Measuring CP violation

& other new opportunities

in the era of precision neutrino physics

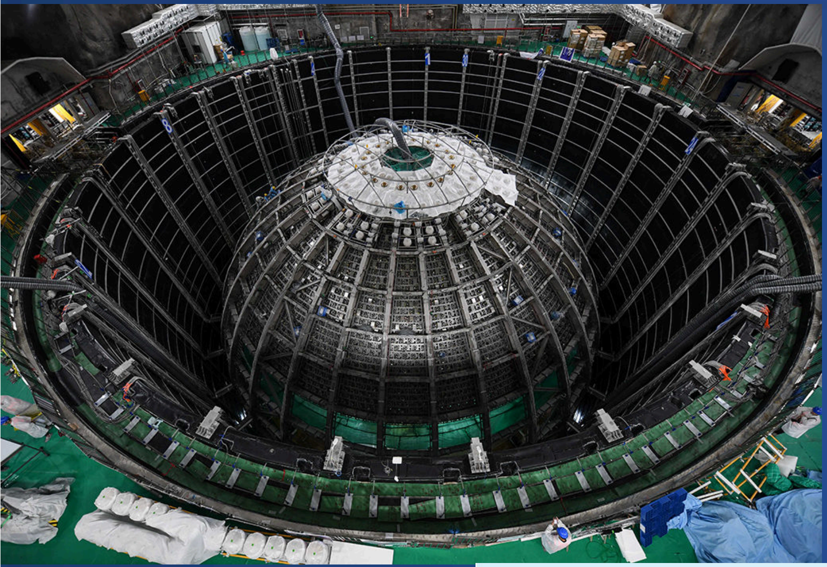
Nicole Bell, The University of Melbourne

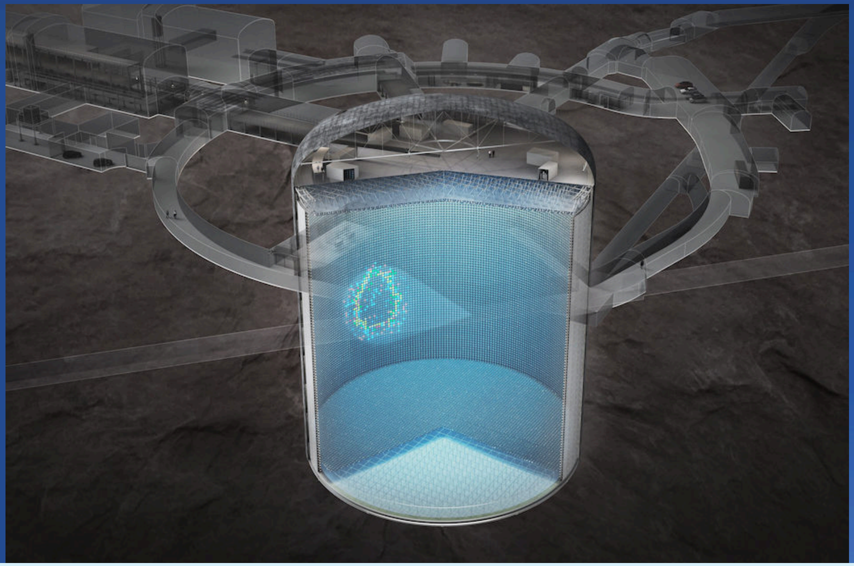
Next-generation neutrino detectors:

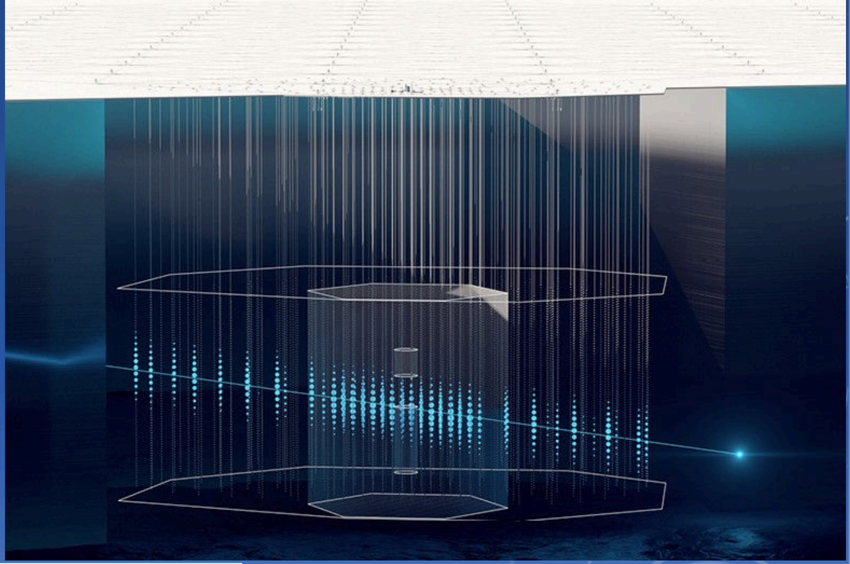
JUNO (China)
2024

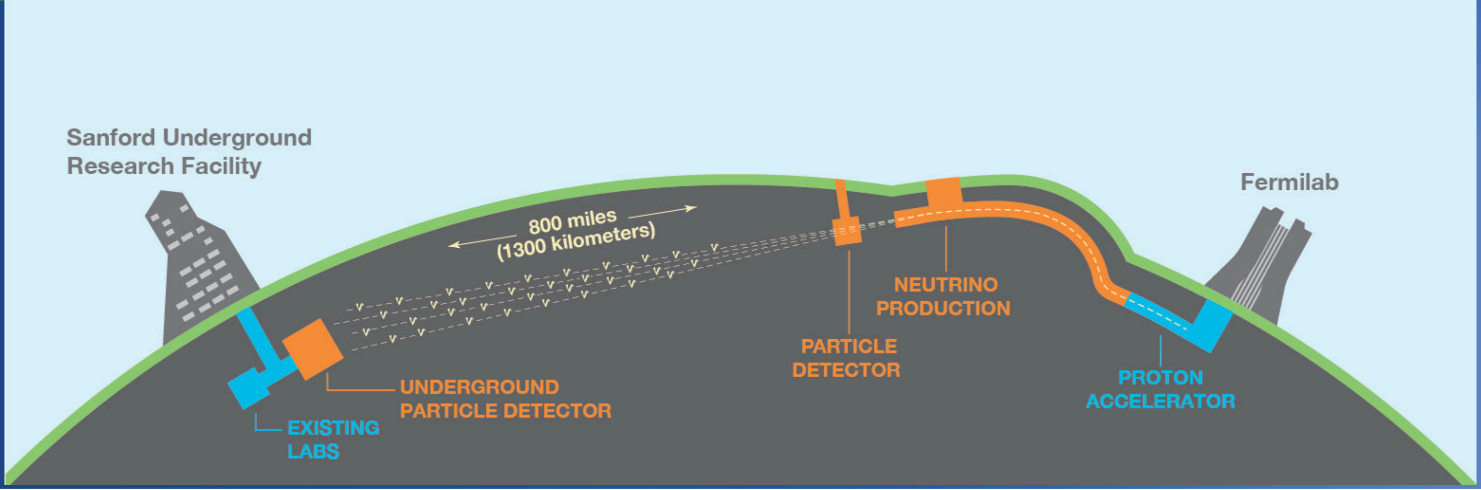
Hyper-Kamiokande (Japan)
2028

IceCube-Gen2 (South Pole)
2032









DUNE (USA)
early 2030s

Outline:

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

CP violation in the neutrino sector

Why does the Universe contain more matter than antimatter?

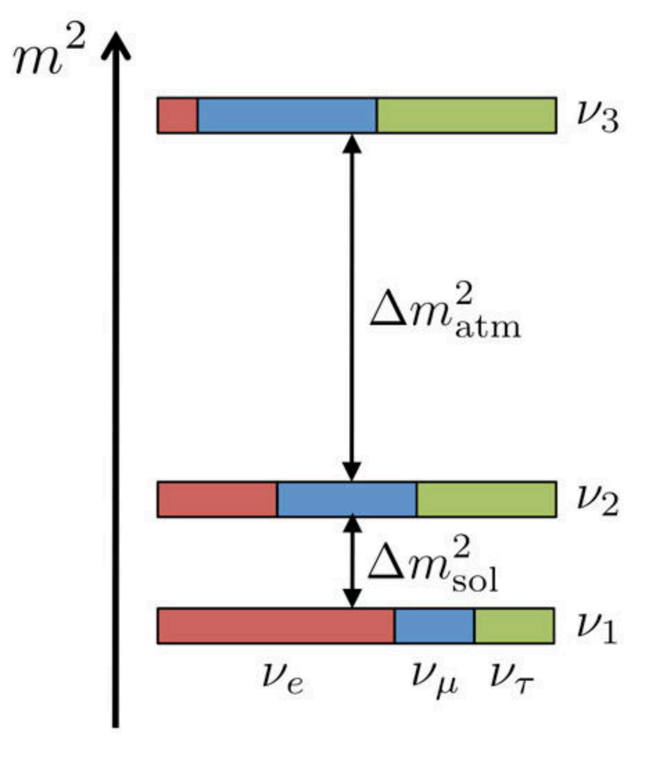
- Dynamical creation of a matter-antimatter asymmetry requires CP violation
- CP violation in the SM quark sector too small to explain the observed cosmological baryon asymmetry

  - ➢ **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 <u>independent</u> way to measure this parameter?**

Neutrino mixing

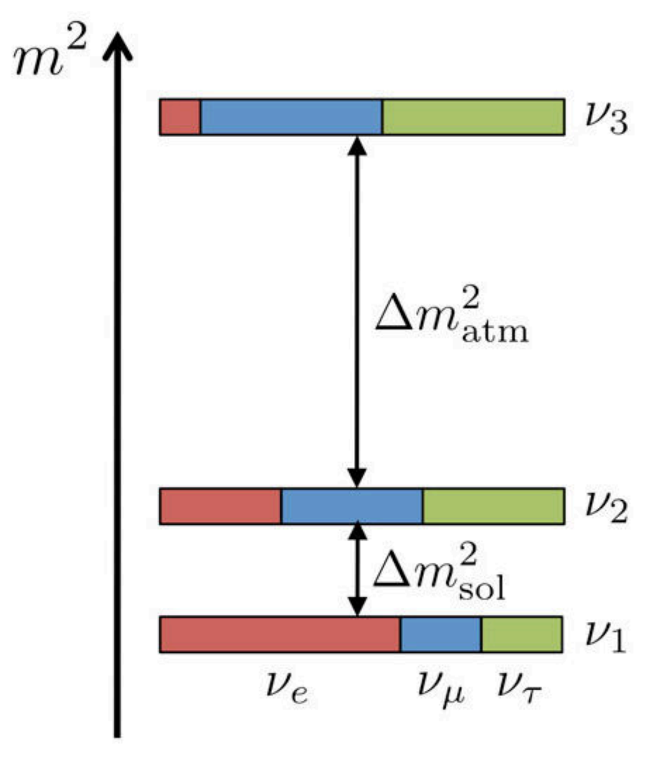


Flavour and mass states related by the neutrino mixing matrix.

Contains three mixing angles & one complex phase.

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

CP violation in neutrino mixing



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 δ_{CP} introduces CP-violation

Neutrino oscillation probability

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

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

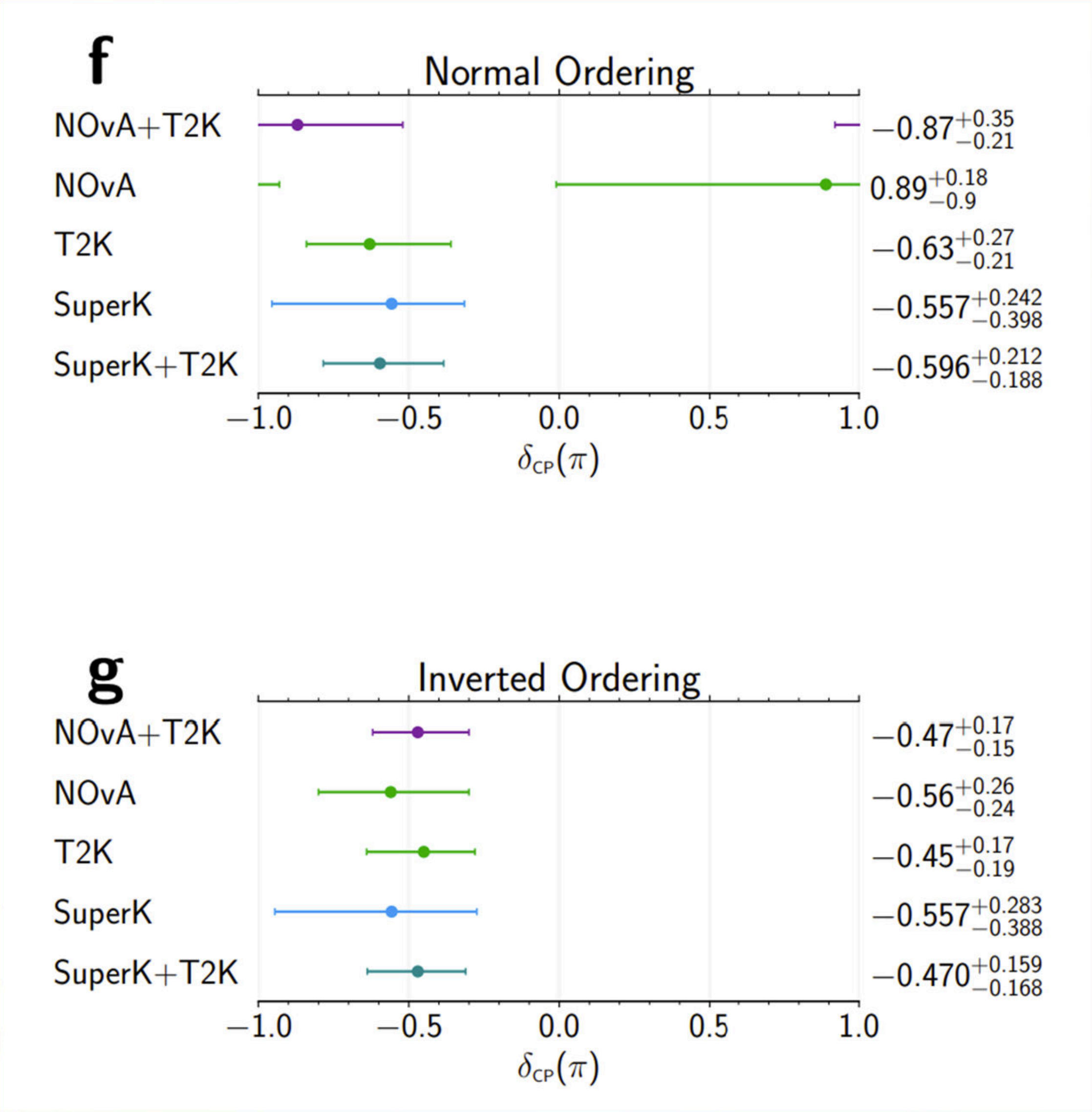
$\boldsymbol{\delta_{CP}}$ - odd terms

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_{21}^2 and Δm_{32}^2 to be in play.

Current data



Early indication the phase is non-zero.

Some preference for $\delta_{CP} = 90°, 270°$ (corresponds to maximal CP violation).

Results depends on mass ordering.

NovA and T2K Collaborations, Nature 646, 818 (2025).

Measuring CP violation with accelerator 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

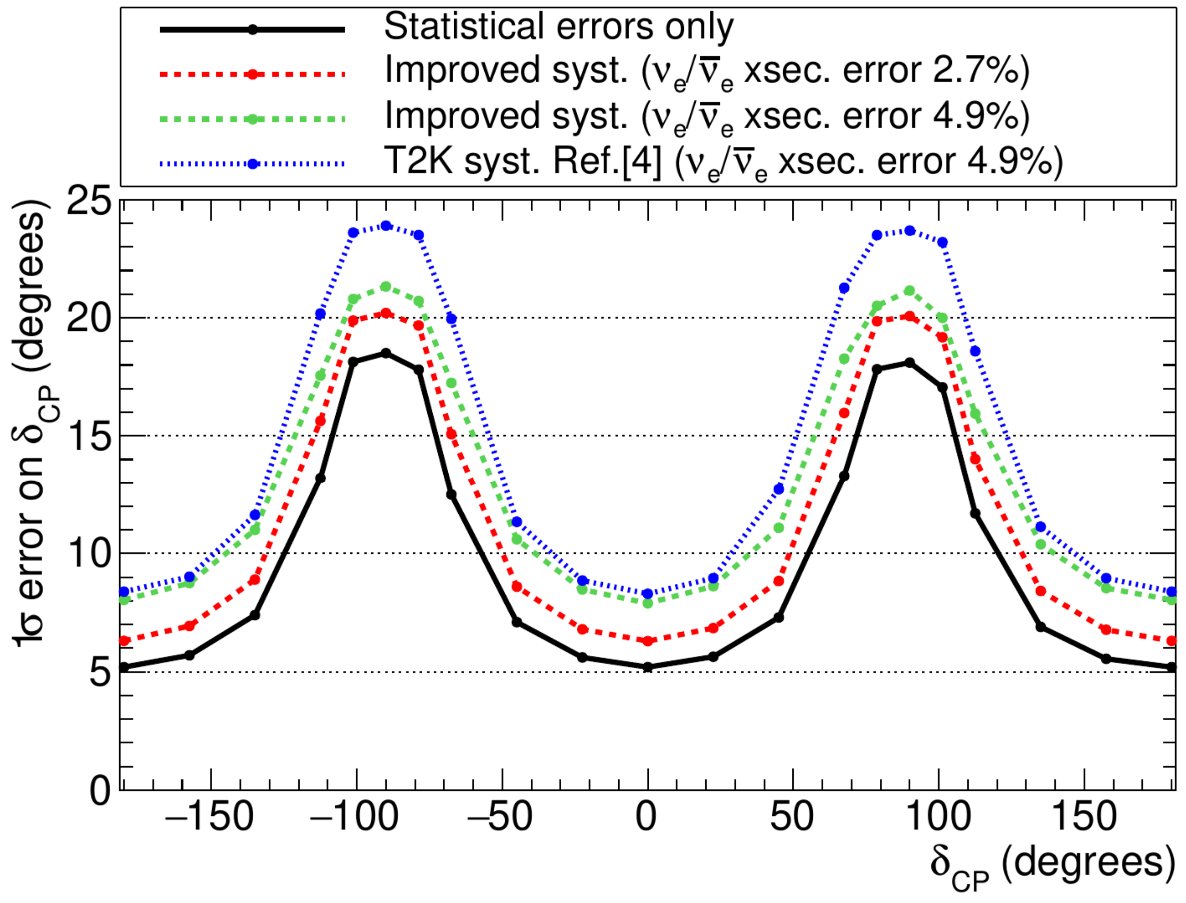
$$P_{\mu e} \sim 0.04(1 + 0.01\cos\delta_{CP} - 0.3\sin\delta_{CP})$$
$$\overline{P_{\mu e}} \sim 0.04(1 + 0.01\cos\delta_{CP} + 0.3\sin\delta_{CP})$$

