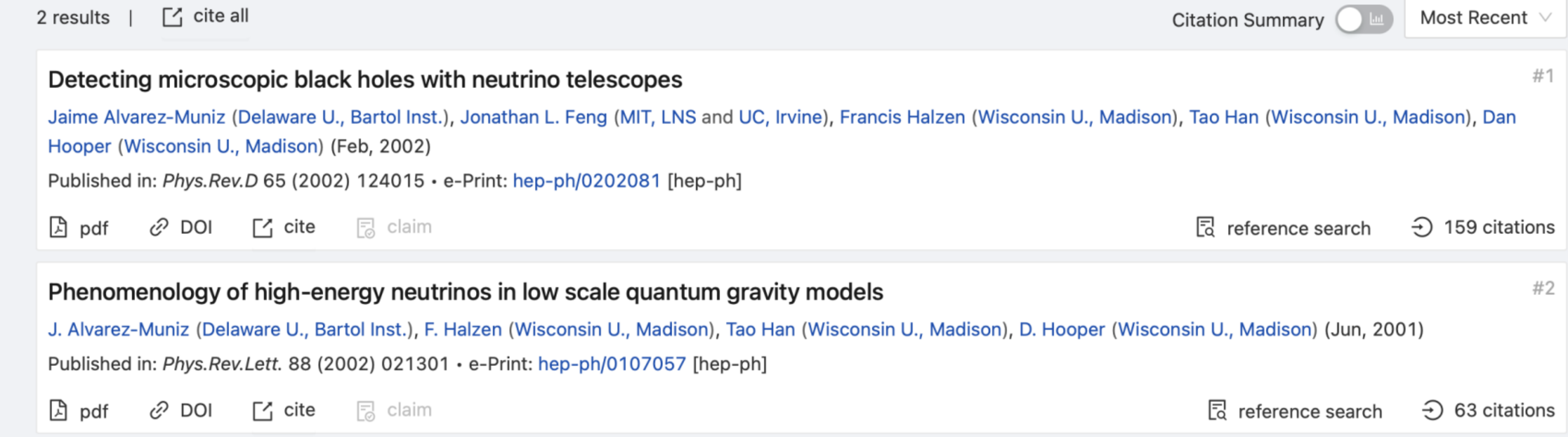
Pheno from Madison to Pittsburgh

Francis Halzen



Detecting microscopic black holes with neutrino telescopes #1

Jaime Alvarez-Muniz (Delaware U., Bartol Inst.), Jonathan L. Feng (MIT, LNS and UC, Irvine), Francis Halzen (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison), Dan Hooper (Wisconsin U., Madison) (Feb, 2002)

Published in: *Phys.Rev.D* 65 (2002) 124015 • e-Print: hep-ph/0202081 [hep-ph]

Phenomenology of high-energy neutrinos in low scale quantum gravity models #2

J. Alvarez-Muniz (Delaware U., Bartol Inst.), F. Halzen (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison), D. Hooper (Wisconsin U., Madison) (Jun, 2001)

Published in: *Phys.Rev.Lett.* 88 (2002) 021301 • e-Print: hep-ph/0107057 [hep-ph]

[Han, Lykken and Zhang]

The Forward Physics Facility: Sites, experiments, and physics potential #1

Luis A. Anchordoqui (Lehman Coll.), Akitaka Ariga (Bern U., LHEP and Chiba U.), Tomoko Ariga (Kyushu U., Fukuoka (main)), Weidong Bai (Zhongshan U.), Kincso Balazs (CERN) et al. (Sep 22, 2021)

Published in: *Phys.Rept.* 968 (2022) 1-50 • e-Print: 2109.10905 [hep-ph]

Forward Physics Facility - Snowmass 2021 Letter of Interest #2

Roshan Mammen Abraham, Henso Abreu, Yoav Afik, Sanjib Kumar Agarwalla, Juliette Alimena et al. (Apr 12, 2020)

arXiv:hep-ph/0202081v1 8 Feb 200

MIT–CTP–3221
UCI–TR–2001–43
MADPH–02–1255
hep-ph/0202081

Detecting Microscopic Black Holes with Neutrino Telescopes

Jaime Alvarez-Muñiz,[1] Jonathan L. Feng,[2,3] Francis Halzen,[4] Tao Han,[4] and Dan Hooper[4]

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Abstract

If spacetime has more than four dimensions, ultra-high energy cosmic rays may create microscopic black holes. Black holes created by cosmic neutrinos in the Earth will evaporate, and the resulting hadronic showers, muons, and taus may be detected in neutrino telescopes below the Earth's surface. We simulate such events in detail and consider black hole cross sections with and without an exponential suppression factor. We find observable rates in both cases: for conservative cosmogenic neutrino fluxes, several black hole events per year are observable at the IceCube detector; for fluxes at the Waxman-Bahcall bound, tens of events per year are possible. We also present zenith angle and energy distributions for all three channels. The ability of neutrino telescopes to differentiate hadrons, muons, and possibly taus, and to measure these distributions provides a unique opportunity to identify black holes, to experimentally constrain the form of black hole production cross sections, and to study Hawking evaporation.

Phenomenology of High Energy Neutrinos in Low-Scale Quantum Gravity Models

J. Alvarez-Muñiz[1], F. Halzen[2], T. Han[2], D. Hooper[2]
[1] *Bartol Research Institute, University of Delaware, Newark, DE 19716*
[2] *Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, WI 53706*
(June, 2001)

We show that neutrino telescopes, optimized for detecting neutrinos of TeV to PeV energy, can reveal threshold effects associated with TeV-scale gravity. The signature is an increase with energy of the cross section beyond what is predicted by the Standard Model. The advantage of the method is that the neutrino cross section is measured in an energy region where i) the models are characteristically distinguishable and ii) the Standard Model neutrino cross section can be reliably calculated so that any deviation can be conclusively identified.

04.50.+h, 04.60.-m, 99.55.Vj, 95.85.Ry, 98.54.Cm, 98.70.Rz

Motivated by the absence of a self-consistent theory of quantum gravity and the unresolved hierarchy problem between the electroweak scale (10^2 GeV) and the Planck scale (10^{19} GeV), a great deal of attention has been given to theories of low-scale quantum gravity which envision significant quantum gravity effects at an energy scale of the order of $M_s \sim 1$ TeV [1,2]. In these scenarios, potentially large effects on high energy processes may occur due to the contributions from, *e.g.*, Kaluza-Klein excitations of gravitons (KK) or other stringy states near M_s. An interesting motivation for models in which cross sections at TeV scale become enhanced is the ultra-high energy cosmic ray problem. Protons above the GZK cutoff ($\sim 10^{19}$ eV) interact with the cosmic microwave background cataclysmically by the Δ-resonance [3,4]. Thus, the cosmic ray events observed above this energy must be produced by local sources, or involve new physics. Local sources of particles of such energy being unlikely, many exotic solutions have been proposed [5]. A solution which has received a great deal of attention in recent literature proposes that neutrinos with enhanced cross sections at GZK energies constitute the highest energy cosmic rays [6–8]. This solution requires neutrino-nucleon cross sections on the scale of 10's of mbarnes. Unfortunately, most scenarios of low-scale quantum gravity as low-energy effective theories are valid only up to the order of $\lesssim M_s$. Above this scale, the naive calculations typically violate unitarity [6,7]. One has to introduce some ad hoc unitarization scheme, since the fundamental theory, such as a realistic string theory, is yet unavailable. It is also very difficult to reliably predict the parton distribution functions needed at GZK energies in neutrino-nucleon interactions. For these reasons, studies of ultra-high energy ($\sim 10^{20}$ eV) quantum gravity enhancements to neutrino-nucleon interactions are extremely speculative.

These problems are far more manageable at energies below or near M_s. Unitarity may not be violated at this scale, calculations are generally perturbative and the relevant parton distributions are known at these energies [9]. The characteristics for different theoretical models can be also qualitatively distinguishable near and slightly above the threshold. Therefore, the TeV regime provides a natural scale for probing the features of low-scale quantum gravity models. These tests include direct searches in colliders such as the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) [10–12]. This letter discusses another class of experiments capable of testing features of low-scale quantum gravity: multi-TeV to PeV neutrino astrophysics.

We have recently witnessed first light of neutrino telescopes optimized to detect neutrinos in the TeV to PeV energy range [13,14]. This is the range of laboratory energies where the onset of TeV-scale gravity effects on the neutrino cross section will first manifest itself. For a neutrino flux Φ, the number of neutral currents events N_ν observed as hadronic showers in a neutrino detector of effective area A is given by the convolution over energy of the quantity $A^{3/2} \times \Phi \times n \times \sigma_\nu$. Here n is the density of the target that interacts with a neutrino with cross section σ_ν to produce a hadronic shower. In our discussion the detected neutrino flux plays a secondary role. It may represent the atmospheric neutrino flux or the flux of neutrinos of hundreds of TeV anticipated from gamma ray bursts.

An increase with energy of the cross section for neutrinos to interact with matter beyond a level calculated in the Standard Model will signal the onset of new physics including the increase anticipated as a consequence of TeV-scale gravity effects. It is important to recognize that the Standard Model cross section is computed from nucleon structure functions probed by HERA experiments in this energy range. The Standard Model baseline against which to measure new physics is known. The important observation here is that due to the geometry of the Earth and detector, the angular distributions of events with new physics can be significantly different from the Standard Model prediction. These measurements, though challenging for existing instruments like AMANDA and the detectors in the Mediterranean, should be feasible for second-generation detectors such as IceCube. Unlike first generation neutrino telescopes, IceCube can separate interesting high energy events from

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Snowmass2021 - Letter of Interest

Synergy of astro-particle physics and collider physics

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) EF06, EF07, NF05, NF06,AF4

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Authors:

Rana Adhikari, Markus Ahlers, Michael Albrow, Roberto Aloisio, Luis A. Anchordoqui, Ignatios Antoniadis, Vernon Barger, Jose Bellido Caceres, David Berge, Douglas R. Bergman, Mario E. Bertaina, Lorenzo Bonechi, Mauricio Bustamante, Karen S. Caballero-Mora, Antonella Castellina, Lorenzo Cazon, Ruben Conceição, Giovanni Consolati, Olivier Deligny, Hans P. Dembinski, James B. Dent, Peter B. Denton, Carola Dobrigkeit, Caterina Doglioni, Ralph Engel, David d'Enterria, Ke Fang, Glennys R. Farrar, Jonathan L. Feng, Thomas K. Gaisser, Carlos García Canal, Claire Guepin, Francis Halzen, Tao Han, Andreas Haungs, Dan Hooper, Felix Kling, John Krizmanic, Greg Landsberg, Jean-Philippe Lansberg, John G. Learned, Paolo Lipari, Danny Marfatia, Jim Matthews, Thomas McCauley, Hiroaki Menjo, John W. Mitchell, Marco Stein Muzio, Jane M. Nachtman, Angela V. Olinto, Yasar Onel, Sandip Pakvasa, Sergio Palomares-Ruiz, Dan Parson, Thomas C. Paul, Tanguy Pierog, Mario Pimenta, Mary Hall Reno, Markus Roth, Grigory Rubtsov, Takashi Sako, Fred Sarazin, Bangalore Sathyaprakash, Sergio J. Sciutto, Dennis Soldin, Jorge F. Soriano, Todor Stanev, Xerxes Tata, Serap Tilav, Kirsten Tollefson, Diego F. Torres, Ralf Ulrich, Michael Unger, Tonia Venters, Thomas J. Weiler, Lawrence Wiencke, David R. Winn, and Stephanie Wissel

`doi:10.5281/zenodo.4009452`

Abstract:

Seeking the fundamental nature of matter and associated mysteries bridges the energy, neutrino, and cosmic frontiers, thus connecting astro-particle physics and accelerator-based particle physics. Ergo, the study of astro-particle physics can have significant implications in the search for physics beyond the Standard Model at the LHC and future colliders. Correspondingly, LHC experiments provide the laboratory for measurements relevant to understand the subtleties of astro-particle physics. This Letter of Interest for SNOWMASS21 highlights some of the synergistic links between astro-particle physics and collider physics, focusing on cosmic rays and neutrinos. Related discussions by the European Community can be found in the European Particle Physics Strategy (EPPS)[1] and the Astroparticle Physics European Consortium (APPEC) roadmap.[*]

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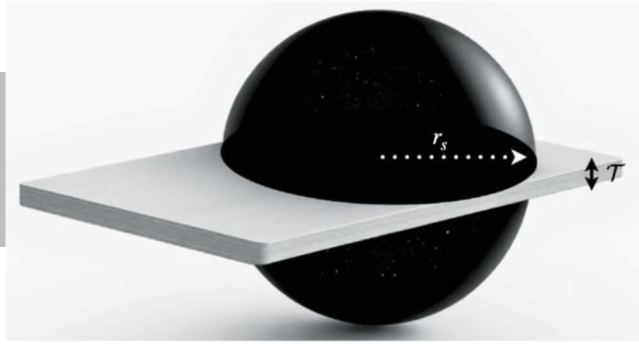
[*] `https://europeanstrategyupdate.web.cern.ch/; https://www.appec.org/roadmap`

Physics with Tao: Large Extra Dimensions or si non e vero e ben trovato



- move the Planck scale to 1 TeV and you solve the hierarchy problem

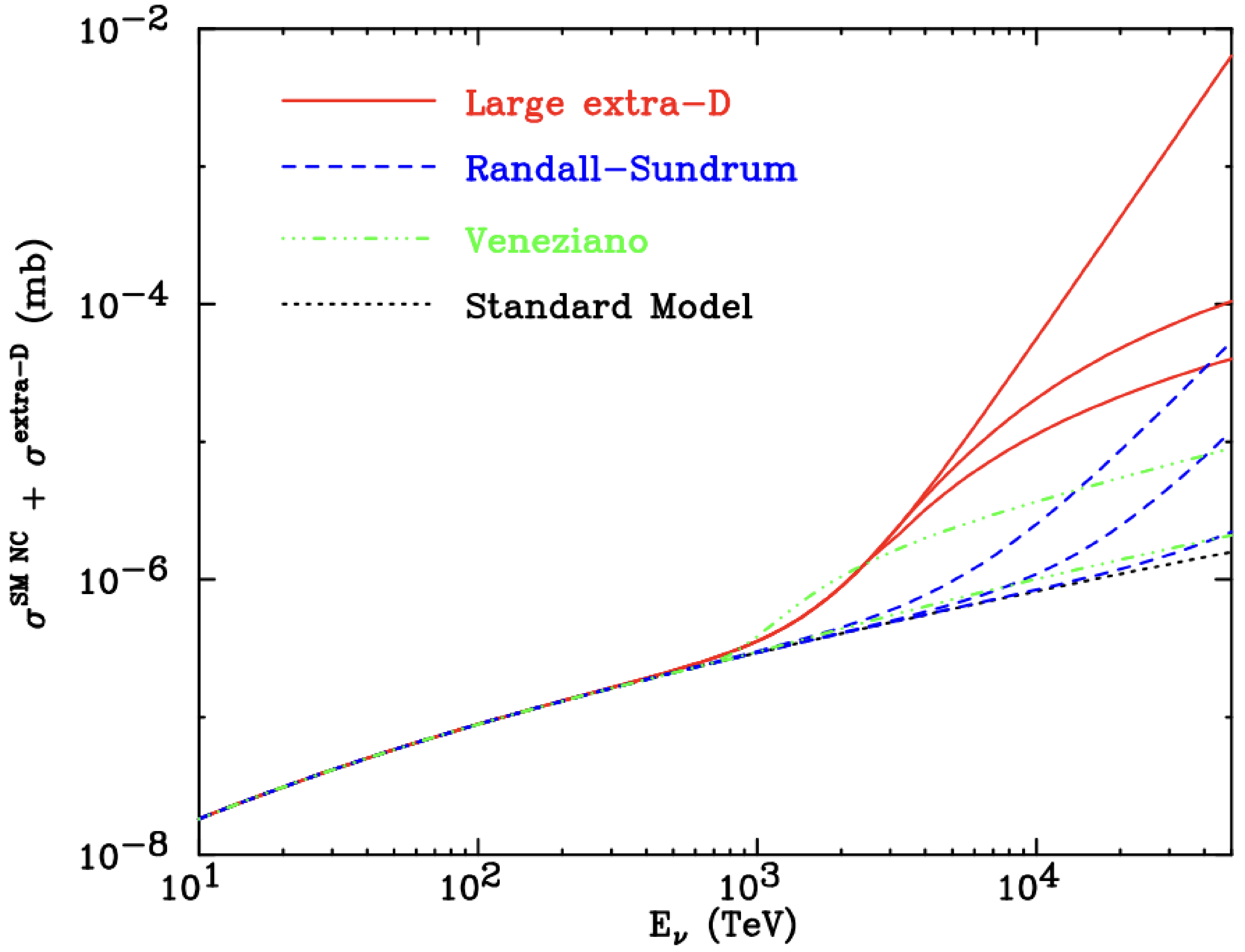
- gravity isn't weak; it just "leaks" into extra dimensions that are curled up at small scales of size R and only become apparent at 1 TeV

- the extra dimensions appear to us in 4D as a series of states with increasing mass, known as a Kaluza-Klein tower; these are just the fundamental and excited states in the extra dimension

- At high energies, the neutrino can transition into these higher-mass KK states. Because there are so many available states to transition into, the total cross section increases suddenly, even though the basic cross section remains weak

- If sufficient energy is deposit in the limited volume R, the space collapses to a (micro) black hole

$$\sigma \approx \frac{1}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^n$$


Large extra-D
Randall-Sundrum
Veneziano
Standard Model
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{1}
10^{2}
10^{3}
10^{4}
$\sigma^{\mathrm{SM\ NC}} + \sigma^{\mathrm{extra-D}}$ (mb)
E_ν (TeV)

