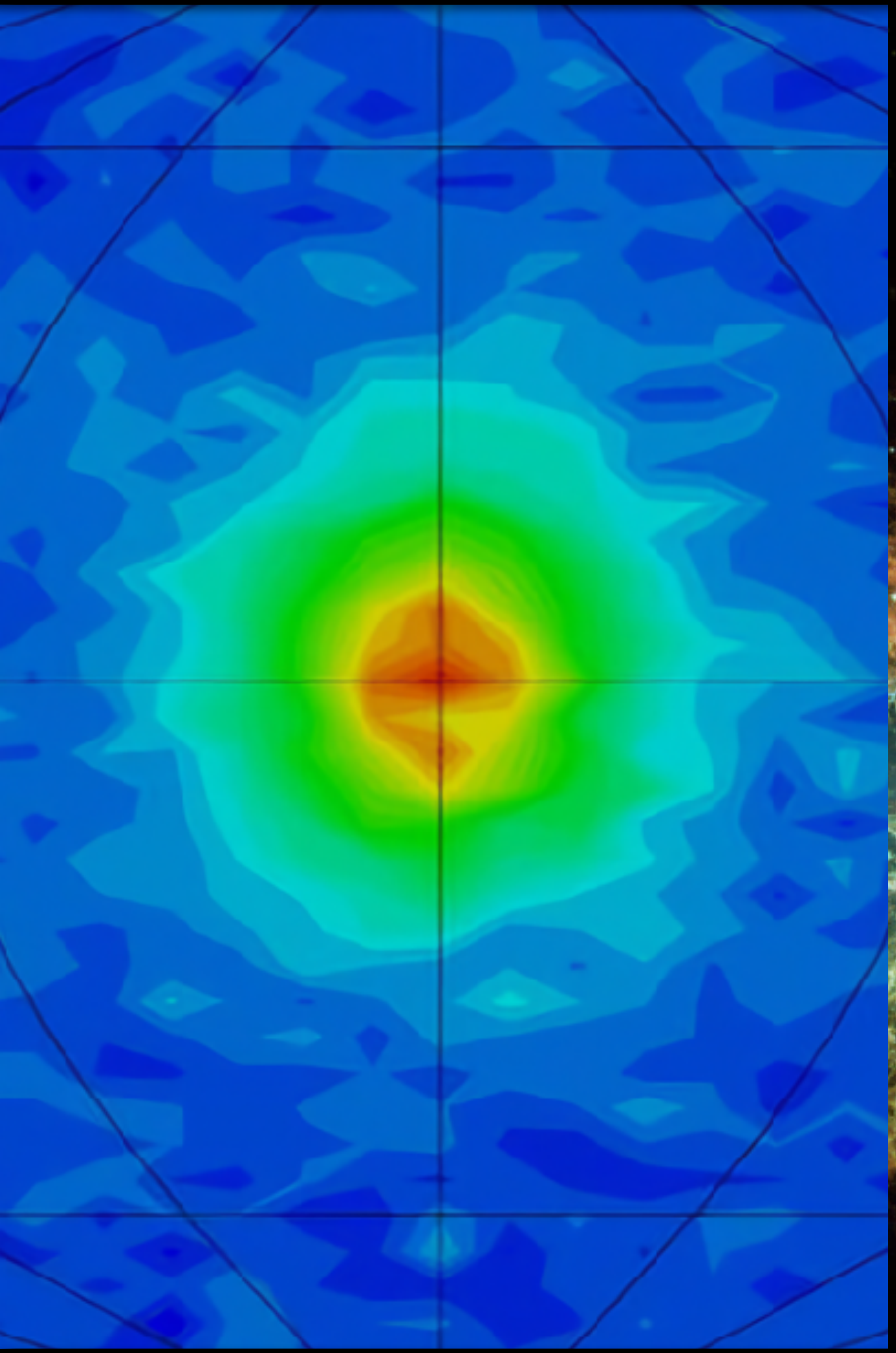
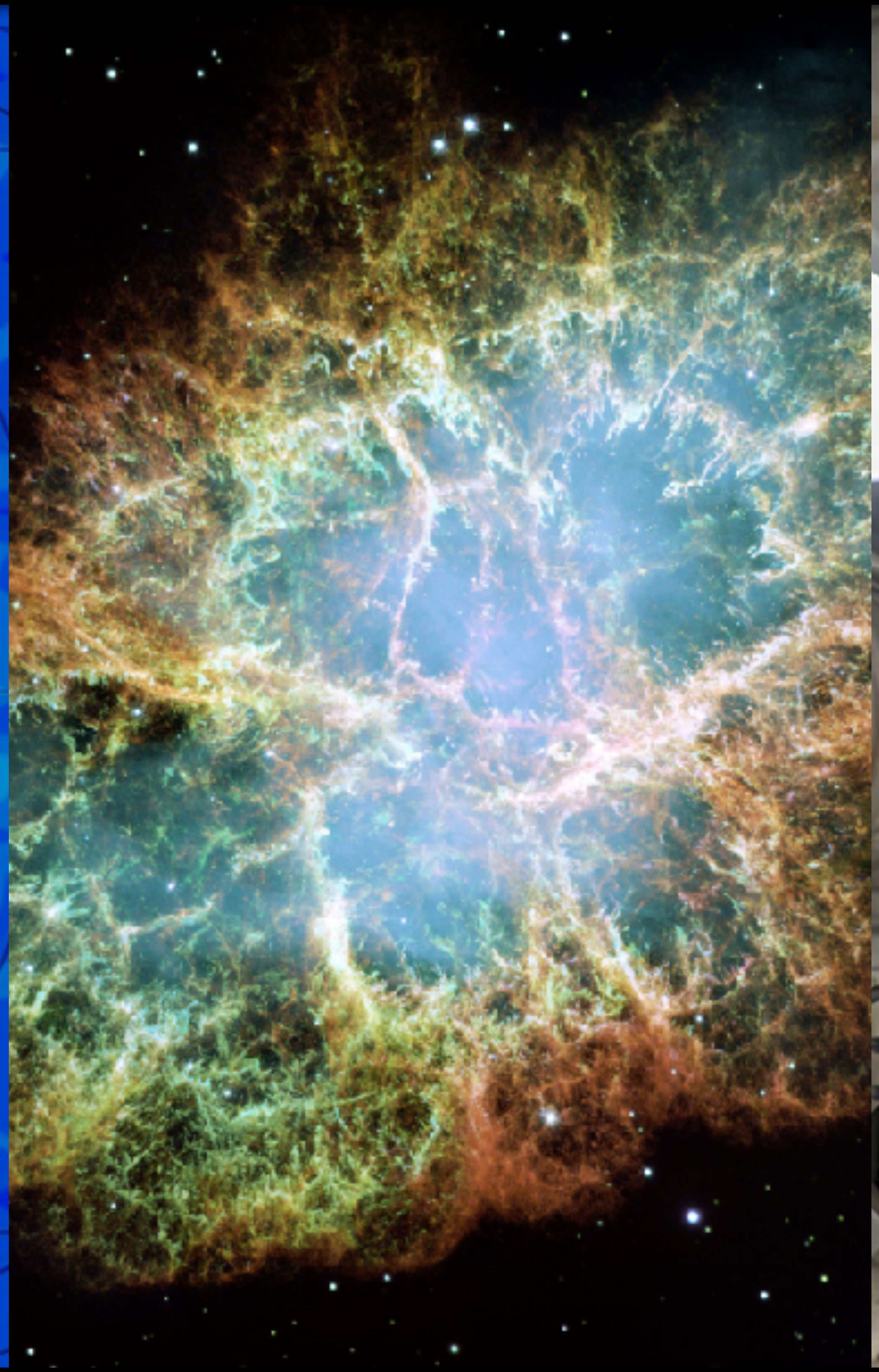
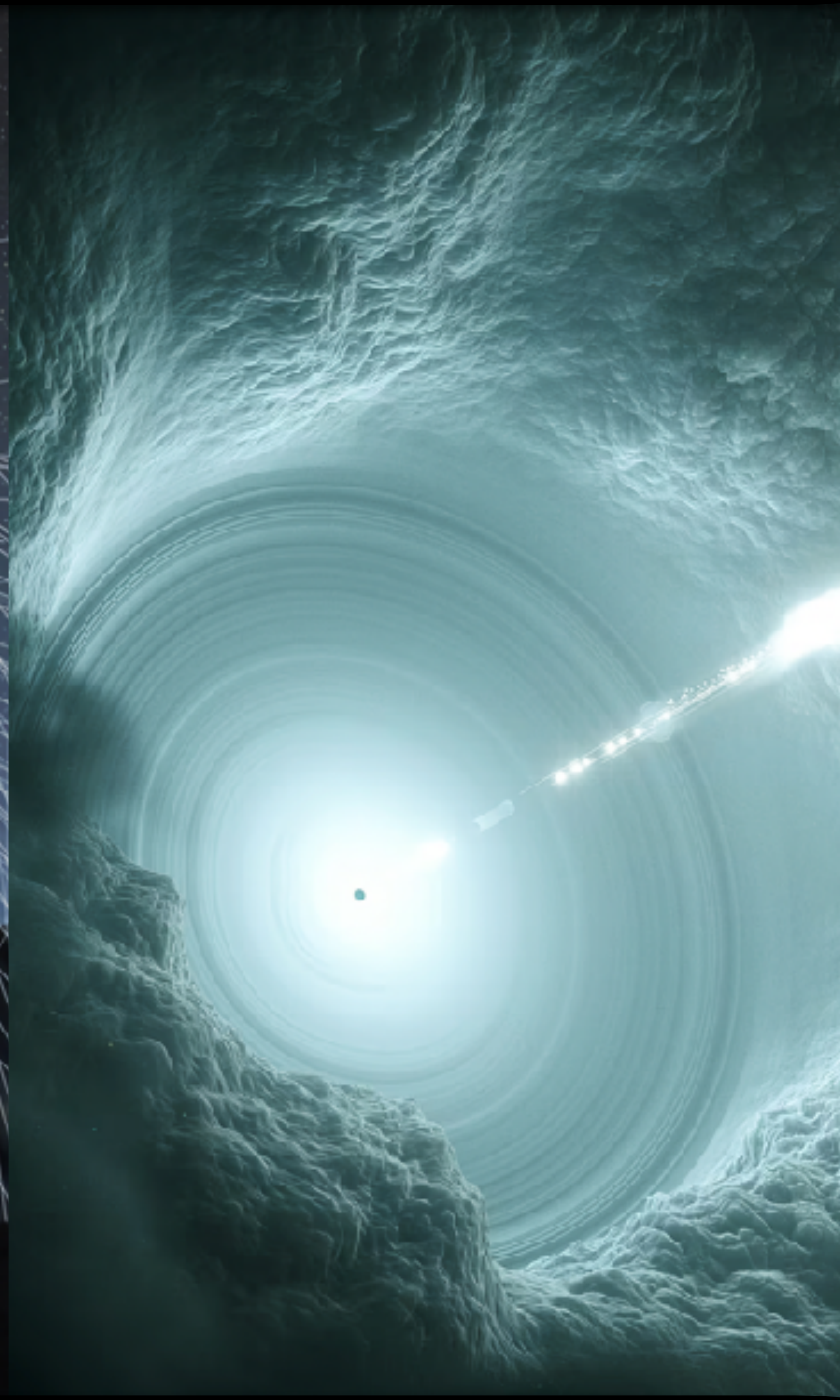
Neutrino Facilities as Versatile Probes of New Physics

APS Global Summit, March 16 2026





Matheus Hostert matheus-hostert@uiowa.edu

University of Iowa

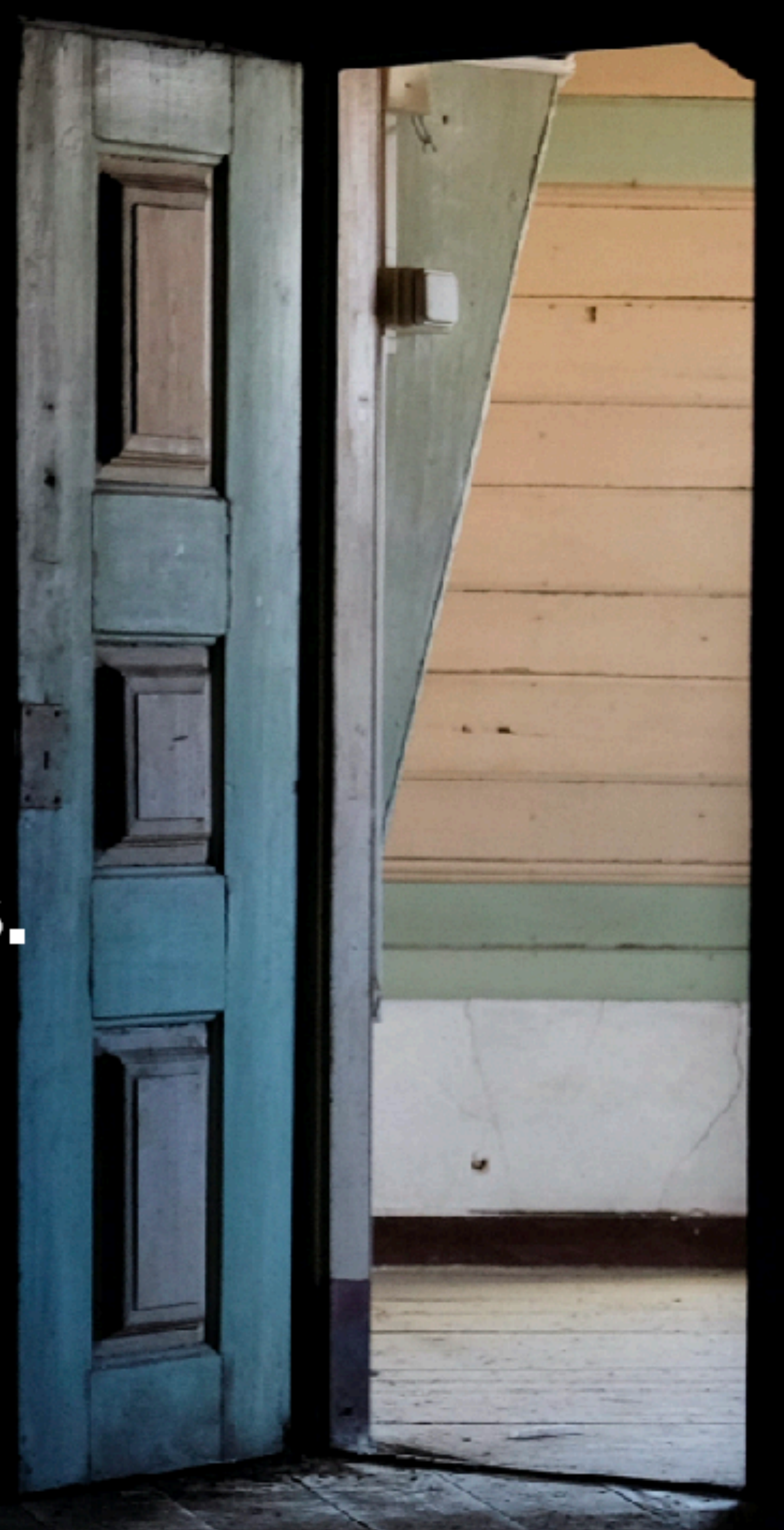
IOWA

1) **Neutrinos as unique building blocks in extensions of the Standard Model.**

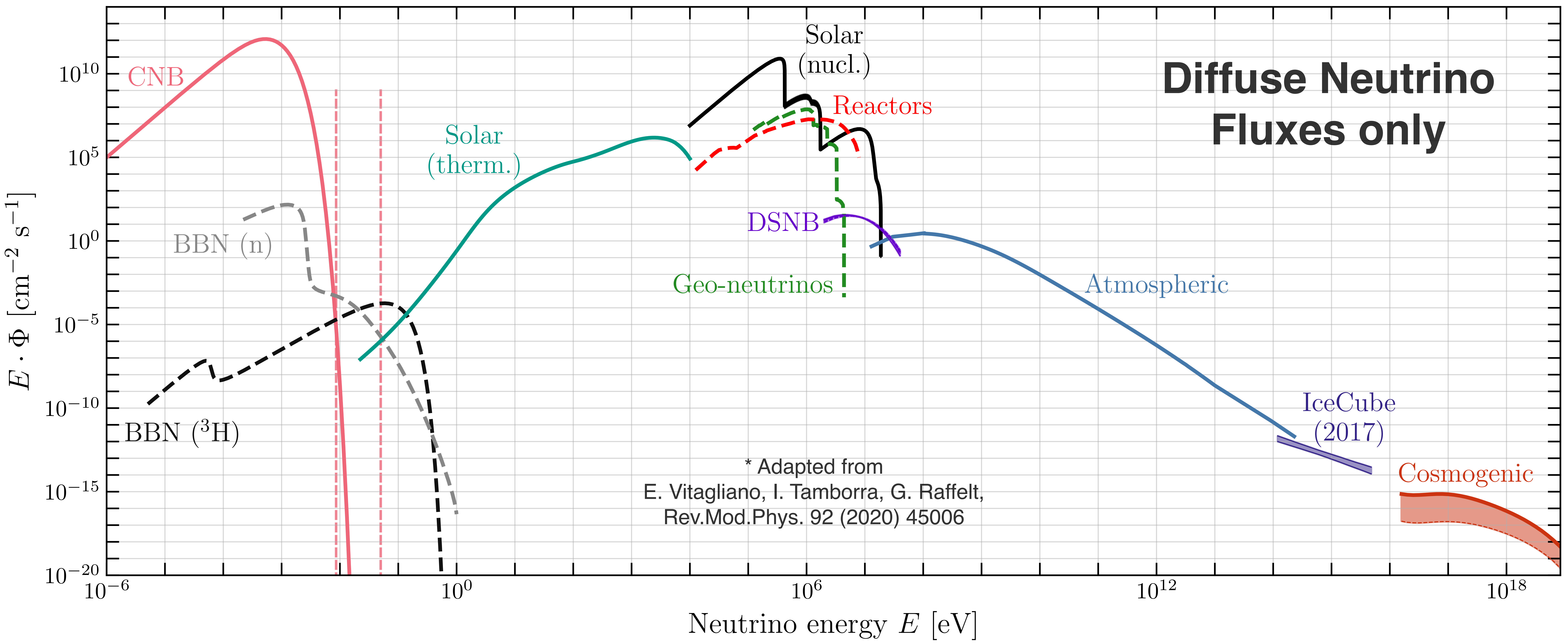
- the only $U(1)_{\mathrm{EM}}$-singlet fermions of the SM,
- mass mechanism unknown.

