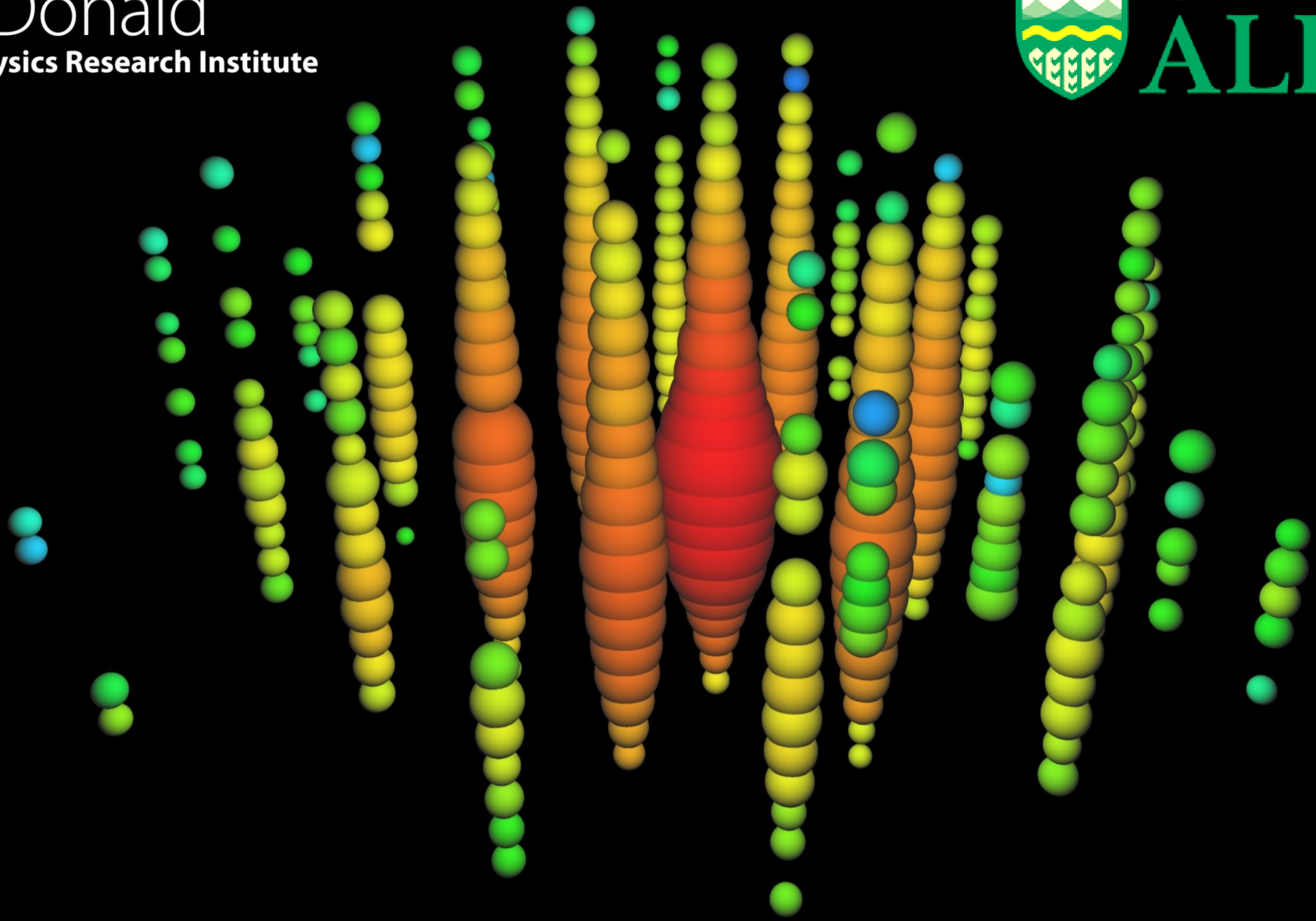
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

UNIVERSITY OF ALBERTA

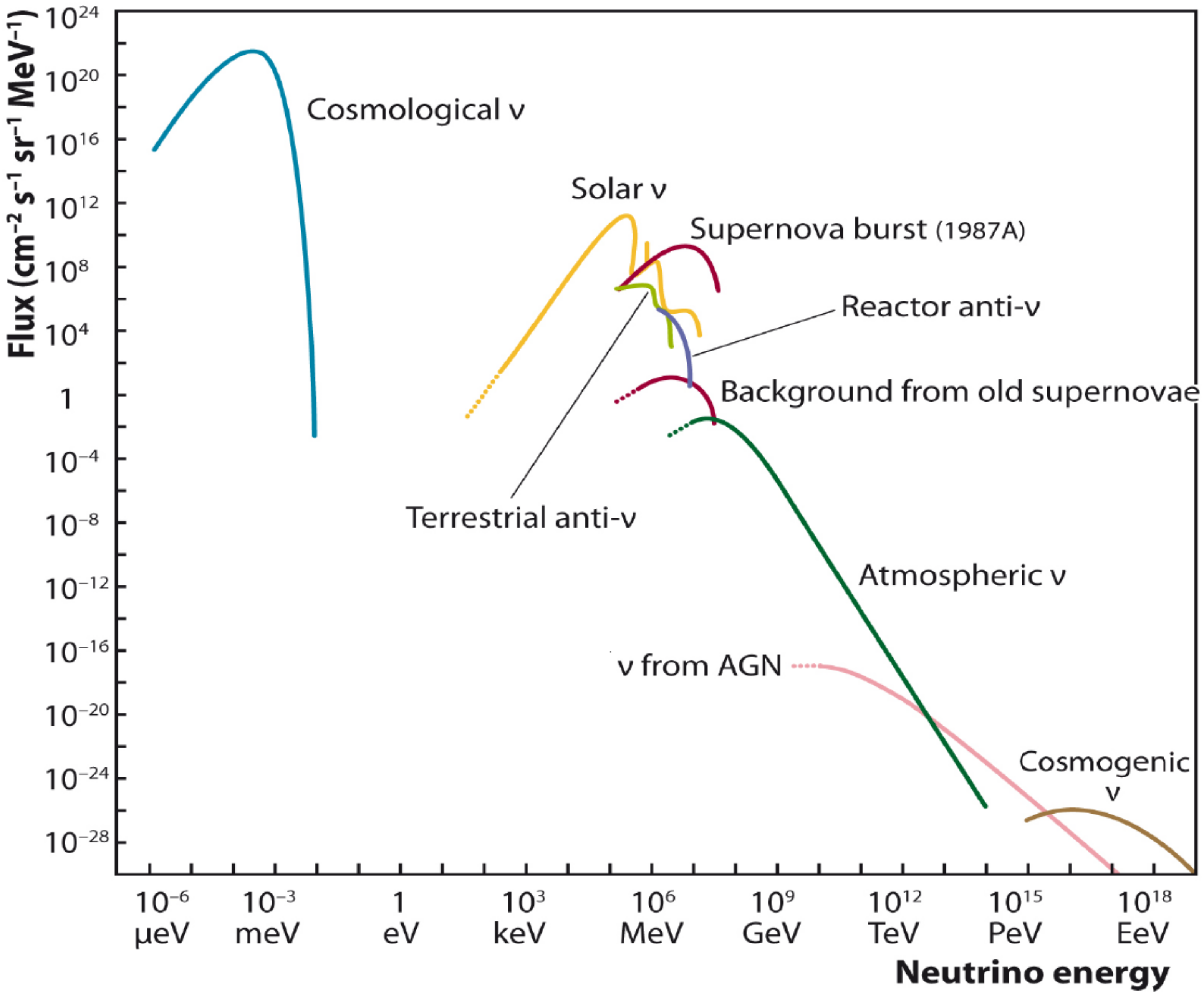


Particle physics at extreme energies using neutrino telescopes

Juan Pablo Yáñez
j.p.yanez@ualberta.ca

why detecting high energy neutrinos?

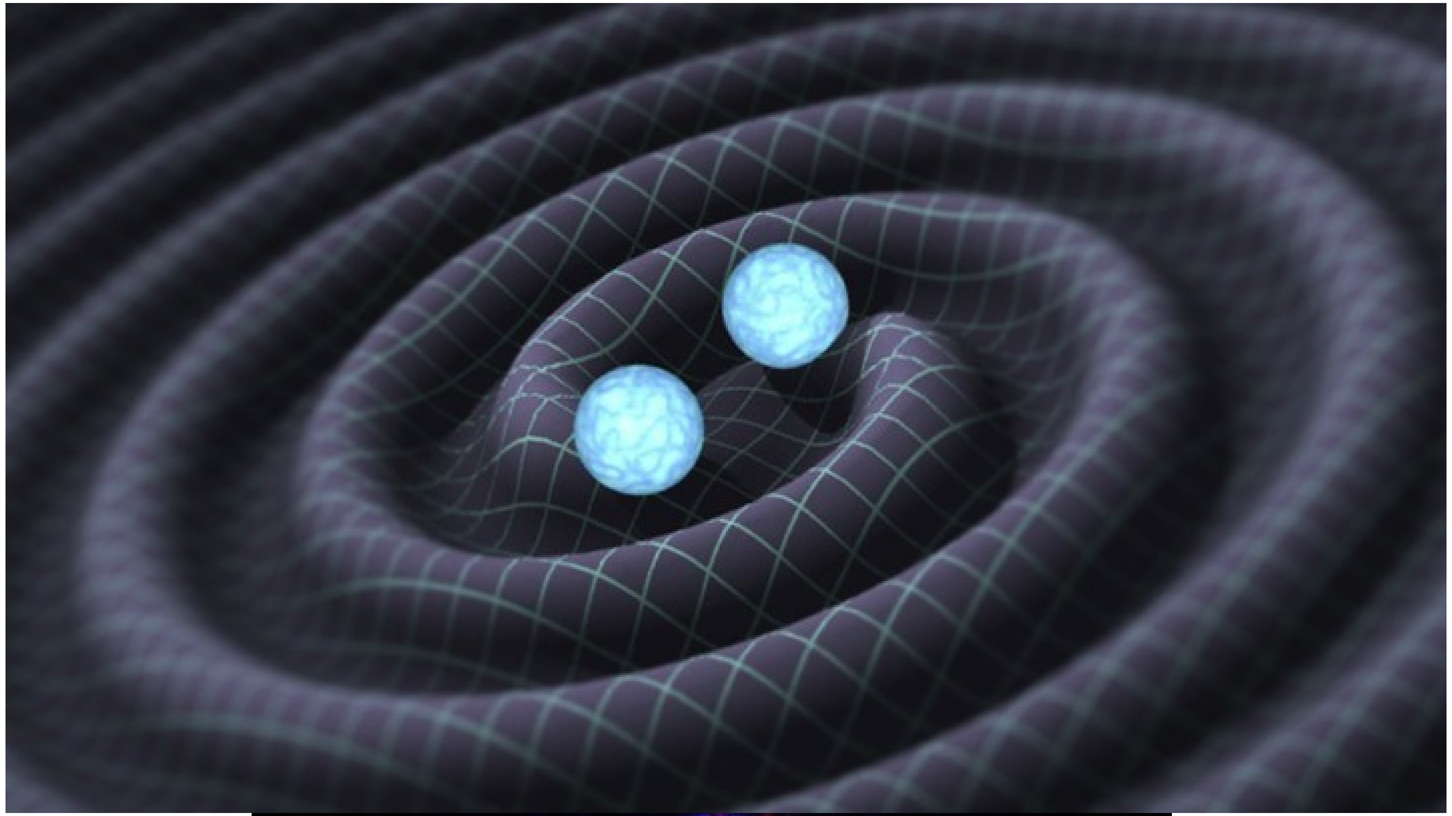
neutrino sources



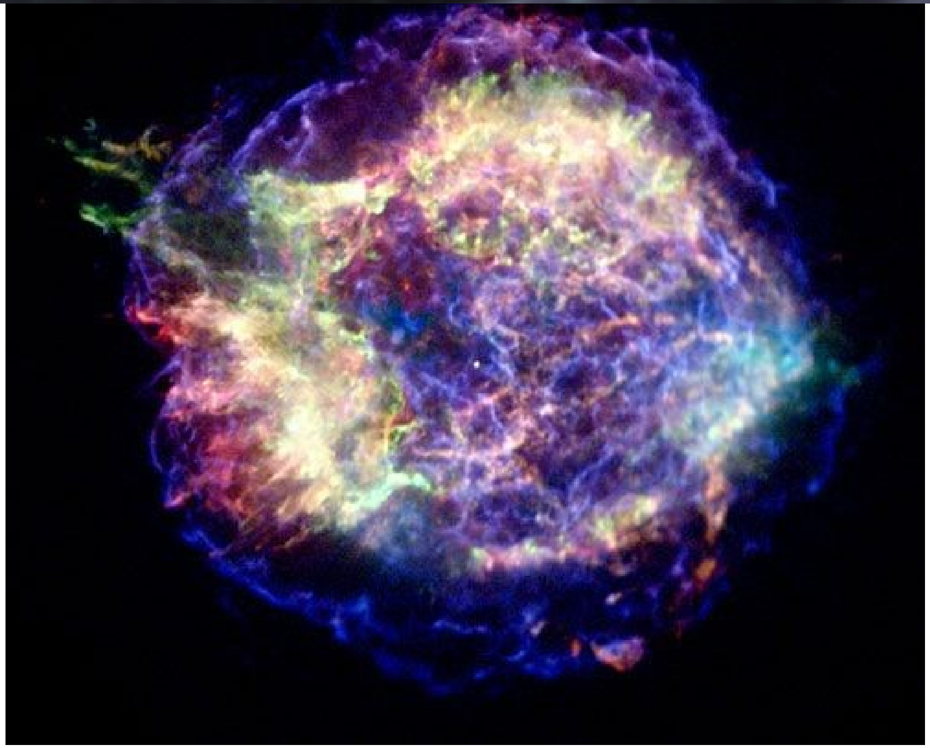
-naturally occurring neutrinos can have extreme energies

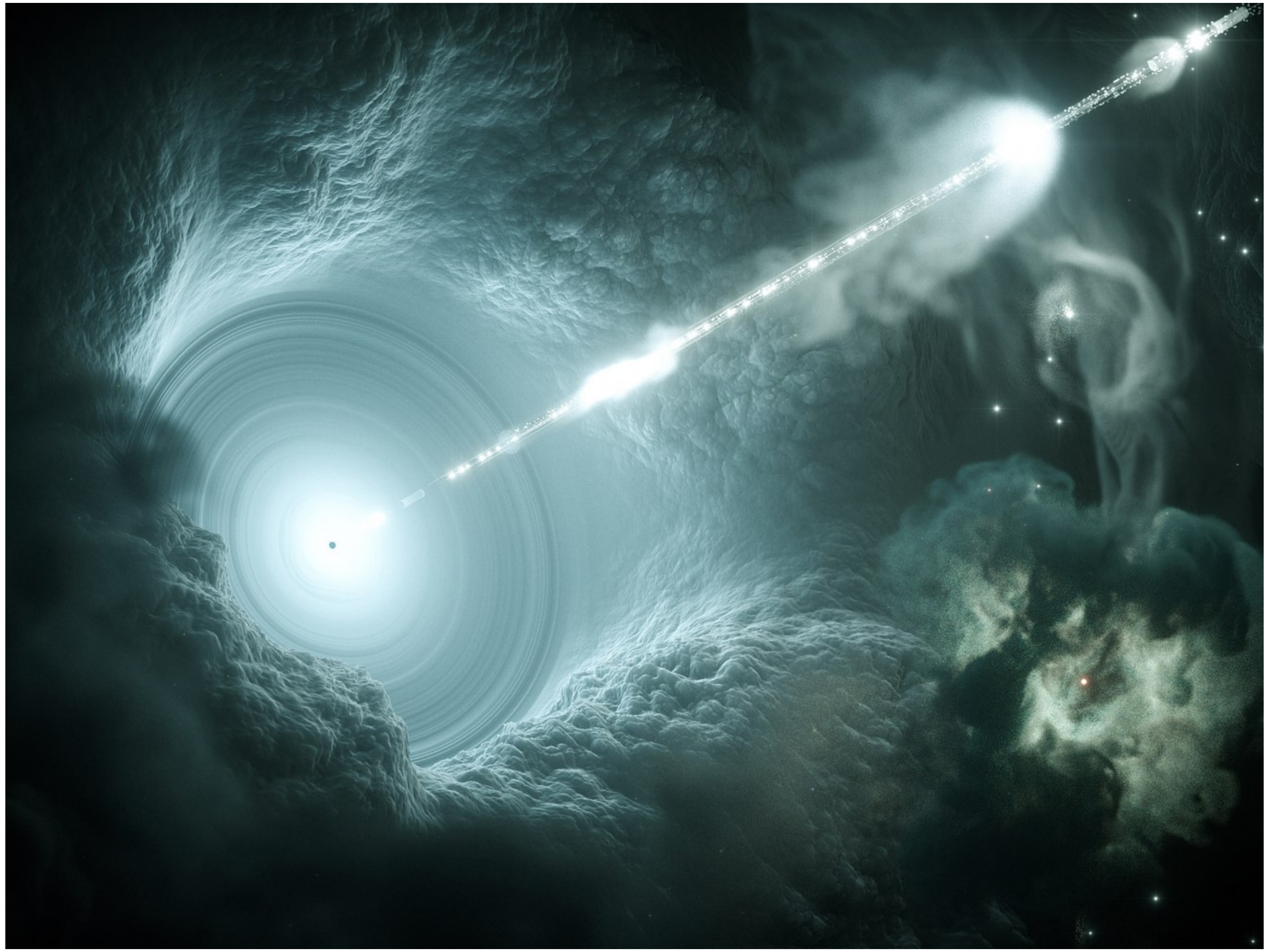
-manmade beams can reach E ~ 50 GeV at most

