Neutrino oscillation measurements with IceCube DeepCore.

Summer Blot

22.06.2020

Neutrino2020 - virtual meeting

DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ICECUBE UPGRADE

The IceCube Neutrino Observatory

The IceCube Neutrino Observatory

The IceCube Neutrino Observatory

Frank-Tamm formula

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

The IceCube Neutrino Observatory

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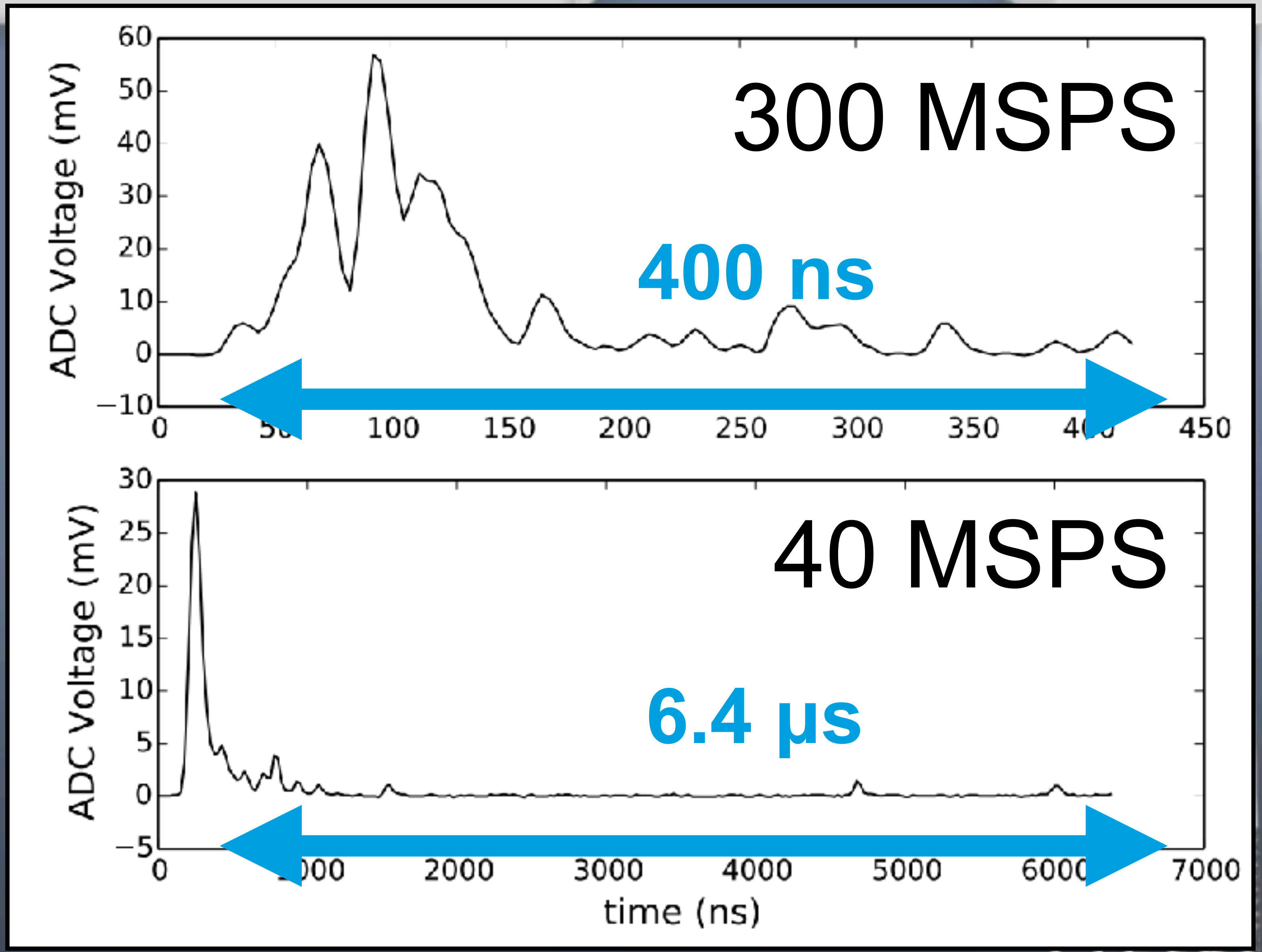

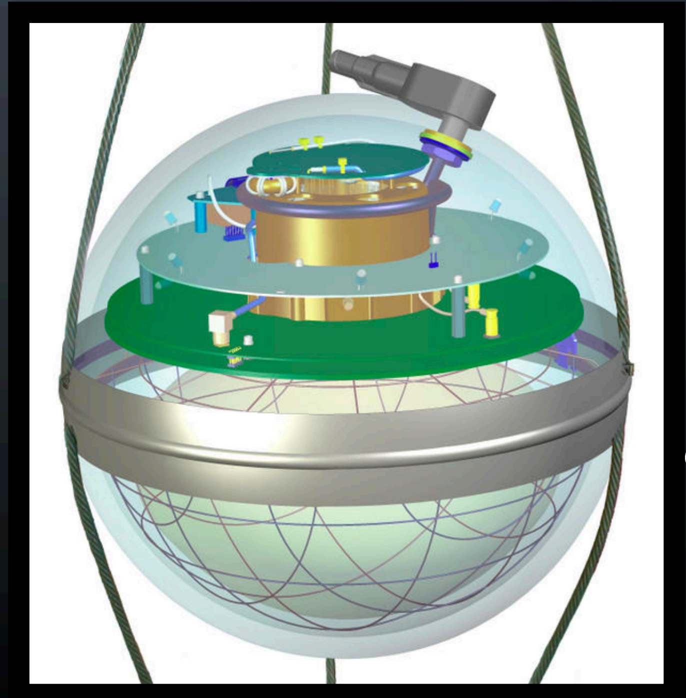

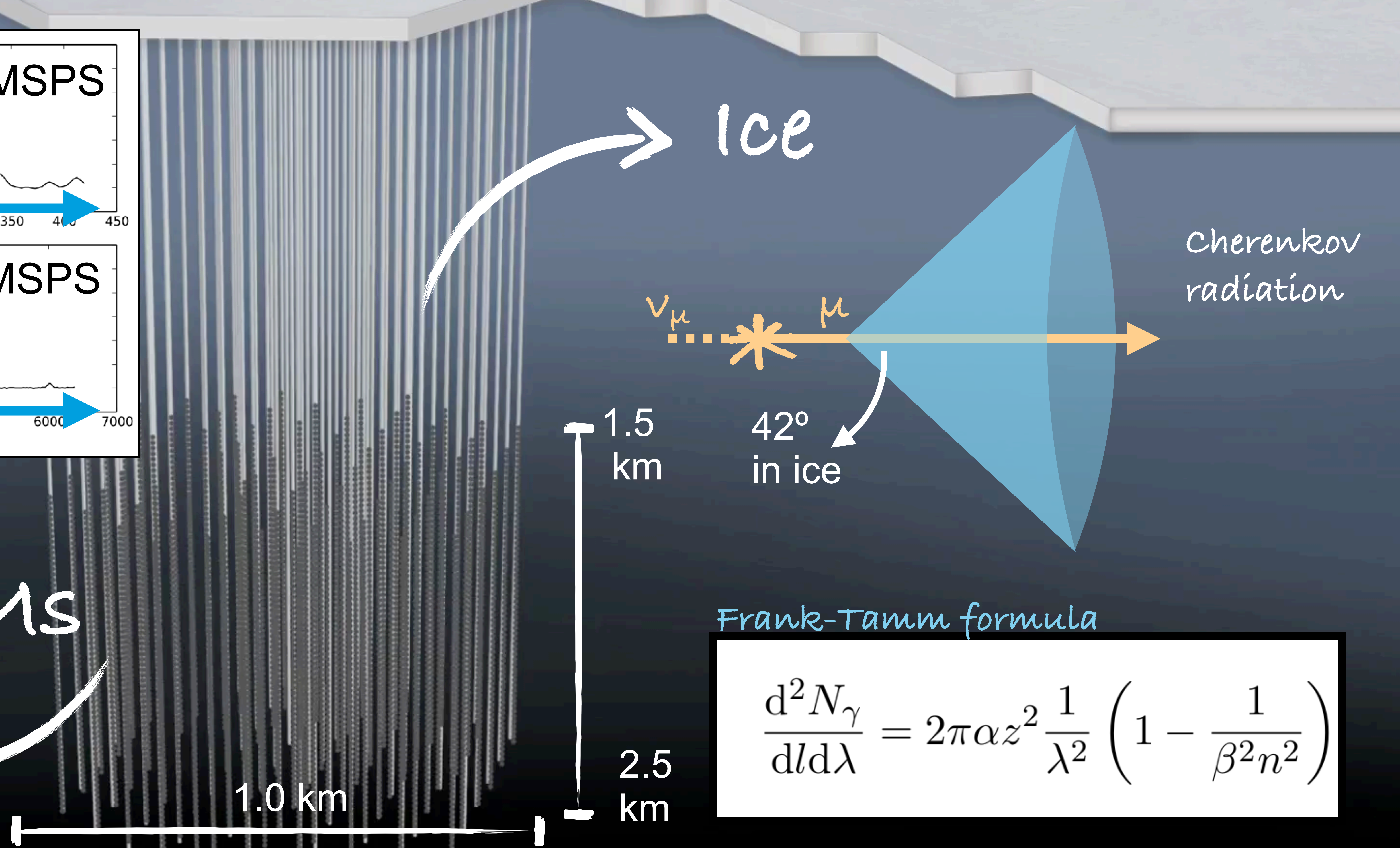

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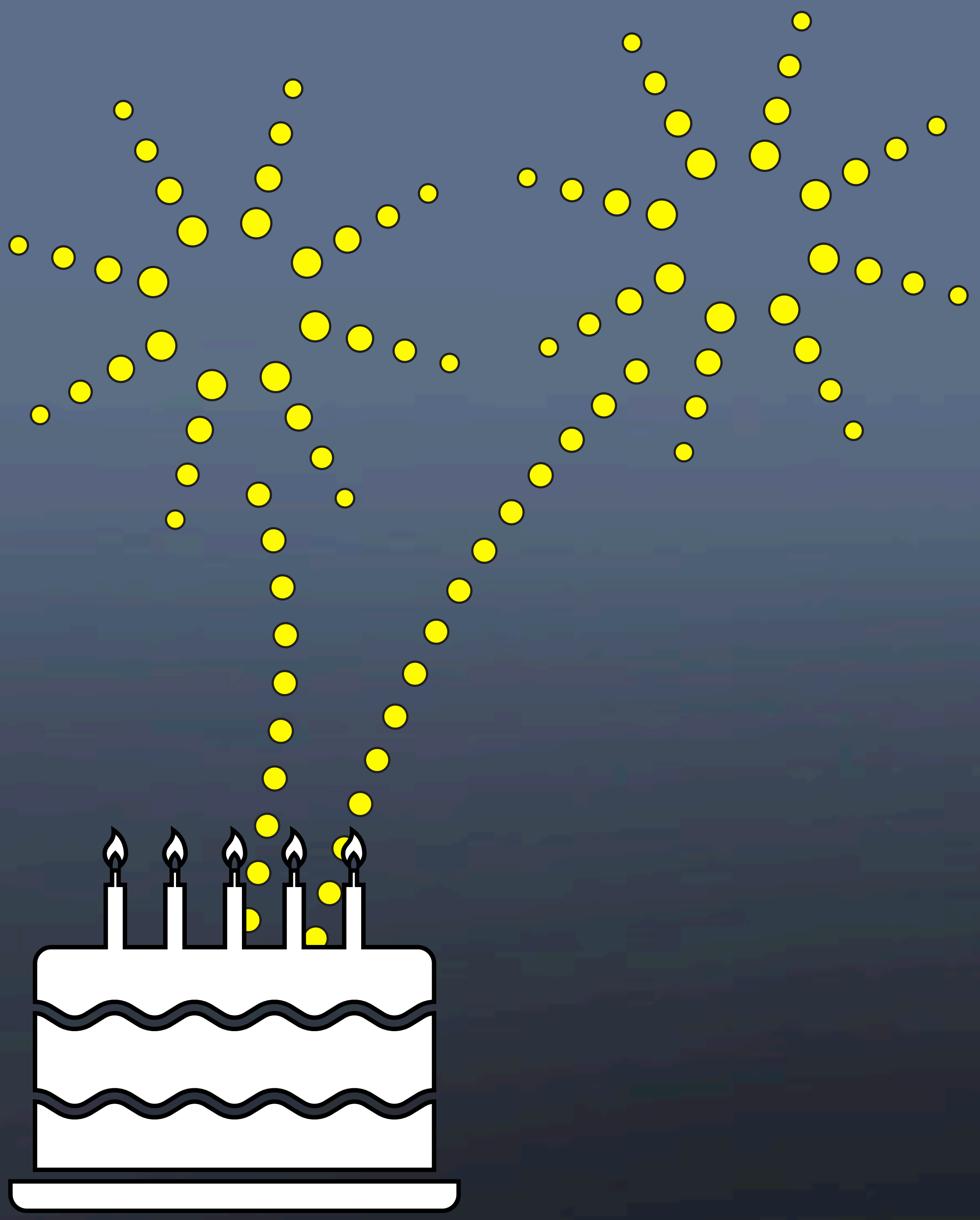
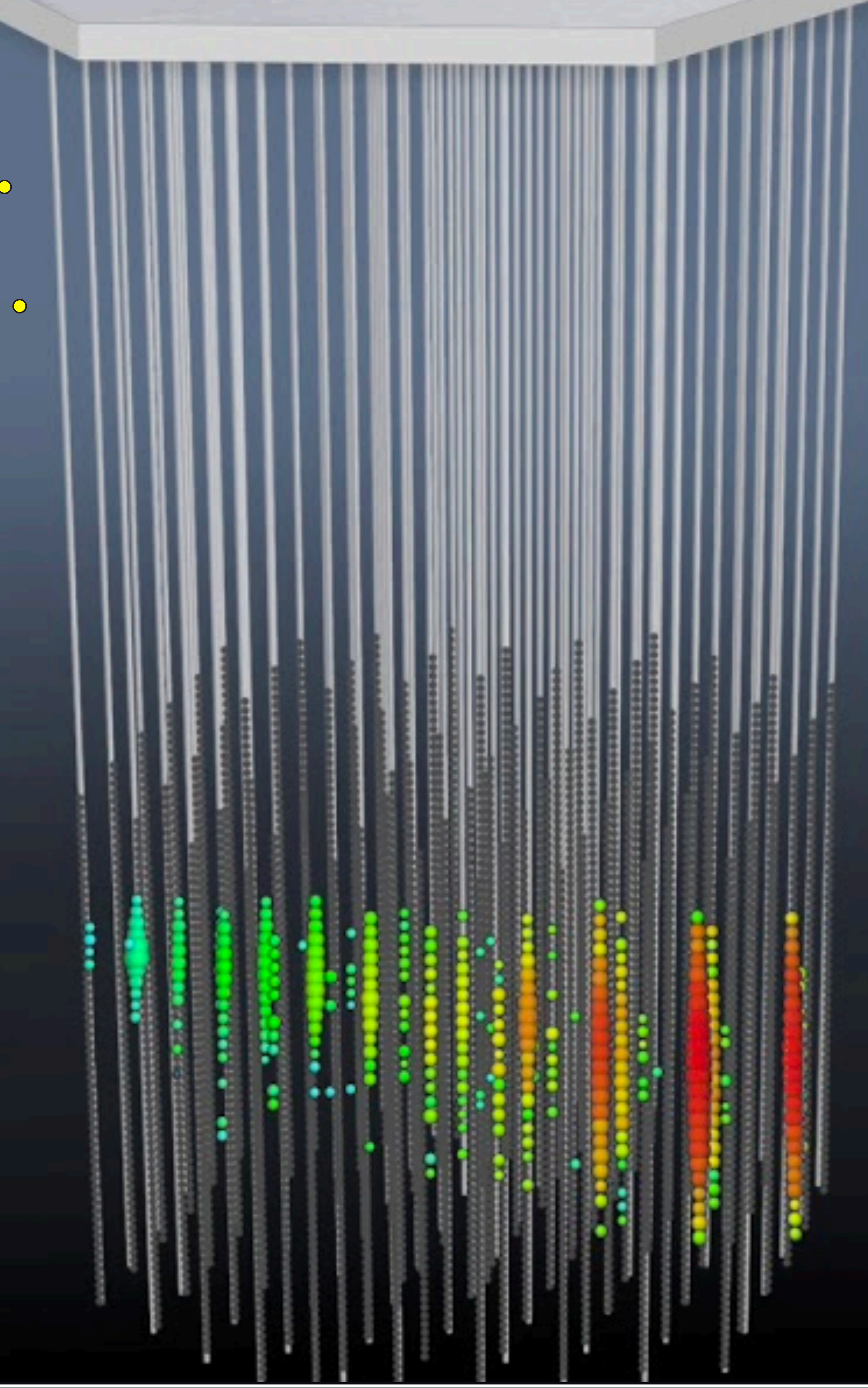


10 Year anniversary for full array!



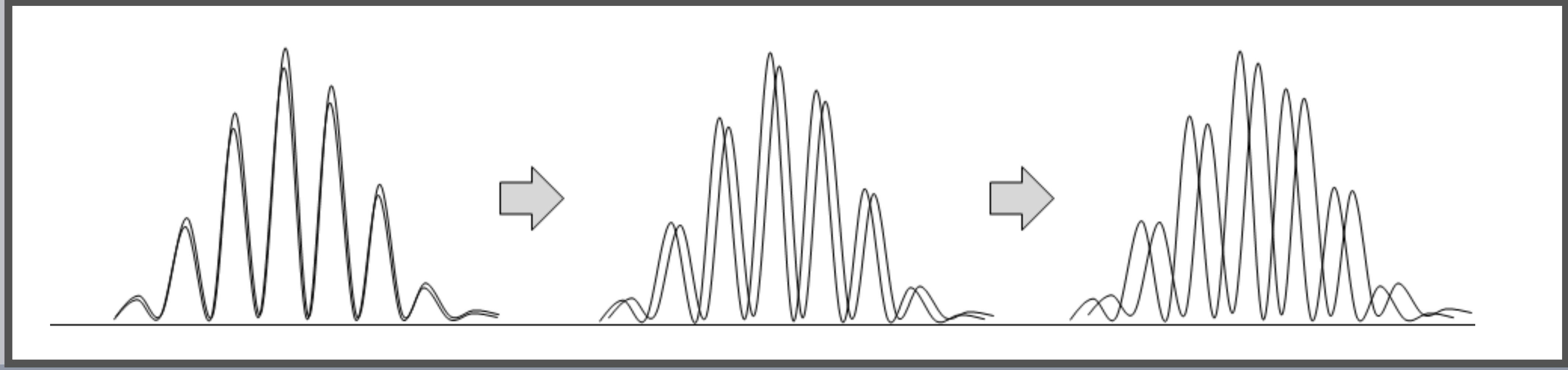
	Spacing [m]		Energy threshold [GeV]
	Horiz.	Vertical	
IceCube	**125**	**17**	**~100**
DeepCore	**~50**	**7**	**~5**

+DeepCore PMTs with higher quantum efficiency

Can access atmospheric neutrino oscillations

Neutrino oscillations

The Standard Paradigm



Flavour

Mass

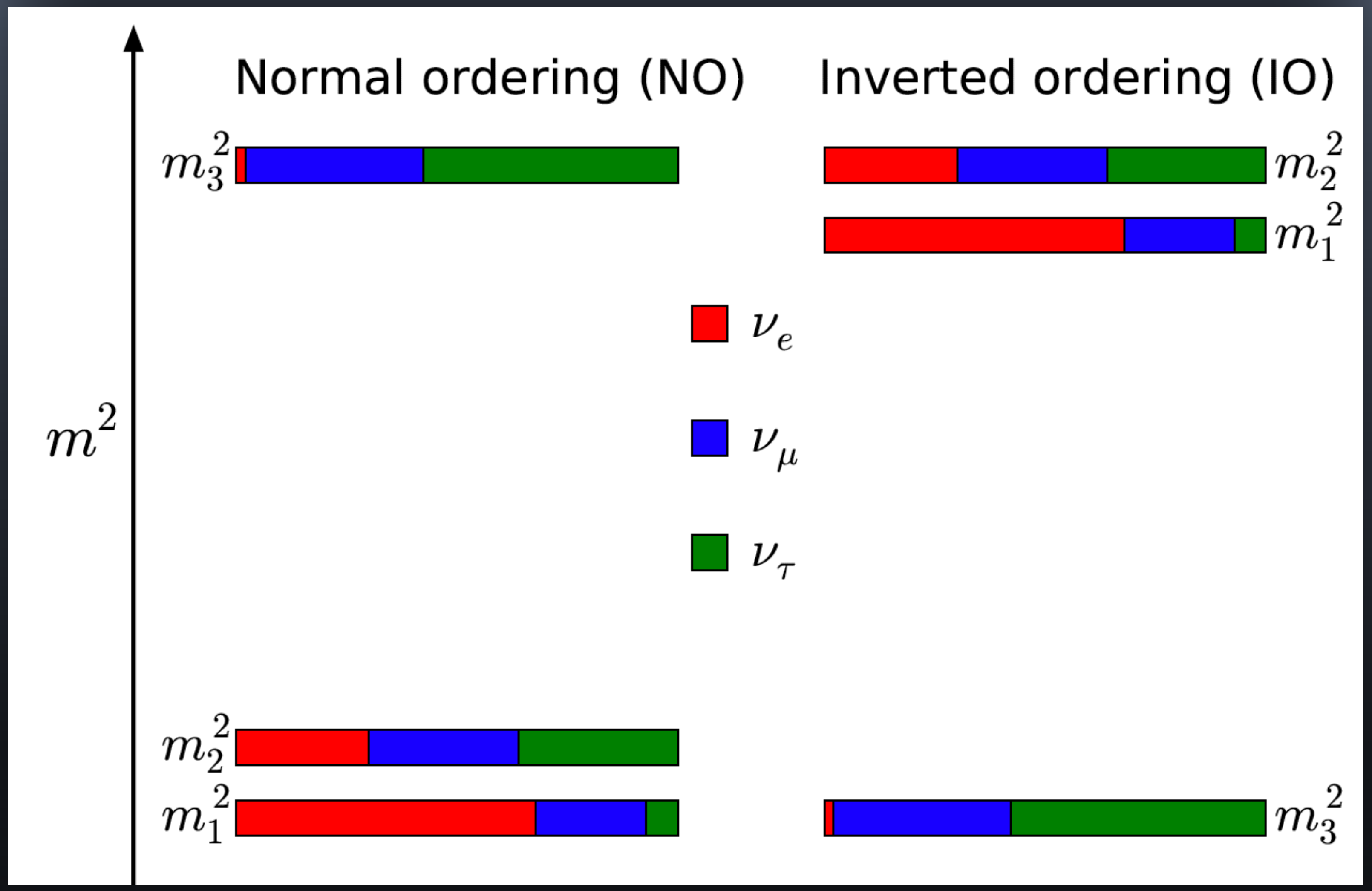
$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle$$

Atmospheric / Accelerator — Accelerator / Reactor — Reactor / Solar

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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



Two-neutrino vacuum approximation:

$\Delta m^2_{21} \sim 10^{-5}\ eV^2$

$\Delta m^2_{32} \sim 10^{-3}\ eV^2$

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

Amplitude Frequency

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

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

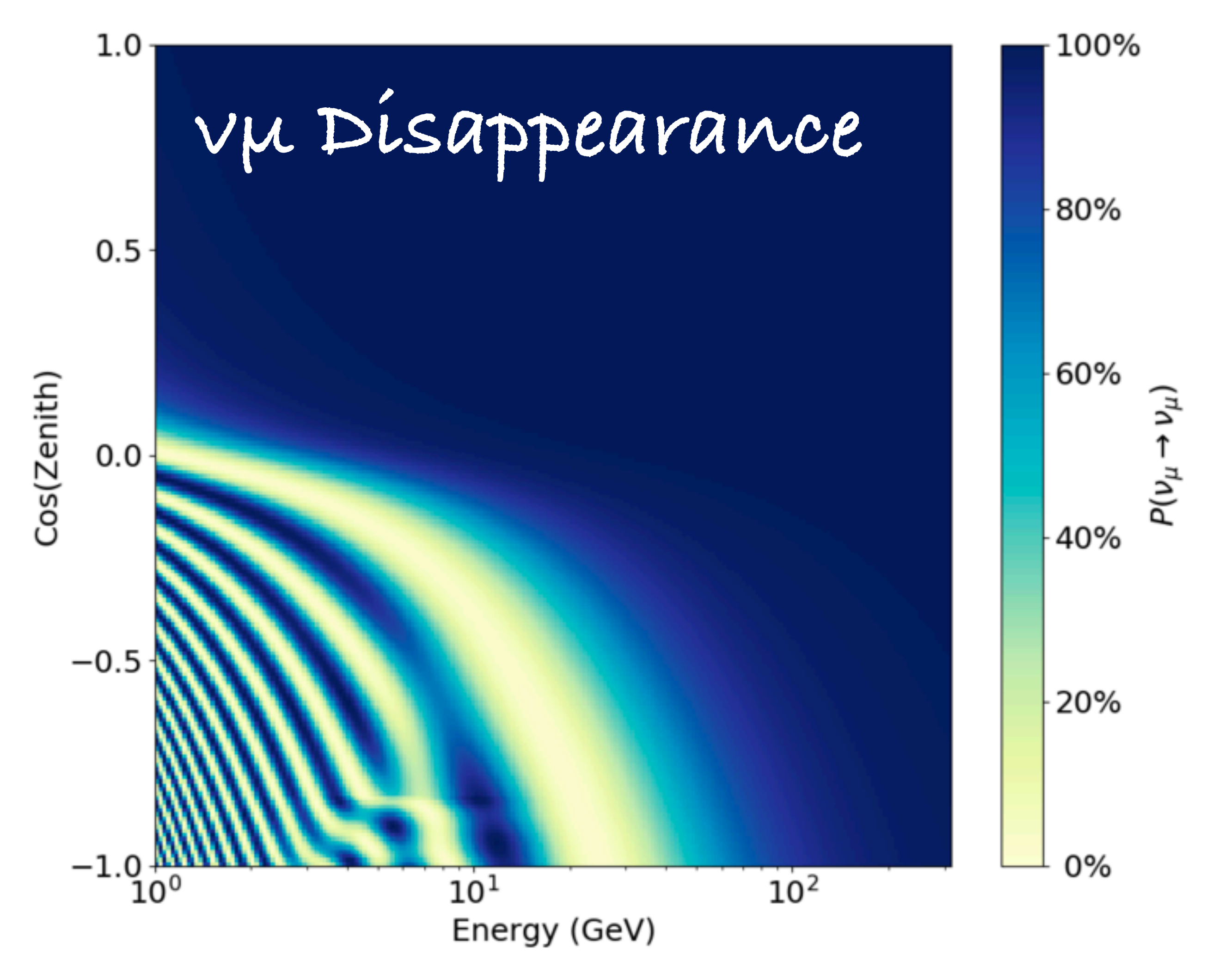
Atmospheric neutrinos

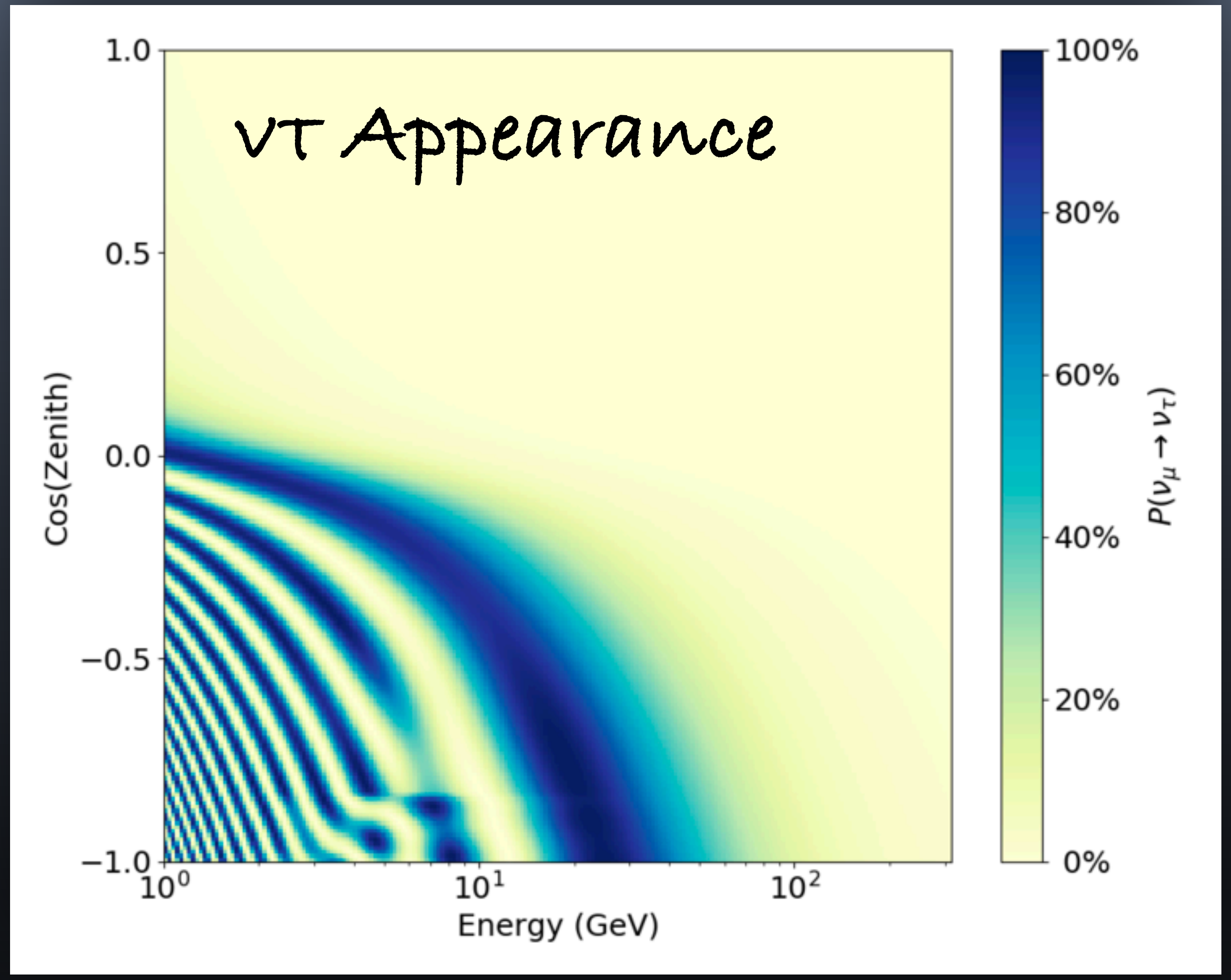
Probe of oscillations at high energies and long baselines

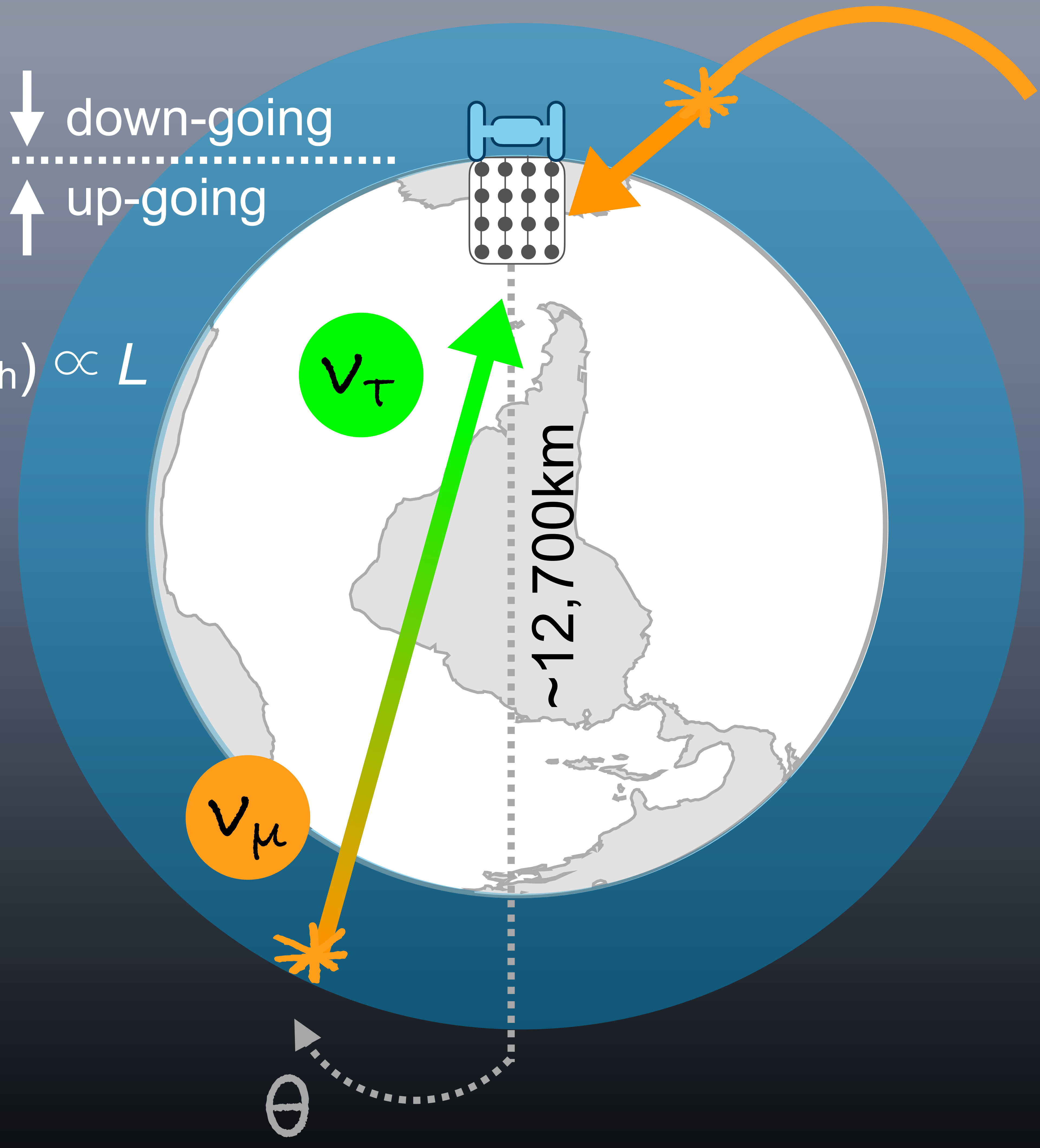
Free neutrino beam from cosmic ray interactions

- 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: $\cos(\theta_{zenith}) \propto L$

At 5 GeV, operating well above tau-production theshold

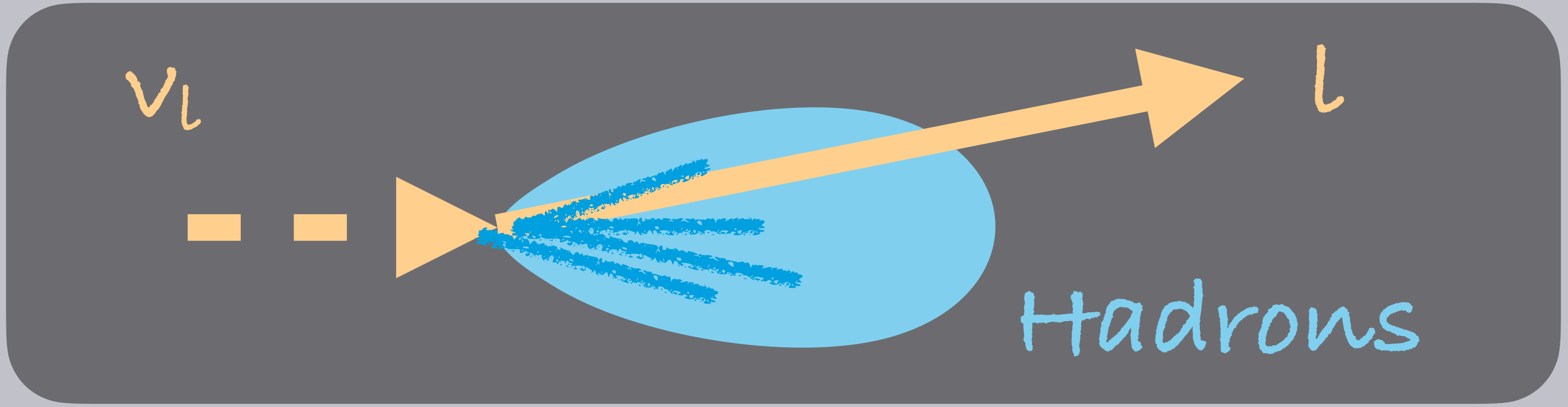




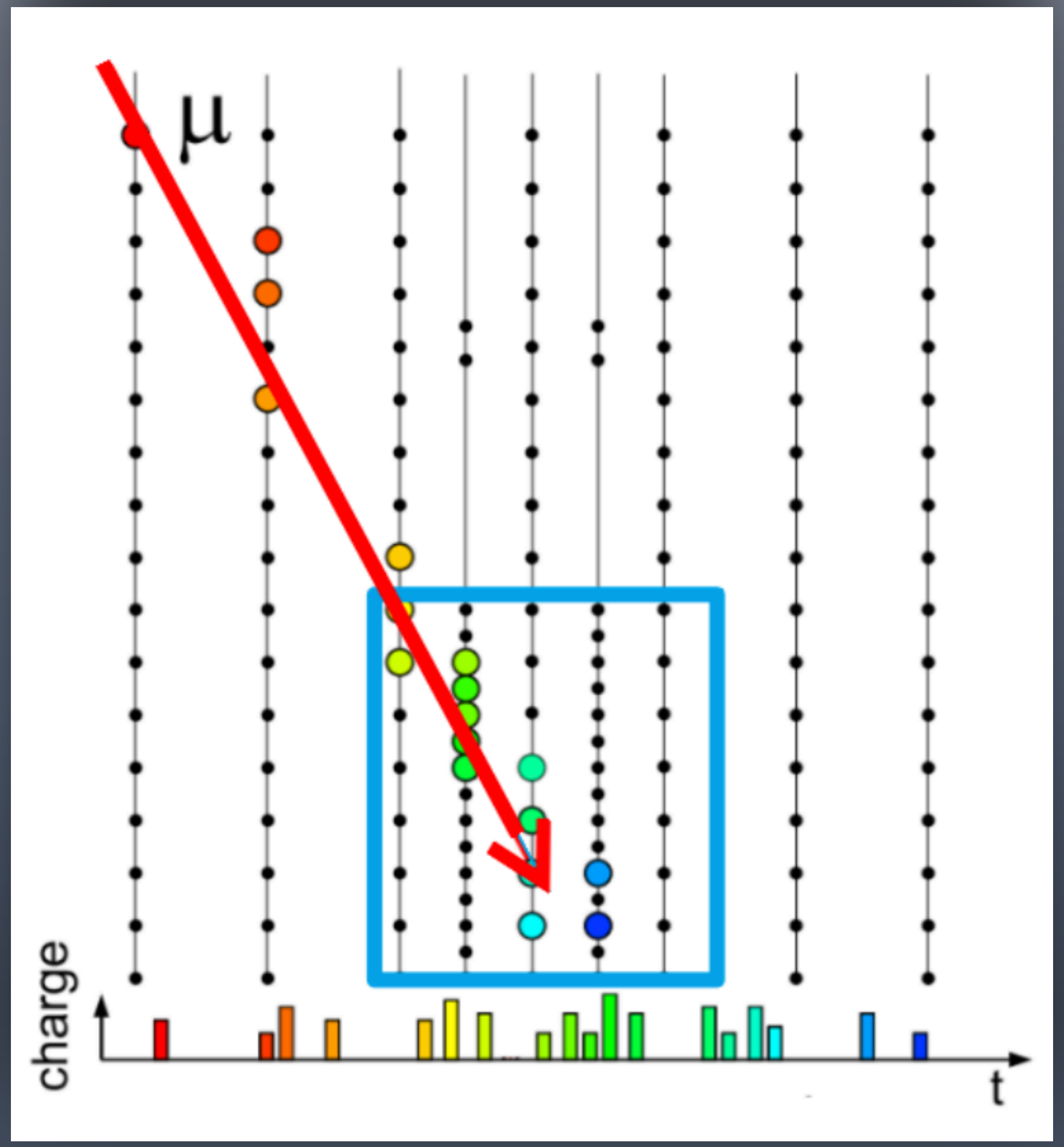


Filtering and reconstruction

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



Background rejection



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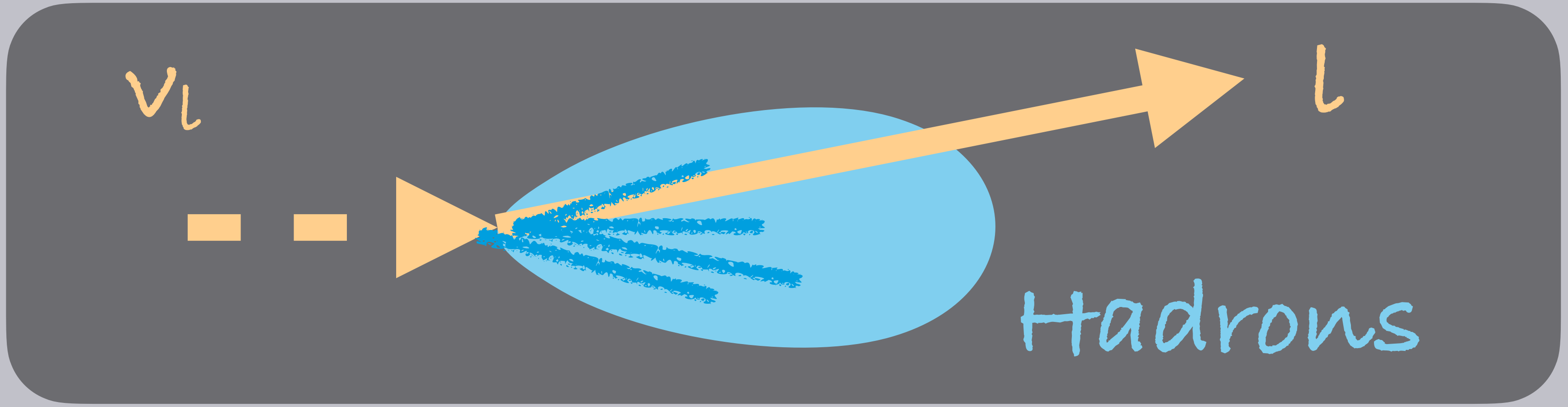

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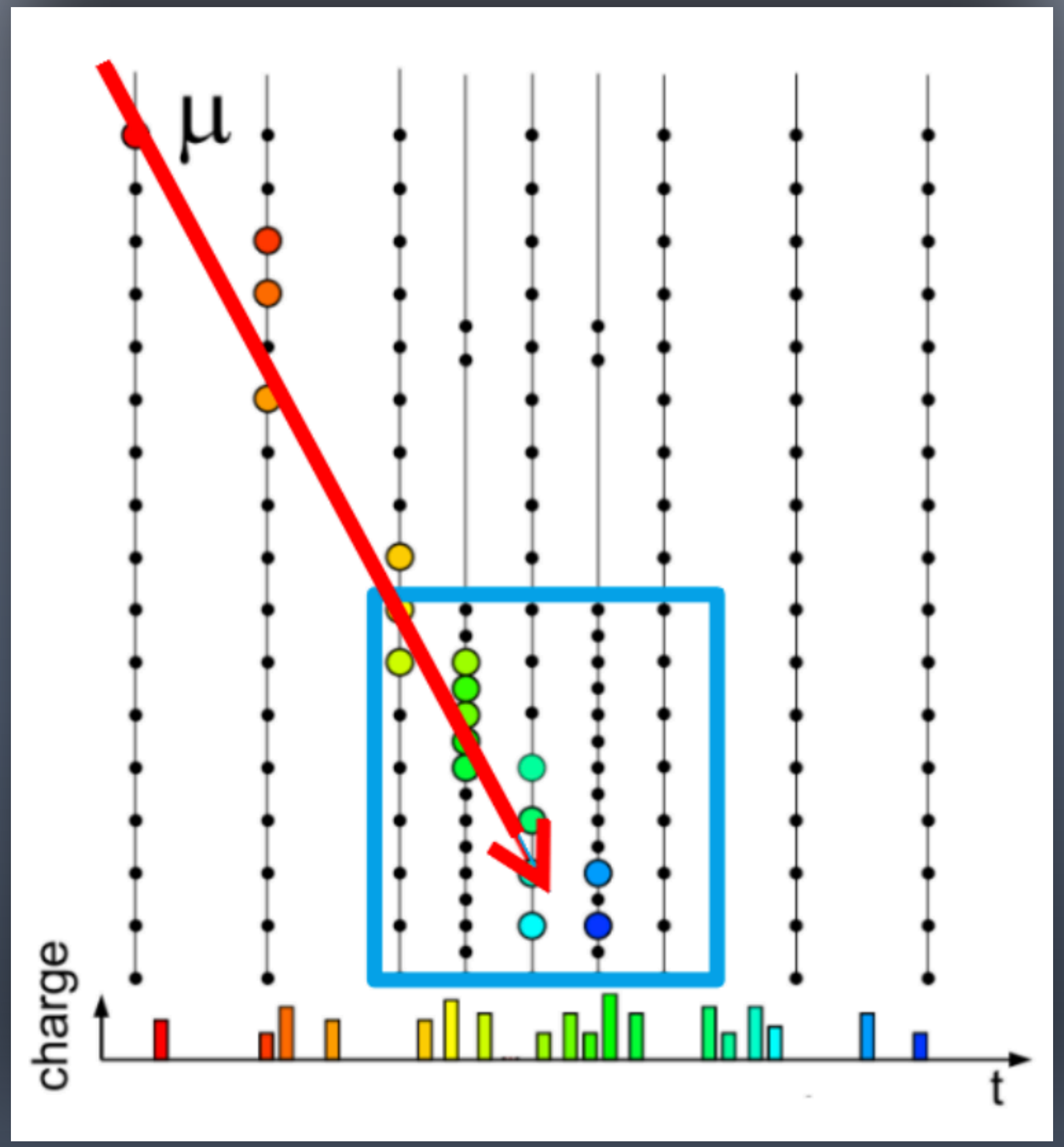
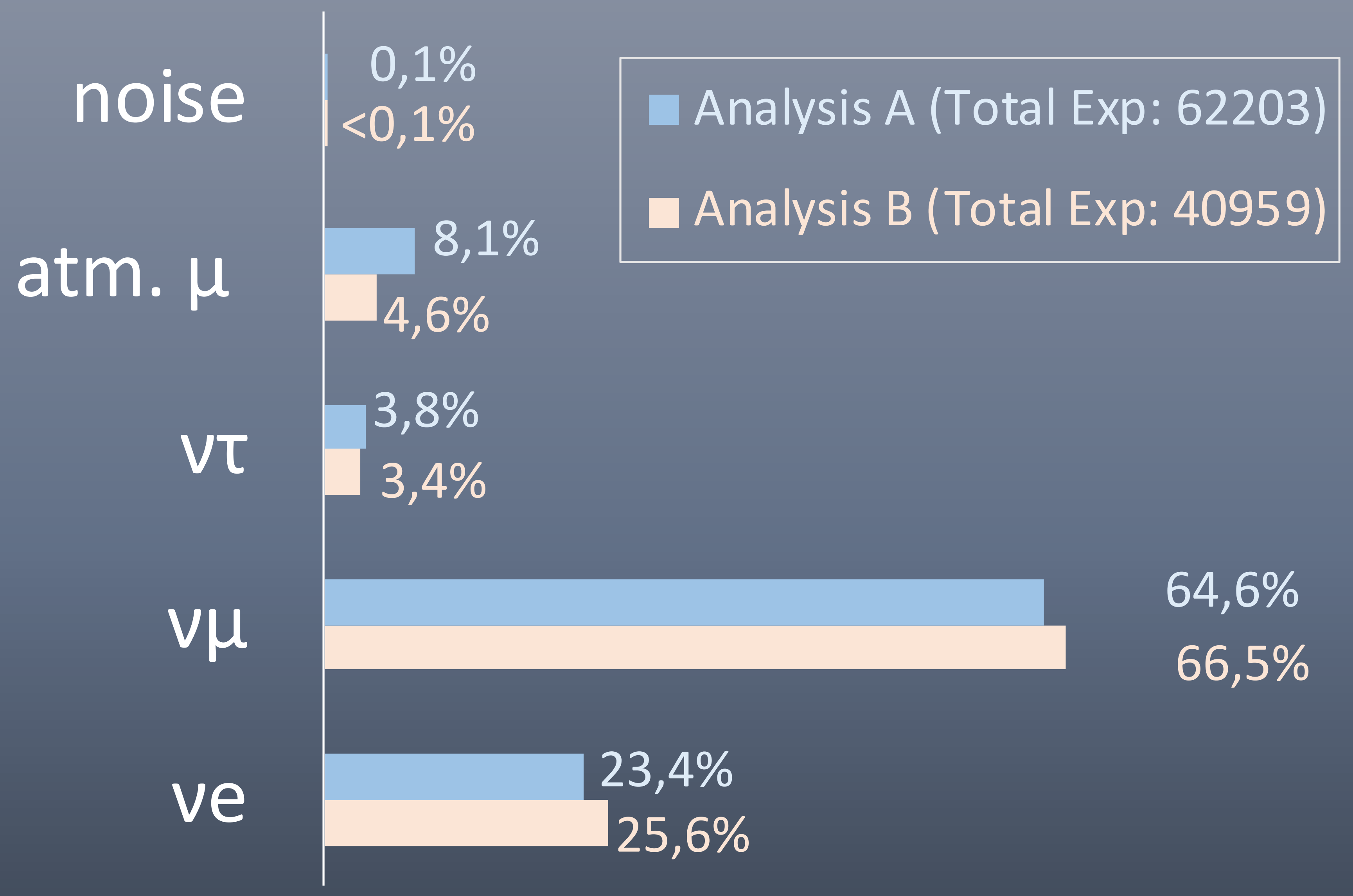


2 data samples, 3 years of data



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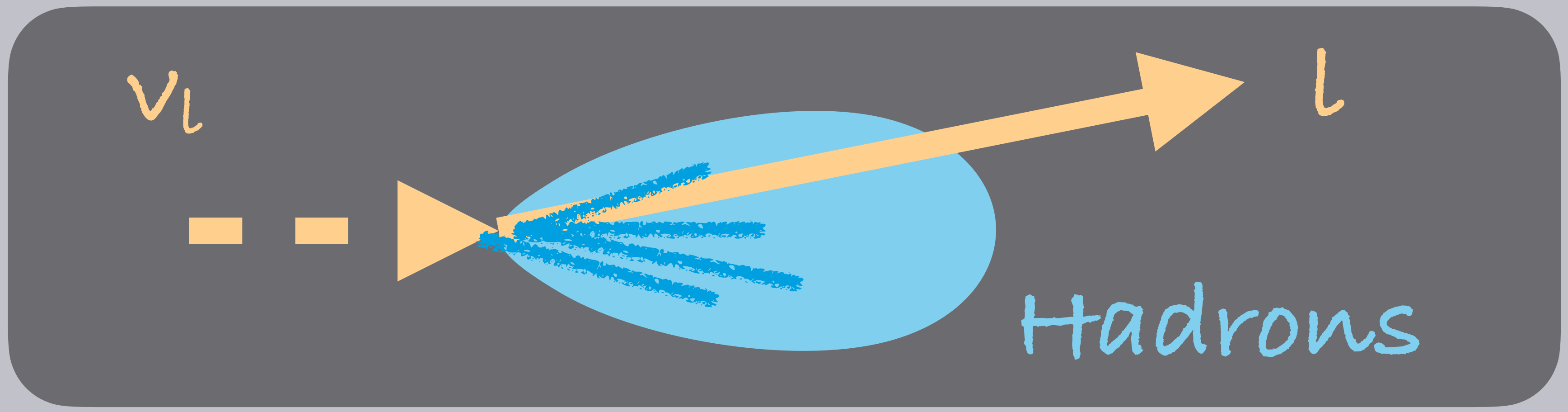

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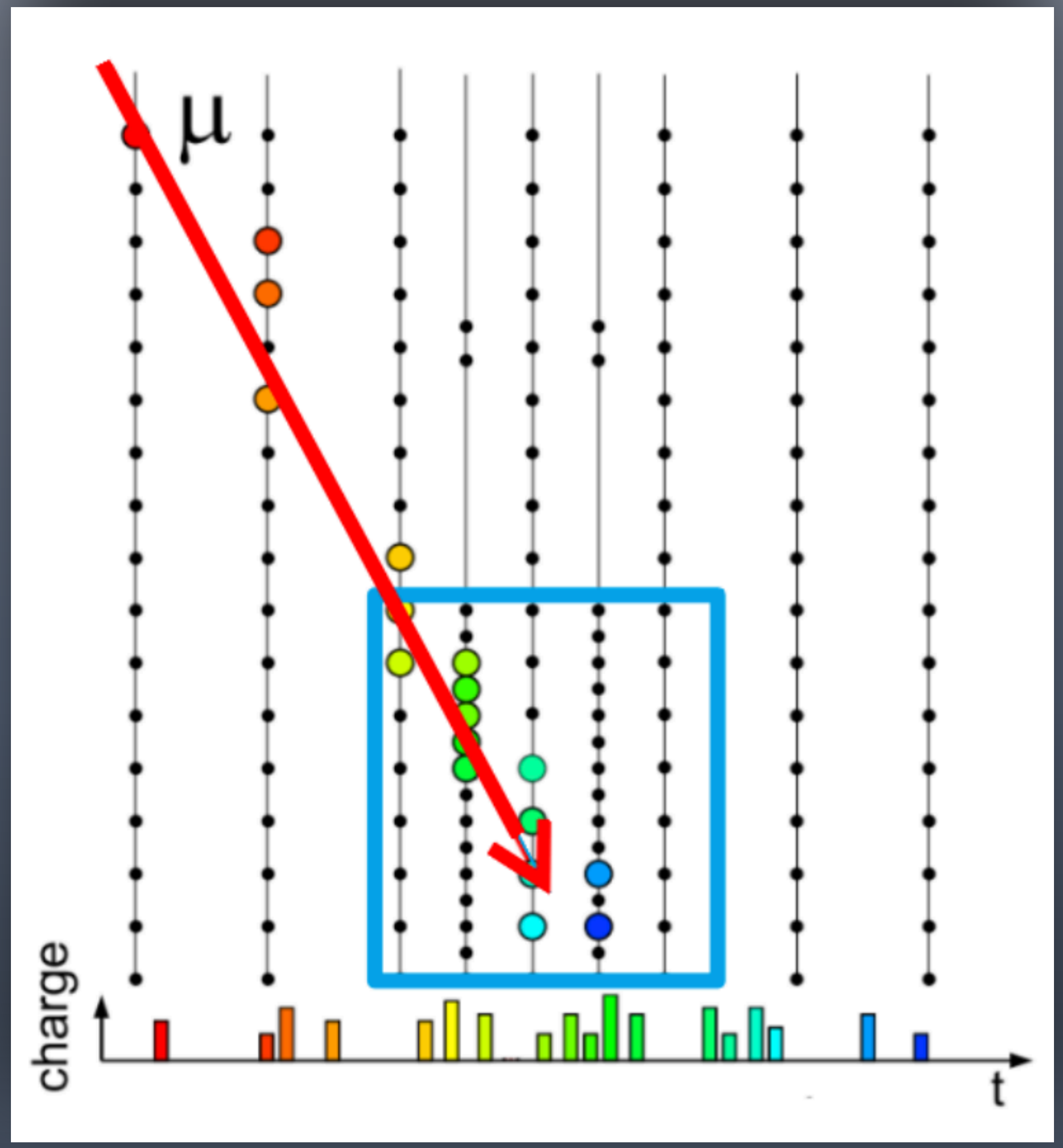

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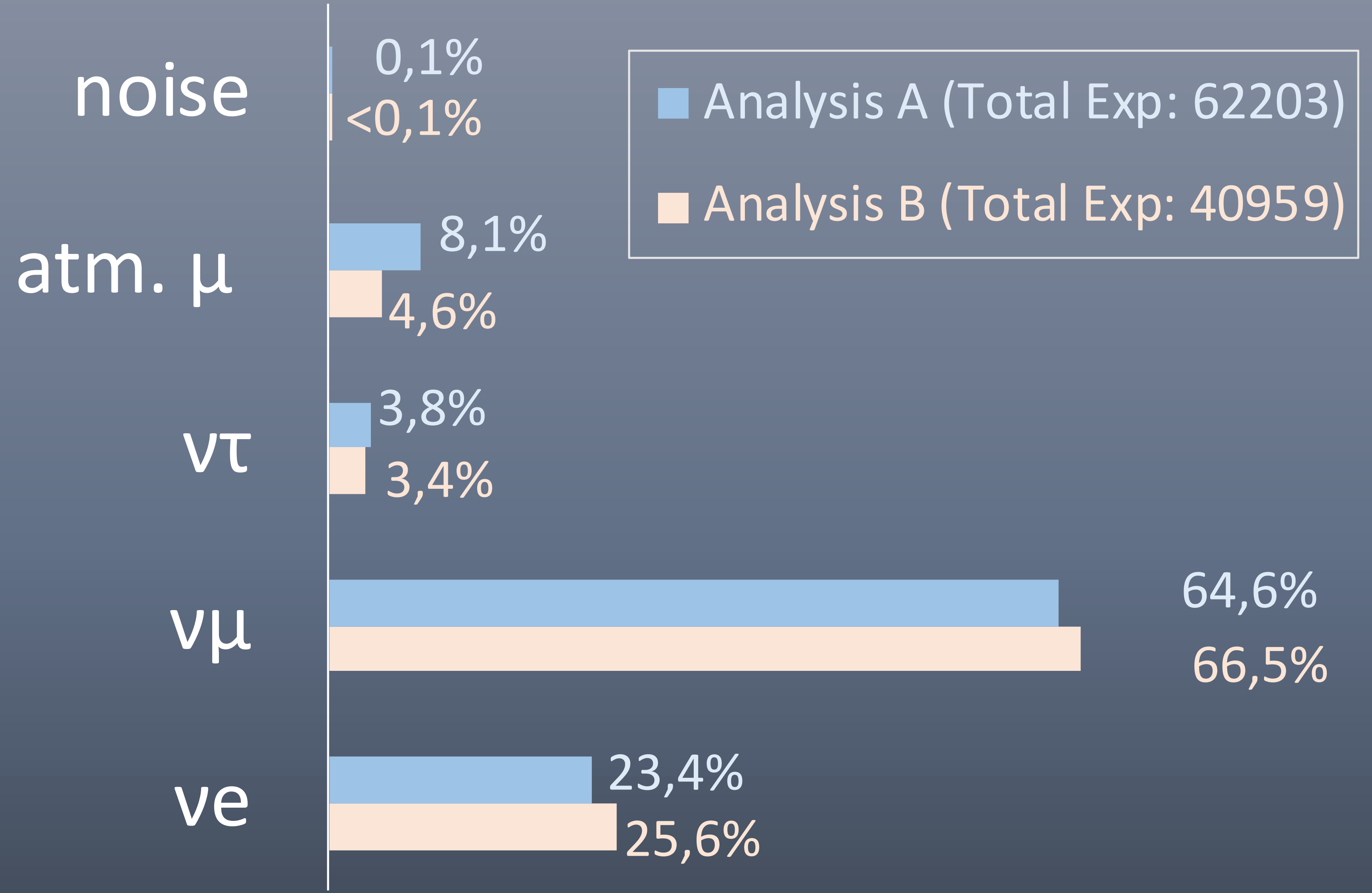
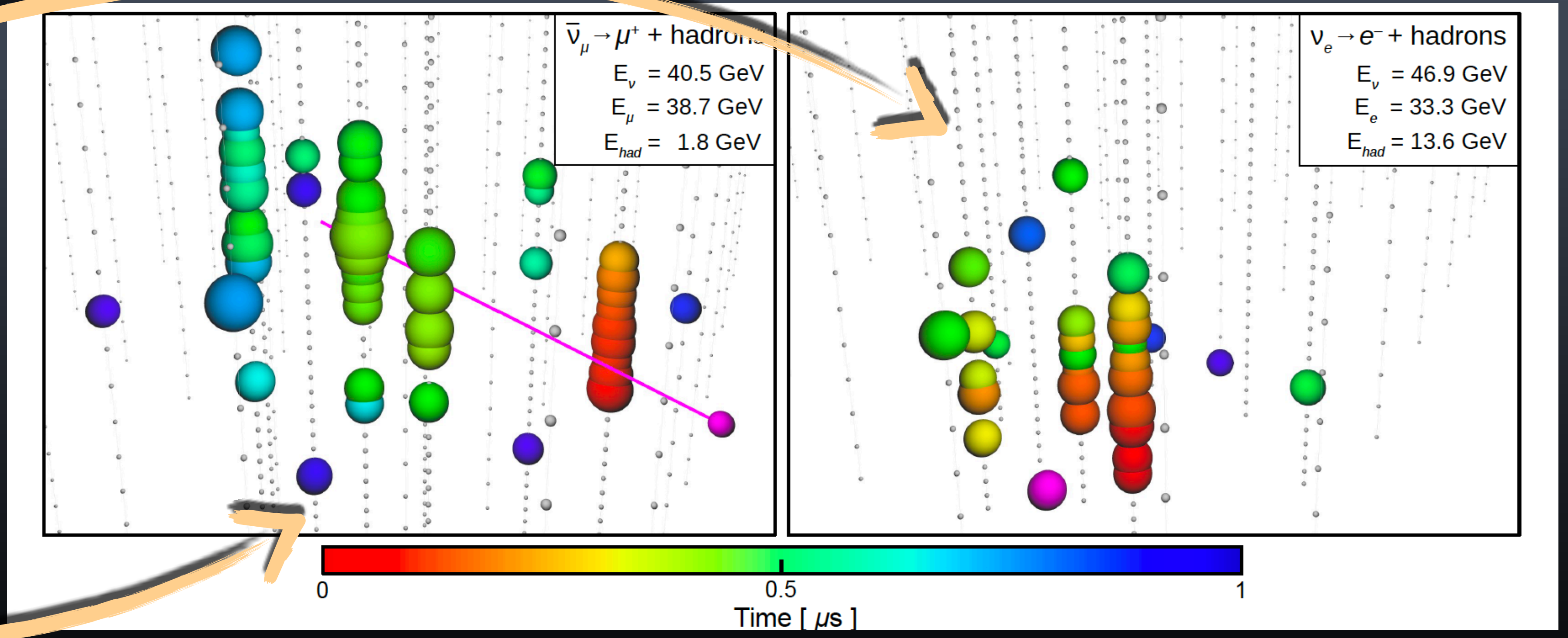


"Cascade-like":

NC interactions, ν_e CC and 83% ν_τ CC

"Track-like":

ν_μ CC and some ν_τ CC (17%)



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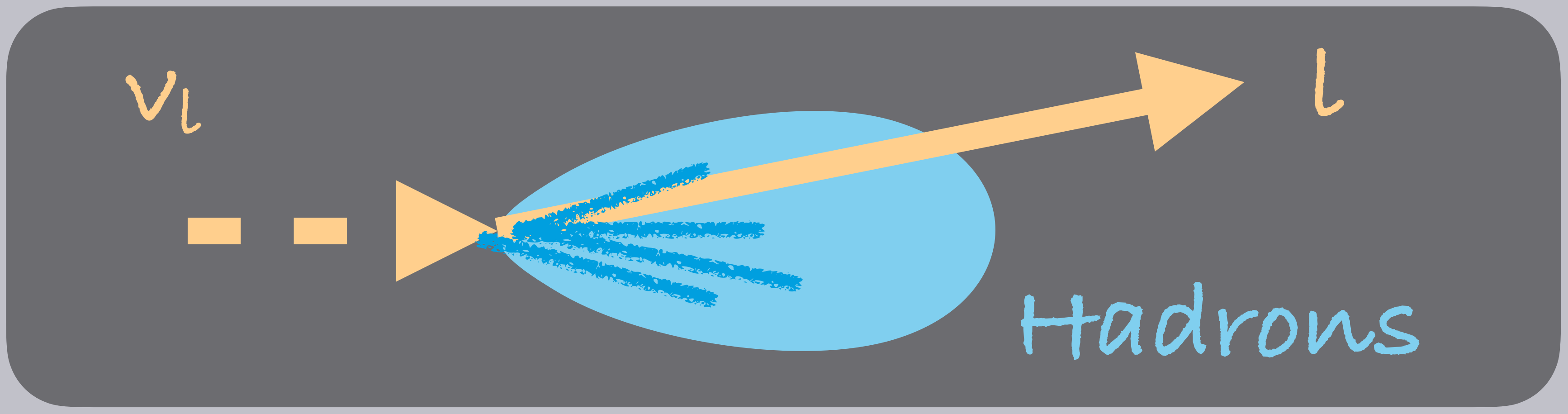