2) **Neutrino experiments as probes of new particles and forces.**

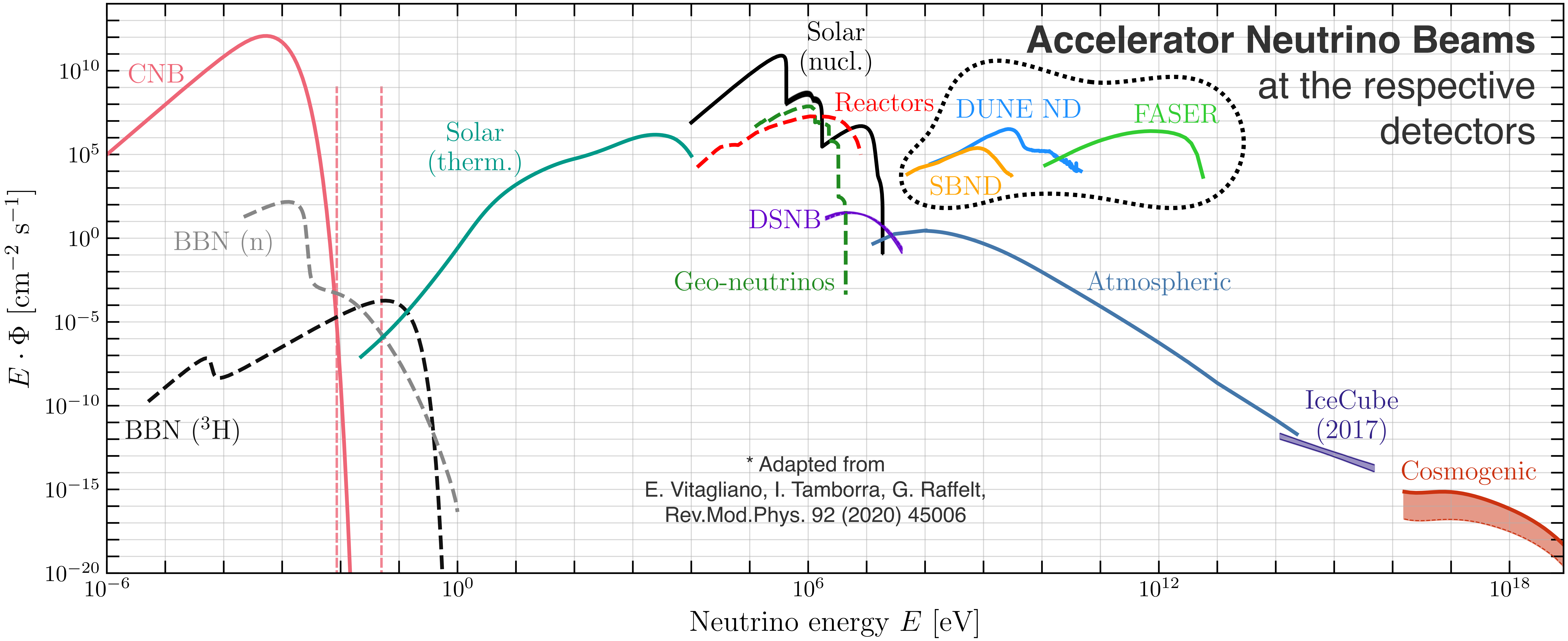
- built for rare phenomena and helping push intensity frontier,
- Several anomalies to be resolved.



Neutrinos Across Energy Scale



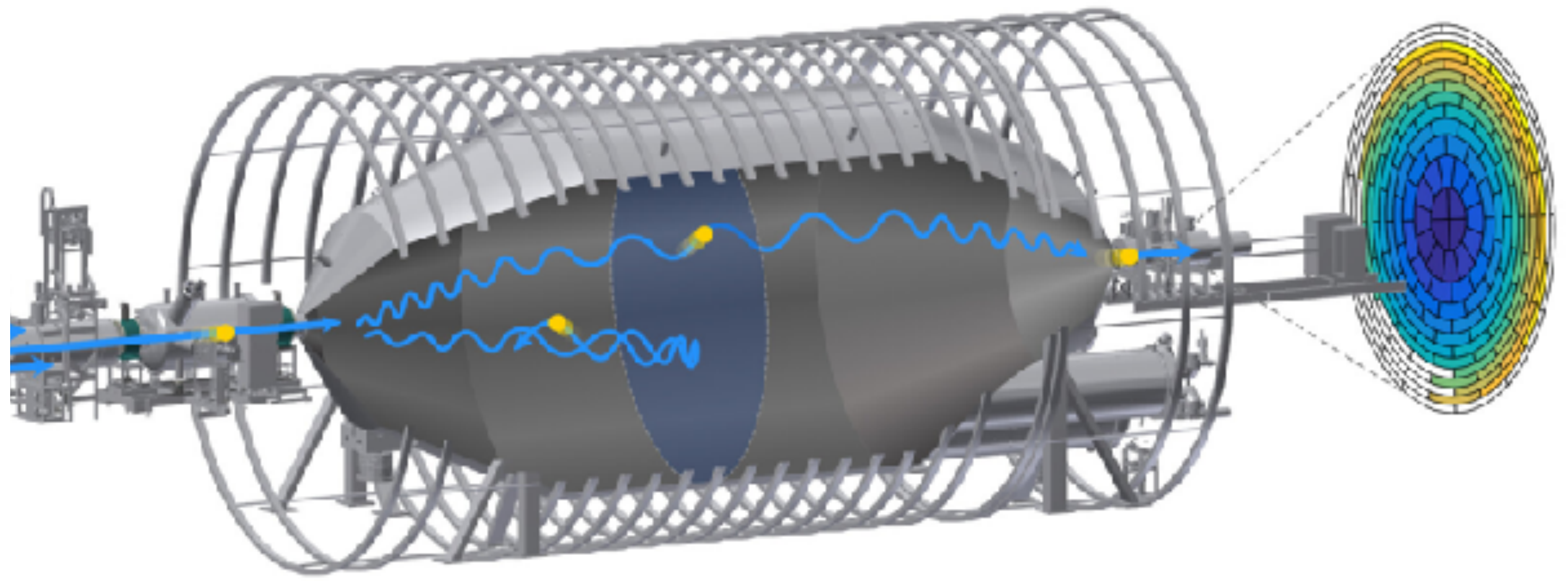
Neutrinos Across Energy Scale



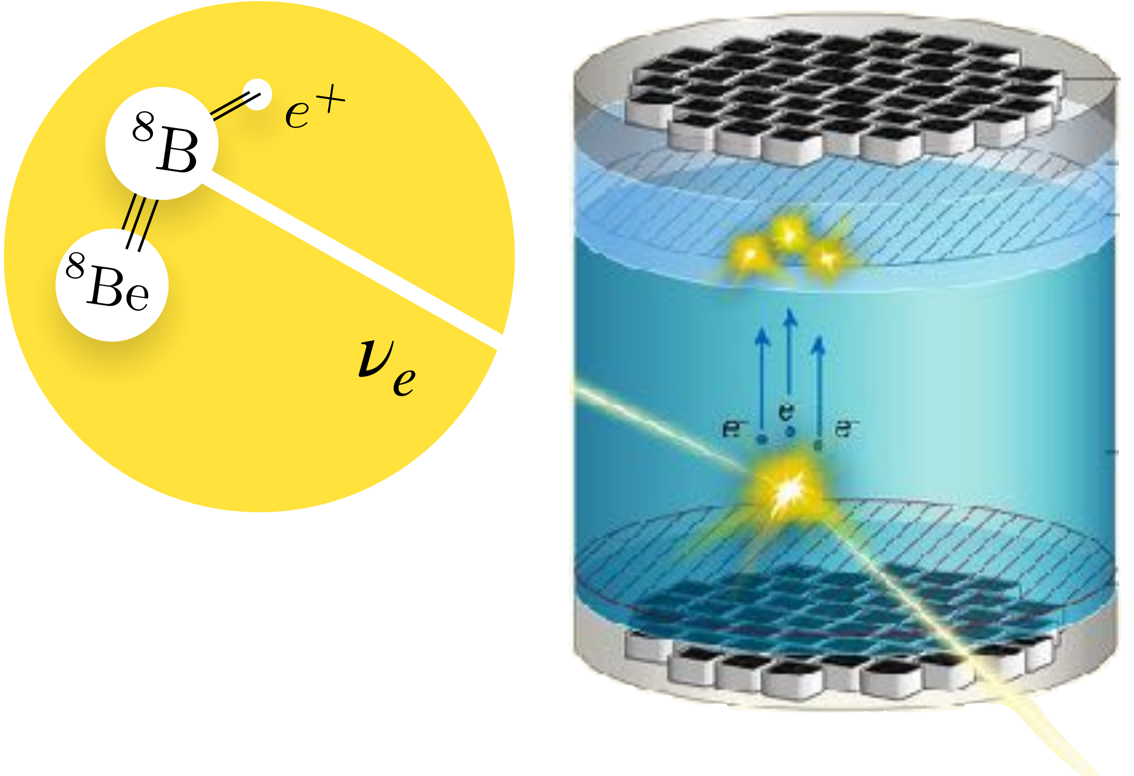
* Adapted from
E. Vitagliano, I. Tamborra, G. Raffelt,
Rev.Mod.Phys. 92 (2020) 45006