-but the fluxes are low, so you need really large detectors

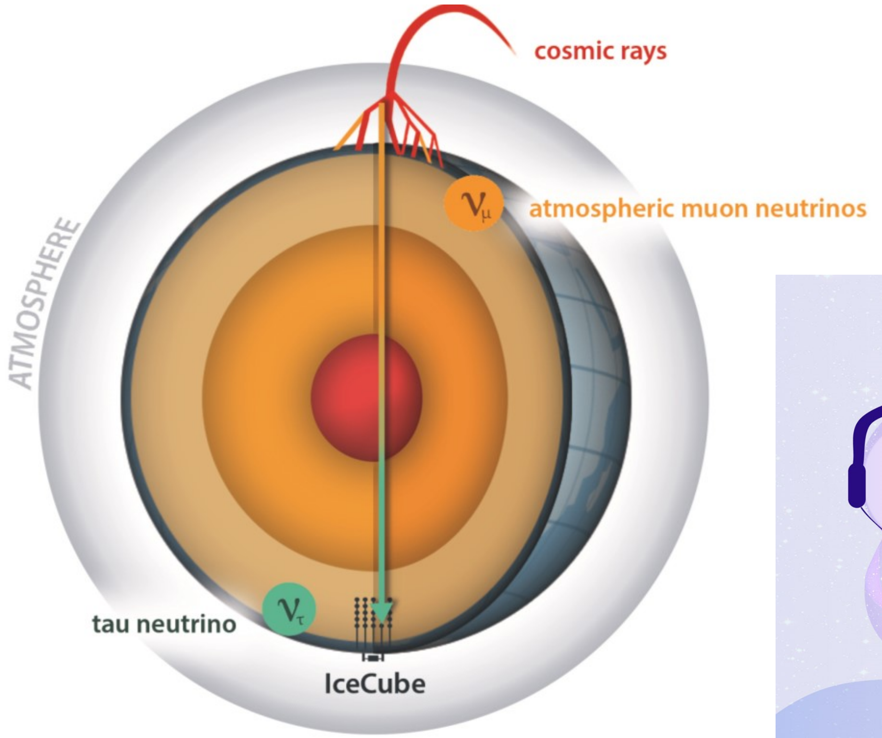


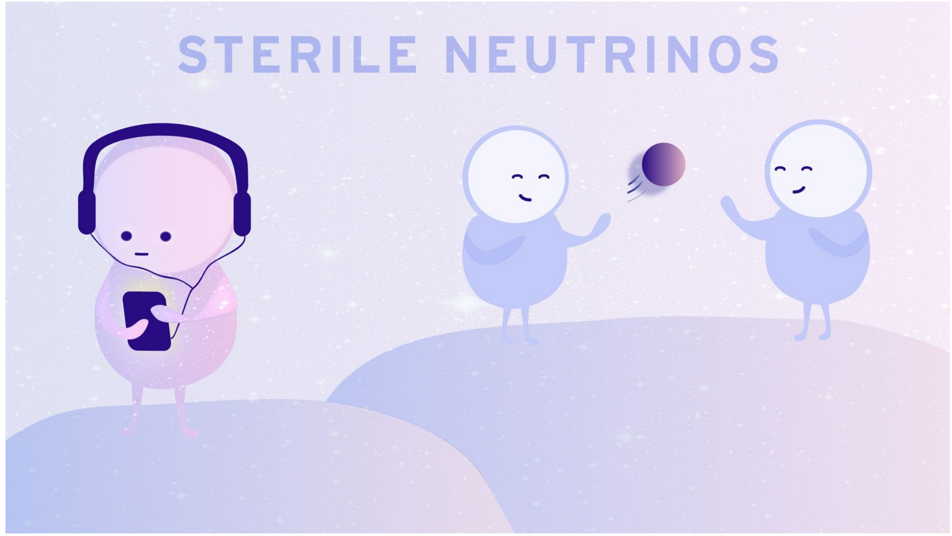
studying their sources

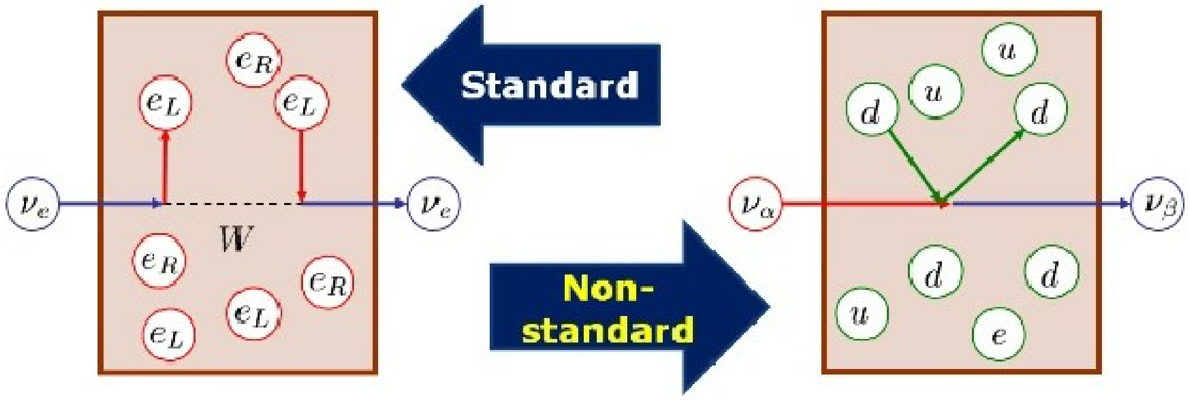


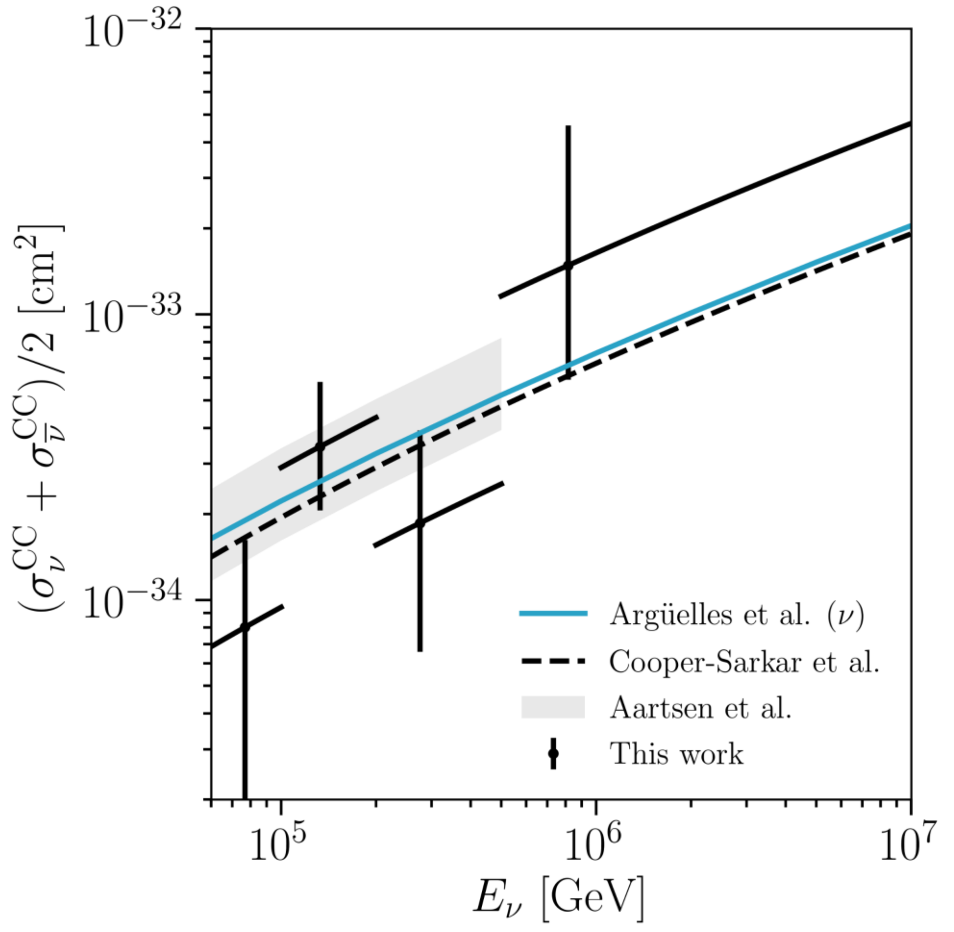


using ν as probes



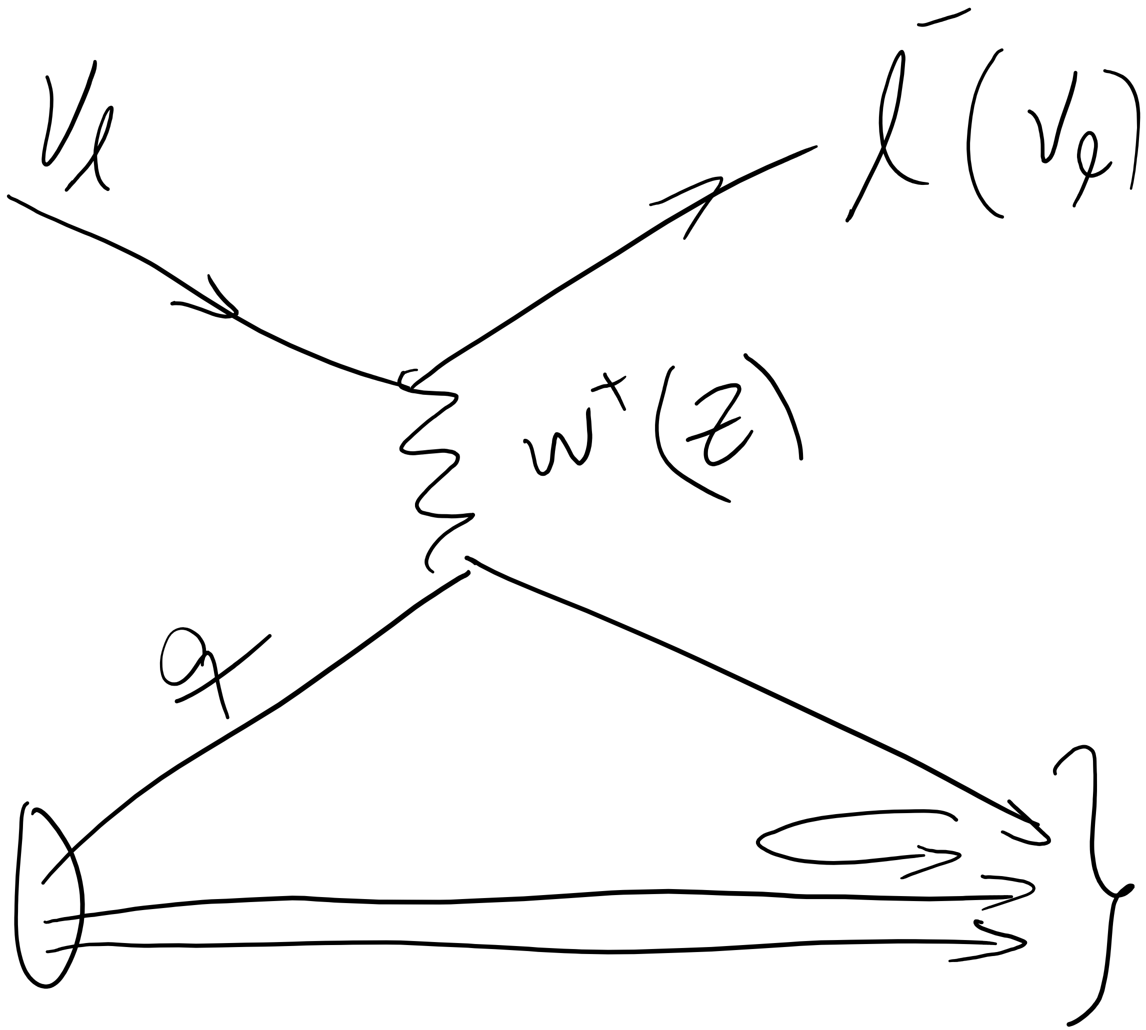




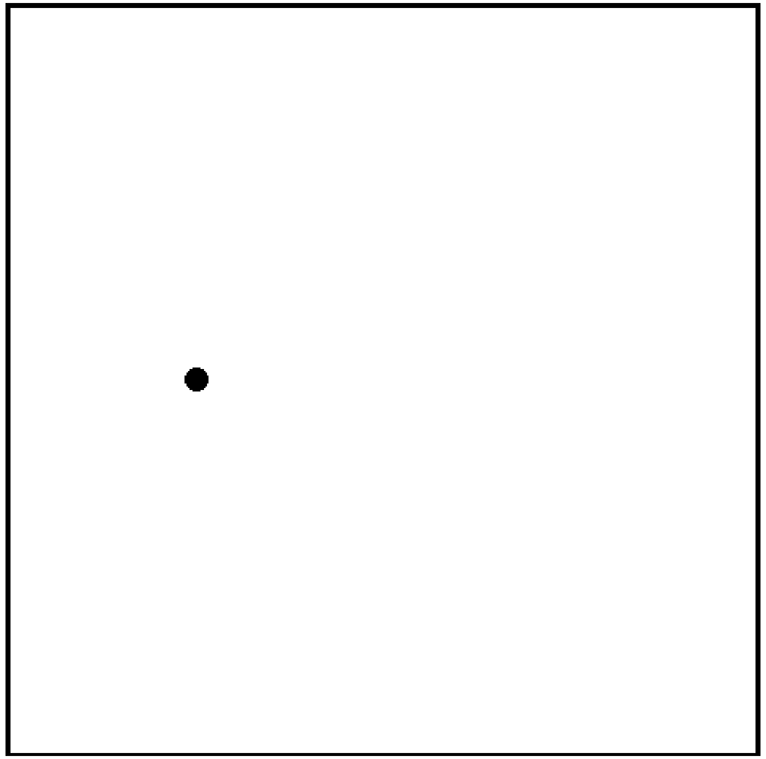


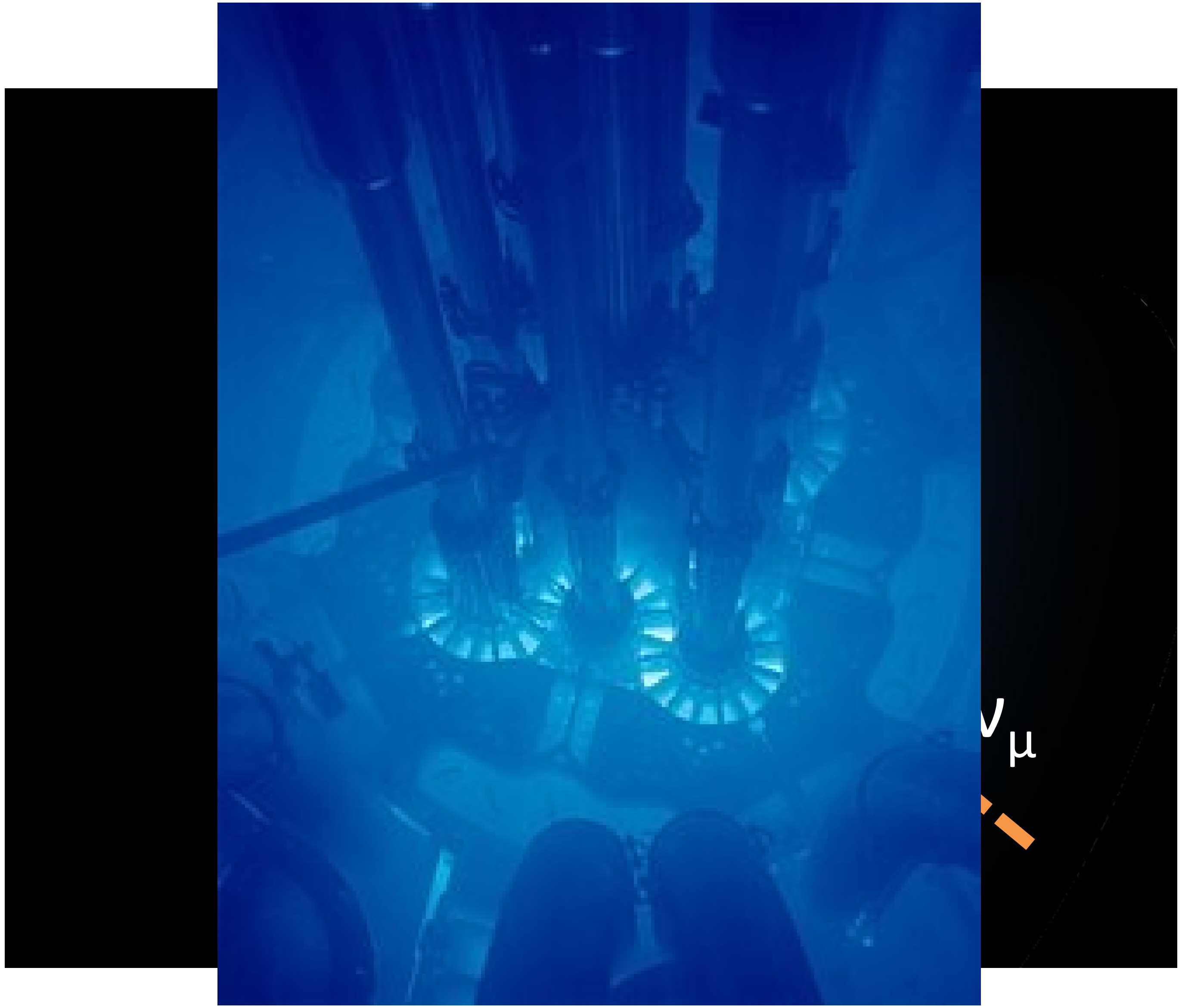
neutrino **telescope** basics

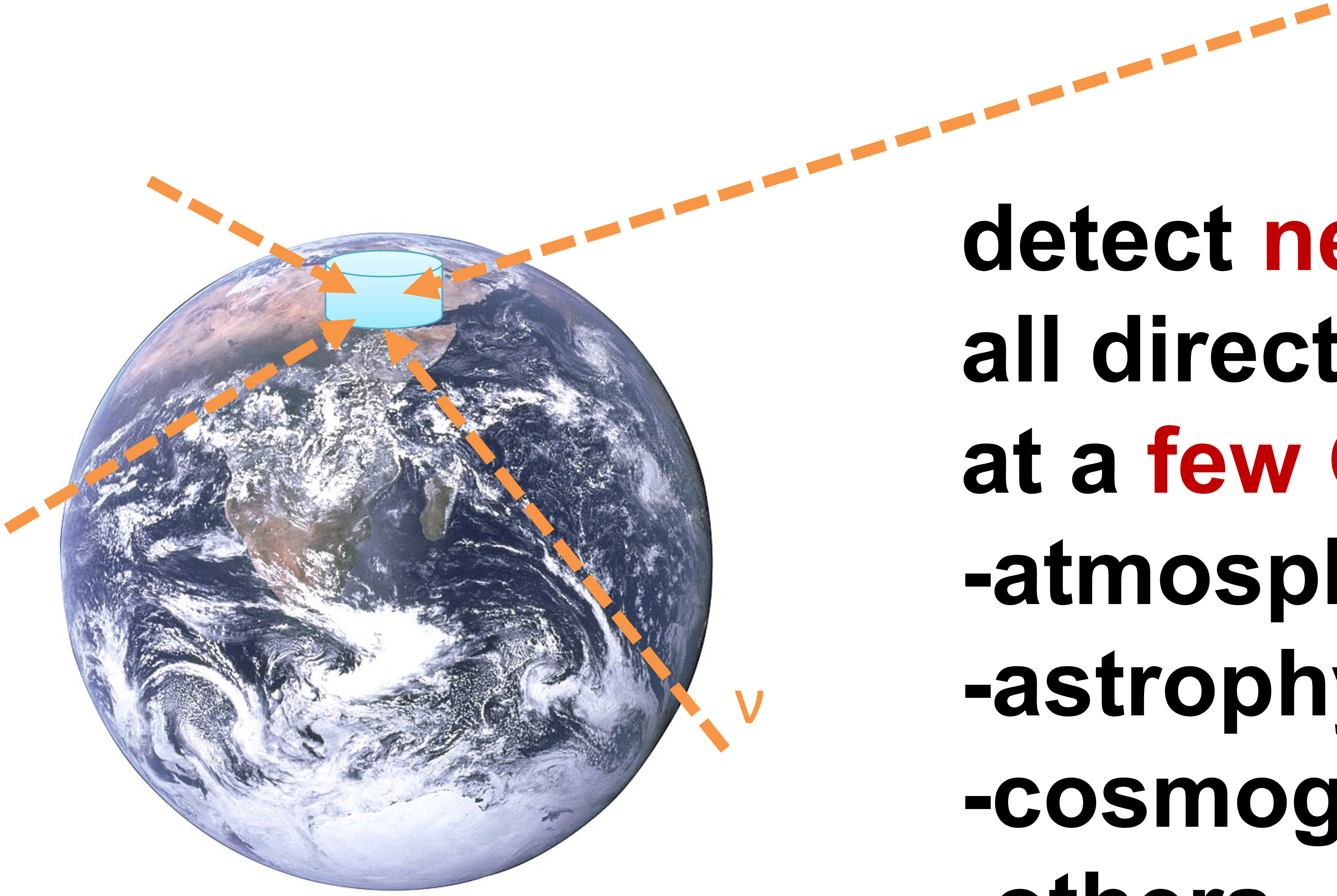
interaction mainly with single quarks in nucleons – simple and well understood



-detection via **Cherenkov** light
-**large**, natural & transparent medium
-**3D** array of sensors
-deep **underground**







detect neutrinos from all directions starting at a few GeV

-atmospheric

-astrophysical

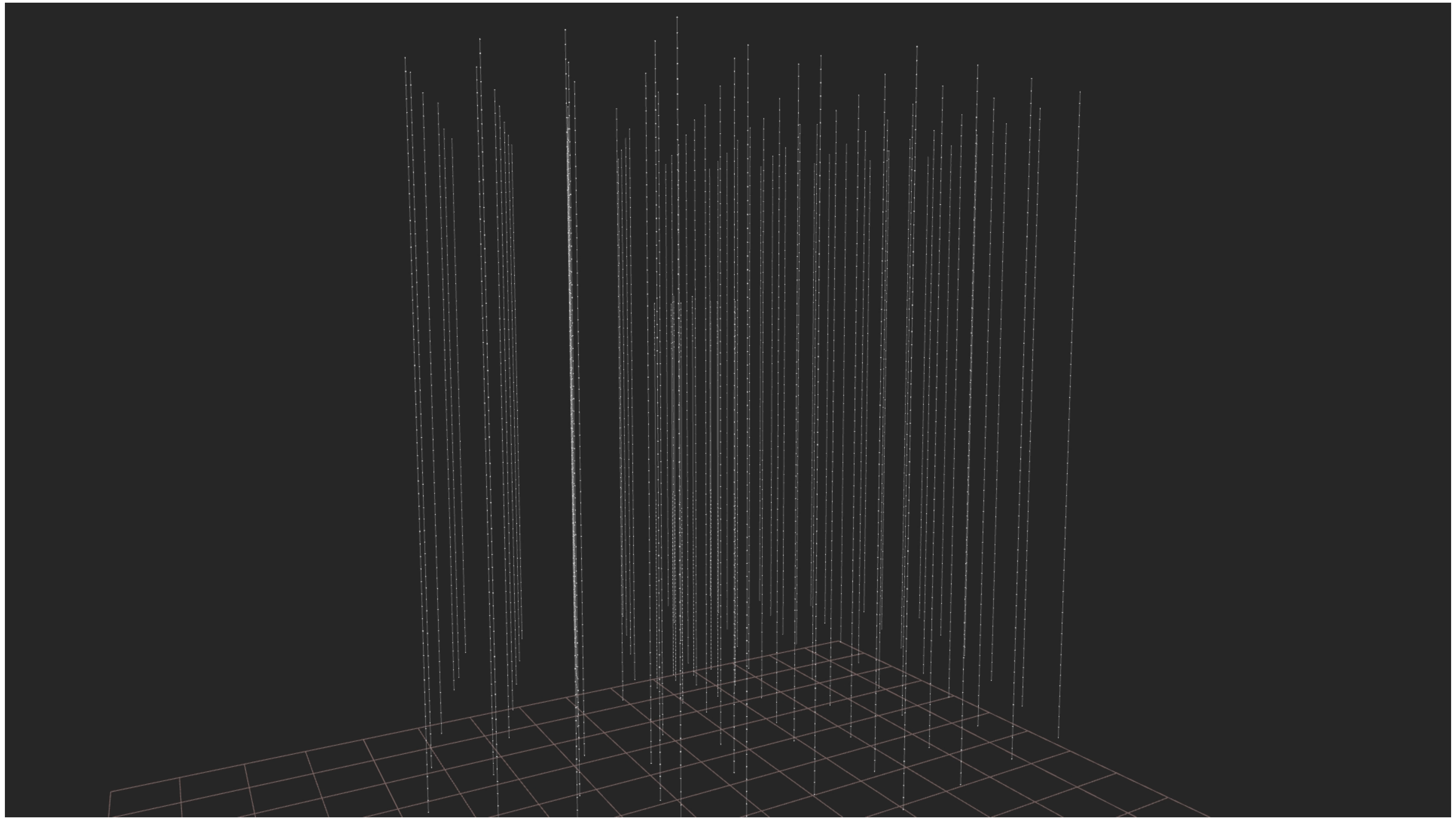
-cosmogenic

-others

-muons travel from tens of meters to several km

-other particles shower

sparsely instrumented detectors work



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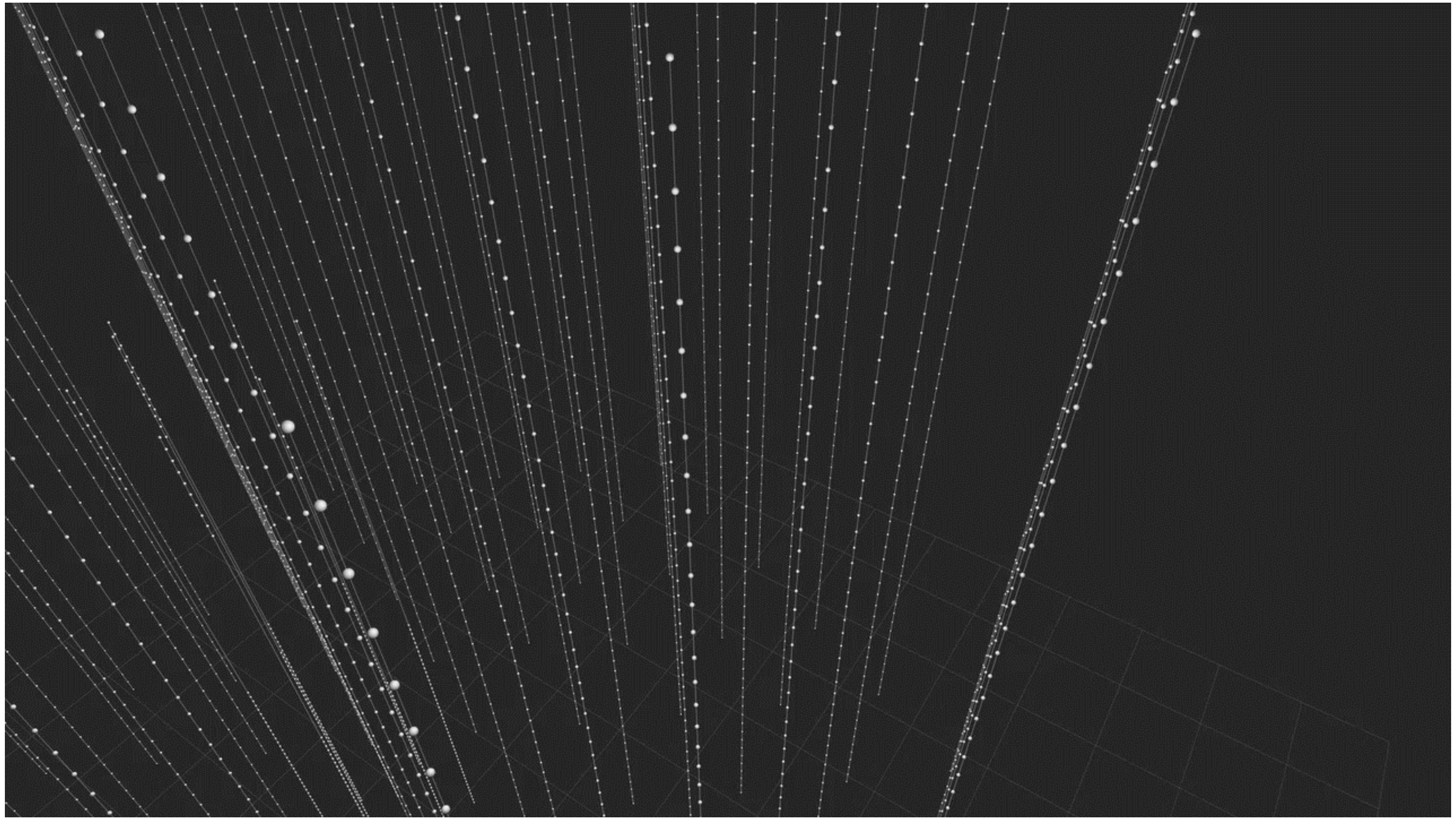
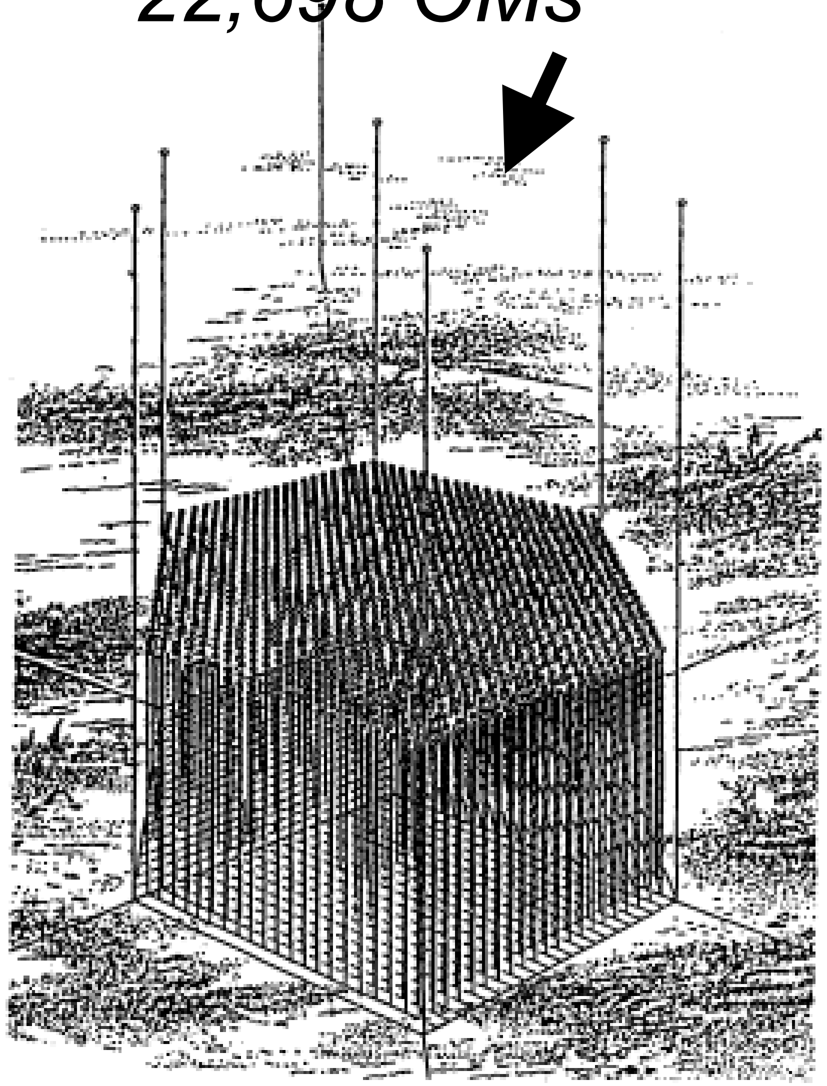


