Prospects for BSM physics searches at HK and T2HKK

-Phill Litchfield

Outline:

(Very) brief introduction to Hyper-K & JPARC beam

Lorentz violation with neutrinos

Sterile Neutrinos

Non-standard interactions

Introduction

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(Very) brief introduction to Hyper-K & JPARC beam

Lorentz violation with neutrinos

Sterile Neutrinos

Non-standard interactions

Apologies:

[What is not covered]

Dark matter in beam

Nucleon Decay

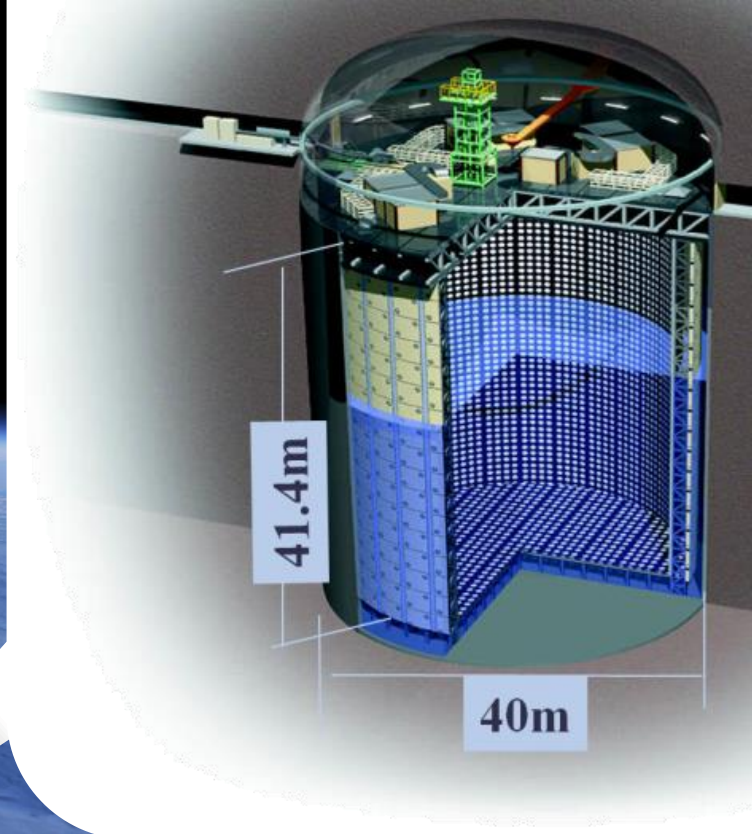
Any astrophysical searches

- Dark matter, Monopoles, …

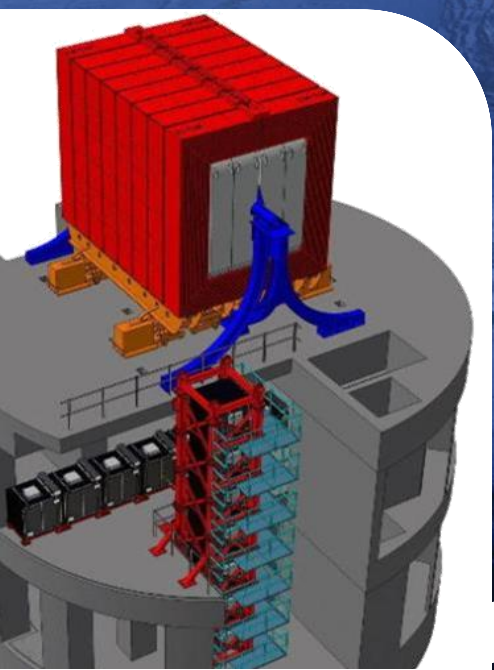
BSM physics affecting solar neutrinos

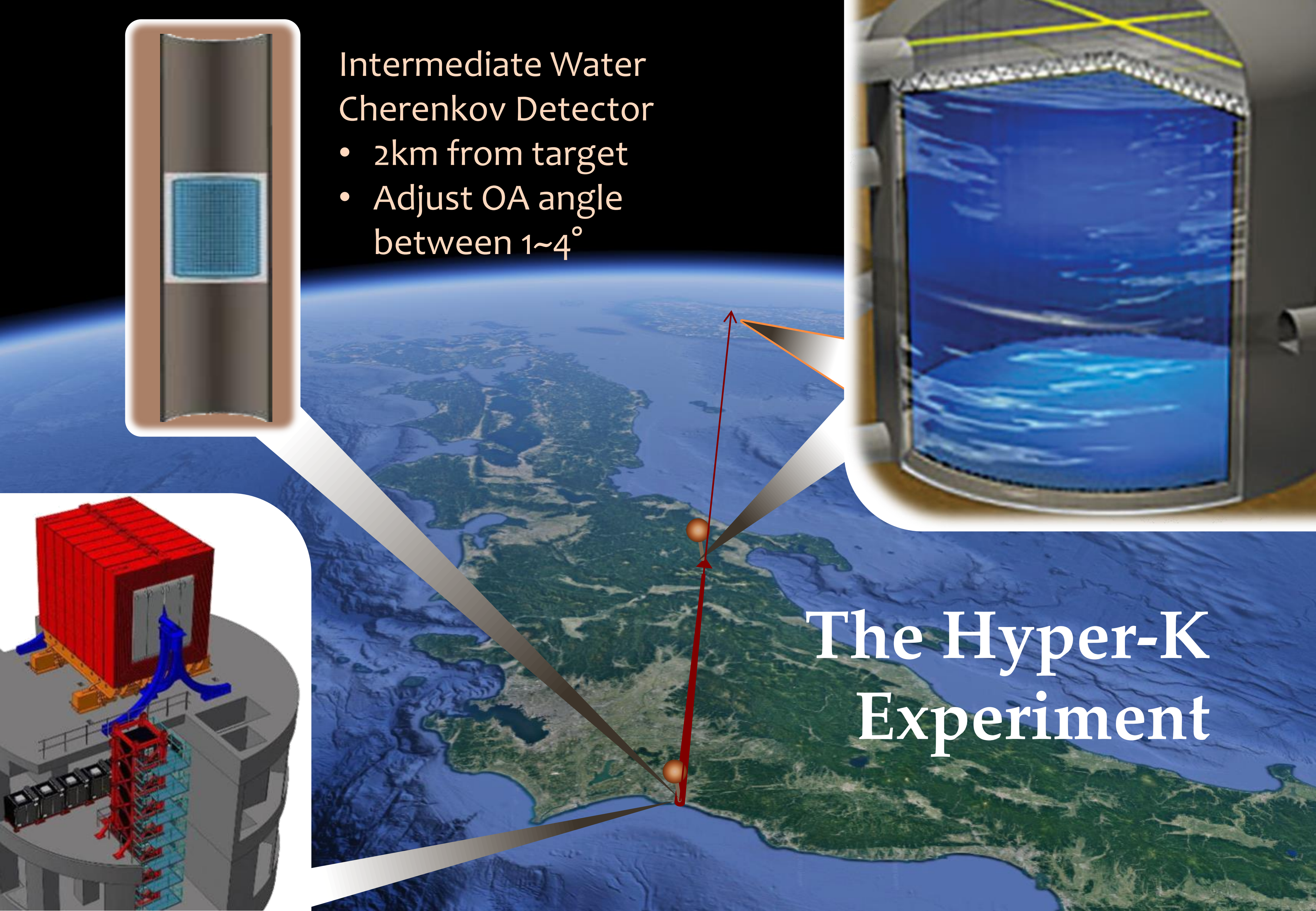
Muon neutrino beam produced at J-PARC on Japan’s east coast

