Heavy Neutral Leptons & Non-Minimal Dark Sectors

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Outline

- Sterile neutrinos in the Type-I seesaw.

- Non-minimal realisations — venturing into dark sectors.

- *Hints* from short-baselines*?* — old data, new approaches.

Heavy Neutral Leptons

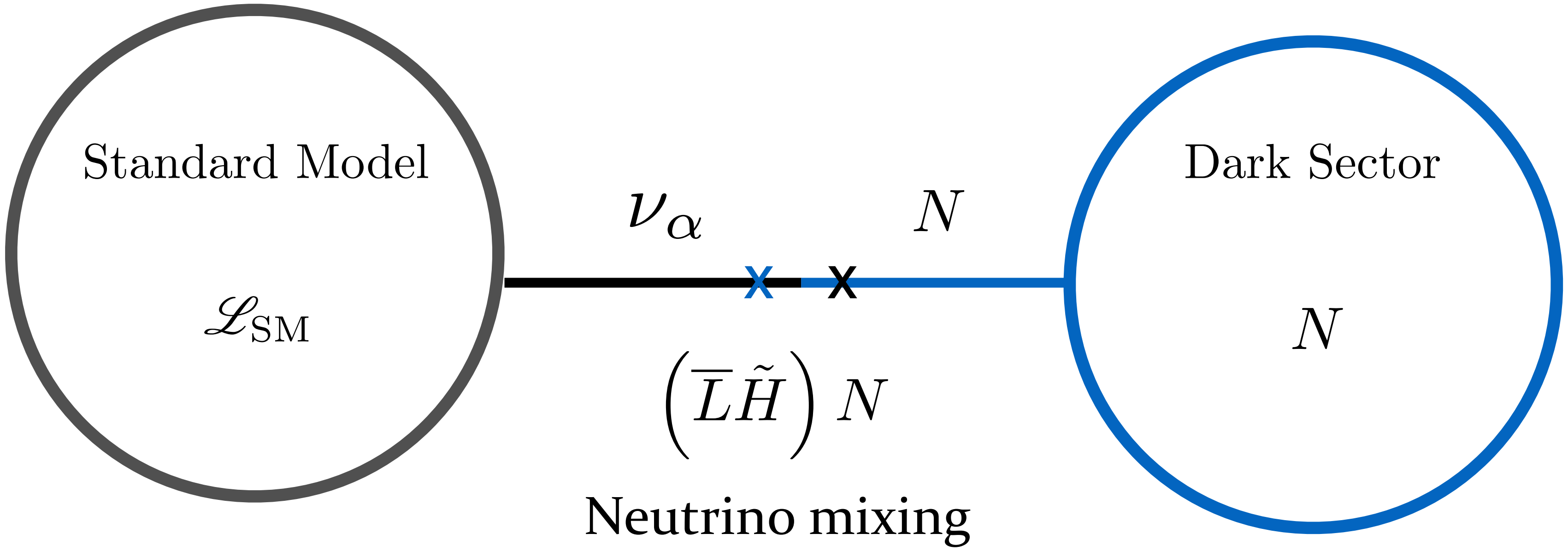
(heavy_neutral_lepton == sterile_neutrino == right_handed_neutrino) == True

Add a RH singlet lepton to the SM that mixes with massive neutrinos — it is then called "sterile, i.e. practically unobservable, since they have the ''incorrect'' helicity.

B. Pontecorvo, Sov.Phys.JETP 26 (1968) 984-988.

↓

SM gauge singlet — trivial and well-motivated extension of the SM



Heavy Neutral Leptons

Simplest Type-I seesaw Lagrangian:

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

Naive scaling to roughy reproduce light neutrino masses (~ 0.1 eV):

$$m_\nu \approx \frac{(y^\nu v_{\text{EW}})^2}{2M_N} \qquad (y^\nu)^2 \approx 3 \times 10^{-15}\,\frac{M_N}{\text{GeV}} \qquad |U|^2 \approx 10^{-10}\,\frac{\text{GeV}}{M_N}$$

Why are neutrino masses small?

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Large hierarchy of scales — large Majorana mass leads to tiny neutrino masses, even for large couplings (M_N >> EW scale)

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New symmetries — large cancellations in full mass matrix make them come out this way. If not "*just the way it is*", this suggests new *symmetries* in Nature (Lepton number).

