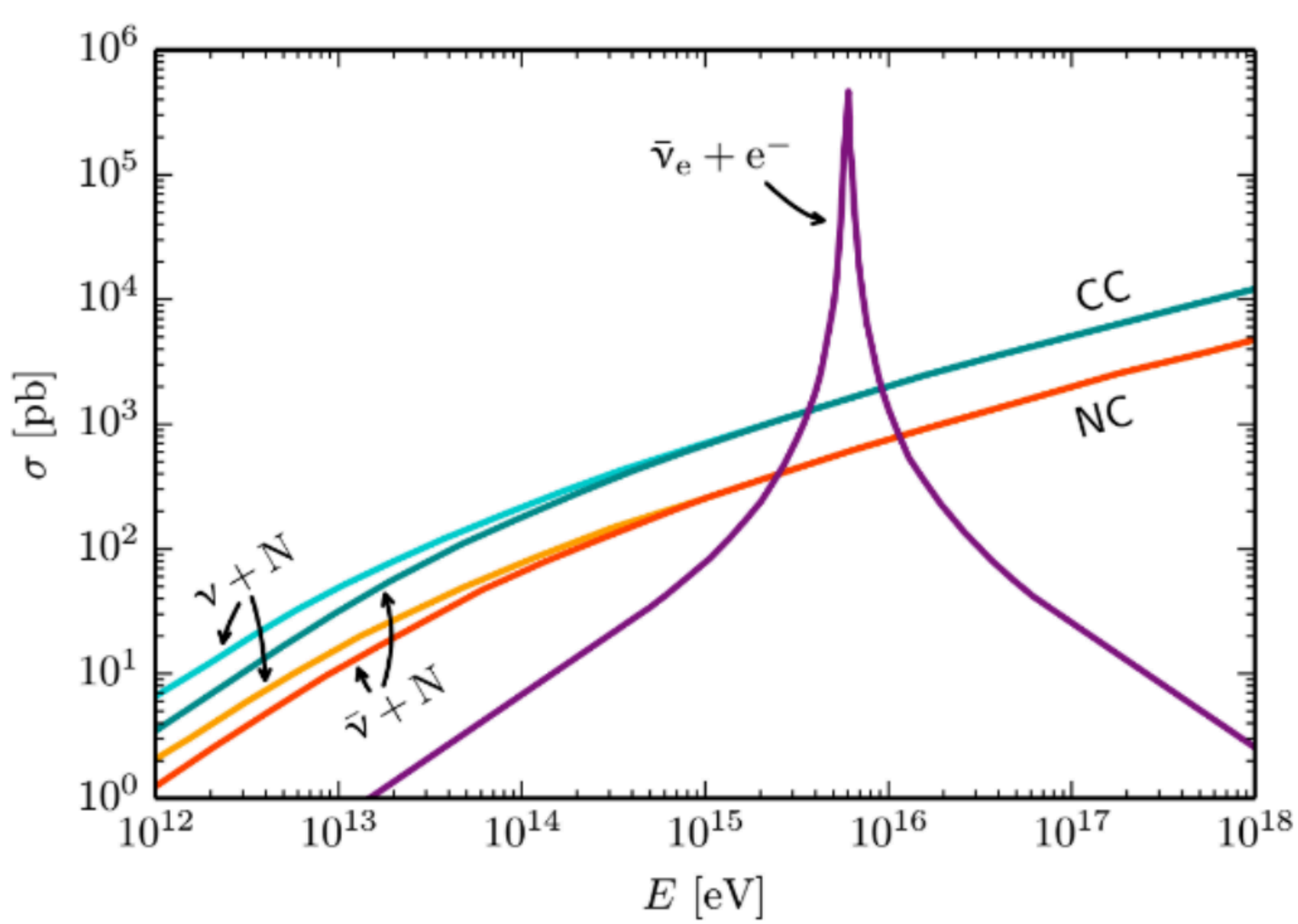


2021 Observation of Glashow resonance event at 6.3PeV



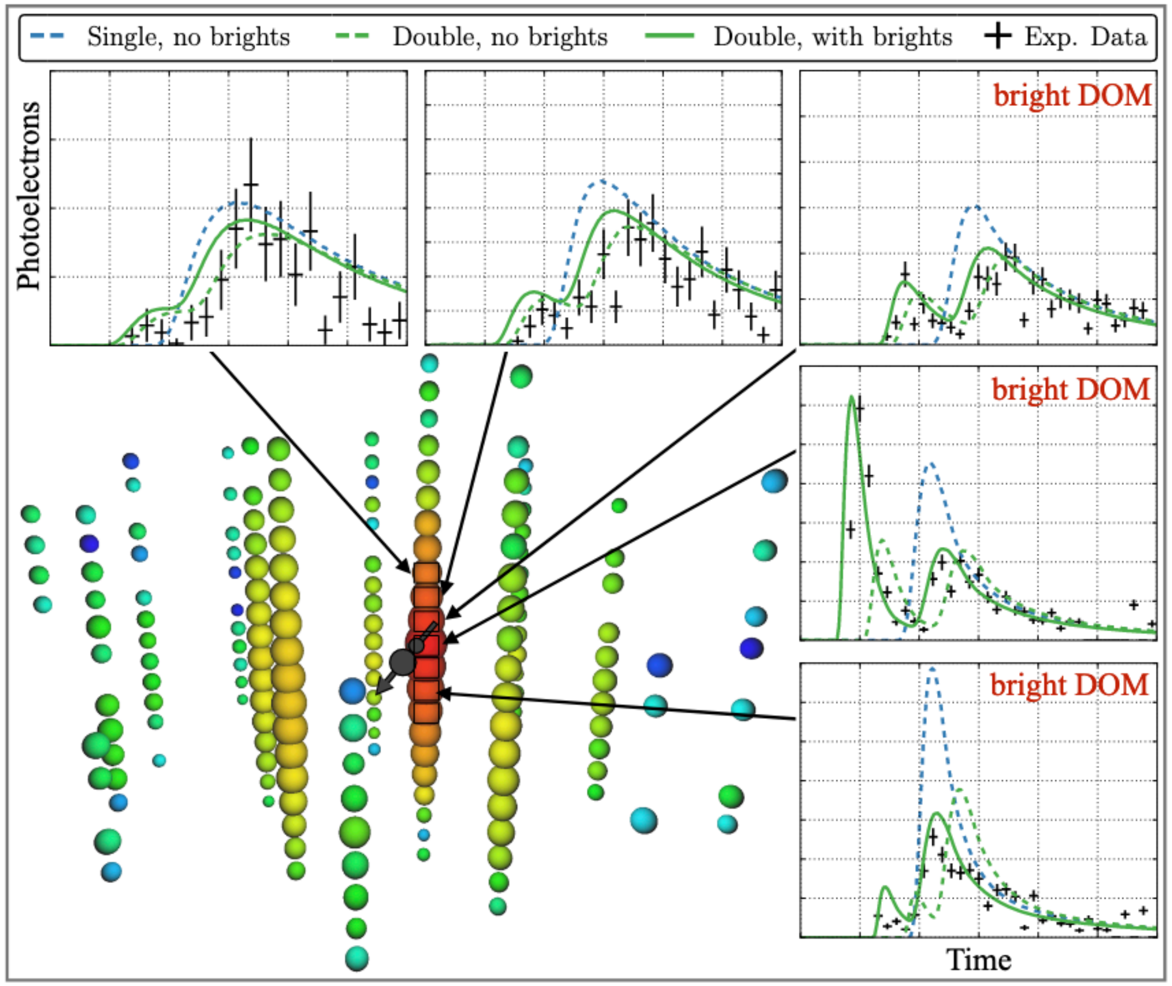
“Detection of a particle shower at the Glashow resonance with IceCube”. **Nature. Vol. 591, pages220–224.**



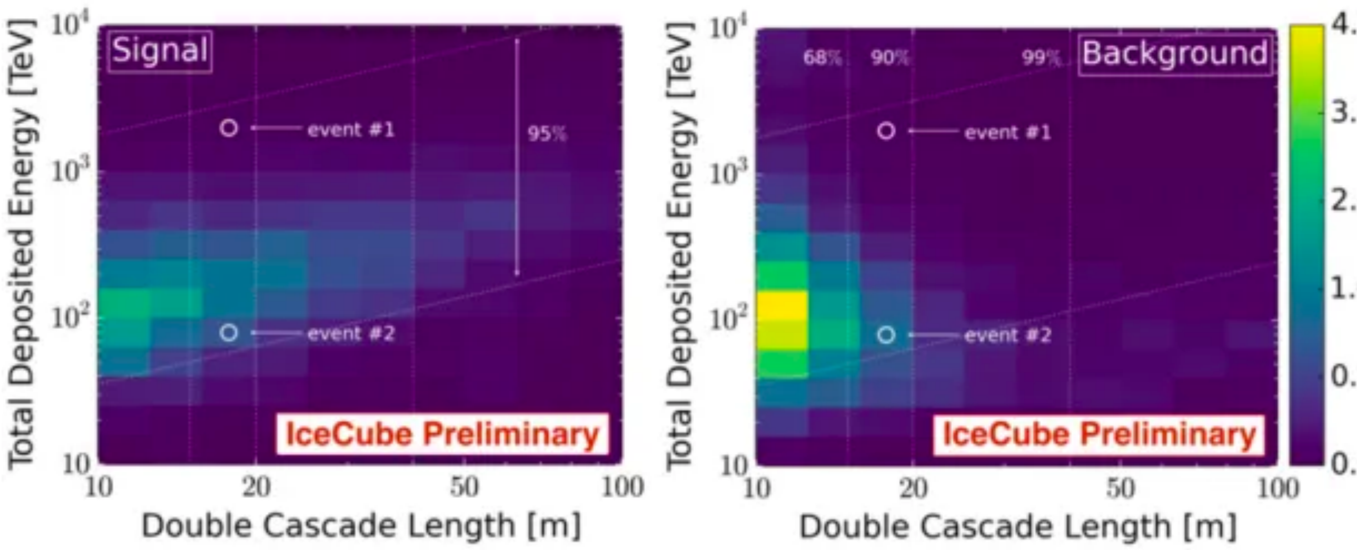


New Window to particle physics & beyond

arxiv:2011.03561



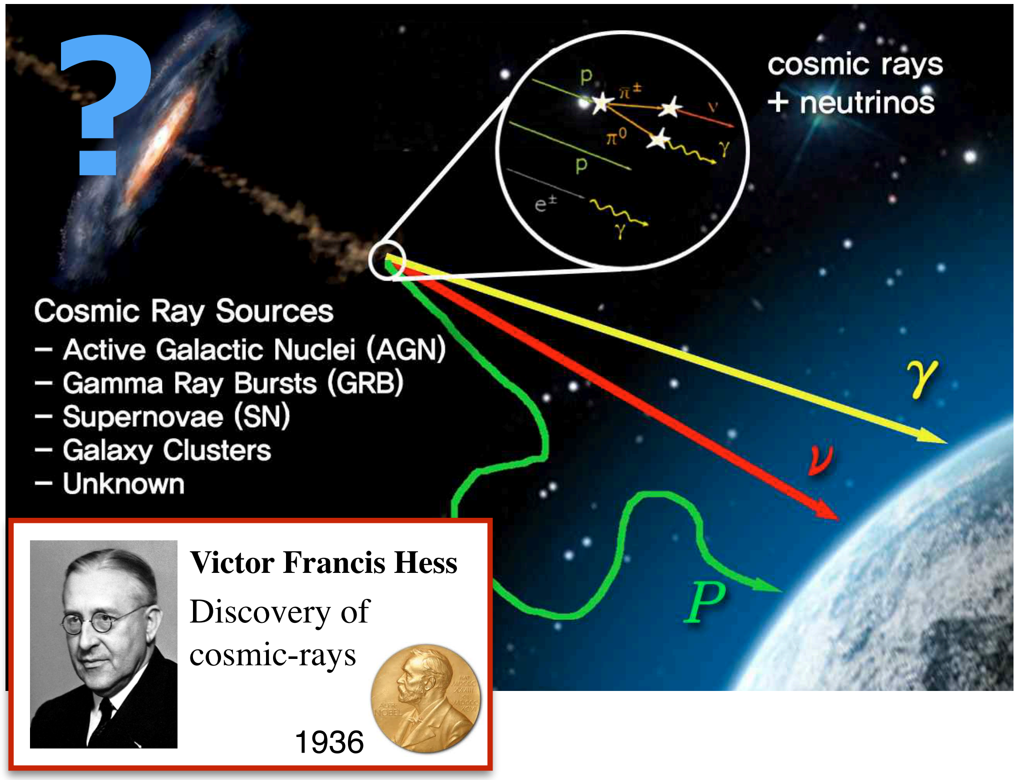
Tau neutrinos

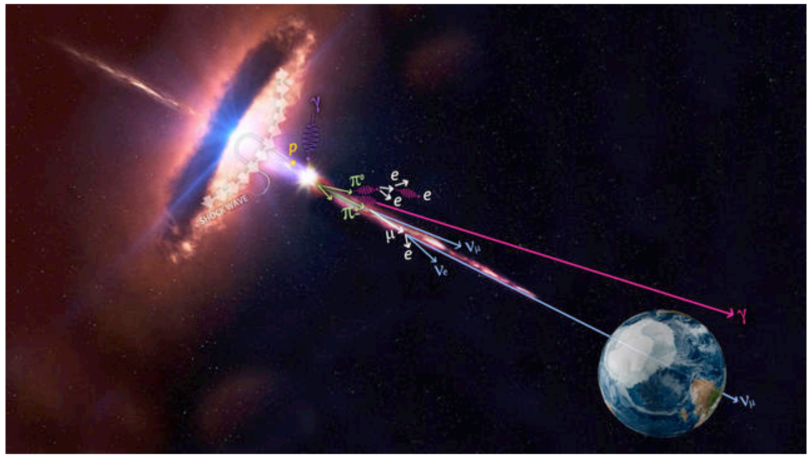


- Other particle physics include:
  - Exploring energy scales beyond the reach of colliders
  - Leading searches for new phenomena beyond the reach of LHC (BSM physics, dark matter, …)

