New Physics Opportunities with Hyper-K and J-PARC Neutrino Beam

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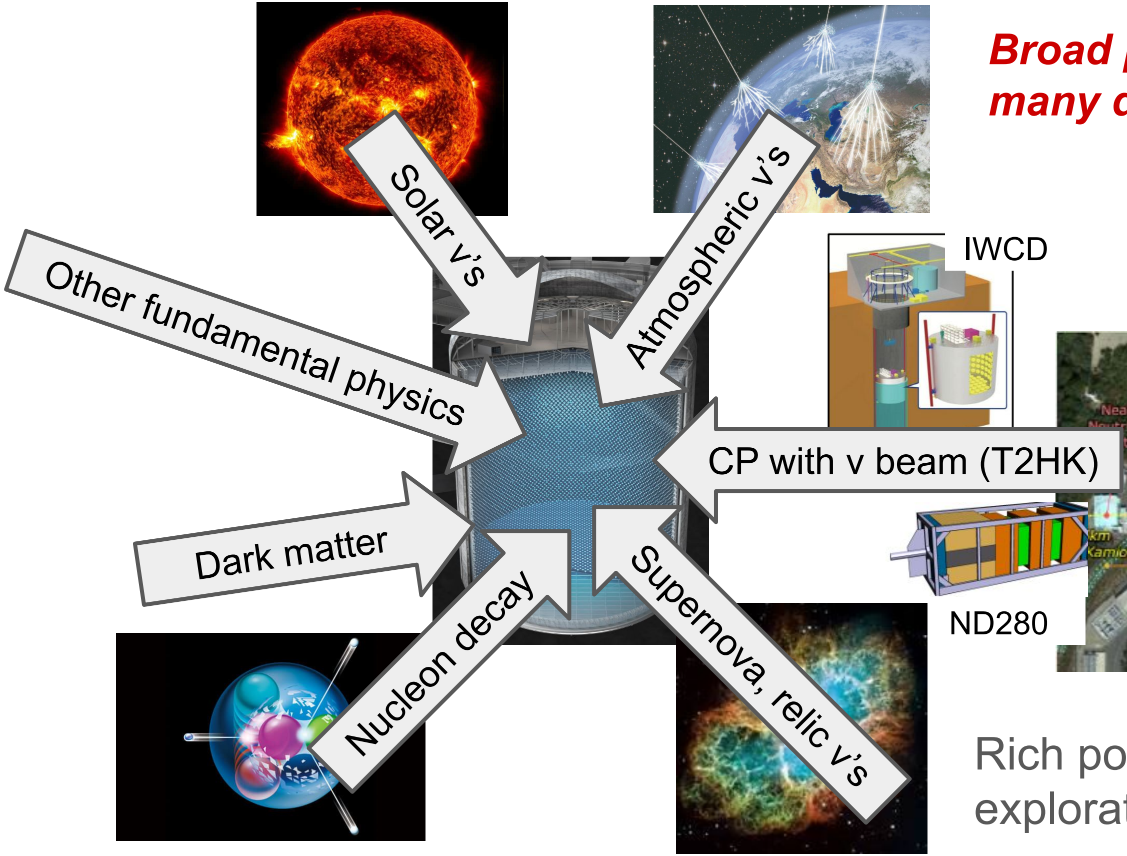
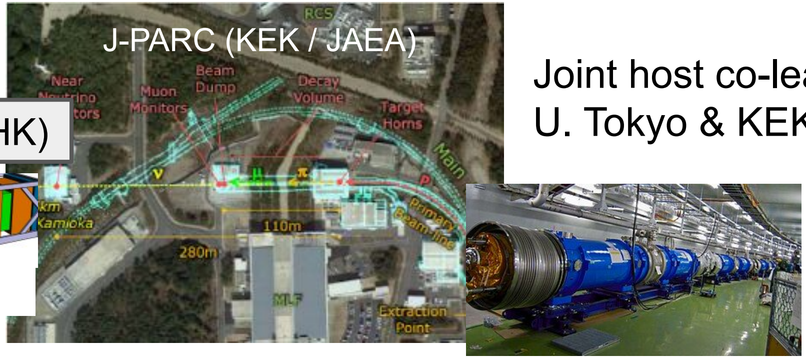
Hyper-K: Spectacular Multipurpose Discovery Experiment



