

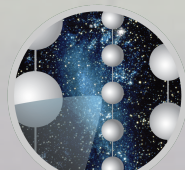
Earth Tomography Results Using High-Energy Atmospheric Neutrinos at IceCube

Alex Wen
for the IceCube Collaboration
alexwen@icecube.wisc.edu

TeVPA 2025
Valencia, Spain
6 November 2025



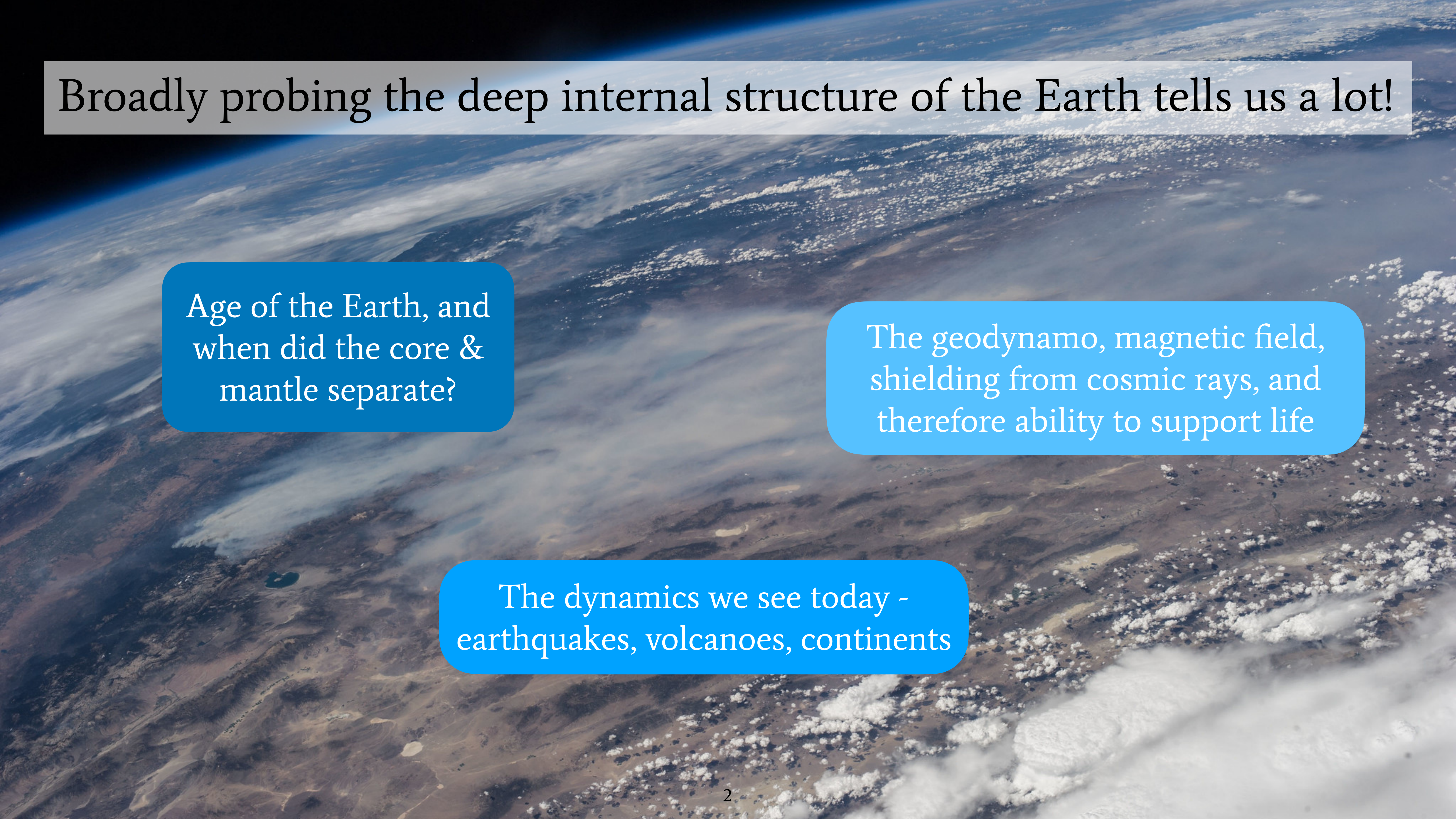
HARVARD
Department of Physics



ICECUBE
NEUTRINO OBSERVATORY



CIFAR



Broadly probing the deep internal structure of the Earth tells us a lot!

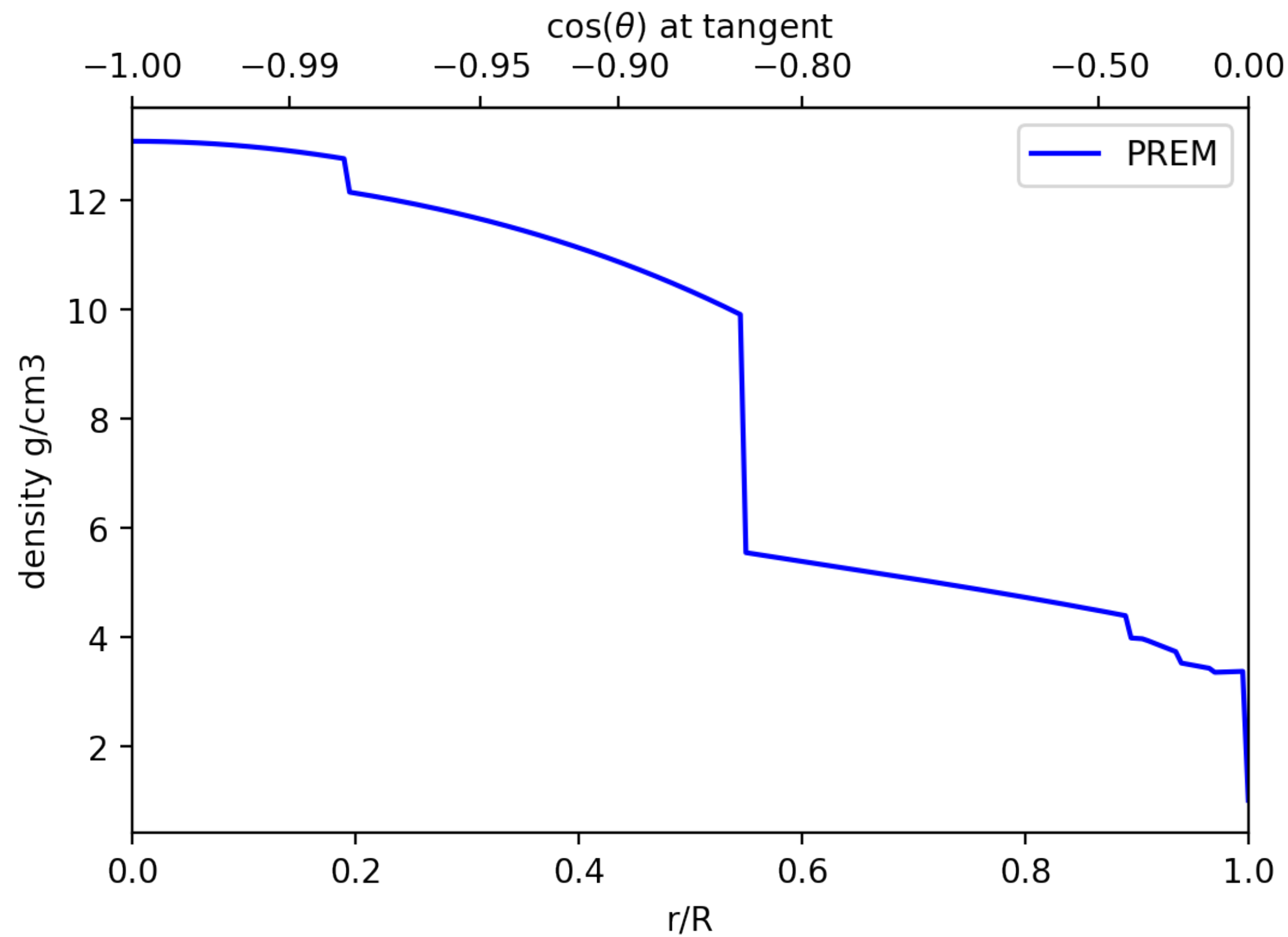
Age of the Earth, and
when did the core &
mantle separate?

The geodynamo, magnetic field,
shielding from cosmic rays, and
therefore ability to support life

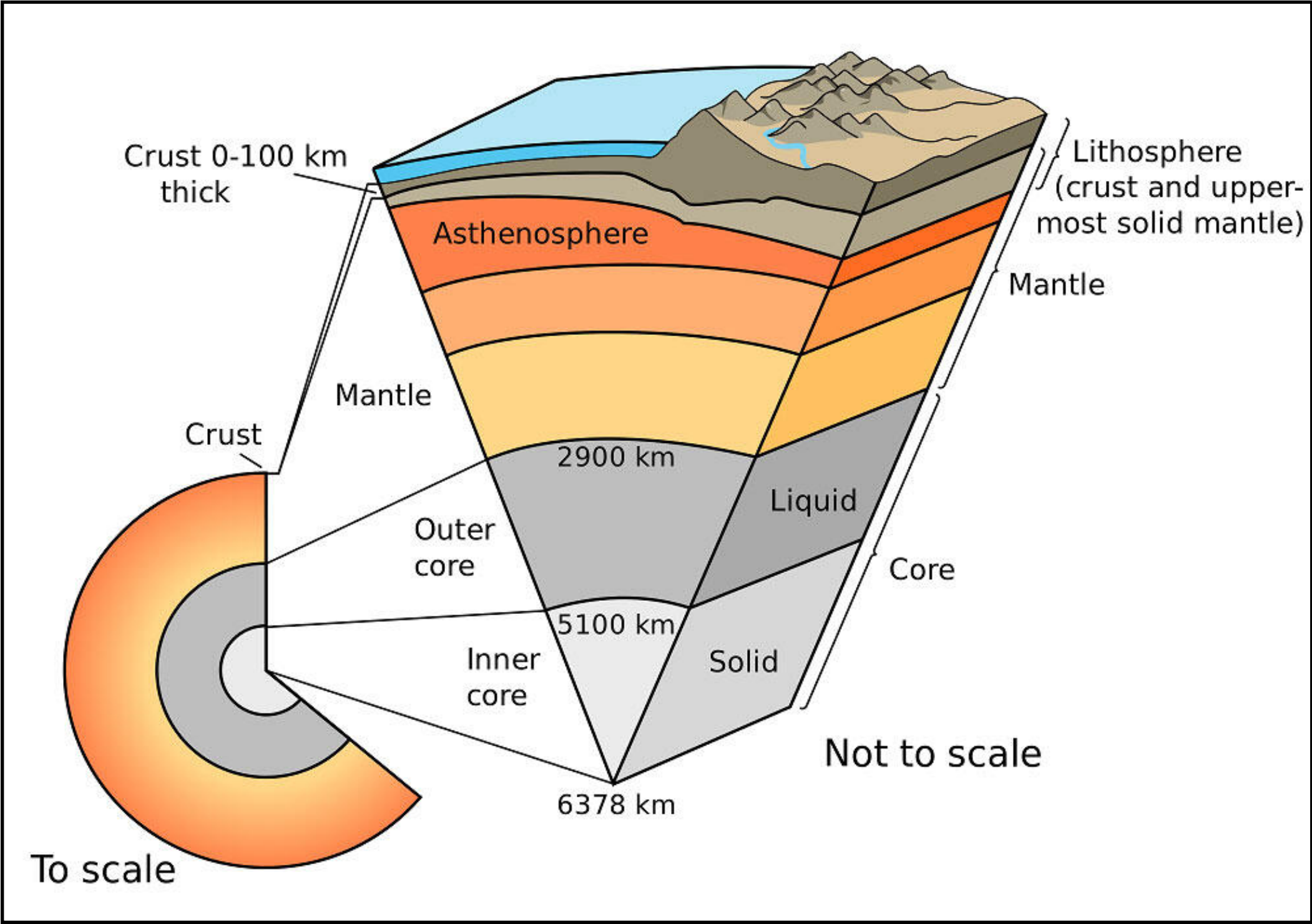
The dynamics we see today -
earthquakes, volcanoes, continents

The Preliminary Reference Earth Model: the current model of the earth density from geophysical/seismic data

PREM: A. Dziewonski, D. Anderson (Physics of the Earth and Planetary Interiors 25, 297-356) 1981

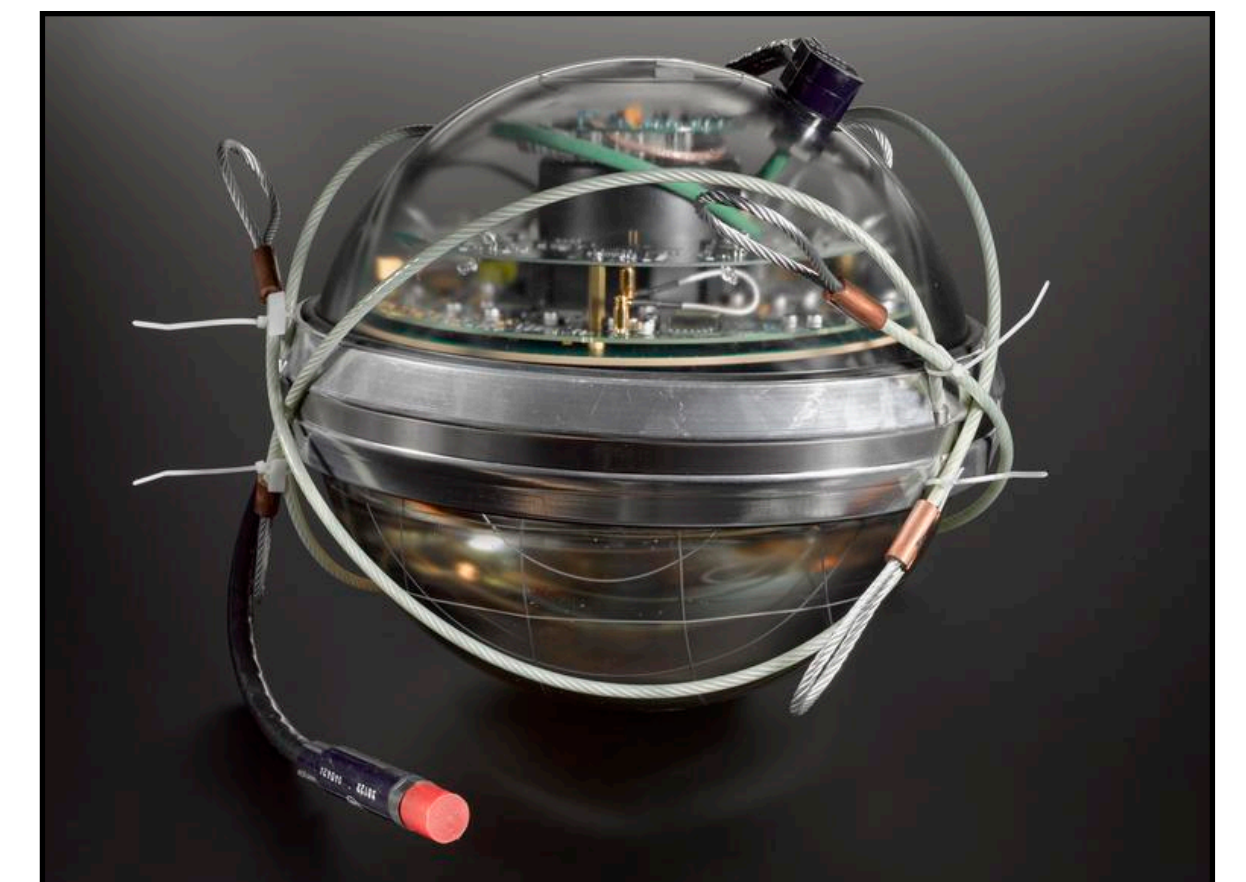
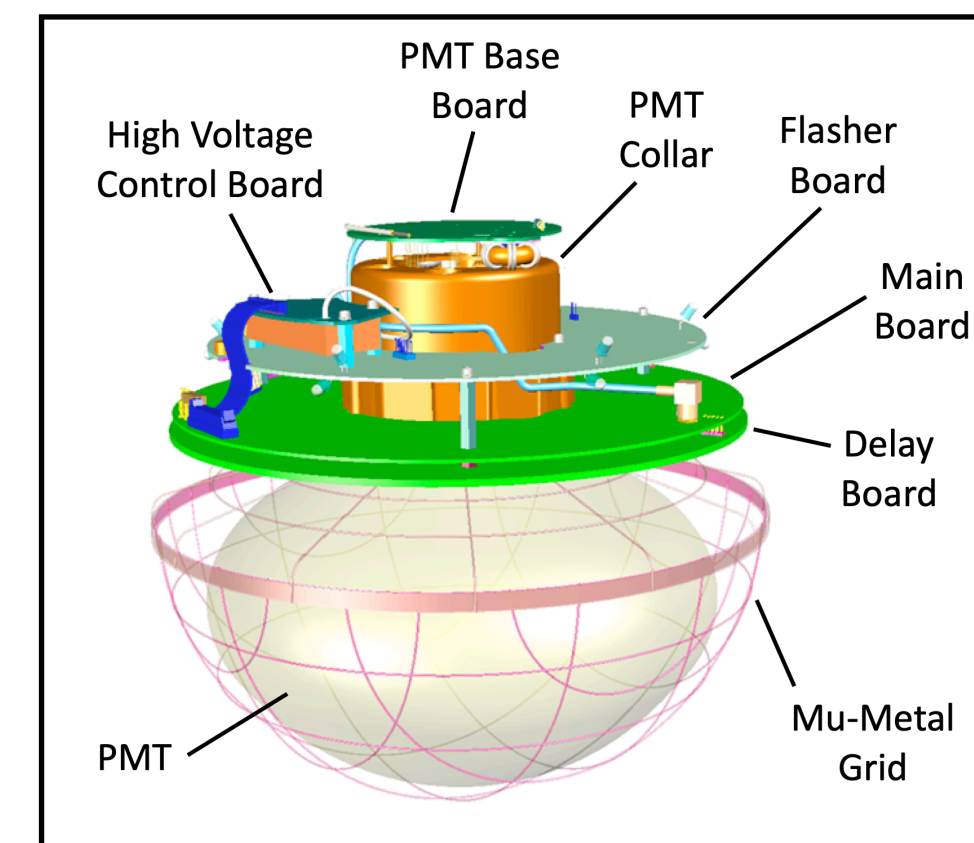
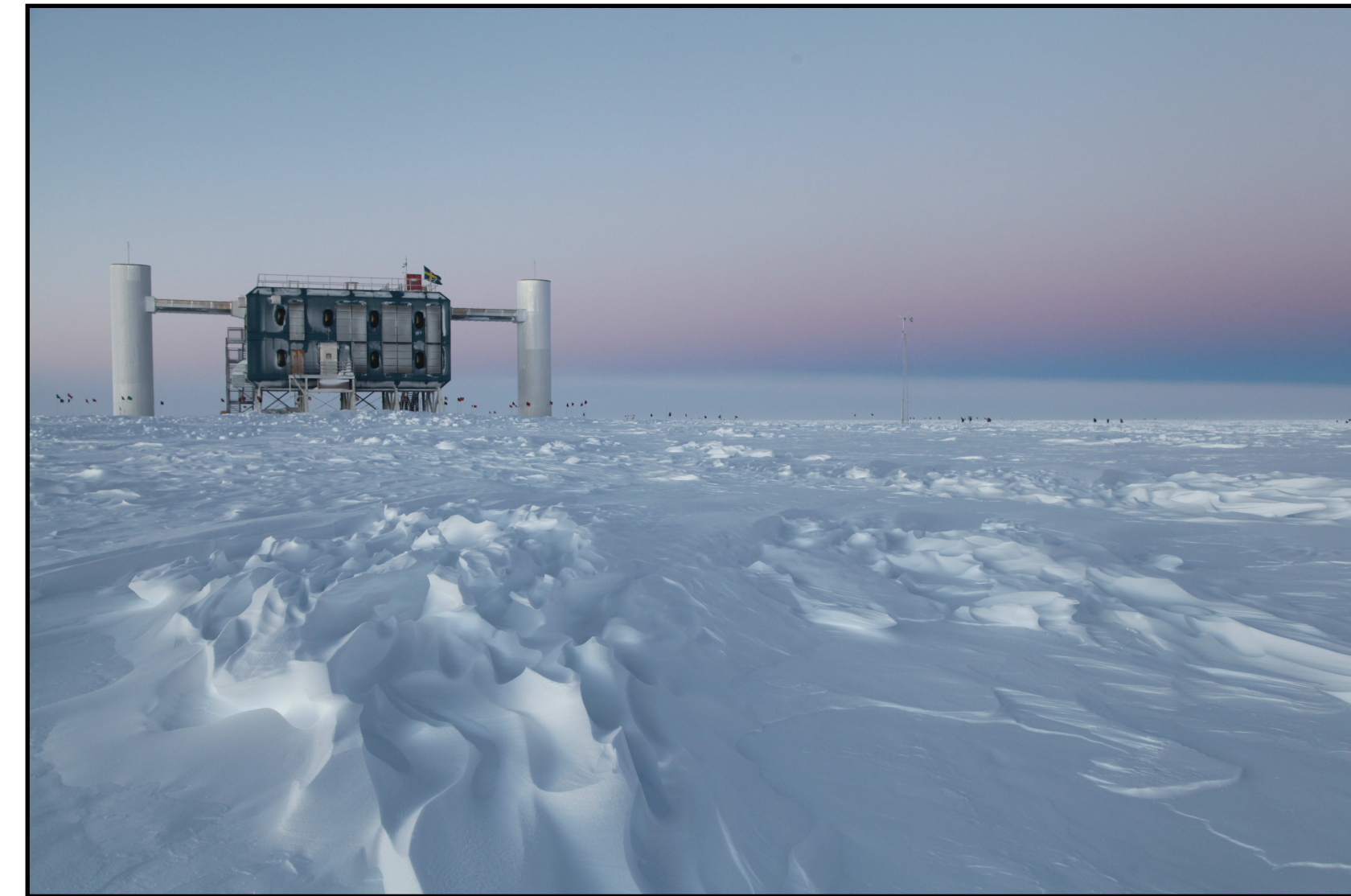
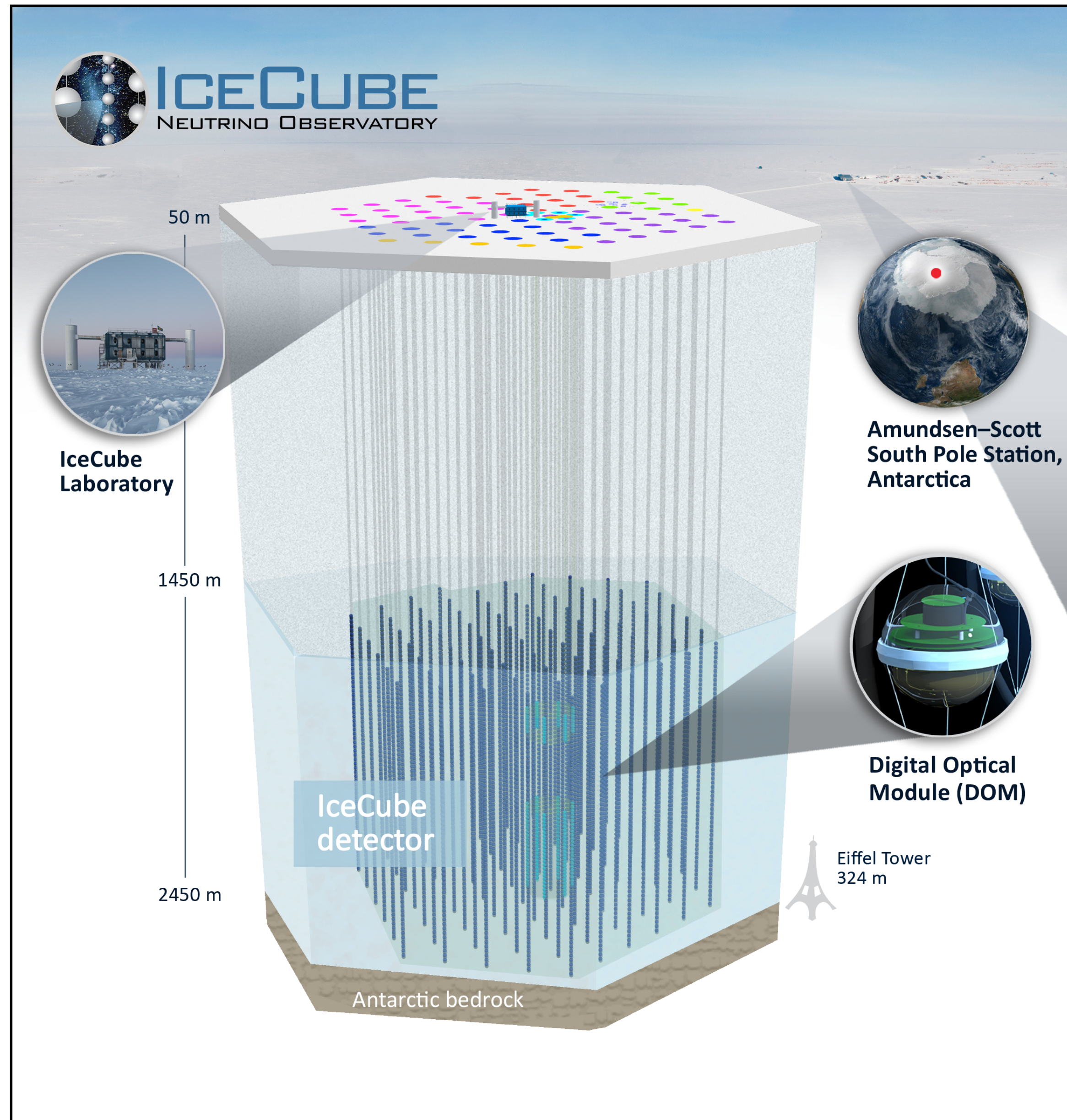


PREM density profile



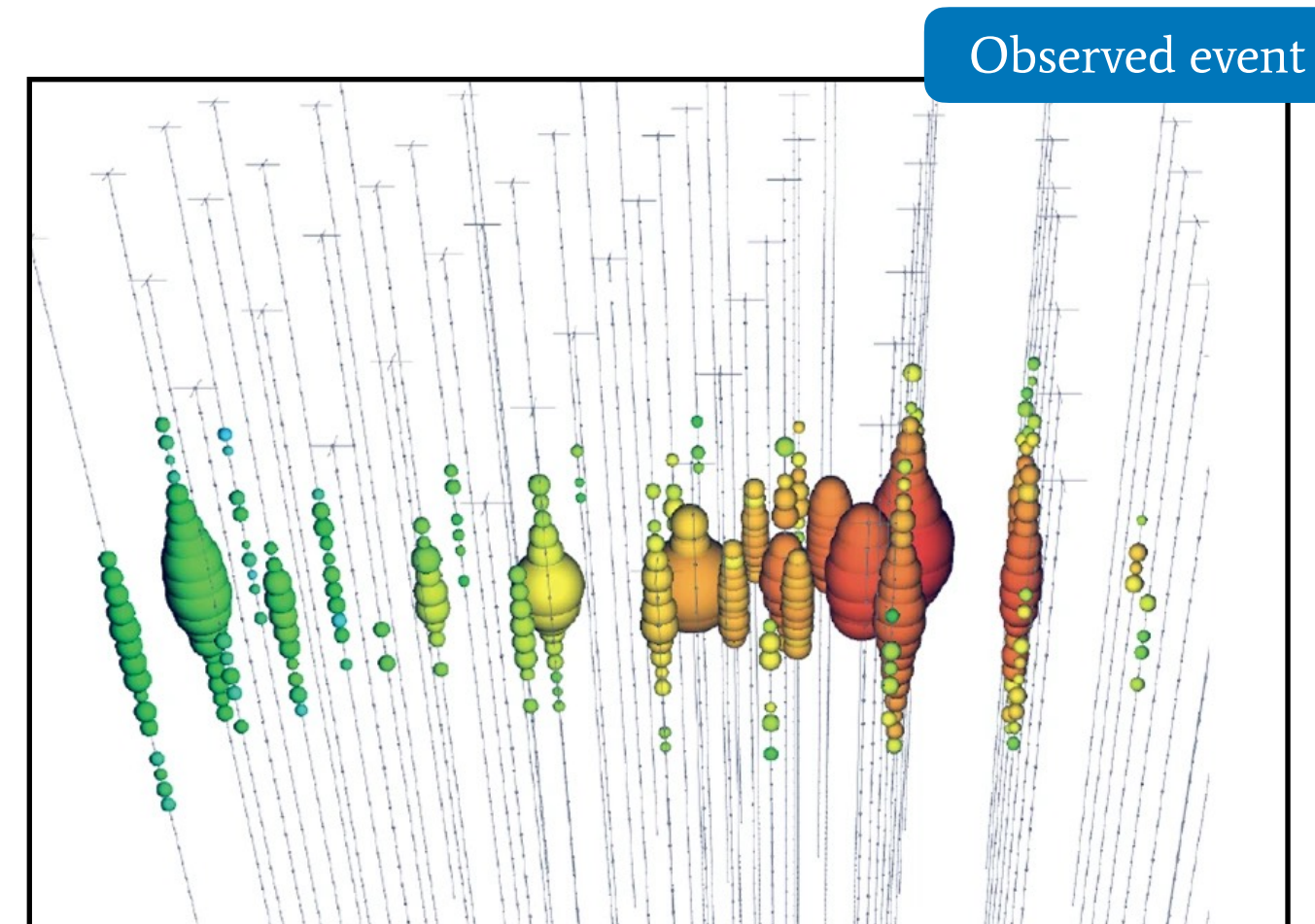
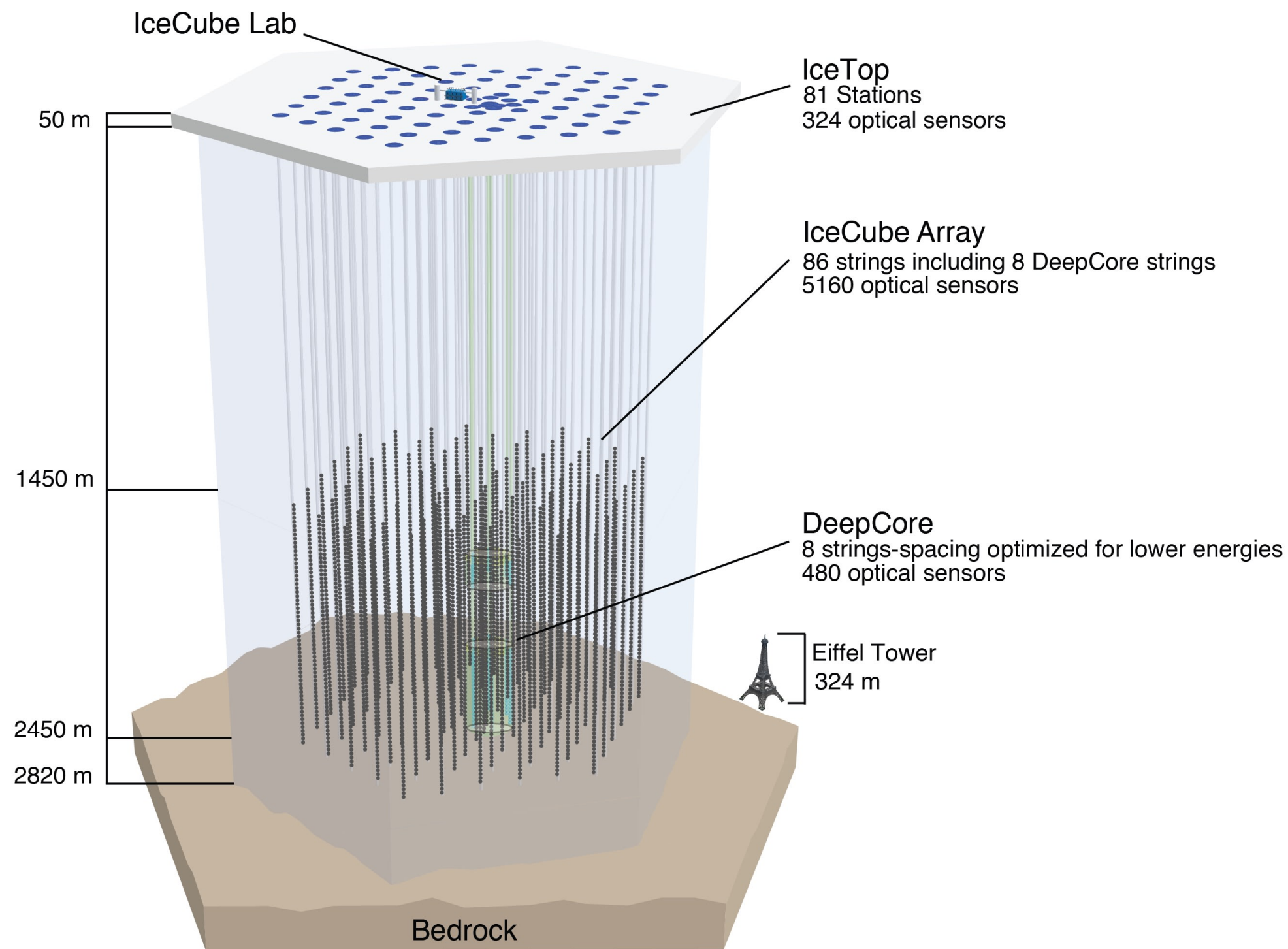
USGS