Questions

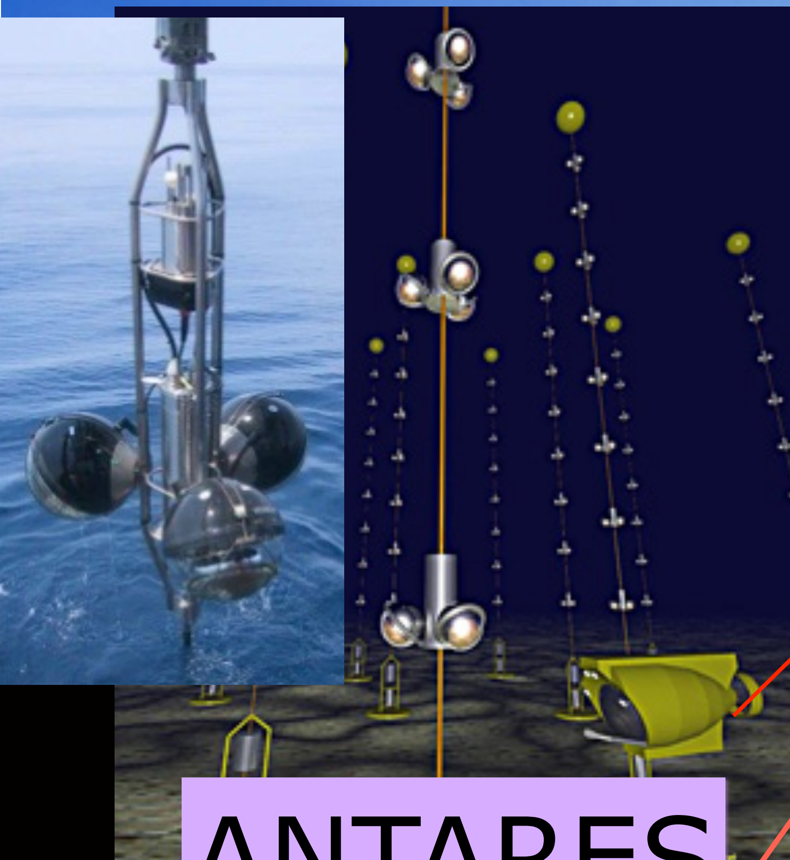
- To continue the path of discovery and the revolutionary effort to observe the Universe in fundamentally new ways
    - Requires next generation instrument
- Fundamental questions we want to answer:
    - What are the sources of the high-energy astrophysical neutrinos ?
    - What are the sources of the high-energy cosmic rays ?
    - What are the phenomena that occur at the most extreme environments in the Universe ?
    - Are there more than three neutrinos ?
    - What is the nature of dark matter ?
    - …





Neutrino Telescope Landscape - Gen2 in context of global neutrino telescope projects

Large Water Cherenkov Neutrino Telescopes



ANTARES

KM3NeT ORCA

P-ONE

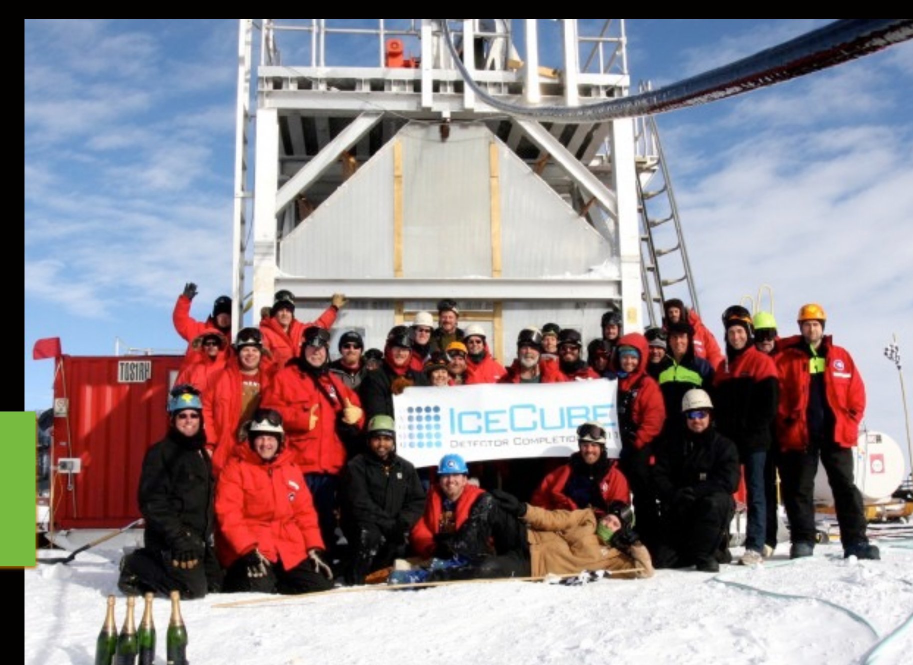
Lake Baikal

GVD

IceCube

Upgrade

IceCube-Gen2



Active

Construction

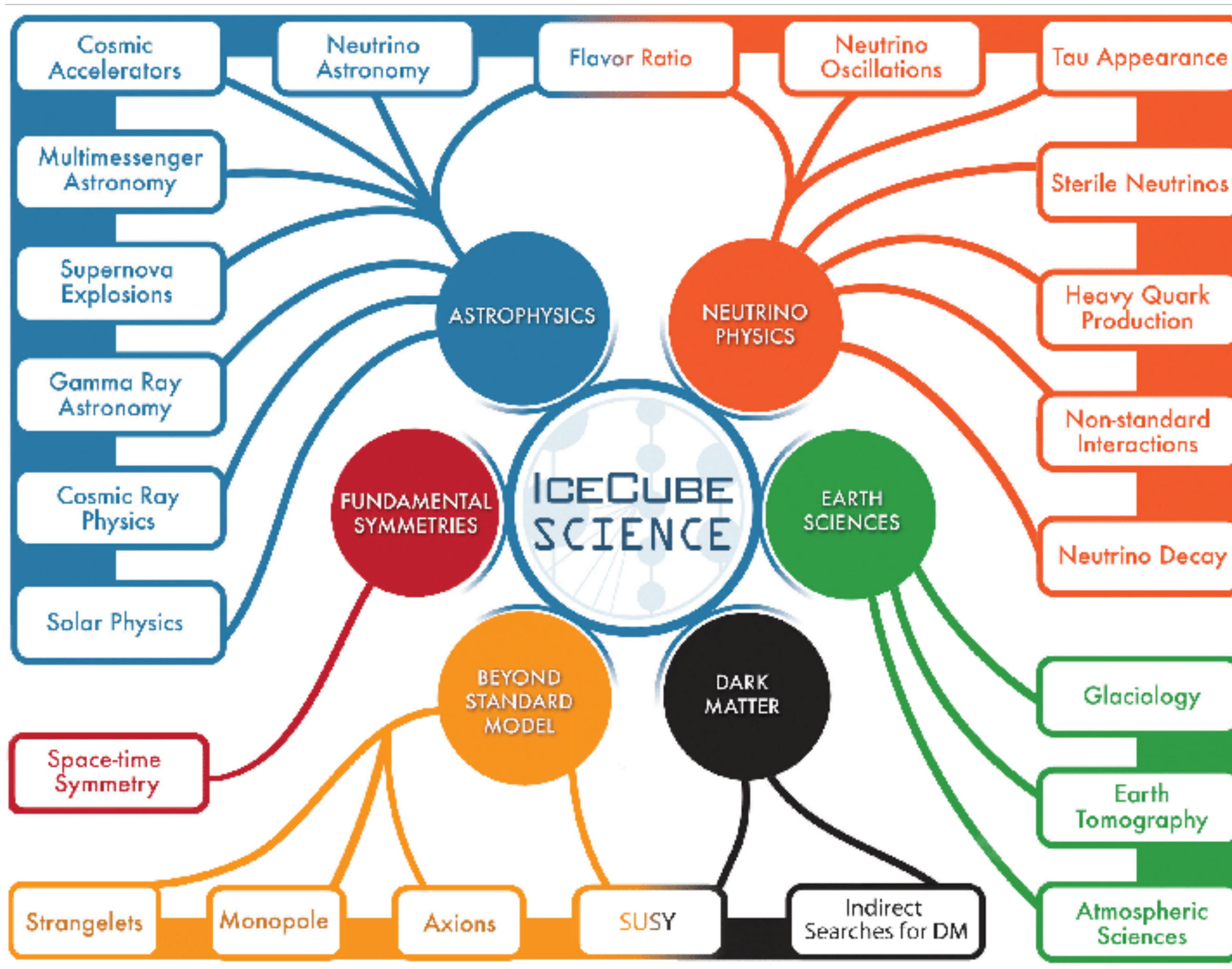
Planned

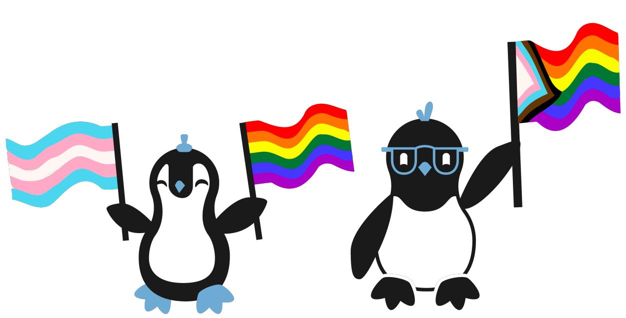
Neutrino Telescope Science

Scientific Scope

- ASTROPHYSICS & NEUTRINO SOURCES
  - Point sources of ν's (SNR, AGN …), extended sources
  - Transients (GRBs, AGN flares …)
  - Solar Atmospheric Neutrinos
  - Diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- BSM PHYSICS & DARK MATTER
  - Indirect DM searches (Earth, Sun, Galactic center/halo)
  - Magnetic monopoles
  - Violation of Lorentz invariance
- PARTICLE PHYSICS
  - ν oscillations, sterile ν's
  - Charm in CR interactions
  - Neutrino Cross Sections
- COSMIC RAY PHYSICS
  - Energy spectrum around "knee", composition, anisotropy
- SUPERNOVAE (galactic/LMC)
- GLACIOLOGY & EARTH SCIENCE

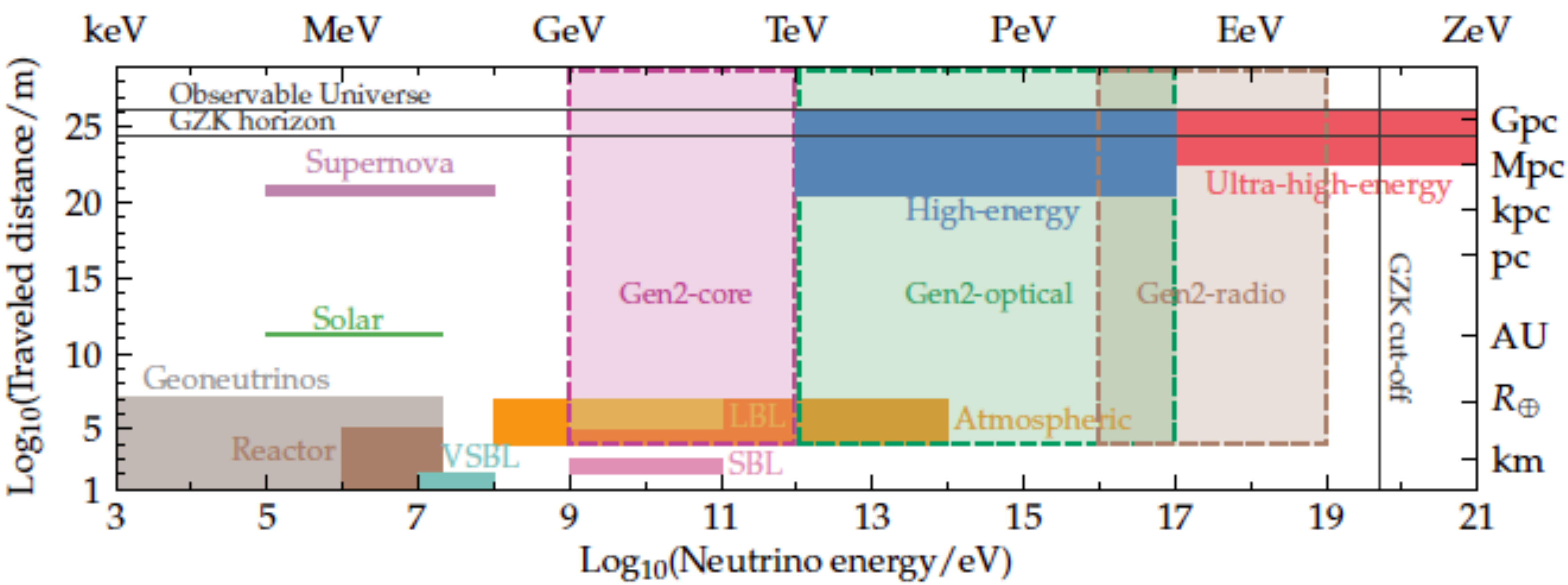
Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos





Comparison

- Uniqueness of the Gen2 facility
  - Coverage of a very broad energy range from MeV to EeV
  - Combination of multiple detector technologies in one facility