- Directed ‘towards’ Super-Kamiokande, 295km away.
- Near Detector complex at 280m (ND280) to study beam and interactions



The T2K Experiment




Intermediate Water Cherenkov Detector
• 2km from target
• Adjust OA angle between 1~4°
The Hyper-K Experiment

University of Glasgow

Hyper-Kamiokande

Lorentz violation

Lorentz violation

Effect of the Lorentz violating term can be expressed with perturbation theory. Using $S_{ab} = e^{-\mathrm{i}H_{ab}t}$:

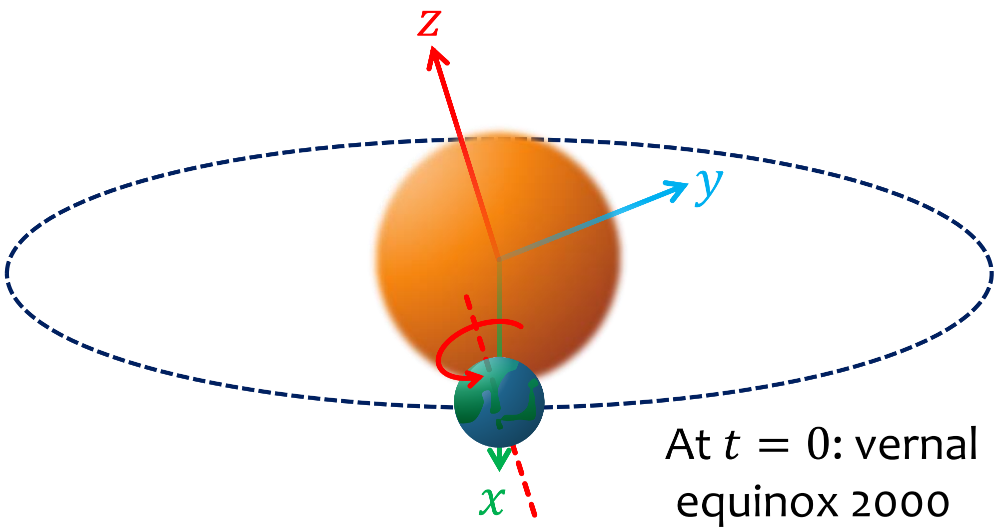
$$P(\nu_a \to \nu_b) \sim \left|S_{ab}^{(0)} + S_{ab}^{(1)} + S_{ab}^{(2)} + \cdots\right|^2$$
$$\sim \left|S_{ab}^{(0)}\right|^2 + 2\Re\mathrm{e}\left[\left(S_{ab}^{(0)}\right)^* S_{ab}^{(1)}\right] + 2\Re\mathrm{e}\left[\left(S_{ab}^{(0)}\right)^* S_{ab}^{(2)}\right] + \left|S_{ab}^{(1)}\right|^2 + \cdots$$

- 0th order → regular PMNS oscillations
- 1st order → LV-enhanced PMNS oscillations
  - Precision measurement at long baselines
- 2nd order → LV-PMNS + pure LV mixing
  - Smaller effect in p.t. but does not require PMNS oscillation to develop
  - Can test with near detectors: **INGRID, ND280+, Intermediate detector**

Lorentz Violation signatures

Encapsulated using the
Standard Model Extension (SME)

- LV manifests as fixed absolute 4-vectors &/or tensors
  - New flavour-changing operators can depend on these



- *Sidereal rotation* of earth will produce oscillations in time with base period $\boldsymbol{T_{\oplus} = 23^{h}56^{m}4.1^{s}}$

- Components parallel to $\boldsymbol{z}$ and $\boldsymbol{t}$ not probed by sidereal variation, but all are proportional to $\boldsymbol{L}$ and $\boldsymbol{L \times E}$
  - Enhancement at Korea site relative to Kamioka

Pure-LV analysis at T2K

T2K analysis uses INGRID near detector ⇒ 2nd order LV-only term

$$P^{\mathrm{SBL}}(\nu_a \to \nu_b) = L^2 \left| \begin{array}{l} \mathcal{C}_{ab} + \mathcal{A}_{ab} \sin \omega_\oplus t + \mathcal{A}'_{ab} \cos \omega_\oplus t \\ \quad + \mathcal{B}_{ab} \sin 2\omega_\oplus t + \mathcal{B}'_{ab} \cos 2\omega_\oplus t \end{array} \right|^2$$

- $\{\mathcal{C}, \mathcal{A}, \mathcal{B}\}$ specific to neutrino direction & energy: $p_\varepsilon = E_\nu(1, -\hat{\boldsymbol{n}})$
- SME coefficients are the vectors & tensors: $\{a_L^\varepsilon, c_L^{\varepsilon\delta}\}$
- Period depends on number of x & y components

Vector - $a_L^\varepsilon p_\varepsilon$:

$a_L^t, a_L^z \to \mathcal{C}$

$a_L^x, a_L^y \to \mathcal{A}, \mathcal{A}'$

Tensor - $c_L^{\varepsilon\delta} p_\varepsilon p_\delta$:

$E[c_L^{tt}, c_L^{tz}, c_L^{zz}] \to \mathcal{C}$

$E[c_L^{tx}, c_L^{ty}, c_L^{zx}, c_L^{zy}] \to \mathcal{A}, \mathcal{A}'$

$E[c_L^{xx}, c_L^{xy}, c_L^{yy}] \to \mathcal{B}, \mathcal{B}'$

Parameter extraction by T2K

Time dependent coefficients $\{\mathcal{A}, \mathcal{B}\}$ can be extracted using a FFT with frequencies up to $4\omega_{\oplus}$

- $\mathcal{C}$ is a normalisation, so poor sensitivity with only 1 detector.
- Don't attempt to fix t=0 ⇒ combine sine and cosine terms
- Null MC used to check significance of Fourier coefficients
  ↳ All consistent with no effect

Marginal Likelihood fit (with flat priors) used to report limits on the SME coefficients $\{a_L^{\varepsilon}, c_L^{\varepsilon\delta}\}$

Parameter limits from T2K are in the range:

$\mathcal{O}(10^{-20})$ for the $c_L^{\varepsilon\delta}$ and $\mathcal{O}(10^{-20})$ GeV for the a_L^{ε}

and currently statistics-limited.

