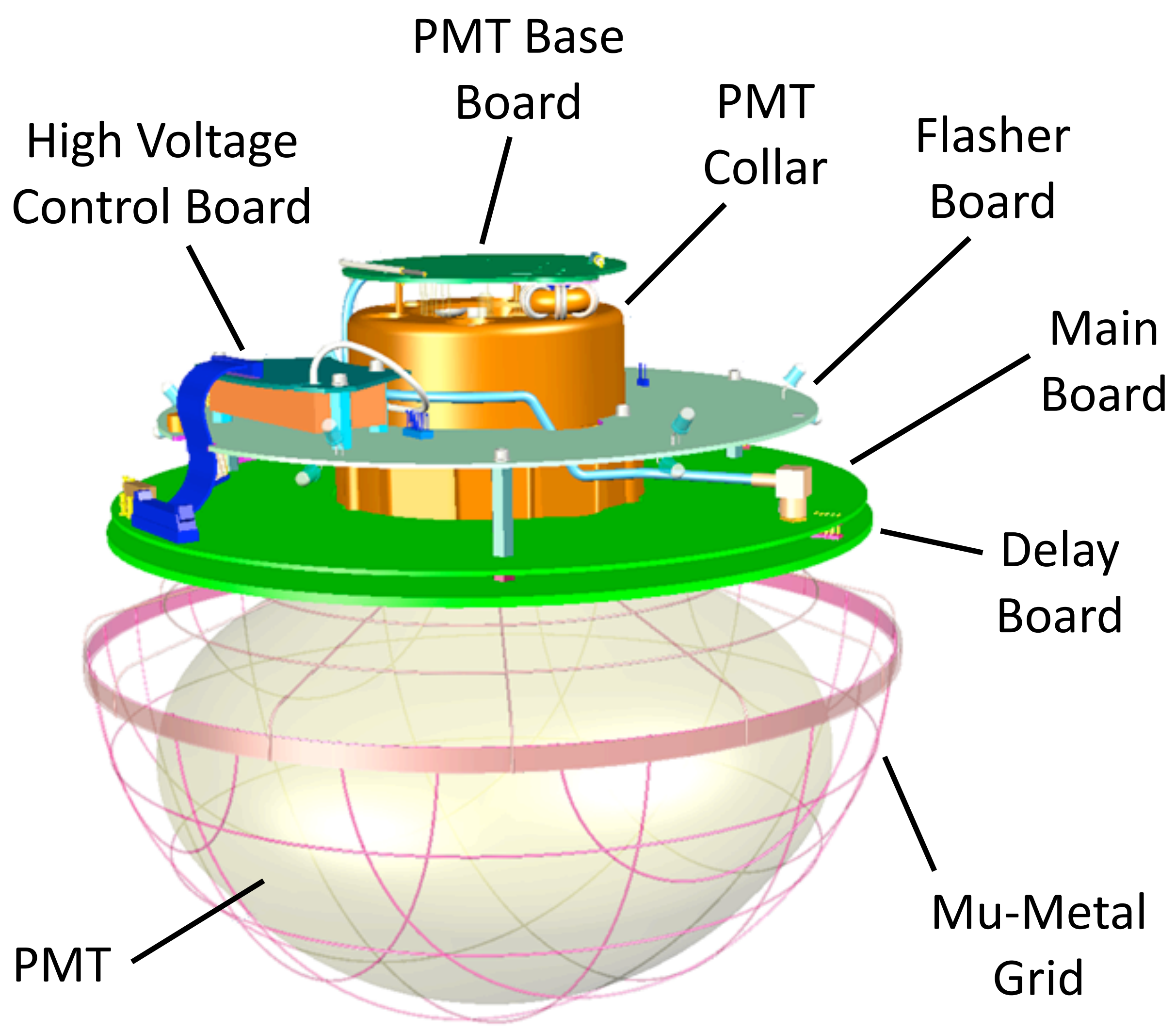
Standard Neutrino Oscillations with IceCube DeepCore

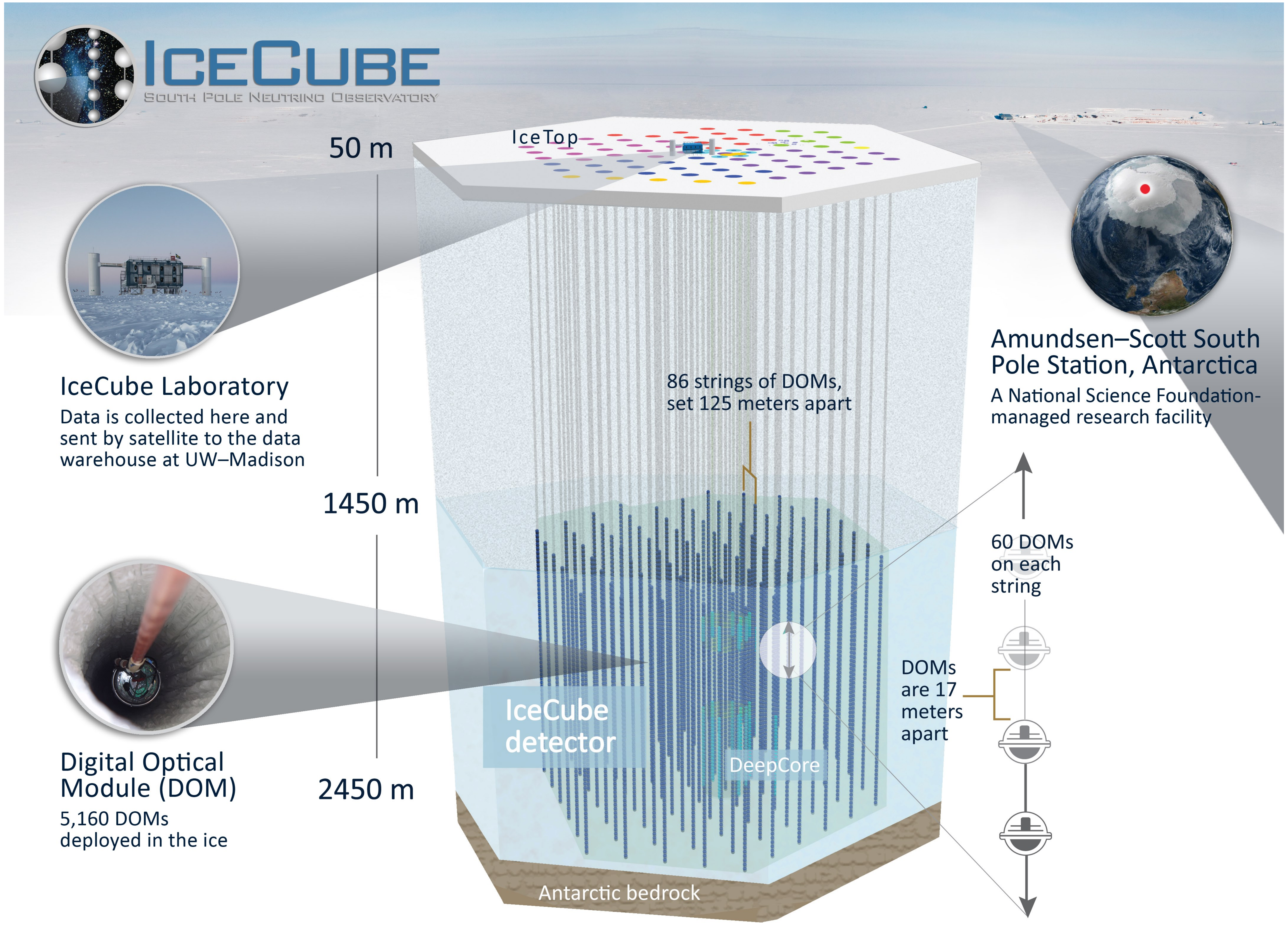
Alexander Trettin
on behalf of the IceCube Collaboration