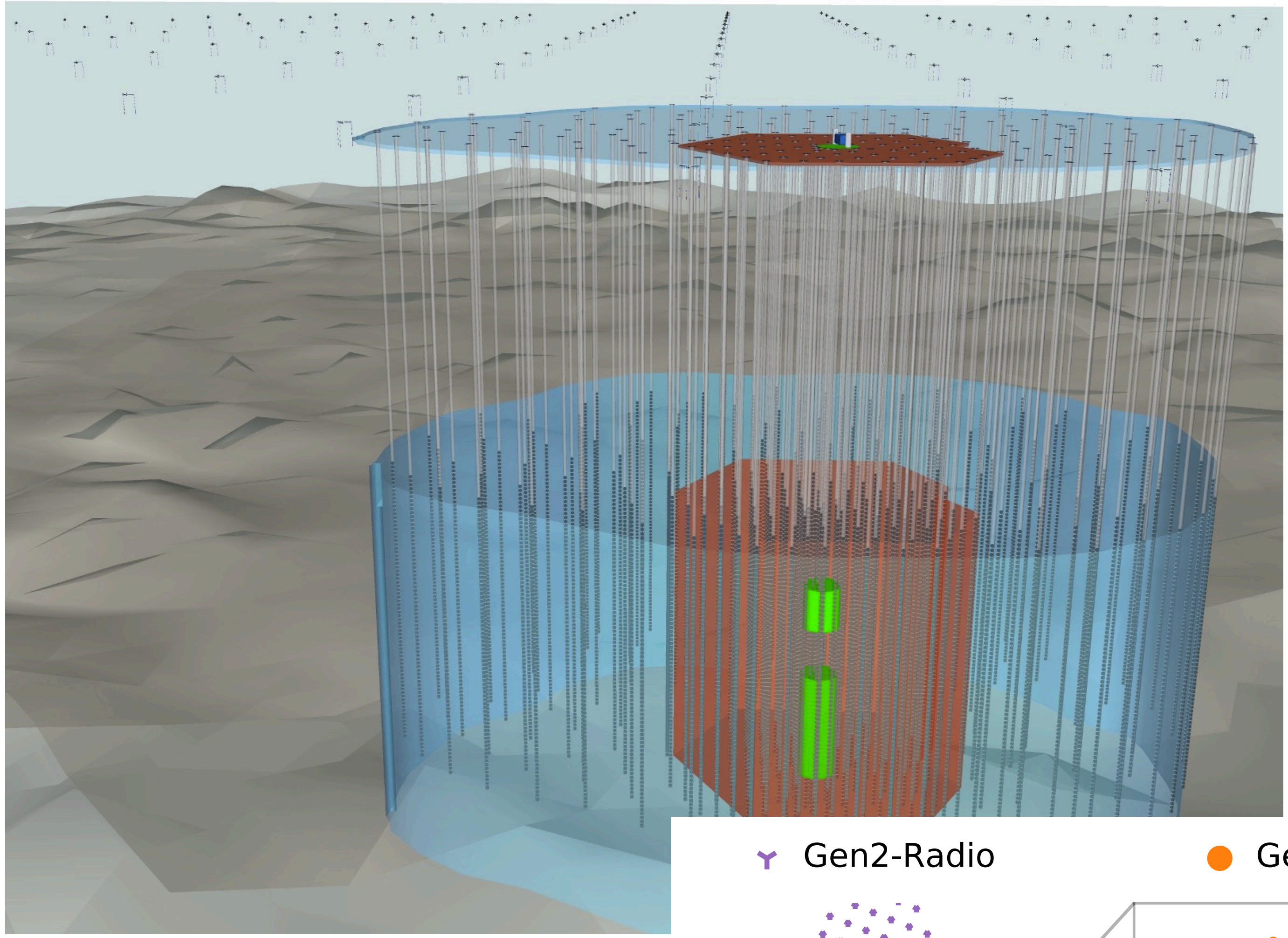


IceCube & Gen2

IceCube Collaboration

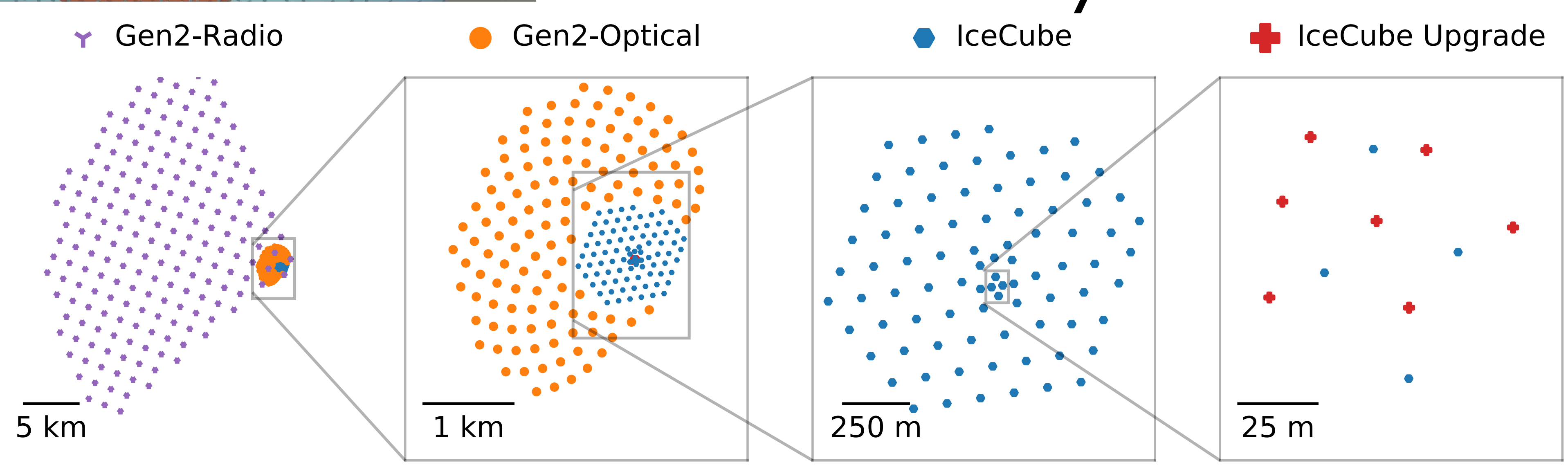
The IceCube-Gen2 Facility

A broadband neutrino observatory



Four new elements, leveraging complimentary technologies, to achieve sensitivity to MeV-EeV neutrinos

- Densely instrumented deep optical array (IceCube Upgrade)
- Extensive deep optical array
- Surface array
- Radio array



IceCube and IceCube-Gen2

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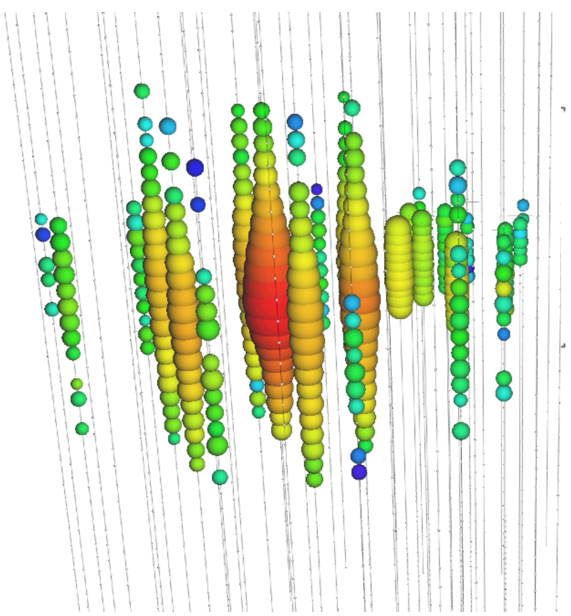
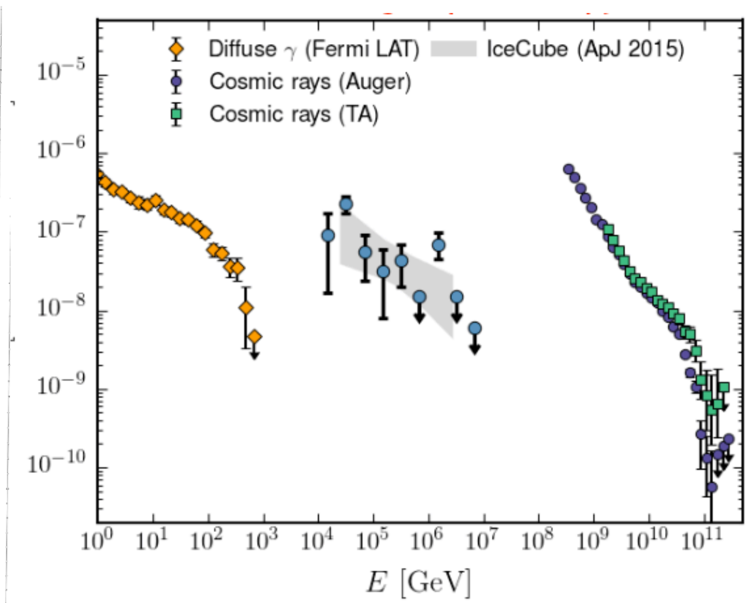
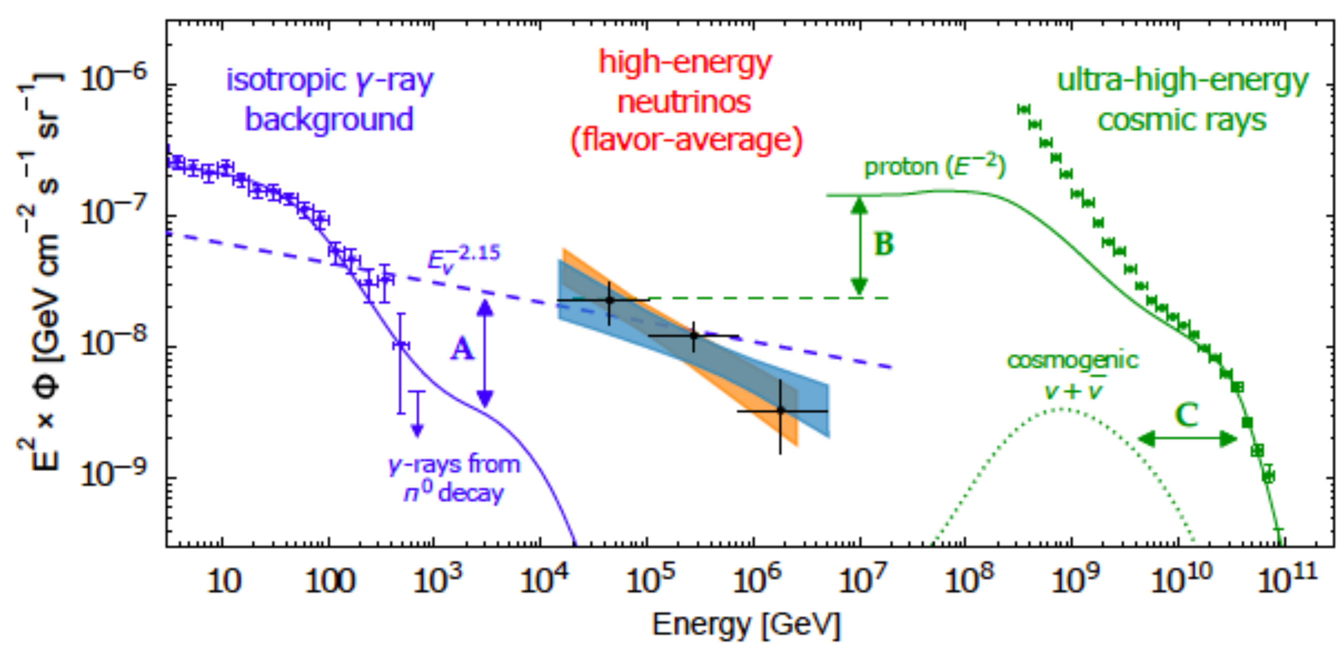
Full detector operation since 2011

ICECUBE GEN2

A high energy extension of IceCube for the next decades of neutrino astronomy





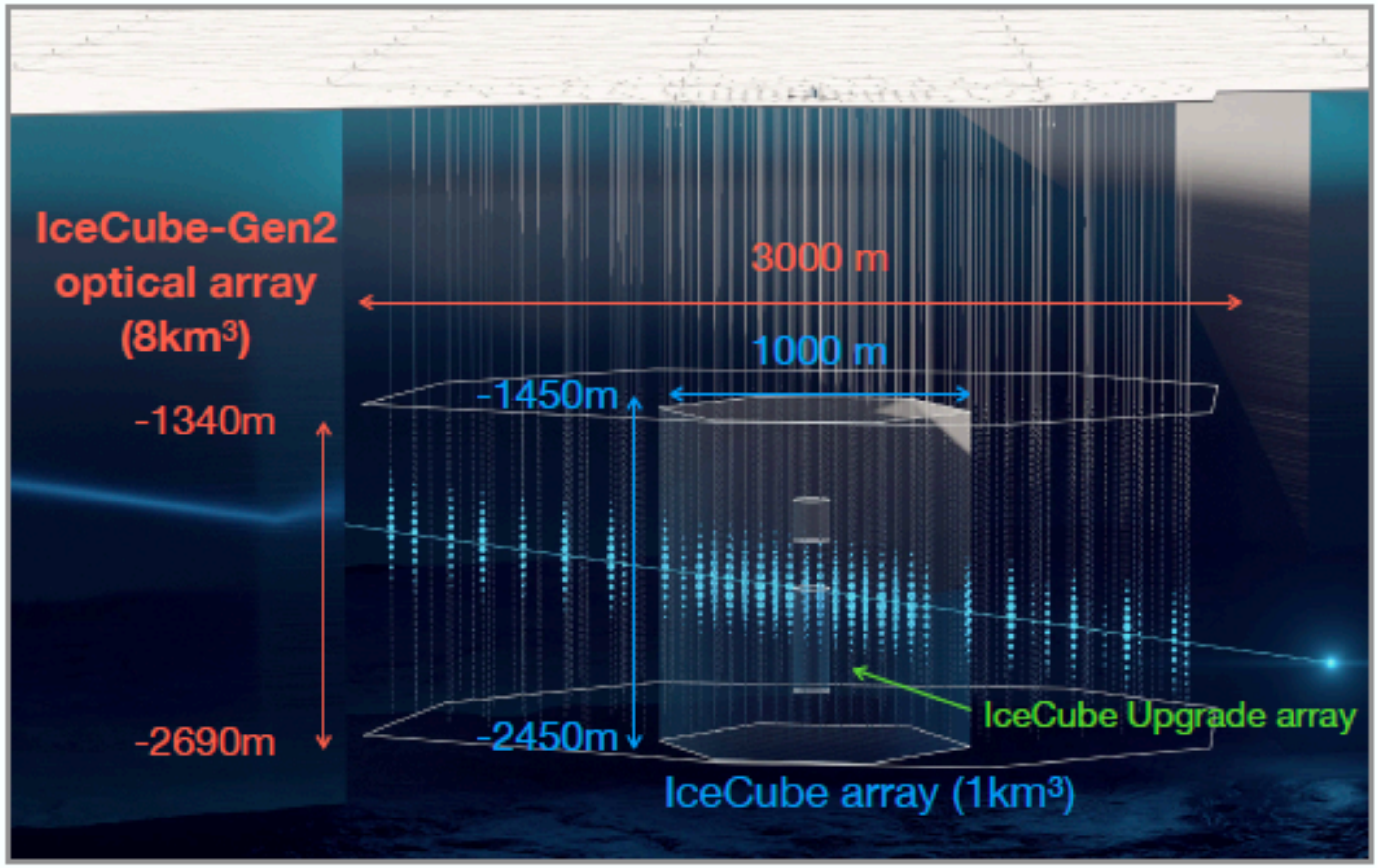


- 2013: Discovery of astrophysical neutrino flux
- 2018: Evidence for Blazars as neutrino sources
- 2020: First astrophysical tau neutrino measurements

