New Measurements in the Era of Precision Neutrino Physics

Nicole Bell, The University of Melbourne

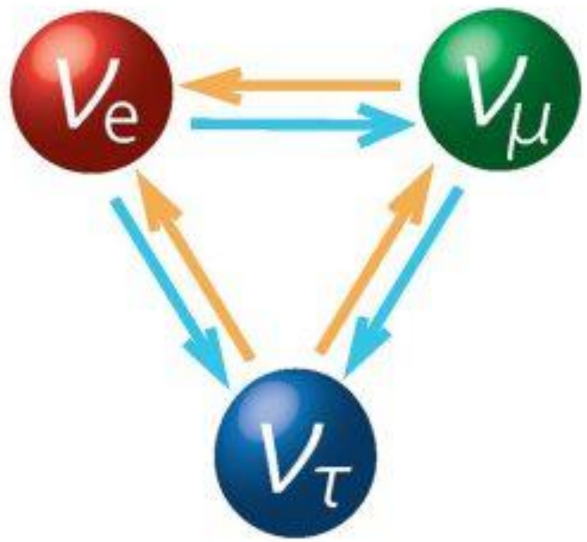
Entering the Era of Precision Neutrino Physics

Massive new experiments now coming online

- Precision measurements of neutrino mixing parameters
- Enable measurements that were previously impossible

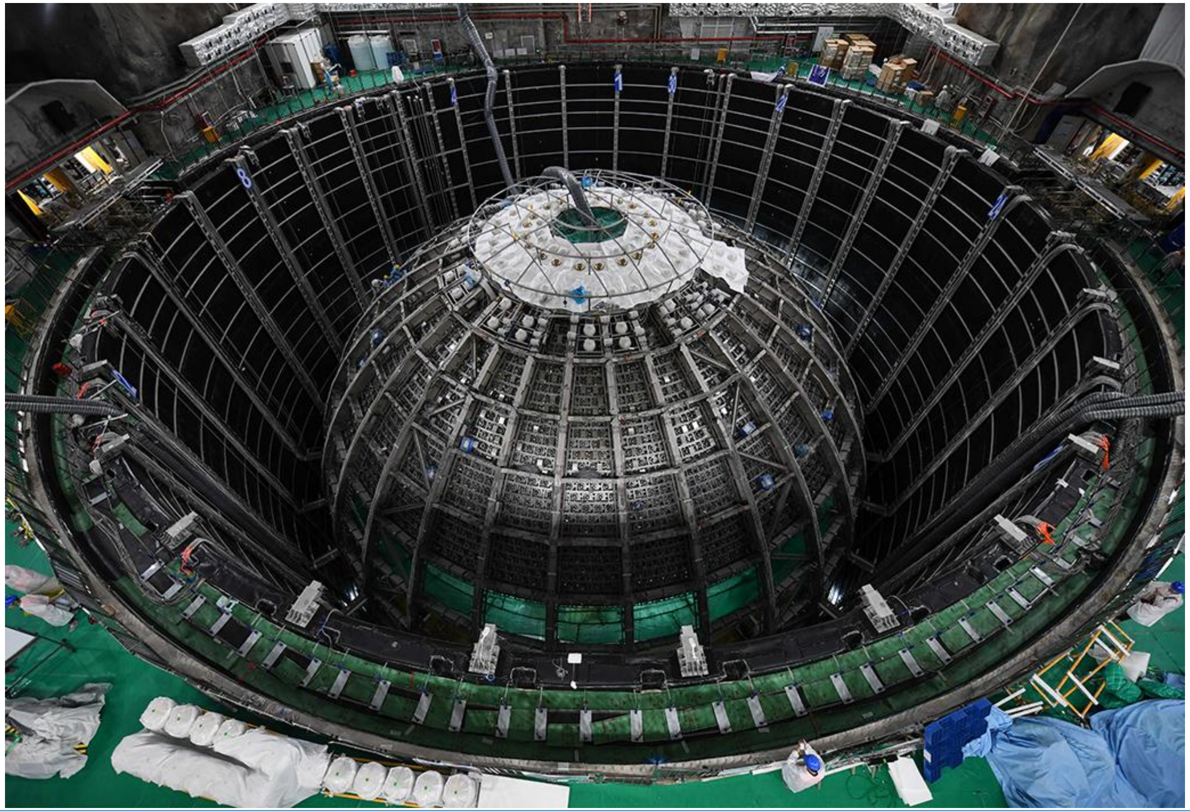
Open questions about neutrinos

- Are neutrinos Majorana or Dirac
- Absolute mass scale? (And, normal or inverted hierarchy?)
- Do neutrino violate CP?
- Is there new physics in the neutrino sector?

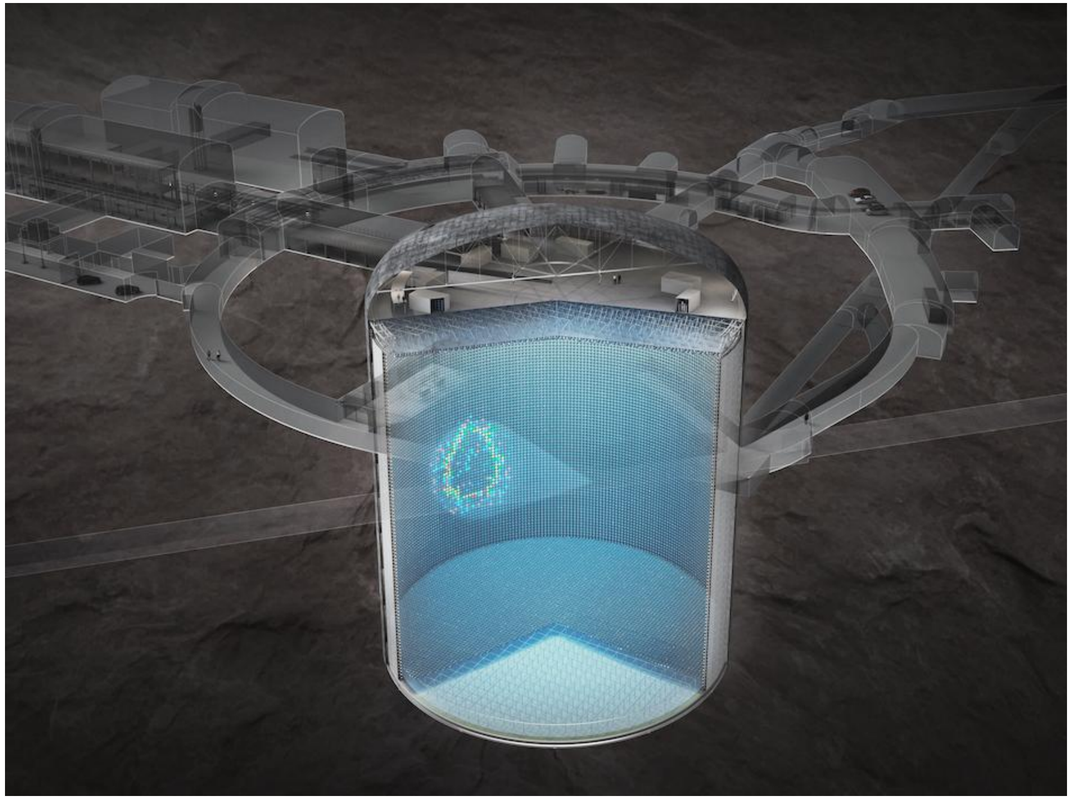


Next-generation neutrino detectors:

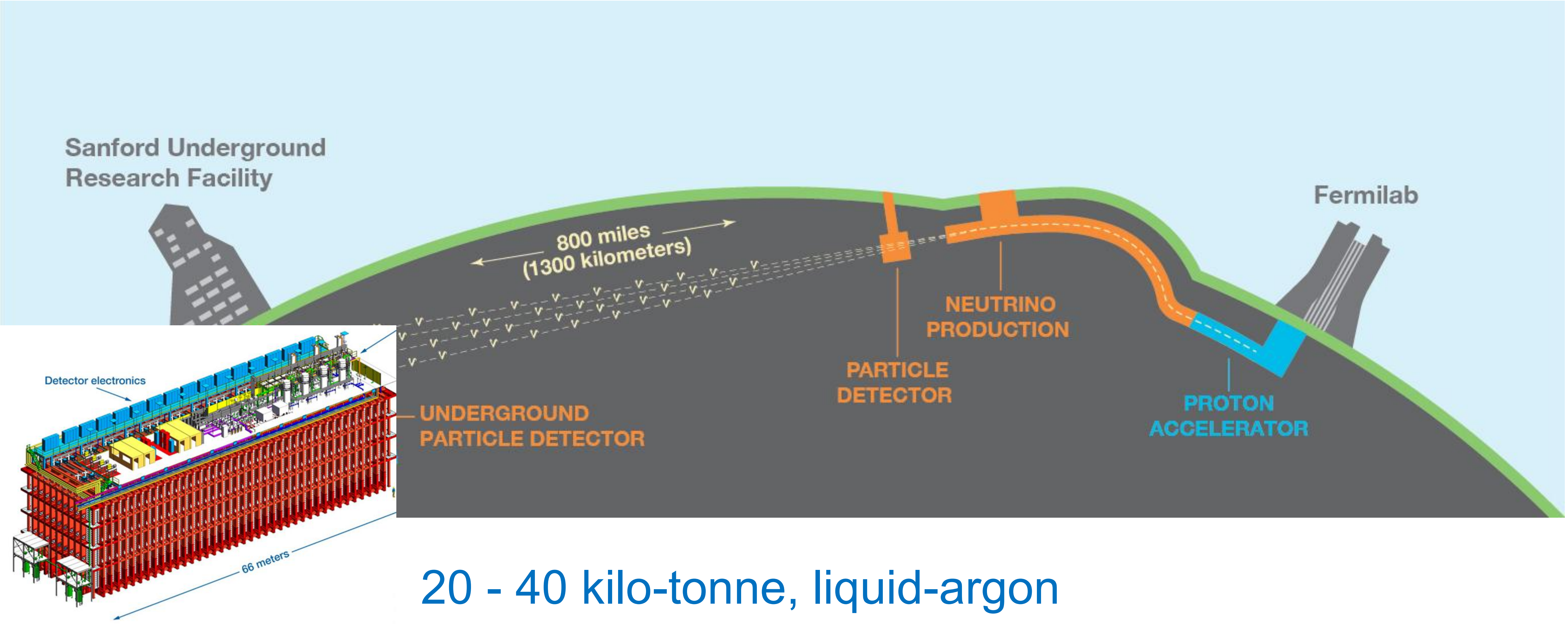
JUNO (China)



Hyper-Kamiokande (Japan)



DUNE (Deep Underground Neutrino Experiment) USA



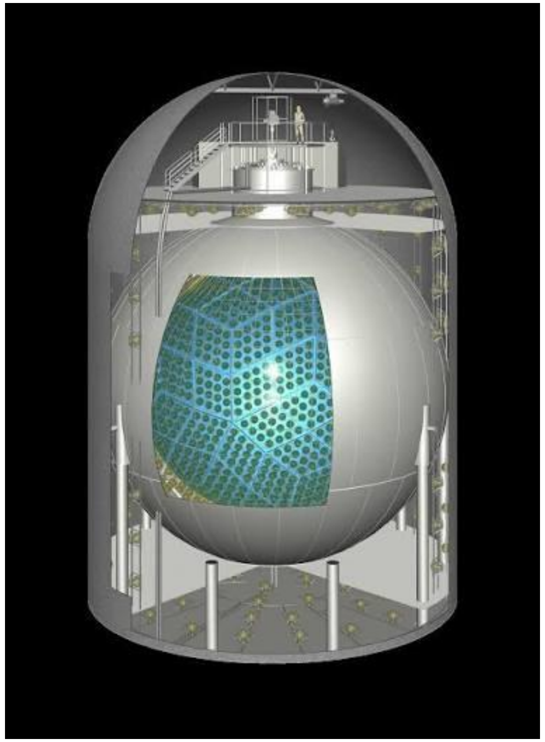
20 - 40 kilo-tonne, liquid-argon

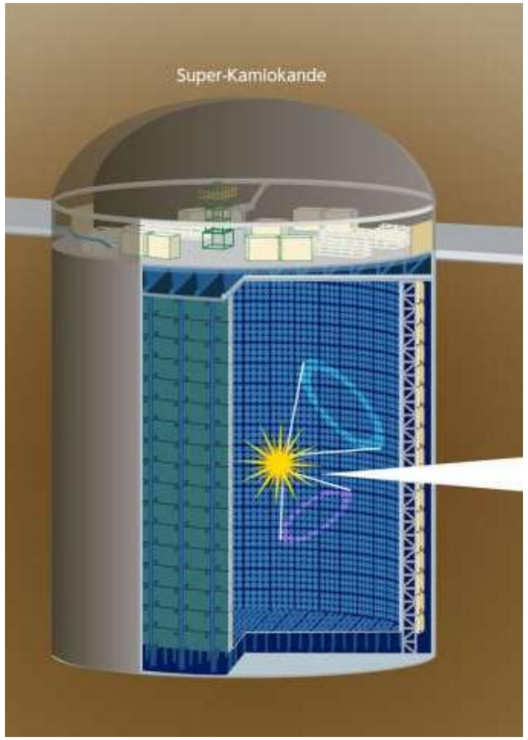
Previous generation experiments

KamLAND

liquid-scintillator
1 kilo-ton

(JUNO ~ 18 kilo-ton)





