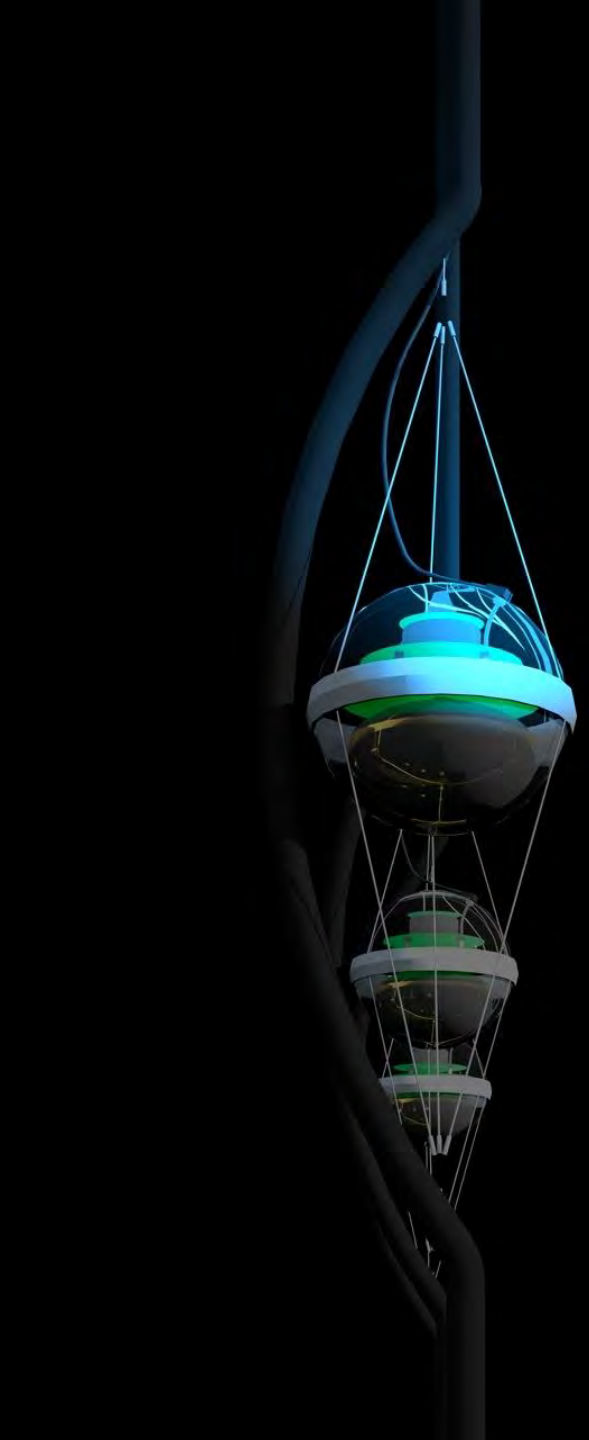


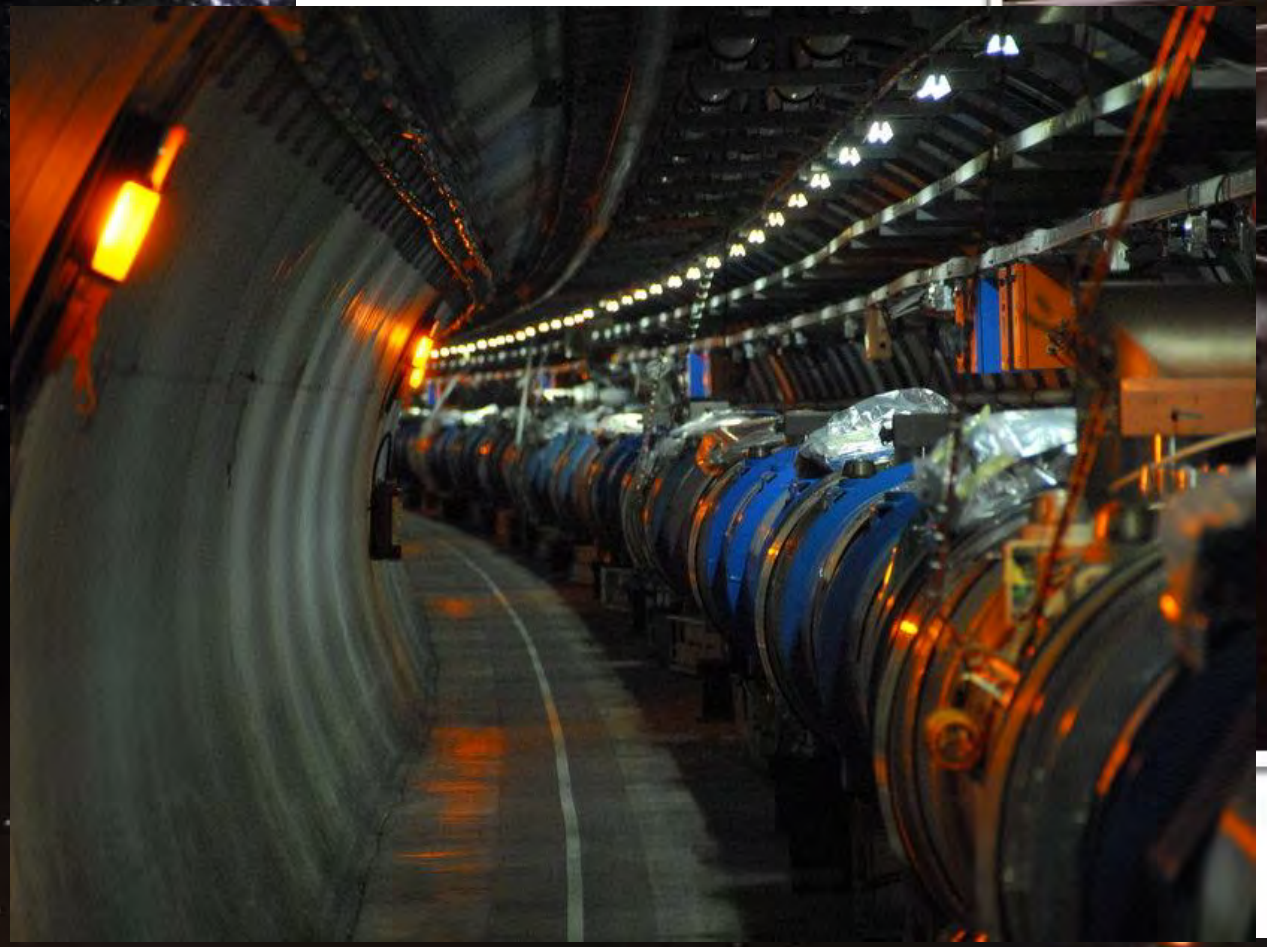
IceCube: the First Decade of Neutrino Astronomy … and neutrino physics

francis halzen

IceCube.wisc.edu

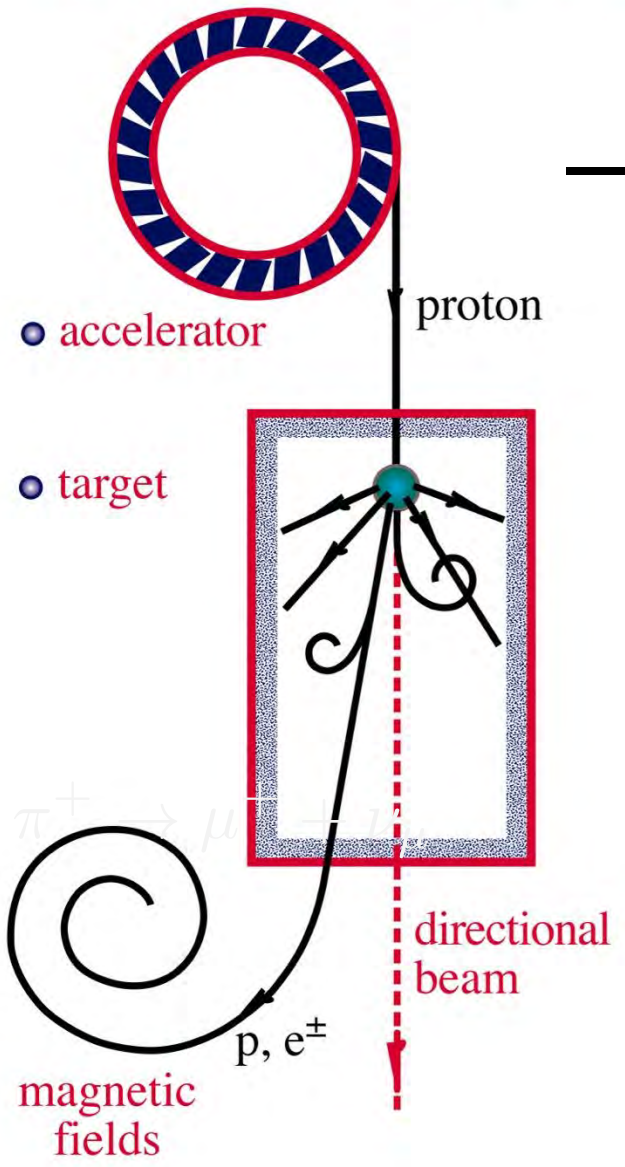
highest energy “radiation” from the Universe: mostly protons !

high energy
high luminosity



Fly’s Eye 1991
300,000,000 TeV

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

nearby radiation

$$p + \gamma \rightarrow n + \pi^+$$

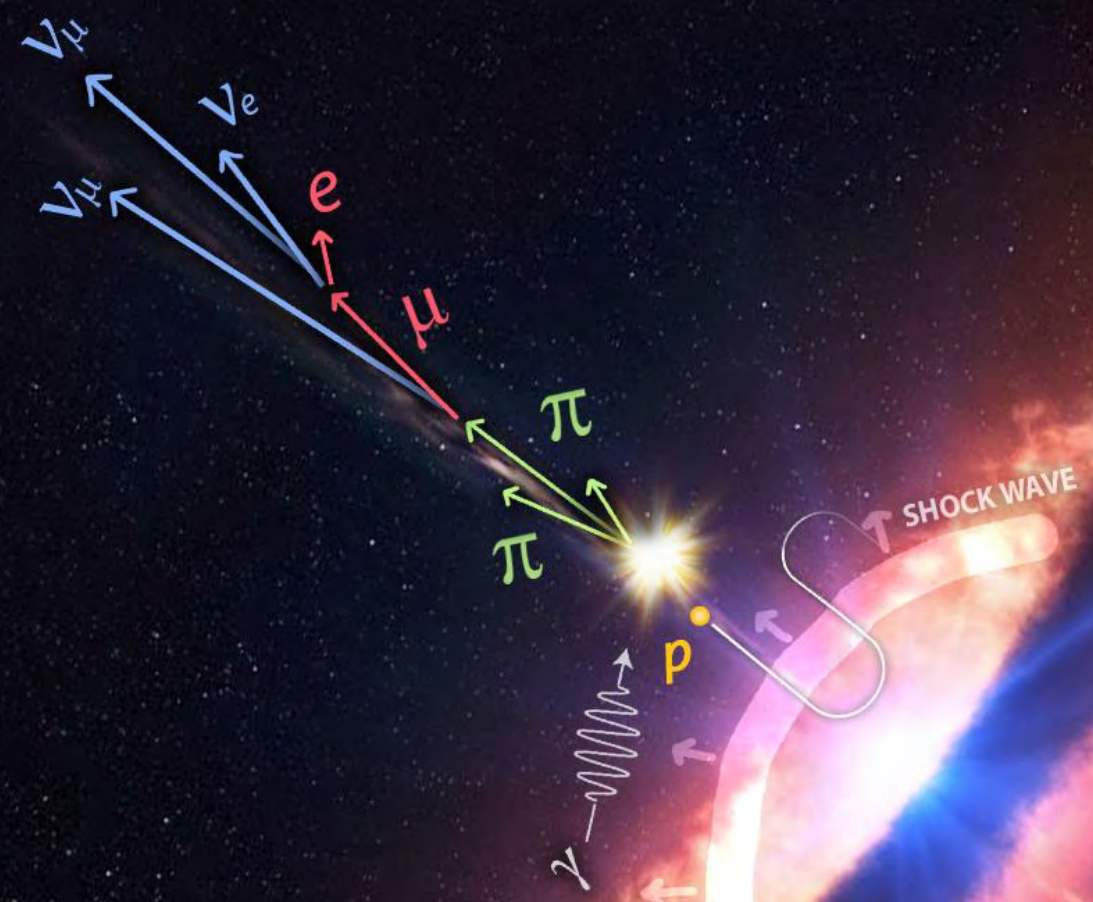
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

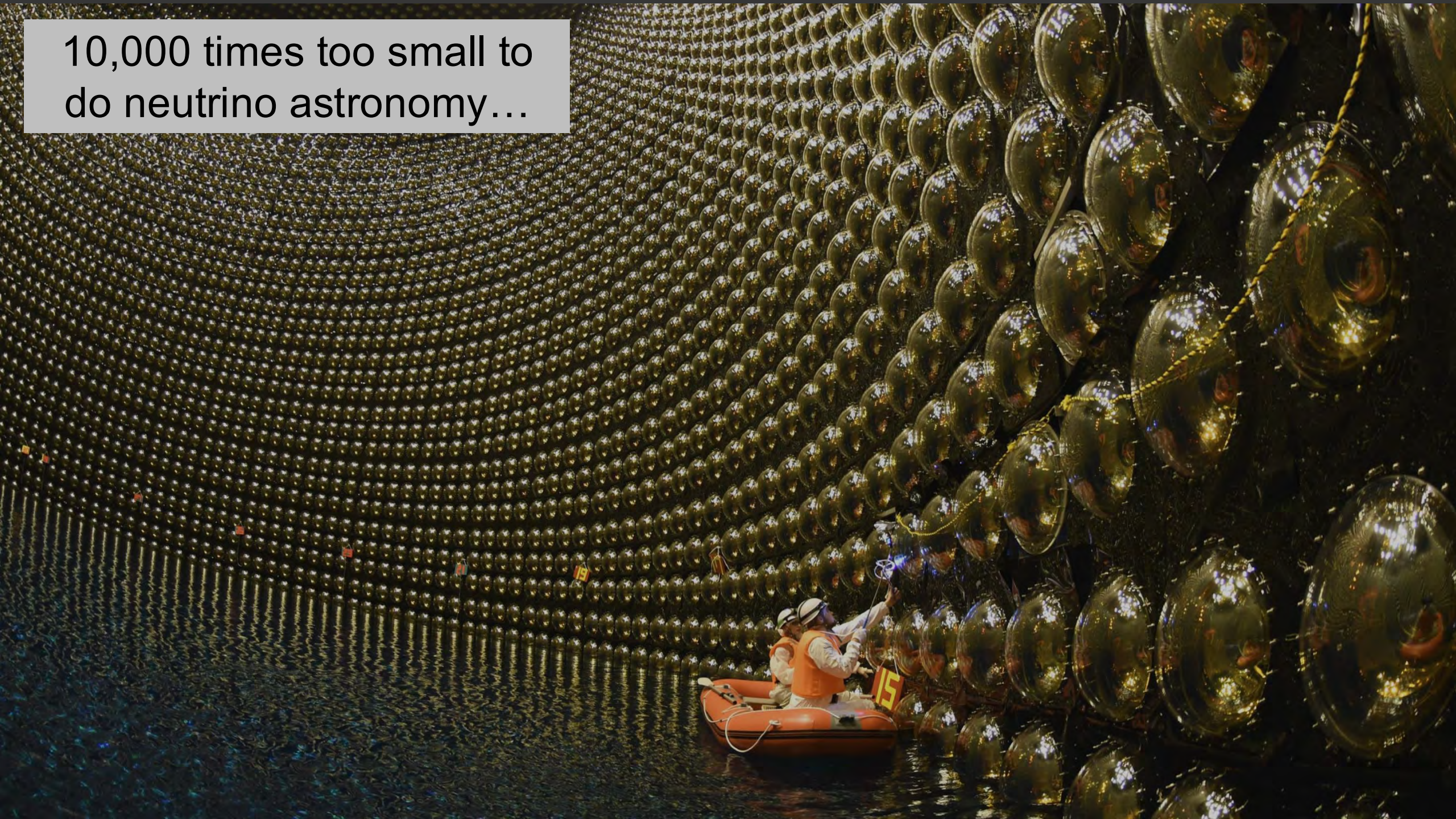
$$\rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

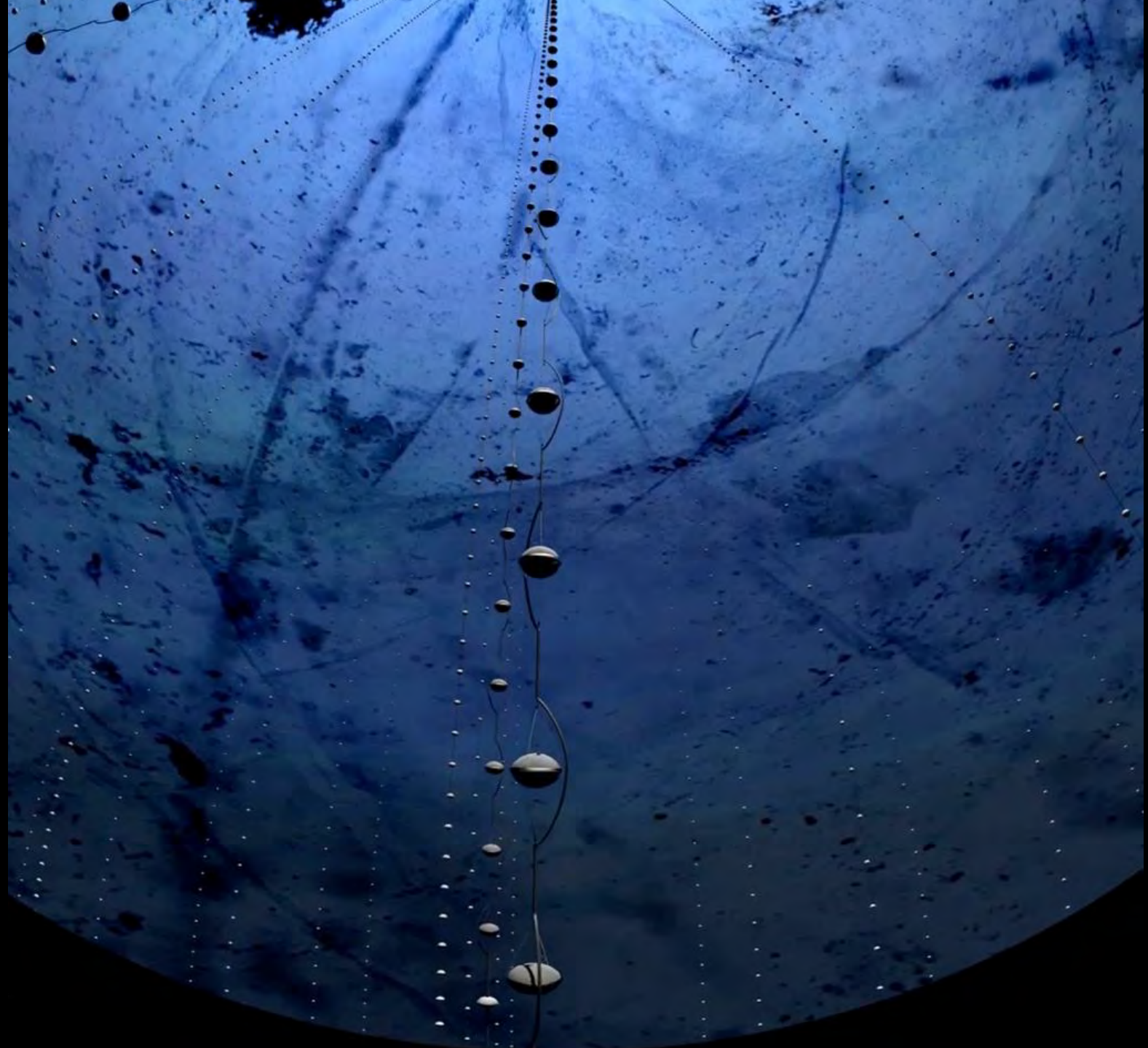
black hole accelerating protons submersed in a target of radiation produce pions



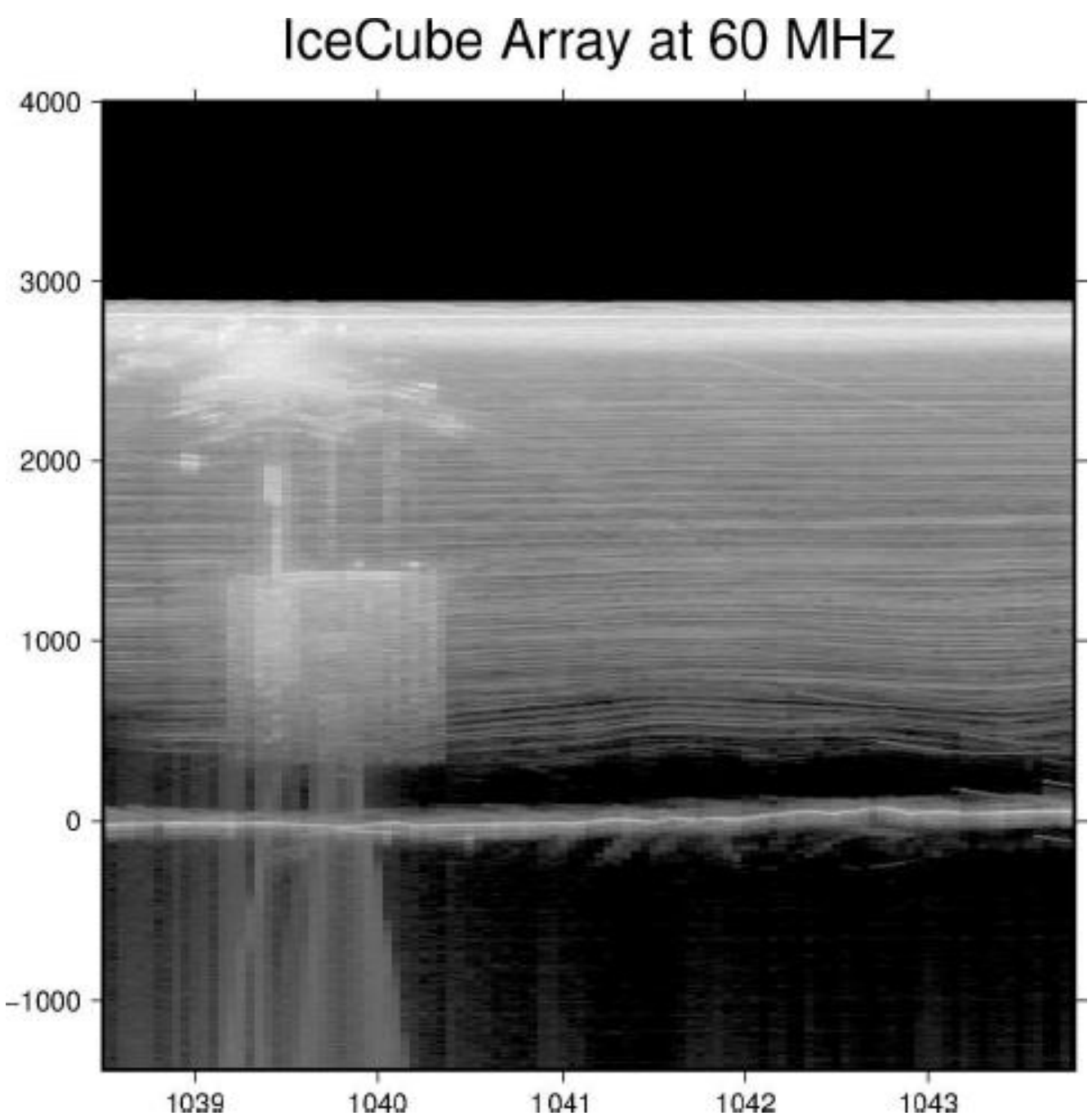
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\pi^0 \rightarrow \gamma + \gamma$$