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Why are neutrino masses small? **We do not know.**

Large hierarchy of scales — large Majorana mass leads to tiny neutrino masses, even for large couplings (M_N >> EW scale)

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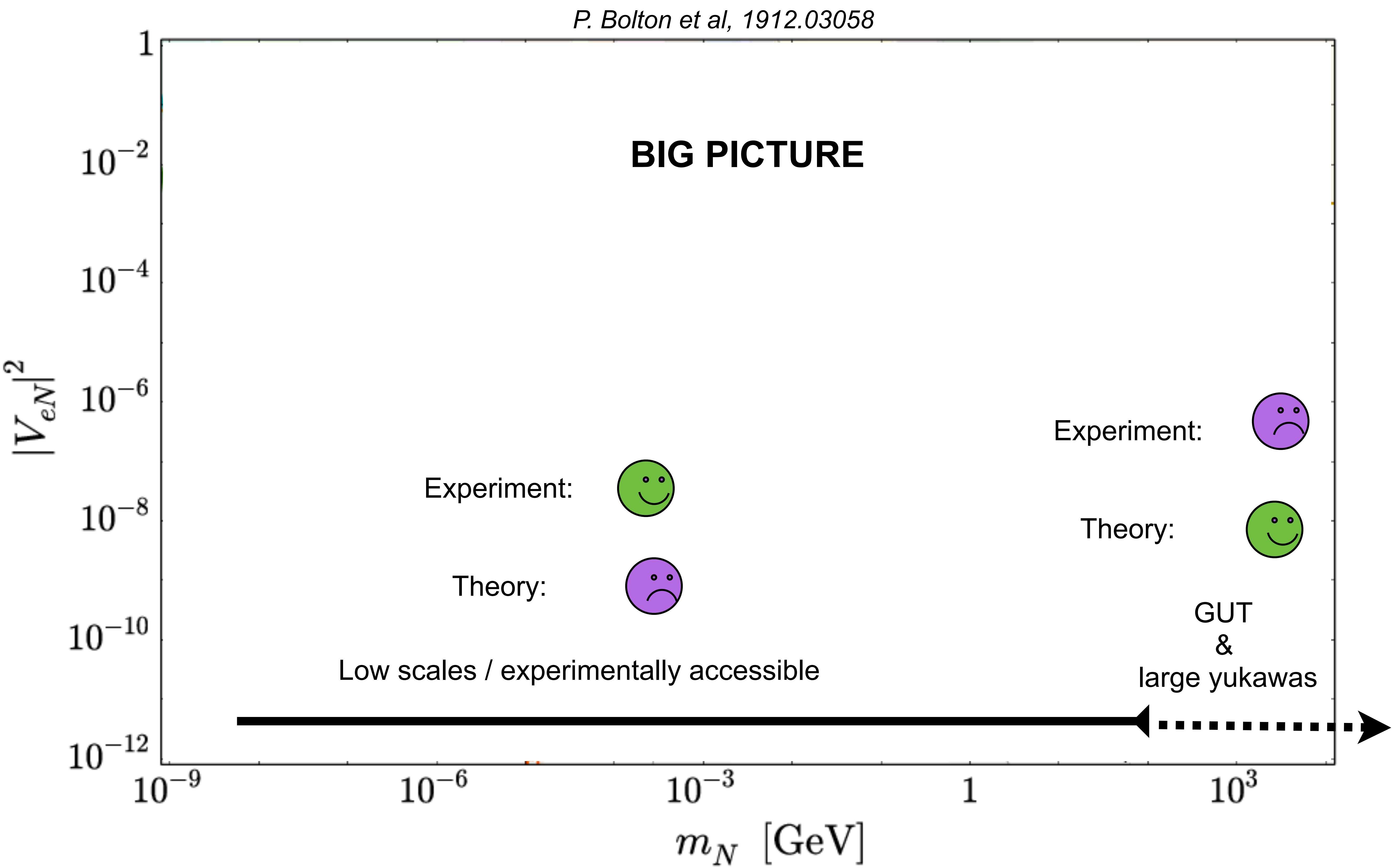
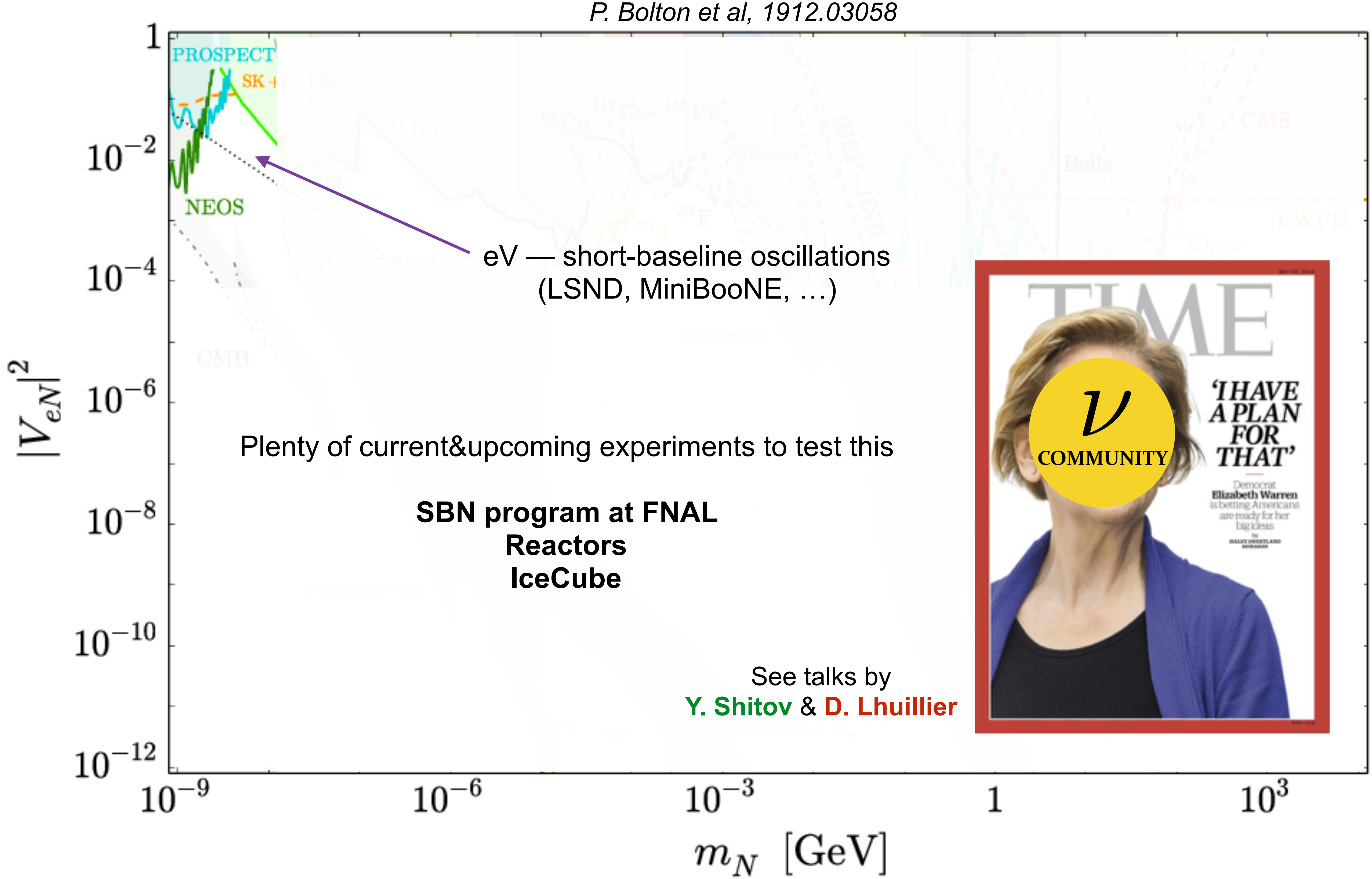