Broad physics program beyond oscillations, many discovery opportunities

2020 - Construction started
2028 - Operations begin



Joint host co-lead
U. Tokyo & KEK

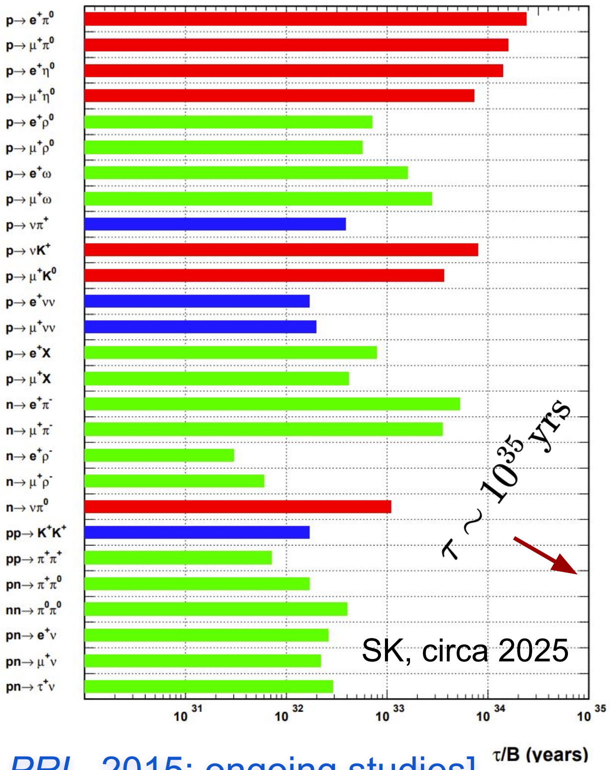
Rich potential for new fundamental physics exploration, complementary to CP violation

Novel Nucleon Decays in Uncharted Territory

- Nucleon decay and related searches enable unique tests of fundamental physics, unification theories and beyond (review [Takhistov, *Encyclopedia of Particle Physics*, 2026])

- Super-K tested 25+ baryon number-violating processes
  → no evidence, set many pioneering and leading limits
  → many processes remain [Heeck, Takhistov, 2020]

- Hyper-K enables probing lifetimes ~10^{35} yrs for channels like $p \to e^+\pi^0$, directly testing fundamental energy scales
  → difficult for any other existing or upcoming experiment



However ….

almost all existing searches assume Standard Model final states, with exceptions such as $p \to e^+X$ [Takhistov+ (SK), *PRL*, 2015; ongoing studies]

