Beyond the Standard Model Searches with Neutrinos

UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

KITP Interdisciplinary Developments in Neutrino Physics
March 30th 2022

Matheus Hostert

Perimeter Institute and University of Minnesota

UNIVERSITY OF MINNESOTA

PERIMETER
INSTITUTE

THE NEUTRINO PORTAL

Neutrino masses

Type-I seesaw, low-scale variants, and more exotic.

Baryon asymmetry of the Universe

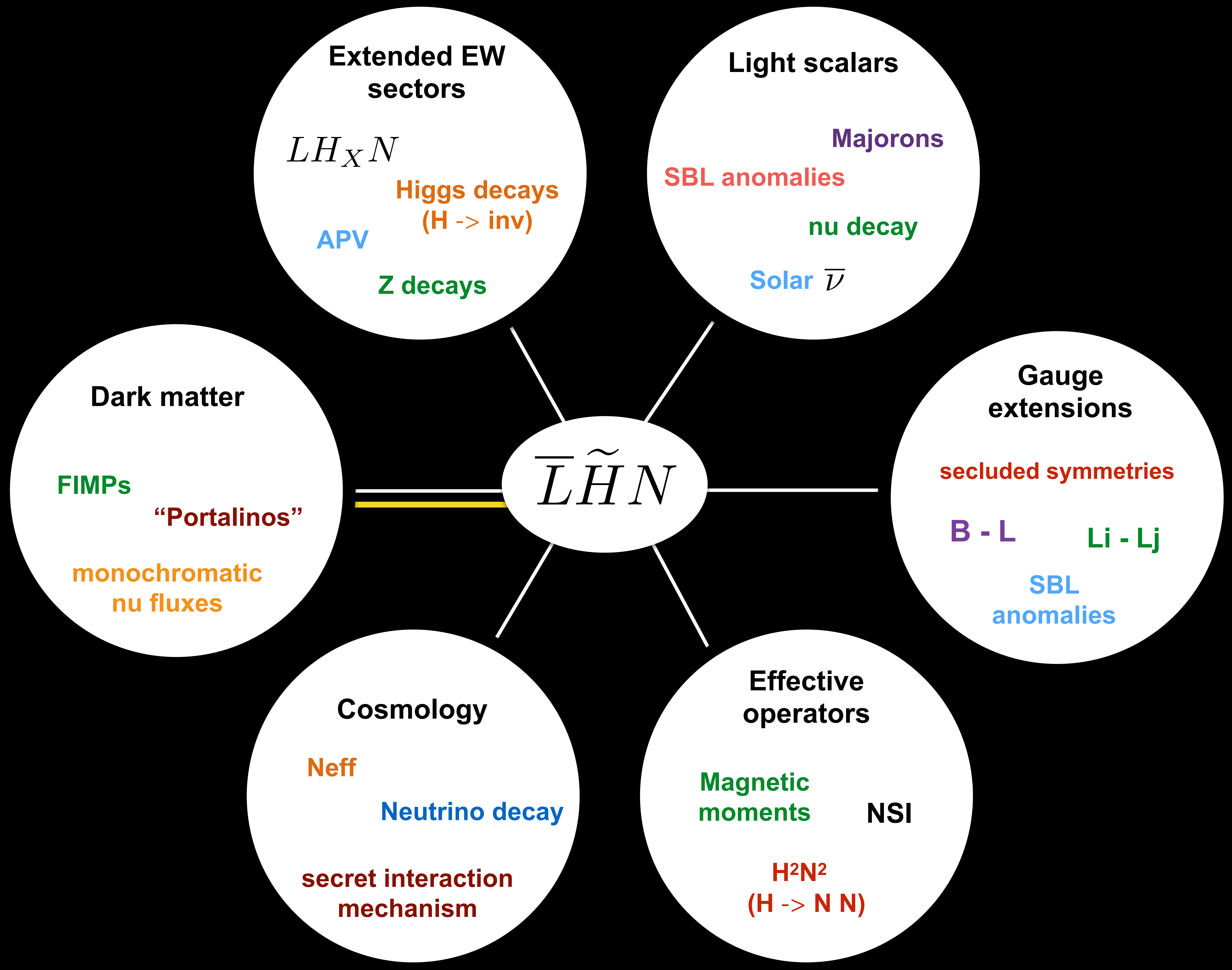
Leptogenesis, nu-assisted EW baryogenesis.

Dark matter

Warm DM or DM annihilation partner.

Experimental anomalies

Short-baselines, Hubble, XENON1T, + others.



$\overline{L}\widetilde{H}N$

Extended EW sectors

$LH_X N$

Higgs decays (H -> inv)

APV

Z decays

Light scalars

Majorons

SBL anomalies

nu decay

Solar $\overline{\nu}$

Dark matter

FIMPs

"Portalinos"

monochromatic nu fluxes

Gauge extensions

secluded symmetries

B - L

Li - Lj

SBL anomalies

Cosmology

Neff

Neutrino decay

secret interaction mechanism

Effective operators

Magnetic moments

NSI

H^2N^2 (H -> N N)

The neutrino portal is one of the most well-motivated extensions of the SM. **It may lead somewhere.**

The seesaw mechanism

Type-I seesaw:

$$\mathscr{L} \supset -y^{\nu}\left(\overline{L}\tilde{H}\right)N - \frac{M_N}{2}\overline{N^c}N + \text{h.c.}$$

This is a matrix problem:

$$\mathscr{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \quad \text{where } M_D = \frac{Y v_{EW}}{\sqrt{2}}$$

$$\boxed{\underset{(3\text{x}3)}{M_\nu} \sim \underset{(3\text{x}?)}{M_D}\underset{(?\text{x}?)}{M_N^{-1}}\underset{(?\text{x}3)}{M_D^T}}$$

We know nothing about M_N. **How many states? Does it carry new symmetries? New dynamics?**

Low Scale Seesaws

LNV = lepton number violating

3 families of neutral leptons — new symmetries in M_N

$$-\mathscr{L}_{\nu-\text{mass}} \supset \frac{1}{2}\left(\overline{\nu_L} \quad \overline{N} \quad \overline{S}\right)\begin{pmatrix} 0 & m & \varepsilon' \\ m & \mu' & \Lambda \\ \varepsilon' & \Lambda & \mu \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix} + \text{h.c.}$$

(L= -1)

(L= +1)

$$\begin{cases} M_D = \begin{pmatrix} m & \epsilon' \end{pmatrix} \\ M_N = \begin{pmatrix} \mu' & \Lambda \\ \Lambda & \mu \end{pmatrix} \end{cases}$$

Light neutrino masses proportional to **LNV** parameters

$$m_\nu \simeq \frac{\mu m^2 - 2\varepsilon' m \Lambda + \varepsilon'^2 \mu'}{\Lambda^2 - \mu\mu'}.$$

Approximate conservation of **Lepton number** ⟶ Small neutrino masses.

Low Scale Seesaws — two kinds of contributions

“Inverse Seesaw” (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

“Minimal Radiative Inverse Seesaw” (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Low Scale Seesaws — two kinds of contributions

“Inverse Seesaw” (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **S** ($\mu \to \infty$)

$$\begin{pmatrix} 0 & m_D \\ m_D & \frac{\Lambda^2}{\mu} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \end{pmatrix}$$

“Minimal Radiative Inverse Seesaw” (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **N** ($\mu' \to \infty$)

$$\begin{pmatrix} \frac{m_D^2}{\mu'} & \frac{\Lambda m_D}{\mu'} \\ \frac{\Lambda m_D}{\mu'} & \frac{\Lambda^2}{\mu'} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$

Low Scale Seesaws — two kinds of contributions

“Inverse Seesaw” (ISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **S** ($\mu \to \infty$)

$$\begin{pmatrix} 0 & m_D \\ m_D & \frac{\Lambda^2}{\mu} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \end{pmatrix}$$

Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2 \mu^2}{\Lambda^4}$

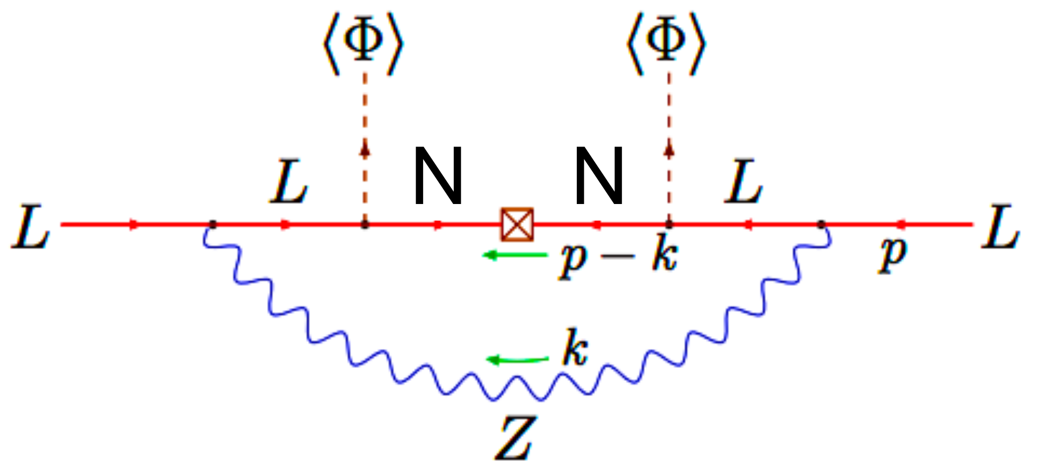
Light state: $m_\nu \simeq \frac{m_D^2}{\Lambda^2} \mu$

“Minimal Radiative Inverse Seesaw” (MRISS)

$$\begin{pmatrix} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Integrate out **N** ($\mu' \to \infty$)

$$\begin{pmatrix} \frac{m_D^2}{\mu'} & \frac{\Lambda m_D}{\mu'} \\ \frac{\Lambda m_D}{\mu'} & \frac{\Lambda^2}{\mu'} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$



Active-heavy mixing: $|U_{\alpha 4}|^2 \simeq \frac{m_D^2}{\Lambda^2}$

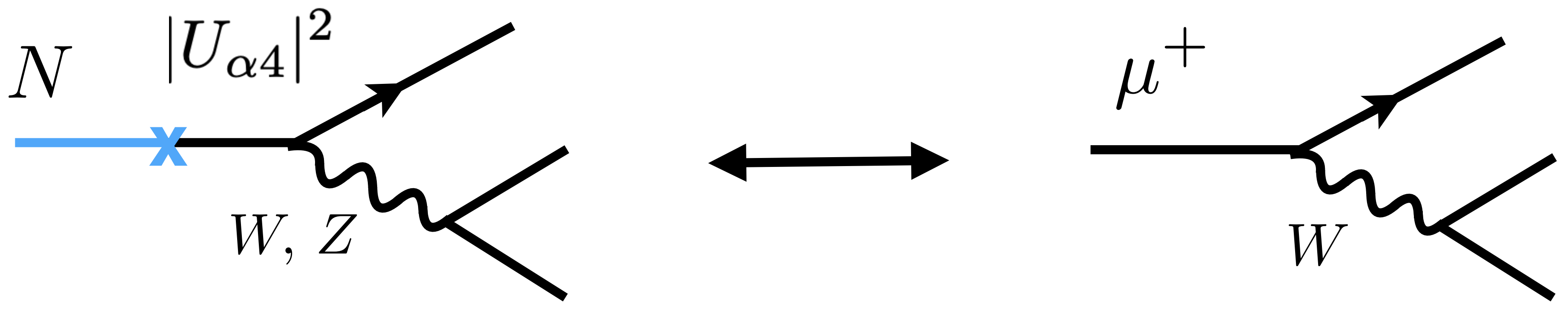
Light state:

$m_\nu^{\text{tree}} = 0$ (Holds provided #S = #N)

$m_\nu^{\text{loop}} \simeq \frac{\alpha_W}{16\pi} \frac{m_D^2}{\mu'} f(m_Z, m_h, \mu')$

Laboratory searches

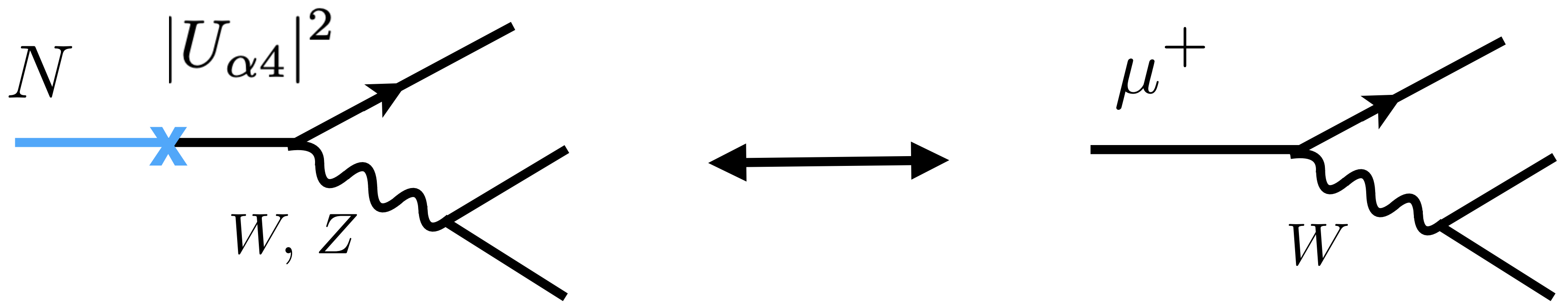
Typically, long-lived particles. $\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$



Production and decay proceed via **“weaker-than-weak”** interactions.

Laboratory searches

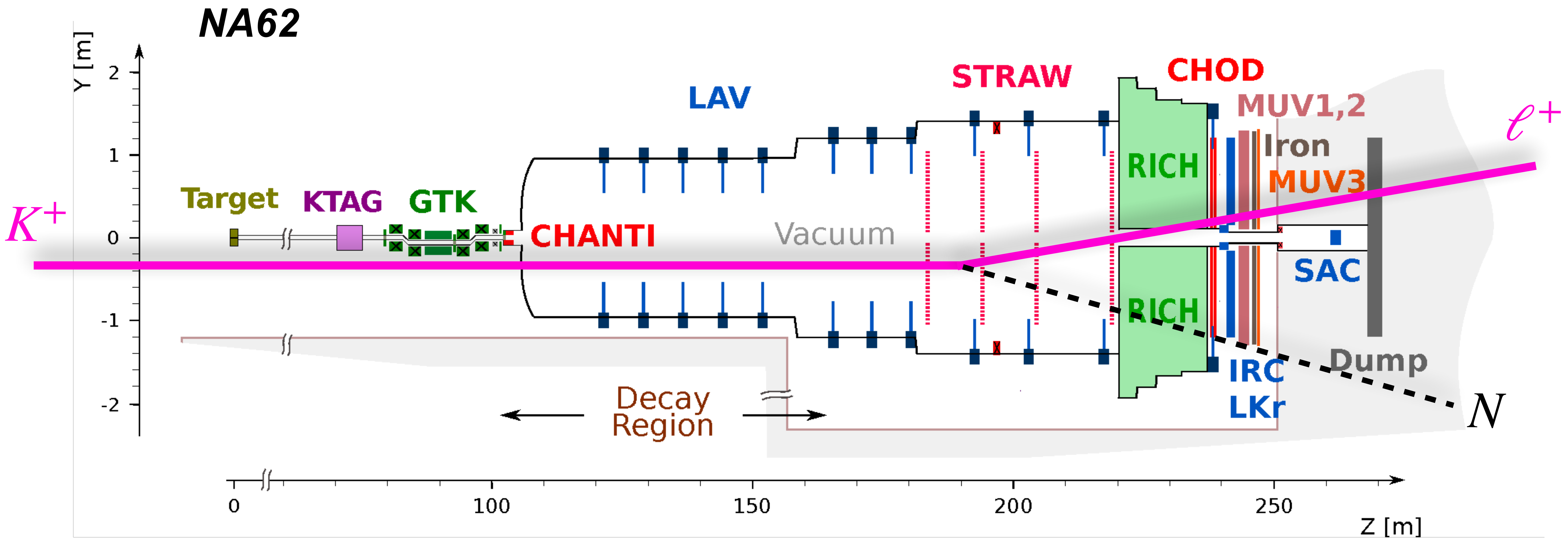
Typically, long-lived particles. $\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$



Missing mass in pion or kaon decays

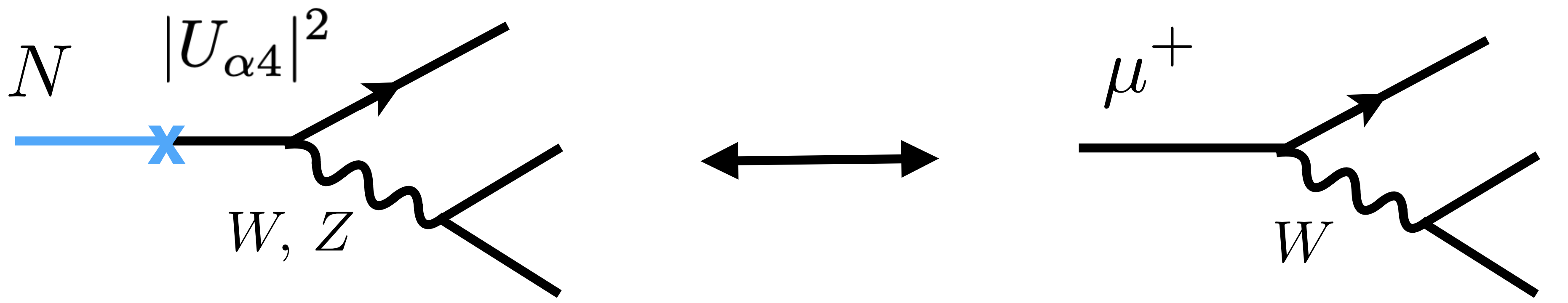
$$\pi/K \to \ell N \quad \longrightarrow \quad (p_{\pi,K} - p_\ell)^2 \overset{?}{=} M_N^2$$

Production and decay proceed via **"weaker-than-weak"** interactions.



Laboratory searches

Typically, long-lived particles. $$\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$$

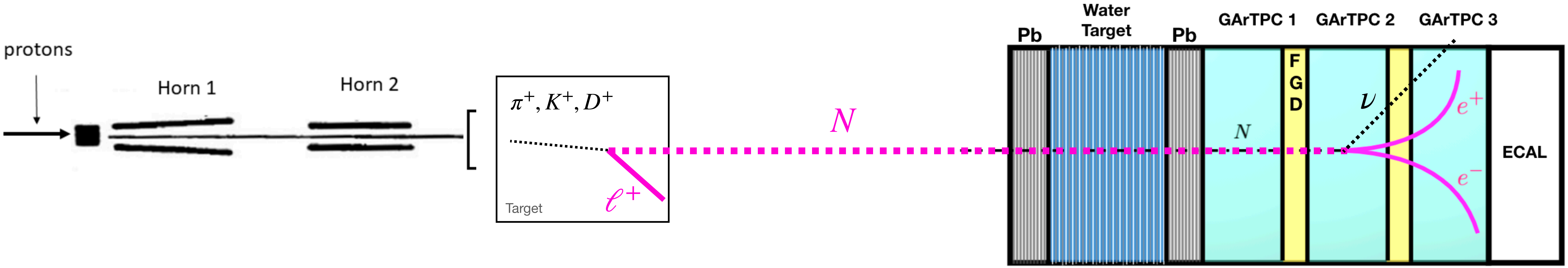


Production and decay proceed via **“weaker-than-weak”** interactions.

Decay-in-flight signatures in neutrino experiments

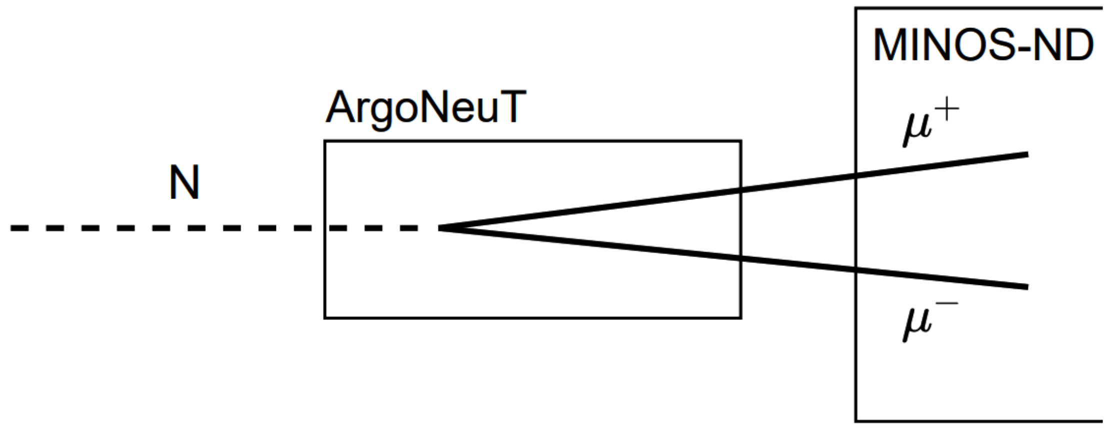
$\pi/K \to \ell N$ → N propagates → N decays visibly

ND280 @T2K



Heavy neutral lepton searches at neutrino experiments
Decay in flight

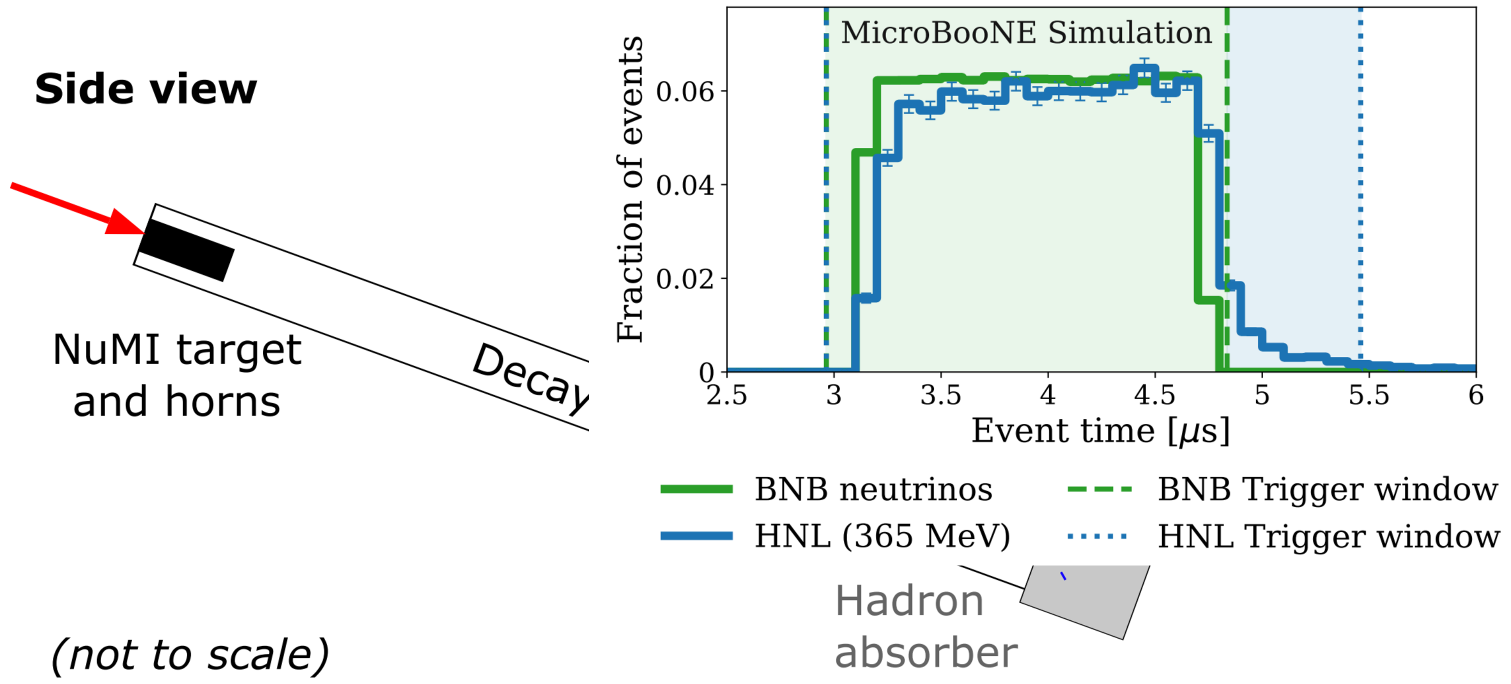
ArgoNeuT



Dimuons, also with MINOS ND reconstruction.

Unique sensitivity to tau flavor.

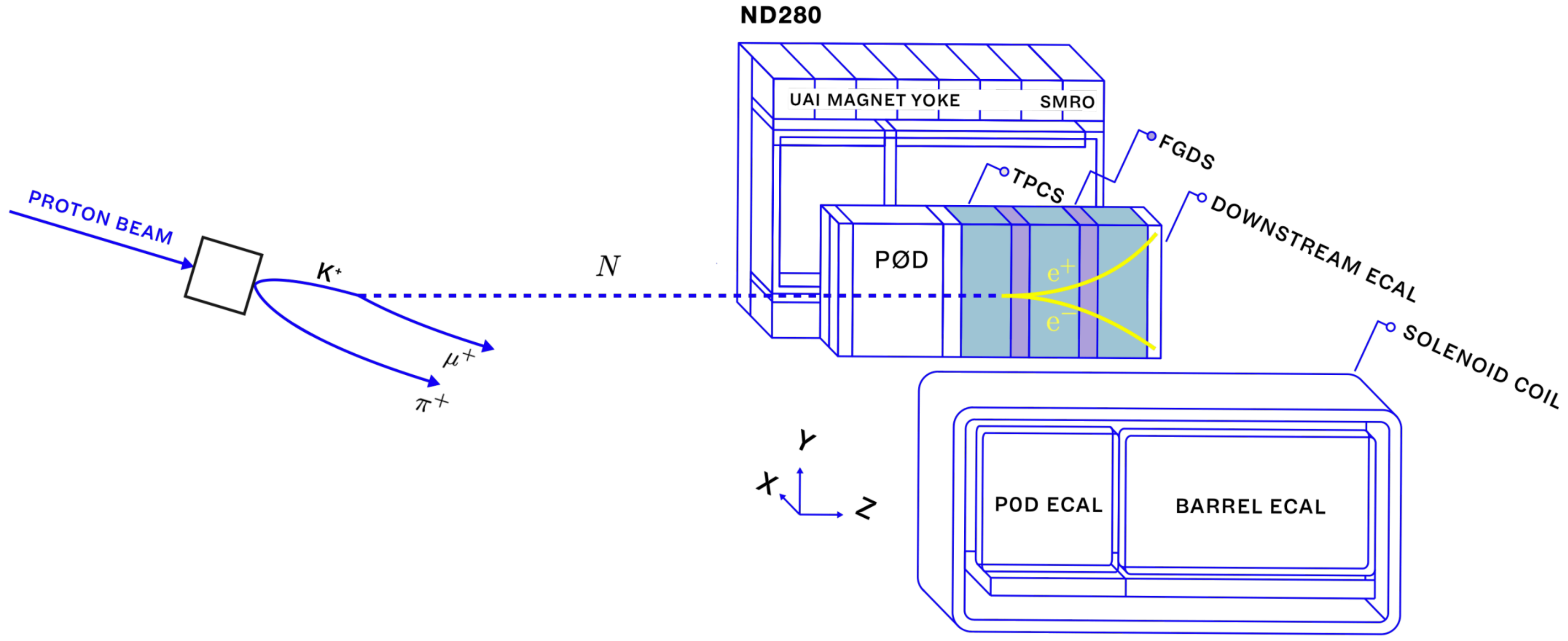
MicroBooNE



Search for $N \to \mu\pi$ in BNB production, and recast of a e^+e^- search from $K_{\mathrm{DAR}} \to \mu N$ decays at the NuMI absorber.

Mostly muon flavor.

