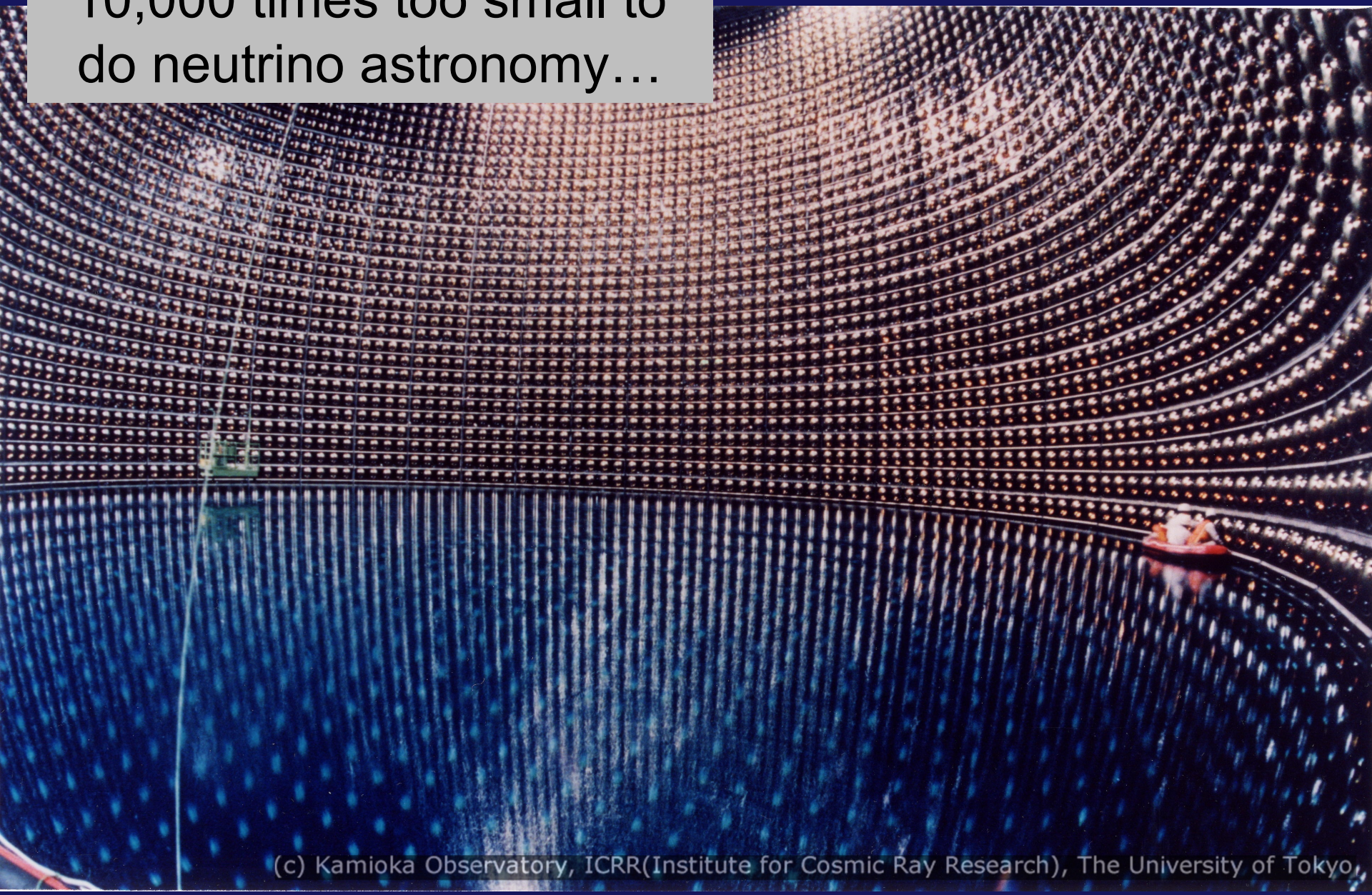
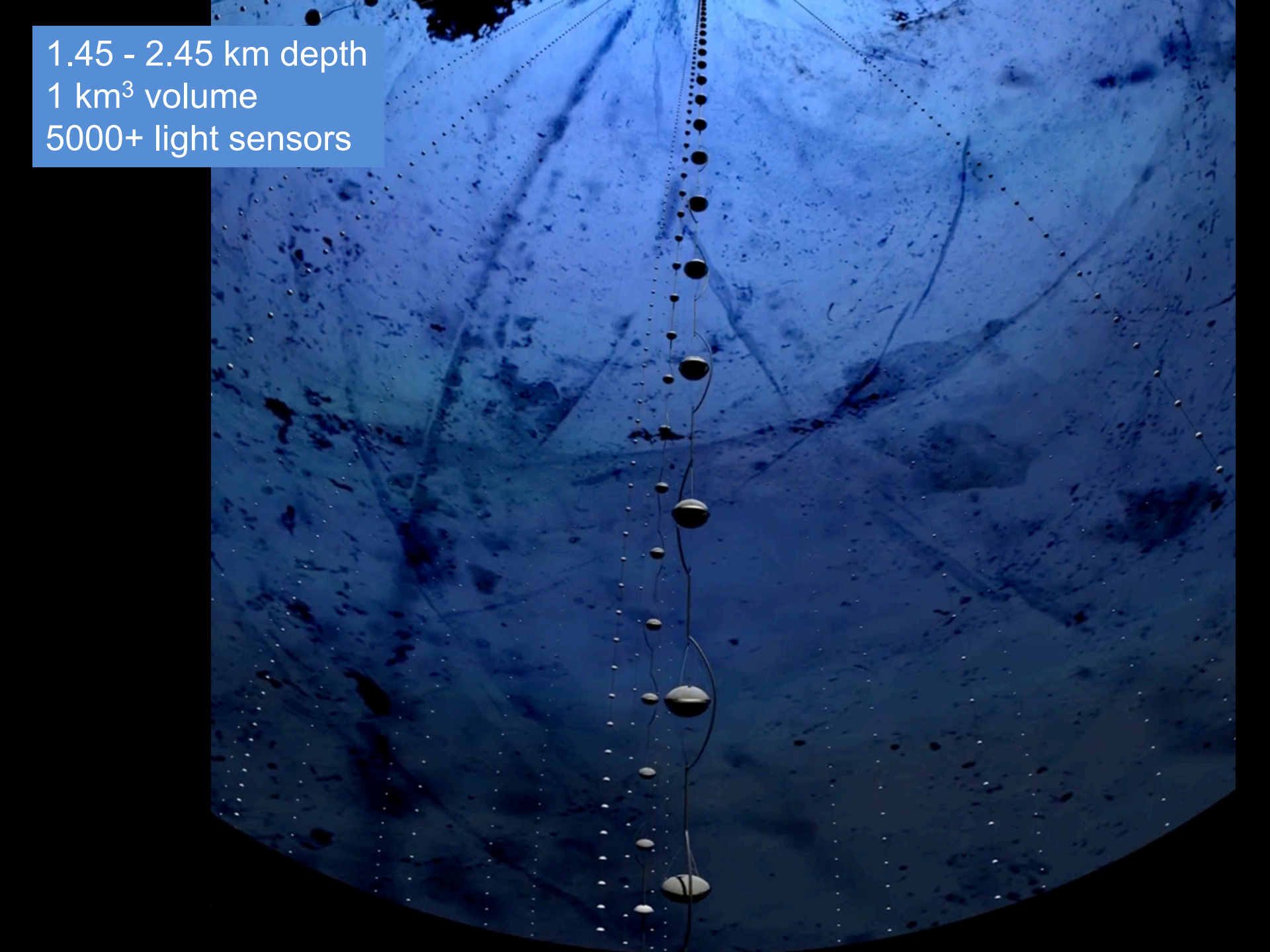
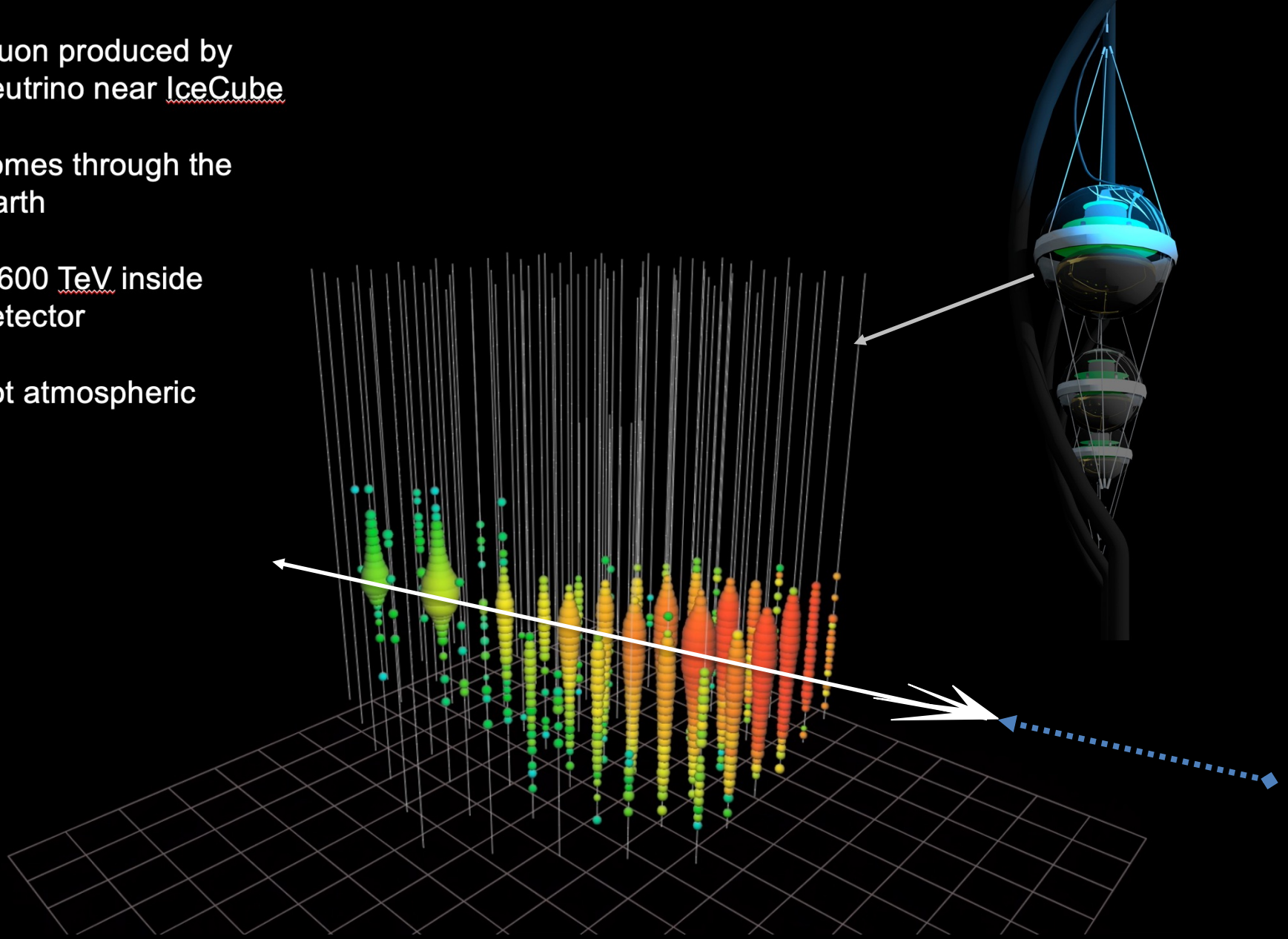

