Fun with Low-Energy Atmospheric Neutrinos

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[1904.02751] and [2304.04689] with many great collaborators

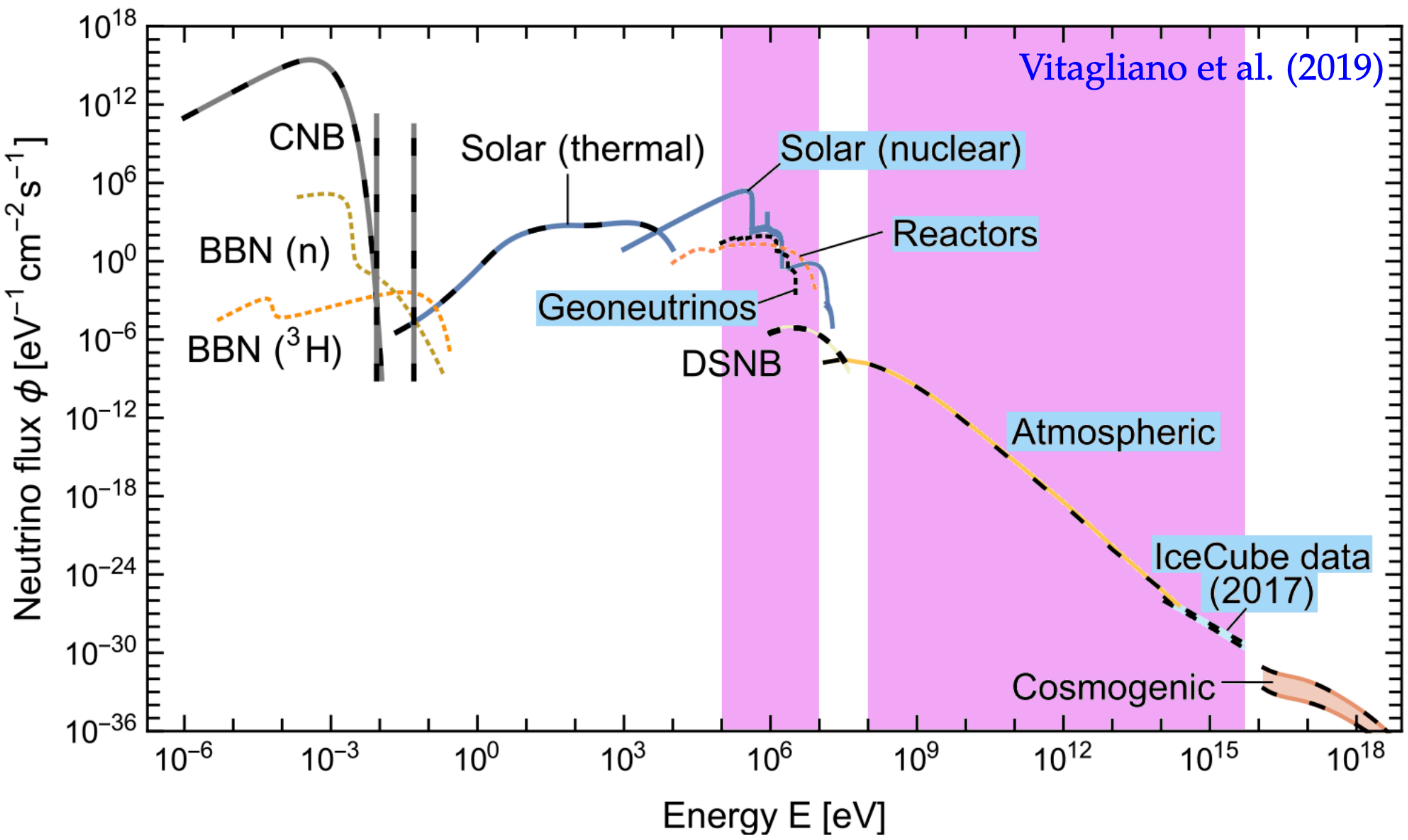
Outline

- Why (low-energy) atmospheric neutrinos?
- CP-complementarity with atmospherics
- Connections between atmospheric neutrinos and the solar cycle

Why (low-energy) atmospheric neutrinos?

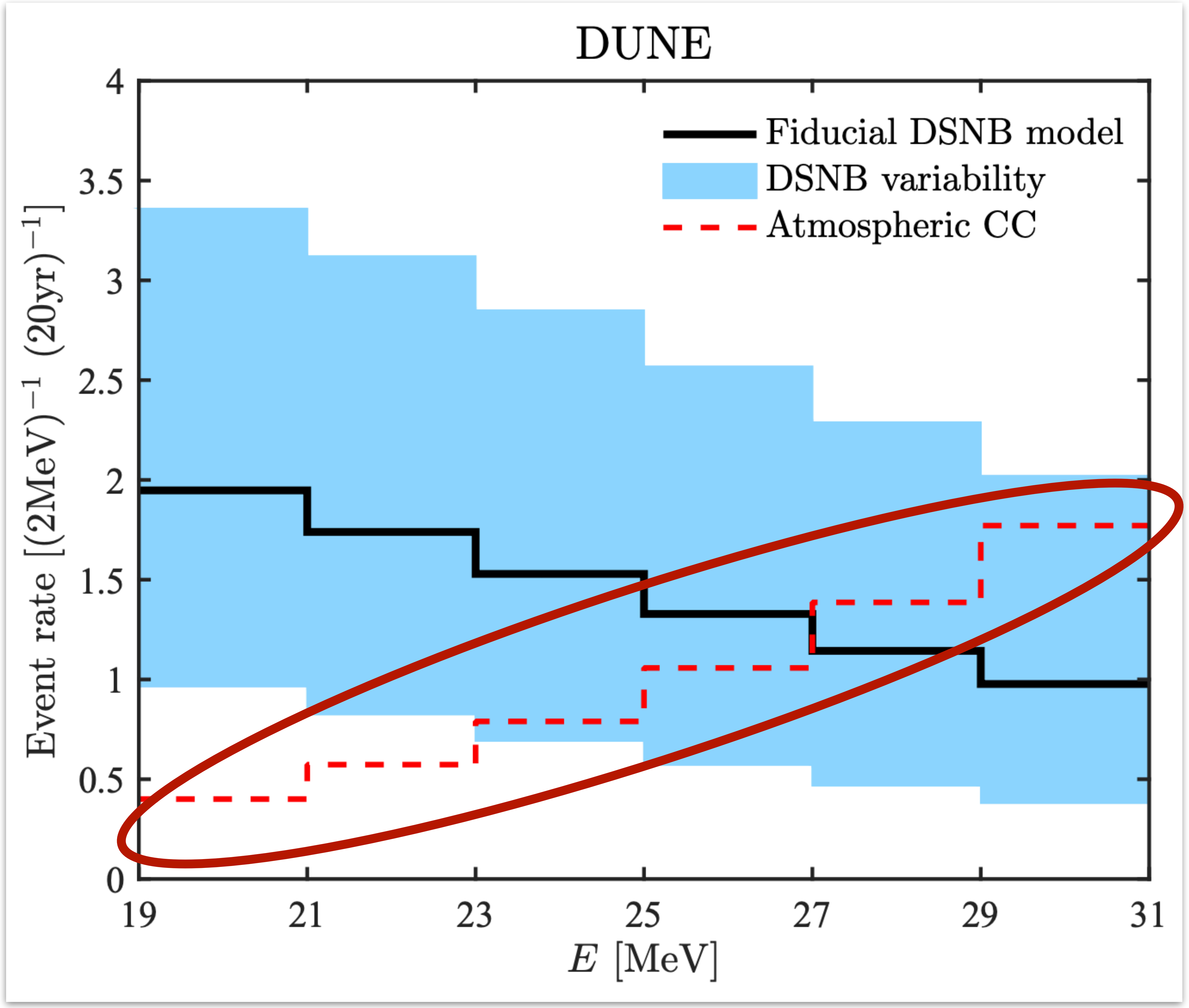
New Regime of Detection

Grand Unified Neutrino Spectrum - Detected Fluxes



From A. Suliga's [talk this morning]

LEATMν as a Background



Møller et al, [1804.03157]

O'Hare, [2109.03116]

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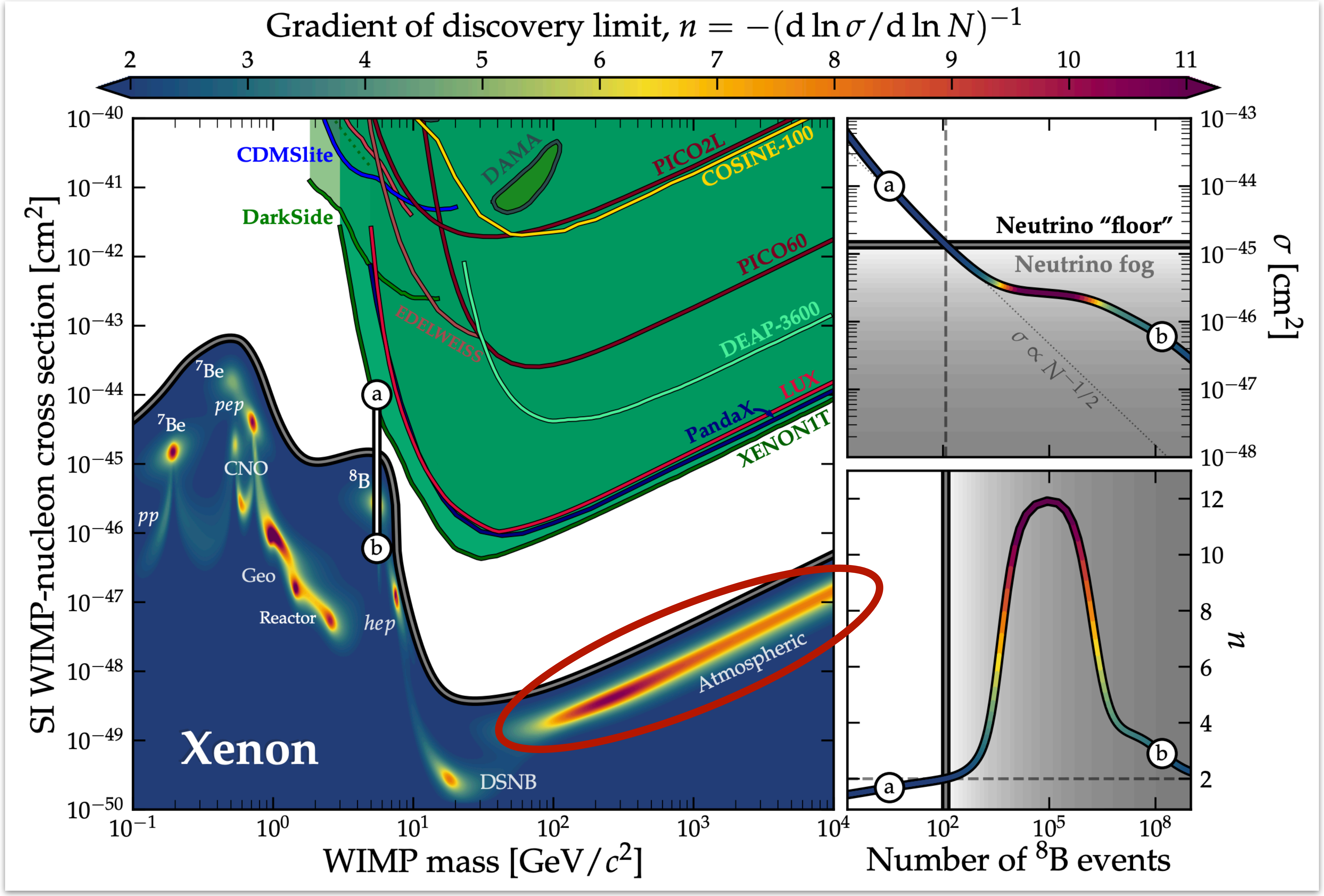


O'Hare, [2109.03116]

CP Violation with Atmospherics

[1904.02751] — with P.A.N. Machado, I. Martinez-Soler, S. Parke, Y.F. Perez-Gonzalez

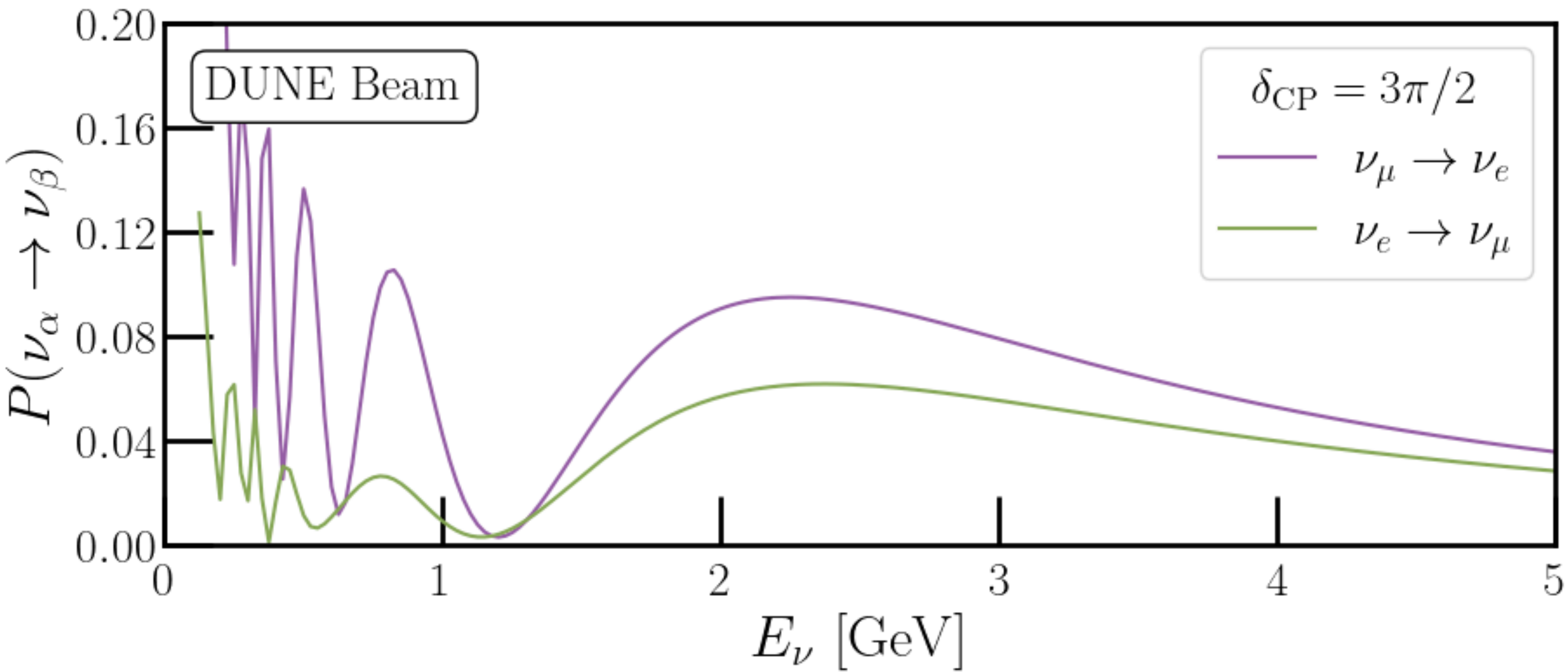
CP Violation in Atmospheric Neutrinos

CP-violating term in (vacuum) oscillation probability:

$$P_{CP} = -8J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

$$\left(\frac{|\Delta_{3j}|}{\Delta_{21}} \approx 30 \right)$$

Challenge: making these all $\mathcal{O}(1)$ simultaneously!