New Journal of Physics
The open–access journal for physics

The particle physics reach of high-energy neutrino astronomy

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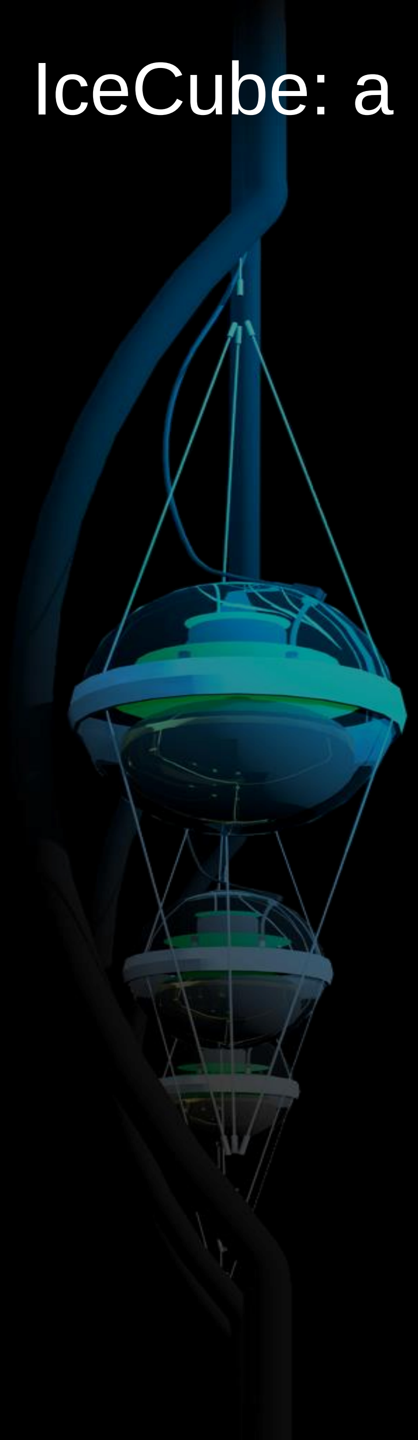
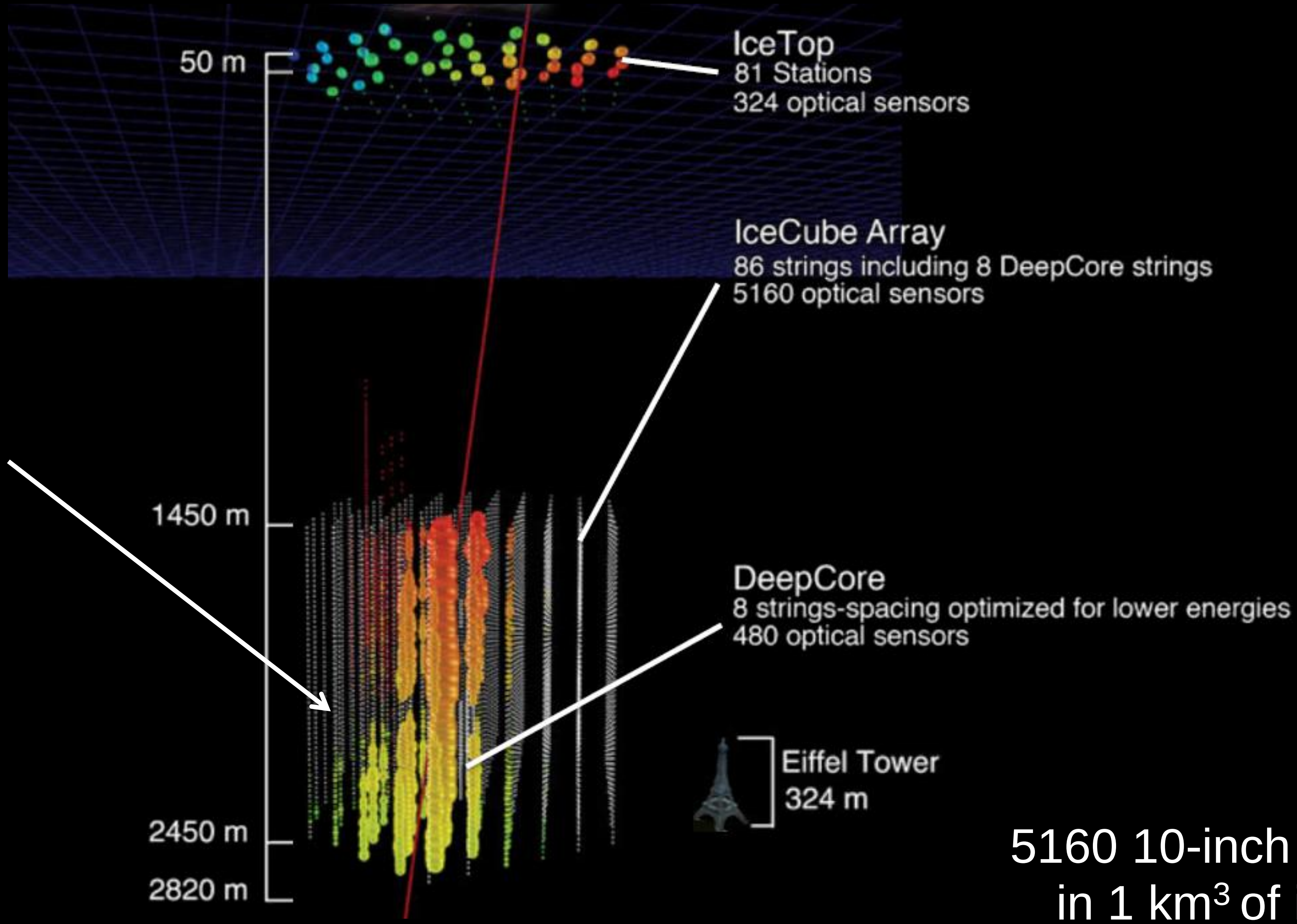
Abstract. We discuss the prospects for high-energy neutrino astronomy to study particle physics in the energy regime comparable to and beyond that obtainable at the current and planned colliders. We describe the various signatures of high-energy cosmic neutrinos expected in both neutrino telescopes and air shower experiments and discuss these measurements within the context of theoretical models with a quantum gravity or string scale near a TeV, supersymmetry and scenarios with interactions induced by electroweak instantons. We attempt to access the particle physics reach of these experiments.

IceCube: a BSM Machine

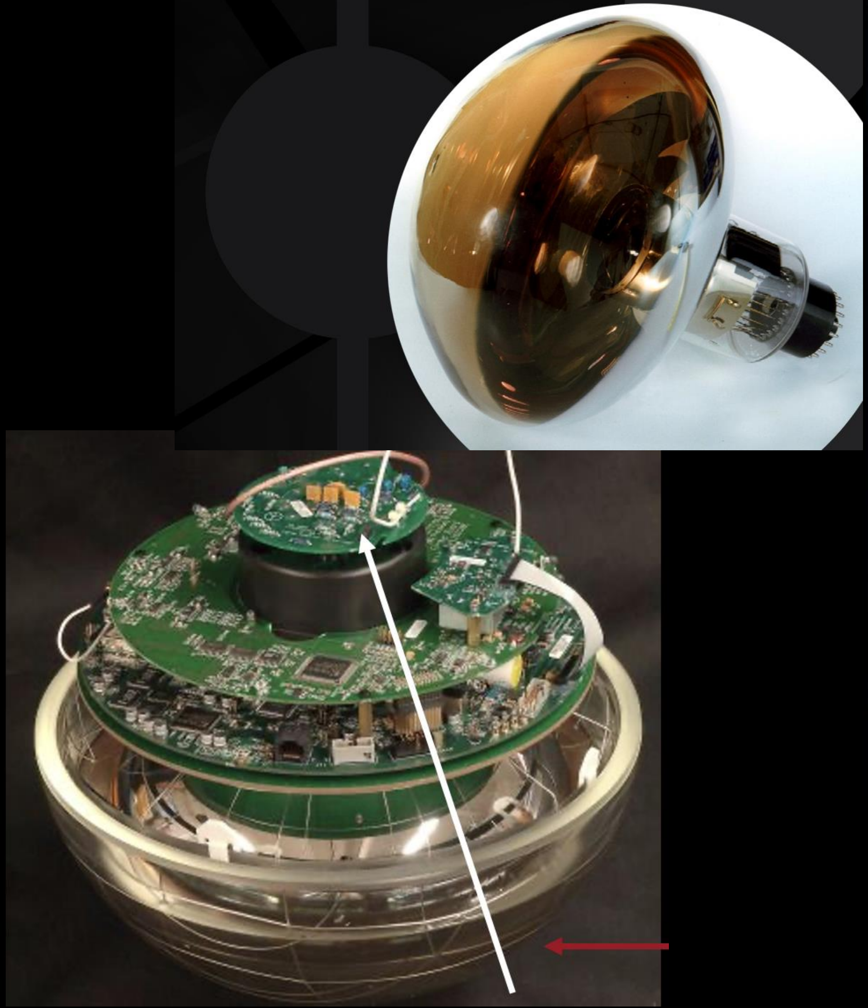


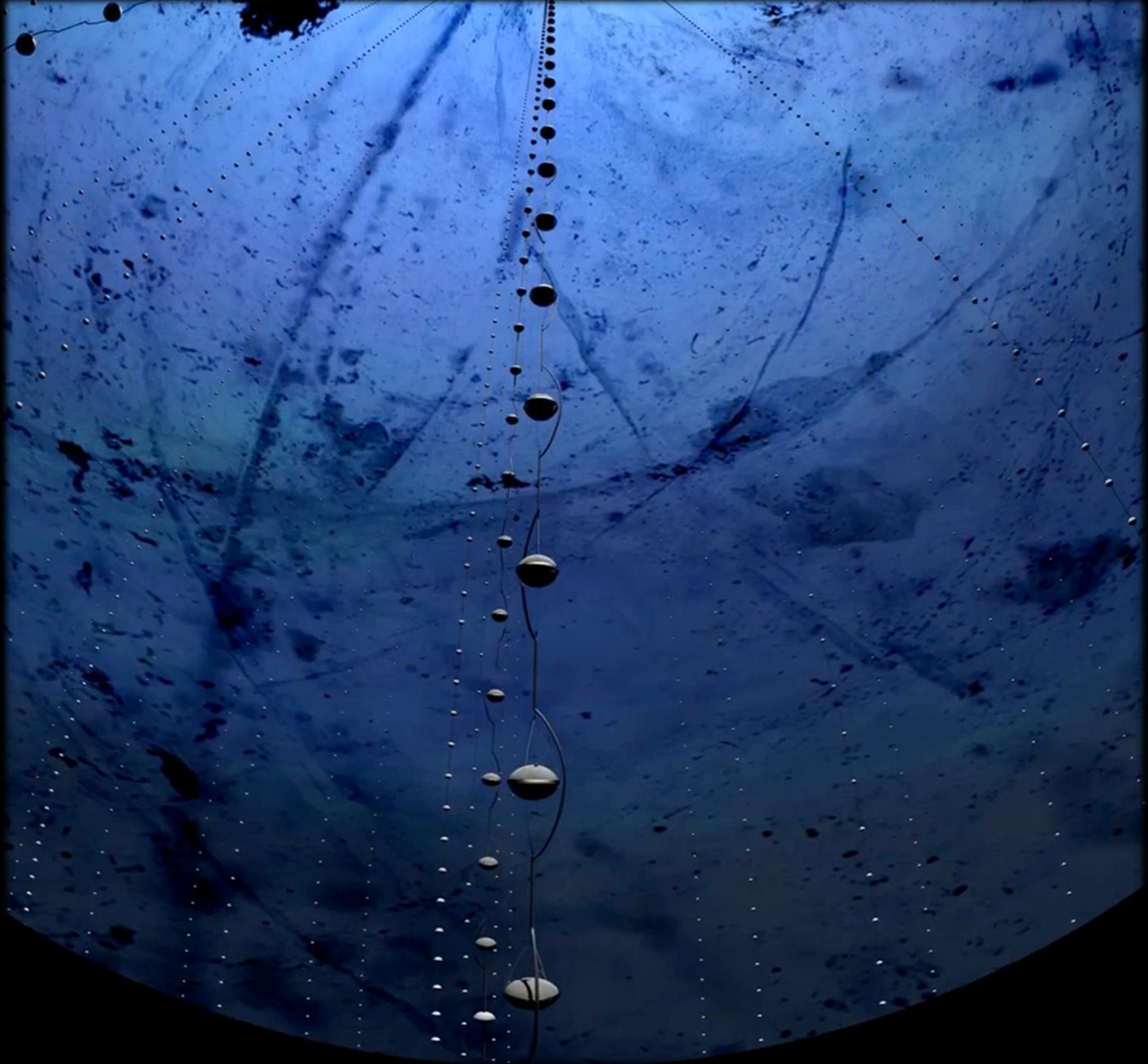


5160 10-inch PMs
in 1 km^3 of ice

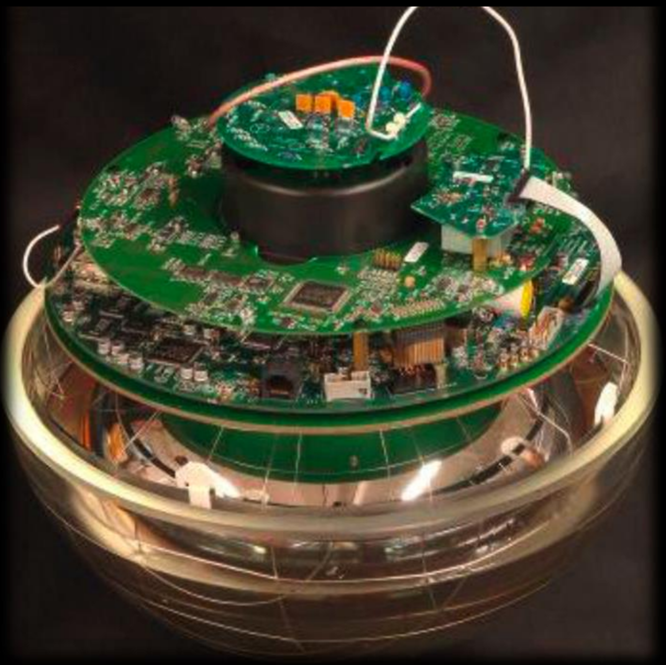
IceCube:

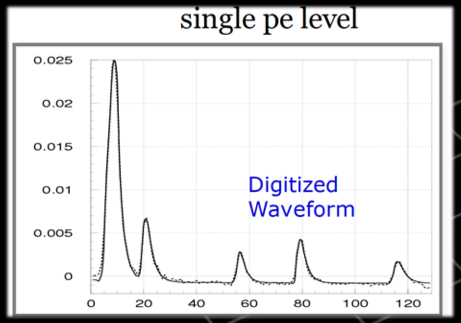
5160 10-inch photomultipliers,
60 per string on 86 strings,
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector

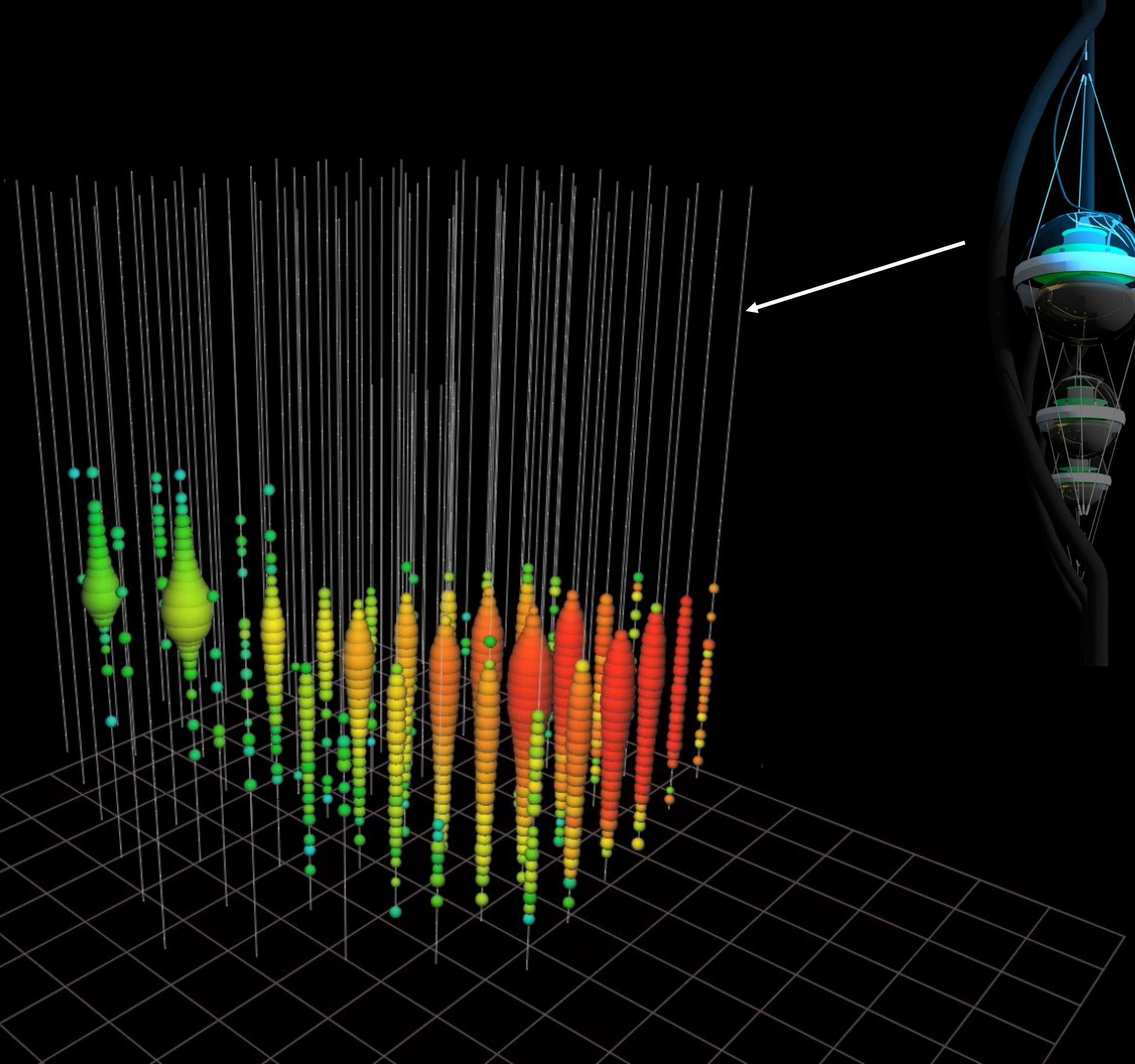




1 km^3 of Antarctic ice instrumented with 5160 PMT (10inch) below 1450m

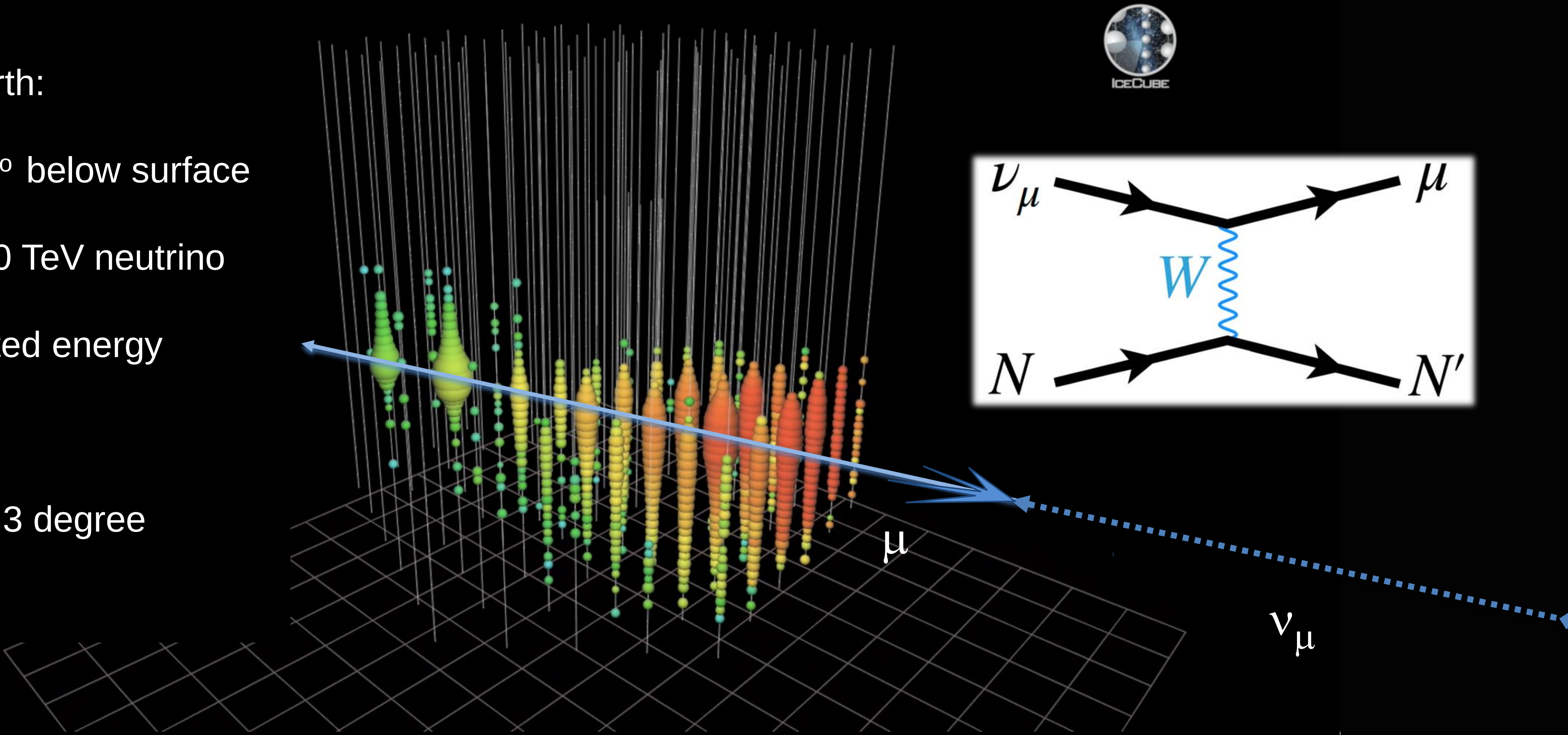


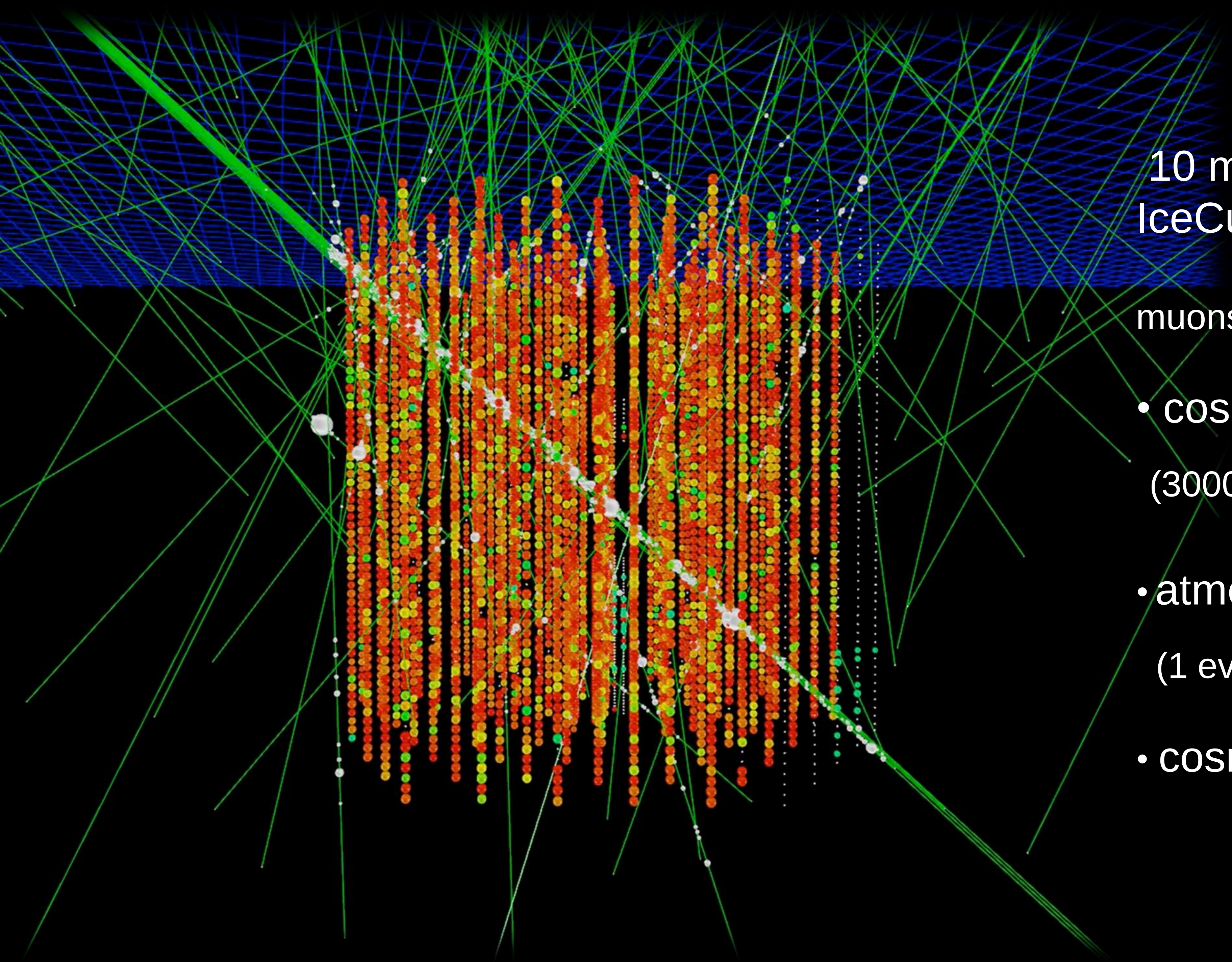




Look through the Earth:

- upgoing muon 11^{o} below surface
- produced by 8,700 TeV neutrino
- 2,600 TeV deposited energy
- not atmospheric
- reconstructed < 0.3 degree
- astronomy





10 msec movie of IceCube taking data

muons detected per year

- cosmic ray muons ~ 10^{11}

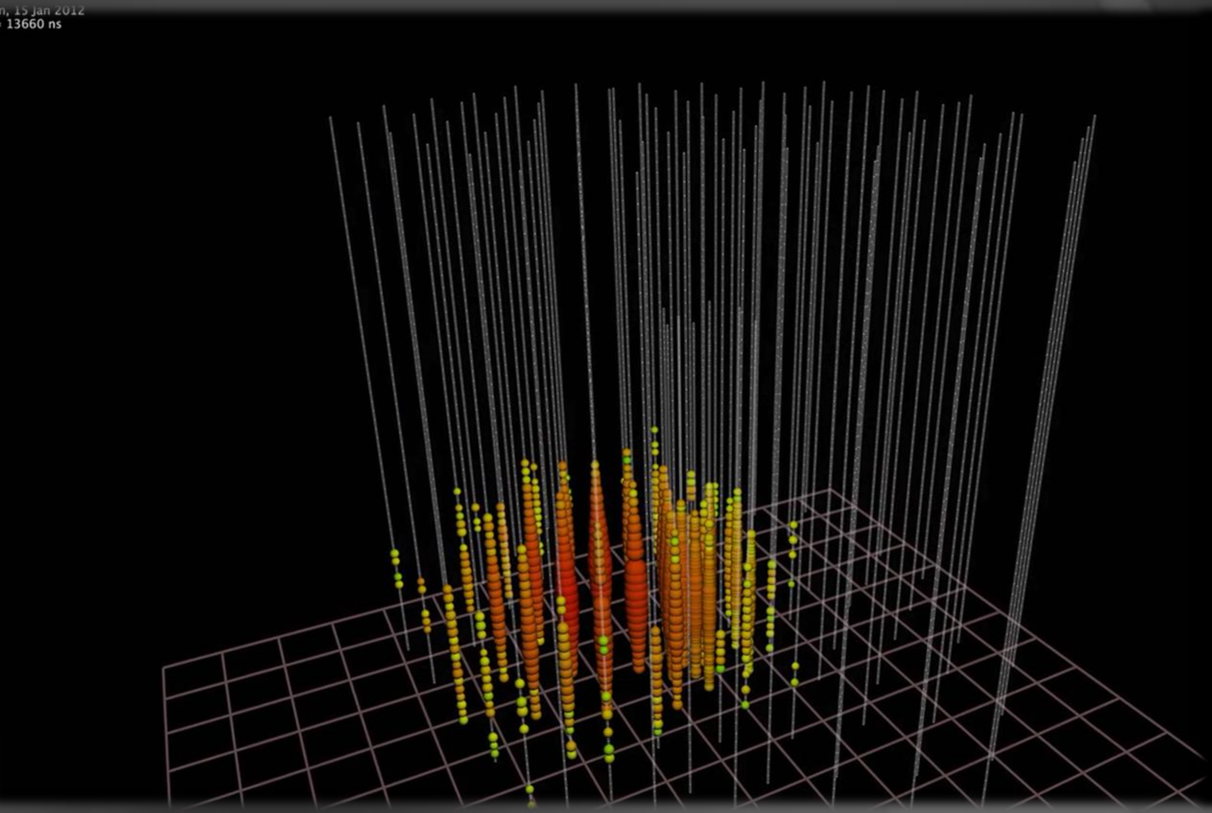
  (3000 per second)

- atmospheric neutrinos ~ 10^{5}

  (1 every 5 minutes)

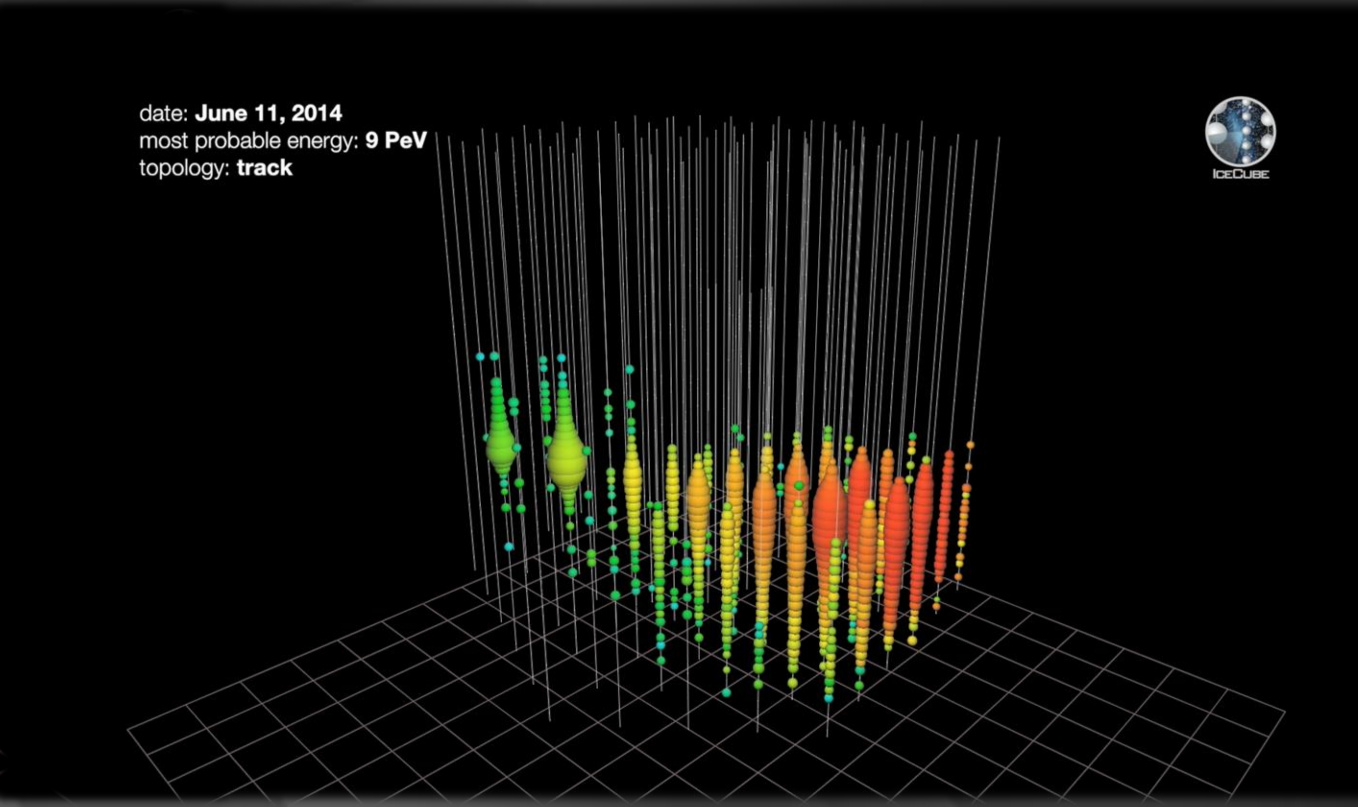
- cosmic neutrinos ~ 200

neutrinos interacting
inside the detector



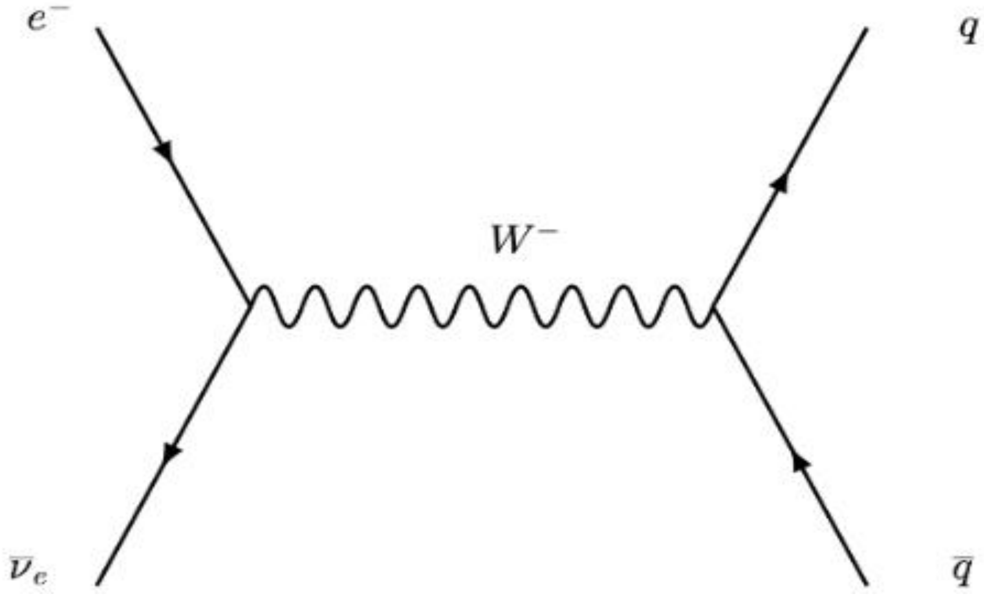
superior total energy
measurement
to 10%, all flavors, all sky