Near future: covering MeV → EeV energies with state-of-the-art measurements

Beta decay spectra

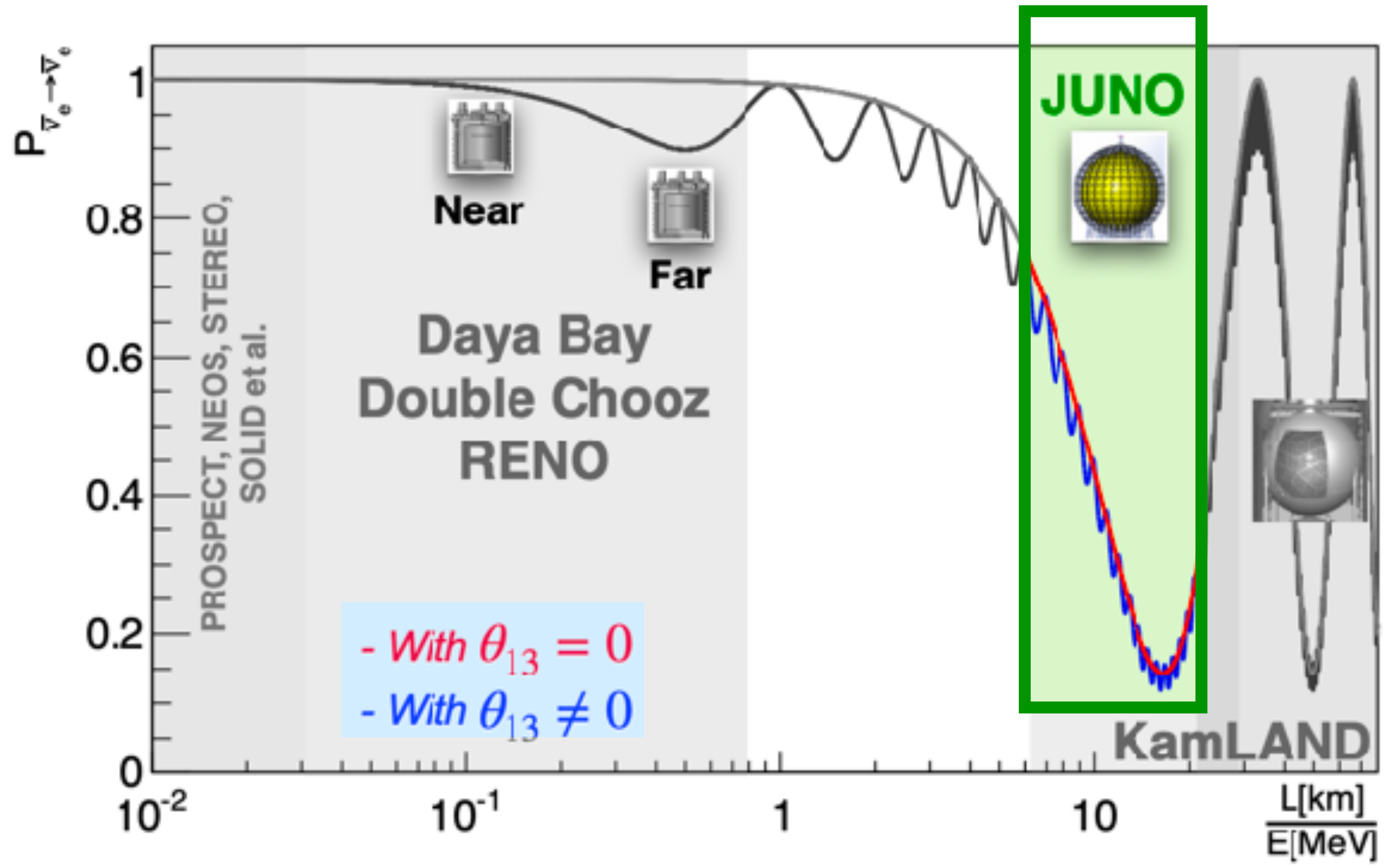


Dark Matter Direct Detection

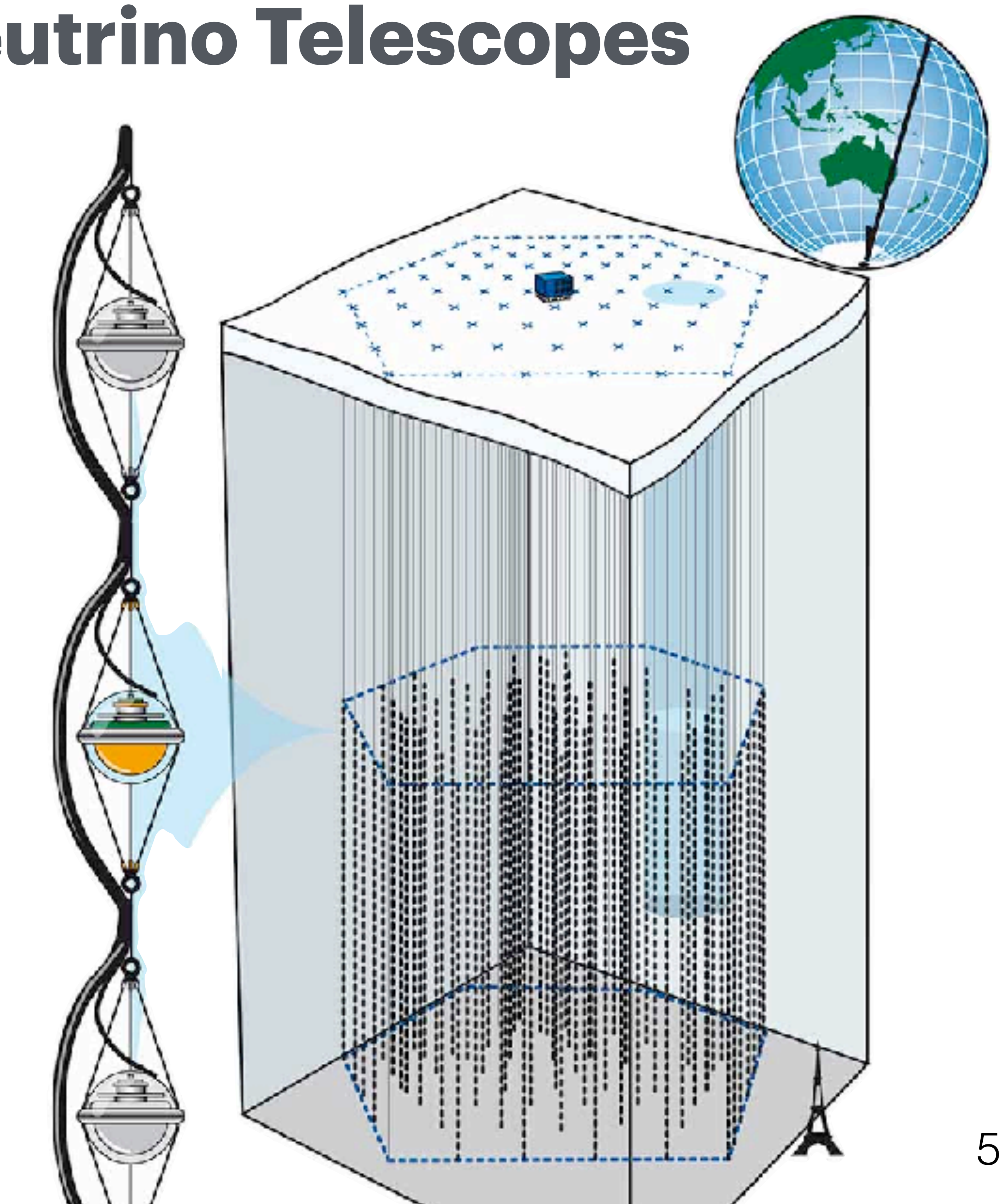


Reactors / Spallation Sources

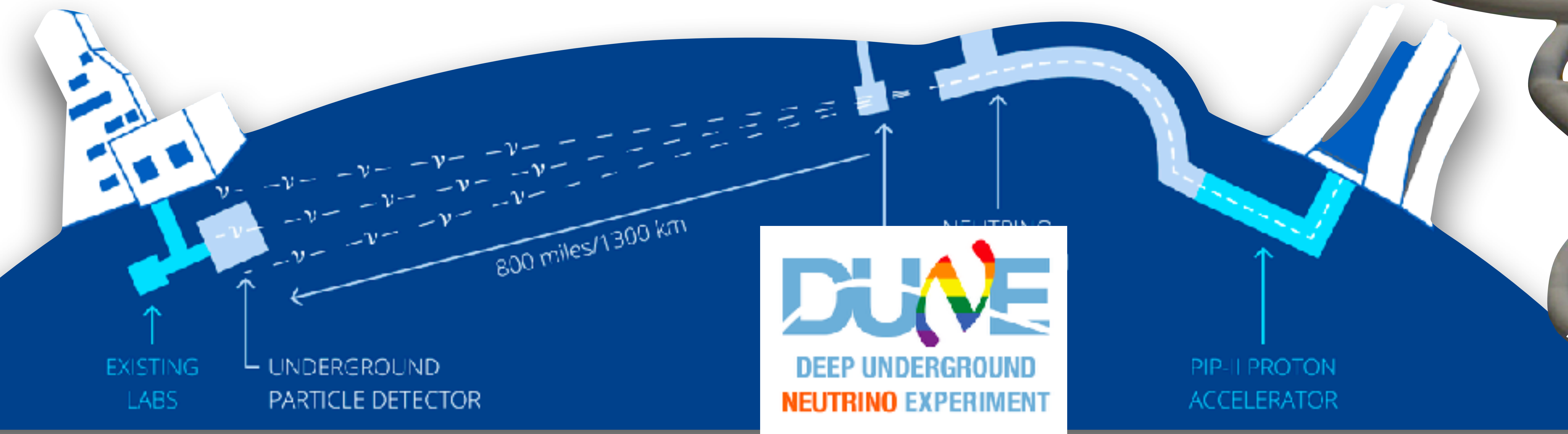
Adapted from P. Ochoa-Ricoux, NPN 2025

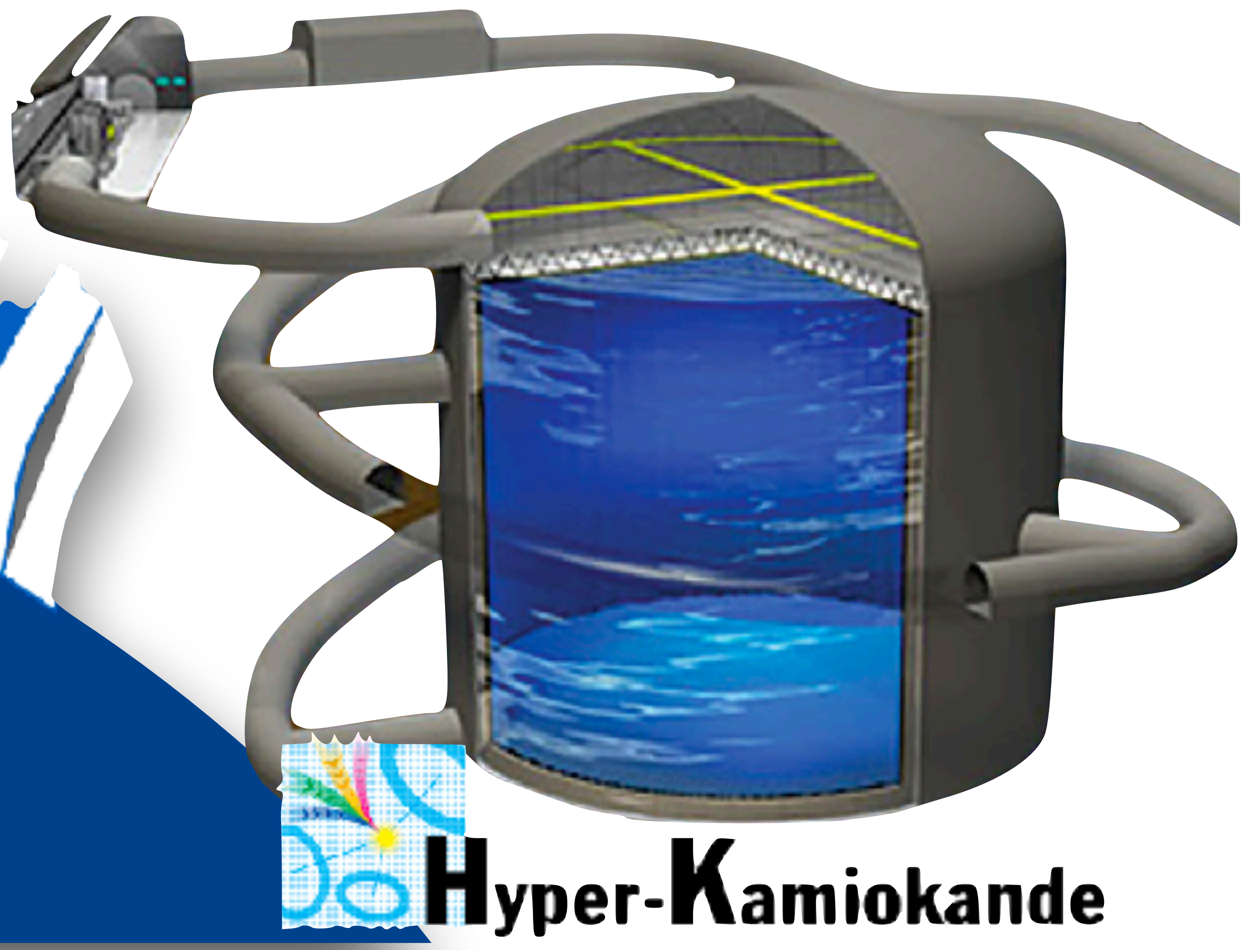


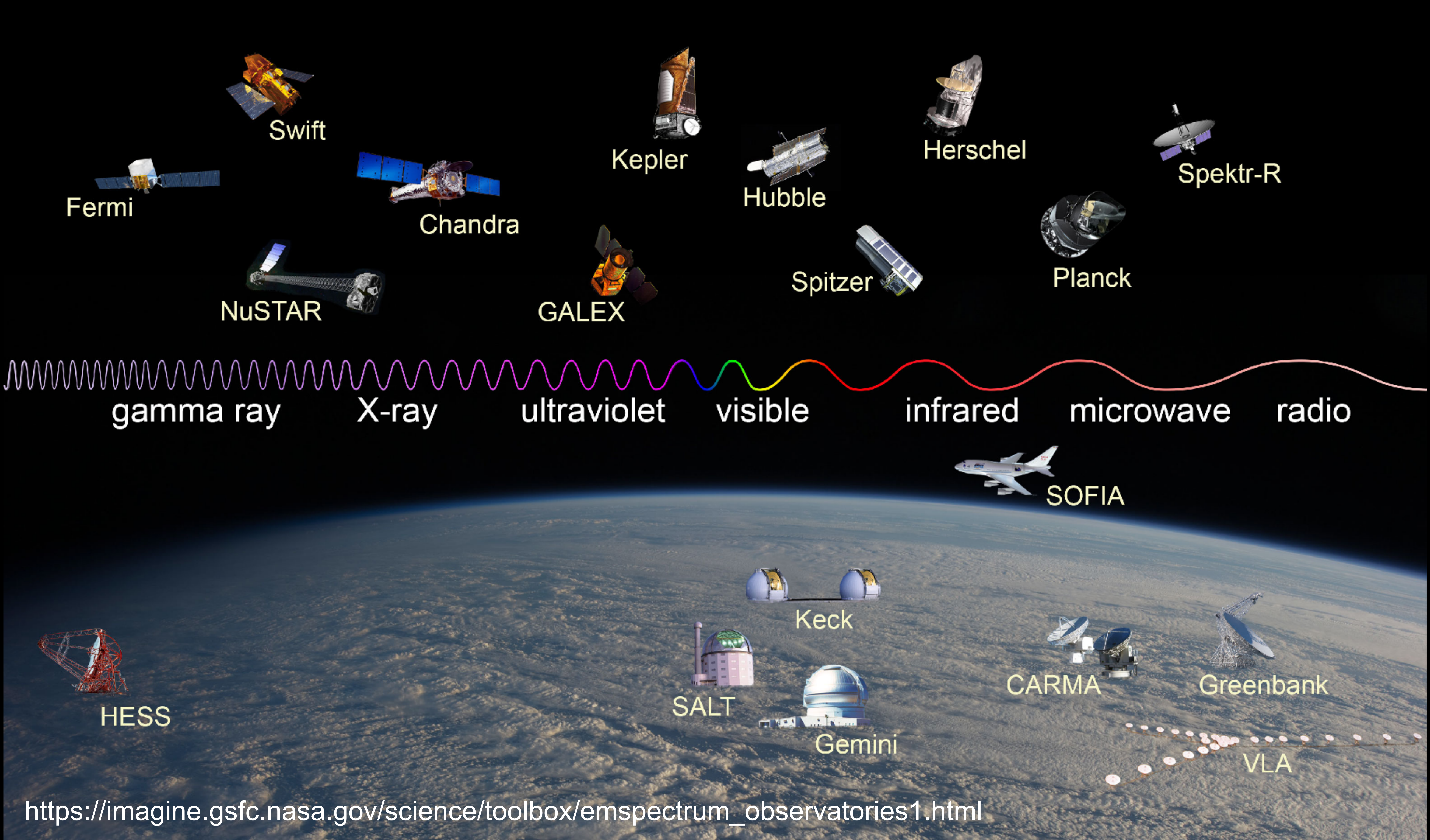
Neutrino Telescopes



Long-Baseline Experiments






Swift
Fermi
Chandra
NuSTAR
Kepler
GALEX
Hubble
Spitzer
Herschel
Planck
Spektr-R
gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
SOFIA
Keck
HESS
SALT
Gemini
CARMA
Greenbank
VLA
https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum_observatories1.html

This talk:

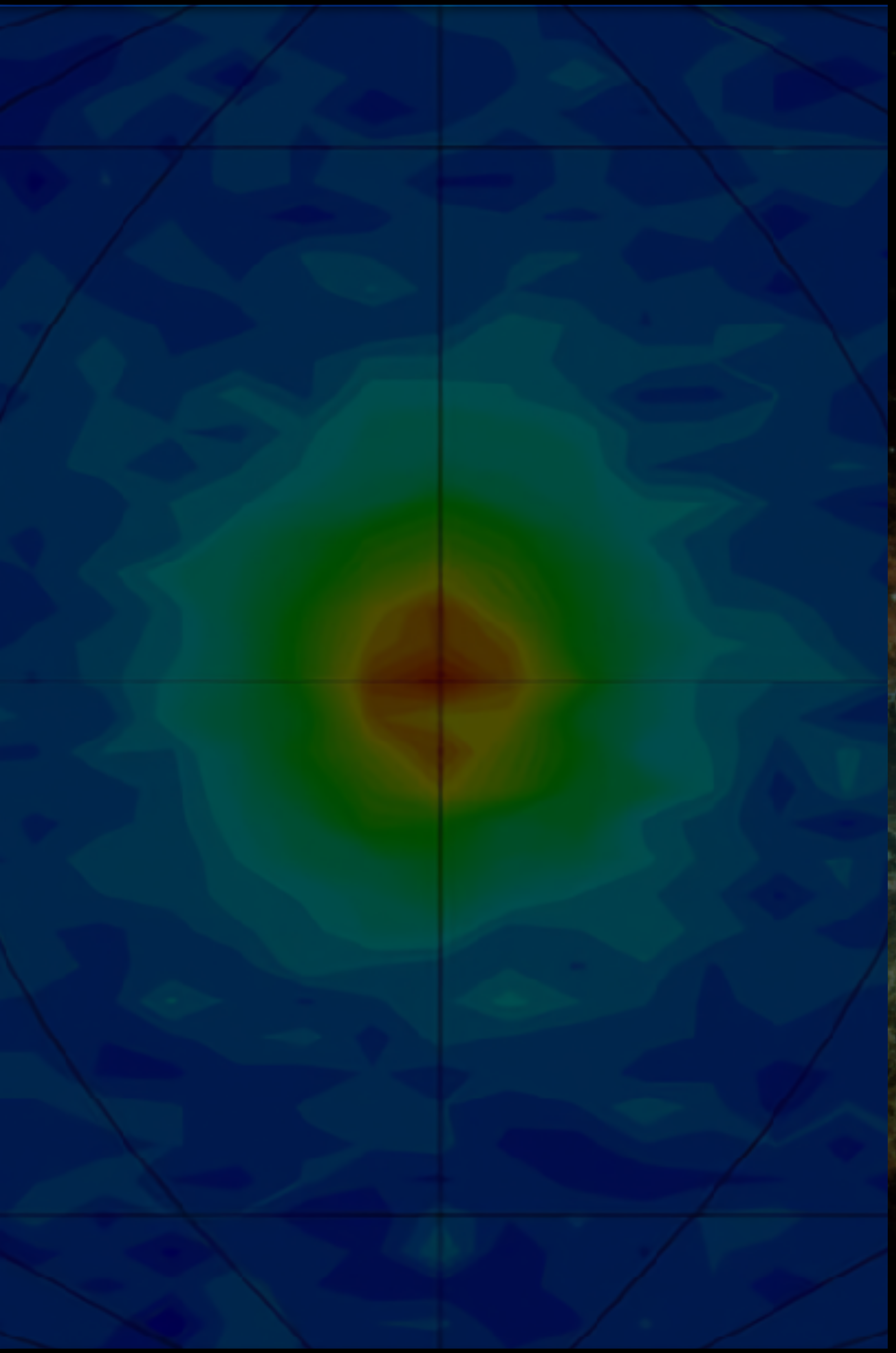
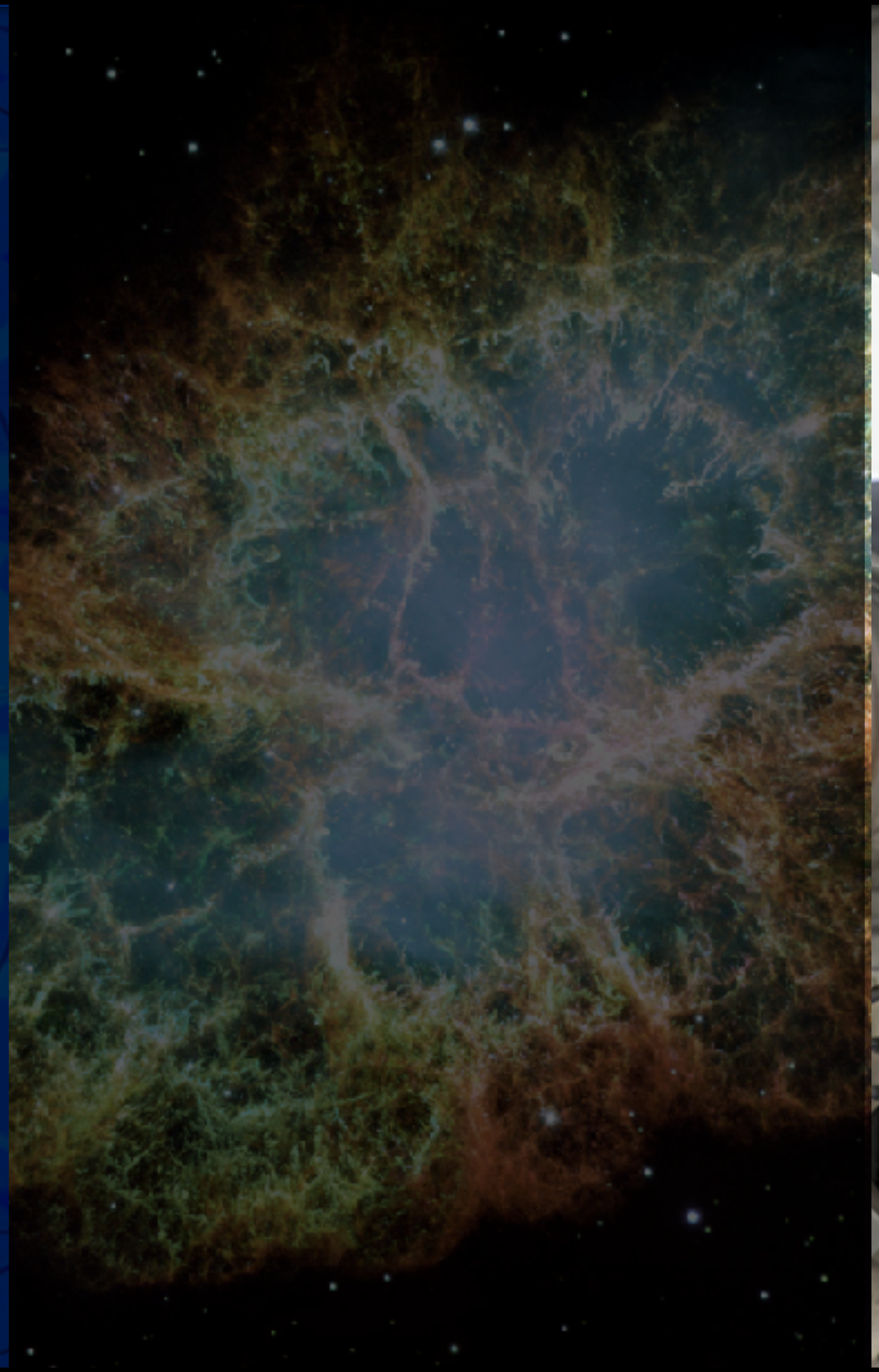
A theorist's perspective on **a few aspects of** beyond the Standard Model physics with **neutrinos**

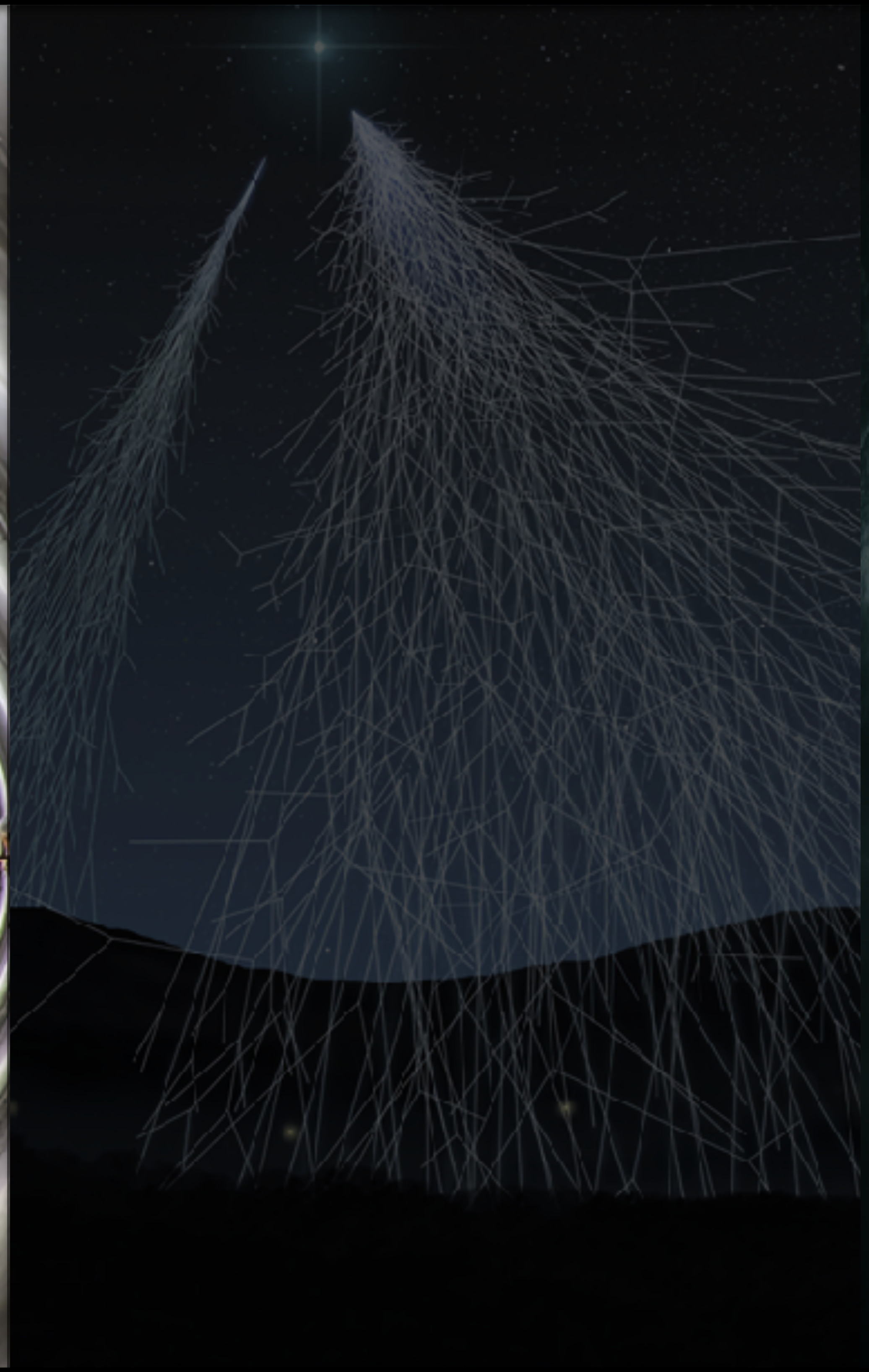
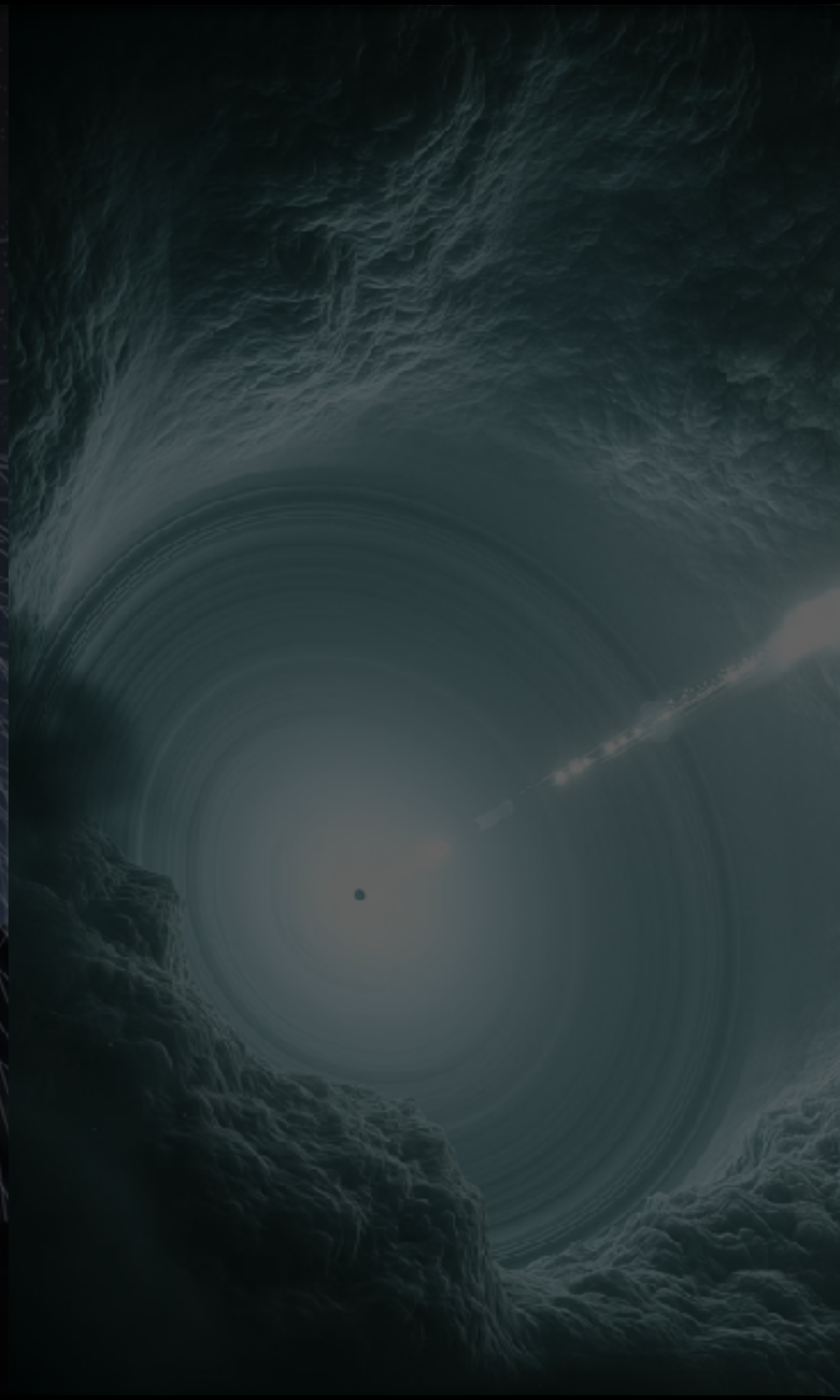
1) Sterile neutrinos at lab-based accelerators