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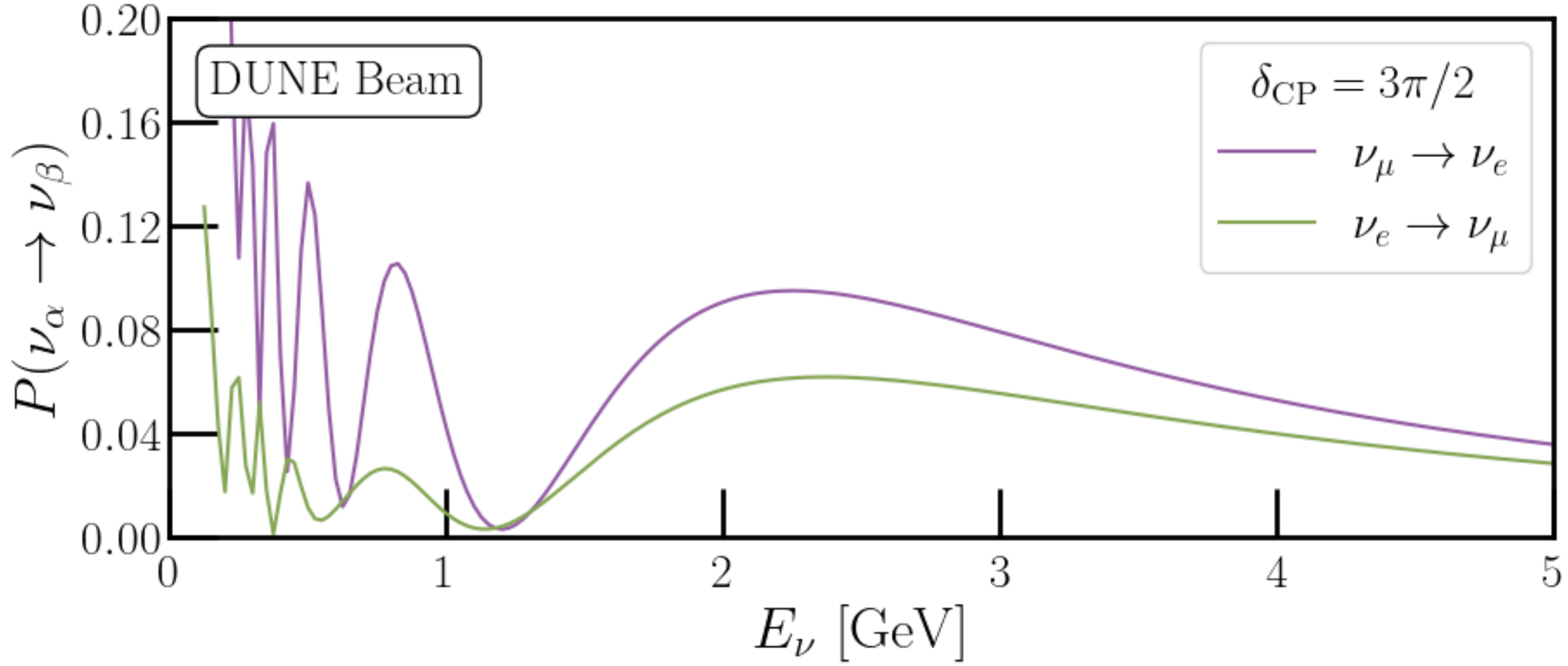
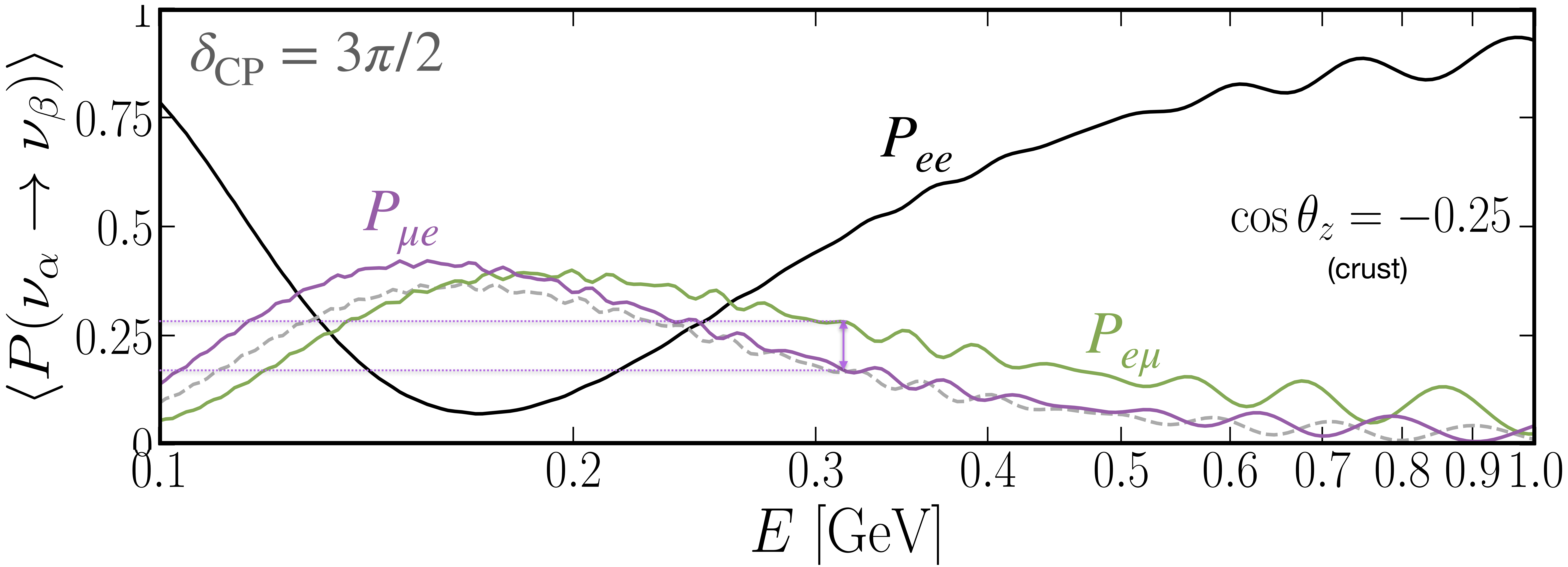


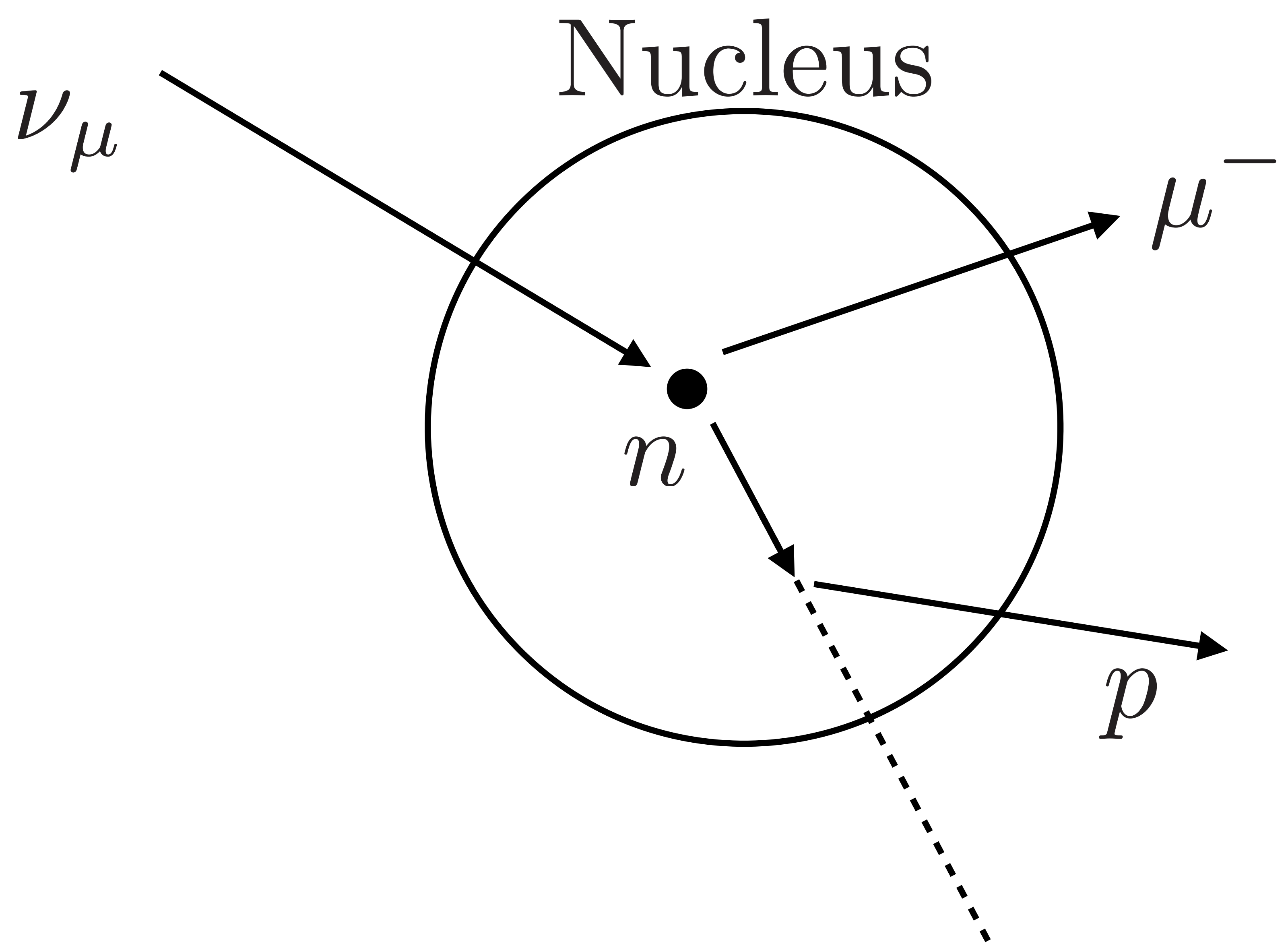


CP Violation in Atmospheric Neutrinos

$$P_{CP} = -8J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

$P_{\mu e} - P_{e\mu}$ is 10x larger in sub-GeV atmospherics than in the GeV-scale beam!

So, why haven’t we done this already?



Especially at low energies, the correlation between the incoming neutrino direction and the outgoing (visible) particles’ direction is muddled.

Best atmospheric measurements to date come from Super-Kamiokande, but water has a Cherenkov threshold for protons of $\sim 1.4\ \mathrm{GeV}$ KE, so lower-energy protons go undetected.

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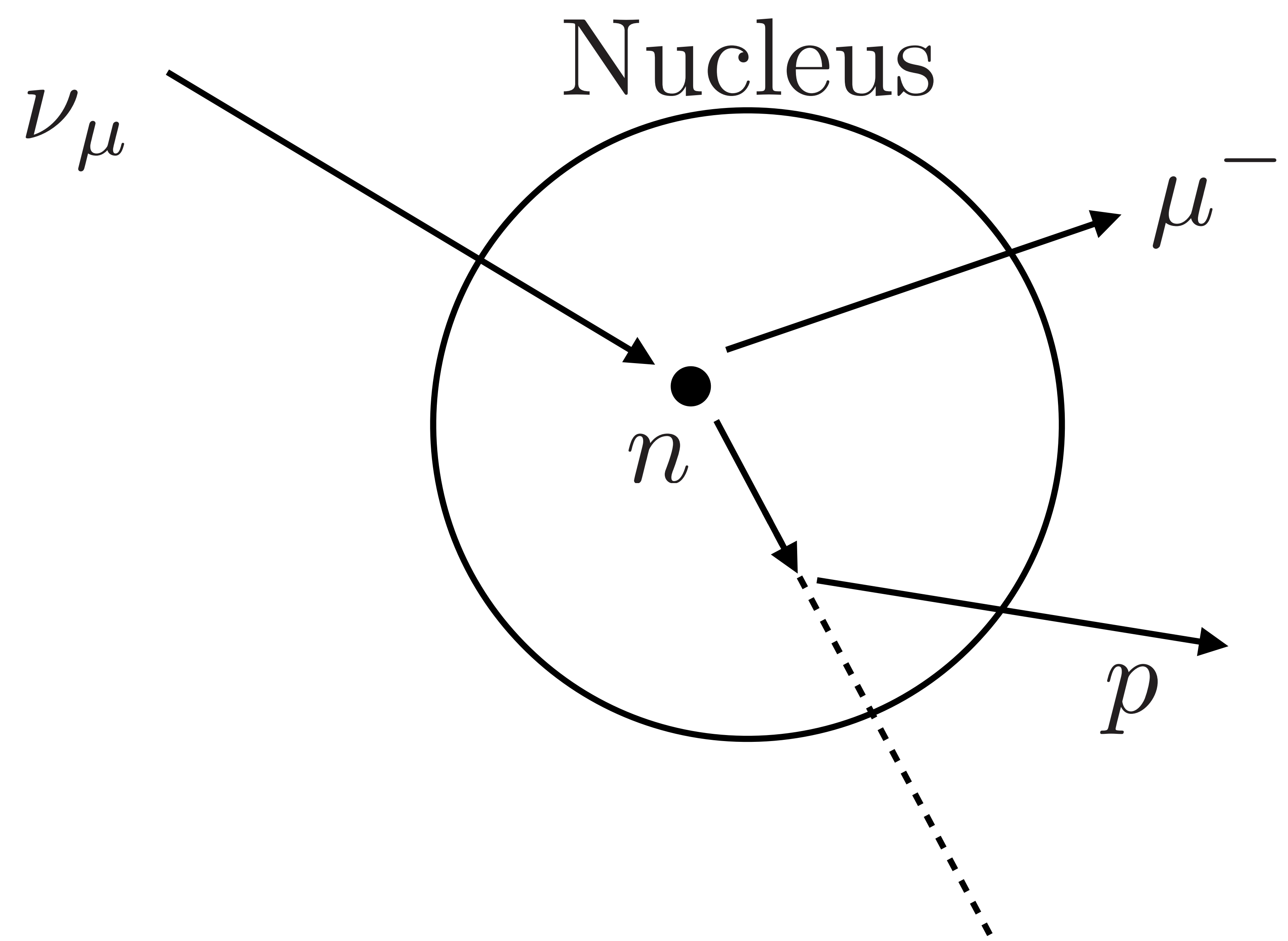
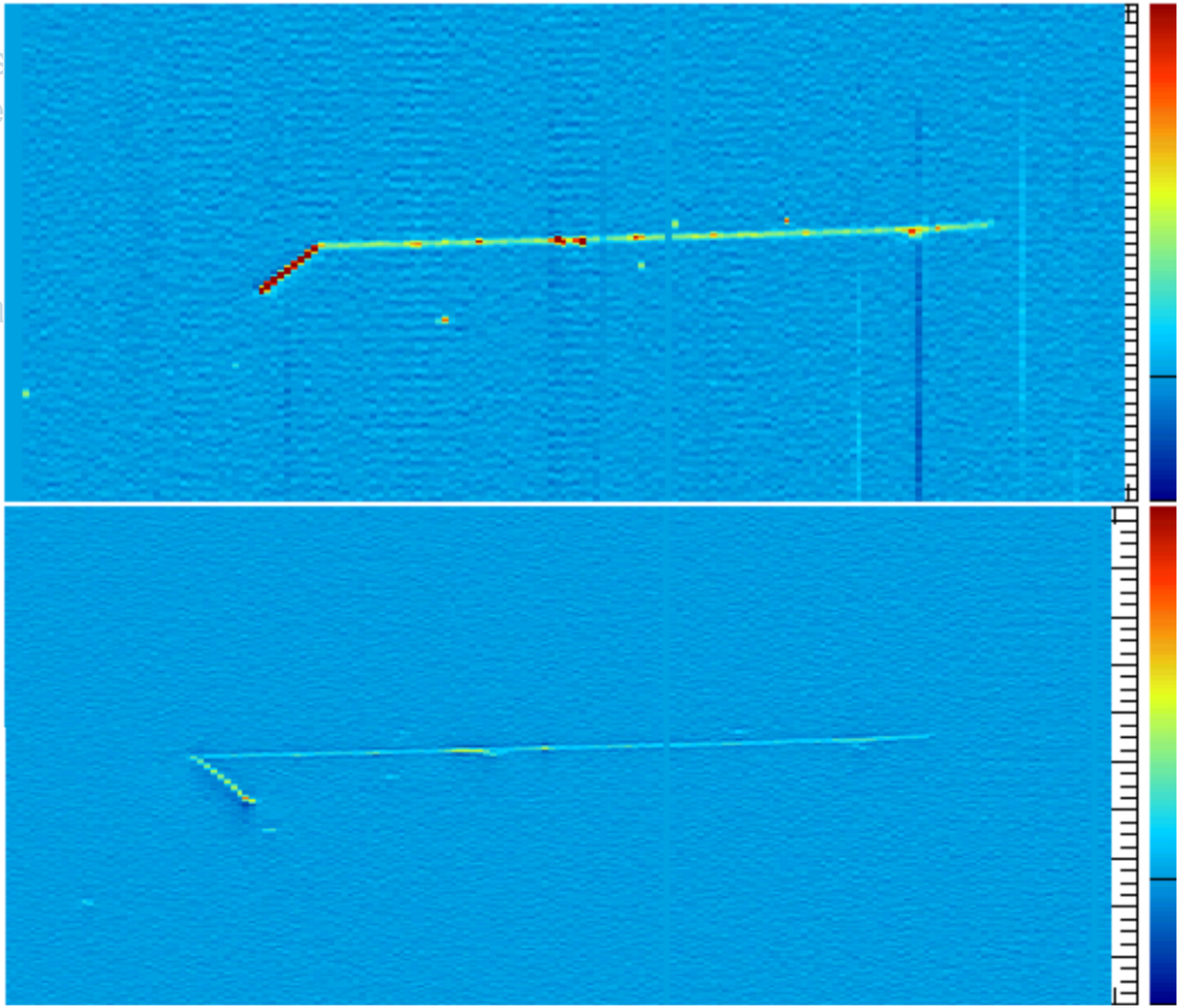