neutrino telescopes history

1978: 1.26 km³

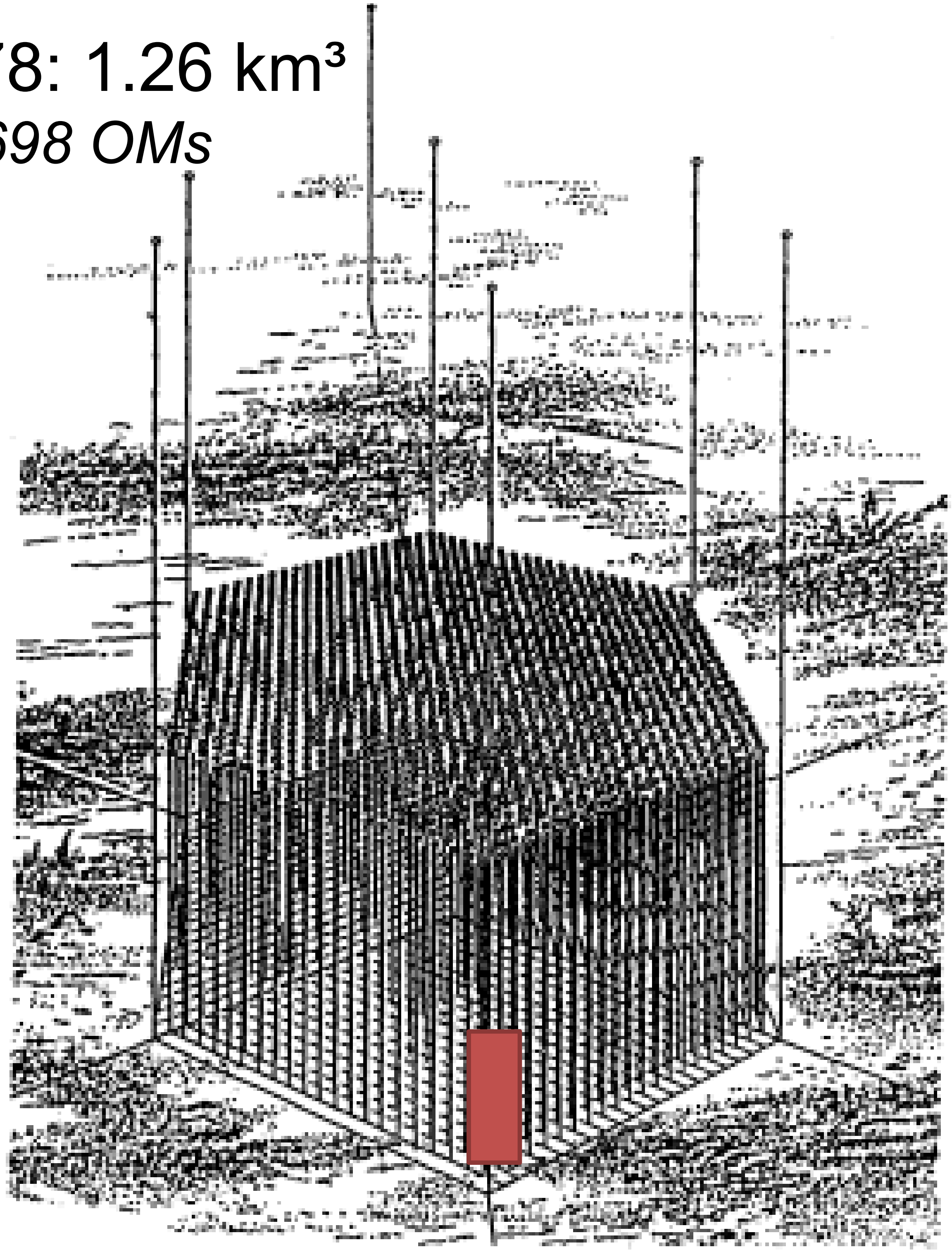
22,698 OMs



DUMAND in Hawaii
first proposed in 1973

1978: 1.26 km³

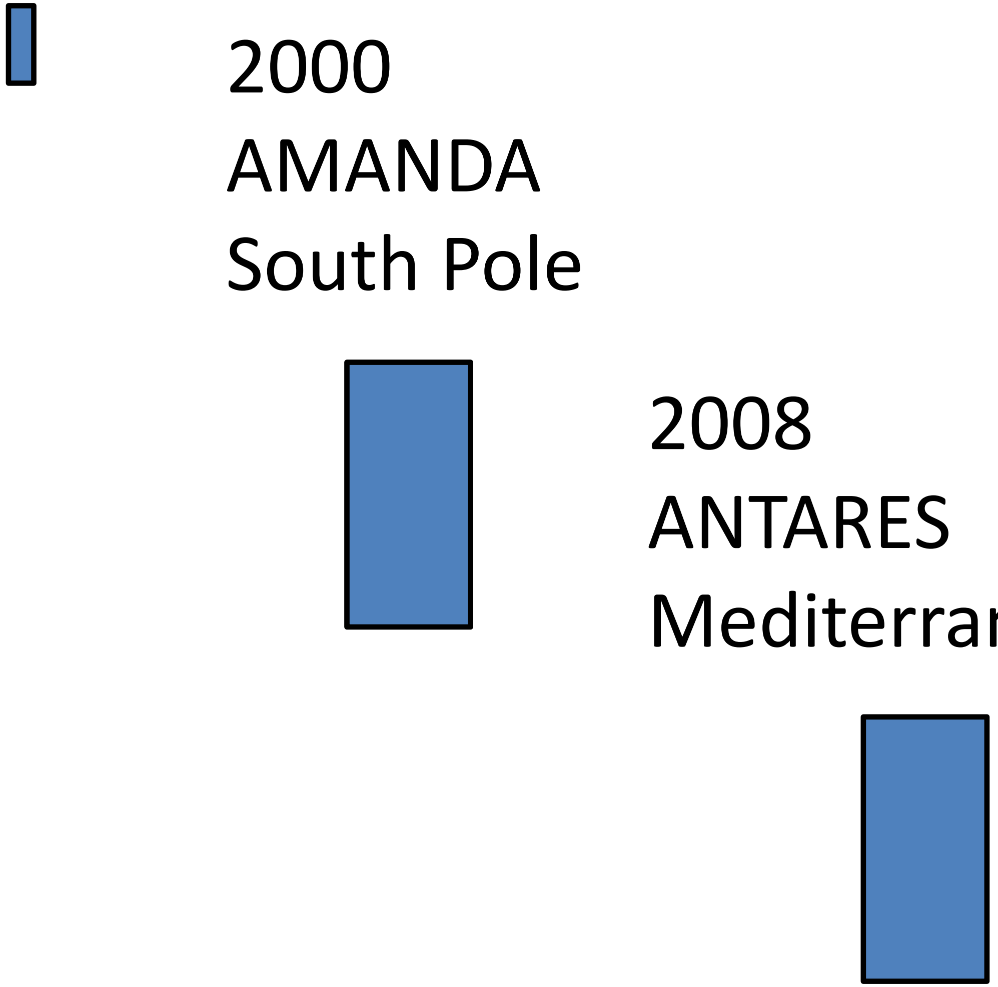
22,698 OMs



1998
NT200
Lake Baikal

2000
AMANDA
South Pole

2008
ANTARES
Mediterranean



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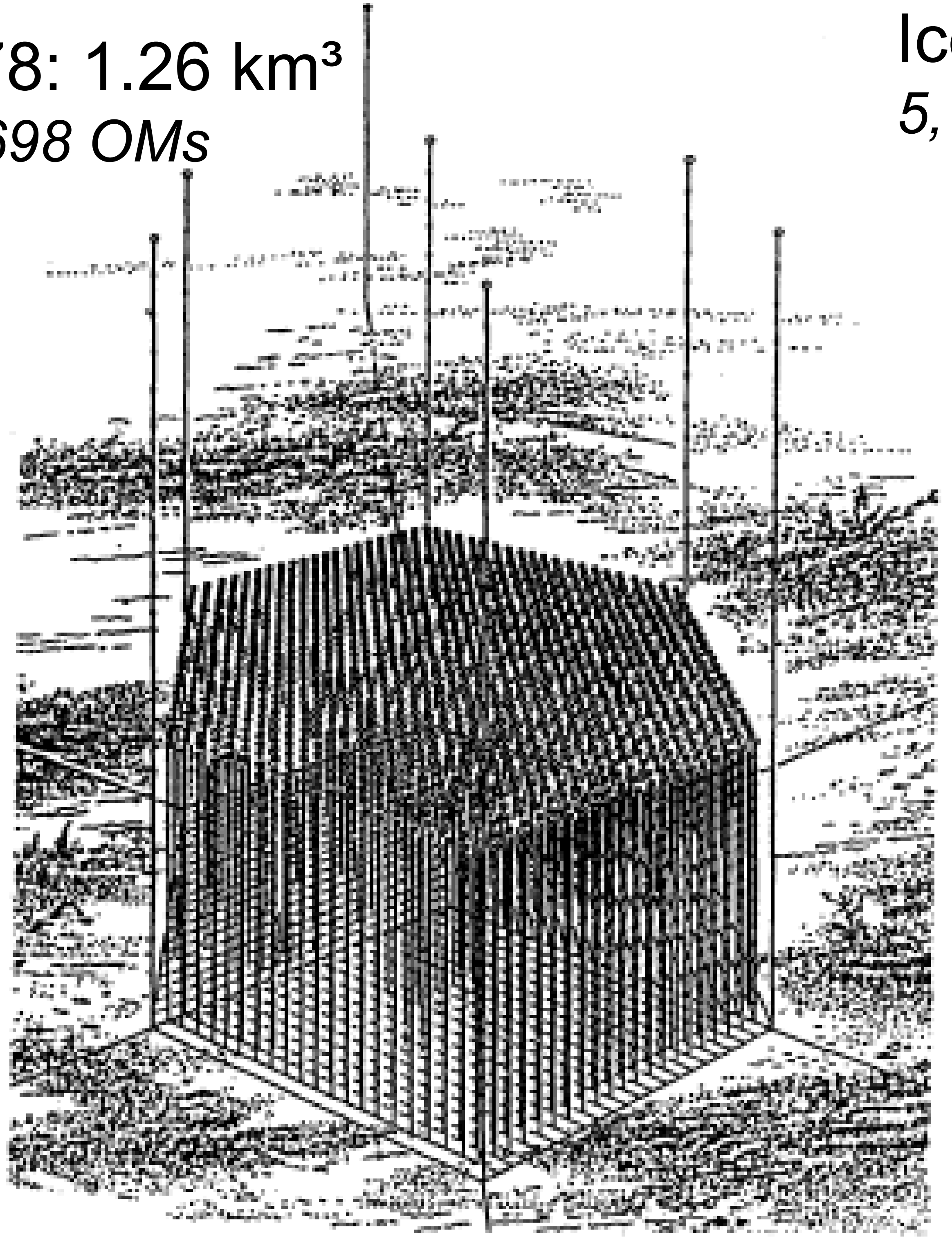
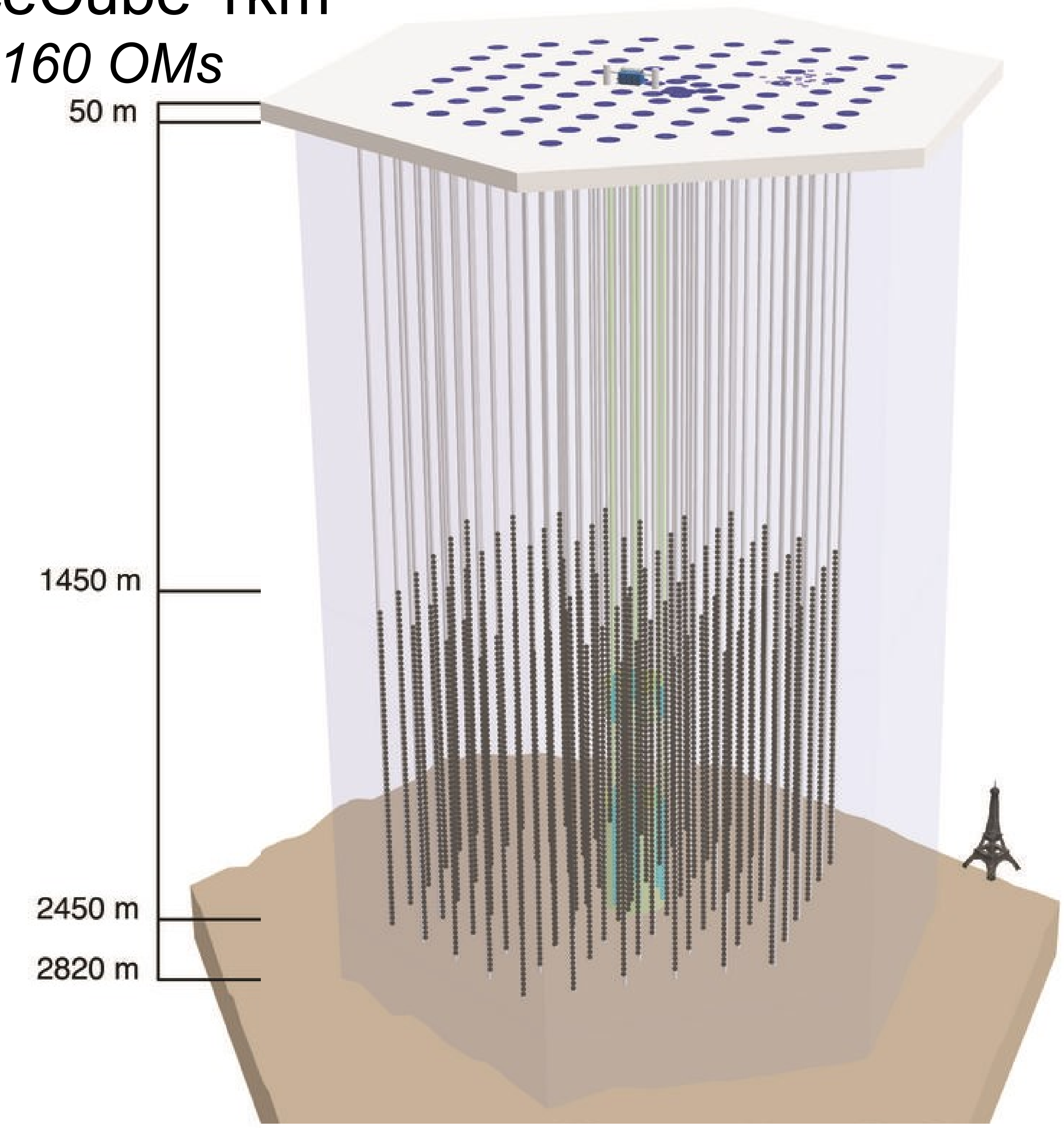