Upgrade Science
Francis Halzen

10,000 times too small to do neutrino astronomy…

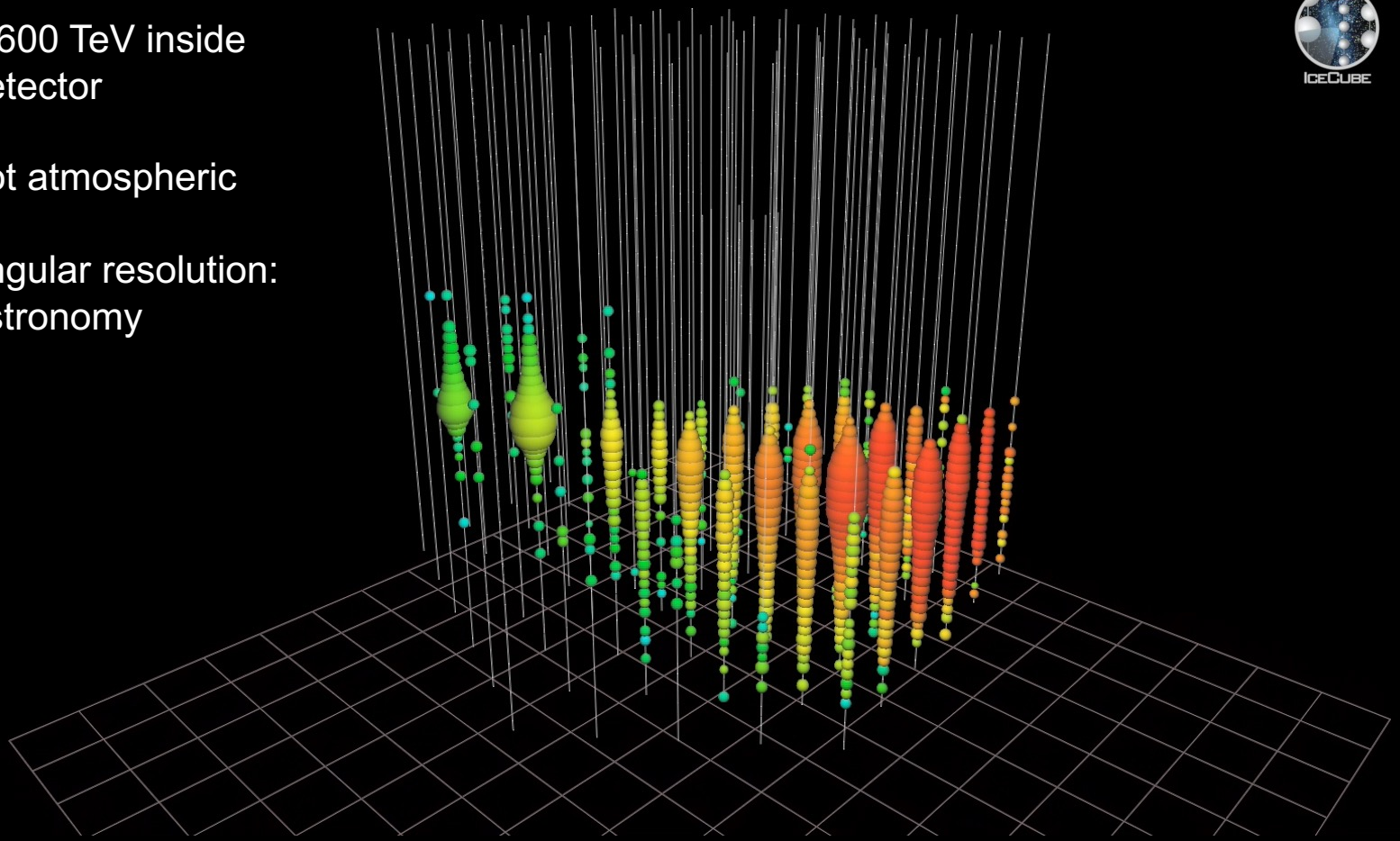



1.45 - 2.45 km depth
1 km^3 volume
5000+ light sensors

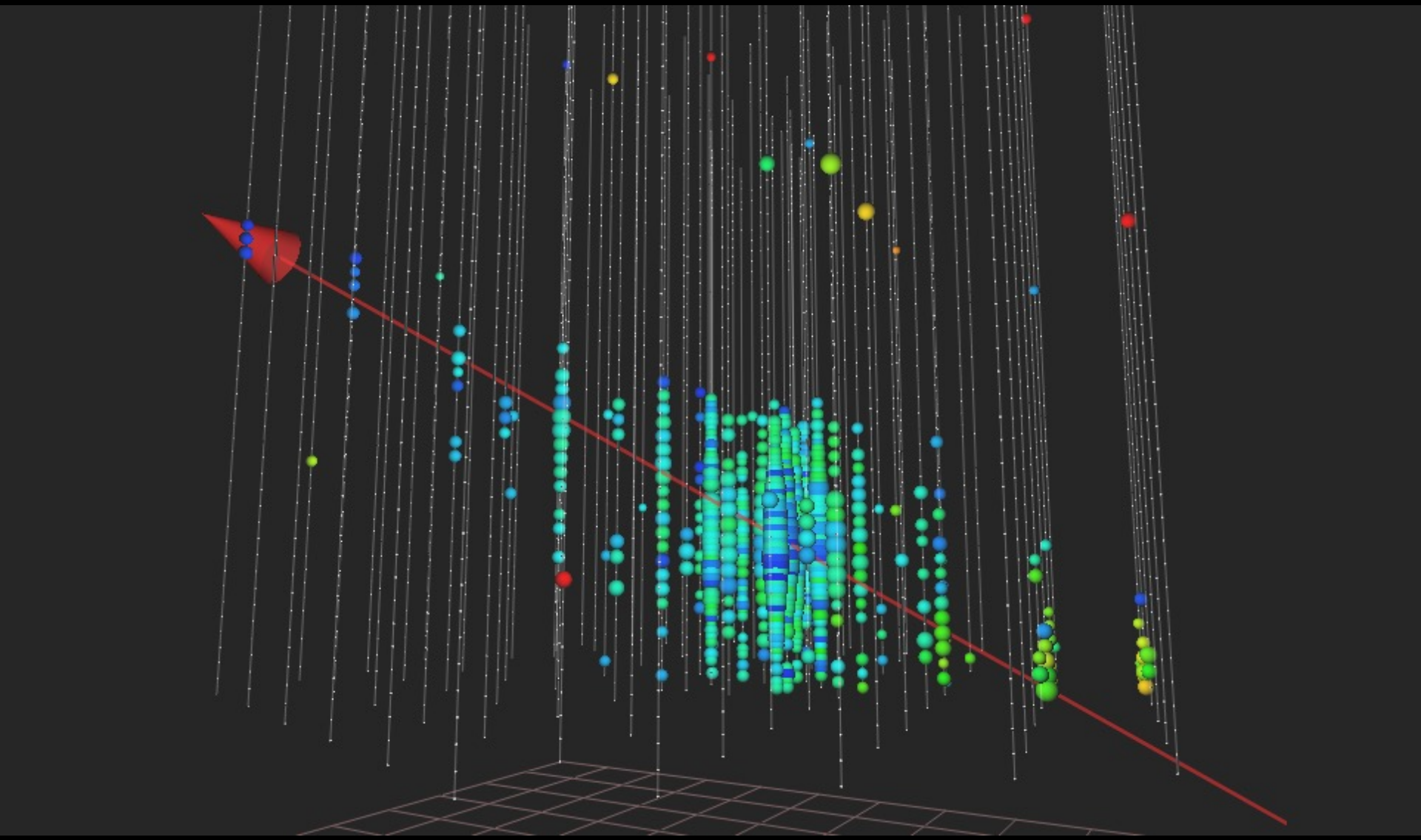
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



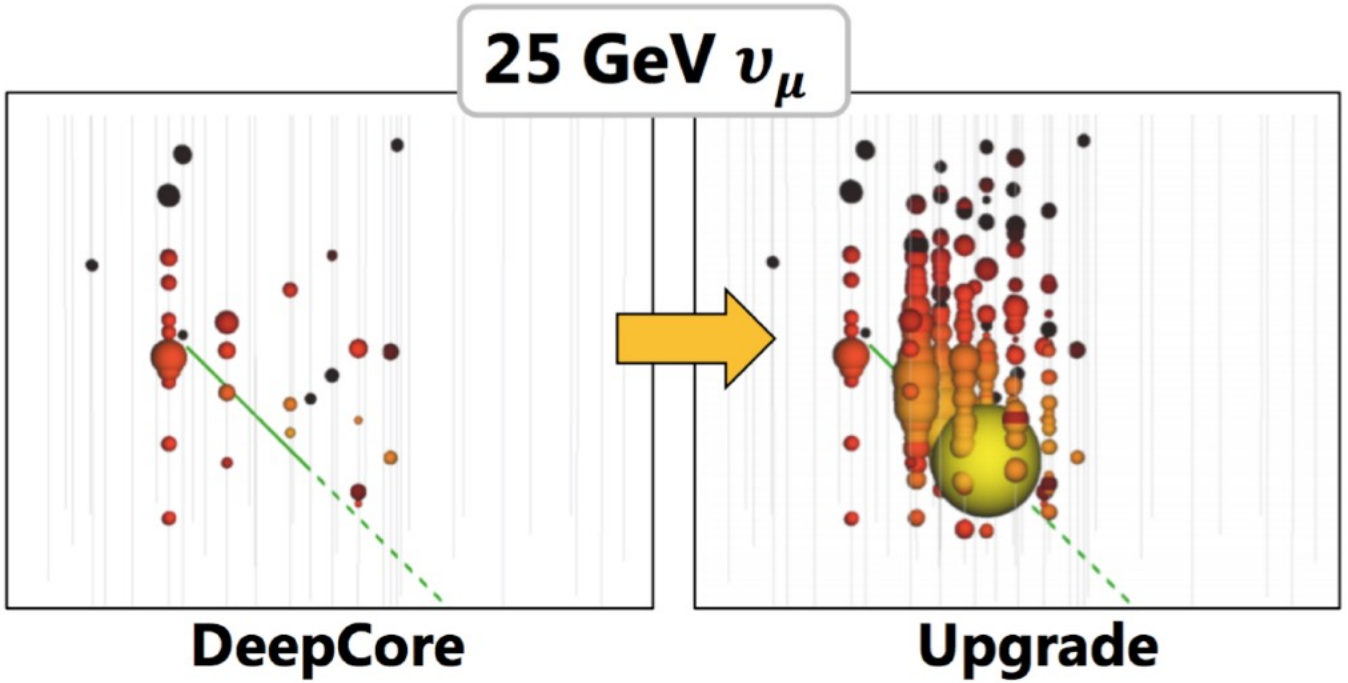
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: astronomy