ArgoNeuT [1810.06502]

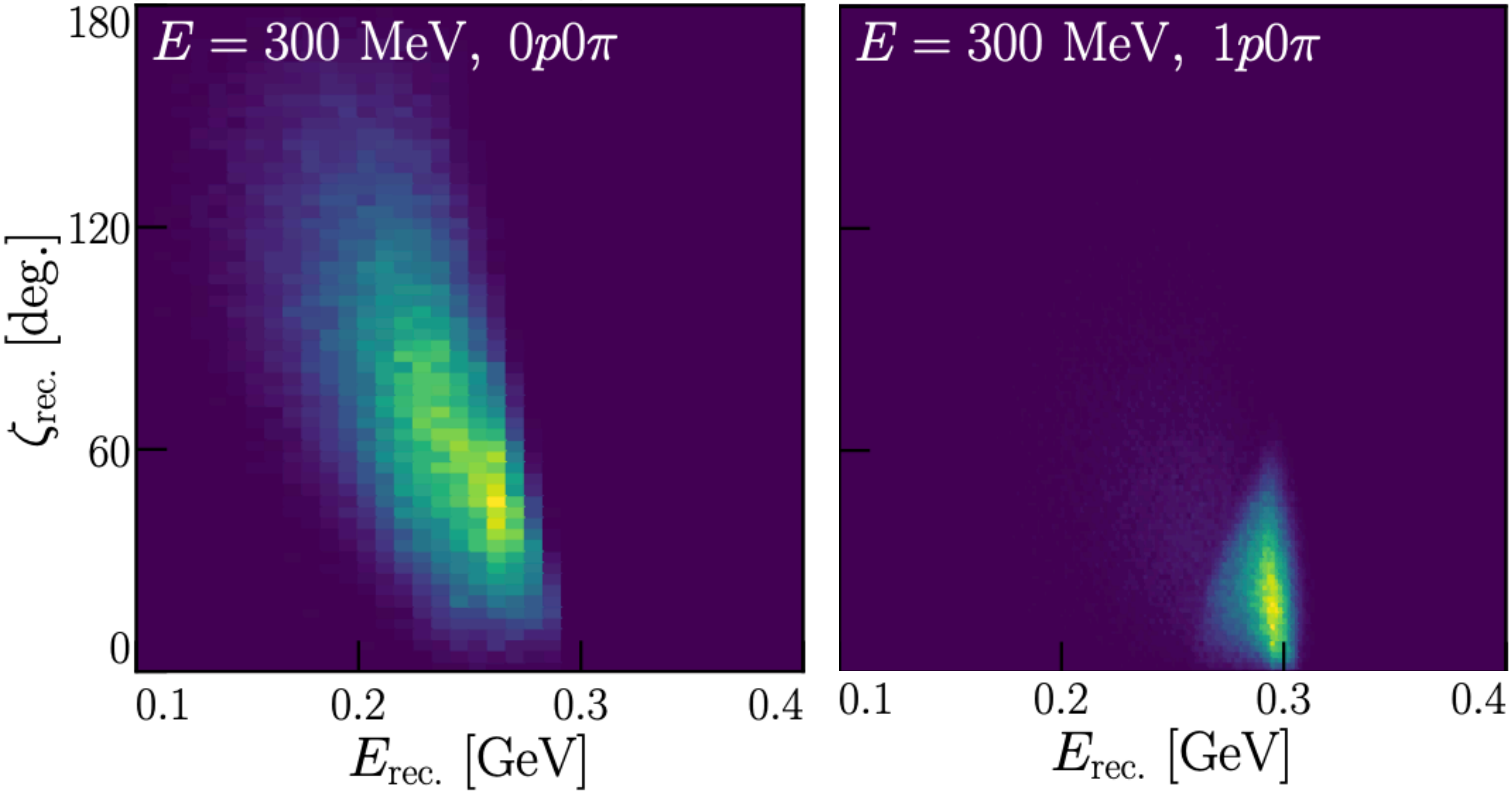


Solution — Liquid Argon TPCs. Capable of particle detection and ID to significantly lower energies.

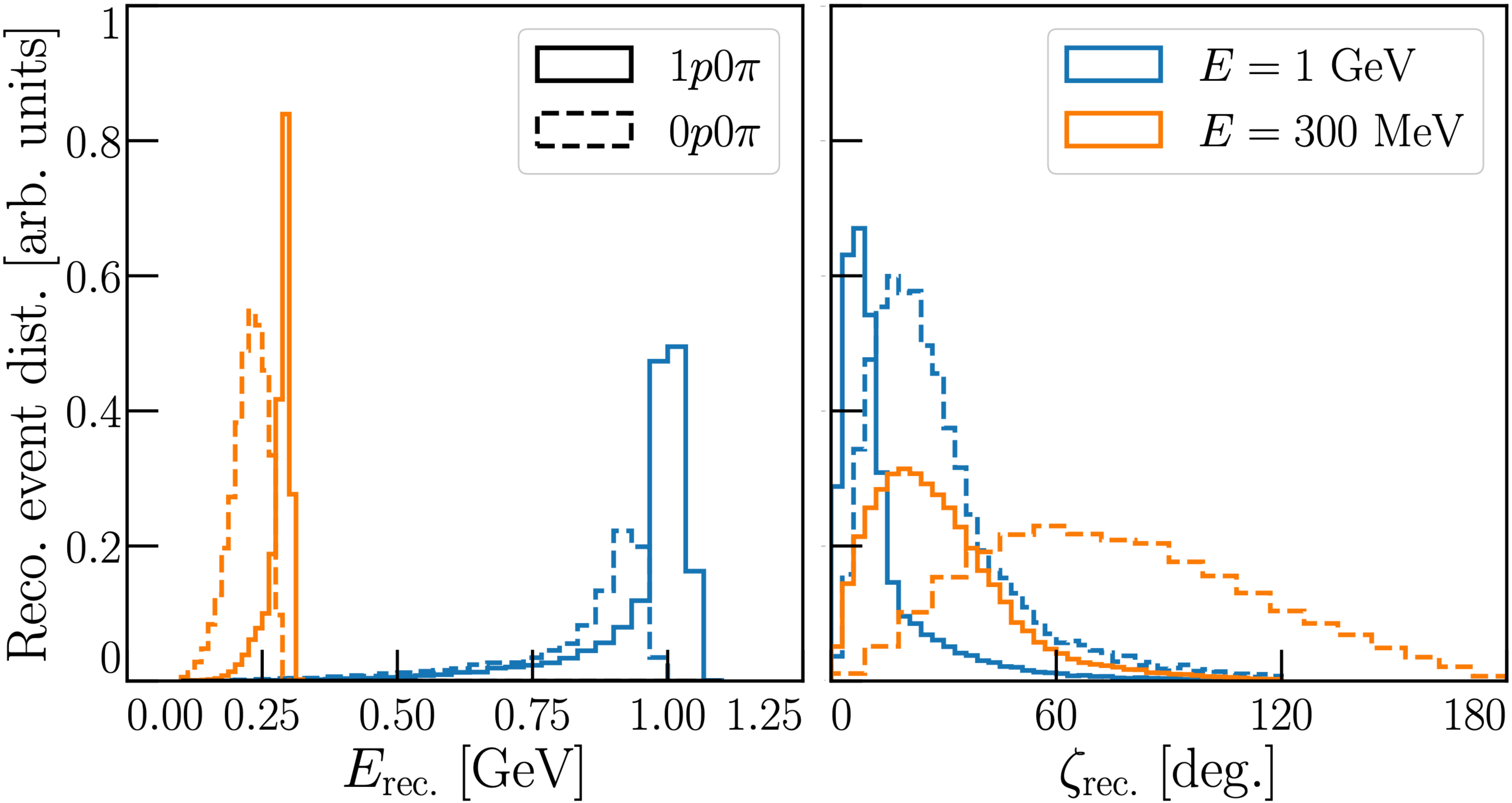
ArgoNeuT identified proton candidates down to 21 MeV of kinetic energy.

Direction/Energy Reconstruction in LArTPCs

KJK et al [2110.00003]

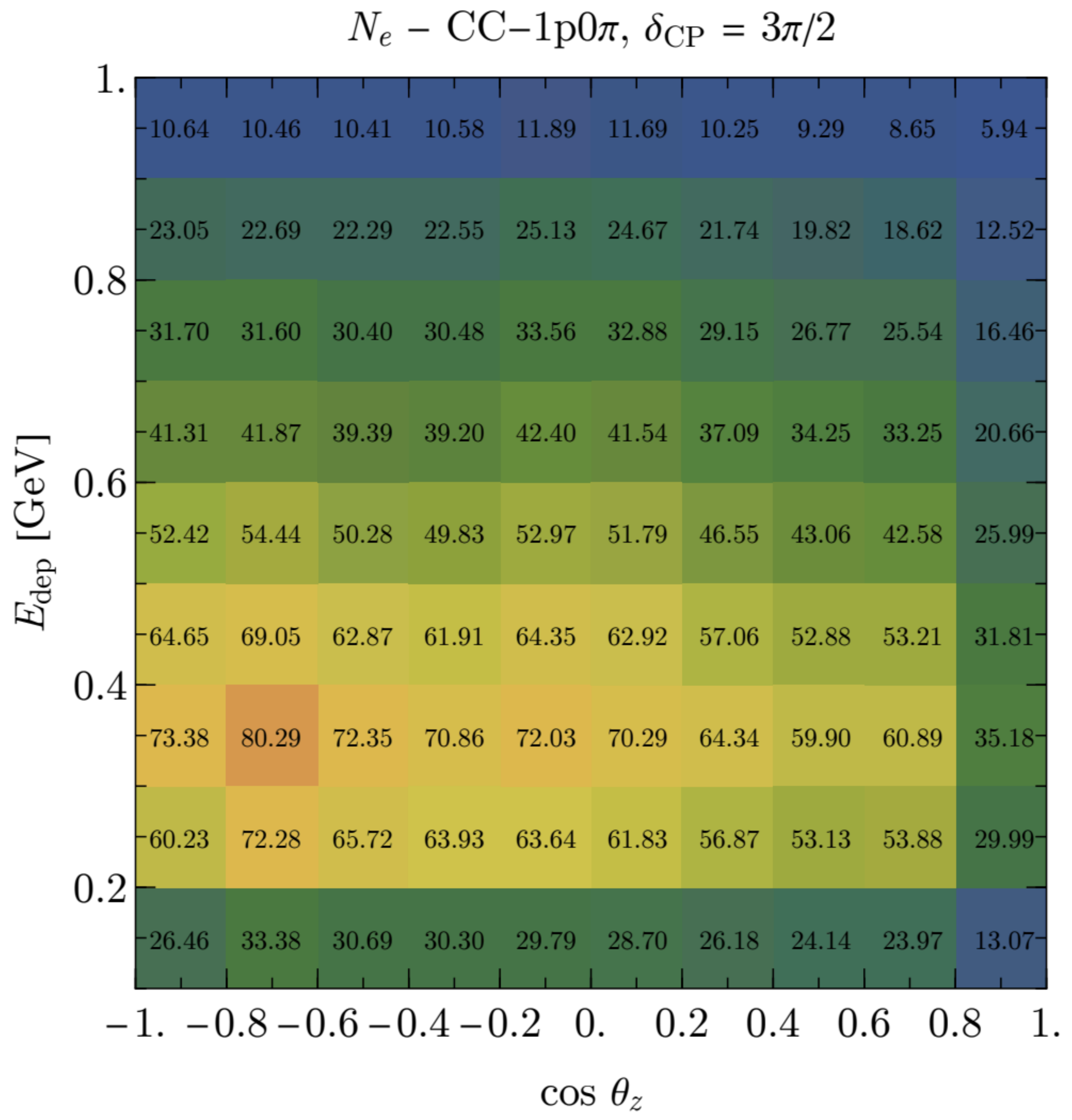


Reconstruction (1D)



Event Rates in 400 kt-yr

KJK et al [1904.02751] (PRL Supplemental Material)