- 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 $\cos\delta_{CP}$

Hyper-K sensitivity using accelerator neutrinos



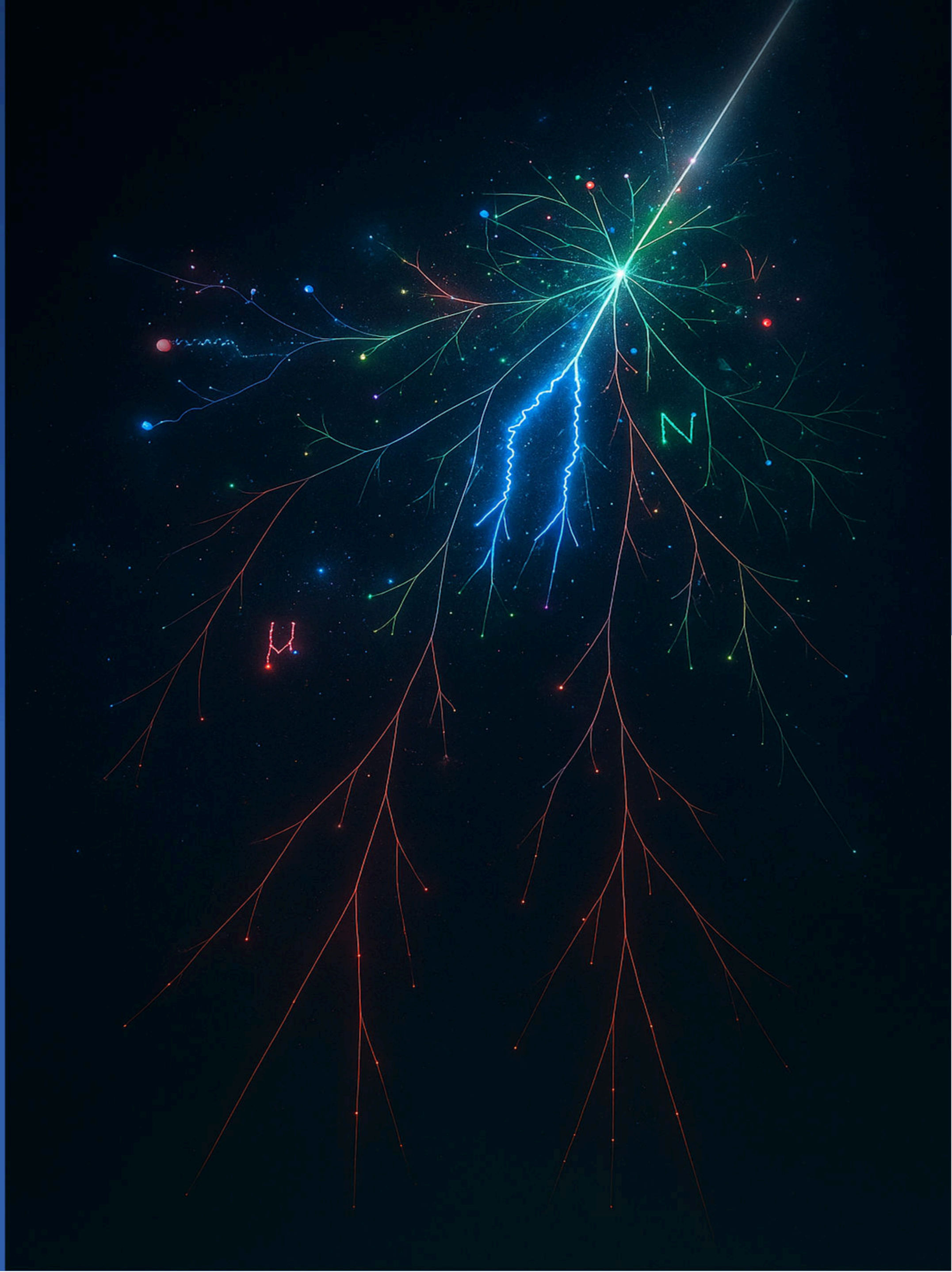
Abe et al. (Hyper-Kamiokande), Eur. Phys. J. C 86, 170 (2026)

T2HK sensitivity to δ_{CP} after 10 years of data taking.

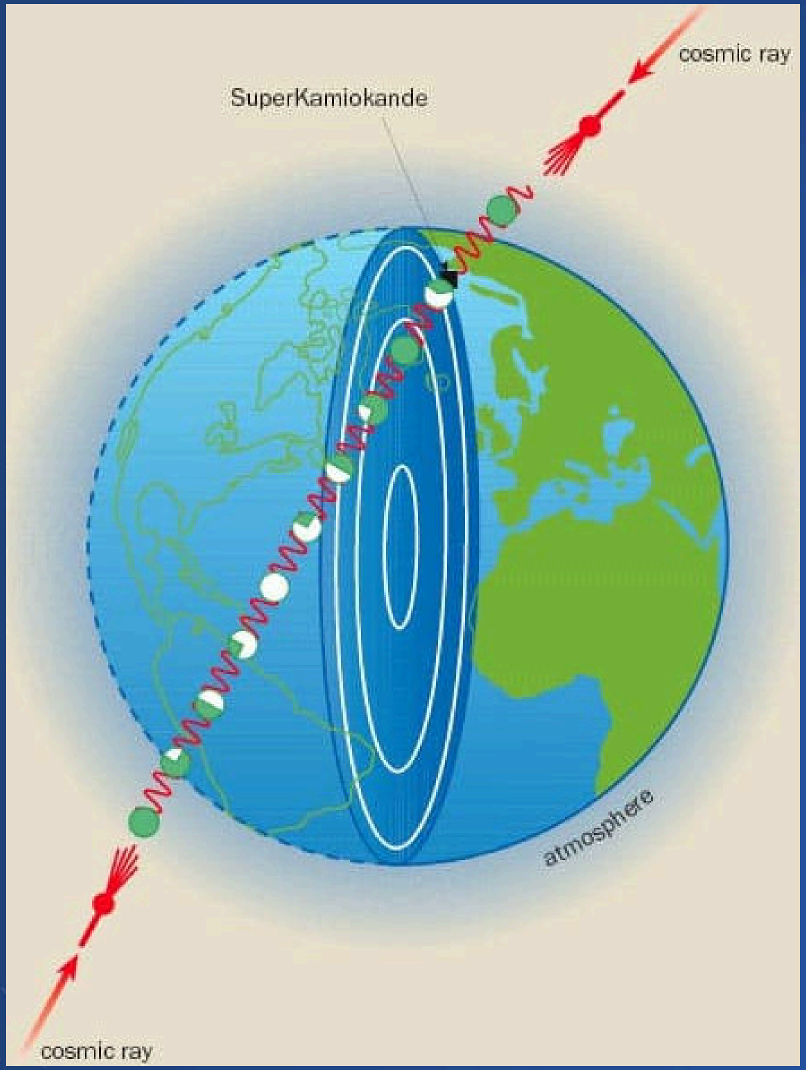
Best sensitivity occurs near the (CP-conserving values) $\delta_{CP} = 0°$ and $180°$.

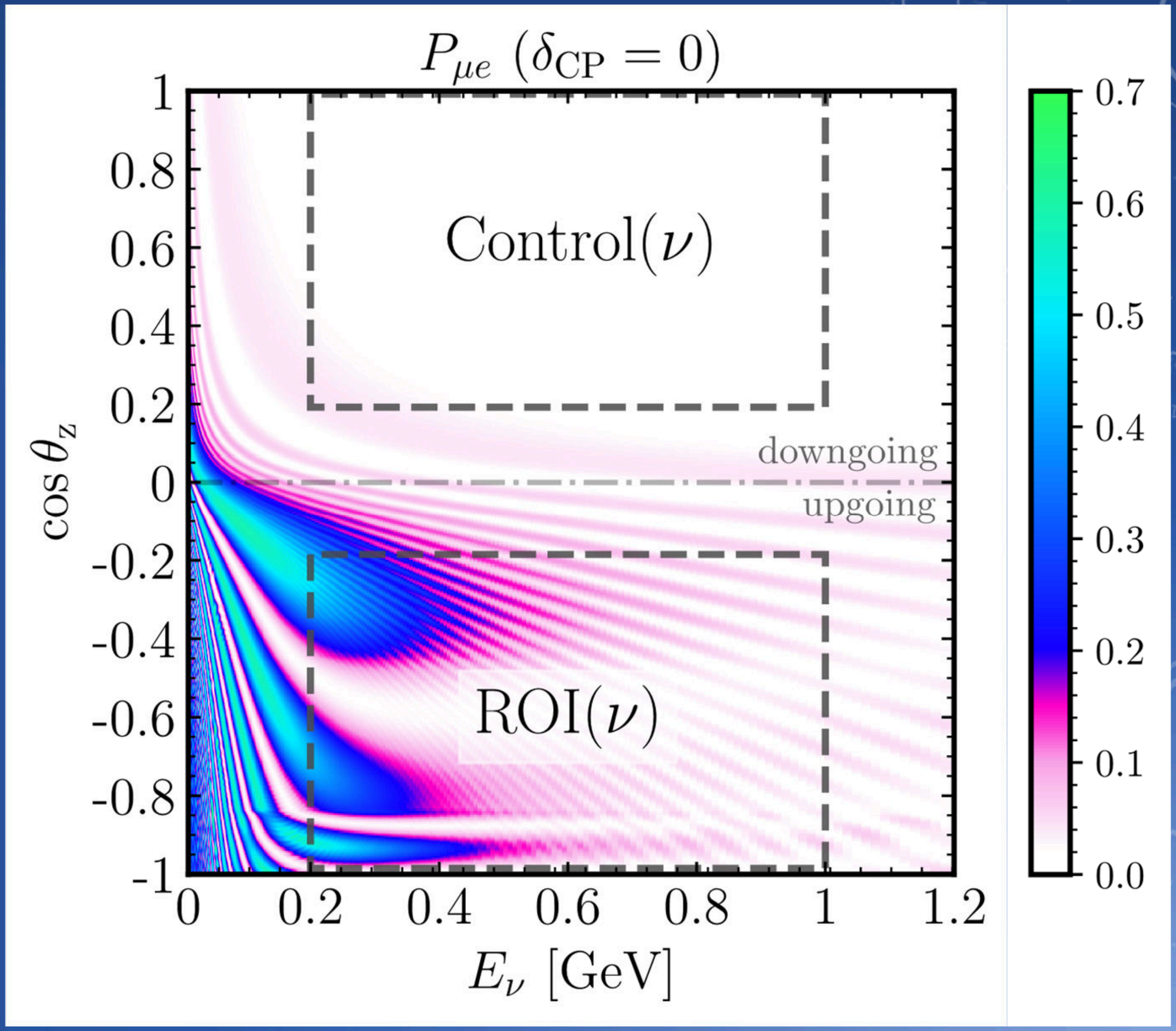
Measuring CP violation with atmospheric neutrinos

