



ICECUBE

# IceCube Upgrade and IceCube-Gen2

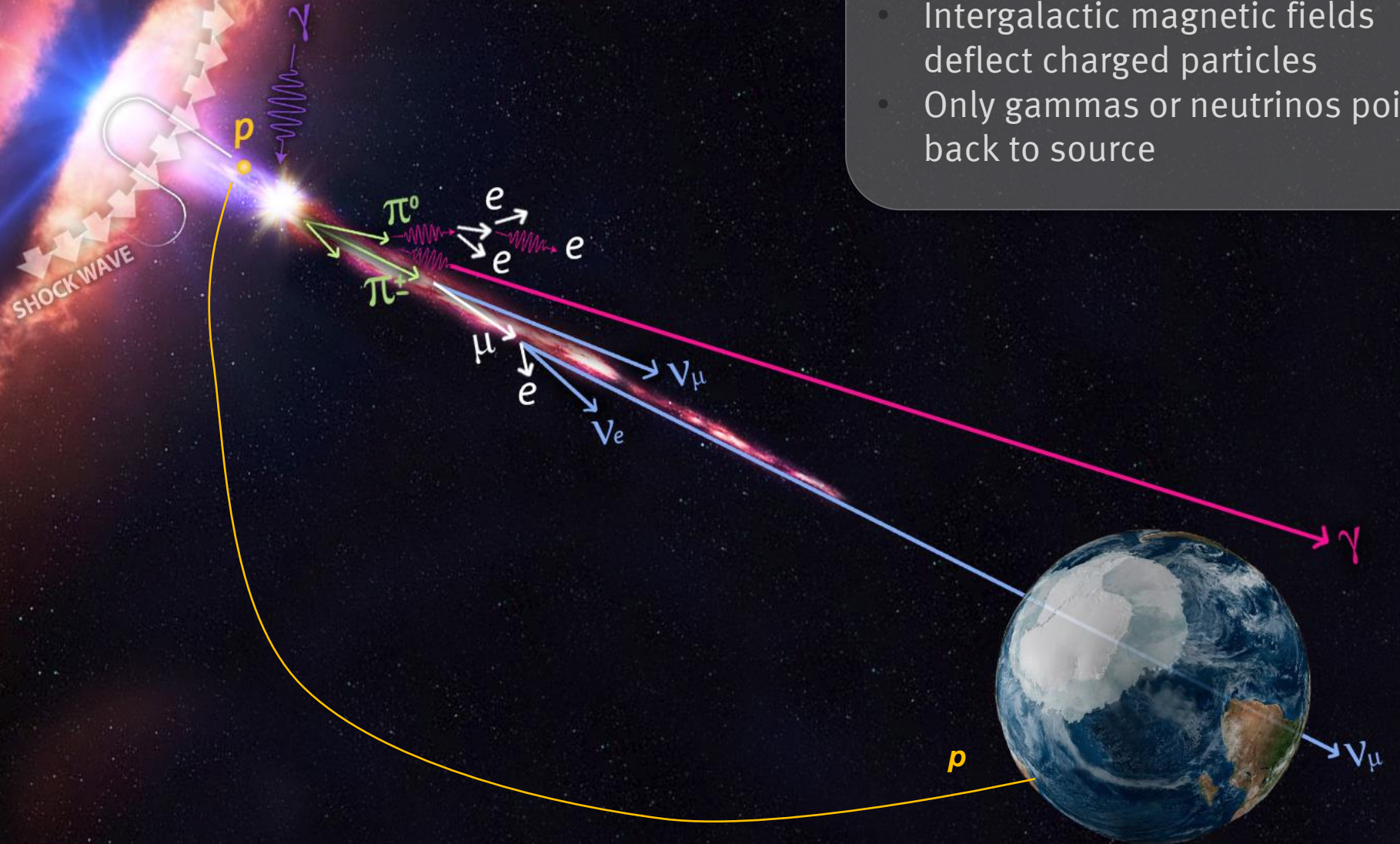
## The future of neutrino astronomy at the South Pole

Martin Unland Elorrieta  
HEP2023, Valparaíso, Chile  
12.01.2023



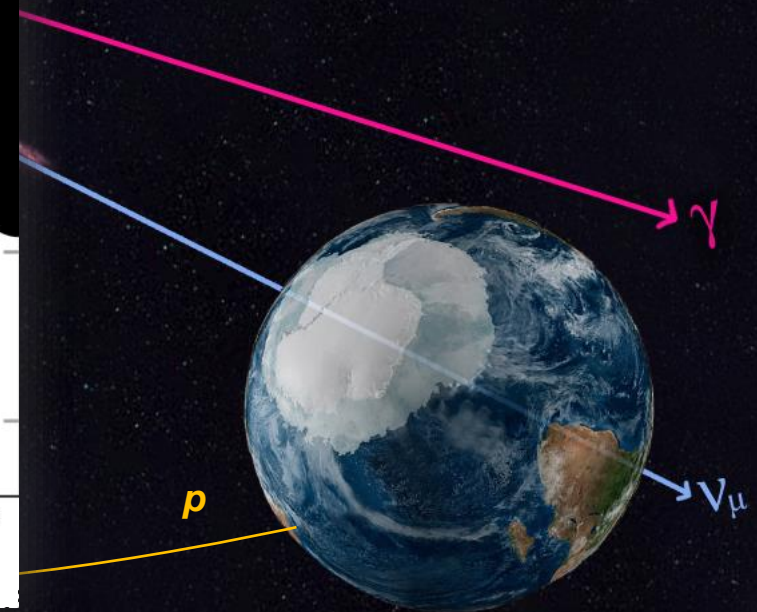
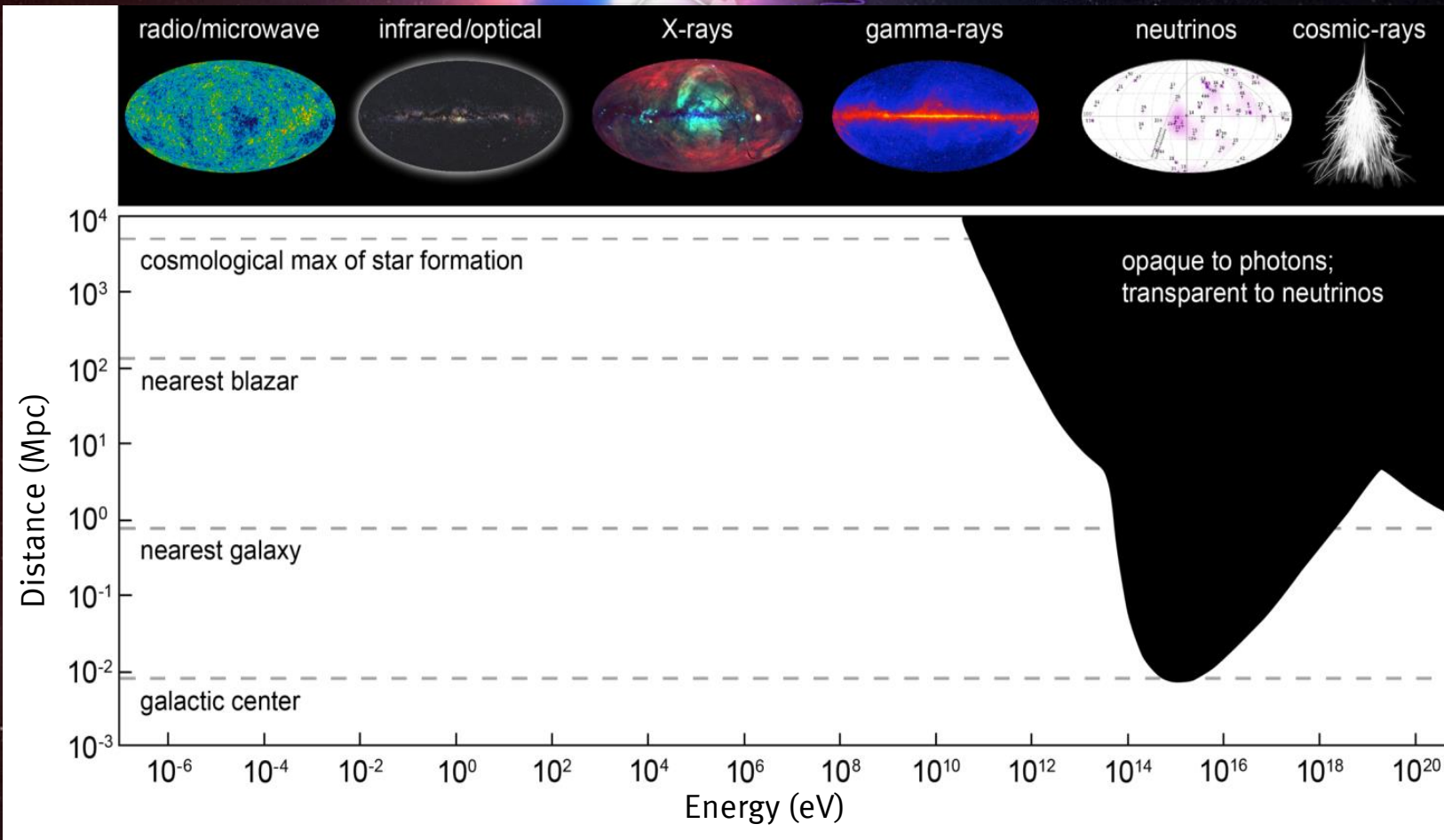
# Why neutrinos...?

- Cosmic ray sources produce various messengers
- Intergalactic magnetic fields deflect charged particles
- Only gammas or neutrinos point back to source



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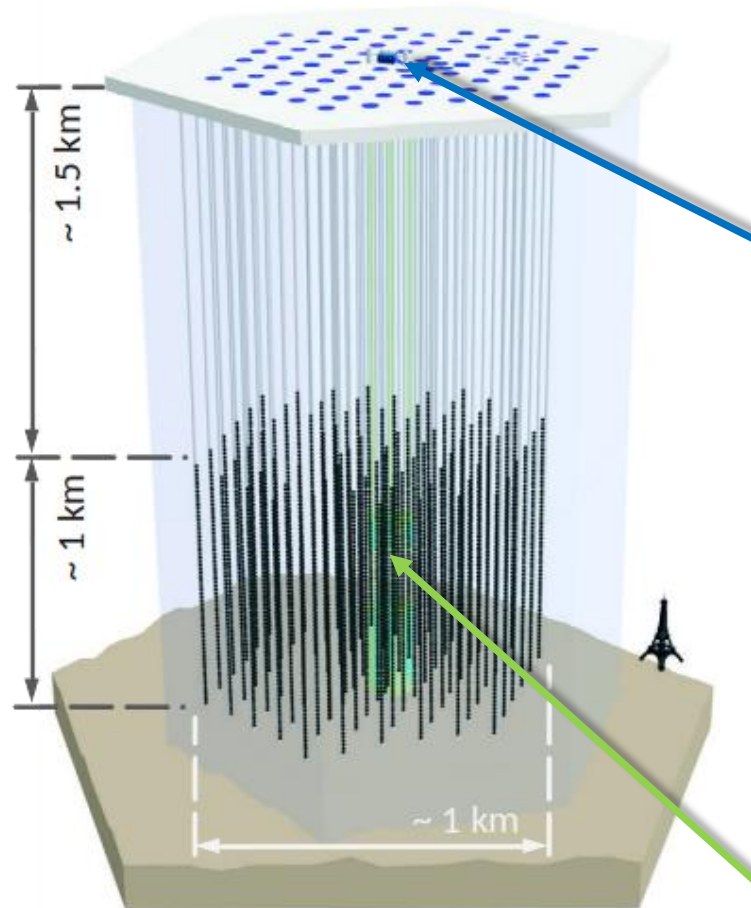
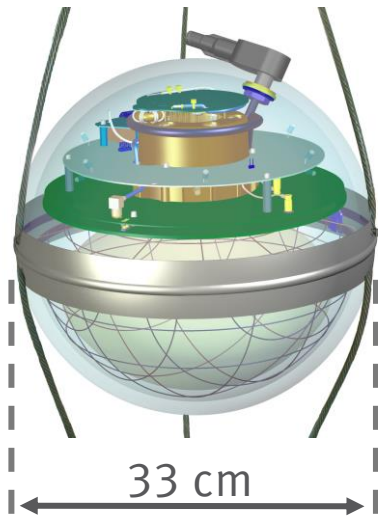
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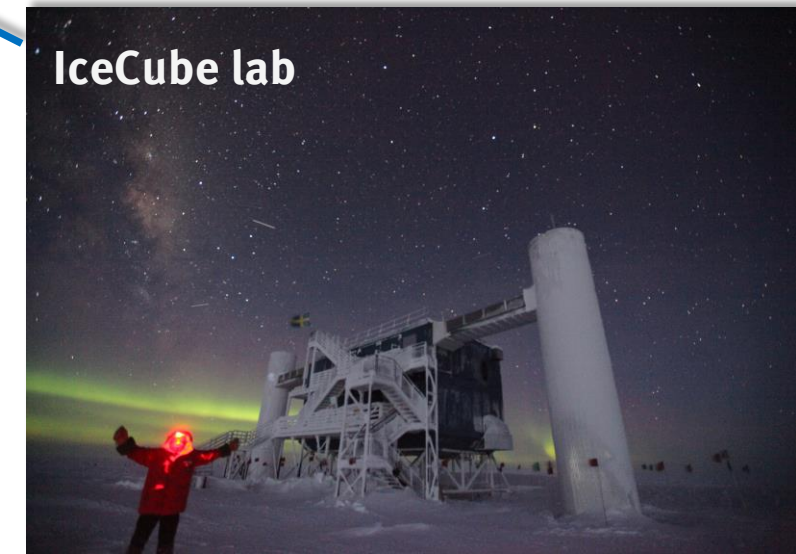
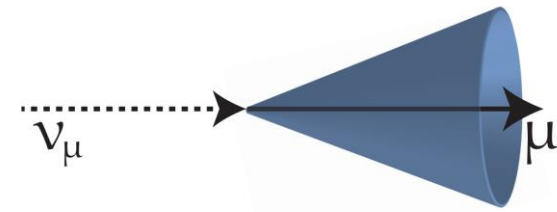
# IceCube Neutrino Observatory