10,000 times too small to
do neutrino astronomy…

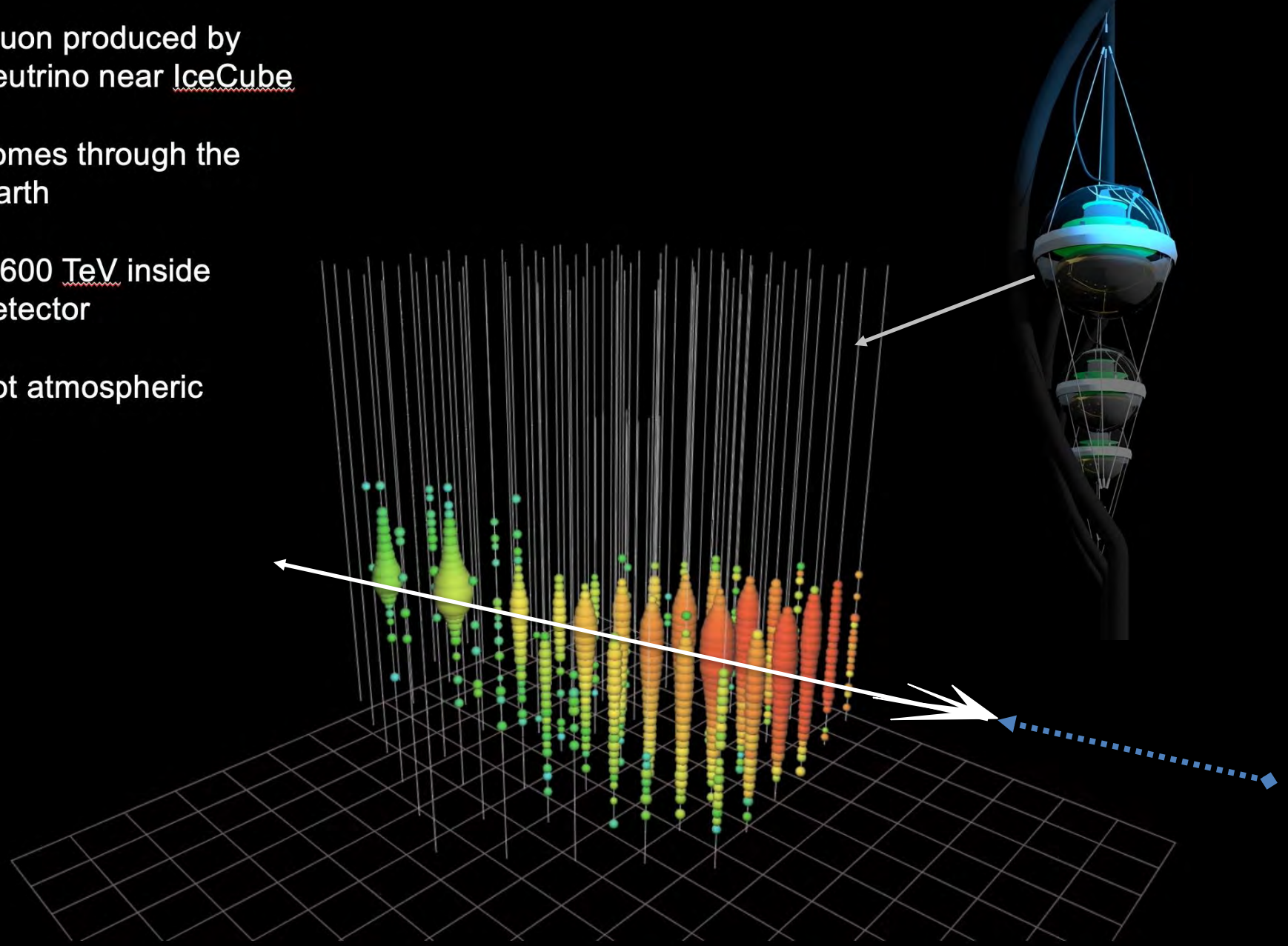
IceCube:
5160 photomultipliers
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector



ground-penetrating radar

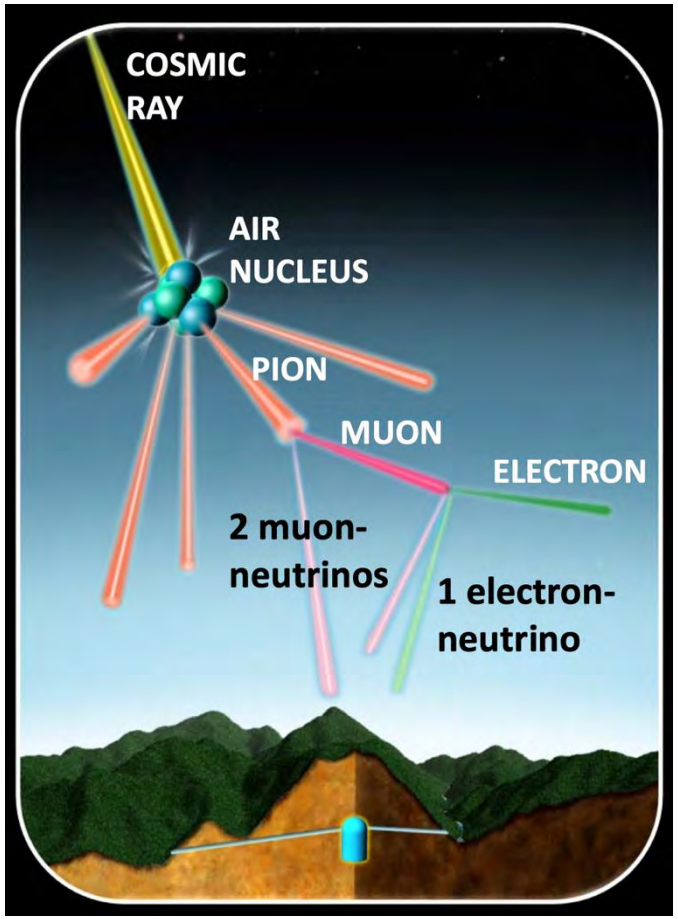


- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



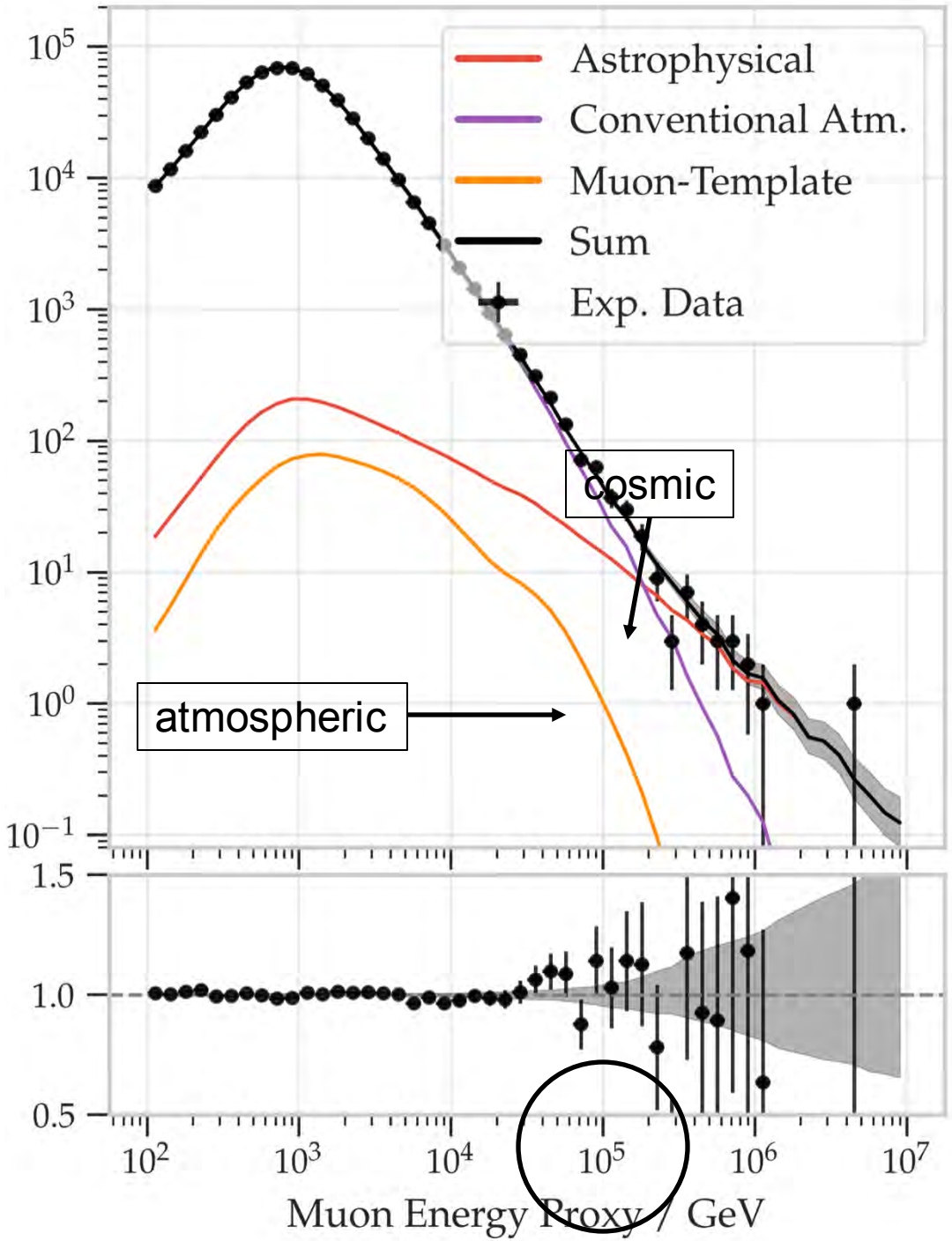
1 km^3 instrumented with 5160 PMT (10inch) below 1450m

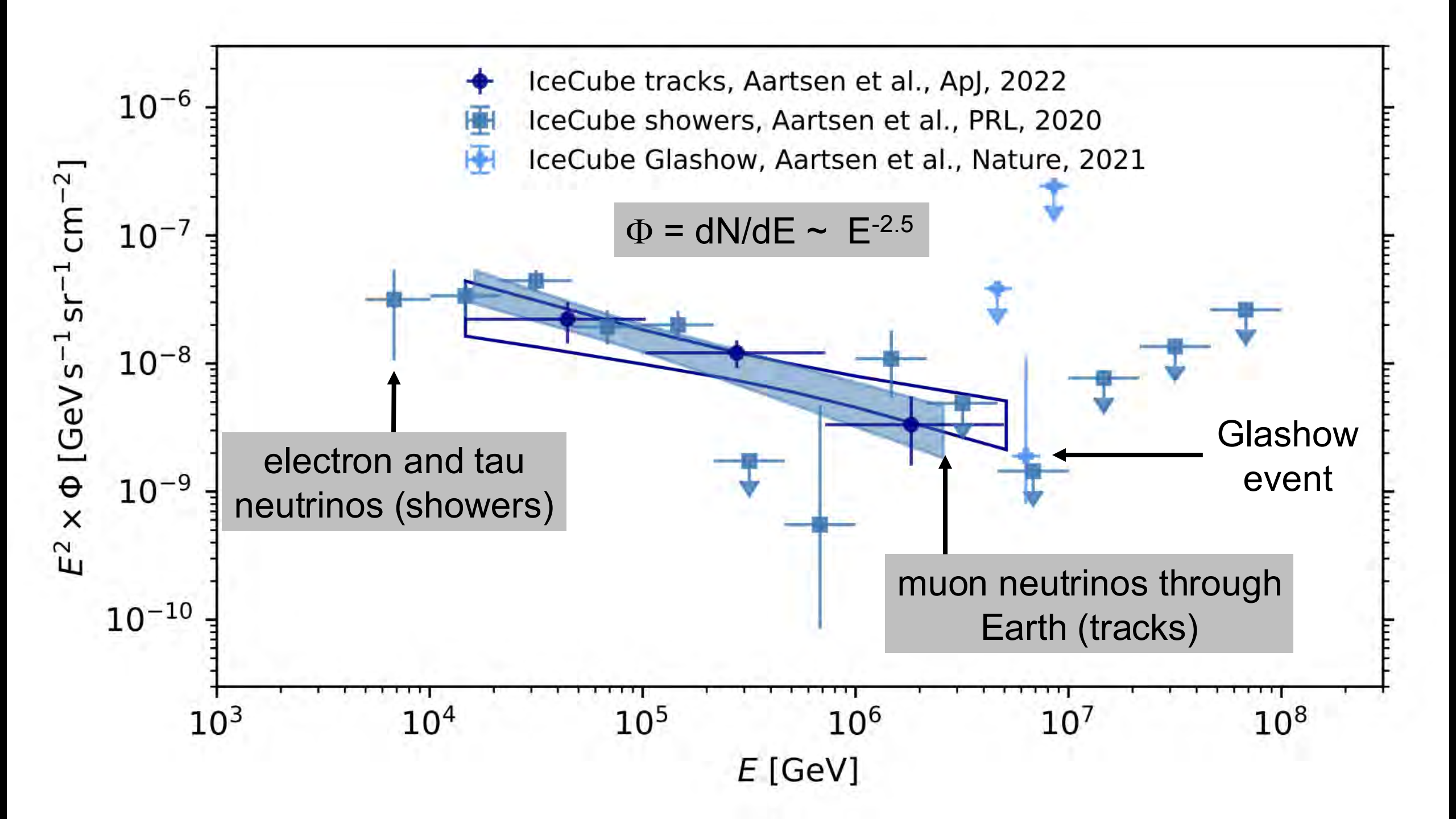
muon neutrino events [filtered by the Earth]: atmospheric vs cosmic



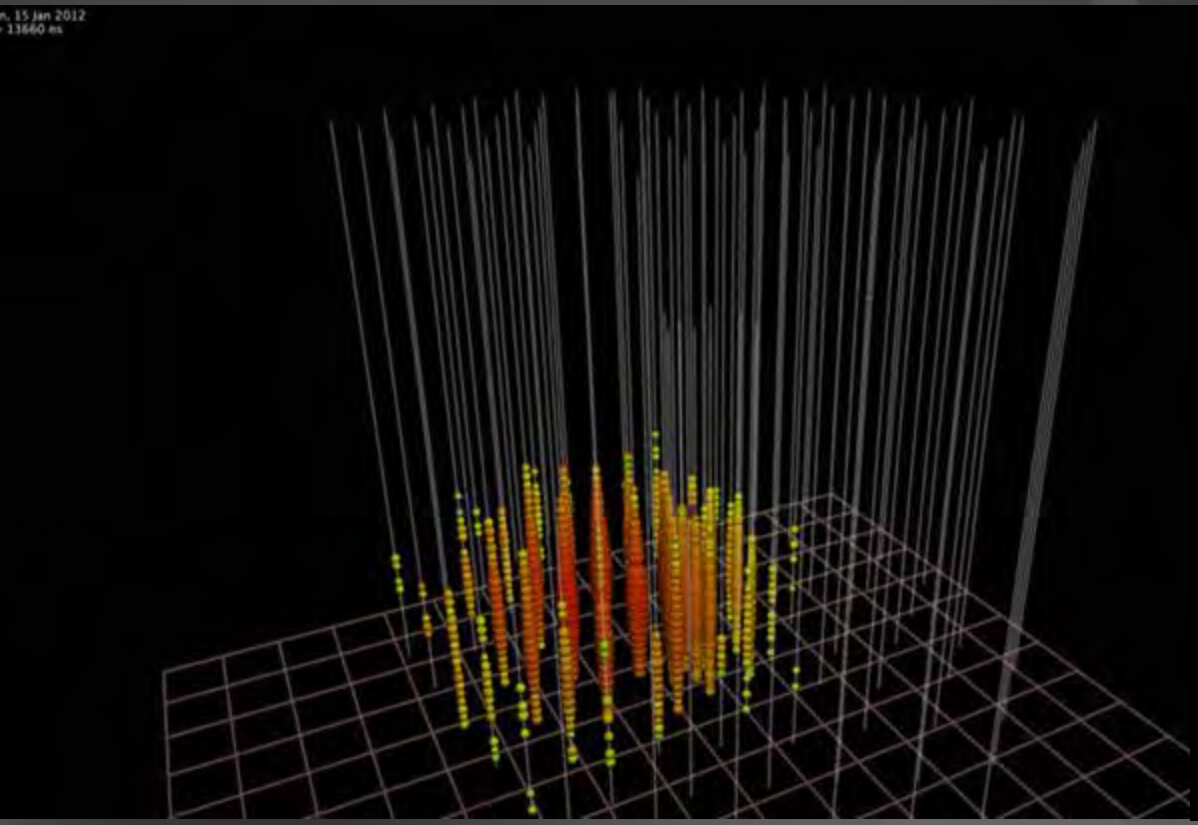
Number of Events

Data/MC



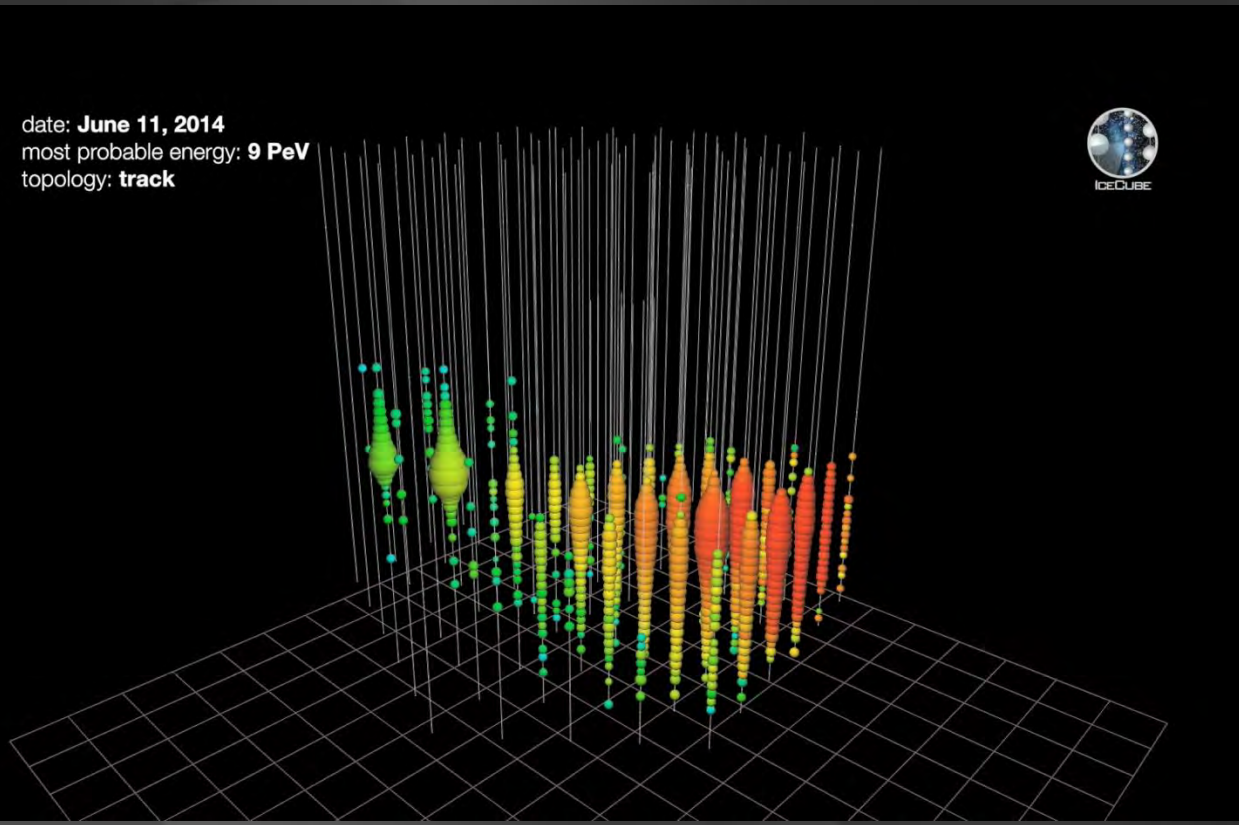

IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi = dN/dE \sim E^{-2.5}$
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8