PPNT Workshop 2019,
Uppsala

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

IceCube Neutrino Observatory



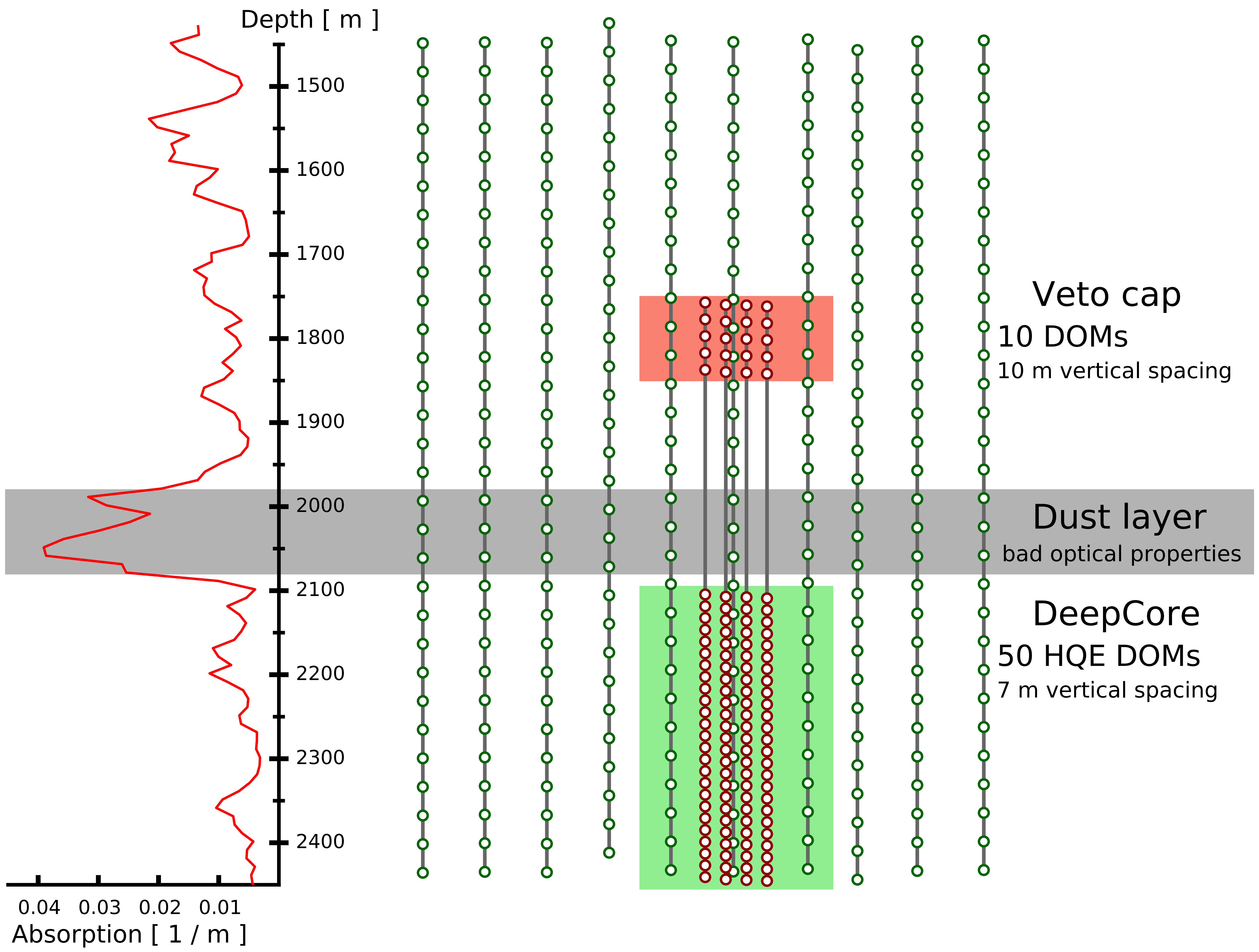


The DeepCore sub-array

> denser instrumentation

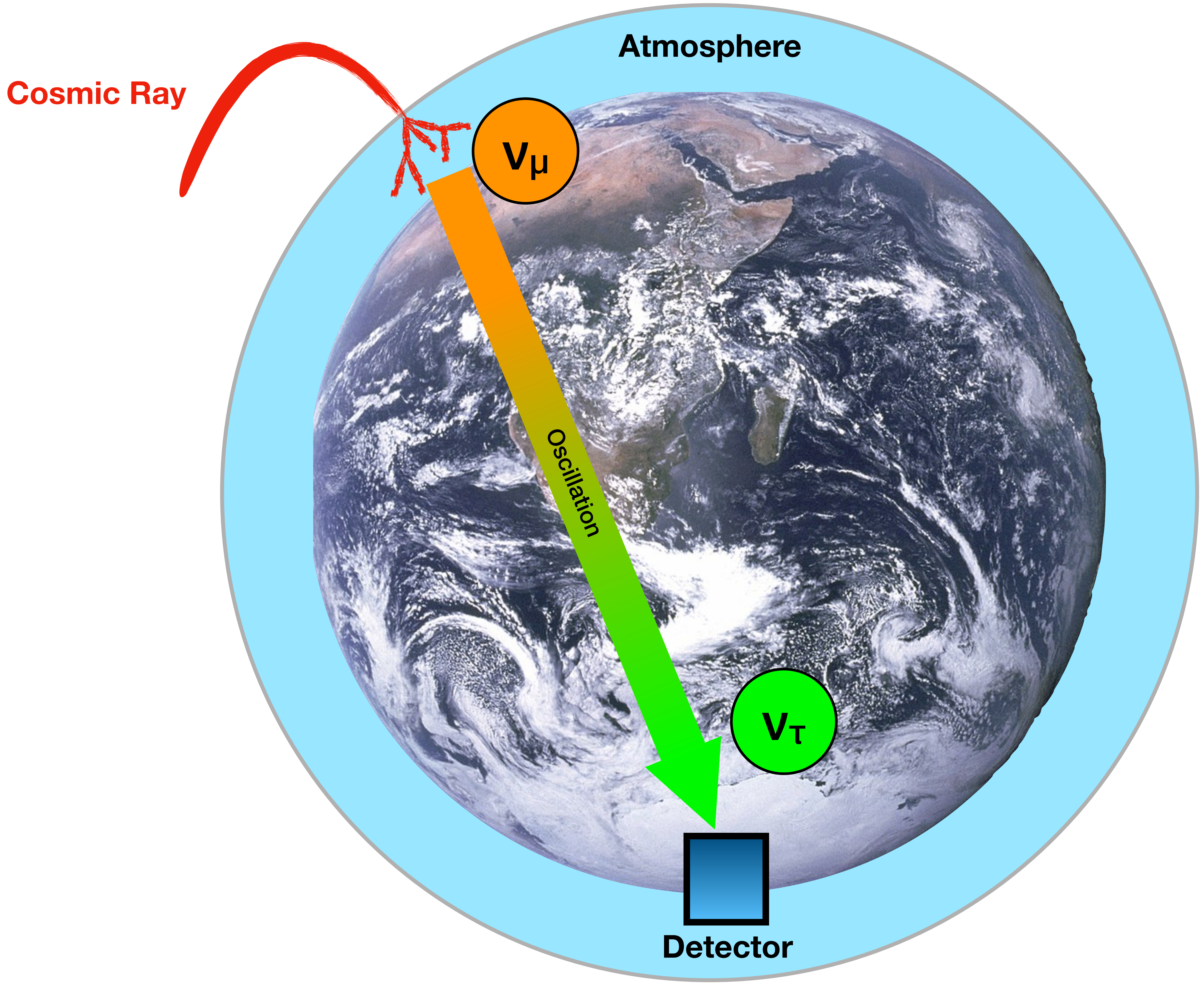
> modules with higher efficiency

> neutrino detection threshold < 10 GeV

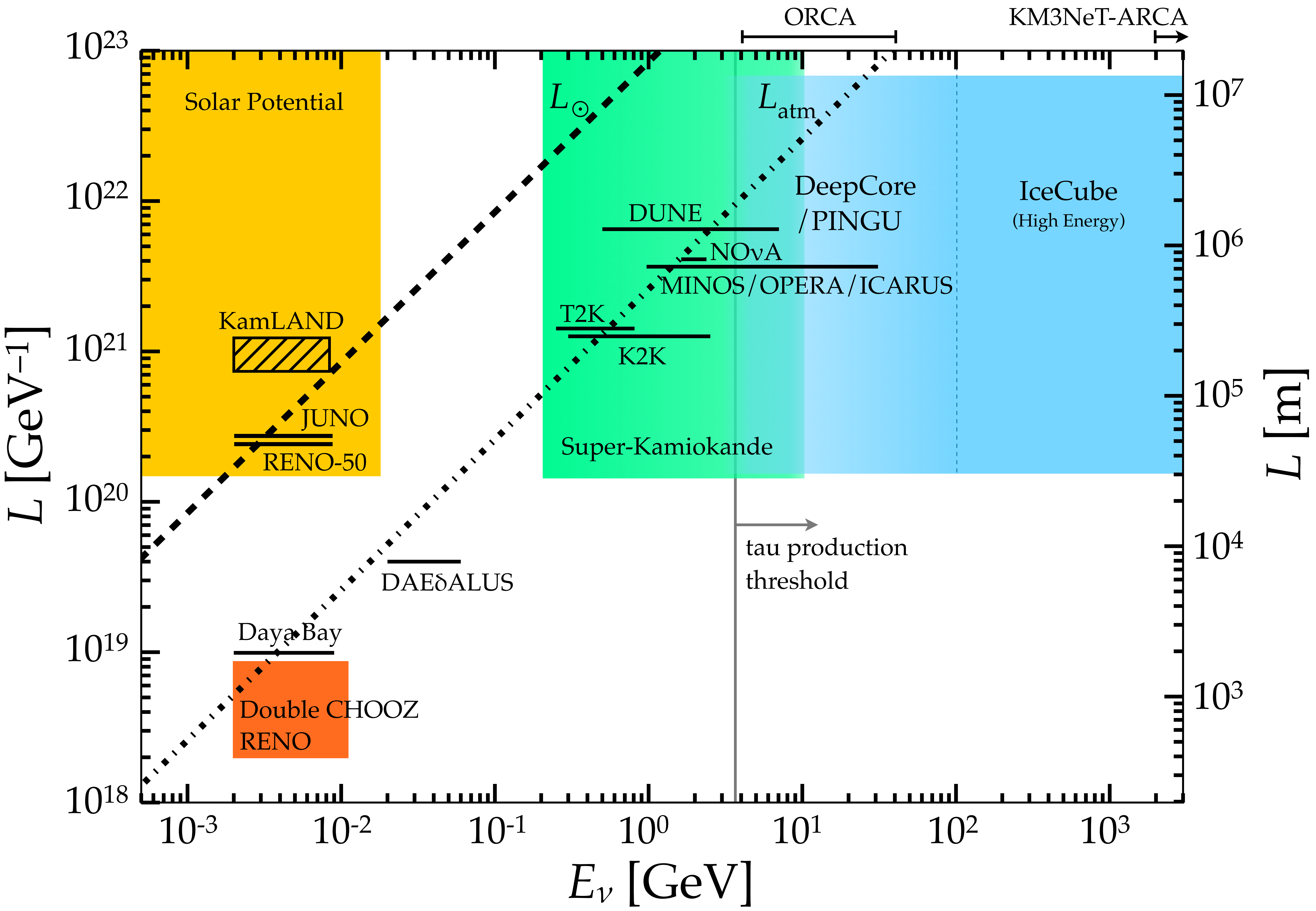


Atmospheric neutrino oscillations

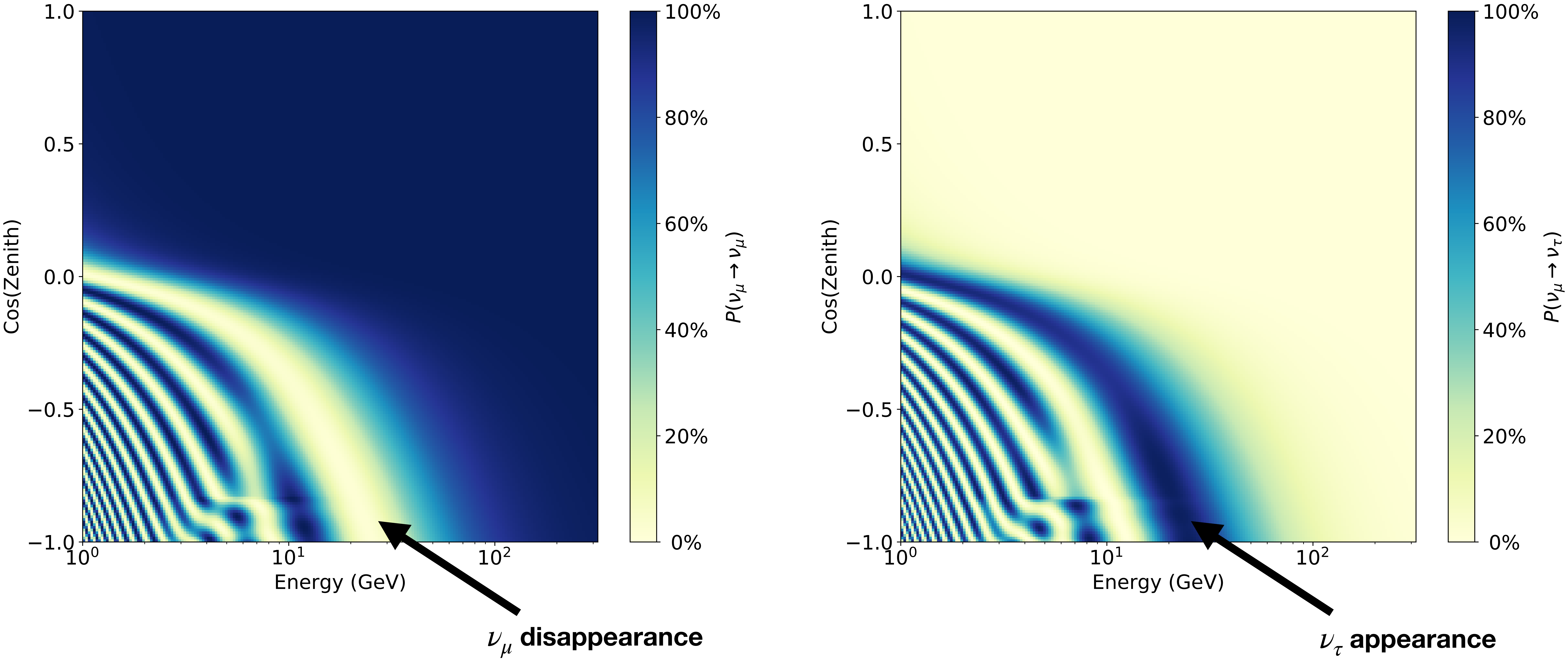
- Cosmic rays interact in atmosphere
- below 100 GeV mostly ν_μ from pion decay
- Oscillate into ν_τ
- zenith angle and energy $\Longrightarrow \dfrac{L}{E}$



