

New Opportunities in Neutrino Measurements



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Matthew Dolan
University of Melbourne

With John Beacom, Nicole Bell, Stephan Meighen-Berger, Jay Newstead, Sandra Robles, Michael Virgato, Ho Man Yim

Introduction

- Neutrino physics is scaling up.

- Many important issues.
 - Mass scale, and Normal/Inverted Hierarchy?
 - Dirac vs Majorana masses?
 - Origin of masses?
 - CP violating phase in PMNS Matrix?
- New Physics in the Neutrino Sector – Dark Matter connection?

Introduction

- Neutrino physics is scaling up.

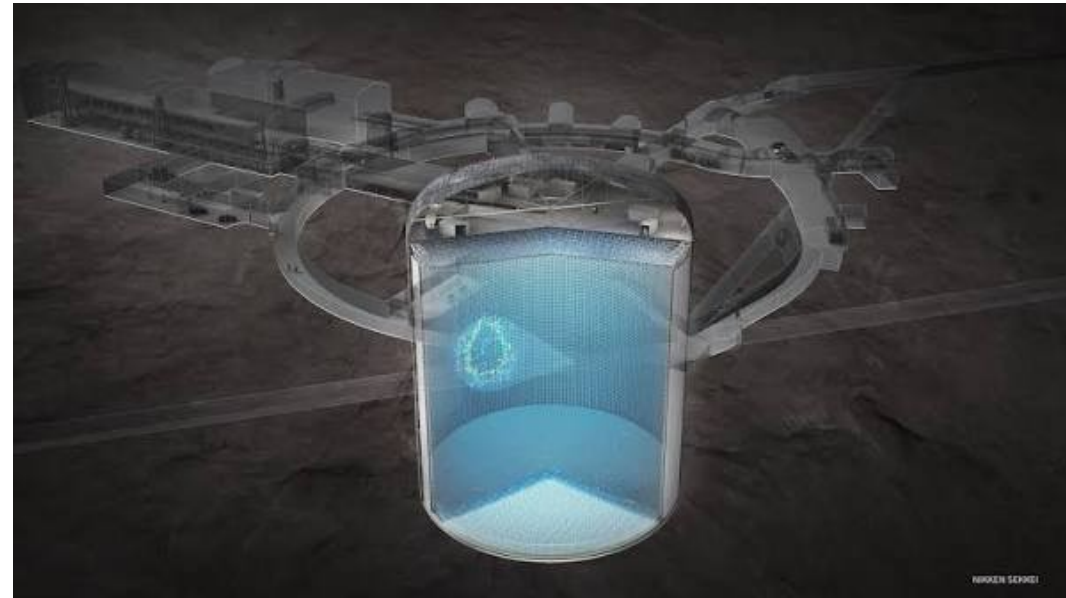
- Many important issues:
 - Mass scale, and Normal/Inverted Hierarchy?
 - Dirac vs Majorana masses?
 - Origin of masses?
 - CP violating phase in PMNS Matrix?
- New Physics in the Neutrino Sector – Dark Matter connection?

This talk will answer none of these questions.

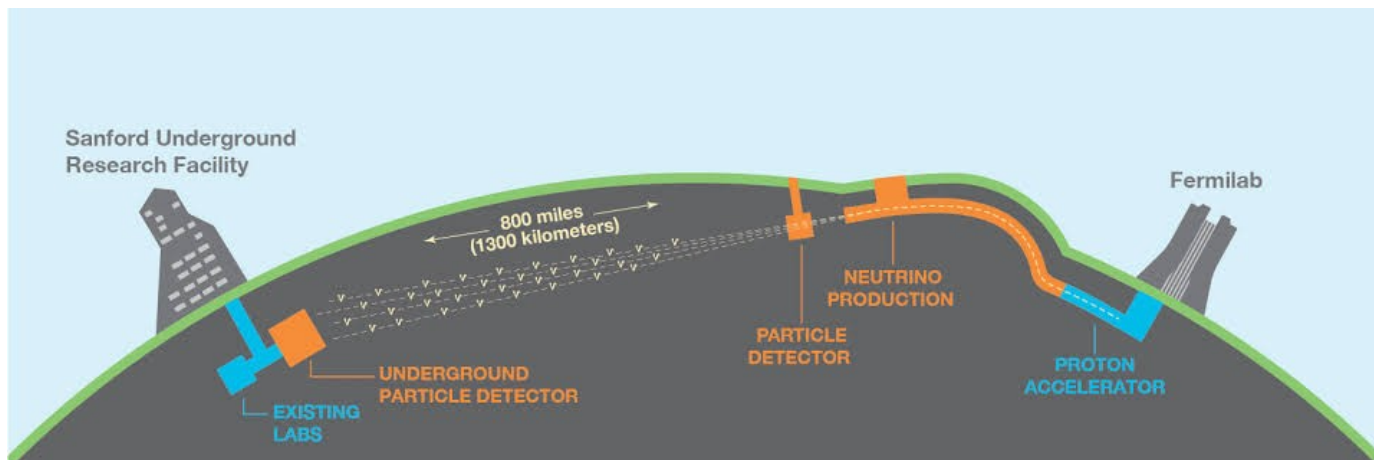
Next Current Generation Experiments



JUNO (2025)



Hyper-Kamiokande (2028)



DUNE
(2030-ish)

Introduction

- Mass scale, and Normal/Inverted Hierarchy?
 - Dirac vs Majorana masses?
 - Origin of masses?
 - CP violating phase in PMNS Matrix?
- New Physics in the Neutrino Sector – DM connection?

- Scope for new analyses:
 - CP Violation with Atmospheric Neutrinos (HK)
 - (Light) Dark Matter annihilating to neutrinos (HK)
 - Precision Solar Neutrino physics at DUNE
- Common factor: sub-GeV neutrino energies.

CP Violation and Neutrino Oscillations

- CP Violation required for baryogenesis ← Sakharov conditions
 - CP Violation in Neutrino Mixing (PMNS) Matrix:

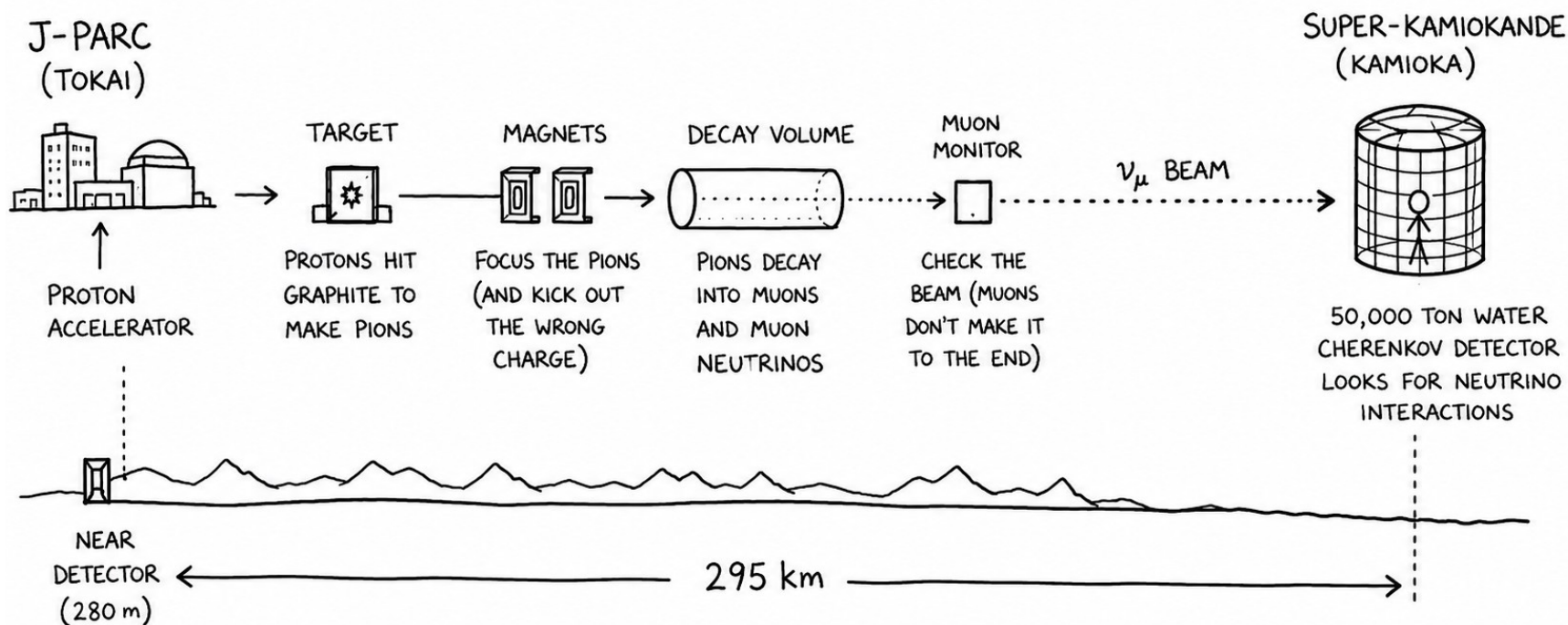
$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} &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