Extensions with Hyper-K

Update the SBL analysis using the IWCD:

- Effect size increases by ~100 due to longer baseline ($\propto L^2$ dependence)

$$P^{\mathrm{SBL}}(\nu_a \to \nu_b) = L^2 \left| \begin{array}{l} \mathcal{C}_{ab} + \mathcal{A}_{ab} \sin \omega_\oplus t + \mathcal{A}'_{ab} \cos \omega_\oplus t \\ \quad + \mathcal{B}_{ab} \sin 2\omega_\oplus t + \mathcal{B}'_{ab} \cos 2\omega_\oplus t \end{array} \right|^2$$

Do a LBL (PMNS-LV interference term) search: (T2K could also do this)

- At Hyper-K (295km)
- At Korean detector (>1000km)
  - Perturbation size grows with L (same benefits as CP term)

$$\Delta P^{\mathrm{LBL}}(\nu_a \to \nu_b) = 2L \left(\begin{array}{l} (P_{\mathcal{C}})_{ab} + (P_{\mathcal{A}})_{ab} \sin \omega_\oplus t + (P'_{\mathcal{A}})_{ab} \cos \omega_\oplus t \\ \quad + (P_{\mathcal{B}})_{ab} \sin 2\omega_\oplus t + (P'_{\mathcal{B}})_{ab} \cos 2\omega_\oplus t \end{array} \right)$$

[Note: Because PMNS term is large, MINOS found LBL search was more sensitive]

Sterile neutrinos

Standard picture of ν oscillations

Oscillations are inevitable consequence of a non-diagonal propagation Hamiltonian [in the flavour basis]:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu} \boldsymbol{U_{PMNS}}\begin{pmatrix}\boldsymbol{0} & & \\ & \boldsymbol{\Delta m^2_{21}} & \\ & & \boldsymbol{\Delta m^2_{31}}\end{pmatrix}\boldsymbol{U^\dagger_{PMNS}} + \begin{pmatrix}\boldsymbol{V_e + V_A} & & \\ & \boldsymbol{V_A} & \\ & & \boldsymbol{V_A}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Vacuum term:

- Parameterise $U_{PMNS} = R(\theta_{23})U(\theta_{13},\delta_{CP})R(\theta_{12})$

Matter term:

- Coherent forward scattering (W, Z)
- $V_e, V_A \propto \rho$, the (number) density
- No $1/E_\nu$ factor $\Rightarrow$ dominates at high E_ν

Extension I: Sterile neutrinos

Can break unitarity of 3×3 PMNS matrix…

…but must preserve unitarity overall

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \vdots\end{pmatrix} = \left[\frac{1}{2E_\nu} U_{3+n}\begin{pmatrix}0 & & & \\ & \Delta m^2_{21} & & \\ & & \Delta m^2_{31} & \\ & & & \ddots\end{pmatrix} U^\dagger_{3+n} + \begin{pmatrix}V_e + V_A & & & \\ & V_A & & \\ & & V_A & \\ & & & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \vdots\end{pmatrix}$$

Add extra neutrinos

- LEP Z^0-pole data rules out low-mass neutrinos with weak charges
- If new mass(es) $m_4 \gtrsim m_e$ can use decays to normal neutrinos to measure mixing ⇒ **Heavy Neutral Leptons**
- If new masses $m_4 < m_e$ no decay signature, but can take part in oscillations ⇒ **Sterile Neutrinos**

Sterile neutrino signatures

Degrees of freedom of $3+n$ mixing matrix grows as n^2, so most experiments stick to $n=1$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix} & \boldsymbol{U_3} & & U_{e4}\\ & & & U_{\mu 4}\\ & & & U_{\tau 4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

Hard (U_{e4}, $U_{\mu 4}$, $U_{\tau 4}$)

Hardest (U_{s1}, U_{s2}, U_{s3})

Harder (U_{s4})

There are two approaches to sterile neutrino searches

Sterile neutrino signatures

Degrees of freedom of $3 + n$ mixing matrix grows as n^2, so most experiments stick to $n = 1$

Hard

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} & \boldsymbol{U_3} & & U_{e4} \\ & & & U_{\mu 4} \\ & & & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Hardest Harder

There are two approaches to sterile neutrino searches:

Look for evidence of the fourth *mass* state: Δm^2_{41}

- Large Δm^2_{41} can generate rapid oscillations among active flavours
- Search for short-baseline $\nu_\mu \to \nu_e,\ \nu_\mu \to \nu_\mu,\ \nu_e \to \nu_e$ signals

Sterile neutrino signatures

Degrees of freedom of $3+n$ mixing matrix grows as n^2, so most experiments stick to $n = 1$

Hard

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} & \boldsymbol{U_3} & & U_{e4} \\ & & & U_{\mu 4} \\ & & & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Hardest Harder

There are two approaches to sterile neutrino searches:

Look for evidence of the fourth *mass* state: Δm^2_{41}

Look for evidence a *flavour* state with no NC interactions

- Depletion of NC events at long baselines
- Distortions of $\nu_\mu \to \nu_\mu$ due to matter effects

Sterile neutrino signatures

Degrees of freedom of $3+n$ mixing matrix grows as n^2, so most experiments stick to $n=1$

Hard

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} & \boldsymbol{U_3} & & U_{e4} \\ & & & U_{\mu 4} \\ & & & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Hardest Harder

There are two approaches to sterile neutrino searches:

Look for evidence of the fourth *mass* state: Δm^2_{41}

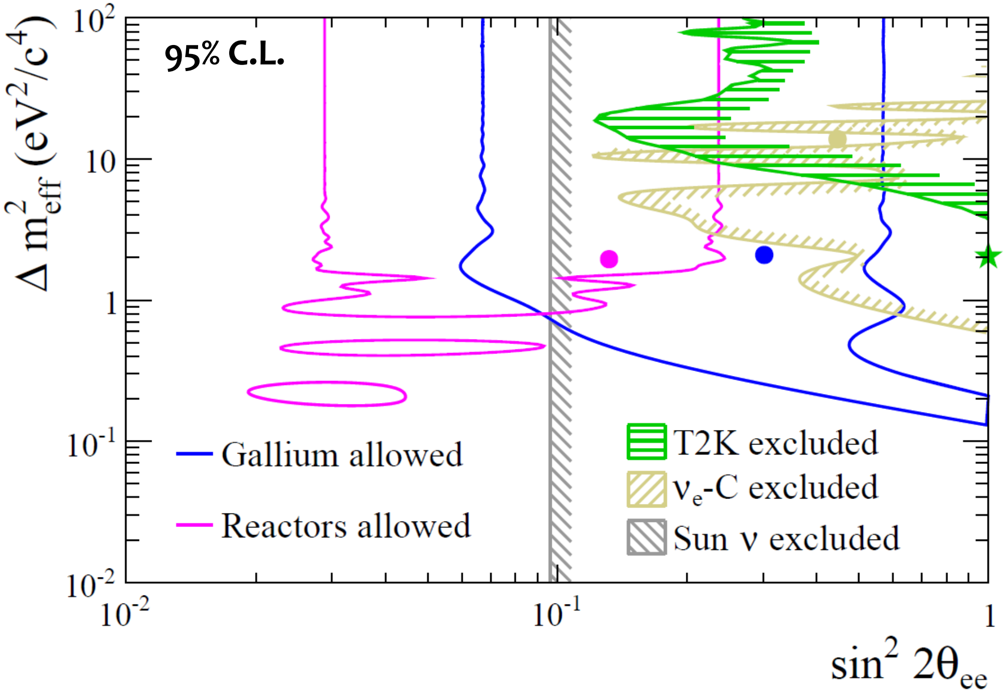
Look for evidence a *flavour* state with no NC interactions

Hyper-Kamiokande can pursue both approaches

Existing analyses at T2K

ND280 Analysis

Phys. Rev. D 91 051102 (2015)

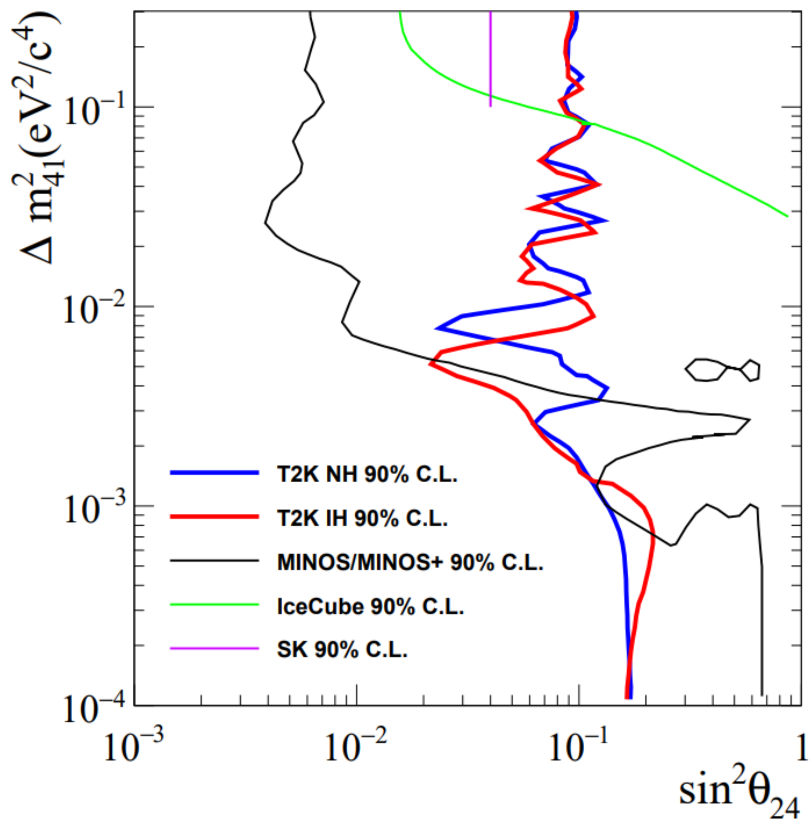


Constrain flux with ν_μ; look for ν_e disappearance.

- Mostly sensitive to $(\Delta m^2_{41}, U_{e4})$

SK Analysis

Phys. Rev. D 99 071103 (2019)