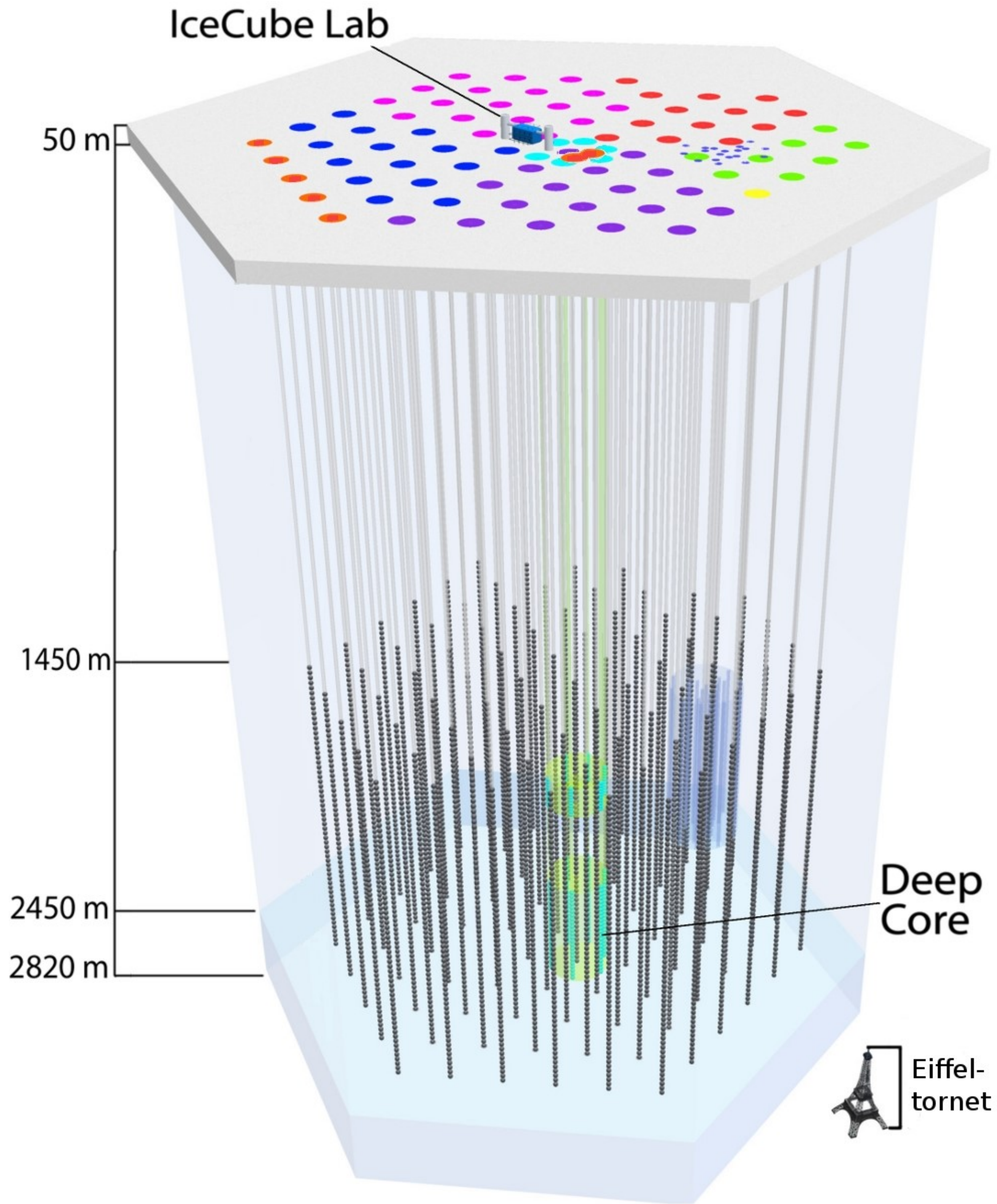
IceCube 1km³

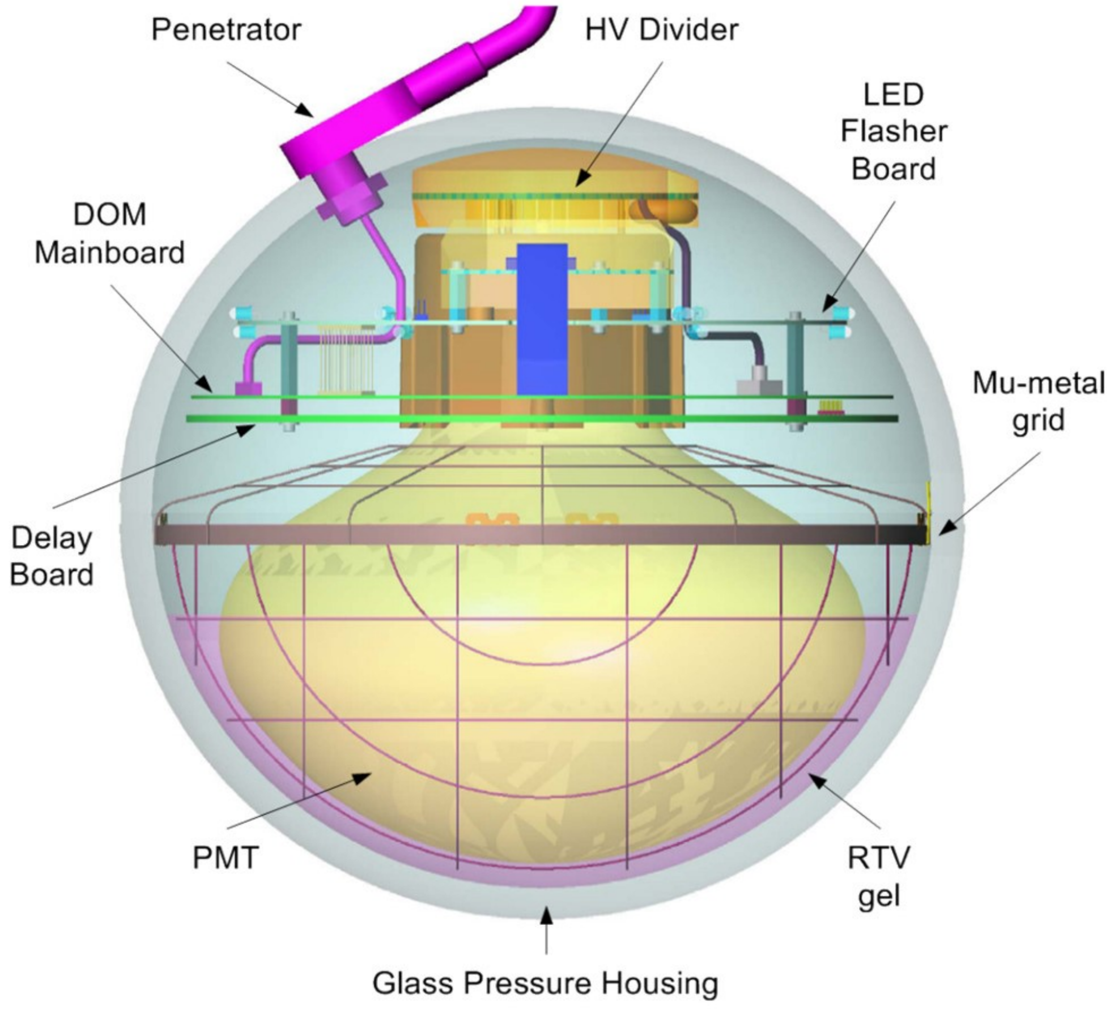
5,160 OMs

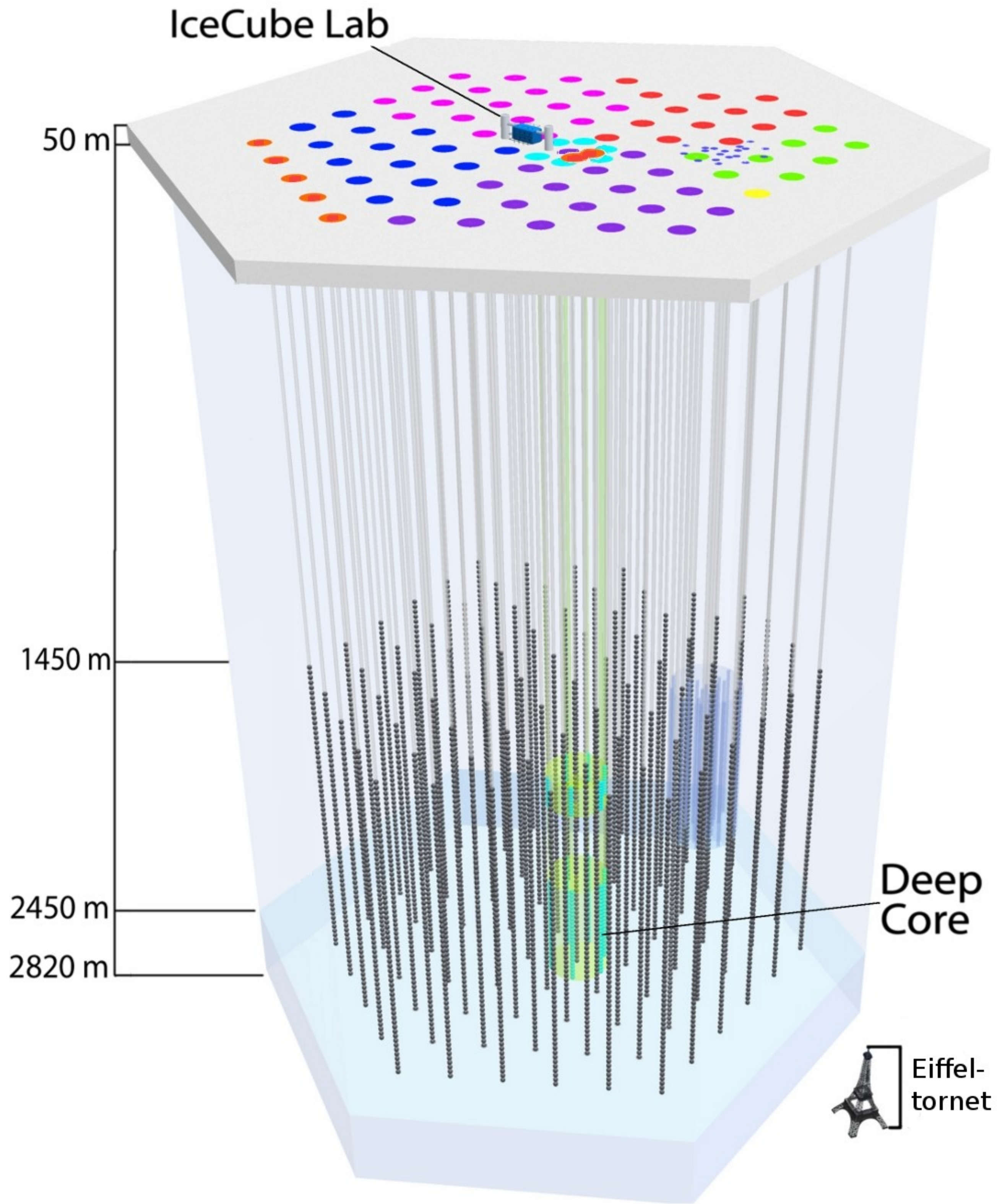


IceCube

the **largest** neutrino detector in the world





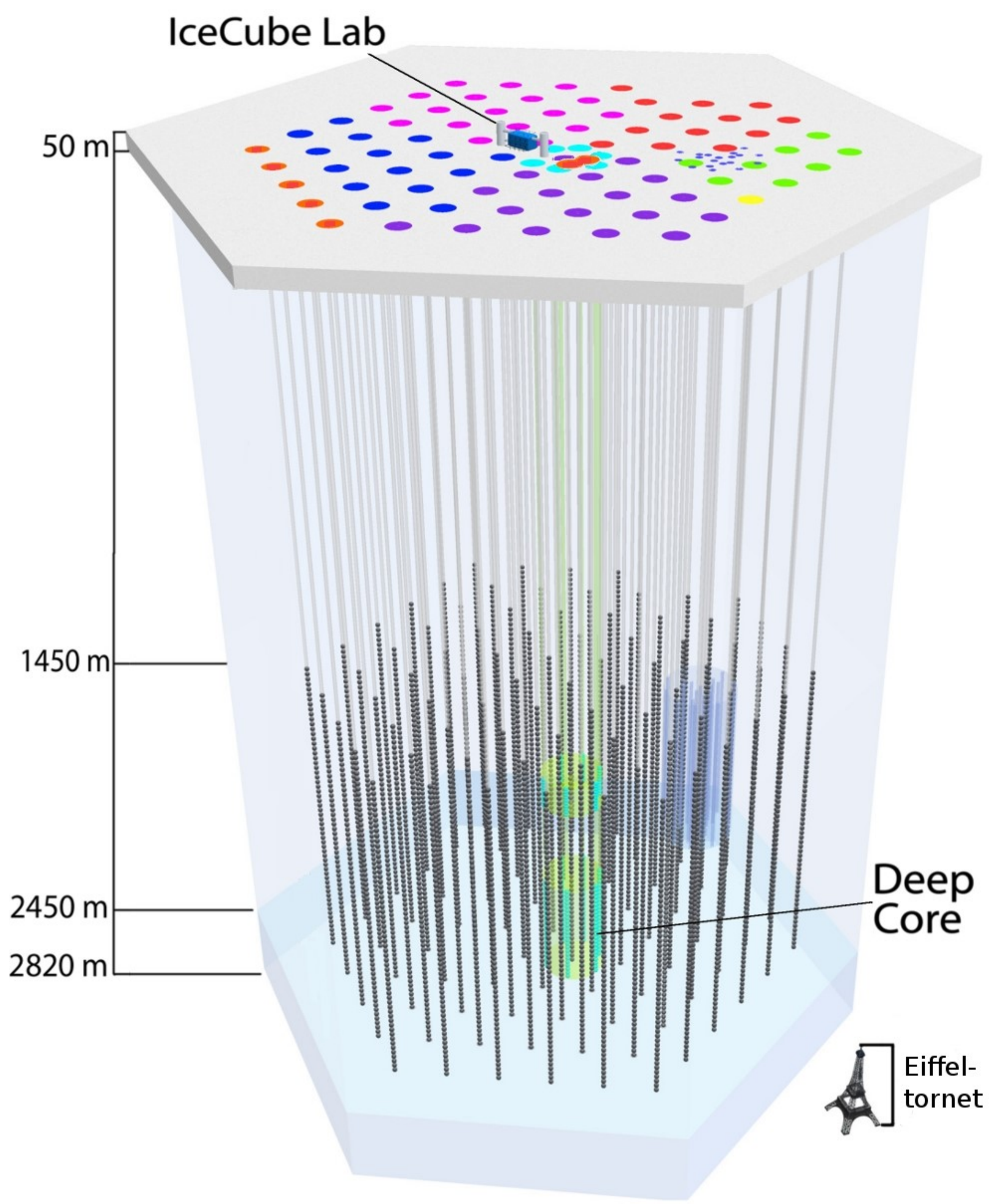


IceCube

the largest neutrino detector in the world

1 km^3 of ice monitored by 5000+ photo-sensors

buried 1.5 km under the surface



IceCube

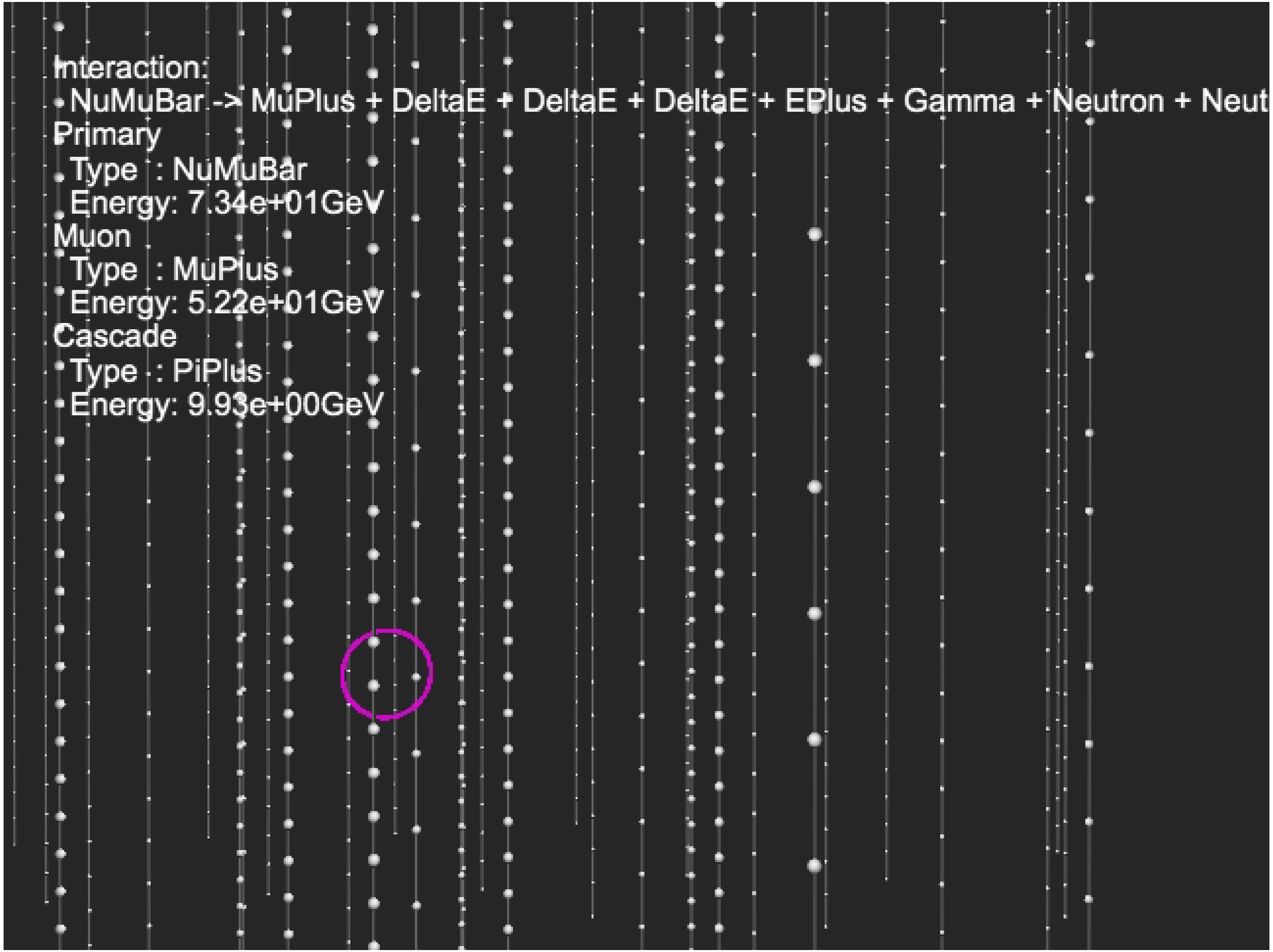
two regions

IceCube

17m spacing in z 125m in x-y

DeepCore

7m in z, 40-70m in x-y


Interaction:
NuMuBar -> MuPlus + DeltaE + DeltaE + DeltaE + EPlus + Gamma + Neutron + Neut
Primary
Type : NuMuBar
Energy: 7.34e+01GeV
Muon
Type : MuPlus
Energy: 5.22e+01GeV
Cascade
Type : PiPlus
Energy: 9.93e+00GeV

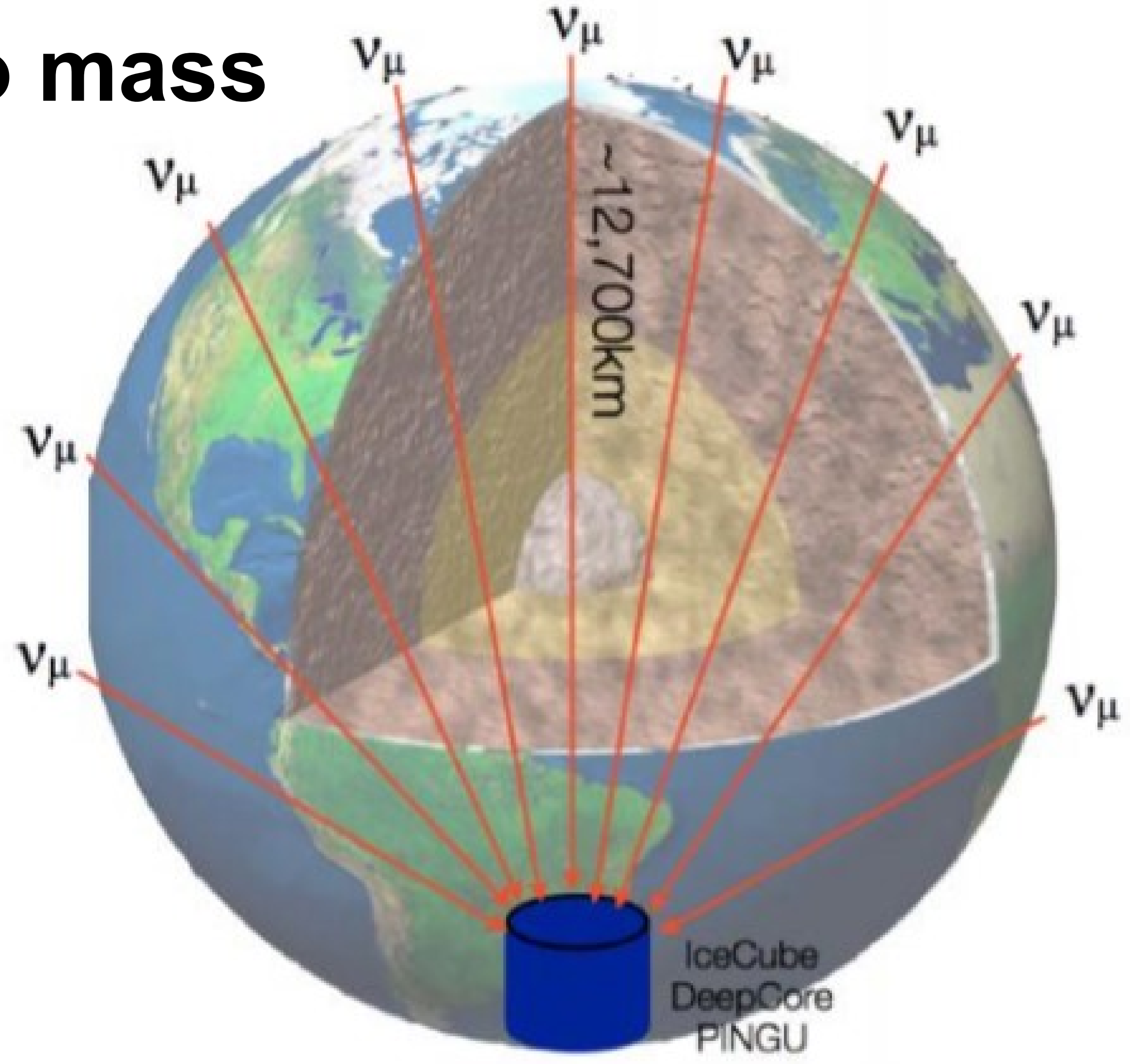
neutrino physics
with IceCube

oscillation parameters

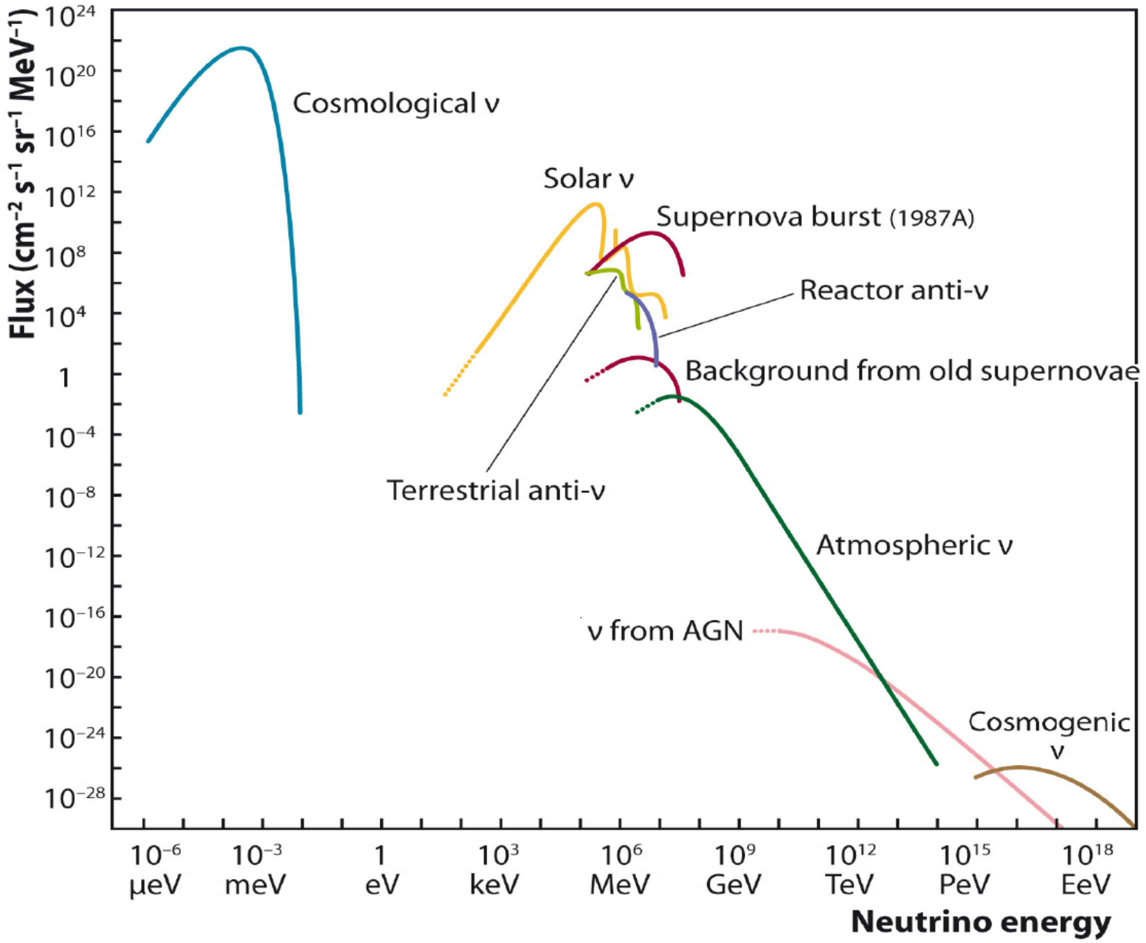
atmospheric neutrino oscillations
-crucial in discovery of neutrino mass
-Nobel prize 2015
-still being understood

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

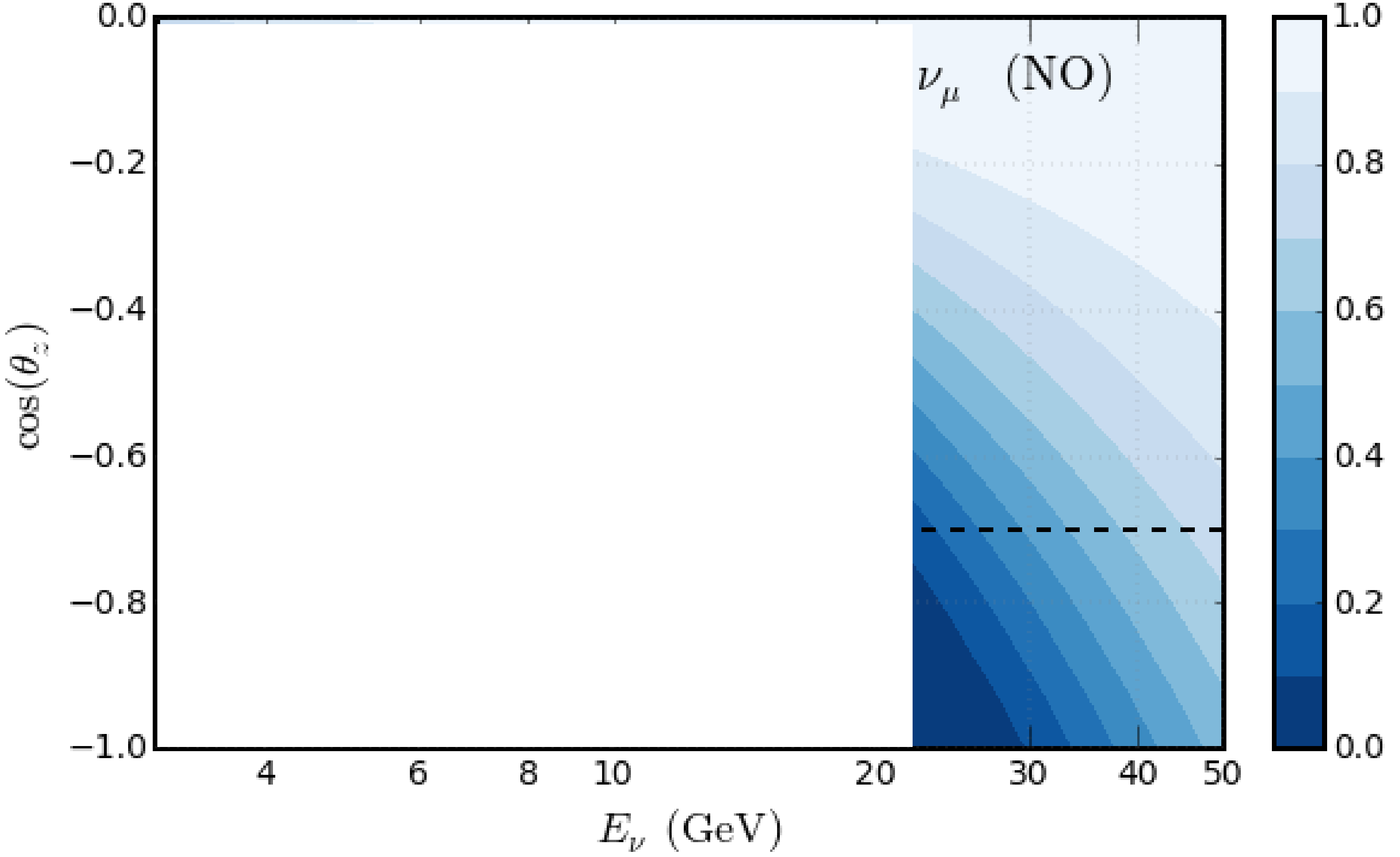
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



neutrino oscillations & DeepCore



neutrino survival probabilities in DeepCore



$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\ \sin^2(\frac{\Delta m^2}{4E} L)$$

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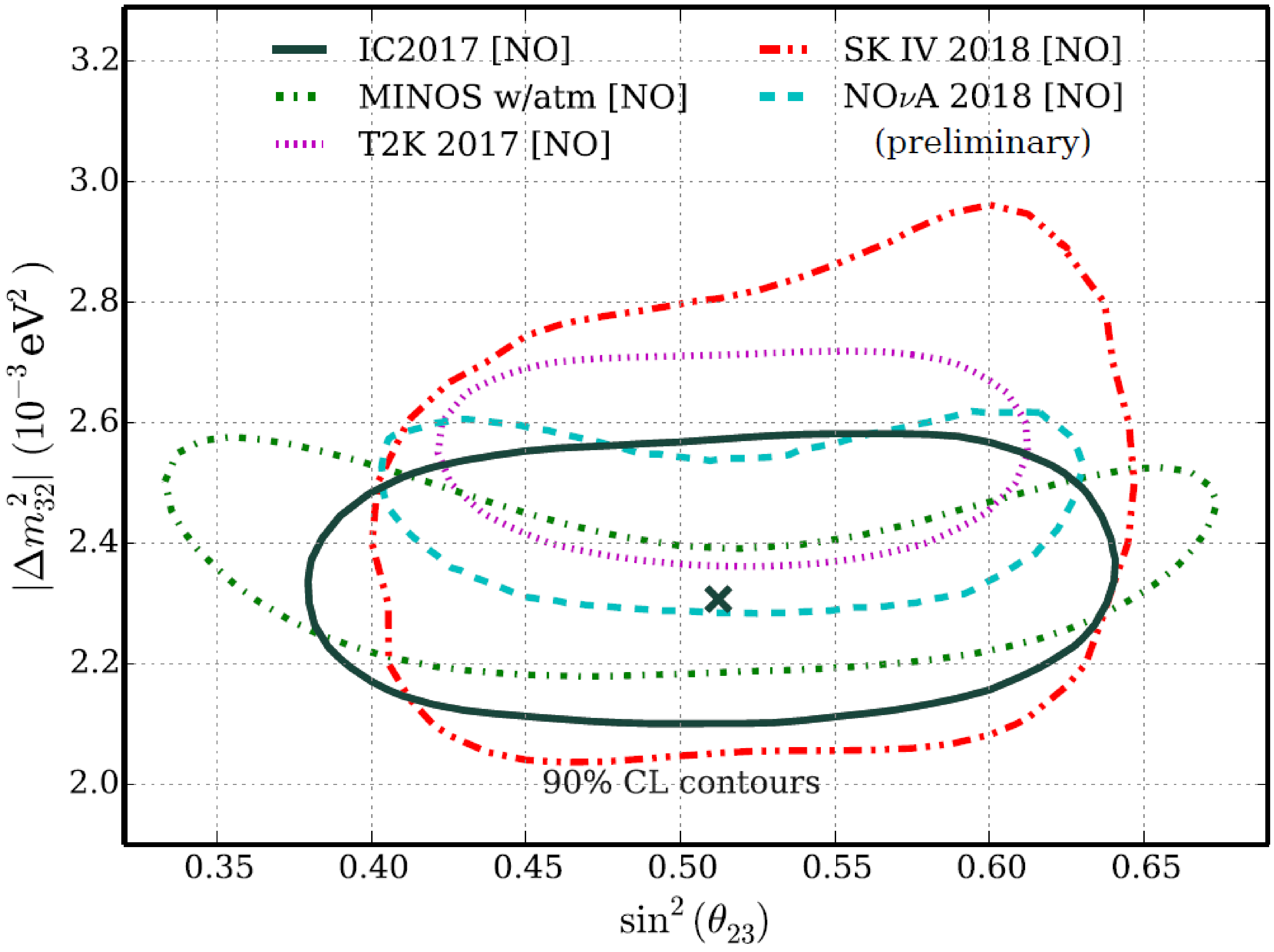
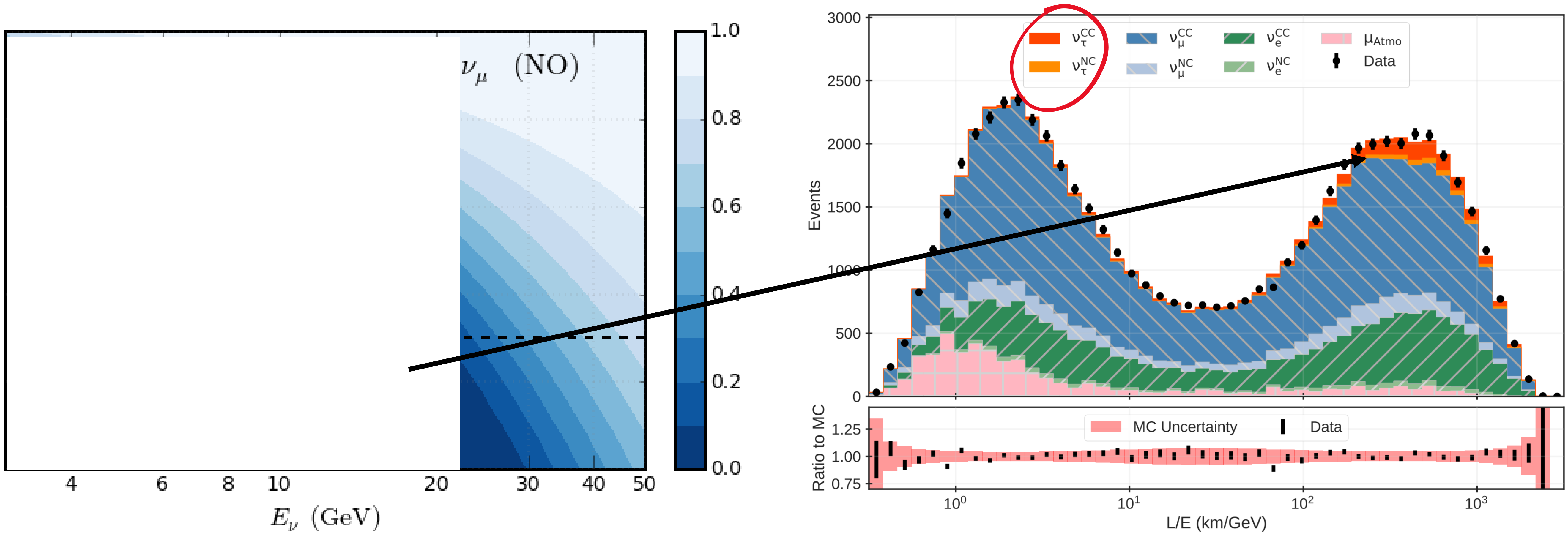


tau neutrino appearance



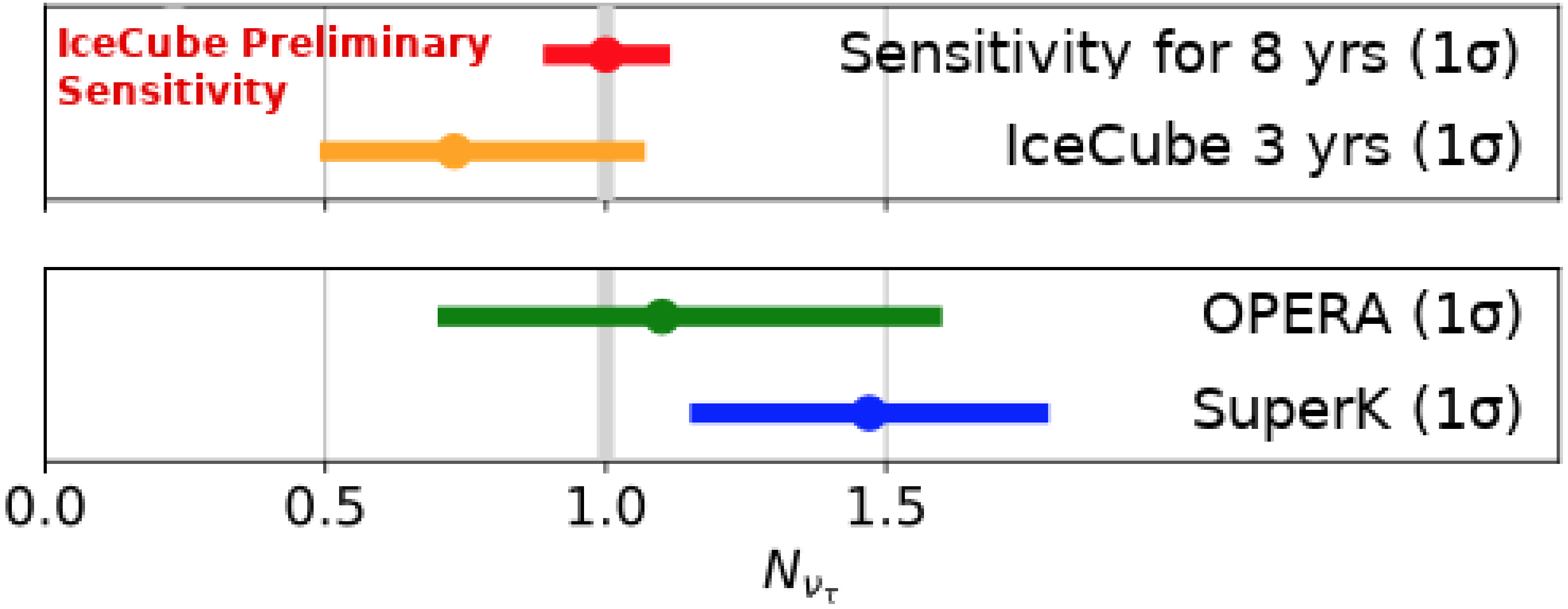
disappeared muon neutrinos mainly go to tau neutrinos

