Atmospheric neutrino physics with IceCube DeepCore.

Thanksgiving edition!

Summer Blot

Institute seminar at Technische Universität Dresden

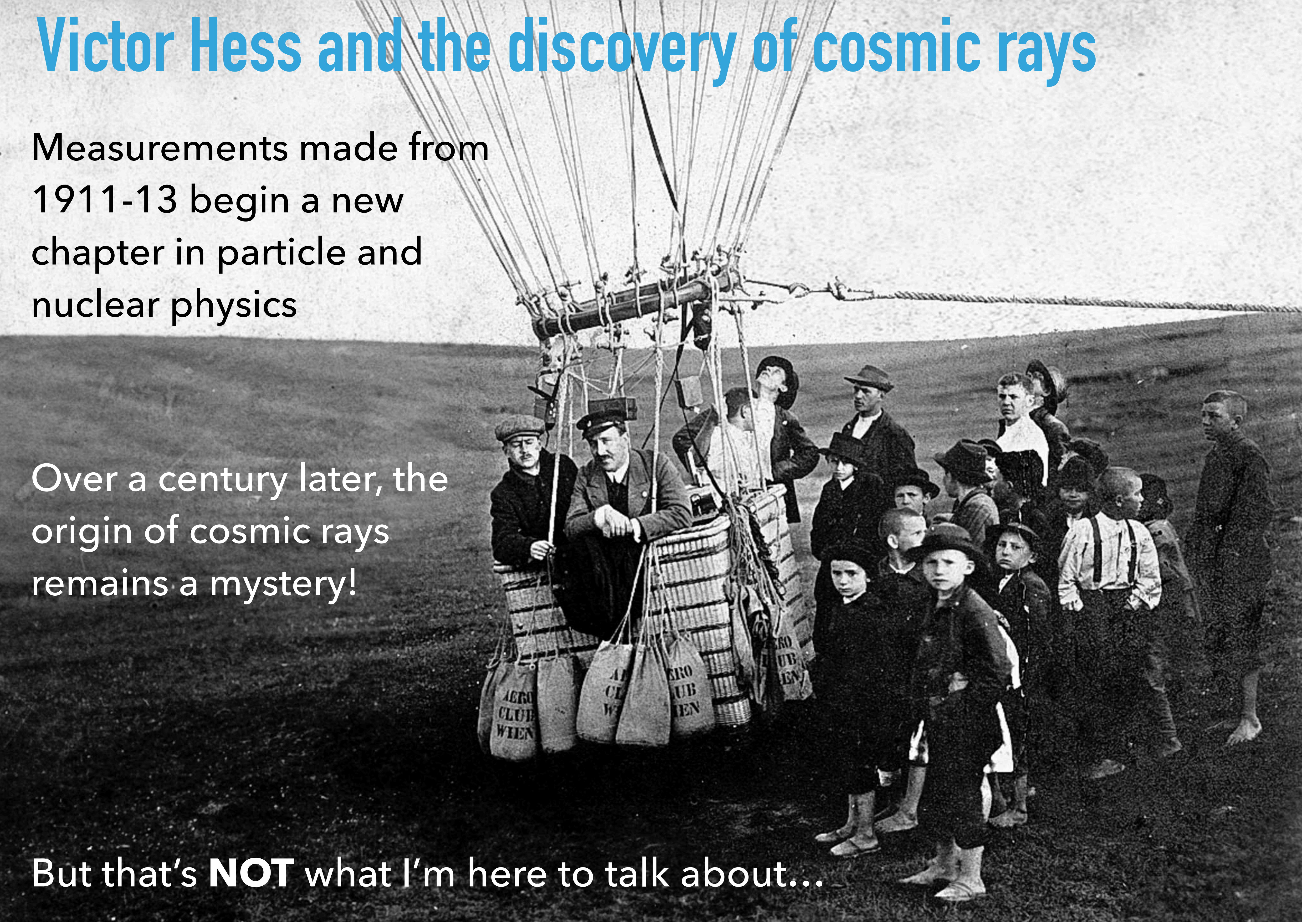
23.11.2017

HELMHOLTZ | ASSOCIATION

DESY

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Victor Hess and the discovery of cosmic rays

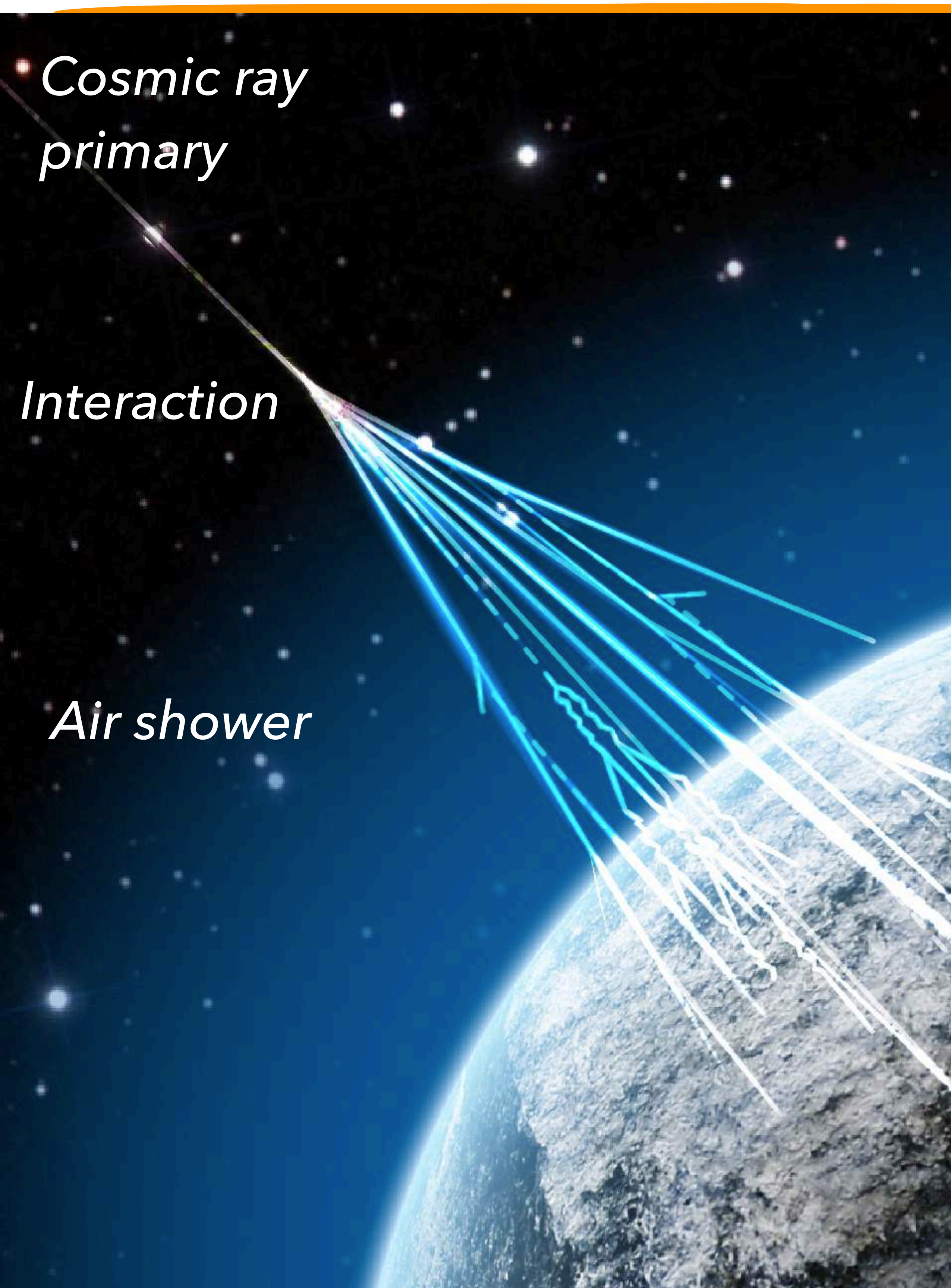


Measurements made from 1911-13 begin a new chapter in particle and nuclear physics

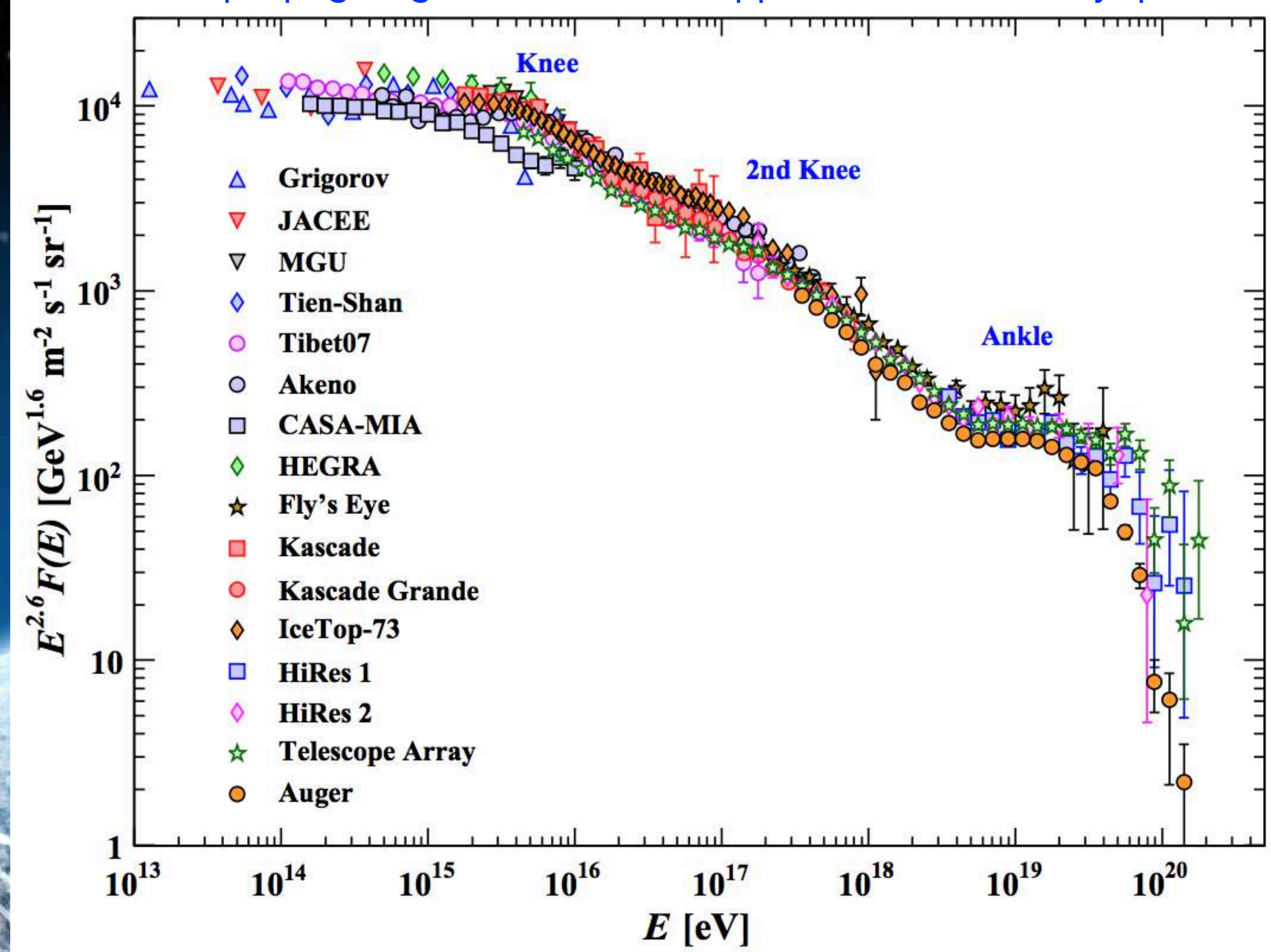
Over a century later, the origin of cosmic rays remains a mystery!

But that's **NOT** what I'm here to talk about…

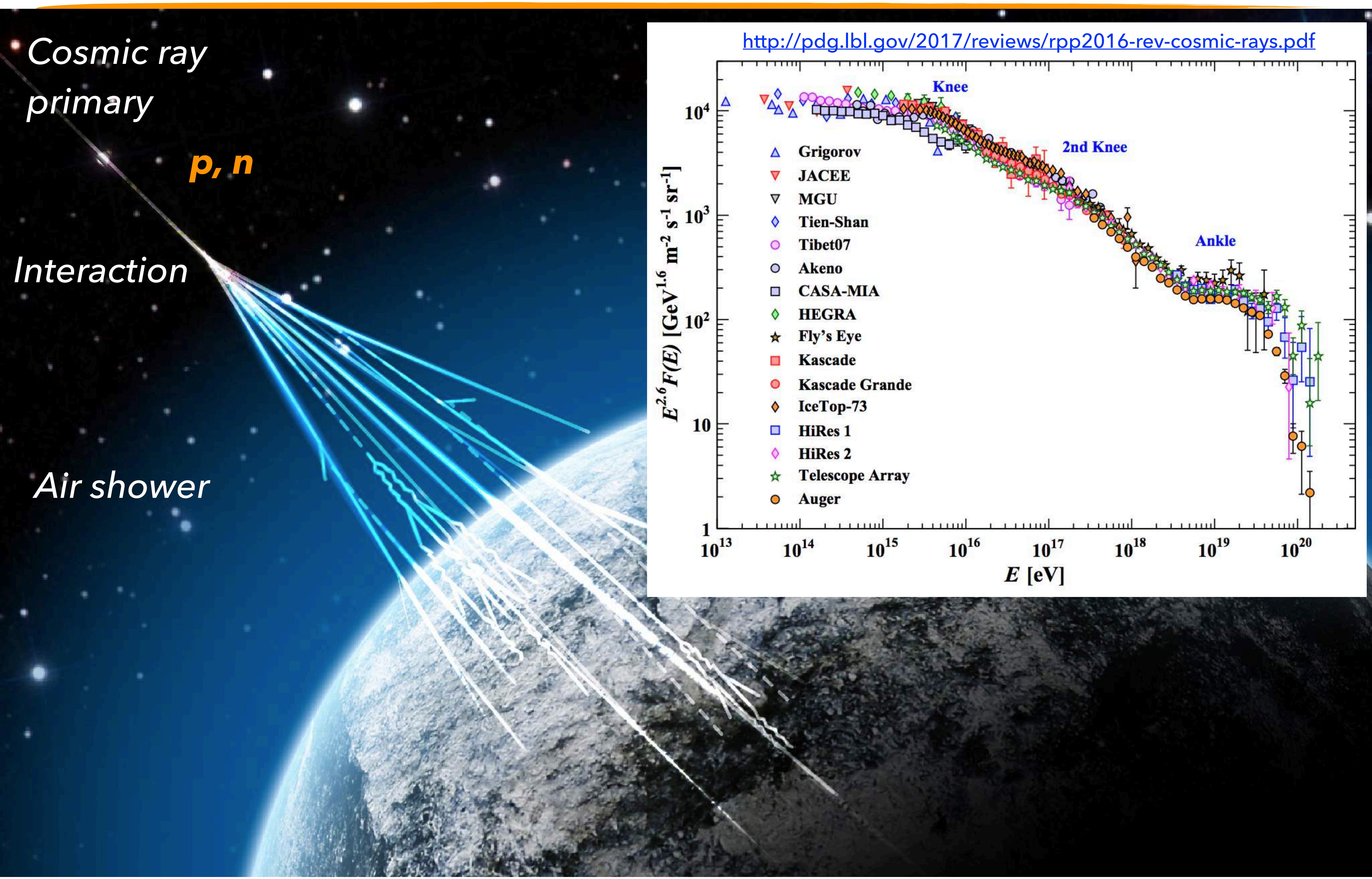
Cosmic ray interactions in the atmosphere



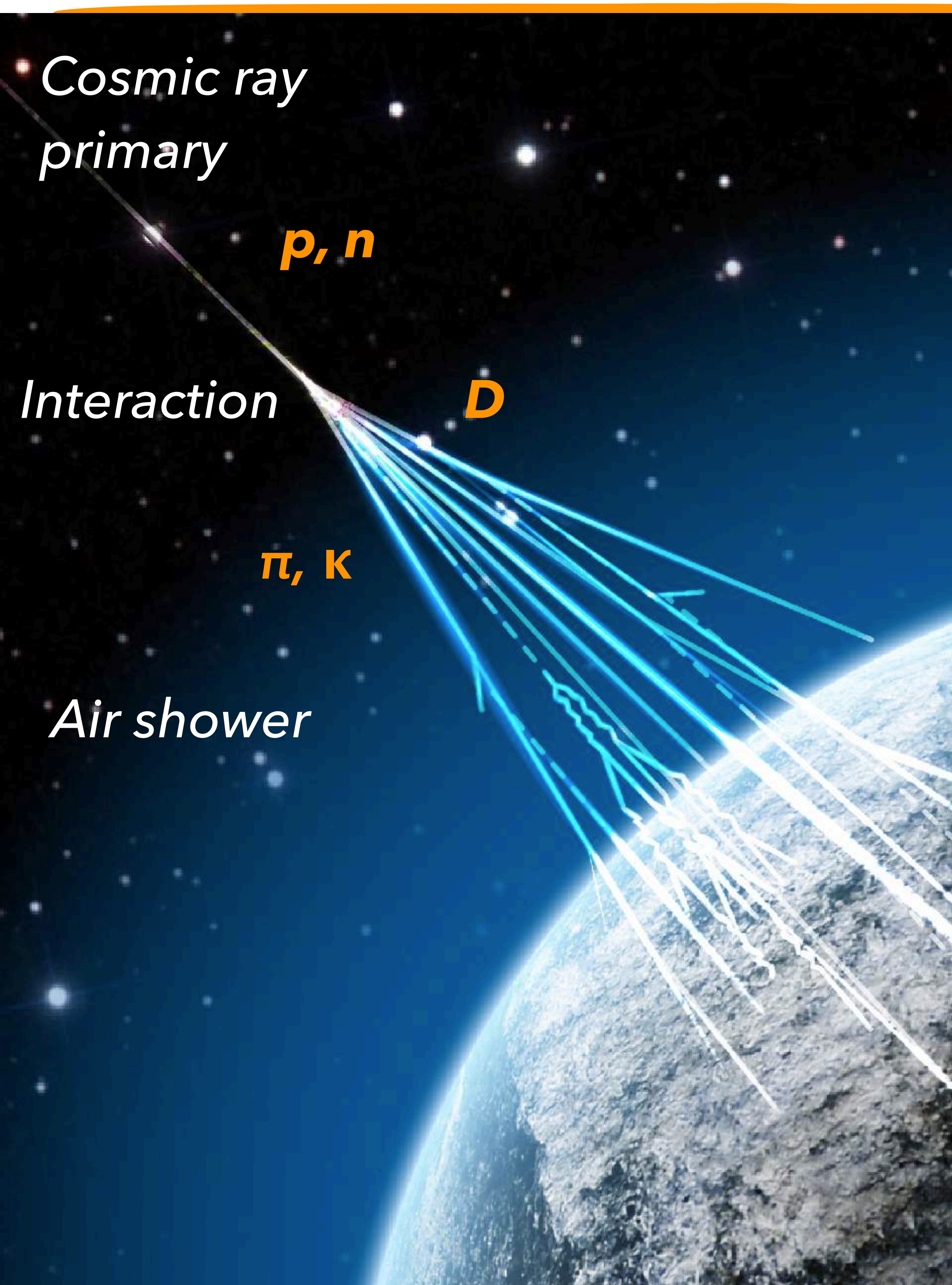
http://pdg.lbl.gov/2017/reviews/rpp2016-rev-cosmic-rays.pdf

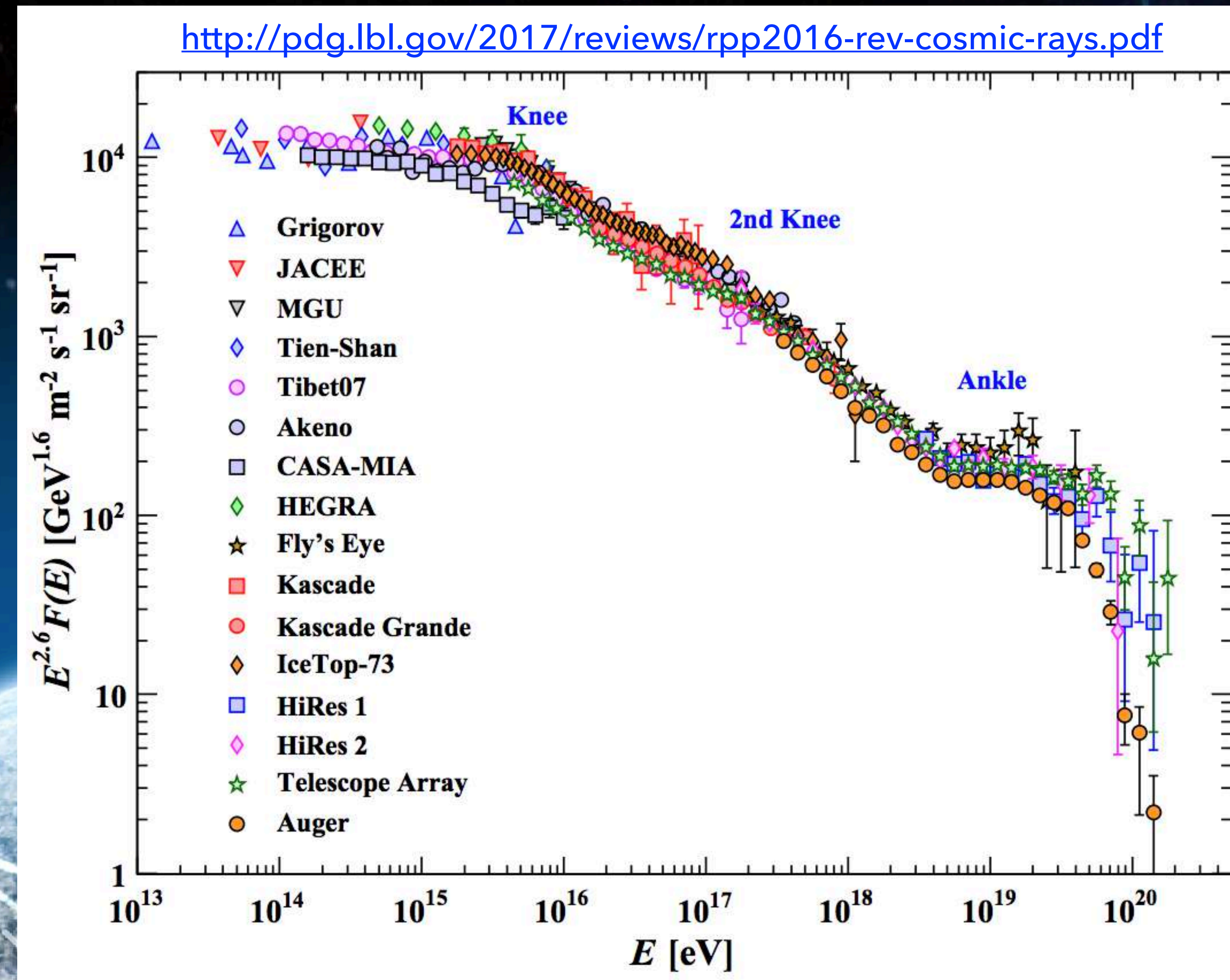


Cosmic ray interactions in the atmosphere

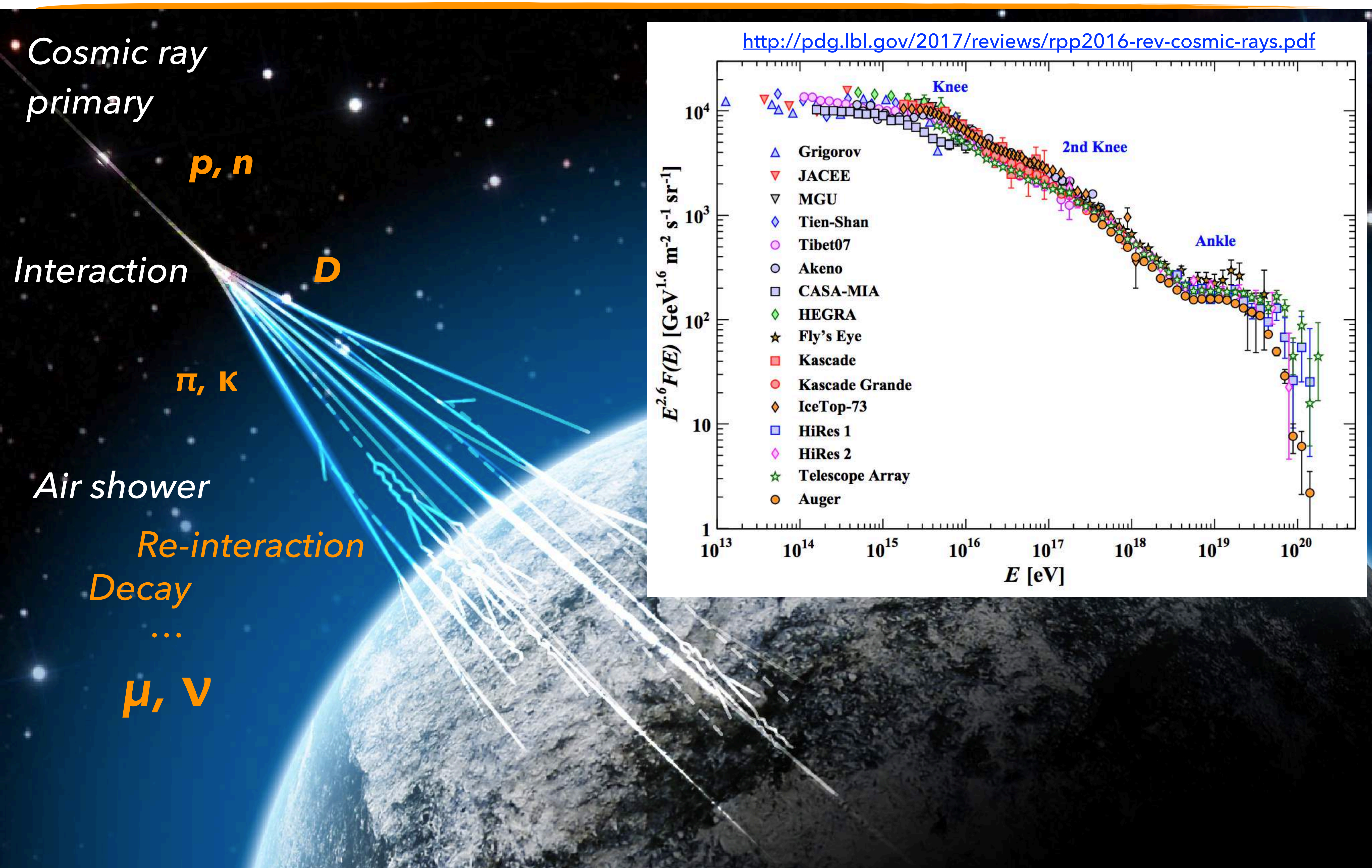


Cosmic ray interactions in the atmosphere

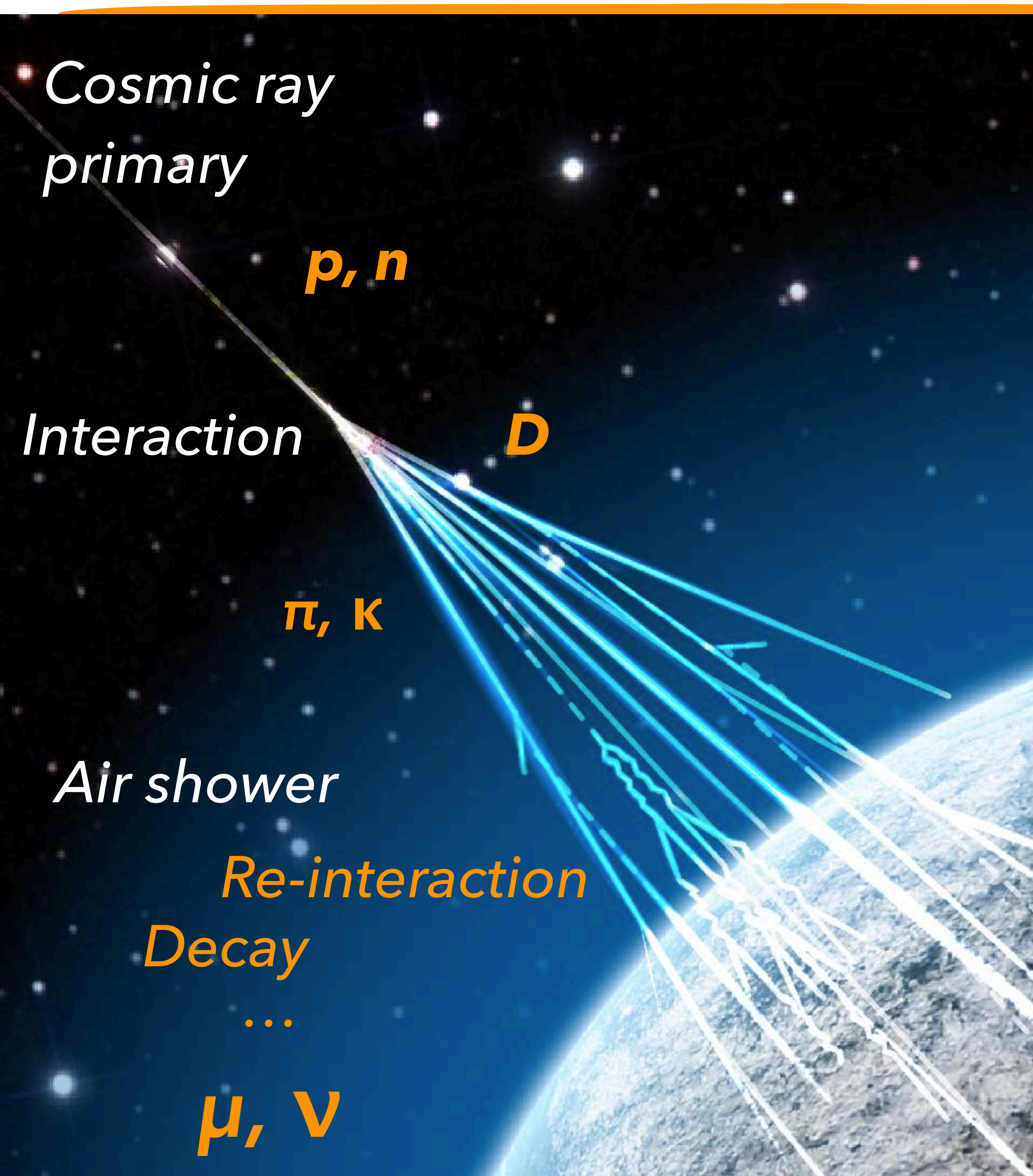


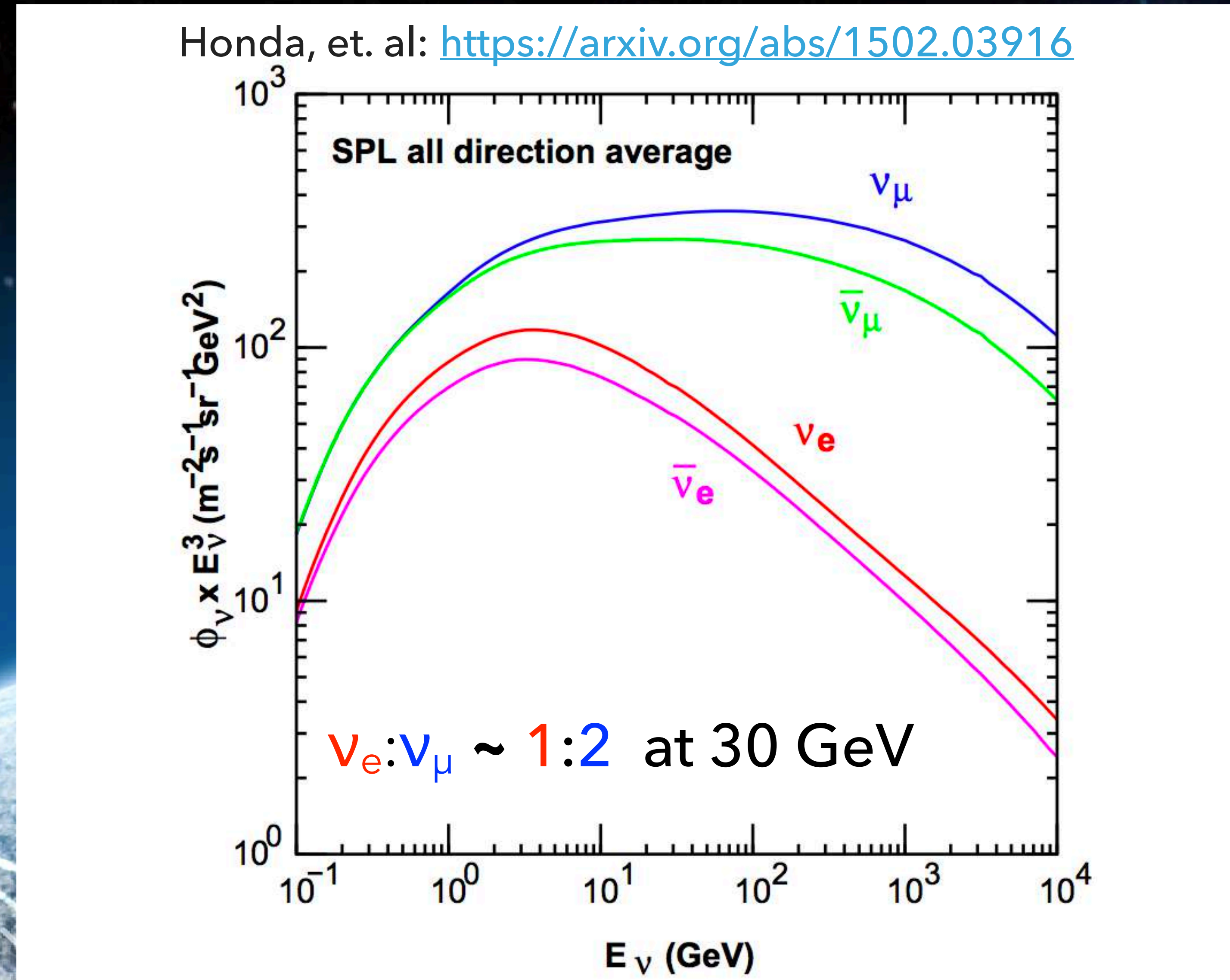


Cosmic ray interactions in the atmosphere



Cosmic ray interactions in the atmosphere



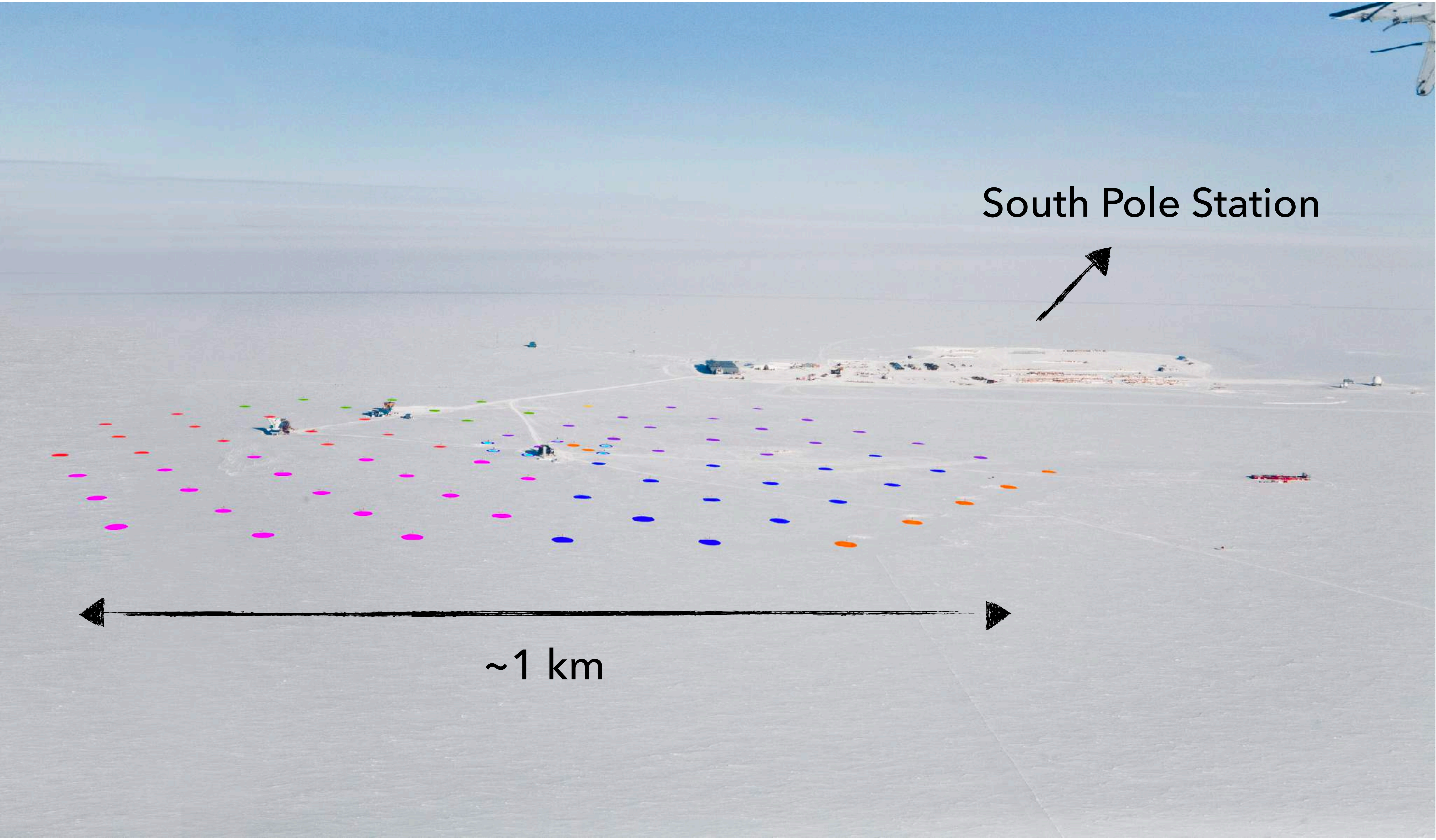


High statistics sample of neutrinos over large energy range for FREE!