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

- How to find CP-phase effects in oscillation experiments?
- Measuring CP-Violation requires genuine 3-flavour mixing
 - 2-flavour mixing: single mixing angle

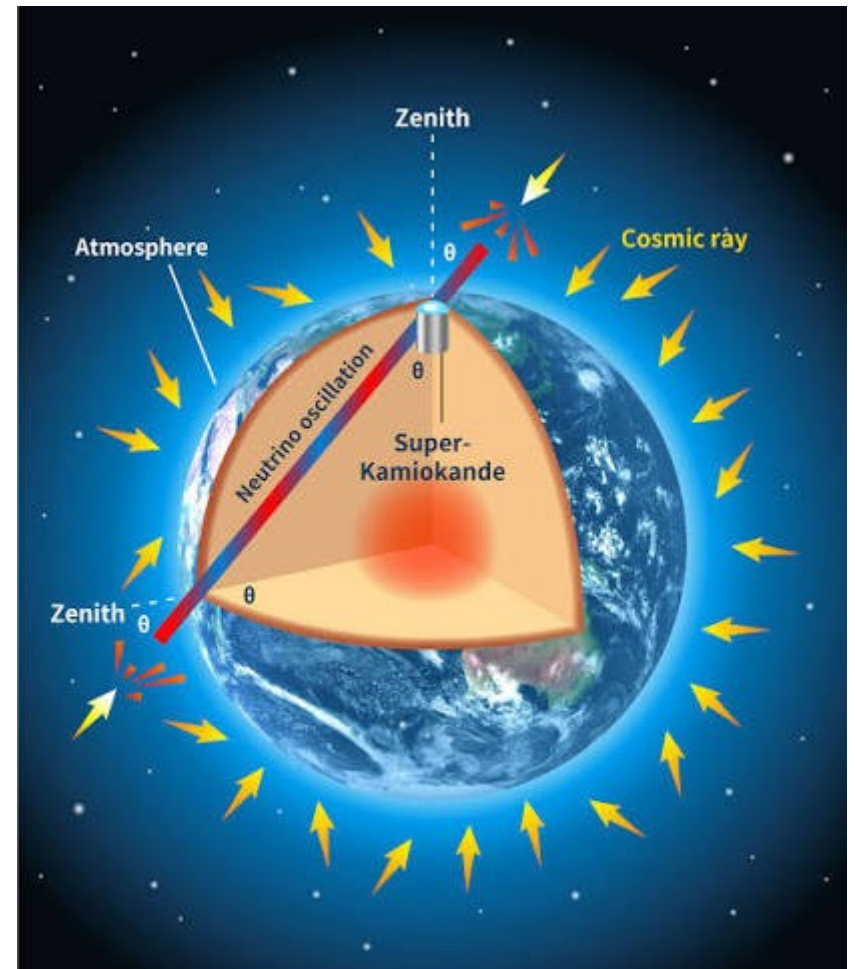
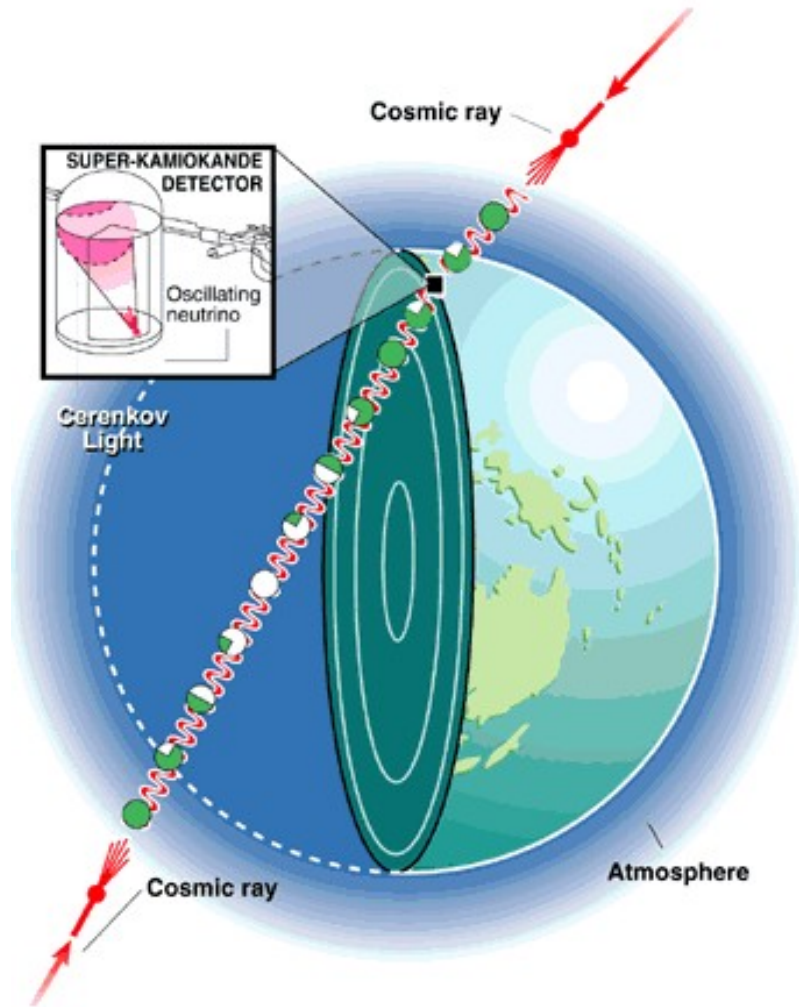
CP Violation: Accelerator Long-Baseline Experiments

WE SHOOT A BEAM OF NEUTRINOS 295 km THROUGH THE EARTH
TO SEE IF THEY CHANGE FLAVOR ALONG THE WAY.
(SPOILER: THEY DO.)



$$P(\nu_\alpha \rightarrow \nu_\beta) \quad \text{vs} \quad P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

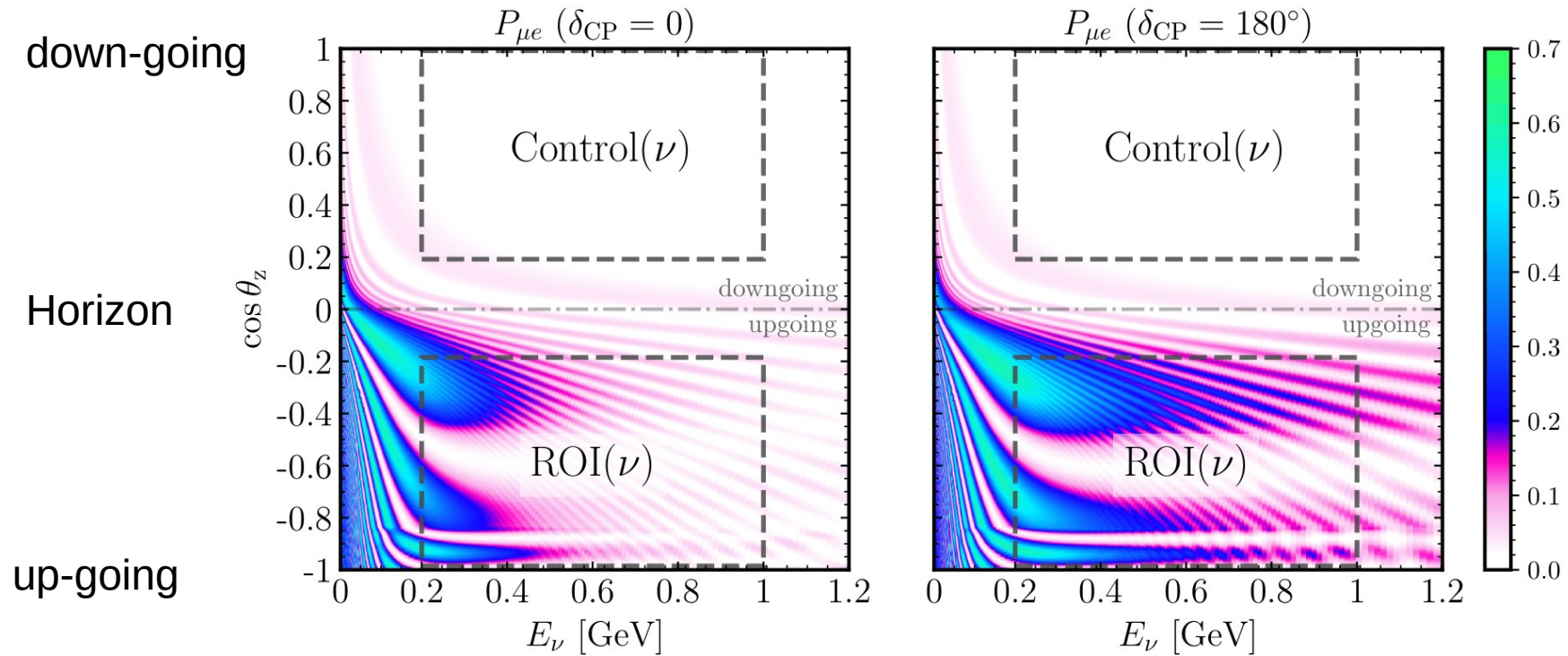
CP Phase with Atmospheric Neutrinos



See Nicole Bell, parallel session (Thurs pm)!

