The sun
through a neutrino lens

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Texas TACOS, October 14th 2025

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*with great emphasis on work led by Ph.D. student Nityasa Mishra, [2407.03174] and [2304.04689]

Two stories…
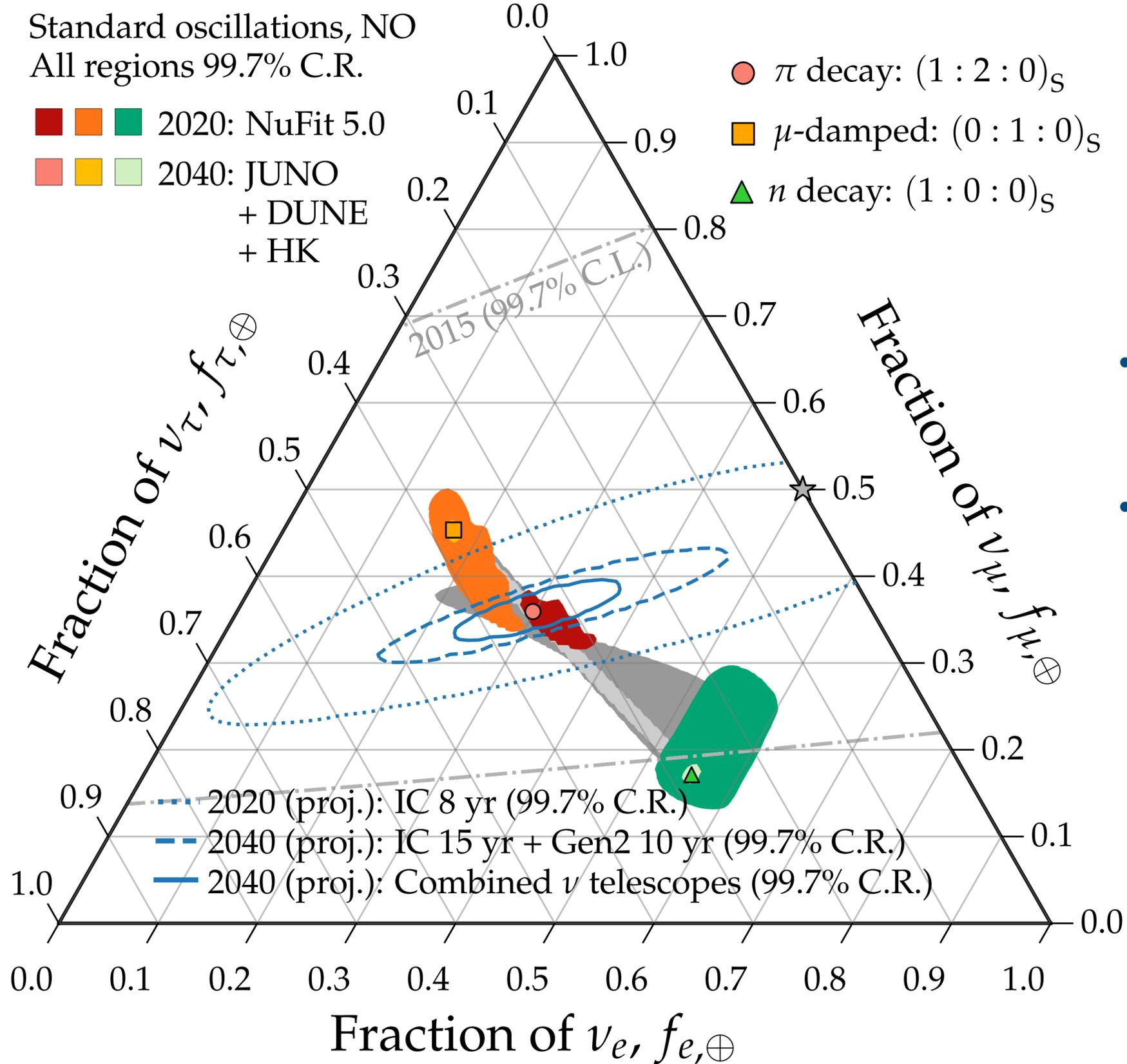
- ○ Flavor composition of solar neutrinos

- ○ Atmospheric neutrinos and the solar cycle

…of how we can better understand the sun

Solar neutrinos and Flavor Composition

First, a word on flavor composition…

Standard oscillations, NO
All regions 99.7% C.R.

2020: NuFit 5.0
2040: JUNO + DUNE + HK

π decay: $(1 : 2 : 0)_S$
μ-damped: $(0 : 1 : 0)_S$
n decay: $(1 : 0 : 0)_S$

Fraction of ν_τ, $f_{\tau,\oplus}$

Fraction of ν_μ, $f_{\mu,\oplus}$

Fraction of ν_e, $f_{e,\oplus}$

2015 (99.7% C.L.)

2020 (proj.): IC 8 yr (99.7% C.R.)
2040 (proj.): IC 15 yr + Gen2 10 yr (99.7% C.R.)
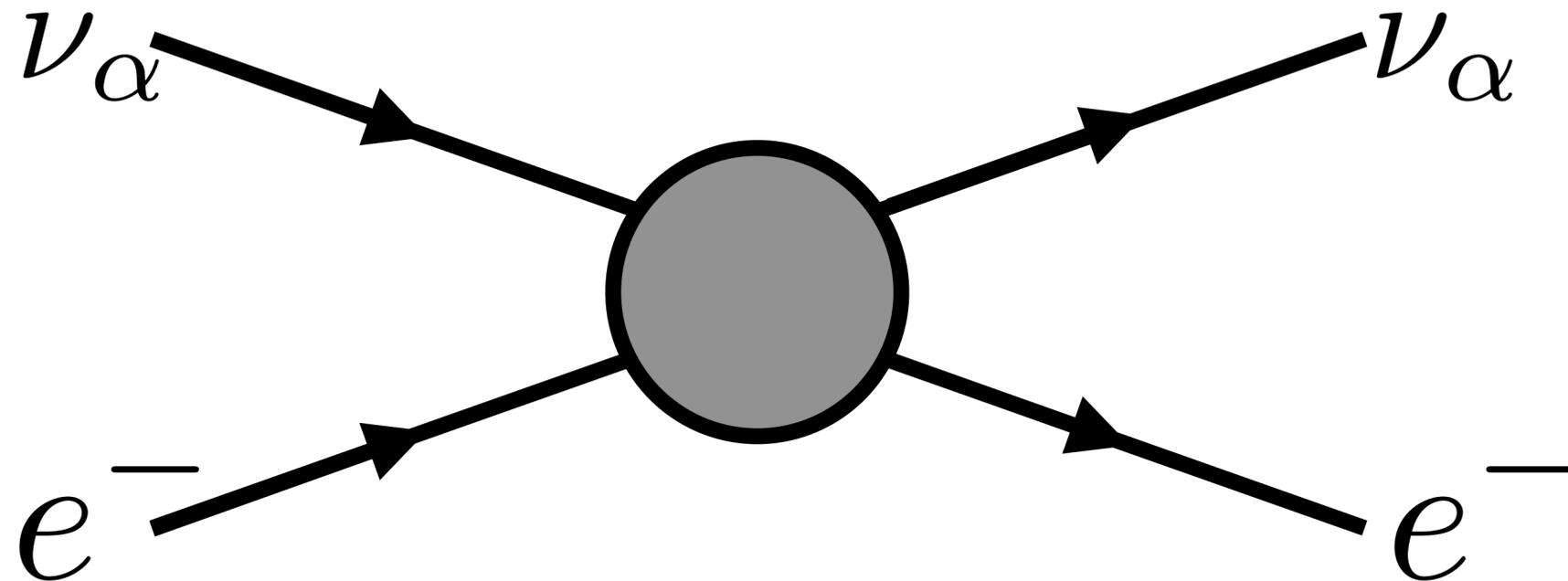2040 (proj.): Combined ν telescopes (99.7% C.R.)

- At very high energies, IceCube can differentiate between all neutrino flavors.

- With enough precision (2040 + beyond?) this can be used for better understanding of oscillation physics and/or the sources of astrophysical neutrinos.

Song et al [2012.12893]

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For low-energy solar neutrinos,