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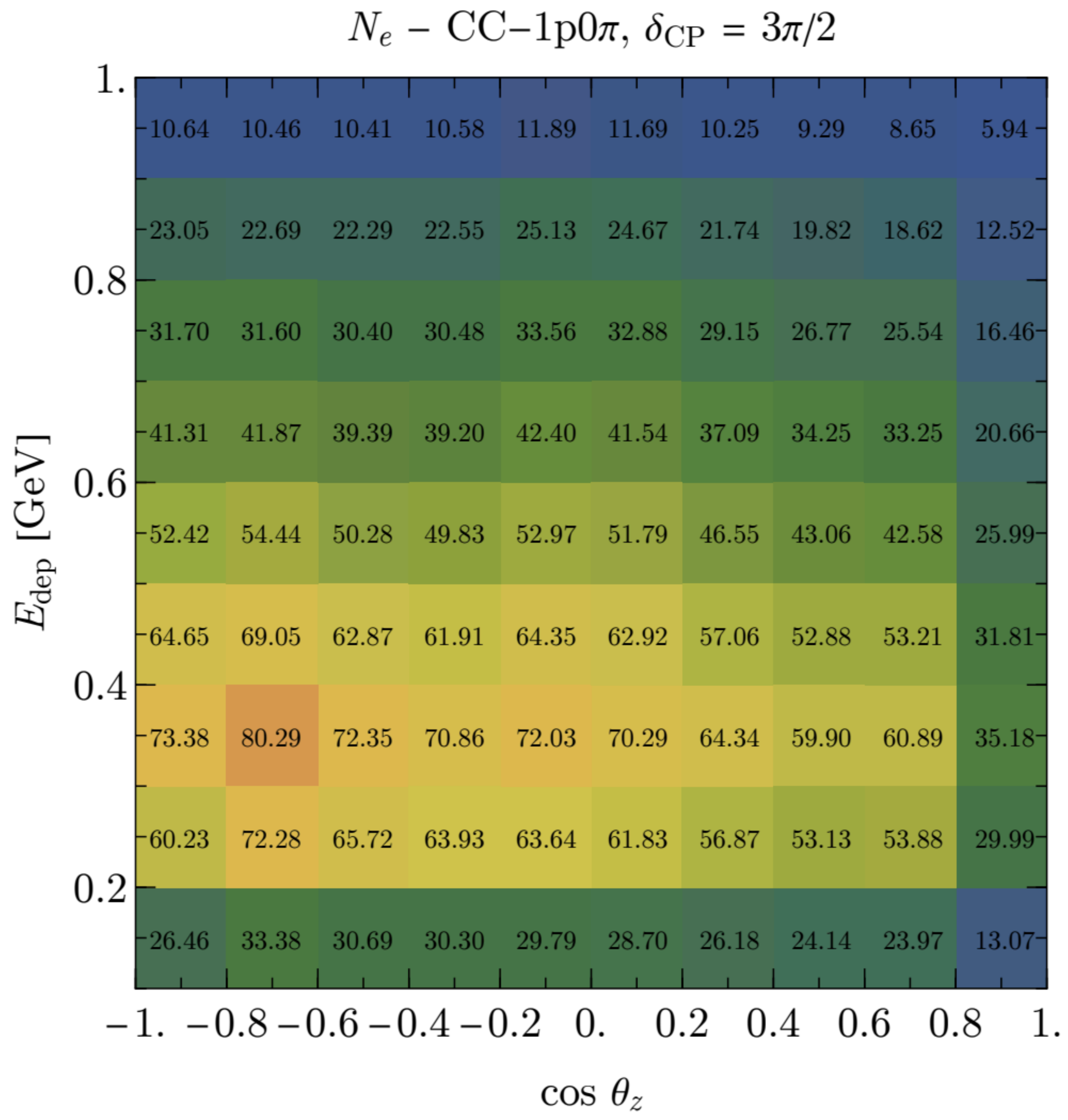
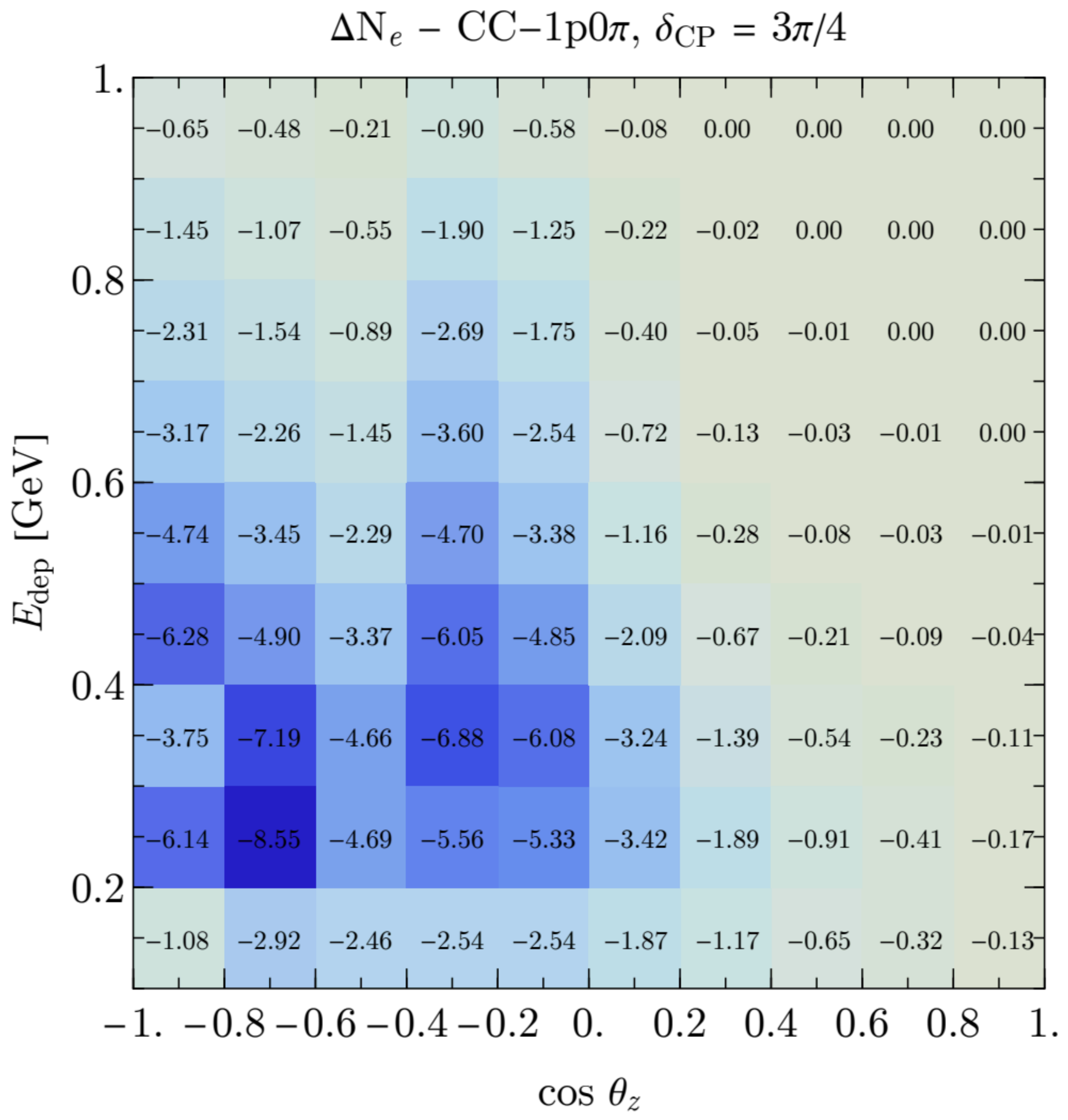




Measuring CP Violation

Goal: determine the measurement capability of 10 years' (400 kt-yr) data collection with DUNE, contrasted with beam measurements

Details:

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

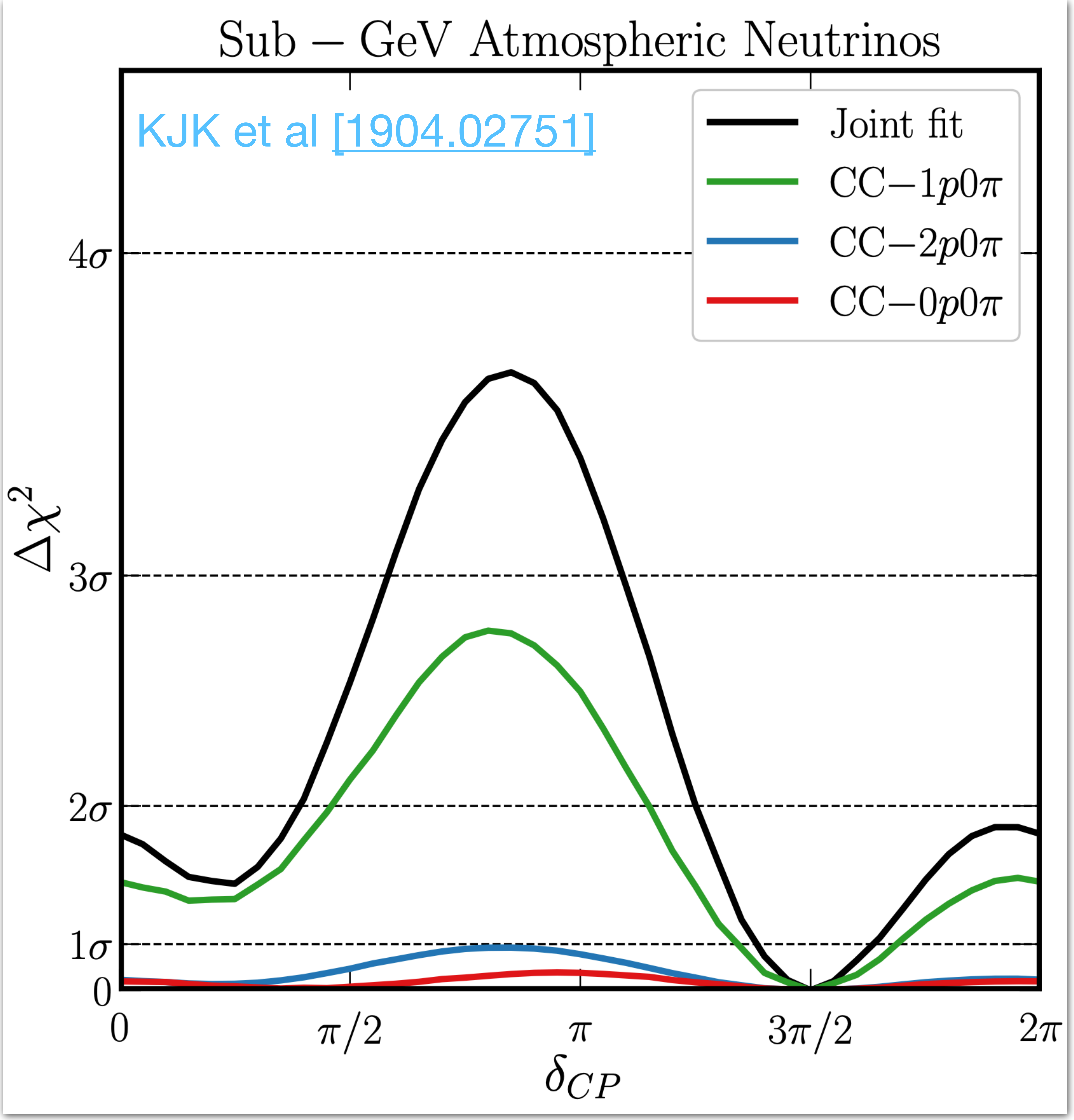
Account for uncertainties of atmospheric neutrino fluxes $\Phi_\alpha(E) = \Phi_{\alpha,0}\, f_\alpha(E) \left(\frac{E}{E_0}\right)^\gamma$

40% normalization, 5% e/μ ratio, 2% nu/nubar ratio, ± 0.2 spectral distortion coefficient

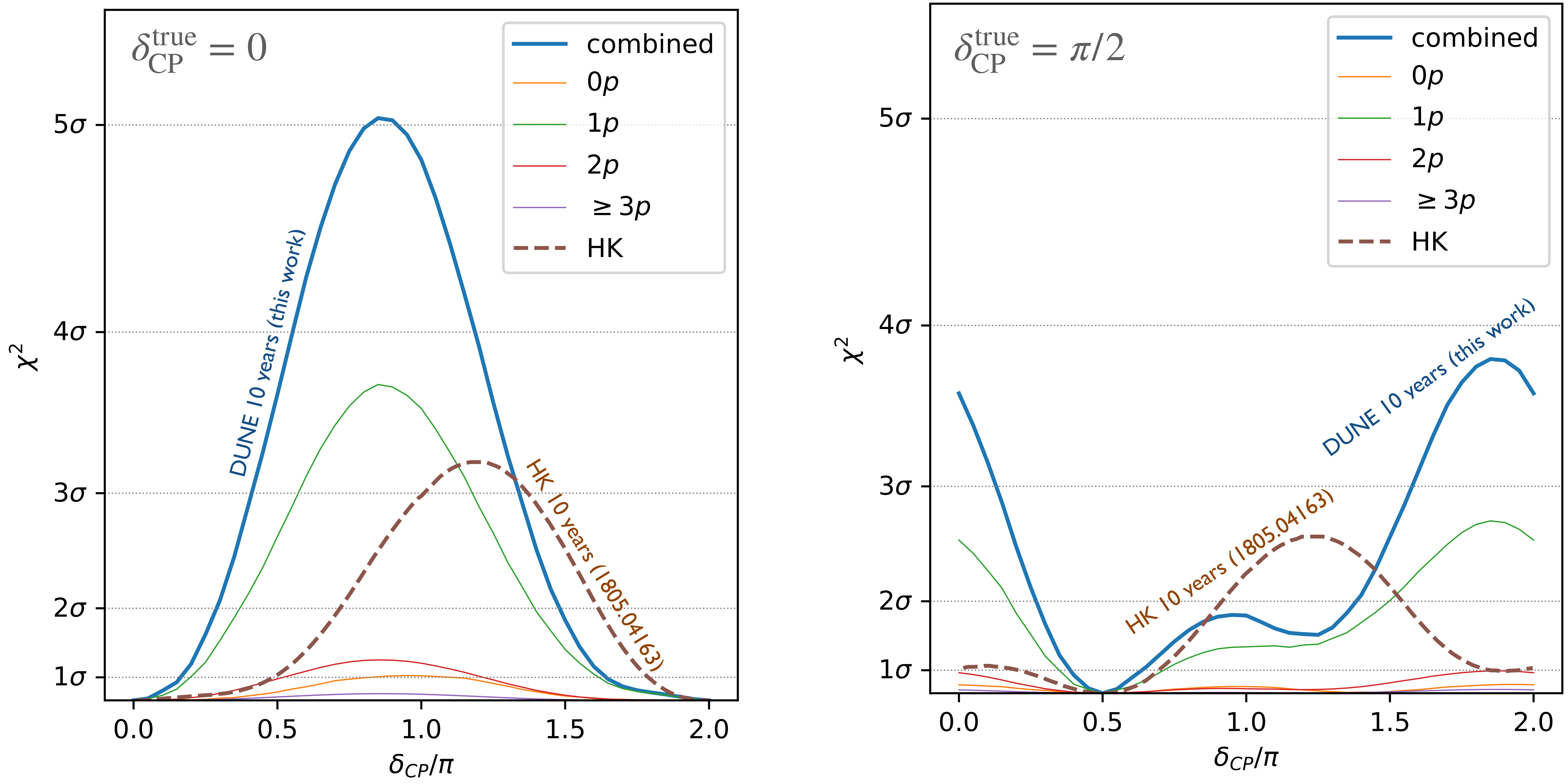
Realistic LArTPC capabilities

Δp = 5%, 5%, 10%, $\Delta\theta$ = 5°, 5°, 10°, for e, μ, p, K_p = 30 MeV

Classify events by final state topology (number of protons)



Contrast with HK Projections



KJK et al [1904.02751]

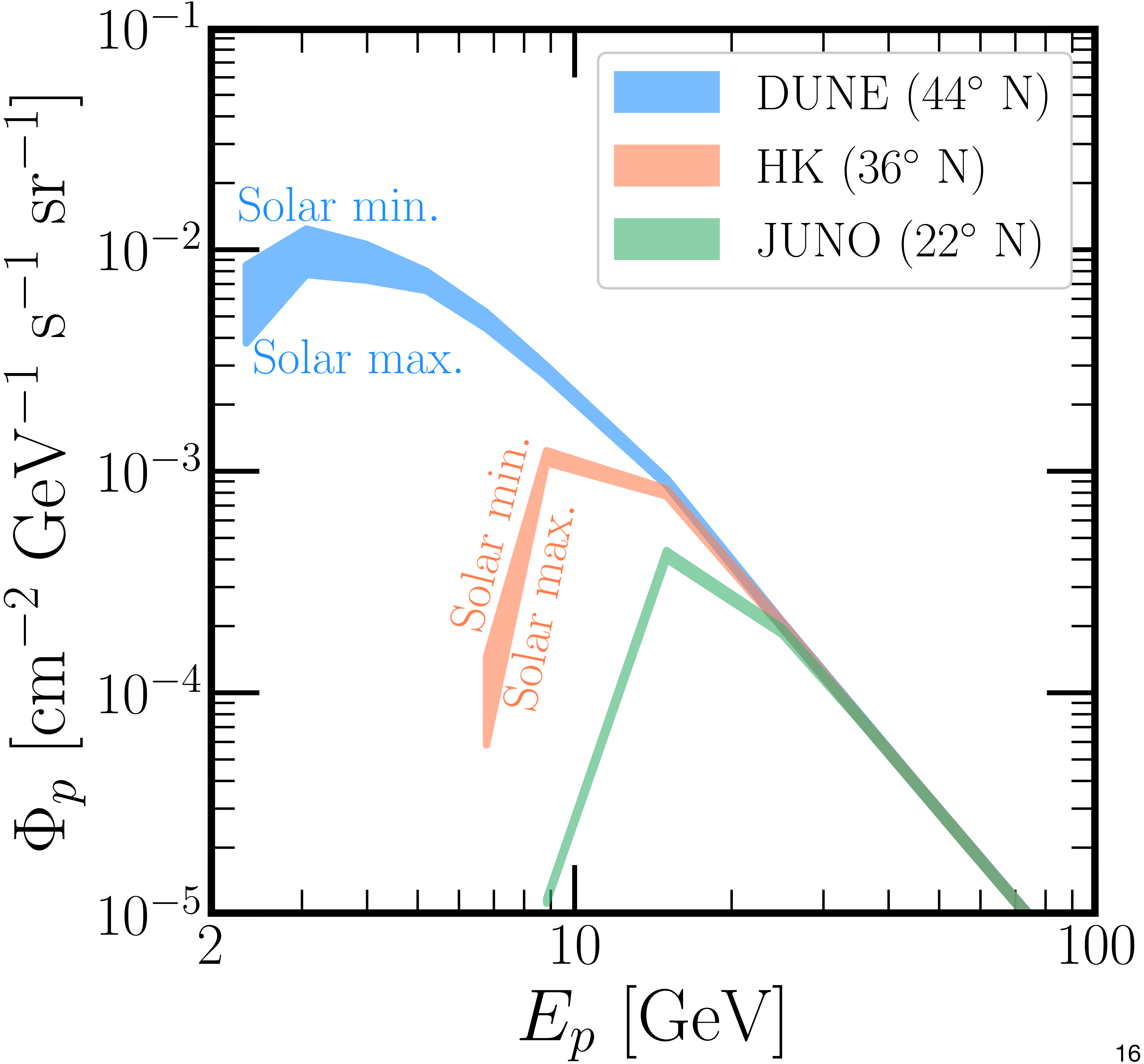
Connections to the Solar Cycle

[2304.04689] — with P.A.N. Machado, **Nityasa Mishra**, L. Strigari, and **Yi Zhuang**