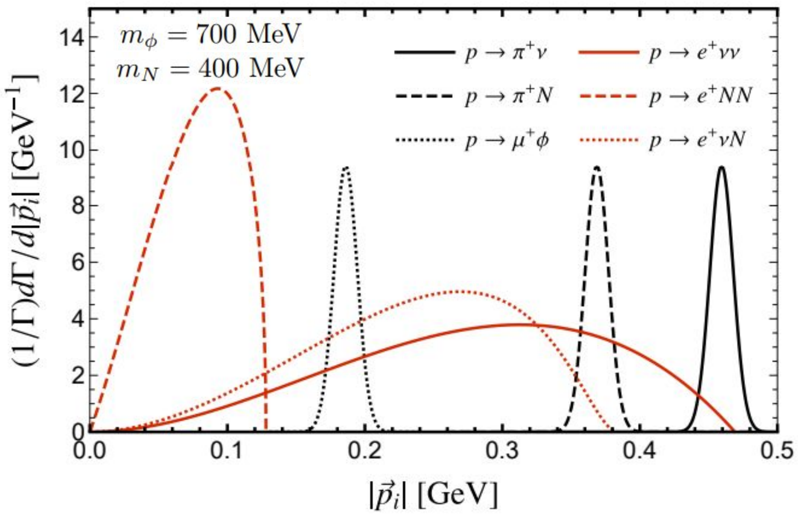
This assumption can be completely wrong

Non-canonical Nucleon Decays and Novel Particles

$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$(1,1)$	6	$p(n) \to \pi^{+(0)} N$	sterile neutrinos
$(1,-1)$	7	$n \to N\gamma$ $p(n) \to \pi^{+(0)} N\gamma$	sterile neutrinos
$(1,1)$	7	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$(1,1)$	7	$n \to \nu X$ $p(n) \to \nu\pi^{+(0)} X$ $n \to e^+\pi^- X$	dark photons
$(1,1)$	8	$n \to \nu\phi$ $n \to e^+\pi^-\phi$	dark scalars, majorons
$(1,1)$	8	$n \to \nu a$ $p(n) \to e^+\pi^{0(-)} a$ $p(n) \to e^+\pi^{0(-)} a$	axion-like particles
$(1,-1)$	8	$n \to Na$ $p(n) \to \pi^{+(0)} Na$	axion-like particles with sterile neutrinos
$(1,1)$	9	$p \to e^+\nu N$ $n \to e^+e^- N$	sterile neutrinos
$(1,3)$	9	$p \to e^+NN$	sterile neutrino

A new way to probe light (~ sub-GeV) fields

dark photons, sterile neutrinos, axion-like particles and more

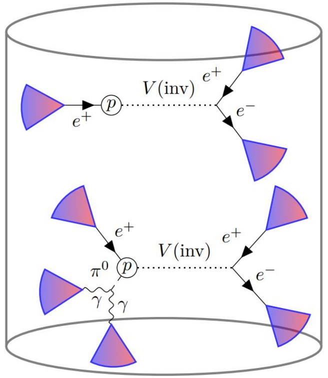


Conventional analyses can misidentify or completely miss

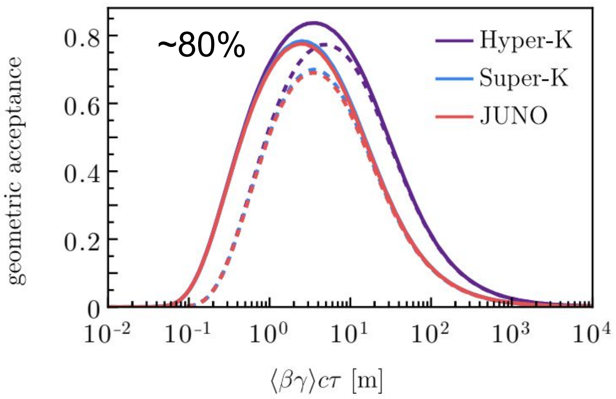
general framework [Fridell, Hati, Takhistov, *PRD Lett.*, 2024]

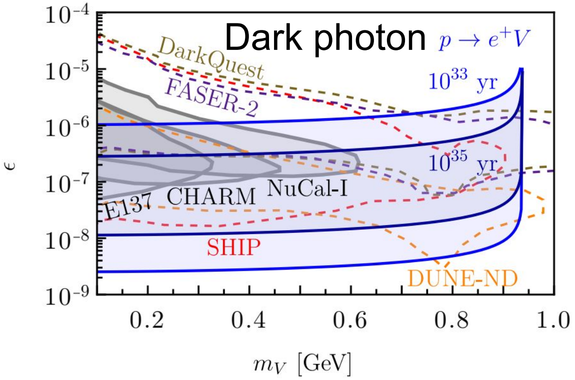
(specific cases [Davoudiasl, 2015; Formal+, 2018; McKeen+, 2018; Helo+, 2018….])

Echoes of Nucleon Decays with Long-Lived Particles

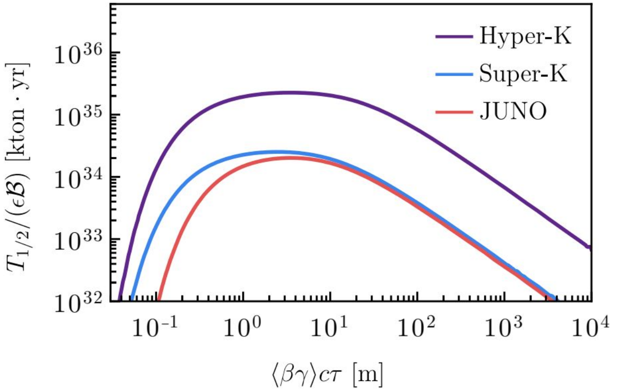


- Long-lived particles appear in many theories, naturally lead to distinct signatures
- **Novel nucleon decay "echo" observables:** Prompt signal + displaced vertex echo → highly distinctive topologies, challenging for atmospheric backgrounds to mimic