$$m_e \ll E_\nu \ll m_\mu \ll m_\tau$$

How do we distinguish flavor?
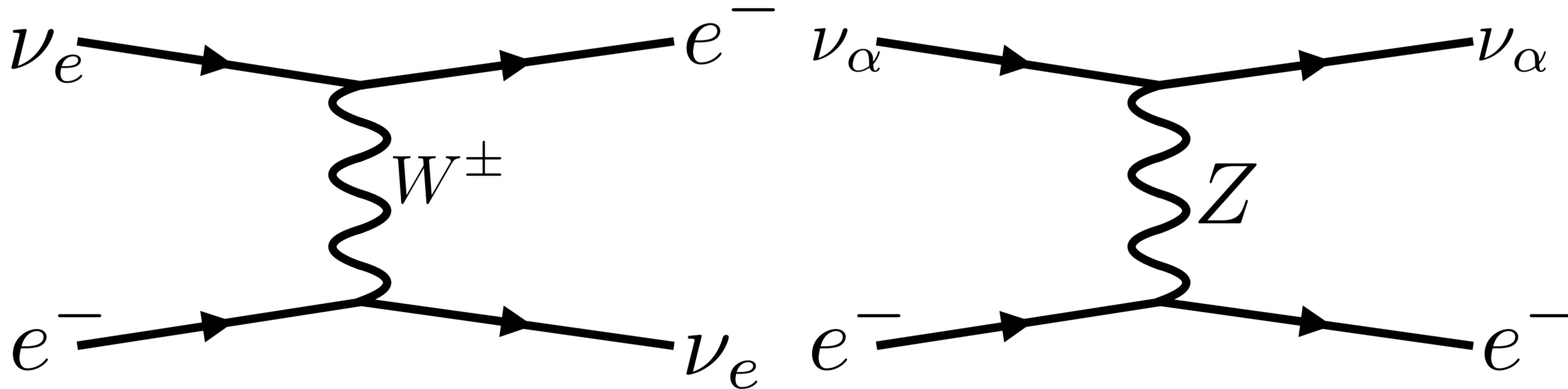
One handle: neutrino/electron scattering —
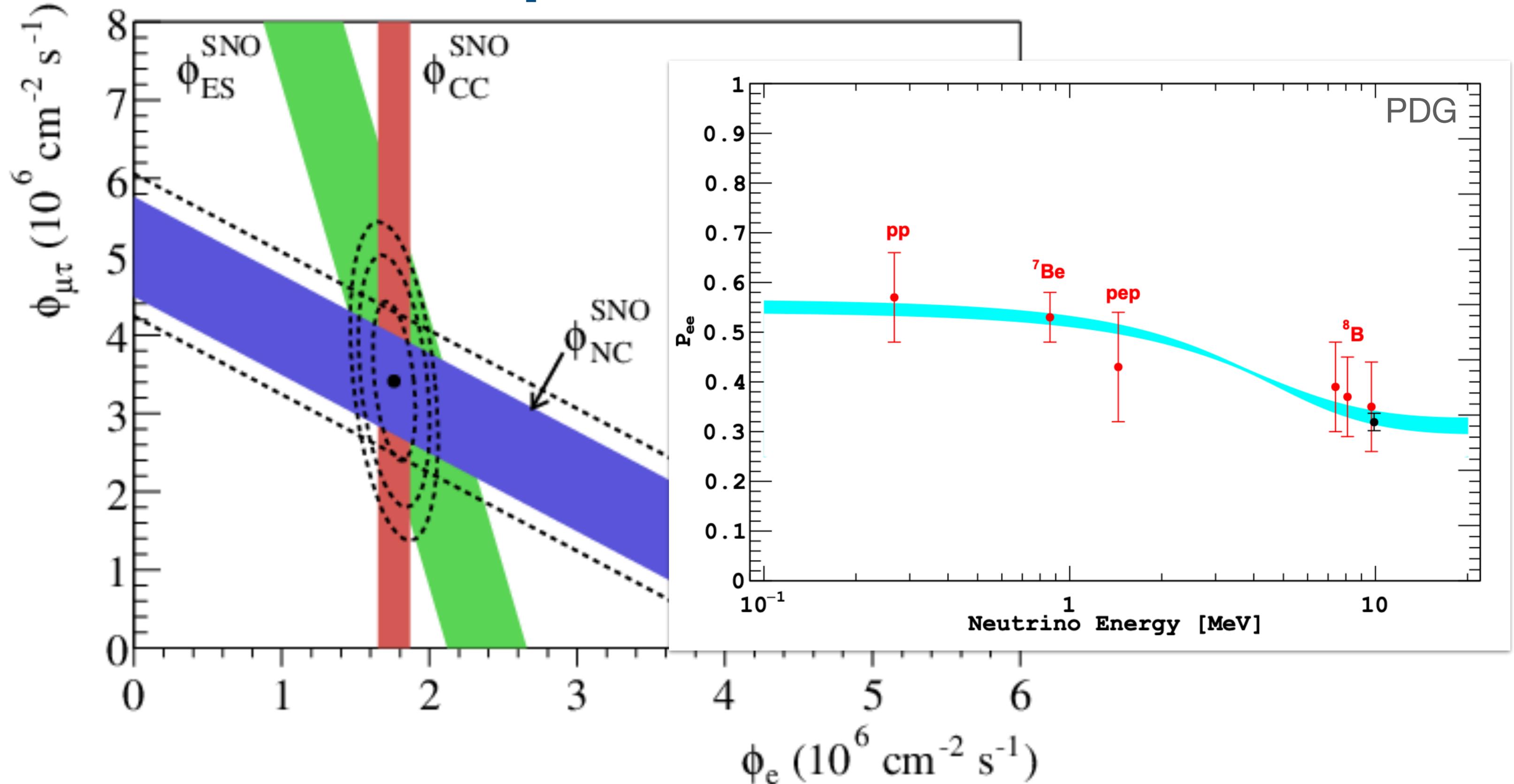
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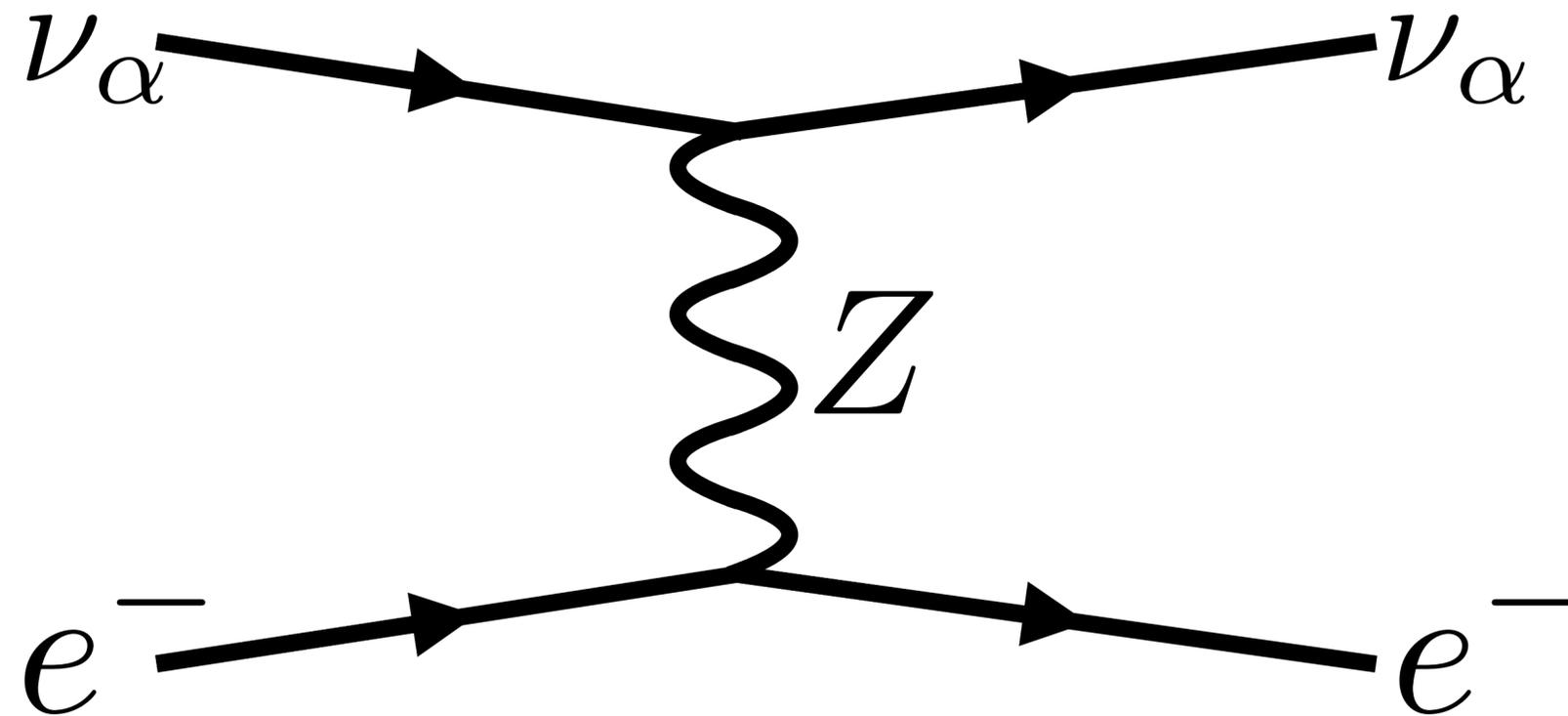
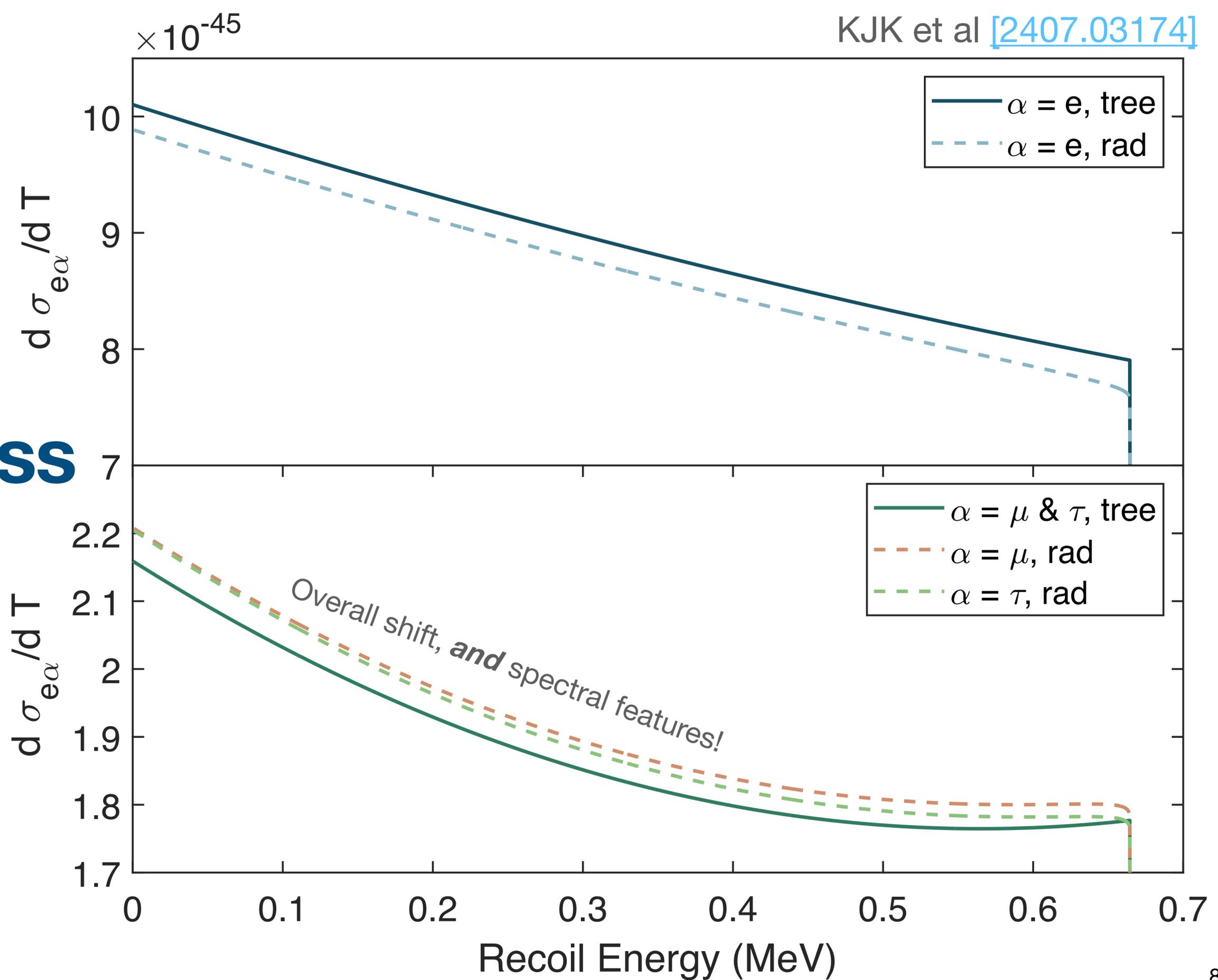One handle: neutrino/electron scattering —
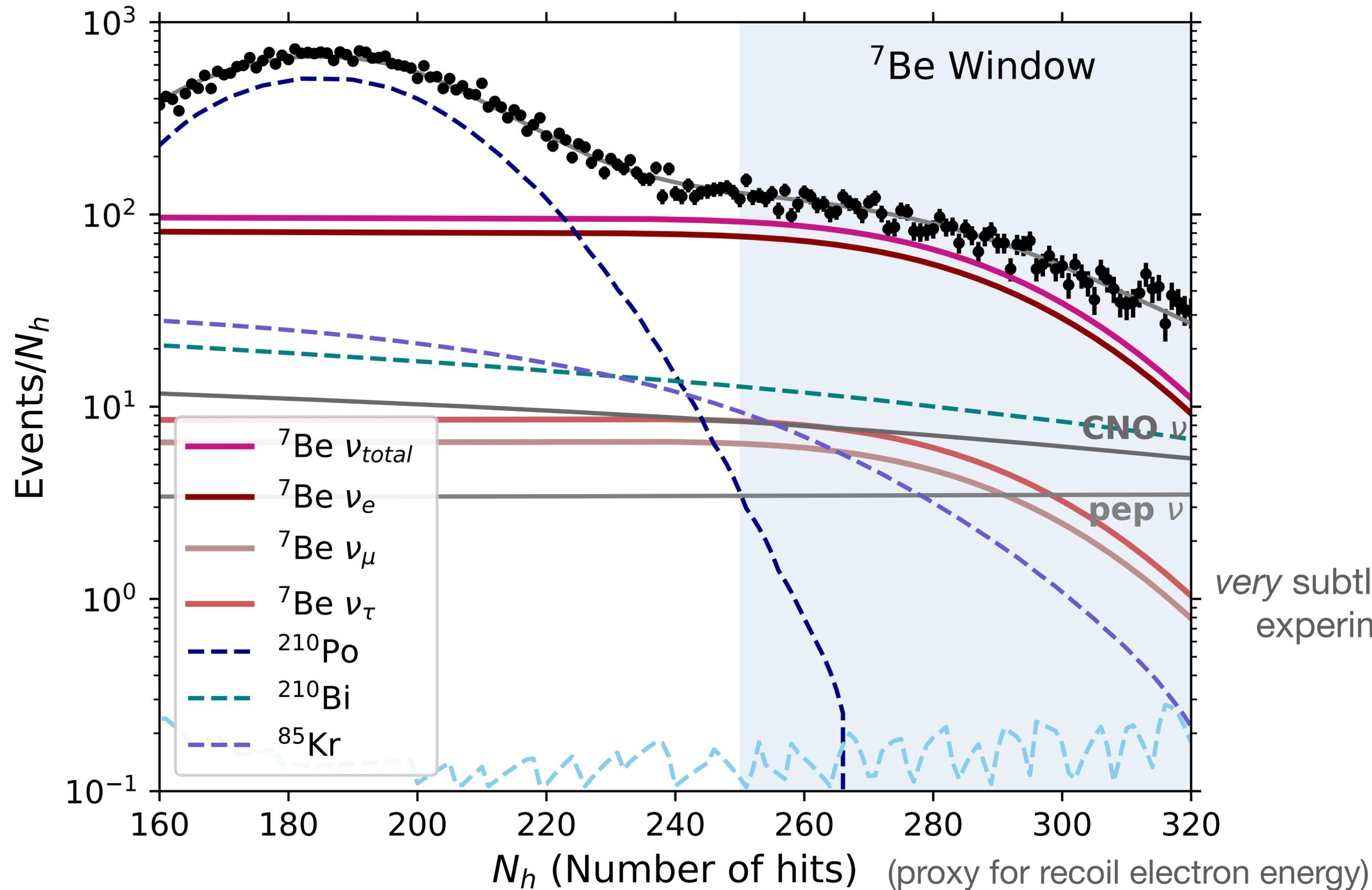
Not a new concept!