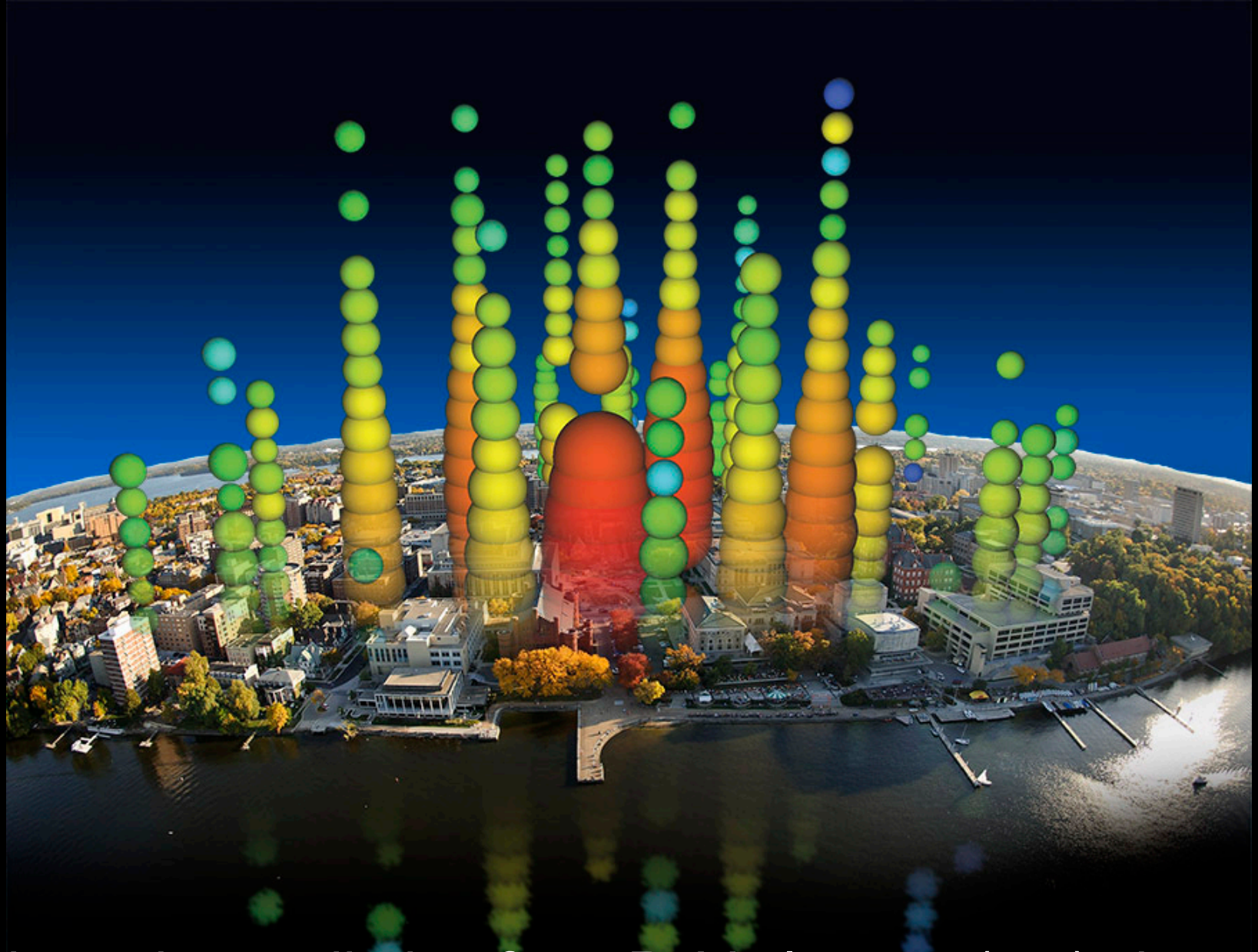


IceCube and DeepCore



Low energy neutrinos in the Upgrade



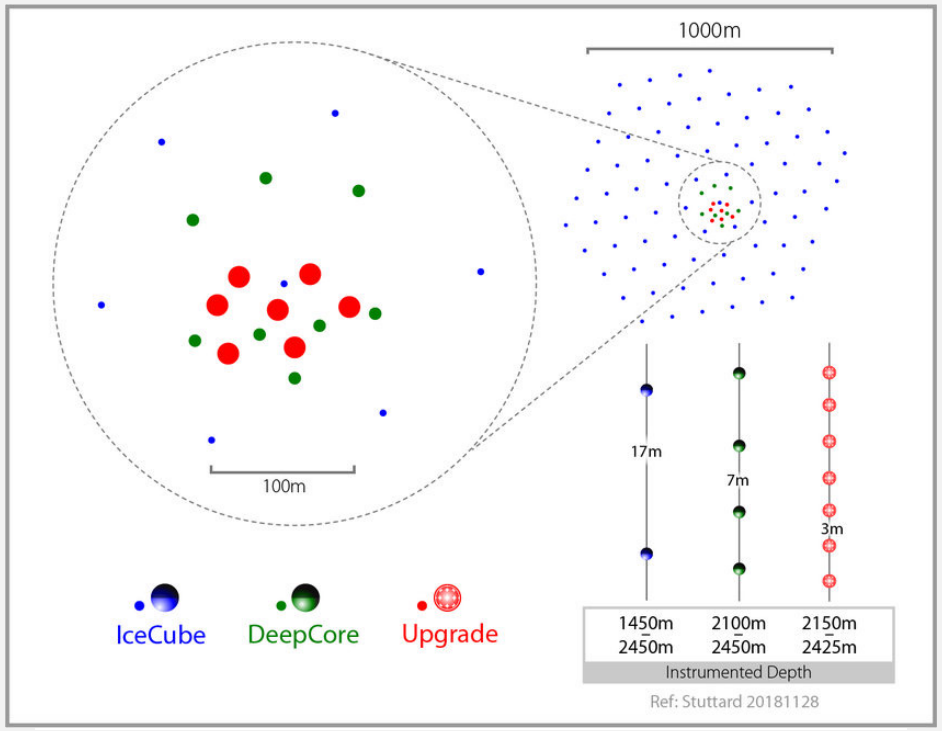


Cherenkov radiation from PeV electron (tau) shower
we detect all 3 flavors of neutrinos

IceCube Overview

- IceCube
  - DeepCore
  - IceTop

  } Done & Delivering
- Upgrade } Underway
- IceCube-Gen2
  - Full } Astro2020 Review Preliminary Design in Preparation



- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

IceCube
South Pole Neutrino Observatory

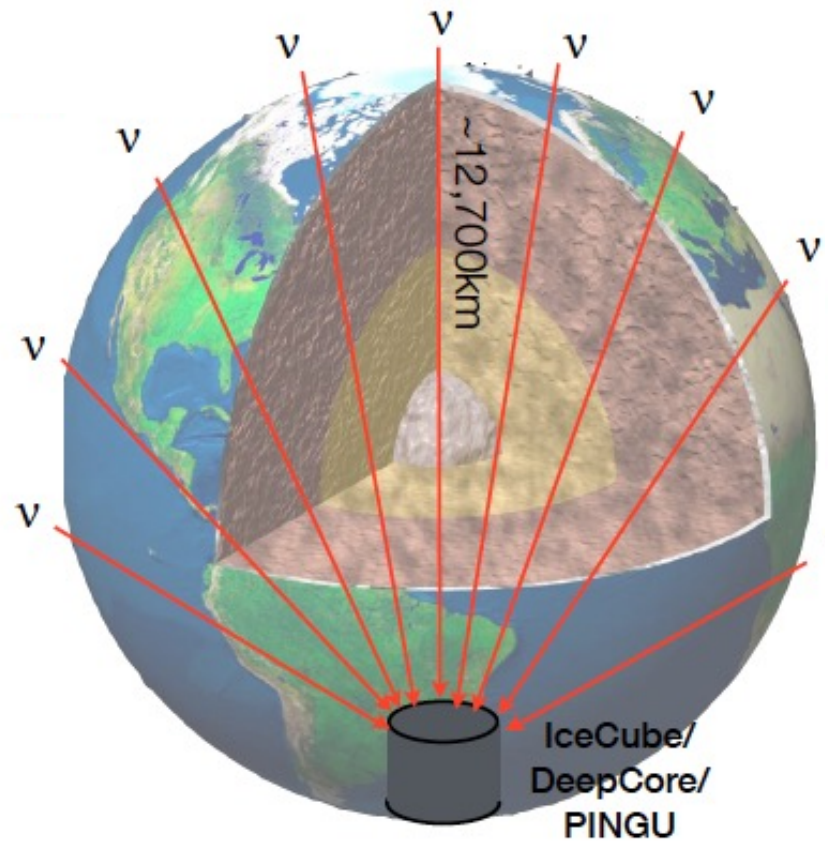
Next step: the IceCube upgrade

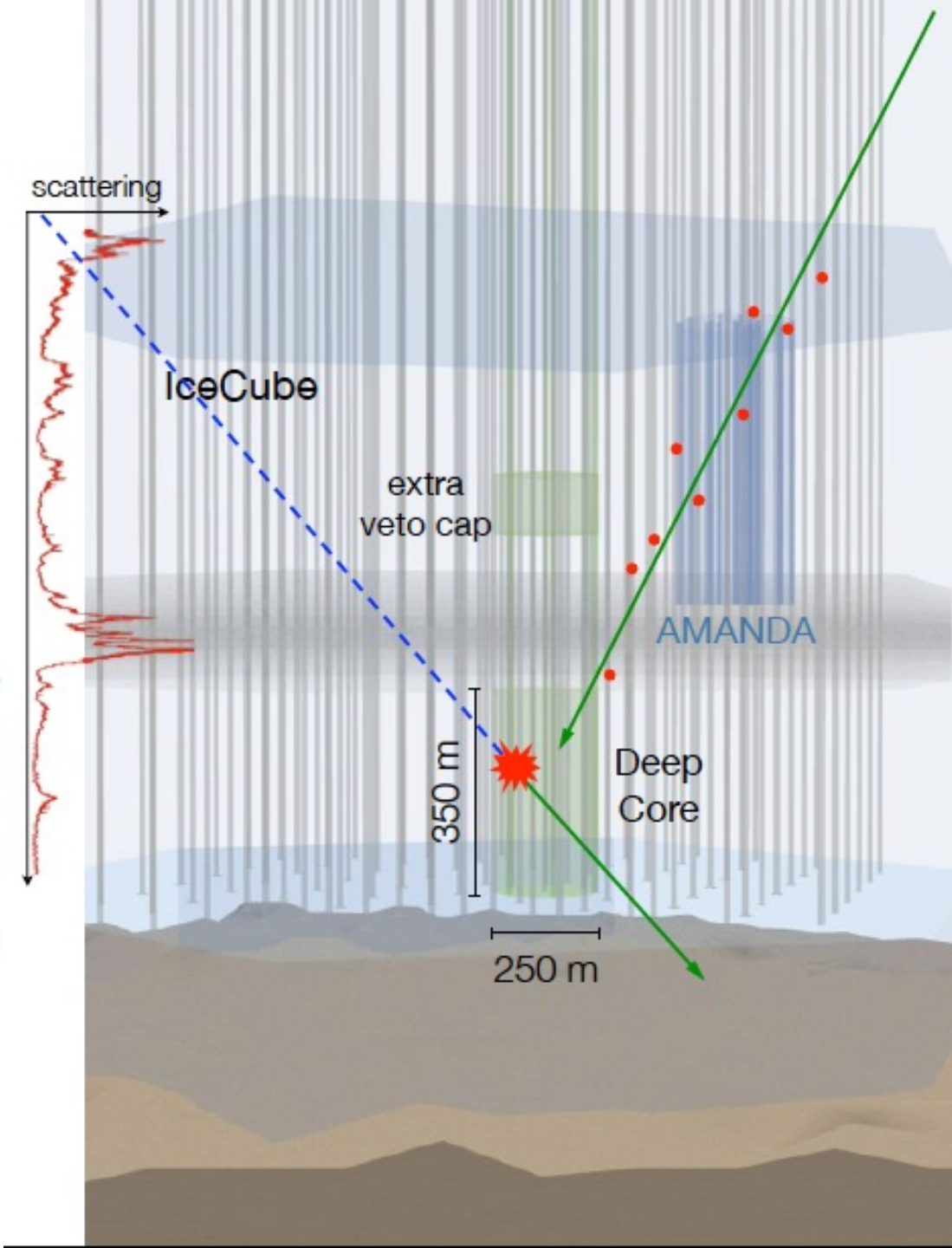
- improve the scientific capabilities of IceCube at low energies
- improve the scientific capabilities of IceCube at high energies with improved optics of the ice using the information obtained with the Upgrade’s small string spacings and novel calibration devices

- one million atmospheric neutrinos
- 10 megaton
- at analysis level:

DeepCore: one every 15 min

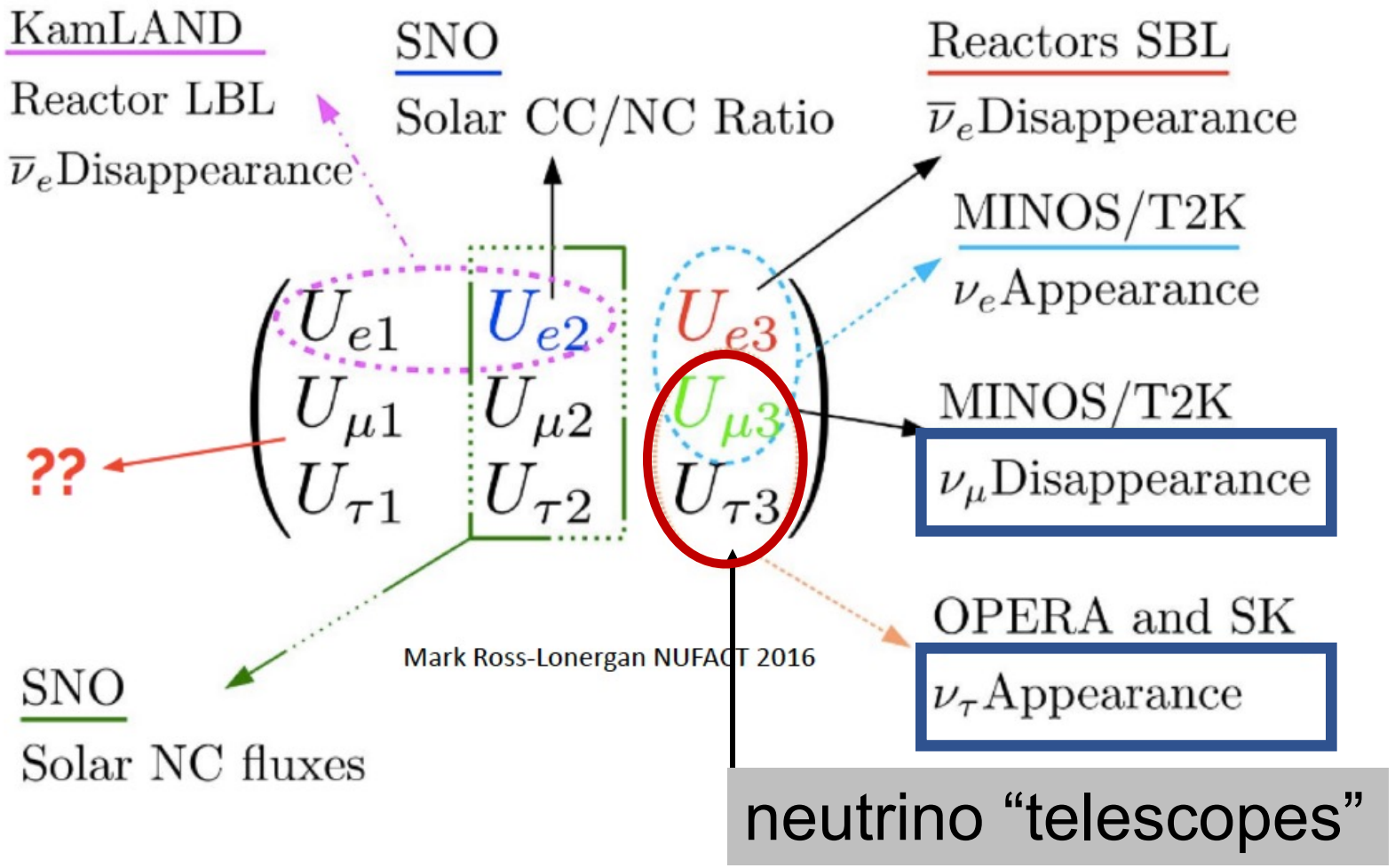
Upgrade: one every 4 min





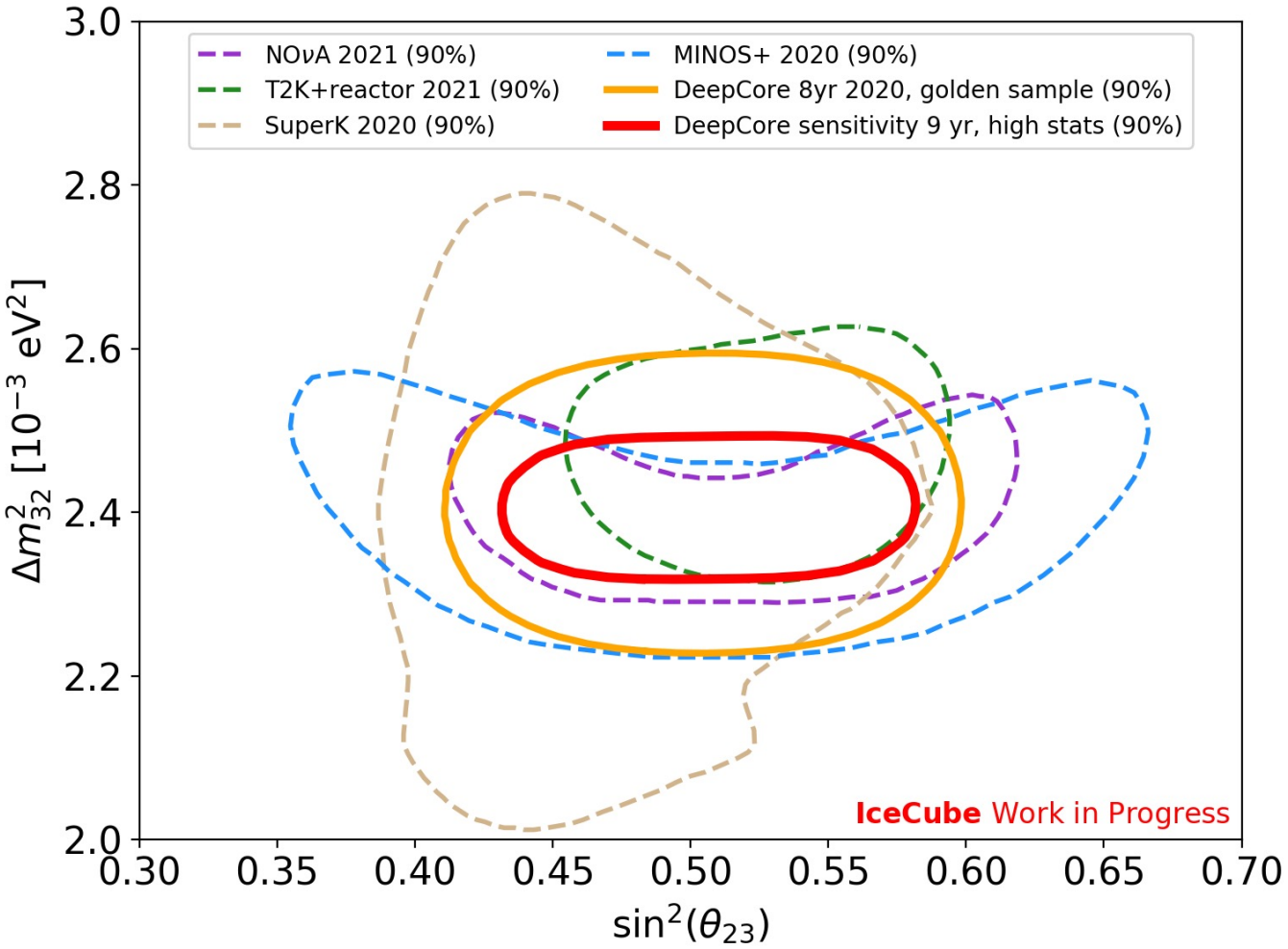
neutrino oscillations with a neutrino telescope:
access to tau neutrinos in the atmospheric (and cosmic beam)

The PMNS mixing matrix



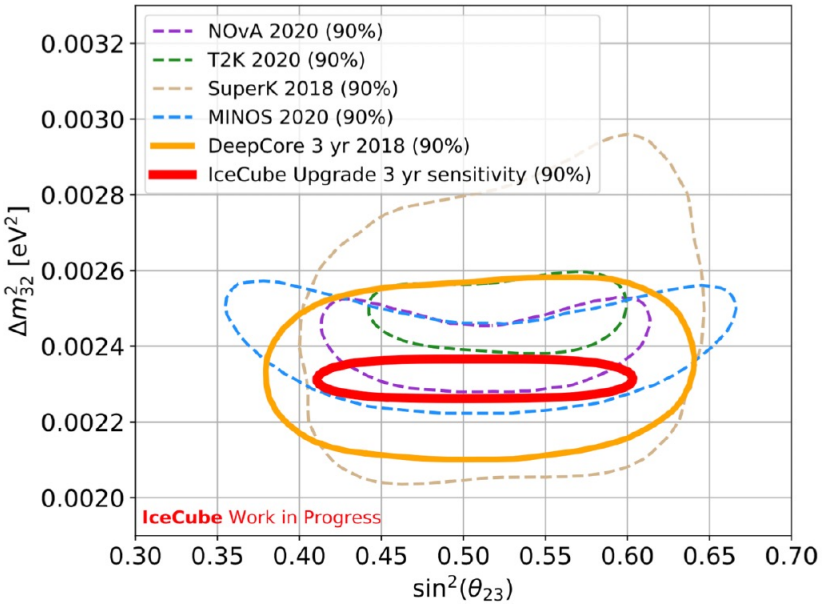
imminent unblinding:

- analysis with a sample of 210,000 neutrinos (9.3 years and 97.3% purity)
- higher energy than accelerator experiments and SuperK (5~55 GeV)
- 6900 tau neutrinos
- improved calibration of the data, event reconstruction using machine learning and new treatment of systematics



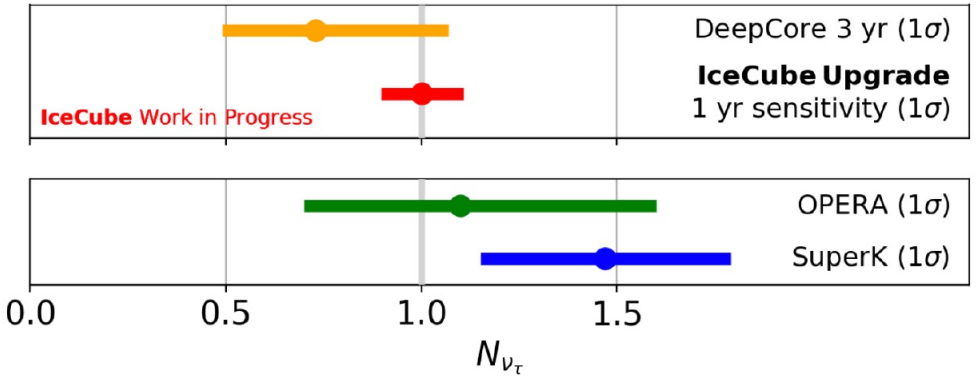
… and with the Upgrade

Atmospheric oscillation parameters



Strong sensitivity in 3 yrs or less

ν_τ normalisation



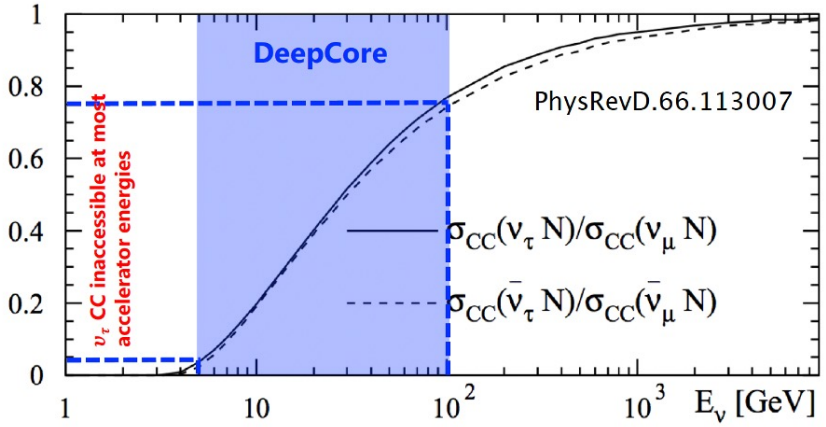
10% ν_τ norm in 1 yr
(6% in 3 yrs)

… and the improvements implemented between the 3 and 9.3-year DeepCore analyses have not been applied !

