

Neutrino oscillation measurements with IceCube DeepCore.

Summer Blot
22.06.2020
Neutrino2020 - virtual meeting



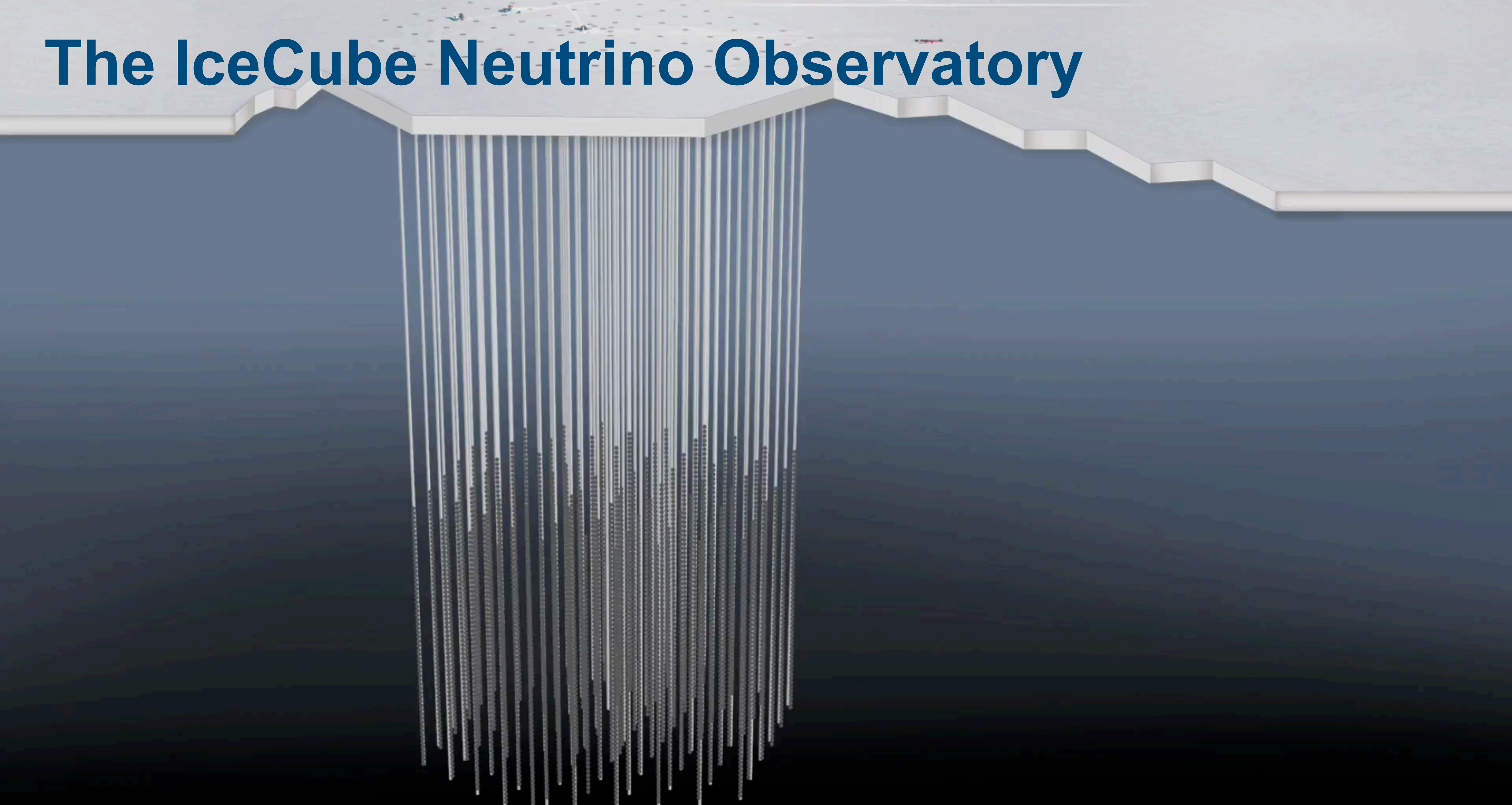
HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

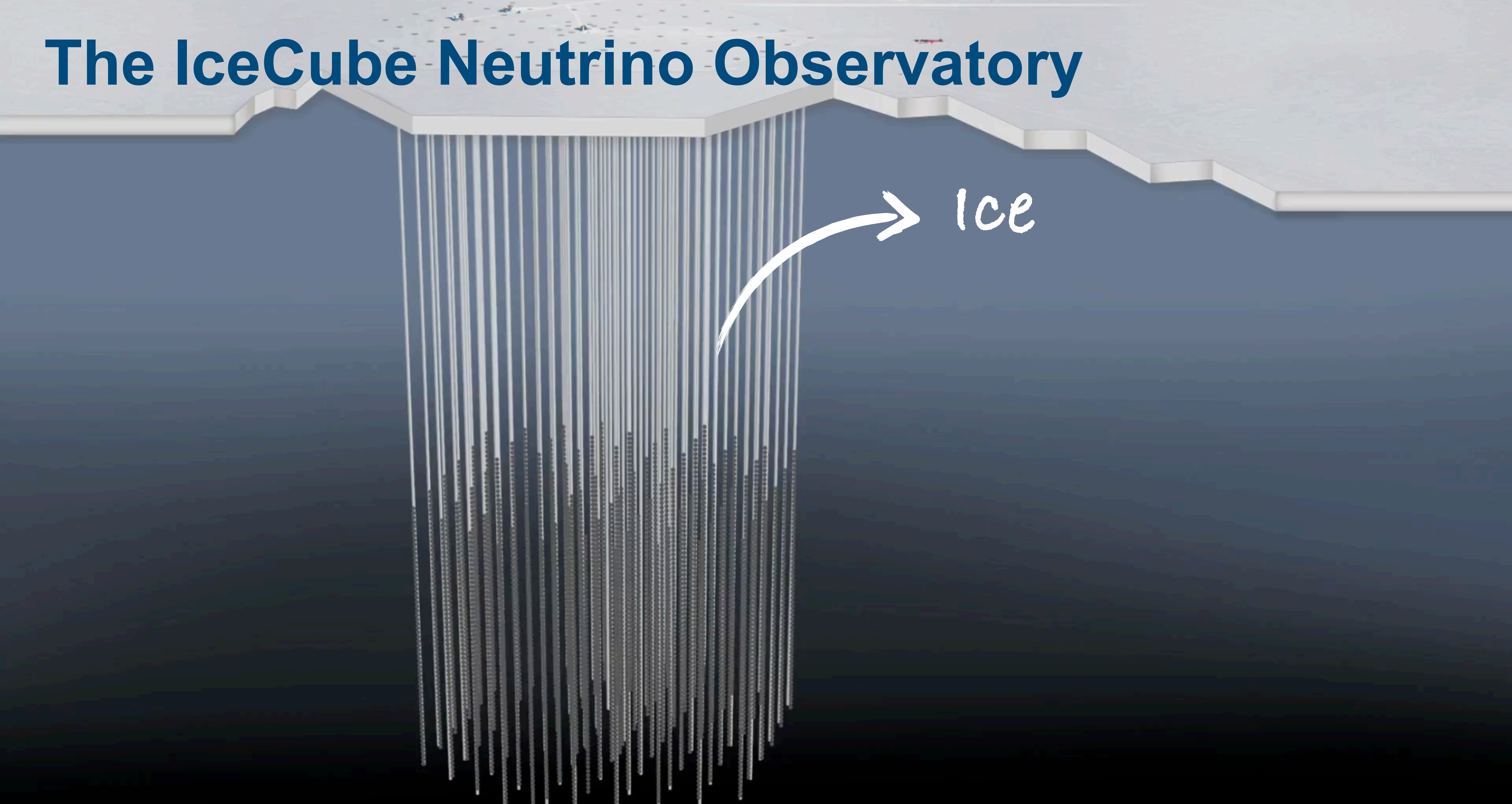


ICECUBE
UPGRADE

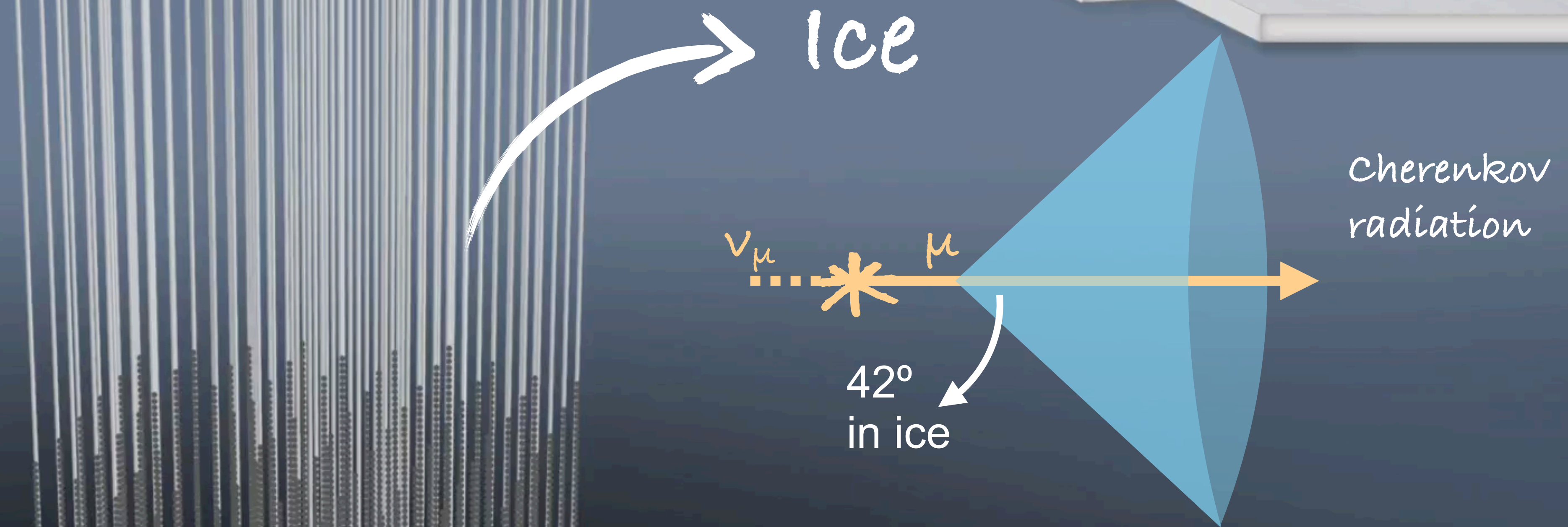
The IceCube Neutrino Observatory



The IceCube Neutrino Observatory



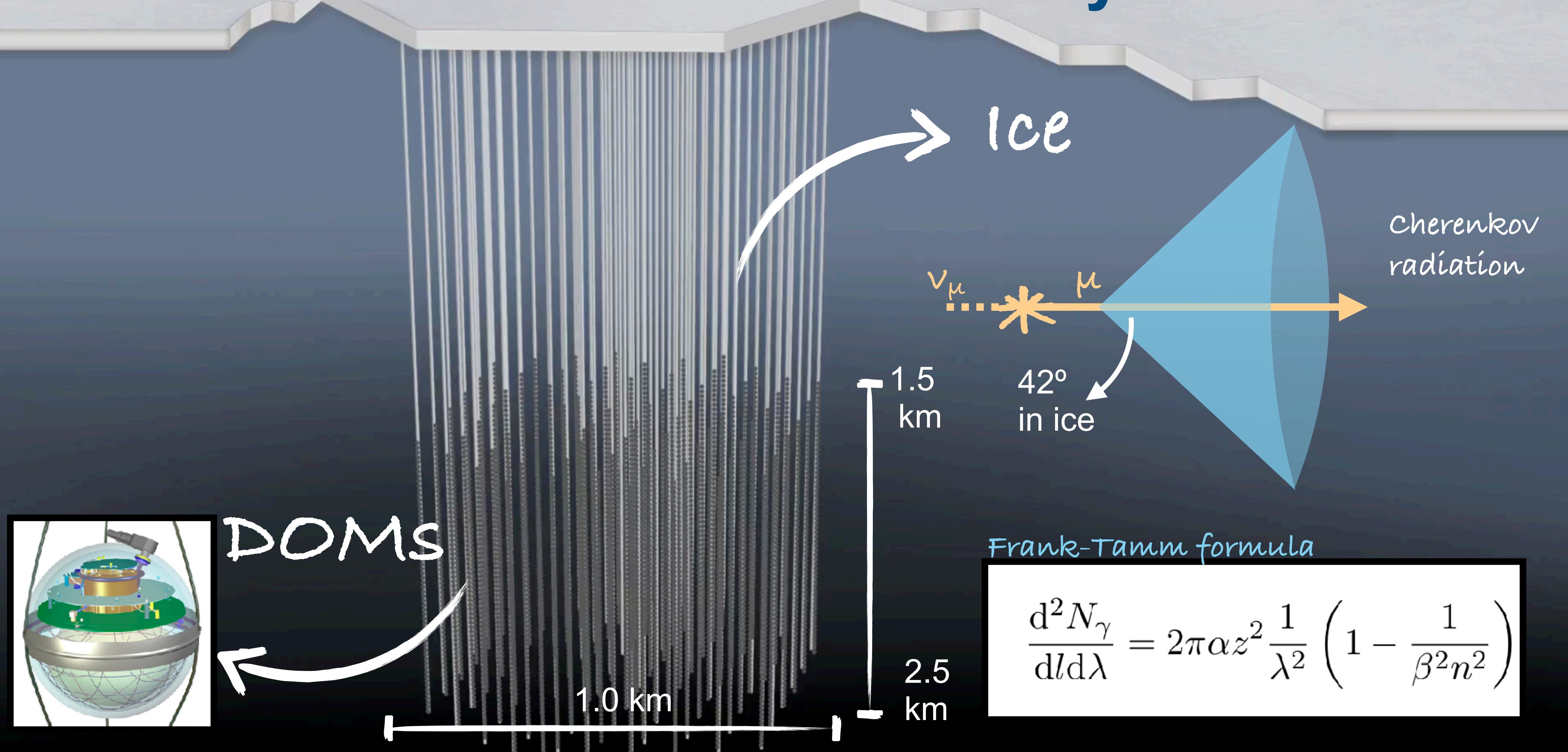
The IceCube Neutrino Observatory



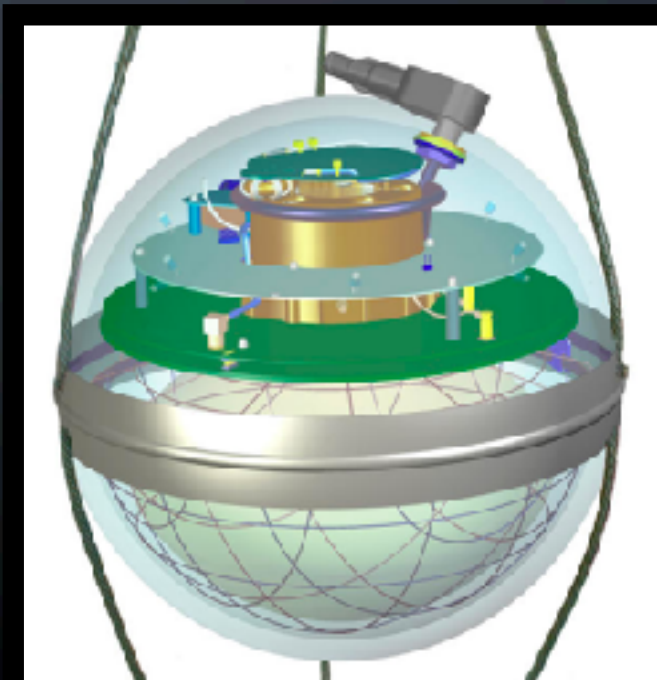
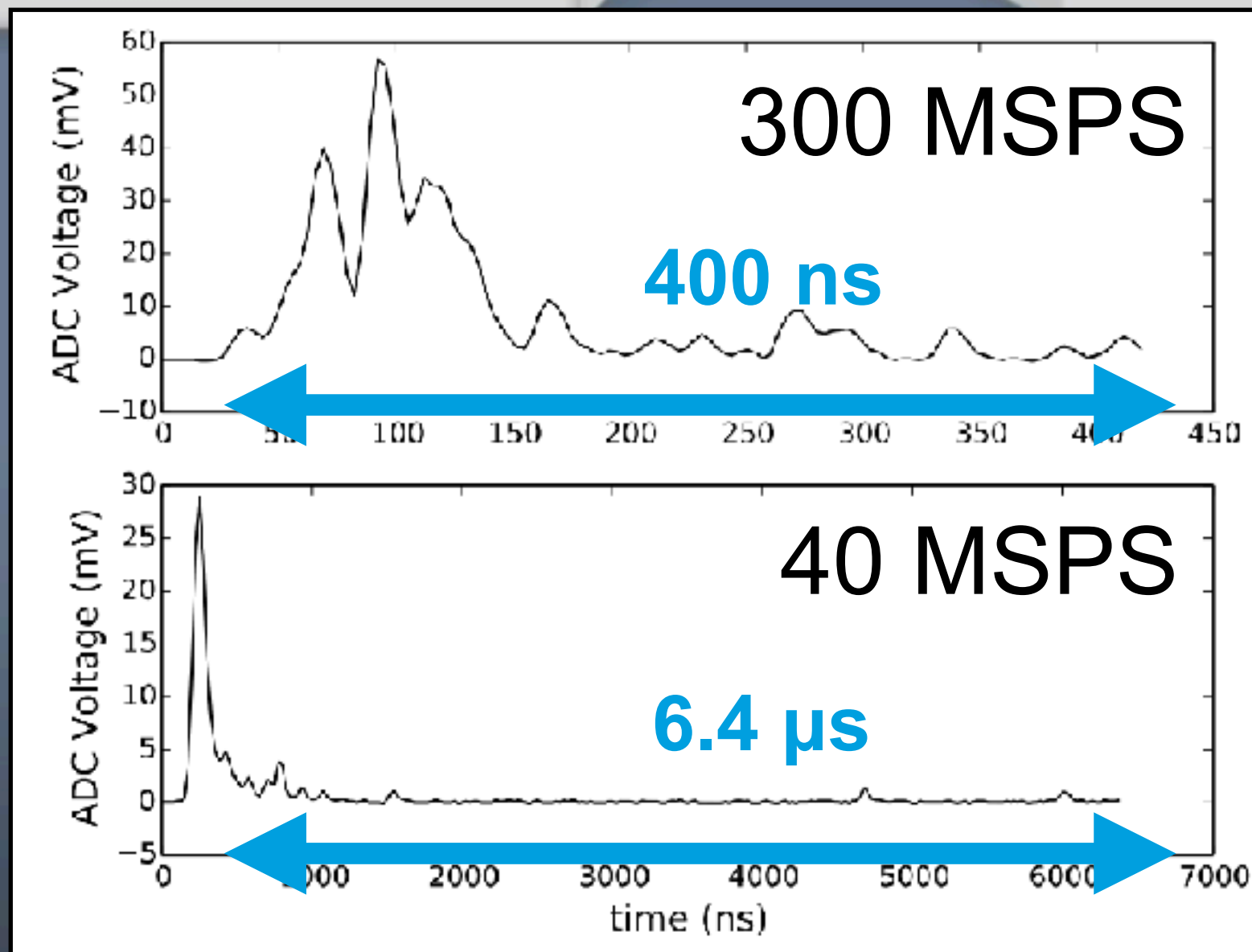
Frank-Tamm formula

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

The IceCube Neutrino Observatory



The IceCube Neutrino Observatory



DOMs

1.0 km

1.5 km

2.5 km

Frank-Tamm formula

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

Ice

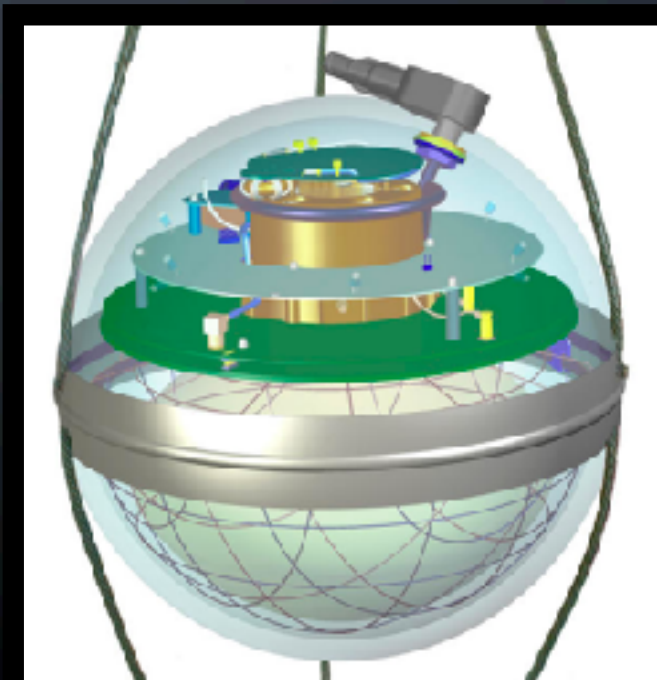
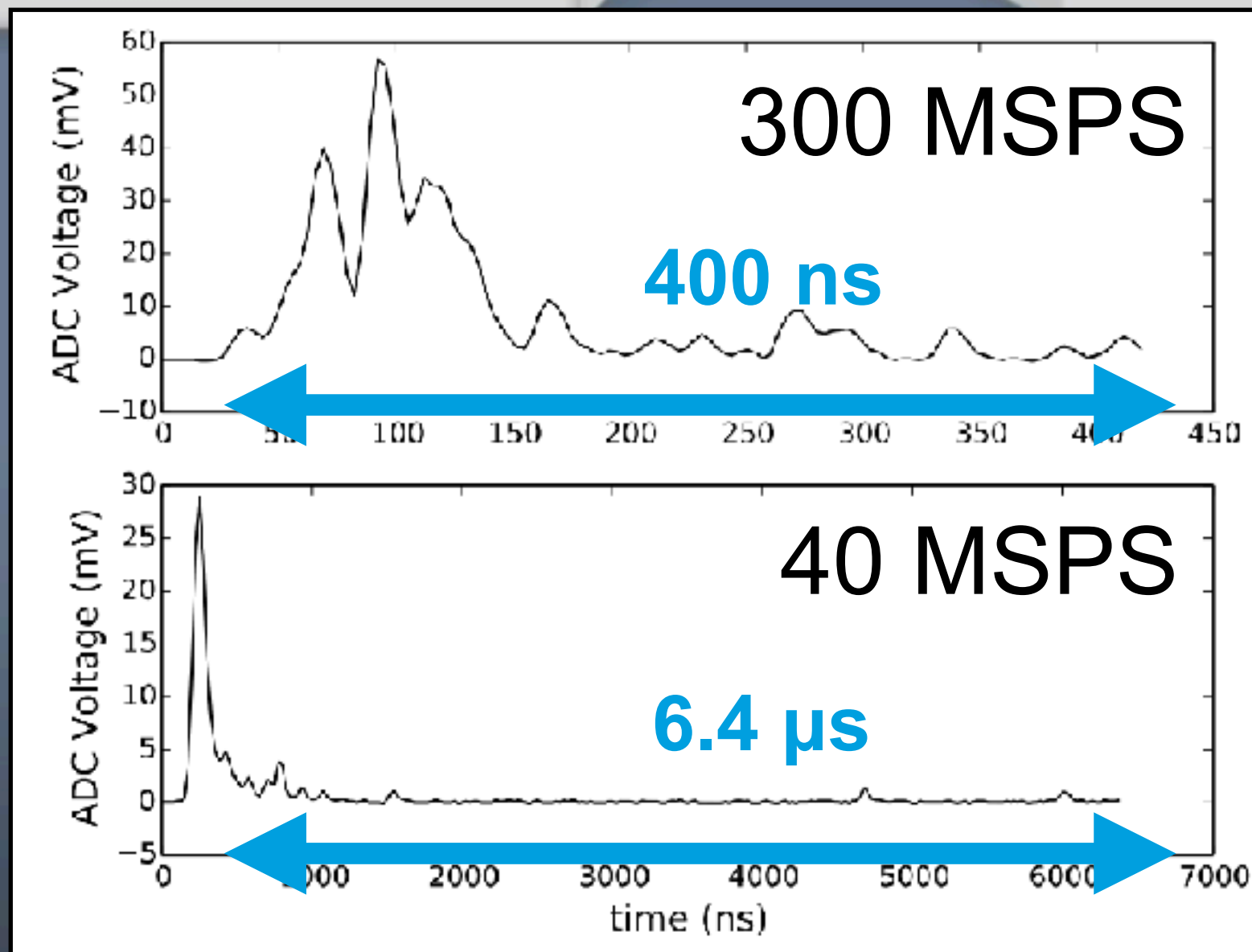
Cherenkov radiation

42°
in ice

ν_μ

μ

The IceCube Neutrino Observatory



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The IceCube Neutrino Observatory



10 Year
anniversary for
full array!

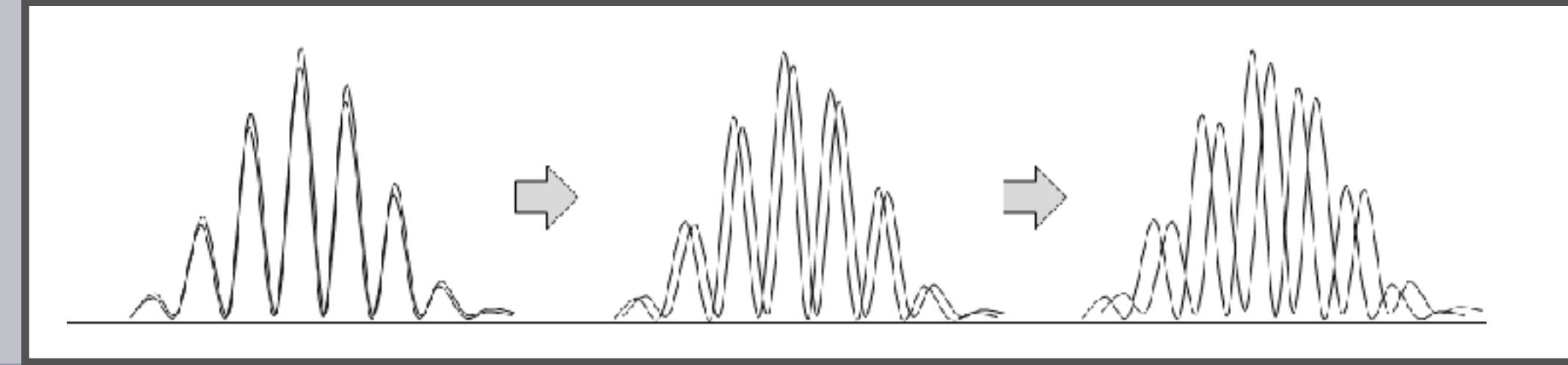
	Spacing [m]		Energy threshold [GeV]
	Horiz.	Vertical	
IceCube	125	17	~100
DeepCore	~50	7	~5

+DeepCore PMTs with higher quantum efficiency

Can access atmospheric
neutrino oscillations

Neutrino oscillations

The Standard Paradigm



Flavour

Mass

$$|\nu_a\rangle = \sum U_{ak}^* |\nu_k\rangle$$

U_{PMNS}

Atmospheric
Accelerator

Accelerator
Reactor

Reactor
Solar

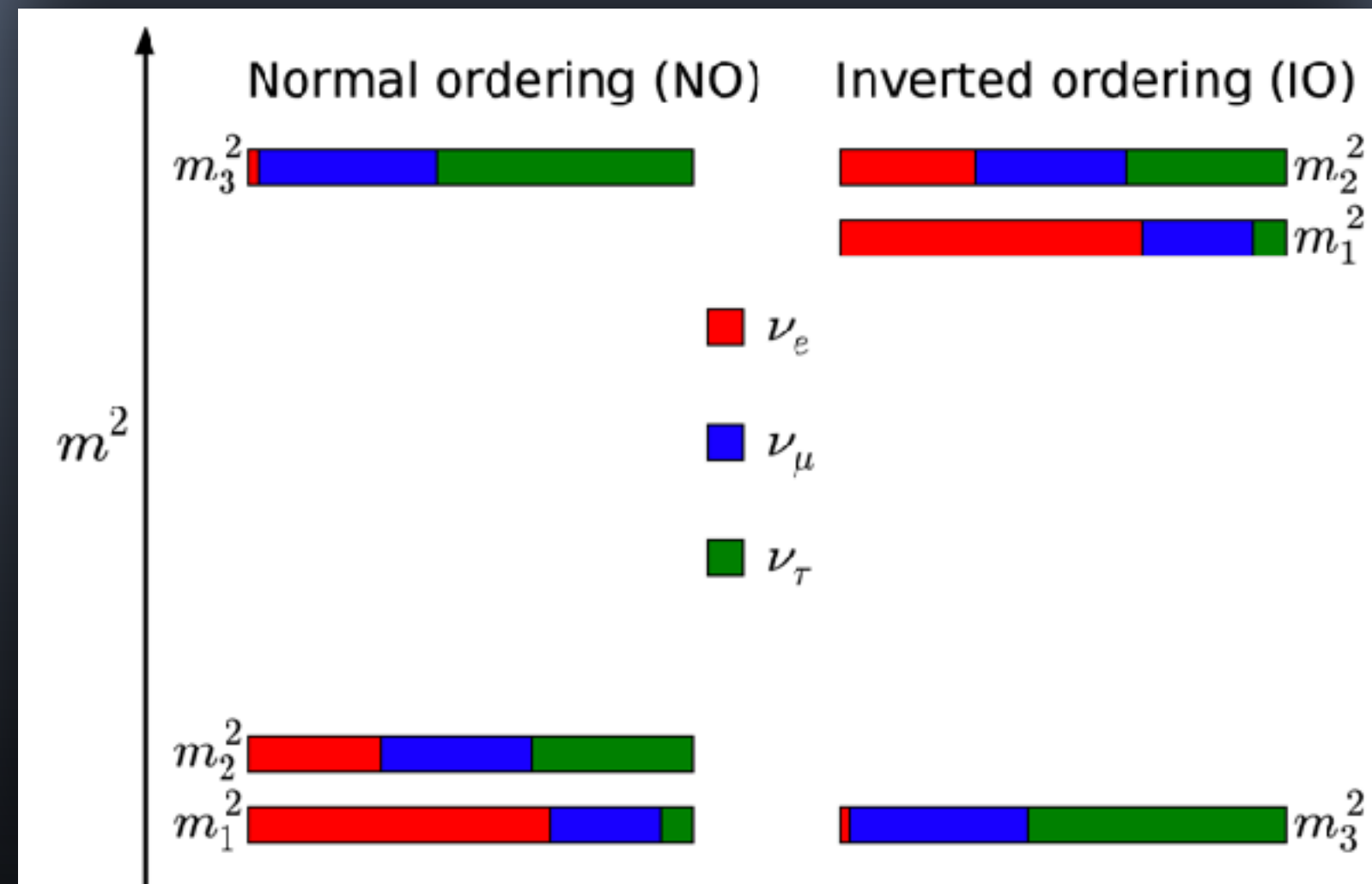
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$\begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix}$$

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$



Two-neutrino vacuum approximation:

$$P_{\alpha \rightarrow \beta} = |\langle \nu_{\beta}(L) | \nu_{\alpha} \rangle|^2$$

Amplitude

Frequency

$$P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \sin^2(1.27 \cdot \Delta m^2 \cdot L / E)$$

To first order, DeepCore is sensitive to Δm_{32}^2 and θ_{23}

$$\Delta m_{21}^2 \sim 10^{-5} \text{ eV}^2$$

$$\Delta m_{32}^2 \sim 10^{-3} \text{ eV}^2$$

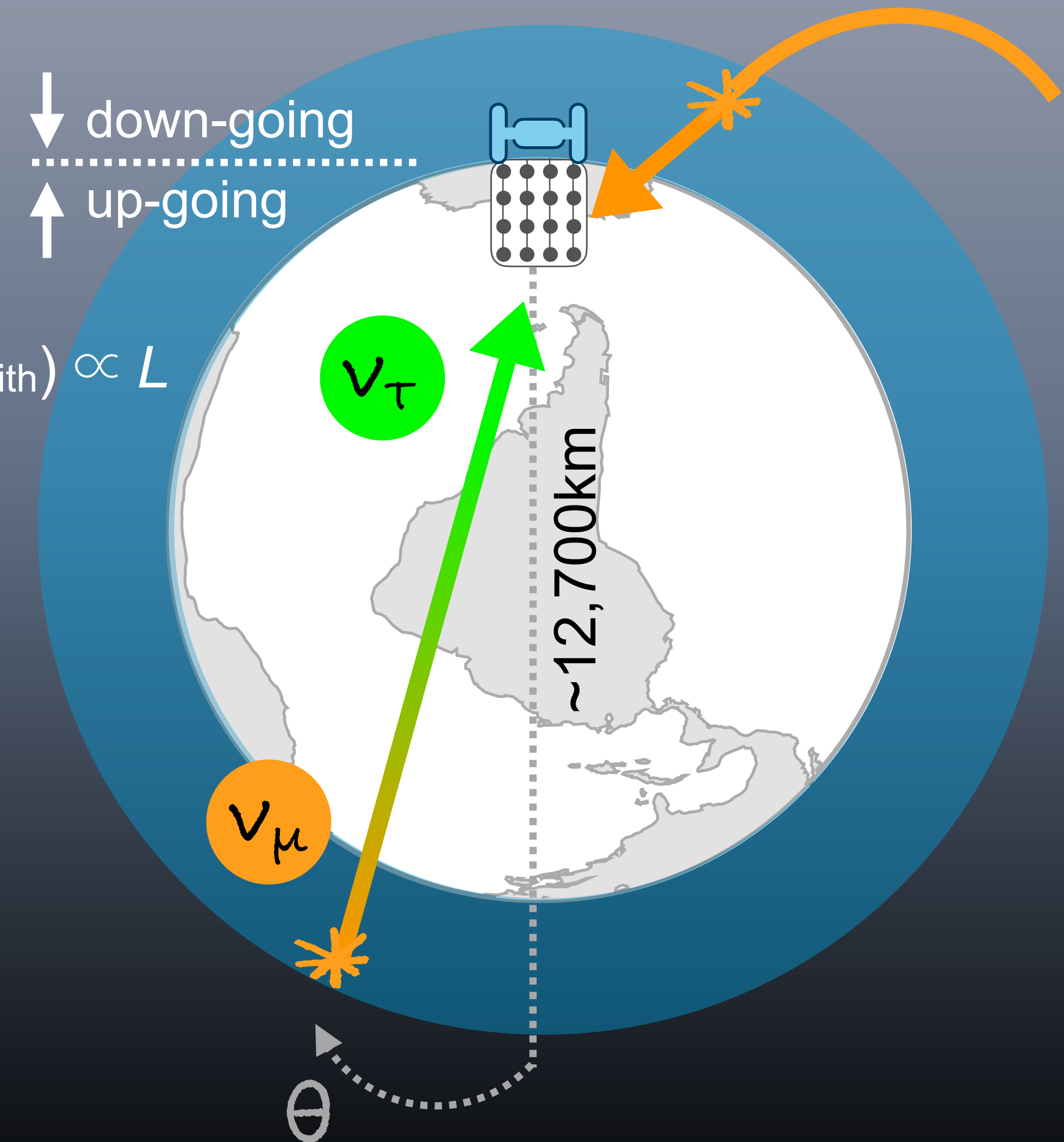
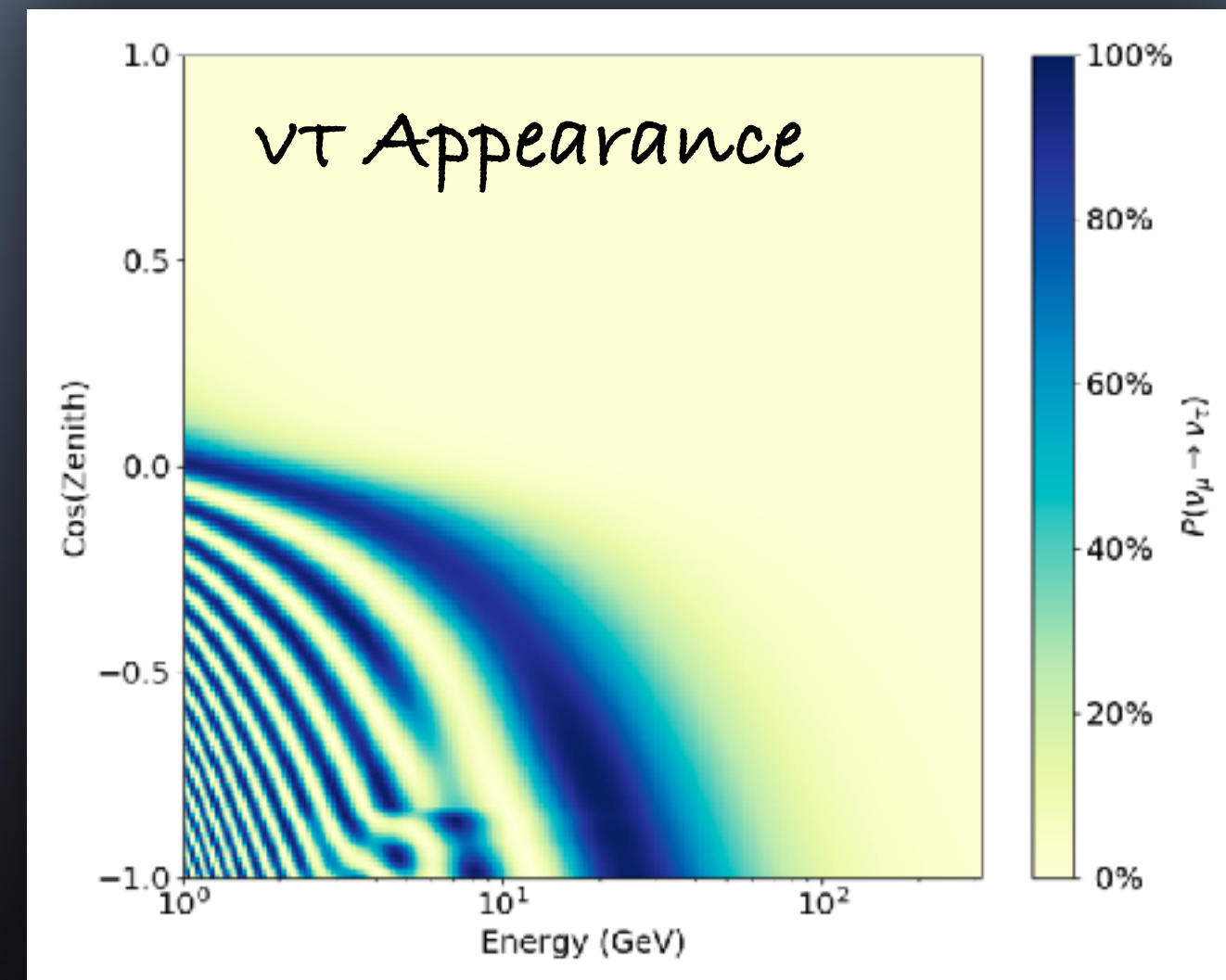
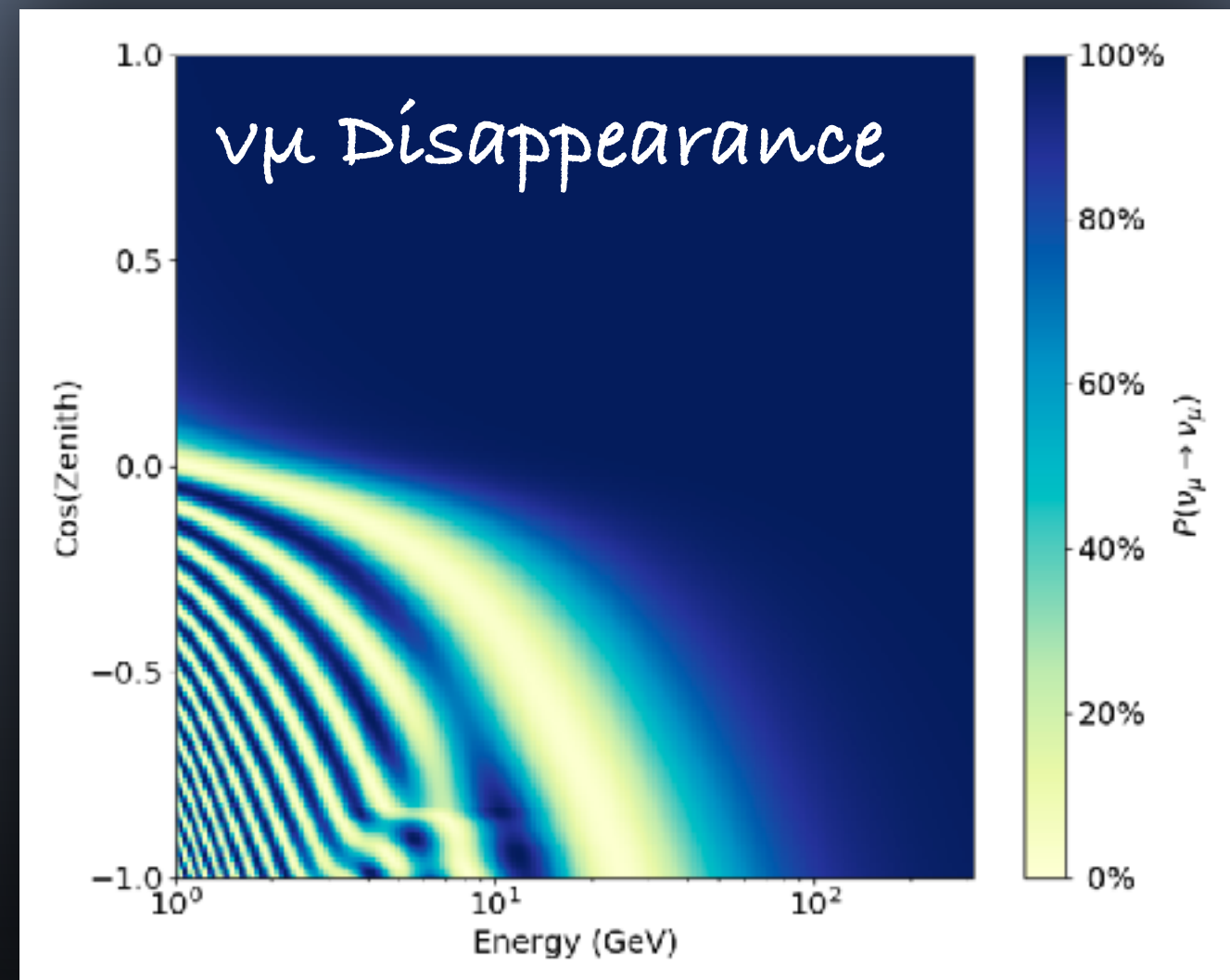
Atmospheric neutrinos

Probe of oscillations at high energies and long baselines

Free neutrino beam from cosmic ray interactions

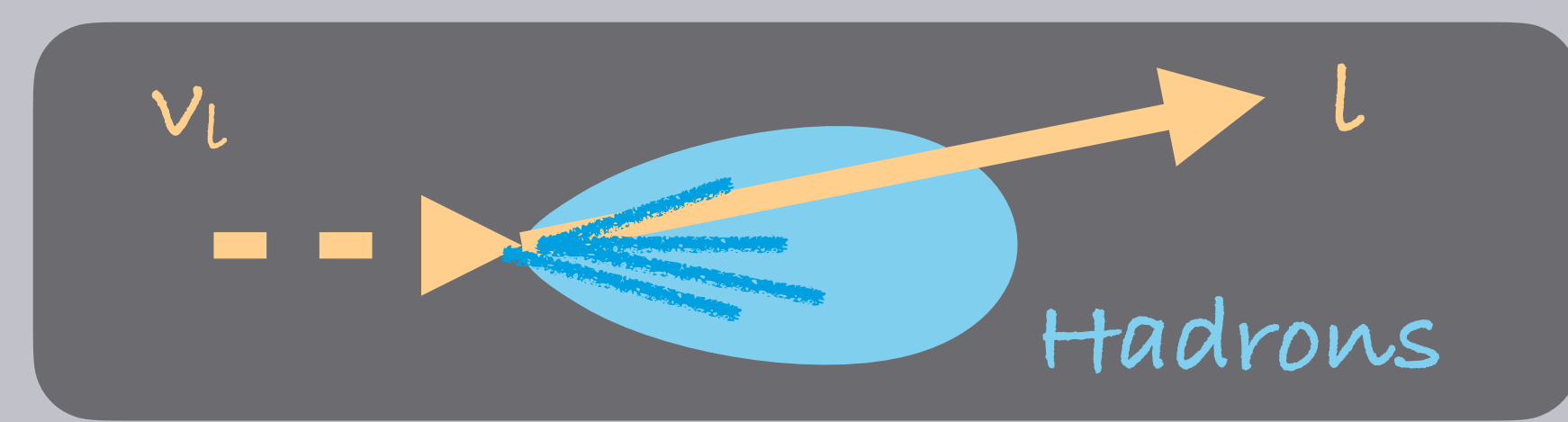
- Mixed composition of (anti-) ν_μ and (anti-) ν_e
- Observable over a wide range, from few GeV — 100's TeV
- Arrival direction used as proxy for distance travelled: $\cos(\theta_{\text{zenith}}) \propto L$

At 5 GeV, operating well above tau-production threshold

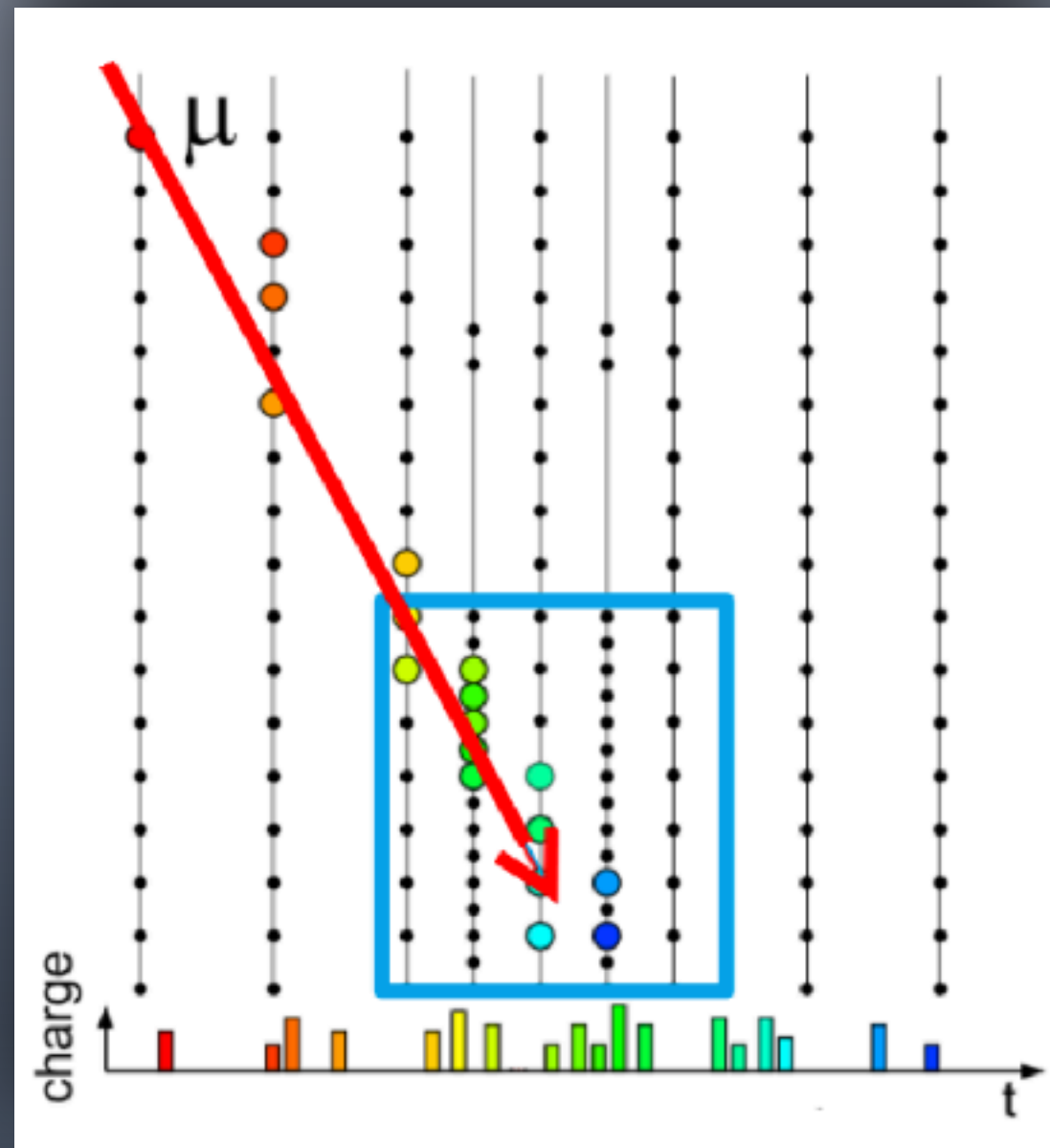


Filtering and reconstruction

See posters #157, #164 for more on DeepCore reconstruction

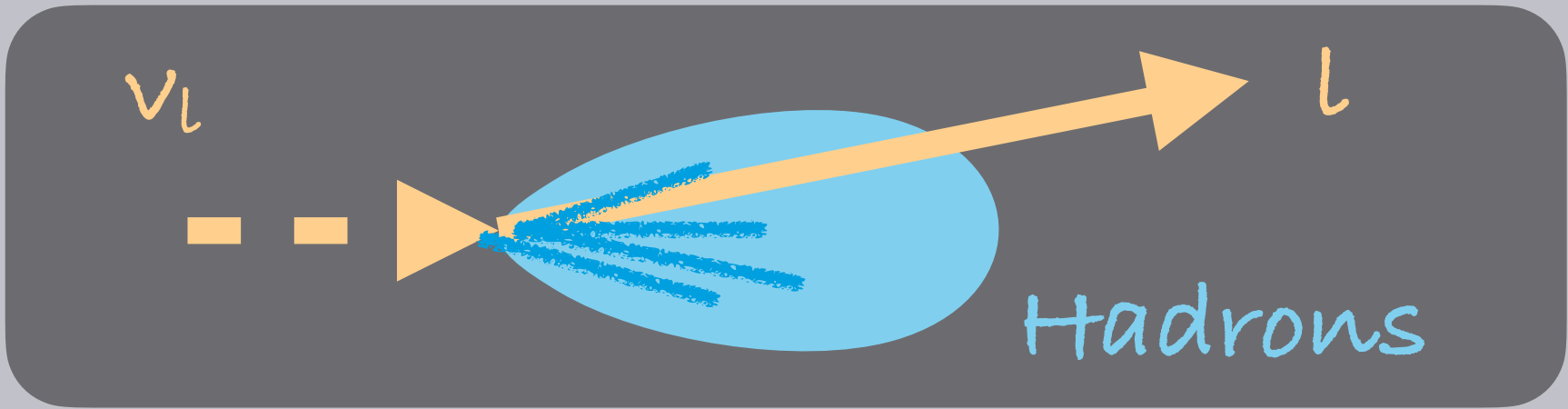


Background rejection

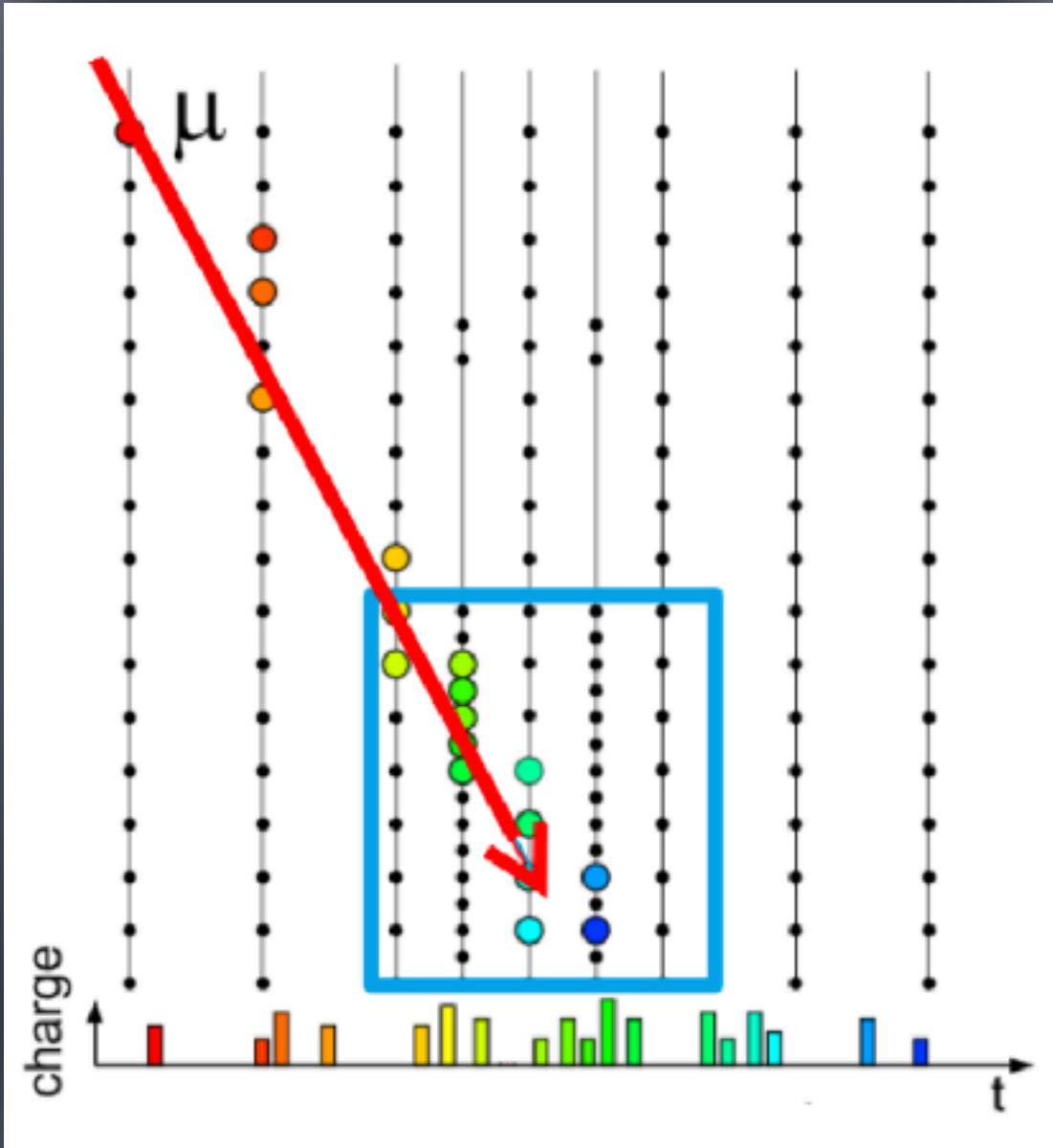


Filtering and reconstruction

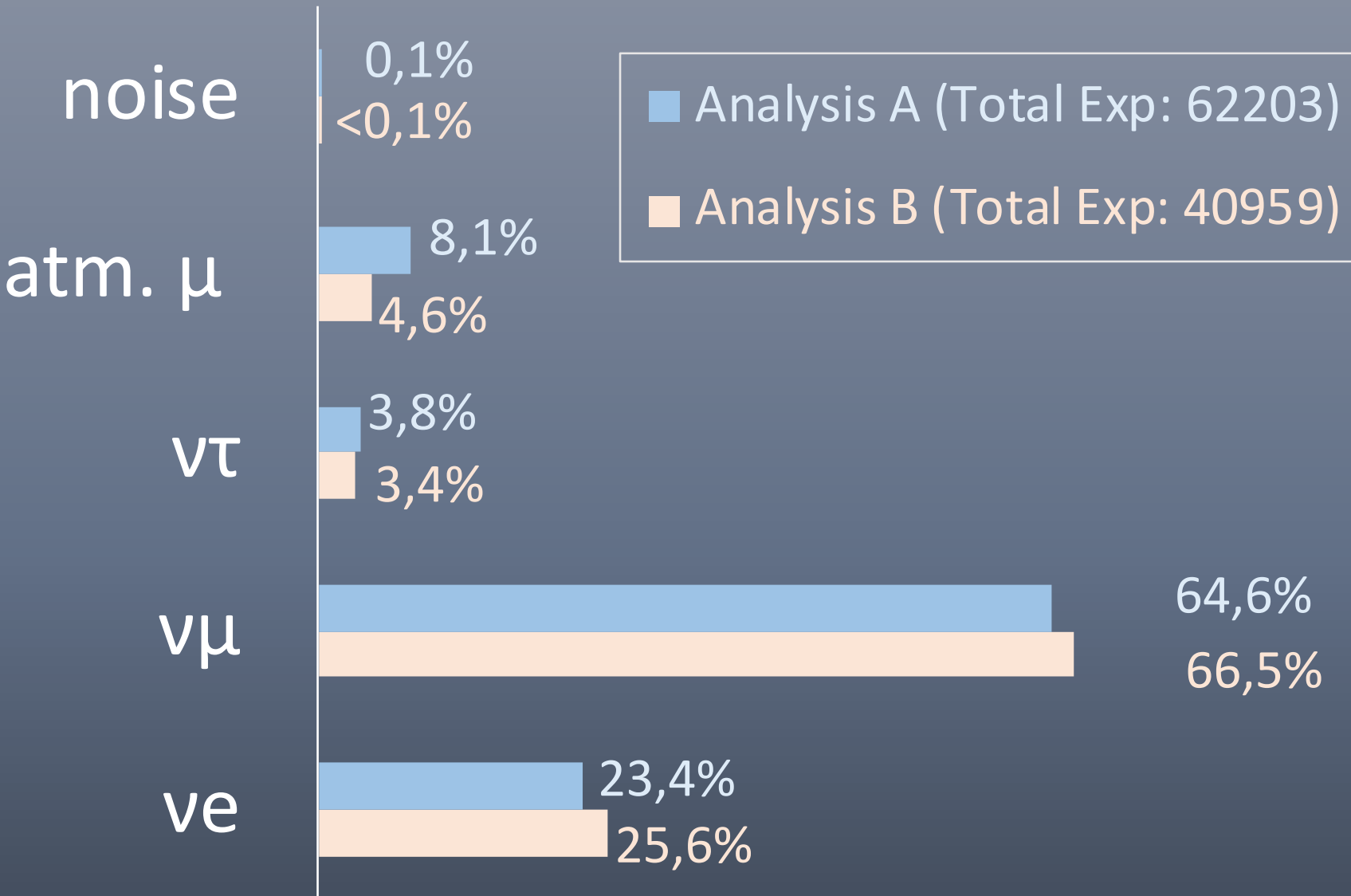
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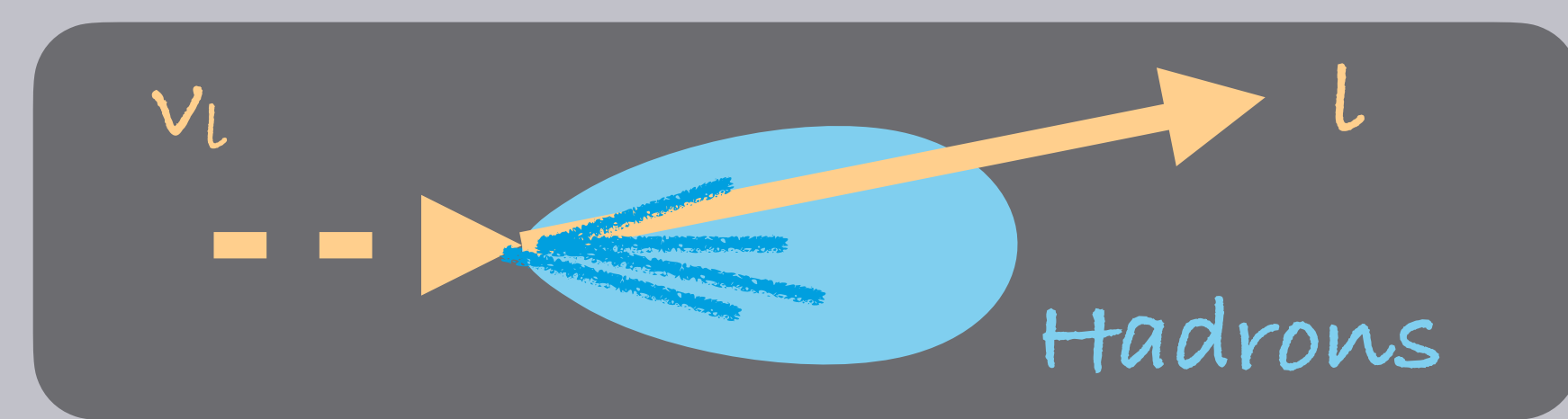


2 data samples, 3 years of data

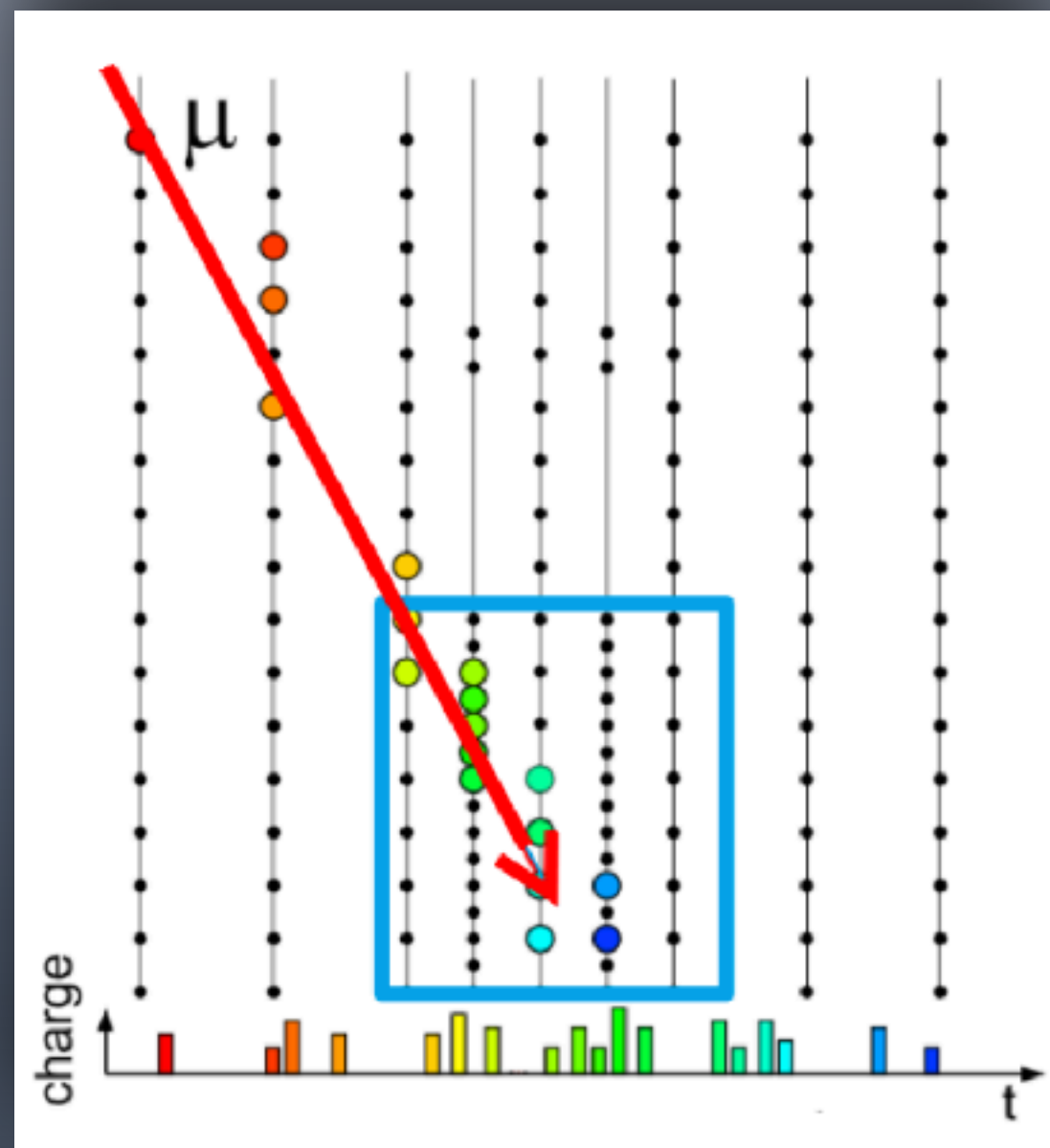


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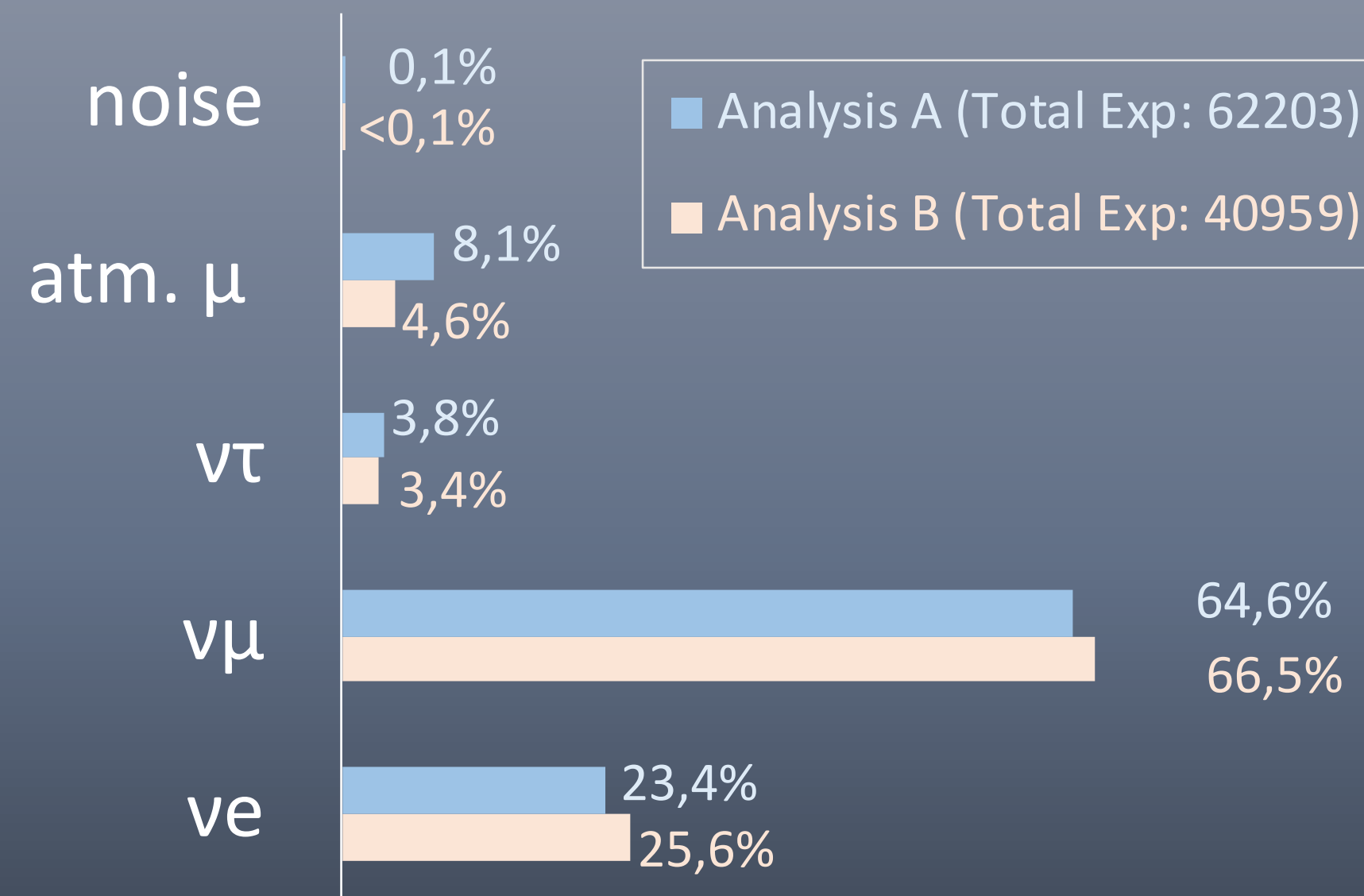
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Background rejection