- Geometric acceptance ~80% over broad decay length range → excellent in Hyper-K
- Probes dark photon/Z' at small couplings, complementary and beyond leading dedicated searches

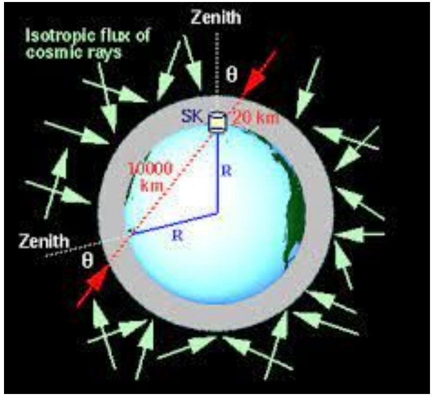


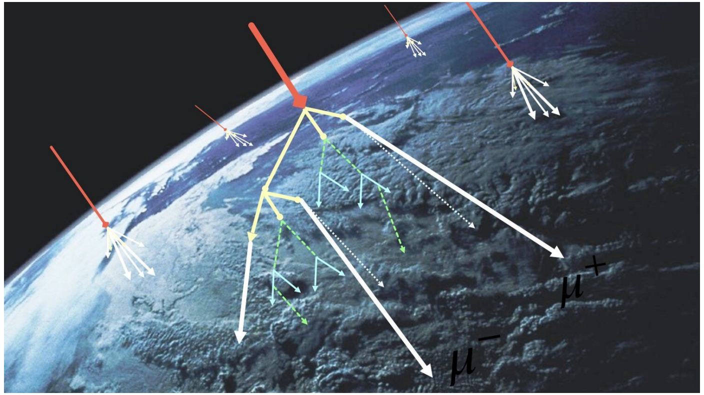
[Adolf, Hati, Hirsch, Takhistov, (2026) 2605.21583]

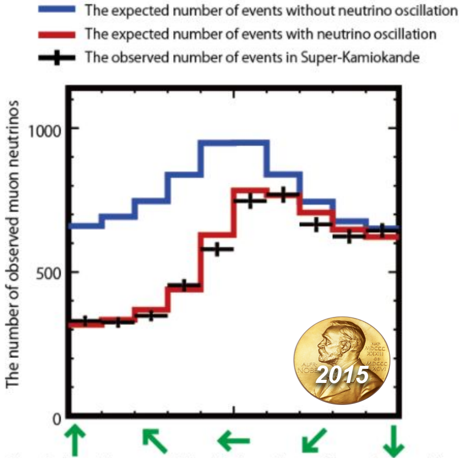
*** EFT, UV completions constructed*

Going Beyond Super-K Discovery of Neutrino Oscillations

- Cosmic rays isotropically bombarding atmosphere lead to copious production of neutrinos
  → fundamental discovery of neutrino oscillations [Fukuda+ (SK), *PRL*, 1998]