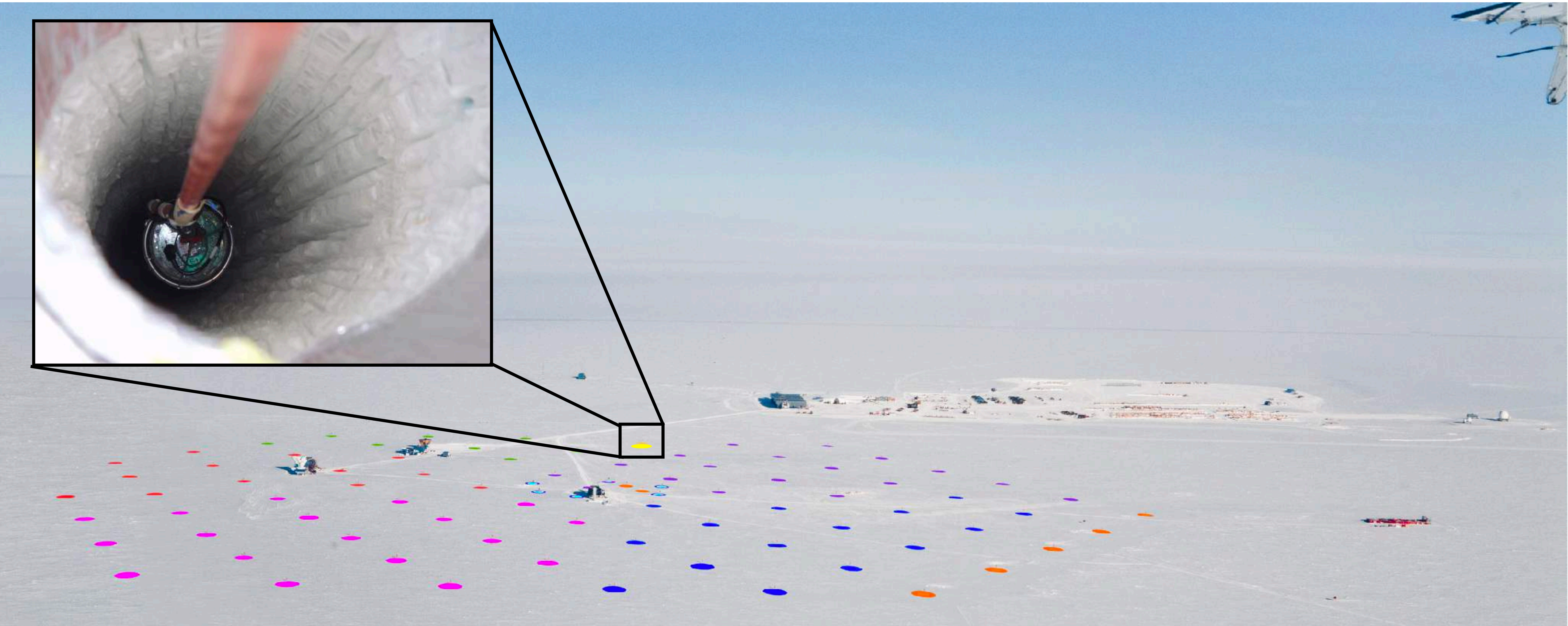
The IceCube Neutrino Observatory

The IceCube Neutrino Observatory

The IceCube Neutrino Observatory



The IceCube Neutrino Observatory

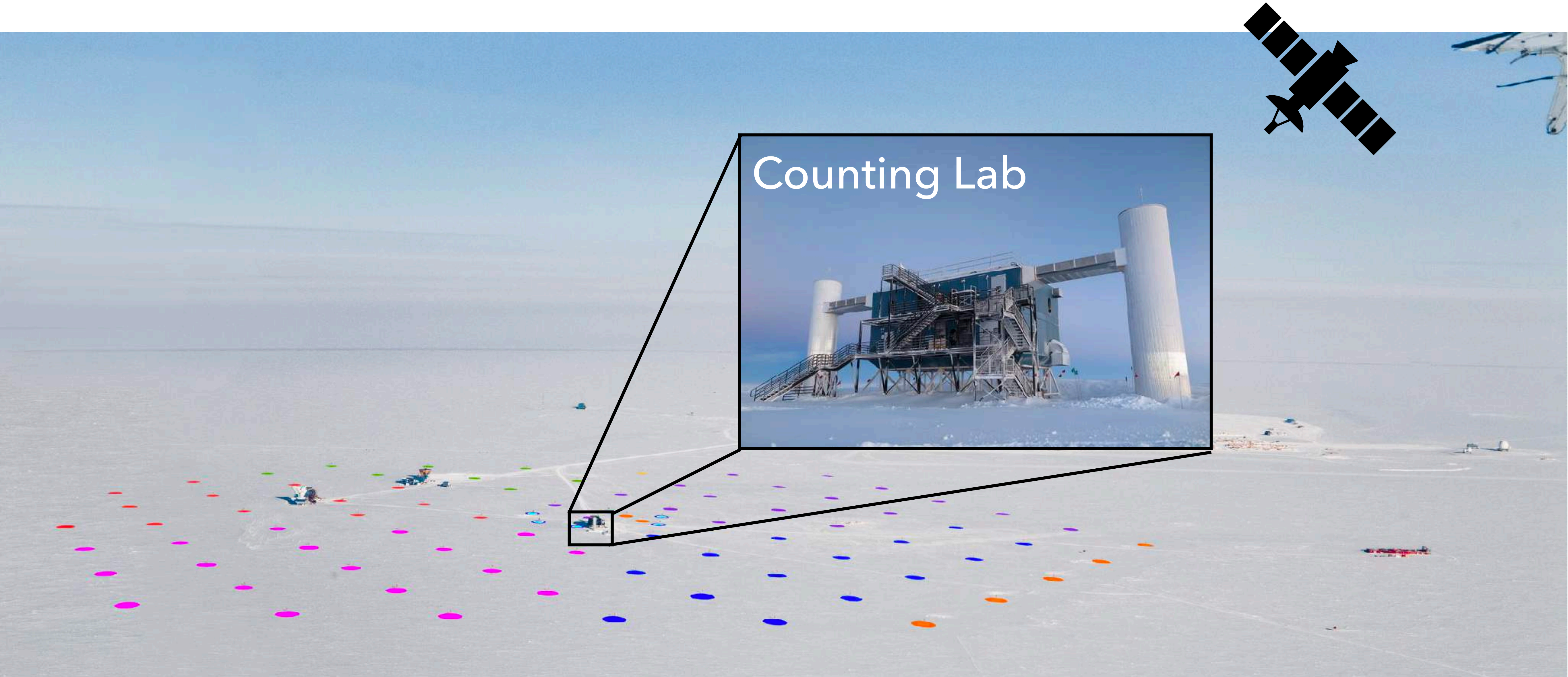


- 1.45 km overburden of ice
- 86 strings, each with 60 Digital Optical Modules (DOMs)

The IceCube Neutrino Observatory

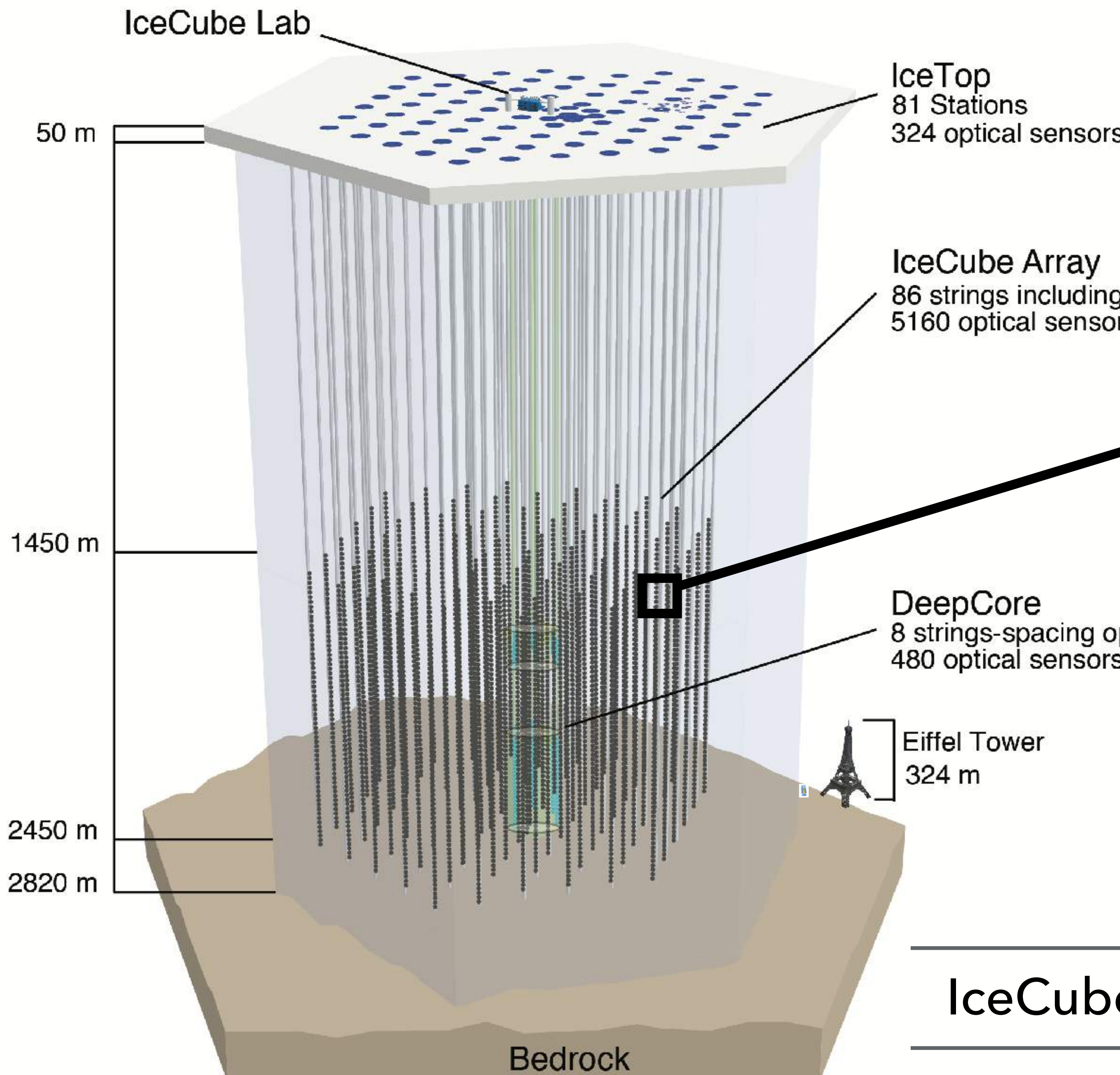
- 1.45 km overburden of ice
- 86 strings, each with 60 Digital Optical Modules (DOMs)
- IceTop array at surface
- 162 tanks with 2 DOMs each
- Cosmic ray shower physics

The IceCube Neutrino Observatory

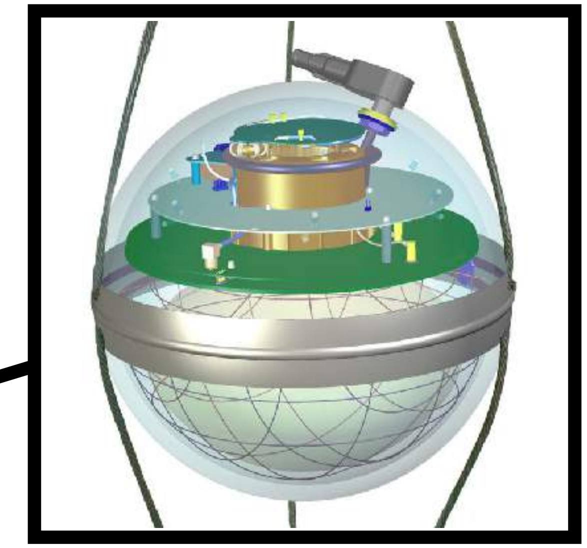


- 1.45 km overburden of ice
- 86 strings, each with 60 Digital Optical Modules (DOMs)
- IceTop array at surface
- 162 tanks with 2 DOMs each
- Cosmic ray shower physics

The IceCube Neutrino Observatory



Digital Optical Module (DOM)

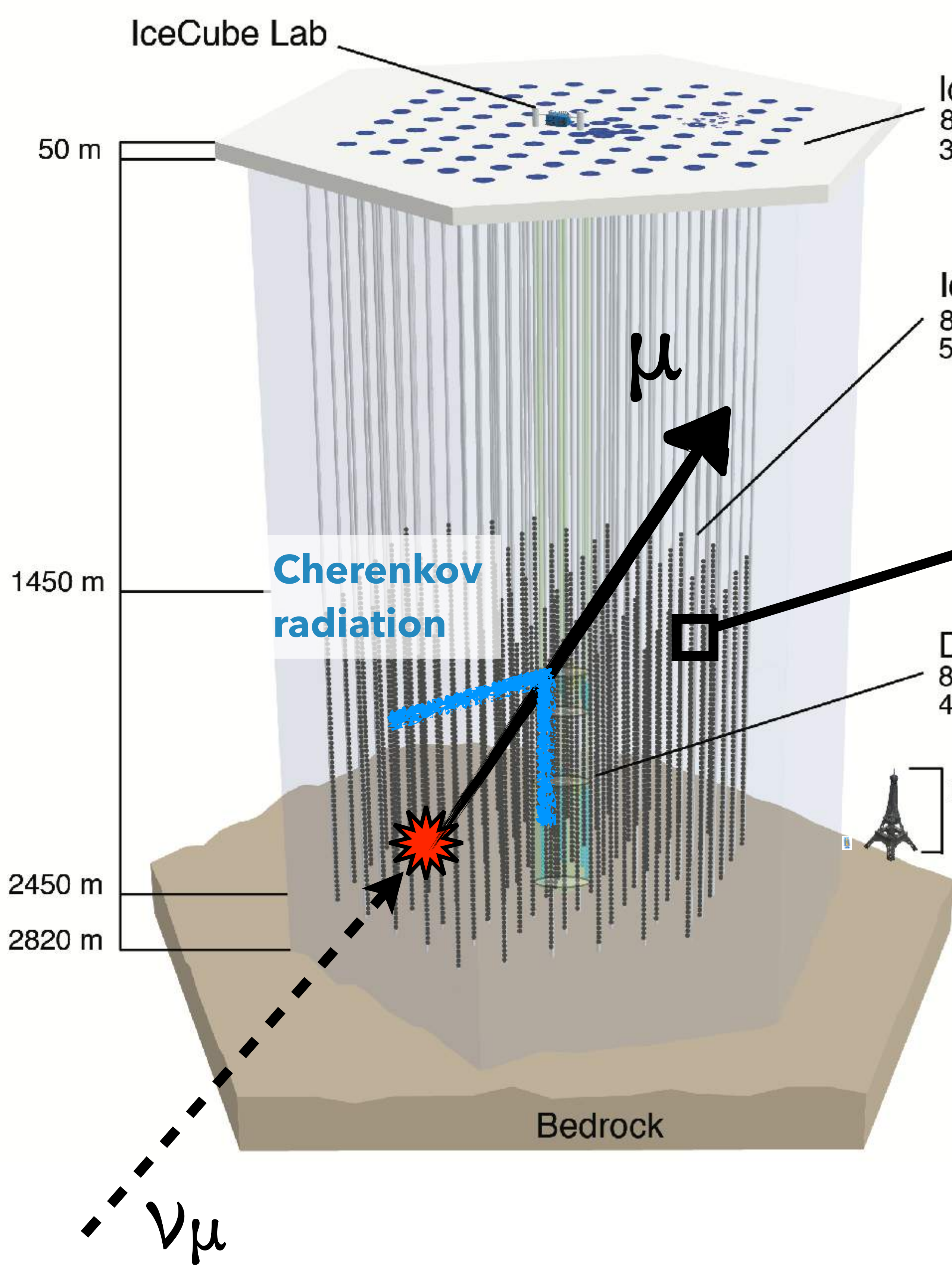


10″ PMT - facing "down"

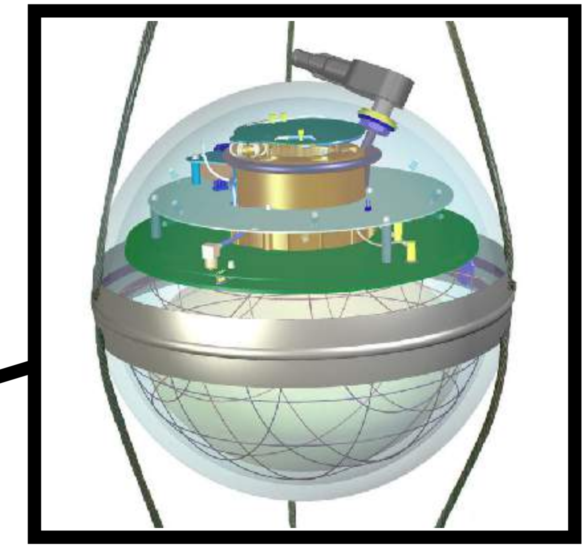
DeepCore DOMs
~35% higher QE

	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	~100
DeepCore	50	7	~5

The IceCube Neutrino Observatory



Digital Optical Module (DOM)



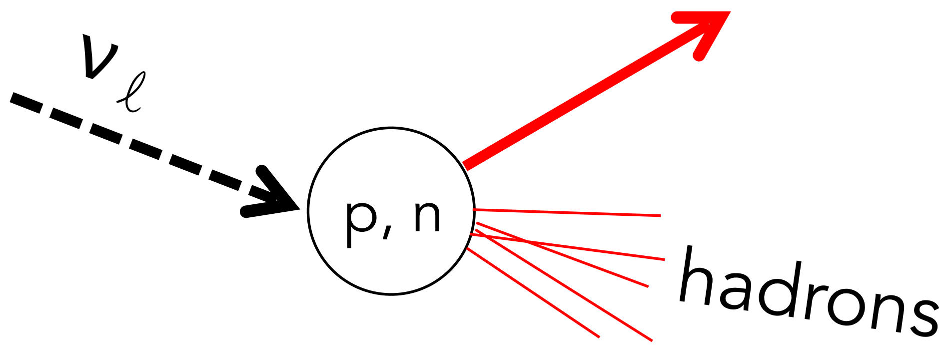
10″ PMT - facing "down"

DeepCore DOMs ~35% higher QE

	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	~100
DeepCore	50	7	~5

Neutrino detection in IceCube

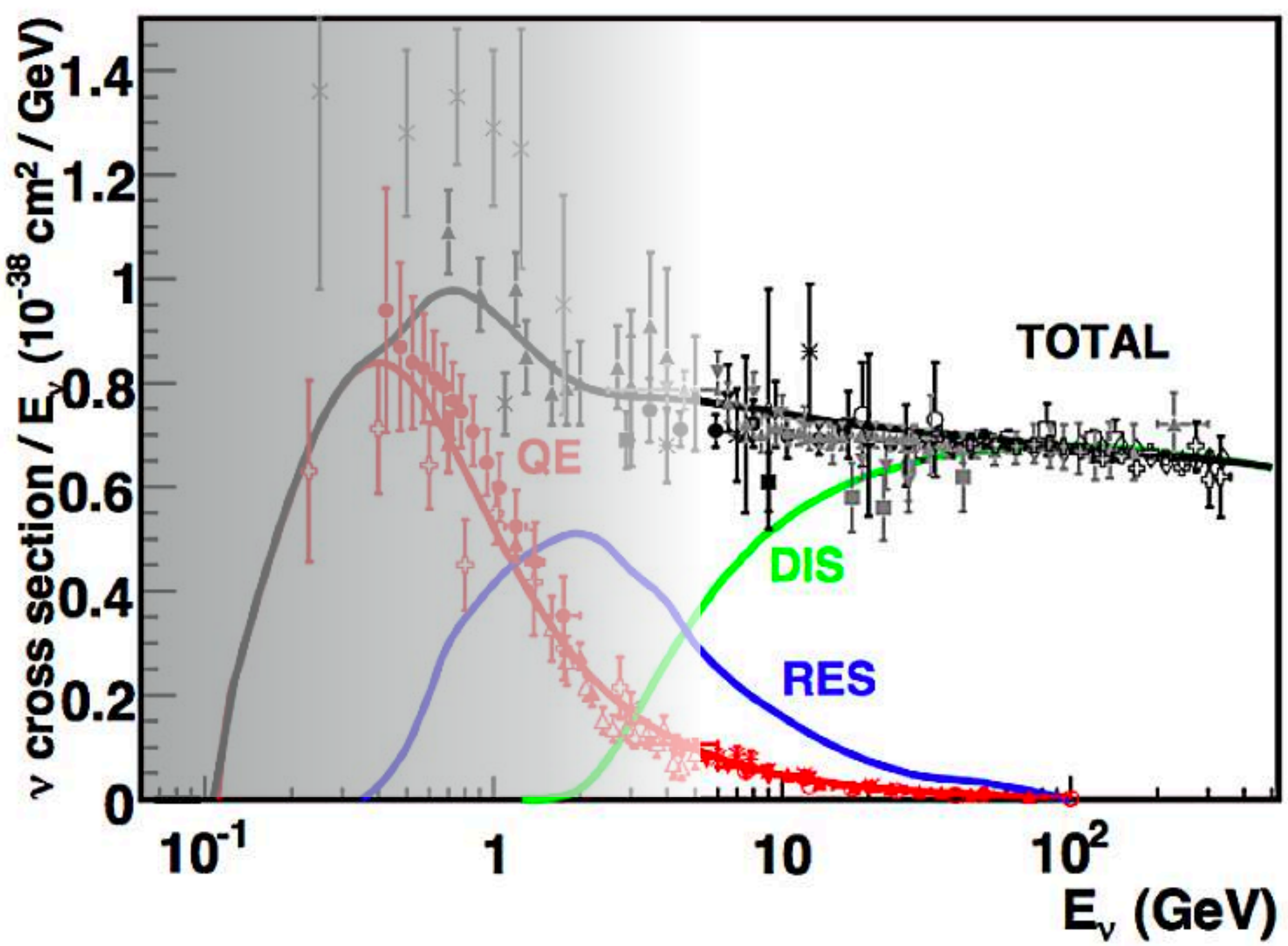
Interaction



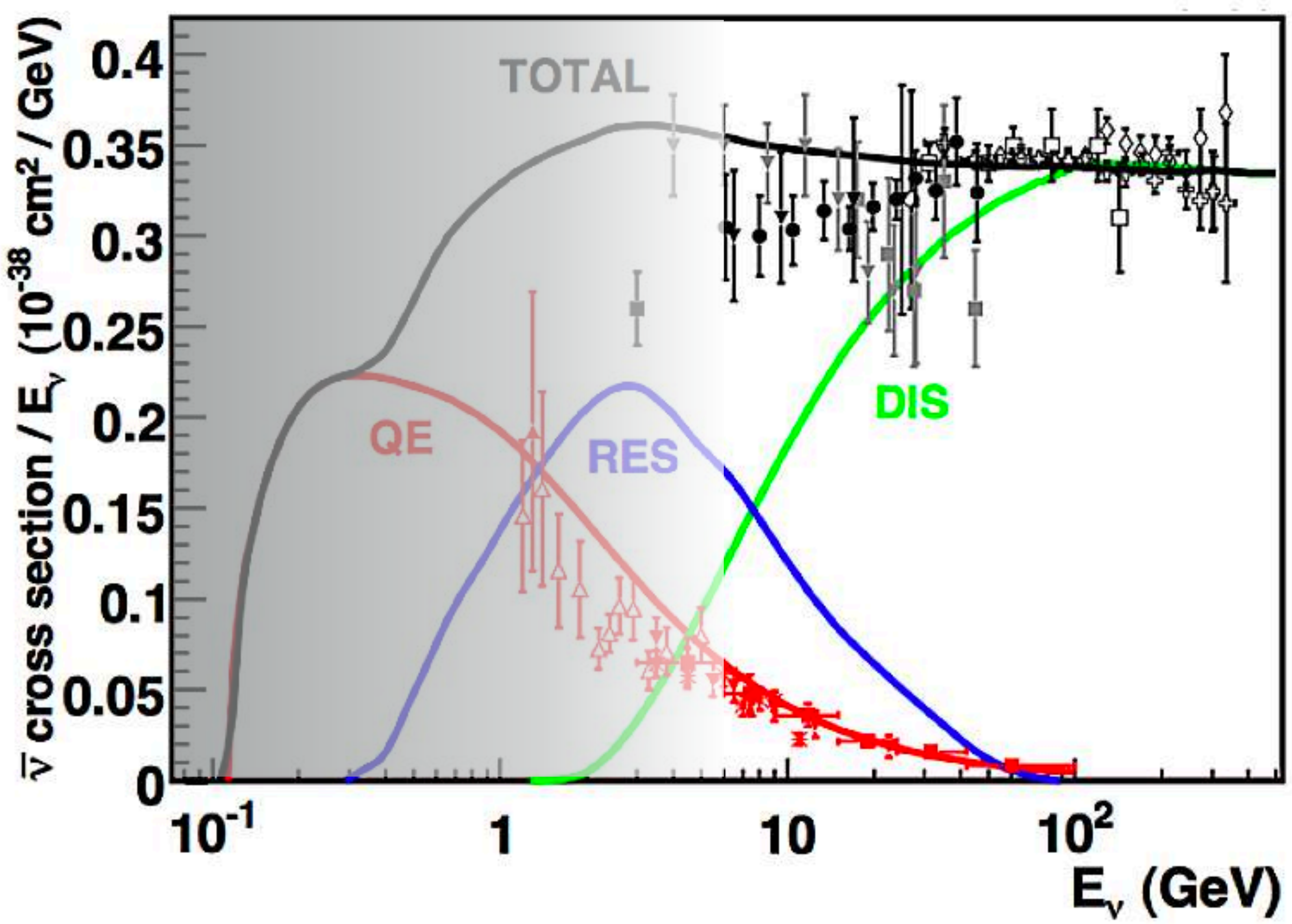
ℓ (**e, μ, τ**) – charged current (**CC**)

ν_ℓ – neutral current (**NC**)

Neutrinos



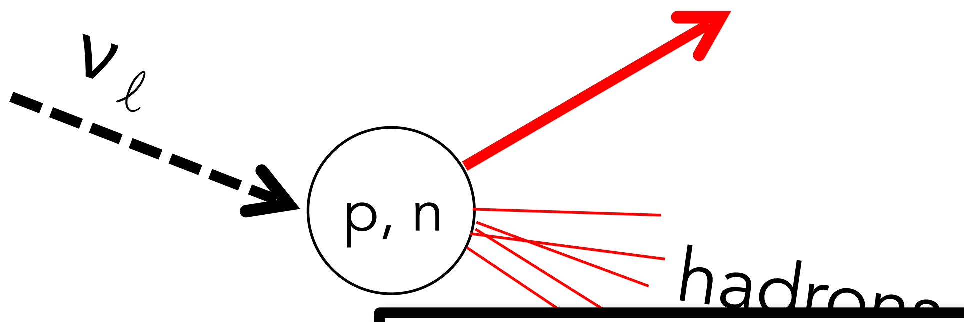
Anti-neutrinos



https://arxiv.org/pdf/1205.2671.pdf

Neutrino detection in IceCube

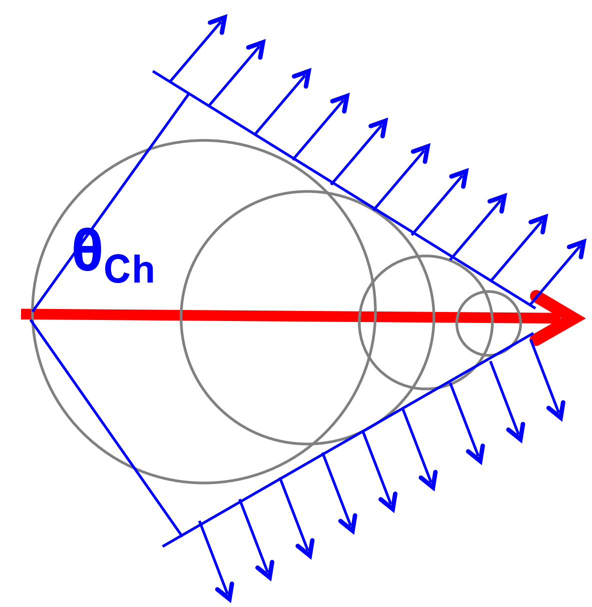
Interaction



ℓ **(e, μ, τ)** – charged current (**CC**)

ν_ℓ – neutral current (**NC**)

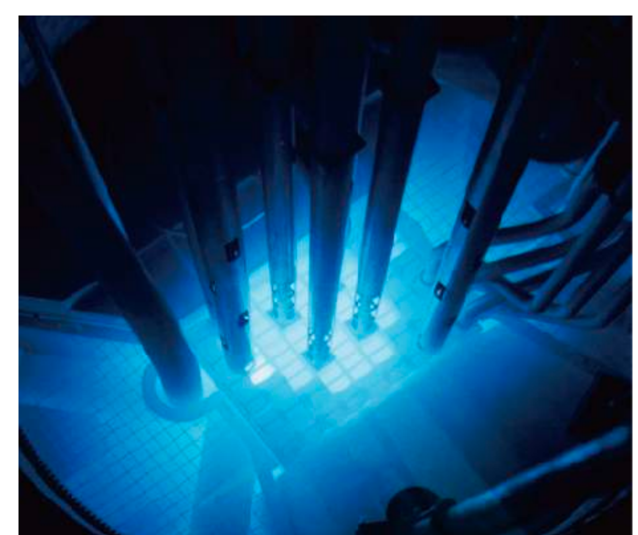
Cherenkov radiation



Relativistic charged particle

Frank-Tamm formula

$$\frac{d^2 N_\gamma}{dl d\lambda} = 2\pi\alpha z^2 \frac{1}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

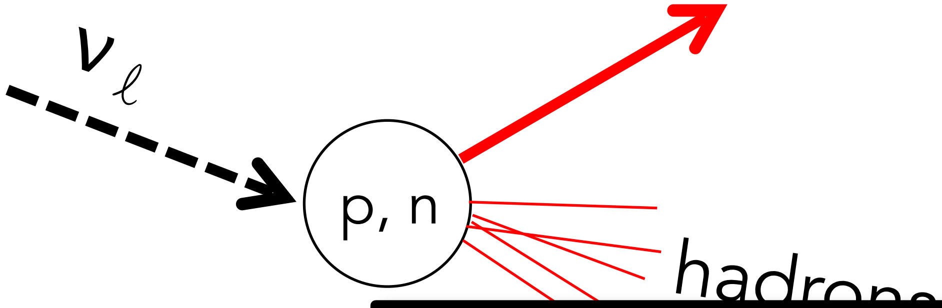


Neutrino detection in IceCube

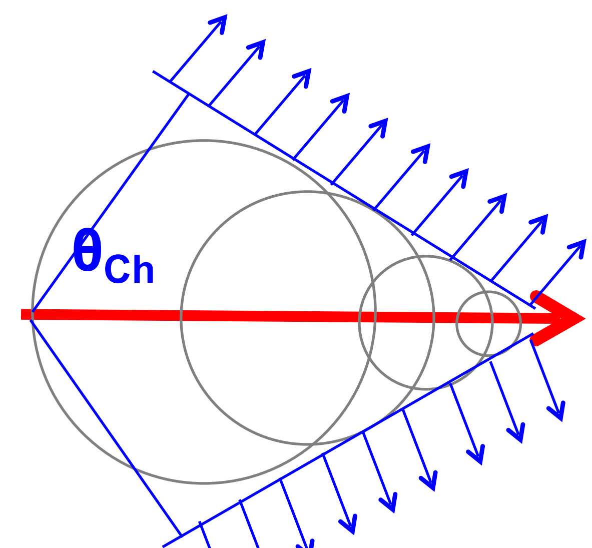
Interaction

ℓ **(e, μ, τ)** – charged current (**CC**)

ν_ℓ – neutral current (**NC**)



Cherenkov radiation



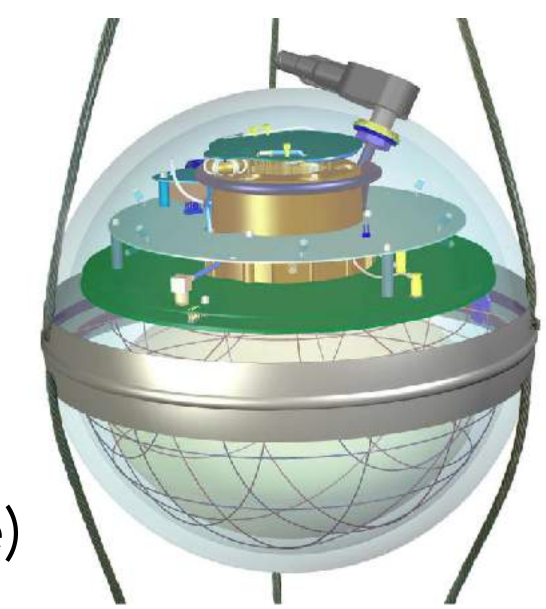
Relativistic charged particle

Detection

Photons arrive at DOM, we measure:

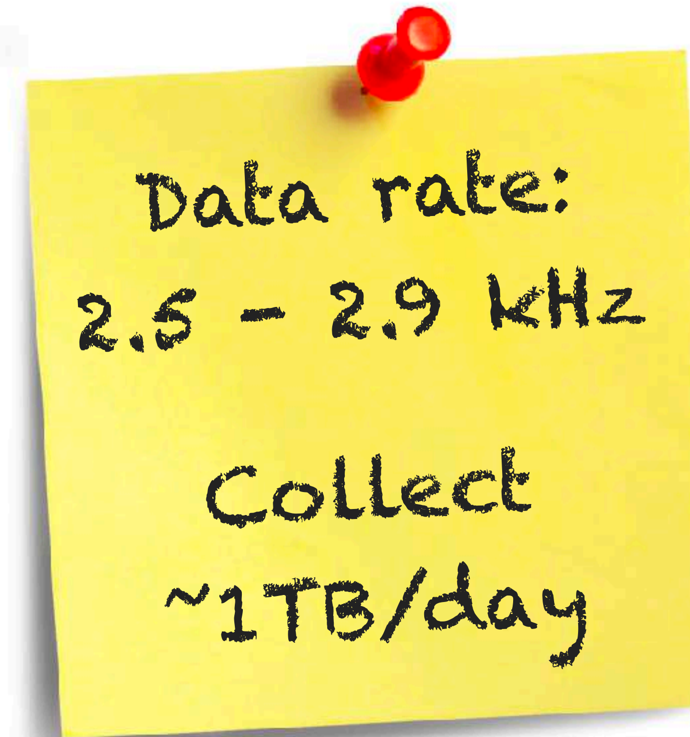
Charge
(n.p.e.)