T2K



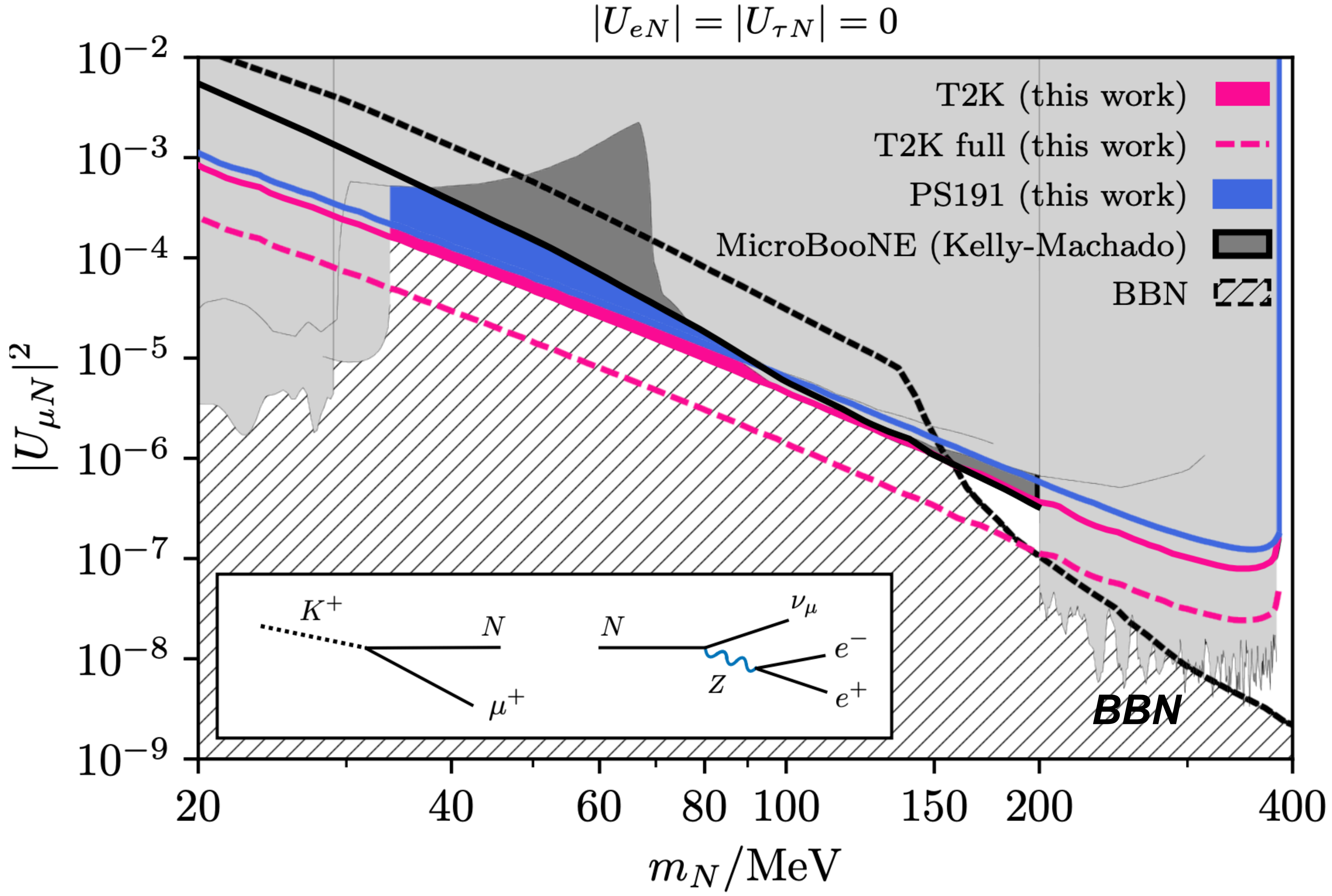
Comprehensive search that benefits from B field. *Will get even better with upgrade due to bigger low-density volume.*

All flavors, except tau.

Heavy neutral lepton searches at neutrino experiments

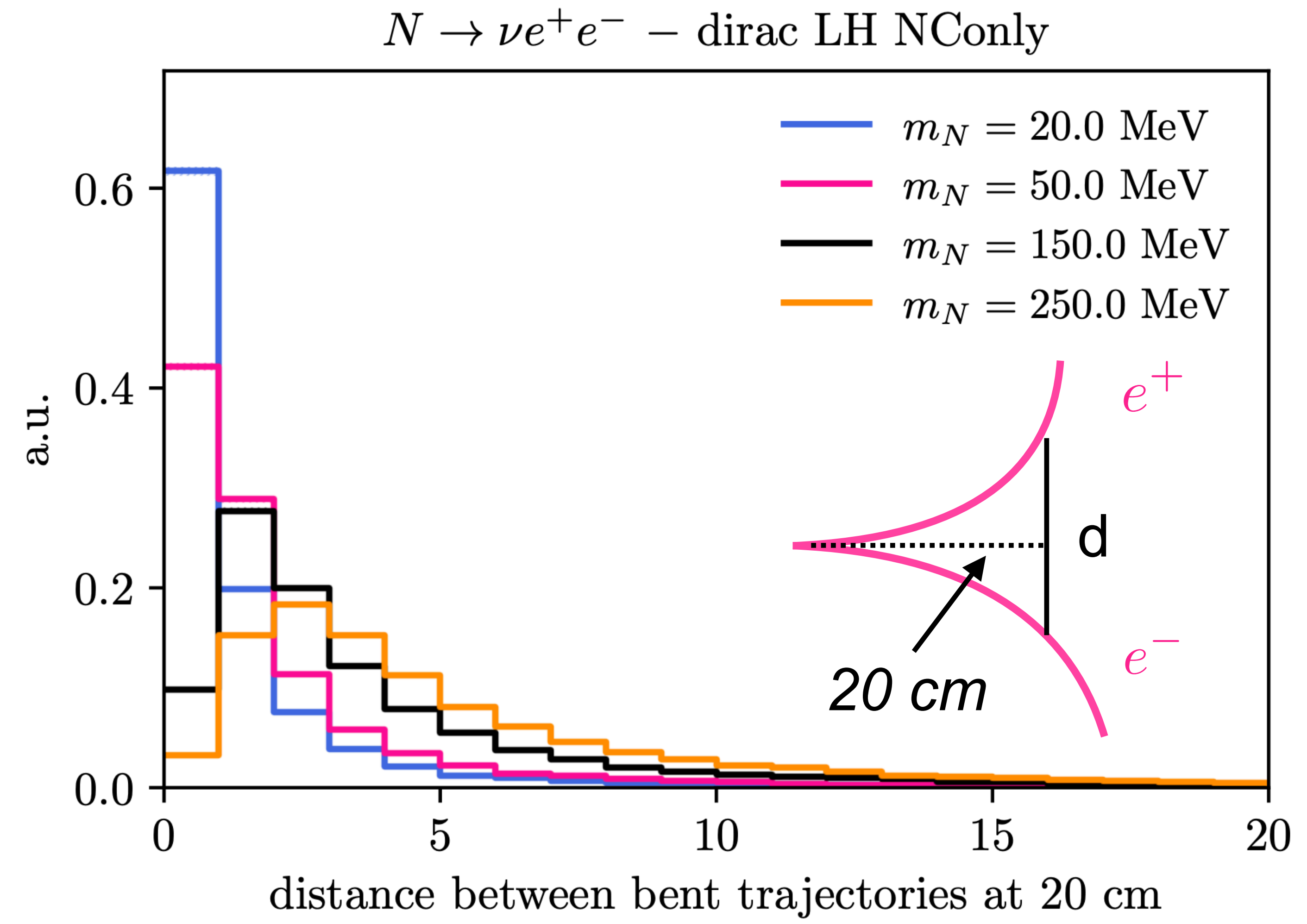
Decay in flight — low-mass region

C. Argüelles, N. Foppiani, MH arxiv:2109.03831



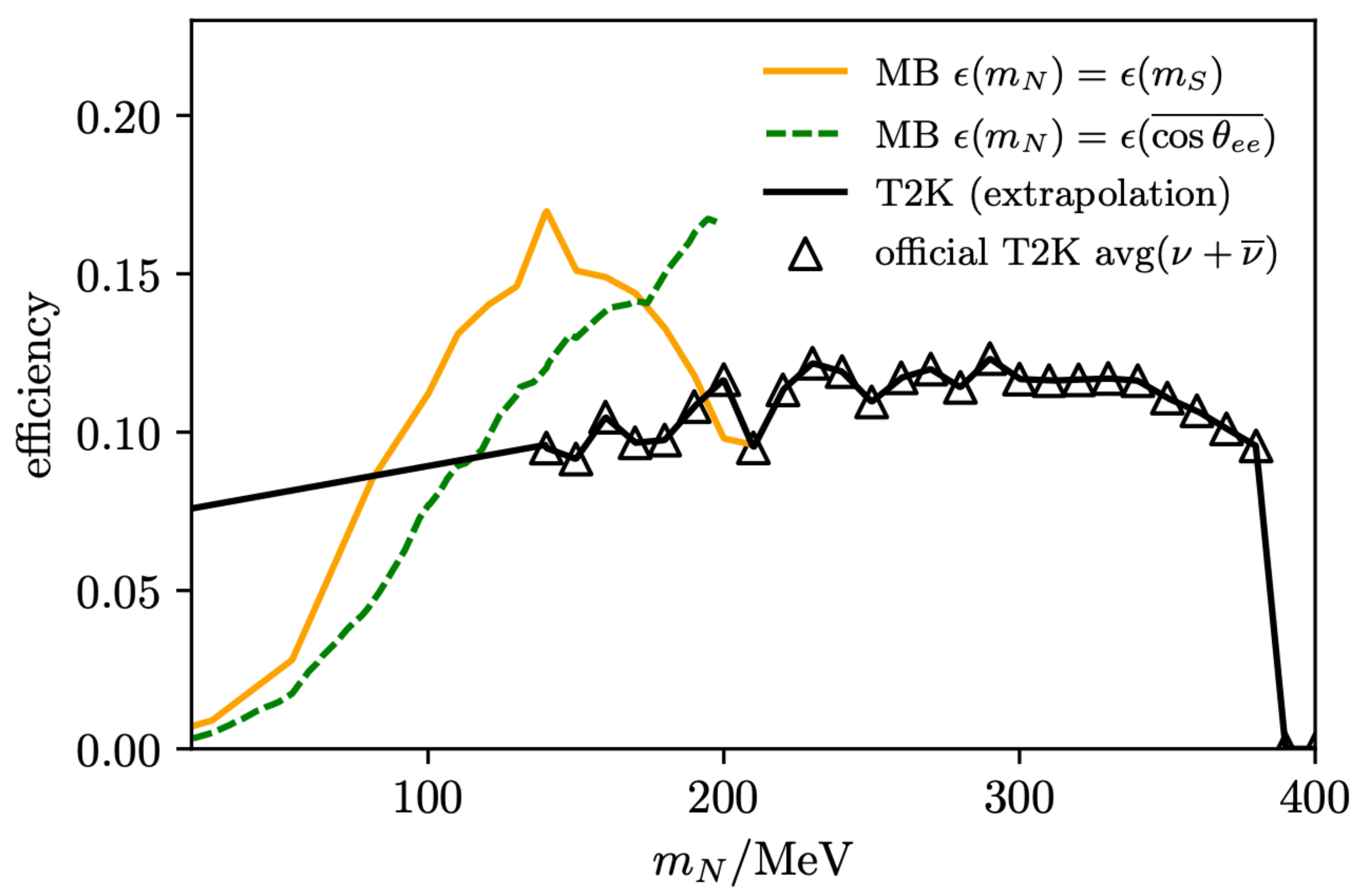
We also showed that previous limits from PS191 were severely overestimated.

T2K and MicroBooNE provide better limits.



$$P_{N\to X} \simeq \frac{\ell_{\rm det}}{\gamma\beta}\,\Gamma_{N\to X}$$

Weak decays



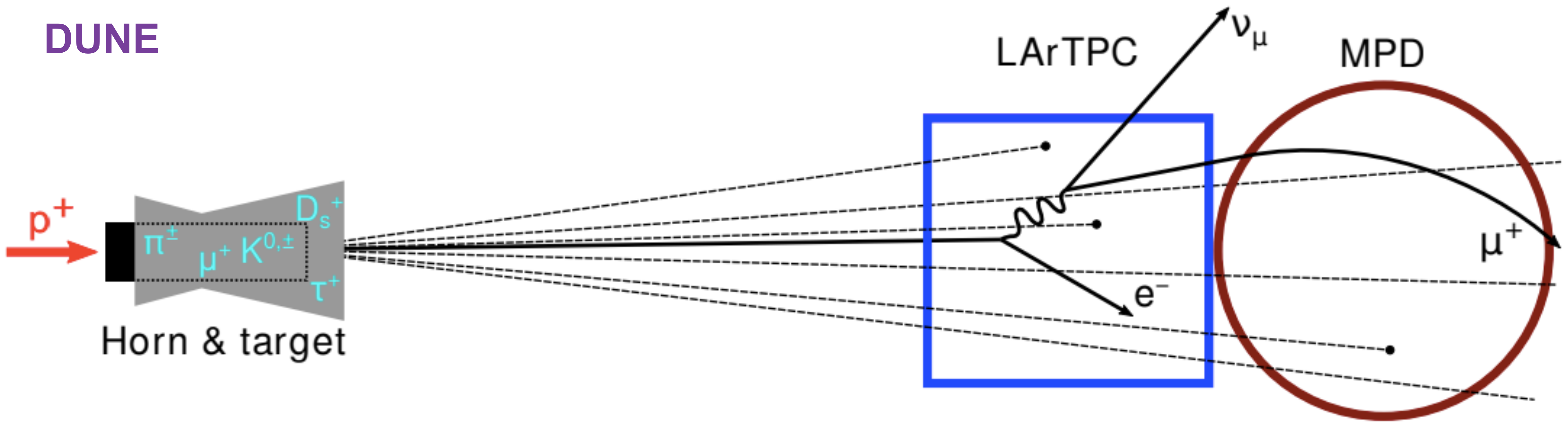
Heavy neutral lepton searches at neutrino experiments
Decay in flight — *future projections*

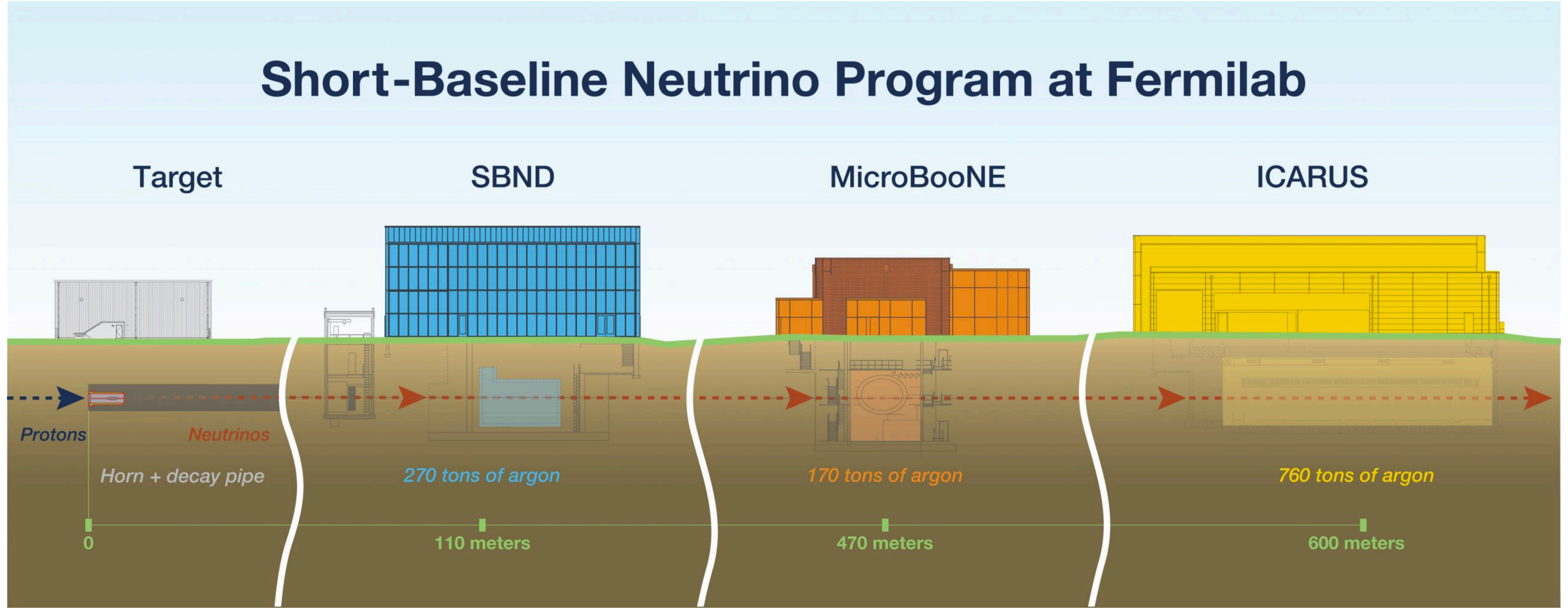
P. Ballett et al, arXiv:1905.00284

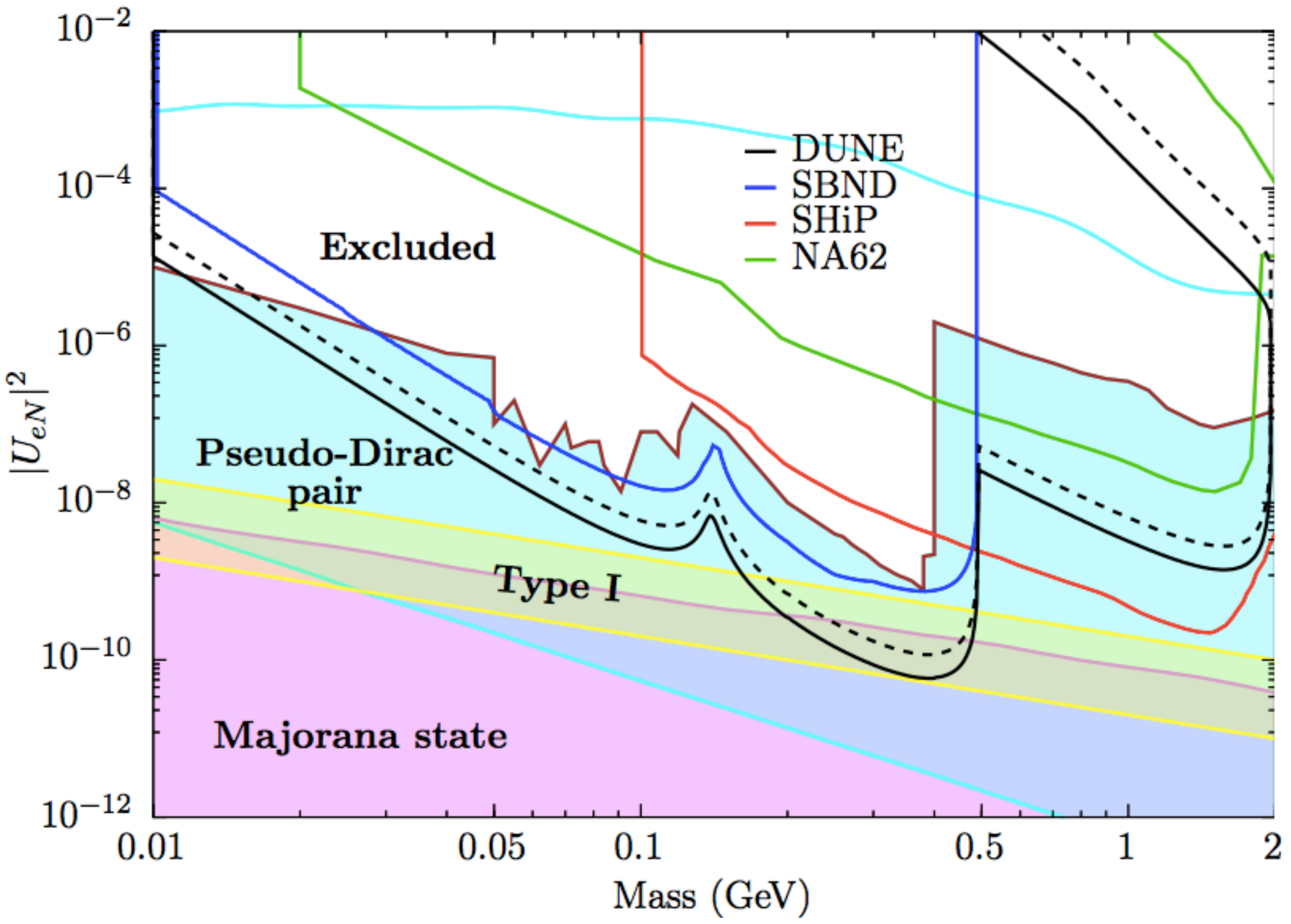
J. Berryman et al, arXiv:1912.07622

M. Breitbach et al, arXiv:2102.03383

DUNE

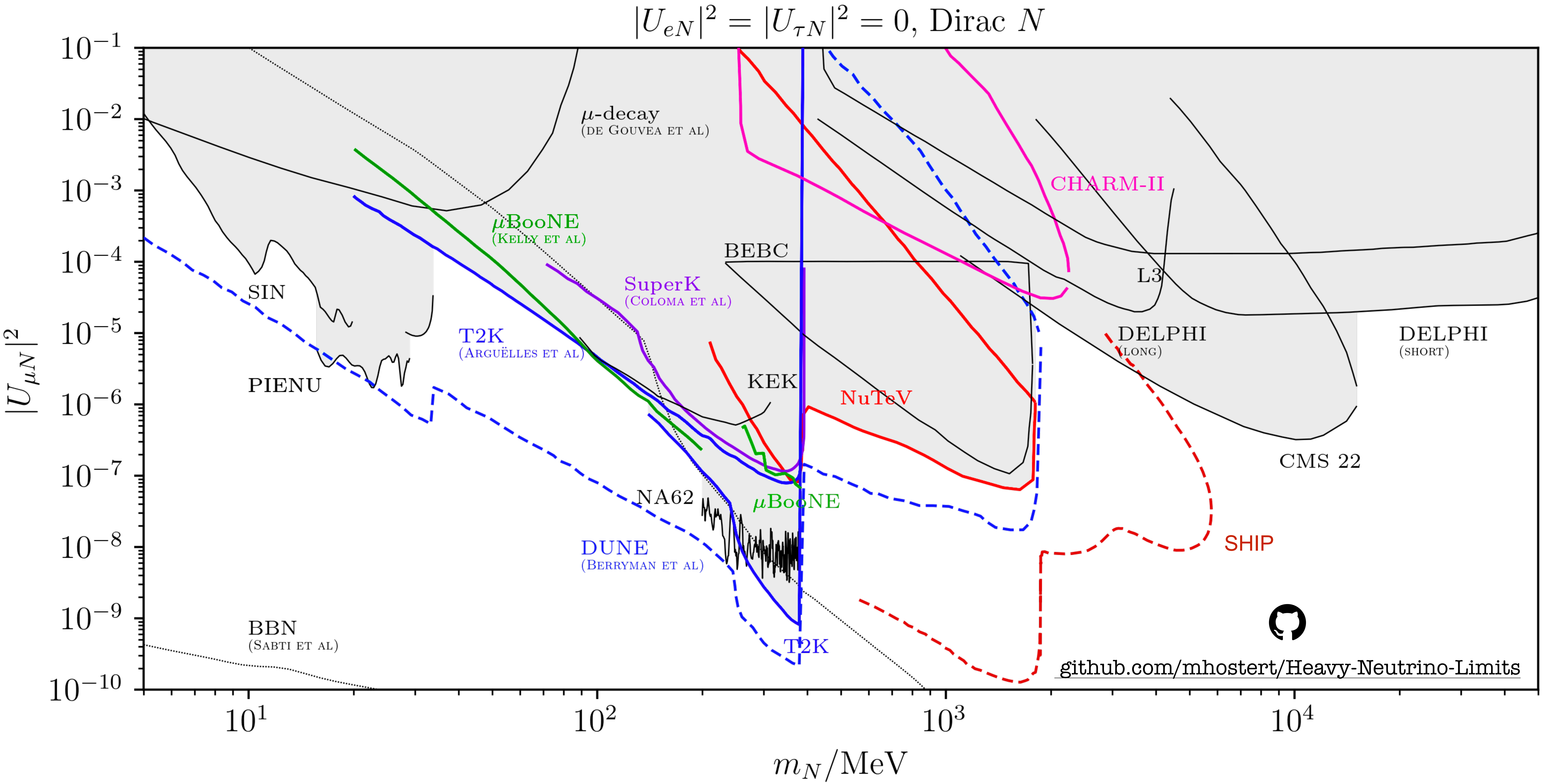






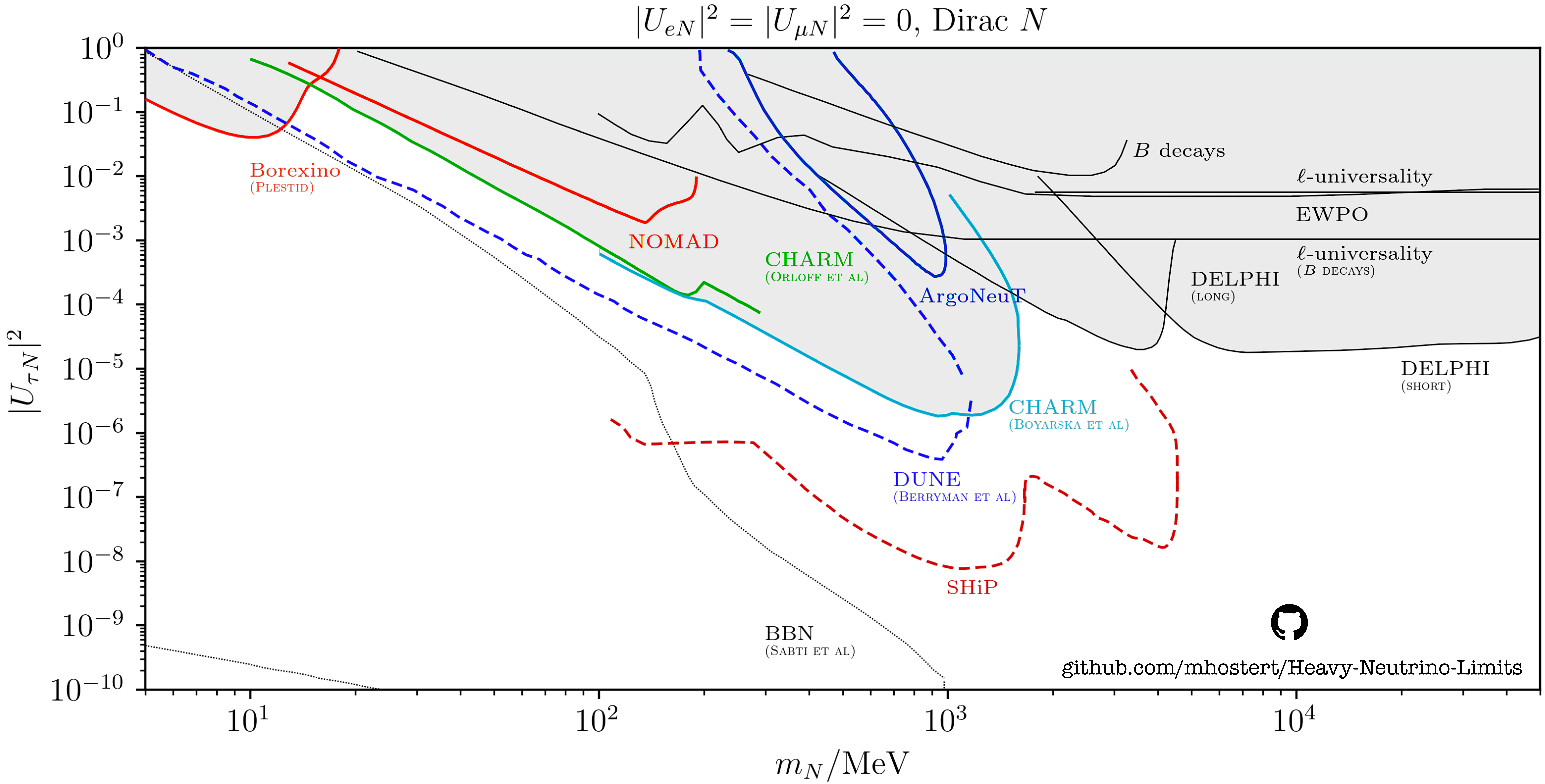
Sensitivity to neutrino mass models,
mostly in pseudo-Dirac regions.

Limits on heavy neutrinos



Questions → *mhostert@pitp.com*

Limits on heavy neutrinos



M. Hostert

Questions → *mhostert@pitp.com*

Portal:
(SM SINGLET) X (DS SINGLET)

DARK SECTOR (DS)

$\mathscr{L}_{\mathrm{SM}}$

$\overline{L}\widetilde{H}N$

Neutrino portal

Heavy neutrinos

$\frac{M_N}{2}\overline{N^c}N$

Neutrino masses

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

Vector portal

Dark photons

$G_{SM} \times U(1)_X$

New fundamental forces?

$S^\dagger S\,(H^\dagger H)$

Scalar portal

Dark scalars

$V(H, S)$

Scalar degrees of freedom

DARK SECTOR (DS)

$\overline{N^c}NS + \overline{N}\not{X}N$

May feel new secret forces…

Can these “leak” back to the SM?