Super-Kamiokande

water-Cherenkov
22.5 kilo-ton

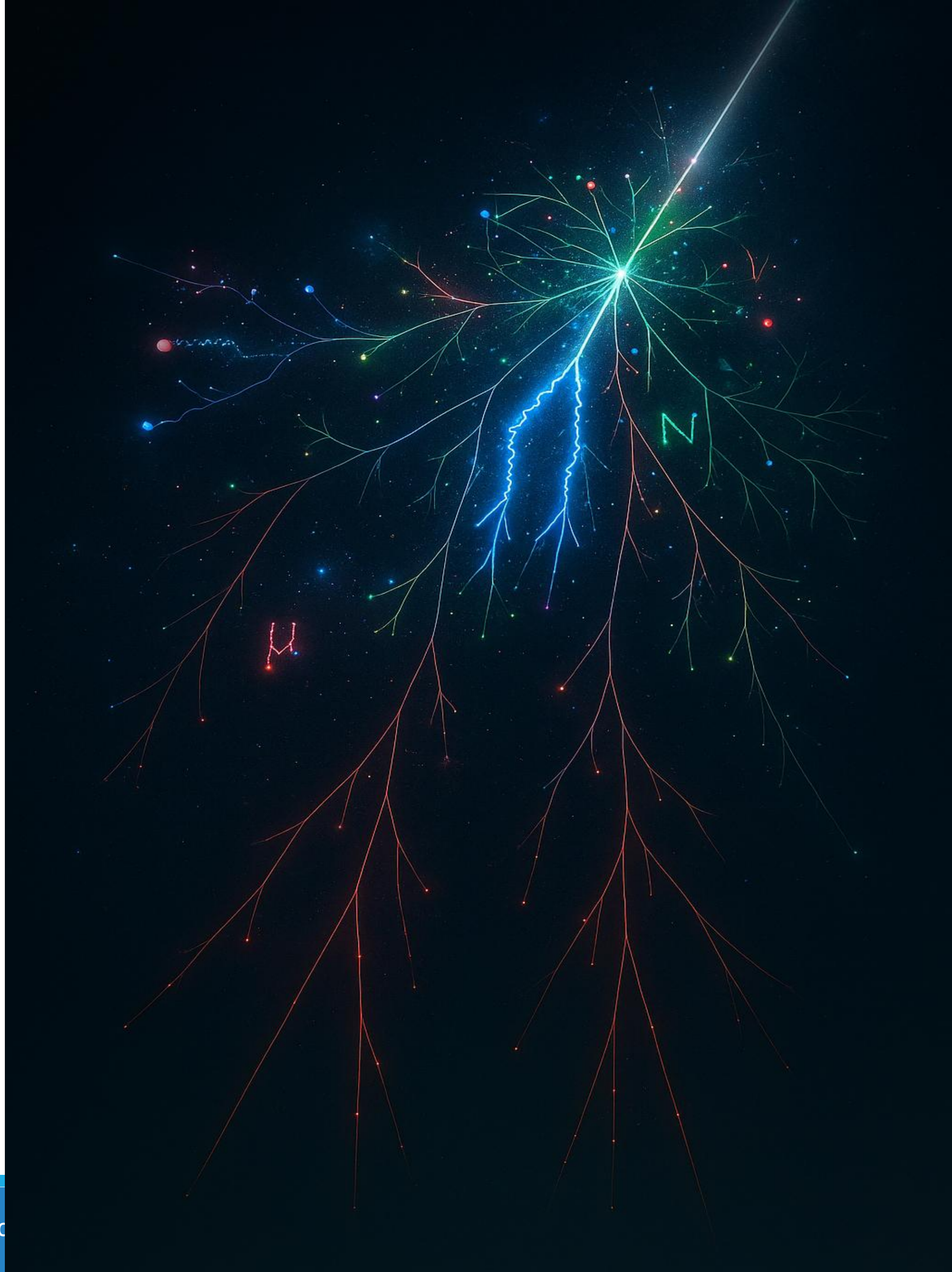
(Hyper-K ~ 190 kilo-ton)

Outline:

- Measuring the CP-violating phase with atmospheric neutrinos
- Precise solar neutrino measurements at DUNE
- Searching for dark matter annihilation to neutrinos

Measuring CP violation with atmospheric neutrinos

Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721



CP violation in the neutrino sector

Why does the Universe contain more matter than antimatter?

- Dynamical creation of a matter-antimatter asymmetry requires CP violation
- CP violation in the SM quark sector too small to explain the observed cosmological baryon asymmetry

  - Essential to test CP violation in the lepton section

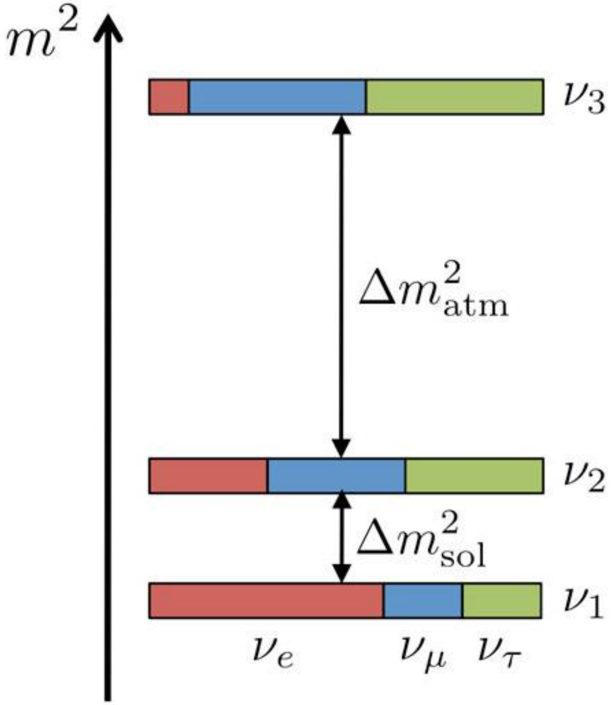
Measuring CP violation in the neutrino sector is a primary aim of accelerator-based long-baseline neutrino oscillation experiments.

- **Is there a viable independent way to measure this parameter?**

Neutrino mixing

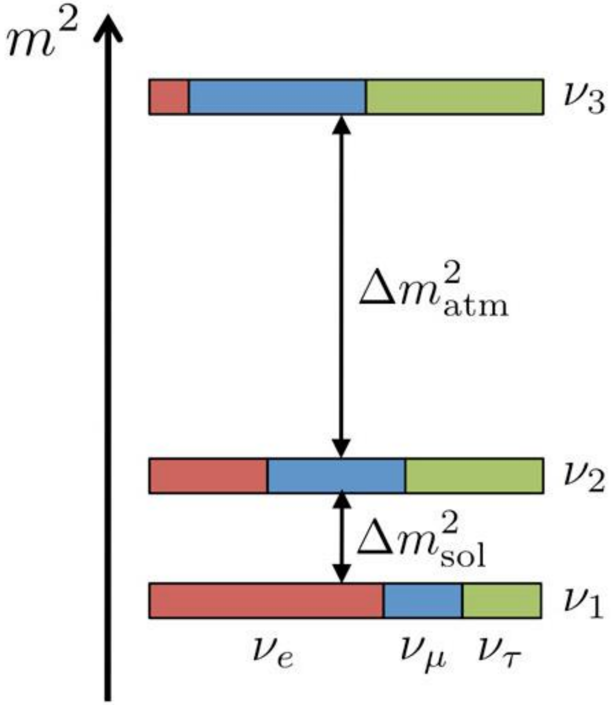
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour and mass states related by the PMNS matrix, which contains one three mixing angles and one phase.



CP violation in the mixing matrix

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$



where $c_{12} = \cos\theta_{12}$ etc

The phase $\boldsymbol{\delta_{CP}}$ introduces CP-violation

Neutrino oscillation probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}\left[U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\right]\sin^2\left(\frac{\Delta m^2_{kj}L}{4E}\right) + 2\sum_{k>j} \mathrm{Im}\left[U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\right]\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)$$

$\boldsymbol{\delta_{CP}}$ - even terms

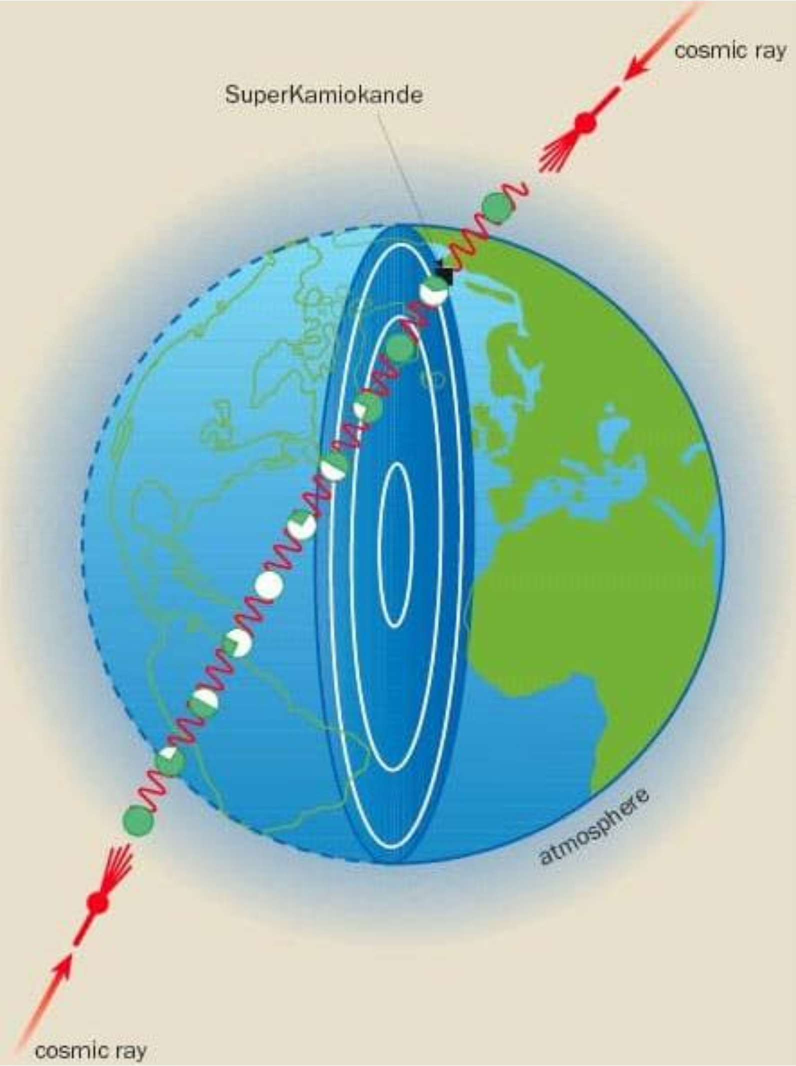
$\boldsymbol{\delta_{CP}}$ - odd terms

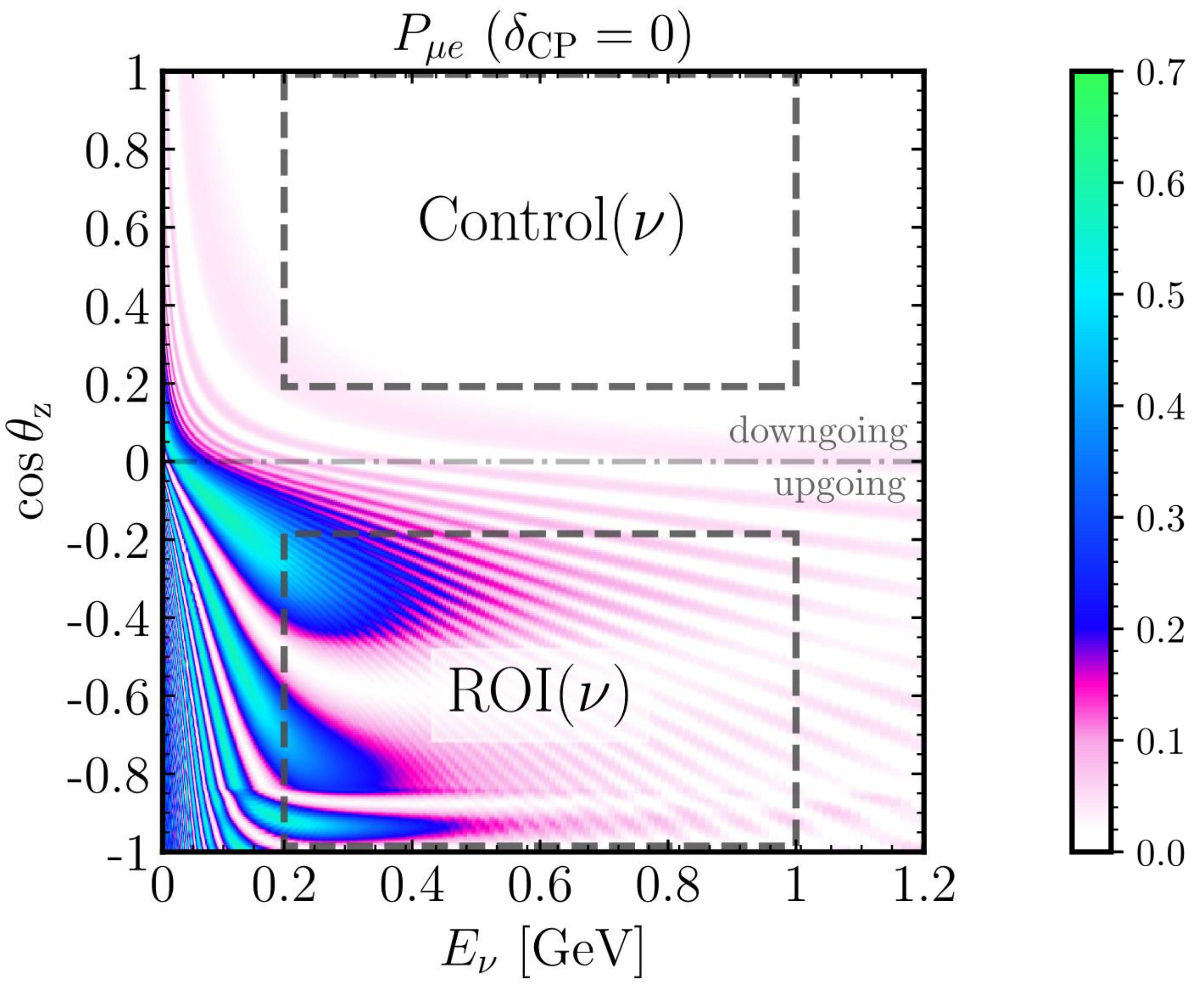
The task is to extract $\boldsymbol{\delta_{CP}}$-dependent effects in neutrino oscillations.

Need a regime where oscillations are not well approximated by a 2-flavour system.

- Two-flavour mixing is controlled by a single mixing angle and no phase. Genuine 3-flavour effects are needed for the complex phase to enter.
- Need oscillations driven by both mass-splittings Δm^2_{21} and Δm^2_{32} to be developed.