What about muon-vs-tau flavor?

$$m_e \ll E_\nu \ll m_\mu \ll m_\tau$$

Effect on differential cross sections?

KJK et al [2407.03174]

$\times 10^{-45}$

$d\sigma_{e\alpha}/dT$

- $\alpha = e$, tree
- $\alpha = e$, rad

$d\sigma_{e\alpha}/dT$

- $\alpha = \mu$ & τ, tree
- $\alpha = \mu$, rad
- $\alpha = \tau$, rad

Overall shift, **and** spectral features!

Recoil Energy (MeV)

Can Borexino observe this?

very subtle differences in a real experimental environment

Borexino measuring muon/tau components

Fixed norm., 5% unc. on f_e

current

30x exp.

b.f.p.

1σ

2σ

unitary mixing

non$-$unitary mixing

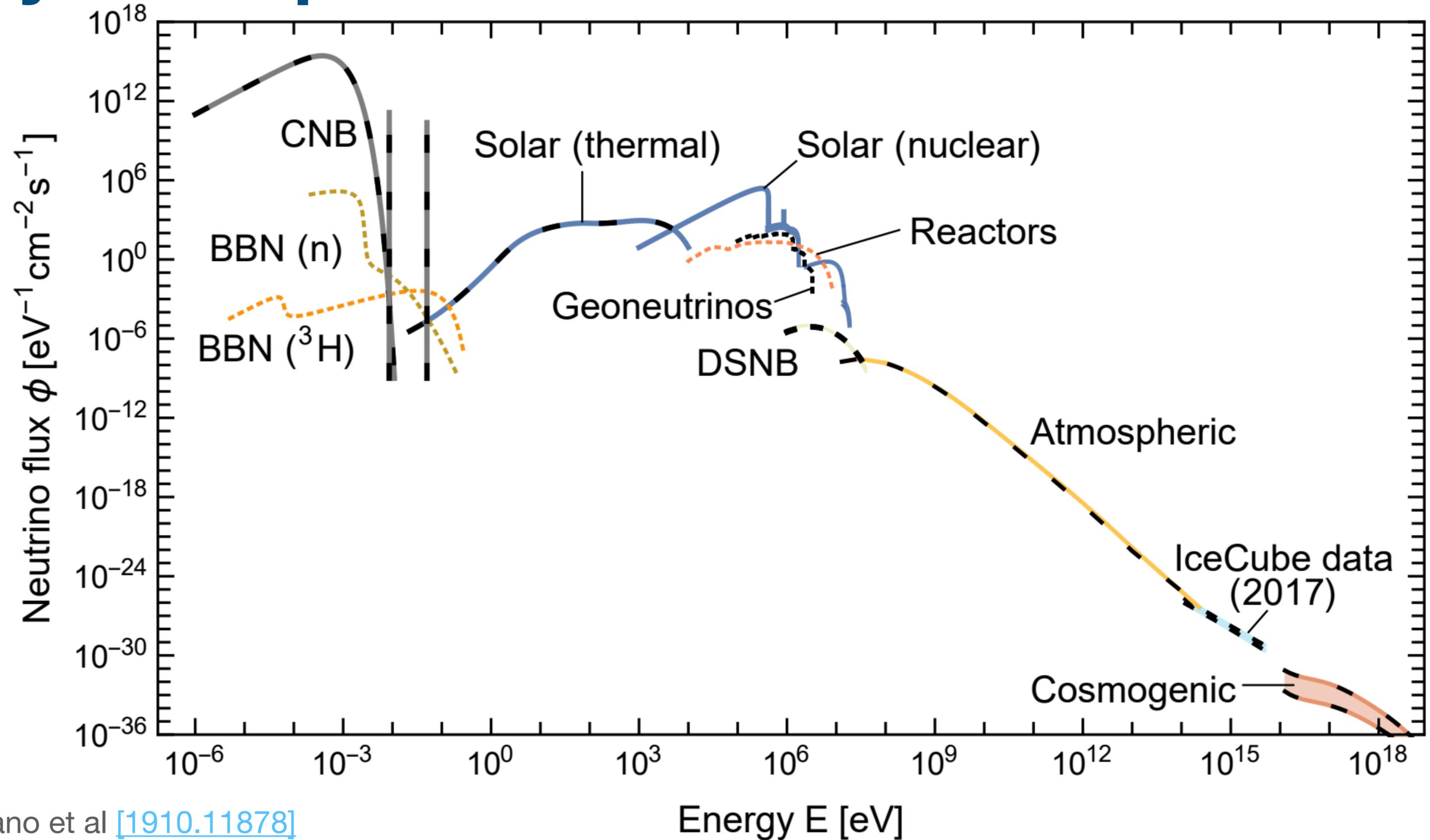f_τ

f_μ

KJK et al [2407.03174]

Converting into flavor triangles,

- Despite its incredible precision, Borexino (or even Borexino x 30) cannot weigh in on the muon-vs.-tau flavor composition.

- Larger exposures *could* help in differentiating between unitary/non-unitary oscillations.

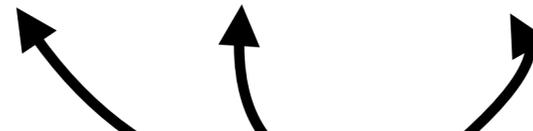- We would need O(3000x) exposure to fully differentiate among flavors :(

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The solar cycle, laundered through the atmosphere

Why Atmospheric Neutrinos?
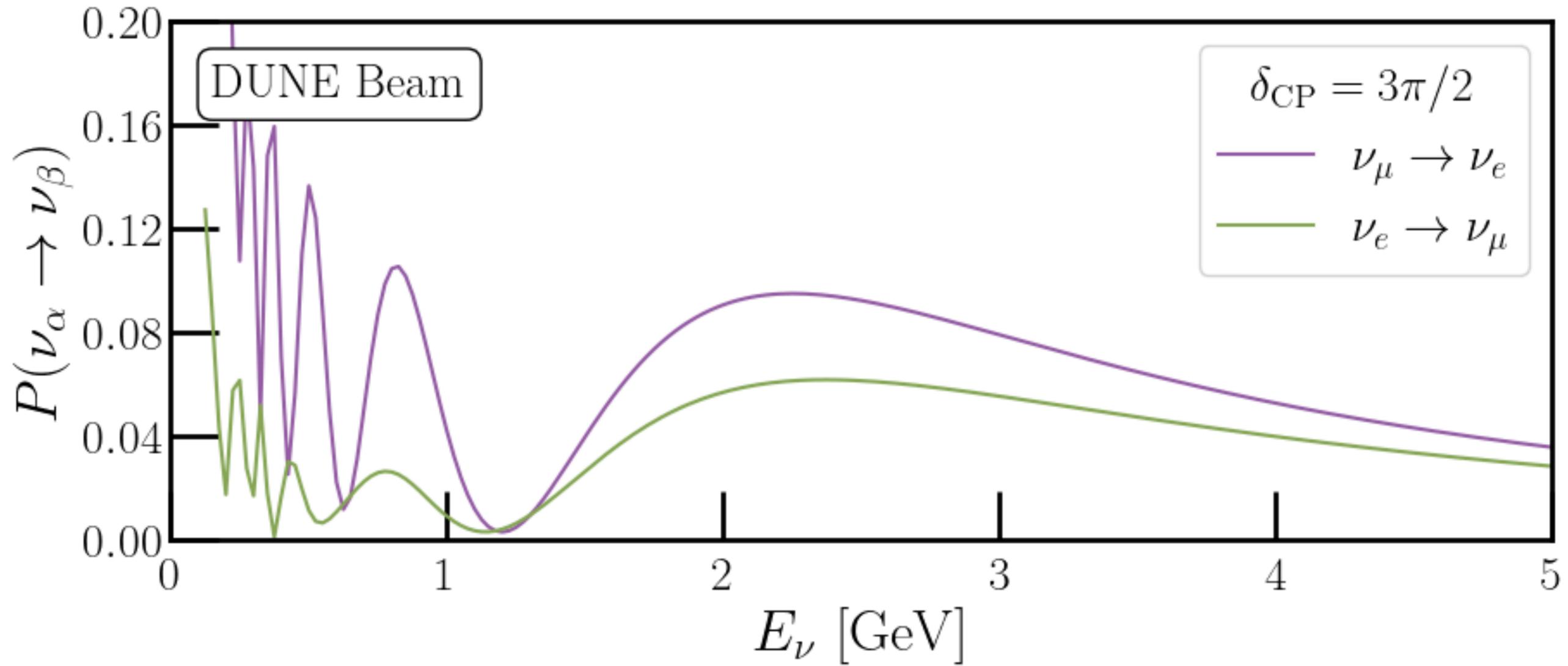

Vitagliano et al [1910.11878]