neutrinos interacting
inside the detector

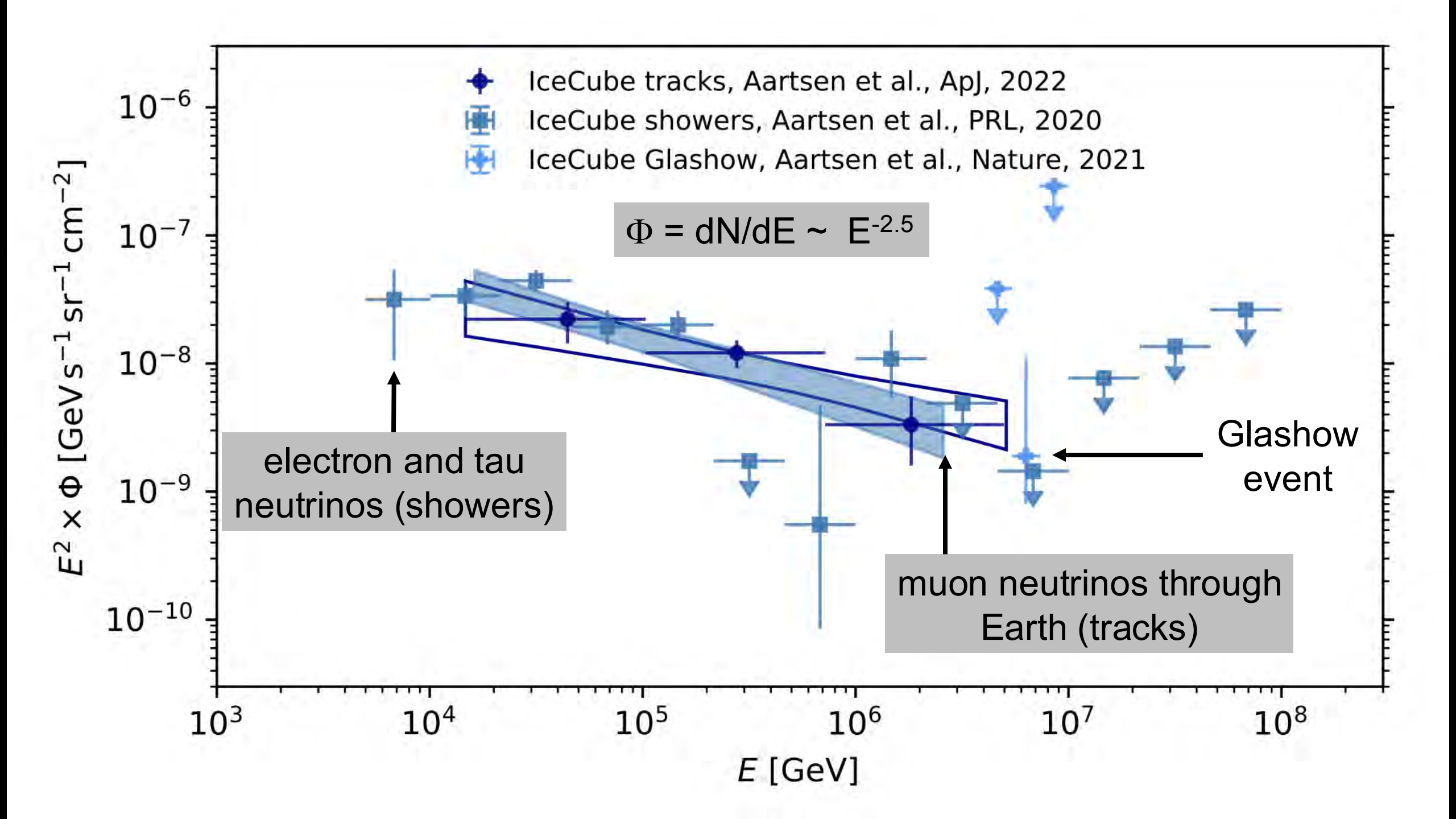


superior total energy
measurement
to 10%, all flavors, all sky

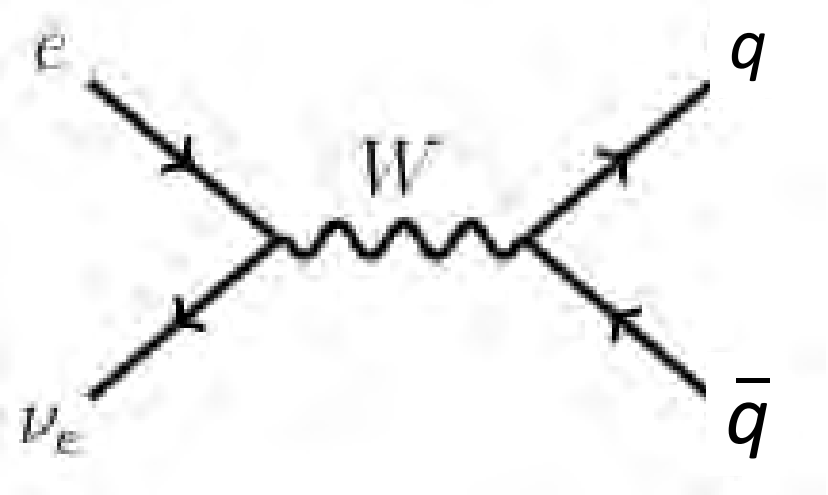
muon neutrinos
filtered by the Earth



superior angular resolution 0.3^{o}
including systematics

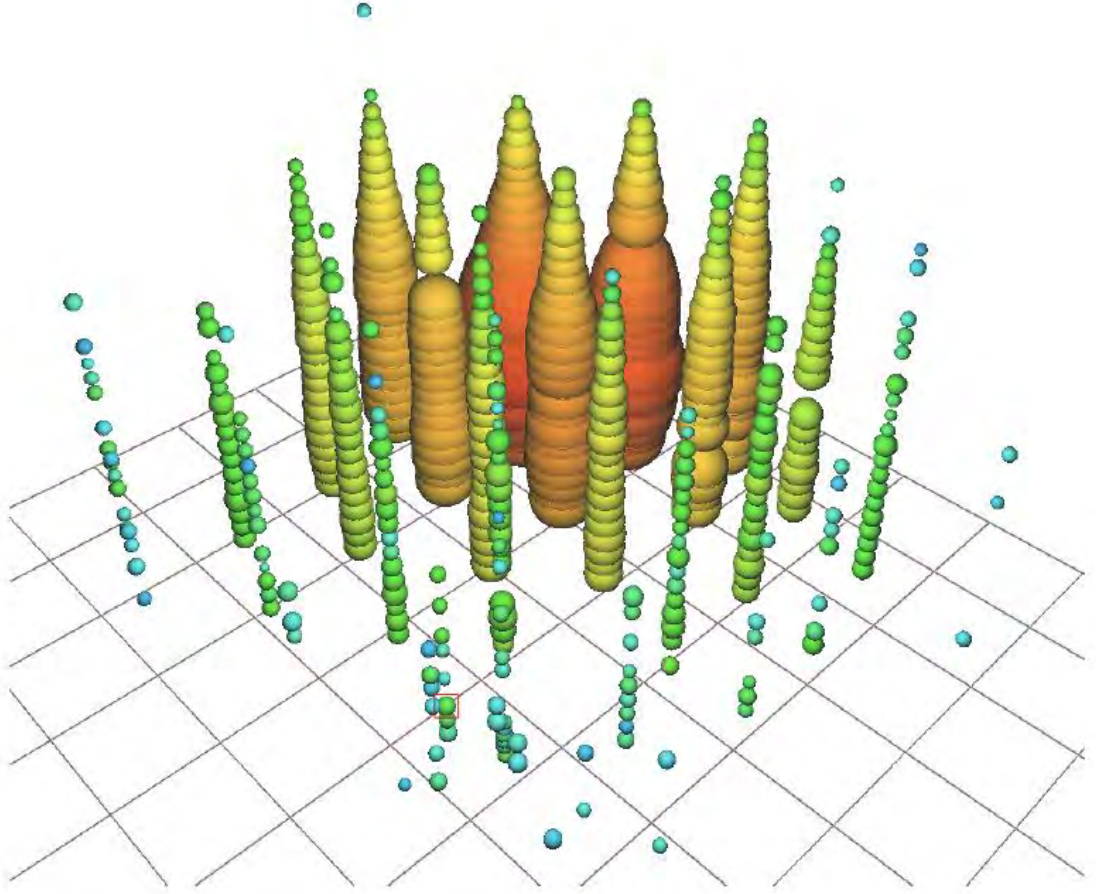

IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi = dN/dE \sim E^{-2.5}$
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8

Glashow resonance event with energy 6.3 PeV

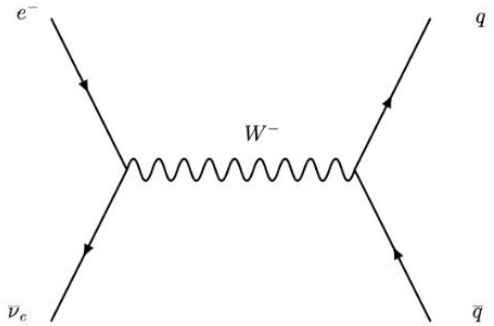


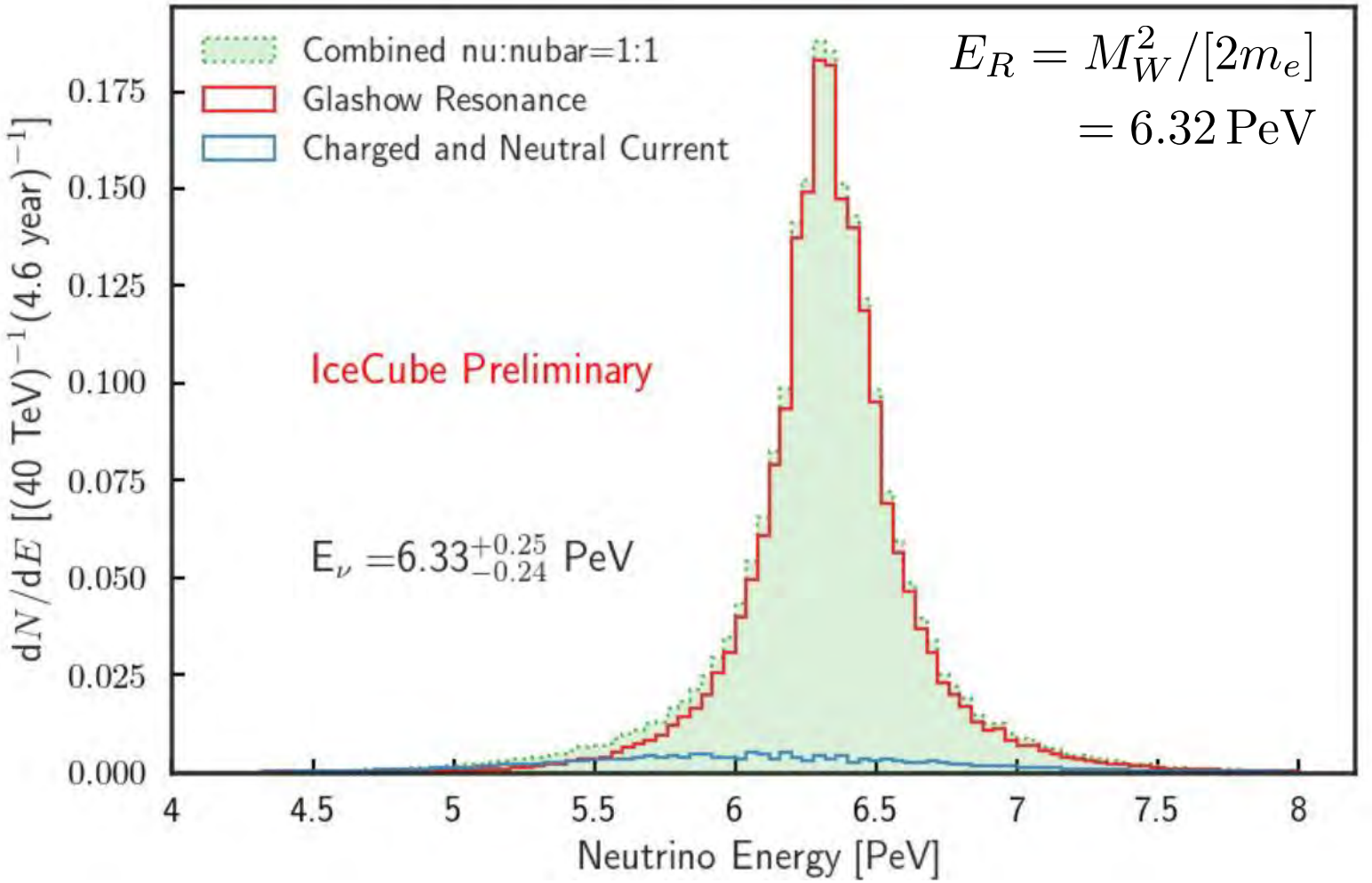
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

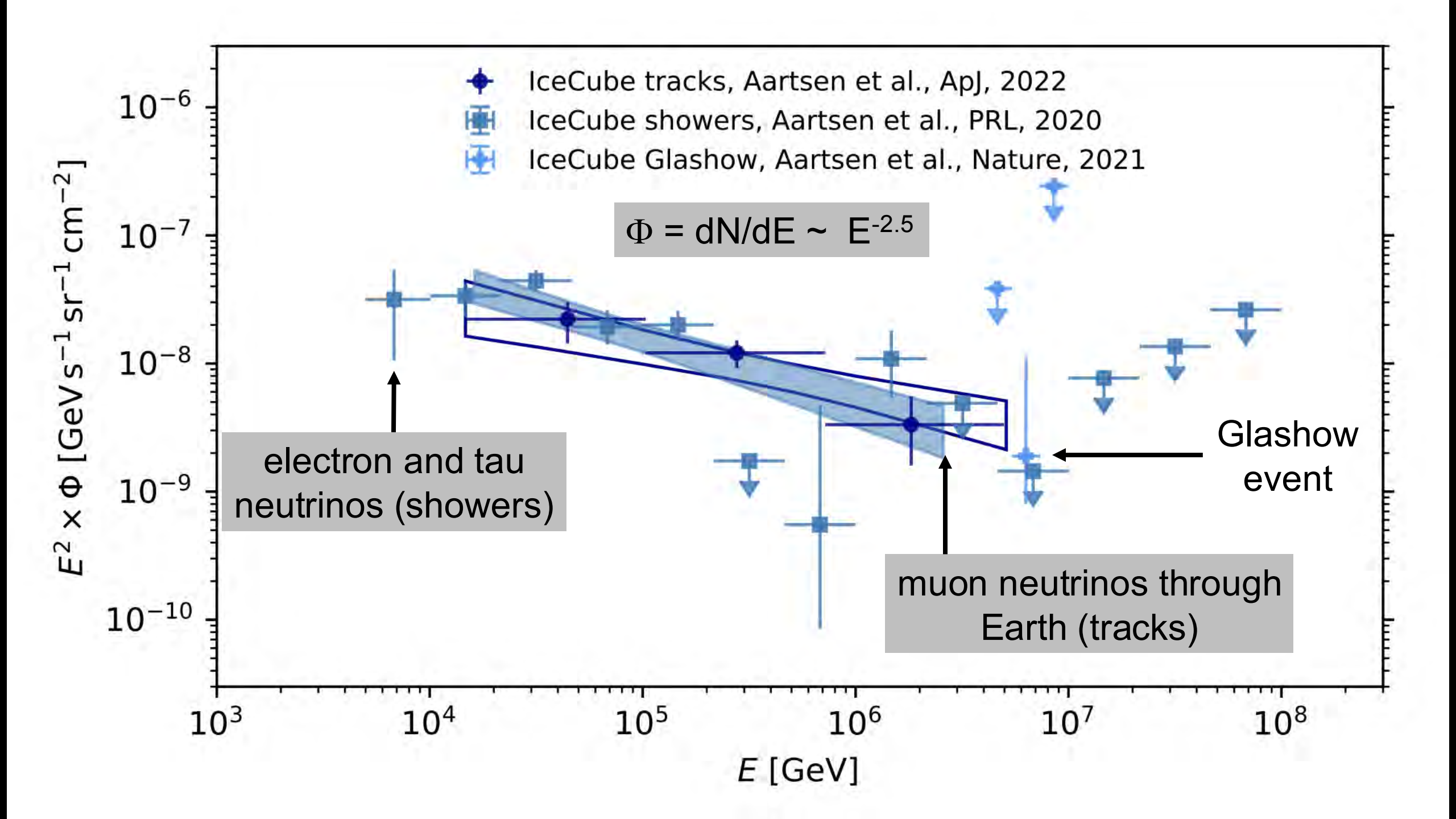
$$E_R = M_W^2/[2m_e]$$
$$= 6.32\,\mathrm{PeV}$$



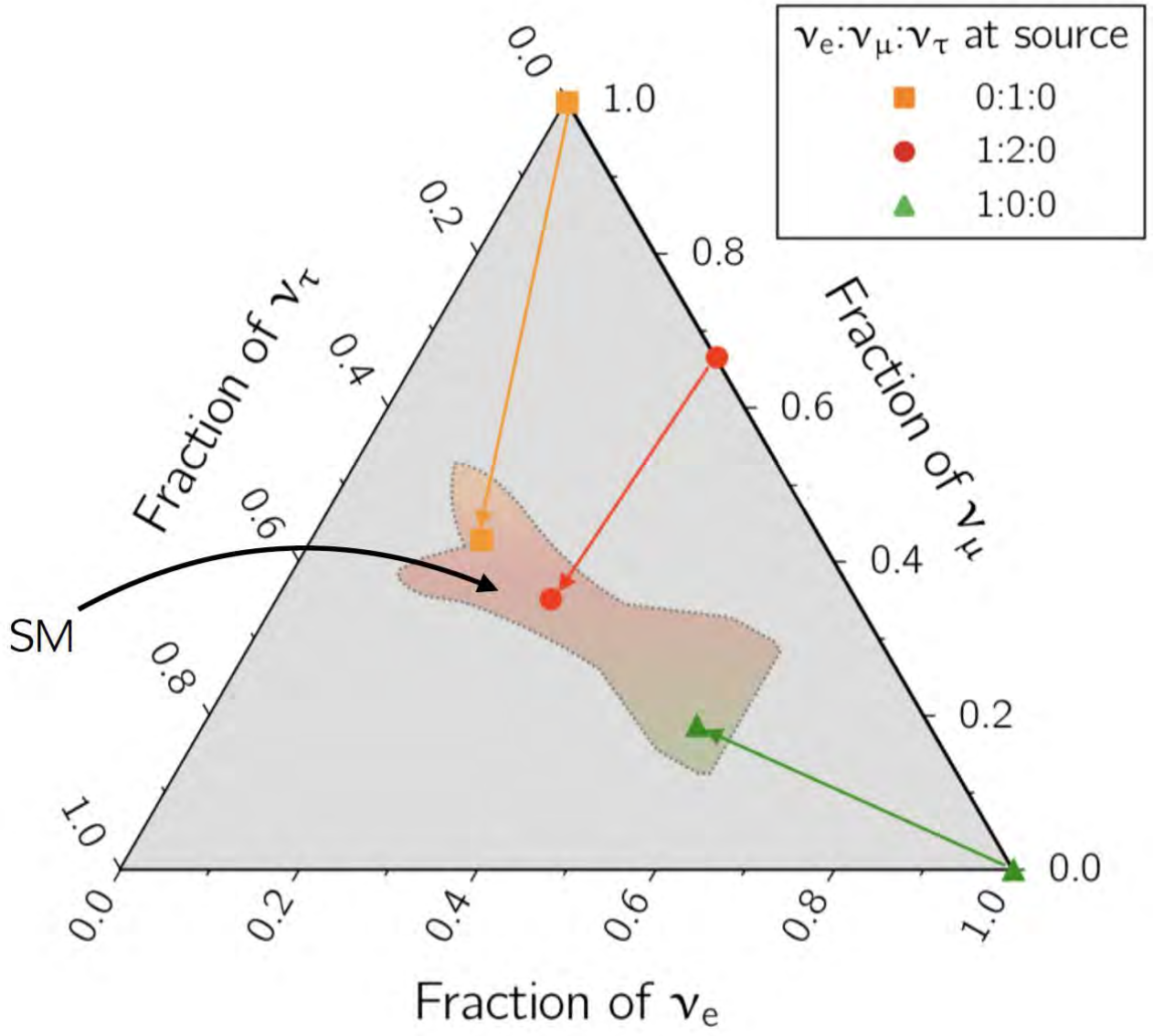
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

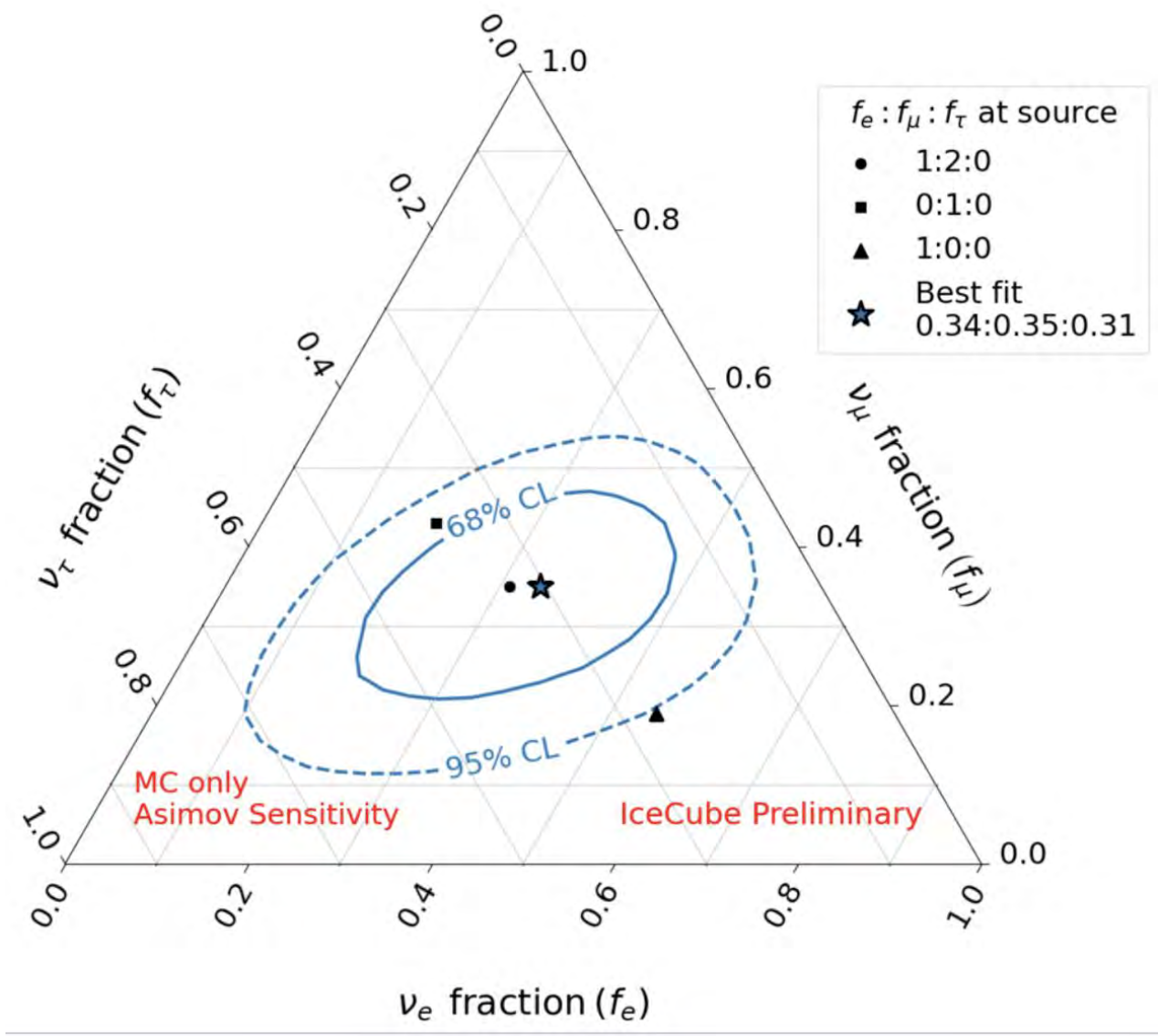





IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi = dN/dE \sim E^{-2.5}$
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8

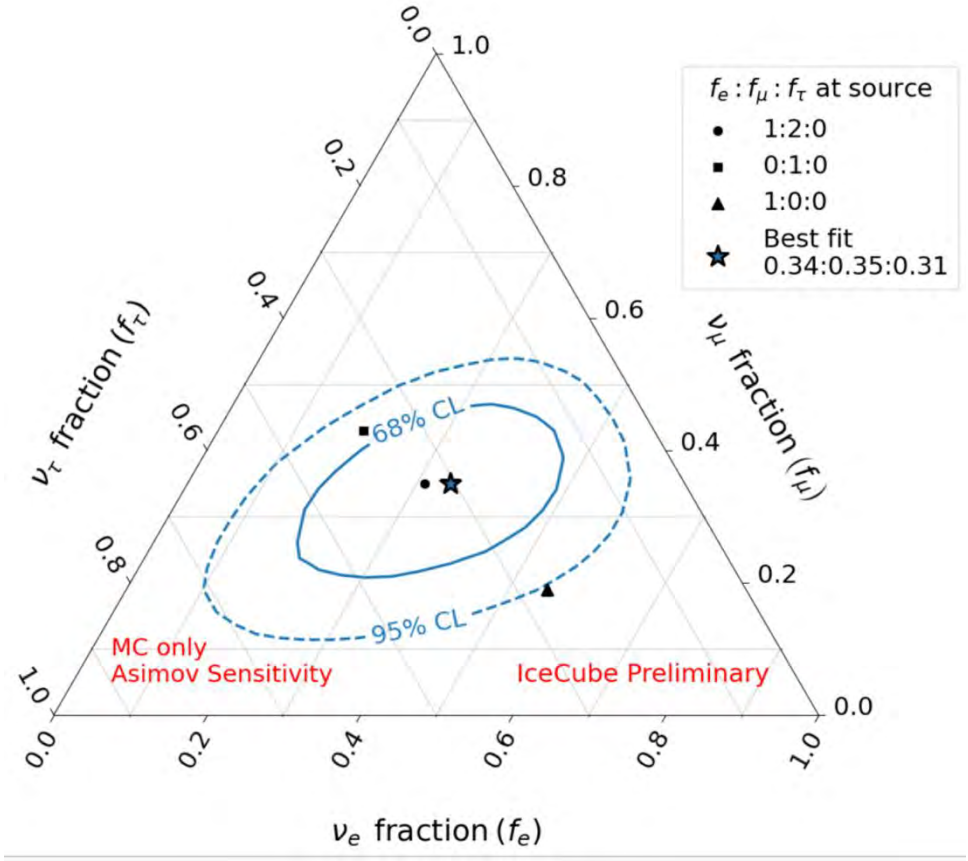
oscillations of PeV neutrinos over cosmic distances to 1:1:1