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



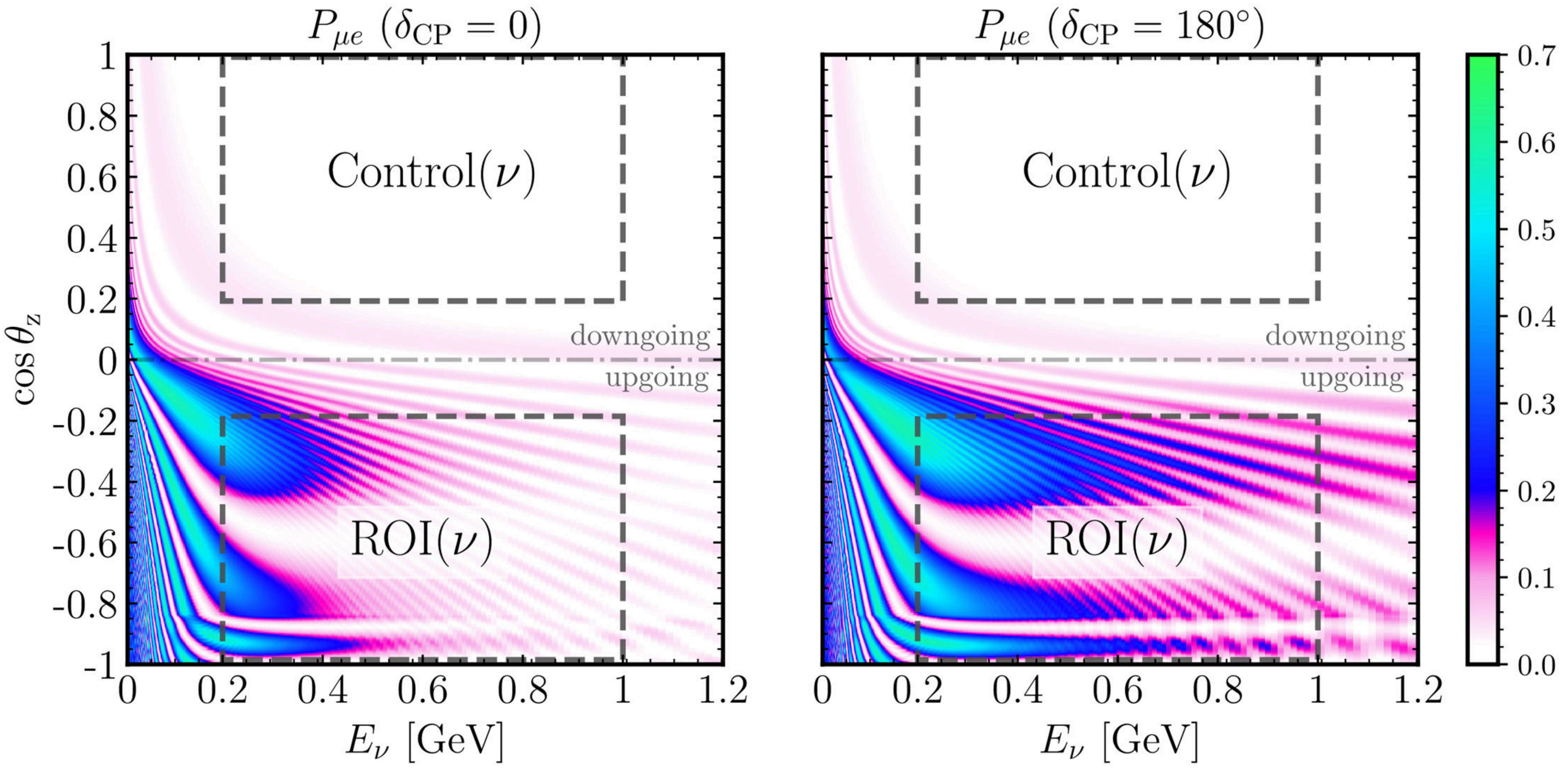
Atmospheric neutrino oscillations





CP violation in atmospheric neutrino oscillations

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

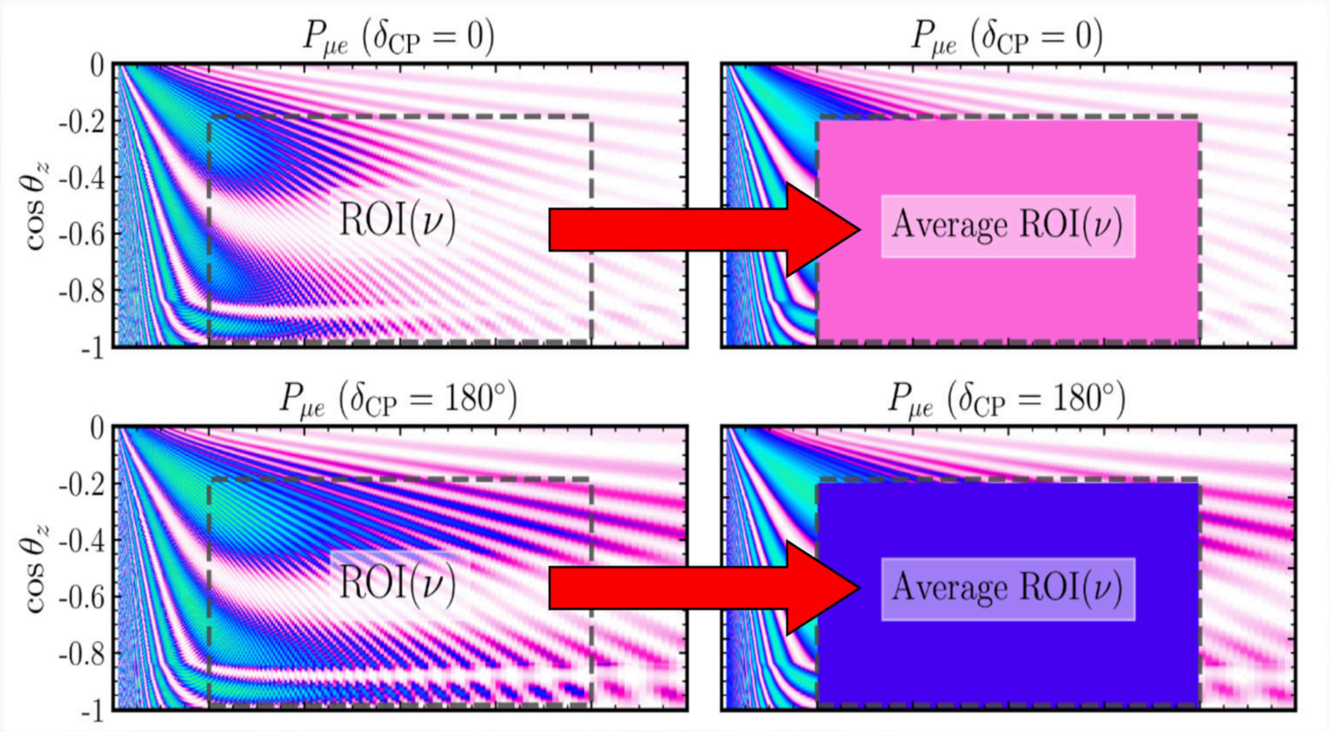


CP violation in atmospheric neutrino oscillations

Oscillograms have detailed structure

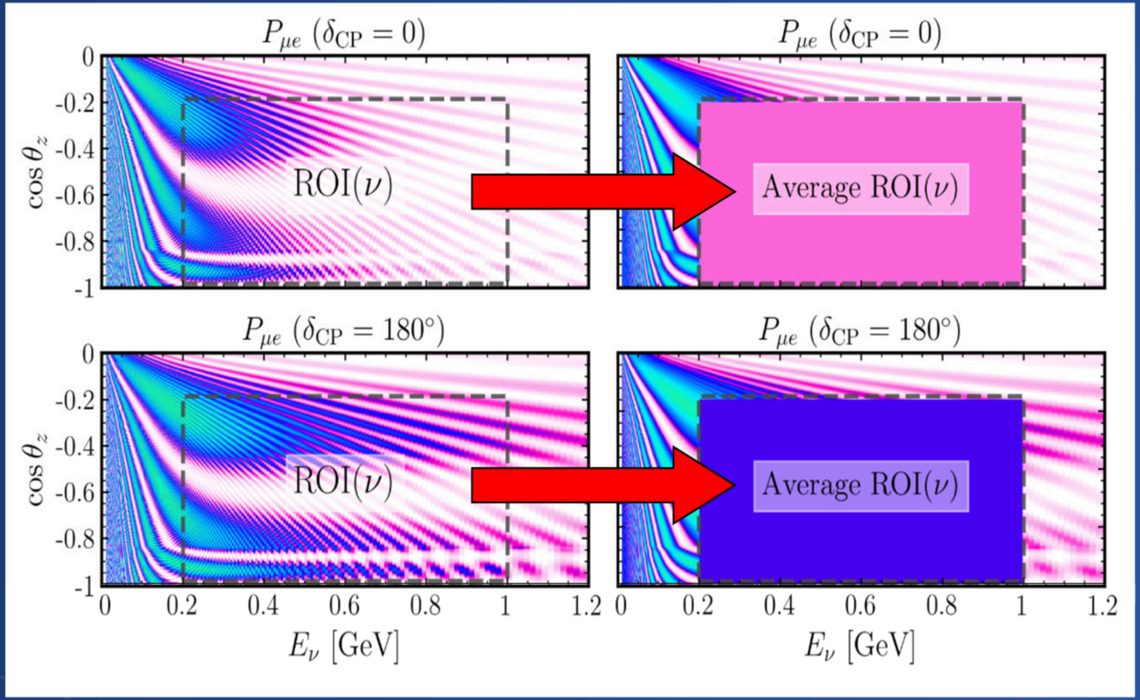
- ***fine details are unresolvable*** given realistic, unavoidable, energy and angular smearing.

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

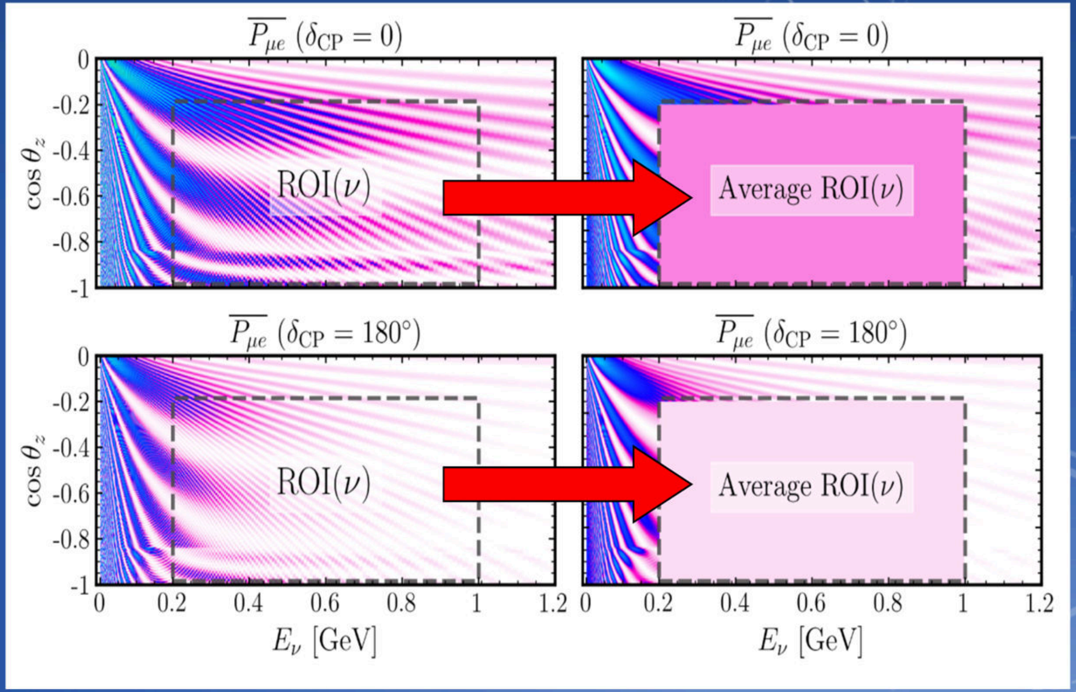


CP violation in atmospheric neutrino oscillations

Neutrinos



Anti Neutrinos

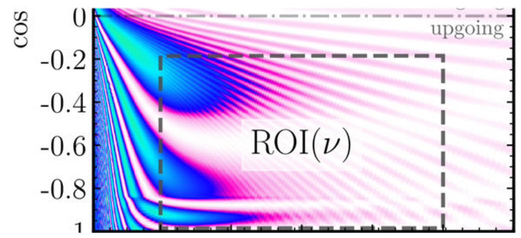


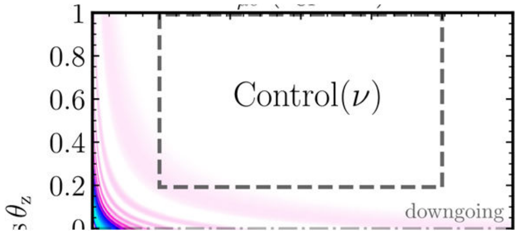
Needed: a robust CP-dependent observable

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

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

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





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

A robust CP-dependent observable

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

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

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

Neutrinos vs antineutrinos

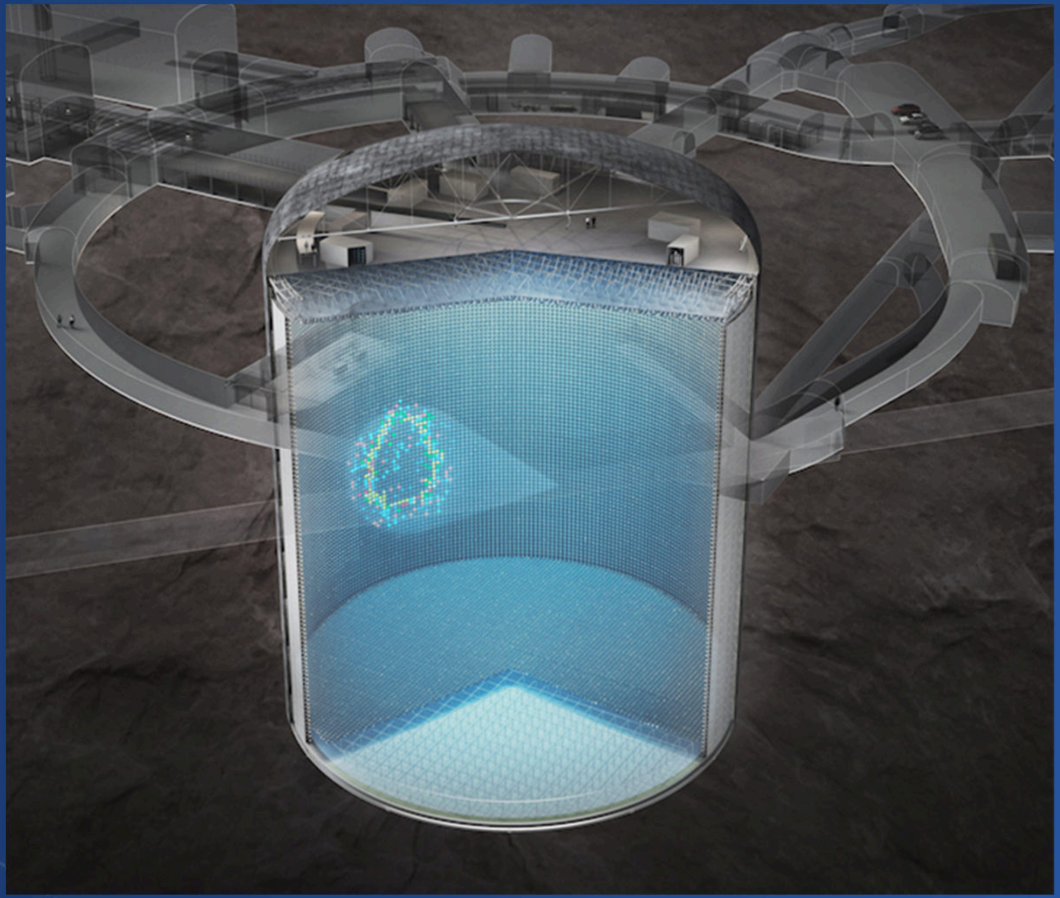
Neutrinos and antineutrinos have opposite-sign δ_{CP} dependence (due to opposite sign matter potential).

electron-type
ν_e: $R_{\mathrm{CP}} \sim (1 - 0.05\cos\delta_{CP})$ neutrinos
$\bar{\nu}_e$: $R_{CP} \sim (1 + 0.04\cos\delta_{CP})$ antineutrinos

muon-type
ν_μ: $R_{\mathrm{CP}} \sim (1 + 0.02\cos\delta_{CP})$
$\bar{\nu}_\mu$: $R_{CP} \sim (1 - 0.01\cos\delta_{CP})$

- Distinguishing neutrinos from antineutrinos would be powerful.
- However, even a $\nu + \bar{\nu}$ measurement will work, as $\bar{\nu}$ cross sections are smaller in the sub-GeV energy range (hence ν dominate over $\bar{\nu}$ in the event rates).

Can we do this at Hyper-K ?



186 kton fiducial volume

We expect:

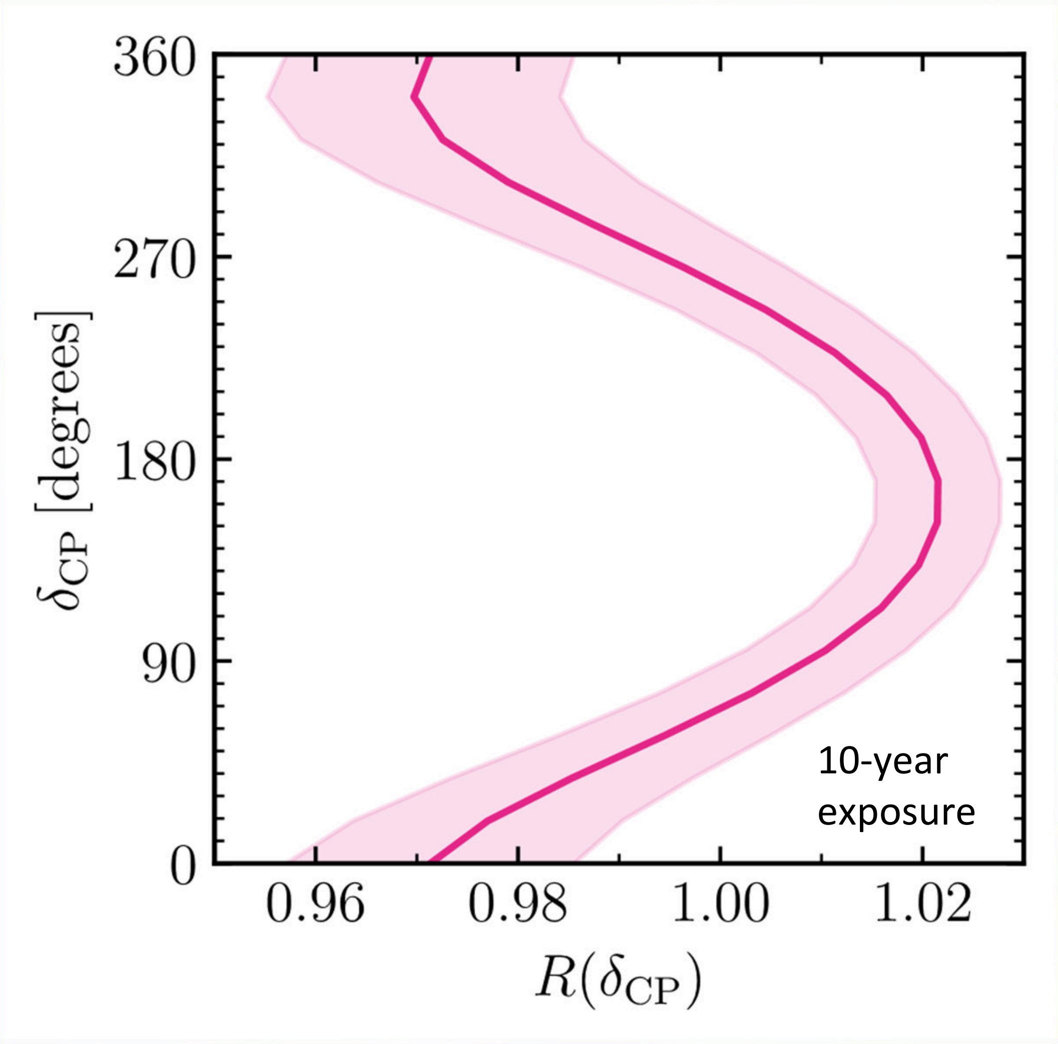
- 2600 sub-GeV e-like events/year
- 2900 sub-GeV μ-like events/year

For a 10-year exposure, the e-like sample alone has a statistical power of <1%

→ good enough to see a 5% effect

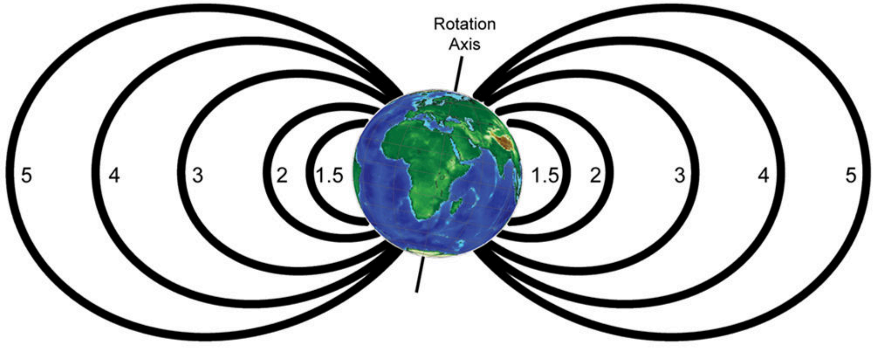
Adding detector effects:

- 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)

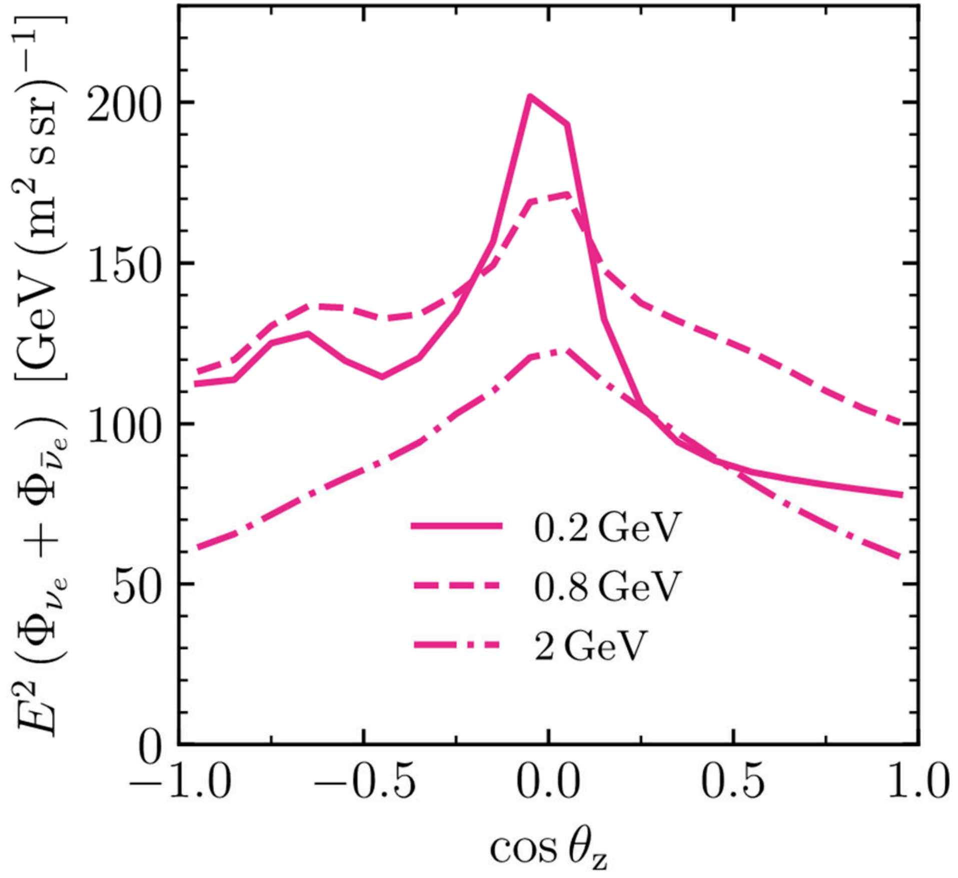


Leading uncertainties:

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

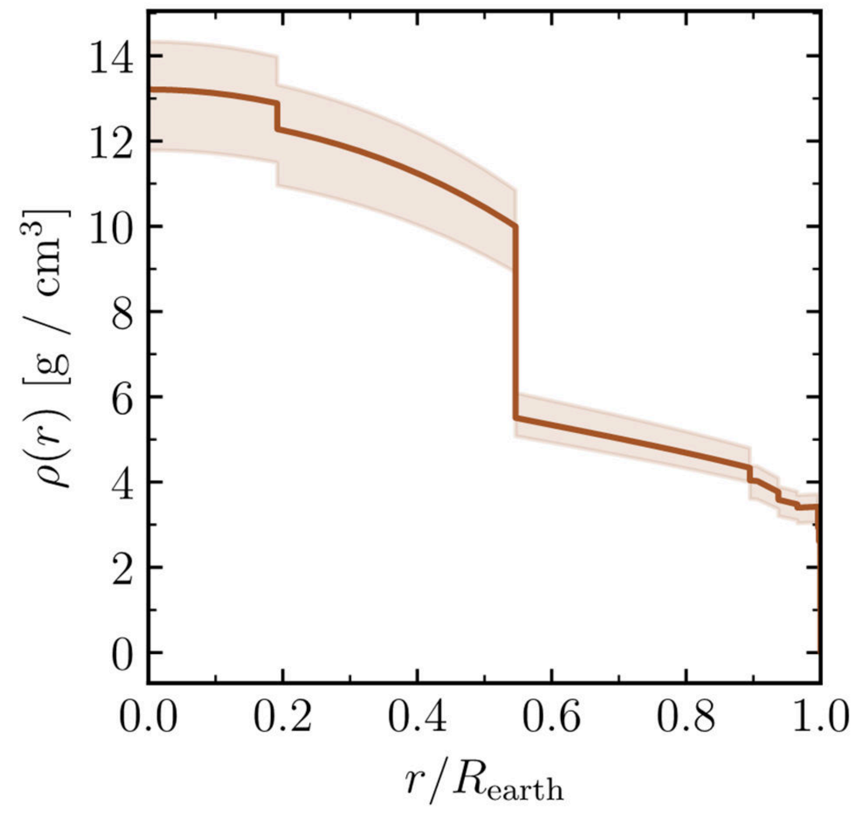


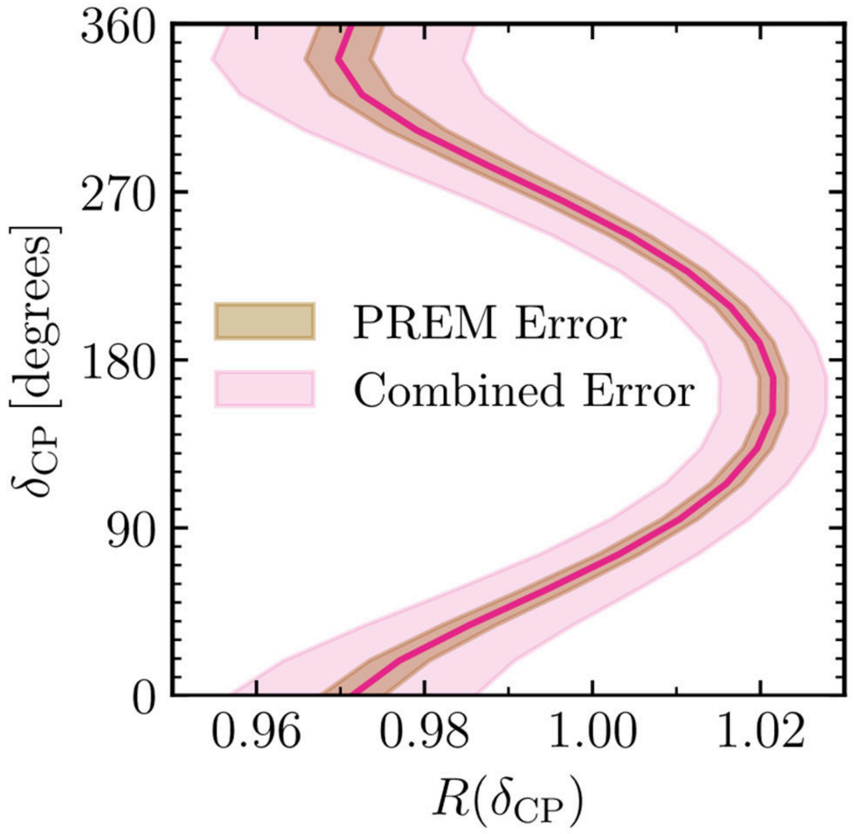
Flux asymmetry



Subdominant uncertainties

- **Largely insensitive to uncertainties in the Earth's density profile.**
  (Ensemble of density profiles; each layer varied up to 10%; with the total mass fixed.)

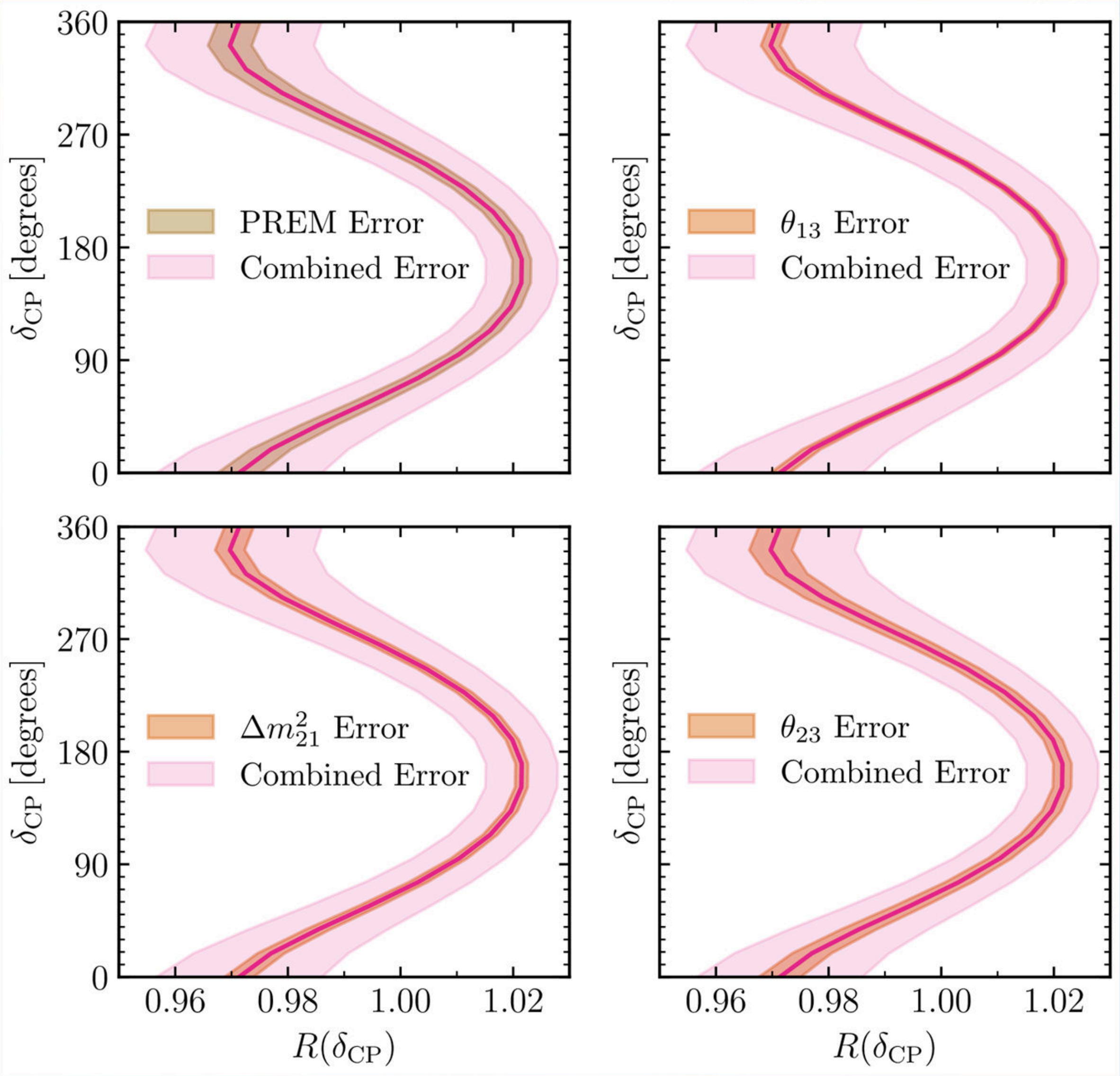




Subdominant uncertainties

- Also largely insensitive to <u>current</u> neutrino mixing parameter uncertainties.

- Greatest (but still small) contribution from θ_{23}, θ_{13} and m_{21}^2.
- Future precision measurements of the mixing parameters will further reduce these errors.
- (Averaging over the region of interest reduces the sensitivity to the other oscillation parameters.)



Projected resolution

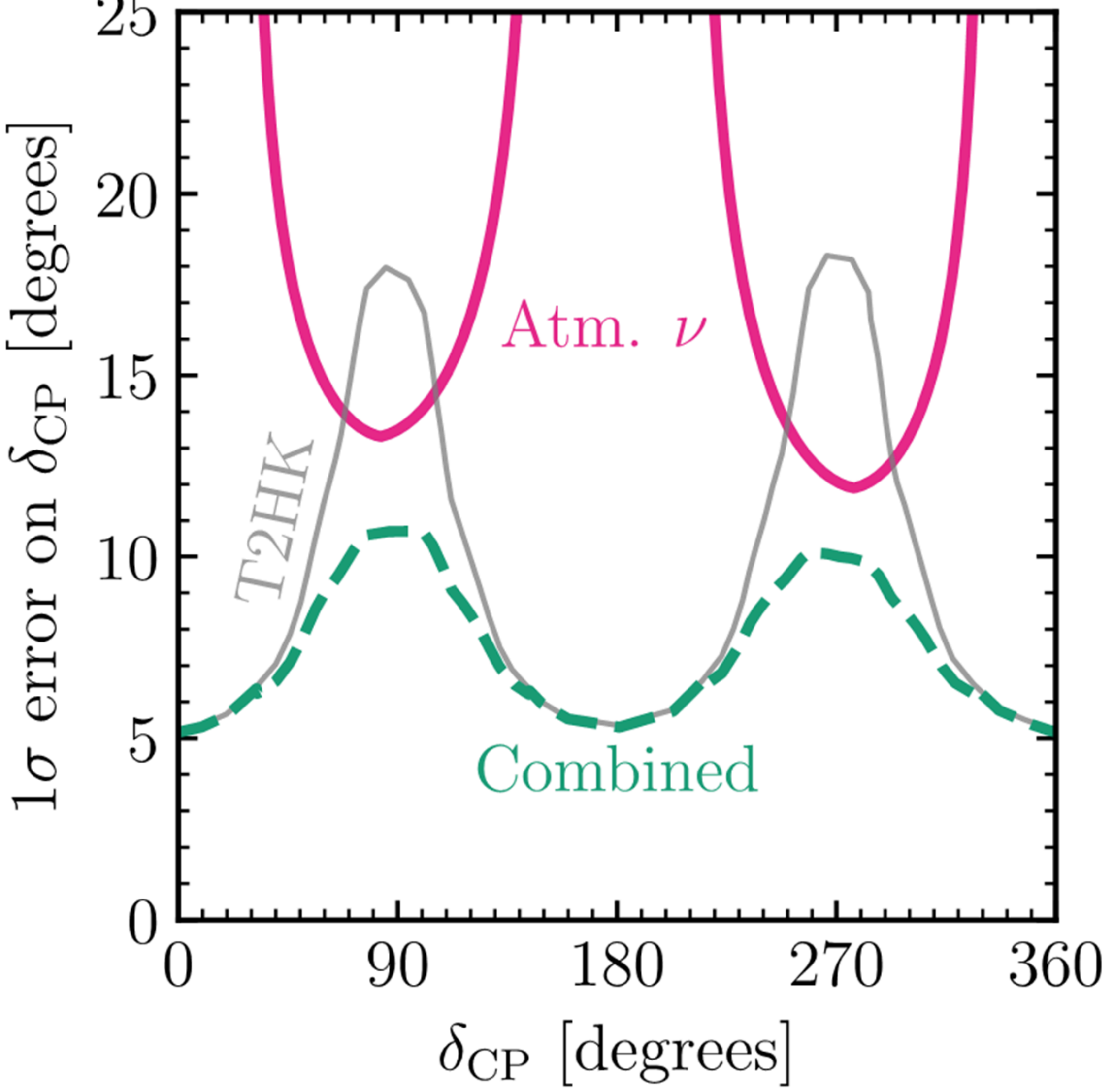
- Atmospheric approach most sensitive where the long-baseline approach is least sensitive.
  (due to $\cos\delta_{CP}$ vs $\sin\delta_{CP}$ dependence)

- Excellent complementarity

- Combined sensitivity is excellent across the full parameter range

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

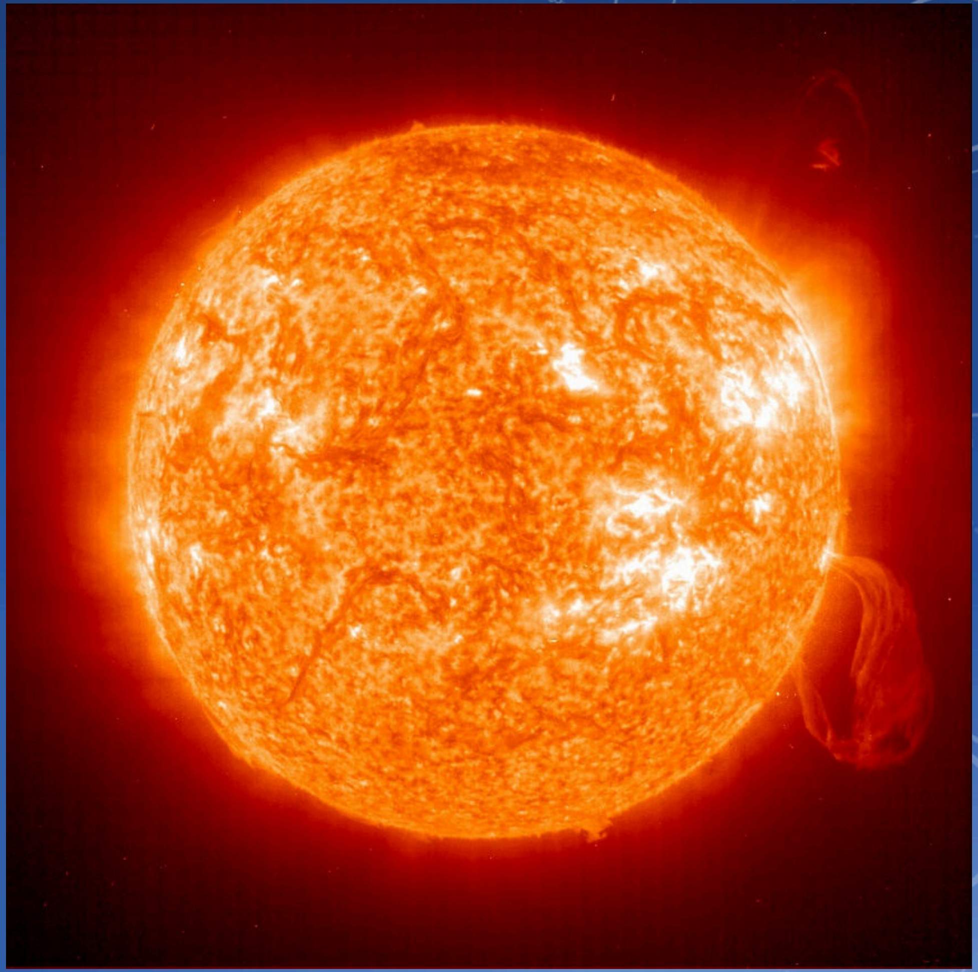
Hyper-K, 10 years



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

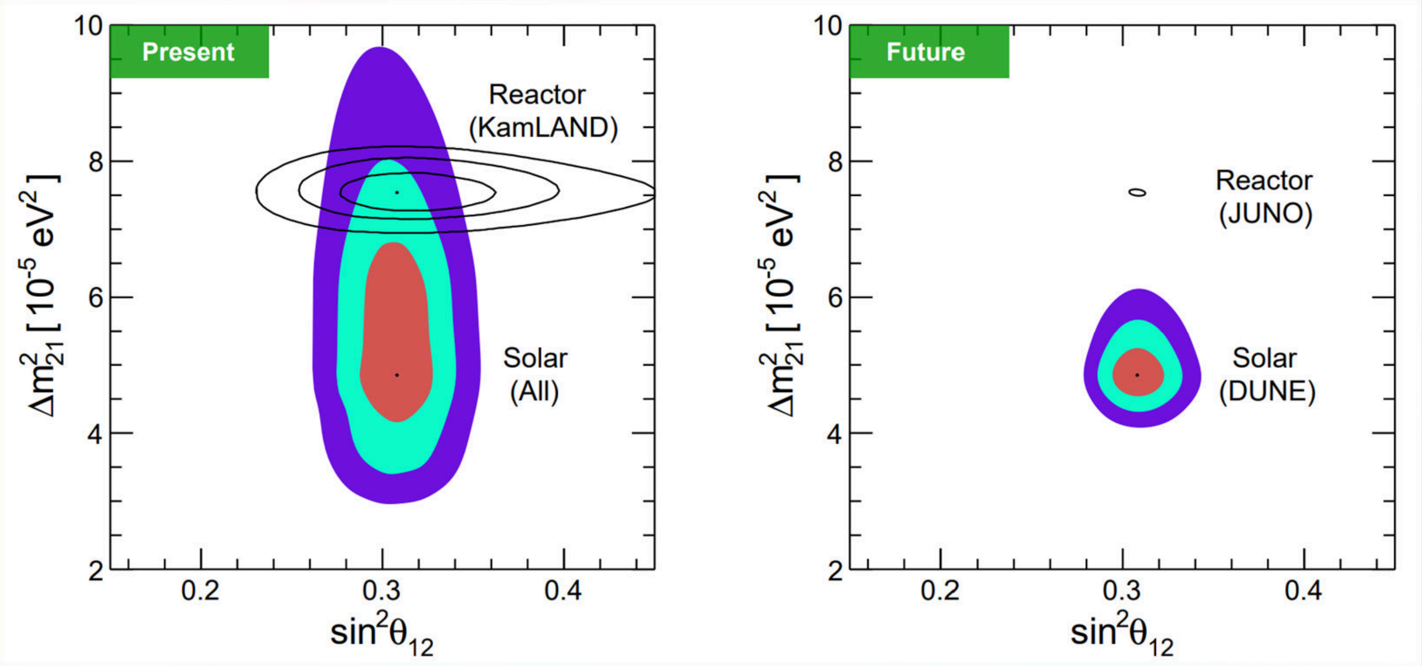
Solar neutrinos: precision measurements at DUNE