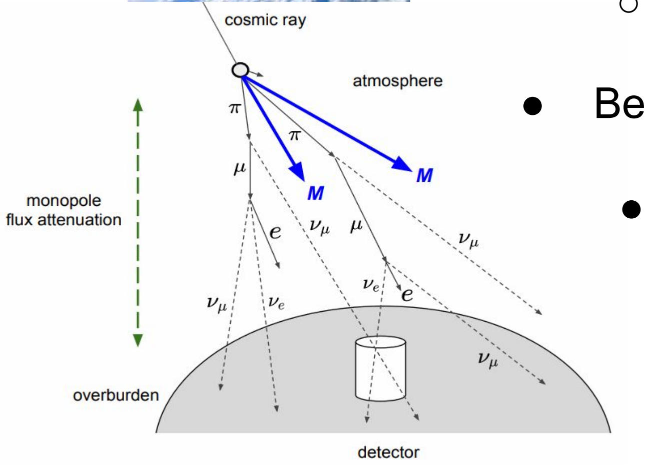




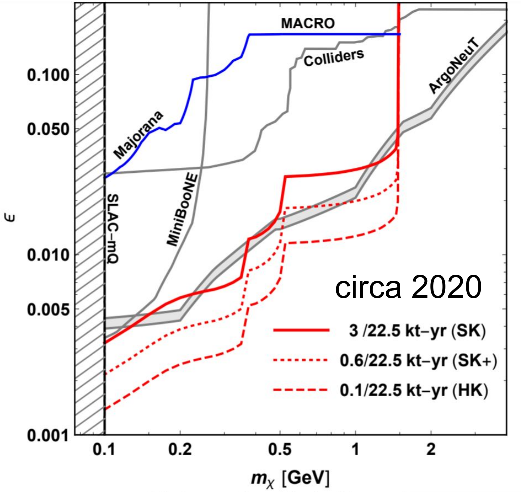


- The same atmospheric production enables searches for new fundamental effects in oscillations (e.g. LIV) and sources novel constituents beyond Standard Model

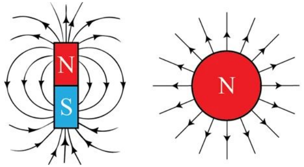
Atmospheric Collider for New Physics



- Production same as for atmospheric ν's
  - Key features include
    - persistent "beam", always ON
    - broad energy spectrum
  - Benefit from HK's enormous volume
    - Excellent source for millicharge particles [Plestid, Takhistov+, *PRD*, 2020] + many follow-ups
      - Complementary to J-PARC searches, distinct production, energies, signatures



- Can source light magnetic monopoles [Iguro, Plestid, Takhistov, *PRL*, 2022]



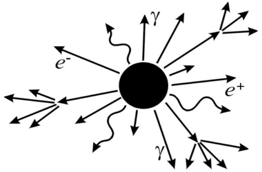
Hyper-K is highly sensitive for probing unusually charged particles and objects

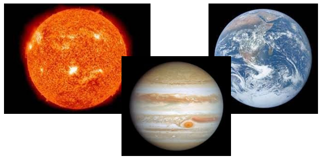
Broad Dark Matter Program at Hyper-K (Direct, Indirect)

Dark matter constitutes ~85% of all matter in the Universe, what is it and how to probe?

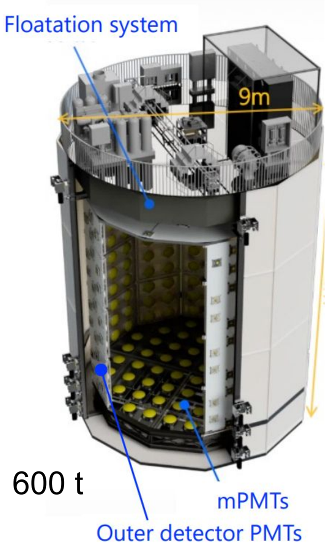
Dark Matter	Dark Matter Mass	(Super) Hyper-Kamiokande Signatures
PBH evaporation to ν (GC, halo)	$M_{\rm PBH} \lesssim 10^{15}$ g	ν scattering, diffuse ν background
Q-ball DM (catalysis)	$M_Q \gtrsim 10^{12} - 10^{16}$ GeV	catalyzed nucleon decay
Baryon-charged DM (e.g. hylogenesis)	$m_\chi \sim$ GeV–TeV	scattering-induced nucleon decay
DM annihilation (GC)	$m_\chi \sim 10$ MeV–100 GeV	ν scattering
DM annihilation (Earth, Sun, Jupiter capture)	$m_\chi \sim 1 - 10^3$ GeV	ν scattering
Cosmic-ray upscattered (boosted) DM	$m_\chi \sim$ MeV–GeV	ν scattering
Millicharged DM (dark cosmic rays)	$m_\chi \sim 1$–10^3 GeV	ionization, ν-like e-scattering
Dark stars (powered by DM annihilation)	$m_\chi \sim 1$–10^5 GeV	energetic diffuse ν background