The IceCube Neutrino Observatory



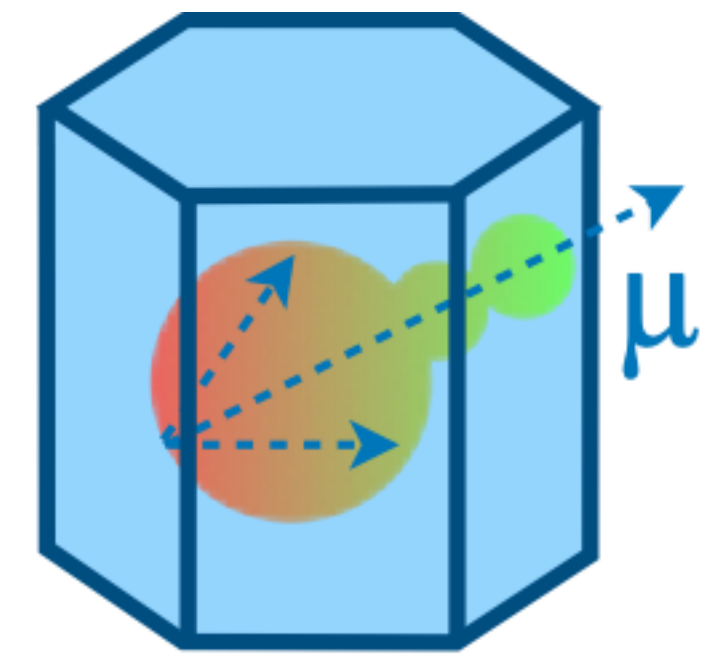
Optical sensors

Types of signals

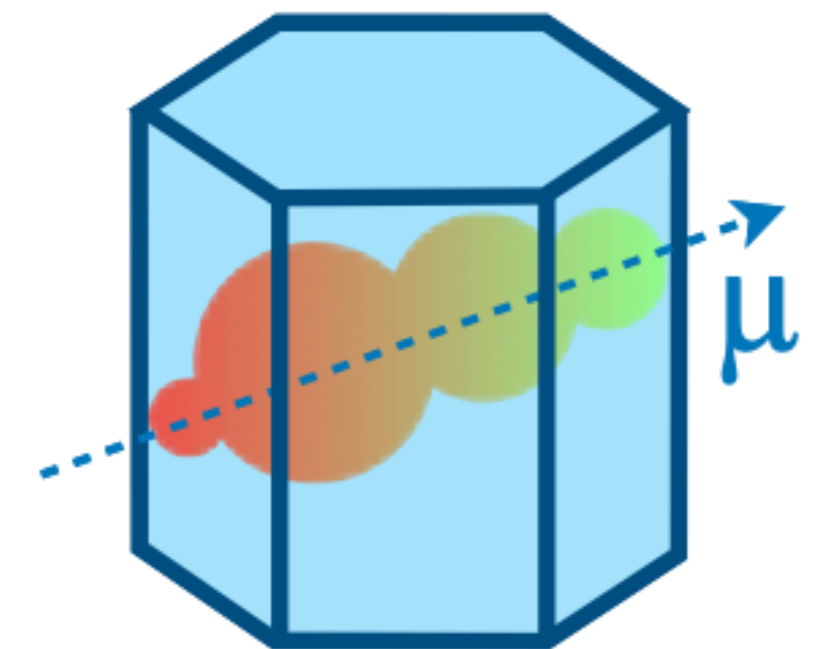


Tracks

- Predominantly
- Cosmic muons
 - Muons from ν_μ charged-current interaction



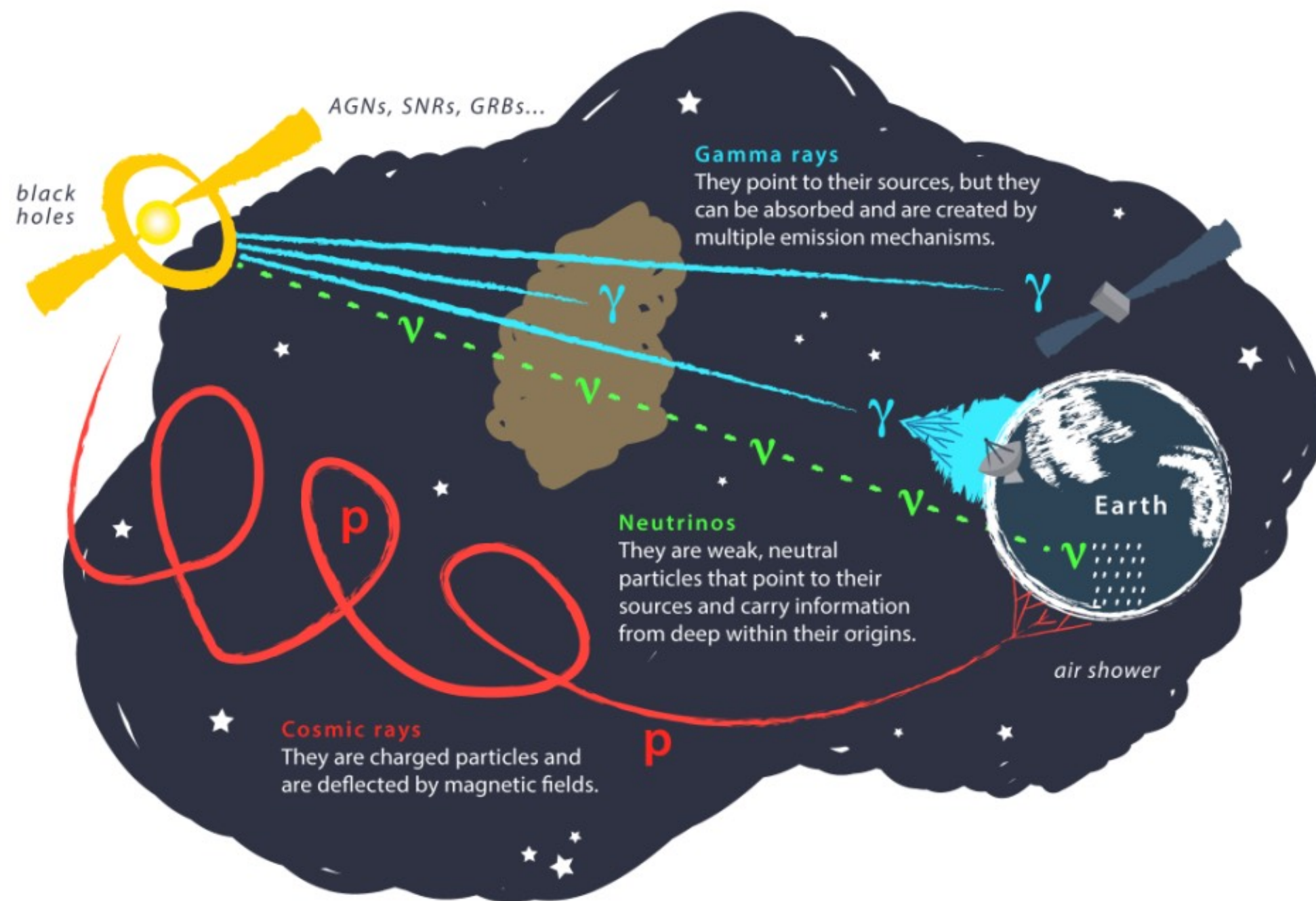
Starting tracks



Throughgoing tracks

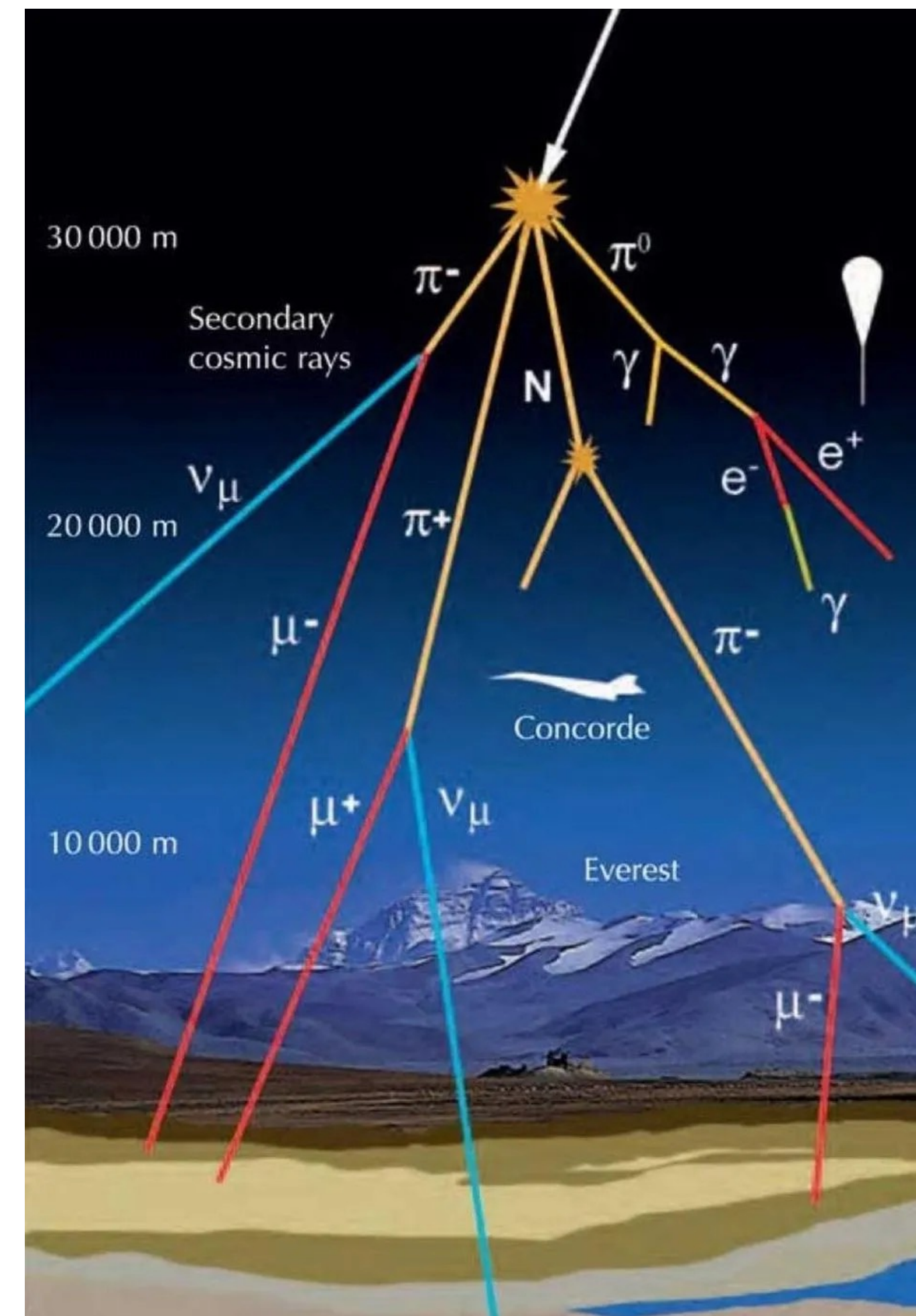
Sources of neutrinos at IceCube (non-exhaustive)

Astrophysical



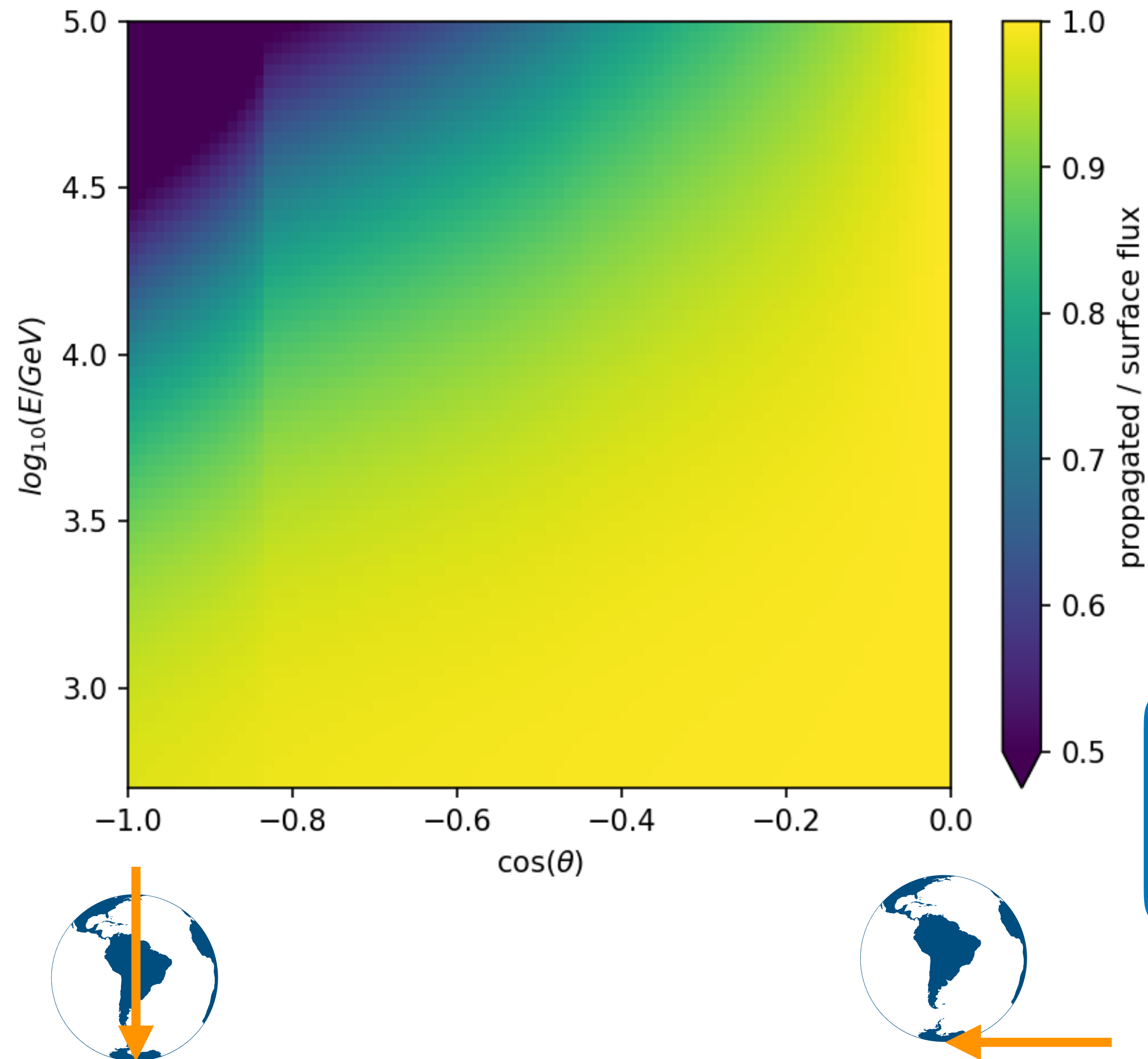
- Black holes, galaxies, supernovae
- Individual sources, or diffuse flux

Atmospheric



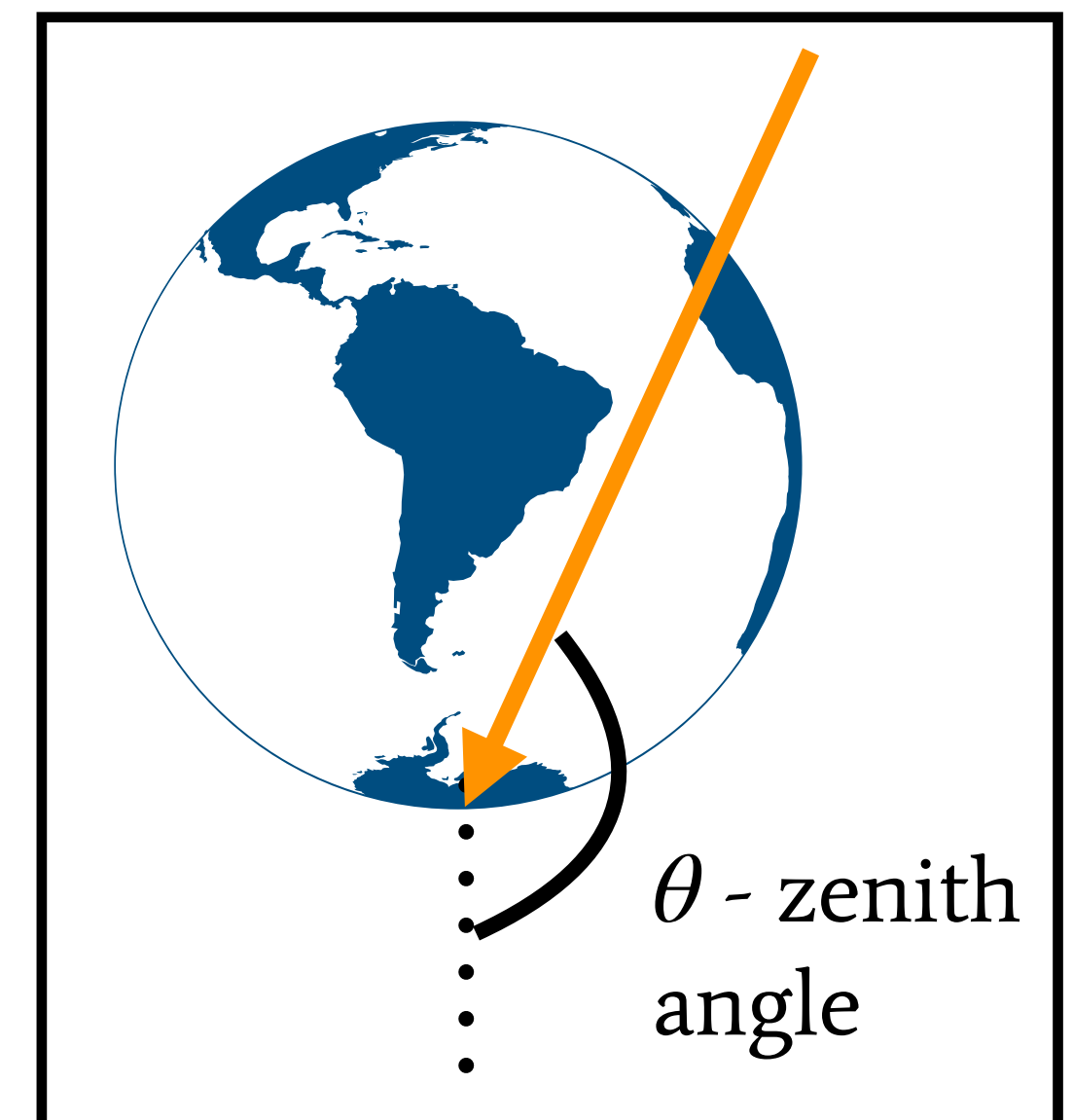
- Cosmic rays hitting the atmosphere
- Pions, kaons decay to neutrinos

The earth blocks these neutrinos



At ~ 10 TeV, earth-scale column depths have non-negligible attenuation on the neutrino flux

Calculated ratio of flux created in atmosphere compared to flux after passing through earth



Previous measurement

Letter | Published: 05 November 2018

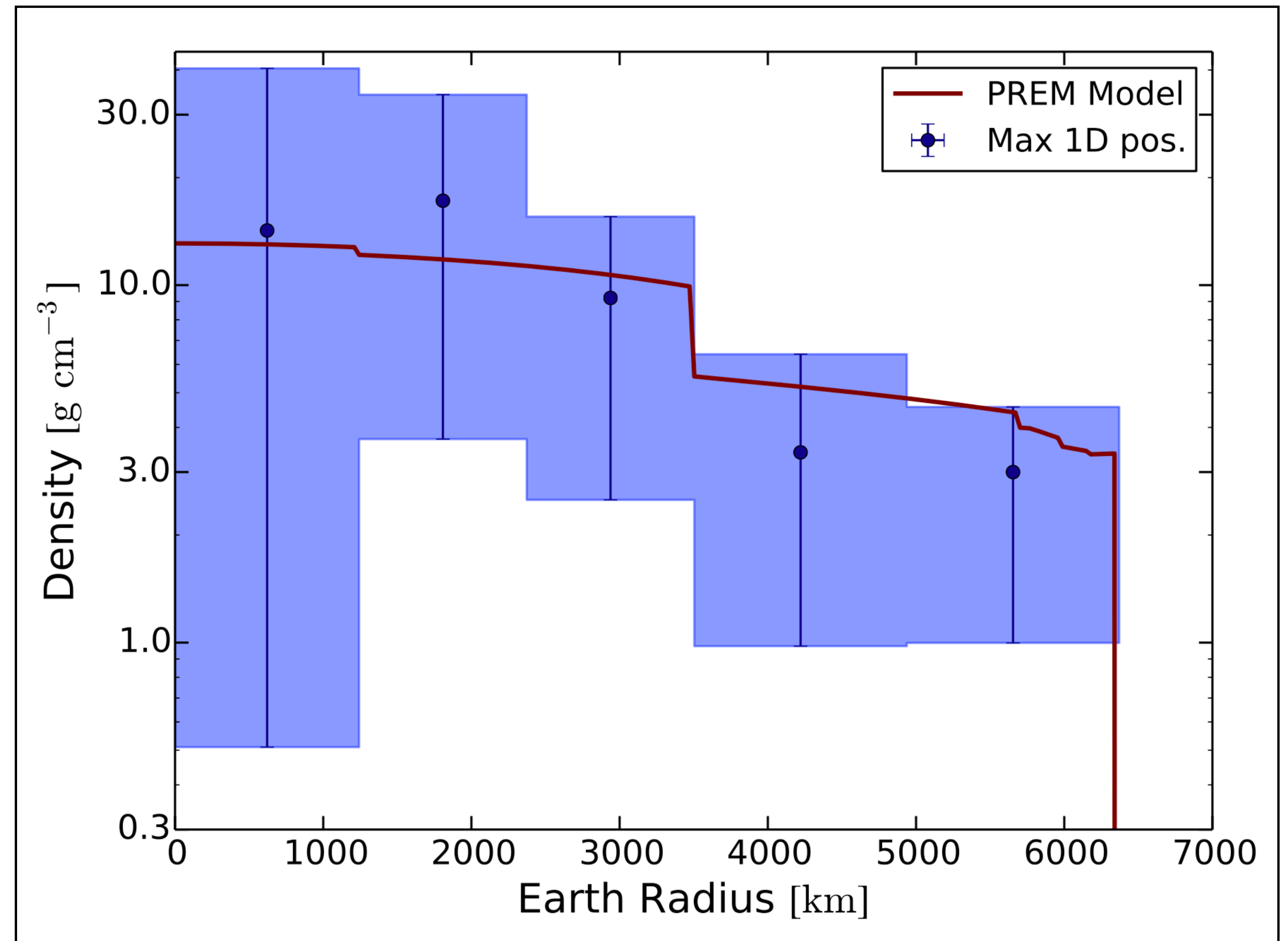
Neutrino tomography of Earth

[Andrea Donini](#), [Sergio Palomares-Ruiz](#) ✉ & [Jordi Salvado](#)

[Nature Physics](#) **15**, 37–40 (2019) | [Cite this article](#)

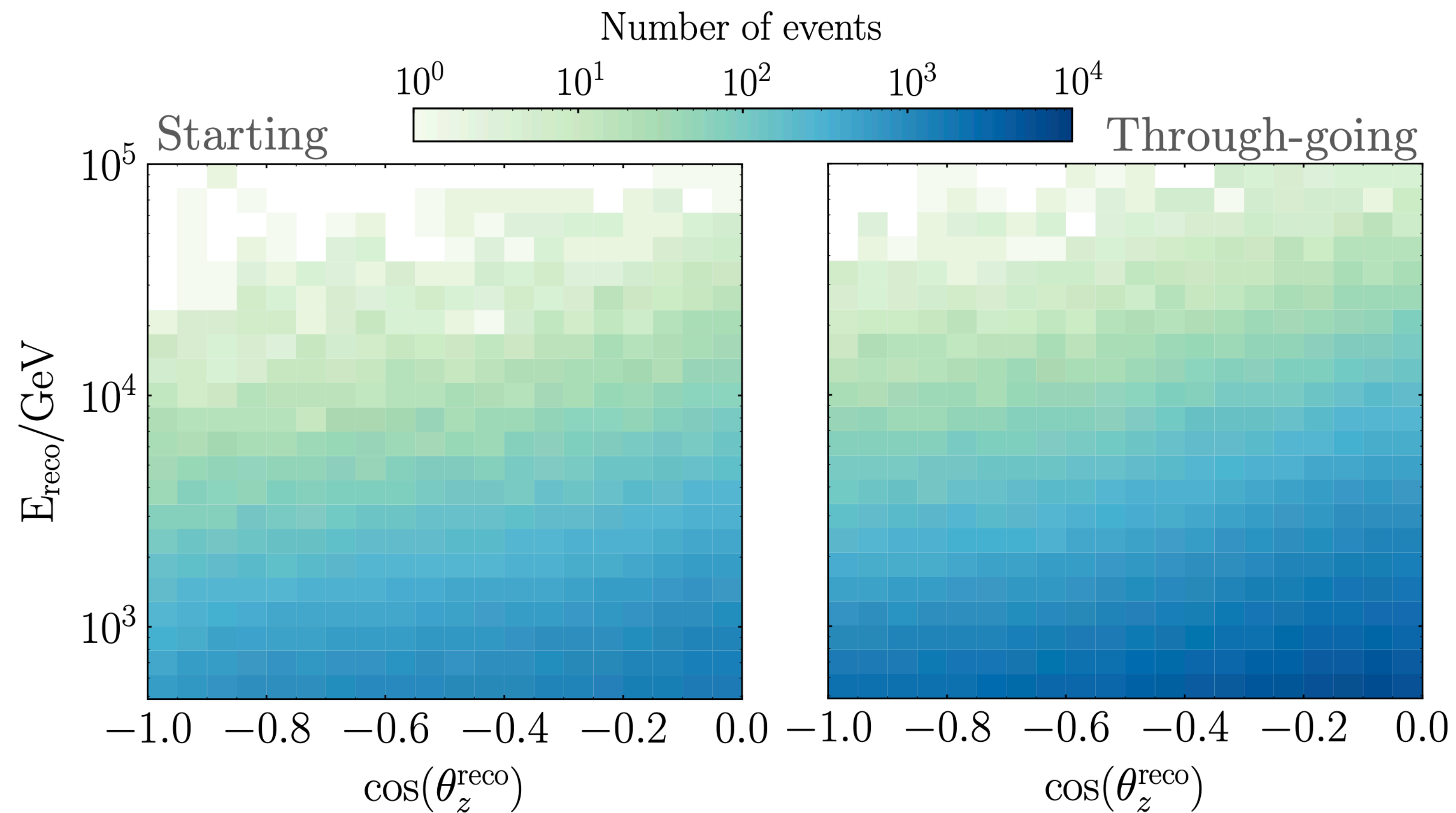
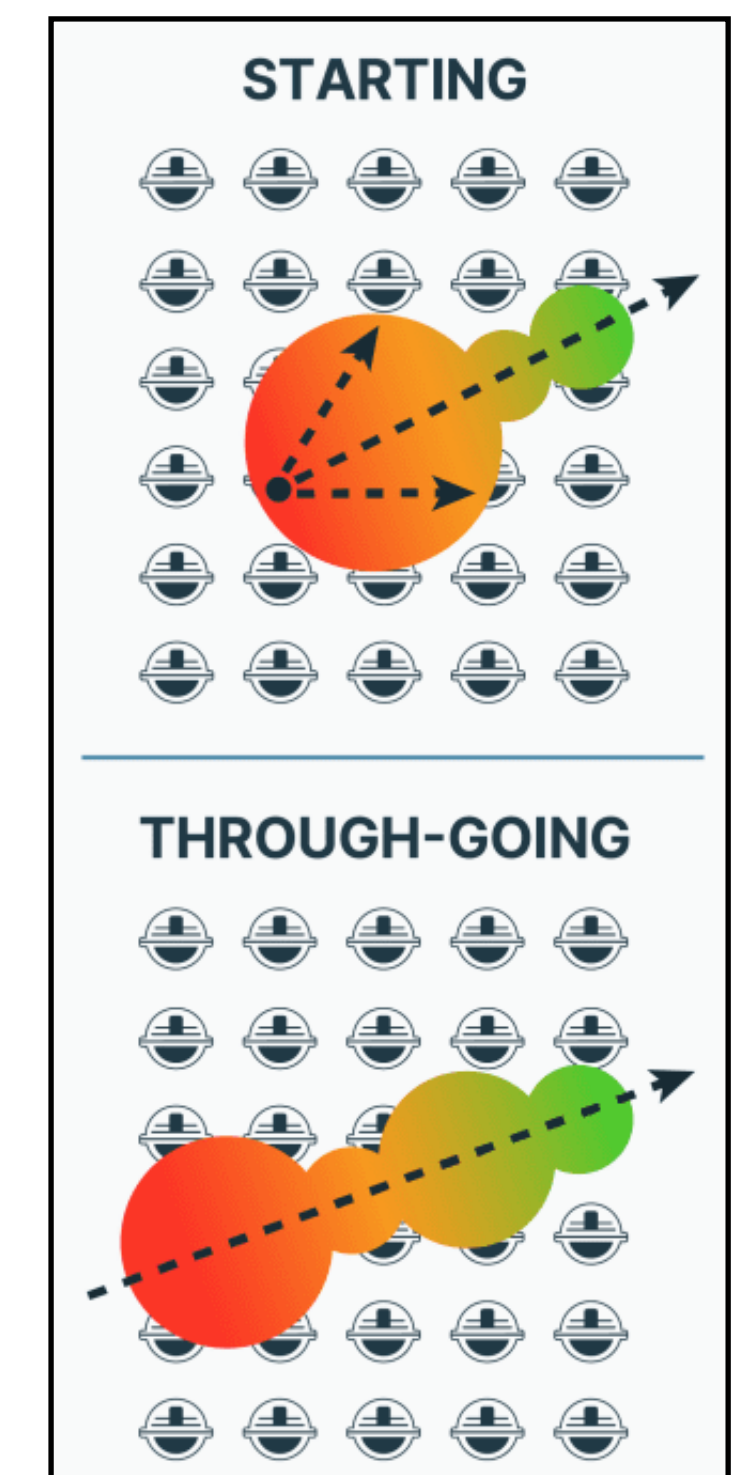
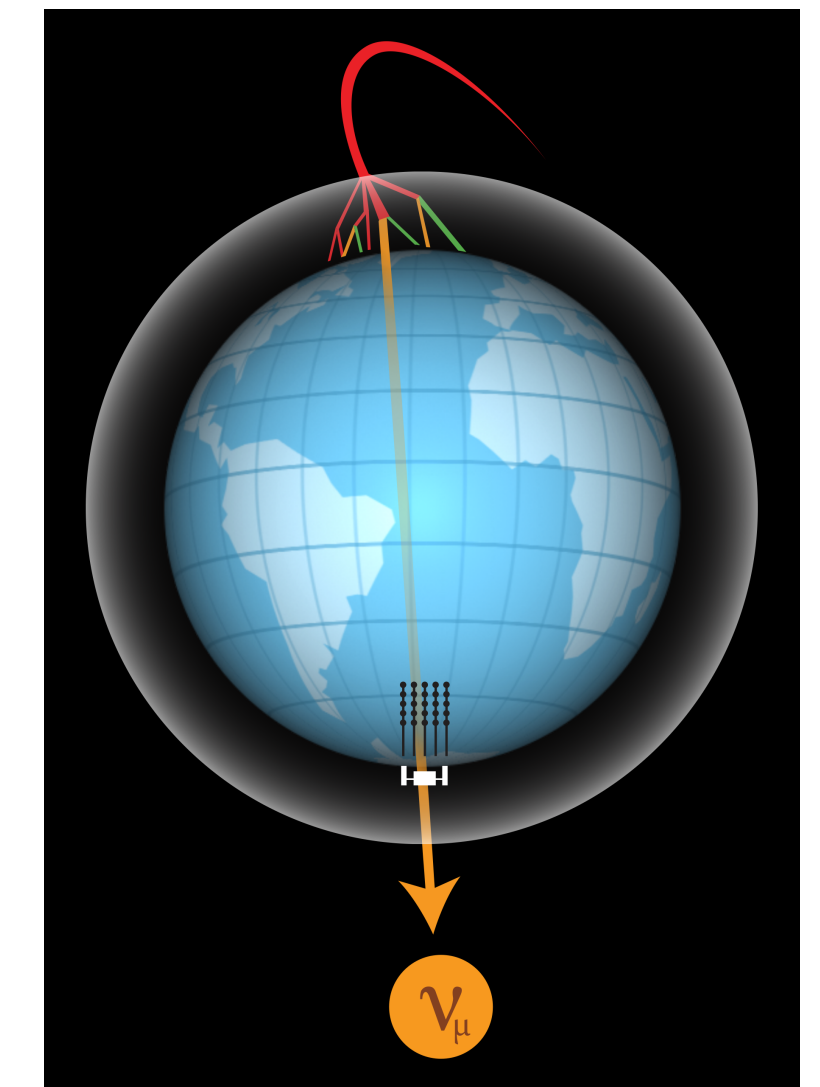
Compared to current IceCube measurement:

- simplified systematics treatment
- ~5% of current data



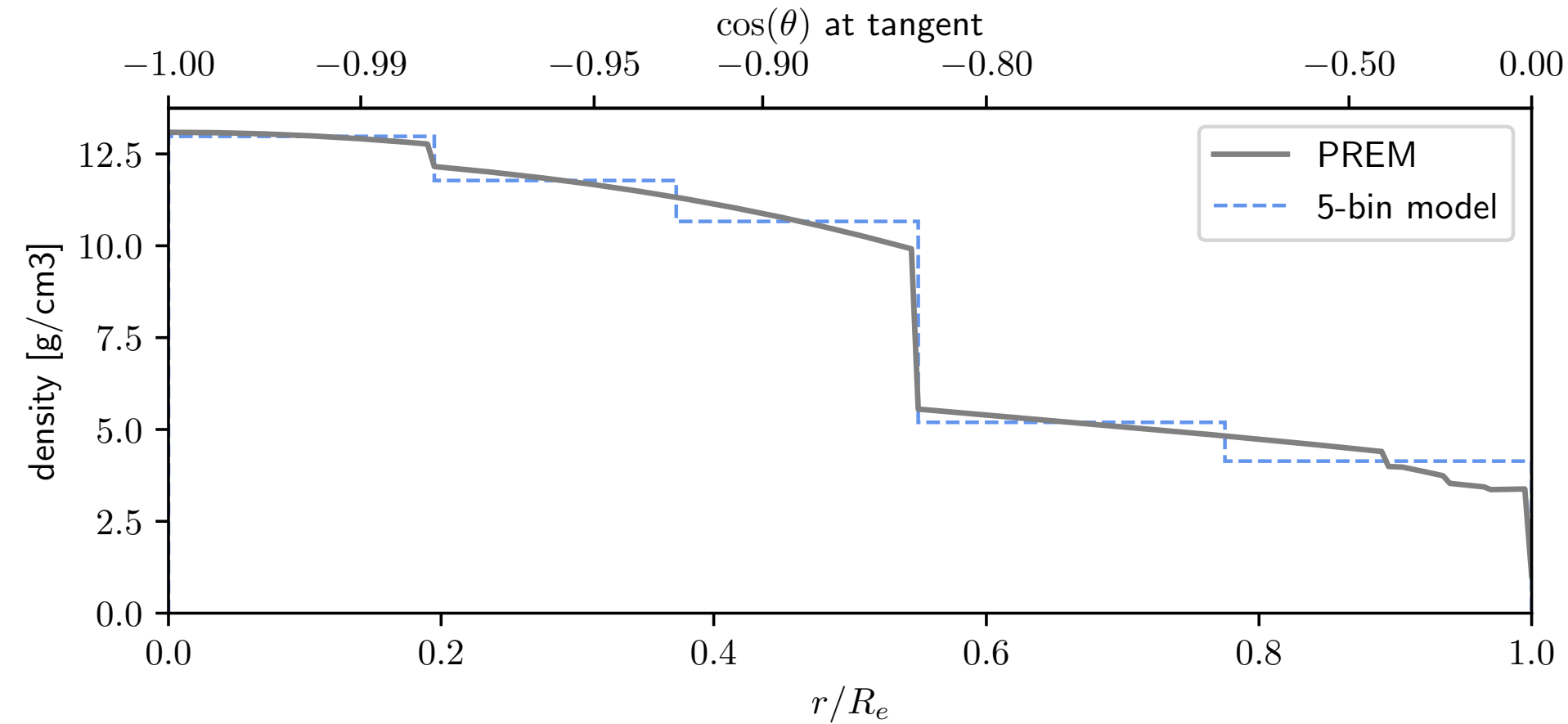
Data

IceCube has a large, pure sample of atmospheric muon neutrino events ($\sim 380,000$)

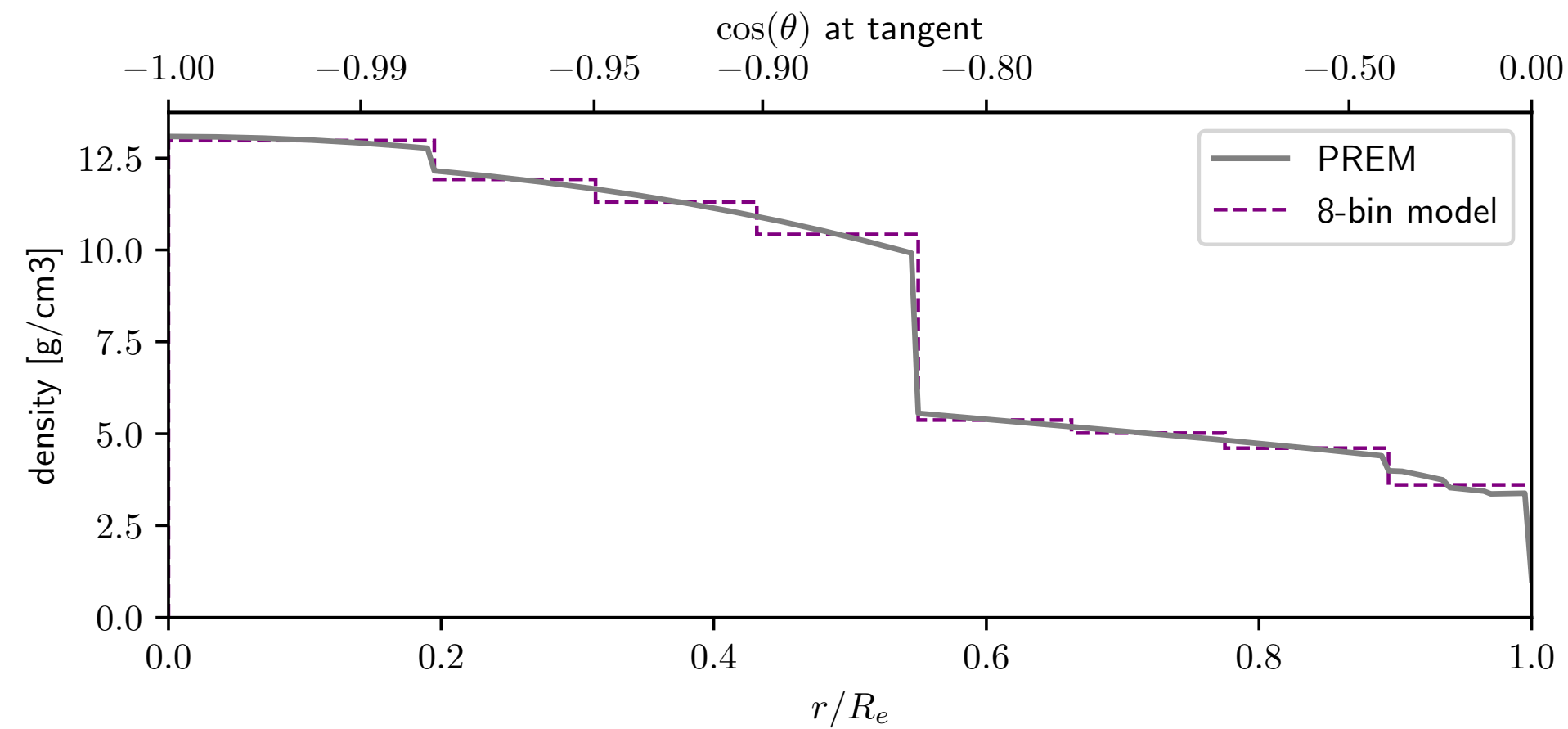


Binning the earth into shells

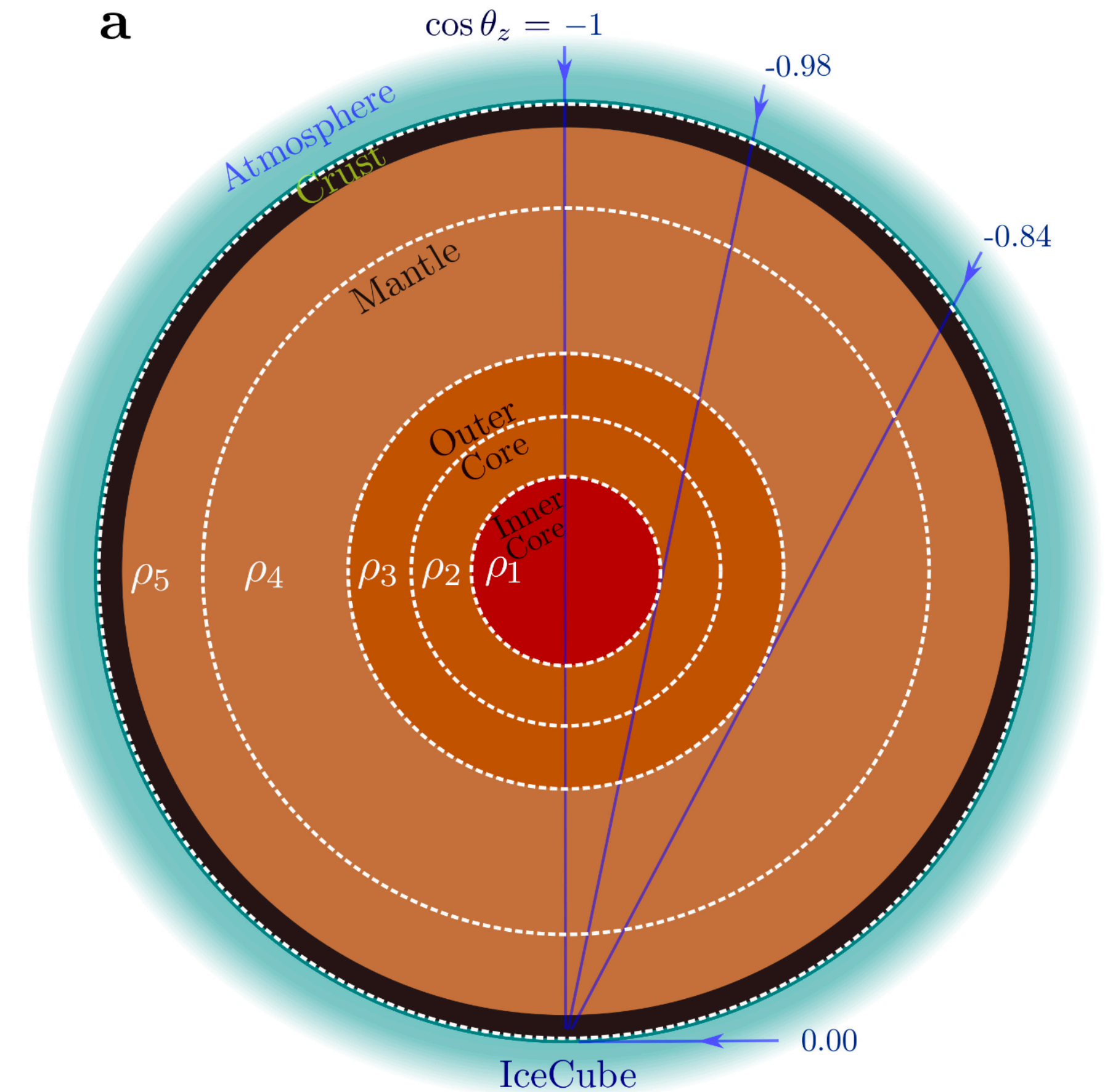
5-shells



8-shells



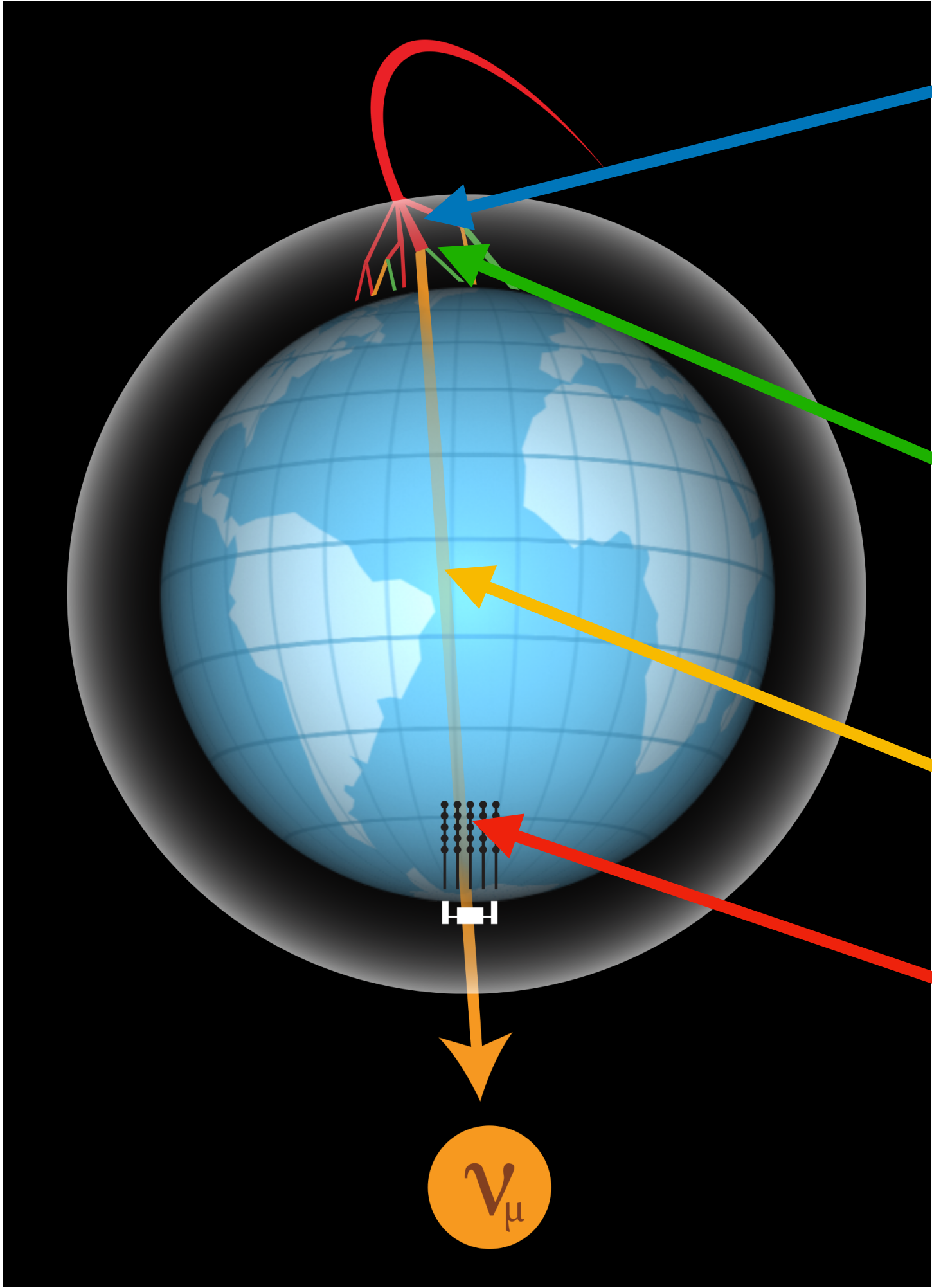
a



Approximate PREM profile with constant density shells - the parameters to infer

Donini et al. (Nature Physics 15, 37-40)

Systematic uncertainties



Conventional
neutrino flux
properties

Non-
conventional
neutrino flux
properties

Cross section
parameters

Detector and
Ice properties

Nuisance parameter	Central value	1 σ width of prior	Allowed range
Conventional Flux Parameters			
Atm. density (ρ_{atm})	0.00	1.00	-3.00,3.00
Kaon energy loss ($\sigma_{\text{K-Air}}$)	0.00	1.00	-3.00,3.00
K_{158G}^+	0.00	1.00	-2.00,2.00
K_{158G}^-	0.00	1.00	-2.00,2.00
π_{20T}^+	0.00	1.00	-2.00,2.00
π_{20T}^-	0.00	1.00	-2.00,2.00
K_{2P}^+	0.00	1.00	-1.00,2.00
K_{2P}^-	0.00	1.00	-1.50,2.00
π_{2P}^+	0.00	1.00	-2.00,2.00
π_{2P}^-	0.00	1.00	-2.00,2.00
p_{2P}	0.00	1.00	-2.00,2.00
n_{2P}	0.00	1.00	-2.00,2.00
GSF_1	0.00	1.00	-4.00,4.00
GSF_2	0.00	1.00	-4.00,4.00
GSF_3	0.00	1.00	-4.00,4.00
GSF_4	0.00	1.00	-4.00,4.00
GSF_5	0.00	1.00	-4.00,4.00
GSF_6	0.00	1.00	-4.00,4.00
Non-conventional Flux Parameters			
Normalization (Φ^{HE})	0.787	0.36	0.00,3.00
$\log_{10}$ of pivot energy, E_{break}^{HE}	-	-	4.00,6.00
$\Delta\gamma_1^{HE}$, tilt from -2.5	0.00	0.36	-2.00,2.00
$\Delta\gamma_2^{HE}$, tilt from -2.5	0.00	0.36	-2.00,2.00
Earth Absorption Parameters			
ν attenuation	1.00	0.10	0.82, 1.18
$\bar{\nu}$ attenuation	1.00	0.10	0.82, 1.18
Detector Parameters			
Overall normalization	1.00	0.2	0.10,3.00
DOM efficiency	1.00	0.10	0.97,1.06
Forward hole ice	-1.00	10.00	-5.35,1.85
Ice amplitude 0	0.00	1.00	-3.00,3.00
Ice amplitude 1	0.00	1.00	-3.00,3.00
Ice amplitude 2	0.00	1.00	-3.00,3.00
Ice amplitude 3	0.00	1.00	-3.00,3.00
Ice amplitude 4	0.00	1.00	-3.00,3.00
Ice phase 1	0.00	1.00	-3.00,3.00
Ice phase 2	0.00	1.00	-3.00,3.00
Ice phase 3	0.00	1.00	-3.00,3.00
Ice phase 4	0.00	1.00	-3.00,3.00

DAEMONFLUX - Yañez
& Fedynitch, Phys. Rev.
D 107, 123037

SnowStorm method -
IceCube Collaboration,
JCAP 10, 048 (2019)

Estimation using Bayesian parameter estimation

- Use a MCMC to sample the posterior depending on
 - physics parameters, i.e. the shell densities
 - and nuisance parameters
- Likelihood supplied by GollumFit
- Sampling done by emcee

emcee

<https://emcee.readthedocs.io/en/stable/>
Goodman & Weare, Commun. Appl. Math.
Comput. Sc. 5 (2010) 1, 65-80

GollumFit

IceCube, “GollumFit: An IceCube Open-Source Framework for Binned-Likelihood Neutrino Telescope Analyses”. arXiv:2506.04491

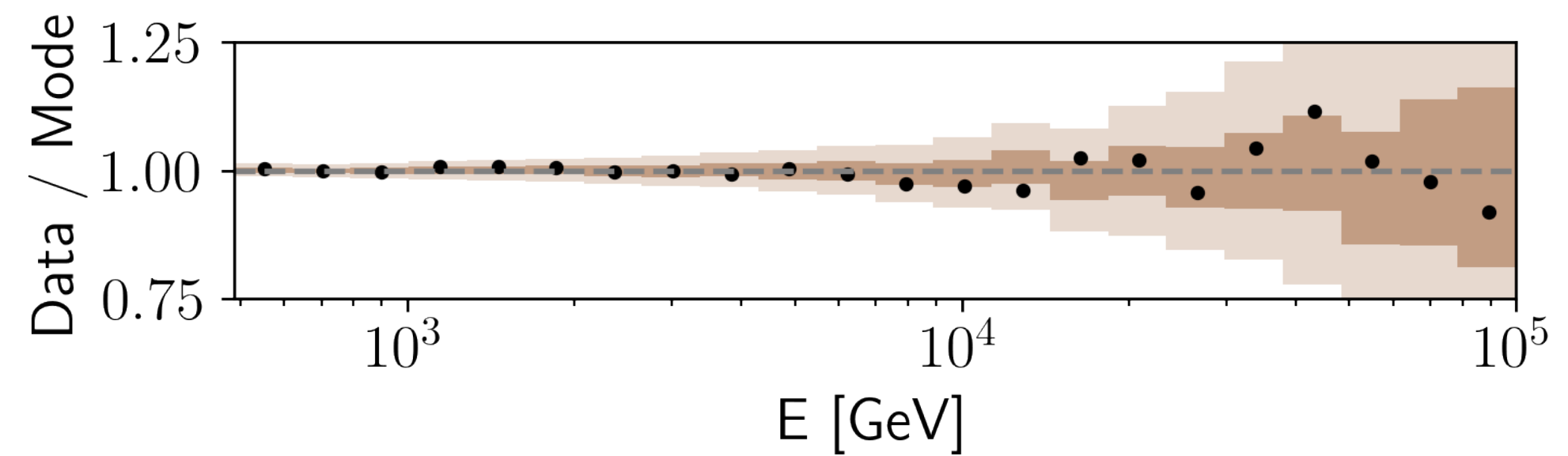
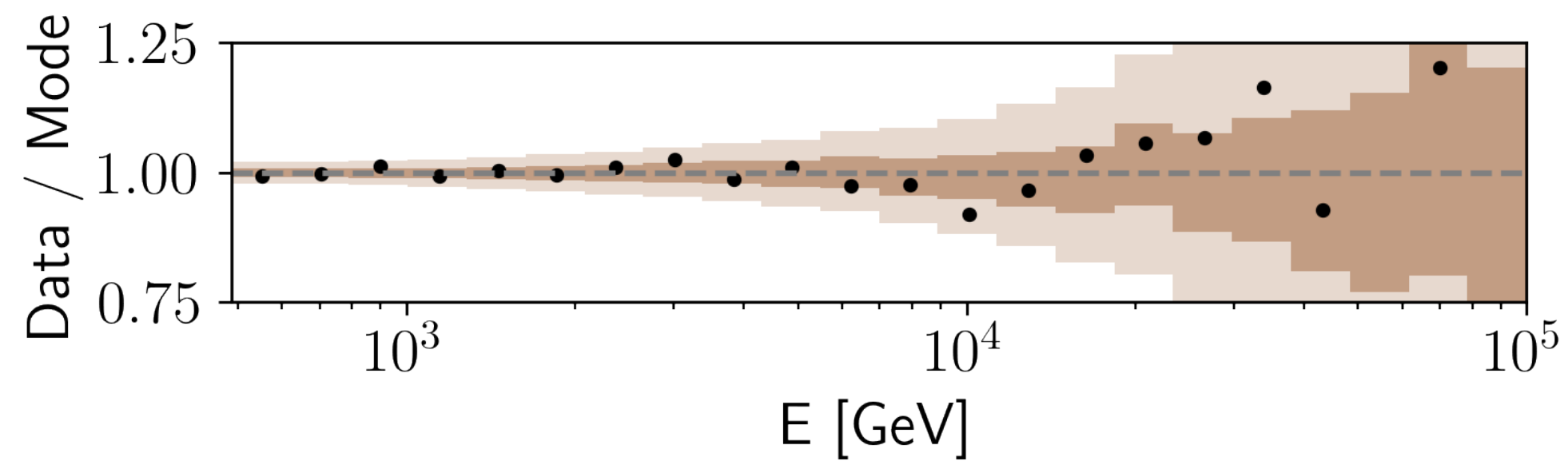
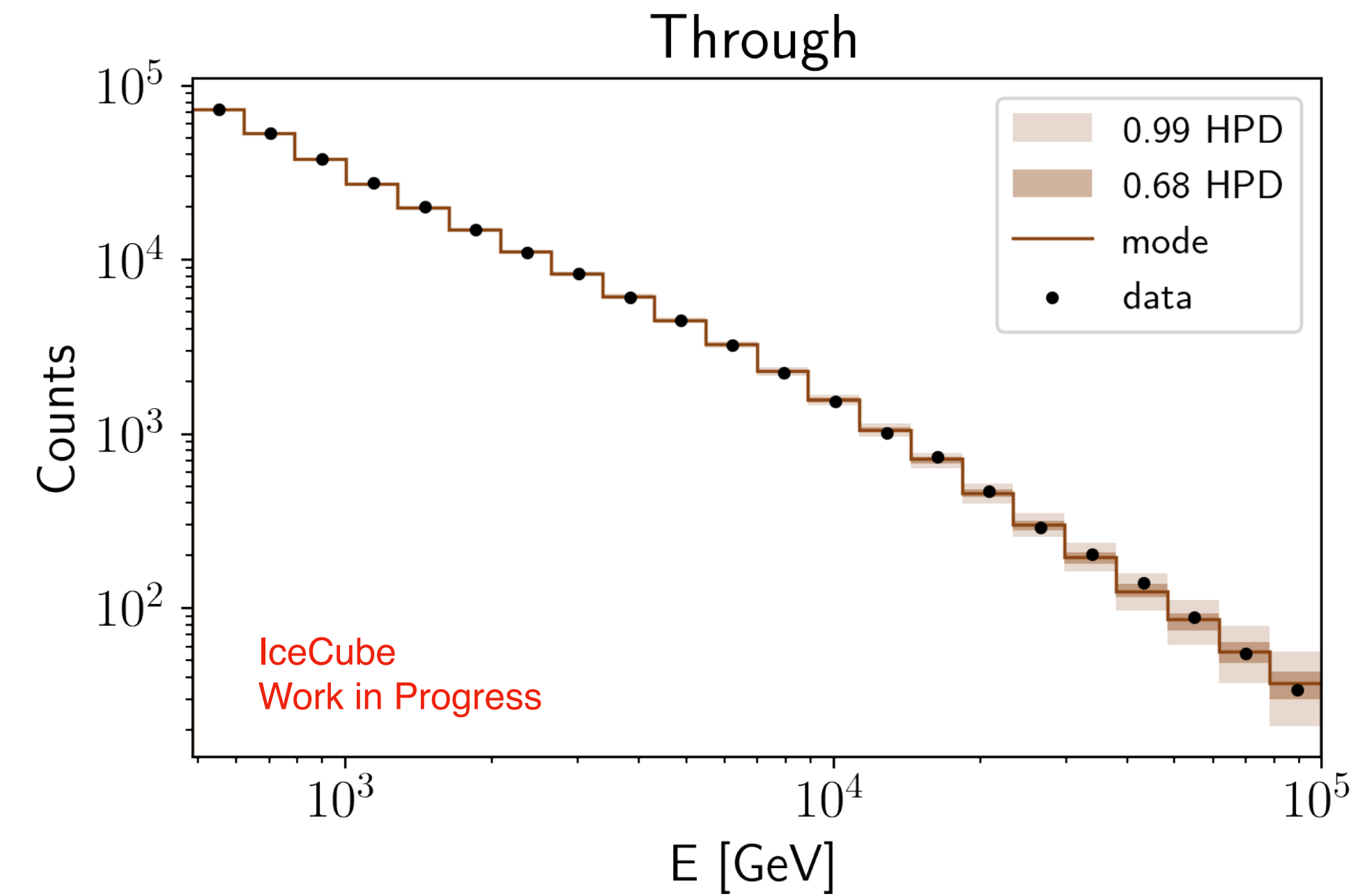
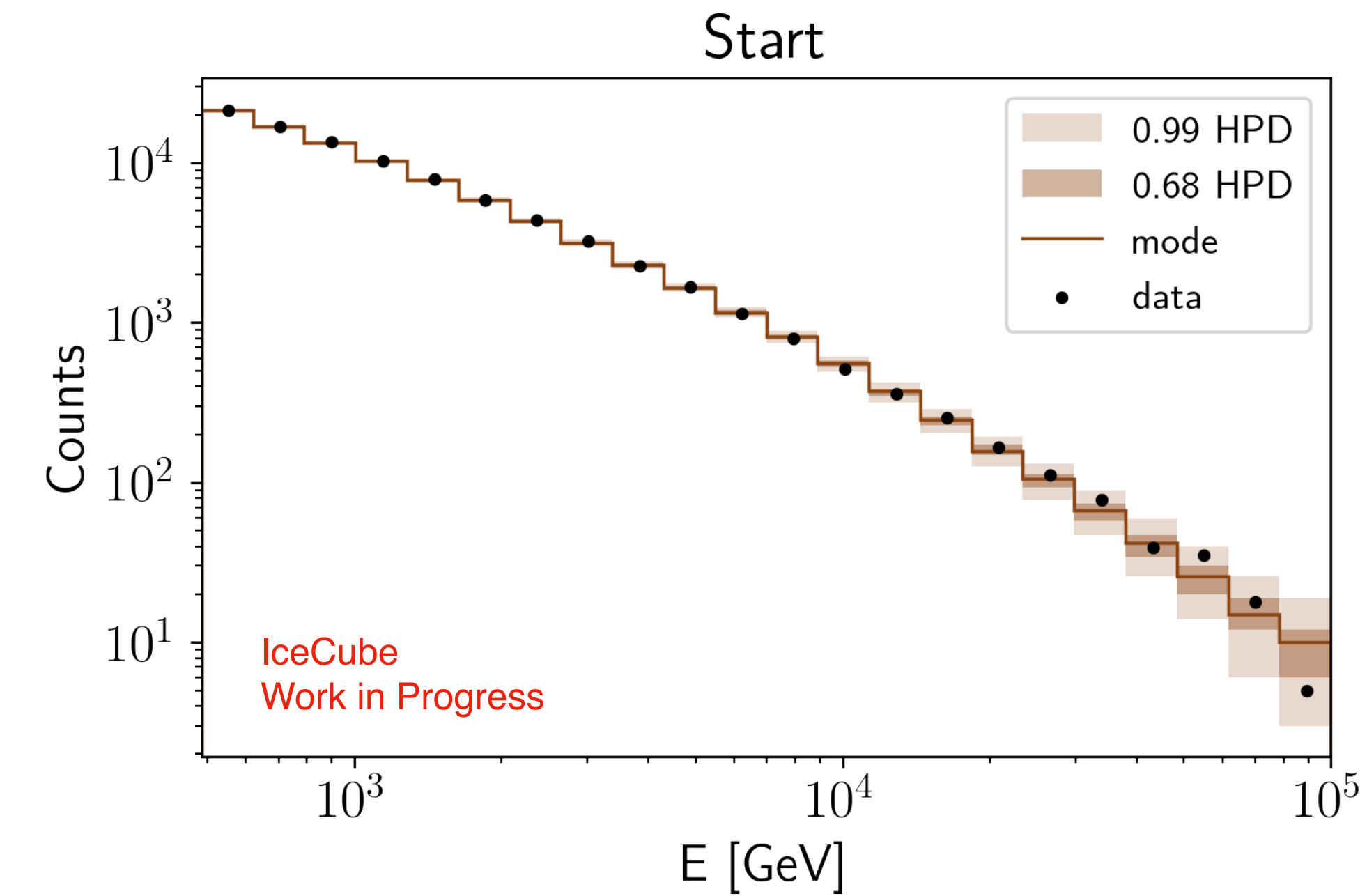
<https://github.com/icecube/GollumFit>