Time
$\sigma_t \sim 3$ns
(< 1 m in ice)

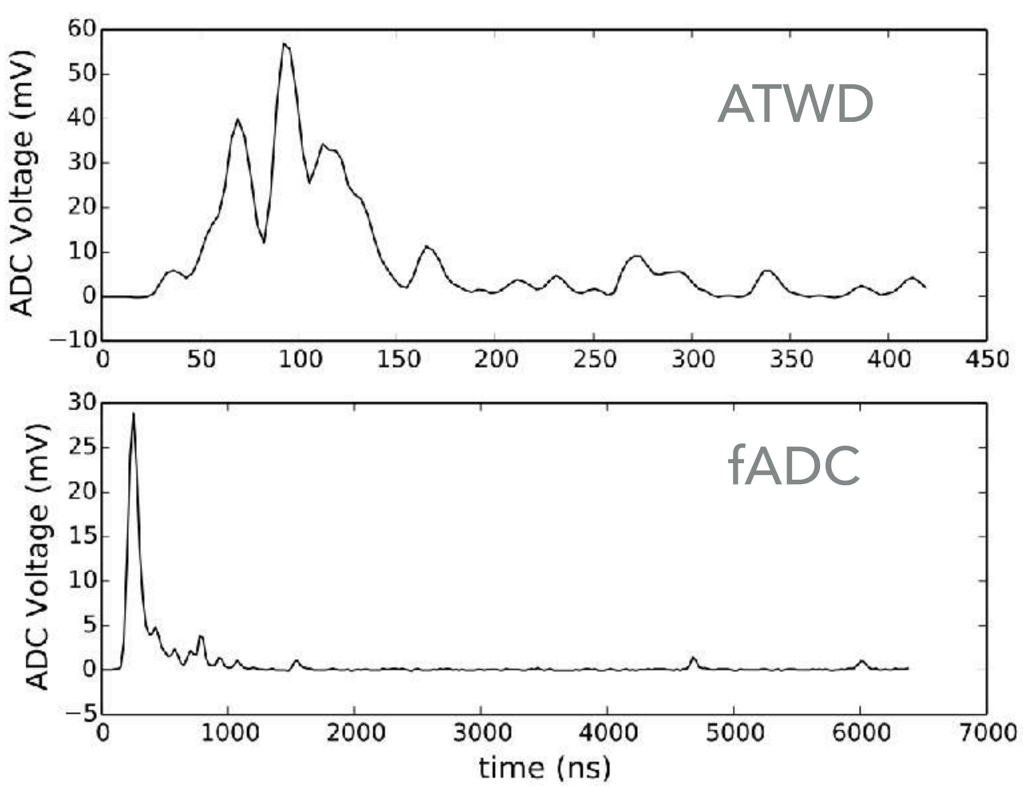


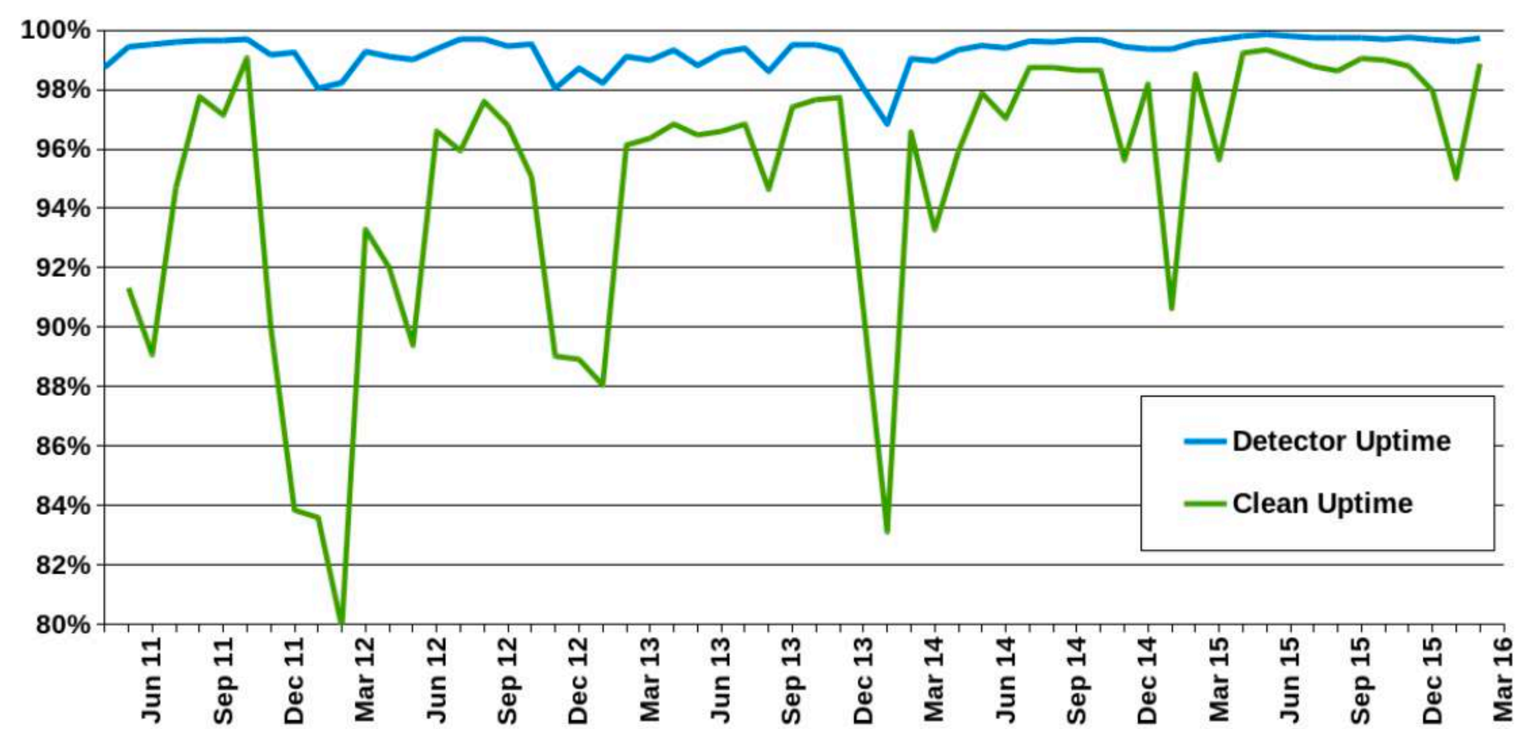
IceCube operations

- Collecting data since 2005
  - Since 2011 (**6.5 y**) taking data with full 86-string configuration
- ~99.8% detector up-time
- 98.4% of DOMs operational

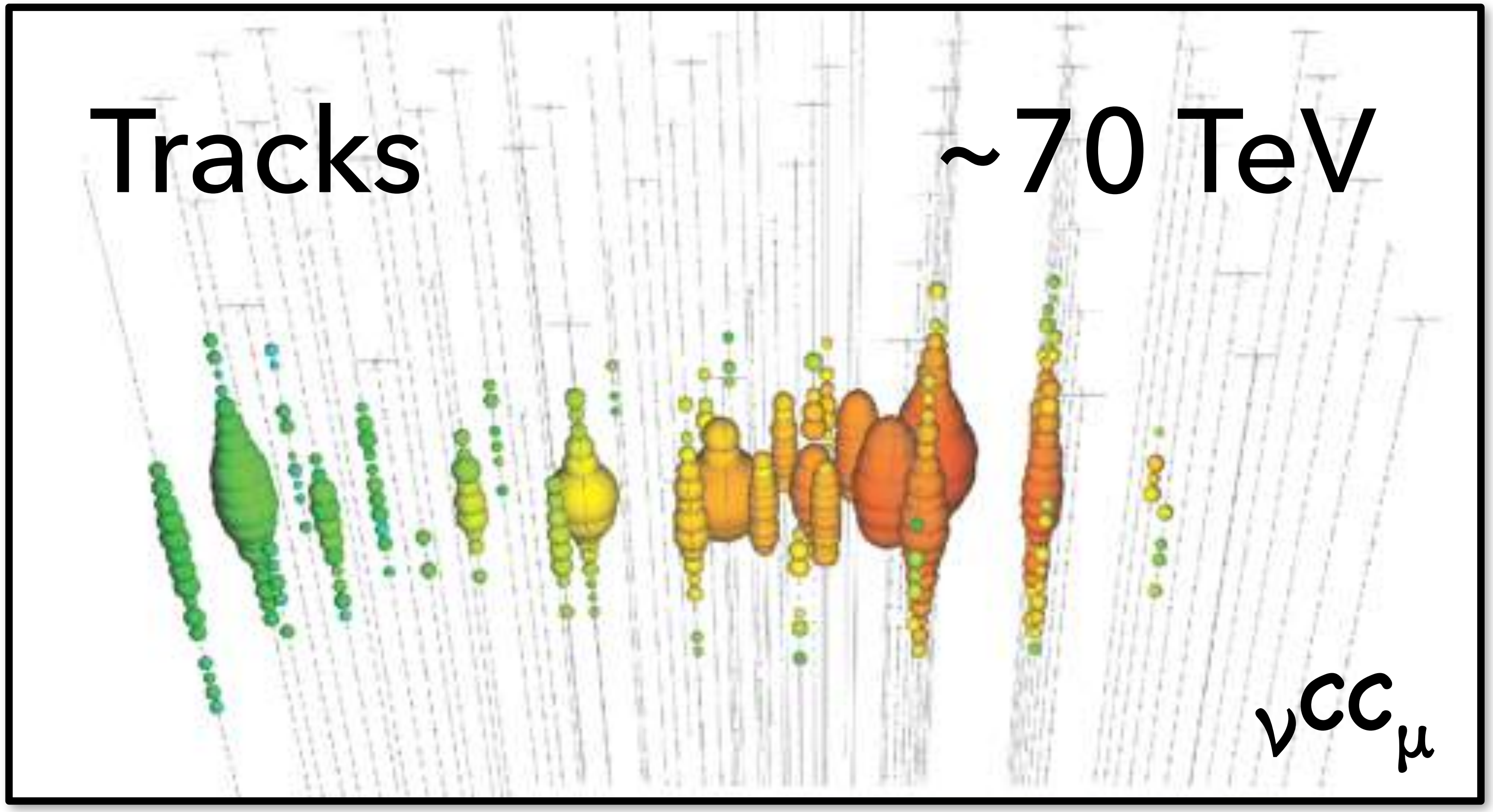


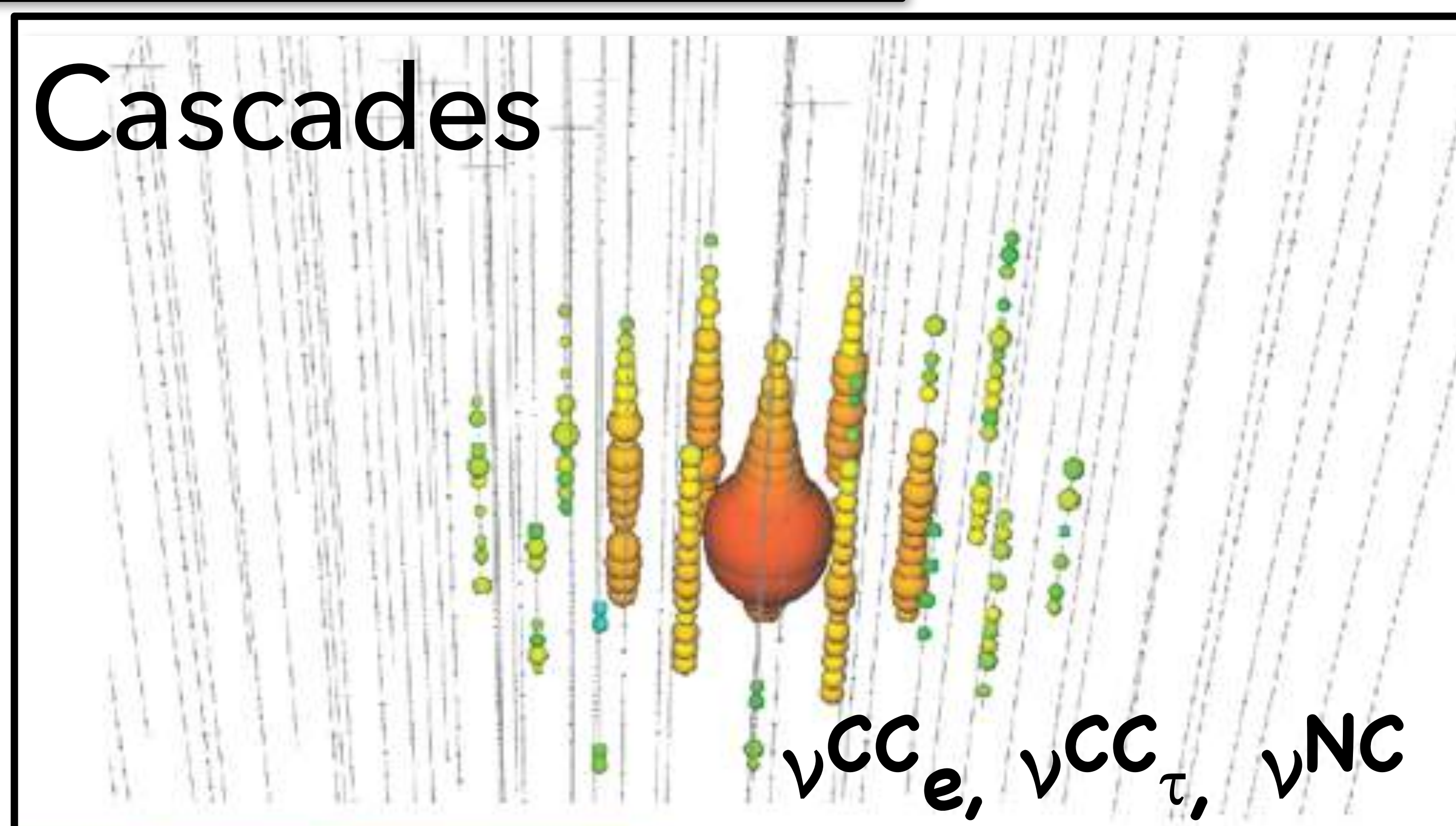
IceCube detector paper: https://arxiv.org/abs/1612.05093

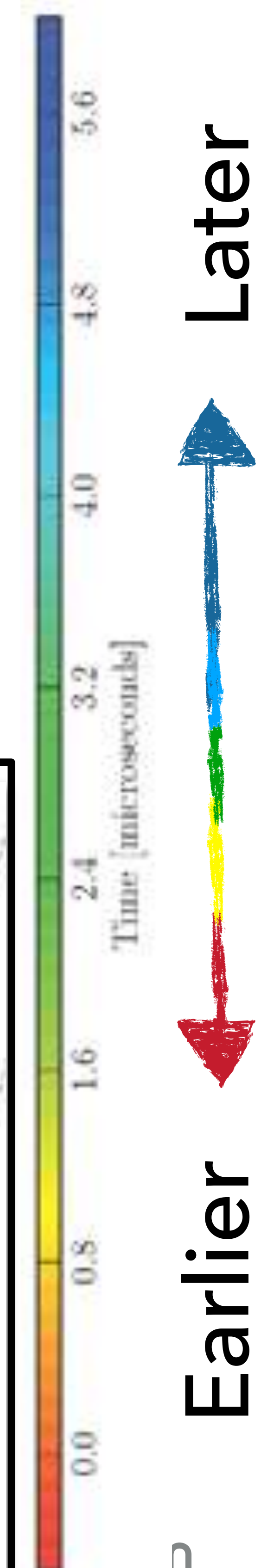




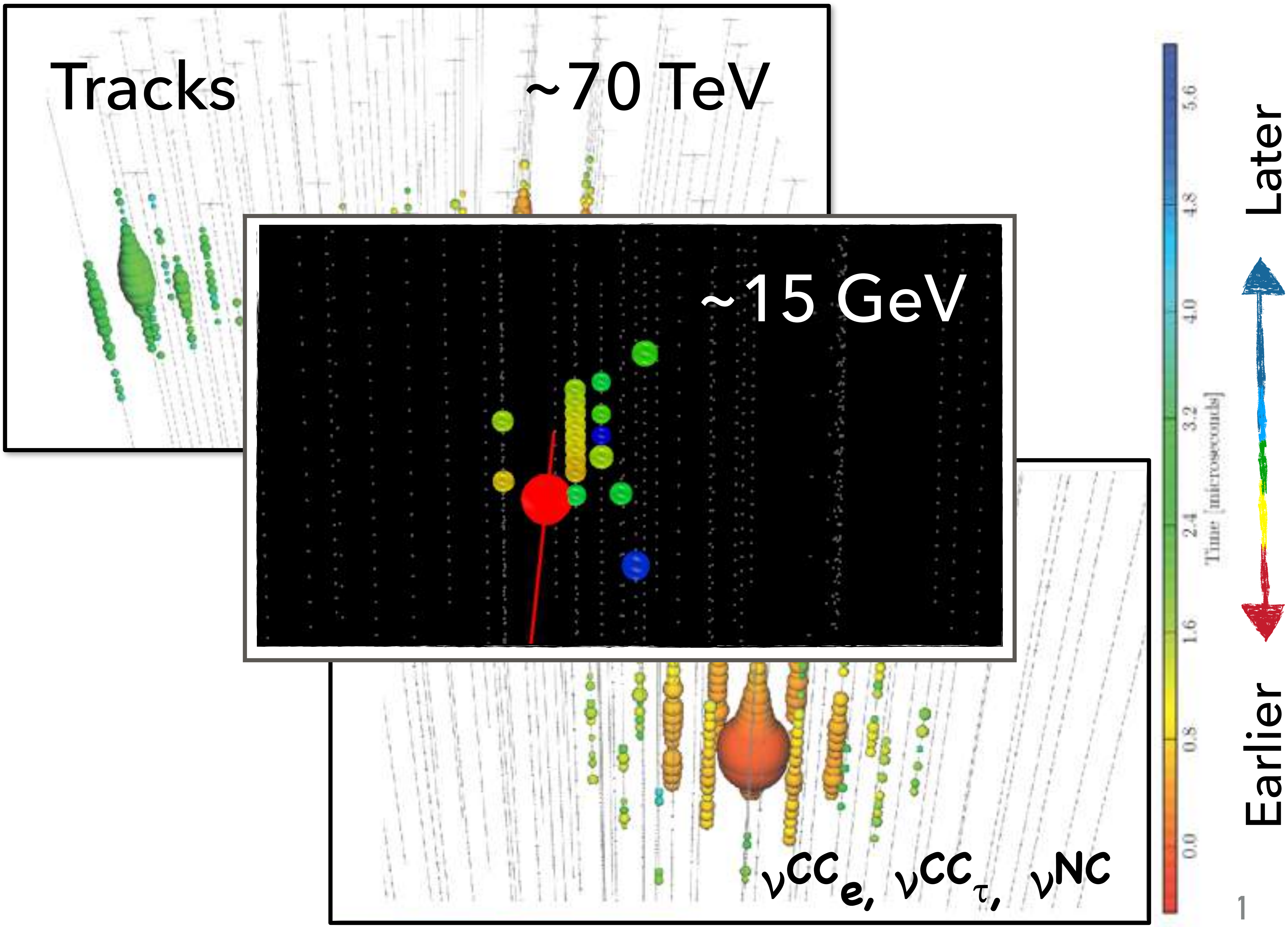
Event topology







Event topology



Ice Properties

- To interpret the light pattern in IceCube, we need to calibrate a cubic kilometre of **natural ice**
- Optical properties such as absorption and scattering lengths are critical
  - Both **globally and locally**
- Large effort spent on reducing the error on ice property measurements in order to improve the physics
  - **Full suite of calibration devices**: LED flashers on each DOM, atmospheric muons, Ni lasers and cameras
  - **Ice model error currently ~10%**

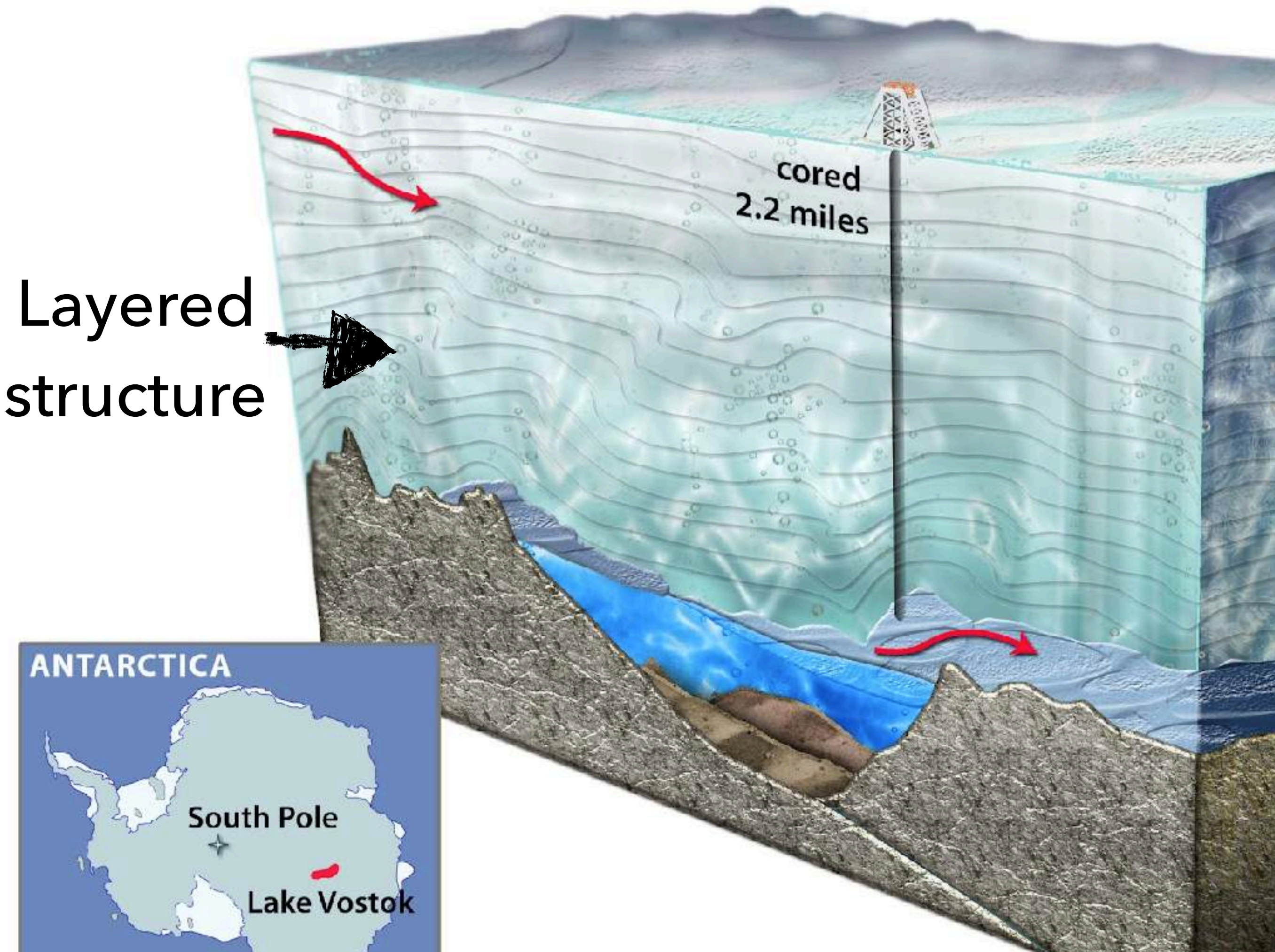
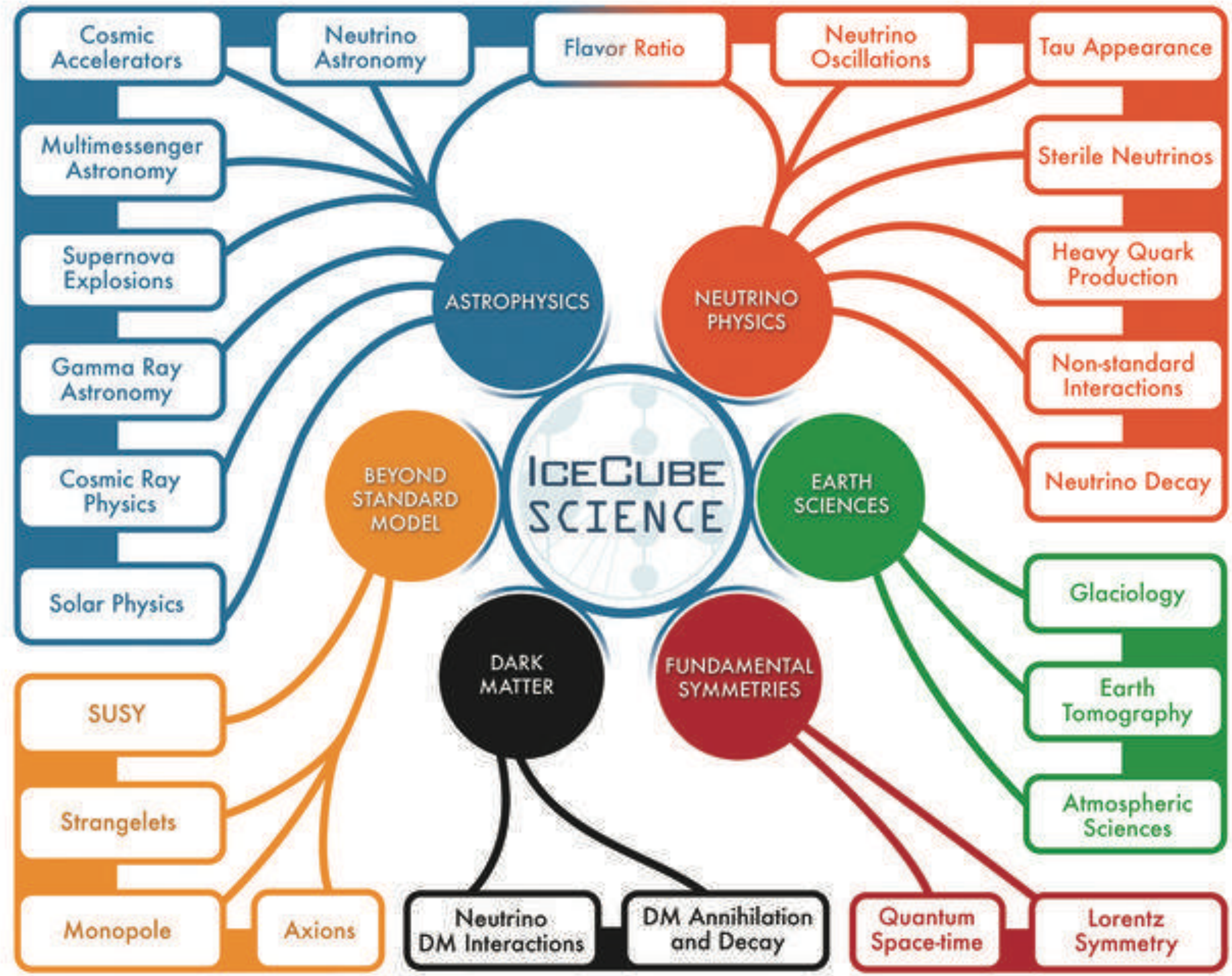
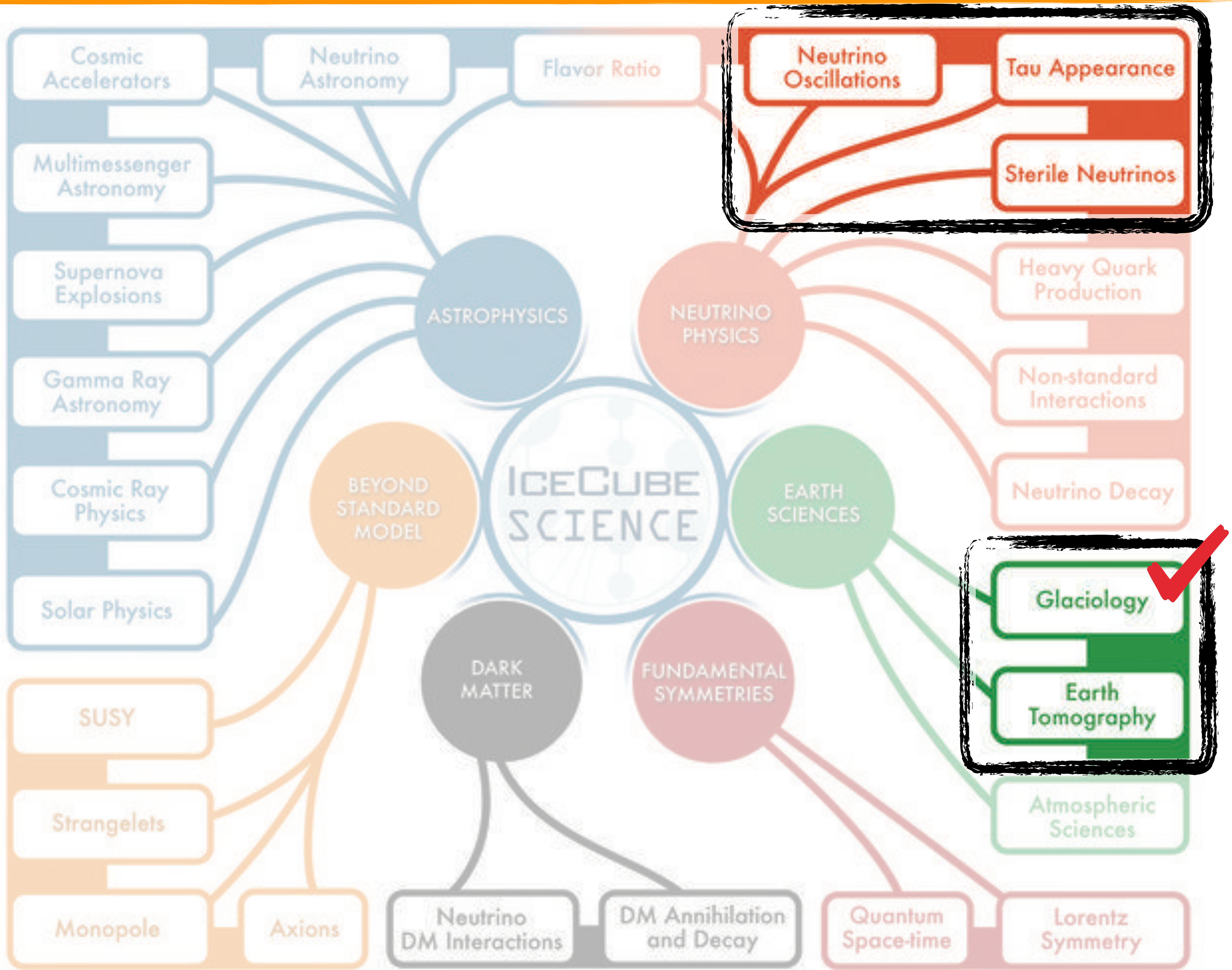


Illustration of Lake Vostok, beneath > 3 km of glacial ice in East Antarctica (Credit: Nicolle Rager Fuller / NSF)

IceCube DeepCore science



IceCube DeepCore science



Neutrino oscillations

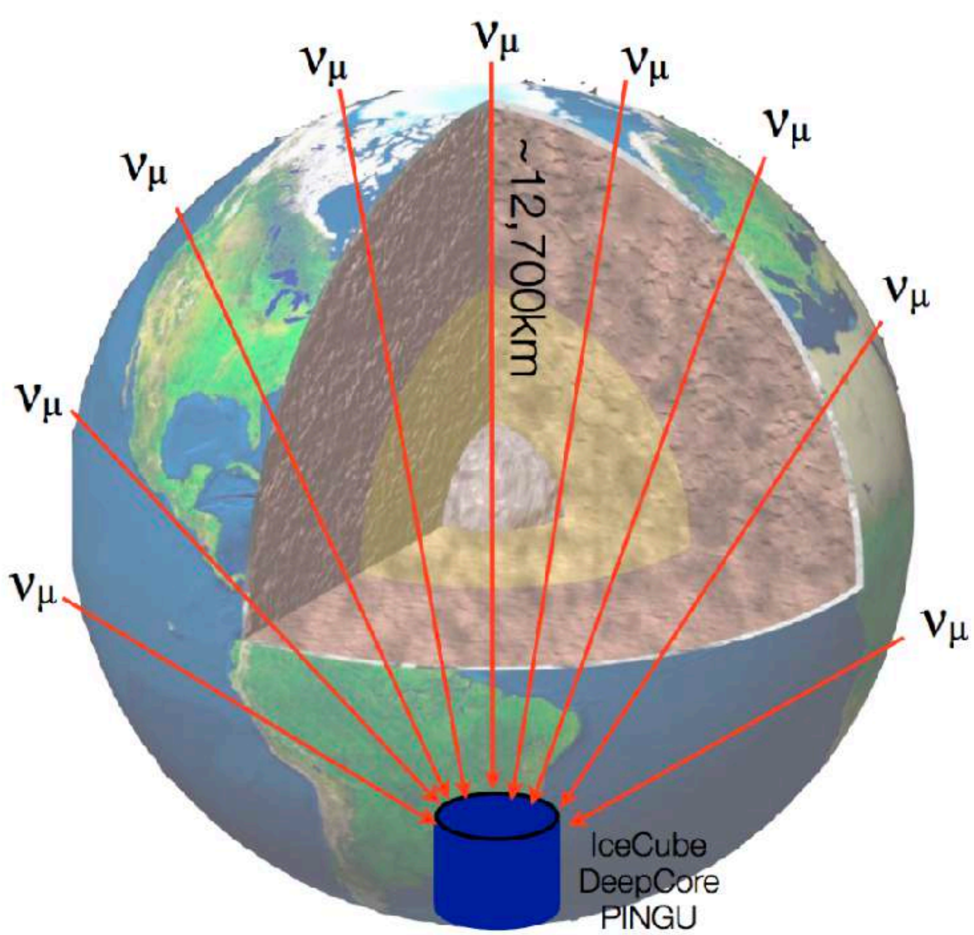
- Neutrinos are produced/detected in flavour eigenstates
- Flavour at production site can be different than at detection site

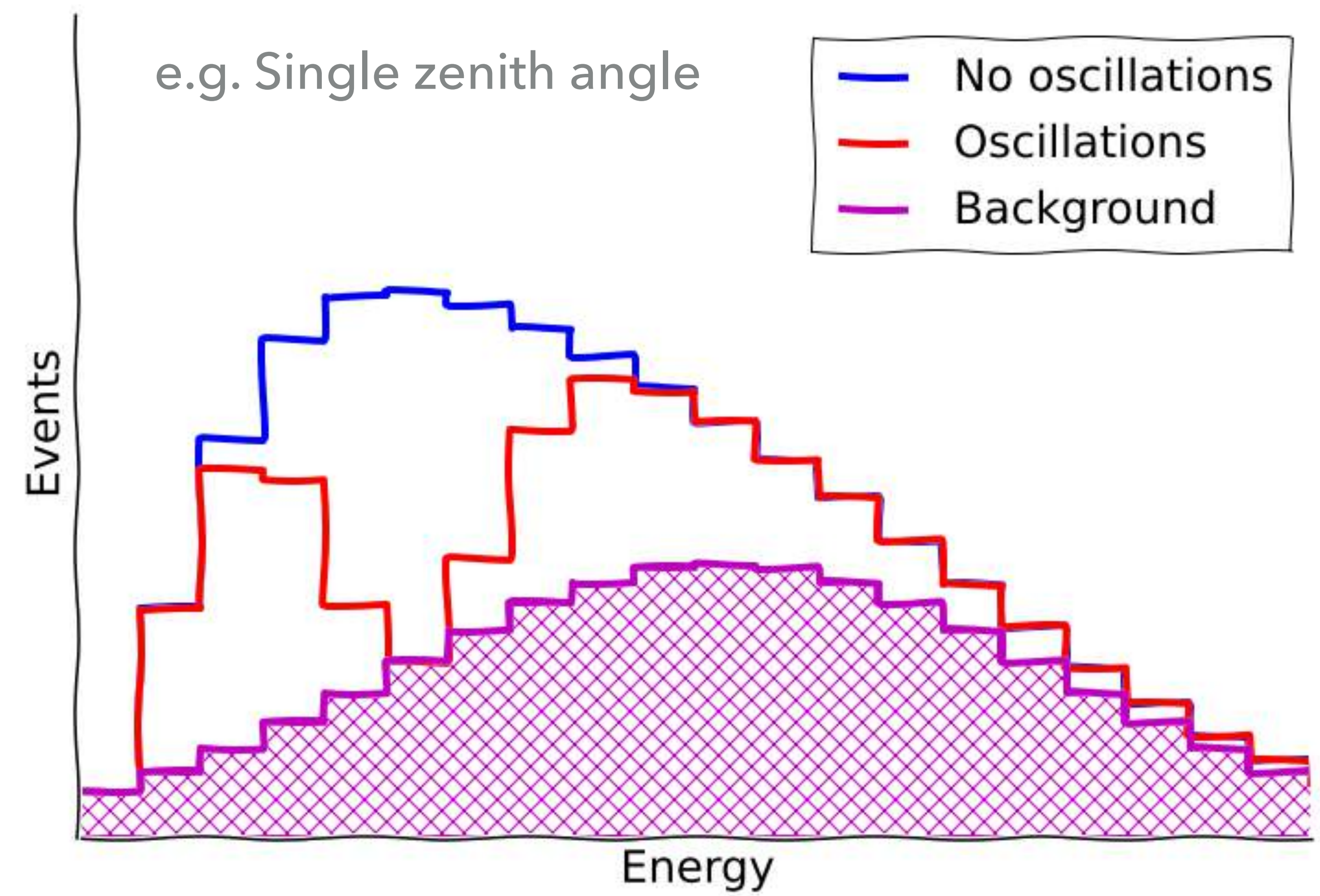
$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 \theta_{23} \sin^2(\Delta m^2_{32} L / 4E)$$

(Two flavour approx.)