$\mathscr{L}_{\mathrm{SM}}$

$\overline{L}\widetilde{H}N$

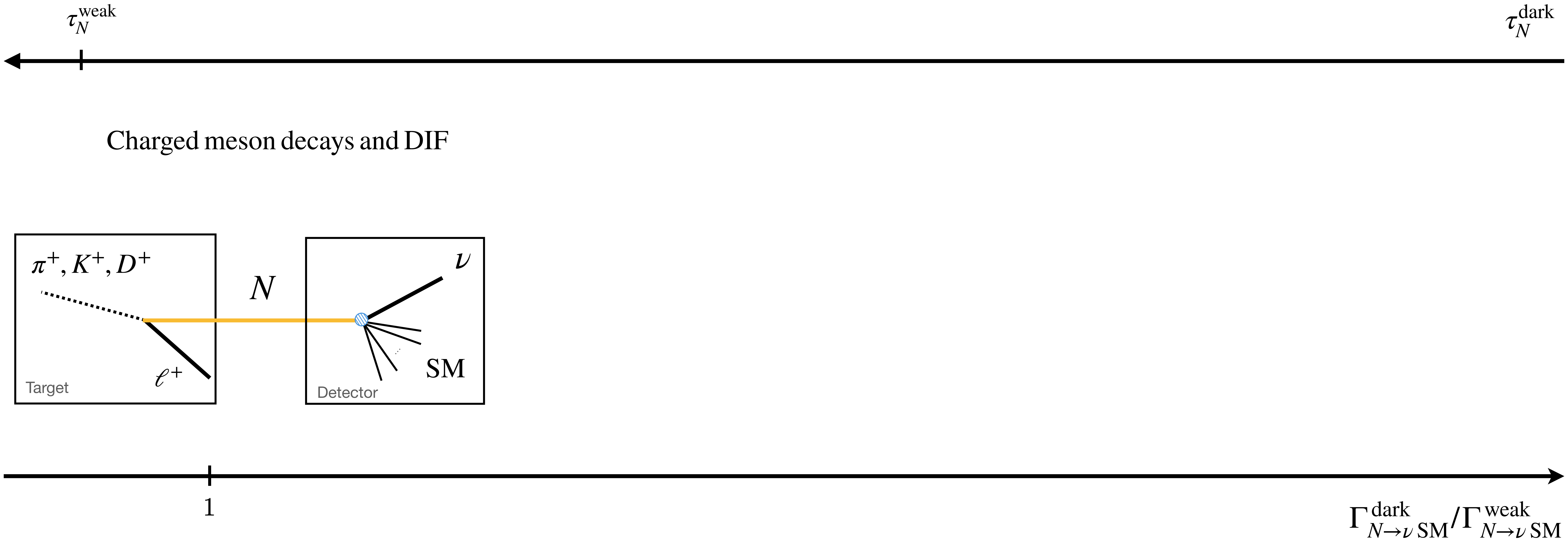
Neutrino portal

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

$S^\dagger S\,(H^\dagger H)$

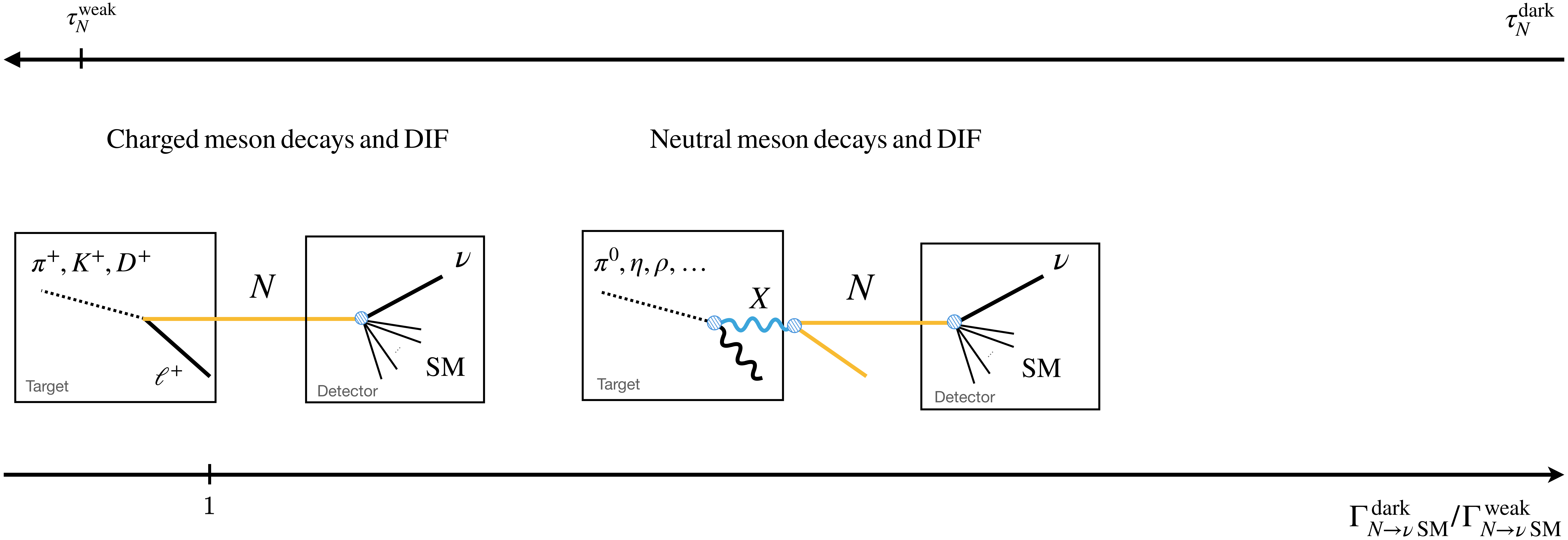
$\vdots$

Dark decay channels of HNLs



- Faster decays.
- CC branching ratios may be small, e.g., no $K^+ \to \mu^+\mu^+\pi^-$ even w/ large LNV.
- Missing energy.

Dark decay channels of HNLs

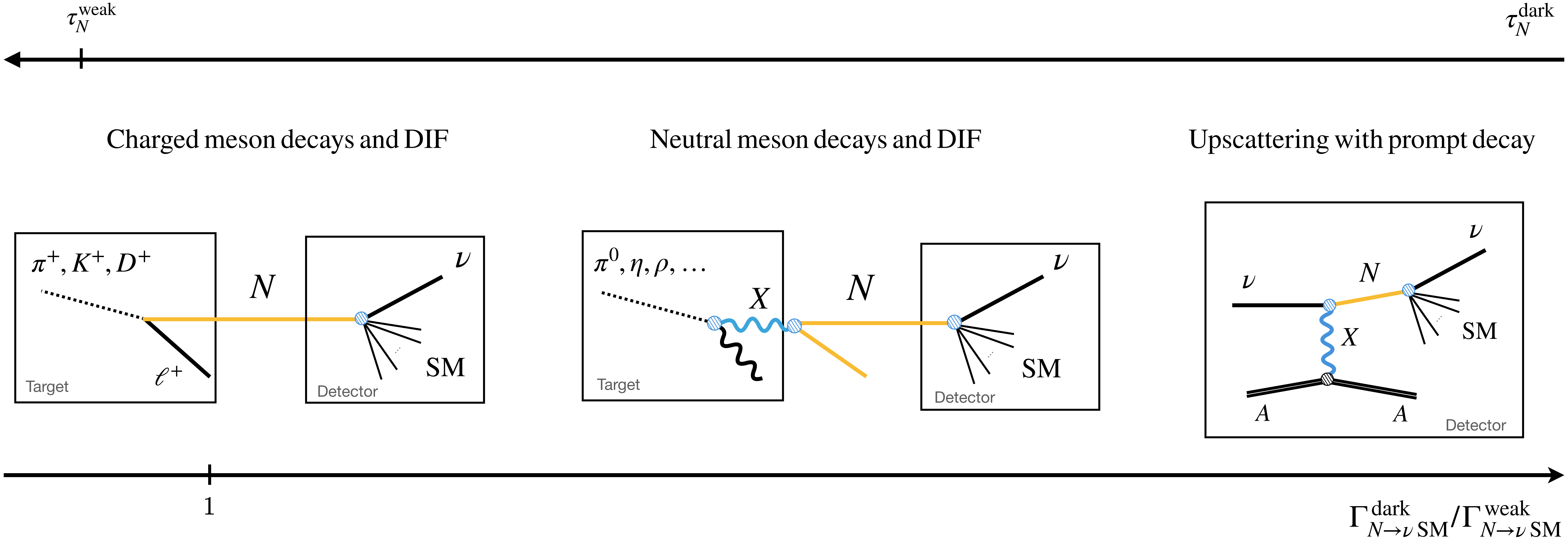


Charged meson decays and DIF

Neutral meson decays and DIF

- Faster decays.
- CC branching ratios may be small, e.g., no $K^+ \to \mu^+\mu^+\pi^-$ even w/ large LNV.
- Missing energy.

Dark decay channels of HNLs

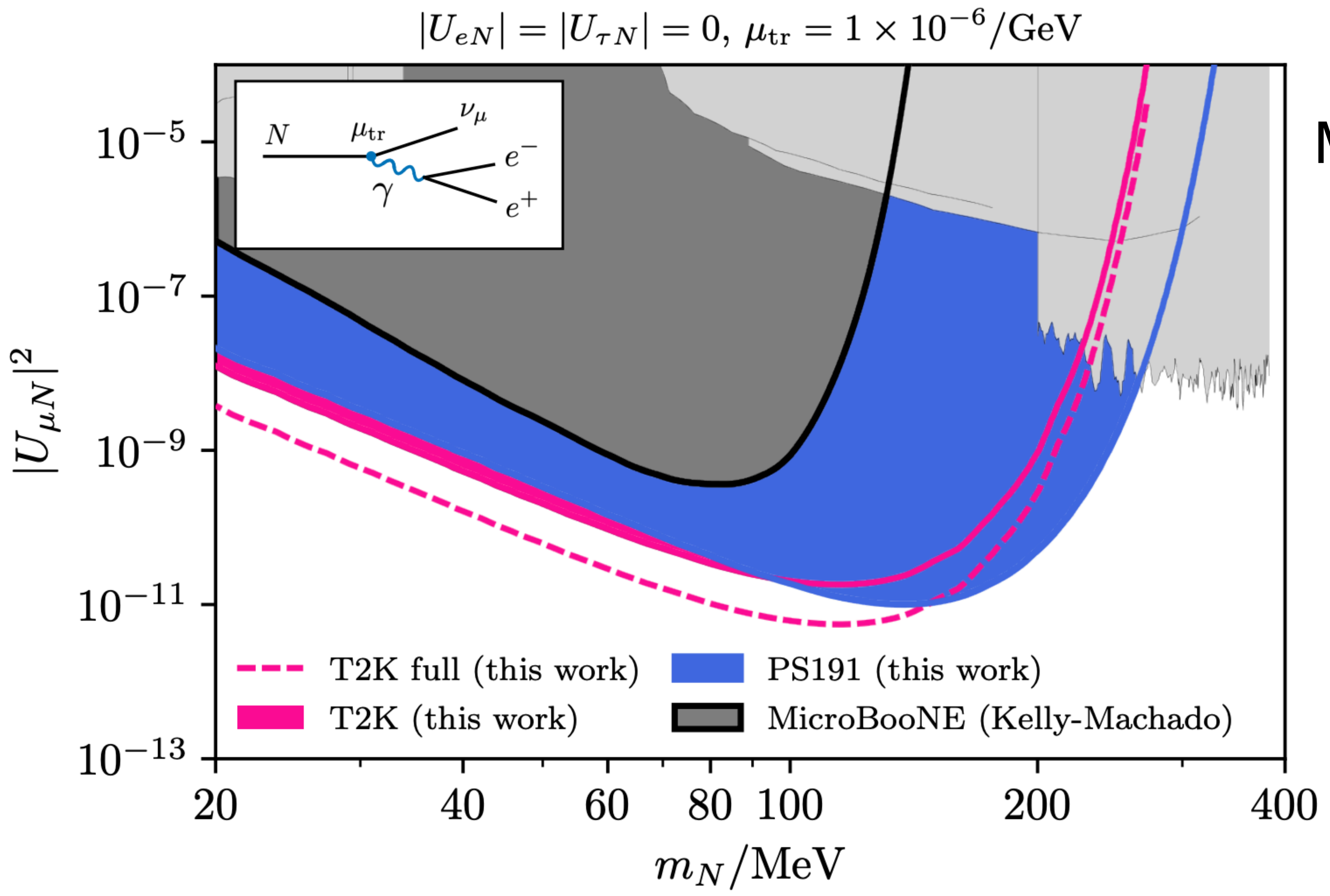


- Faster decays.
- CC branching ratios may be small, e.g., no $K^+ \to \mu^+\mu^+\pi^-$ even w/ large LNV.
- Missing energy.

Long-lived HNLs Decaying in flight

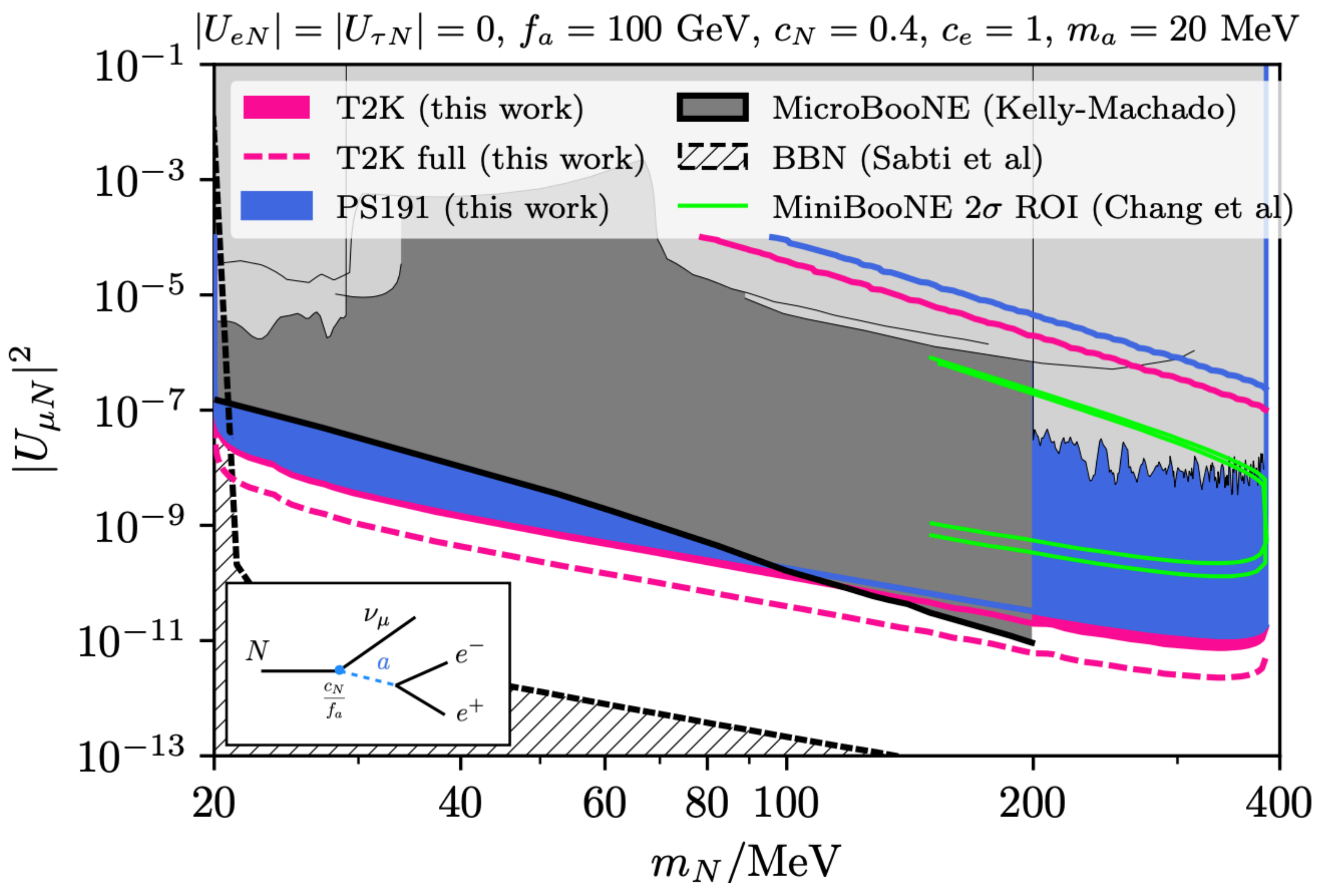
The role of new forces

C. Argüelles, N. Foppiani, MH arxiv:2109.03831



Main decay into real photons: unfortunately, no good for low-density detectors like ND280.

Virtual photon rate is still competitive. Collimated e+e- a challenge, but B = 0.2 T makes the difference.



ALP decays to e^+e^-

Transition magnetic moment

$$-\mathscr{L}_{\rm int} \supset \frac{\mu_{\rm tr}}{2}\overline{\nu_\alpha}\sigma^{\mu\nu}NF_{\mu\nu} + \text{h.c.}$$

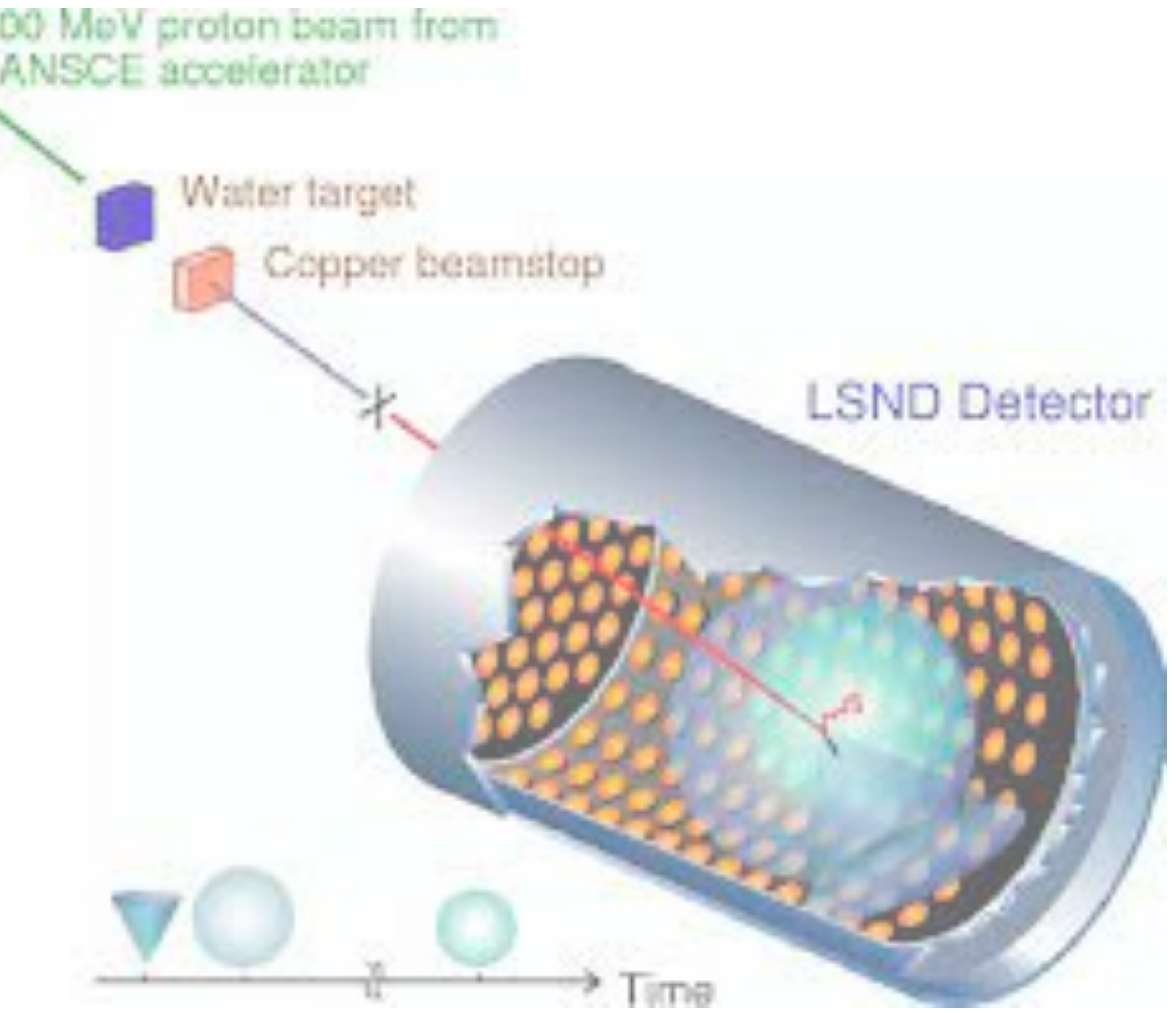
$$-\mathcal{L} \supset \frac{\partial_\mu a}{2f_a}\left(c_N\overline{N}\gamma^\mu\gamma^5 N + c_e\overline{e}\gamma^\mu\gamma^5 e\right)$$

Relaxed BBN limits

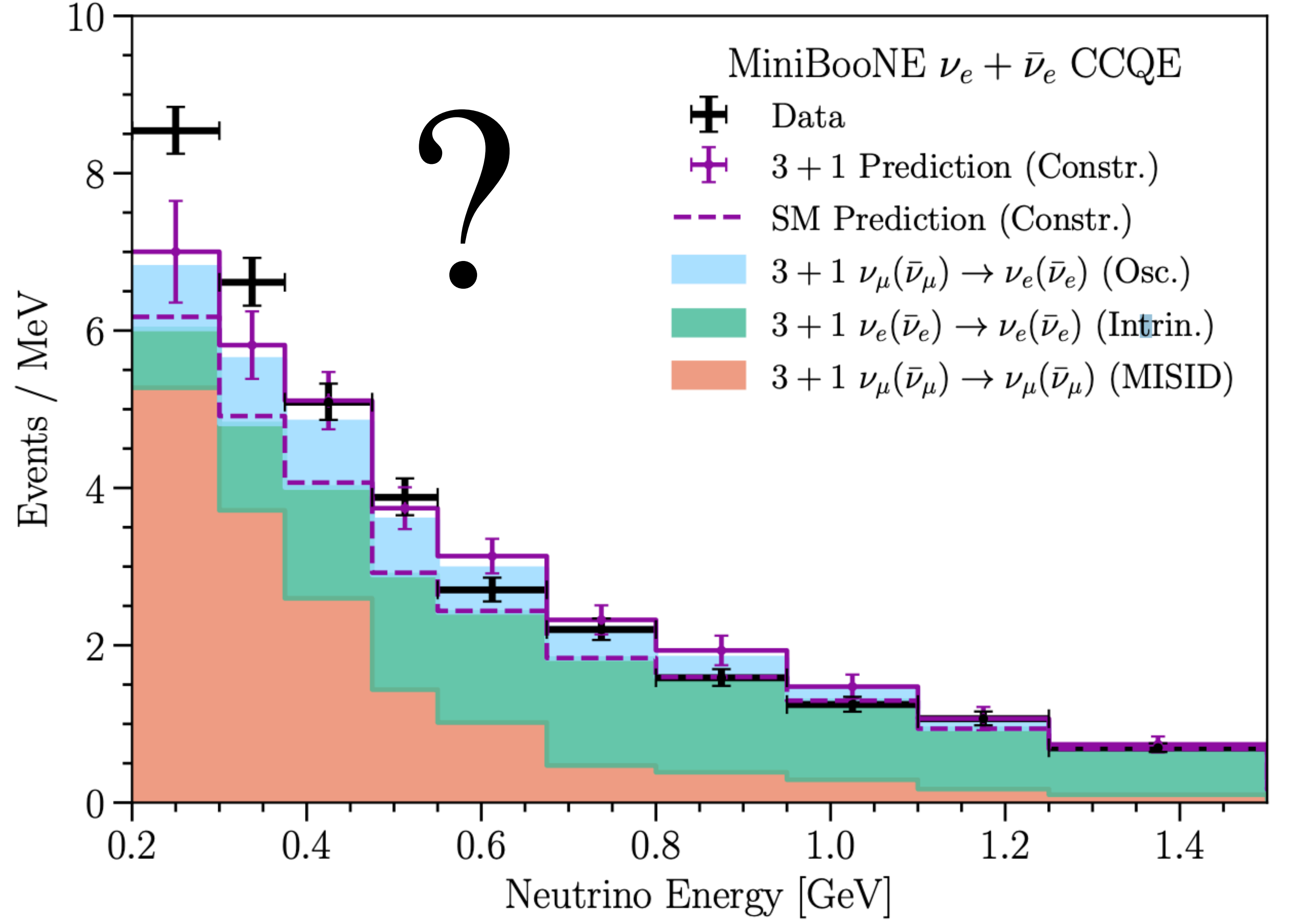
HNLs can be long-lived in the Lab, but short-lived in the cosmos.

ALP decays to e^+e^-

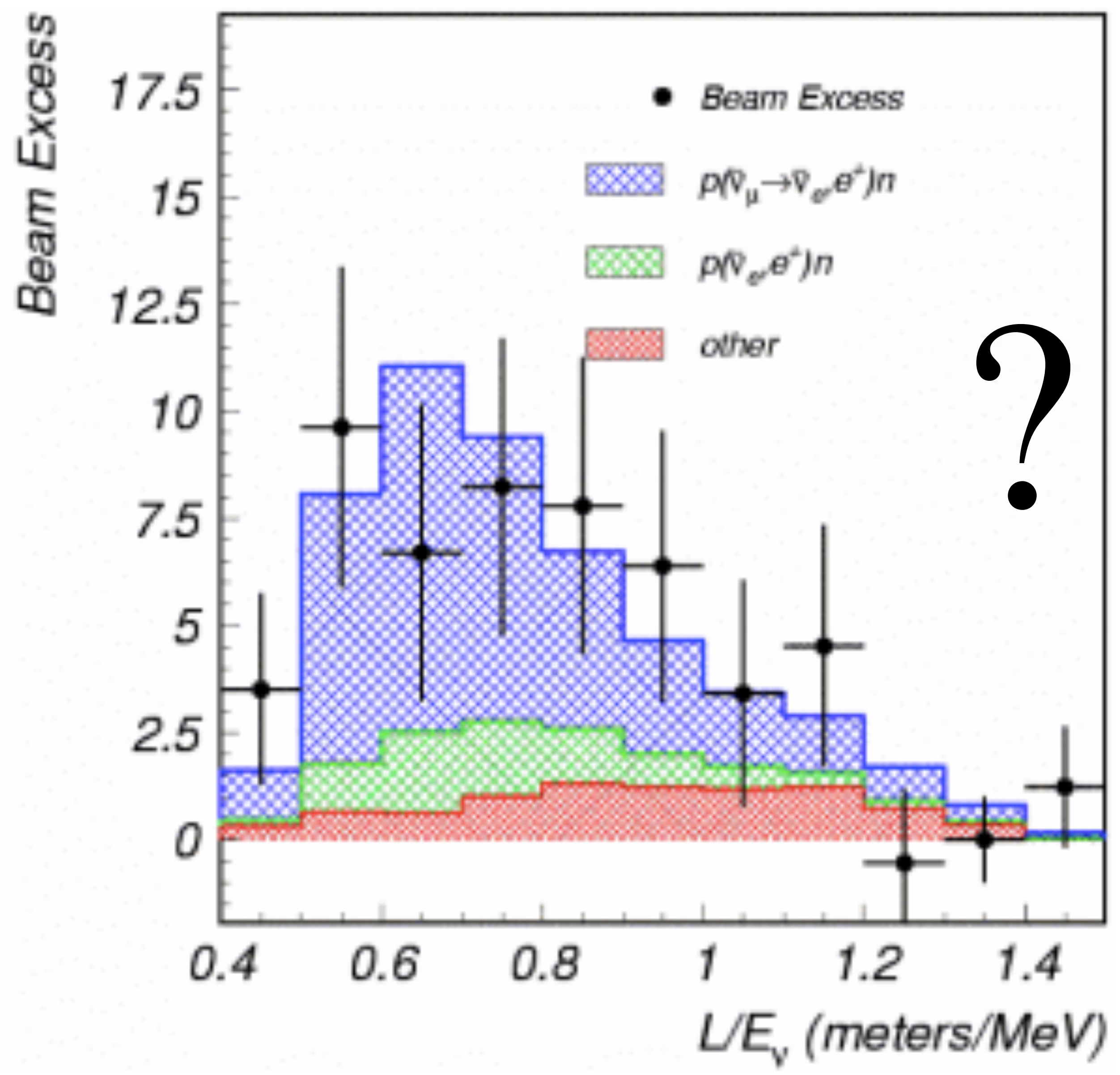
$$N \to \nu a \to \nu e^+e^-$$



MiniBooNE coll., **arXiv:2201.01724**



Short-baseline anomalies



Short-baseline explanations

Going beyond oscillations

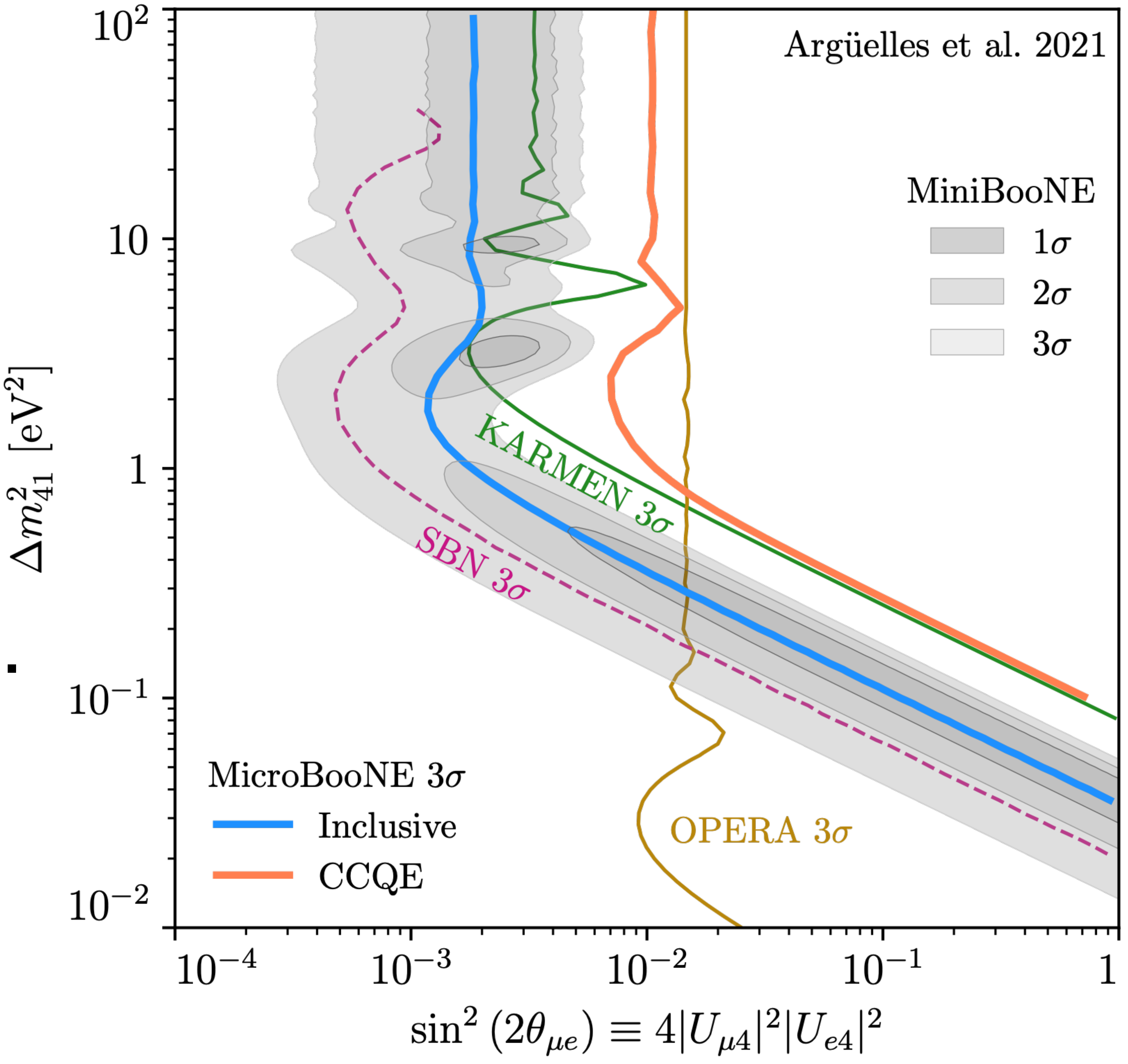
See J. Kopp's talk

Oscillations are not a good fit for global data, however, I think it is **too early to give up.**