Combination of CC and NC channels, sensitive to $(\Delta m^2_{41}, U_{\mu 4})$

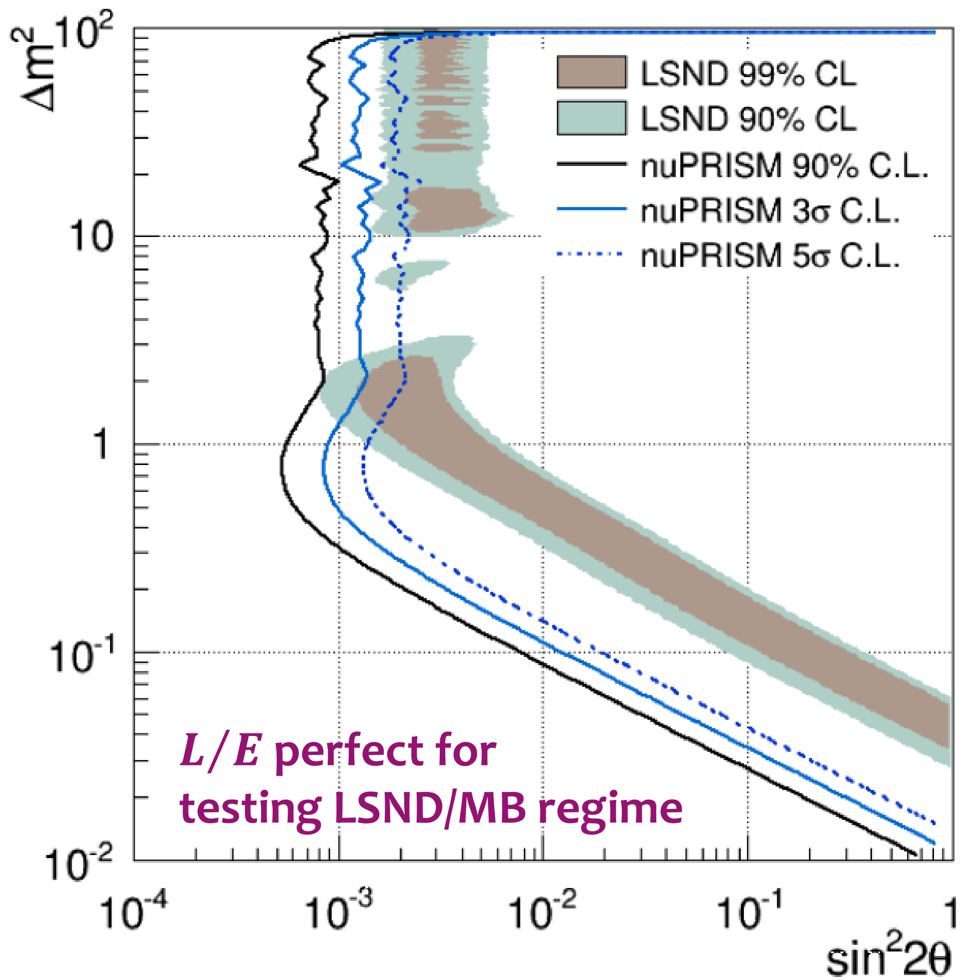
Sterile analyses with Hyper-K

Can simply extend/improve on T2K analyses, with more statistics and improved systematic controls.

- Possibly do $P(\nu_\mu \rightarrow \nu_\mu)$ as well
- Also update SK search for ν_s with atmospheric neutrinos
  - Uses active-sterile matter effect in the core.

More interesting is prospects from IWCD at 2km

- **Via $\nu_\mu \rightarrow \nu_e$ channel**
- Still have ND280 constraint
- Use OA variation to constrain BGs



Non-standard interactions

Extension II: Non-Standard Interactions

Hyper-Kamiokande

Oscillations are inevitable consequence of a non-diagonal propagation Hamiltonian [in the flavour basis]:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu}\; U_{PMNS}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{PMNS} + \boldsymbol{V_e}\begin{pmatrix}\boldsymbol{1+\varepsilon_{ee}} & \boldsymbol{\varepsilon_{e\mu}} & \boldsymbol{\varepsilon_{e\tau}}\\ \boldsymbol{\varepsilon^*_{e\mu}} & \boldsymbol{\varepsilon_{\mu\mu}} & \boldsymbol{\varepsilon_{\mu\tau}}\\ \boldsymbol{\varepsilon^*_{e\tau}} & \boldsymbol{\varepsilon^*_{e\mu}} & \boldsymbol{\varepsilon_{\tau\tau}}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Non-standard Interaction matter term:

- New contributions in many models of neutrino mass generation
- Can have non-trivial flavour structure
- Parametrise as fractions of standard matter potential $V_e = \sqrt{2}G_{\mathrm{F}}\rho$

Existing limits on element magnitude

Limits set by global analyses are both non-Gaussian and quite variable, but are typically $\mathcal{O}(0.1) \sim \mathcal{O}(1)$

$$V_{\mathrm{NSI}} \simeq V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

90% limits from NPB 936, (2018) 91:
[As quoted in SK Kang plenary talk]

$$\left|\varepsilon_{ee}^{\oplus}\right| \lesssim 4.2 \quad \left|\varepsilon_{e\mu}^{\oplus}\right| \lesssim 0.33 \quad \left|\varepsilon_{e\tau}^{\oplus}\right| \lesssim 3.0$$

$$\varepsilon_{\mu\mu}^{\oplus} \lesssim 0.07 \quad \left|\varepsilon_{\mu\tau}^{\oplus}\right| \lesssim 0.33$$

$$\left|\varepsilon_{\tau\tau}^{\oplus}\right| \lesssim 21$$

[I didn't work out how all $\varepsilon_{\alpha\alpha} \neq 0$…]

Existing limits on element magnitude

Limits set by global analyses are both non-Gaussian and quite variable, but are typically $\mathcal{O}(0.1) \sim \mathcal{O}(1)$

$$V_{\mathrm{NSI}} \simeq V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Approx-2σ limits from JHEP 06 (2019) 055:
[Global fit; the strongest limits I found]

$$|\varepsilon_{ee}^{\oplus}| \lesssim 0.55 \quad |\varepsilon_{e\mu}^{\oplus}| \lesssim 0.17 \quad |\varepsilon_{e\tau}^{\oplus}| \lesssim 0.4$$

$$\varepsilon_{\mu\mu}^{\oplus} \equiv 0 \quad |\varepsilon_{\mu\tau}^{\oplus}| \lesssim 0.03$$

$$|\varepsilon_{\tau\tau}^{\oplus}| \lesssim 0.5$$

[As with normal matter effect, trace of matrix is not measurable, so set $\varepsilon_{\mu\mu} \equiv 0$]