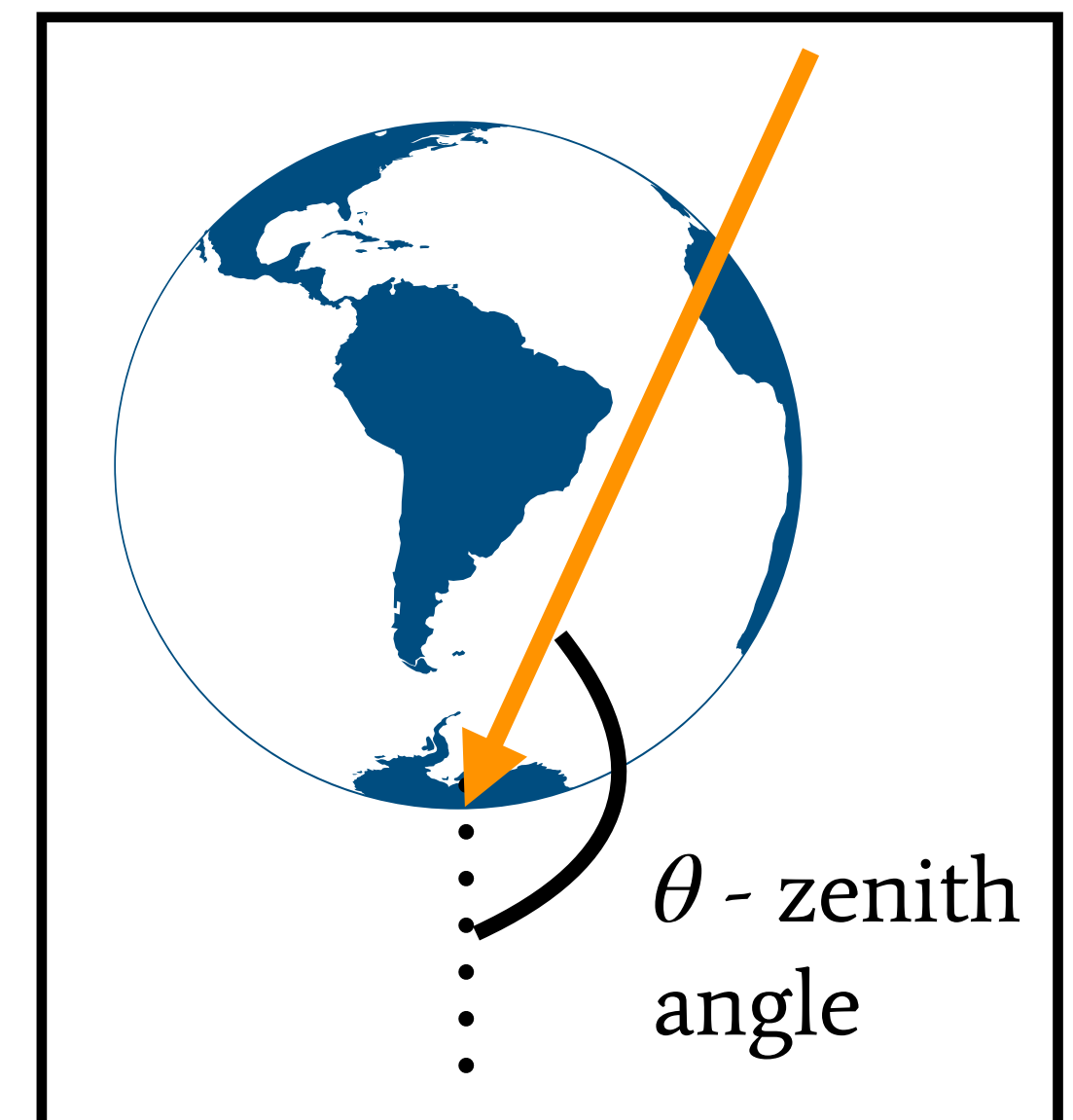
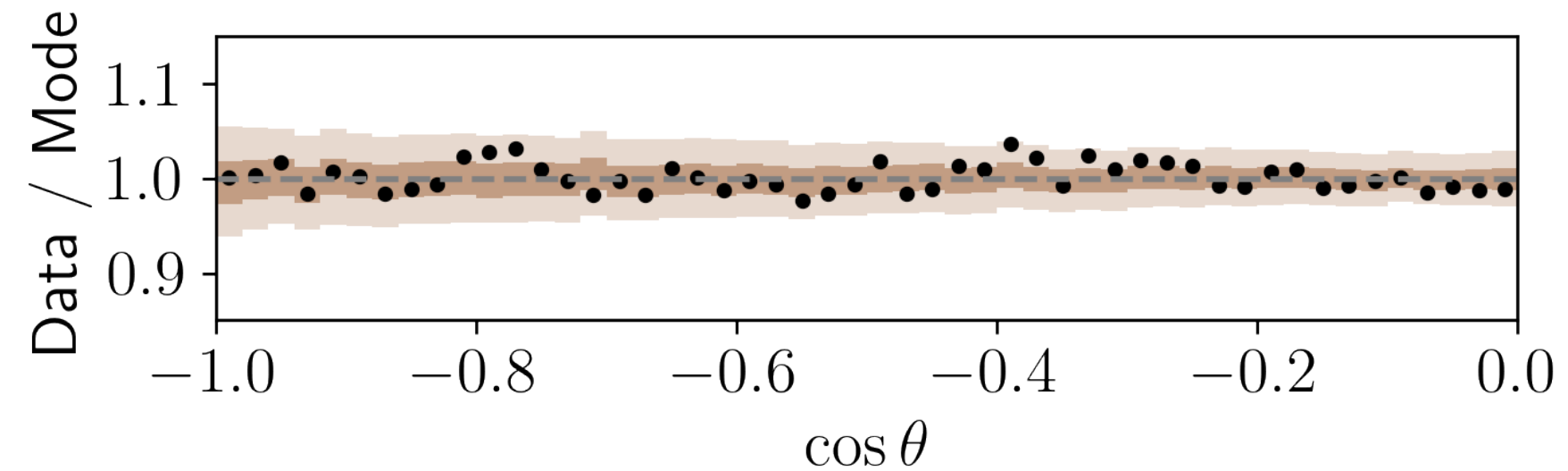
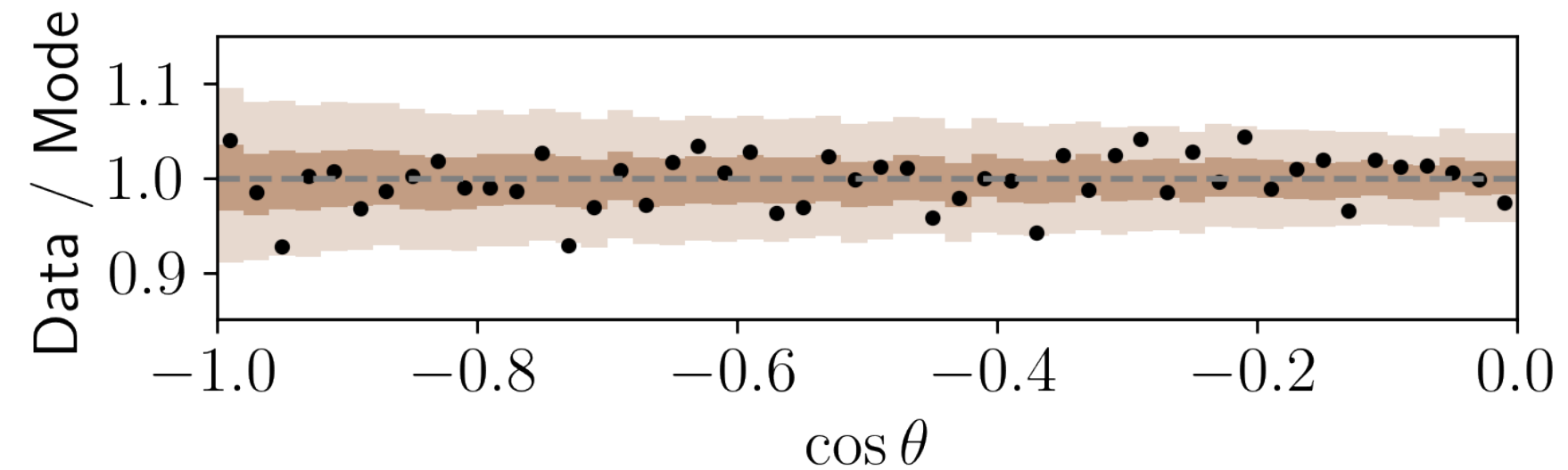
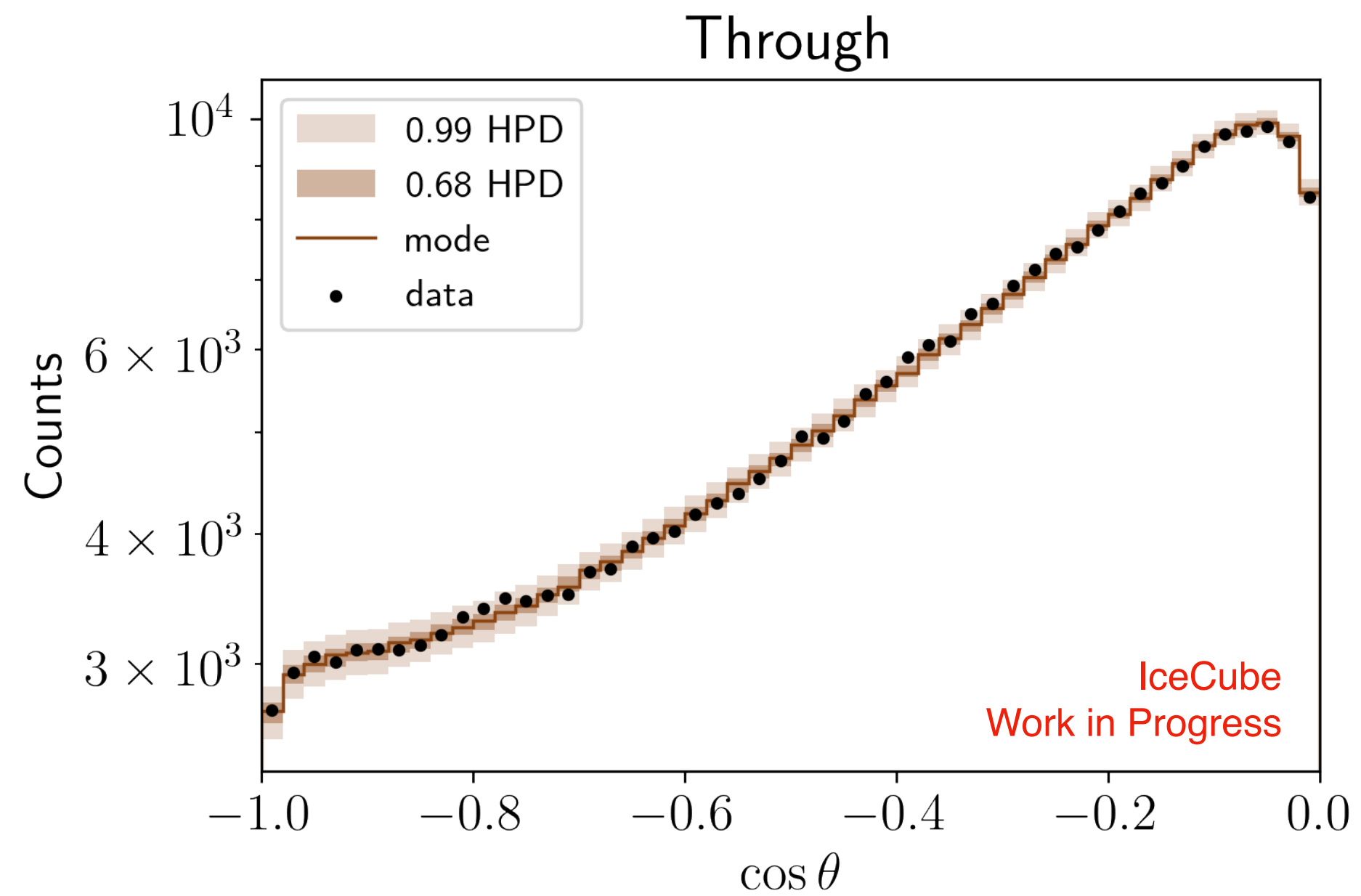
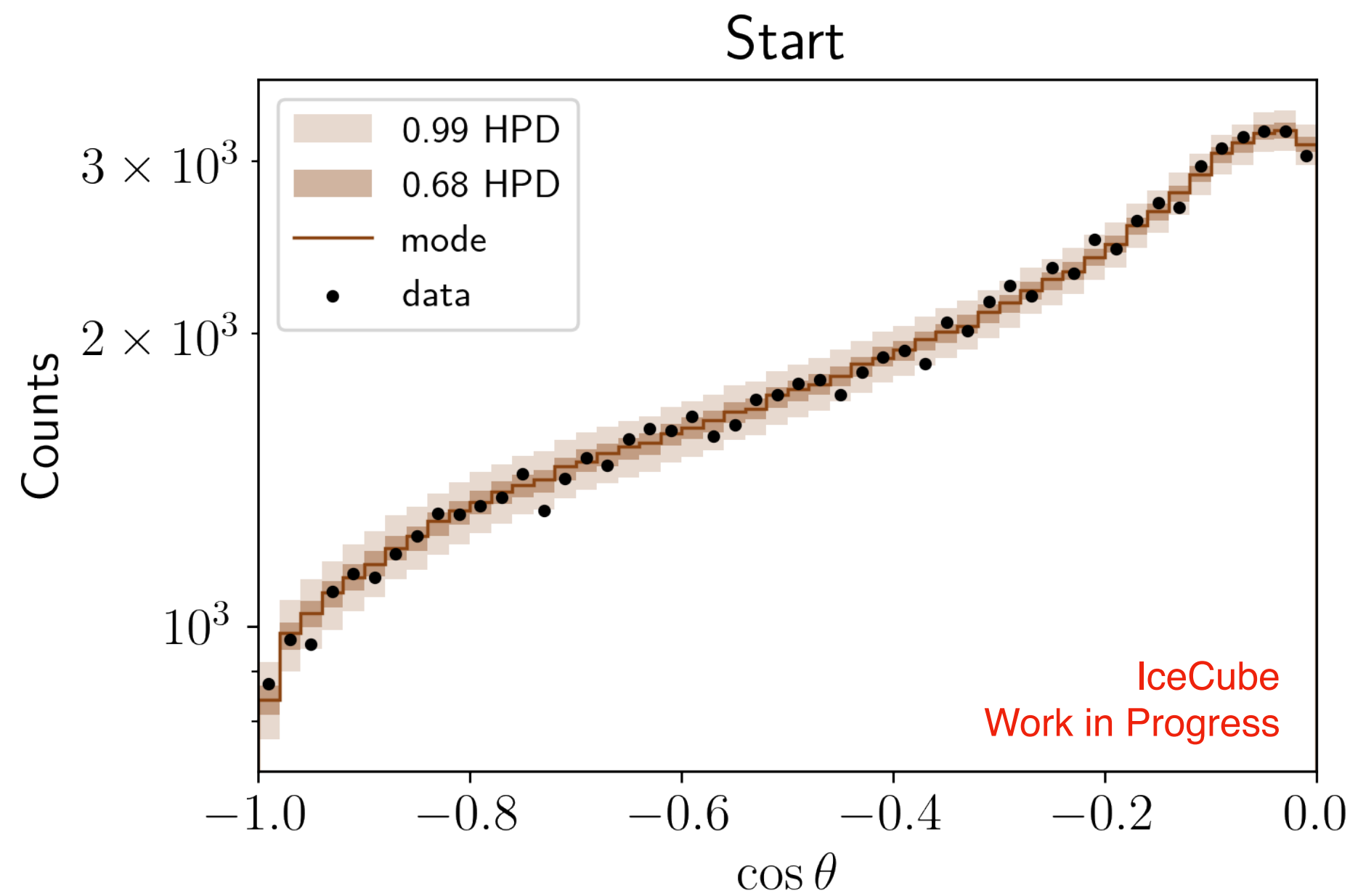
Results of measurement



Energy distributions - data-MC agreement

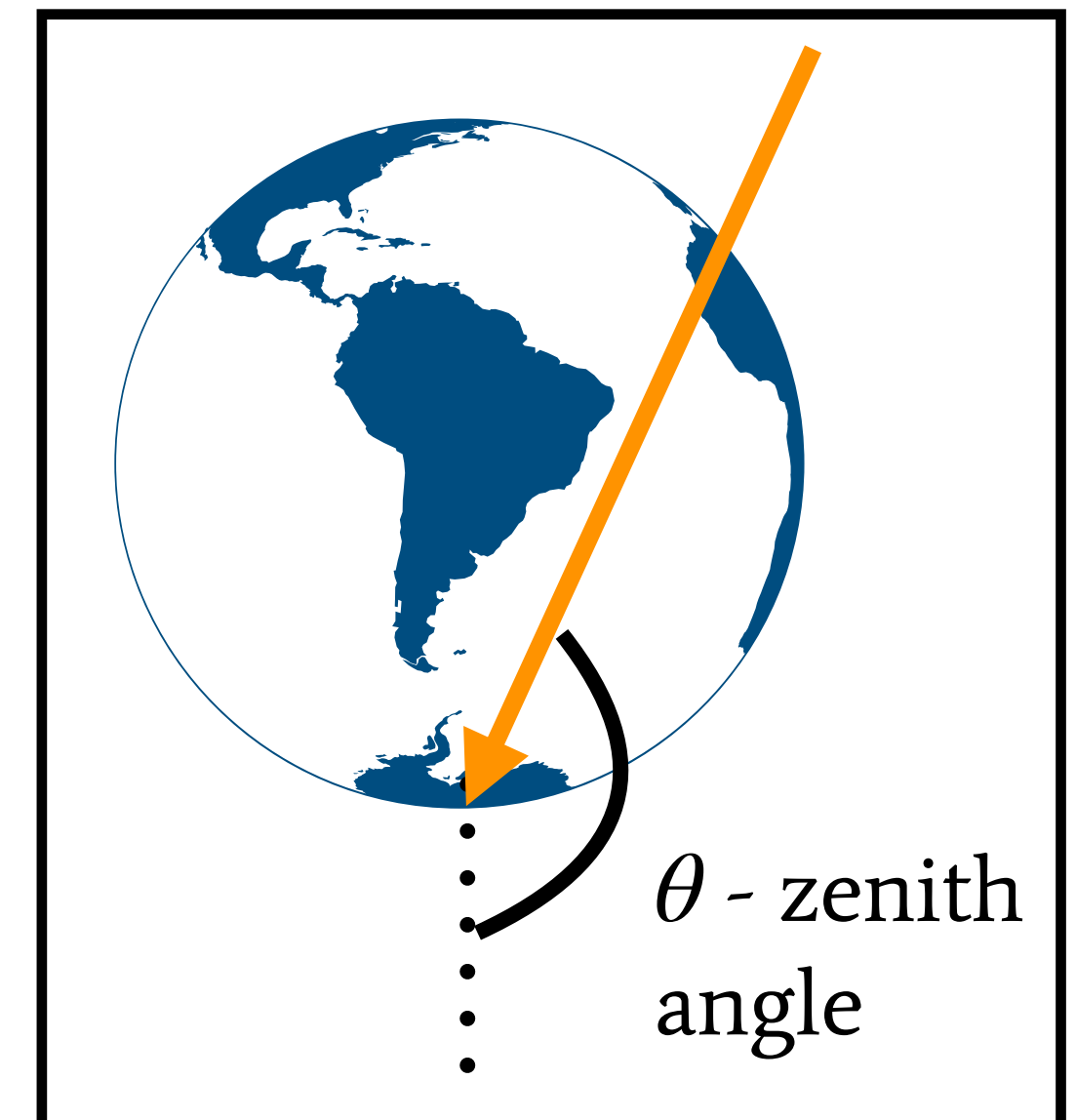
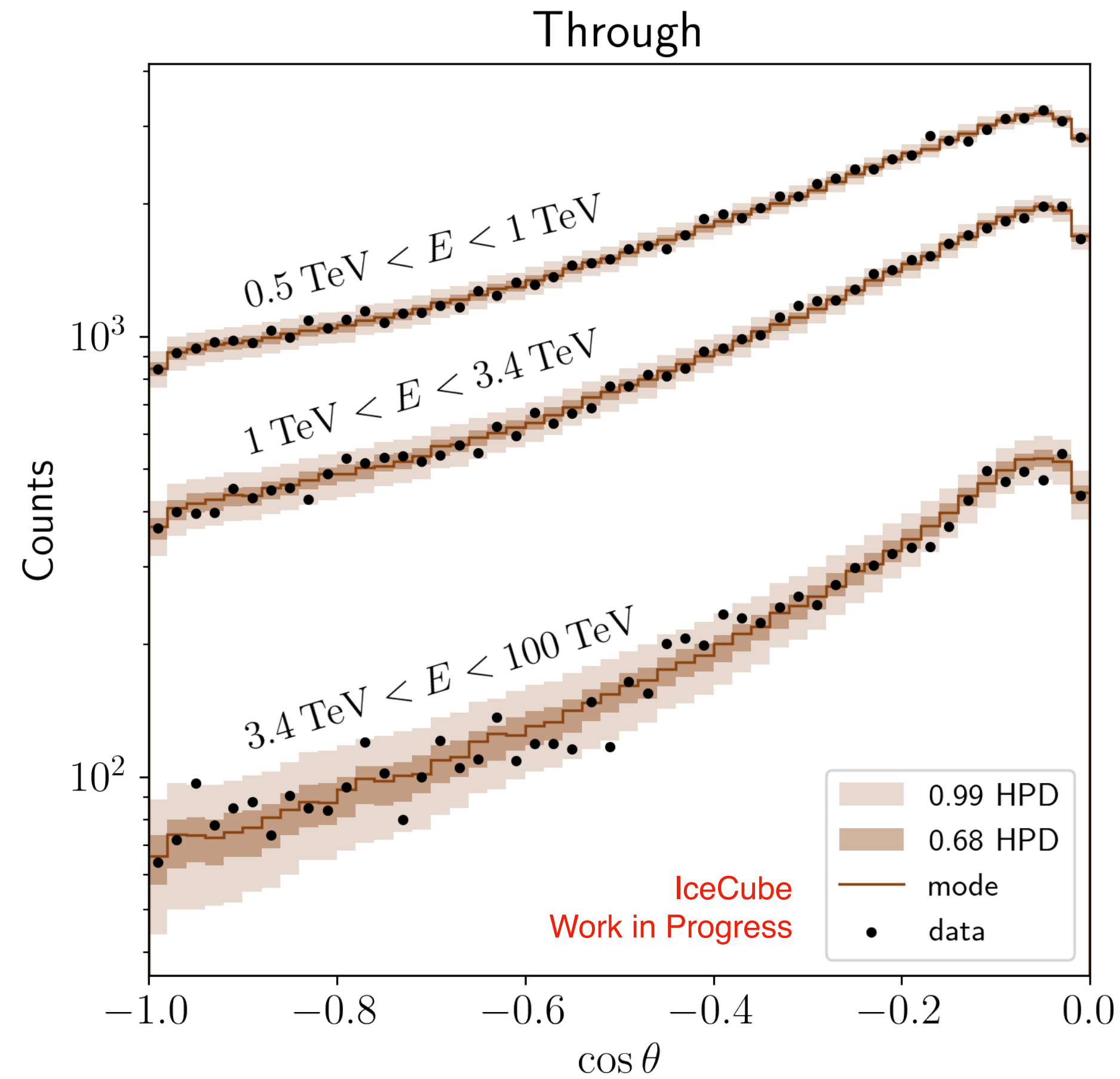
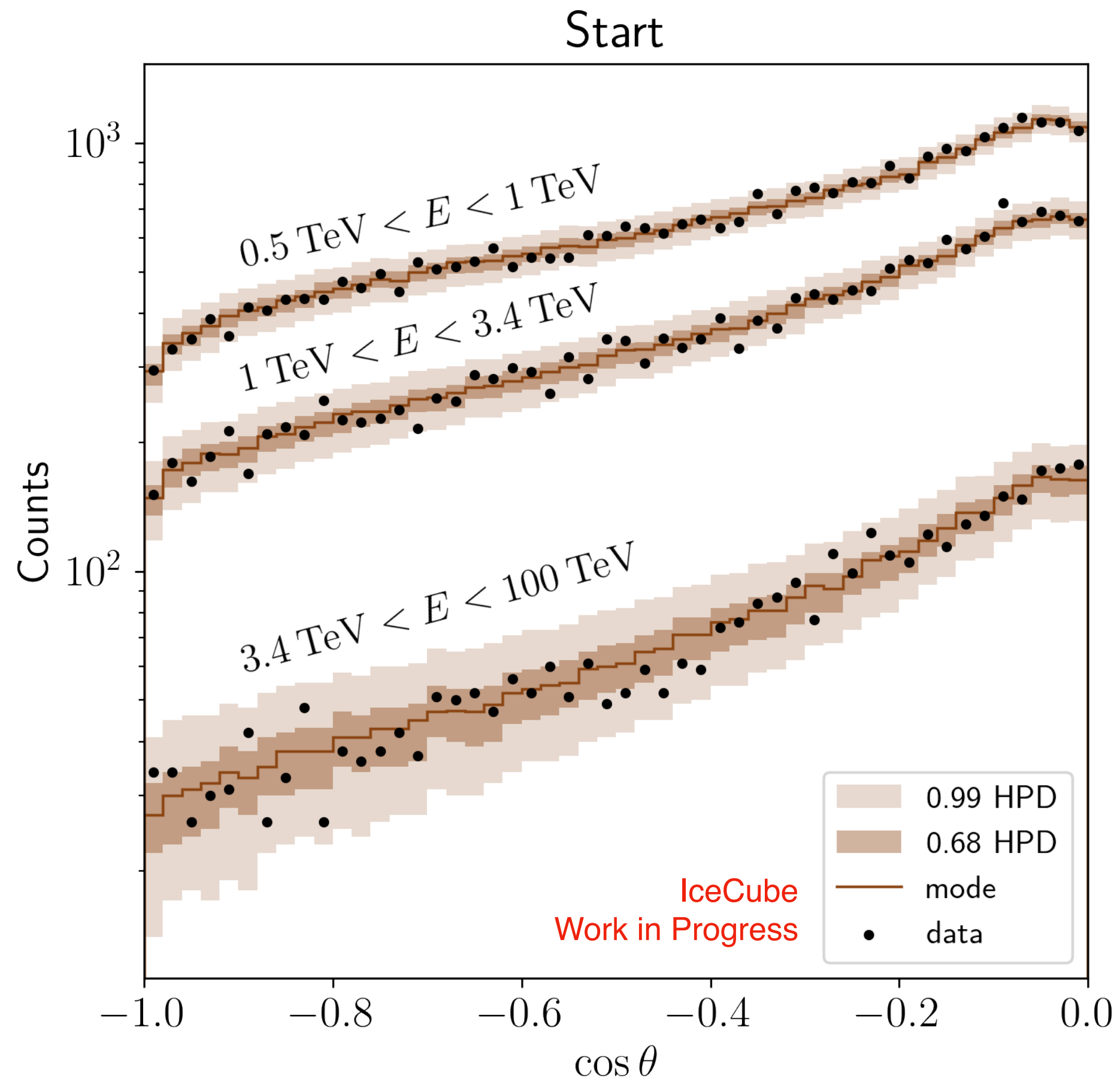