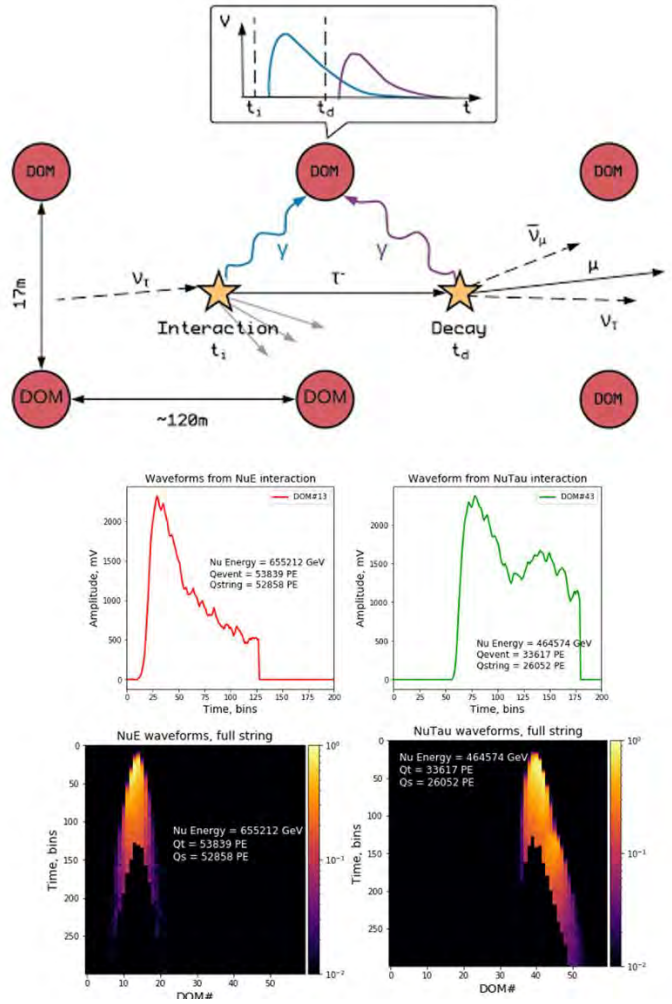


- oscillations of PeV neutrinos over cosmic distances to 1:1:1
- high energy (> PeV) nutau neutrinos are of cosmic origin

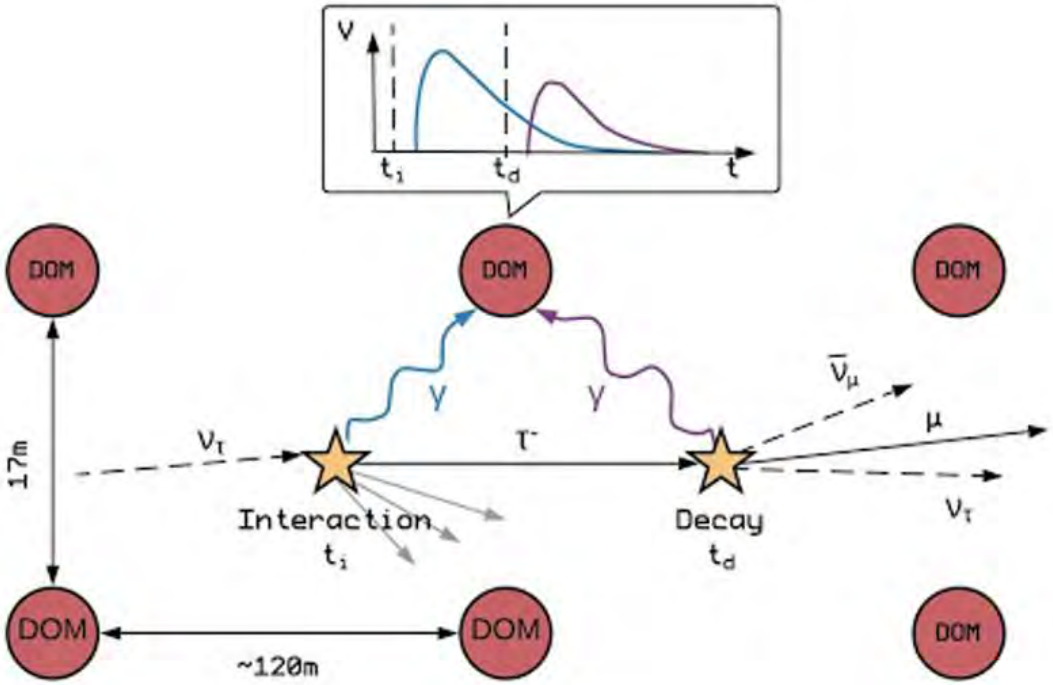
starting events
(medium energy)

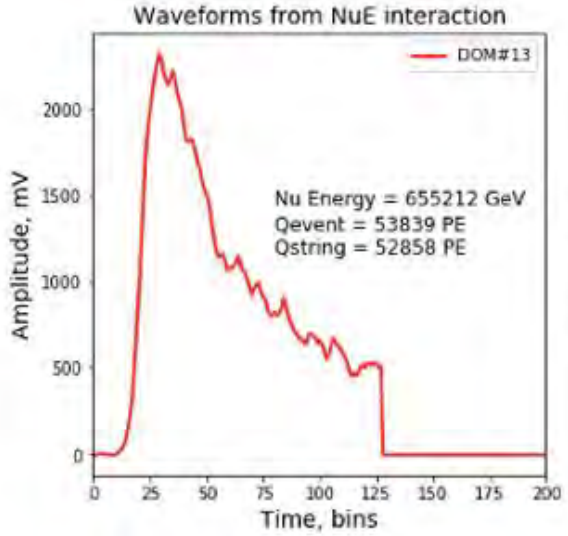


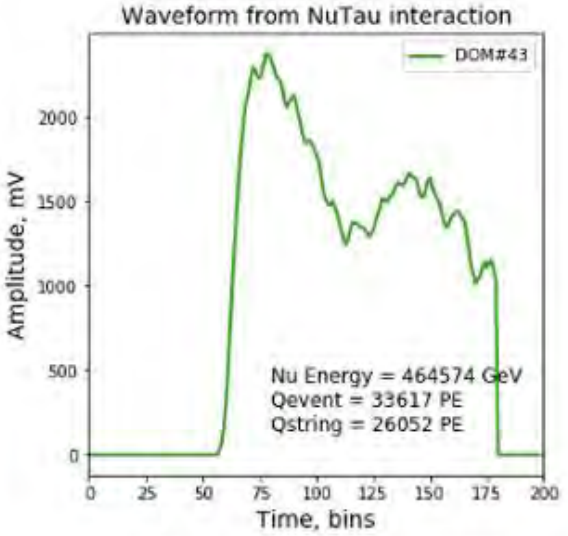
machine learning
PMT signals

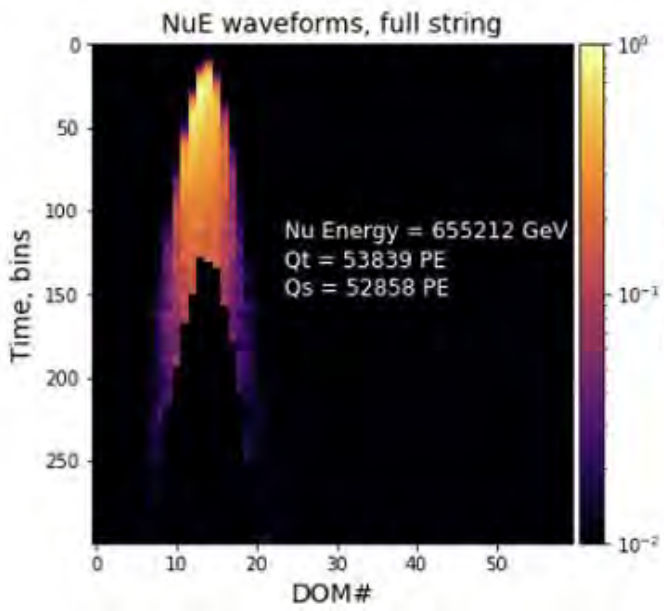


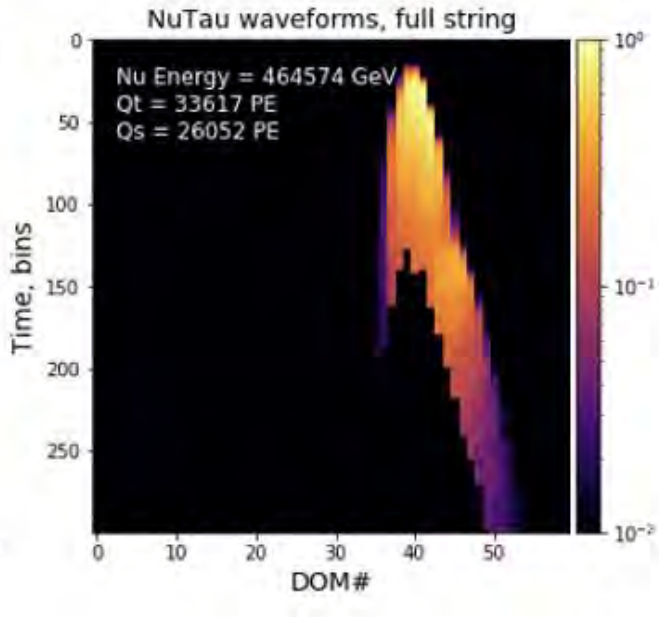
- double bang events: 8 predicted on a background of 1 and 7 observed
  - each nutau event is an extragalactic neutrinos search





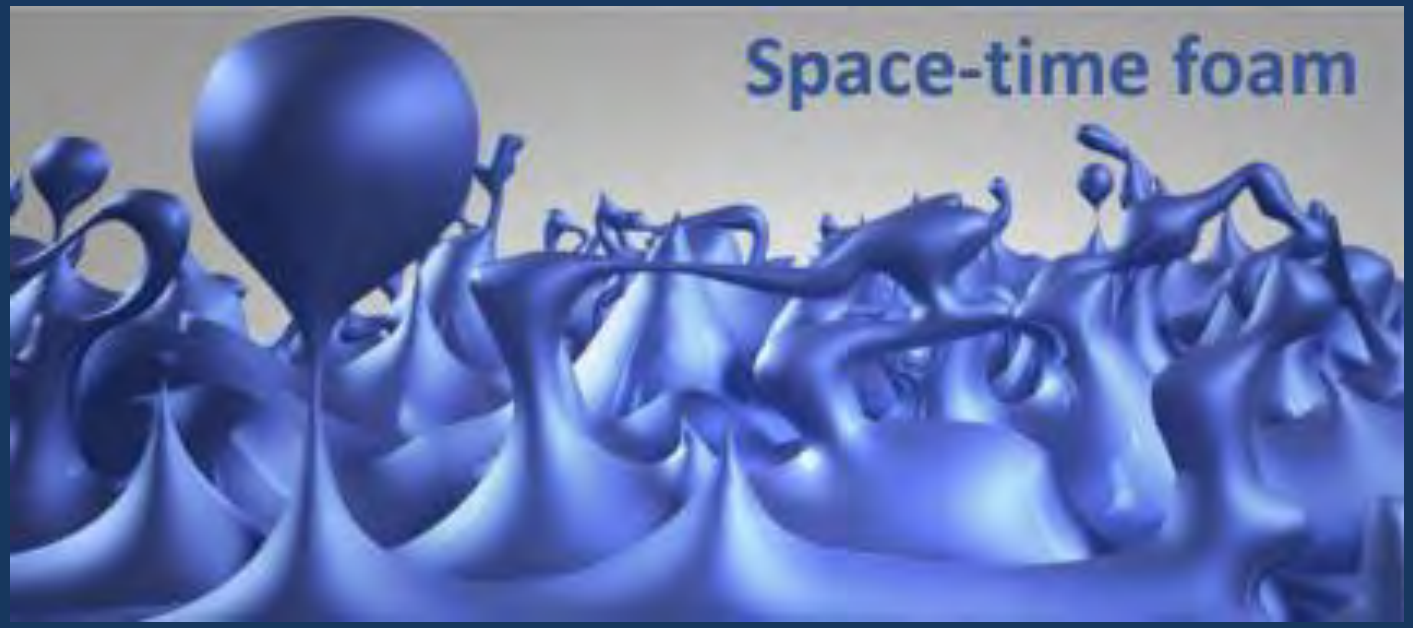






$$\lambda \sim \frac{1}{E} \rightarrow 10^{-33}\ cm$$

quantized space: quantum fluctuations of space-time geometry is activated



- neutrino decoherence from quantum gravitational space-time fluctuations
- modifies the neutrino dispersion relation over long baselines
- IceCube reaches record sensitivities at the Planck scale even using atmospheric neutrinos

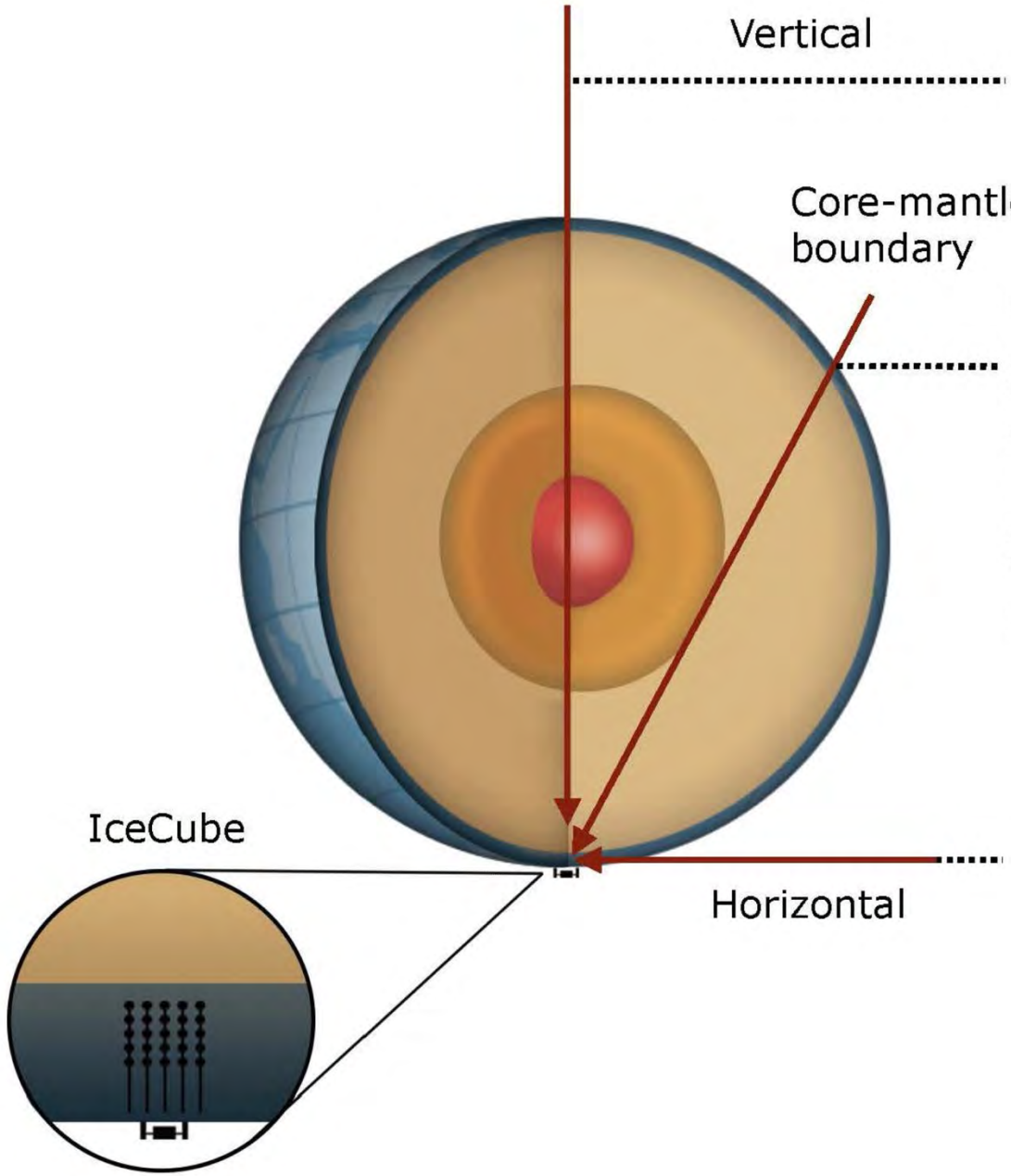
Quantum Gravity at the Planck scale

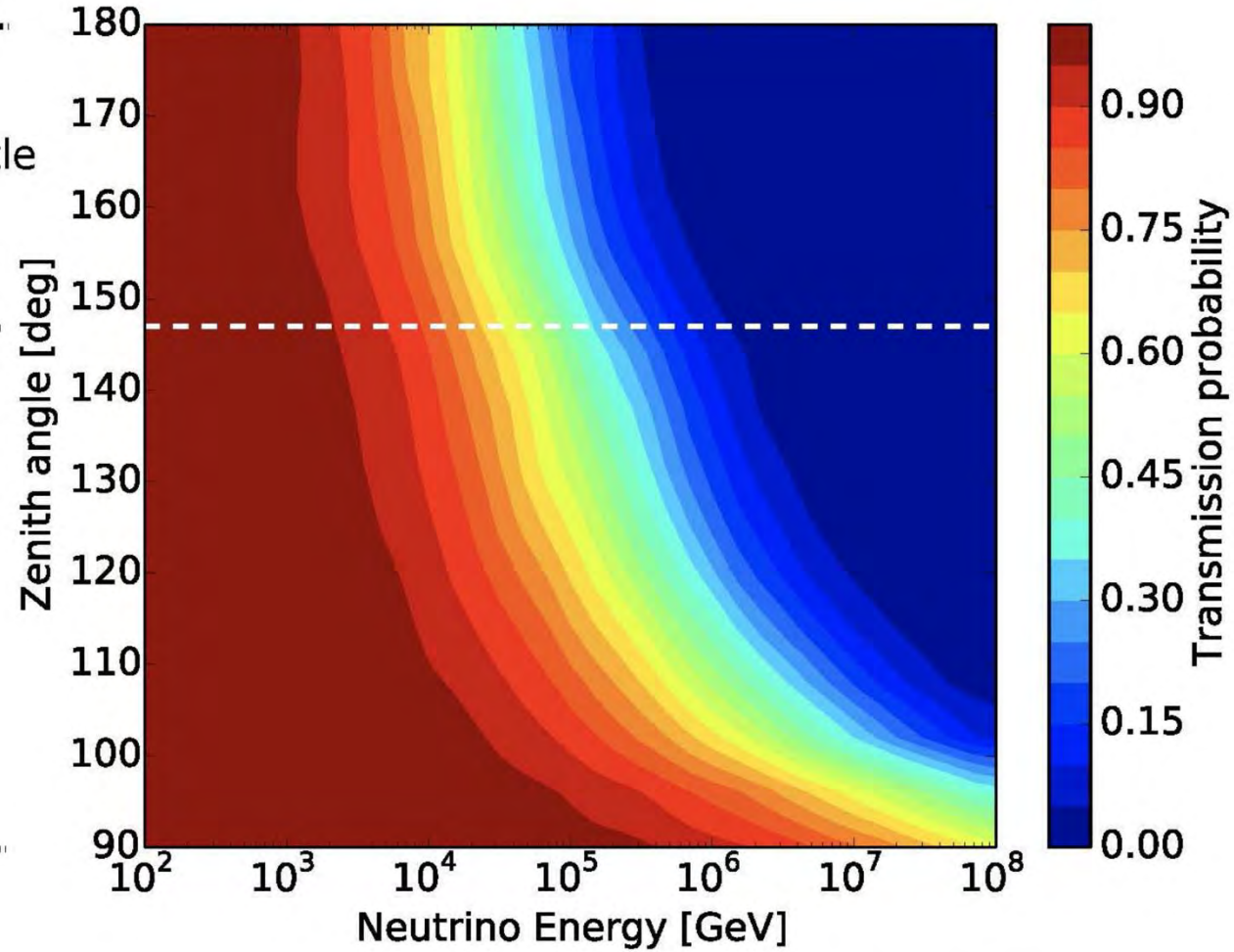
- speed of photons and neutrinos depends on their energy, like photons in a crystal

- Planck scale vacuum fluctuations probed by high energy particles

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$

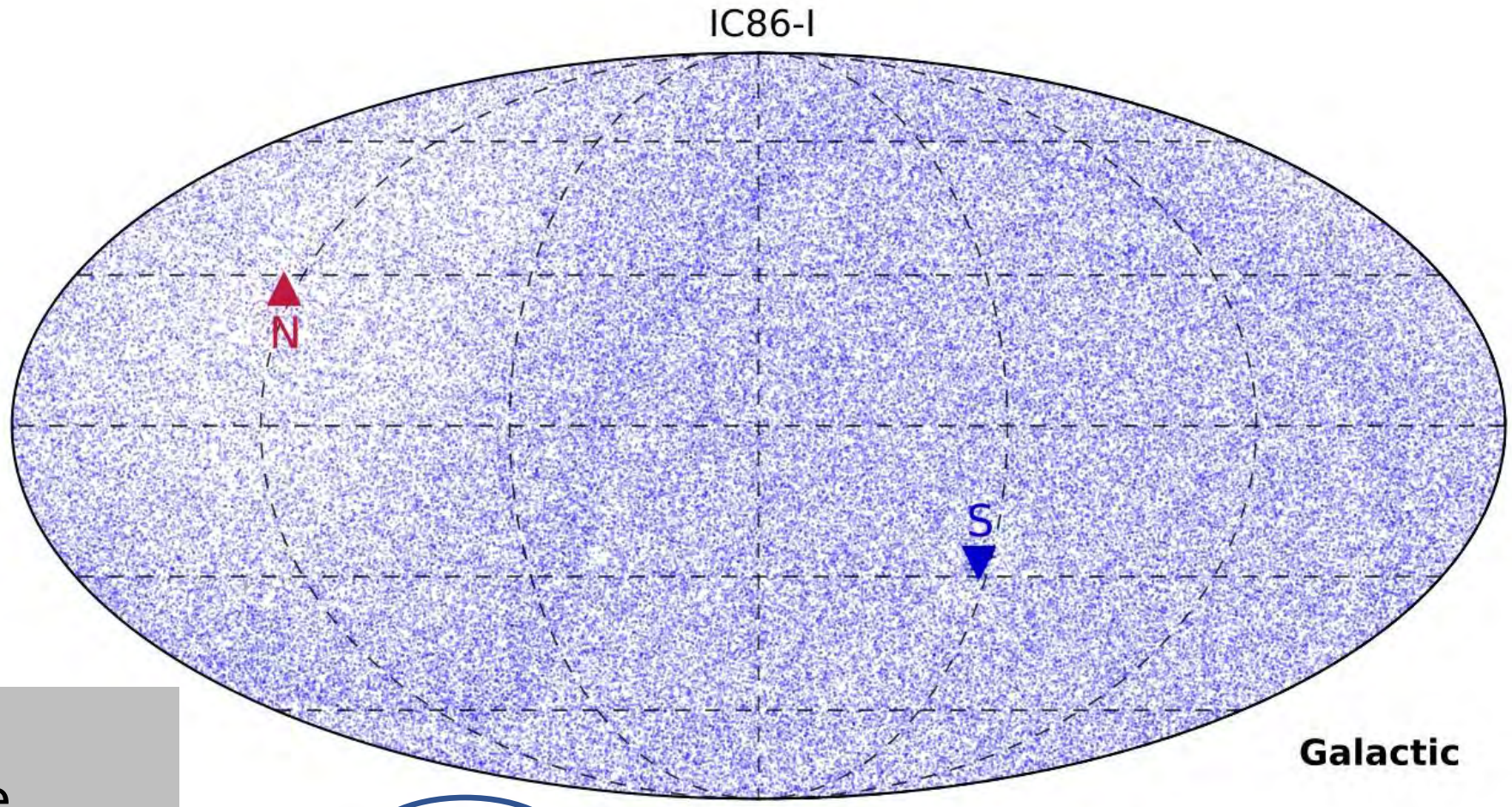
- modification to dispersion relation leads to an energy dependent speed of light: Lorentz invariance violation