-tau lepton E threshold → only HE detection

-test of unitarity of PMNS matrix

-test of NuTau CC cross section

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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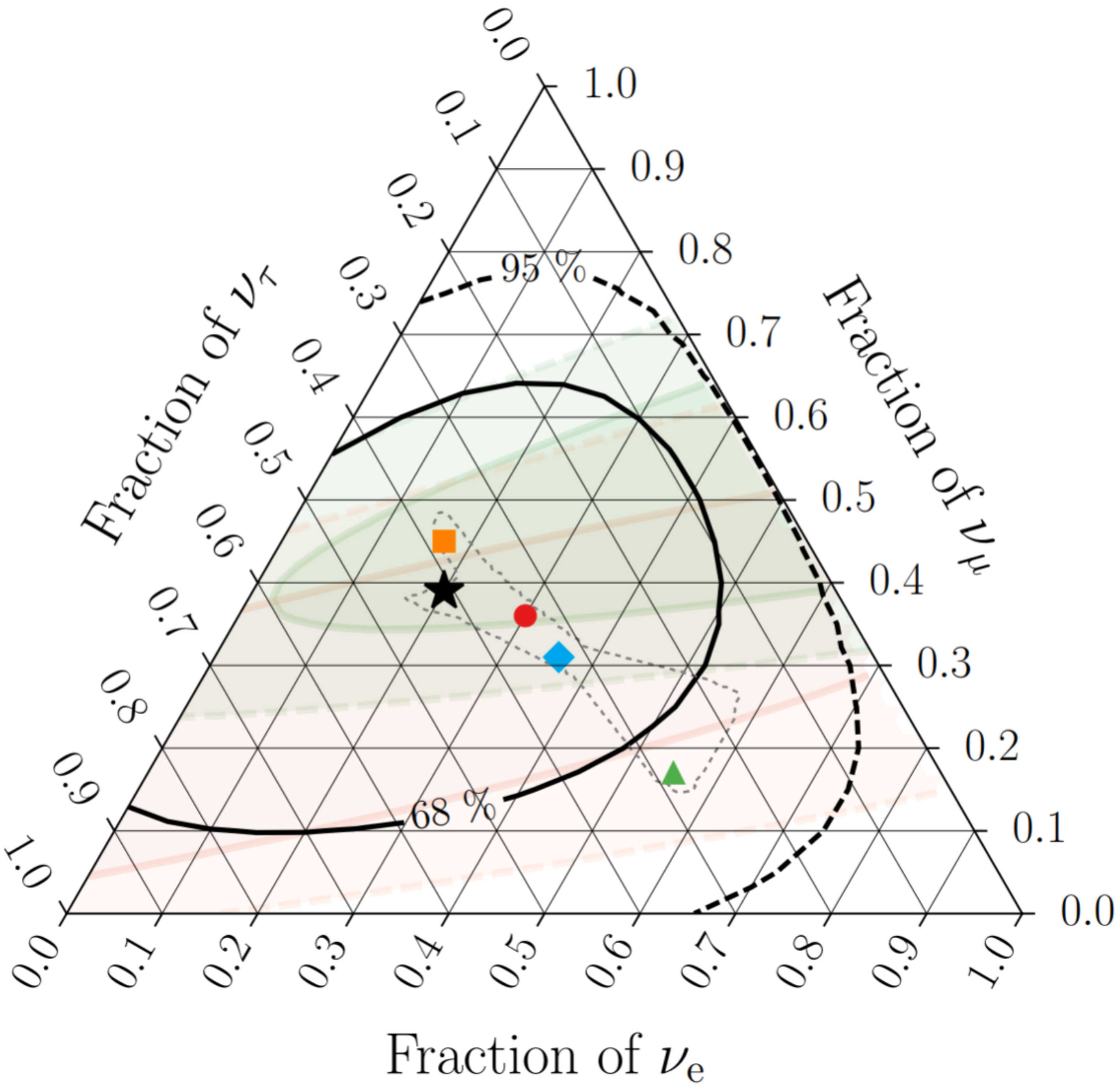
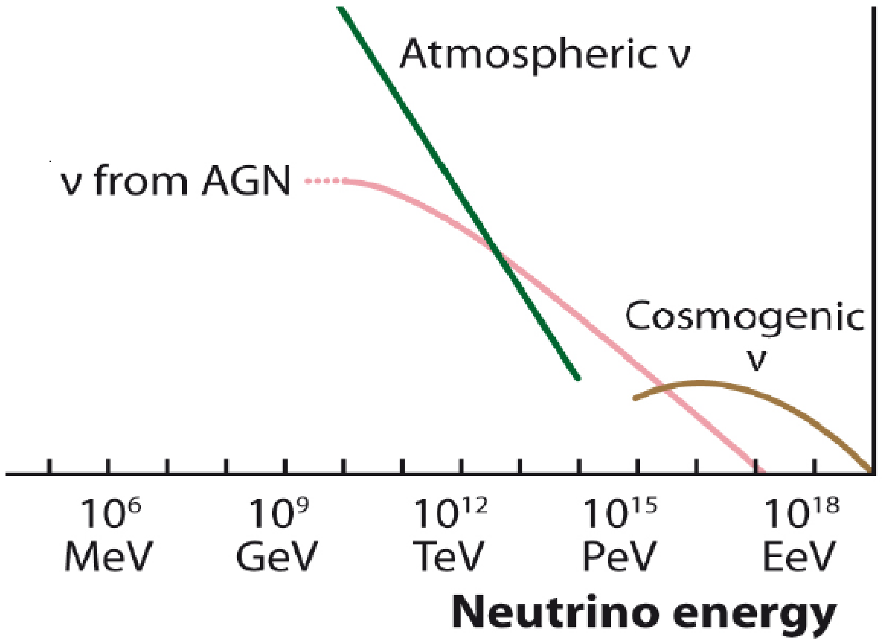




https://arxiv.org/pdf/2011.03561.pdf

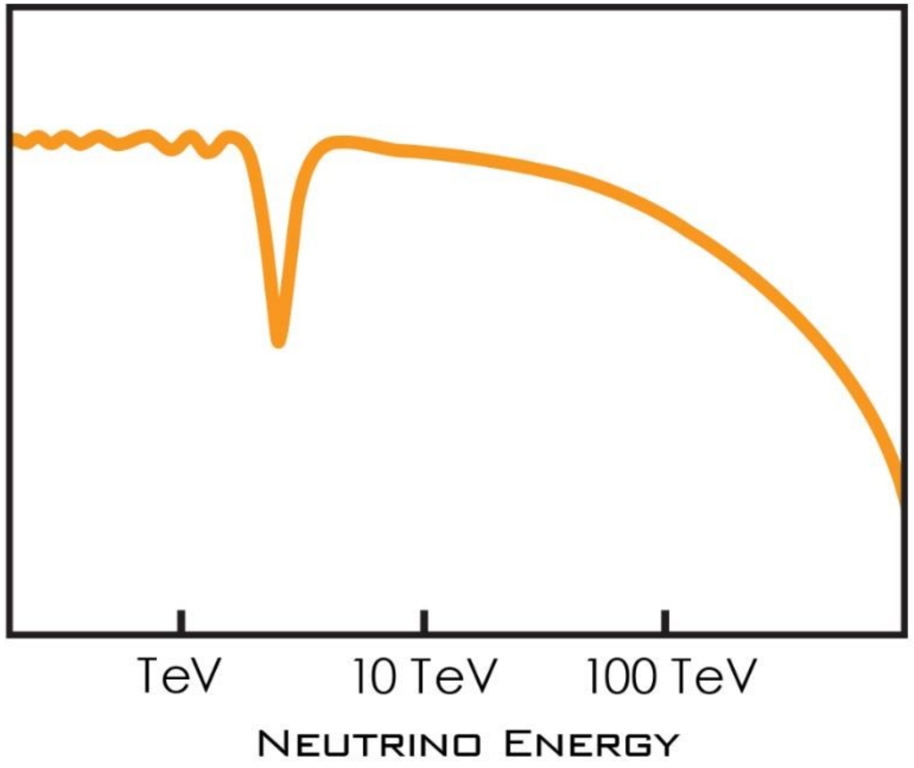
sterile neutrino searches

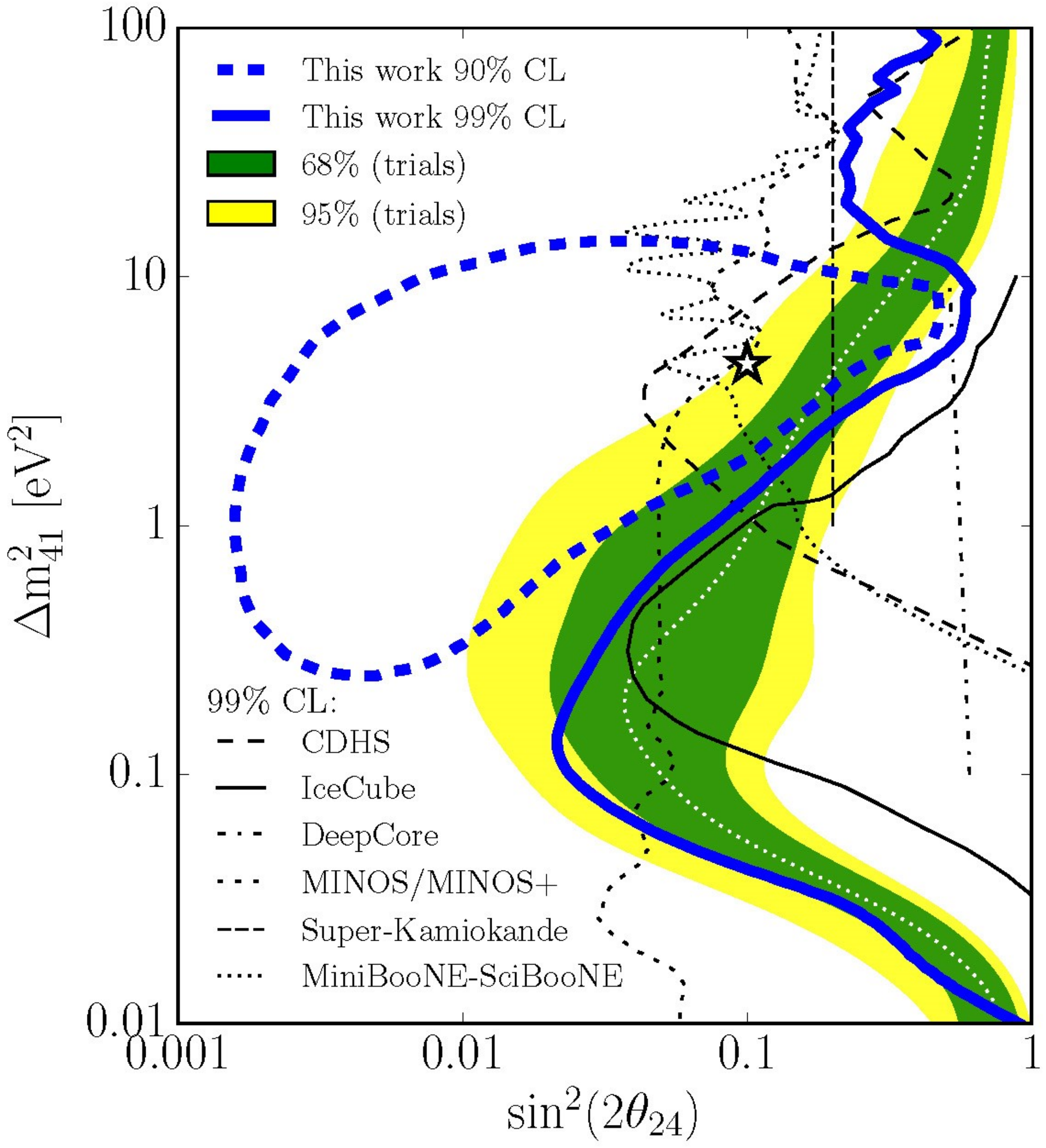
some odd neutrino results suggest extra neutrinos that you can obtain via oscillations, but do not interact directly with the world (sterile)

NTs can probe this hypothesis with high precision

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Muon neutrinos in ICECUBE



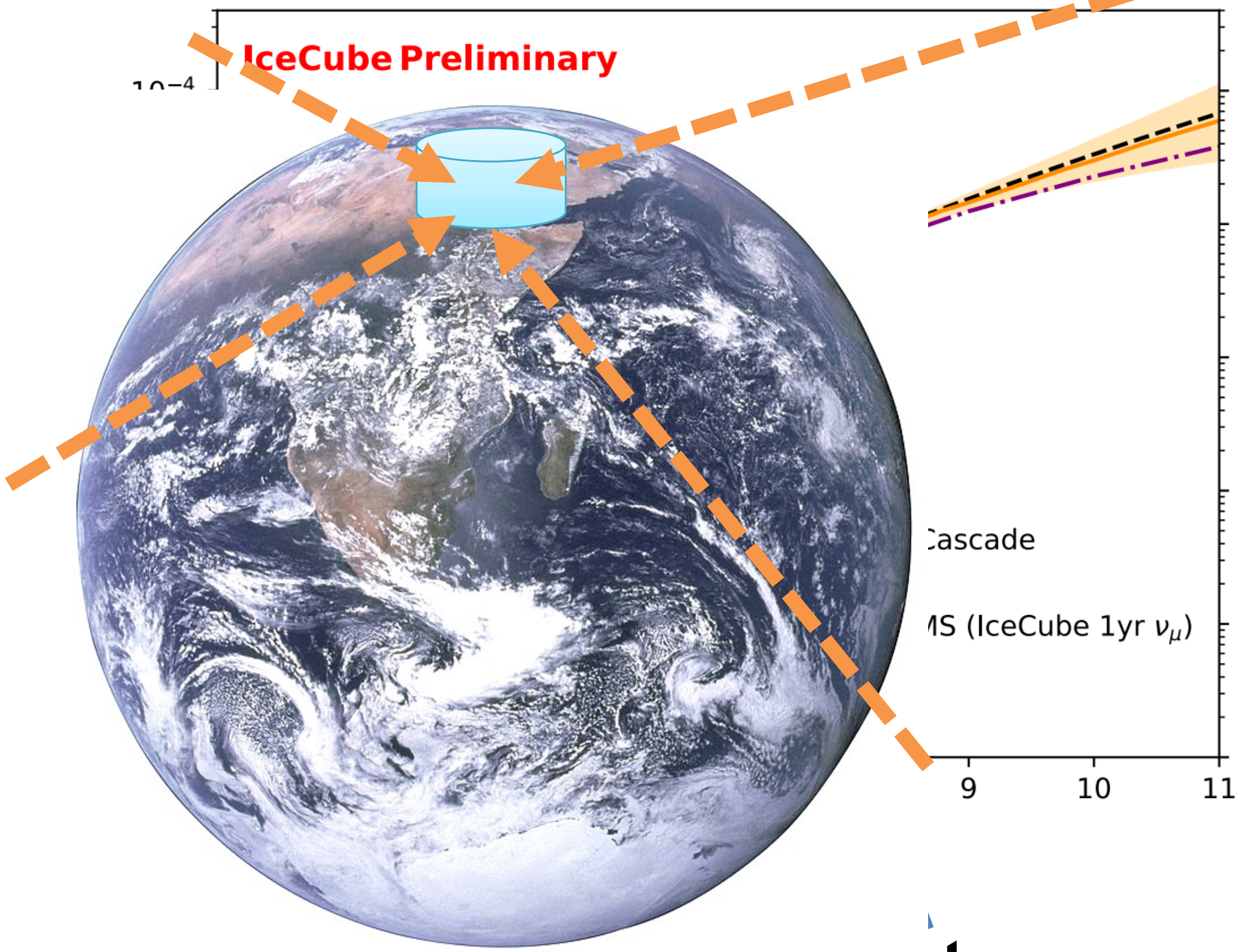


arxiv.org/abs/2005.12942

EHE neutrino cross section

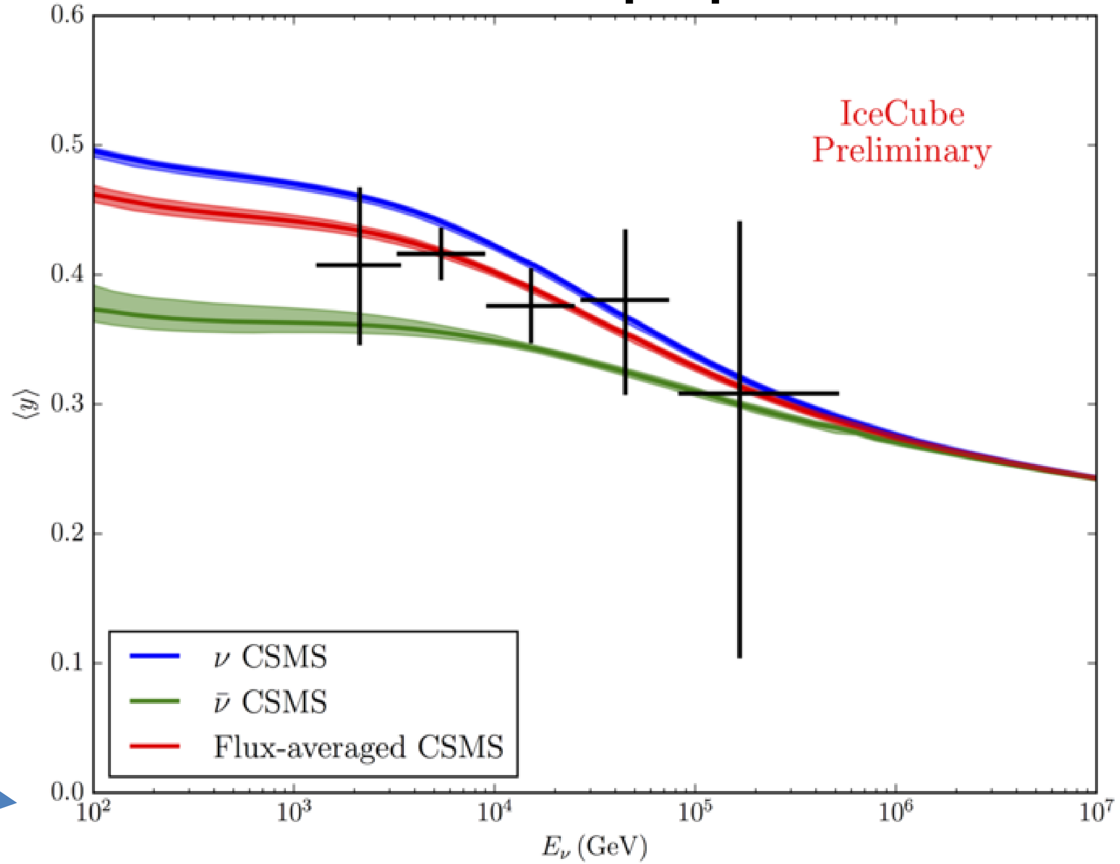
study of interactions of **extreme high energy neutrinos** using the Earth as the target

interaction rate

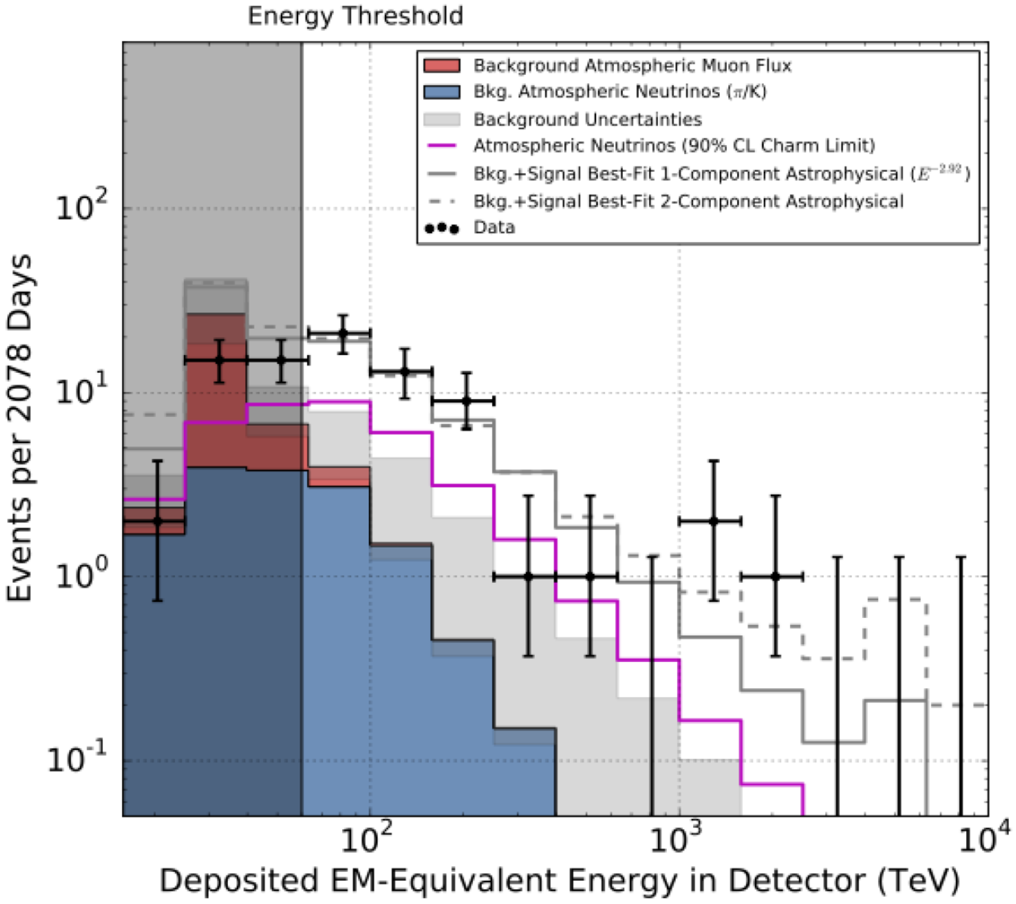


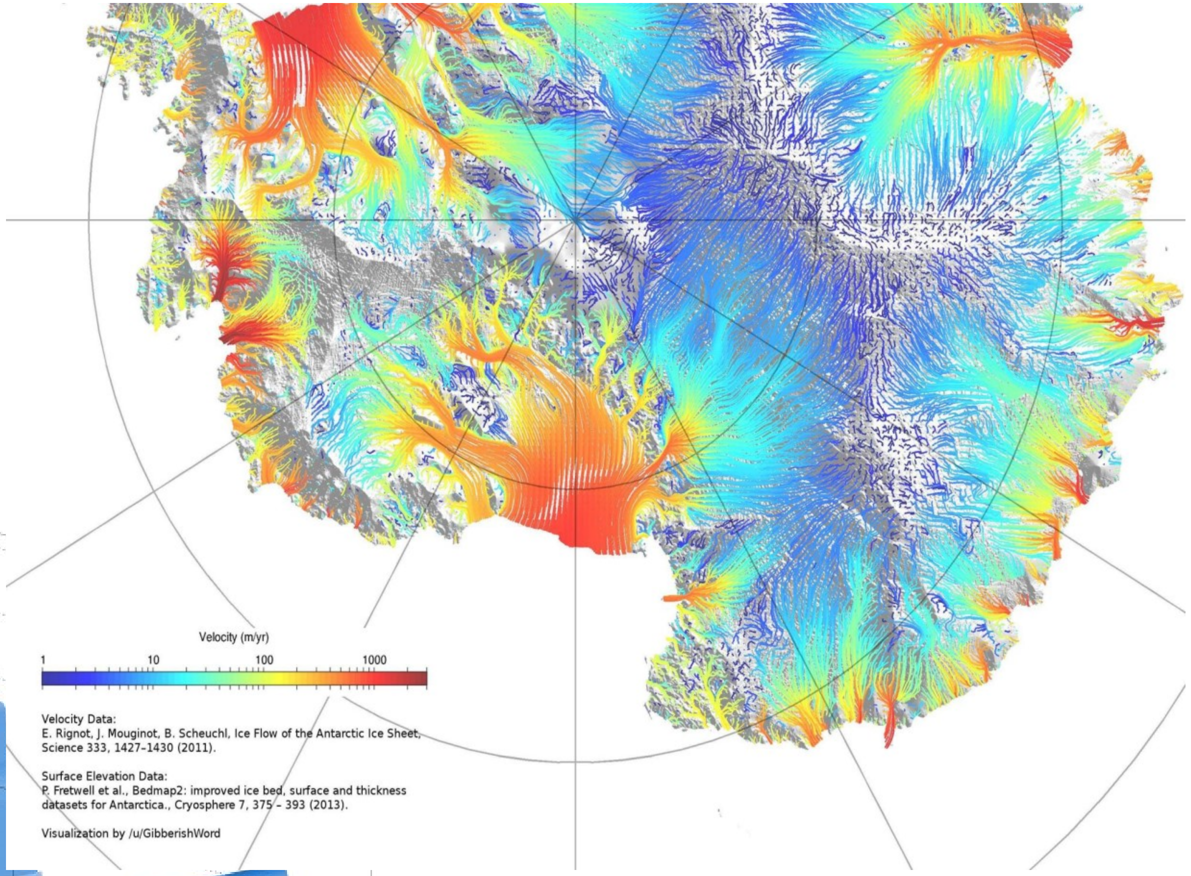
energy scale is inaccessible to man-made experiments