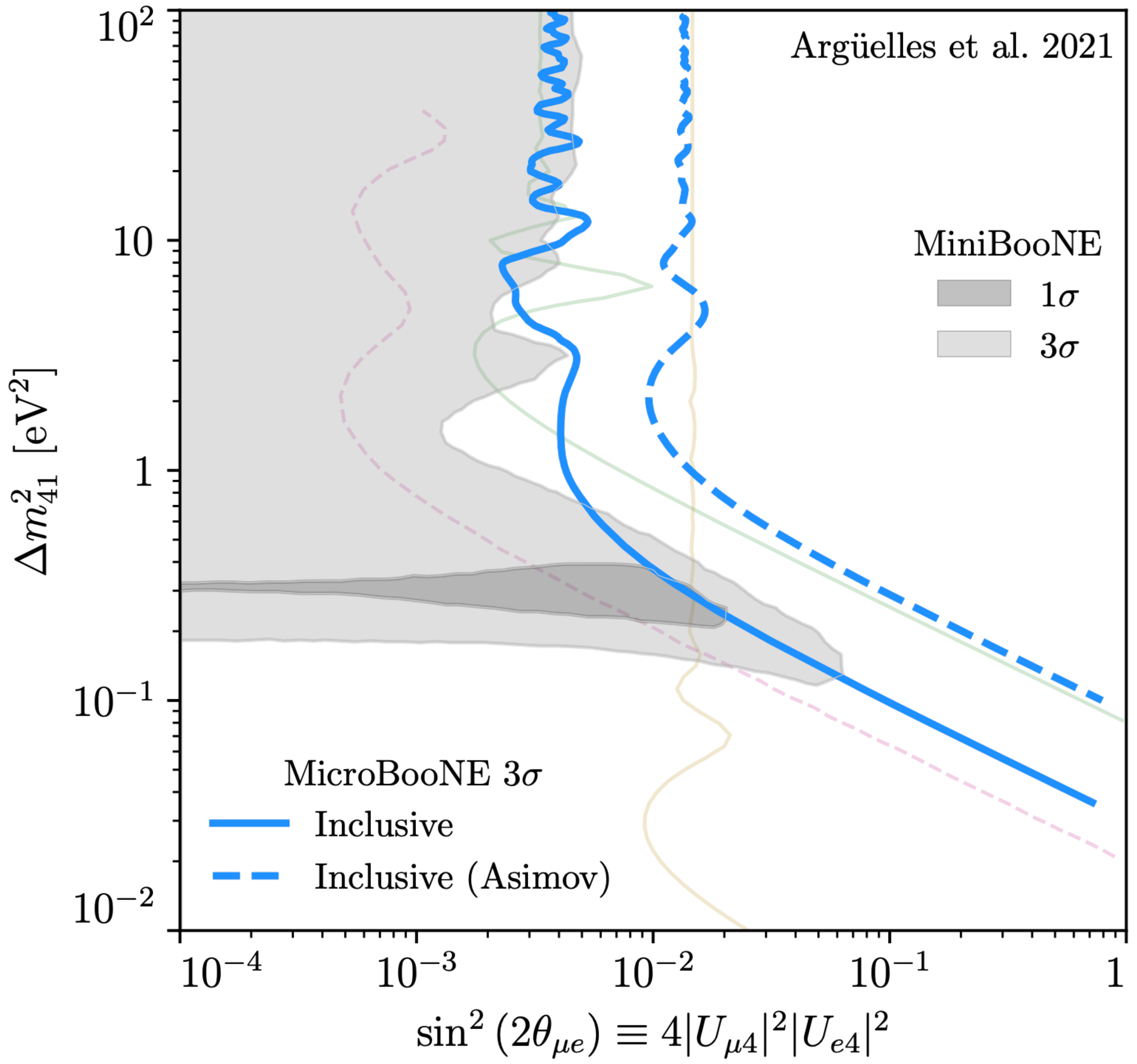
We are looking forward to future analyses by **MicroBooNE as well as by the full SBN program.**

Pheno analyses already show that we have not fully been addressed by MicroBoonE yet (right →).

Argüelles et al, arXiv:2111.10359

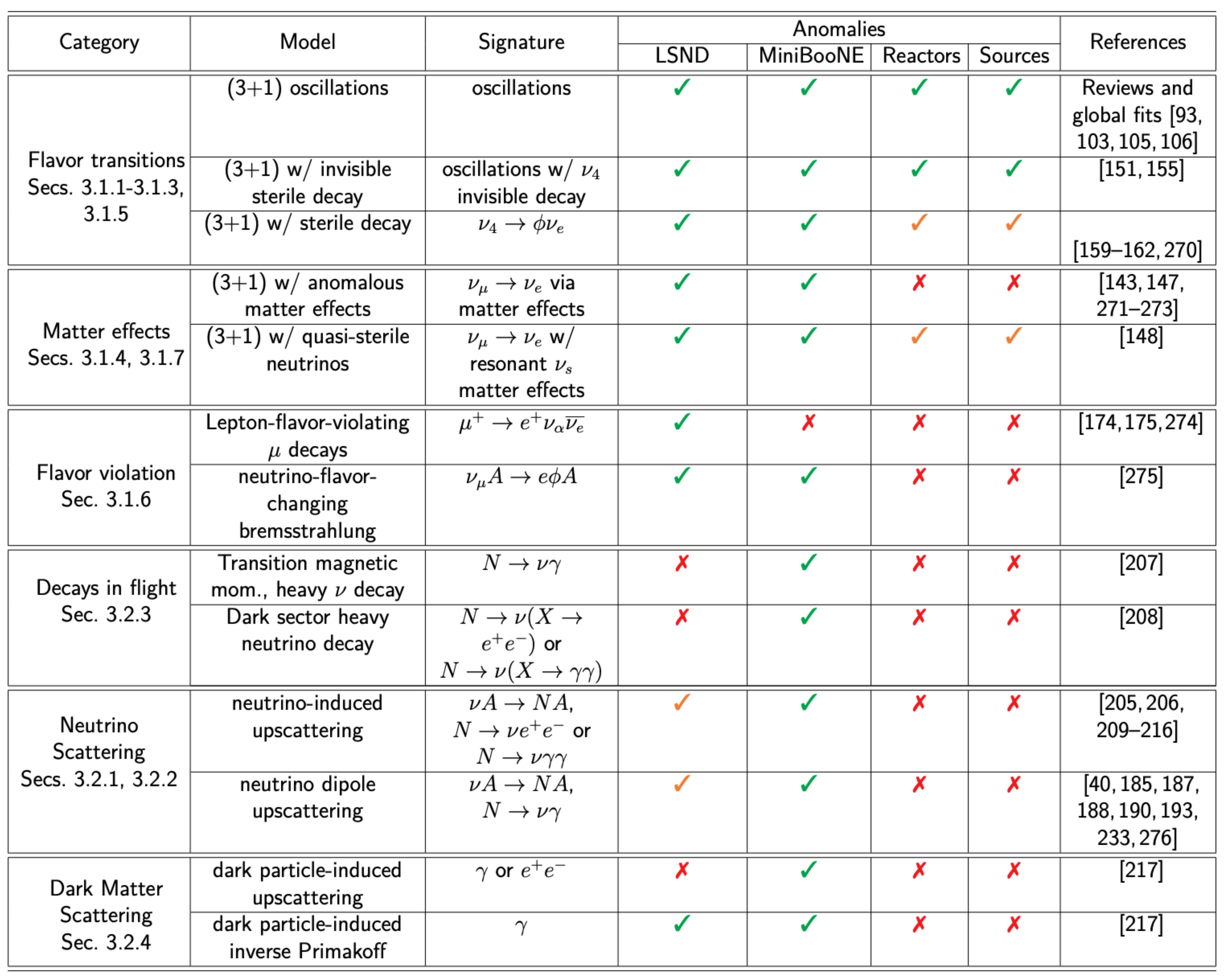


Argüelles et al, arXiv:2111.10359



NF02 White Paper: arXiv:2203.07323. Questions (and complaints) → *mhostert@pitp.com*

Table of explanations of the short-baseline anomalies



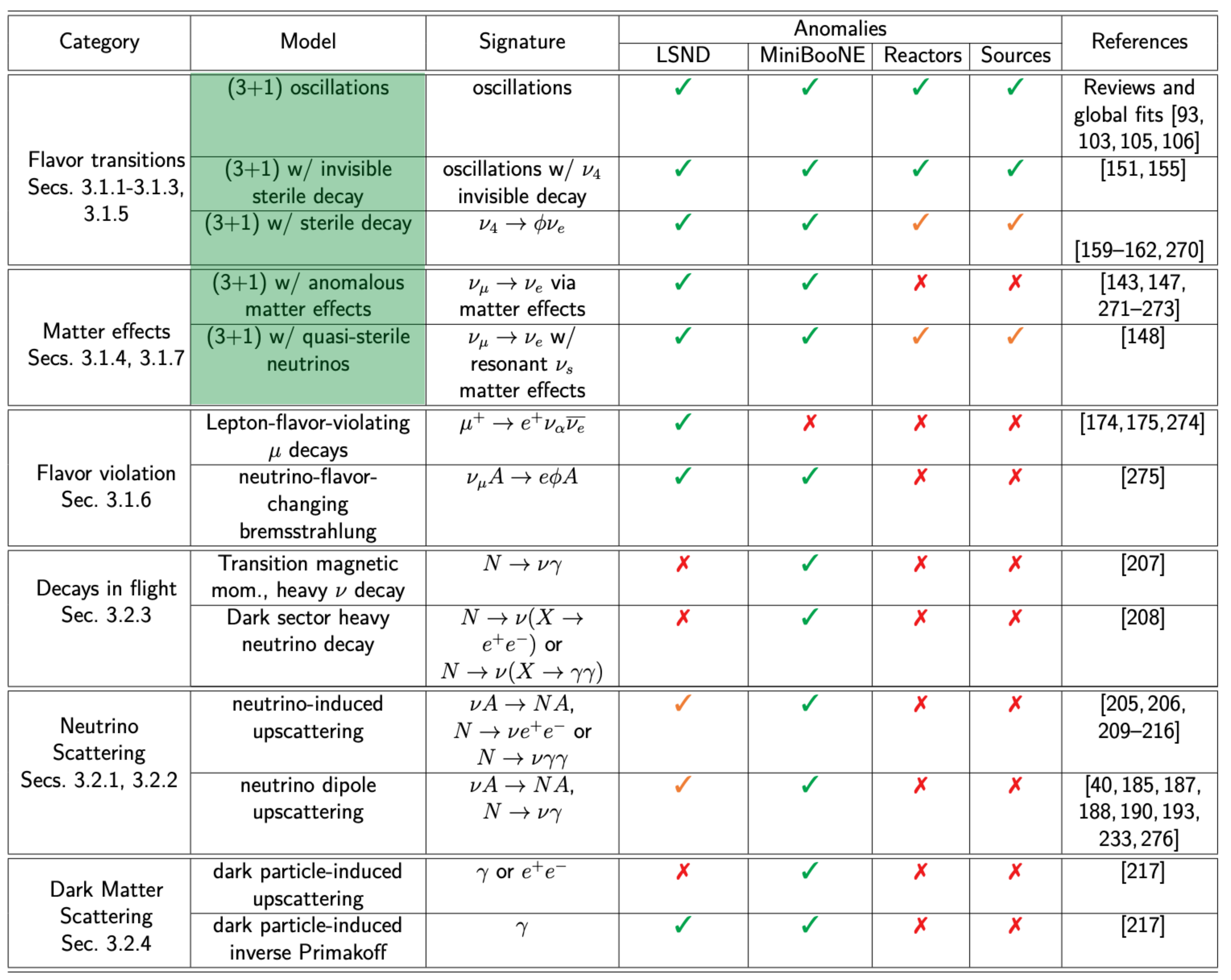
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

NF02 White Paper: arXiv:2203.07323. Questions (and complaints) → *mhostert@pitp.com*

Table of explanations of the short-baseline anomalies

See J. Kopp's talk

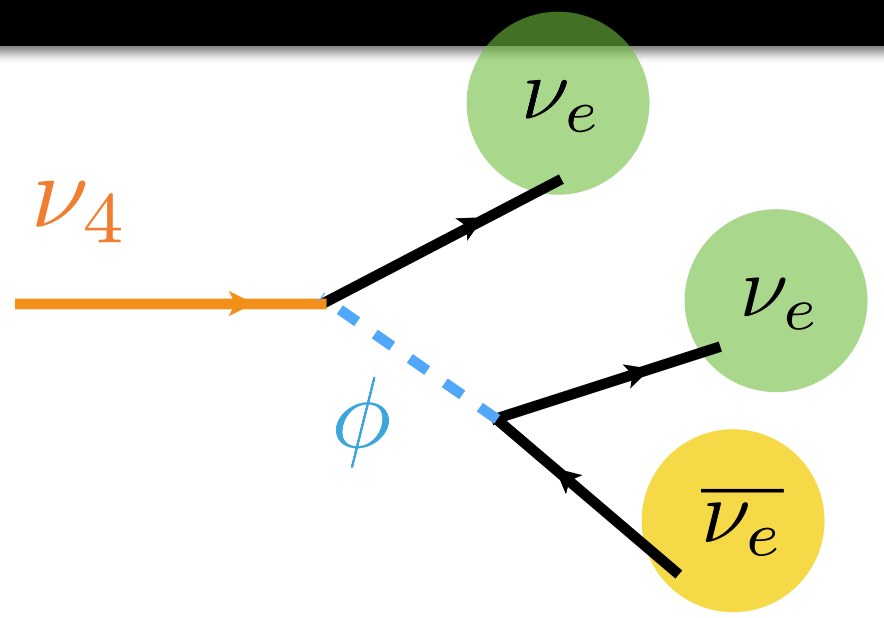
To be tested



Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to N A$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

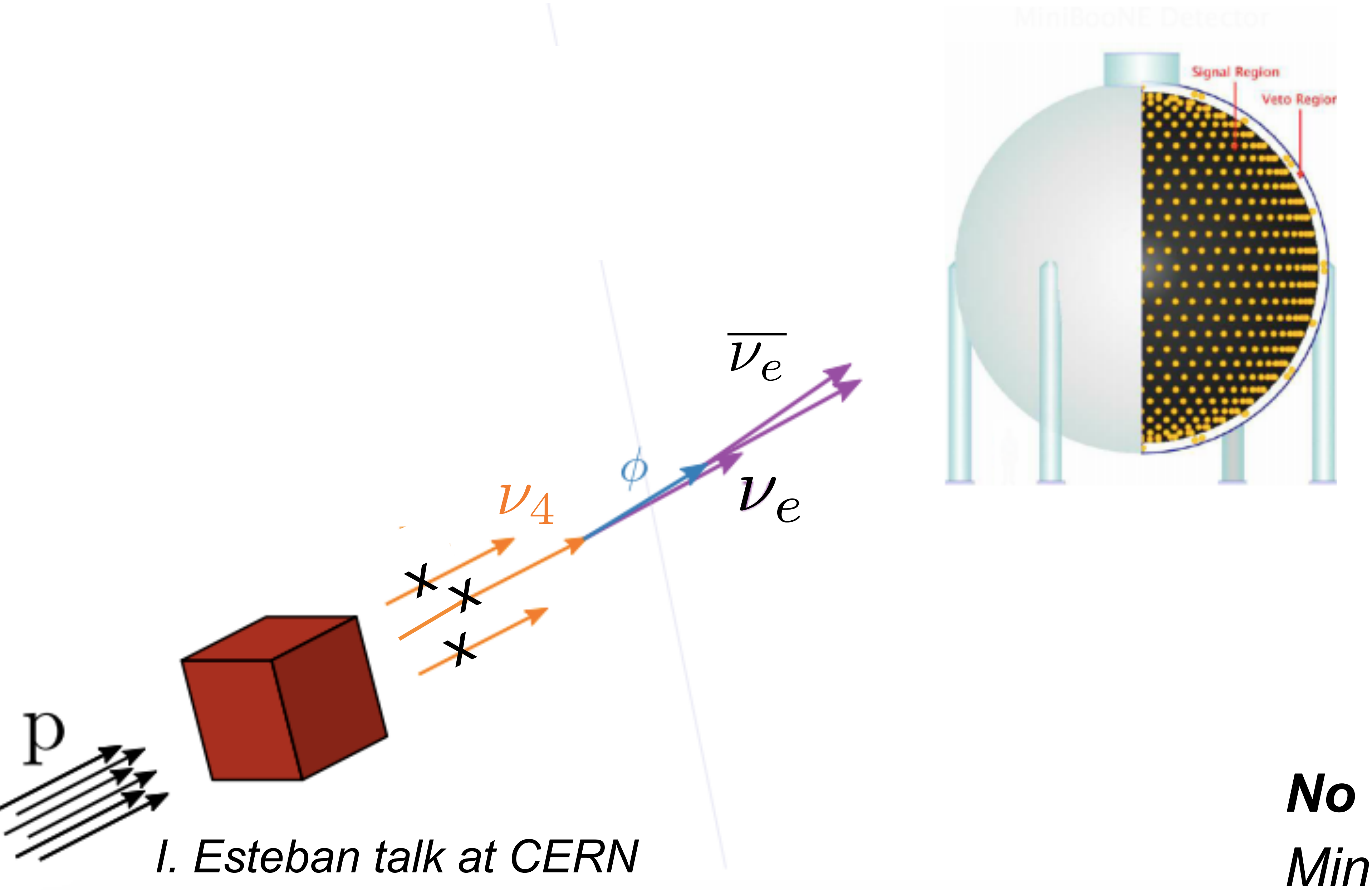
Decaying sterile neutrinos
Effective appearance without disappearance

S. Palomares-Ruiz *et al*, JHEP09(2005)048
Z. Moss *et al* , PRD 97, 055017 (2018)
M. Dentler *et al*, PRD101(2020) 115013.
A. deGouvea *et al*, JHEP07(2020)141



Dirac sterile neutrino visible decays:

$$-\mathcal{L} \supset g_s \overline{\nu}_s \nu_s \phi + m_{ab} \overline{\nu_a} \nu_b .$$



I. Esteban talk at CERN
10.5281/zenodo.3509890:

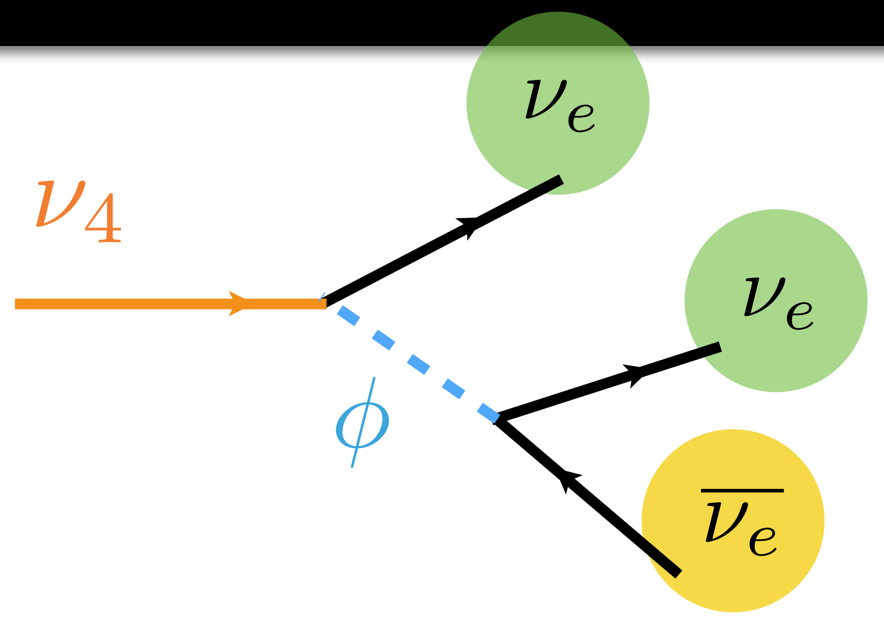
No tension with disappearance:

MiniBooNE signal: $|U_{\mu 4}|^2$

ν_μ *disappearance:* $|U_{\mu 4}|^2$

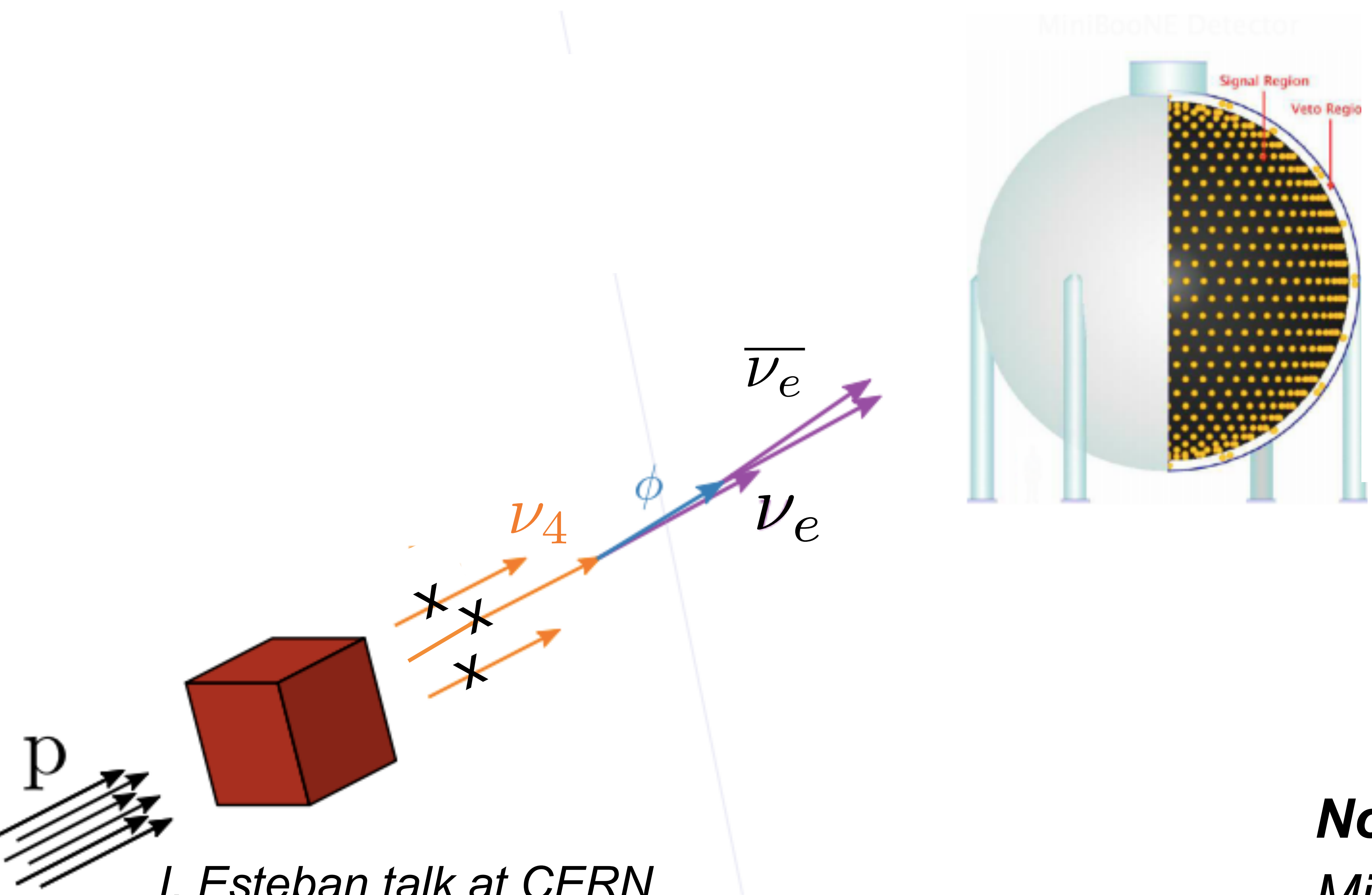
Decaying sterile neutrinos
Effective appearance without disappearance

S. Palomares-Ruiz *et al*, JHEP09(2005)048
Z. Moss *et al* , PRD 97, 055017 (2018)
M. Dentler *et al*, PRD101(2020) 115013.
A. deGouvea *et al*, JHEP07(2020)141