muon neutrinos
filtered by the Earth



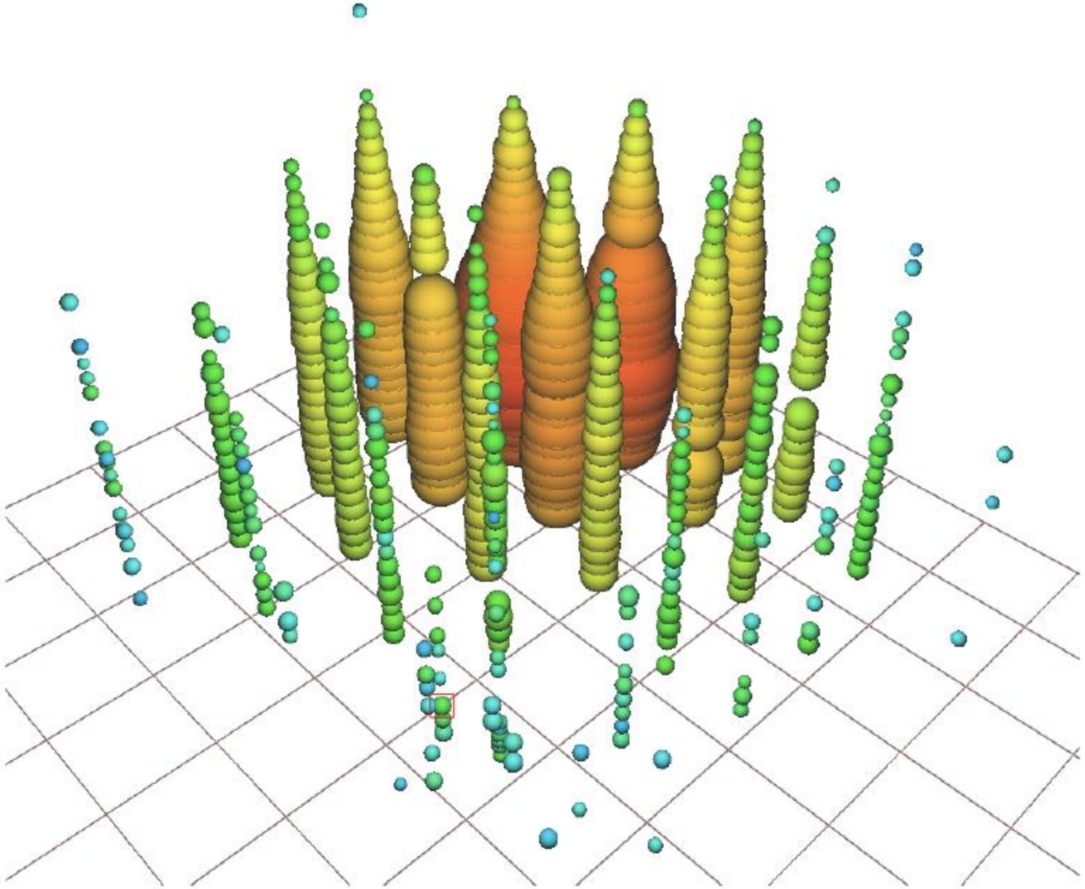
superior angular resolution < 0.3^o
including systematics

Glashow resonance event with energy 6.3 PeV

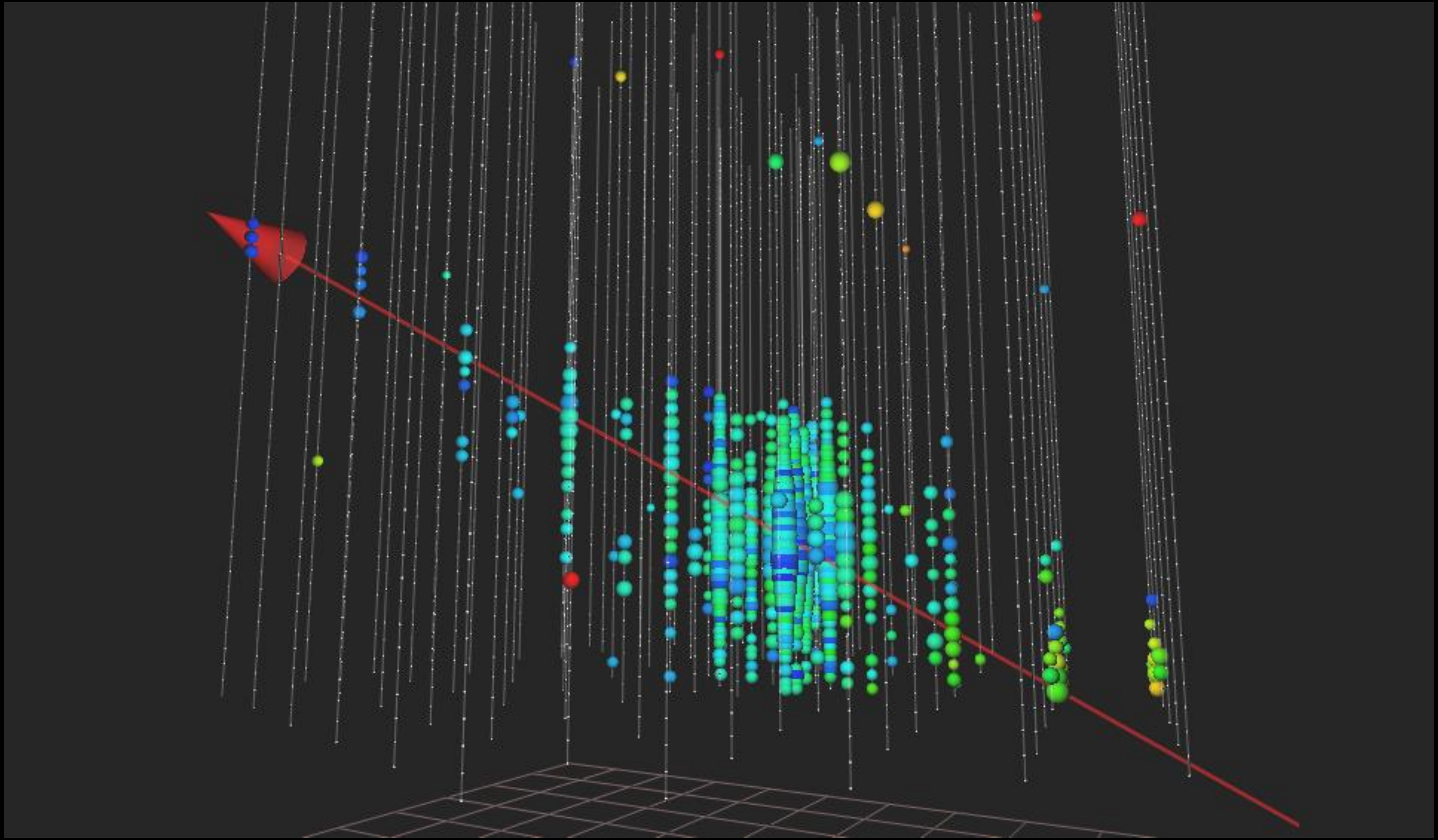


$$E_R = M_W^2/[2m_e]$$
$$= 6.32\,\mathrm{PeV}$$

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

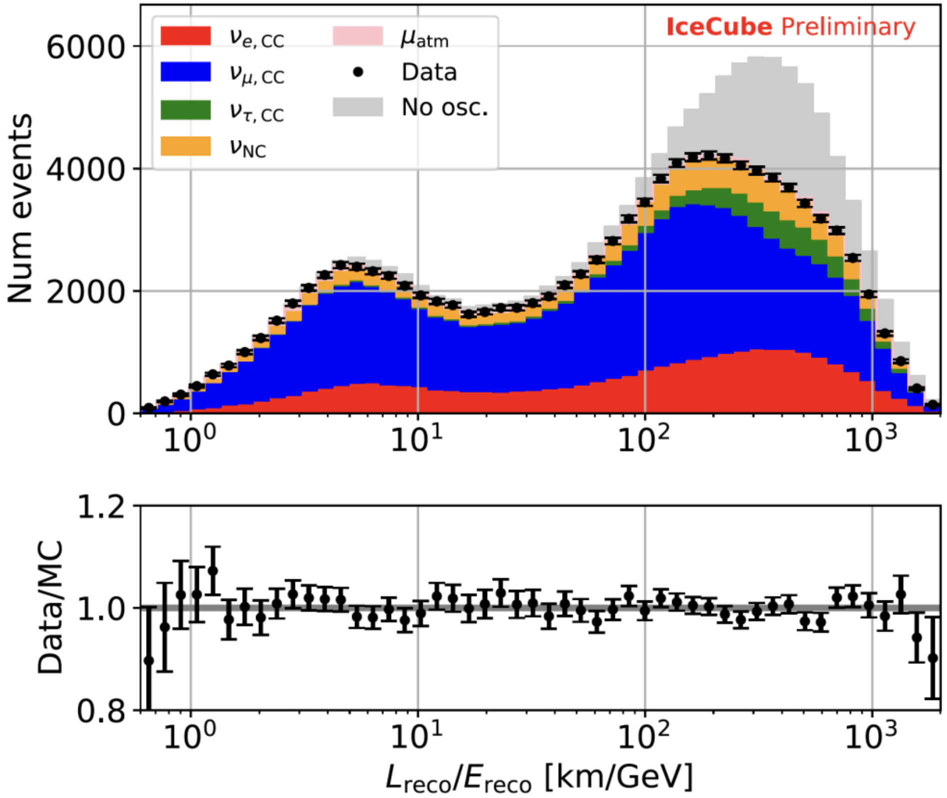


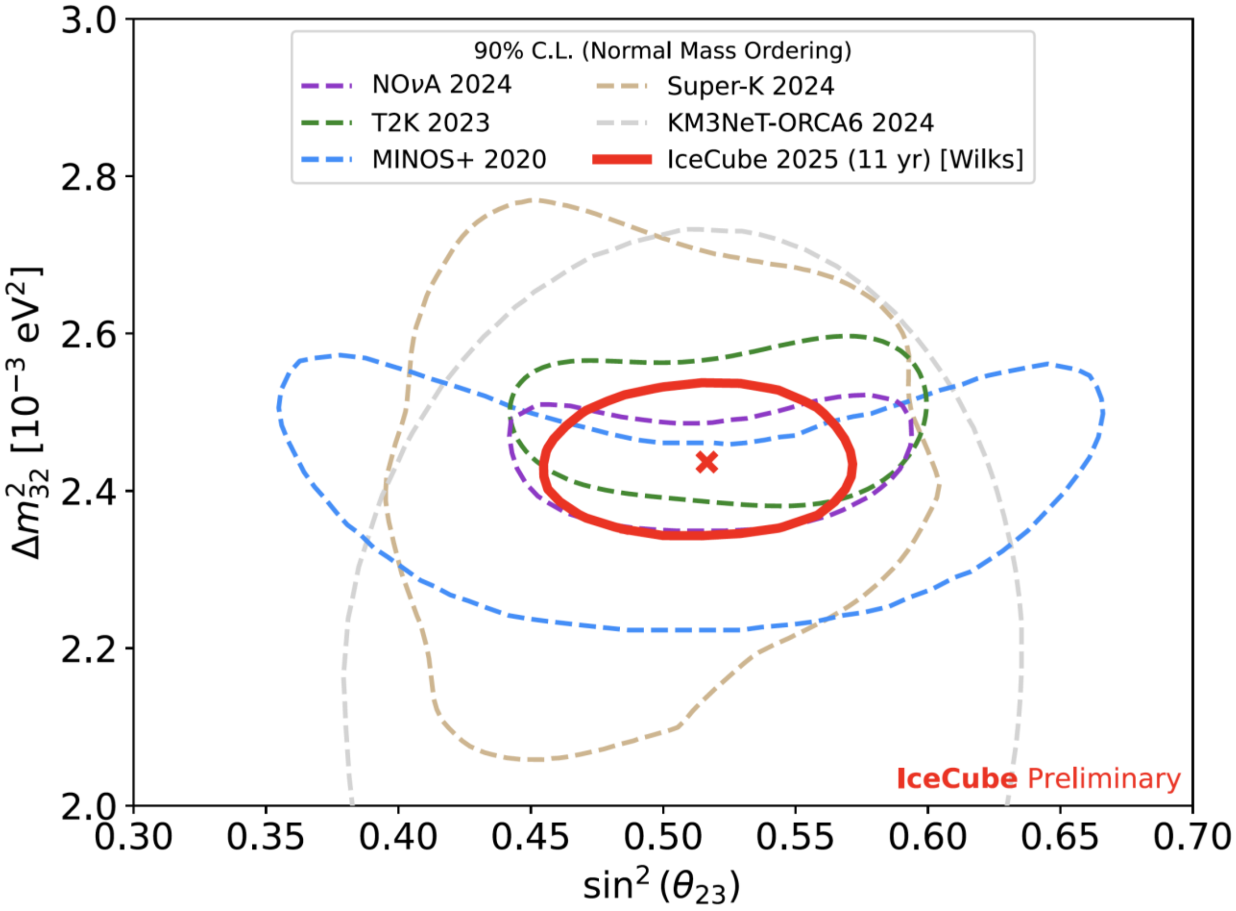
IceCube and DeepCore

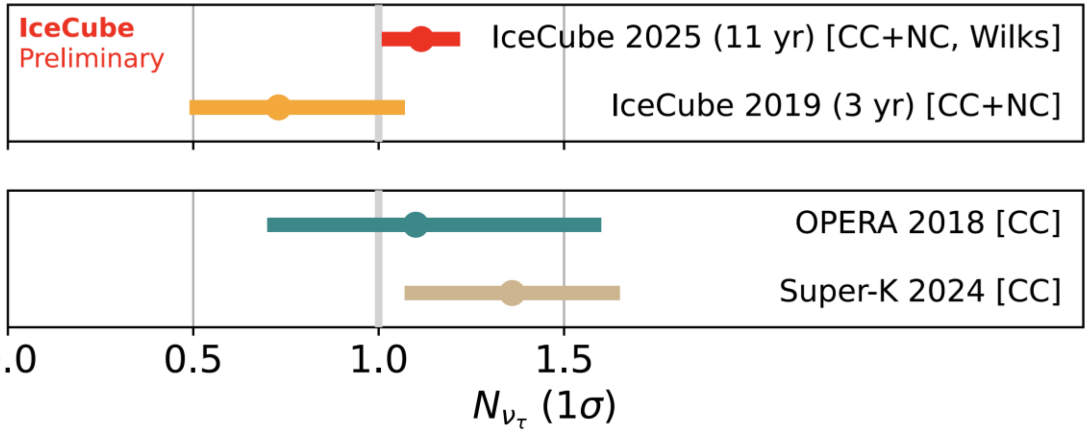


- one million neutrinos [5-55 GeV]
- low background (IceCube veto)
- see ν_τ disappear and appear

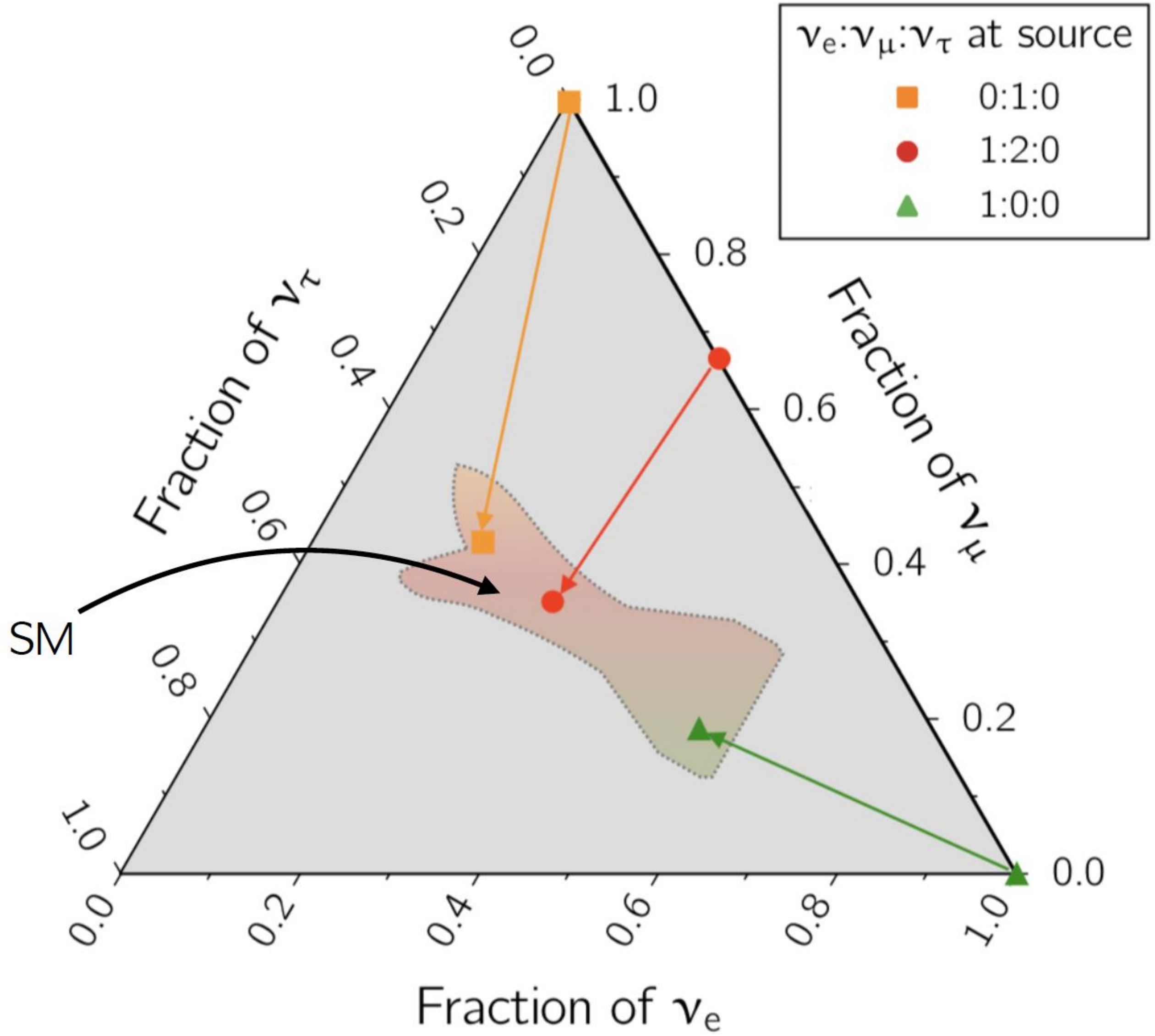
- higher energies, same oscillation parameters
- fit both the atmospheric flux and the oscillation parameters
- blind analysis