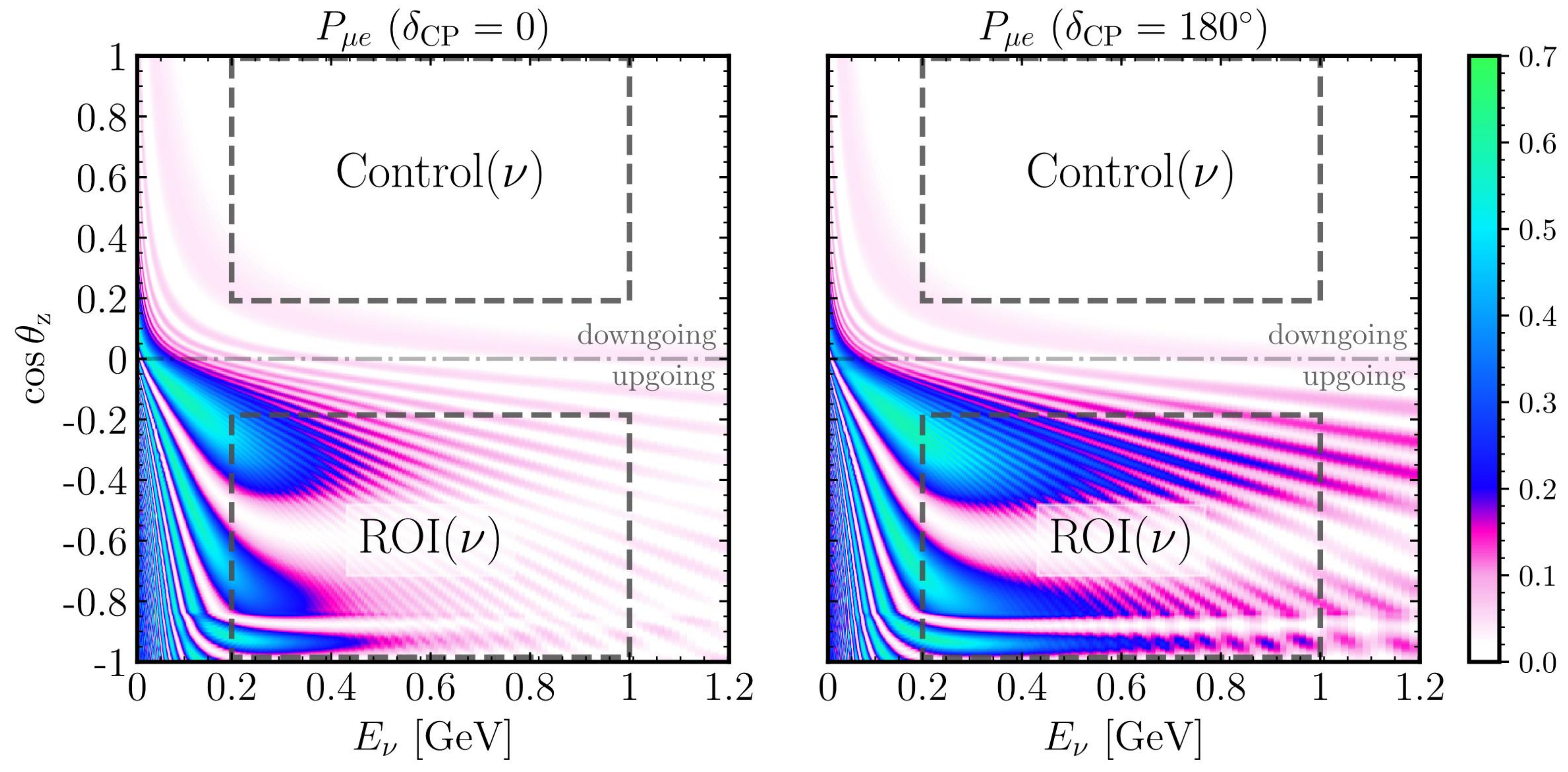
Atmospheric neutrino oscillations





CP violation in atmospheric neutrino oscillations

$\boldsymbol{\delta_{CP} = 0}$ $\boldsymbol{\delta_{CP} = 180^o}$

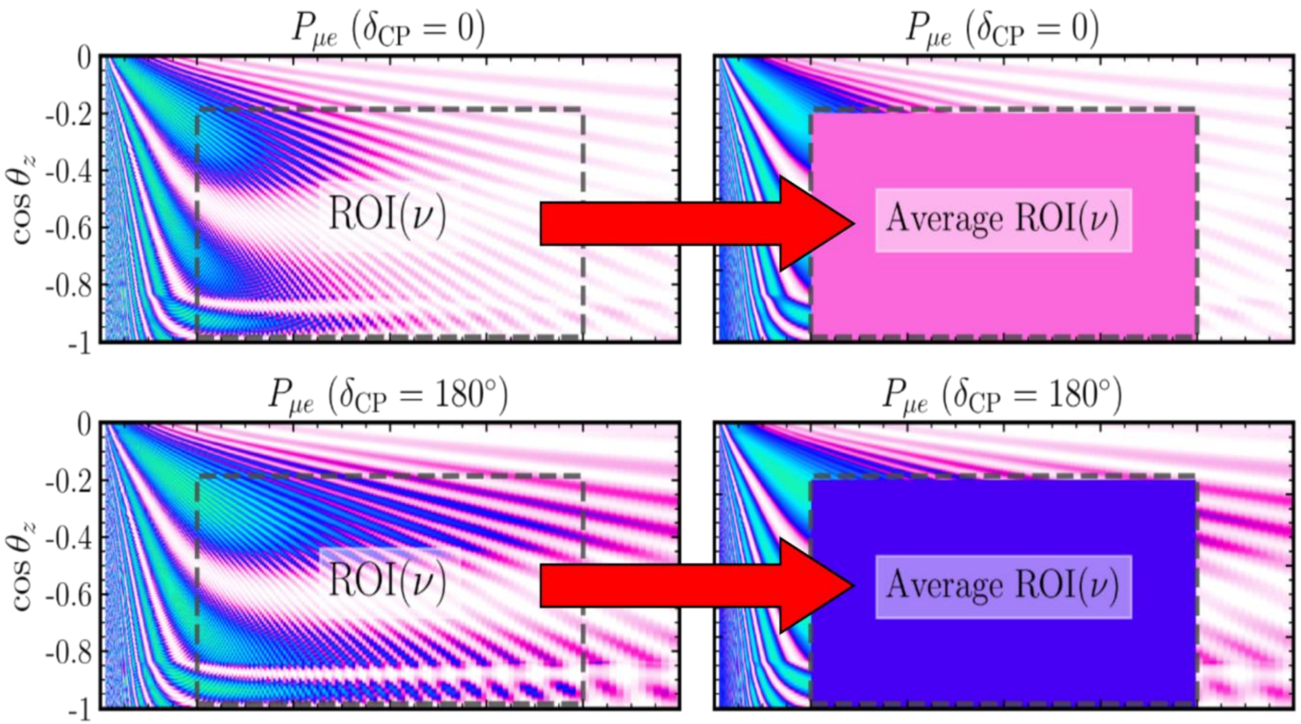


CP violation in atmospheric neutrino oscillations

Oscillograms have detailed structure

- ***fine details are unresolvable*** given realistic, unavoidable, energy and angular smearing.

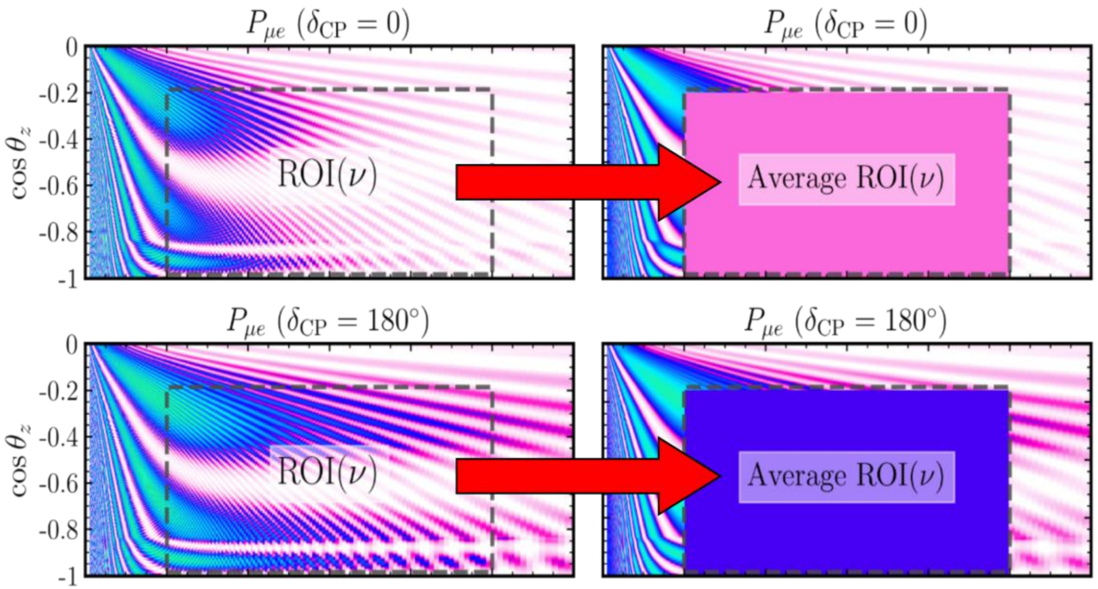
- ***CP-dependent effects survive averaging***

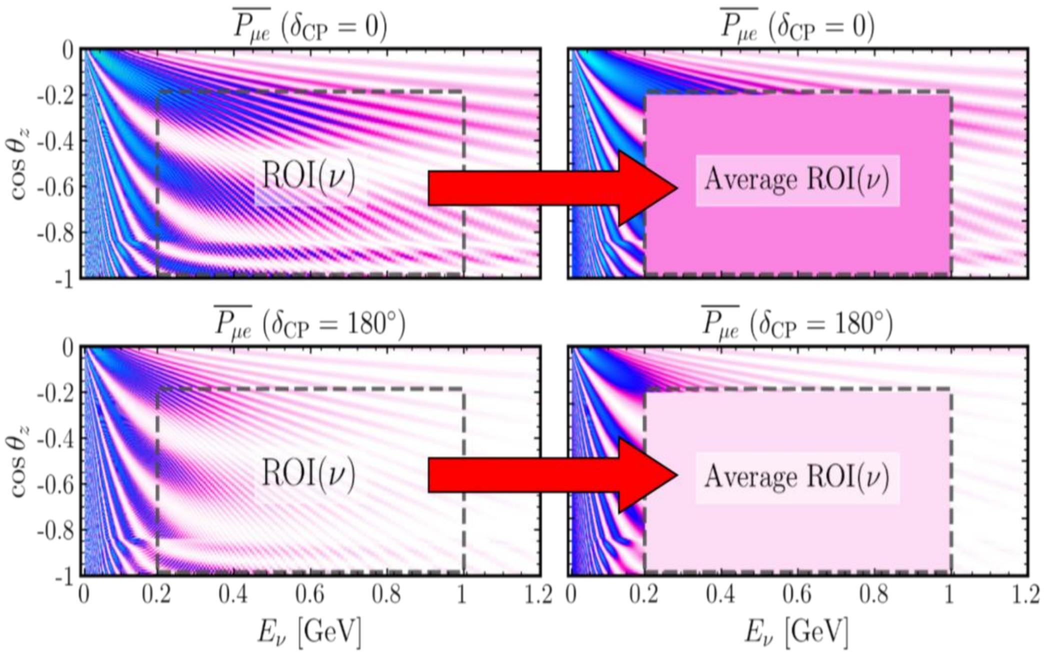


CP violation in atmospheric neutrino oscillations

Neutrinos

Anti Neutrinos



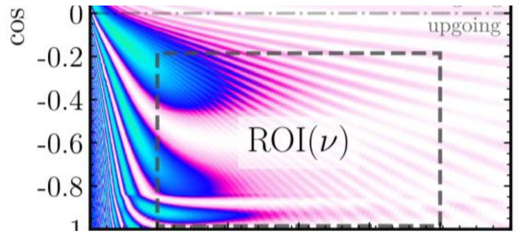


Needed: a robust CP-dependent observable

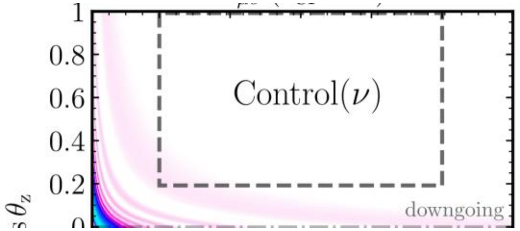
- Initial (unoscillated) fluxes have: $\phi_e : \phi_\mu : \phi_\tau = 1:2:0$

- Rate of **electron-type up-going events** is $\boldsymbol{\delta_{CP}}$-dependent:

$$\Gamma_{\text{up-going}} \propto \iint_{\textbf{ROI}} d\cos\theta_z \, dE_\nu \left(P_{ee} + 2P_{\mu e}\right)$$



- $\Gamma_{\text{down-going}}$ defined similarly over the **Control** region (and is $\boldsymbol{\delta_{CP}}$-independent)



A robust CP-dependent observable

- ***$\cos\delta_{CP}$*-dependent observable:**
  - most oscillations averaged out over the energy-angle region chosen
  - This removes $\sin\delta_{CP}$ terms, but not $\cos\delta_{CP}$ terms.

- **Up-down ratio to cancel leading flux & cross section uncertainties:**

$$R_{\mathrm{CP}} = \frac{\Gamma_{\text{up-going}}(\delta_{CP})}{\Gamma_{\text{down-going}}} = \frac{\mathrm{ROI}}{\mathrm{Control}} \sim (1 - 0.05\cos\delta_{CP})$$

Accelerator neutrinos vs atmospheric neutrinos

Accelerator long-baseline experiments – primarily sensitive to $\sin\delta_{CP}$

- For typical parameters ($E_\nu = 0.6$ GeV $L = 300$km), neglecting matter effects

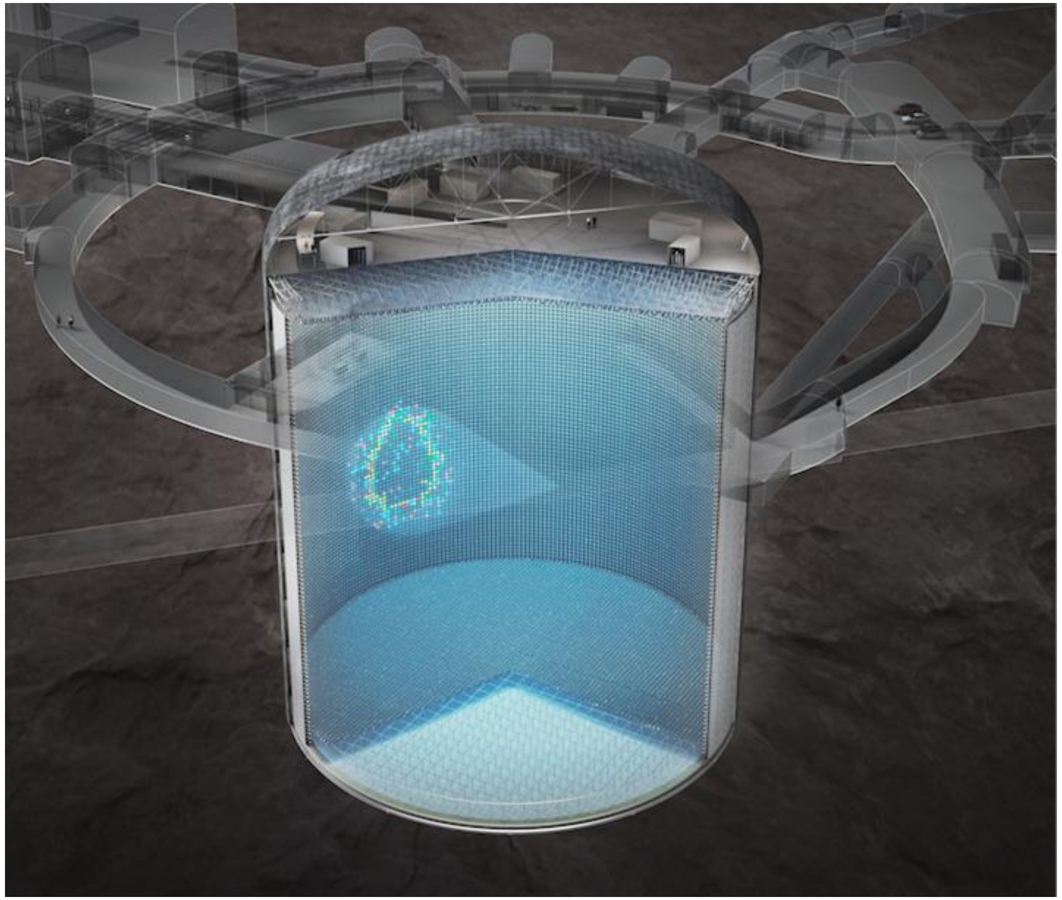
$$P_{\mu e} \sim 0.04(1 + 0.01\cos\delta_{CP} - 0.3\sin\delta_{CP})$$
$$\overline{P_{\mu e}} \sim 0.04(1 + 0.01\cos\delta_{CP} + 0.3\sin\delta_{CP})$$

- L/E_ν chosen to enhance sensitivity $\sin\delta_{CP}$. Comparing neutrino & antineutrino sensitivity cancels some systematics.