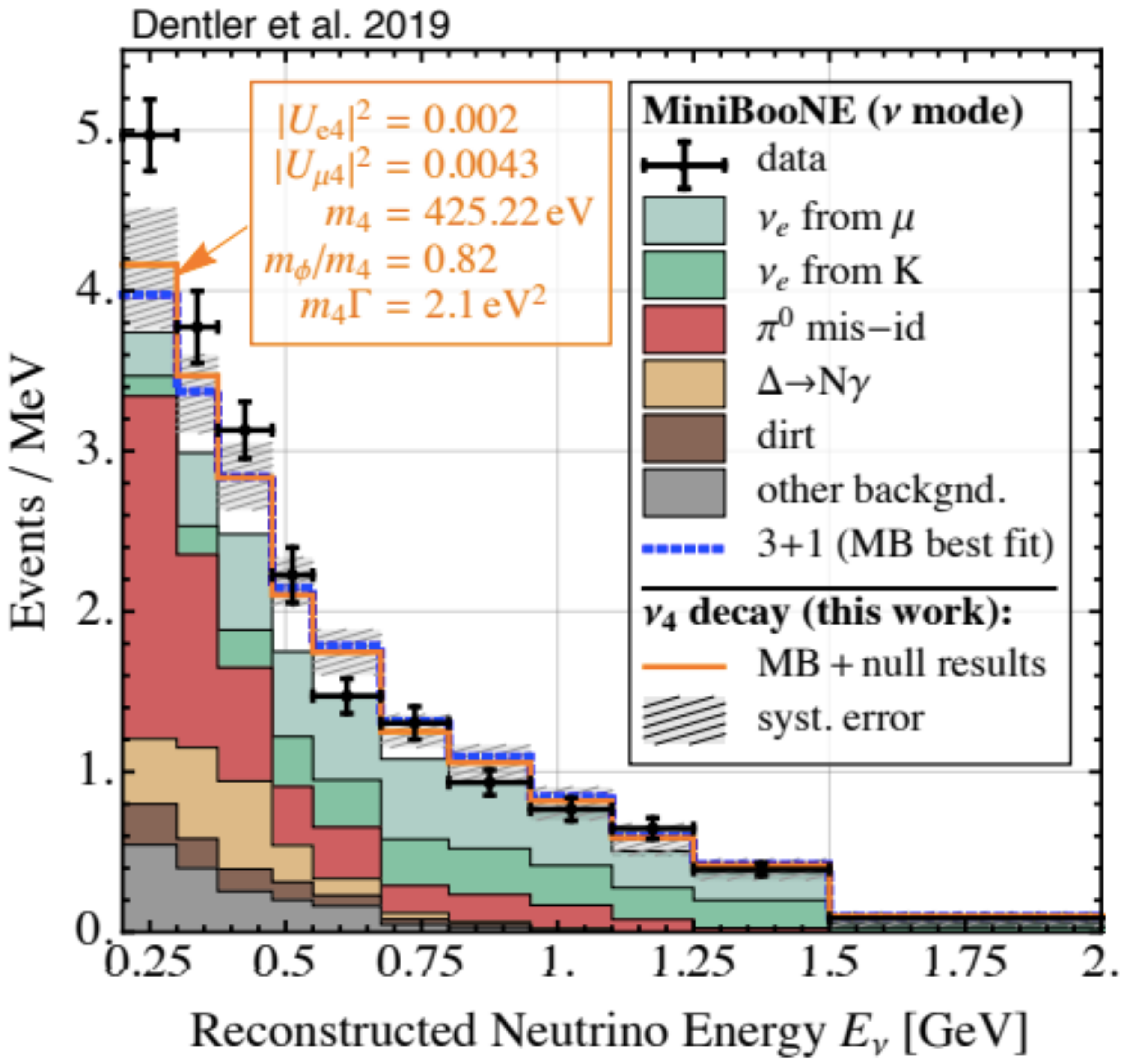


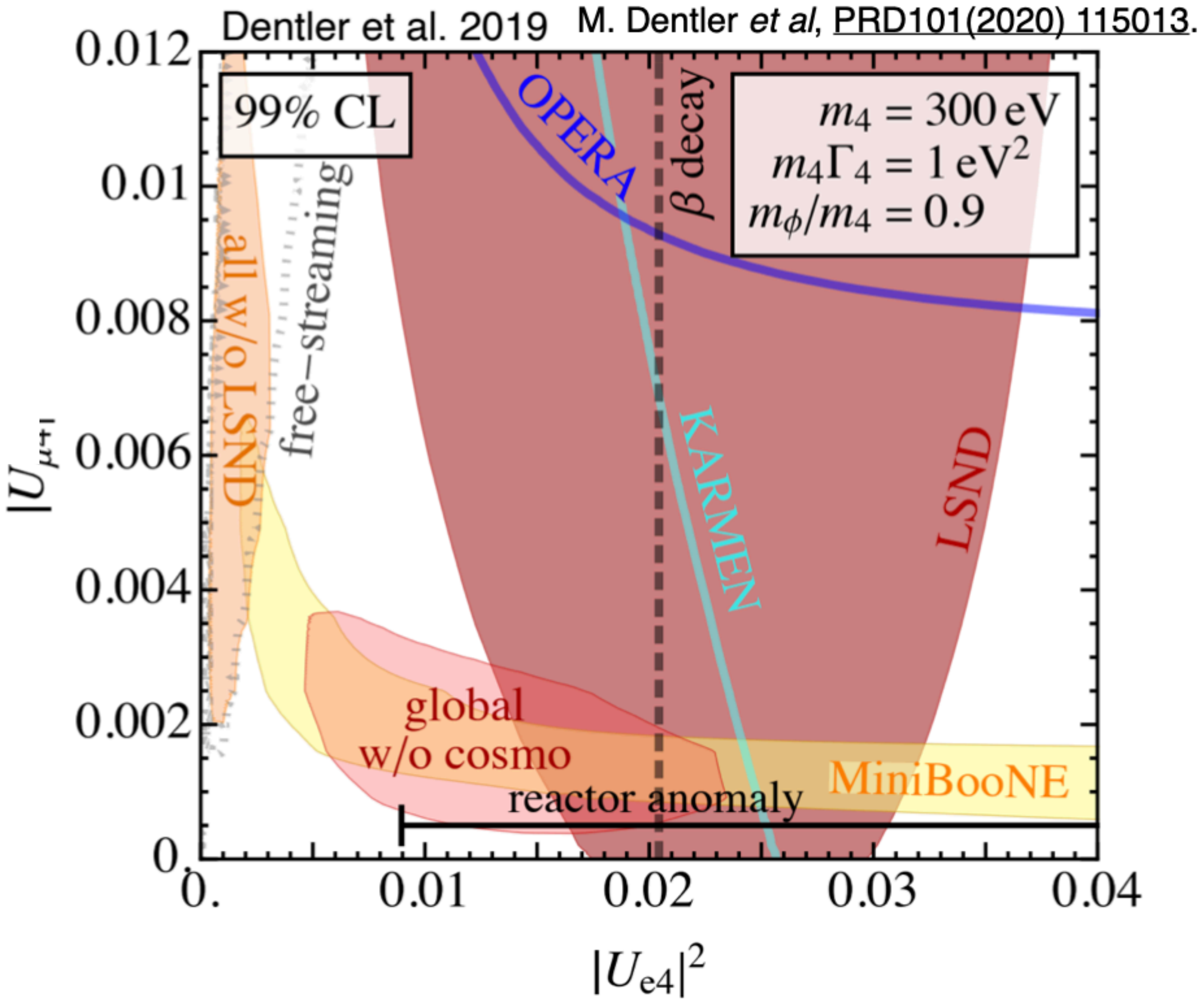
Dirac sterile neutrino visible decays:

$$-\mathcal{L} \supset g_s \overline{\nu}_s \nu_s \phi + m_{ab} \overline{\nu_a} \nu_b .$$



I. Esteban talk at CERN
10.5281/zenodo.3509890



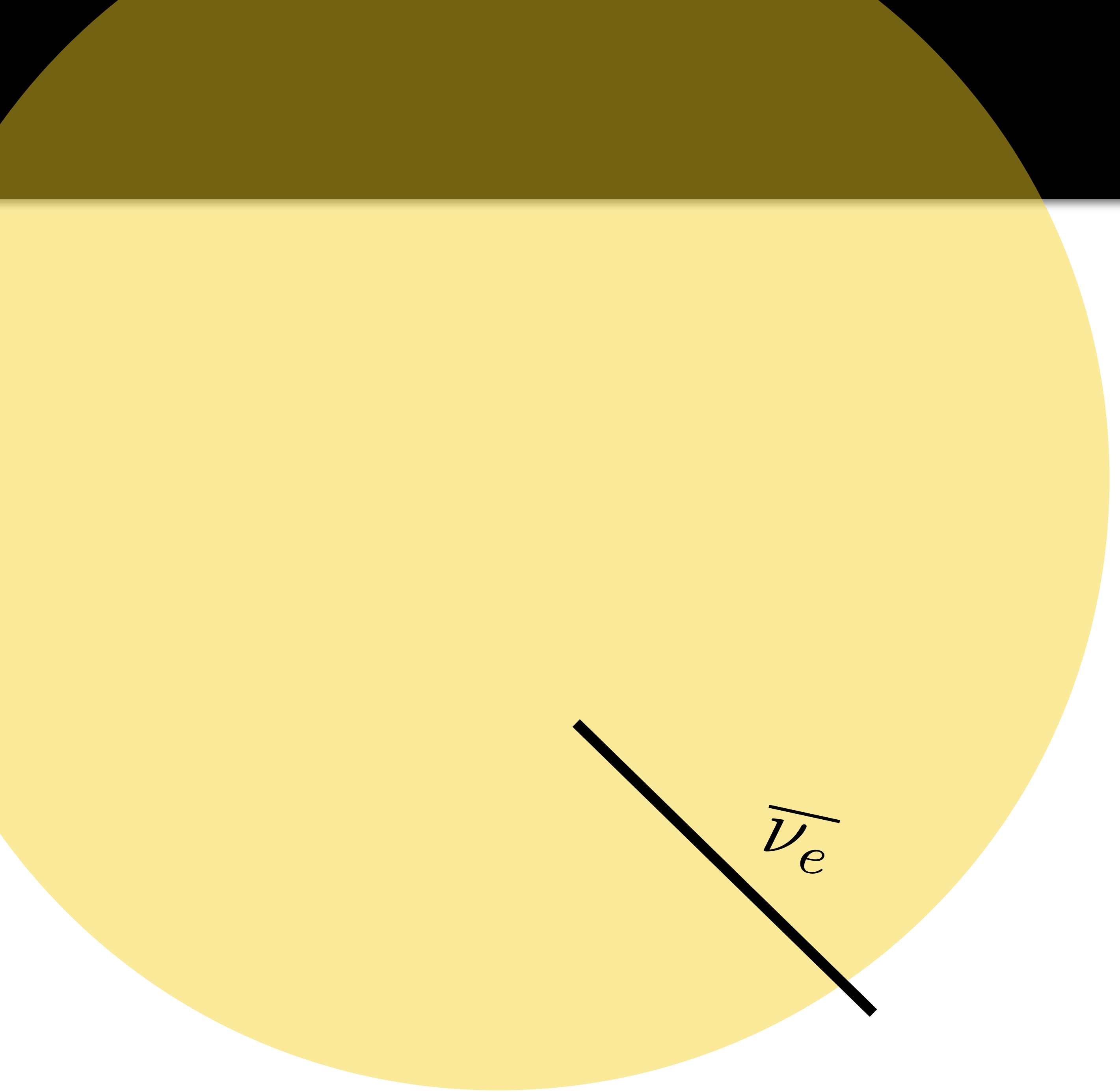


No tension with disappearance:

MiniBooNE signal: $|U_{\mu4}|^2$

ν_μ *disappearance:* $|U_{\mu4}|^2$

Solar antineutrinos



Nuclear fusion cauldron of the Sun massively overwhelms antineutrino emission at MeV energies:

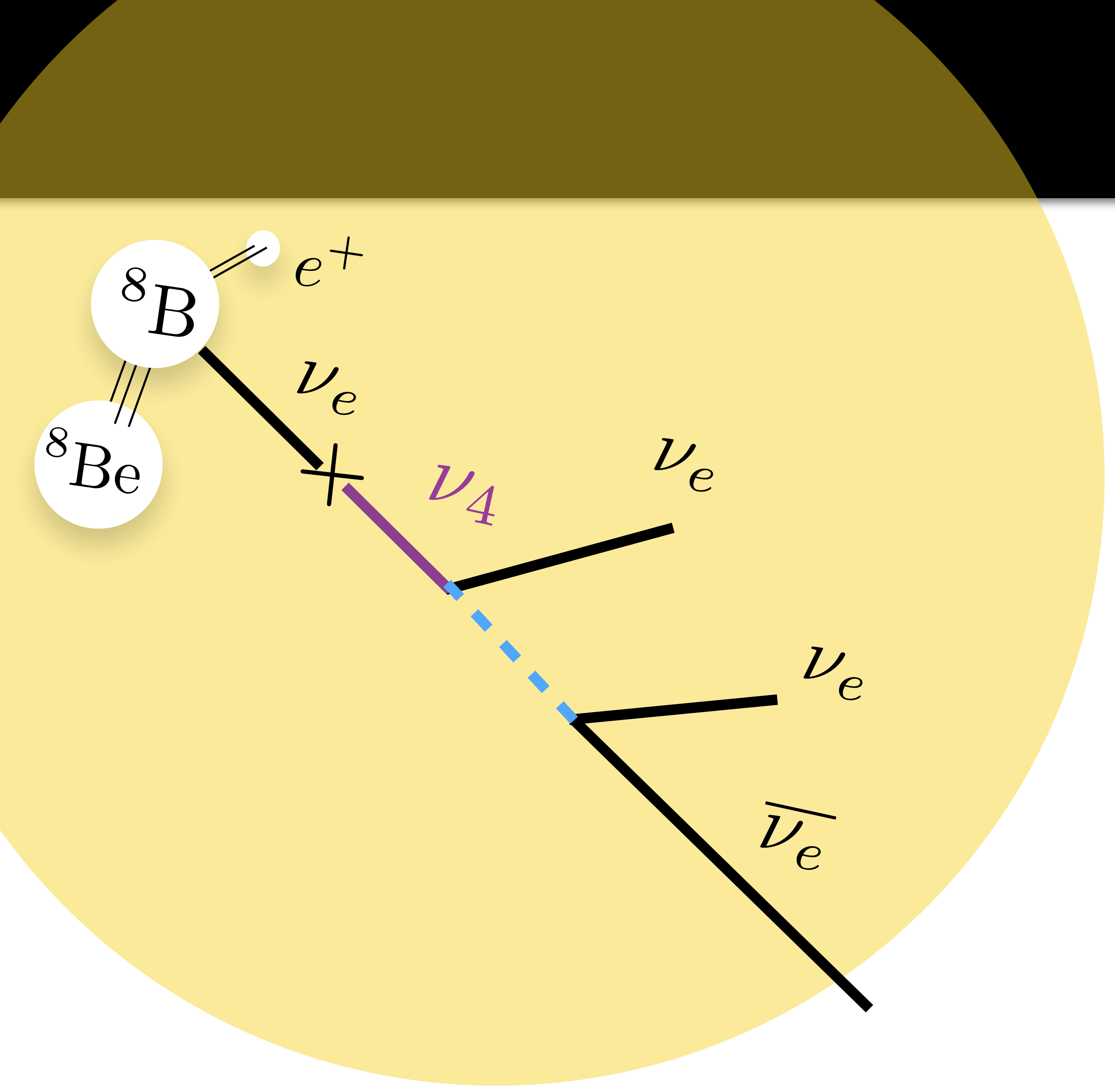
R. A. Malaney et al, Atrophy's. J 352 767 (1990)

Long-lived isotopes: $\Phi_{\overline{\nu}_e} \sim 200\ \nu/\mathrm{cm}^2/s$ for $E_\nu \lesssim 3$ MeV

Photo-fission: $\Phi_{\overline{\nu}_e} \sim 10^{-3}\ \nu/\mathrm{cm}^2/s$ for $E_\nu \sim 3 - 9$ MeV

For comparison, $\Phi_{^8B} \sim 5 \times 10^6\,\nu/\mathrm{cm}^2/\mathrm{s}$.

Solar antineutrinos

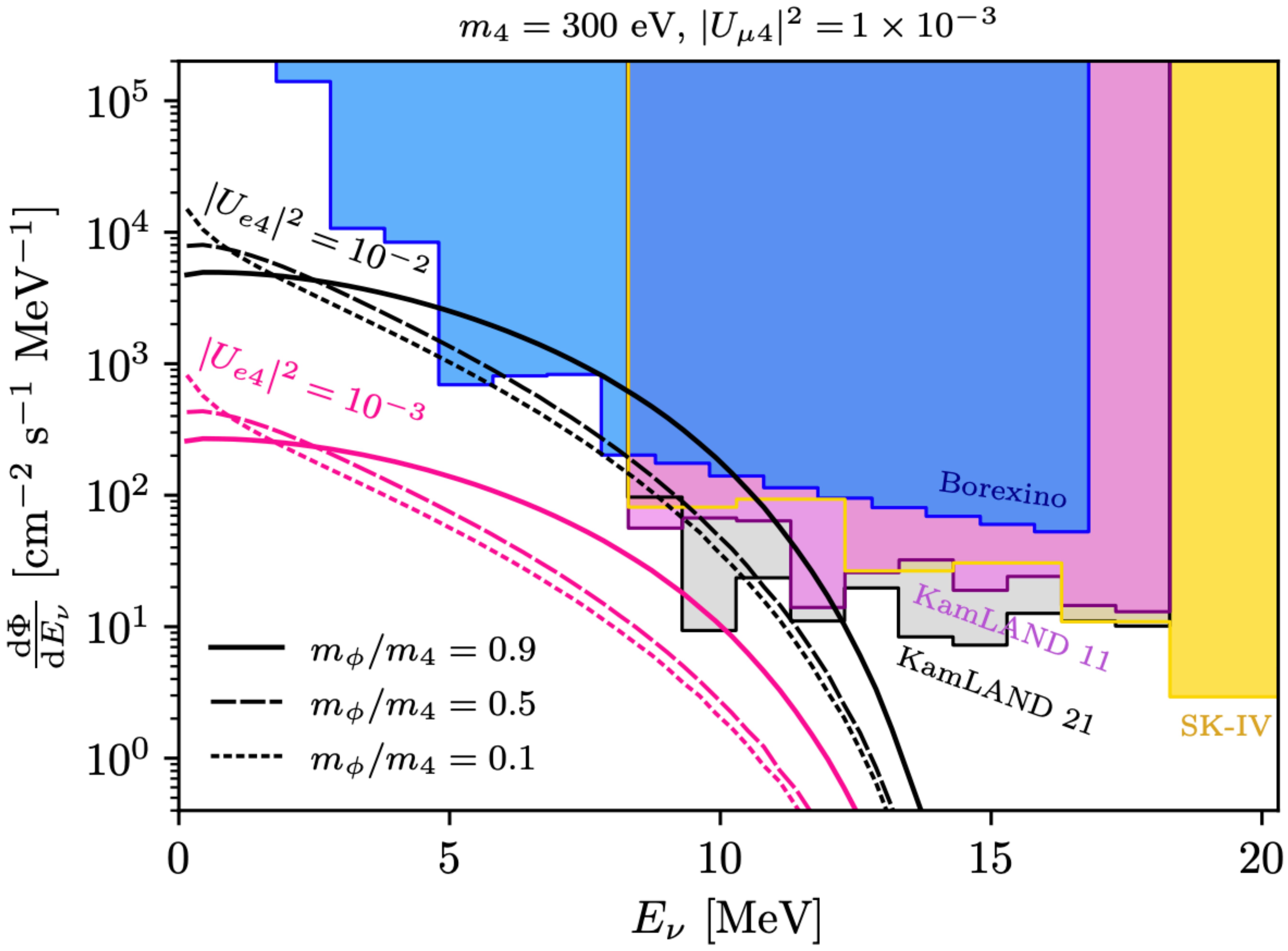


$$\overline{\nu_e} + p^+ \to e^+ + n$$

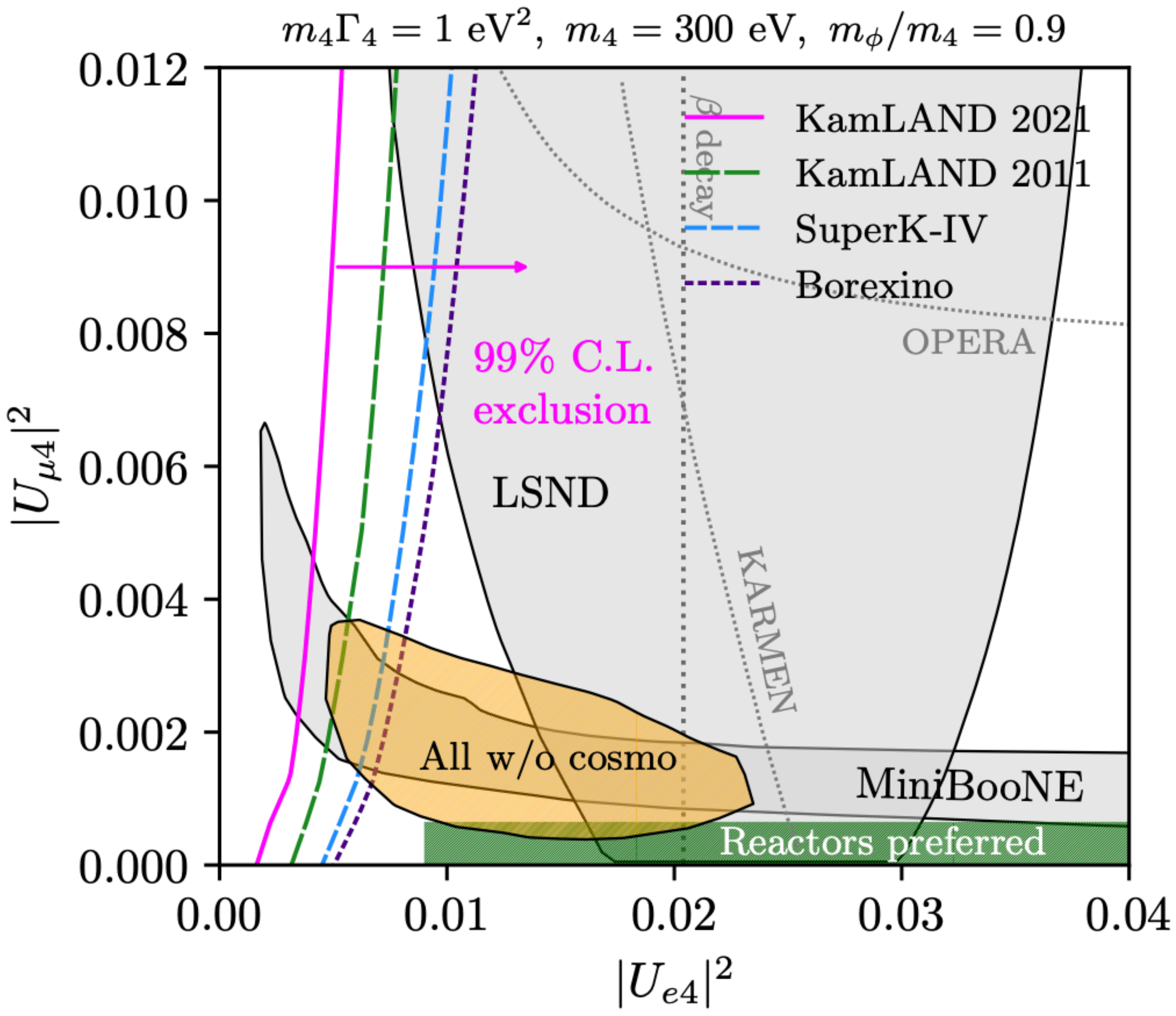
IBD has **small backgrounds** and much **larger cross section** than nu-e elastic!

$$\sigma_{\mathrm{IBD}} \gg \sigma_{\nu-e}$$

When produced, $\overline{\nu_e}$ undergoes **matter-suppressed** flavor transitions.



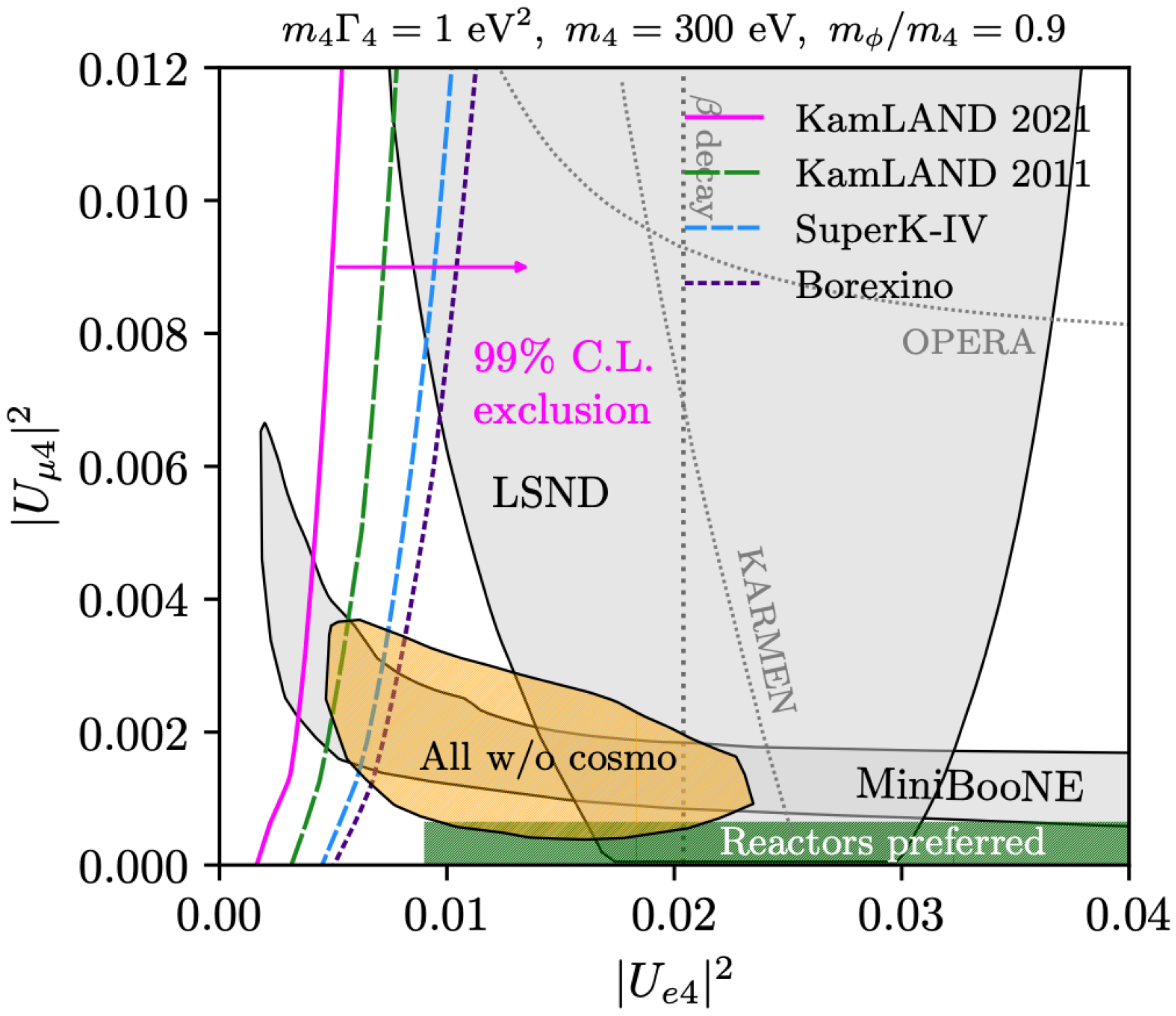
Decaying sterile prediction



A simultaneous explanation of LSND and MiniBooNE is in tension with Solar antineutrino searches.

Improvement expected at JUNO and SK-Gd:
S.J. Li *et al*, Nucl.Phys.B 944(2019)114661

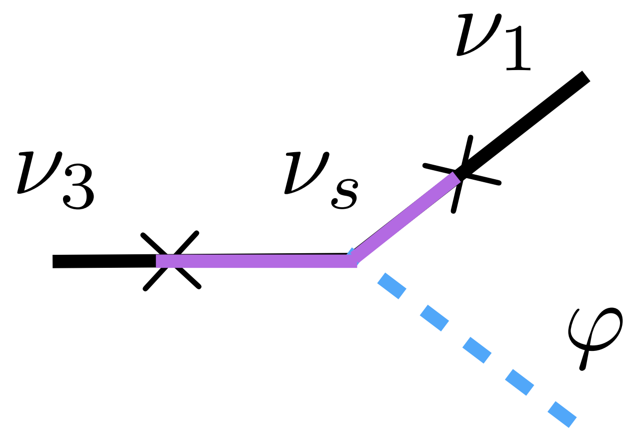
Decaying sterile prediction



A simultaneous explanation of LSND and MiniBooNE is in tension with Solar antineutrino searches.

Improvement expected at JUNO and SK-Gd:
S.J. Li *et al*, Nucl.Phys.B 944(2019)114661

- Massless scalars would not decay to antineutrinos, but would also predict light neutrino decays. For $m_1 = 0$,



NH: $c\tau_3^{\mathrm{LAB}} \approx$

IH: $c\tau_2^{\mathrm{LAB}} \approx$

$$0.03\ \mathrm{AU}\left(\frac{10^{-5}}{|U_{s1}U_{s3}|^2}\right)\left(\frac{E_3}{10\ \mathrm{MeV}}\right)$$

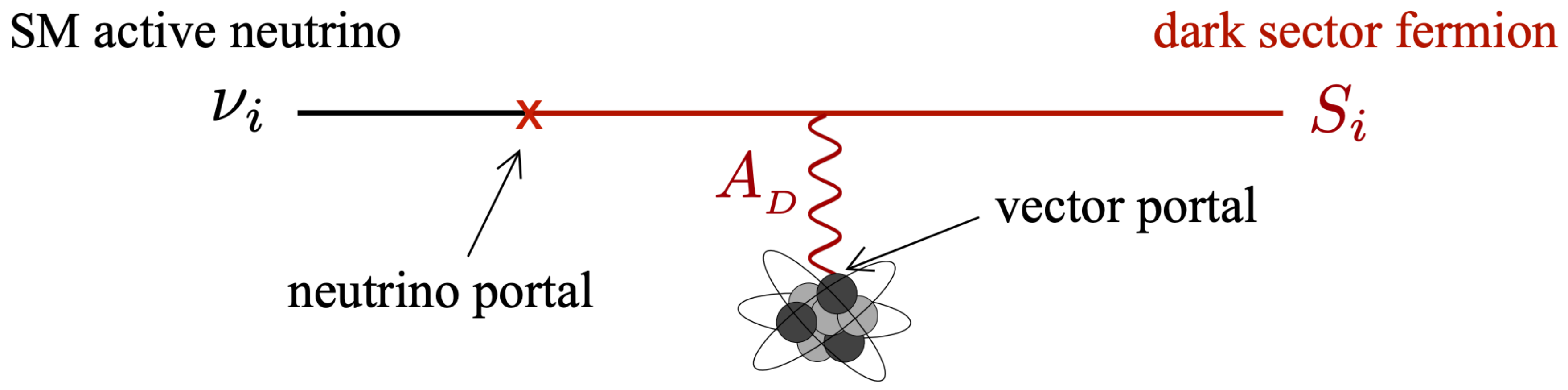
- **Majorana** neutrinos are even more strongly constrained due to $\nu_4 \to \overline{\nu}_e \phi$ decay.

- Sterile decay may proceed via higher-dimensional operators: $\phi(LH)^2$, or $\phi(LH)\nu_s$, which do not necessarily require mixing with electron sector, predicting no production of sterile in the Sun.