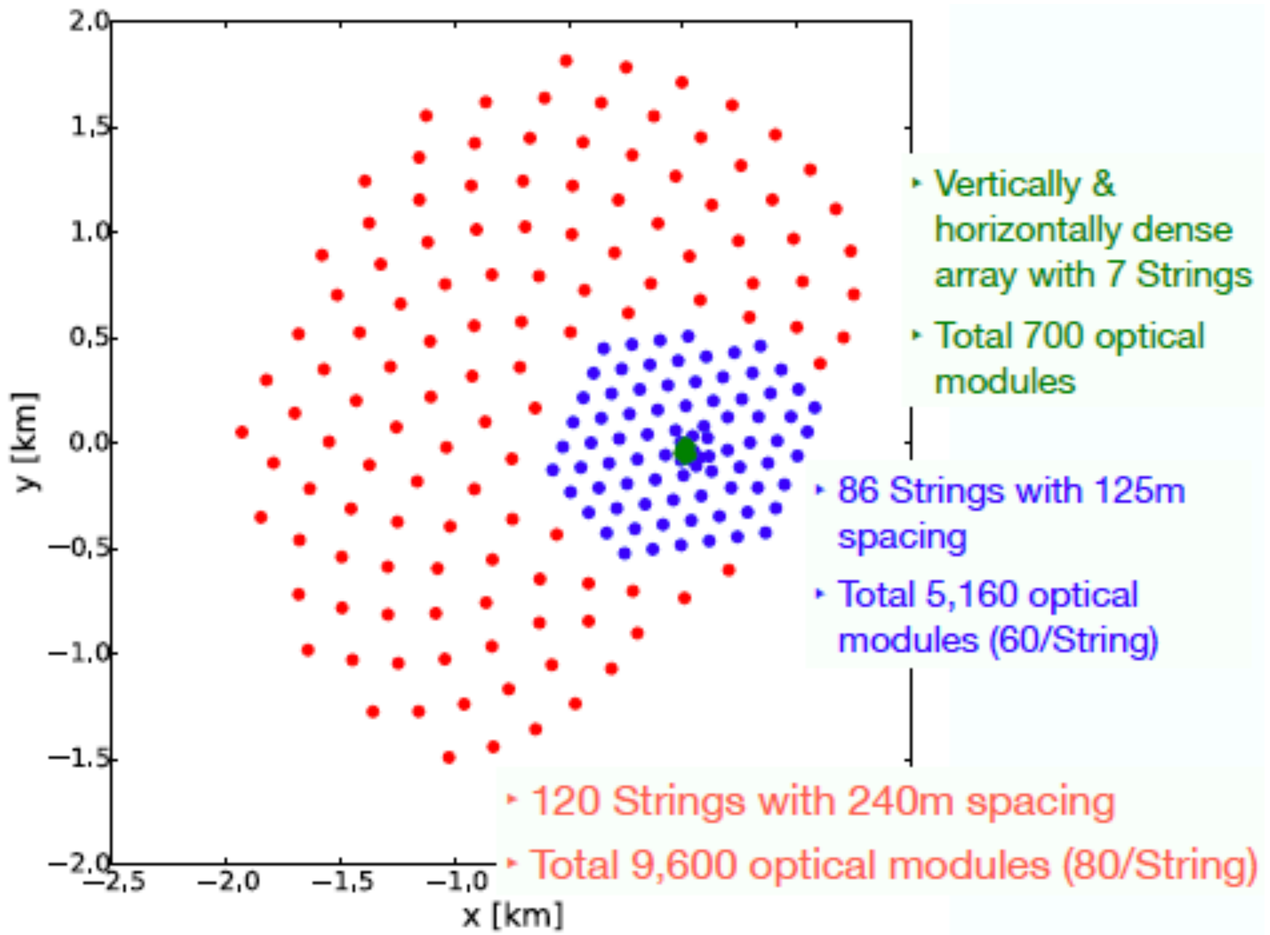
- Aims 5x sensitivity from IceCube
- From discovery to astronomy
- Resolving high energy sky from TeV to EeV

IceCube-Gen2 Array

We aim 5x improvement on the neutrino sensitivity with a 8 km^3 instrumented volume



Gen2 also plans surface & in-ice radio arrays (J. Phys. G 48 2021)



Improvement of Optical Module design is the key to success of IceCube-Gen2

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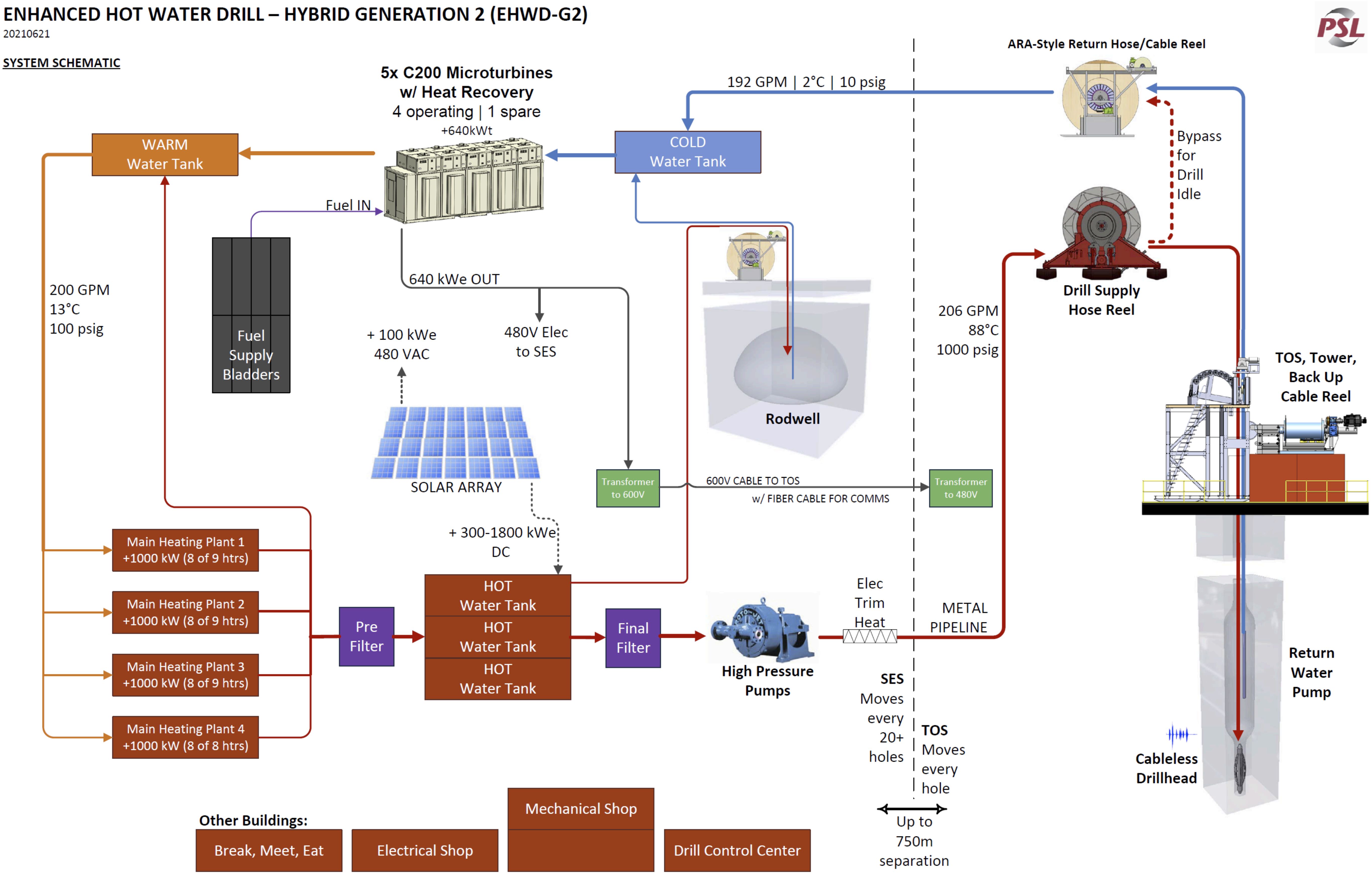
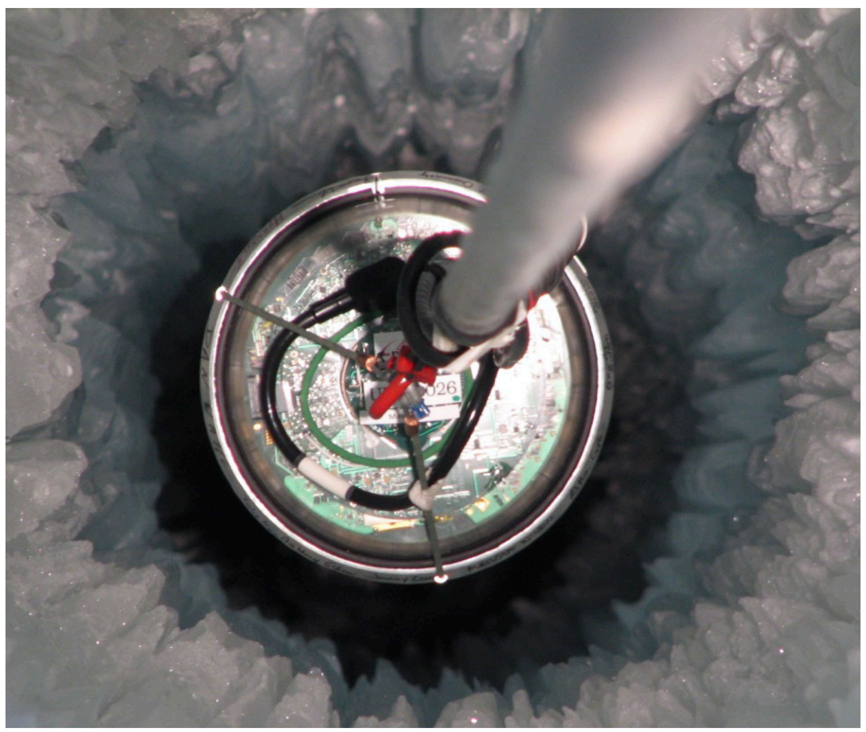
Enhanced Hot Water Drill - Gen2

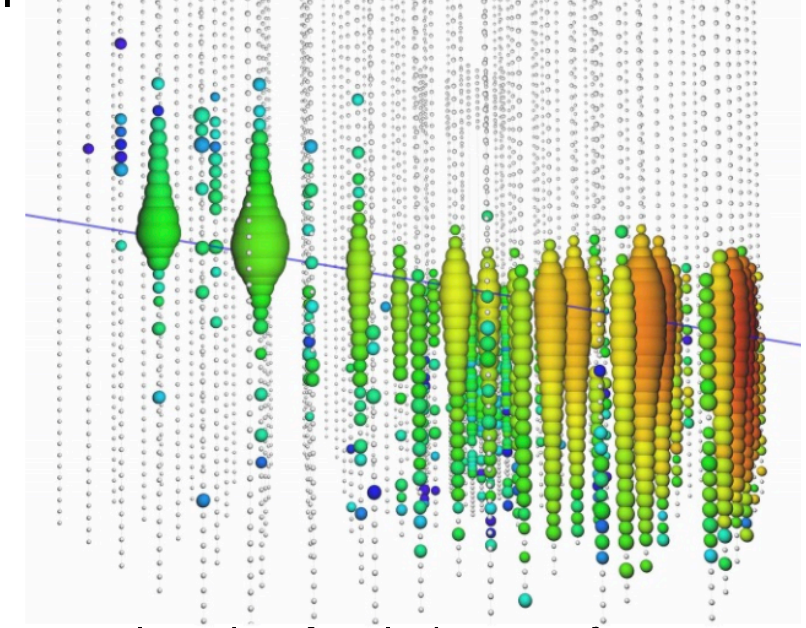


Optical Modules

We aim 5x improvement on the neutrino sensitivity with a 8 km^3 instrumented volume