Flavour state ≠ mass state
$m_1 \neq m_2 \neq m_3$





Neutrino oscillations

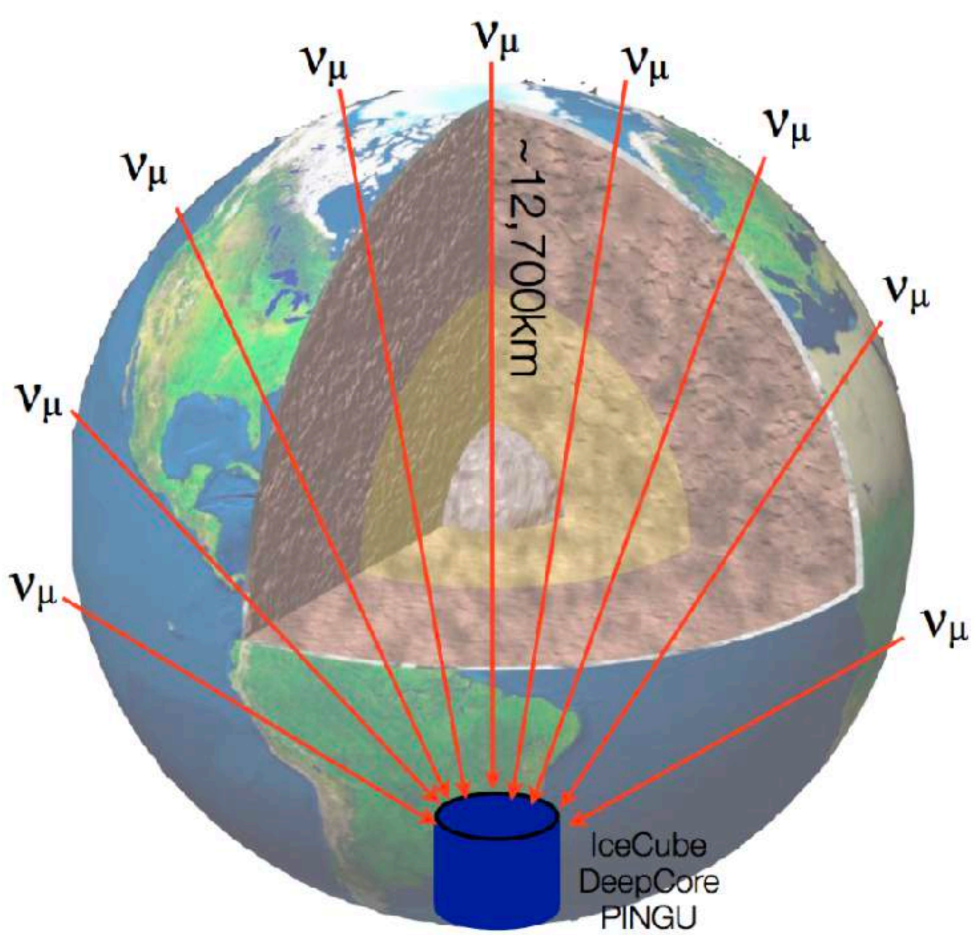
- Neutrinos are produced/detected in flavour eigenstates
- Flavour at production site can be different than at detection site

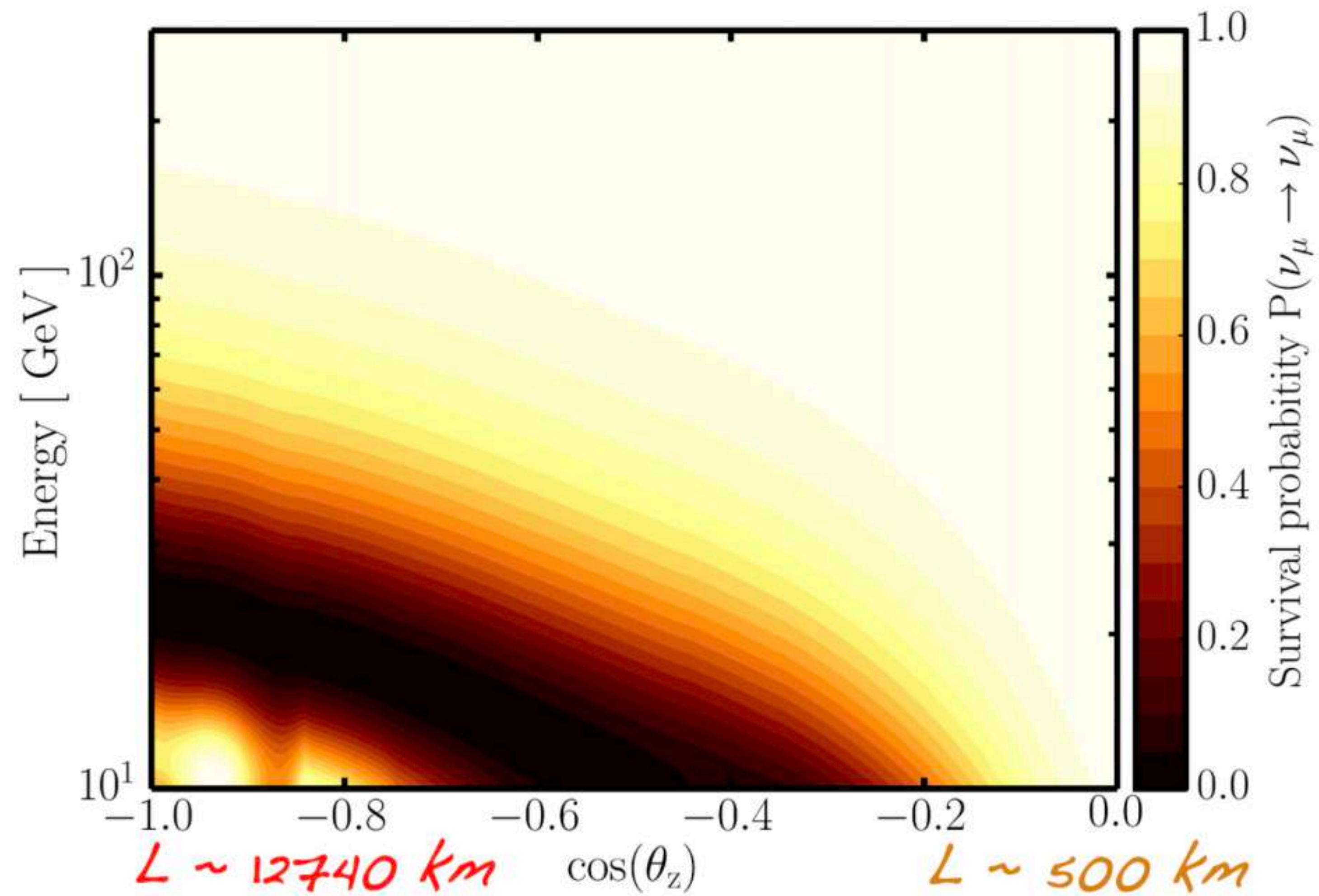
Flavour state ≠ mass state
$m_1 \neq m_2 \neq m_3$

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

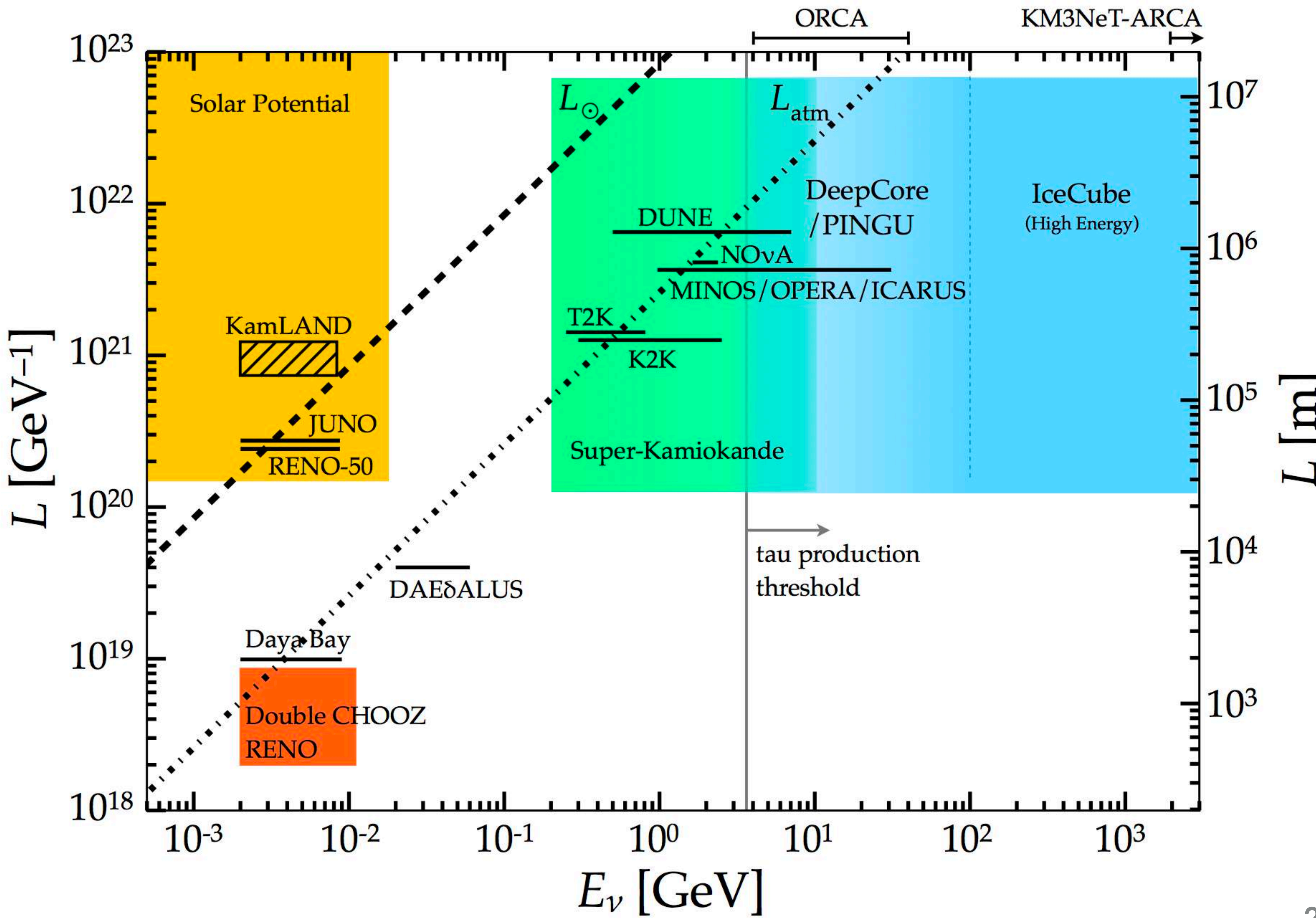
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

(Two flavour approx.)





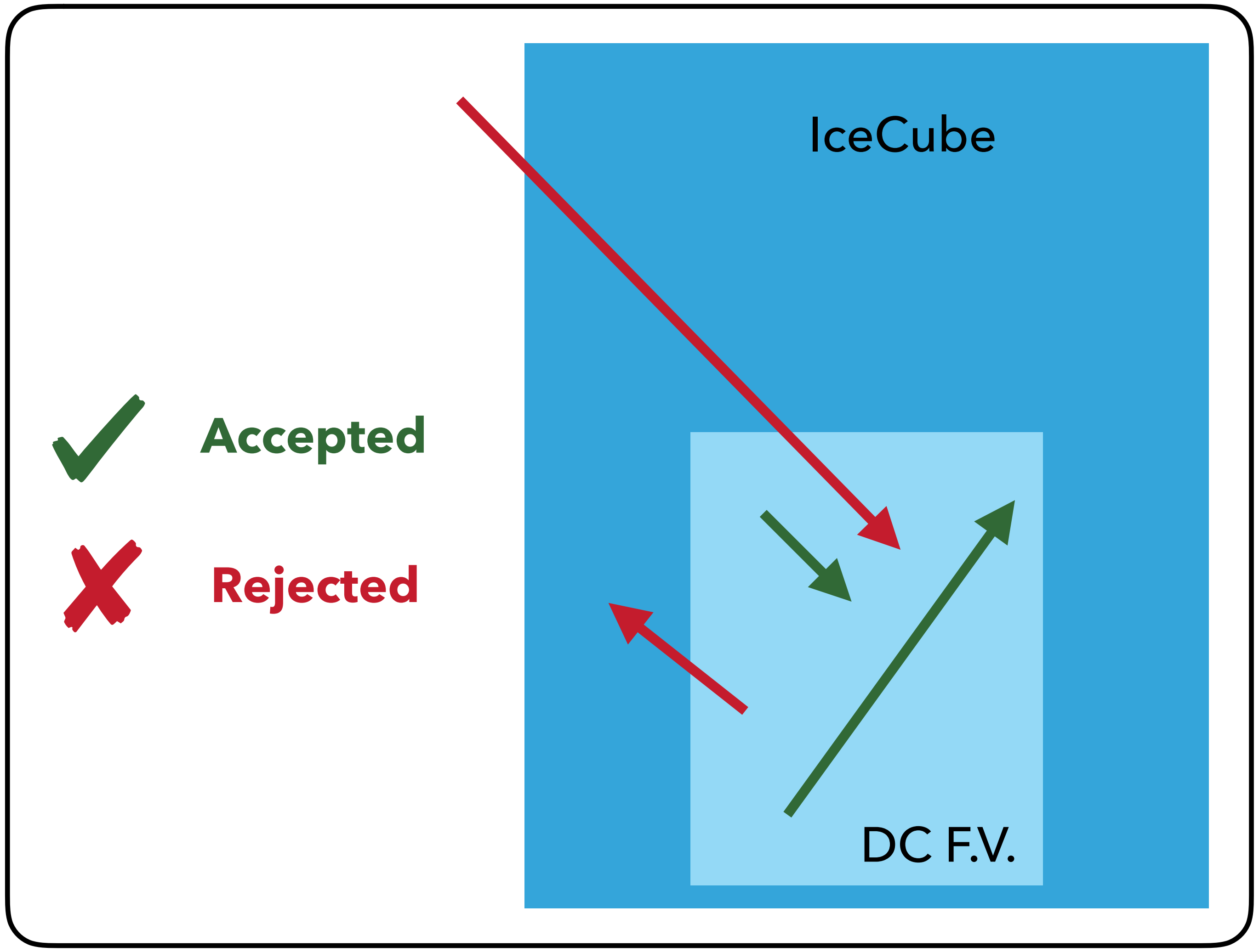
The bigger picture



NuMu disappearance analysis

https://arxiv.org/abs/1707.07081

- Select starting, contained events in DeepCore Fiducial Volume (F.V.)
- 3 years of data (41,599 events)
  - ~5% atmospheric muon background
- Median resolutions @ 20 GeV for tracks (cascades):
  - 10° (16°) zenith
  - 24% (29%) in energy

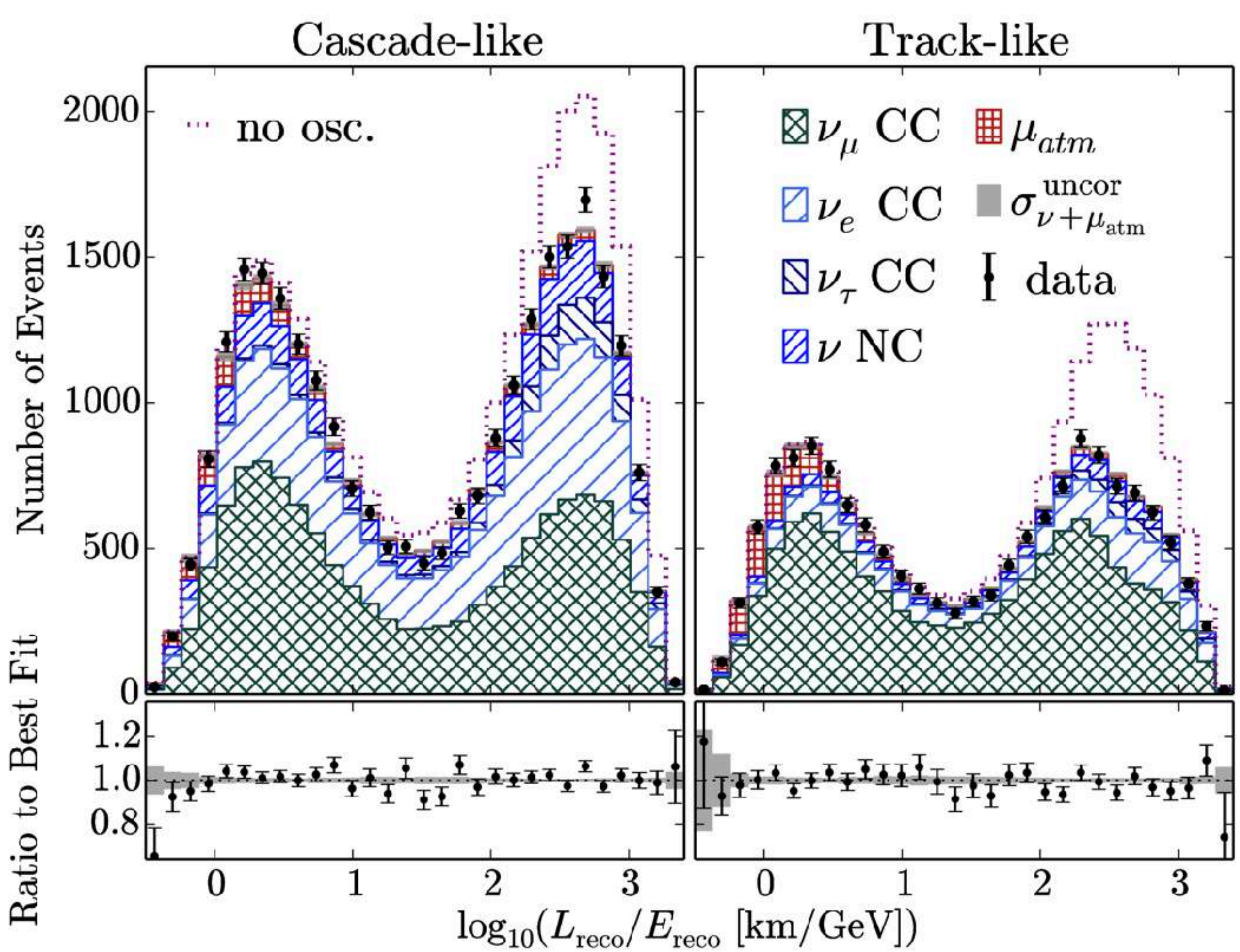


NuMu disappearance analysis

https://arxiv.org/abs/1707.07081

- Best fit obtained through χ2 minimisation with Gaussian penalty terms for nuisance parameters with priors

$$\chi^2 = \sum_{i \in \{\text{bins}\}} \frac{(n_i^{\nu+\mu_{\text{atm}}} - n_i^{\text{data}})^2}{(\sigma_i^{\text{data}})^2 + (\sigma_{\nu+\mu_{\text{atm}},i}^{\text{uncor}})^2} + \sum_{j \in \{\text{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{s_j}^2},$$



Fit performed in 8x8 bins for tracks and cascades:

log10(E$_{reco}$):
[0.75, 1.75]
(6 – 56 GeV)

cos(θ$_{reco}$):
[-1, 1]
(full sky)

χ^2/dof = 117.4 / 119

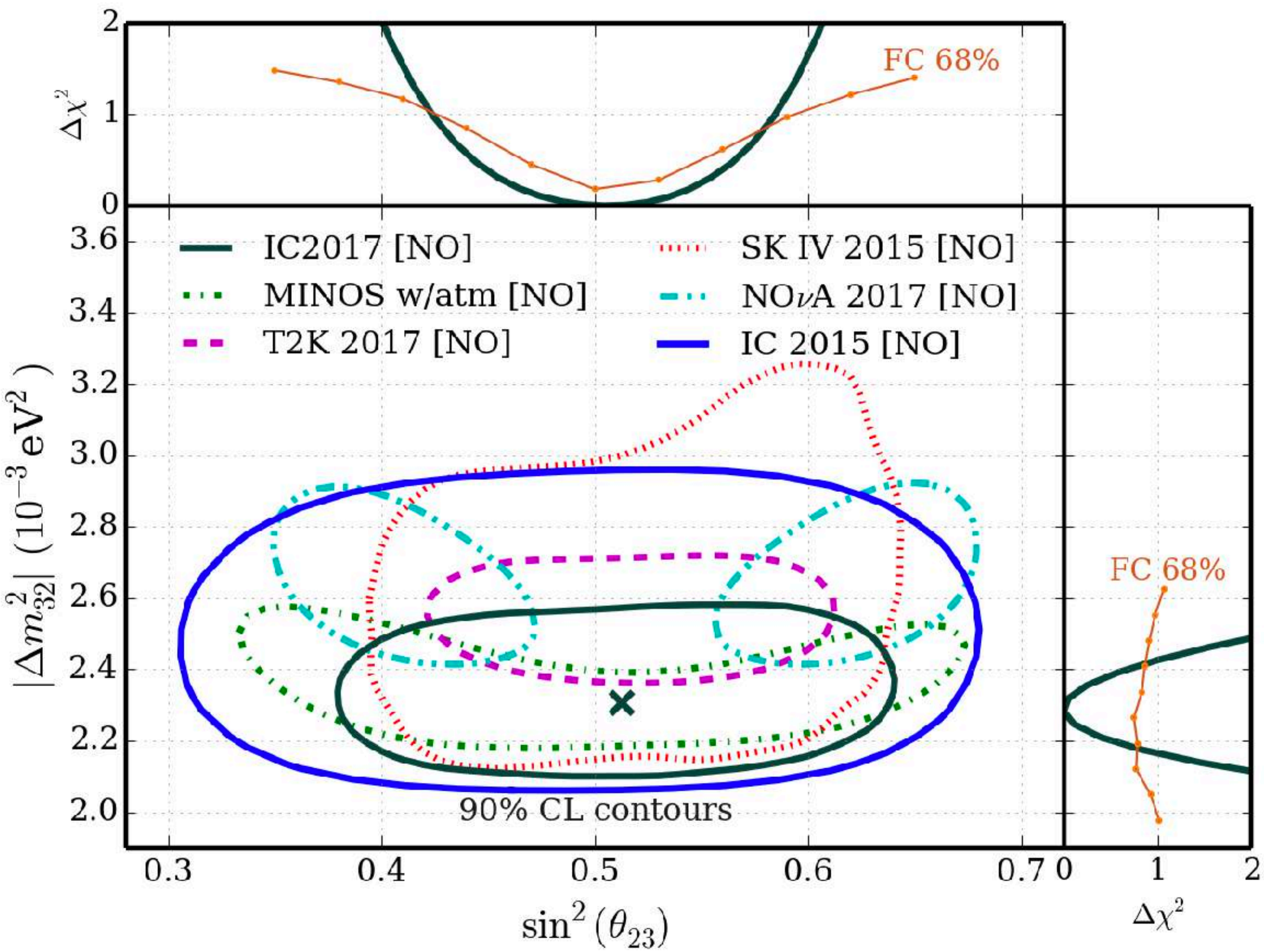
NuMu disappearance results

https://arxiv.org/abs/1707.07081

Best Fit*:

*Normal Ordering

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2 \qquad \sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$



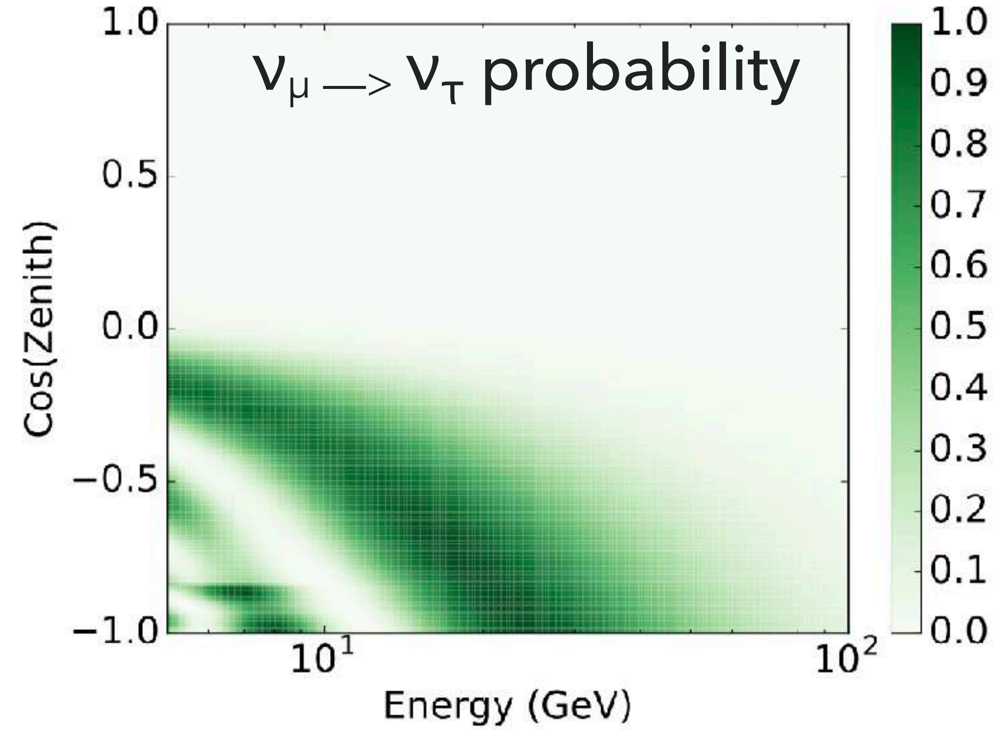
Contribution to 1σ

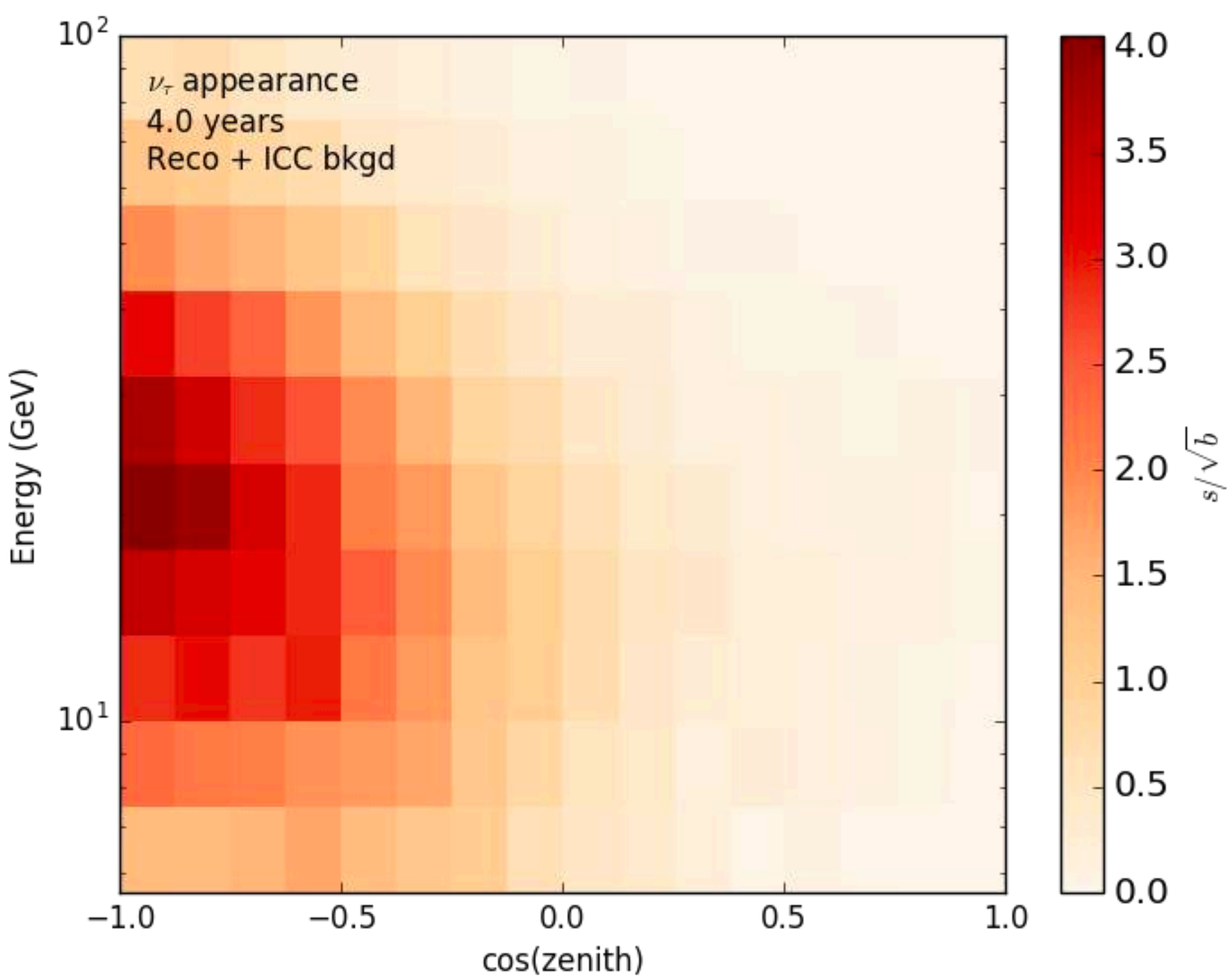
Δm^2_{32}	$\sin^2\theta_{23}$
Atmospheric ν Flux	
~4 %	~2 %
Cross section	
~2 %	< 1 %
Detector	
~23 %	~2 %
$\sin^2\theta_{13}$	
<1 %	

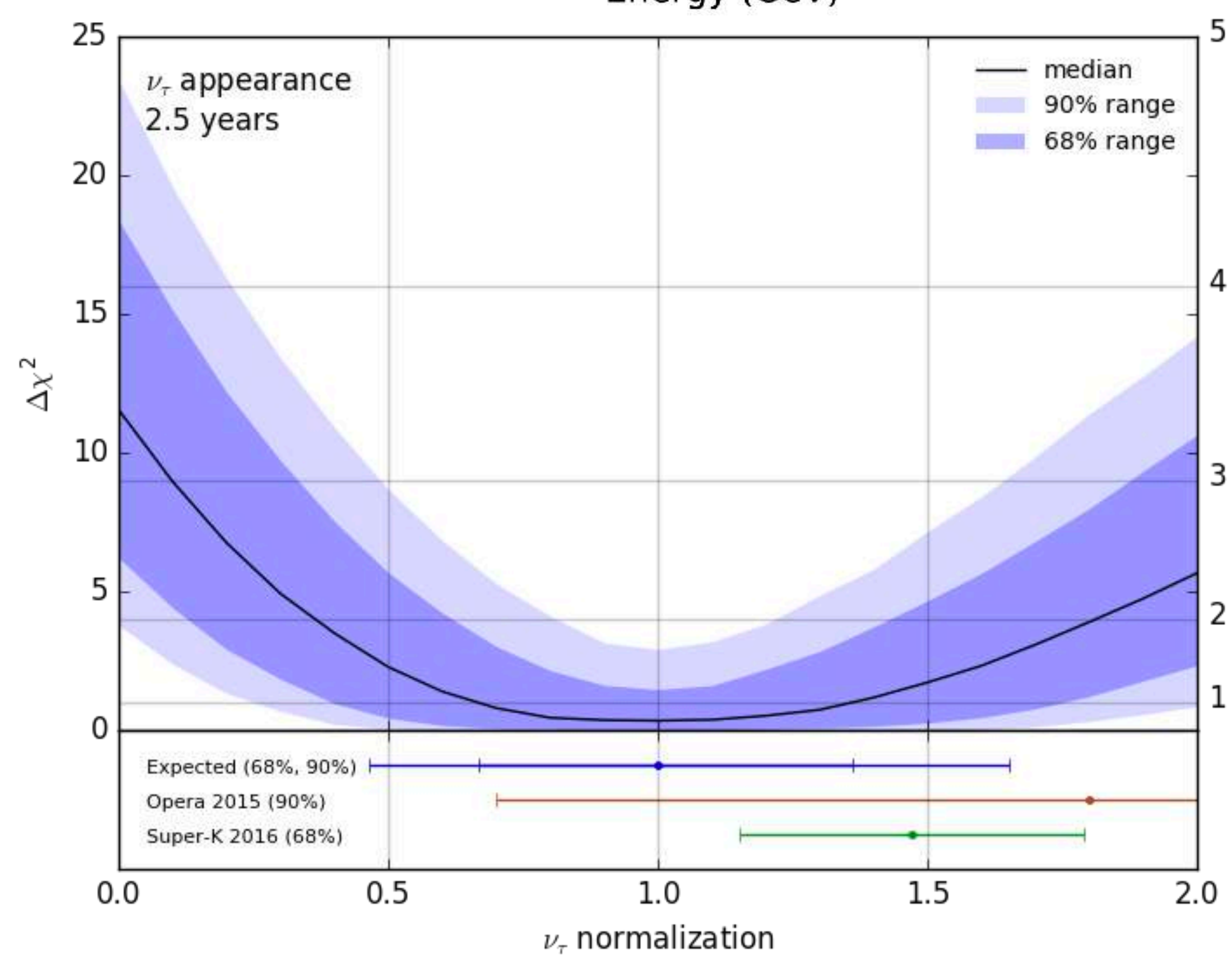
Normalisation of ν_τ **fixed** to 1.0 (standard 3x3 mixing)

NuTau Appearance Analysis

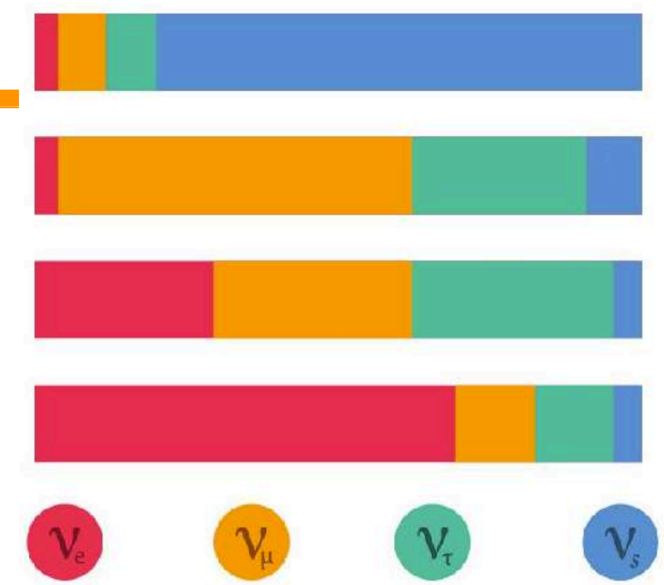
- Can use same neutrino sample to search for ν_τ appearance
- Rejection of no ν_τ appearance @ ~2.5σ if normalisation = 1 (SM)
- Expected precision ~30% @ 68%CL







Sterile neutrinos



- Are there only 3 neutrino mass states?
  - Additional states can not couple to the weak interaction, i.e. sterile
  - Massive sterile ν's can still oscillate with active states
- Motivated by anomalies in previous neutrino oscillation experiments
  - Oscillations happening where they "shouldn't"
- New model adds:
  - 1 new mass - Δm^2_{41}
  - 2 new CP phases - assume 0
  - 3 new mixing angles - θ_{14}, θ_{24}, θ_{34}

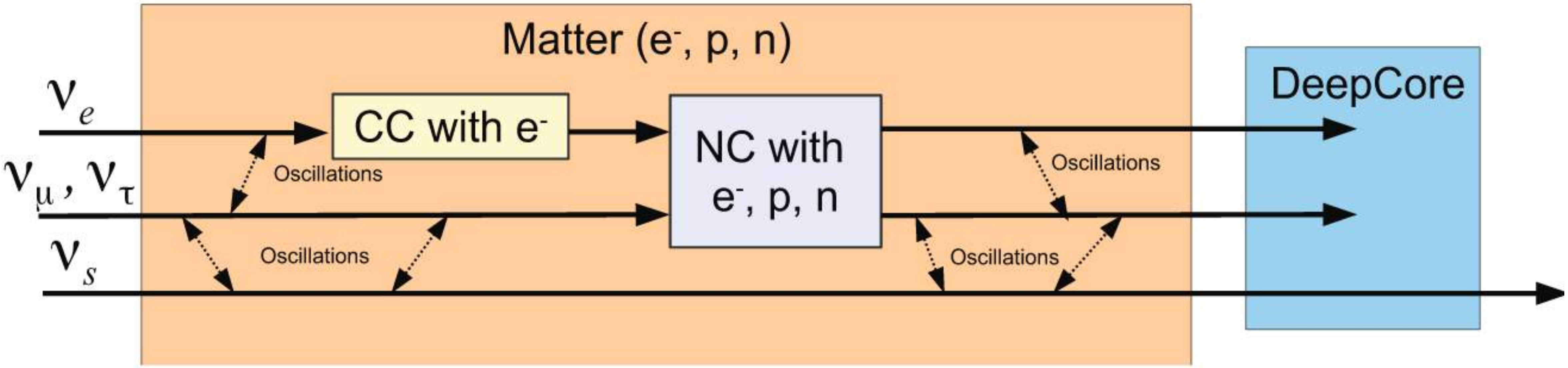
PMNS 3x3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$
$$|U_{\mu 4}|^2 = \sin^2\theta_{24} \cdot \cos^2\theta_{14}$$
$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24} \cdot \cos^2\theta_{14}$$

> Modifies detected atmospheric neutrino flux

Searching for sterile neutrinos – matter effects



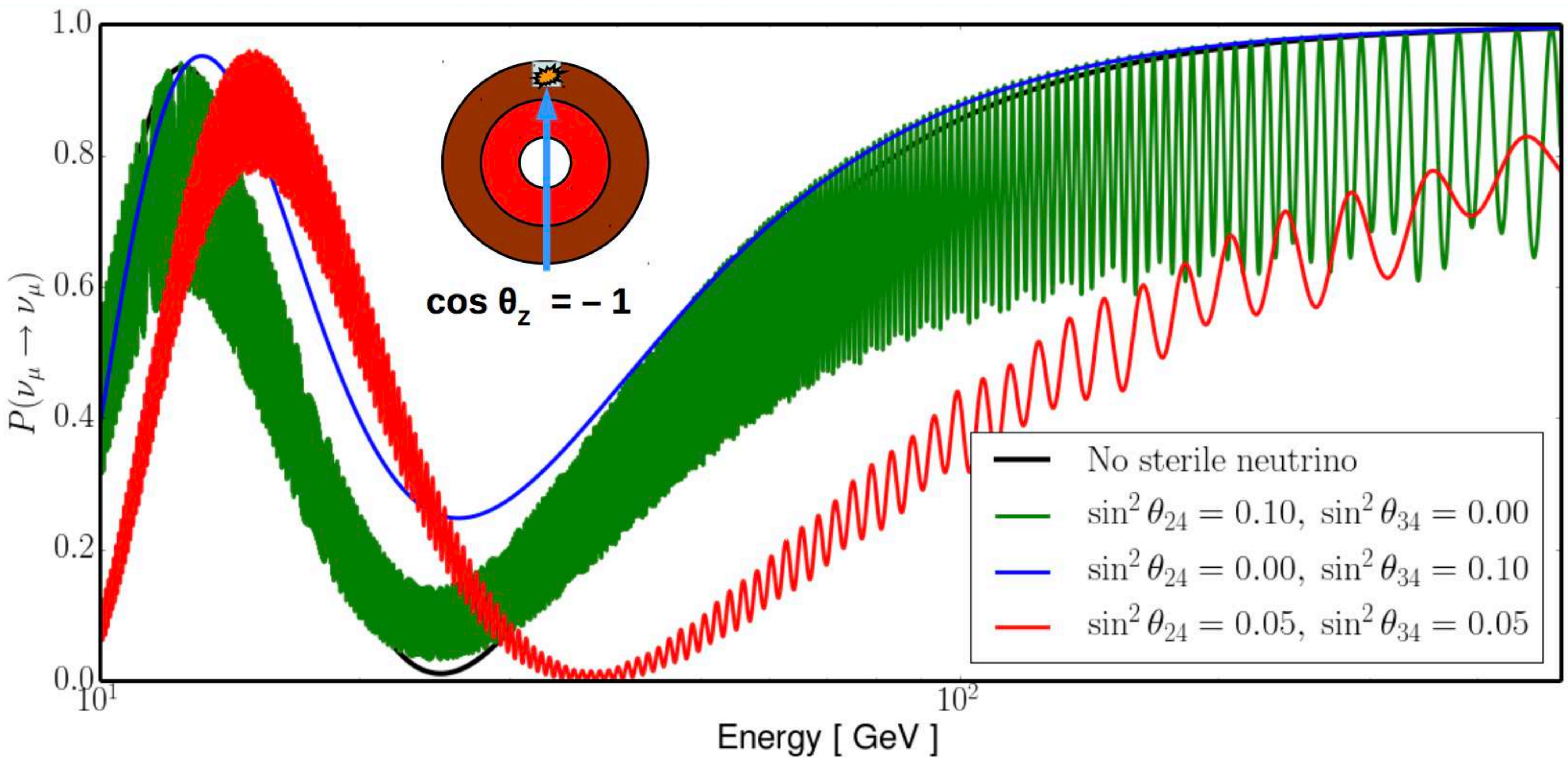
- Active neutrinos feel effects of matter potential when crossing Earth
- This modifies their propagation in a way that we typically express through effective mixing parameters:

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 \pm \frac{2 E V_{int}}{\Delta m^2 \cos 2\theta}} \qquad \Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta \pm 2 E V_{int})^2 + (\Delta m^2 \sin 2\theta)^2}$$

- Can achieve maximal mixing at resonance

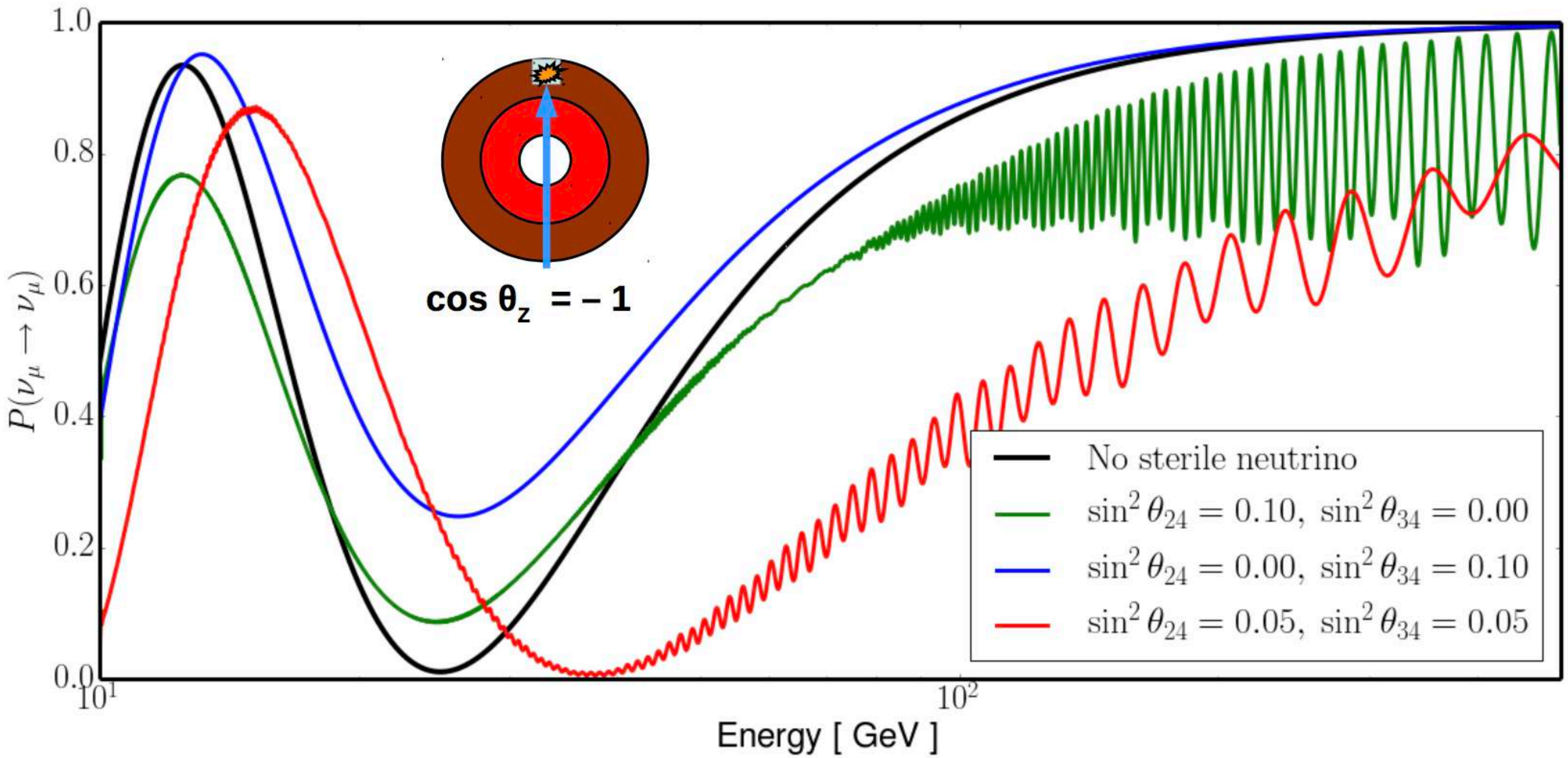
$$E_R = \frac{\Delta m^2 \cos 2\theta}{2 V_{int}} \rightarrow \theta_M = \frac{\pi}{4} \qquad \Delta m_M^2 = \Delta m^2 \sin 2\theta$$

Searching for sterile neutrinos - low energies



- For **E_ν~10-100 GeV,** smaller effective matter potential leads to less disappearance, and/or shift in minimum
- Independent of Δm^2_{41} for values > 0.3 eV^2
  - Oscillations are too fast for detector resolution - only see average effect

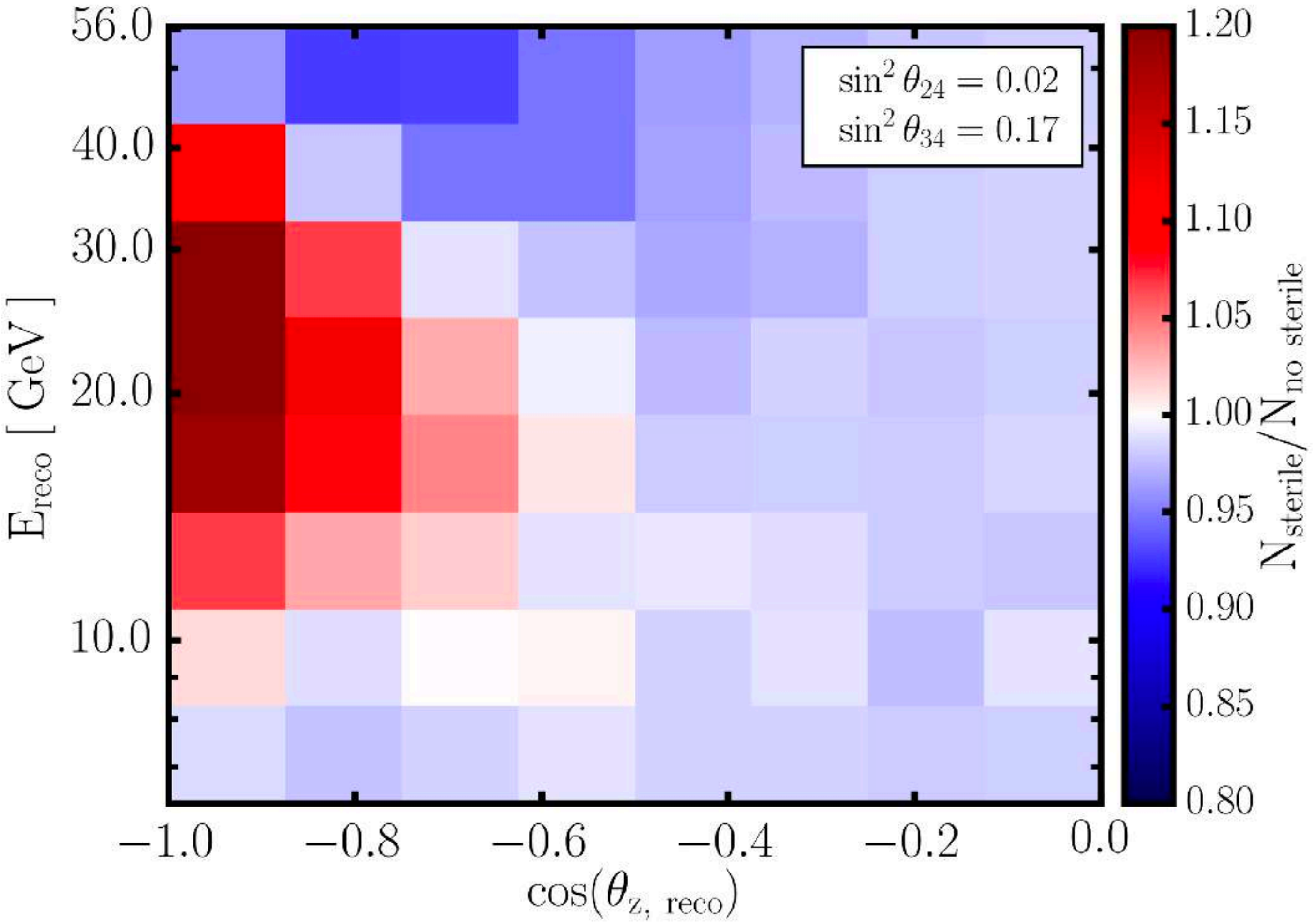
Searching for sterile neutrinos - low energies

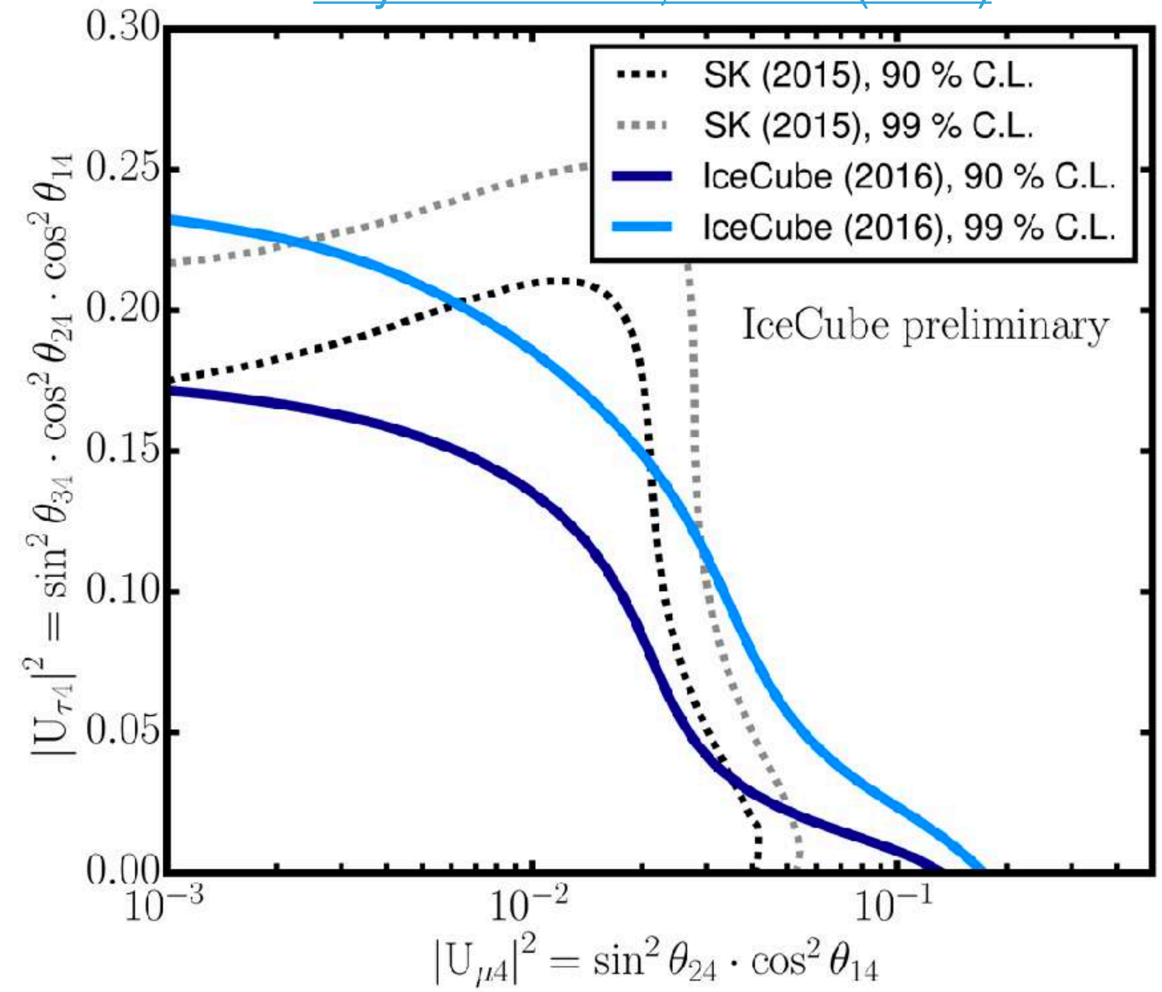


- For **E_ν~10-100 GeV,** smaller effective matter potential leads to less disappearance, and/or shift in minimum
- Independent of Δm^2_{41} for values > 0.3 eV^2
  - Oscillations are too fast for detector resolution - only see average effect

Searching for sterile neutrinos – low energies

Phys. Rev. D 95, 112002 (2017)





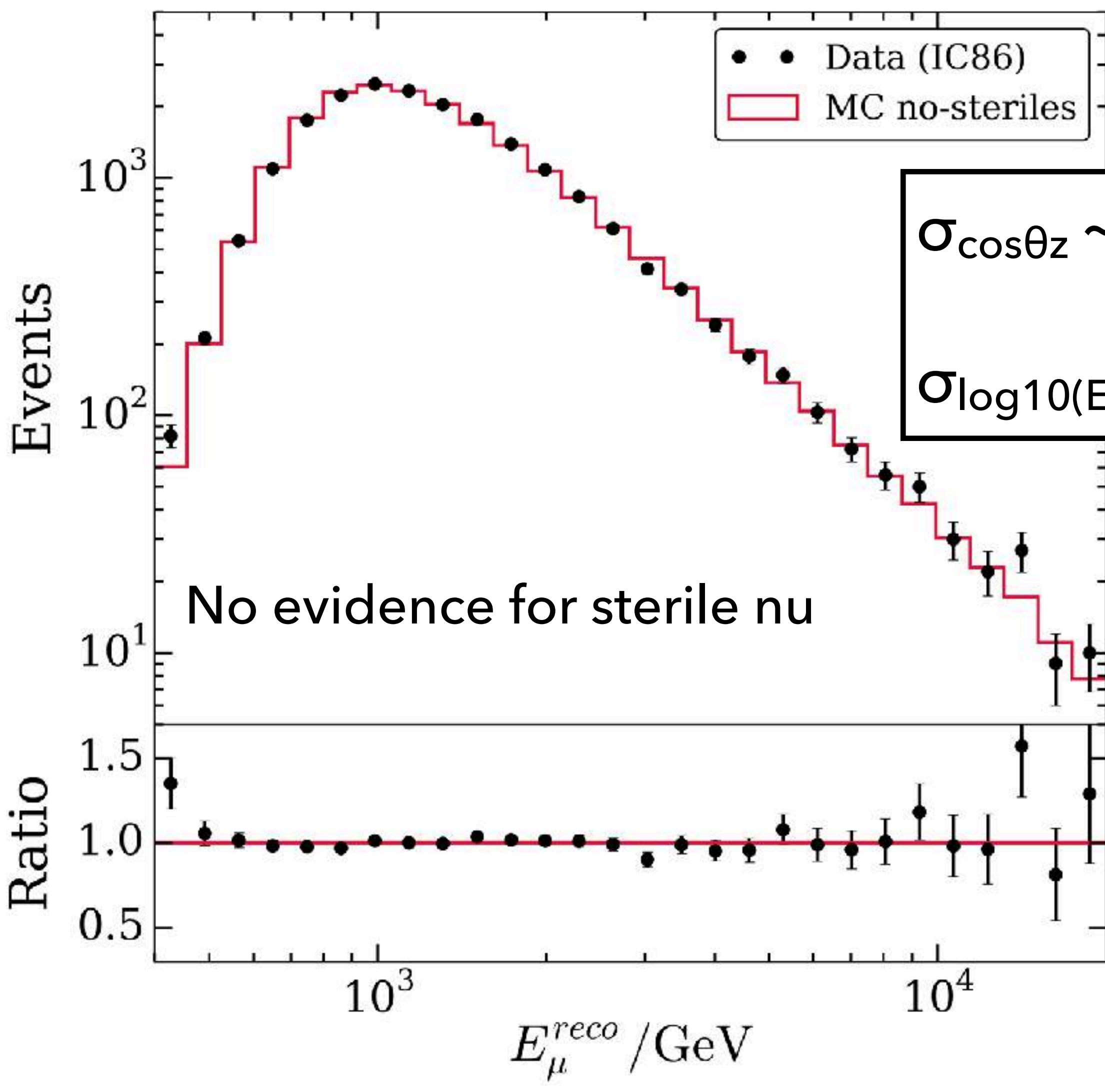
Maximum log-likelihood

$$-\ln\mathcal{L} = \sum_i (\mu_i - n_i \ln \mu_i) + \sum_k^{n_{priors}} \frac{(\phi_k - \phi_k^0)^2}{2\sigma_{\phi_k}^2},$$

- 3 years of track-like events with energies 6 – 56 GeV
- Oscillations consistent with standard 3x3 mixing
- Strong constraints on $U_{\tau 4}$ mixing element

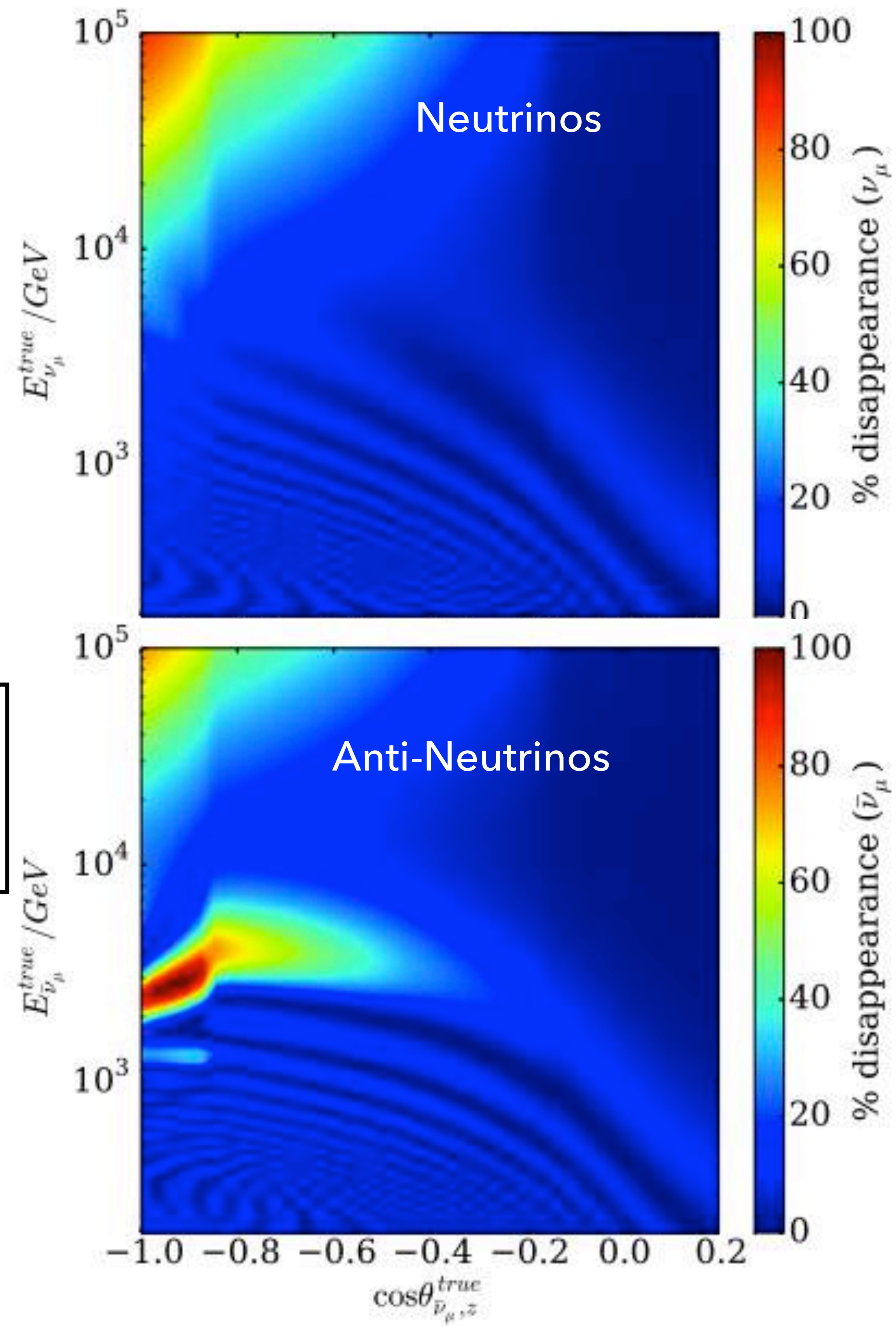
Searching for sterile neutrinos – high energies

- For **E_ν ~ TeV scale,** we look for resonant enhancement of oscillations for anti-ν
- Position of resonance proportional to Δm^2_{41}
- Using 1 year of up-going neutrino data



$\sigma_{\cos\theta z}$ ~ 0.005-0.015

$\sigma_{\log10(E\mu/GeV)}$ ~0.5

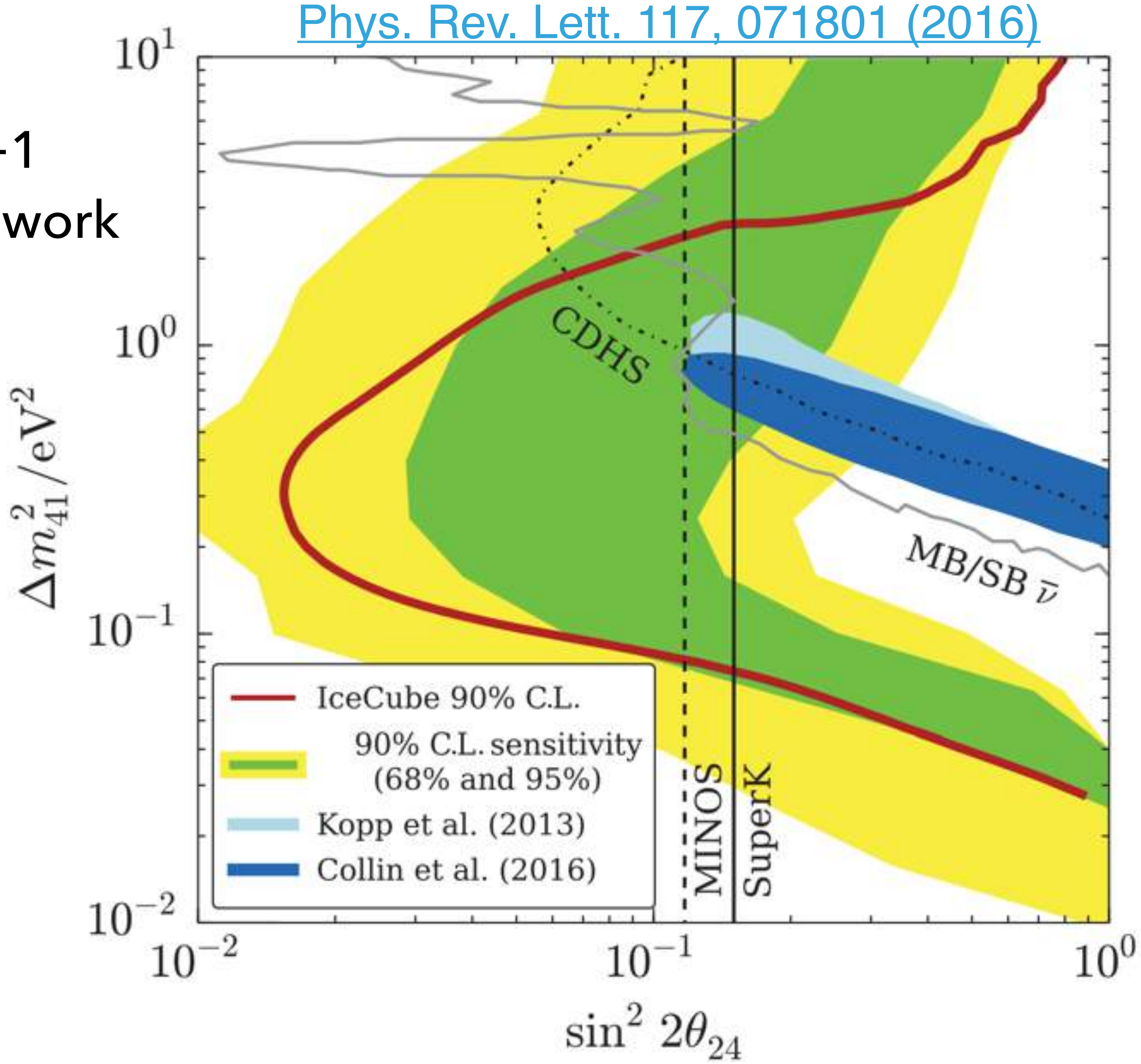


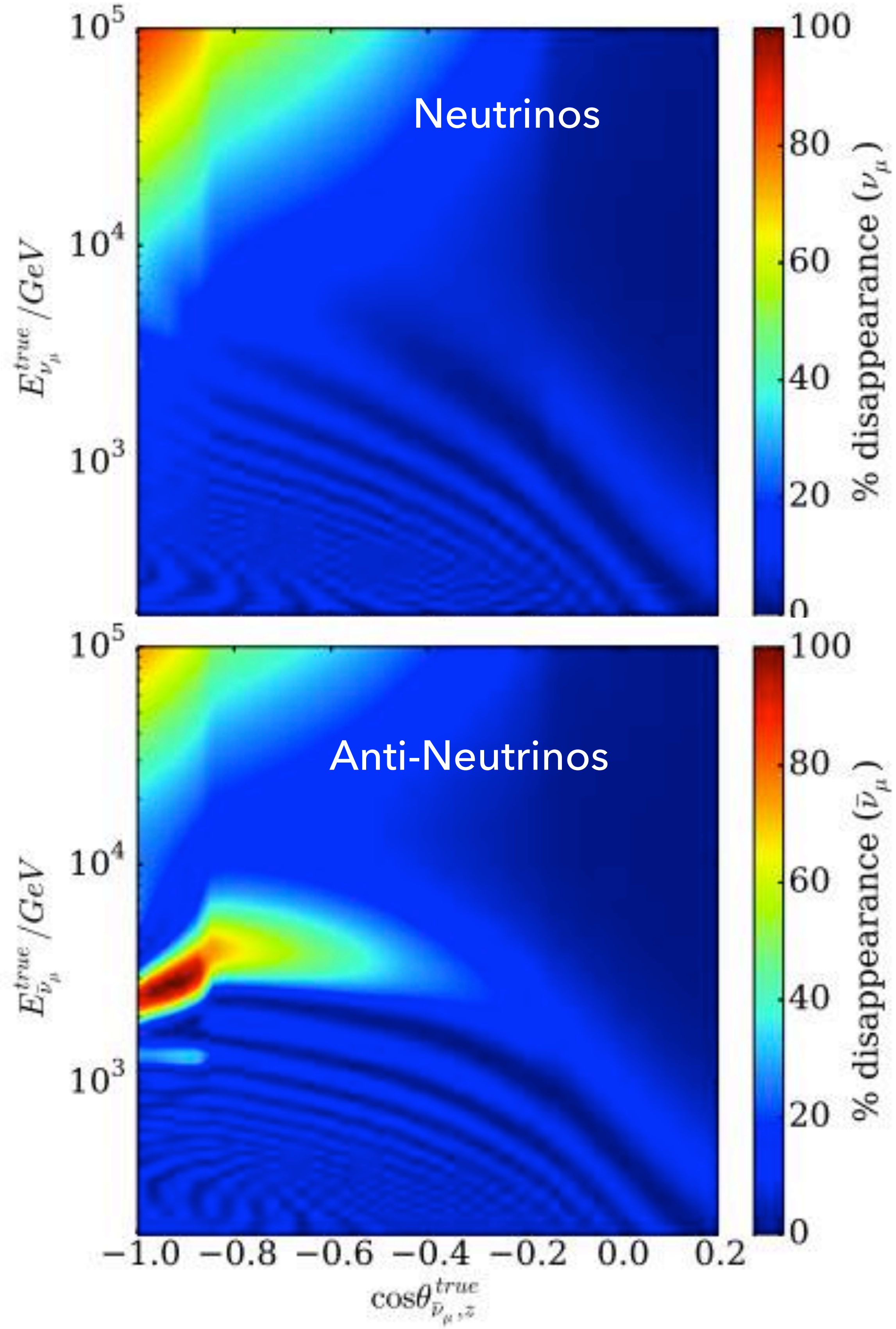
Searching for sterile neutrinos - high energies

- For **E_ν ~ TeV scale,** we look for resonant enhancement of oscillations for anti-ν
- Position of resonance proportional to Δm^2_{41}
- Using 1 year of up-going neutrino data

3+1 framework

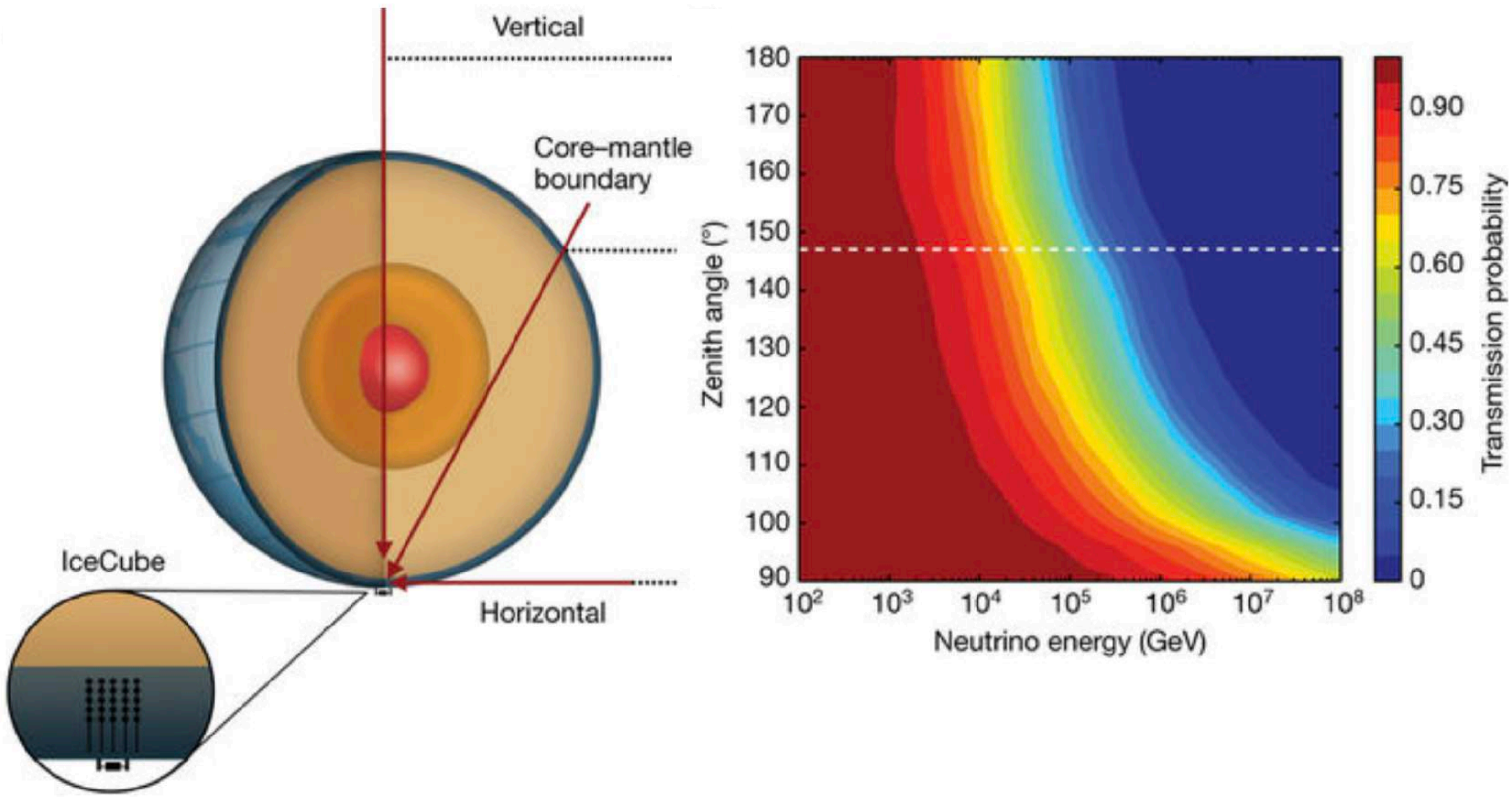
[Phys. Rev. Lett. 117, 071801 (2016)](#)





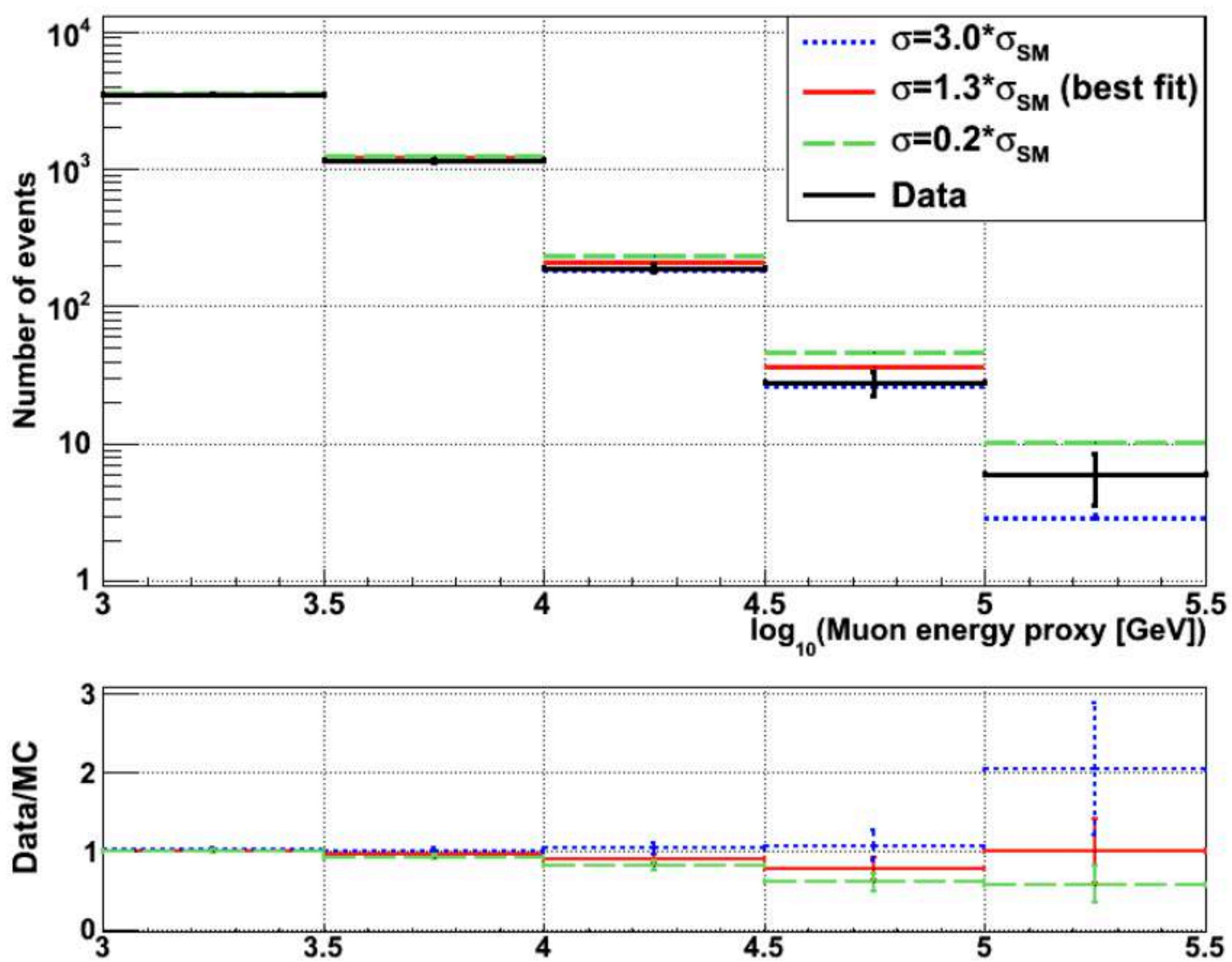
Neutrino-nucleon cross section measurement

- At very high energies, no atmospheric neutrino oscillations are expected
- But earth becomes more opaque at these energies
- Can use the Earth as a target to measure neutrino-nucleon cross section



Neutrino-nucleon cross section measurement

- At very high energies, no atmospheric neutrino oscillations are expected
- But earth becomes more opaque at these energies
- Can use the Earth as a target to measure neutrino-nucleon cross section
- **First measurement of CC neutrino cross section at 6.3 - 980 TeV**



Hot off the press!