Limits from T2HK/T2HKK

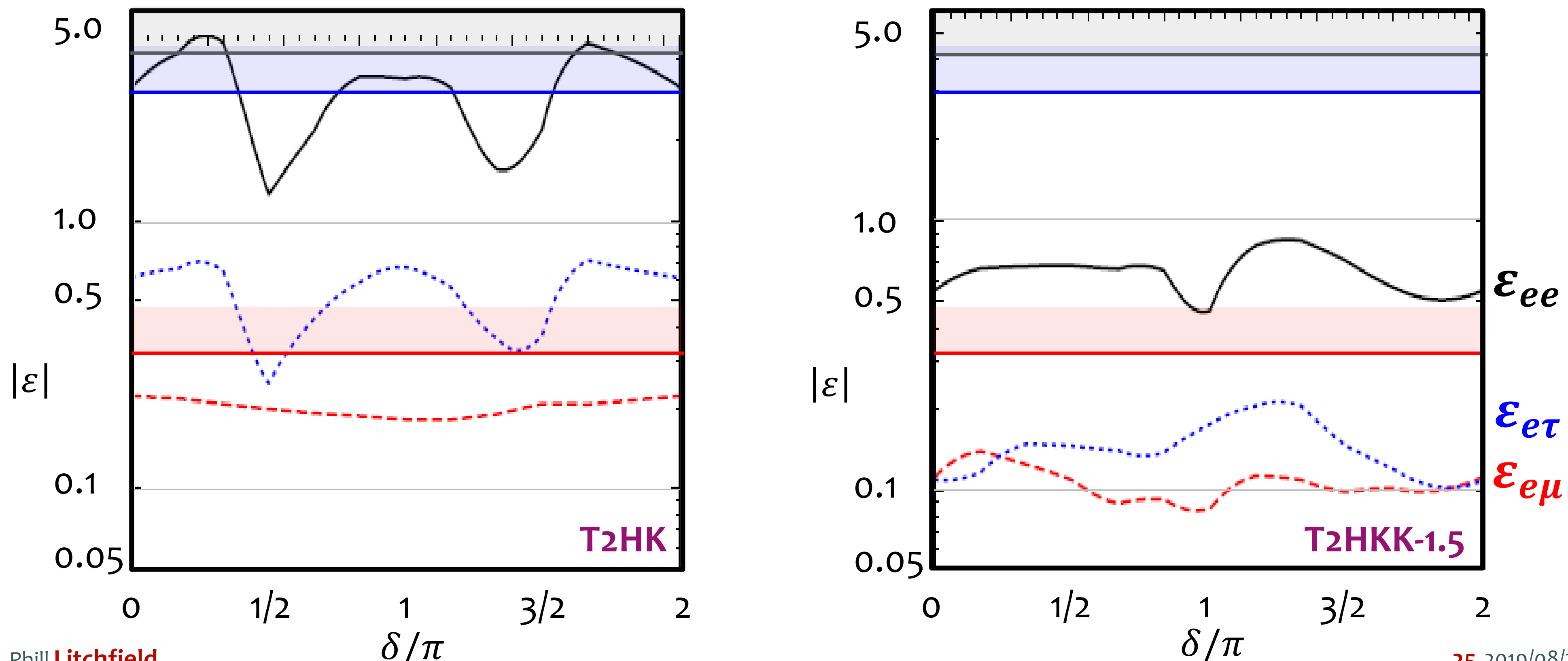
JHEP 01 (2017) 071

- ν_μ disappearance improves $\varepsilon_{\tau\tau}$:

  ~21 → 0.3~0.4

- Limits ε_{ex} row from ν_e appearance (below):

$$V_{\mathrm{NSI}} \simeq V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$



Independence of phase effects

Another effect:

NSI can resemble the CP-violation signal that we are looking for!

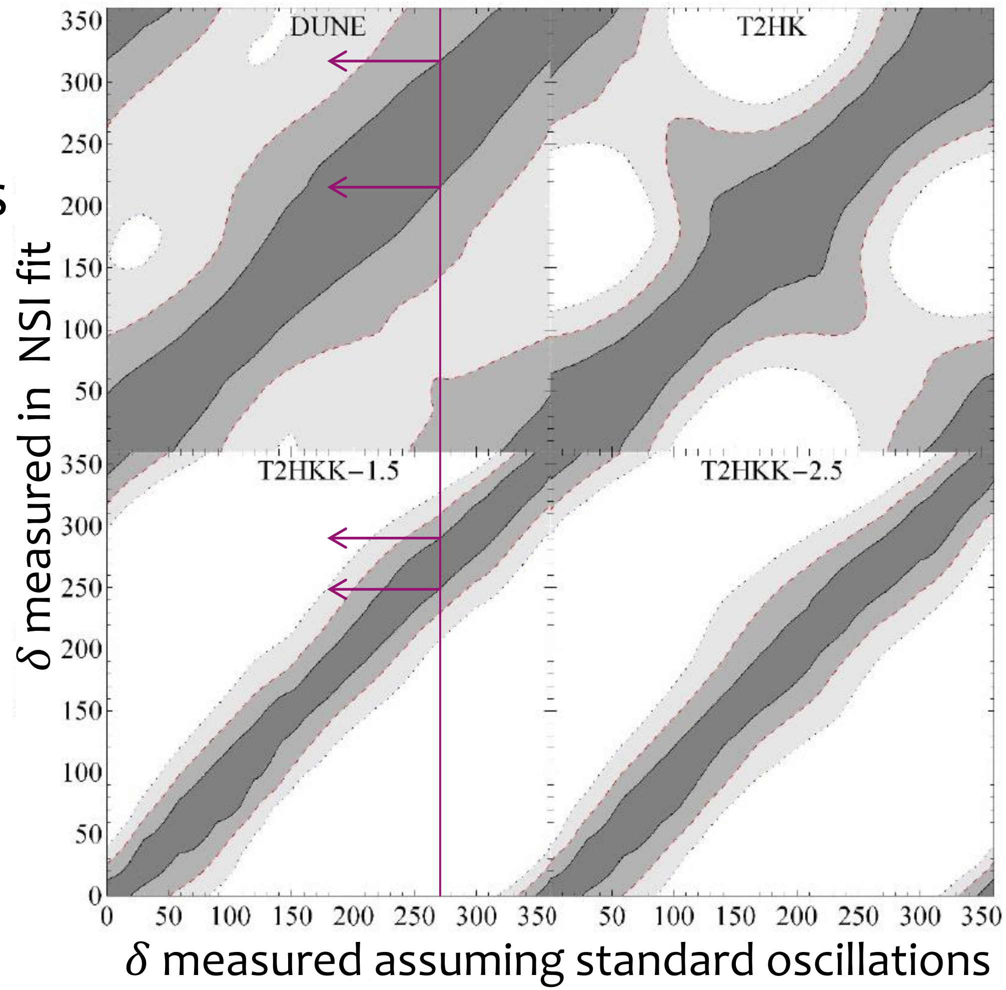
More specifically:

Some NSI parameter combinations are near-degenerate with normal mixing.

↳ **We couldn't discover NSI, but we would still get δ_{CP} wrong.**

Also analysed in JHEP 01 (2017) 071:

- T2HKK only exp't with any good control of degeneracy: $\delta_{NSI} \sim \delta$



Summary

Shown 3 BSM models that can be investigated Hyper-K ⊗ J-PARC beam

	Lorentz Violation	Sterile Neutrinos	Non-standard interactions
Studied by T2K?	✓	✓	
Systematic limit	Not yet	Same as 3ν	
Hyper-K design study?		✓ (SBL)	✓
Prospects and notes	Larger effect at IWCD	IWCD near-perfect LSND/MB test	Order of magnitude improvement
	LBL analysis	Unify SBL and LBL analyses	T2HKK only exp't with robust result on δ_{CP}
	4 baselines can break degeneracies	Not yet studied for T2HKK	

Plenty more! Non-beam, non-ν models not covered:

Nucleon decay, DM, Heavy neutral leptons, …

Beyond Standard... Maps?