P. Bolton et al, 1912.03058
BIG PICTURE
Experiment:
Theory:
Experiment:
Theory:
GUT
&
large yukawas
Low scales / experimentally accessible
$|V_{eN}|^2$
m_N [GeV]
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}

Minimal HNL Phenomenology *P. Bolton et al, 1912.03058*

P. Bolton et al, 1912.03058



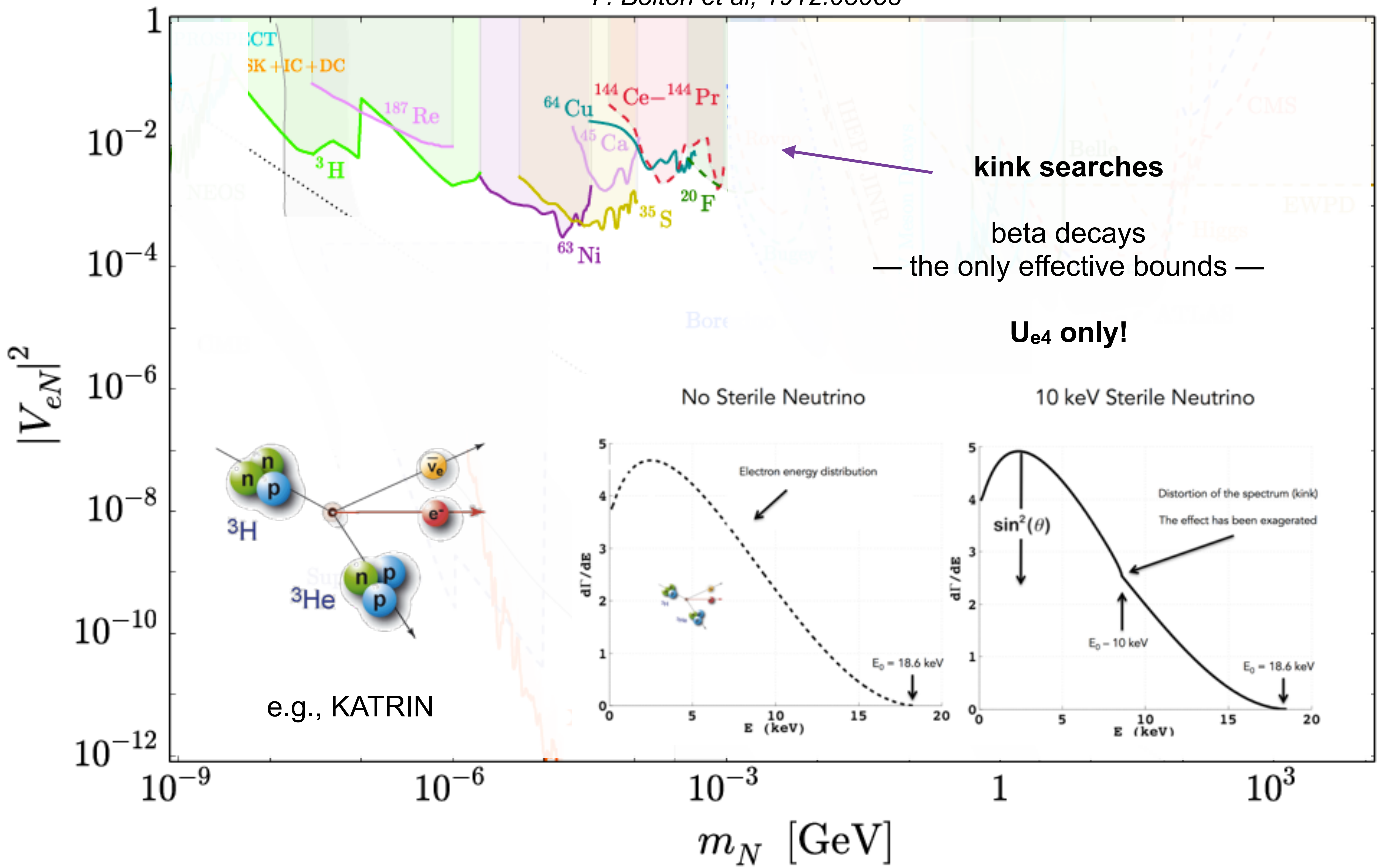
eV — short-baseline oscillations
(LSND, MiniBooNE, …)