CP Violation in Atmospheric Neutrinos

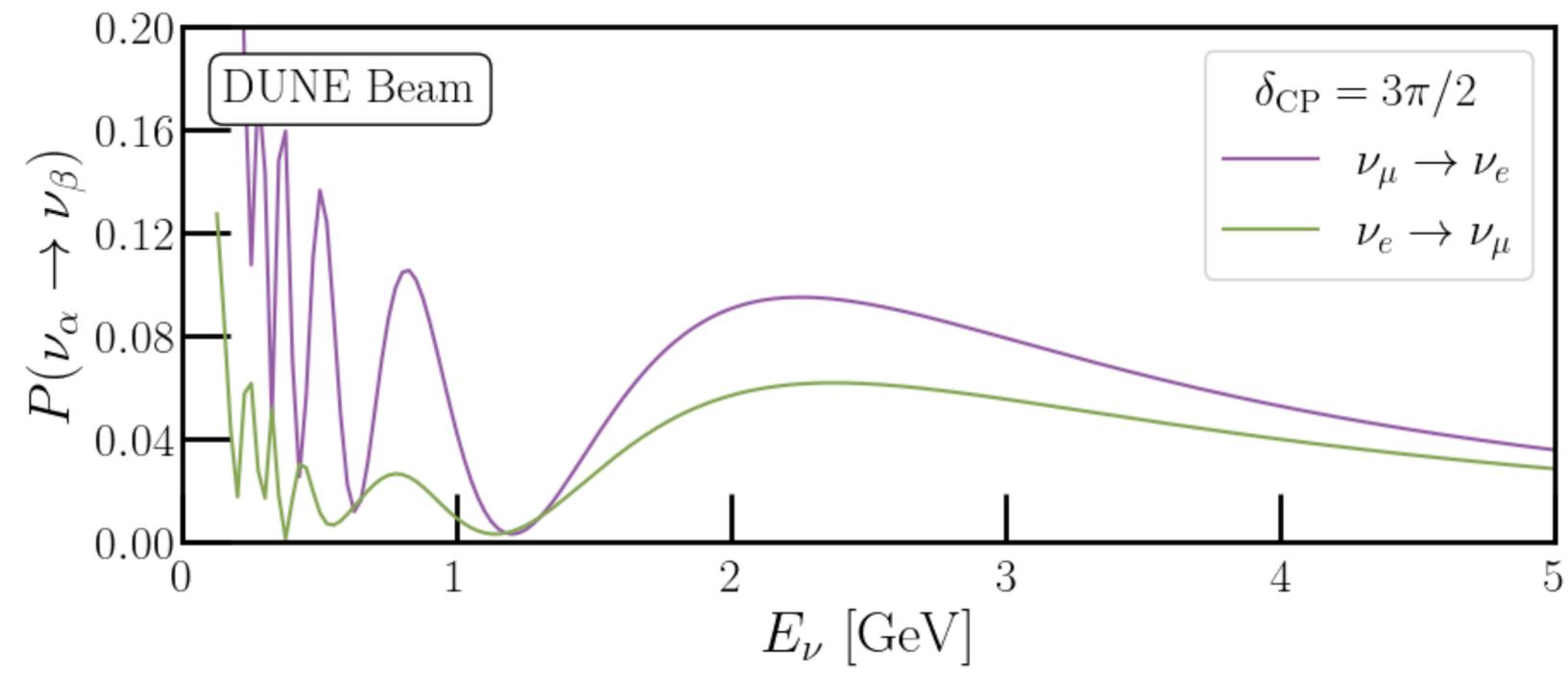CP-violating term in (vacuum) oscillation probability:

$$P_{CP} = -8J_r \sin \delta_{CP} \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32} \qquad \left(\frac{\left| \Delta_{3j} \right|}{\Delta_{21}} \approx 30 \right)$$
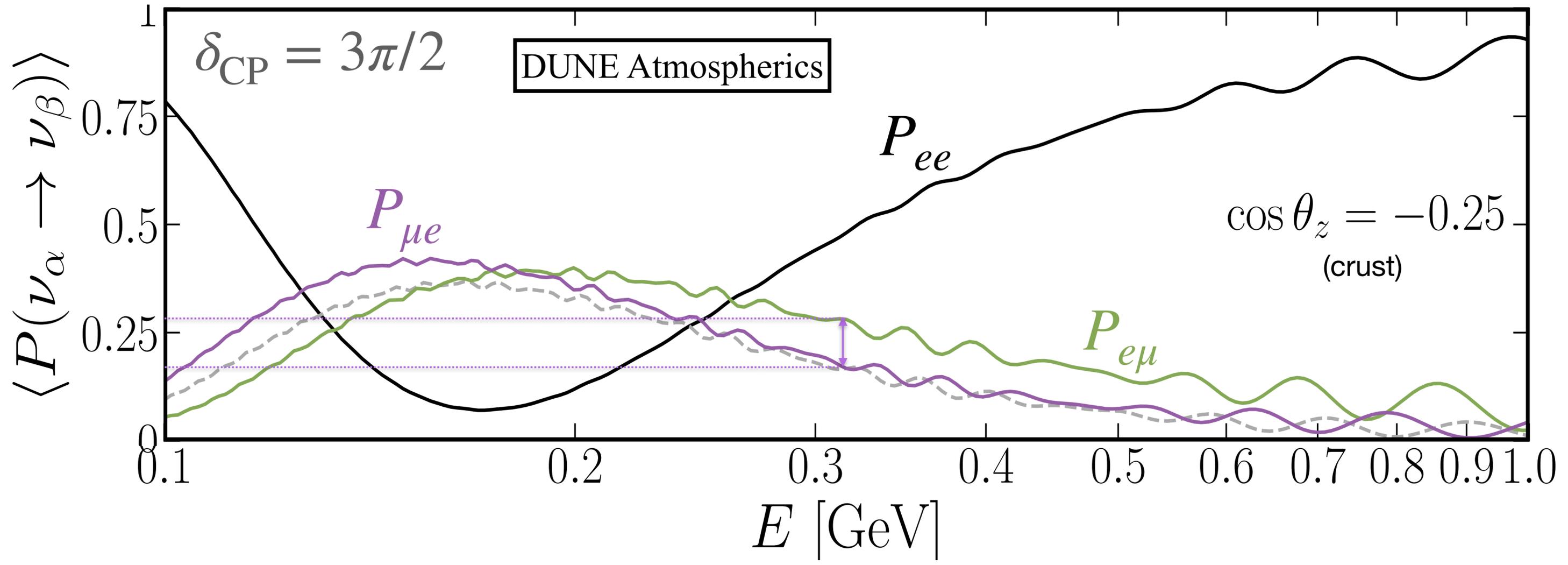
Challenge: making these all $\mathcal{O}(1)$ simultaneously!

CP Violation in Atmospheric Neutrinos

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

DUNE Beam

$\delta_{\mathrm{CP}} = 3\pi/2$

$\nu_\mu \to \nu_e$

$\nu_e \to \nu_\mu$

$P(\nu_\alpha \to \nu_\beta)$

E_ν [GeV]

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

$\delta_{\mathrm{CP}} = 3\pi/2$

DUNE Atmospherics

P_{ee}

$P_{\mu e}$

$\cos \theta_z = -0.25$

(crust)

$P_{e\mu}$

$\langle P(\nu_\alpha \to \nu_\beta) \rangle$

E [GeV]

Measuring CP Violation

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

Details:

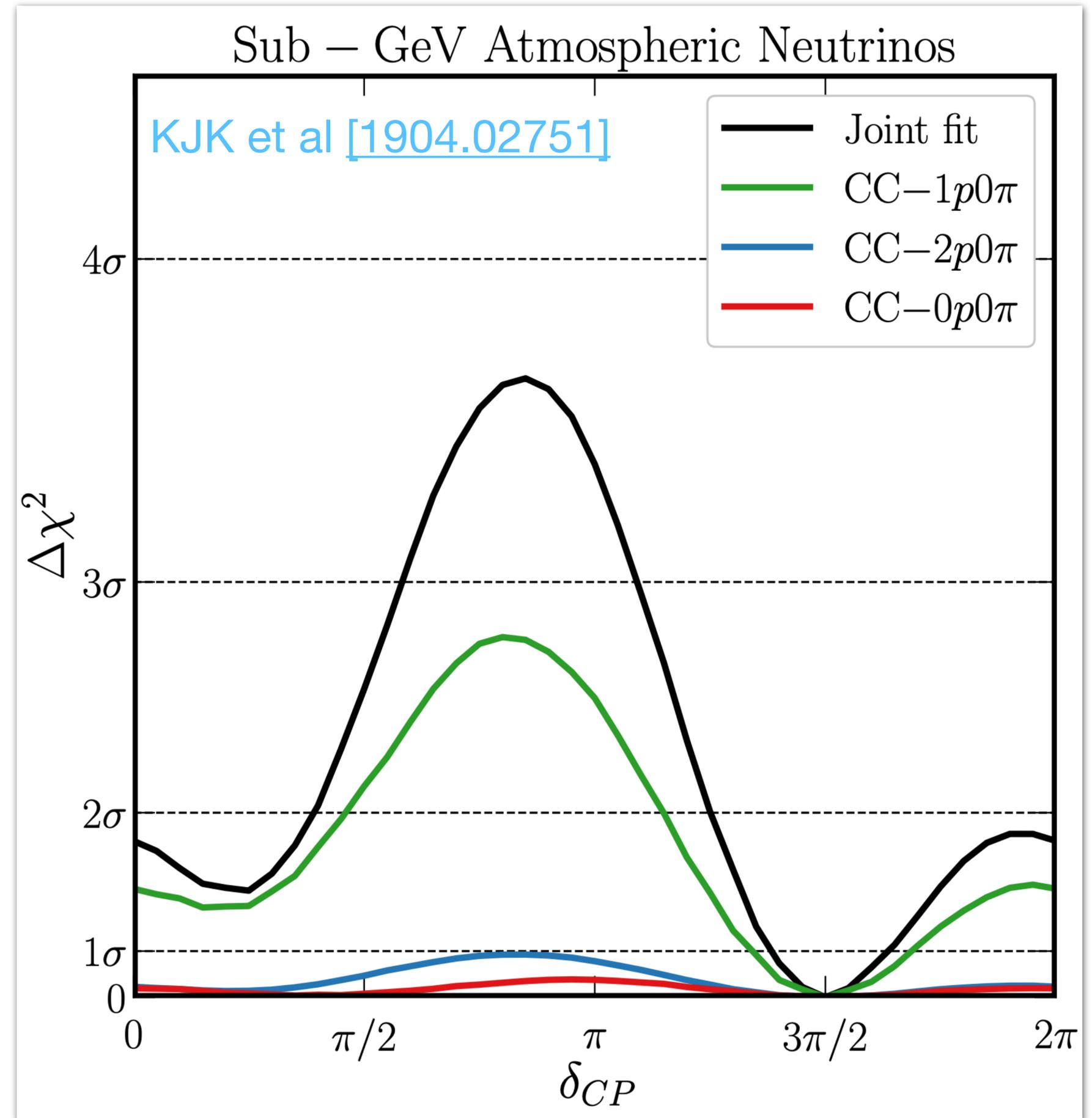Simulate neutrino-argon interactions with event generators