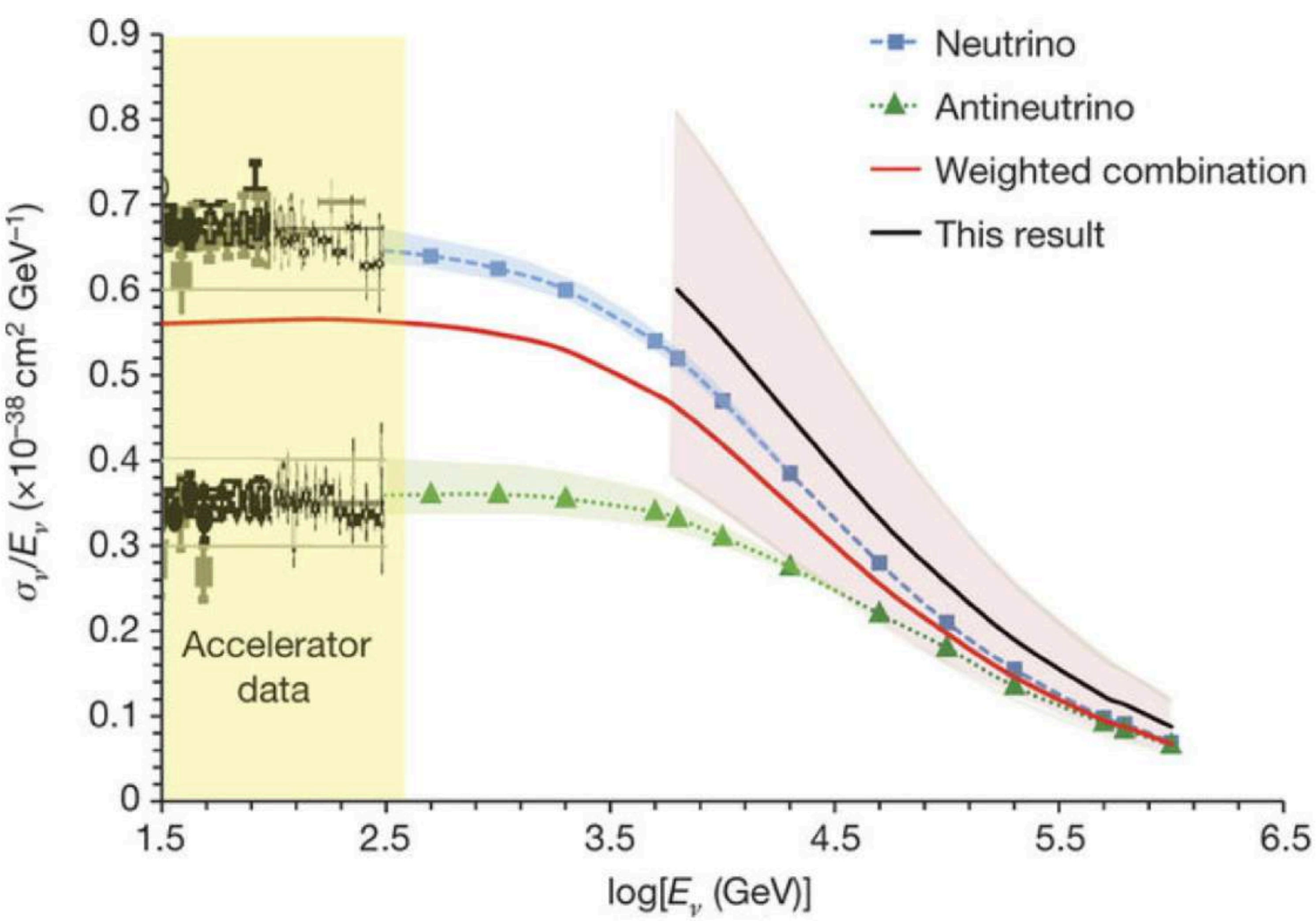
[Published in Nature]

[SymmetryMag]

[YouTube]

Neutrino-nucleon cross section measurement

- At very high energies, no atmospheric neutrino oscillations are expected
- But earth becomes more opaque at these energies
- Can use the Earth as a target to measure neutrino-nucleon cross section
- **First measurement of CC neutrino cross section at 6.3 - 980 TeV**



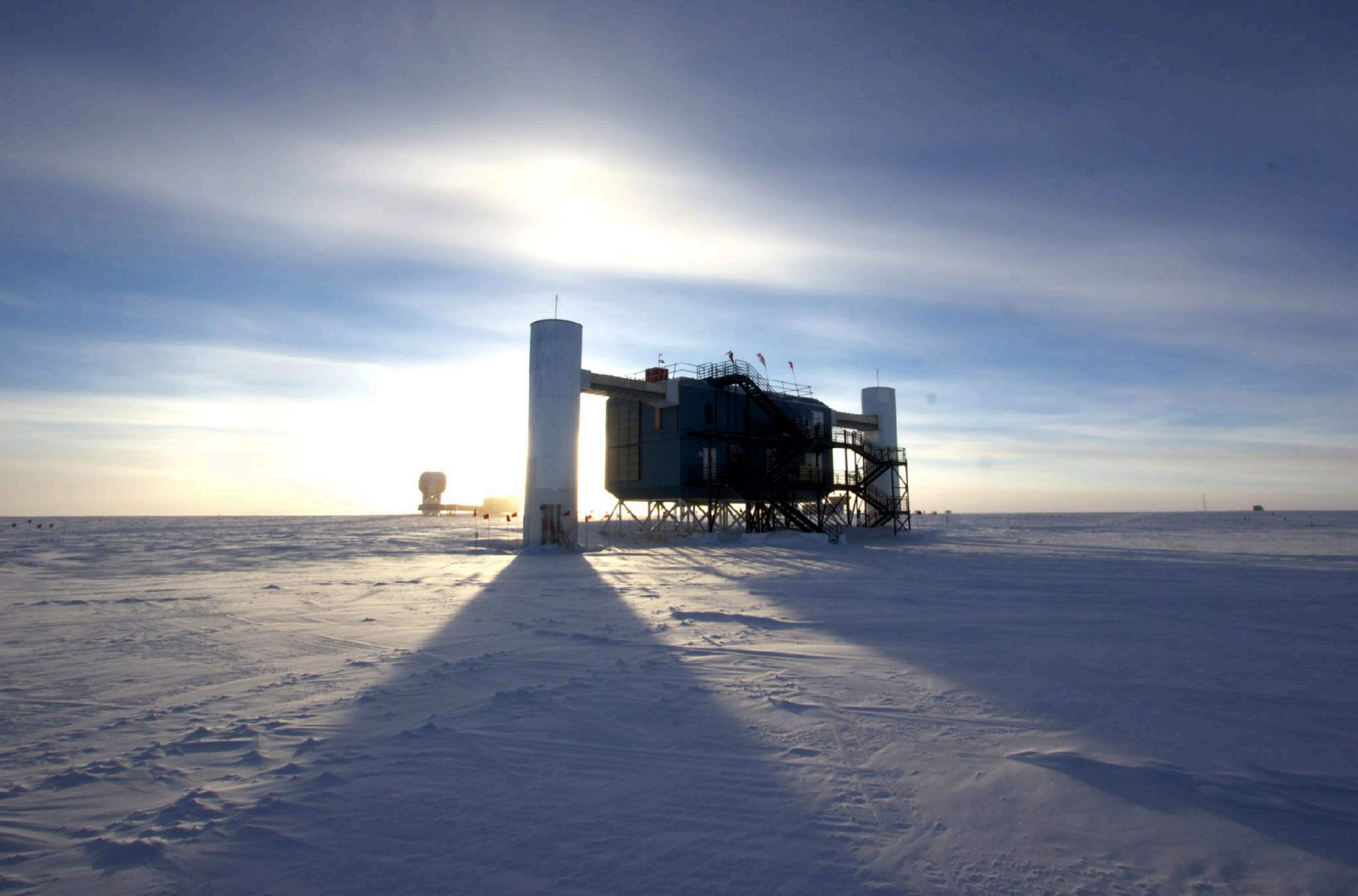
Hot off the press!

Published in Nature

SymmetryMag

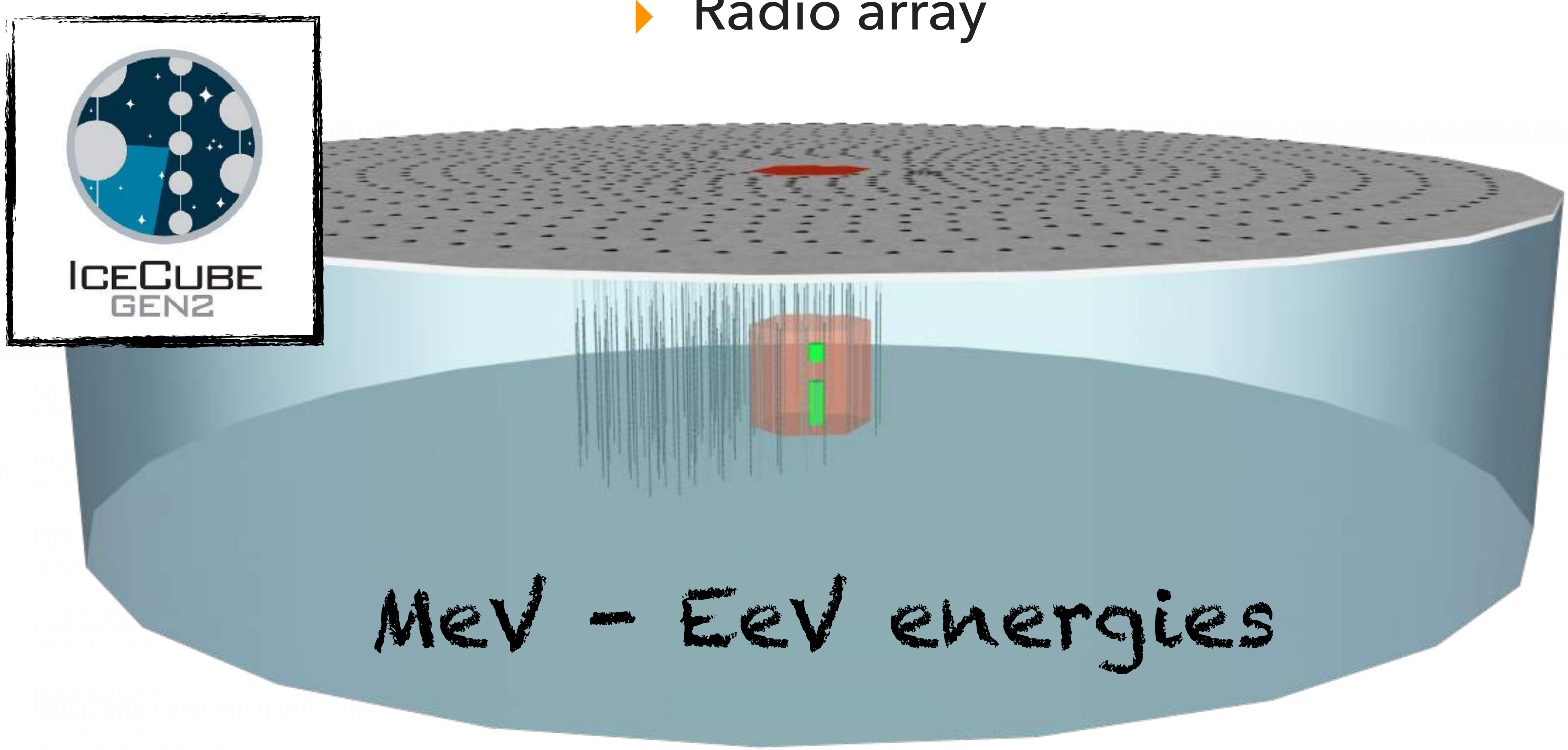
YouTube

Looking towards the future …



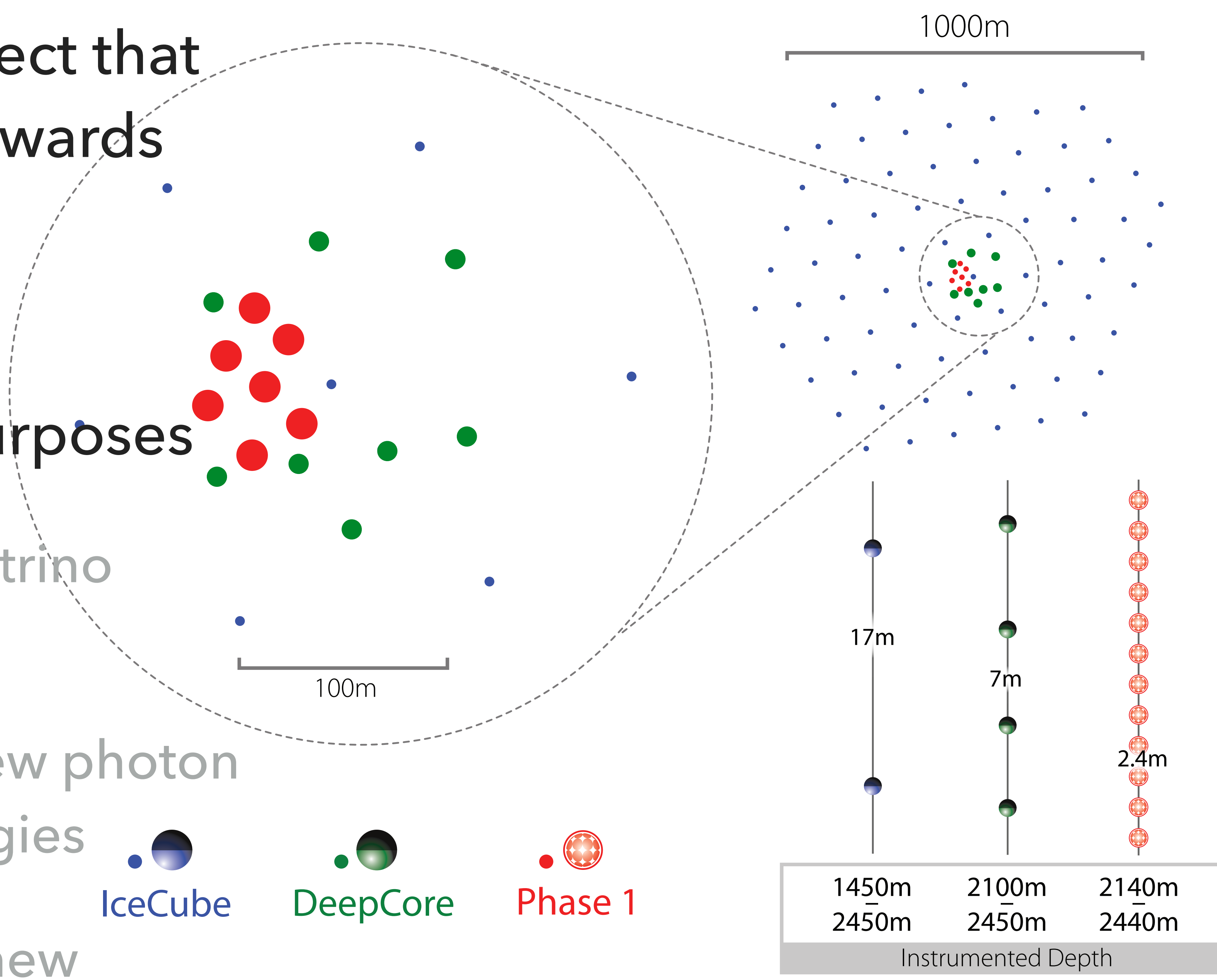
Upgrade to IceCube Gen2

- Goal:
    - 5x better sensitivity to detect point sources
    - 10x more statistics
- Larger instrumented volume
- Surface array for veto/air shower physics
- **Denser center (PINGU) for precision neutrino physics** https://arxiv.org/abs/1401.2046
  LOI Version 2
- Radio array



IceCube Upgrade

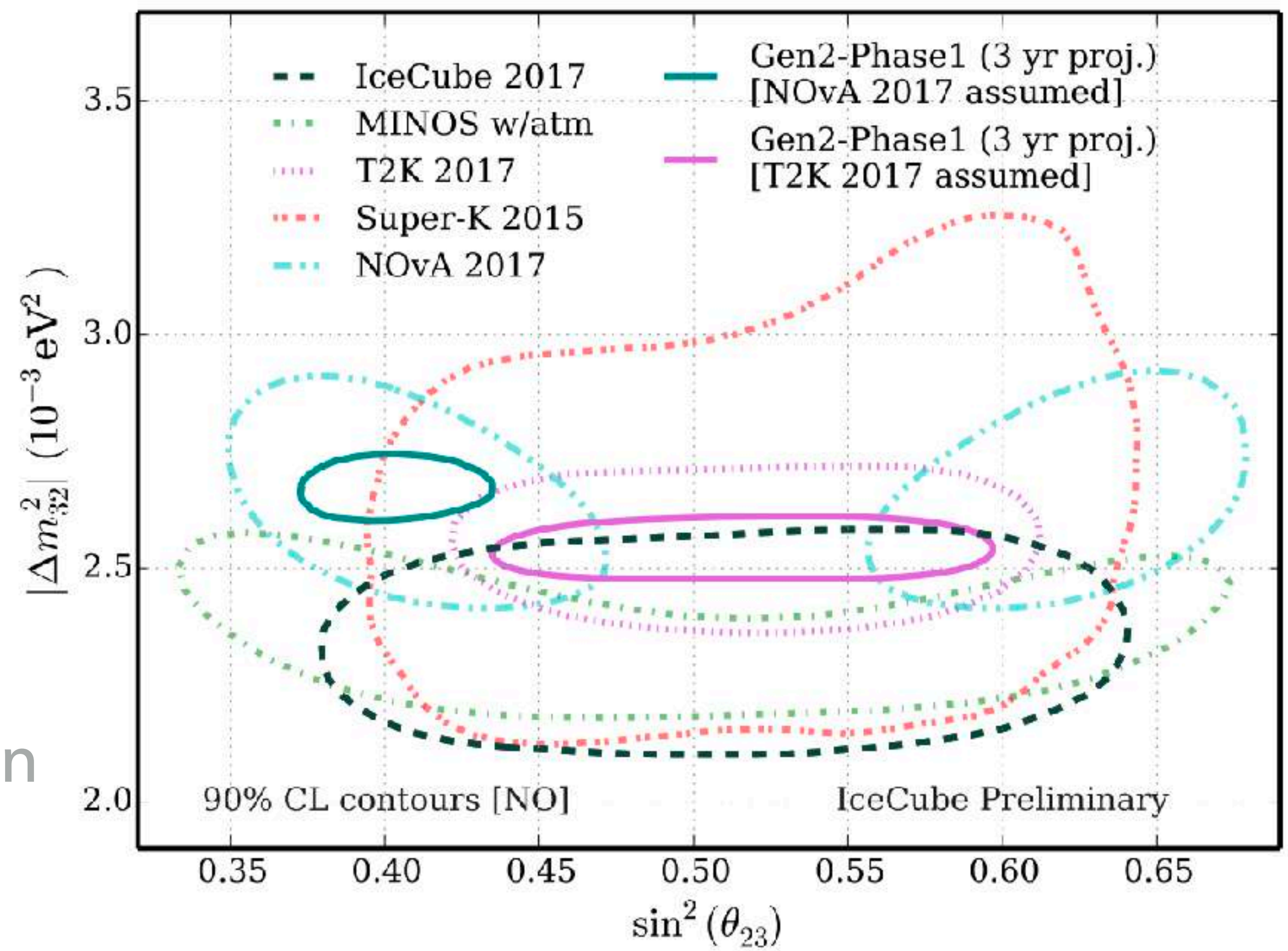
- Stand-alone project that also paves the towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices



IceCube Upgrade

- Stand-alone project that also paves the towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices

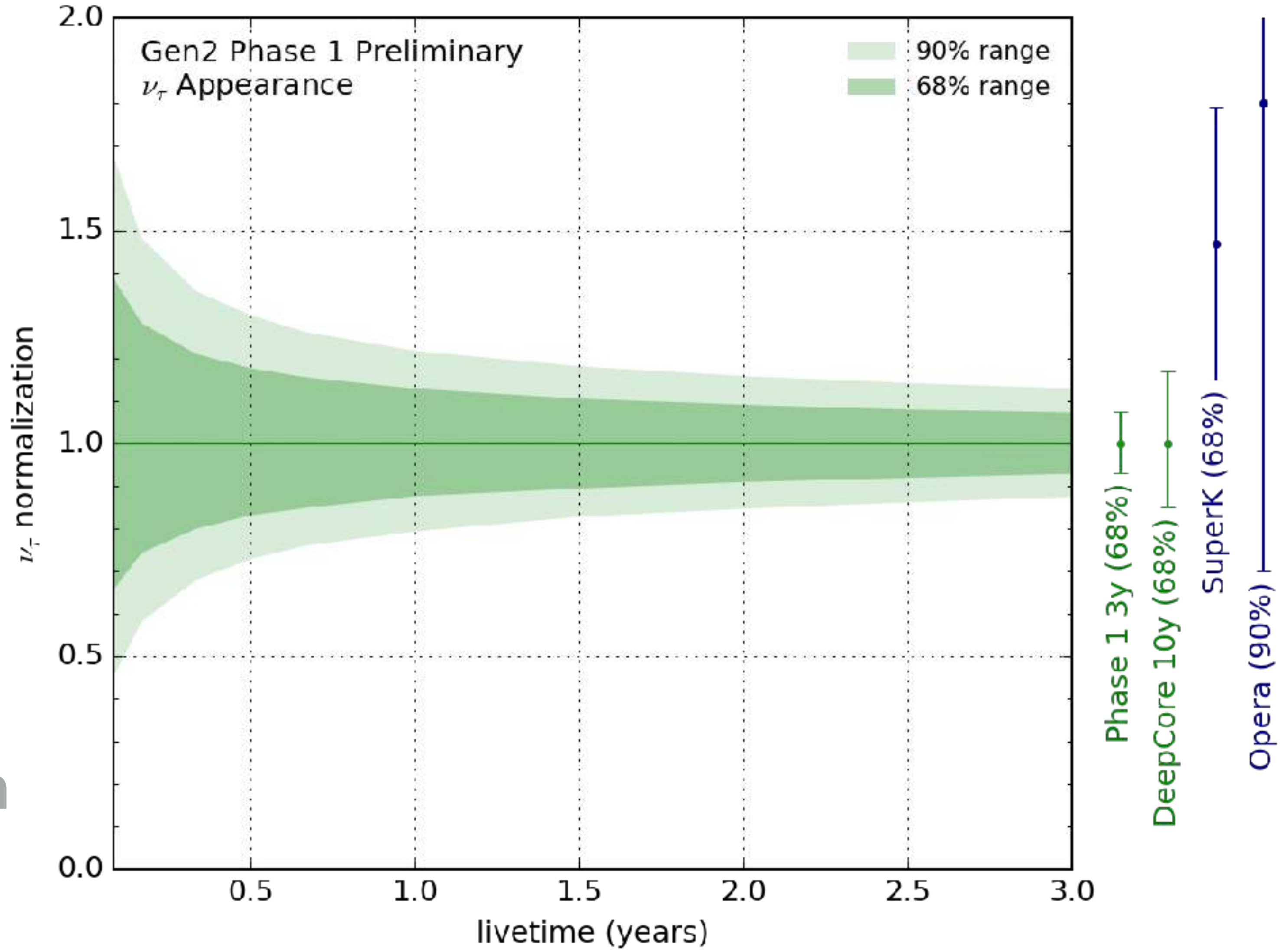
NuMu Disappearance



IceCube Upgrade

- Stand-alone project that also paves the towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices

NuTau Appearance



IceCube Upgrade

- Stand-alone project that also paves the towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices

mDOM

36 cm

- Directional information
- More sensitive area per module

IceCube Upgrade

- Stand-alone project that also paves the towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices

Difficult to calibrate refrozen ice in drill holes with current devices/methods

Precision Optical Calibration Device (POCAM)

Prototype deployed at Lake Baikal

K. Krings, E. Resconi, ICRC2017

CCD CMOS

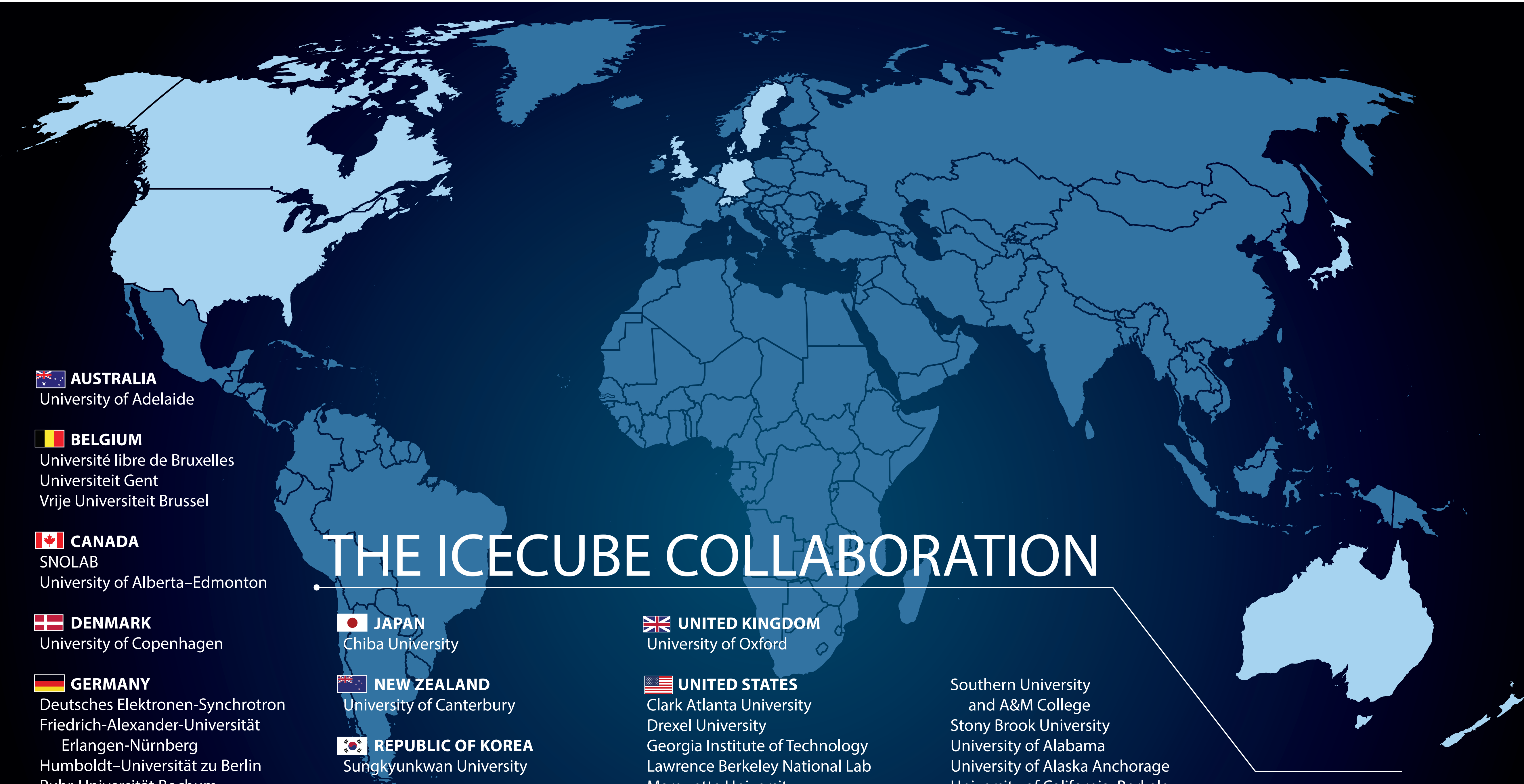
M. Jeong, W. Kang, ICRC2017

With large data set of GeV - PeV neutrinos, wide range of physical phenomena accessible with IceCube DeepCore.

With IceCube Gen2, physics reach would be even greater, and we hope to demonstrate this with the IceCube Upgrade!

BACKUPS

A global endeavour



THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms Universitet
Uppsala Universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
South Pole Neutrino Observatory

Beating the background

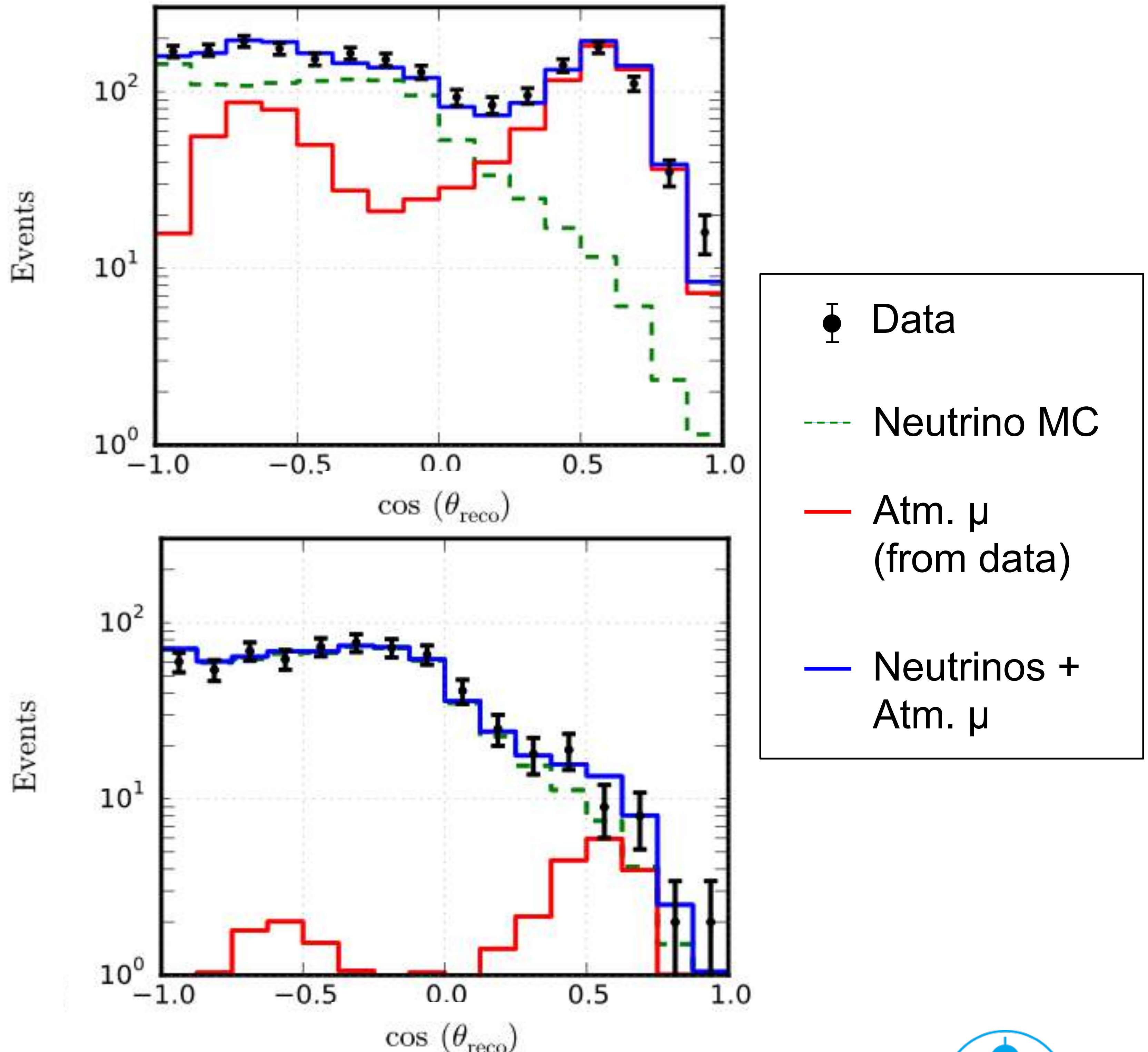
Trigger level

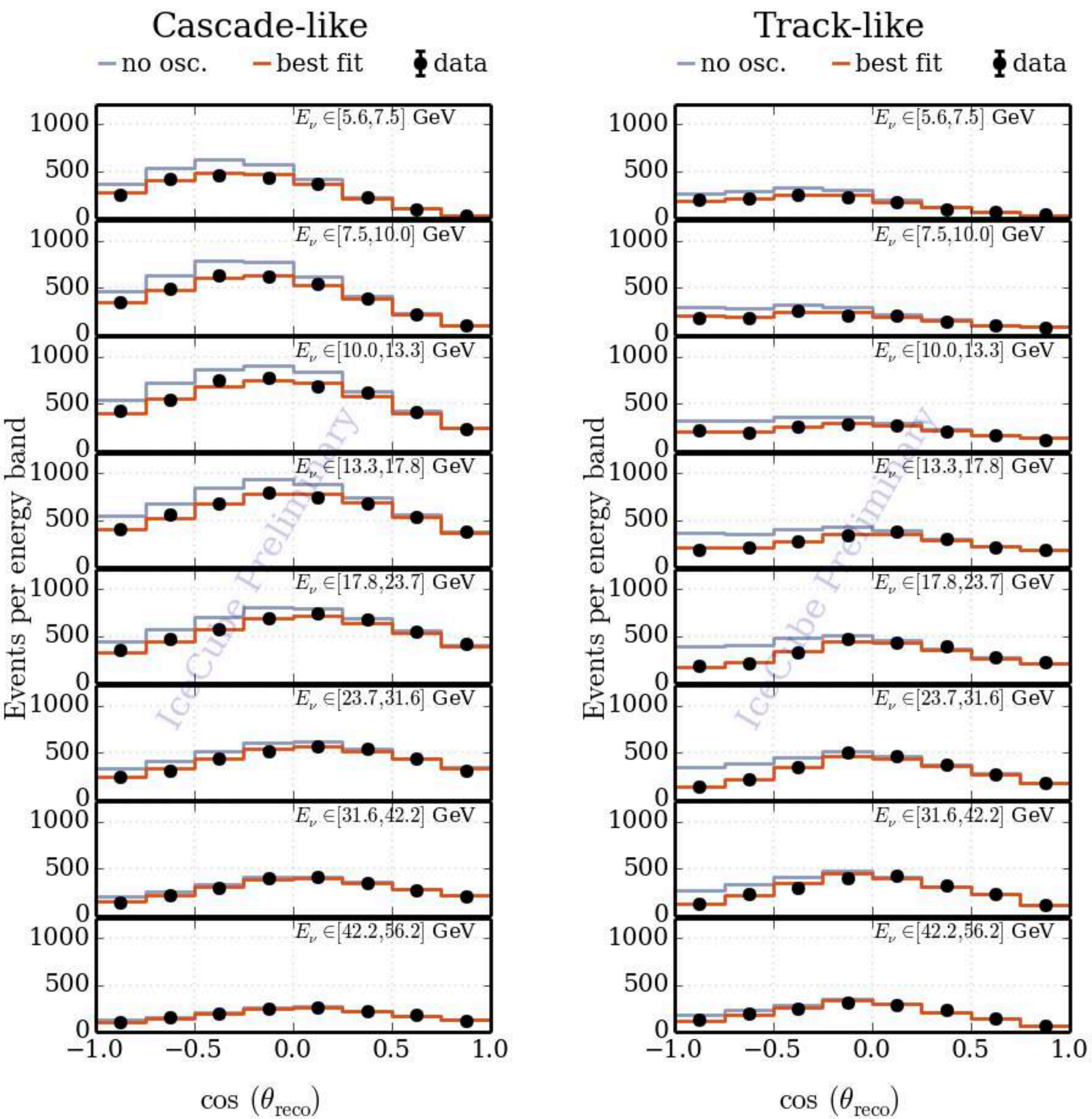
~$10^6\mu$: 1ν

- Veto
  - Up-going events: use Earth as a veto
  - Outer layers of IceCube
  - Veto cap
- Starting events with first hits inside fiducial volume