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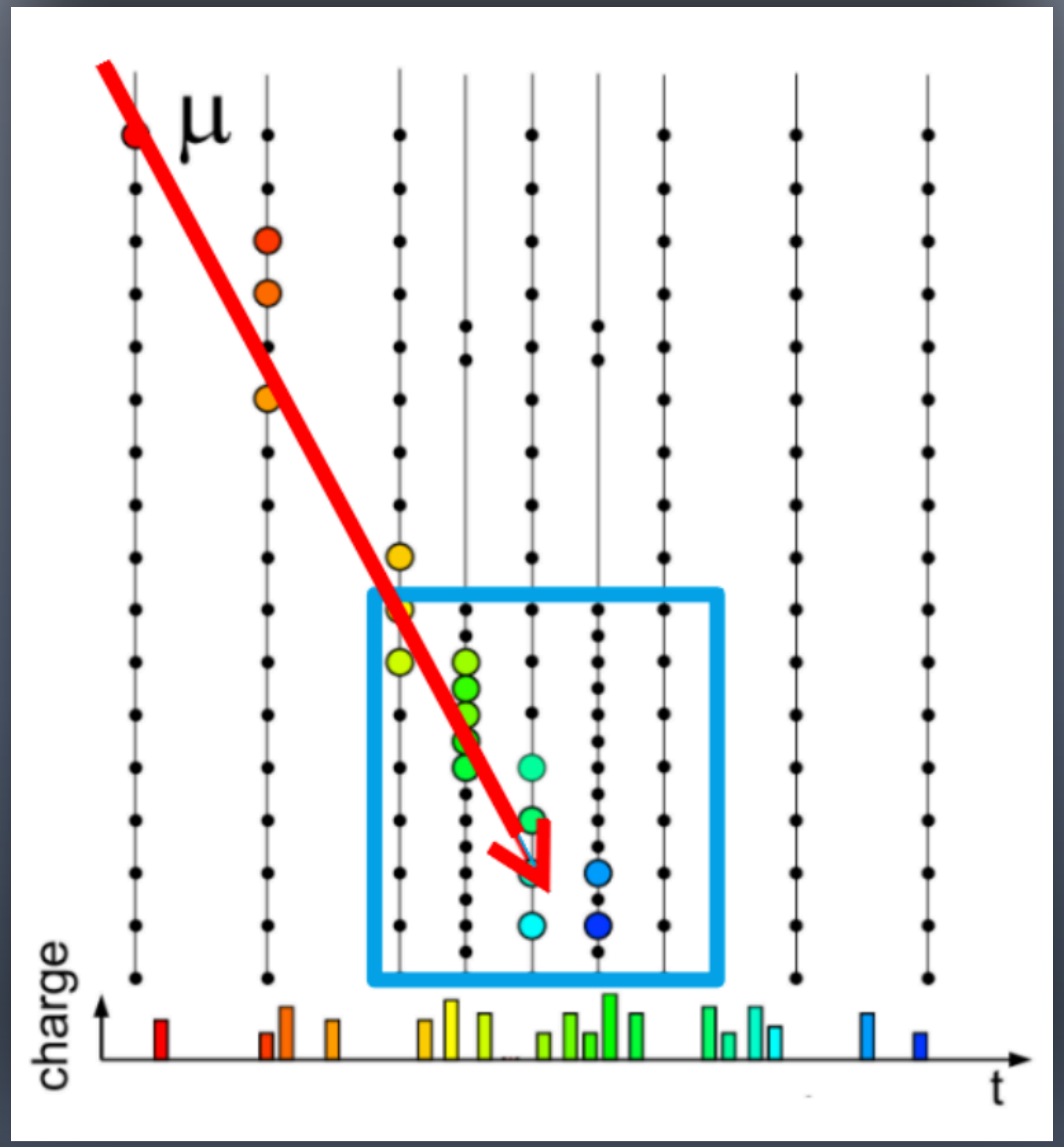

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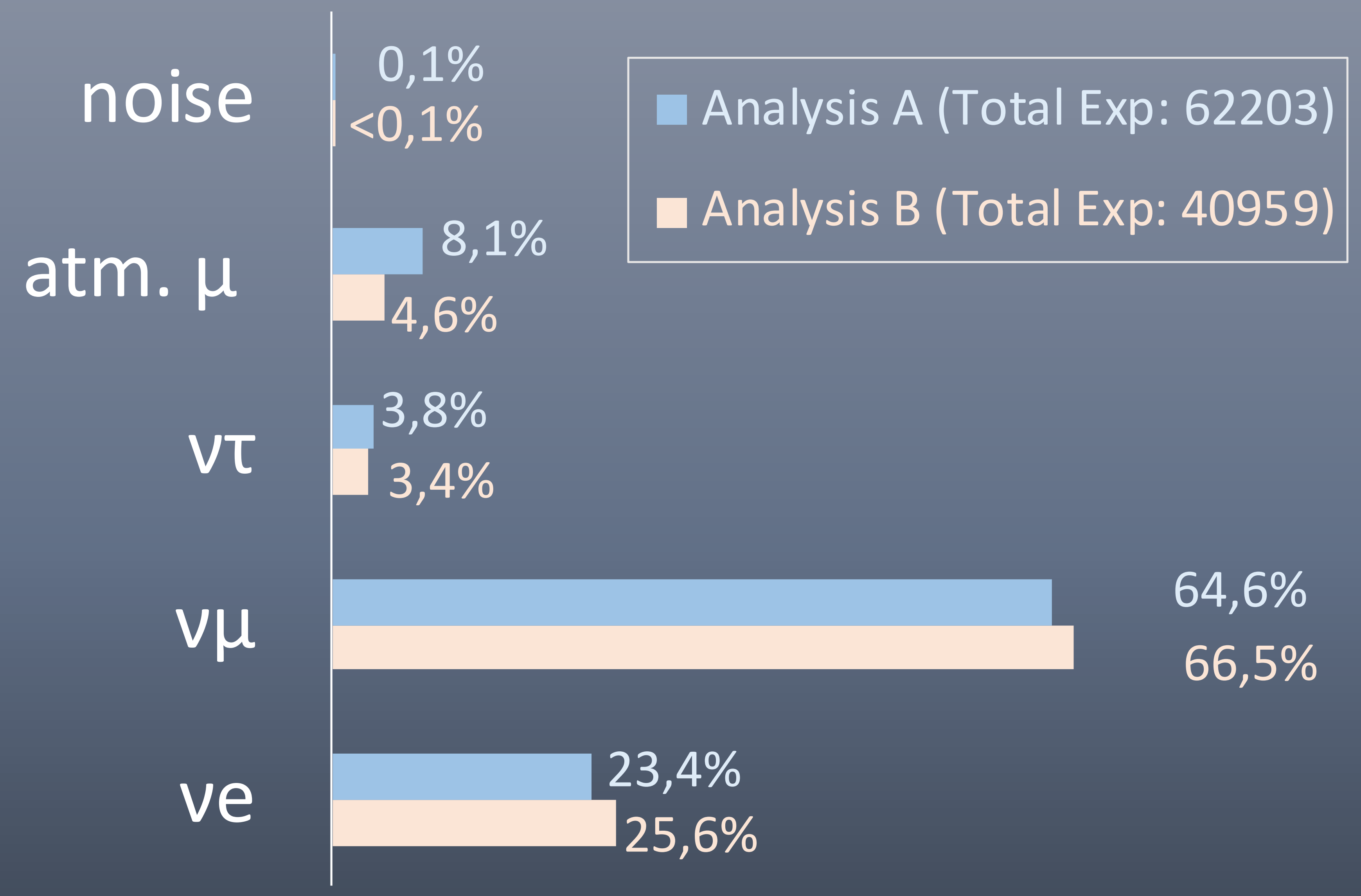
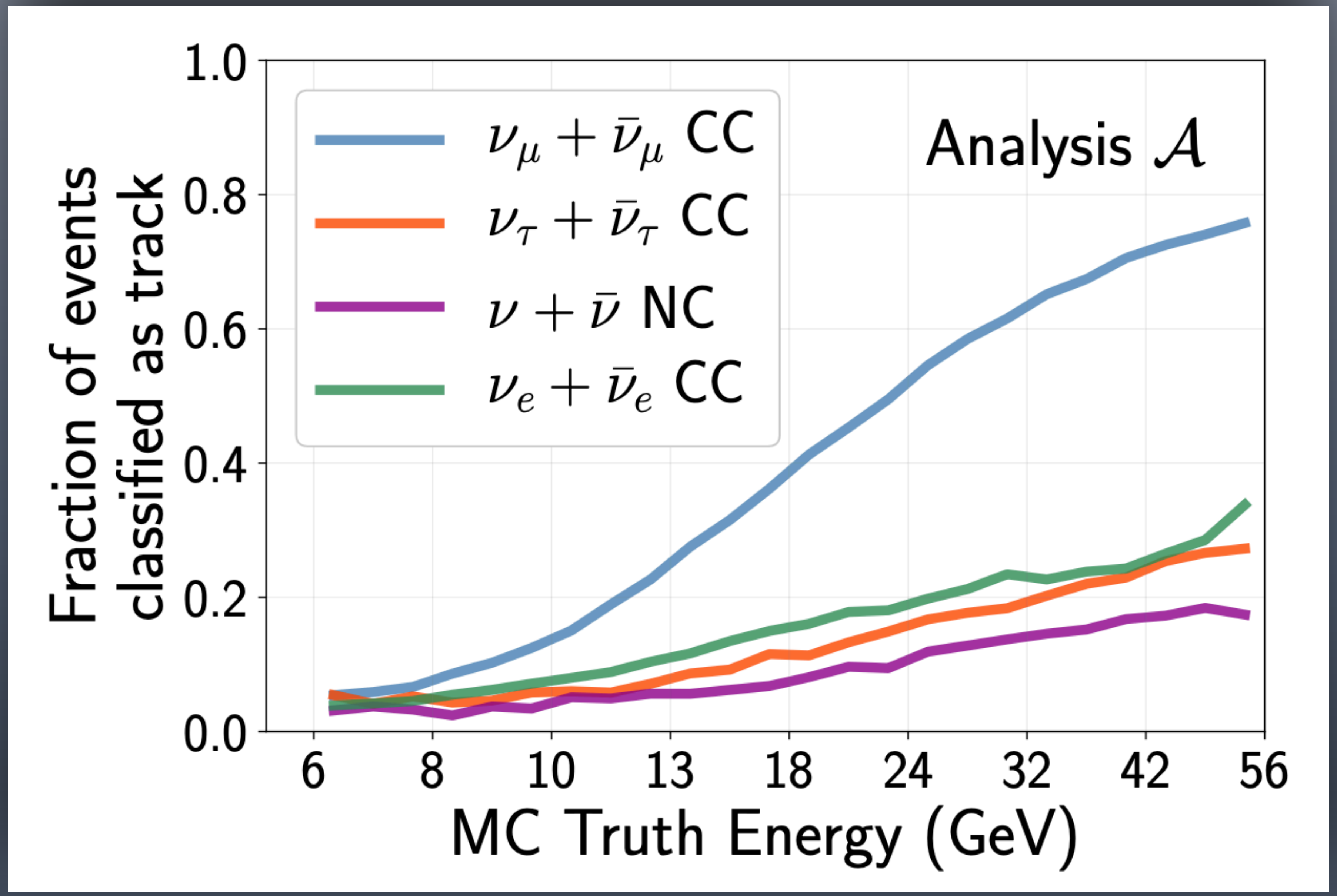


Using track length as Flavour ID



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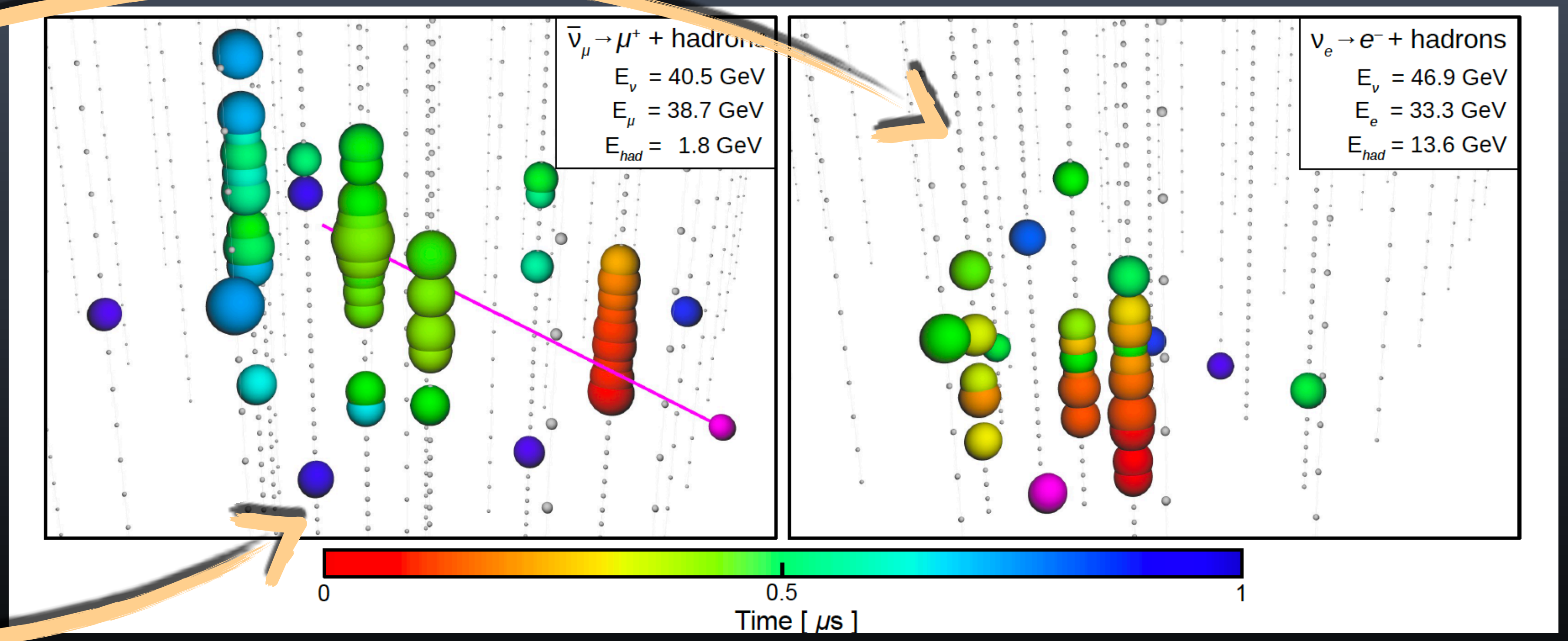


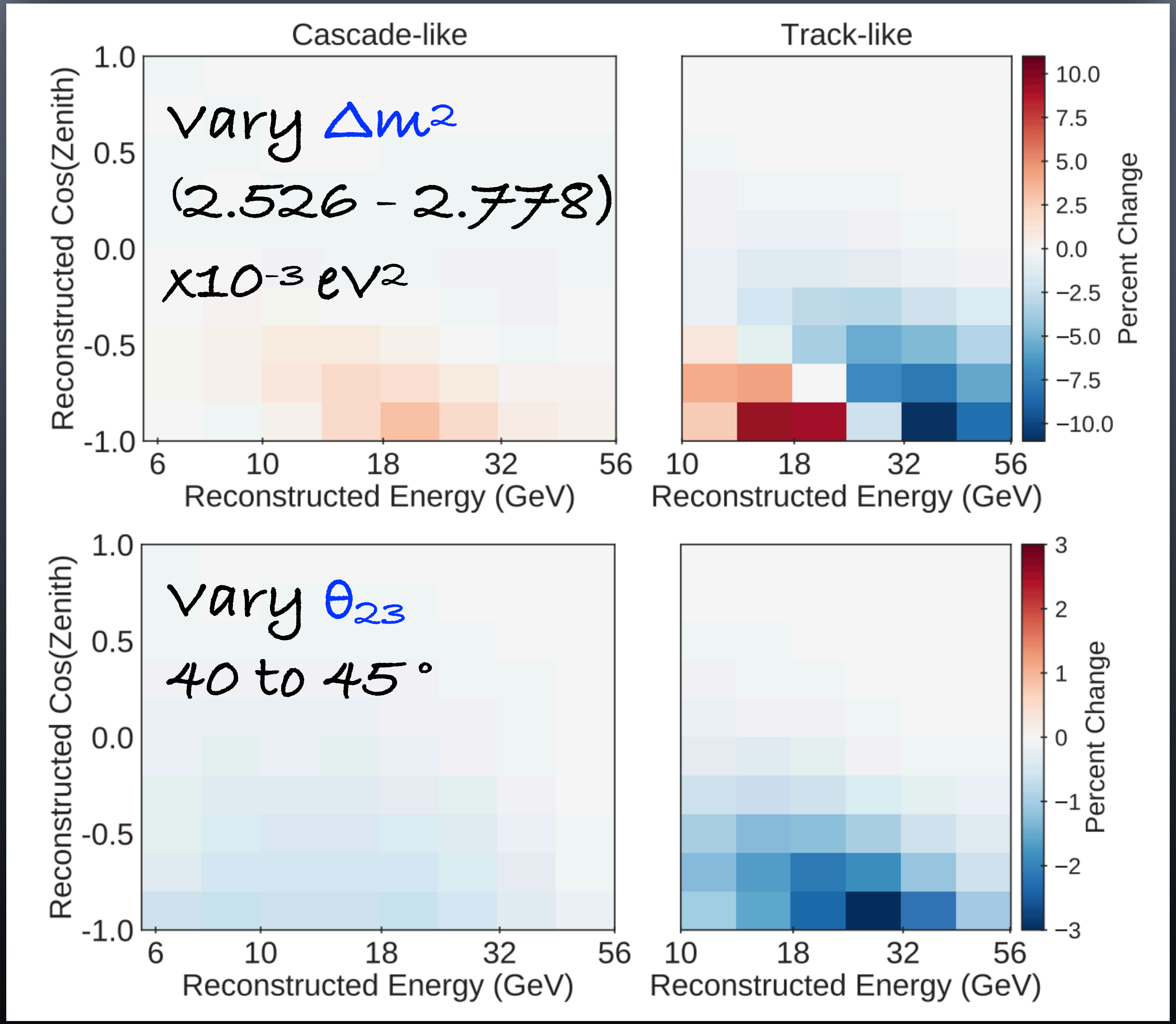
Resolutions @20 GeV:

	Tracks	Cascades
Energy	24 %	29 %
Zenith	10º	16º

Analysis strategy

Shape-only comparison between data and weighted MC

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



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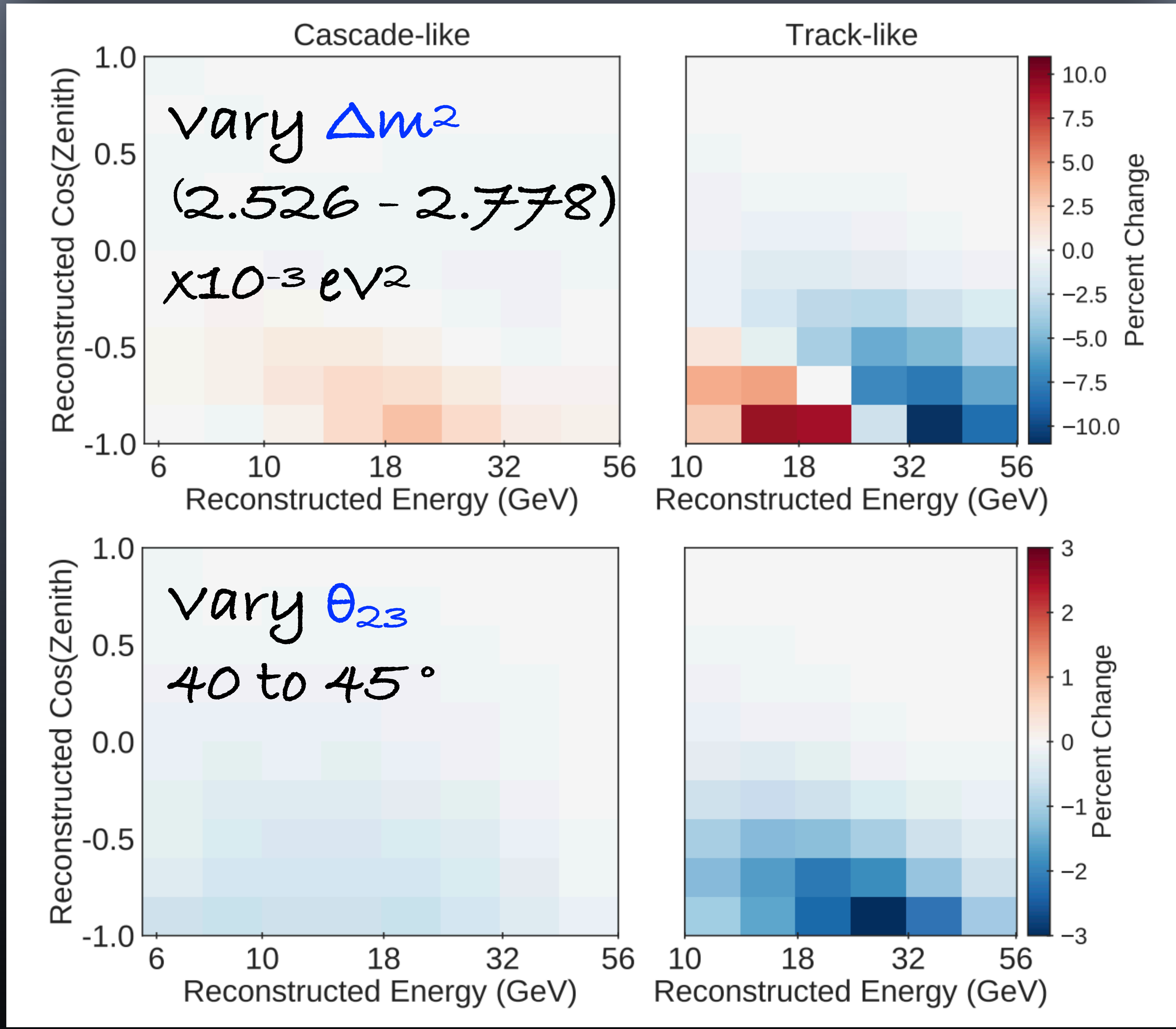


Nuisance parameters for syst. uncertainties:

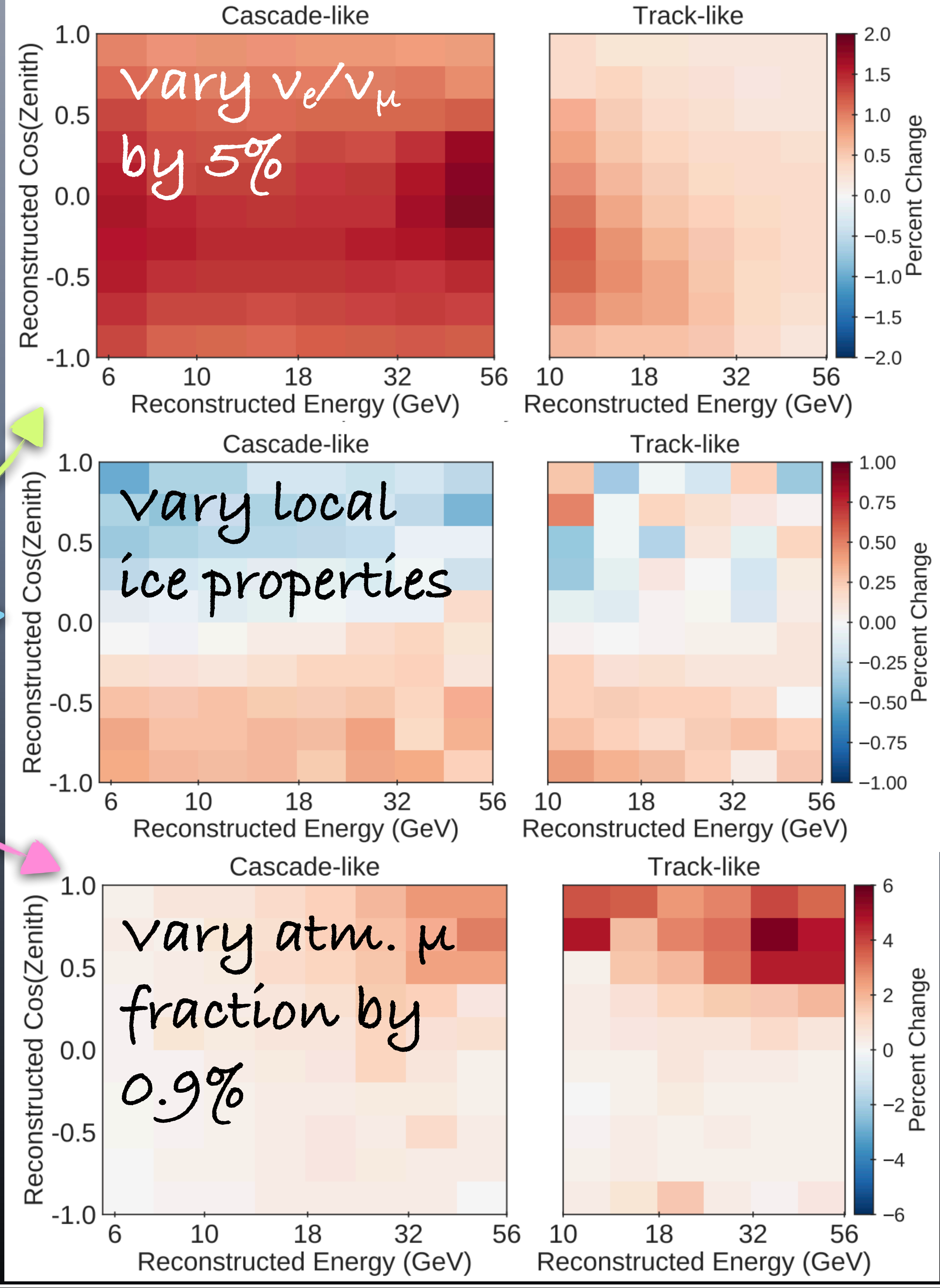
Intial Flux

Detector

Cross-section,

Background

and subdominant oscillation params



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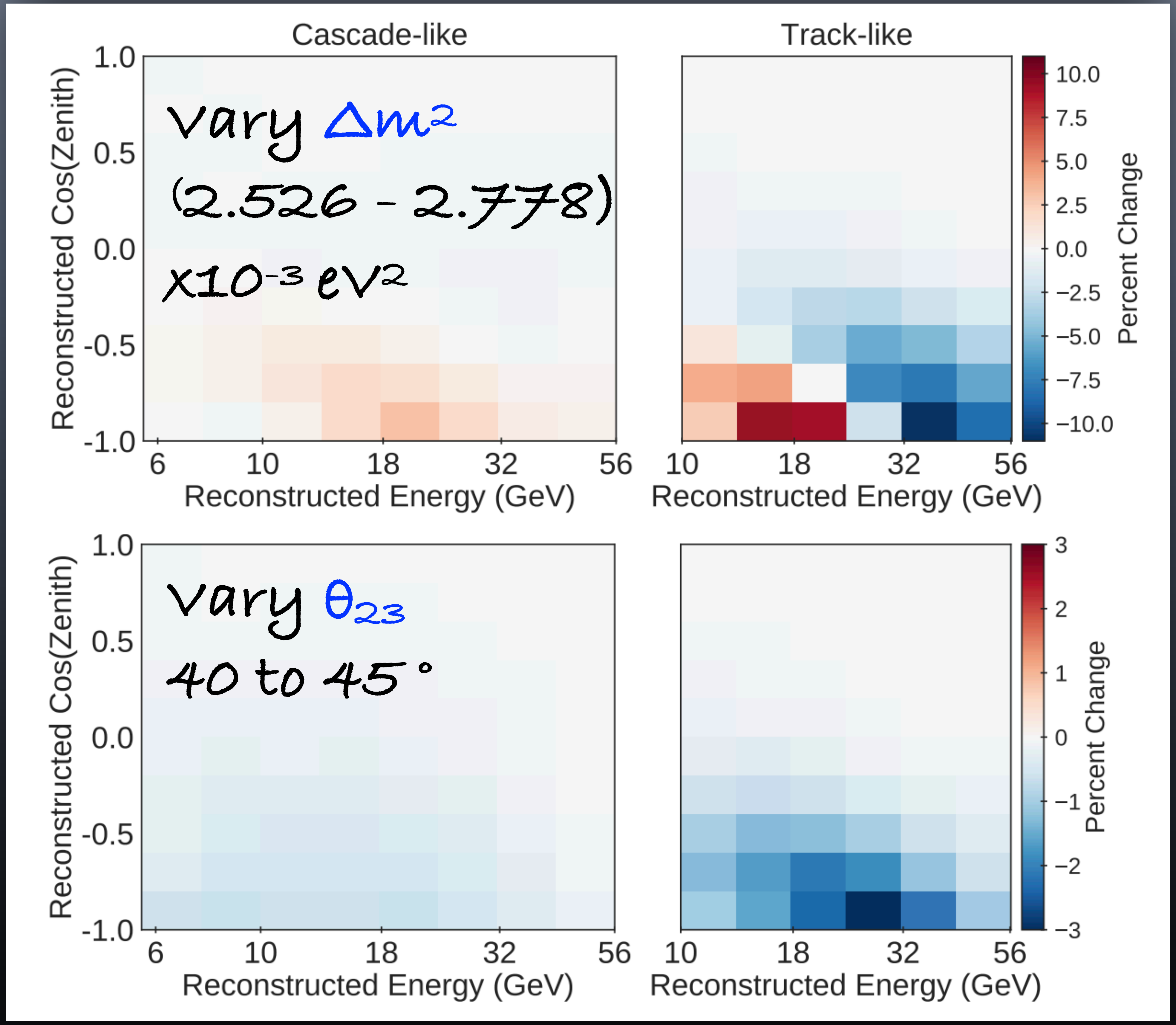
$$\chi^2 = \sum_{i \in bins} \frac{(n_i^{\nu+\mu} - n_i^{data})^2}{(\sigma_i^{\nu+\mu})^2 + (\sigma_i^{data})^2} + \sum_{j \in \{syst\}} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{sj}^2}$$



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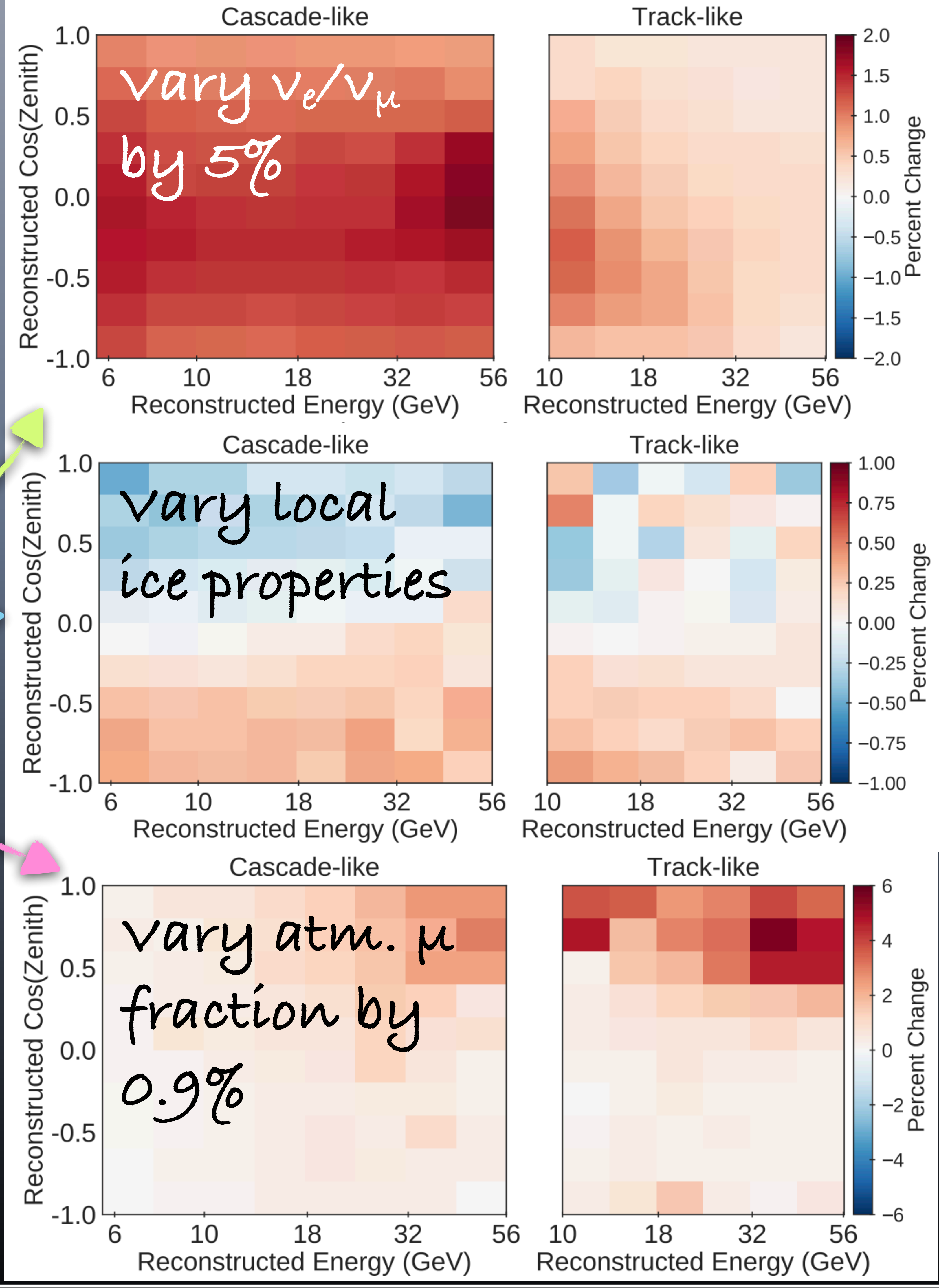
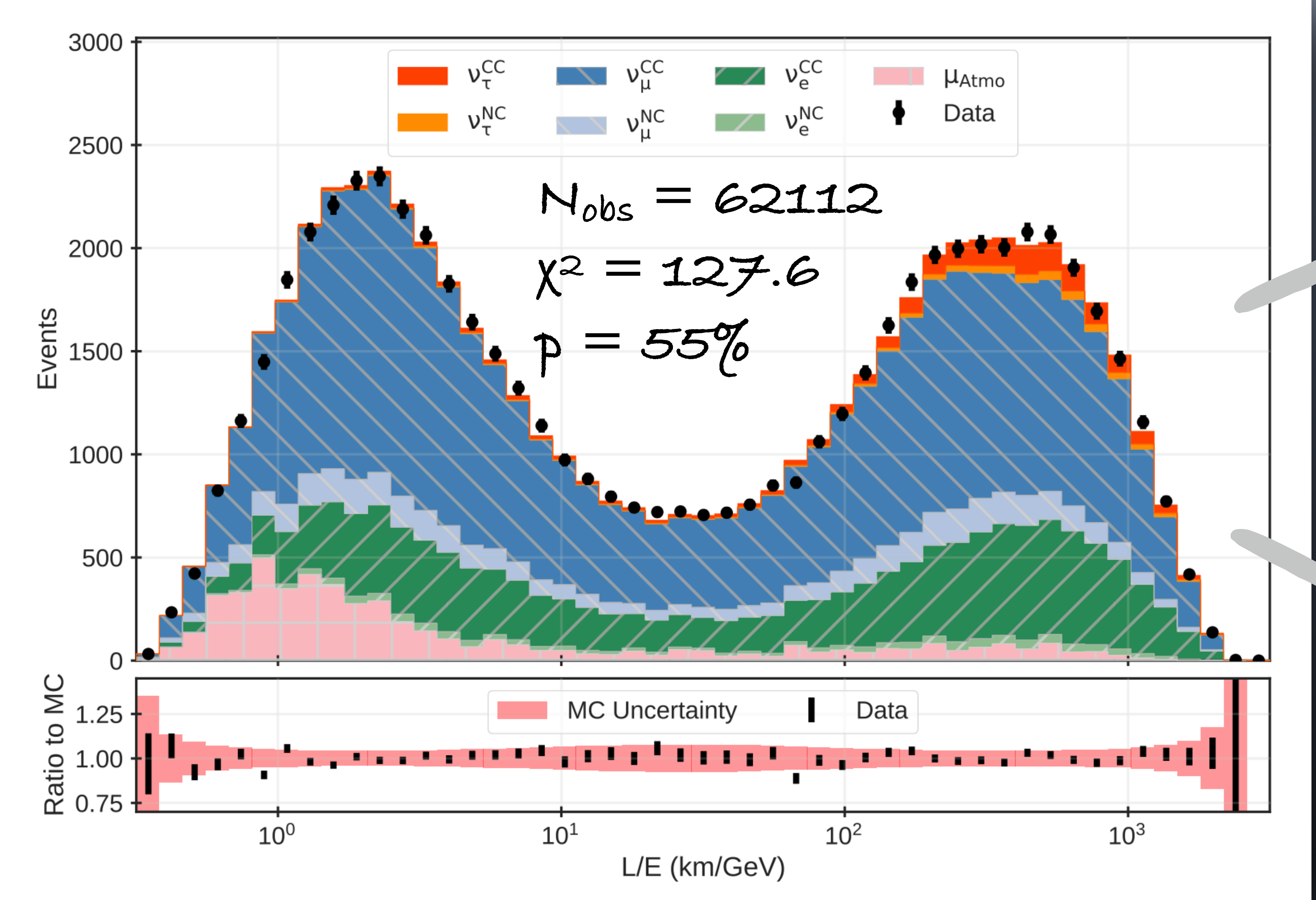
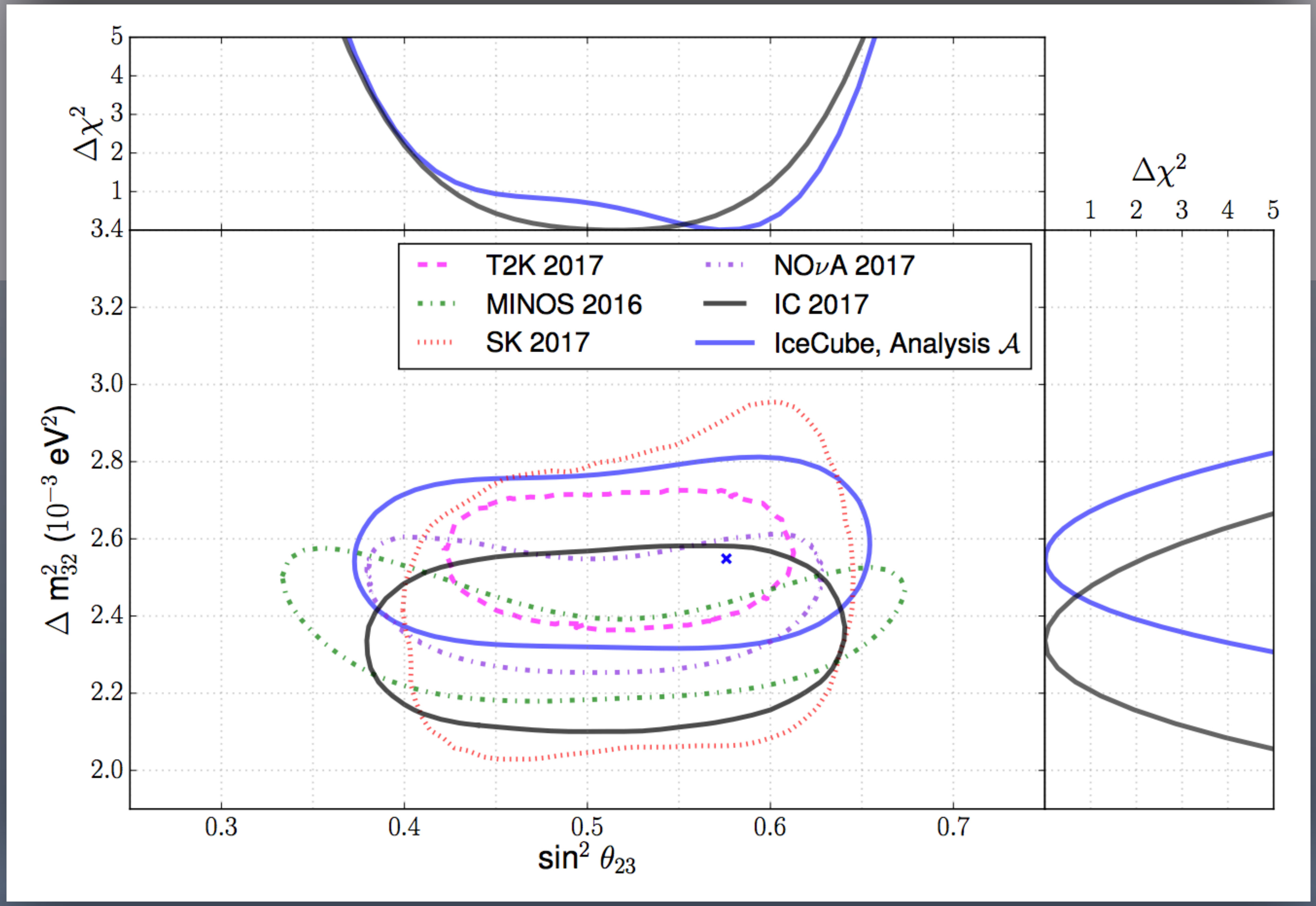


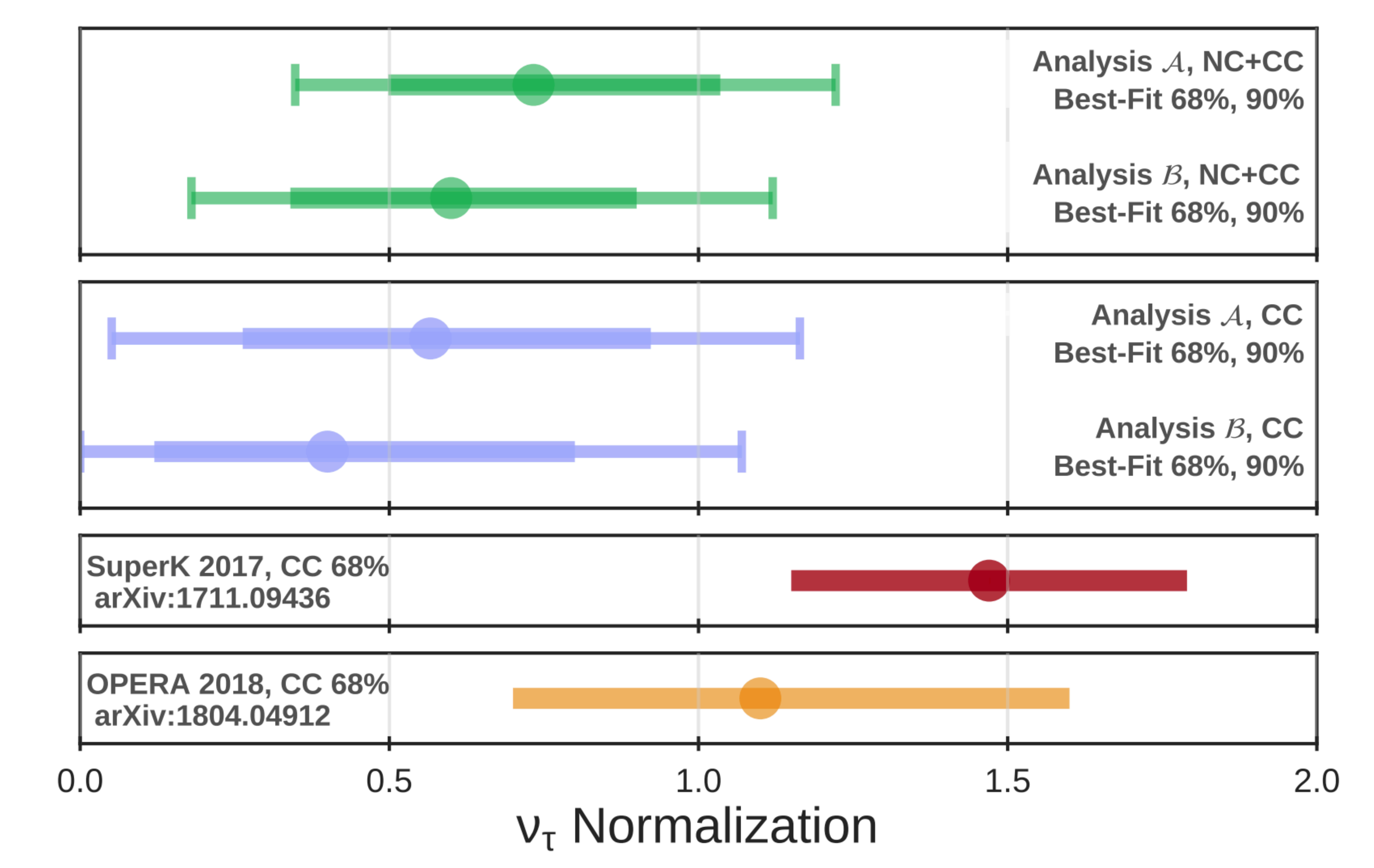
Standard oscillation results

Phys. Rev. D 99, 032007 (2019)

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







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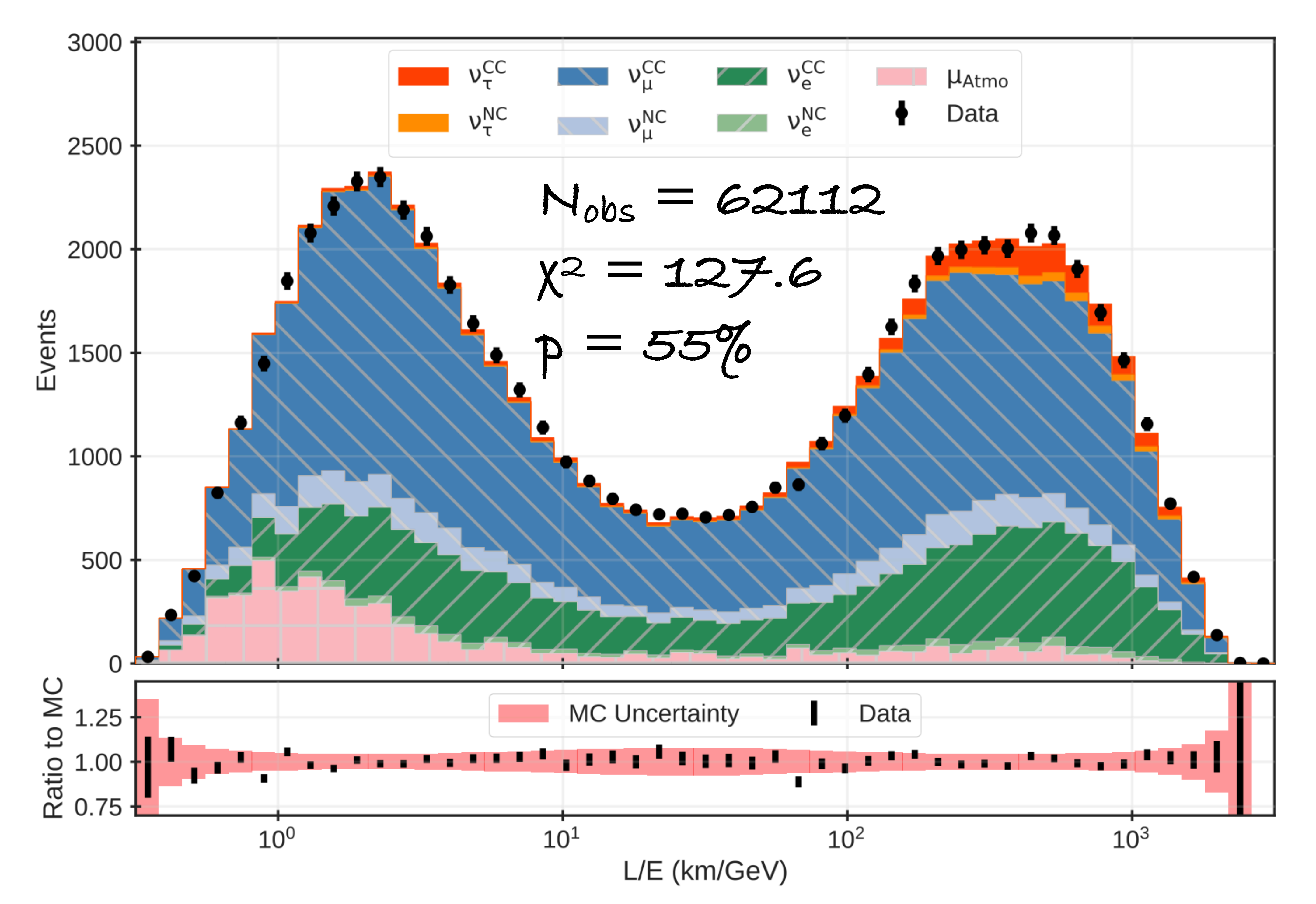

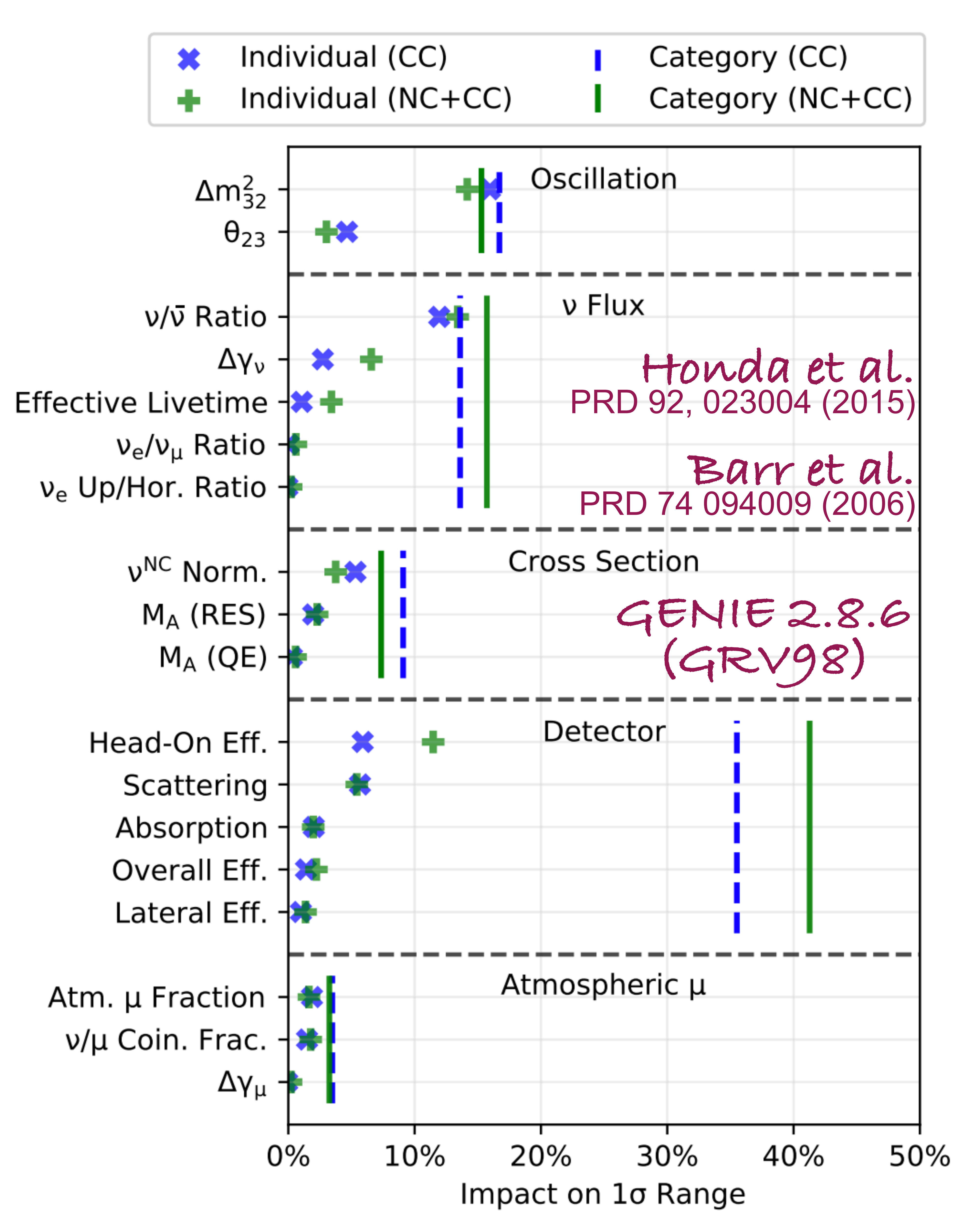

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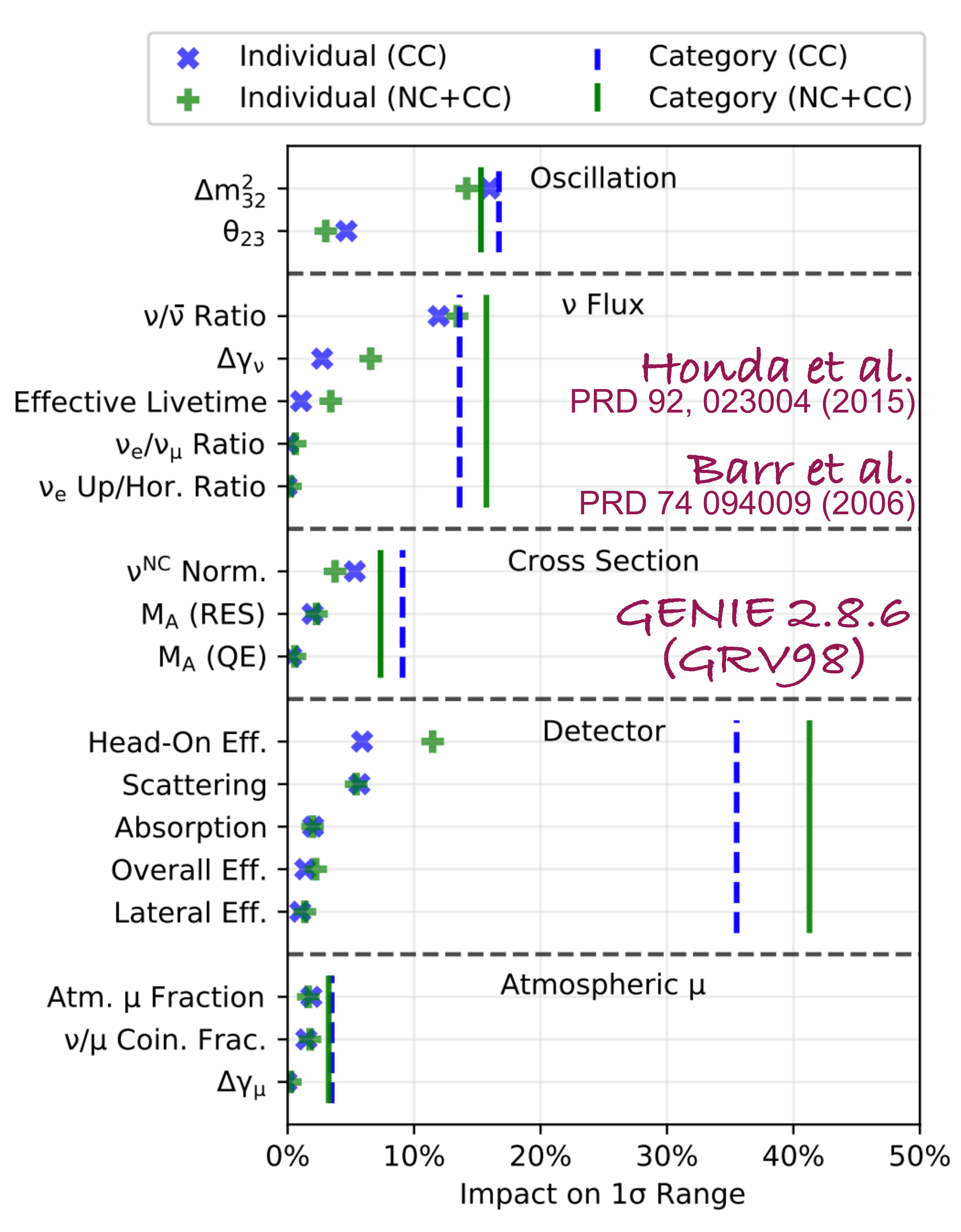
On the horizon…

8 y oscillation sample with > 300k neutrinos



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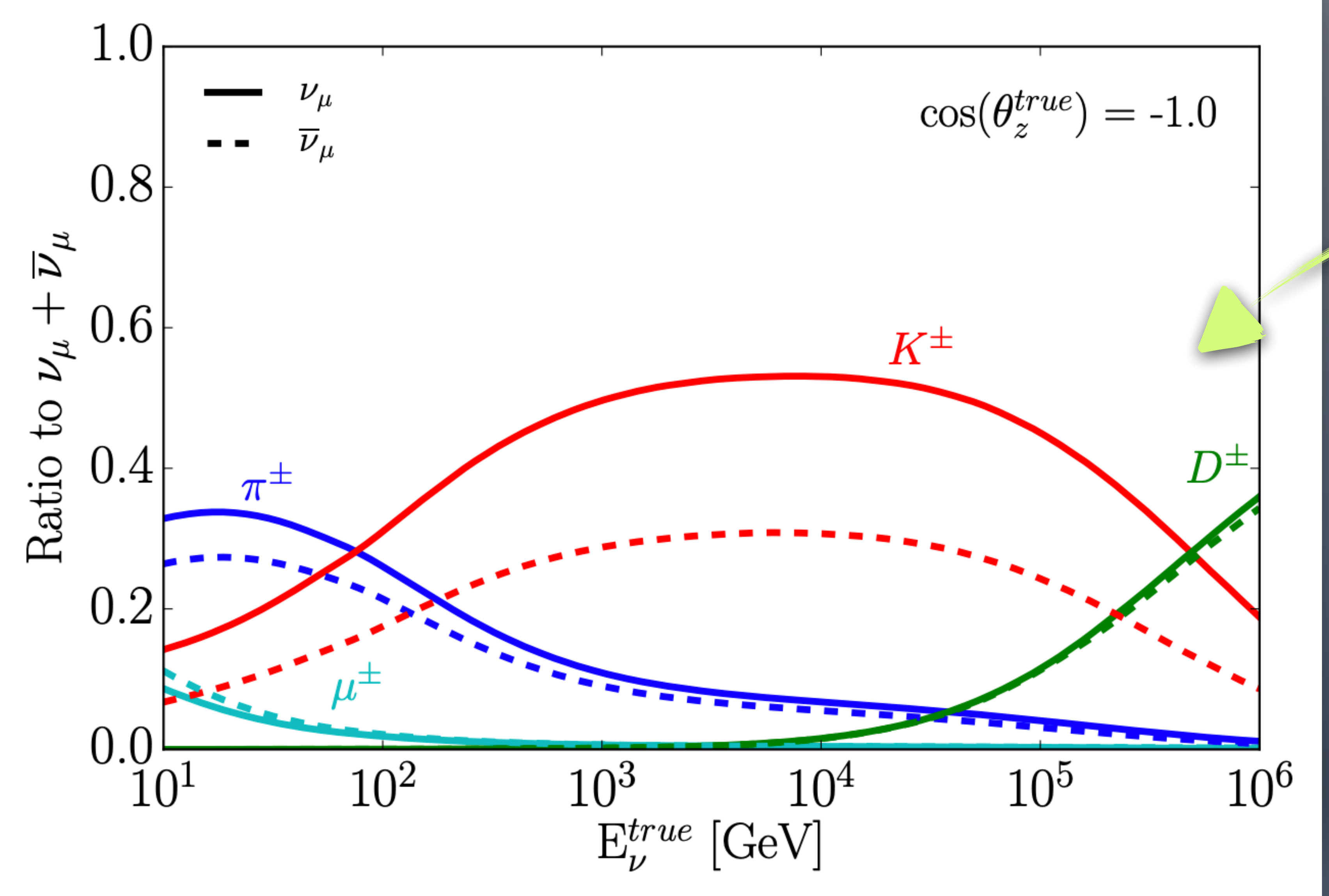
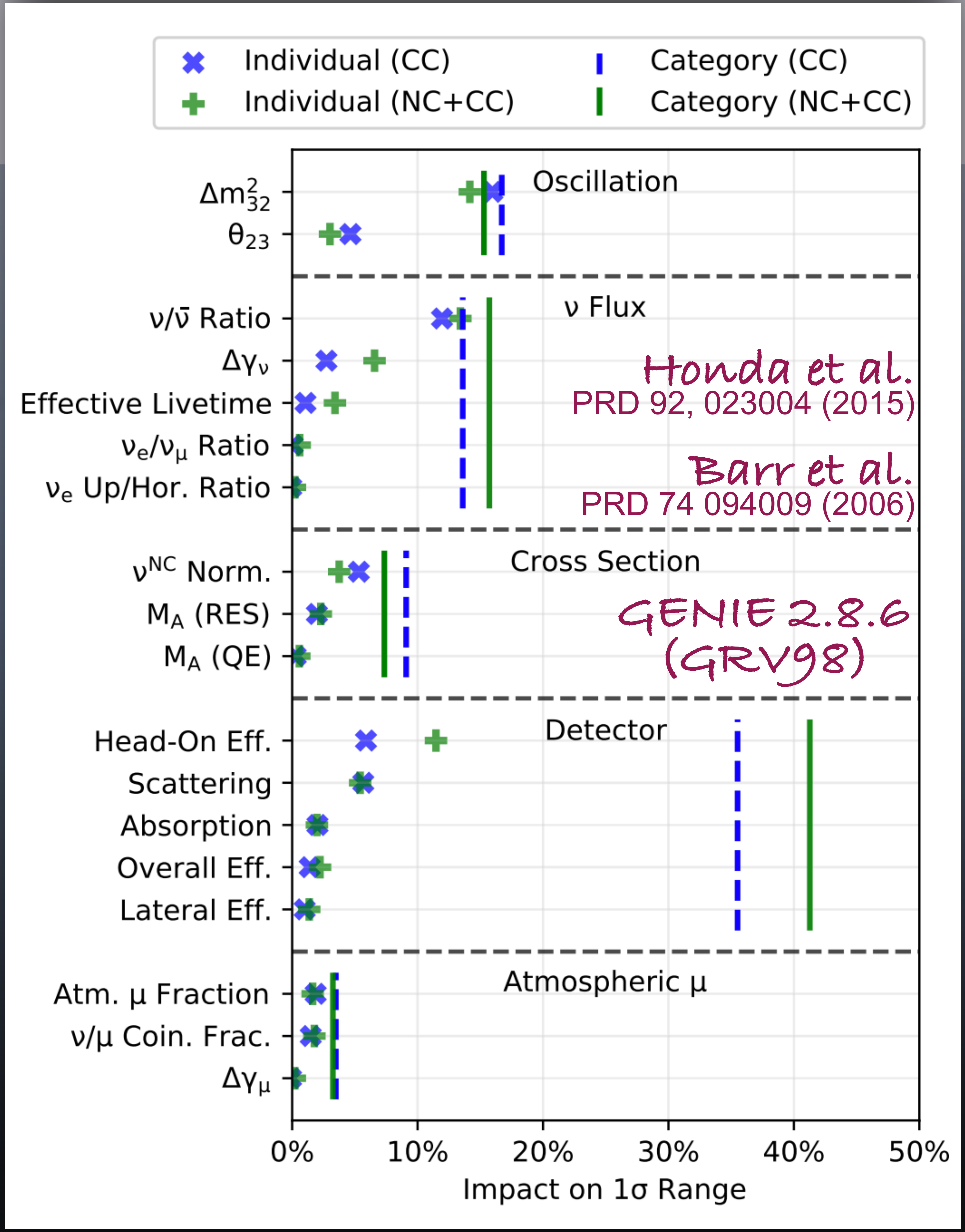


Flux

[Link to MCEq on github]