Vertical
Core-mantle
boundary
IceCube
Horizontal


180
170
160
150
140
130
120
110
100
90
Zenith angle [deg]
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
0.90
0.75
0.60
0.45
0.30
0.15
0.00
Transmission probability

IceCube neutrinos >100 GeV (one year shown)

(reaches neutrino purity of > 97% but overwhelmingly atmospheric)

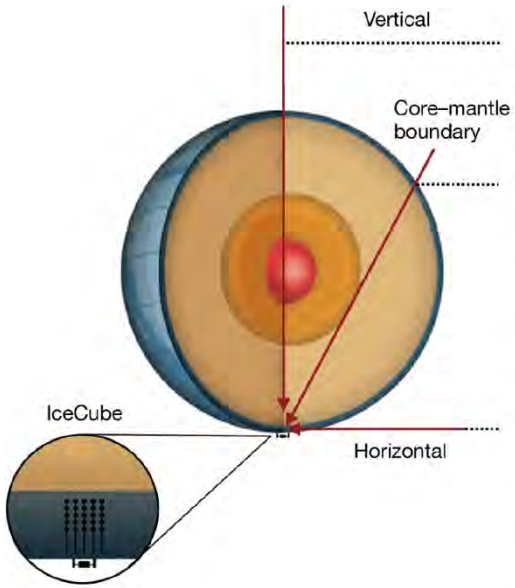


138322 neutrino candidates in one year

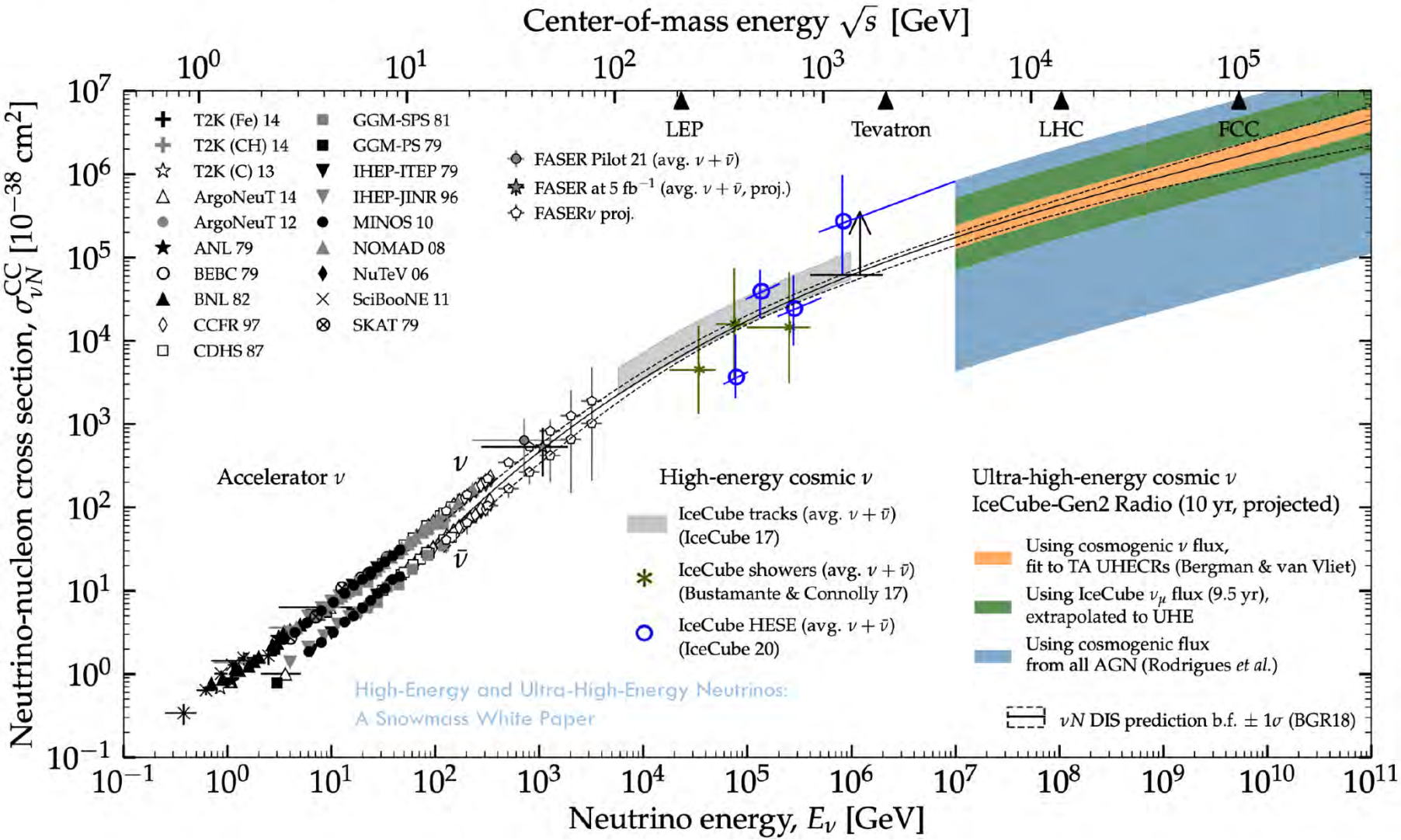
~ 200 cosmic neutrinos

~12 separated from the atmospheric background with E>60 TeV

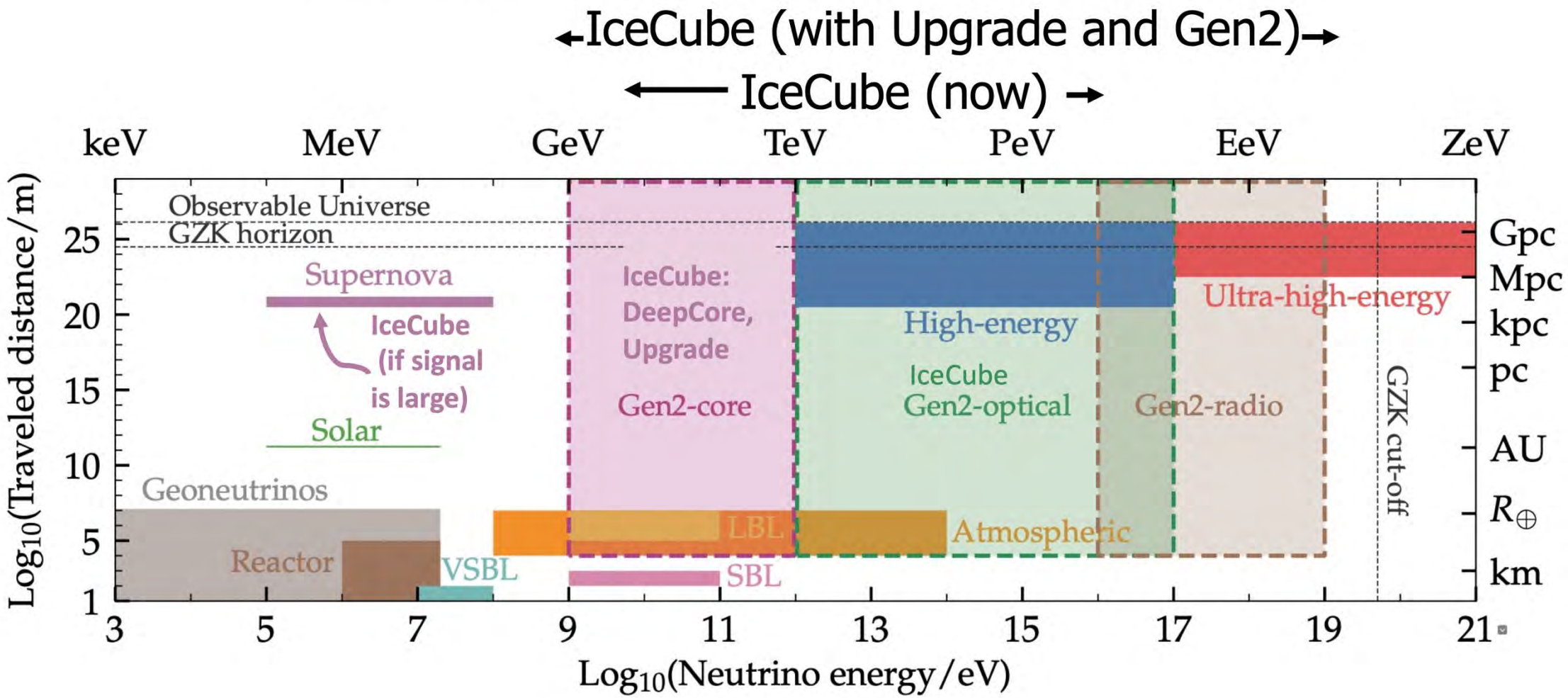
CROSS SECTION WITH EARTH AS THE TARGET



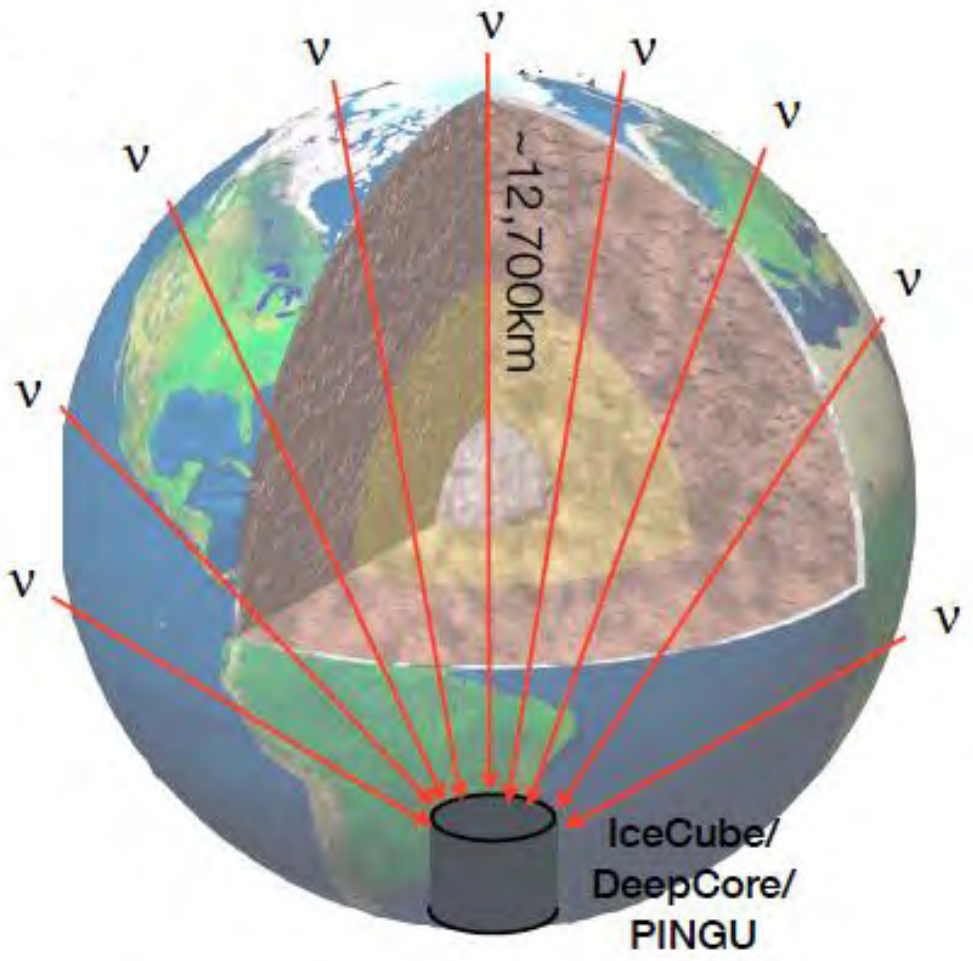
Extending x-section measurements to energies beyond Earth-based accelerators

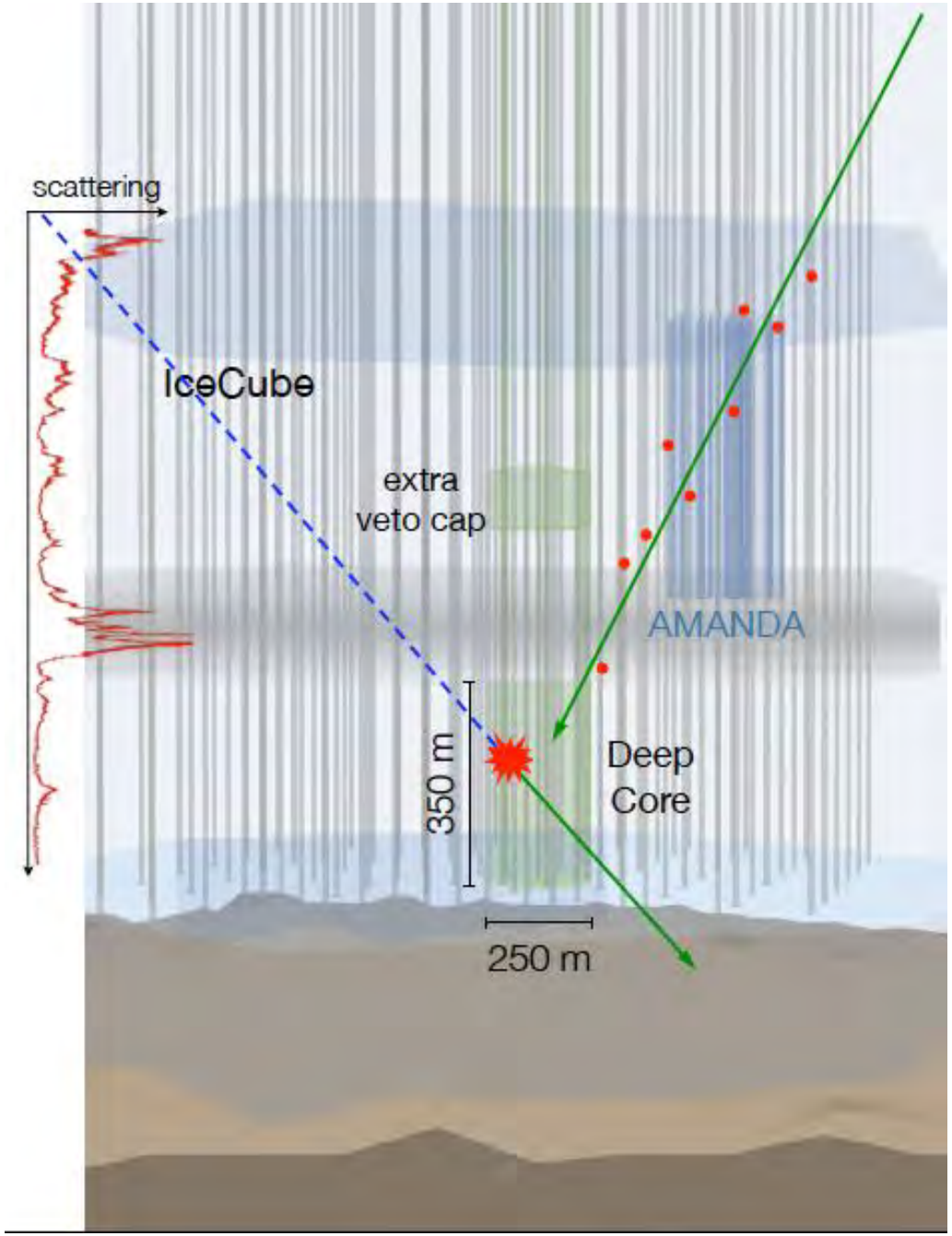


The energy landscape for IceCube



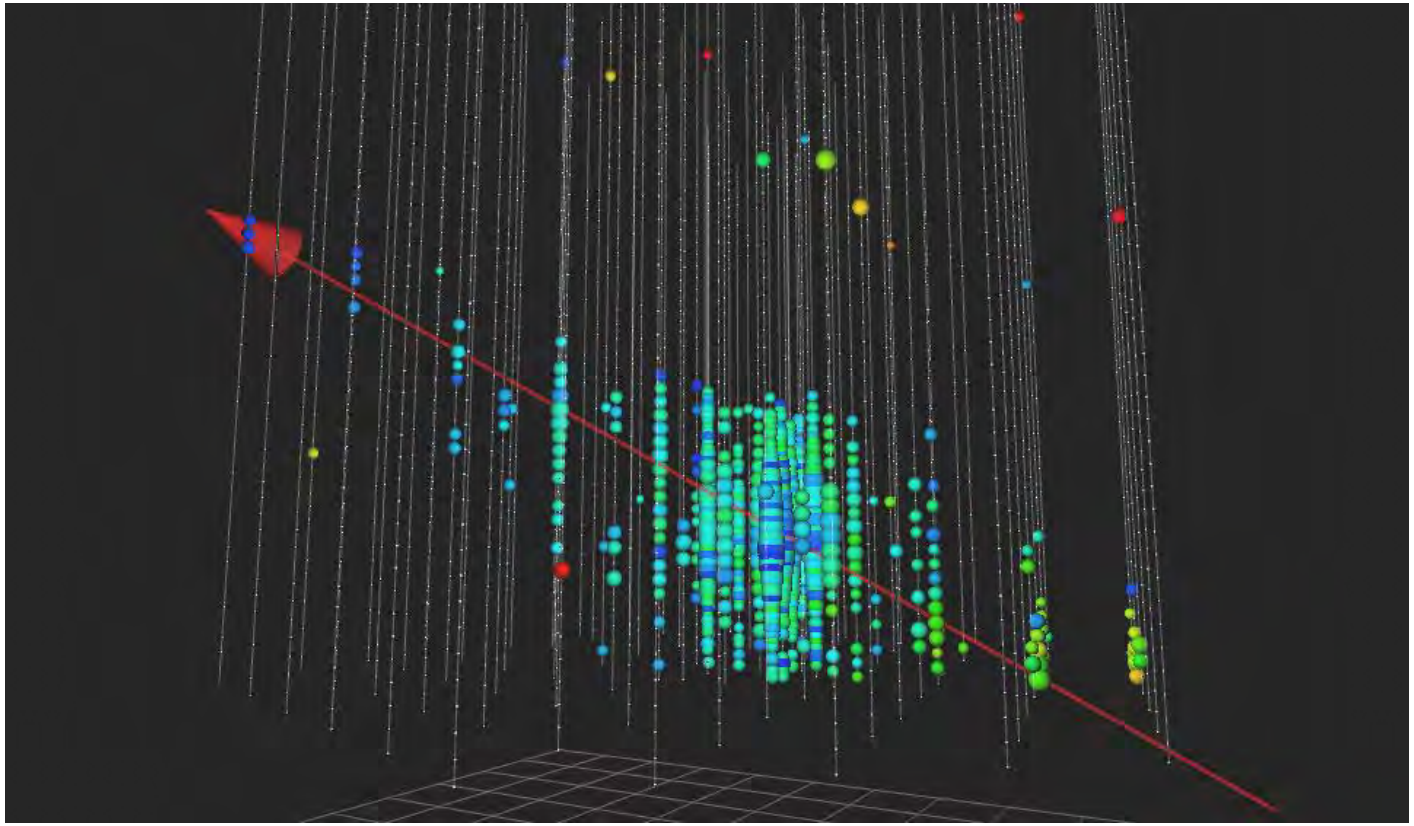
- one million atmospheric ν's
- at analysis level in DeepCore one every 15 min and with Upgrade one every 4 min



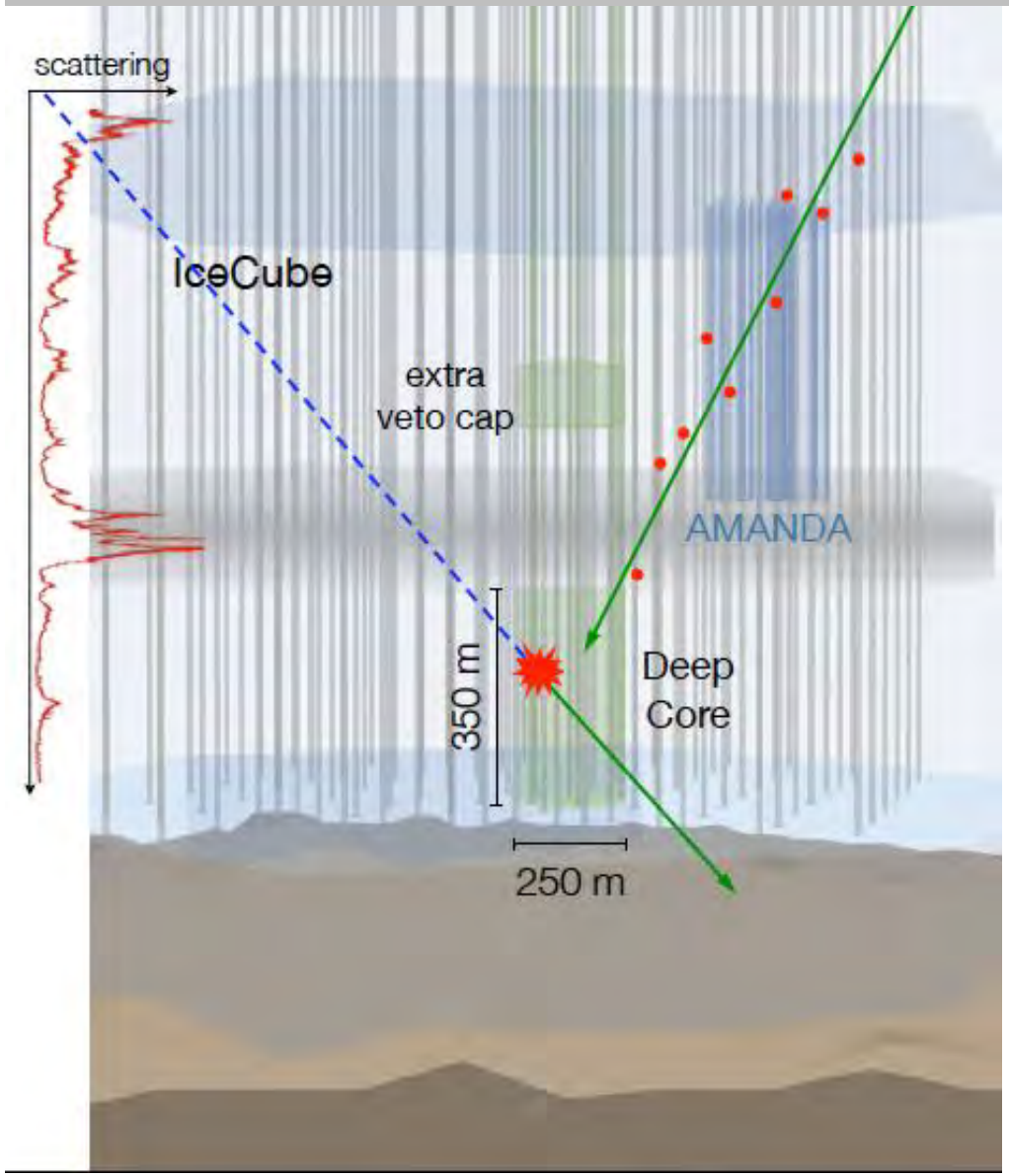


one million atmospheric neutrinos:

- > 2 megaton detector
- near 25 GeV energy nearly all muon neutrinos reappear as tau neutrinos. We measure both!