- 1 km<sup>3</sup> of instrumented volume
- 5160 optical modules
- Optimised for energies from 100 GeV to PeV

## Digital Optical Module (DOM)



[IceCube collaboration]



[IceCube collaboration]

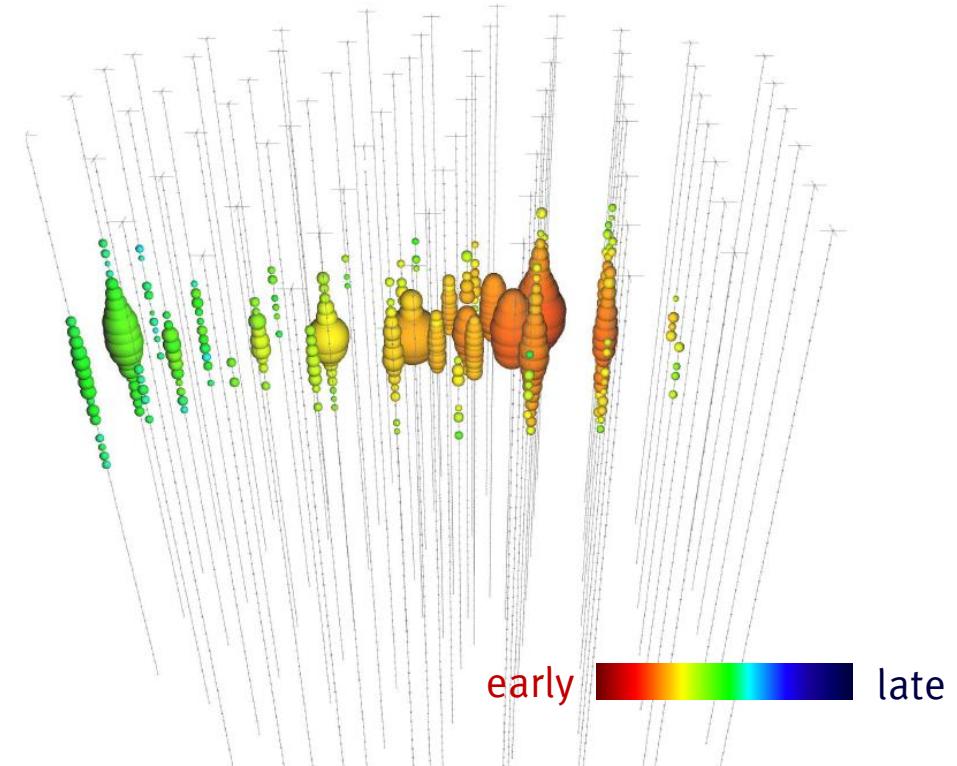
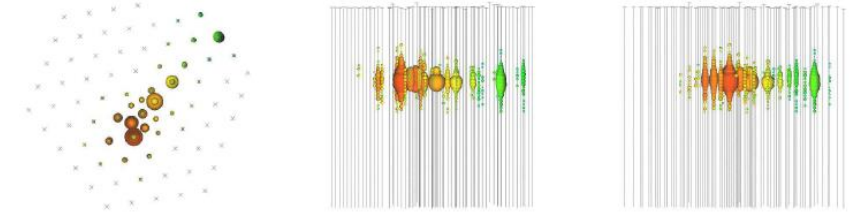
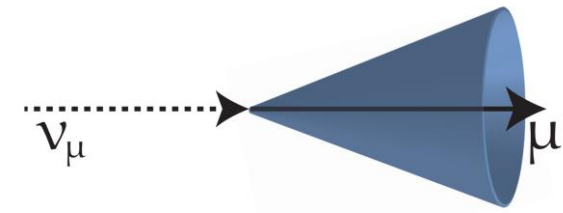
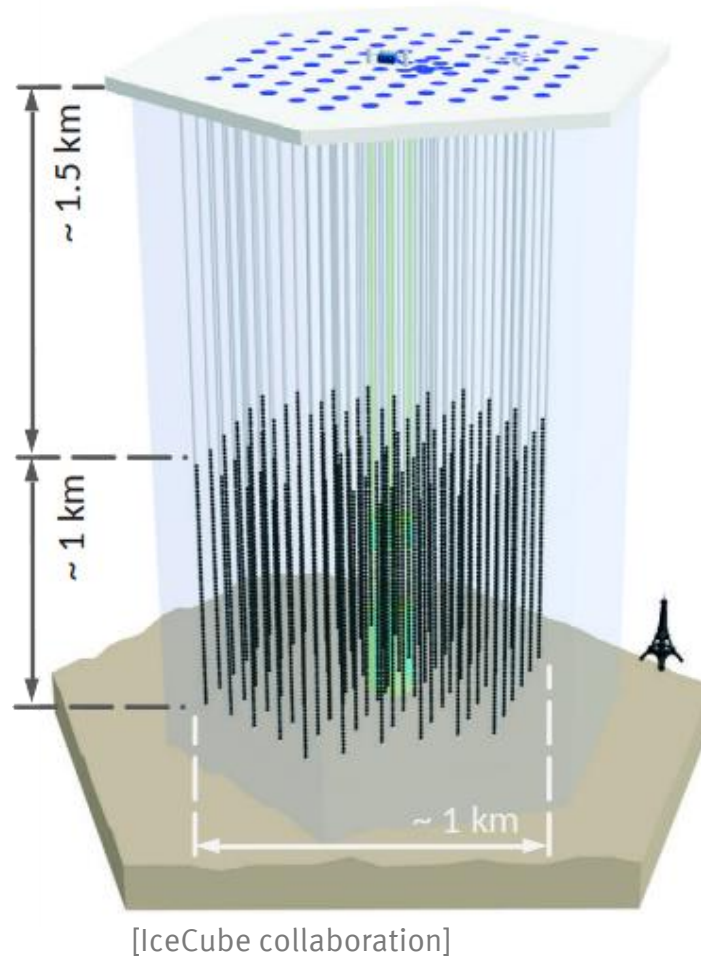
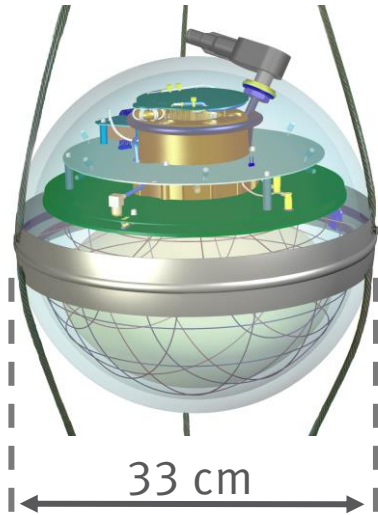
## DeepCore

- Denser array composed of 8 strings
- Optimised for energies from 10 GeV to 100 GeV

# IceCube Neutrino Observatory

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## Digital Optical Module (DOM)



# Evidence for astronomical neutrino sources: TXS 0506+056 (blazar)

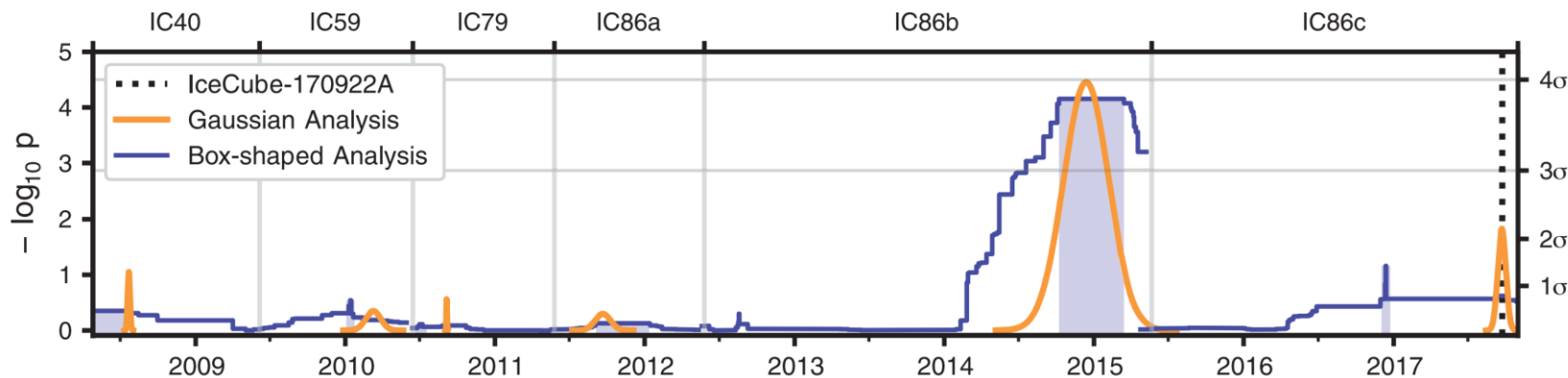
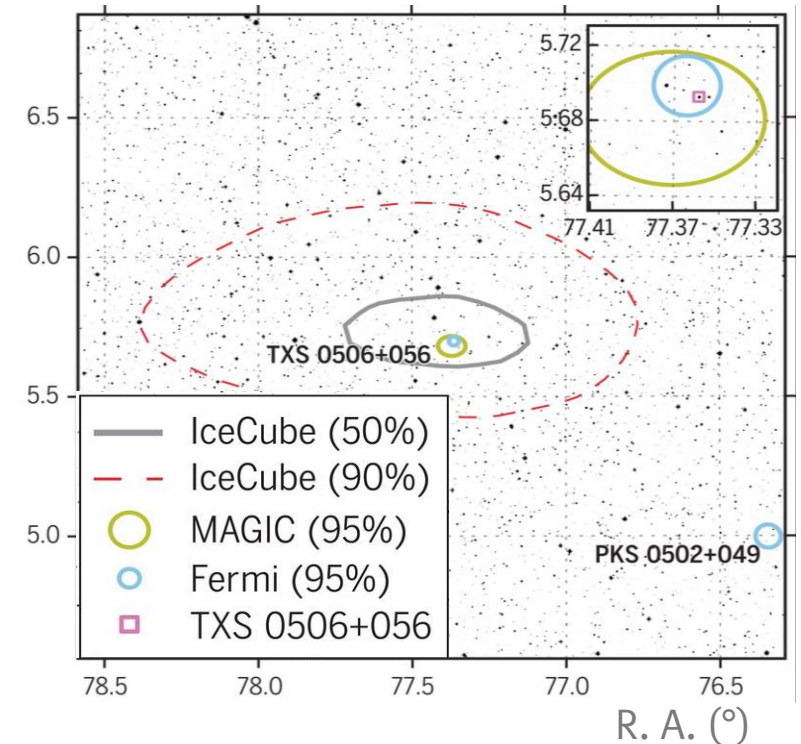
## Multimessenger event 2017:

- 22 Sept 2017 IceCube sent high energy neutrino alert
- Follow-up by 23 observatories with detections across electromagnetic spectrum
- Archival IceCube data showed excess of 13  $\nu$  from TXS 0506+056 clustered in time
- Evidence ( $3.5\sigma$ ) for first astronomical  $\nu$ -source since SN 1987A!