E_{dep} ~ 2.6 PeV track => 1e5 photoelectrons observed in total



Imaging & calorimetry of neutrino events with a 3D array of Optical Modules

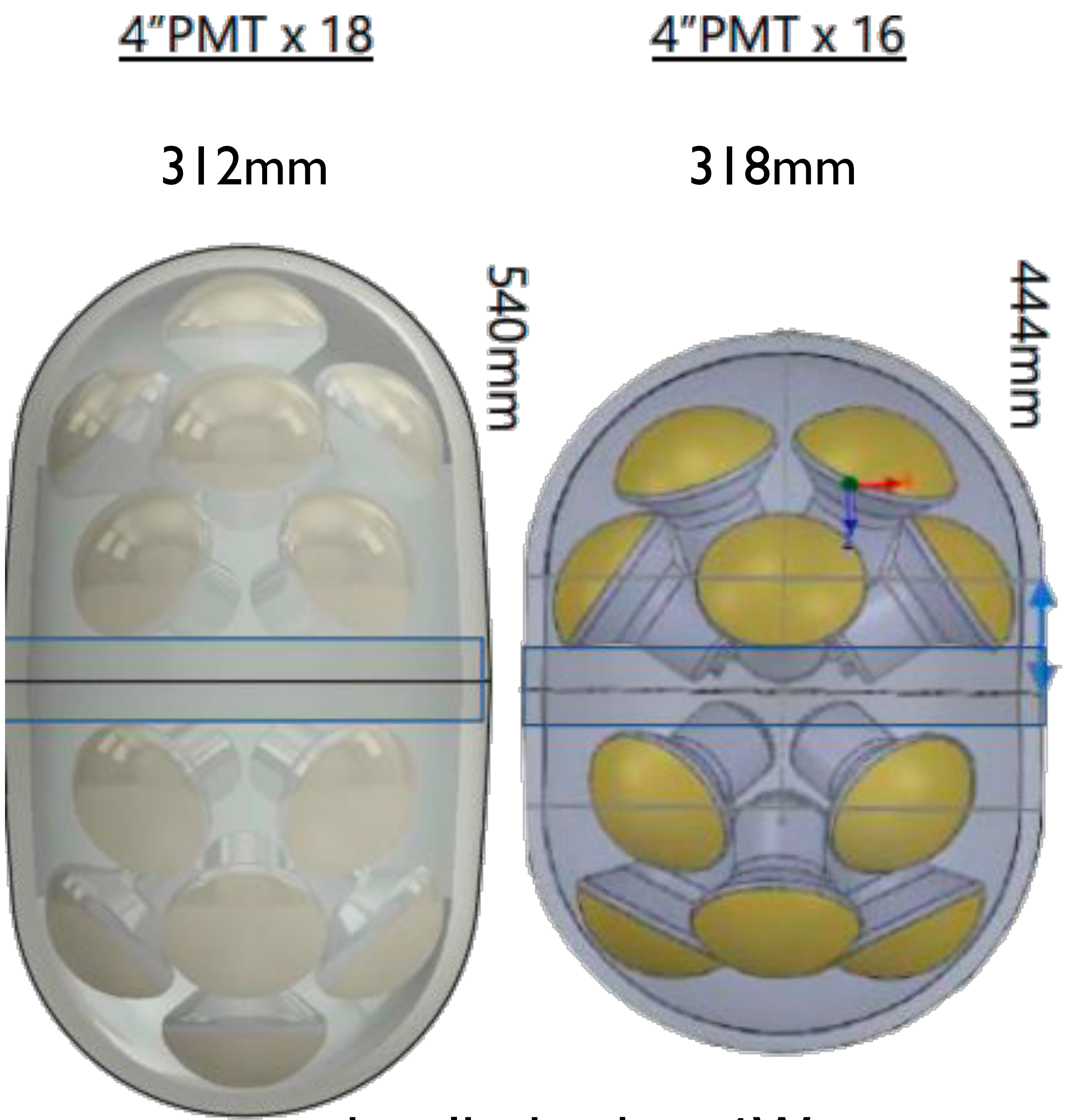
- Photo sensor (PMT) & electronics in a pressure vessel
- 70 MPa during installation (pressure peaks at re-freezing phase)
- Operations temperature from -40C to -20C
- High reliability (DOMs @ IceCube >98% modules operating reliable after more than 10 years of operations)
- Cost saving opportunity: Module diameter reduction can reduce drilling costs and time

Upgrade mDOM (24x3"PMTs)

Upgrade D-Egg (2x8"PMTs)

Long Optical Module (LOM)

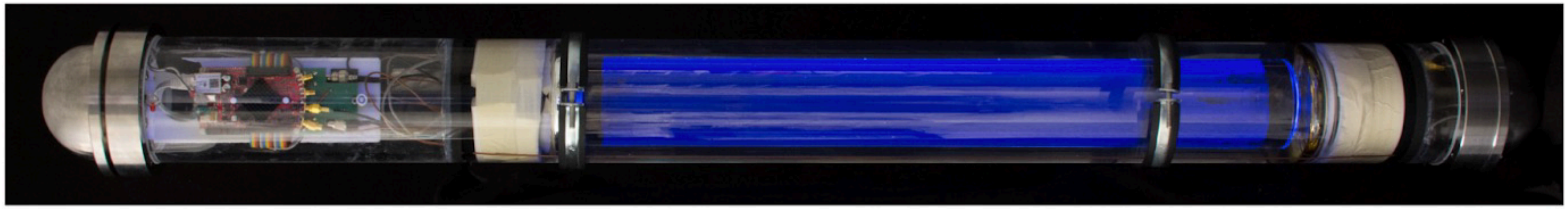
ICRC(2021)1062

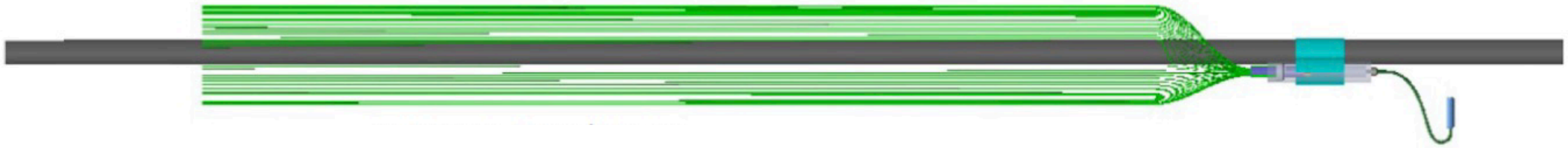


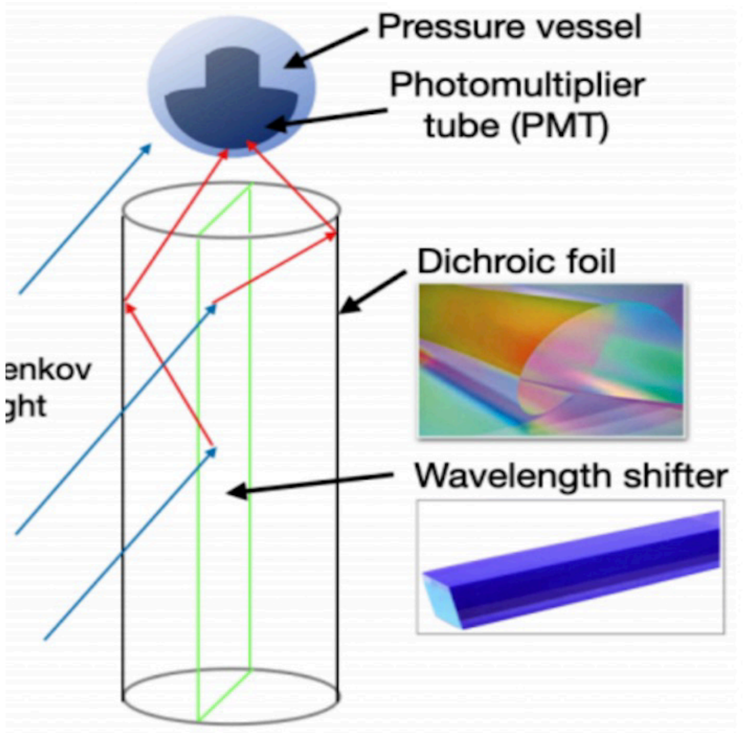
- Power consumption limited to 4W
- Lower digitisation rate of 60 MSPS
- Waveform processing shifted to PMT bases
- Due to Gen2's large string spacing (~240m), a lower ADC rate has only a modest effect on reconstructions

Alternative sensor modules

Alternative photosensor modules could complement array:
Enhance photon collection


WOM


FOM

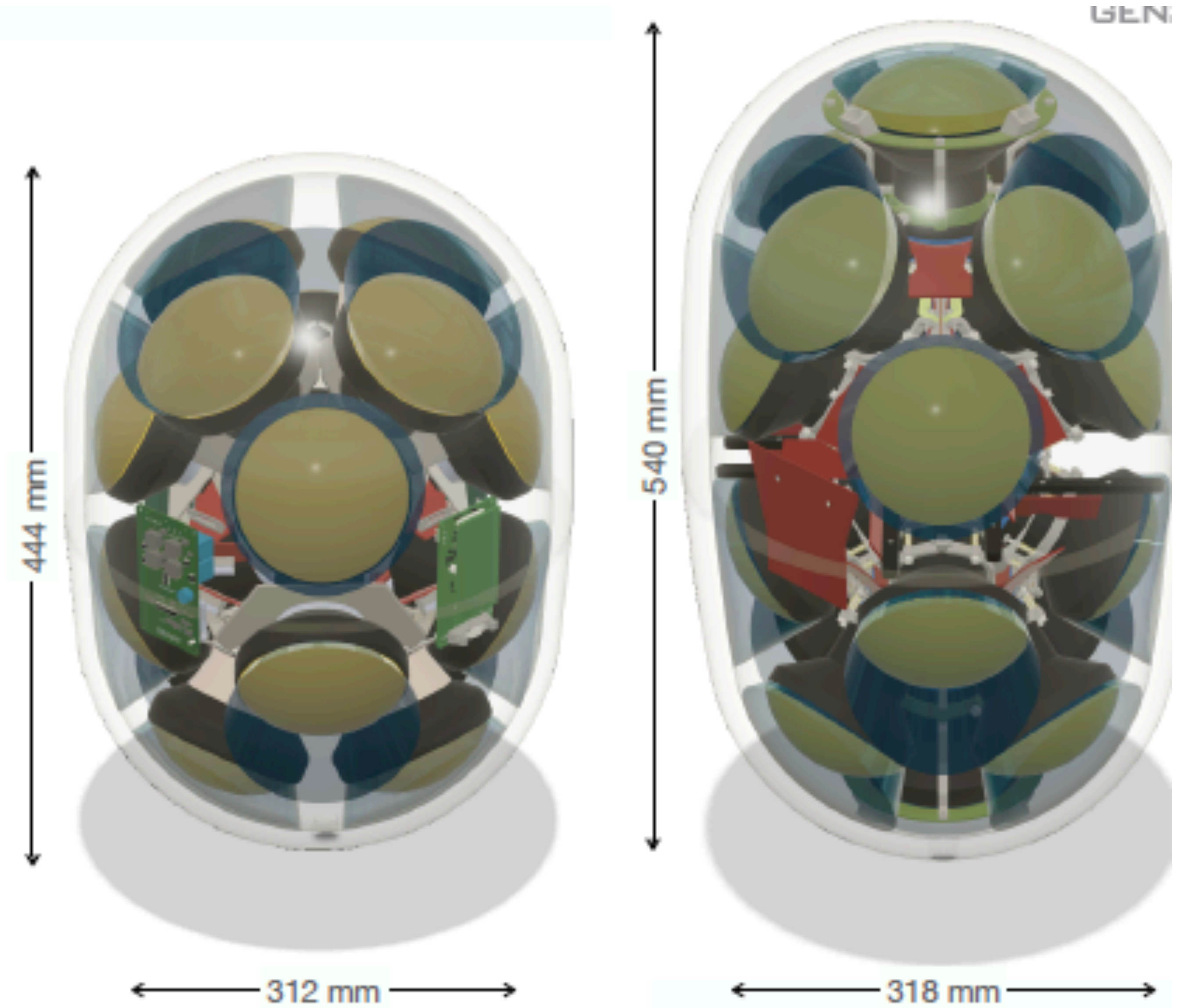


- WOM - Wavelengthshifting Optical Module
  - ICRC2021- PoS(ICRC2021)1038
- FOM - Fiber Optical Module
  - ICRC2021
- Enhanced photon traps
  - ICRC2021 - 10.22323/1.395.1039
  - JINST 2017 10.1088/1748-0221/12/11/P11021

Promising concepts for alternative modules for calorimetry

Gen2 Optical Module Design Candidates

- Two design candidates; 16 and 18 PMT options
  - Custom non-spherical pressure vessels for both options
- 4” PMT is the best pick to maximize effective area
  - Back-to-back layout not feasible with > 4” PMTs
  - (*) Does not exist in the current lineups of PMT vendors
- PMTs are coupled to pressure vessels through “gel pads”
  - Cone shape enhances the effective area
  - Coupling PMTs and pressure vessel optically&mechanically
- Custom electronics designed for Gen2 needs
  - Tuned for high energy array (dynamic range)
  - Low power consumption (infrastructure)
  - In-module data buffering (bandwidth)

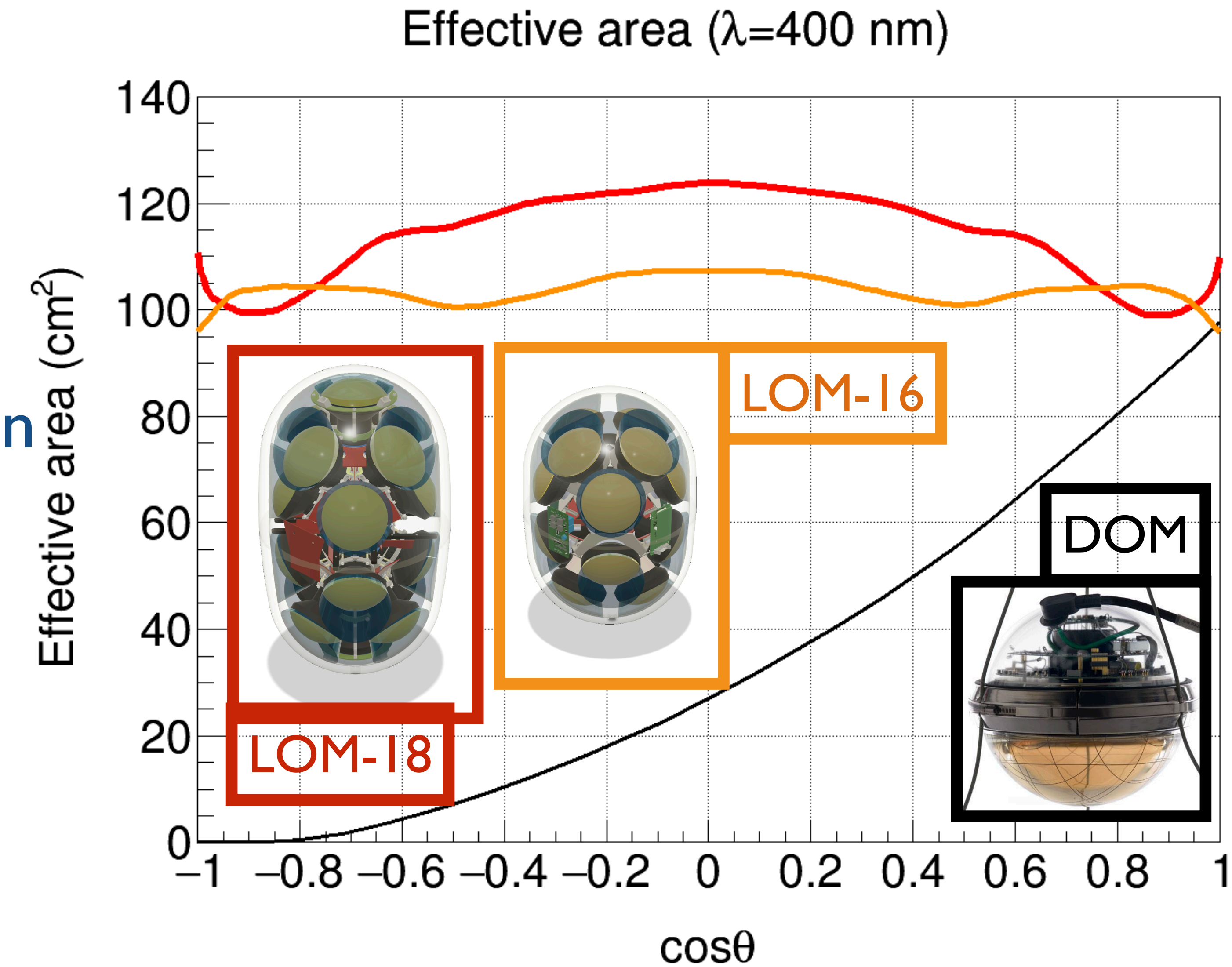


16 PMT option

18 PMT option

Expected Performances

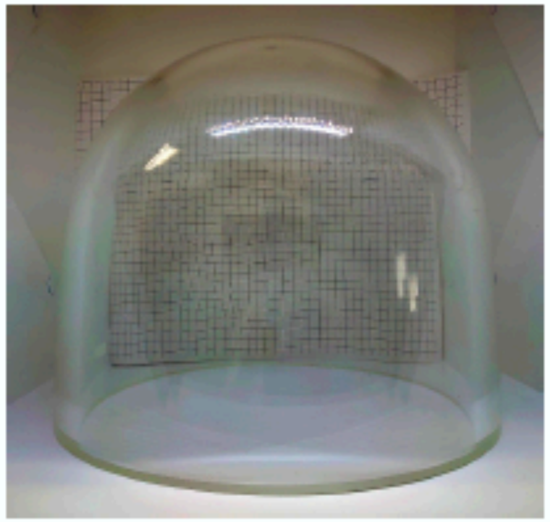
- 16/18 PMT options show 3.1/3.5x better effective areas compared to IceCube DOM
  - Estimated by Geant4-based simulation
  - Measured pressure vessel and gel transparencies, and PMT responses (e.g. photo detection efficiency as a function of photocathode positions) are taken into account
- Great improvements in the horizontal directions
  - Critical considering the 240m inter-string spacing