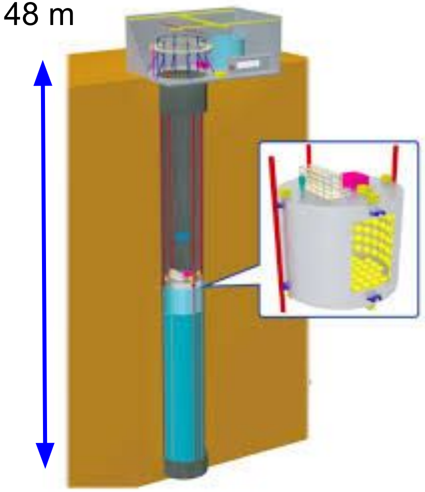
- Remarkable breadth spanning particle physics, astrophysics and cosmology

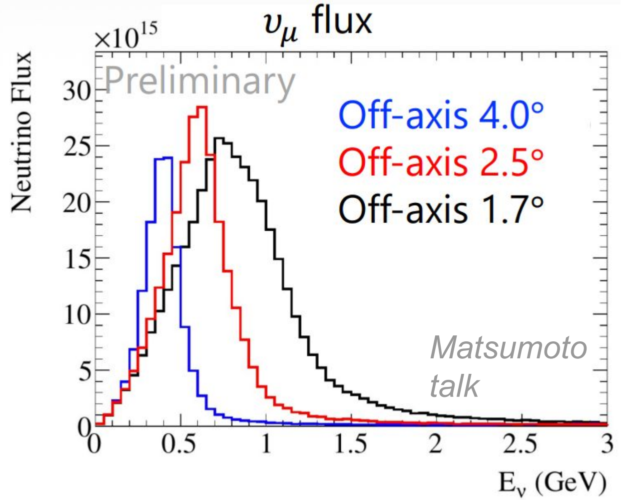




IWCD @ J-PARC as Uniquely Tunable Neutrino Detector







- Use powerful J-PARC beam 500 kW (2019) → 1.3 MW

- Enables same beam, detector but different energy spectra, correlated systematics

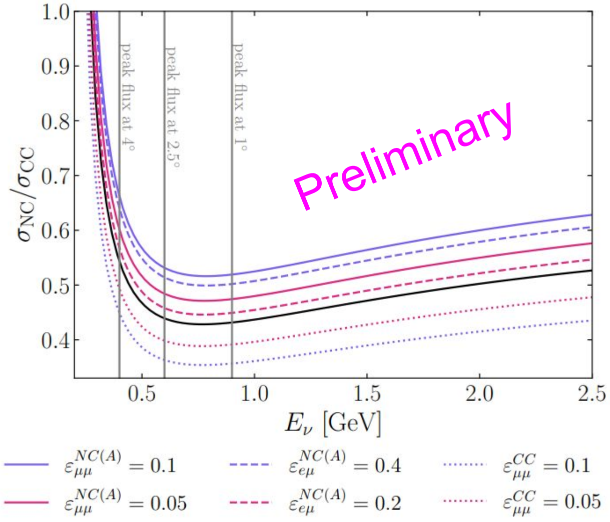
Movable detector enables distinct classes of new physics observables

New Physics at IWCD: Observables and Opportunities

- Movable IWCD enables unique opportunities to test energy-dependent effects
- *How?* Use ratios of measurements as new physics observables across detector positions
  → suppress common-mode uncertainties, normalization
- Strategy illustrated by NSI