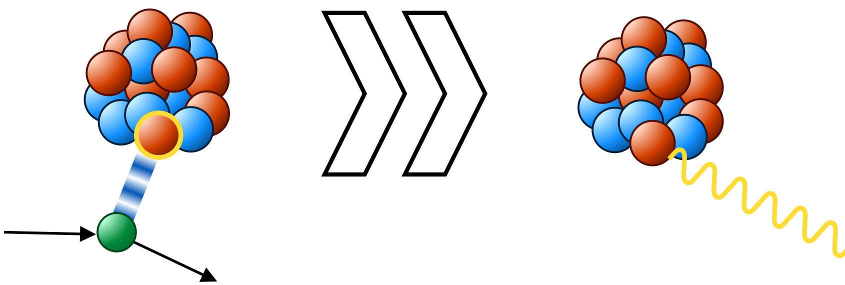
Report on Russia Today, 2019/08/19

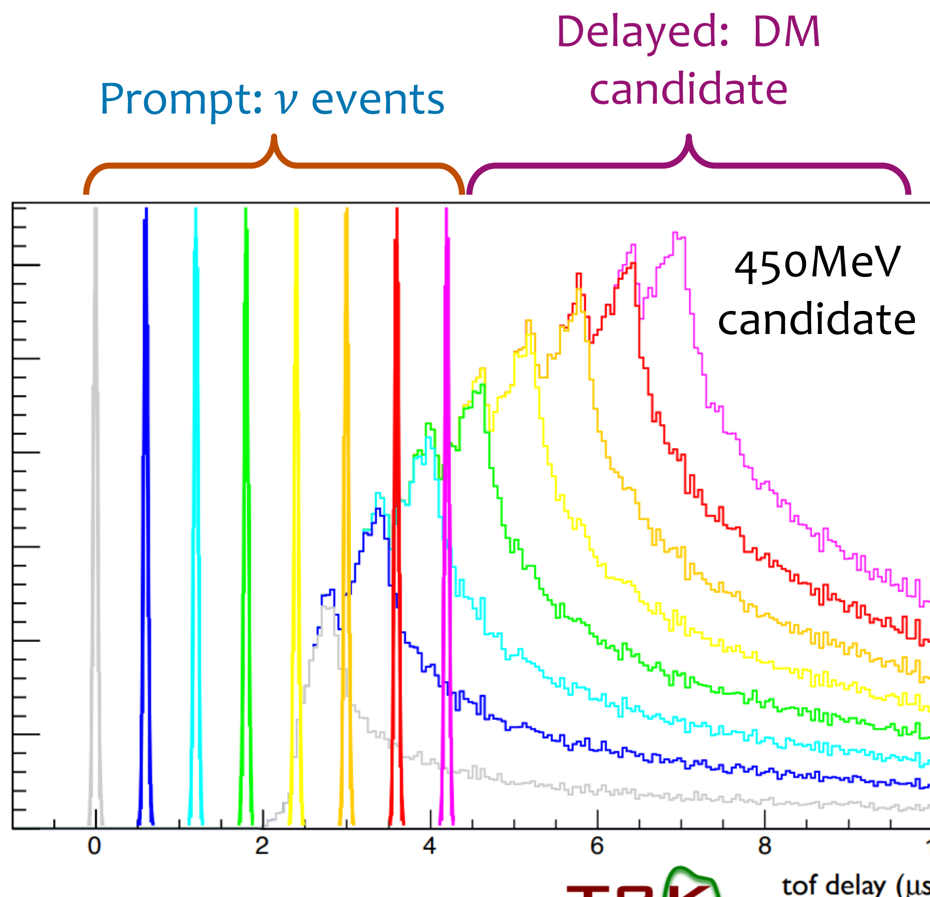
Extras

Dark matter searches

Neutrino beams are produced in high-intensity proton collisions.

- Includes DM candidates, provided they can be produce in a 30 GeV p beam.
- Can search for low mass ($m \lesssim 500\text{MeV}$) DM candidates





- Detect *delayed* de-excitation photon From oxygen $p_{3/2}$ is dominant (6MeV)
- Analysis being developed for T2K

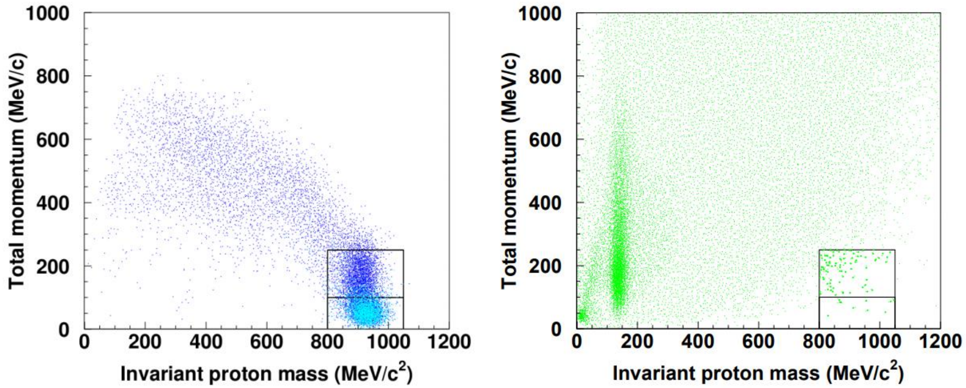


FIG. 161. Reconstructed invariant mass and total momentum distributions for the $p \to e^+\pi^0$ MC (left) and atmospheric neutrino MC (right) after all event selections except the cuts on these variables. The final signal regions are shown by two black boxes in the plane. In the signal plot decays from bound and free protons have been separated by color, dark blue and cyan respectively. Background events have been generated for a 45 Mton·year exposure and those falling in the signal regions have been enlarged for visibility.