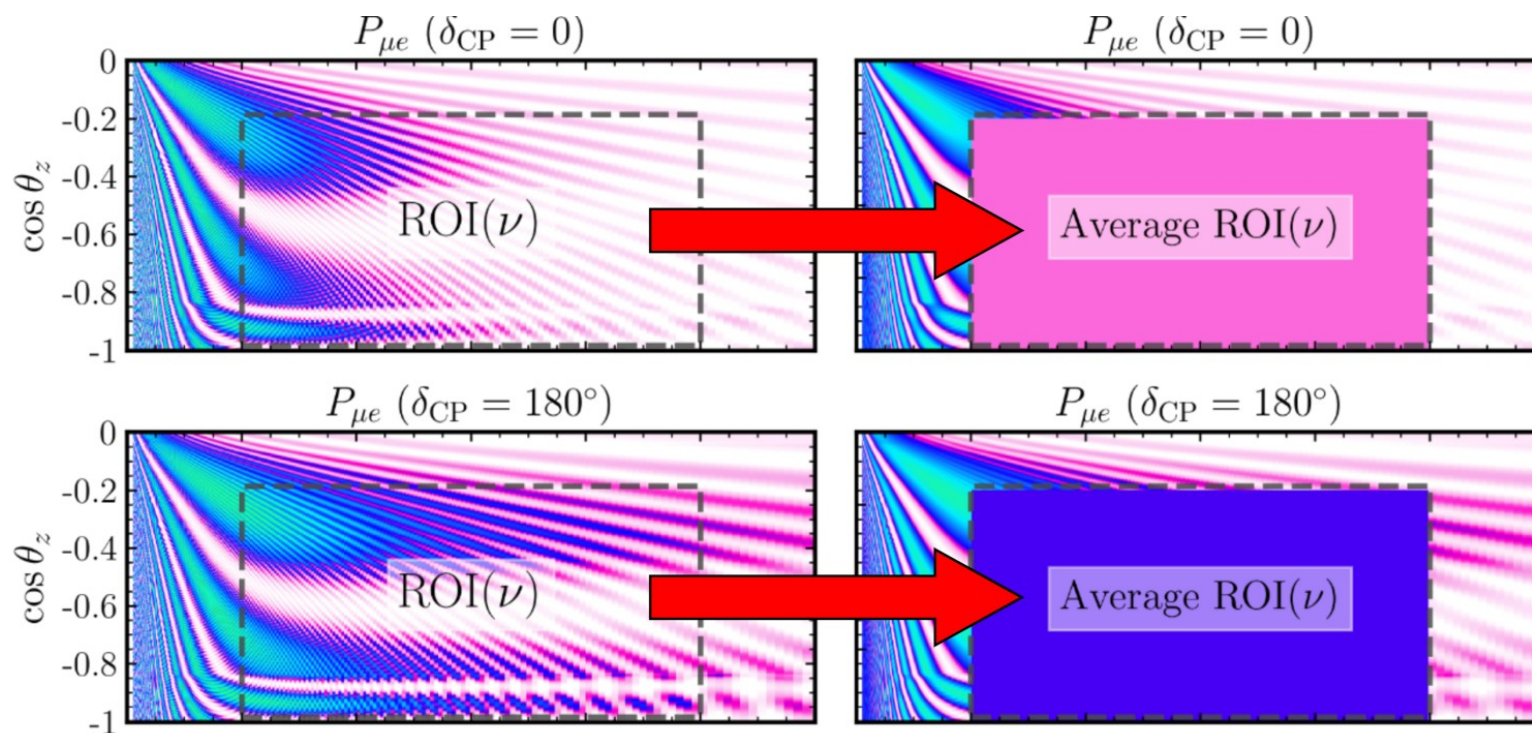
From SuperK...

CP Phase with Atmospheric Neutrinos



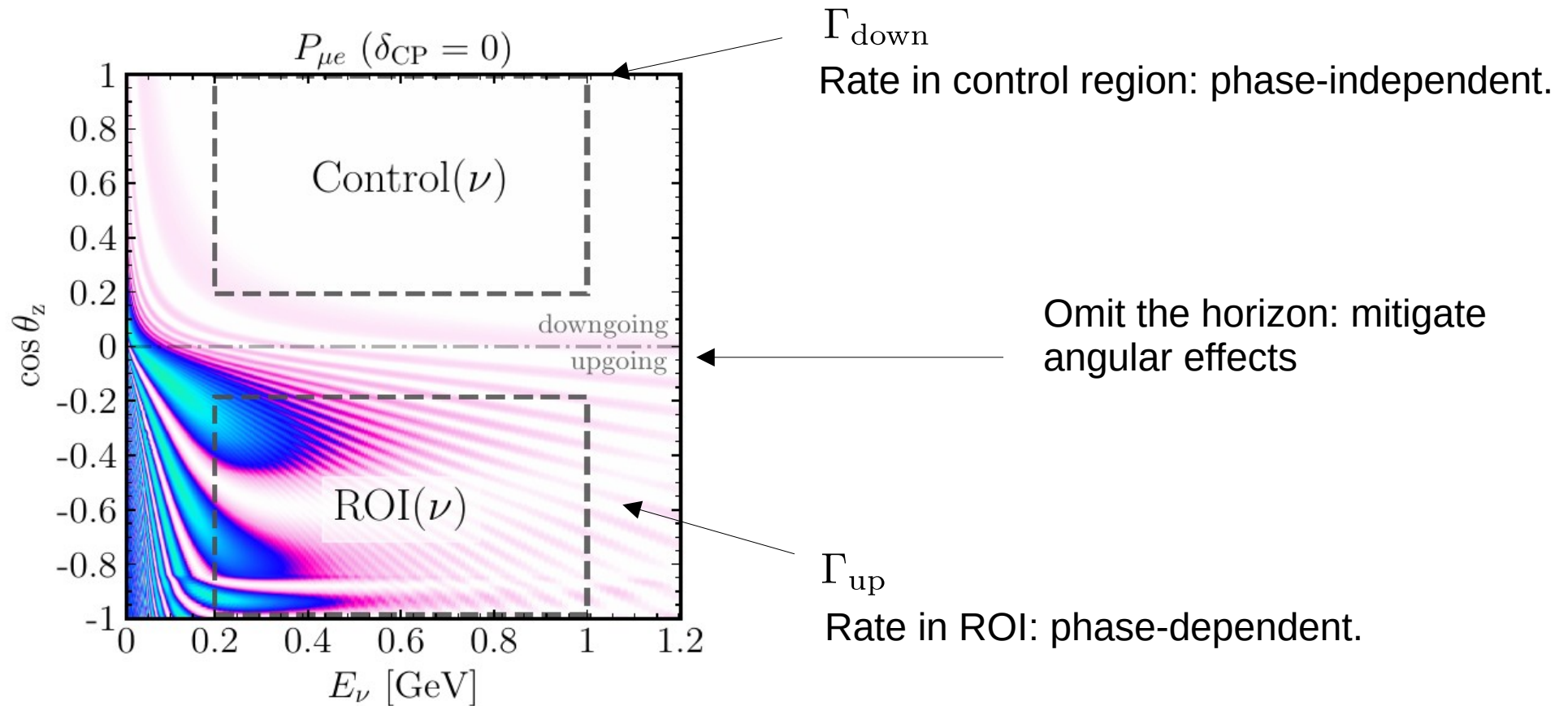
- Downgoing: no CP sensitivity: effectively two-flavours
 - Upgoing: Exhibits CP sensitivity.