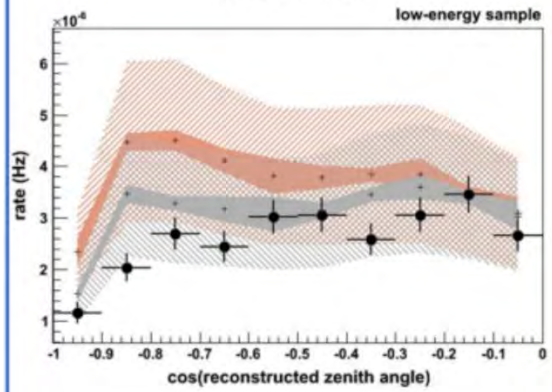


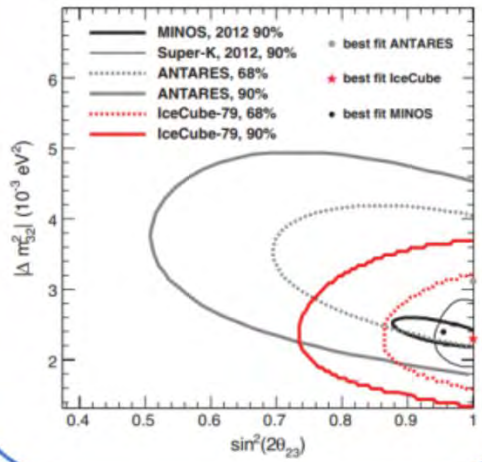
IceCube veto: puts DeepCore at an effective depth well below SNOLAB



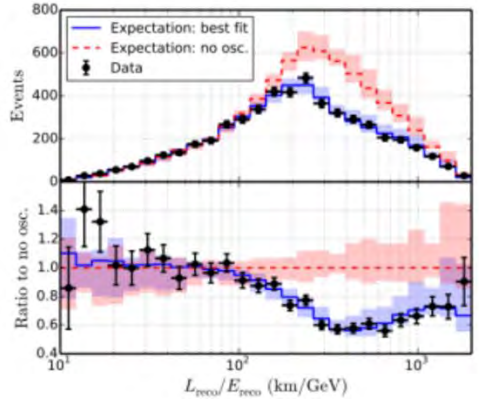
Atmospheric oscillations progression

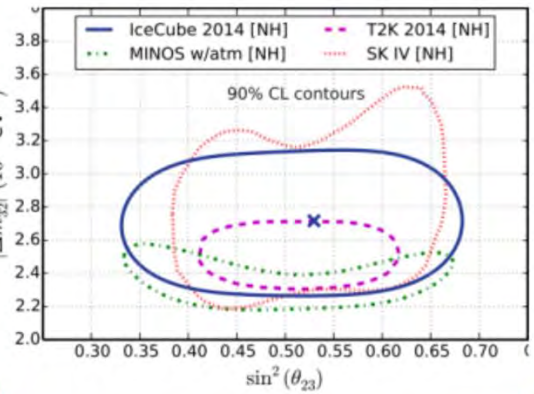
IceCube, PRL 111, 081801 (2013)
700 events



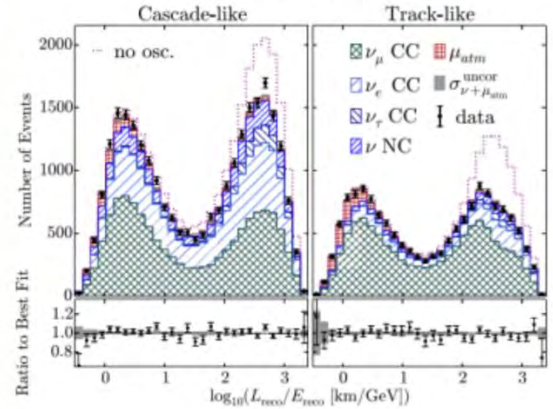


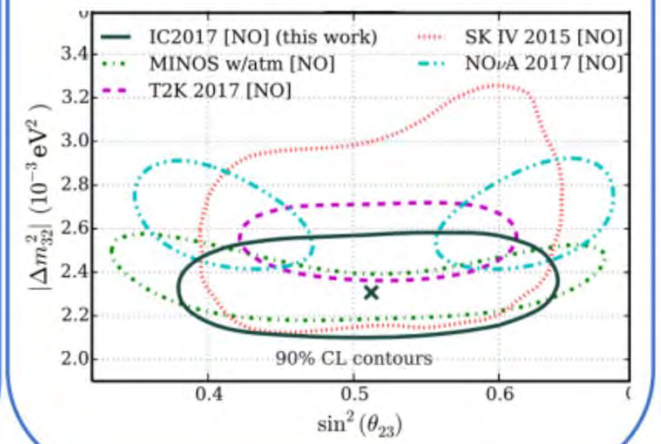
IceCube, PRD 91, 072004 (2015)
~5k events



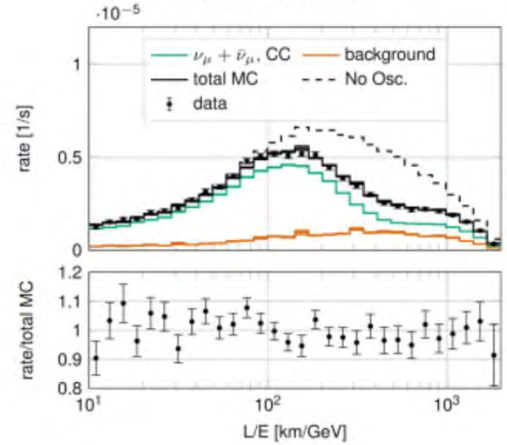


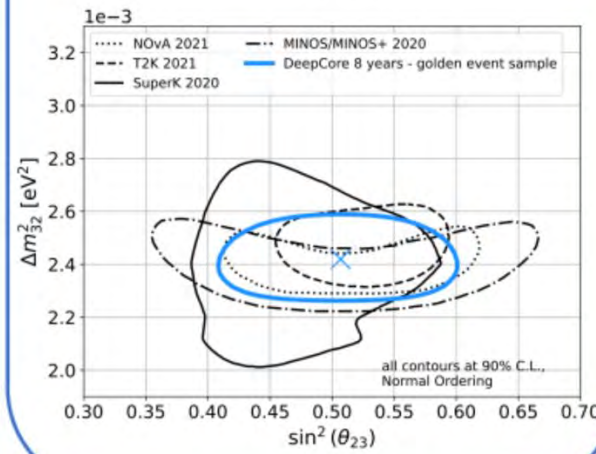
IceCube, PRL 120, 071801 (2018)
~35k events





IceCube, PRD 108, 012014 (2023)
~22k events





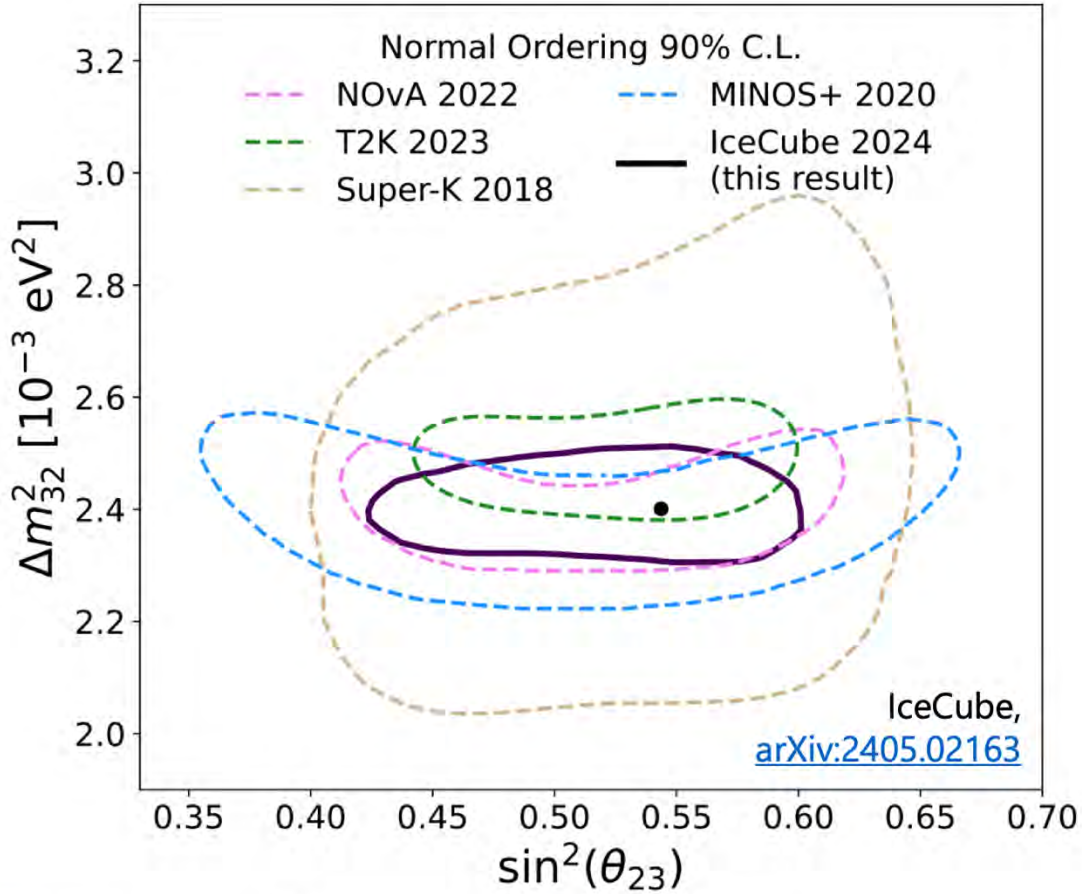
Atm. Osc. - **Newest result**

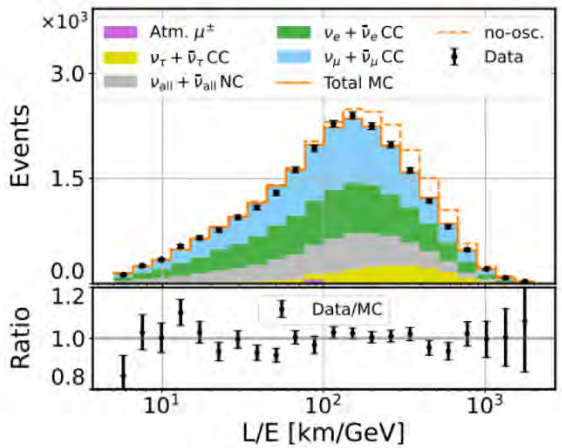
- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit

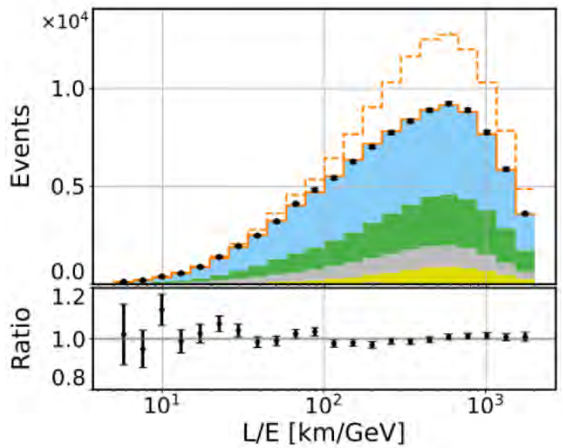
  $\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$

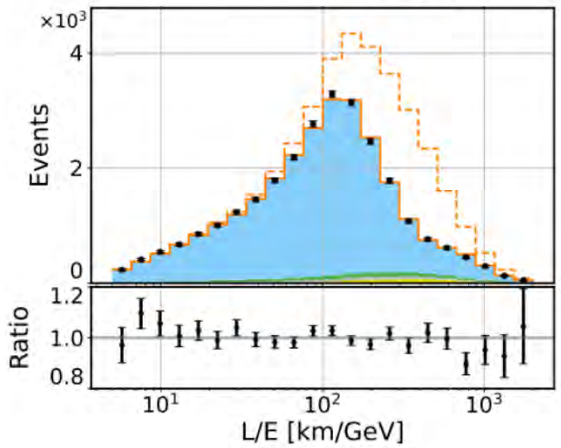
  $\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}$ eV²

  GoF *p*-value: 19%

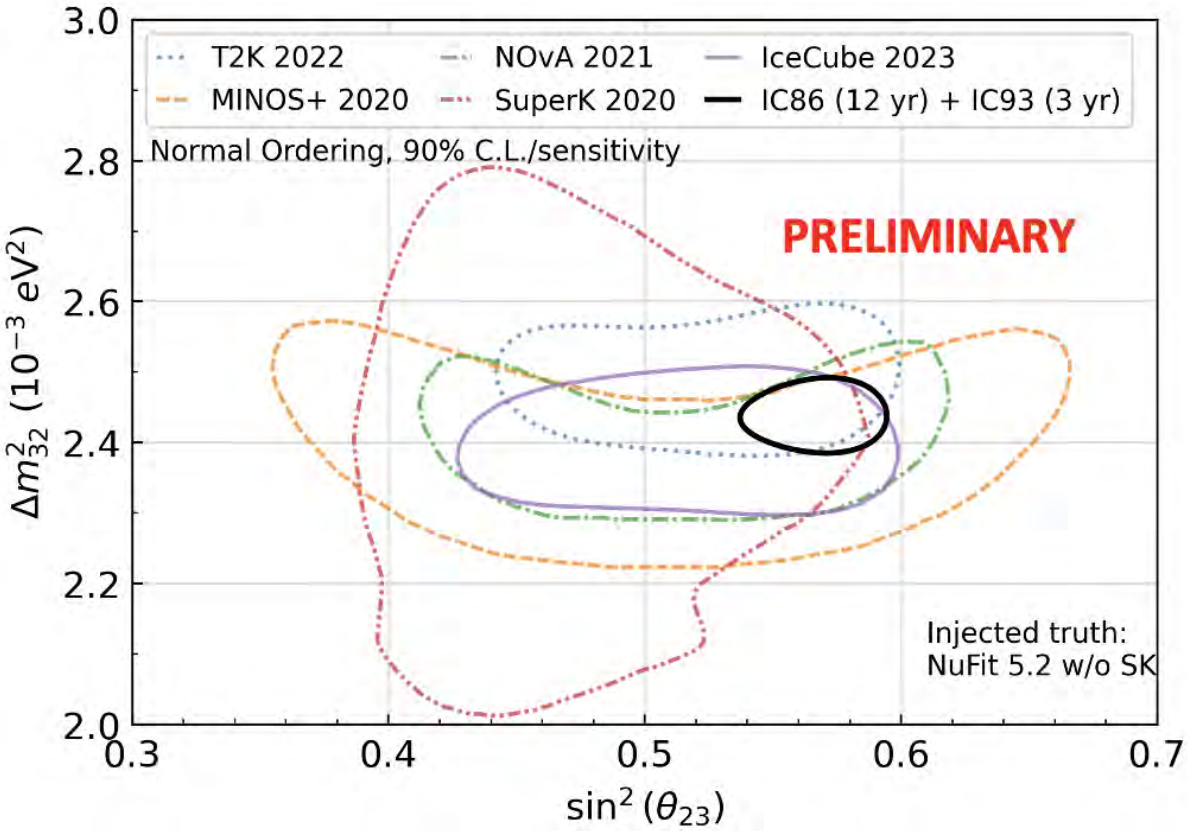


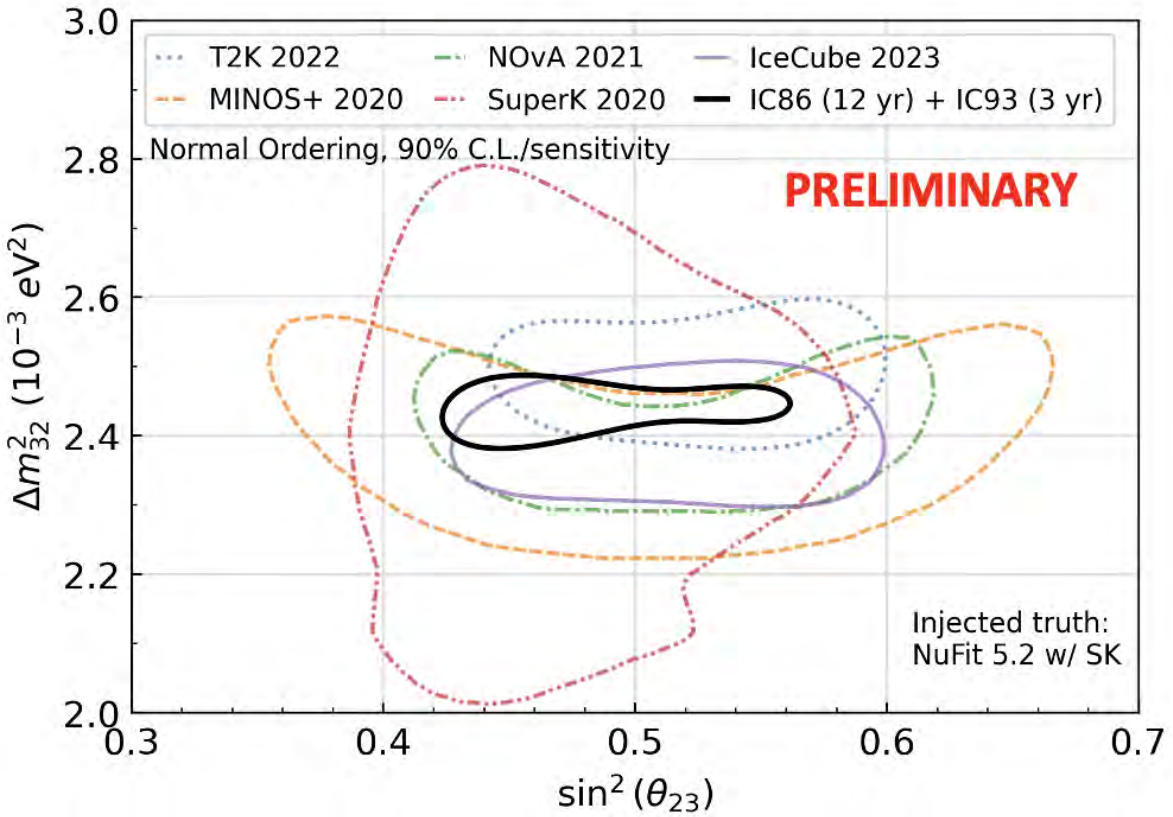






IceCube Upgrade Physics: Oscillation Sensitivity

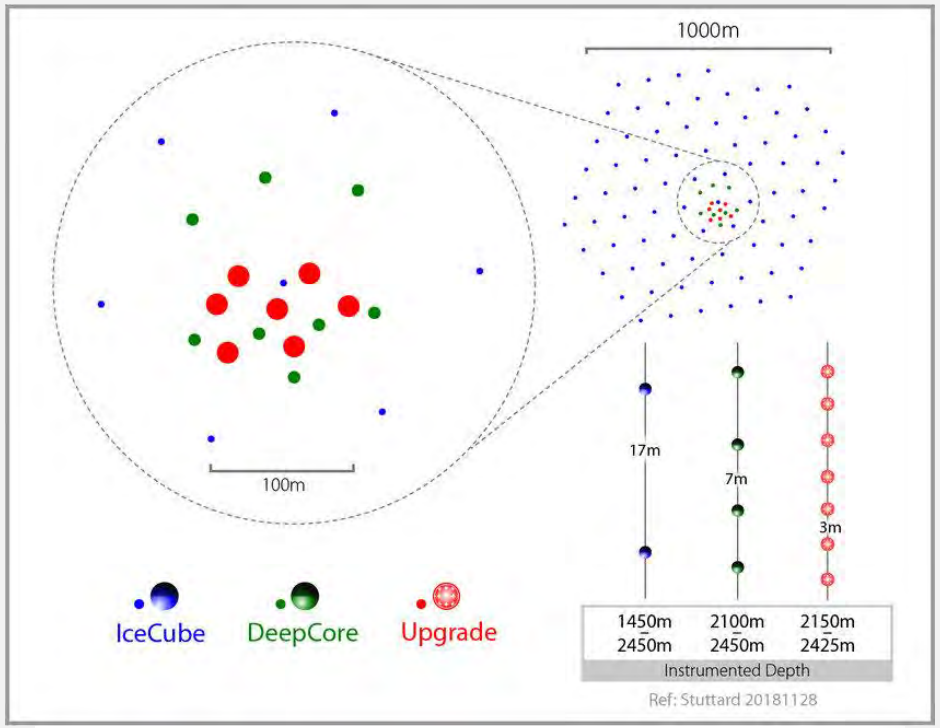




IceCube Overview

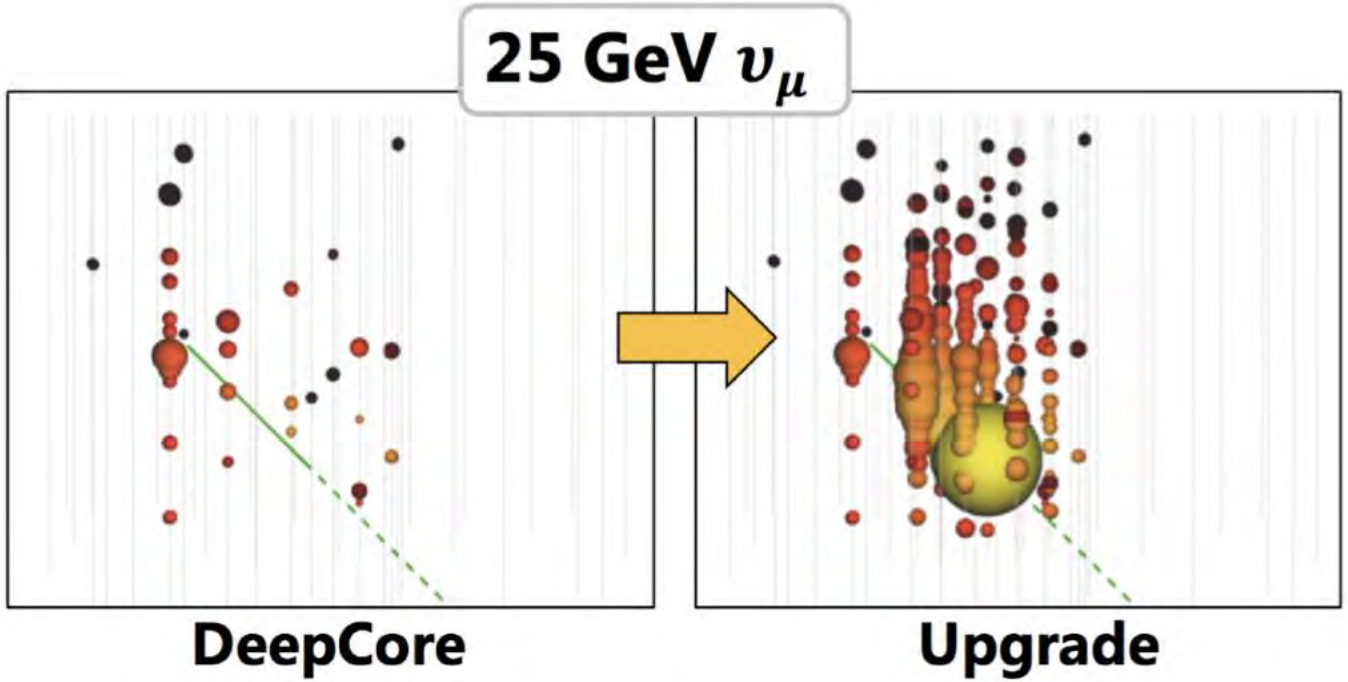
- IceCube
  - DeepCore
  - IceTop

  } 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

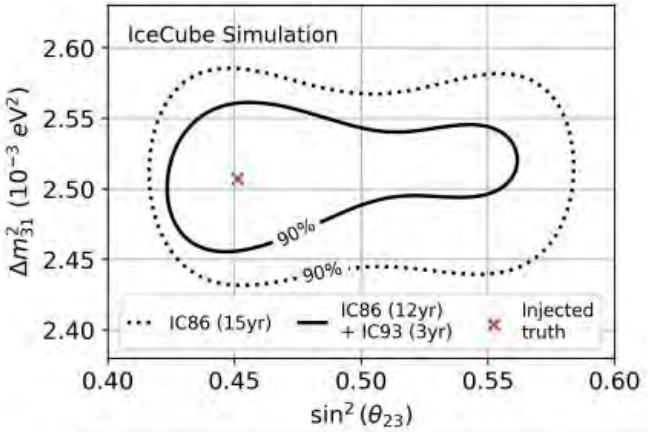
IceCube Upgrade 2025

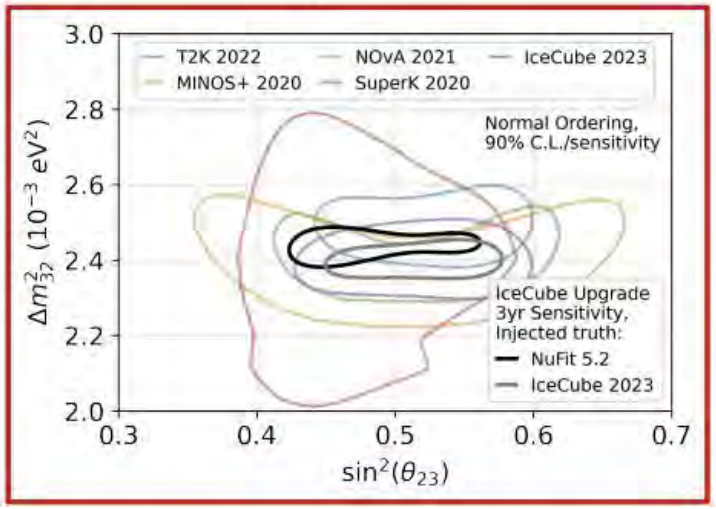


and with the Upgrade strings in 2025…

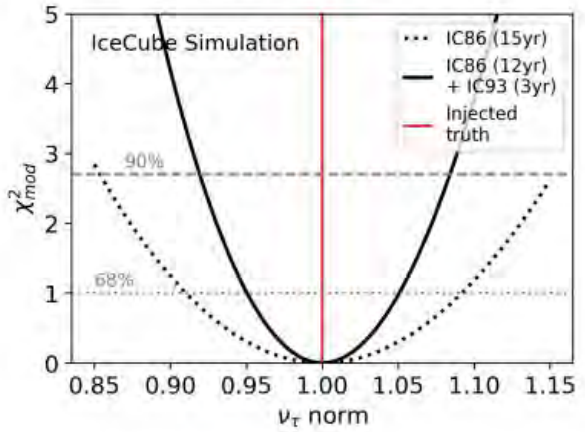
IceCube + JUNO !