Plenty of current&upcoming experiments to test this

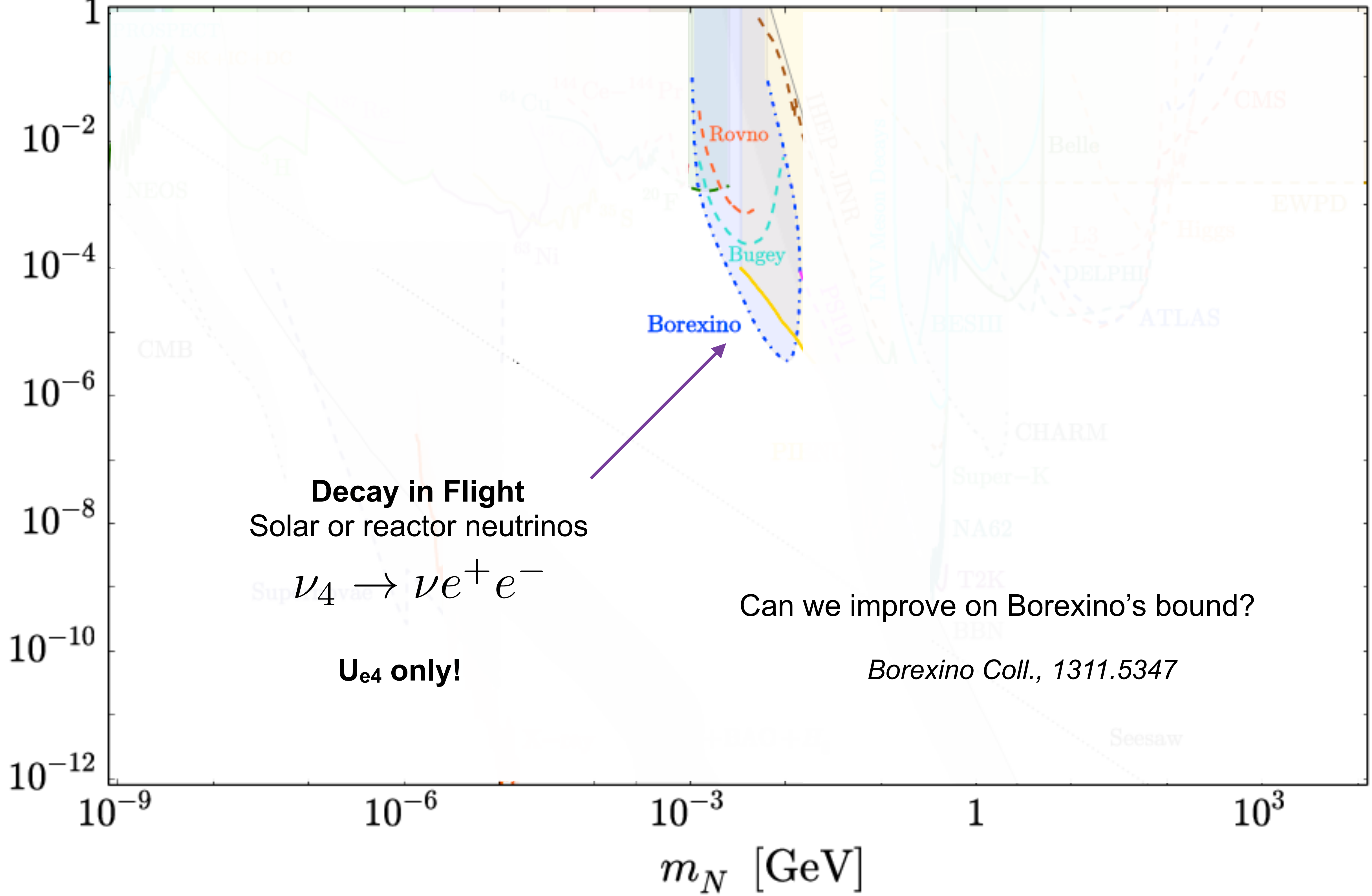
SBN program at FNAL
Reactors
IceCube

See talks by
Y. Shitov & **D. Lhuillier**

P. Bolton et al, 1912.03058



P. Bolton et al, 1912.03058



Decay in Flight
Solar or reactor neutrinos

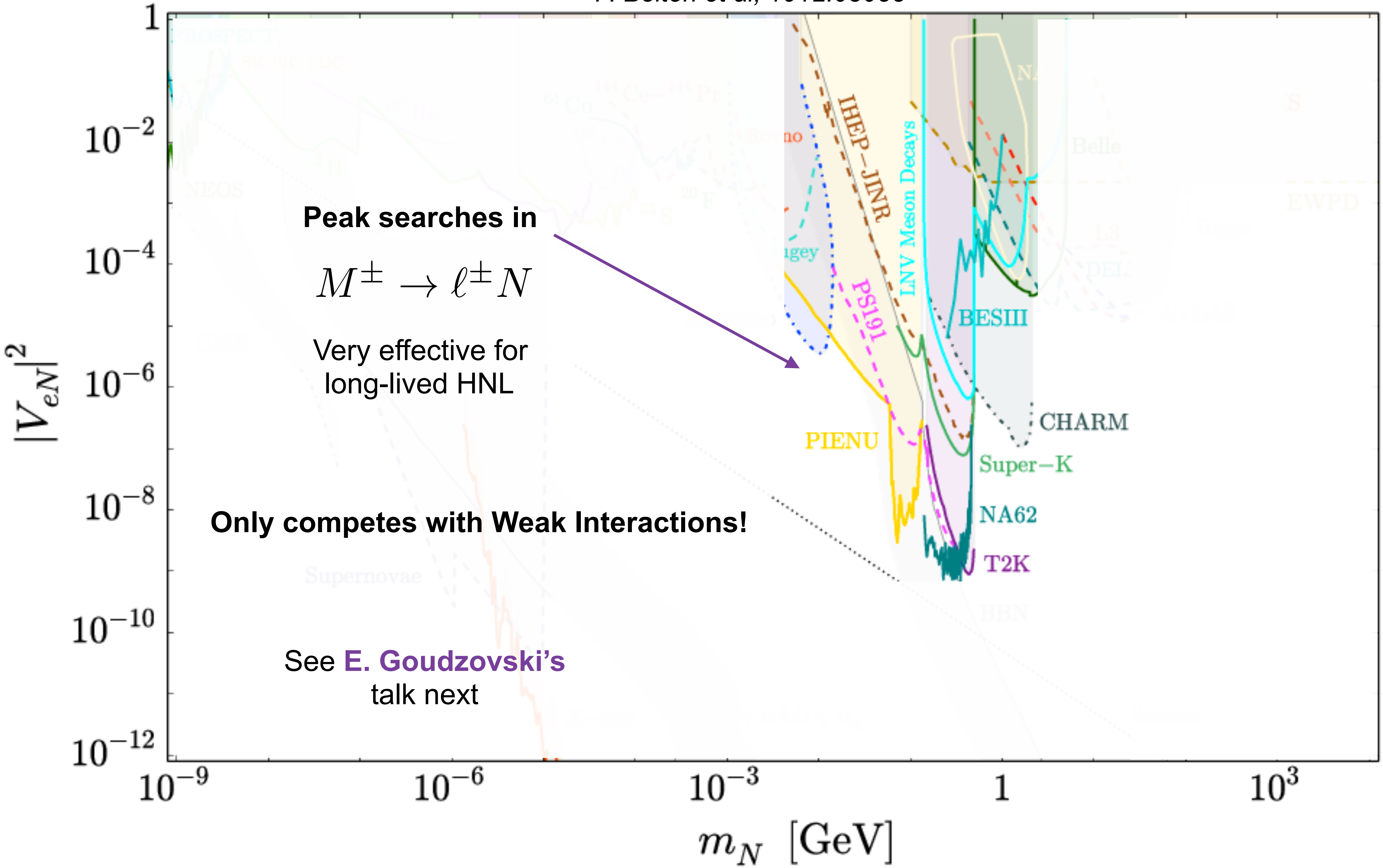