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



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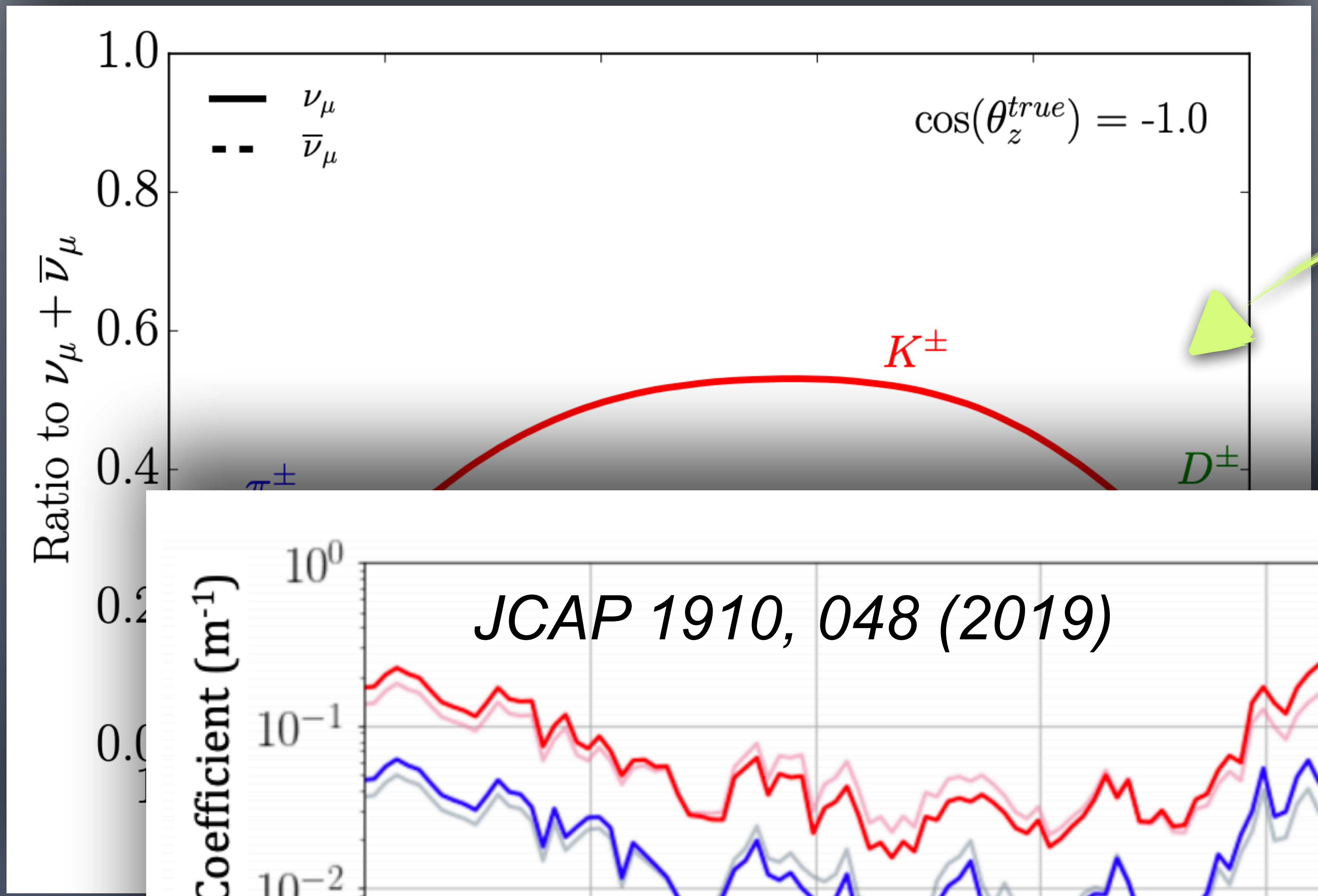

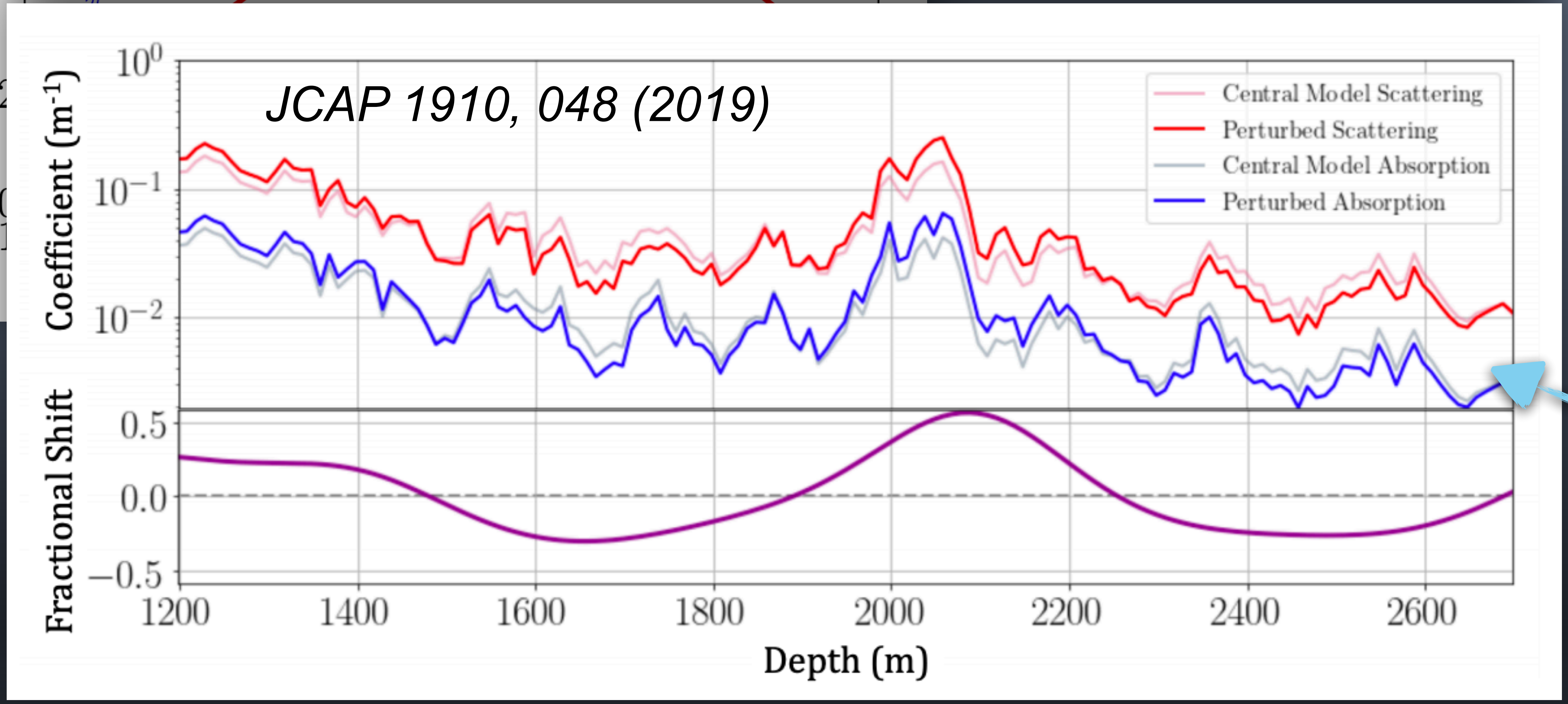

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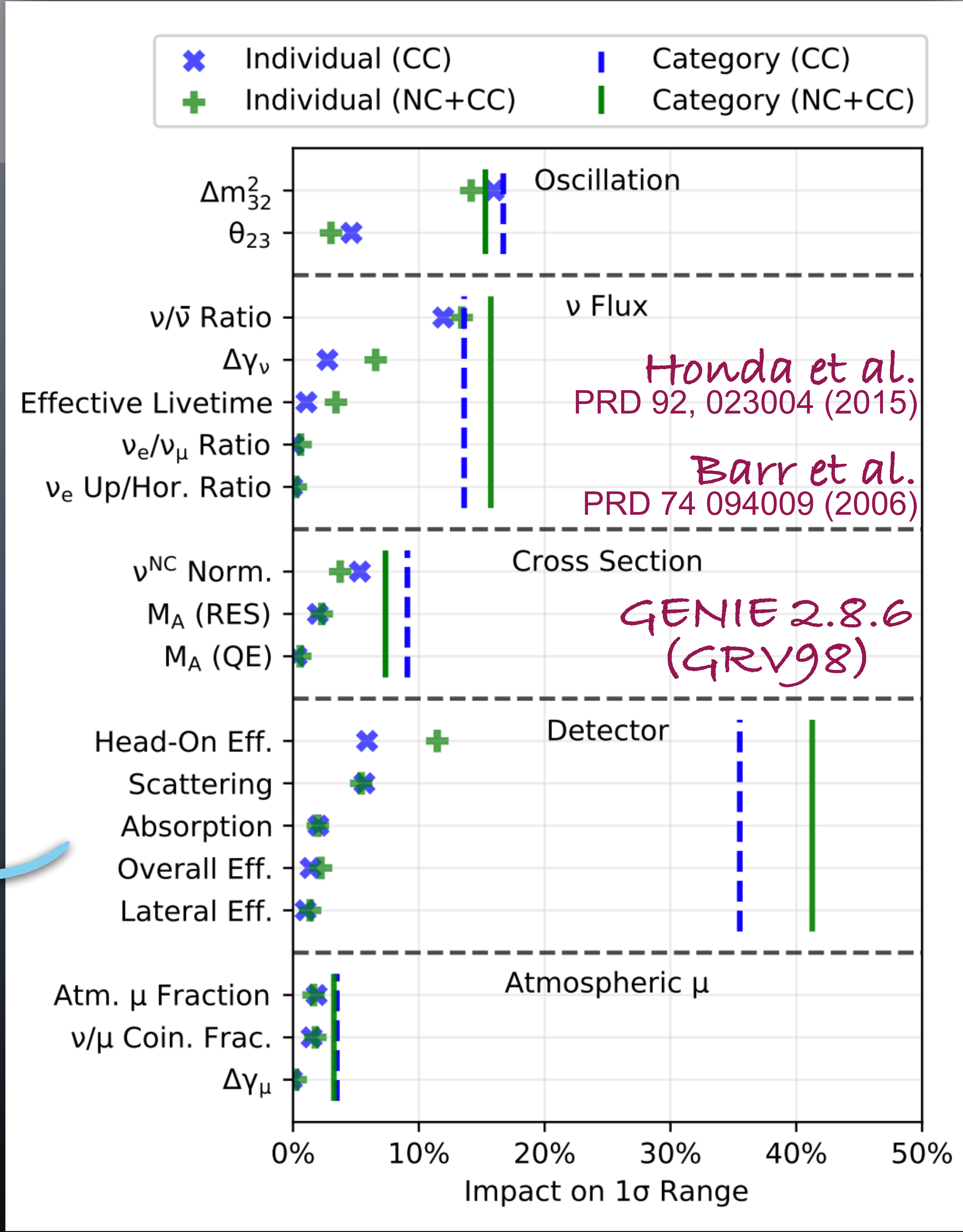
Ice



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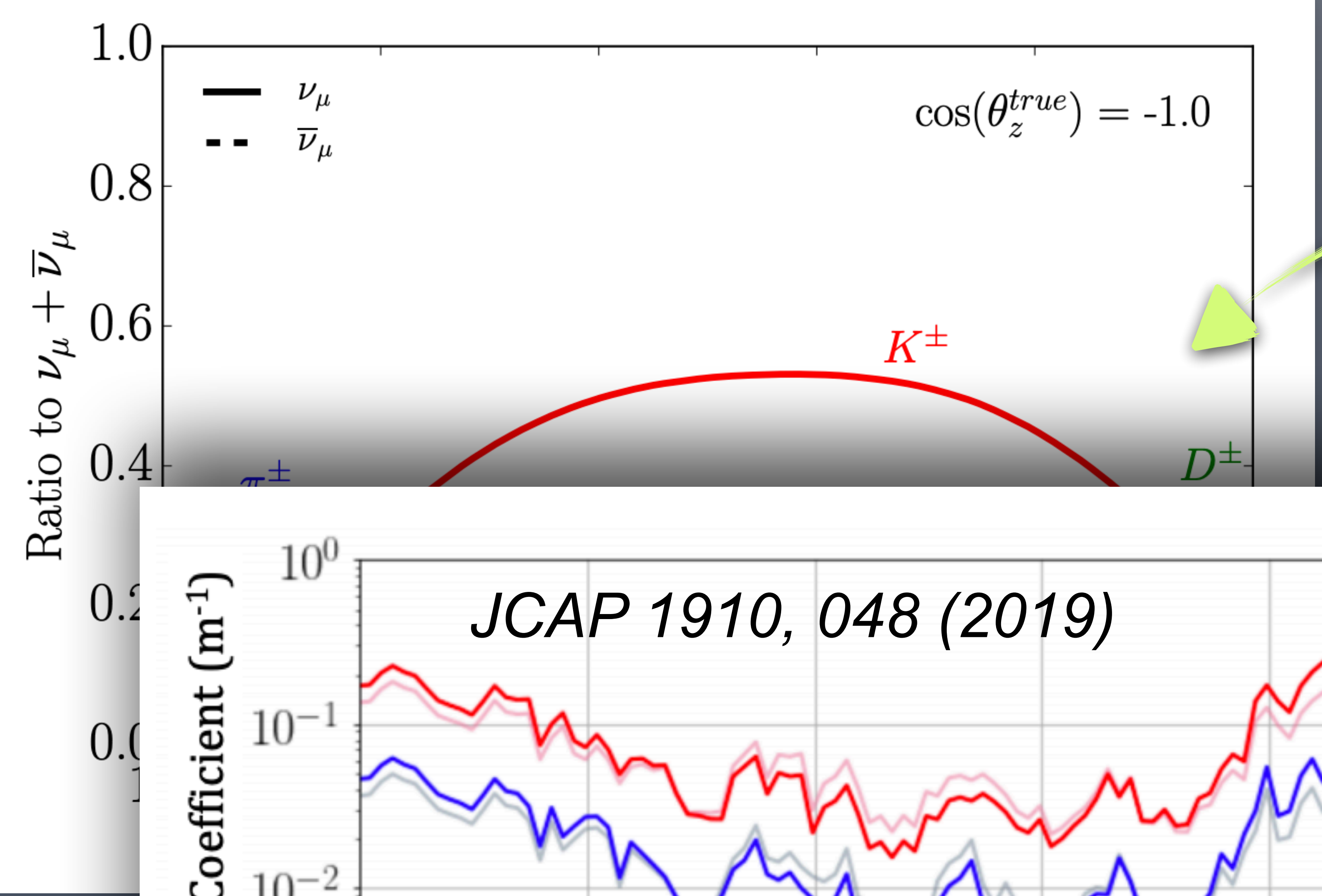

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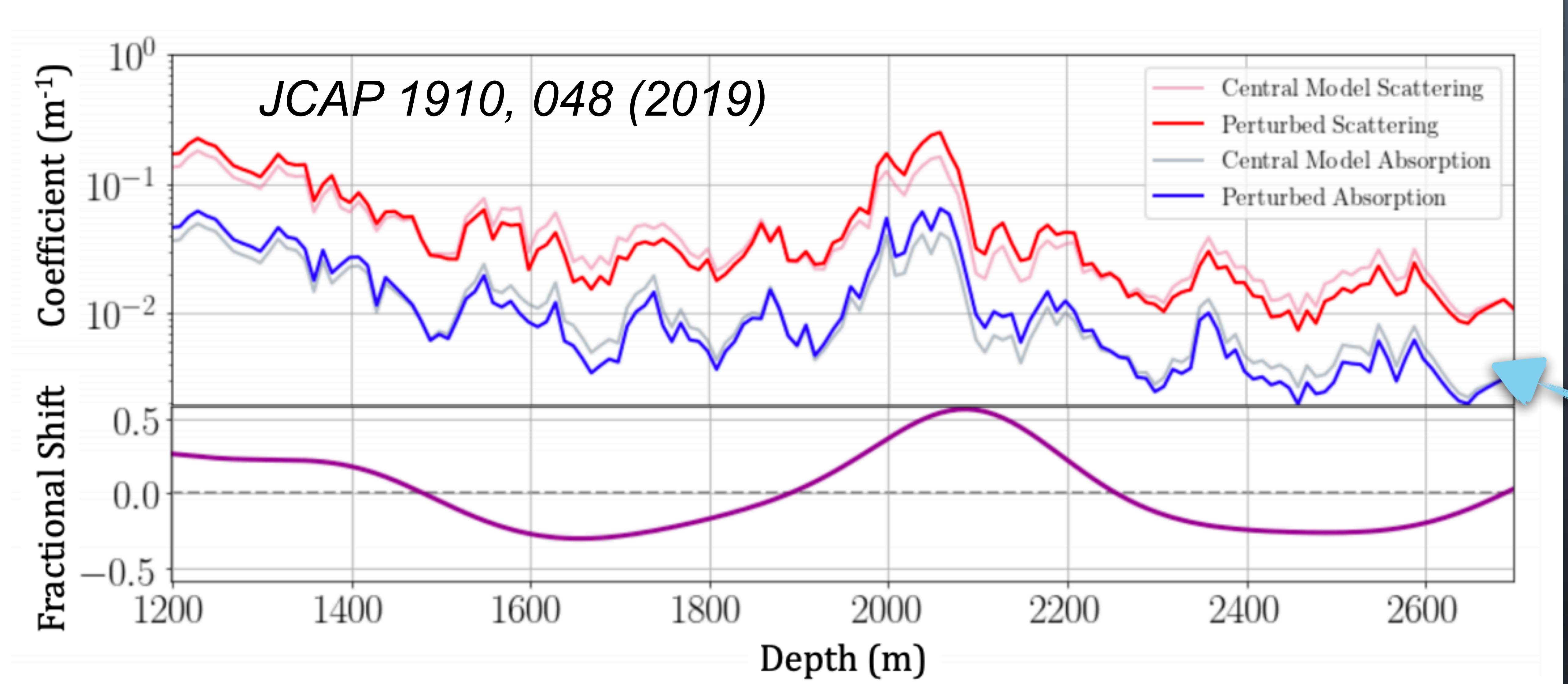

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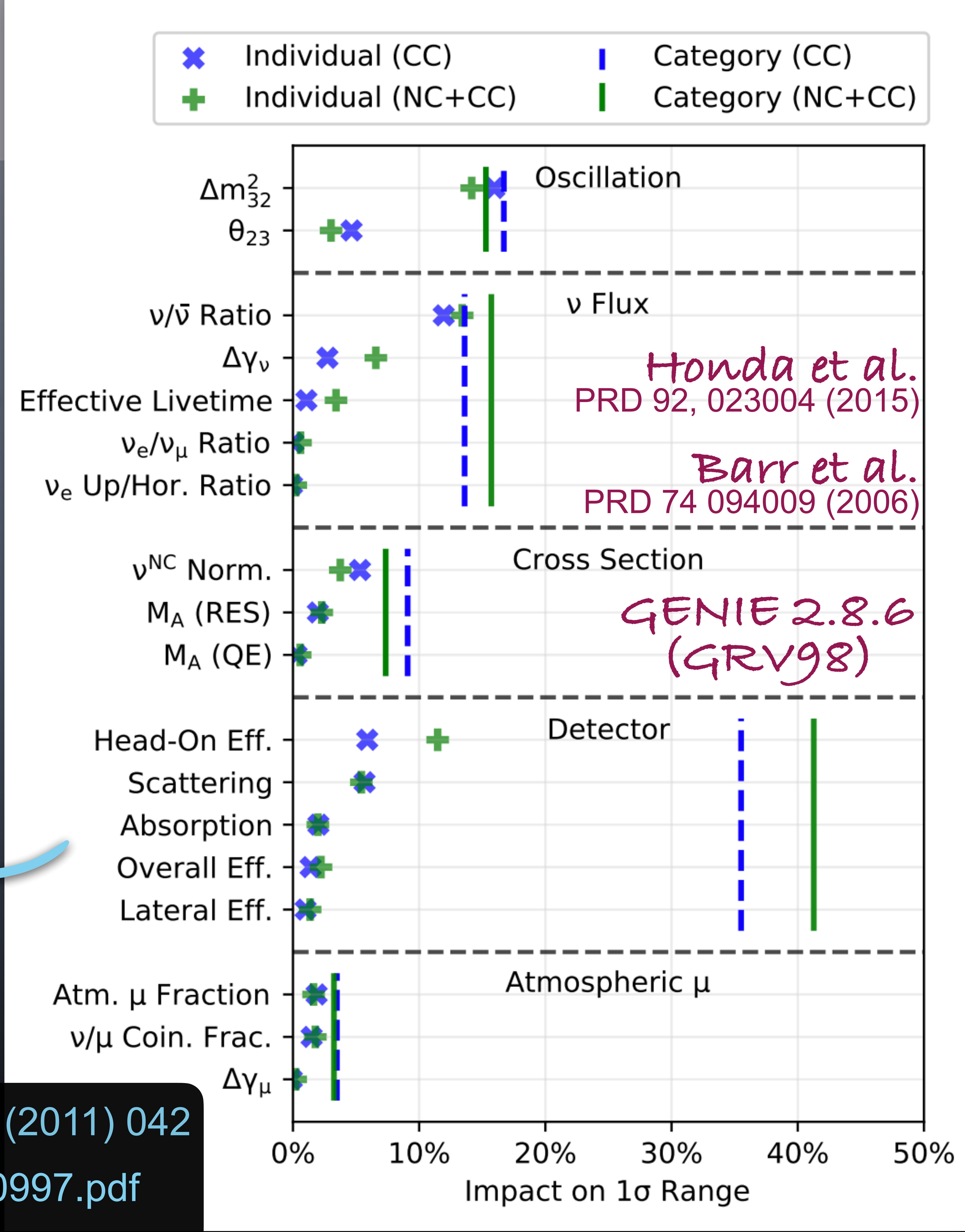


Honda et al.
PRD 92, 023004 (2015)

Barr et al.
PRD 74 094009 (2006)

GENIE 2.8.6
(GRV98)

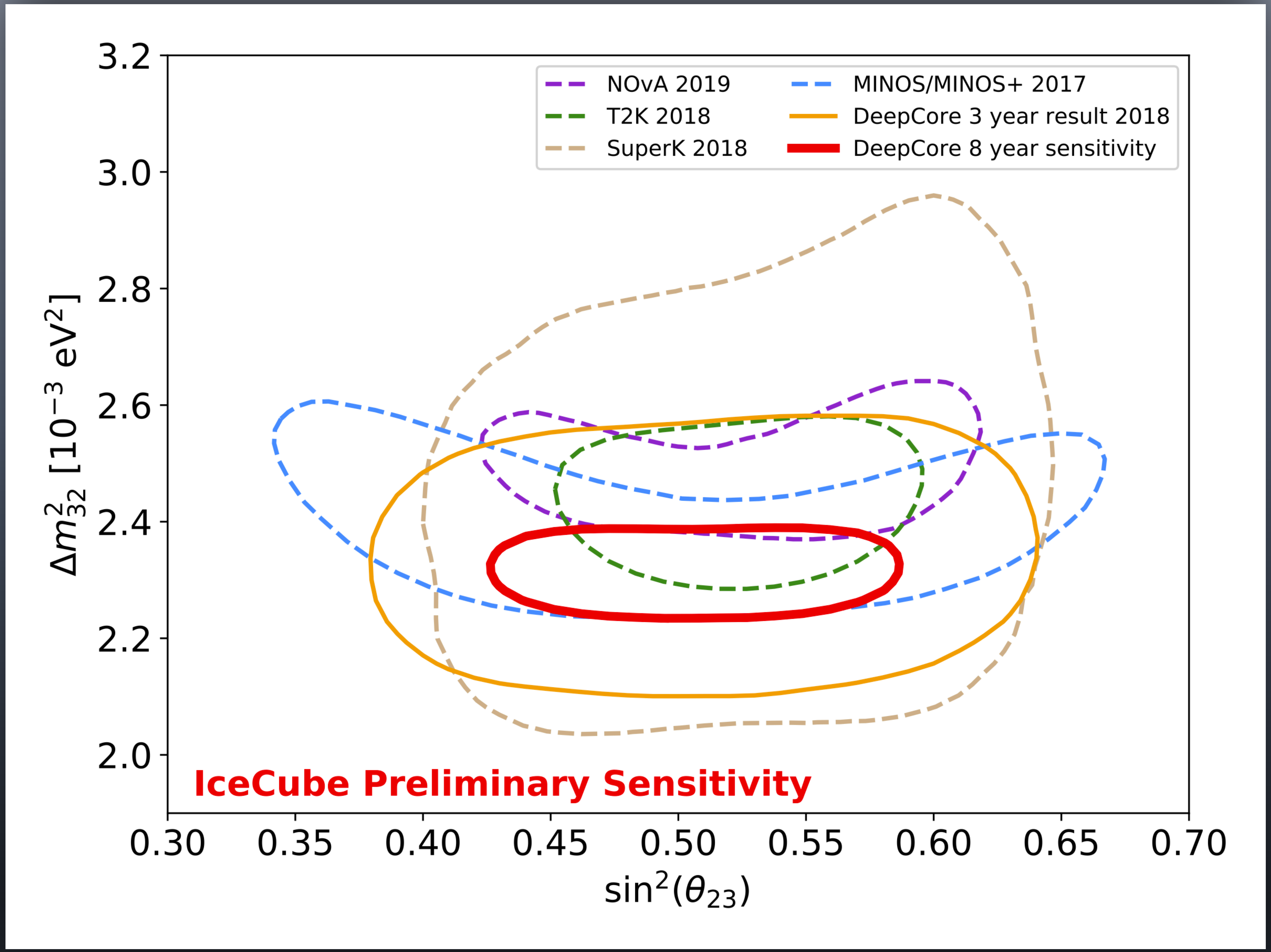
+ alternative xsec models (CSMS), see A. Cooper-Sarkar, et al. JHEP 08 (2011) 042

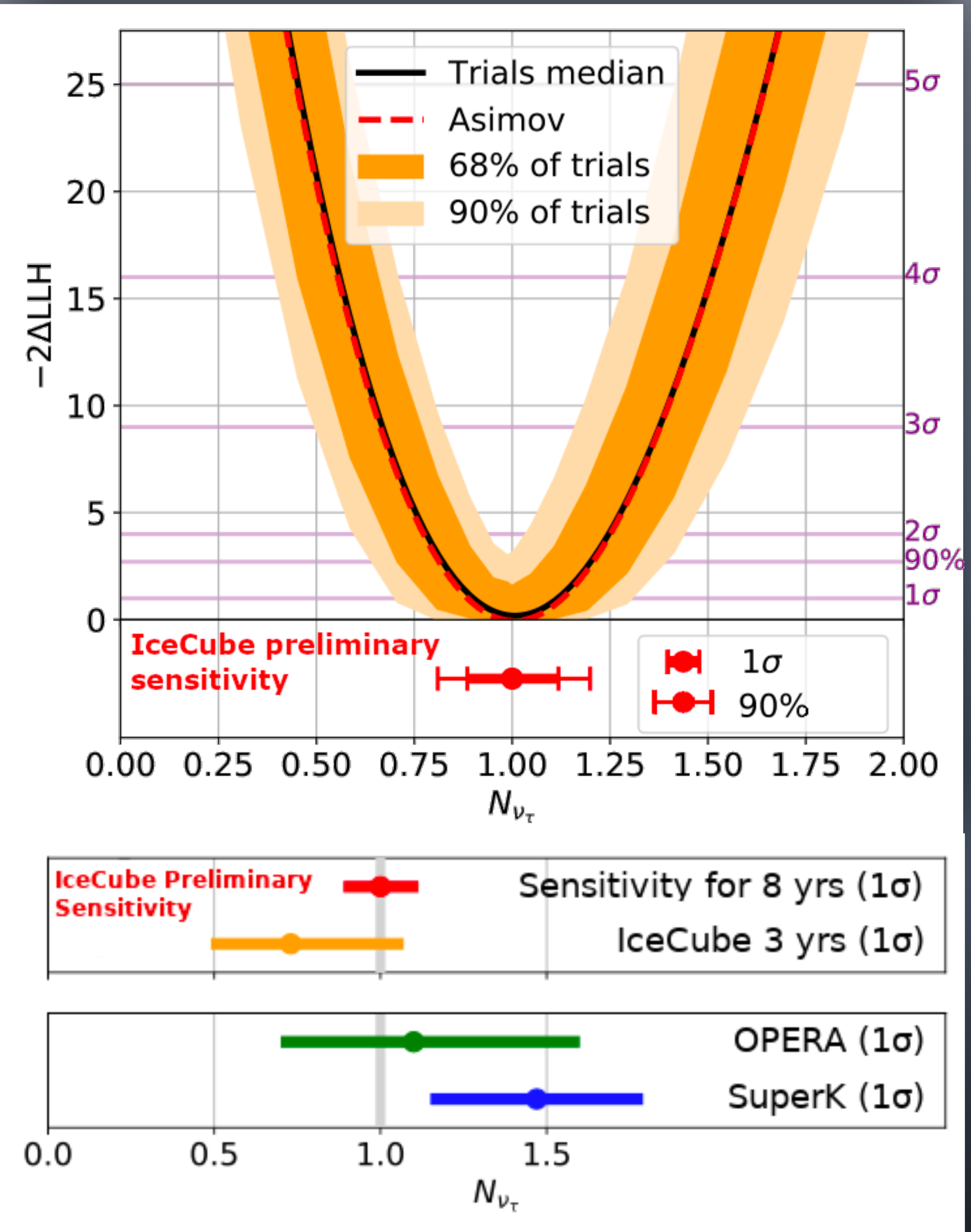
+ improved modeling of DOM response, see https://arxiv.org/pdf/2002.00997.pdf

Standard oscillation 8 y projections

See posters #547 and #167 for more details

Unprecedented with atmospheric neutrinos





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

Searching beyond the νSM

Non-standard oscillation patterns

Favourable phase space

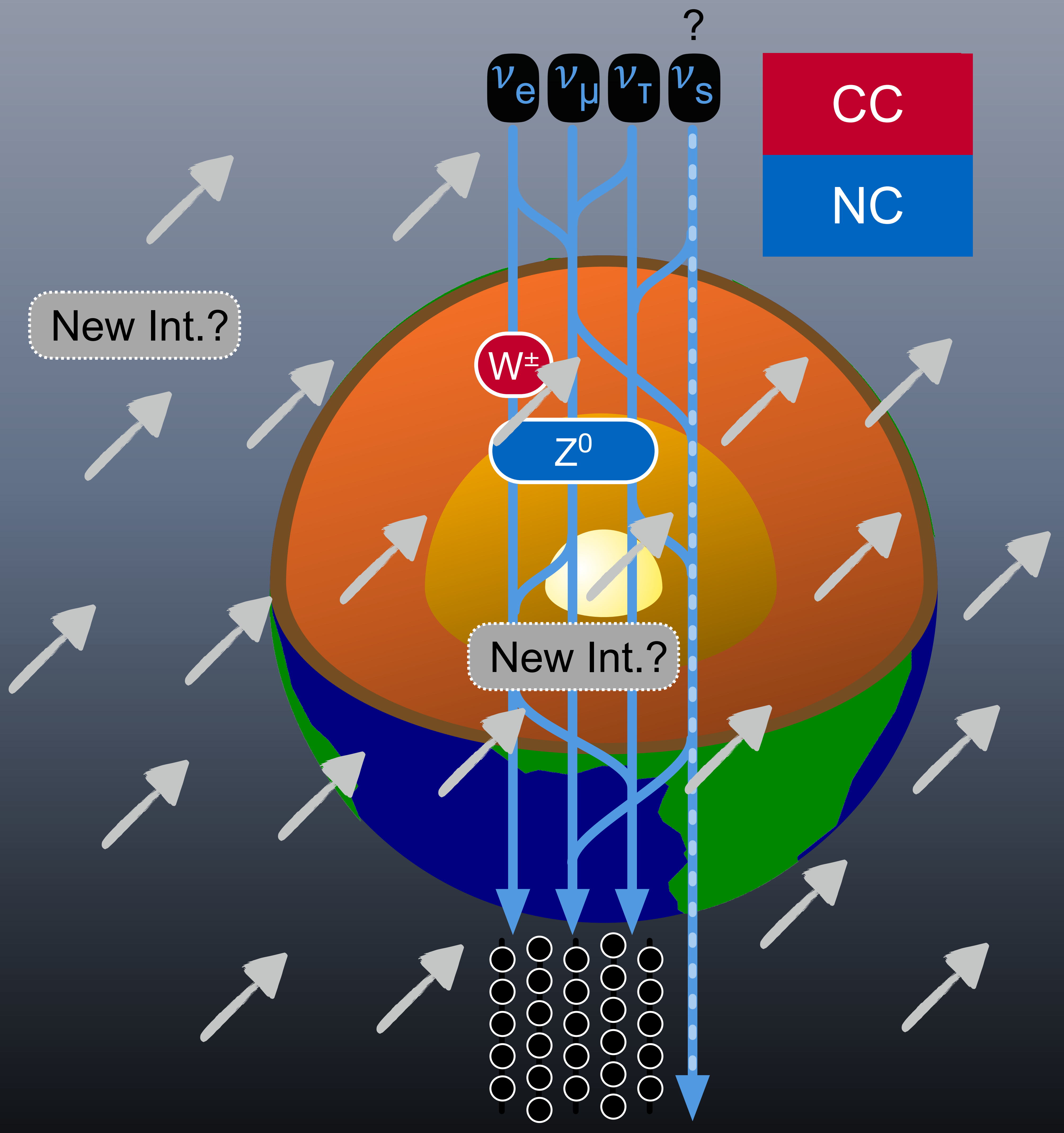
- High energies: access new physics coupling to τ-sector
- Long trajectories: exposure to new fields/interactions

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

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



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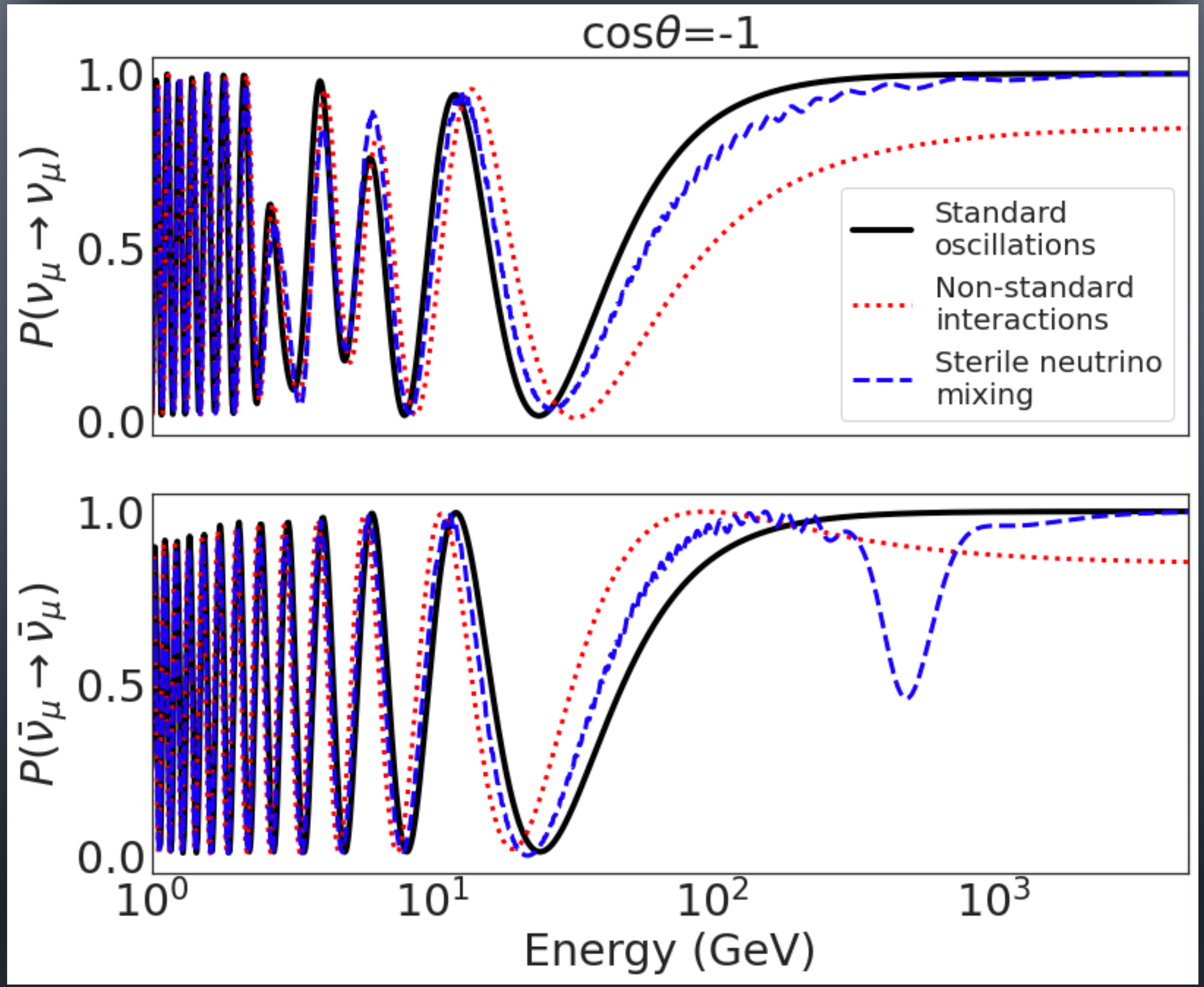
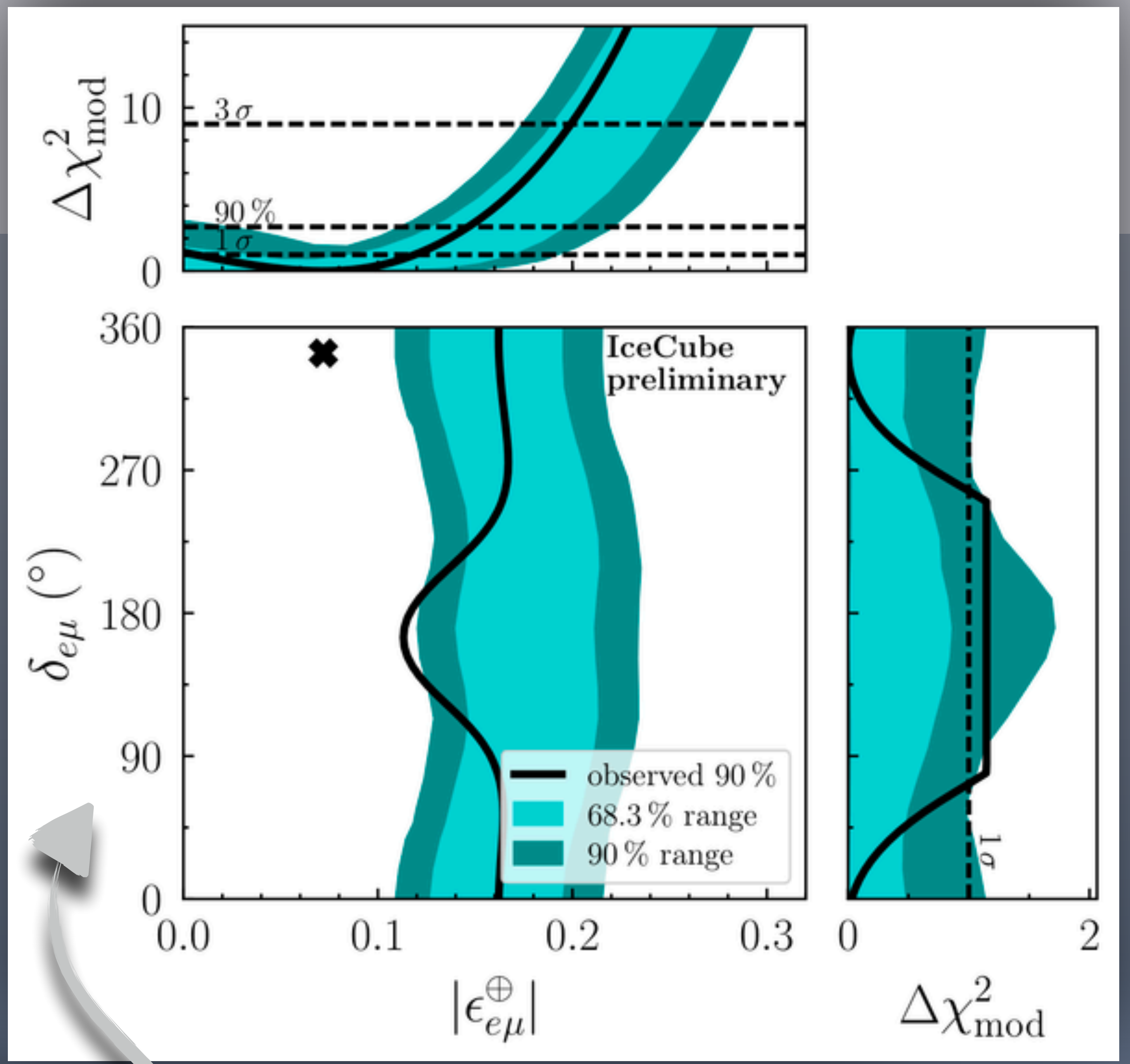


For particular realisations of non-standard physics

Non-standard interactions

New constraints from 3-year DeepCore sample

See poster #364 for more details

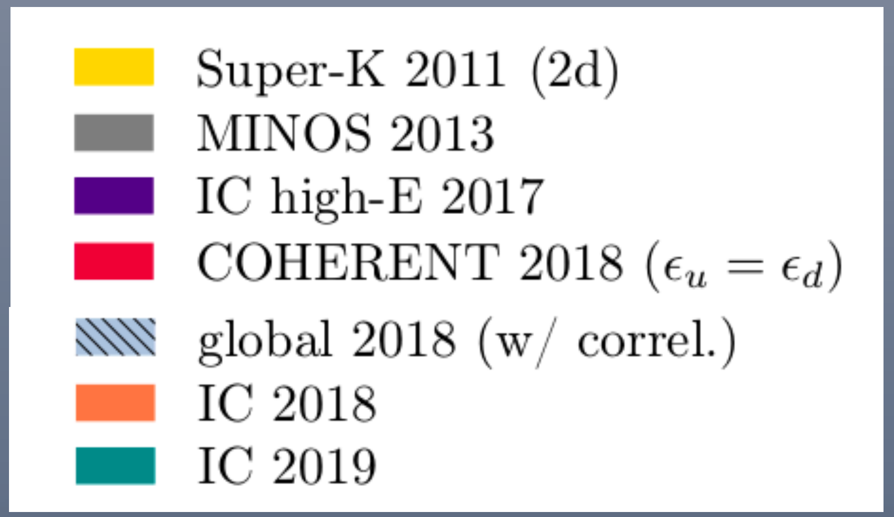


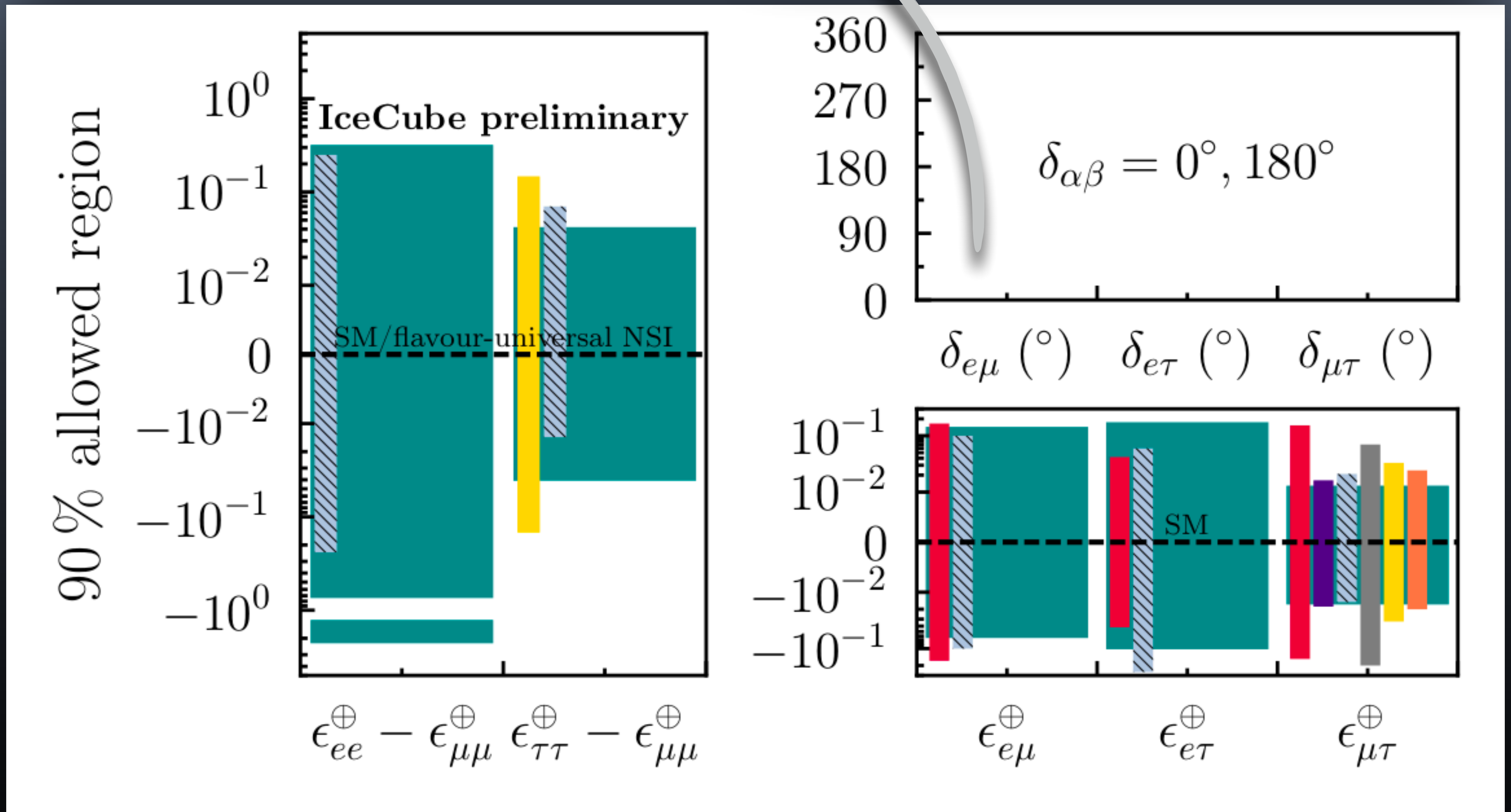
New mediators, e.g. Z'

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

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

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





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^2_{41}, 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

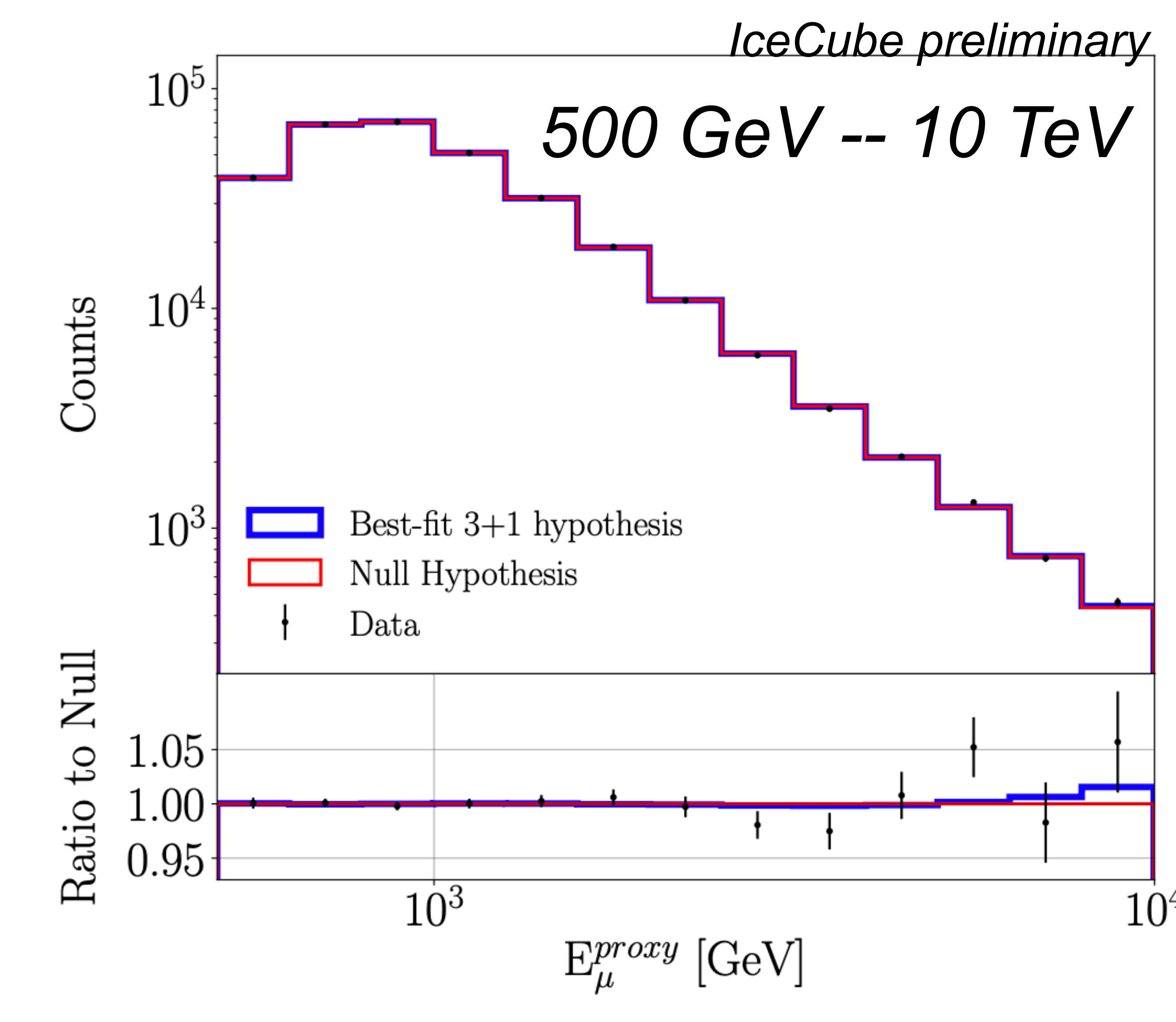
Two searches, both results consistent with null hypothesis

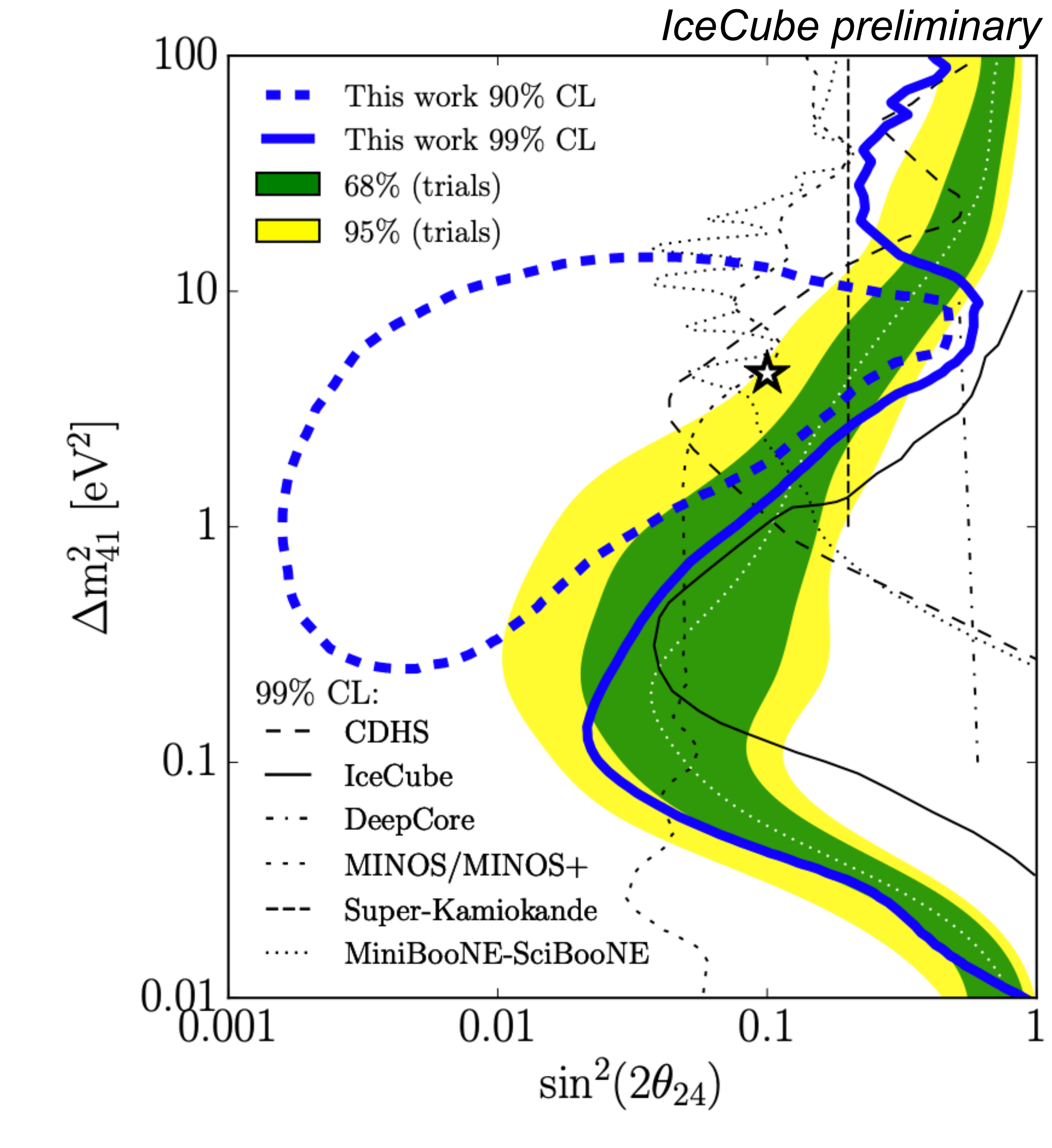
Analysis I: $\Delta m = 4.47\ eV^2$, $\sin^2(2\theta_{24}) = 0.10$ ($\theta_{34} = 0$), $p = 8\%$

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

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

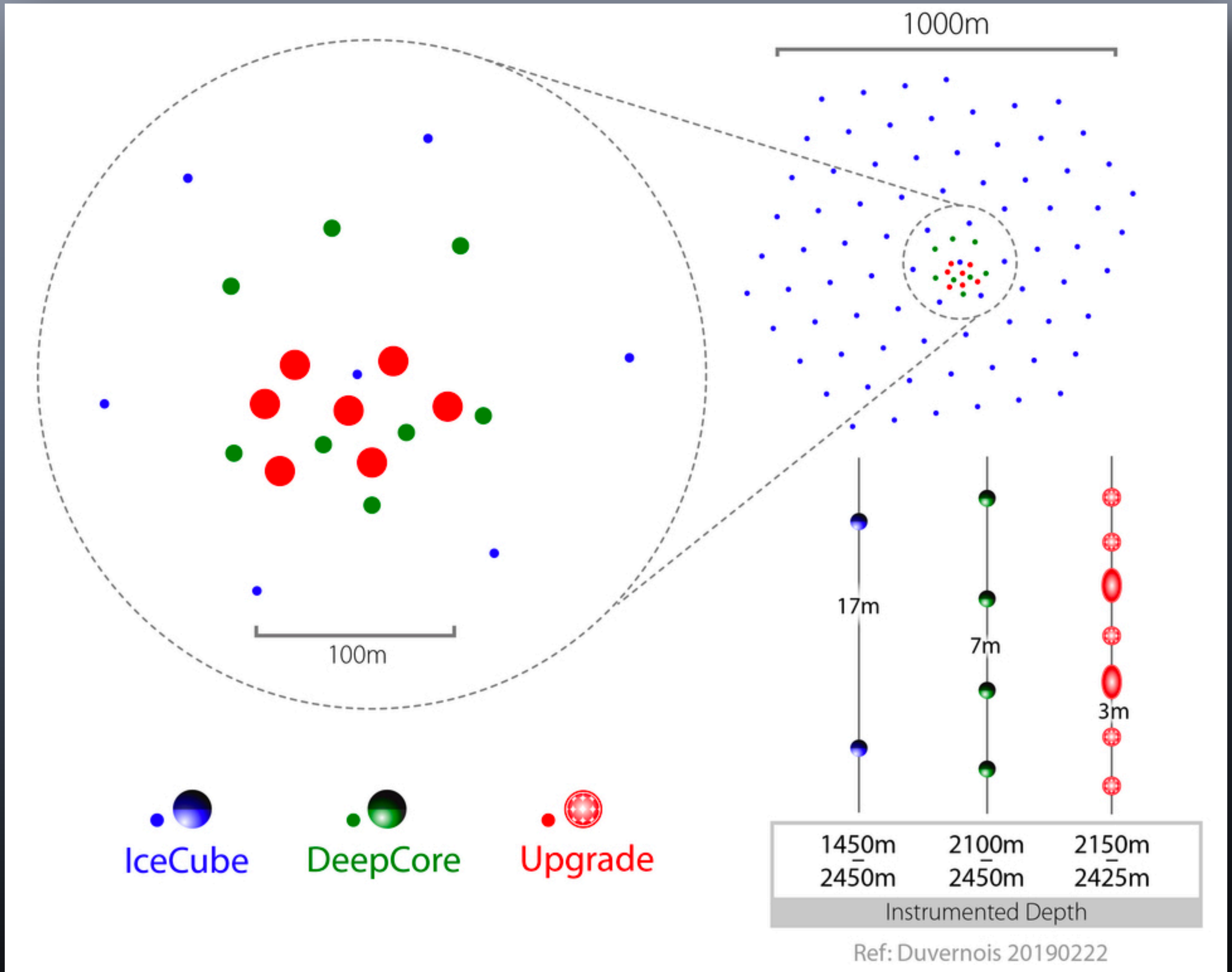
A multipurpose detector

IceCube Upgrade goals:

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

Key features

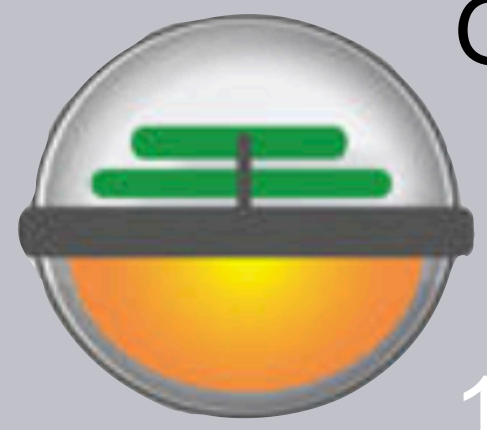
- > 800 new devices
- Reduced spacing between devices
- Explore the deep ice down to 2600 m