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

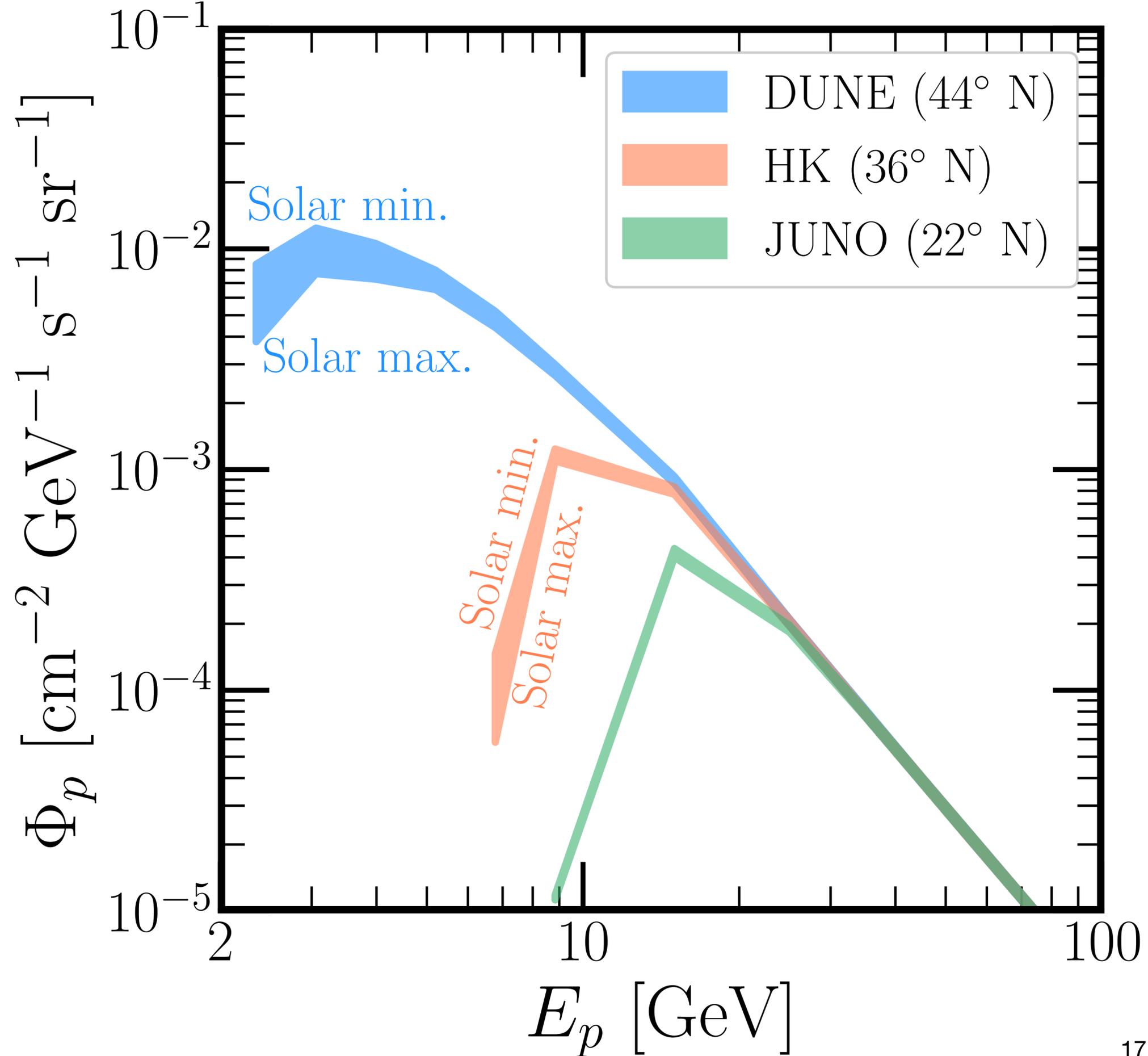Classify events by final state topology (number of protons)

Sub − GeV Atmospheric Neutrinos

KJK et al [1904.02751]

Legend:
- Joint fit
- CC−1p0π
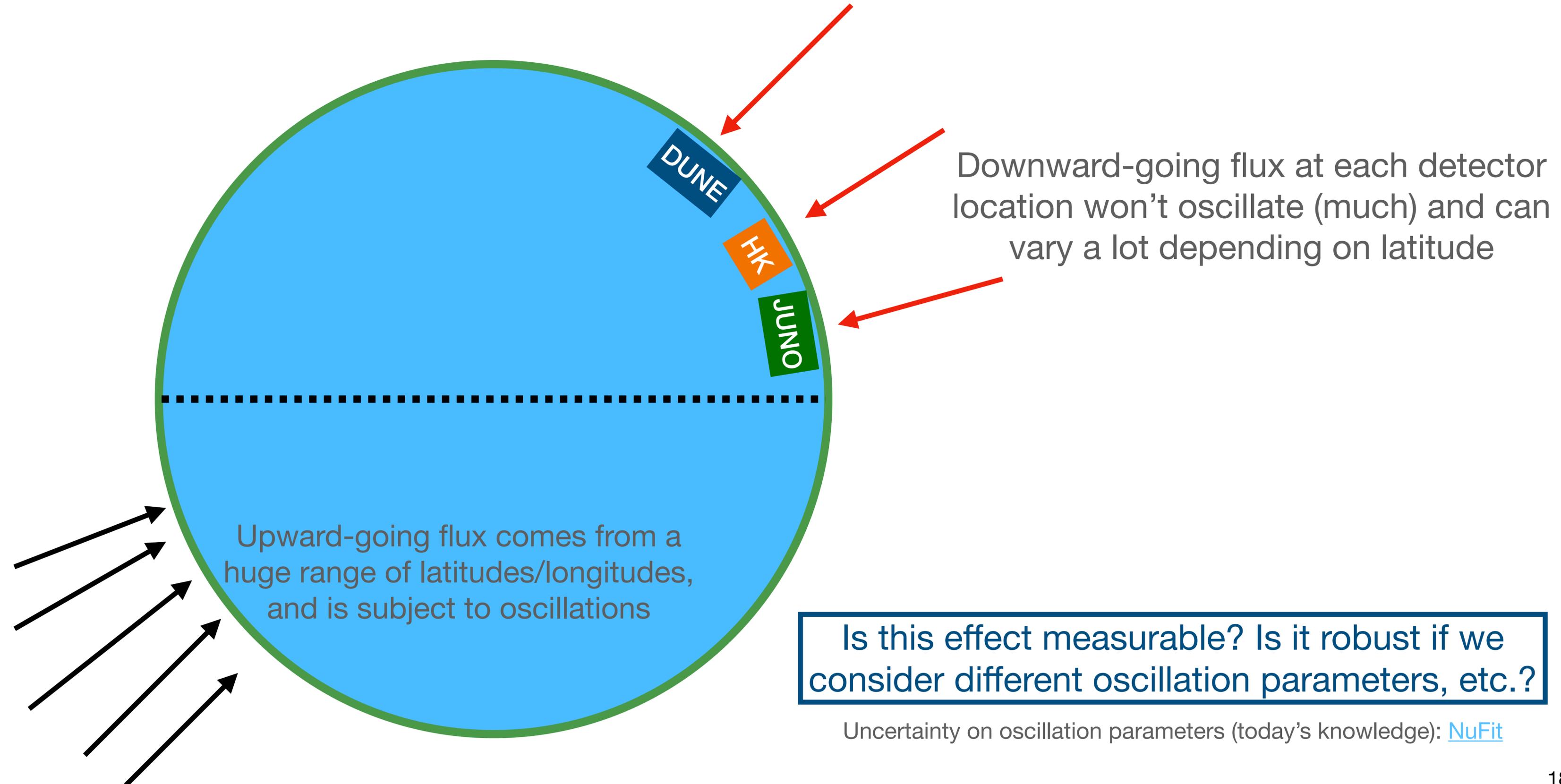- CC−2p0π
- CC−0p0π

$\Delta\chi^2$ vs δ_{CP}

The Sun's 11-year Solar Cycle

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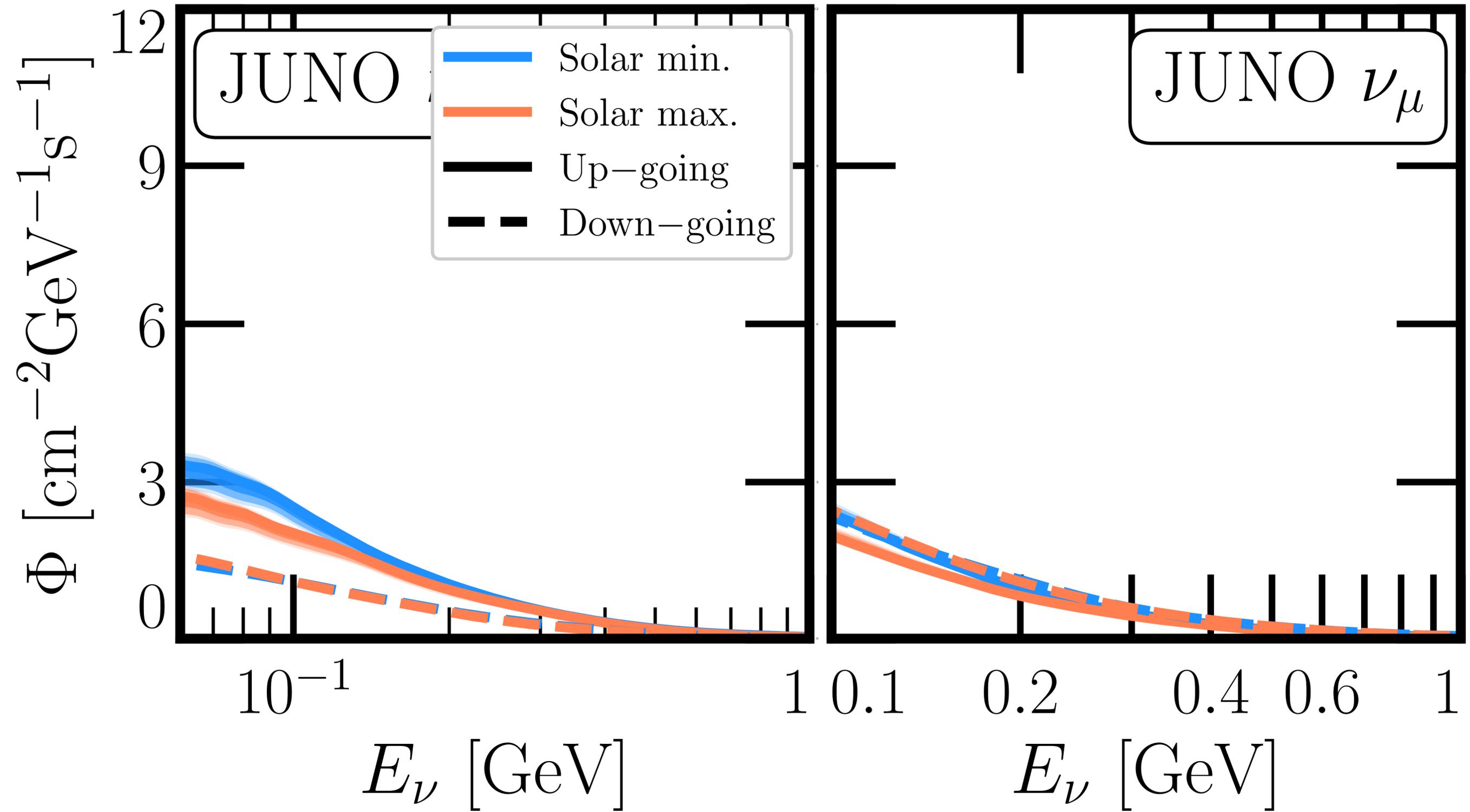
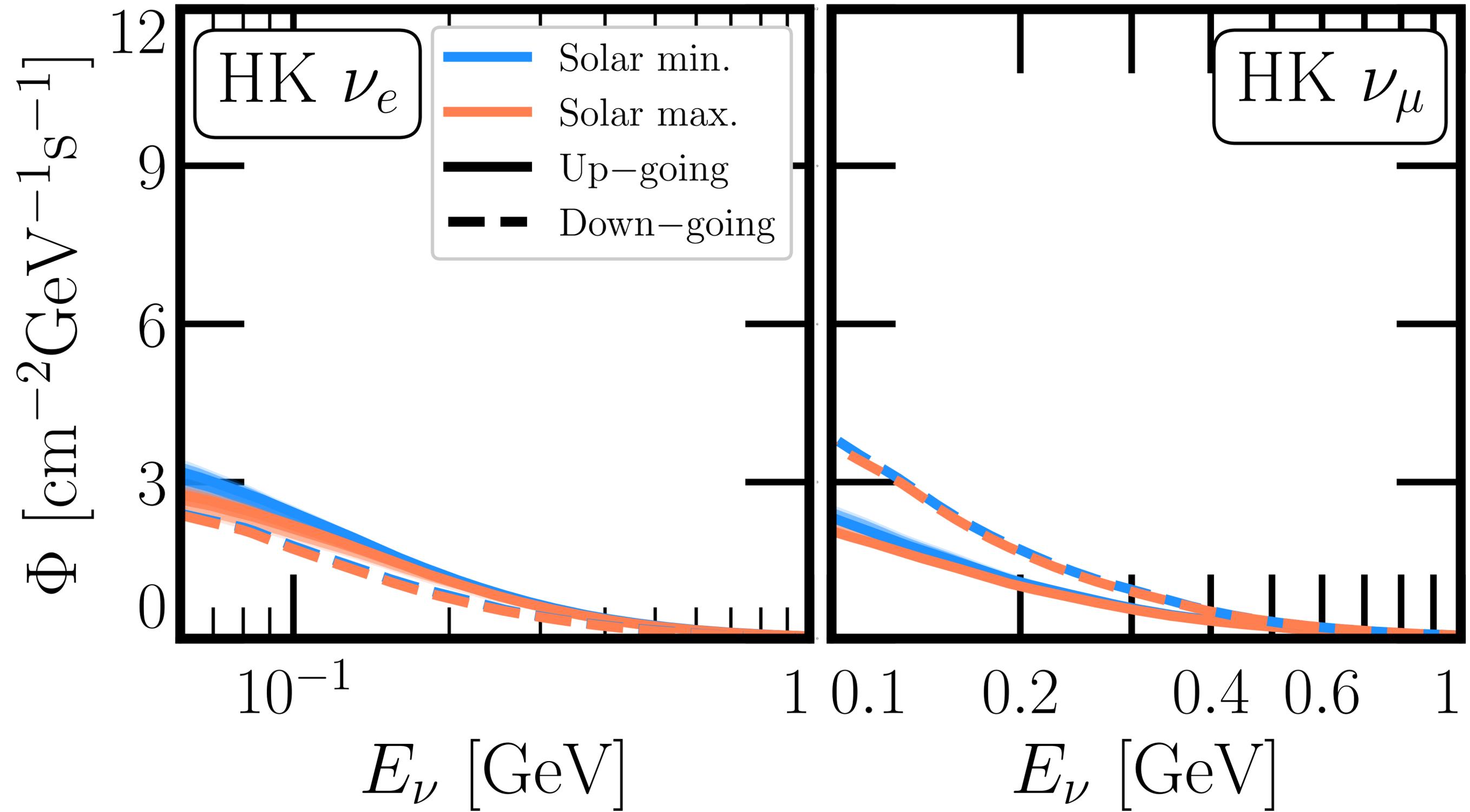Lower-energy CRs — more variance over the course of the solar cycle (11 years)