[[Science 361 \(2018\) eaat1378](#)]

[[Science 361 \(2018\) aat2890](#)]

Declination(°)

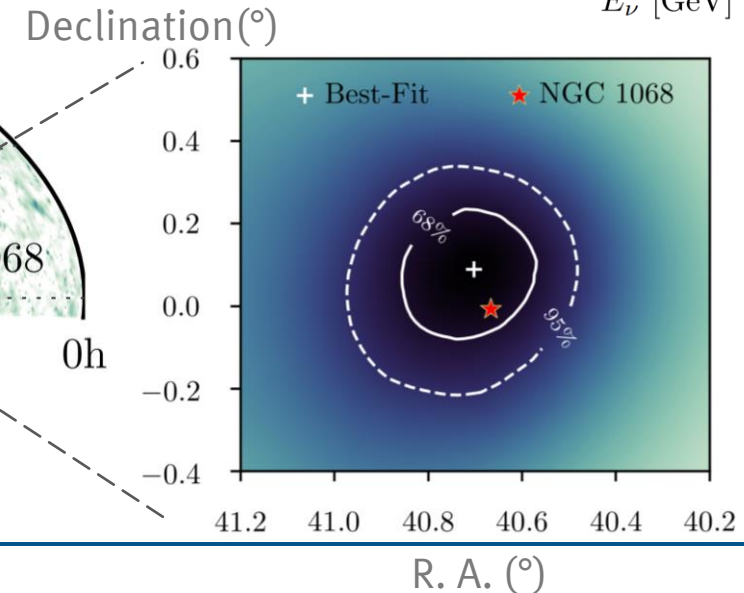
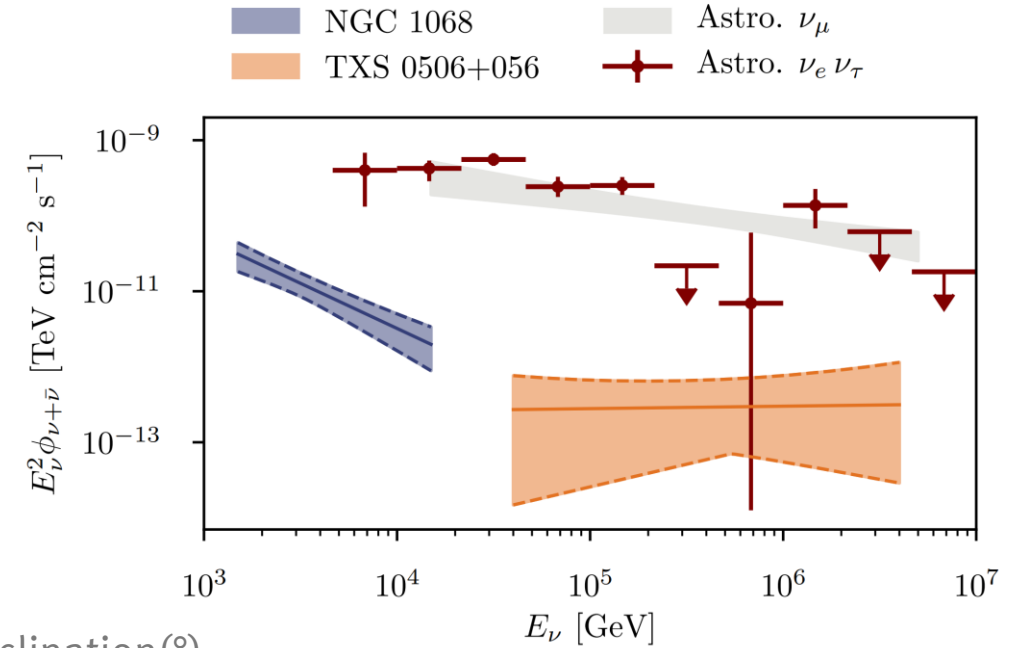
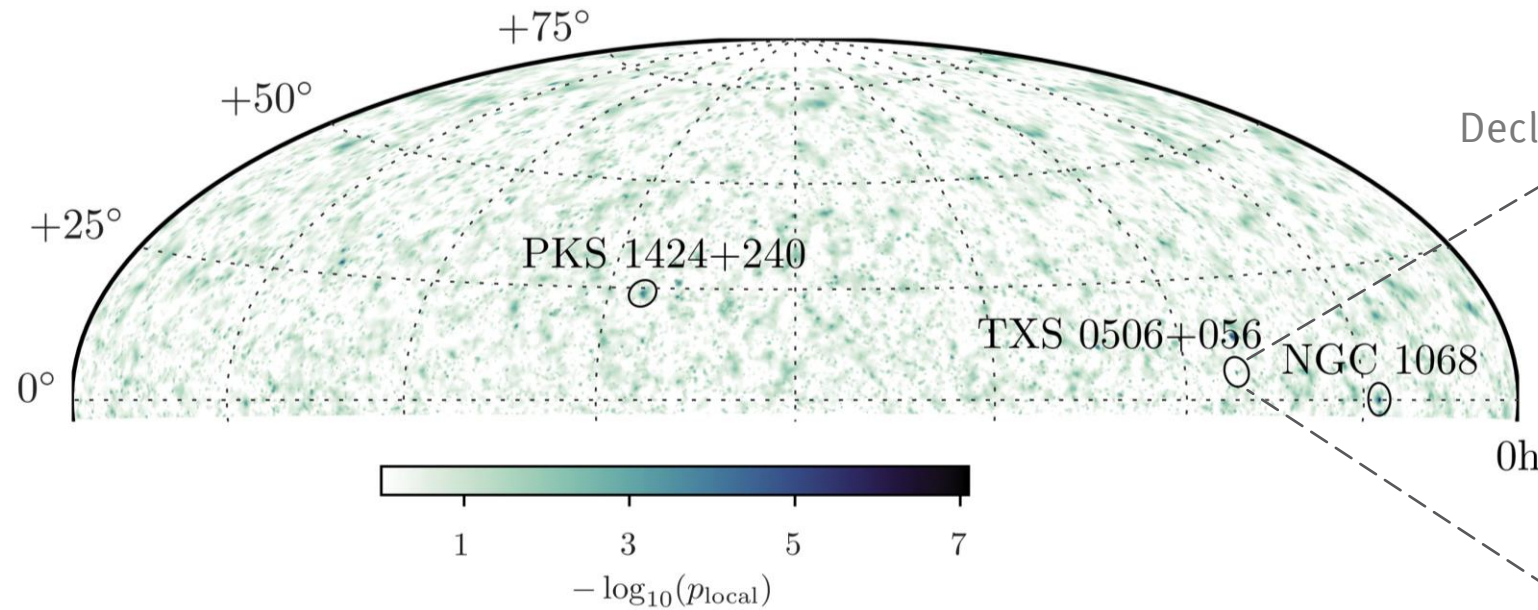


# Evidence for astronomical neutrino sources: NGC 1068

## Most significant point source NGC 1068:

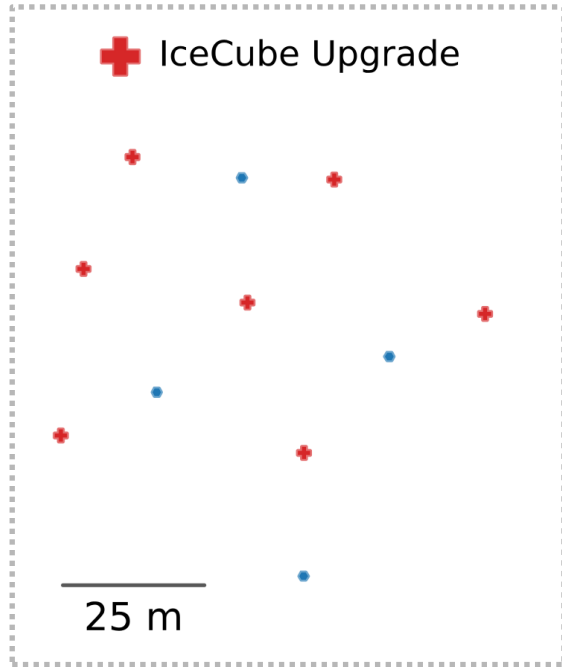
- 79  $\nu_\mu$  in  $\sim 9$  years, significance  $4.2\sigma$
- NGC 1068 and TXS 0506+056  $< 1\%$  of total  $\nu$ -flux
- AGNs may cause significant fraction of  $\nu$ -flux
- Evidence for at least two populations of  $\nu$ -sources

[Science 378 (2022) abg3395]

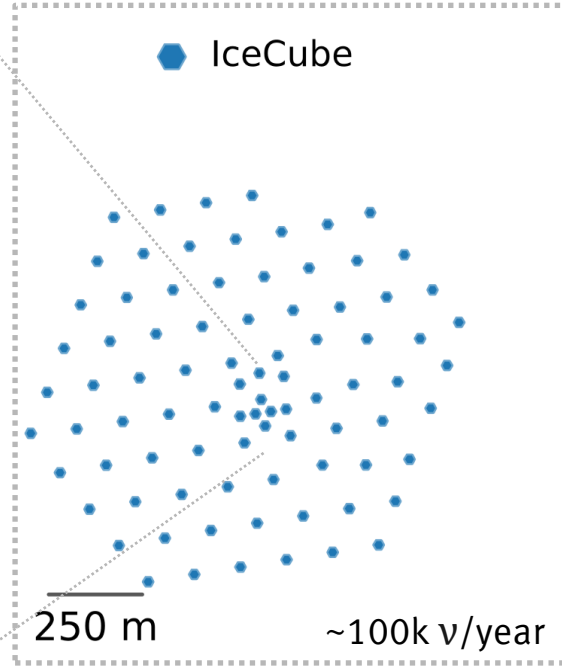


# Towards IceCube-Gen2

Summer 2025-2026

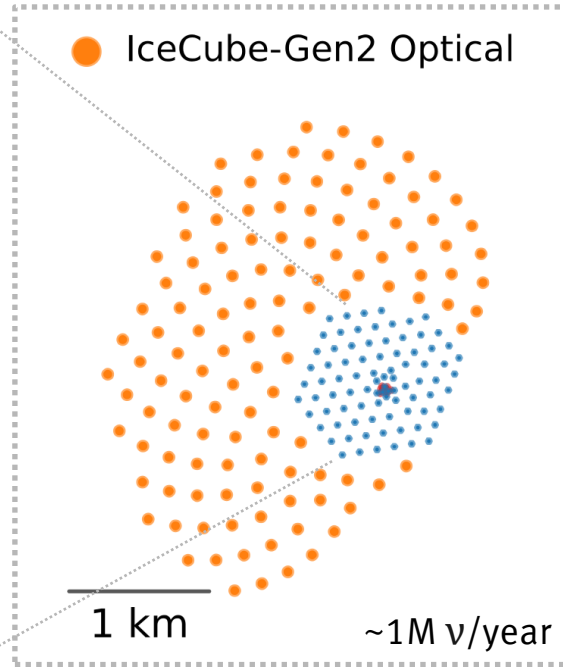


IceCube

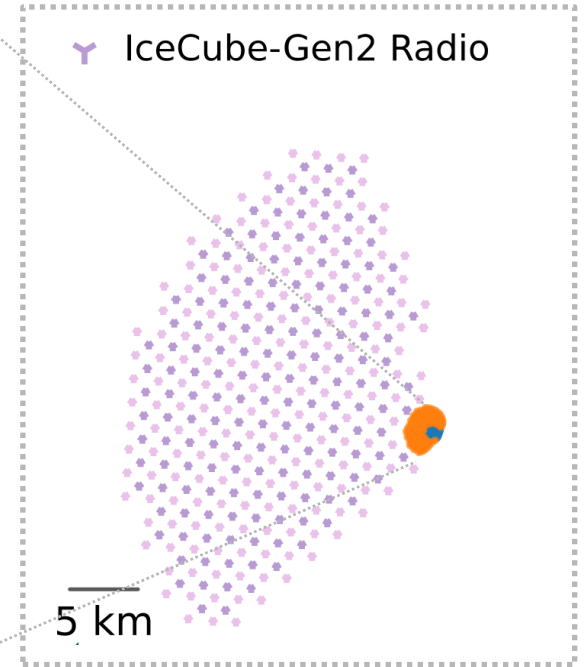


Starts 2027, completion 2035

IceCube-Gen2 Optical



IceCube-Gen2 Radio



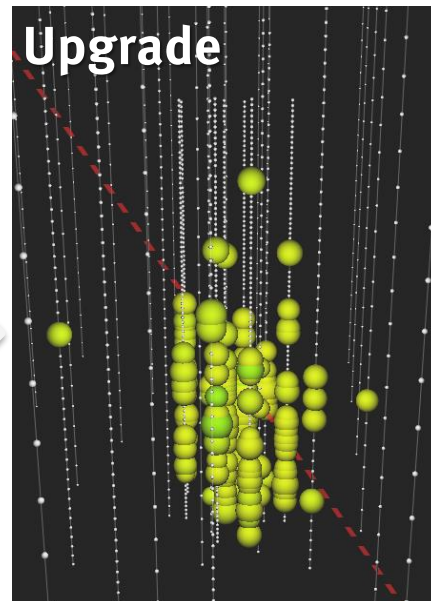
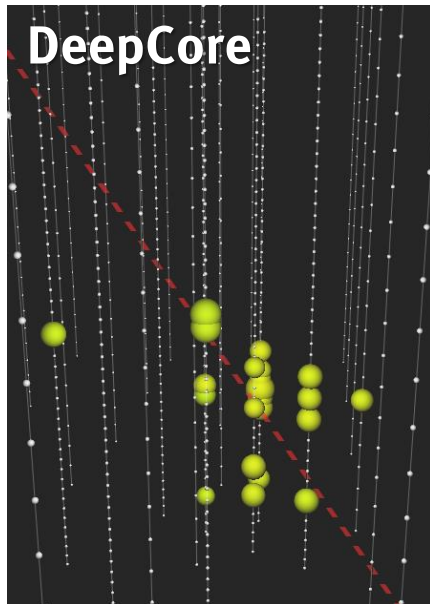
Optimised for neutrino energy:

[arXiv:2008.04323]





- Seven additional strings in DeepCore region
- ~ 700 optical modules in clearest ice (physics region)
- Increased sensor density for lower energy threshold
- Precision stand-alone calibration devices
- Novel and advanced optical module designs