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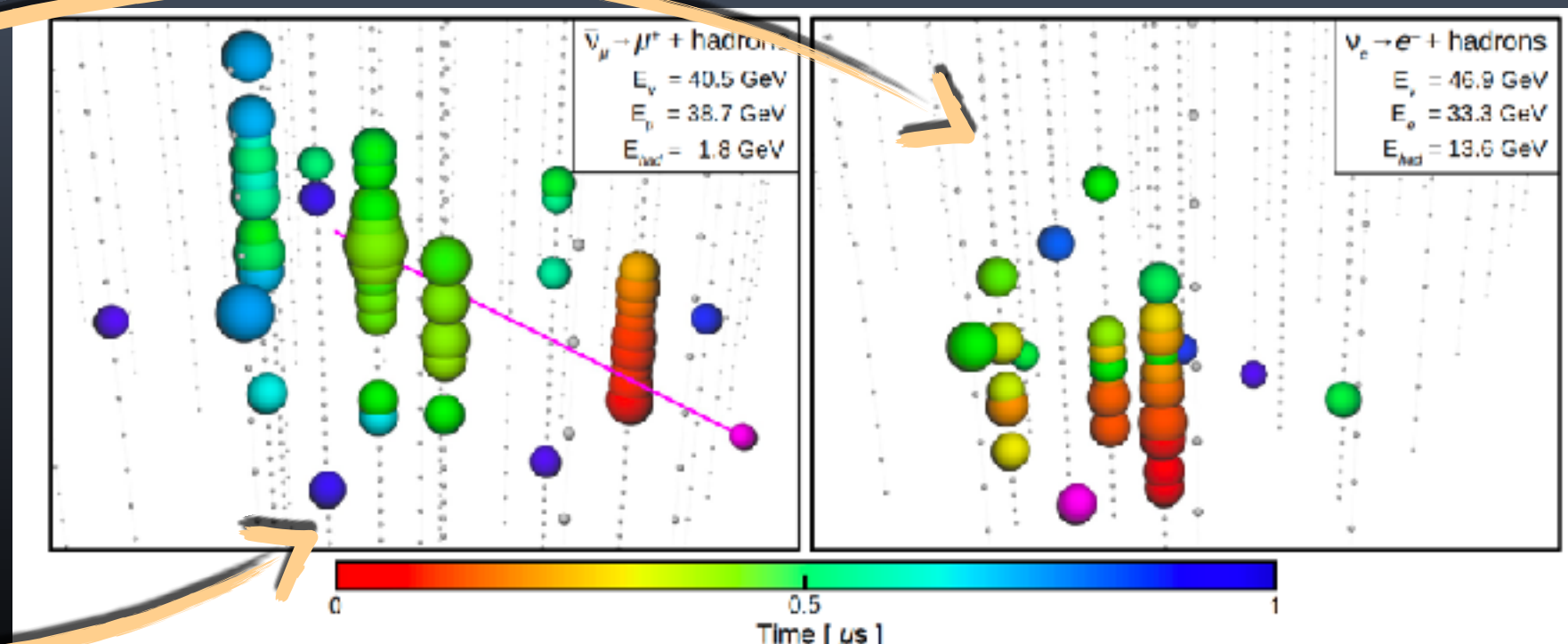


“Cascade-like”:

NC interactions, νe CC and 83% $\nu\tau$ CC

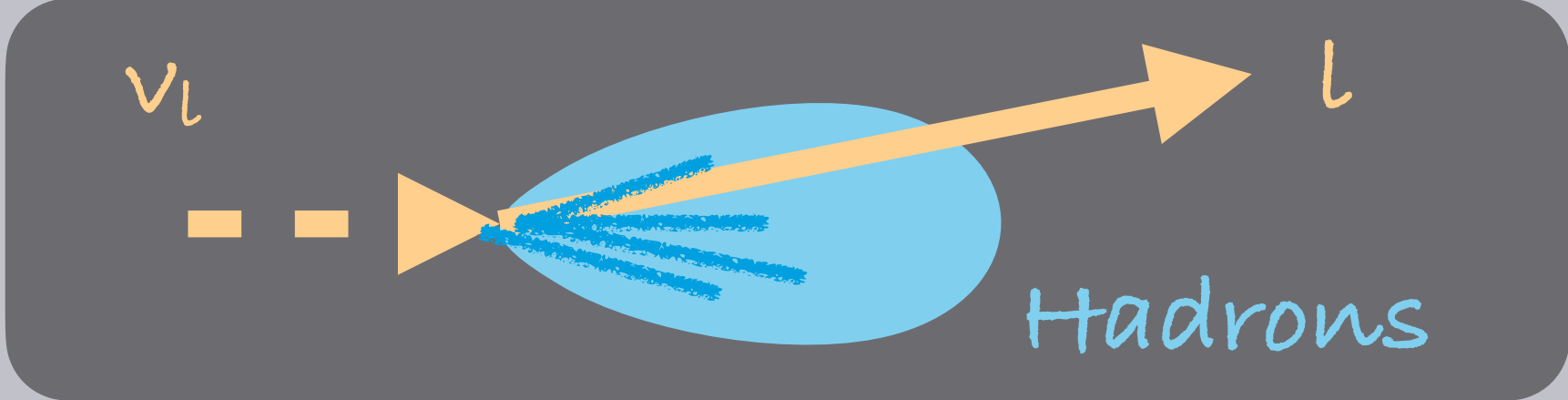
“Track-like”:

$\nu\mu$ CC and some $\nu\tau$ CC (17%)

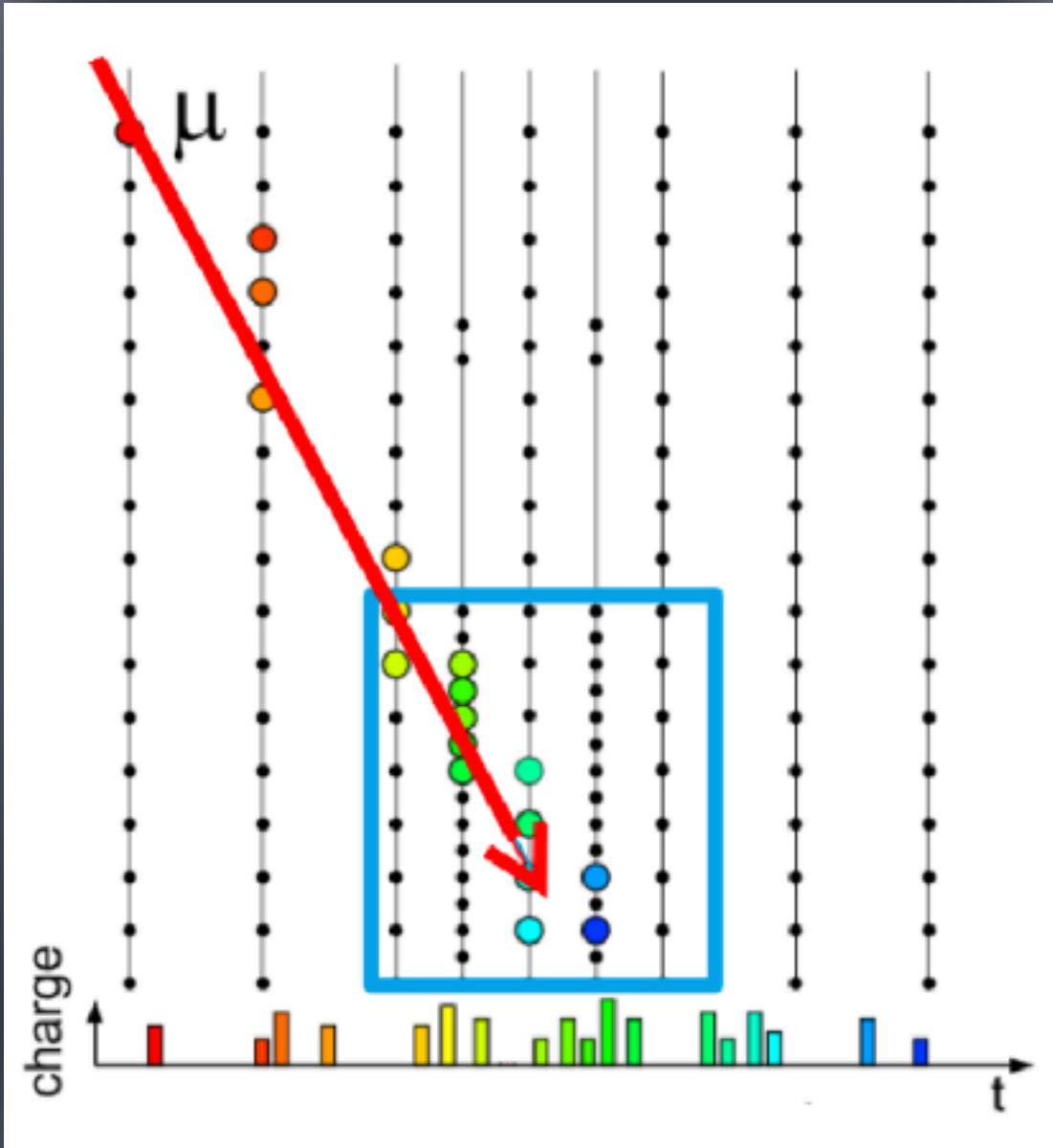


Filtering and reconstruction

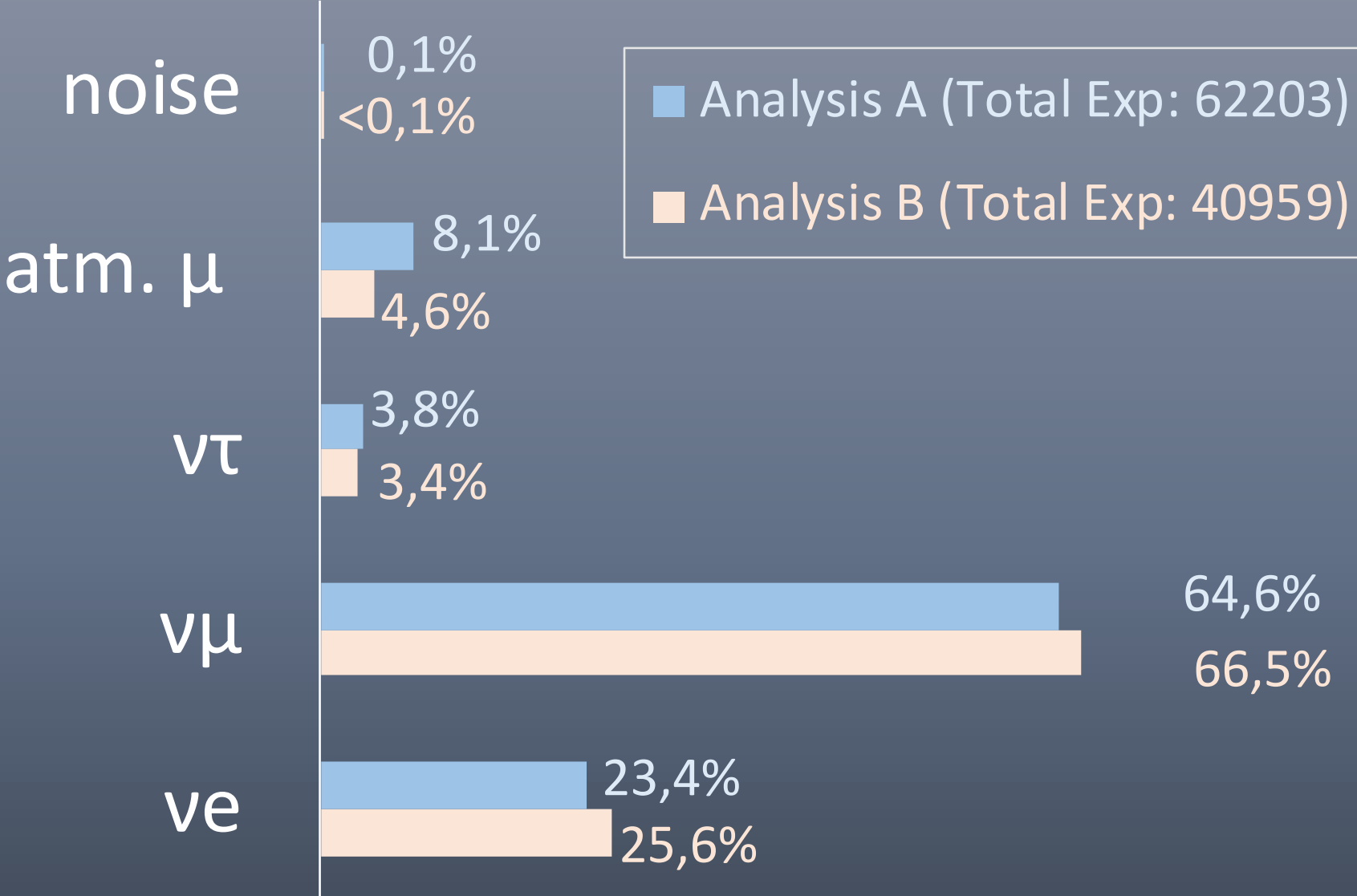
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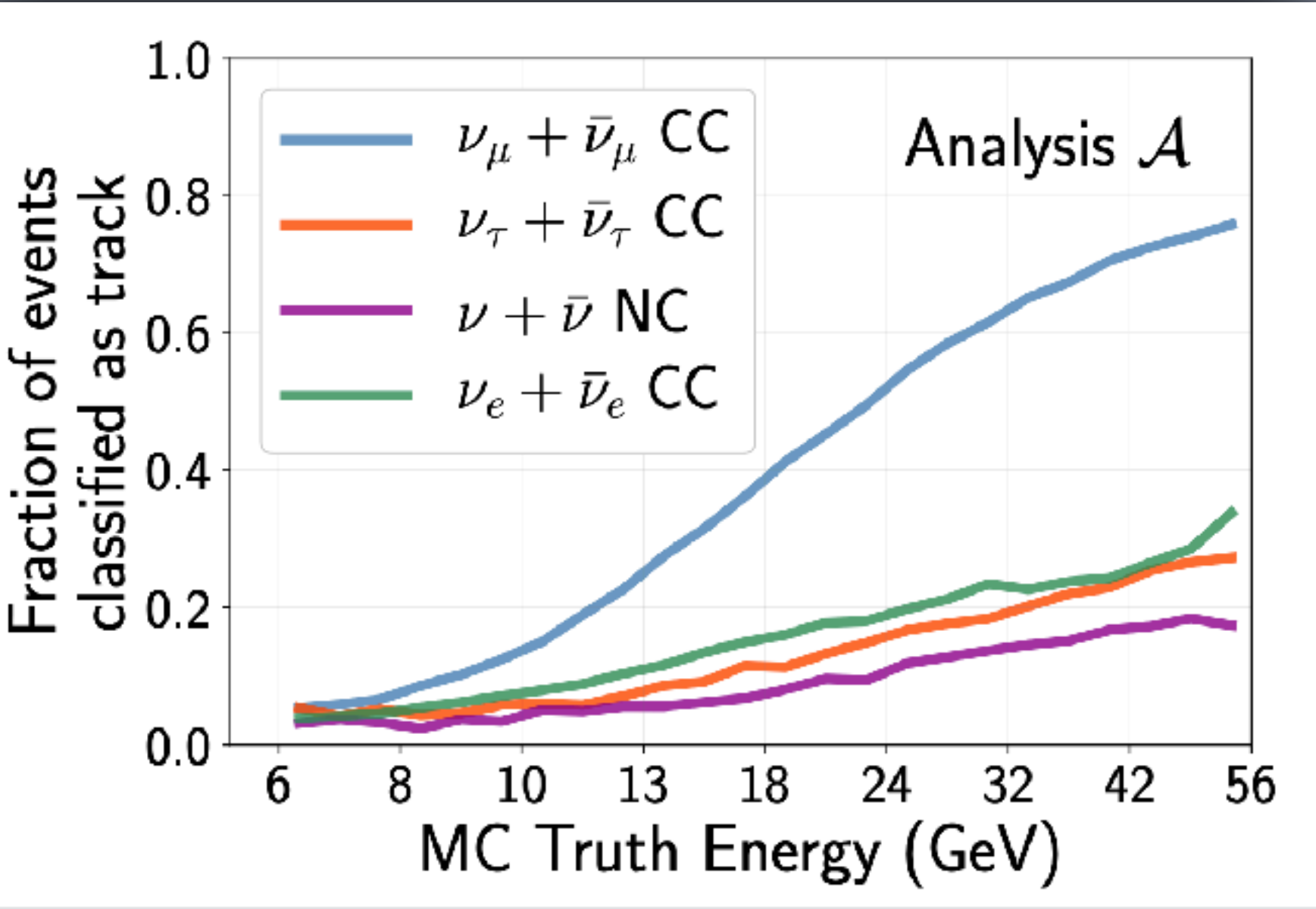
Background rejection



2 data samples, 3 years of data

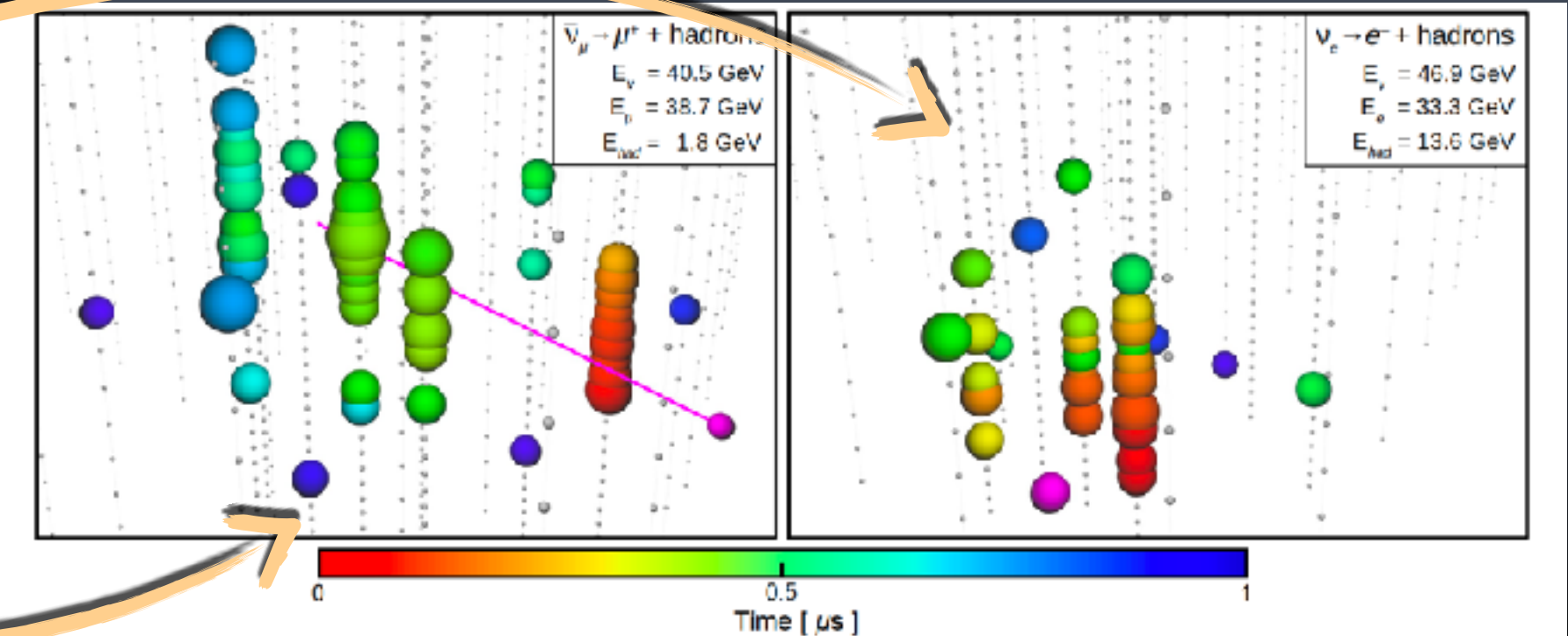


using track length as Flavour ID



“Cascade-like”:
NC interactions, ν_e CC and
83% ν_τ CC

“Track-like”:
 ν_μ CC and some ν_τ CC (17%)



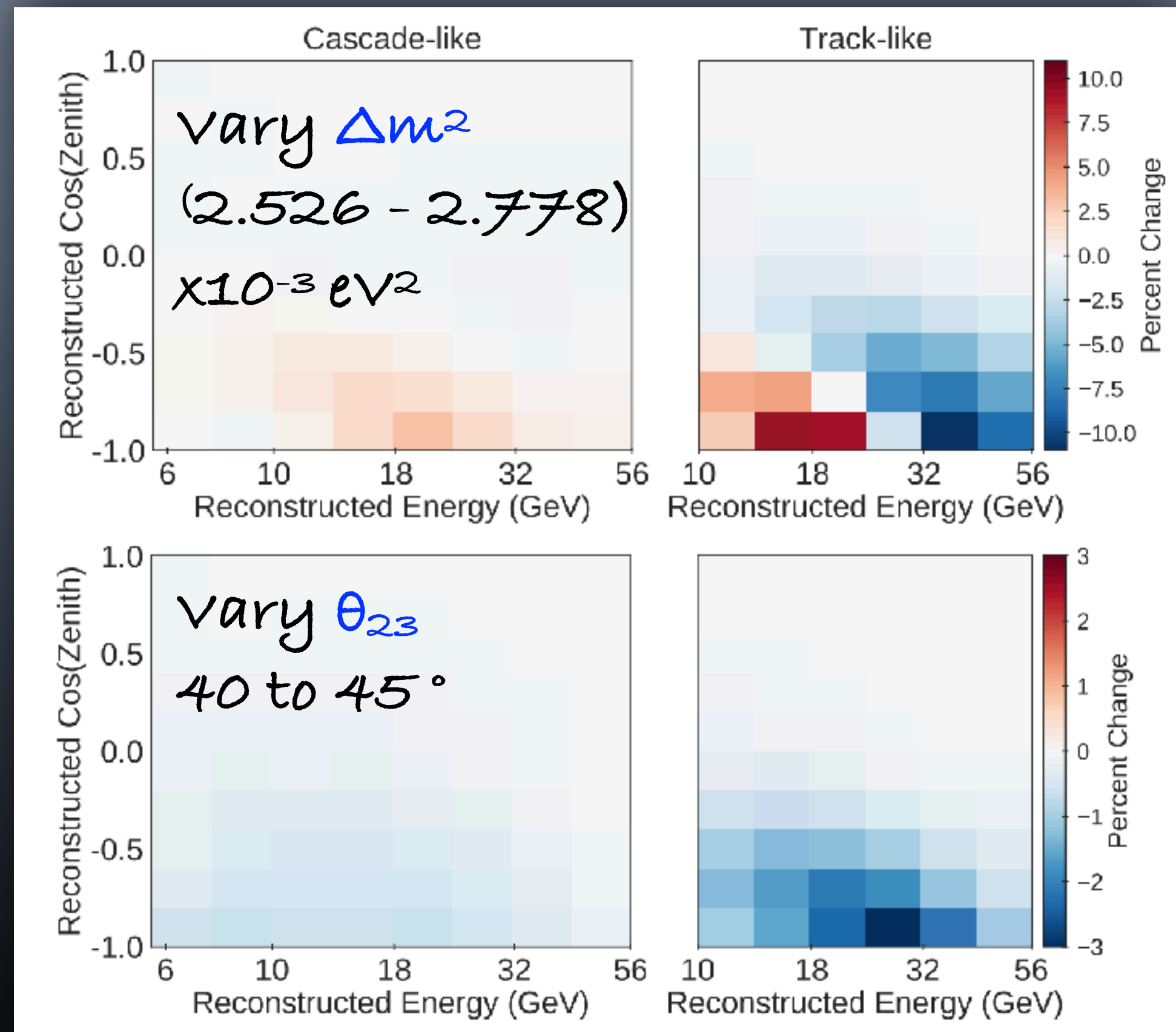
Resolutions

@20 GeV:	Tracks	Cascades
Energy	24 %	29 %
Zenith	10°	16°

Analysis strategy

Shape-only comparison between data and weighted MC

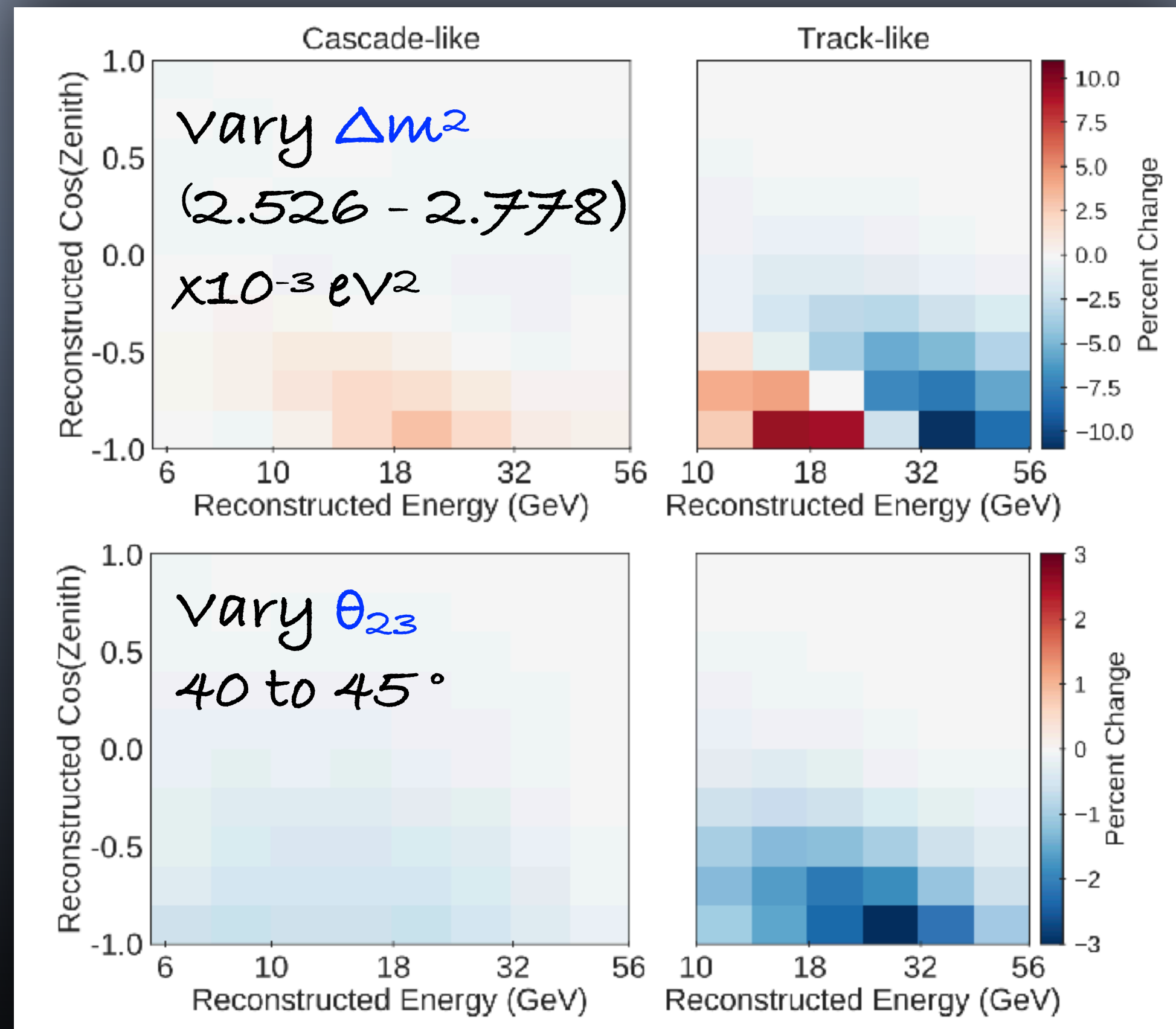
$$\chi^2 = \sum_{i \in \text{bins}} \frac{(n_i^{v+\mu} - n_i^{\text{data}})^2}{(\sigma_i^{v+\mu})^2 + (\sigma_i^{\text{data}})^2}$$



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Nuisance parameters
for syst. uncertainties:

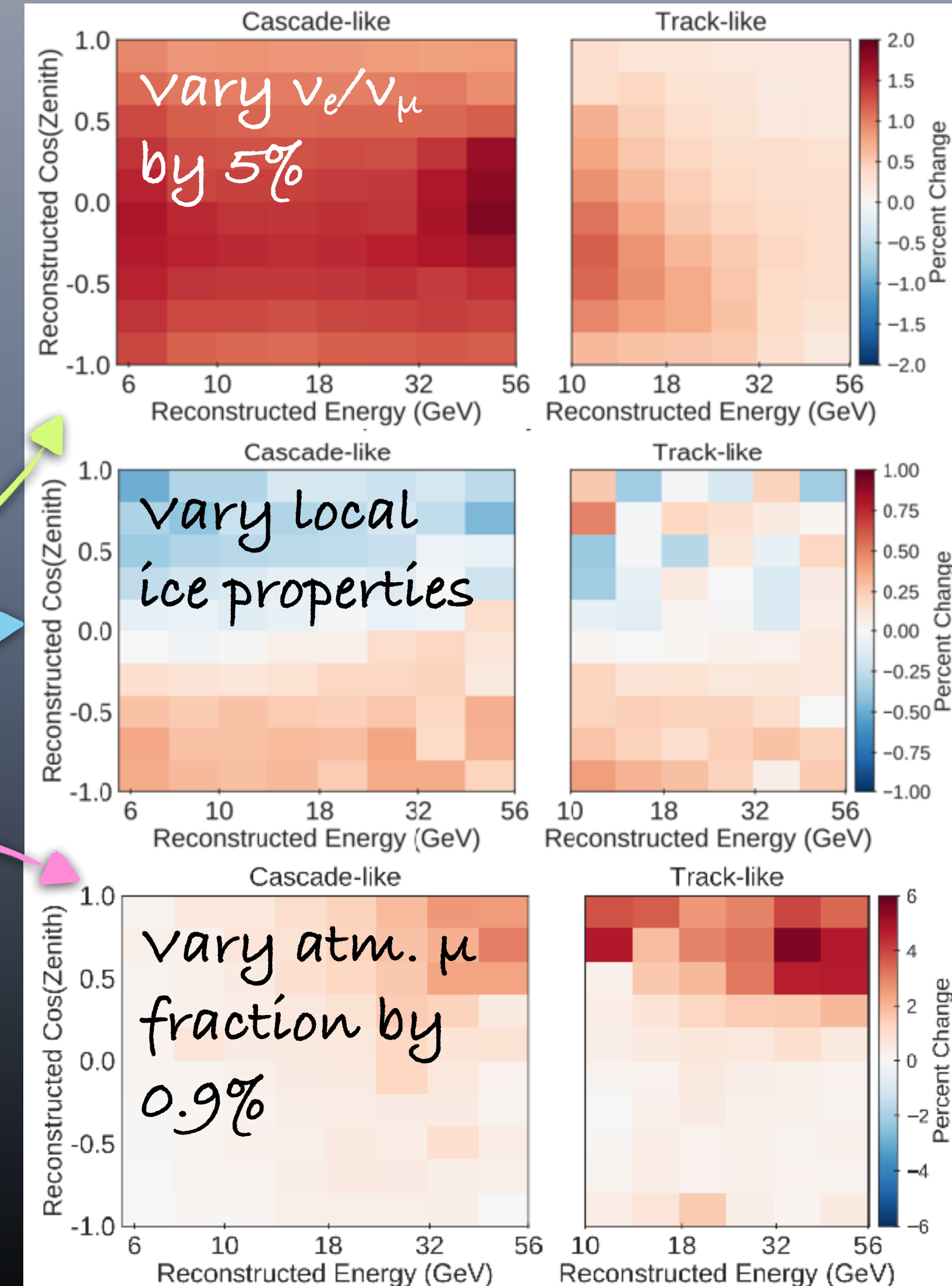
Initial Flux

Detector

Cross-section,

Background

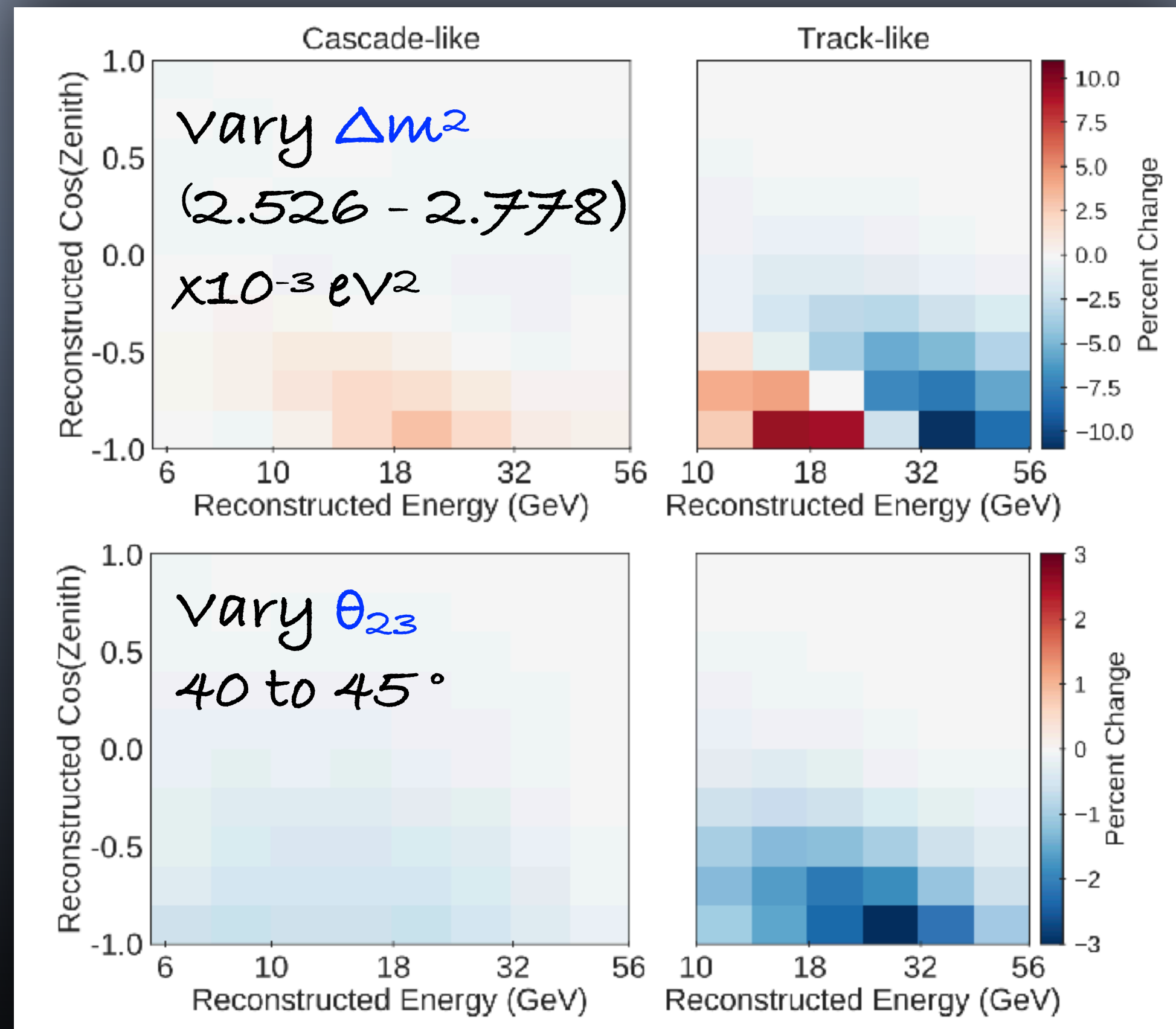
and subdominant
oscillation params



Analysis strategy

Shape-only comparison between data and weighted MC

$$\chi^2 = \sum_{i \in \text{bins}} \frac{(n_i^{v+\mu} - n_i^{\text{data}})^2}{(\sigma_i^{v+\mu})^2 + (\sigma_i^{\text{data}})^2} + \sum_{j \in \{\text{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{s_j}^2}$$



Nuisance parameters
for syst. uncertainties:

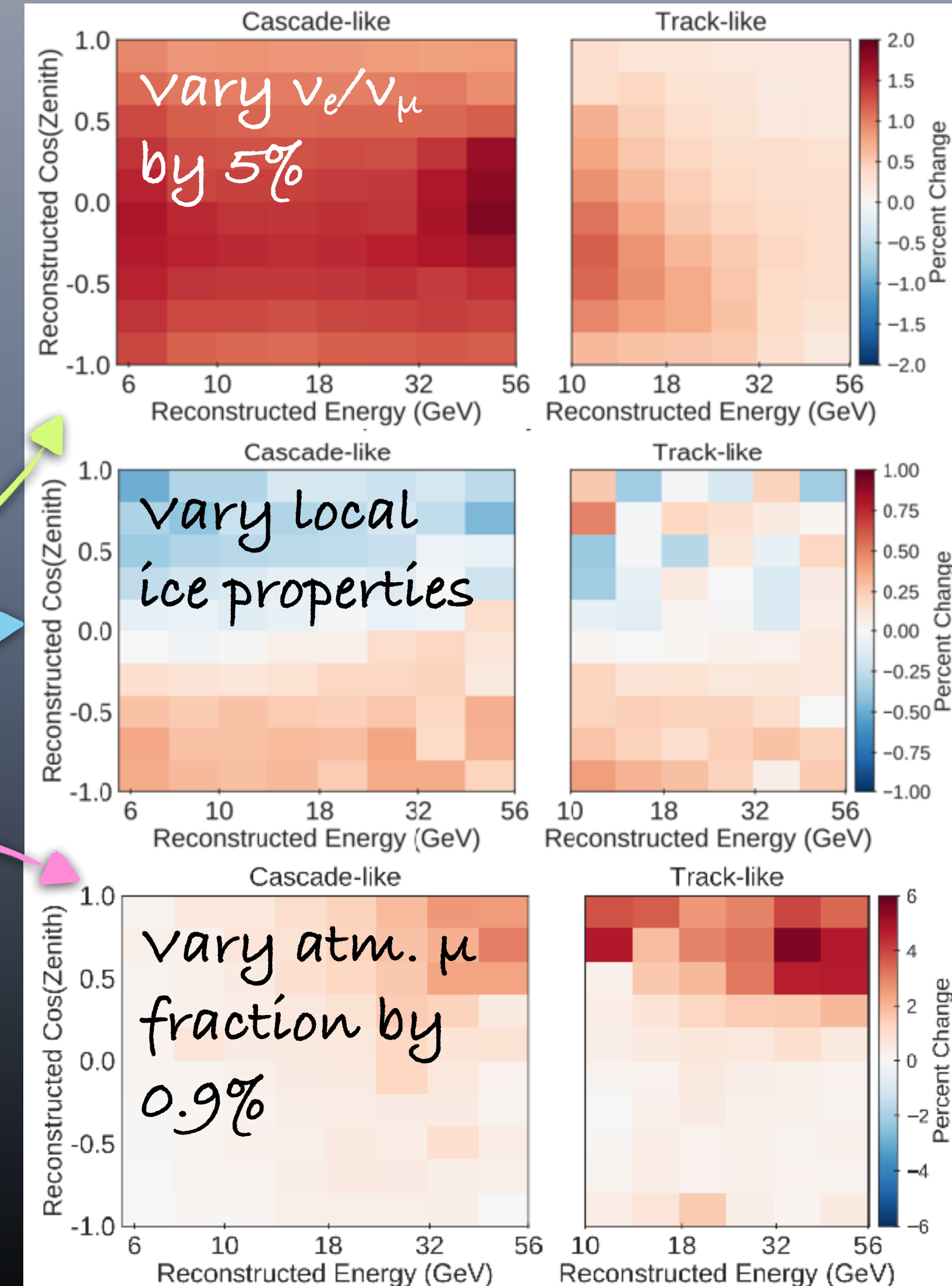
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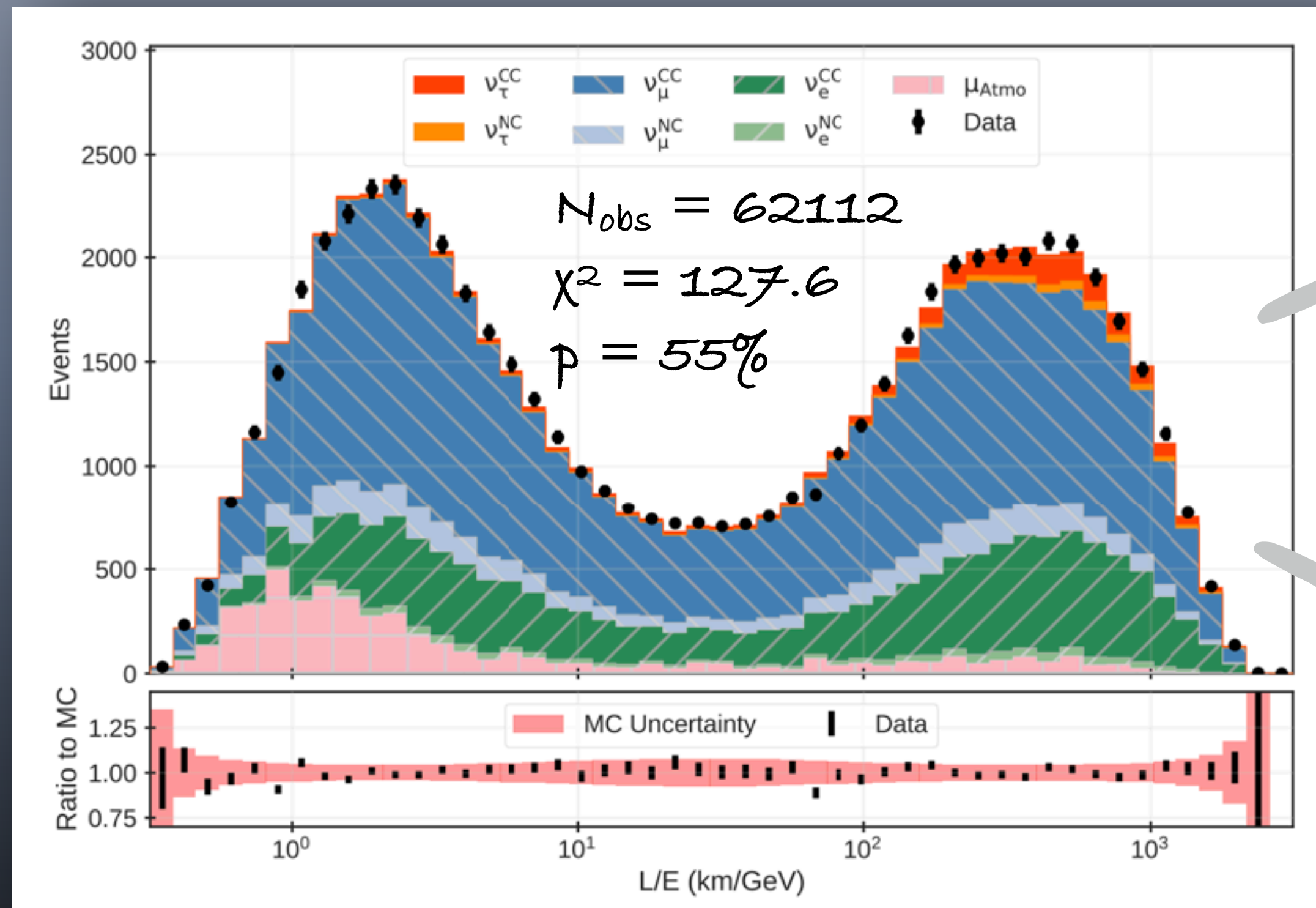
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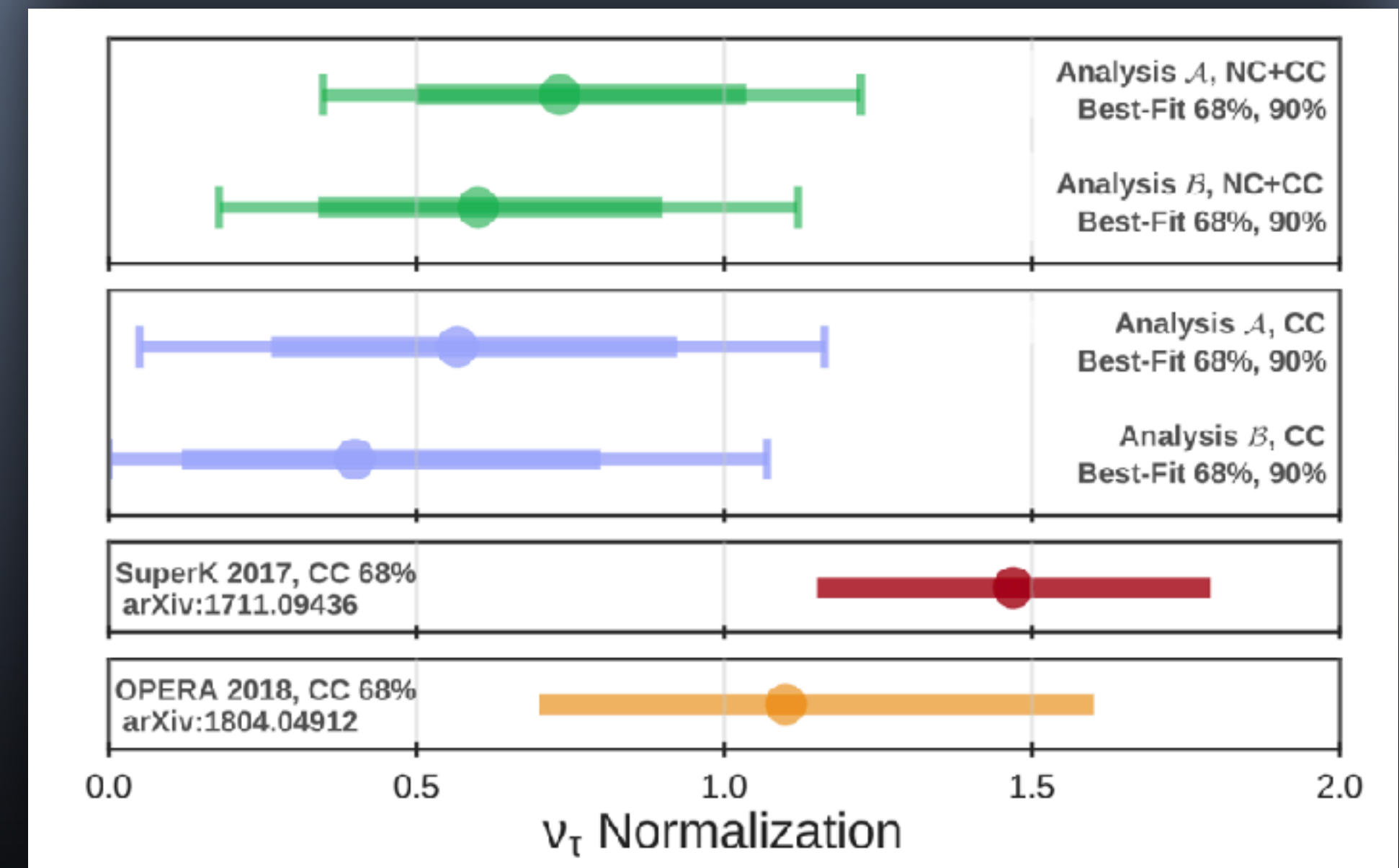
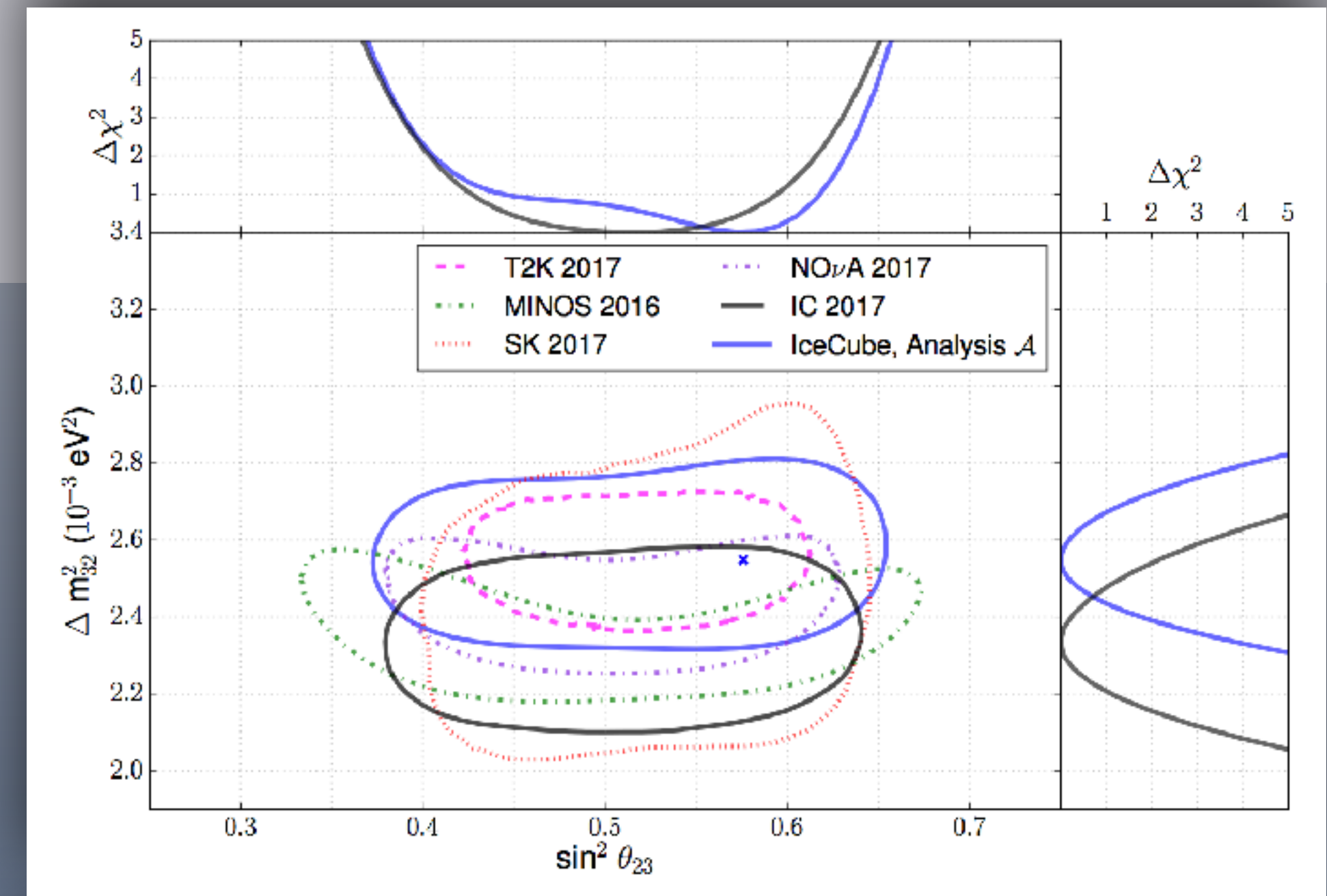
Standard oscillation results

Phys. Rev. D 99, 032007 (2019)

$$\Delta m_{32}^2 = 2.55^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2 \quad \sin^2 \theta_{23} = 0.58^{+0.04}_{-0.13}$$



$$\text{Norm } \nu_{\tau}^{\text{(CC+NC)}} = 0.73^{+0.34}_{-0.24} \quad \text{Reject no-}\nu_{\tau} \text{ with } 3.2\sigma \text{ (CC+NC)}$$

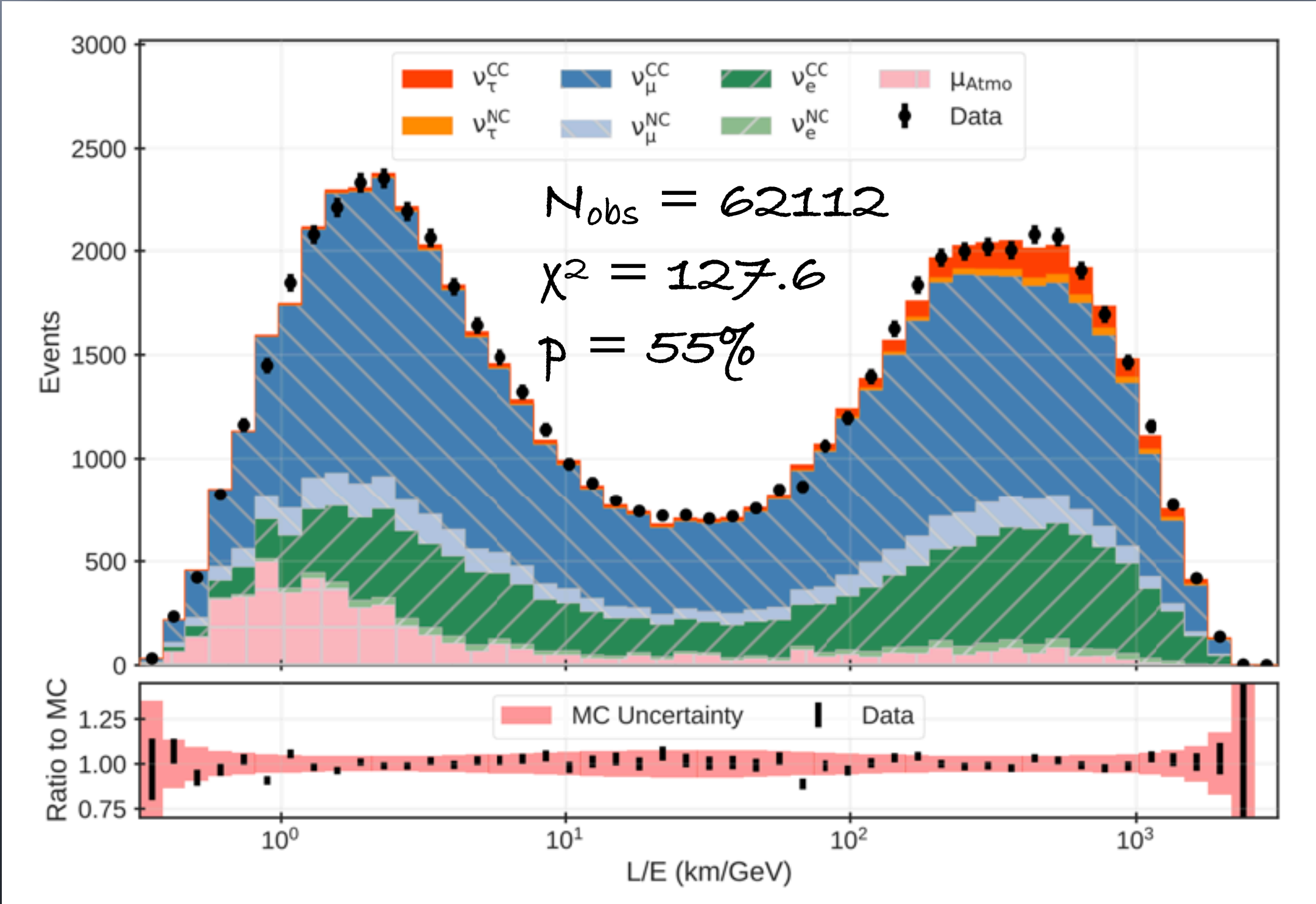


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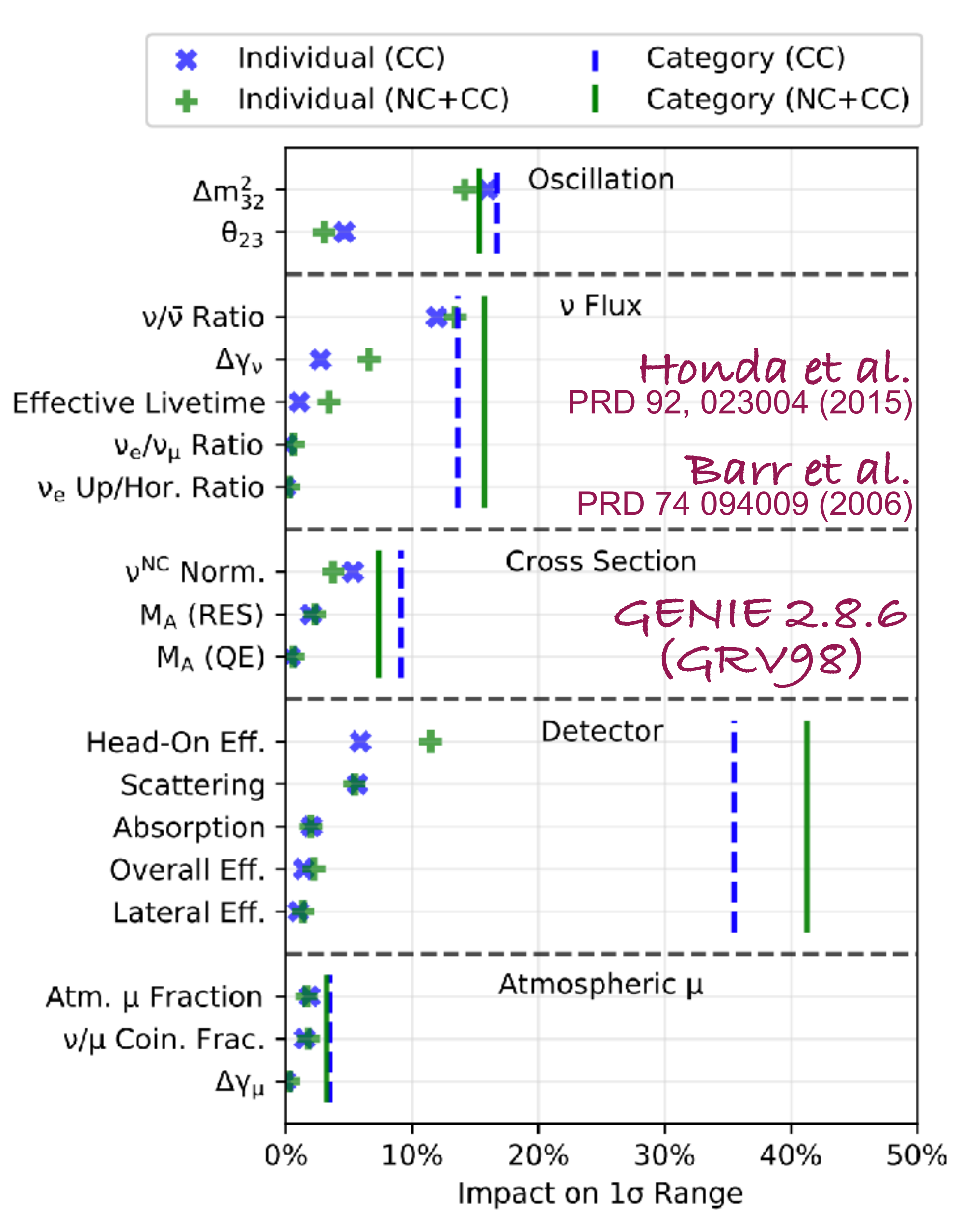
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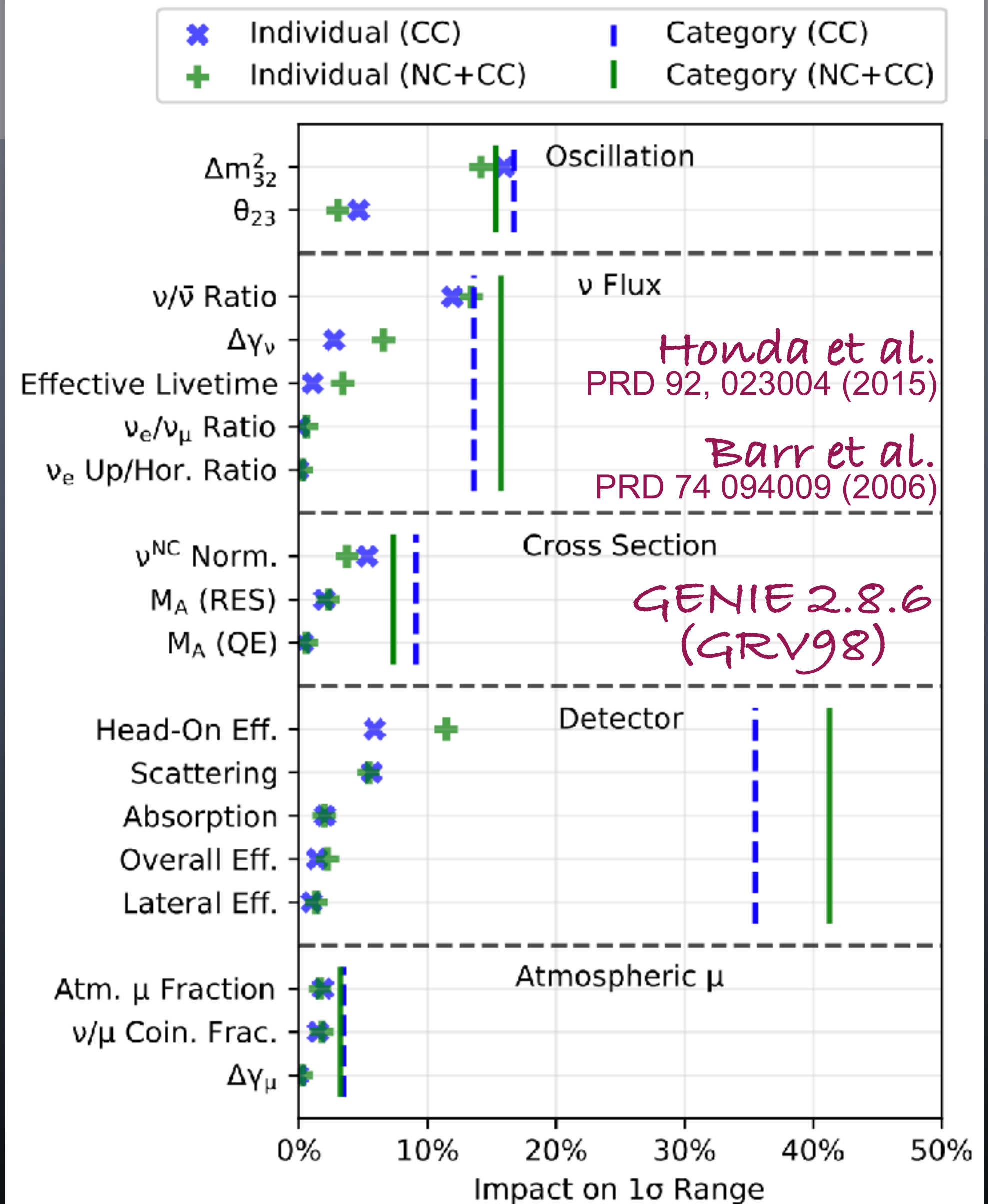
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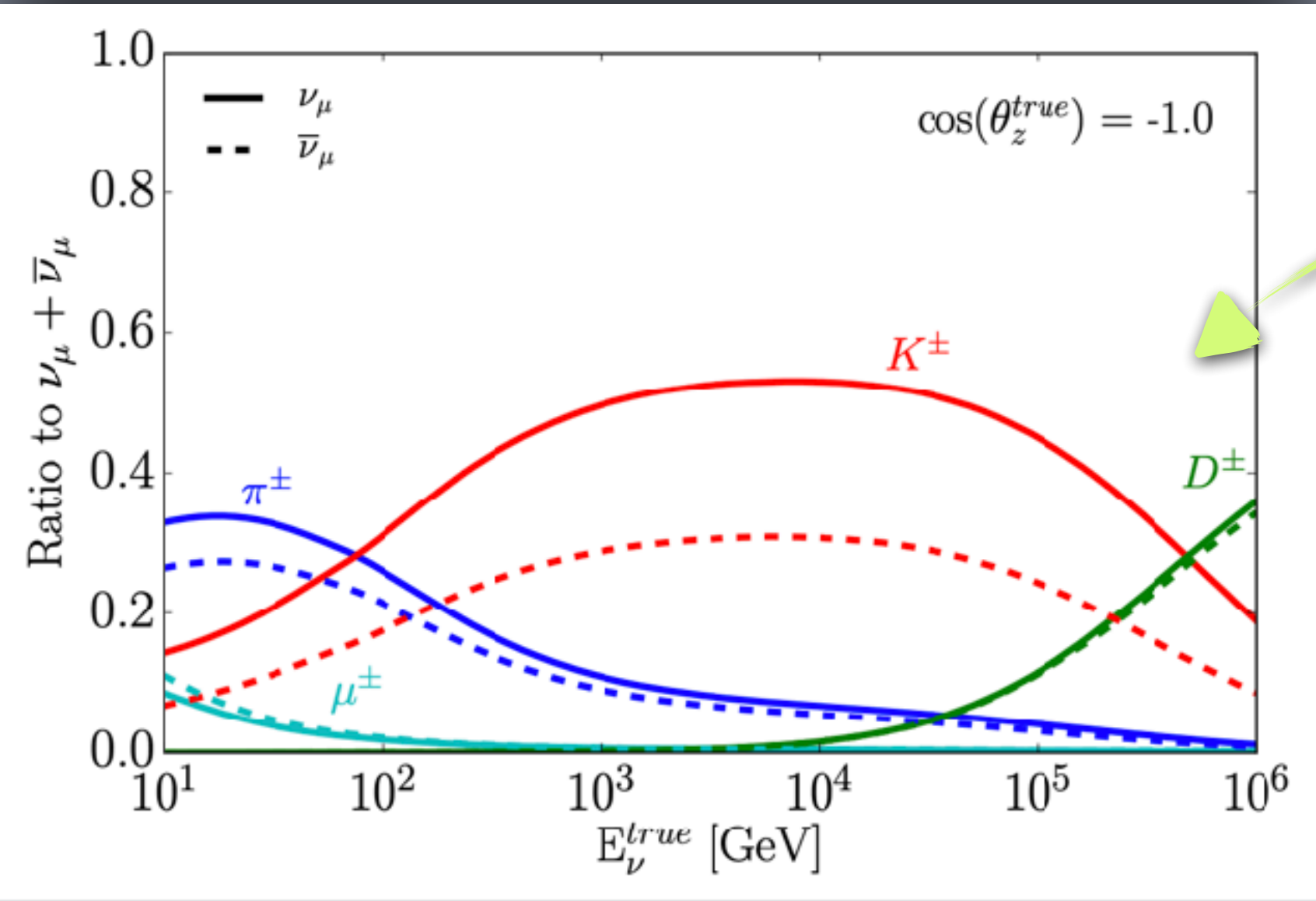
On the horizon...