KJK et al [2304.04689]

Up- vs. Down-going Fluxes

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

Upward-going flux comes from a huge range of latitudes/longitudes, and is subject to oscillations

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

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

DUNE

HK

JUNO

Fluxes at Detector Locations

Downward-going fluxes vary significantly based on detector location — significant modulation.
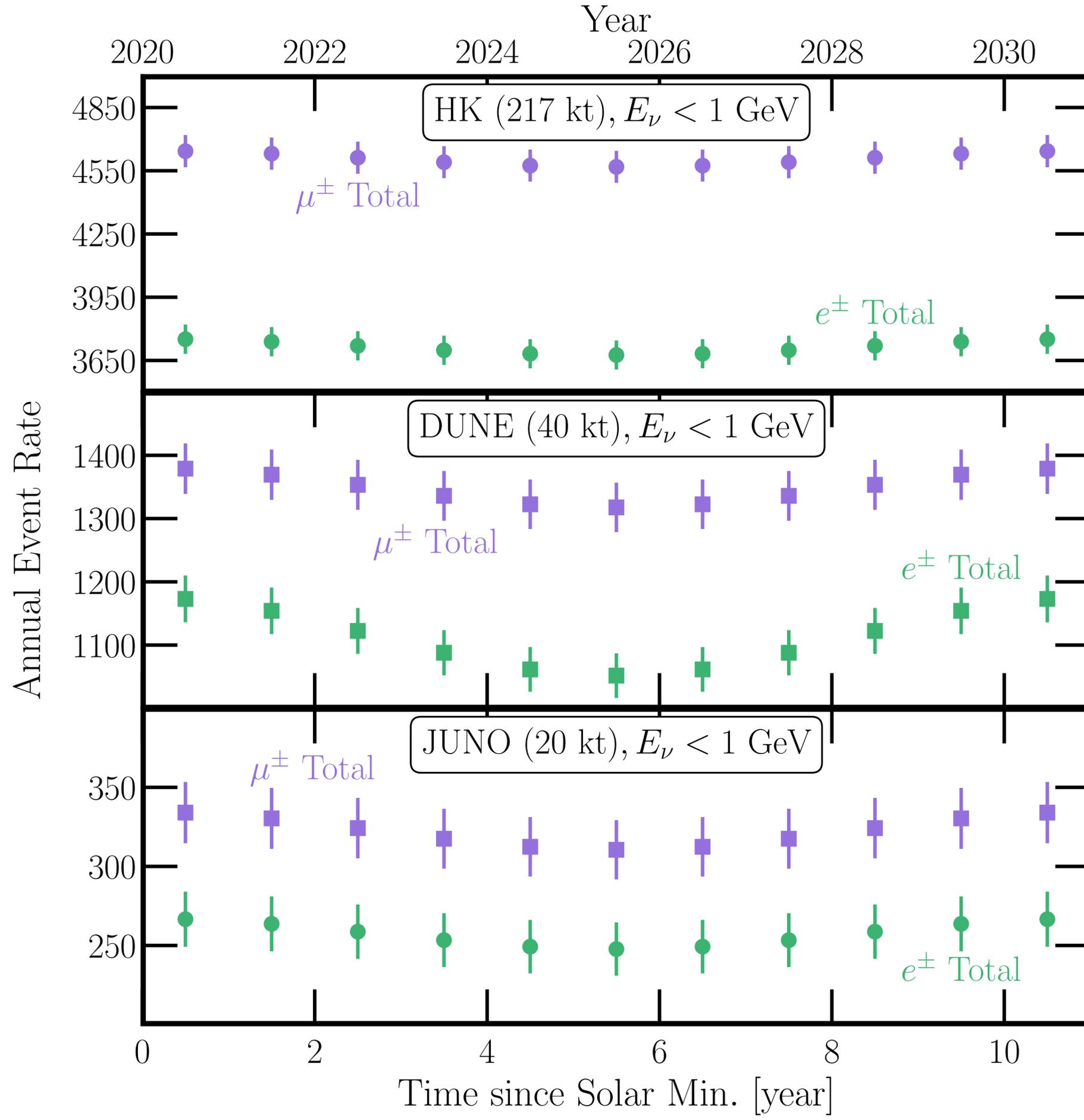
Upward fluxes look very similar because they sample all over the globe (plus oscillations)

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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

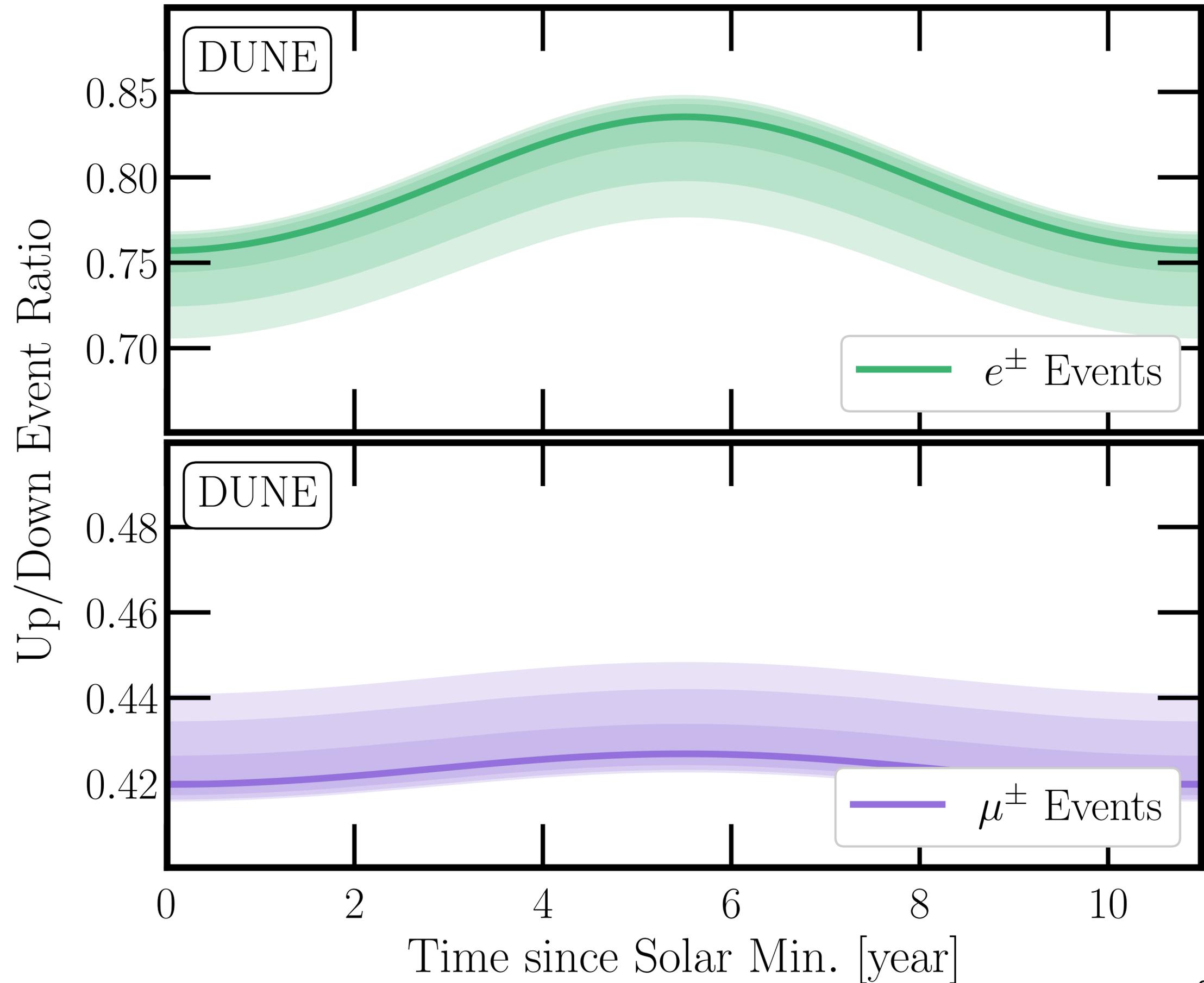Thick line: median expectation as solar cycle varies.