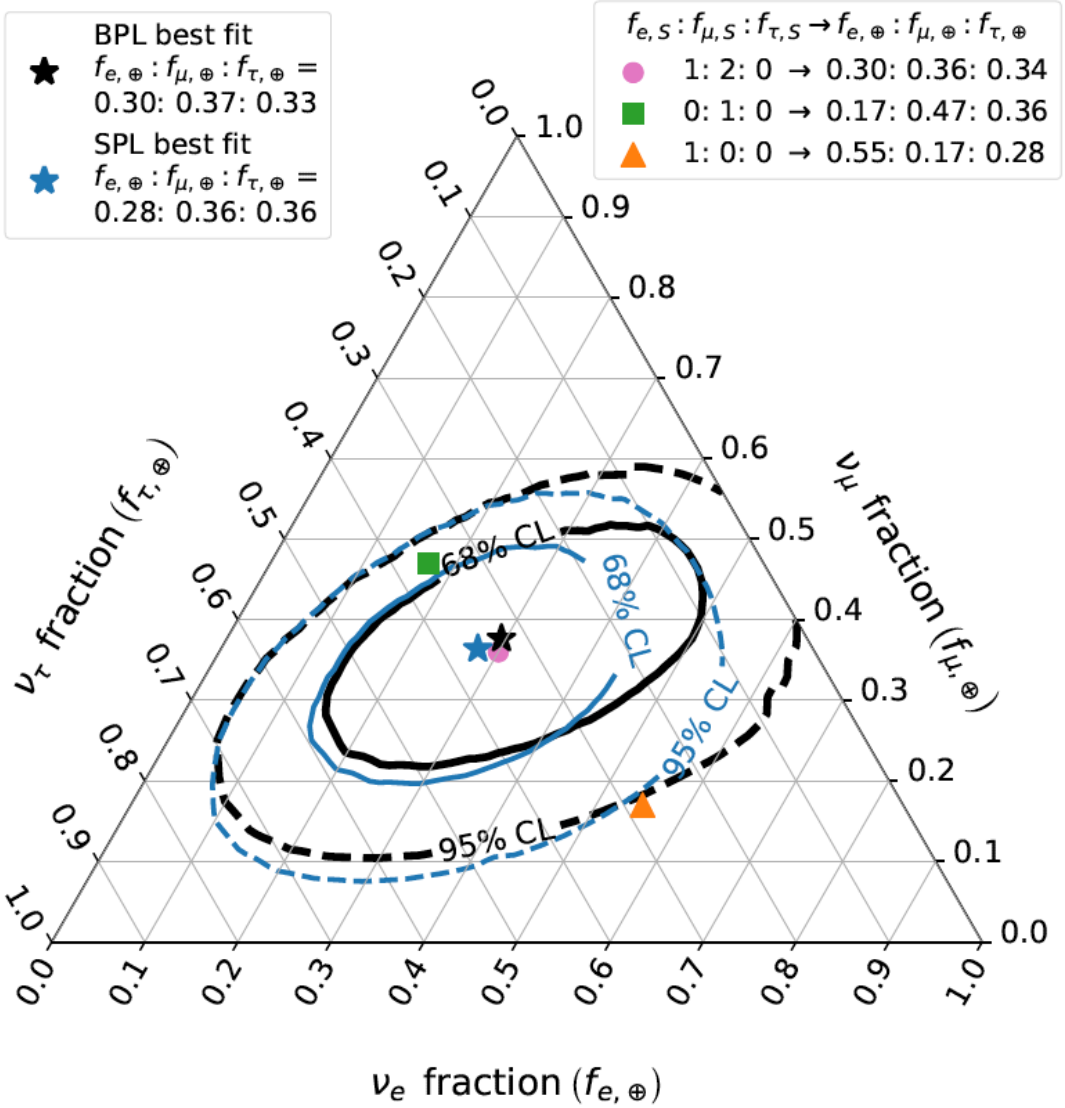


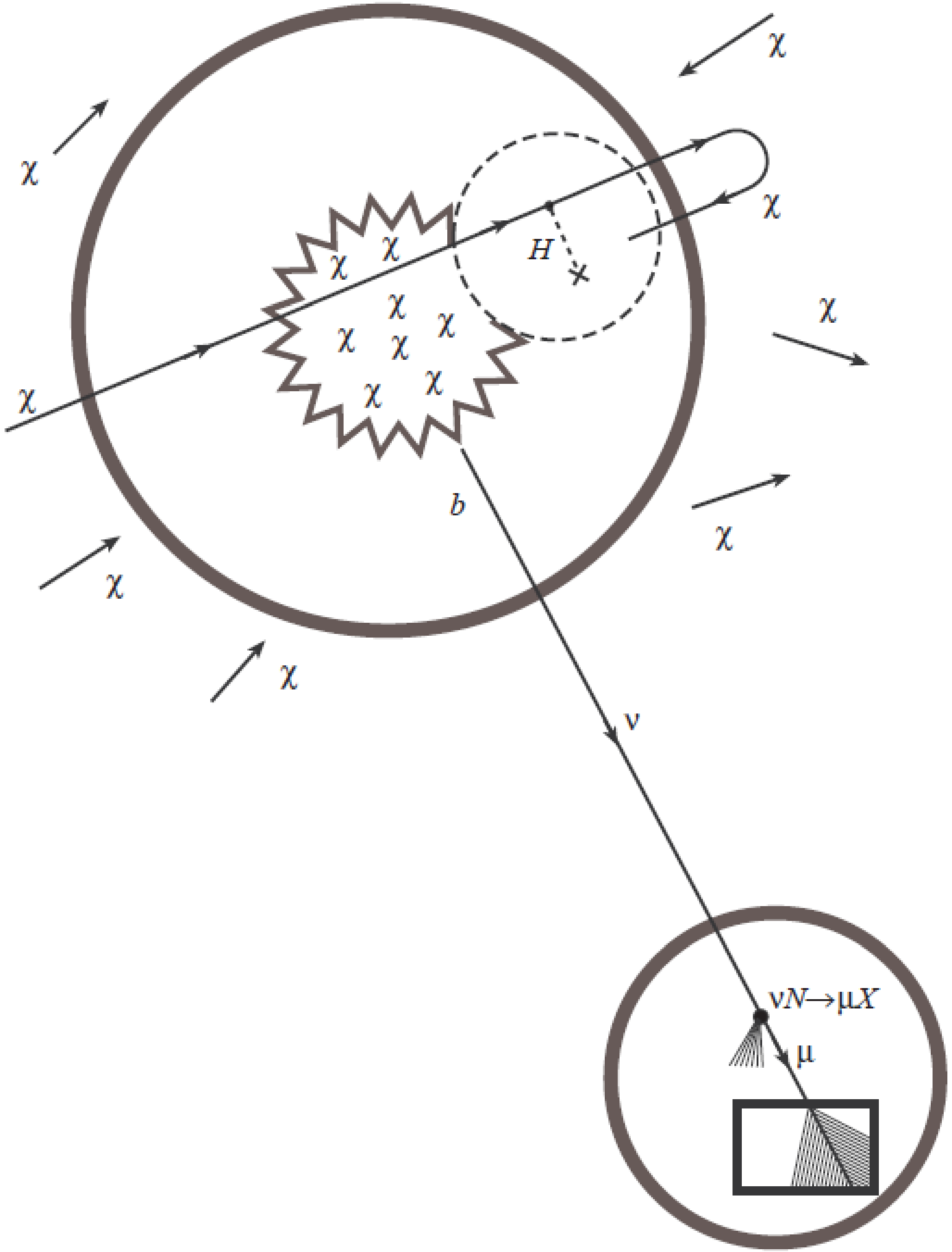




oscillations of PeV neutrinos over cosmic distances to 1:1:1

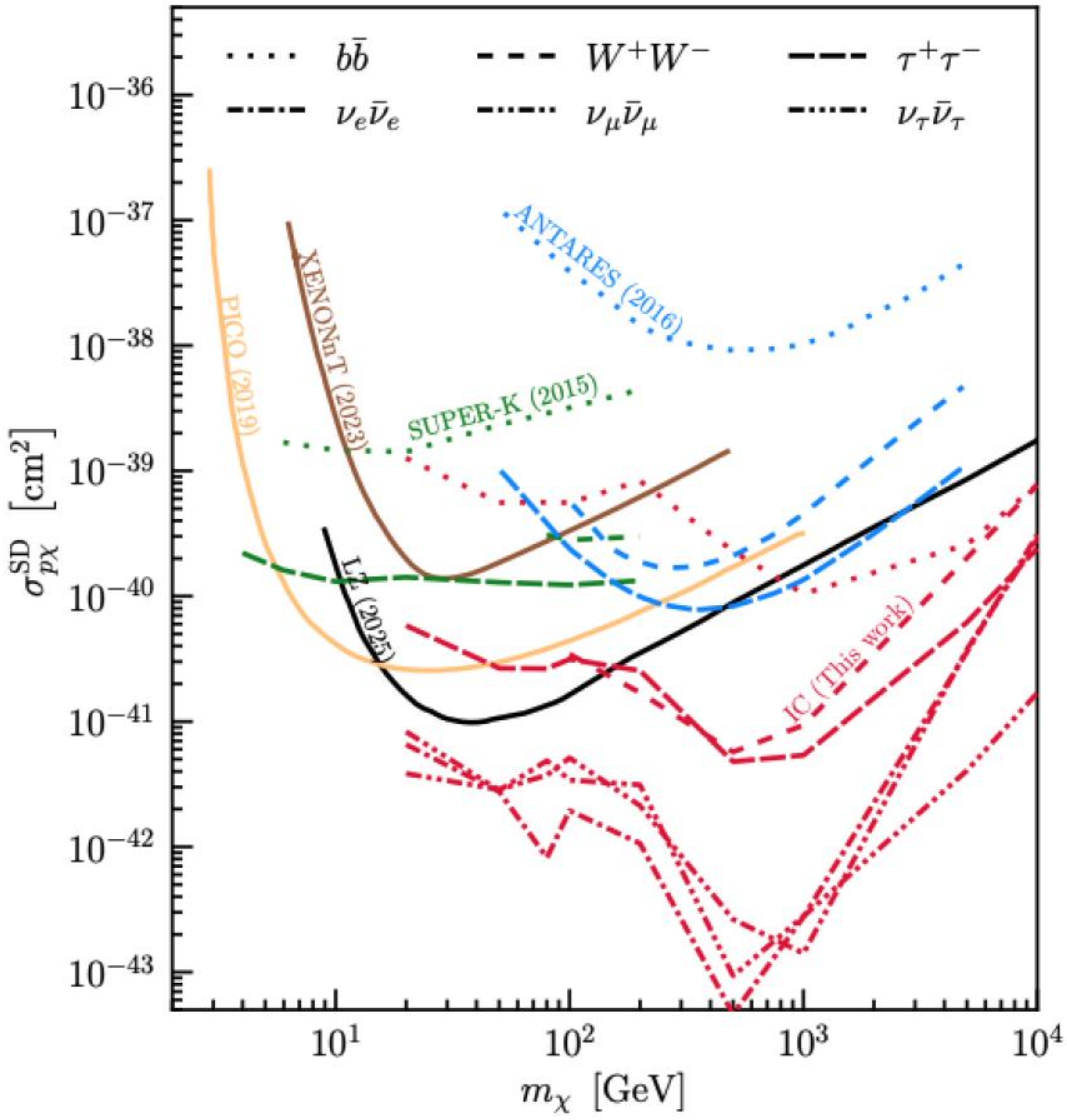






supersymmetry on
the back of an
envelope
arXiv 9404252

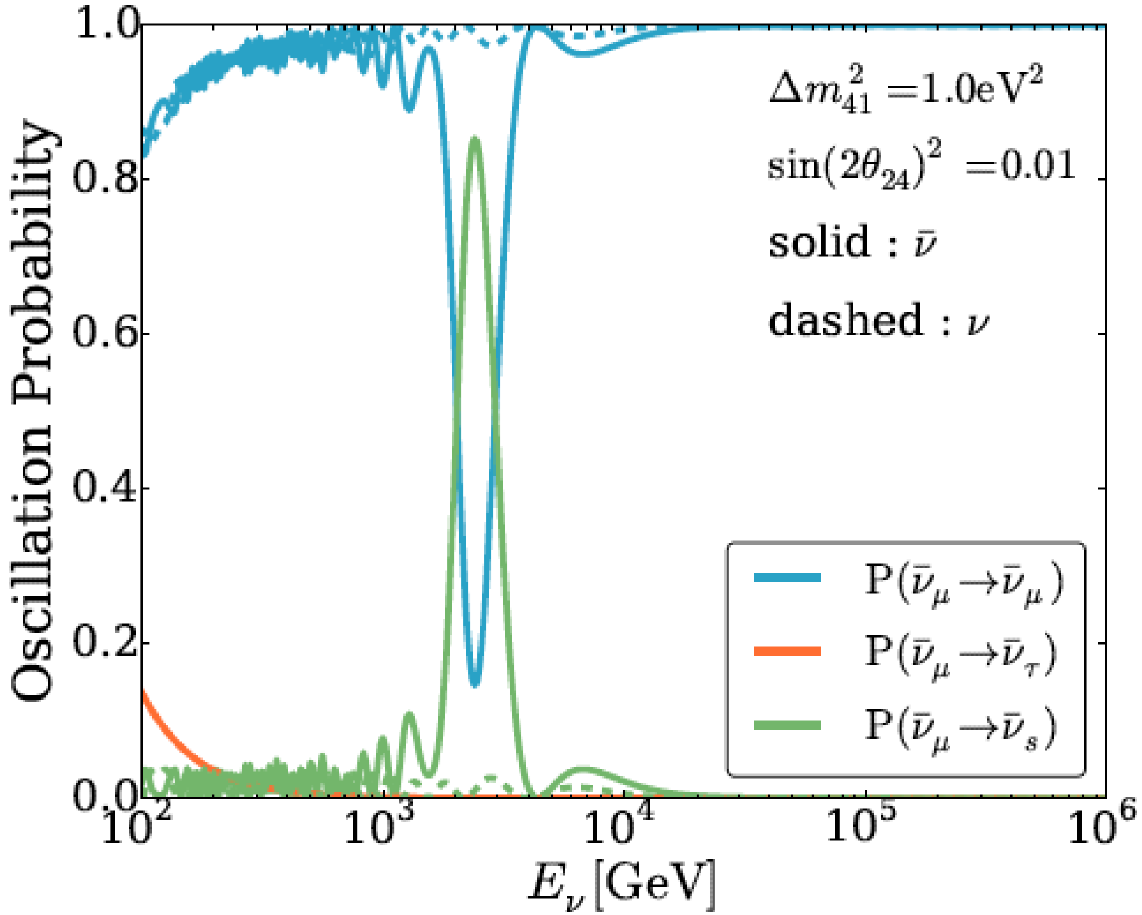
world-leading limits on the spin-dependent interactions of dark matter particles with ordinary matter