Final level

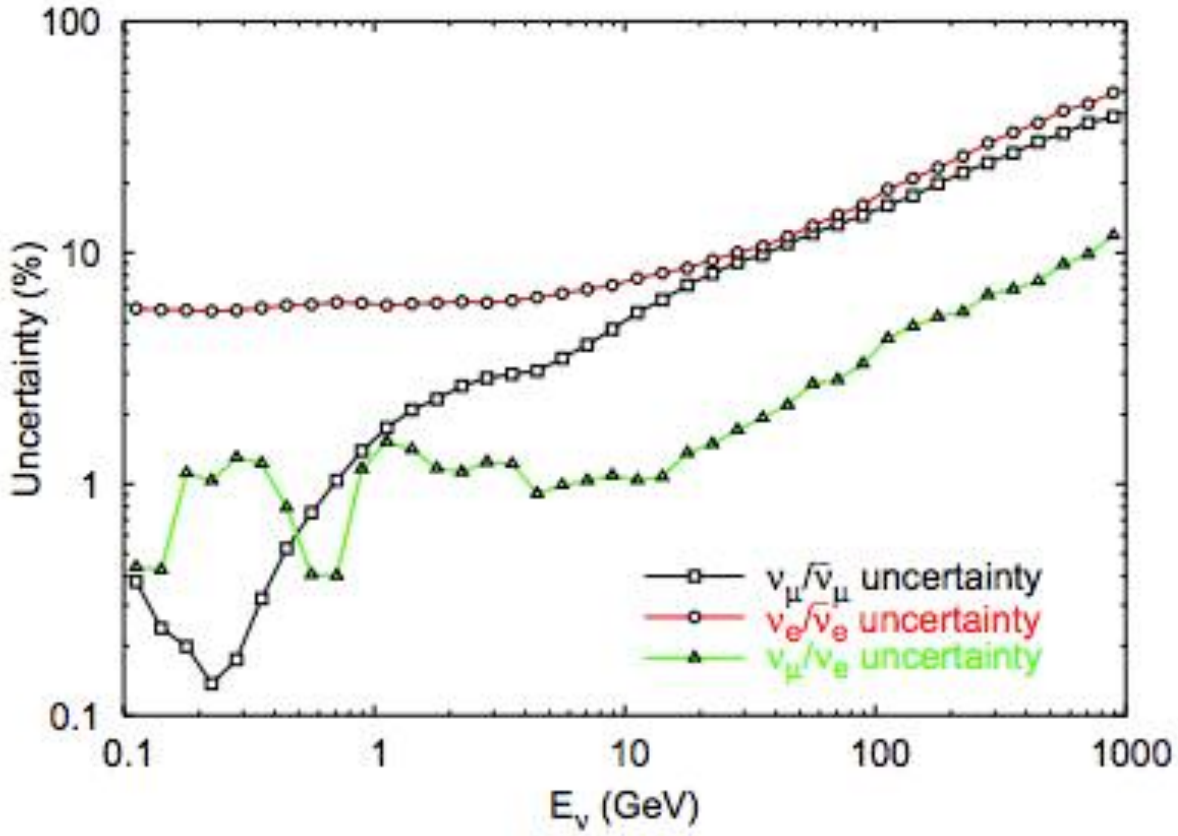
<1% μ

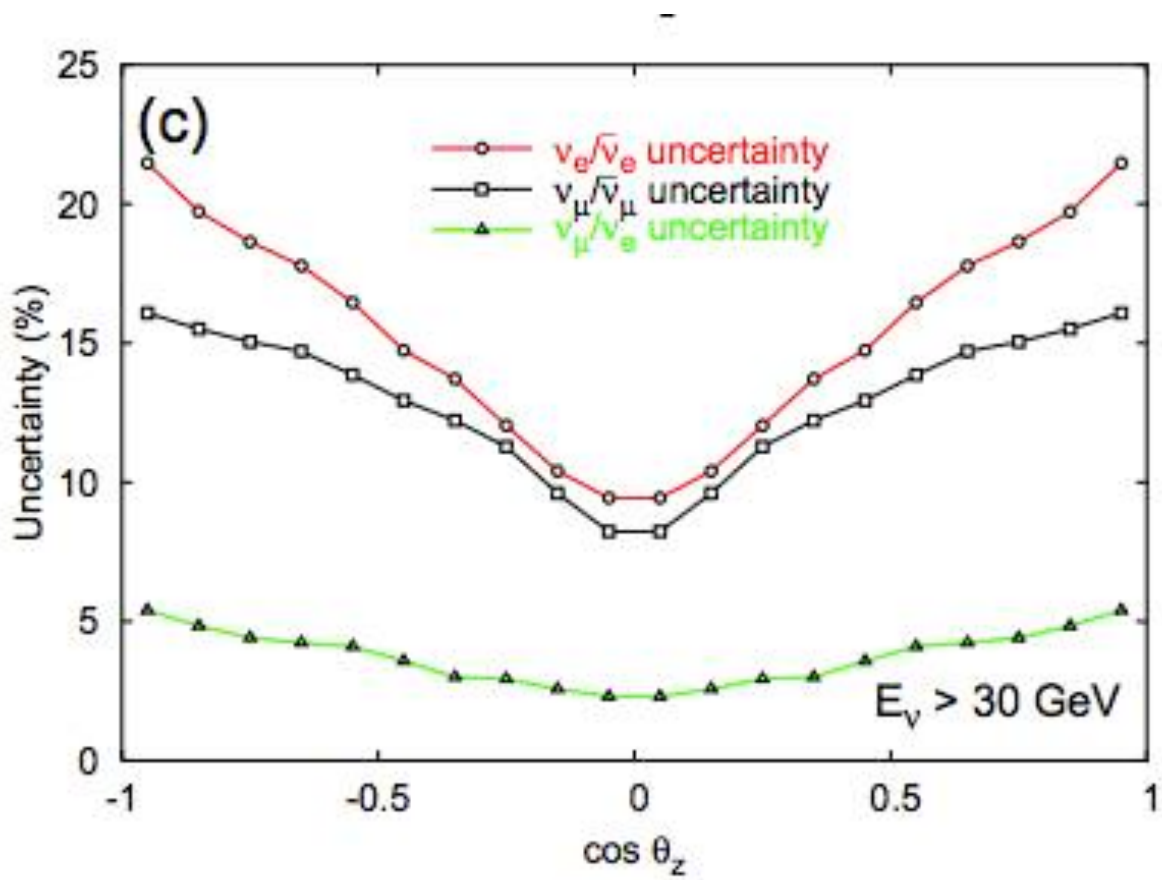


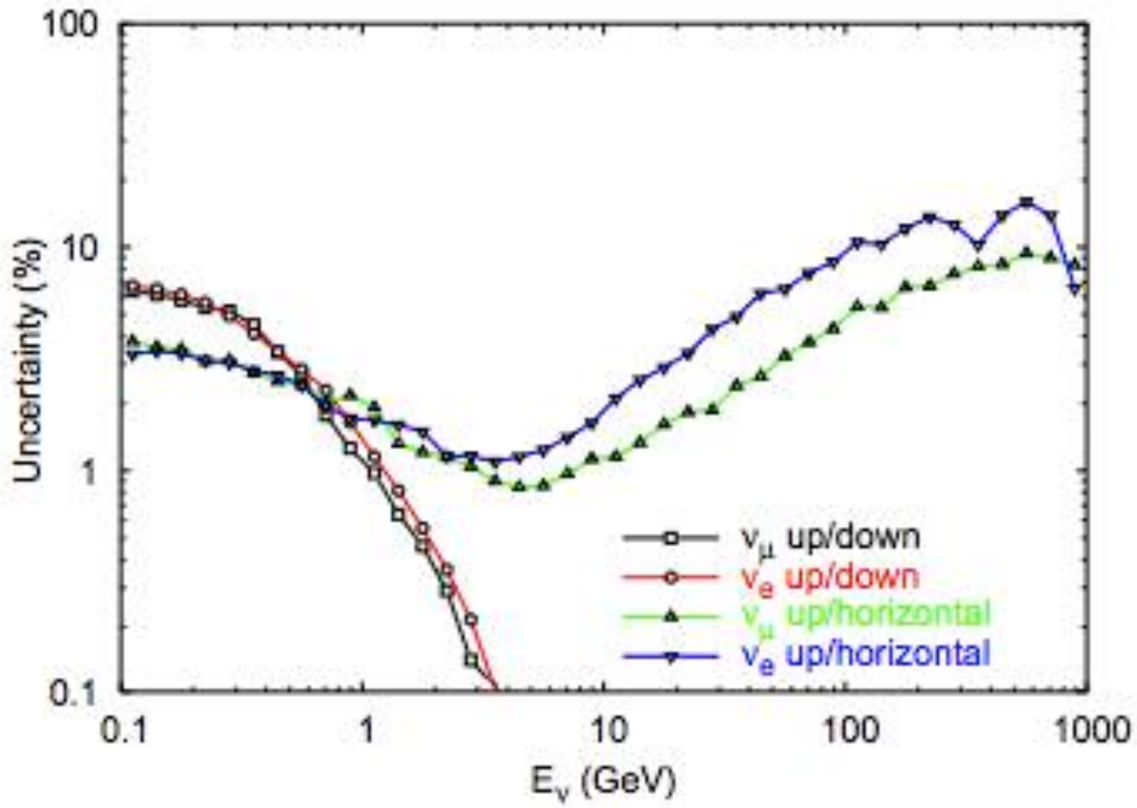


Cascade-like
no osc.
best fit
data
Track-like
no osc.
best fit
data
Events per energy band
$E_\nu \in$[5.6,7.5] GeV
$E_\nu \in$[7.5,10.0] GeV
$E_\nu \in$[10.0,13.3] GeV
$E_\nu \in$[13.3,17.8] GeV
$E_\nu \in$[17.8,23.7] GeV
$E_\nu \in$[23.7,31.6] GeV
$E_\nu \in$[31.6,42.2] GeV
$E_\nu \in$[42.2,56.2] GeV
IceCube Preliminary
$\cos(\theta_{reco})$

Atmospheric flux uncertainties in detail







Uncertainties based on Barr *et al*: https://arxiv.org/pdf/astro-ph/0611266v1.pdf

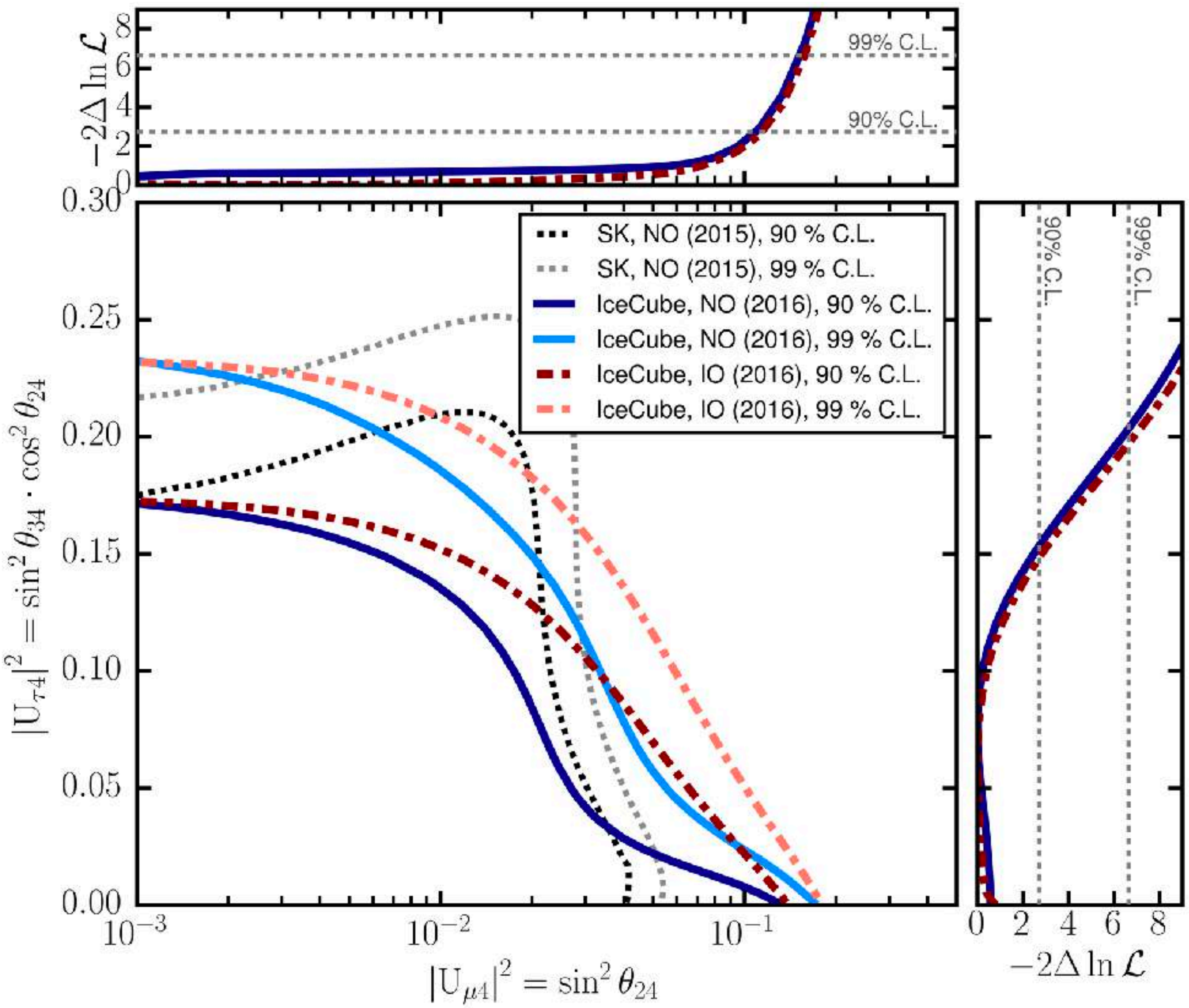
NuMu Disappearance – best fit point for all parameters

TABLE I. Table of nuisance parameters along with their associated priors, if applicable. The right two columns show the results from our best fit for normal mass ordering and inverted mass ordering, respectively.

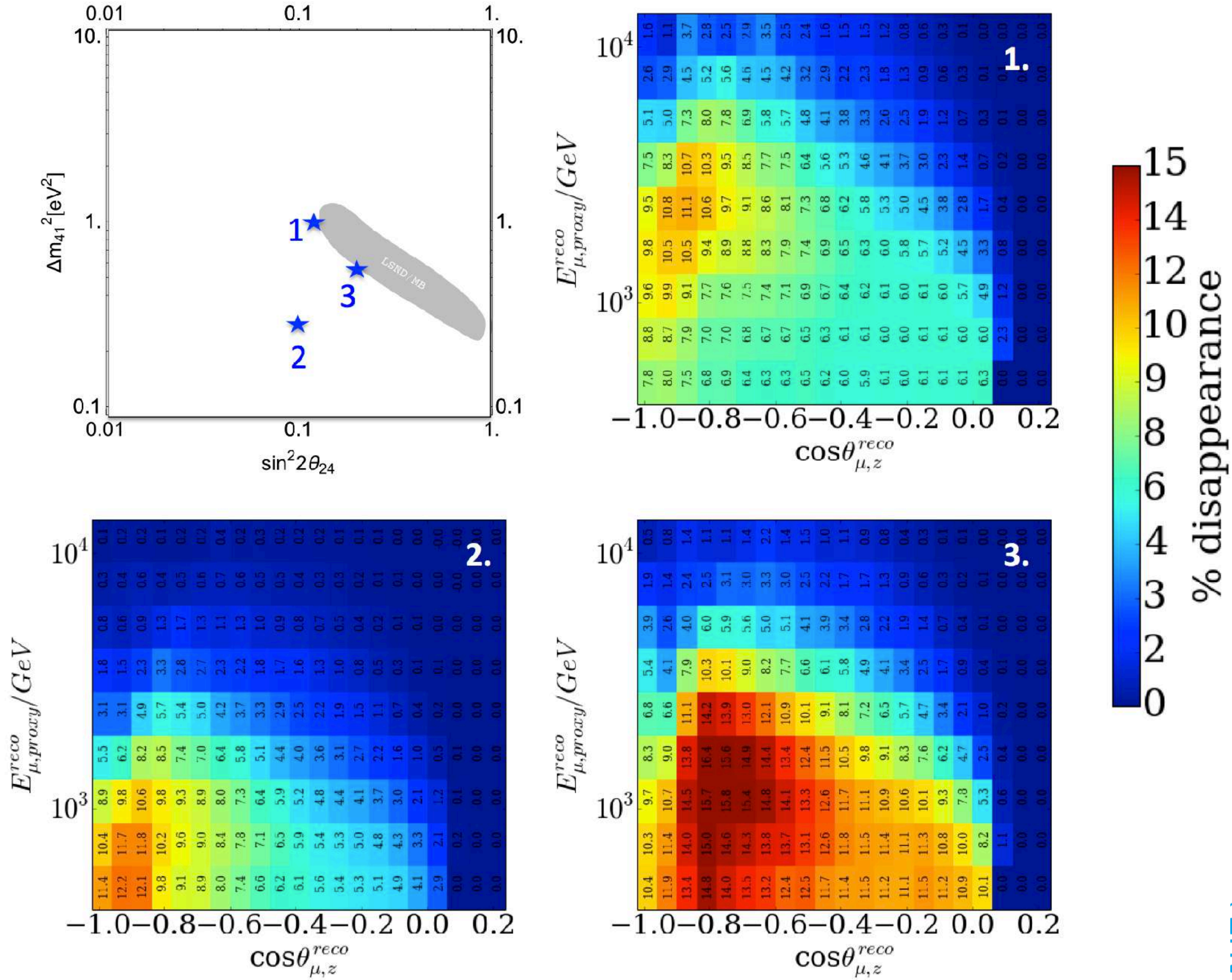
Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent [46]	0.00±1.00	-0.56	-0.59
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent [46]	0.00±1.00	-0.55	-0.57
Detector parameters			
overall optical eff. [%]	100±10	102	102
relative optical eff., lateral [σ]	0.0±1.0	0.2	0.2
relative optical eff., head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

Sterile neutrinos at low energies

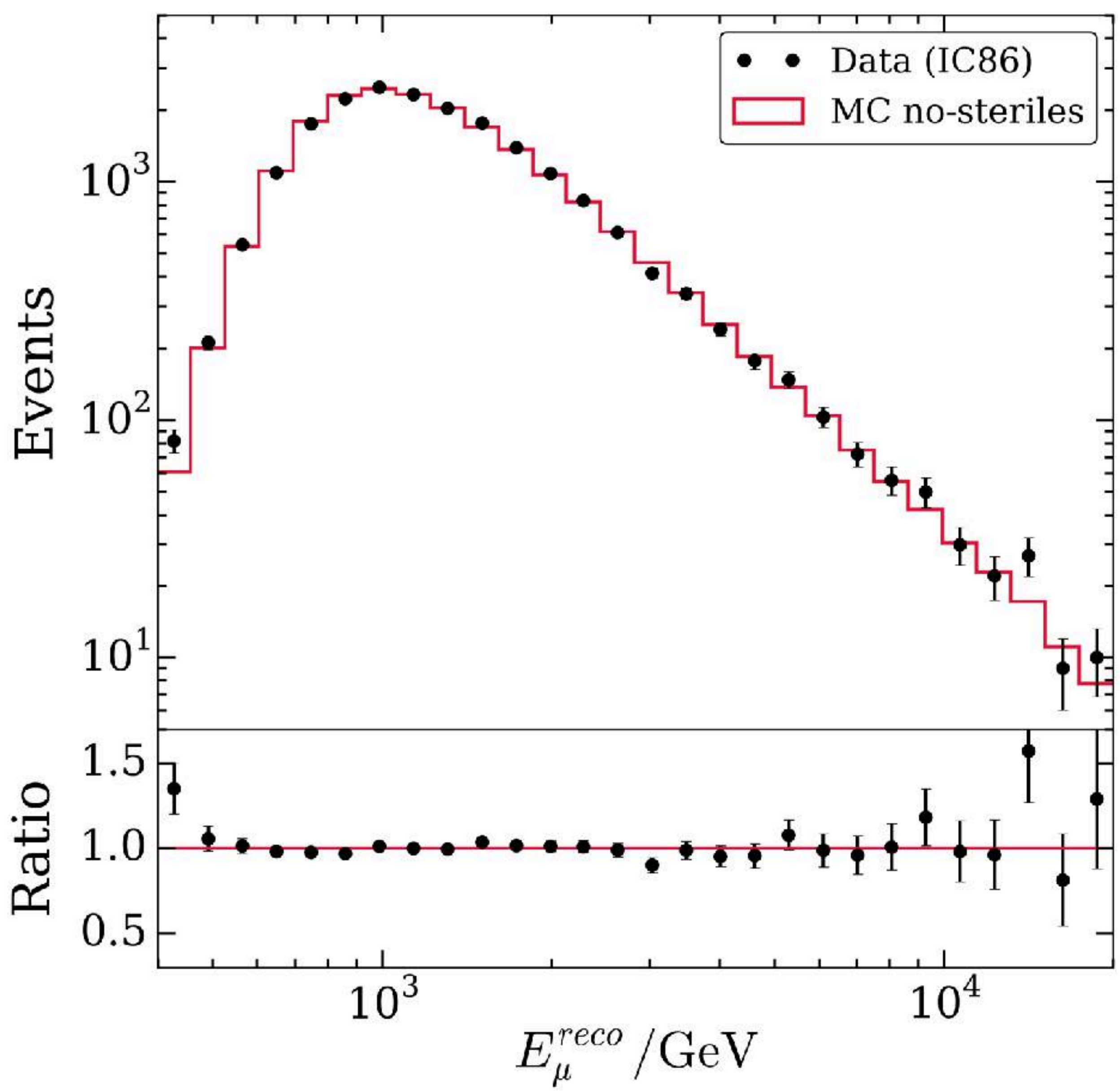
- χ^2/d.o.f. = 55.2/57
- Strongest constraint on $|U_{\tau 4}|^2$
- In regime where $U_{\tau 4}$ and $U_{\mu 4}$ are both non-zero, measurement would have sensitivity to standard neutrino mass ordering as well

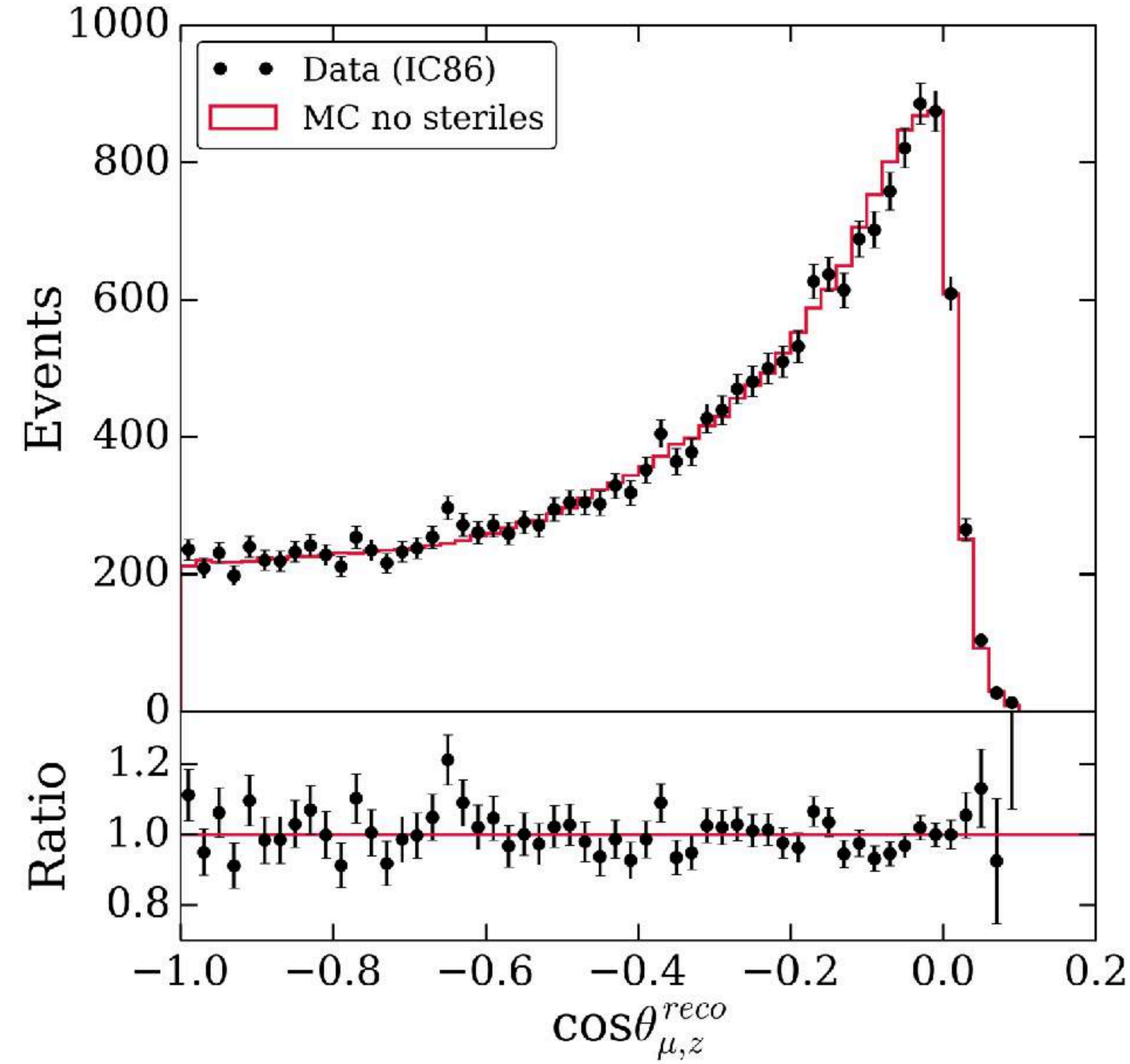


Sterile neutrinos at high energies: e.g. Reco distributions



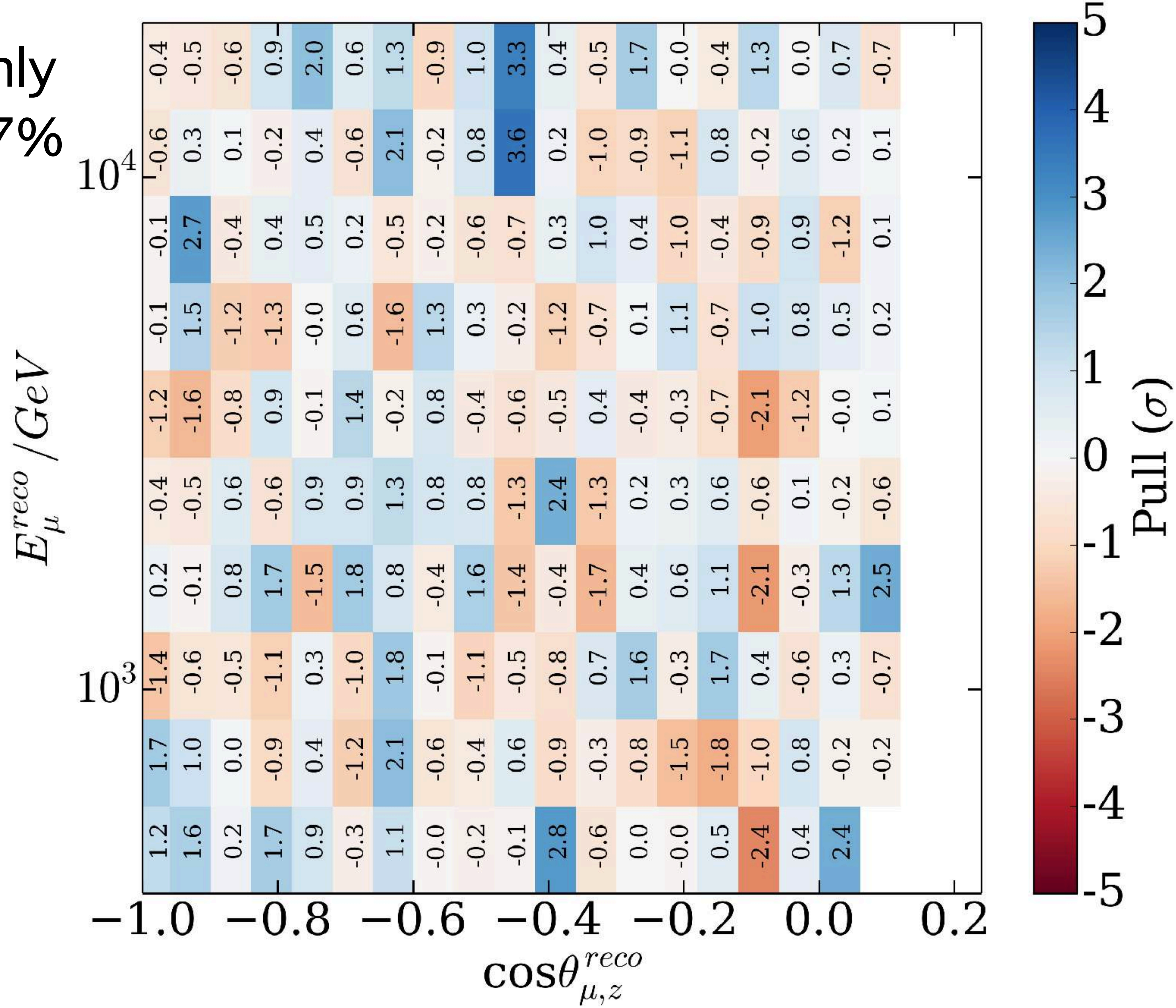
Sterile neutrinos at high energies





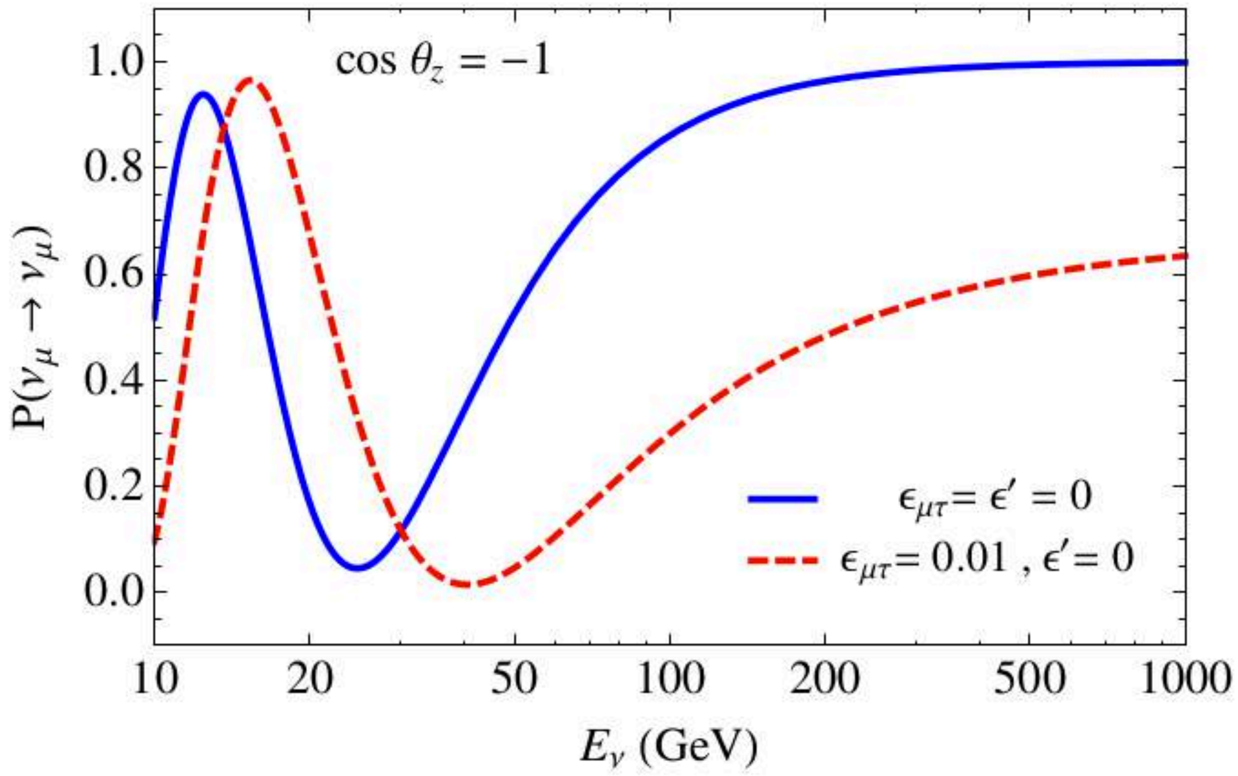
Sterile neutrinos at high energies

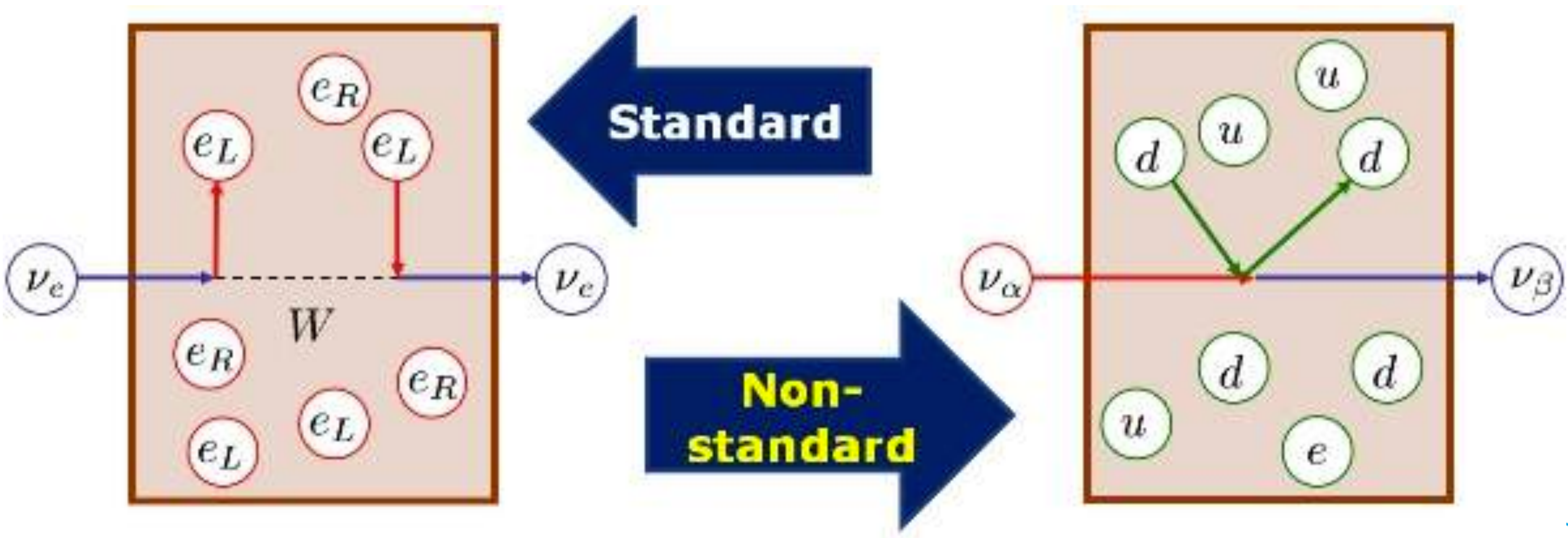
Statistics only
p-value = 17%



Non-standard interactions

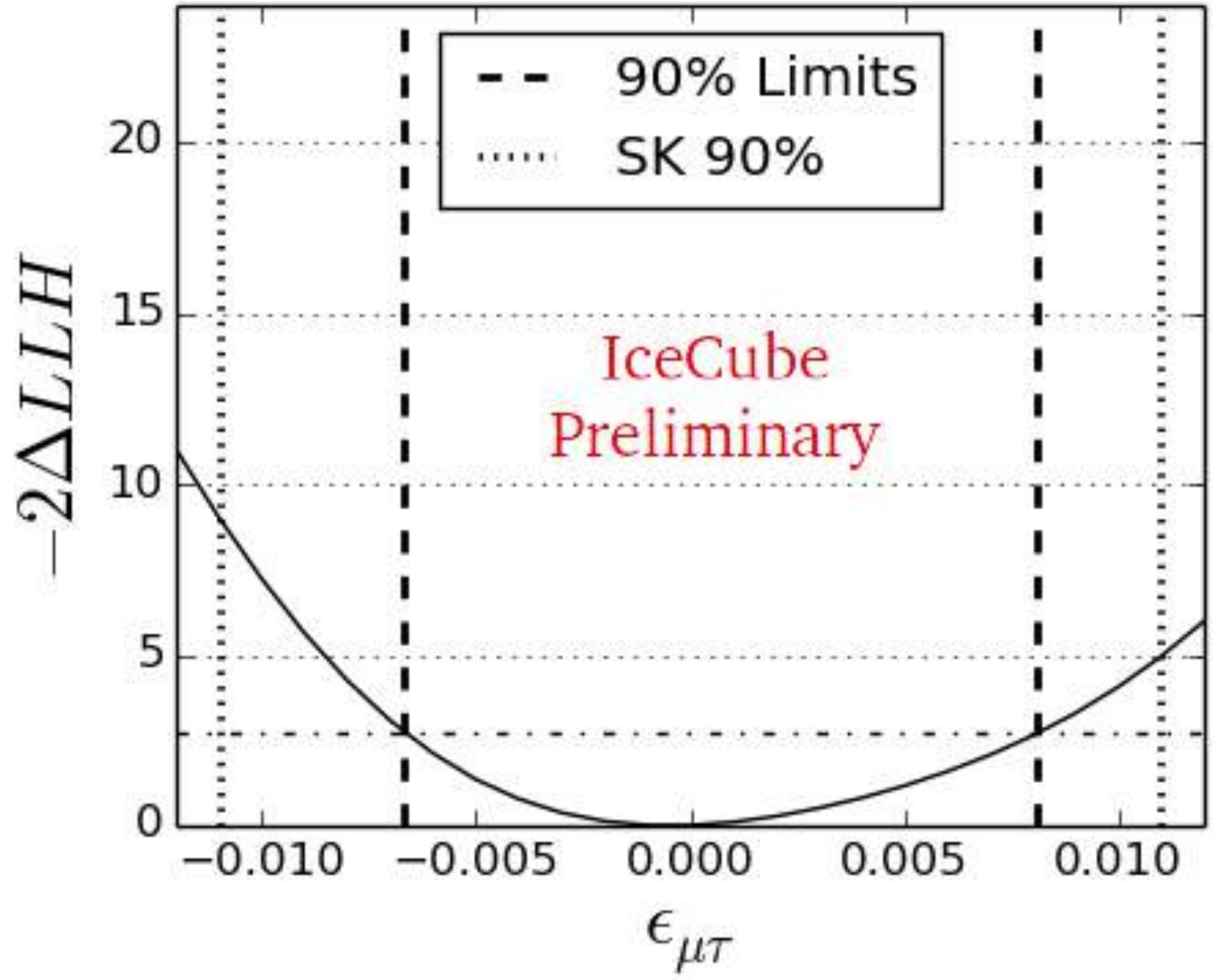
- New vector bosons (e.g. W', Z') could mediate weak interaction
- Impacts effective potential for neutrinos crossing the earth
  - Matter effects