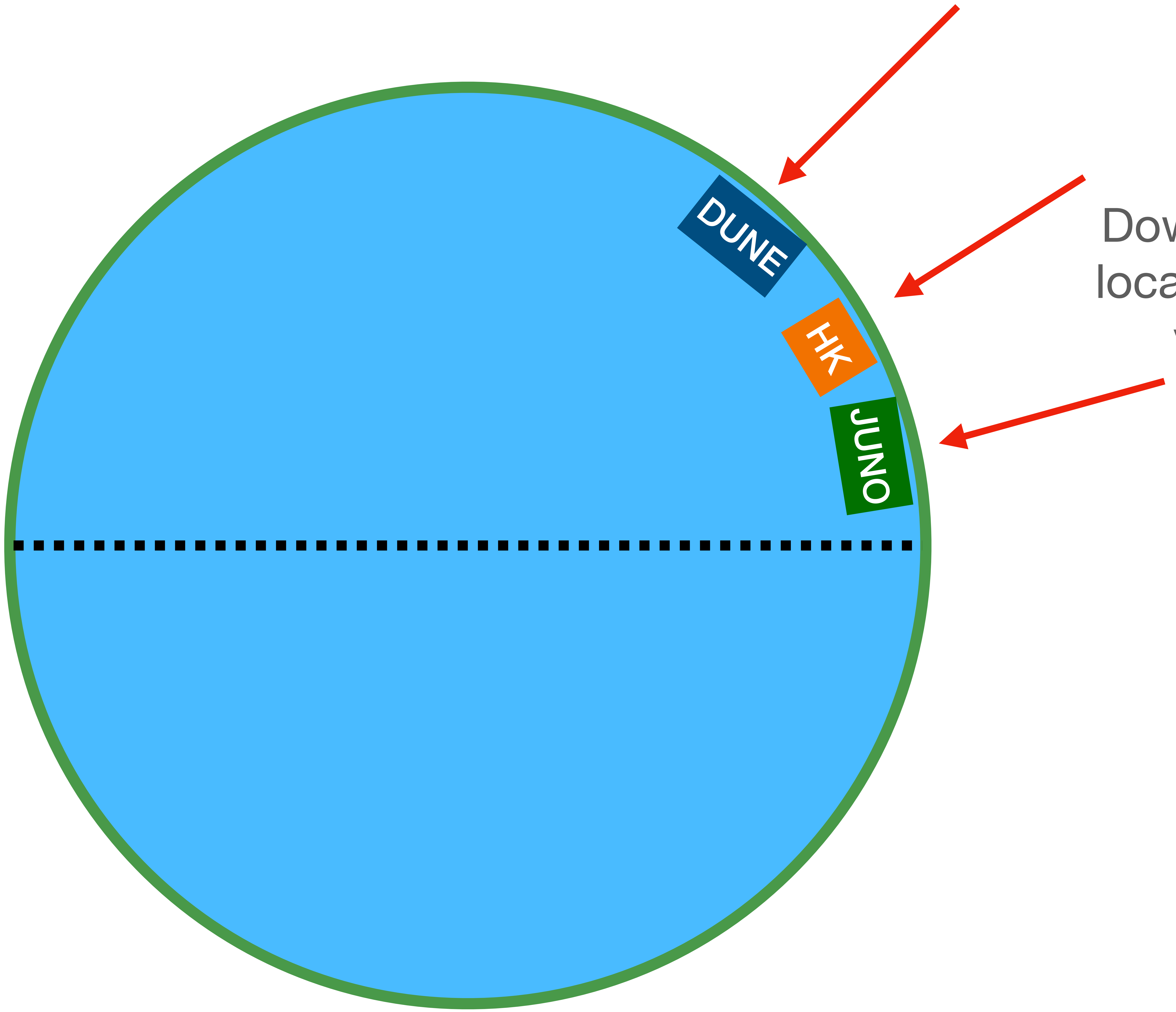
Magnetic fields & Cosmic Rays

Downward-going neutrino flux at a location is tied to the rigidity of the magnetic field there —lower rigidity means that lower-energy protons can contribute to the neutrino flux at that location

Lower-energy CRs — more variance over the course of the solar cycle (11 years)



Up- vs. Down-going Fluxes



Downward-going flux at each detector location won't oscillate (much) and can vary a lot depending on latitude

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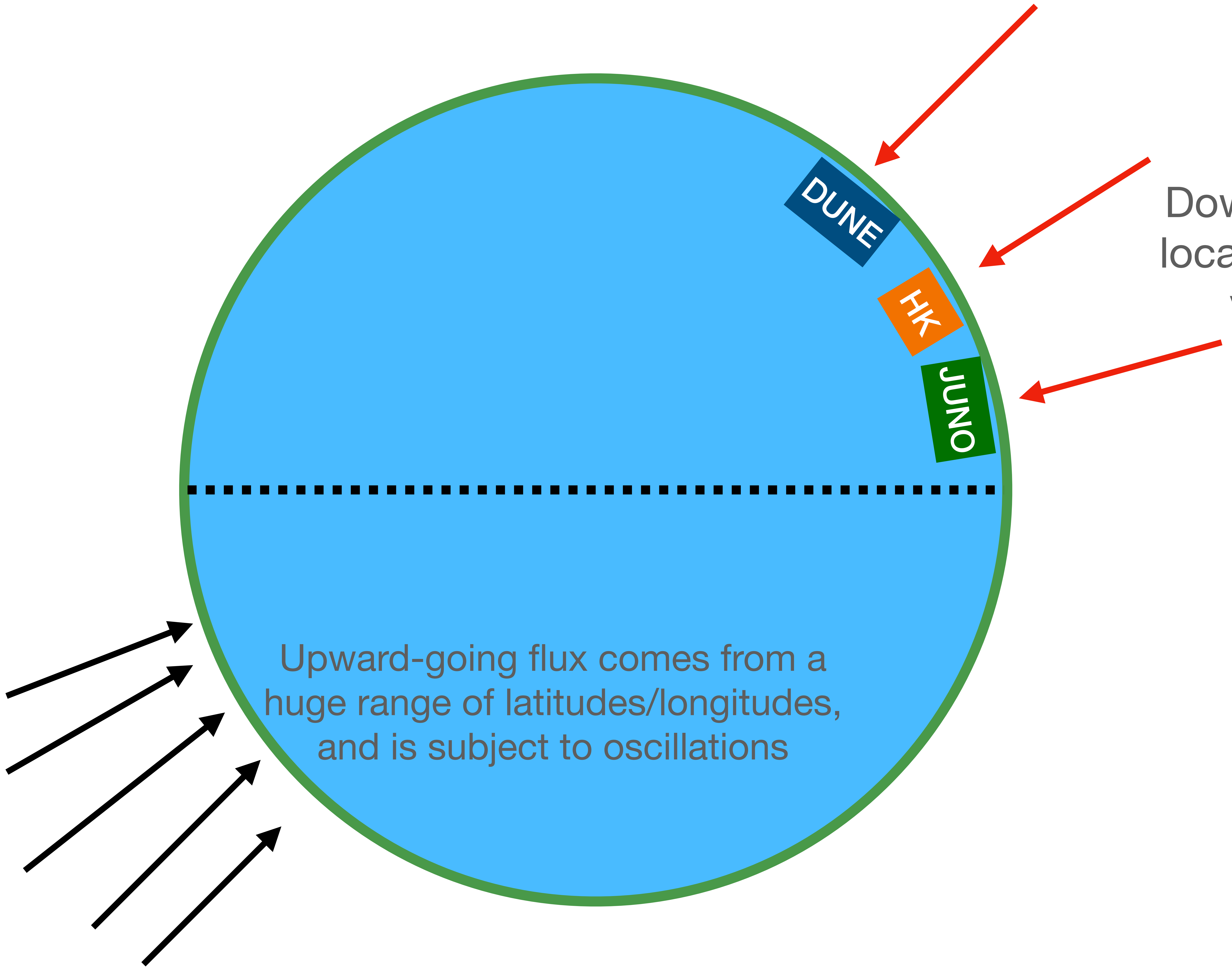

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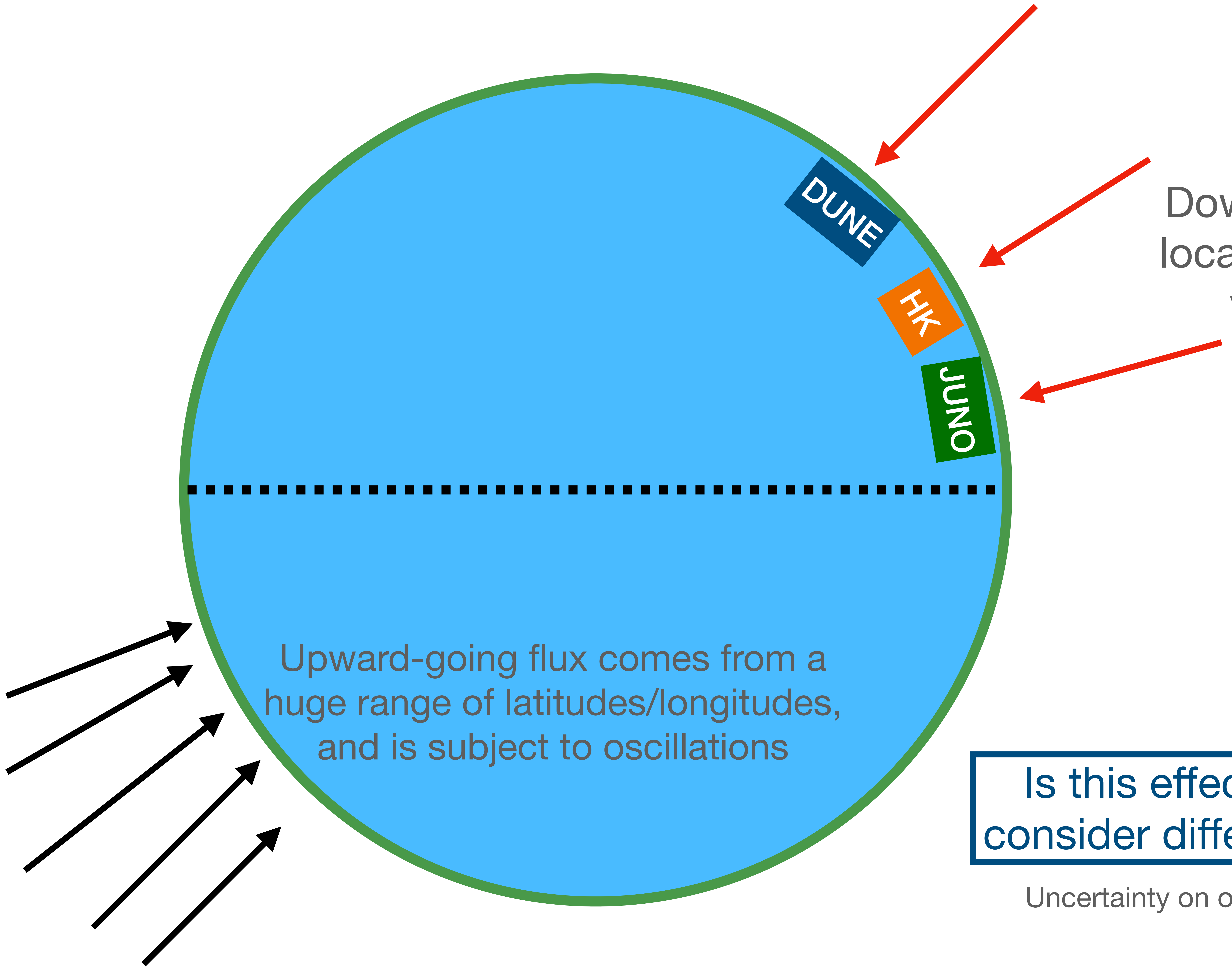

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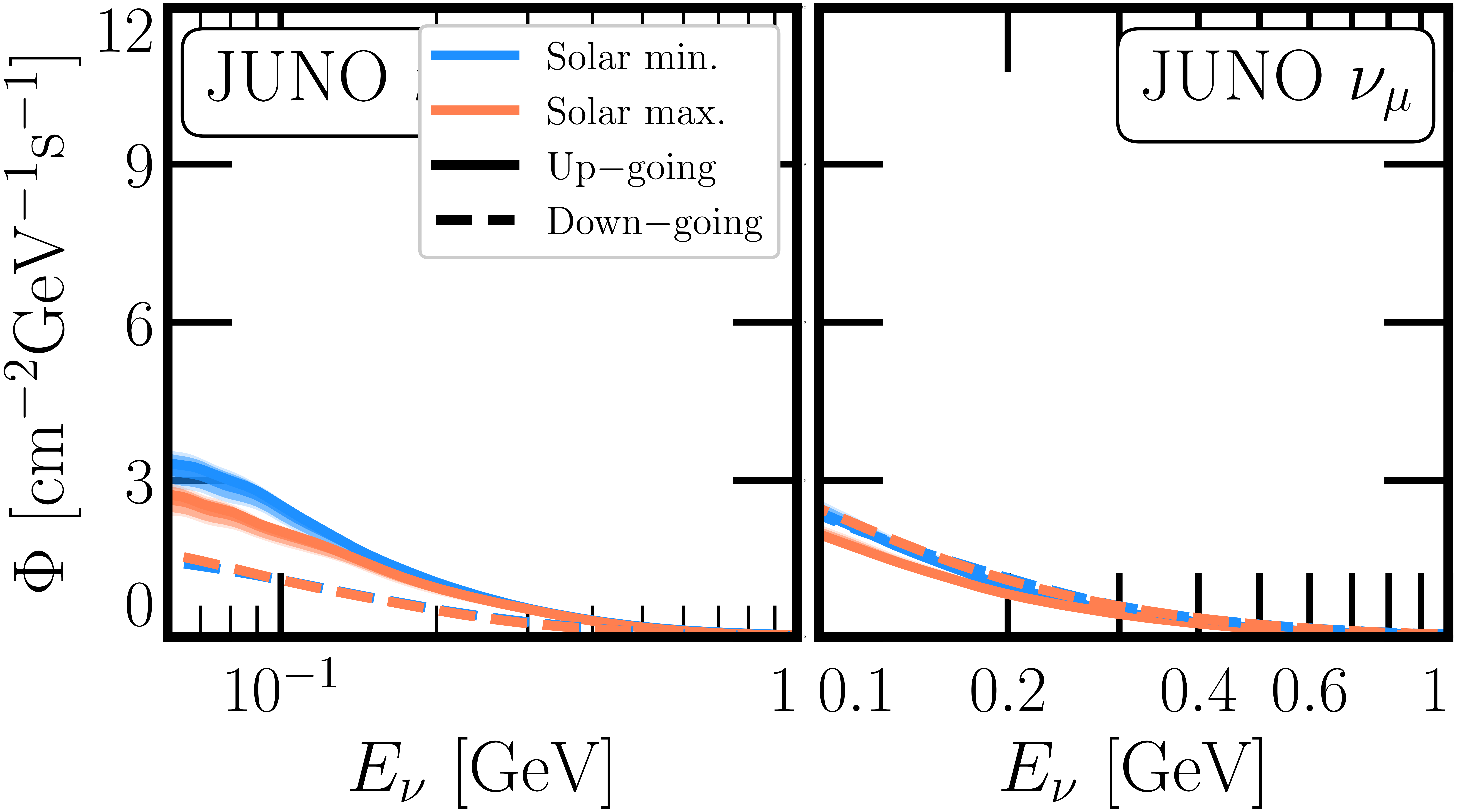
Is this effect measurable? Is it robust if we consider different oscillation parameters, etc.?

Uncertainty on oscillation parameters (today's knowledge): NuFit

Fluxes at Detector Locations



Downward-going fluxes vary significantly based on detector location — significant modulation.