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**

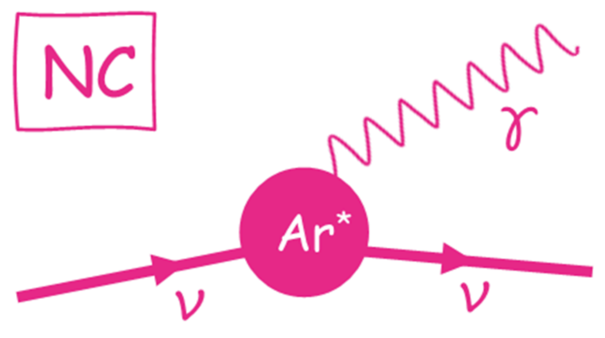


Capozzi et al, PRL 123, 131802, 2019

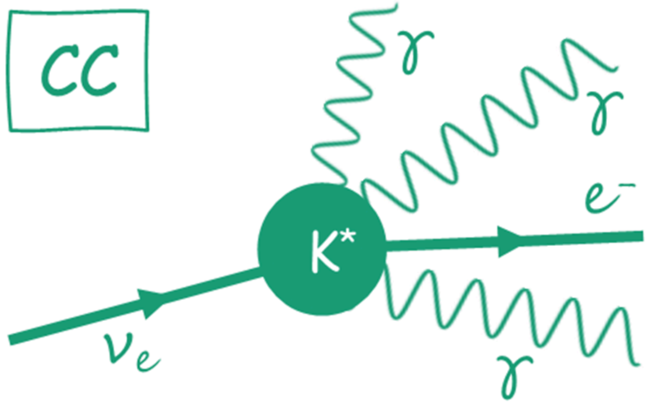
(charged current + elastic scattering at DUNE)

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 $\sin^2\theta_{12}$



$$\nu + 40\mathrm{Ar} \to \nu + 40\mathrm{Ar}^*$$



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

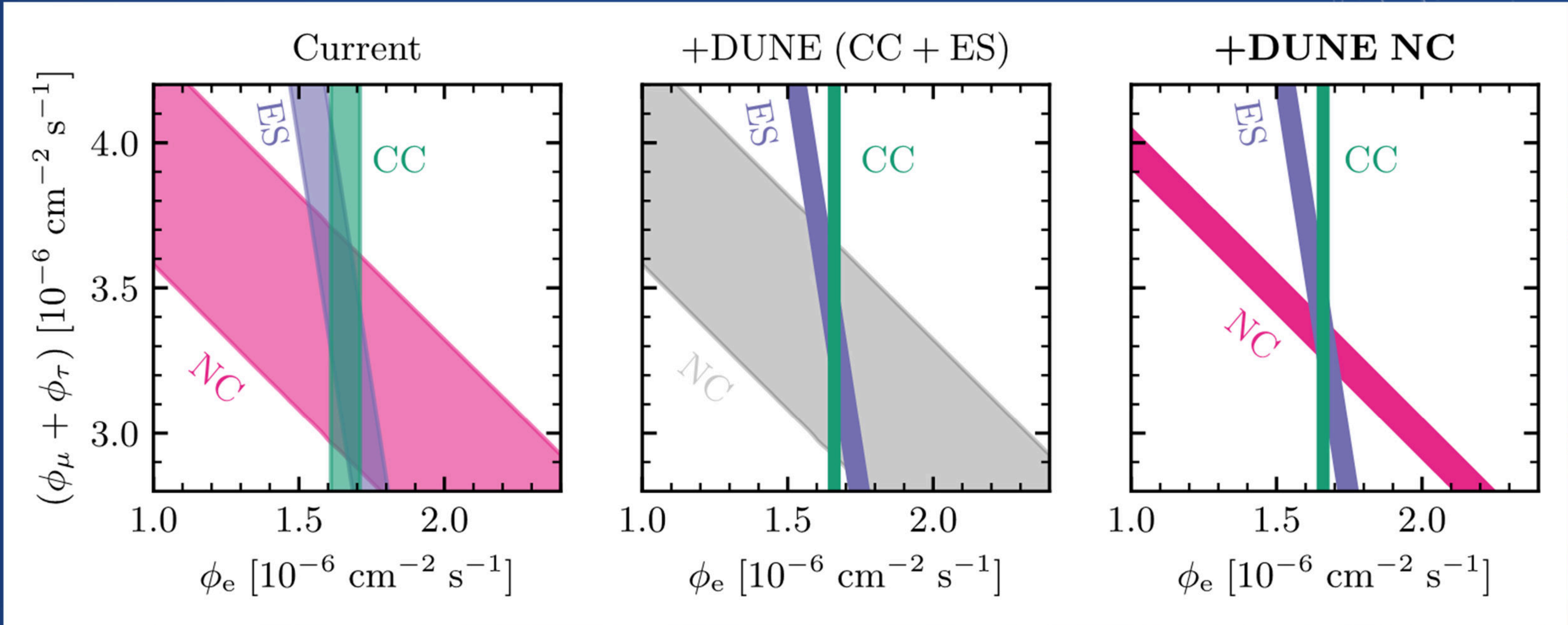
Charged current vs Neutral current vs Elastic scattering

Charged current	$R^{CC} \propto \phi_e$	$\propto \sin^2\theta_{12} \times \phi_{total}$
Neutral current	$R^{NC} \propto \phi_e + \phi_\mu + \phi_\tau$	$\propto \phi_{total}$
Elastic scattering	$R^{ES} \propto \phi_e + \frac{1}{6}(\phi_\mu + \phi_\tau)$	$\propto (1 + \frac{1}{6}\sin^2\theta_{12}) \times \phi_{total}$

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.

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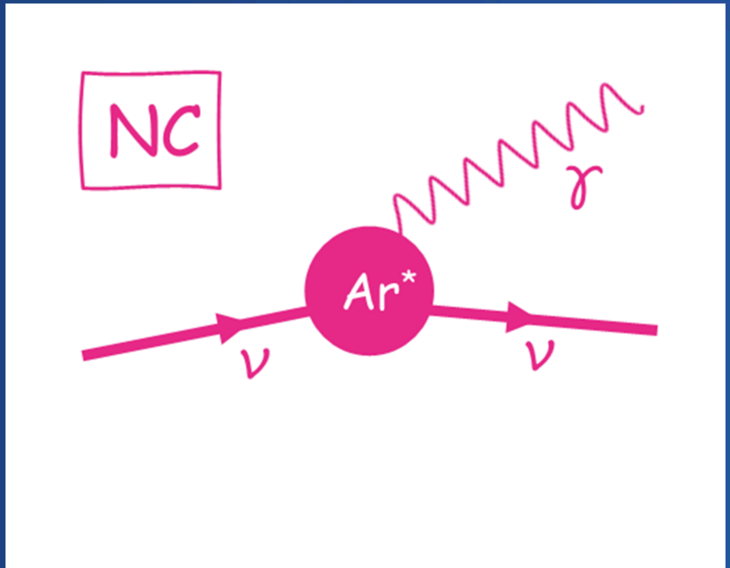
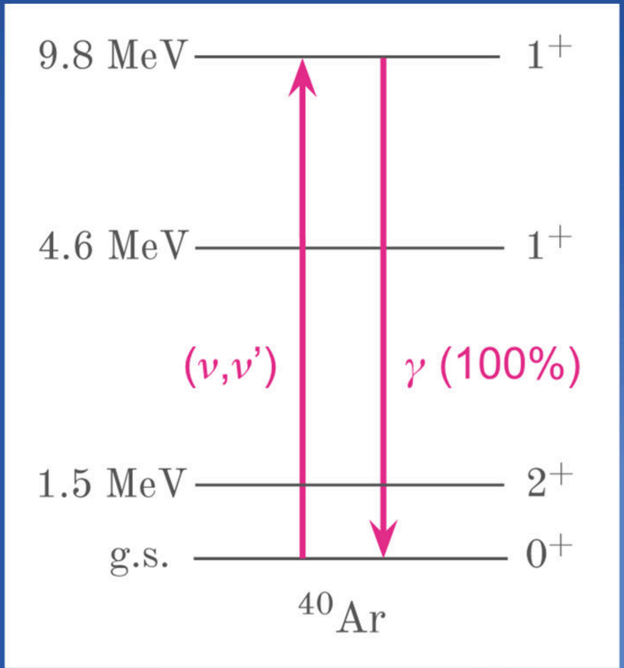
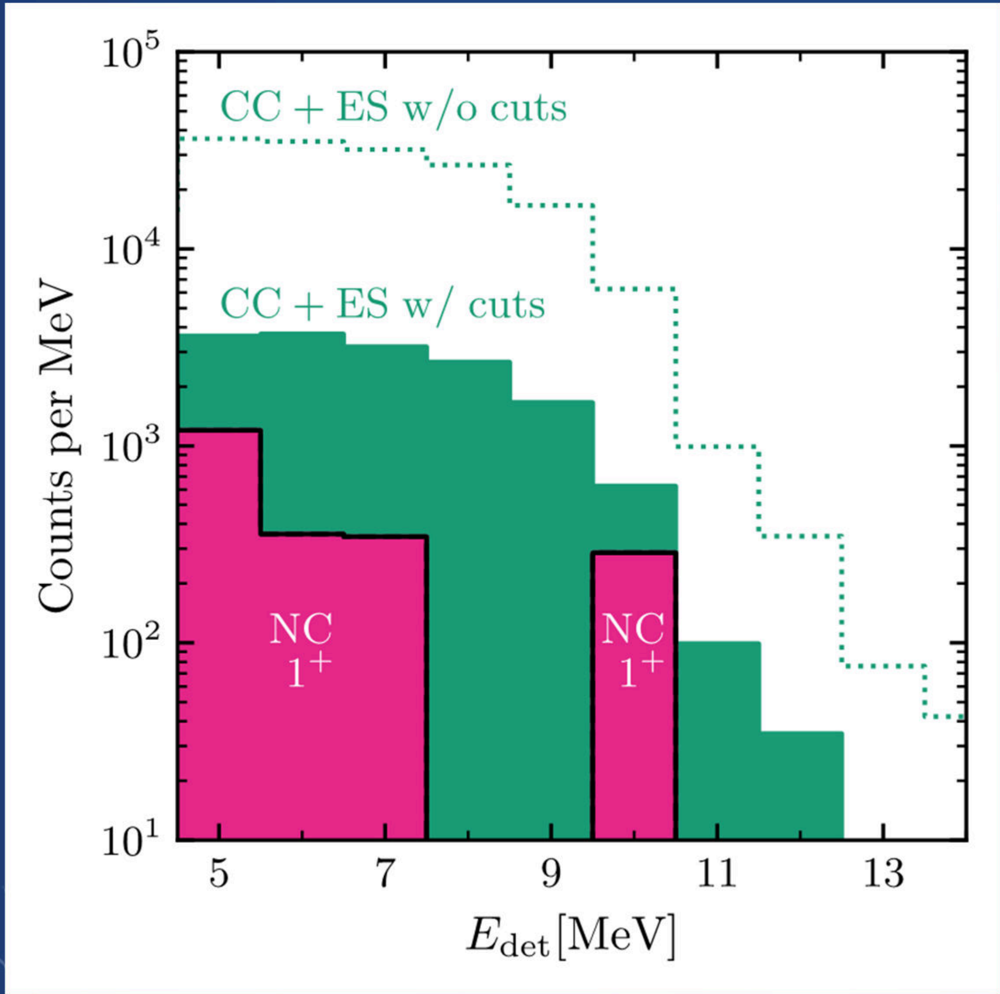


$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow \nu_e + {}^{40}\mathrm{Ar}^*$$

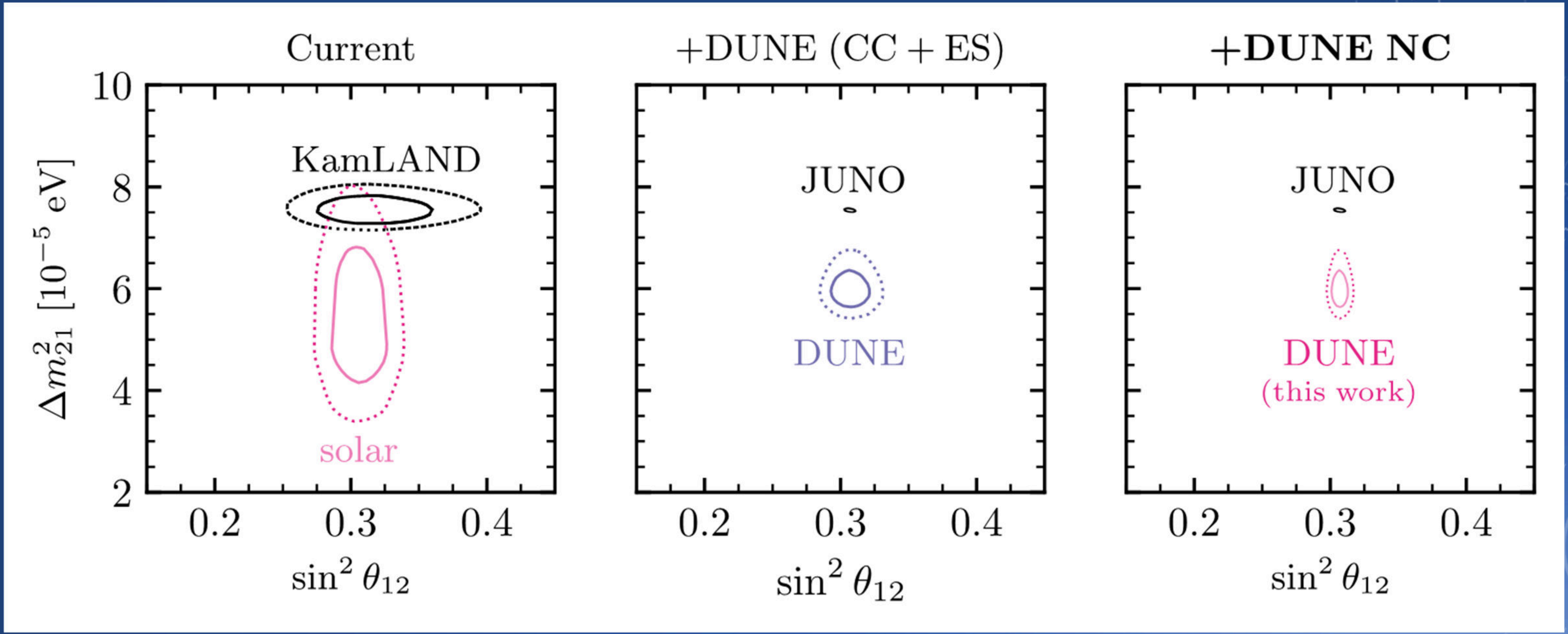


Expected spectra



DUNE exposure of 100 kton-years

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

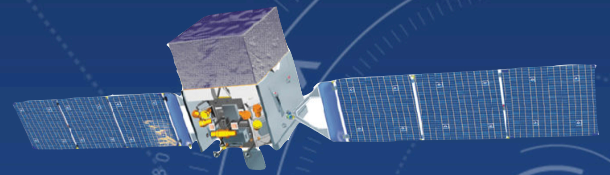


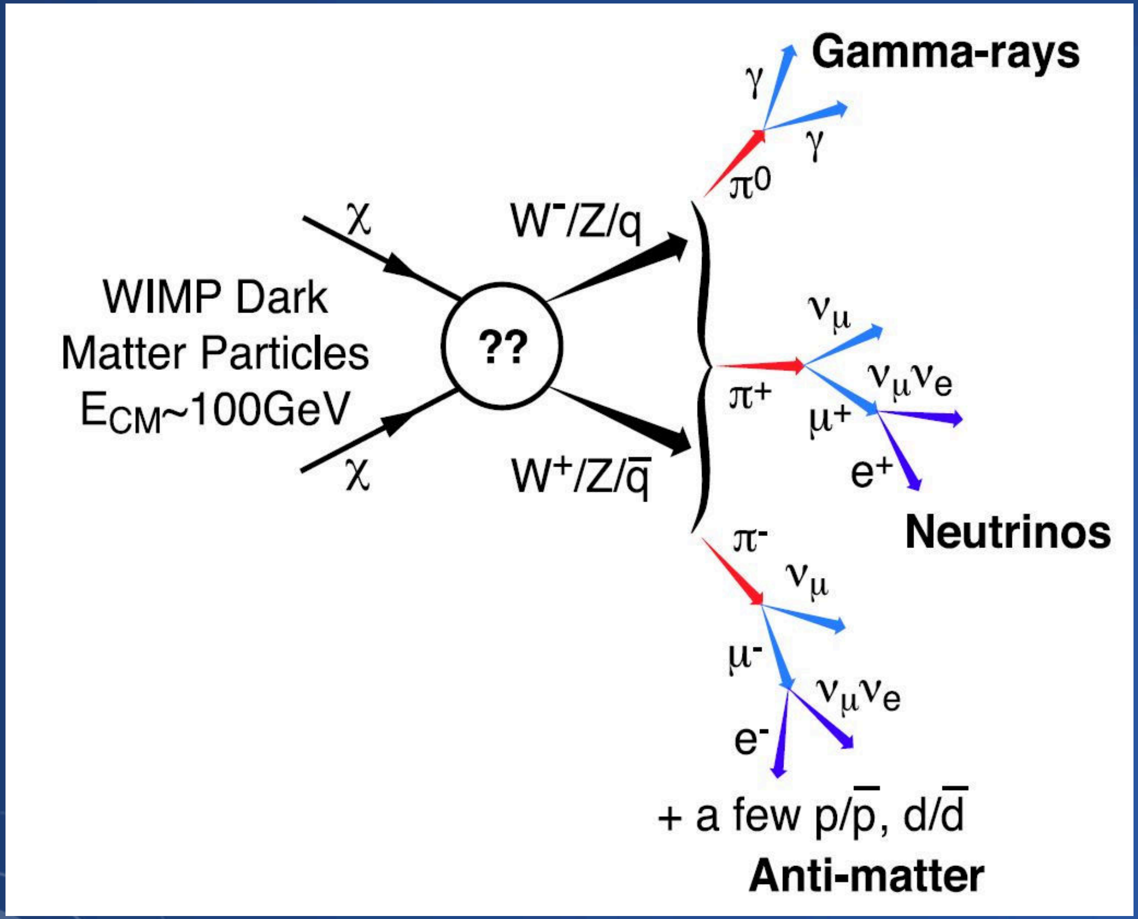
Meighen-Berger, Newstead, Beacom, NFB, Dolan, Phys. Rev. Lett. 135, 011803, 2025.