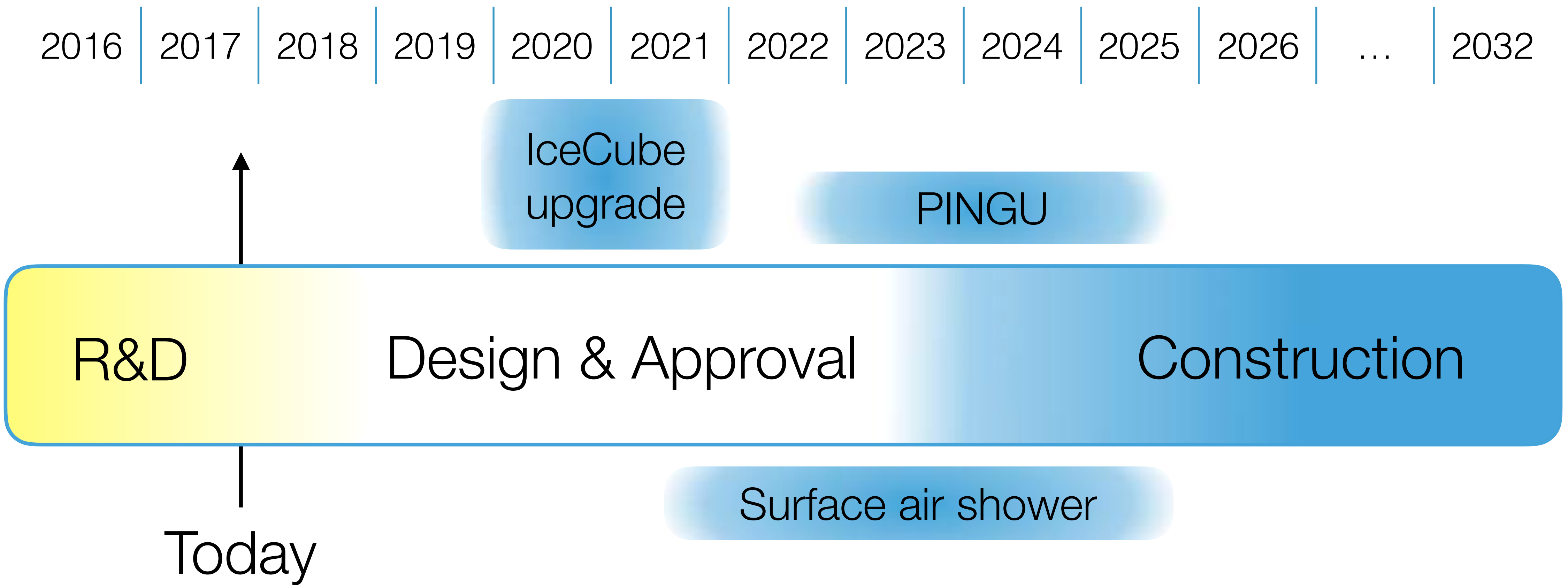


Non-standard interactions

- Using 3-year low energy up-going track sample
- Data consistent with null-hypothesis
  - Only standard interactions
- Exclusion contour derived for non-standard coupling $\varepsilon_{\mu\tau}$



Preliminary timeline - Gen2



New optical module designs

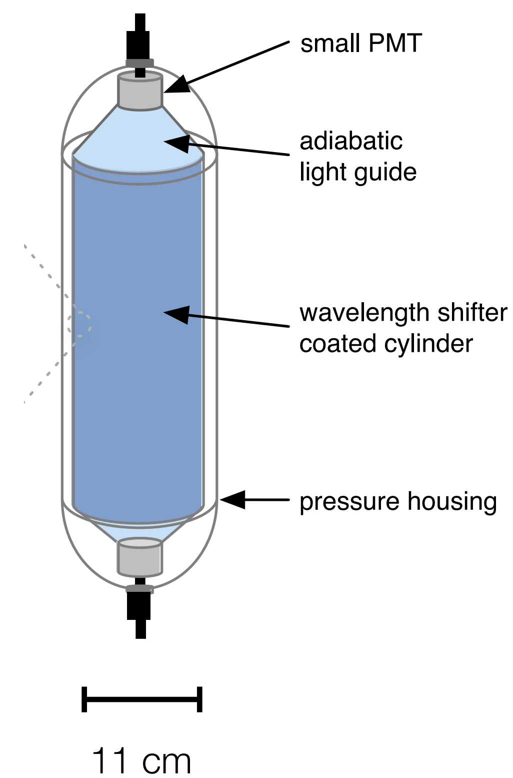
mDOM

- Directional information
- More sensitive area per module

D-Egg

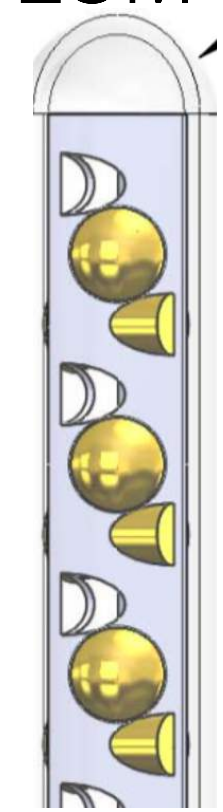
- Directional information
- More sensitive area per module
- Smaller geometry

WOM



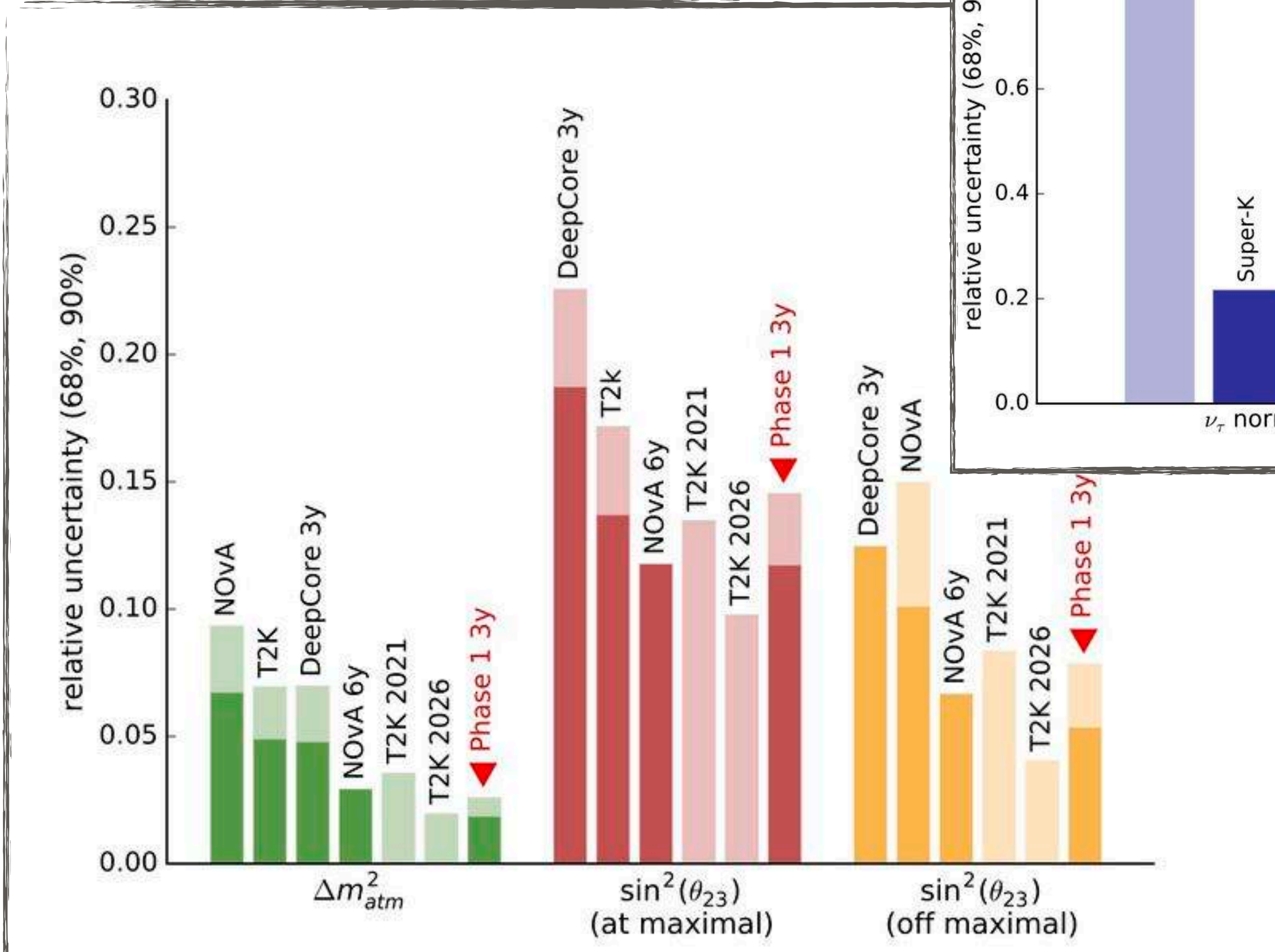
- more sensitive area per $
- Small diameter
- Lower noise rate

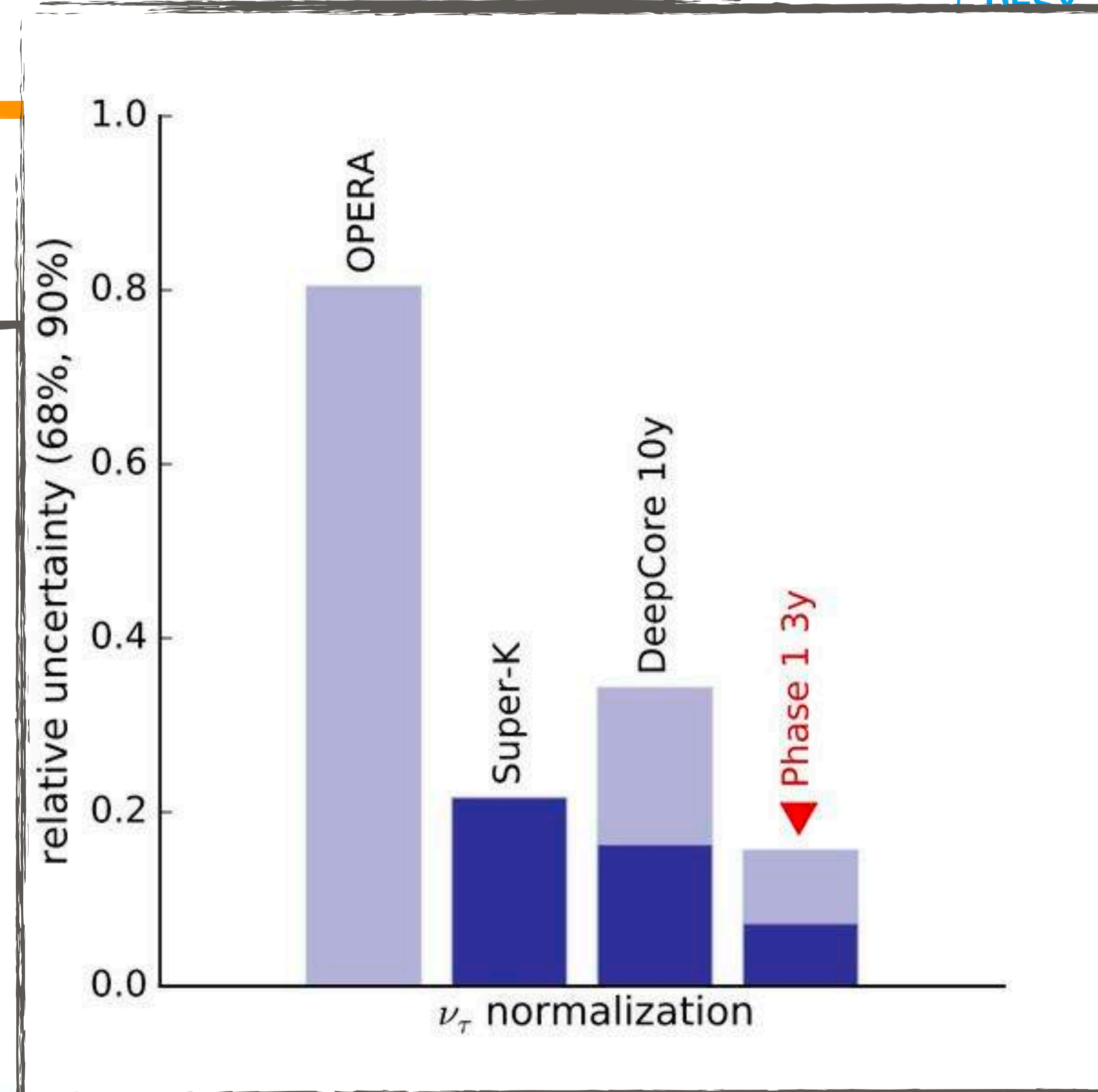
LOM



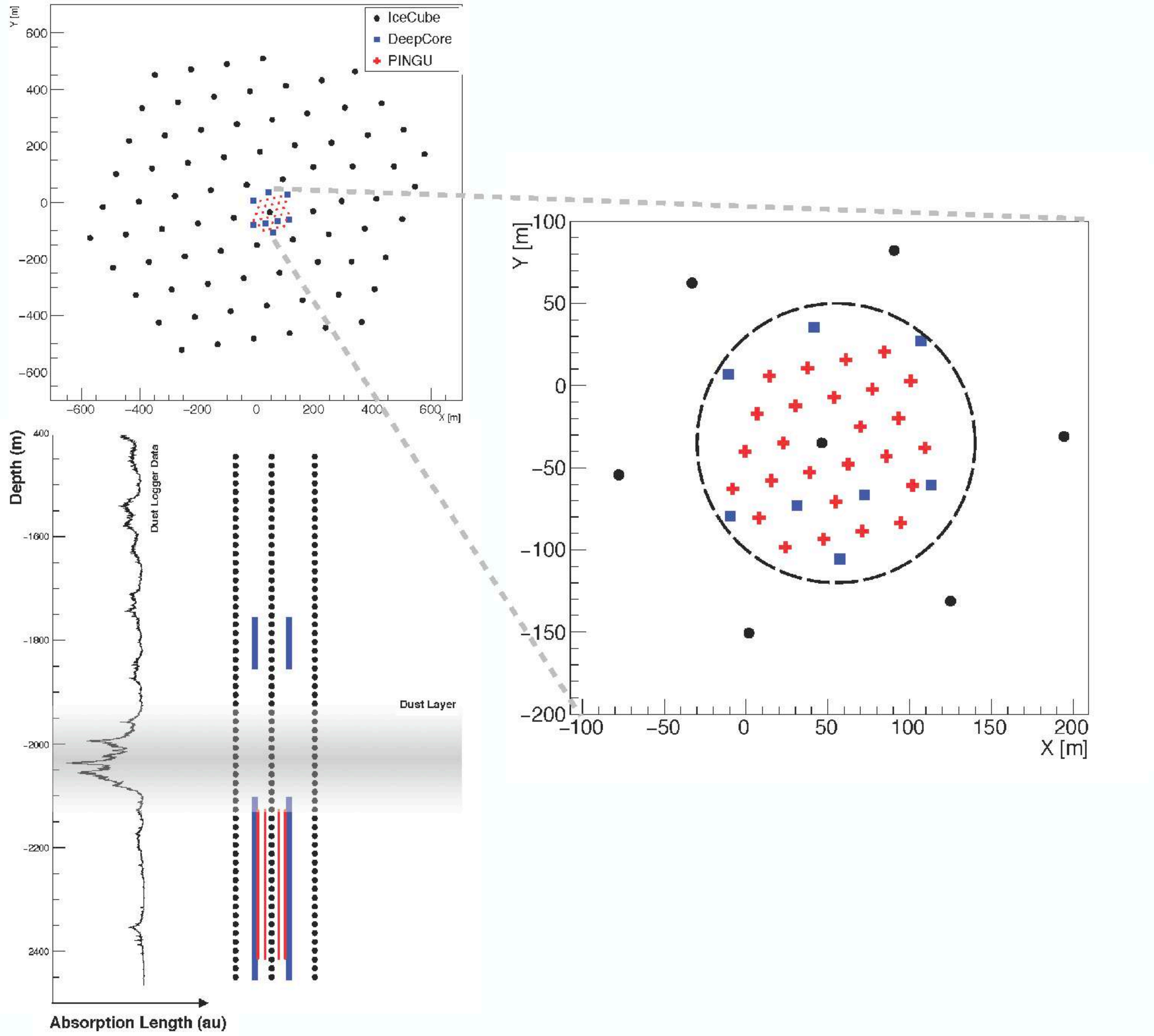
- Small diameter
- Directional info.
- More area per module

IceCube Gen2-Phase1

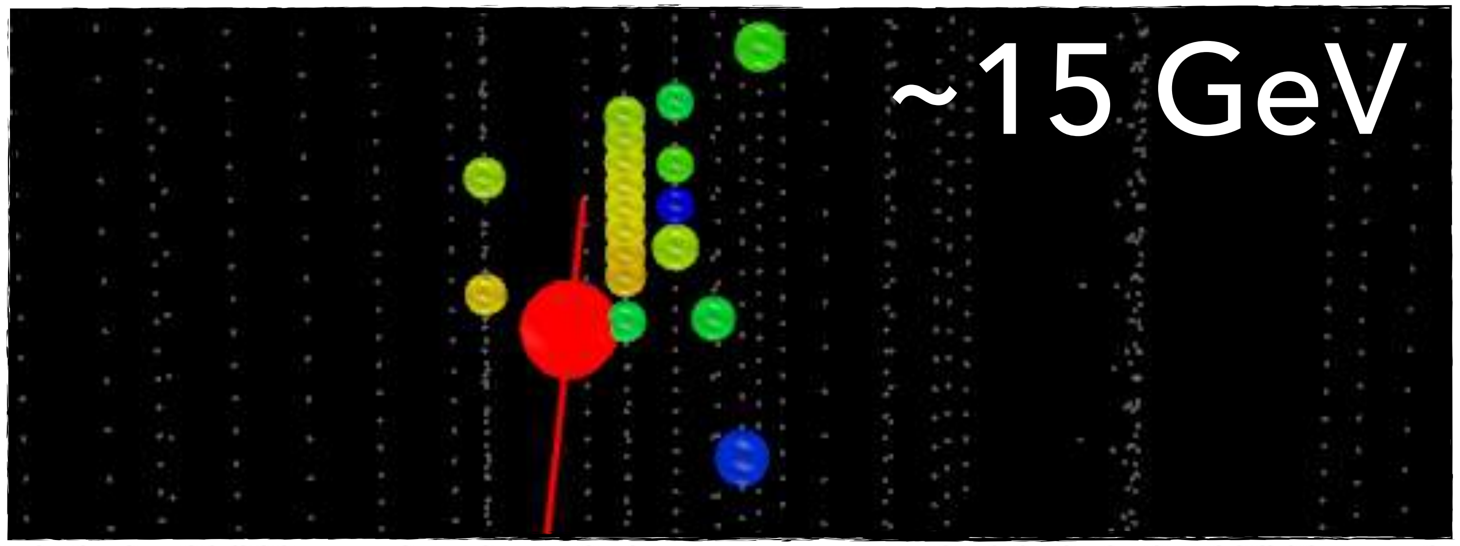




PINGU


IceCube
DeepCore
PINGU
Y [m]
X [m]
Depth (m)
Dust Logger Data
Dust Layer
Absorption Length (au)
Y [m]
X [m]

PINGU – LOI v2



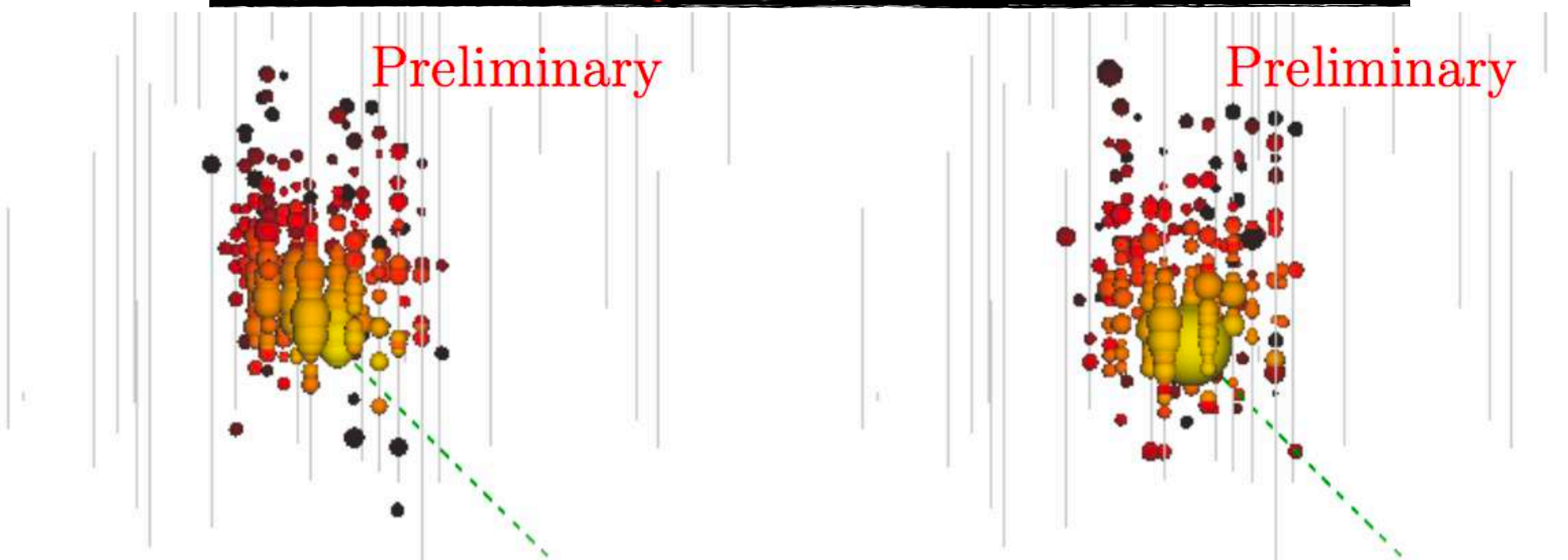
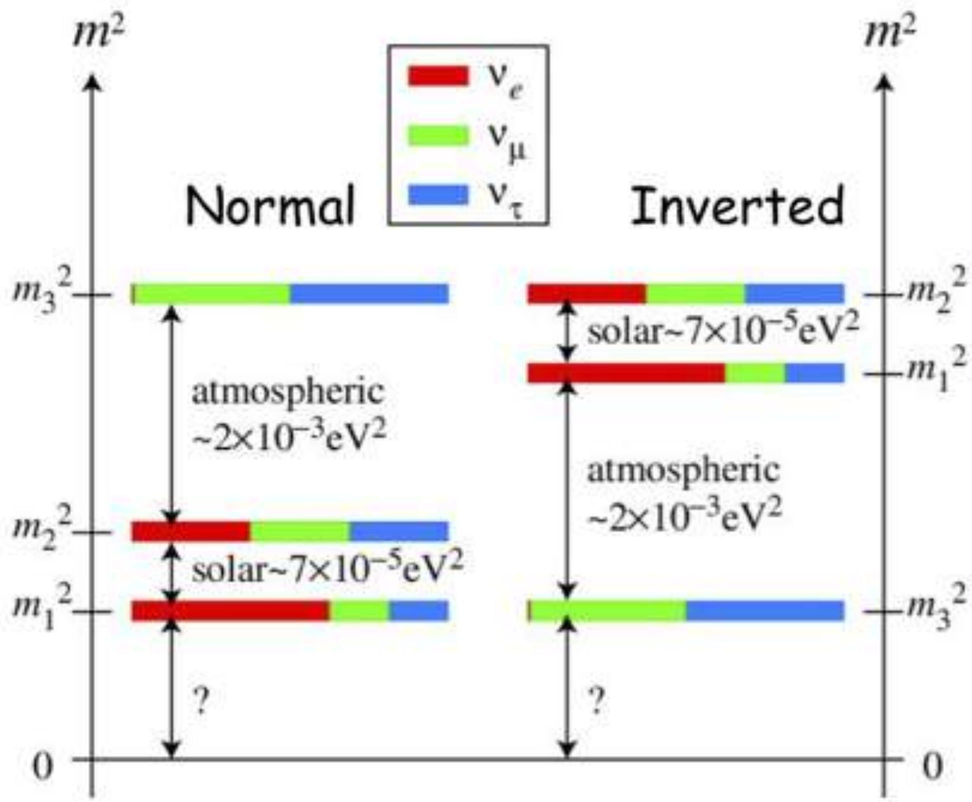
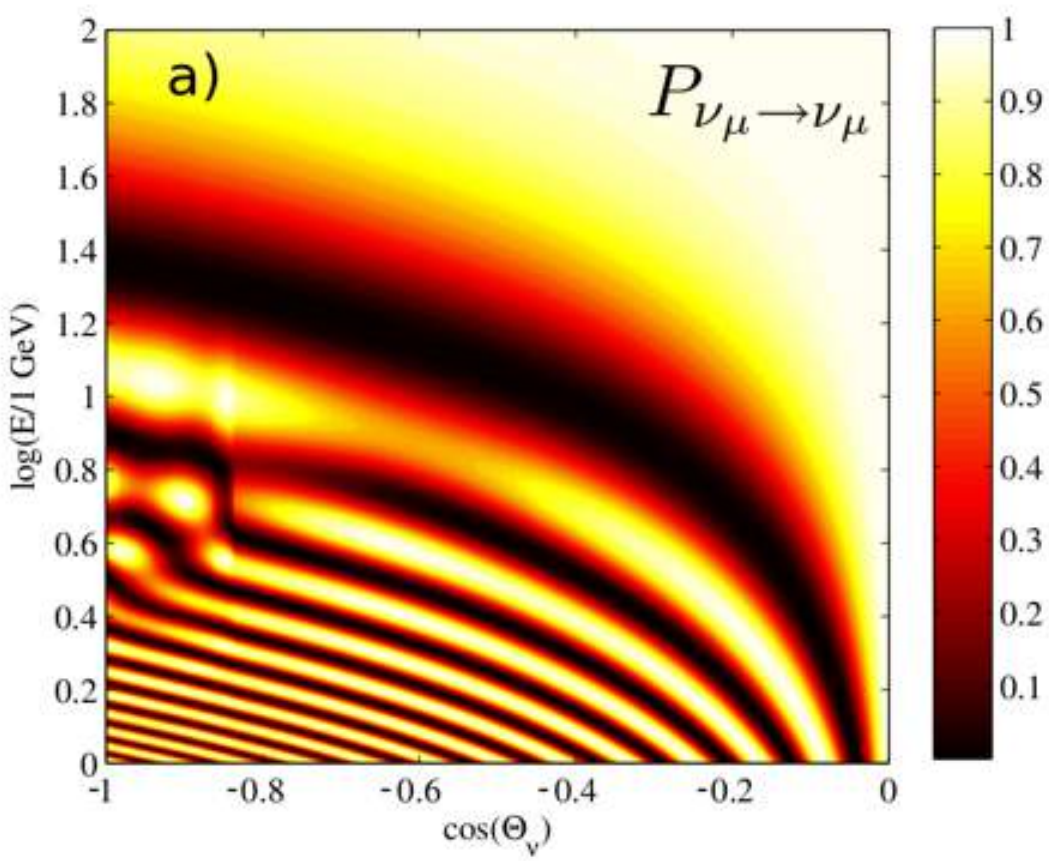


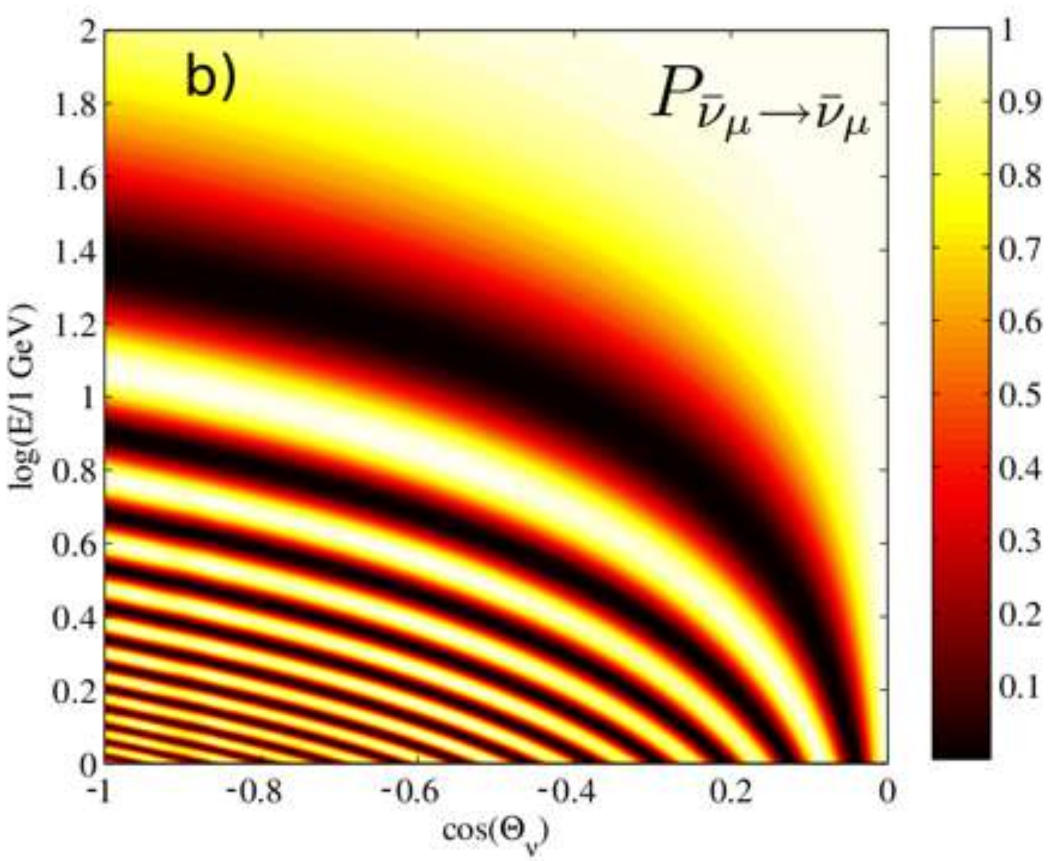
Figure 9: Event displays of a CC ν_μ (left) and a CC ν_e (right) event. The spheres indicate the DOMs which recorded photons where the total amount of charge is indicated by the size of the sphere. The color indicates the time when the DOM observed the first photon, while the dashed line shows the true neutrino direction direction. In both panels are shown 12 GeV CC ν producing a 10 GeV lepton (μ or e) crossing the detector leaving several groupings of hits on consecutive strings in a short time interval. In both cases the interaction vertex and direction is identical to make the comparison between events easier. We can distinguish the CC ν_μ and CC ν_e events by comparing if the charge is extended in the diagonal (which happens in CC ν_μ events) or more concentrated around the vertex (which indicates no μ is present in the event).

PINGU – neutrino mass ordering

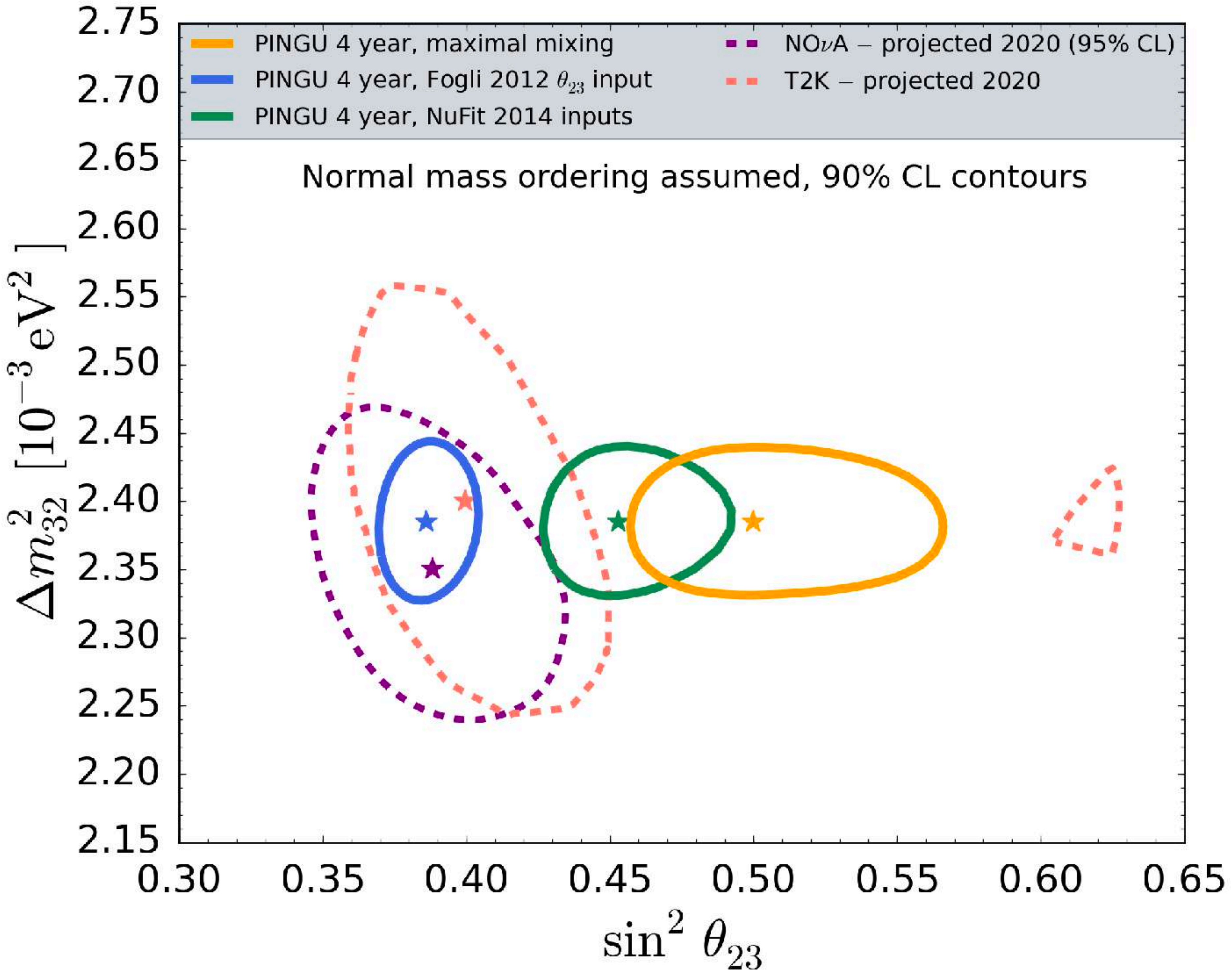
- Ordering of mass states 3 and 1(2) not known
- Matter effects induce resonance for
  - Neutrinos for normal ordering
  - Anti-nu's for inverted ordering
- Difference in flux & cross section





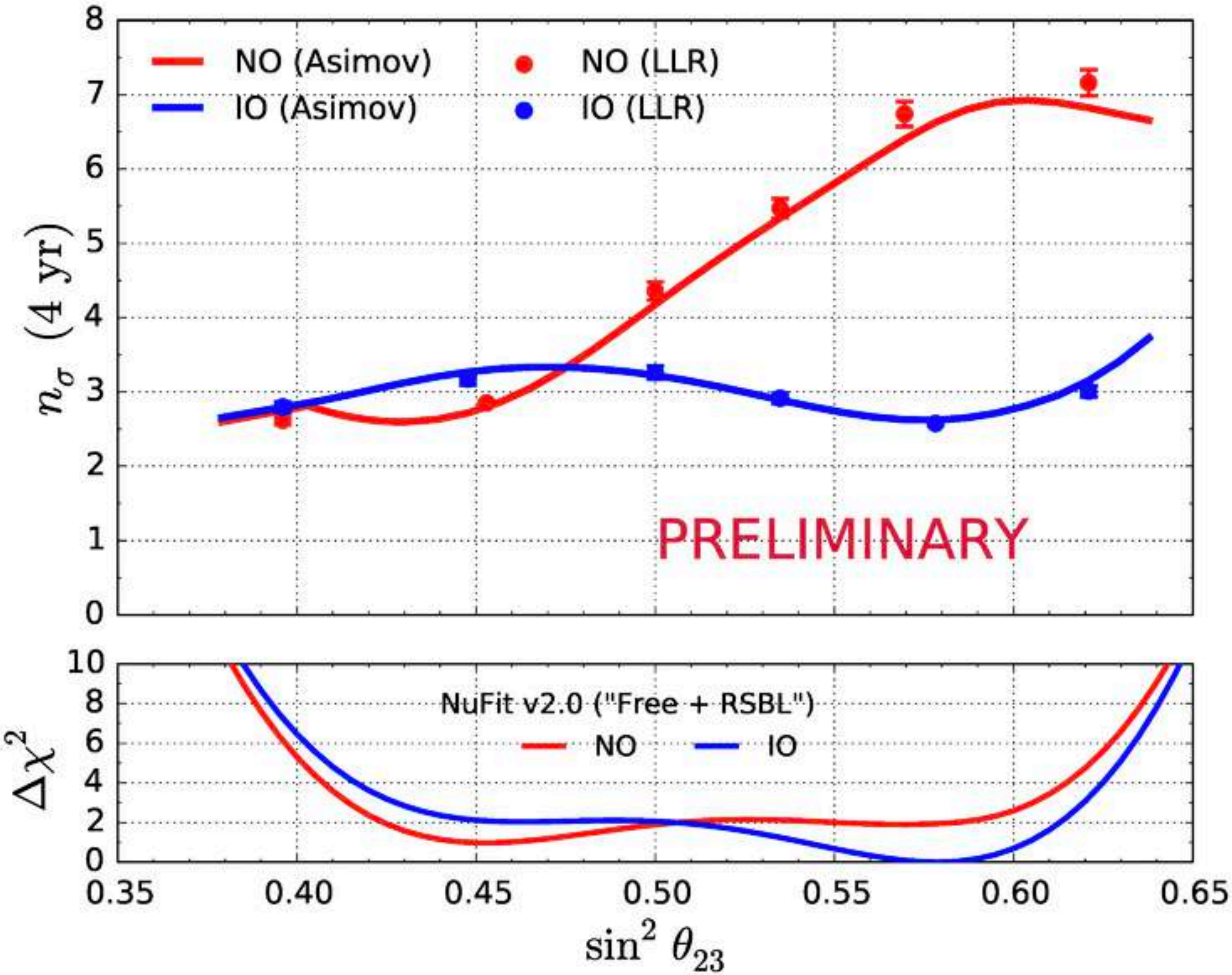


PINGU



PINGU 4 year, maximal mixing
PINGU 4 year, Fogli 2012 θ_{23} input
PINGU 4 year, NuFit 2014 inputs
NOνA – projected 2020 (95% CL)
T2K – projected 2020
Normal mass ordering assumed, 90% CL contours
Δm^2_{32} [10^{-3} eV^2]
2.75
2.70
2.65
2.60
2.55
2.50
2.45
2.40
2.35
2.30
2.25
2.20
2.15
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2\theta_{23}$

PINGU



NO (Asimov)
IO (Asimov)
NO (LLR)
IO (LLR)
PRELIMINARY
n_σ (4 yr)
NuFit v2.0 ("Free + RSBL")
NO
IO
$\Delta\chi^2$
$\sin^2\theta_{23}$
0.35
0.40
0.45
0.50
0.55
0.60
0.65