New sensor designs

Increased effective area

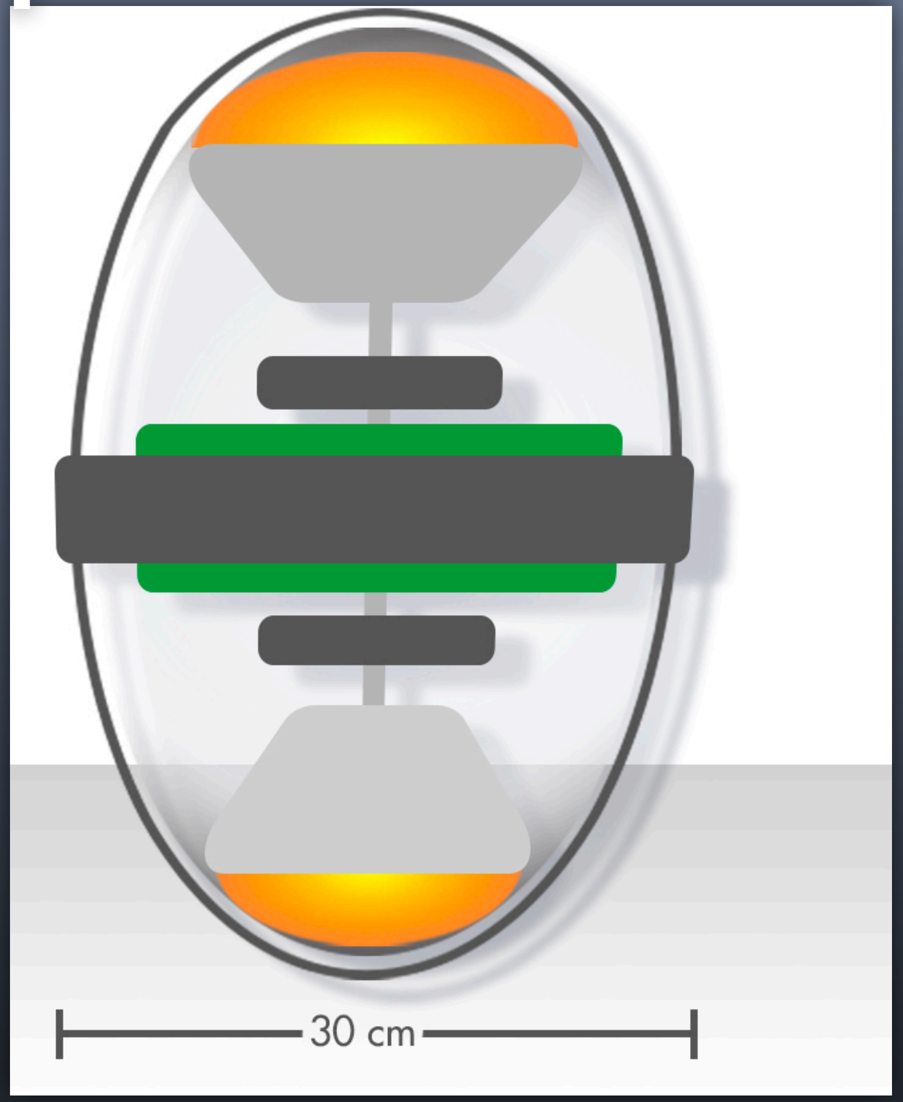
Gen1

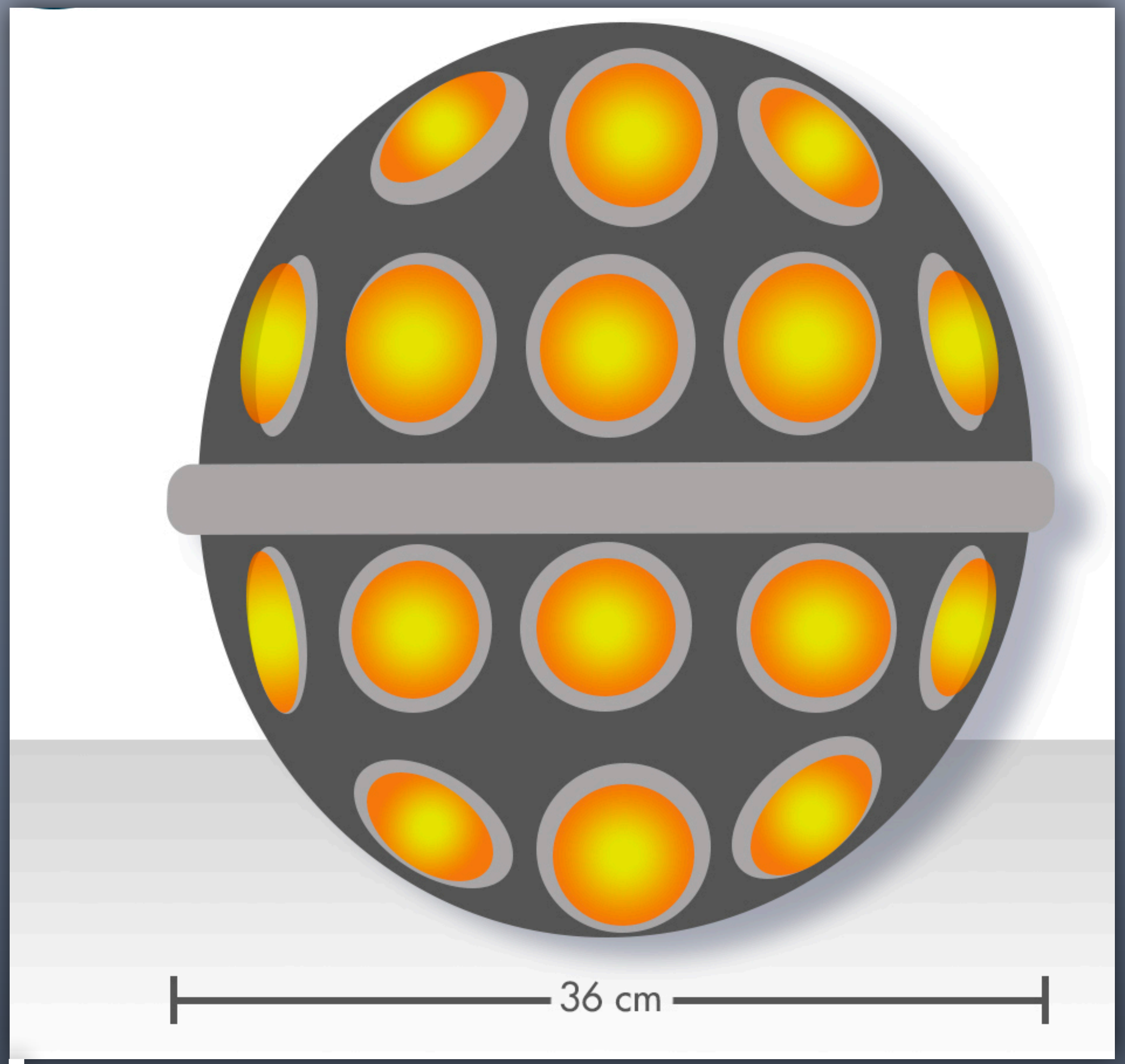


1x10” PMT

DEgg

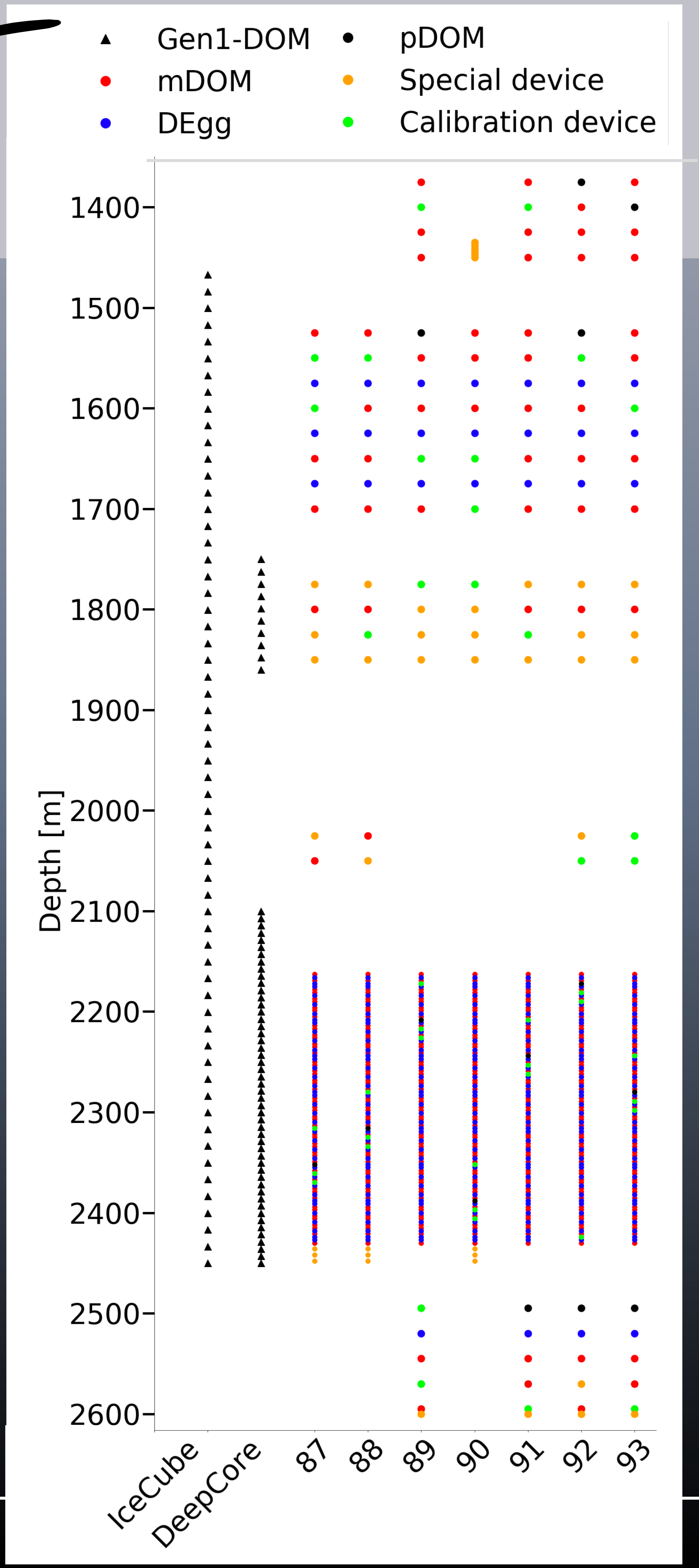
2x8” PMT
Produced at Chiba
Deploy ~300





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

mDOM



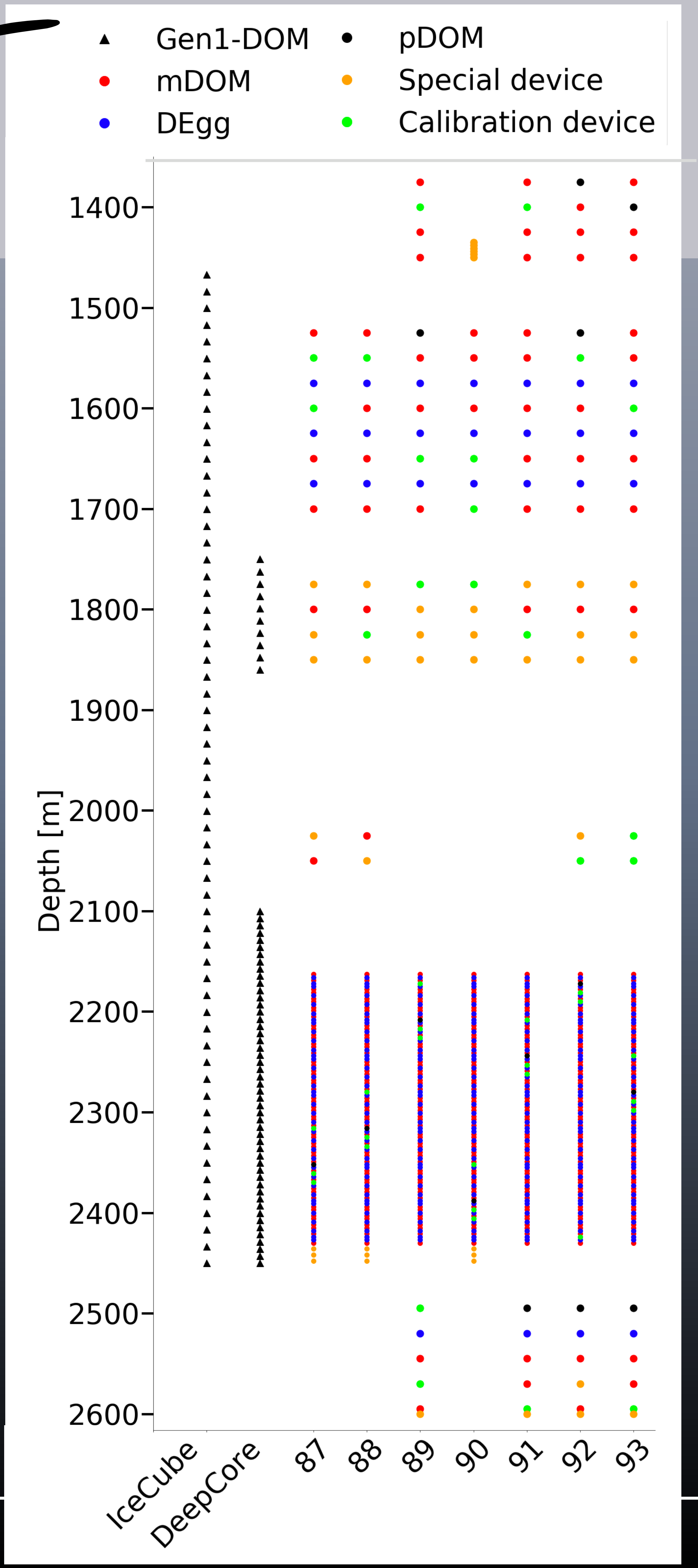
More total photocathode area, increased wavelength and angular acceptance

New sensor designs

Increased effective area

Gen1

1x10” PMT



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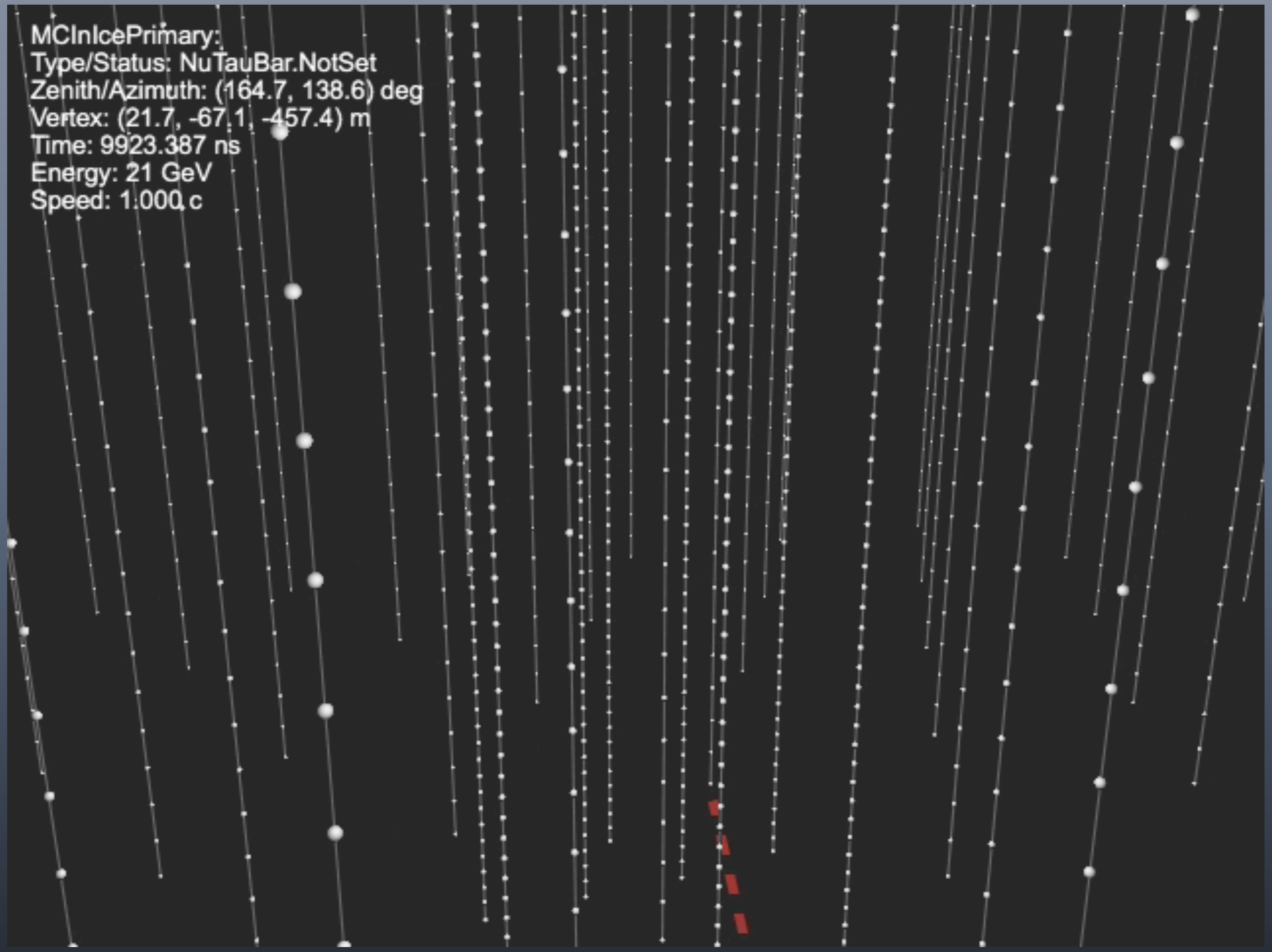
mDOM

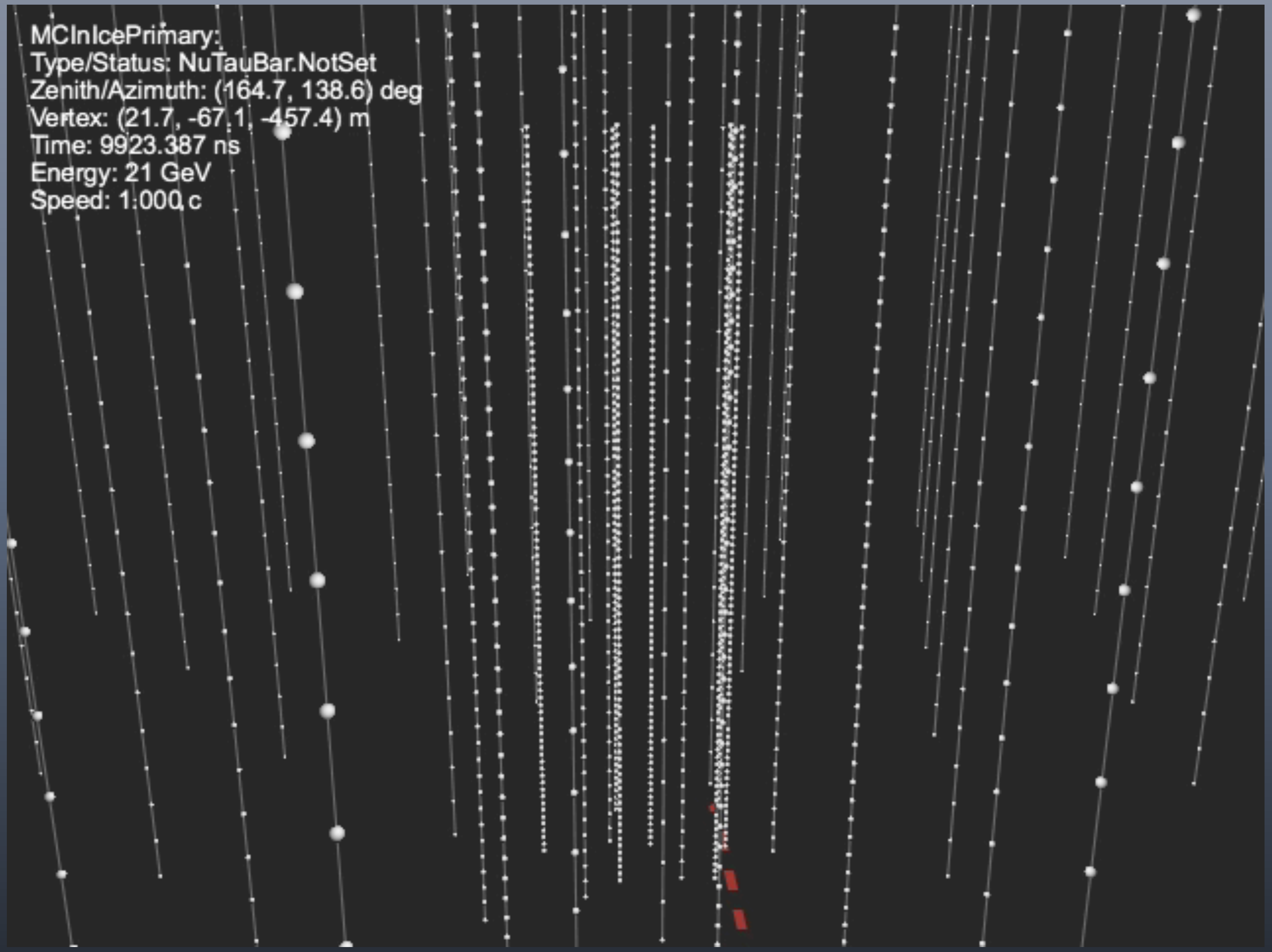
More total photocathode area, increased wavelength and angular acceptance

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)

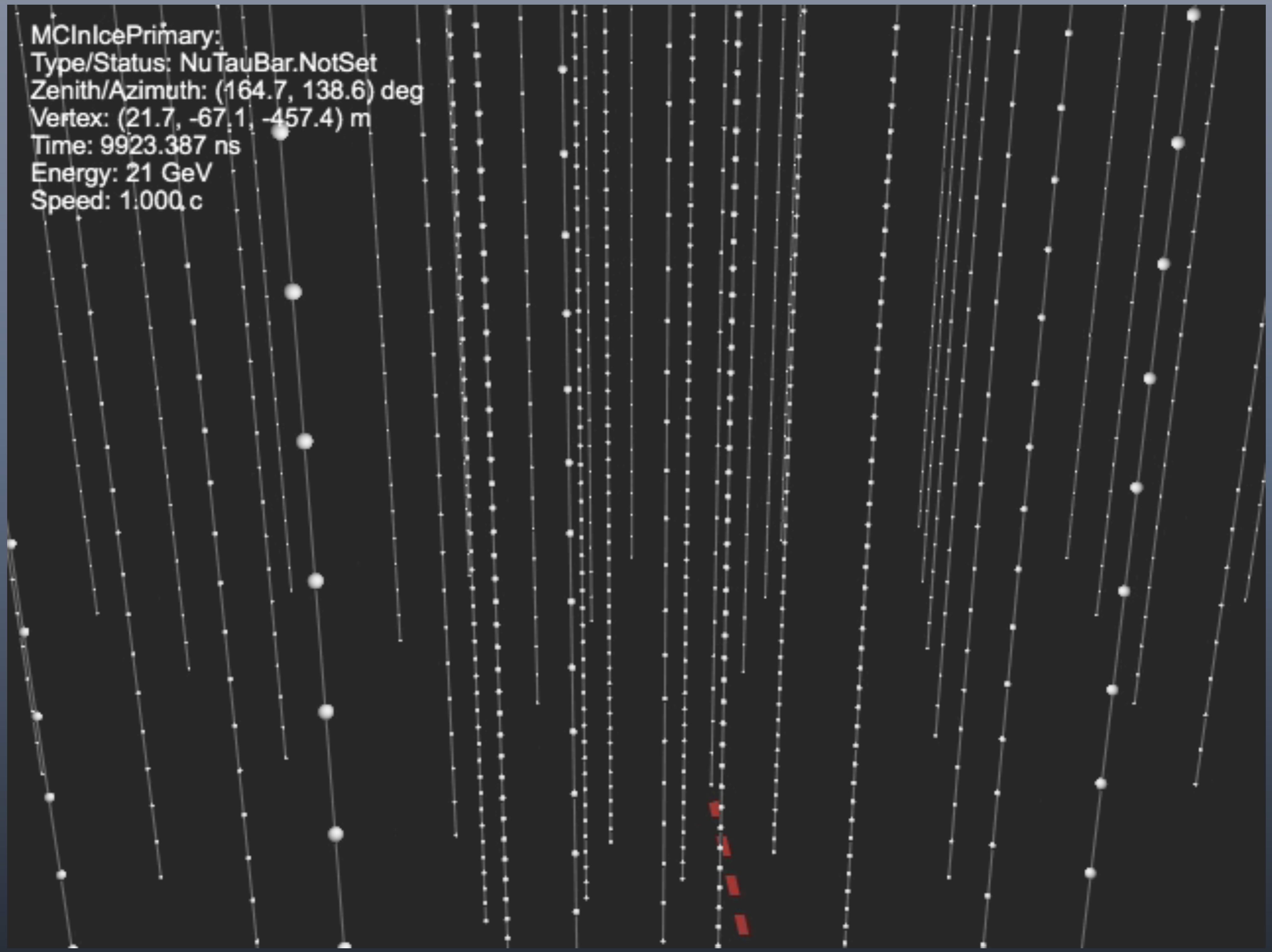
IceCube Upgrade Events

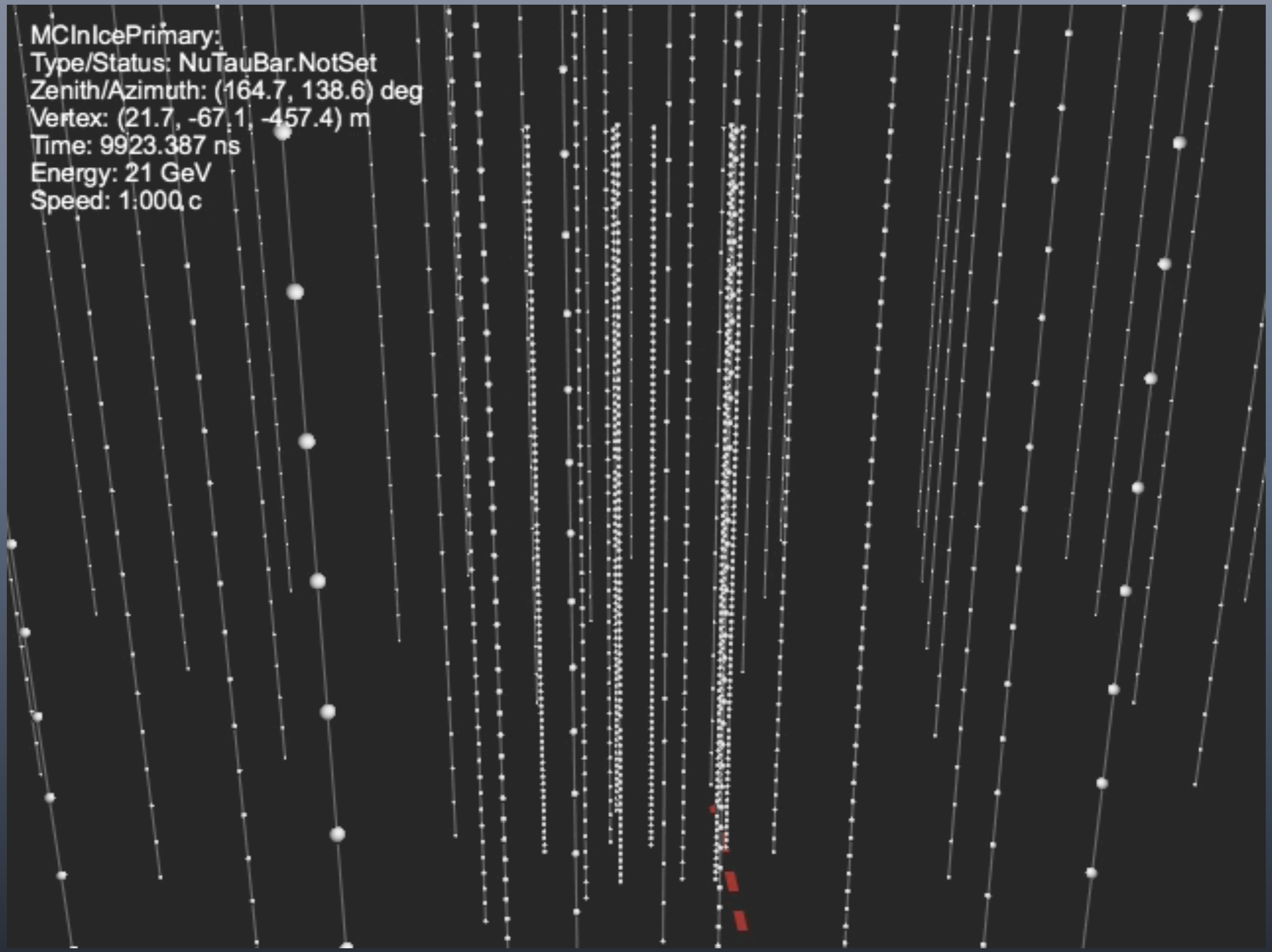
More detail in every event

DeepCore

21 GeV ν_τ interaction

Upgrade





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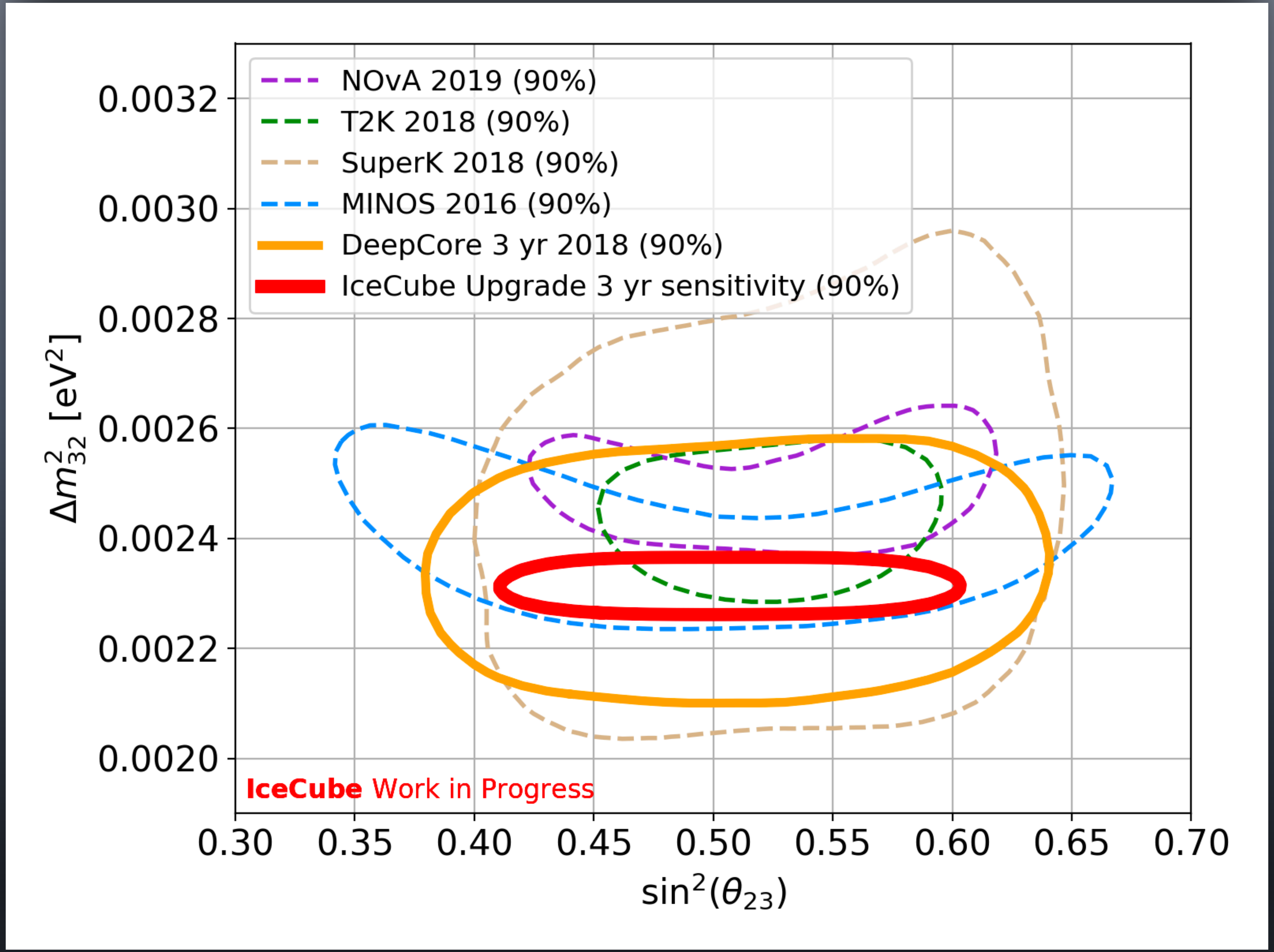
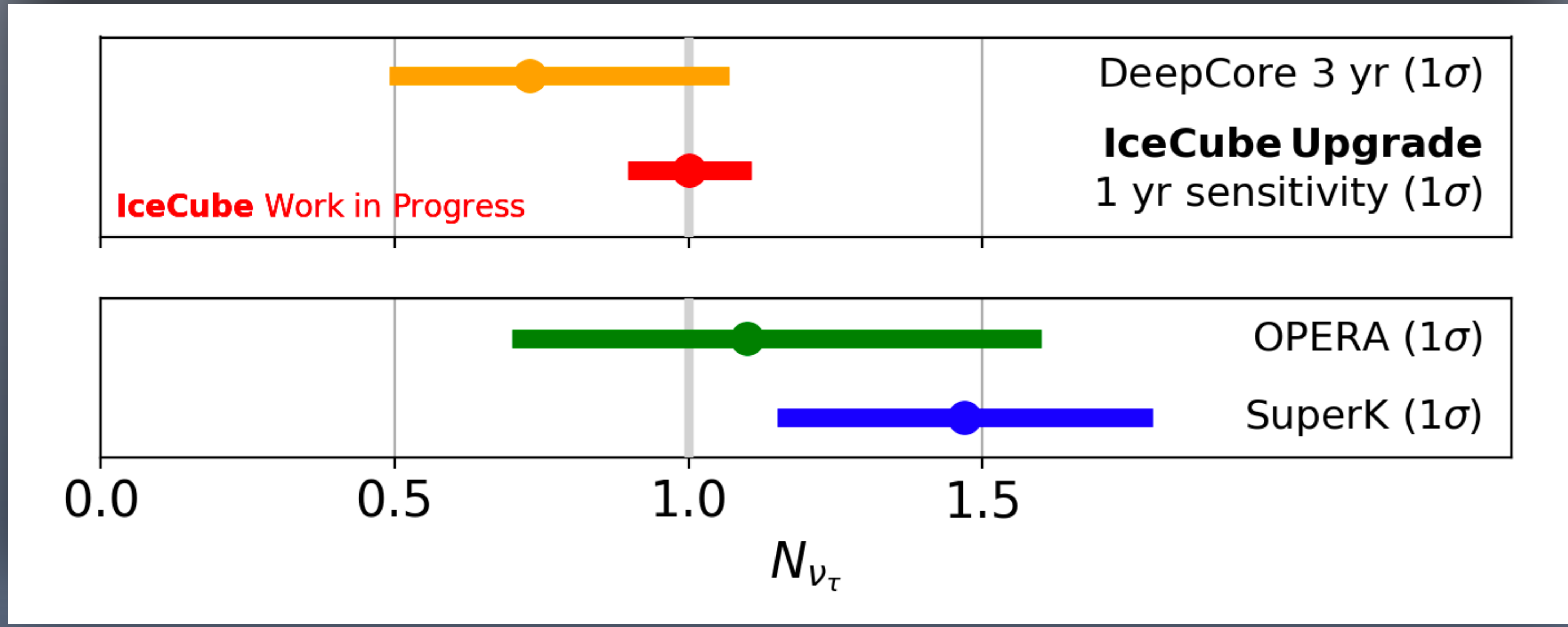
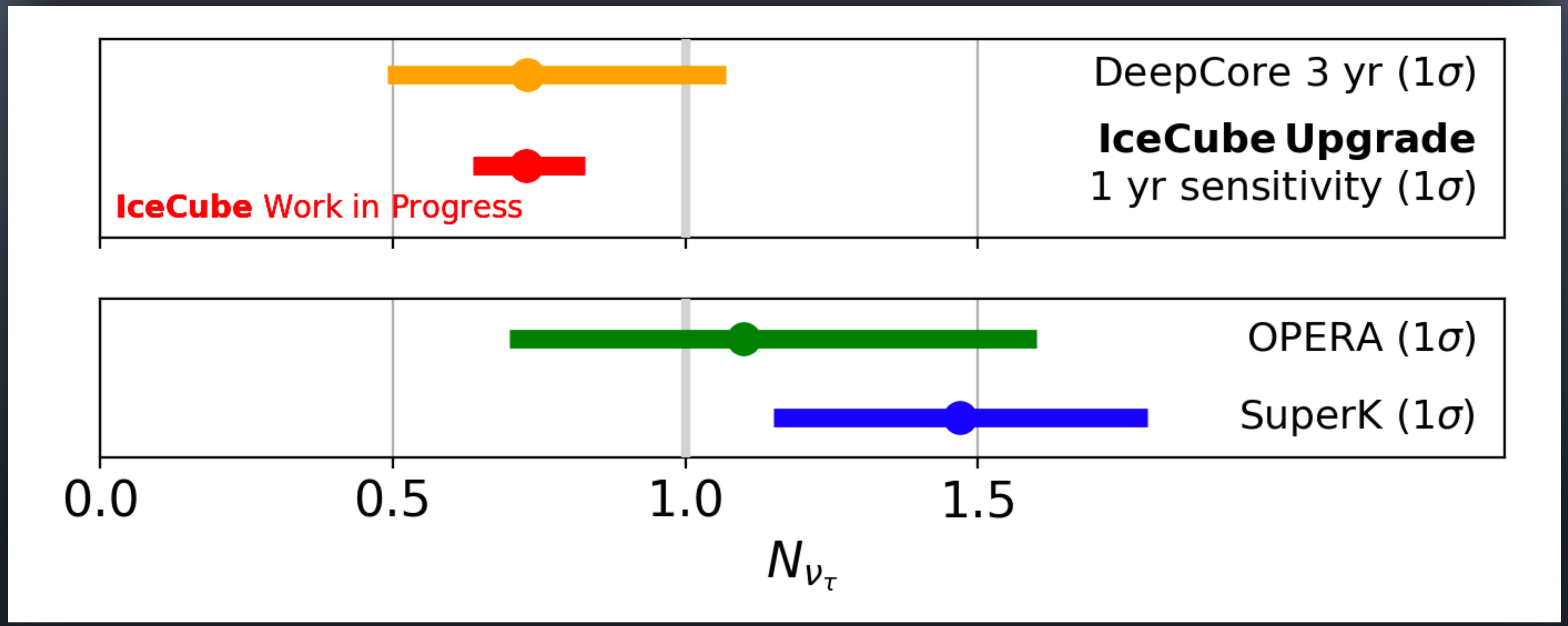
IceCube Upgrade Potential

Precision measurements of standard oscillations







Similar improvements expected in Beyond νSM searches

IceCube Upgrade

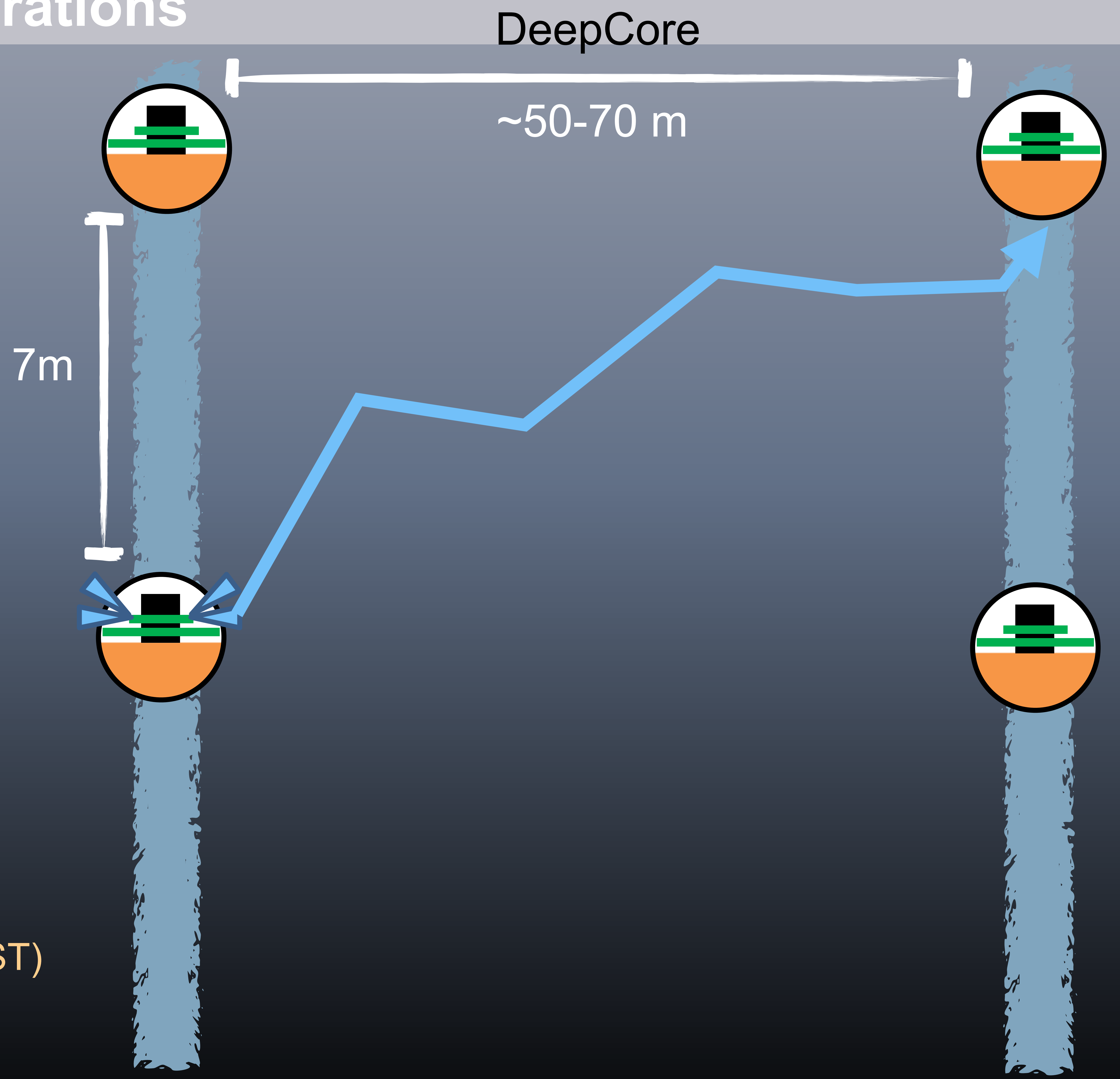
Opportunities for improved detector calibrations

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)

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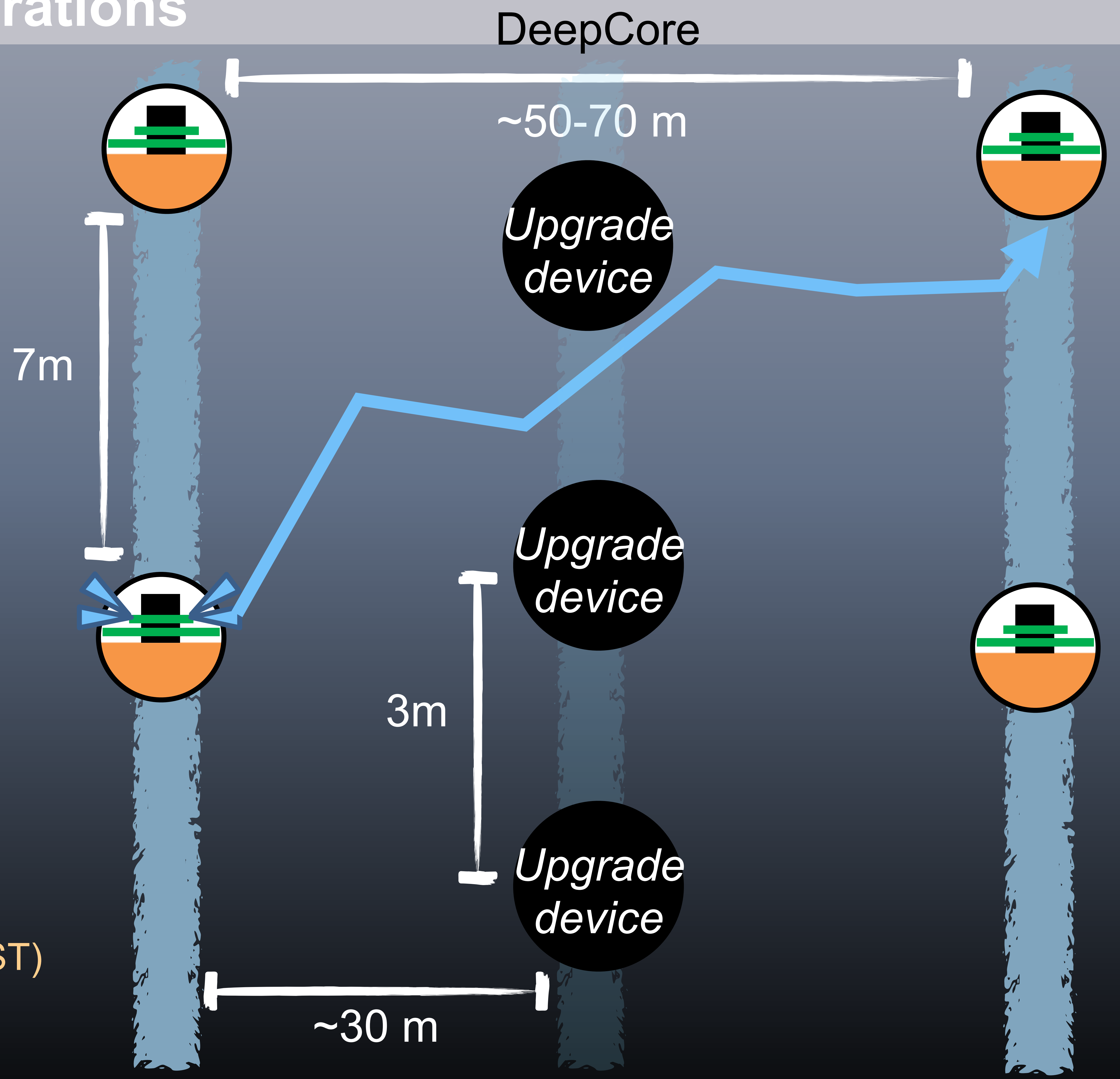

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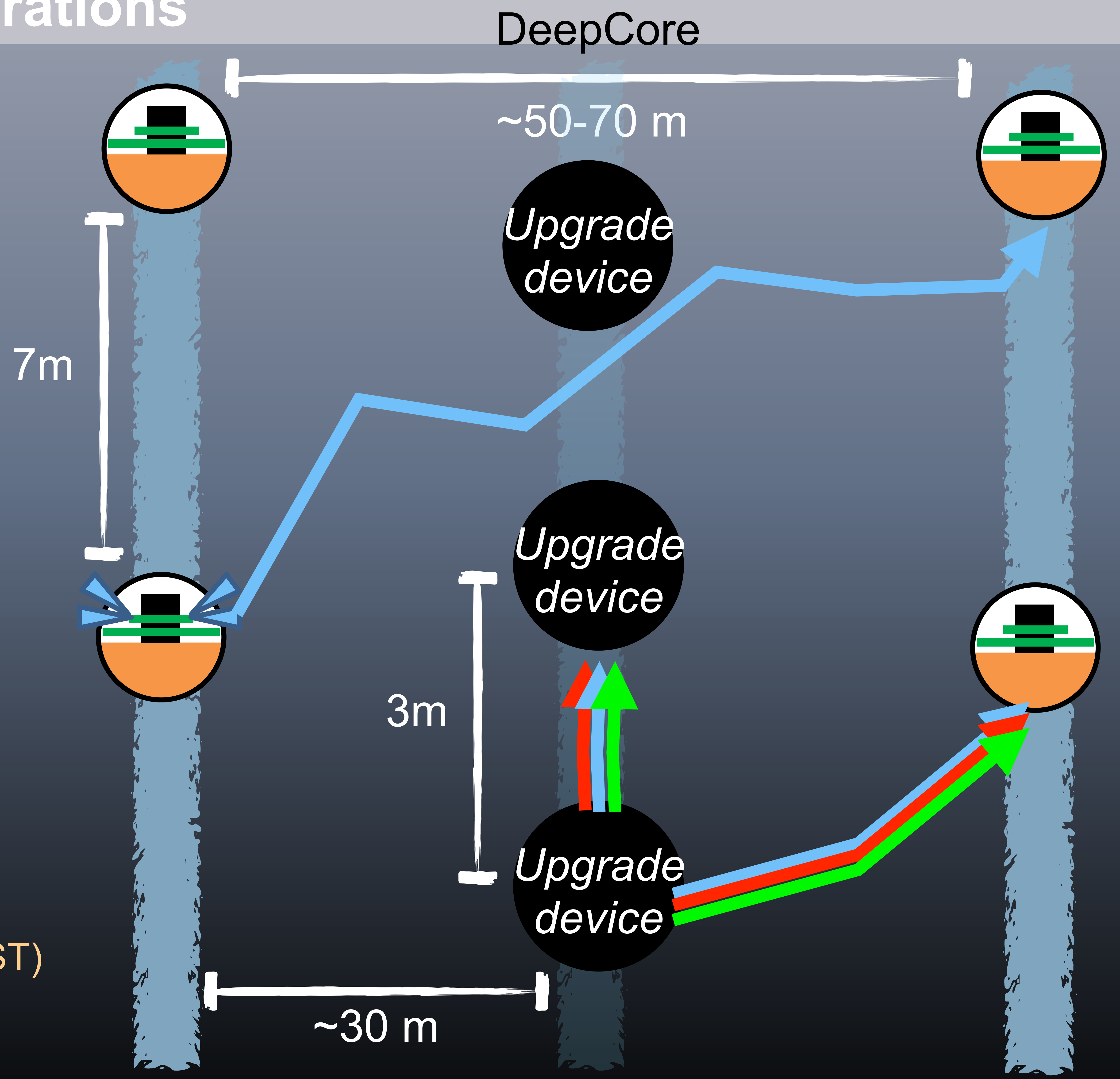

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Summary

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.

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

177. Search for Light Sterile Neutrinos With Eight Years of IceCube Data
Dr Carlos Arguelles (MIT)
Poster Session 2

364. Non-standard neutrino interaction search with IceCube DeepCore
Mrs Elisa Lohfink (Johannes Gutenberg-Universität, Mainz)
Poster Session 2

529. Light Unstable Sterile Neutrino Search in IceCube
Marjon Moulai (Massachusetts Institute of Technology)
Poster Session 2

Backup

Neutrino oscillations

The experimental landscape

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

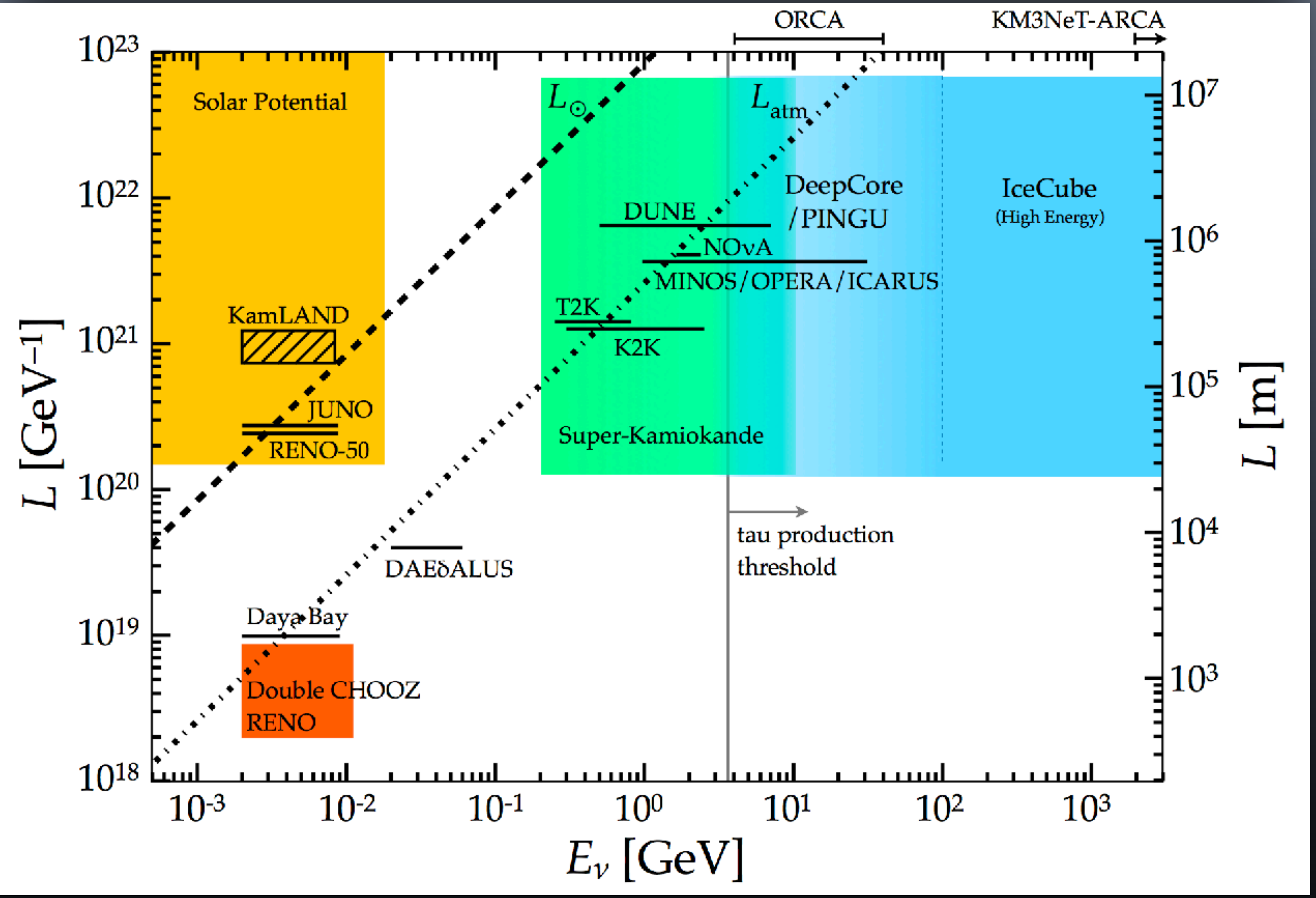
Well above the tau production threshold

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & \boxed{U_{\mu 3}} \\ U_{\tau 1} & U_{\tau 2} & \boxed{U_{\tau 3}} \end{pmatrix}$$

DeepCore

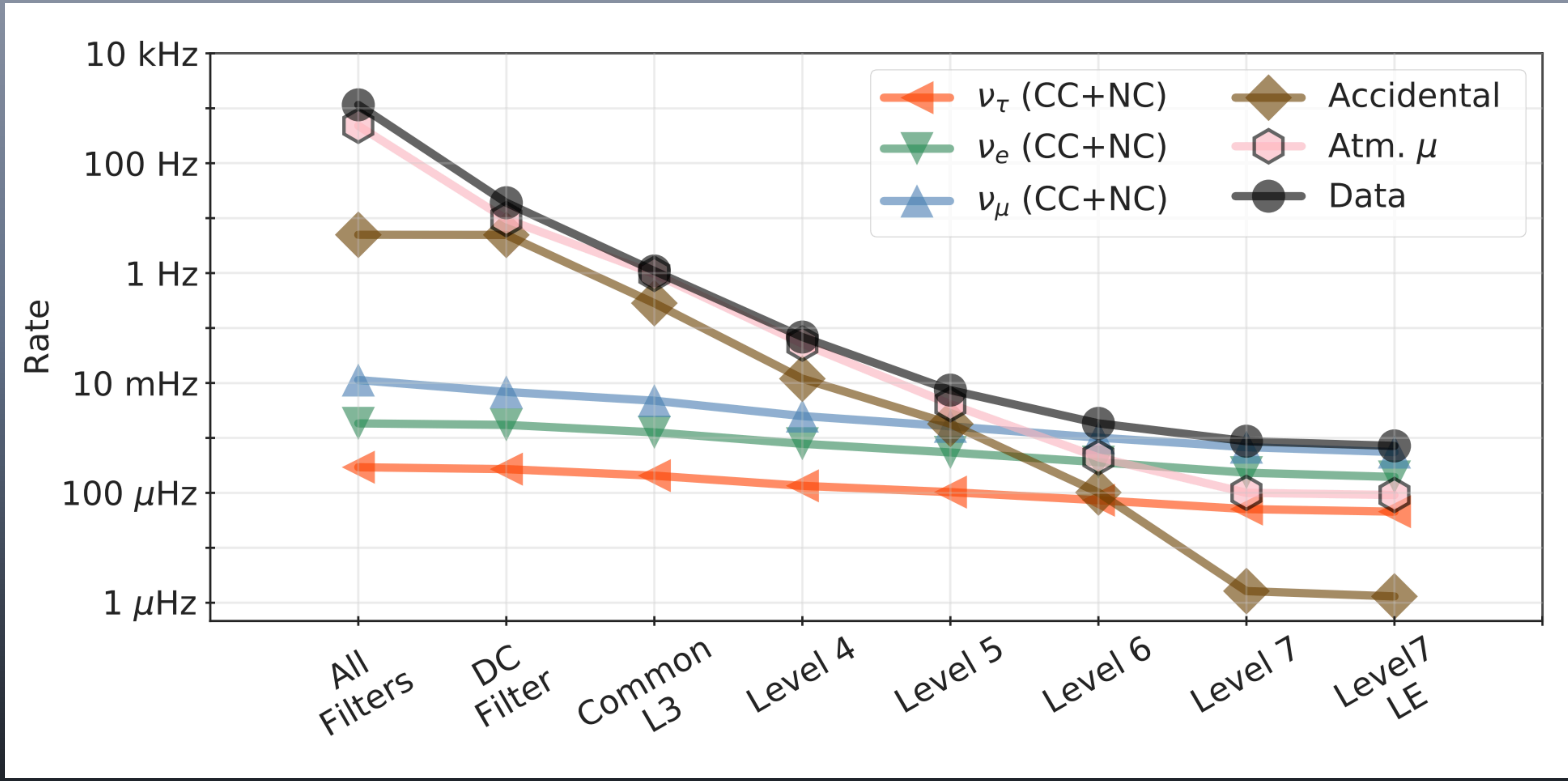
U_{PMNS} unitarity implies, e.g.:

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$



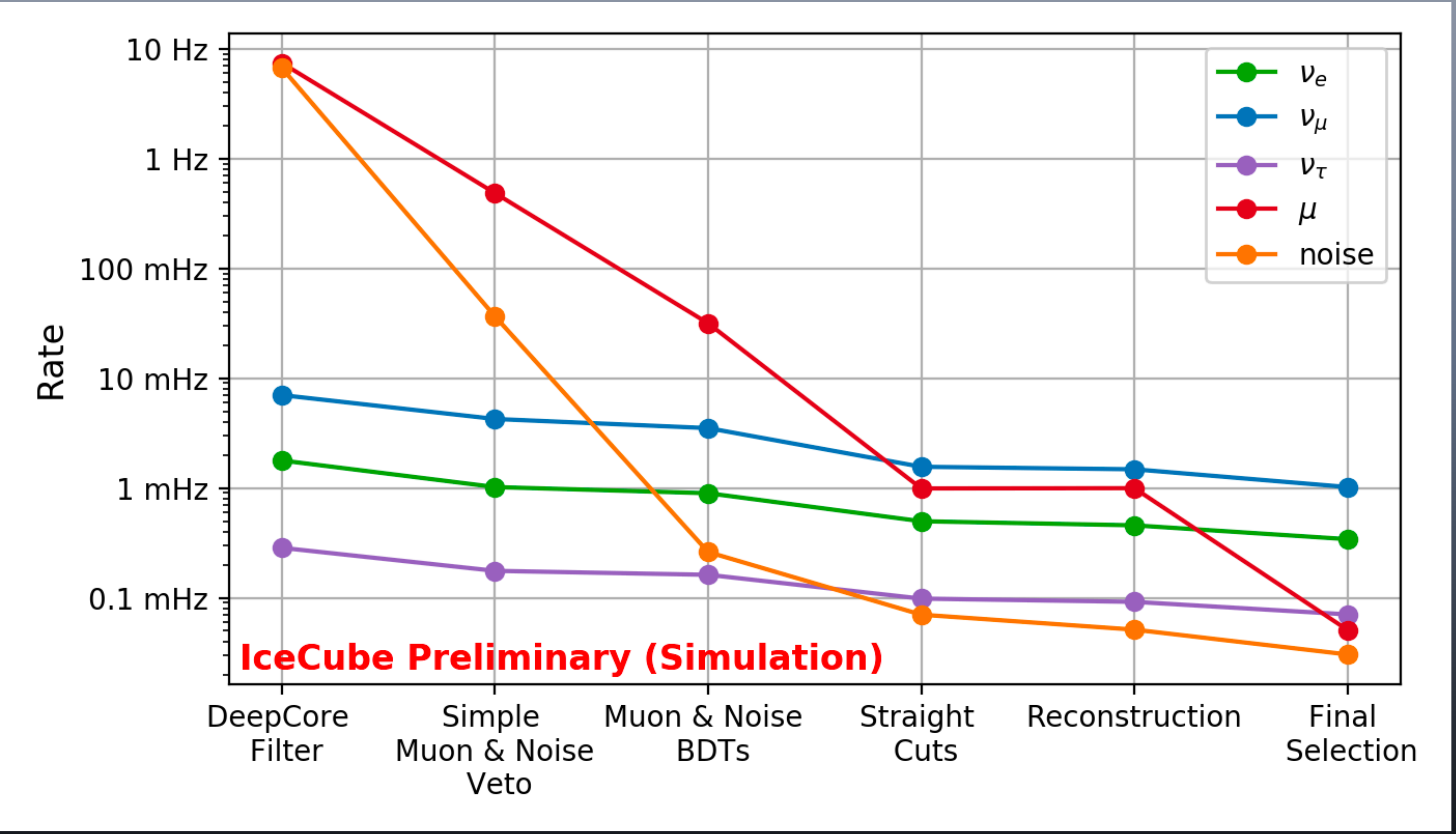
DeepCore 3 year sample

Event rates vs. Selection



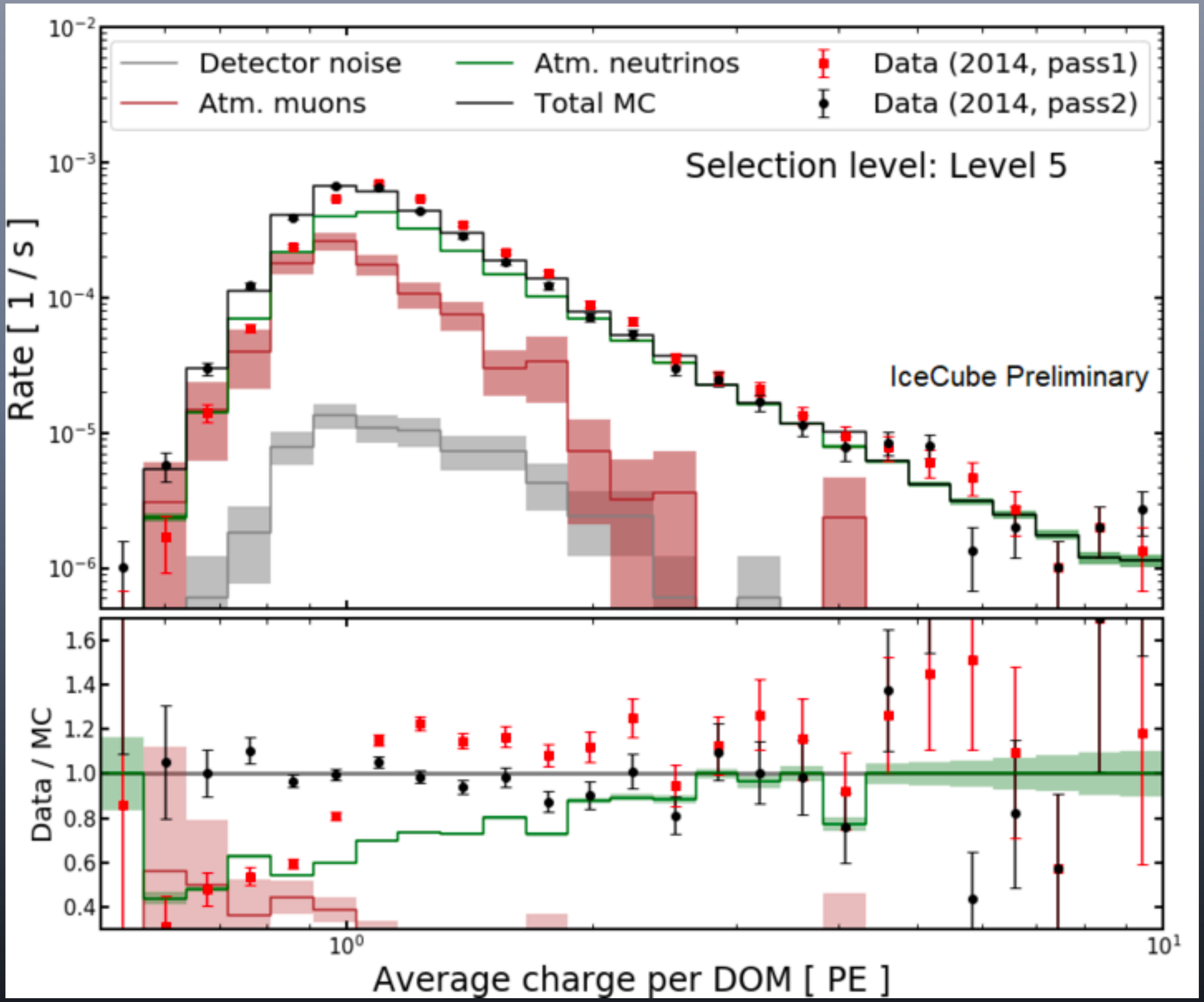
DeepCore 8 year sample

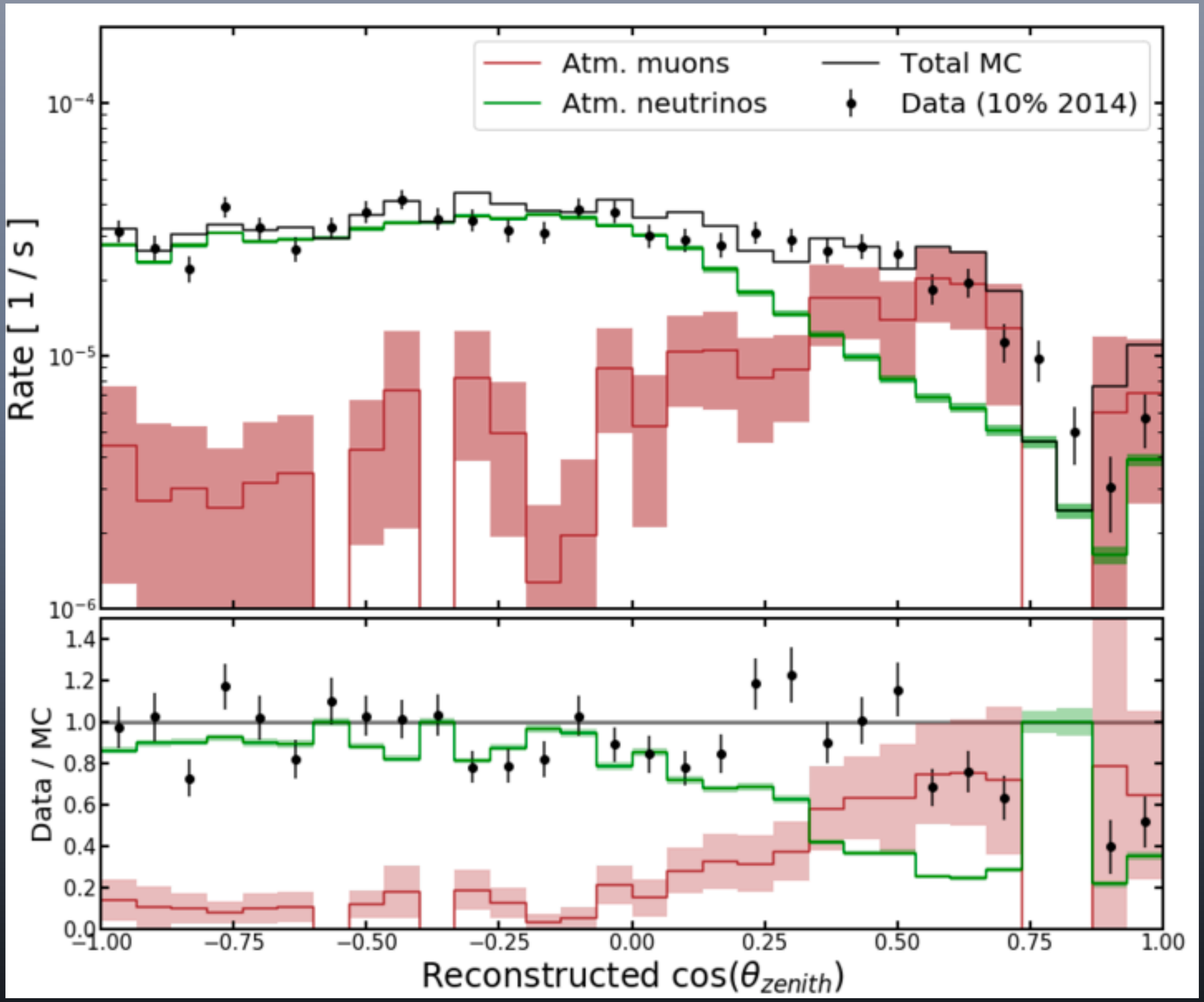
Revised event selection for better background rejection + higher signal efficiency