$\nu_\mu$  track  
@30 GeV

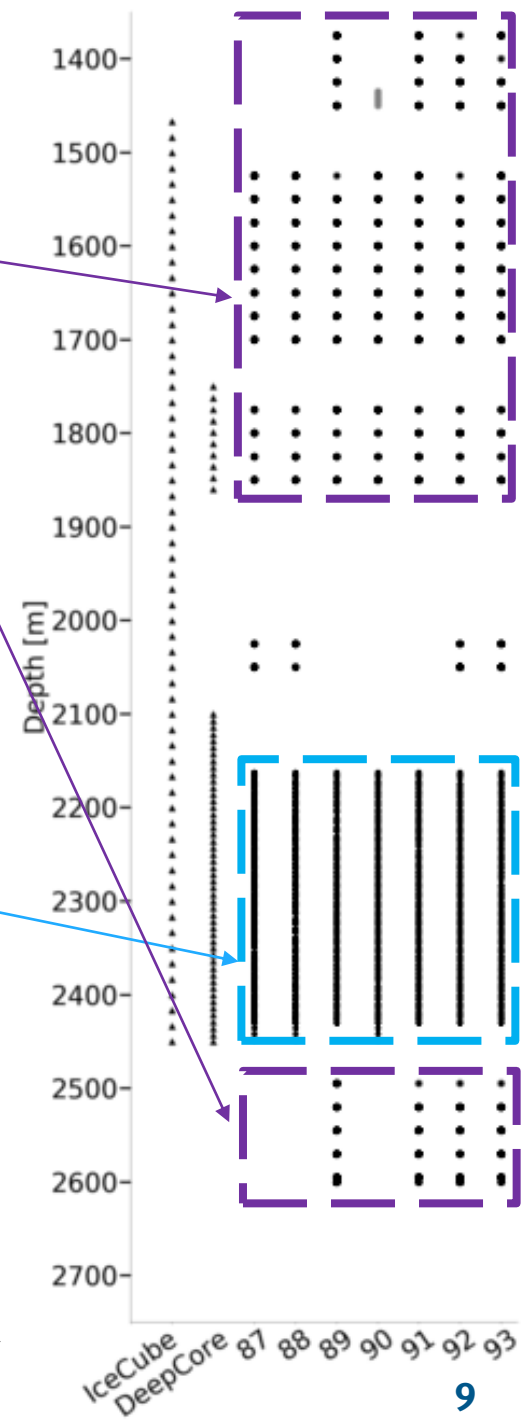
Veto & special calibration region for Gen2 depths

Low energy physics region

dusty ice

clear ice

scattering length (AU)

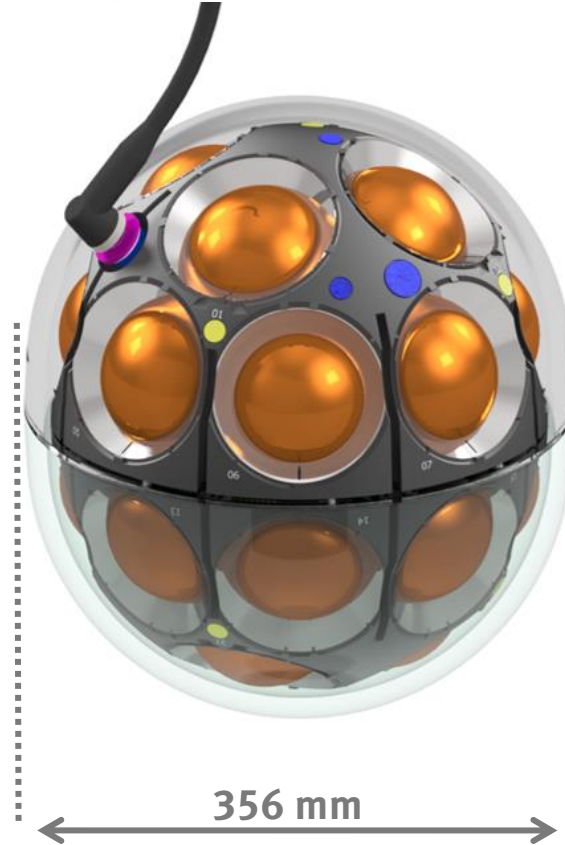


# Segmented optical modules

277 x D-Egg  
(2 x 200mm PMTs)

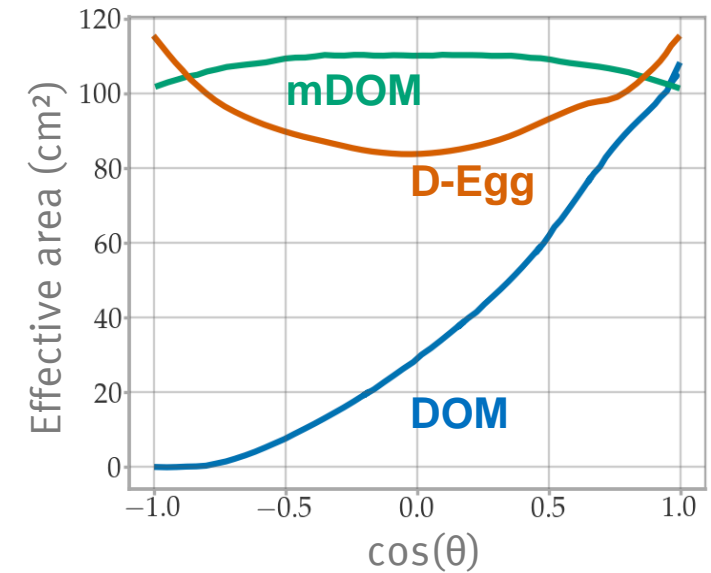


402 x mDOM  
(24 x 80mm PMTs)



## Benefits of segmentation:

- Large sensitive area
- $4\pi$  solid angle coverage
- Intrinsic directional information
- Better photon counting



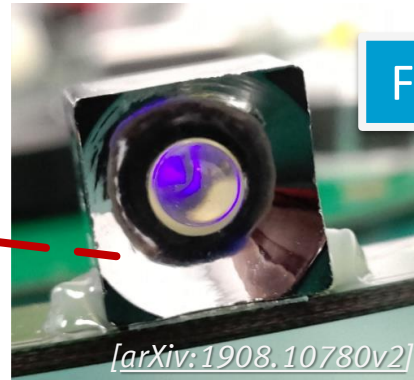
# More than photomultipliers...



Cameras

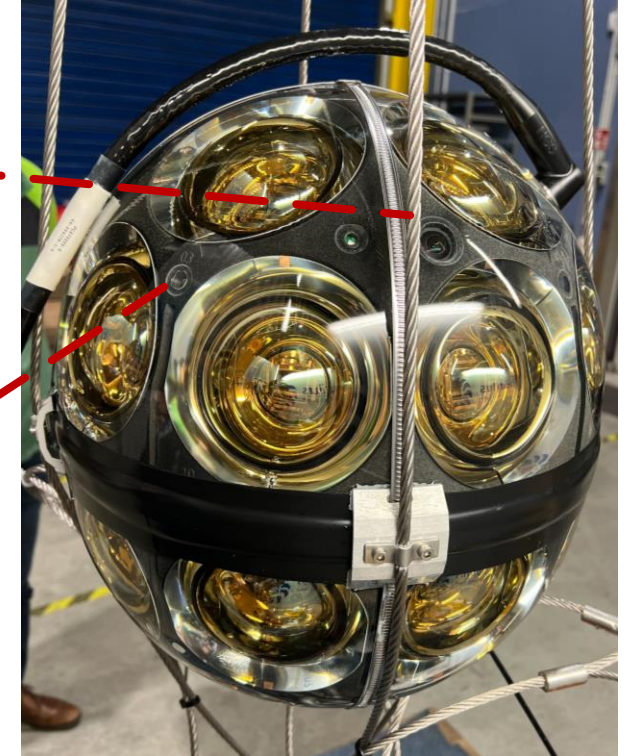
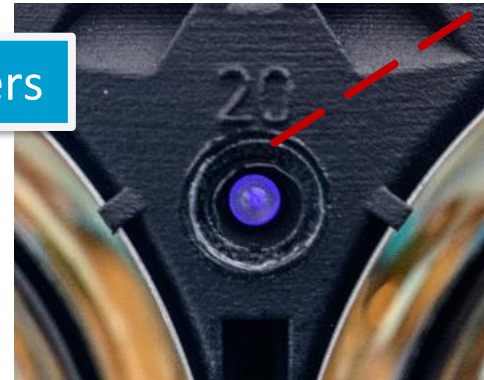


[PoS(ICRC2019)928]



Flashers

[arXiv:1908.10780v2]



- In-module calibration devices: LED flashers and camera systems
- Further stand-alone calibration devices (photon point source, steerable camera, rotary laser, and acoustic emitters & receivers)



In-situ **calibration of optical sensors** and improved measurement of **ice optical properties**

# Expected performance

## More neutrinos!

- Reduced energy threshold  $\sim 1$  GeV
- Higher neutrino detection rate ca.  $4 \times$  DeepCore

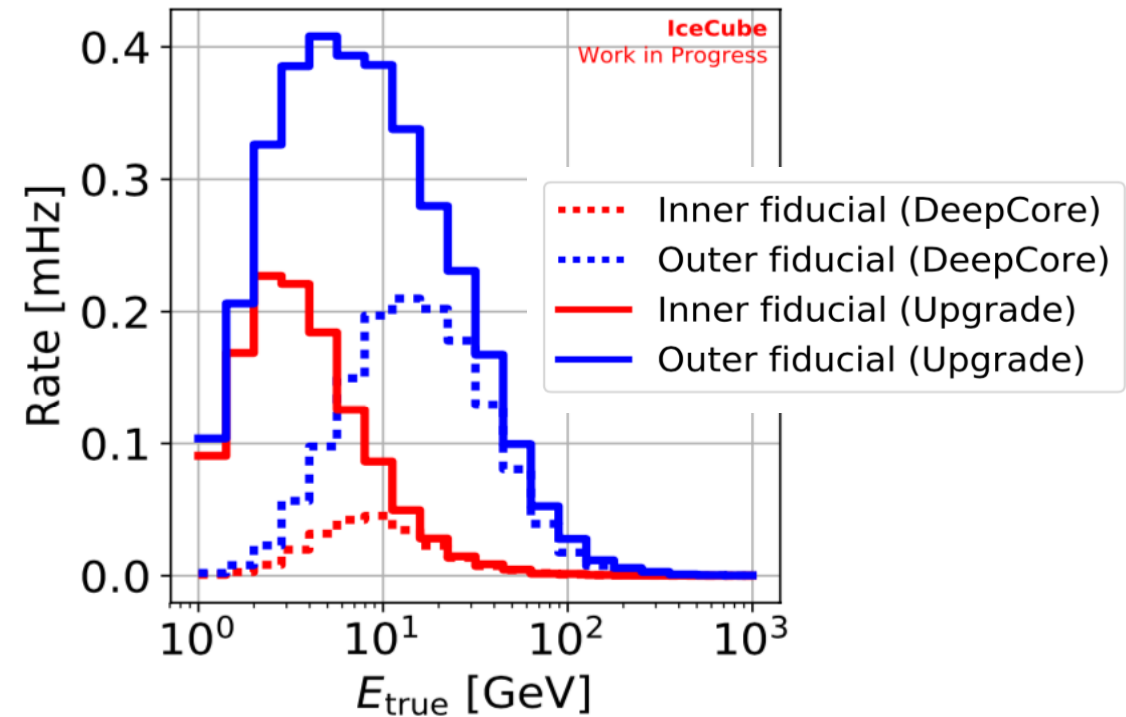
## Higher precision!

- Factor  $\geq 3$  better zenith angle reconstruction
- Factor  $\geq 2$  better energy reconstruction

## Enhanced oscillation analyses!

- Tighter  $(\theta_{23}, \Delta m_{32}^2)$  parameter space from  $\nu_{\mu}$  disappearance
- Stringent test of unitarity of the PMNS matrix from  $\nu_{\tau}$  appearance (6% precision,  $>4$ -fold improvement on current world best)

## $\nu_{\mu}$ charged current interactions



[arXiv:1908.09441]