2) Other weakly-interacting particles at accelerators

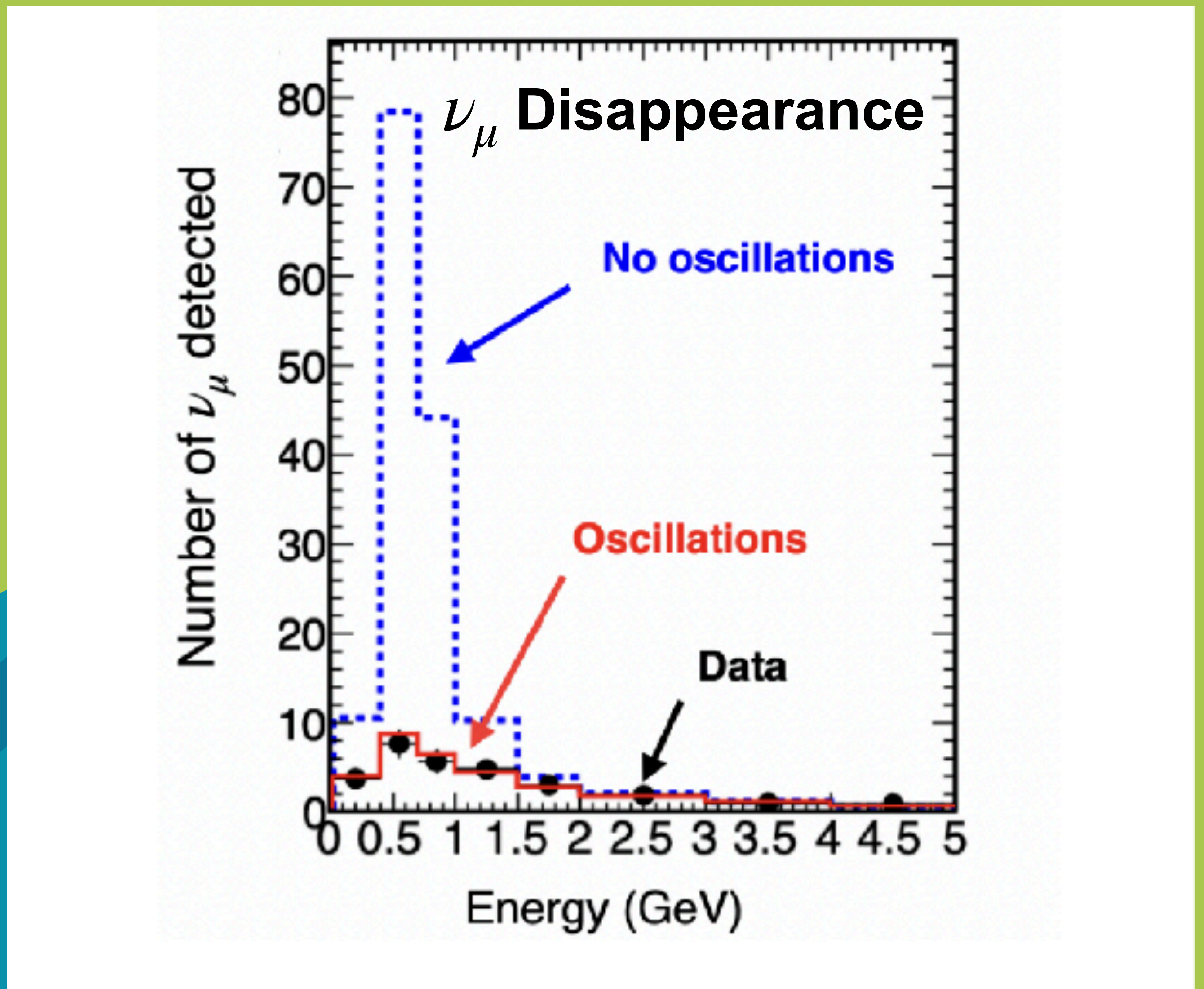
3) Ultra-long-distance neutrino propagation

Rare Events at Accelerator Experiments

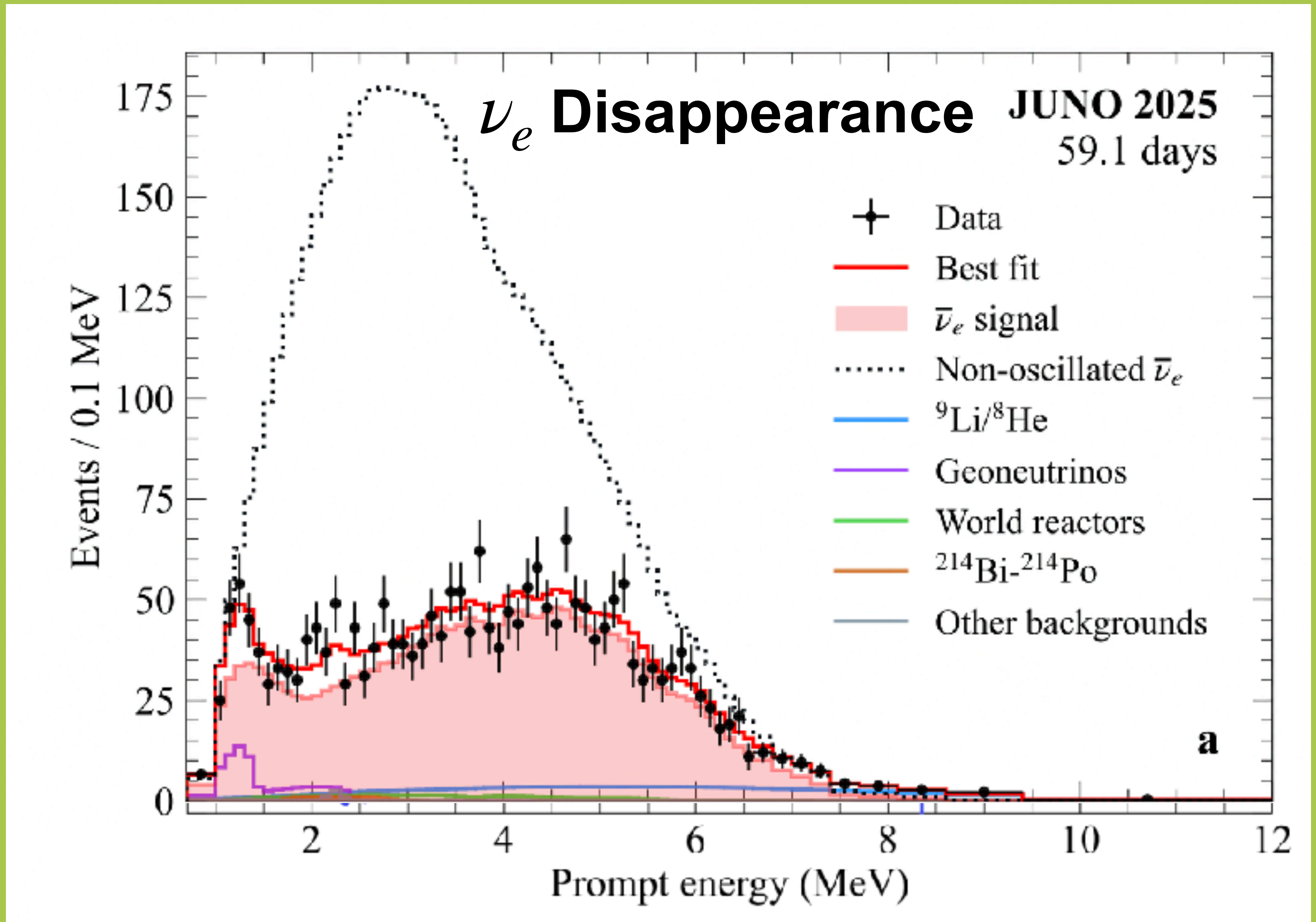



“Earth-Sized Quantum Flavor Interferometers”



Adapted from T2K coll., 10.1103/PhysRevD.96.011102



The Ambiguity of Neutrino Masses

Neutrino masses

New scalar particles

Exotic Matter Potentials

ν_R exists

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

ν_L only

$$m_L = \frac{\langle h \rangle^2}{\Lambda}$$

The Ambiguity of Neutrino Masses

Neutrino masses

New scalar particles

Exotic Matter Potentials

ν_R exists

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

ν_L only

$$m_L = \frac{\langle h \rangle^2}{\Lambda}$$

Effective theory

Λ scale

Majorana ν

L violation

$$m_R = 0$$

Dirac νs

L conservation

$$0 < m_R \ll m_D$$

Quasi-Dirac ν

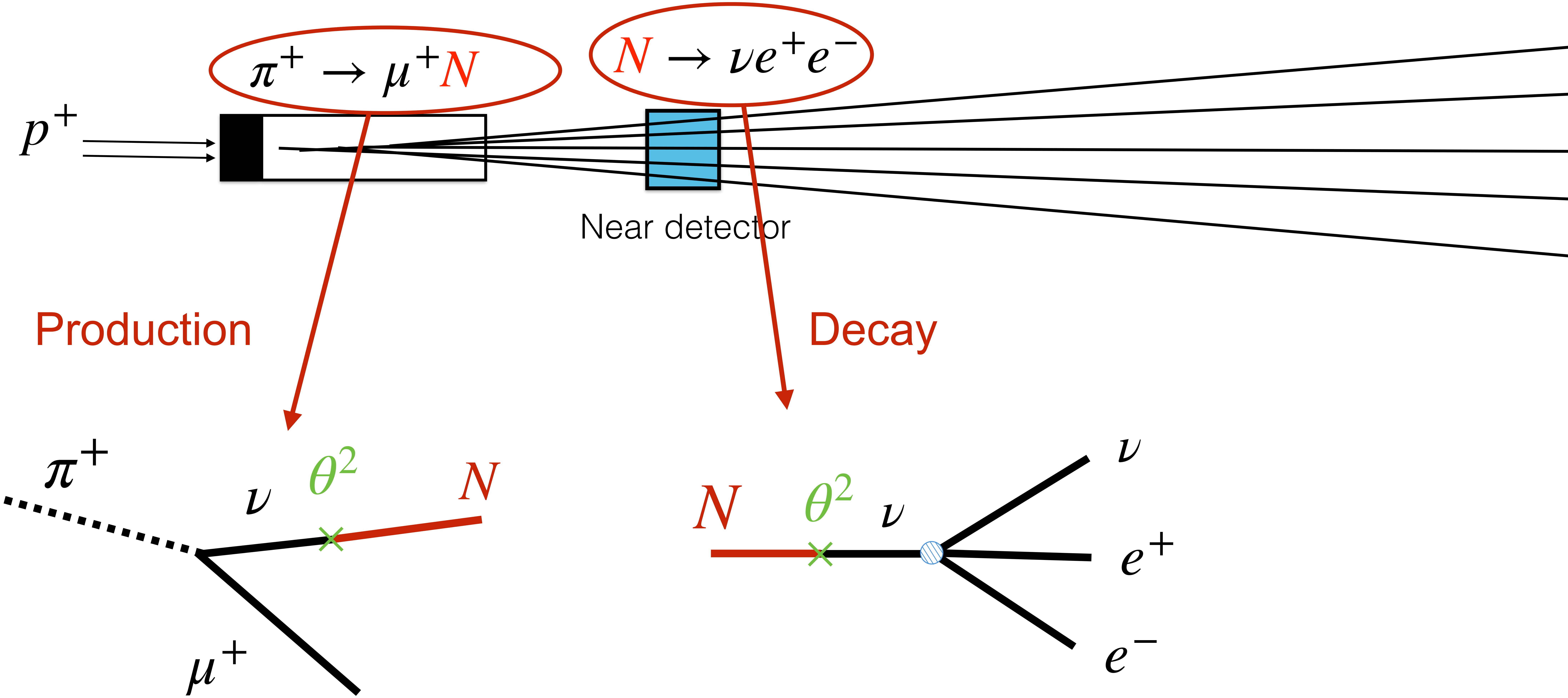
L quasi-conservation

The Ambiguity of Neutrino Masses

STANDARD MODEL
G_F
ν_μ
μ^+
ν_e
e^+
Weak interaction
$G_F \sim \frac{1}{m_W^2}$
ν
θ
N
Neutrino portal
HIDDEN SECTOR
Heavy Neutrinos
$\theta \times G_F$
ν
N
e^-
μ^+
Weaker-than-Weak interactions
$(\theta \ll 1)$
Long-lived particle
$\Gamma \sim \theta^2 G_F^2 M_N^5$

Accelerator Neutrino Experiments

Near detectors / short-baselines



3+1 oscillations | Cosmo & β-decay | Decays in flight & Rare meson decays | Colliders

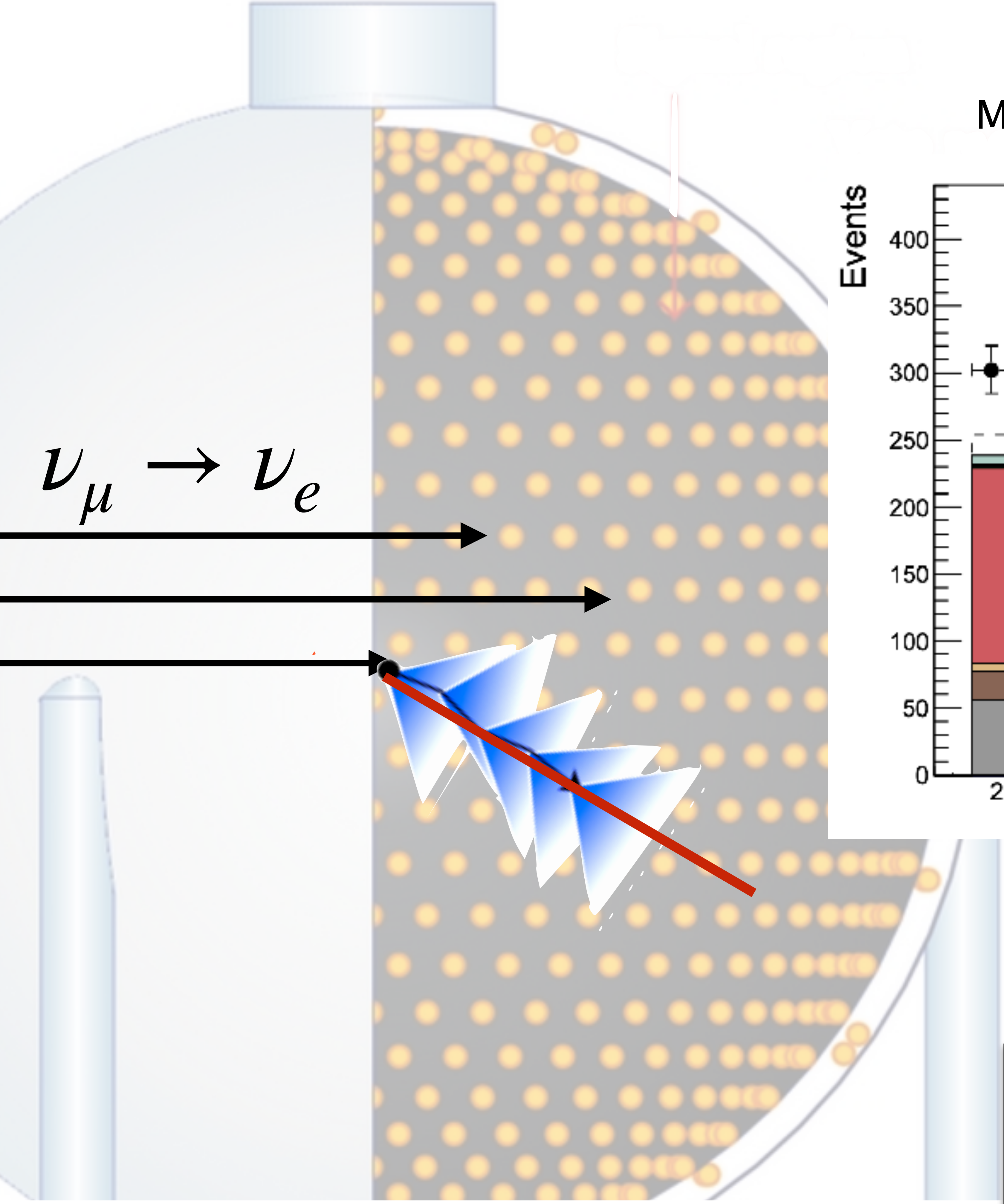
$0\nu\beta\beta$

LFV
$(\mu^- \to e^\pm)$

E. Fernández-Martínez, M.González-López, J. Hernández-García, MH, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

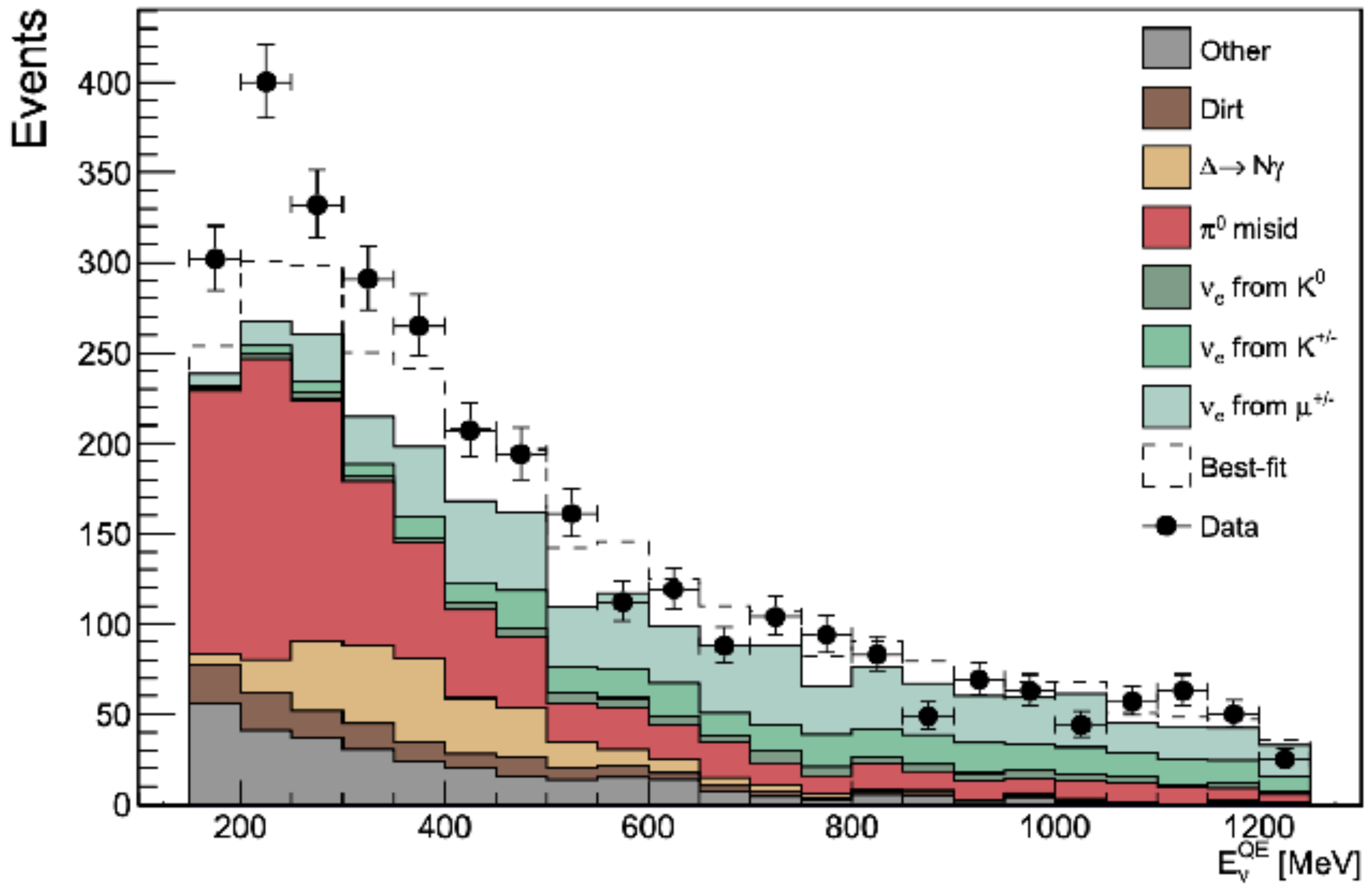
The Short-Baseline Puzzle: appearance signals?