Zenith distributions - data-MC agreement

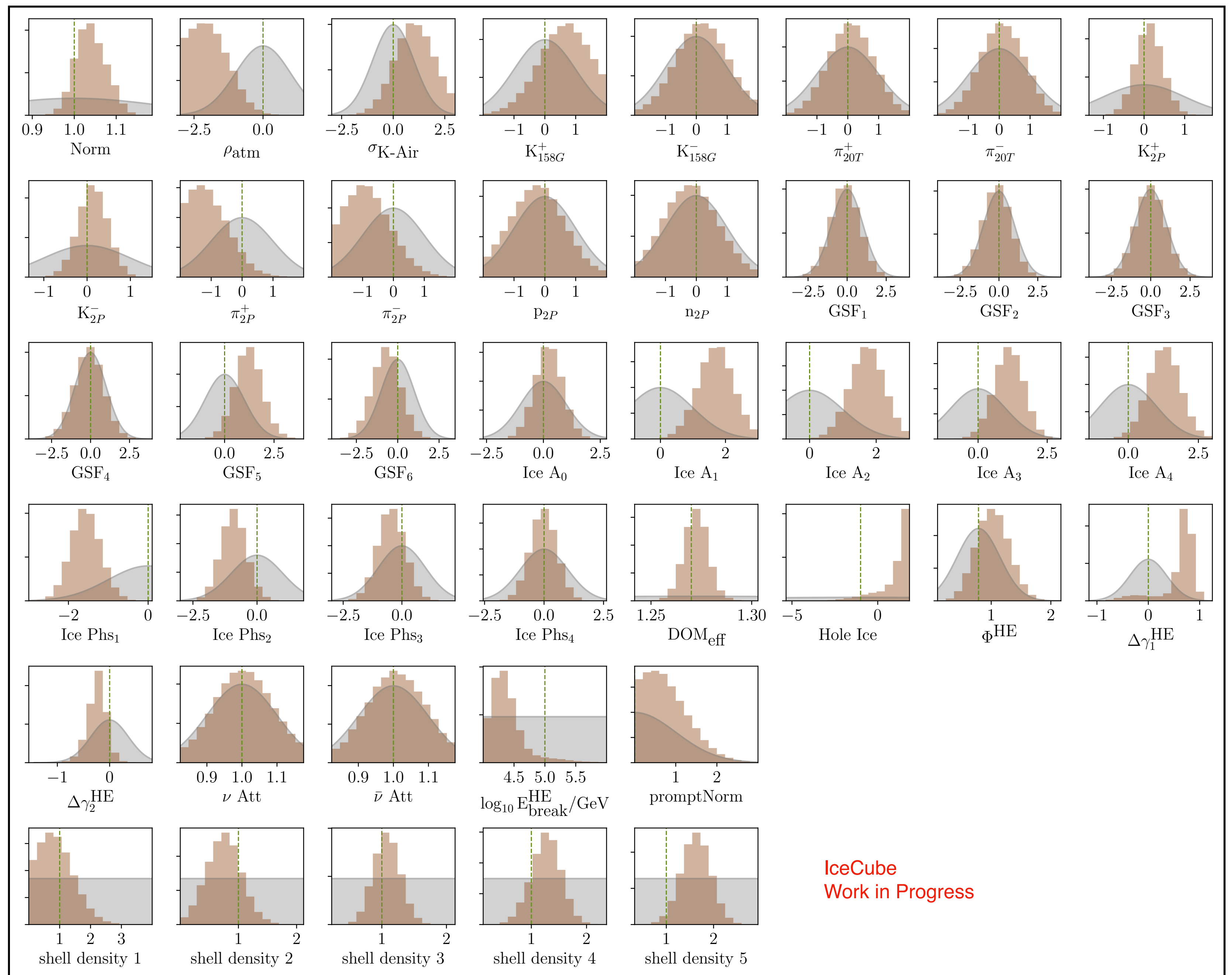


Zenith distributions - data-MC agreement

As before, but now broken down into different energy ranges

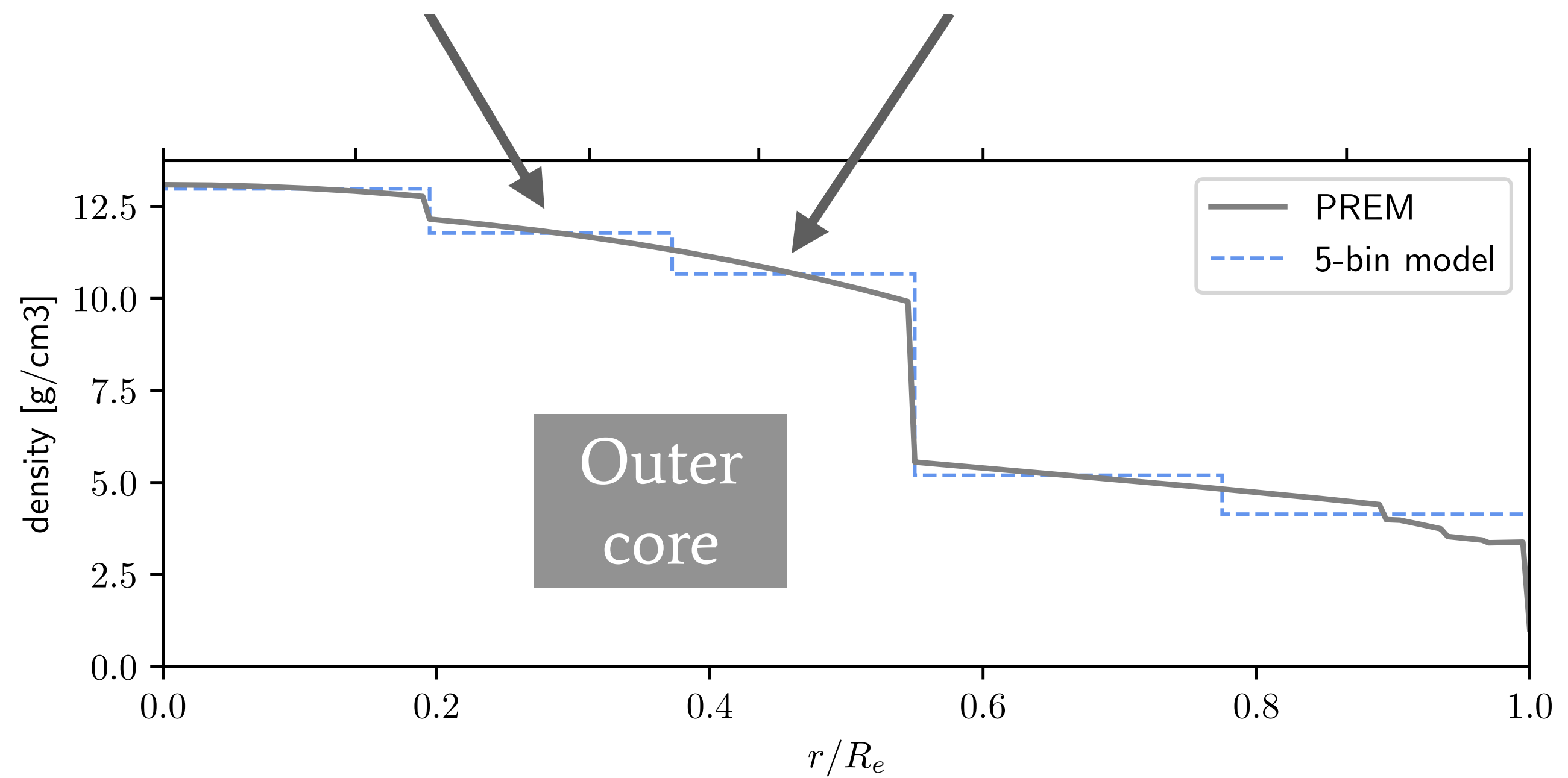
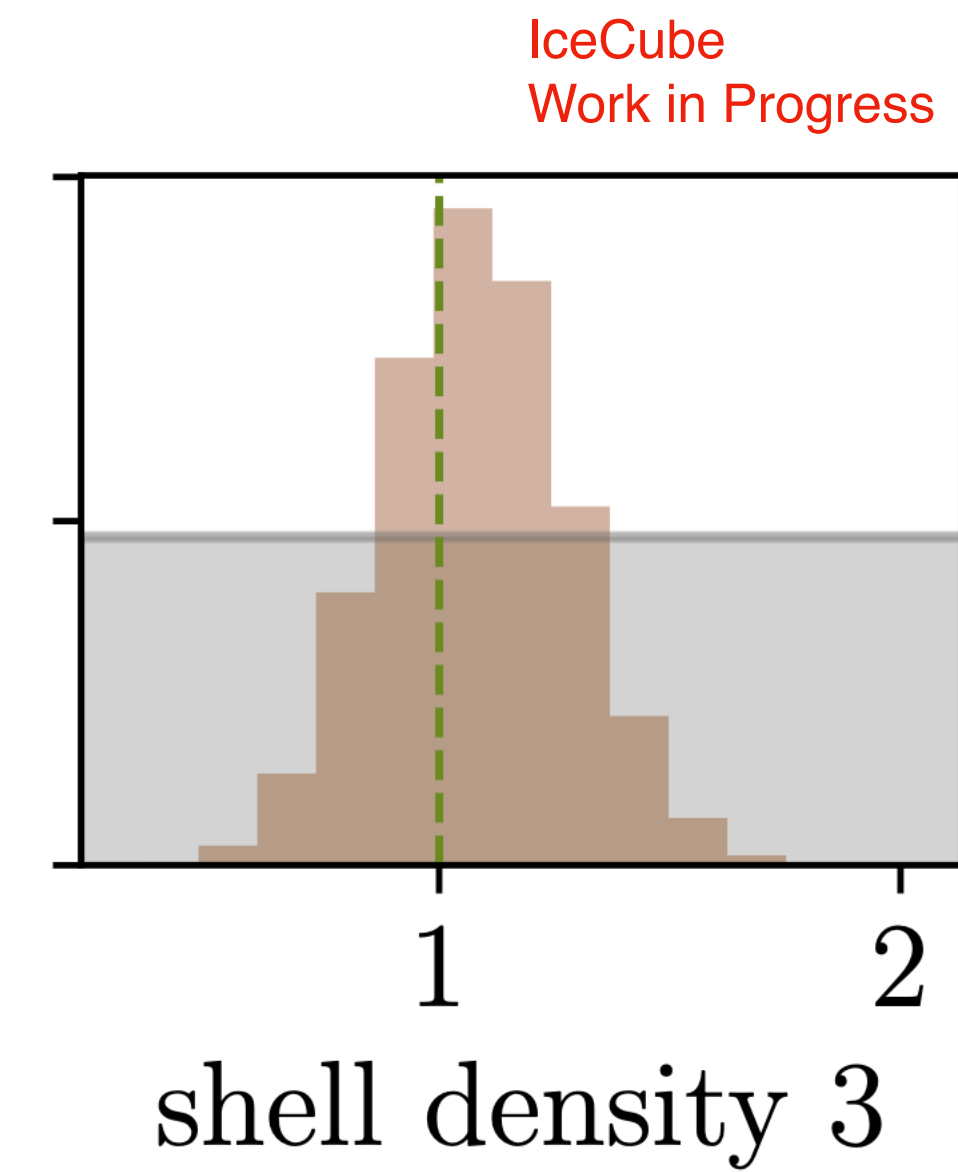
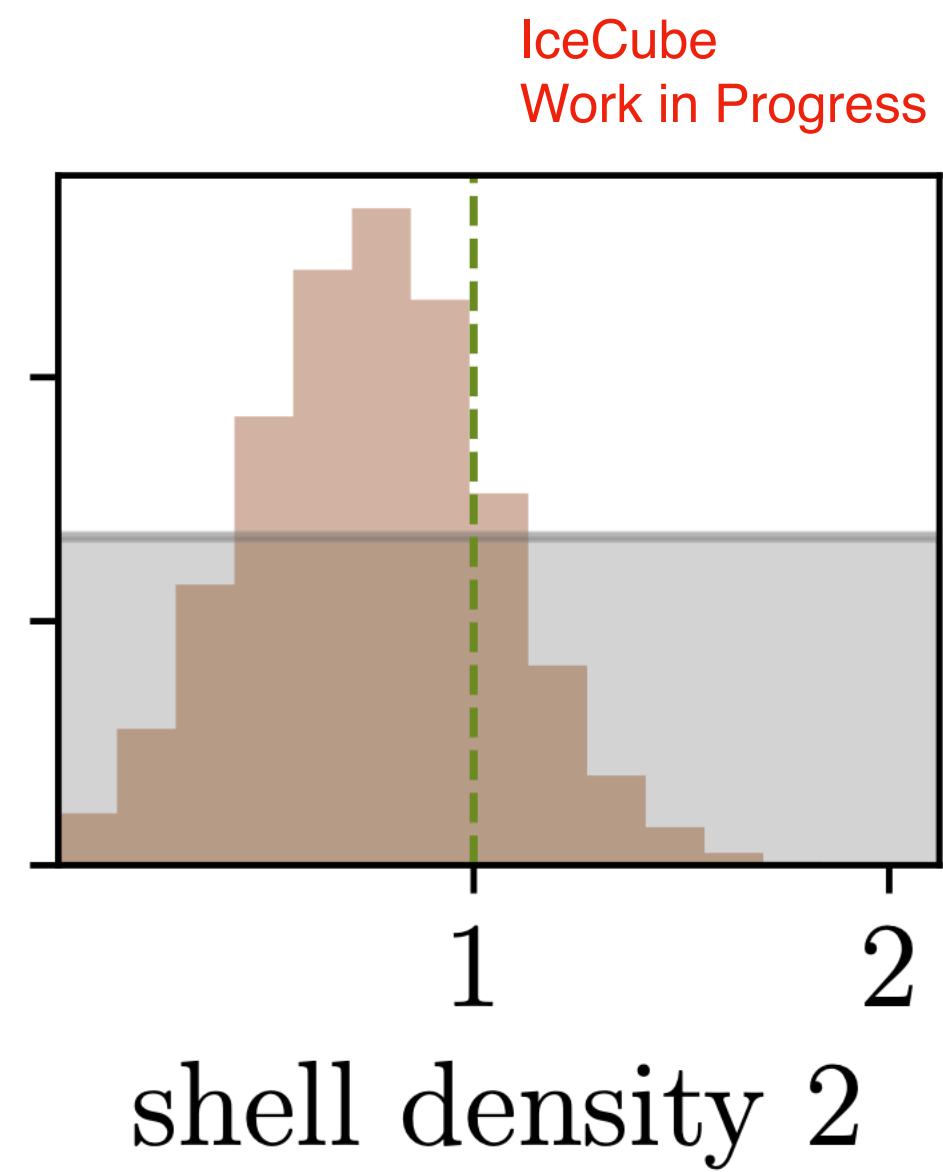


Measurement

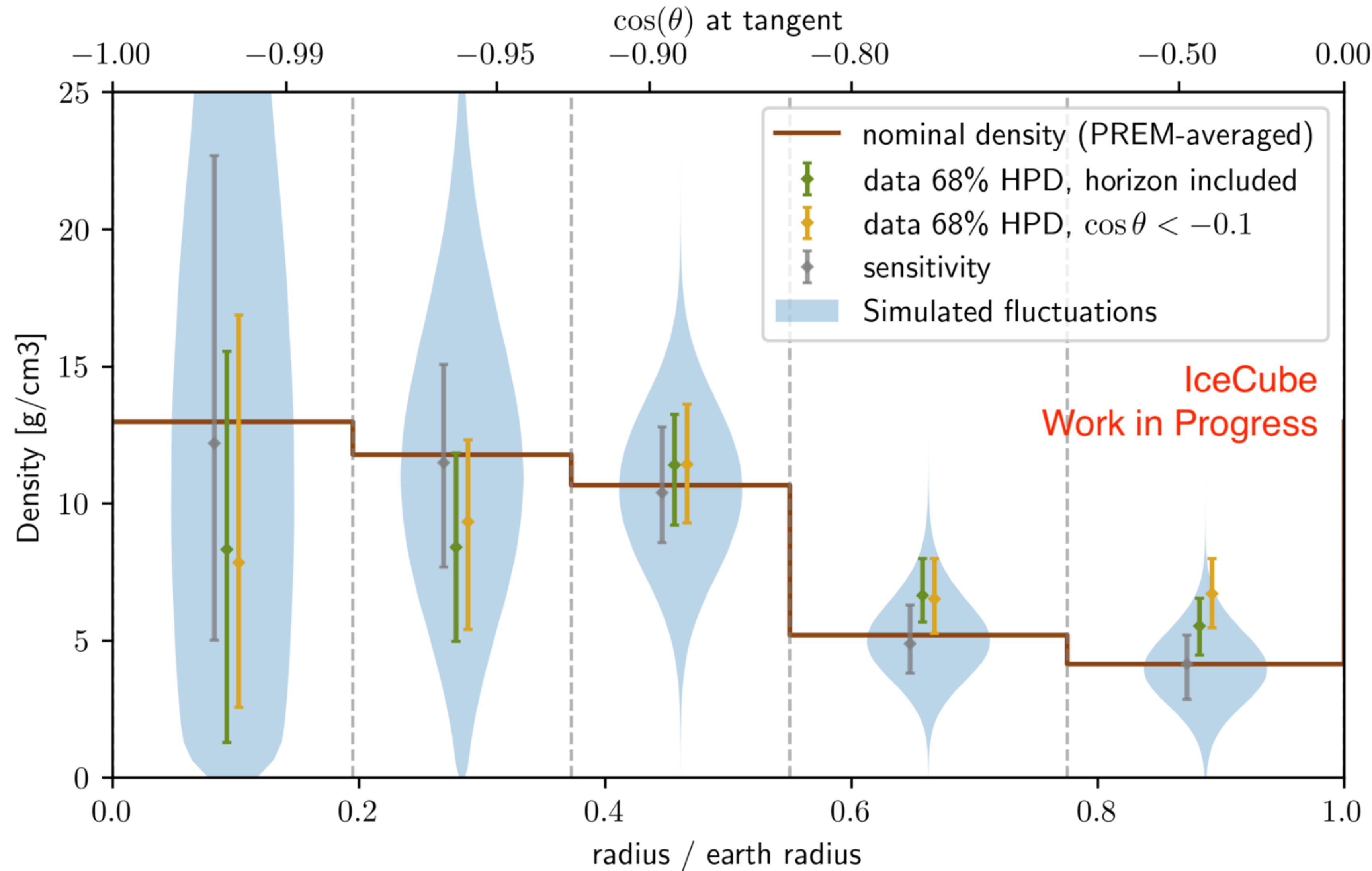


IceCube
Work in Progress

What the “error bars” correspond to...

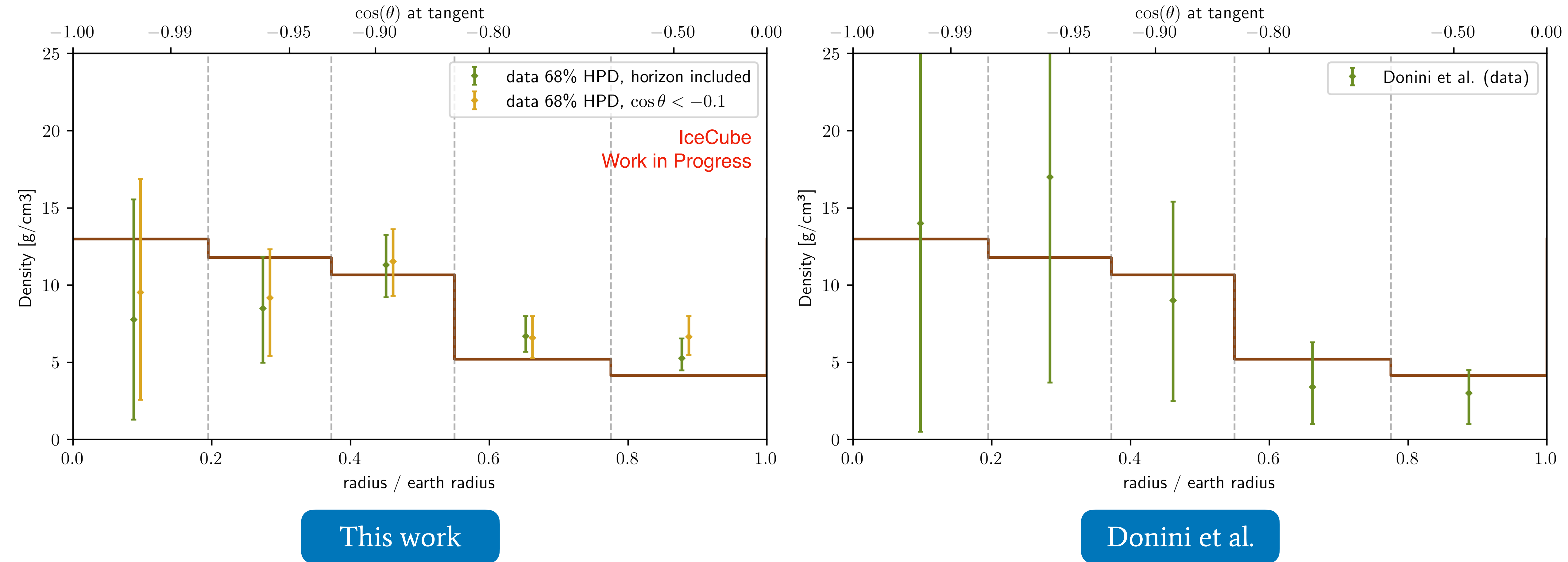


Density profile result - 5 bin model

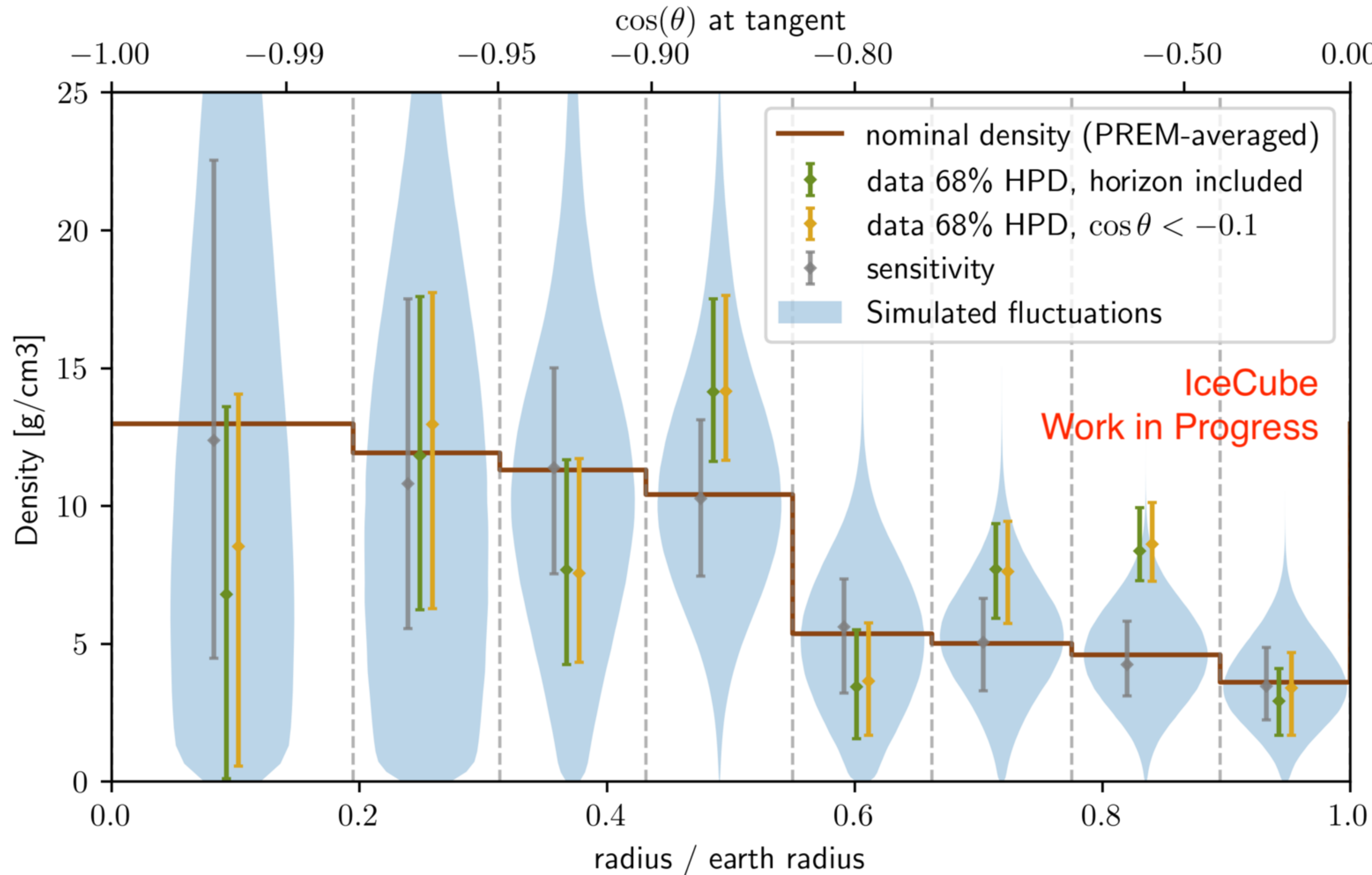


- Measurement compared with projected sensitivity, PREM-averaged density and simulated fluctuations
- Overall goodness of fit p-value: ~20%

Density profile result - comparison

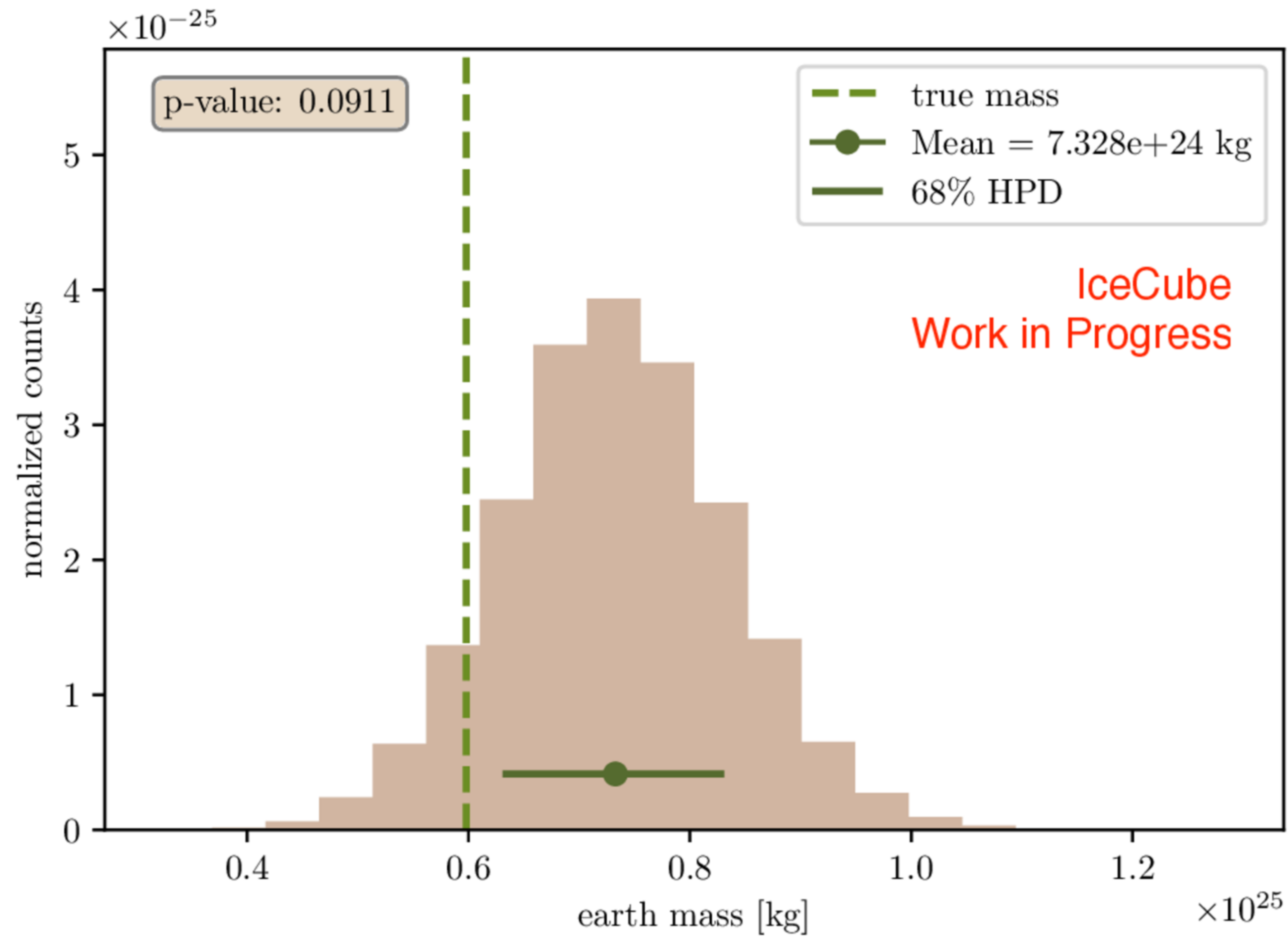


Density profile result - 8 bin model

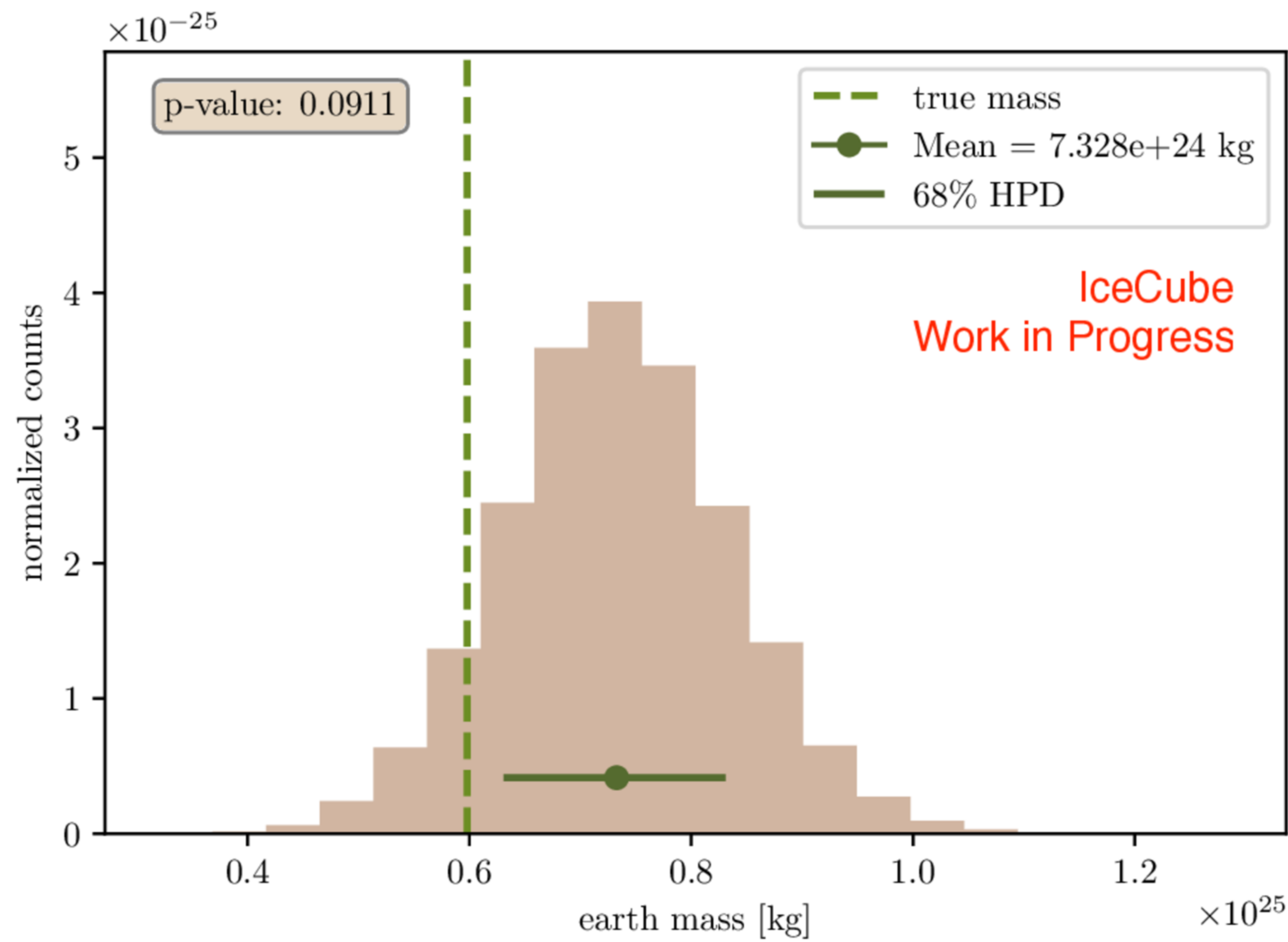


- Same as before, but with 8-layer model
- Overall goodness of fit p-value: ~6%

Earth mass



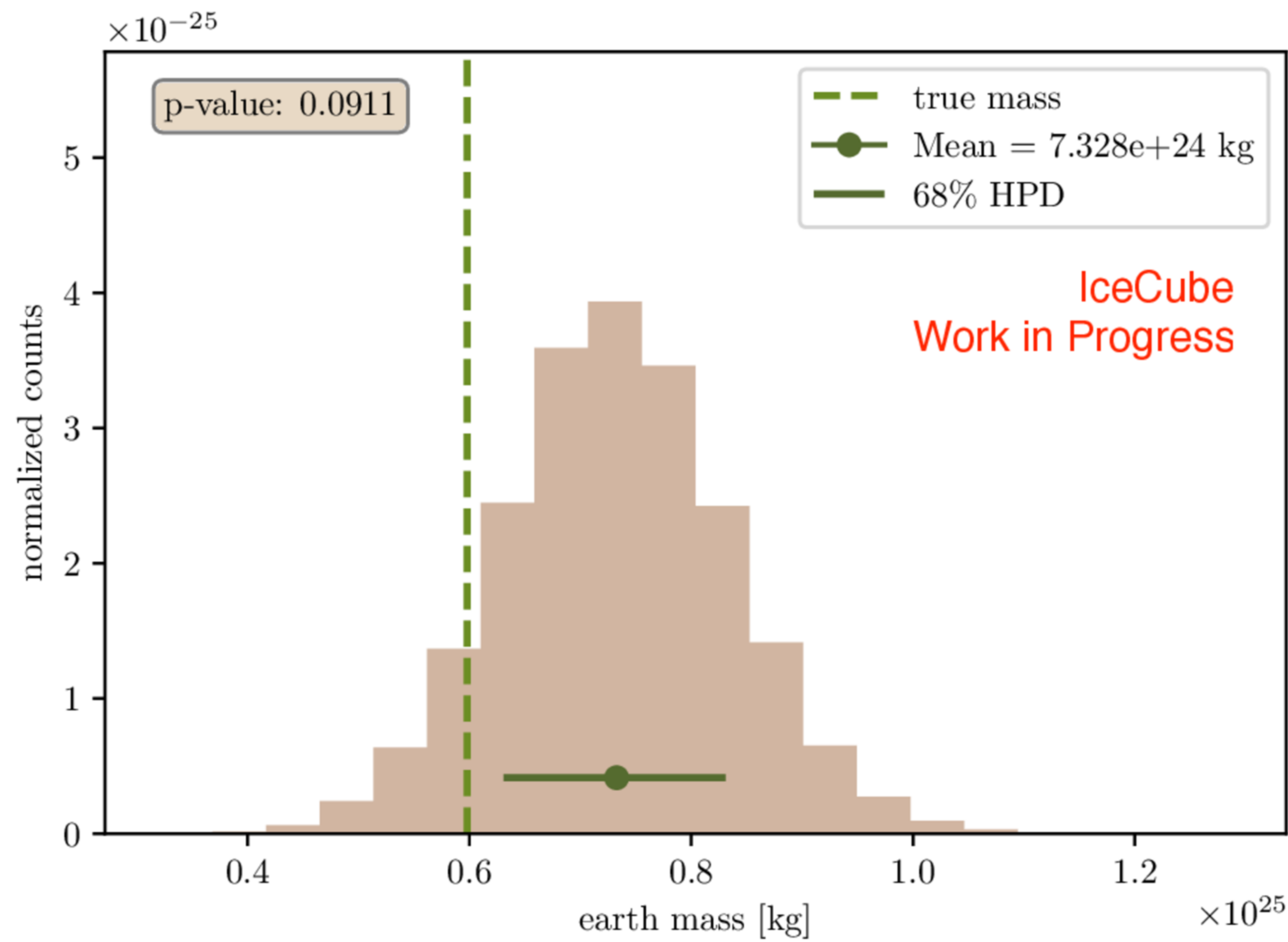
Earth mass



Main force used	Relative uncertainty
Gravity	$\sim 0.01\%$
EM (seismology)	$\sim 1\%$
Weak	$\sim 10\%$