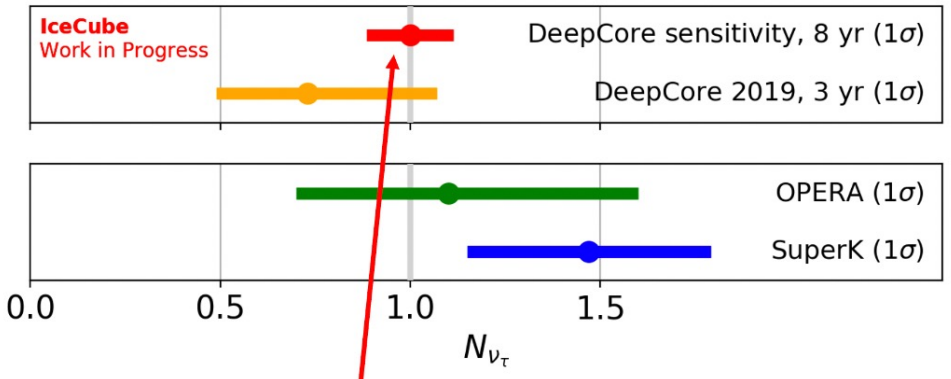
ν_τ appearance before Upgrade

- IceCube is the only experiment that observes the tau neutrino event produced by the disappearance of the muon neutrino
- Upgrade will be the leading neutrino physics experiment worldwide before the commissioning of HyperK (2027) and DUNE

ν_τ CC cross section suppression



ν_τ appearance sensitivity



New 8 yr analysis sensitivity → 11,000 υ_τ expected

12% precision expected → 2.5x current world best

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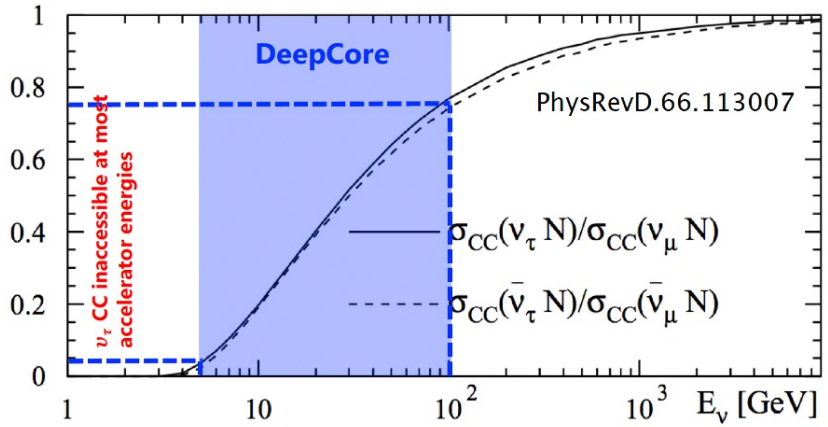
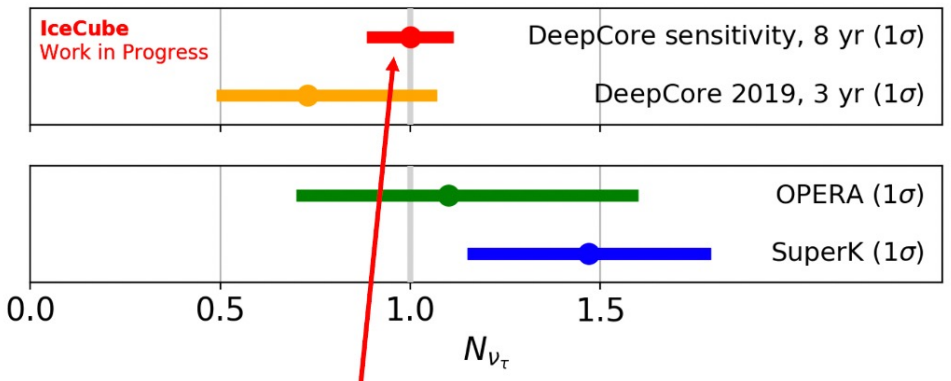


ν_τ appearance sensitivity



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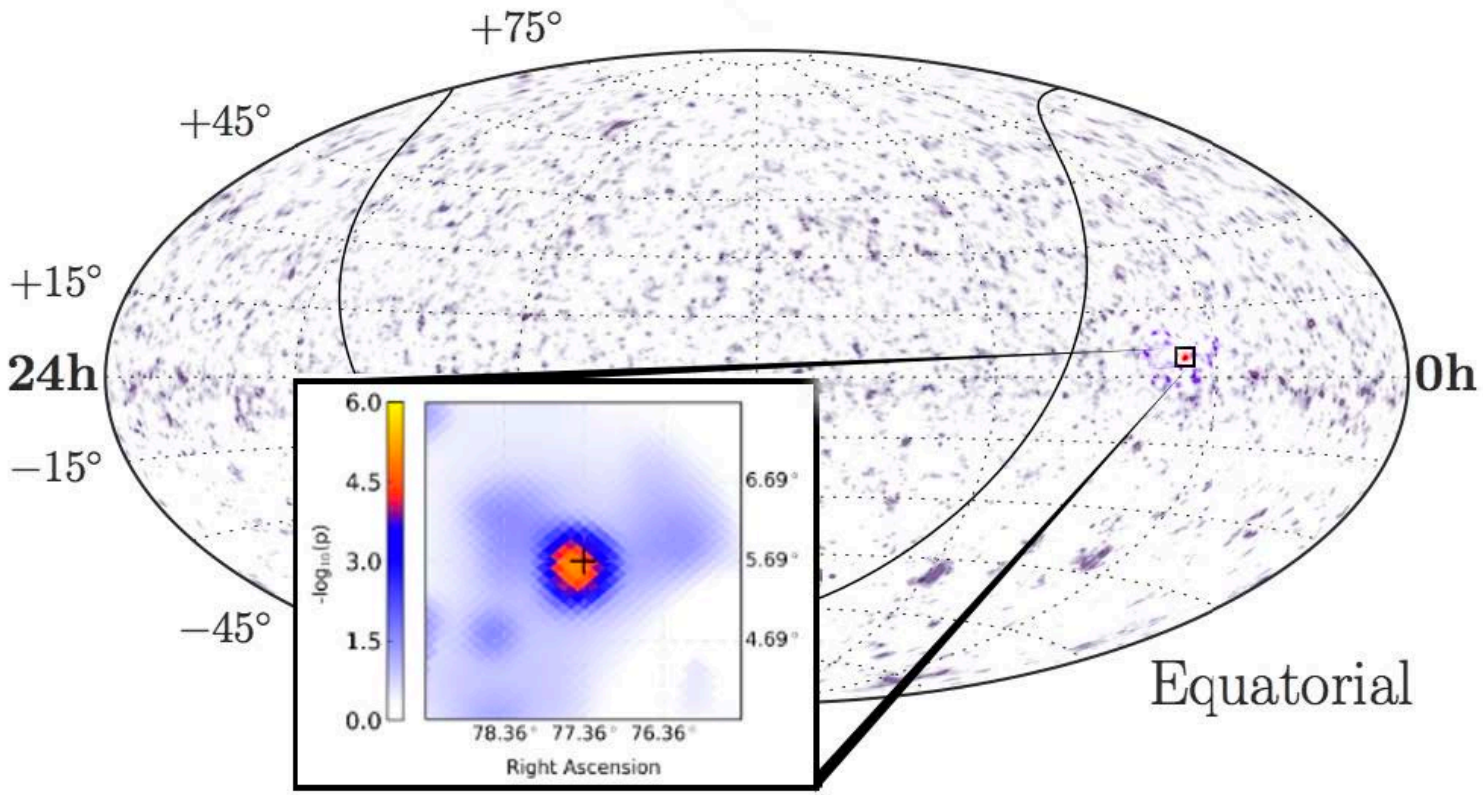
https://www.scientificamerican.com/article/troubled-u-s-neutrino-project-faces-uncertain-future-and-fresh-opportunities/#

Next step: the IceCube upgrade

- improve the scientific capabilities of IceCube at low energies
- improve the scientific capabilities of IceCube at high energies with improved optics of the ice using the information obtained with the Upgrade's small string spacings and novel calibration devices

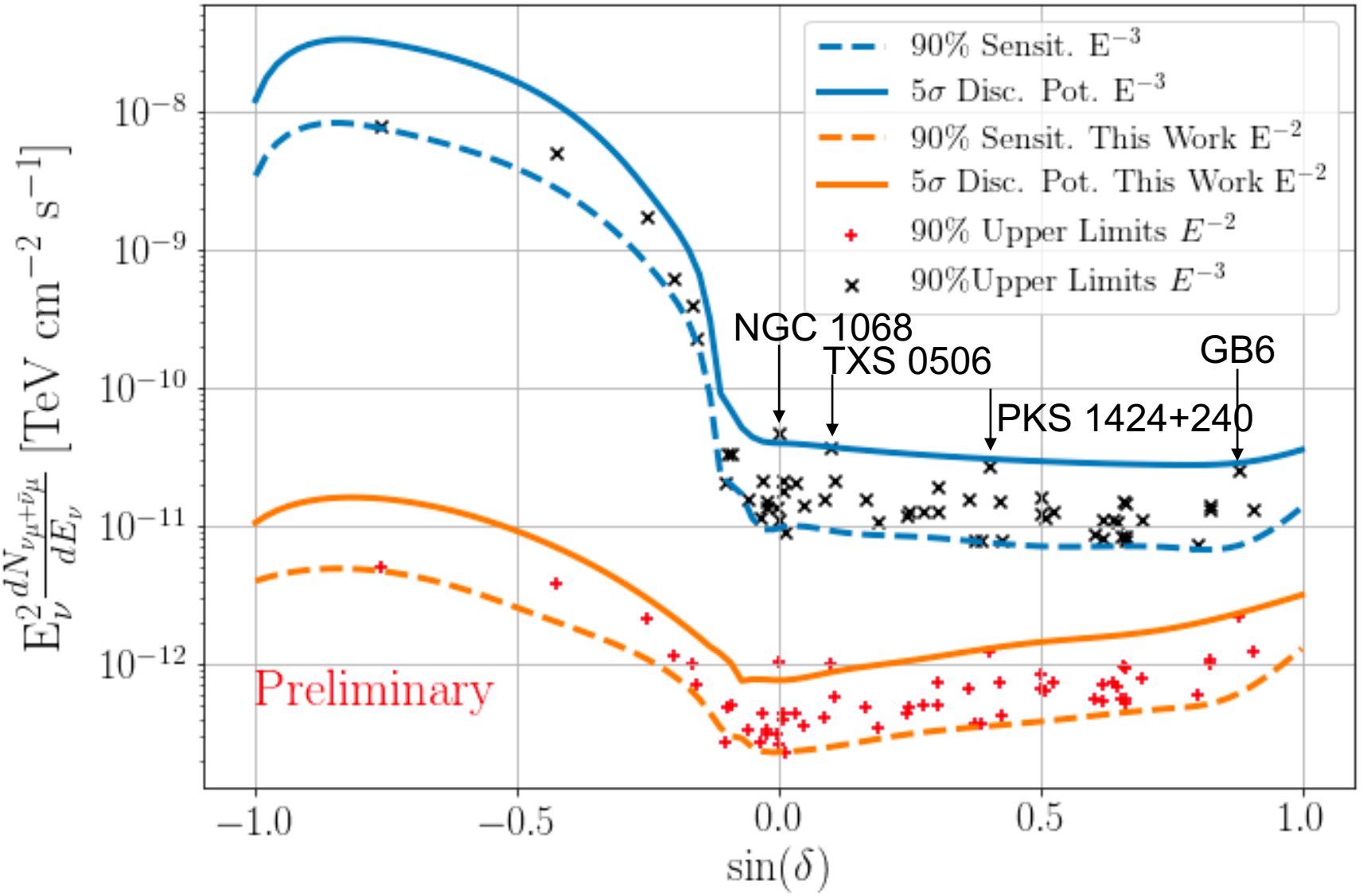
pre-trial p-value for clustering of high energy neutrinos



- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

evidence for non-uniform skymap in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates

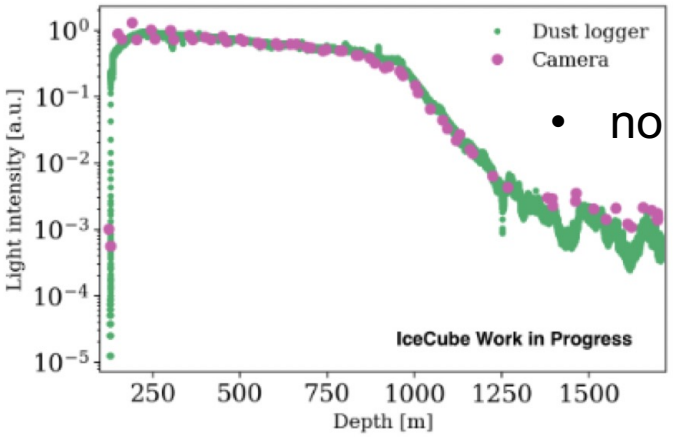
limits and interesting fluctuations (?)



improve calibration, event selection and reconstruction

ice: step by step

- hole ice ?