MiniBooNE detector



MiniBooNE

MiniBooNE coll., PRD 103, 052002 (2021)



Reconstructed $E_\nu^{\rm QE}$ / MeV

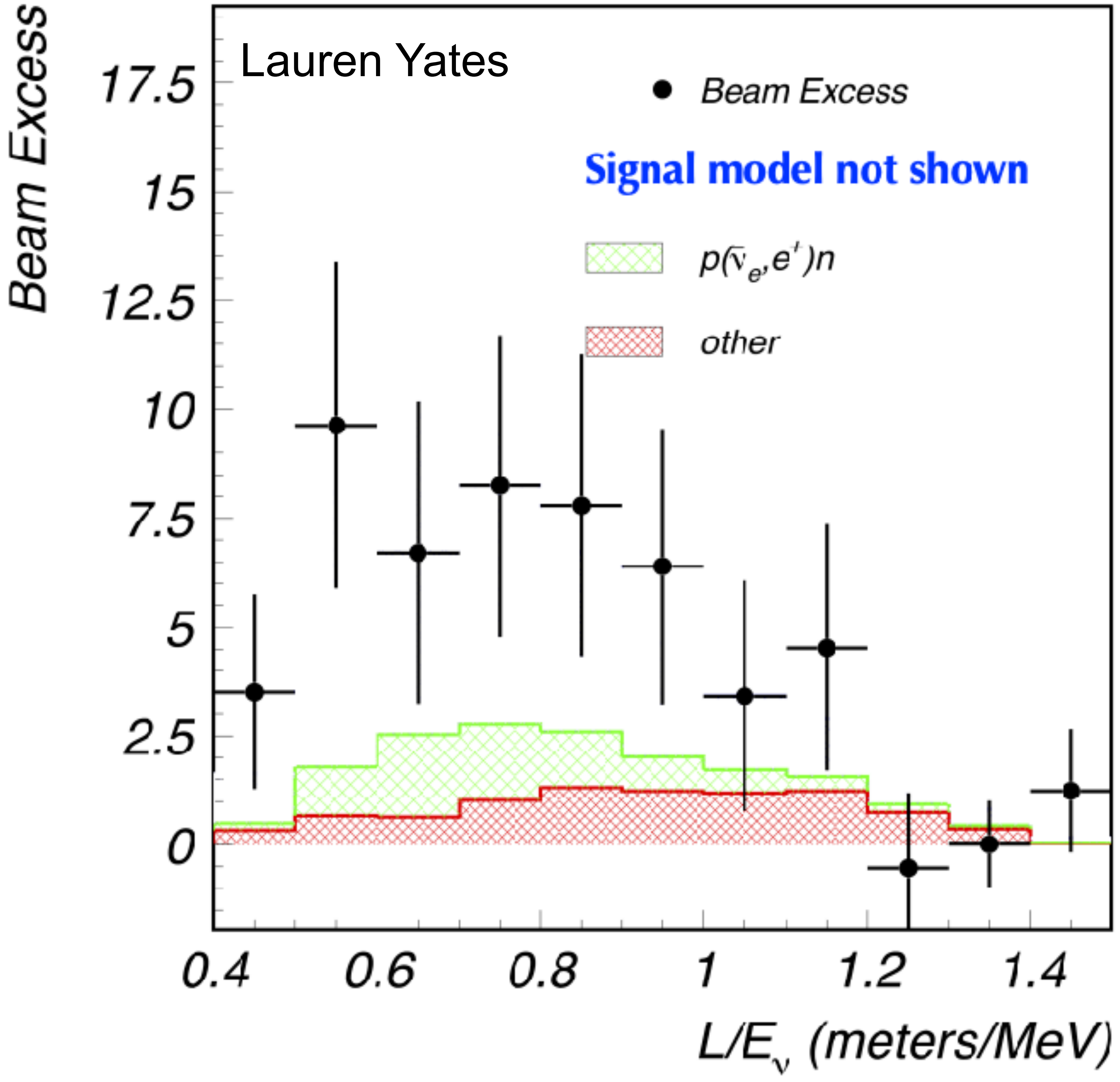
Excess:

638 ± 52(stat.) $\pm\ 122.2$(sys.)

4.8σ significance

LSND

LSND coll. PRD 64 (2001) 112007

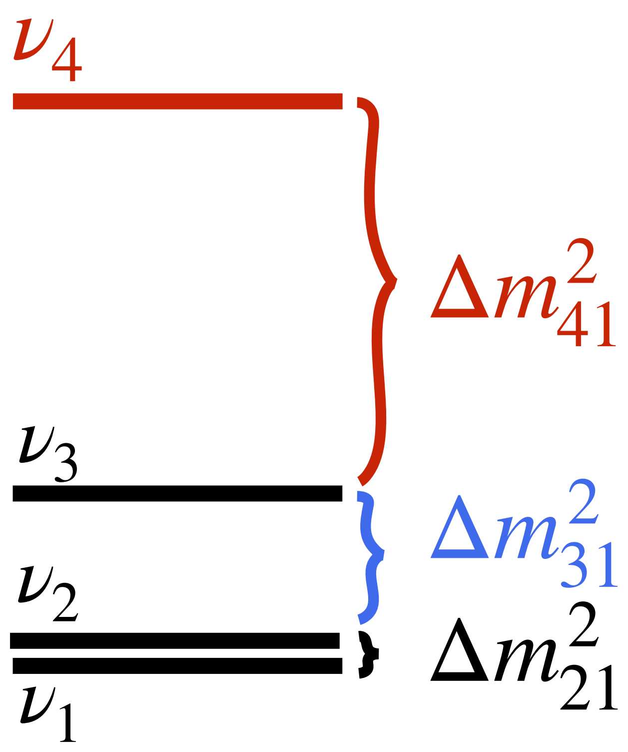


Excess: $87.9 \pm 22.4 \pm 6$ events

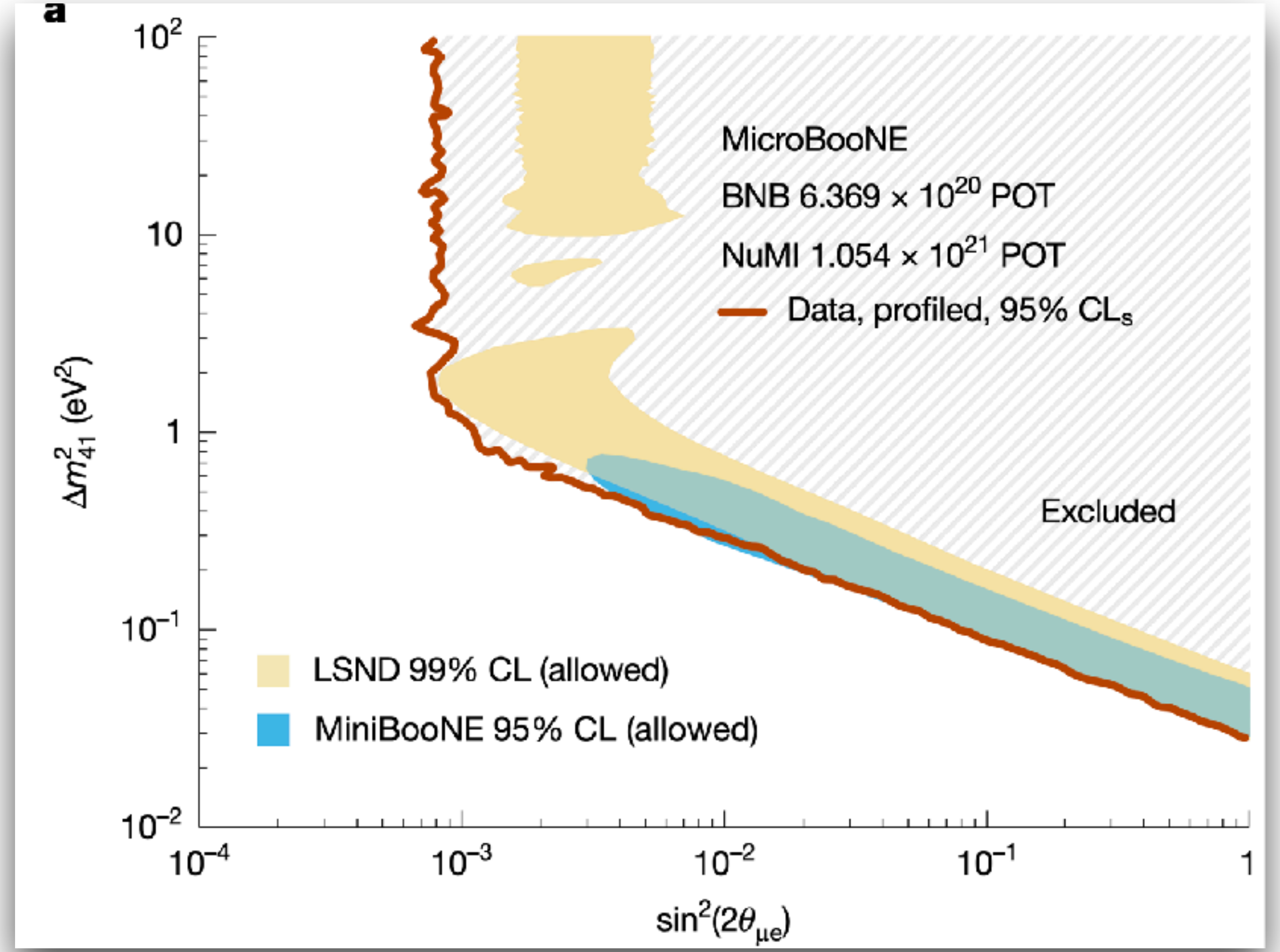
3.8σ significance

Light Sterile Neutrino Oscillations

Latest results from MicroBooNE experiment



$$\Delta \equiv \frac{\Delta m^2_{41} L}{4E}$$



Article | Open access | Published: 03 December 2025

Search for light sterile neutrinos with two neutrino beams at MicroBooNE

The MicroBooNE Collaboration

Nature **648**, 64–69 (2025) | Cite this article

Appearance

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{e\mu} \sin^2 \Delta = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \Delta$$

Fresh off the Press

First time the LSND + MiniBooNE regions are fully covered using a single detector.
(1 detector, 2 beams!)

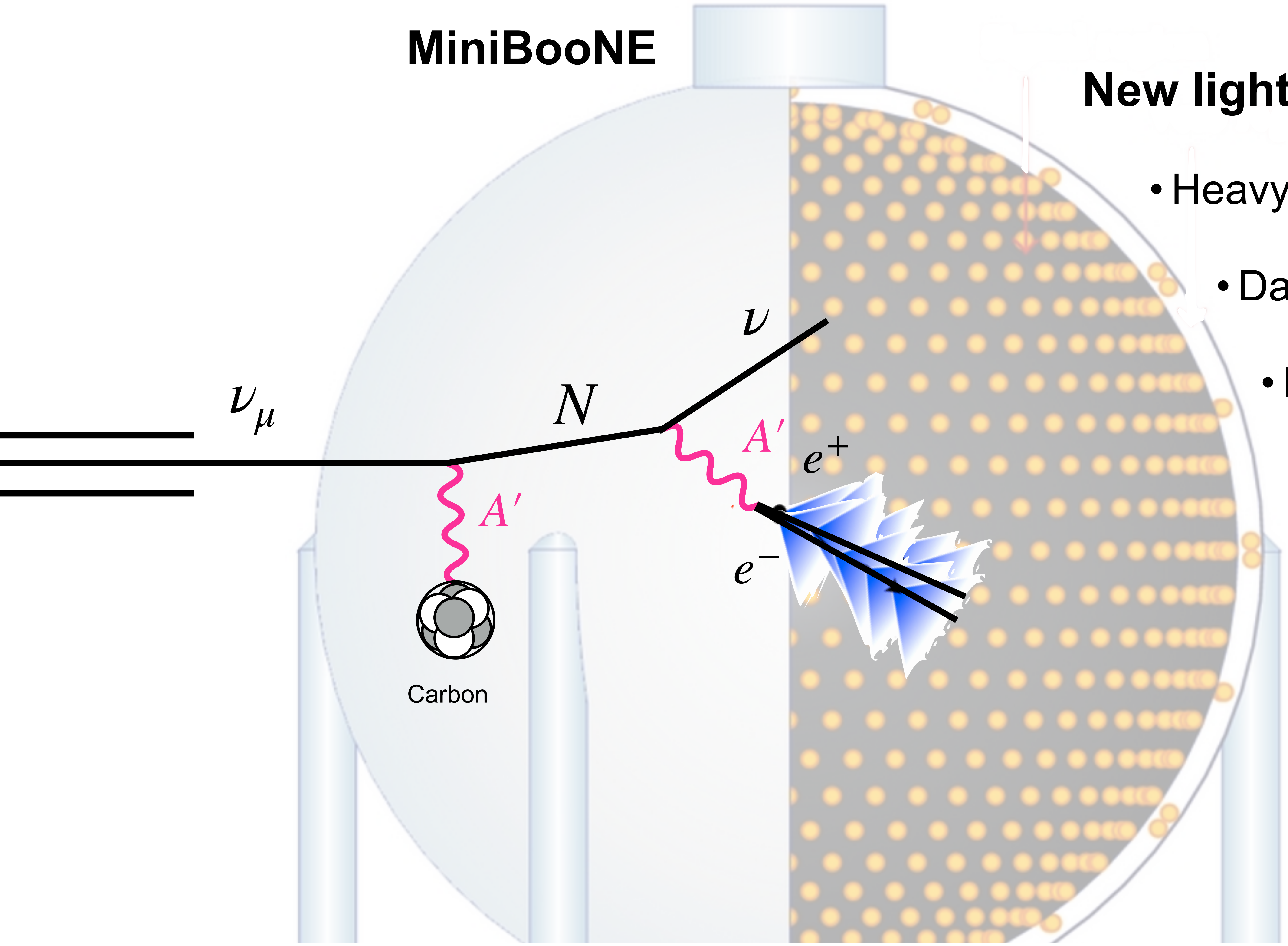
No resolution to the anomalies, but minimal model is disfavored by global oscillation picture.
Many questions remain open.

Dark Neutrinos

A multi-portal exploration of dark sectors

E. Bertuzzo, S. Jana, P. A. N. Machado, R. Z. Funchal, PRL 121, 241801 (2018)
P. Ballett, M. Ross-Lonergan, S. Pascoli, PRD 99, 071701 (2019)

C. Argüelles, MH, Y. Tsai, PRL 123, 261801 (2019)
P. Ballett, MH, S. Pascoli, PRD 101, 115025 (2020)



New light particles produced in neutrino interactions:

- Heavy Neutrinos?
- Dark Photons?
- Dark Higgses?