Note: Any manifestly CP violating (neutrino-antineutrino) observable must be proportional to the Jarlskog invariant, thus $\propto \sin\delta_{CP}$

Atmospheric neutrinos – our approach is sensitive to $\cos\delta_{CP}$

Can we do this at Hyper-K ?



186 kton fiducial volume

We expect:

- 2600 sub-GeV e-like events/year
- 2900 sub-GeV μ-like events/year

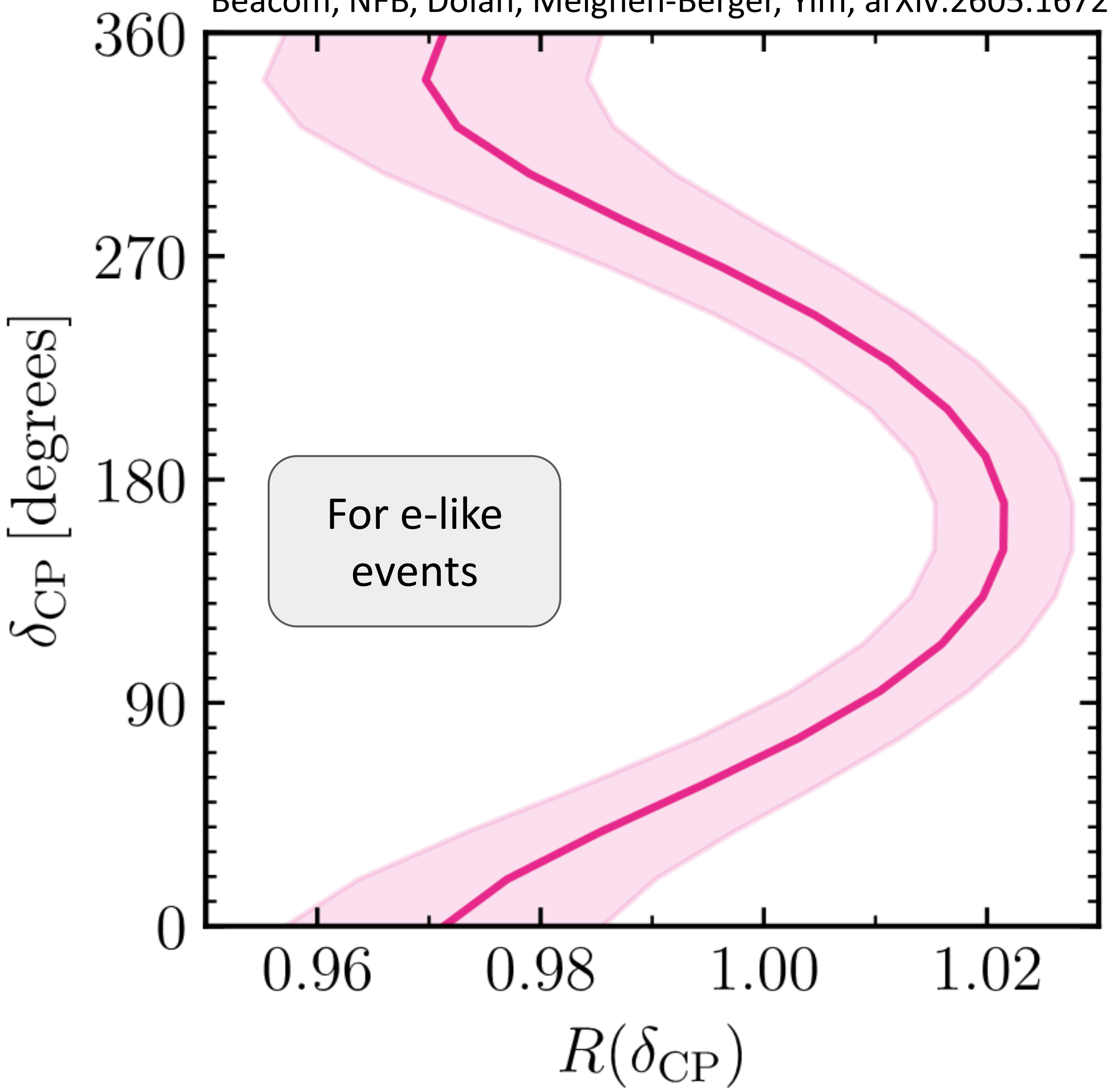
That means the e-like sample alone has a statistical power of <1%!

→ good enough to see a 5% effect

Adding detector effects:

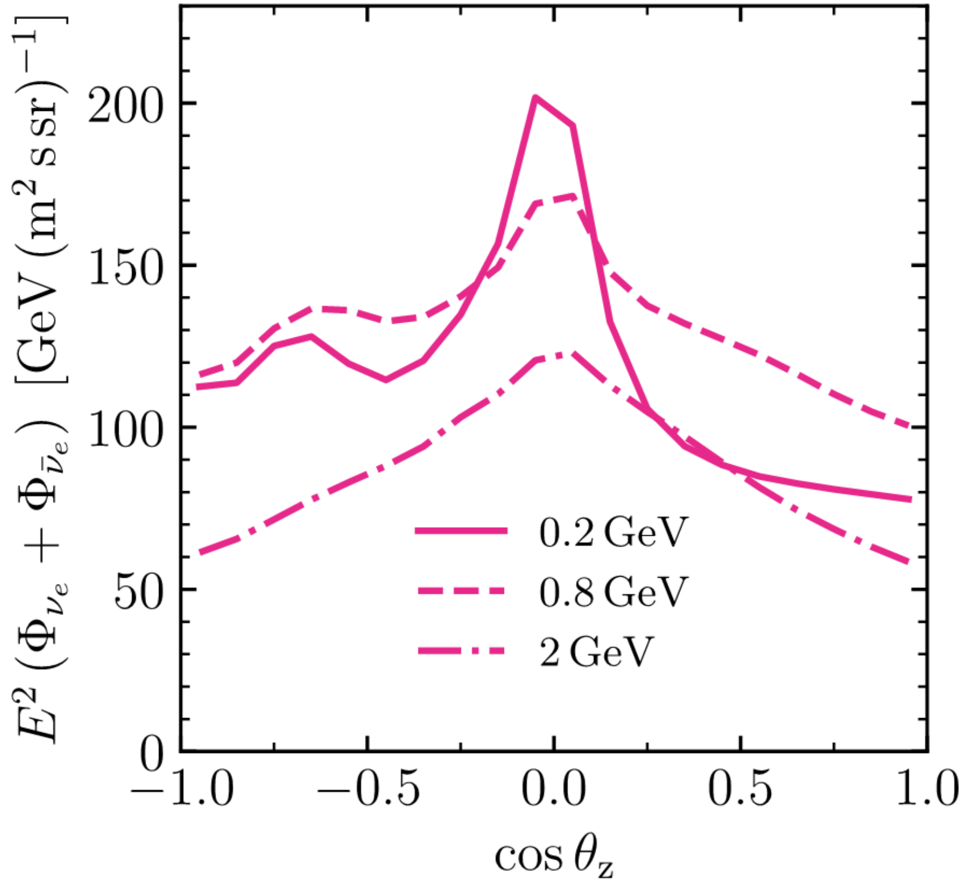
- Detector energy and angular smearing
- Fundamental limitation is the correlation between the charged lepton direction and the true neutrino direction
    - To reduce up/down smearing: zenith-angle cut $|\cos\theta_z| > 0.2$ (i.e. remove the horizon)
- Rate uncertainties taken to be 16% (combination of flux and cross section)

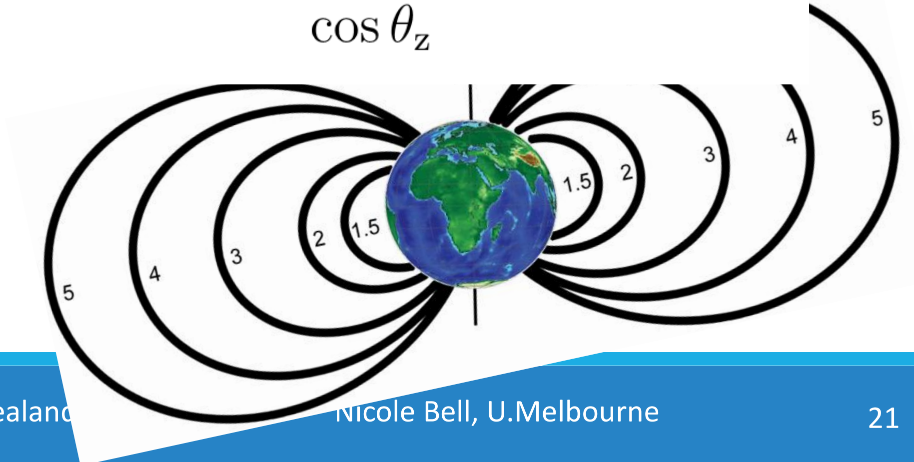
Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721



Leading uncertainties:

- The up/down ratio cancels leading flux and cross section uncertainties.
- It is not a perfect cancellation due to flux asymmetries as low energies
- Arise from geomagnetic effects (Earth's magnetic field imposes location – dependent, low energy cut-off on primary cosmic rays)



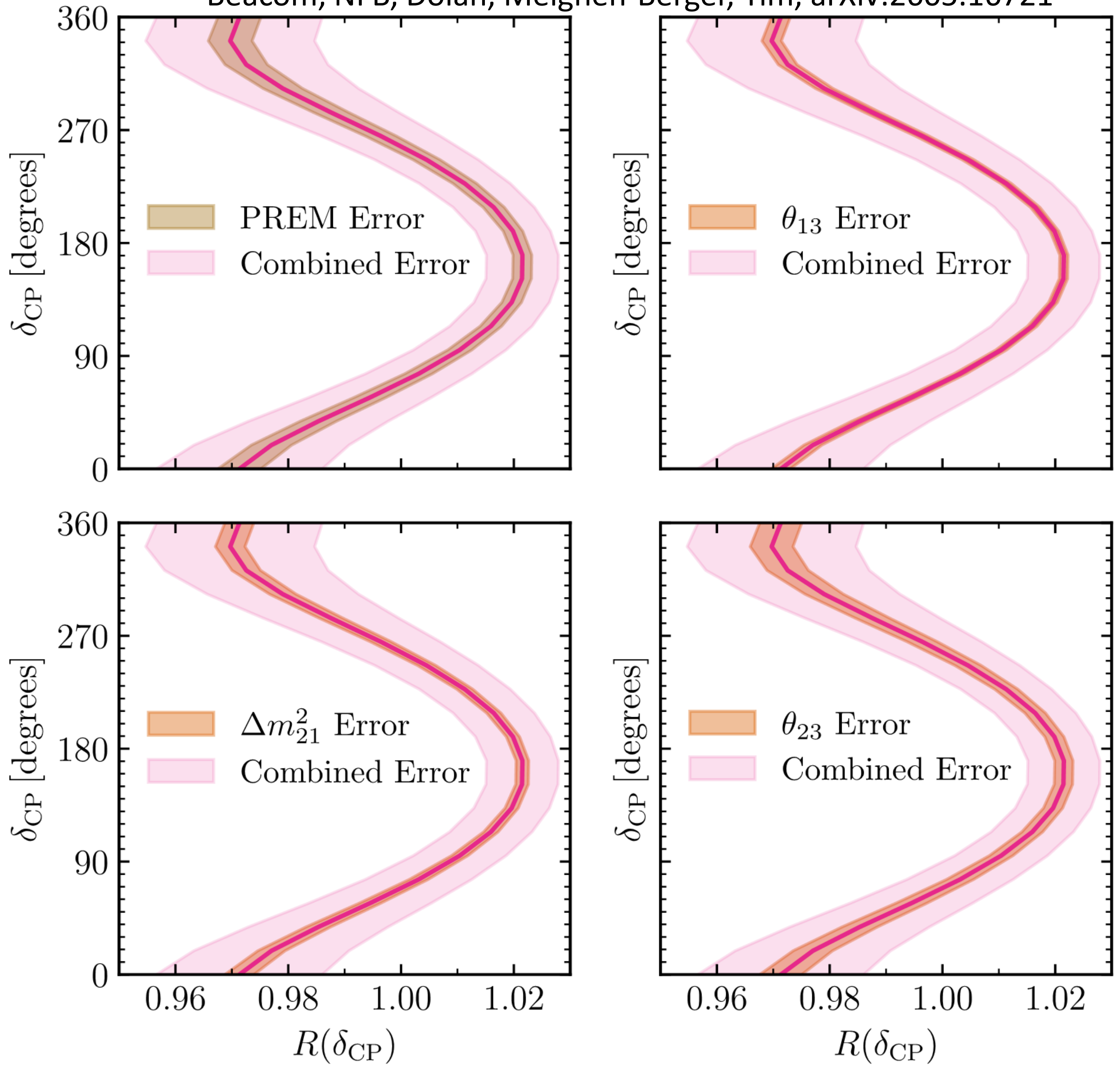


Subdominant uncertainties

- Largely insensitive to neutrino mixing parameter uncertainties
- Also insensitive to uncertainties in the Earth's density profile

(Averaging over the region of interest reduces the sensitivity to these parameters.)

Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721



Projected resolution

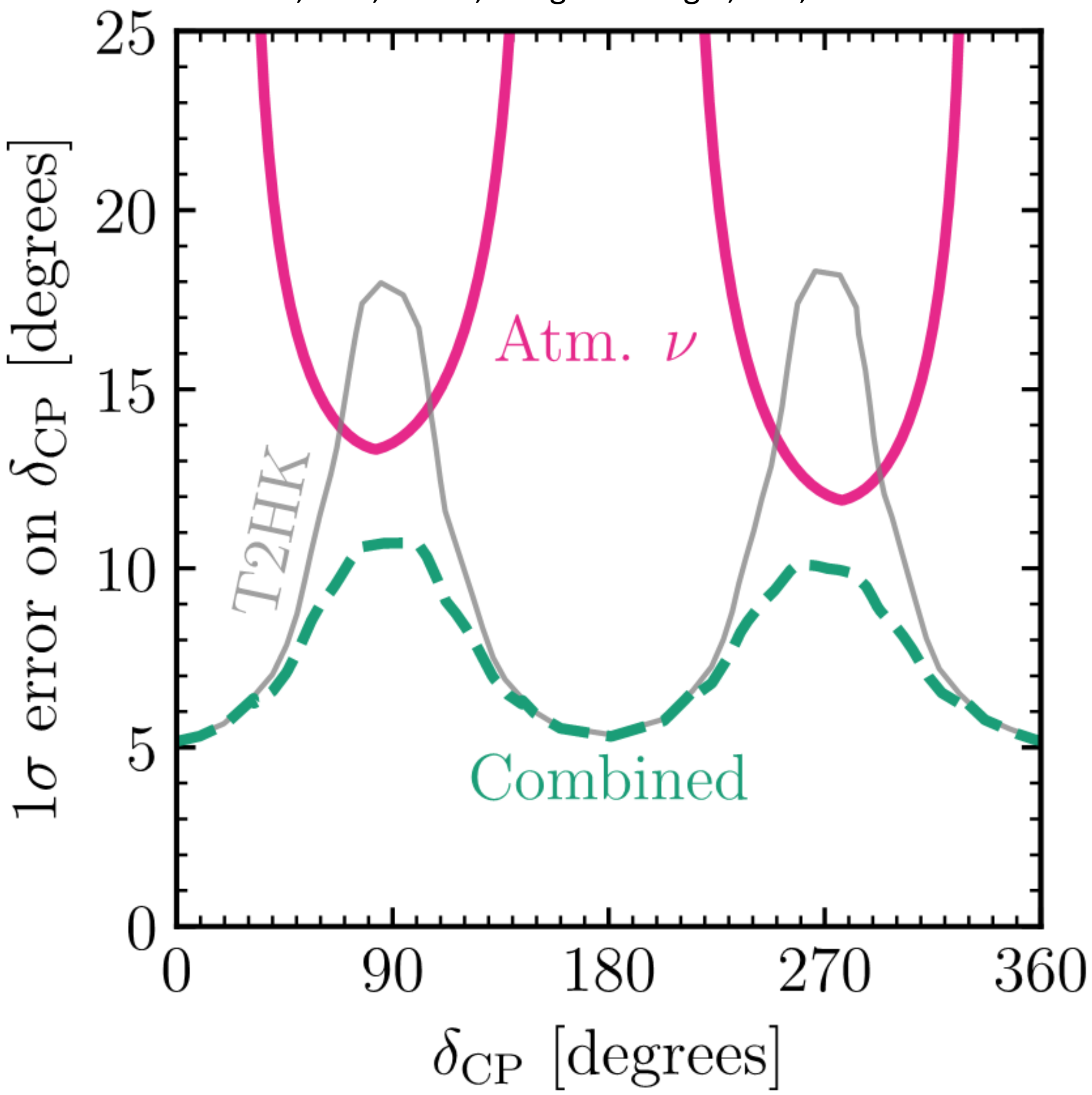
- ➢ Atmospheric approach most sensitive where the long-baseline approach is least sensitive.
  (due to $\cos\delta_{CP}$ vs $\sin\delta_{CP}$ dependence)

- ➢ Excellent complementarity

- ➢ Combined sensitivity is excellent across the full parameter range

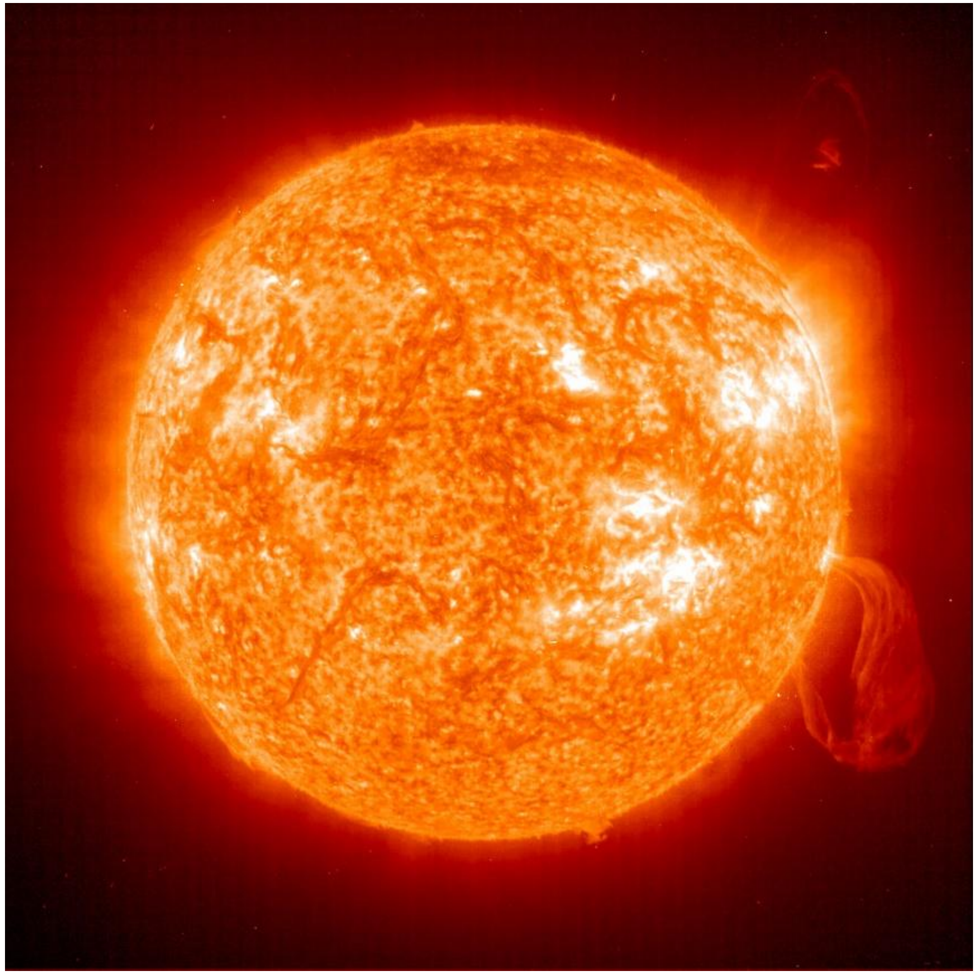
Atmospheric approach optimal near 90° & 270°
(maximal CP-violation; favoured by current data)

Beacom, NFB, Dolan, Meighen-Berger, Yim, arXiv:2605.16721



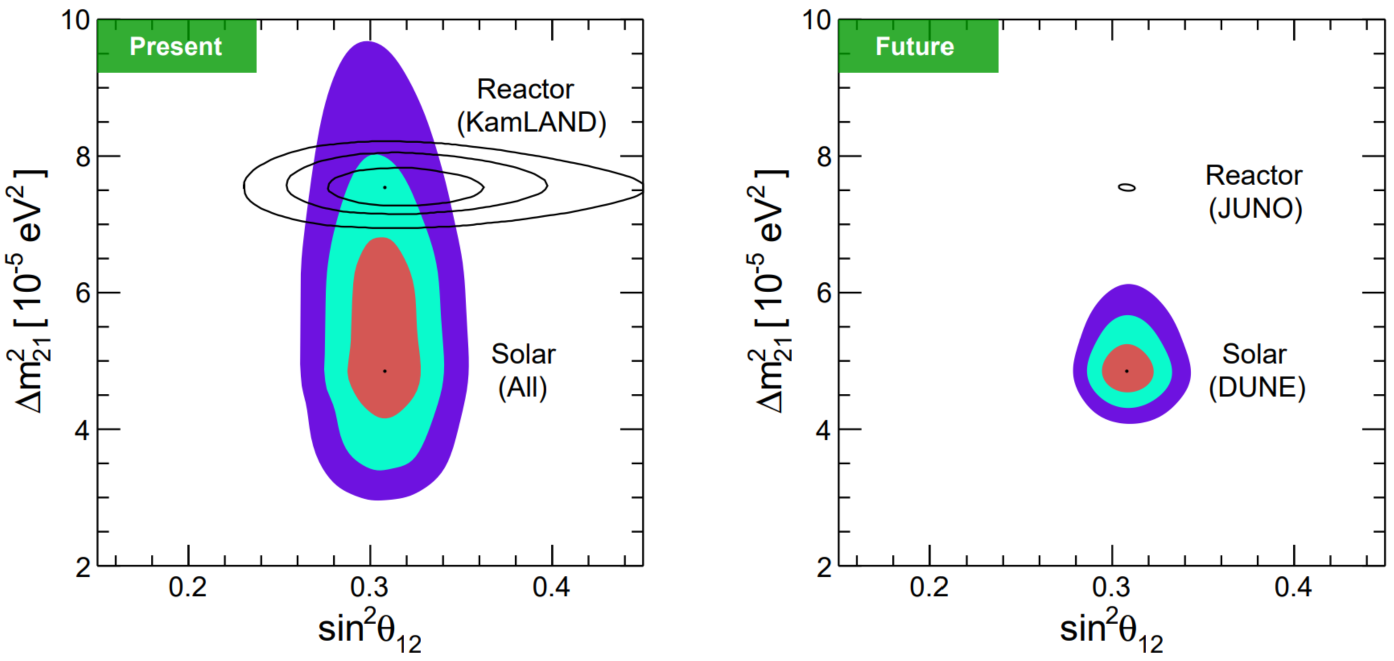
Solar neutrinos: precision measurements at DUNE

Meighen-Berger, Newstead, Beacom, NFB, Dolan, Phys. Rev. Lett. 135, 011803, 2025.



Measuring the solar neutrino mixing parameters

- JUNO (**using reactor antineutrinos**) will soon achieve sub-percent level precision on the solar mixing parameters: Δm^2_{21} , $\sin^2\theta_{12}$
- Comparing JUNO with a high precision measurement using **neutrinos from the Sun** would enable **sensitive tests of new physics**



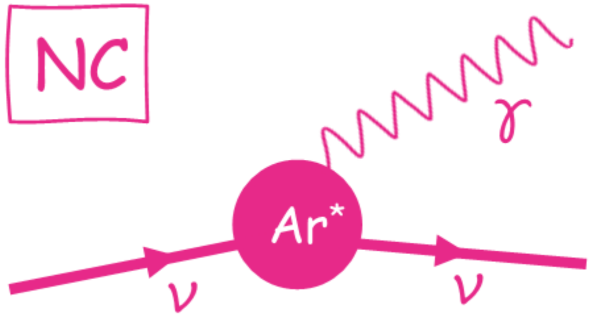
Capozzi et al, PRL 123, 131802, 2019

(charged current + elastic scattering at DUNE)

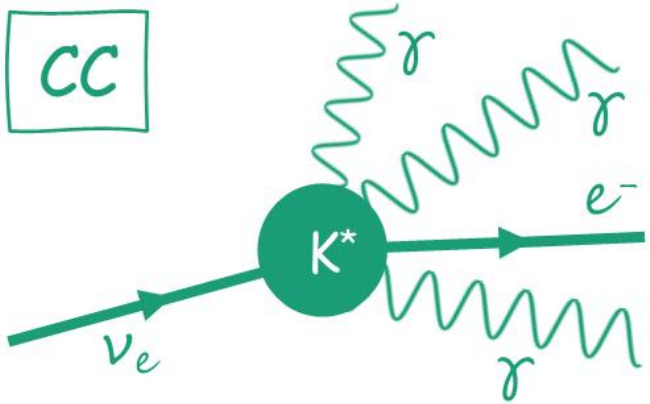
Solar neutrino measurements at DUNE

- Measure the total flux of ^{8}B neutrinos via neutral-current (NC) interactions with argon

- Make a SNO-like CC/NC comparison to precisely measure $\sin^2\theta_{12}$



$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow \nu_e + {}^{40}\mathrm{Ar}^*$$



$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Charged current (CC) – vs Neutral current (NC)

$$R^{CC} \propto \phi_e$$

$$R^{NC} \propto \phi_e + \phi_\mu + \phi_\tau$$

$$R^{ES} \propto \phi_e + \frac{1}{6}\left(\phi_\mu + \phi_\tau\right)$$

$$R^{CC} \propto \sin^2\theta_{12} \times \phi_{\text{total}}$$

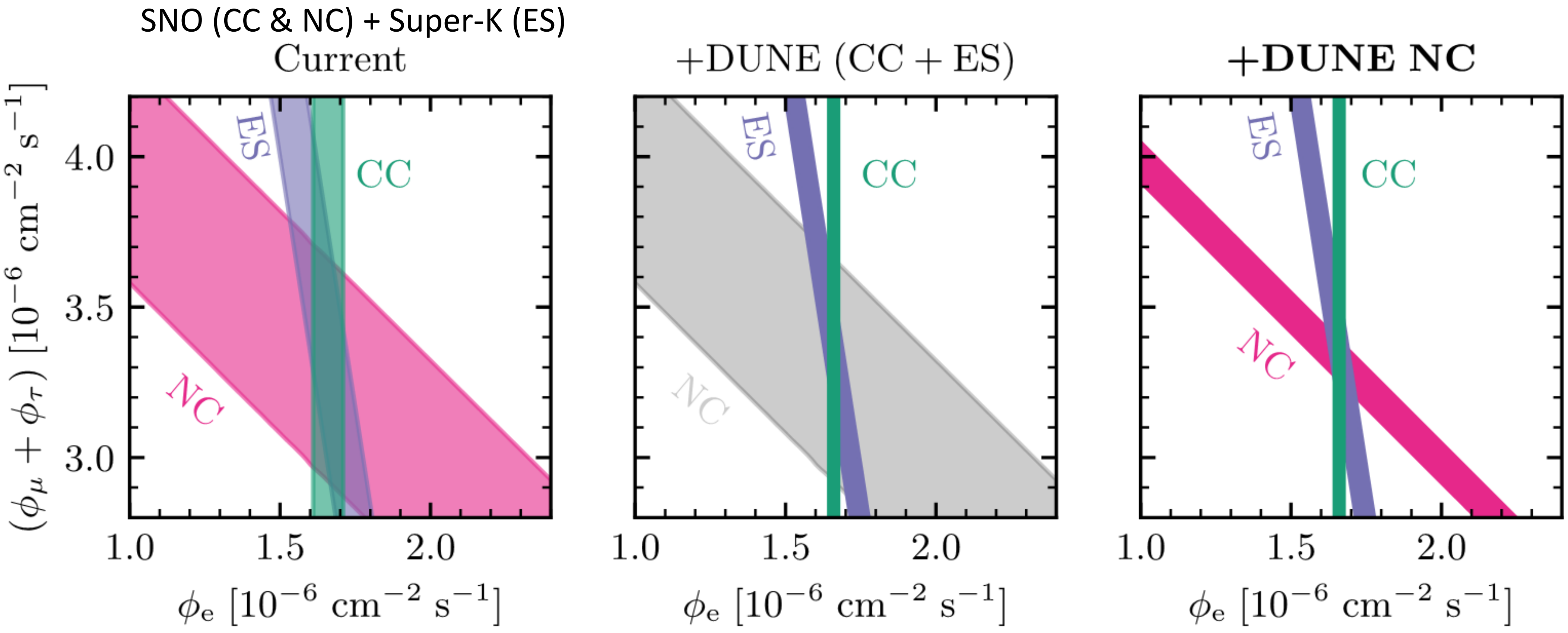
$$R^{NC} \propto \phi_{\text{total}}$$

$$R^{ES} \propto \left(1 + \frac{1}{6}\sin^2\theta_{12}\right) \times \phi_{\text{total}}$$

The CC / NC ratio directly determines the solar mixing angle

$$\frac{R^{CC}}{R^{NC}} = \sin^2\theta_{12}$$

High-precision CC-NC comparison



Meighen-Berger, Newstead, Beacom, NFB, Dolan, Phys. Rev. Lett. 135, 011803, 2025.