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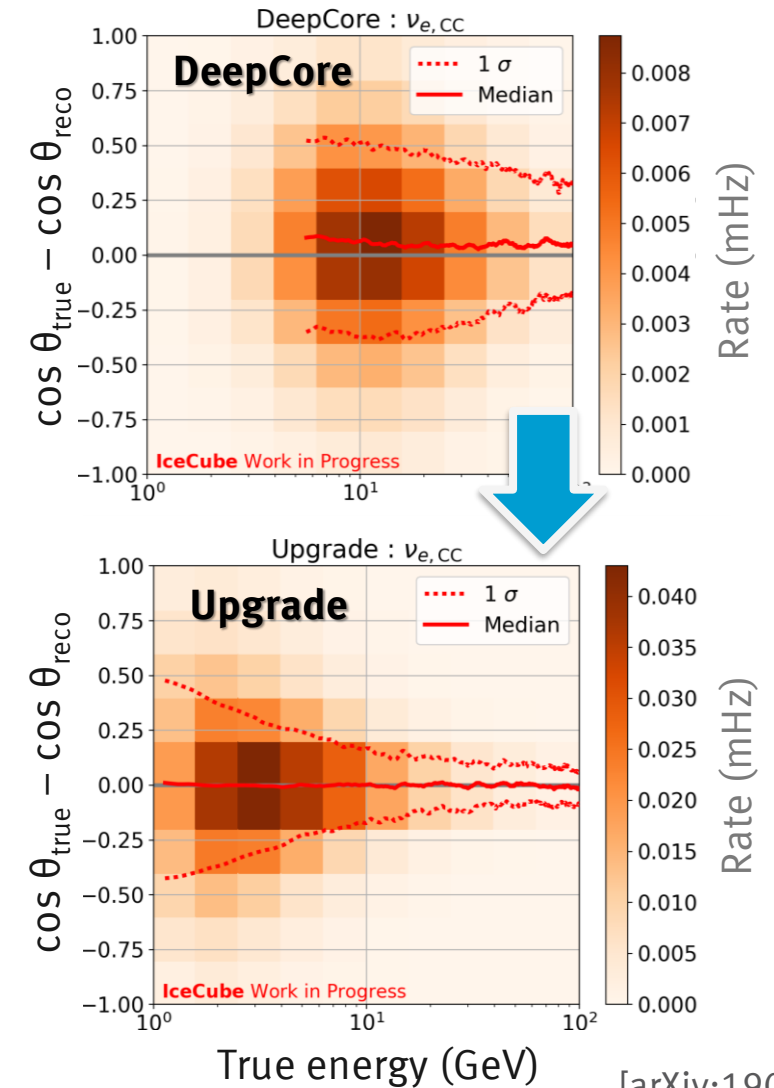
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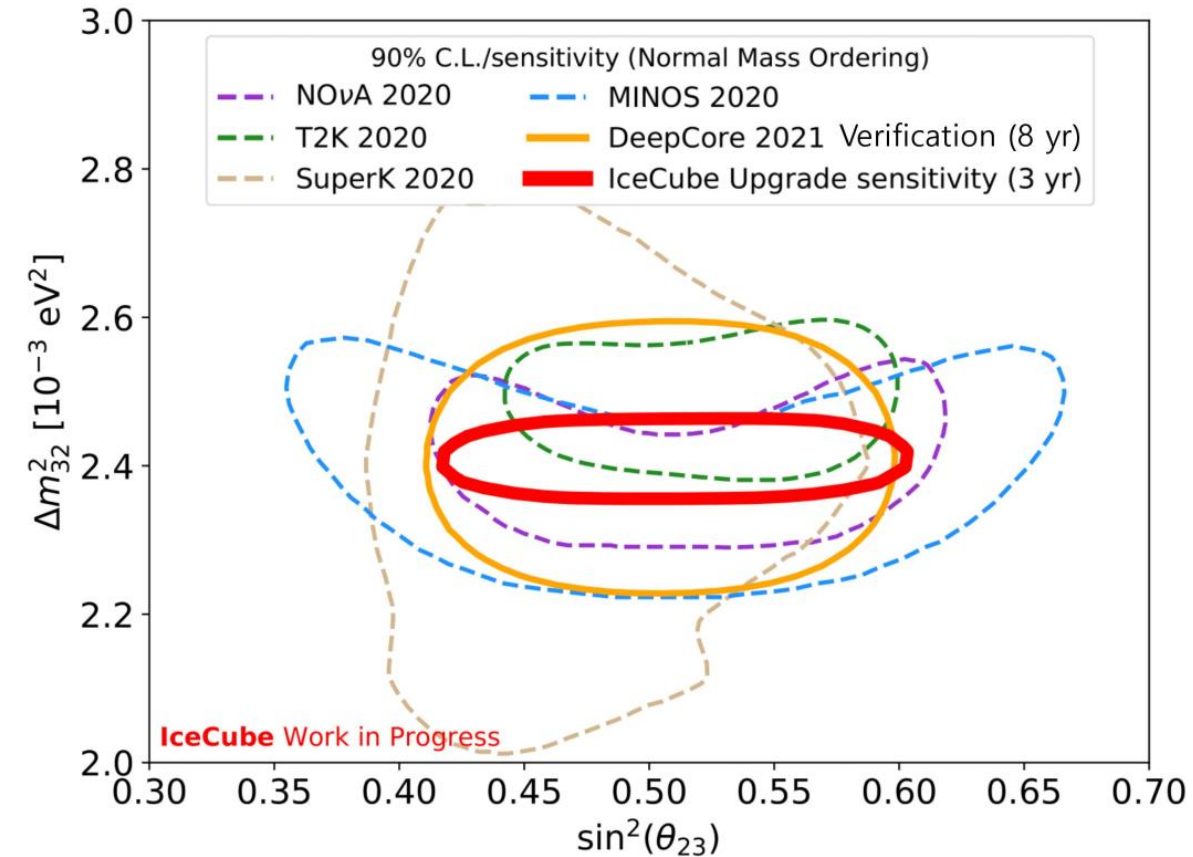
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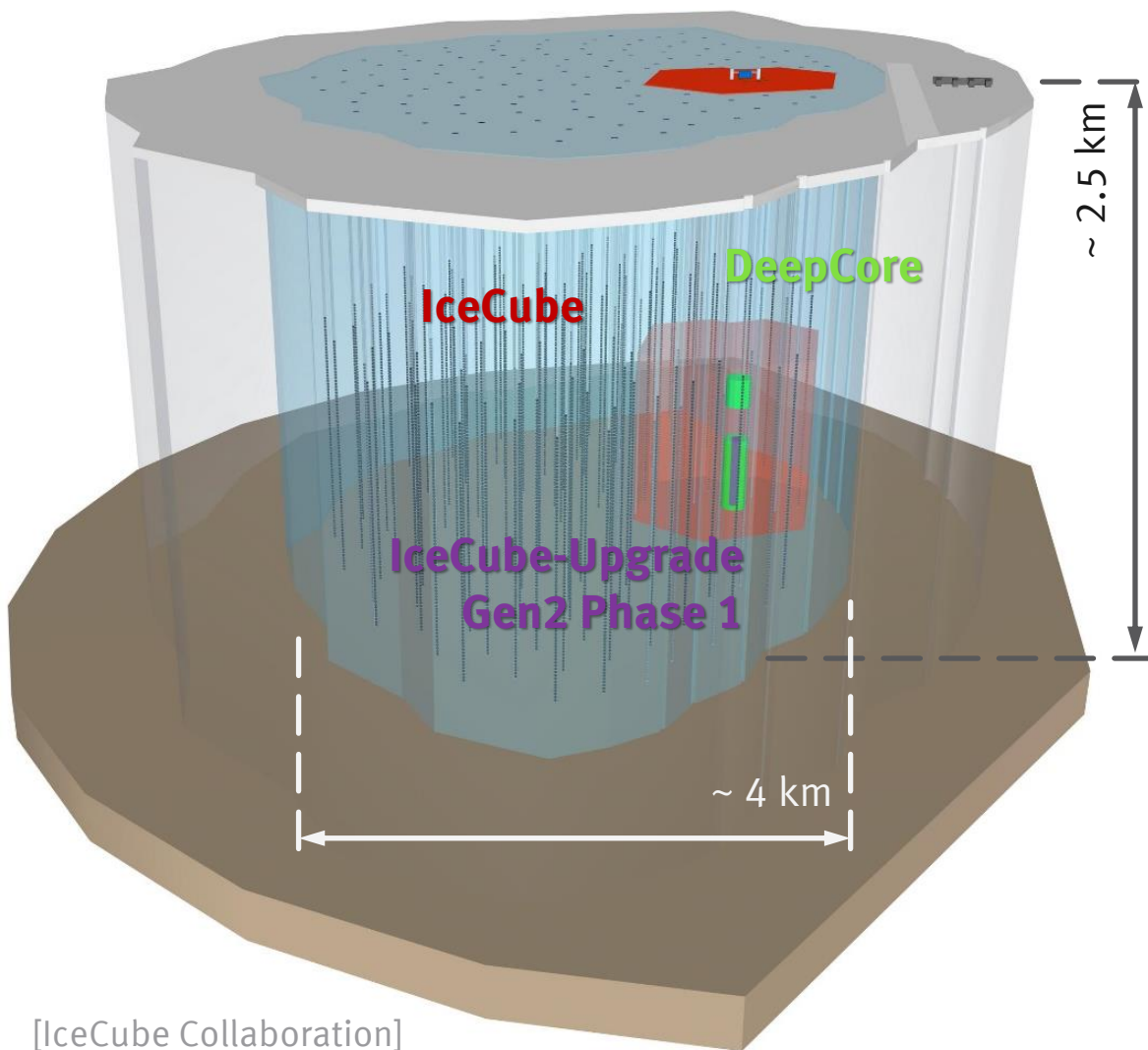
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[10.5281/zenodo.6805121]



# ICECUBE GEN2

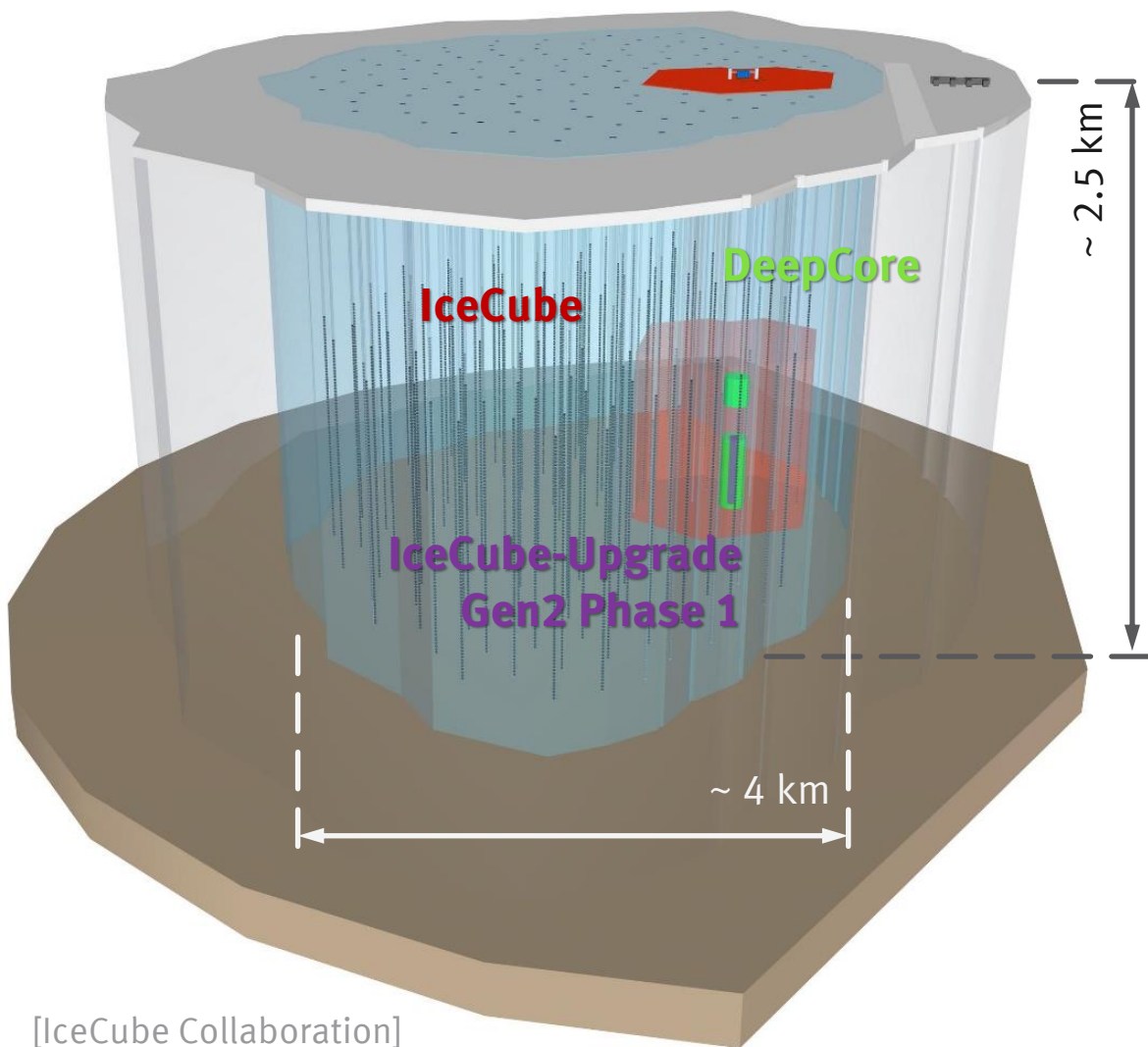


- $\sim 8 \text{ km}^3$  instrumented volume (optical array)
- 9600 additional modules @ 120 strings
- New optical sensor technology
- Scintillator-radio surface array for cosmic-rays
- Shallow in-ice radio array for  $\sim 10^{18} \text{ eV}$  neutrinos

[IceCube Collaboration]