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)

GENIE 2.8.6

Hadronization with KNO and PYTHIA, GRV98 PDFs

Photon propagation

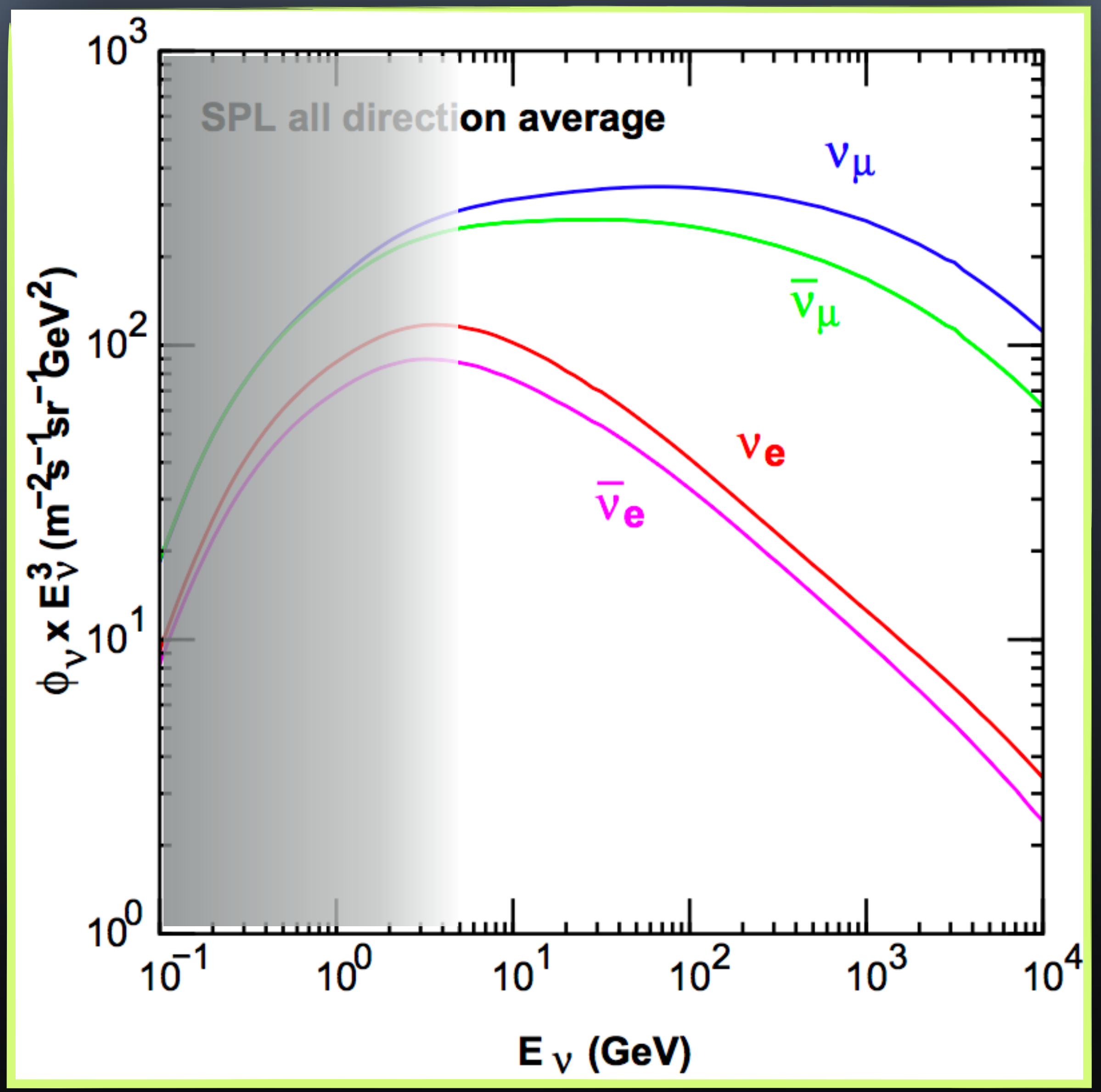
DOM response

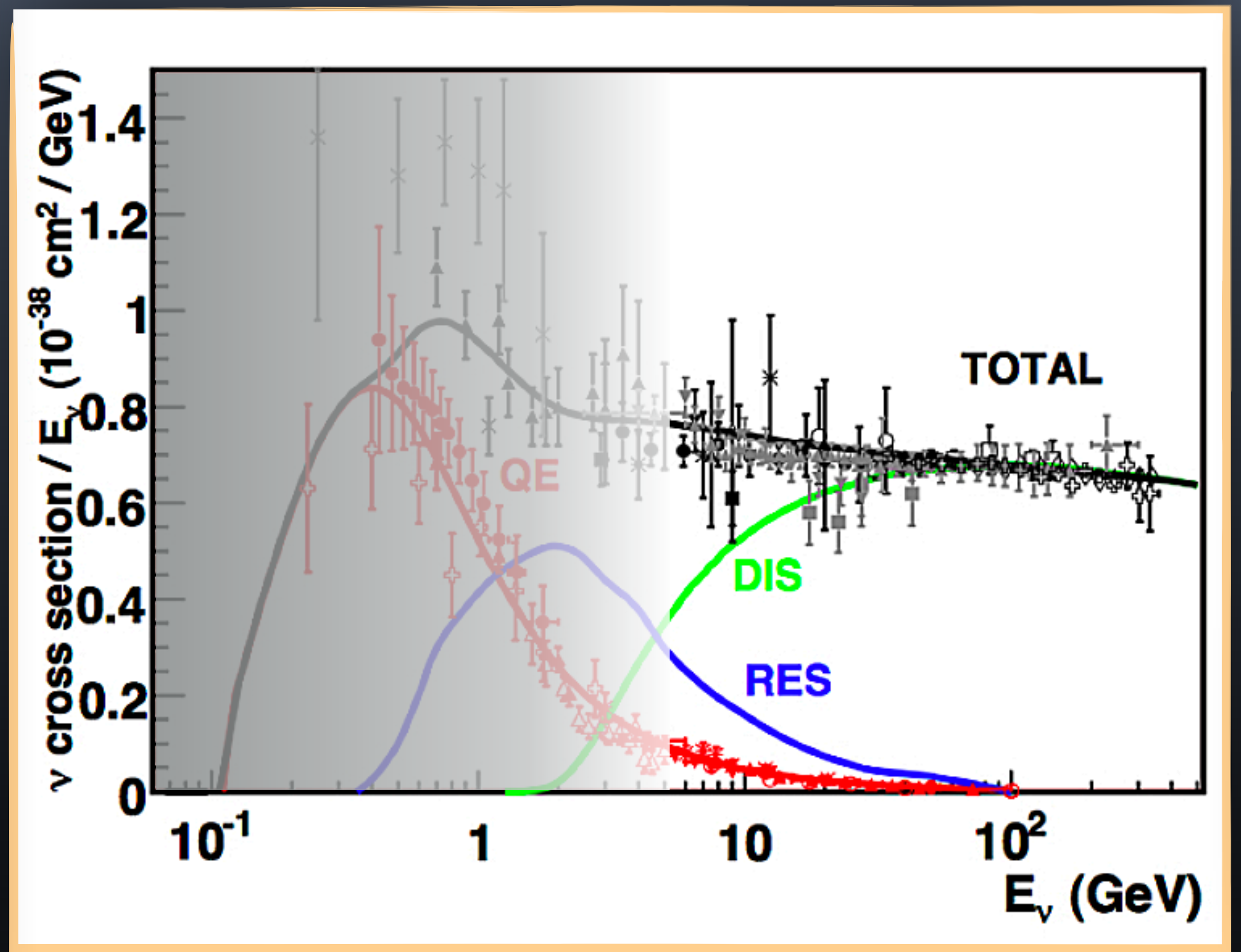
Trigger

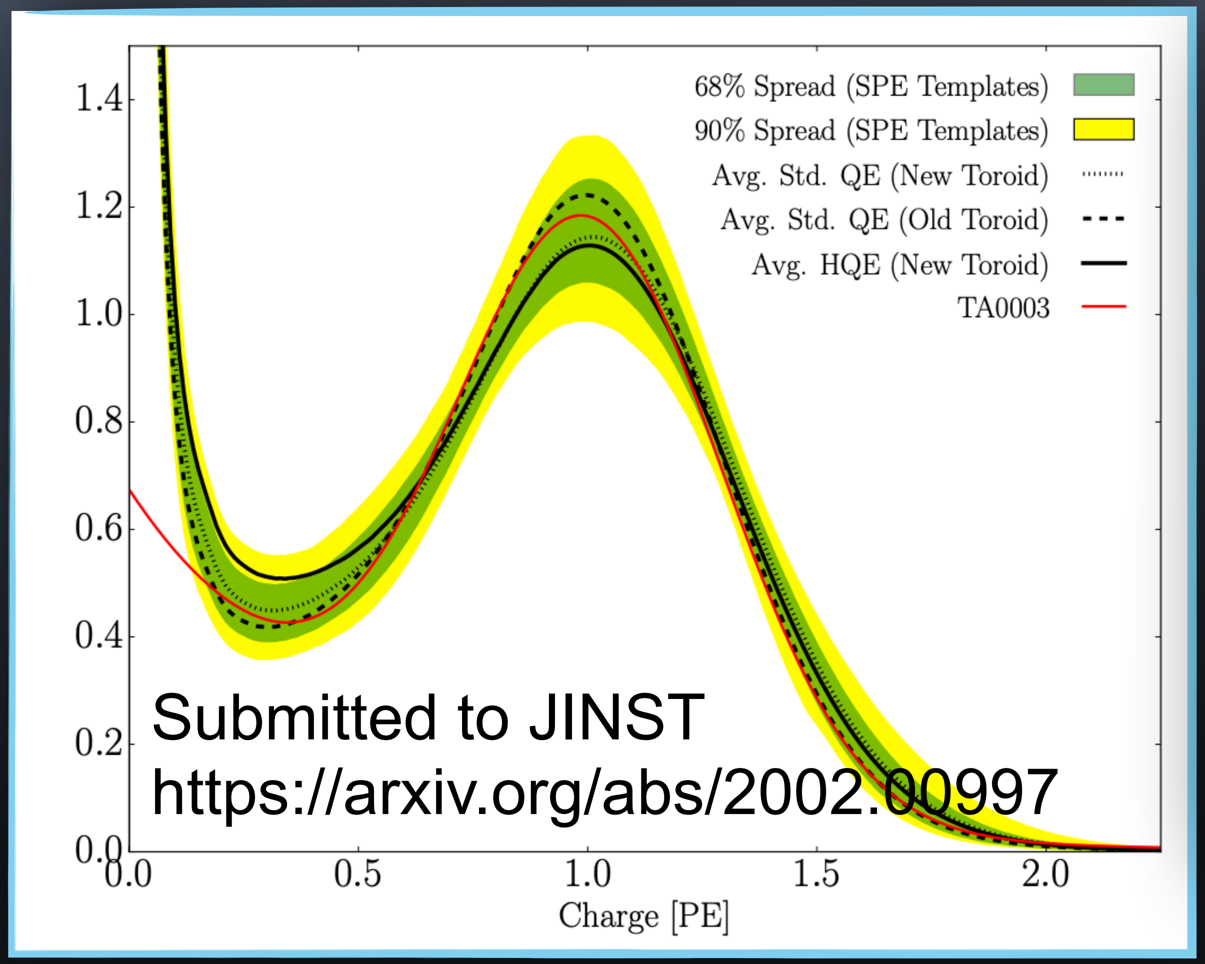
Remove atm. muons and pure noise triggers

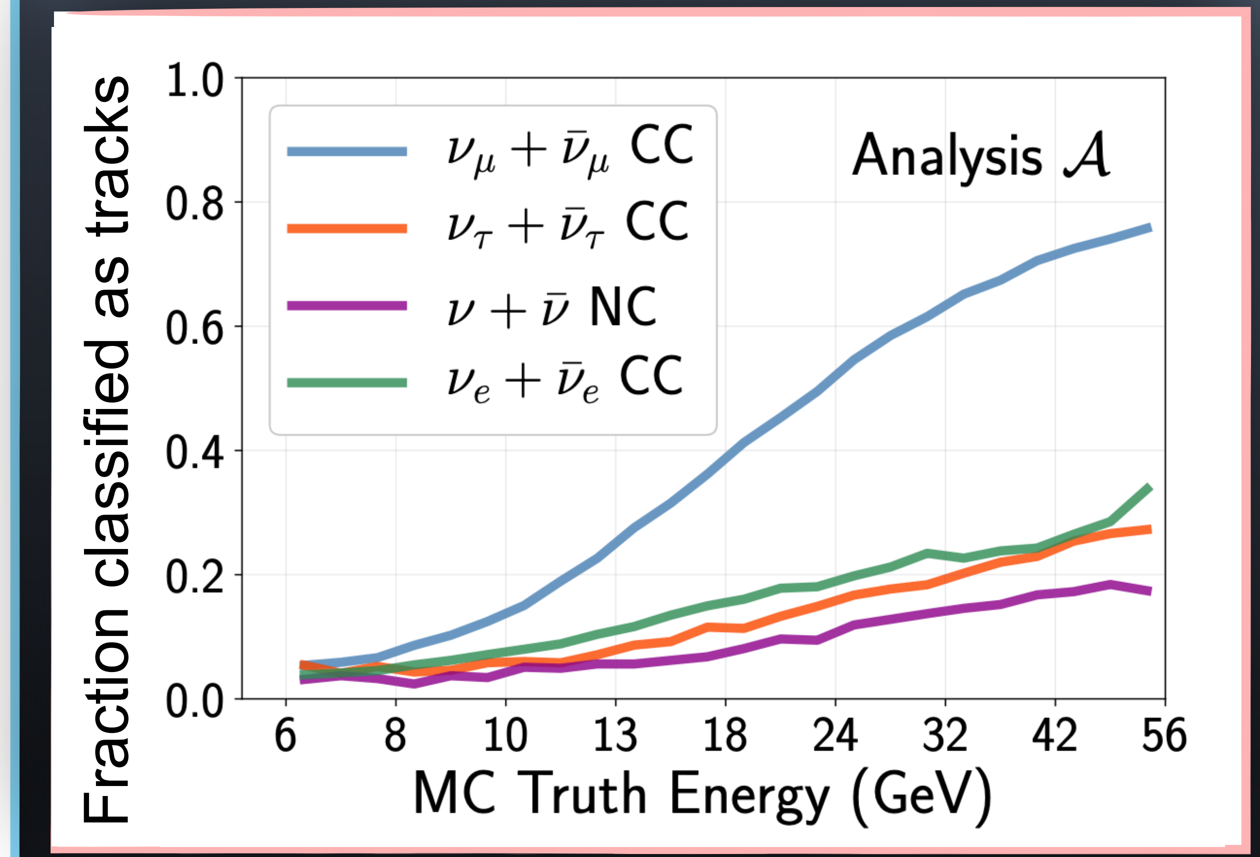
Energy, zenith, PID

Φ unosc. | Interaction | Detection | Filter/Reco





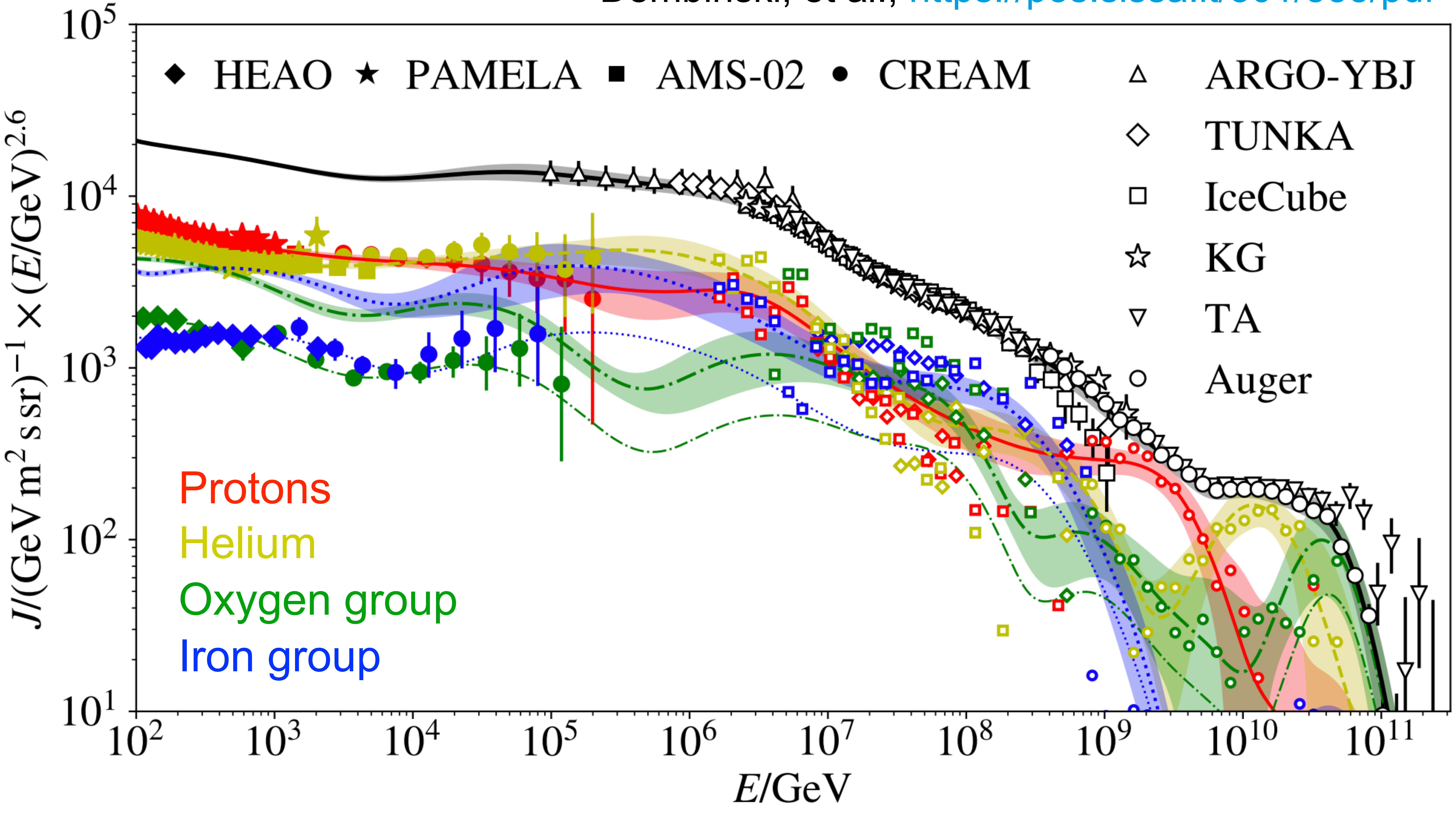




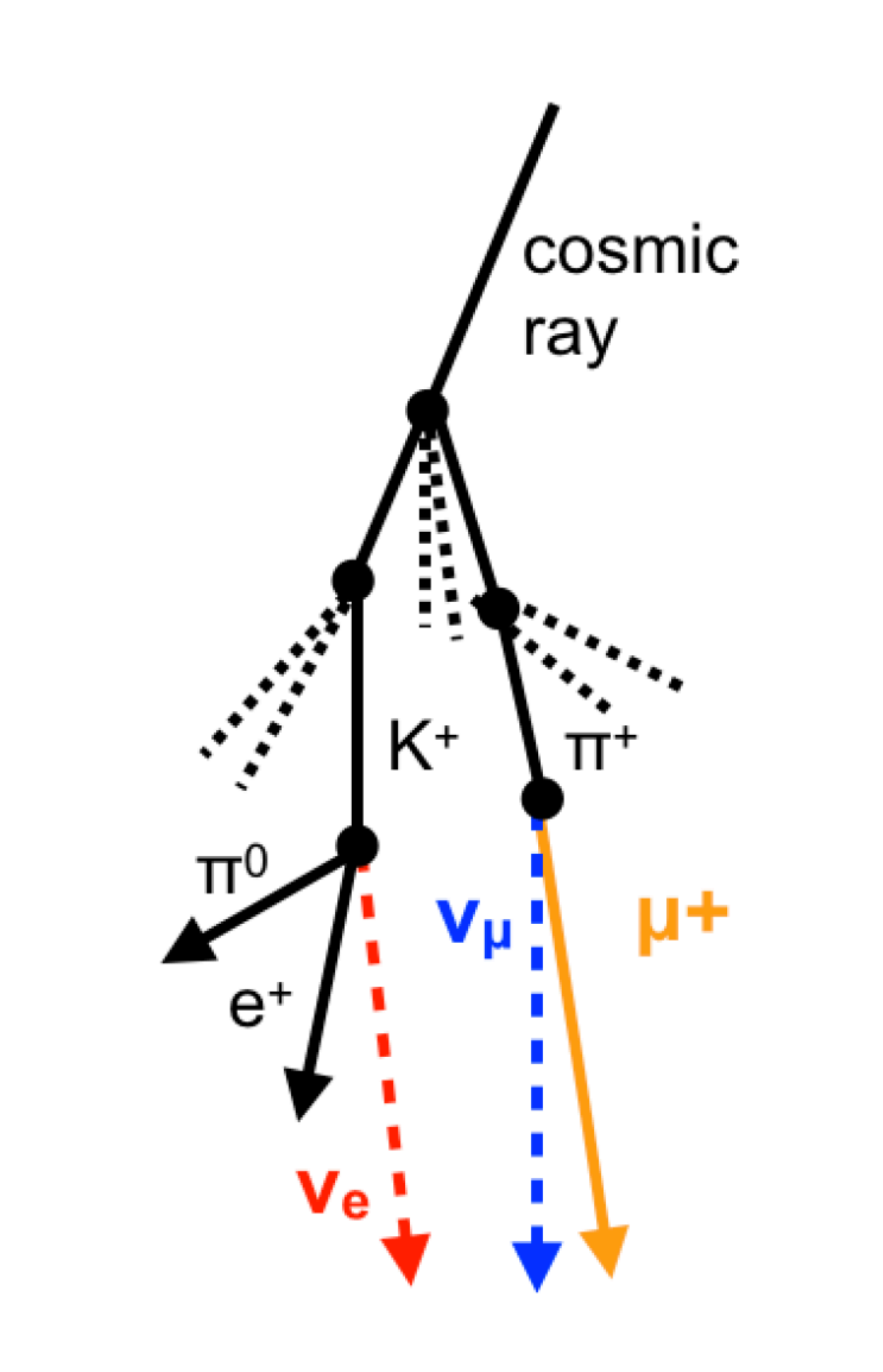
Primary cosmic ray model

Spectrum and composition

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



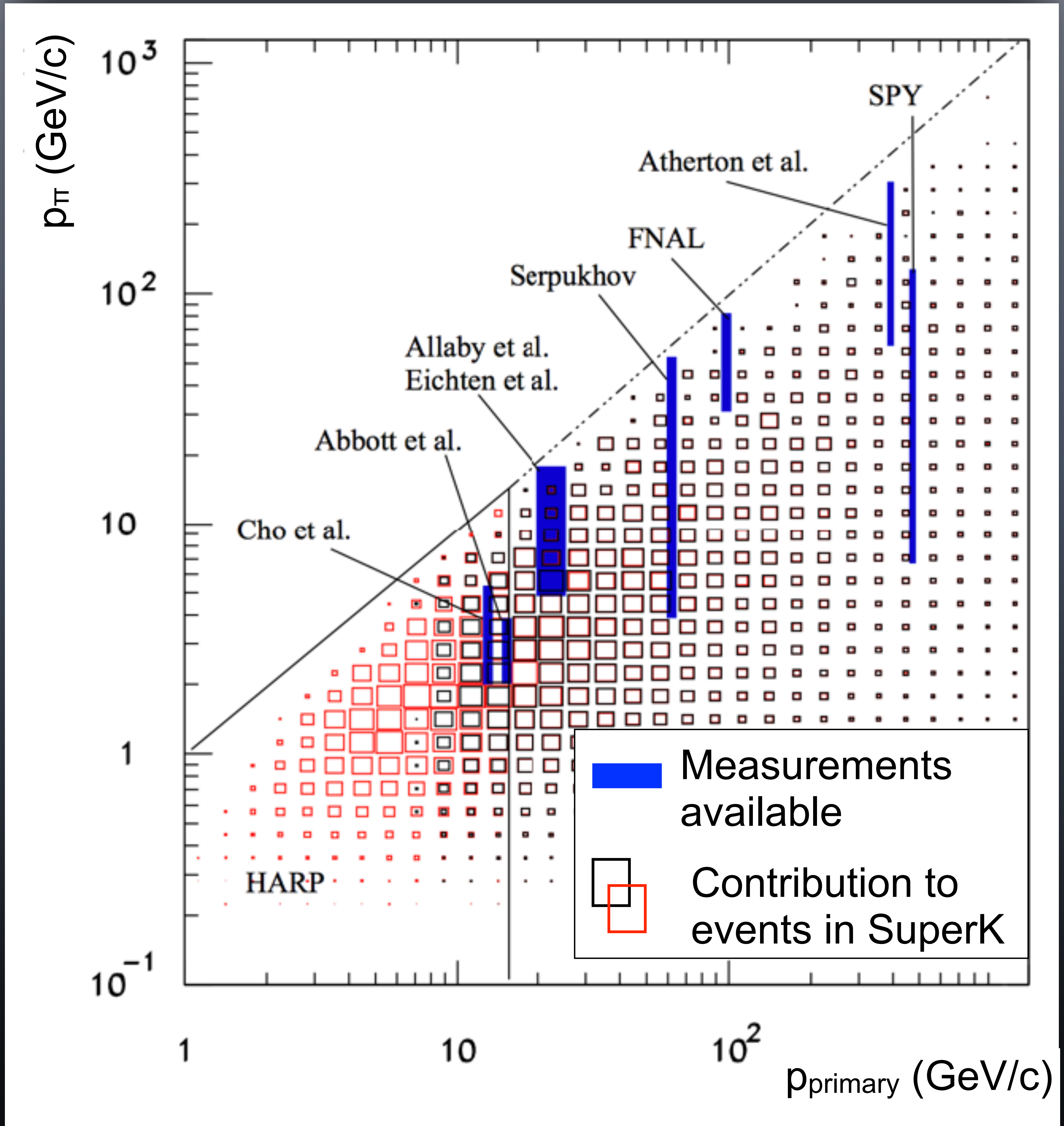
Flux uncertainties



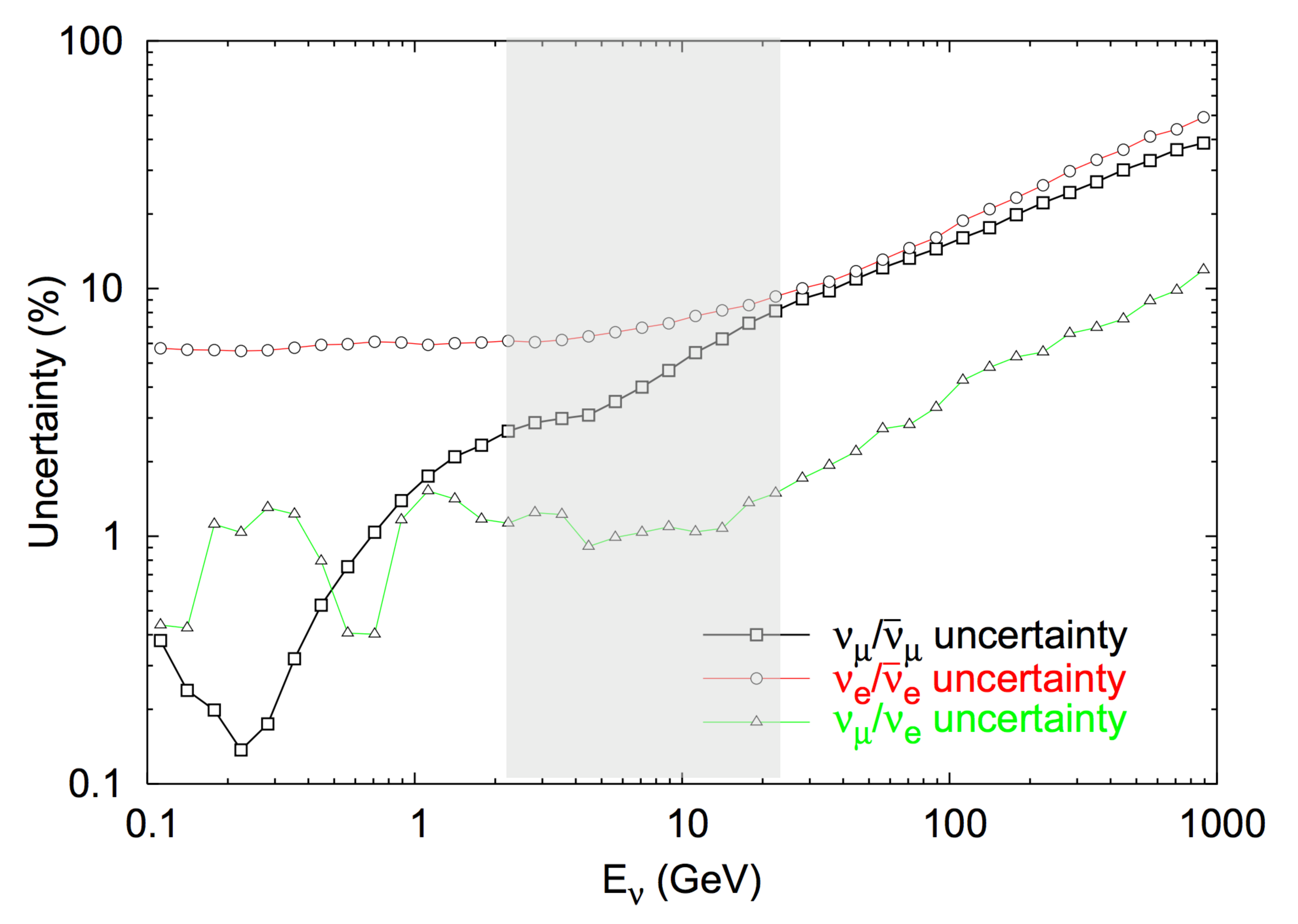
Production uncertainty:
π± ~10-30%
K± ~10-40%

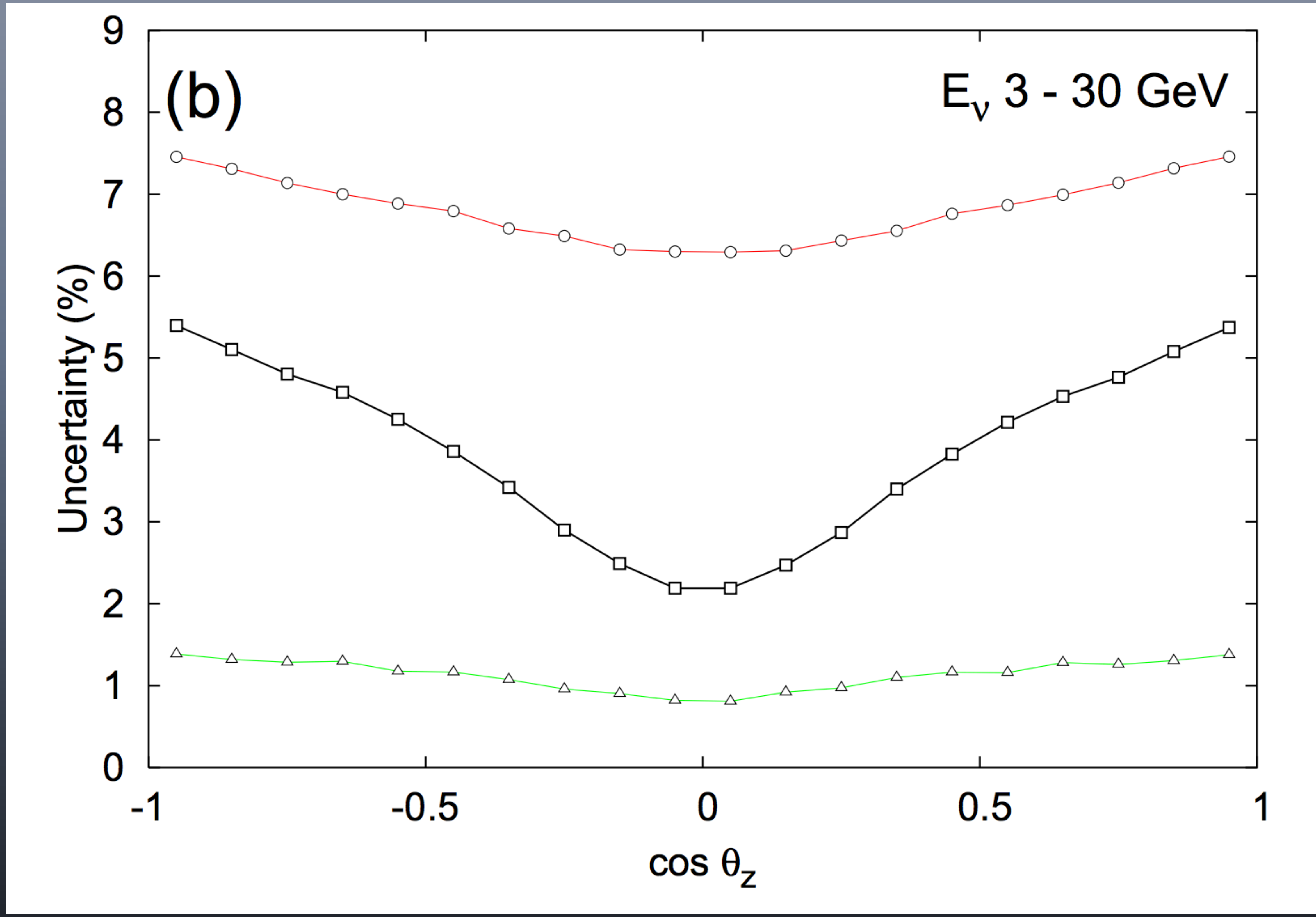
Barr et al. https://arxiv.org/pdf/astro-ph/0611266.pdf

Experimental coverage
of single π production yield



Flux uncertainties

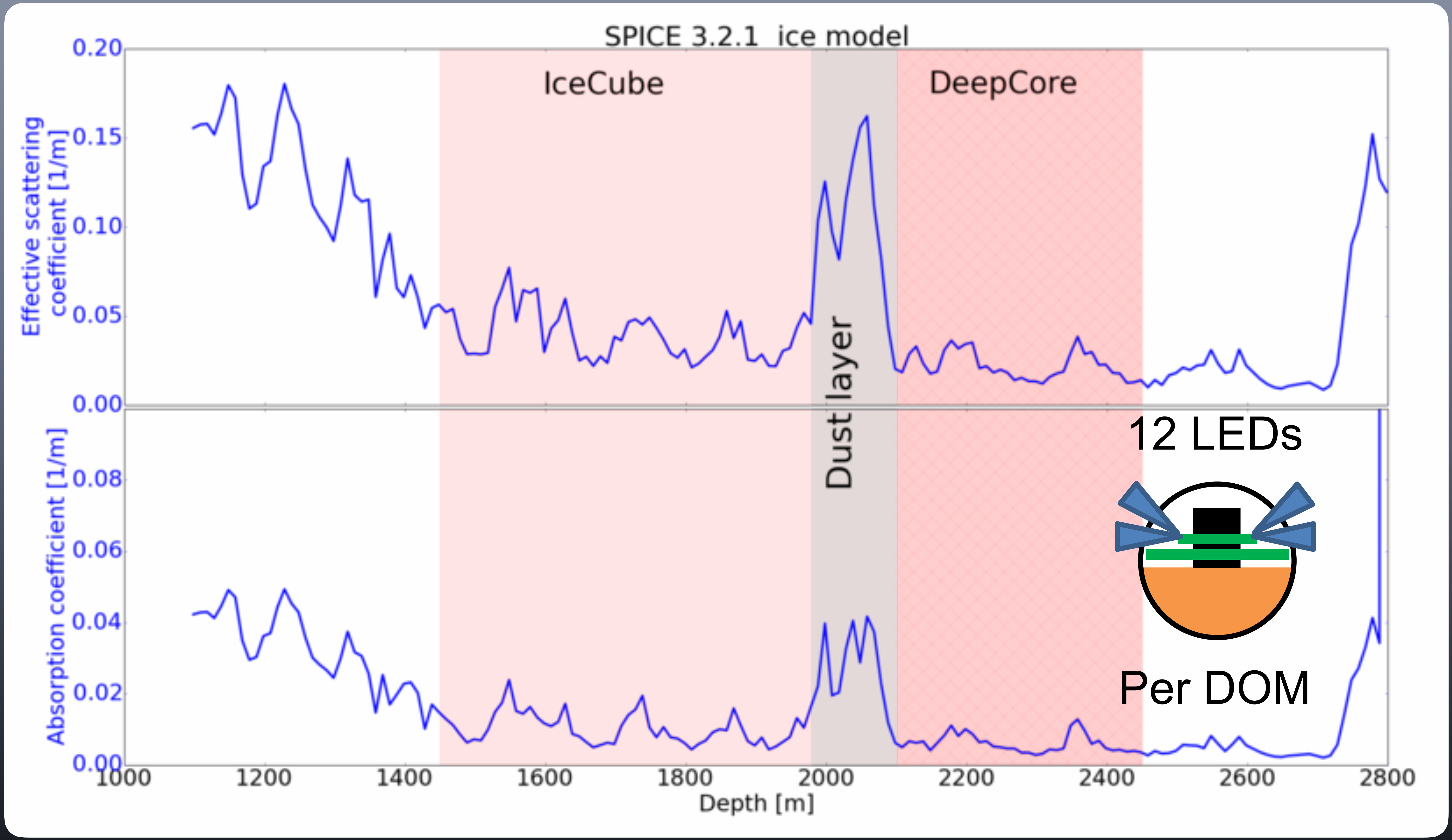


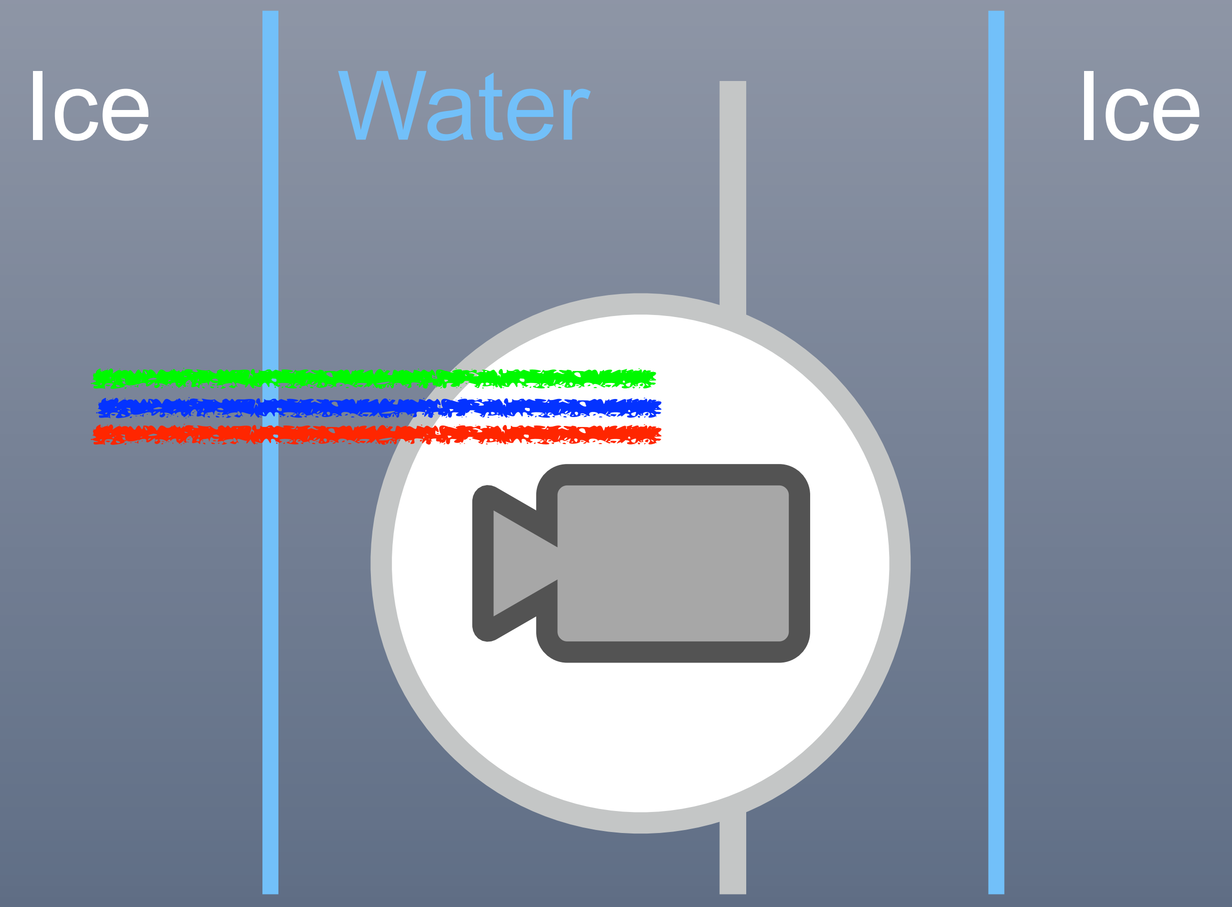


Barr et al. https://arxiv.org/pdf/astro-ph/0611266.pdf

Photon propagation

Complex, natural detector medium





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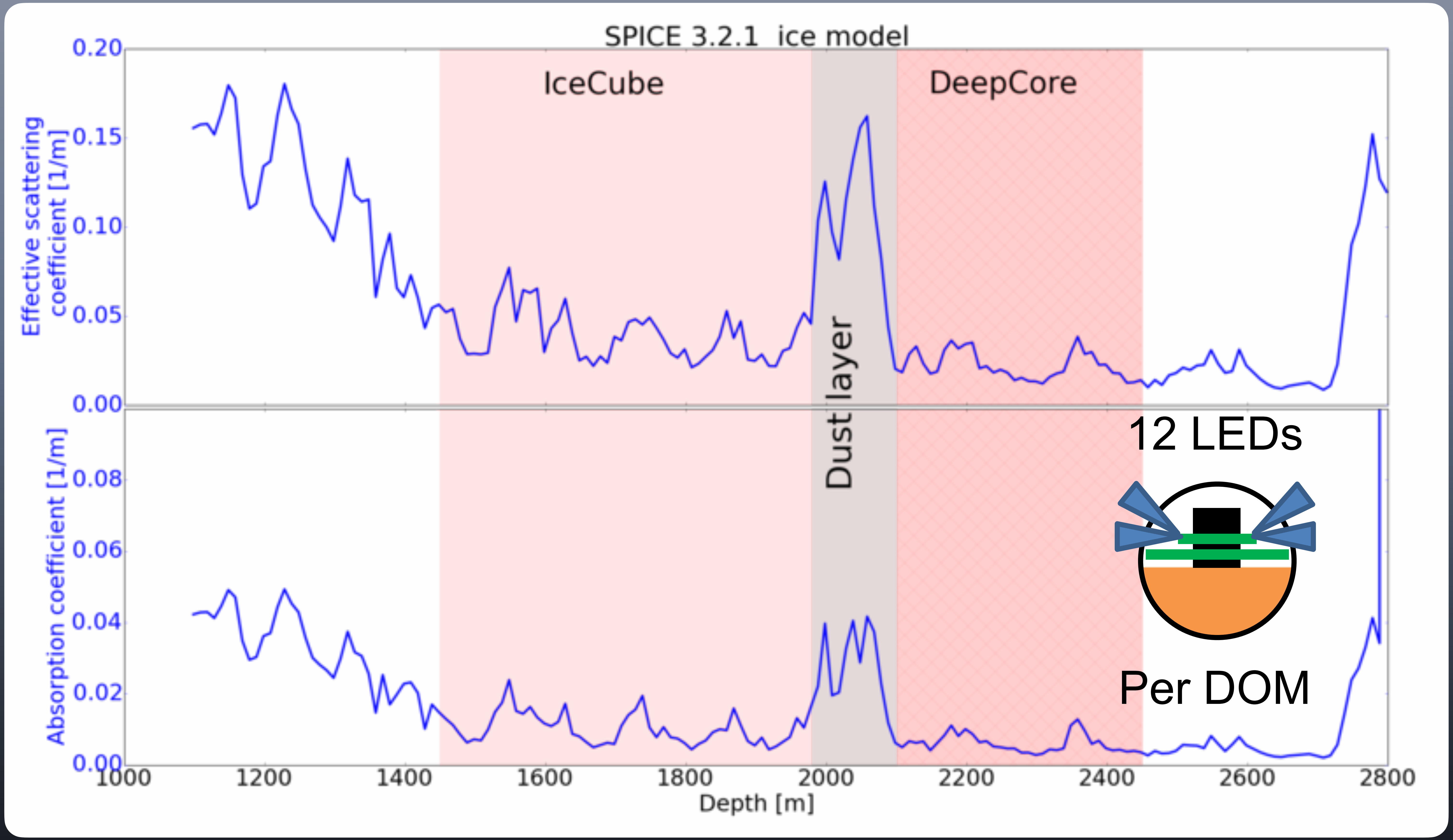
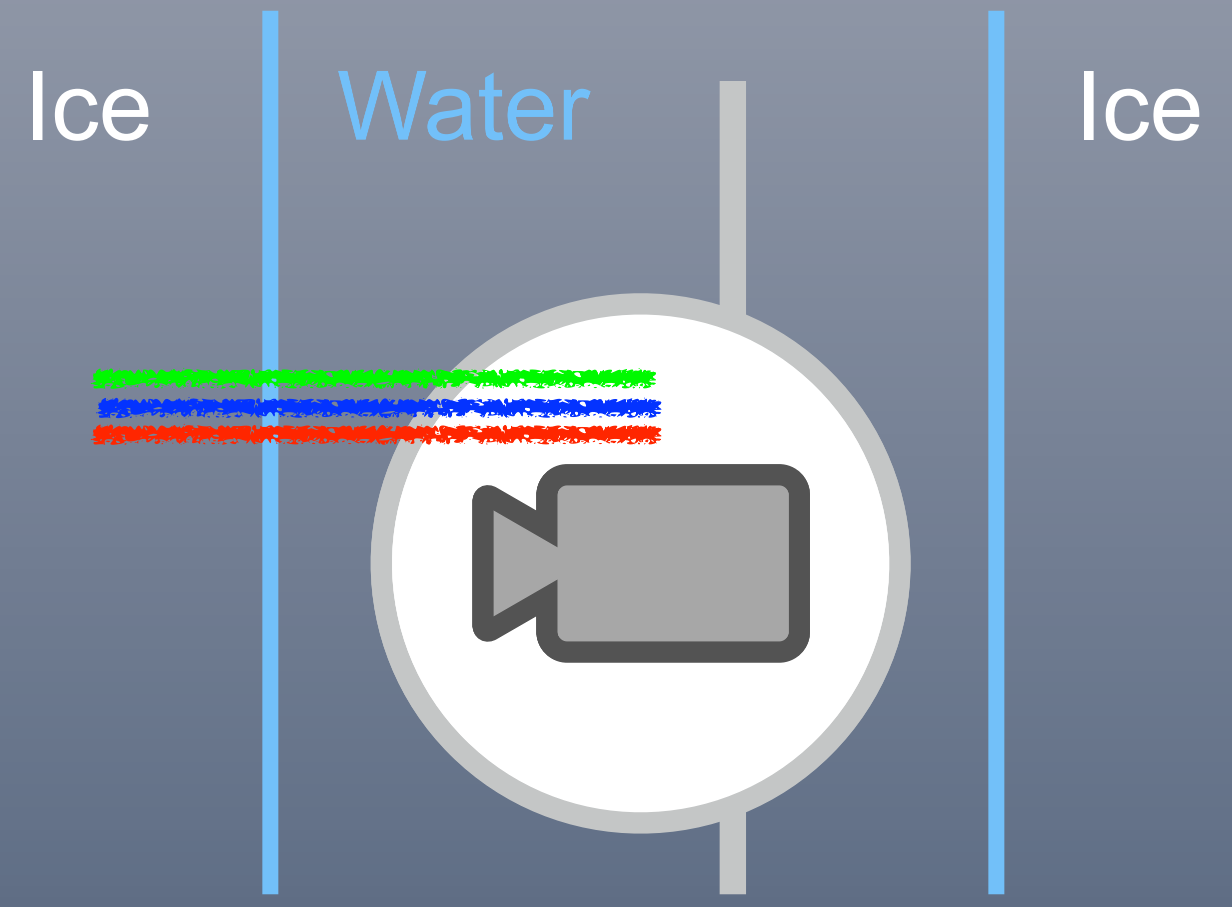
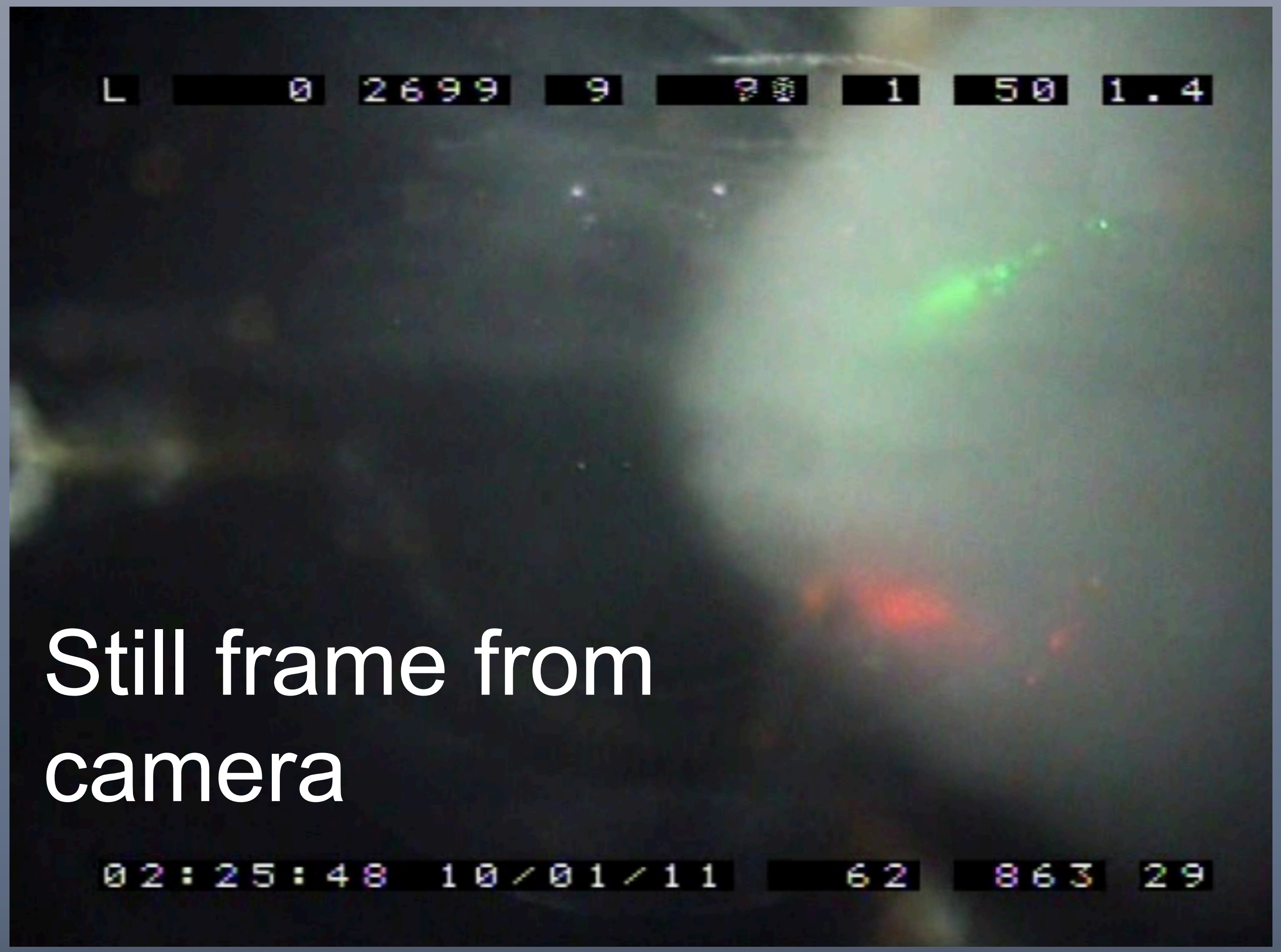
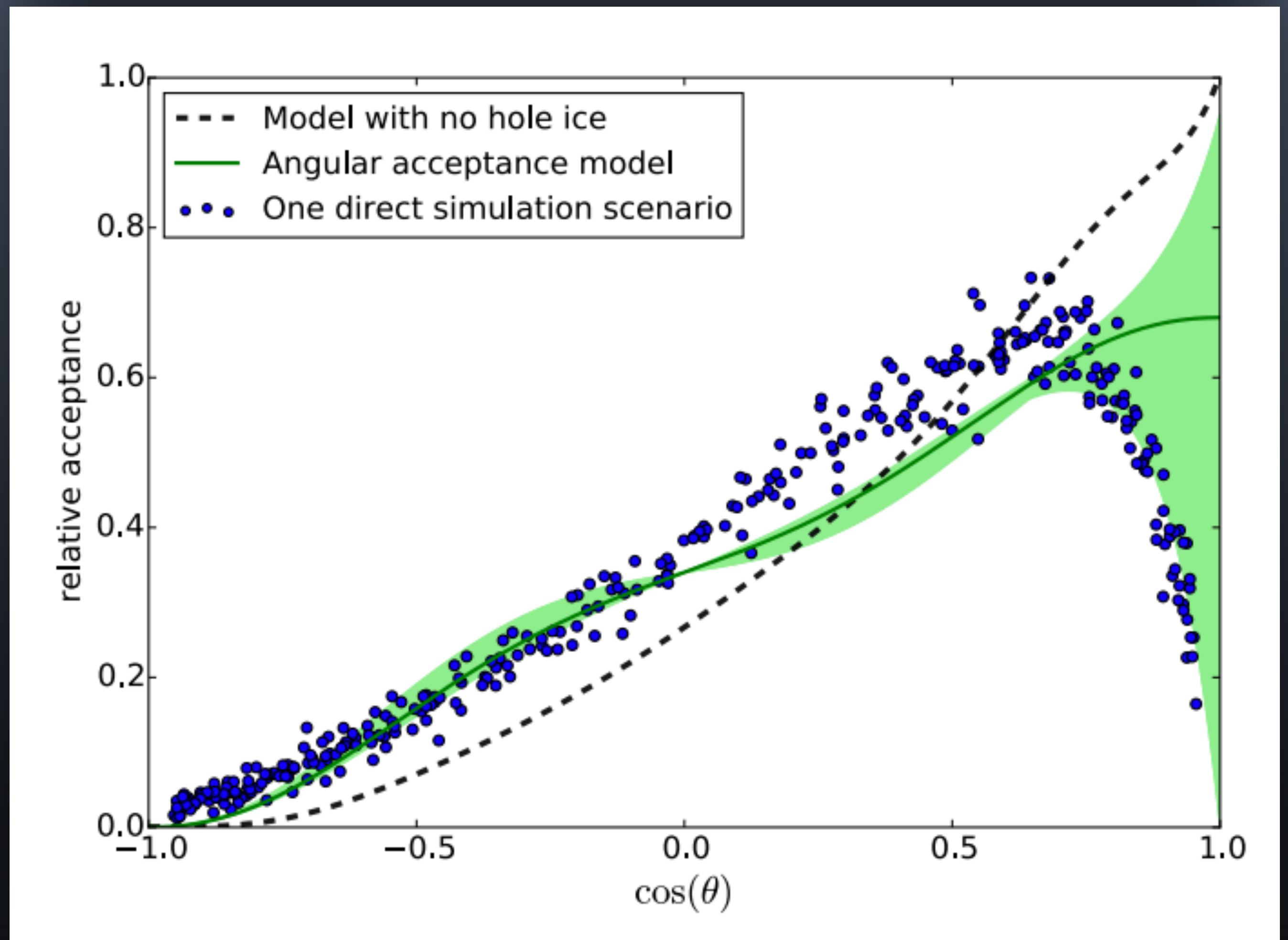
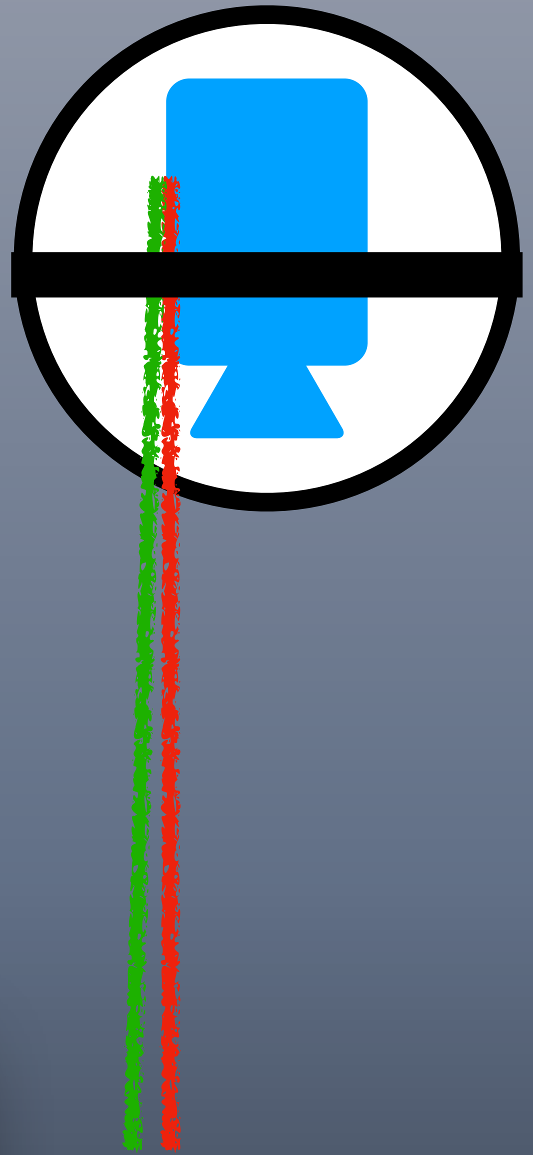