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.**

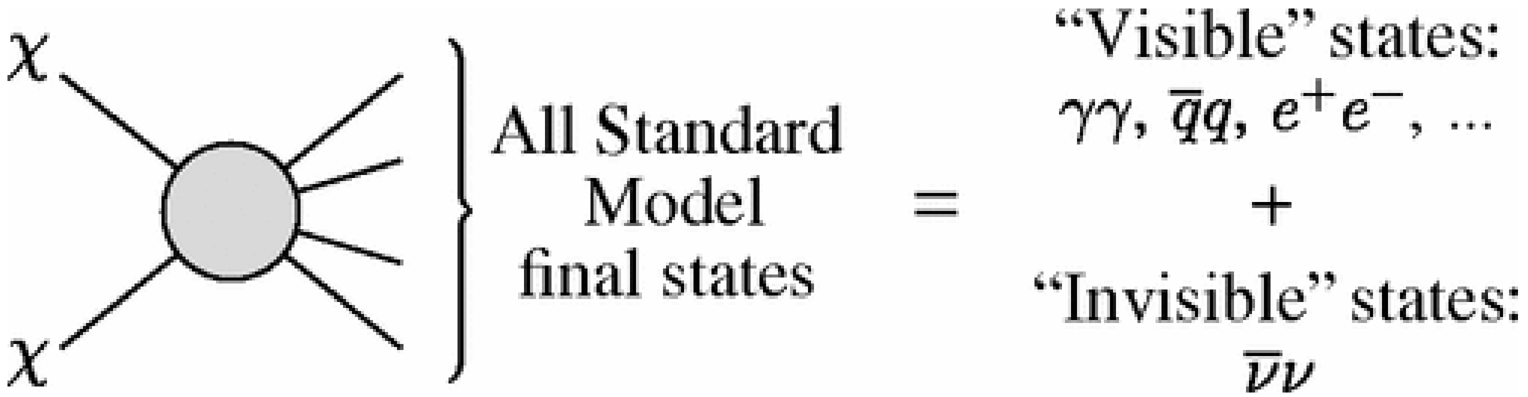
It is the **only direct test of annihilation cross section that sets the relic density.**

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**?

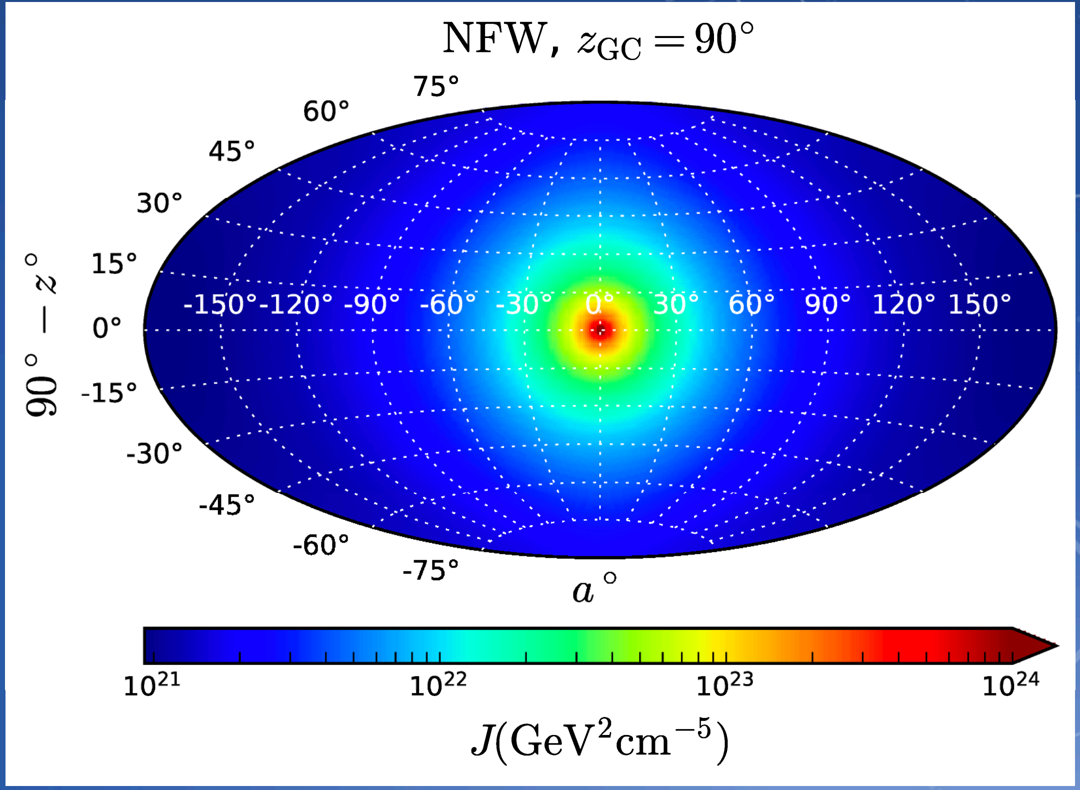
Dark matter annihilation at the Galactic Centre

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

Annihilation cross section

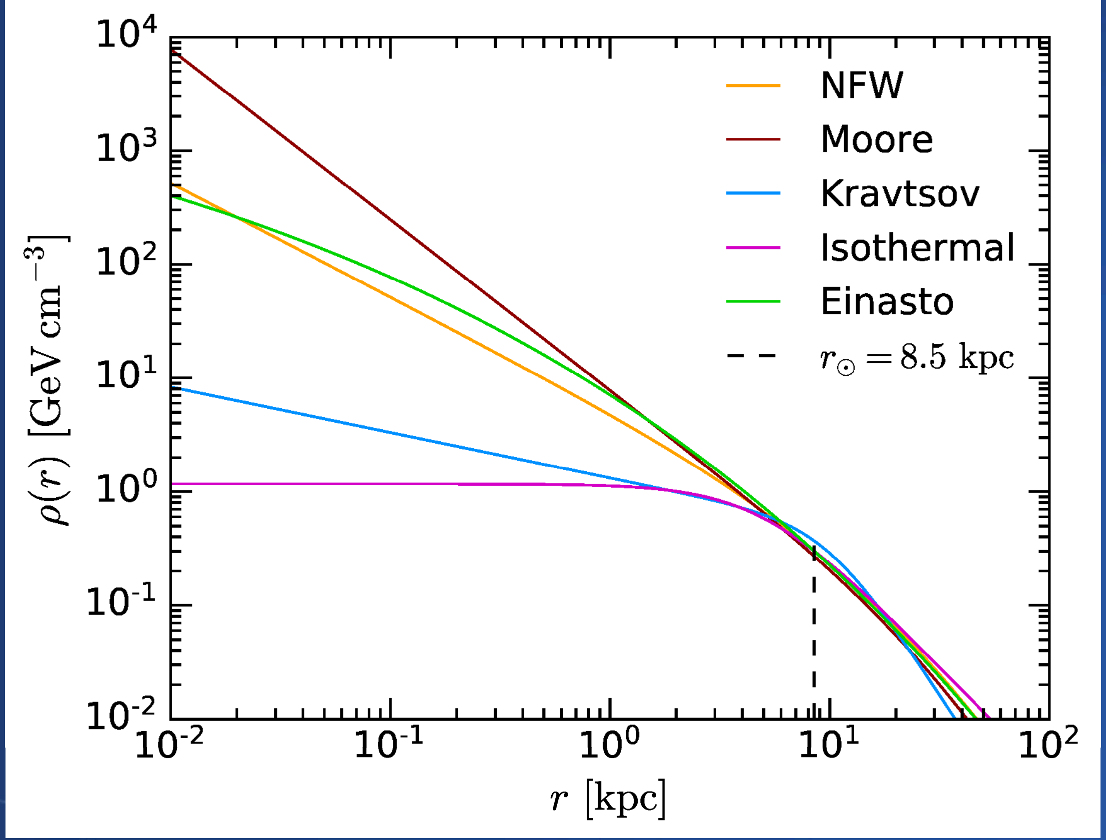
Integral of (density)^2 along line of sight

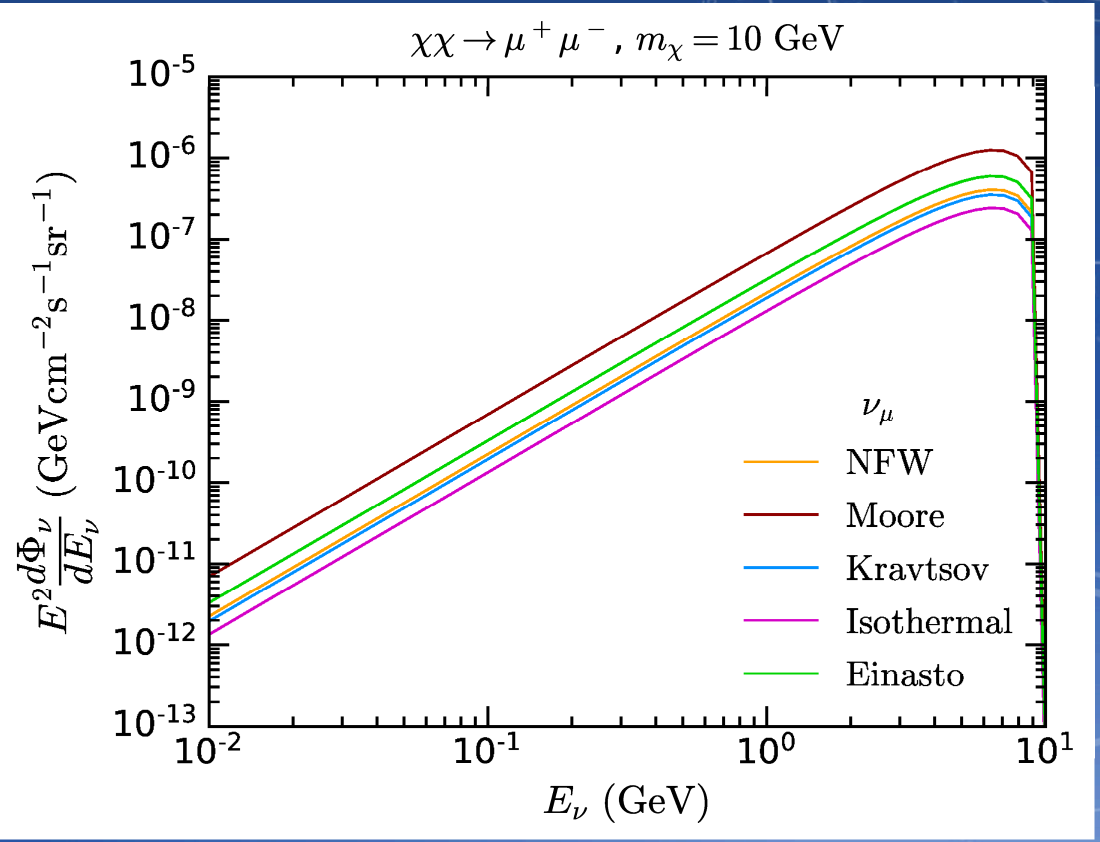
Spectrum per annihilation



NFB, Dolan, Robles, arXiv: 2005.01950

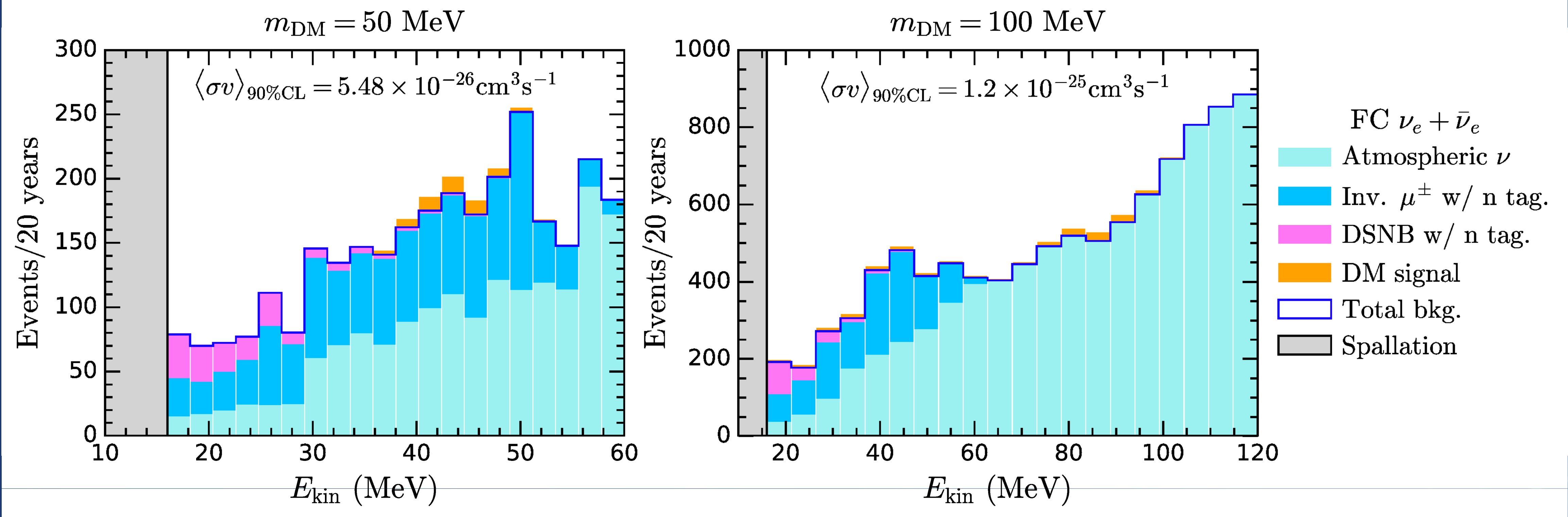
Dependence on halo profile is mild, as we undertake an all-sky analysis





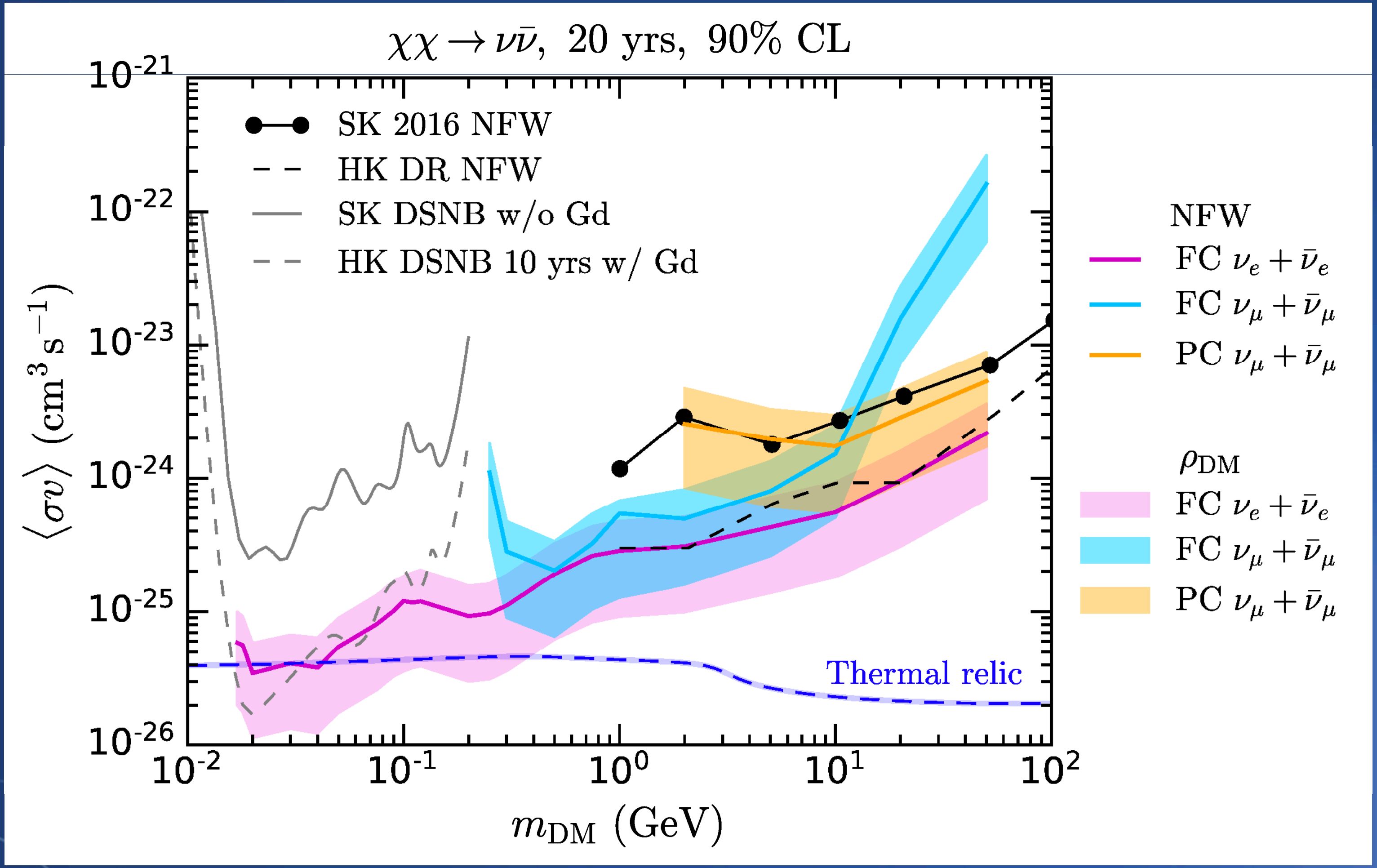
NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation signal sits on top of atmospheric neutrino background