S. Palomares-Ruiz *et al*, JHEP09(2005)048
A. deGouvea *et al*, JHEP07(2020)141

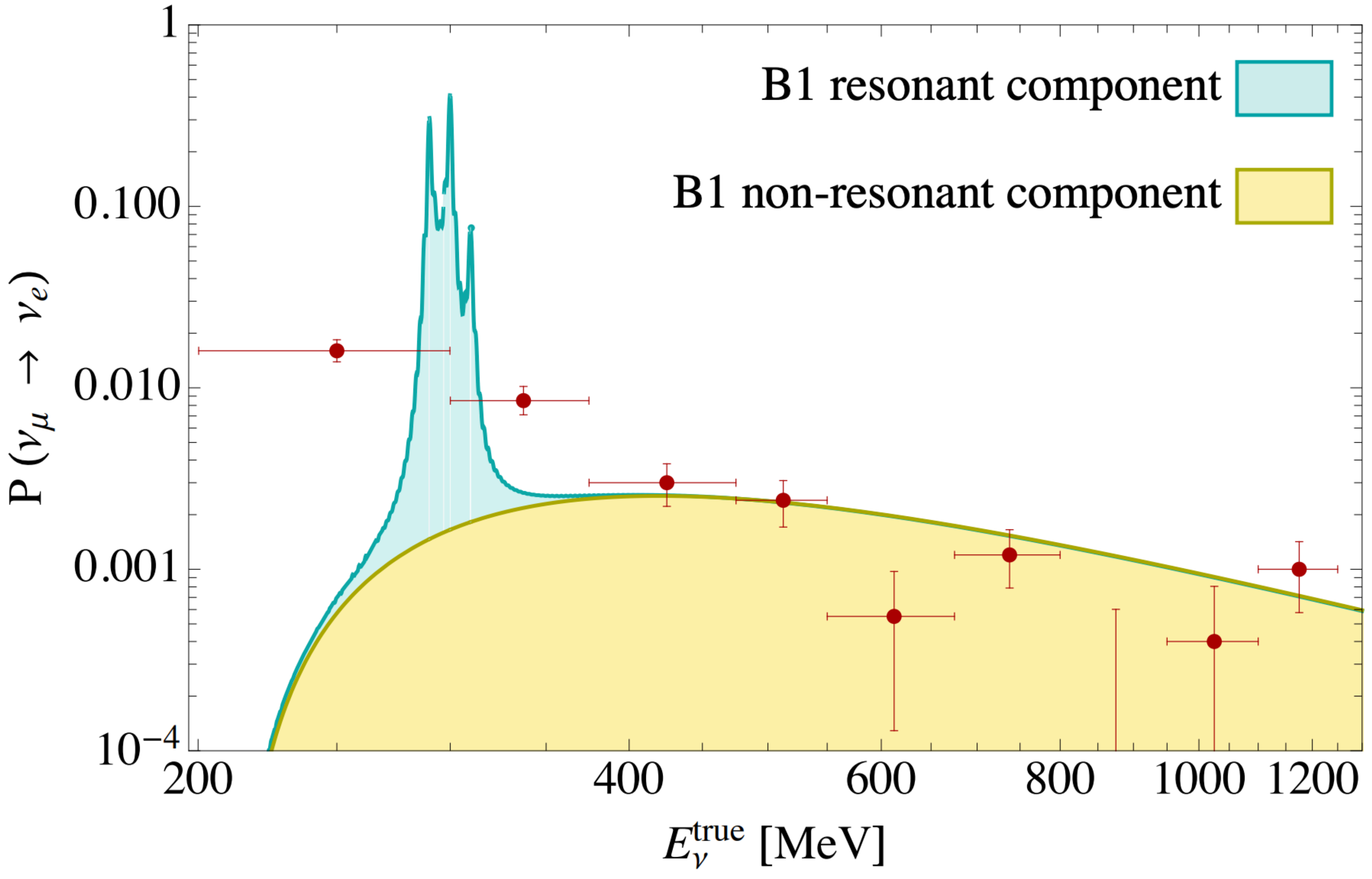
Resonant matter effects
Quasi-sterile neutrinos

D.S. M. Alves et al arXiv: 2201.00876



Quasi-sterile neutrinos with large interactions with matter.

$$\Delta V\big|_{\rm matter} = (V_{S_3} - V_{\nu_i})\big|_{\rm matter} = -\frac{(g_S - g_\nu)}{2\,m_{A_D}^2}\sum_{f=e,p,n} g_f\, n_f$$



$$E^{\rm res}_{\nu_3} = \frac{\delta M_3^2\,\cos 2\theta_{S_3}}{2\,|\Delta V|}$$

Not discussed:

Same resonance appears in the **air**: $E_\nu^{\rm RES} = 300$ GeV, interesting particularly for $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$. at IceCube.

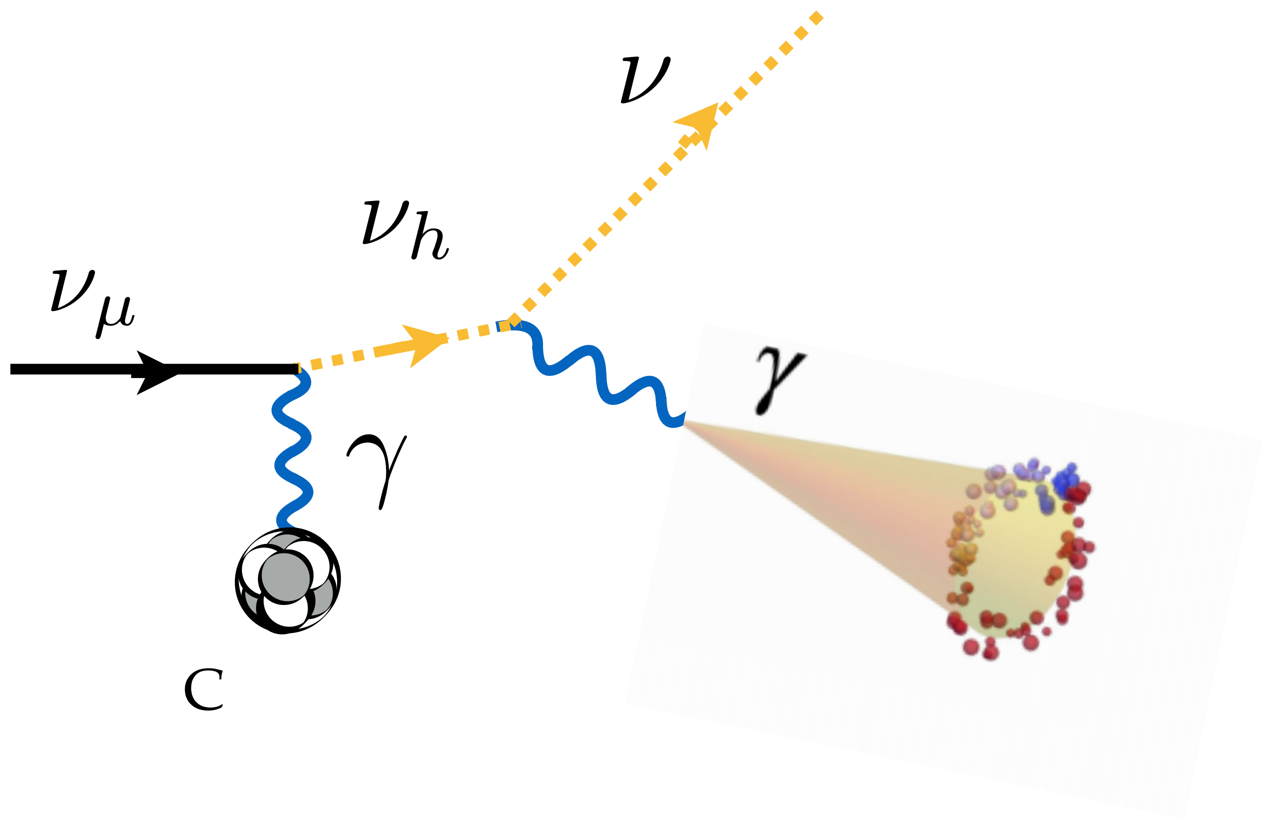
Challenging to find a UV model yet with such large potentials.

Transition magnetic moments

Now in upscattering

S. Gninenko, [arXiv:0902.3802],
S. Gninenko, [arXiv:1201.5194],
M.Masip et al, [arXiv:1210.1519],
G. Magill et al, [arXiv:1803.03262],
Vergani et al, [arXiv:2105.06470],
Luis Alvarez-Ruso et al [arXiv:2111.02504]

Transition magnetic moment in scattering.

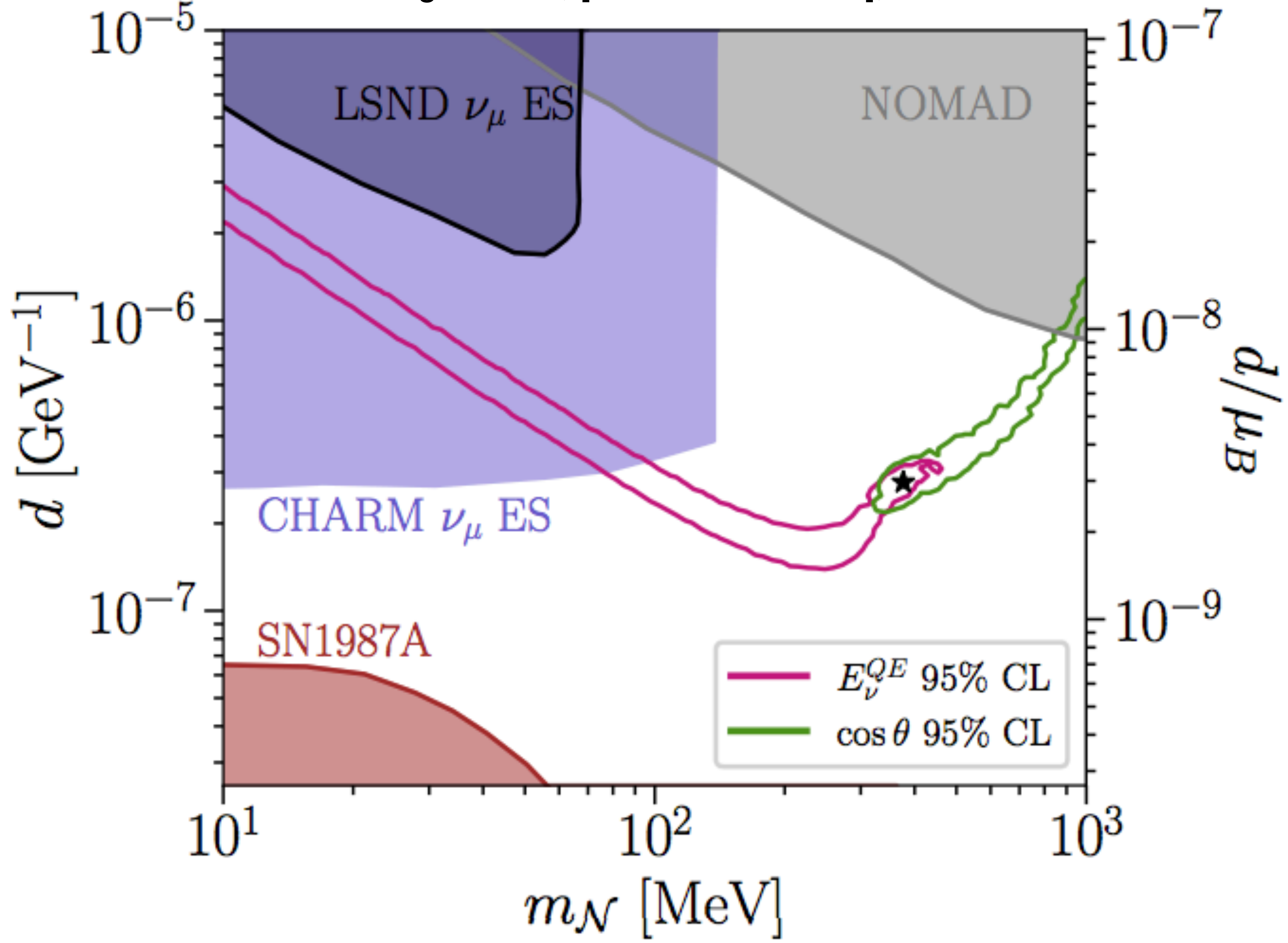


$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu} \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R \, .$$

Also goes by the name of **dipole operator**:

$$d = \frac{\mu_\nu}{2}$$

Vergani et al, [arXiv:2105.06470],



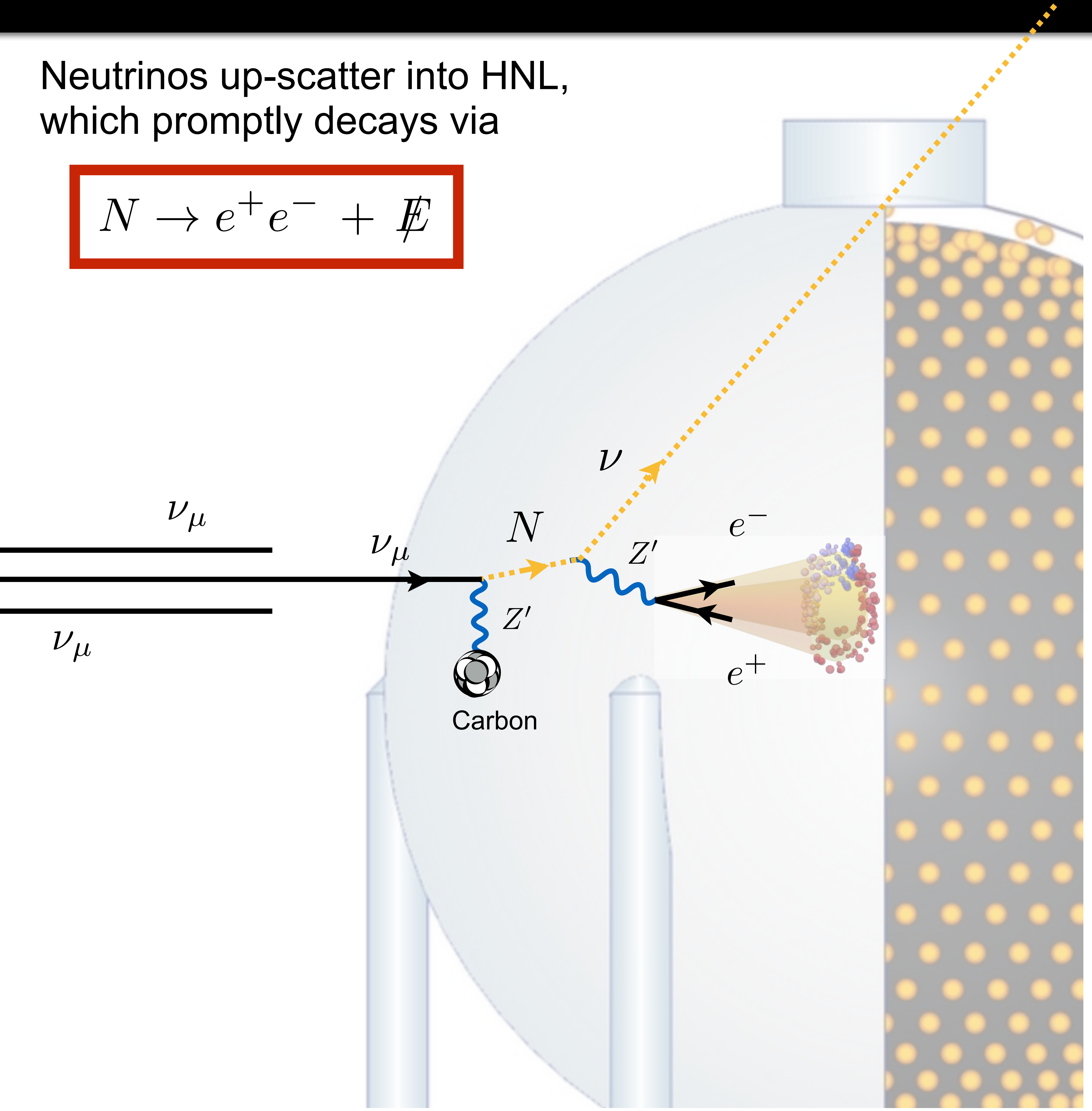
Dark neutrinos

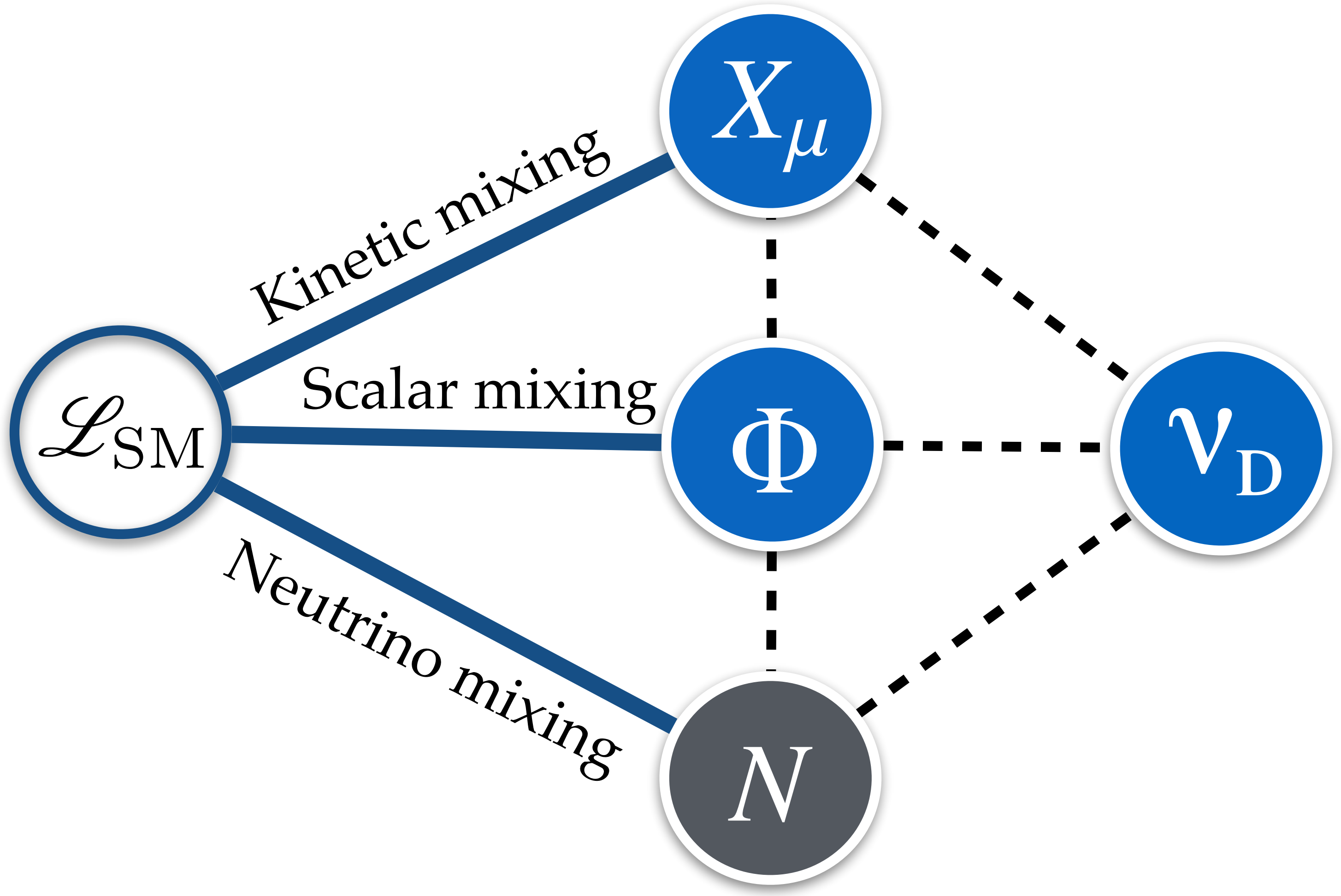
Heavy neutrinos interacting via the dark photon

P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]
E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett et al, [arxiv:1808.02915]

Neutrinos up-scatter into HNL, which promptly decays via

$$\boxed{N \to e^+e^- + \not{E}}$$





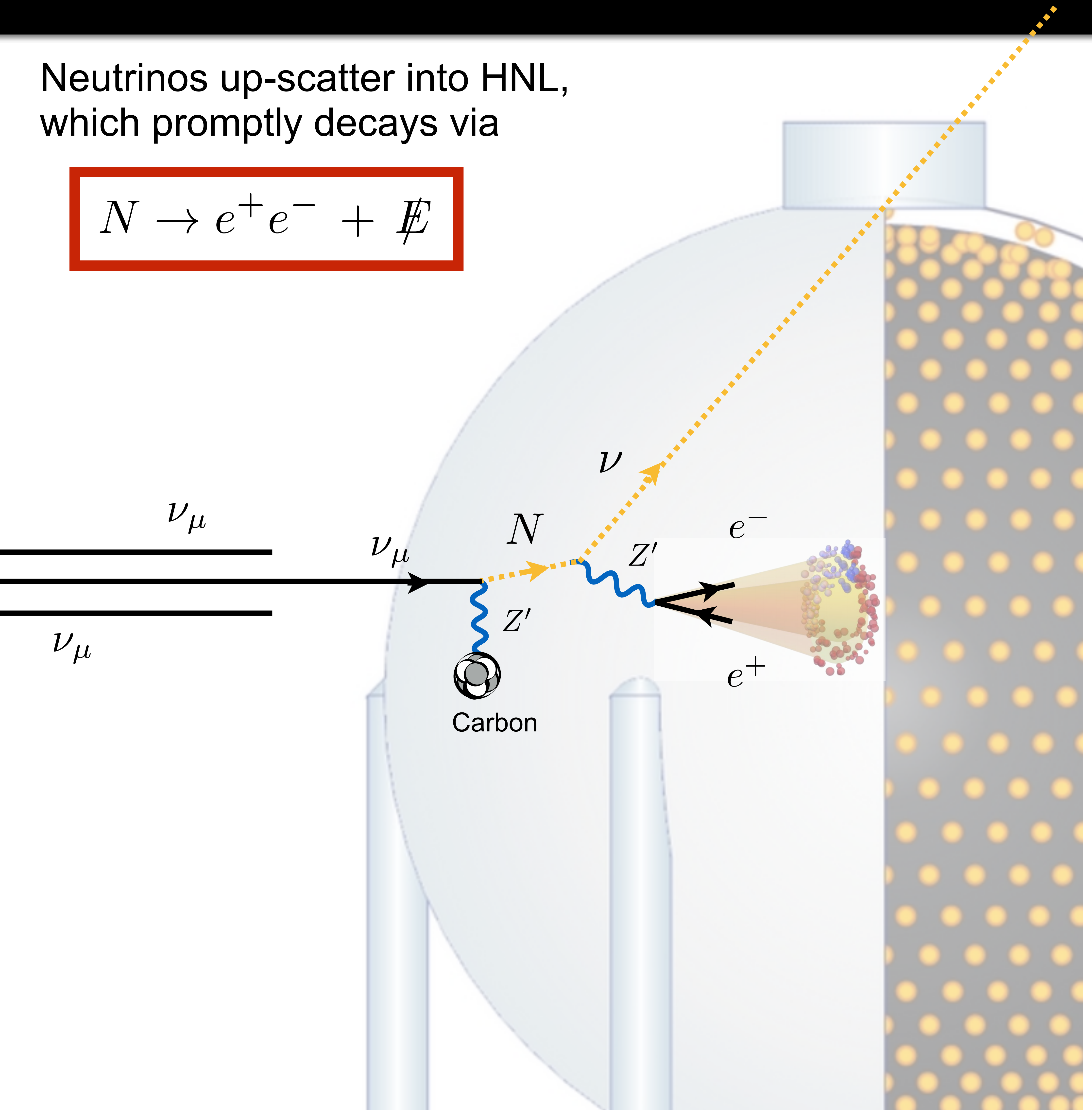
$$y^\nu (LH)N + M_N NN + y_N N\nu_D\Phi + M_X \nu_{D_L}\nu_{D_R}$$

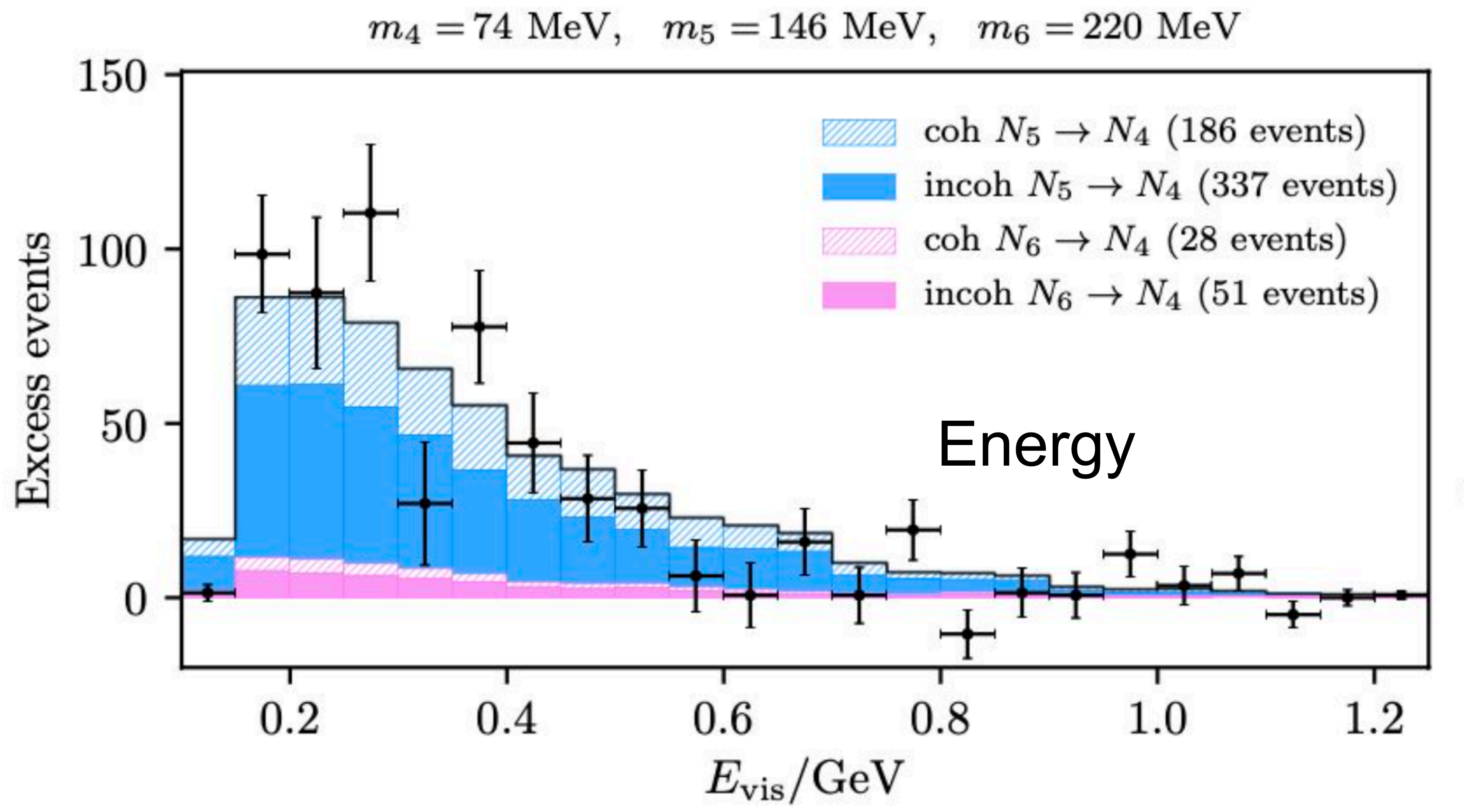
Dark neutrinos
Heavy neutrinos interacting via the dark photon