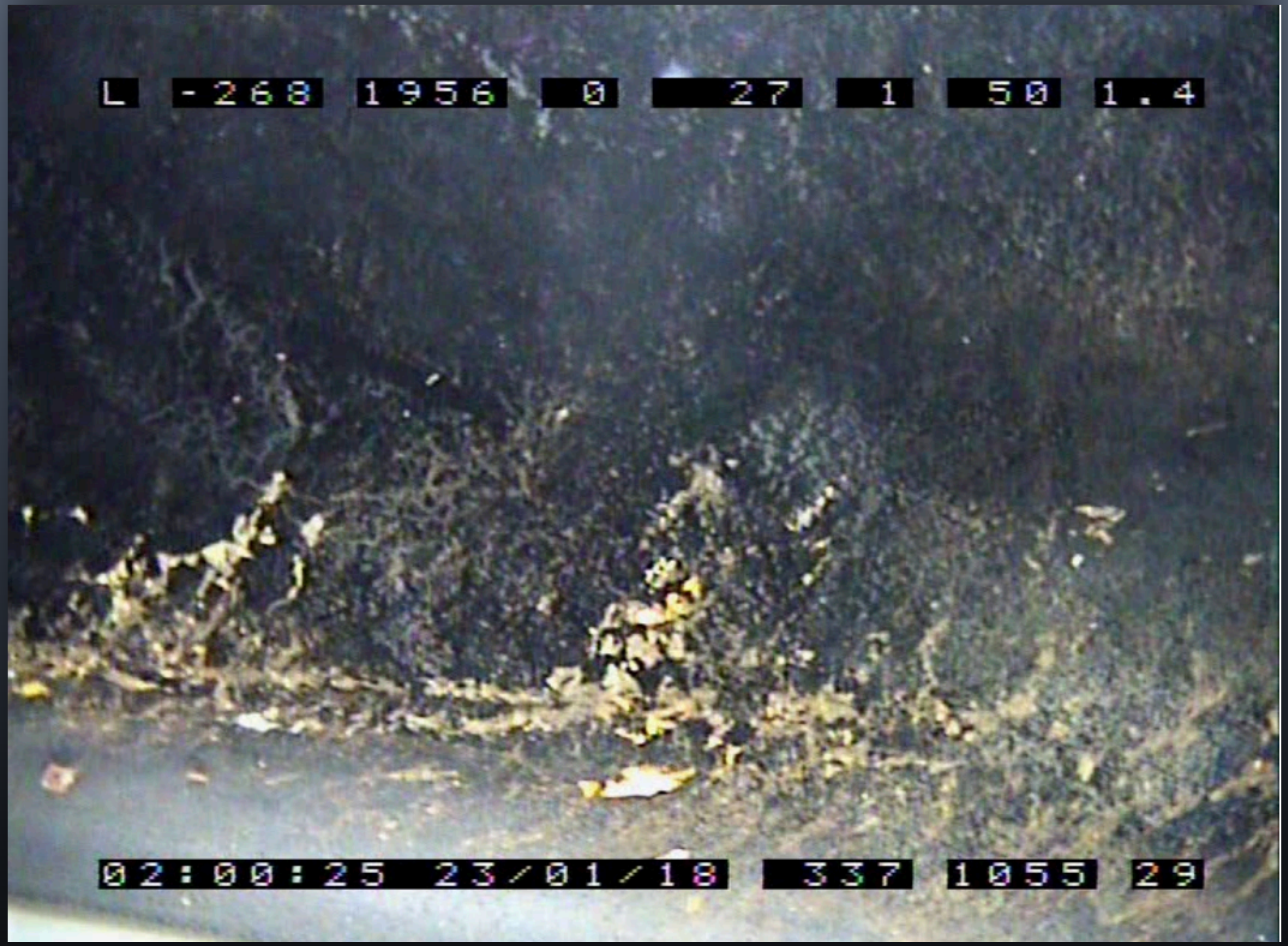


Local ice/DOM features





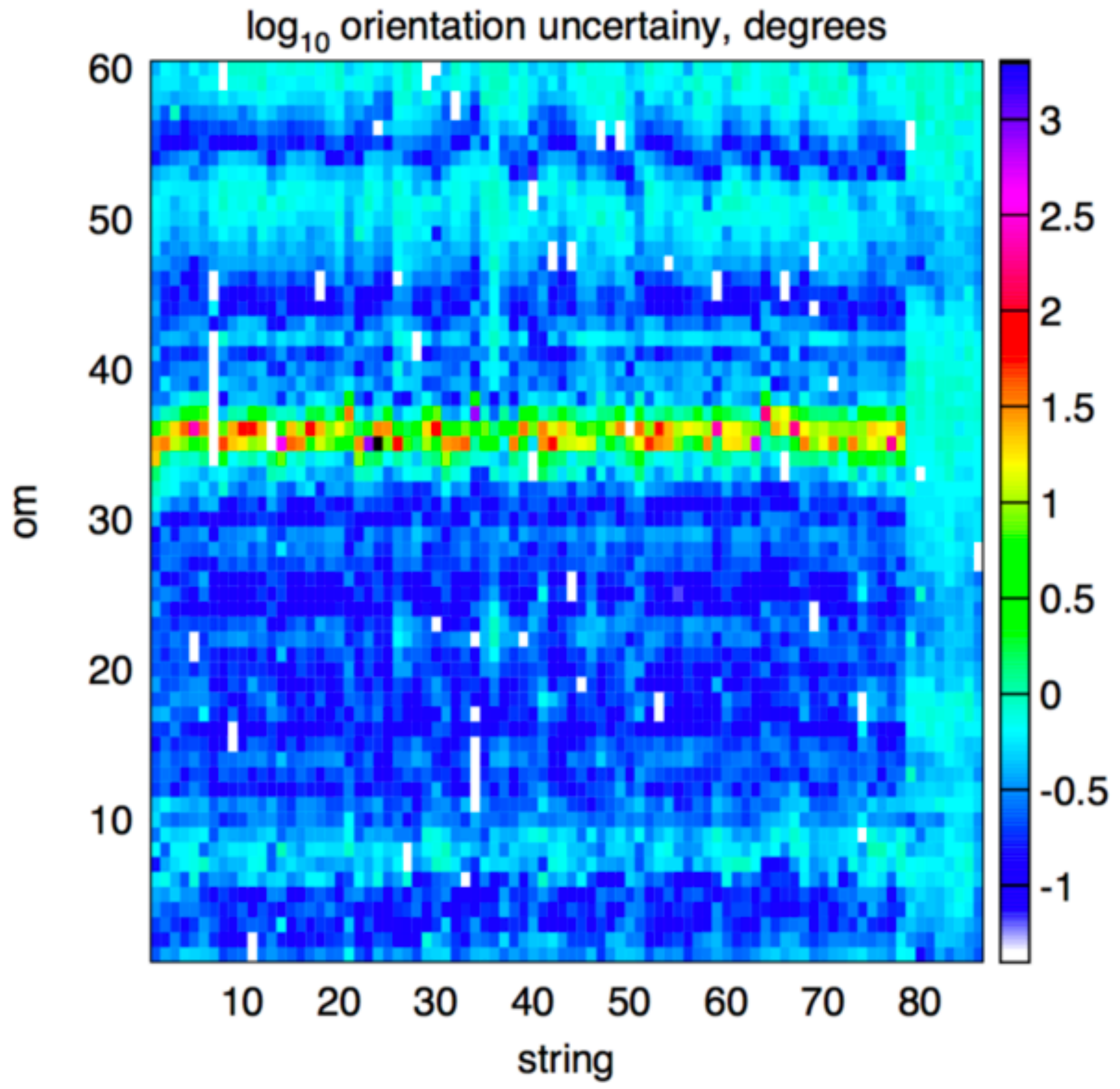


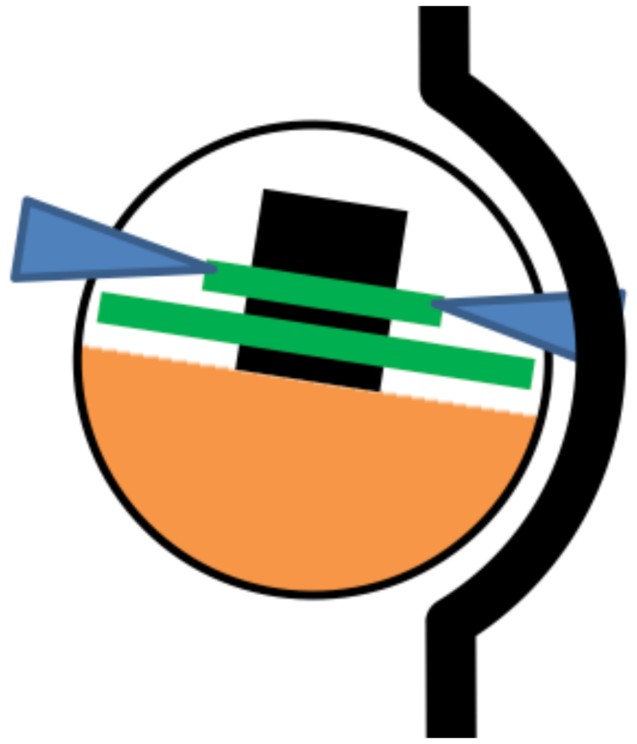


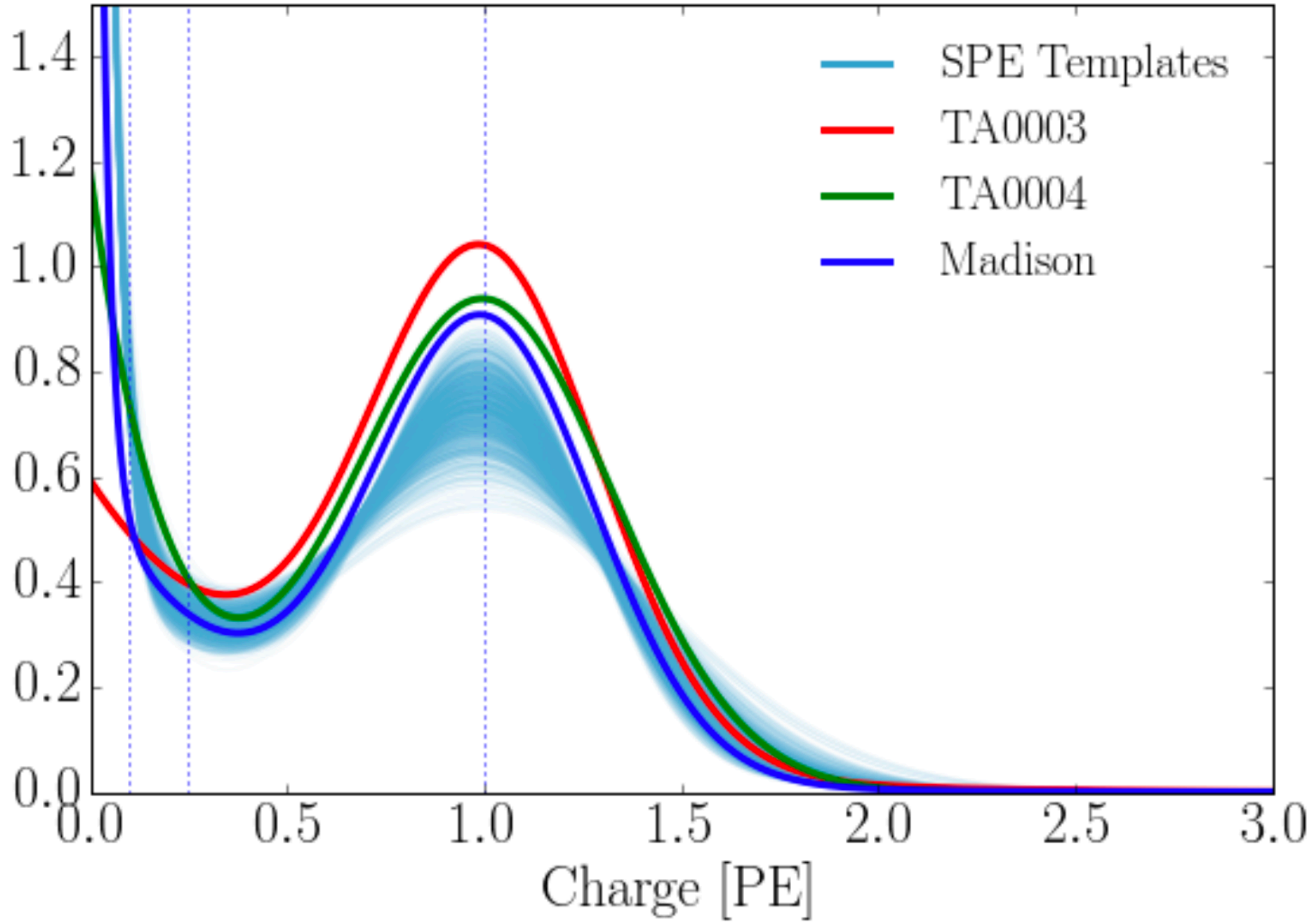
Detector recalibration

“With great statistics comes great responsibility”

https://arxiv.org/abs/2002.00997

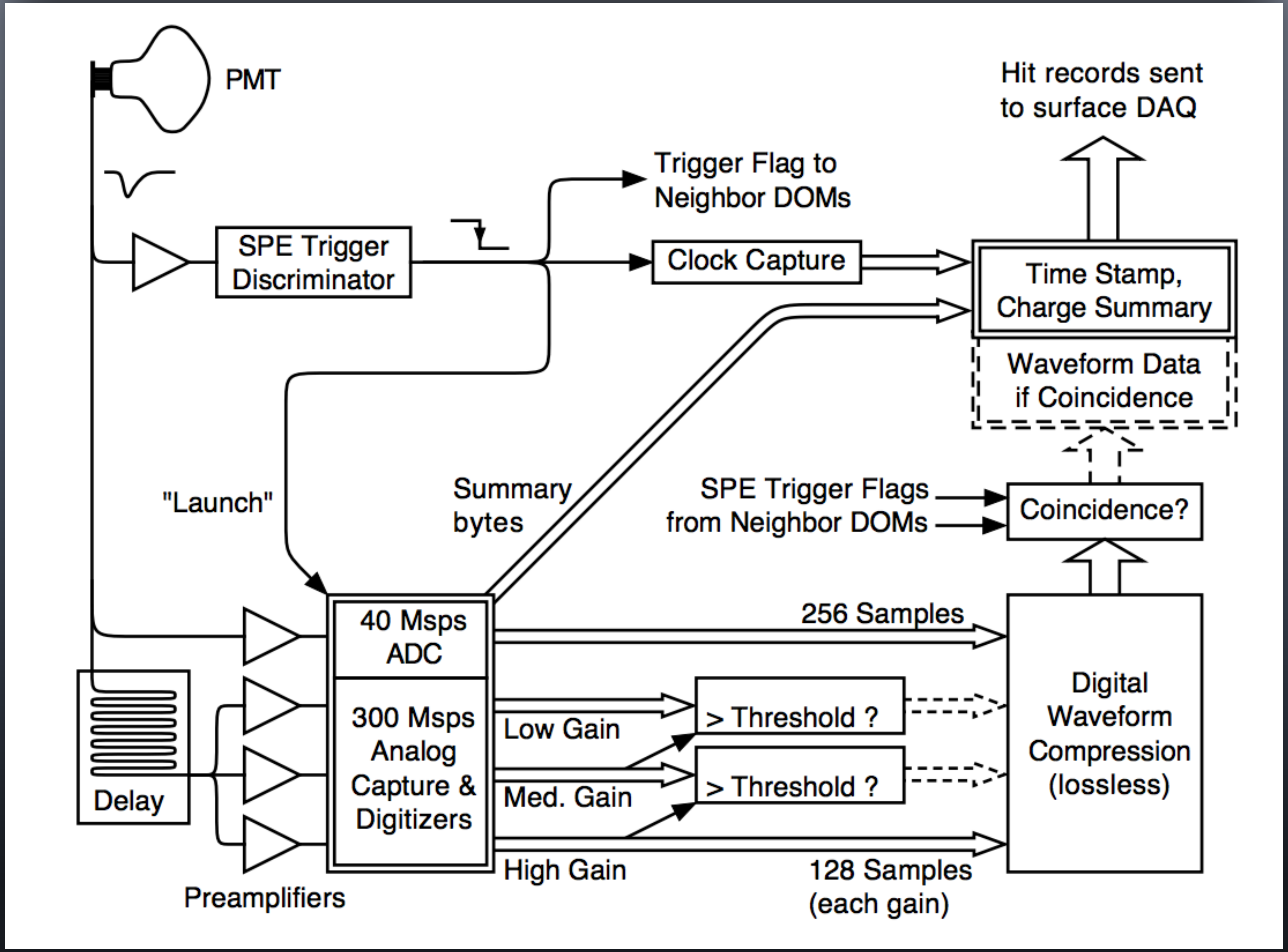






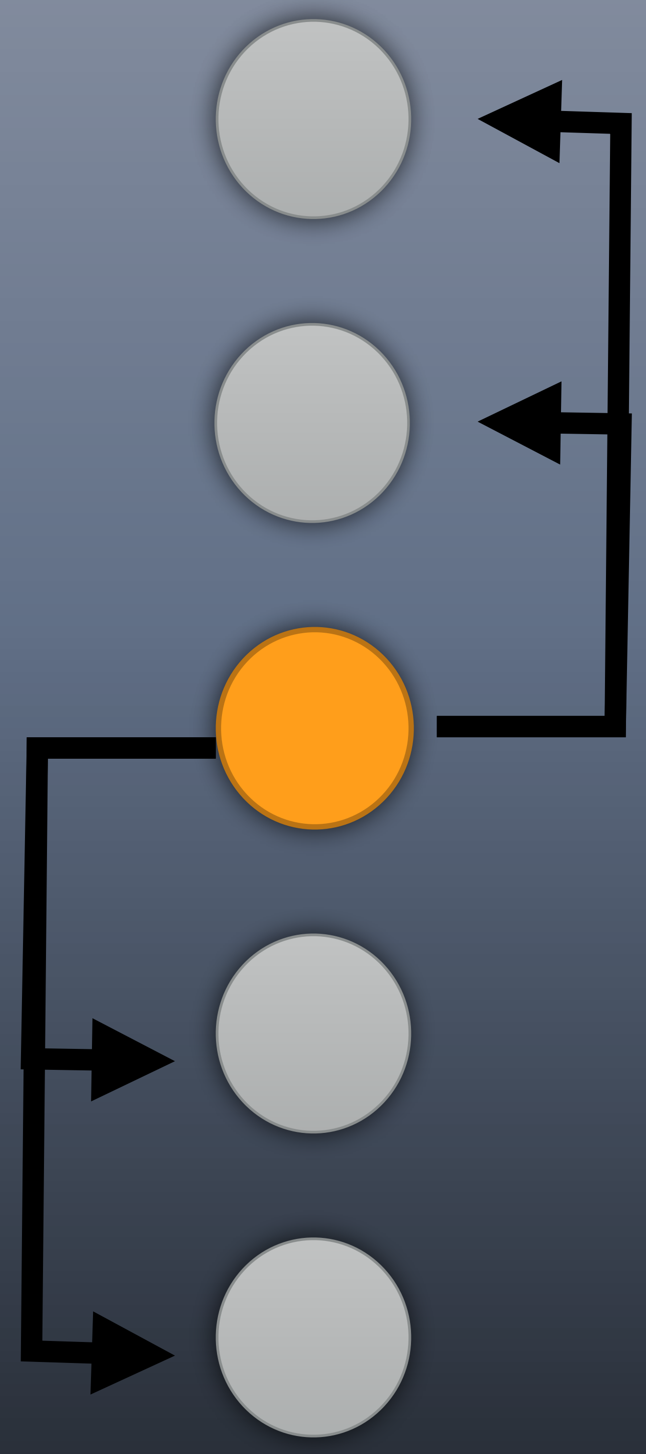
Event readout

Waveform sampling & trigger



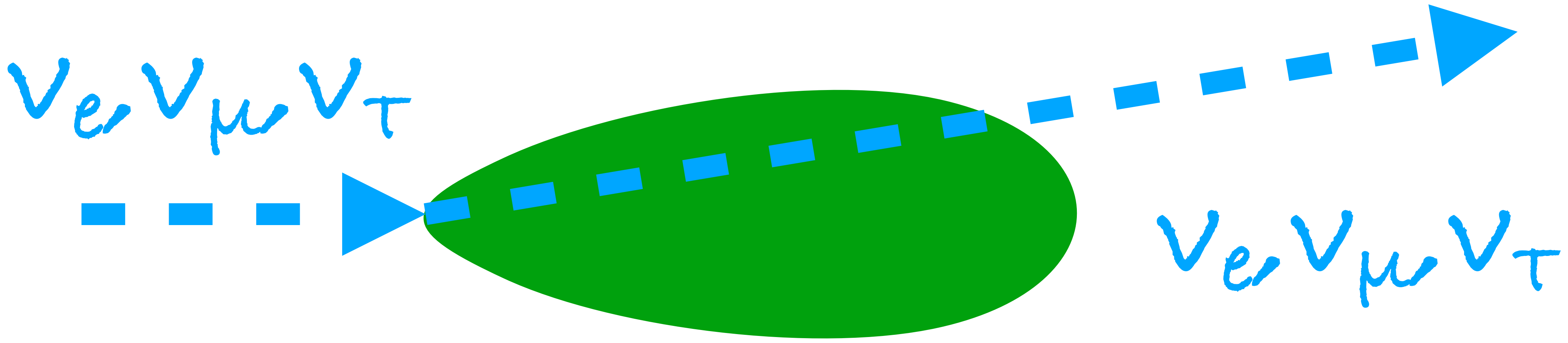
“Hard local coincidence” HLC

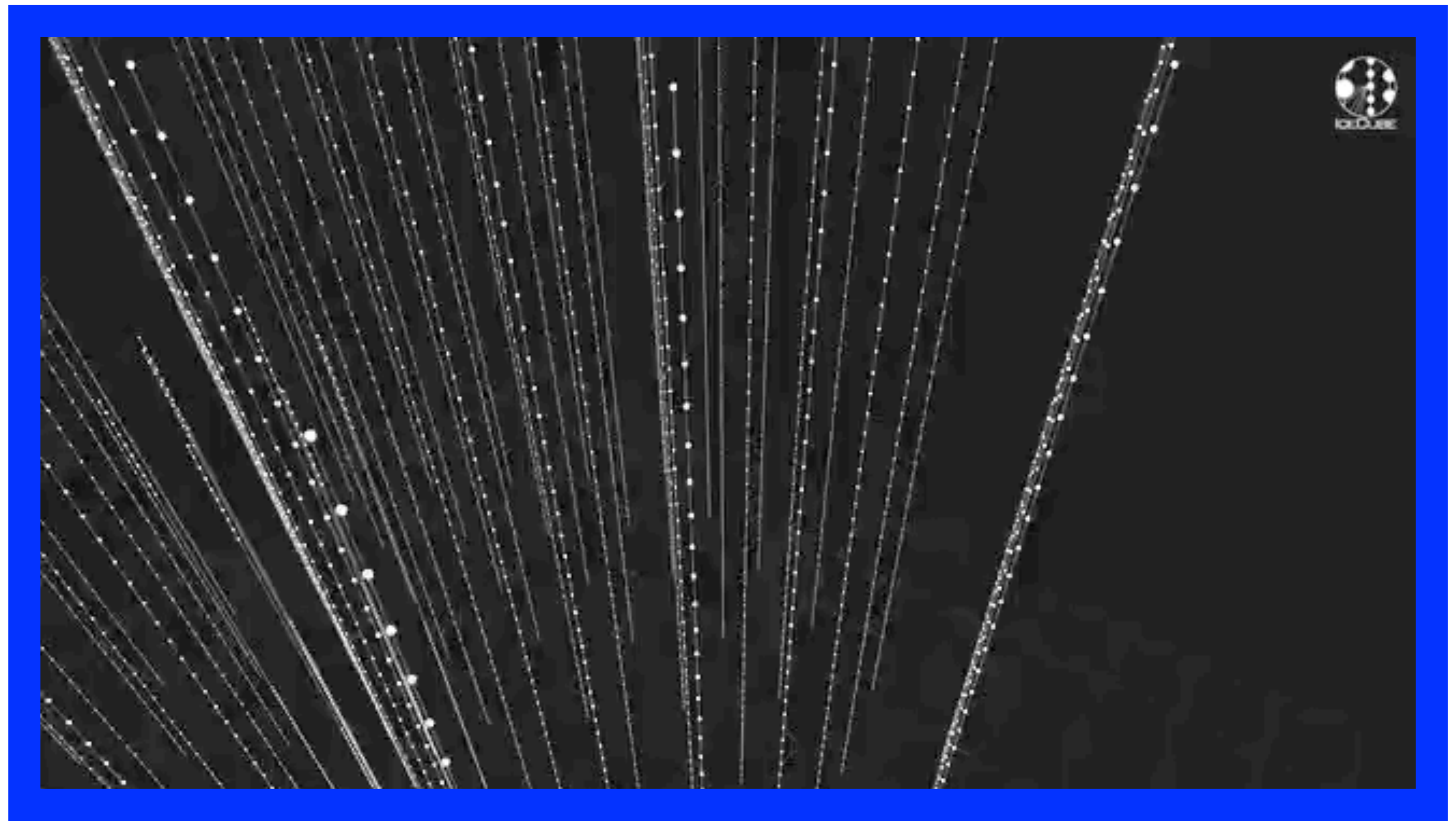
Trigger decision based on number of HLCs (+ optionally volume)



Neutrino interactions in IceCube

Event signatures





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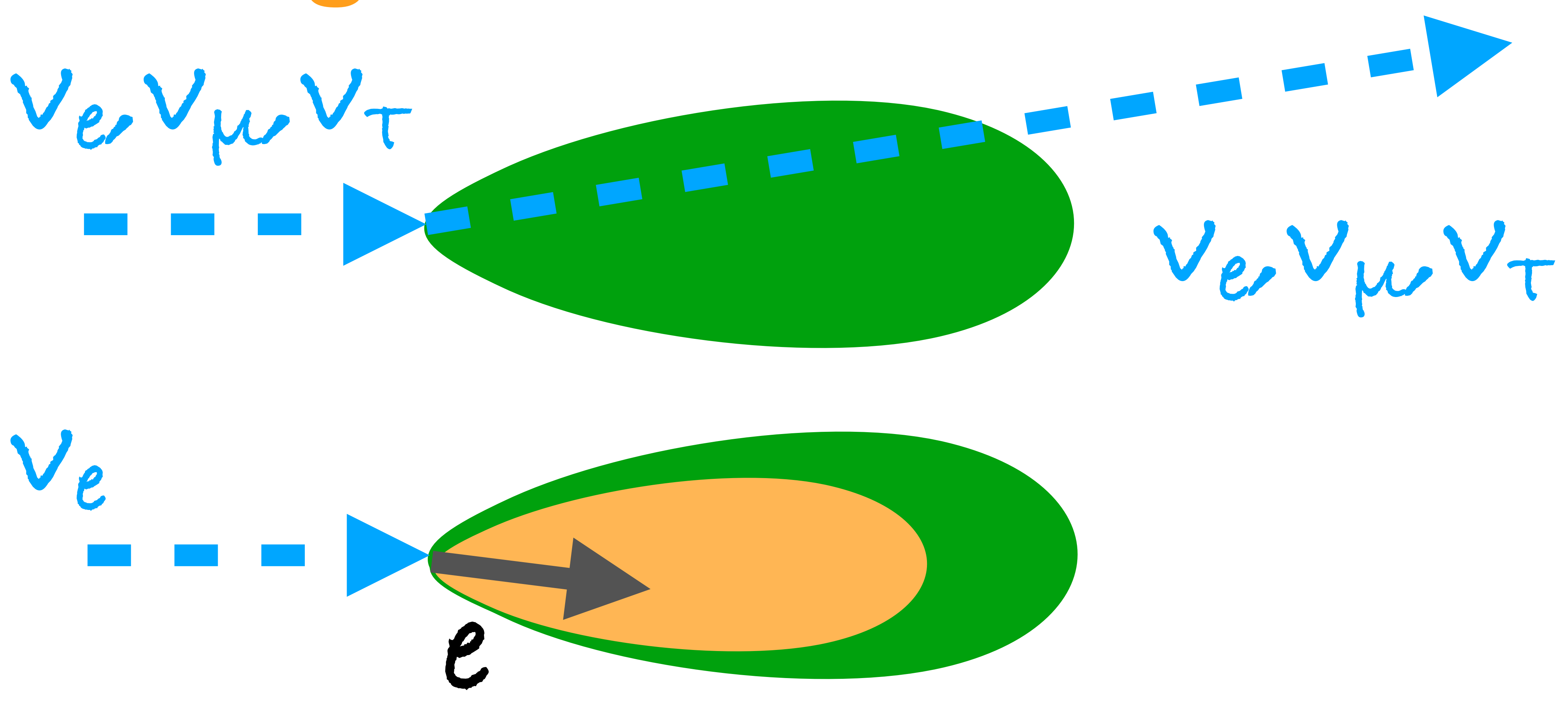

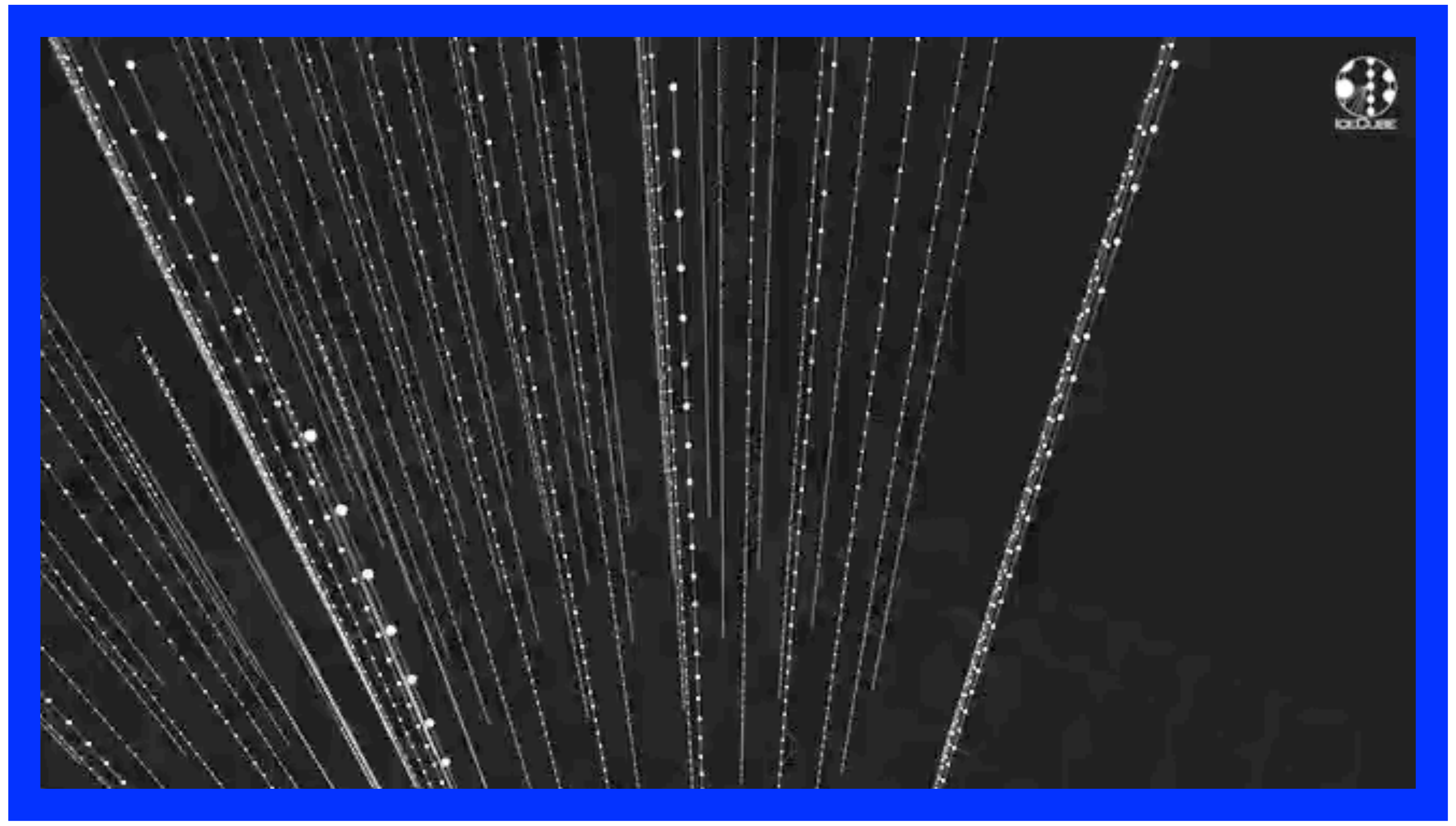

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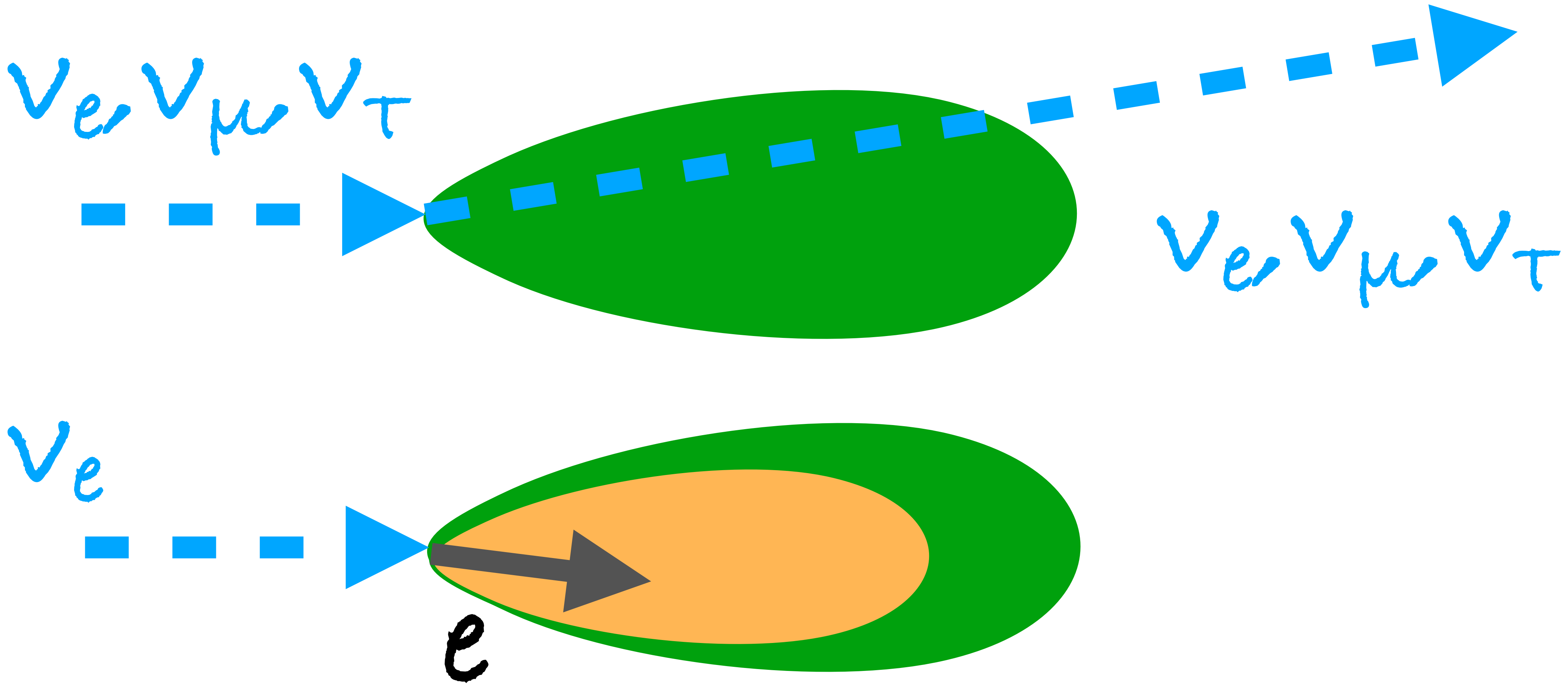

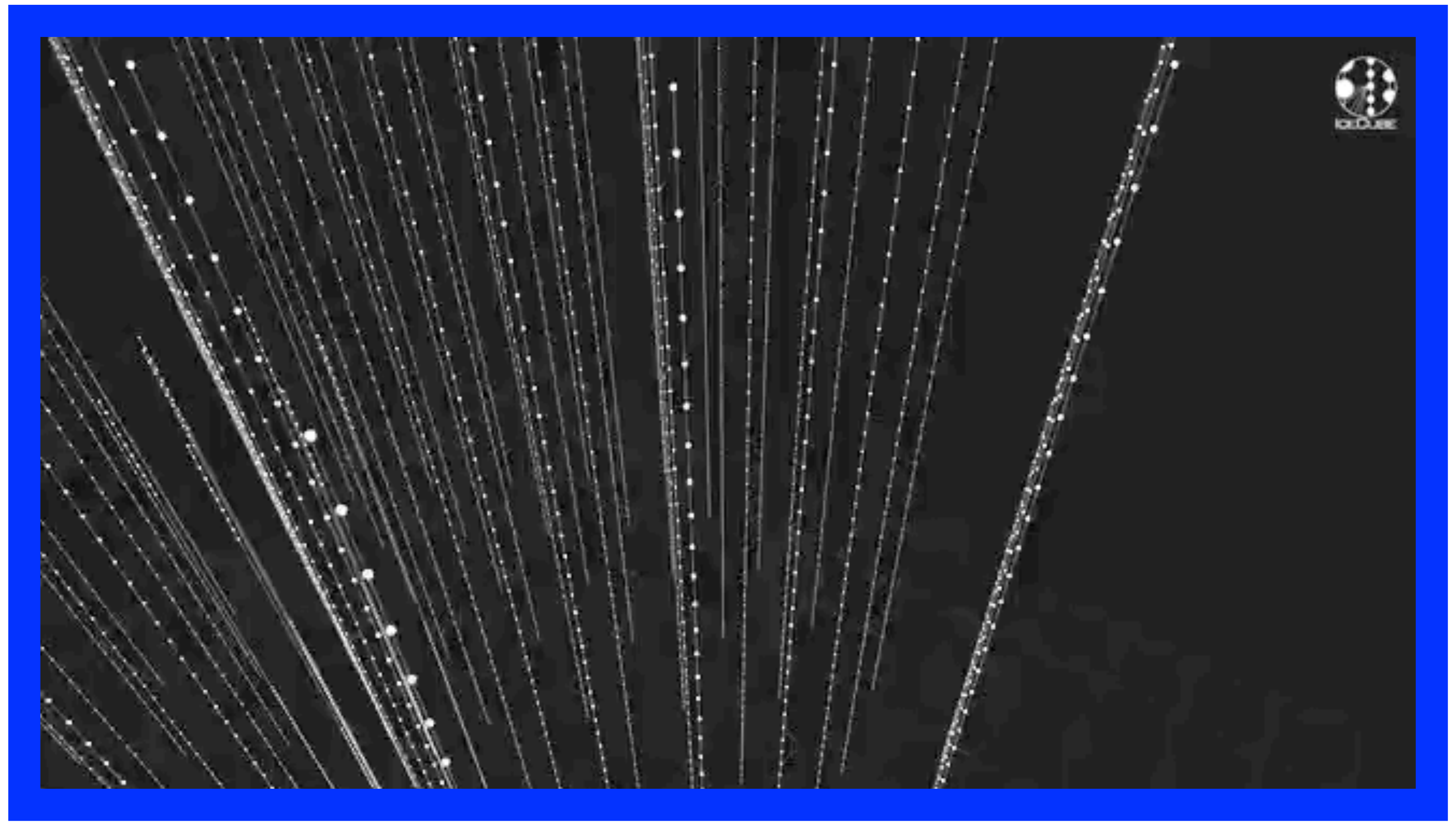

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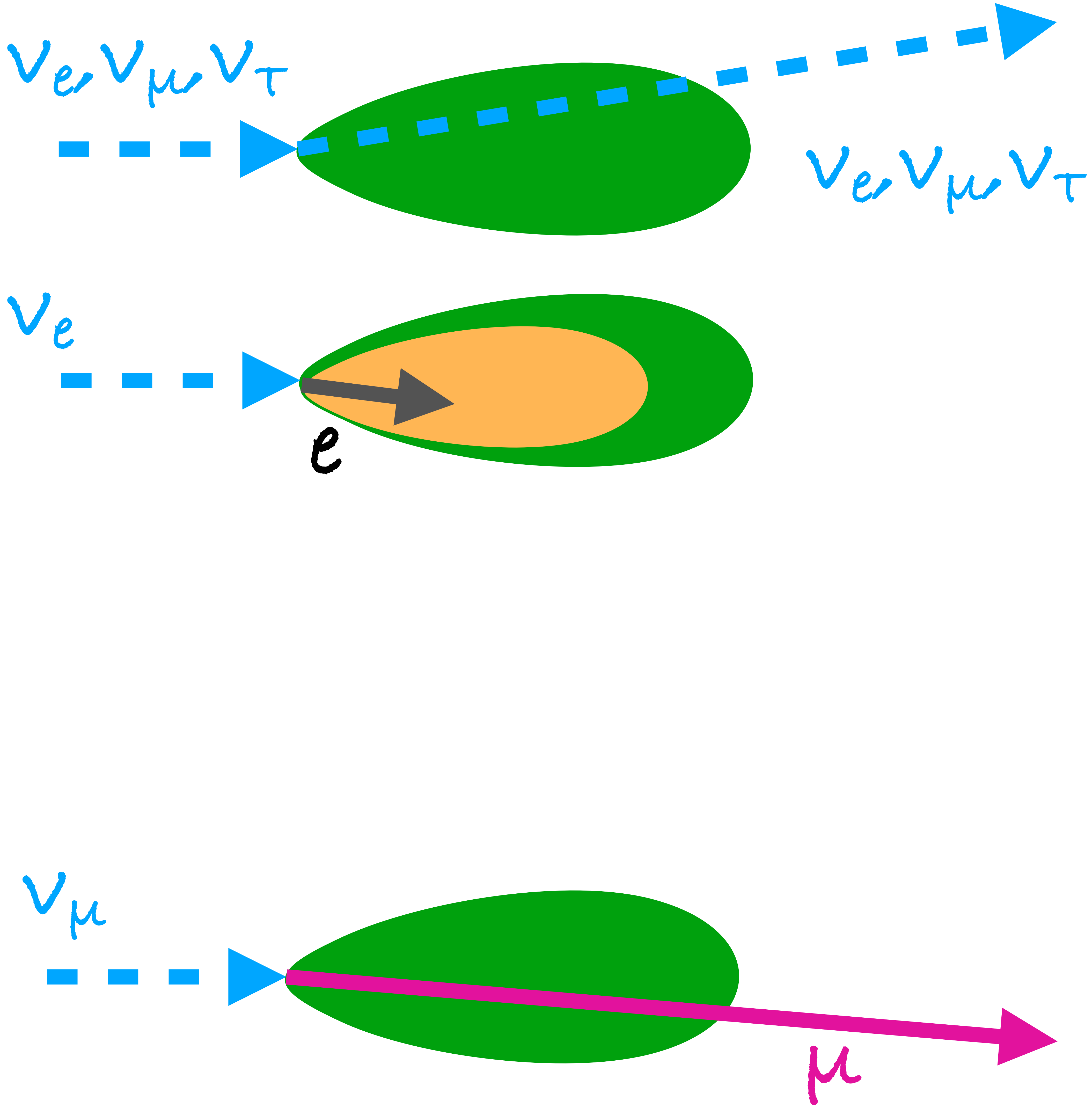

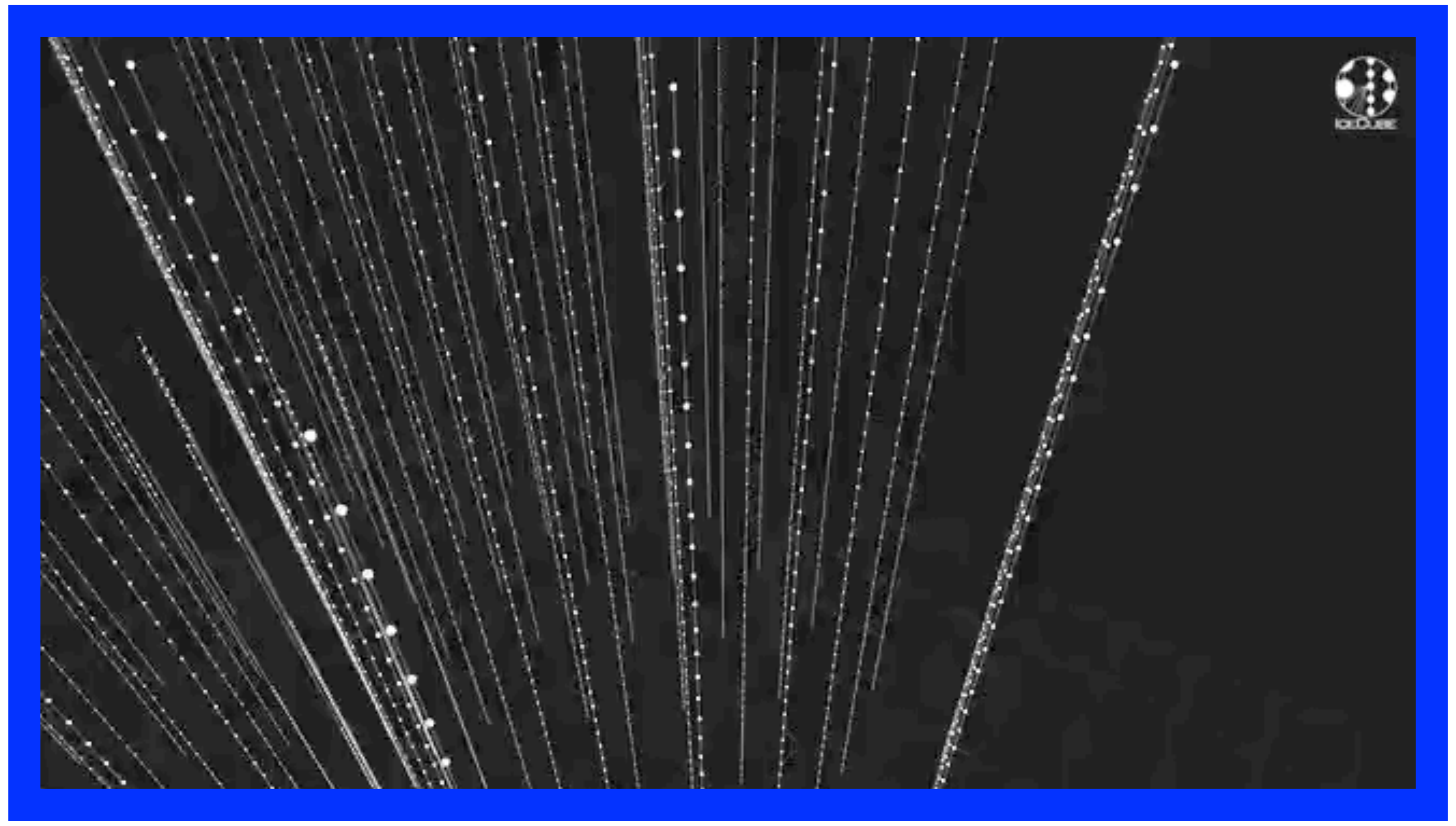

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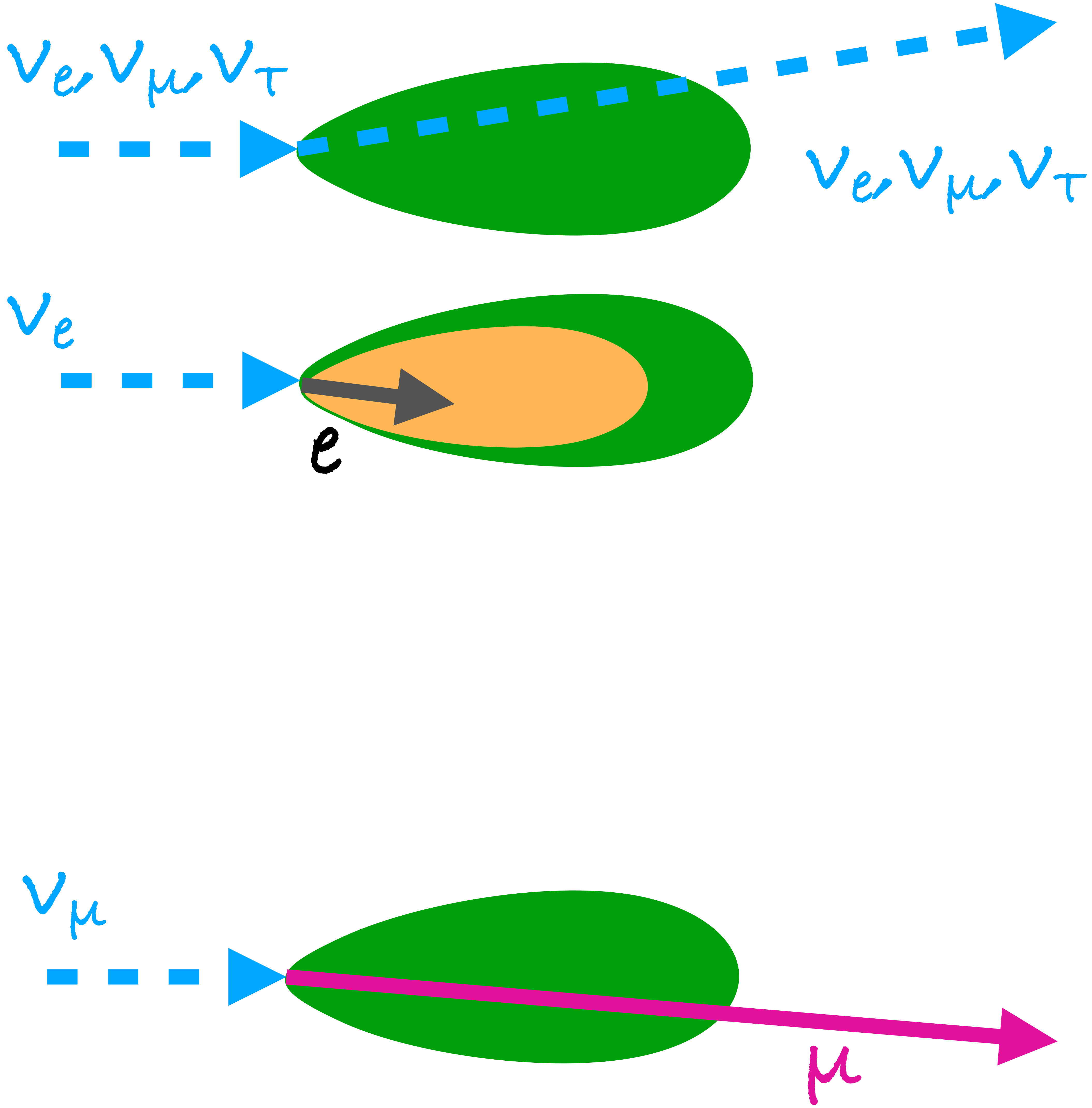
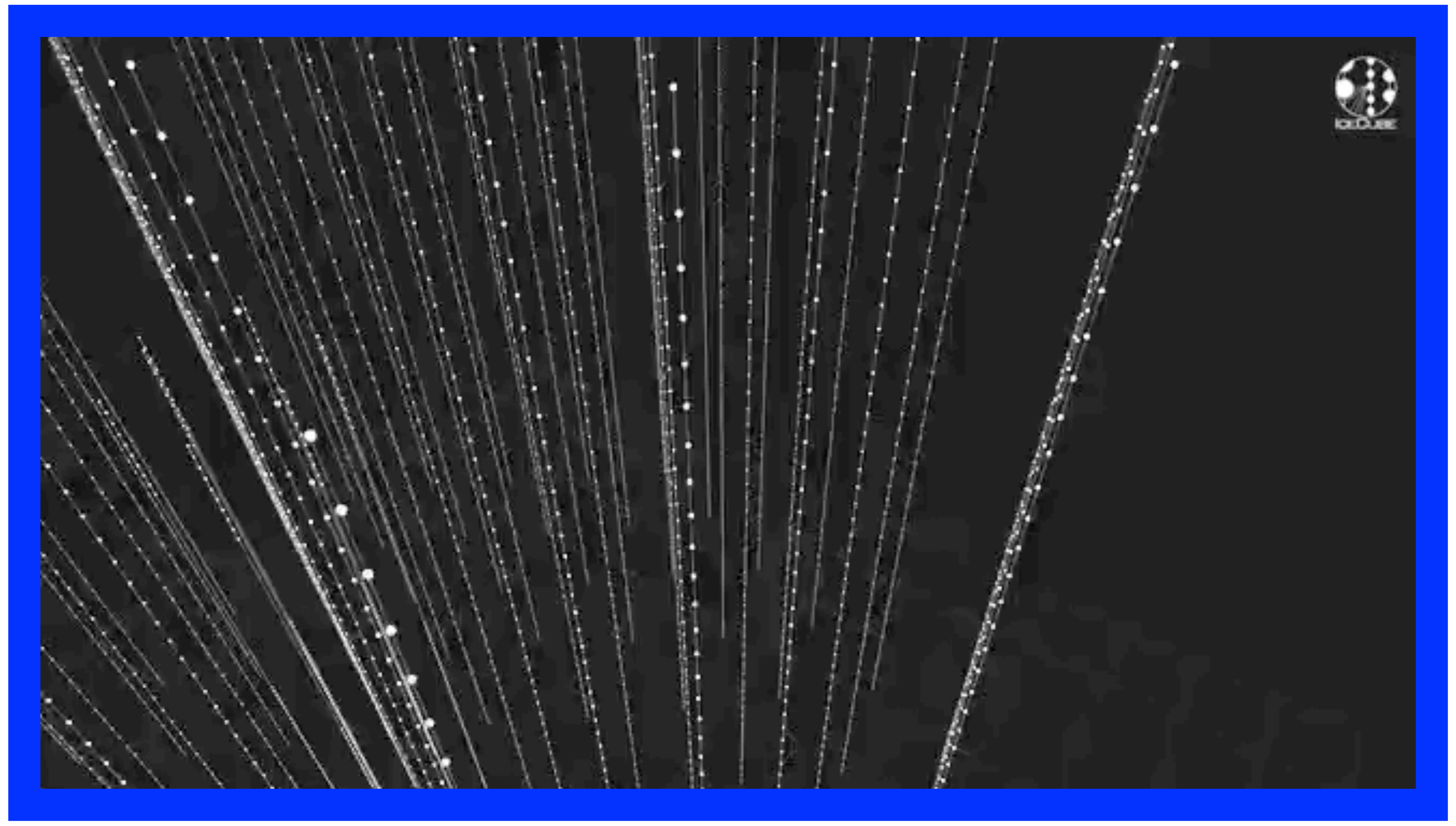
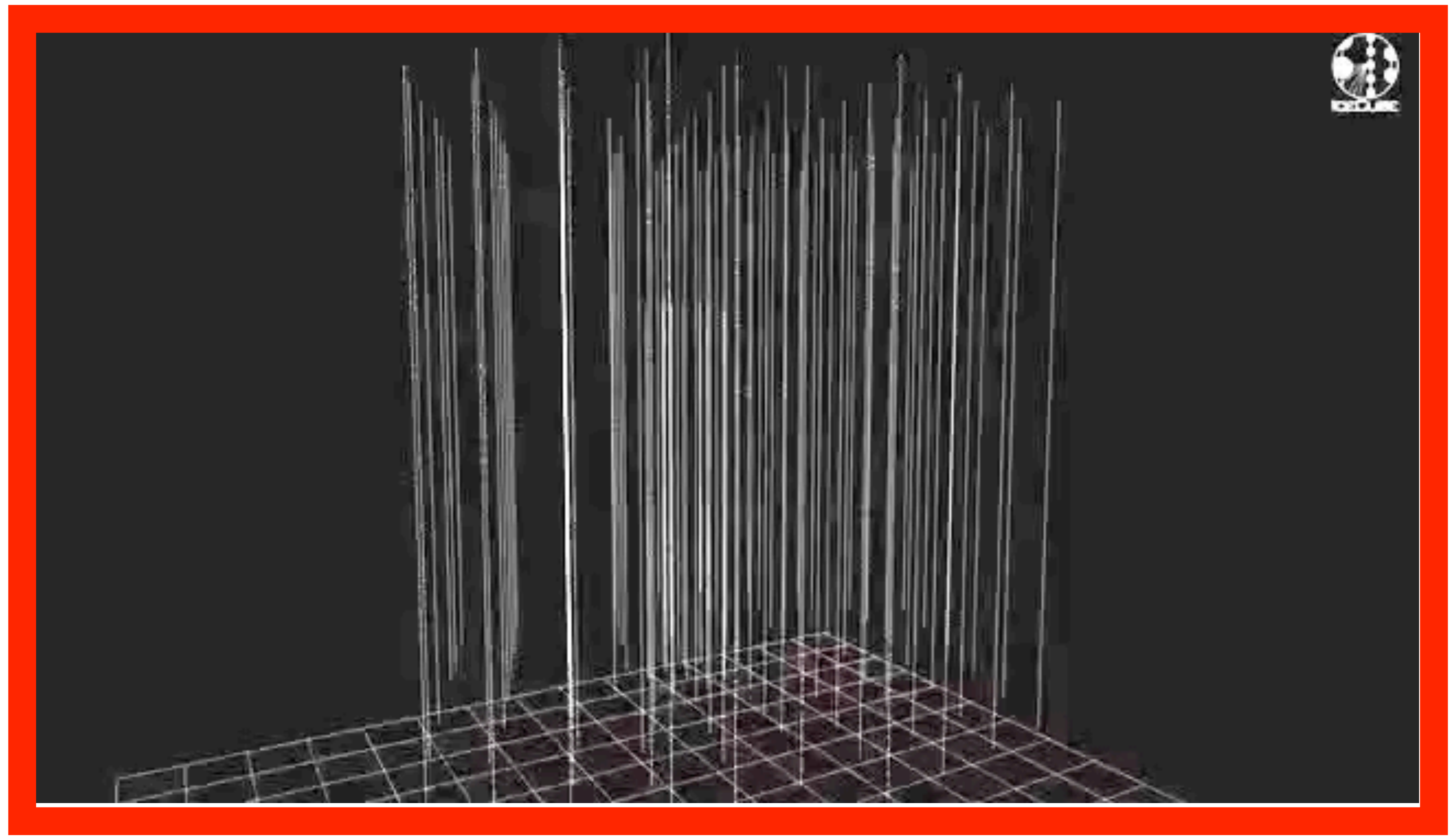
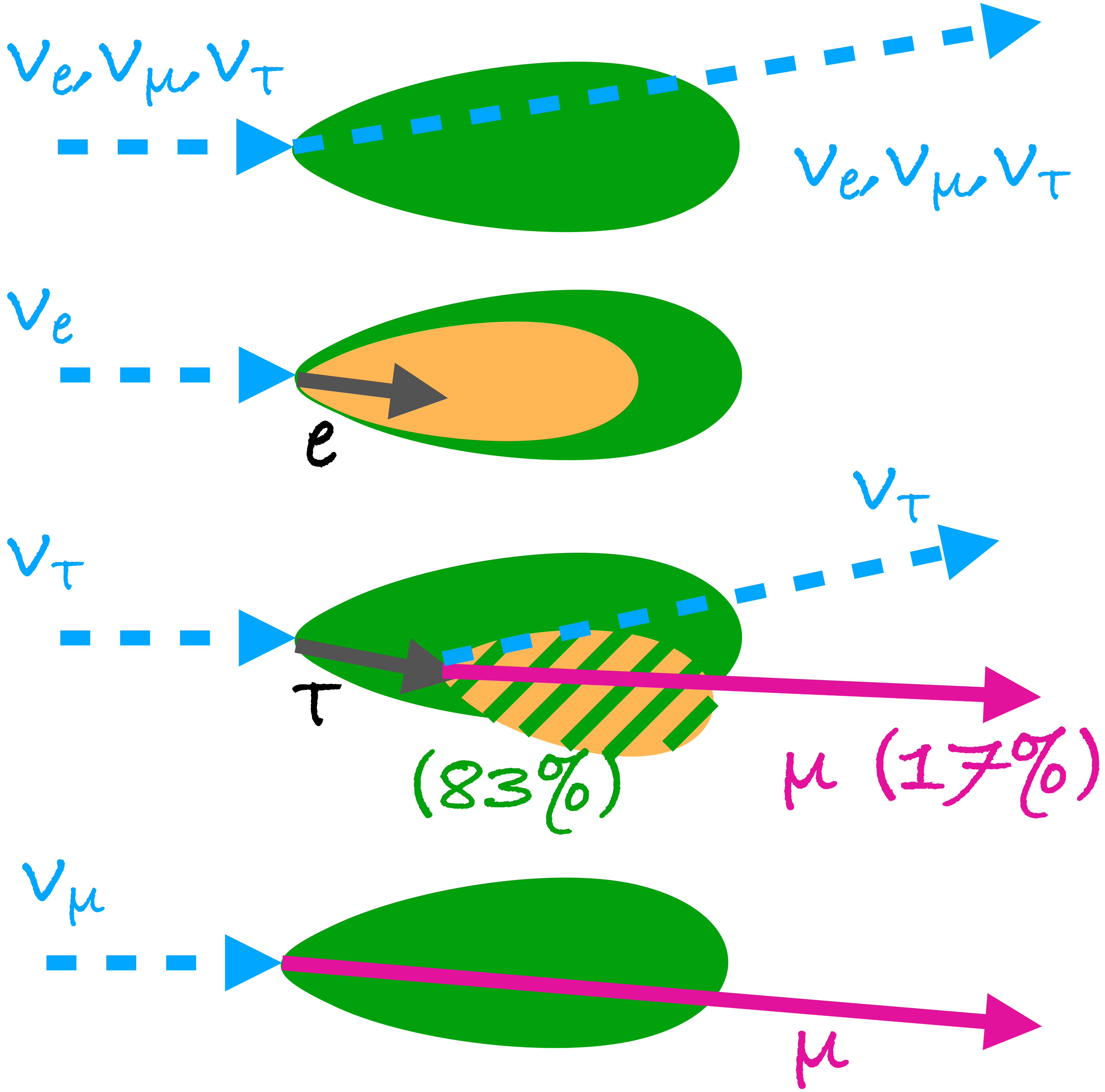