Upward fluxes look very similar because they sample all over the globe (plus oscillations)

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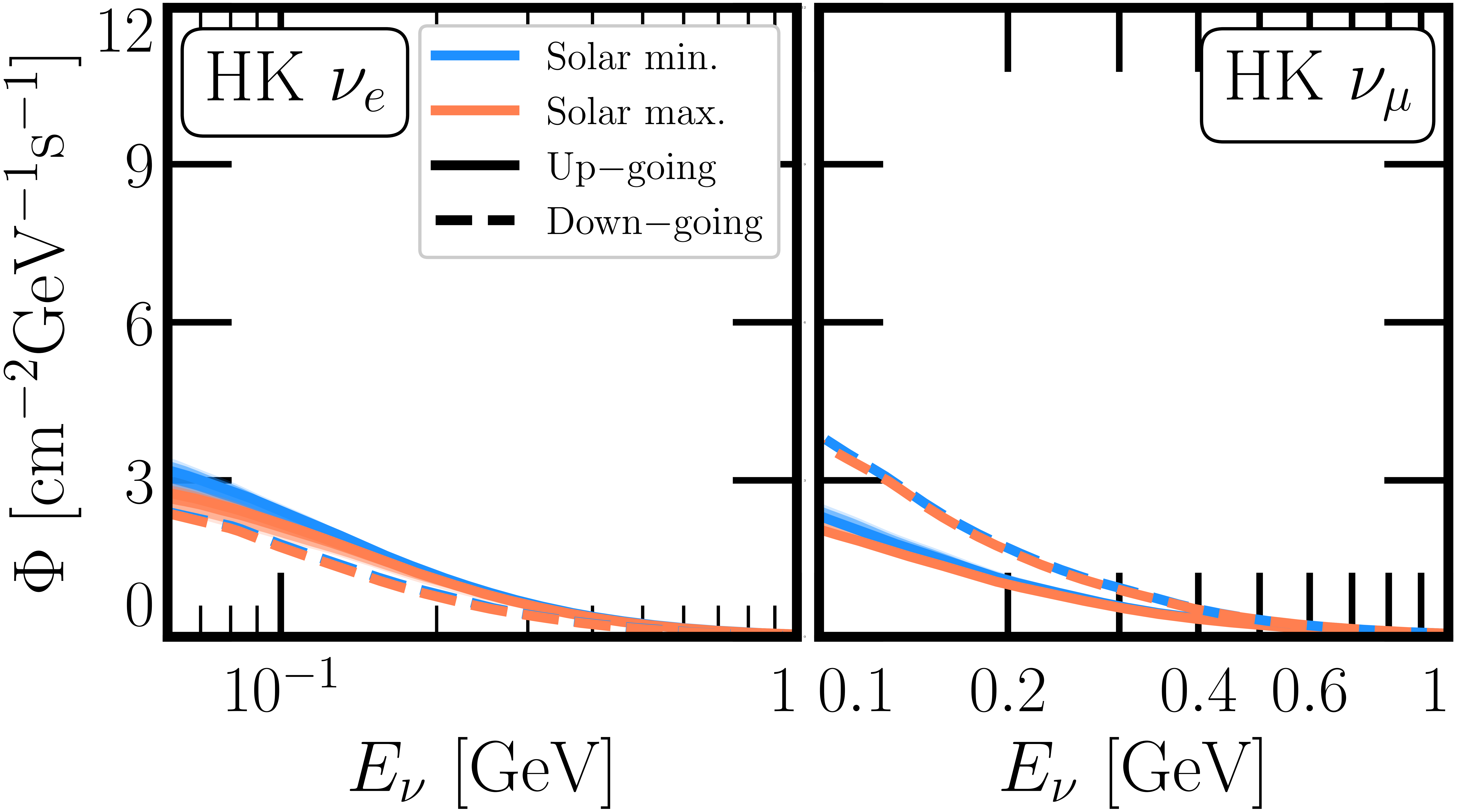

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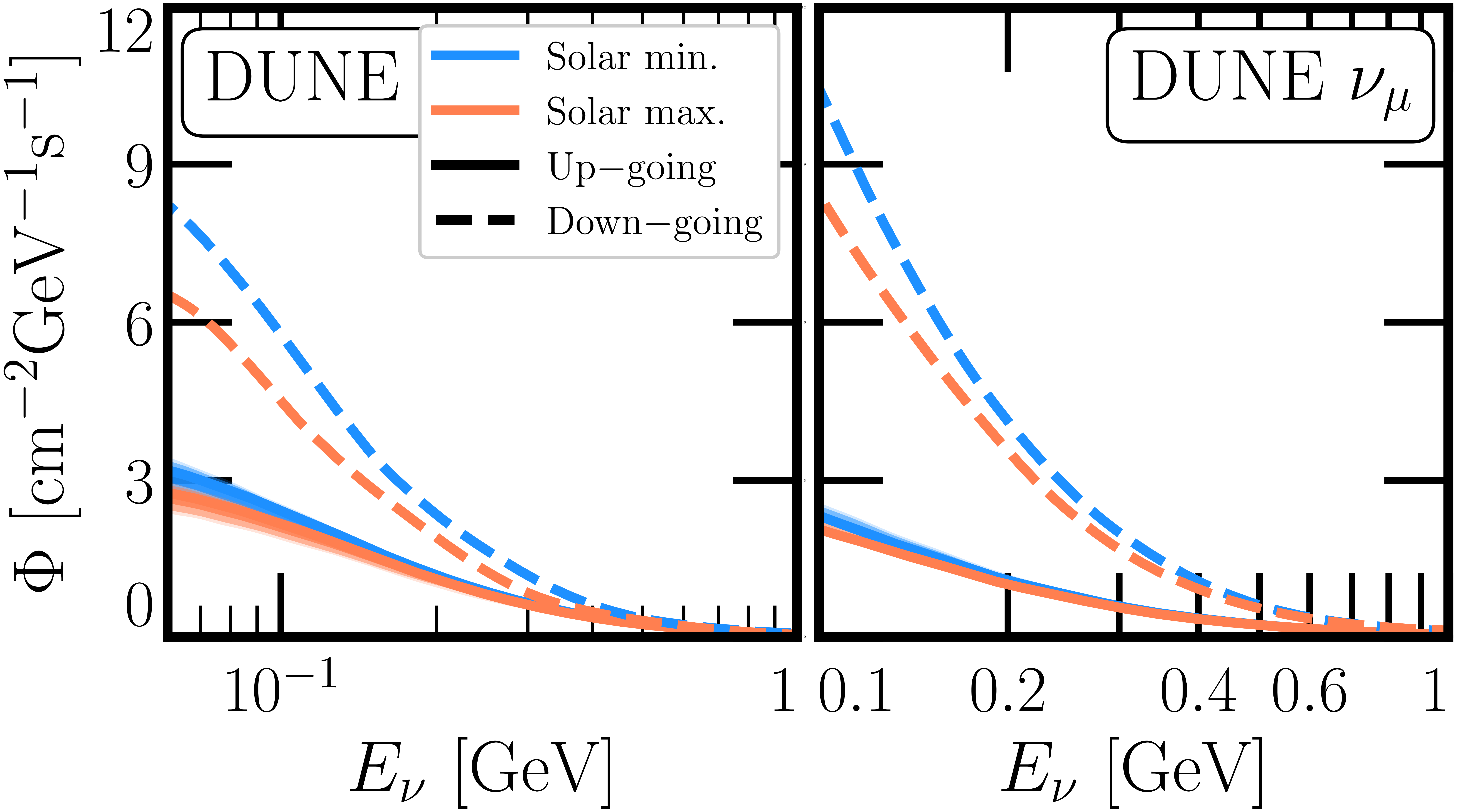

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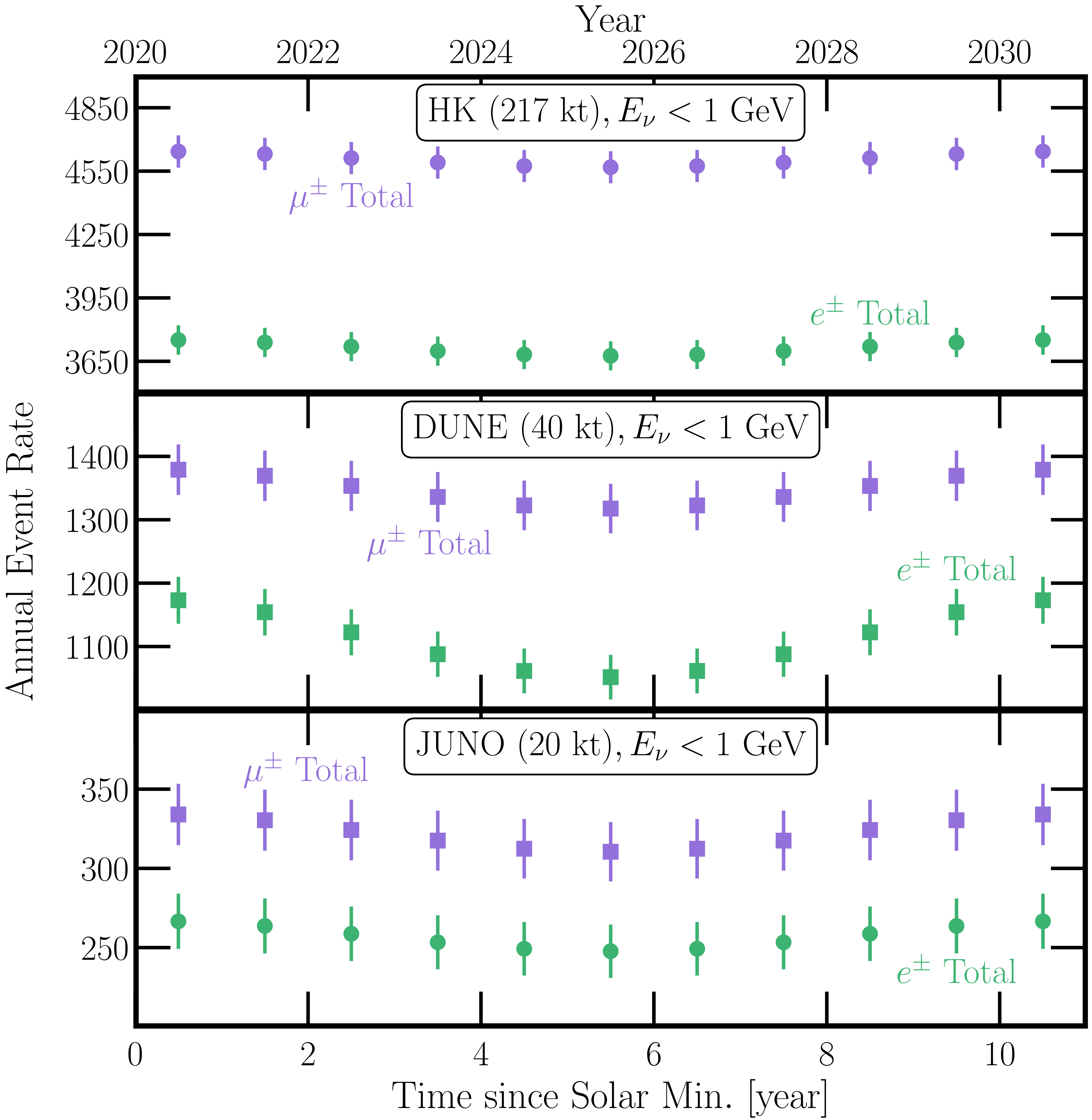


Event-rate Modulation

Significant modulation in each dataset. HK sees largest statistics, but smallest predicted fractional modulation.

HK: 2.0σ

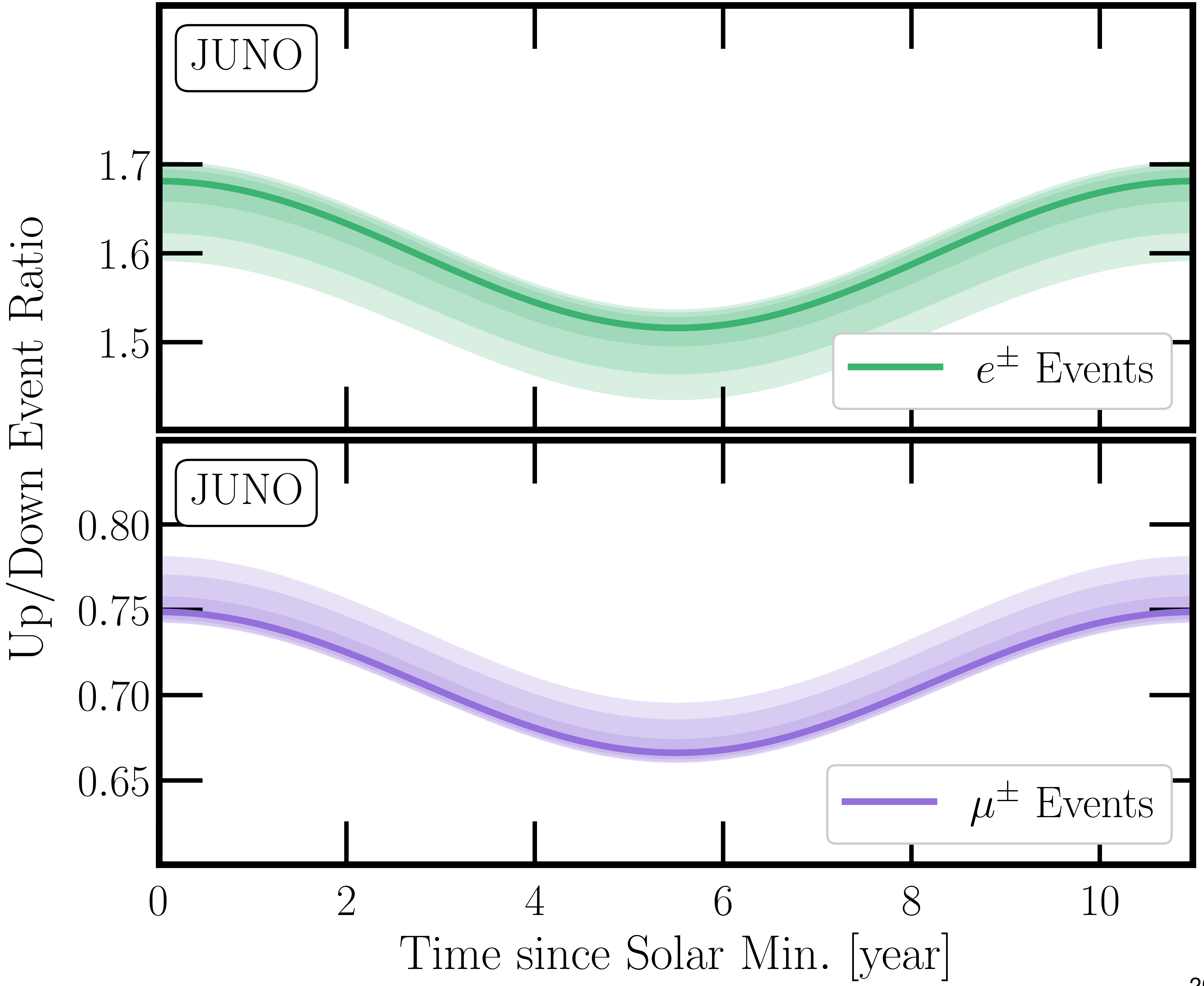
DUNE: 4.8σ

JUNO: 2.0σ

Up/Down Ratio

Thick line: median expectation as solar cycle varies.