8 y oscillation sample with > 300k neutrinos



On the horizon...

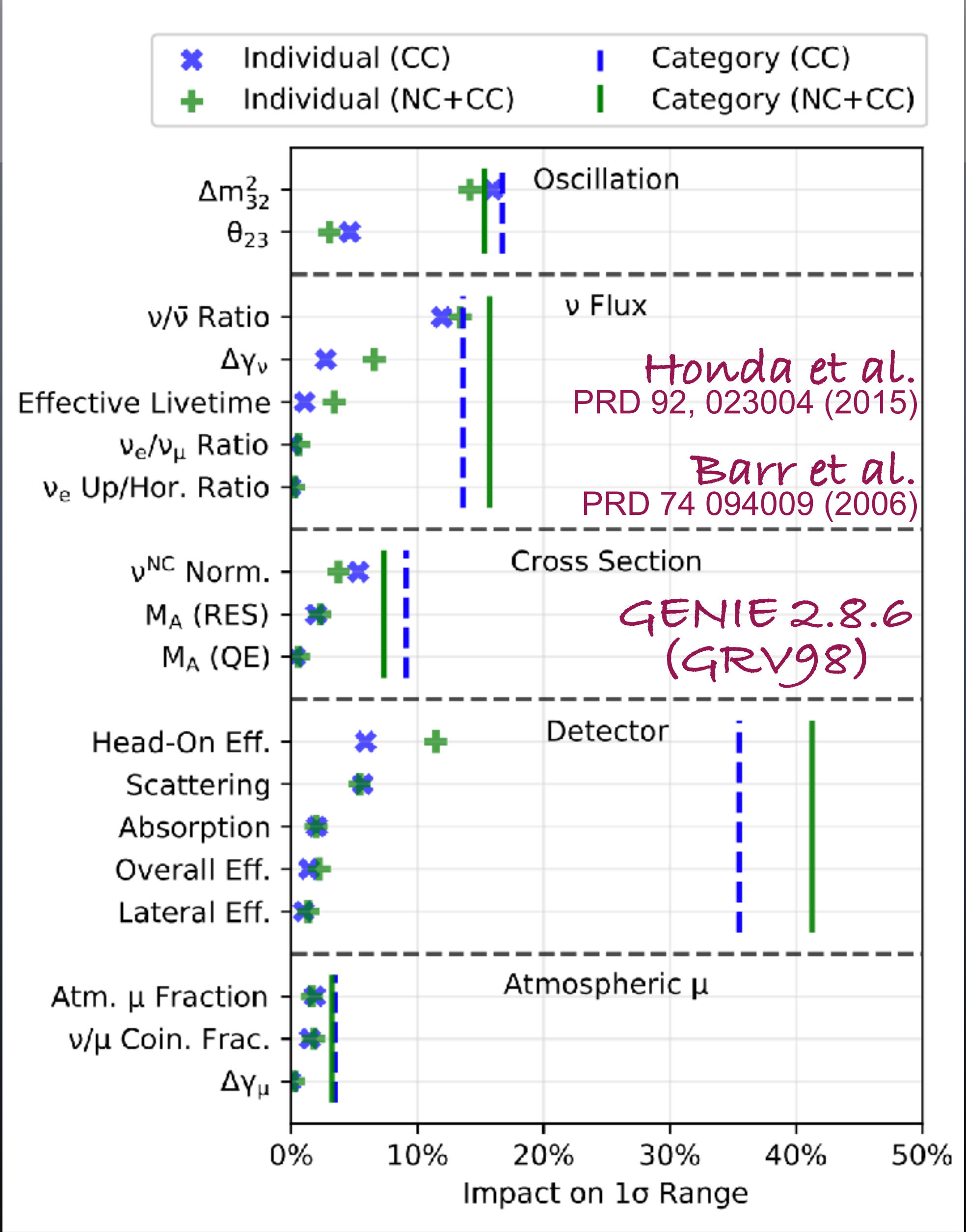
8 y oscillation sample with > 300k neutrinos



Flux

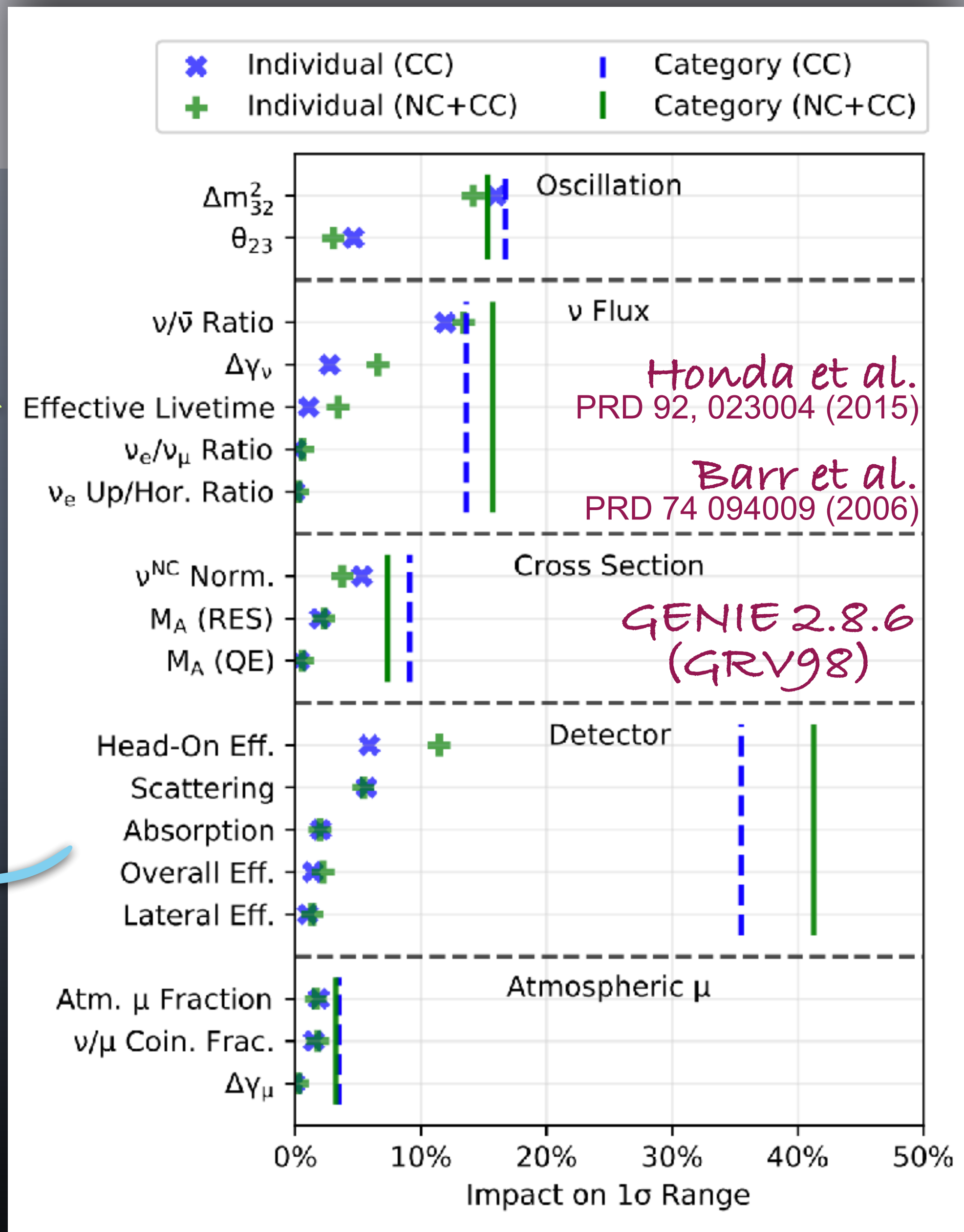
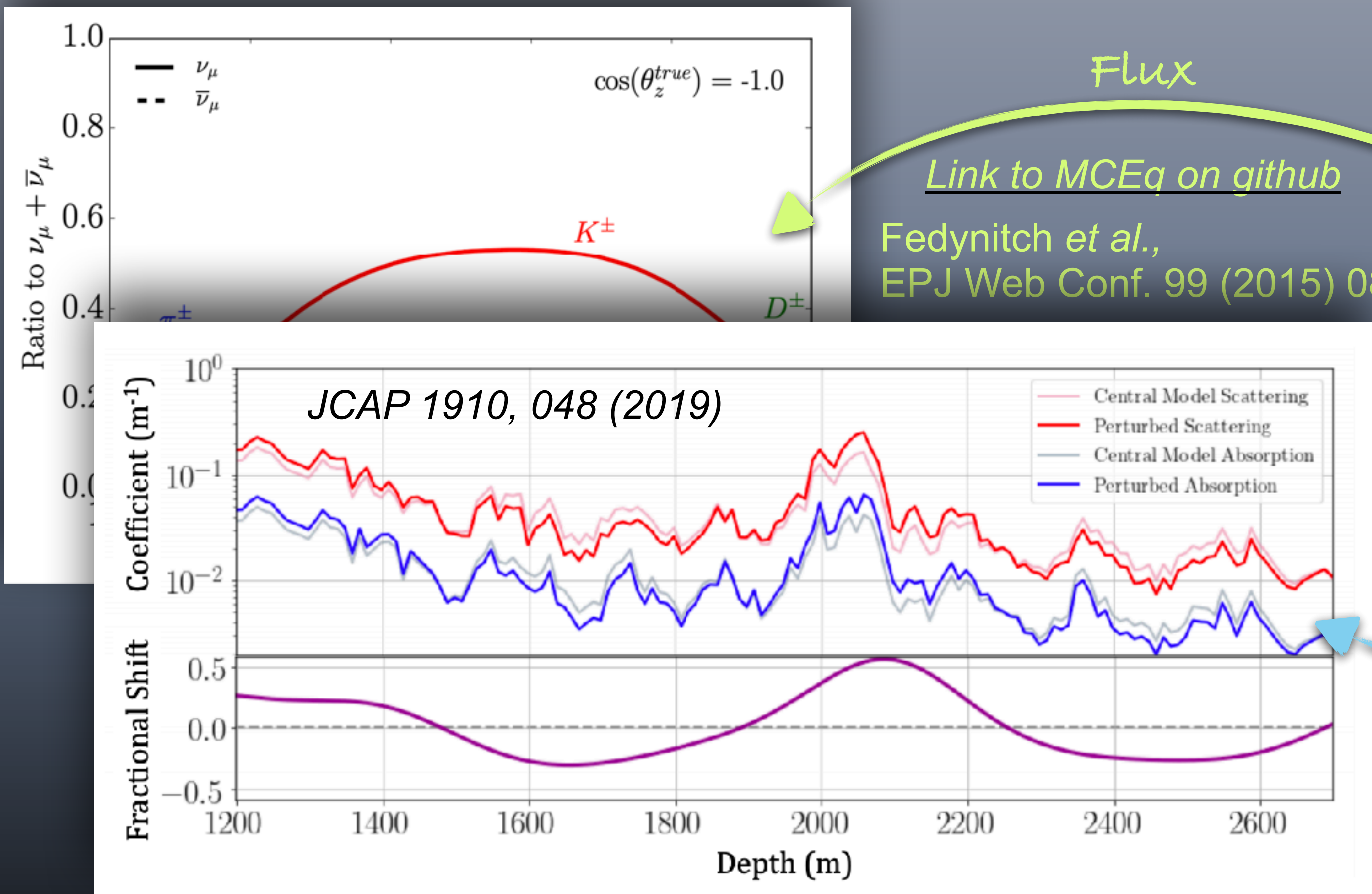
[Link to MCEq on github](#)

Fedynitch et al.,
EPJ Web Conf. 99 (2015) 08001.



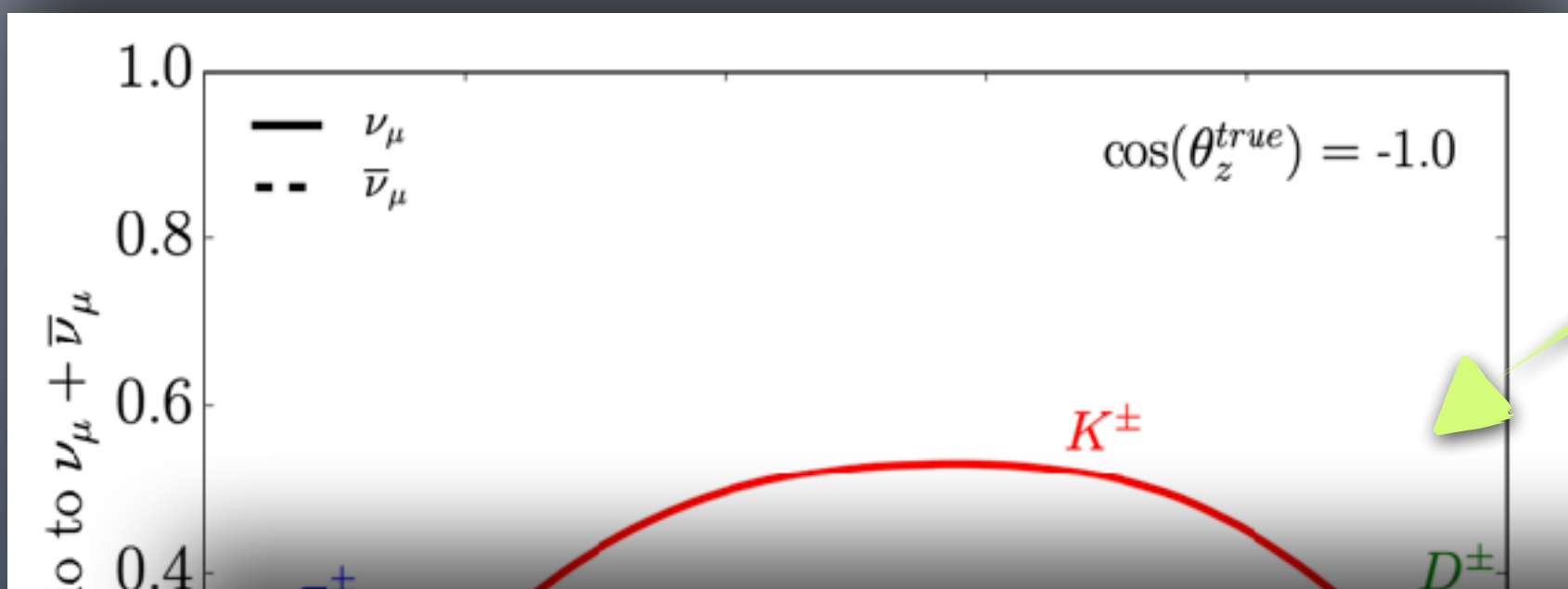
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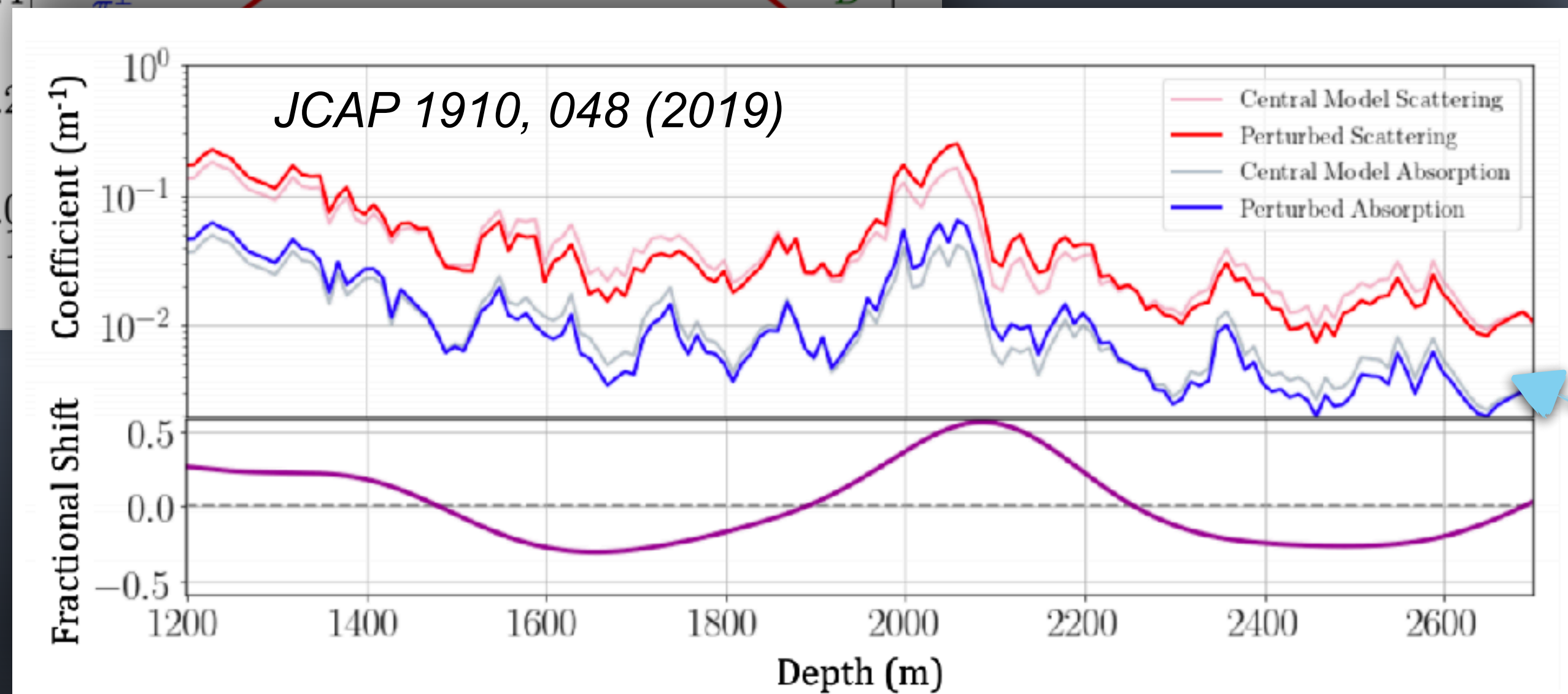
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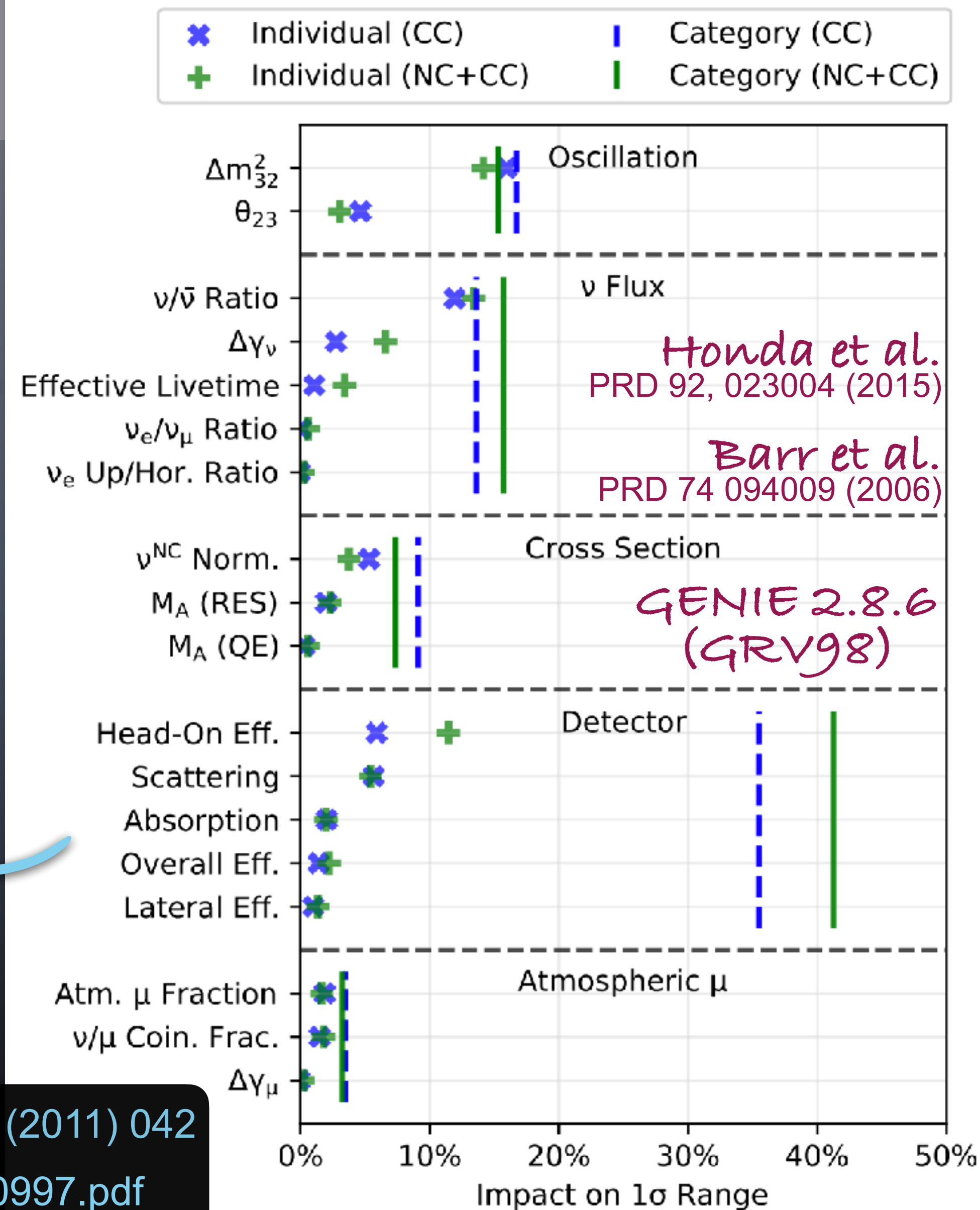
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Ice

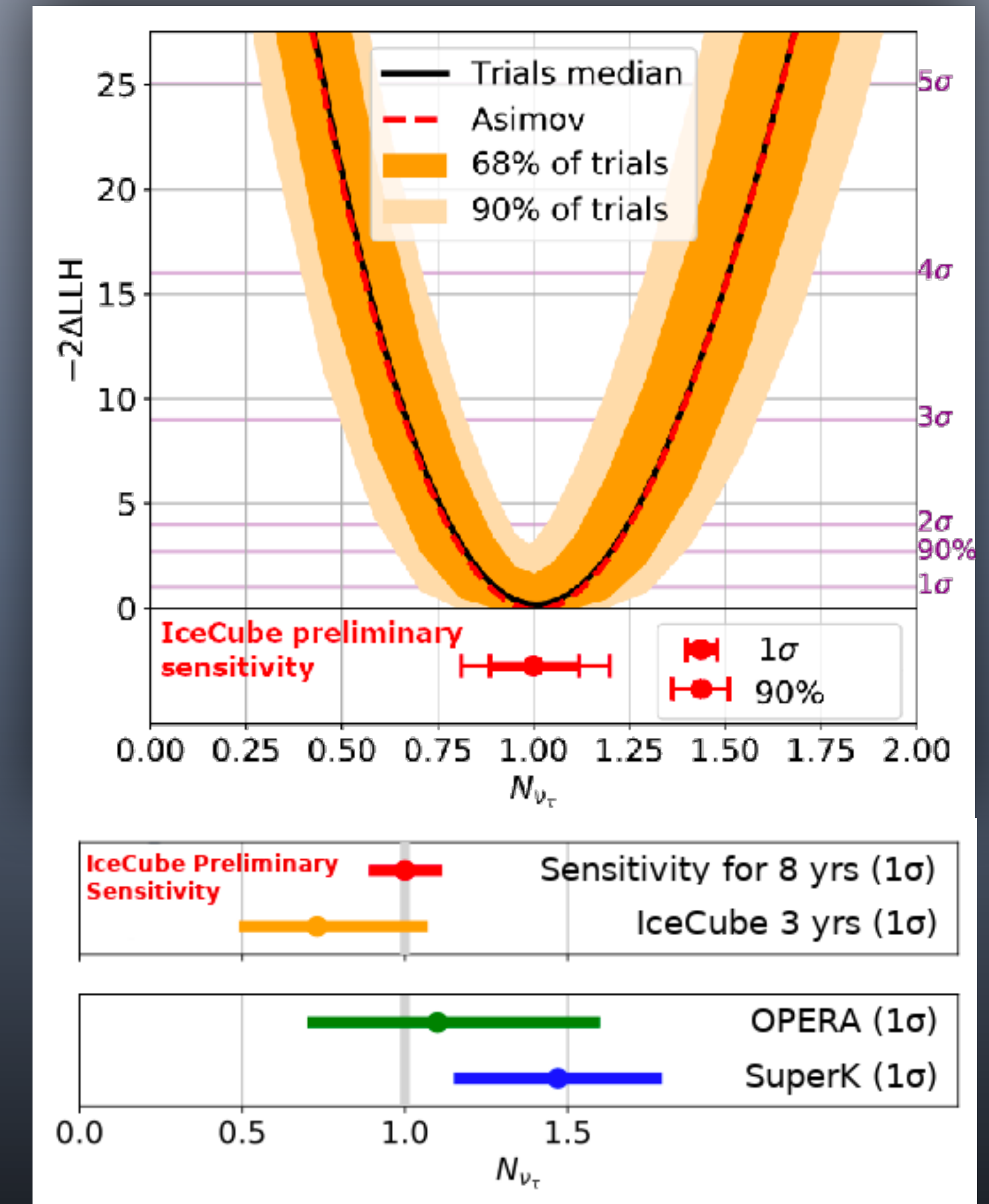
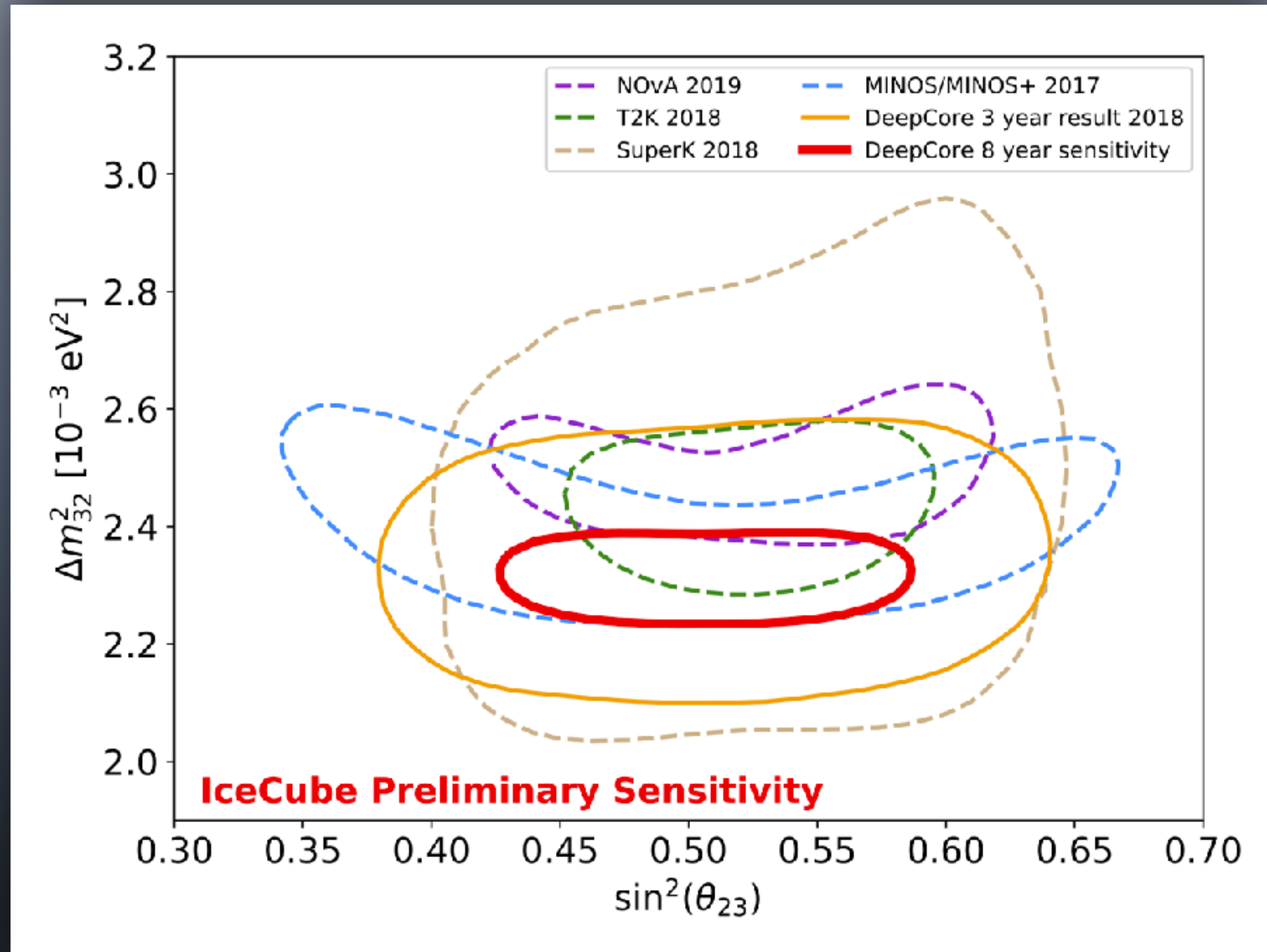
+ alternative xsec models (CSMS), see A. Cooper-Sarkar, et al. JHEP 08 (2011) 042
+ Improved modeling of DOM response, see <https://arxiv.org/pdf/2002.00997.pdf>



Standard oscillation 8 y projections

Unprecedented with atmospheric neutrinos

See posters #547 and #167 for more details



Improved detector calibration, event selection, reconstruction, PID and systematic treatment

Searching beyond the ν SM

Non-standard oscillation patterns

Favourable phase space

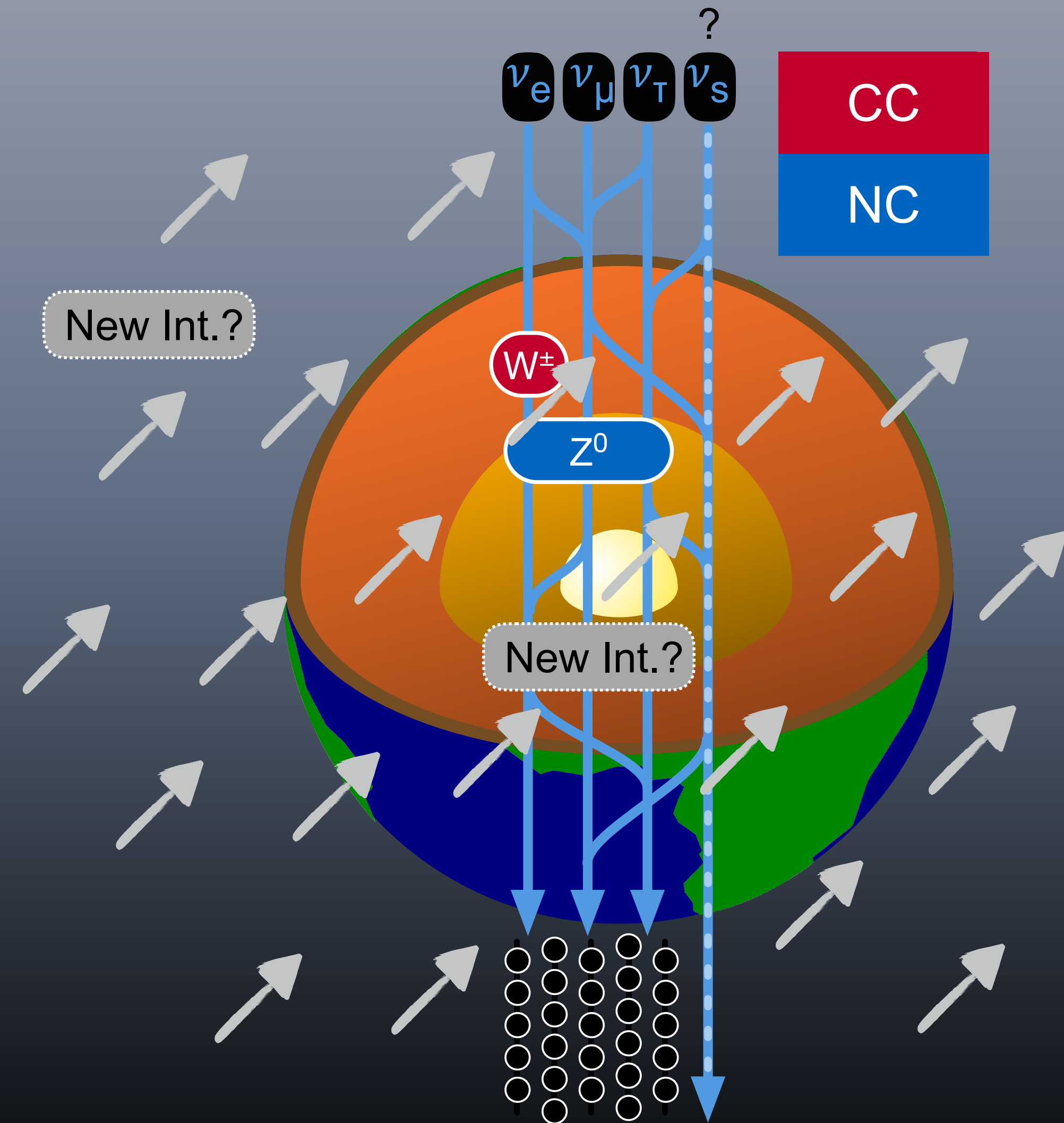
- High energies: access new physics coupling to τ -sector
- Long trajectories: exposure to new fields/interactions

Model dependent searches for new physics, e.g.:

- eV-scale sterile neutrinos
- Non-standard interactions
-+ much more!

Expected signatures are assessed by modifying neutrino mixing matrix and potential

$$\hat{H} = \frac{1}{2E} U \hat{M}^2 U^\dagger + \hat{V}_{\text{int}}$$



Searching beyond the ν SM

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Favourable phase space

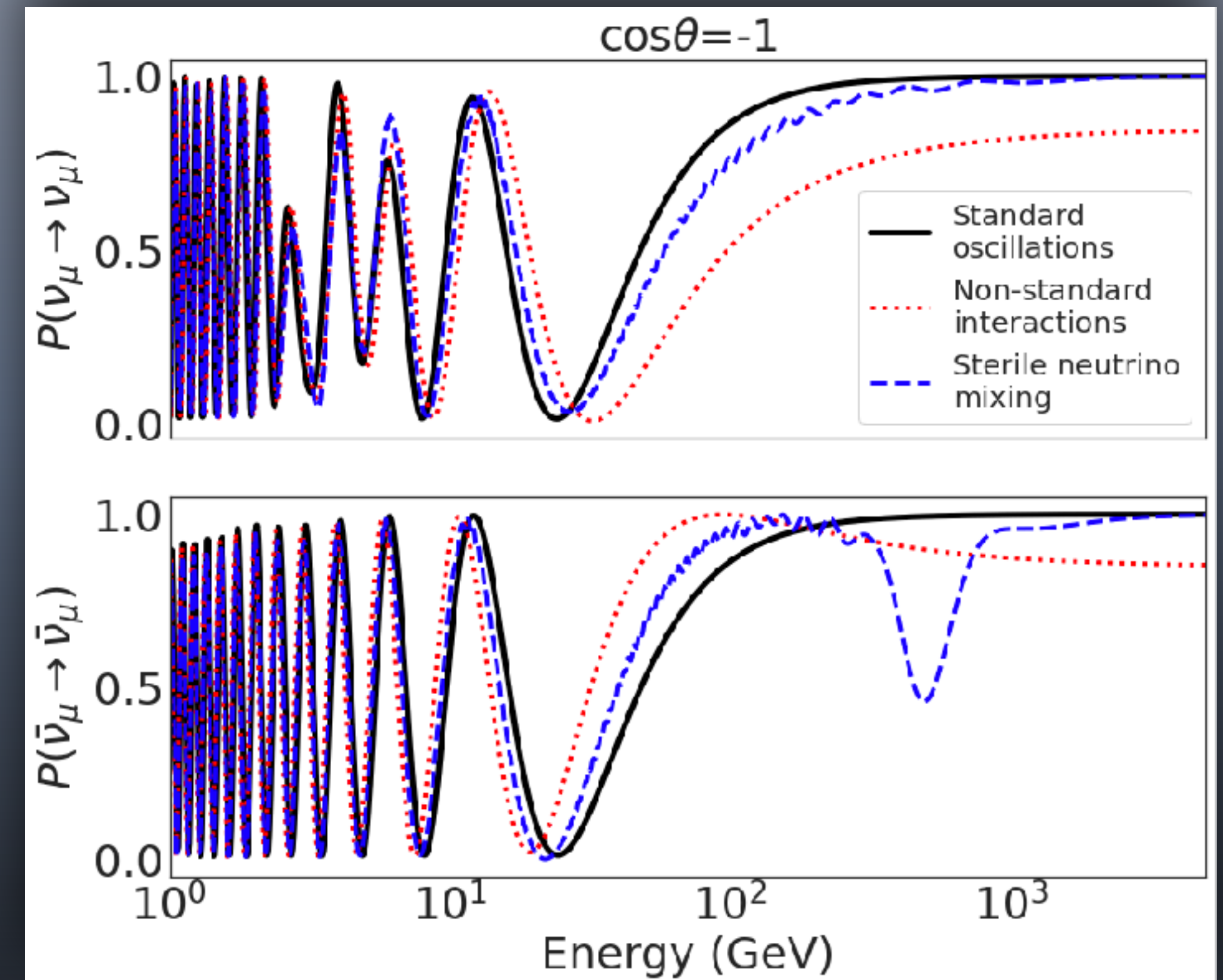
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Expected signatures are assessed by modifying neutrino mixing matrix and potential

$$\hat{H} = \frac{1}{2E} U \hat{M}^2 U^\dagger + \hat{V}_{\text{int}}$$



For particular realisations of non-standard physics

Non-standard interactions

New constraints from 3-year DeepCore sample

See poster #364 for more details

New mediators, e.g. Z'

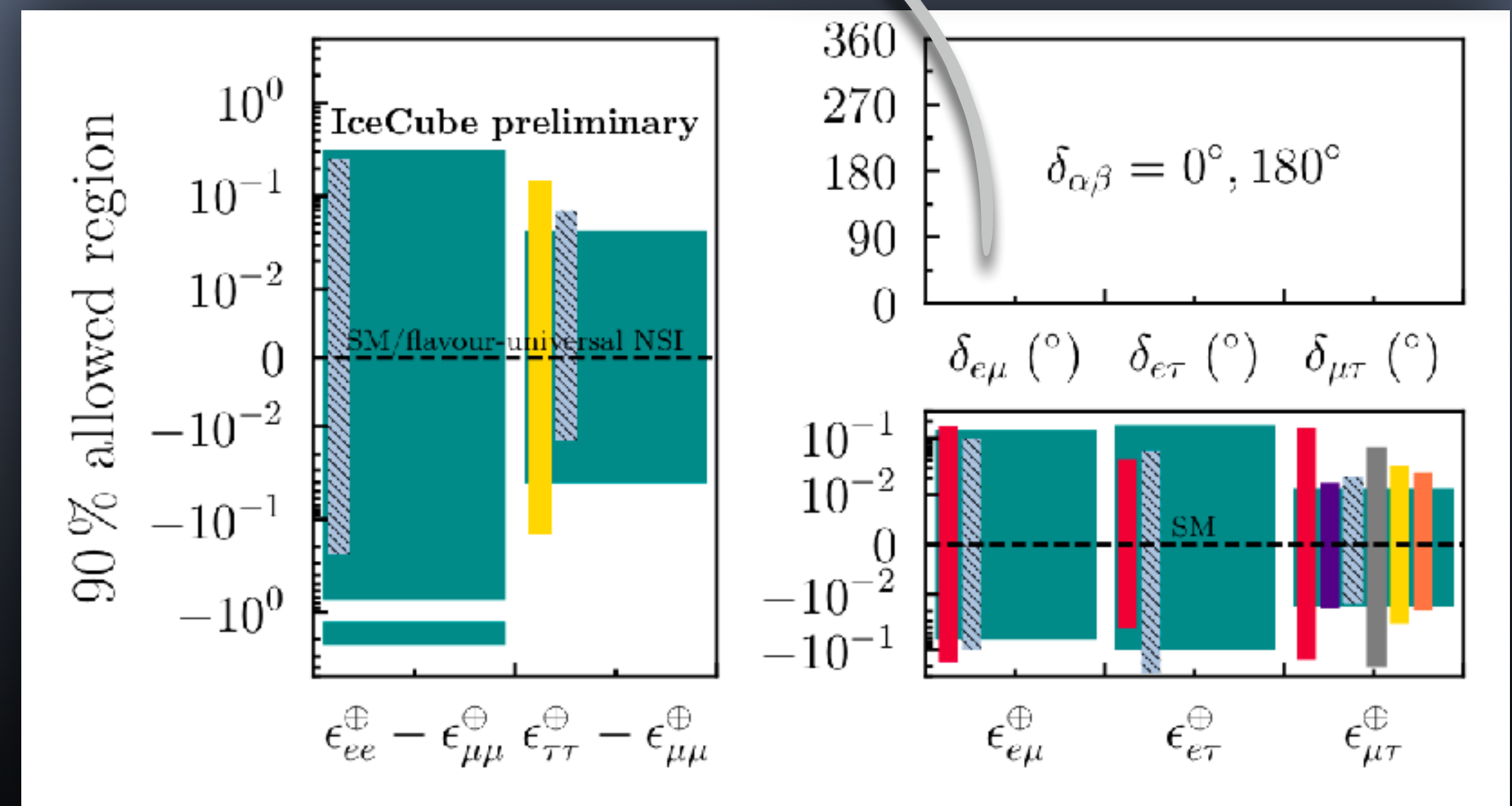
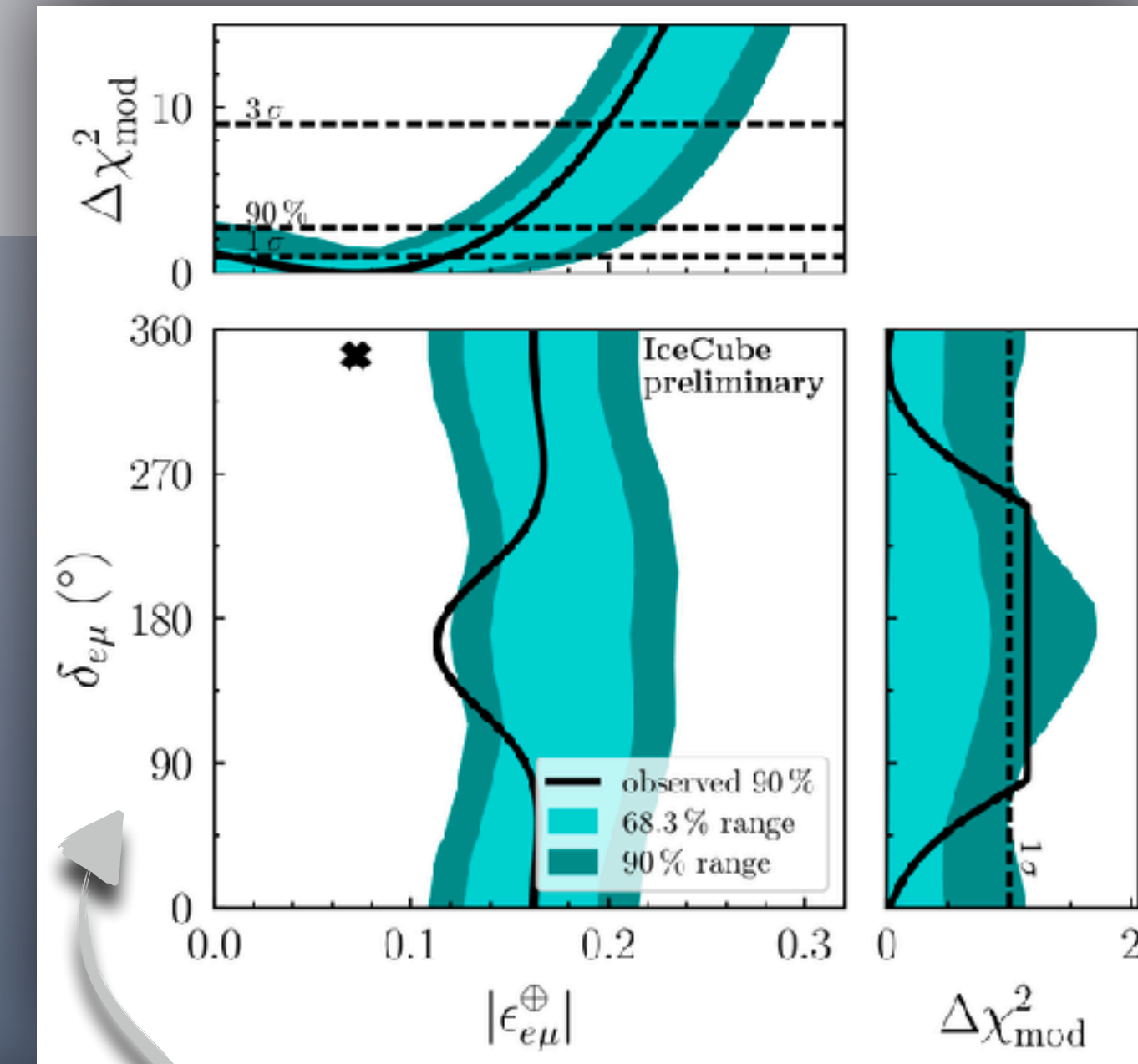
- Creates non-standard flavour changes
- Modifies effective matter potential experienced by neutrinos in transit through the Earth

$$H_{\text{mat}}(x) = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + (\epsilon_{ee}^{\oplus} - \epsilon_{\mu\mu}^{\oplus})(x) & \epsilon_{e\mu}^{\oplus}(x) & \epsilon_{e\tau}^{\oplus}(x) \\ \epsilon_{e\mu}^{\oplus*}(x) & 0 & \epsilon_{\mu\tau}^{\oplus}(x) \\ \epsilon_{e\tau}^{\oplus*}(x) & \epsilon_{\mu\tau}^{\oplus*}(x) & (\epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus})(x) \end{pmatrix}$$

for Earth: $\epsilon_{\alpha\beta}^{\oplus}(x) \approx \epsilon_{\alpha\beta}^{\oplus} = \epsilon_{\alpha\beta}^e + \epsilon_{\alpha\beta}^p + 1.051 \epsilon_{\alpha\beta}^n$

Results are consistent with the null hypothesis

- Constrain real couplings with phases fixed to 0
- New - full parameter fit includes complex phases



Sterile Neutrinos

Resonant disappearance of anti- ν_μ

See poster #177
for more details

3+1 model: probes Δm_{41}^2 , θ_{24} , θ_{34}

- Using 8 years of high-energy, through-going tracks ($\cos\theta_z < 0$)
- 305,735 events with >99% purity ν_μ
- High statistical precision required significant investment in modelling of systematic uncertainties

Two searches, both results consistent with null hypothesis

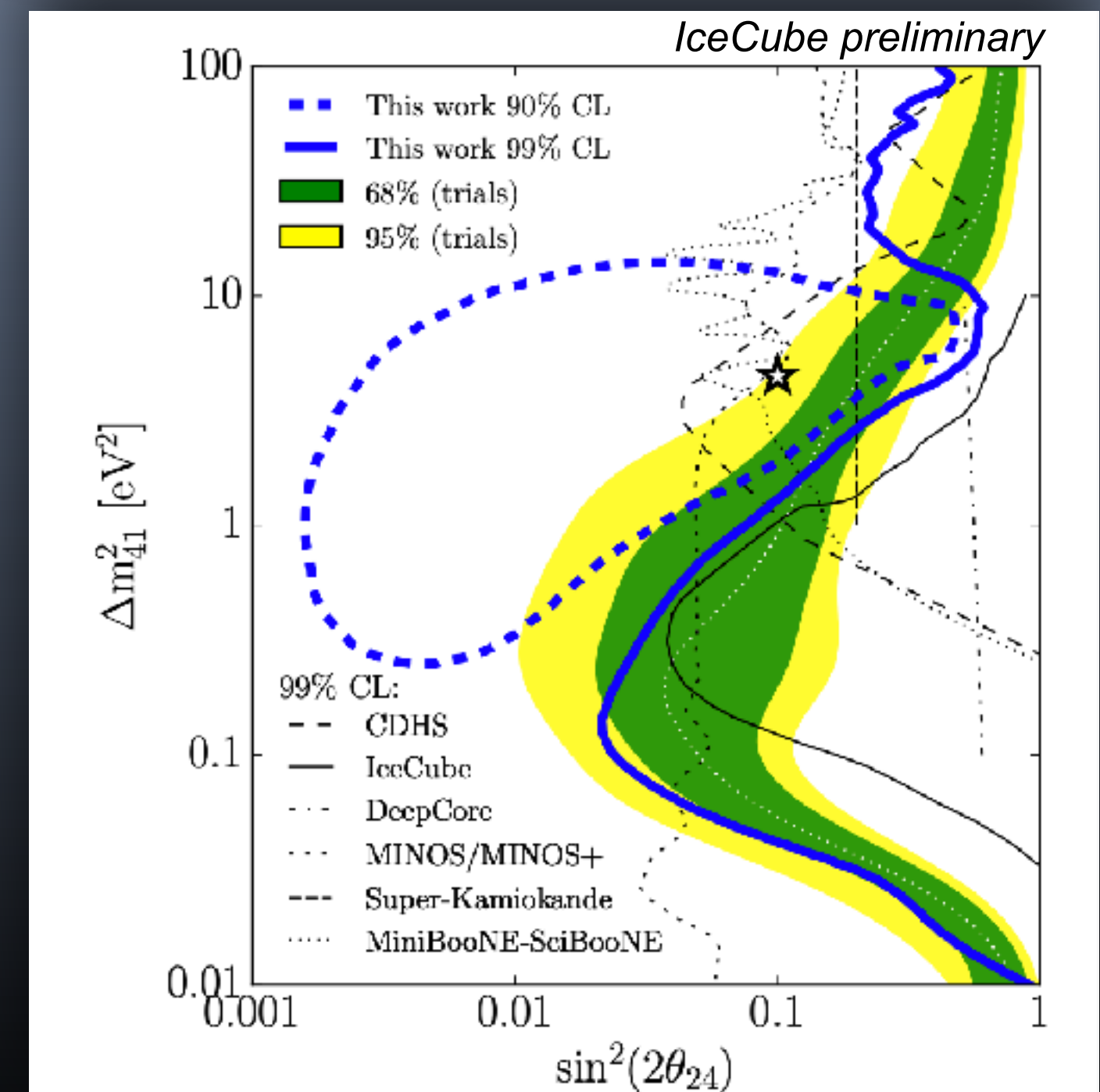
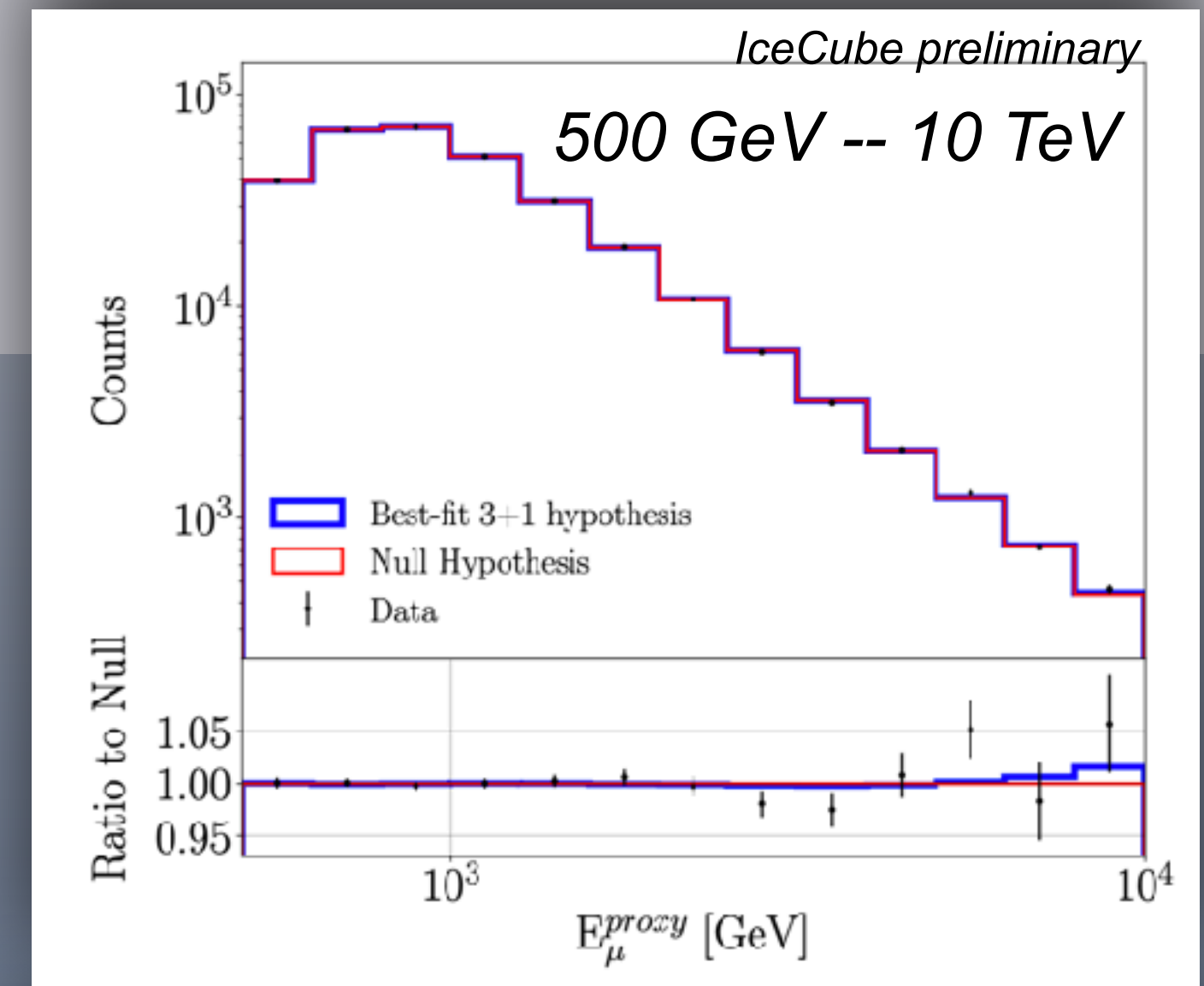
Analysis I: $\Delta m = 4.47 \text{ eV}^2$, $\sin^2(2\theta_{24}) = 0.10$ ($\theta_{34} = 0$), $p = 8\%$

Analysis II: $\sin^2(2\theta_{24}) = 0.006$, $\sin^2(2\theta_{34}) = 0.40$, ($\Delta m = 50 \text{ eV}^2$), $p = 19\%$

Results are robust against the removal of any single year of data or systematic uncertainty

<https://arxiv.org/abs/2005.12942v3>

<https://arxiv.org/abs/2005.12942>



The IceCube Upgrade

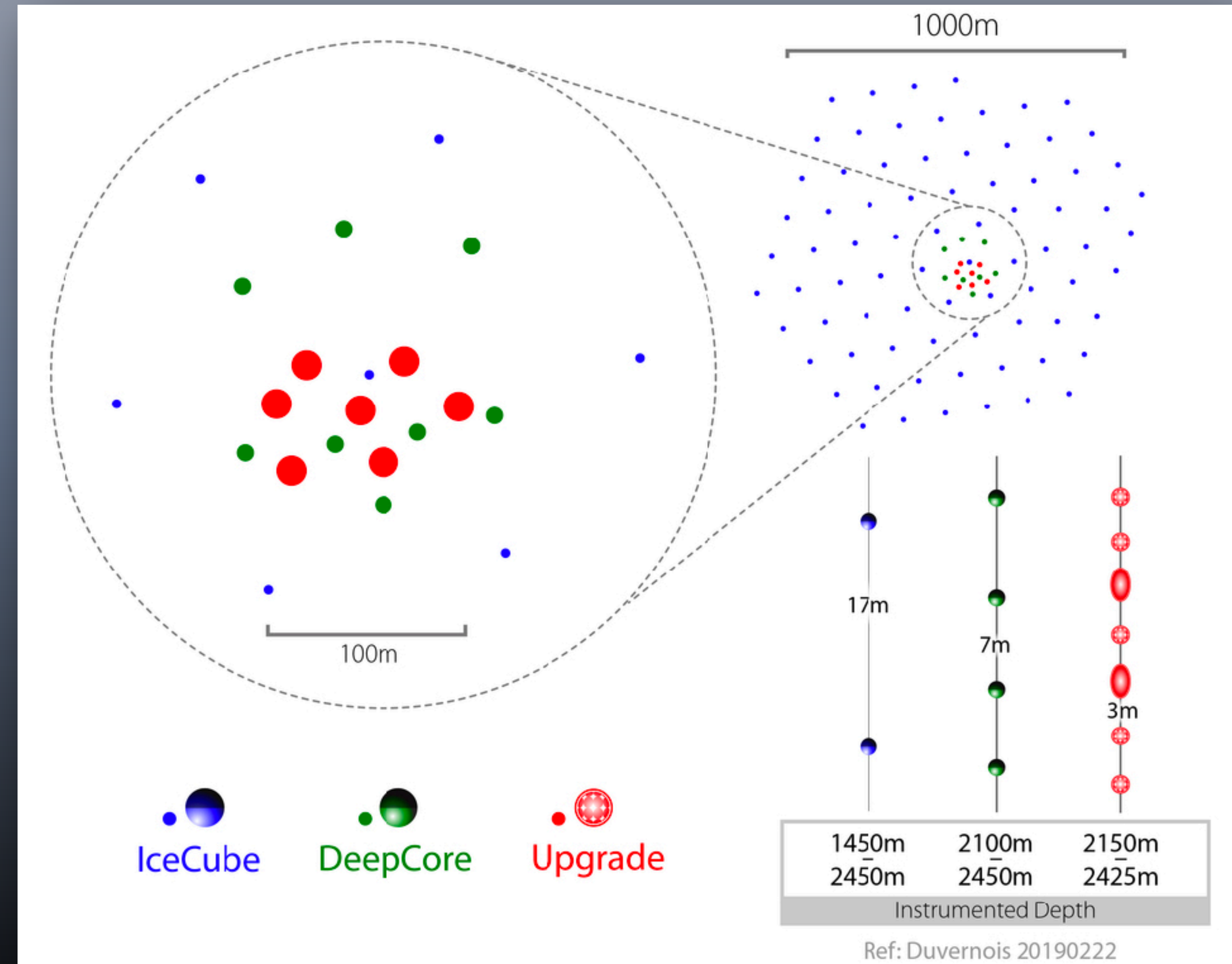
A multipurpose detector

IceCube Upgrade goals:

- Precision oscillation measurements
- Improved detector calibrations
- R&D for IceCube-Gen2

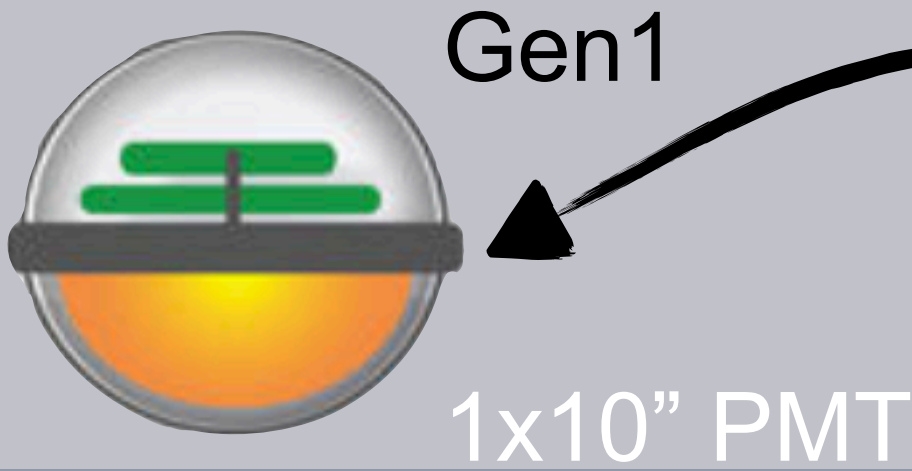
Key features

- > 800 new devices
- Reduced spacing between devices
- Explore the deep ice down to 2600 m