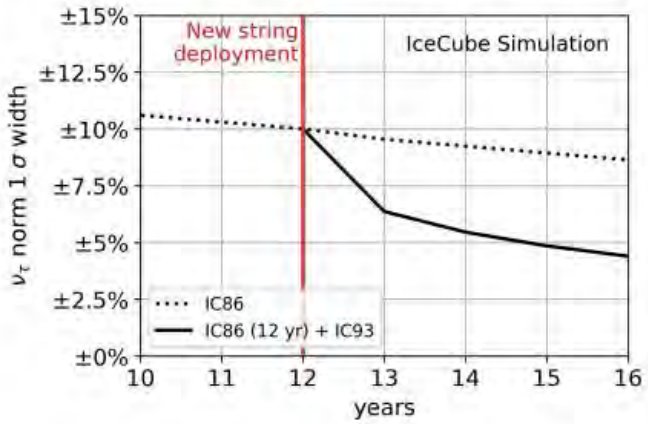
Sensitivities - Atm. Osc. Params



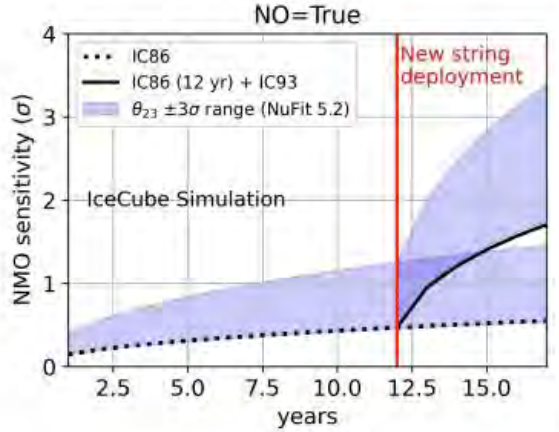


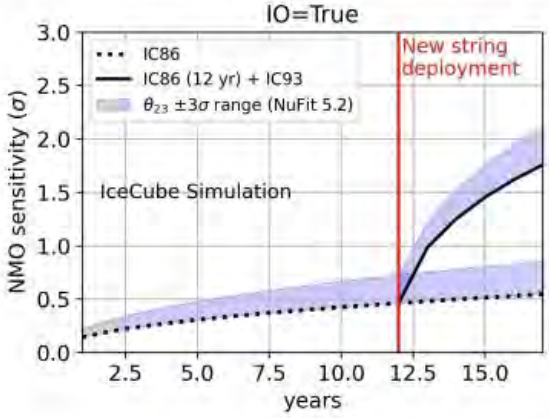
Tau Neutrino Norm





NMO

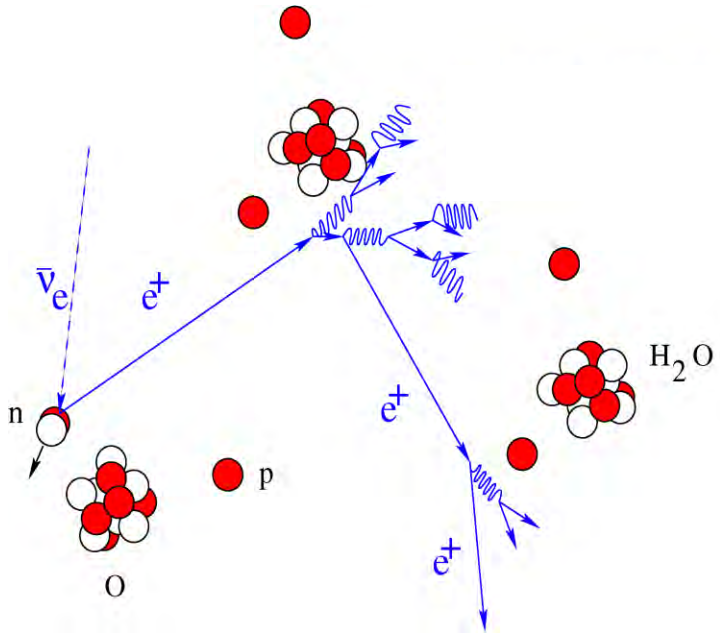


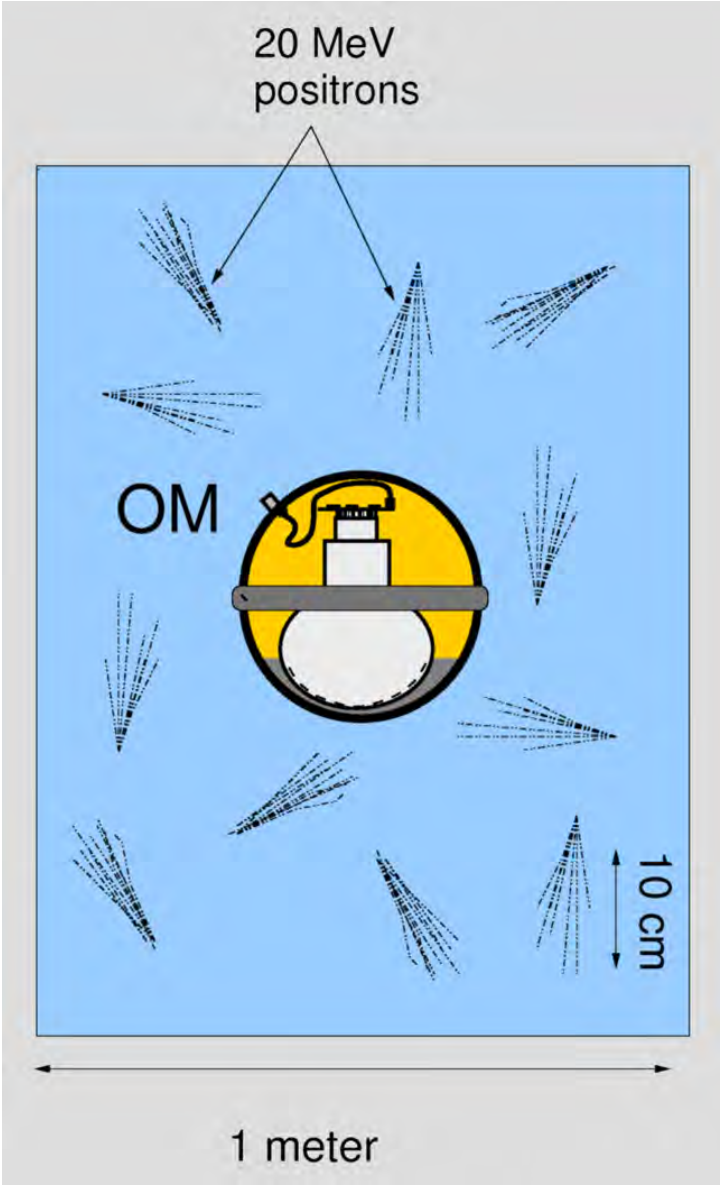


leading atmospheric beam detector until the advent of HyperK in 2028

supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

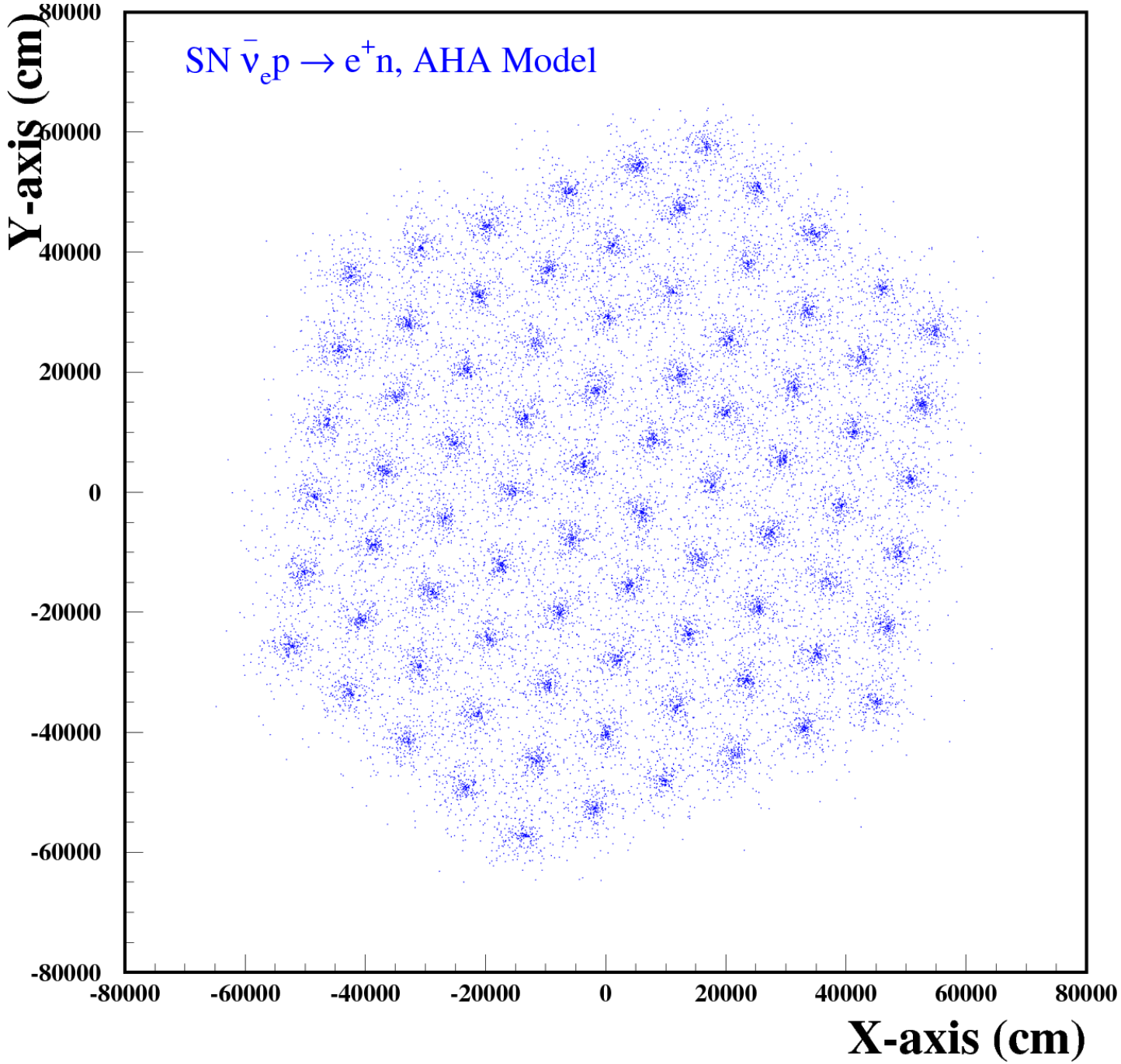
- ☞ PMT noise low (280 Hz)
- ☞ detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector





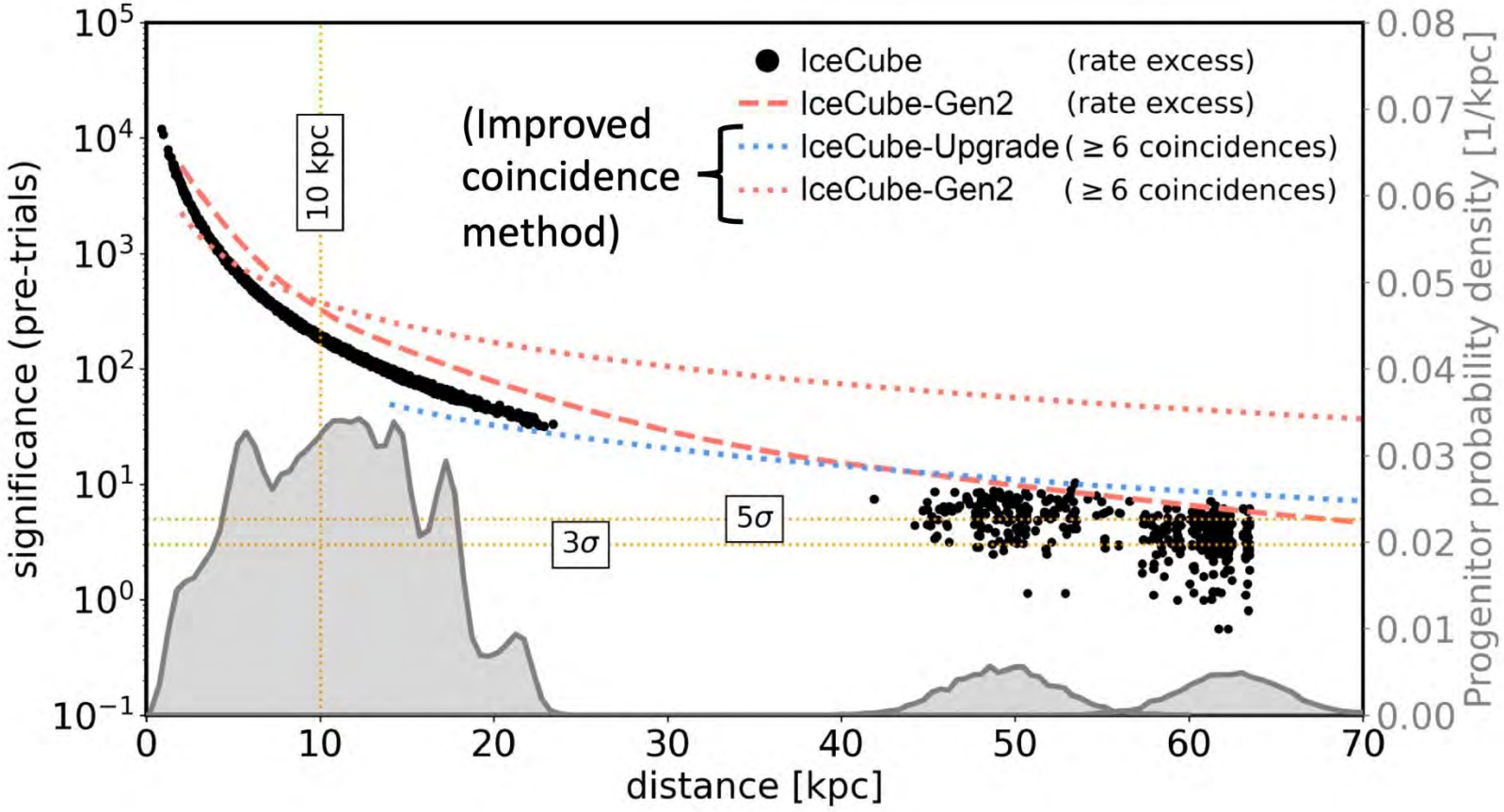
starting points of neutrino showers from supernova neutrinos

- equivalent detection volume of a 2 megaton SuperK-style detector
- 1 million events from 10 kpc
- neutronization electron neutrinos
- energy measurement from two-photon correlation

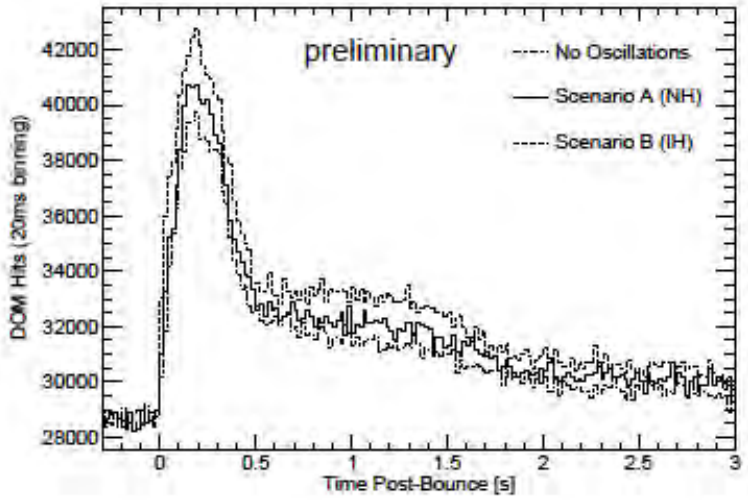


MeV neutrinos in the Upgrade and Gen2

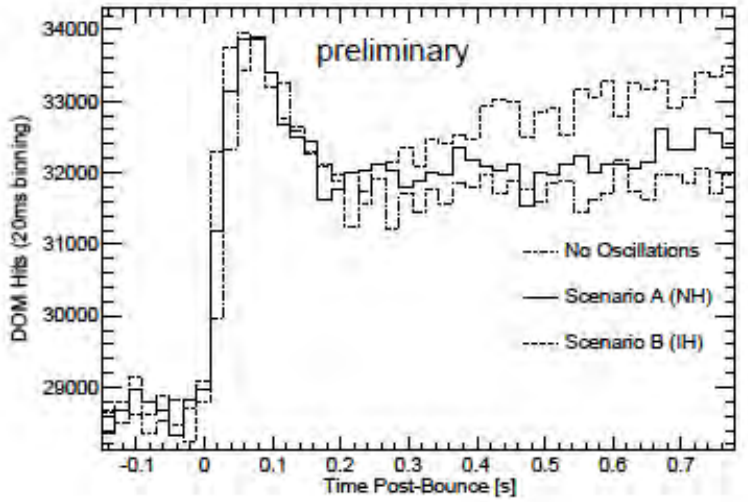
Require coincidences between nearby phototubes to reduce noise