Shaded regions: variance of oscillation parameters given *current* knowledge



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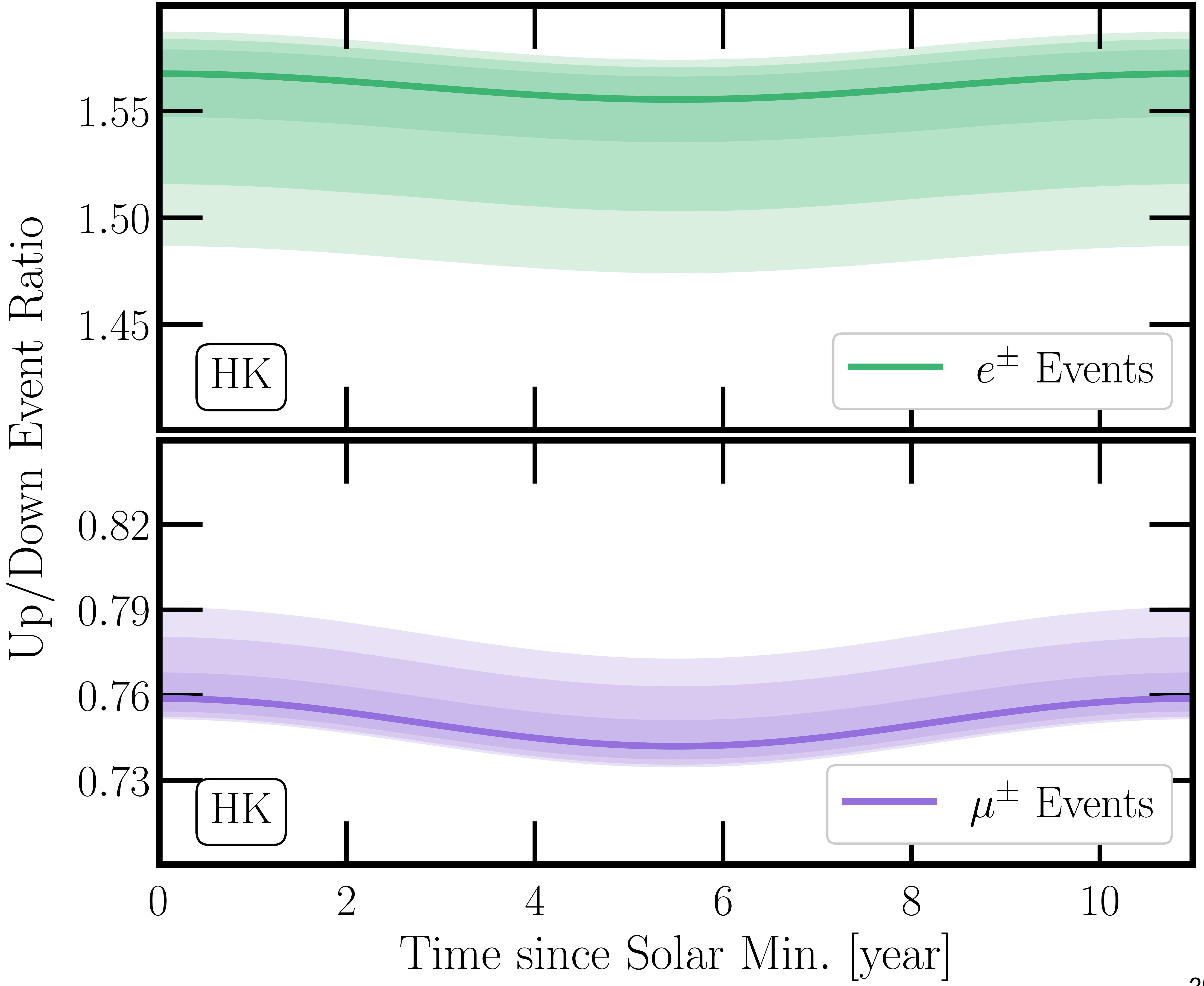

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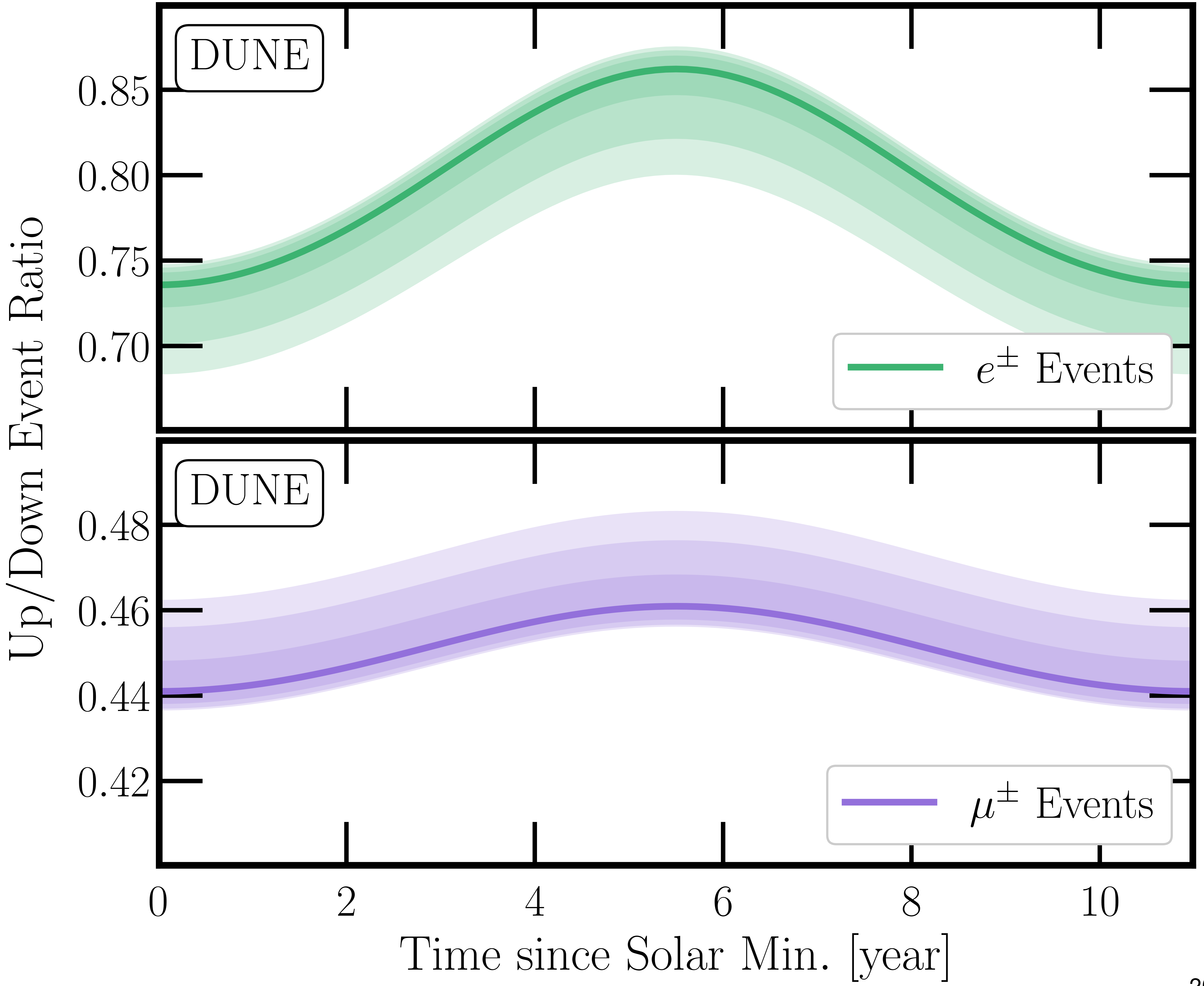
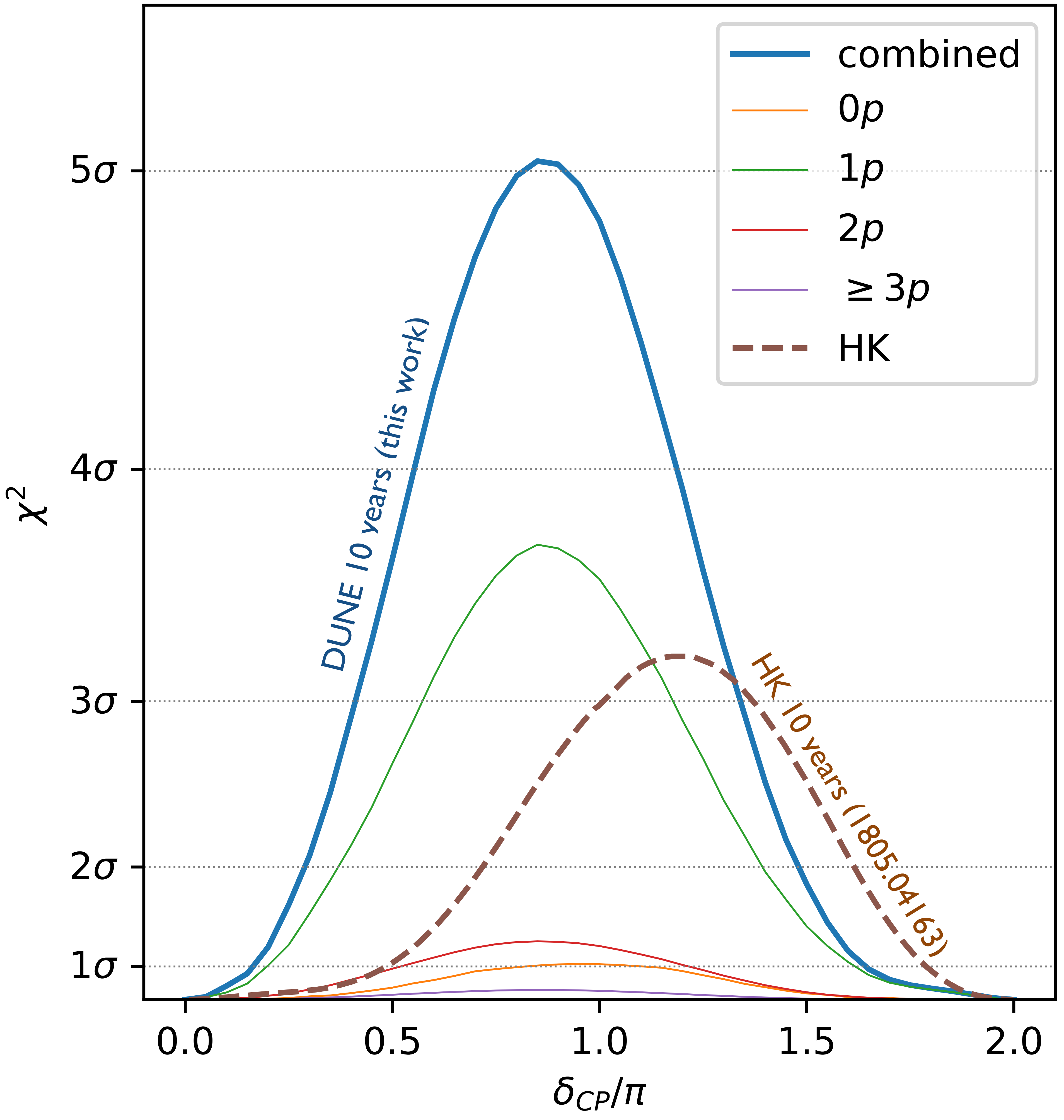


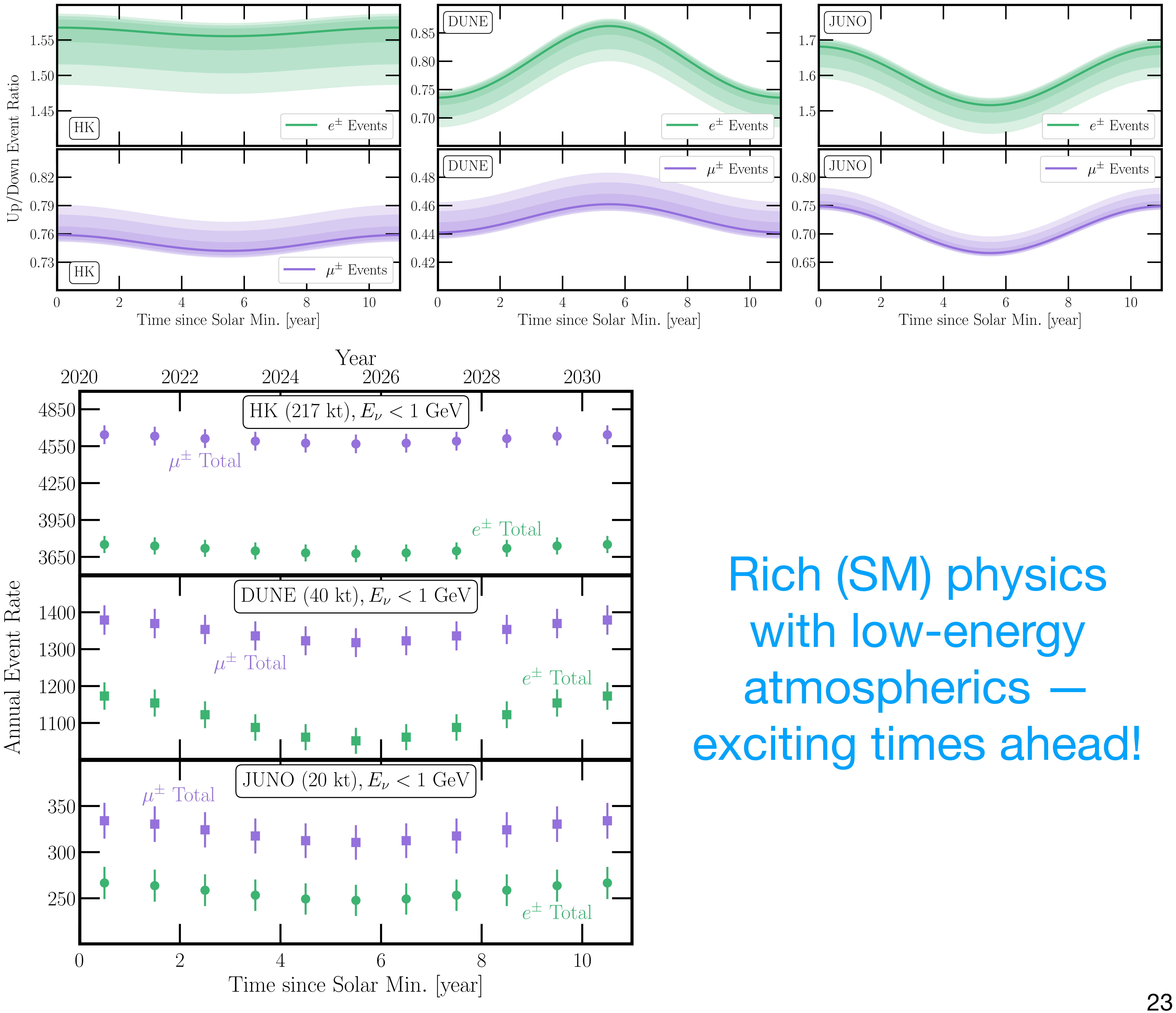
Three Comparisons

Combined measurement in three detectors — strong evidence for connection between atmospheric neutrinos and solar cycle variance

Takeaways

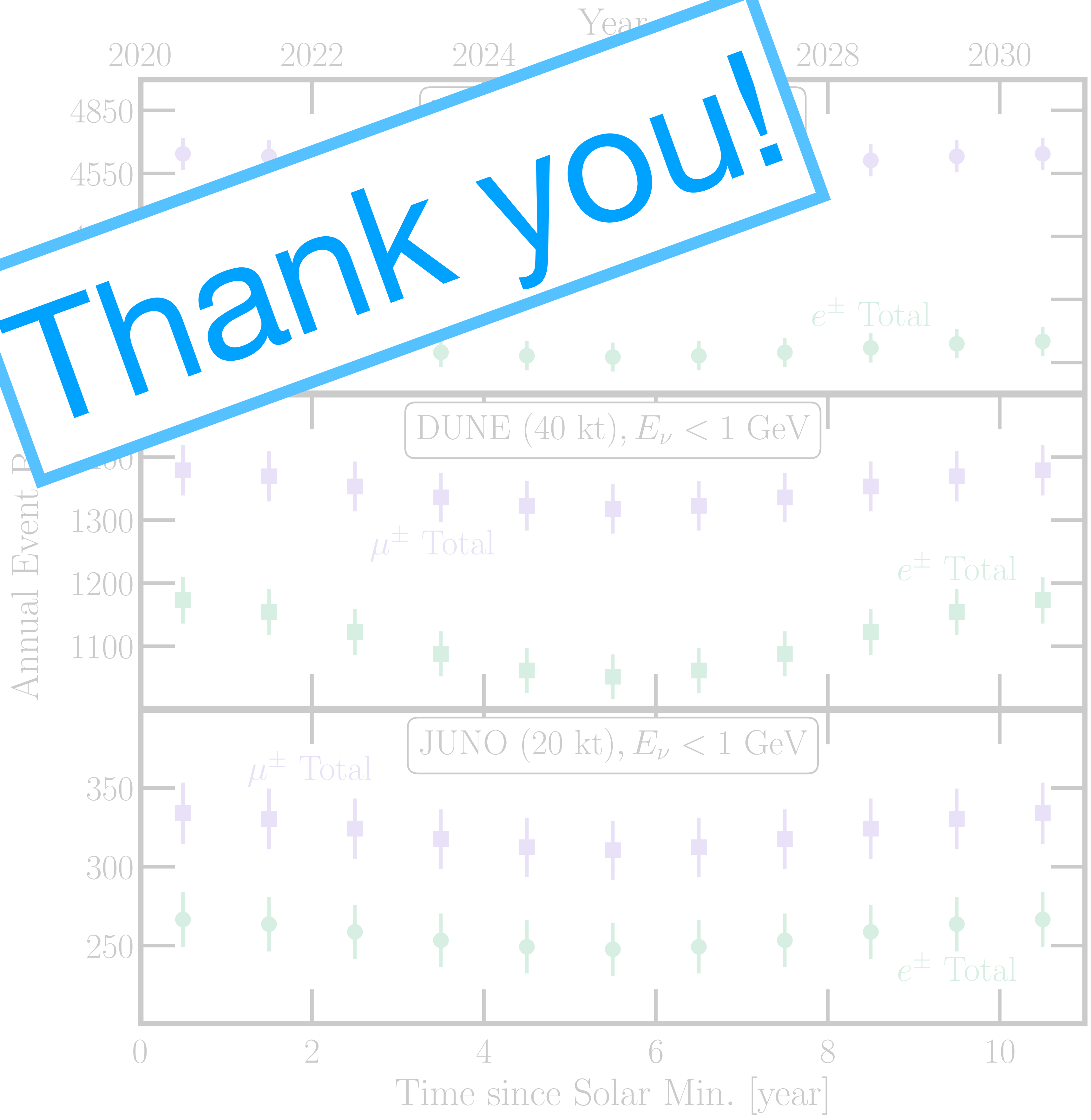
Conclusions





Rich (SM) physics with low-energy atmospherics — exciting times ahead!