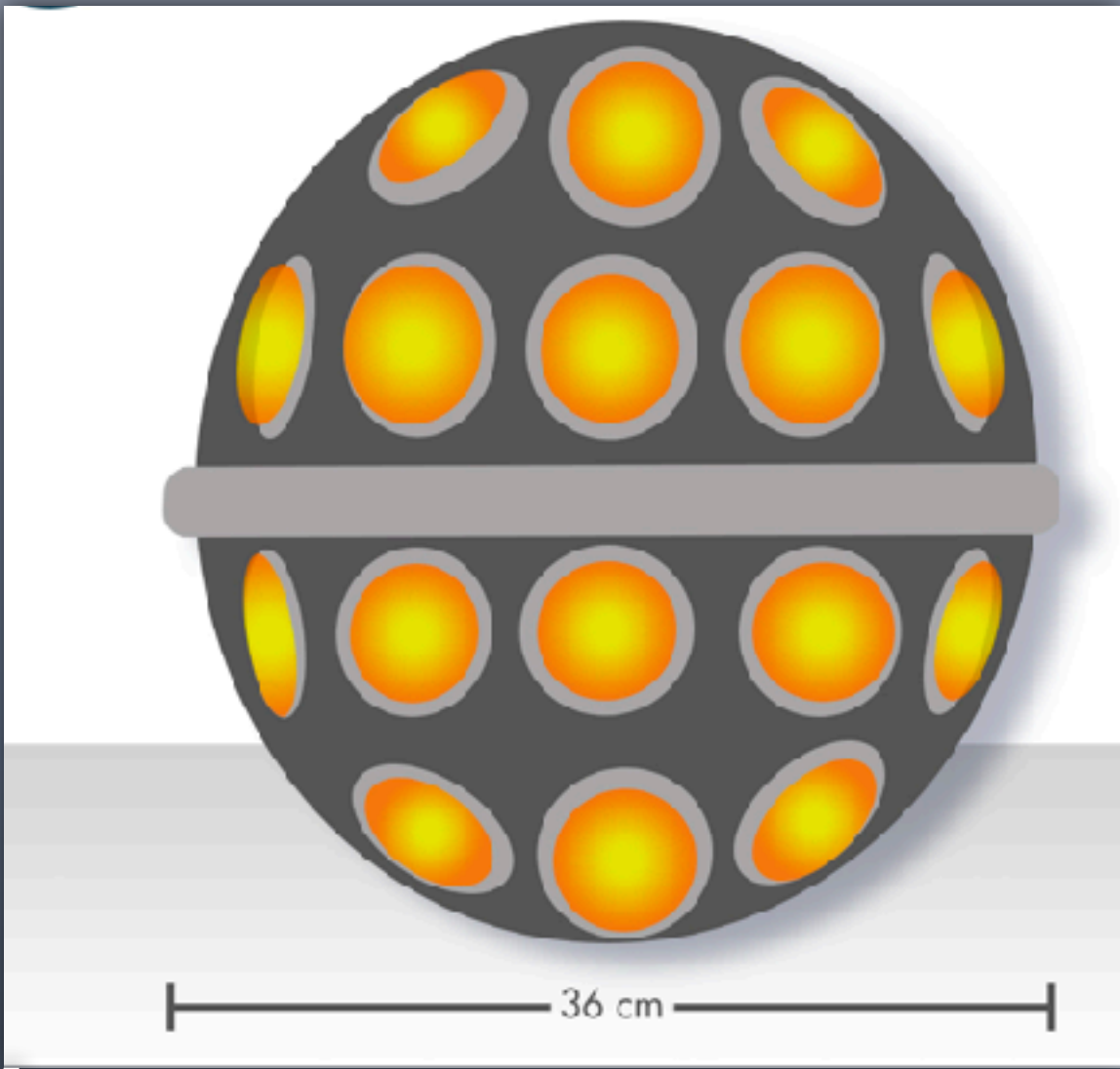
New sensor designs

Increased effective area



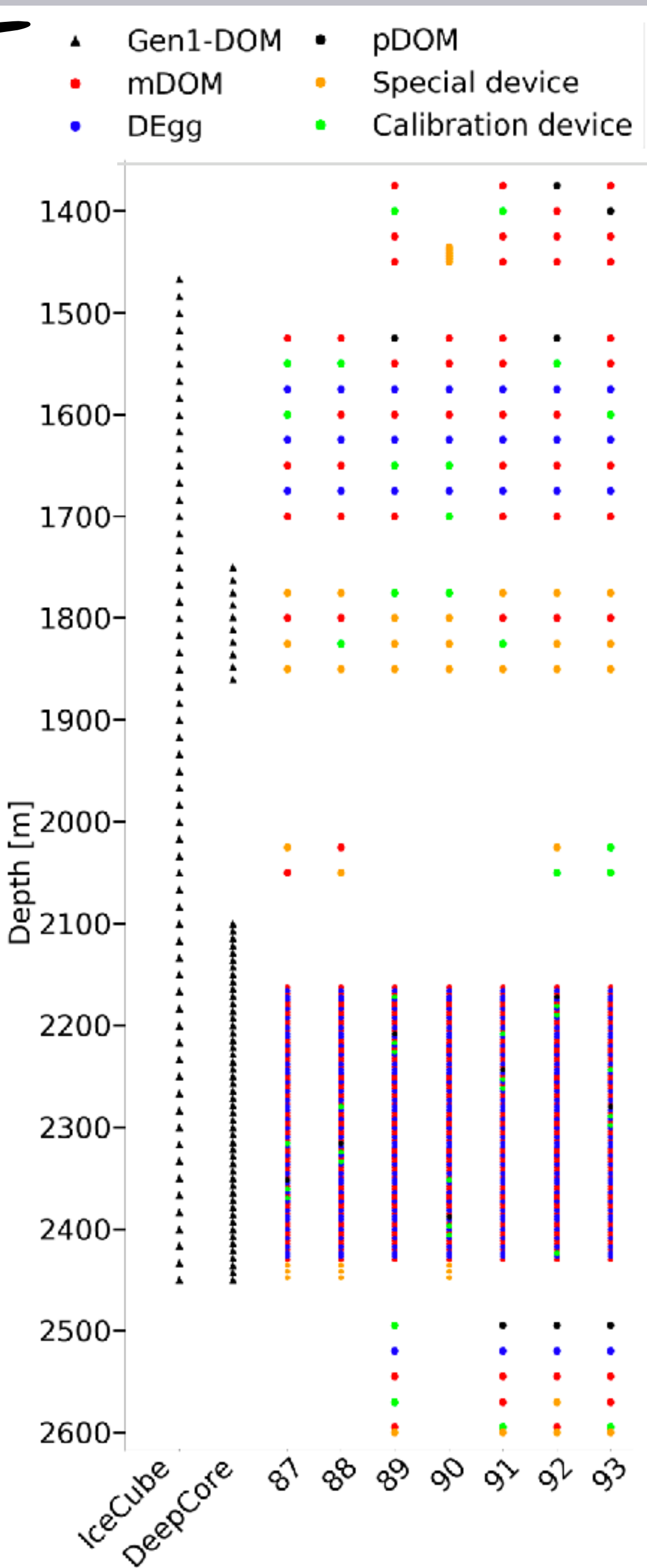
DEgg

2x8" PMT
Produced at Chiba
Deploy ~300



24x3" PMT
Produced at DESY&MSU
Deploy ~400

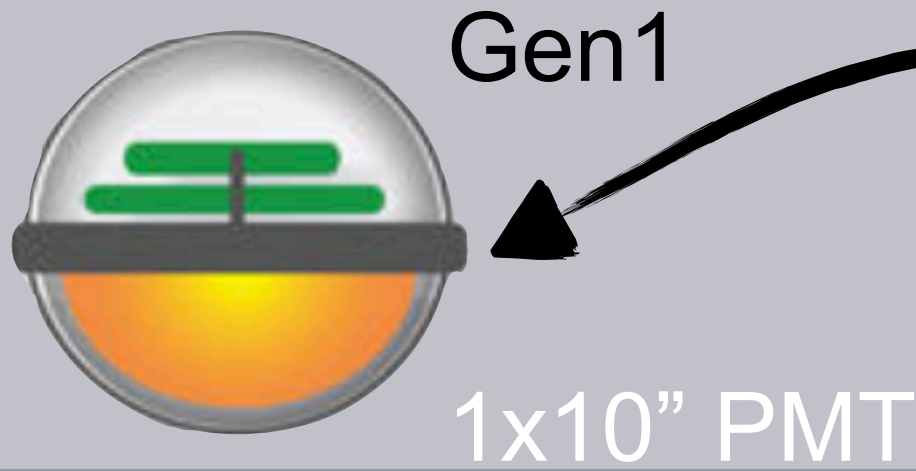
mDOM



More total photocathode area, increased wavelength and angular acceptance

New sensor designs

Increased effective area



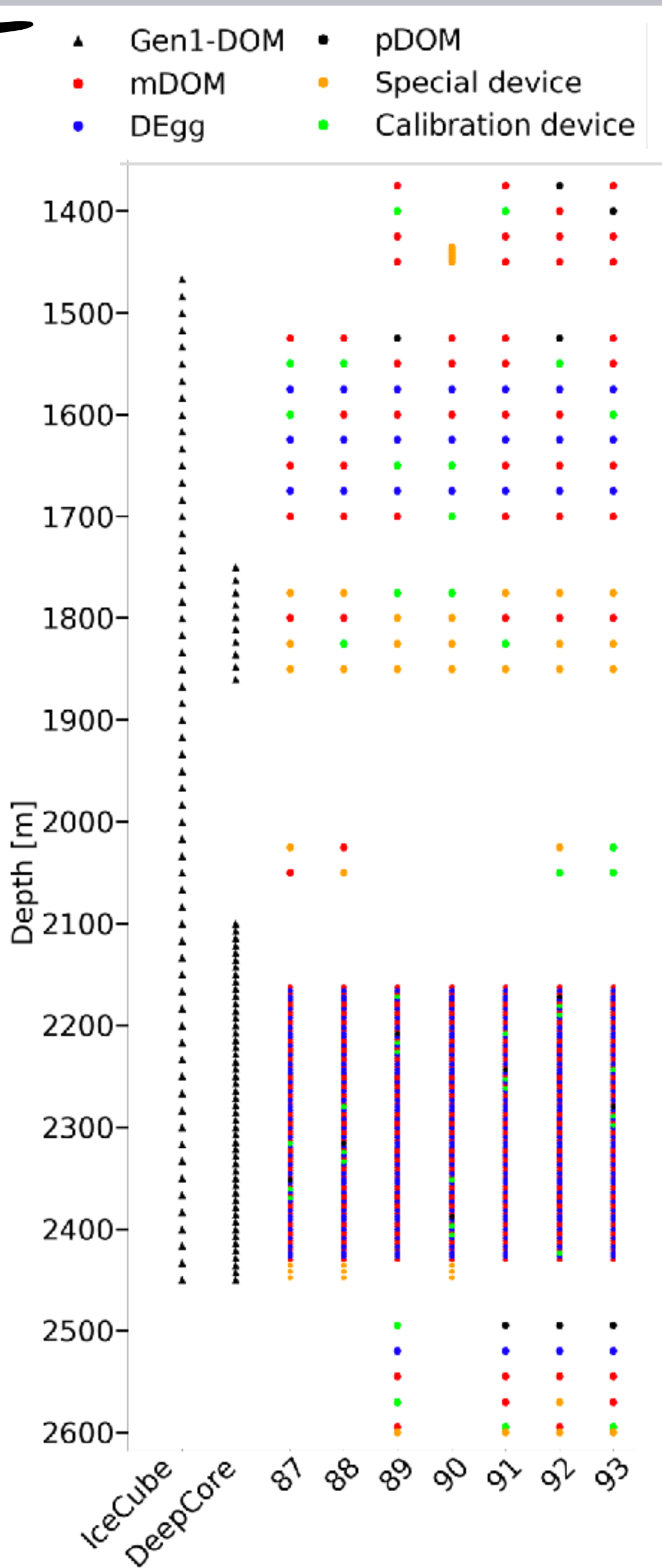
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mDOM



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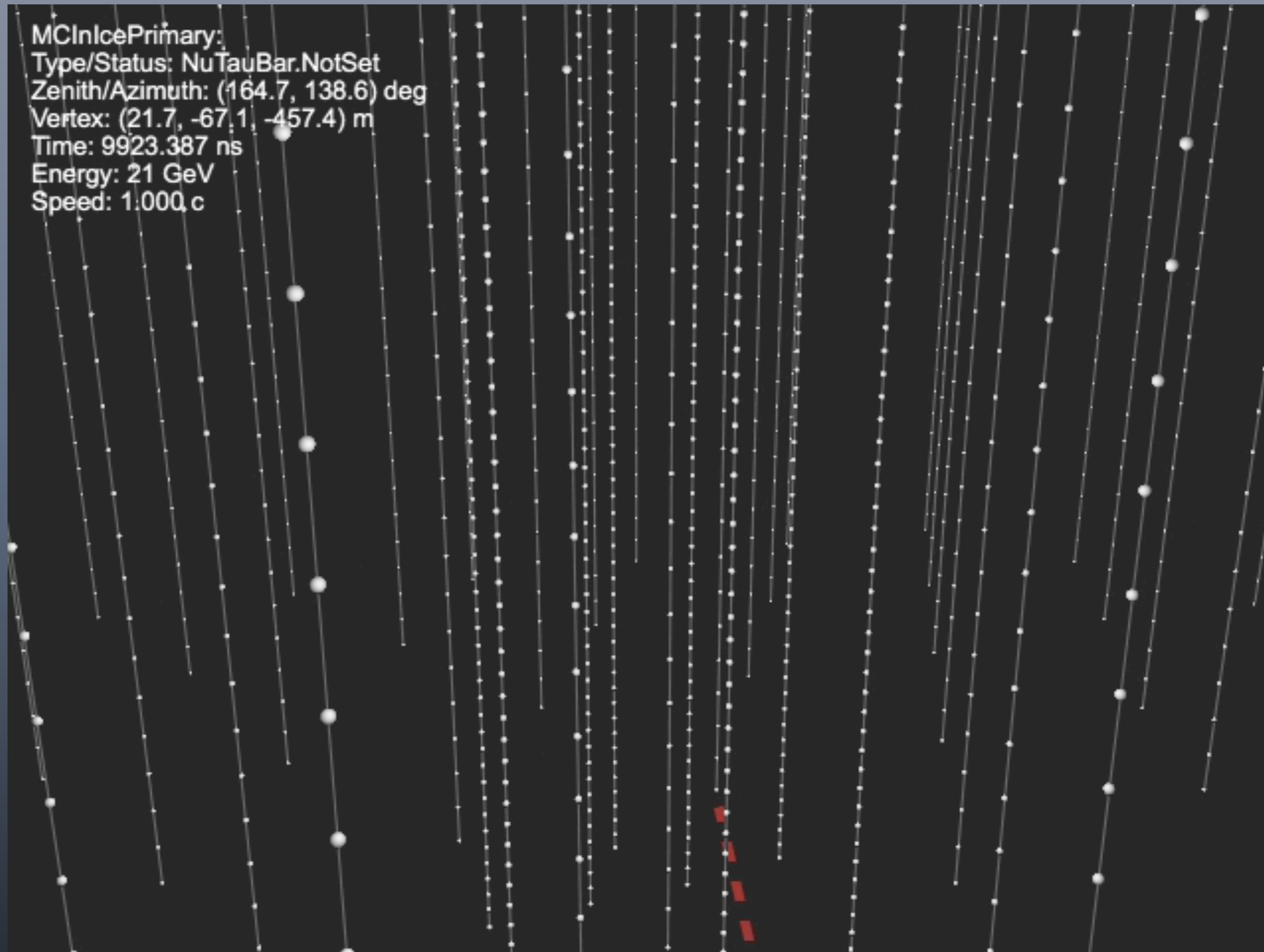
IceCube Upgrade Events

More detail in every event

DeepCore

21 GeV ν_τ interaction

Upgrade



+ factor 2-4 increase in rates over DeepCore (depending on energy/interaction type)

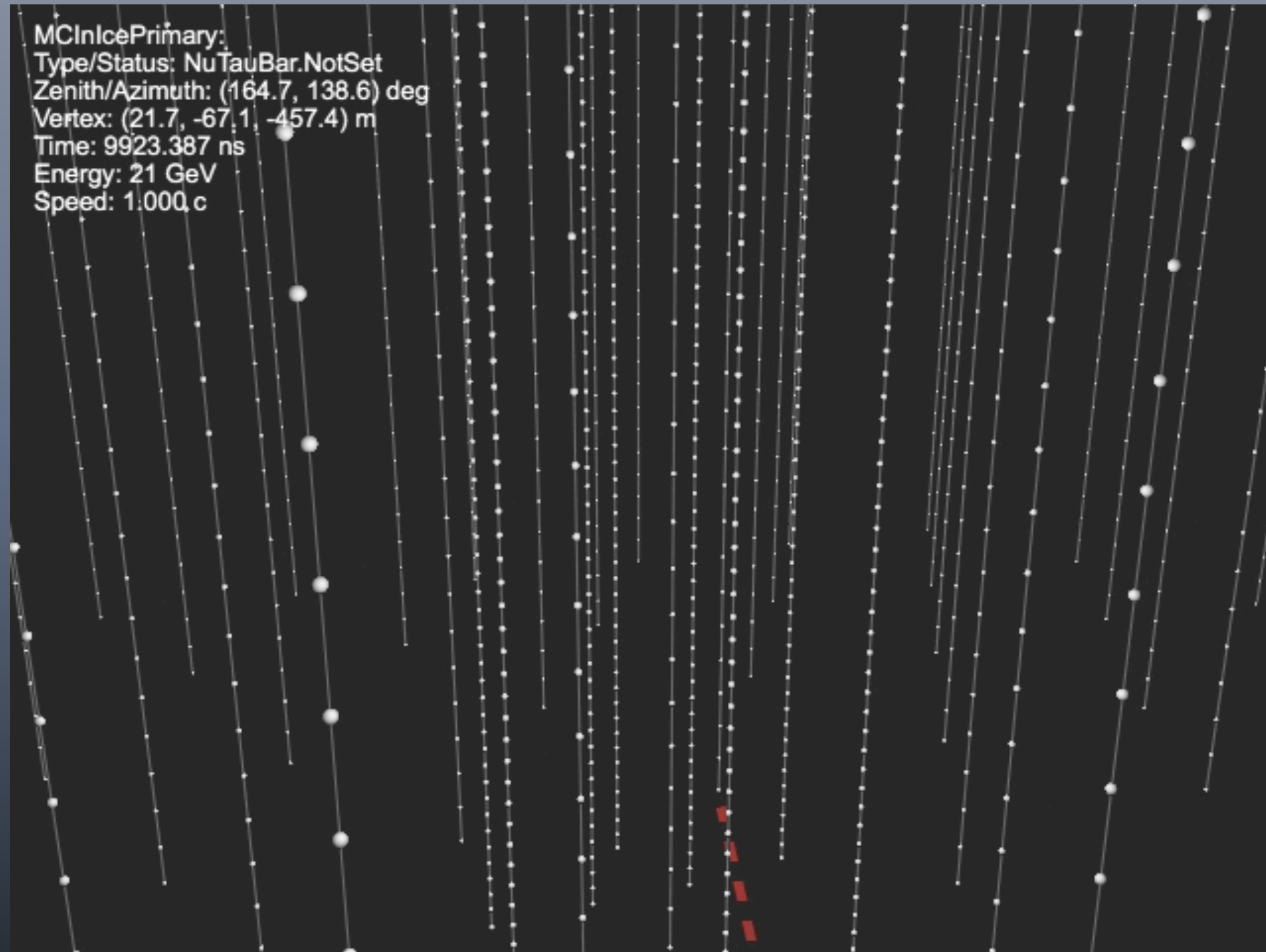
IceCube Upgrade Events

More detail in every event

DeepCore

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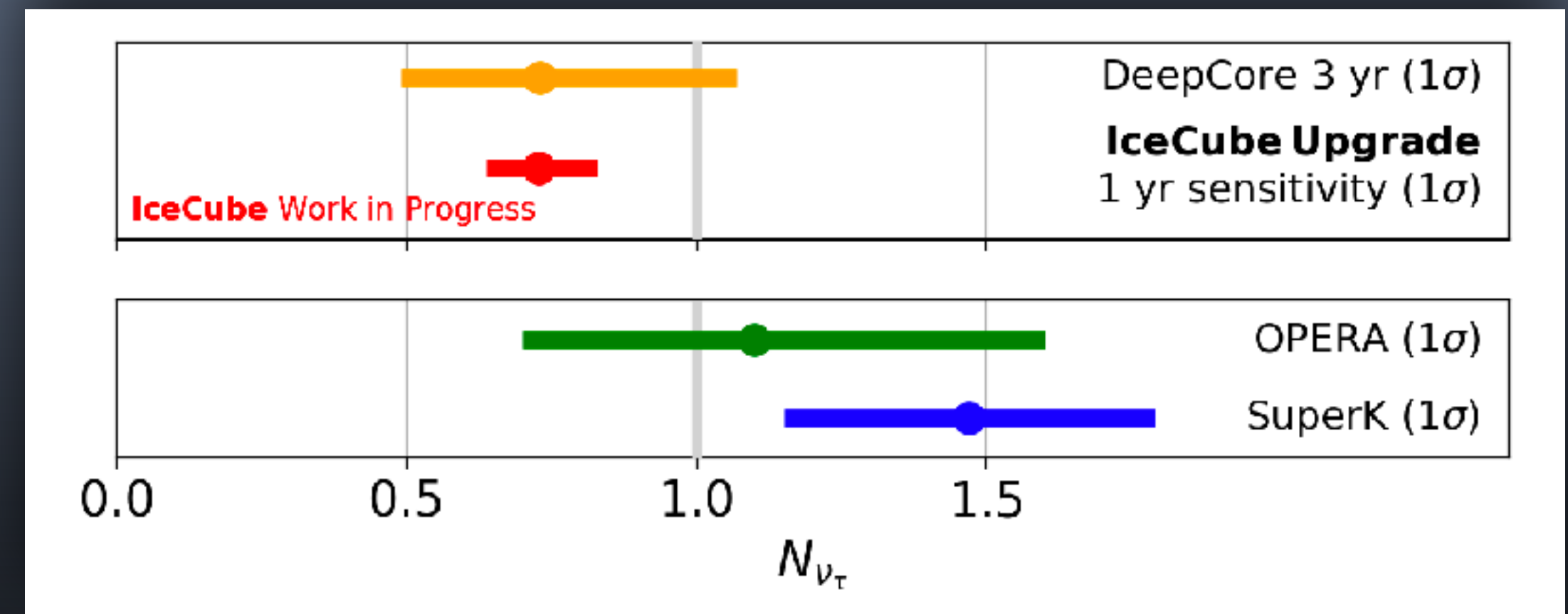
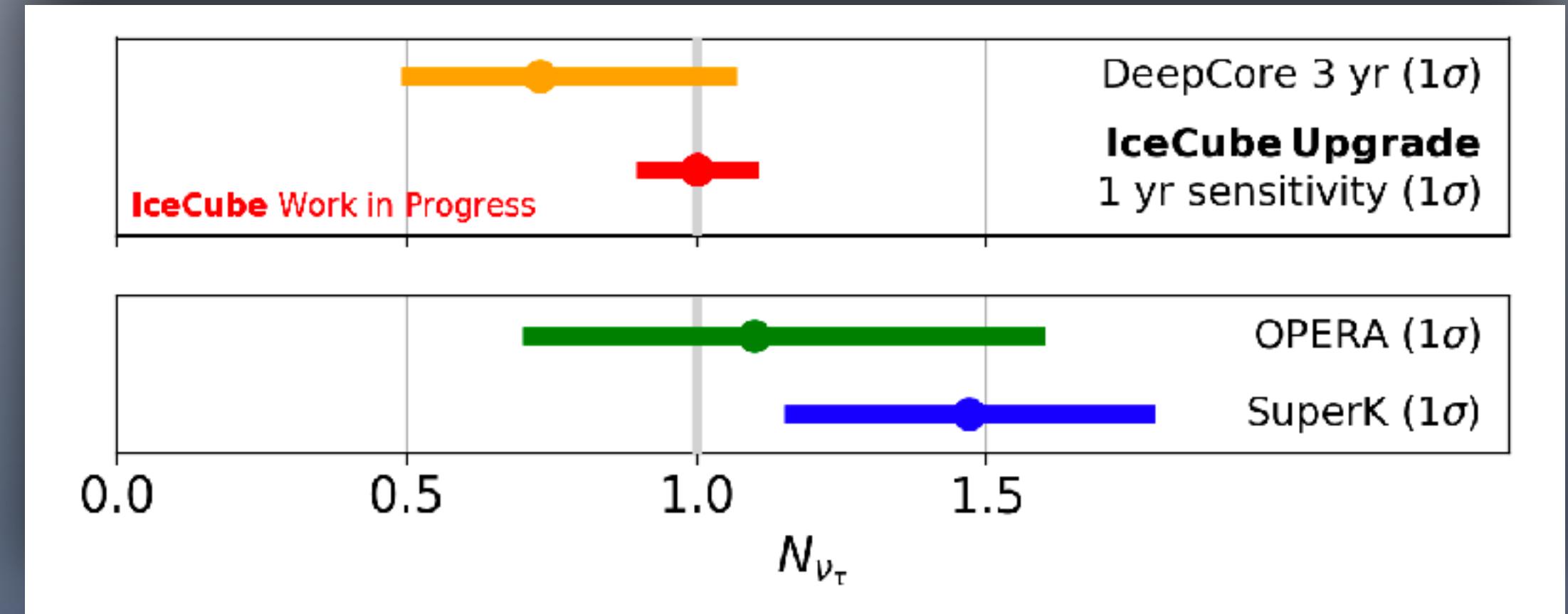
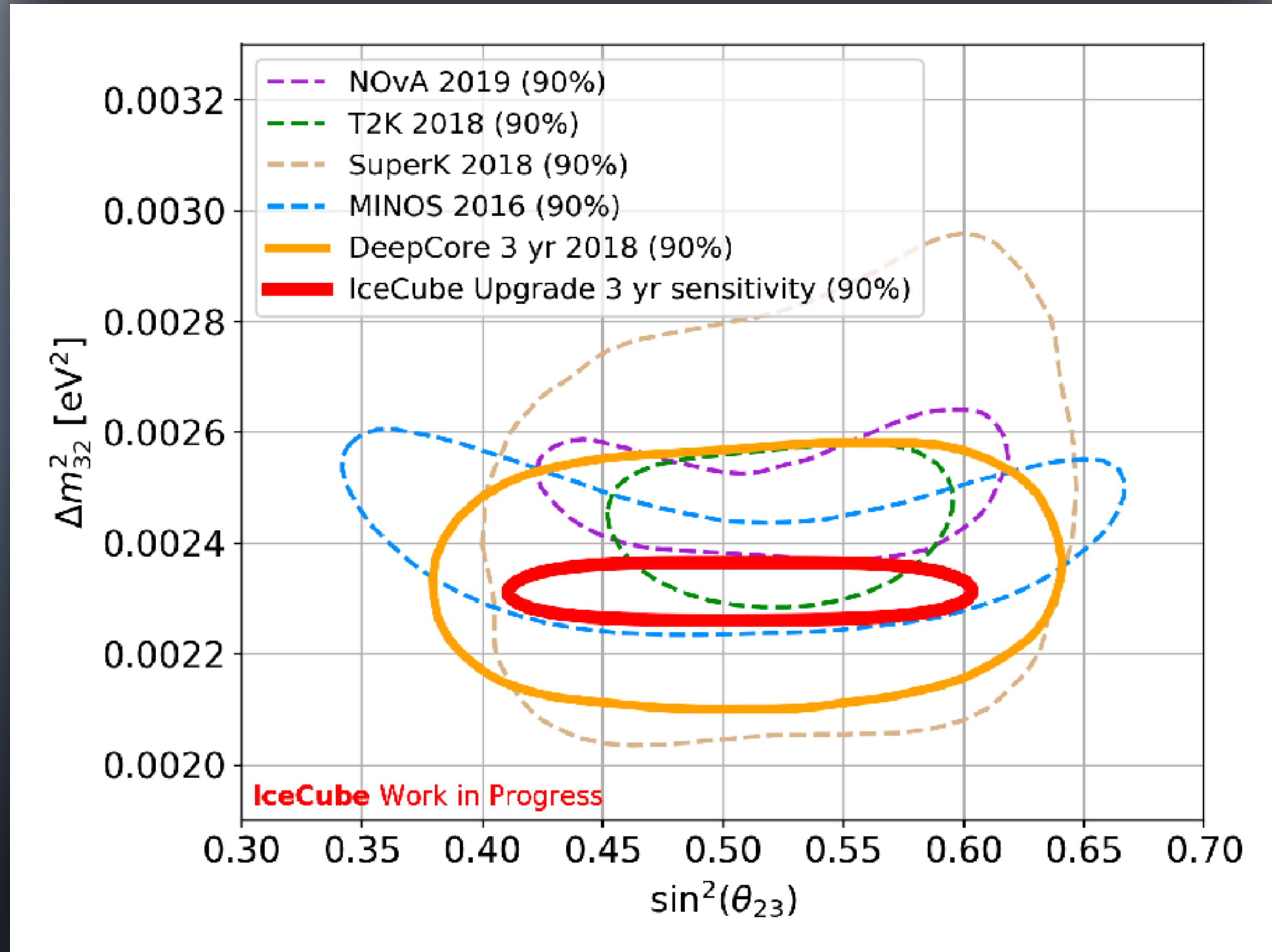
Upgrade



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IceCube Upgrade Potential

Precision measurements of standard oscillations



Similar improvements expected in Beyond νSM searches

IceCube Upgrade

Opportunities for improved detector calibrations

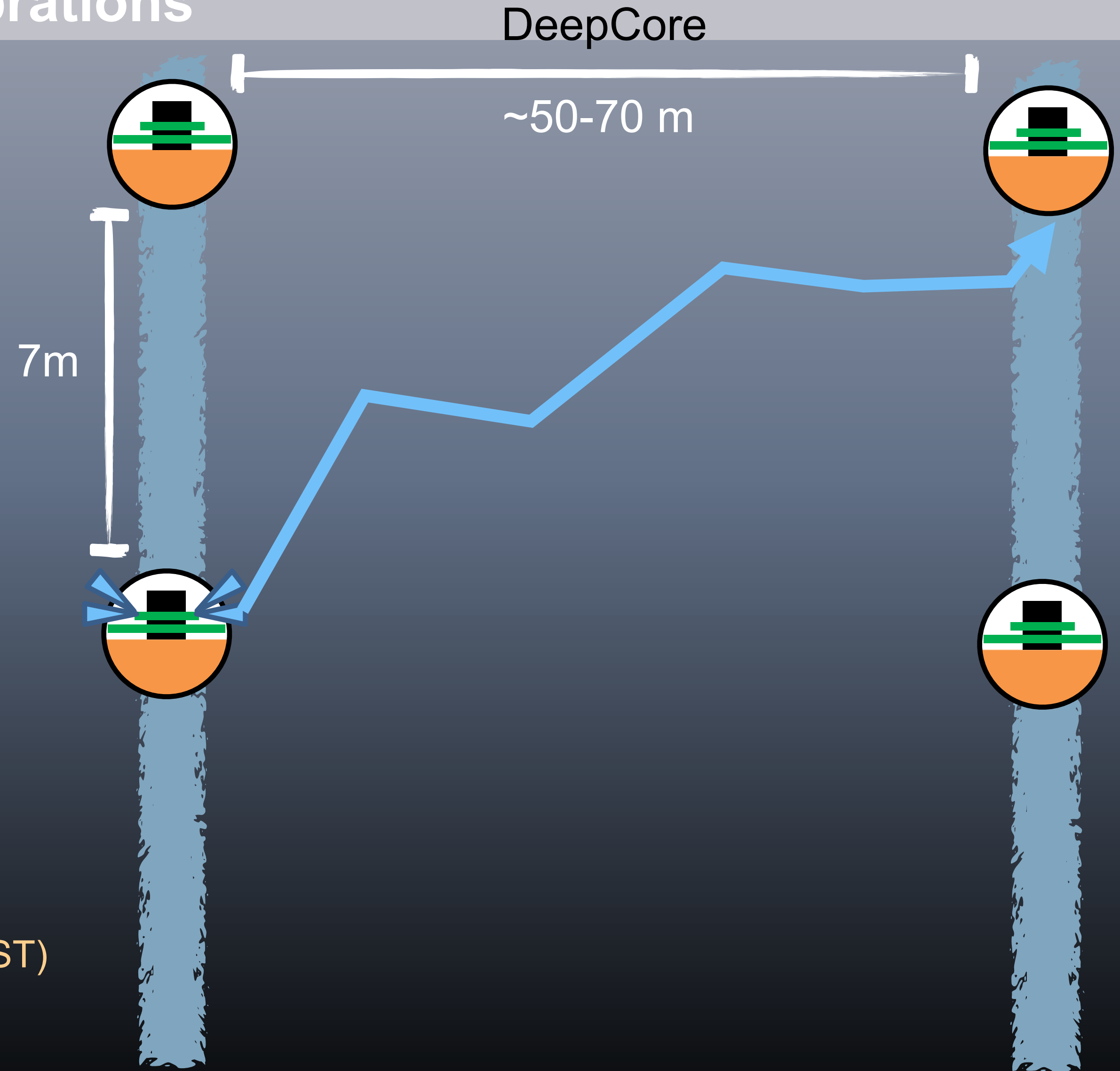
New calibration devices at shorter distances

- Multi-wavelength
- Both isotropic and (rotating) beamed emission profiles
- Self-monitoring light sources
- Large dynamic range

Impact on science

- Reduced detector-related uncertainties for *entire* detector, including archival data
- New opportunities for ice studies/glaciology

POCAM: <https://arxiv.org/pdf/2005.00778.pdf> (Accepted by JINST)
Cameras: <https://arxiv.org/pdf/1908.07734.pdf> (ICRC 2019)
Acoustic: <https://arxiv.org/pdf/1909.02047.pdf> (ICRC 2019)



IceCube Upgrade

Opportunities for improved detector calibrations

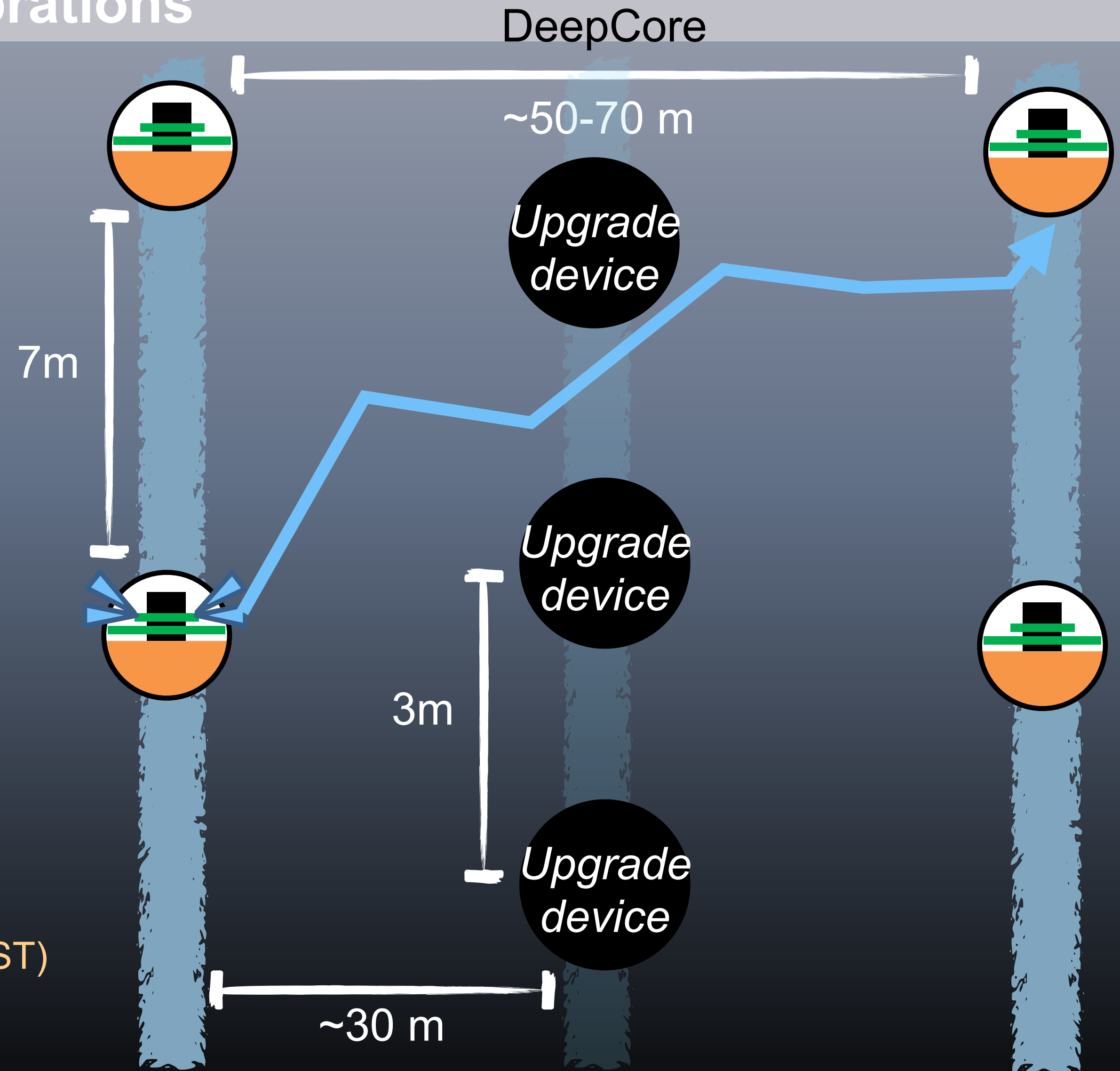
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IceCube Upgrade

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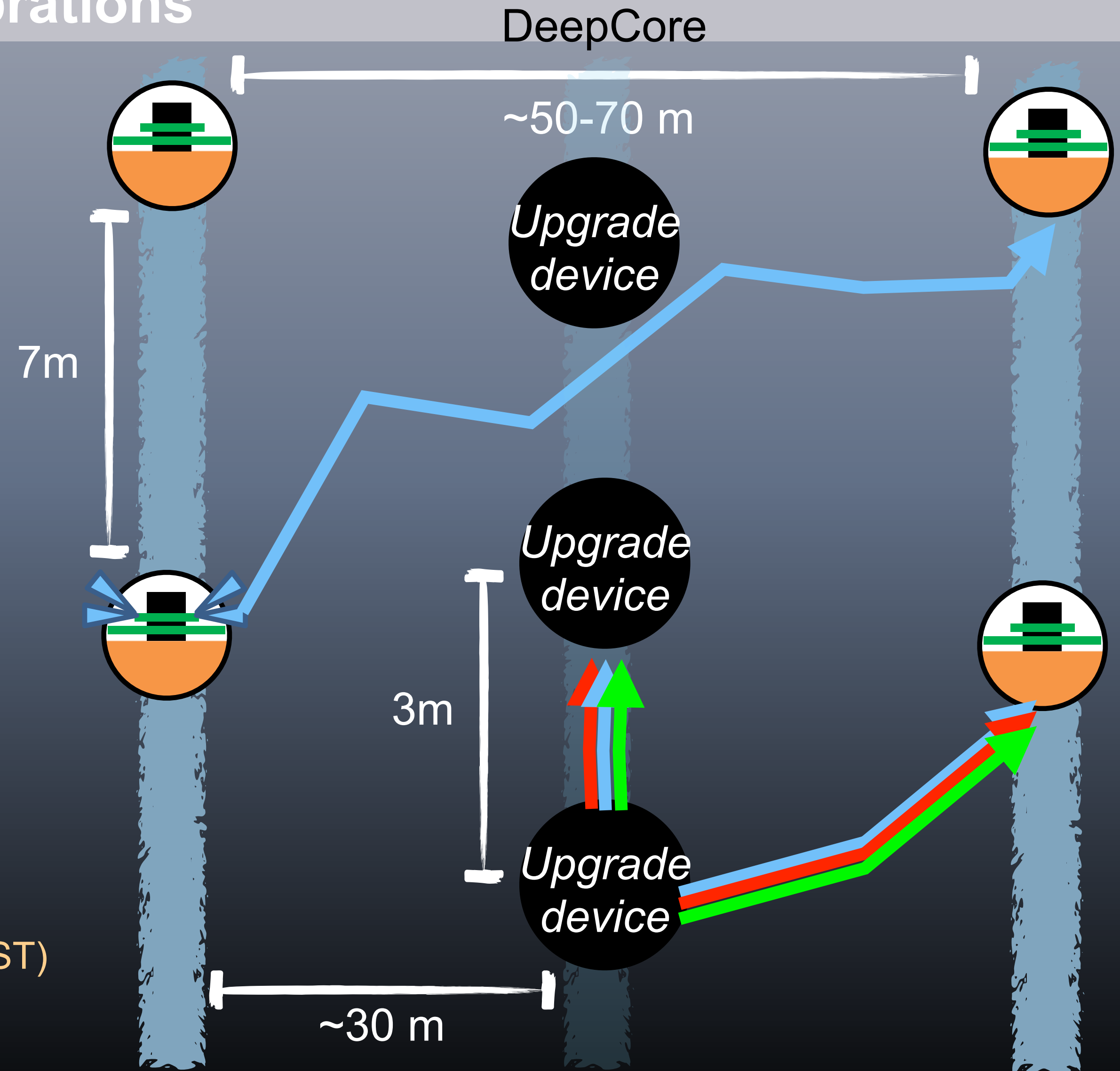
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Summary

IceCube DeepCore provides complementary measurements of standard atmospheric mixing parameters.

Higher energies and longer baselines provide unique sensitivity to New Physics and world-leading constraints.

New oscillation measurements from IceCube DeepCore with 8 y live time are coming soon.

IceCube Upgrade will enable more precise measurements of low energy neutrino properties, and better calibrations will benefit entire IceCube science program.



HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES



ICECUBE
UPGRADE

Thank you!

Want more? Checkout these posters!

Novel reconstruction tools

164. Application of Convolutional Neural Networks to Reconstruct GeV-Scale IceCube Neutrino Events

Jessica Micallef (Michigan State University)

Poster session 4

157. Deep Learning Classifier for Low-Energy Events in IceCube

Maria Prado Rodriguez (University of Wisconsin-Madison)

Poster Session 1

Interactions/cross section

203. Measuring neutrino cross-section with IceCube at intermediate energies (~100 GeV to a few TeV)

Sarah Nowicki (Michigan State University)

Poster session 4

171. Measurement of the Earth Density Profile with Atmospheric Muon Neutrinos Collected by IceCube

Kotoyo Hoshina (University of Wisconsin Madison)

Poster Session 1

Standard Oscillations

547. Atmospheric Neutrino Oscillations in IceCube DeepCore

Kayla Leonard (University of Wisconsin - Madison)

Poster session 4

167. Tau Neutrino Appearance with 8 years of IceCube Neutrino Data

Mr Étienne Bourbeau (NBI)

Poster session 3

Beyond Standard Oscillations

320. Searching for neutrino decoherence from quantum gravitational space-time fluctuations with IceCube.

Dr Tom Stuttard (Niels Bohr Institute, IceCube)

Poster session 3

364. Non-standard neutrino interaction search with IceCube DeepCore

Mrs Elisa Lohfink (Johannes Gutenberg-Universität, Mainz)

Poster Session 2

177. Search for Light Sterile Neutrinos With Eight Years of IceCube Data

Dr Carlos Argüelles (MIT)

Poster Session 2

529. Light Unstable Sterile Neutrino Search in IceCube

Marjon Moulai (Massachusetts Institute of Technology)

Poster Session 2



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RESEARCH FOR
GRAND CHALLENGES



ICECUBE
UPGRADE

Backup

Neutrino oscillations

The experimental landscape

DeepCore measures oscillations at higher energies and over longer baselines (with differing matter profile) than accelerator experiments

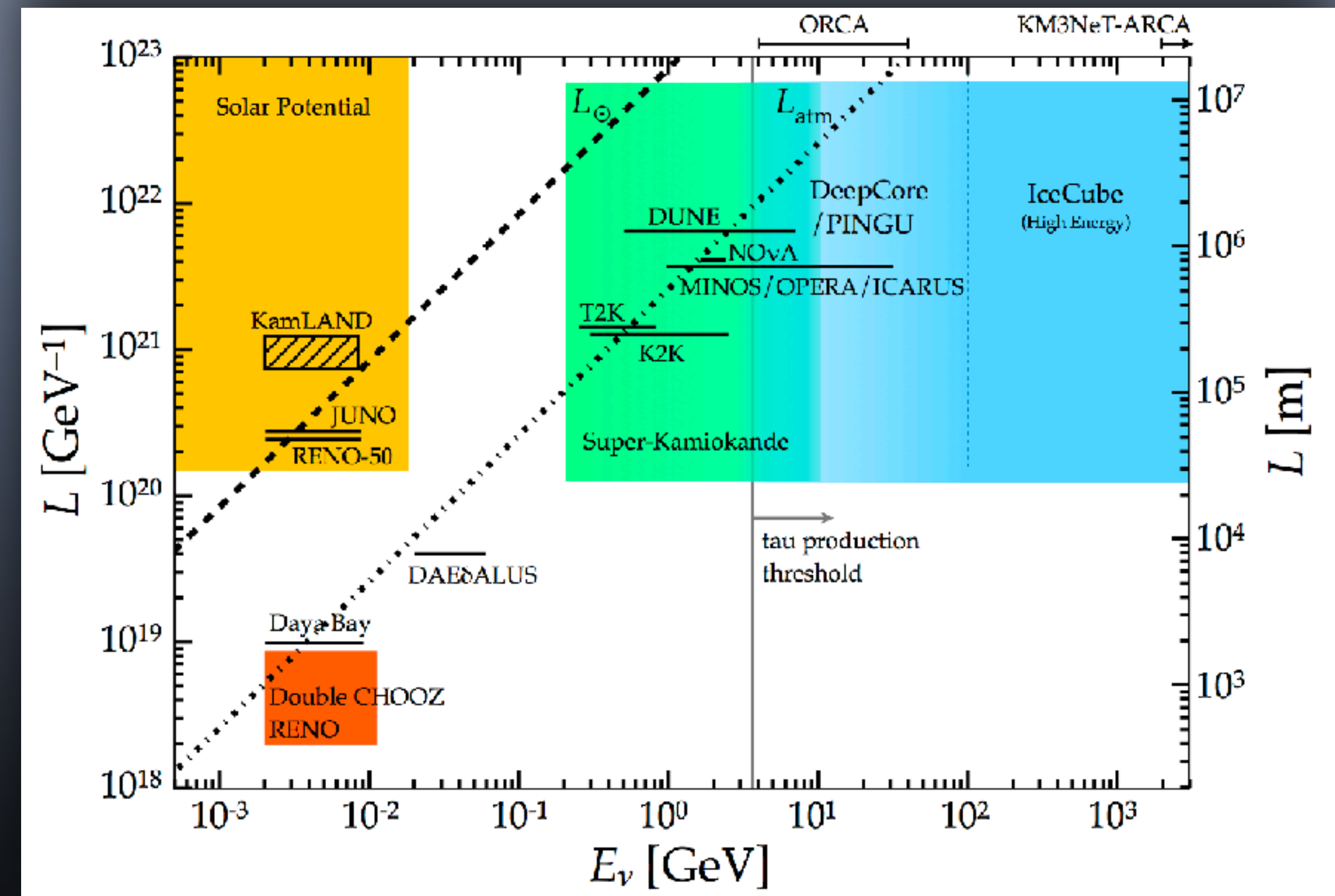
Well above the tau production threshold

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

DeepCore

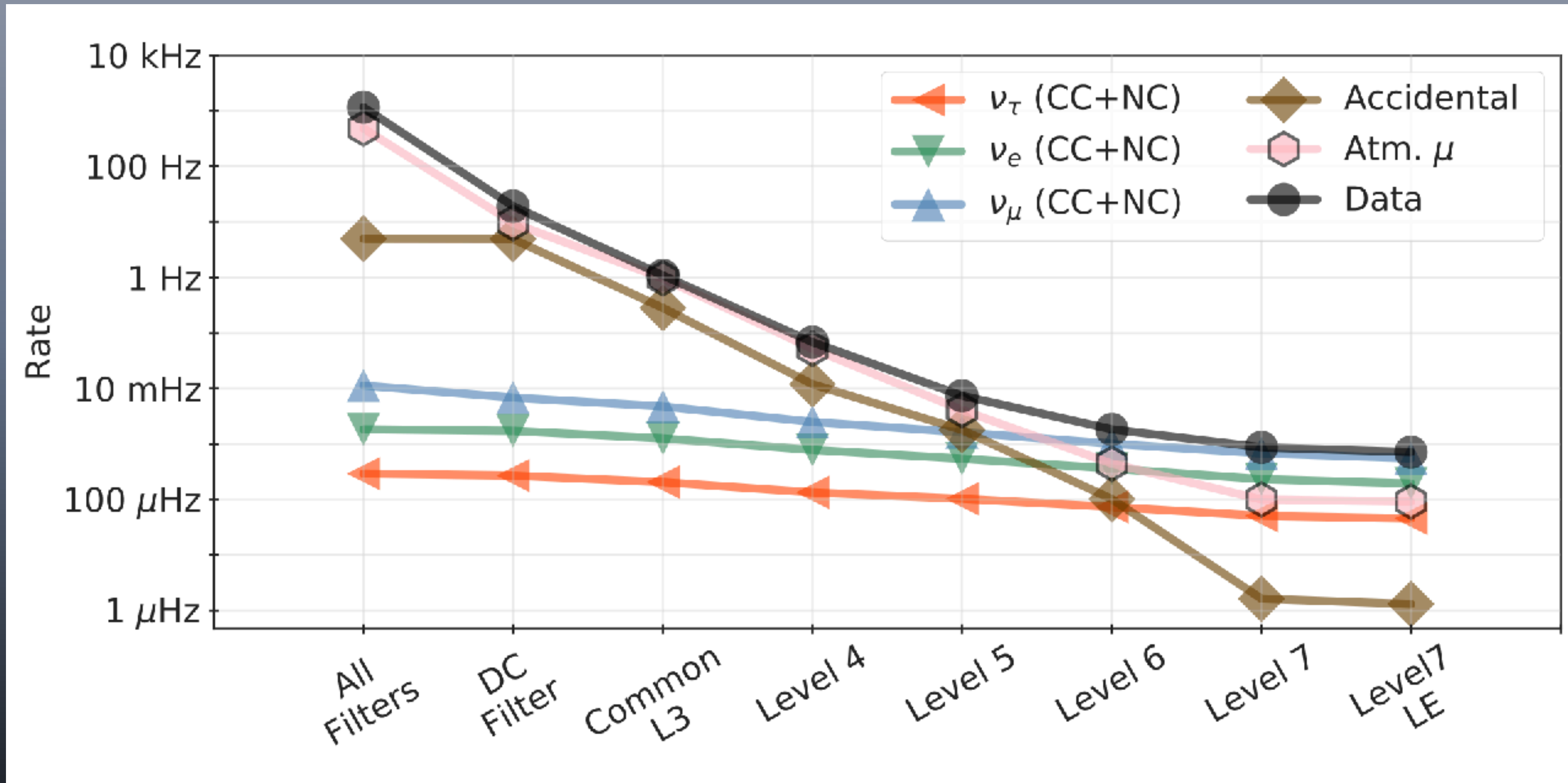
U_{PMNS} unitarity implies, e.g.:

$$|U_{e3}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2 = 1$$



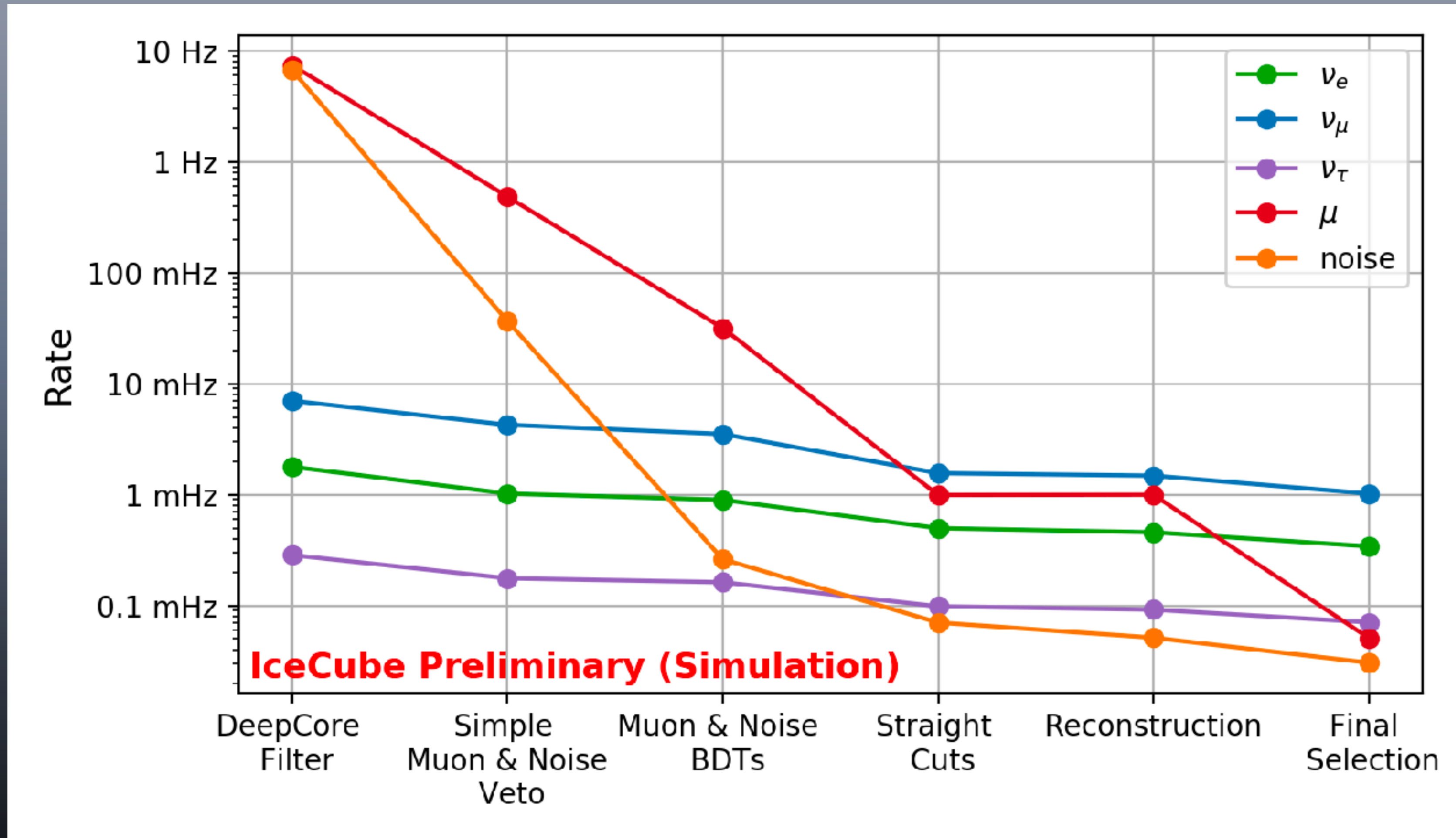
DeepCore 3 year sample

Event rates vs. Selection



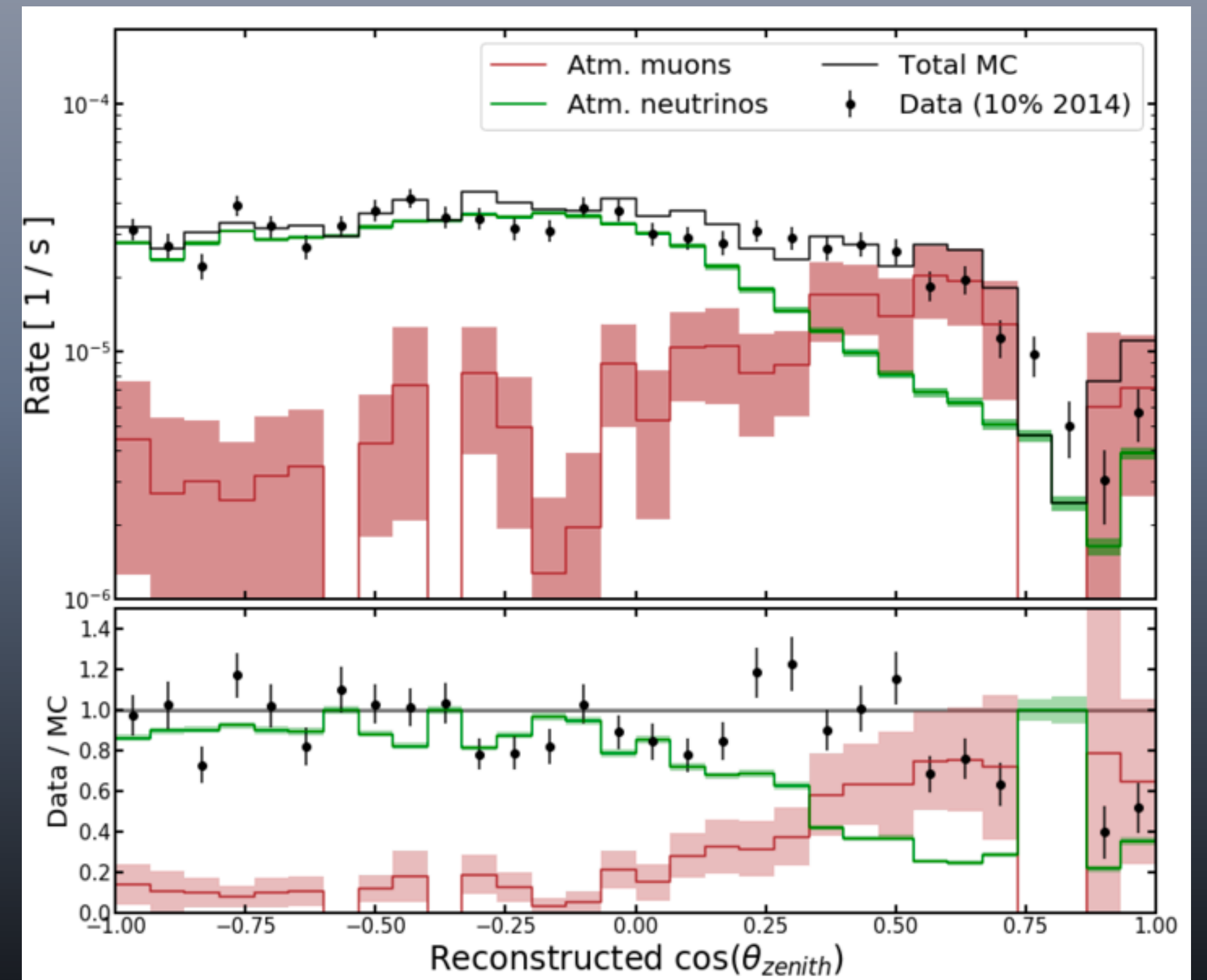
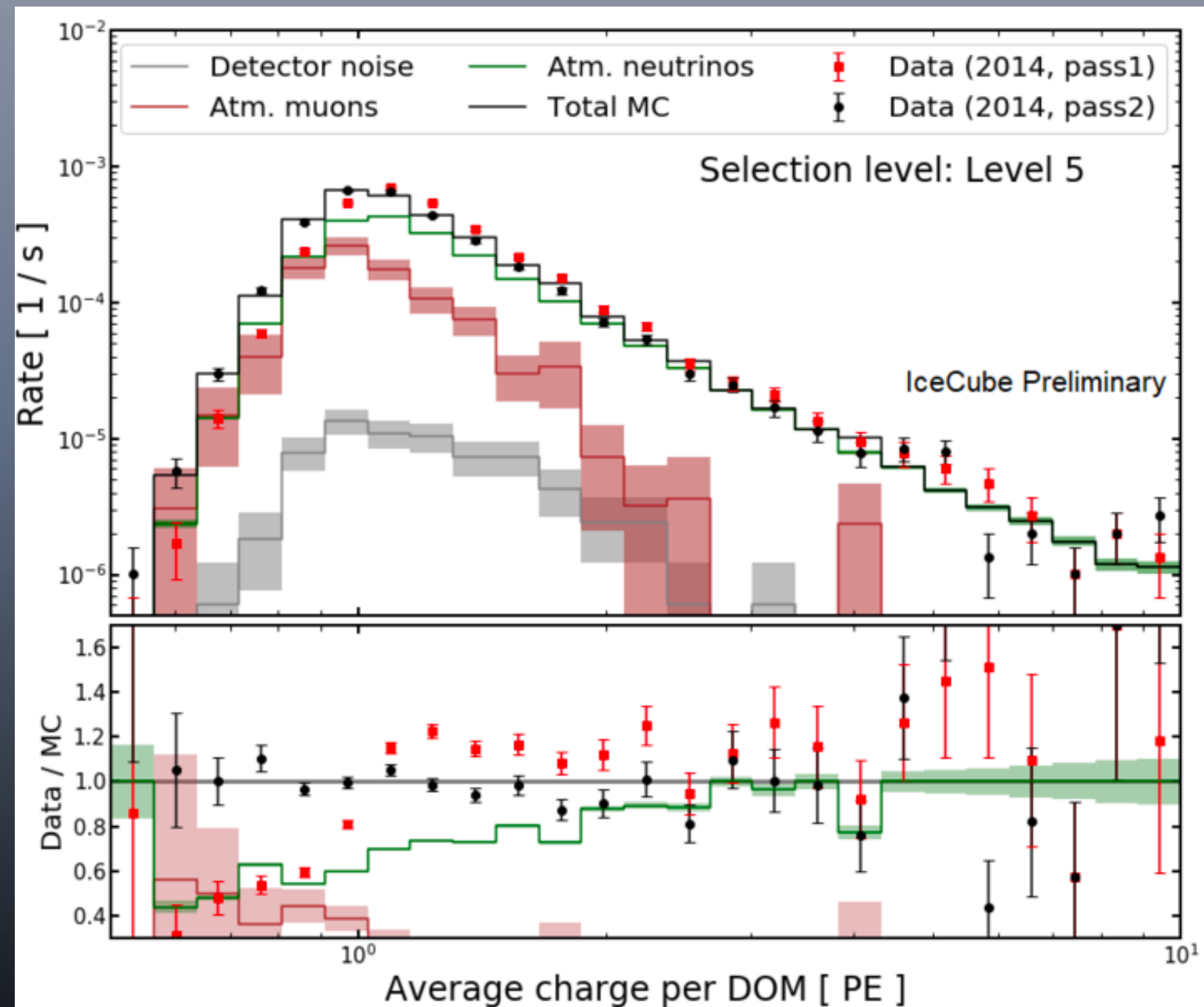
DeepCore 8 year sample

Revised event selection for better background rejection + higher signal efficiency



DeepCore 8 year sample

Data/MC Agreement



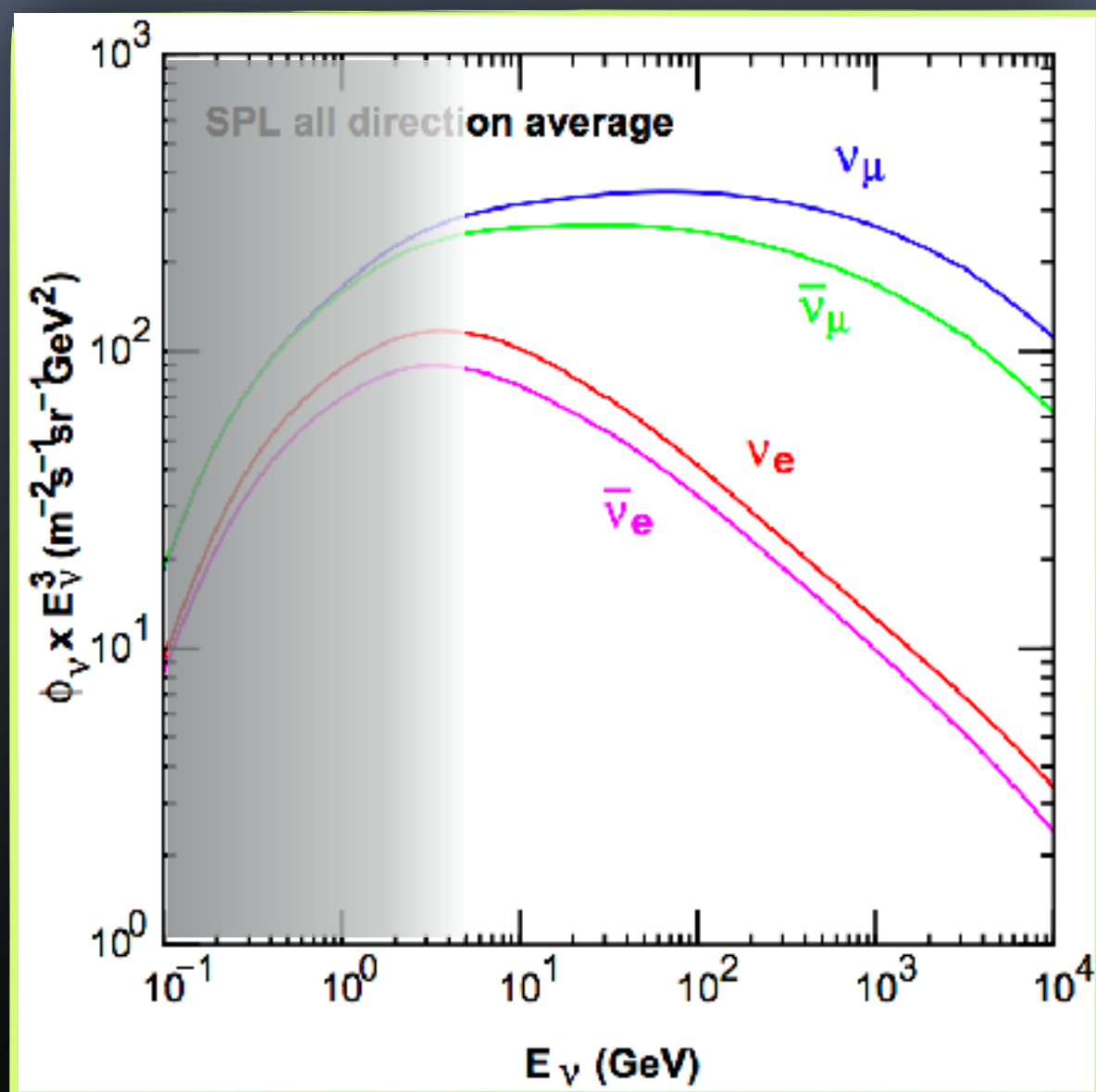
Analysis strategy

Pipeline overview

CR, hadron production/
interaction, atmosphere

Honda, et al
Phys. Rev. D 92, 023004 (2015)