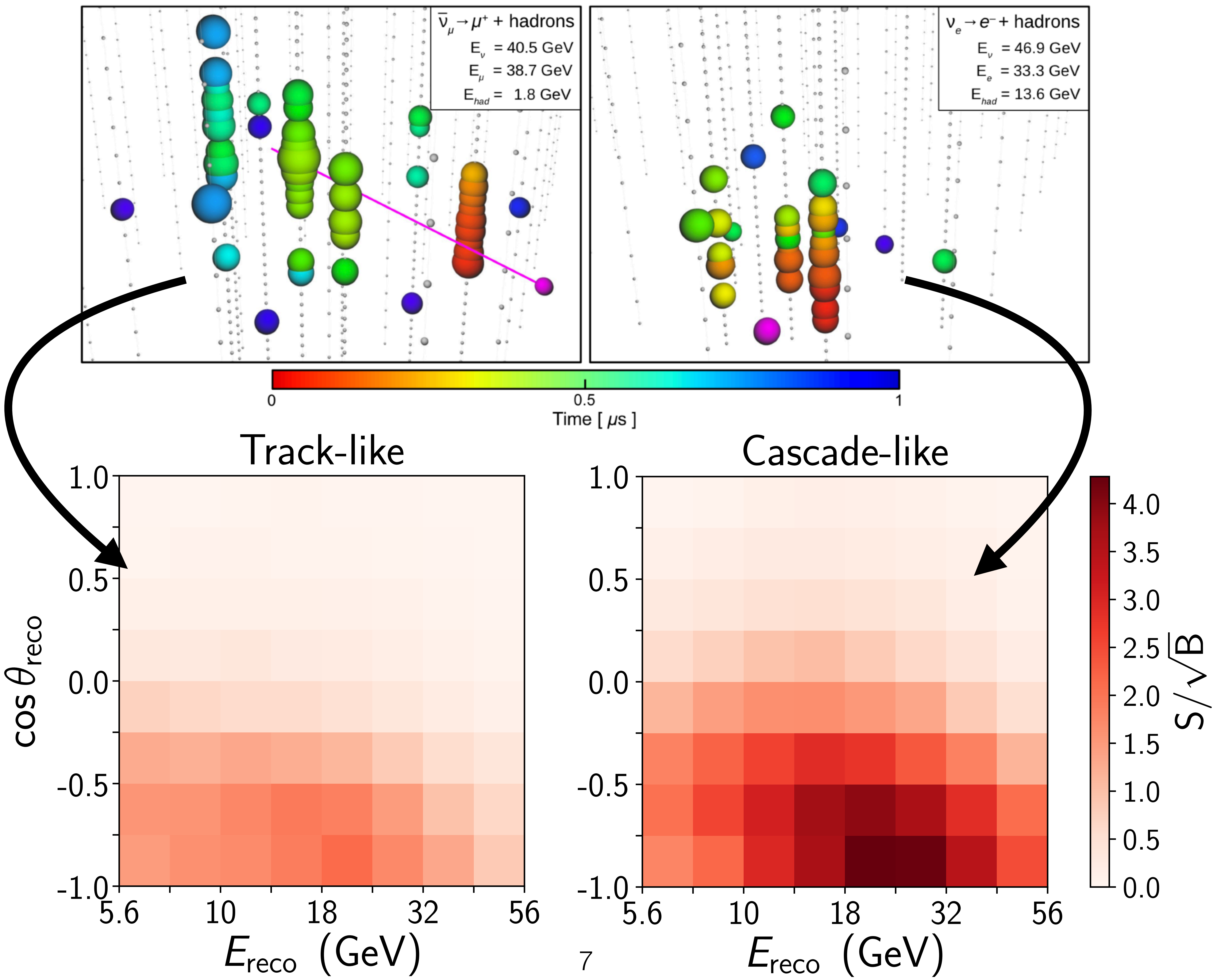
Atmospheric neutrino oscillations



Atmospheric neutrino oscillations



Signatures in DeepCore

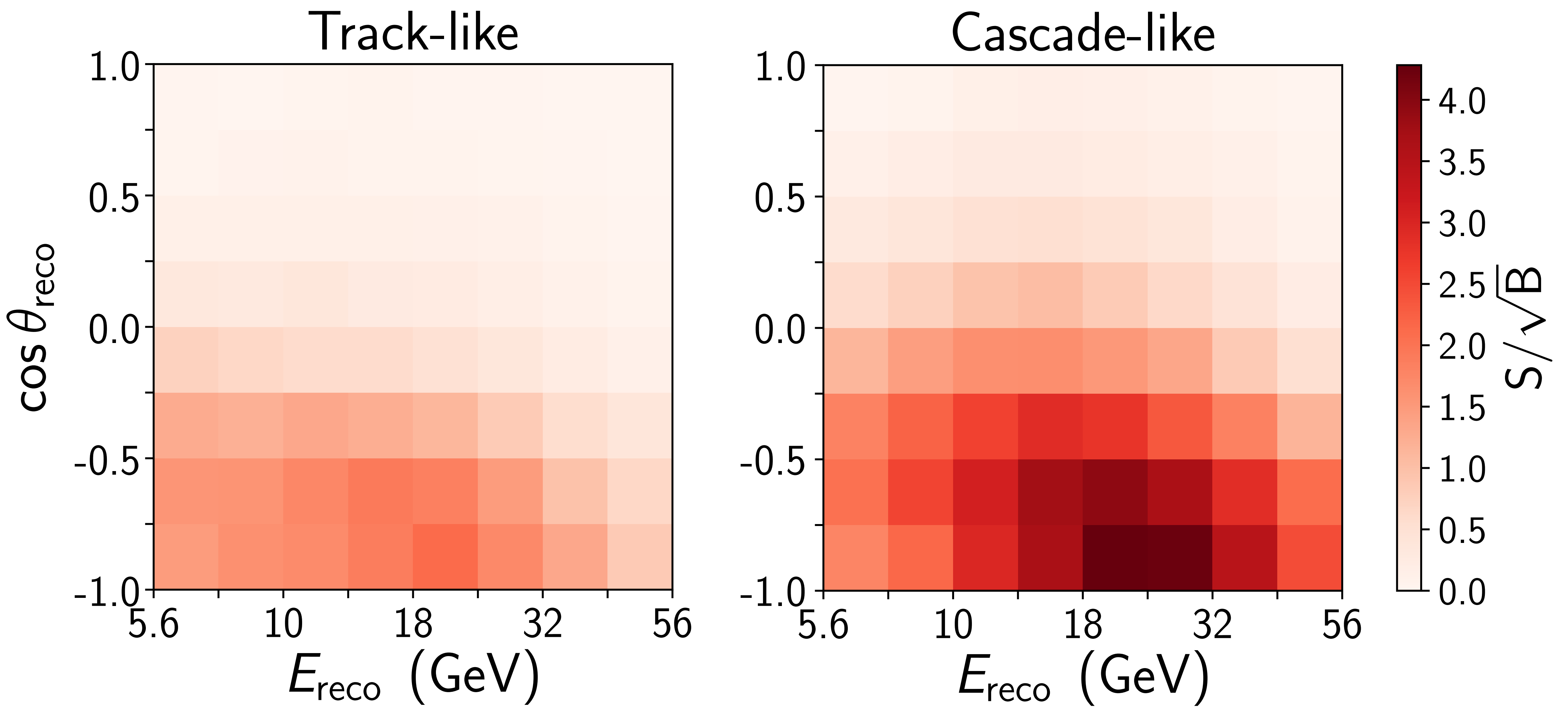


DeepCore analysis

> to get nominal expectation in each bin:
  > simulate neutrino interactions (GENIE), muons and noise
  > weigh by flux (Honda) + cross-section

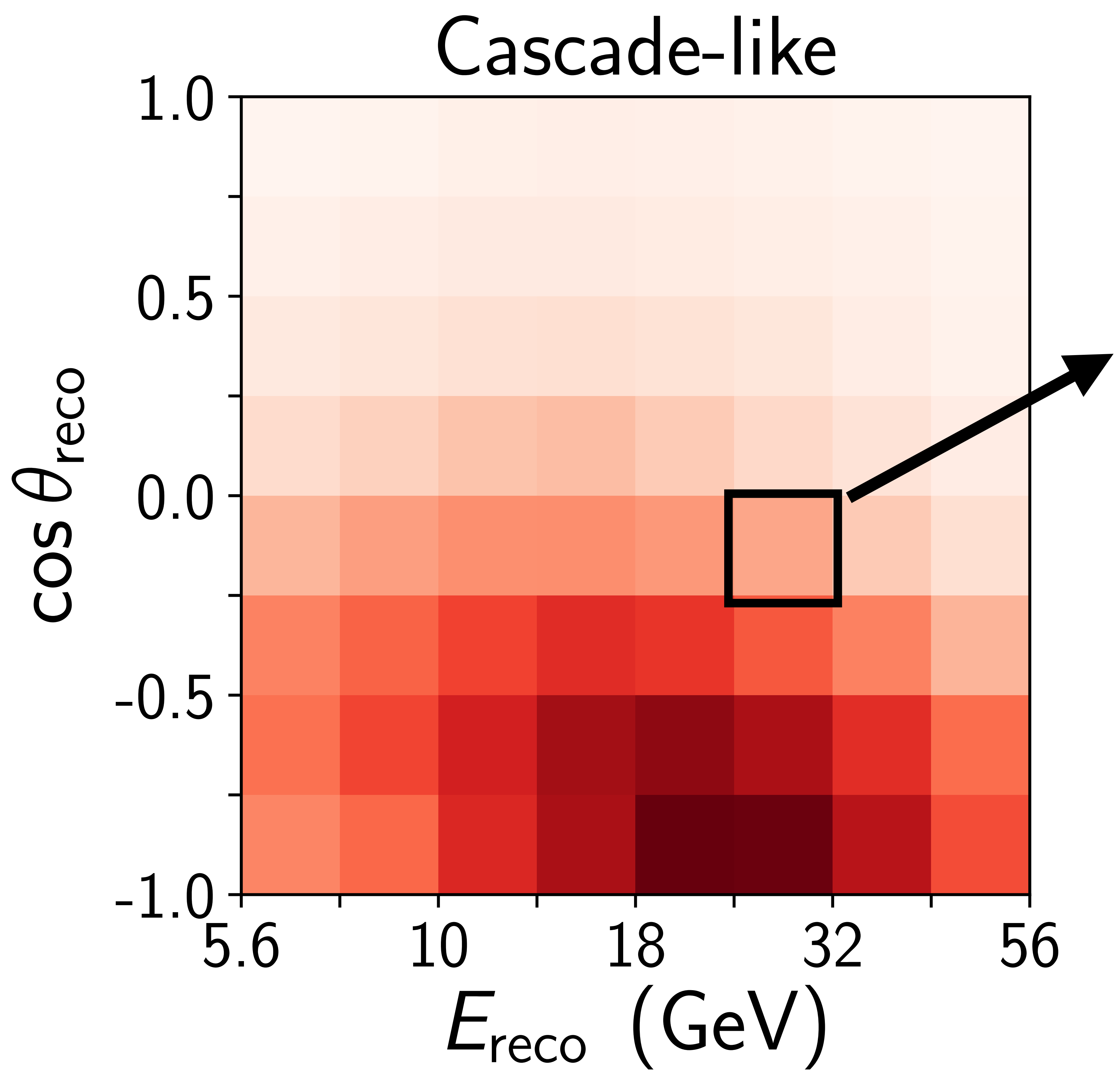
> modified χ^2 - fit with uncertainty on MC expectation and penalty on priors

$$\chi^2 = \sum_{i \in \{\text{bins}\}} \frac{\left(N_i^{\text{exp}} - N_i^{\text{obs}}\right)^2}{N_i^{\text{exp}} + \left(\sigma_i^{\text{exp}}\right)^2} + \sum_{j \in \{\text{syst}\}} \frac{\left(s_j - \hat{s}_j\right)^2}{\sigma_{s_j}^2}$$



Systematic uncertainties

- sources of systematic uncertainty:
  - detector
  - neutrino flux
  - cross-section
  - muons
- detector systematics largest contribution to uncertainty (≈ 40%)
- need re-simulation of entire MC set with varied parameters
- how to calculate expected change in bin content for arbitrary combination of parameters?



$$\frac{N^{\mathrm{exp}}_{i,\mathrm{variation}}}{N^{\mathrm{exp}}_{i,\mathrm{nominal}}} = ?$$

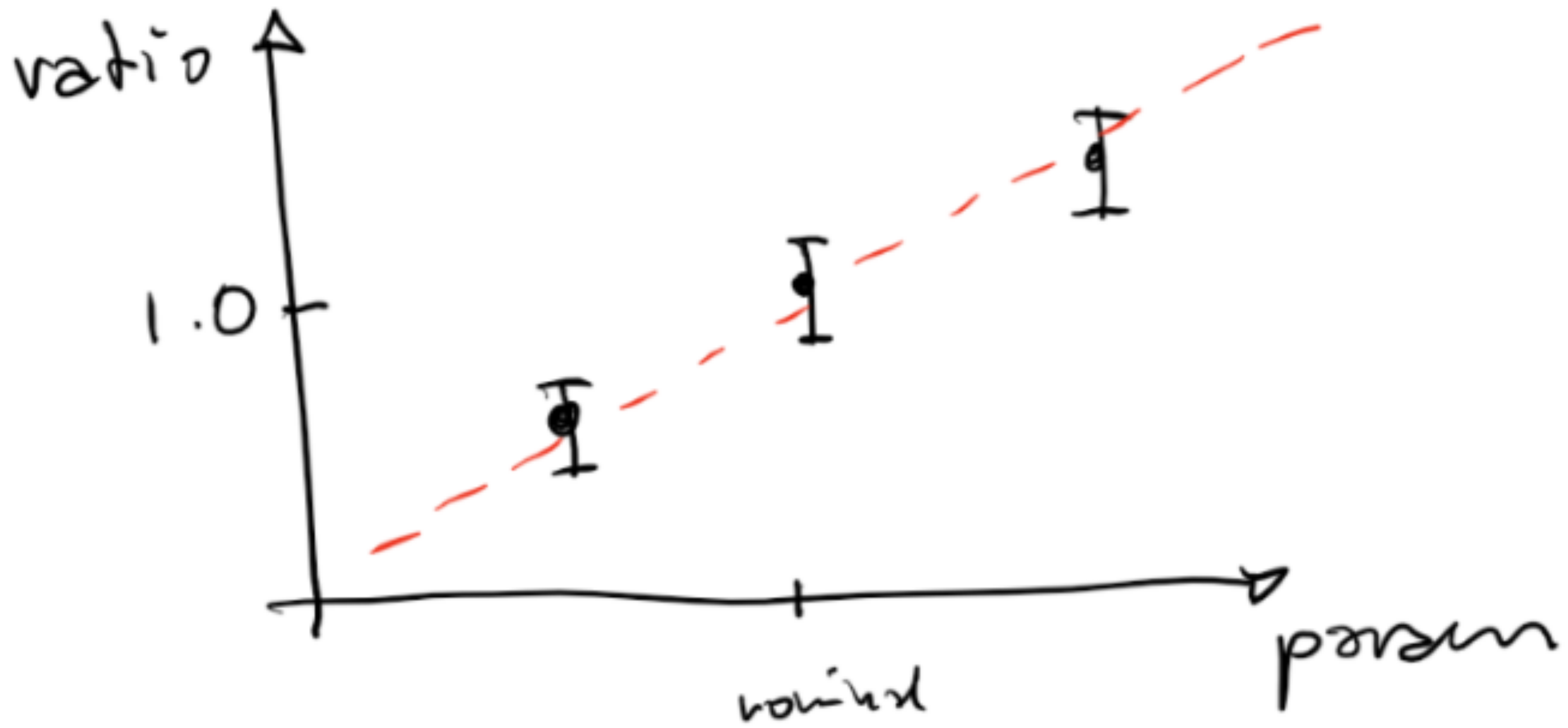
Hyperplane fits

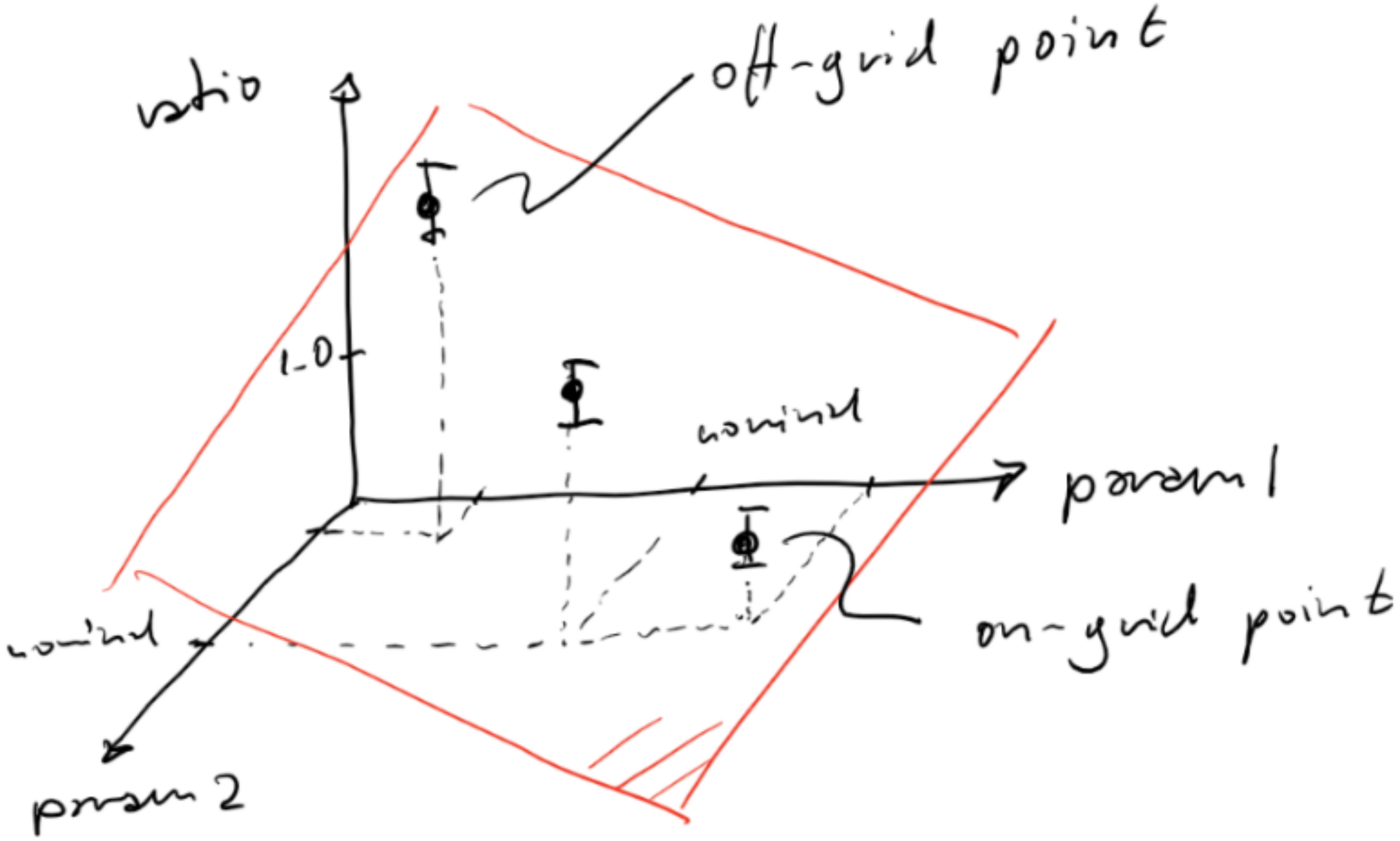
> fit linear model to ratio of bin count to nominal value: $\frac{N^{\text{exp}}_{i,\text{variation}}}{N^{\text{exp}}_{i,\text{nominal}}} = f(p_1, \ldots, p_N)$