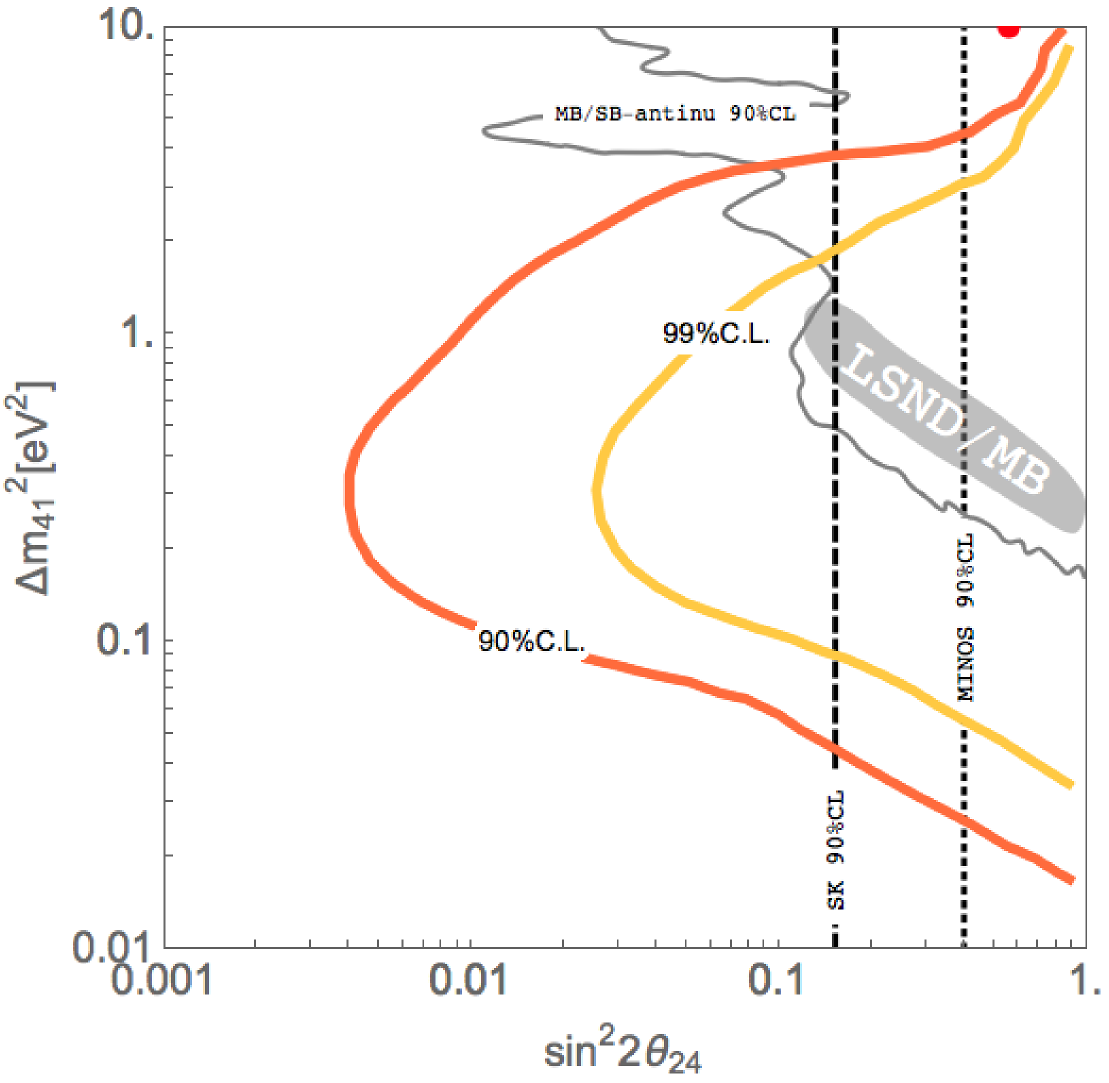


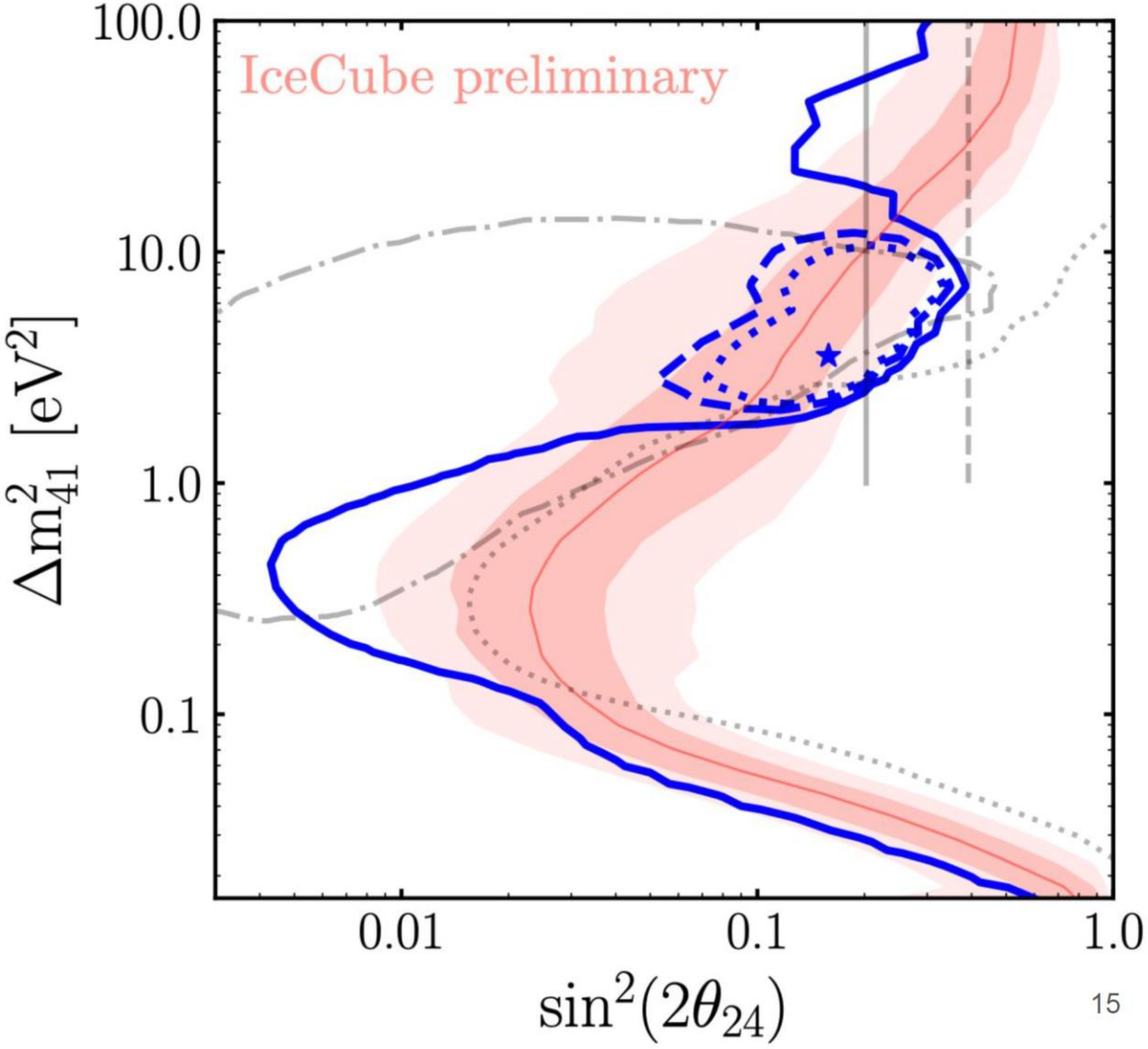
eV sterile neutrino → Earth MSW resonance for TeV neutrinos

In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

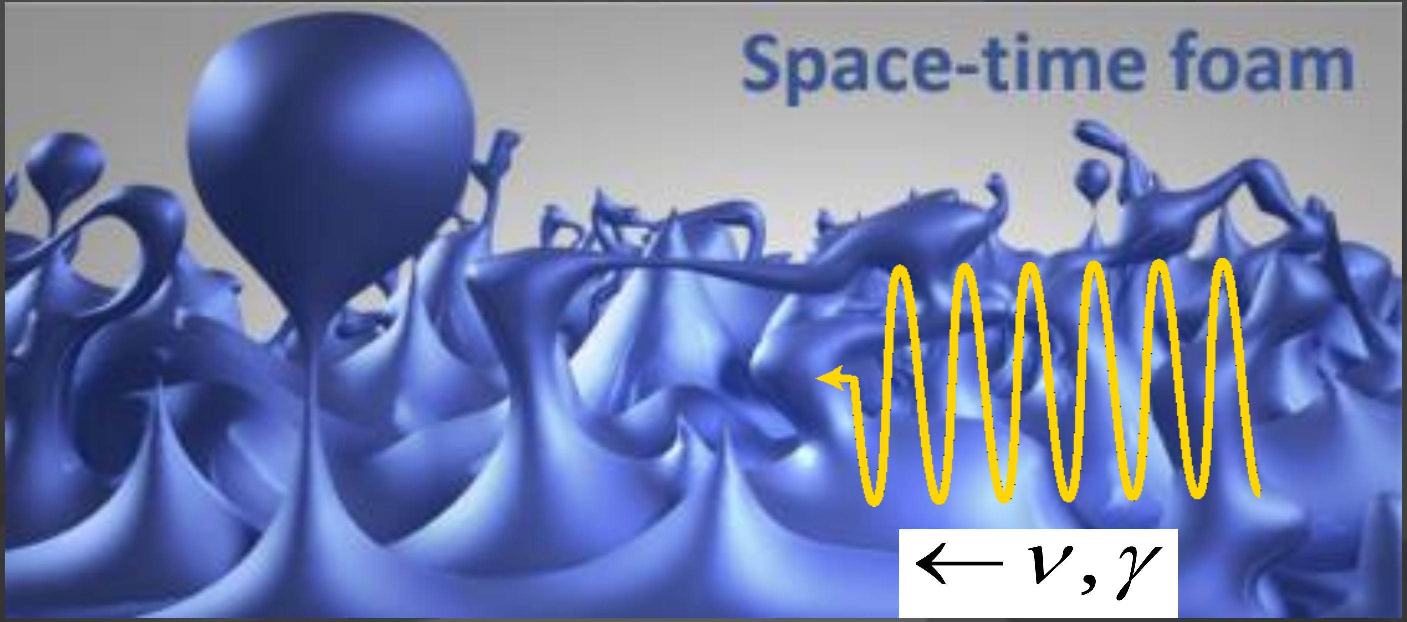
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$







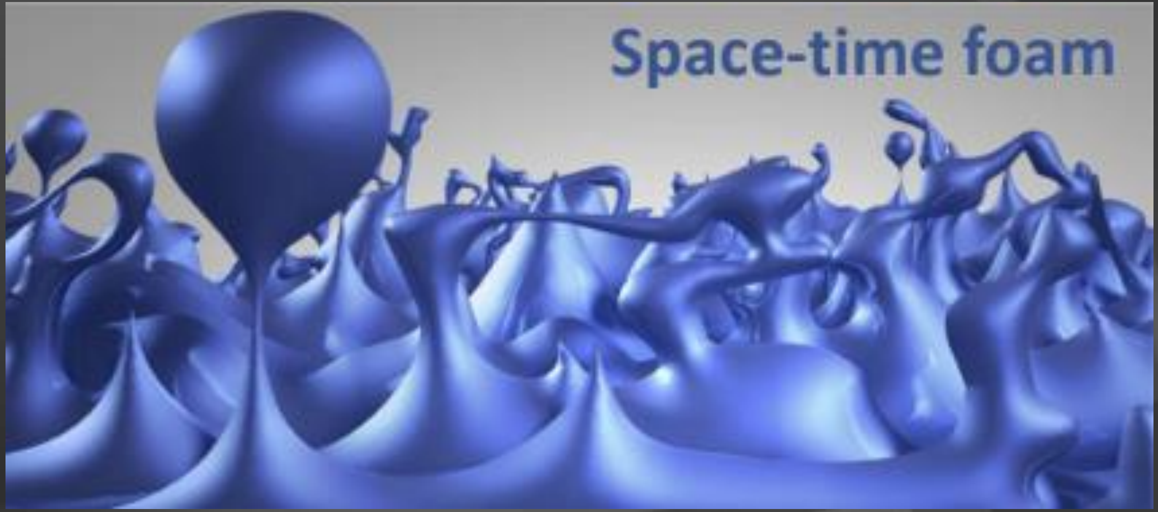
sterile neutrino?



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

- oscillations as interferometer sensing quantum fluctuations

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



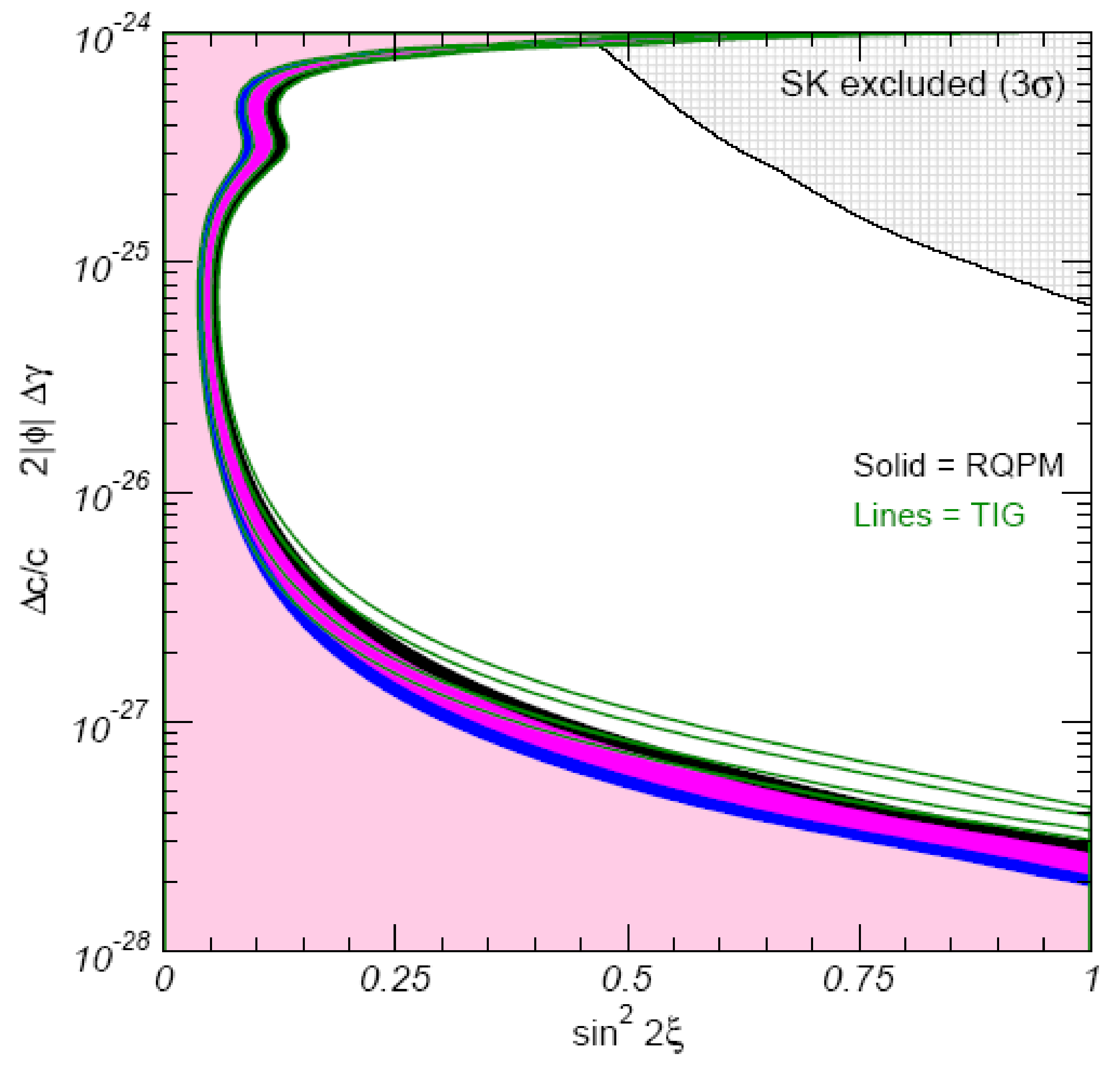
$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$

so far standard oscillations prevail over decoherence reaching $M_{QG} > M_{Planck}$

- the effects are small but become observable for high energies and long distances
- speed of neutrinos depends on their energy, like photons in a crystal
- modification to dispersion relation leads to an energy dependent speed of light
- for some coefficients IceCube yields world-best limits with atmospheric neutrinos

[2308.00105 [hep-ex]]

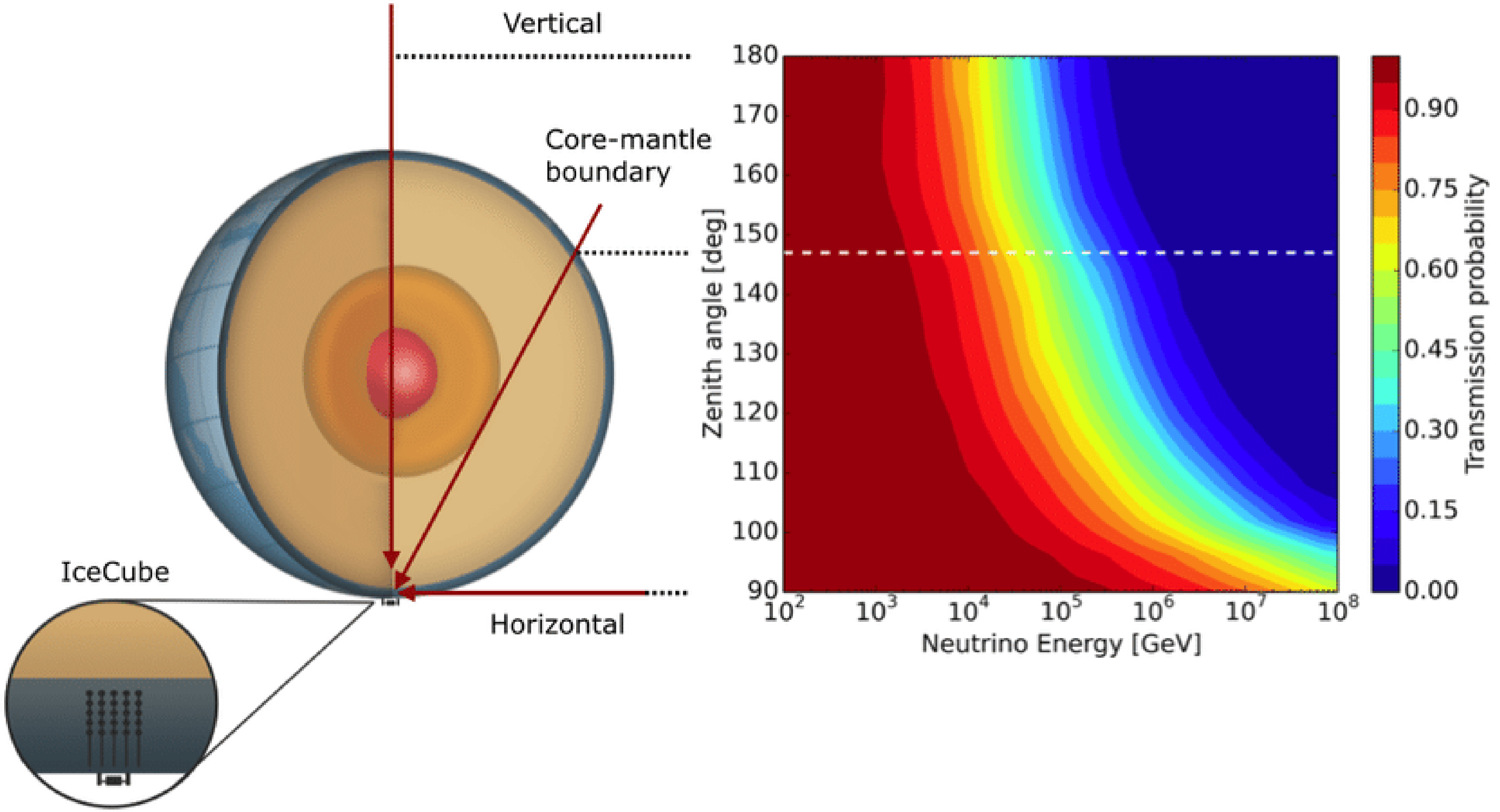
- equivalence principle
and
- Lorentz invariance