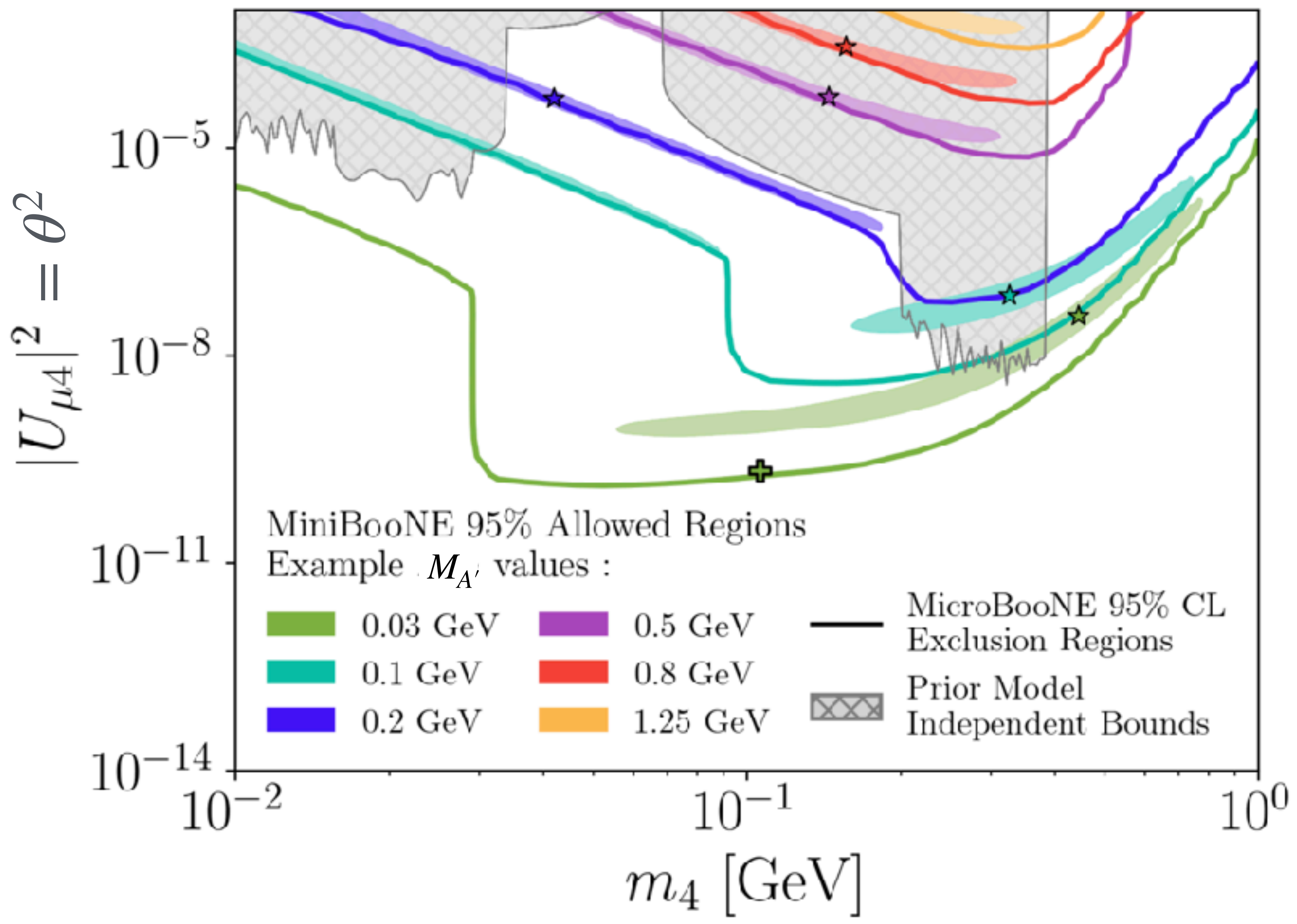
Dark Neutrinos @ MicroBooNE
First (modern) exp limits on neutrino upscattering

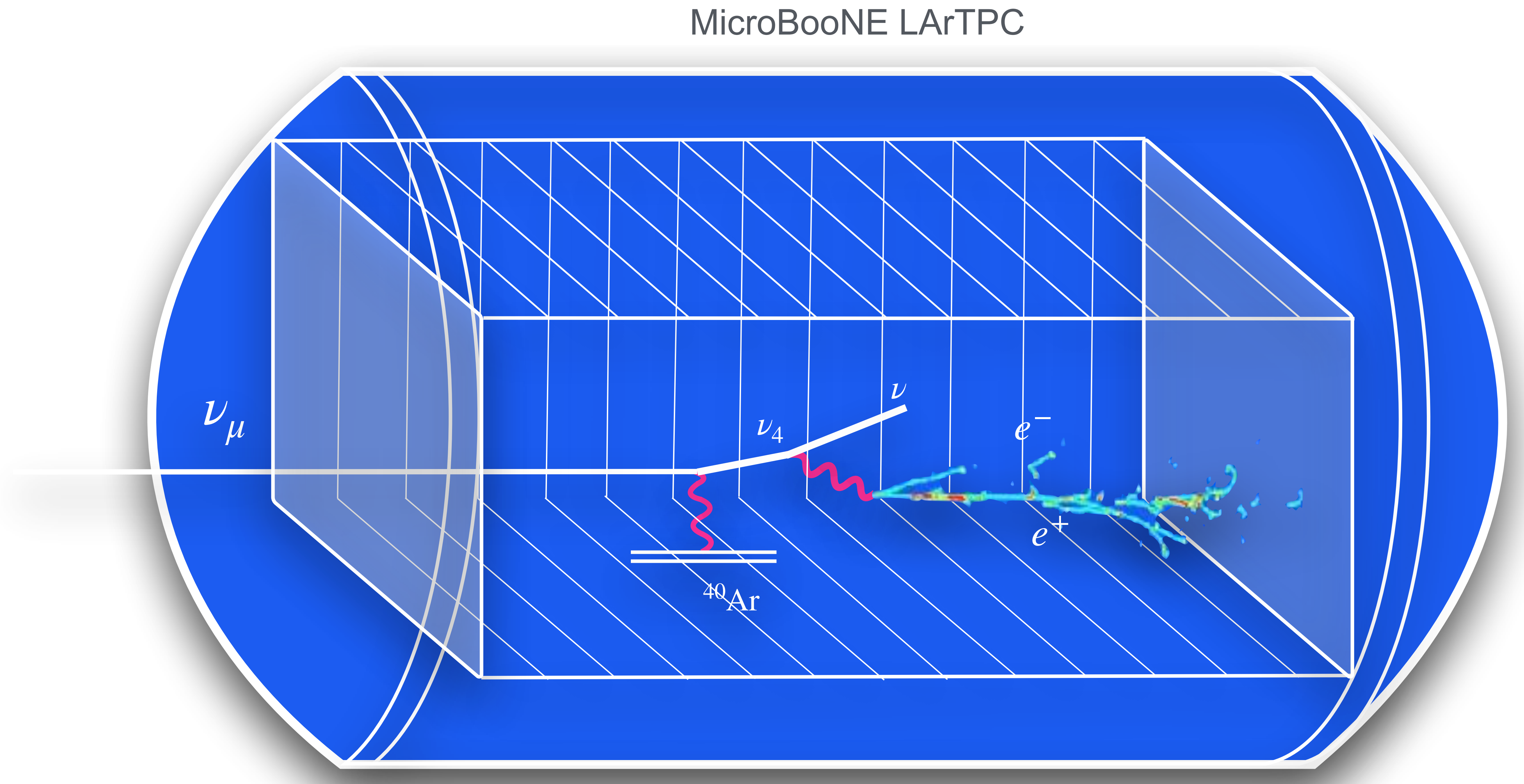
MicroBooNE coll. +
A. Abdullahi, MH, D. Massaro, S. Pascoli, J. Zink.
arxiv.org/abs/2502.10900

First dedicated experimental search for neutrino-induced e^+e^- pairs:

MicroBooNE excludes minimal dark neutrino explanations to the MiniBooNE anomaly

E. Bertuzzo, S. Jana, P. A. N. Machado, R. Z. Funchal, PRL 121, 241801 (2018)
P. Ballett, M. Ross-Lonergan, S. Pascoli, PRD 99, 071701 (2019)





DarkNews
github.com/mhostert/DarkNews-generator

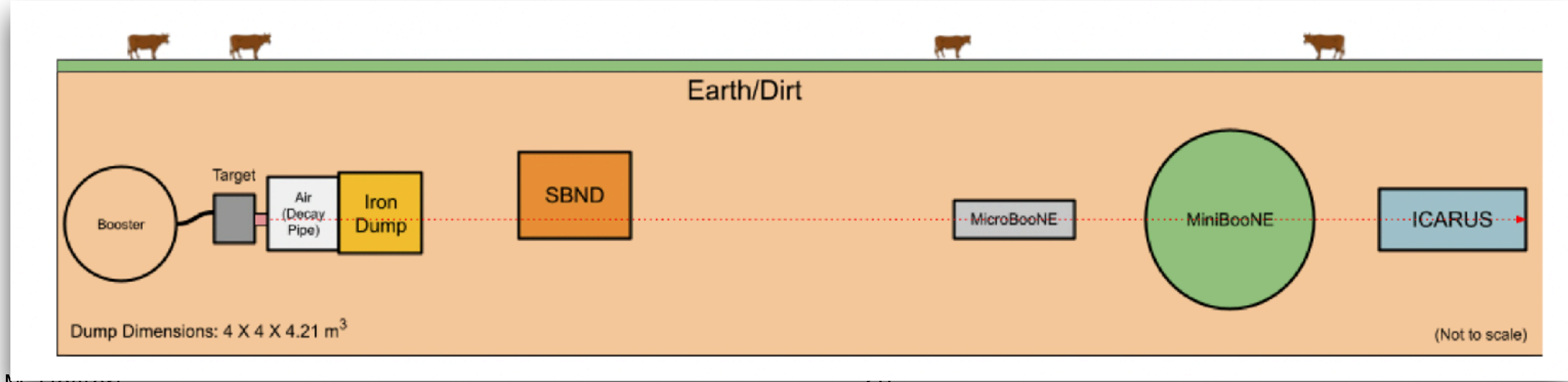
More Opportunities at the Booster Neutrino Beam

SBND and ICARUS will have even more statistics to search for light particles:

SBND: ~7,000 neutrino interactions /day!

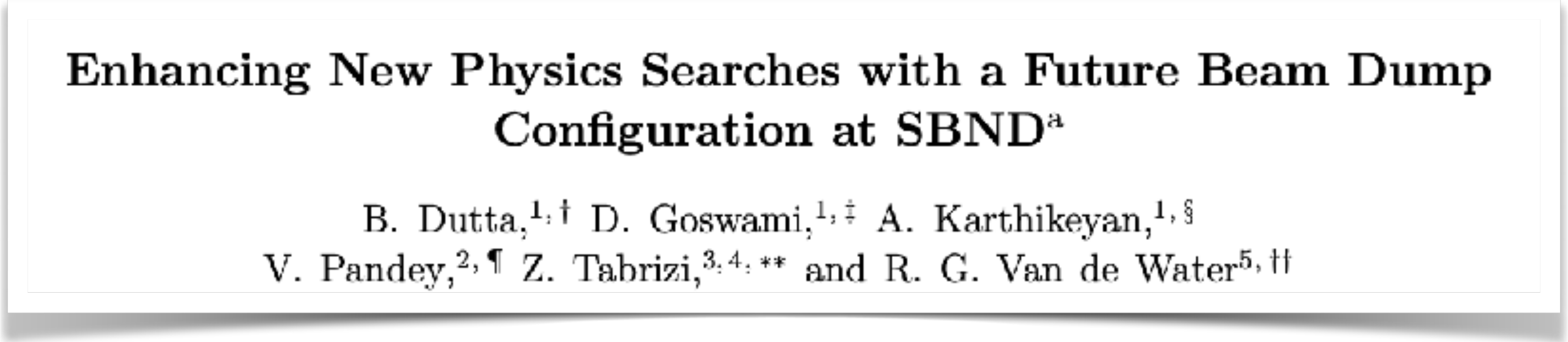
In addition, several opportunities for antineutrino or beam-dump mode running modes being discussed.

B. Dutta, D. Goswami, A. Karthikeyan, K. J. Kelly, JHEP 05 (2025) 240



Beam dump mode would enable significantly more light particle production and potentially meson decay-at-rest measurement at ~100 t LArTPC

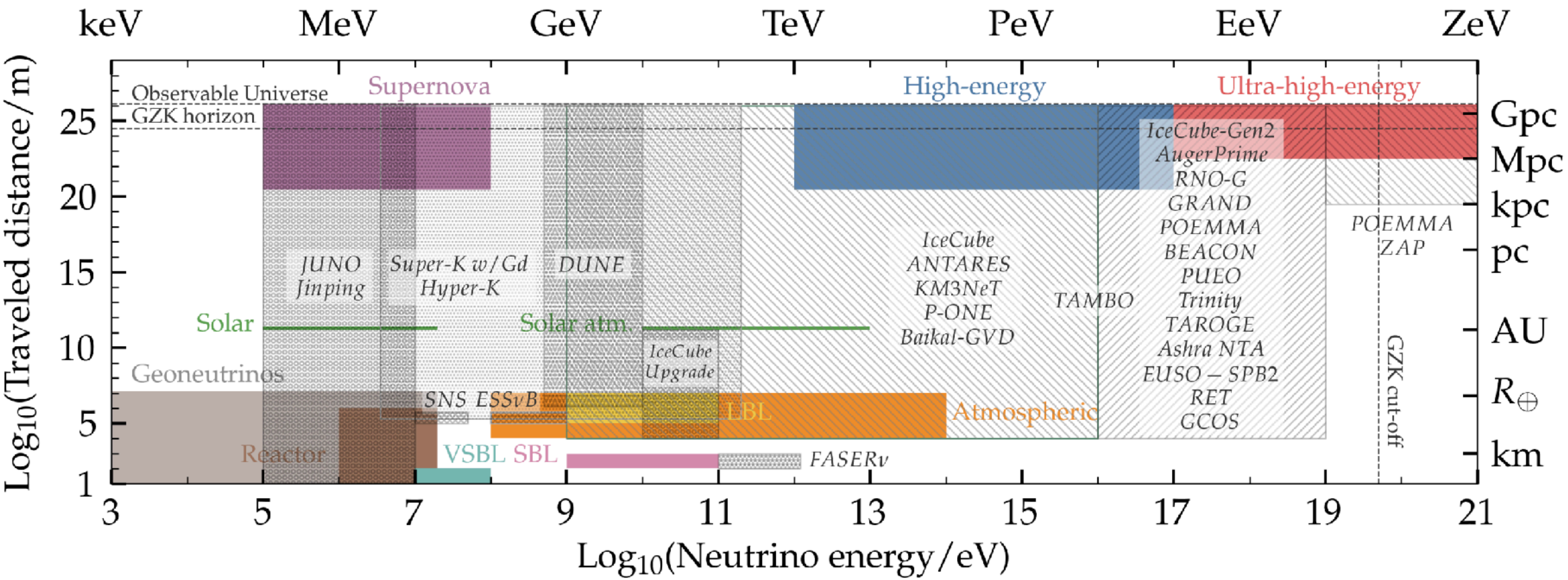
Input to European Strategy for Particle Physics 2026 Update


Enhancing New Physics Searches with a Future Beam Dump Configuration at SBND[a]

B. Dutta,[1,†] D. Goswami,[1,‡] A. Karthikeyan,[1,§] V. Pandey,[2,¶] Z. Tabrizi,[3,4,**] and R. G. Van de Water[5,††]

Ultra-long-distance neutrino propagation

Ultra-long baseline propagation



$$e^{-i(E_1-E_2)t} \longrightarrow e^{-i\frac{\Delta m^2 t}{2E}} \times e^{-it\epsilon_{\text{new physics?}}}$$

Neutrino Spin Flavor Precession

Resonant spin-flavor rotation:
C.S. Lim, W. J. Marciano (1988)
E. Akhmedov (1988)

Transition magnetic moment couples to background B-field to precess the neutrino spin and leads to:

$\nu_e^L \to \bar{\nu}_\mu^R$ (for Majorana ν)

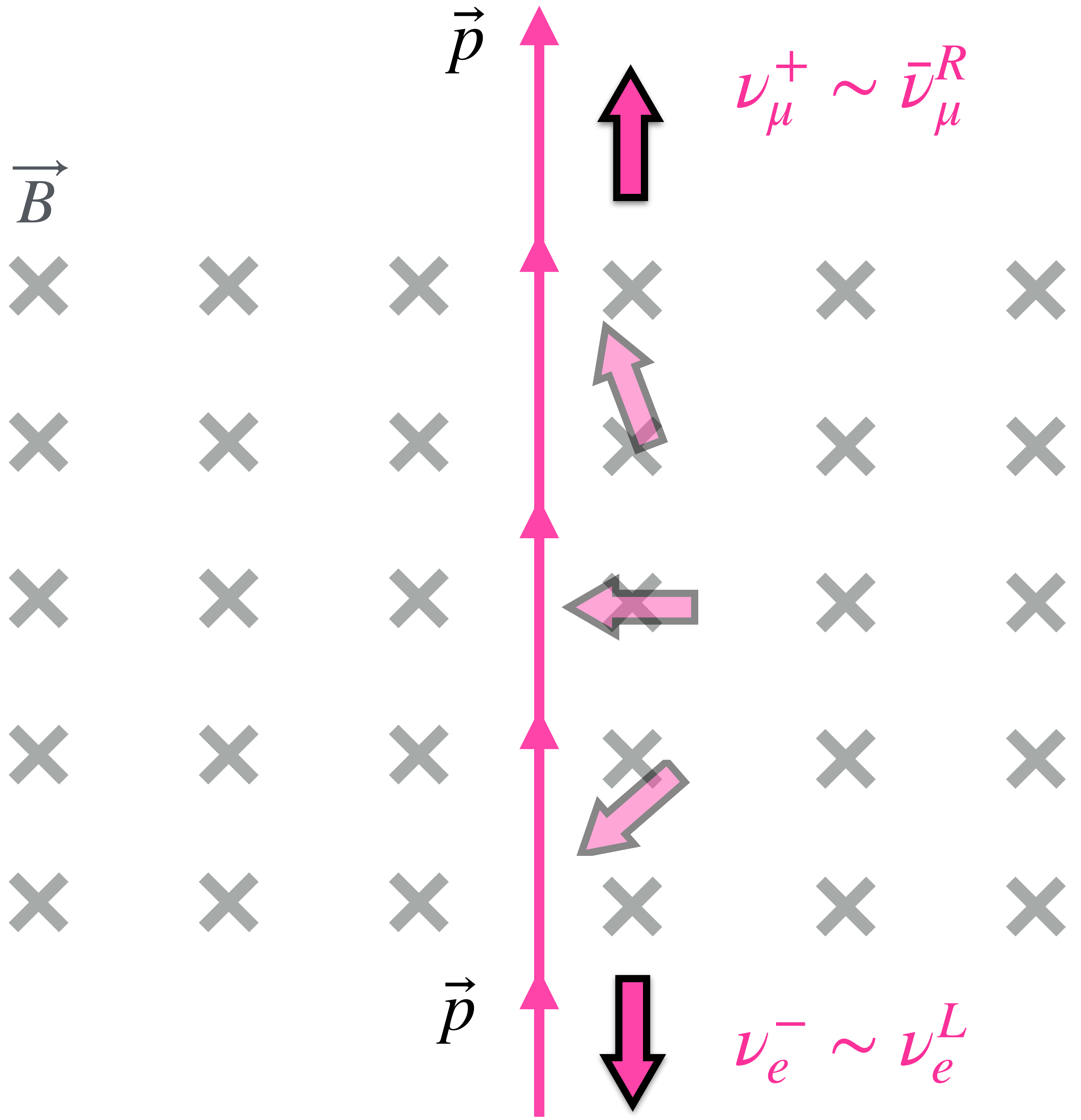
For Majorana, have flavor off-diagonal moments:

$$\mathscr{L} = \frac{\mu}{2}\bar{\nu}_e \sigma_{\mu\nu} F^{\mu\nu} \nu_\mu$$

See for example:

J. Kopp, T. Opferkuch, E. Wang, JCAP 03 (2024) 043

V. Brdar, T. Cheng, H-J. Kuan,Y-Y. Li, JCAP 07 (2024) 026



Propagation of Majorana Neutrinos through an Ultra-Light Dark Matter Background

A Dark Vector Dark Matter background can couple to an axial-vector Majorana neutrino current:

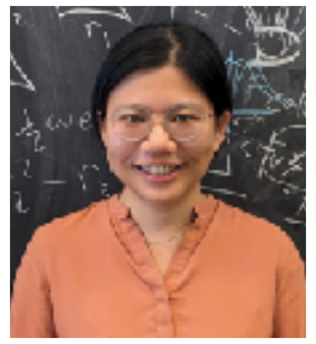
$$\mathscr{L} \supset e' A'_\mu (\bar{\nu}\gamma^\mu \gamma^5 \nu)$$