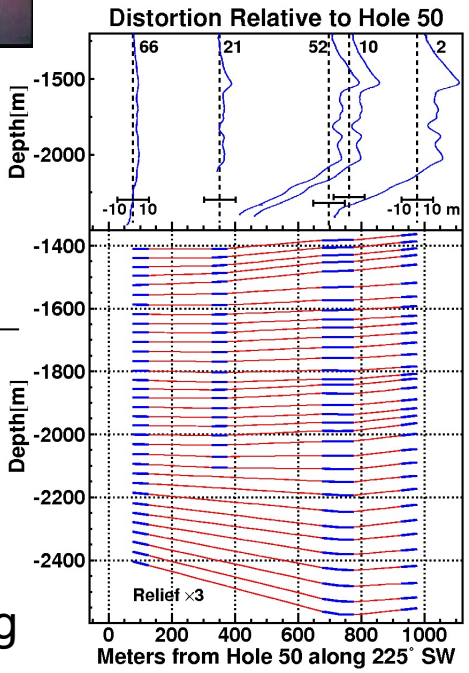


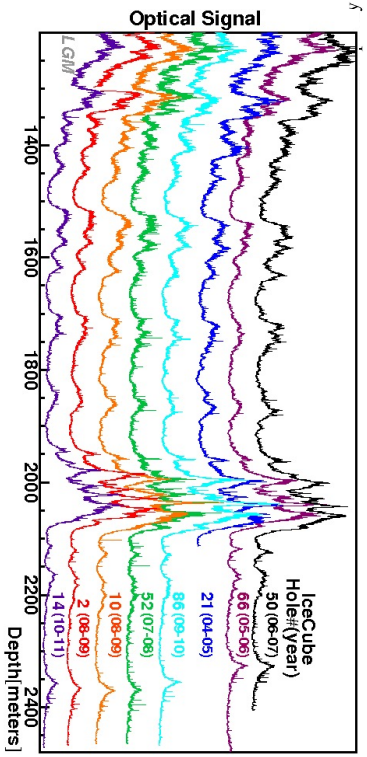
- no air bubbles/hydrates below 1350 m

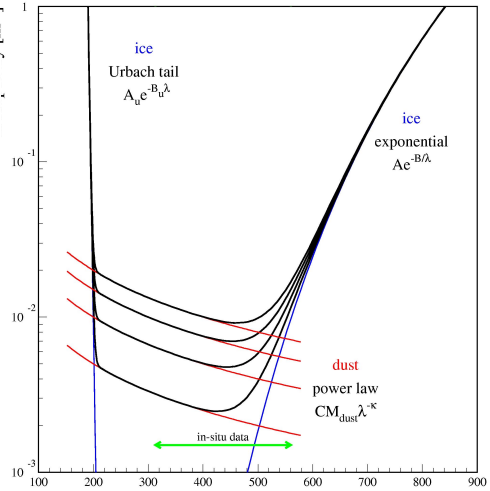
- > 100 m absorption length limited by dust

- ice layers

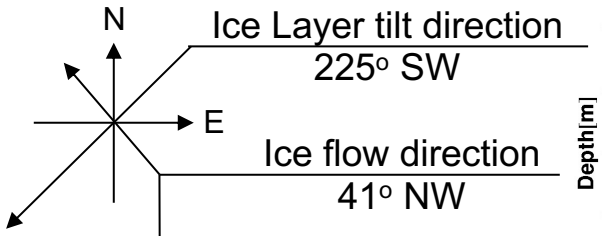
- tilted ice layers







- birefringence

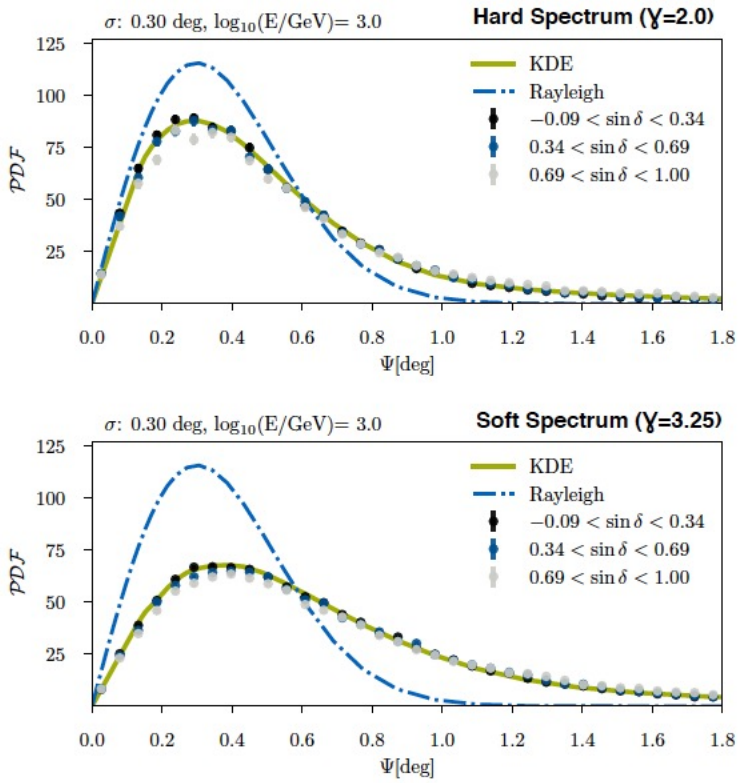


- anisotropy

~8% less scattering

41^0 NW

- improved detector calibration (pass 2)
- improved modeling of the optics of the ice
- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics

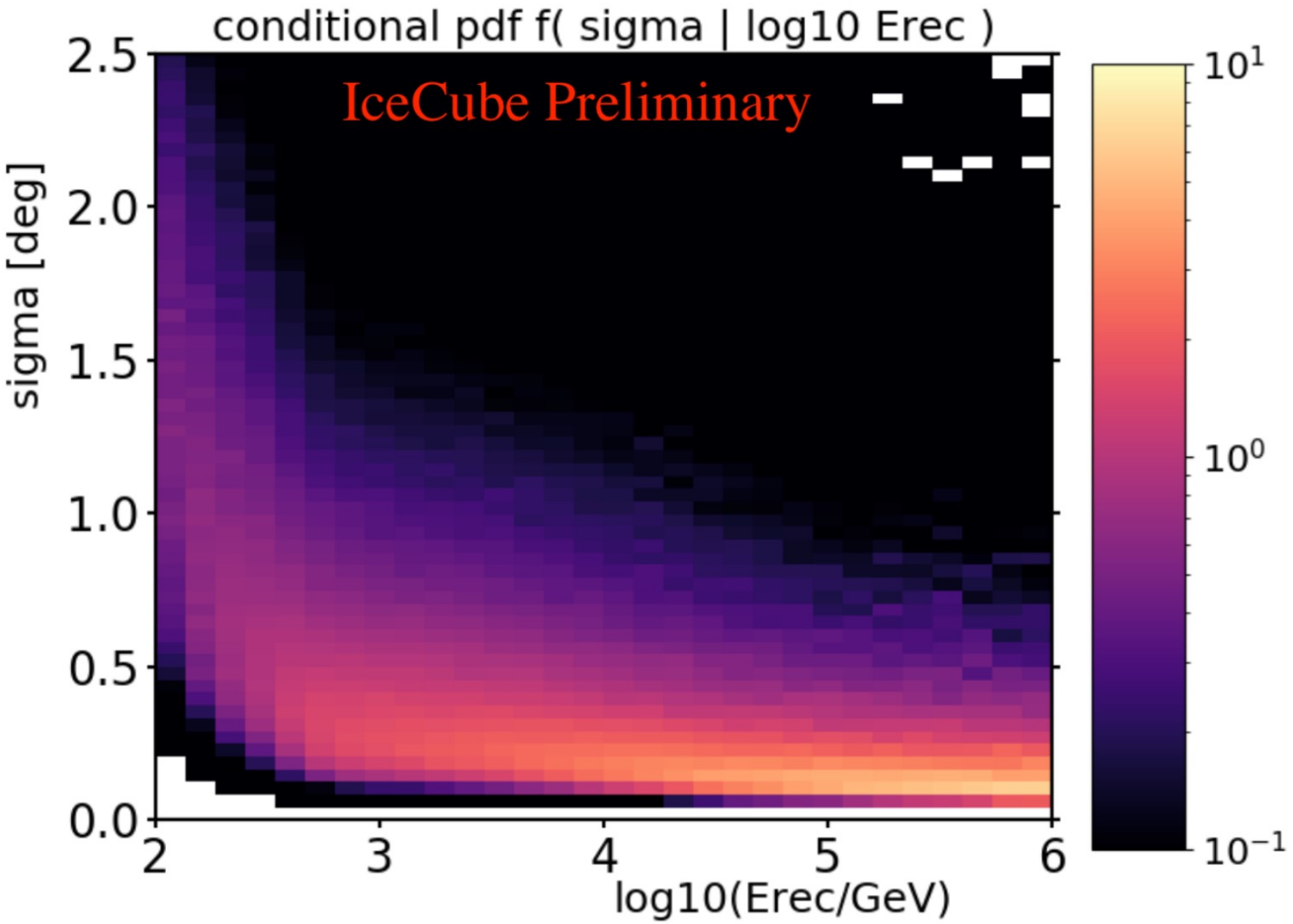


- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the γ-dependent spatial term from MC simulation (for example using KDEs)