Neutral current measurements at DUNE

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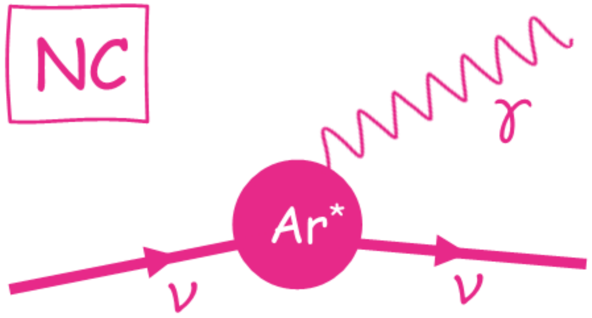

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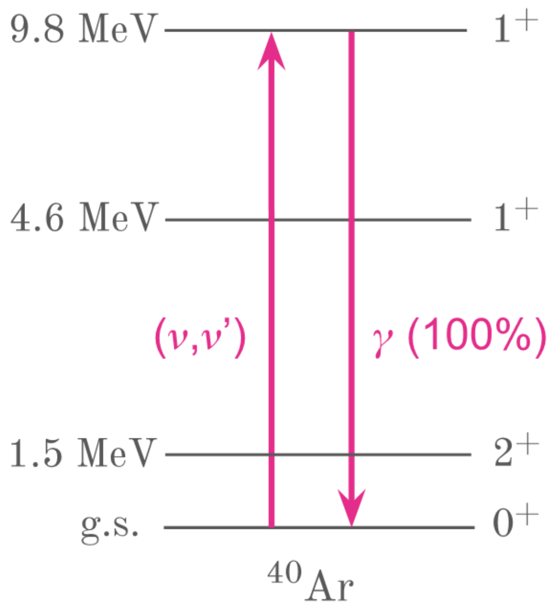
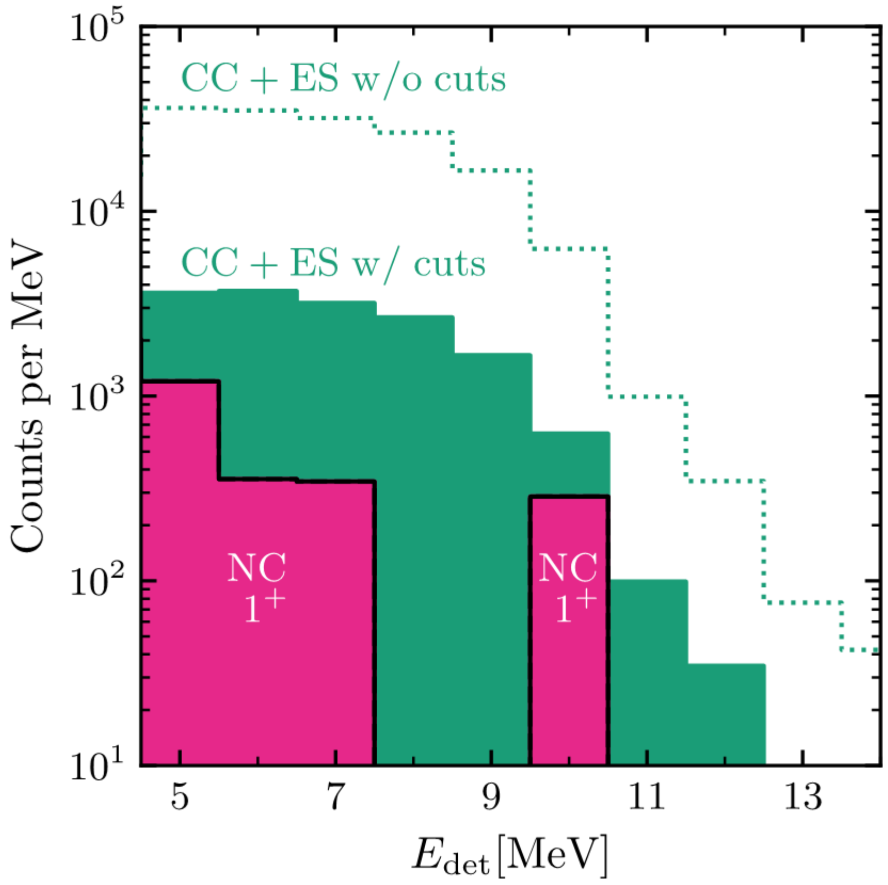
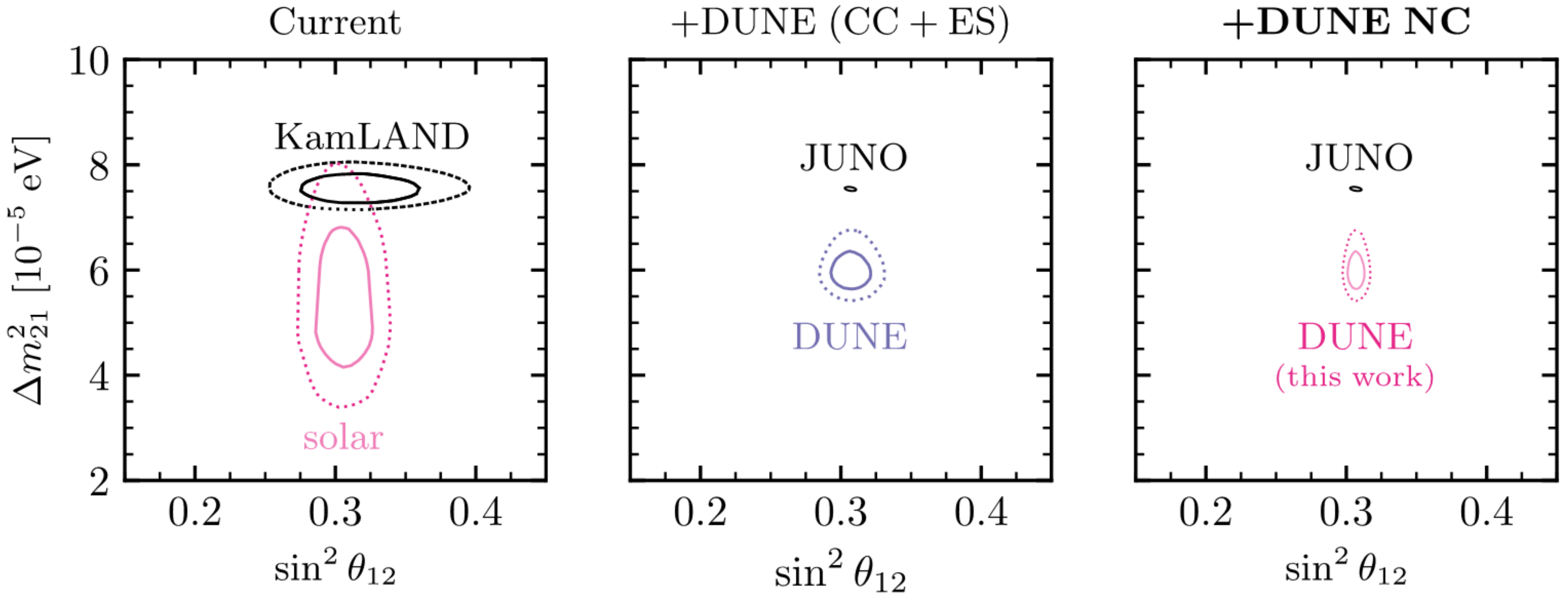


Expected spectra

DUNE exposure of 100 kton-years

After cuts:
~ 2200 NC events
~ 15000 CC+ES events



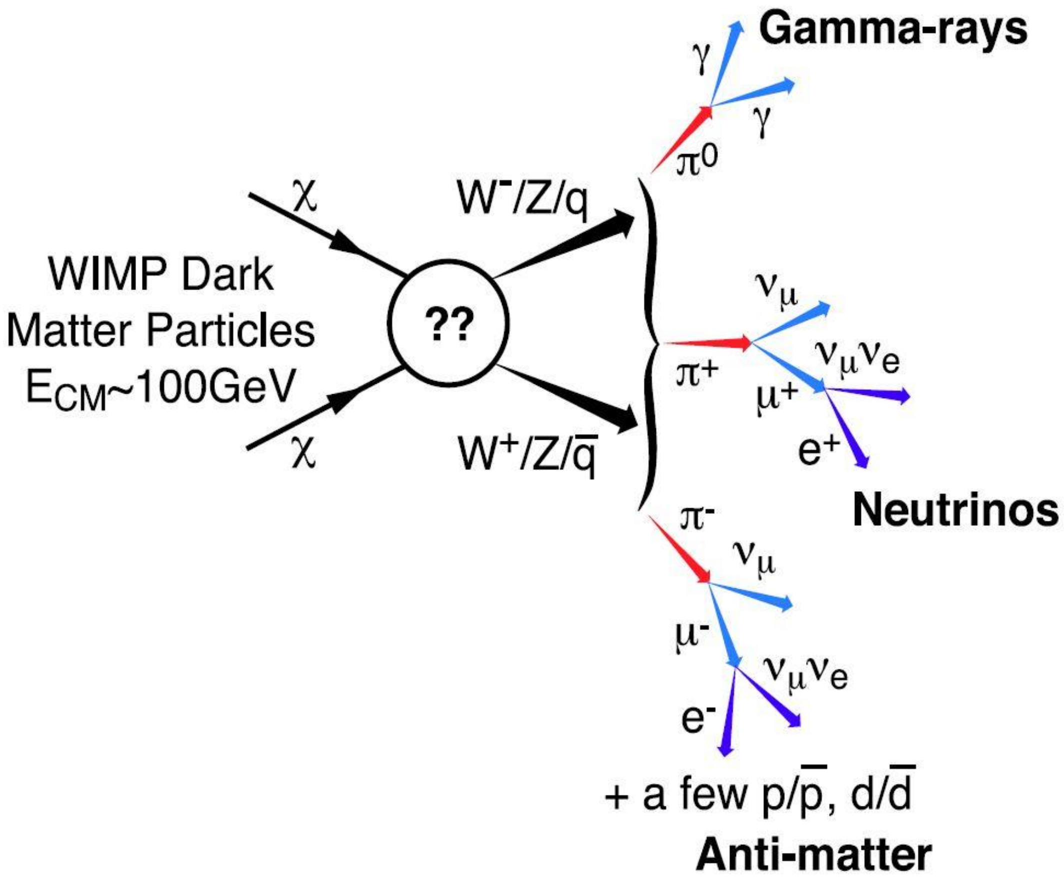


Meighen-Berger, Newstead, Beacom, NFB, Dolan, Phys. Rev. Lett. 135, 011803, 2025.

Searching for Dark Matter Annihilation to Neutrinos

NFB, Dolan, Robles, JCAP 09 019, (2020); JCAP 11, 004 (2021).

Dark Matter Indirect detection



Dark matter ***indirect detection*** is the **most direct test of the WIMP paradigm.**

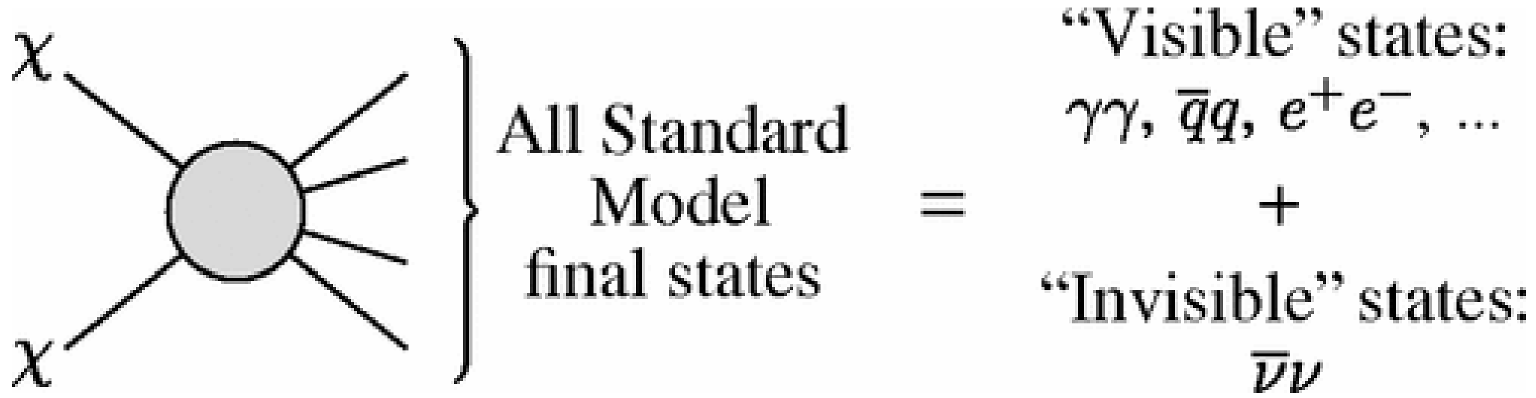
It is the **only direct test of annihilation cross section that sets the relic density.**

Annihilation cross section:

$$\langle \sigma v \rangle_{ann} \sim 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

Annihilation to neutrinos

- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to "invisible" or hard-to-detect final states.



- Can DM annihilate to neutrinos without producing charged fermions?
  - Yes, e.g., "neutrino portal" models
- **Annihilation to neutrinos – can we probe thermal-relic cross sections**?