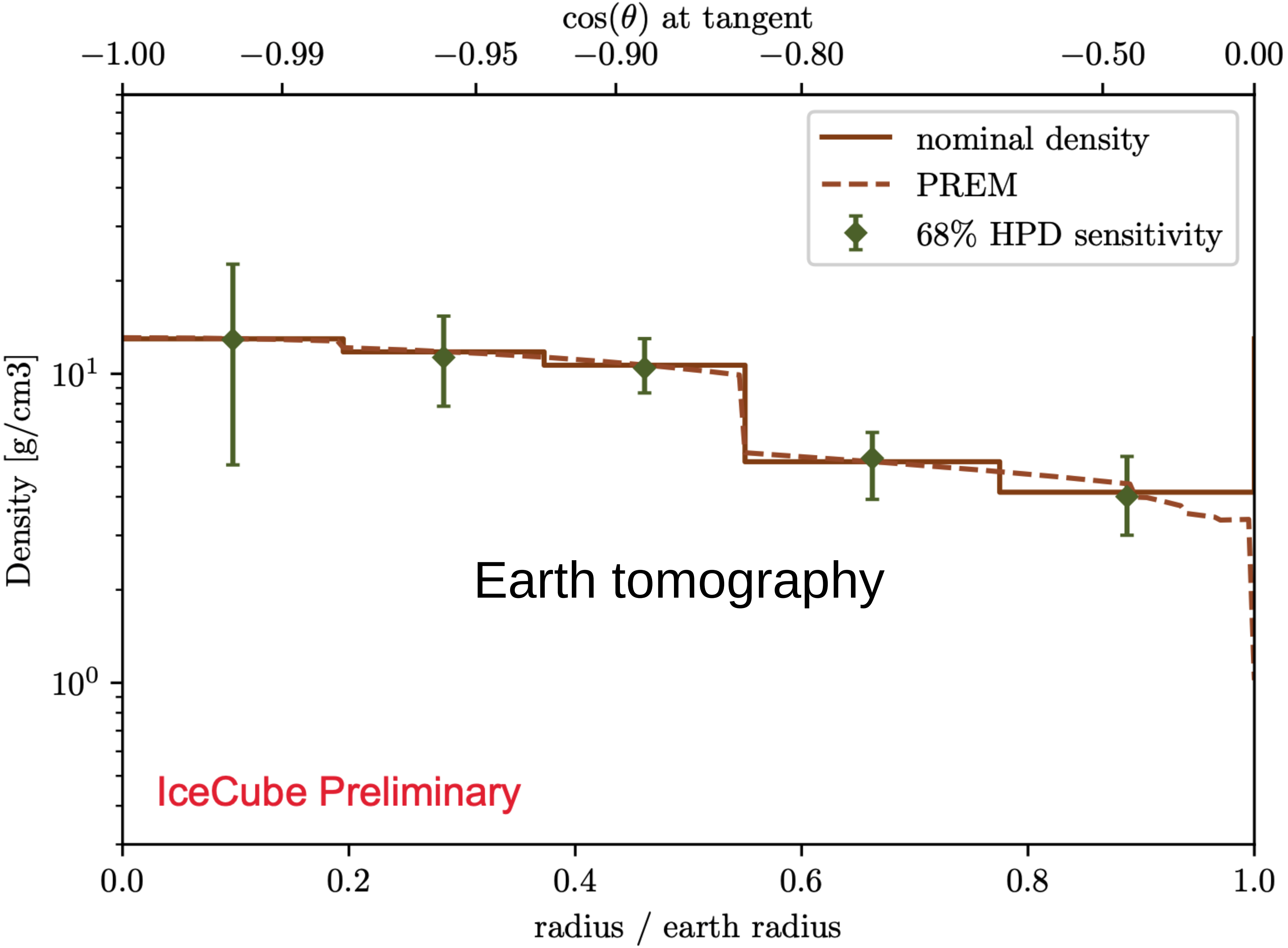
Physics with Tao: si non e vero e ben trovato

- move the Planck scale to 1 TeV and you solve the hierarchy problem
- gravity isn't weak; it just "leaks" into extra dimensions that are curled up at small scales of size R and only become apparent at 1 TeV
- the extra dimensions appear to us in 4D as a series of states with increasing mass, known as a Kaluza-Klein tower; these are just the fundamental and excited states in the extra dimentsion
- At high energies, the neutrino can transition into these higher-mass KK states. Because there are so many available states to transition into, the total cross section increases suddenly, even though the basic cross section remains weak
- If sufficient energy is deposit in the limited volume R, the space collapses to a (micro) black hole

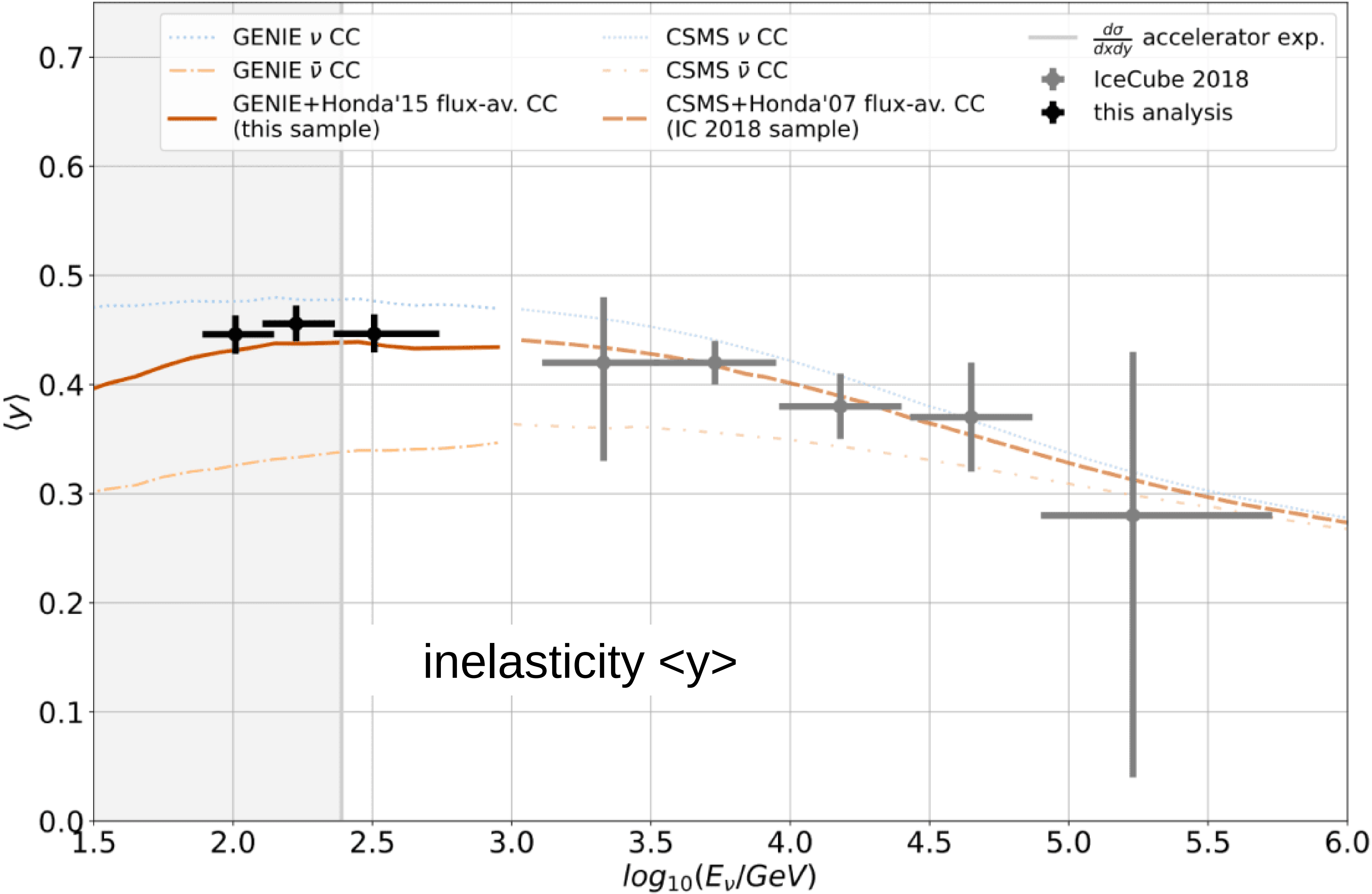
$$\sigma \approx \frac{1}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^n$$



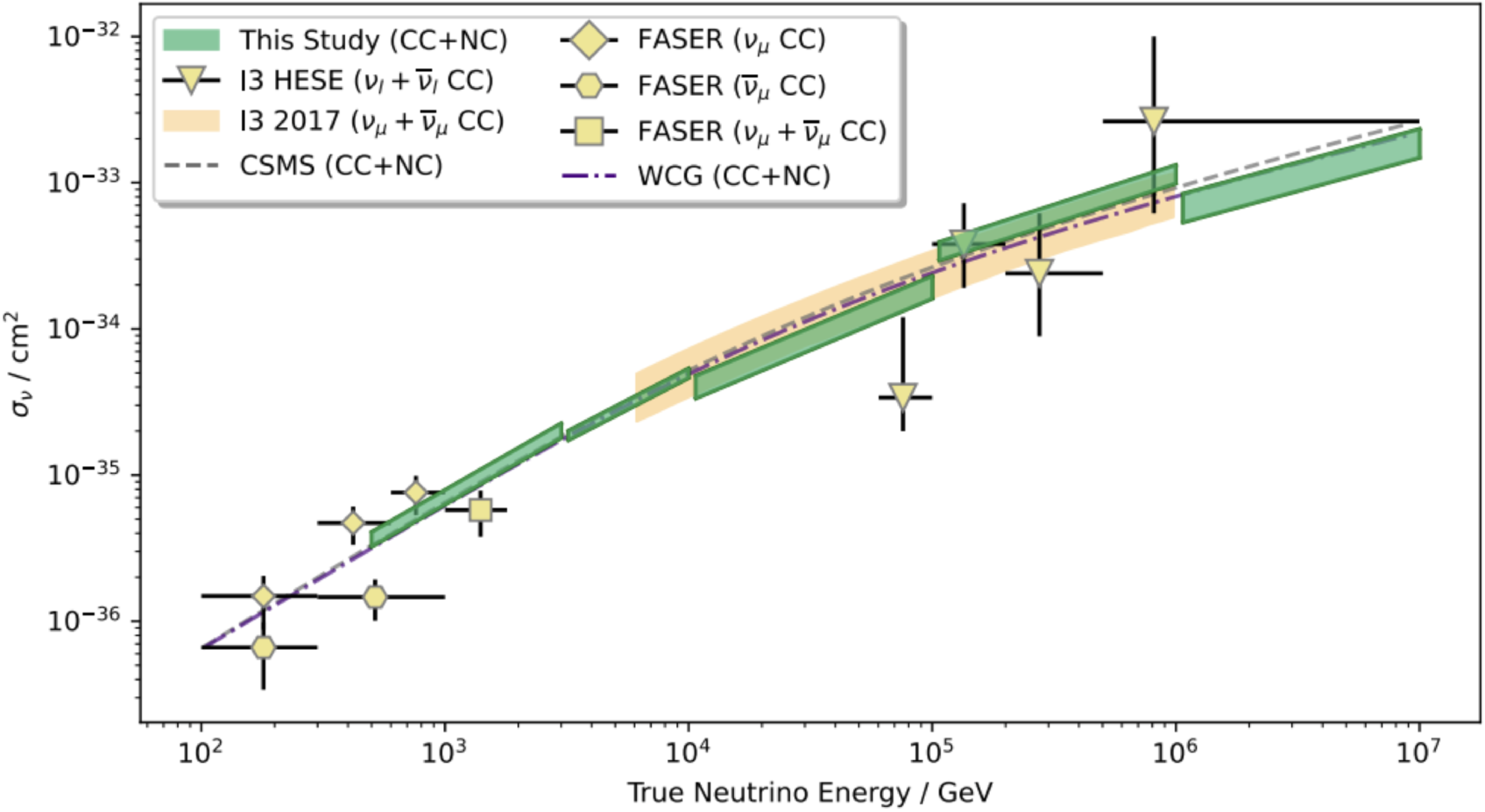
absorption length of a neutrino is 12,500 km at 70 TeV

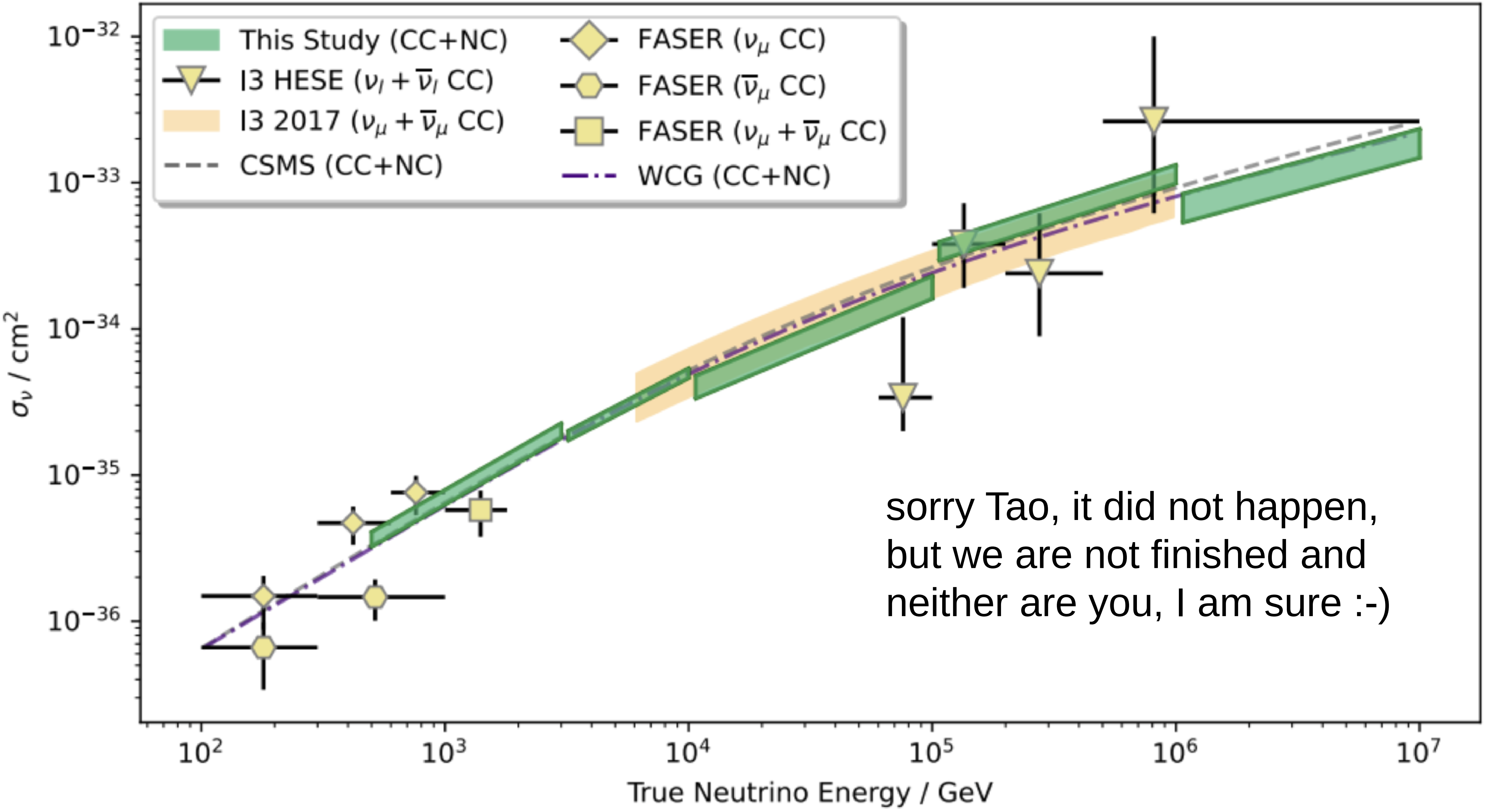


Earth tomography



inelasticity <y>

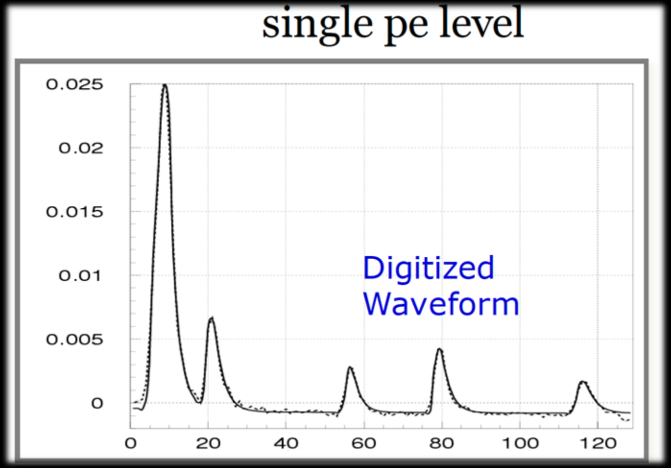

This Study (CC+NC)
I3 HESE ($\nu_l + \overline{\nu}_l$ CC)
I3 2017 ($\nu_\mu + \overline{\nu}_\mu$ CC)
CSMS (CC+NC)
FASER (ν_μ CC)
FASER ($\overline{\nu}_\mu$ CC)
FASER ($\nu_\mu + \overline{\nu}_\mu$ CC)
WCG (CC+NC)
σ_ν / cm^2
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^2
10^3
10^4
10^5
10^6
10^7
True Neutrino Energy / GeV