NC NSI $$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P f)$$

CC NSI $$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}\gamma_\mu P f)$$



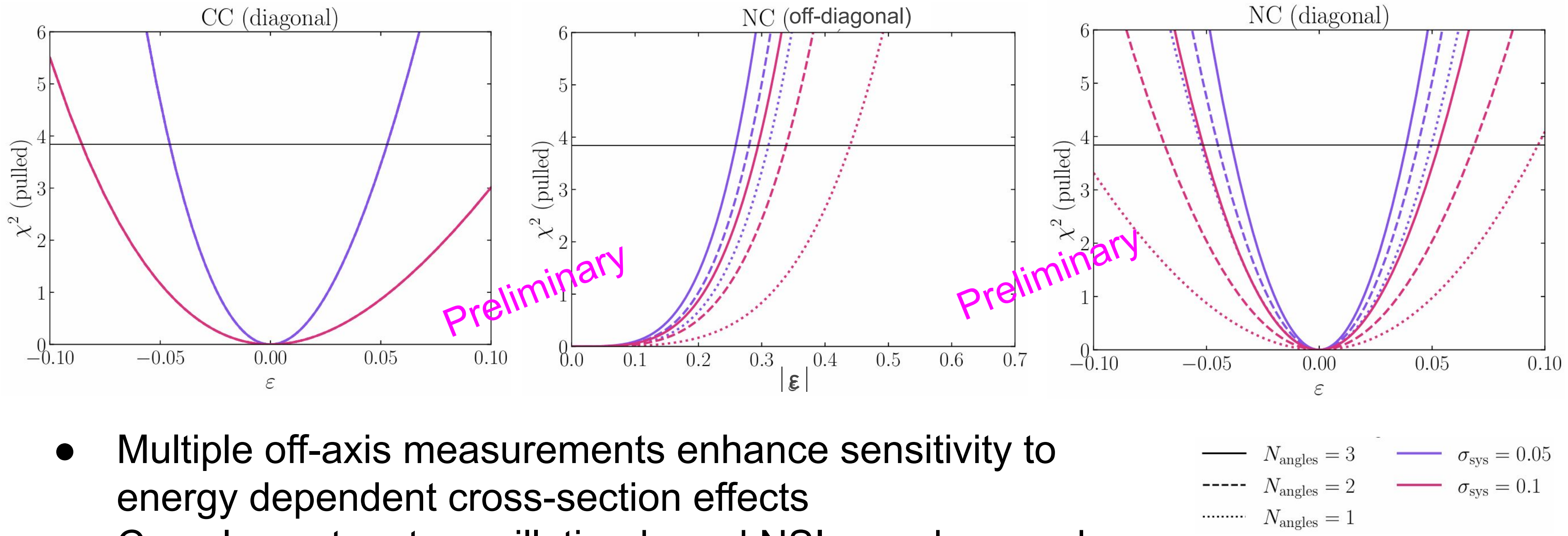
- Interaction new physics modify NC/CC spectral behavior

$$R(\theta) = \frac{N_{\rm NCQE}(\theta)}{N_{\rm CCQE}(\theta)} \sim \frac{\int dE_\nu\, \sigma_{\rm NC}(E_\nu)\, \Phi^\theta(E_\nu)}{\int dE_\nu\, \sigma_{\rm CC}(E_\nu)\, \Phi^\theta(E_\nu)}$$

- IWCD enables correlated multi-angle NC/CC interaction ratio measurements

[Schwemberger, Takhistov, *in preparation*]

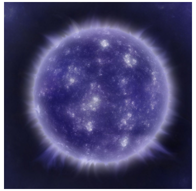
NSI with Movable IWCD: Multi-Angle Sensitivity



- Multiple off-axis measurements enhance sensitivity to energy dependent cross-section effects
- Complementary to oscillation-based NSI searches, probe interaction effects rather than propagation effects

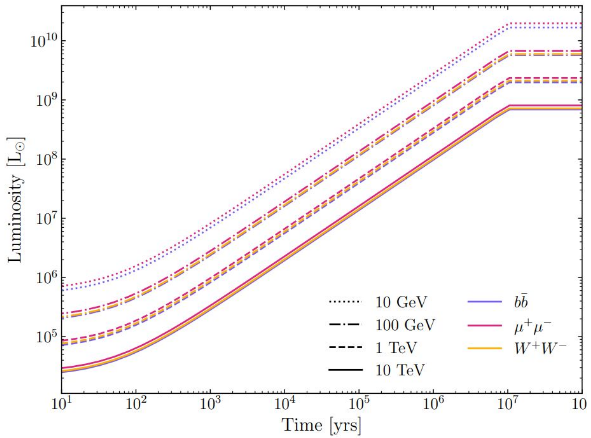
[Schwemberger, Takhistov, *in preparation*]