CP Violation with Atmospheric Neutrinos



- “Peacock” fan effects washed out by angular and energy smearing.
 - But CP effects survive
- Similar in electron neutrinos. Similar in antineutrinos.

Constructing an Observable



$$R_{\text{CP}} = \frac{\Gamma_{\text{up}}}{\Gamma_{\text{down}}} \simeq 1 - 0.05 \cos \delta_{\text{CP}}$$

Cancels leading uncertainties

CP Phase with Atmospheric Neutrinos

$$R_{\text{CP}} = \frac{\Gamma_{\text{up}}}{\Gamma_{\text{down}}} \simeq 1 - 0.05 \cos \delta_{\text{CP}}$$

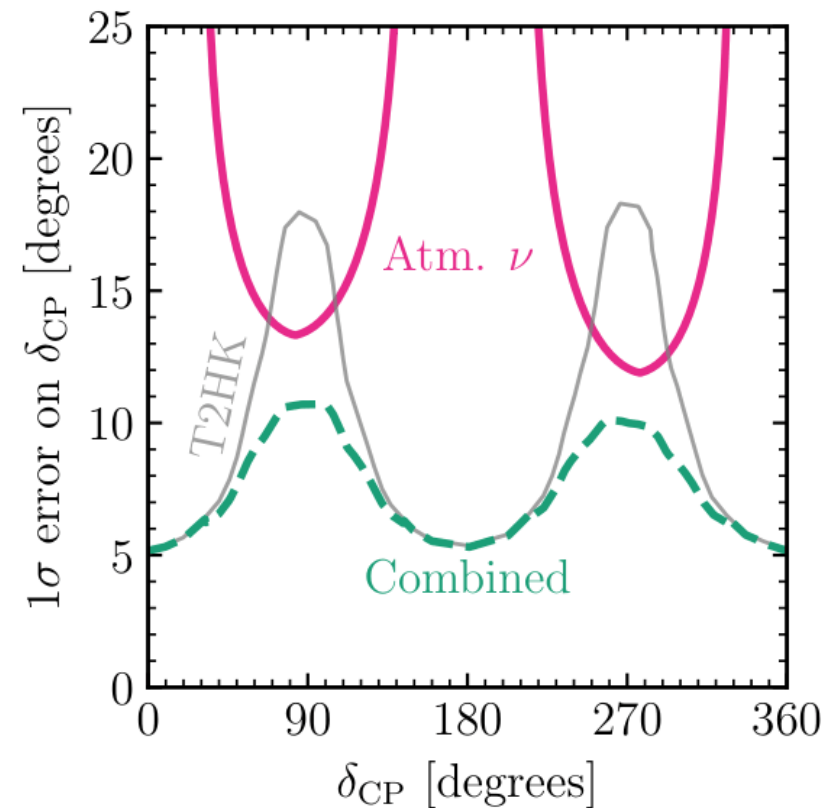
- Observable is proportional to $\cos \delta_{\text{CP}}$
 - CP-violating effects depend on Jarlskog invariant $J \propto \sin \delta_{\text{CP}}$
- Sensitive to phase as oscillation parameter, not CPV effect.
 - Contrasts with Long-baseline experiments.

- Include energy and angular smearing as detector effects
- Weak correlation between charged lepton and neutrino direction
 - Flux and cross-section uncertainties
- Uncertainties from mixing angles and Earth model (subdominant)

Sensitivity to CP Phase

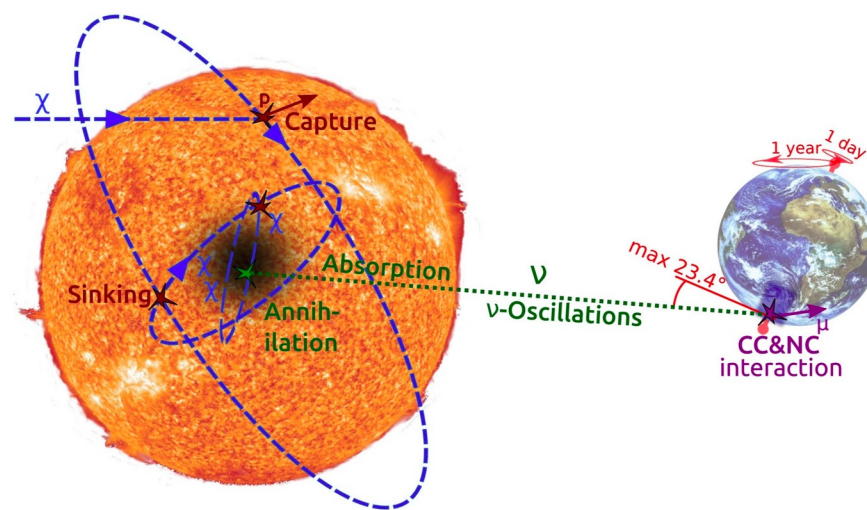
- Combine electron and muon channels
 - 10 years exposure
- Atmospheric analysis has max sensitivity for maximal CP violation.
- Complementary sensitivity to long-baseline experiments (T2HK)

$\cos \delta_{CP}$ vs $\sin \delta_{CP}$

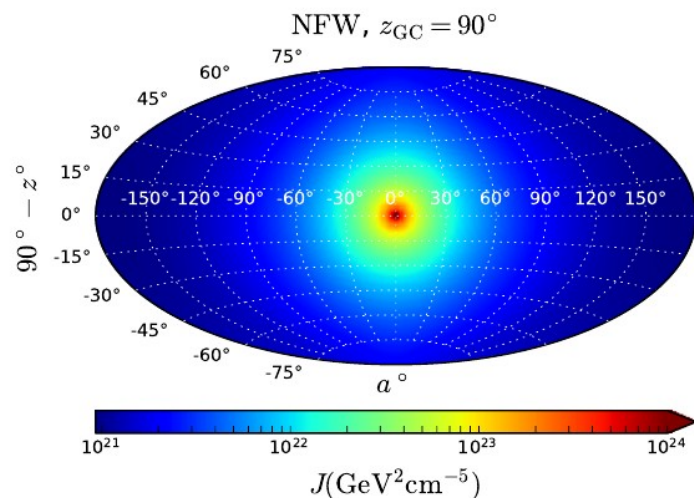


Dark Matter Searches at Hyper-K

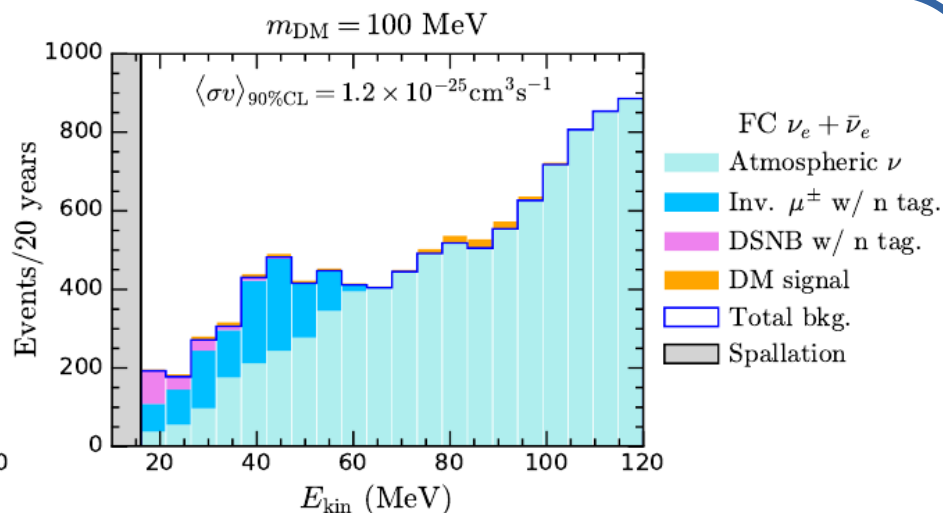
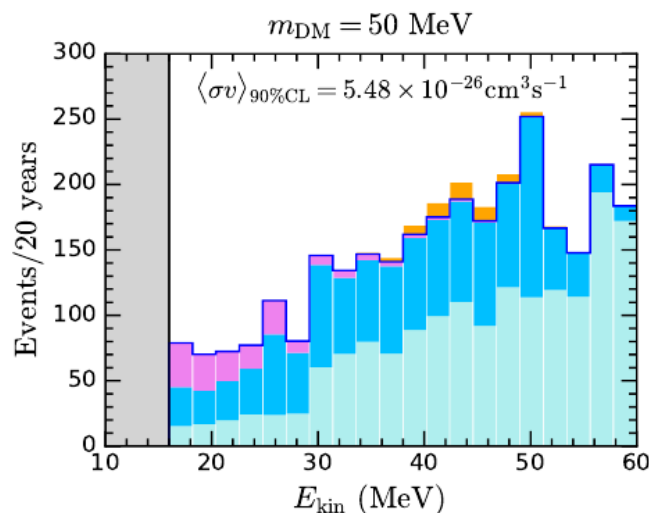
- Large-scale neutrino experiments are sensitive to (annihilating) dark matter: Galactic Centre, Sun, Earth, boosted DM...
 - Particularly interesting for light dark matter