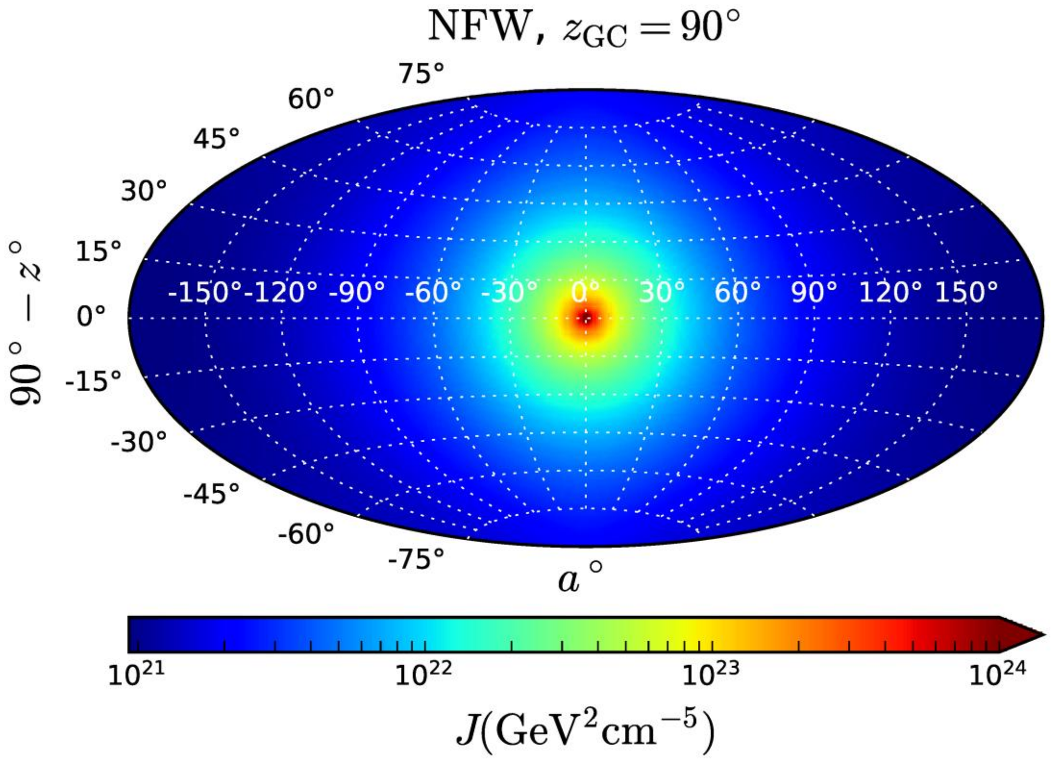
Dark matter annihilation at the Galactic Centre

$$\frac{d\Phi_{\nu\Delta\Omega}}{dE_\nu} = \langle\sigma v\rangle \frac{J_{\Delta\Omega}}{8\pi m_{DM}^2} \frac{dN_\nu}{dE_\nu}$$

Annihilation cross section

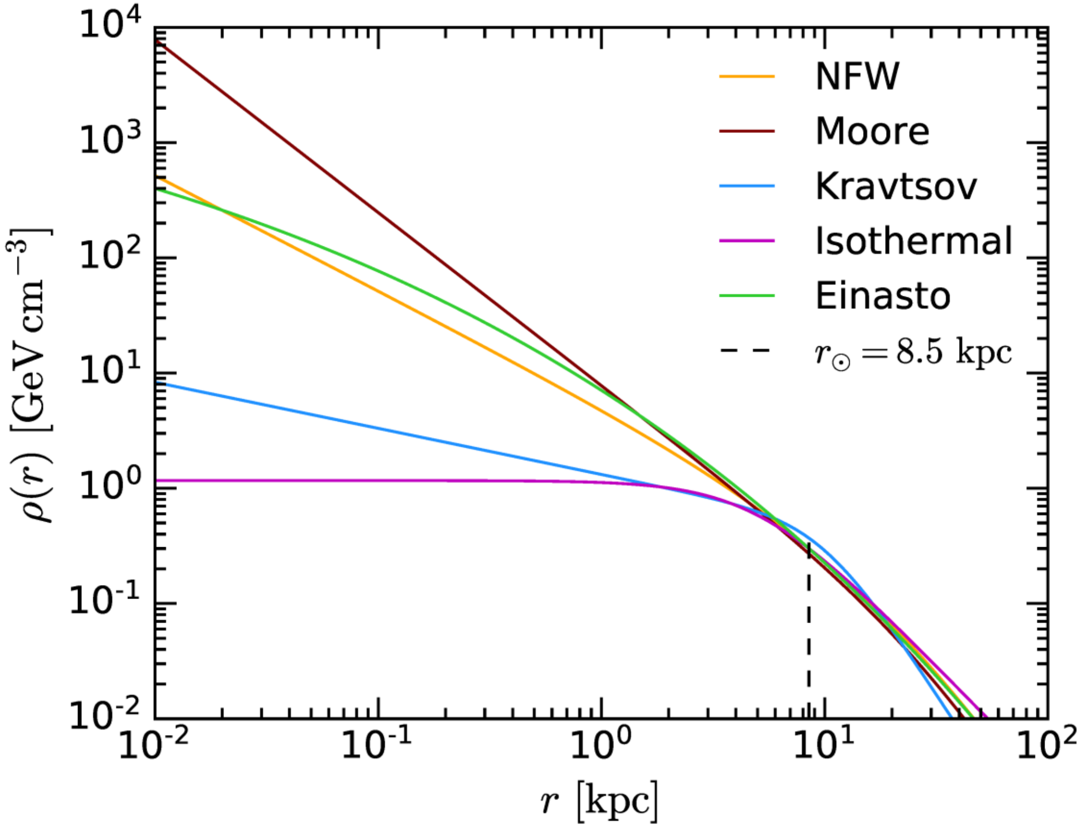
Integral of (density)^2 along line of sight

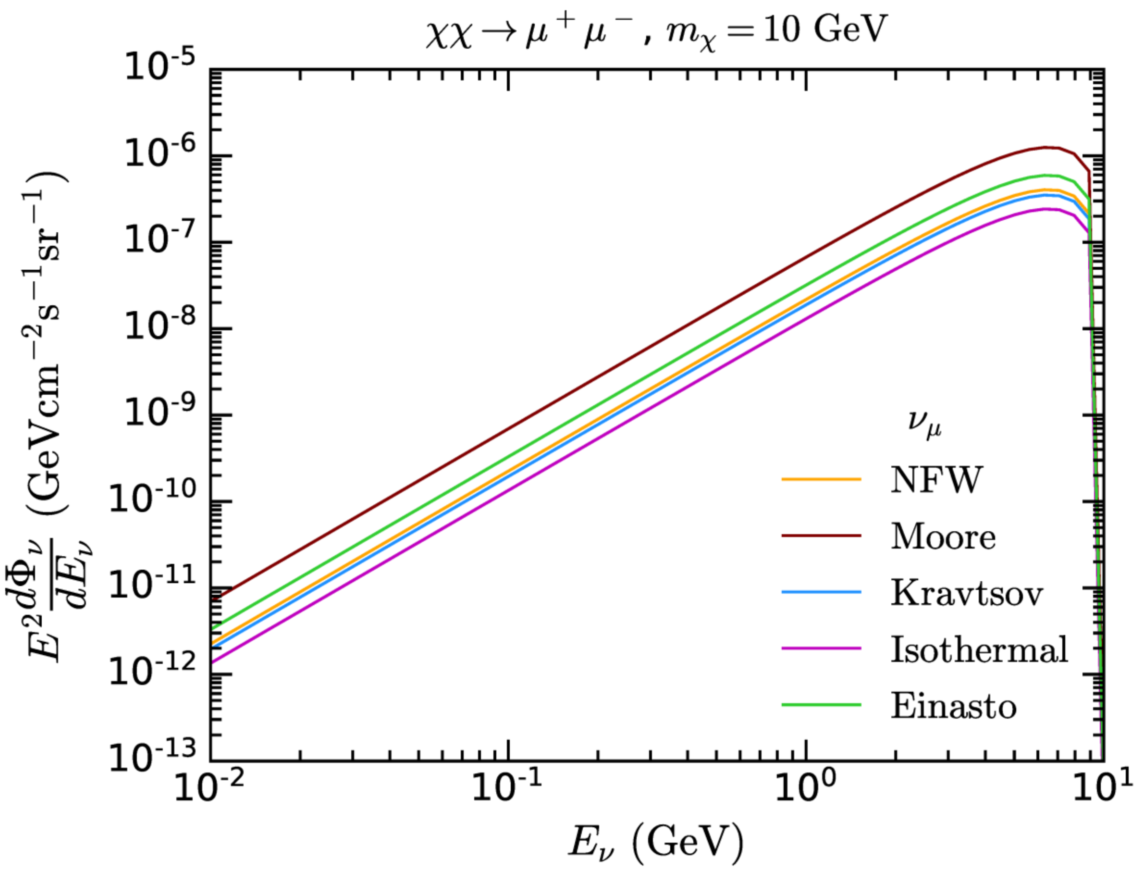
Spectrum per annihilation



NFB, Dolan, Robles, arXiv: 2005.01950

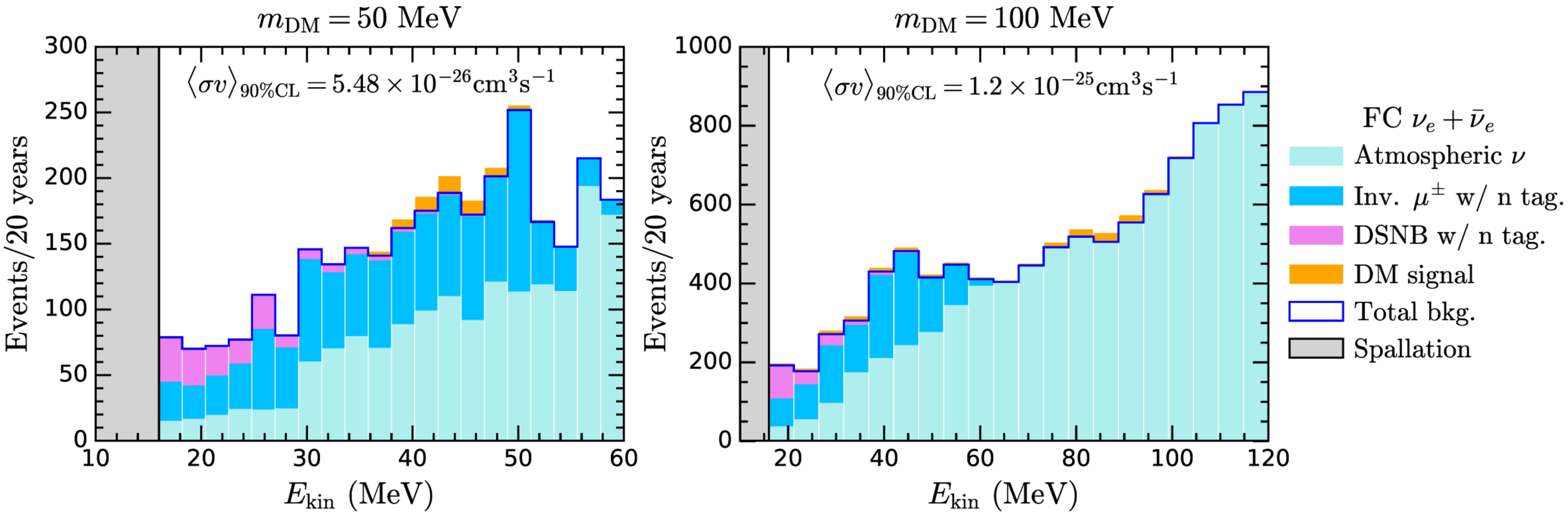
Dependence on halo profile is mild, as we undertake an all-sky analysis





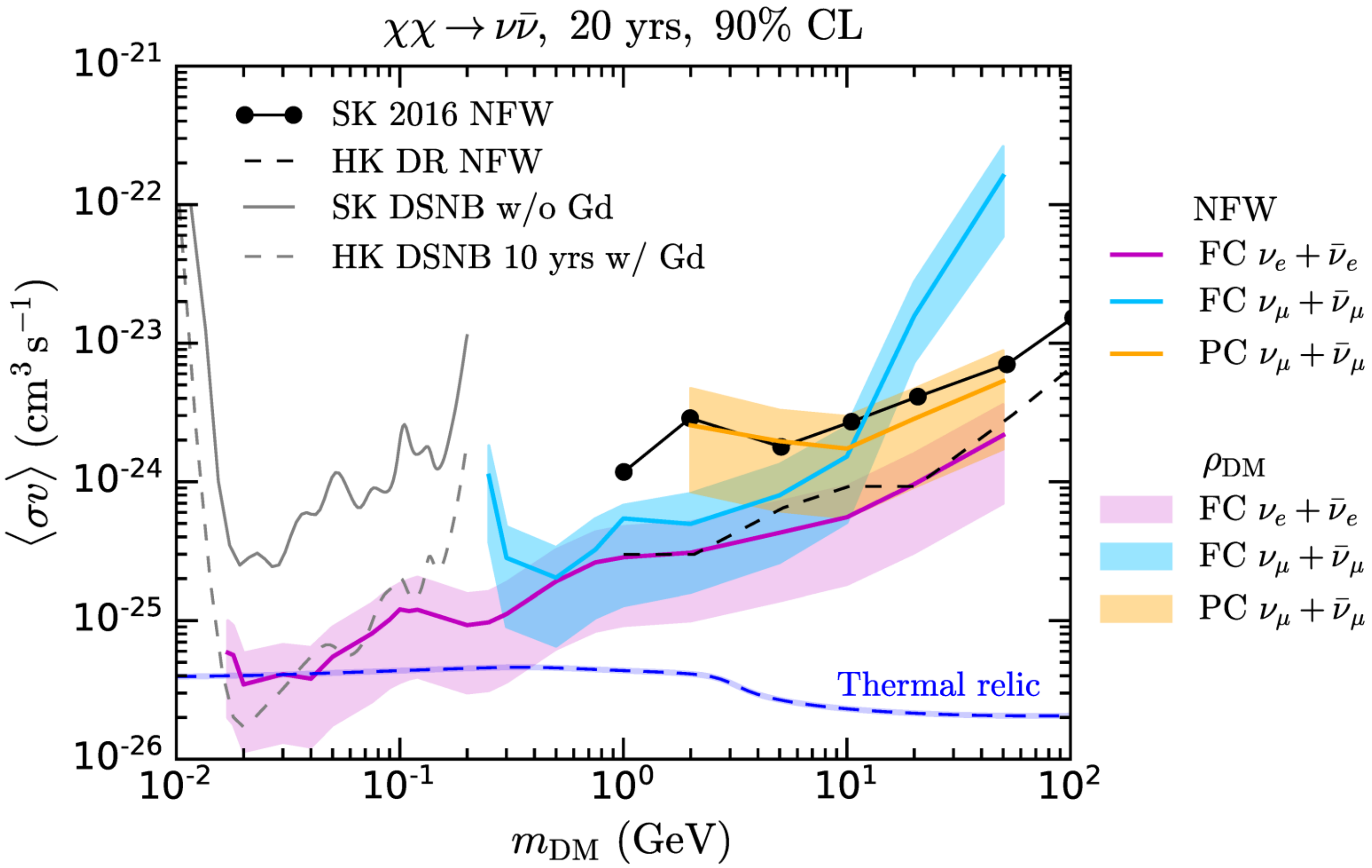
NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation signal sits on top of atmospheric neutrino background