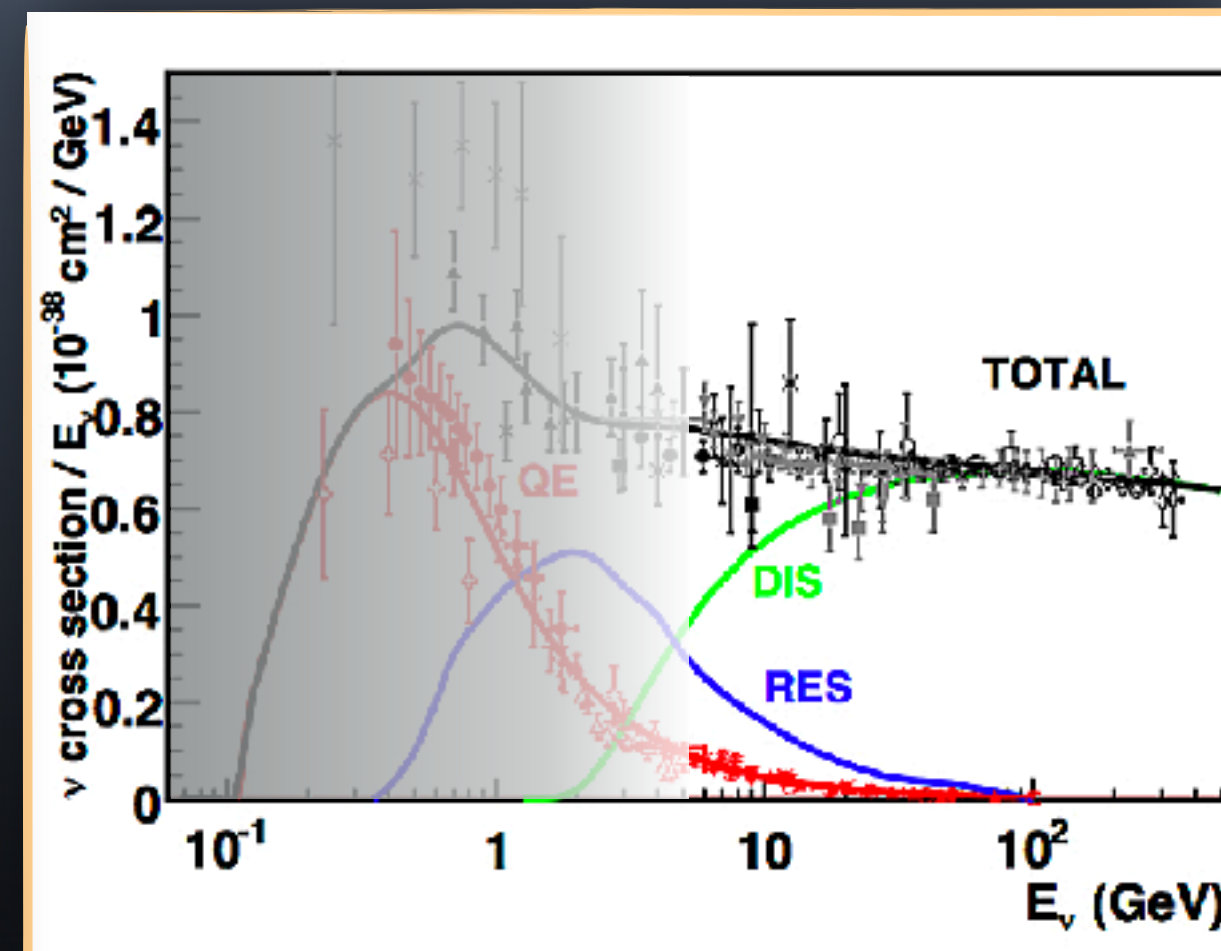
$\Phi_{\text{UNOSC.}}$



GENIE 2.8.6

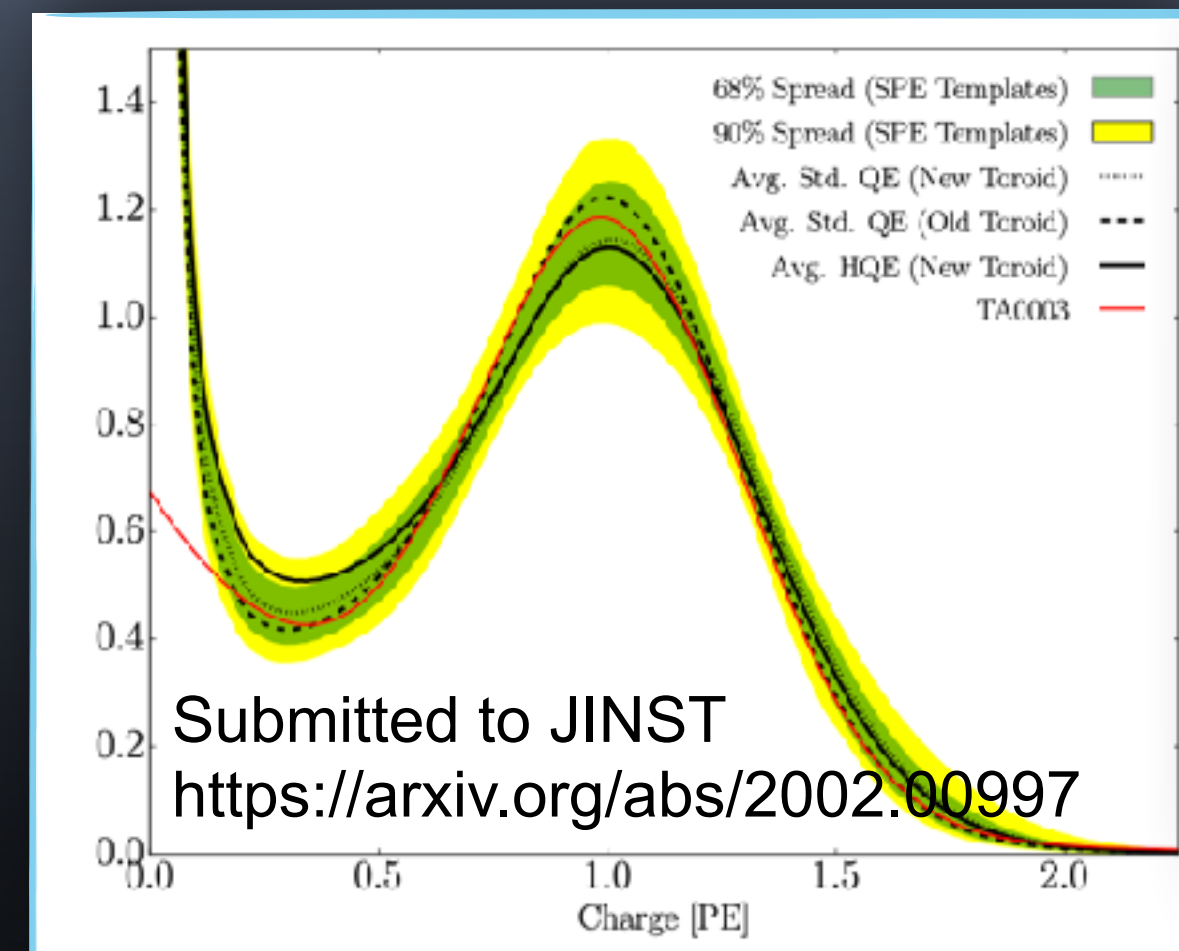
Hadronization with
KNO and PYTHIA,
GRV98 PDFs

Interaction



Photon propagation
DOM response
Trigger

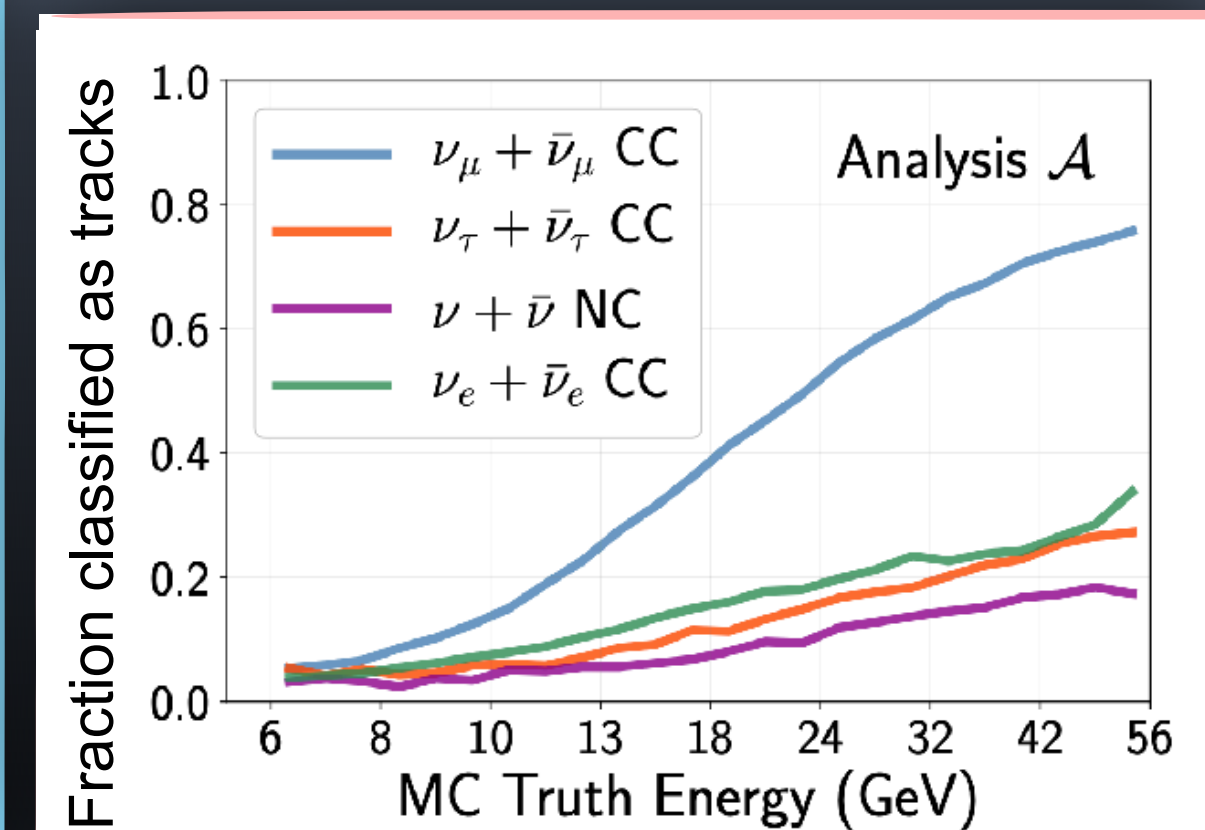
Detection



Remove atm. muons
and pure noise triggers

Energy, zenith, PID

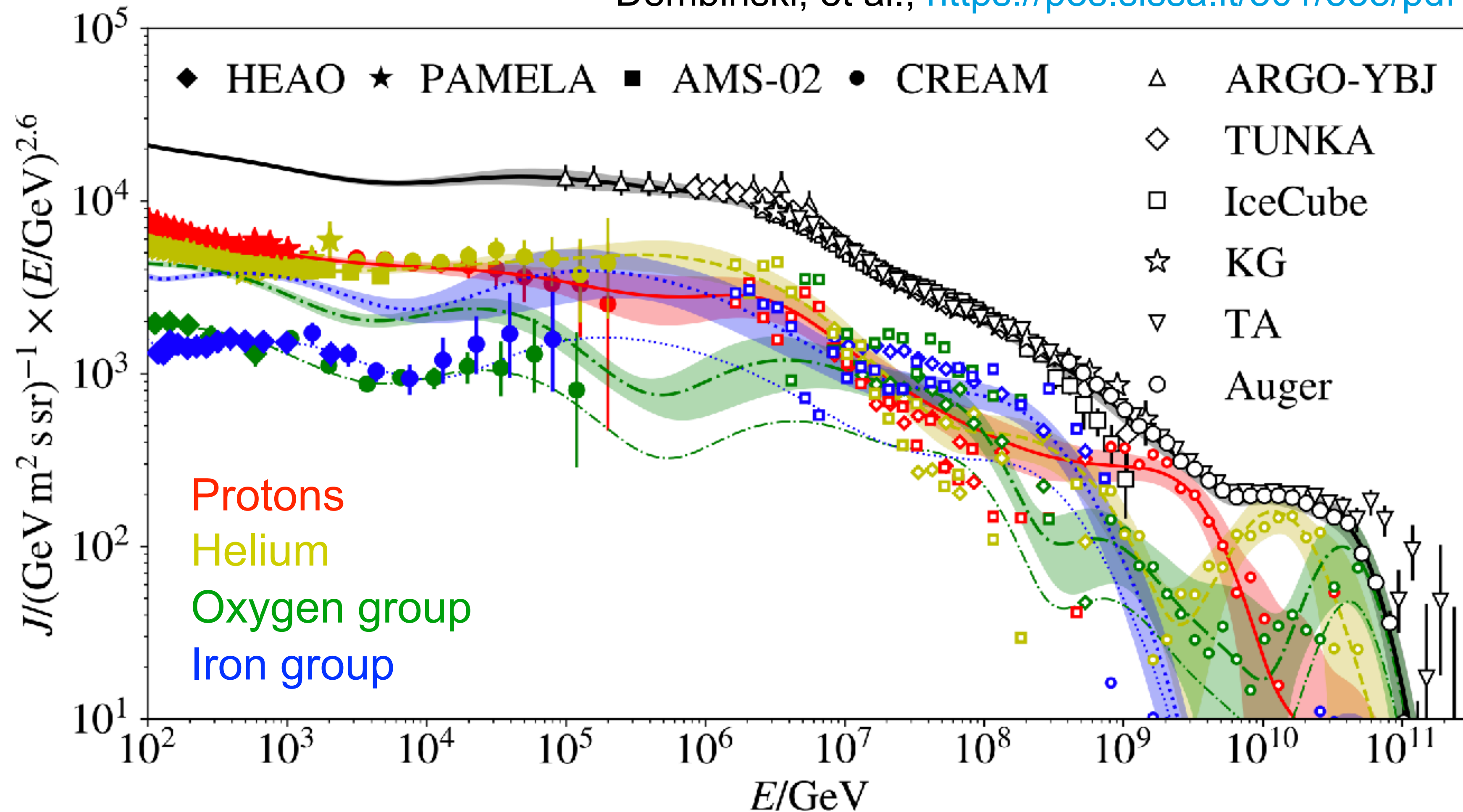
Filter/Reco



Primary cosmic ray model

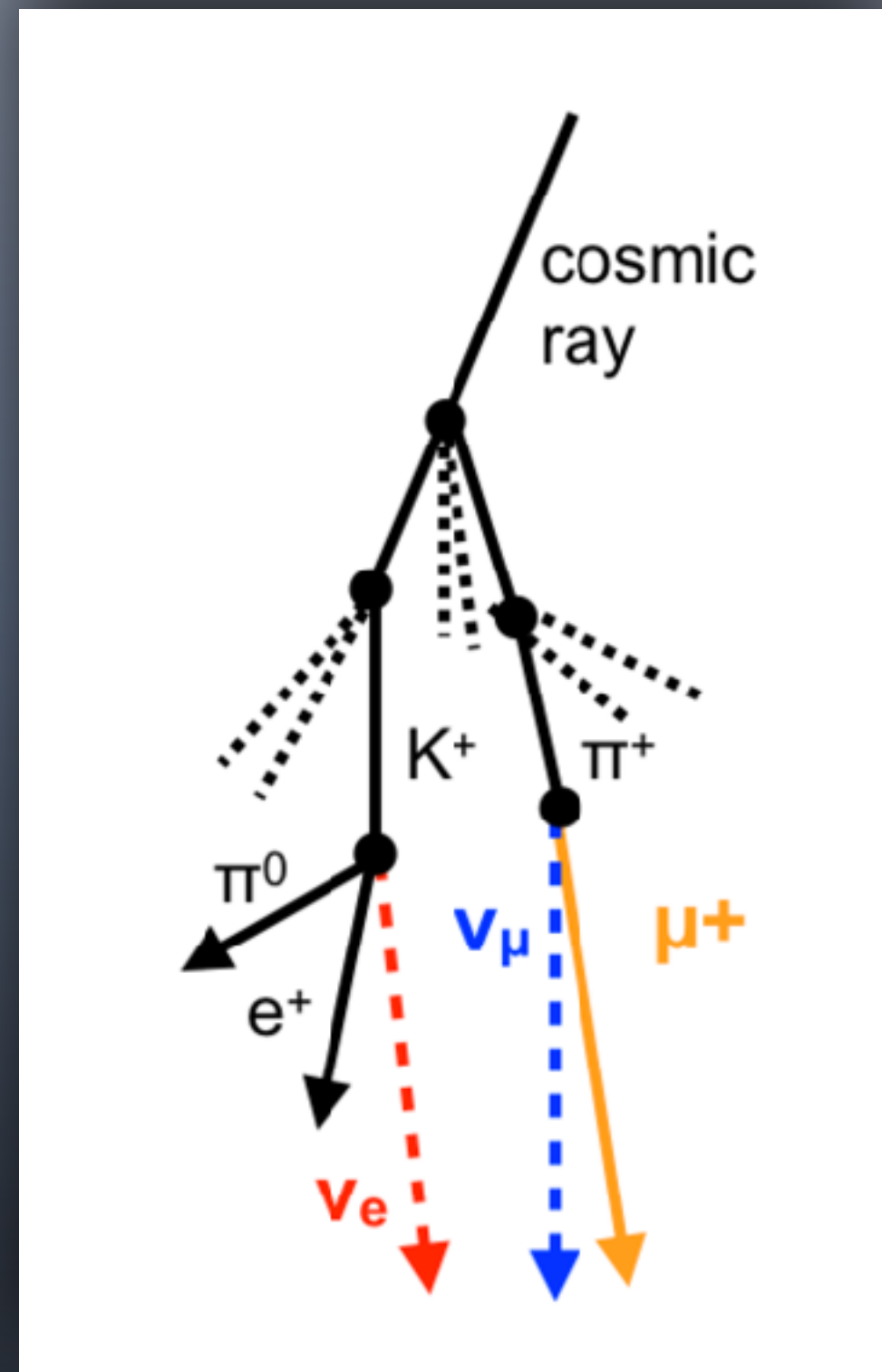
Spectrum and composition

Dembinski, et al., <https://pos.sissa.it/301/533/pdf>



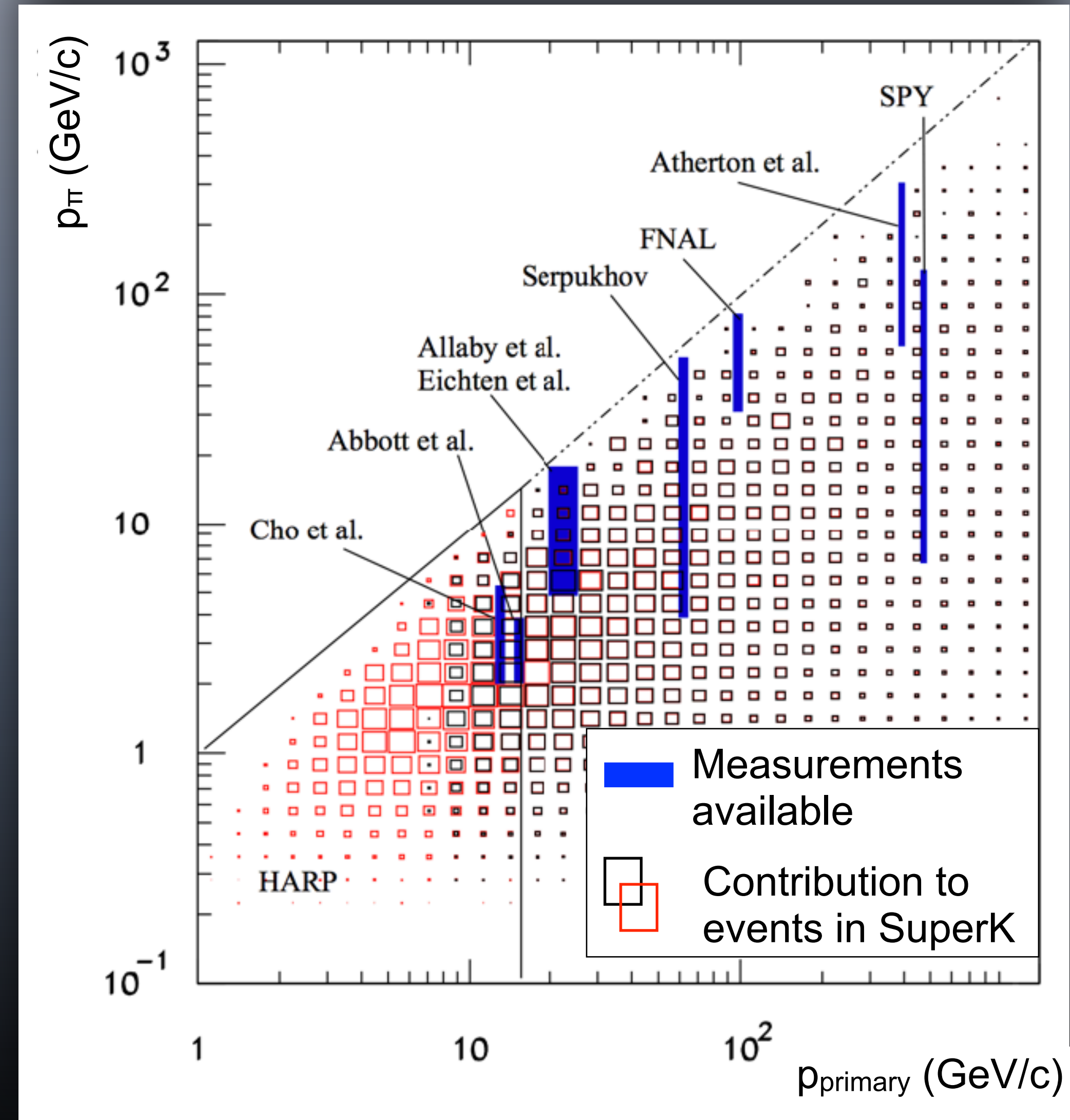
Flux uncertainties

Experimental coverage
of single π production yield

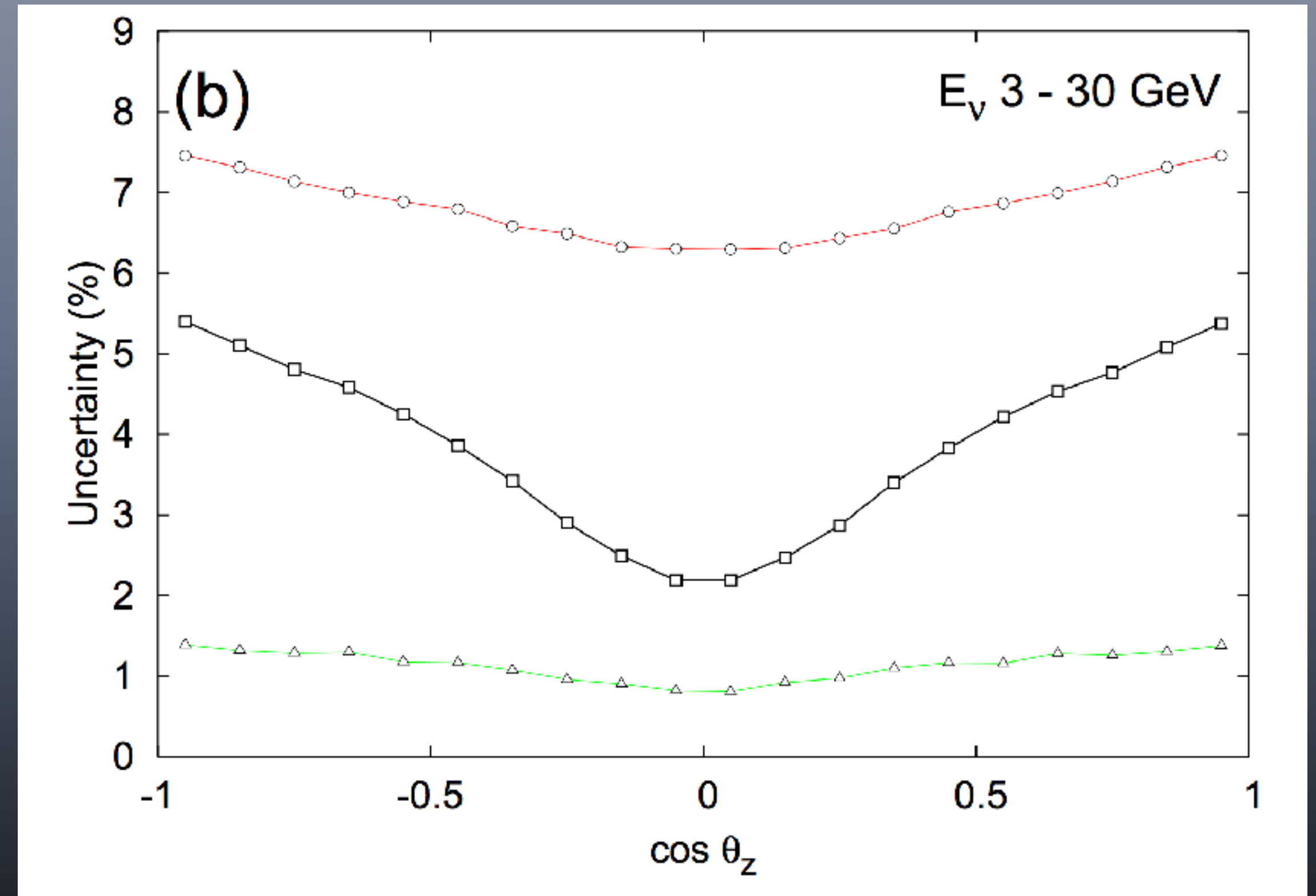
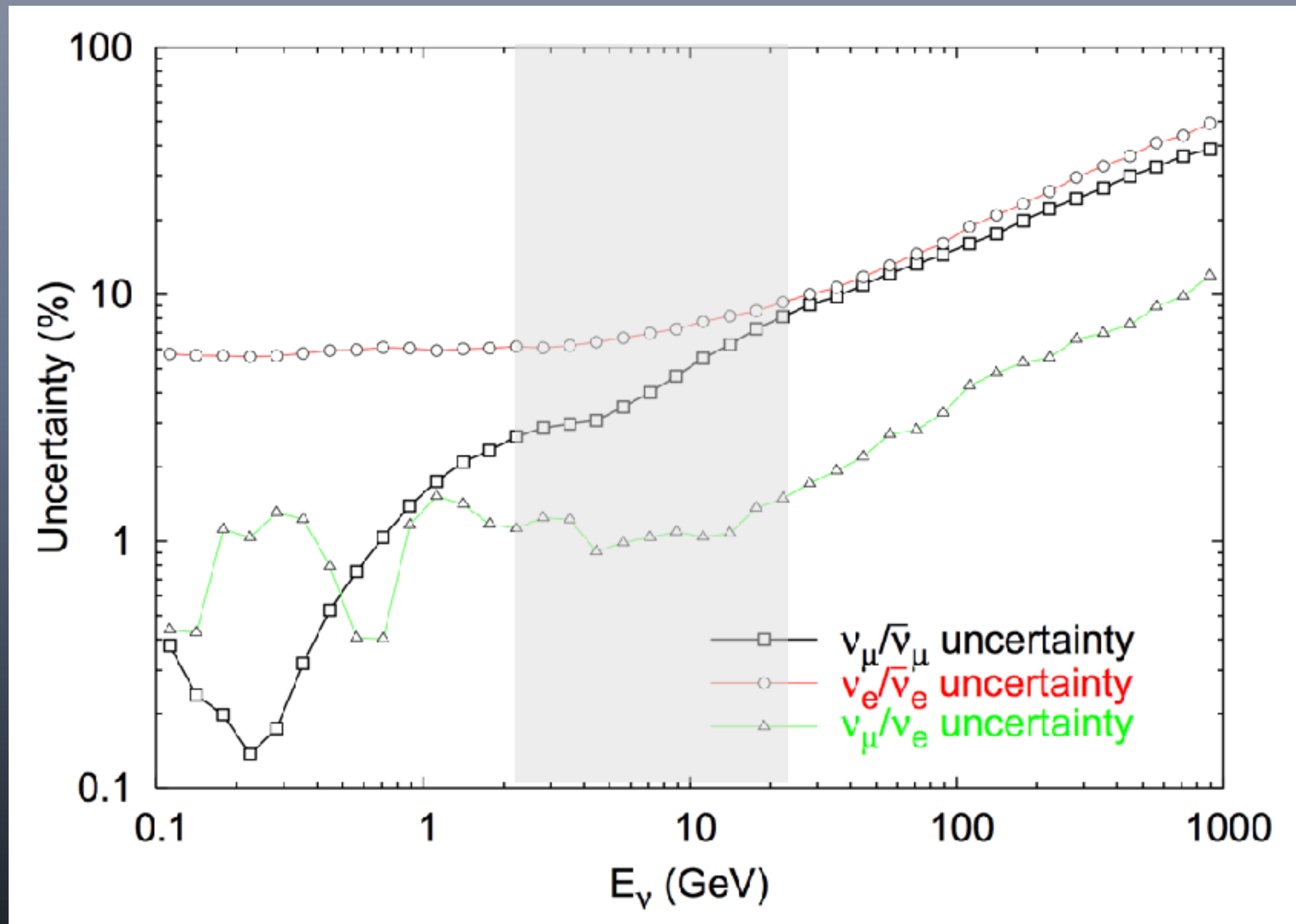


Production
uncertainty:
 $\pi^\pm \sim 10\text{-}30\%$
 $K^\pm \sim 10\text{-}40\%$

Barr et al. <https://arxiv.org/pdf/astro-ph/0611266.pdf>



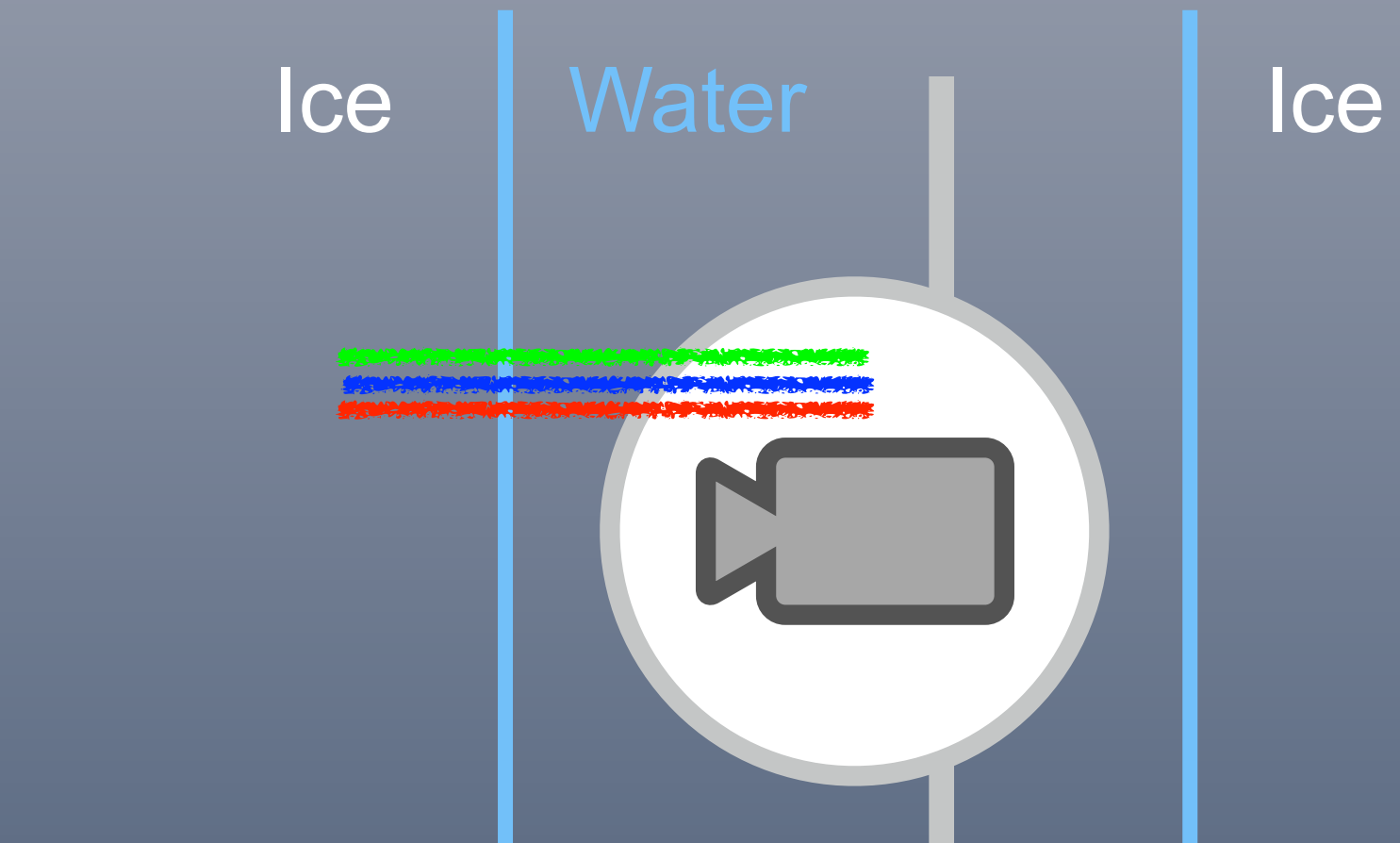
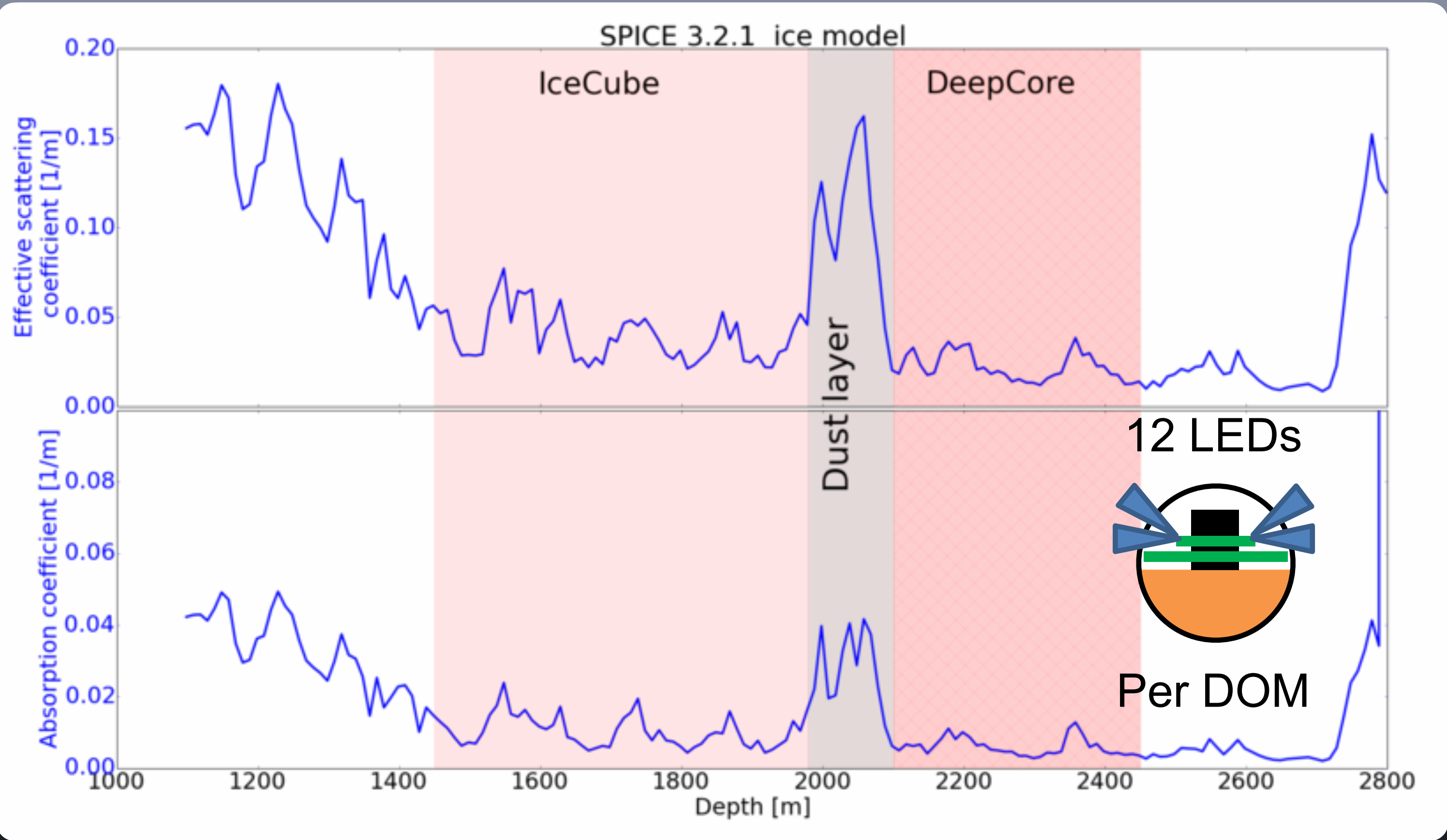
Flux uncertainties



Barr et al. <https://arxiv.org/pdf/astro-ph/0611266.pdf>

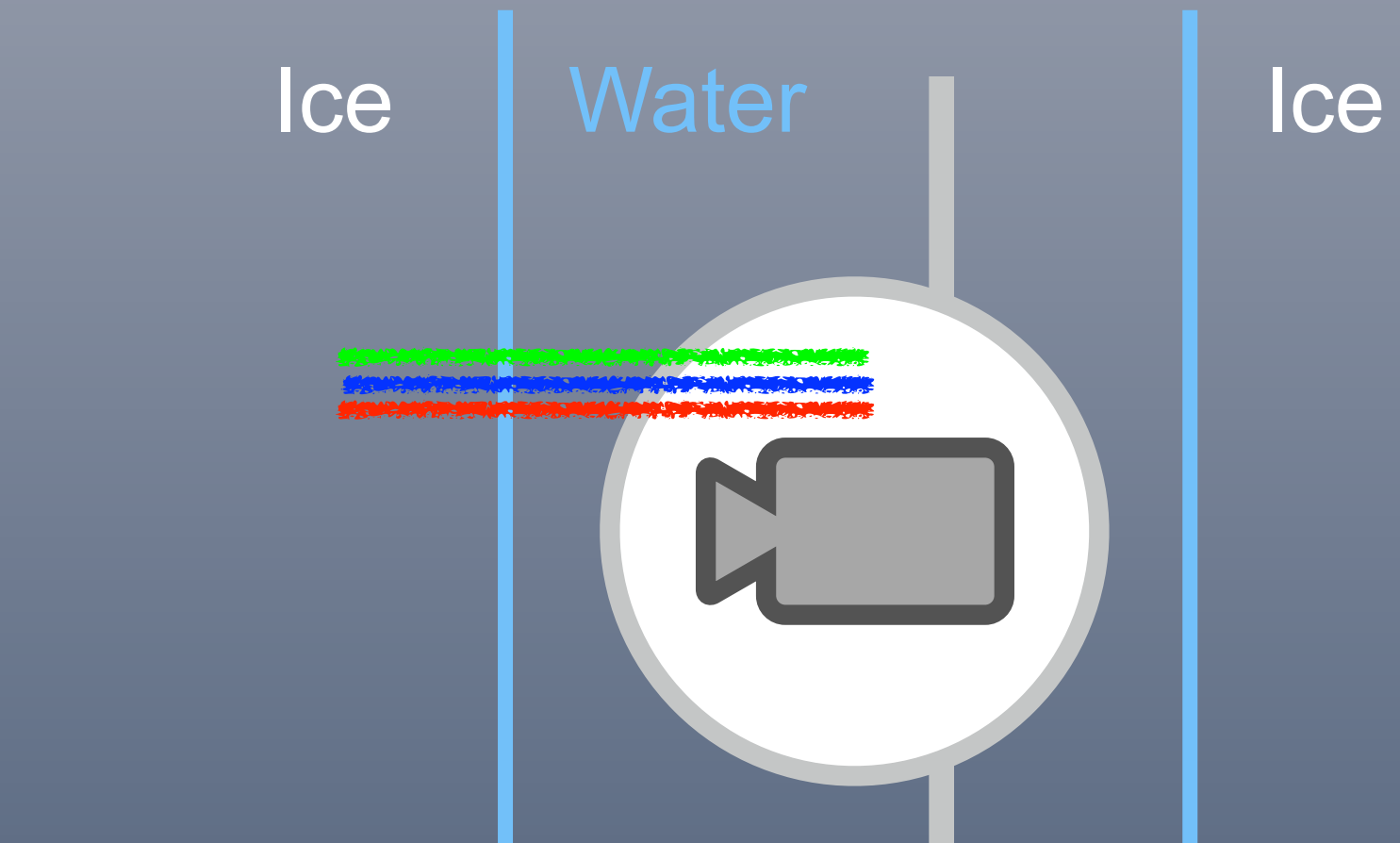
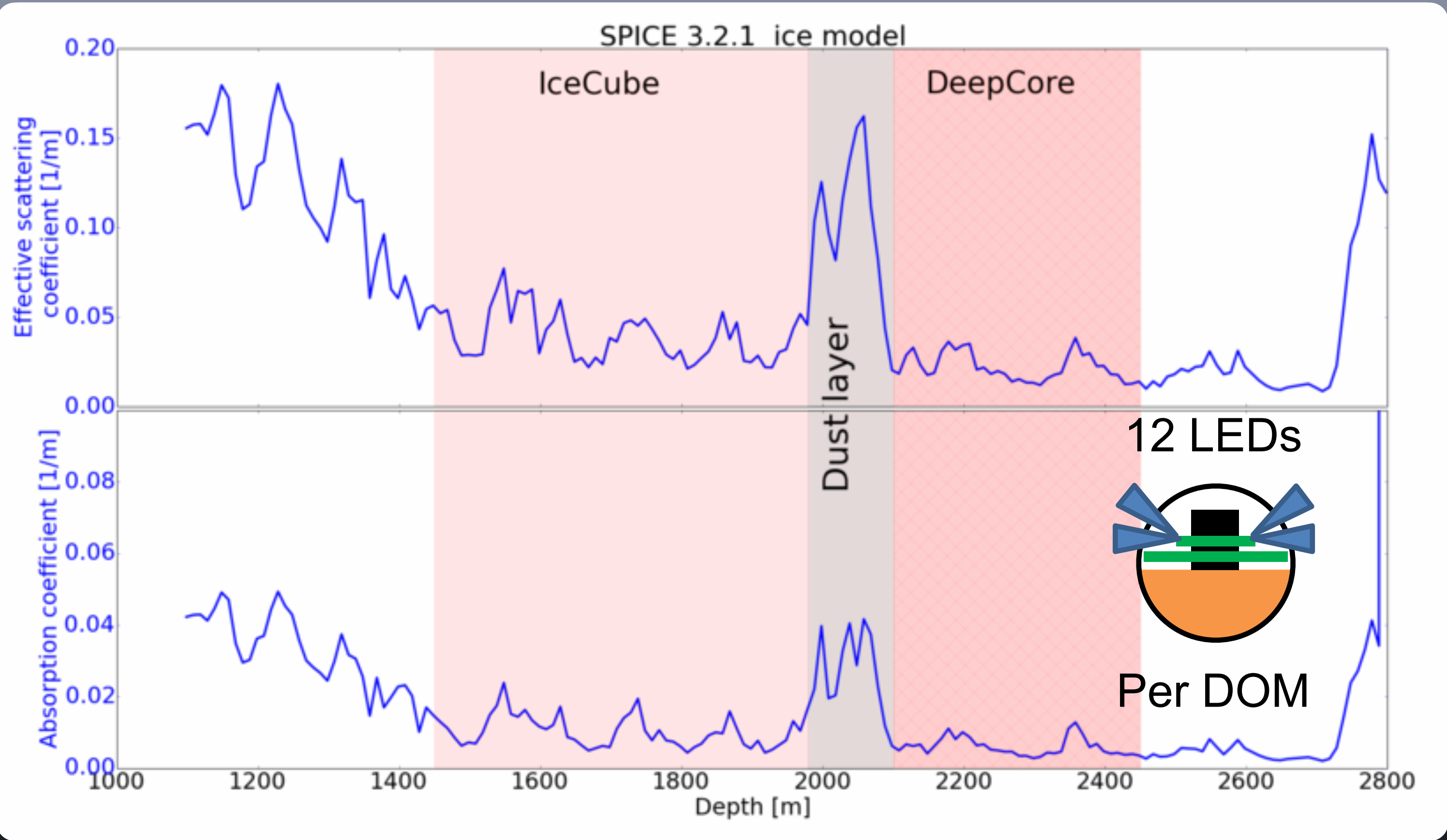
Photon propagation

Complex, natural detector medium

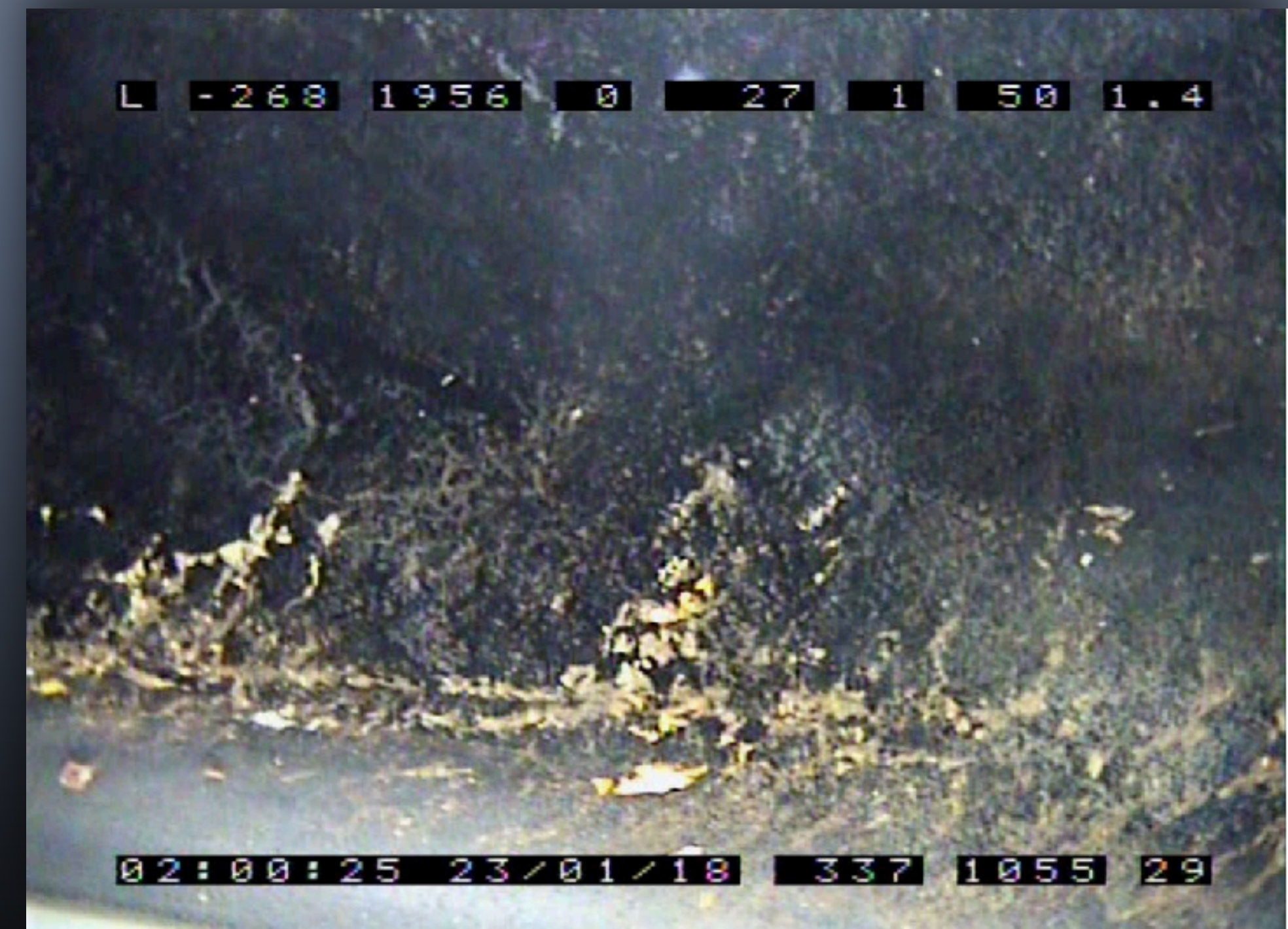
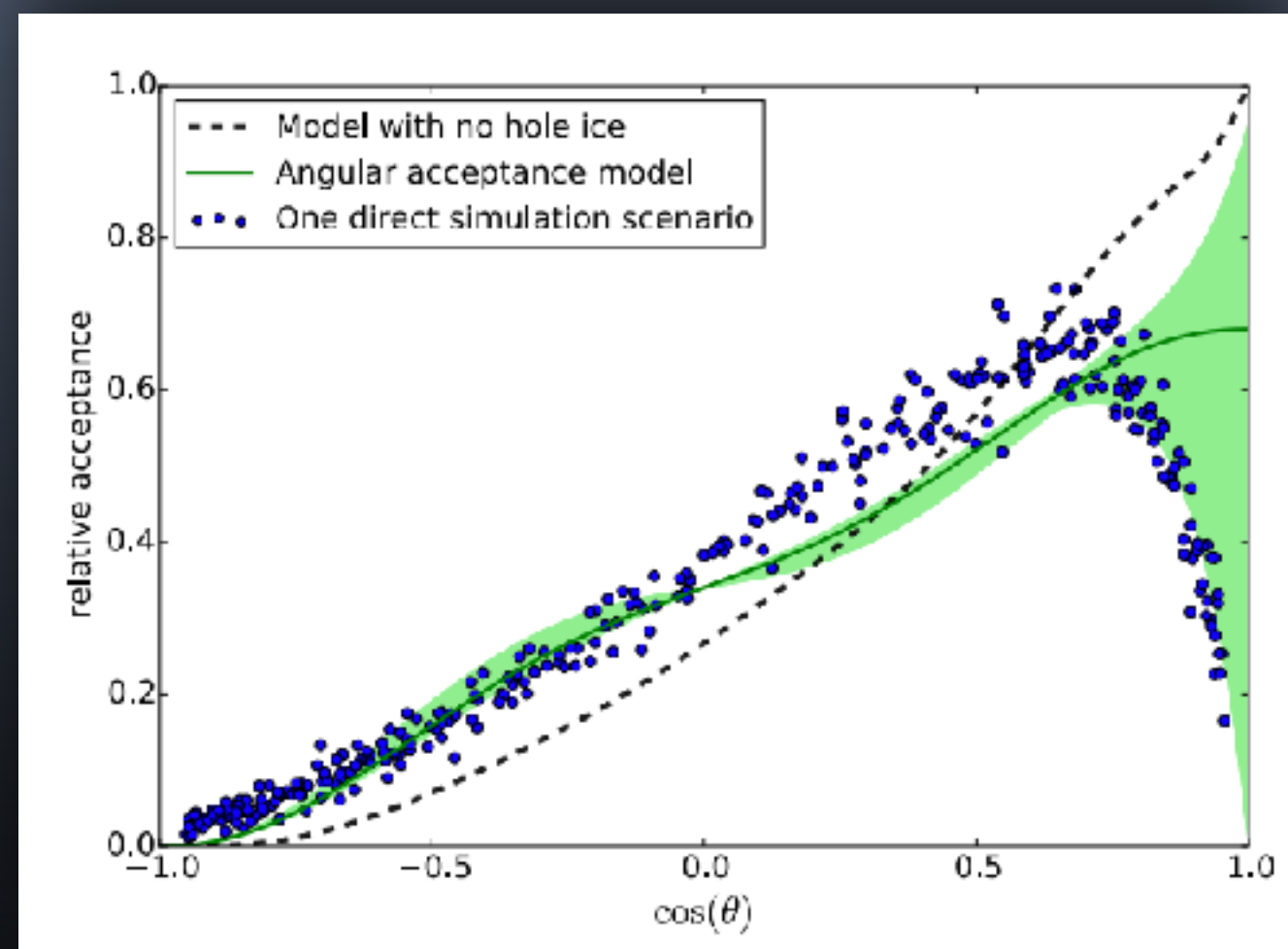
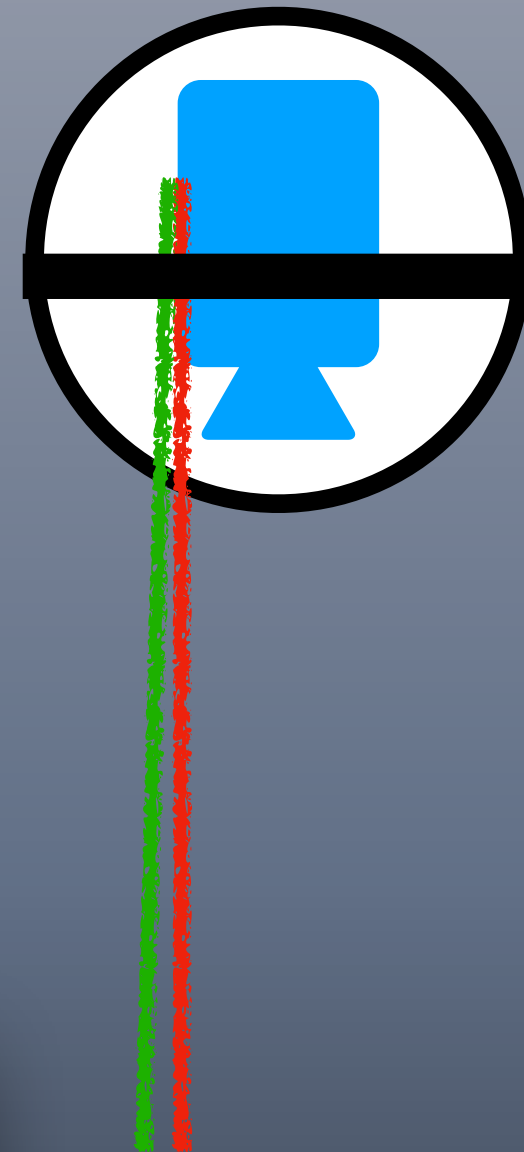
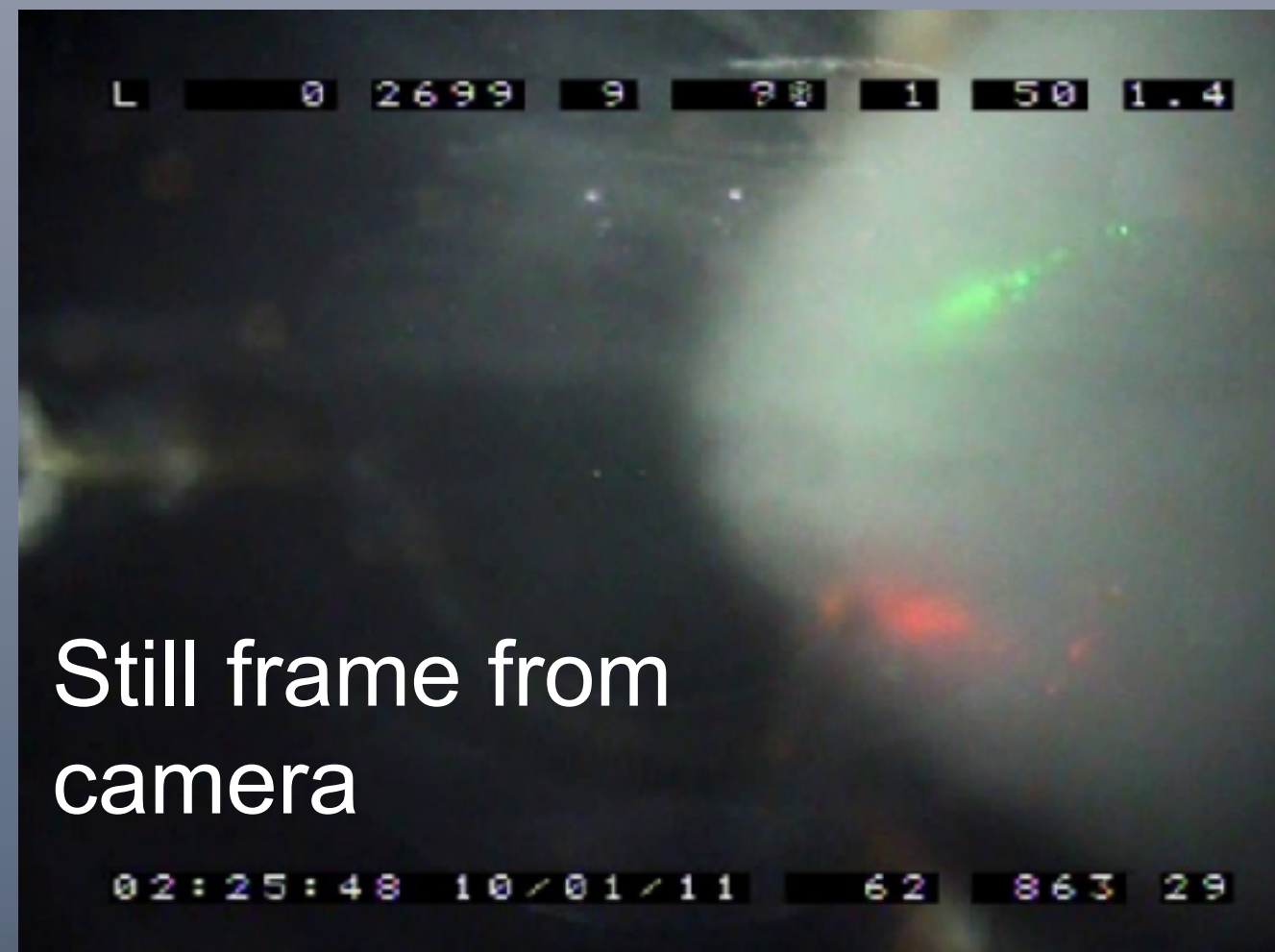


Photon propagation

Complex, natural detector medium



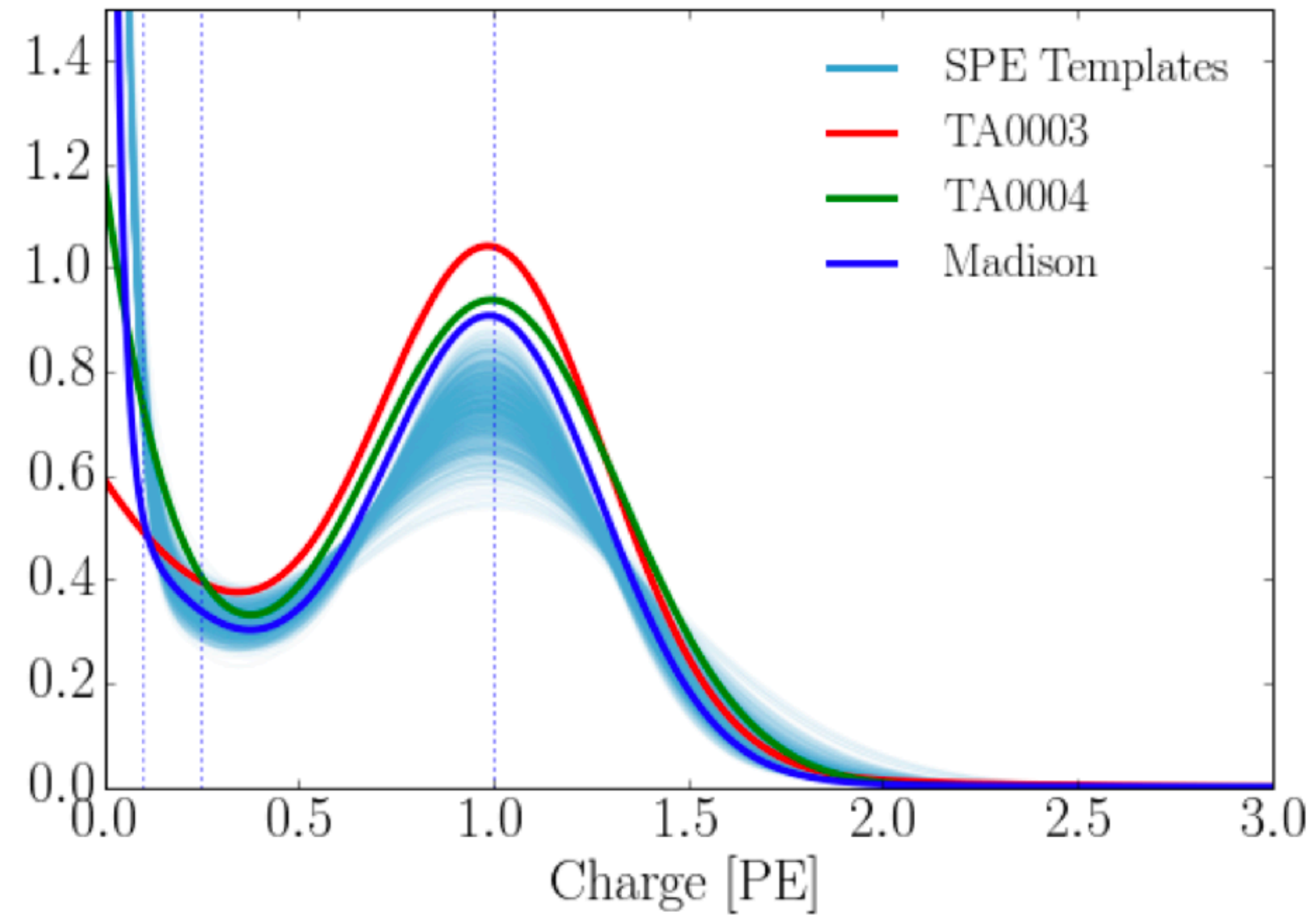
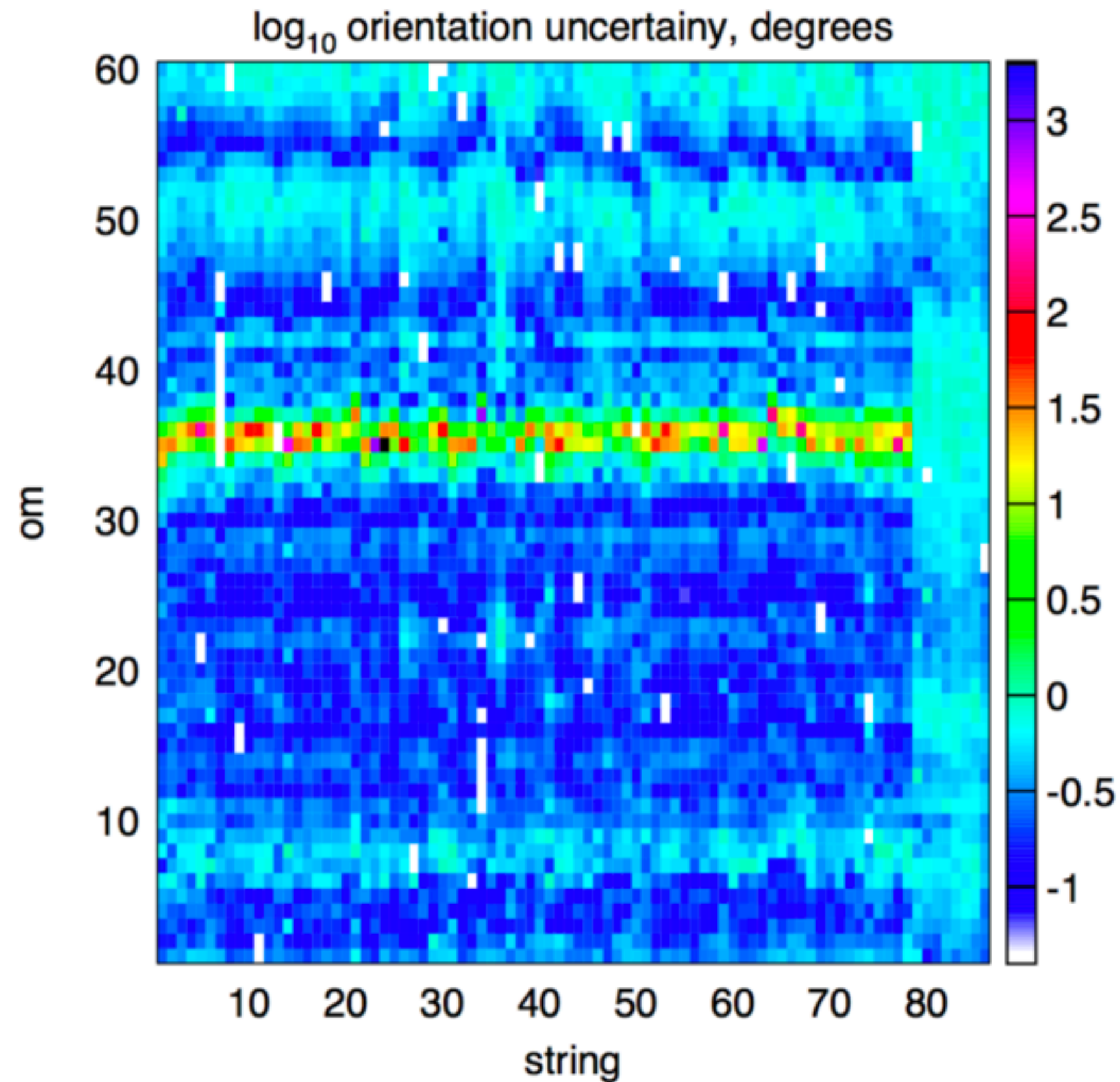
Local ice/DOM features