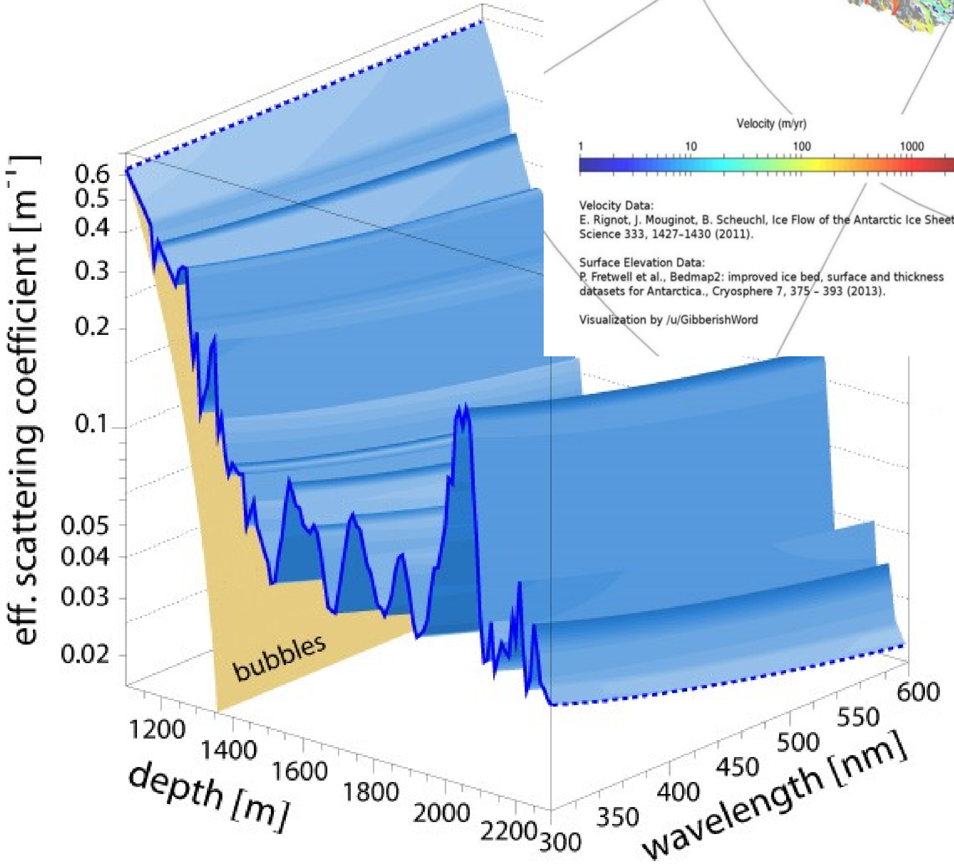
interaction properties



the challenges of IceCube data







the challenges to its
operation & construction

Water km^3 scale neutrino telescopes under construction

-Km3NeT – Mediterranean sea
-GVD-Baikal – Lake Baikal

serious technical challenges in deployment and operations – salt water is tough

enters Ocean Networks Canada

AN INITIATIVE OF University of Victoria

OCEAN NETWORKS CANADA

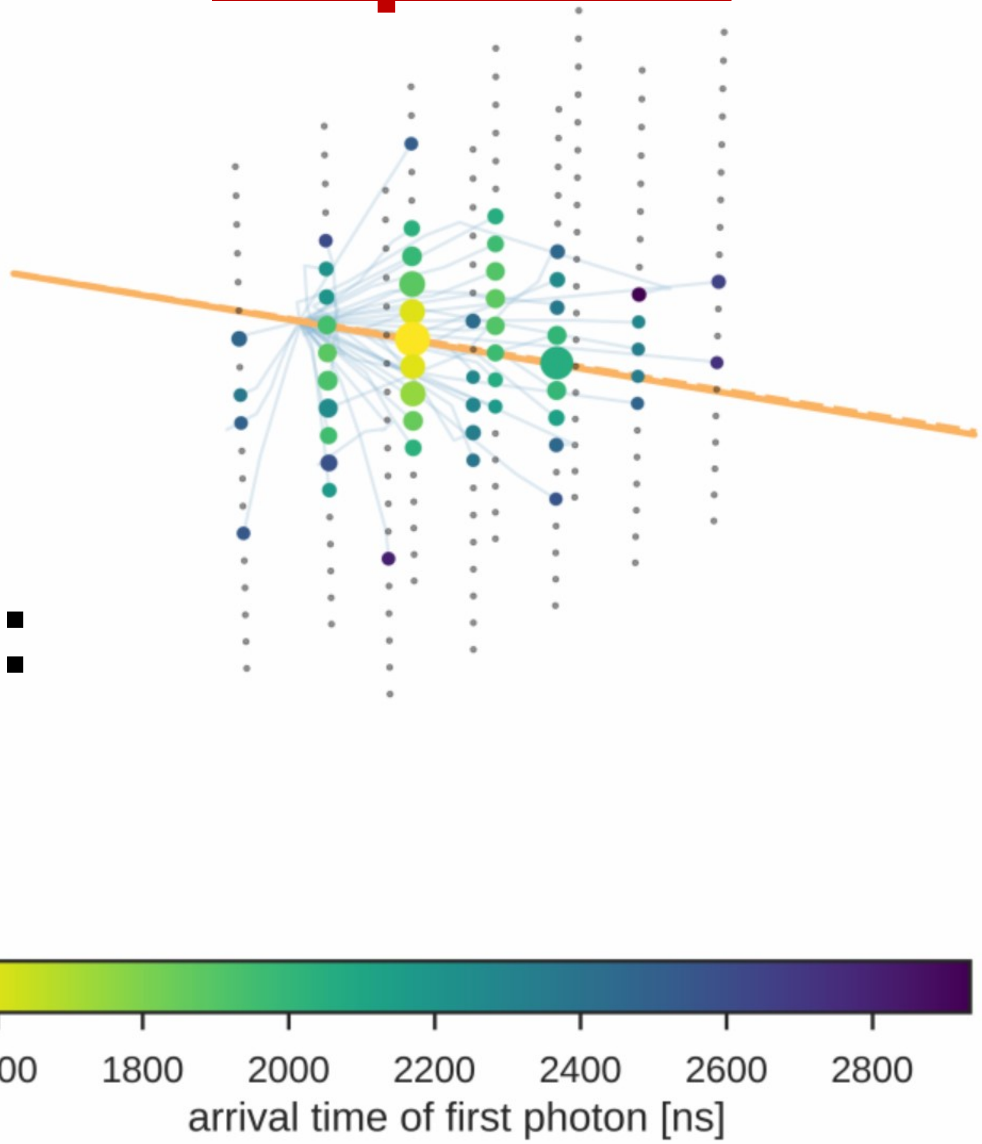
established in 2007
operates Ocean observatories
provides deep sea research infrastructure

UofA & TUM researchers established **cooperation** in 2017

"**potential** installation"

first step forward: P-ONE
Pacific Ocean Neutrino Explorer

- -200 modules
- -10 strings/lines
- -order 100m spacing
- -exploring potential for:
  - tau neutrinos
  - charm production
  - exotic oscillations



first step forward: P-ONE
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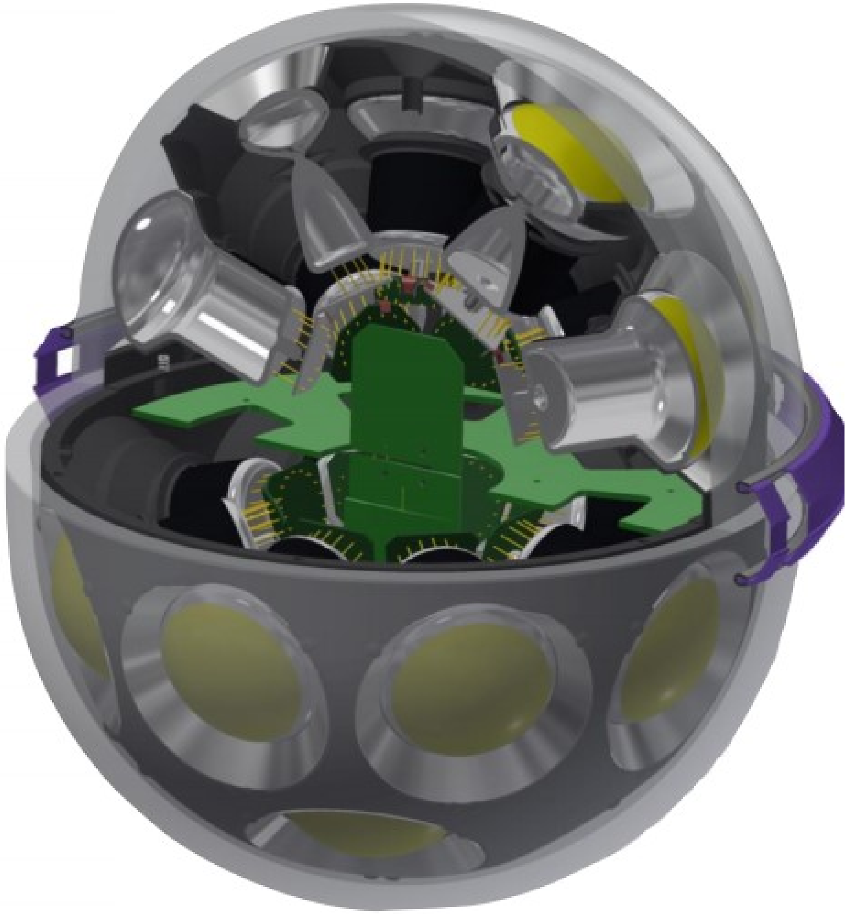
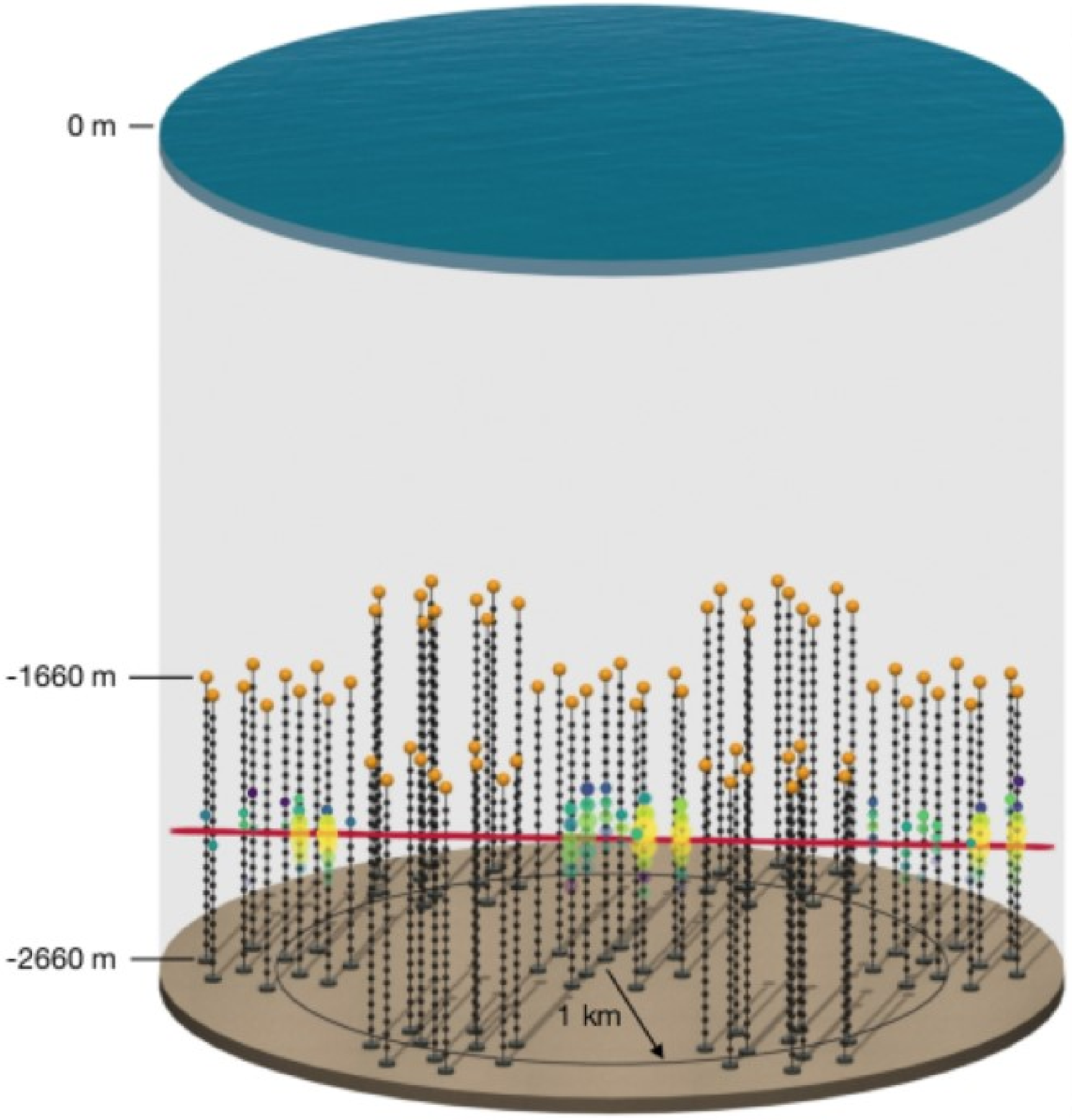


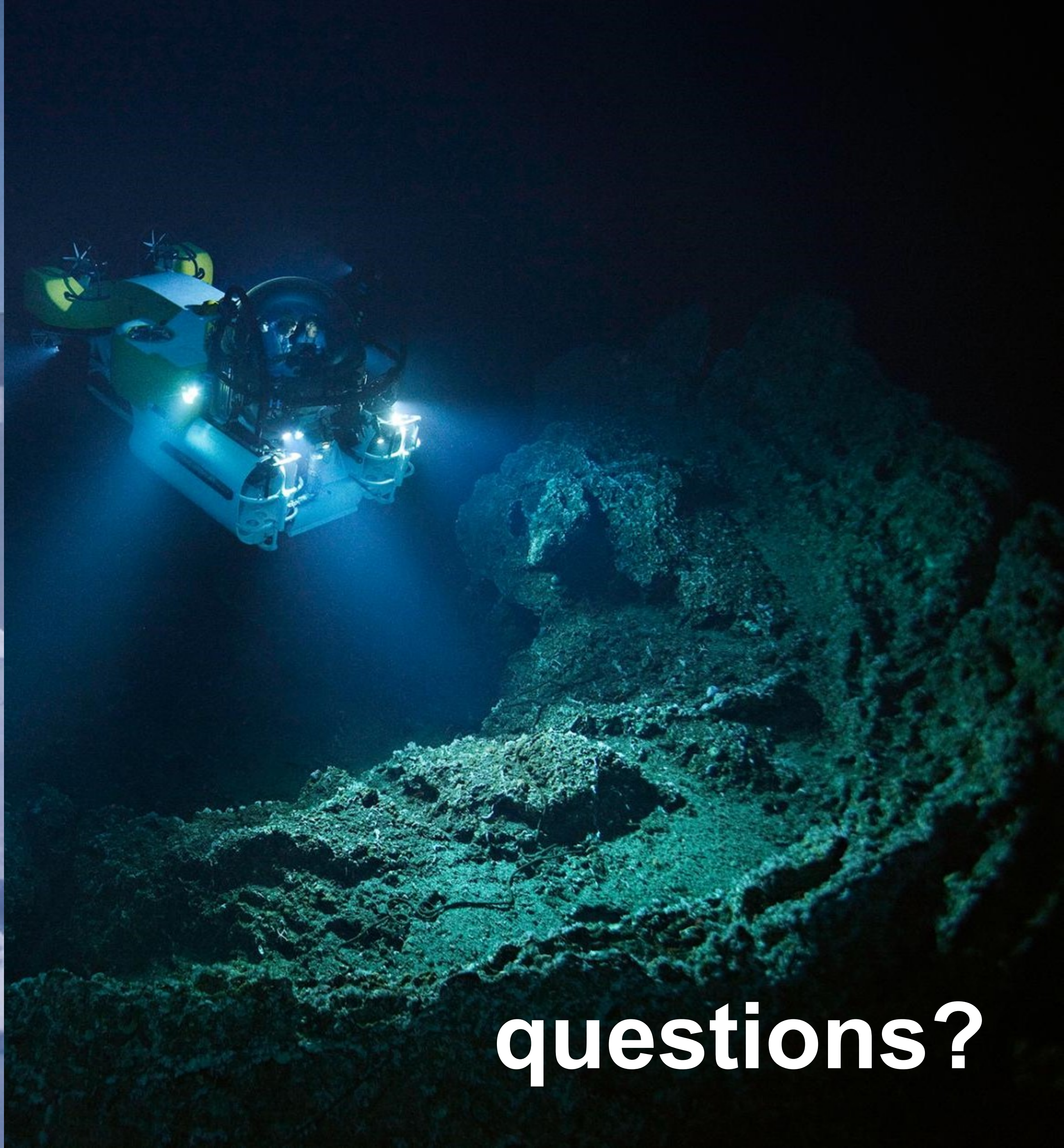
and after P-ONE?

an array large enough to see TeV-PeV events with large statistics:

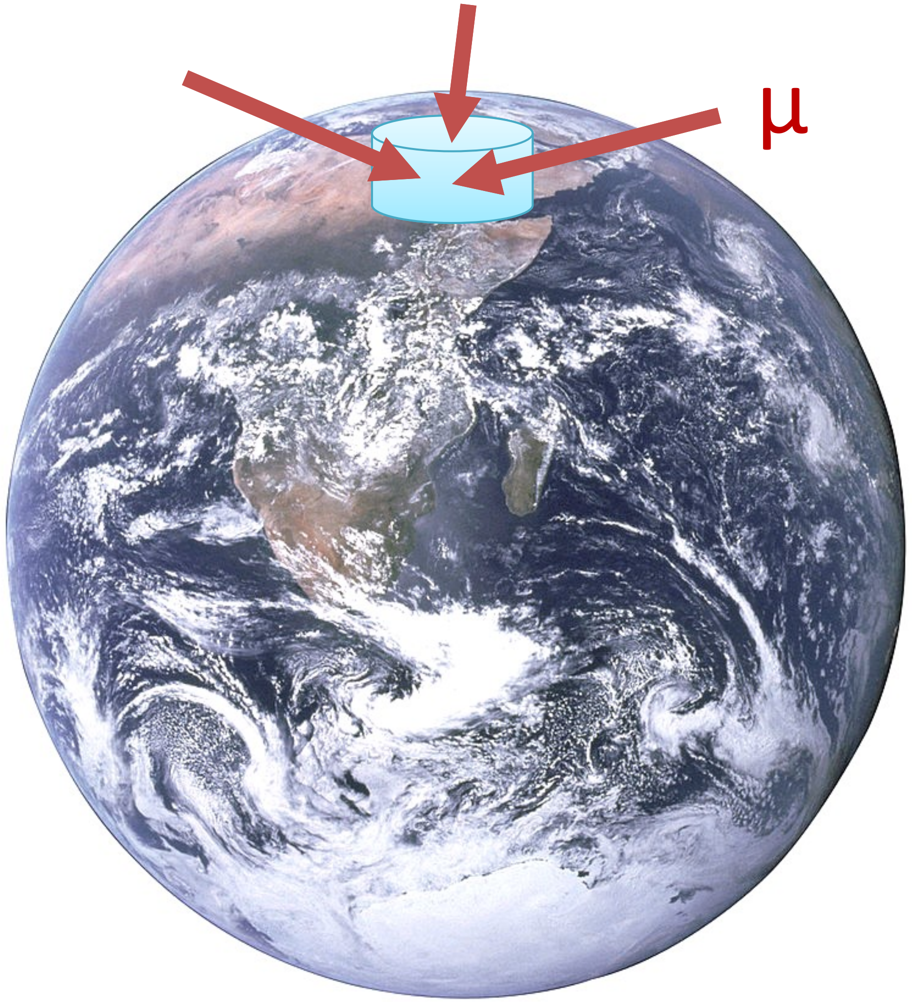
- do real **neutrino astronomy**
- study **extreme** high energy interactions



To know more, pay us a visit in http://www.pacific-neutrino.org/


thank you

questions?

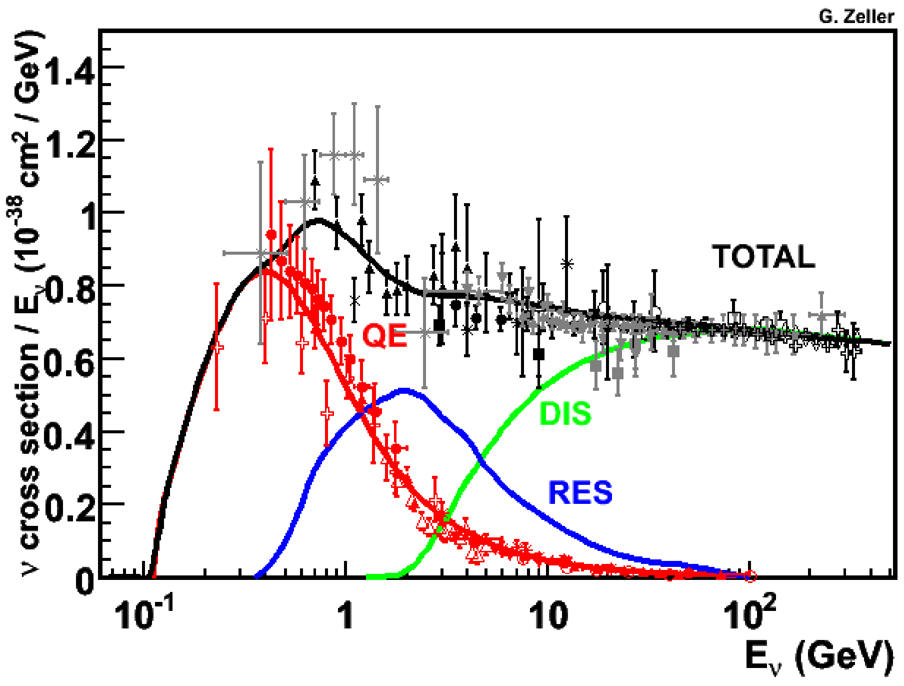
backup

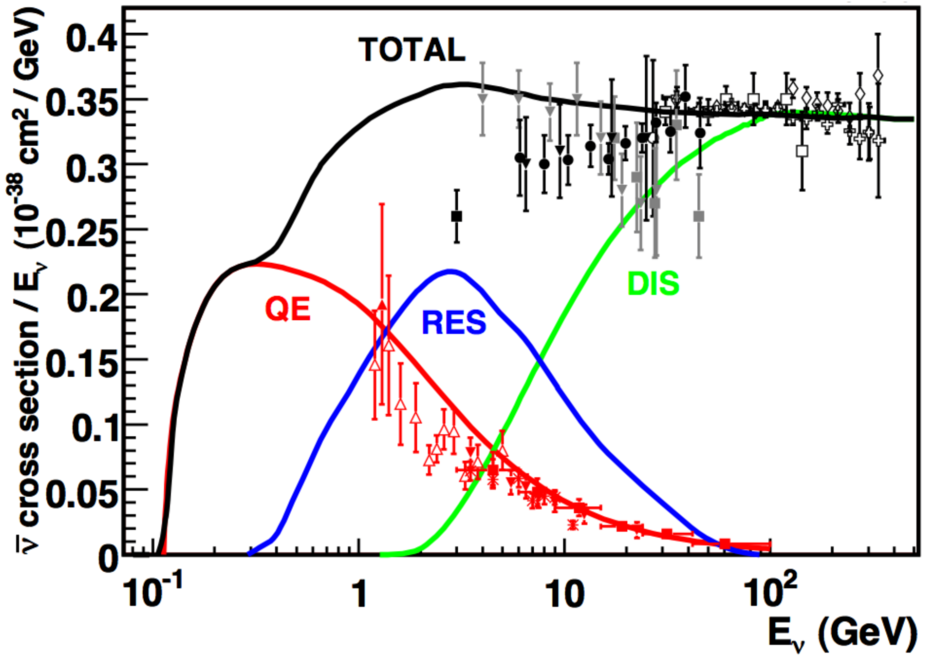


detect **muons** from cosmic ray showers **“above”** the detector

lots of them
2 kHz rate in IceCube

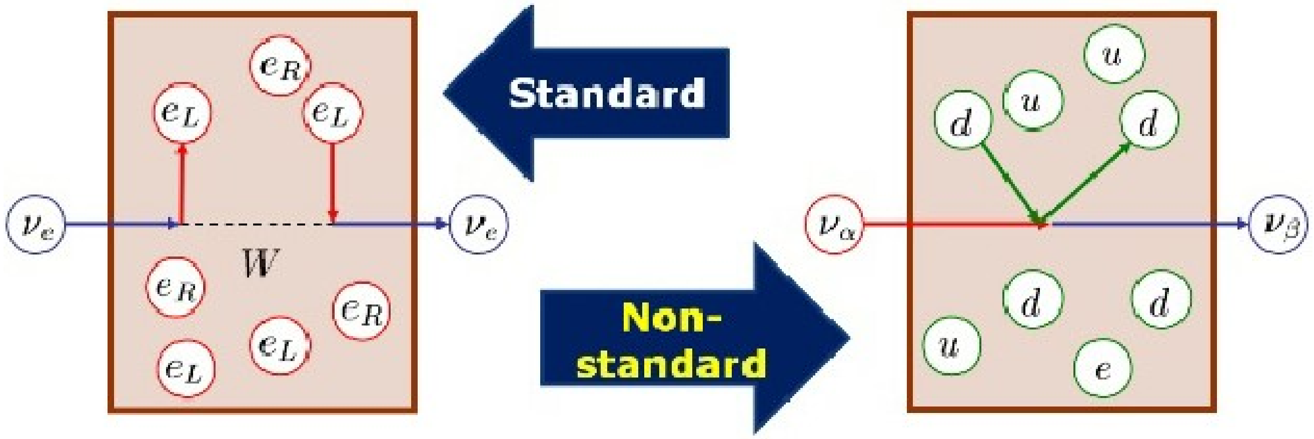
dominant interaction channel is deep inelastic scattering – well understood