> in 1D: $f(p) = b + mp$, with offset b and slope m

> in ND: $f(p_1, \ldots, p_N) = b + \sum_{n=1}^{N} m_n p_n$

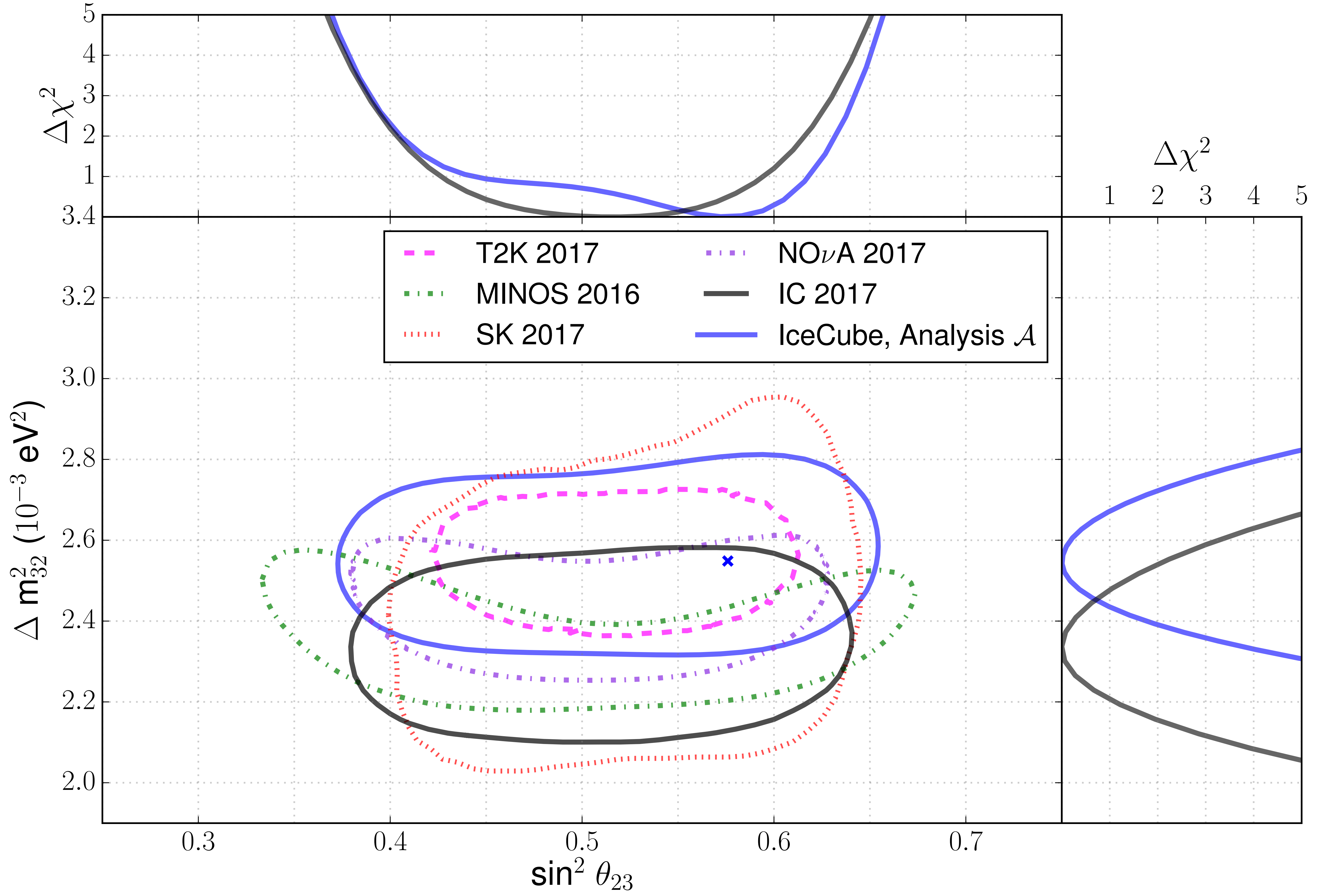
> allows variation of more than one parameter at a time (off-grid point)





Recent Results from DeepCore Data

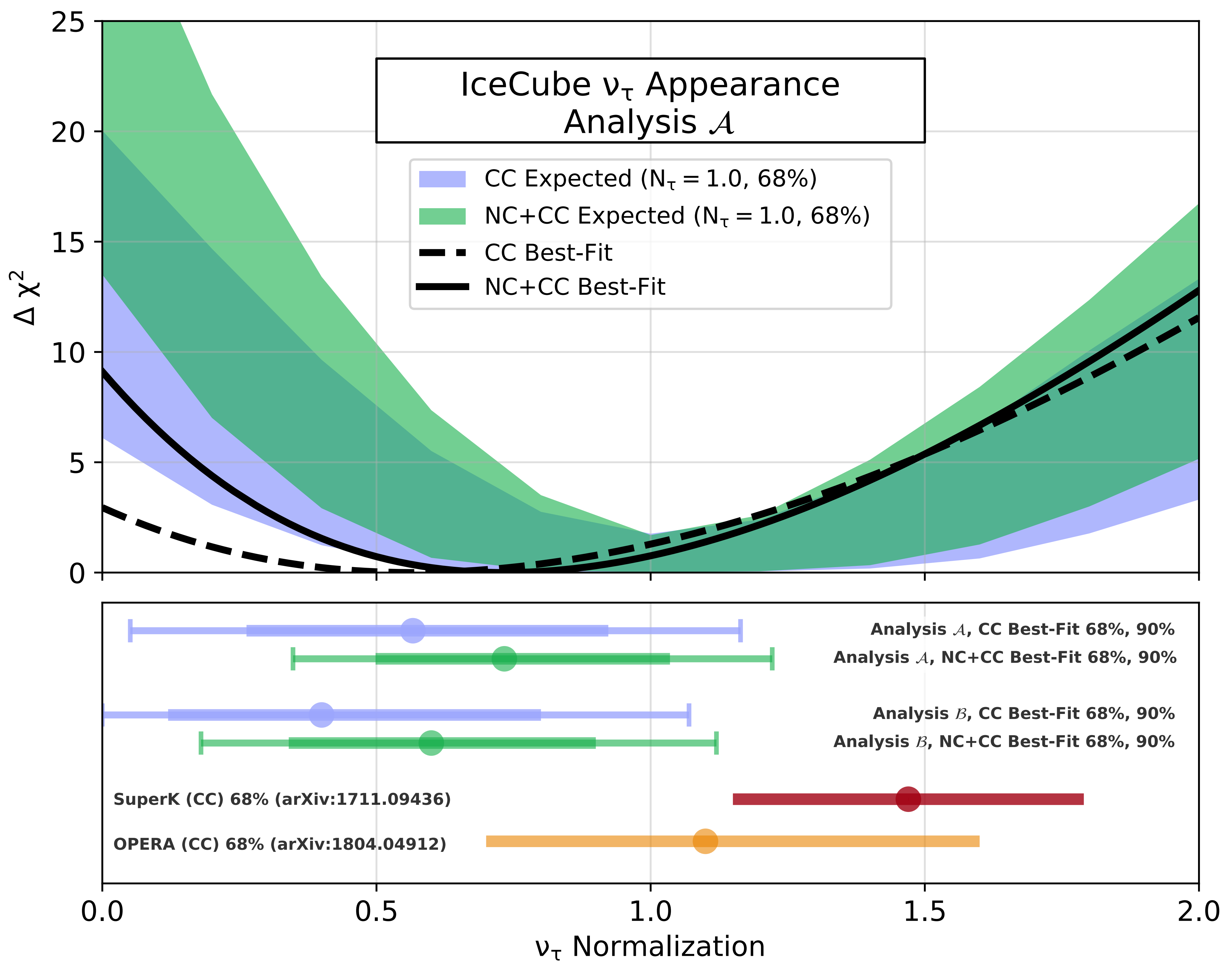
- ν_μ disappearance study 2017 (IC 2017), DOI: `10.1103/PhysRevLett.120.071801`
- ν_τ appearance study 2019 (Analysis $\mathscr{A}$), DOI: `10.1103/PhysRevD.99.032007`
- both with three years of data, but different selection, systematics, reconstruction
  - IC 2017: 40902 observed events
  - Analysis $\mathscr{A}$: 62112 observed events



lines correspond to 90% CL contours

Recent Results from DeepCore Data

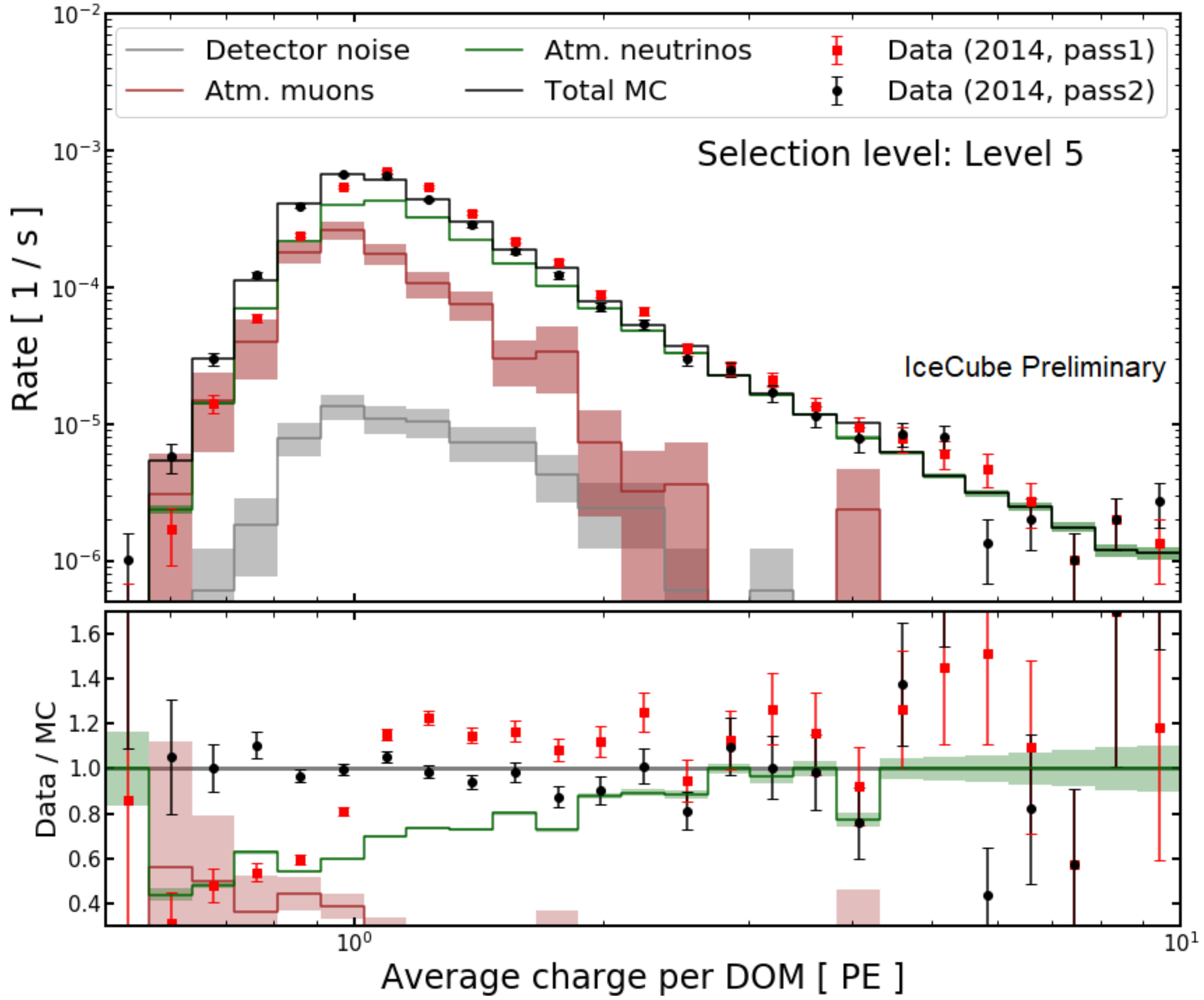
- ν_μ disappearance study 2017 (IC 2017), DOI: `10.1103/PhysRevLett.120.071801`
- ν_τ appearance study 2019 (Analysis $\mathscr{A}$), DOI: `10.1103/PhysRevD.99.032007`
- both with three years of data, but different selection, systematics, reconstruction
  - IC 2017: 40902 observed events
  - Analysis $\mathscr{A}$: 62112 observed events