$$\nu_4 \to \nu e^+ e^-$$

U_{e4} only!

Can we improve on Borexino's bound?

Borexino Coll., 1311.5347

P. Bolton et al, 1912.03058



Peak searches in

$$M^{\pm} \to \ell^{\pm} N$$

Very effective for long-lived HNL

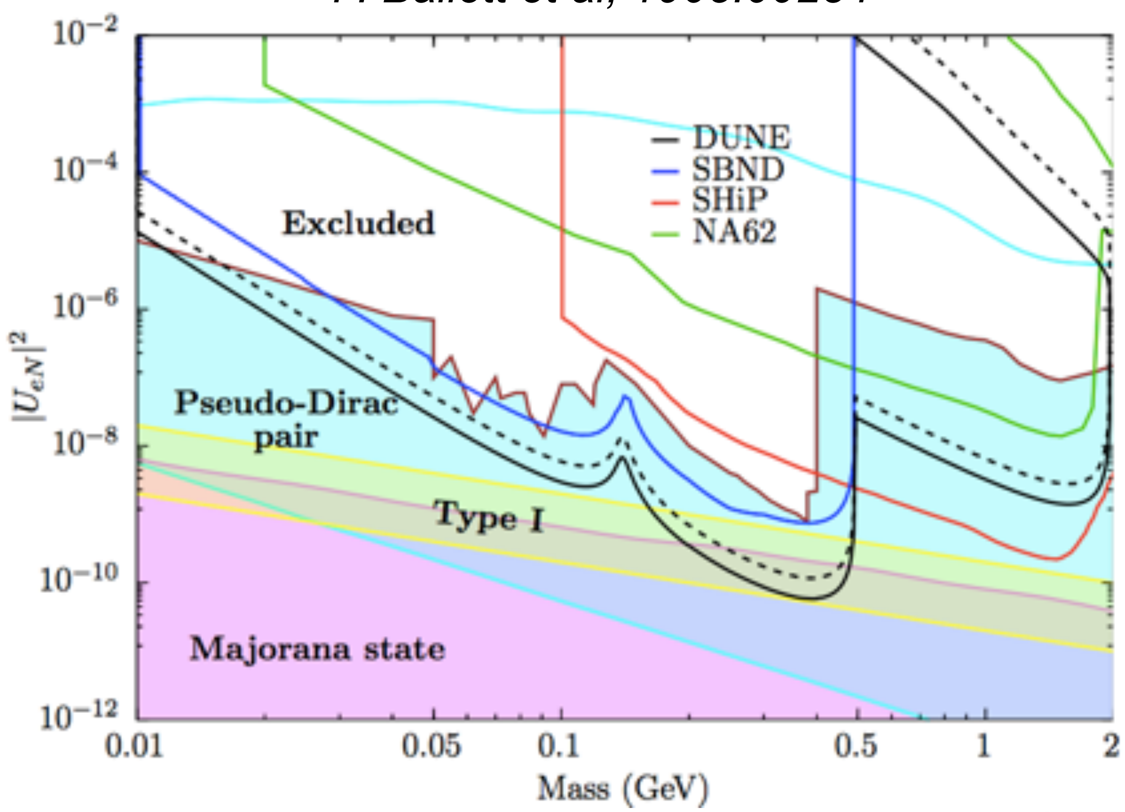
Only competes with Weak Interactions!