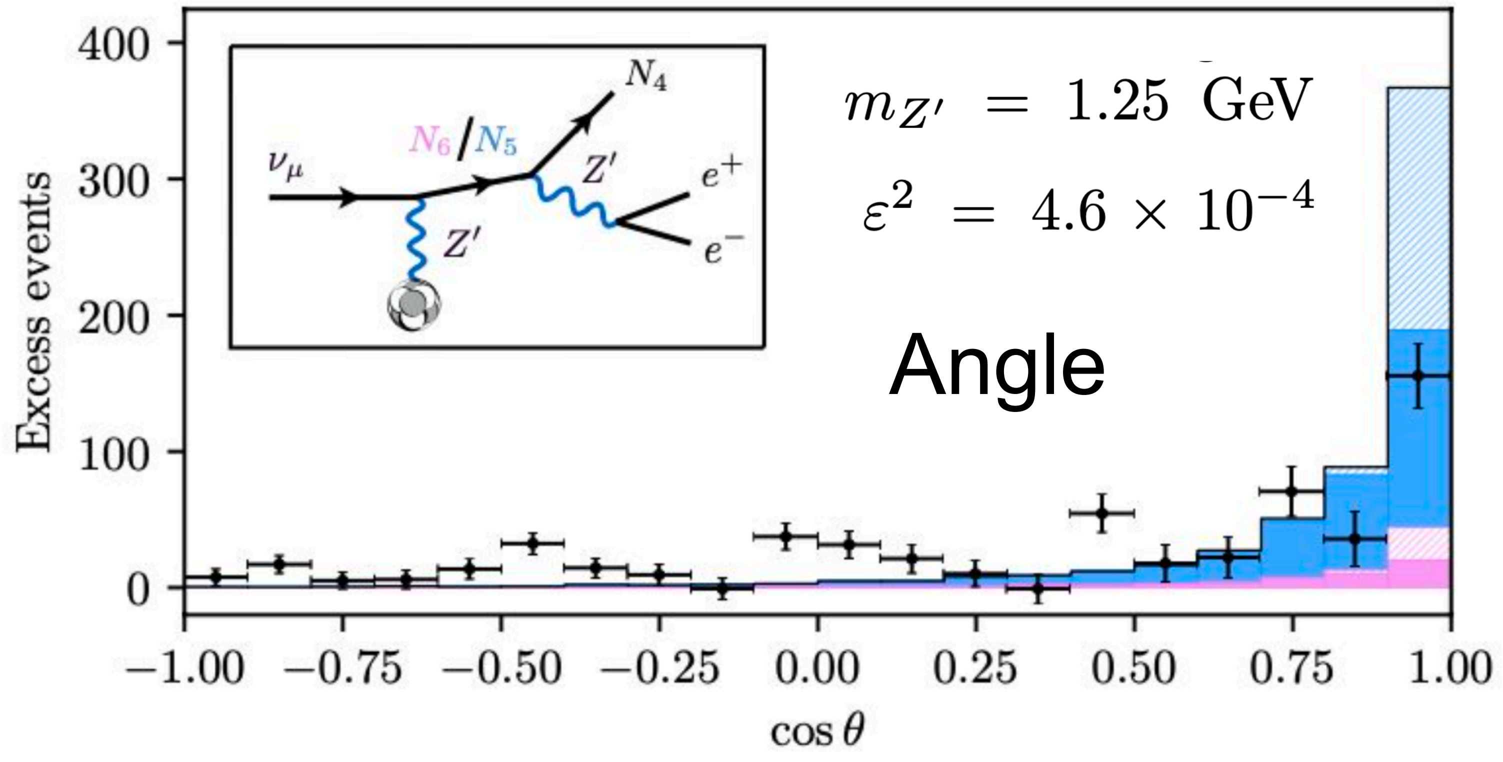
P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]
E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett et al, [arxiv:1808.02915]

Neutrinos up-scatter into HNL, which promptly decays via

$$\boxed{N \to e^+e^- + \not{E}}$$

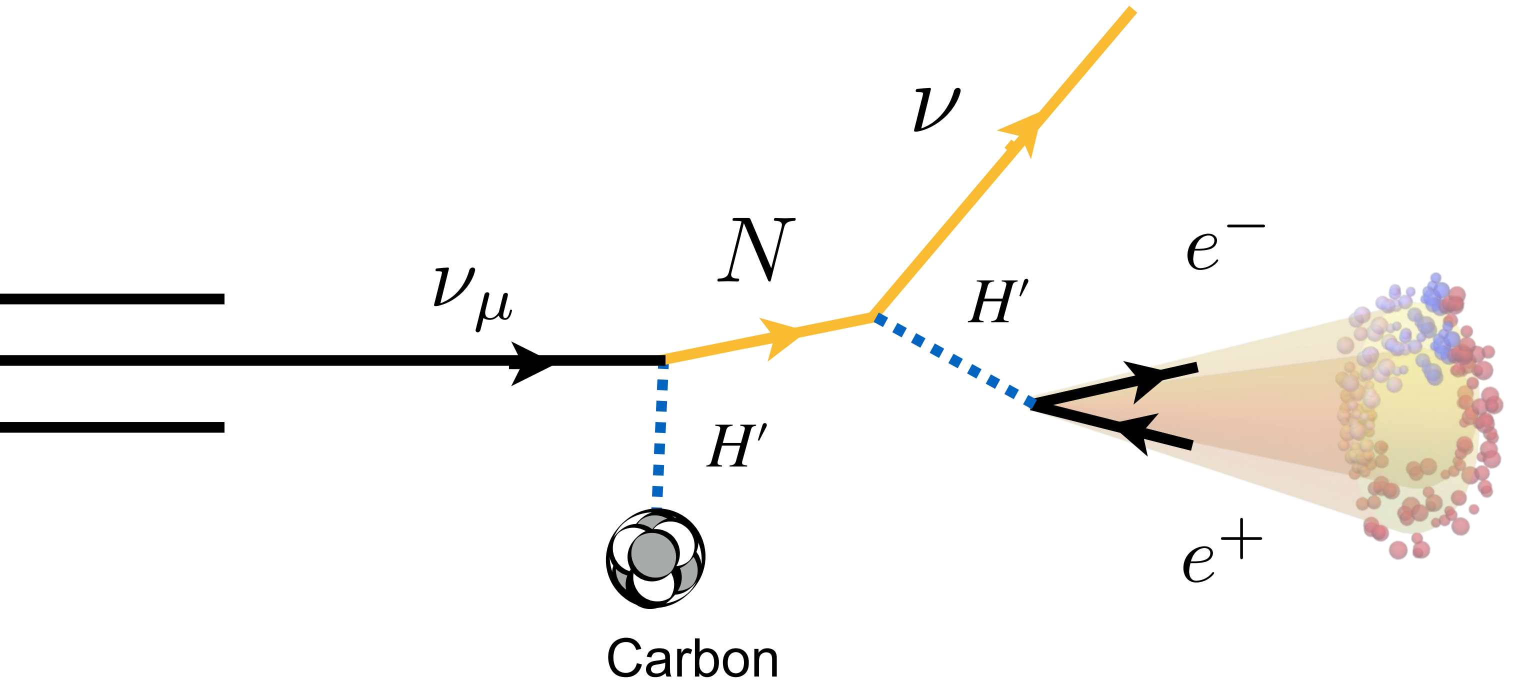






Dark neutrinos
Scalar mediators

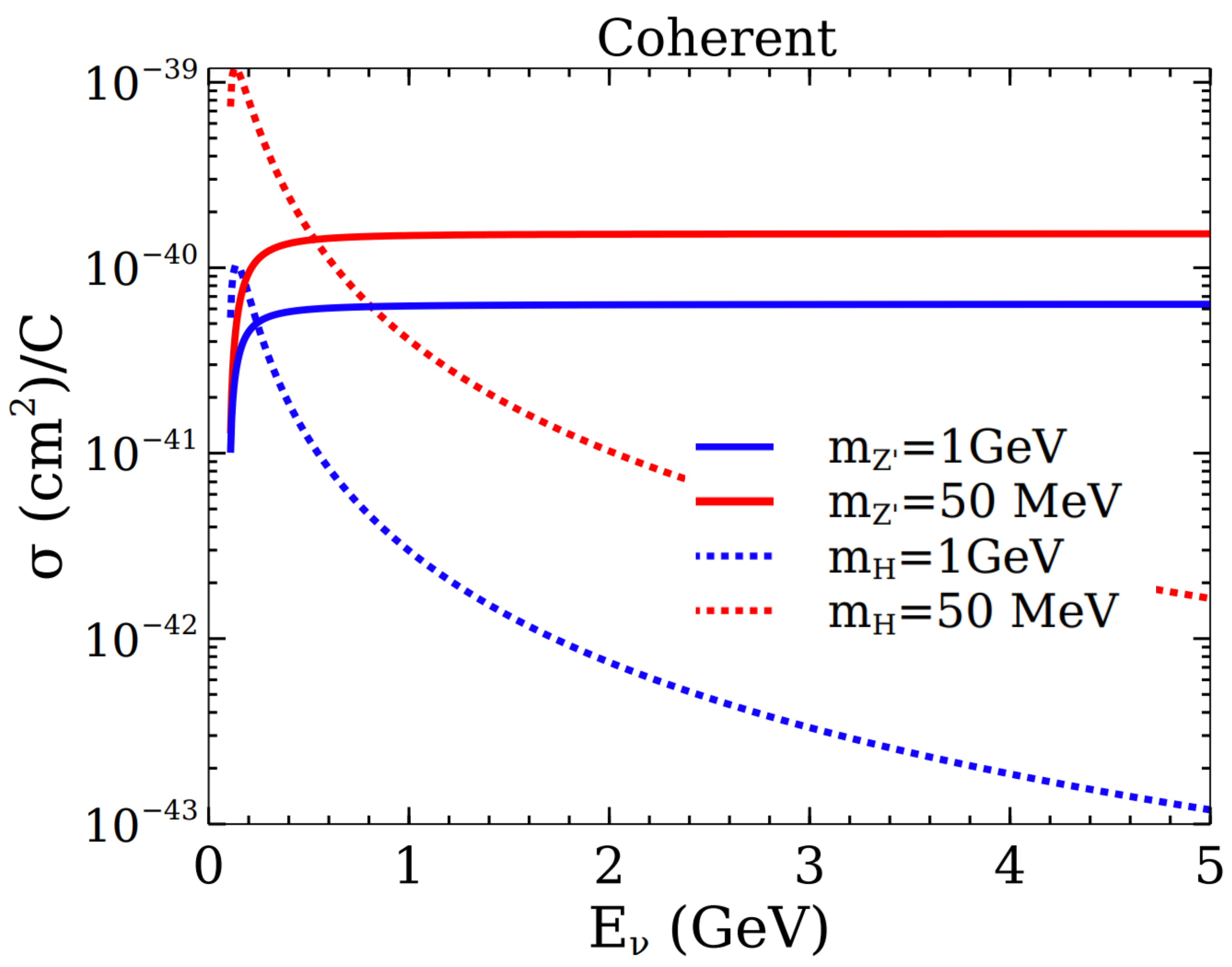
B. Dutta et al, [arxiv:2006.01319]
A. Datta et al, [arXiv:2005.08920]
B. Dutta et al, [arxiv:2006.01319]
W. Abdallah et al, arXiv:2202.09373



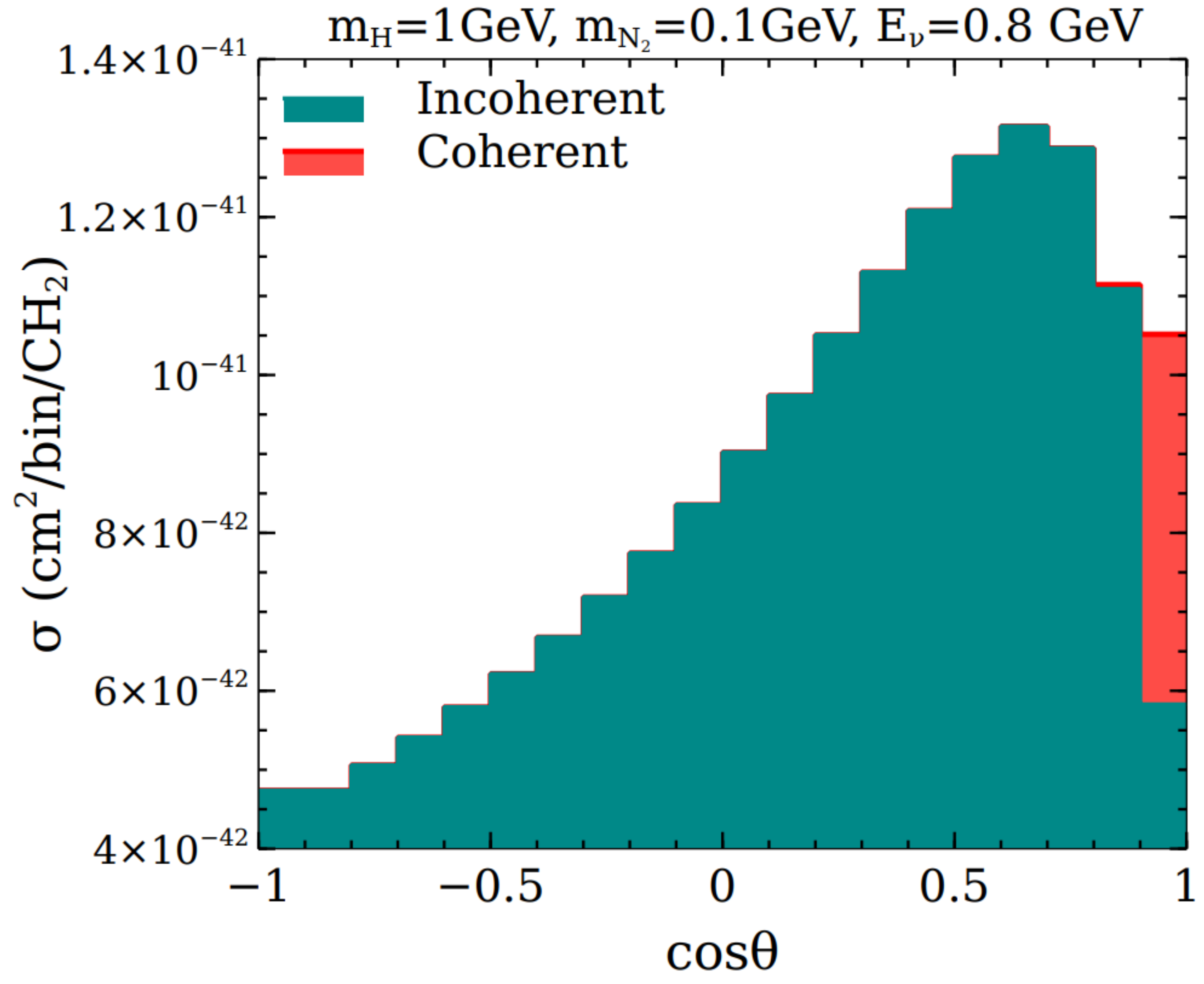
In addition to e+e-, scalars can also have a large BR into $\gamma\gamma$, mimicking a π^0

$$\mathscr{L} \supset \kappa H' F_{\mu\nu} F^{\mu\nu}$$

Several models proposed with connections to $(g-2)_\mu$ and flavor anomalies.



No t-channel singularity for scalar exchange. Cross section goes down in energy.



Angular distribution is broader.

Dark neutrinos
Heavy neutrinos interacting via the dark photon

A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, *in progress*

Upcoming: **`DarkNews,`** a fast MC generator for new physics in neutrino-nucleus scattering.
Including vector, scalar, and dipole mediators. Models with up to 3 HNLs.

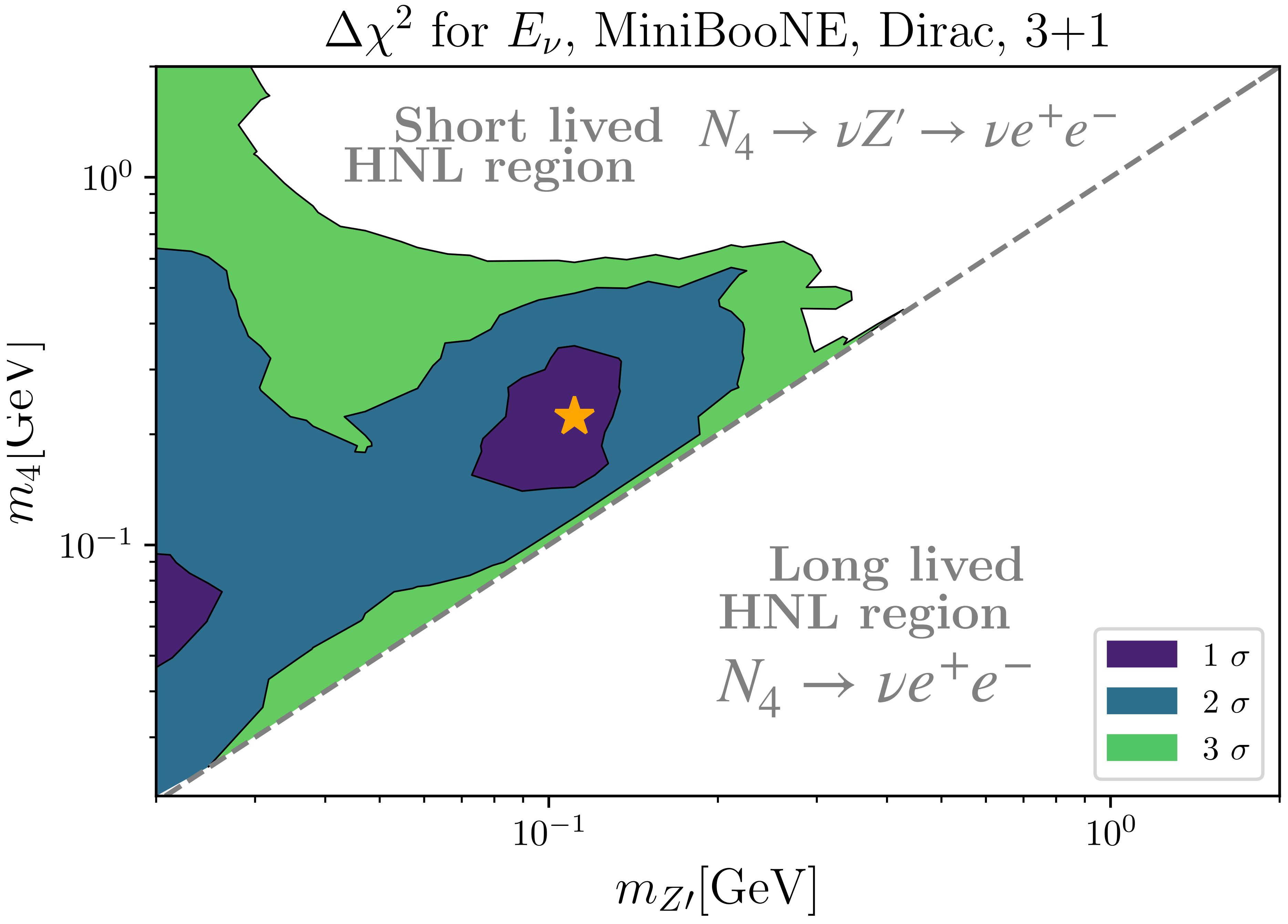
Dark neutrinos

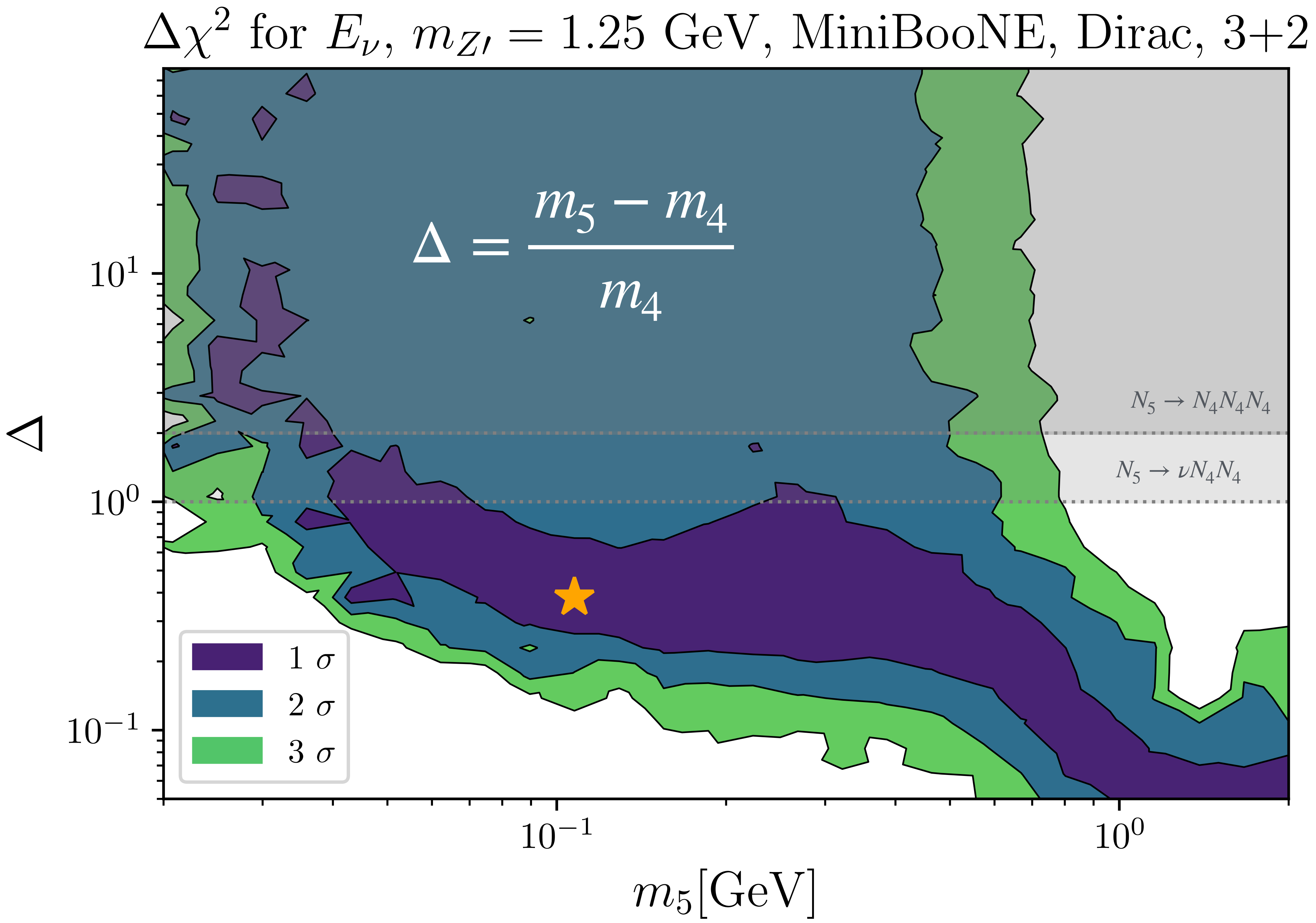
Heavy neutrinos interacting via the dark photon

A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, *in progress*

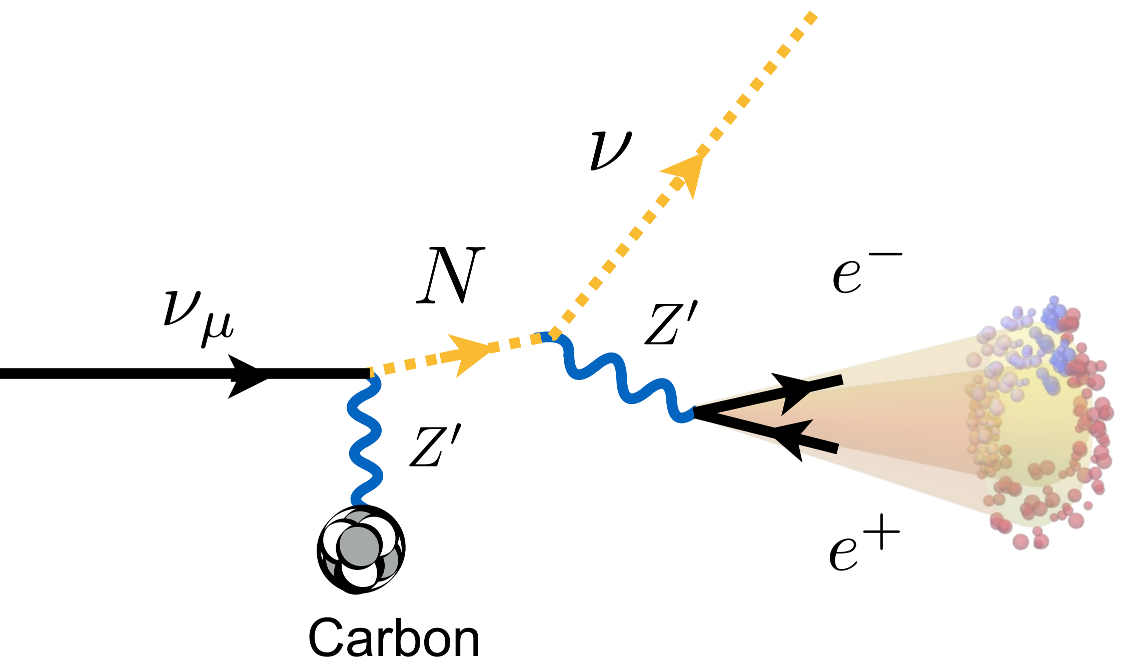
Upcoming: **`DarkNews`**, a fast MC generator for new physics in neutrino-nucleus scattering.
Including vector, scalar, and dipole mediators. Models with up to 3 HNLs.

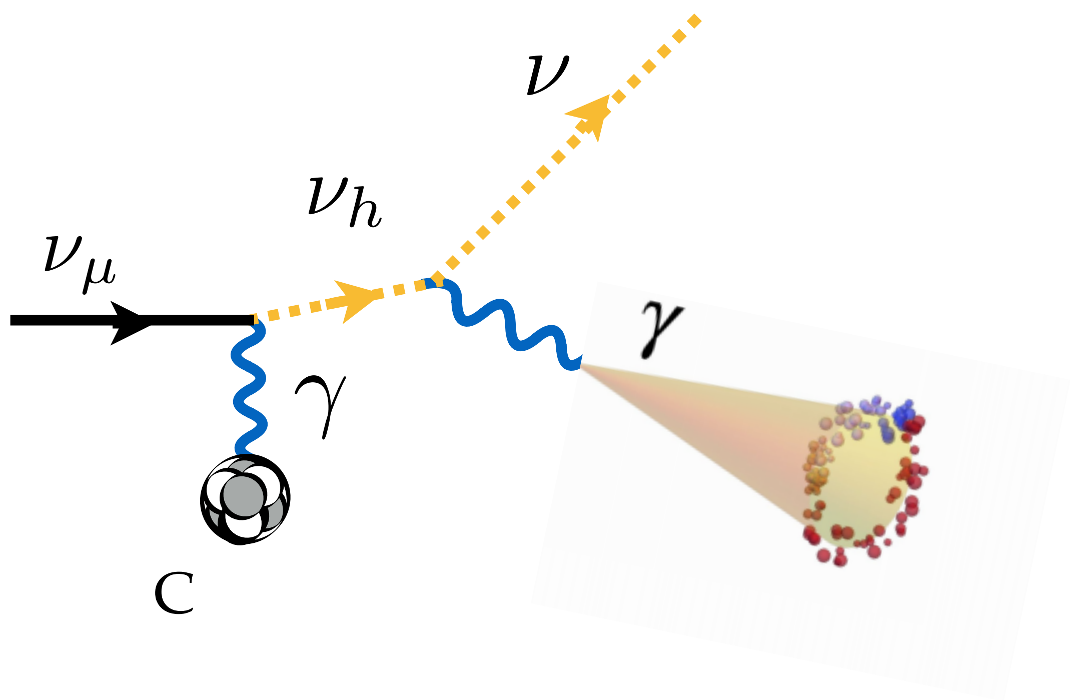
MiniBooNE E_ν^{reco} fits to a model with 1 and 2 Dark Neutrinos.





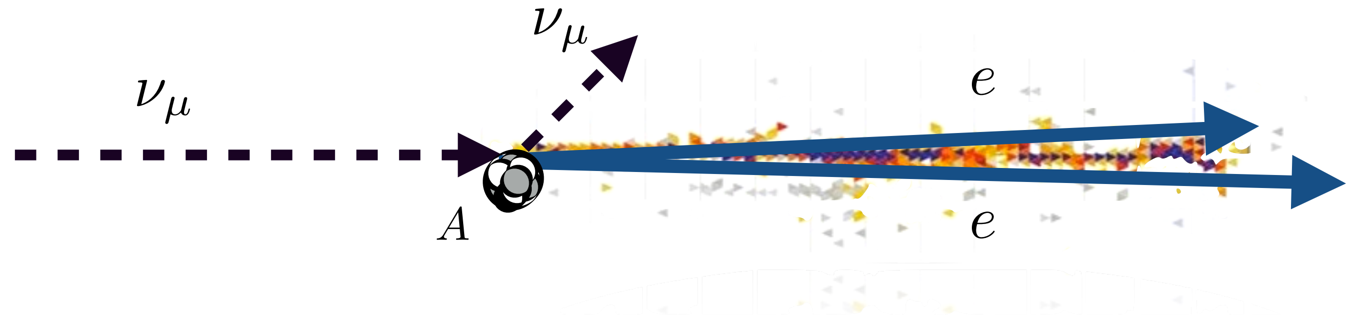
Models with upscattering signatures
Other predictions





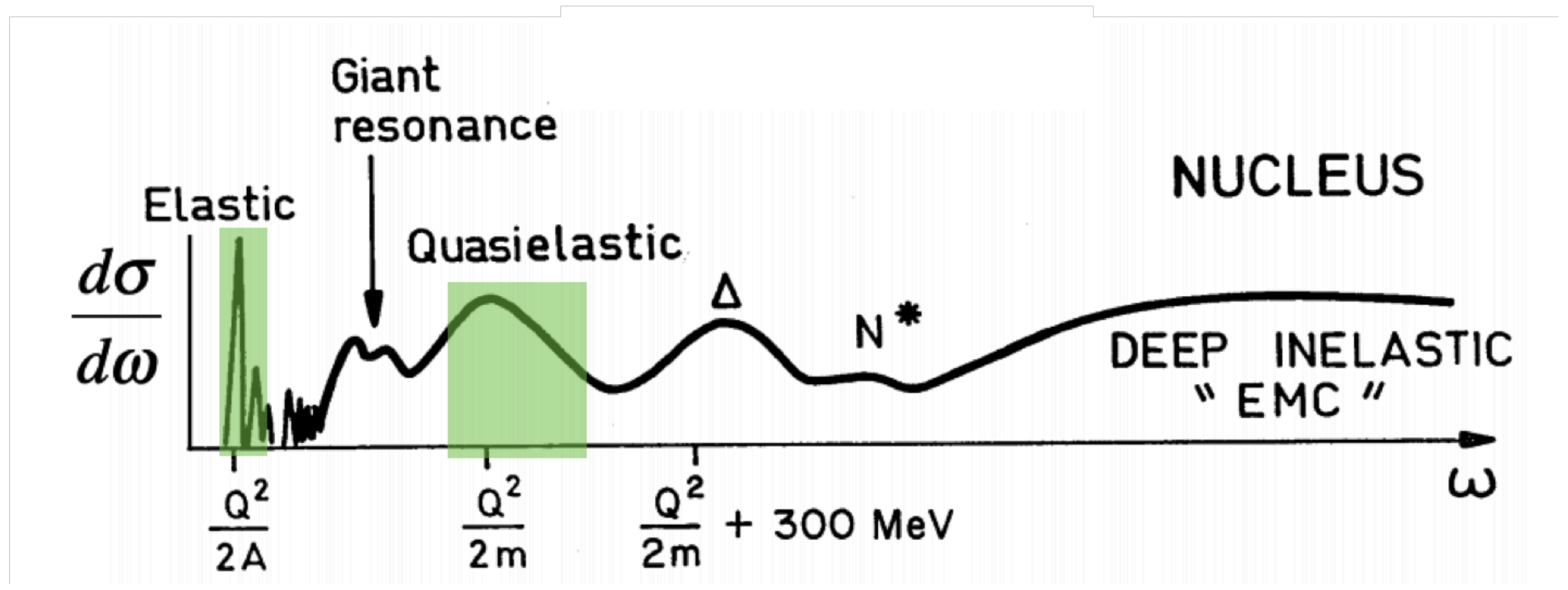
Pseudo single photons at ν detectors:

More info soon w/ **NOvA** and **MINERvA**?