NFB, Dolan, Robles, arXiv: 2005.01950

Cross section limits: $\chi\chi \to \nu\bar{\nu}$

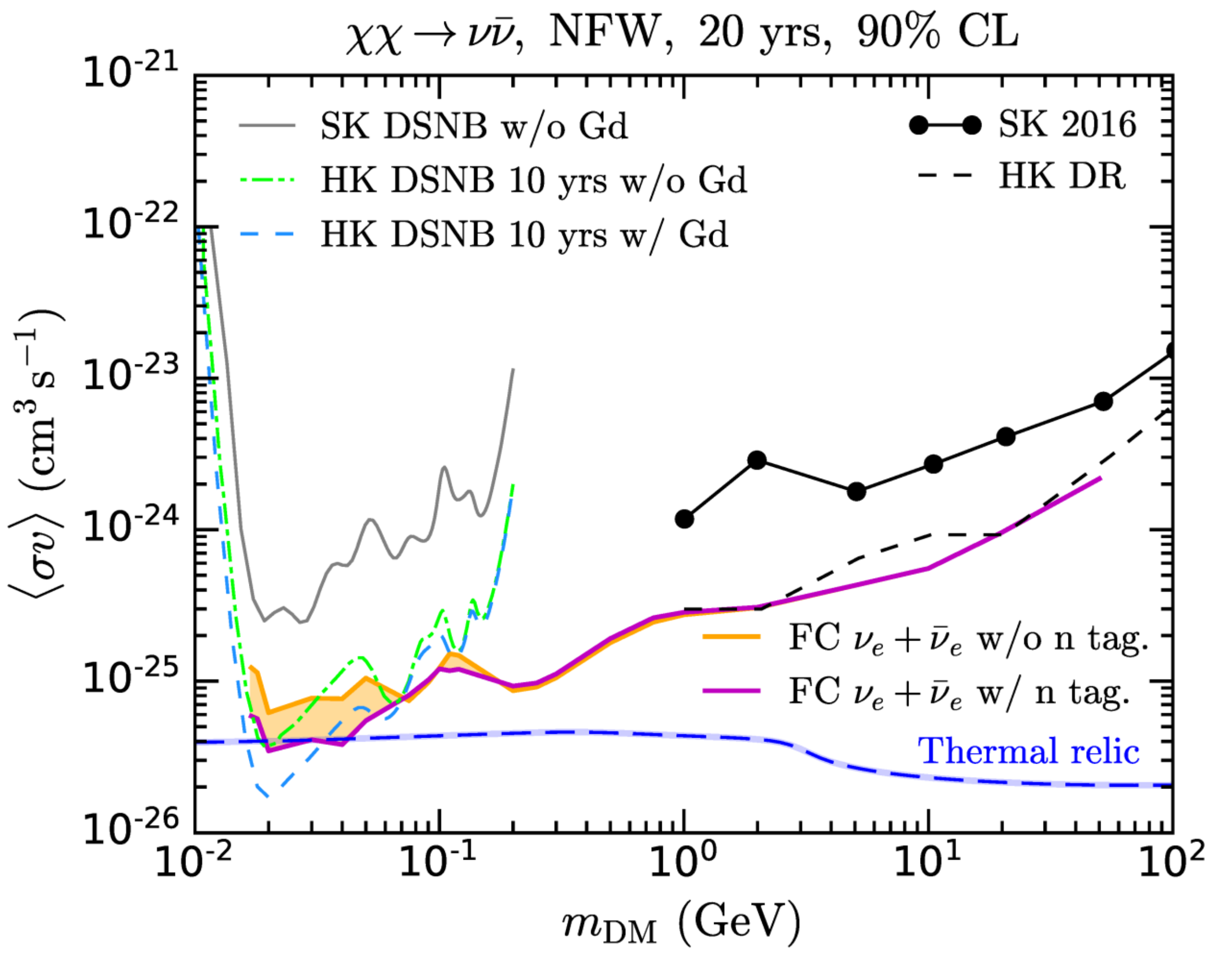


Thermal relic sensitivity for DM mass of ~ 30 MeV

NFW – central lines
Isothermal – upper
Moore - lower

NFB, Dolan, Robles, arXiv: 2005.01950

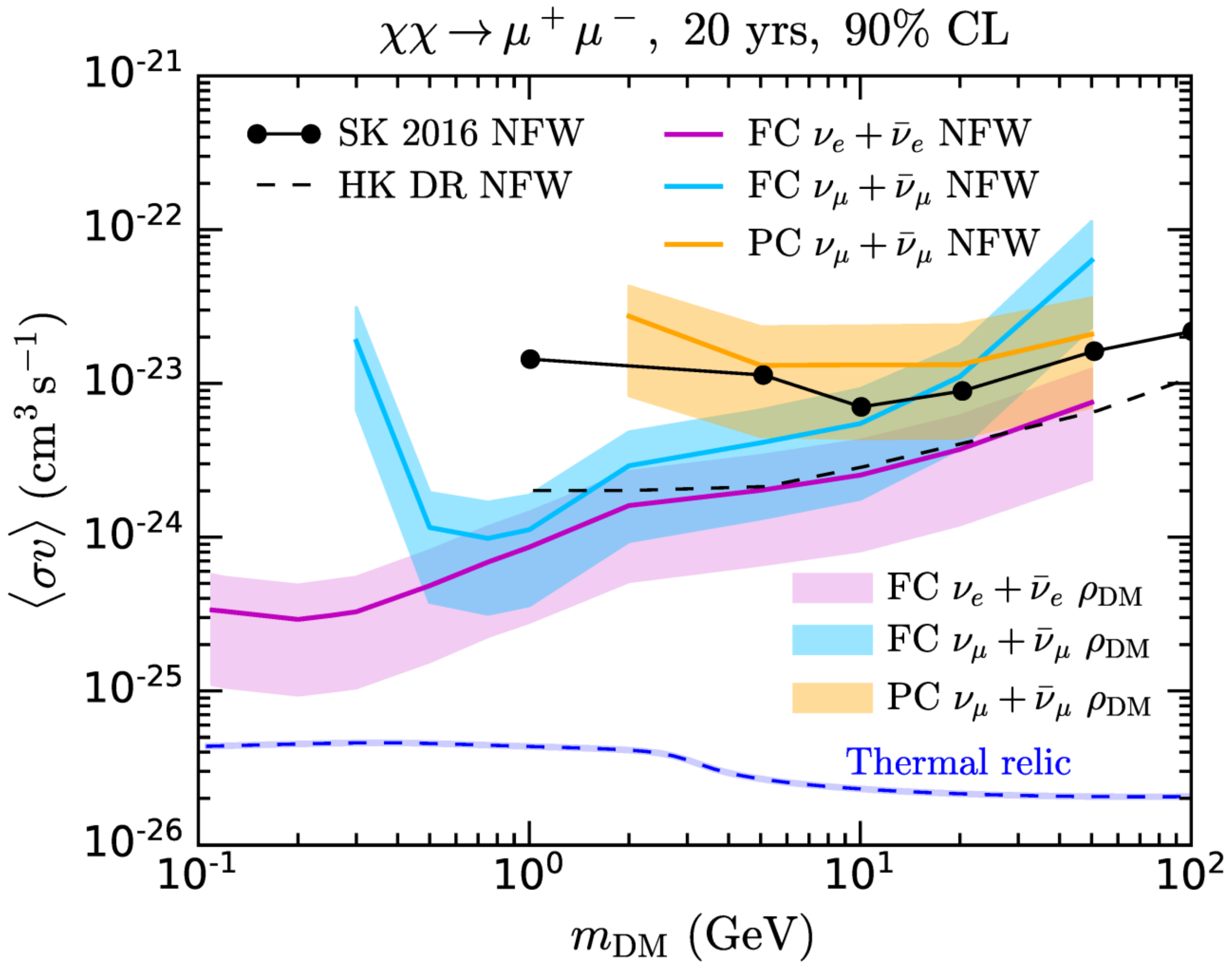
With and w/out neutron tagging



Assumes 70% tagging efficiency

NFB, Dolan, Robles, arXiv: 2005.01950

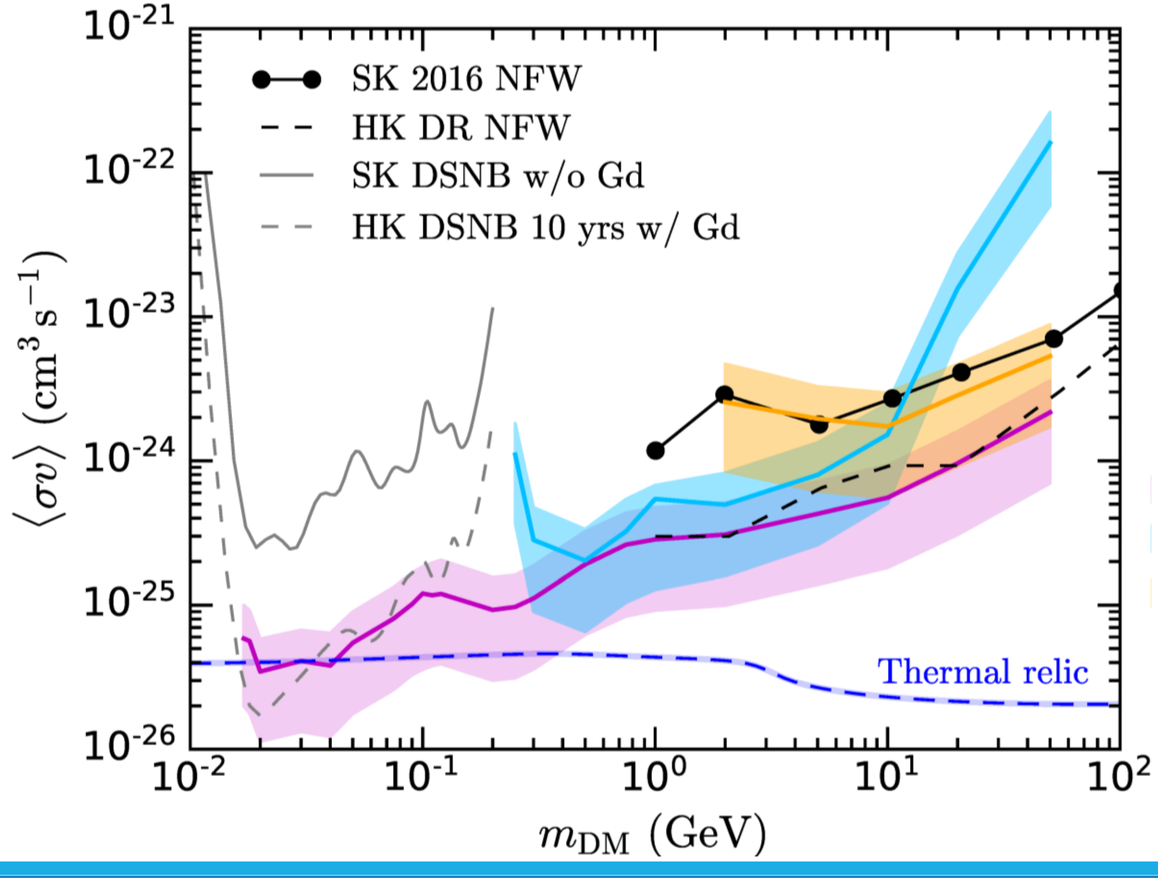
Cross section limits: $\chi\chi \rightarrow \mu^+\mu^-$



NFB, Dolan, Robles, arXiv: 2005.01950

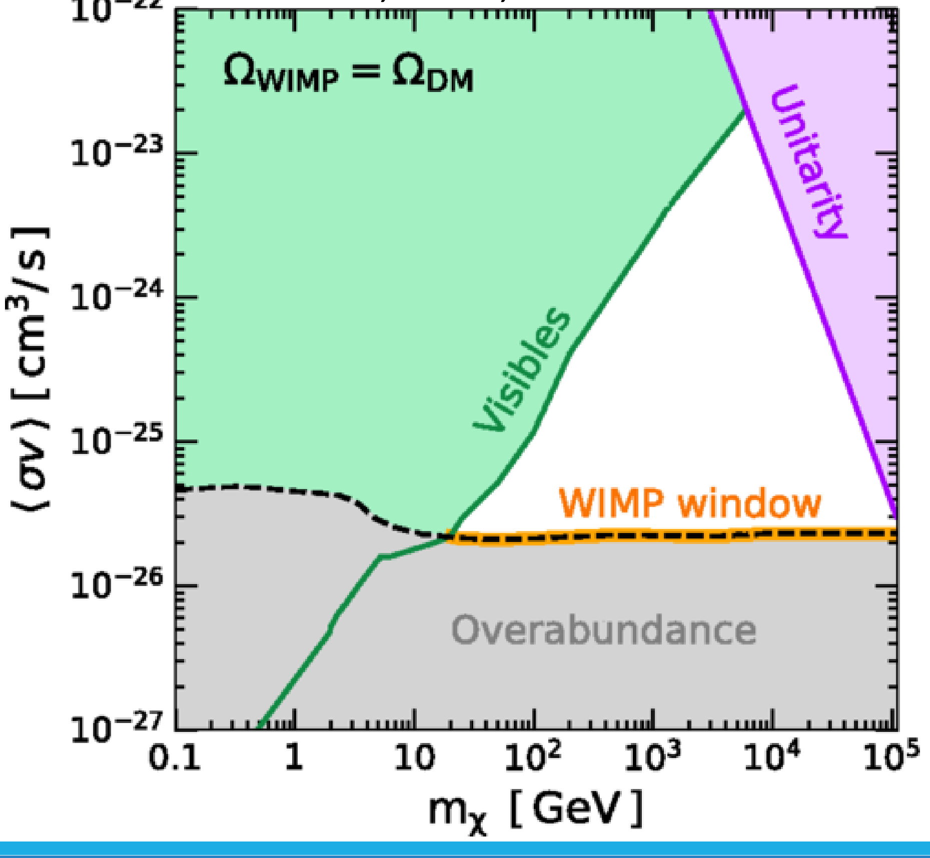
Conservative indirect detection limits

Annihilation to "invisible" SM states



Annihilation to "visible" SM states

R. Leane, et al., arXiv:1805.10305



Summary

- Measuring the CP phase with atmospheric neutrinos
  - Surpass the sensitivity of T2HK near $\delta_{CP} = 90^{\circ}$ & 270°, where CP maximally violated.
- Precision solar neutrino measurements at DUNE
  - Neutral current measurement → improve precision on the total ^{8}B solar neutrino flux.
  - JUNO (reactor neutrino) vs DUNE (solar neutrino) comparison will enable stringent tests of new physics.
- DM annihilation to neutrinos at the Galactic Centre
  - Hyper-K will reach the thermal relic scale for DM mass below about 30 MeV