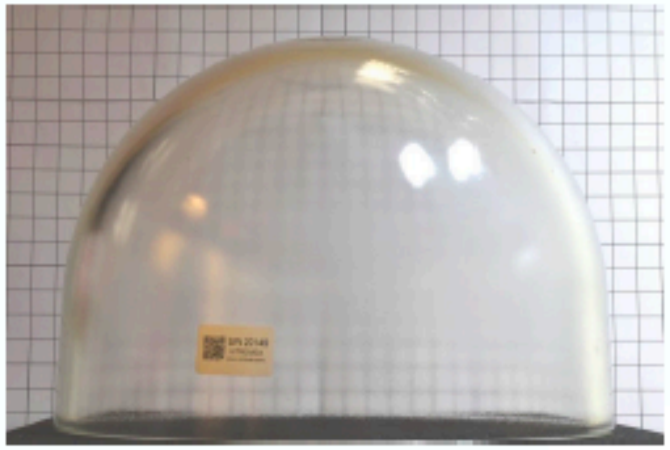
Pressure Vessel

Diameter < 12.5” / 70 MPa rated / high UV transmittance / radioactivity as low as possible

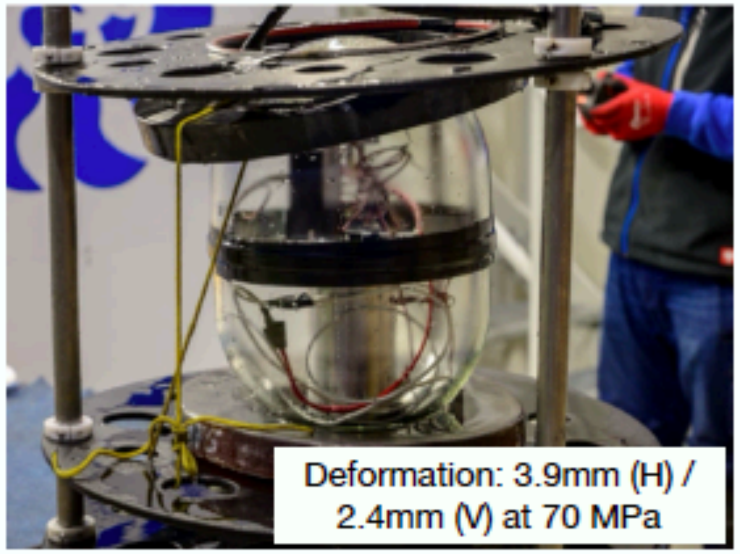
- Two vendors: Okamoto (Japan) & Nautilus (Germany)
  - Since IceCube Upgrade
  - Keep-multiple-vendors strategy for essential components in Gen2
- Improved optical performances
  - >50% transmittance at 320 nm
  - Reduced K^{40}: 0.74 Bq/kg (Okamoto)
- Pressure rating have been proved with prototypes
- New harness design studies to minimize PMT-shadowing effect



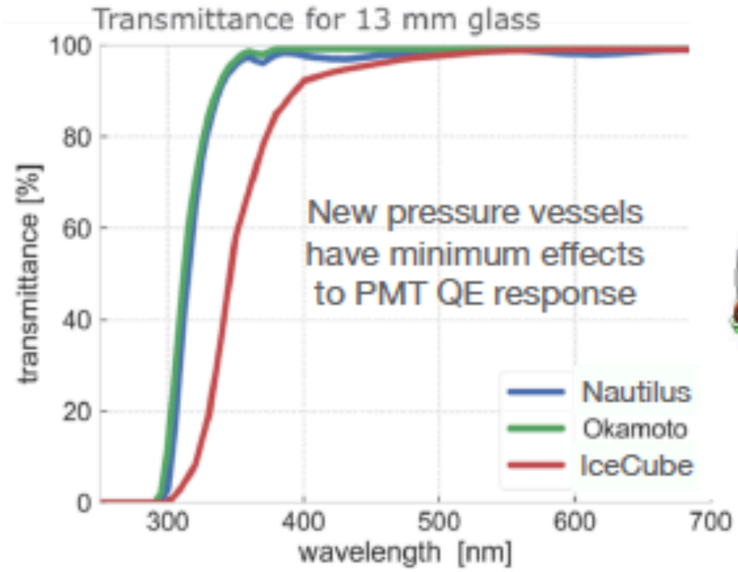
for 18 PMT option



for 16 PMT option



Deformation: 3.9mm (H) / 2.4mm (V) at 70 MPa



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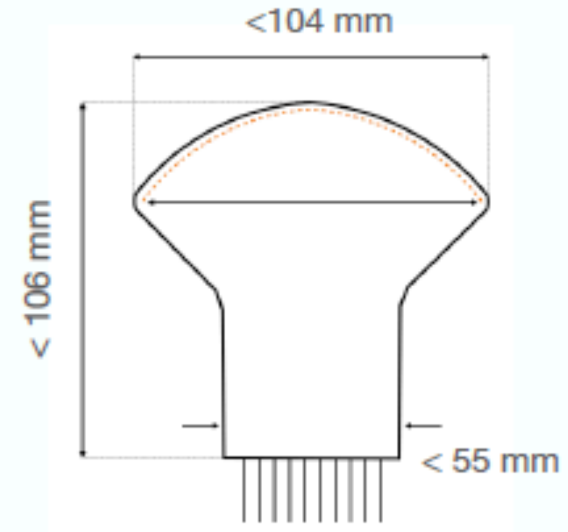
4 inch PMT

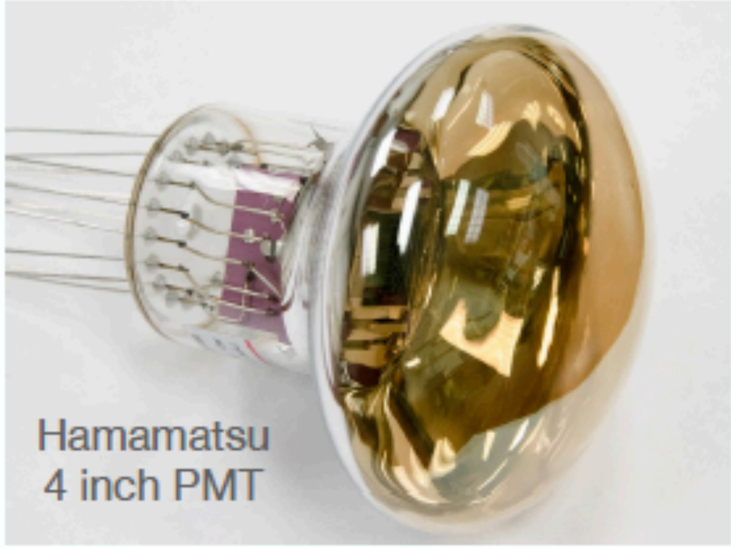
As short as possible accepting minimum compromise in performance

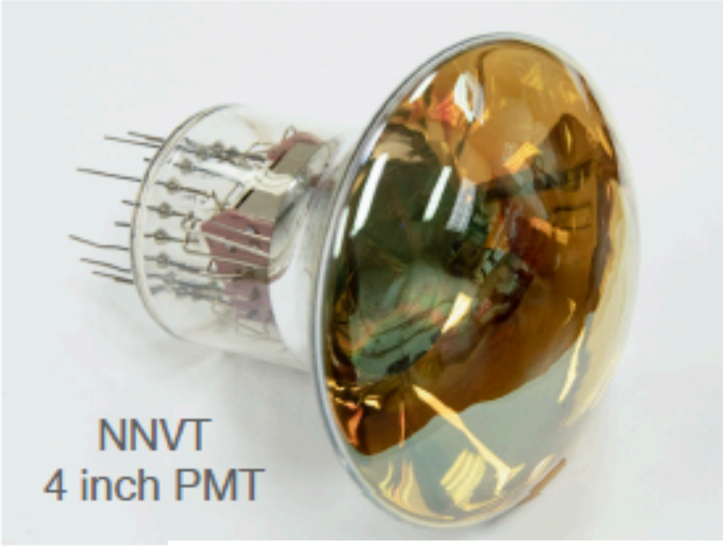
- Two vendors: Hamamatsu and North Night Vision Technology (NNVT)
  - Newly-designed 4inch box&line style dynode PMTs
  - NNVT has produced 15,000pcs 20" MCP-PMTs for JUNO
  - Keep multiple vendors for for Gen2!
- Very compact, 106mm (abs max.) long
  - (Potential) Caveat is moderate cathode uniformity (transit time and/or collection efficiency, for example)
- Confirmed prototypes from both vendors meet the requirements
  - No public plots/numbers yet
  - Development/Improvement still ongoing



Target numbers

Parameter	Target value
Gain	5e6 @ <1500V
Transit Time Spread	< 8ns (FWHM)
Peak/Valley	>2
QE	>25% @400nm
Pre/late/after pulses	Less than 1/5/10%





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PMT Optical Coupling

Silicone gel optically couples PMTs and pressure vessel

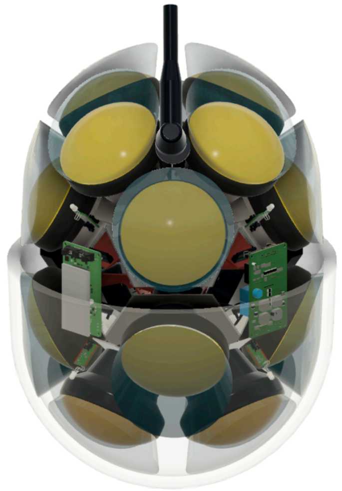
- ShinEtsu X3547-HE developed for IceCube-Upgrade
- High UV transmittance & good performance at low temp