Signal and Background Calculation



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

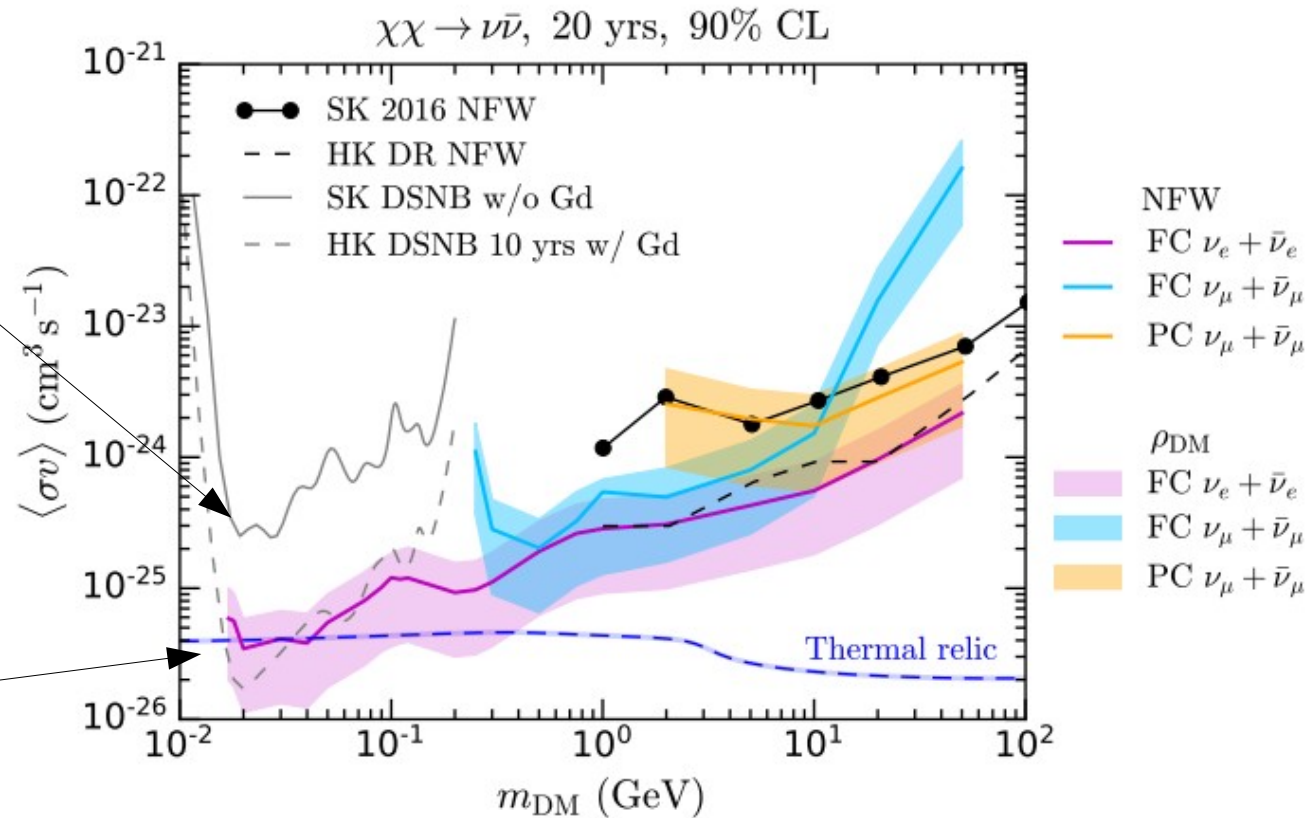


GC Search Projections: Neutrinos

Limit and projection
from SK DSNB search

0710.5420
1805.09830

Palomares-Ruiz, Pascoli,
Olivares-Campo et al



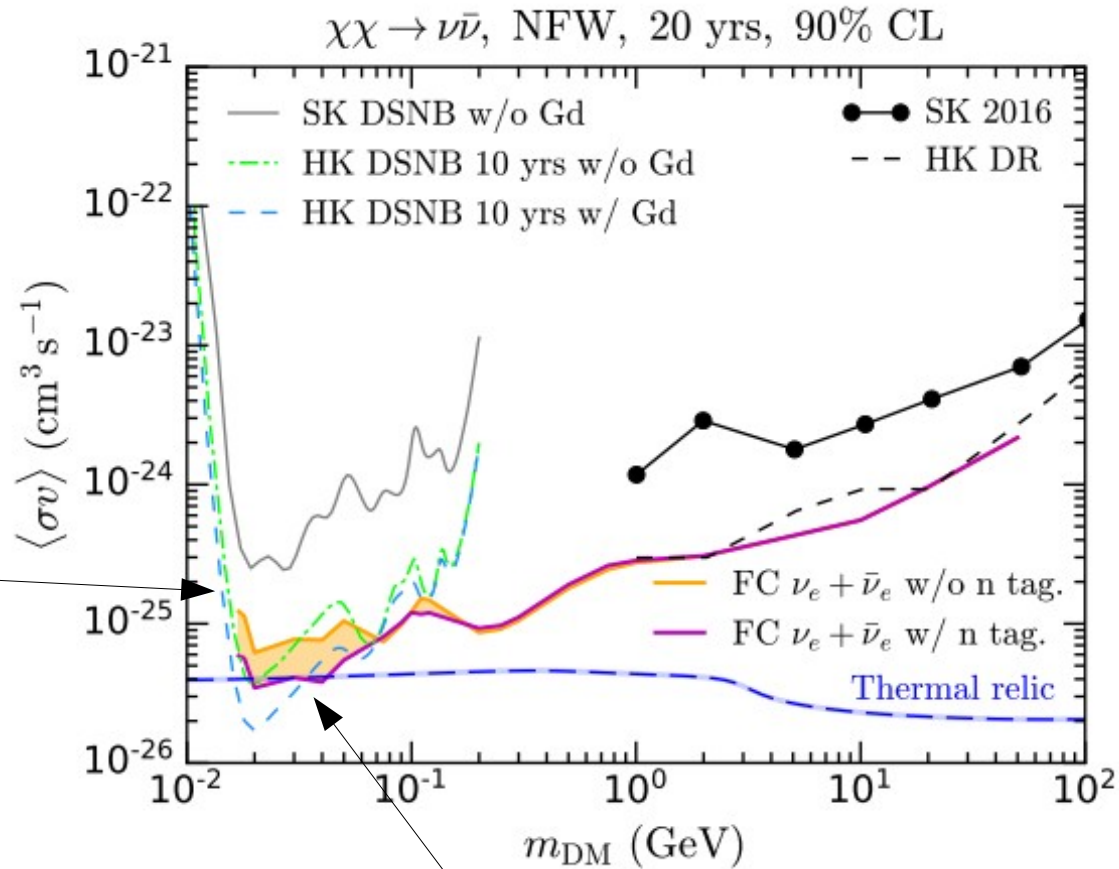
HyperK sensitive to
thermal annihilation
cross-sections at low
masses.