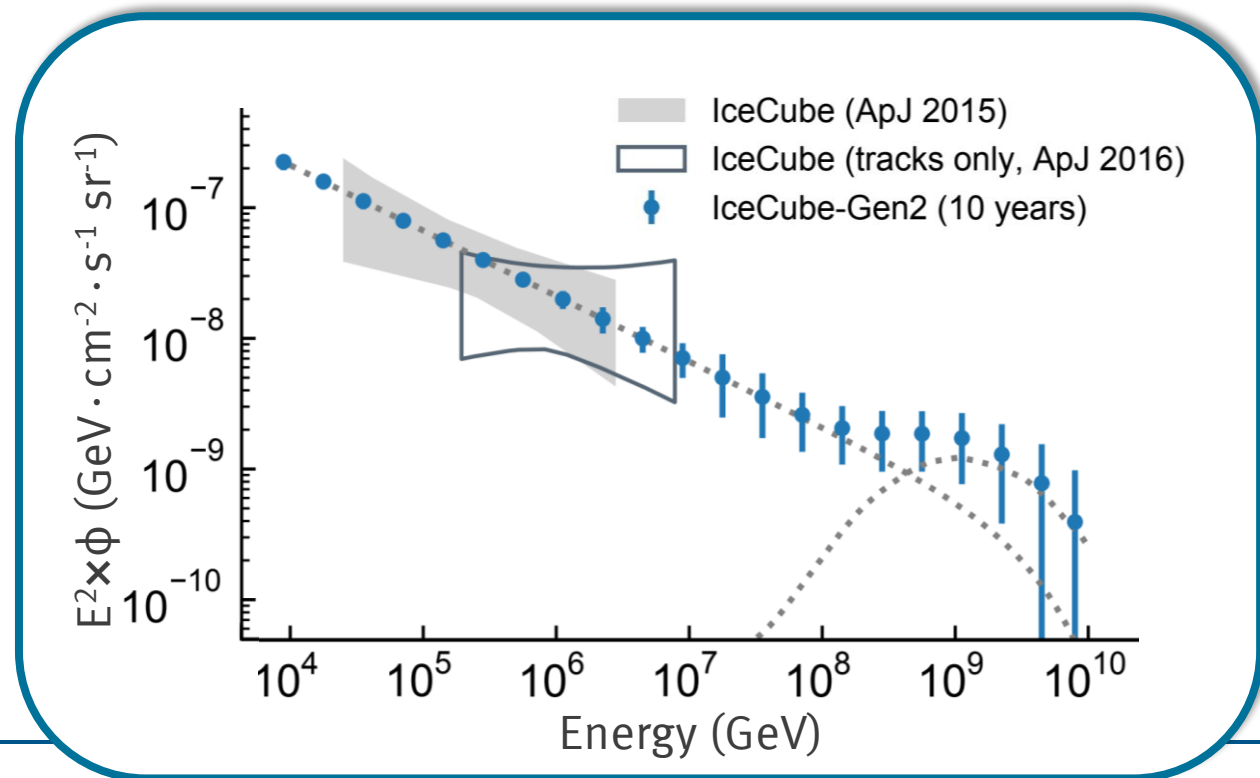


# ICECUBE GEN2



[IceCube Collaboration]

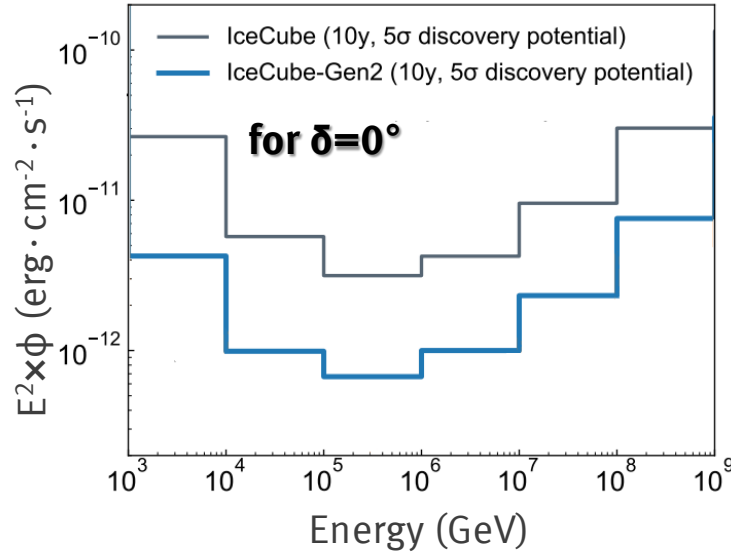
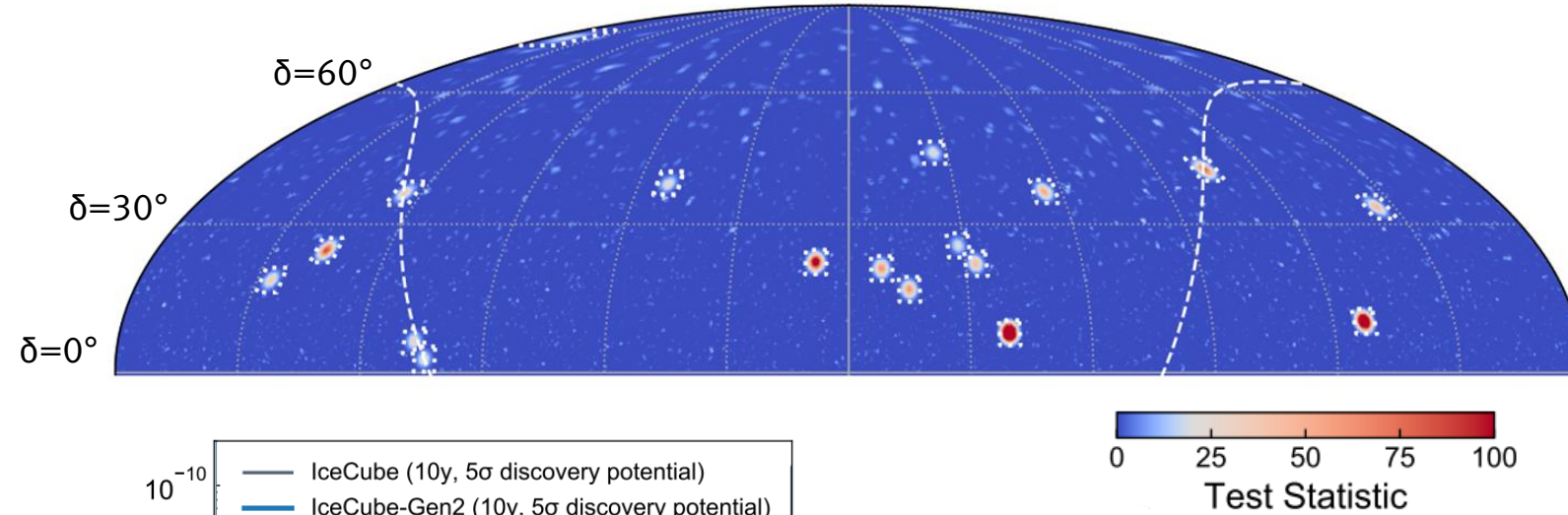
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# Resolving the neutrino sky

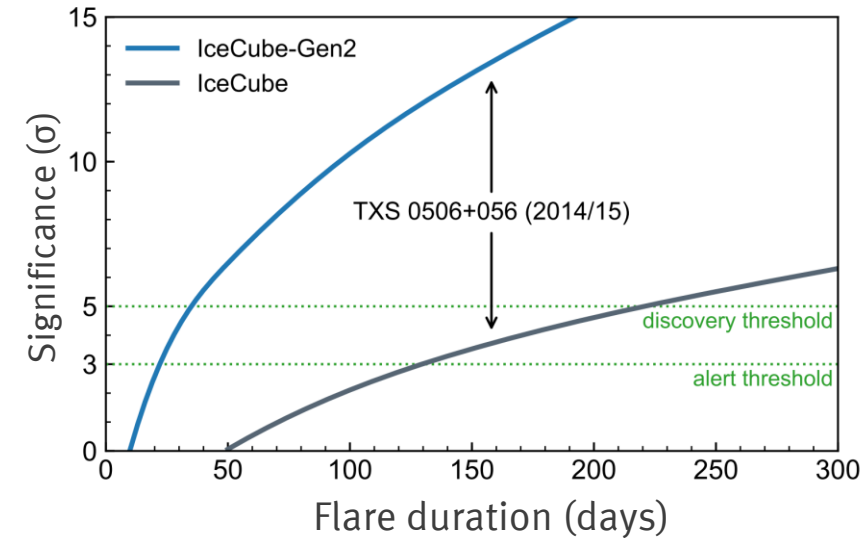
Sky map mock-simulation for point source searches



Optical array of IceCube-Gen2  
 x5 more sensitive than current  
 IceCube detector

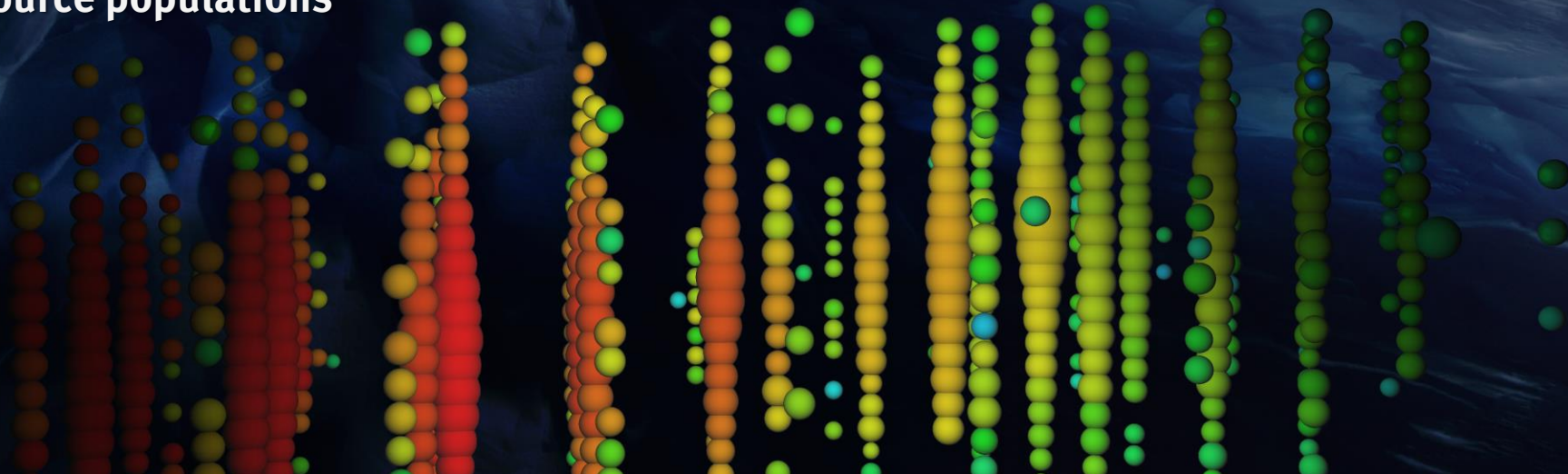
[arXiv:2008.04323]

Large increase in sensitivity to neutrino flares



# Summary

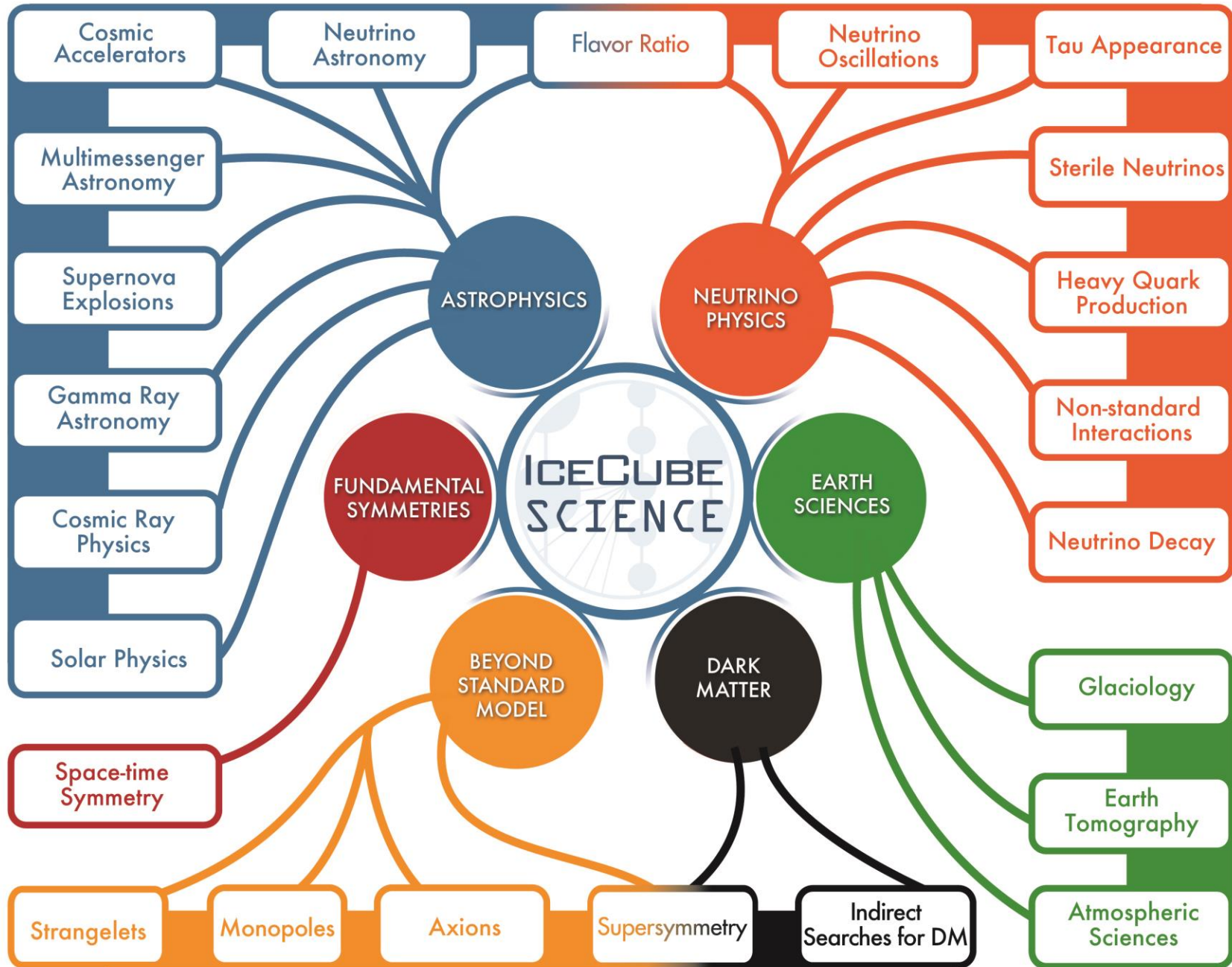
- The IceCube Neutrino Observatory is a unique facility that has produced several results from neutrino particle physics to neutrino astrophysics, including first findings of astrophysical high energy neutrino sources
- IceCube to be expanded by new strings instrumented using novel technology
- IceCube Upgrade, a low energy extensions, will enhance oscillation studies and improve detector calibration resulting in better pointing and energy resolution
- IceCube-Gen2 will dramatically increase the detection rate in order to understand neutrino sources and source populations