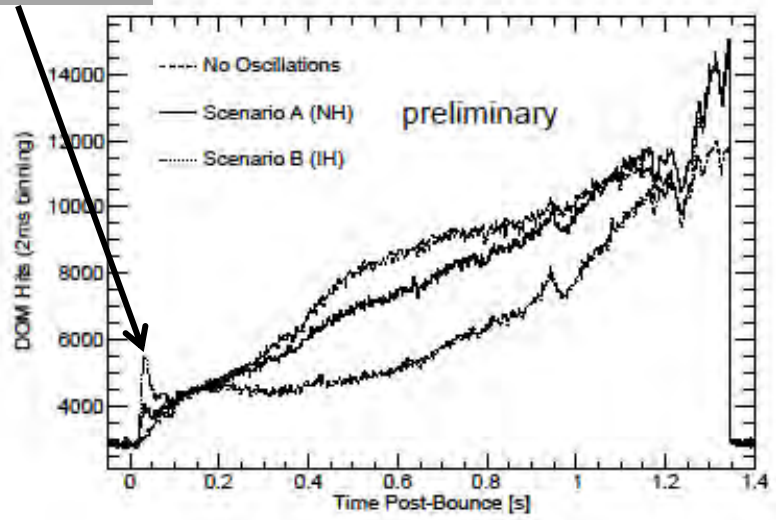
Livermore



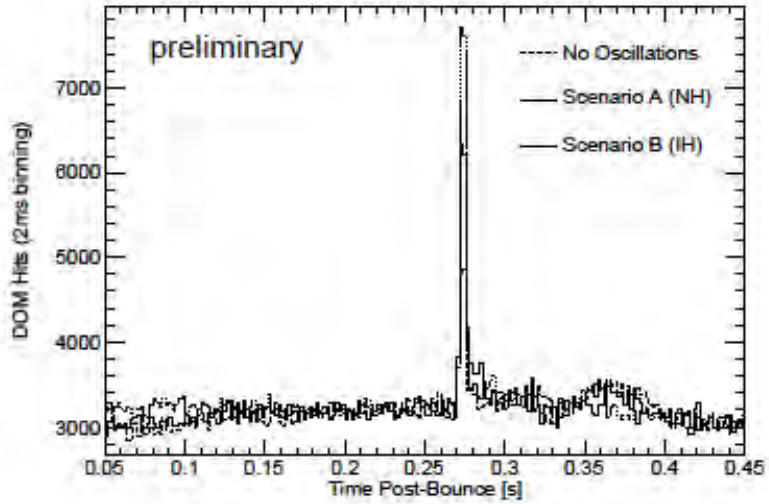
Garching



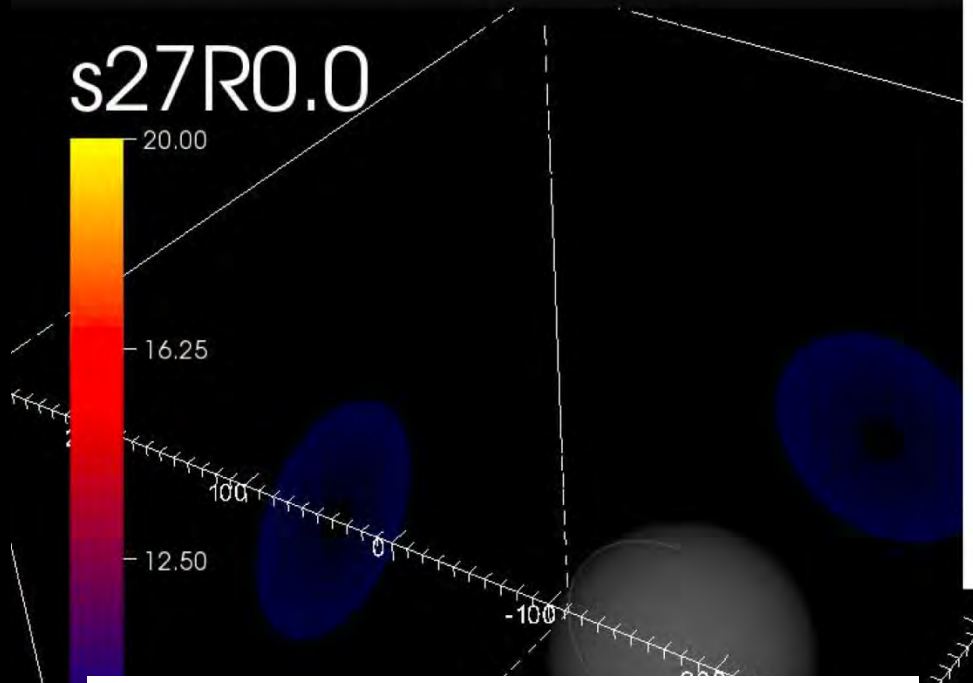
quark star

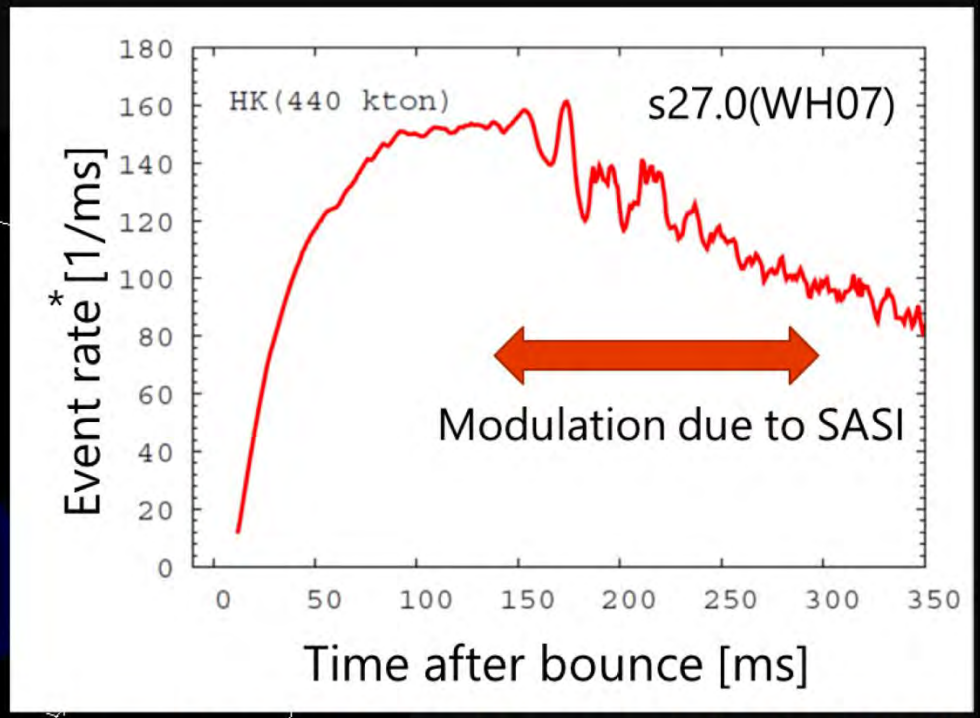


black hole



27 M_{sun} progenitor (WH07)

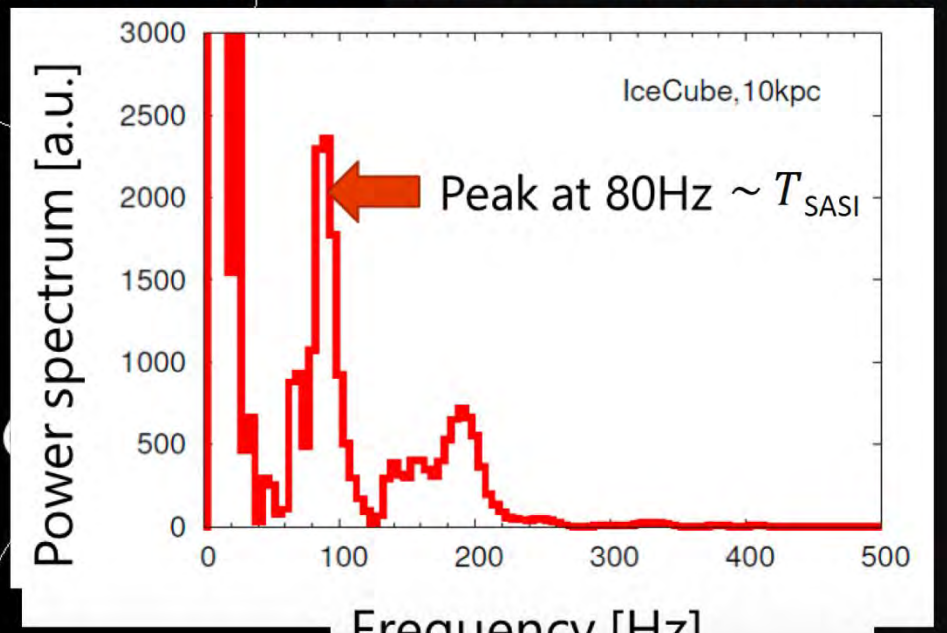




(consistent with Tamborra et al. (2013,2014))

gravitational wave with fundamental frequency:

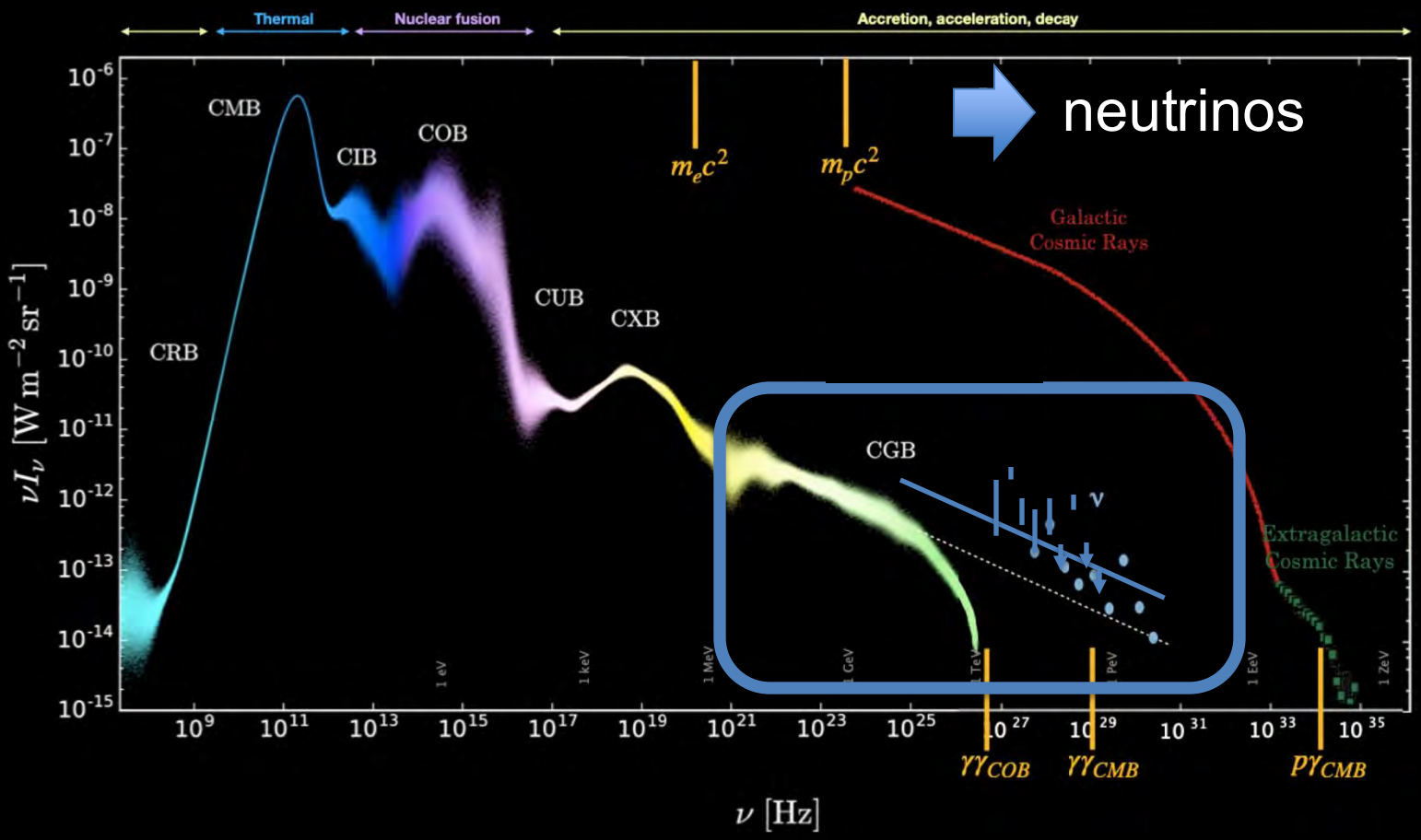
$$f_{GW} = 2 \times f_{\nu}$$



Takiwaki, KK, Foglizzo (2021)

Angular resolution~1deg.

in the extreme universe the energy in neutrinos is larger than the energy in gamma rays observed at GeV energies



one gamma ray for every neutrino?

THE ICECUBE COLLABORATION

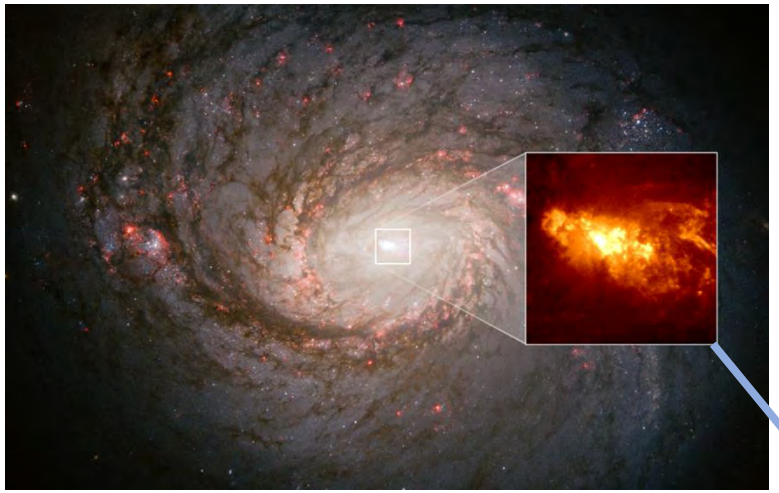
...ALIA 1

... 1

...ED KINGDOM 1

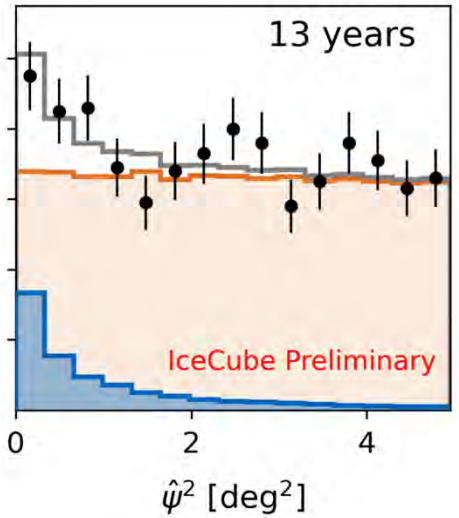
UNITED STATES 25

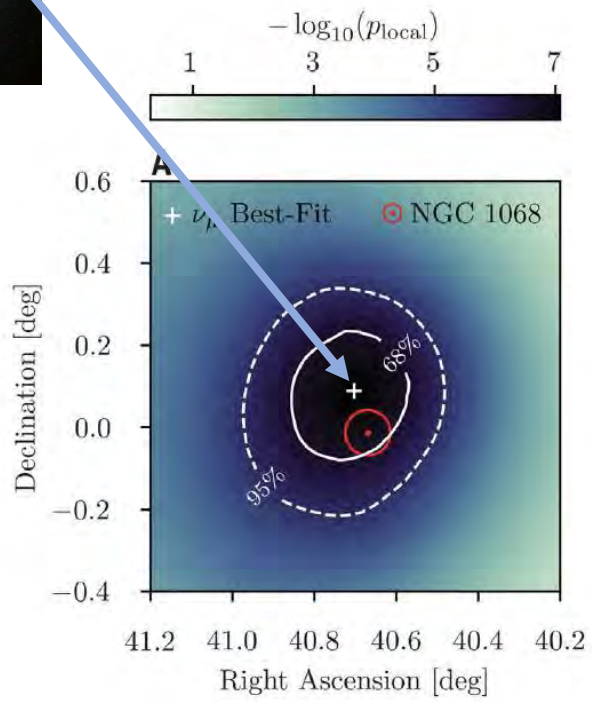
IceCube
South Pole Neutrino Observatory

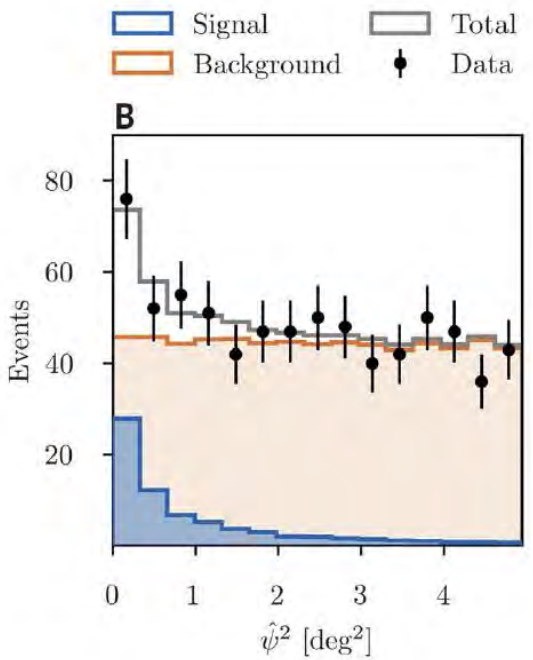


80 high-energy neutrinos from the direction of the active galaxy NGC 1068

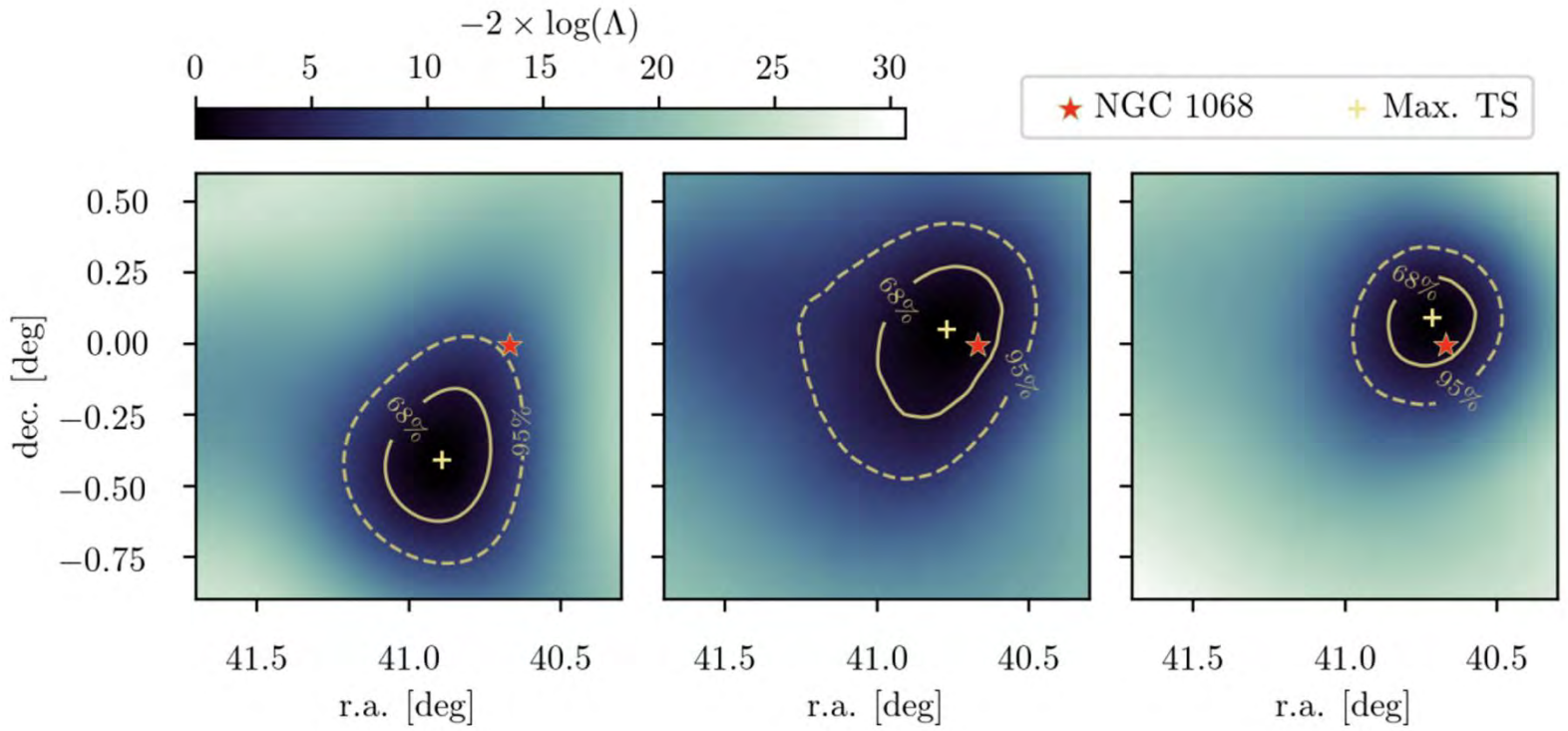
update







NGC 1068 comes into focus



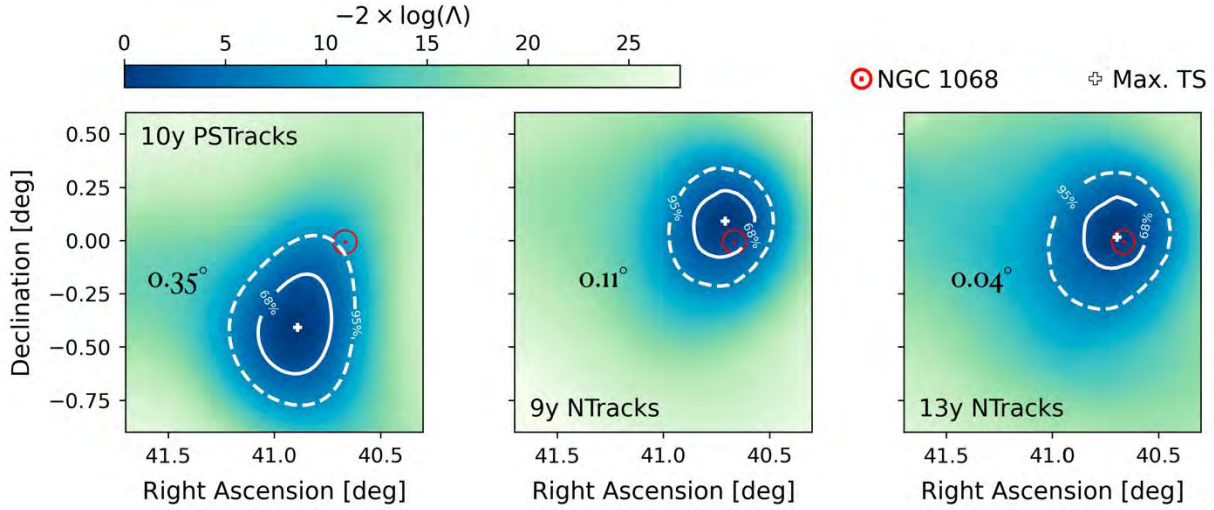
5.2σ local significance

2.9σ
- 10-year analysis

3.3σ
- new likelihood method

4.2σ
- pass 2

update

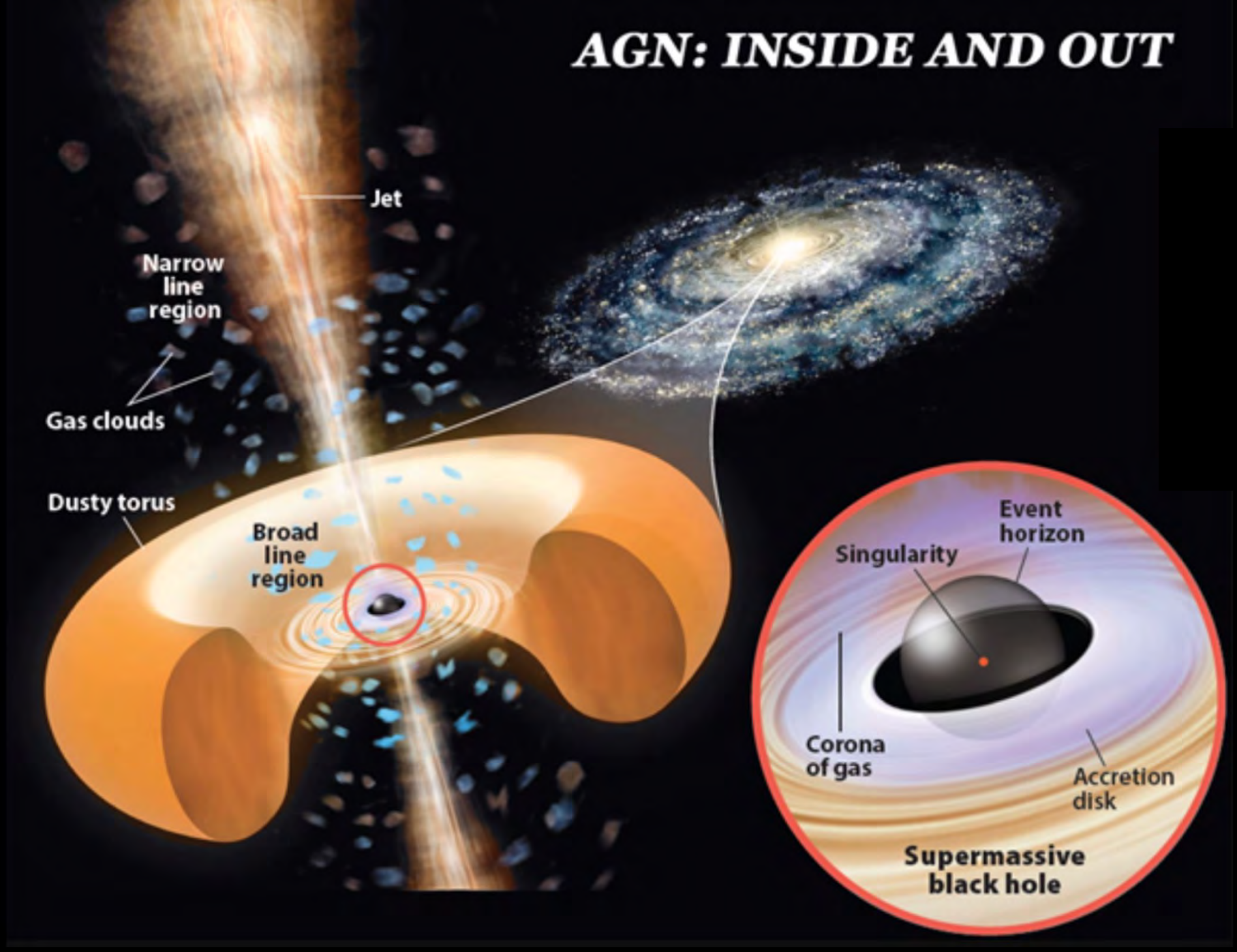


cores of active galaxies

target densities required

- to produce the neutrino flux
- to suppress the flux of the accompanying gamma ray from π^0s

requires a target density only found within < 100 Schwarzschild radii of the black hole



THE ICECUBE COLLABORATION

...ALIA 1

... 1

...ED KINGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory

overflow sides

Lorentz violation: ΔE vs Δt

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

$$\Delta t \approx \frac{1+n}{2}\left(\frac{d}{c}\right)\left(\frac{E_\nu}{M_{QG}}\right)^n$$

from a source at a distance d

It is a small effect → integrate over long distances