See **E. Goudzovski's** talk next

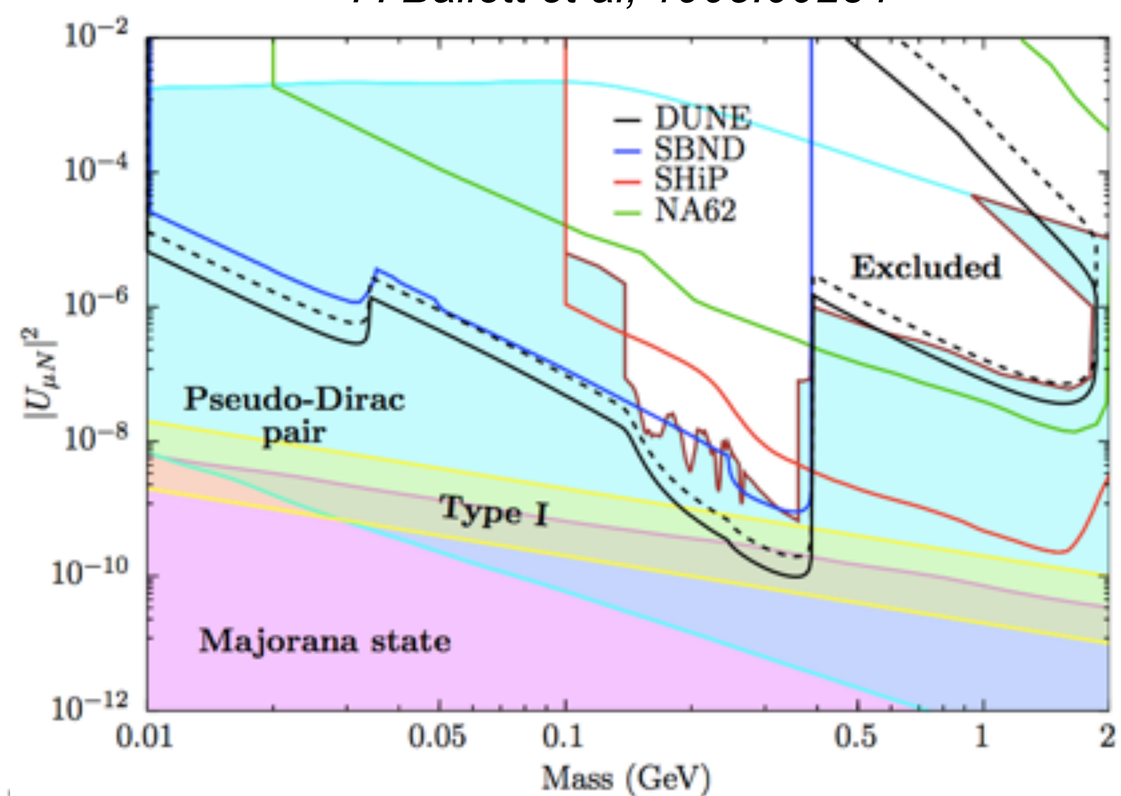
P. Bolton et al, 1912.03058

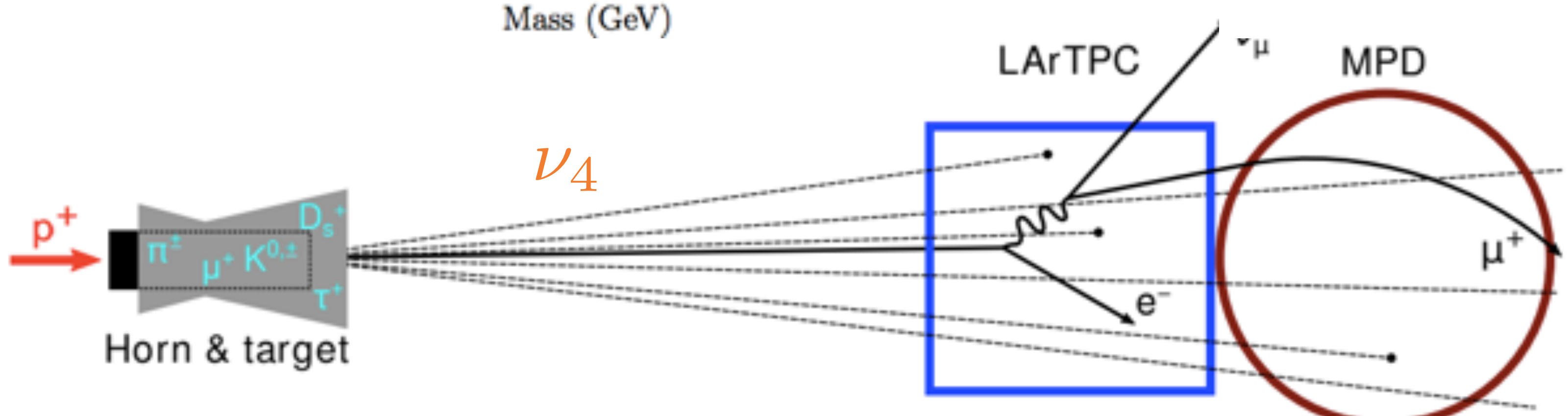
Decay in Flight at accelerator experiments $N \to \nu ee,\, \nu e\mu,\, \nu\mu\mu,\, \nu\pi^0,\, e\pi,\, \mu\pi$