HK as Cosmology Messenger Observatory: Earliest (Dark) Stars

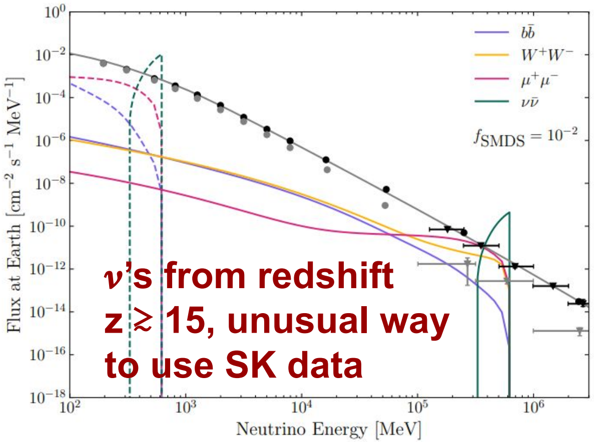


- Earliest stars could be “dark stars” fueled by DM annihilation heating instead of nuclear fusion [Spolyar, Freese, Gondolo, *PRL* (2008)]
- Dark stars can be significantly more massive ($\sim 10^6 M_\odot$) than Pop III stars
- Upon collapse → early massive seeds for galactic supermassive black holes
- Possible candidate interpretations in JWST, redshifts z ~ 11-14 [Ilie, Paulin, Freese, *PNAS* (2023)]

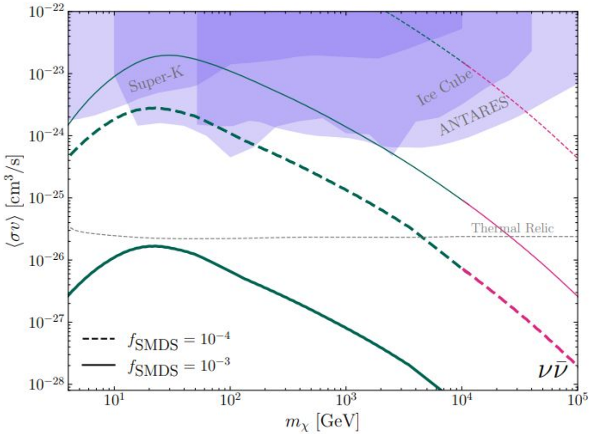
Dark star luminosity



SK neutrino flux



Dark matter annihilation



$$L_{\rm DM} \simeq (1-f_\nu)\int_0^R dr 4\pi r^2 \frac{\langle\sigma v\rangle \rho_\chi^2}{m_\chi}$$

[Schwemberger, Takhistov, *ApJ. Lett.*, 2025;
Manno, Schwemberger, Takhistov, (2025) 2512.04061]

*** consistent with JWST*

Hyper-K and J-PARC: Discovery Platform Across Signal Classes

Signal Class	Source	Examples
Intrinsic and induced processes	Inside detector volume	Non-canonical nucleon decays, LLP echo signatures, Q-ball catalysis
Controlled beam flux	J-PARC accelerator	NSI at IWCD, dark photons, heavy neutral leptons
Natural continuous flux	Atmospheric cosmic rays	Millicharged particles, monopoles, LIV, sterile ν
Diffuse (astro-, cosmo-) flux	Astrophysical, cosmological	Dark star neutrinos, DSNB modifications, PBH evaporation
Transient bursts	Supernovae, mergers, etc.	SN neutrinos with new physics, multimessenger emission

- Each signal class requires distinct analysis strategies, many remain underdeveloped
  → timely opportunities

Conclusions

- Hyper-K and J-PARC together form a discovery platform across several qualitatively different signal classes – far beyond precision oscillation physics alone
- Non-canonical nucleon decays and LLP echo signatures illustrate large unexplored parameter space and observables within existing mature physics programs
- Unique features, such as IWCD movability, enable new classes of measurements, such as correlated multi-spectrum measurements sensitive to interaction new physics
- Directions are already being formulated as concrete analyses, with broader opportunities emerging

A ripe time for unexpected discoveries