Sources: IAU 2009 Recommendation;
Masters & Gubbins, On the Resolution of
Density within the Earth. <https://doi.org/10.1016/j.pepi.2003.07.008>

Earth mass

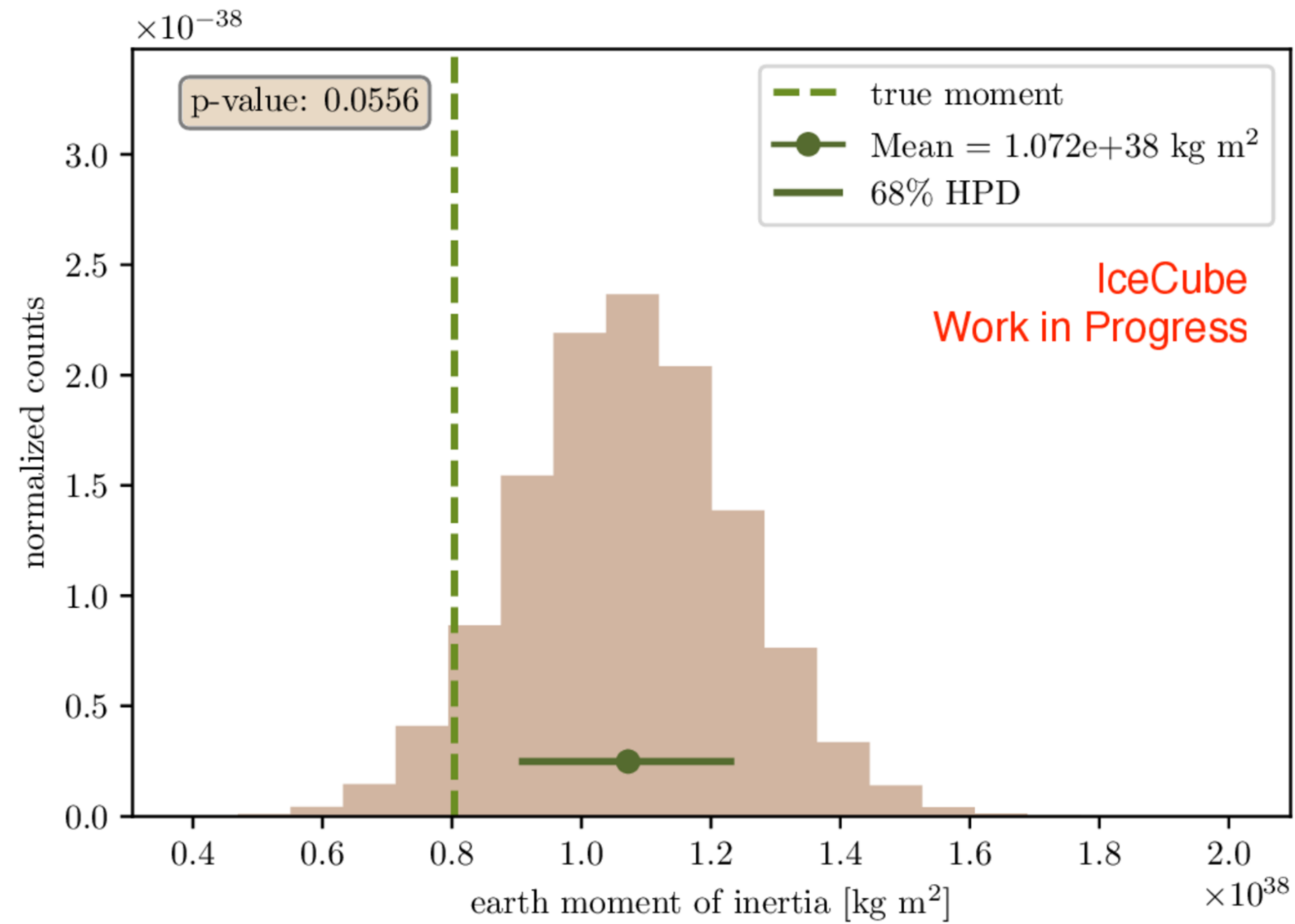


Main force used	Relative uncertainty
Gravity	$\sim 0.01\%$
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Weak	$\sim 10\%$

Neutrinos rule out vacuum Earth hypothesis at $>5\sigma$!

Sources: IAU 2009 Recommendation; Masters & Gubbins, On the Resolution of Density within the Earth. <https://doi.org/10.1016/j.pepi.2003.07.008>

Earth MoI



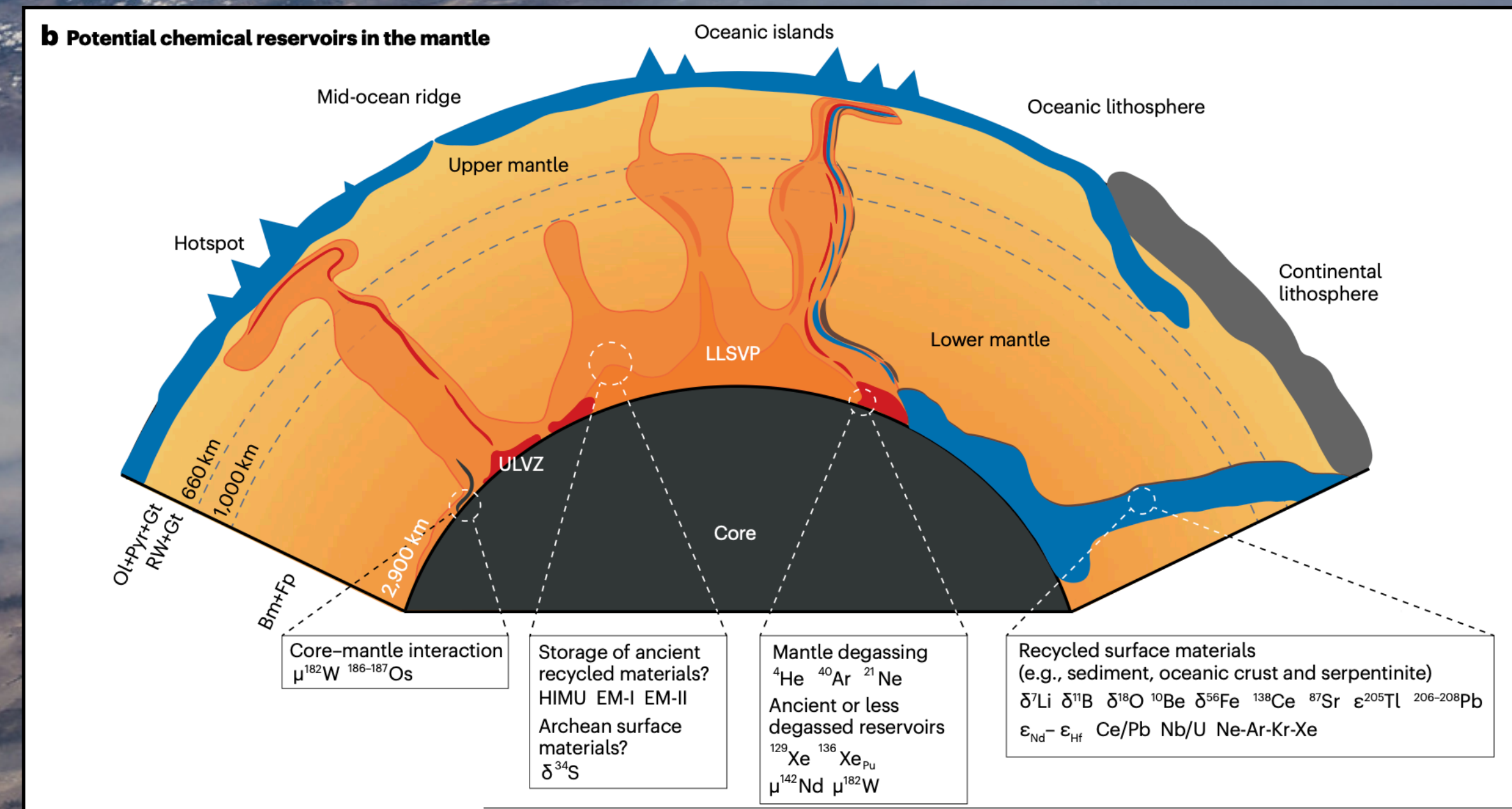
Looking ahead: tomography using global constellation of neutrino telescopes



Upcoming publication:
W. Thompson, C.
Argüelles, et al.

Figure: Jack Pairin

Looking ahead: tomography using global constellation of neutrino telescopes



Weis, D., Harpp, K.S., Harrison, L.N. et al. Earth's mantle composition revealed by mantle plumes. *Nat Rev Earth Environ* 4, 604–625 (2023).

Upcoming publication:
W. Thompson, C.
Argüelles, et al.

Figure: Jack Pairin

Summary

- IceCube is well-suited to a measurement of the Earth using high energy neutrinos
- We have performed the most precise measurement of the earth density and mass as measured by the weak force

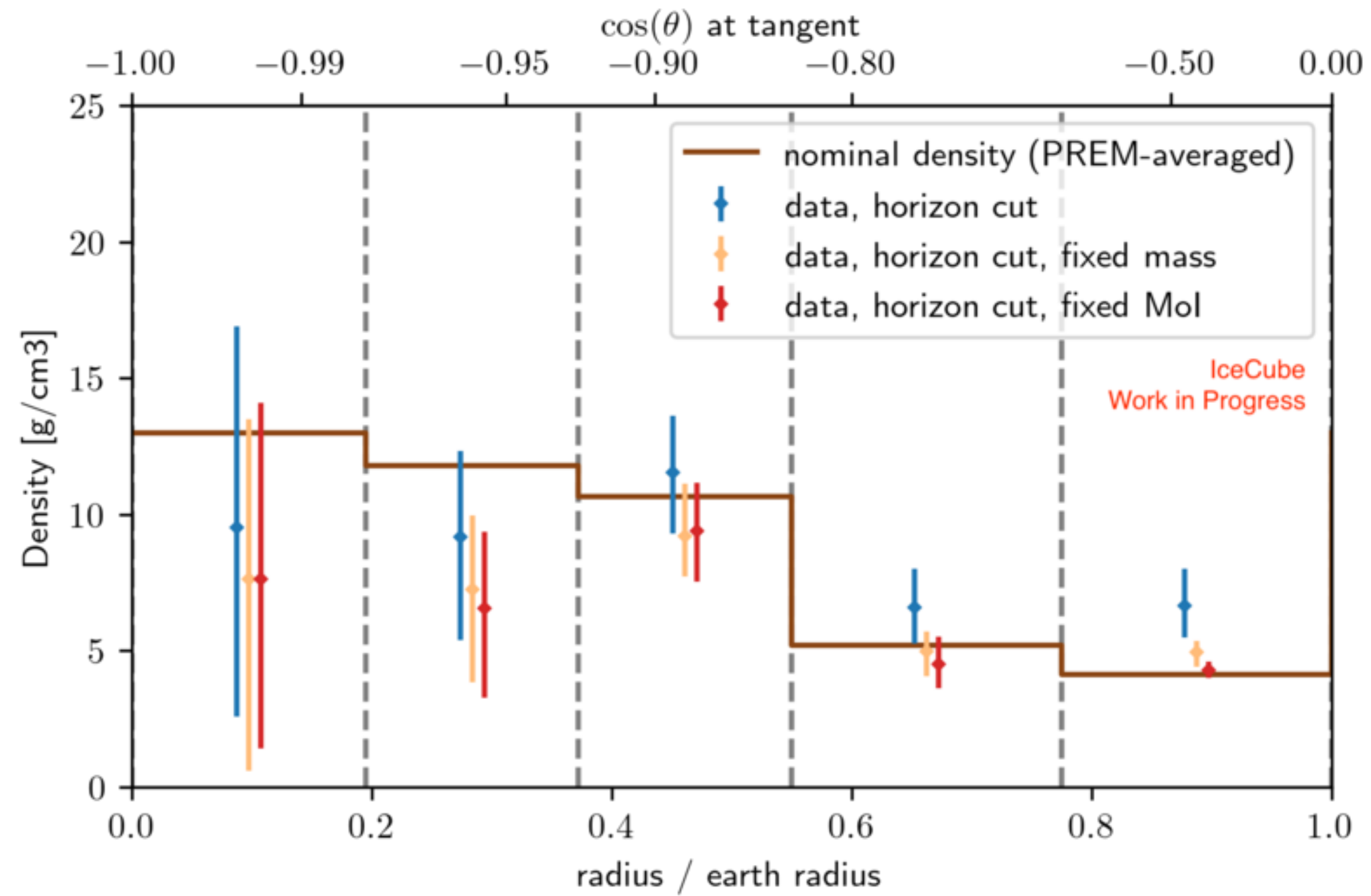
The end. Thank you!

alexwen@icecube.wisc.edu

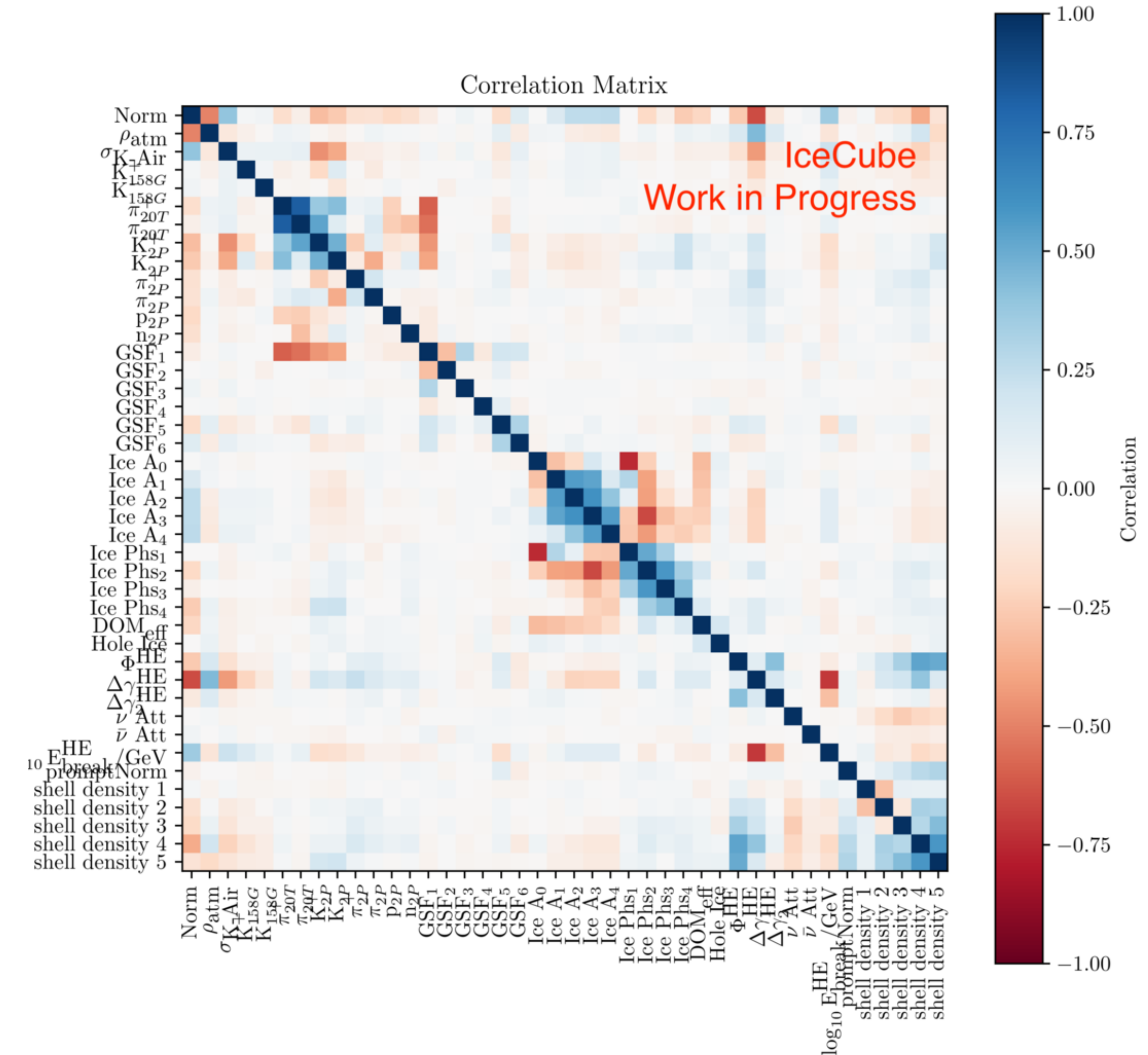
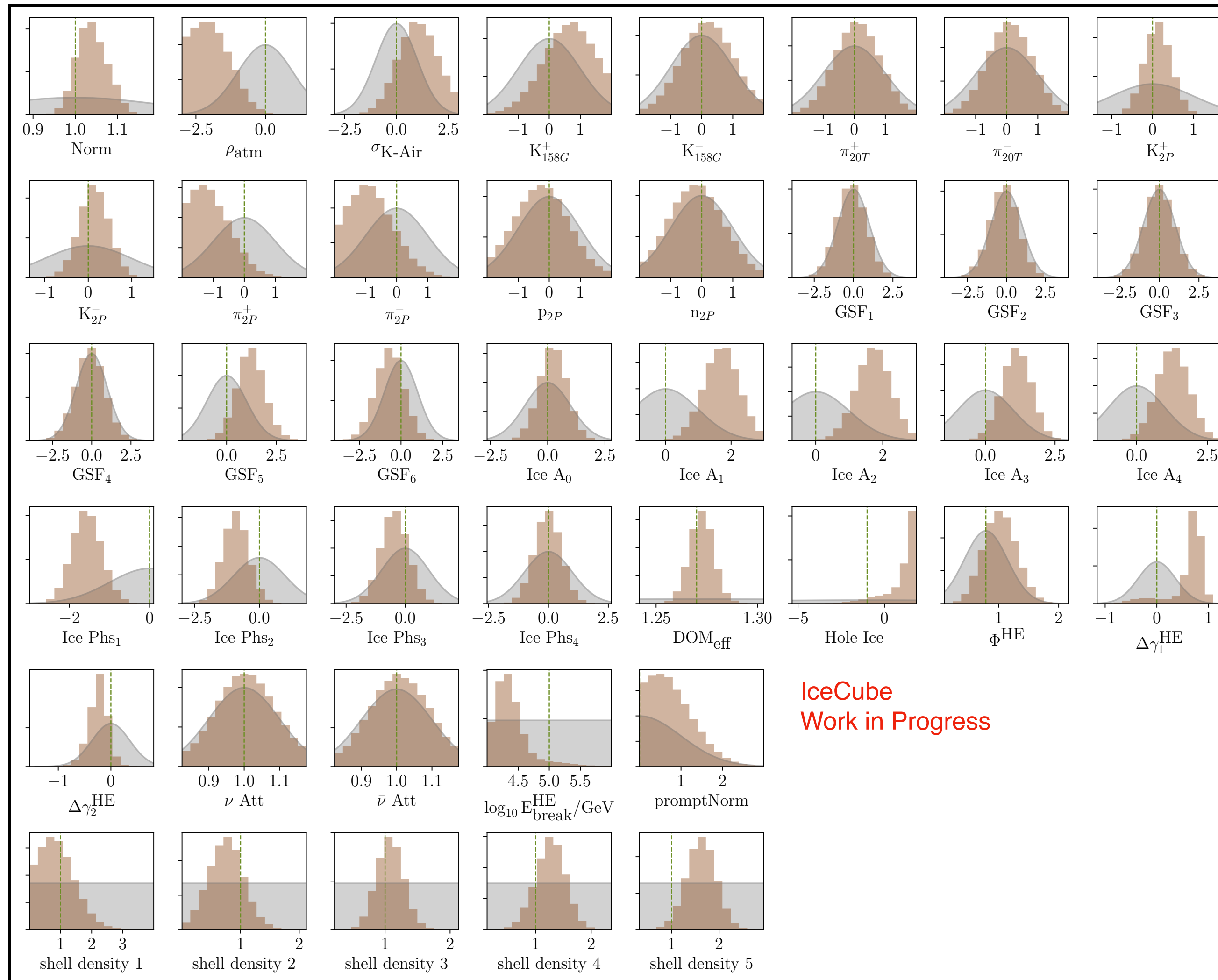
Backup



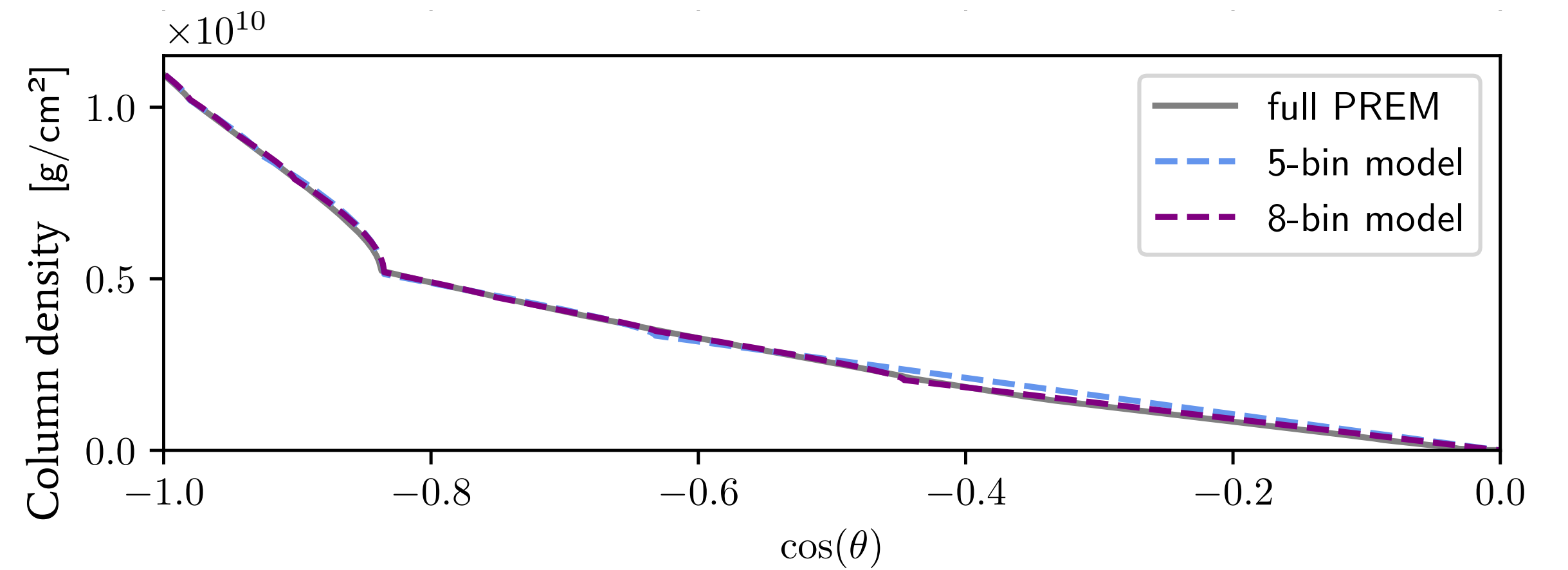
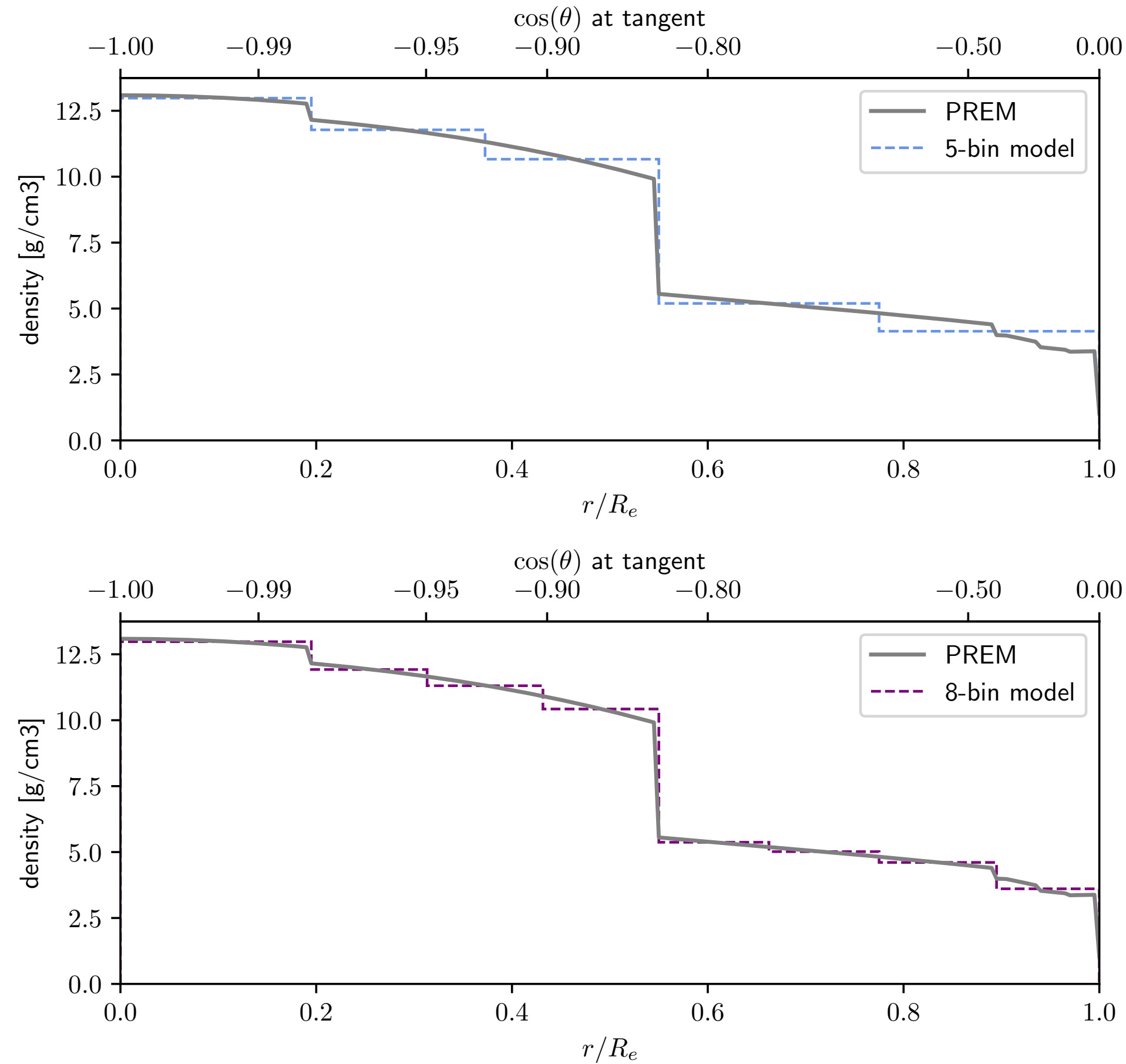
Fixing the mass or MoI



Measurement of nuisance parameters & correlations



Binning the earth into shells



Column density

Approximate PREM profile with constant density shells - use uniform priors

From:



Physics of the Earth and Planetary Interiors

Volume 140, Issues 1–3, 28 November 2003, Pages 159–167



On the resolution of density within the Earth

Guy Masters^a , David Gubbins^b

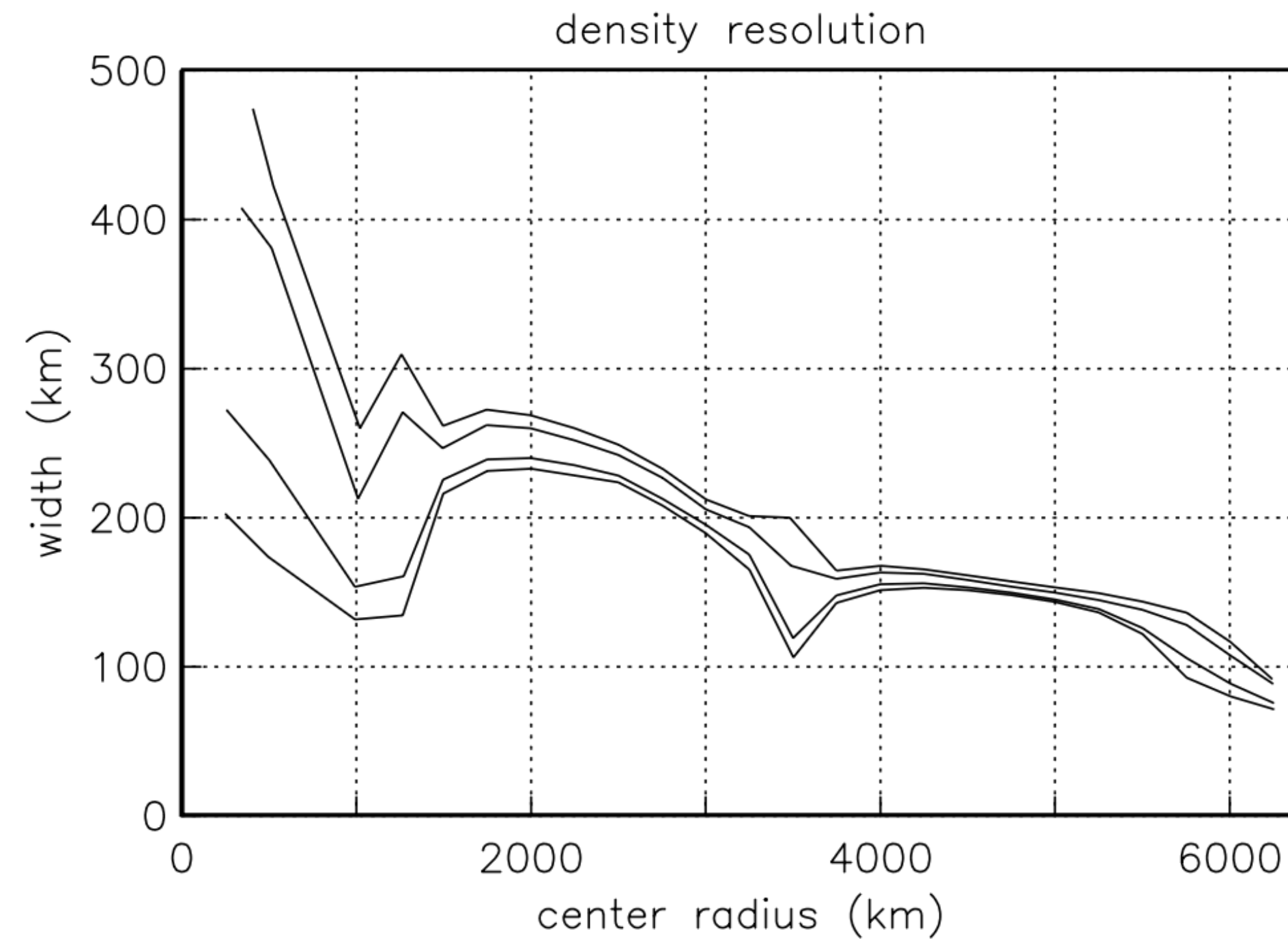
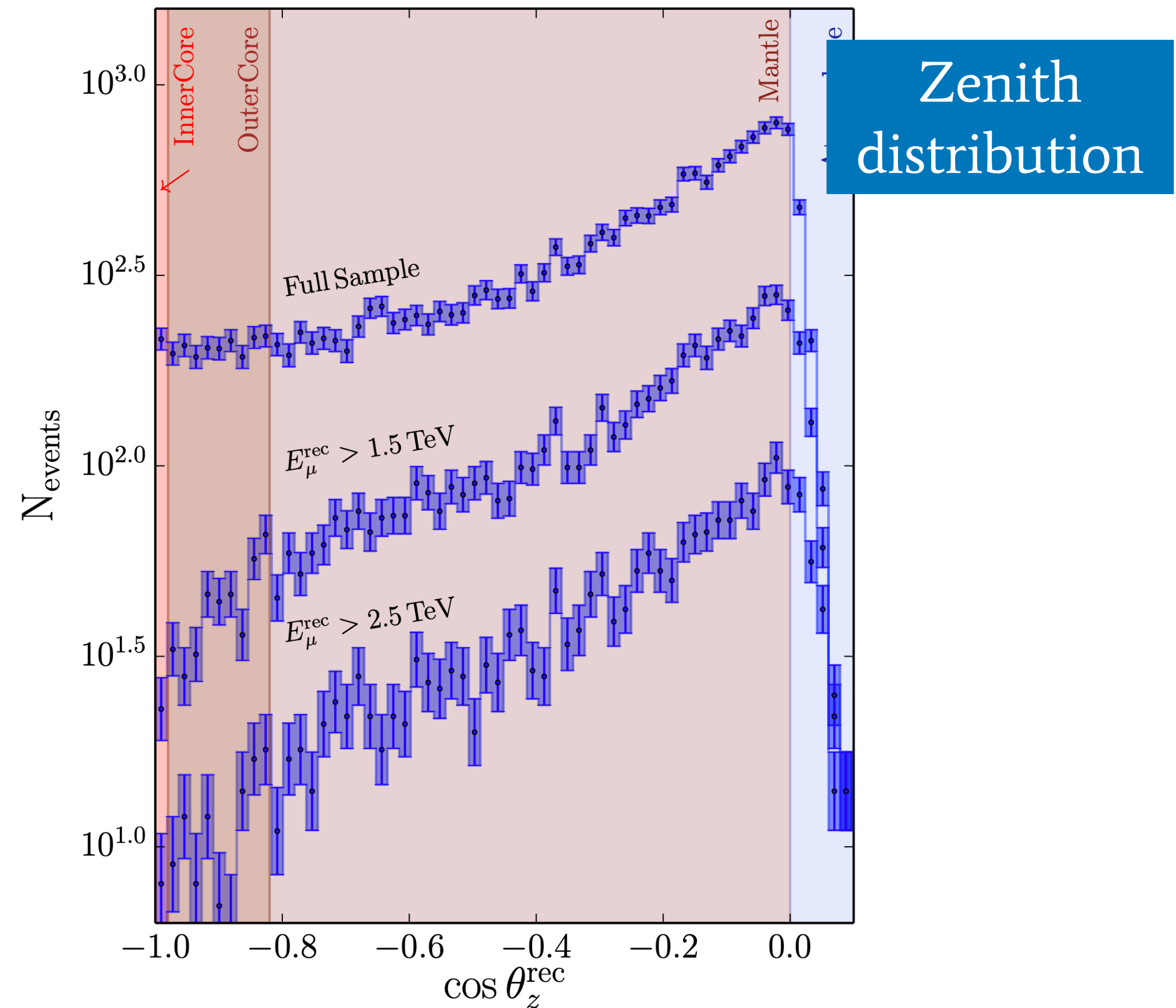
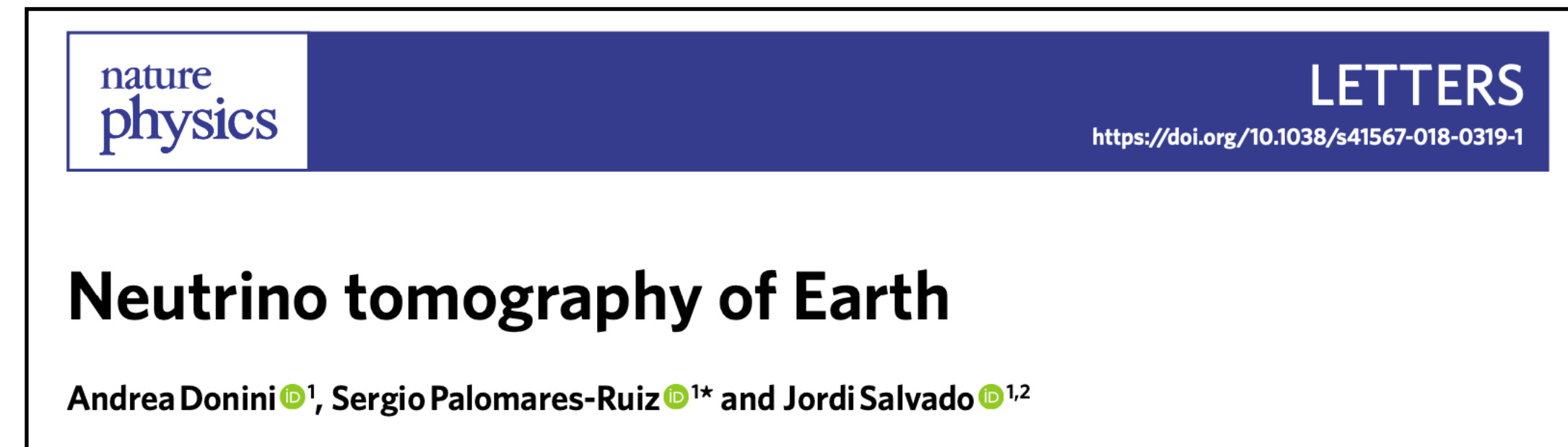
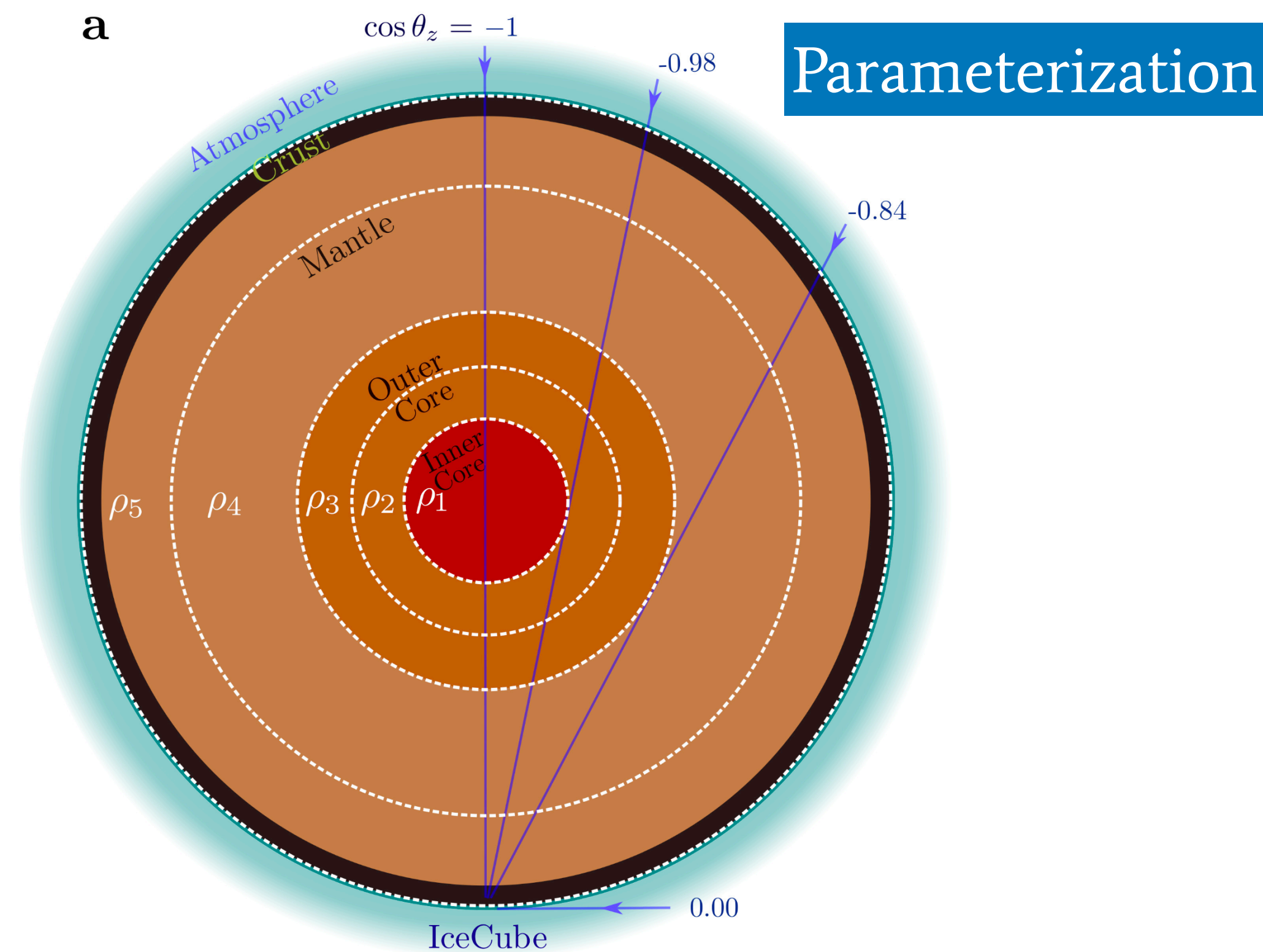


Fig. 1. Theoretical resolution of density in the Earth by the free-oscillation data set for various target error levels. Starting from the top curve, the target errors are 0.5, 1, 5, and 10%. As an example of how to read this plot, the density at a radius of 2000 km is known to an error of 0.5% if averaged over a resolving length of about 270 km.

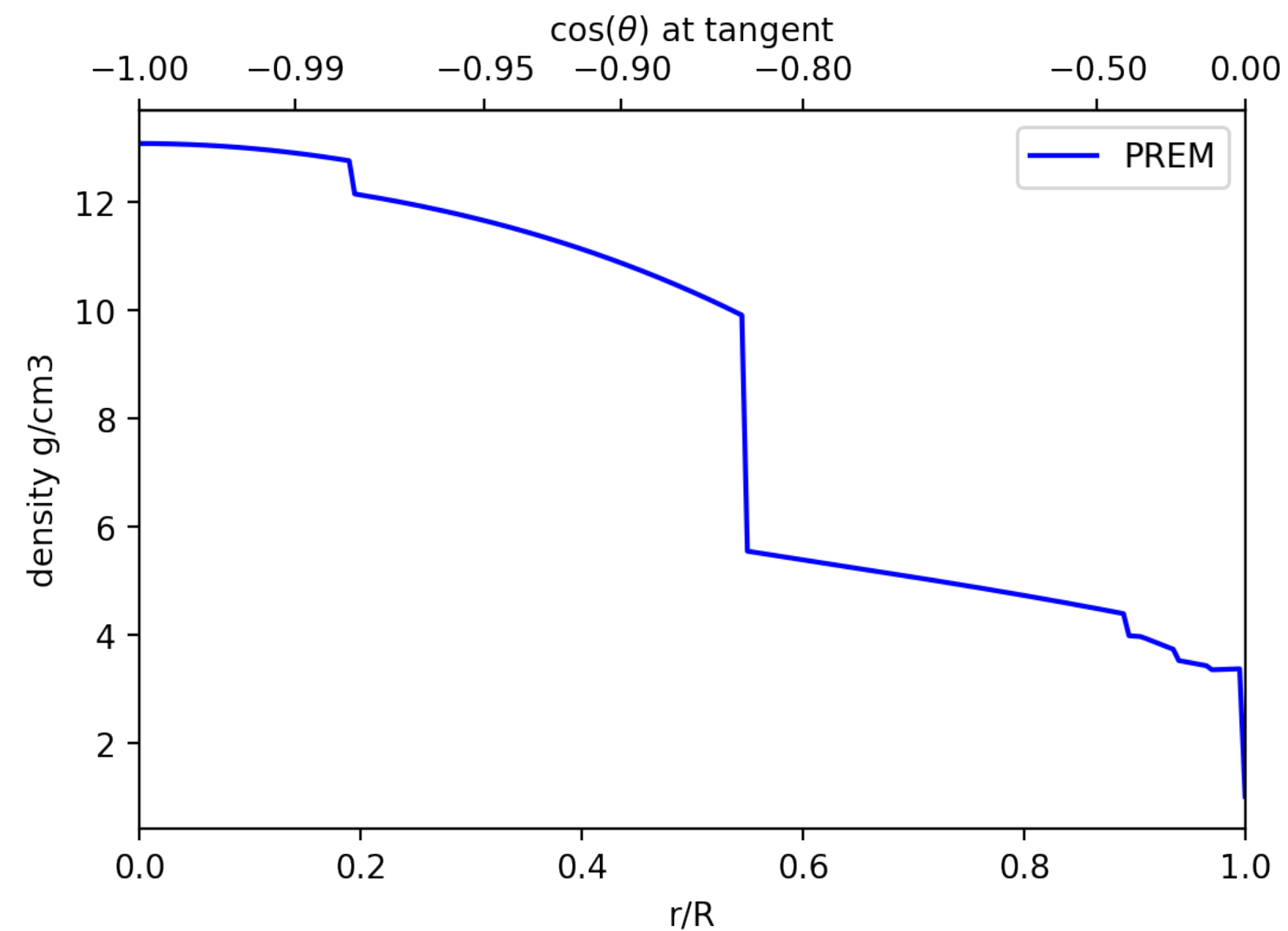
One previous earth inference analysis performed in 2018

- 2011-2012 IC86 data (344 days)
- 20145 muons
- 400 GeV - 20 TeV
- Event selection from [Phys. Rev. Lett. 115, 081102](#)

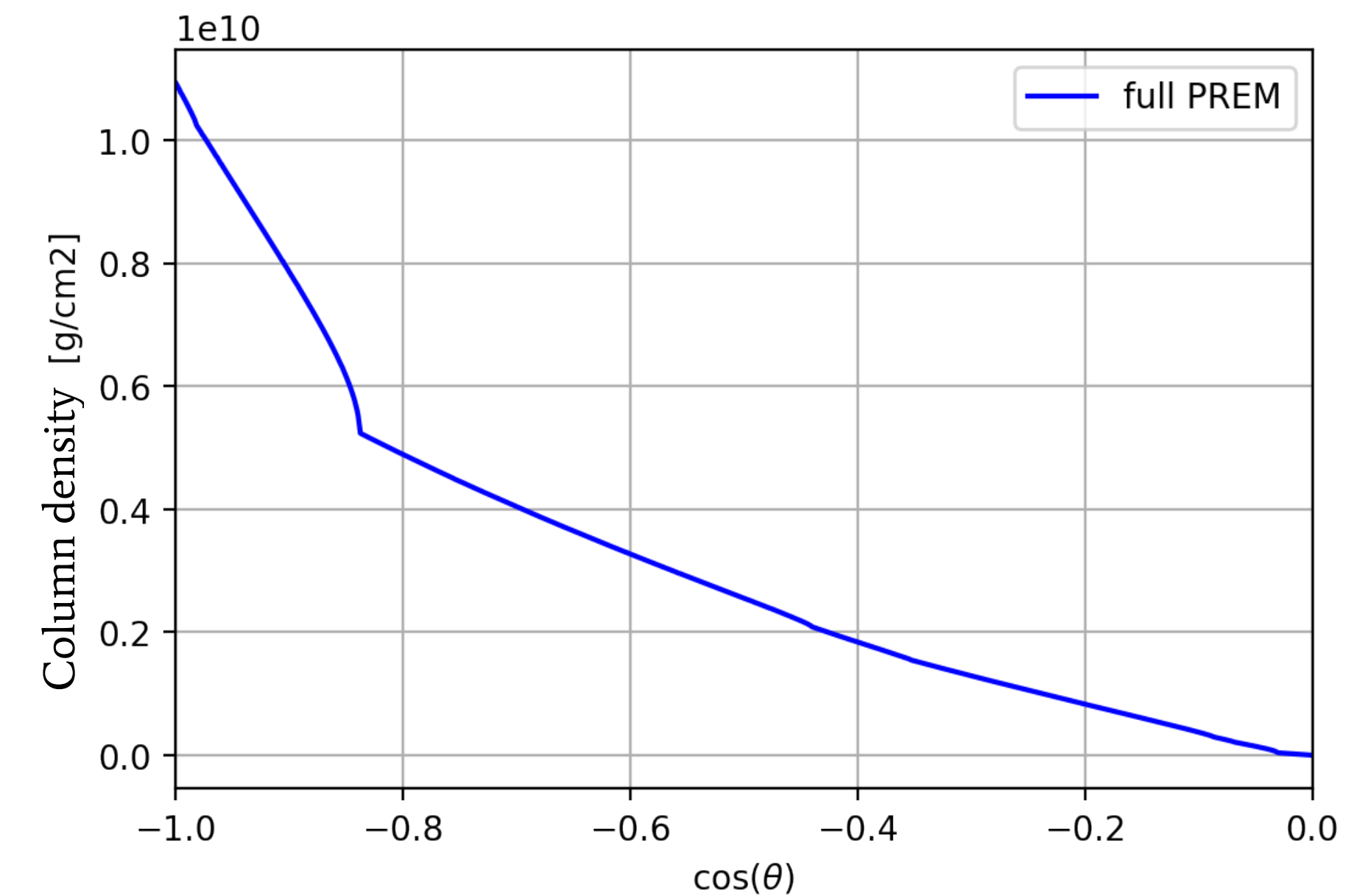
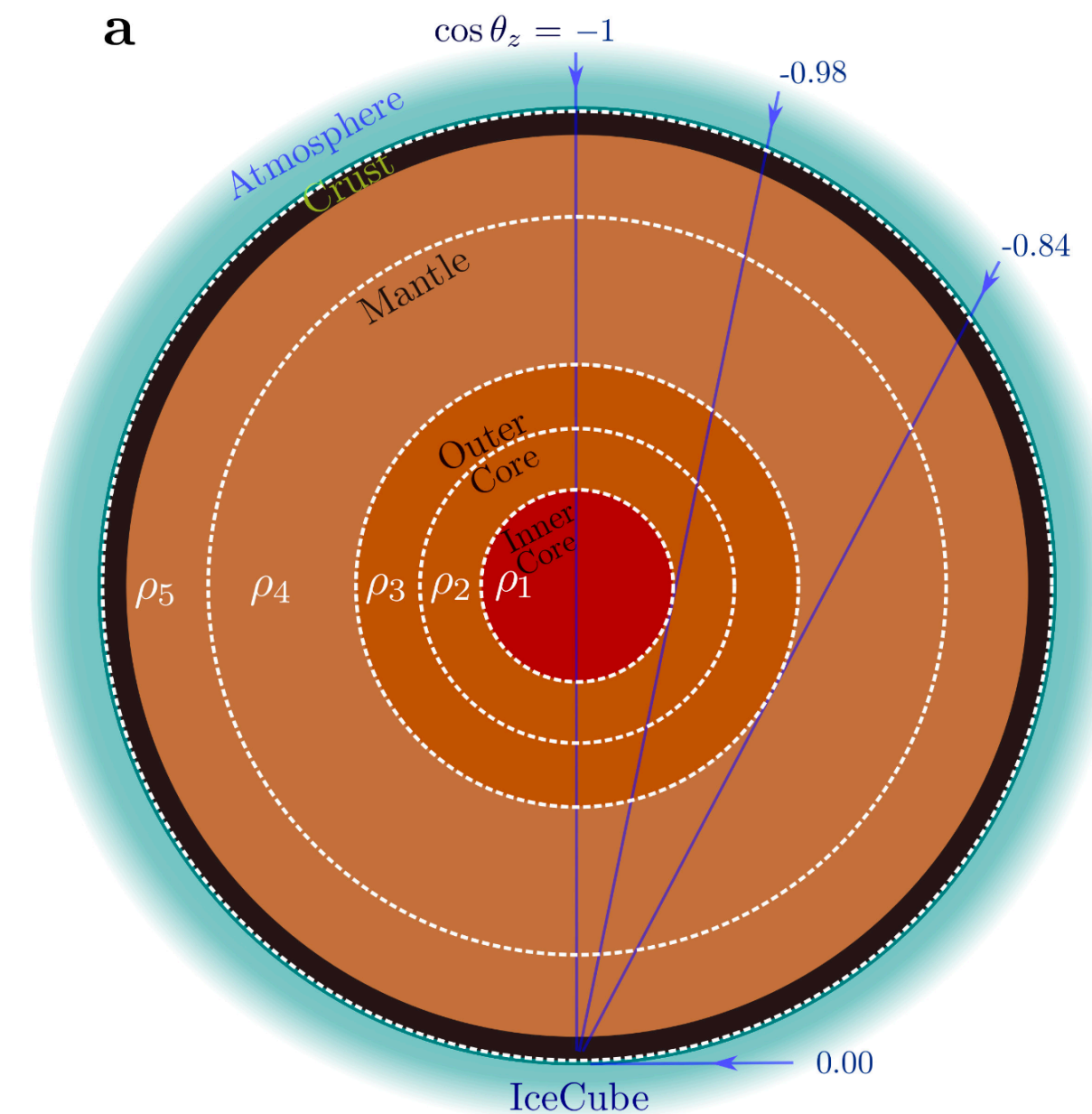


The Preliminary Reference Earth Model: the current model of the earth density from geophysical/seismic data

PREM: A. Dziewonski, D. Anderson (Physics of the Earth and Planetary Interiors 25, 297-356) 1981



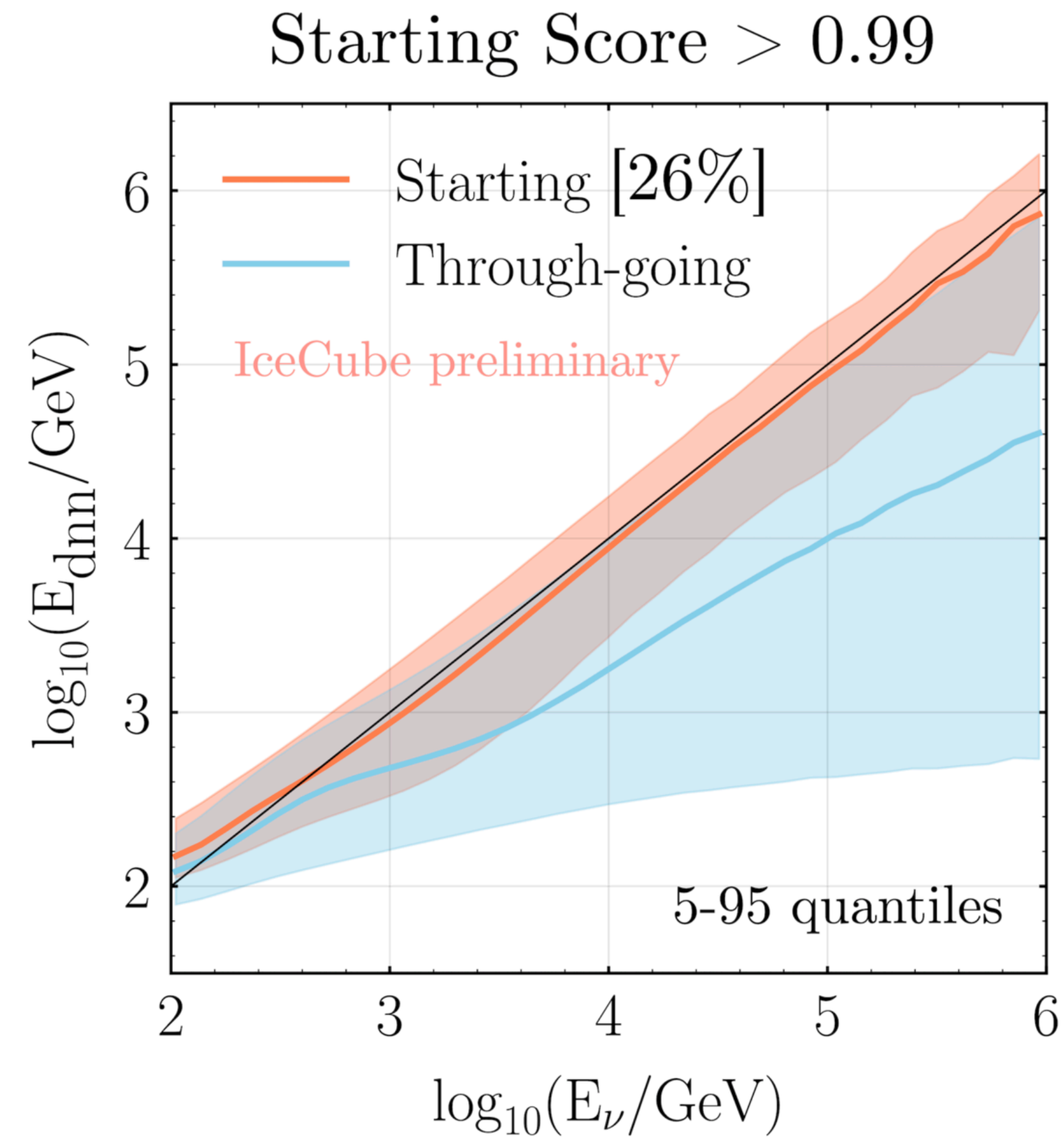
PREM density profile



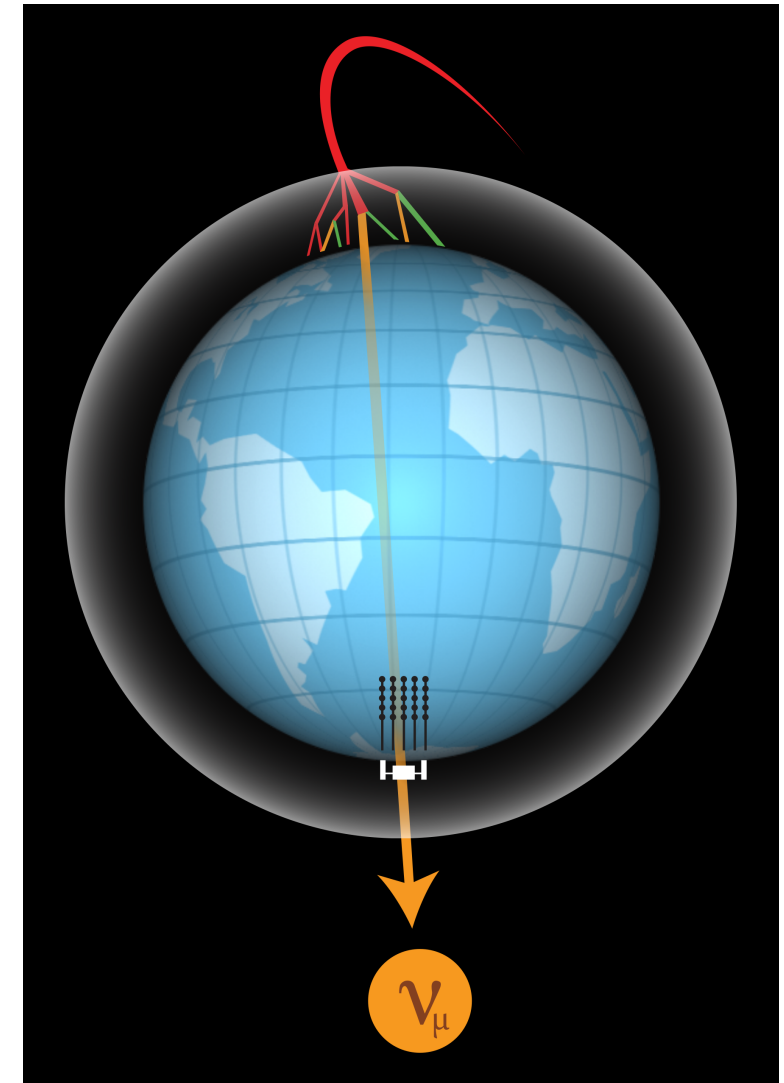
Column density as a function of cos θ

Donini et al. (Nature Physics 15, 37-40)