New DeepCore Developments

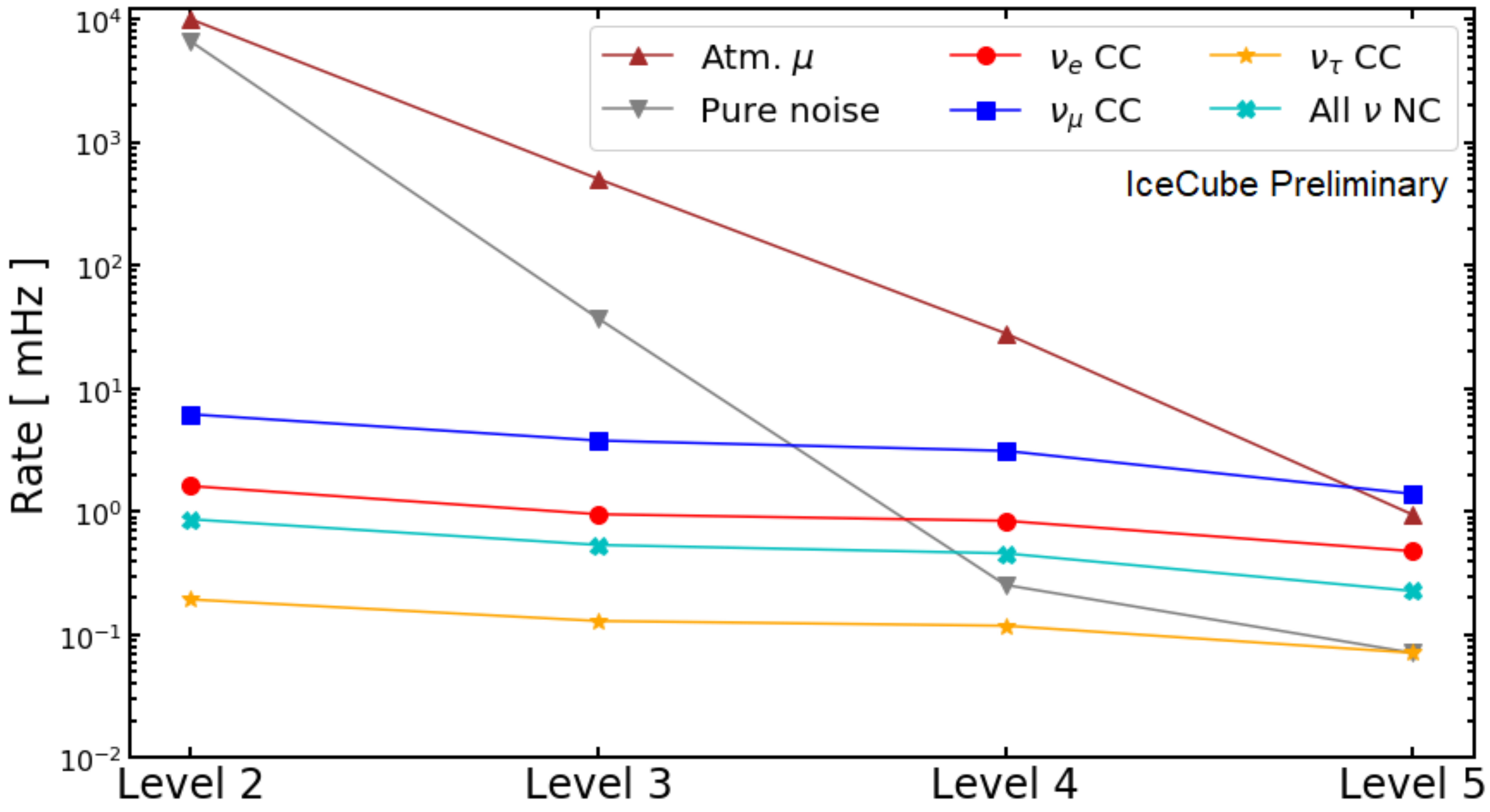
New DeepCore developments

- re-calibrated detector from raw data
- new charge calibration significantly improves data/MC agreement
- are developing new event selection
  - unify best practices
  - variables less charge-dependent
  - common basis for DeepCore studies



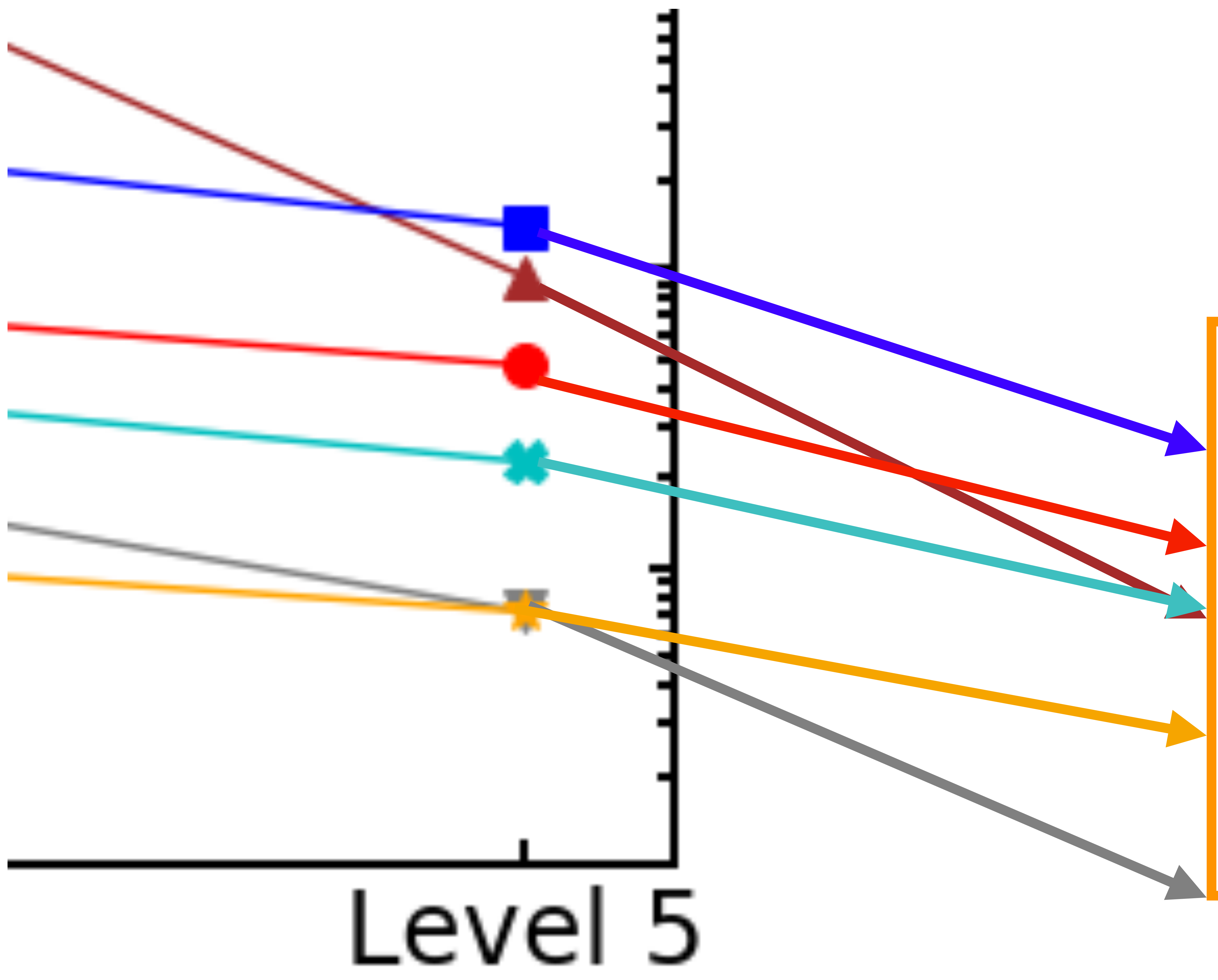
Distribution at last pre-reconstruction selection level

New DeepCore event selection



Levels of event selection before event reconstruction

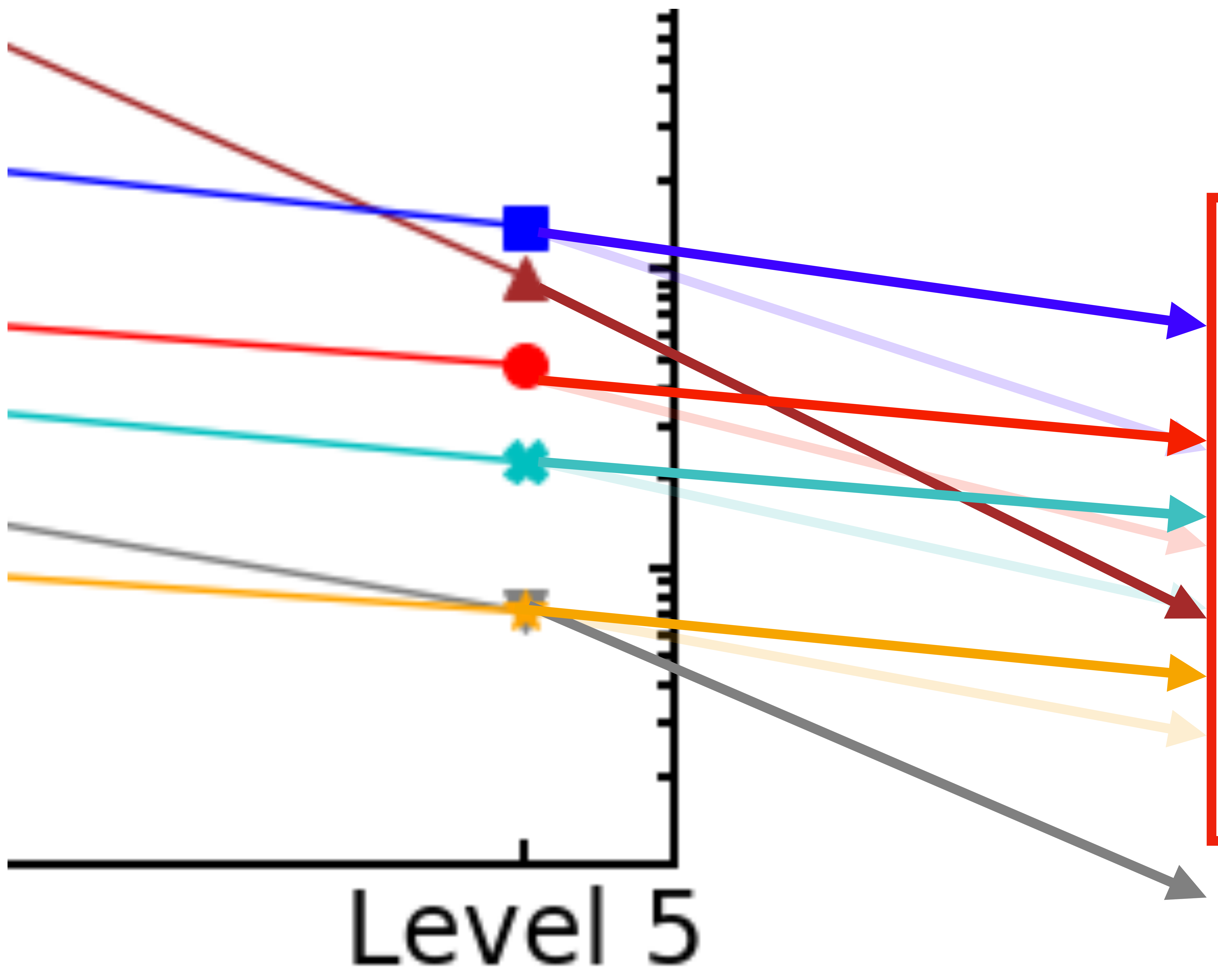
New DeepCore event selection



Verification Sample

- simple and fast reconstruction
- needs additional cleaning, lowering efficiency
- 13 000 events/year expected
- 2.8% muon contamination

New DeepCore event selection



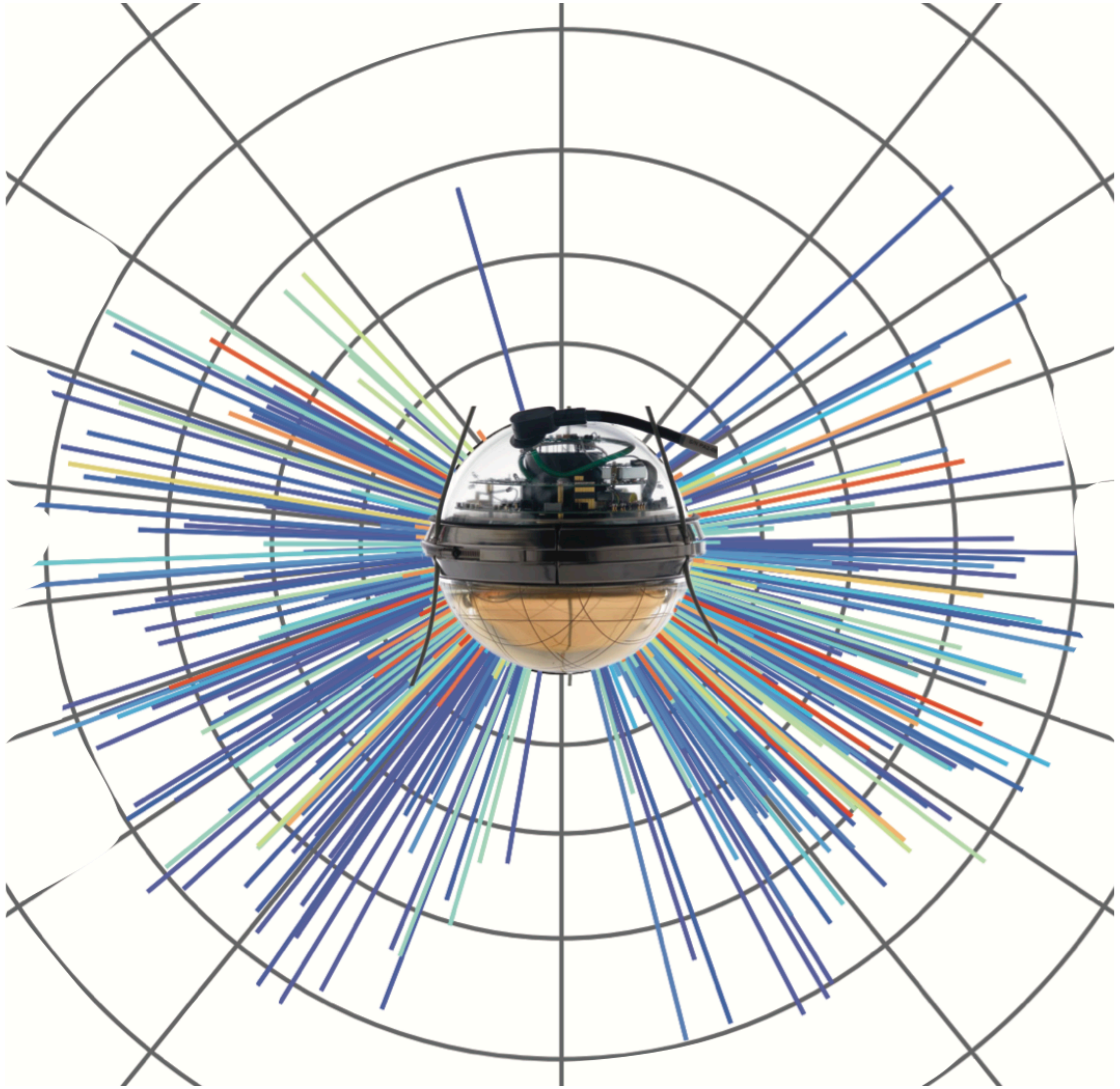
High-stats analysis sample

- new, highly efficient reconstruction method
- 100 000 events/year including ≈ 30% muons
- final muon rejection cut being developed
  - hard cut: expect ~40 000 events/year with ≈ 1% muons