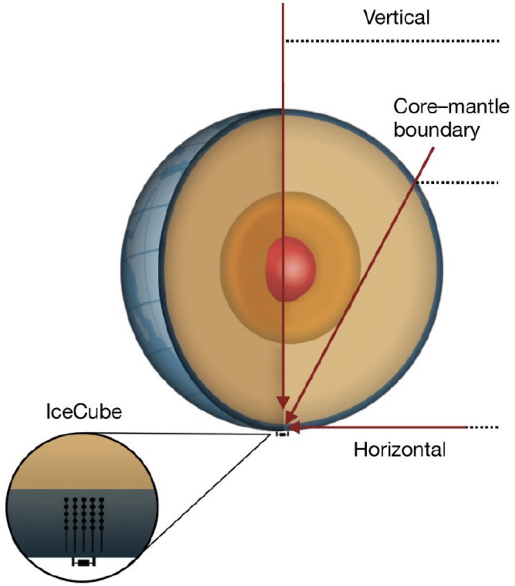
sorry Tao, it did not happen,
but we are not finished and
neither are you, I am sure :-)

overflow slides

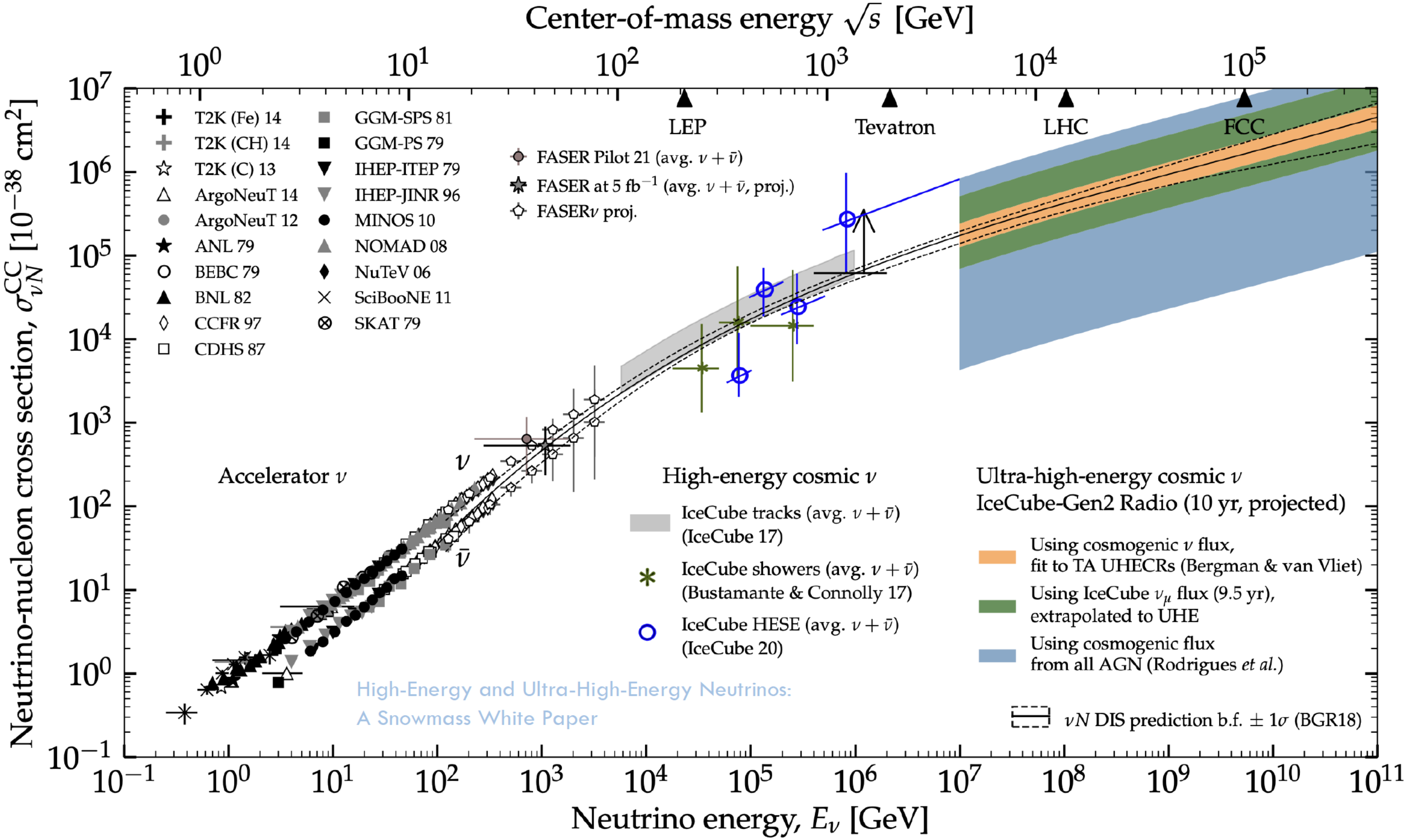
light signals from 10 inch photomultiplier embedded in the deep ice are digitized and sent to computers at surface


single pe level

CROSS SECTION WITH EARTH AS THE TARGET

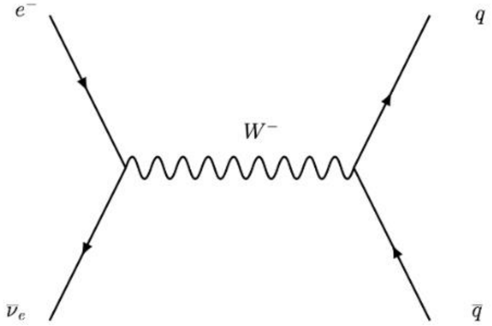


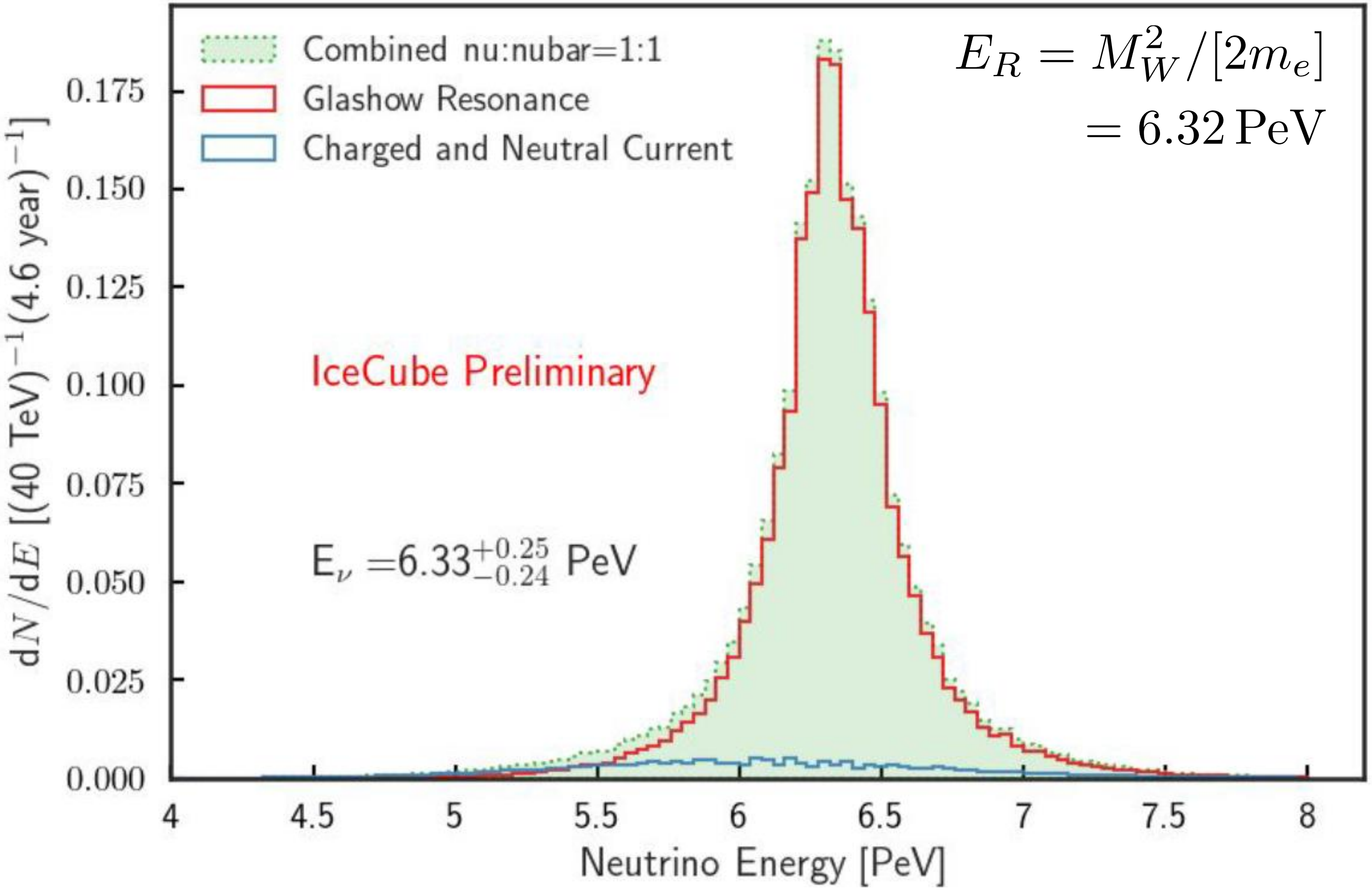
Extending x-section measurements to energies beyond Earth-based accelerators



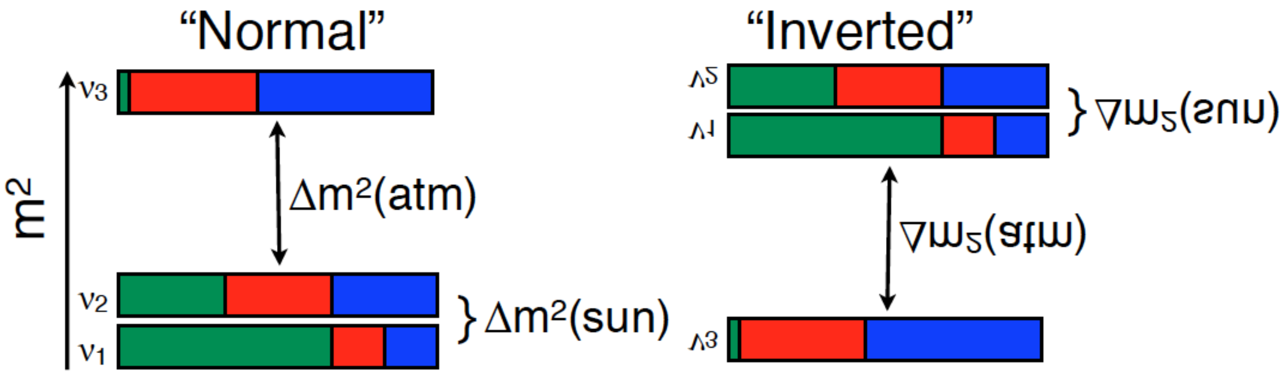
High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

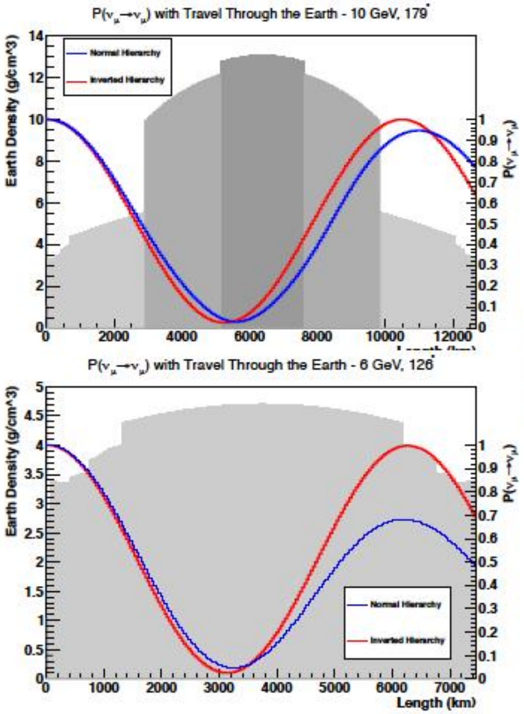
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

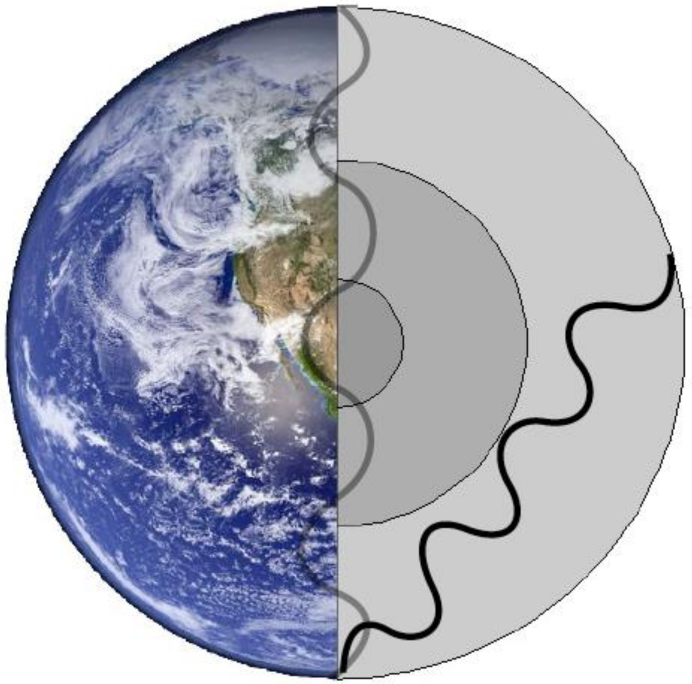




$$E_R = M_W^2/[2m_e] = 6.32\,\mathrm{PeV}$$







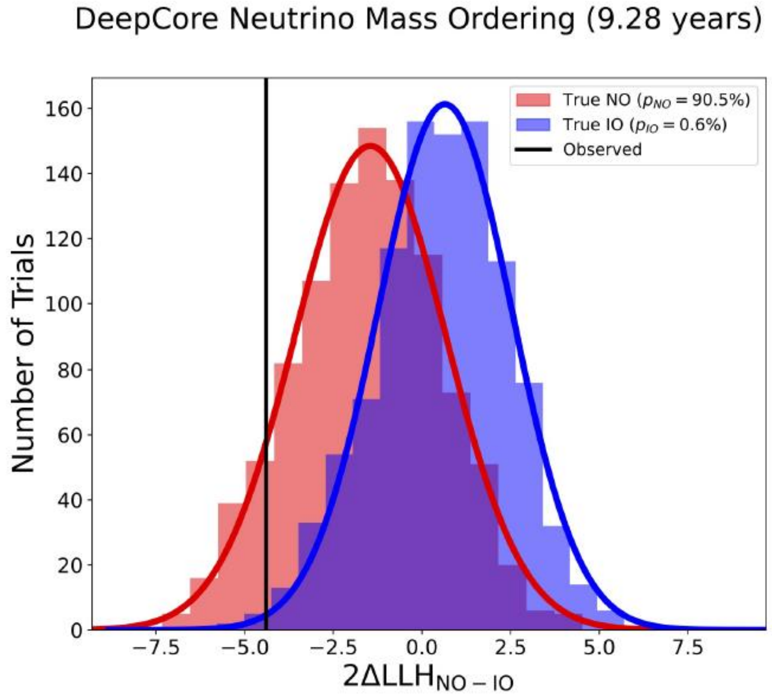


Figure 8.2: Results of the NMO analysis using 9.28 years of IceCube DeepCore data. The analysis observes a preference for the normal ordering over the inverted ordering at $2\Delta\mathrm{LLH}_{\text{NO-IO}} = -4.398$, leading to a disfavoring of the inverted ordering at a 93.7% exclusion level, or 1.86σ.

Maria Prado UW-Madison thesis

	3-Year DeepCore	9.28-Year DeepCore (this work)
Observed $2\Delta\mathrm{LLH}_{\text{NO-IO}}$	-0.738	-4.398
p_{IO}	15.7%	0.6%
p_{NO}	71.1%	90.5%
CL_s	53.3%	6.3%

Table 8.2: Comparison between the 3-year DeepCore NMO results [40] and this work. Clear improvement in the robustness of the results can be observed, where a much stronger preference for the normal ordering is now found.