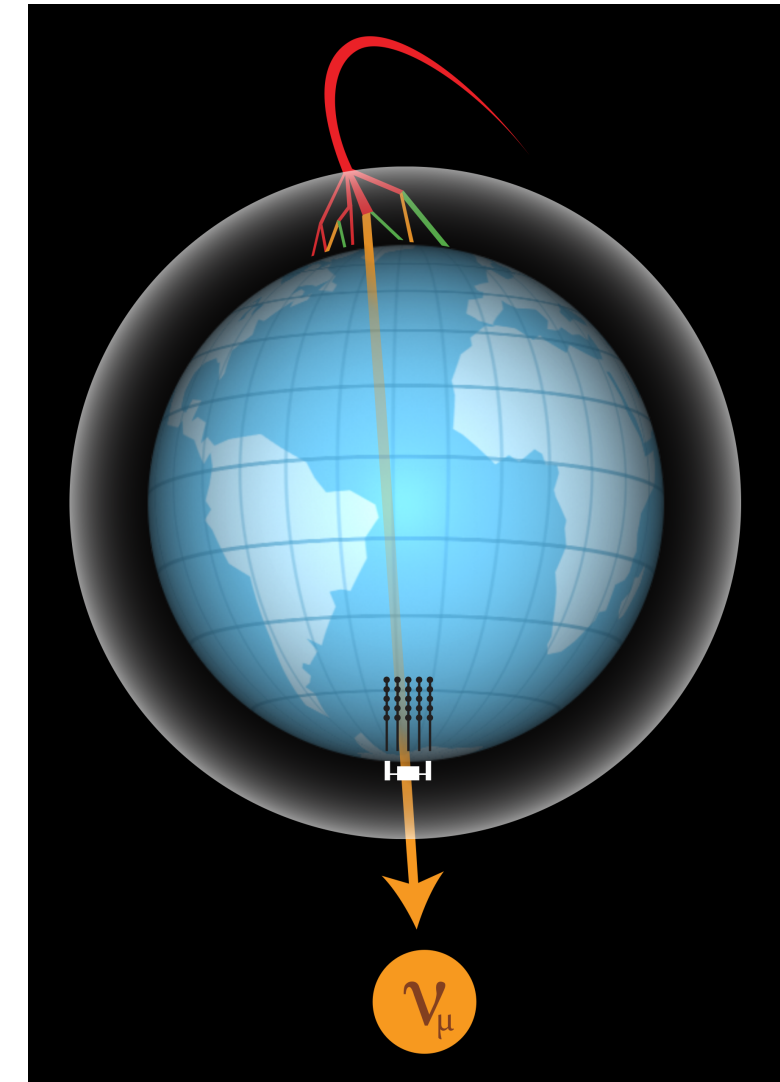
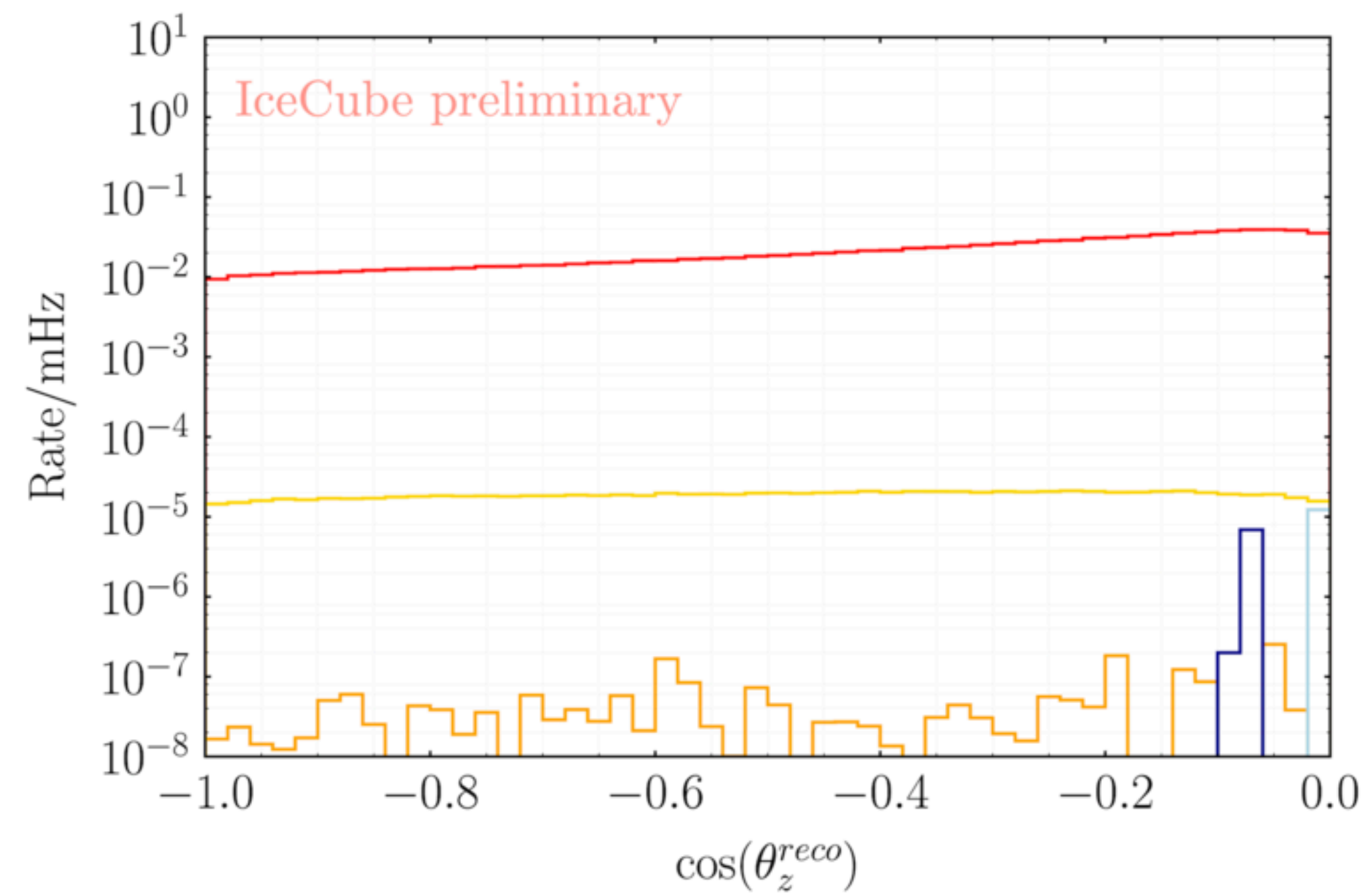
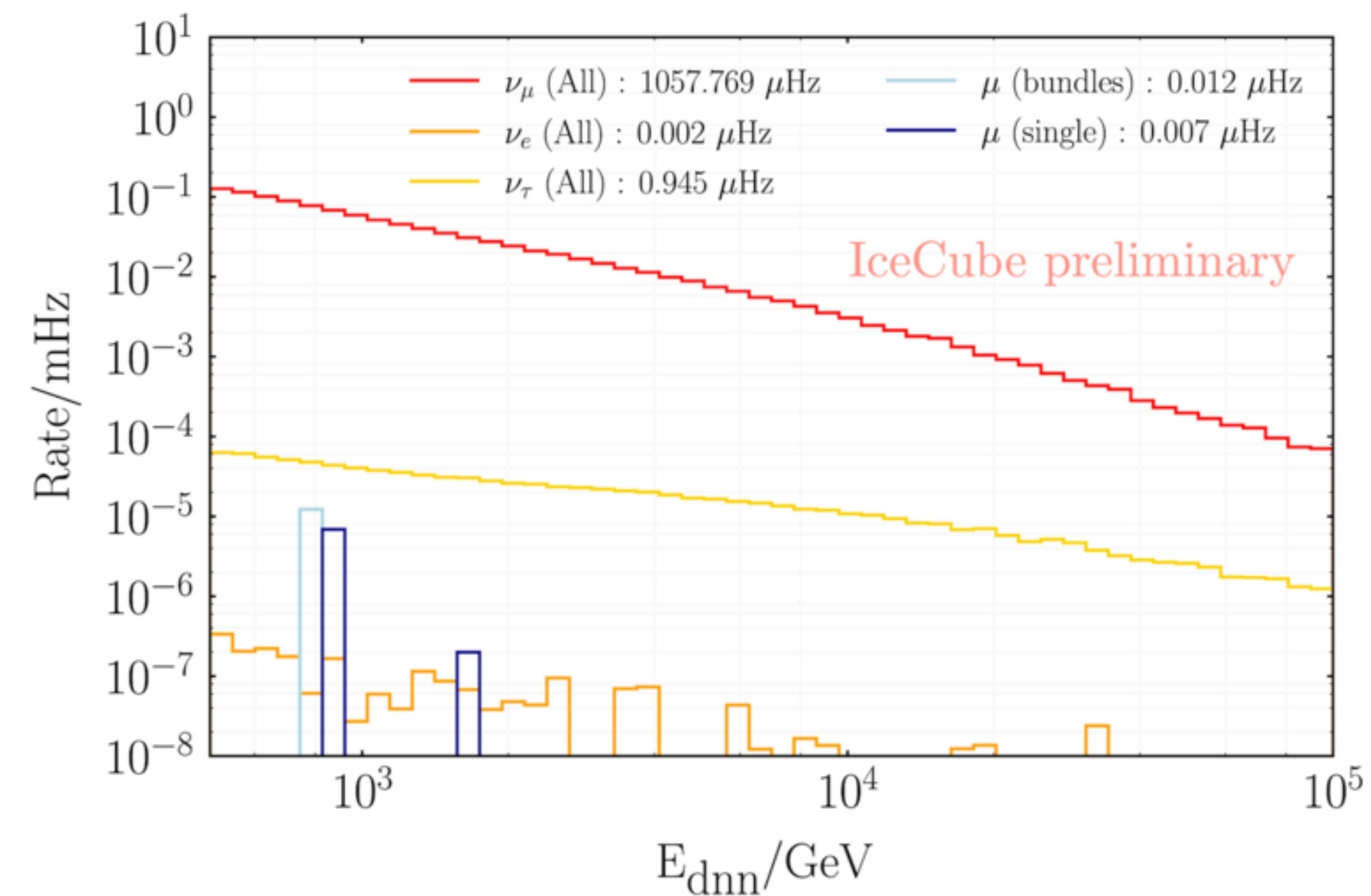
Data selection and reconstruction



Energy estimation done
with CNN

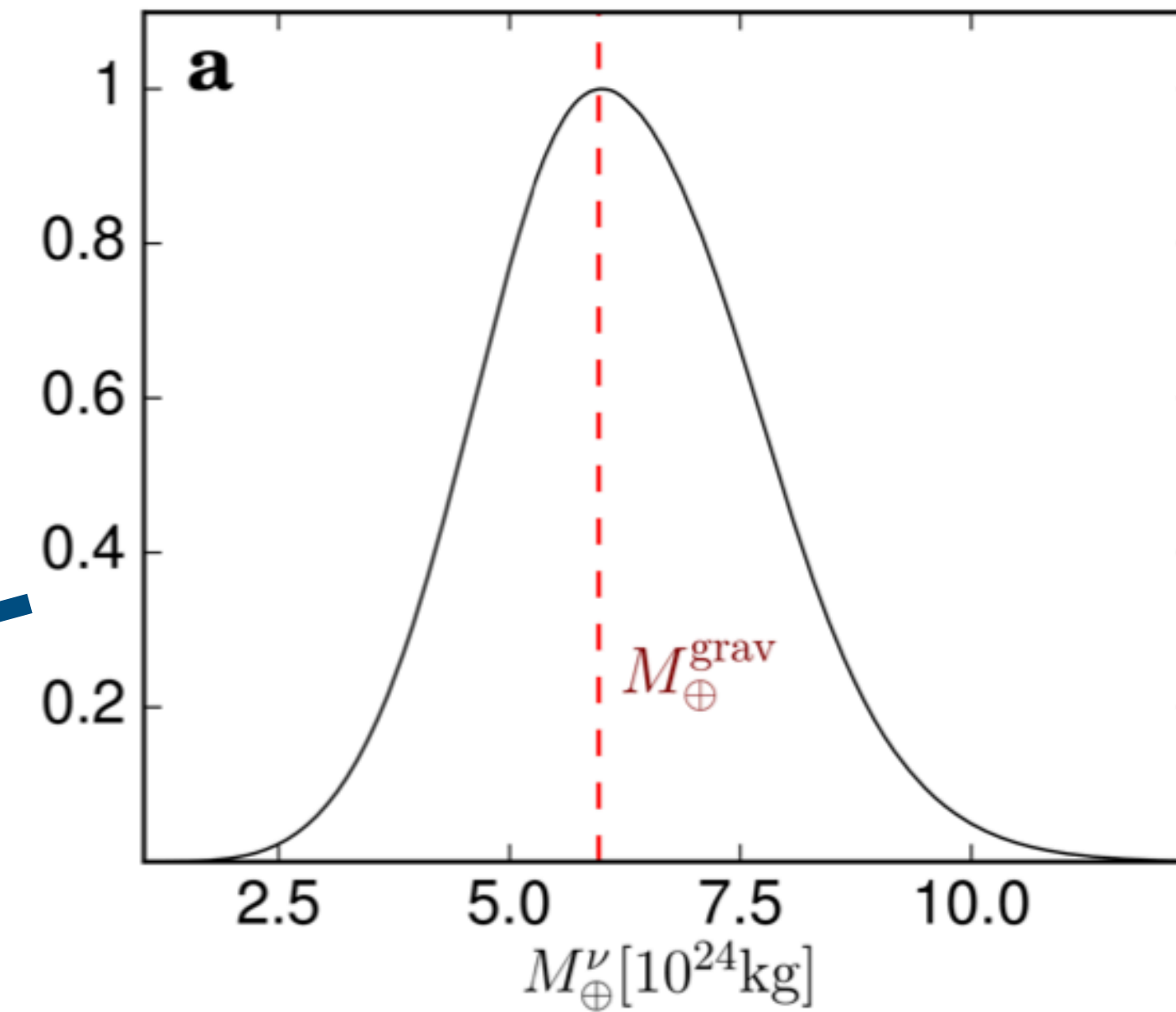
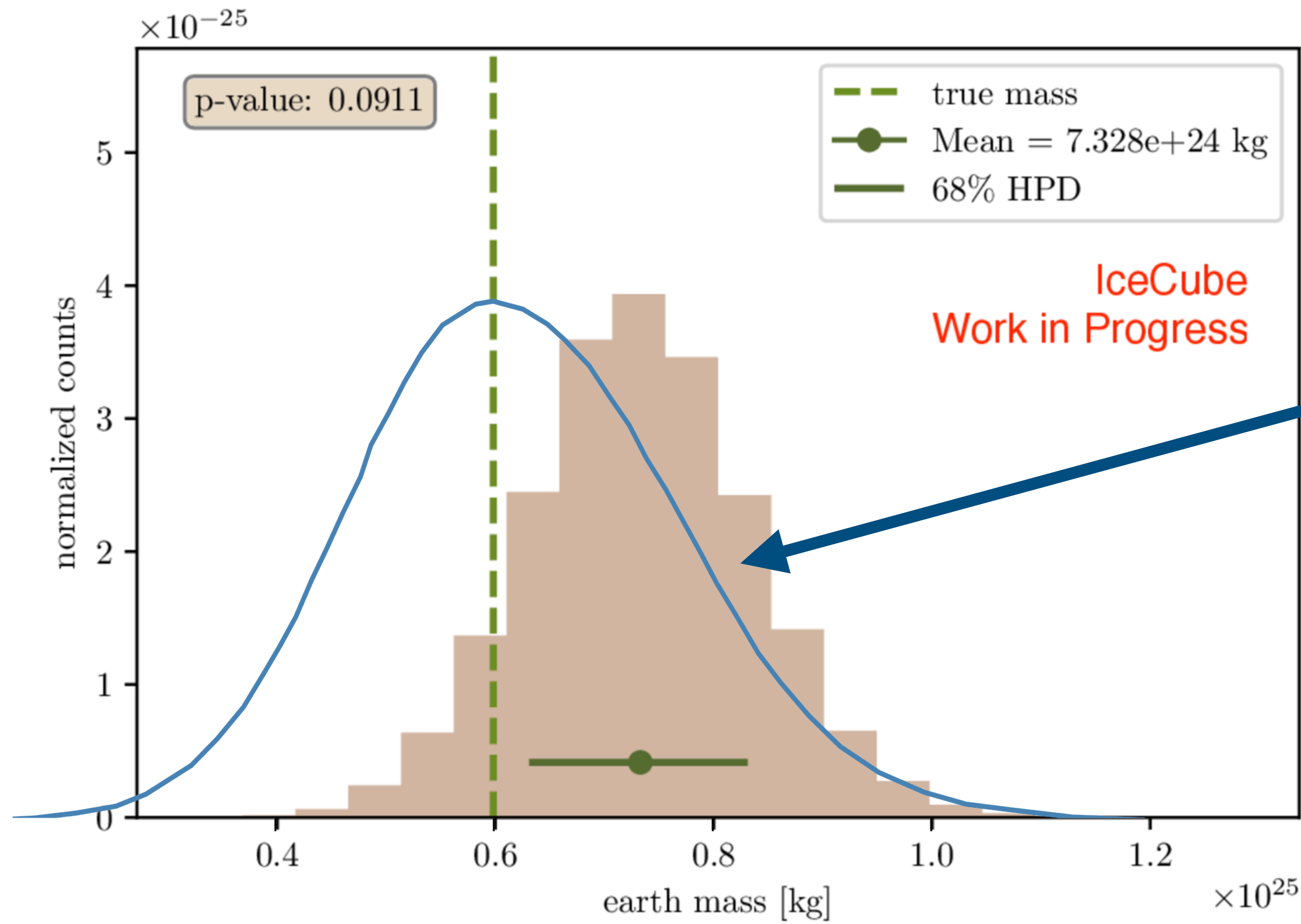


Data selection and reconstruction



MC distribution of reconstructed events

Earth mass



Donini et al.

This work

Letter | Published: 05 November 2018

Neutrino tomography of Earth

[Andrea Donini](#), [Sergio Palomares-Ruiz](#)  & [Jordi Salvado](#)

[Nature Physics](#) **15**, 37–40 (2019) | [Cite this article](#)

Conventional atmospheric flux

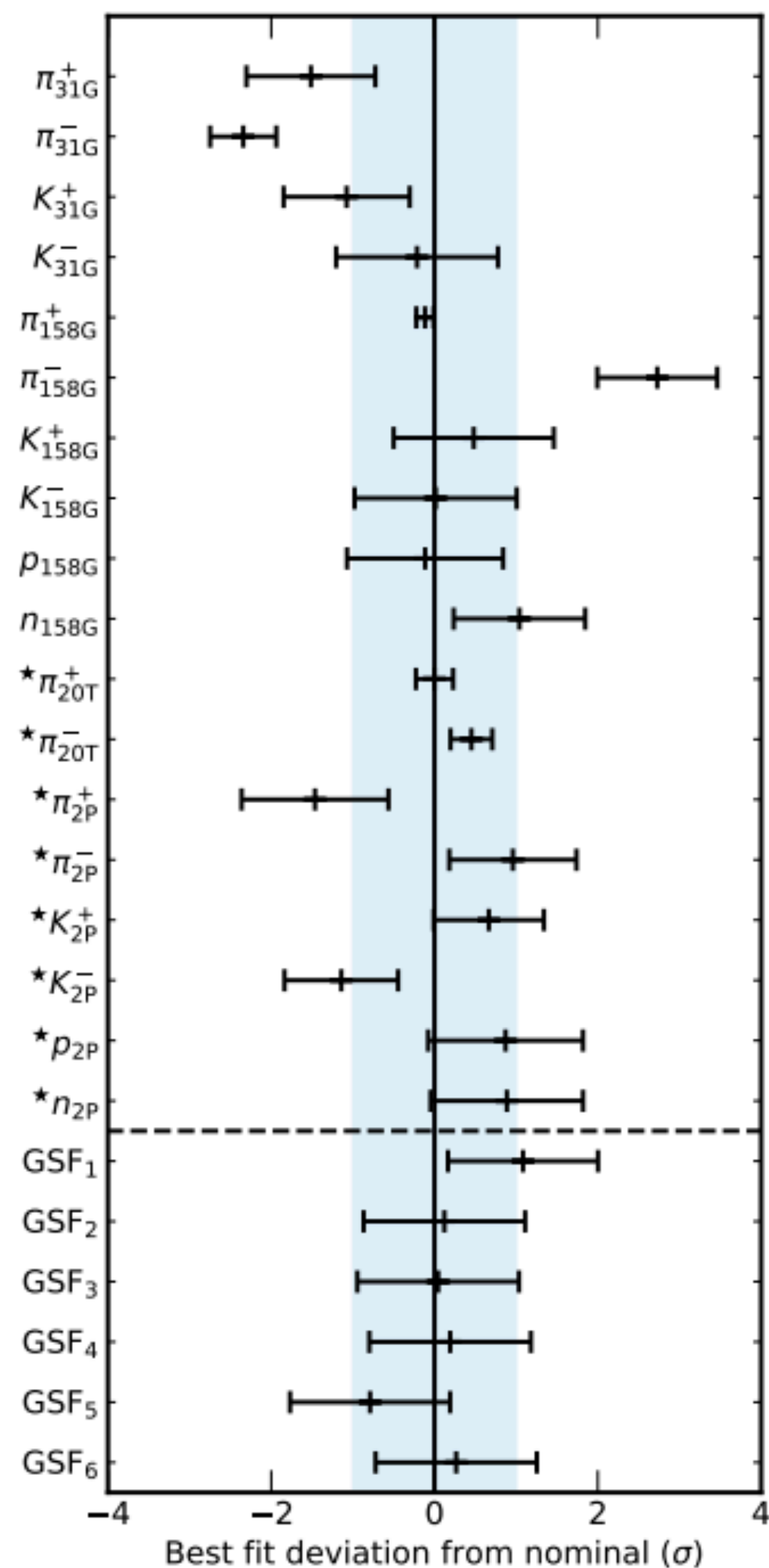
Spectrum of
cosmic rays

Development of
hadronic shower



IceCube

We use the DaemonFlux model and its parameters, which describe CR spectrum and hadronic shower



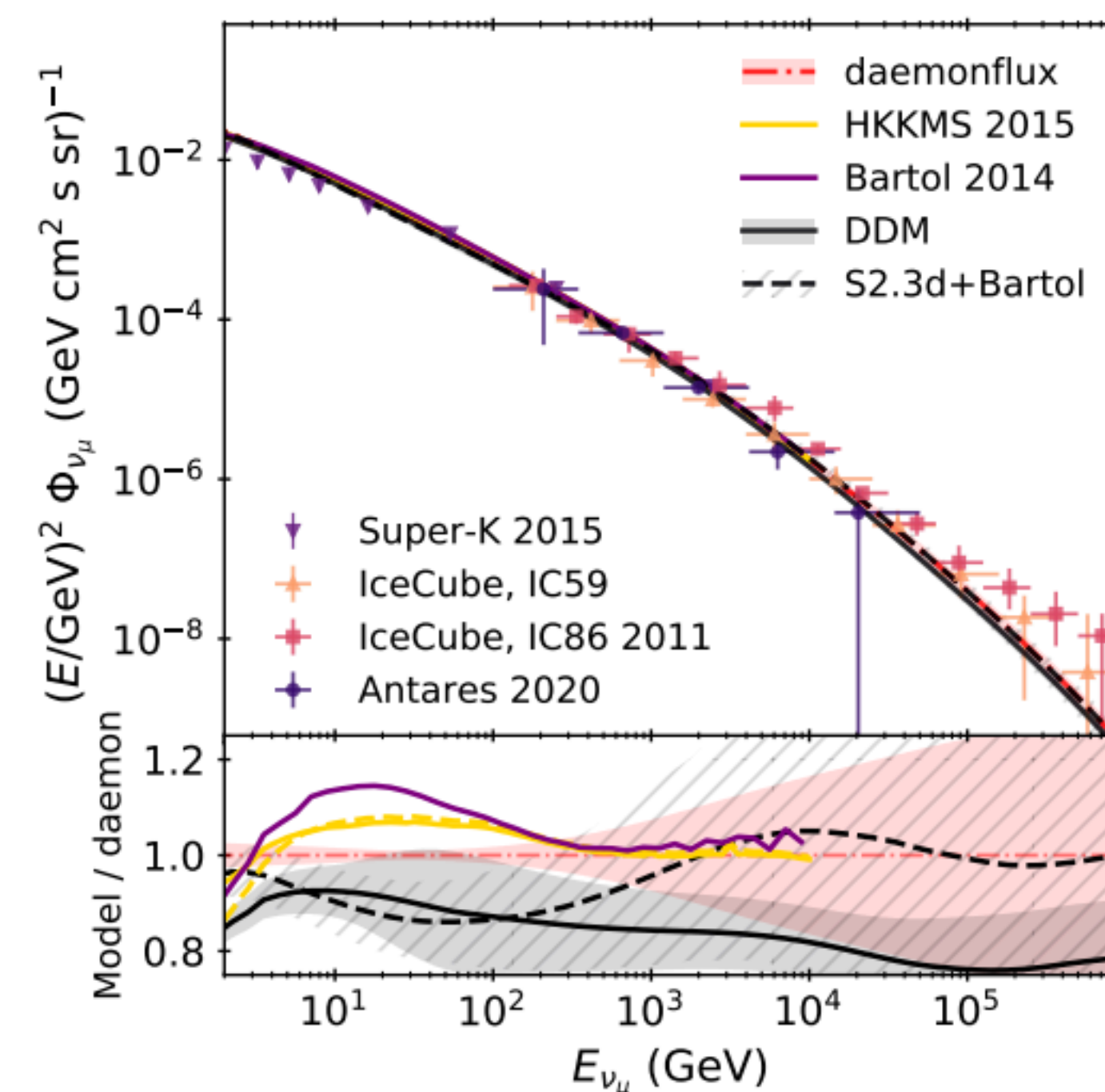
Data-driven muon-calibrated neutrino flux

Juan Pablo Yañez^{*}

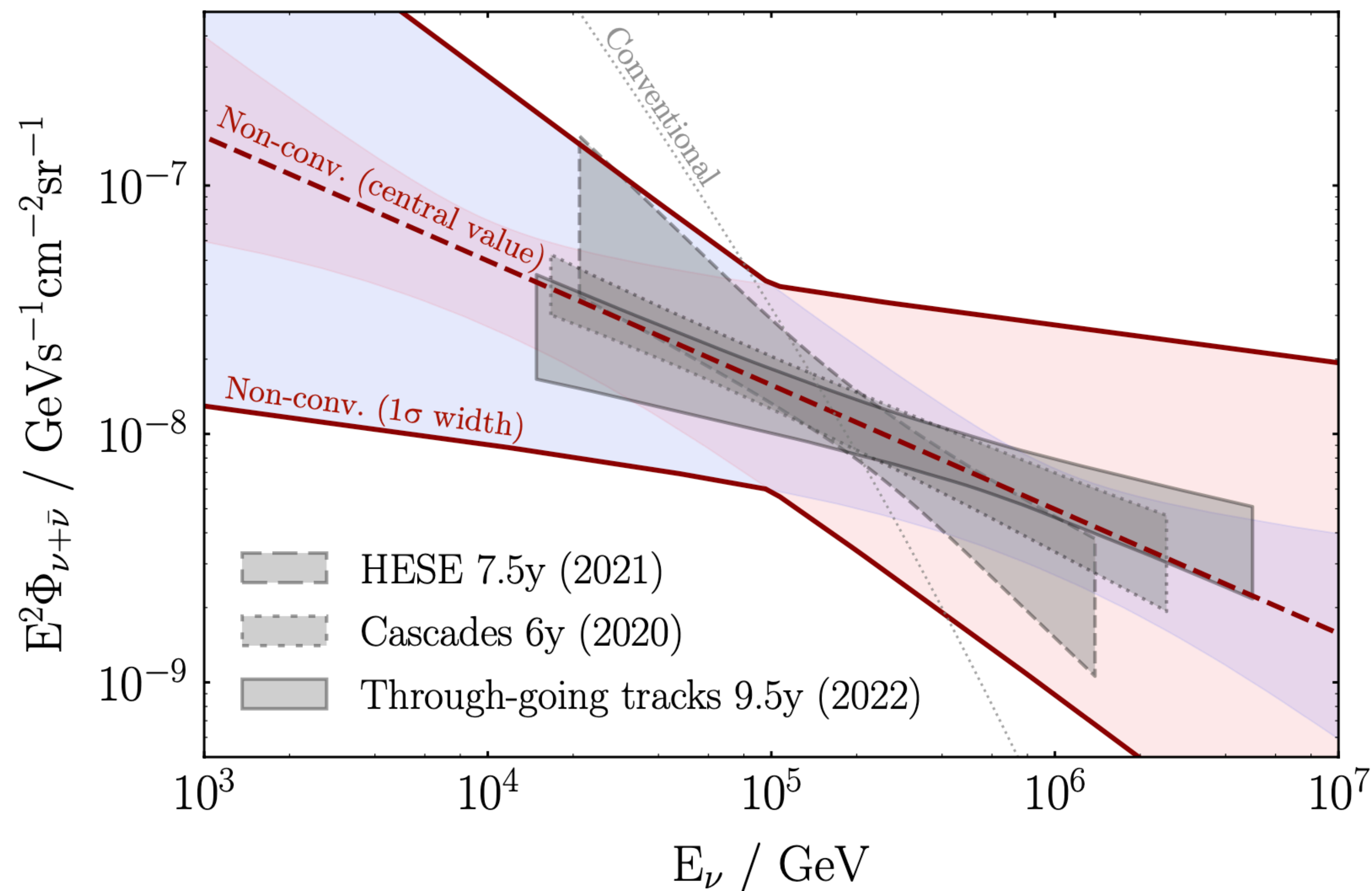
Department of Physics, University of Alberta Edmonton, Alberta, Canada T6G 2E1

Anatoli Fedynitch[†]

Institute of Physics, Academia Sinica, Taipei City, 11529, Taiwan
and Institute for Cosmic Ray Research, the University of Tokyo,
5-1-5 Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan



Non-conventional flux



Assume a broken power law with enough variation to encompass existing measurements of astrophysical flux

Prompt atmospheric component - negligible contribution

Misc. references

A few other works re: neutrino attenuation tomography:

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M.C. Gonzalez-Garcia et al., Phys.Rev.Lett.
100 (2008) 061802

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IceCube, Phys. Rev. D 110, 092009

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Yañez & Fedynitch, Phys. Rev. D 107, 123037

P-value

Gelman, Andrew, Xiao-Li Meng, and Hal
Stern. 1996. “Posterior Predictive
Assessment of Model Fitness via Realized
Discrepancies.” Statistica Sinica, 733–60.