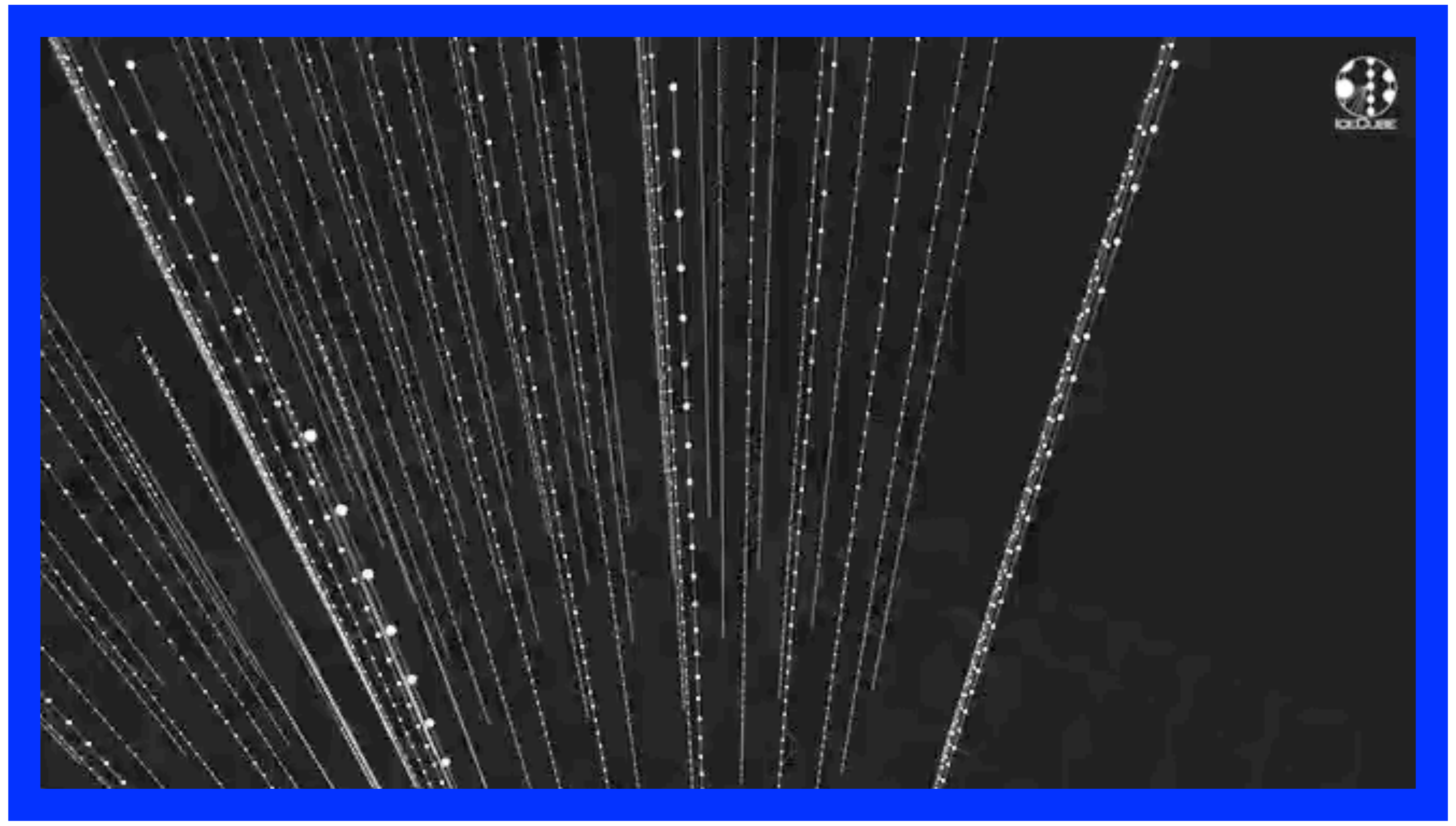


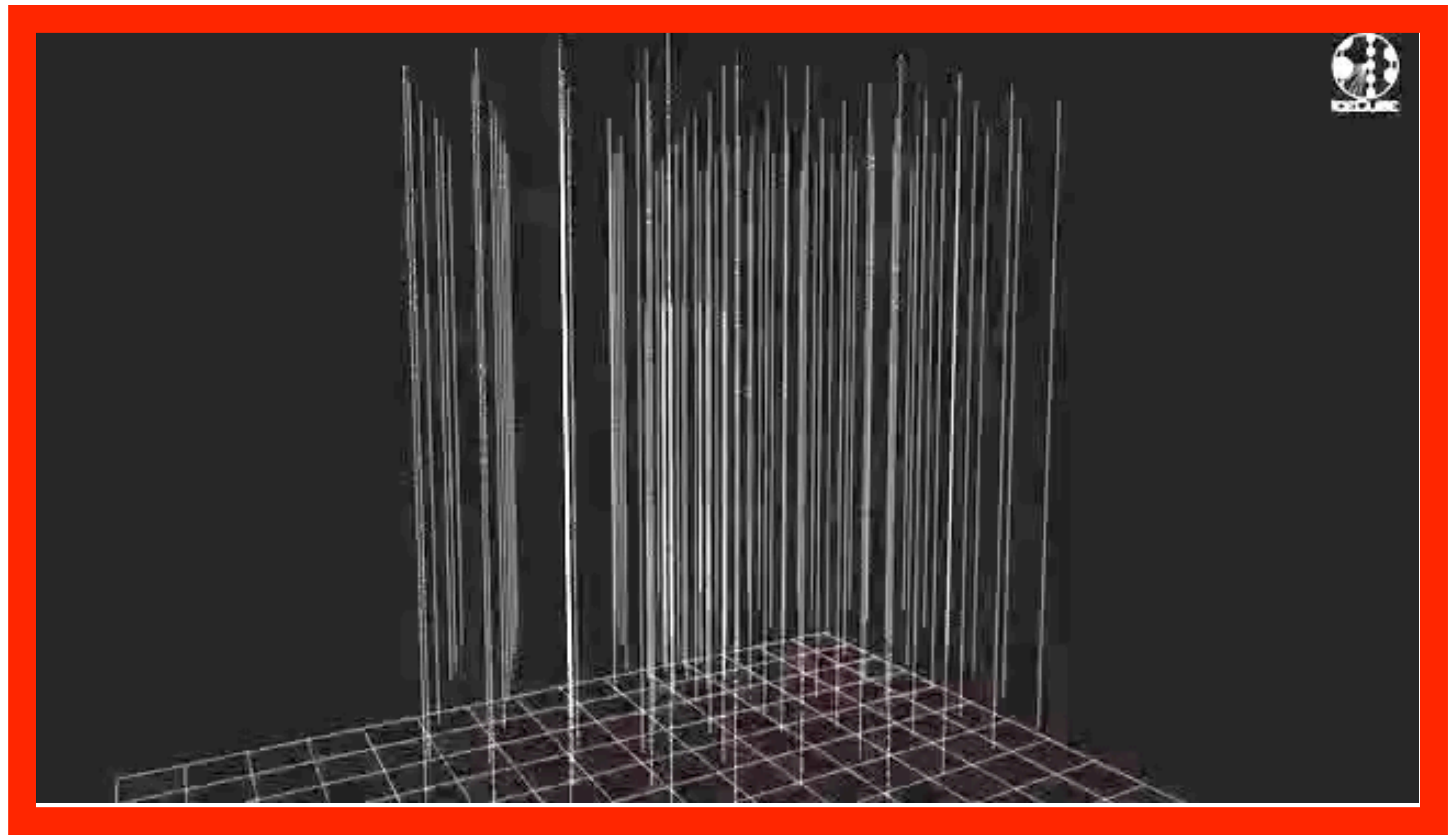


Neutrino interactions in IceCube

Event signatures

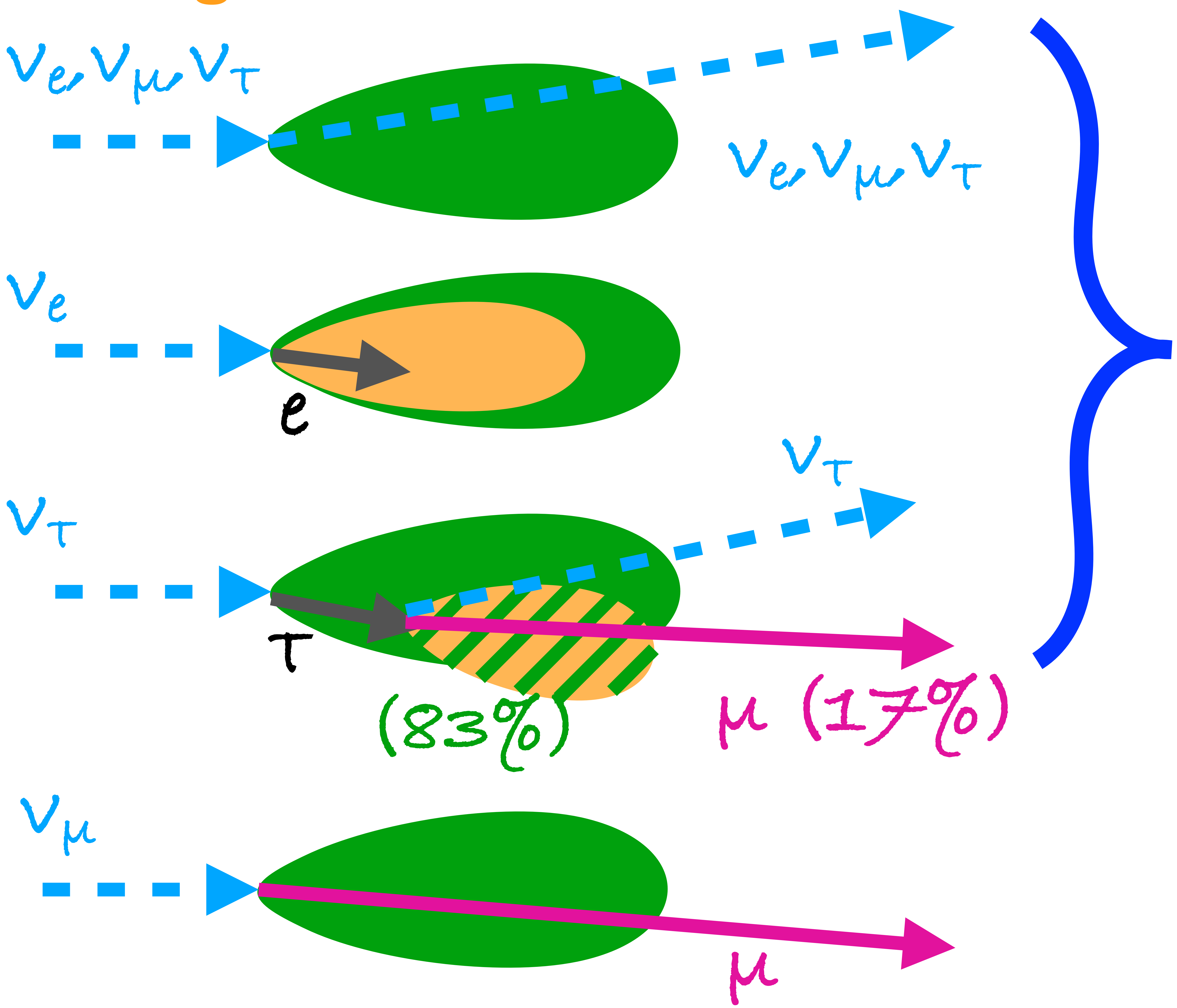


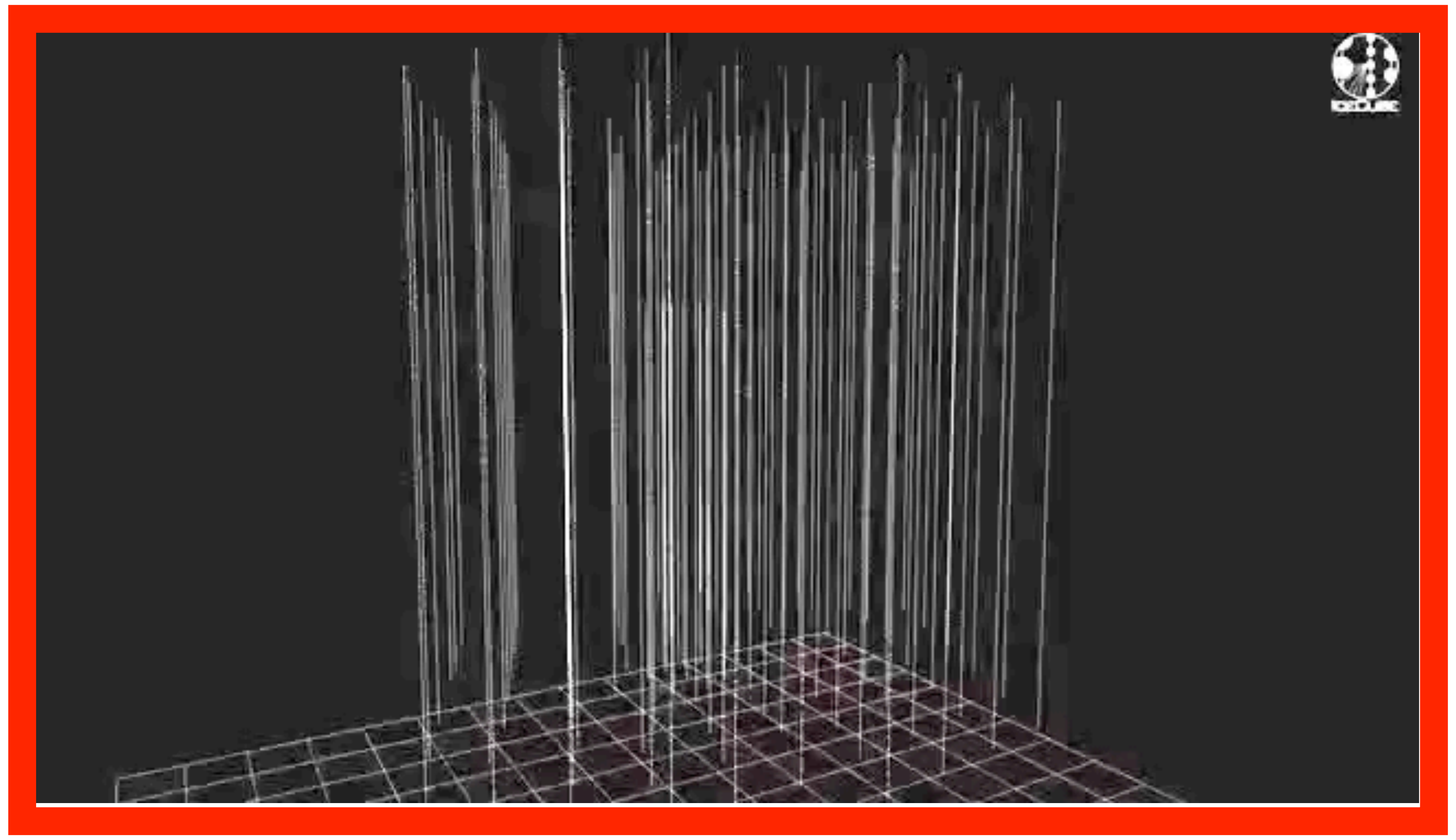




Neutrino interactions in IceCube

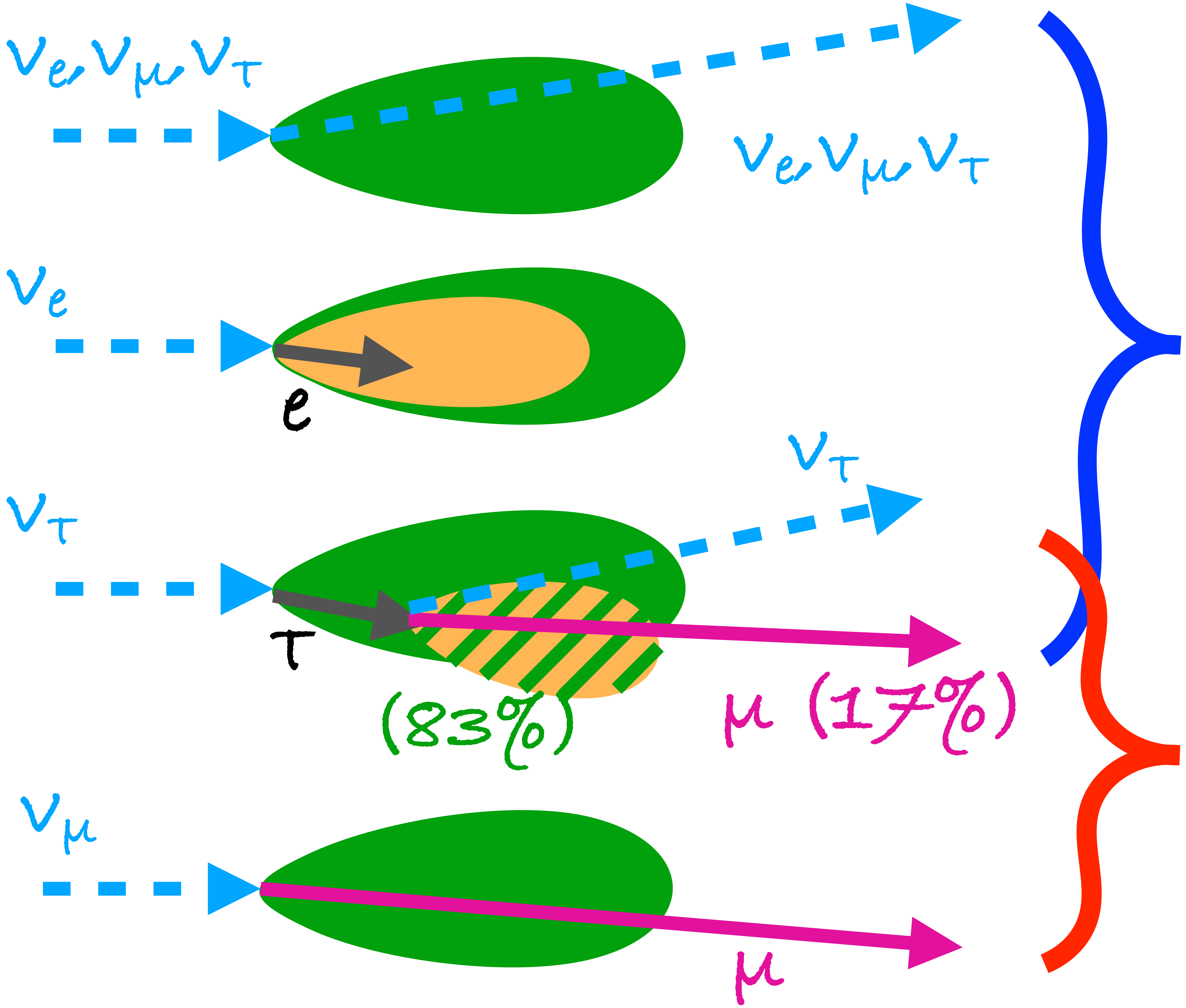
Event signatures

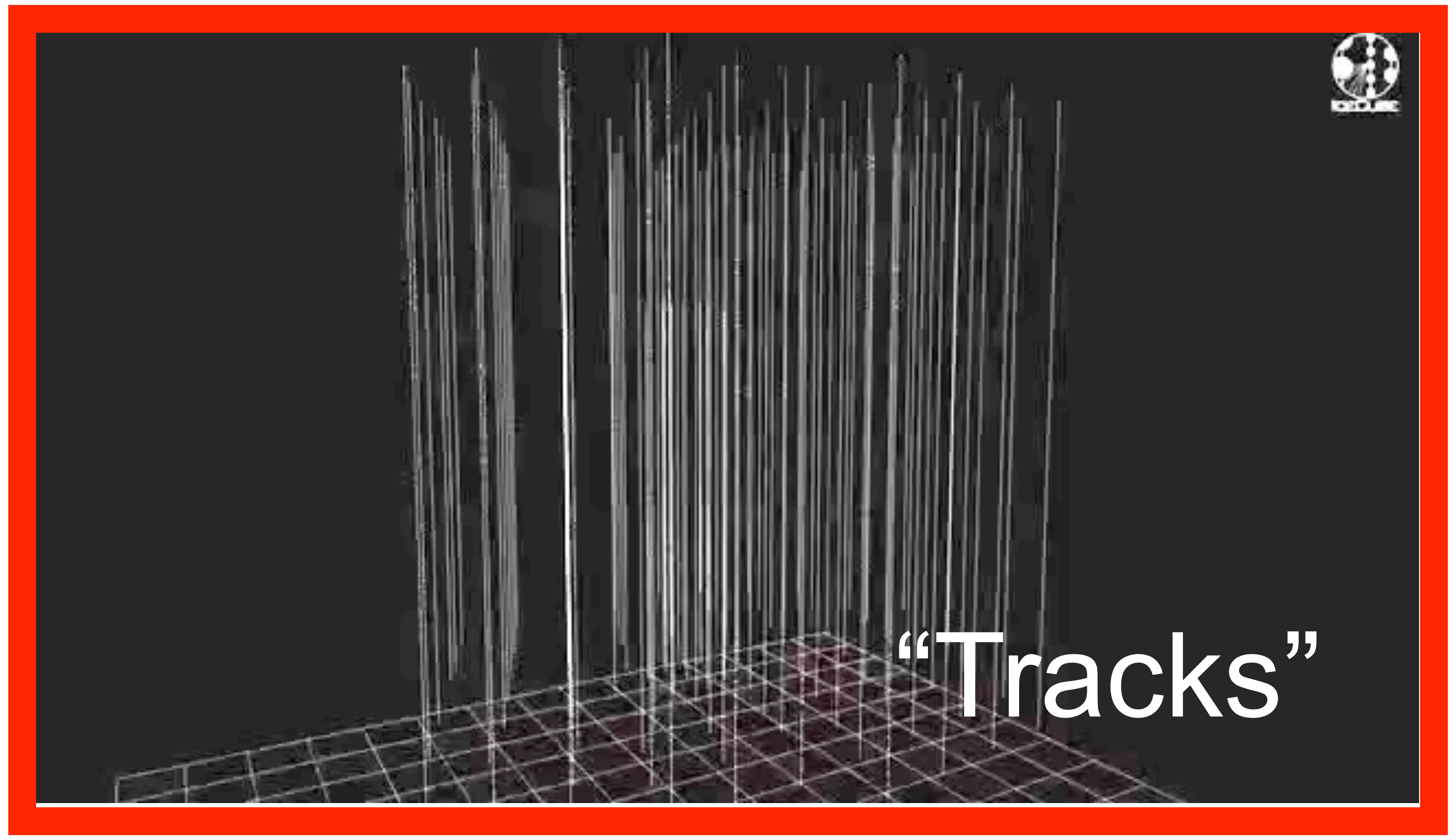




Neutrino interactions in IceCube

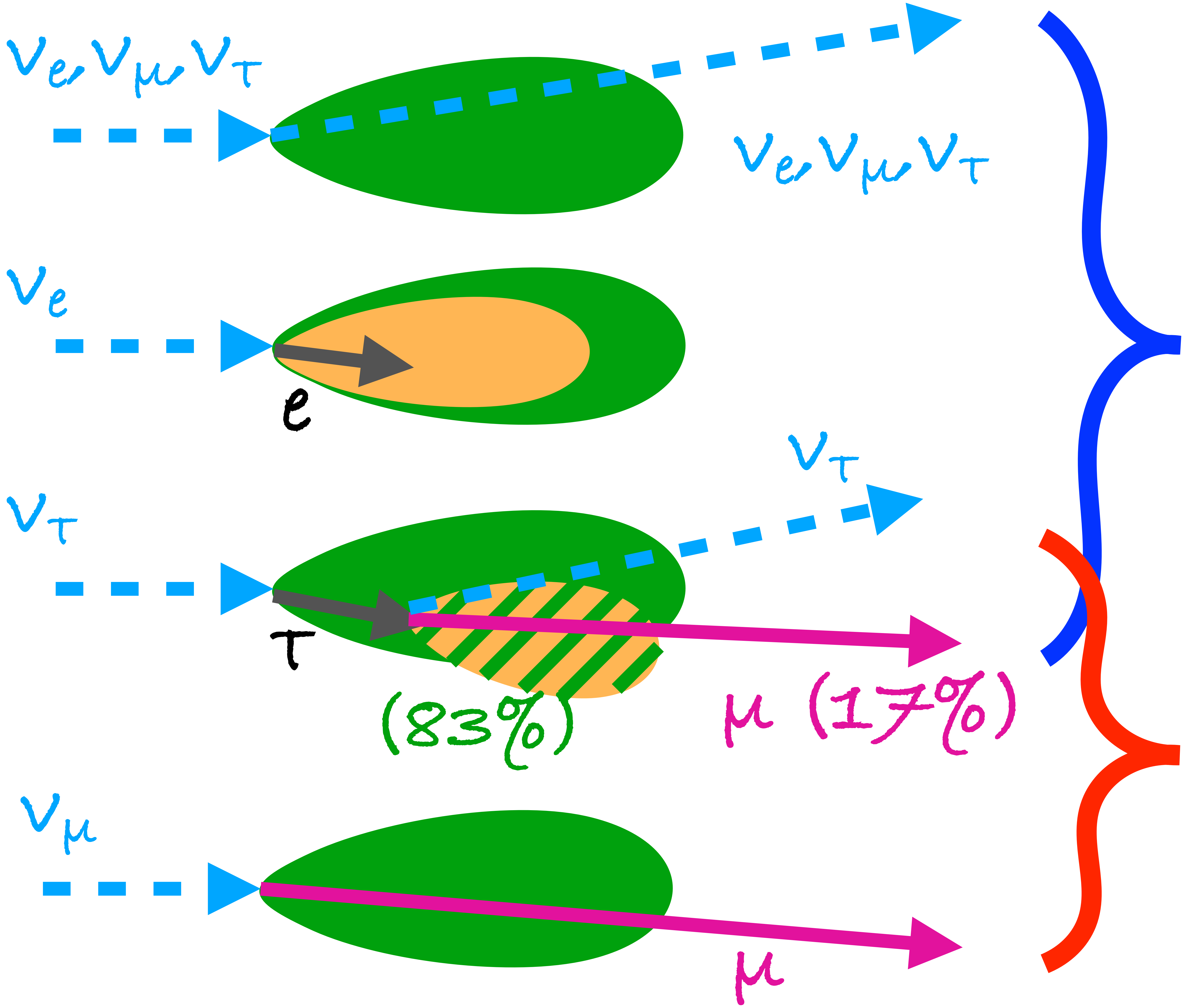
Event signatures

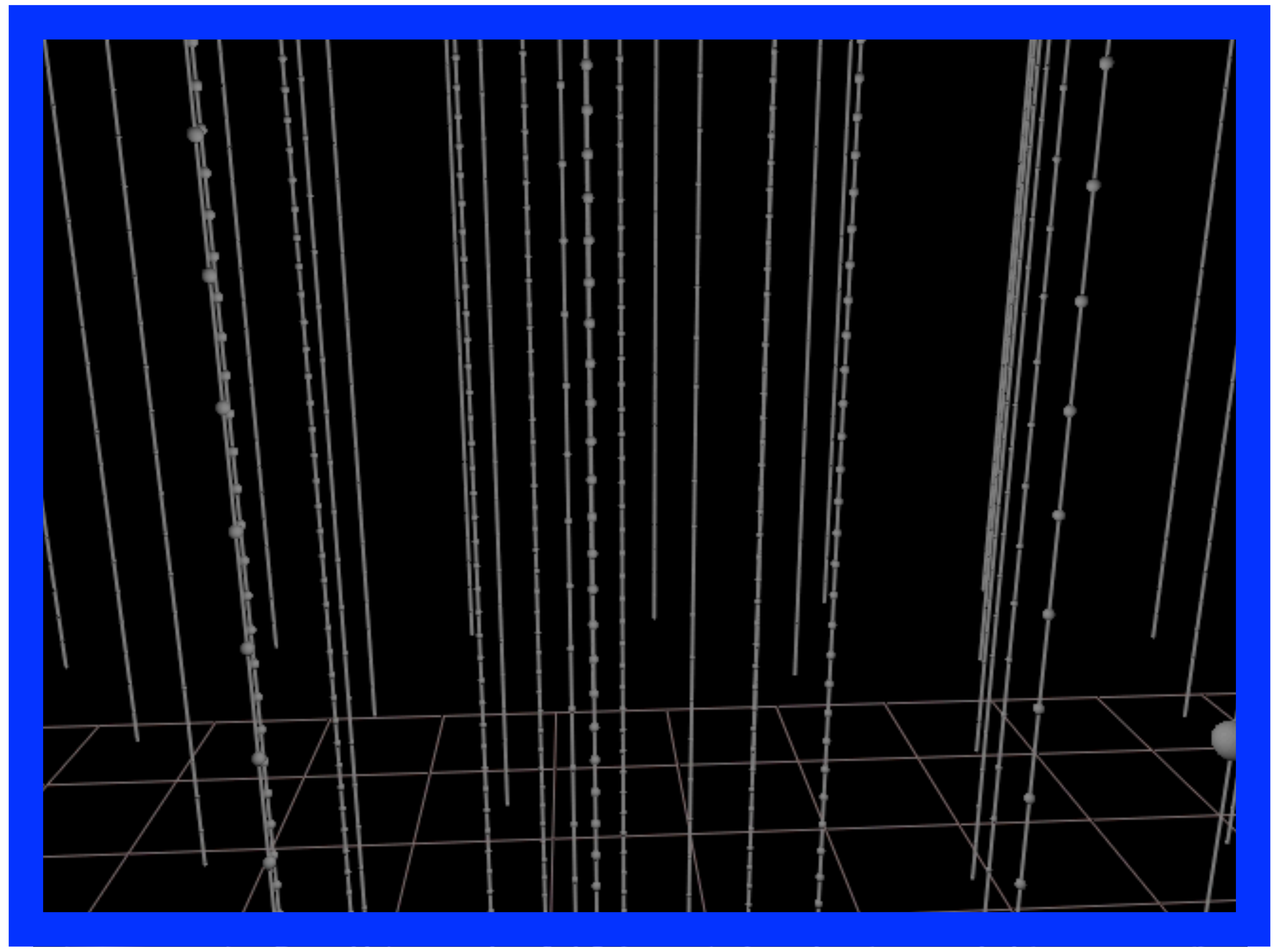


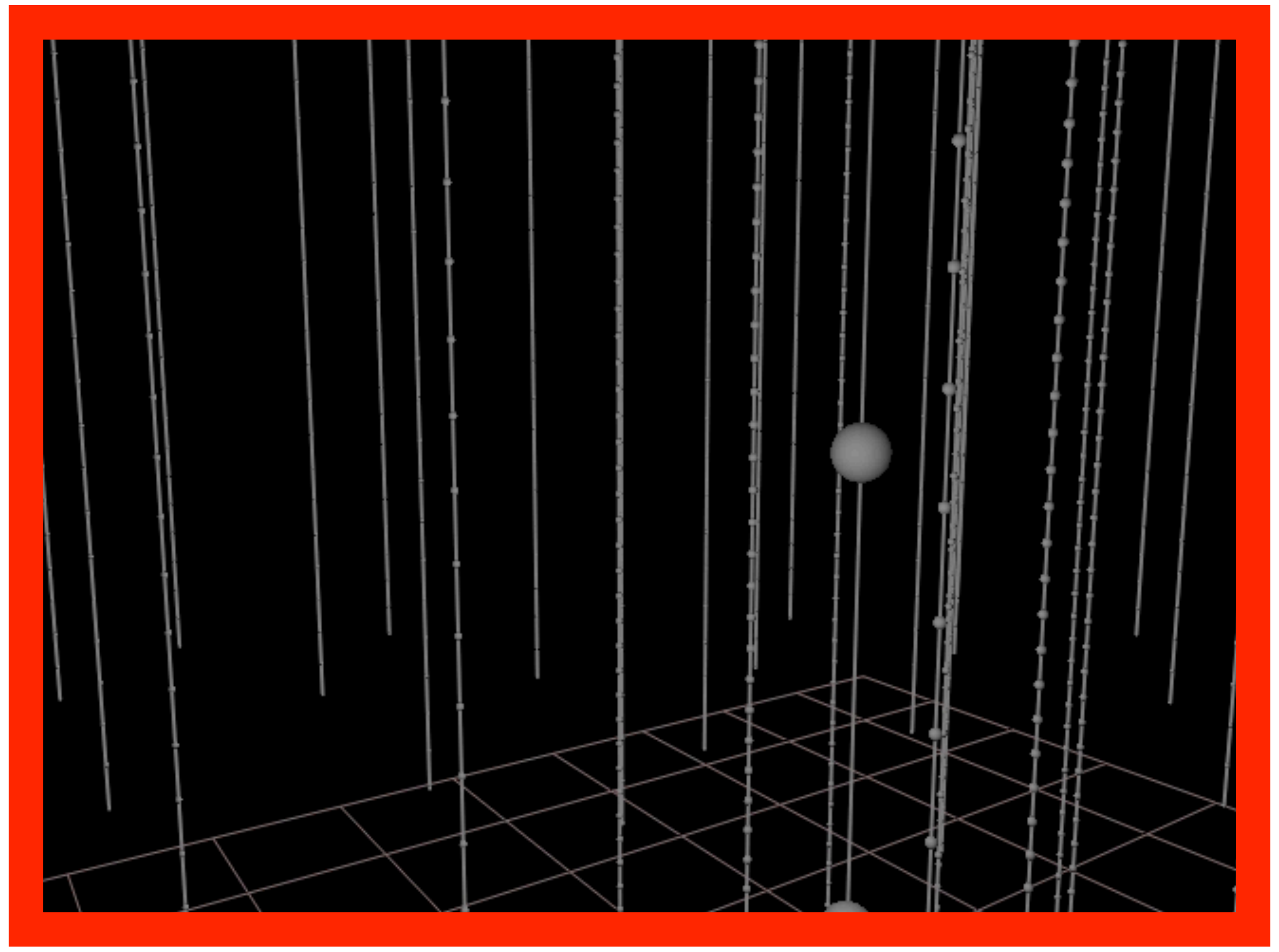


Neutrino interactions in IceCube

Event signatures

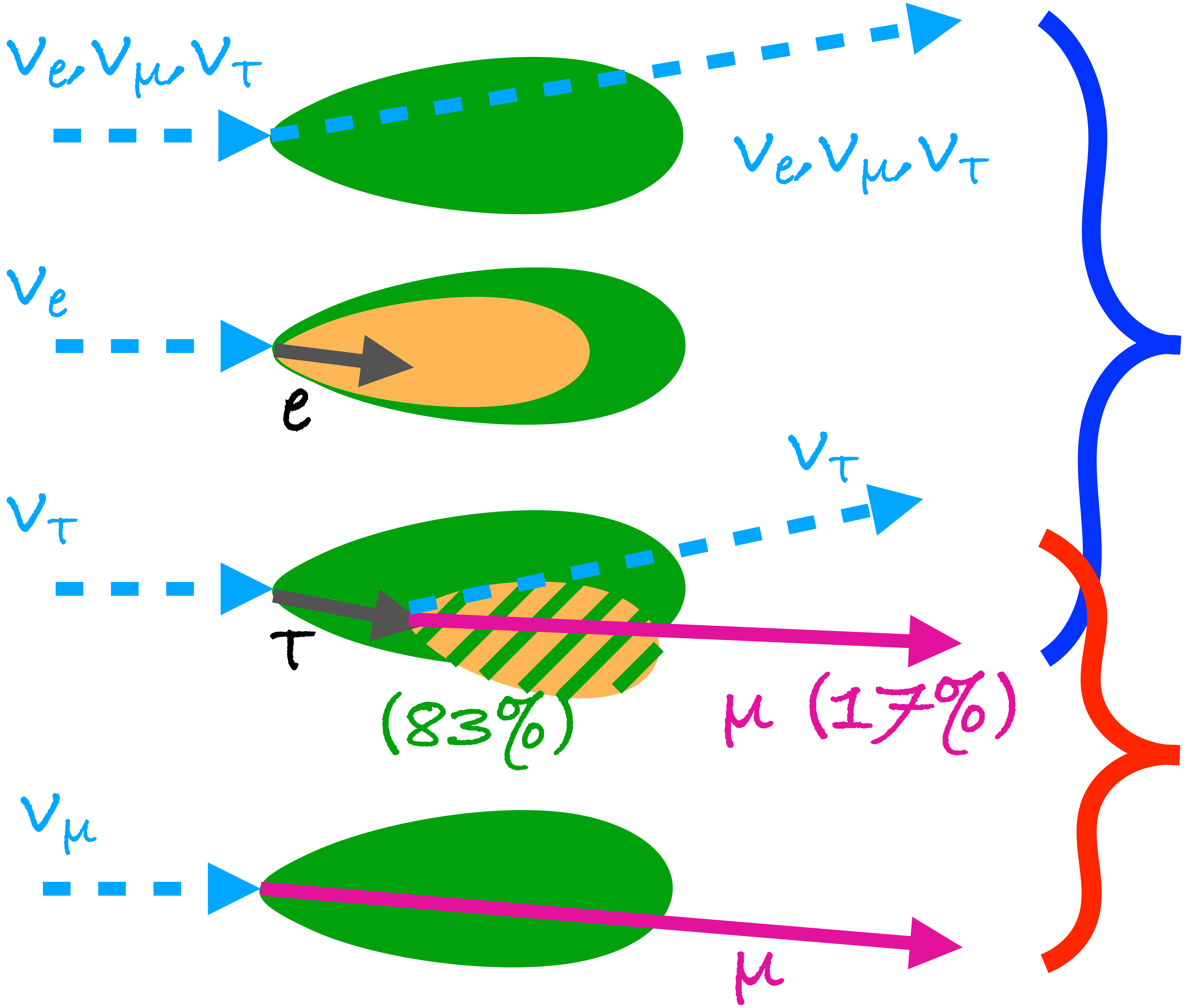


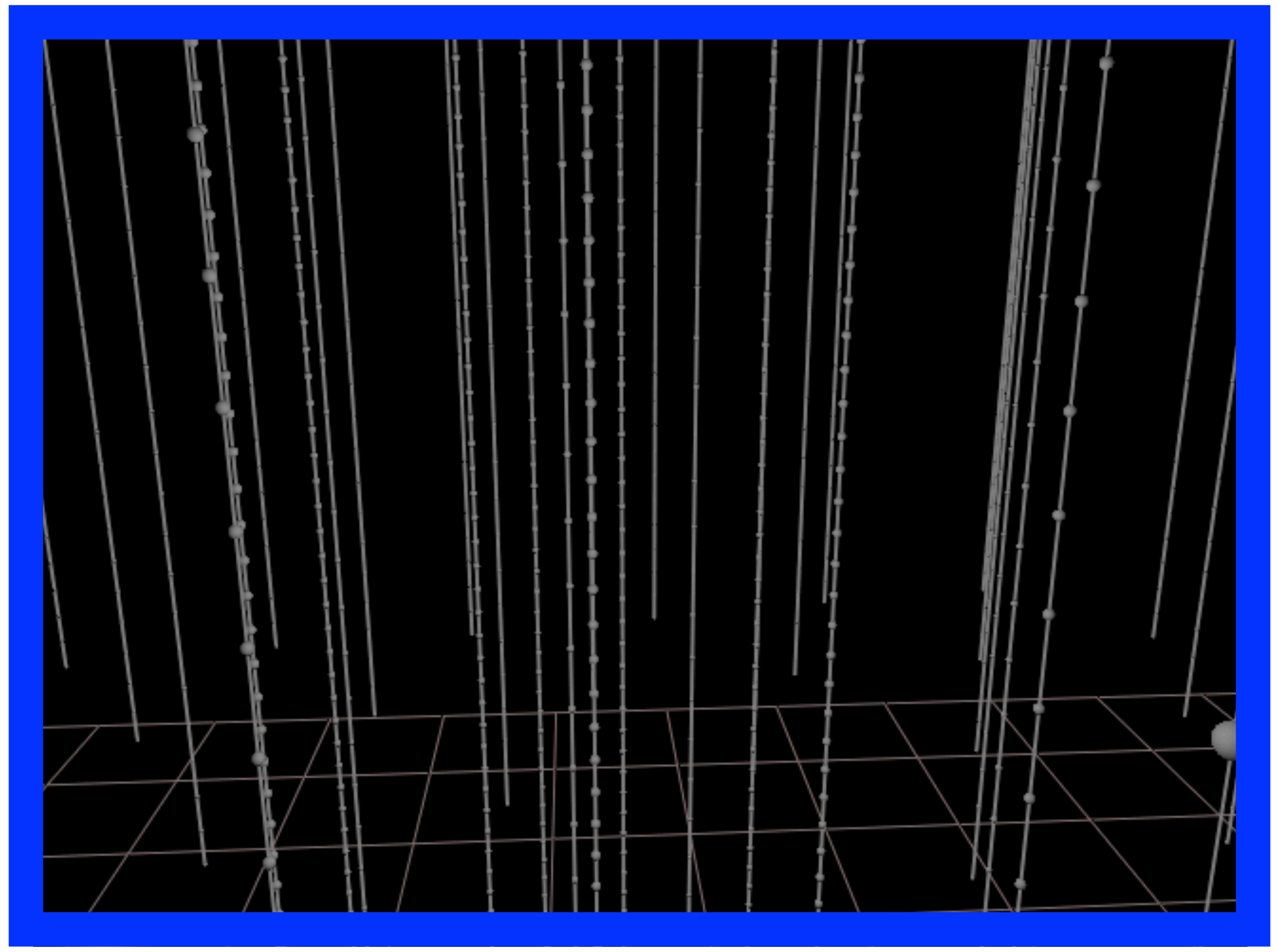


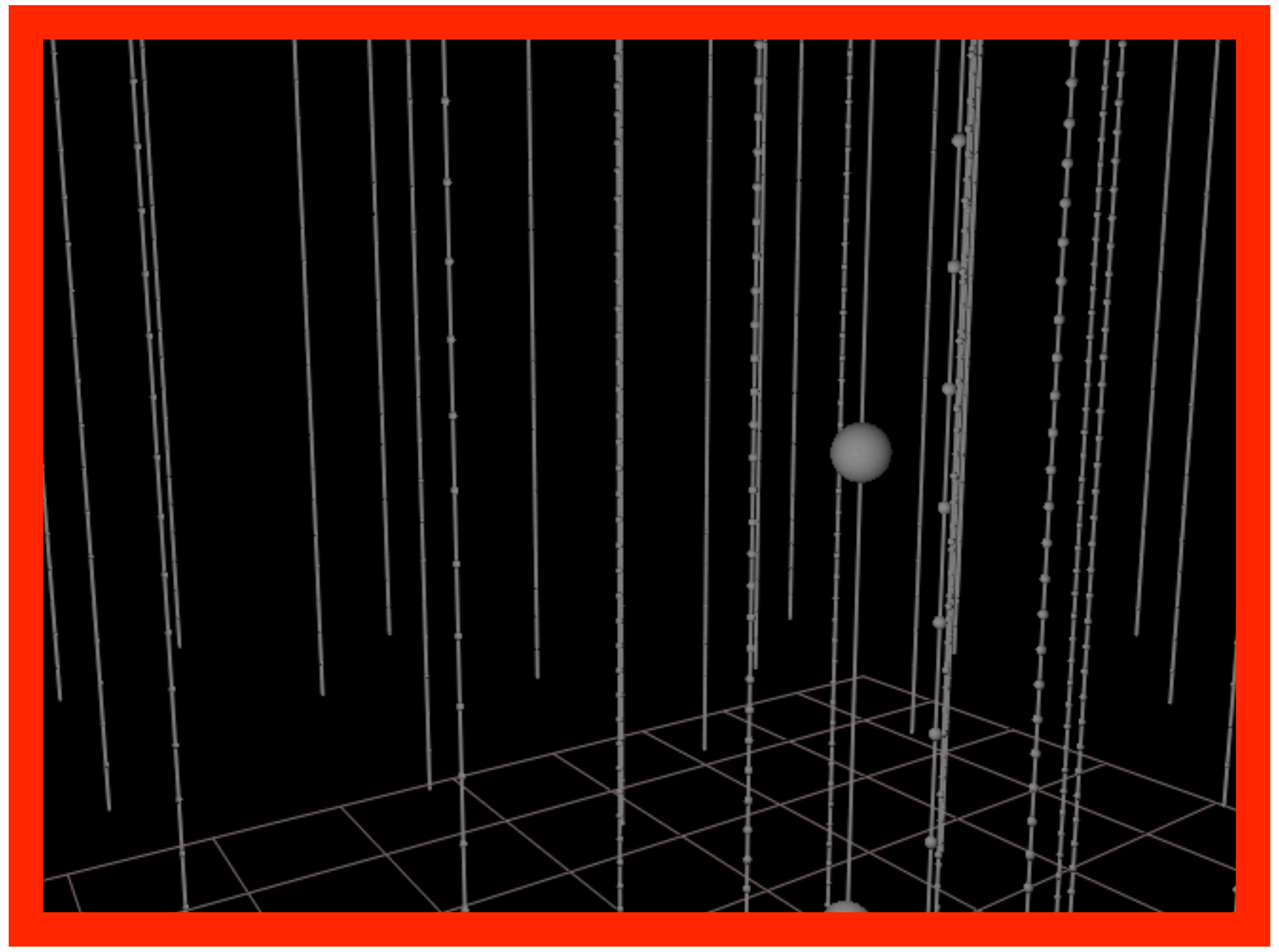


Neutrino interactions in IceCube

Event signatures







Event reconstruction

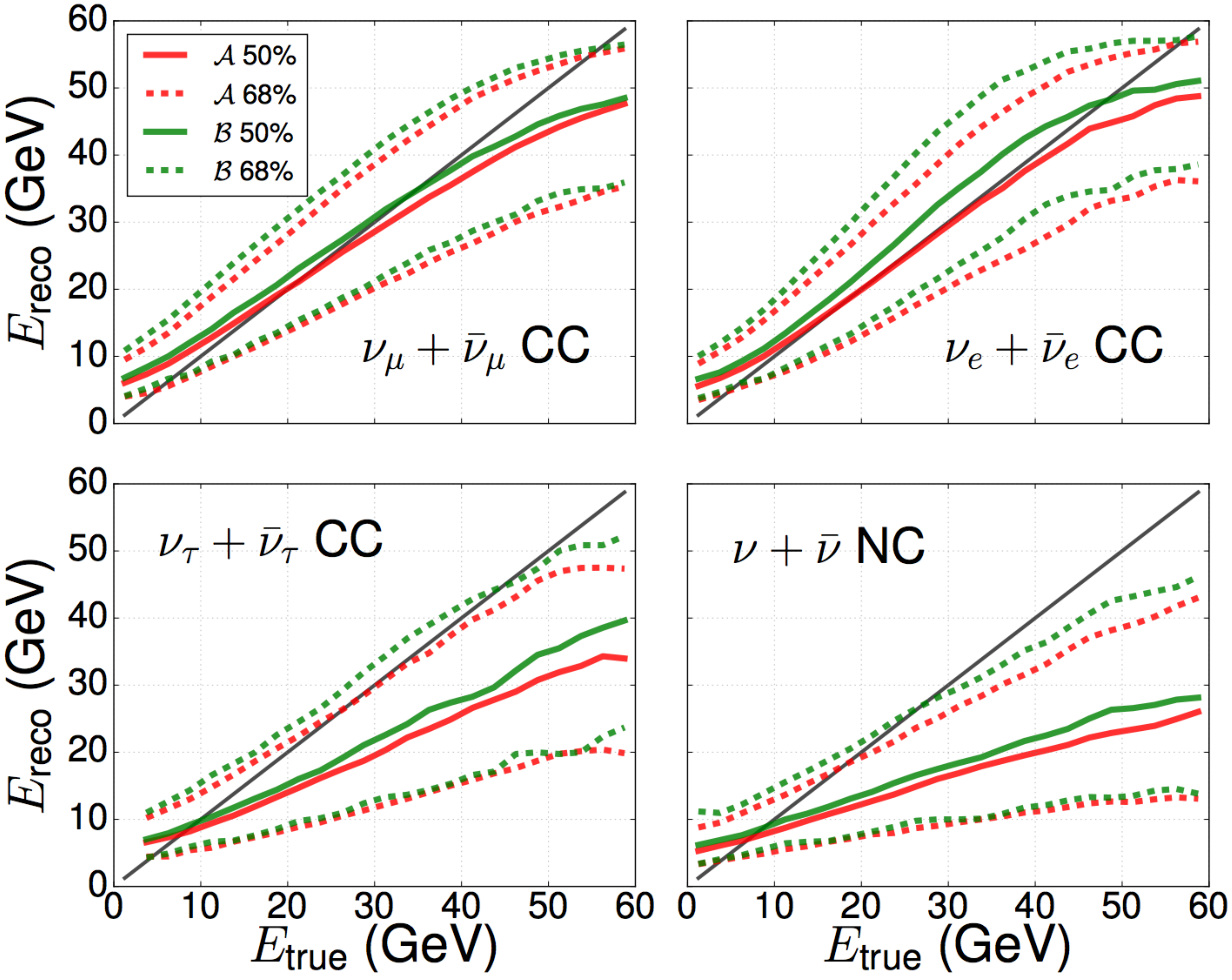
Performance

Resolution @ 20 GeV for tracks (cascades):

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

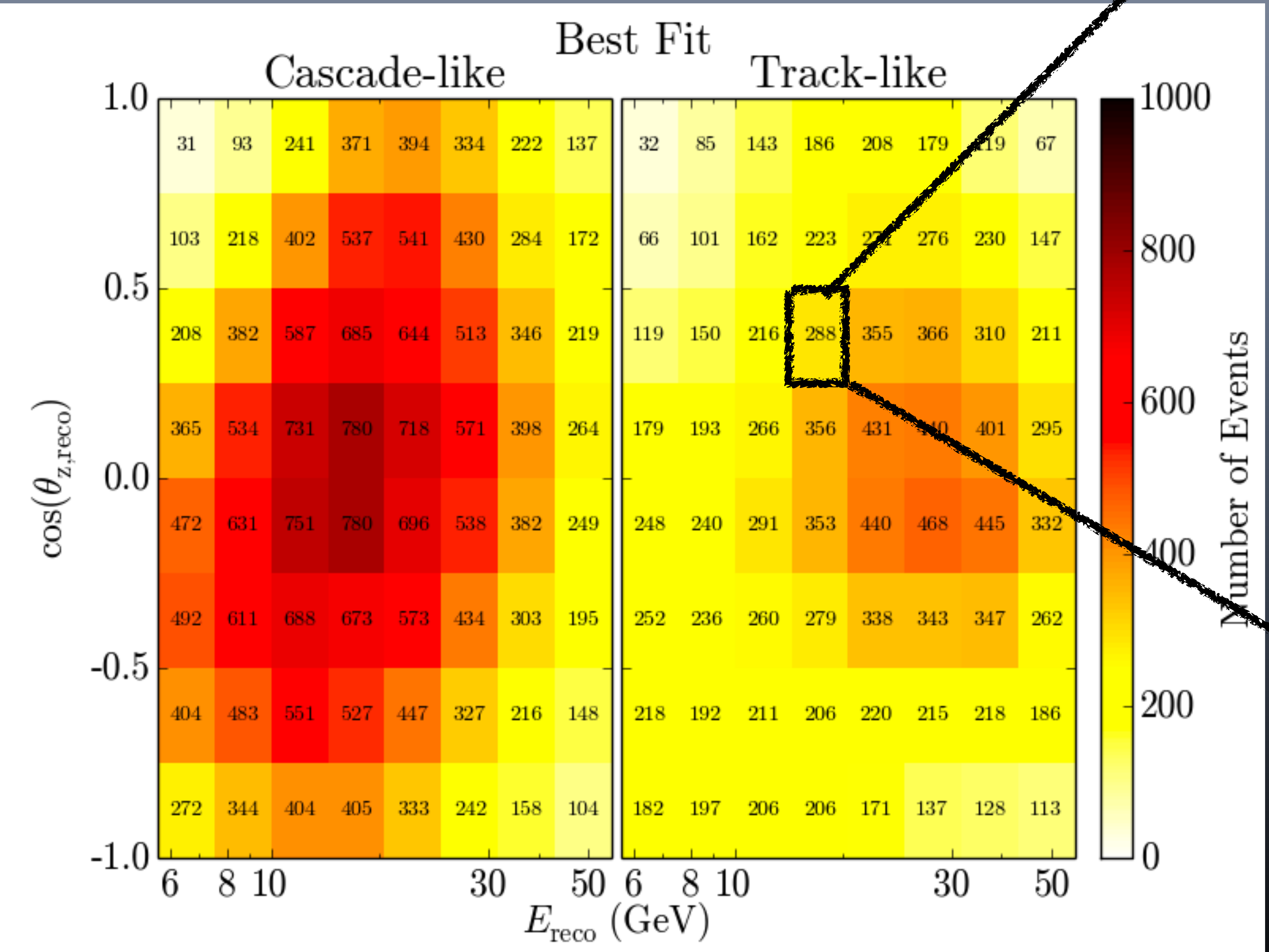
Classification @ 20 GeV:

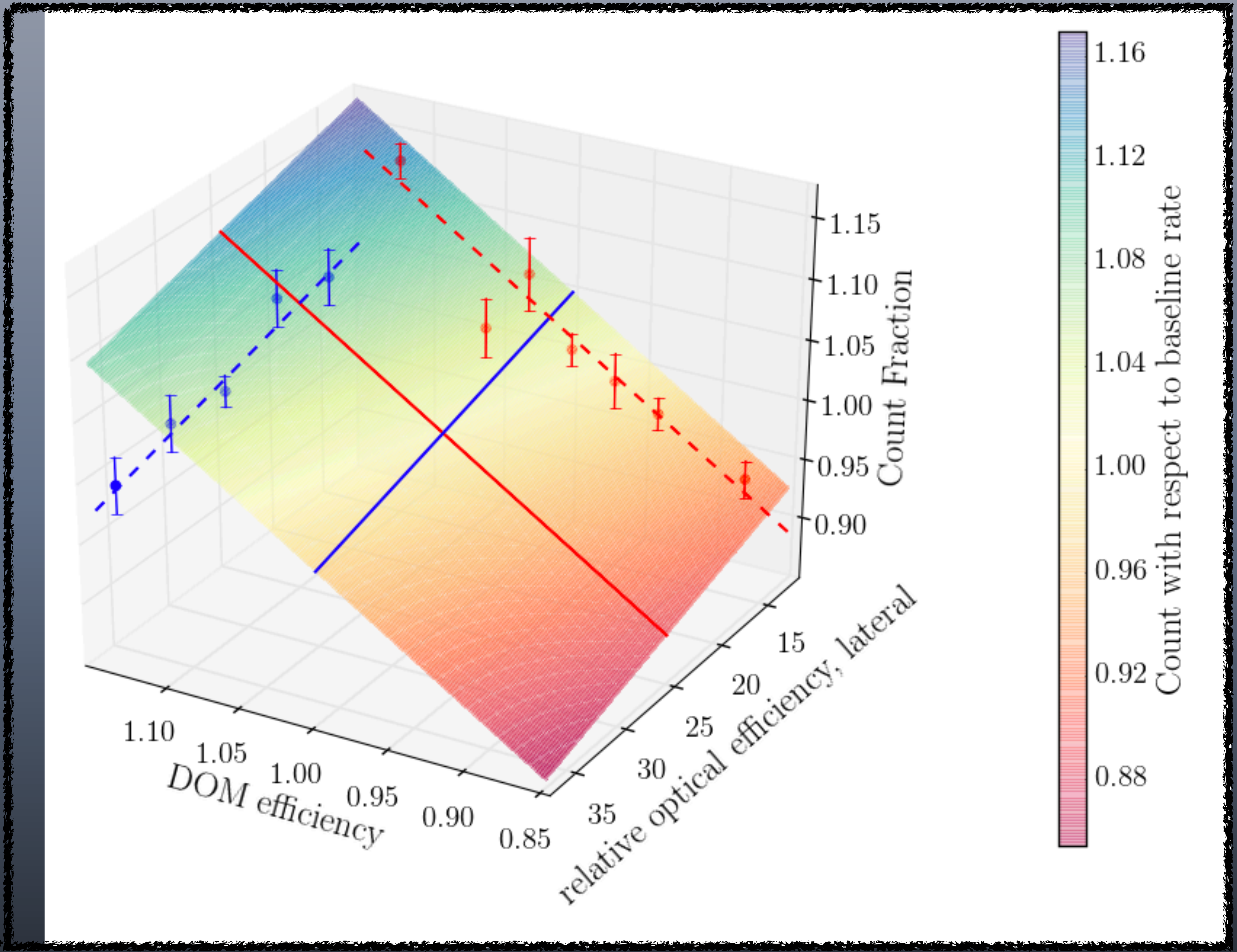
- 50% of νμ CC events correctly classified as tracks



Detector systematics

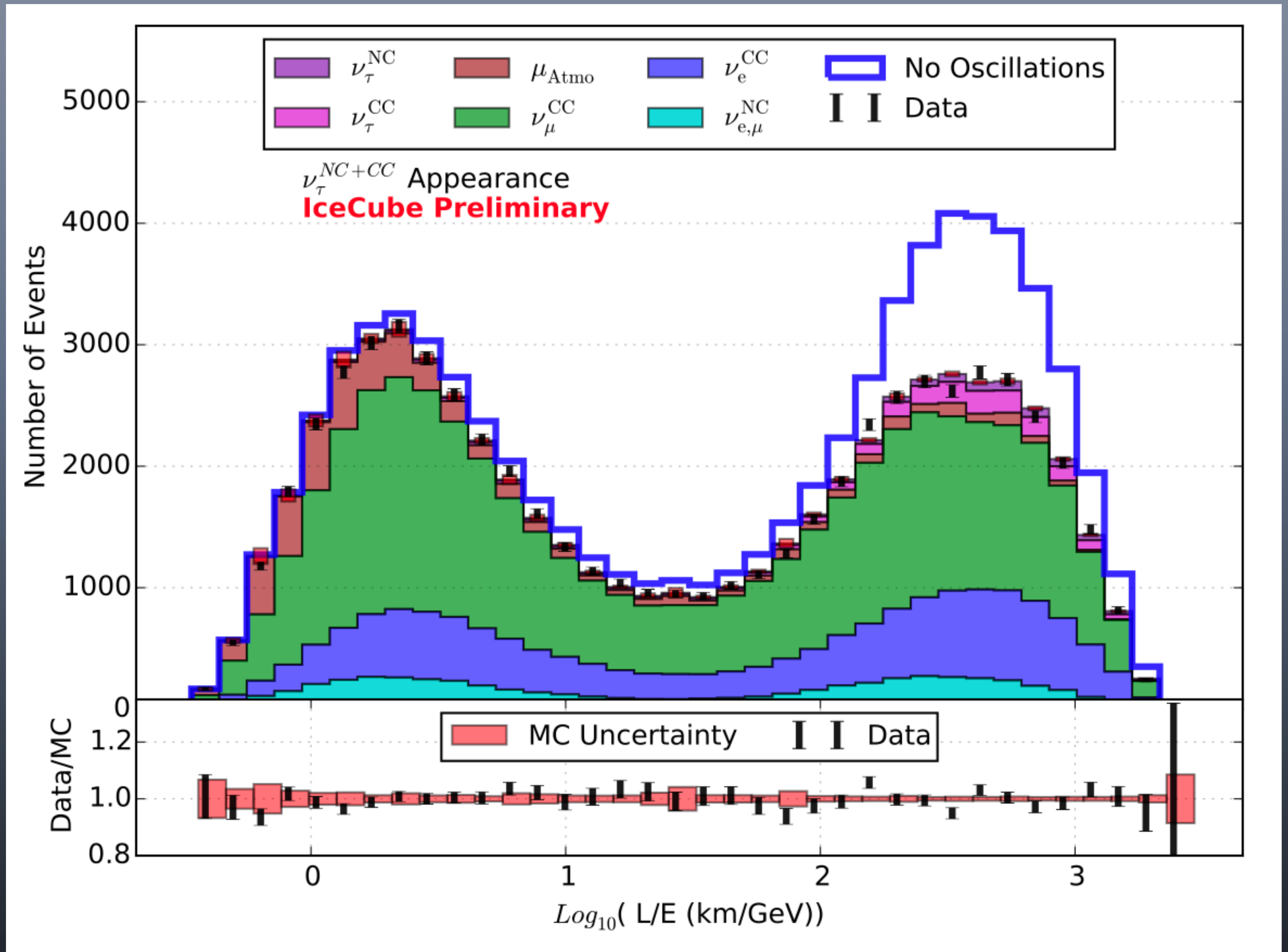
Discrete MC sets mapped to continuous reweighing scheme





Neutrino oscillations

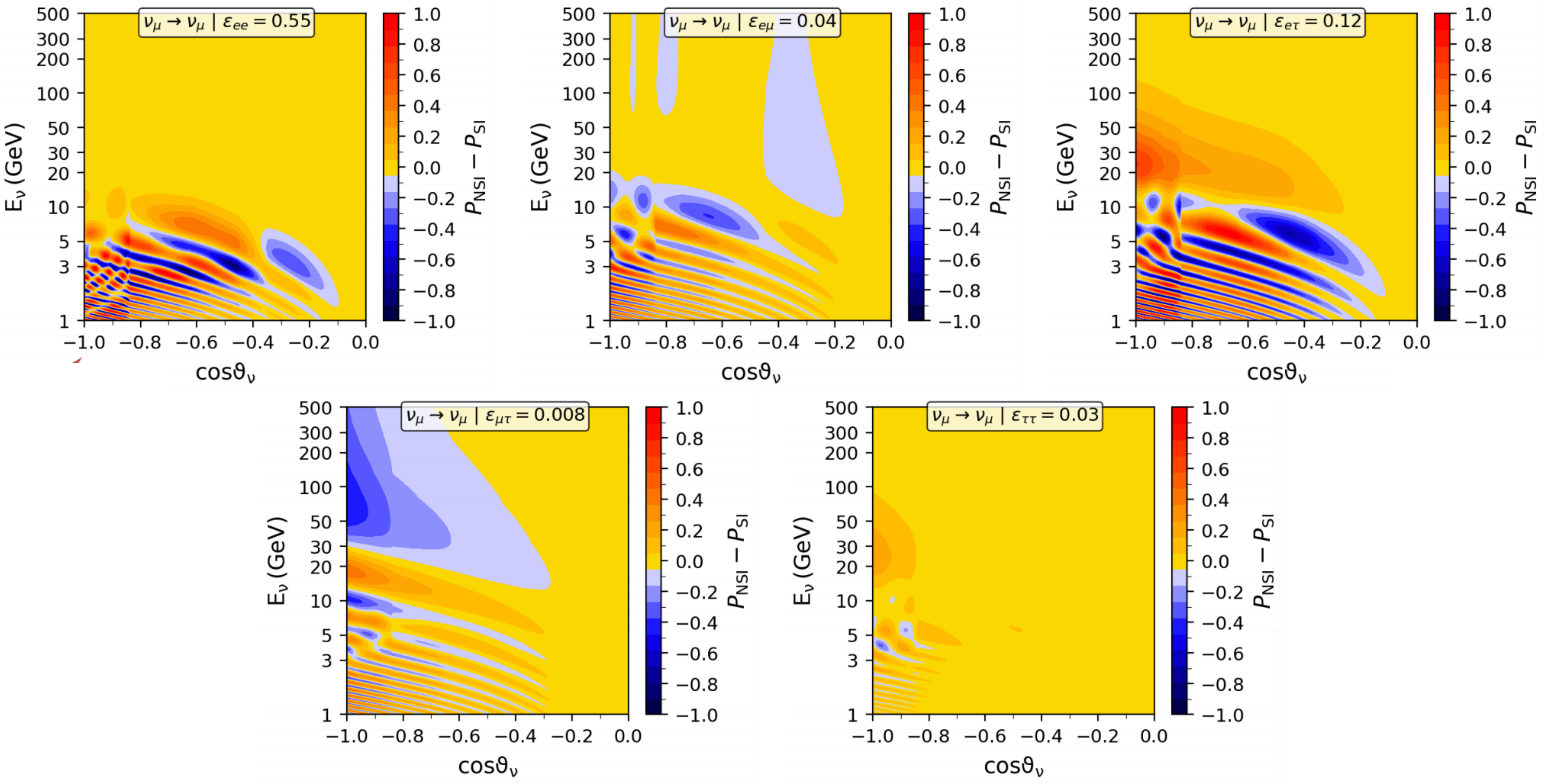
Best fit systematics



Parameter	Prior	Analysis $\mathcal{A}$ Best fit (CC+NC)	Analysis $\mathcal{A}$ Best fit (CC)	Analysis $\mathcal{B}$ Best fit (CC+NC)	Analysis $\mathcal{B}$ 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} (°)	8.5 ± 0.21	-	-	8.5	8.5
θ_{23} (°)	-	49.8	50.2	46.1	45.9
Δm^2_{32} (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

NSI

Effect of different NSI couplings

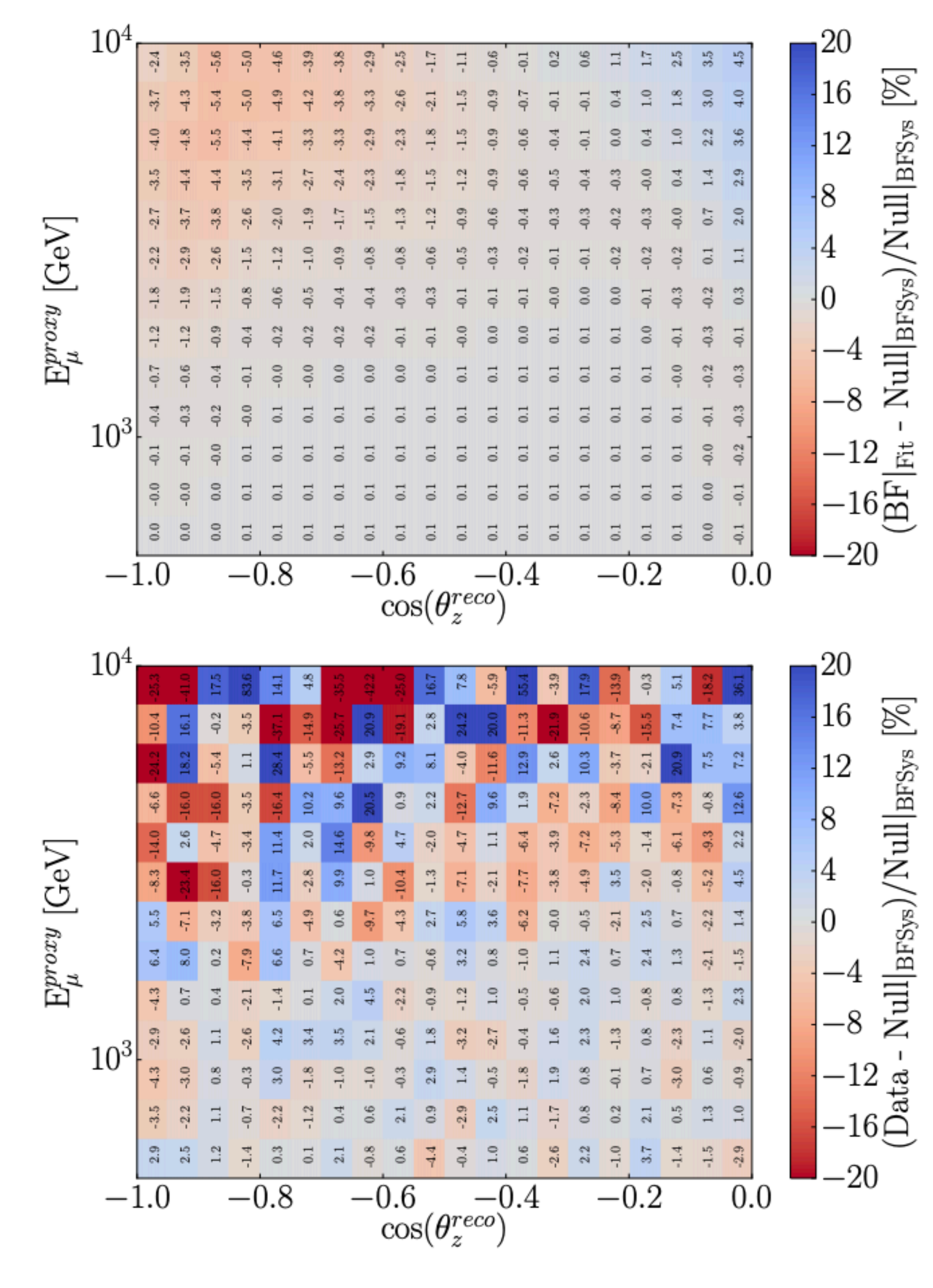


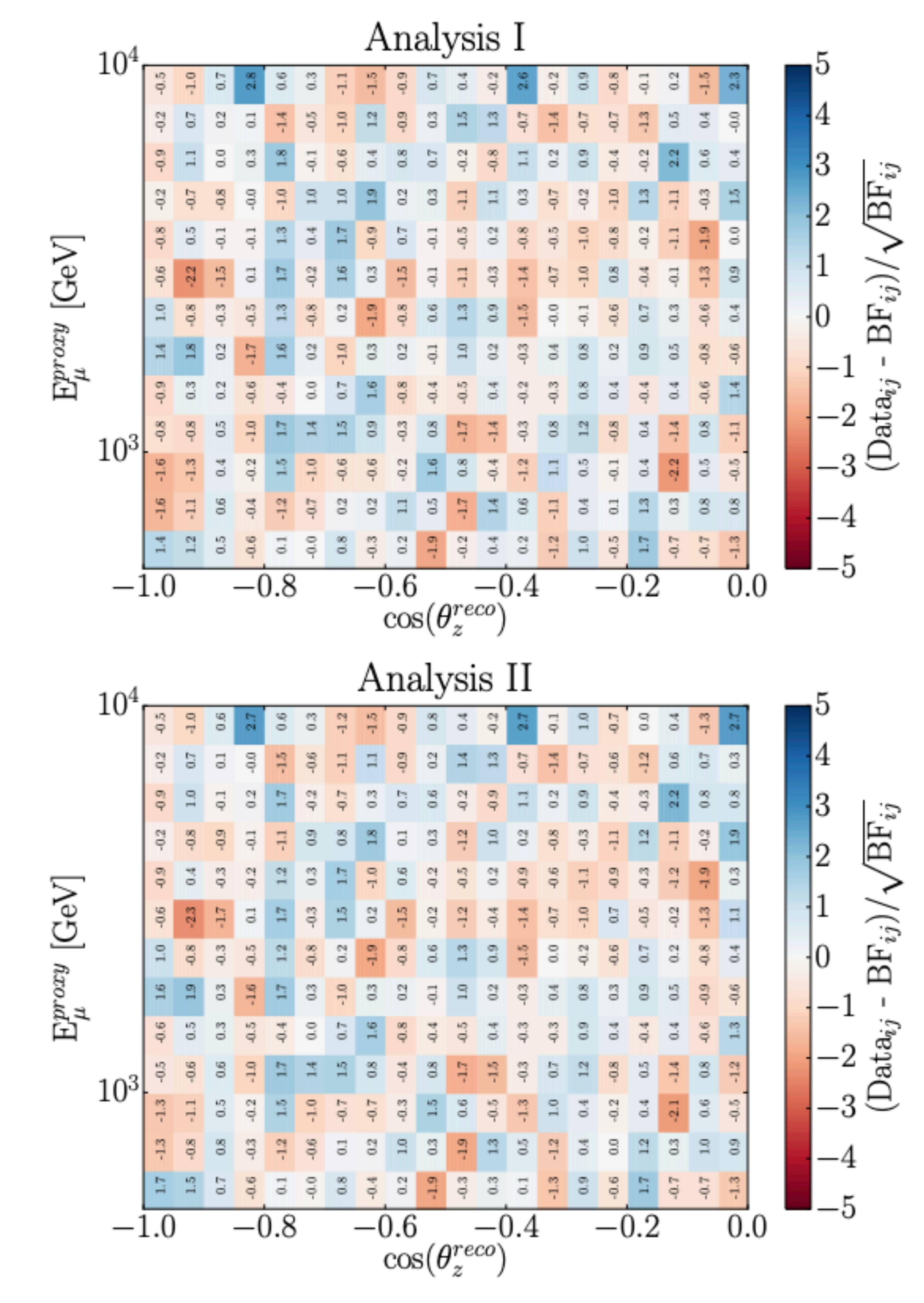
Non-standard disappearance at high energy due to $\varepsilon_{e\mu}$ & $\varepsilon_{\mu\tau}$