# The IceCube Collaboration



**Backup**



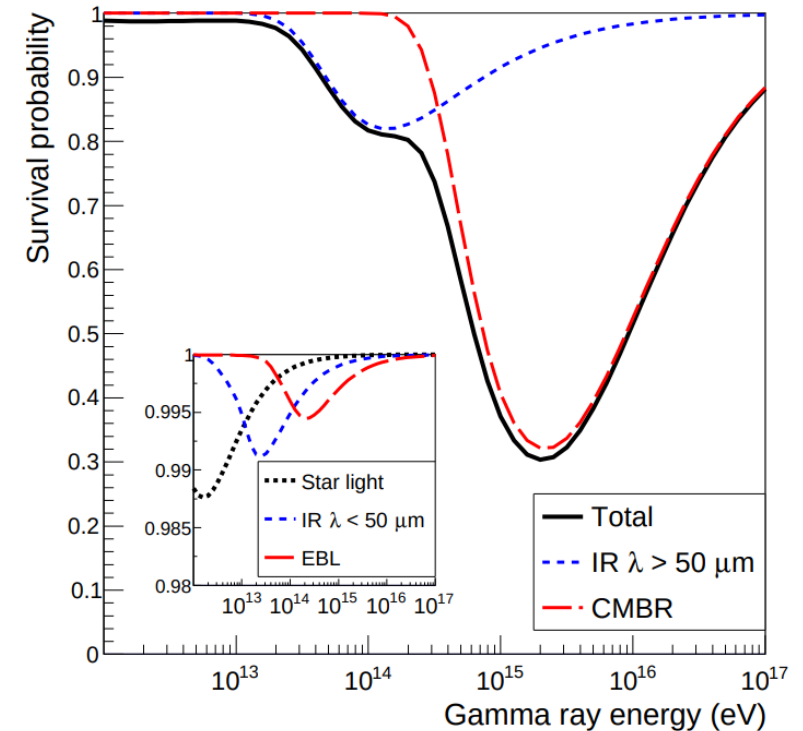
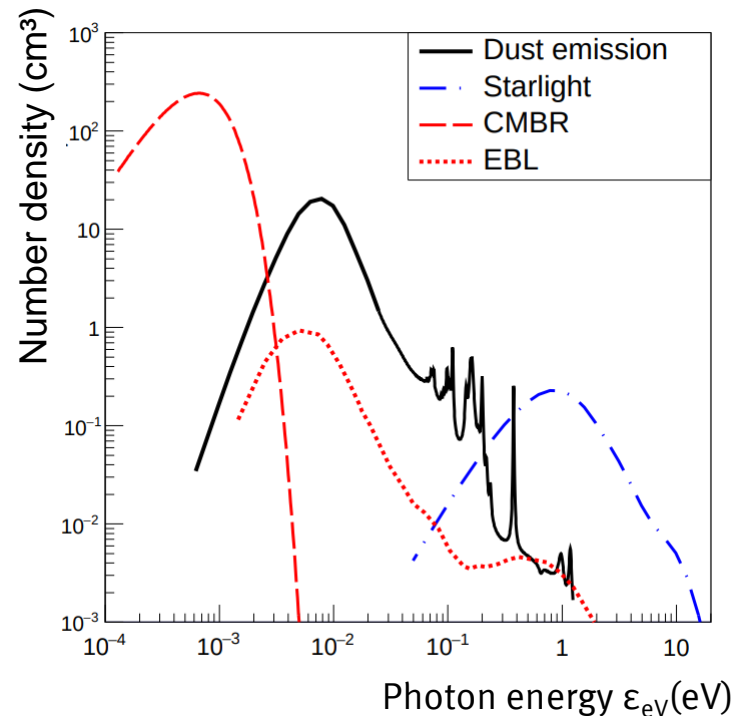
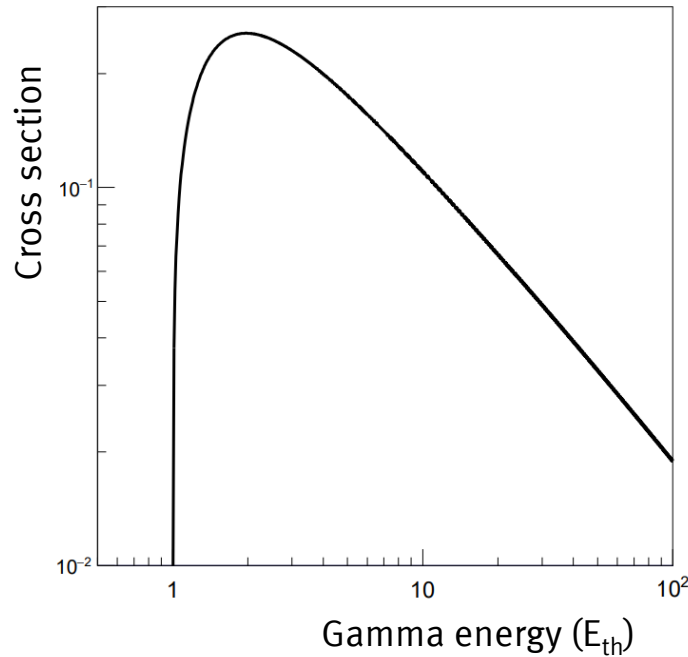
# Gamma pair production

[arXiv:1608.01587]

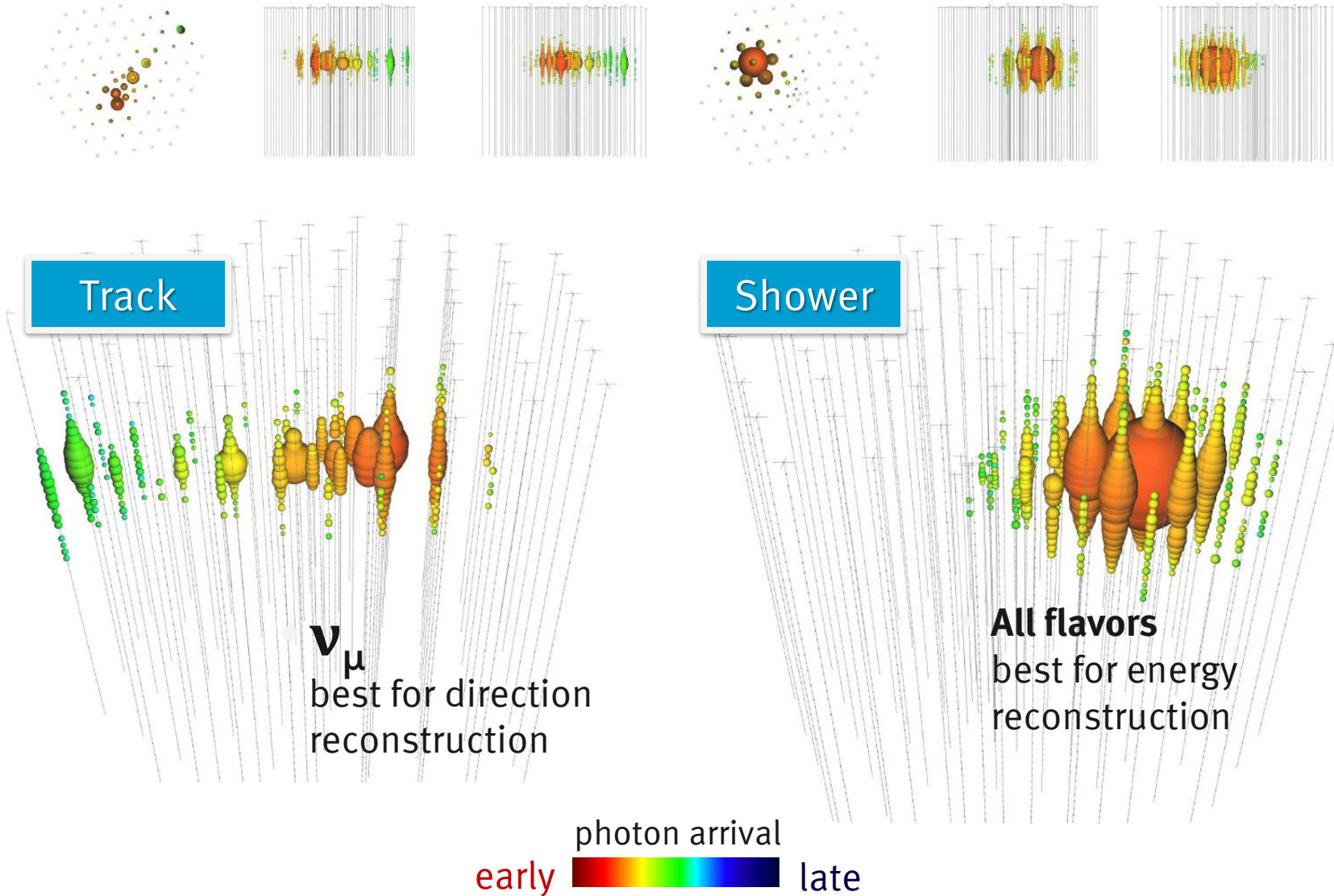
- Energy threshold for pair production

$$E_{\gamma}^{\text{th}} = \frac{2 m_e^2}{\varepsilon (1 - \cos \theta)} \simeq \frac{0.52}{\varepsilon_{\text{eV}} (1 - \cos \theta)} \text{ TeV}$$

Target photon energy



# IceCube event signatures



Track

Shower

$\nu_{\mu}$   
best for direction reconstruction

All flavors  
best for energy reconstruction

early  late

Information

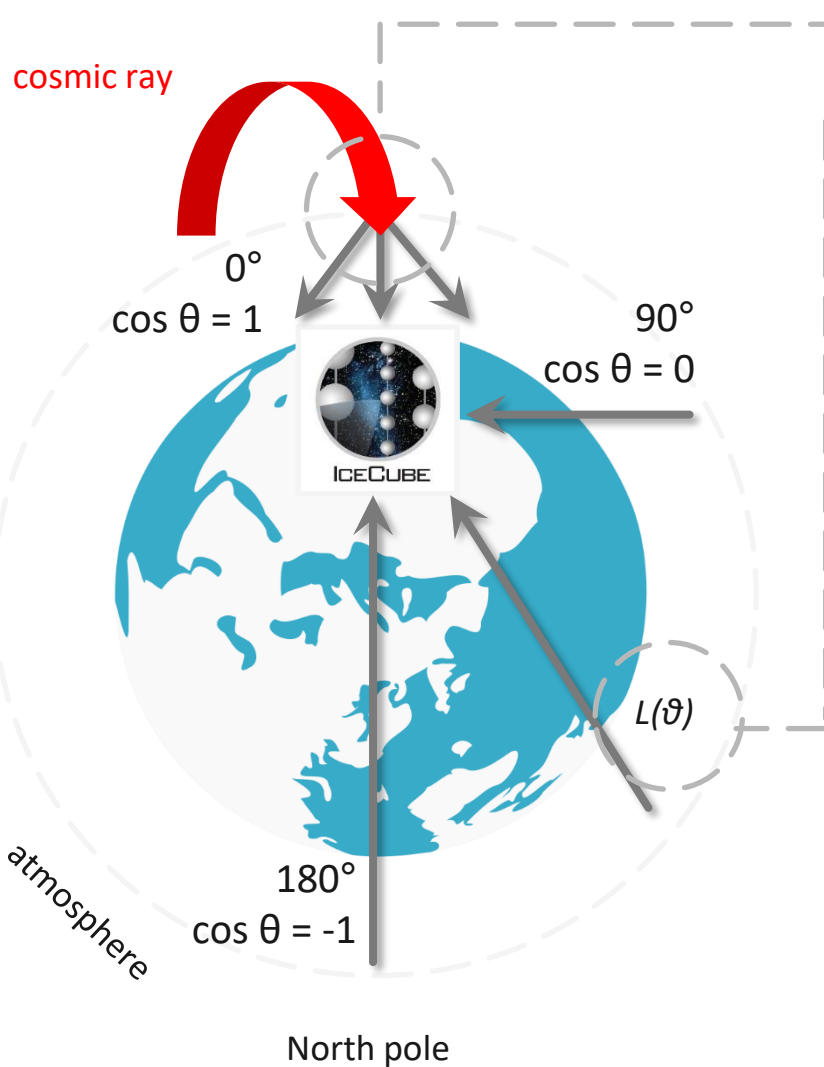
- Module positions
- Number of photons
- Arrival time