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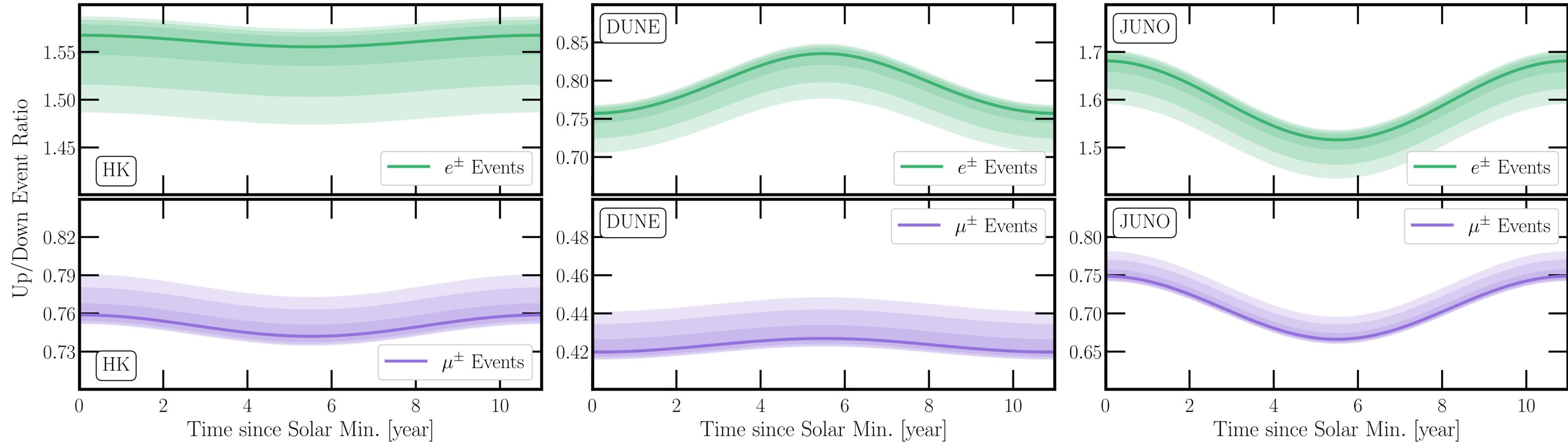
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Three Comparisons

KJK et al [2304.04689]

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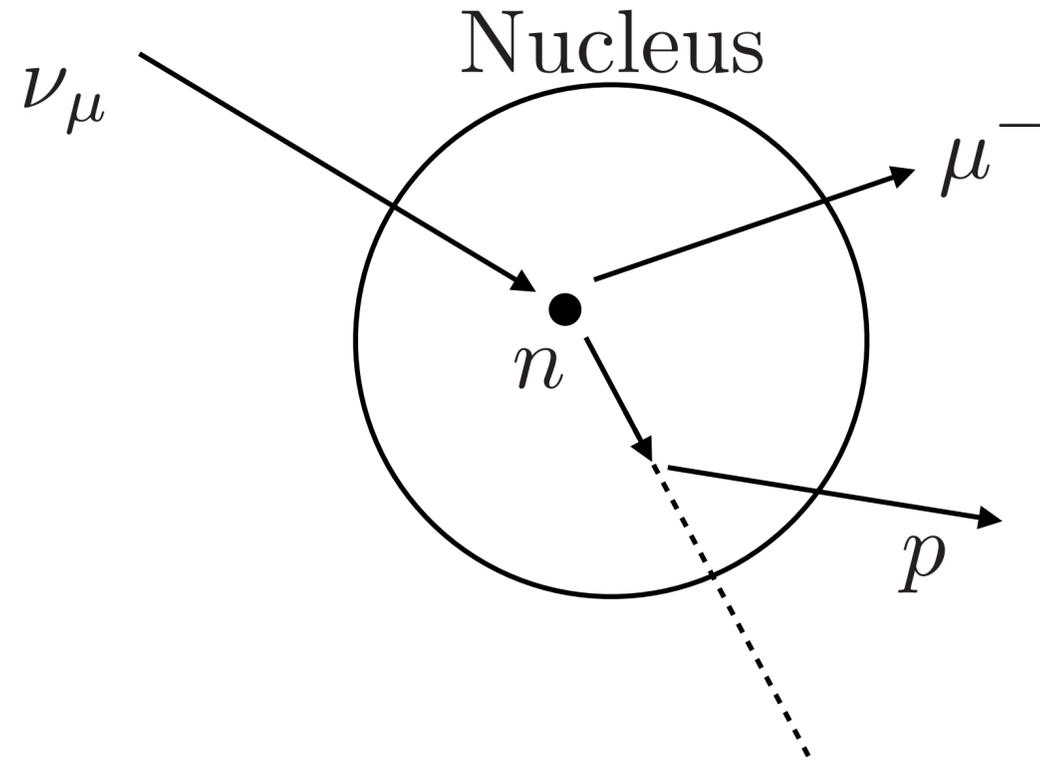
Takeaways

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- Neutrino facilities are multipurpose, and can allow us to scrutinize natural, astrophysical sources with increasing precision.

- We are continuously reconsidering all possible neutrino sources, envisioning new perspectives on certain measurements.

- With this, we can unlock both Standard-Model and beyond-Standard-Model effects.

Thank you!

Backup

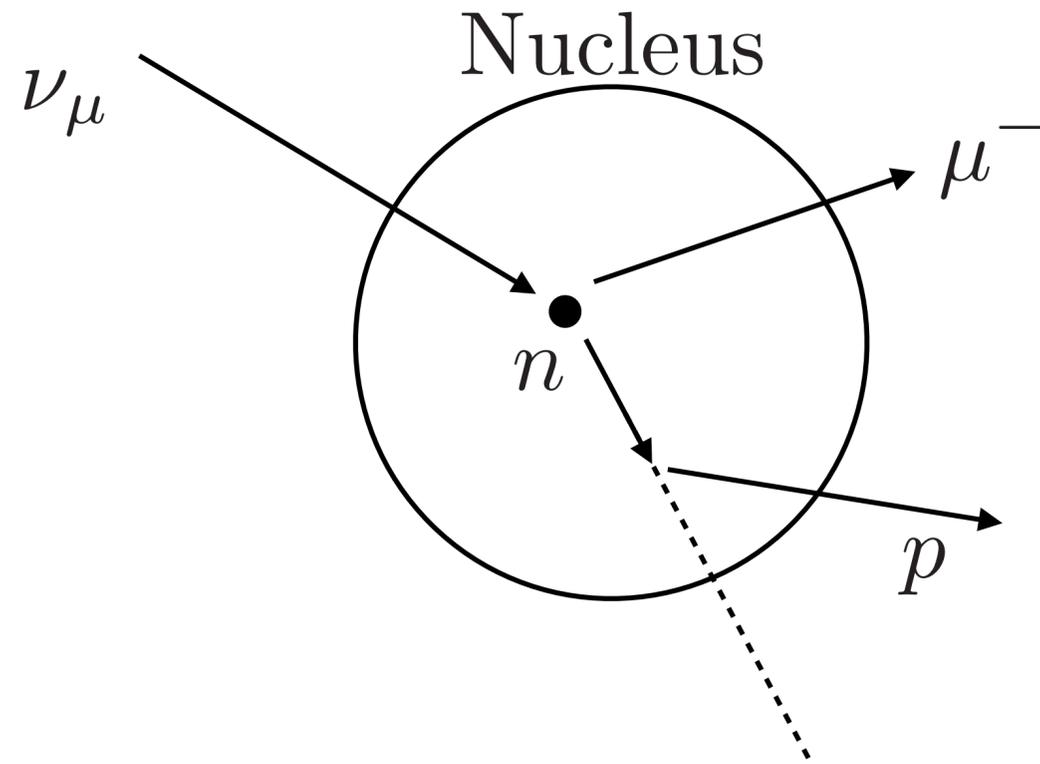# So, why haven't we done this already?

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 ~ 1.4 GeV KE, so lower-energy protons go undetected.
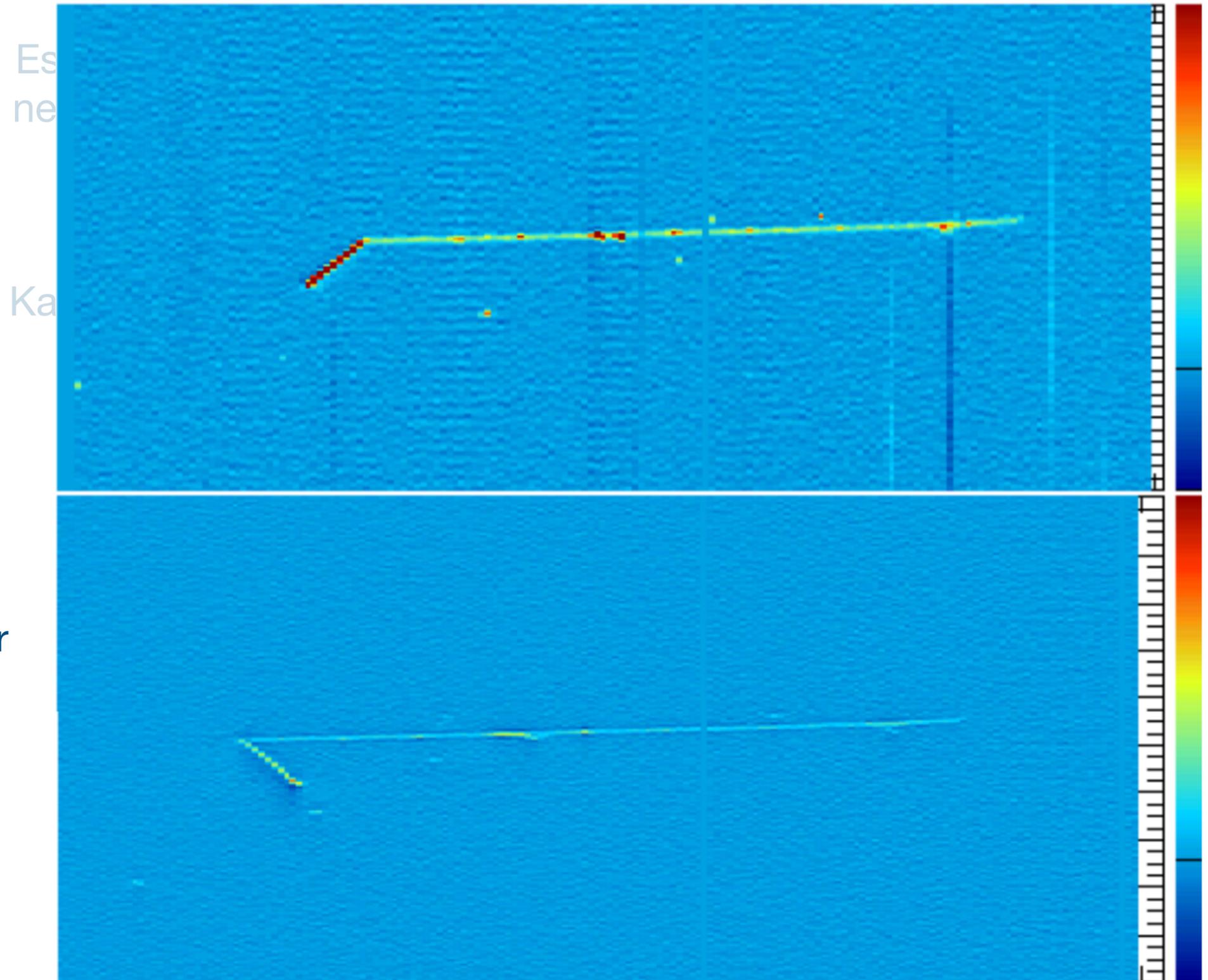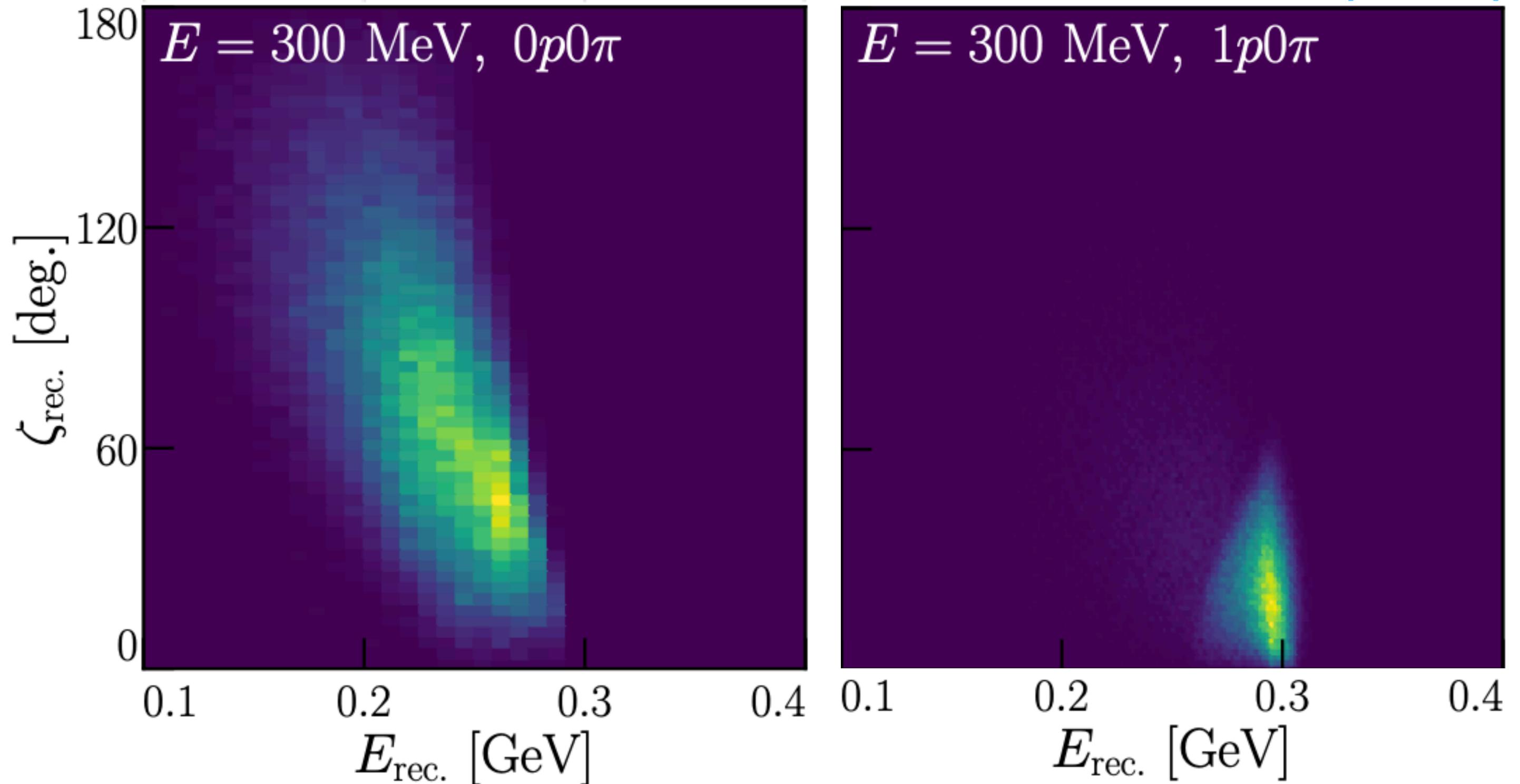
So, why haven't we done this already?