- Impact of alternate DM halo profiles shown by coloured bands
 - Isothermal (top): Worse by ~ 2
 - Moore (bottom): Better by ~ 2

GC Search Projections: Neutron tagging

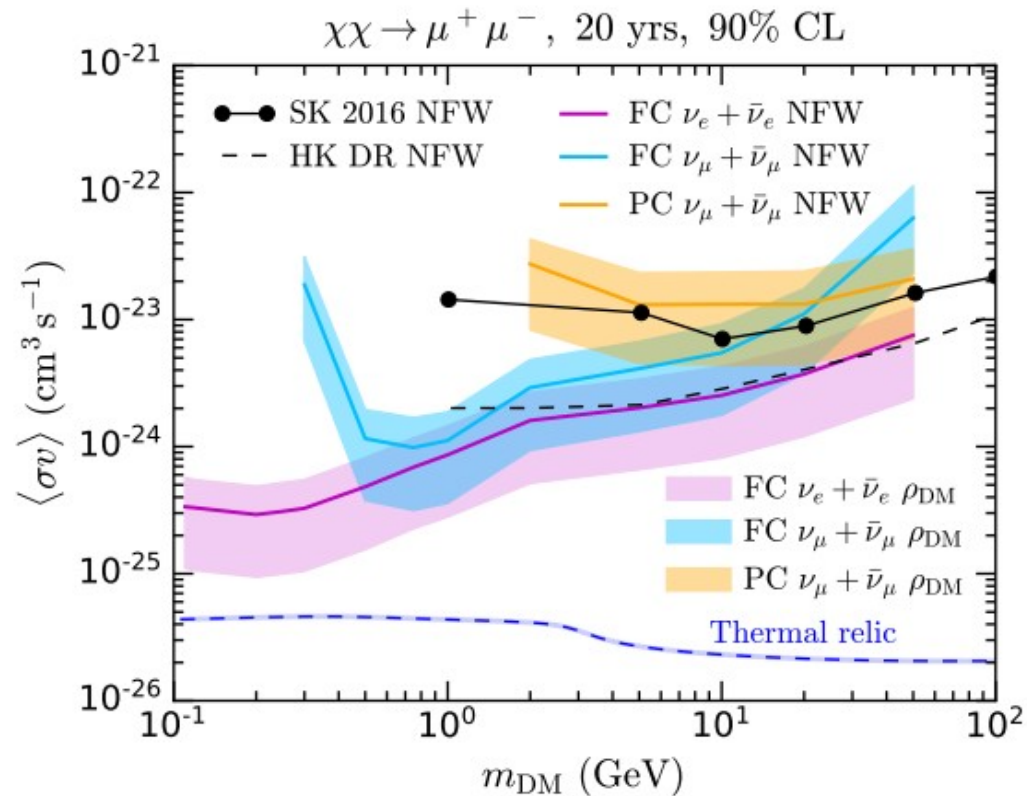
Limit and projection
from SK DSNB search
Green: w/out tagging
Blue: w /tagging

0710.5420
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Neutron tagging important for
achieving thermal relic sensitivity

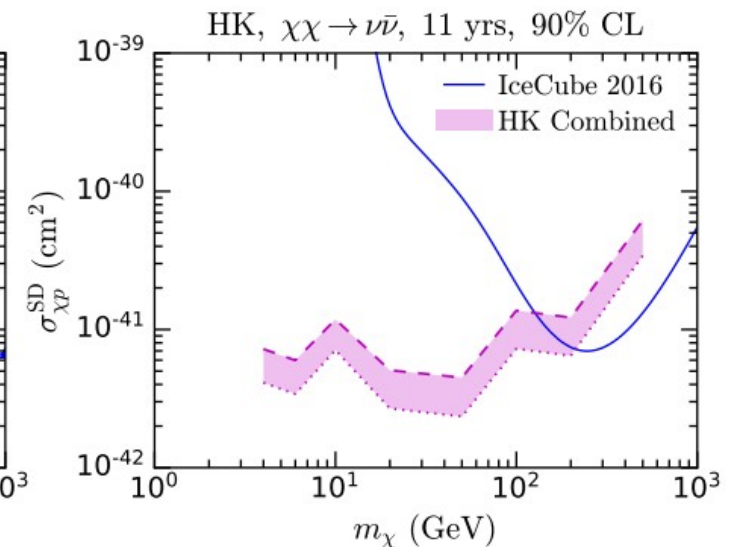
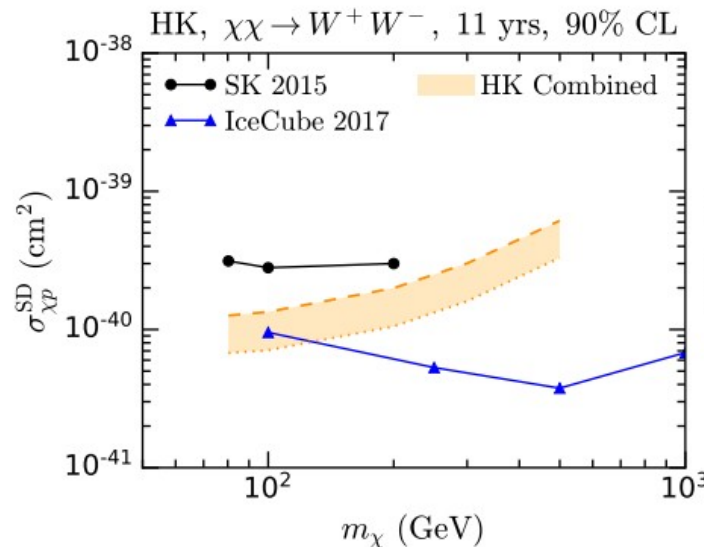
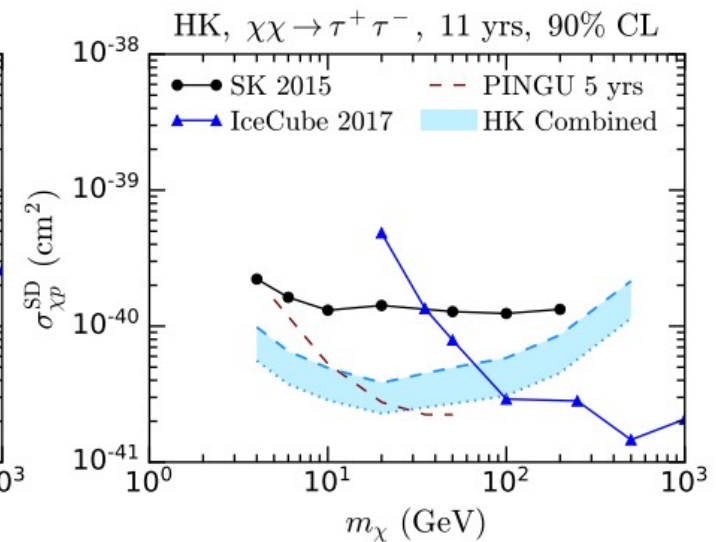
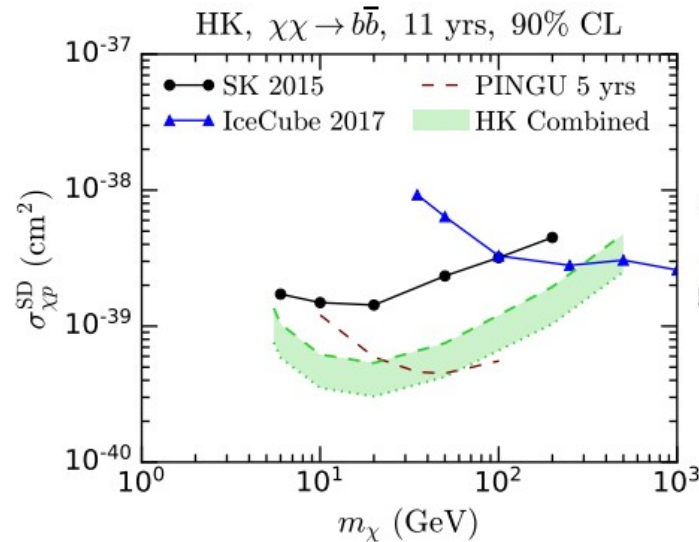
Galactic Centre Search Projections: Muons



- Impact of alternate DM halo profiles shown by coloured bands
 - Isothermal (top)
 - Moore (bottom)