NFB, Dolan, Robles, arXiv: 2005.01950

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



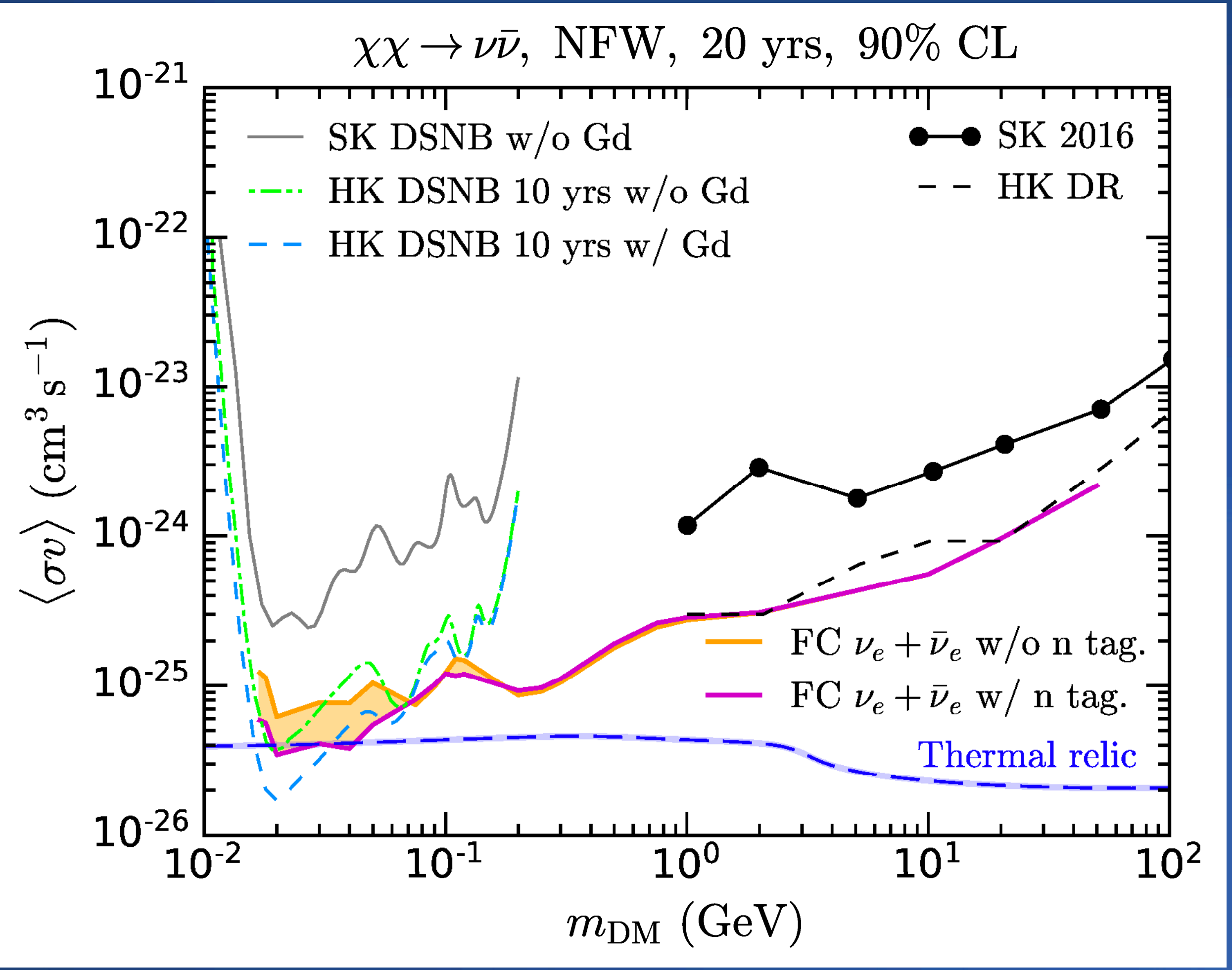
NFB, Dolan, Robles, arXiv: 2005.01950

Thermal relic sensitivity for DM mass of about 30 MeV

Central lines – NFW profile.

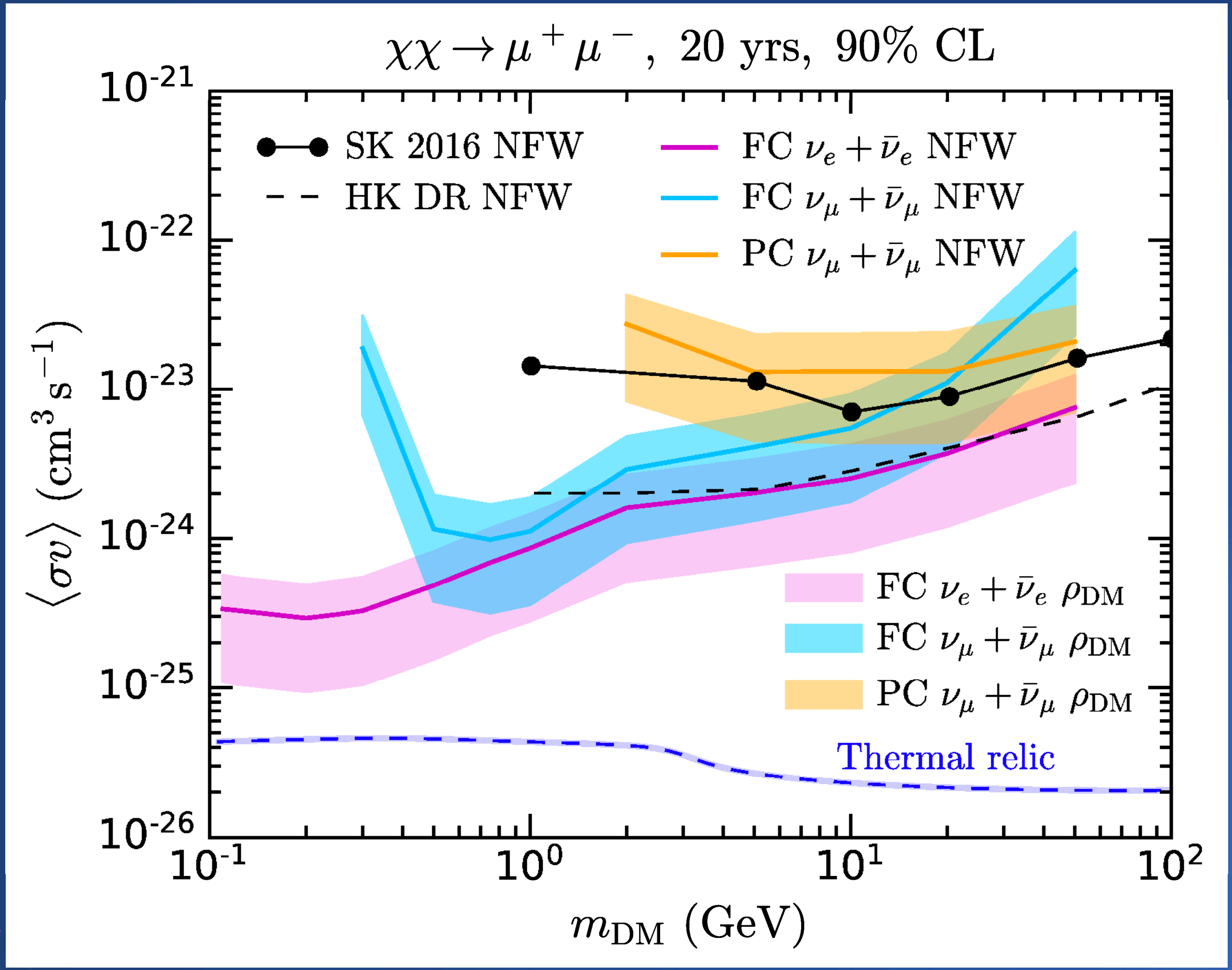
The shaded bands span isothermal (upper) and Moore (lower) profiles.

With and w/out neutron tagging



Assumes 70% neutron-tagging efficiency

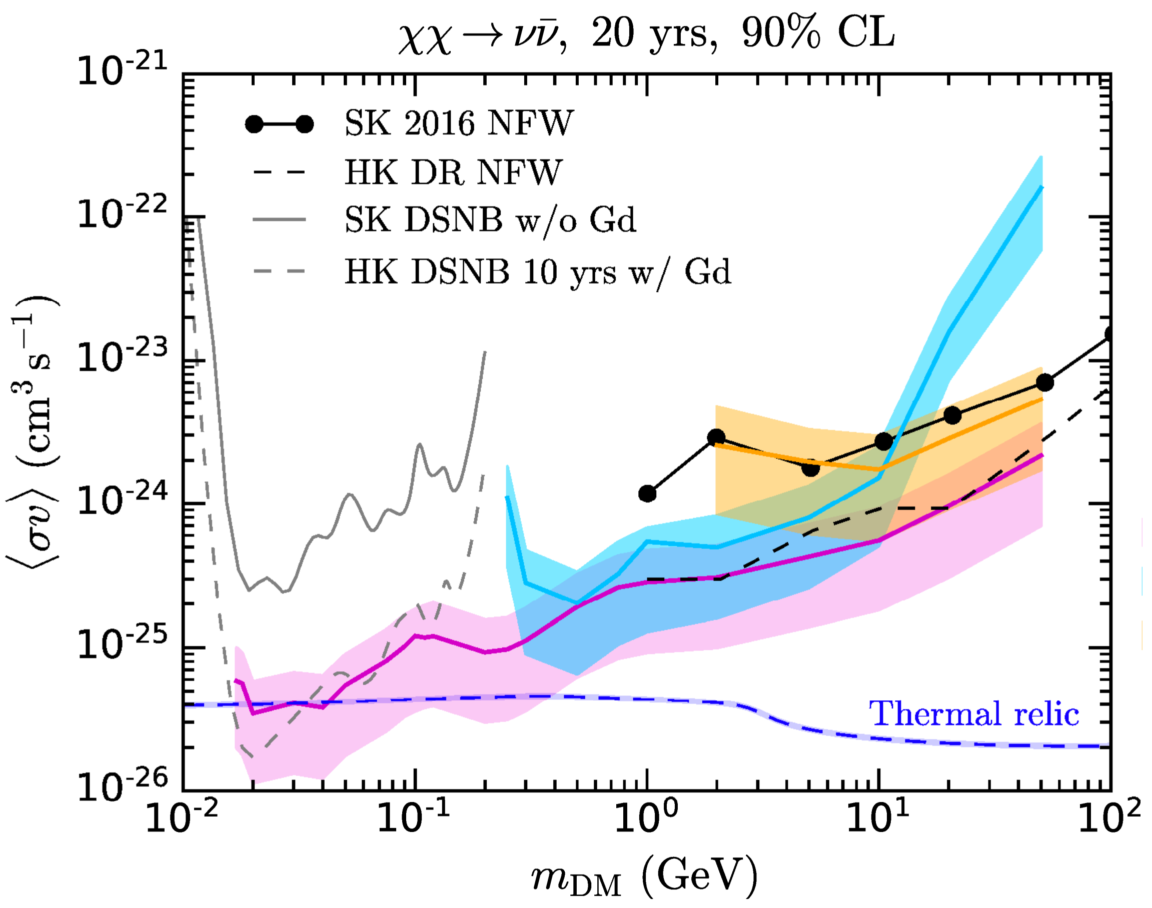
Cross section limits: $\chi\chi \rightarrow \mu^+\mu^-$



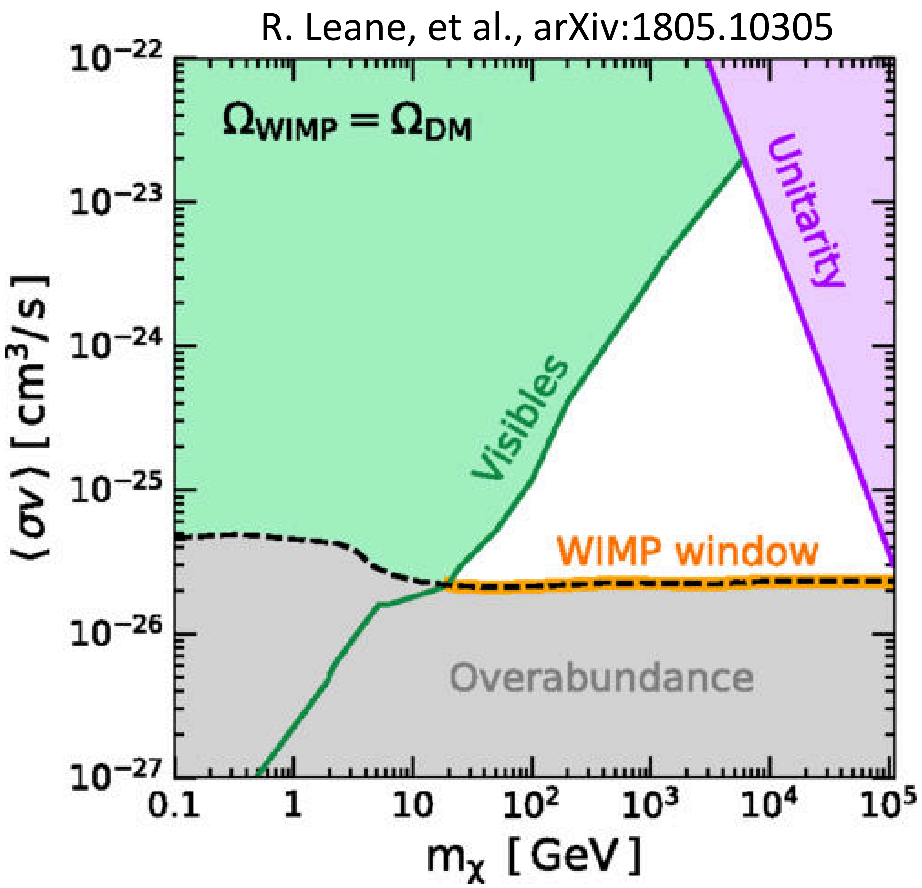
NFB, Dolan, Robles, arXiv: 2005.01950

Conservative indirect detection limits

Annihilation to "invisible" SM states

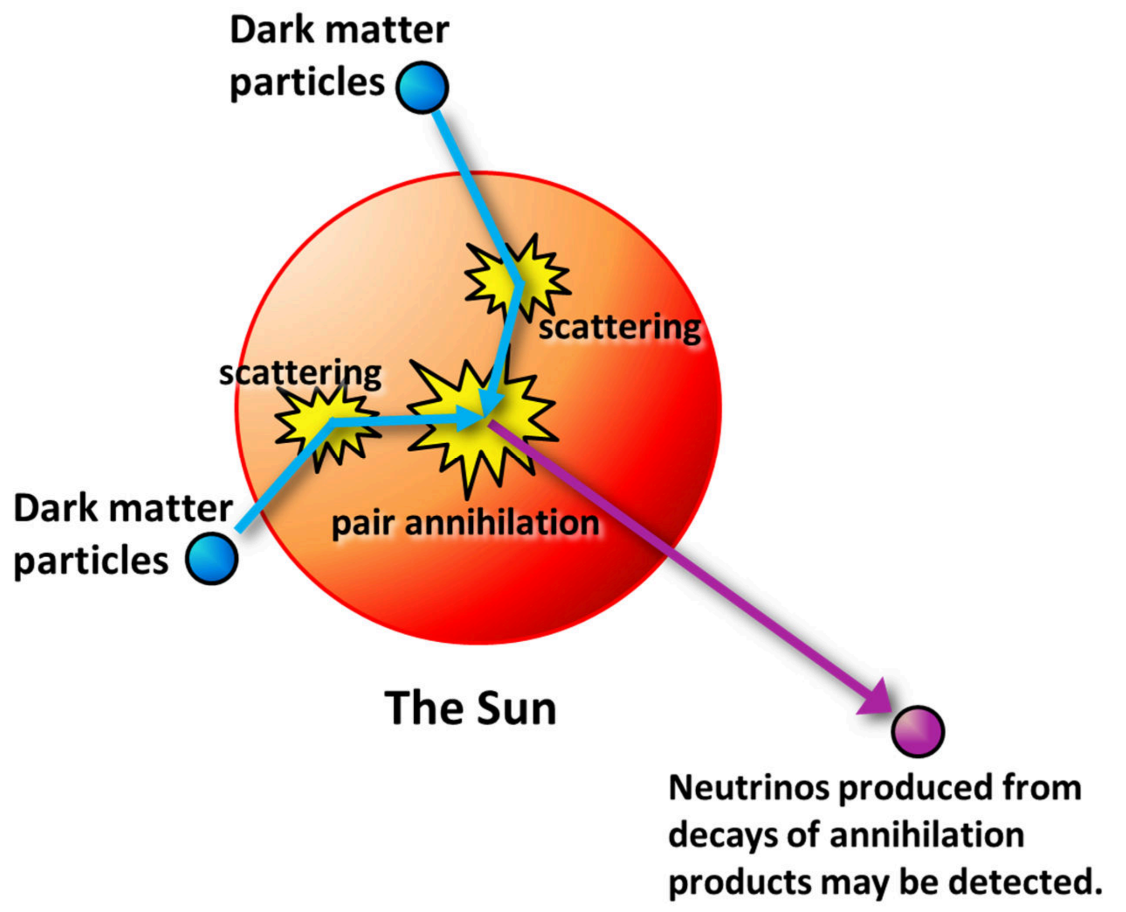


Annihilation to "visible" SM states



Dark Matter Capture in Stars

→ an alternative approach to Dark Matter Direct Detection experiments



- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of the star → neutrinos escape