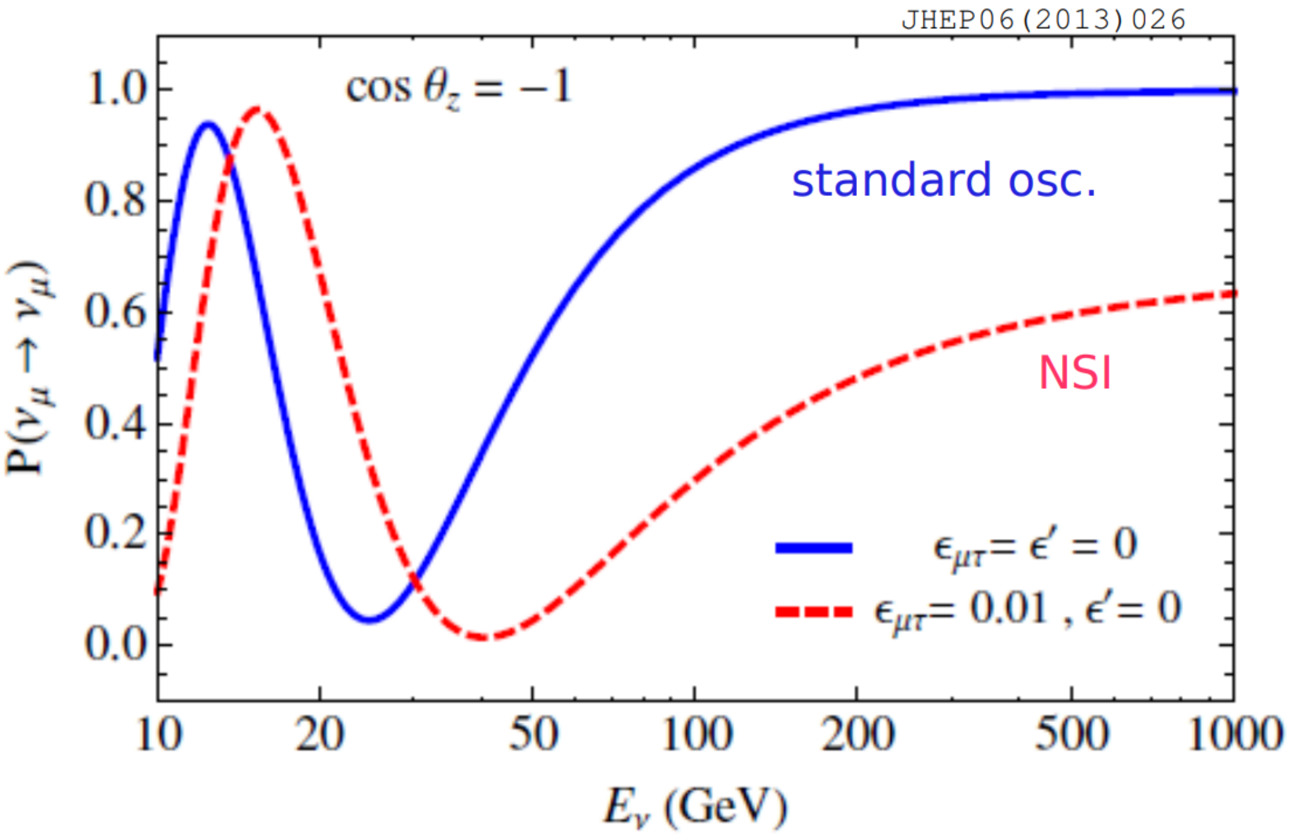


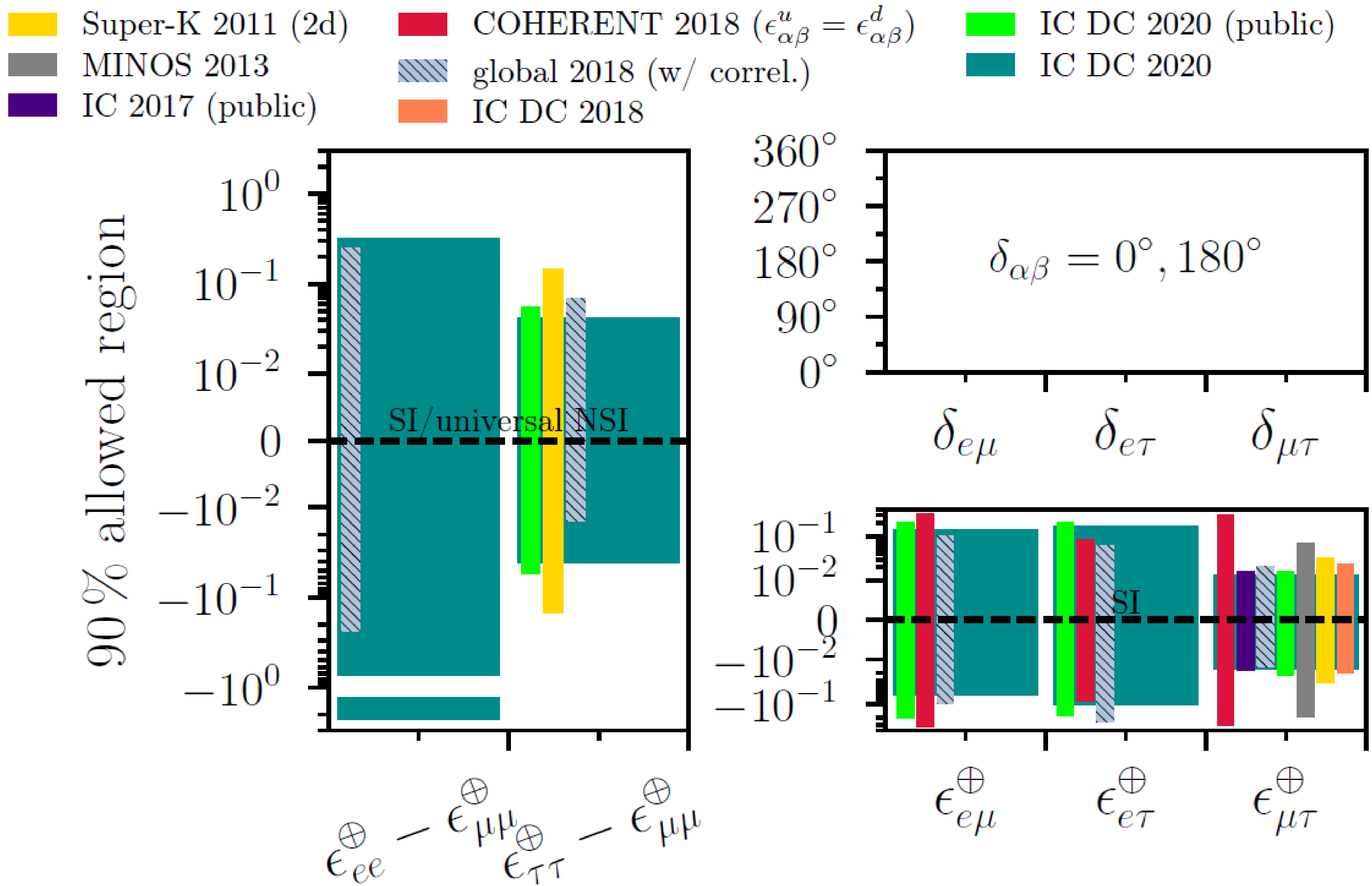


non-standard interactions

mediated by non-SM bosons
modify neutrino rates at all energies

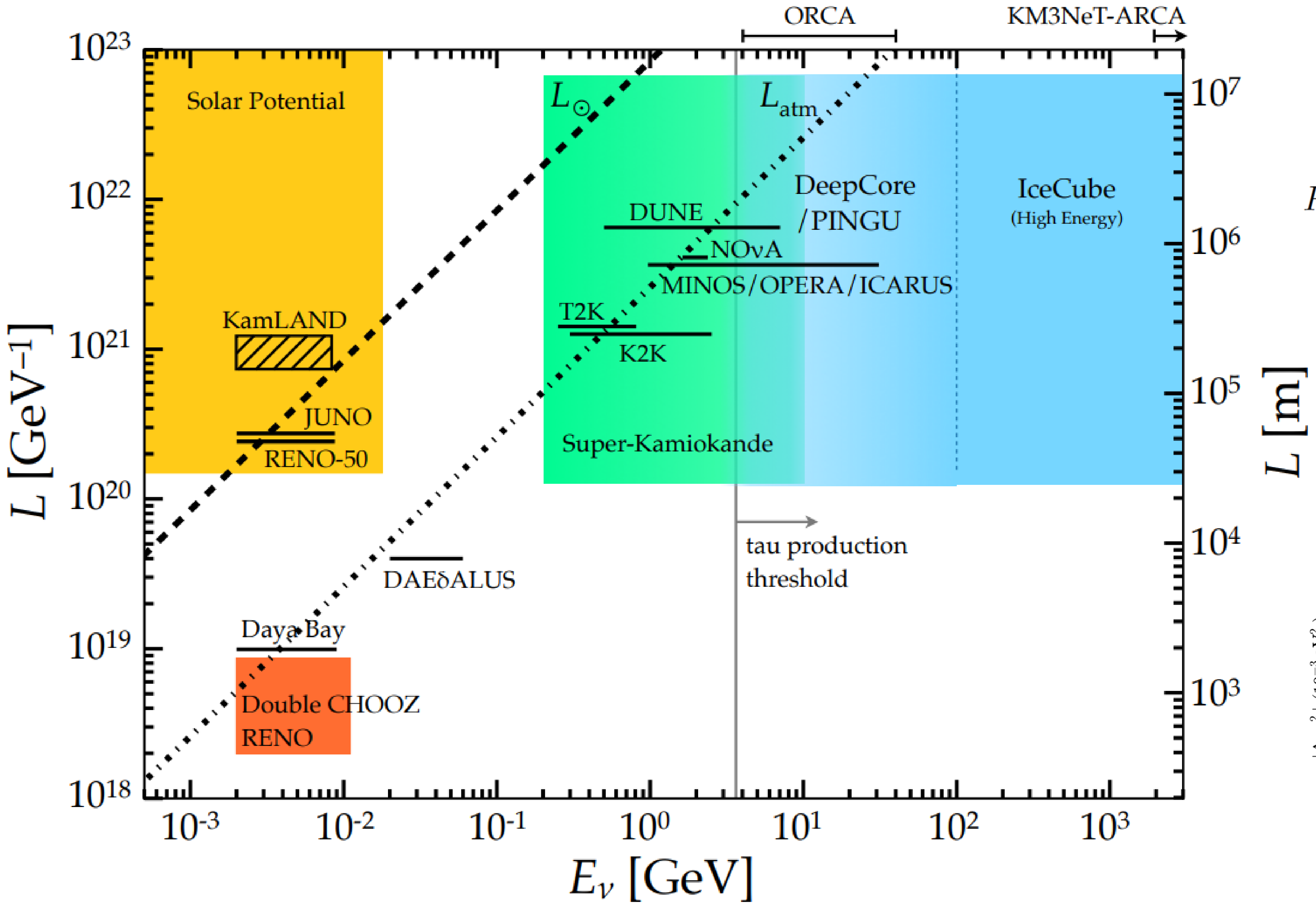




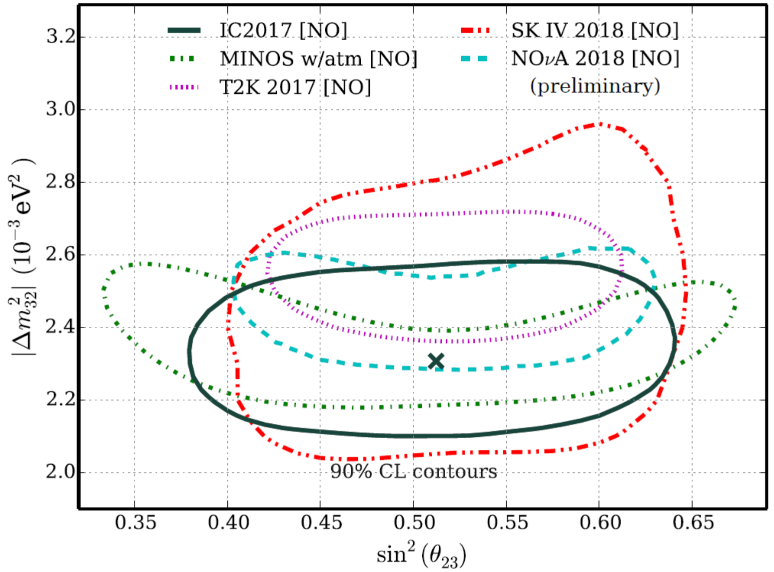


Super-K 2011 (2d)
MINOS 2013
IC 2017 (public)
COHERENT 2018 ($\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta}$)
global 2018 (w/ correl.)
IC DC 2018
IC DC 2020 (public)
IC DC 2020
90 % allowed region
10^0
10^{-1}
10^{-2}
0
-10^{-2}
-10^{-1}
-10^0
SI/universal NSI
$\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$
$\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$
$360°$
$270°$
$180°$
$90°$
$0°$
$\delta_{\alpha\beta} = 0°, 180°$
$\delta_{e\mu}$
$\delta_{e\tau}$
$\delta_{\mu\tau}$
SI
$\epsilon^{\oplus}_{e\mu}$
$\epsilon^{\oplus}_{e\tau}$
$\epsilon^{\oplus}_{\mu\tau}$

oscillation parameters

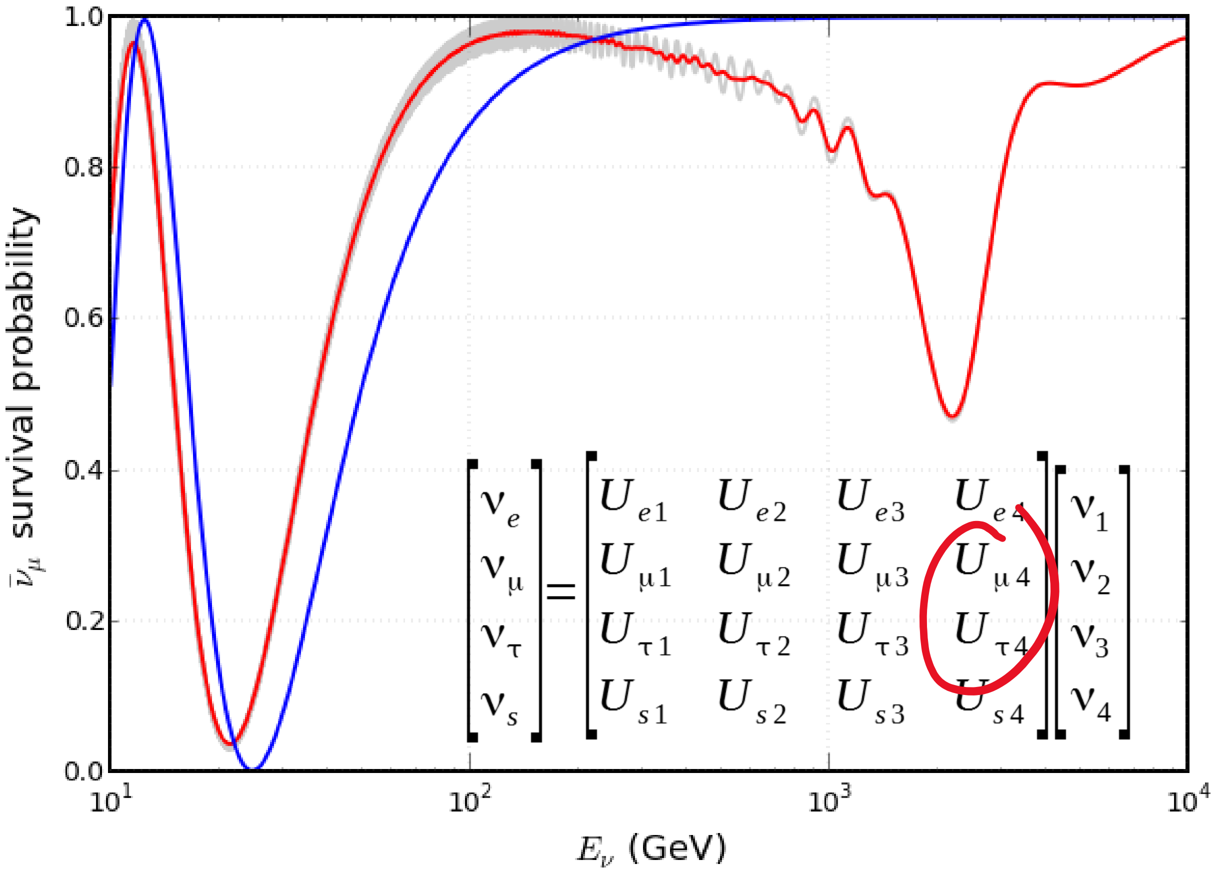


$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$



sterile neutrino searches

effects in low & high energy regions



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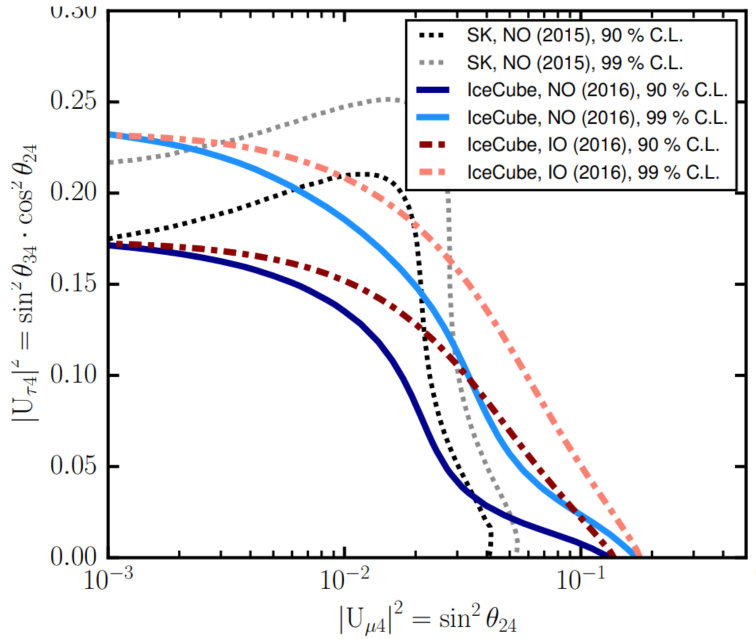
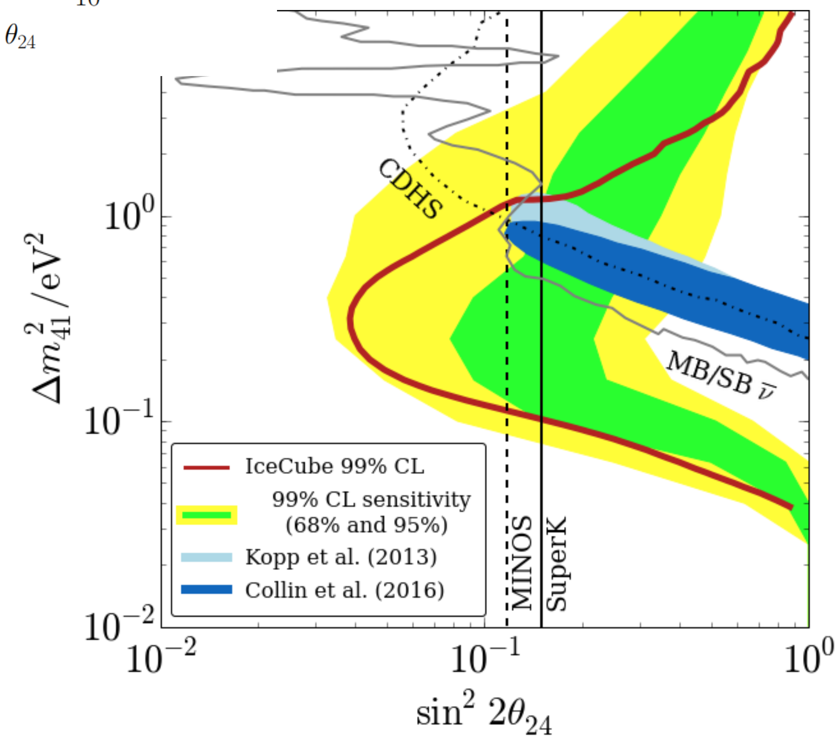


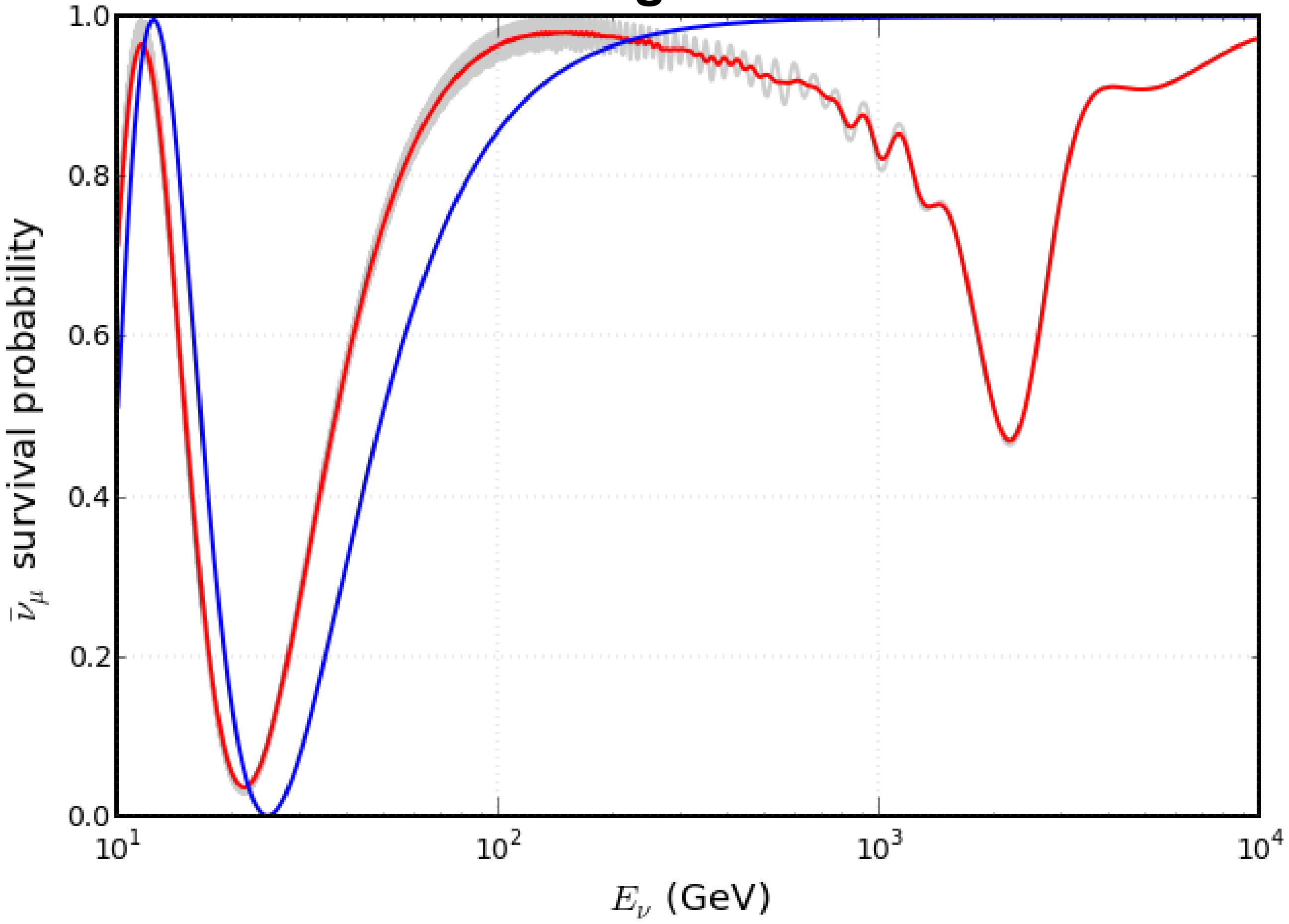


sterile neutrino searches

some experiments have obtained odd neutrino results - a potential explanation: extra neutrinos that you can obtain via oscillations, but do not interact directly with the world (sterile)