New reconstruction developments

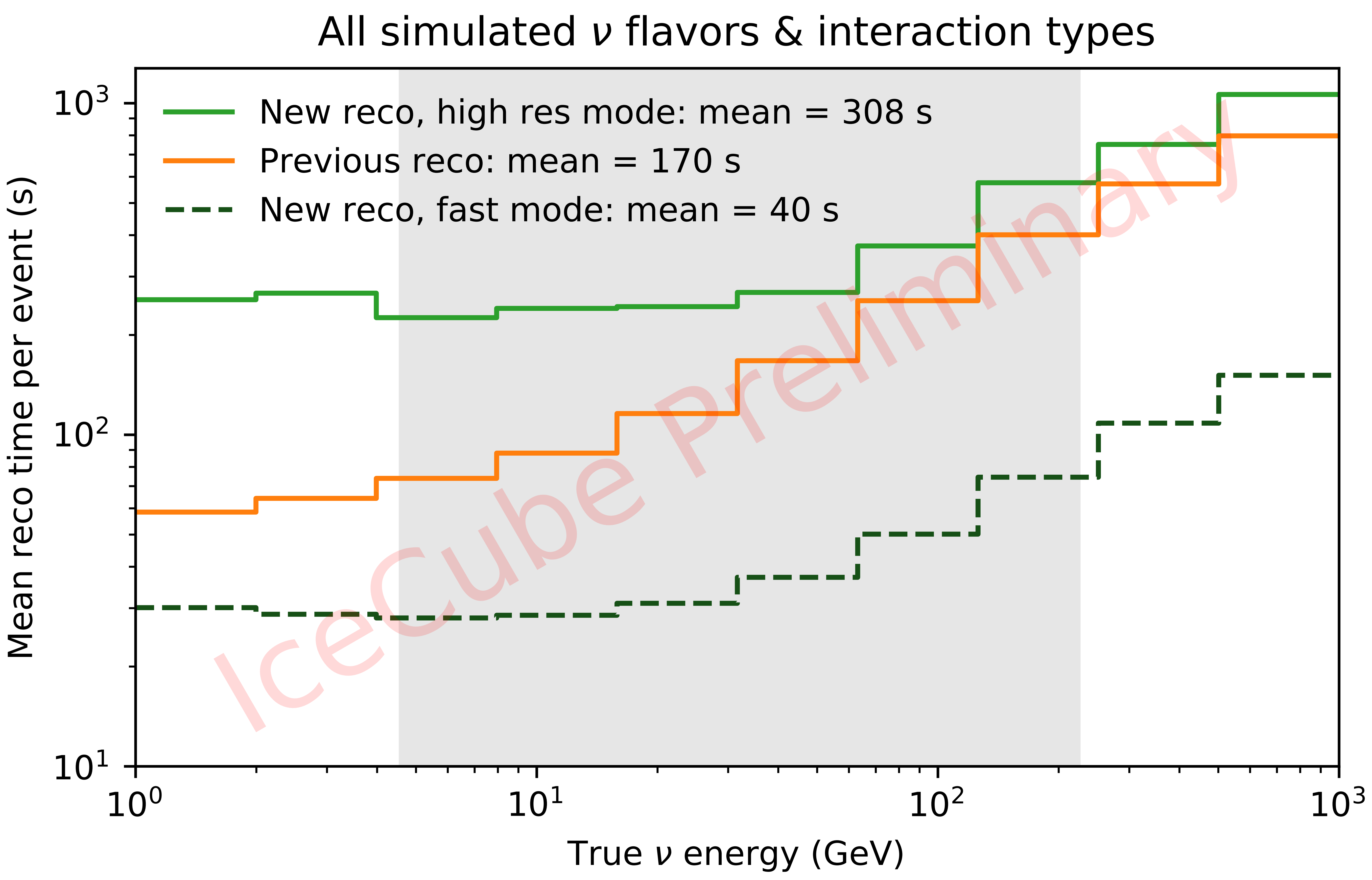
New reconstruction developments

- previously: “forward” tables starting from interaction point
- novel approach: backwards (“retro”) tables
  - act as if sensor was light source
  - trace photons originating from sensor
  - store for each spacetime bin photon content and average direction
- improved speed and accuracy compared to previous reconstruction methods
- more flexible in the event hypotheses that can be modeled