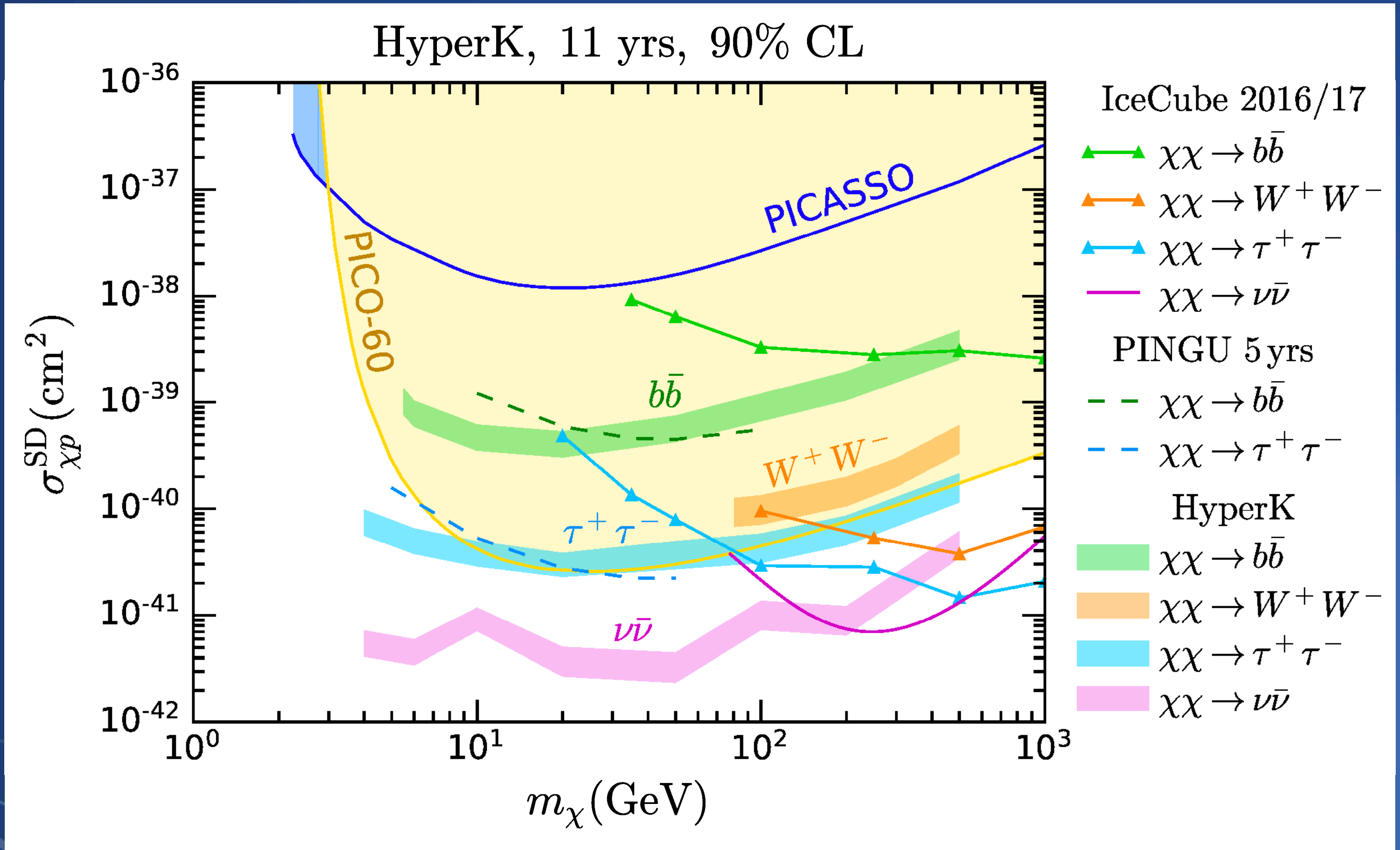
In equilibrium:
Annihilation rate = Capture rate

→ controlled by $\sigma^{\text{scattering}}_{\text{darkmatter–nucleon}}$

→ probes the same quantity as nucleon-recoil dark matter experiments

Annihilation of DM captured in the Sun to Neutrinos

Spin-Dependent (SD)



Spin-dependent (SD) interactions:
→ solar DM capture competitive with direct detection experiments

Spin-independent (SI) interactions
→ direct detection wins

NFB, Dolan & Robles, arXiv:2107.04216

Summary

Measuring CP violation with atmospheric neutrinos

- Surpass the sensitivity of accelerator long-baseline expts near $\delta_{CP} = 90°, 270°$ (where CP is maximally violated; currently favoured).

Precision solar neutrino measurements at DUNE

- Neutral current measurement → improved precision on total ^{8}B solar nu flux.

DM annihilation to neutrinos at the Galactic Centre

- Hyper-K will reach the thermal relic scale for DM mass below about 30 MeV.

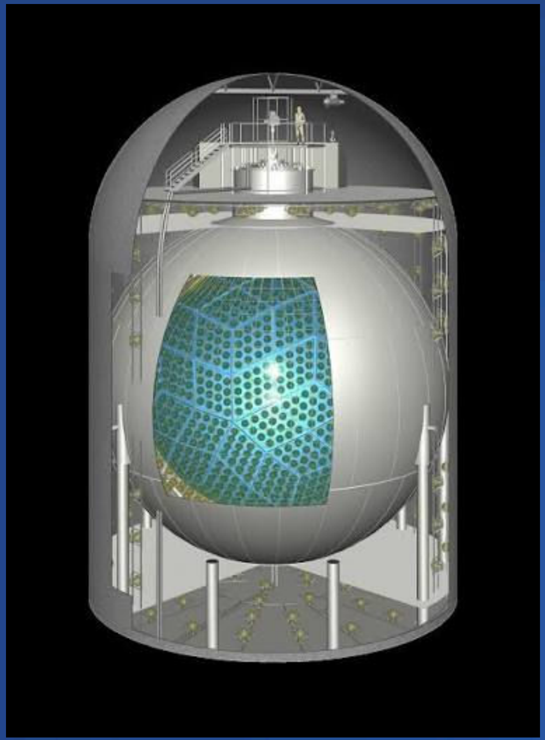
Back-up slides

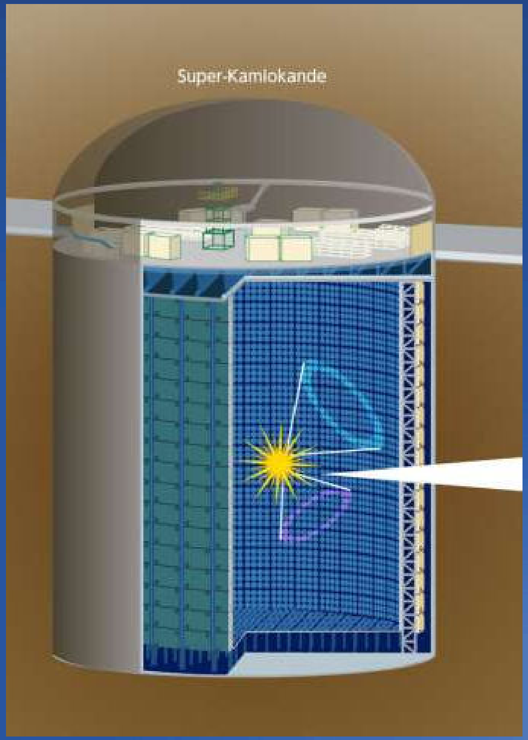
Previous generation experiments

KamLAND

liquid-scintillator
1 kilo-ton

(JUNO ~ 18 kilo-ton)





Super-Kamiokande

water-Cherenkov
22.5 kilo-ton

(Hyper-K ~ 190 kilo-ton)

The WIMP Miracle

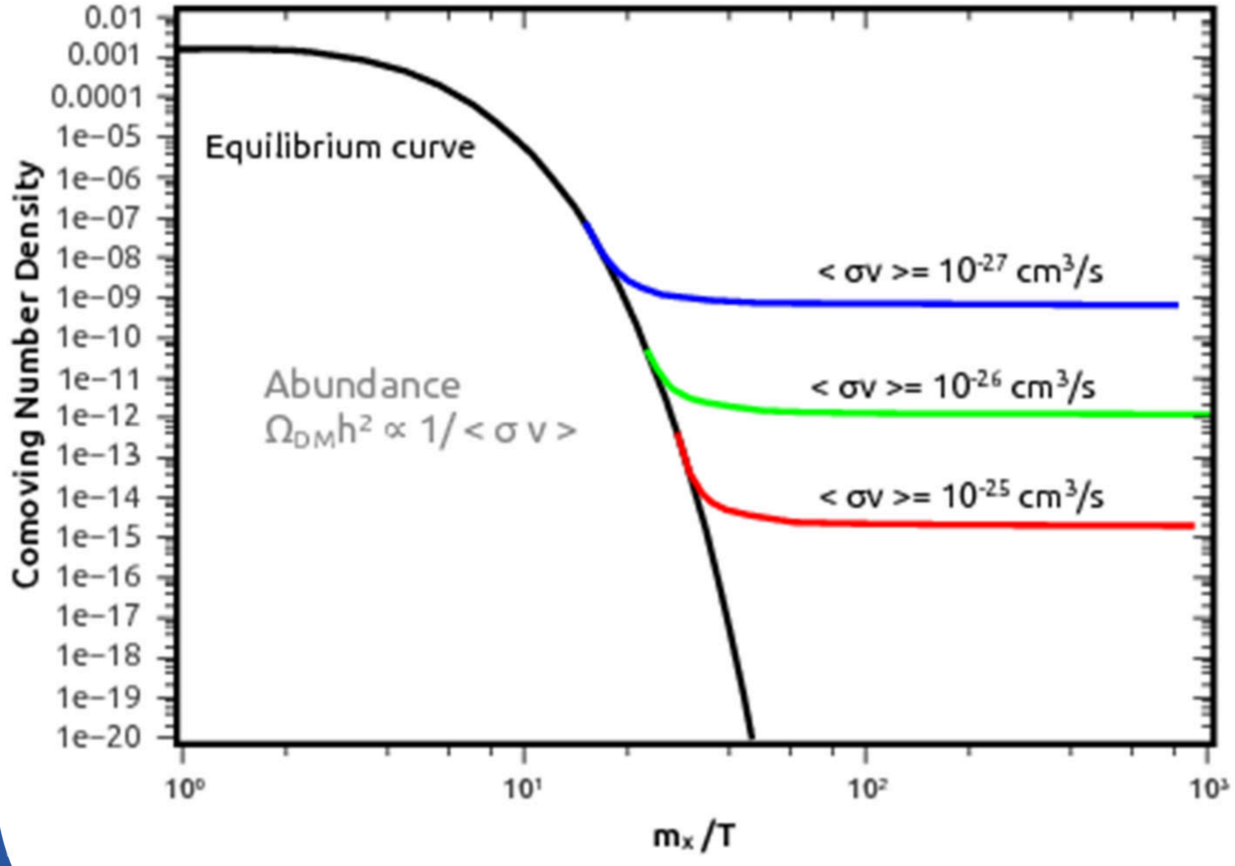
Dark matter density determined by annihilation rate in the early universe.

Larger annihilation rate
→ Less dark matter (and vice versa).

Required annihilation cross section:

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

$$\chi + \chi \leftrightarrow \text{regular matter}$$



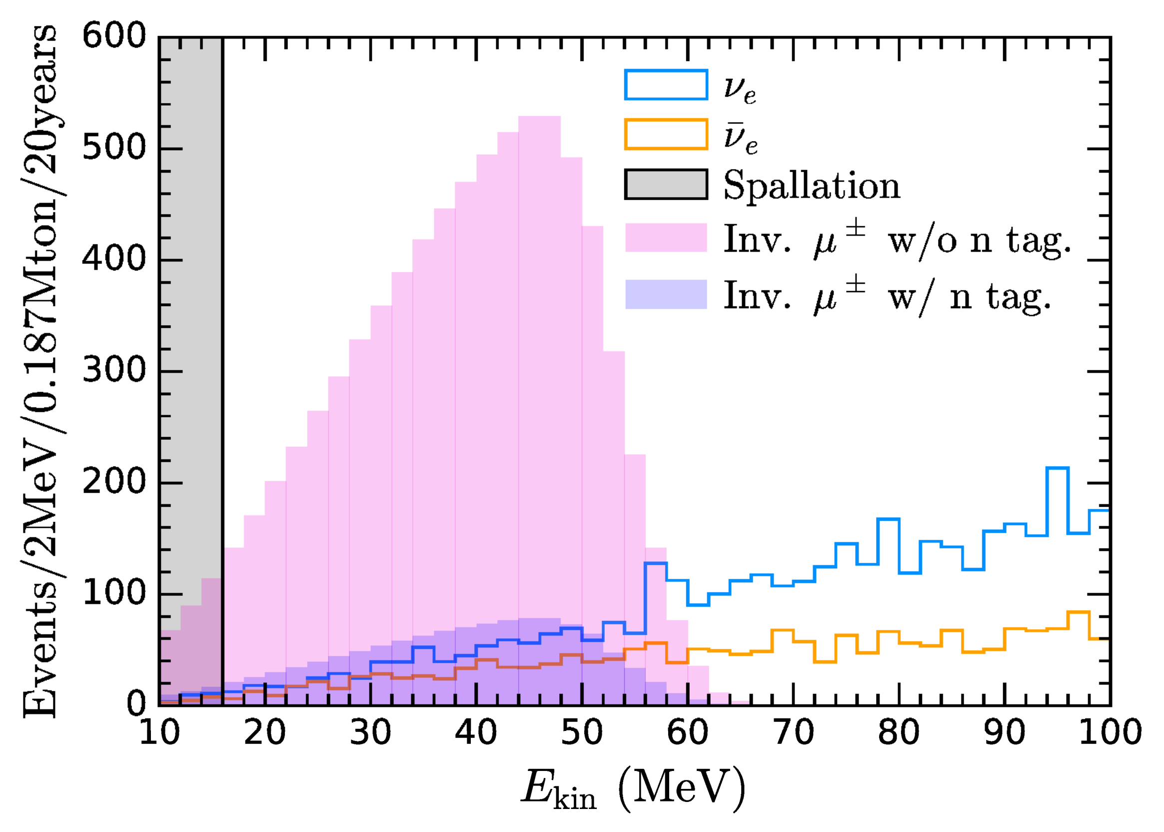
Neutron tagging to remove invisible muons

"Invisible muons" are an important background at sub-GeV energies

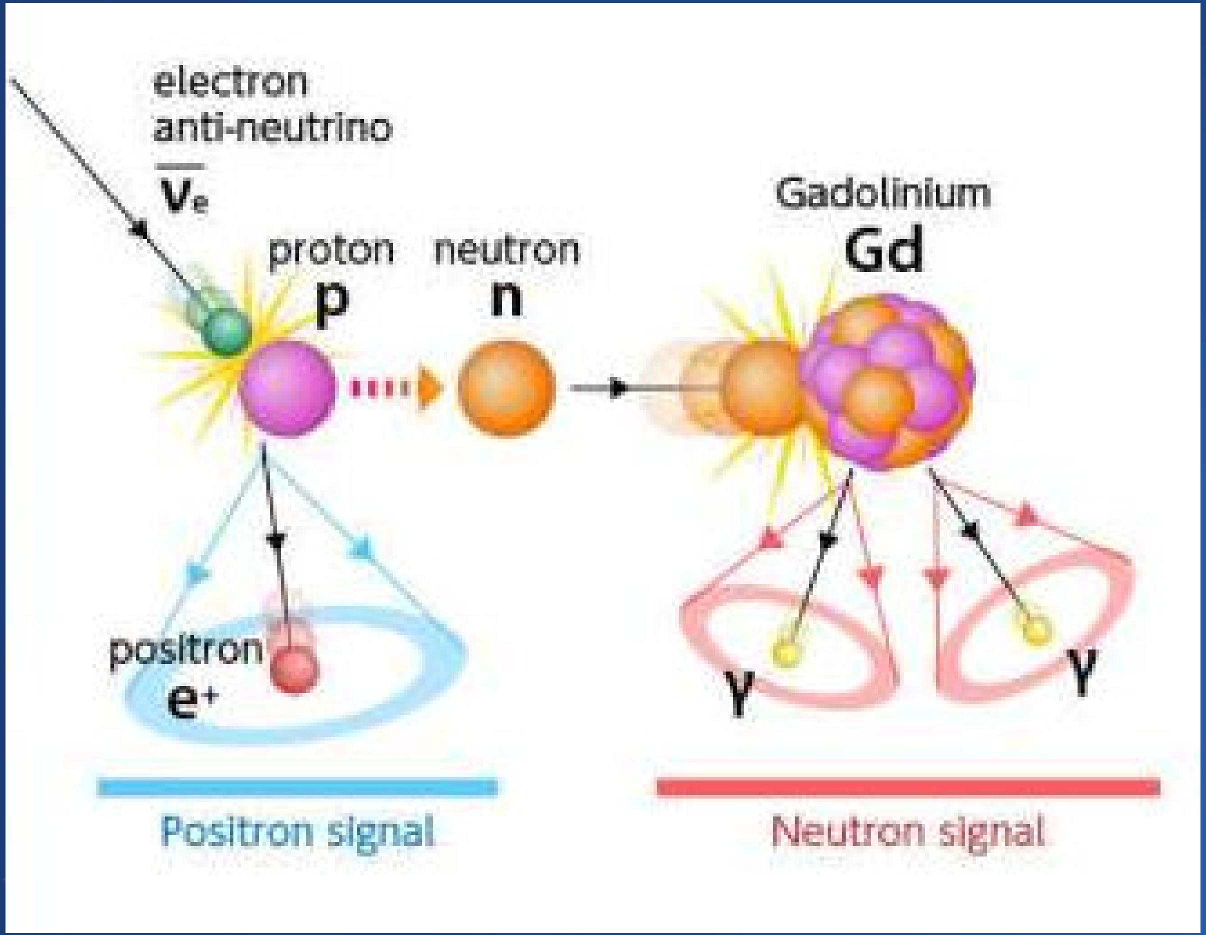
- $\mu^\pm$ of energy < 50 MeV (produced from interaction of low energy atm neutrinos) are invisible in the detector
- When they decay, the resulting $e^\pm$ cannot be associated with the parent muon.
- Looks like a ν_e or $\overline{\nu}_e$ or event.

Neutron tagging allows invisible muons to be distinguished from true IBD:

$$\overline{\nu}_e + p \to n + e^+$$



Neutron tagging on Gadolinium



Gadoliniun has a large neutron capture cross section.

It de-excites via emission of an easily identifiable photon cascade of 8 MeV.

Neutron tagging on Hydrogen may possible too:

$$n + p \rightarrow d + \gamma(2.2 \text{ MeV})$$