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

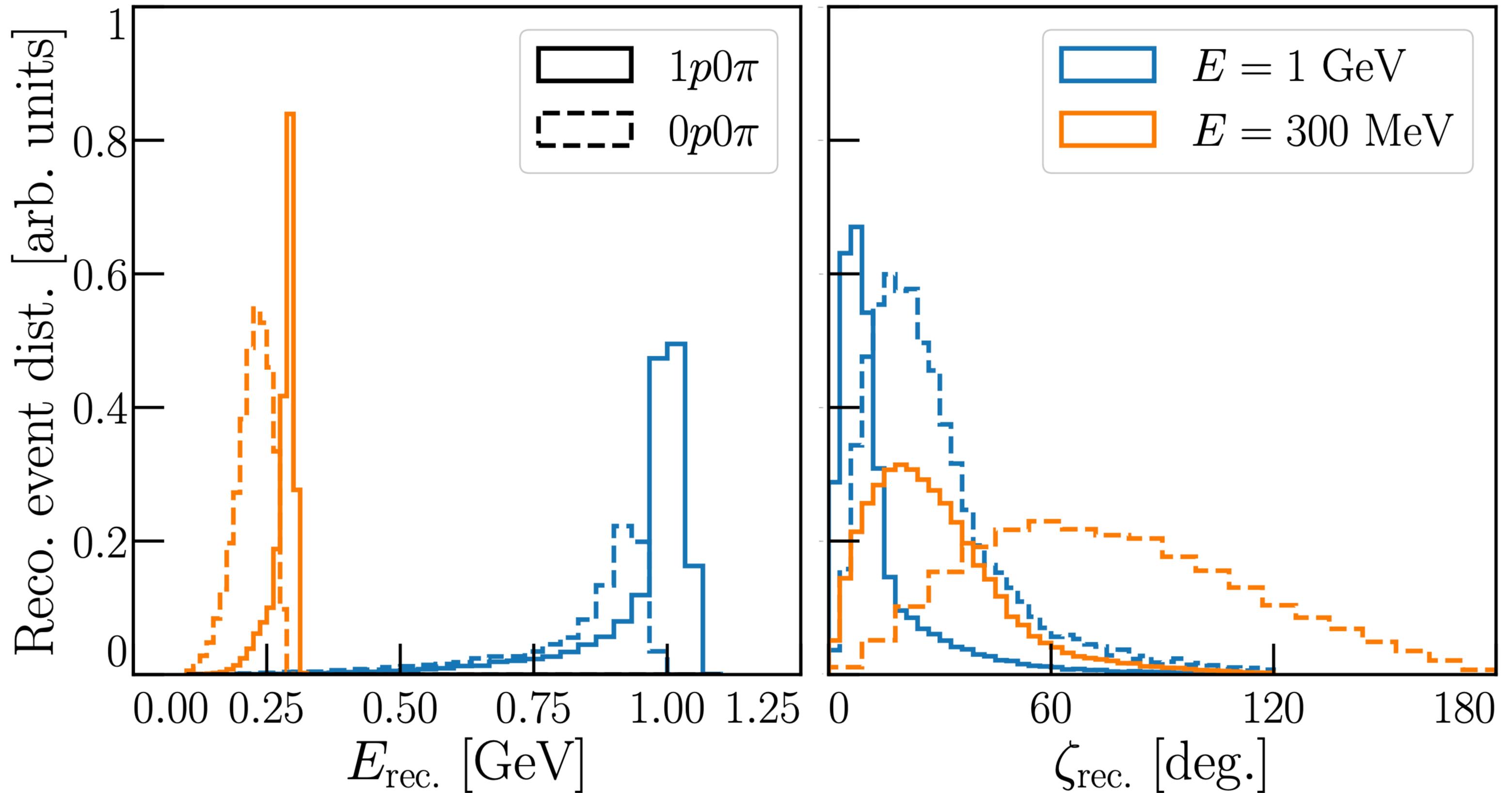ArgoNeuT identified proton candidates down to 21 MeV of kinetic energy.
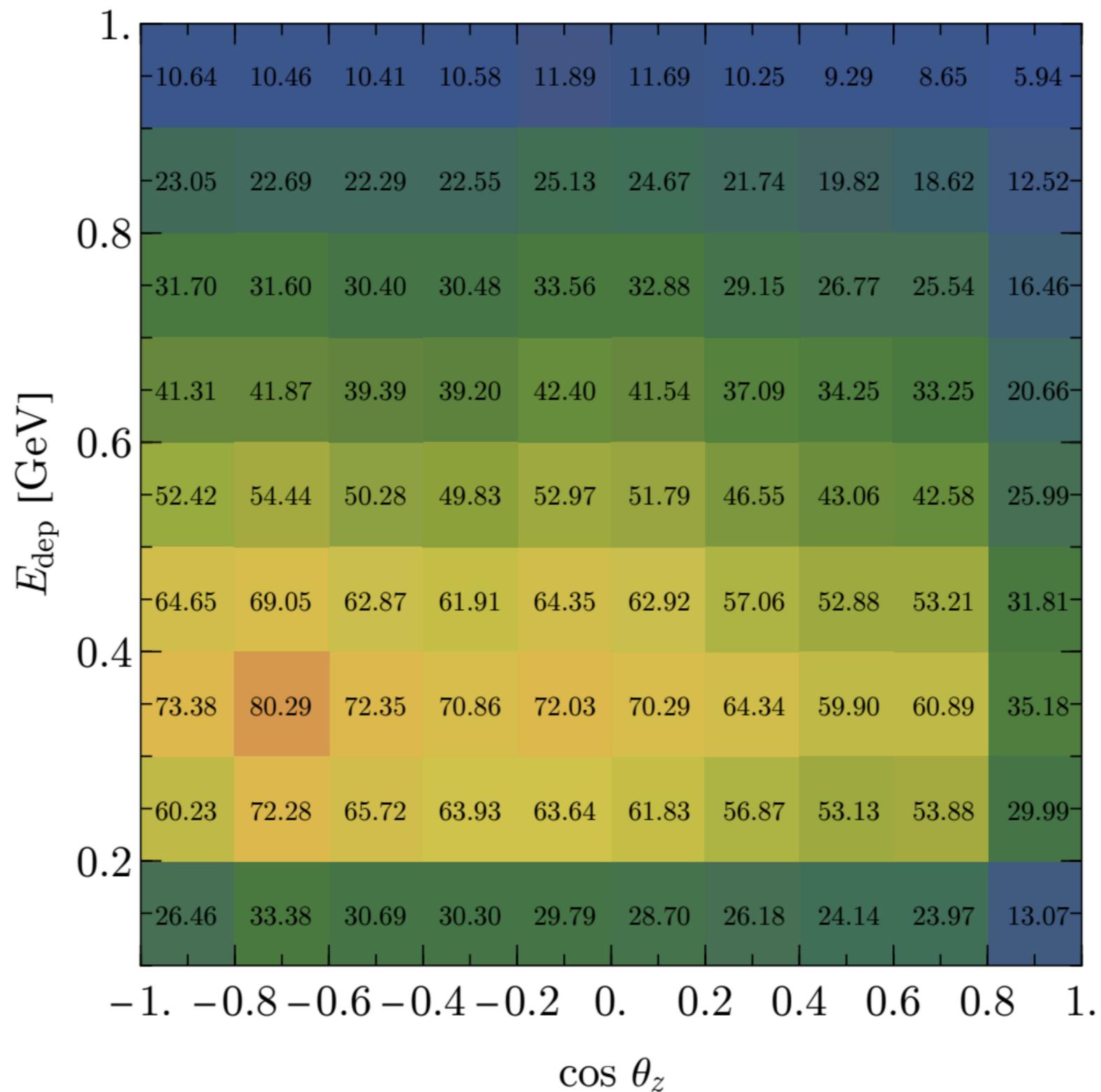
Direction/Energy Reconstruction in LArTPCs

Reconstruction (1D)

Event Rates in 400 kt-yr

$N_e - \text{CC}-1\text{p}0\pi$, $\delta_{\text{CP}} = 3\pi/2$

$\Delta N_e - \text{CC}-1\text{p}0\pi$, $\delta_{\text{CP}} = 3\pi/4$