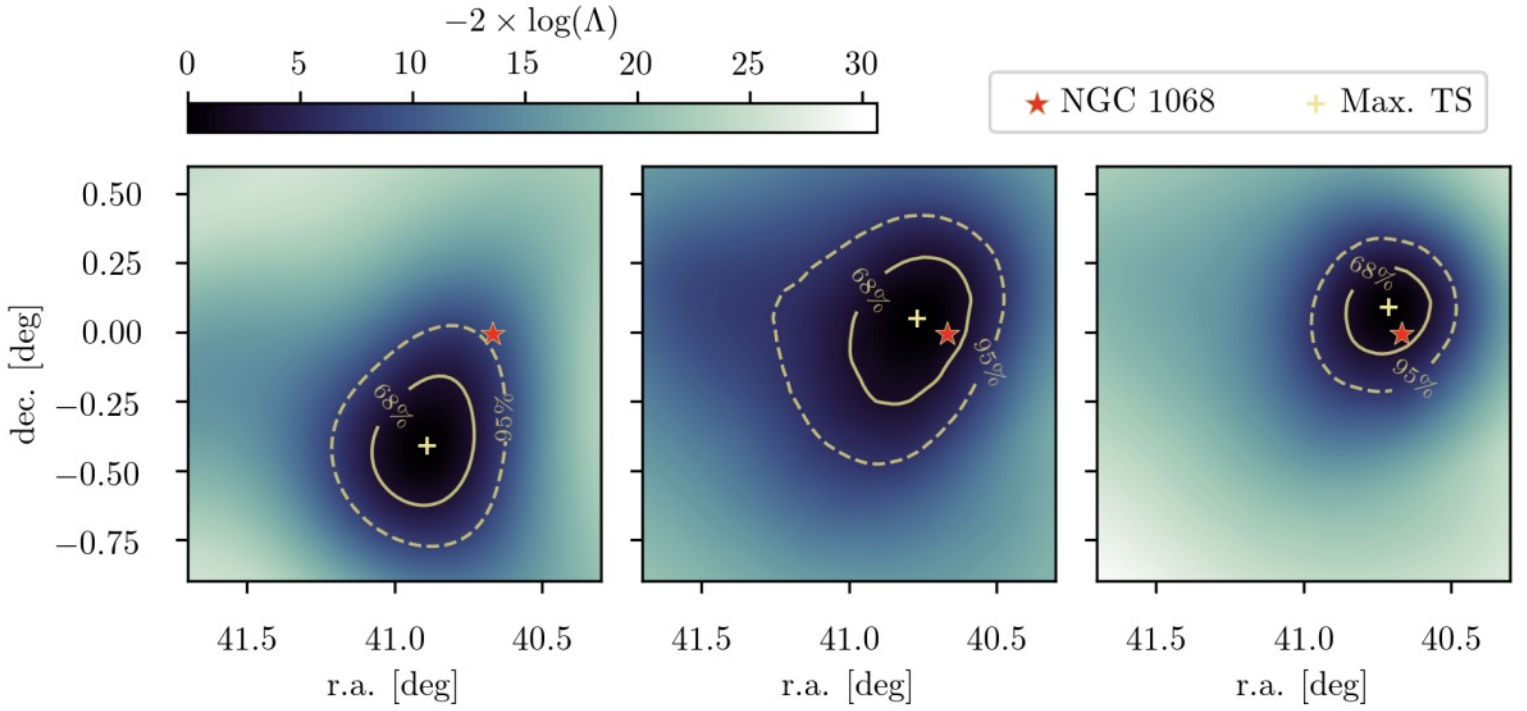
$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}\left(\psi \,|\, \sigma,\, E_\mu,\, \gamma\right)$$

very soon!

sources come into focus: angular resolution < 0.3°



NGC 1068 comes into focus:



2.9σ

- 10-year analysis

3.3σ

- new likelihood method

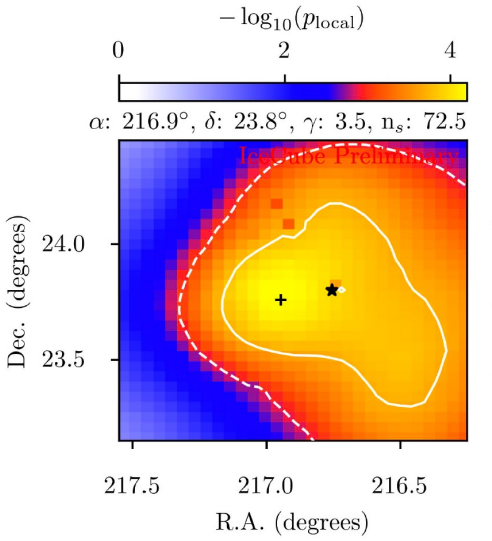
4.2σ

- 10-year analysis
- new likelihood method
- new reconstructions energy/direction
- 1 pe calibration of individual DOMs

submitted to *Science*

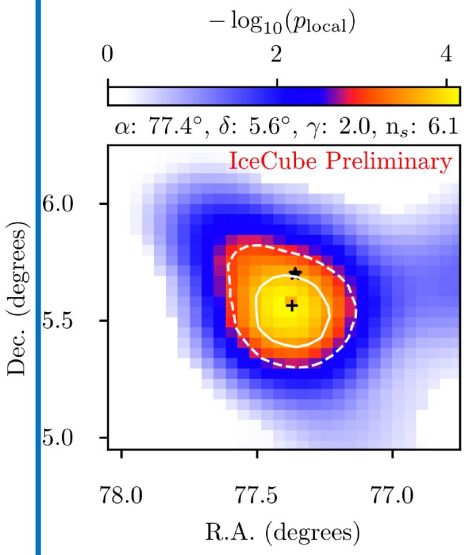
what about the other sources?

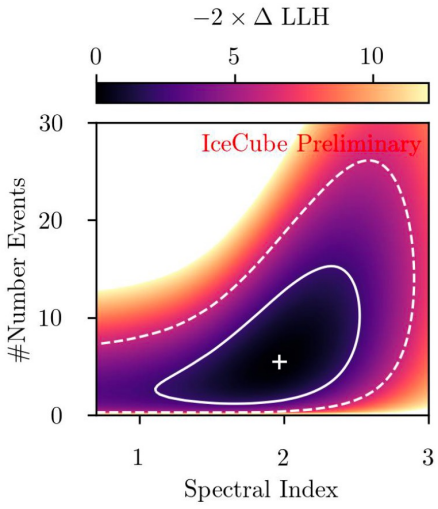
- TXS 0506+056: 3.6σ → 3.7σ
- PKS1424+240 : 3.0σ → 3.7σ

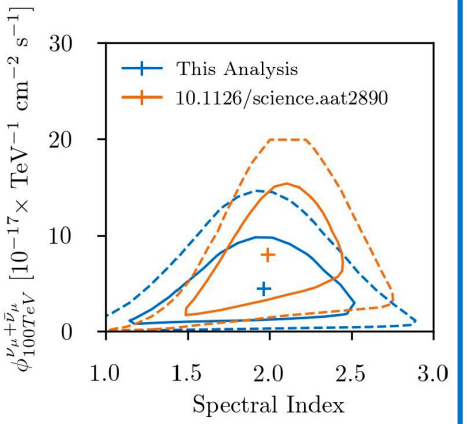


PKS 1424+240

3.0σ -> 3.7σ





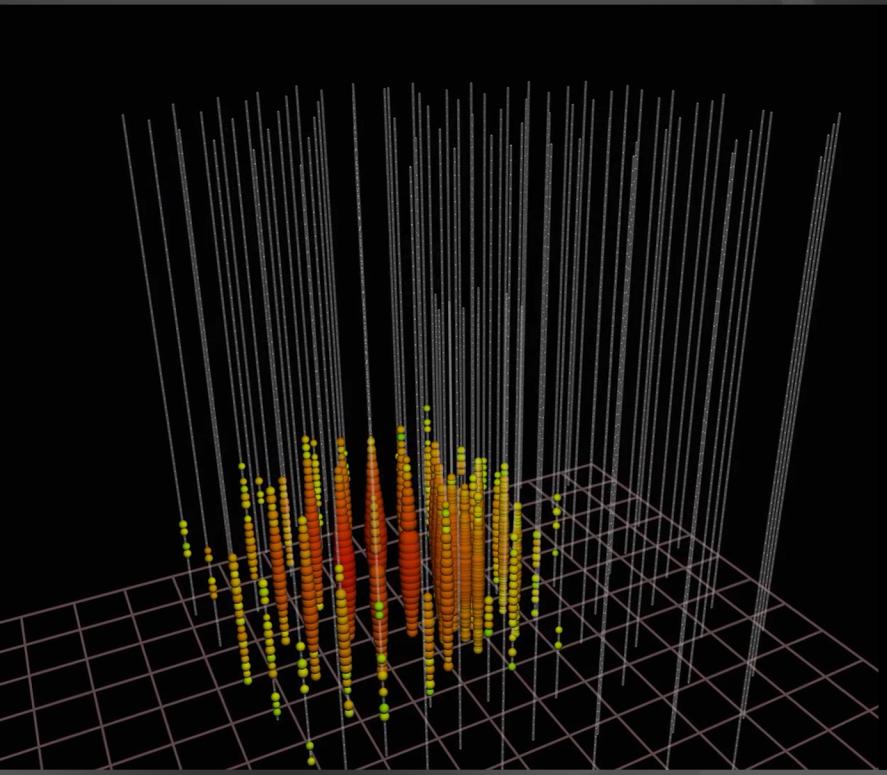


results broadly consistent with previous work.

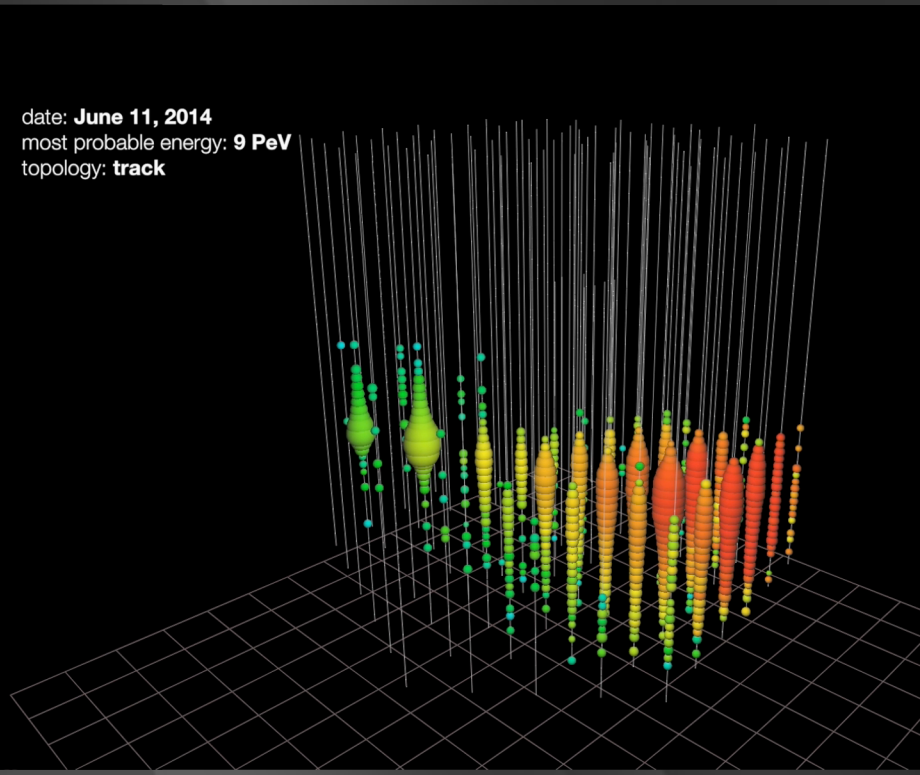
TXS 0506+056

ongoing program to improve the focus of the neutrino telescope will receive another boost with the information on the ice obtained with the Upgrade's small string spacings and the new calibration devices