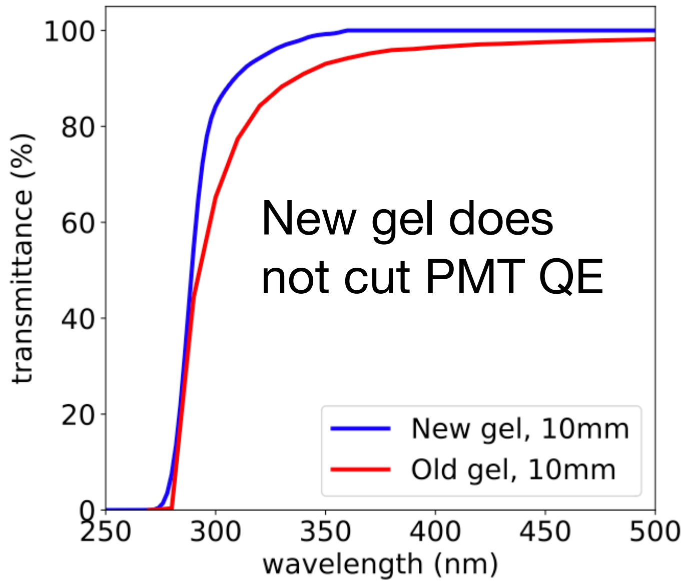
Investigating "gel pad" approach

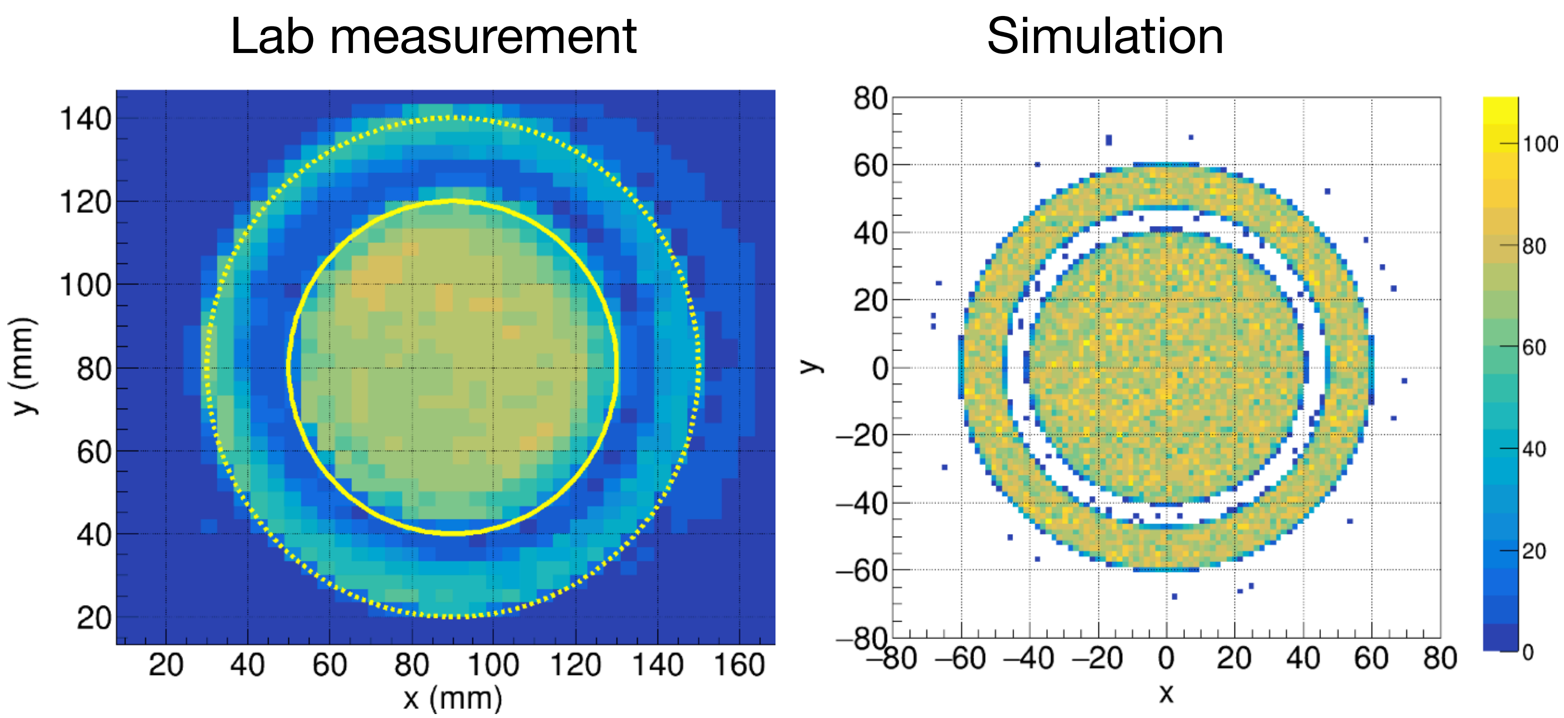
- Pre-casted gel on a PMT unlike conventional in-place potting styles used in other Optical Modules (NIM A 958 (2020))
- Alternative idea to avoid expensive (3D-printed) support structures

Gel pad works as a photon collector, +65% effective area confirmed compared to a bare PMT

- No reflector, but use total reflection at the cone surface
- Lab measurement showed a good agreement with the simulation prediction







Gap is an artifact due to the prototype gel pad shape

In-Module Electronics

In-Module Electronics

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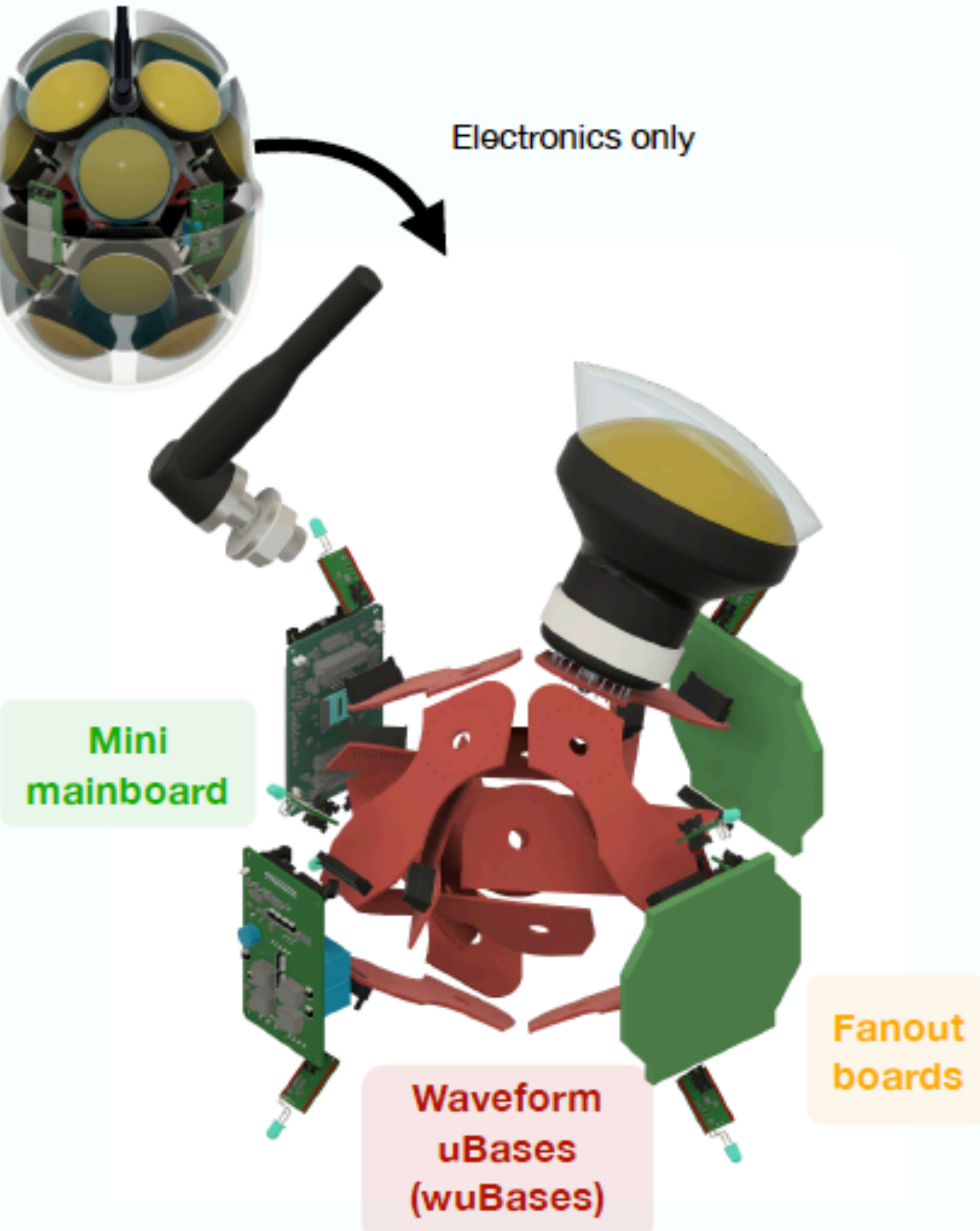

Limited space, Low power consumption,
Dynamic range from SPE to highest energy neutrino events

- Combination of specialized boards instead of a "big&central" board
  - Good match with the limited available space & No need for big / resource-expensive FPGAs
  - Re-purposing existing solutions from IceCube Upgrade
- Features
  - Generate/regulate HV to each PMT
  - Digitization of signal waveforms from each PMT
  - Low level signal processing

  → **Waveform uBases (wuBases)**
  - Command and data I/O multiplexing & data buffering → **Fanout boards**
  - Communication with surface computers for high level triggering and processing

  → **Mini mainboard**

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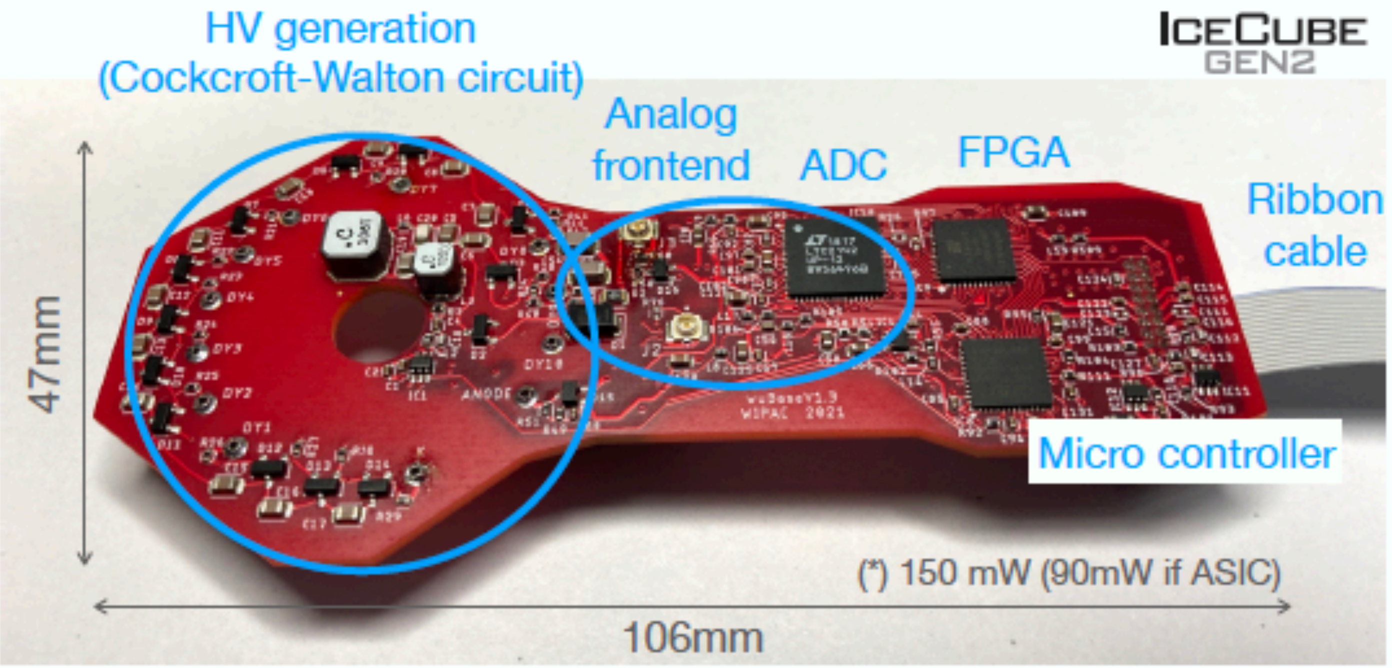
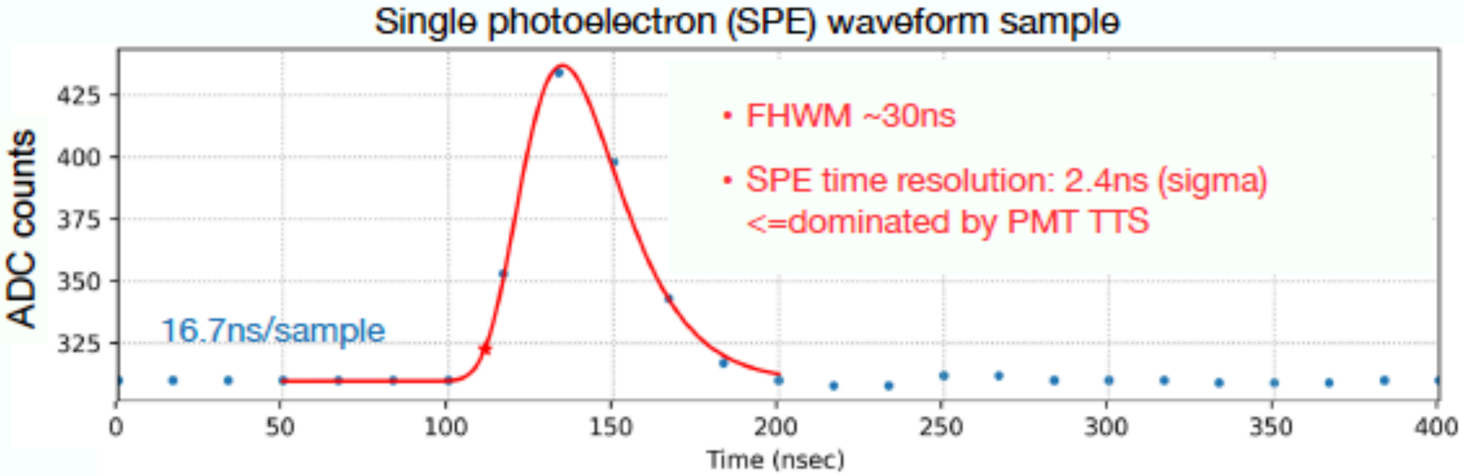
Waveform MicroBase

- Add DAQ feature to the existing custom HV base
  - HV base developed for the IceCube-Upgrade project
    - MicroBase (ref: PoS(ICRC2021) 1070)
  - Ribbon cable for controlling and data transfer
- DAQ functionalities
  - Continuous digitizing with 2-channel 12 bit ADC at 60MSPS and captured in a low-power consumption FPGA
  - Record Anode (high gain) and 8th Dynode (low gain) signals
  - Microcontroller manages control and regulation of HV, and buffering and low-level processing of digital waveform data