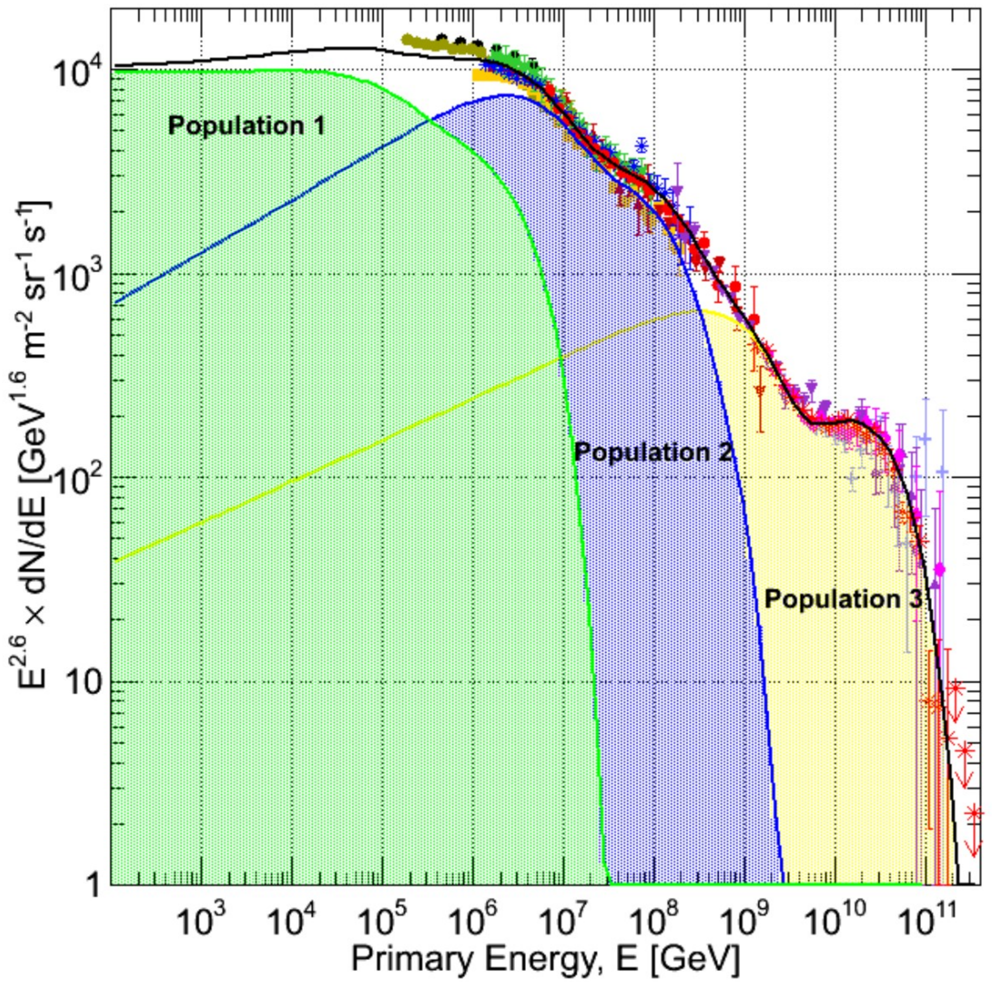
NTs can probe this hypothesis with high precision

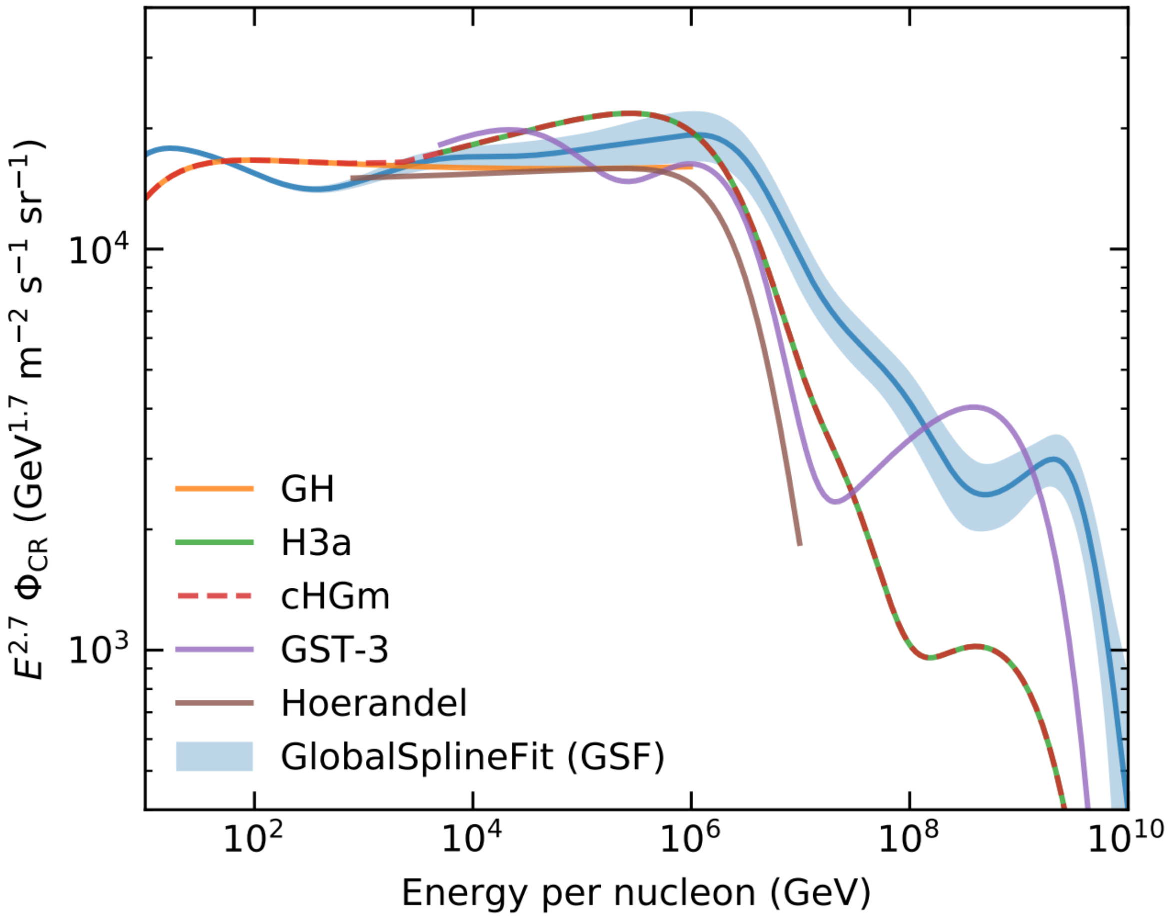
survival probability for neutrinos crossing the Earth



CR composition around the knee

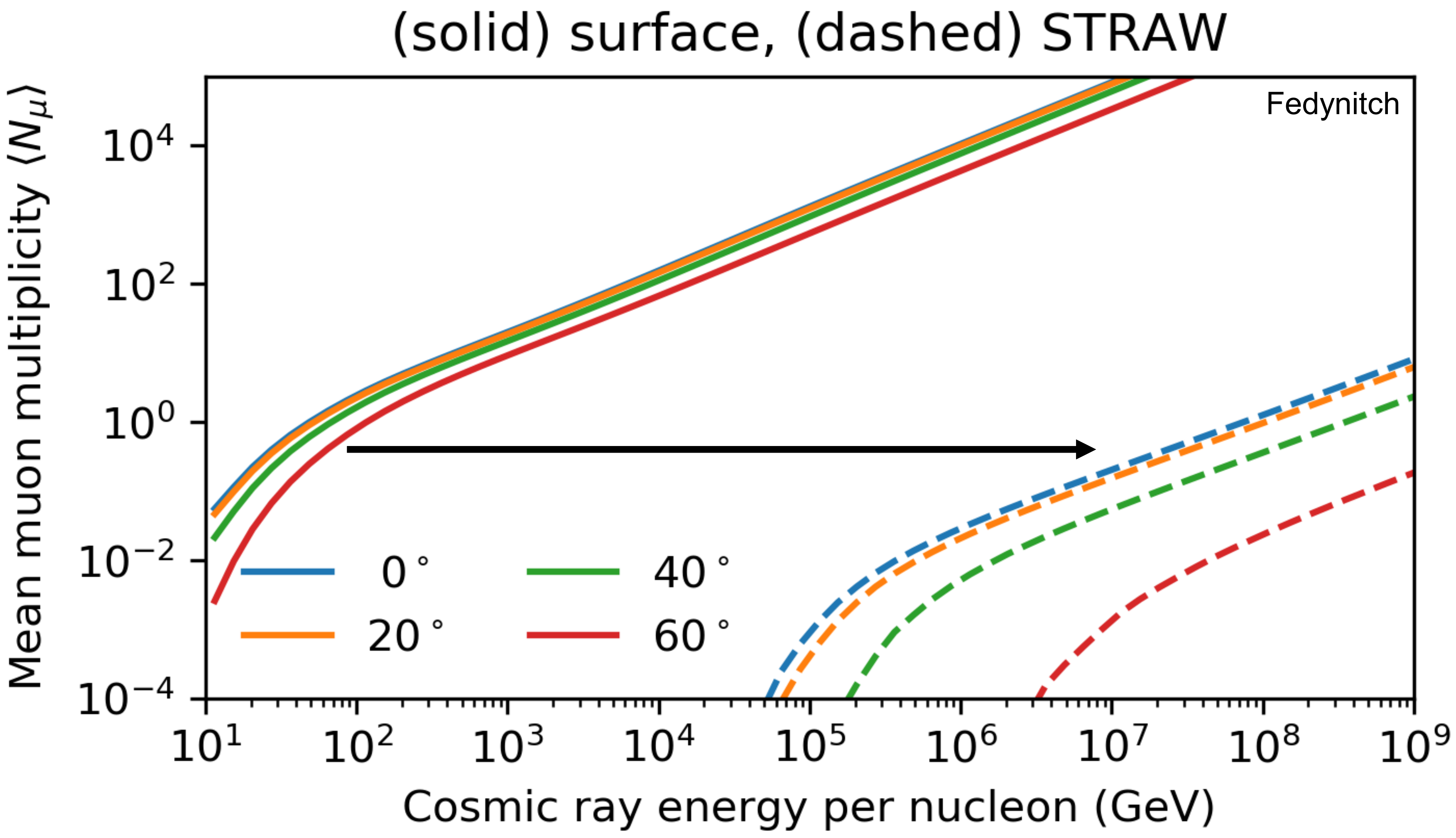
origin of the CR knee is unknown
change in composition or acceleration mechanism?



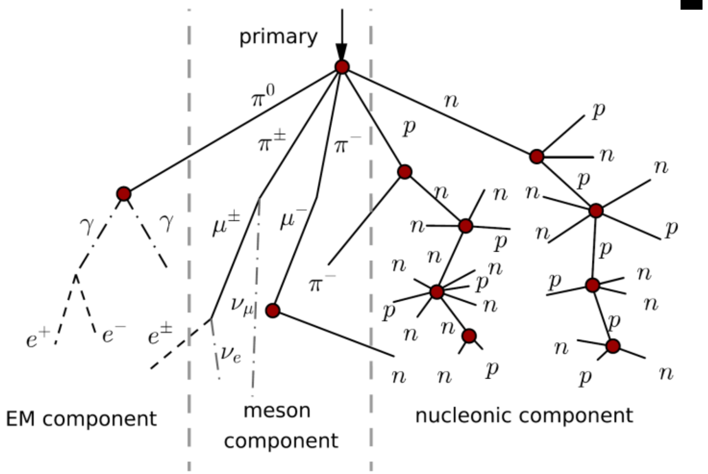


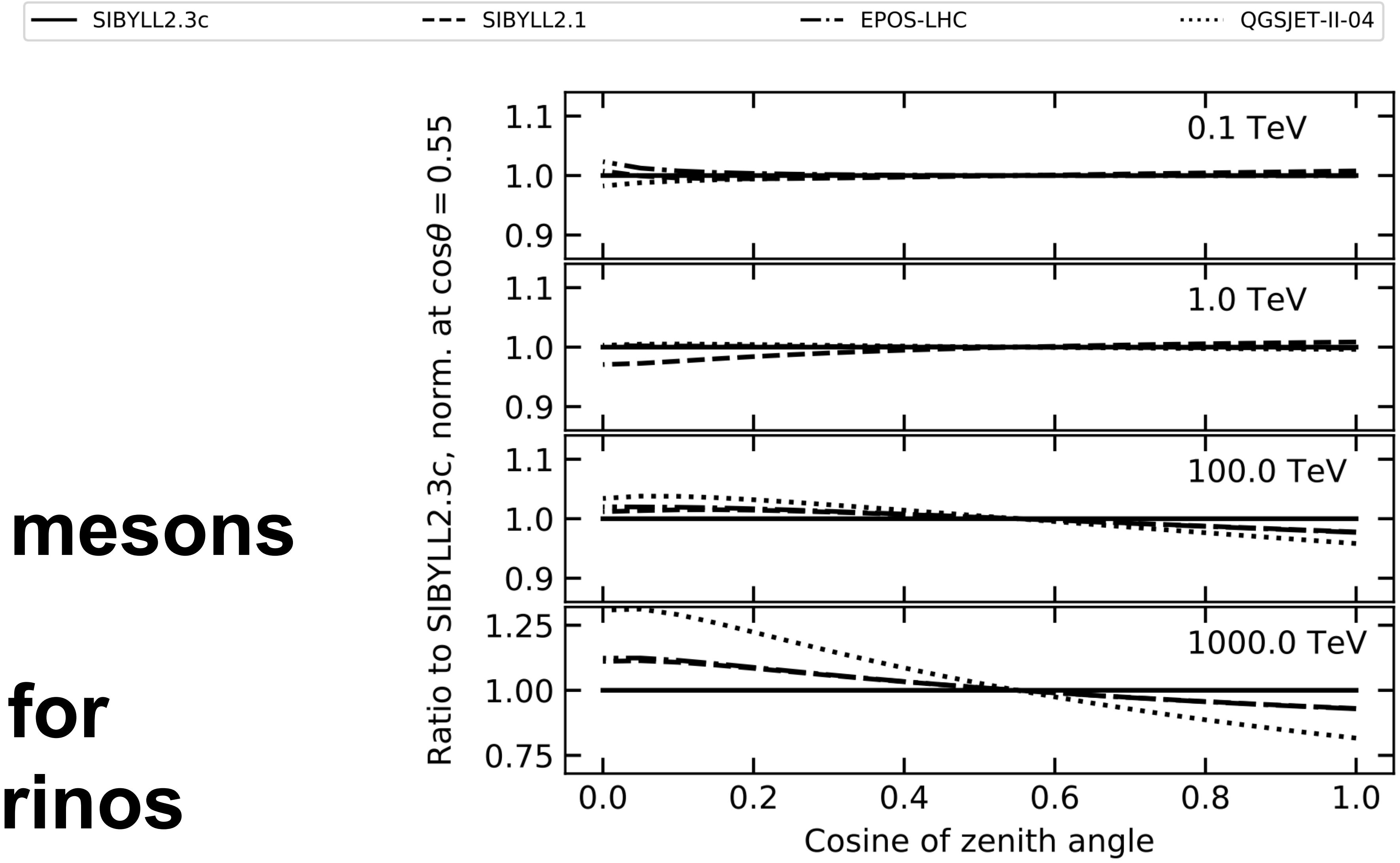
CR composition around the knee

muon multiplicity can differentiate between heavy/light nuclei



prompt muon production



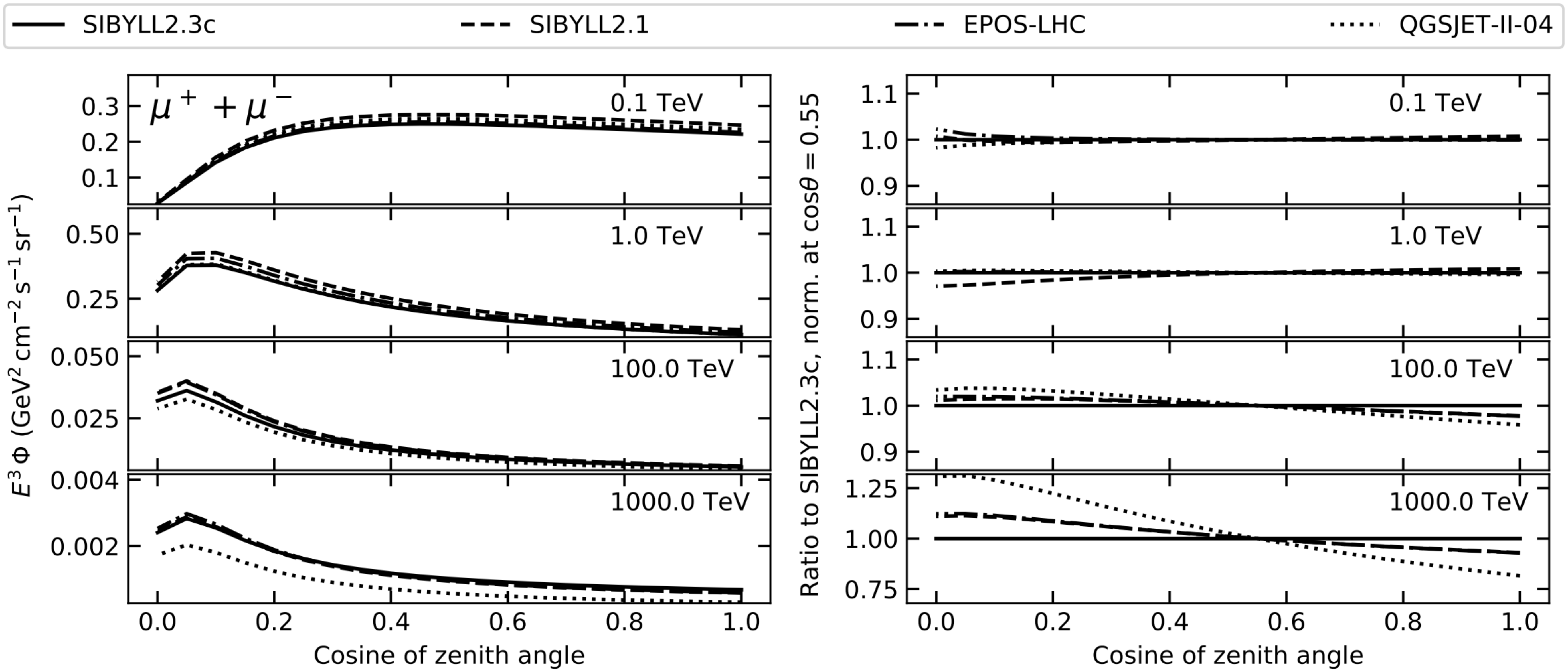


prompt decay of charm+unflavored mesons

-still unobserved

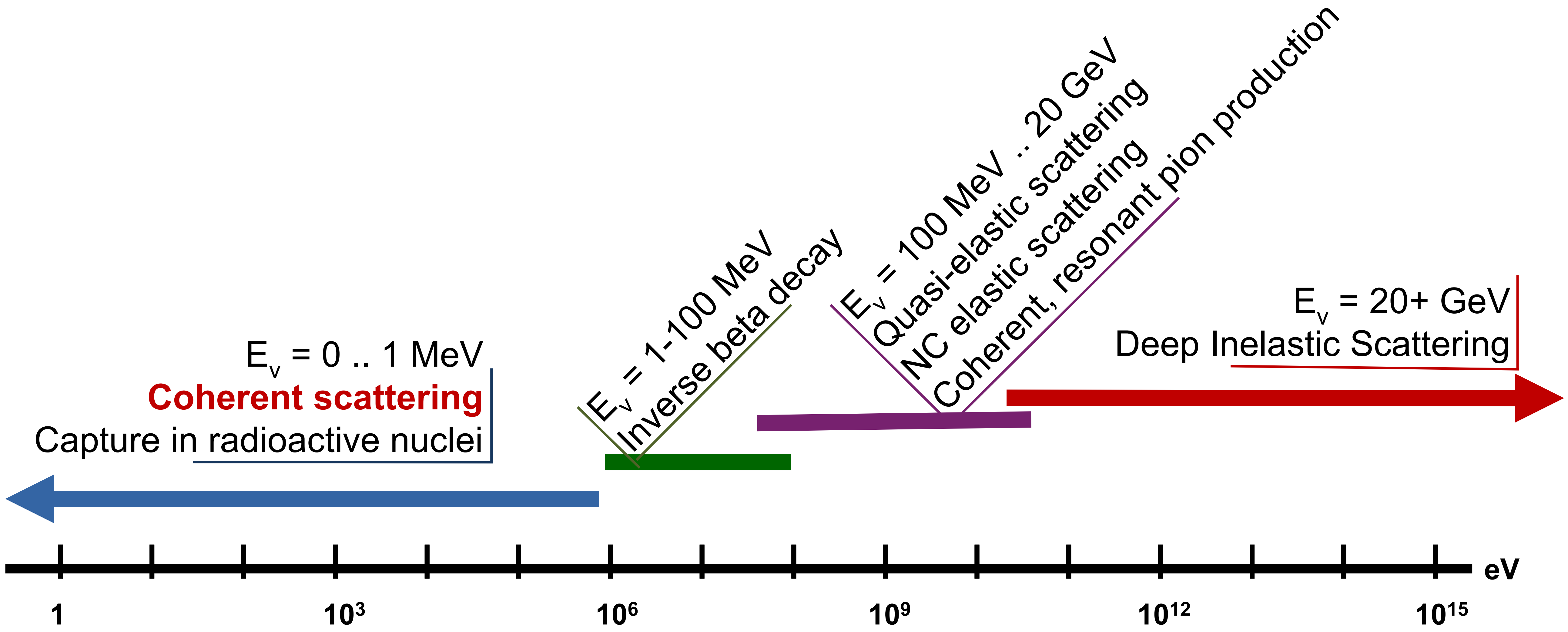
-main background for astrophysical neutrinos

Fedynitch, arXiv:1806.04140

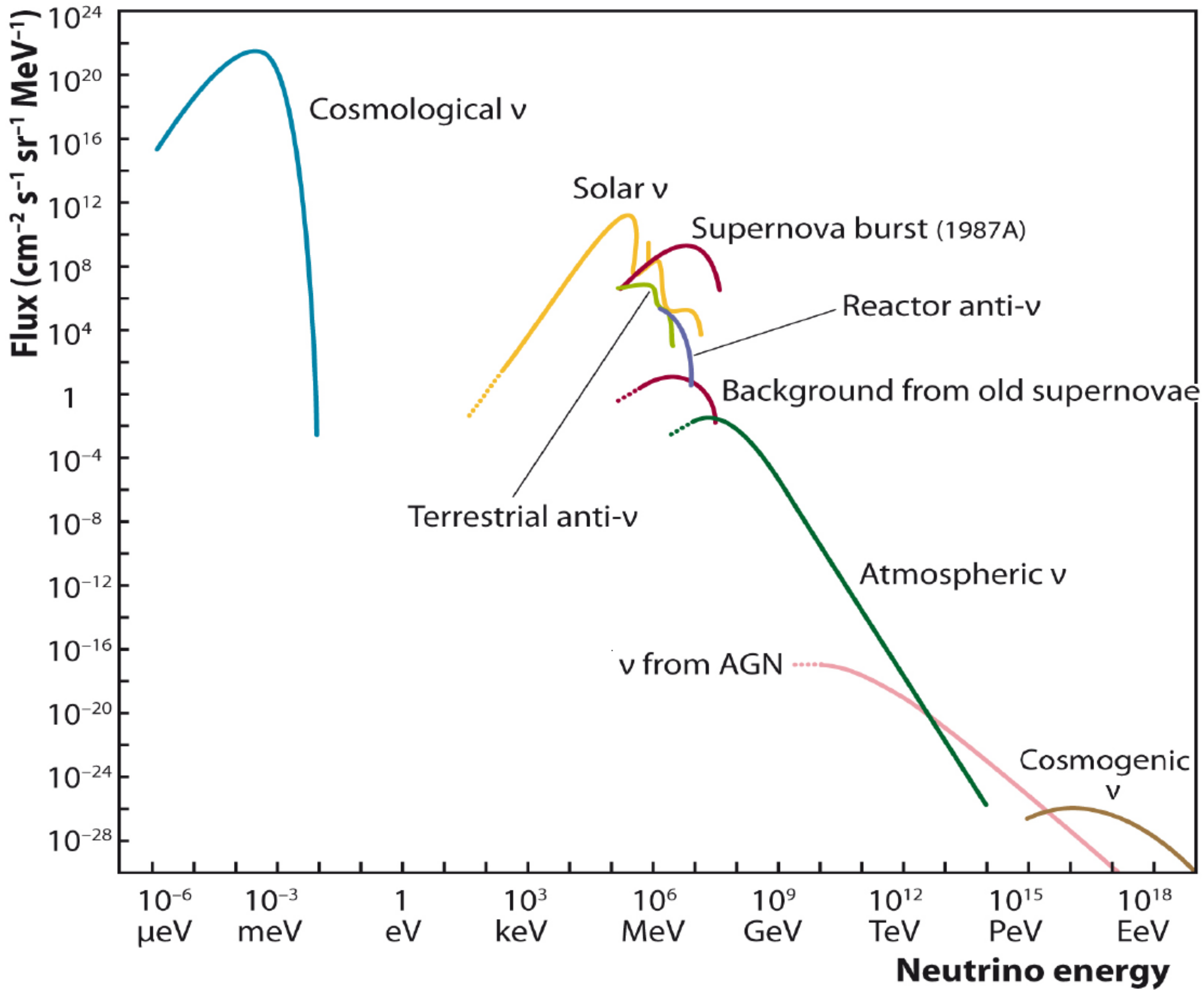


SIBYLL2.3c
SIBYLL2.1
EPOS-LHC
QGSJET-II-04
$\mu^+ + \mu^-$
0.1 TeV
1.0 TeV
100.0 TeV
1000.0 TeV
$E^3\,\Phi$ (GeV^2 cm^{-2} s^{-1} sr^{-1})
Ratio to SIBYLL2.3c, norm. at $\cos\theta = 0.55$
Cosine of zenith angle
Cosine of zenith angle

neutrino detection



neutrino sources



- relic neutrinos from the early Universe
- solar neutrinos
- neutrinos from supernova
- atmospheric neutrinos
- cosmic HE neutrinos