neutrinos interacting inside the detector



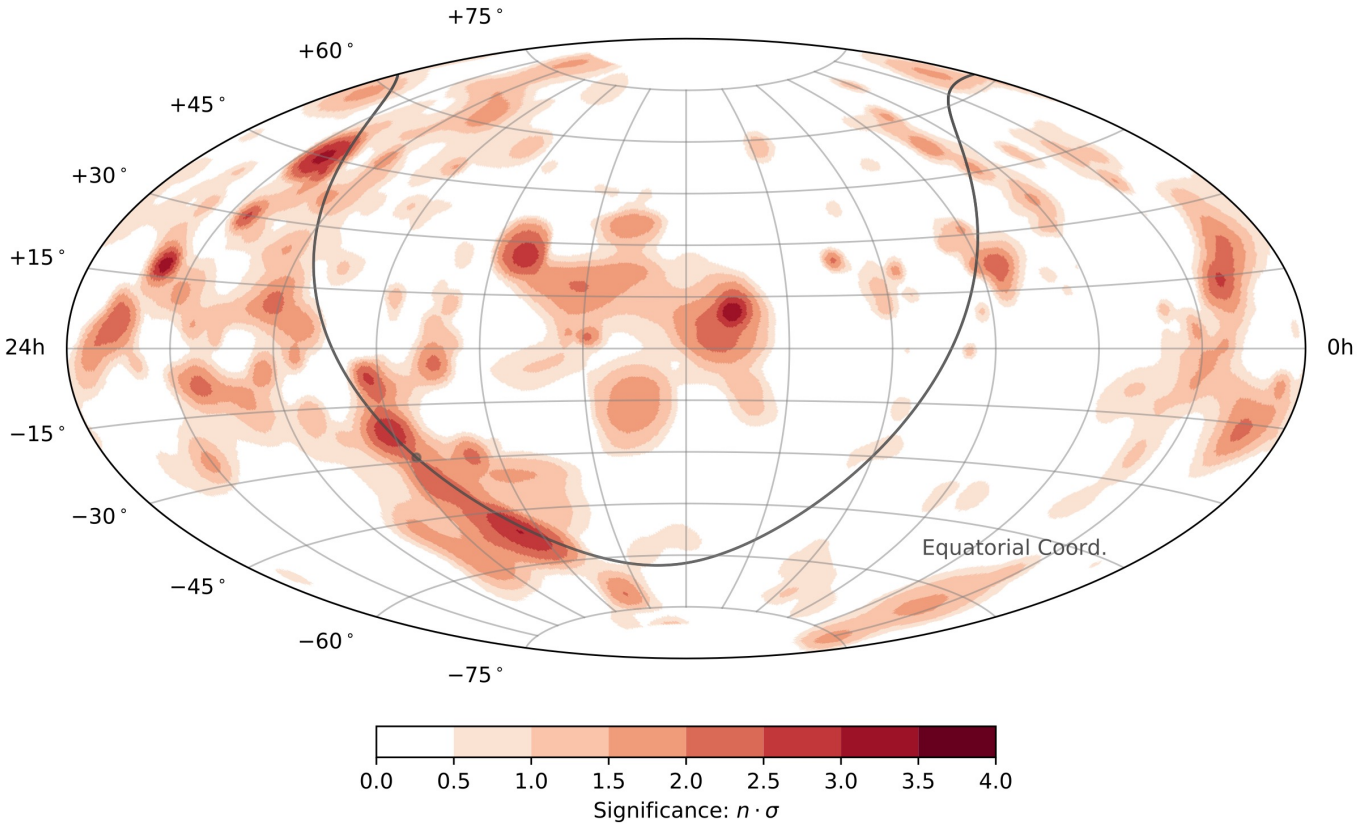
muon neutrinos filtered by the Earth

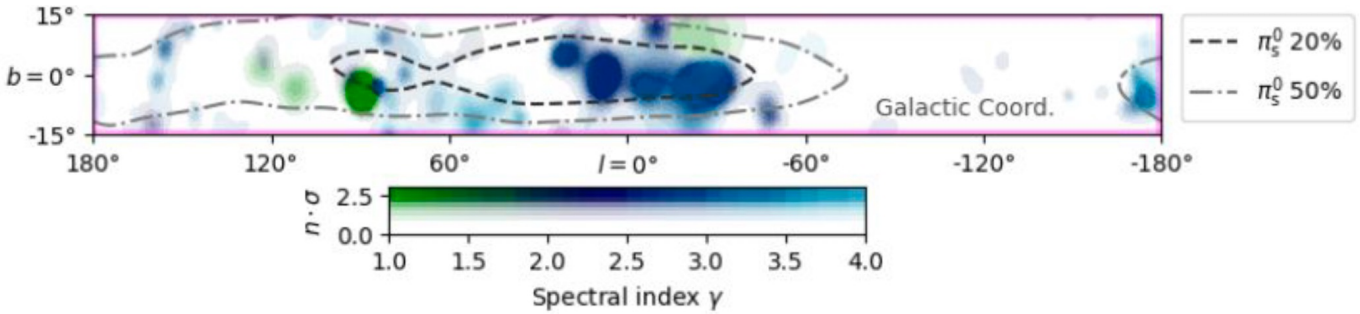


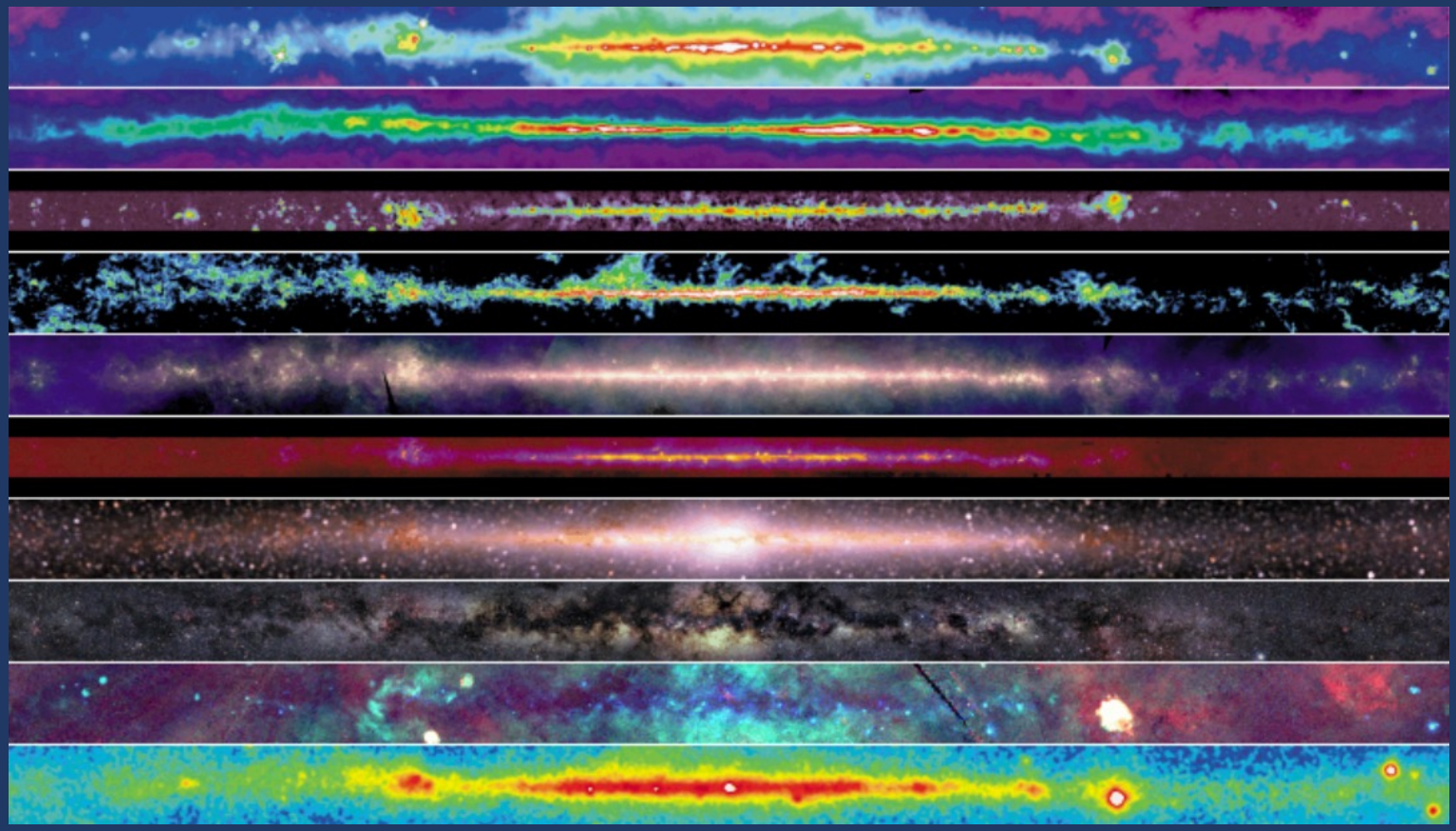
superior total energy measurement to 10%, all flavors, all sky

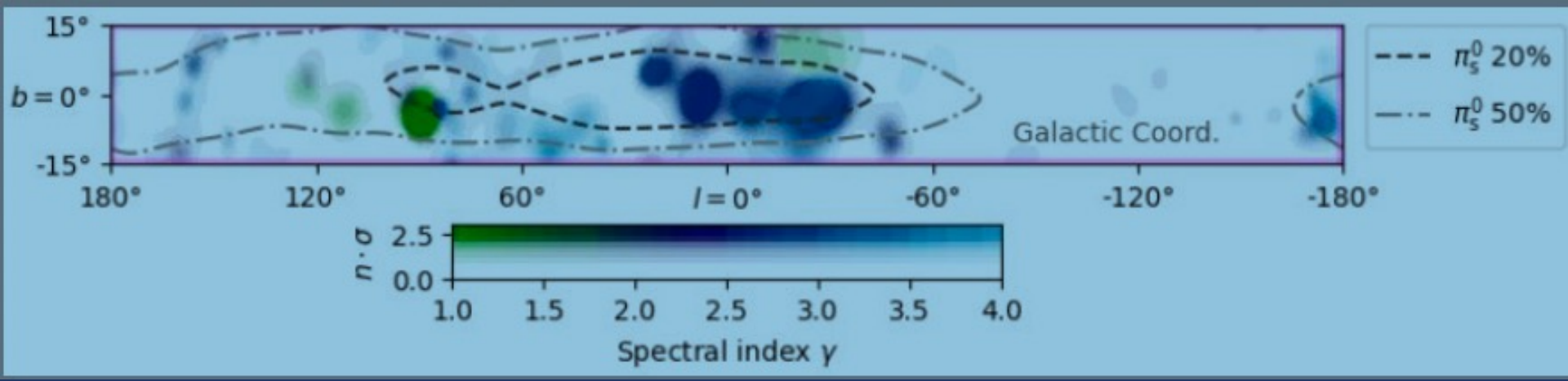
astronomy: superior angular resolution superior (< 0.3º)

we finally found our own Galaxy

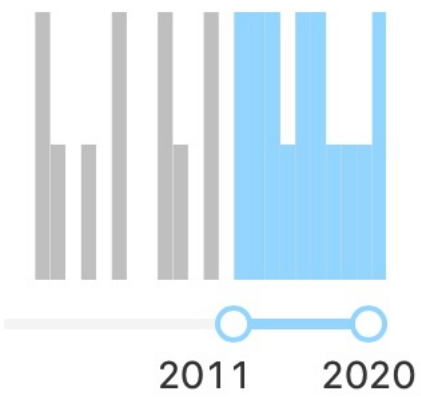




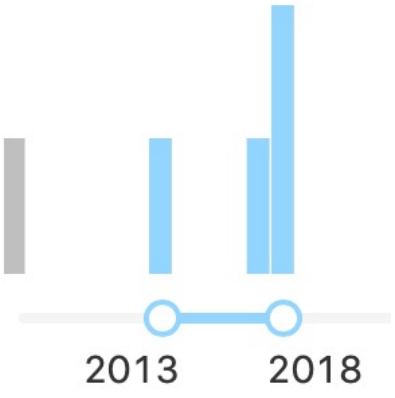



15°
b = 0°
-15°
180°
120°
60°
l = 0°
-60°
-120°
-180°
Galactic Coord.
π_s^0 20%
π_s^0 50%
n · σ
2.5
0.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Spectral index γ

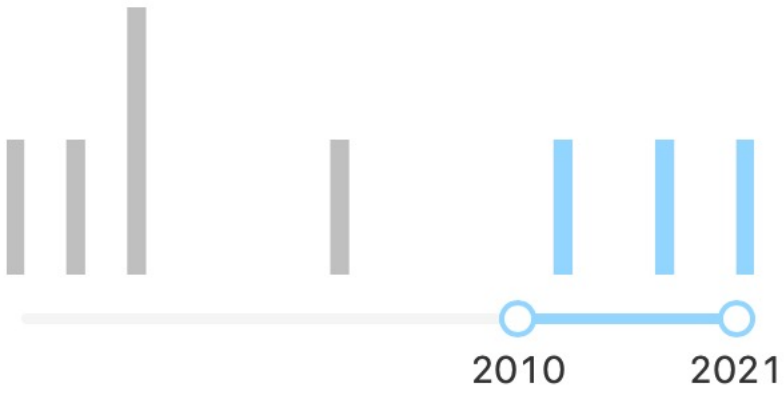
IceCube high profile papers



Phys. Rev. Lett. (16)



Science (4)



Nature (3)

no evidence of decline of new results in 10 years