Conclusions



Thank you!

Rich (SM) physics with low-energy atmospherics — exciting times ahead!

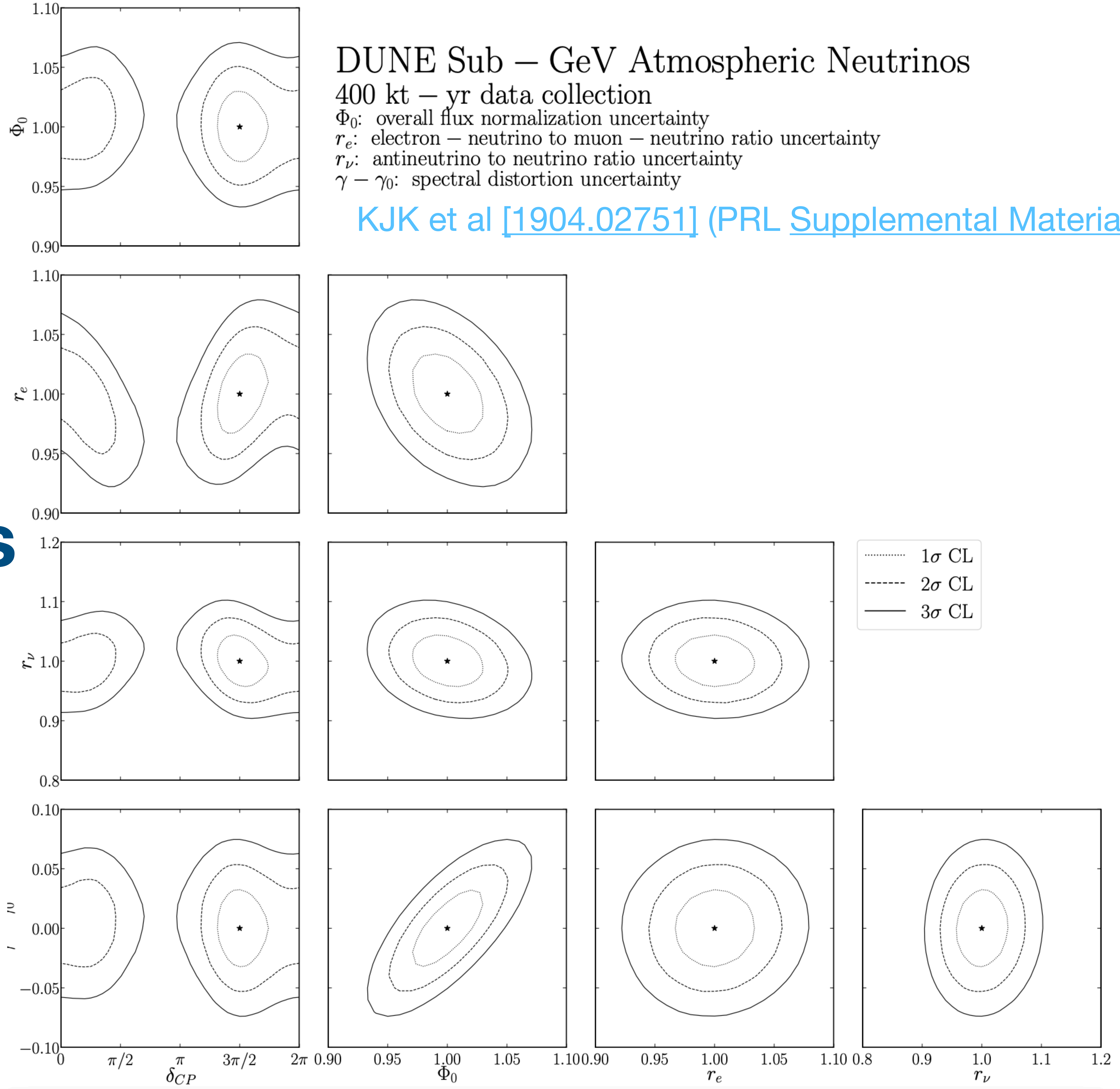
Backup

Thresholds, etc., for Particle Reconstruction

Table 1. Assumptions of DUNE Far Detector reconstruction and identification capability that enter our analysis.

Particle	Minimum K.E.	Angular Uncertainty	Energy Uncertainty
Proton	30 MeV	10°	10%
Pion	30 MeV	10°	10%
Λ	30 MeV	10°	10%
$\mu^\pm$	5 MeV	2°	5%
$e^\pm$	10 MeV	2°	5%

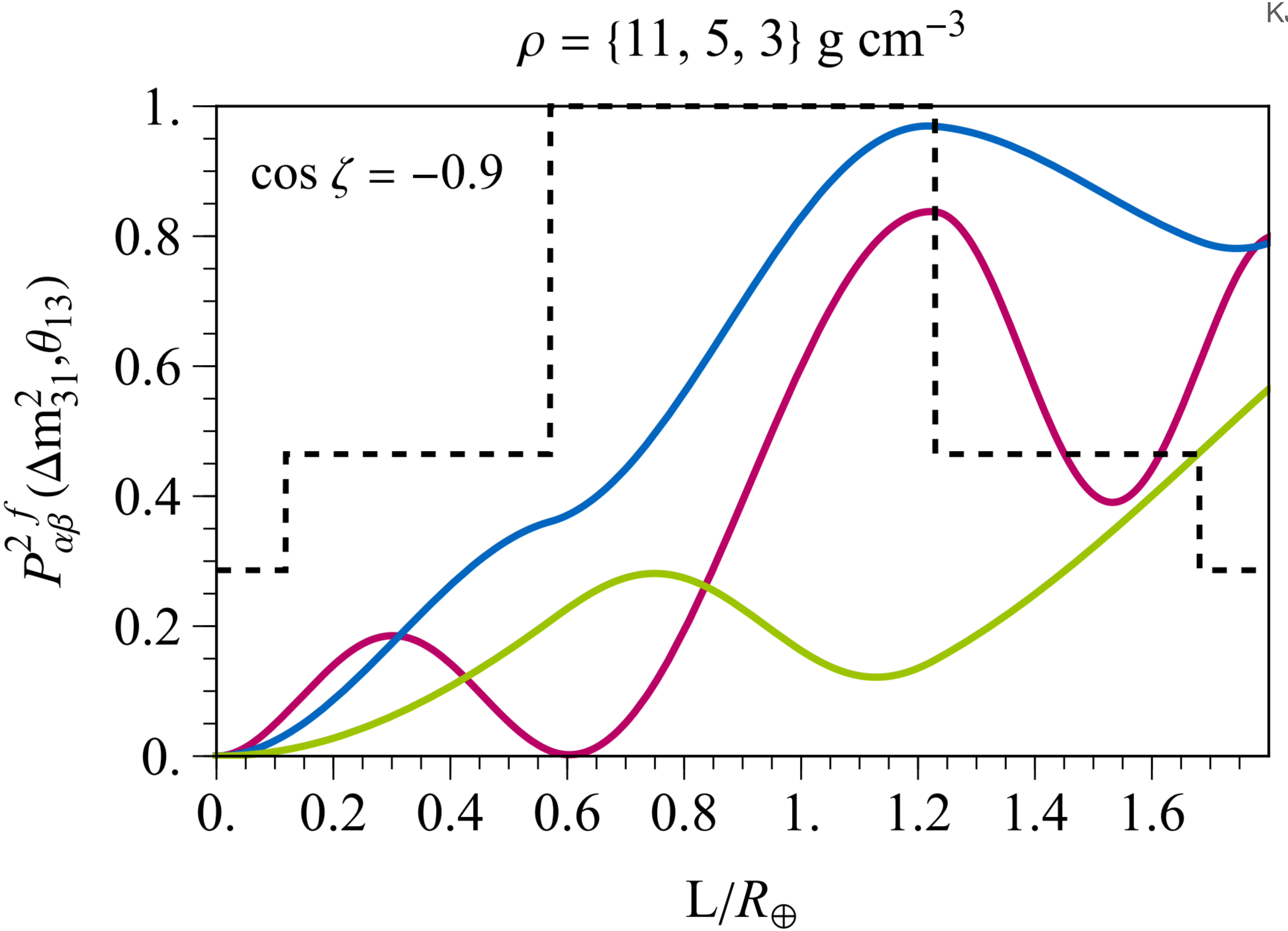
Sub-GeV Systematics



KJK et al [1904.02751] (PRL Supplemental Material)

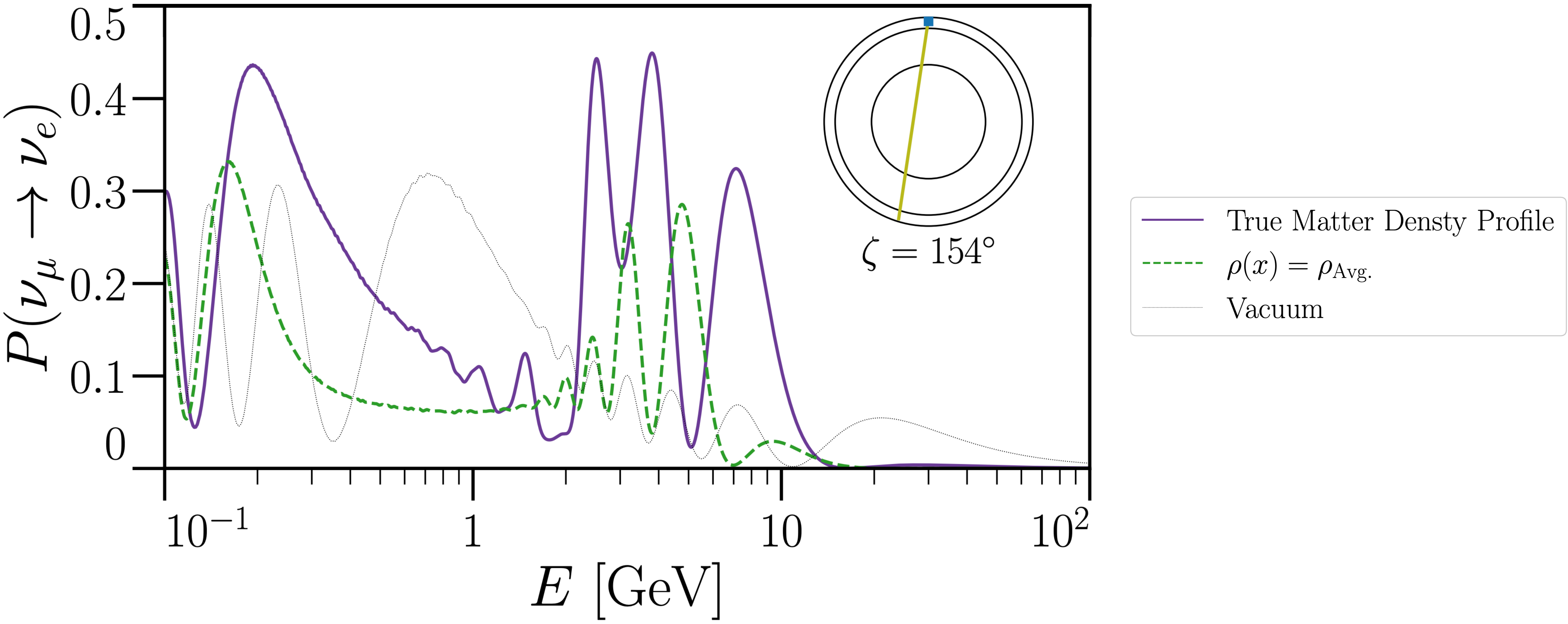
Earth Tomography & Parametric Resonances

KJK et al [2110.00003]



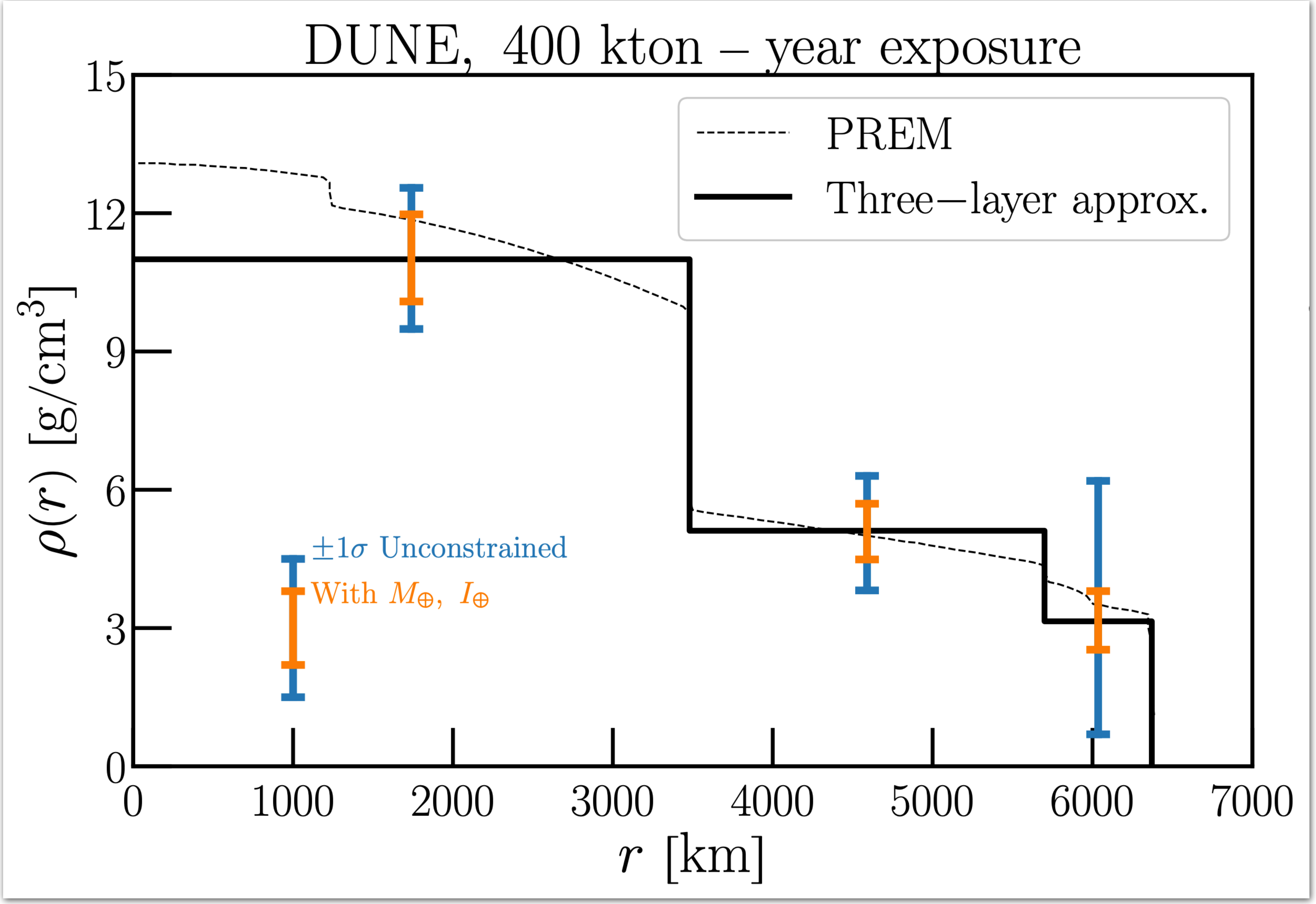
Effect of Matter Density Profile Shape

KJK et al [2110.00003]



Neutrino Tomography with Atmospherics

KJK et al [2110.00003]



Compare with IceCube (utilizing HE absorption) — Donini et al [1803.05901]

Measuring the Earth’s Mass

KJK et al [2110.00003]