Detector recalibration

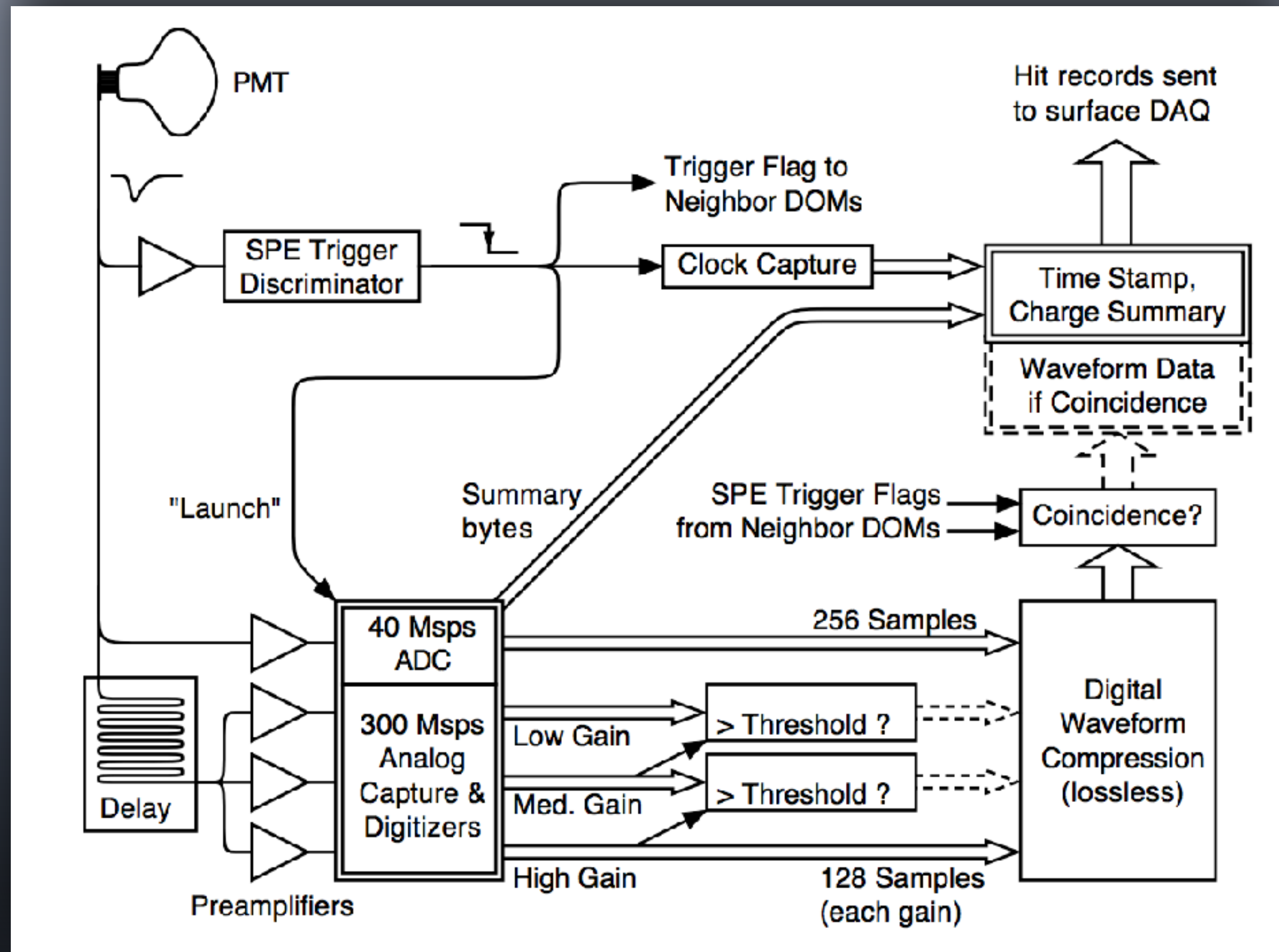
“With great statistics comes great responsibility”

<https://arxiv.org/abs/2002.00997>



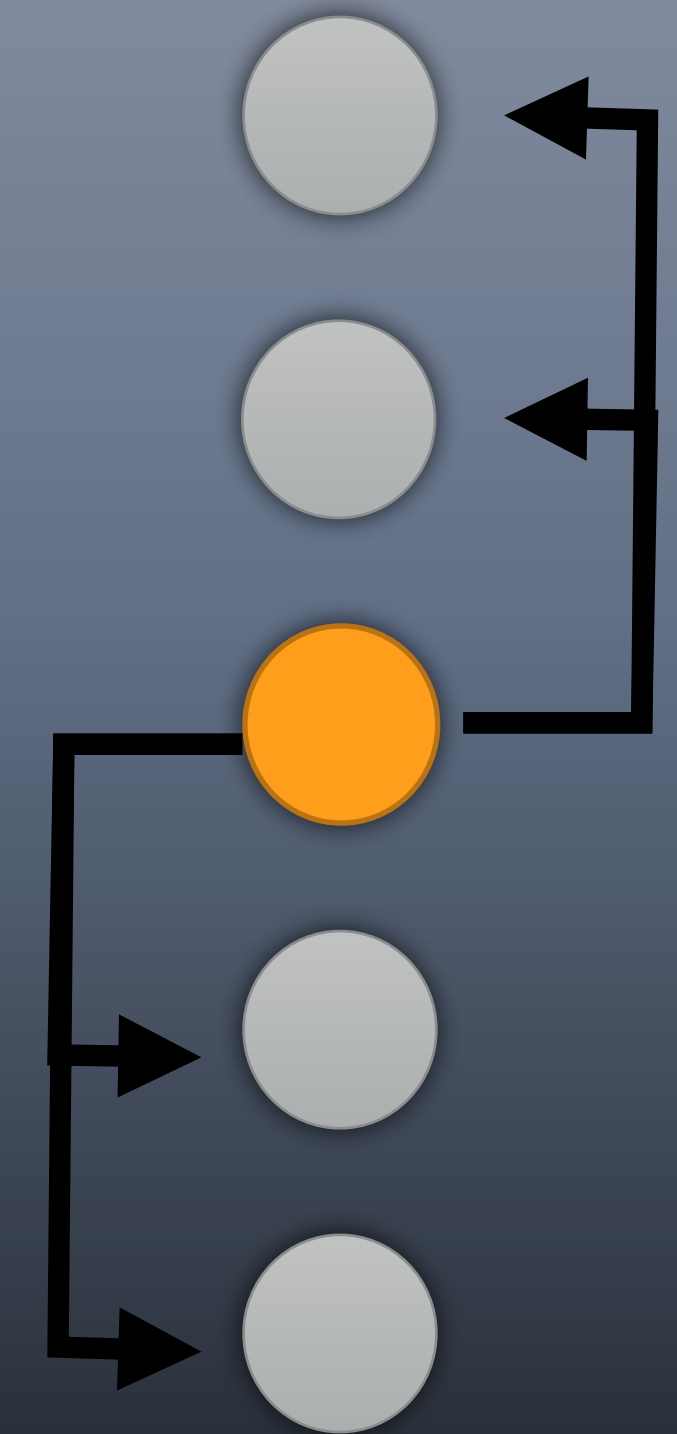
Event readout

Waveform sampling & trigger



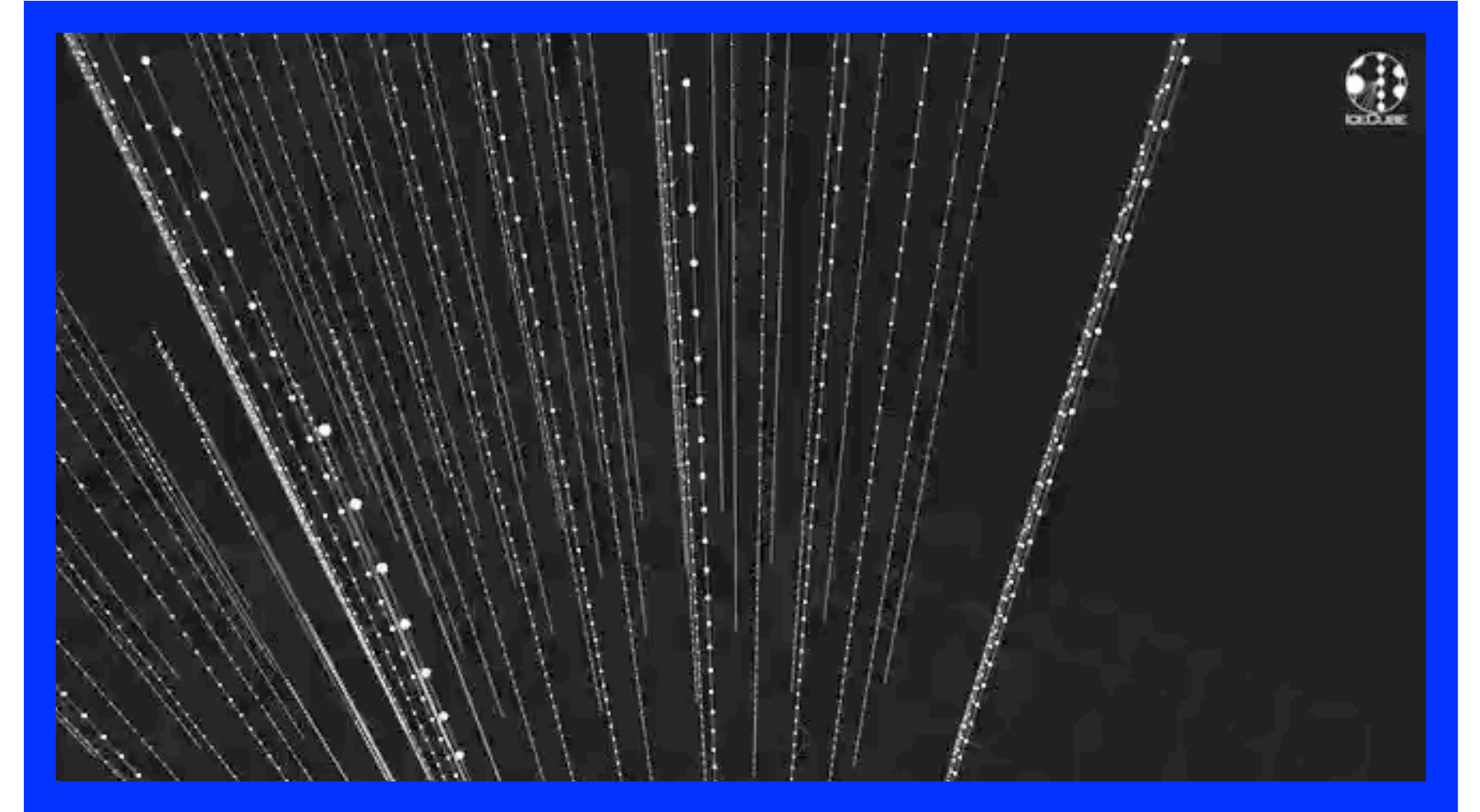
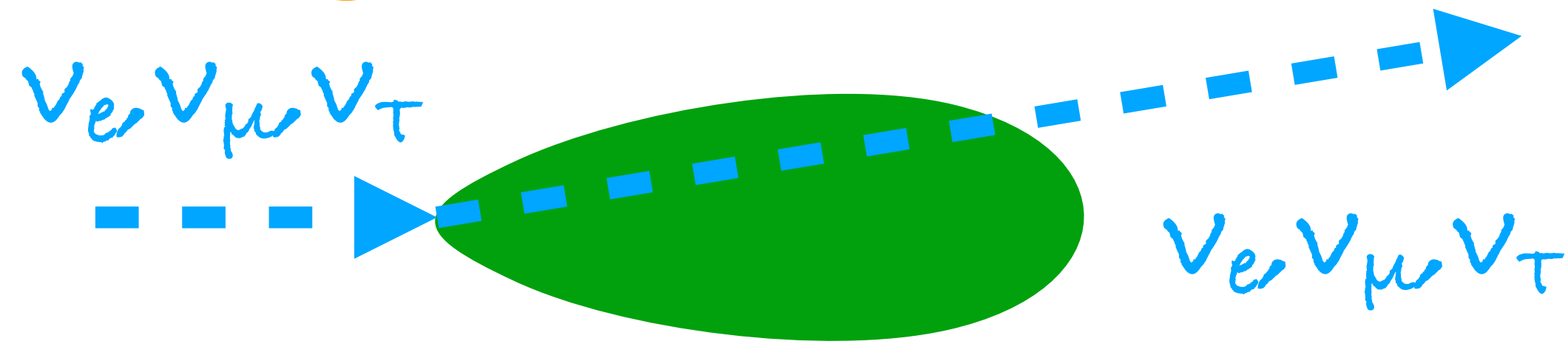
“Hard local coincidence” HLC

Trigger decision based on number of HLCs (+ optionally volume)



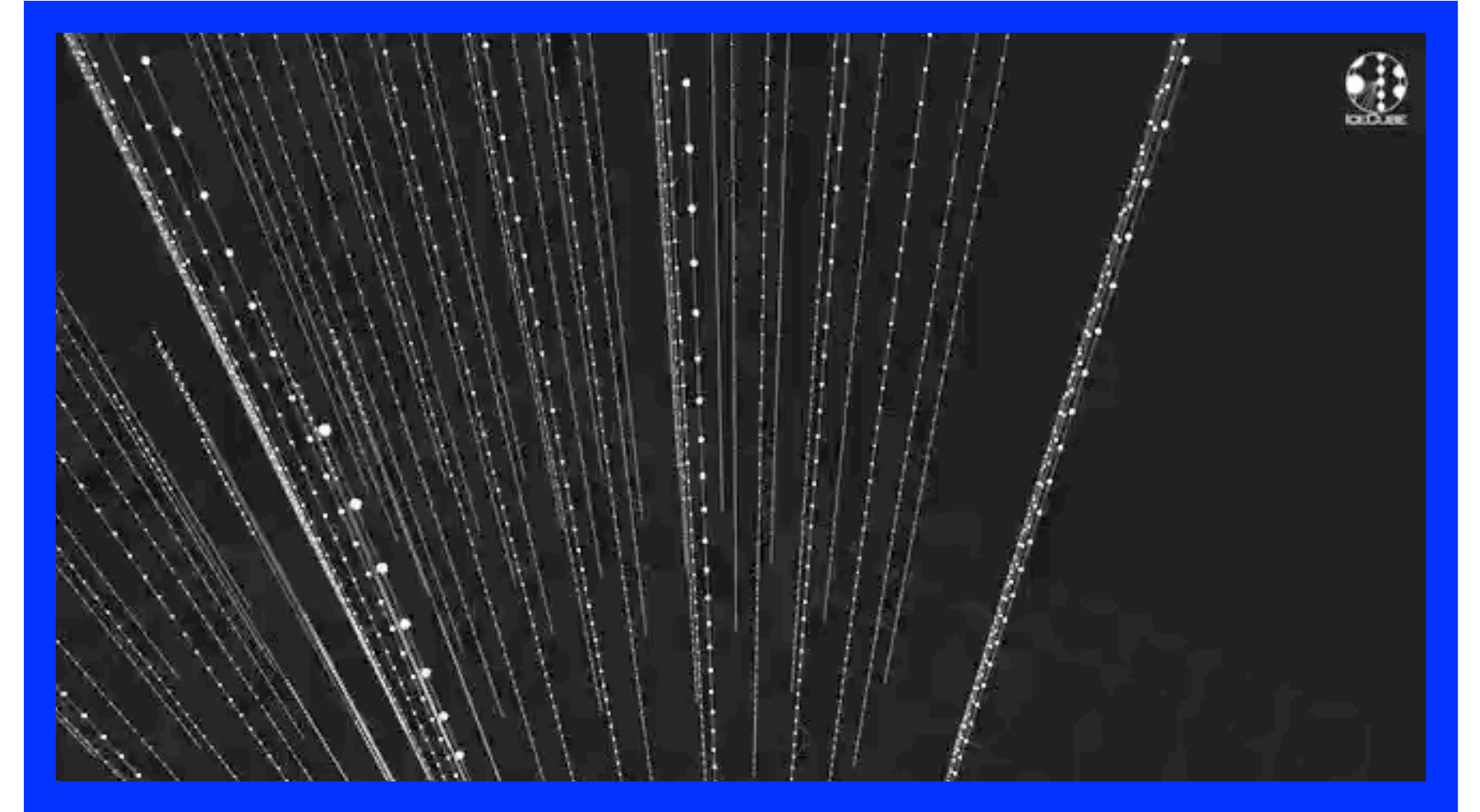
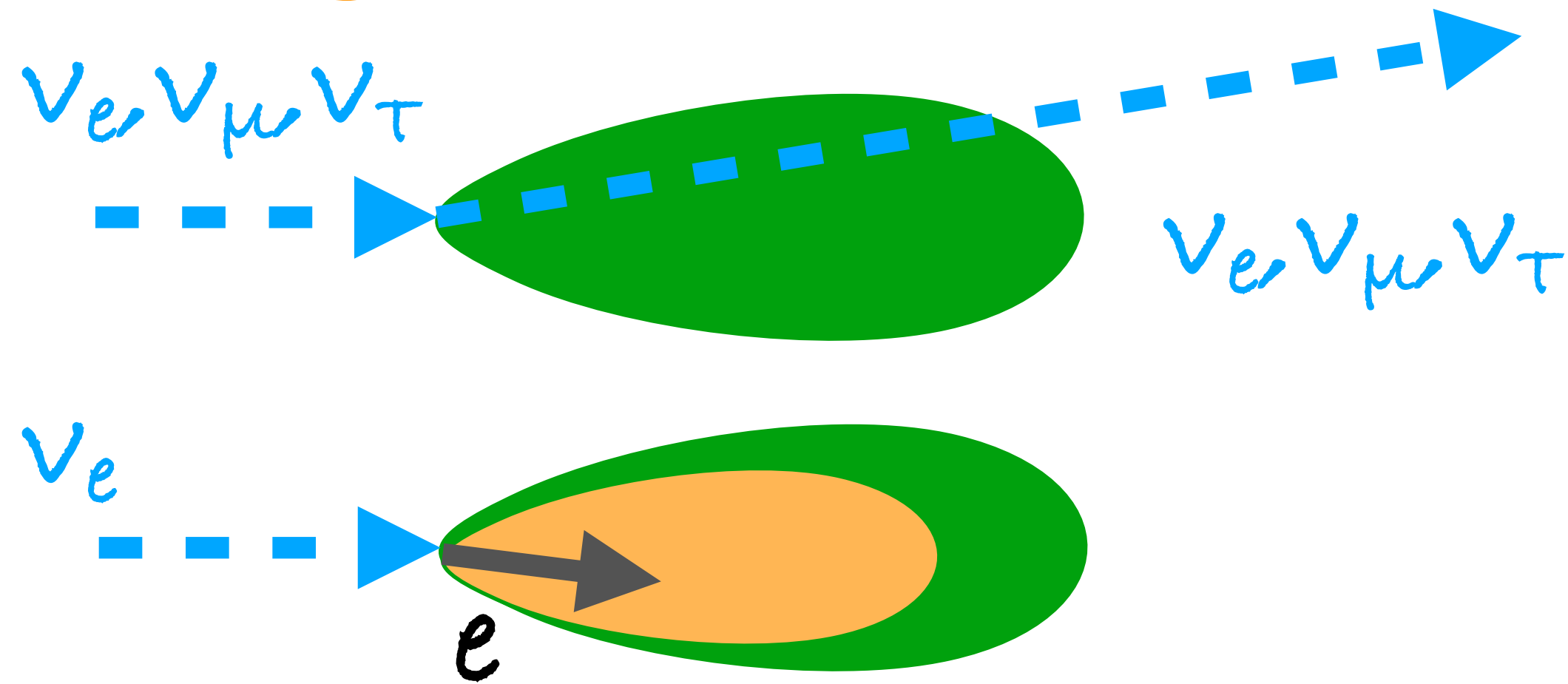
Neutrino interactions in IceCube

Event signatures



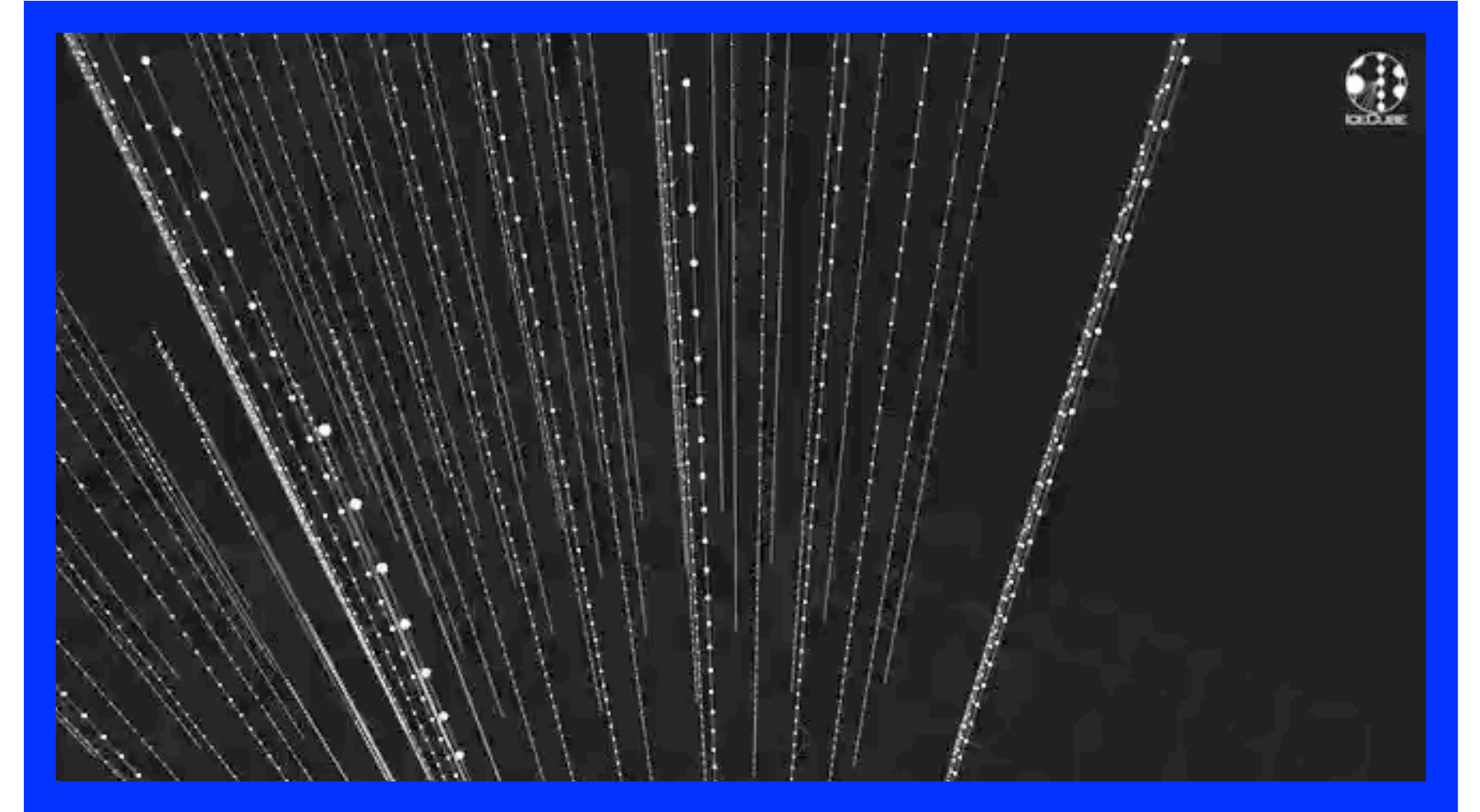
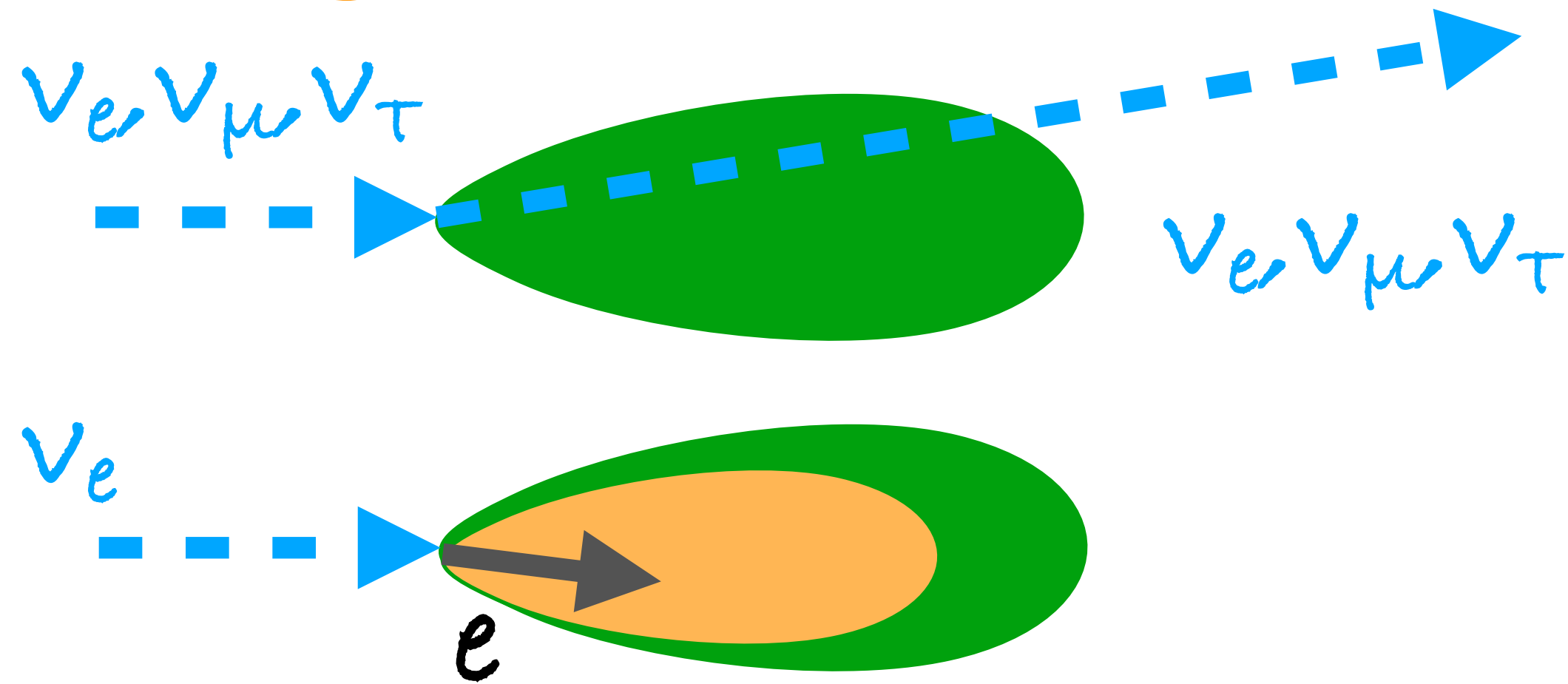
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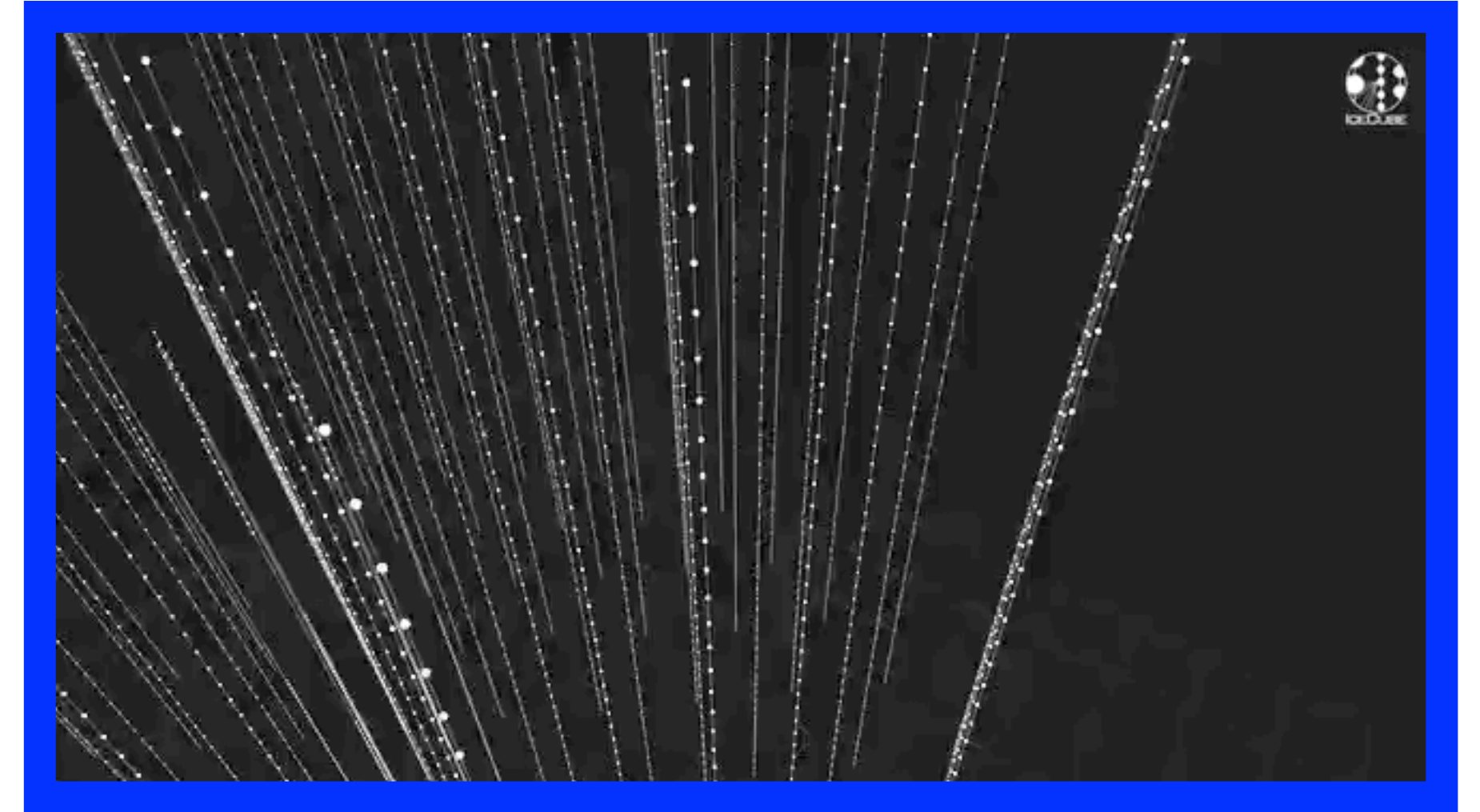
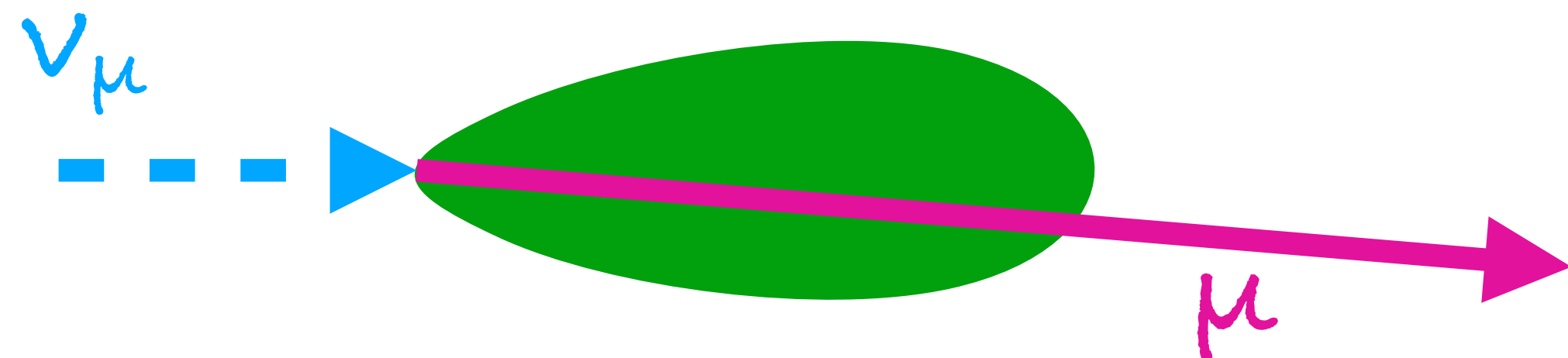
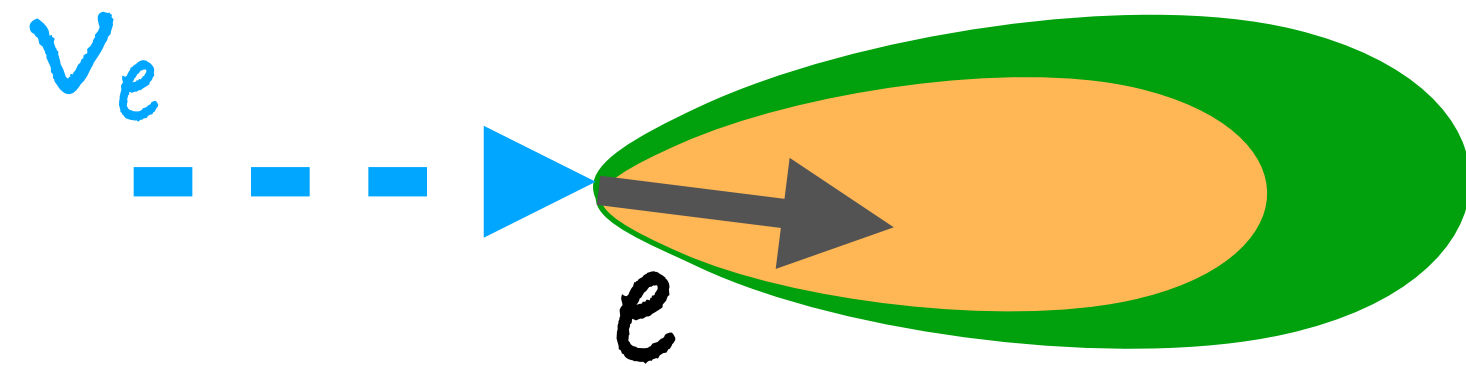
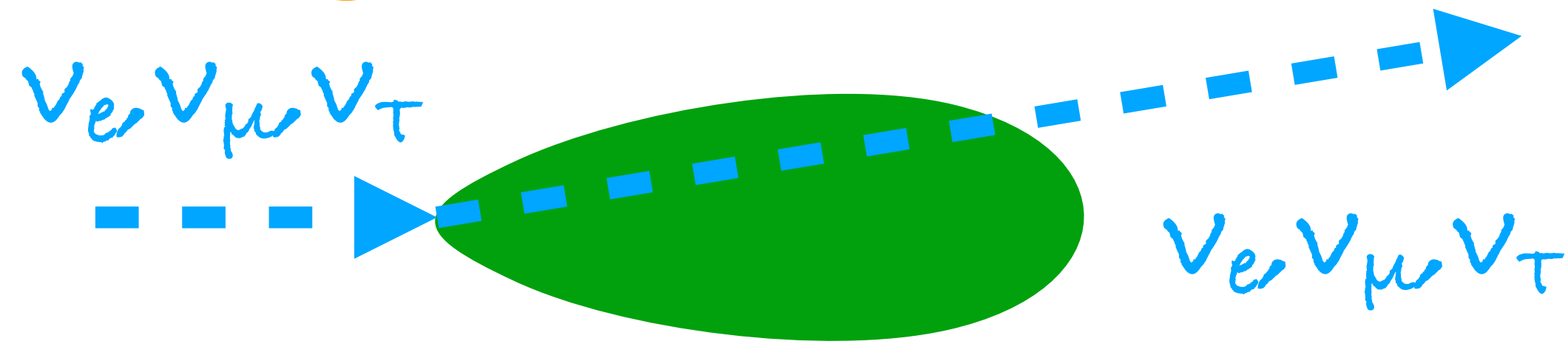
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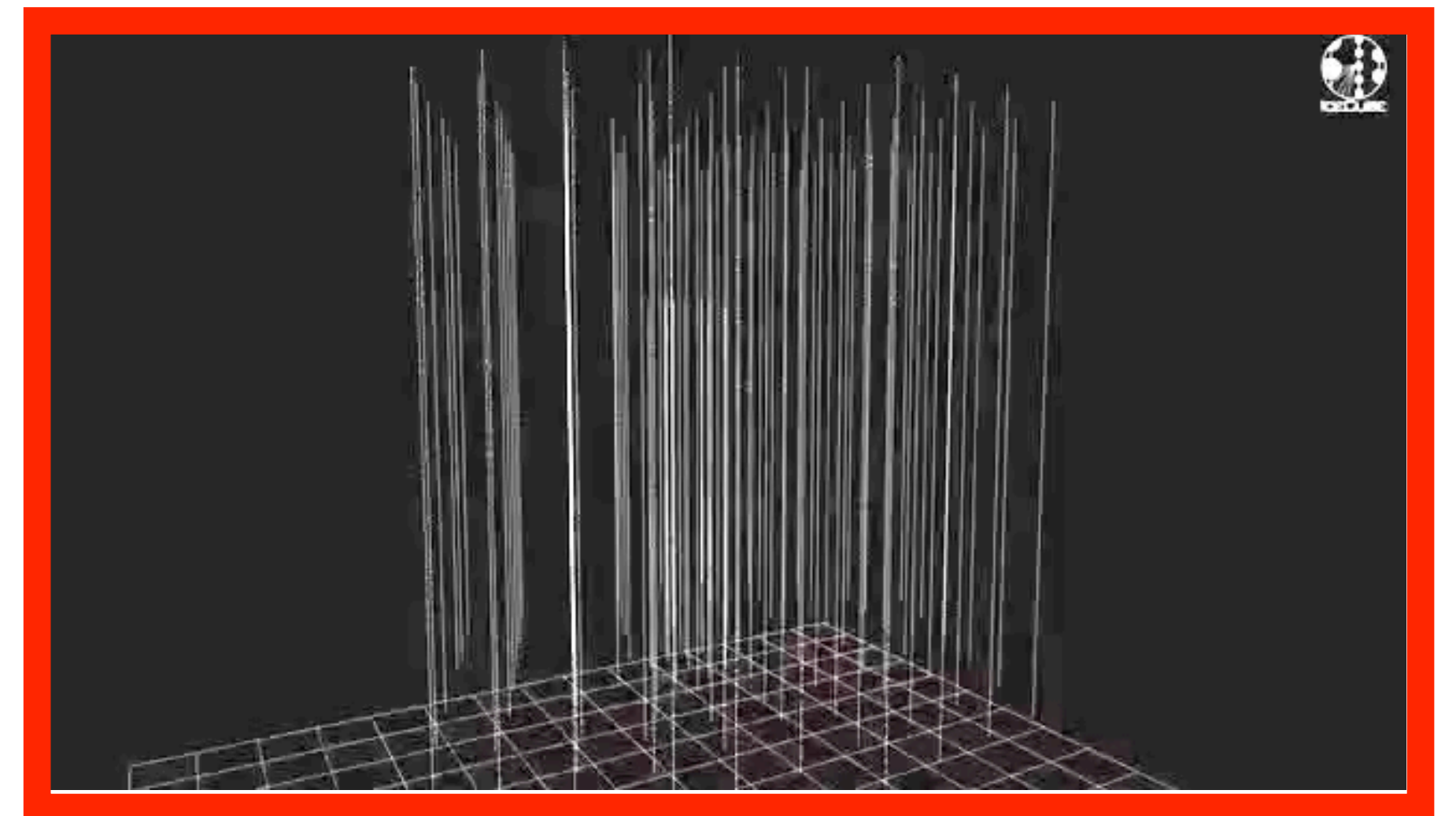
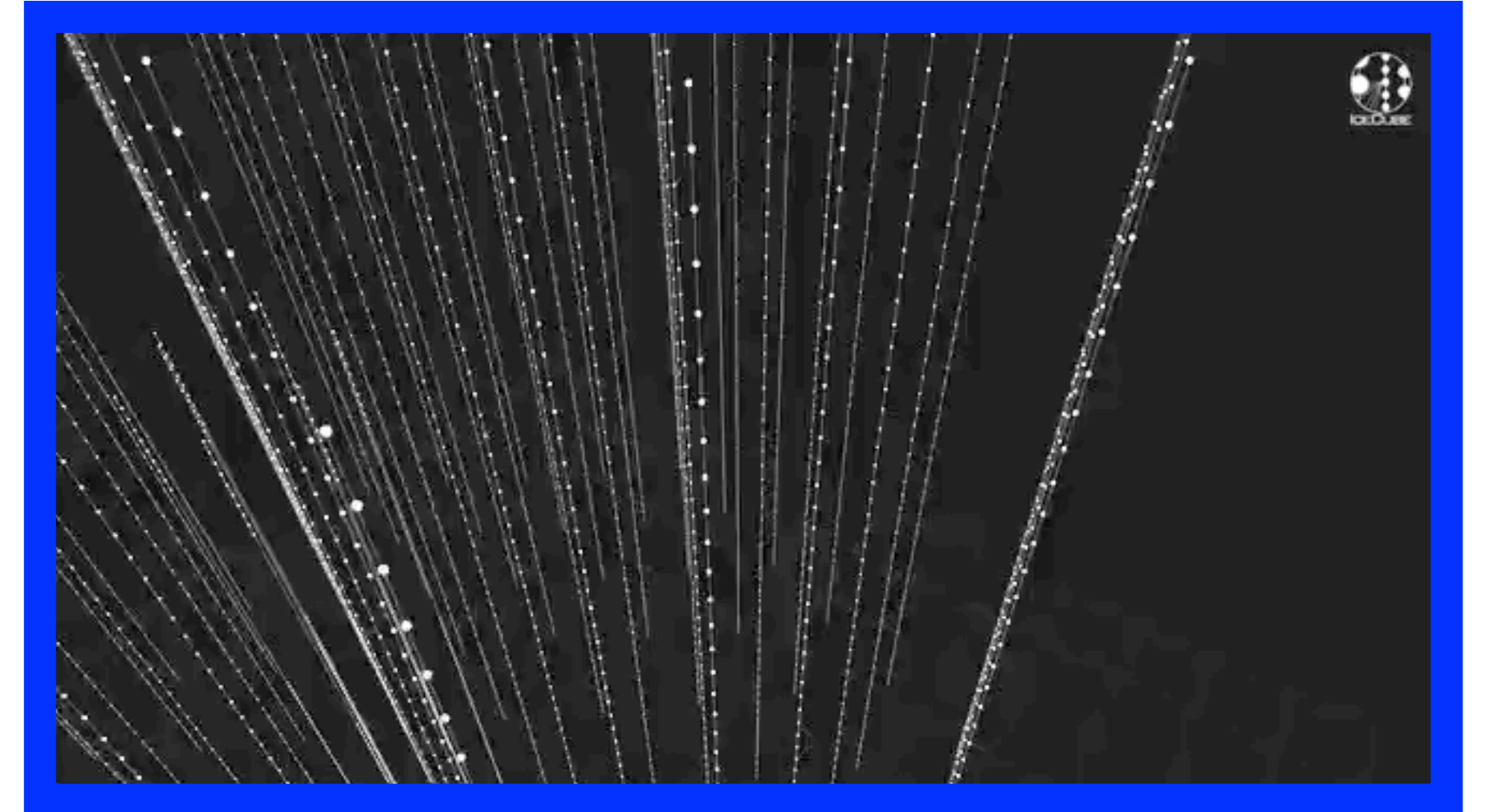
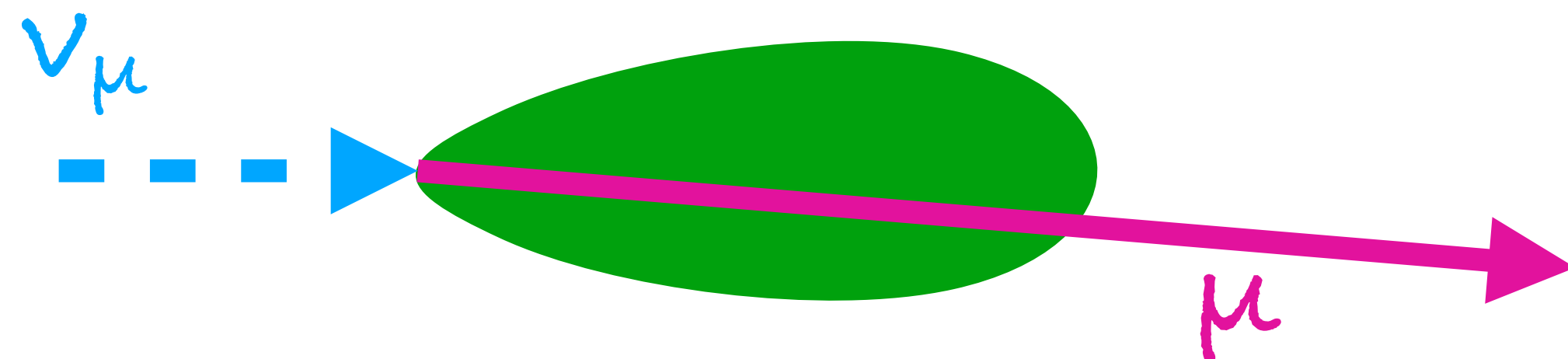
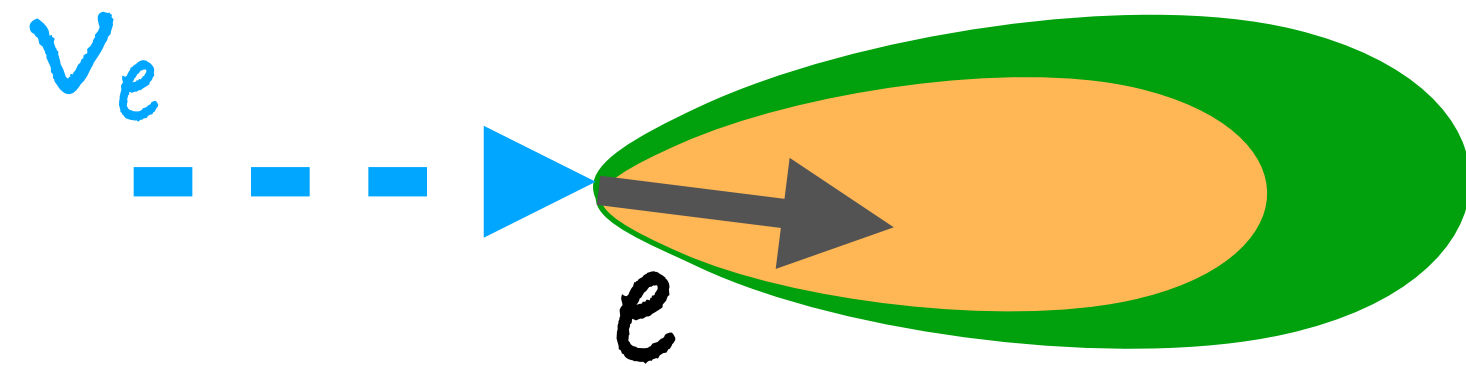
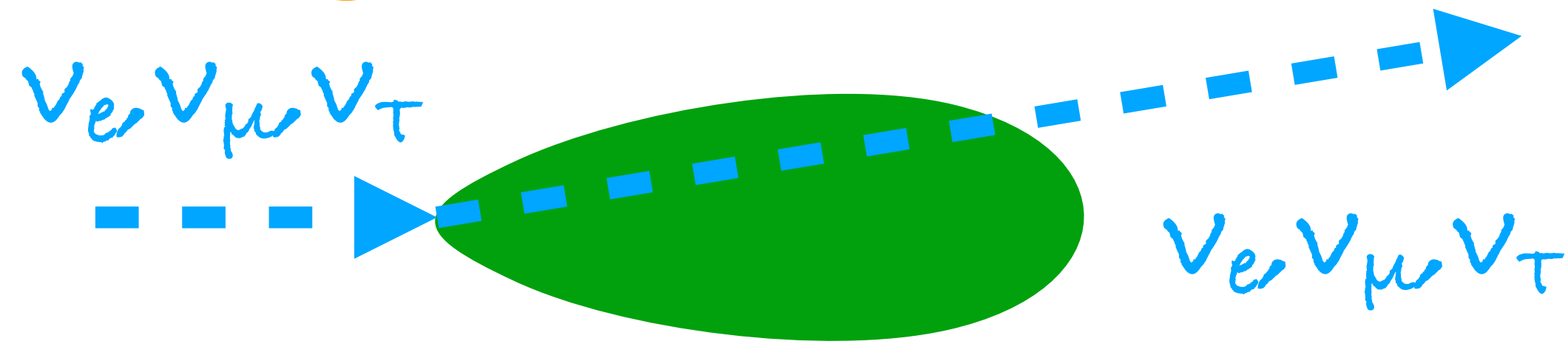
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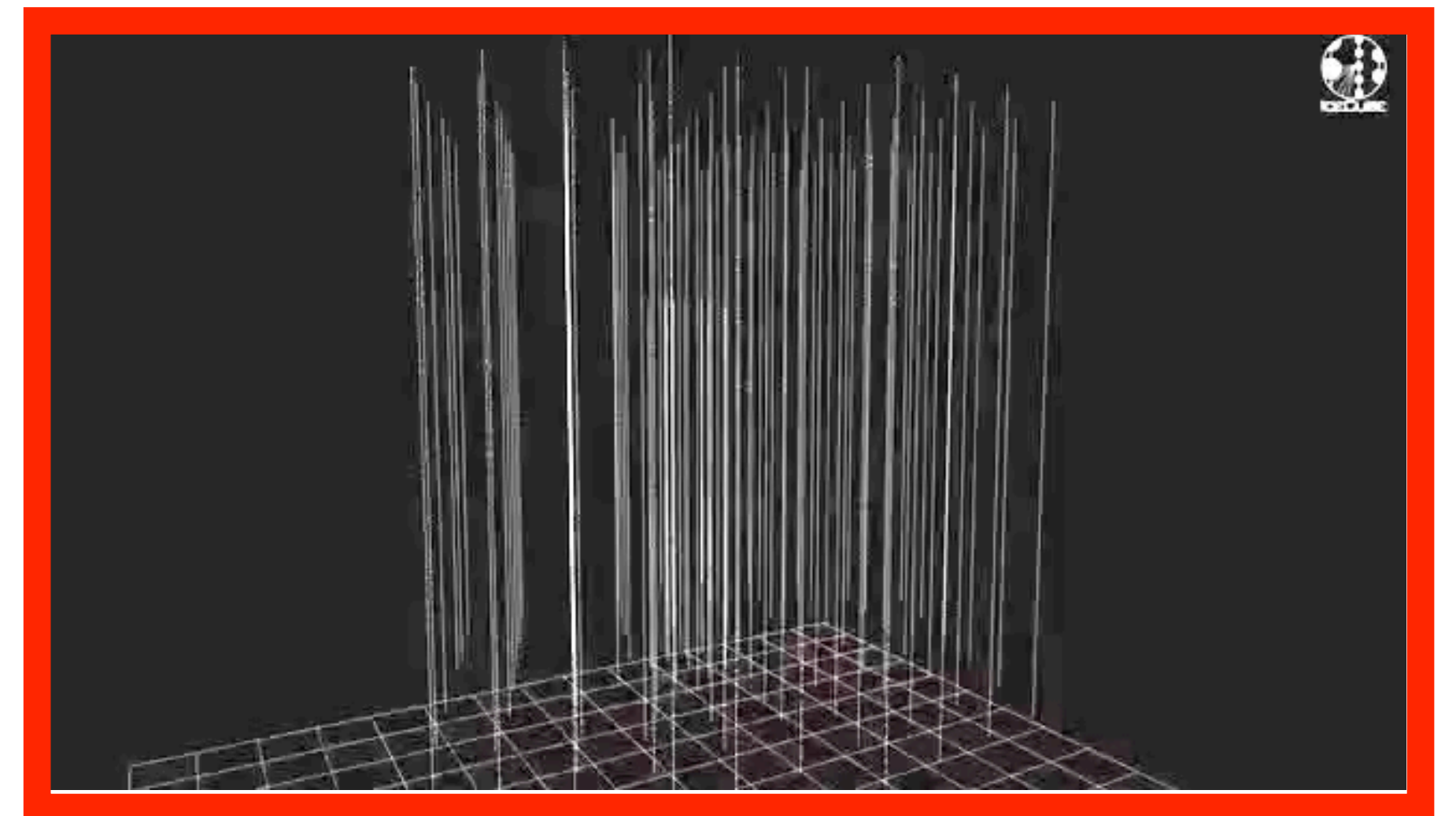
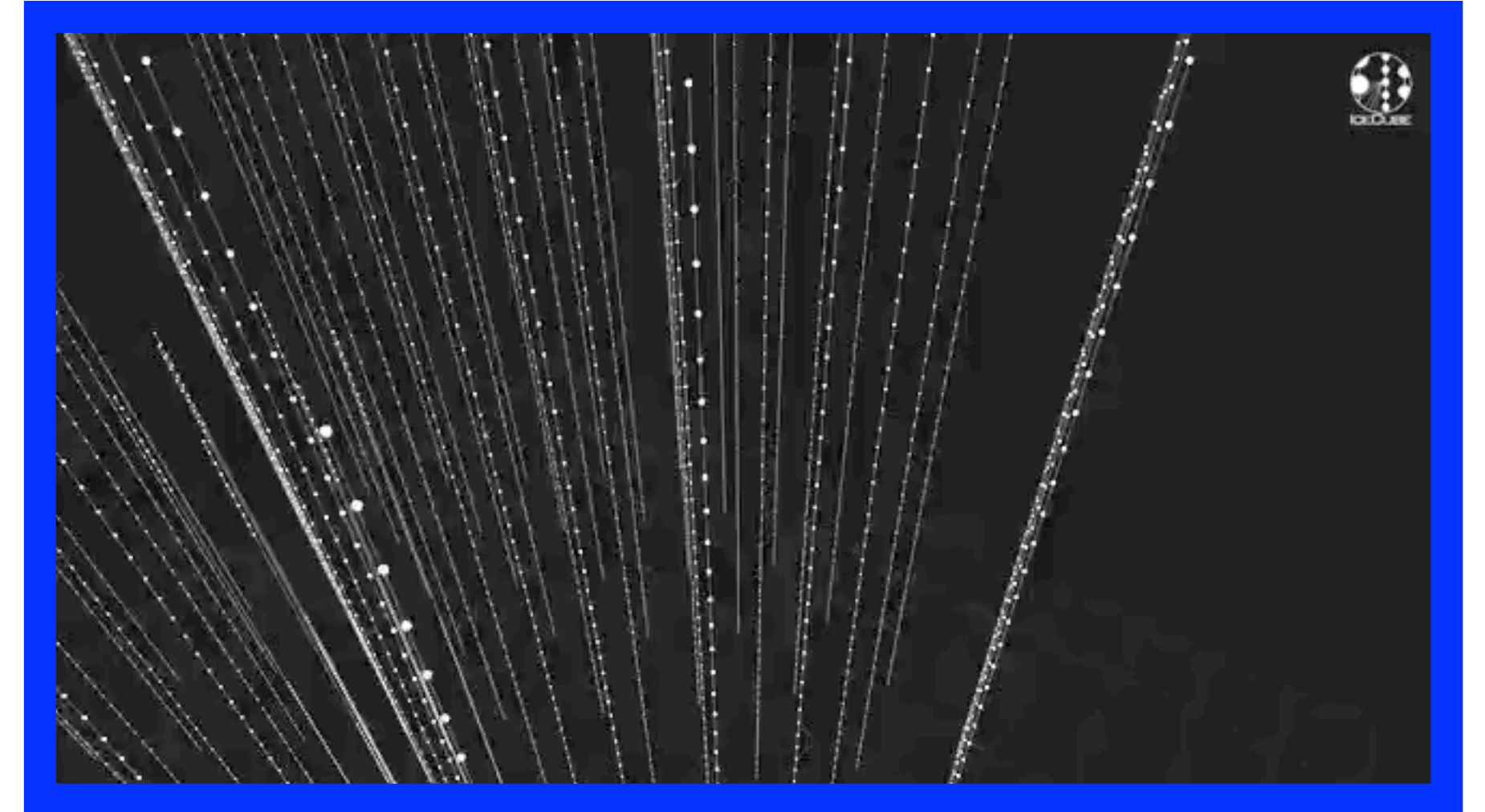
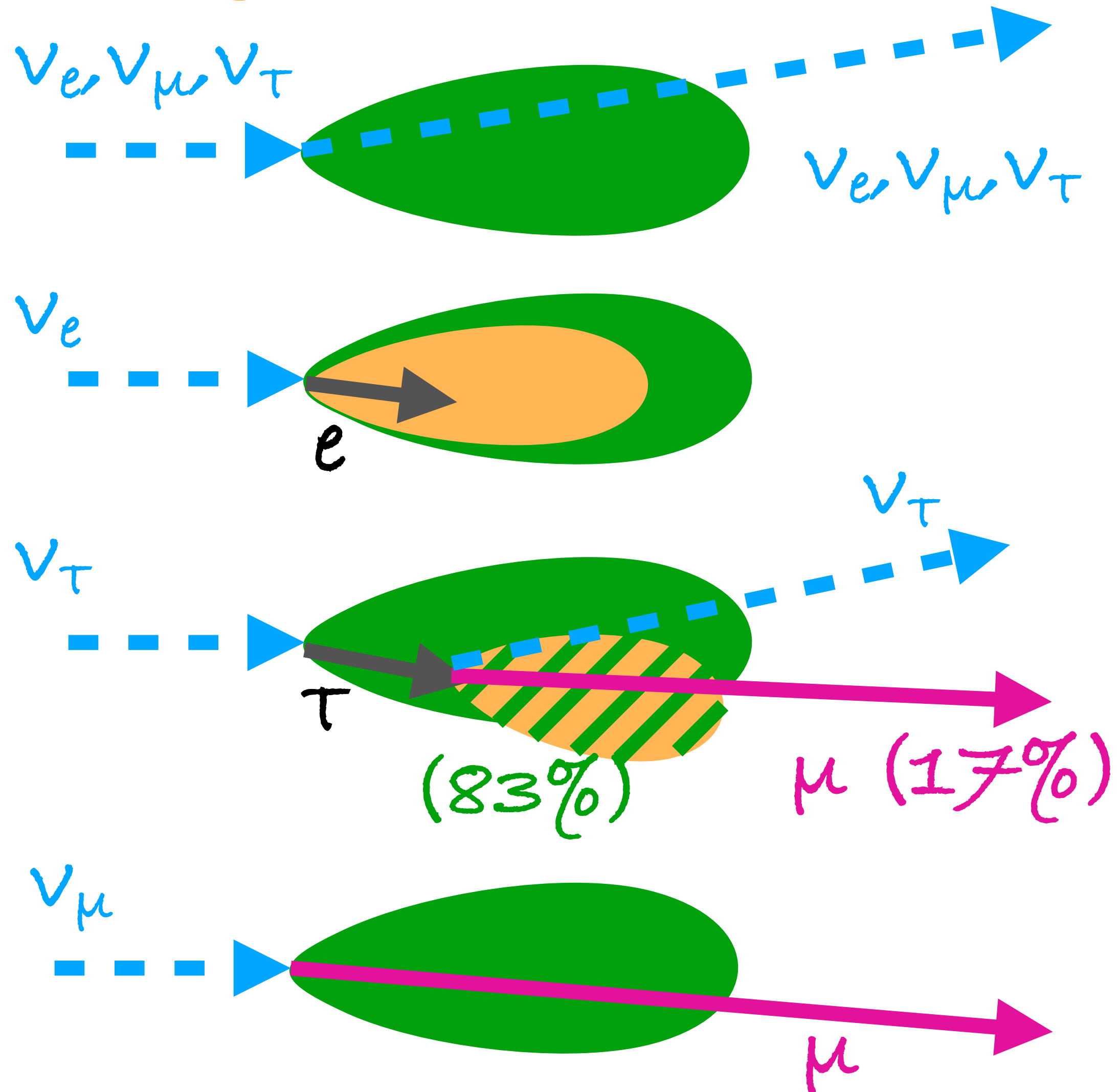
Neutrino interactions in IceCube

Event signatures



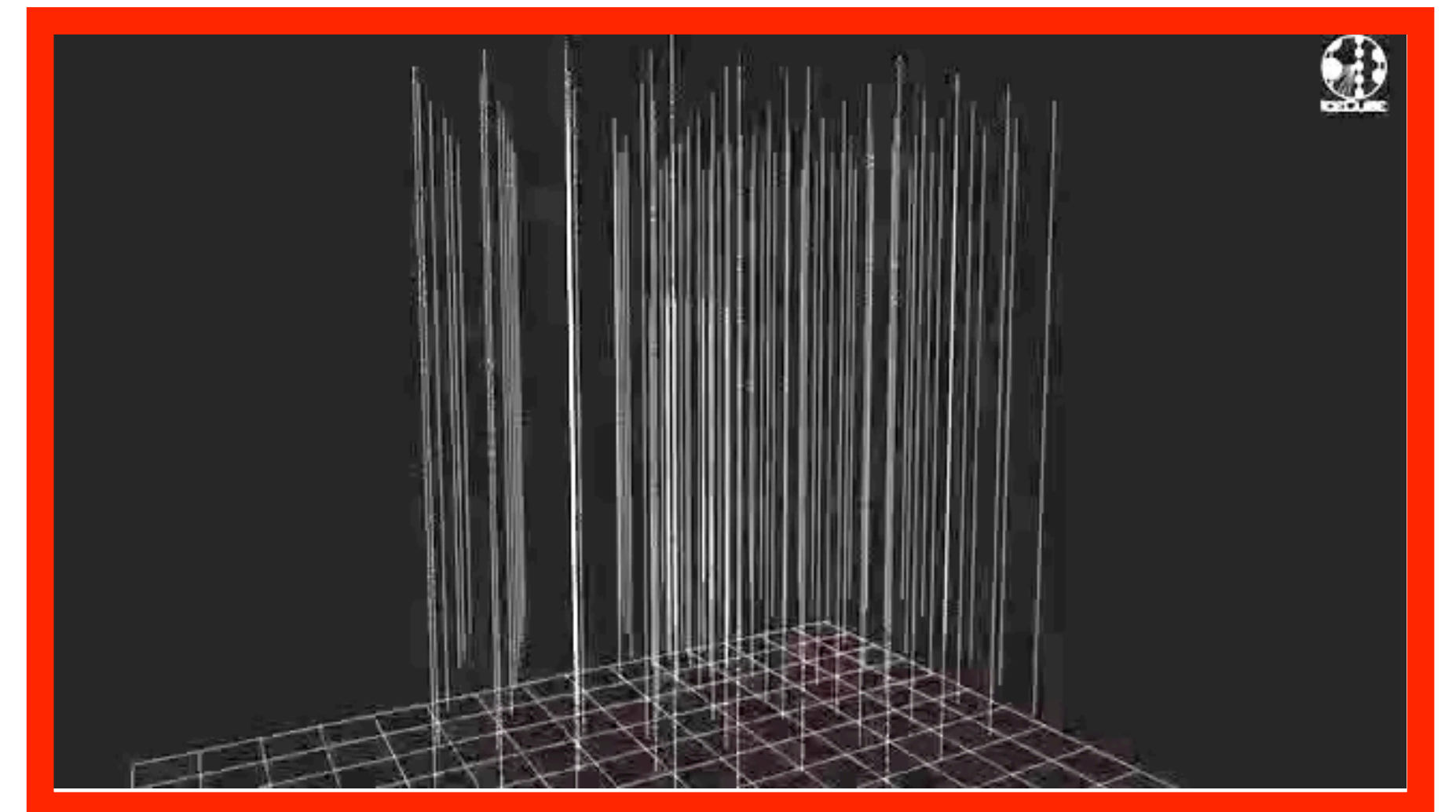
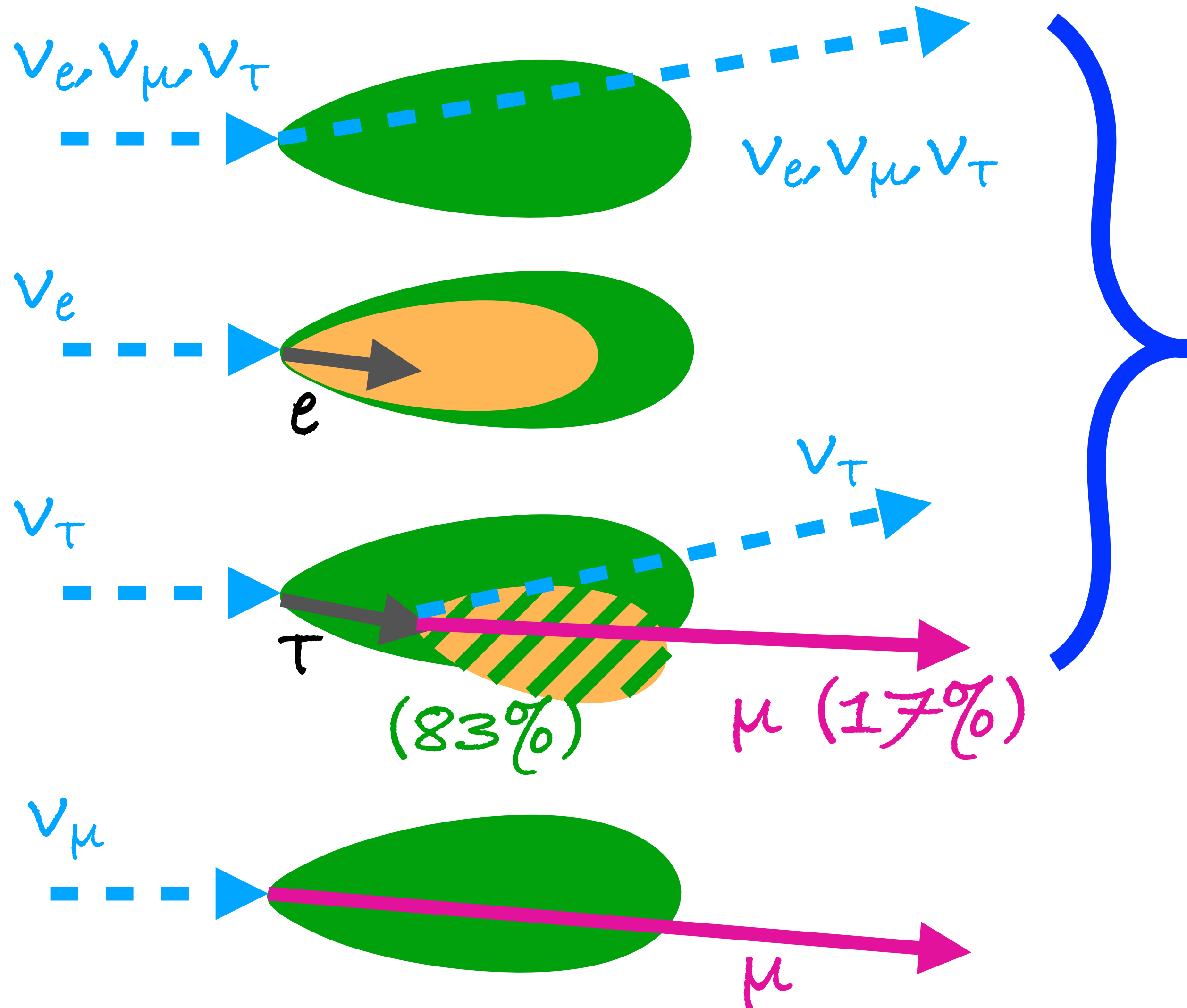
Neutrino interactions in IceCube