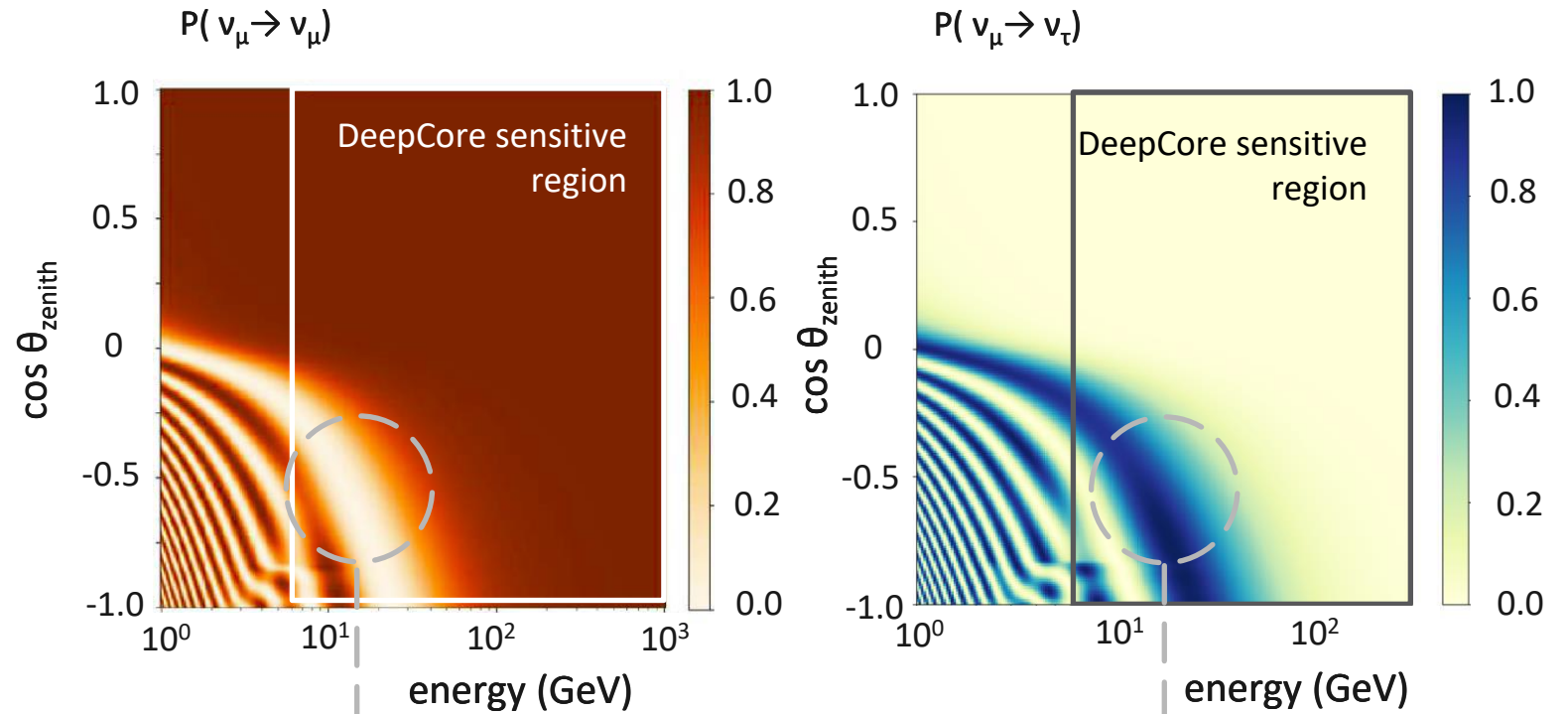
Reconstruction

- Energy
- Direction
- Flavor: track/shower (statistically)

# Measuring neutrino oscillations with DeepCore



- initial composition
- path length



- test predictions in these regions

[L. Classen]



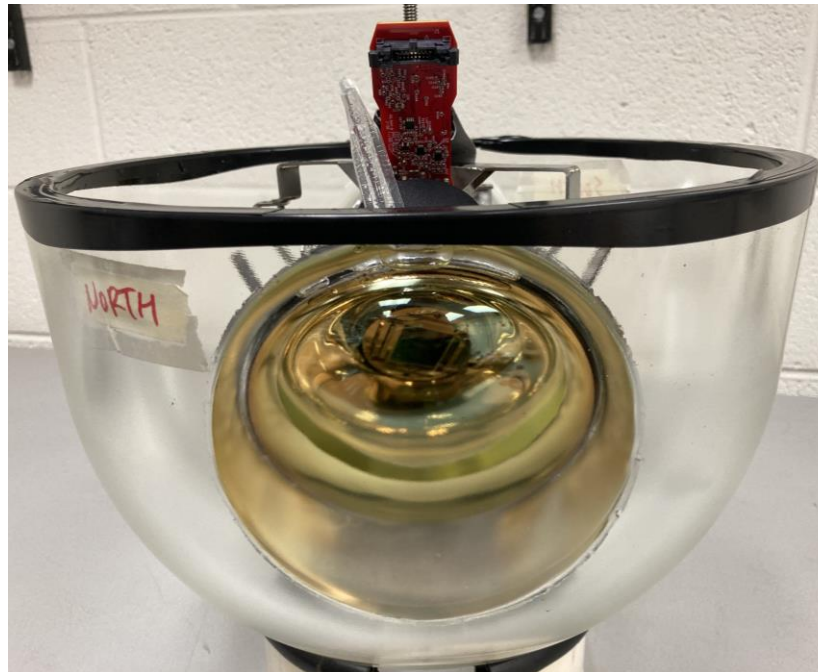
# Further R&D in progress for Gen2



ICECUBE  
GEN2

- Based on research of Upgrade optical modules
- Reduced diameter lowers drilling cost
- Use of “gel pads” to couple PMTs to pressure vessel
- Total internal reflection in gel pads replace reflectors

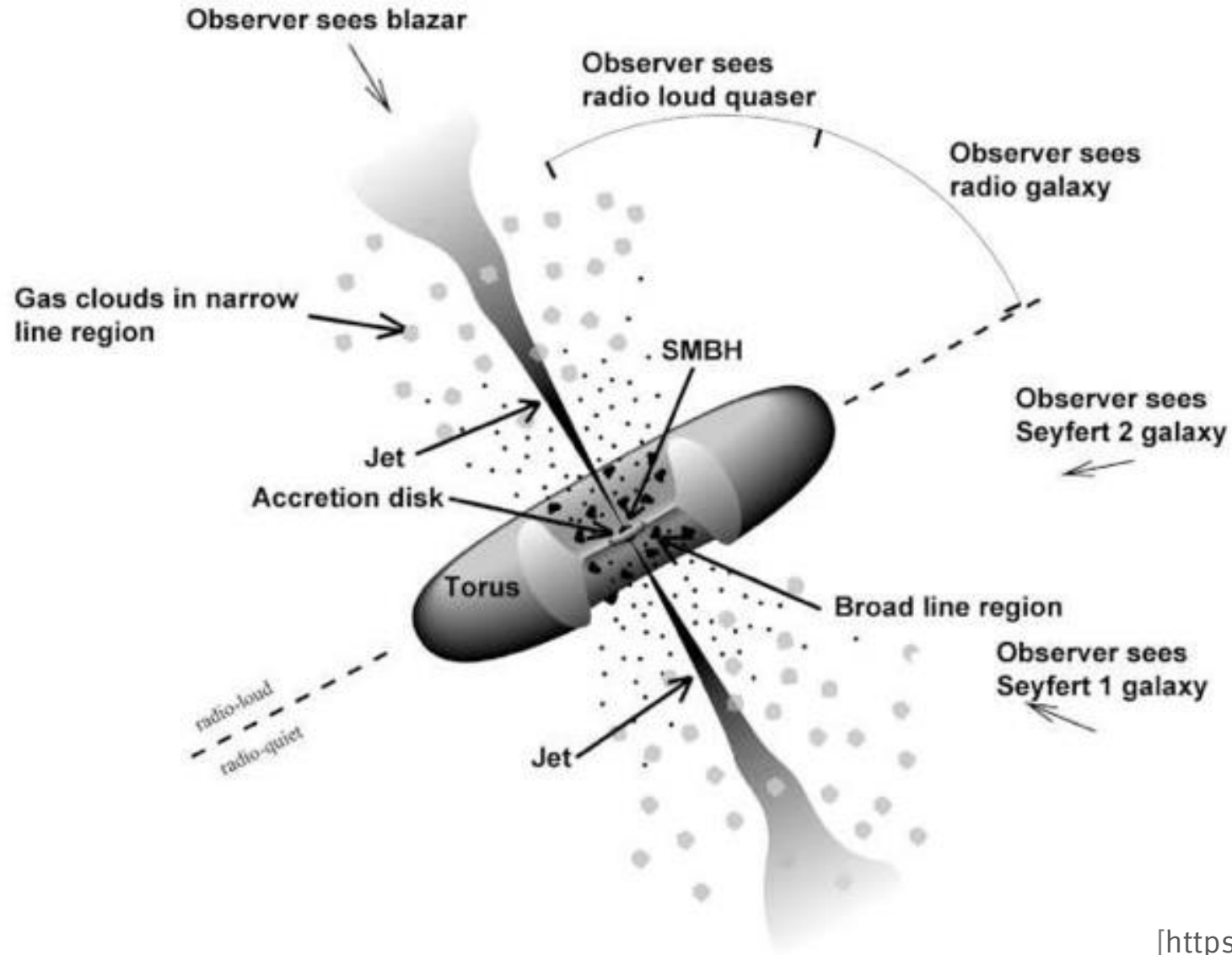
Pad matches pressure vessel curvature



~9600  
16/18 x 104 mm PMTs

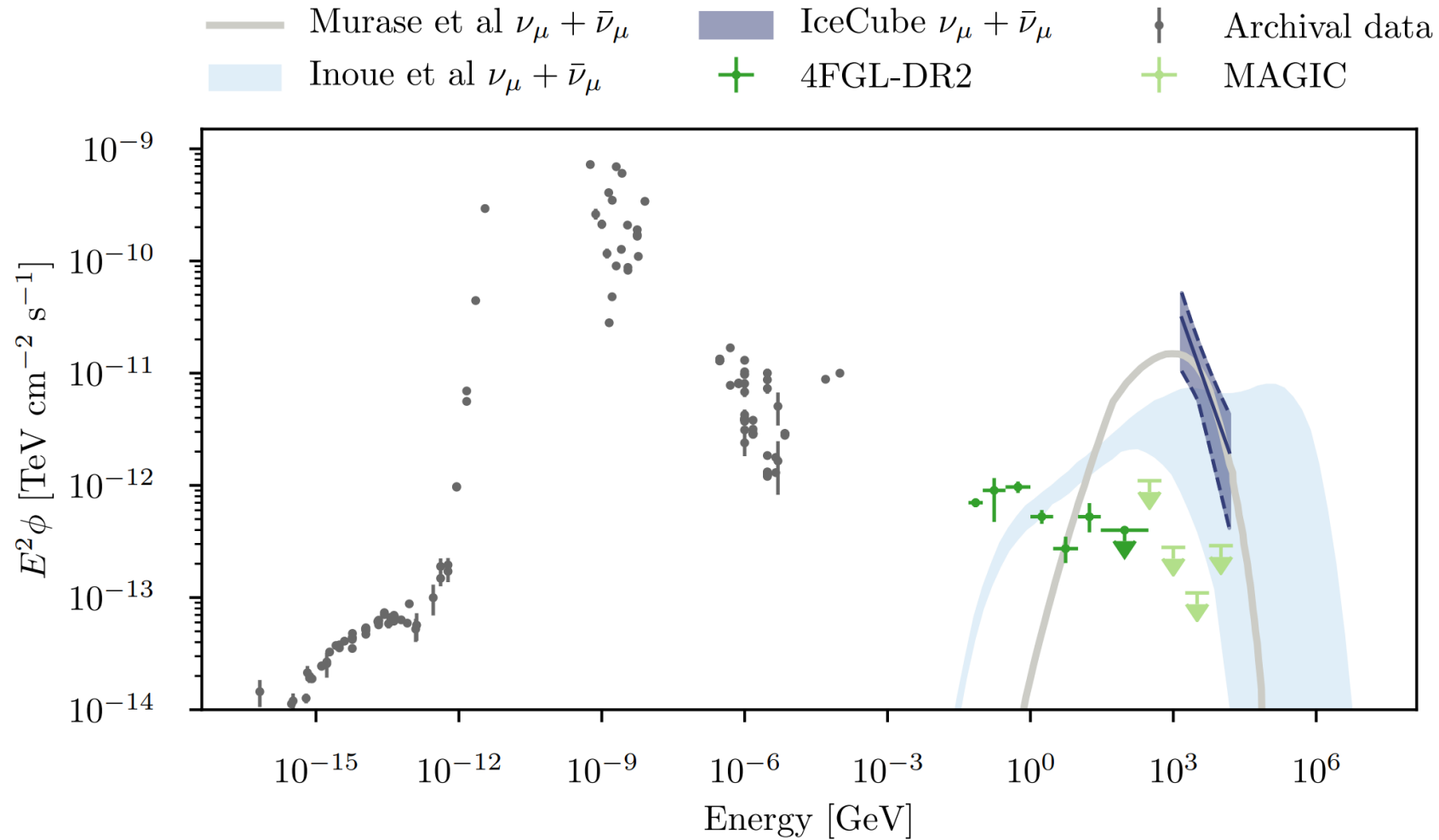


# AGNs



[<https://fermi.gsfc.nasa.gov/science/eteu/agn/>]

# Spectral energy distribution NGC 1068



[arXiv:2211.09972]