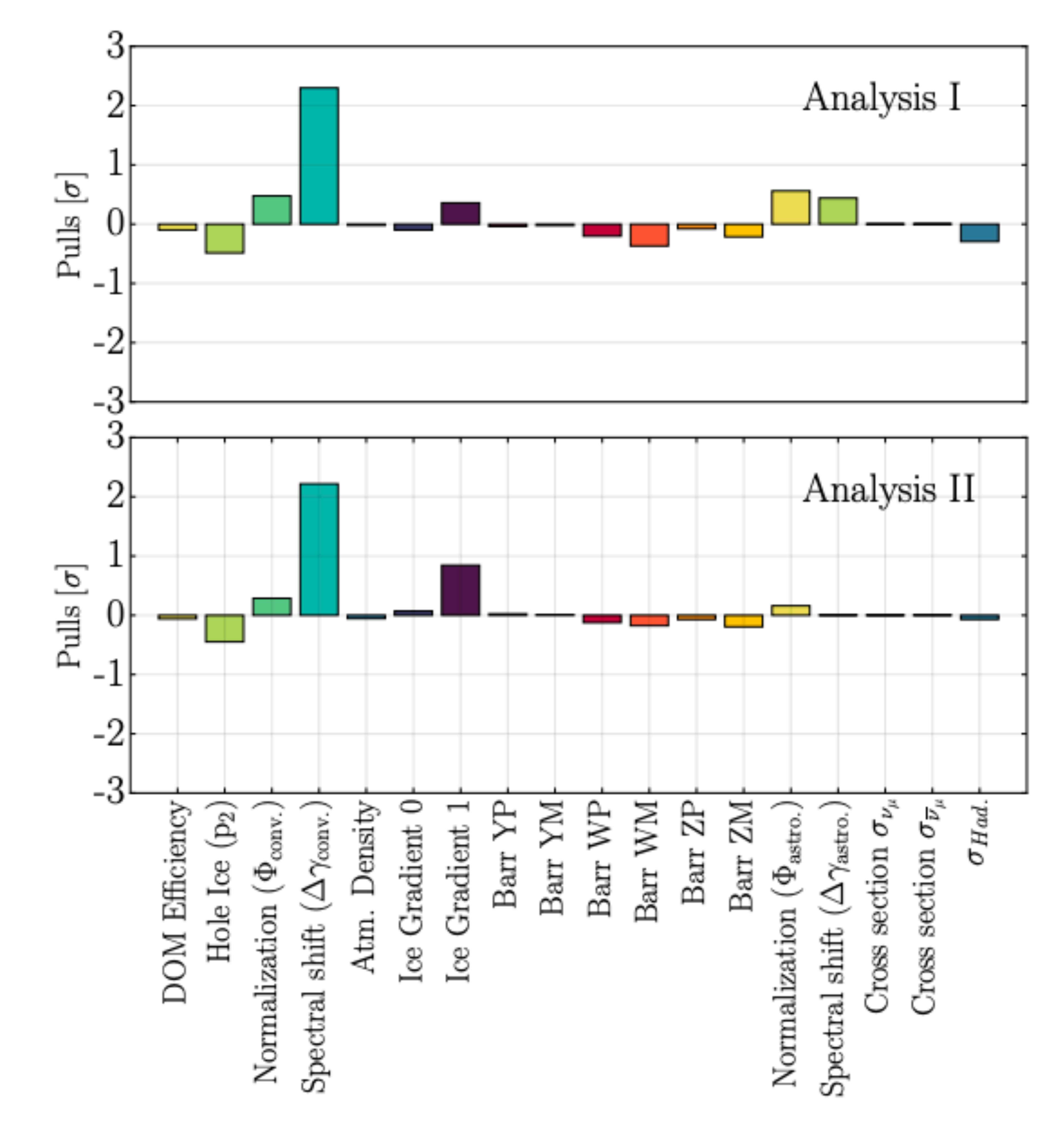
Less disappearance at high energy due to $\varepsilon_{e\tau}$ & $\varepsilon_{\tau\tau}$

eV Sterile Search

Impact of systematics

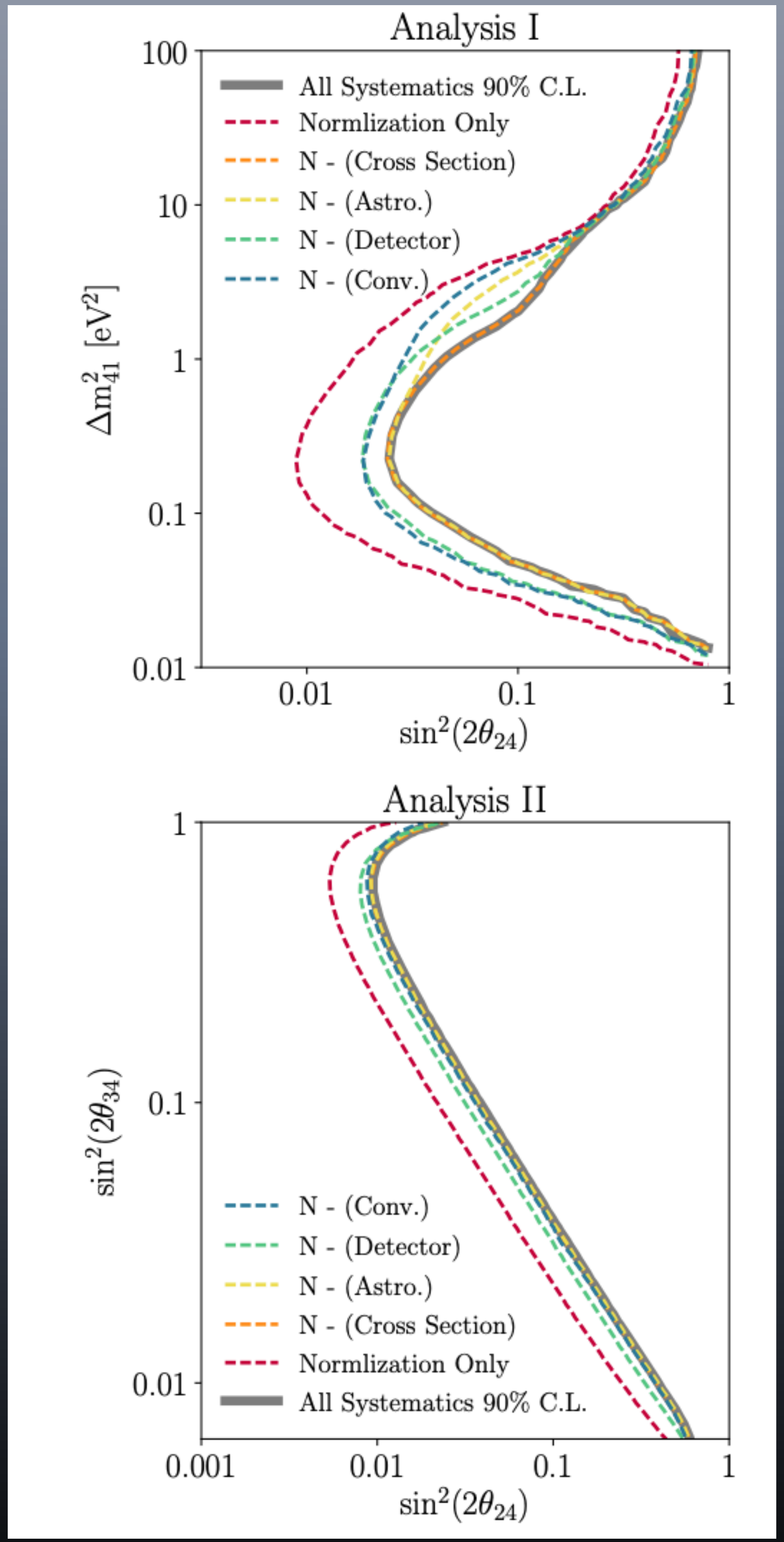


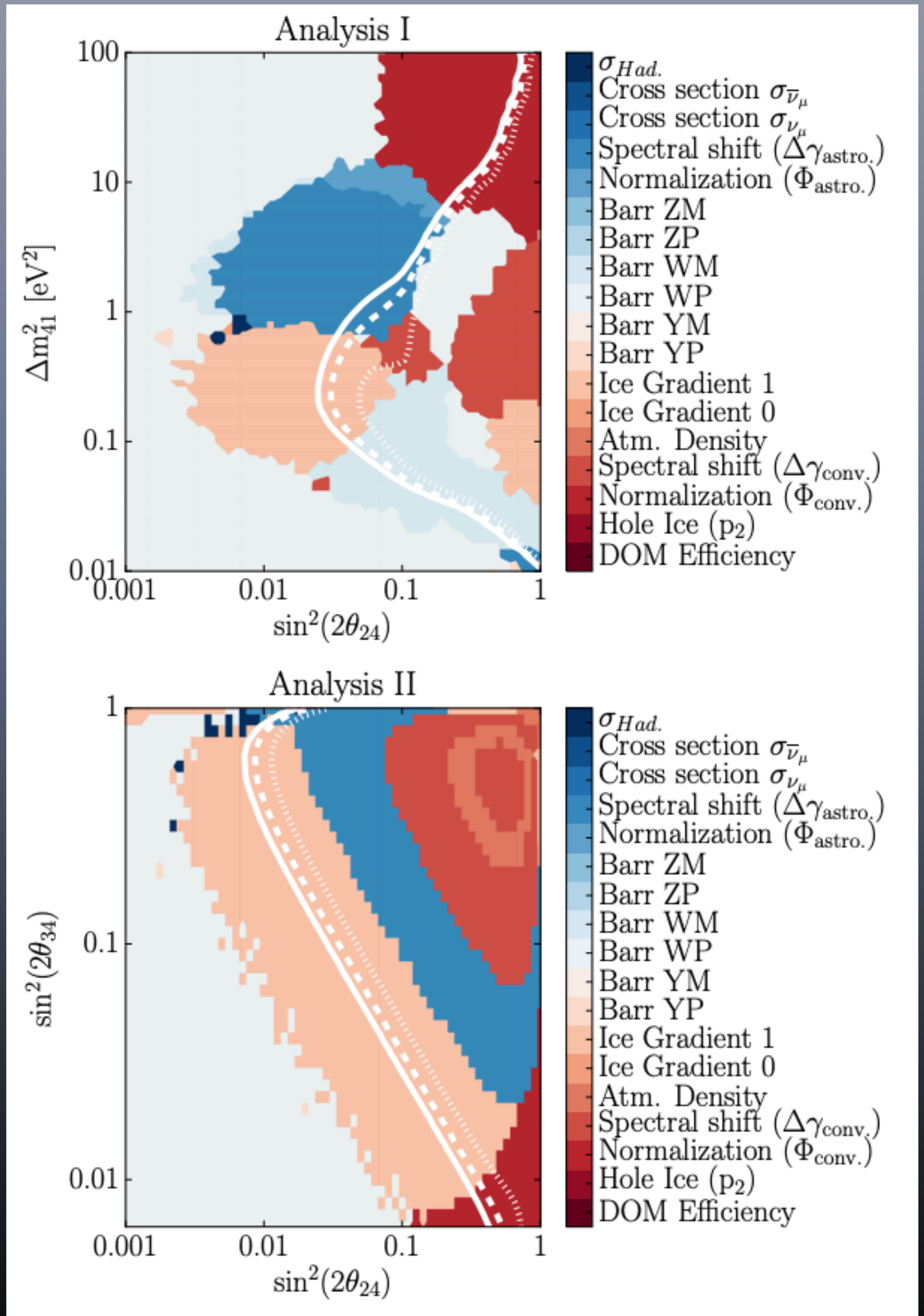


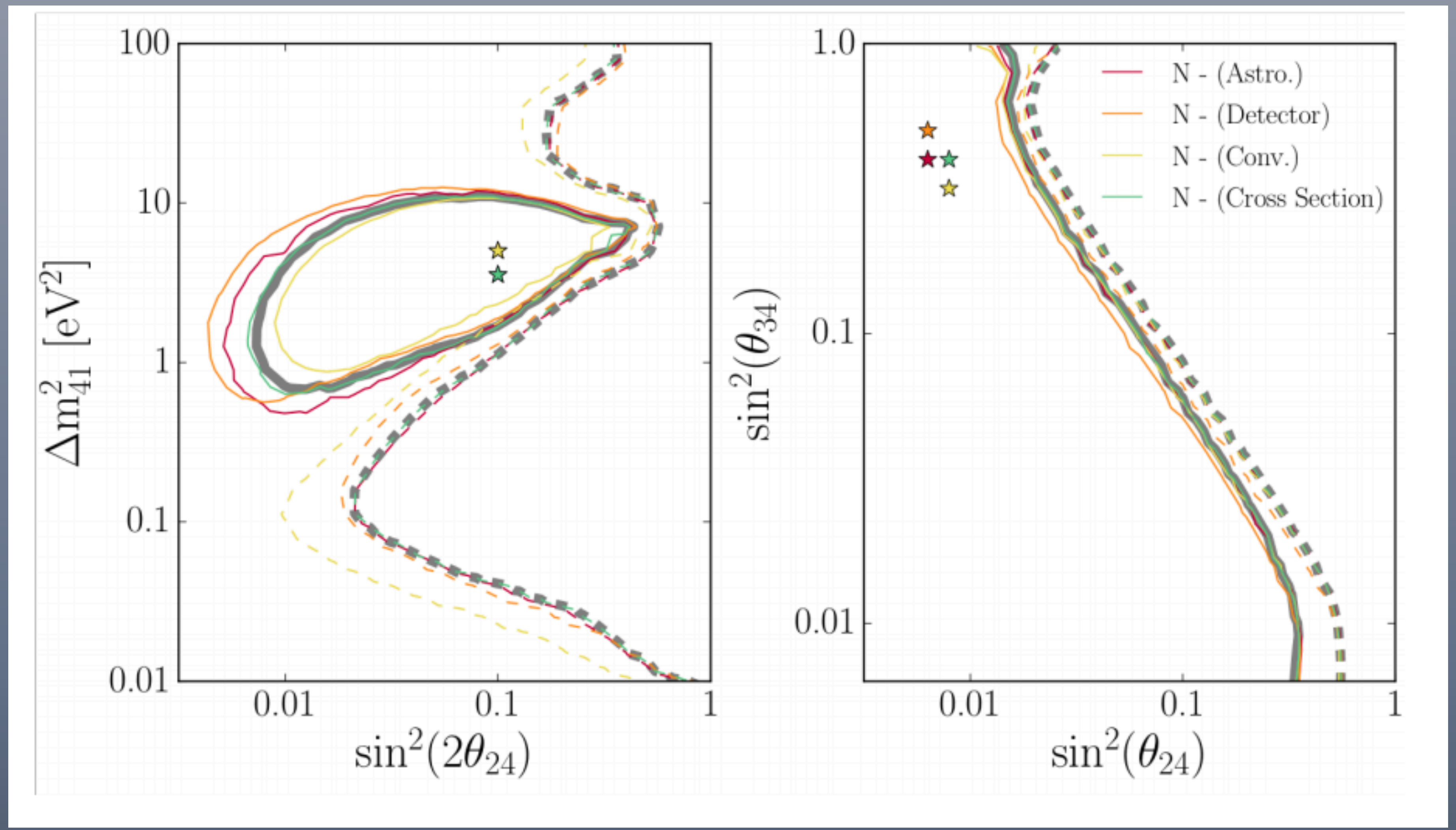


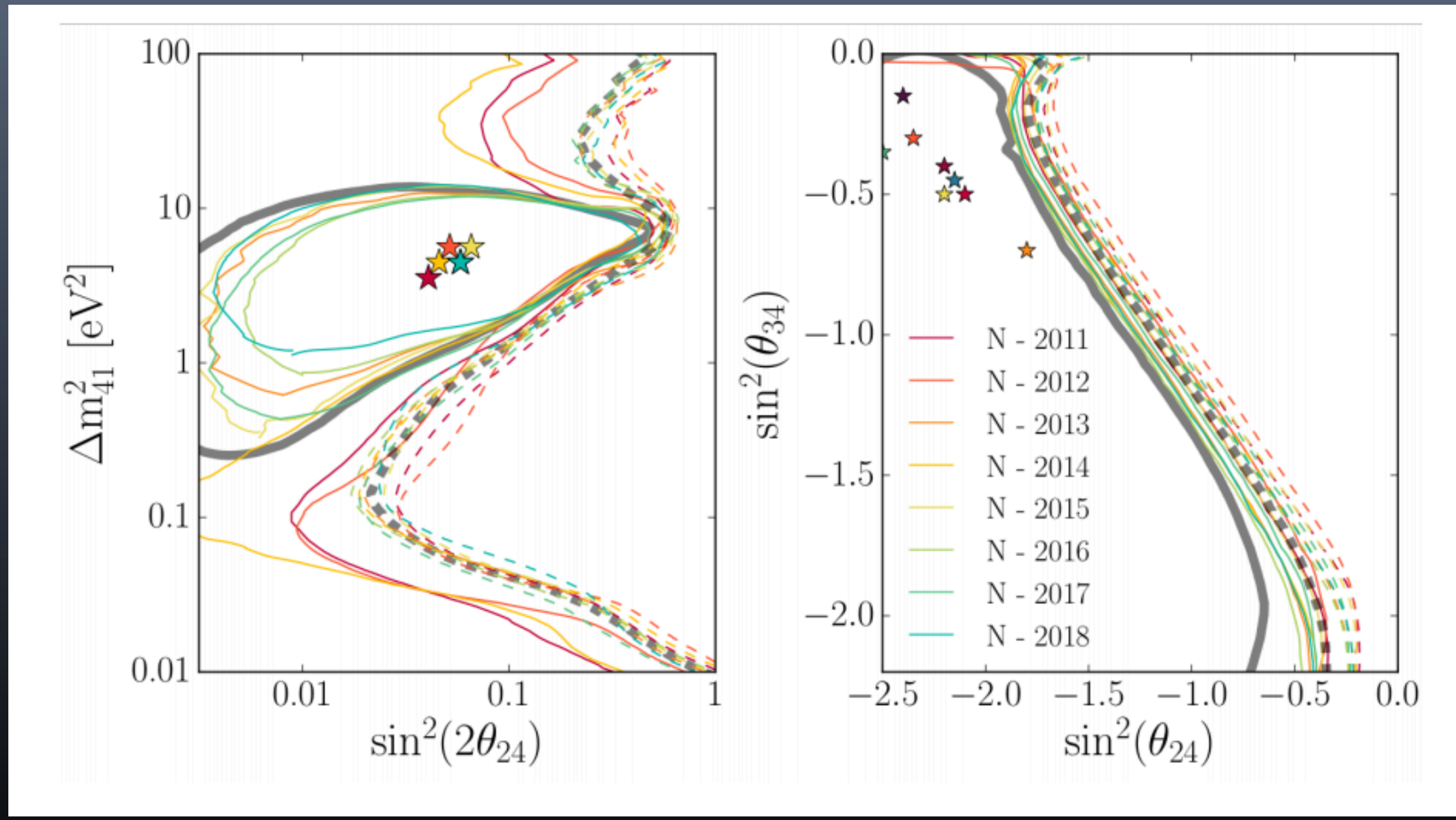
eV Sterile Search

Impact of systematics



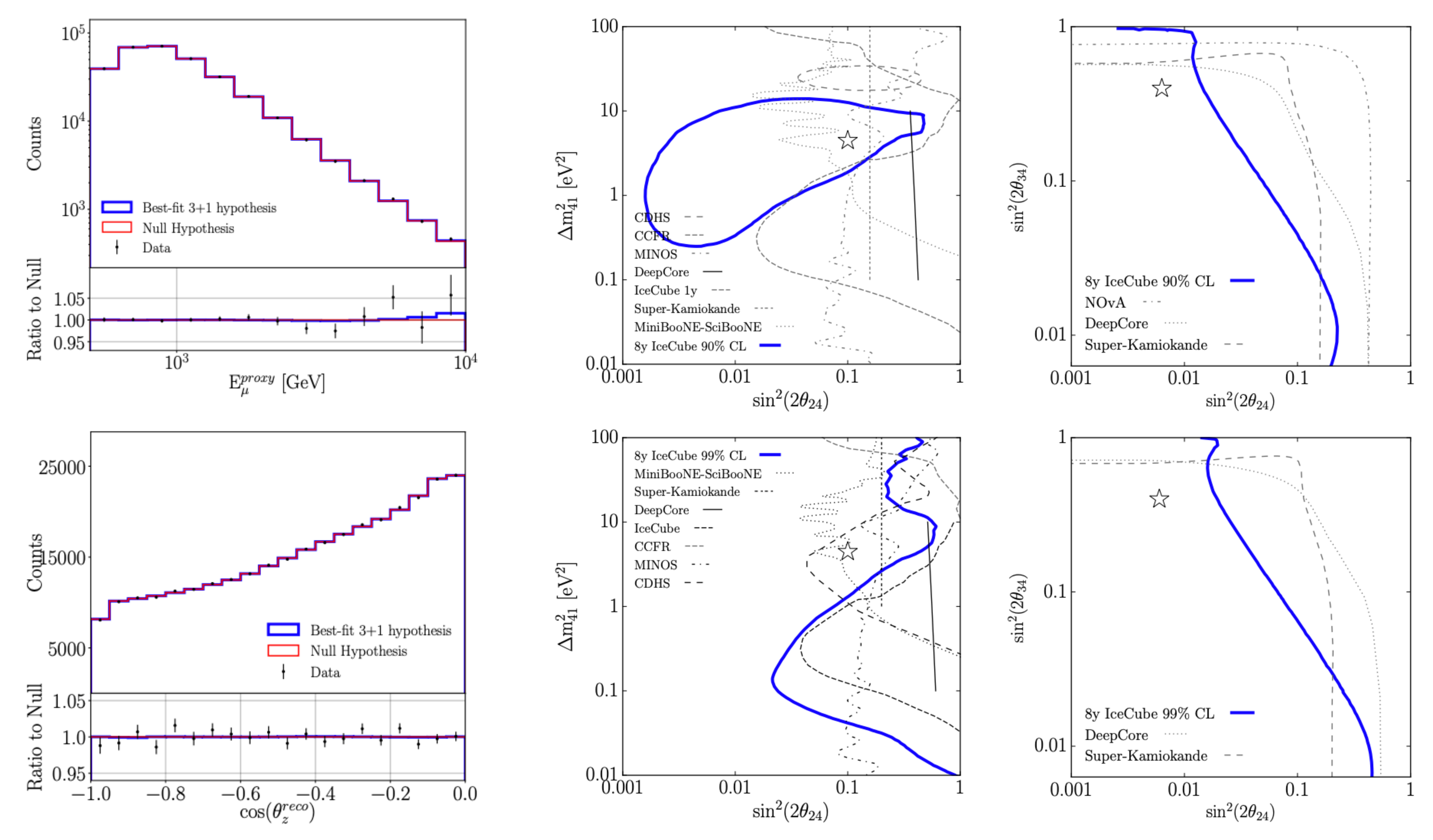






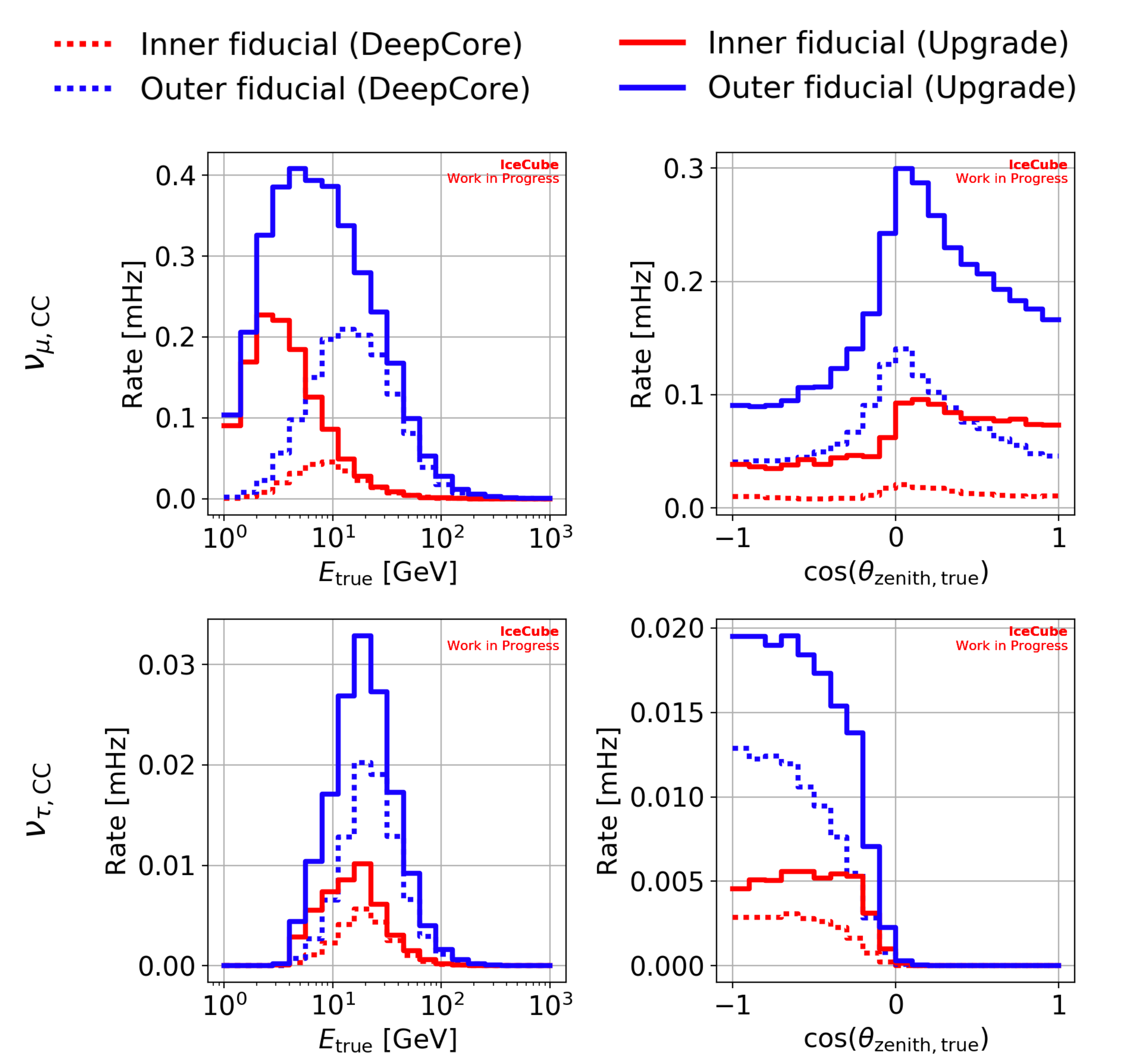
eV Sterile Search

Impact of systematics

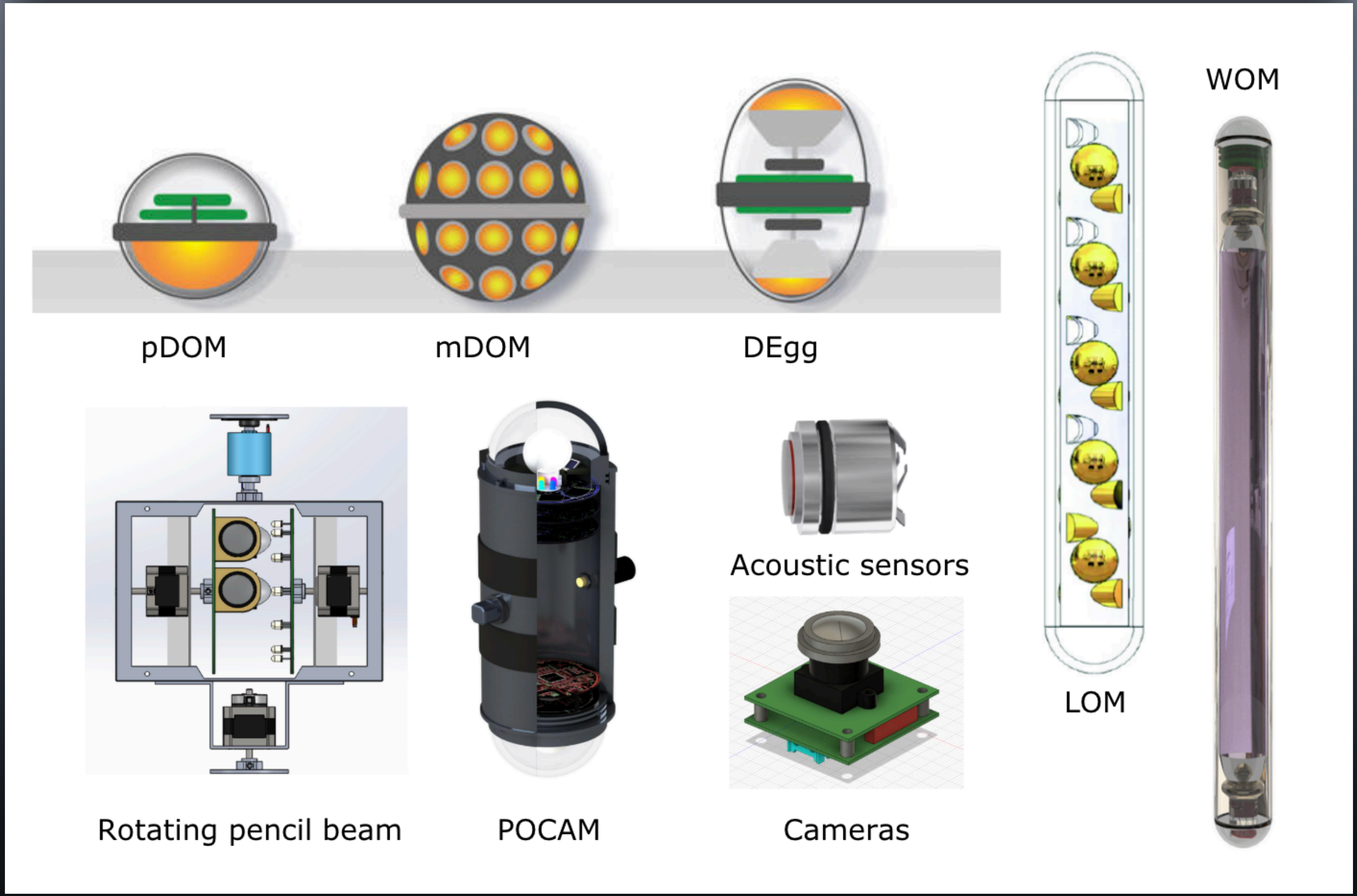


IceCube Upgrade Events

More detail in every event



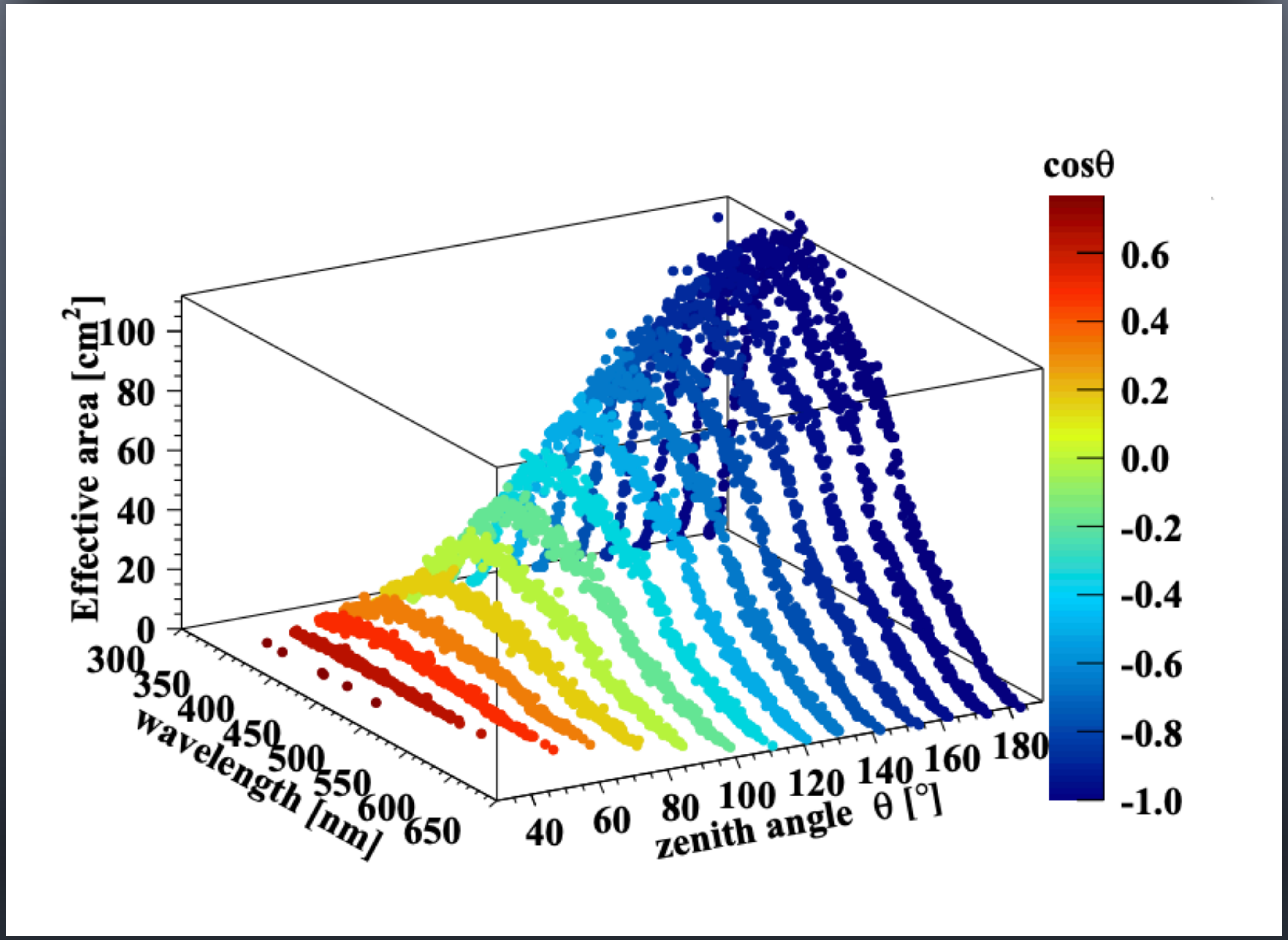
The IceCube Upgrade
New technology



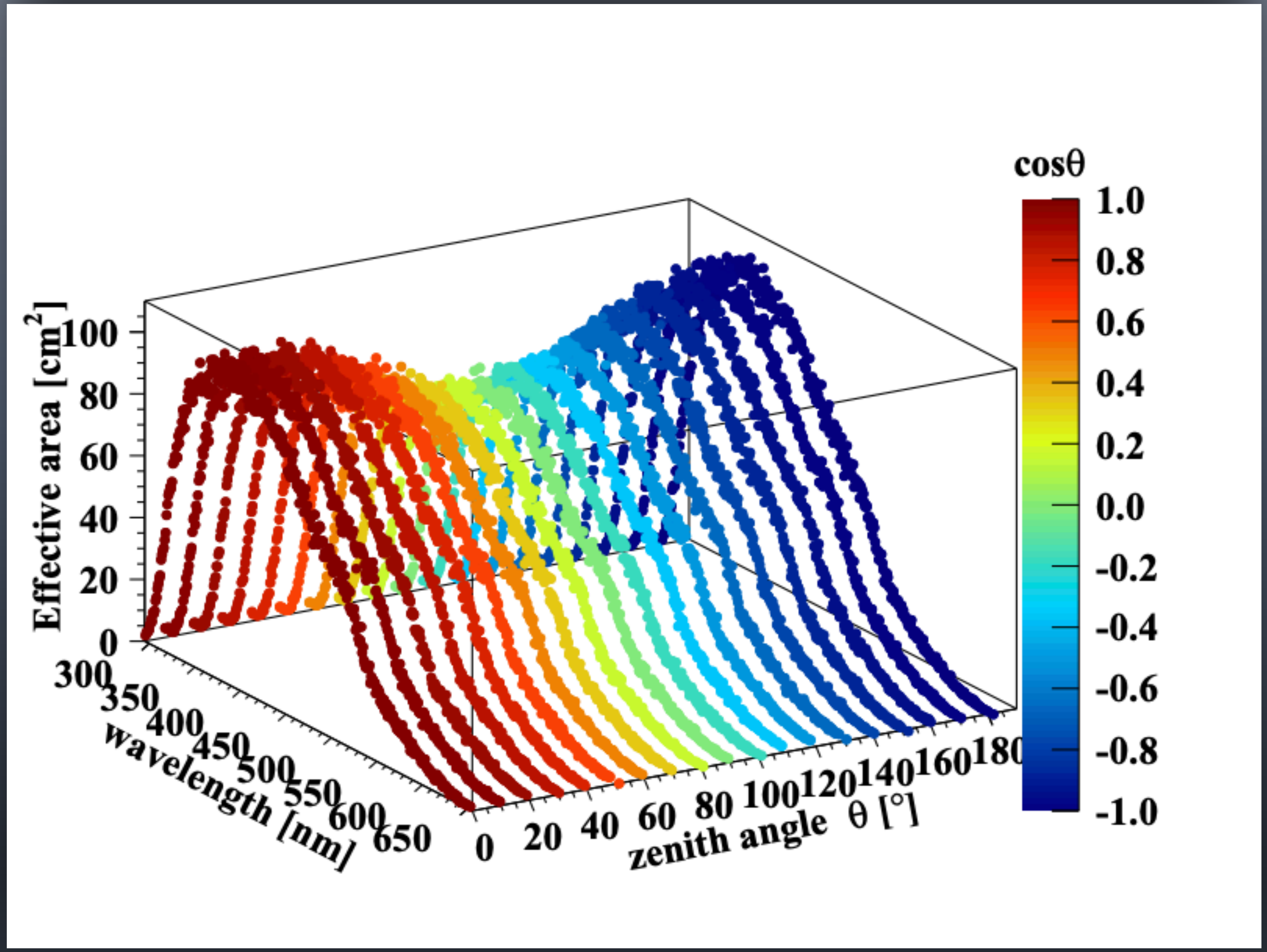
The IceCube Upgrade

New technology

IceCube Gen1 DOM



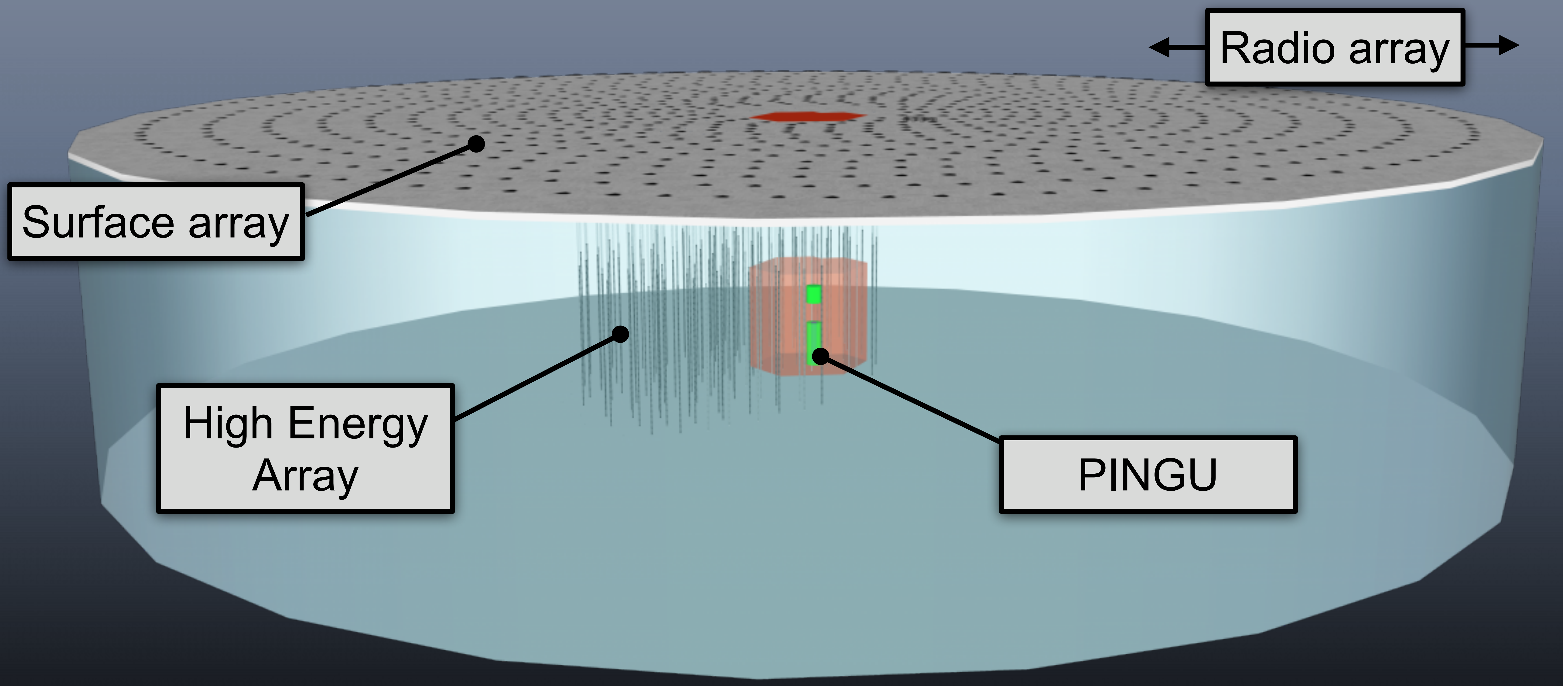
Upgrade module: DEgg

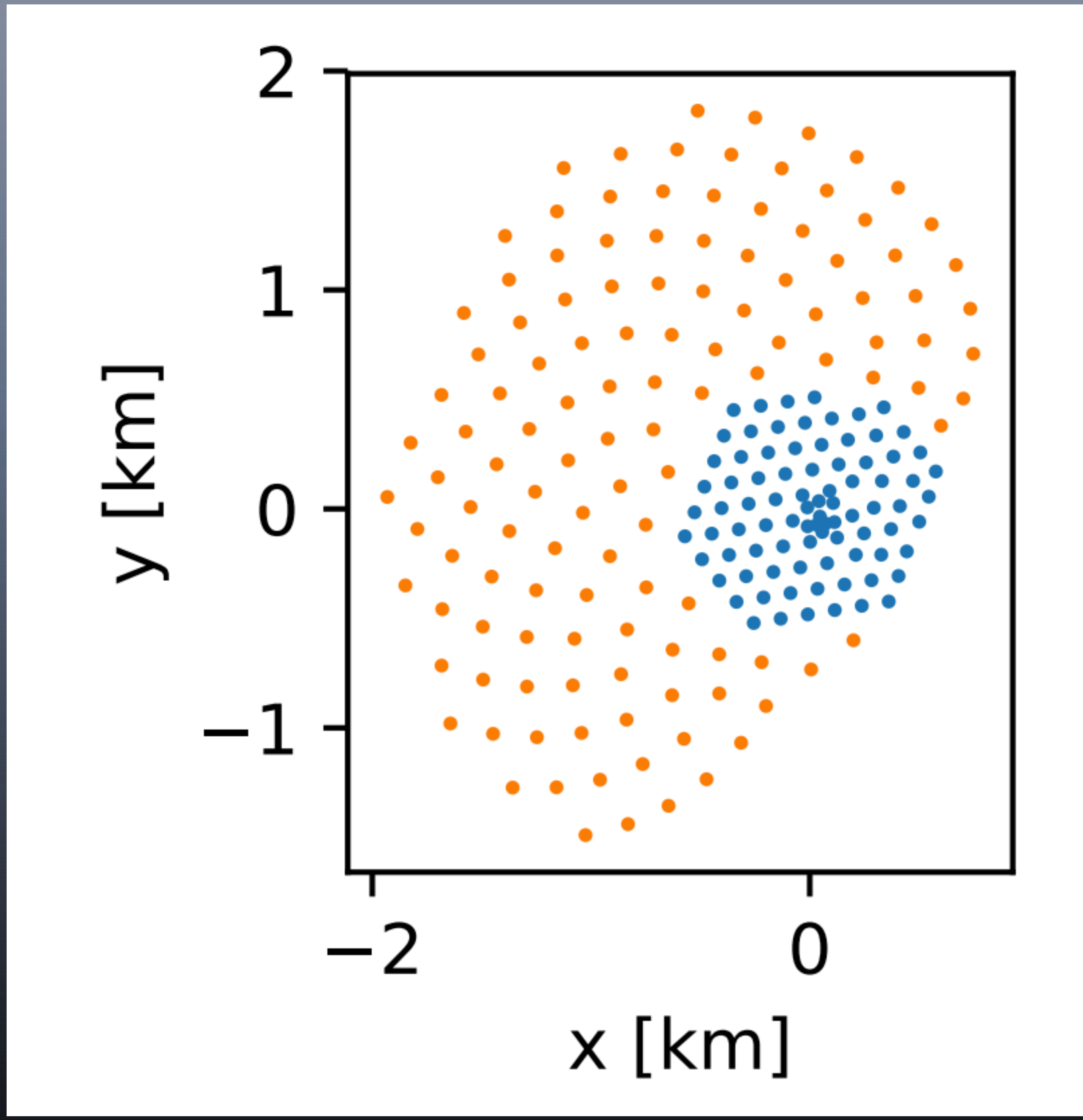


PINGU LOI v2: https://arxiv.org/pdf/1401.2046.pdf

IceCube-Gen2

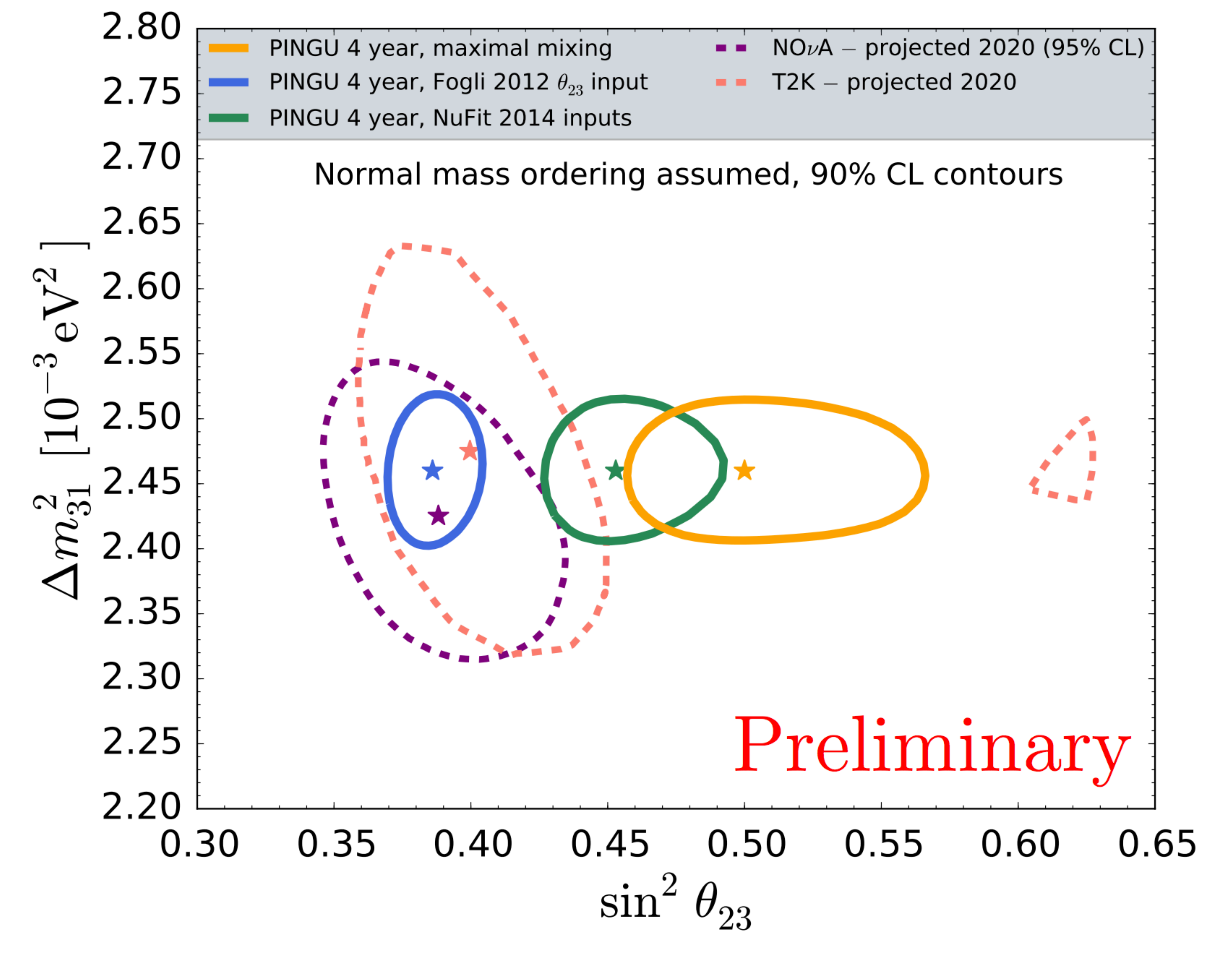
A vision for the future of neutrino astroparticle physics at the South Pole





Neutrino oscillations

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



Expected precision:

$\Delta m^2_{32} \sim 1\%$ (1σ)

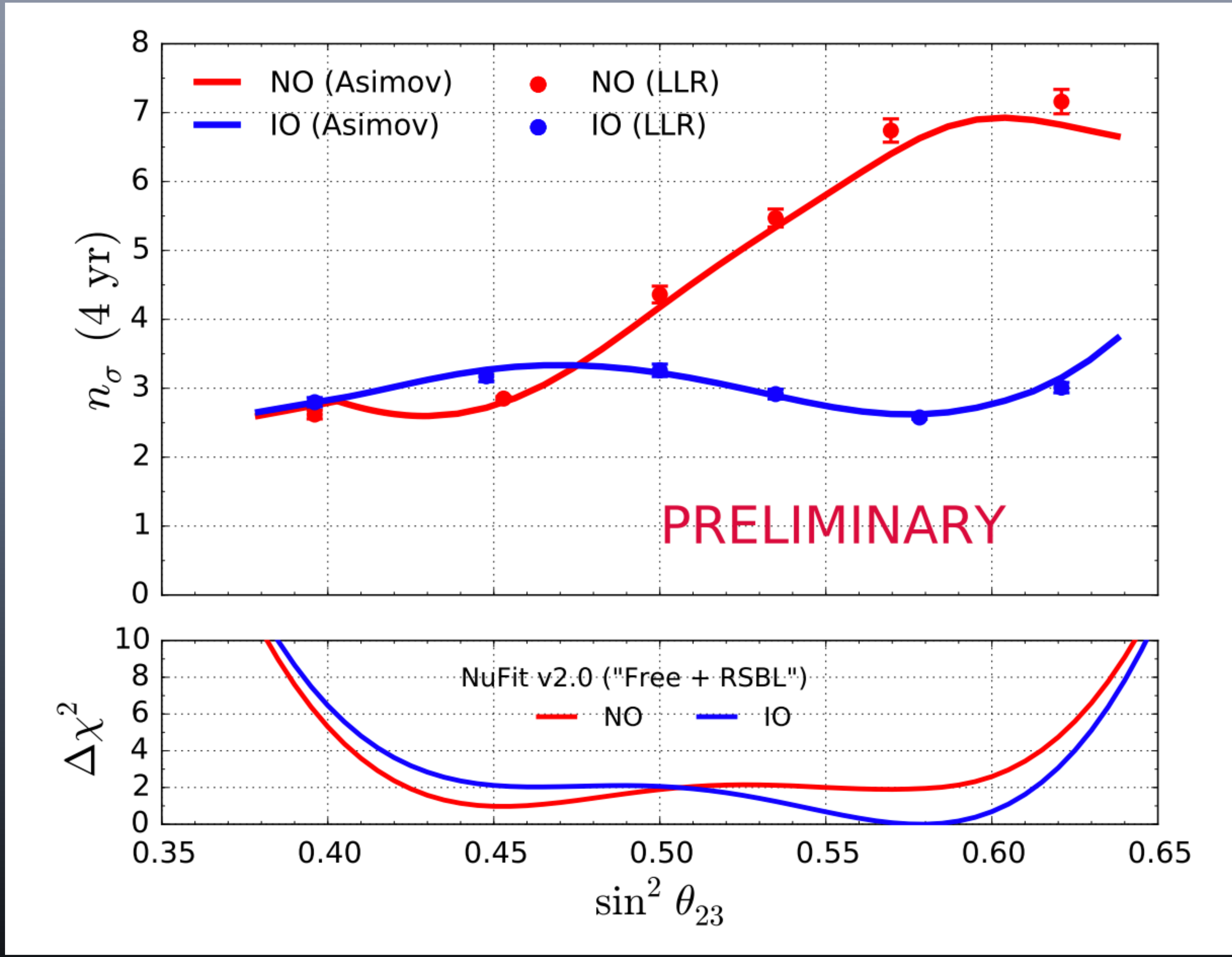
$\theta_{23} \sim 4\%$ (1σ)

depends on NMO and true θ_{23}

Neutrino oscillations

Neutrino Mass Ordering

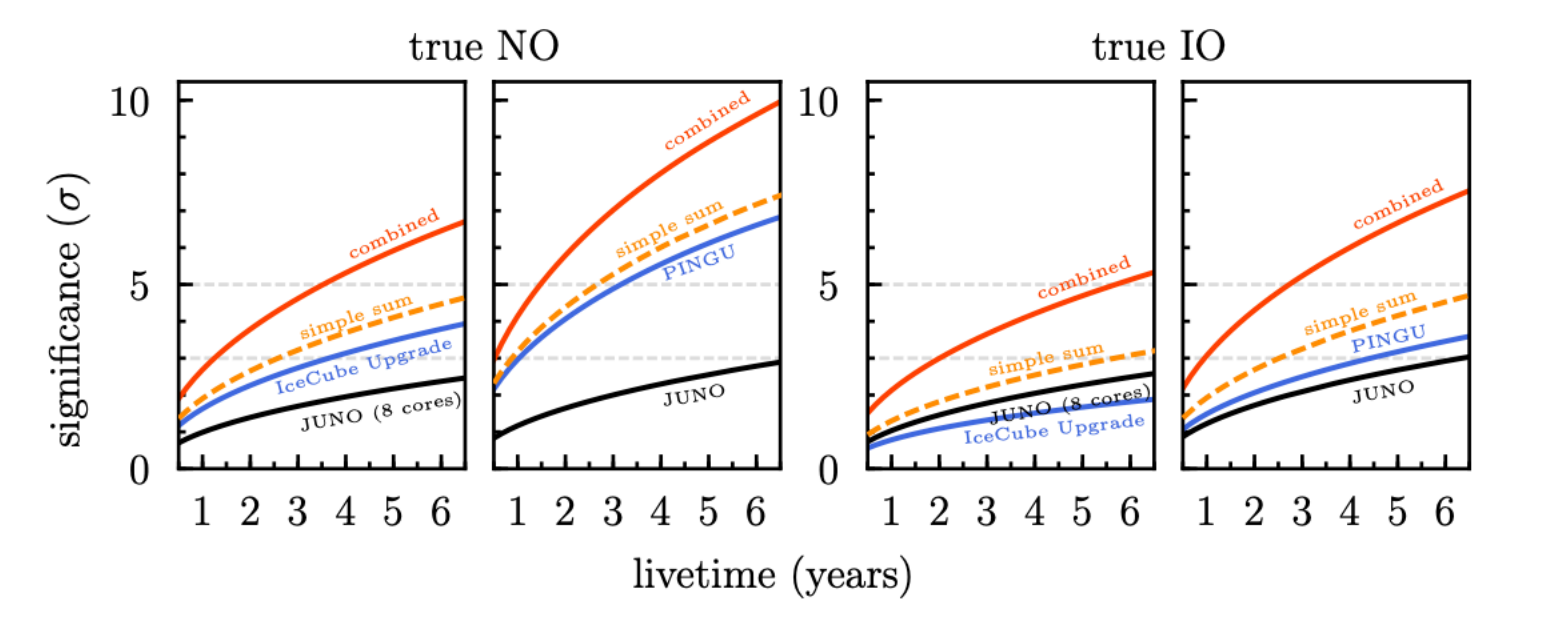
PINGU LOI Version 2 @ arXiv:1401.2046v2



NMO

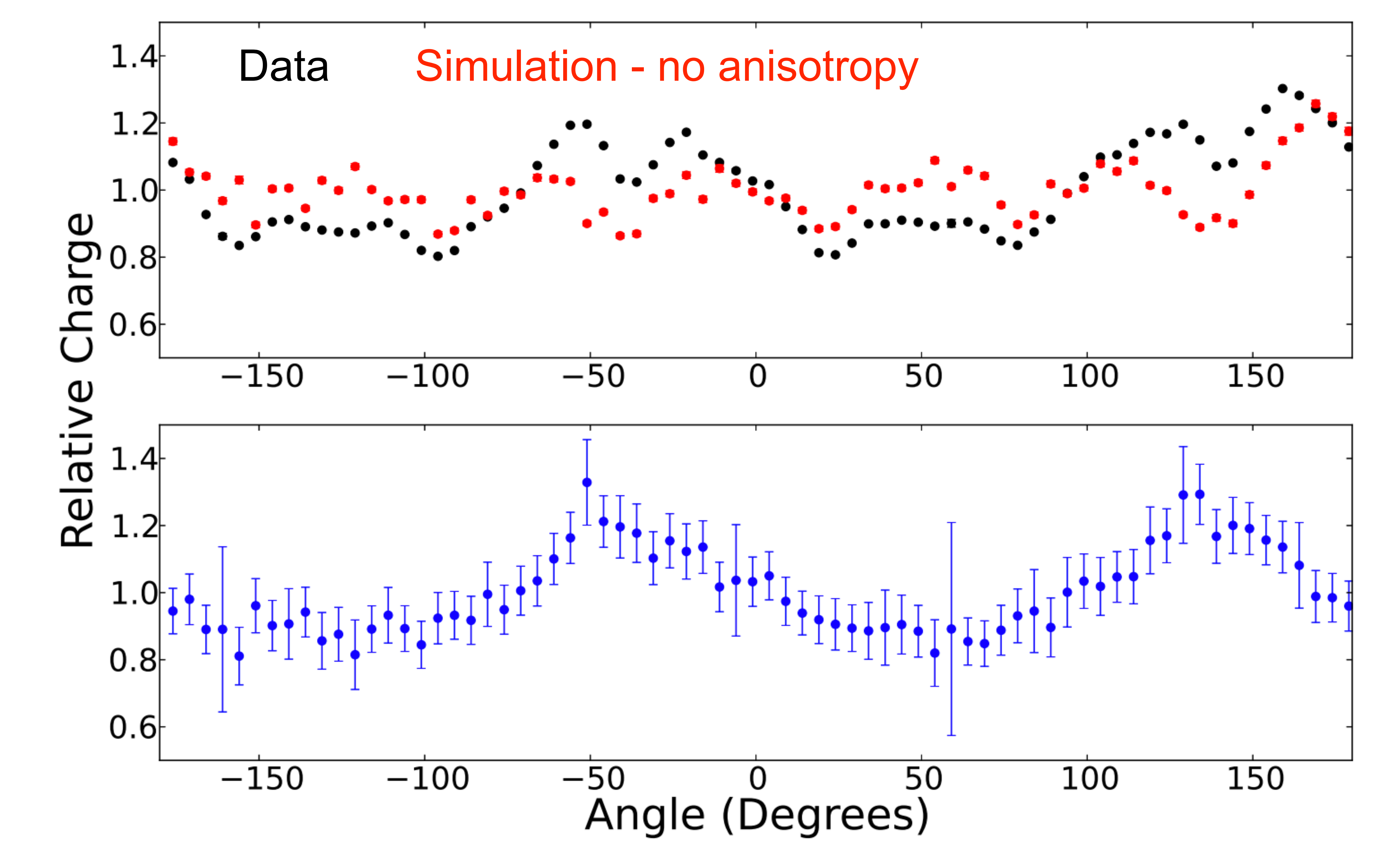
Exploit synergy between JUNO and IceCube Upgrade

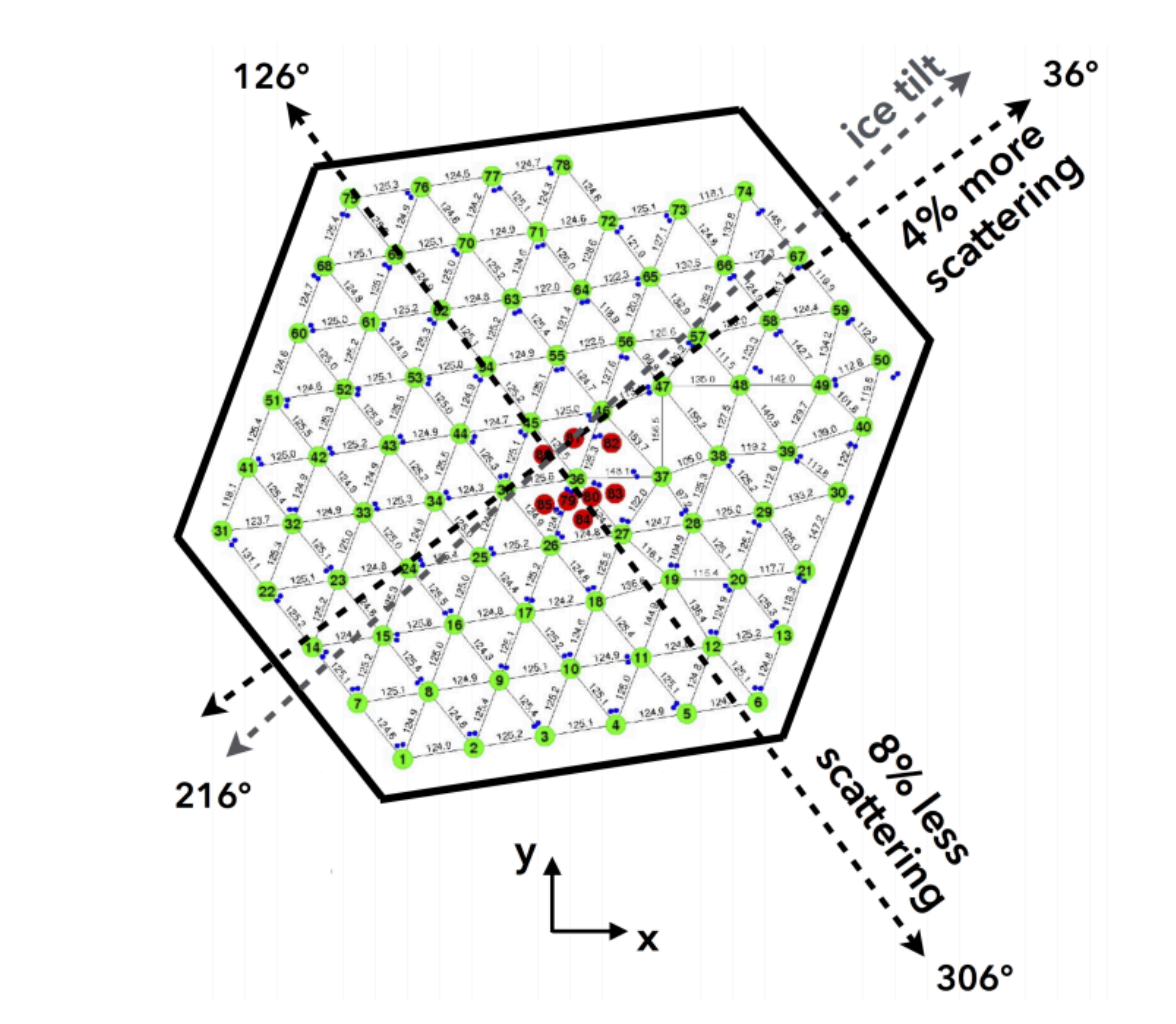
Phys. Rev. D 101, 032006 (2020)



Ice anisotropy

South Pole ice anisotropy: Proceedings of ICRC2013 0580, 2014





SPICEcore

Many devices:
Dust logger
UV logger
Luminescence logger
Camera logger