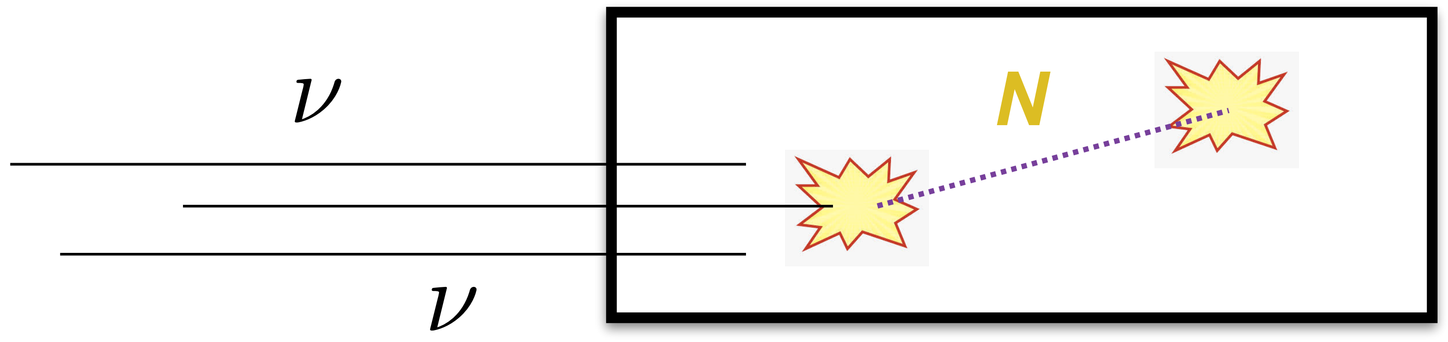


C. Arguelles, MH, Y. Tsai, PRL123.261801

No nuclear model — how important are non-QE non-COH contributions?



Double-bangs: *scatter + decay.*
Searched for at **CCFR** (1990).



9 NC/NC observed on a background of $3\pm0.2\,(\mathrm{stat.})\pm0.4\,(\mathrm{syst.})$

P. de Barbaro, doi.org/10.1063/1.43269

Future opportunity for IceCube and DUNE,
[P. Coloma et al, arxiv:2105.09357]

Upscattering in dense neutrino detectors

T2K near detector (ND280)

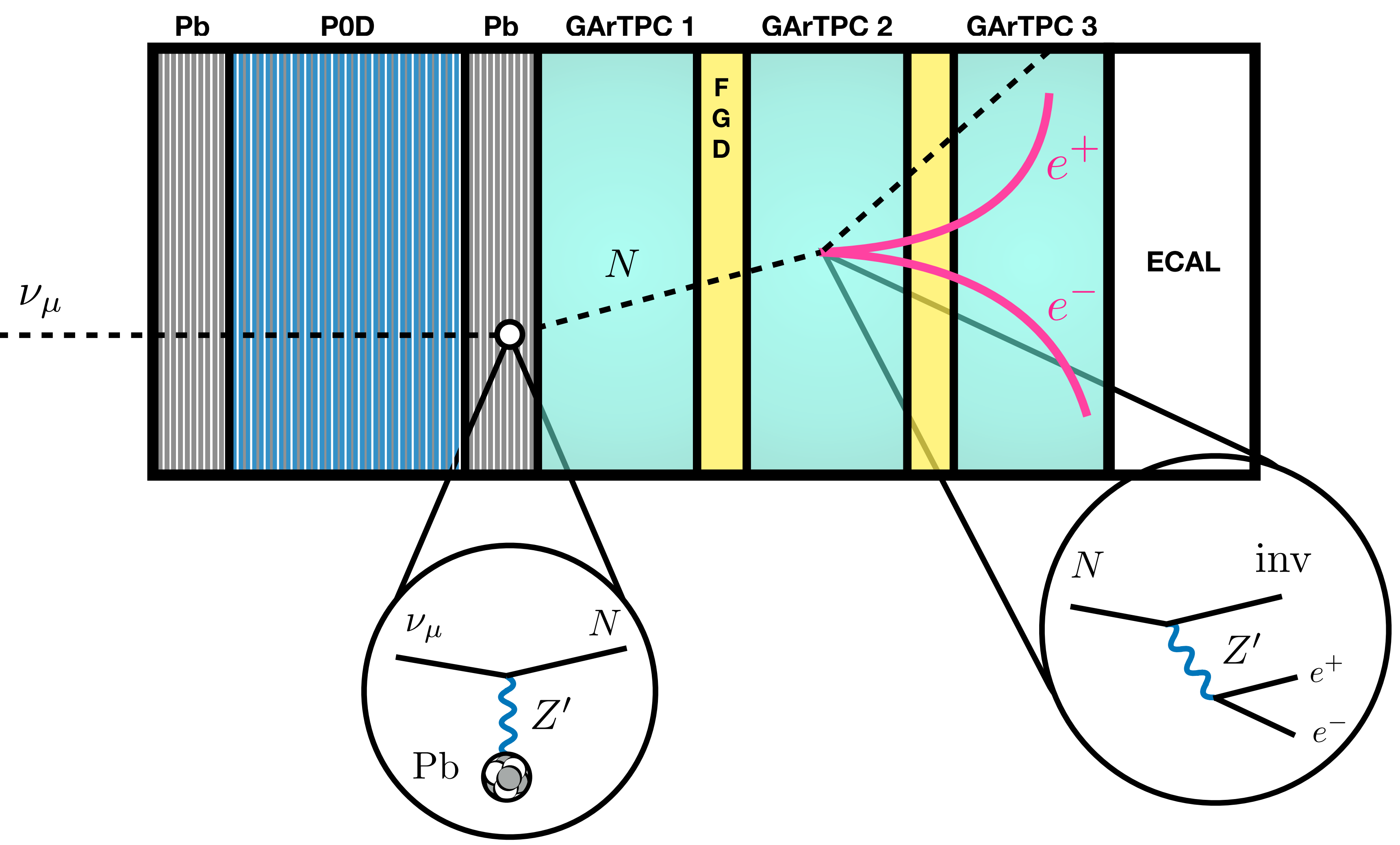
T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, arXiv:2007.14411

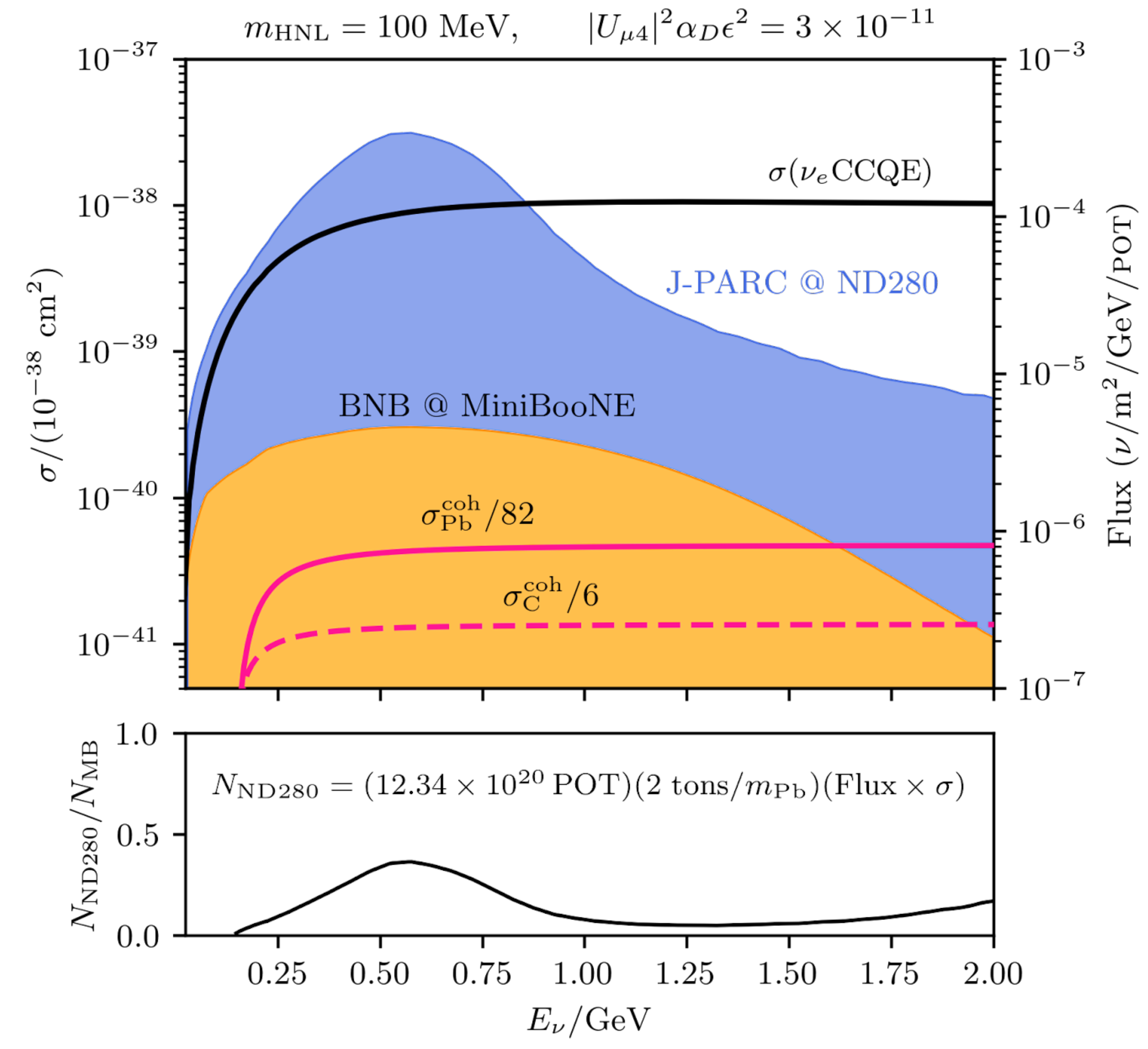
C. Arguelles, MH, N. Foppiani, in preparation.

Heavy **lead** plates

+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-





Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

Upscattering in dense neutrino detectors
T2K near detector (ND280)

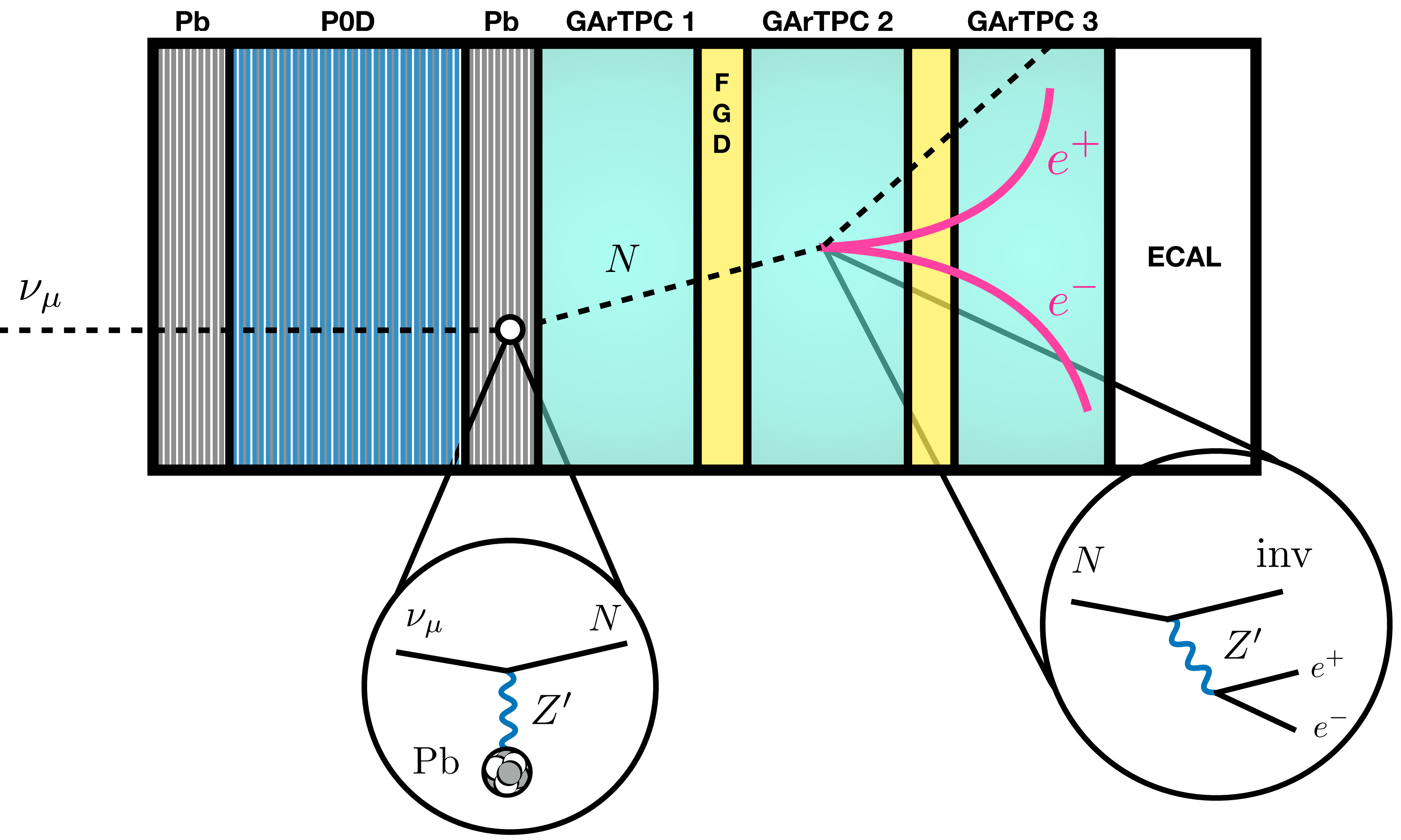
T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, arXiv:2007.14411

C. Arguelles, MH, N. Foppiani, in preparation.

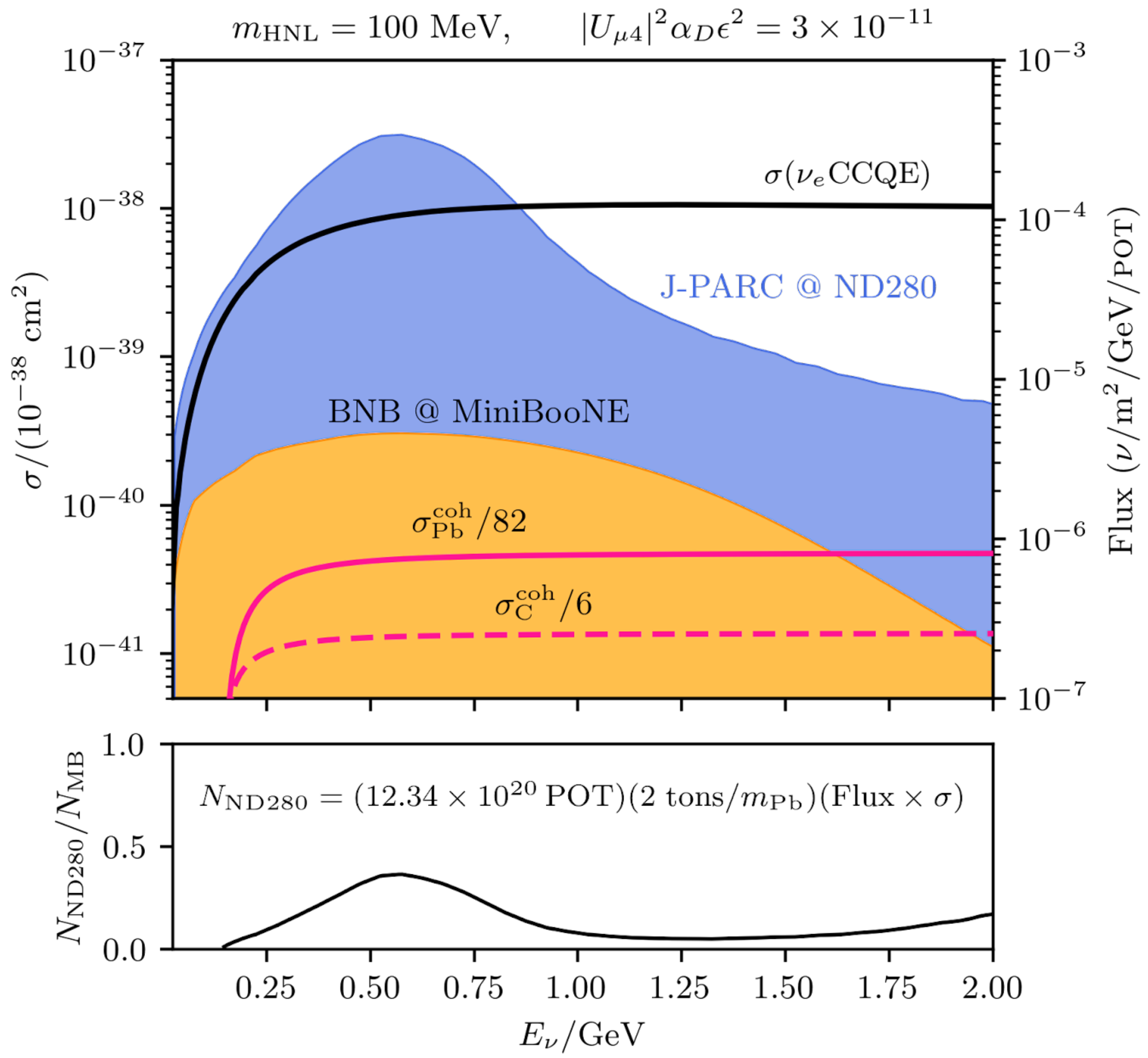
Heavy **lead** plates

+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-

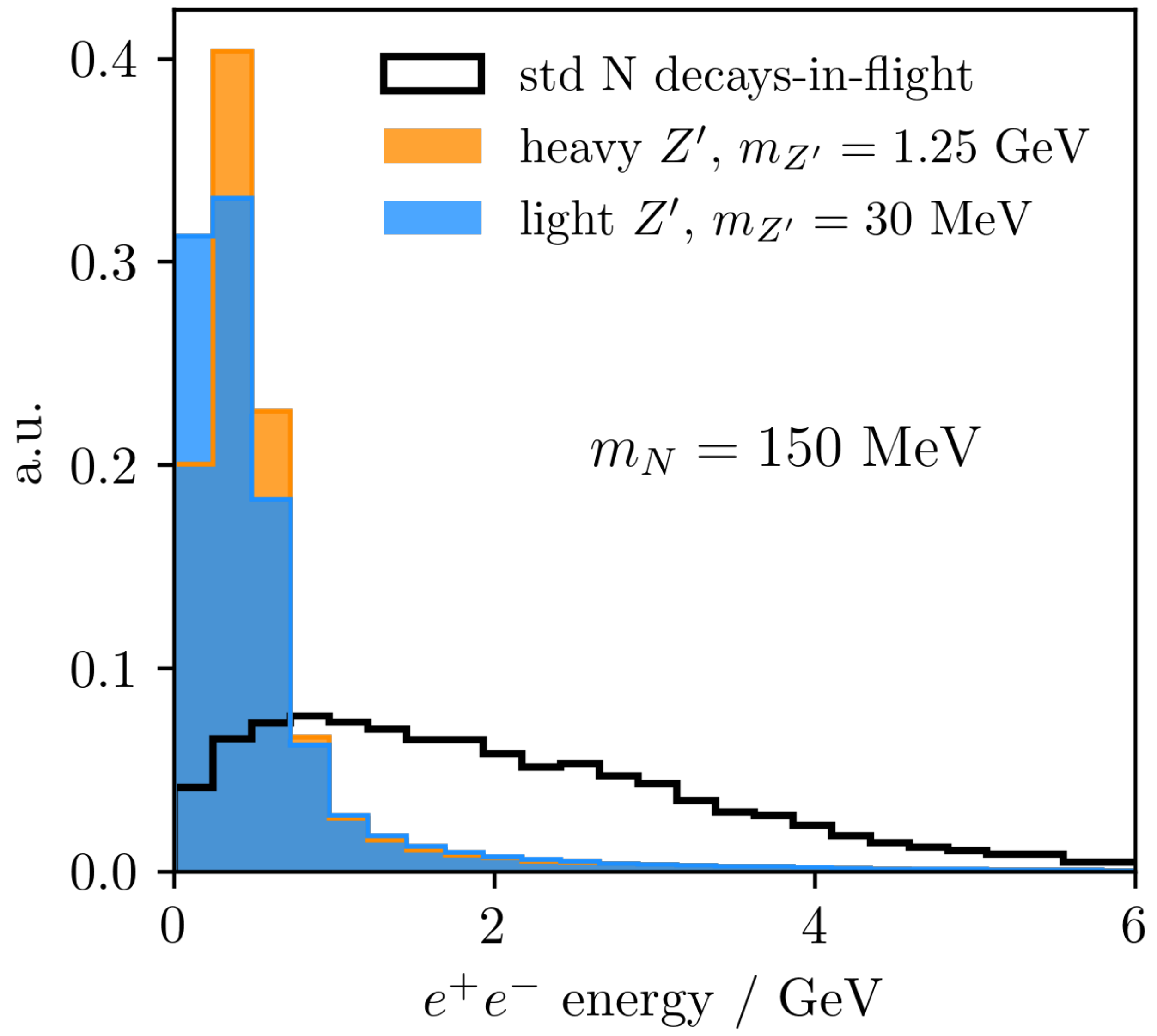


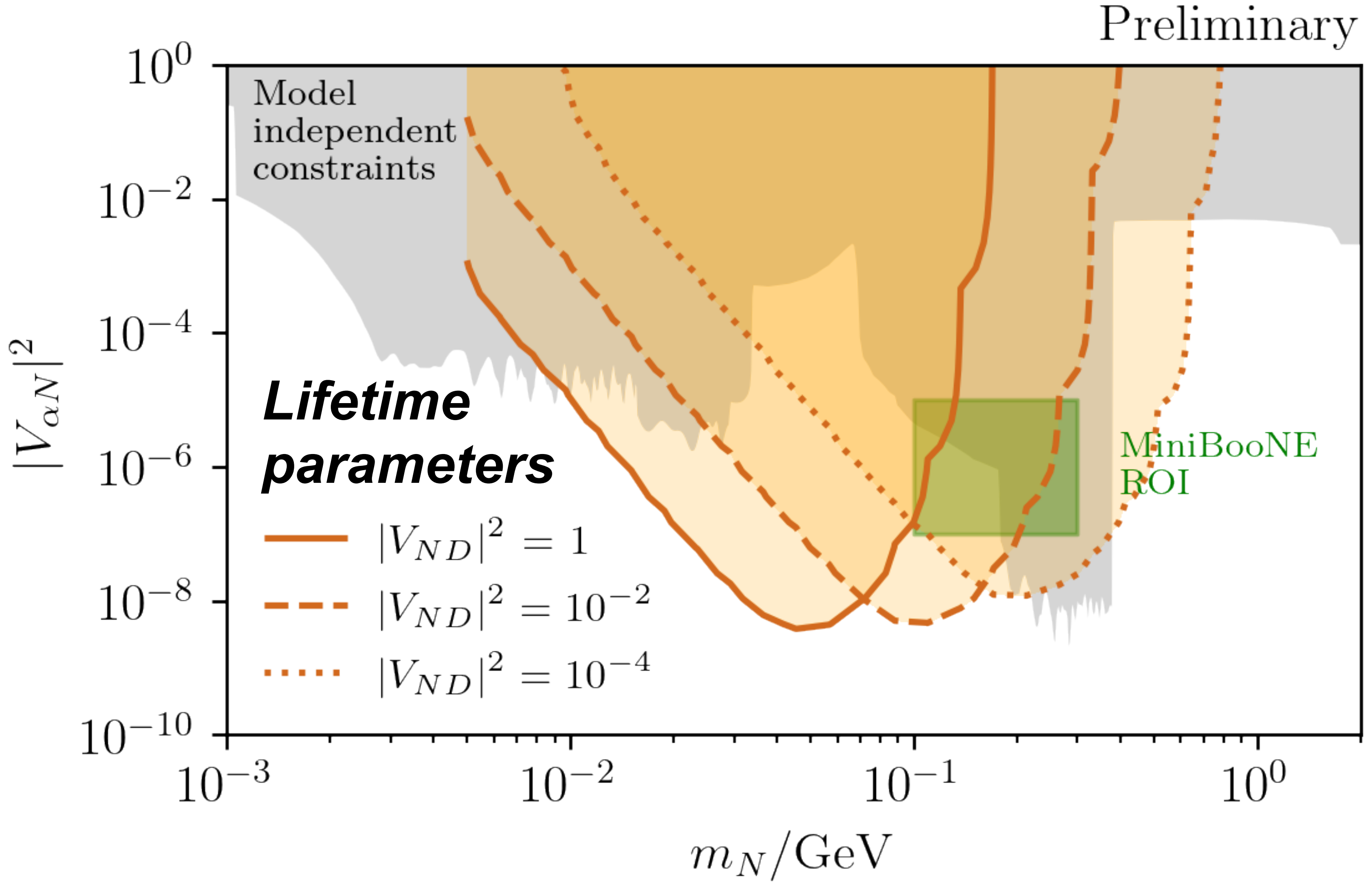
Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.



Precludes any signature of upscattering at other existing neutrino experiments for

$$c\tau \gtrsim 10 - 15\ {\rm cm}$$

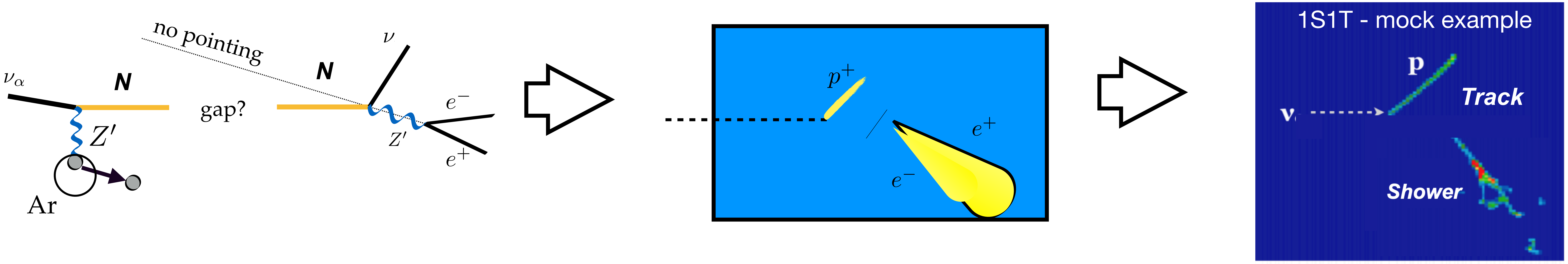




Upscattering in dense neutrino detectors

Searches for e+e- at the SBN program

New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events and will test MiniBooNE results.



Some total rates for the model for 6×10^{20} POT with a BP of $m_4 = 420$ MeV and $m_{Z'} = 30$ MeV (before efficiencies):

SBND: 16,800 events /112 t @ 110 m baseline

MicroBooNE: 715 event /87 t @ 470 m baseline

Icarus: 2,401 events /476 t @ 600 m baseline

Z^2 scaling really helps the rate at LAr experiments.

Conclusions:

The existence of heavy neutral leptons could open a door into dark sectors.

Neutrino experiments are probing new forces that are much weaker-than-Weak

The Short-baseline puzzle remains unsolved.

New ideas with light particles are on the market. They are all testable.

Experiment-theory collaboration is currently of utmost importance:

Theorists can start by providing new tools (MC generators, databases, theory-exp maps).

Experimentalists can continue to provide data releases (and more data).