Event signatures



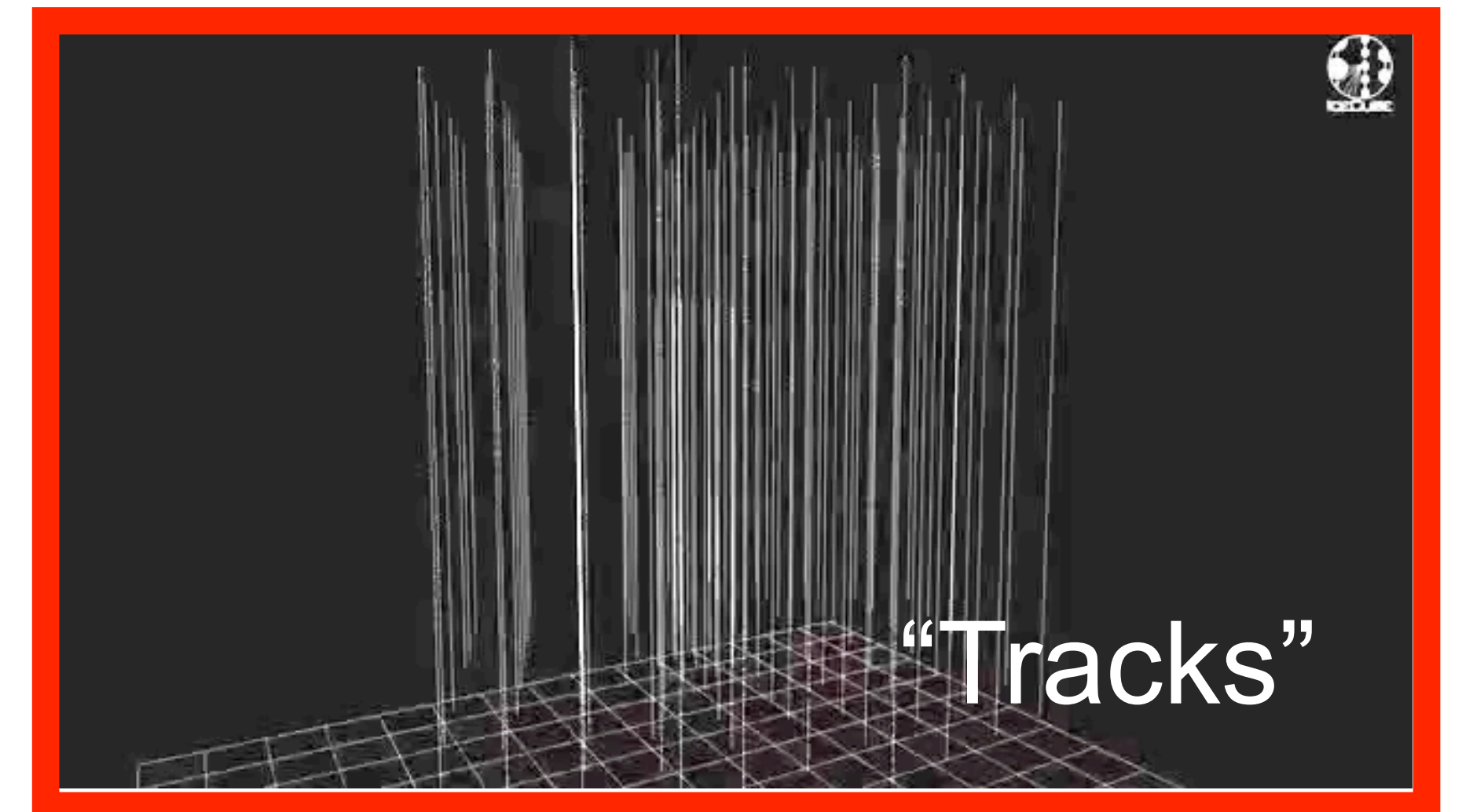
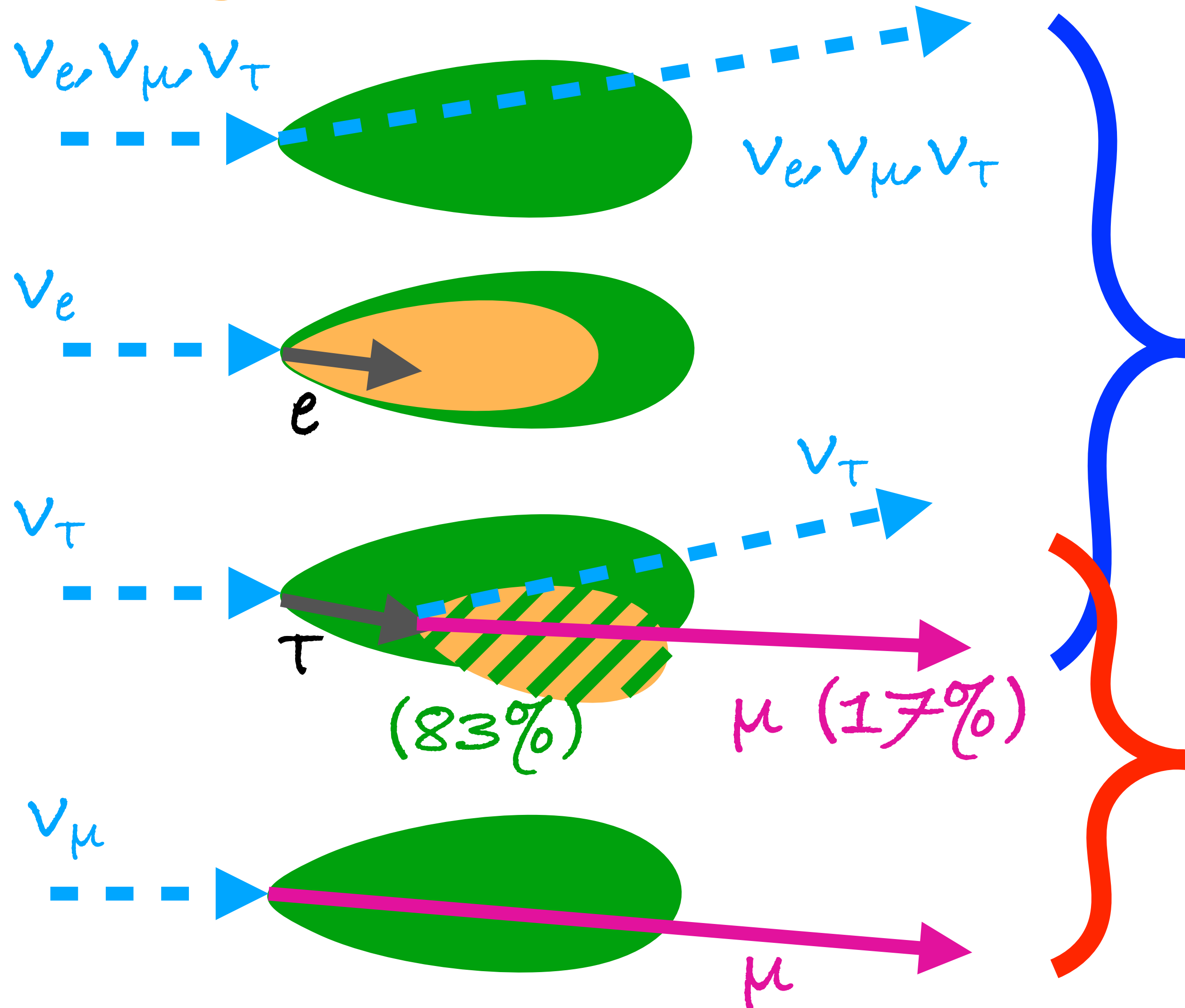
Neutrino interactions in IceCube

Event signatures



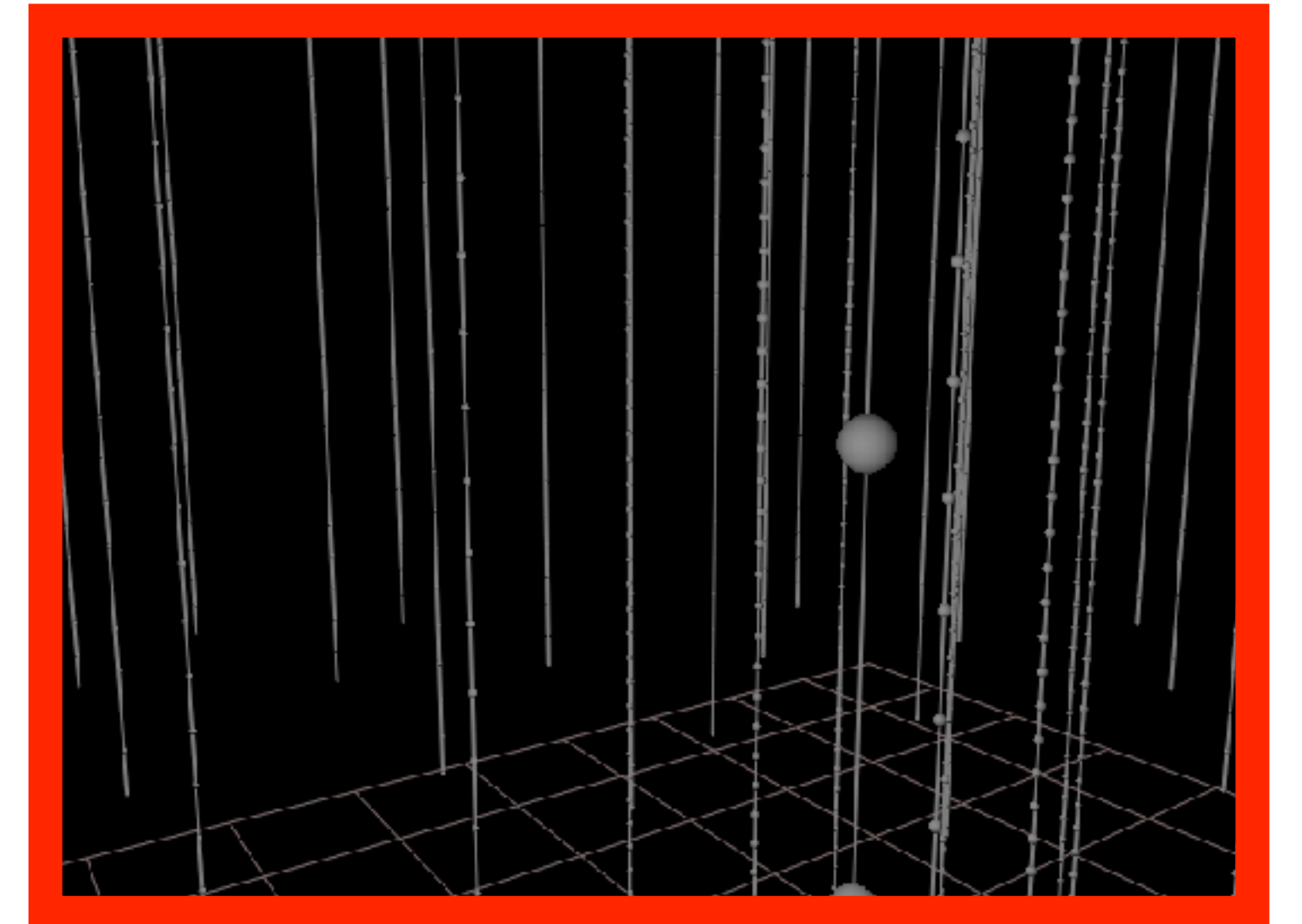
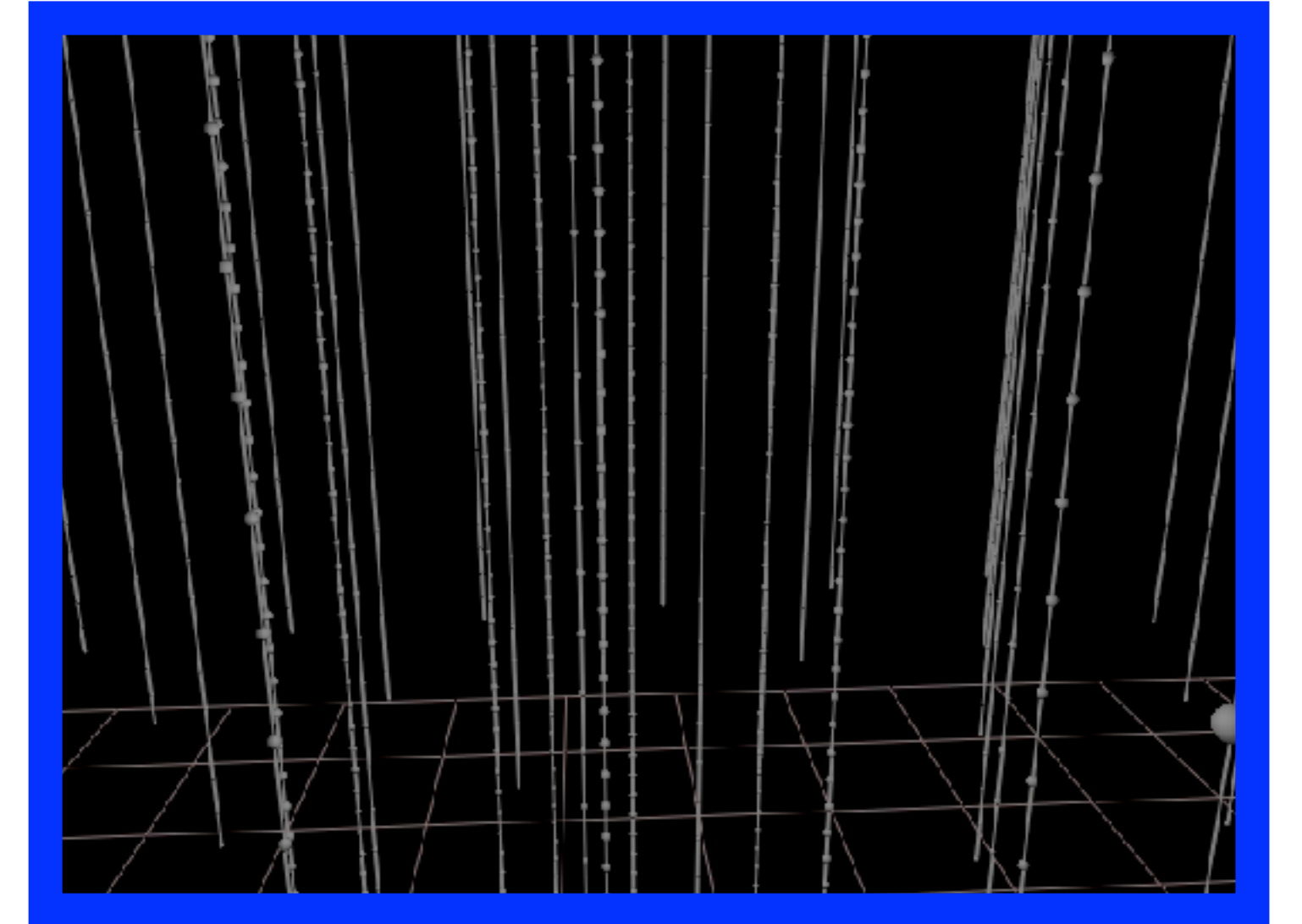
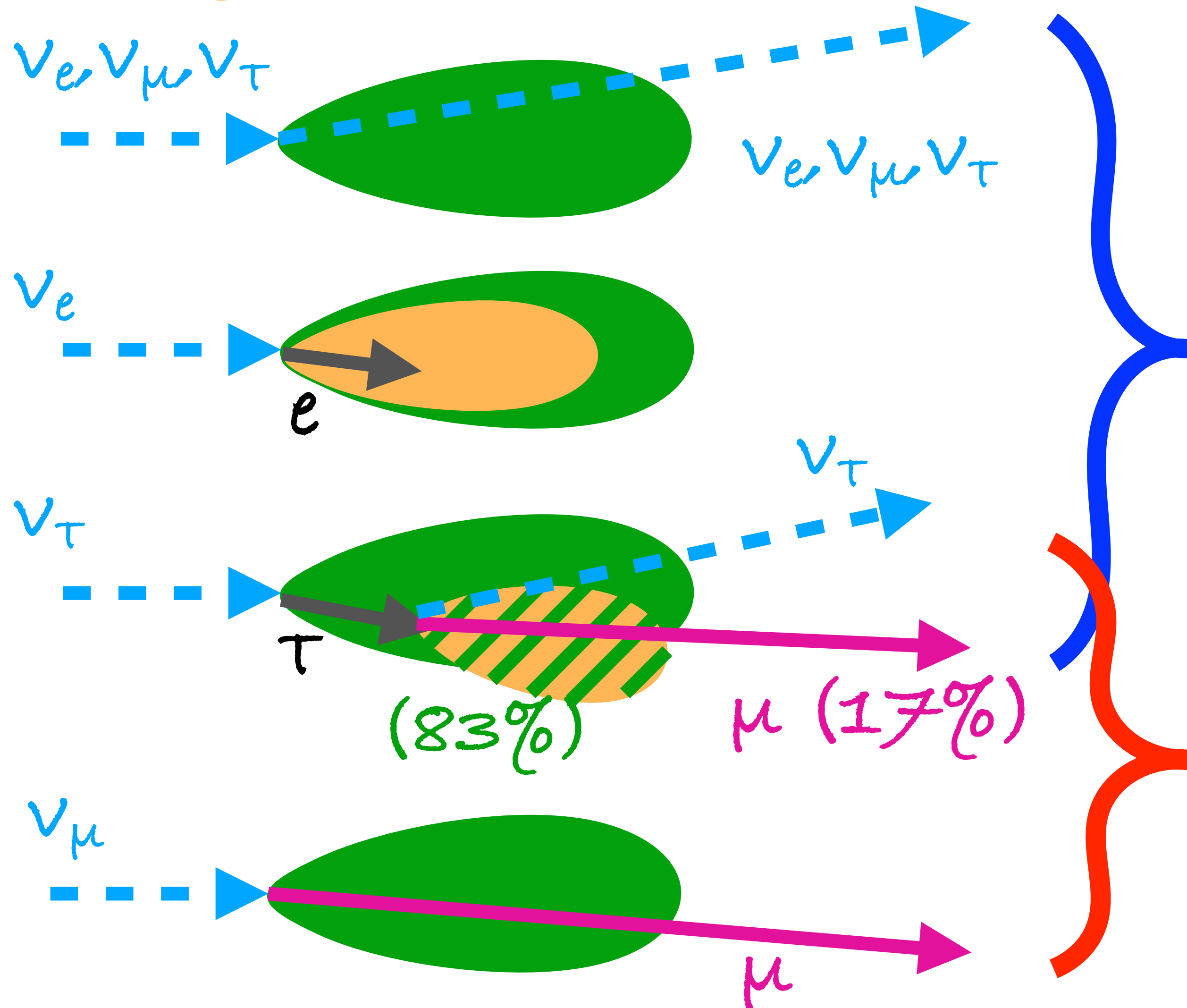
Neutrino interactions in IceCube

Event signatures



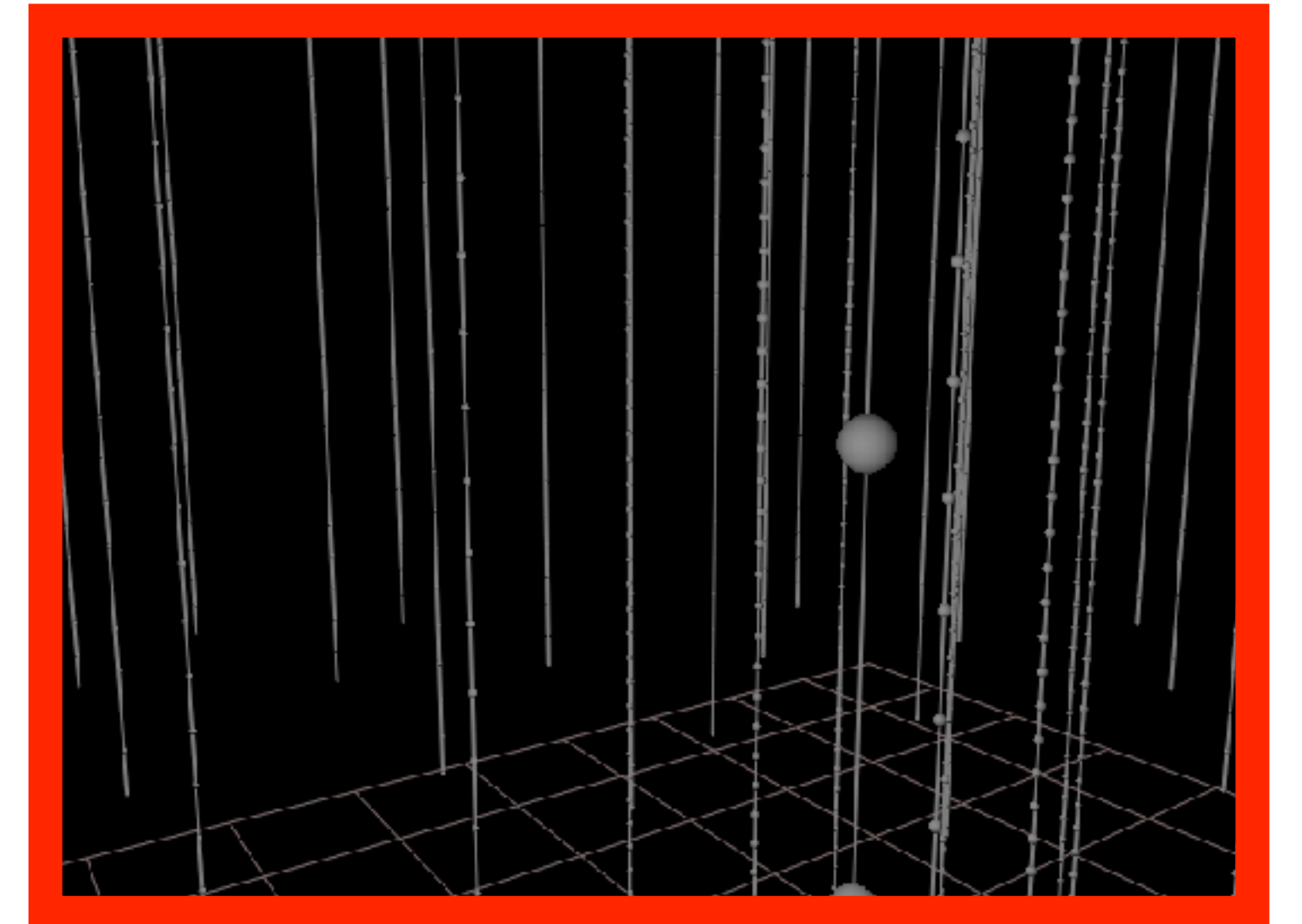
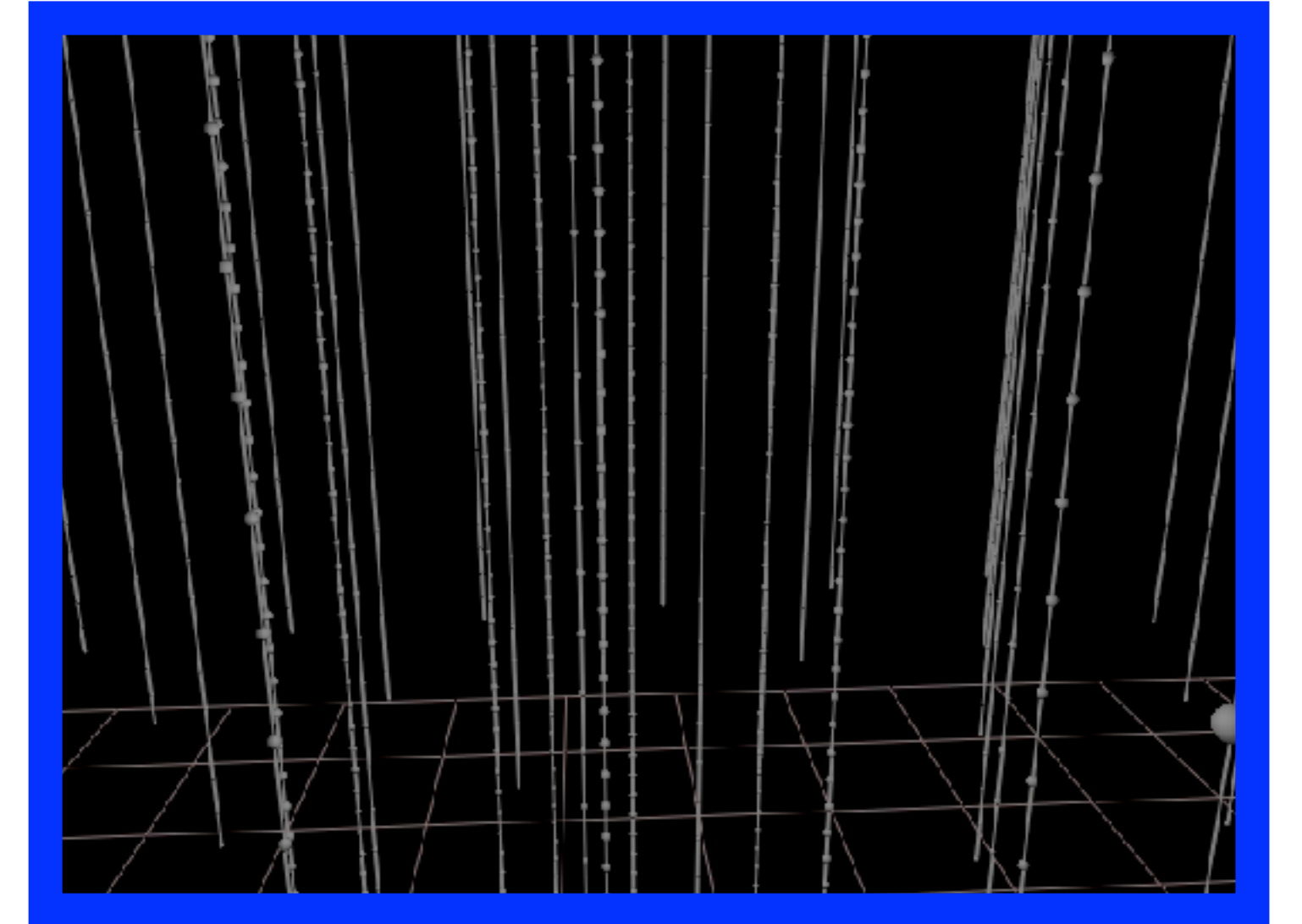
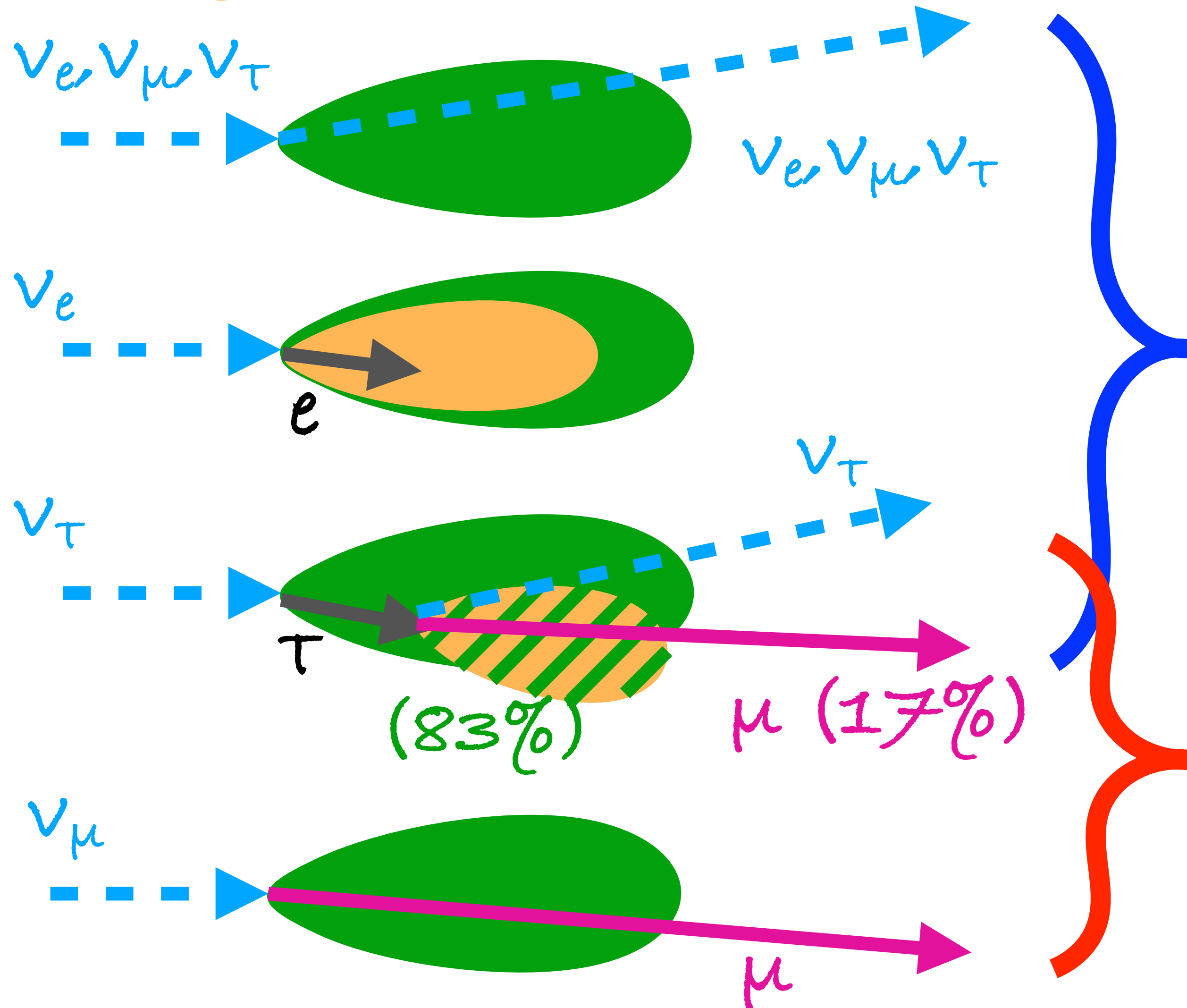
Neutrino interactions in IceCube

Event signatures



Neutrino interactions in IceCube

Event signatures



Event reconstruction

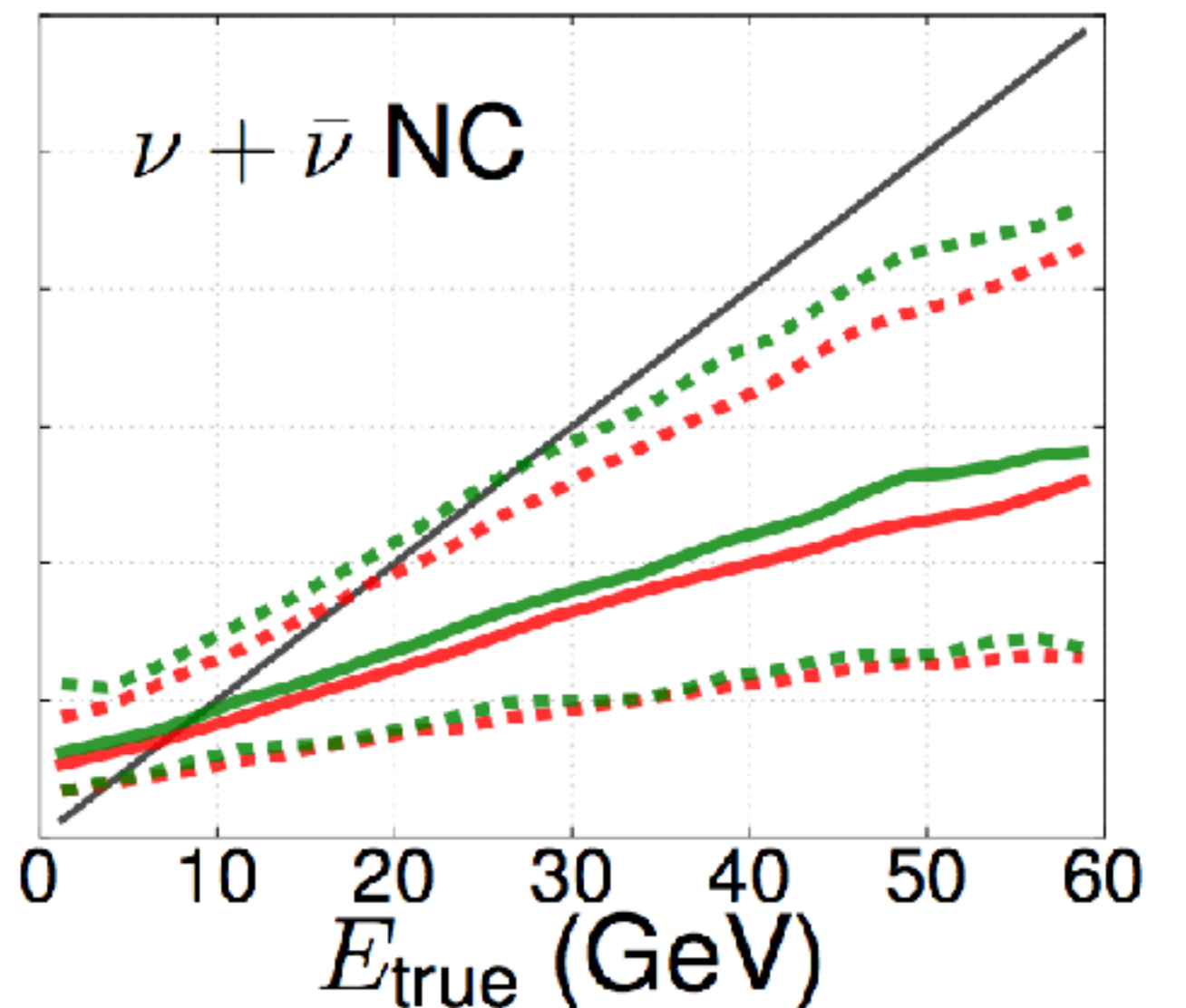
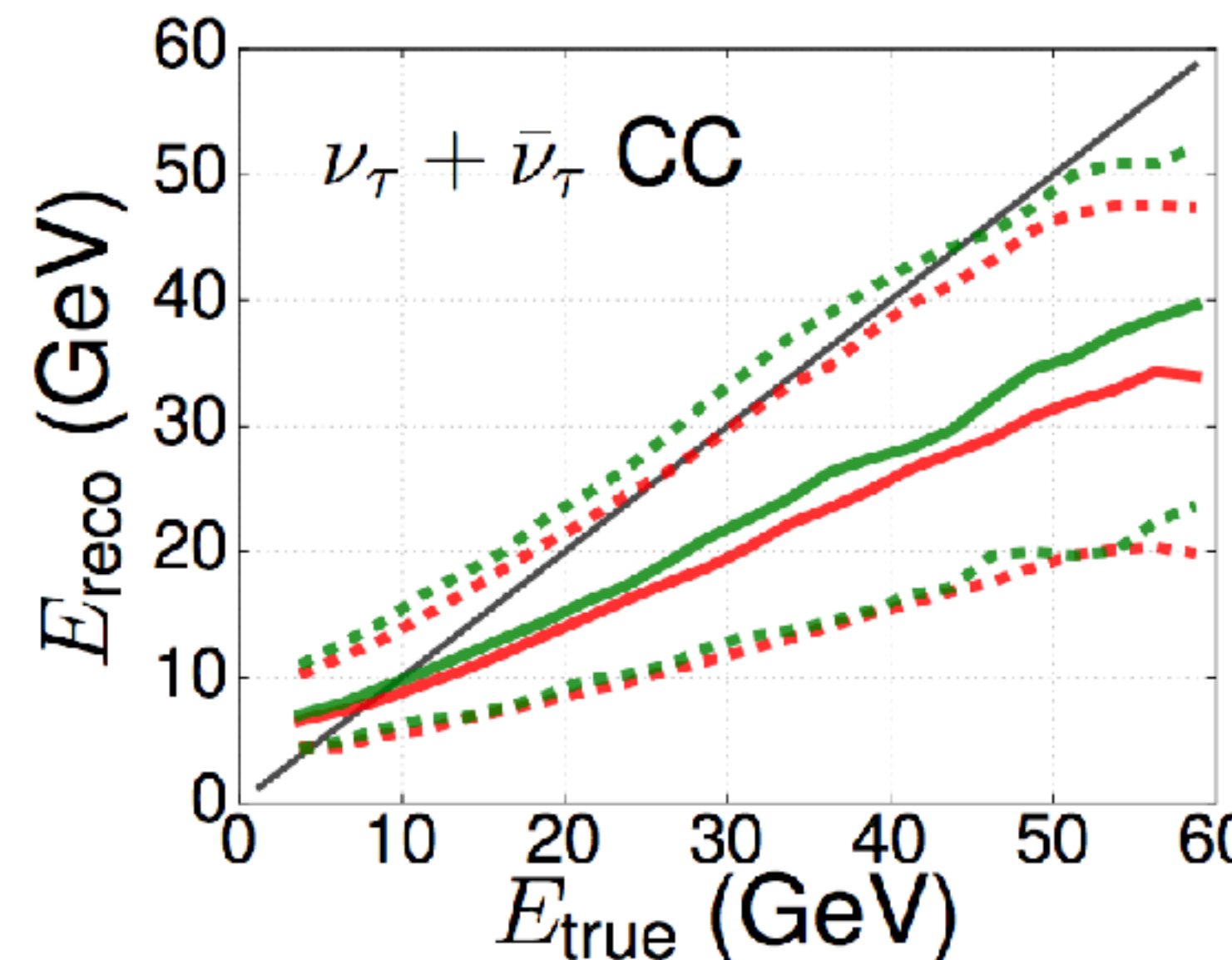
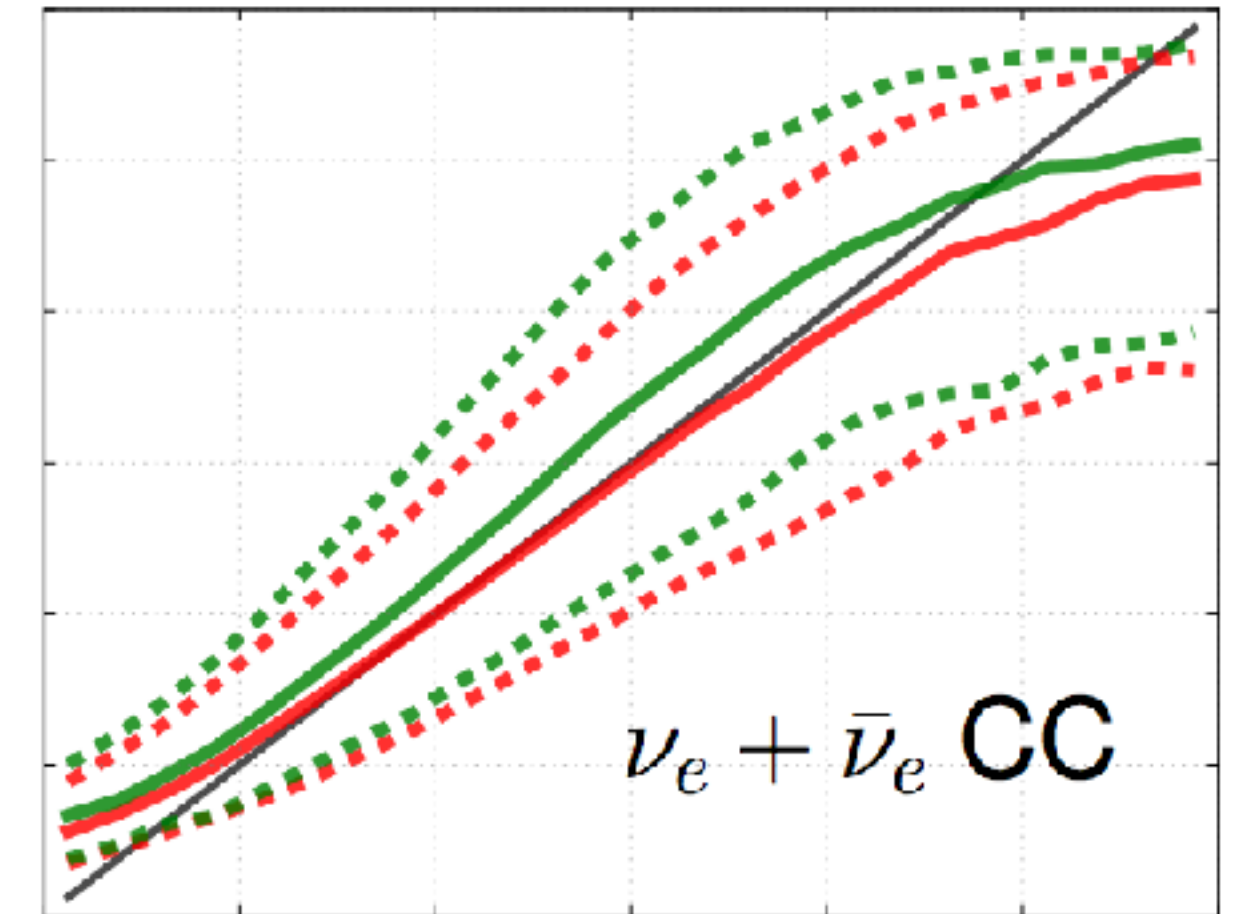
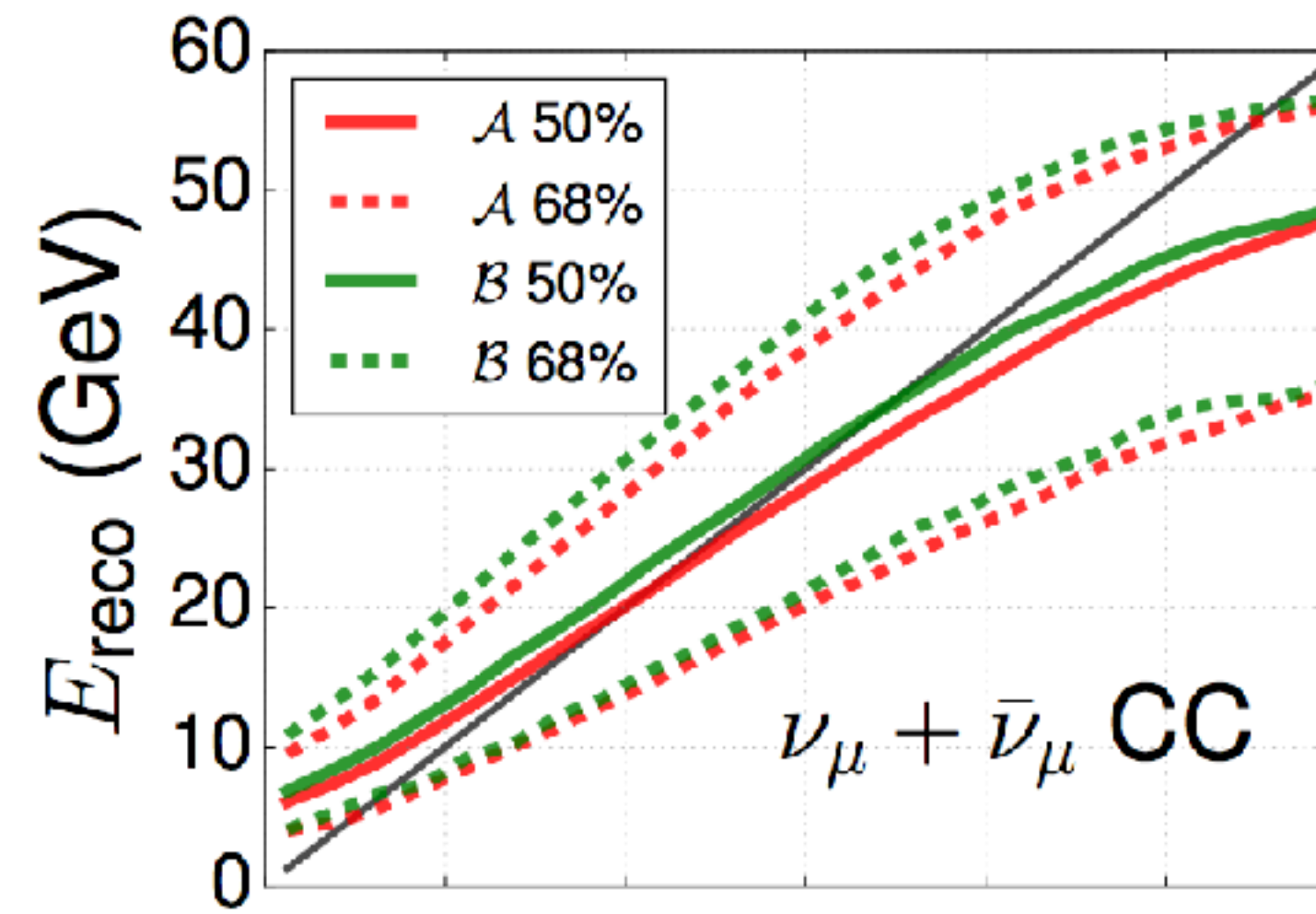
Performance

Resolution @ 20 GeV for tracks (cascades):

- 24% (29%) in energy
- 10° (16°) zenith

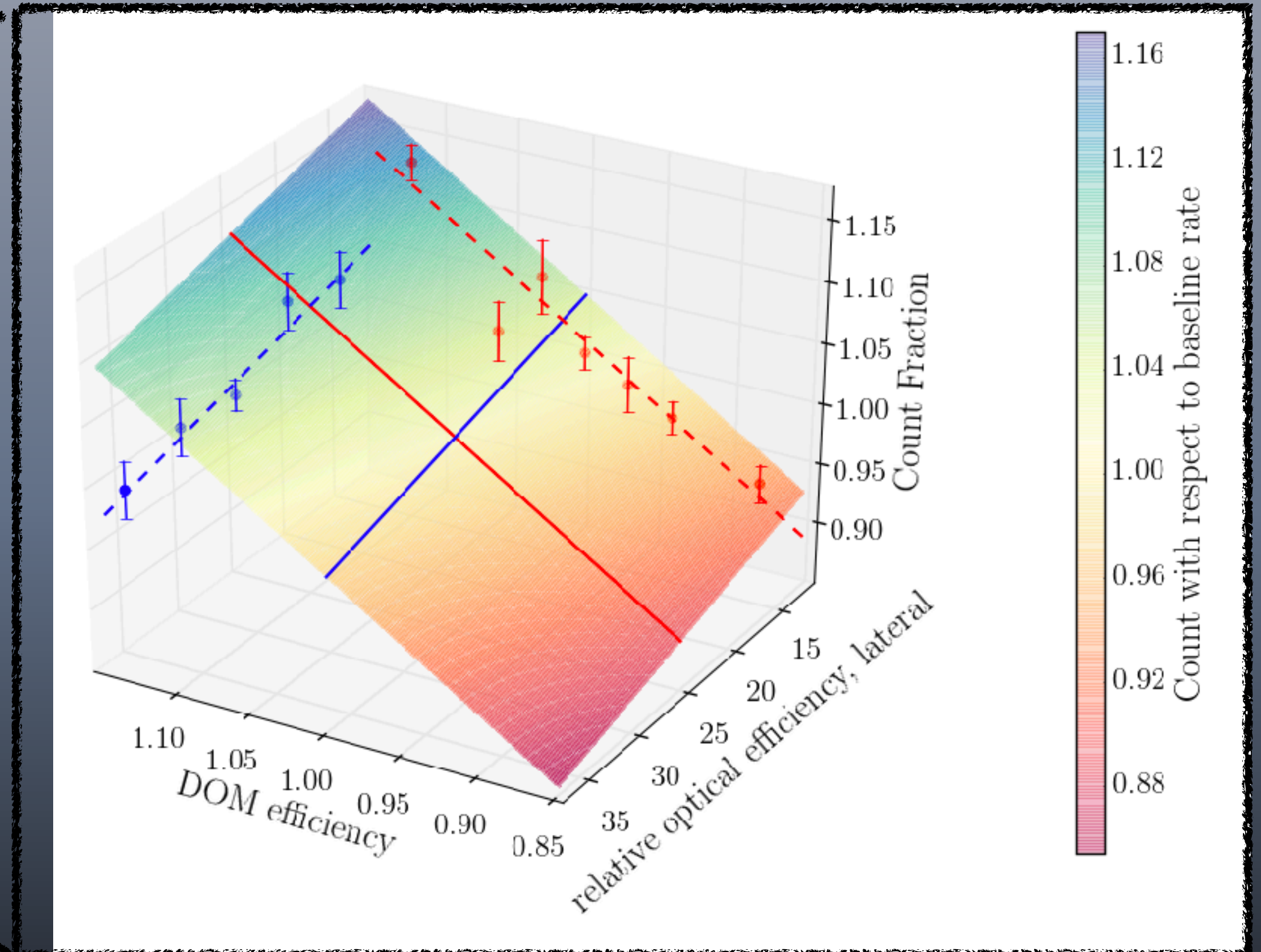
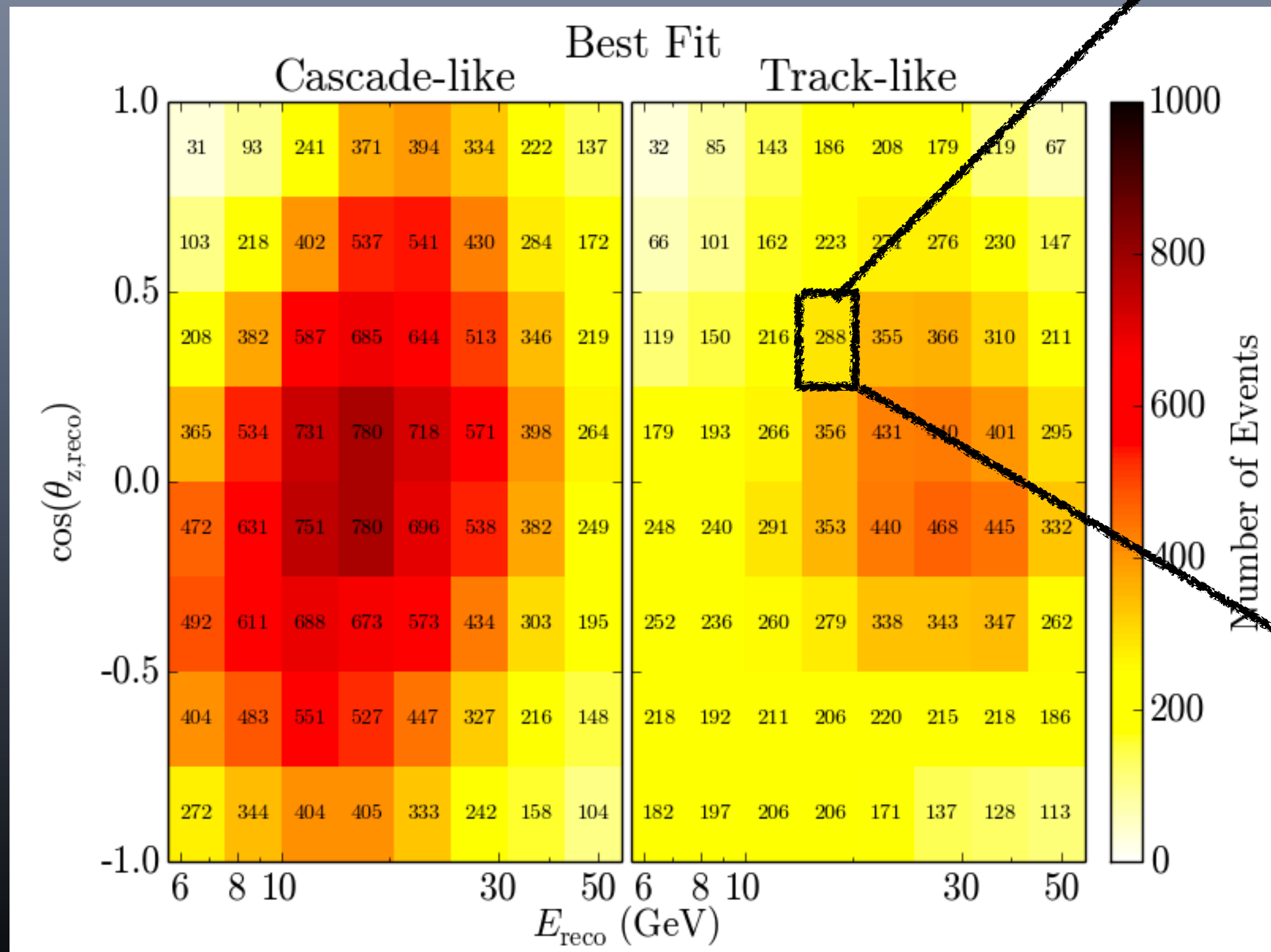
Classification @ 20 GeV:

- 50% of ν_μ CC events correctly classified as tracks



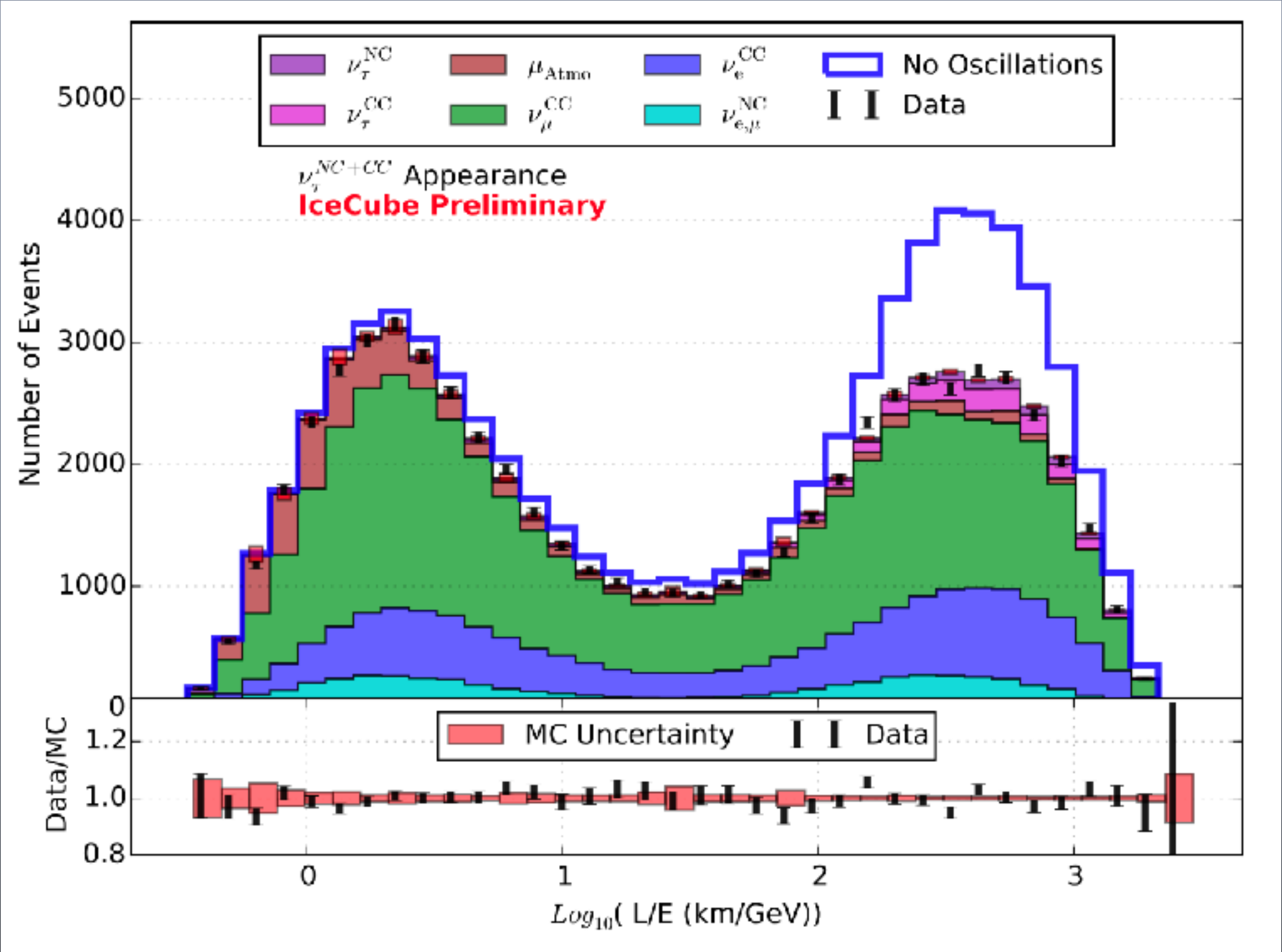
Detector systematics

Discrete MC sets mapped to continuous reweighing scheme



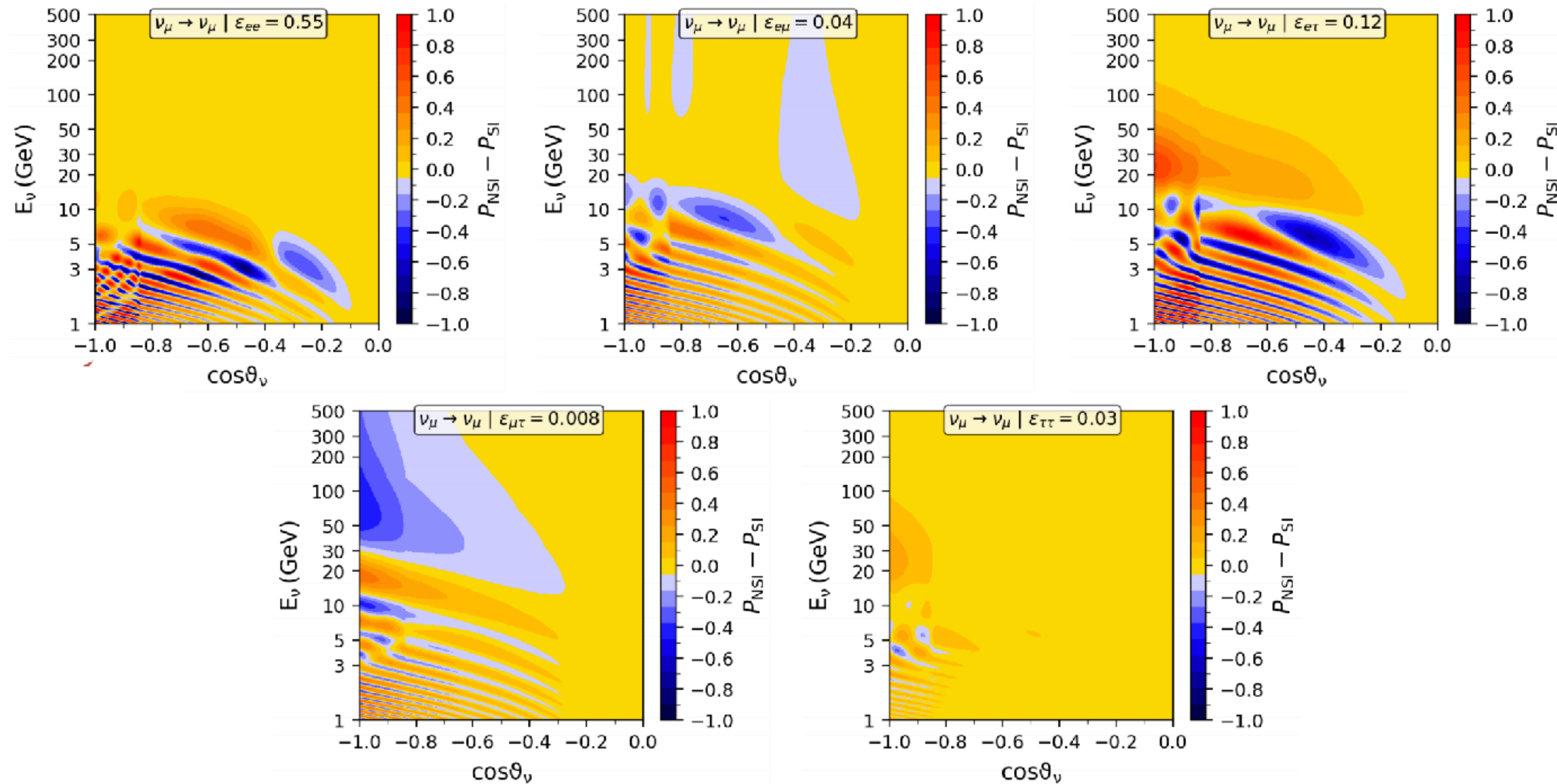
Neutrino oscillations

Best fit systematics



Parameter	Prior	Analysis \mathcal{A}		Analysis \mathcal{B}	
		Best fit (CC+NC)	Best fit (CC)	Best fit (CC+NC)	Best fit (CC)
Neutrino Flux & Cross Section:					
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03	1.03	1.03
ν_e Up/Hor. Flux Ratio (σ)	0.0 ± 1.0	-0.19	-0.18	-0.25	-0.24
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	-0.42	-0.33	0.01	0.04
$\Delta\gamma_\nu$ (Spectral Index)	0.0 ± 0.1	0.03	0.03	-0.05	-0.04
Effective Livetime (years)	-	2.21	2.24	2.45	2.46
M_A^{CCQE} (Quasi-Elastic) (GeV)	$0.99^{+0.248}_{-0.149}$	1.05	1.05	0.88	0.88
M_A^{res} (Resonance) (GeV)	1.12 ± 0.22	1.00	0.99	0.85	0.85
NC Normalization	1.0 ± 0.2	1.05	1.06	1.25	1.26
Oscillation:					
θ_{13} ($^\circ$)	8.5 ± 0.21	-	-	8.5	8.5
θ_{23} ($^\circ$)	-	49.8	50.2	46.1	45.9
Δm_{32}^2 (10^{-3}eV^2)	-	2.53	2.56	2.38	2.34
Detector:					
Optical Eff., Overall (%)	100 ± 10	98.4	98.4	105	104
Optical Eff., Lateral (σ)	0.0 ± 1.0	0.49	0.48	-0.25	-0.27
Optical Eff., Head-on (a.u.)	-	-0.63	-0.64	-1.15	-1.22
Local Ice Model	-	-	-	0.02	0.07
Bulk Ice, Scattering (%)	100.0 ± 10	103.0	102.8	97.4	97.3
Bulk Ice, Absorption (%)	100.0 ± 10	101.5	101.7	102.1	101.9
Atmospheric Muons:					
Atm. μ Fraction (%)	-	8.1	8.0	4.6	4.6
$\Delta\gamma_\mu$ (μ Spectral Index, σ)	0.0 ± 1.0	0.15	0.15	-	-
Coincident $\nu + \mu$ Fraction	0.0 ± 0.1	0.01	0.01	-	-
Measurement:					
ν_τ Normalization	-	0.73	0.57	0.59	0.43