Spin-Dependent (Solar) Projections

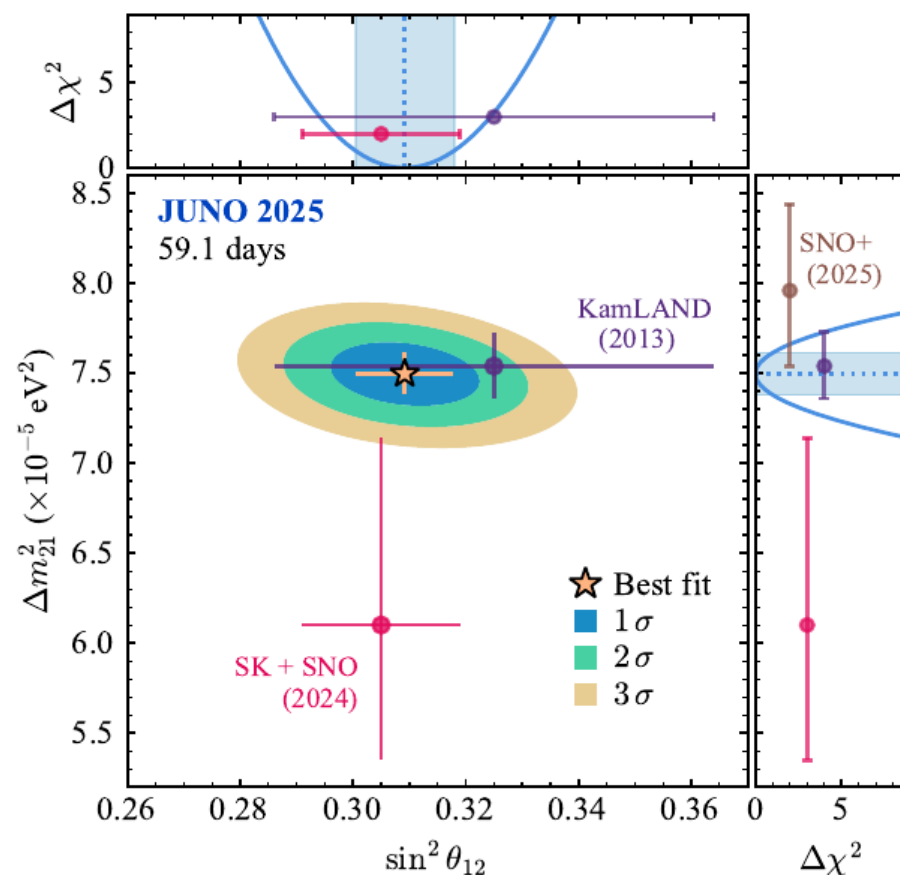
- Projections for 11 years at HK
- Combination over event categories
- Dashed: current SK systematic errors
- Dotted: half current SK systematic errors



- Improve on SuperK by ~ 3
- Consistent with Earth search projections in HyperK Design Report

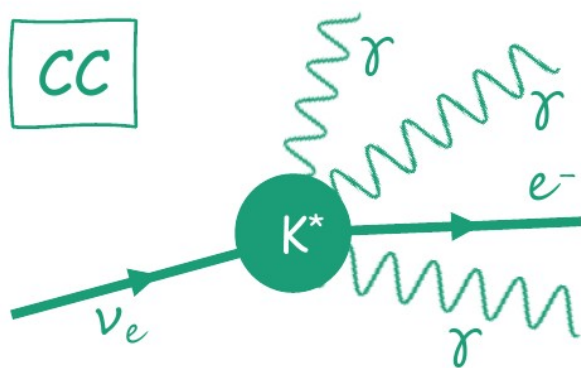
Precision Solar Neutrino Measurements at DUNE

- JUNO measured solar mixing parameters
 Δm_{21}^2 , $\sin^2 \theta_{12}$
 - Only 59 days of data!
- Reactor antineutrino measurement
- Can also be measured with solar neutrinos → comparison tests New Physics scenarios

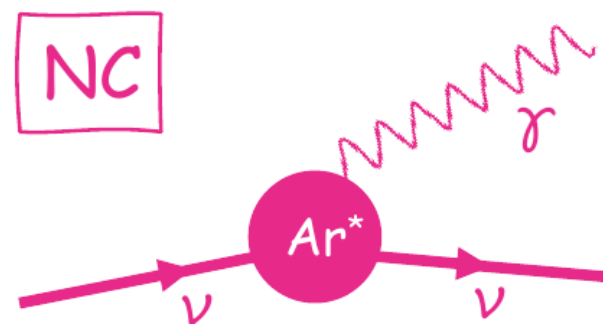


Precision Solar Neutrino Measurements at DUNE

- Idea: Measure the flux of solar 8B neutrinos with Neutral Current interactions
- Use inelastic Argon transitions.
- Compare Charged-current and Neutral-current rates to determine $\sin^2 \theta_{12}$

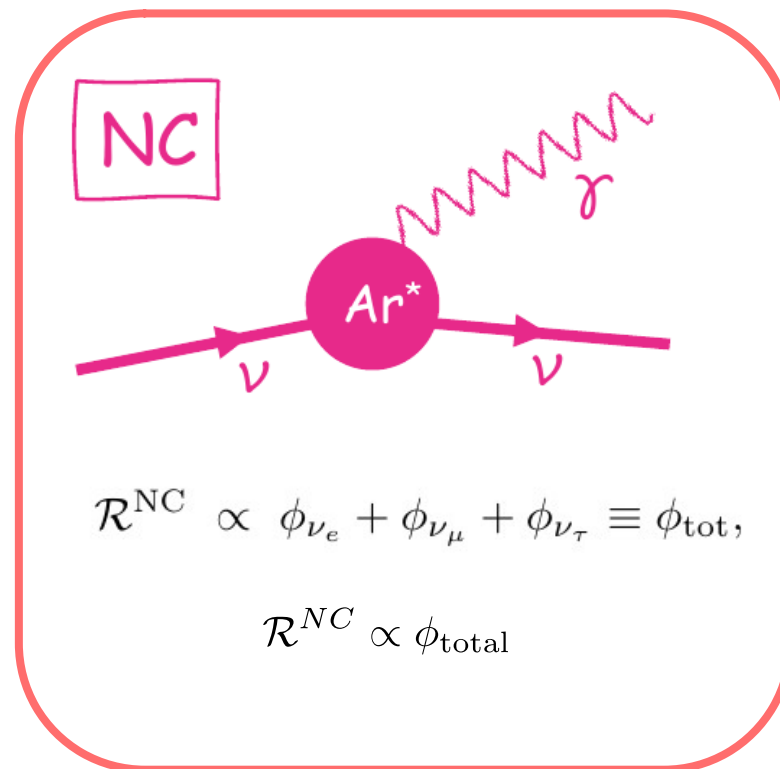
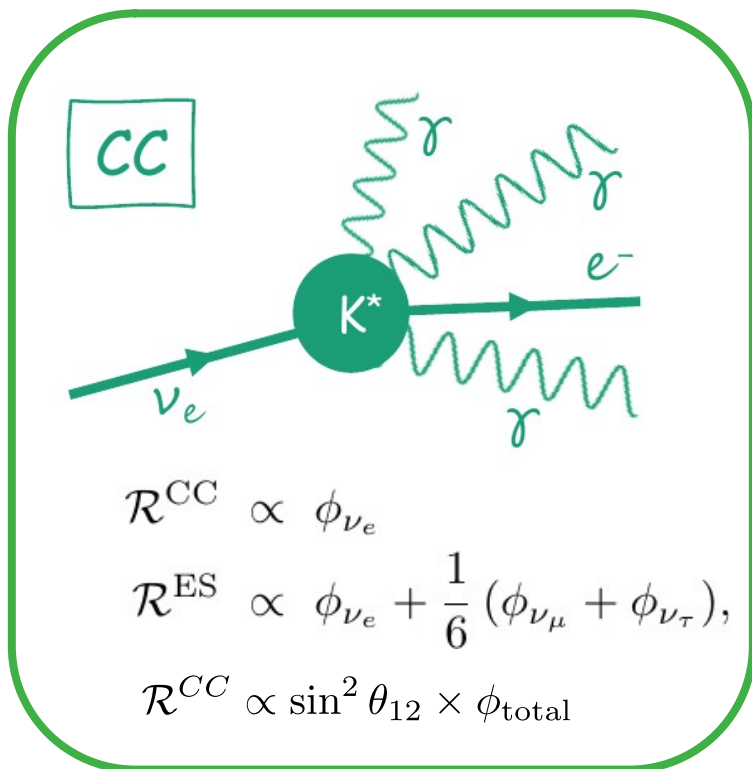