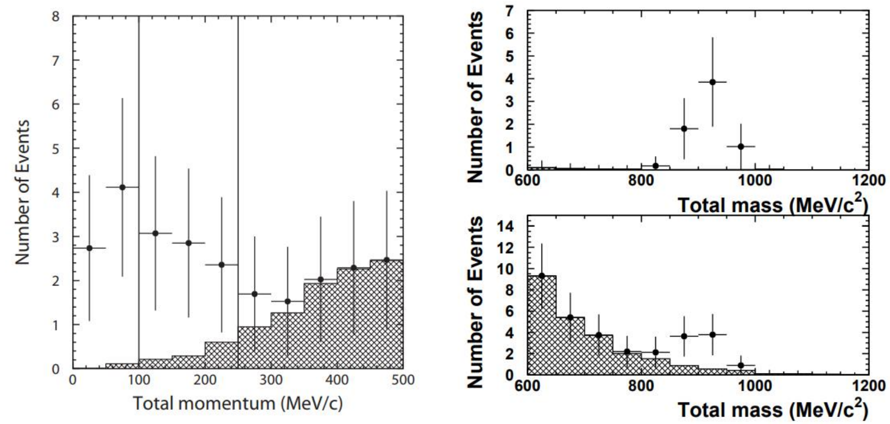
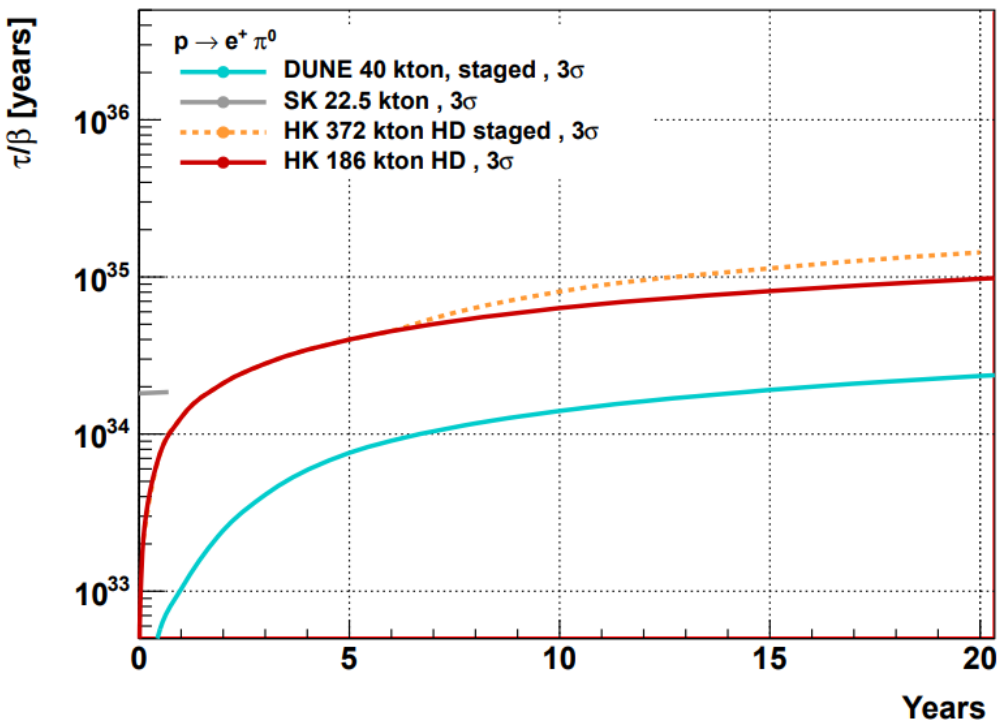


FIG. 162. Total momentum distribution of events passing all steps of the $p \to e^+\pi^0$ event selection except the momentum cut after a 10 year exposure of a single Hyper-K tank (left). Reconstructed invariant mass distribution of events passing all steps of the $p \to e^+\pi^0$ event selection except the invariant mass cut after a 10 year exposure of a single Hyper-K tank (right). The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, 1.7×10^{34} years, just beyond current Super-K limits. The free and bound proton-enhanced bins are shown by the lines in the left plot, and are the upper and lower panels of the right plot.

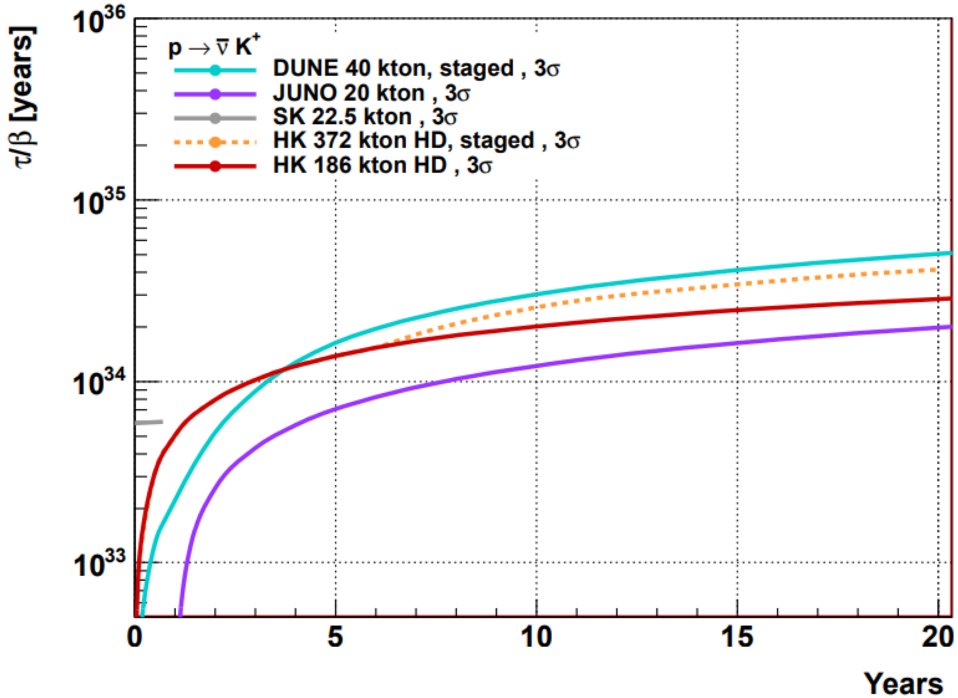
Proton decay ($e^+\pi^0$)



[…]-Kamiokande flagship channel

FIG. 163. Comparison of the 3 σ $p \to e^+\pi^0$ discovery potential as a function of year Hyper-K (red solid) assuming a single tank as well as that of the 40 kton liquid argon detector DUNE (cyan solid) following [176]. In the orange dashed line an additional Hyper-K tank is assumed to come online six years after the start of the experiment. Super-K's discovery potential in 2026 assuming 23 years of data is also shown.

Proton decay ($\bar{\nu}$ K$^+$)



Dune CDR [1512.06148]
Assumes ~97% efficiency
Reconstruction performance not yet demonstrated (~25%)

FIG. 167. Comparison of the 3 σ $p \to \bar{\nu}K^+$ discovery potential as a function of year for the Hyper-K as well as that of the 40 kton DUNE detector (cyan solid) based on [176] and the 20 kton JUNO detector based on [39]. The red line denotes a single Hyper-K tank, while the orange line shows the expectation when a second tank comes online after six years. The expected discovery potential for Super-K by 2026 assuming 23 years of data is also shown.

c.f. Most aggressive limits

- Disappearance improves $\varepsilon_{\tau\tau}$:
  ~0.5 → 0.3~0.4
- Limits ε_{ex} row from ν_e appearance (below):

$$V_{\rm NSI} \simeq V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

JHEP 01 (2017) 071