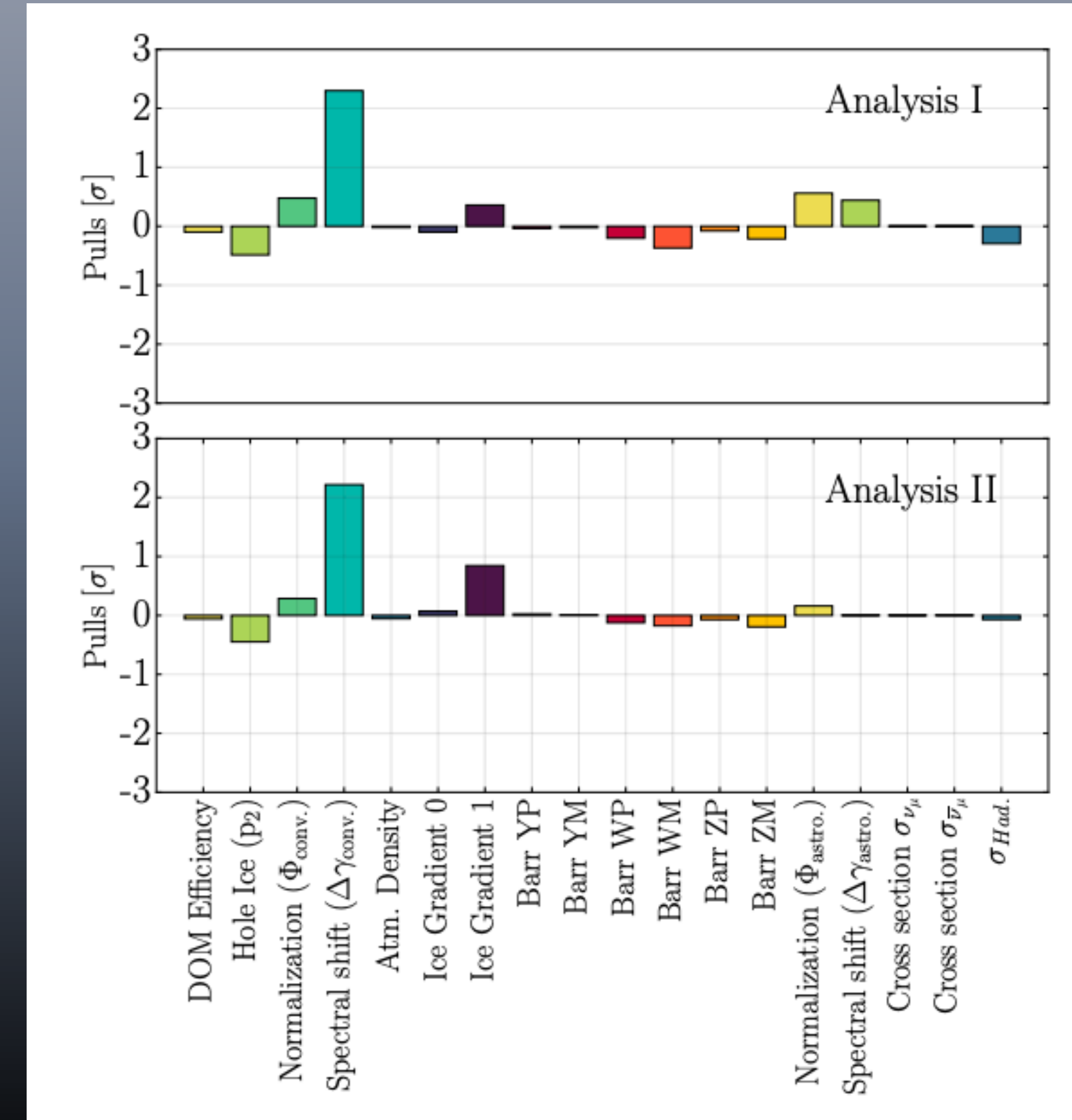
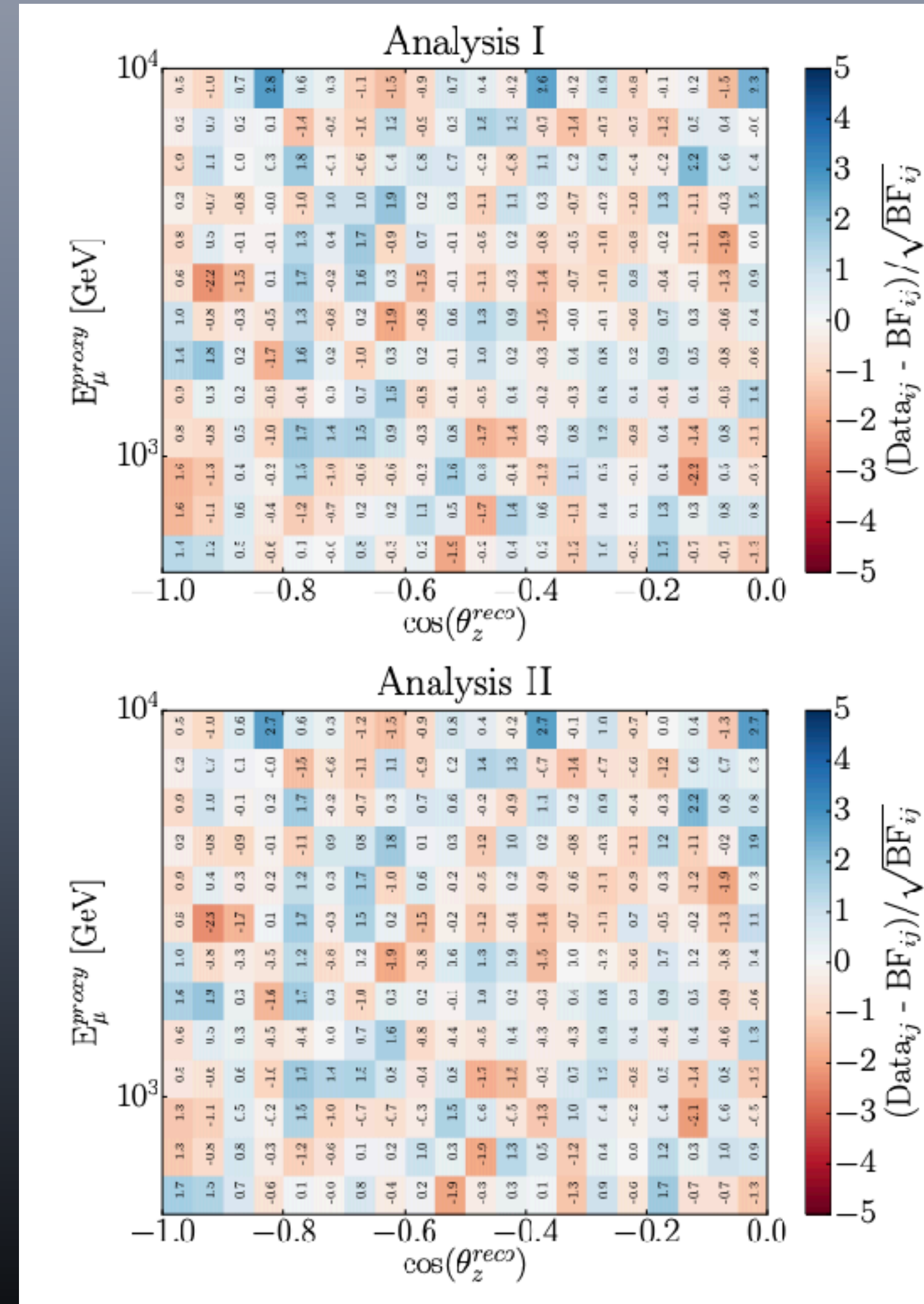
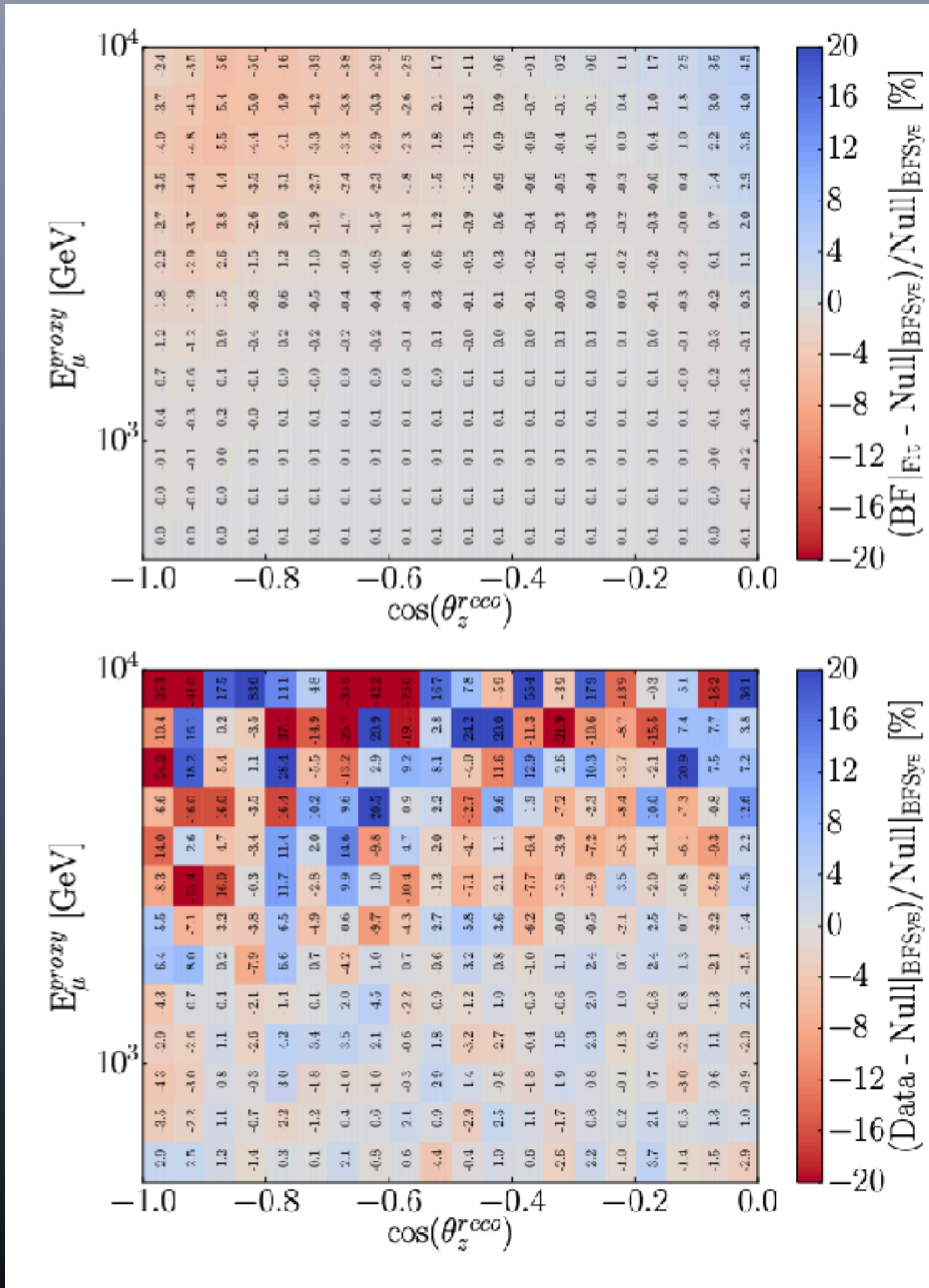
Effect of different NSI couplings



Non-standard disappearance at high energy due to $\varepsilon_{e\mu}$ & $\varepsilon_{\mu\tau}$
 Less disappearance at high energy due to $\varepsilon_{e\tau}$ & $\varepsilon_{\tau\tau}$

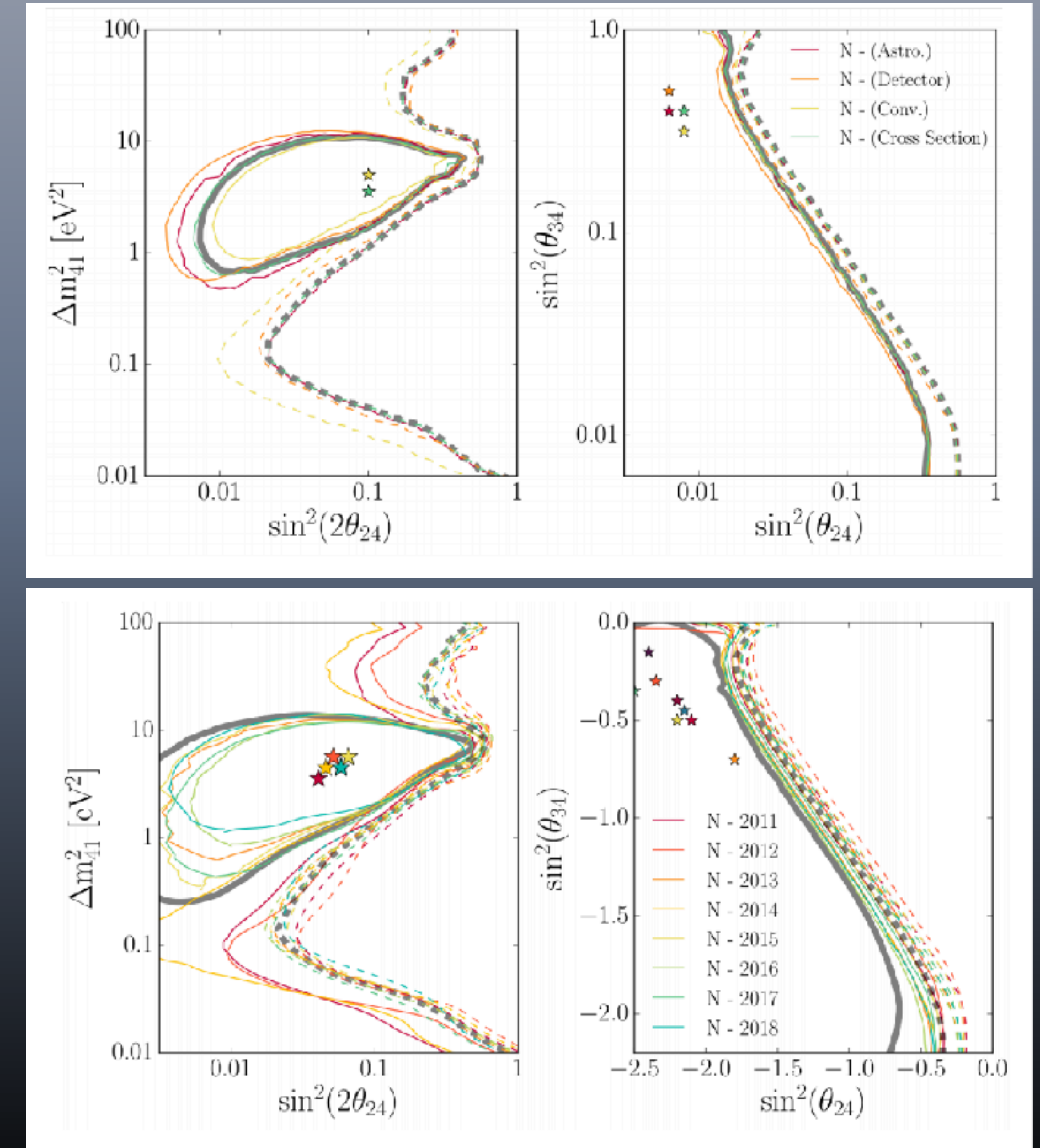
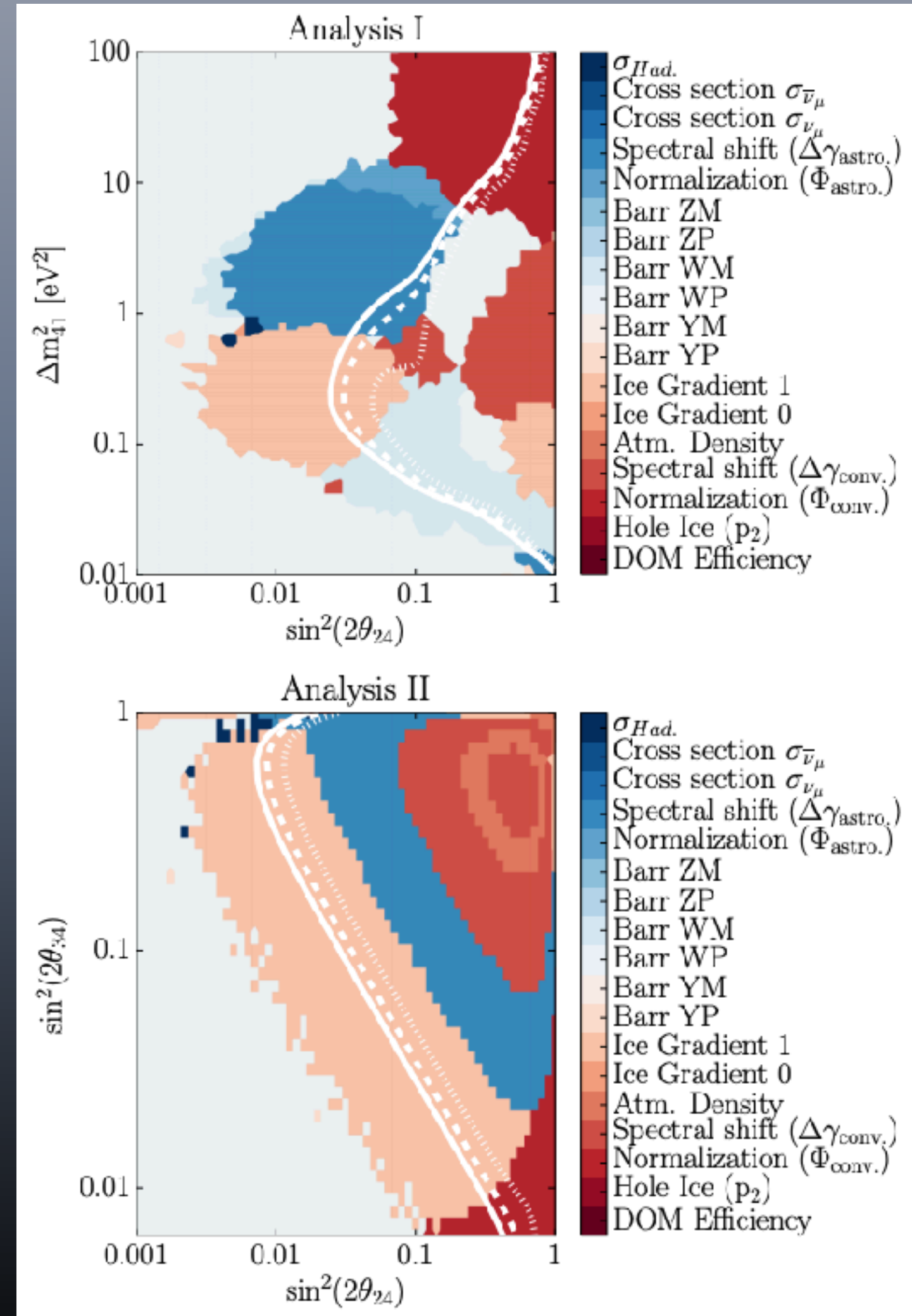
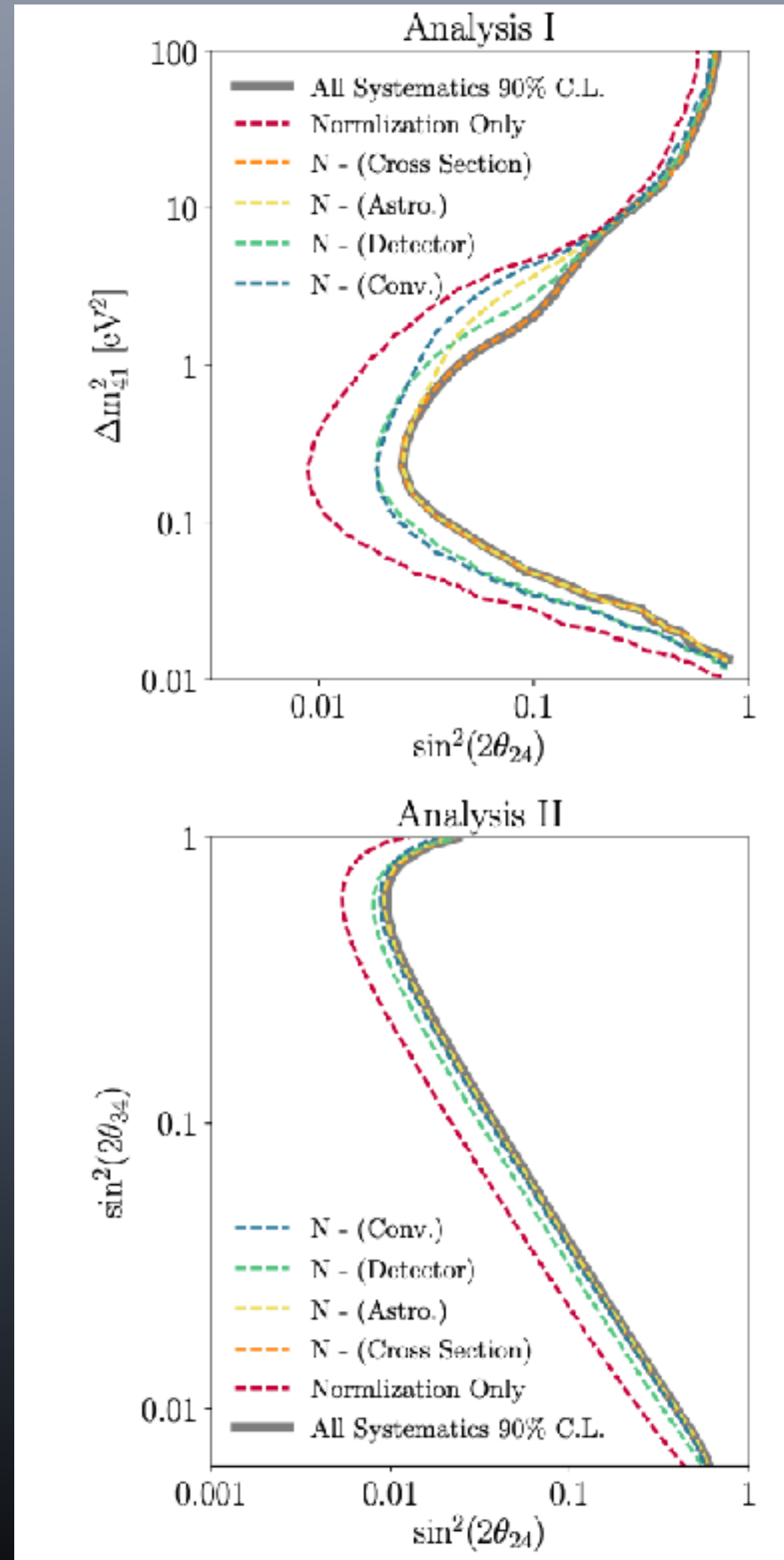
eV Sterile Search

Impact of systematics



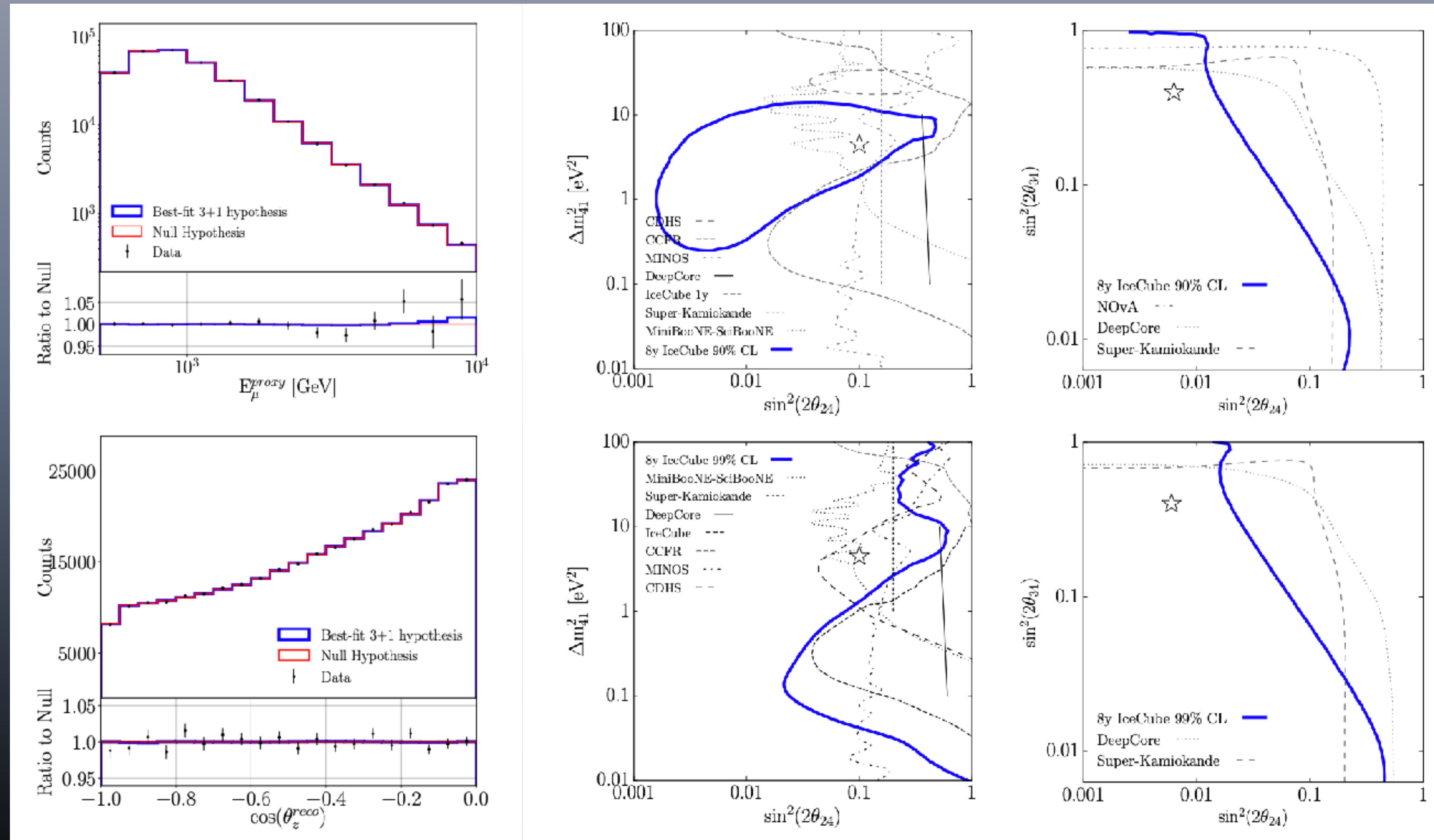
eV Sterile Search

Impact of systematics



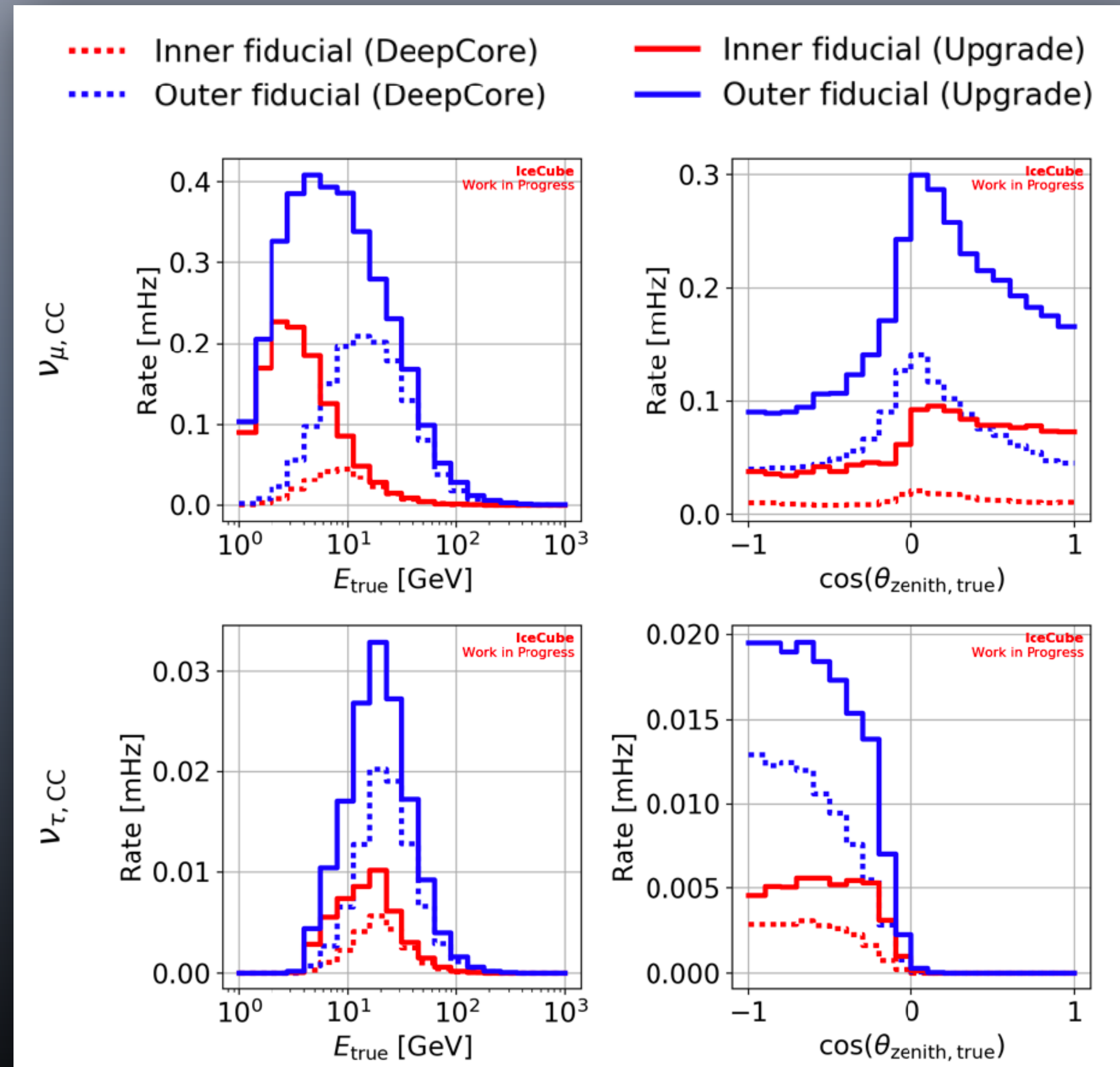
eV Sterile Search

Impact of systematics



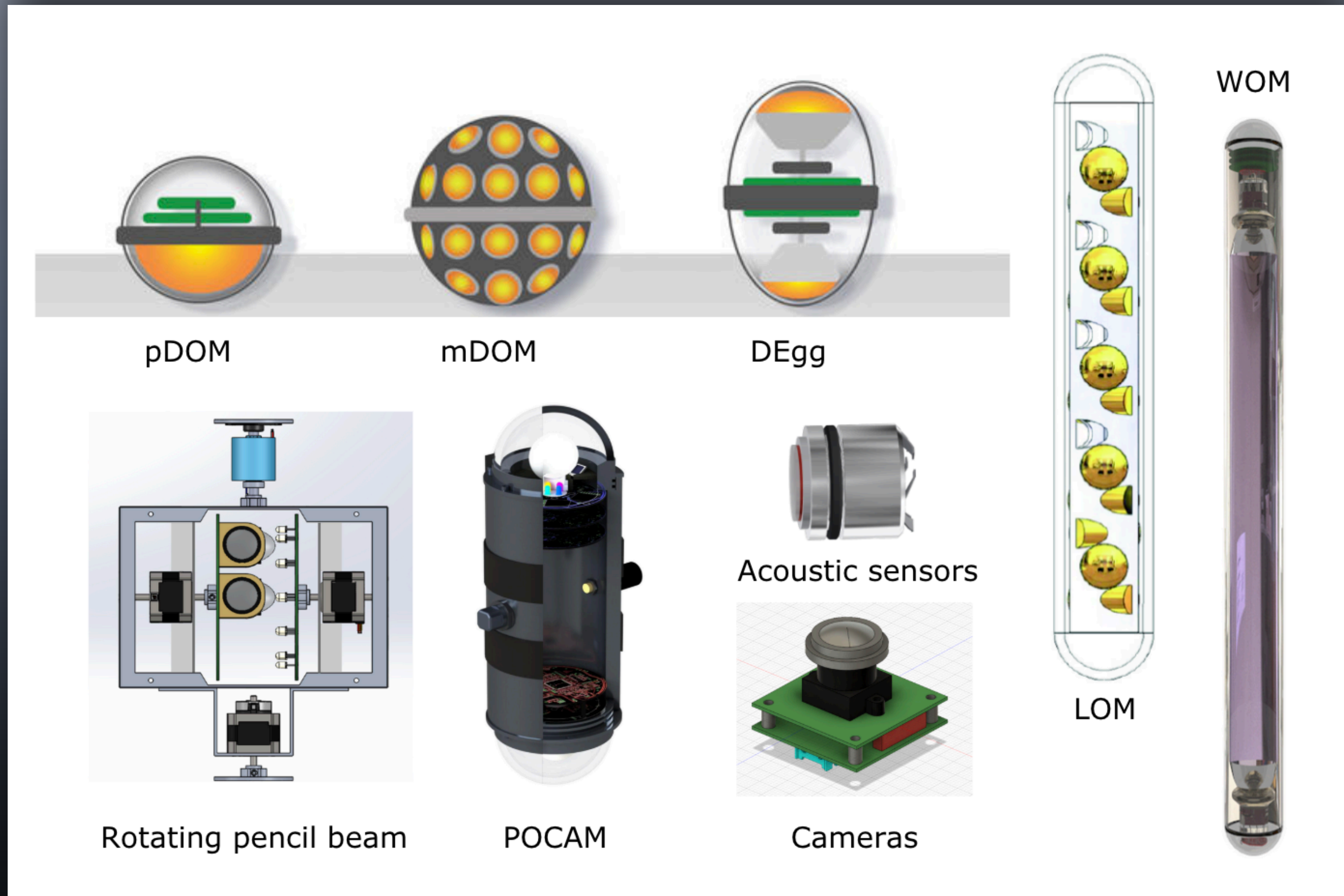
IceCube Upgrade Events

More detail in every event



The IceCube Upgrade

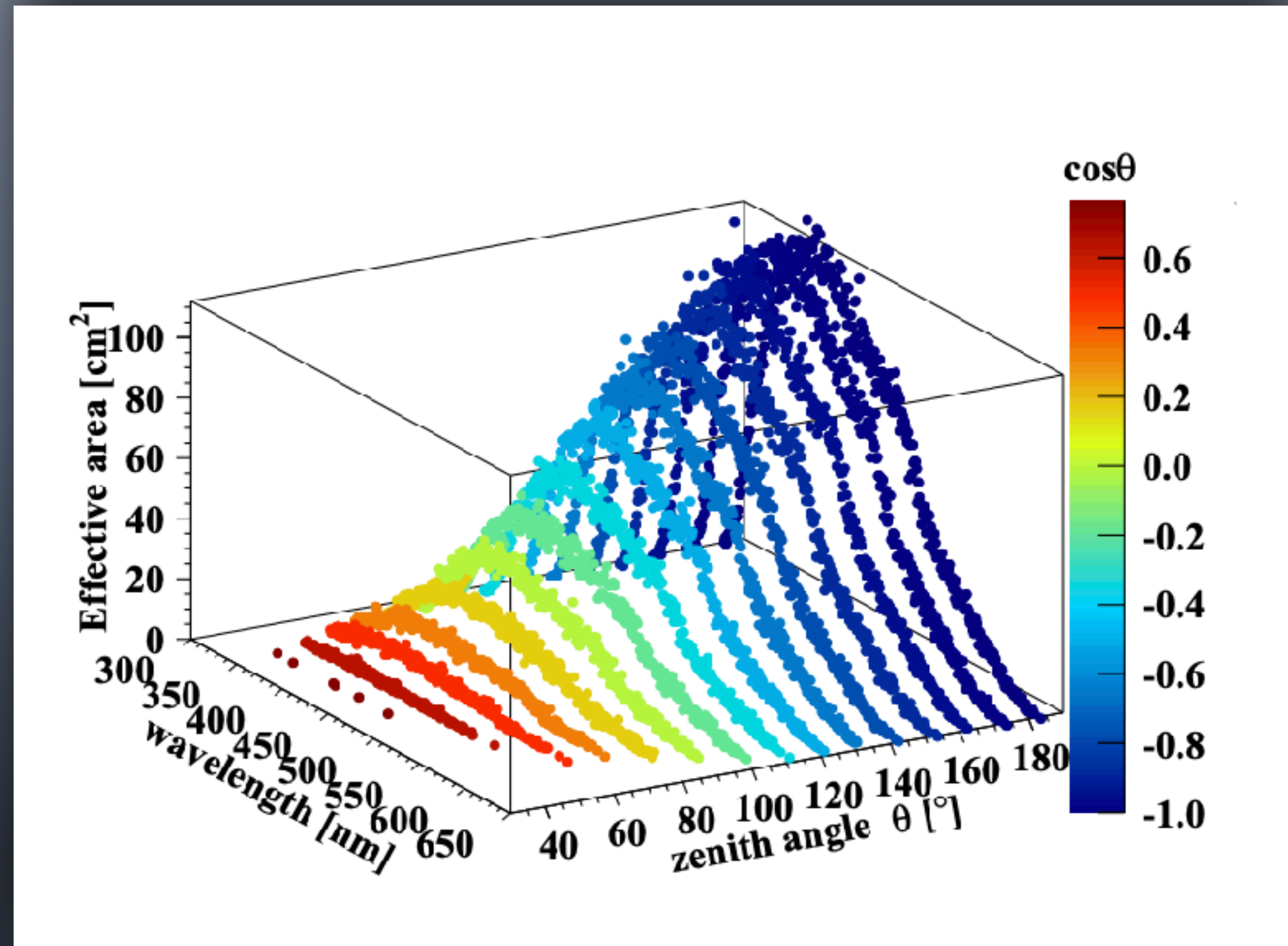
New technology



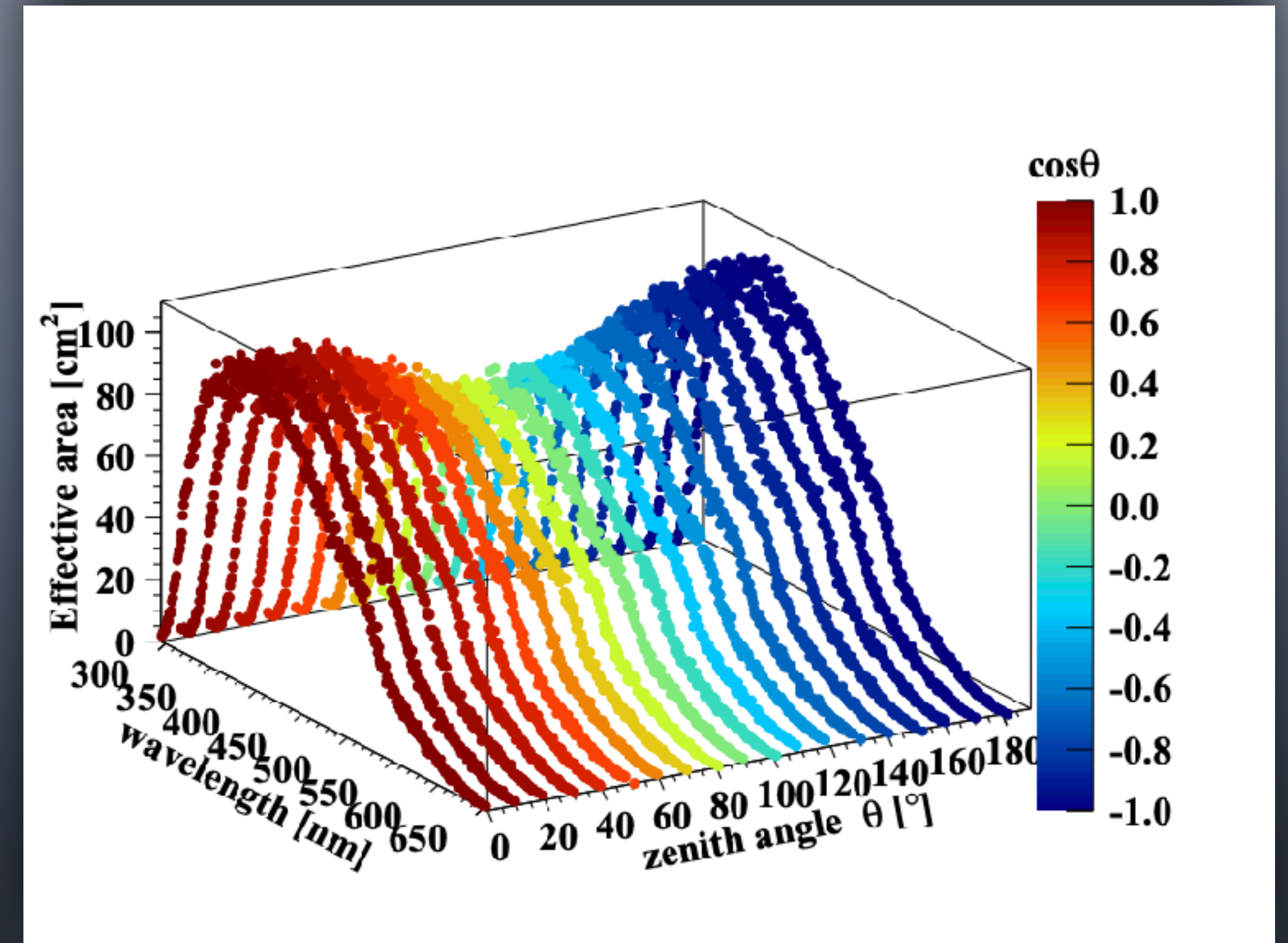
The IceCube Upgrade

New technology

IceCube Gen1 DOM



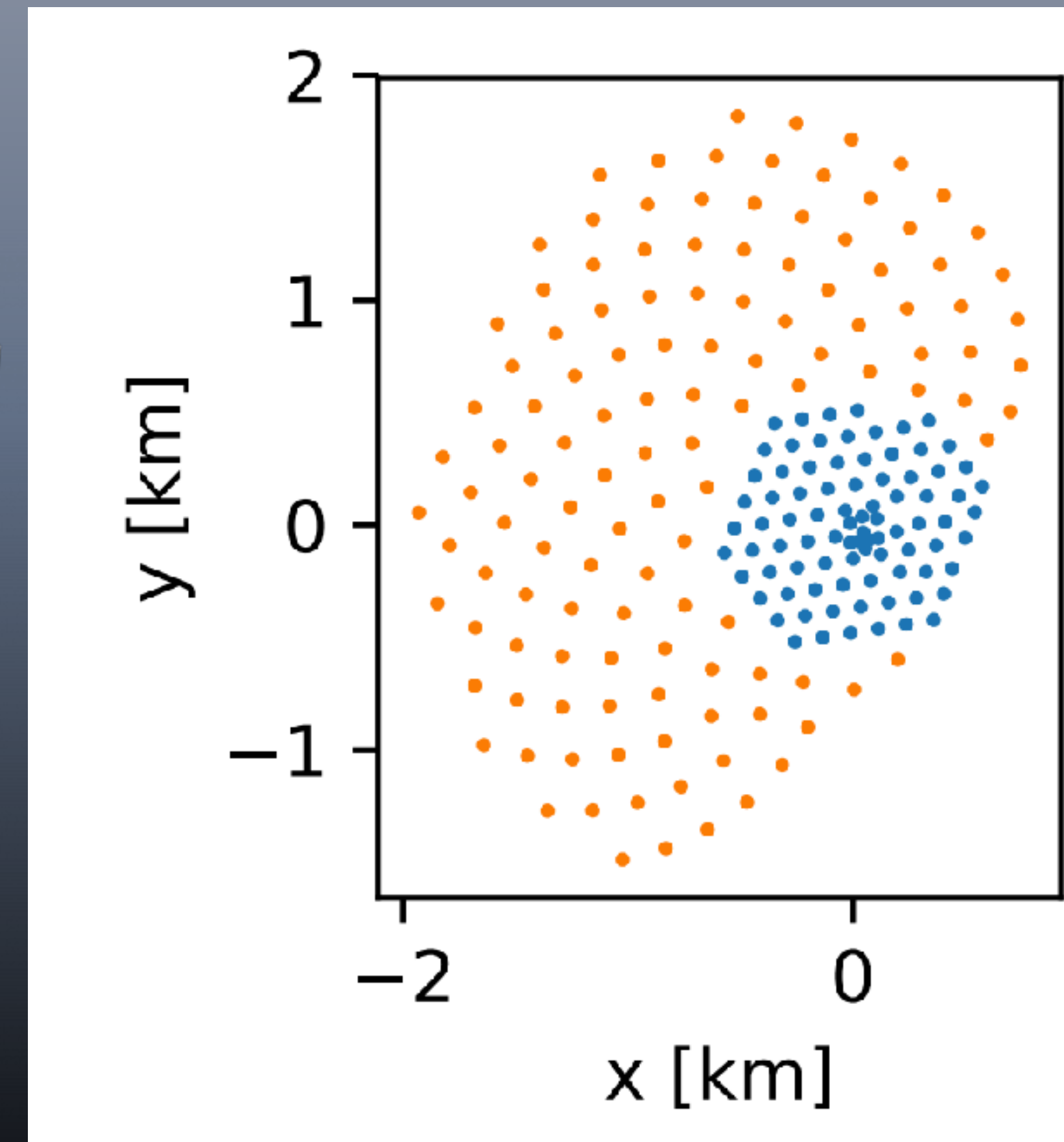
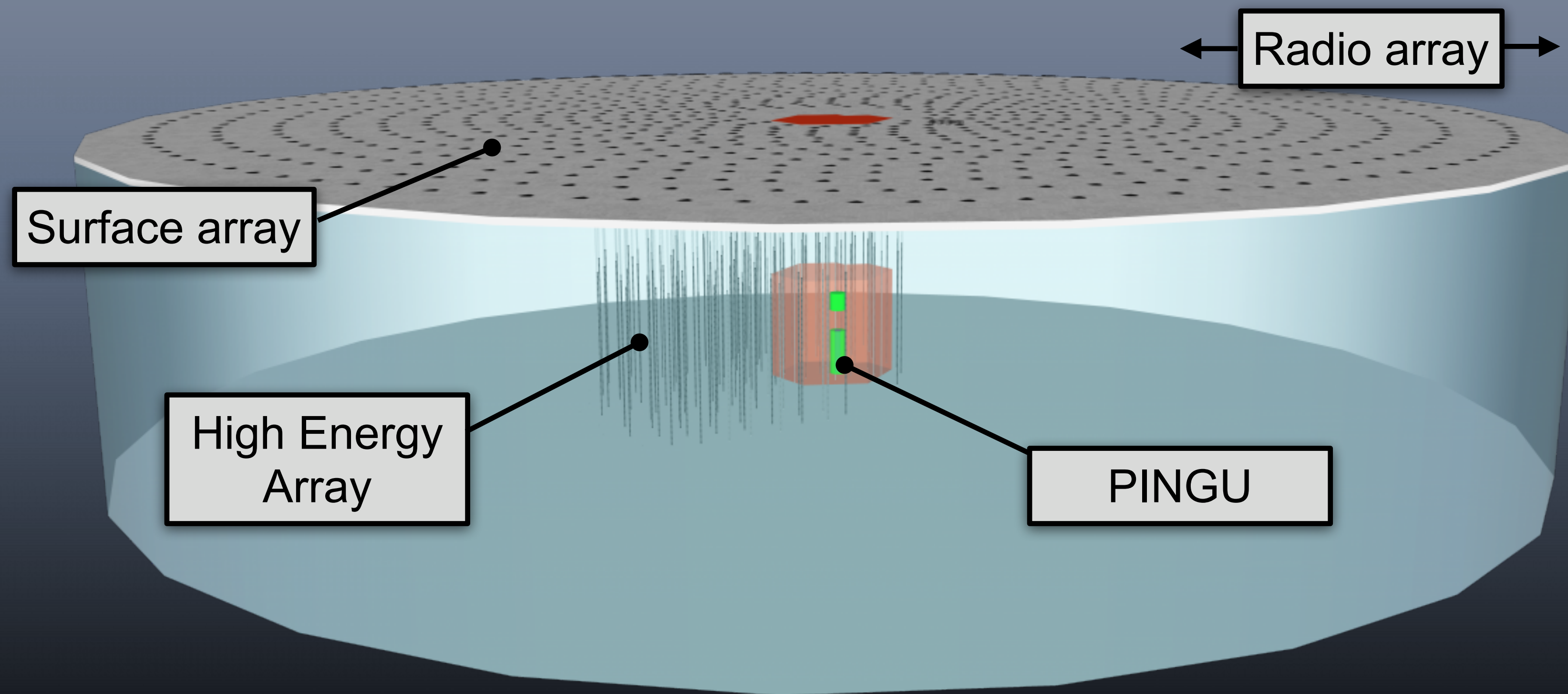
upgrade module: DEgg



PINGU LOI v2: <https://arxiv.org/pdf/1401.2046.pdf>

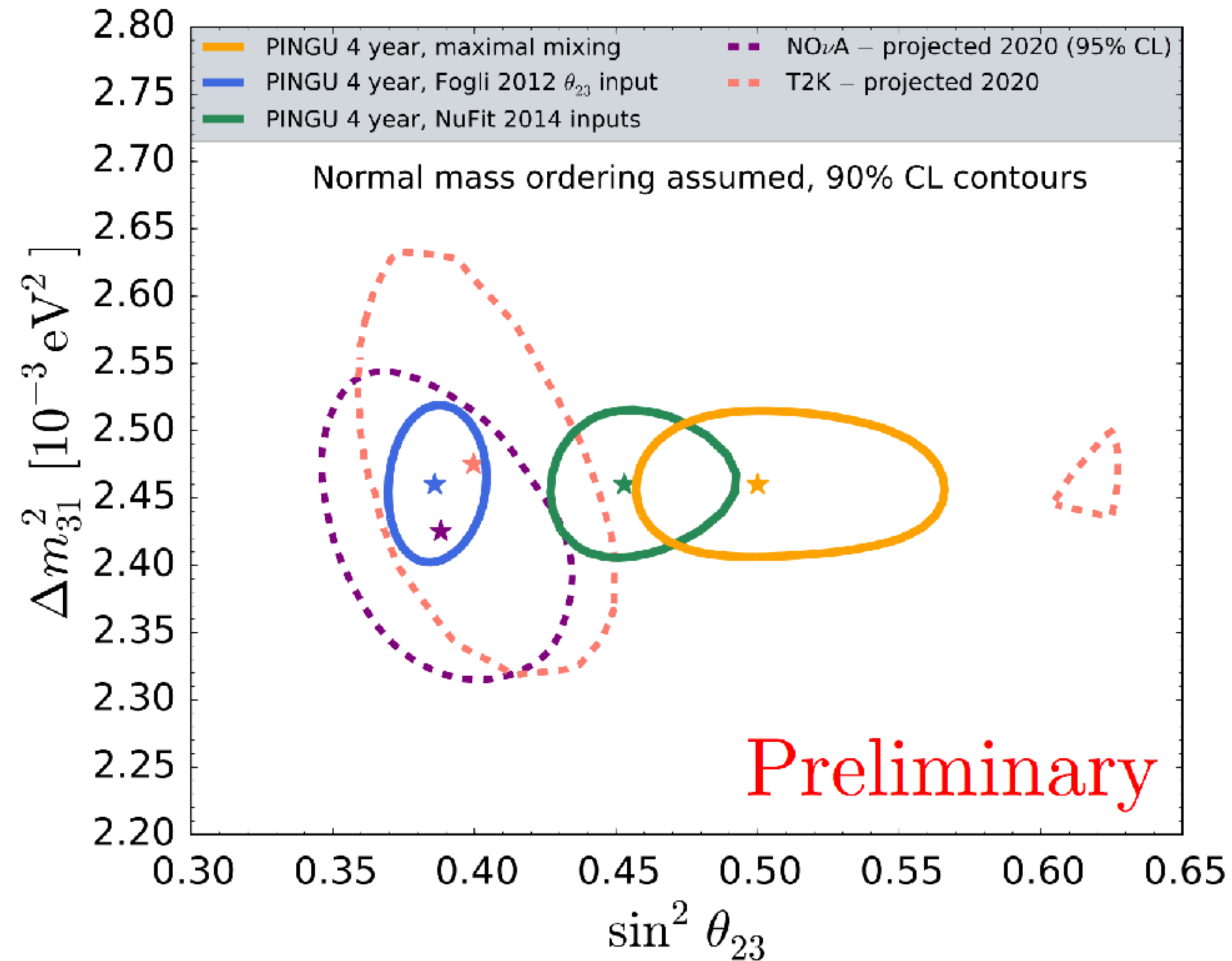
IceCube-Gen2

A vision for the future of neutrino astroparticle physics at the South Pole



Neutrino oscillations

Highest energy probe of atmospheric $\nu_\mu \rightarrow \nu_\tau$ mixing



Expected precision:

$$\Delta m^2_{32} \sim 1\% (1\sigma)$$

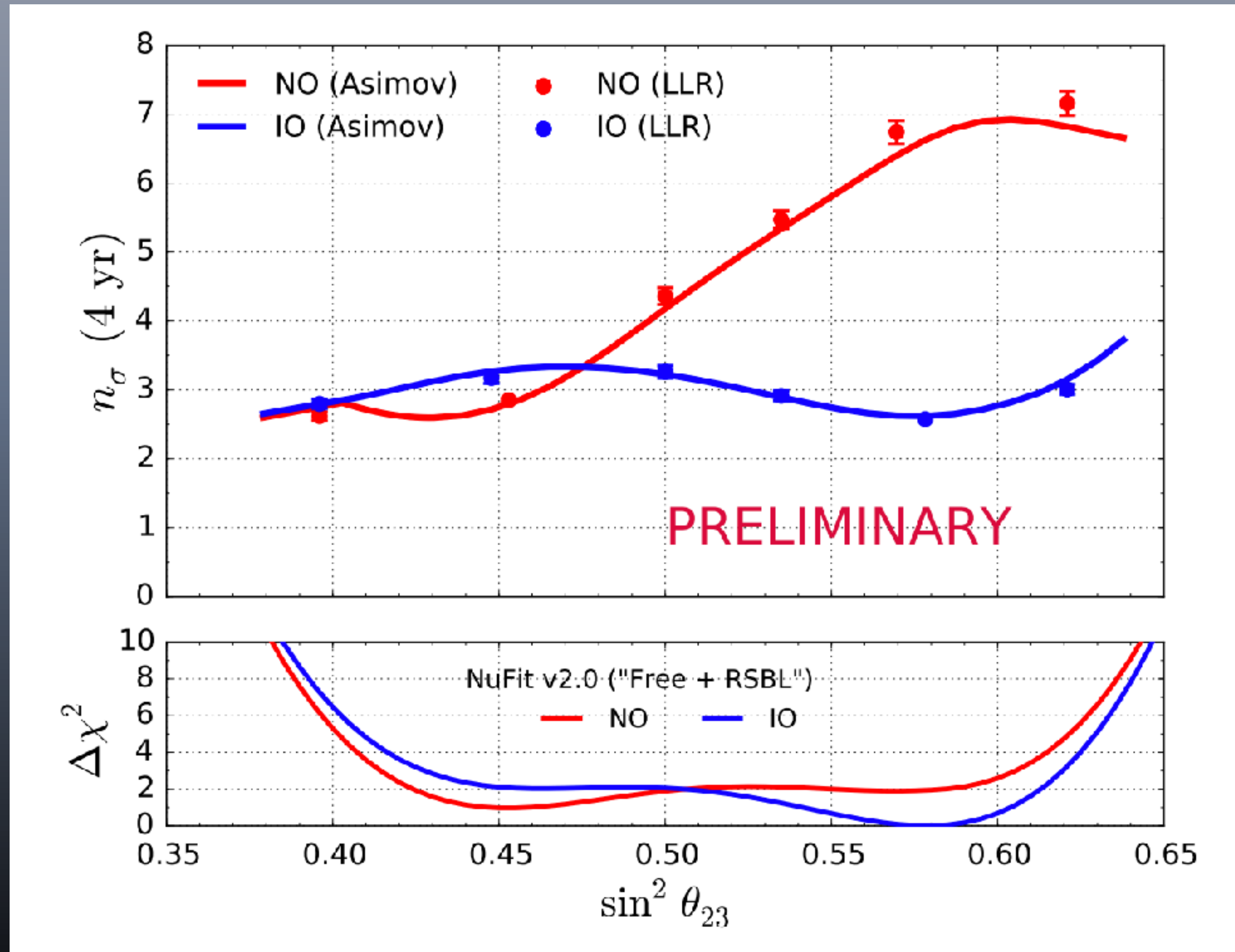
$$\theta_{23} \sim 4\% (1\sigma)$$

depends on NMO and true θ_{23}

Neutrino oscillations

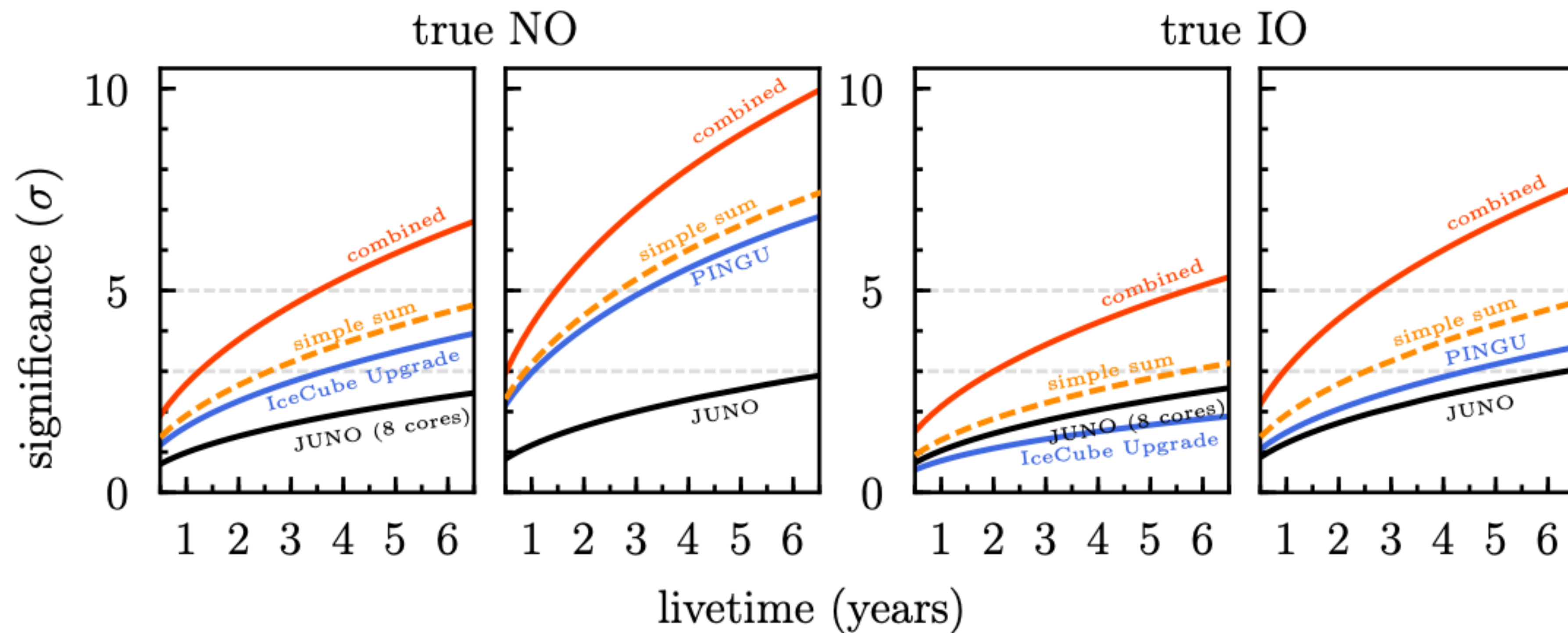
Neutrino Mass Ordering

PINGU LOI Version 2 @ [arXiv:1401.2046v2](https://arxiv.org/abs/1401.2046v2)



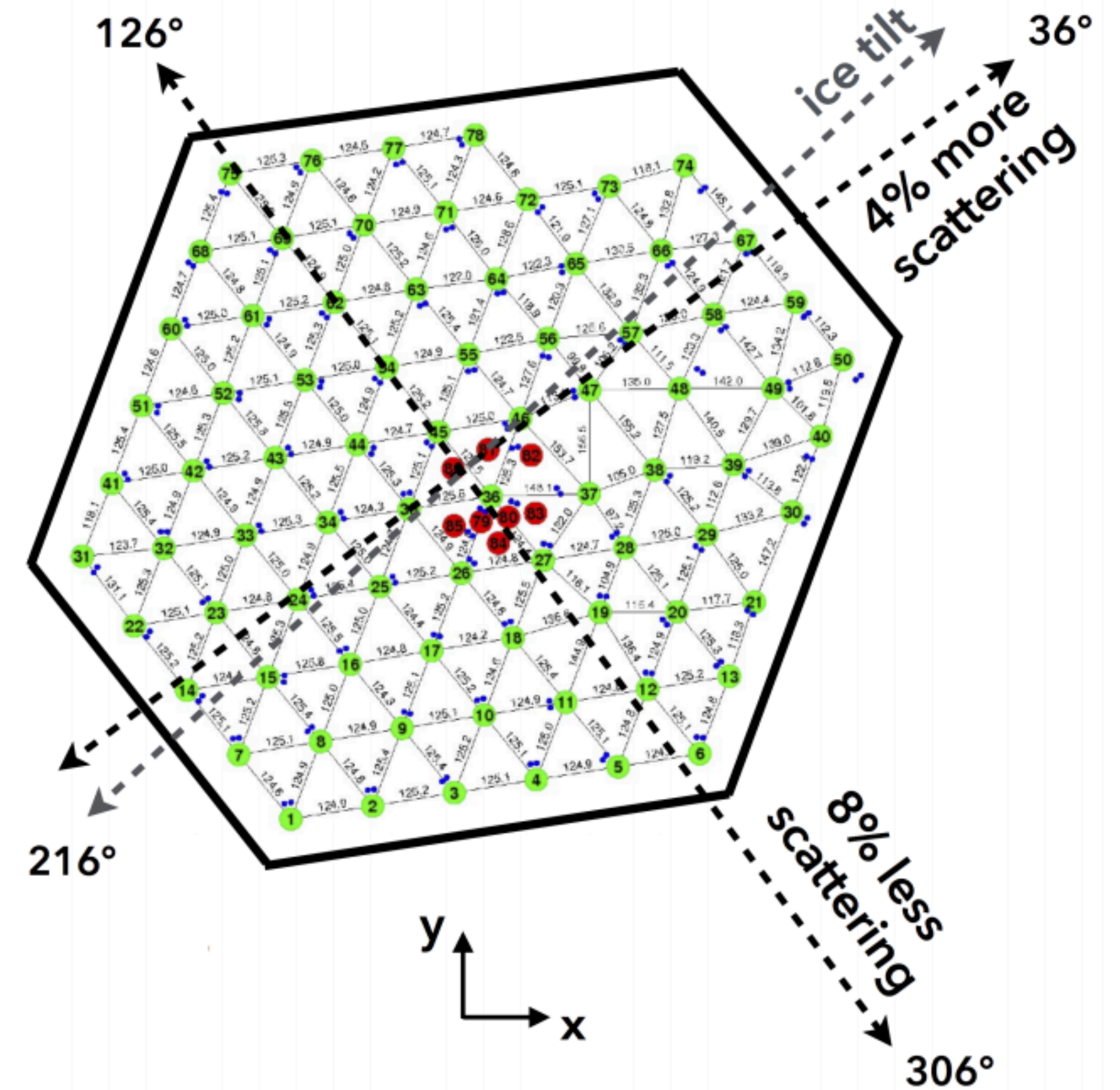
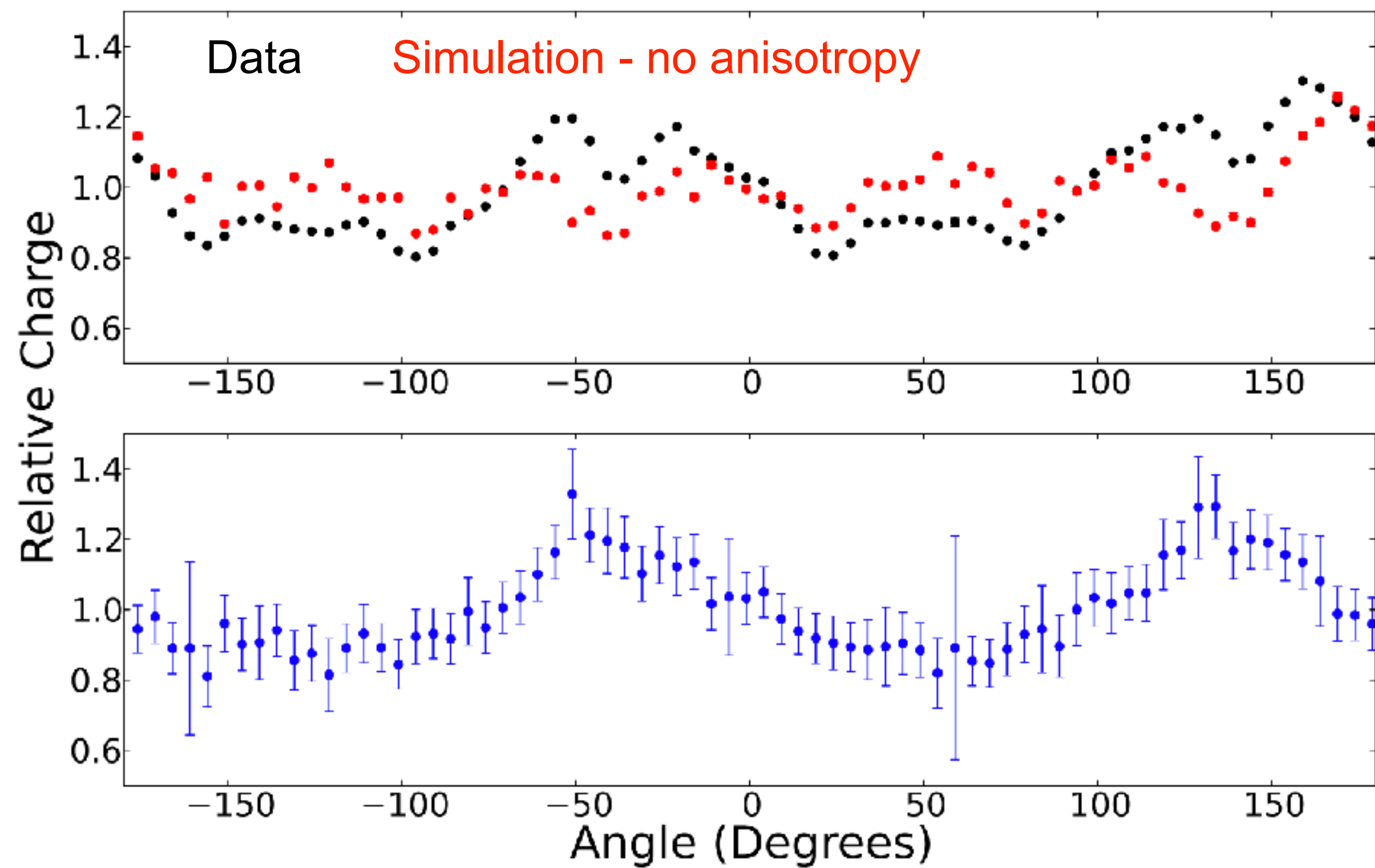
Exploit synergy between JUNO and IceCube Upgrade

Phys. Rev. D 101, 032006 (2020)



Ice anisotropy

South Pole ice anisotropy: Proceedings of ICRC2013 0580, 2014



SPICEcore

Many devices:

Dust logger

UV logger

Luminescence logger

Camera logger

1.5km

350 m

1.7km
⊕ 12.7 cm

Ice tilt

*Borehole drilled for
glaciology purposes*