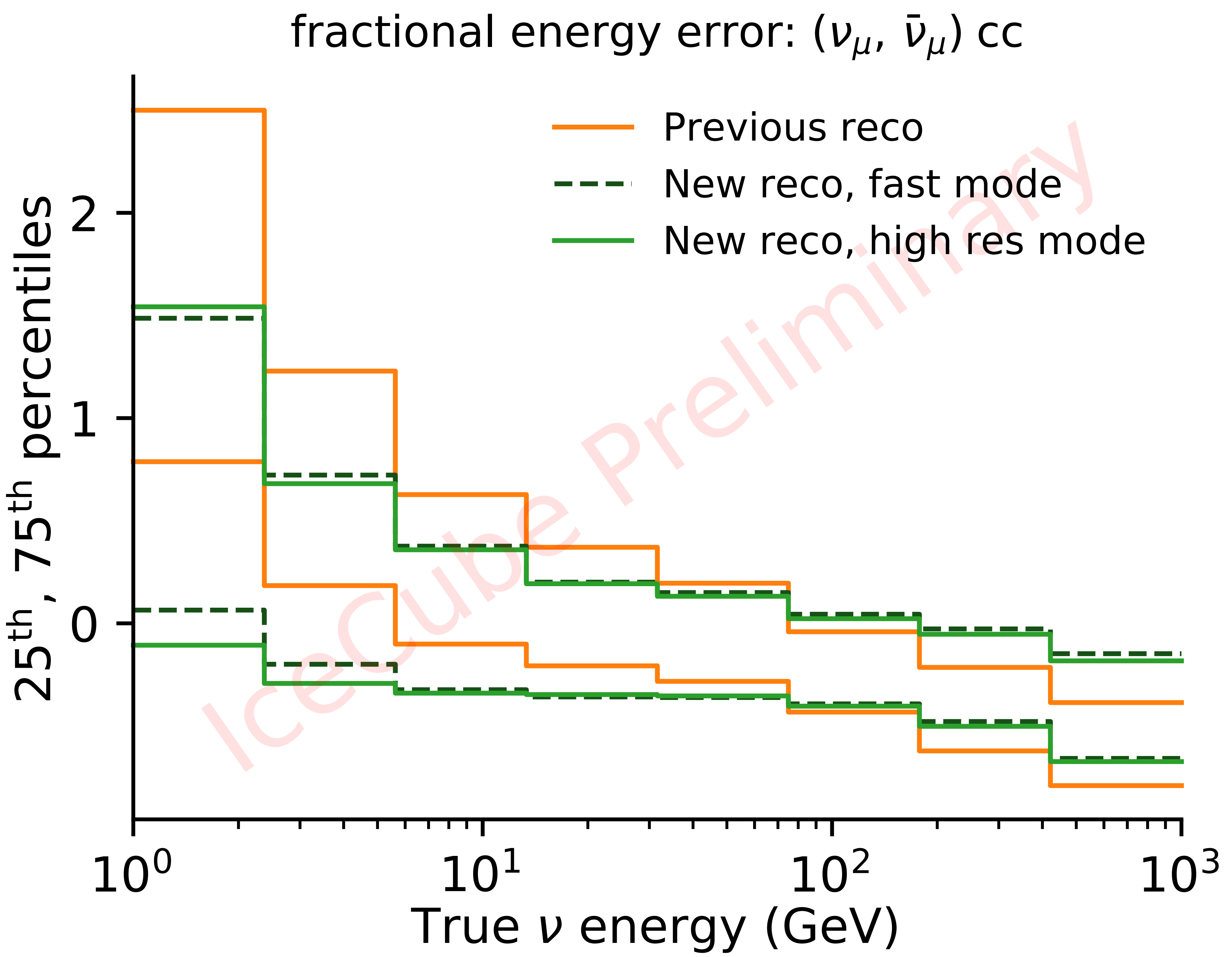
`github.com/philippeller/retro`

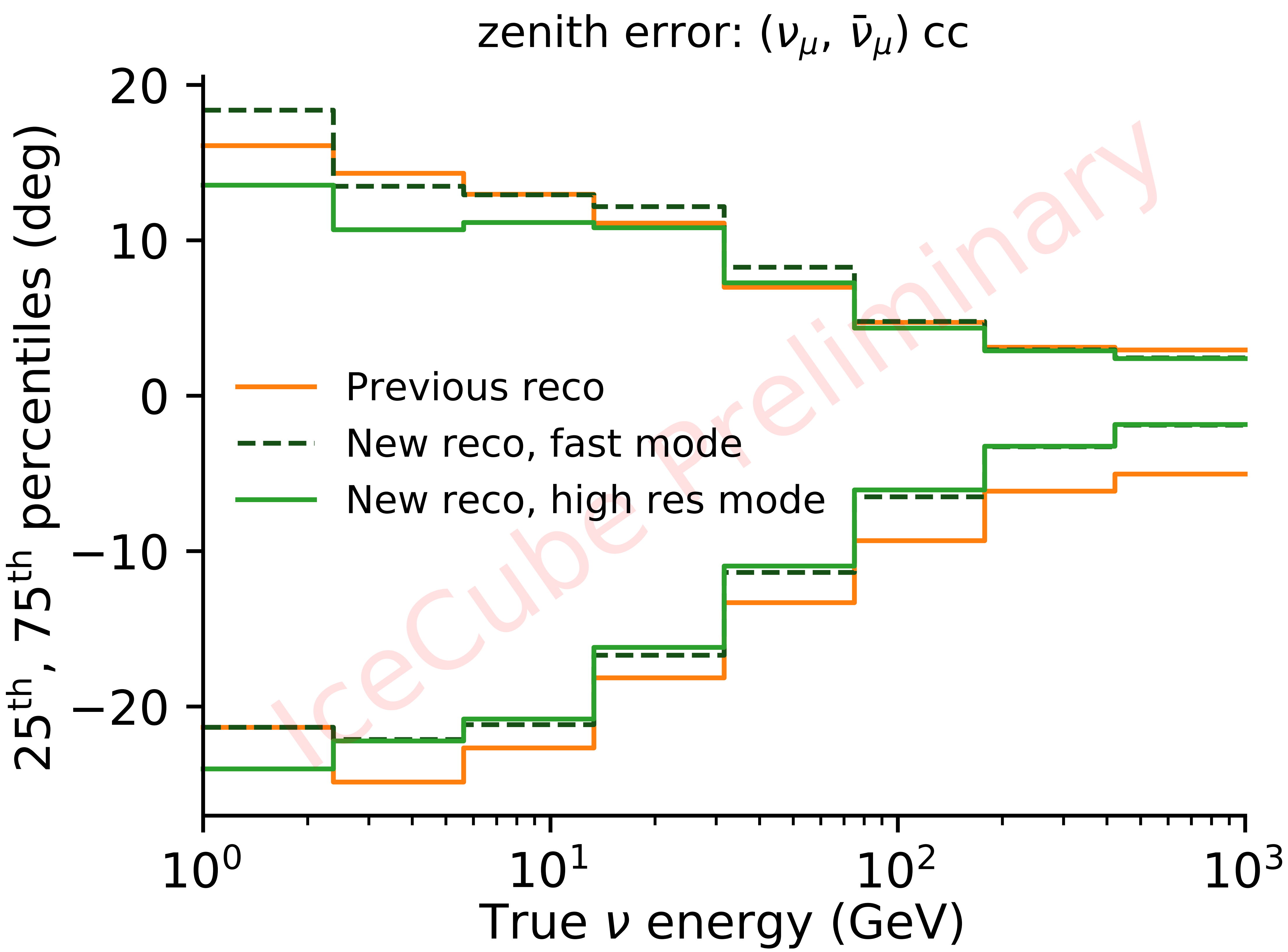
New reconstruction developments



> "previous reco" = reconstruction used in Analysis $\mathscr{A}$

New reconstruction developments





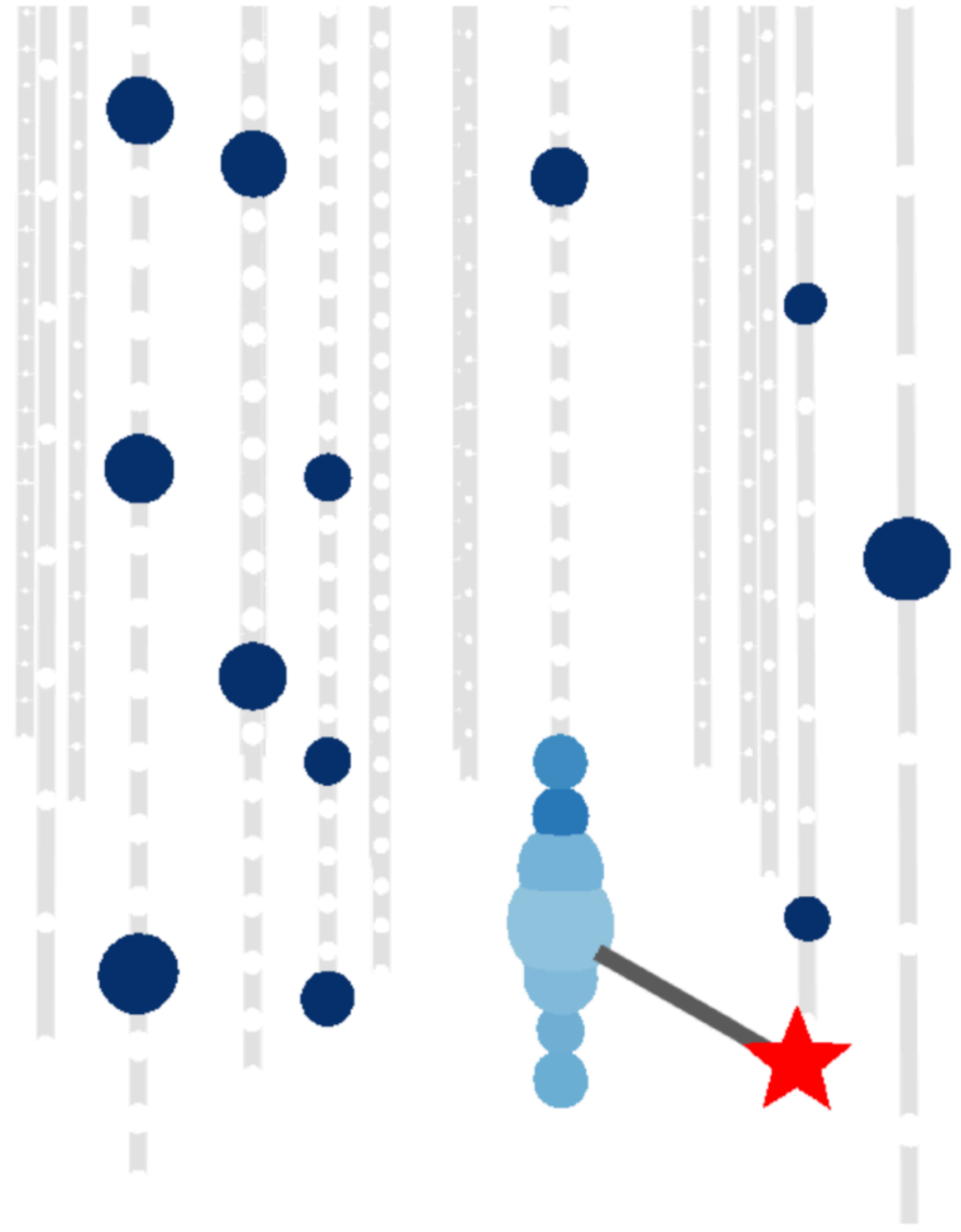
> "previous reco" = reconstruction used in Analysis $\mathscr{A}$

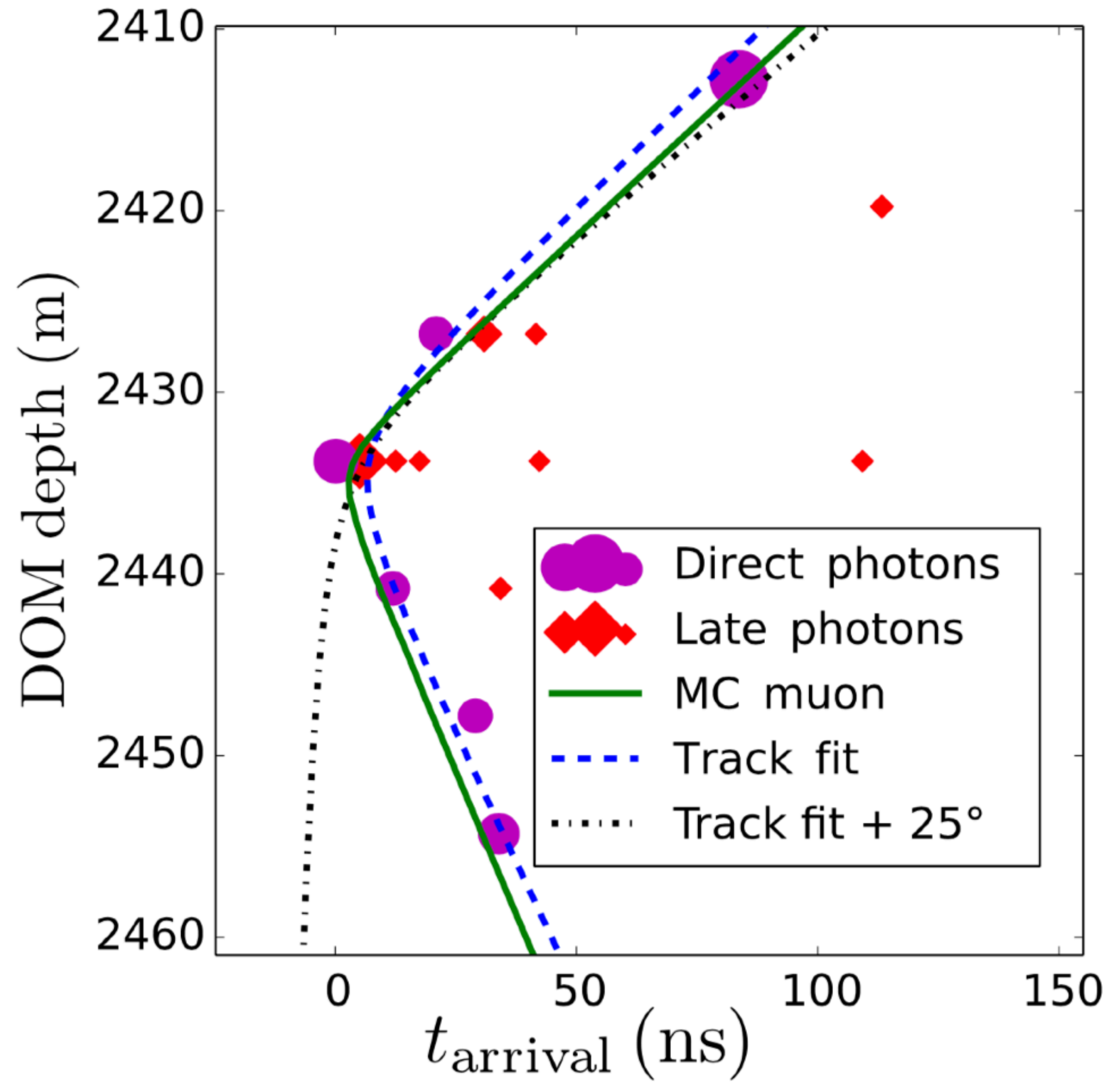
Verification sample reconstruction

Low-efficiency reconstruction for verification

Vertex and Direction

- χ^2 fit w.r.t. geometric time
- needs hit cleaning to remove scattered light
- several fits per second
- able to reconstruct ≈ 40% of all events from common selection (including background)
- reconstructs ≈ 45% of neutrino events

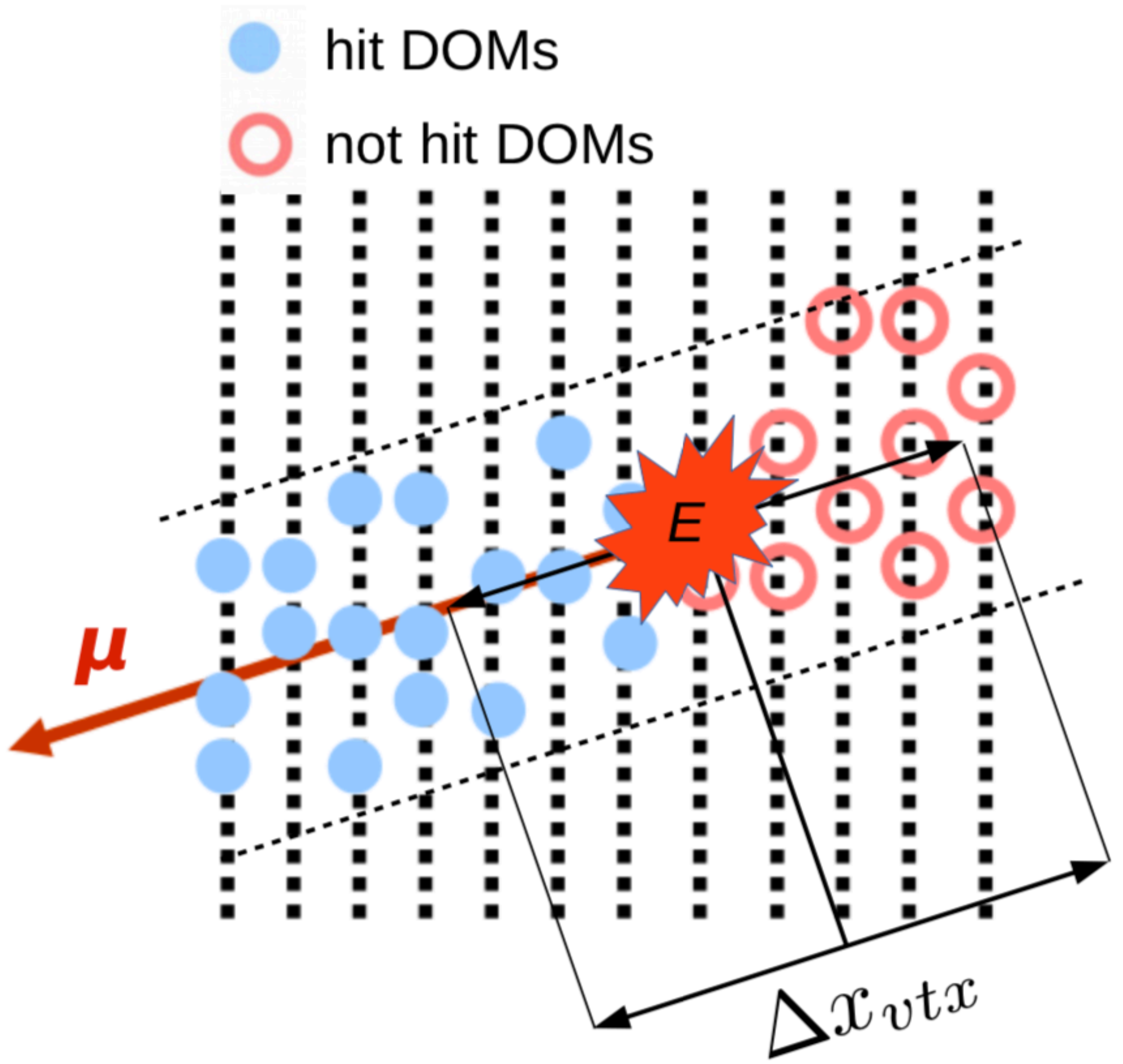




Low-efficiency reconstruction for verification

Energy

- uses all light including scattered photons
- only hit/no-hit probability to reduce charge dependence
- light expectation from interpolated tables
- requires successful vertex and direction reconstruction
- ca. 5 sec per fit