$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

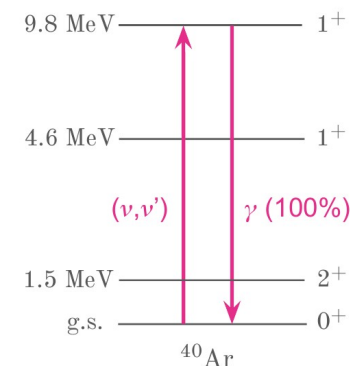


$$\nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar}^*,$$

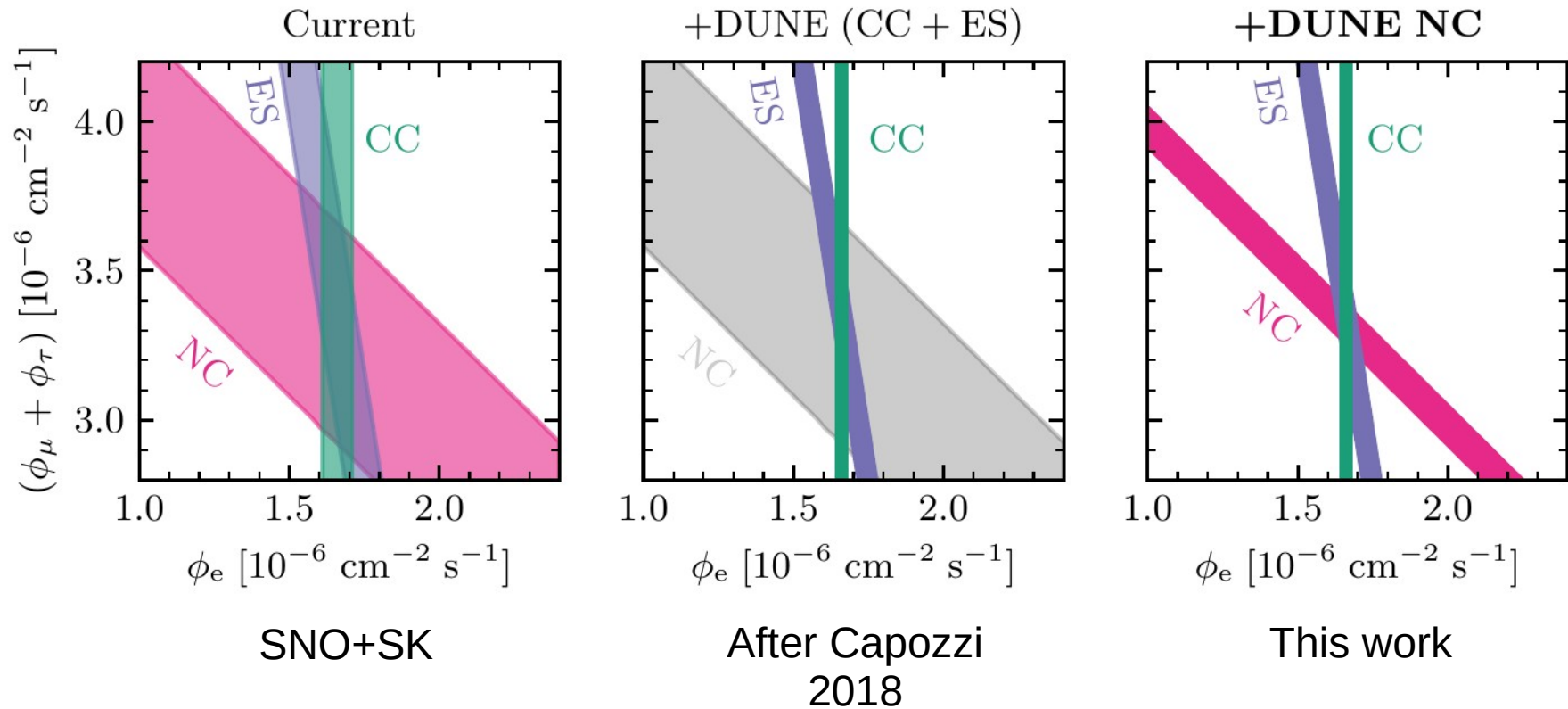
Precision Solar Neutrino Measurements at DUNE



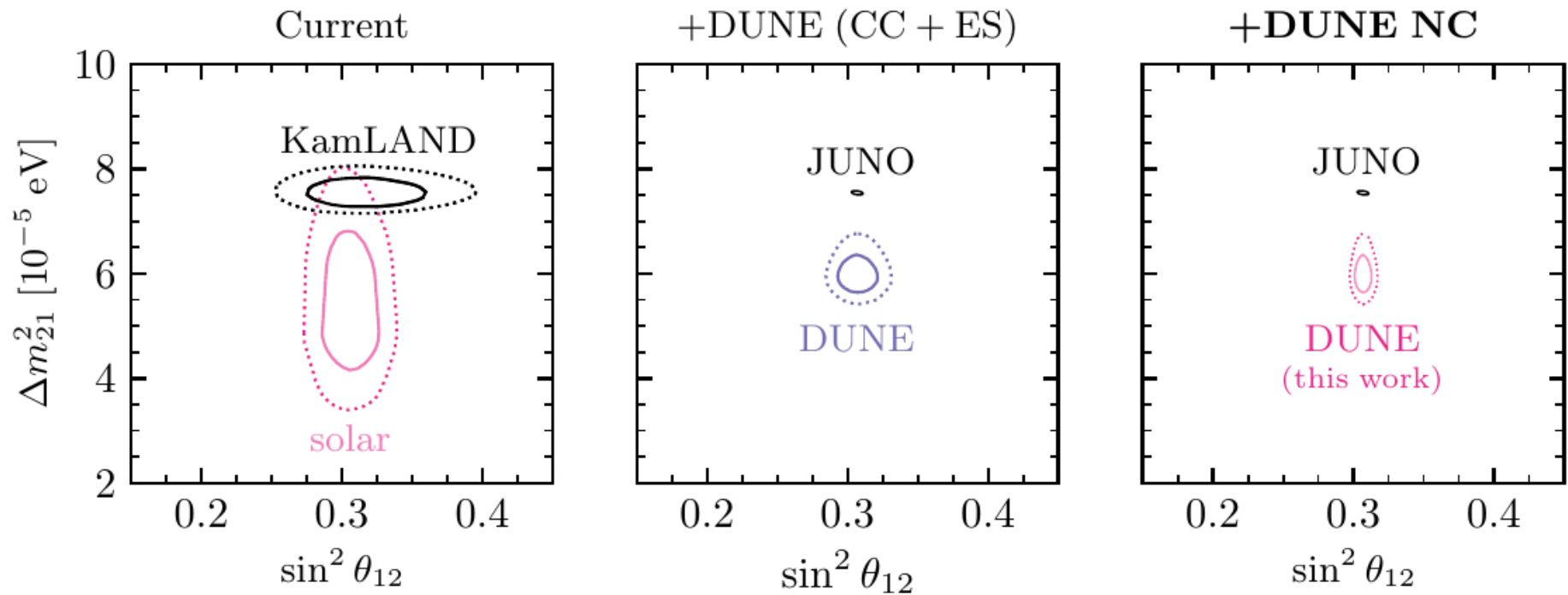
$$\frac{\mathcal{R}^{\text{CC}}}{\mathcal{R}^{\text{NC}}} = \sin^2 \theta_{12}$$



Constraints on Solar Neutrino Fluxes



Solar Neutrinos at DUNE



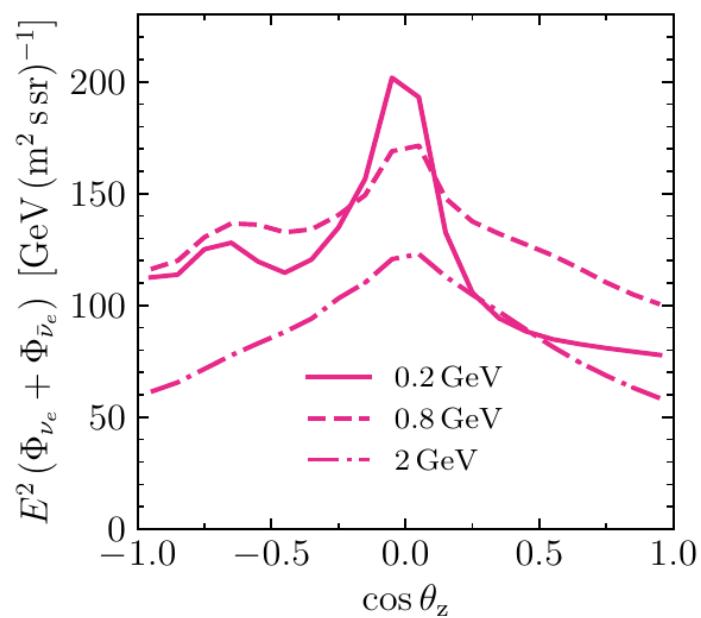
- After 100 kton-years:
 - 2200 NC events
 - 15000 CC+ES events

Outlook

- New experiments → Opportunities for new analyses and measurements
 - CP Violating Phase with Atmospheric Neutrinos (HK)
 - (Light) Dark Matter annihilating to neutrinos (HK)
 - Precision Solar Neutrino physics at DUNE...

The future is bright extremely difficult to detect.

CP-Phase@HK: Detector Effects & Uncertainties



Zenith-angle distribution for sub-GeV atmospheric electron neutrinos