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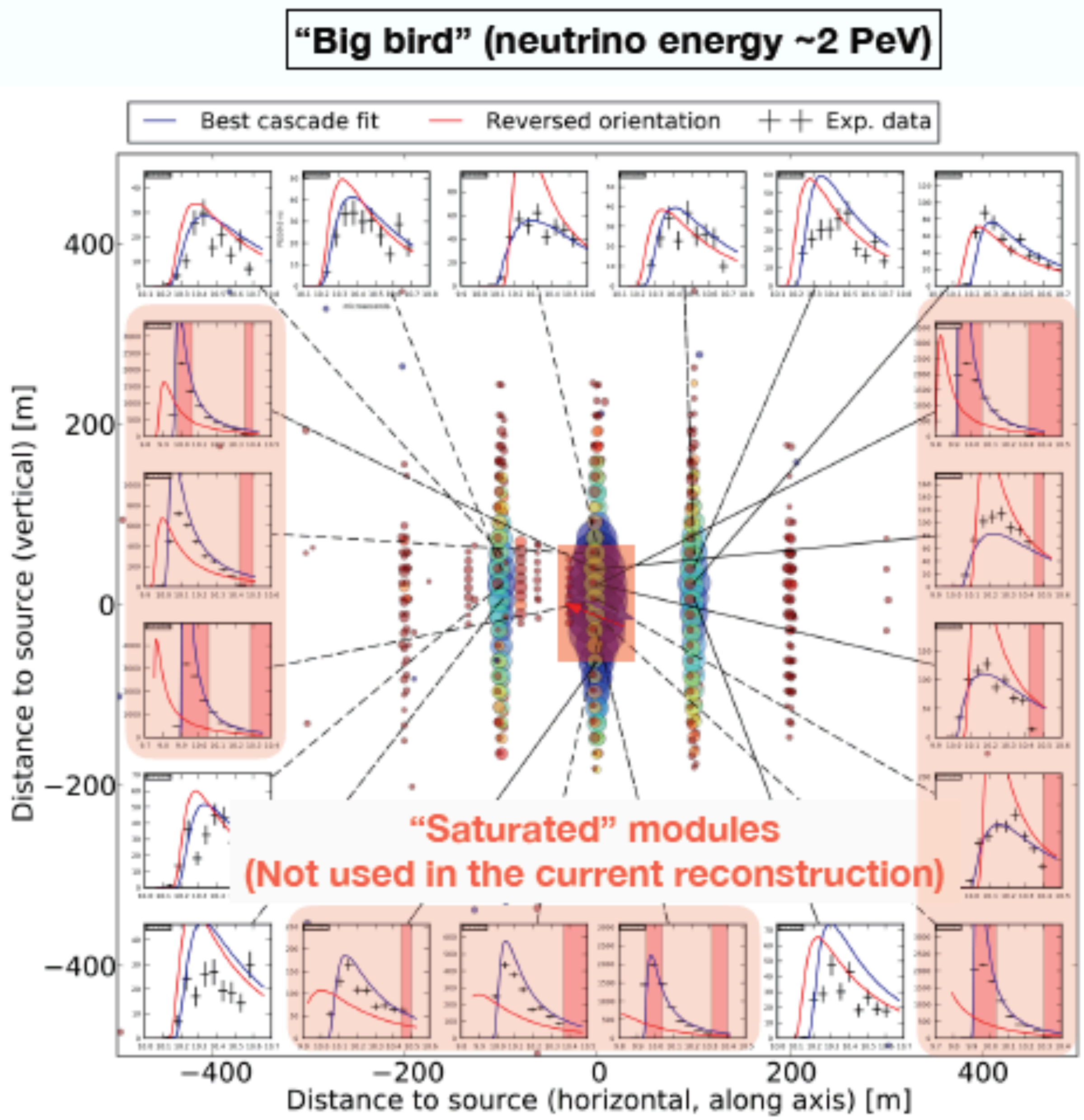
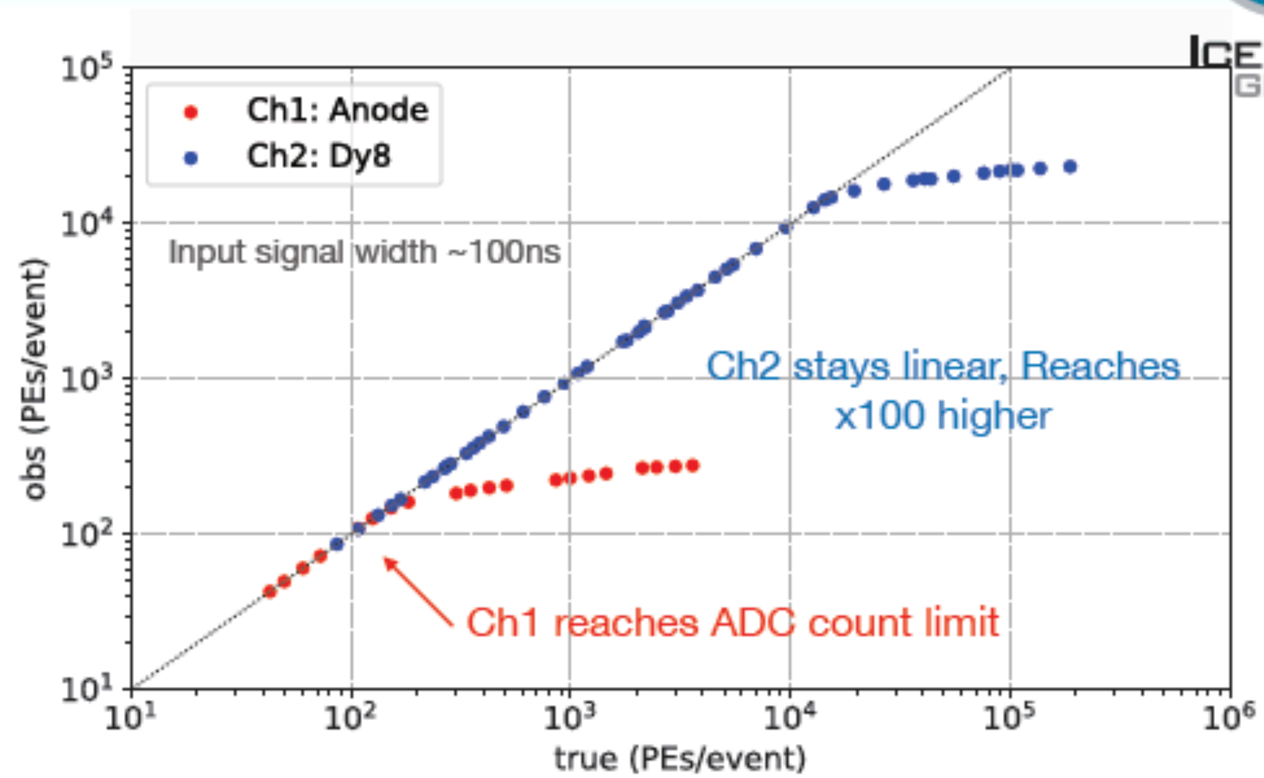
Specialized for high energy events

Specialized for high energy events





- Significant improvement with Anode & 8th dynode readout with 12 bit ADCs
  - IceCube DOM's main ADC: 3ch (all see anode, different gains), 10bit
- Confirmed dynamic range from SPE to 10,000 PEs/PMT
  - Response remains linear for even nearby PeV-class neutrino events
  - Improvement in both energy and angular reconstruction expected

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ASICs for multi-PMT DOMs for Neutrino Telescopes like IceCube Gen2

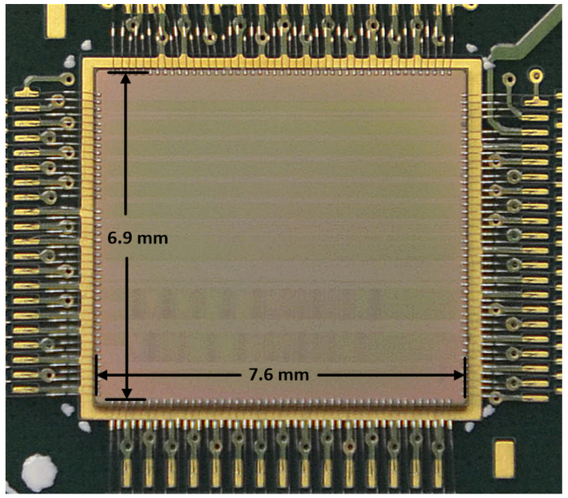
Spencer Klein, LBNL & UC Berkeley

Multi-PMT optical modules

Benefits and costs of a digitization ASIC

Role in IceCube

for IceCube-Gen2 - ASIC for the PMT signal readout (100Msps, 12 bit, 2 channels)

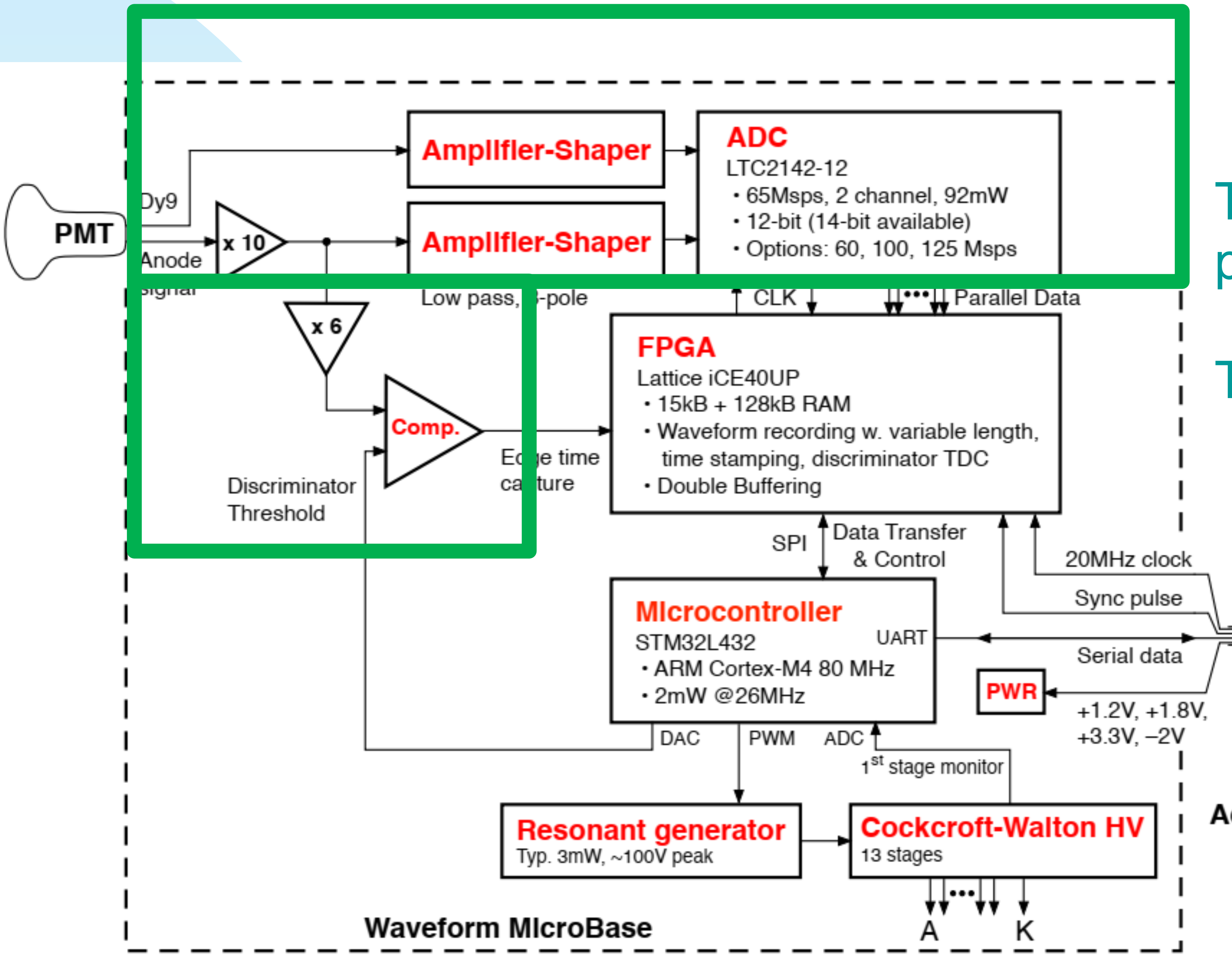


mDOM readouts

- Modern/next generation optical modules for neutrino telescopes have many (10-25) smaller photomultipliers, each of which needs to be individually read out
- A typical readout system includes an analog preamplifier/shaper, trigger (typically at the 1 spe level) plus a fast analog-to-digital converter, plus data compression.
  - A DAQ system mounted on the PMT base is optimal to simplify cabling, etc
- A solution based on a single ASIC will save money (compared to a discrete solution), power, and volume in the DOM
- A large next-generation array like IceCube Gen2 (10,000 optical modules) will have ~150,000 channels. At this volume, the cost of IC design are more than amortized over the production run, and an ASIC system is also significantly cheaper.

IceCube Gen2 as an example

- The proposed Gen2 DAQ architecture:



The blocks in green are part of the proposed ASIC

This saves
power
cost
volume

Block diagram from Chris Wendt

Power savings

- Commercial ADCs generally have very high analog fidelity
  - Full-power bandwidth (750 MHz for LTC2142-12), nonlinearity, SFDR (spurious-free dynamic range) etc.
- By relaxing some AC design parameters that are not important for neutrino telescopes, ADC power consumption can be significantly lowered
- Can also use a lower power process (65 nm)
- Can save power by only transmitting non-zero (with a low-threshold trigger) data off-chip.
- In the IceCube case, the expected power reduction is from 107 mW/channel for the discrete case to 22 mW (for a baseline design) to 76 mW (for a fallback design)
- Nothing in any of these designs is pushing the state-of-the-art

Design proposal from the LBNL IC Design group:
Carl Grace and Katerina Papadopoulou

Cost savings

- The estimated costs are
  - $35/channel for the discrete solution ($5.3M for 150K channels)
    - The ADC dominates the cost
  - $12/channel for an ASIC solution ($1.8M for 150K channels)
- The ASIC solution costs include about $1.2 M for the chip design, which dominates the cost
- This cost comparison does not account for the money saved in the power supplies and transmission system, or for the savings in the cost of the power.
- At the South Pole, the power cost is substantial, and there are limits on how much power is available. A lower per-channel power could allow us to build more channels.

ASIC Conclusions

- Next-generation neutrino telescopes will have very high PMT counts
  - 150,000 PMTs for IceCube
- At these large volumes, custom ASIC solutions save money and power
  - This makes sense no matter where the system is deployed. For a system to be deployed in a remote environment, the advantages are multiplied.

Conclusions

Conclusions

- The last decade has seen a transformative progress in astroparticle physics, observation of high-energy astrophysical neutrino flux, multi-messenger observation of astrophysical neutrino source, …
- IceCube continues to be the primary science driver in neutrino astroparticle physics, but astrophysical sample is significantly statistics limited at highest energies
- Gen2 is building on the highly successful technology utilized for IceCube
  - Fundamental technology ready for Gen2, however investment in R&D can reduce costs and further optimize the detector
- Gen2 optical moduels, first integration test planned early next year. Planning to deploy prototype modules at the South Pole as a part of IceCube-Upgrade in 2025/26
- Technological advancements in the optical array design
  - Optical sensor module with 16/18 PMTs - 3 x larger sensitivity of IceCube sensor, directional 4 π sensitivity,
  - New PMT of 4 inch size with short stem in development by two manufacturers
  - Optimized trigger and data acquisition scheme to allow factor 10 reduction in bandwidth, factor of 3 reduction in cables
  - More efficient drill and energy saving technology, including solar power
  - Integrated radio+scintillator air shower array on the footprint of the optical array
- RD opportunities
  - ASIC for the PMT signal readout (100Msps, 12 bit, 2 channels) — A significant cost and power saving could be realized

Backup

Design progress

- Design progress
  - Optimized trigger and data acquisition scheme to allow factor 10 reduction in bandwidth
  - Factor of 3 reduction in cables