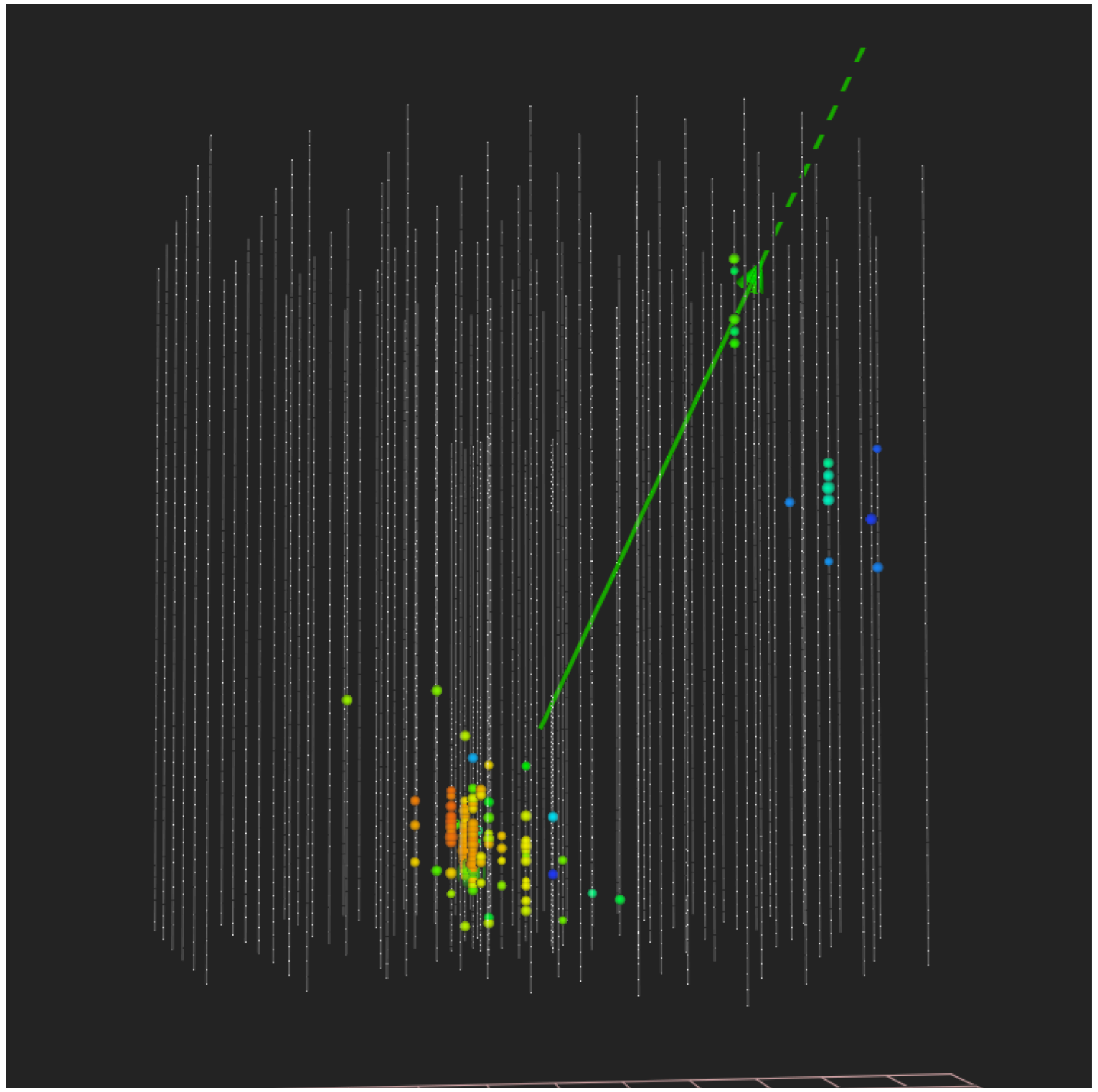
Verification sample

- low-statistics sample used to verify event selection and data/MC agreement

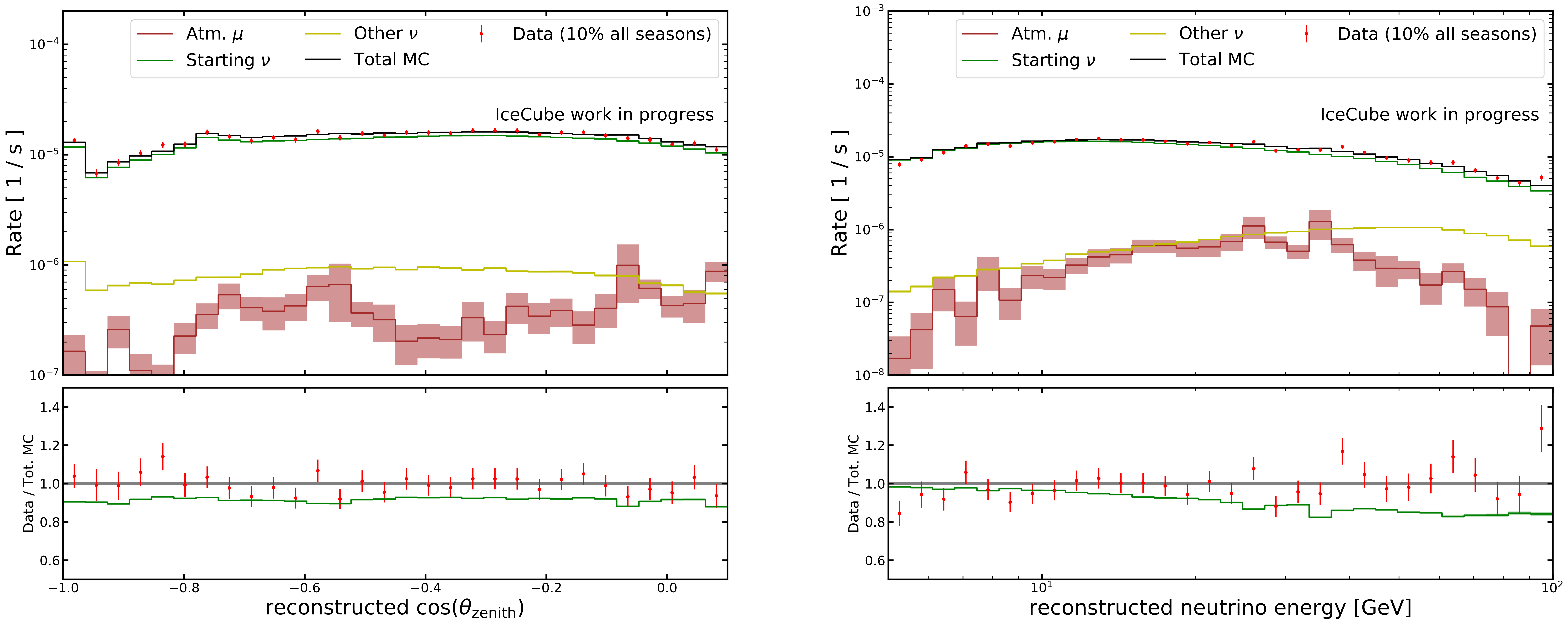
- final level cuts:
  - $\cos(\theta_{\rm reco}) < 0.1$
  - cut on fit quality
  - co-incident muon rejection
  - …etc.

- ≈ 13 000 events per year with less than 3% muon contamination
  - comparable to IC 2017, but with lower muon contamination (2.8% vs. 4.6%)

- good agreement between data and simulation even before any fit



Verification sample



Summary

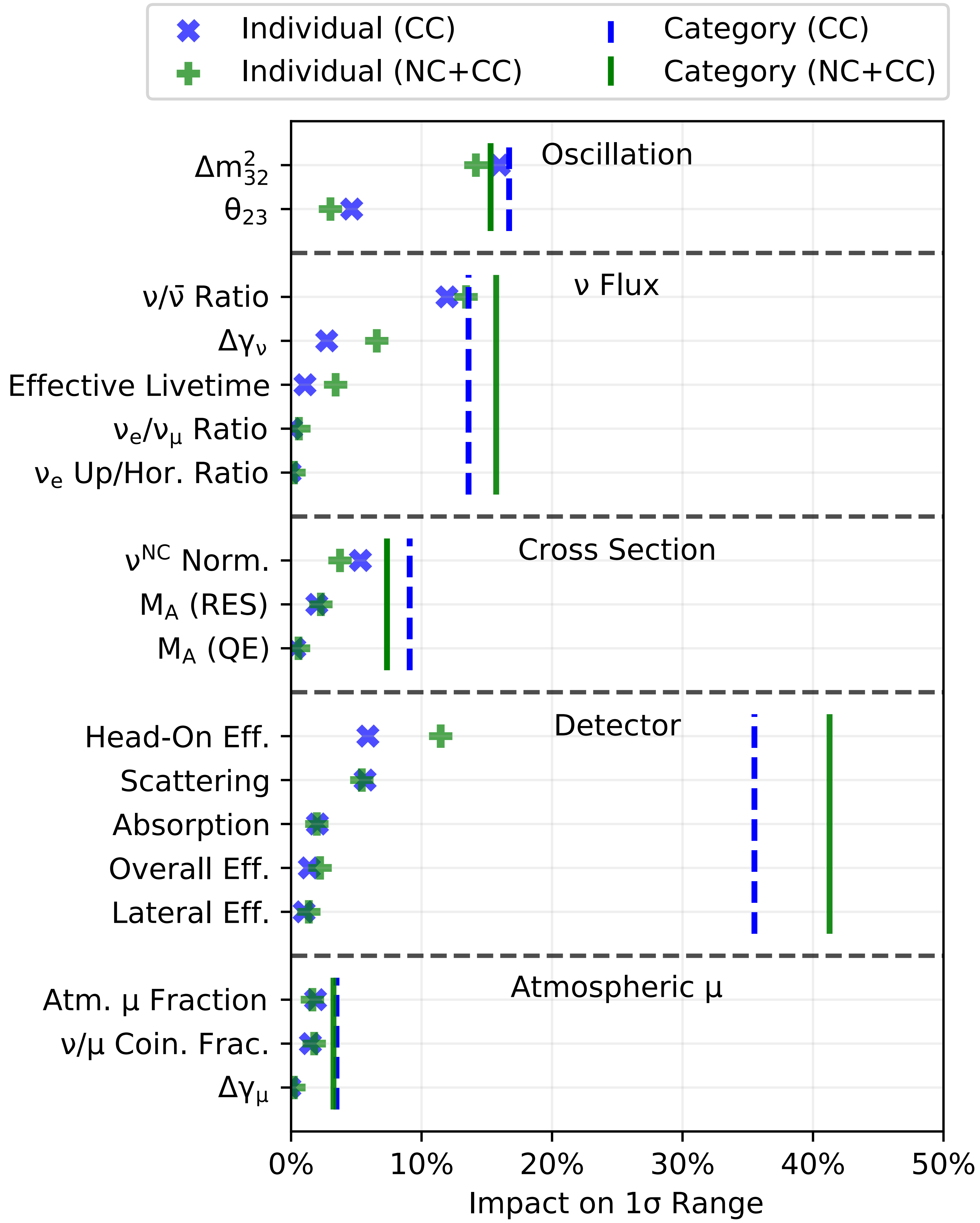
- New event selection for future DeepCore studies in final stages of development
- developing high-statistics sample with better reconstruction methods than any previous IceCube study
- low-statistics sample developed for verification of event selection
- neutrino oscillation studies with significantly improved sensitivity upcoming

Backup

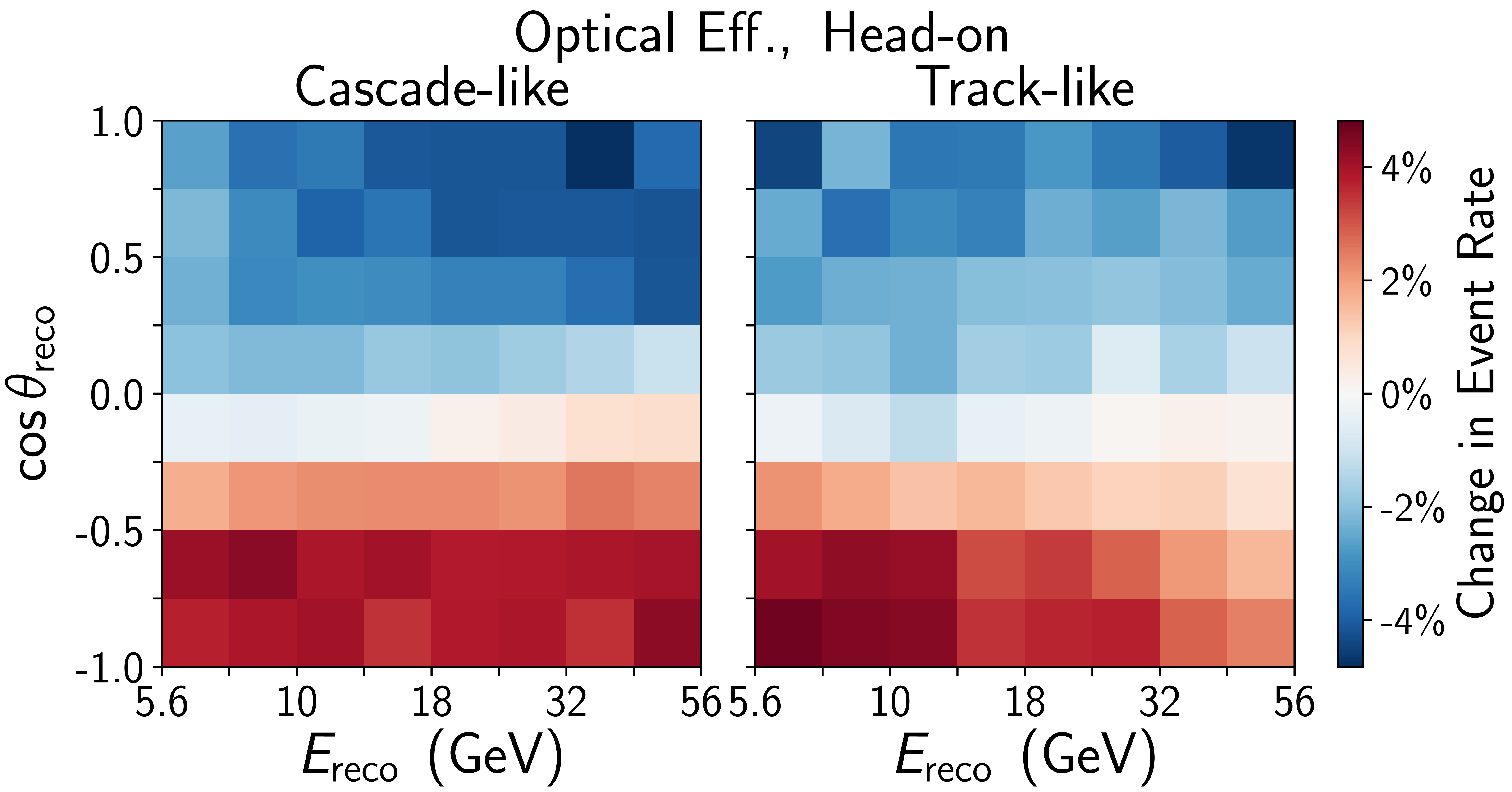
Nuisance parameters

Parameter	Prior	Analysis $\mathcal{A}$ (CC + NC)	Analysis $\mathcal{A}$ Best fit (CC)	Analysis $\mathcal{B}$ Best fit (CC + NC)	Analysis $\mathcal{B}$ Best fit (CC)
Neutrino flux and 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} (Quasielastic) (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

Impact of systematics



Systematics impact on event rates



shown: head-on optical efficiency +1