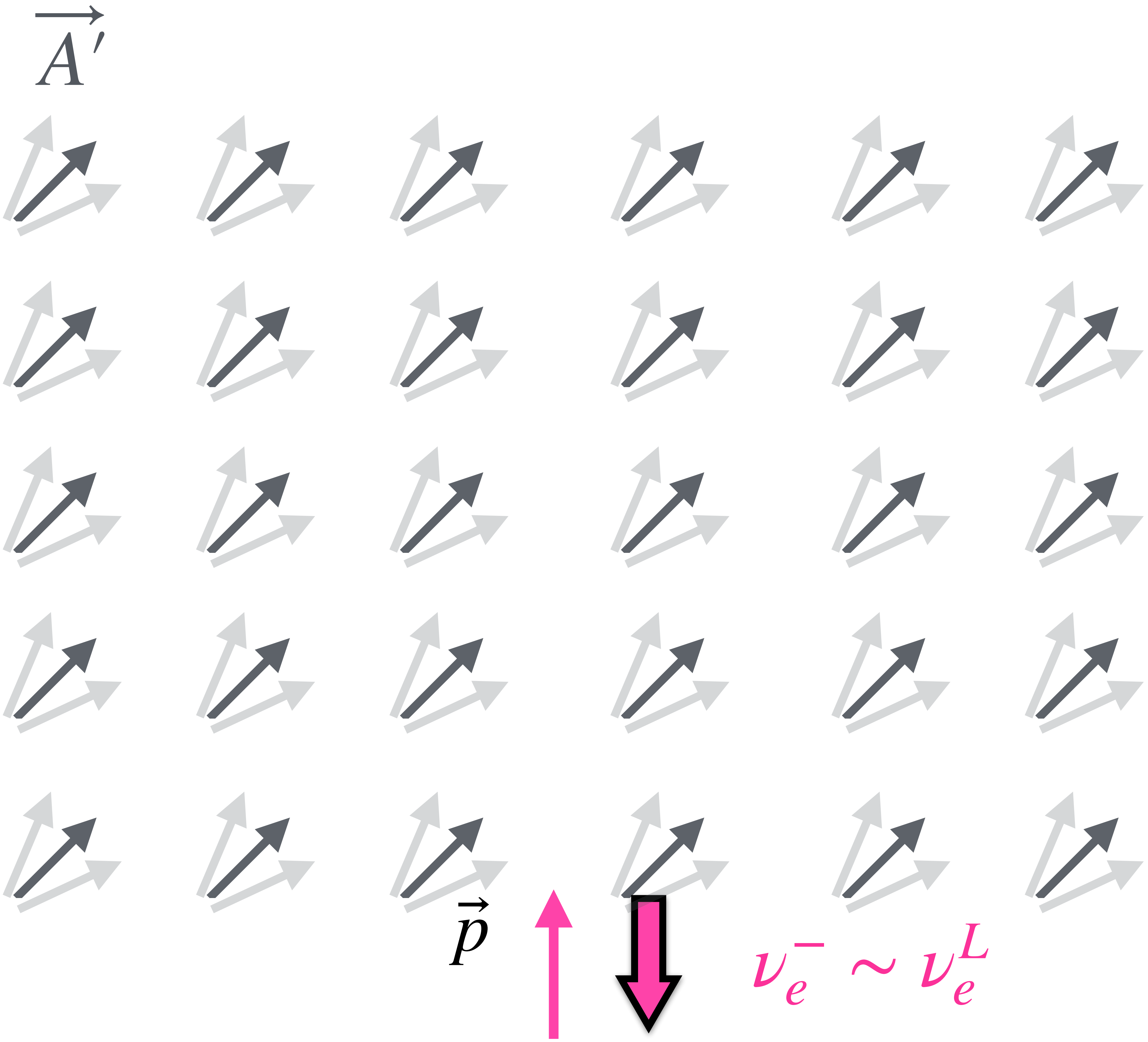
Classical field background with $m_{A'} \ll 1$ eV.

$$\vec{A'}(t) \simeq \frac{\sqrt{2\rho_{\rm DM}/3}}{m_{A'}} \,\mathrm{Re}\left[e^{i m_{A'} t} \sum_{i=1}^{3} \alpha_i \, e^{i\phi_i} \, \hat{n}_i \right]$$

In progress and in collaboration with:
A. Berlin, R. Capdevilla, T. Cheng, P. Machado (FNAL)





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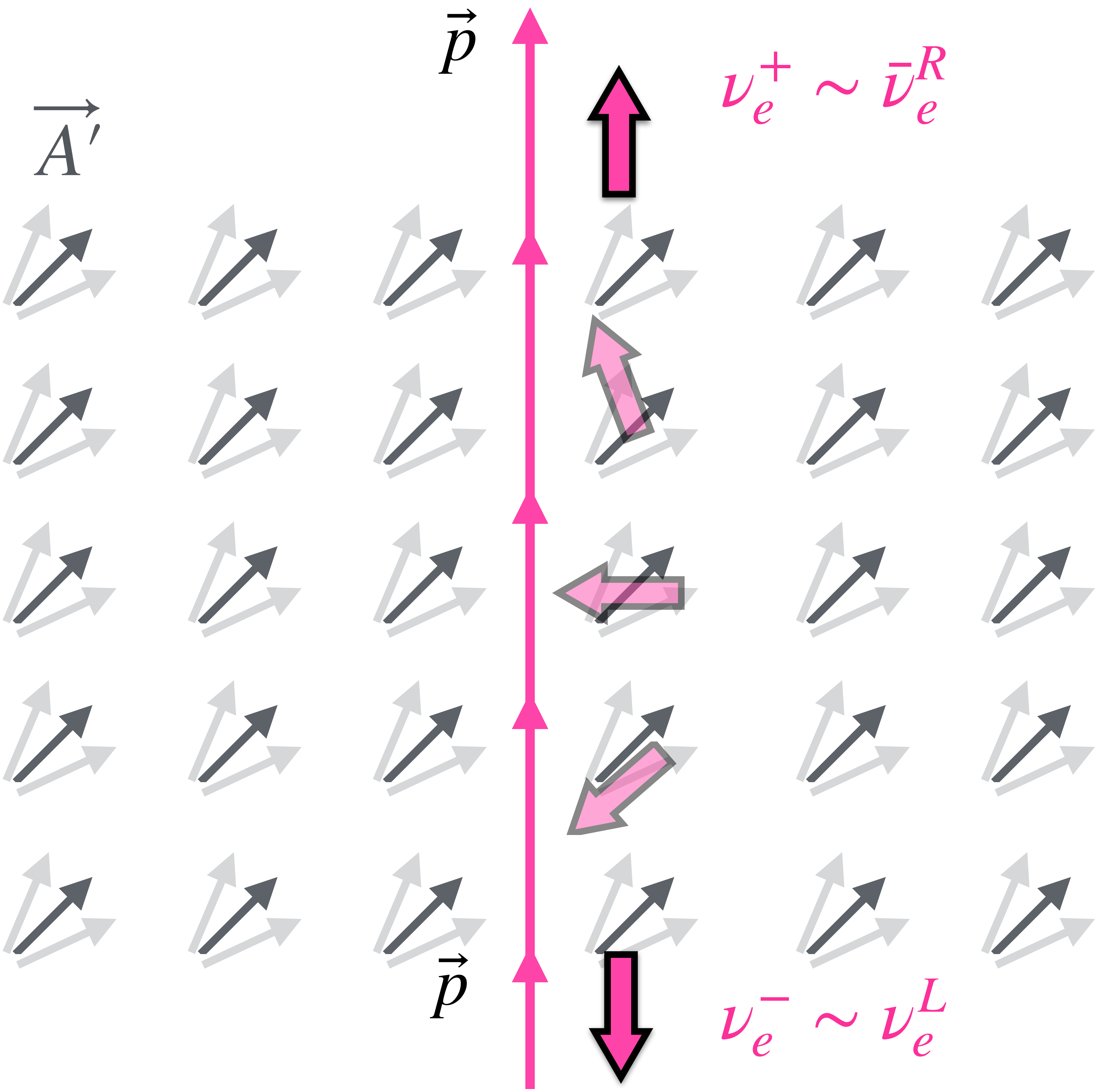


Note: For illustrative purposes only.

The neutrino spin flip is far slower!

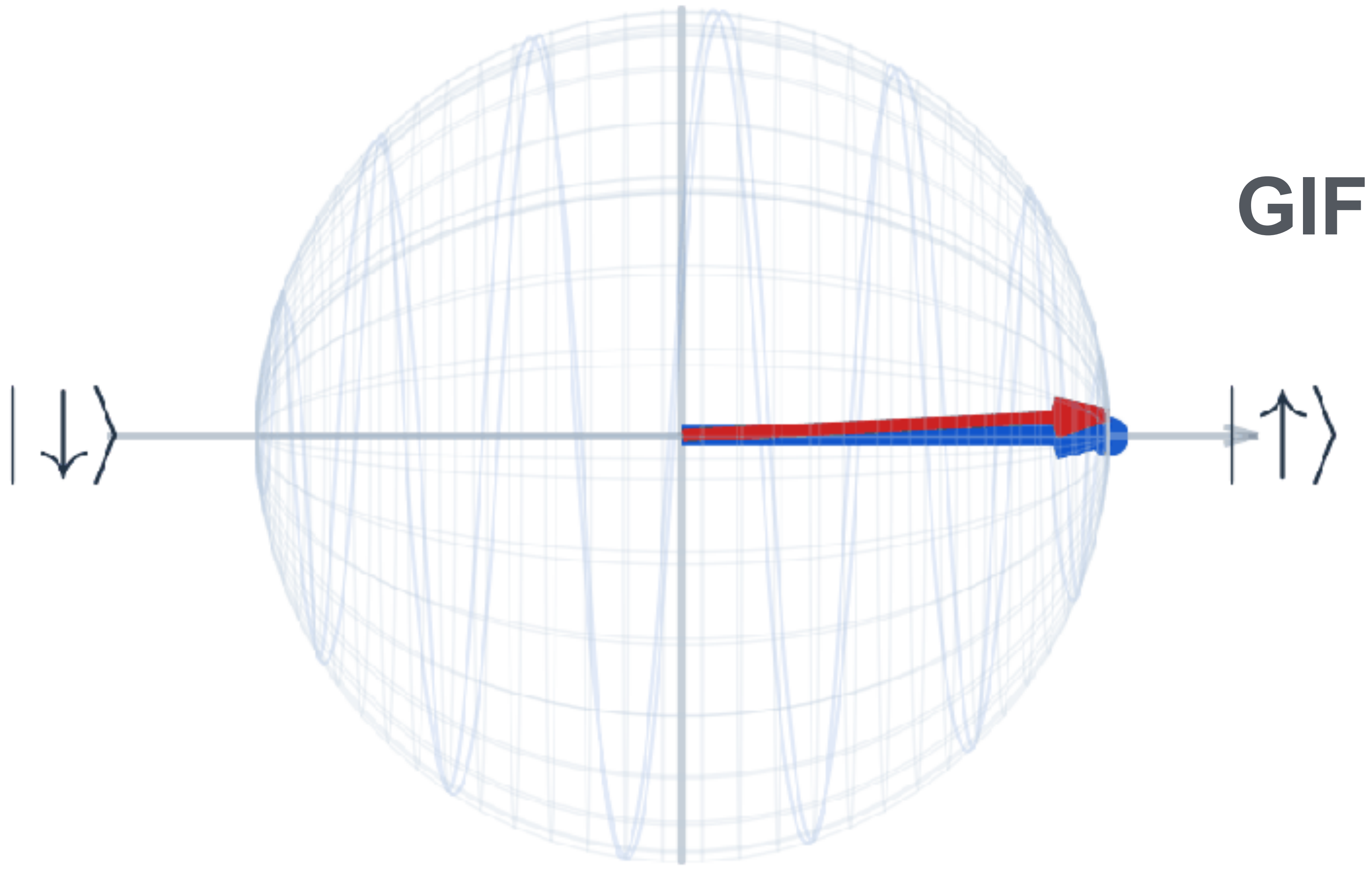
Neutrino "Rabi Oscillations"

The neutrino spin $\vec{s}$ precesses around the DM polarization vector $\overrightarrow{A'}$

From the ν rest frame $A'_\perp \ll A'_\parallel$, so the field is mostly longitudinal.

Polarization of DM field is randomized at each spatial-coherent patch.

For sufficiently long propagation time, spin flip implies $\nu \to \bar{\nu}$ for Majorana neutrinos.



GIF

Neutrino Propagation

$\mathbf{B}(t)$ (total field) **(Dark Matter polarization vector)**

spin $\langle \mathbf{S} \rangle$ **(Neutrino Spin)**

Effective Hamiltonian of dark matter V interaction with the neutrino spin

$$H = V_{\parallel} \cos(\omega_0 t + \phi_z)\, \sigma_z + V_{\perp} \left(\cos(\omega_0 t + \phi_x)\, \sigma_x + \cos(\omega_0 t + \phi_y)\, \sigma_y\right)$$

Rabi oscillation with elliptically-polarized field

$\omega_0 \sim \gamma m_{A'}$, $\quad V_{\parallel} \sim \gamma V_{\perp}$, $\quad V_{\perp} \sim e'\sqrt{2\rho_{\mathrm{DM}}}/m'_A$ where. $\gamma = E_\nu/m_\nu$

With the rotating wave approximation, the spin flip probability gives

$$P_{\nu\to\bar{\nu}} \simeq \sin^2(\Omega_{\mathrm{eff}}\, t) \xrightarrow{\text{Small } t} P_{\nu\to\bar{\nu}} \sim \frac{e'\sqrt{2\rho_{\mathrm{DM}}}\, L}{\gamma^2\, m_{A'}\, v_{\mathrm{DM}}} \times \varepsilon^2$$

$$\varepsilon \equiv \sqrt{\sin^2(\phi_z - \phi_y) + \sin^2(\phi_z - \phi_x)}$$

"Ellipticity"

$\phi_{x,y,z}$ random phases in each coherent patch

Supernova $\nu \to \bar{\nu}$ conversion

Huge ν_e burst from neutronization burst:

$$e^- + p^+ \to n + \nu_e$$

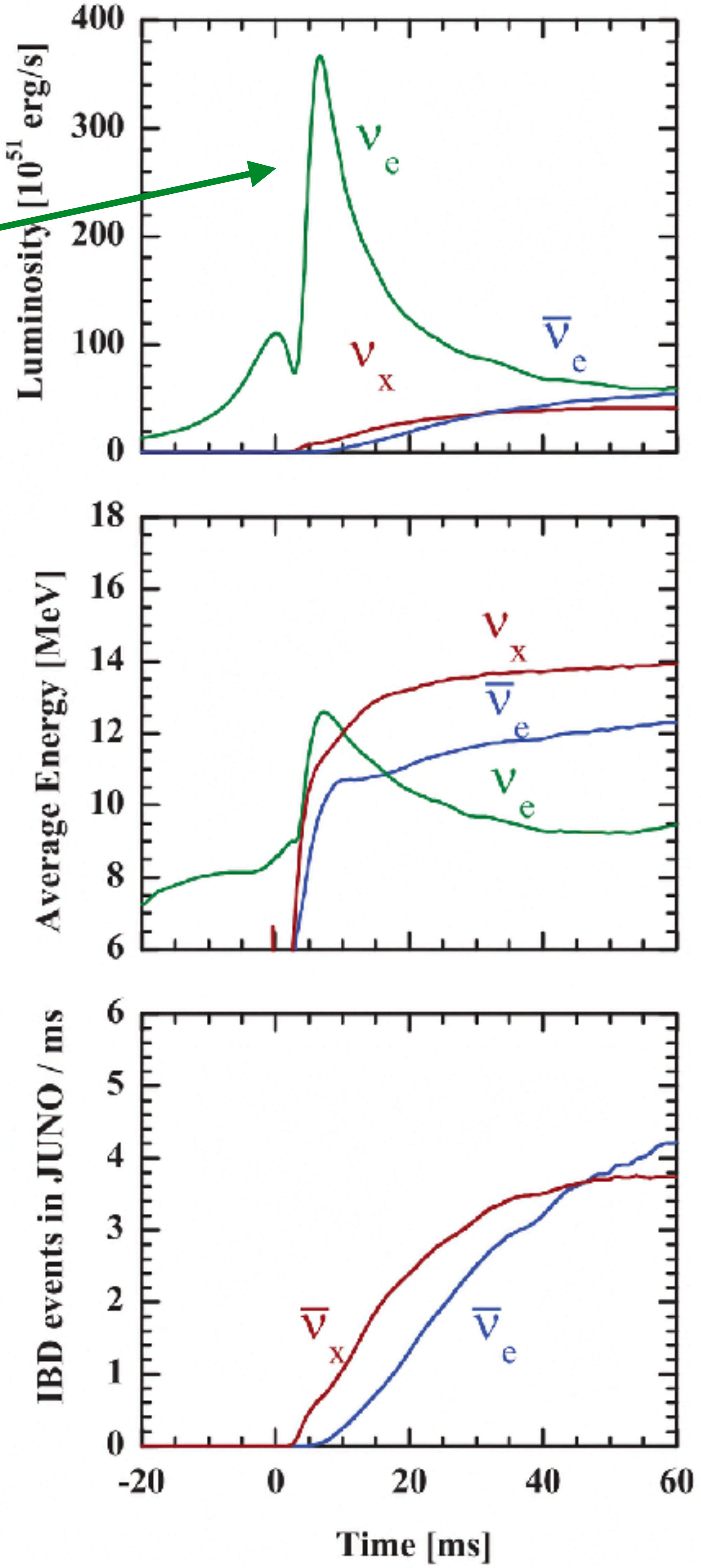
This feature is rather robust in supernovae:

$$F_{\nu_e} > F_{\bar{\nu}_e} \gtrsim F_{\nu_x} = F_{\bar{\nu}_x}$$

Especially interesting for **DUNE** that can see ν_e through

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

Neutronization $\mathcal{O}(30\,\text{ms})$



+ **Accretion phase** $\mathcal{O}(1\text{ s})$ duration

Cooling phase + $\mathcal{O}(10\,\text{s})$ duration

Supernova $\nu \to \bar{\nu}$ conversion

Huge ν_e burst from neutronization burst:

$$e^- + p^+ \to n + \nu_e$$

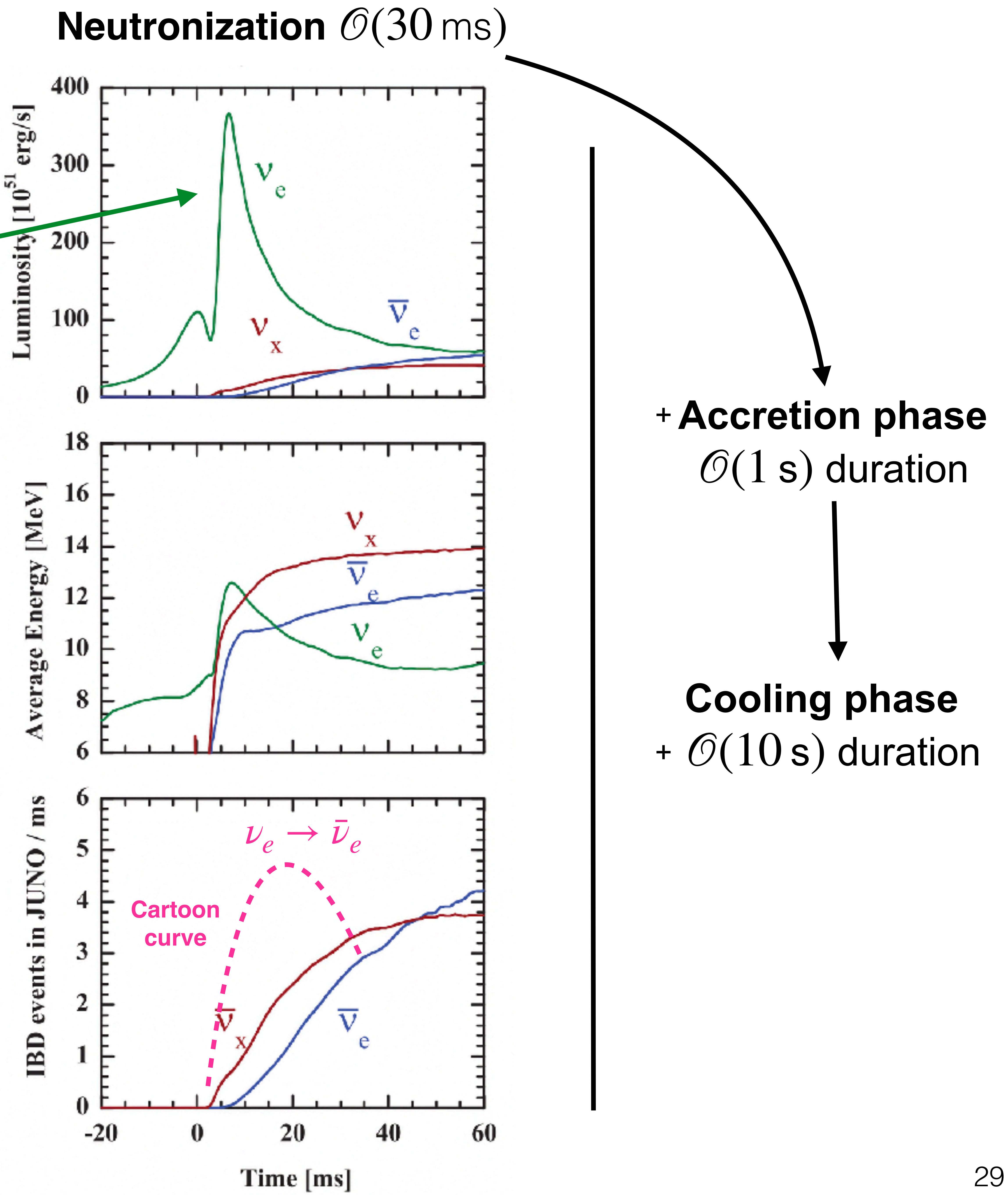
This feature is rather robust in supernovae:

$$F_{\nu_e} > F_{\bar{\nu}_e} \gtrsim F_{\nu_x} = F_{\bar{\nu}_x}$$

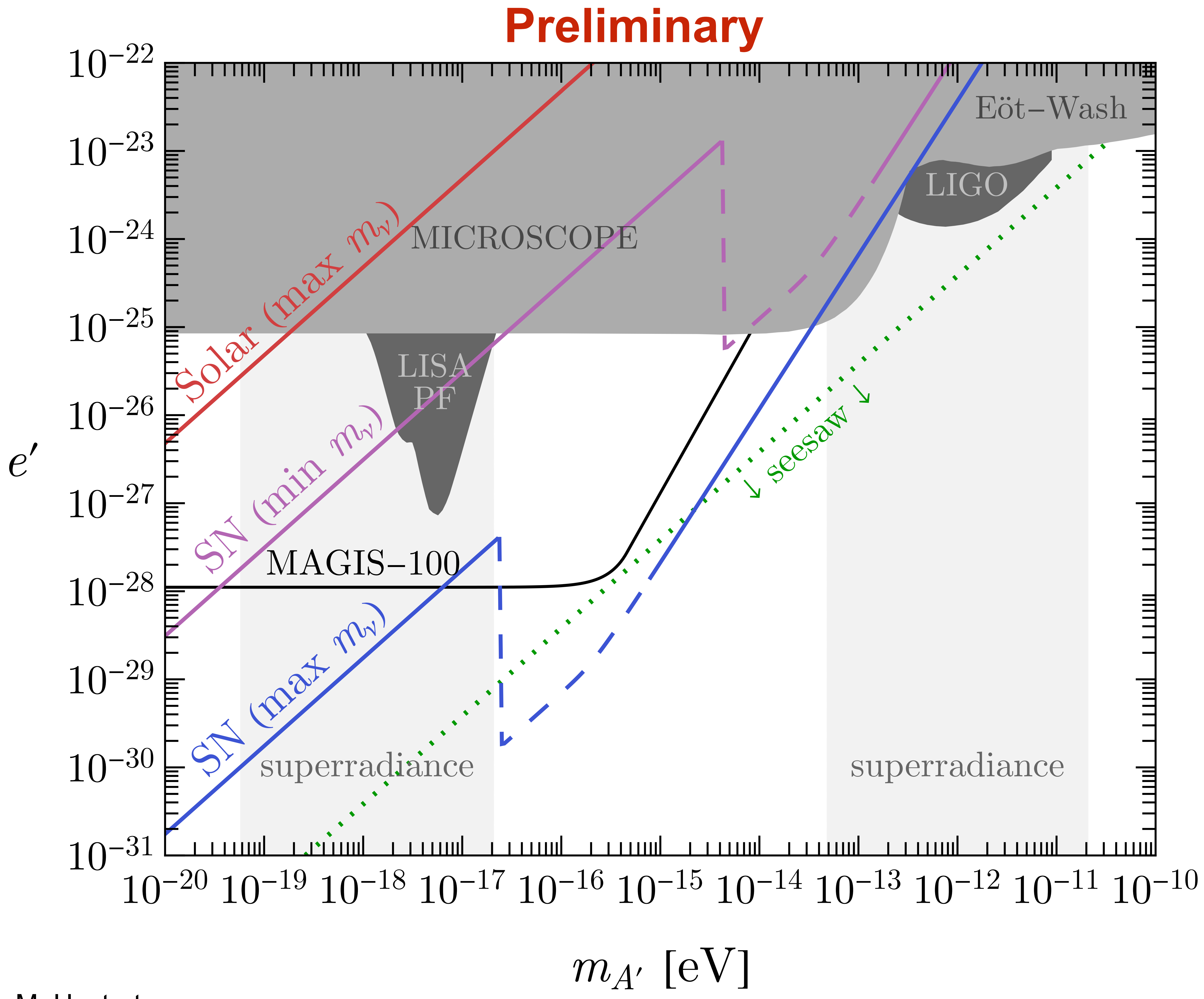
Especially interesting for **DUNE** that can see ν_e through

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

The subsequent $\bar{\nu}_e$ components can be detected with IBD events at, e.g., **JUNO** and **Hyper-K.**



Neutrino Spin Flip in the Vector Dark Matter Parameter Space



Regions of Interest

Vector dark matter coupled to Majorana ν.

max: largest ν mass
min: smallest ν mass

Equilibration between ν and $\bar{\nu}$.

Take Home

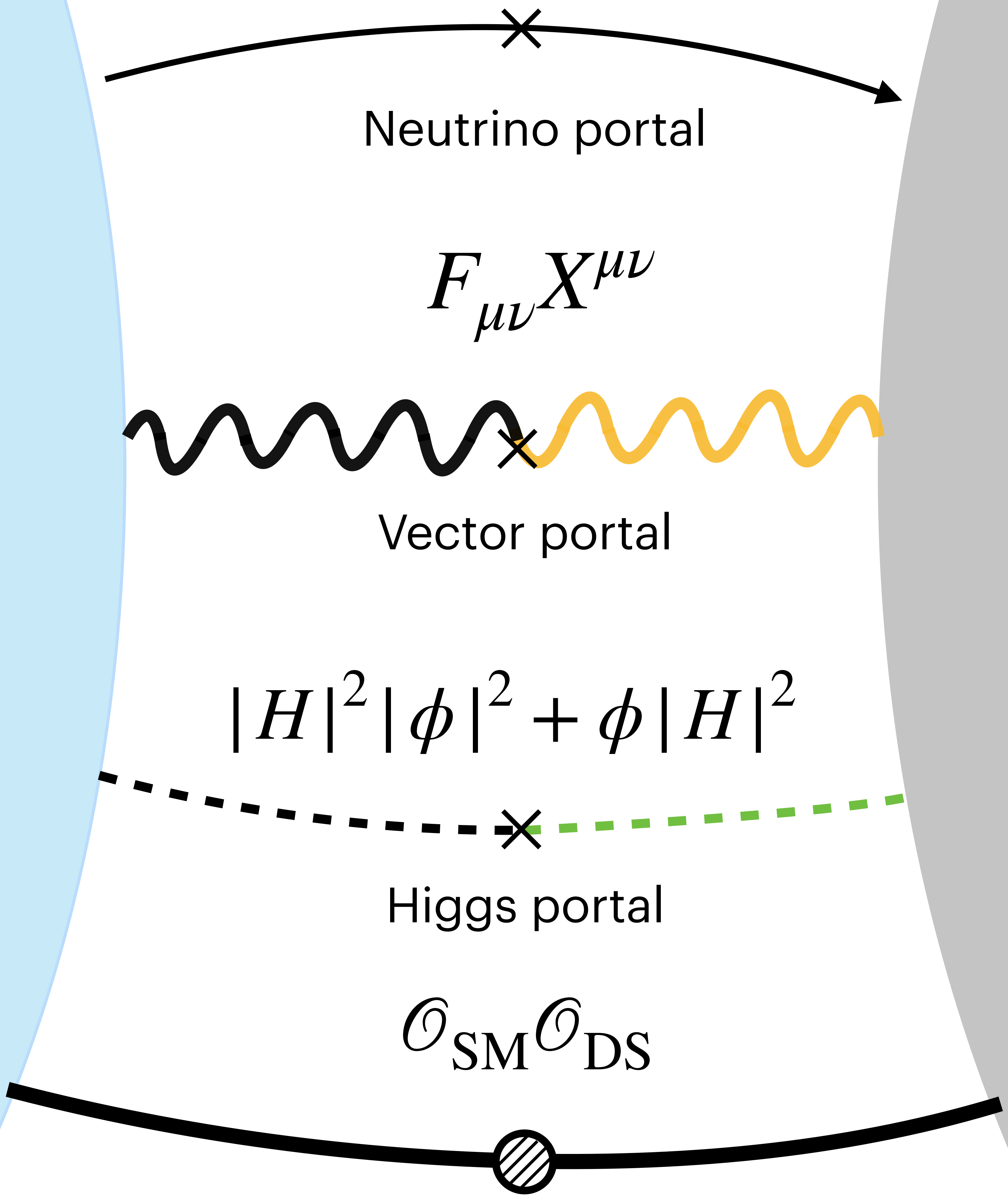
The SM may be incomplete already **at low energies.**
Neutrino masses are one crucial piece of the puzzle.

Right-handed neutrinos provide a unique opportunity in the lepton sector.
We are exploring it across multiple energy scales.

Neutrinos cast a wide net on new physics,
from **ultra-light** to **ultra-heavy dark matter**, new fermion **mass mechanisms**, and a whole range of **lamppost dark sectors**.

STANDARD MODEL

Context



$(LH)N$

Neutrino portal

Neutrino masses and mixing.
Seesaw partners.

$F_{\mu\nu}X^{\mu\nu}$

Vector portal

New $U(1)'$ gauge symmetry.
DM-SM force mediator.

$|H|^2|\phi|^2 + \phi|H|^2$

Higgs portal

Extremely general.
Scalar potential.

$\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DS}$

Non-renormalizable portals

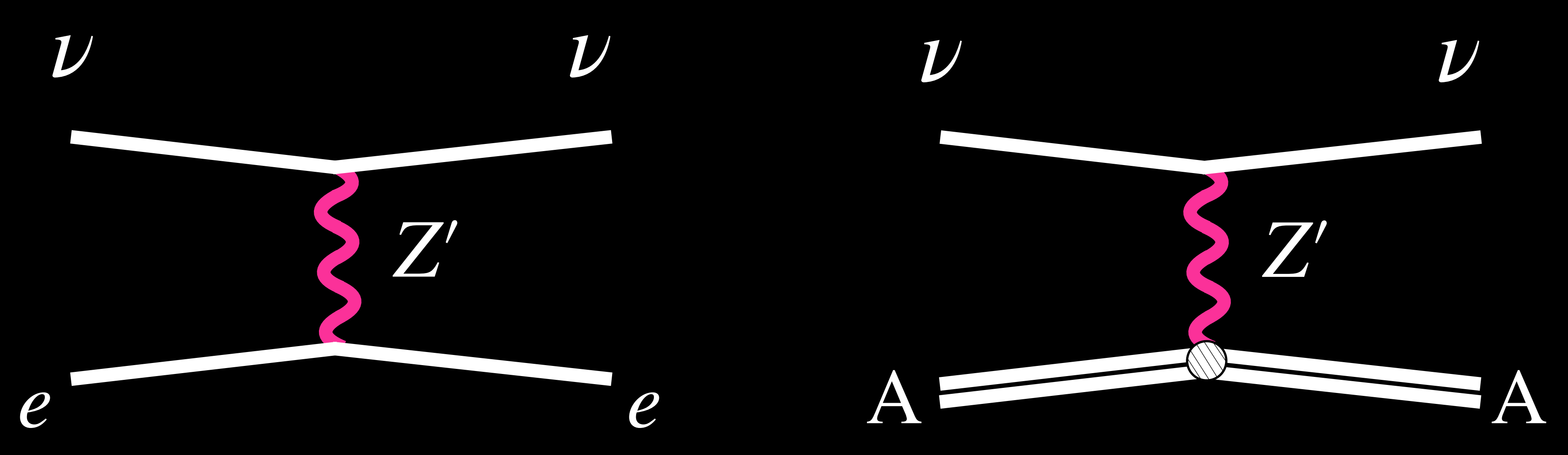
Hybrid approach:
light particles as messengers of UV scale.


STANDARD MODEL
Decay width of dark particle to SM
ν_α
$U_{\alpha N}$
N
Neutrino portal
Heavy Neutrinos
$\Gamma \sim |U_{\alpha N}|^2 G_F^2 M_N^5$
weaker-than-Weak
γ
ε
A'
Vector portal
Dark photons
$\Gamma \sim (e\varepsilon)^2 m_{A'}$
weaker-than-EM
h
θ
ϕ
Higgs portal
Dark Higgs
$\Gamma \sim \theta^2 y_f^2 m_S$
weaker-than-Yukawa
$\frac{1}{\Lambda^{D-4}}$
Non-renormalizable portals
Axion-like-particles,
χSMEFT, νSMEFT, etc.
$\Gamma \sim \frac{m_a m_e^2}{\Lambda^2}$
e.g. ALP decay constant Λ

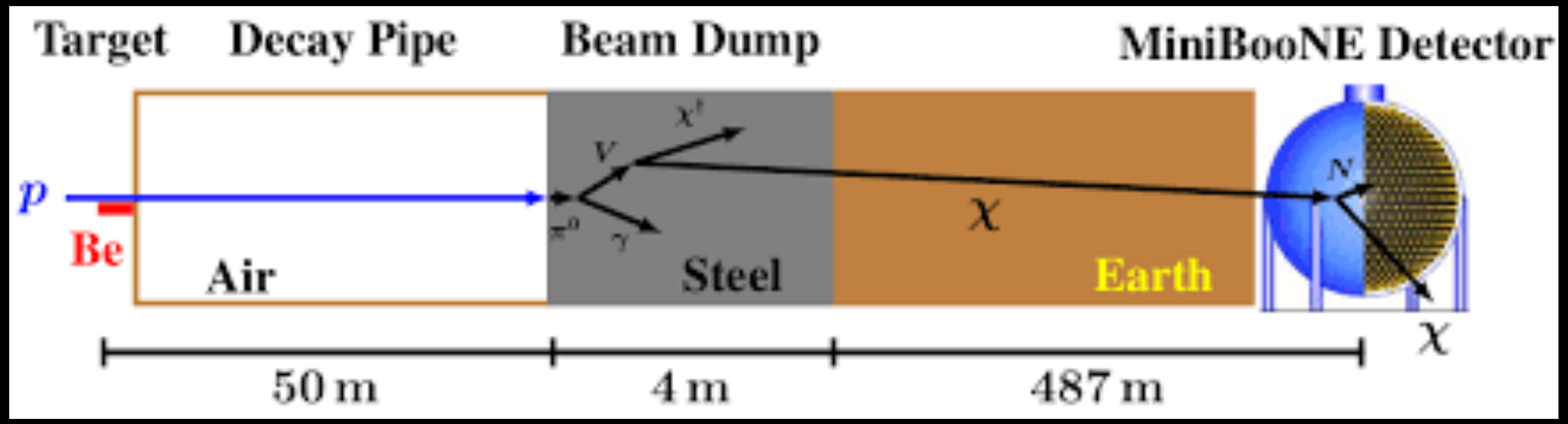
Other examples of beyond-the-Standard Model applications:

New Forces

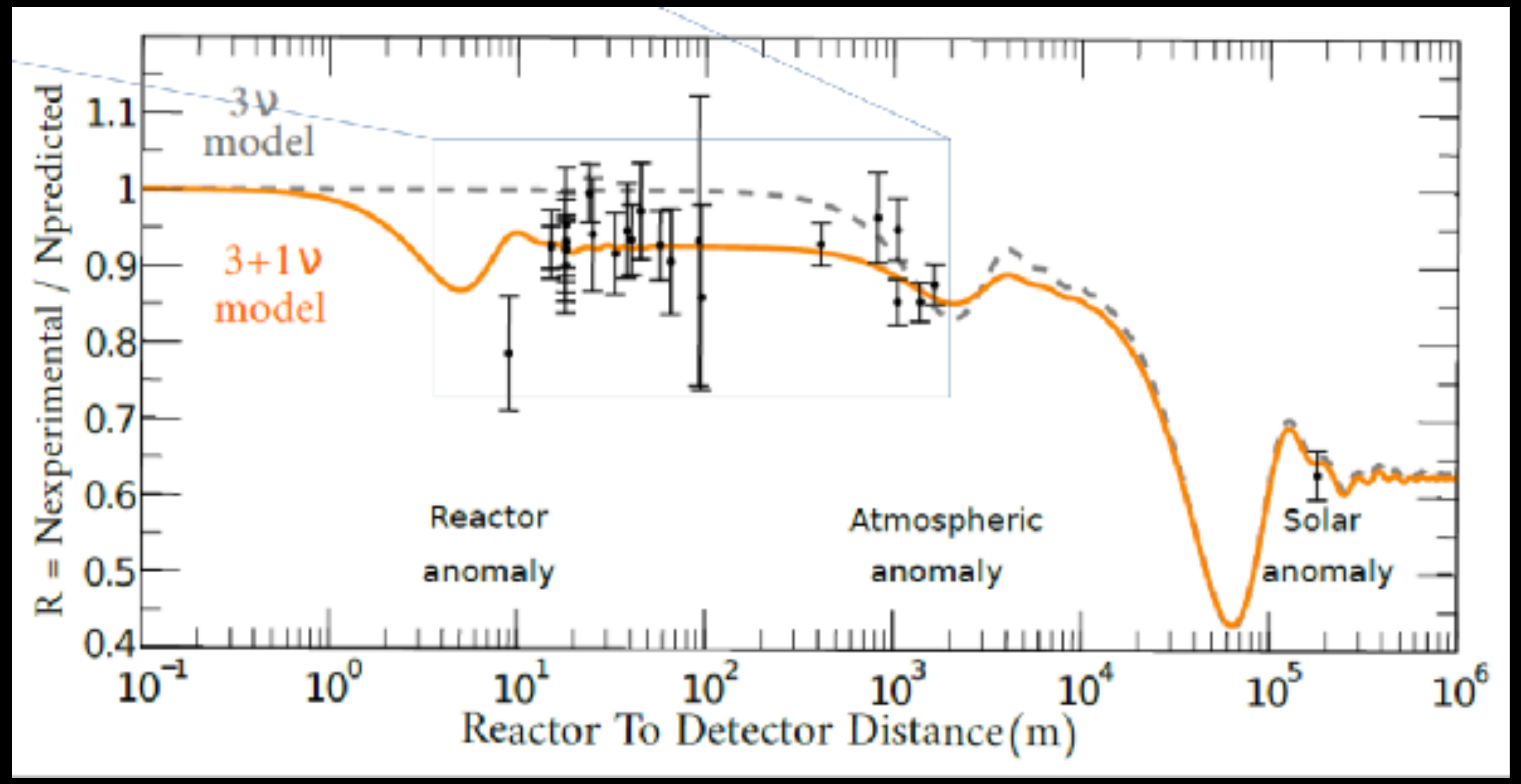
Non-Standard Interactions (NSIs)



Light Dark Matter



Sterile Neutrino Oscillations



Long-Lived Particles