P. Ballett et al, 1905.00284



P. Ballett et al, 1905.00284



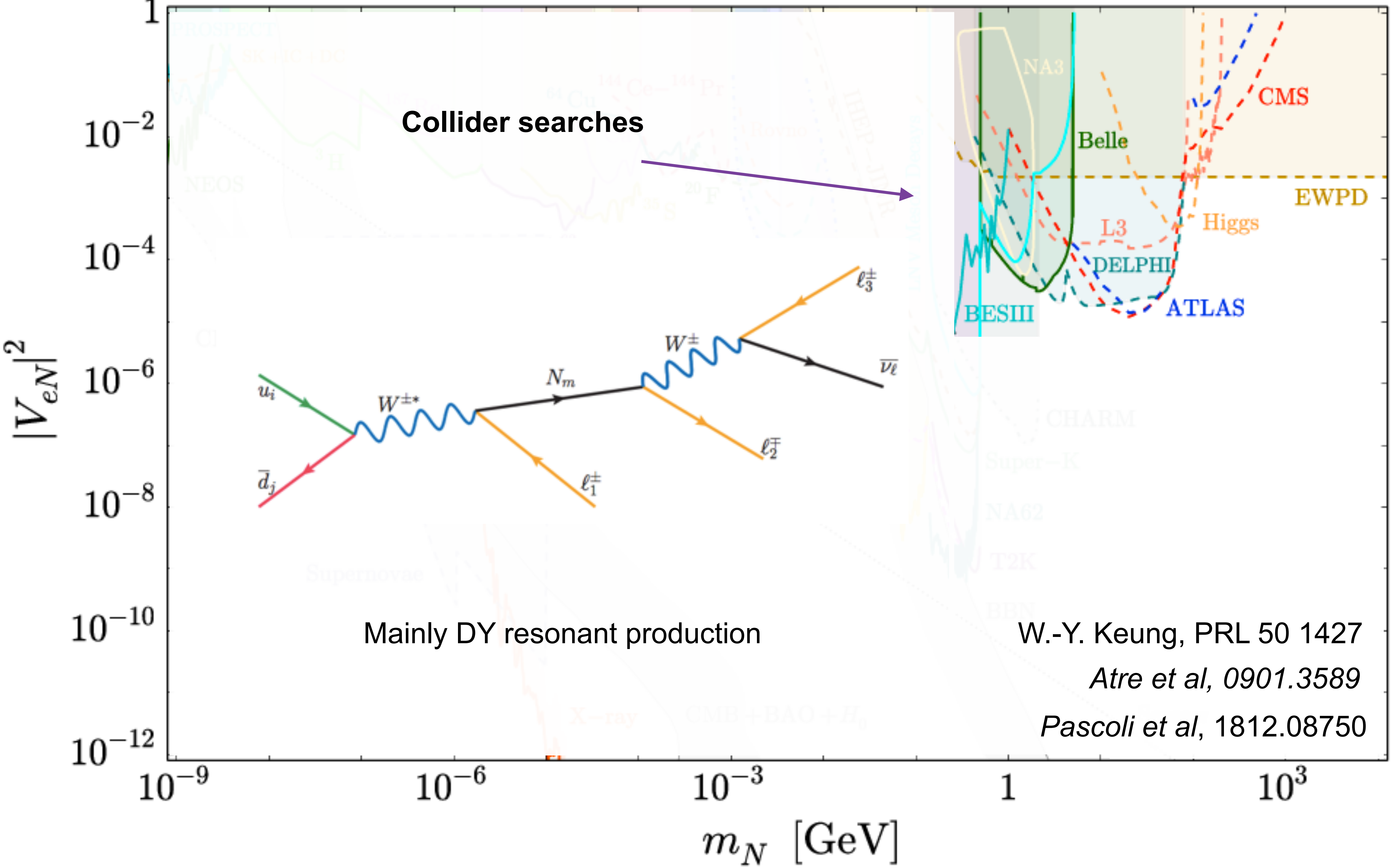


by T. Boschi

P. Ballett et al, 1610.08512

P. Ballett et al, 1905.00284

P. Bolton et al, 1912.03058



W.-Y. Keung, PRL 50 1427

Atre et al, 0901.3589

Pascoli et al, 1812.08750

Minimal HNL Phenomenology *P. Bolton et al, 1912.03058*

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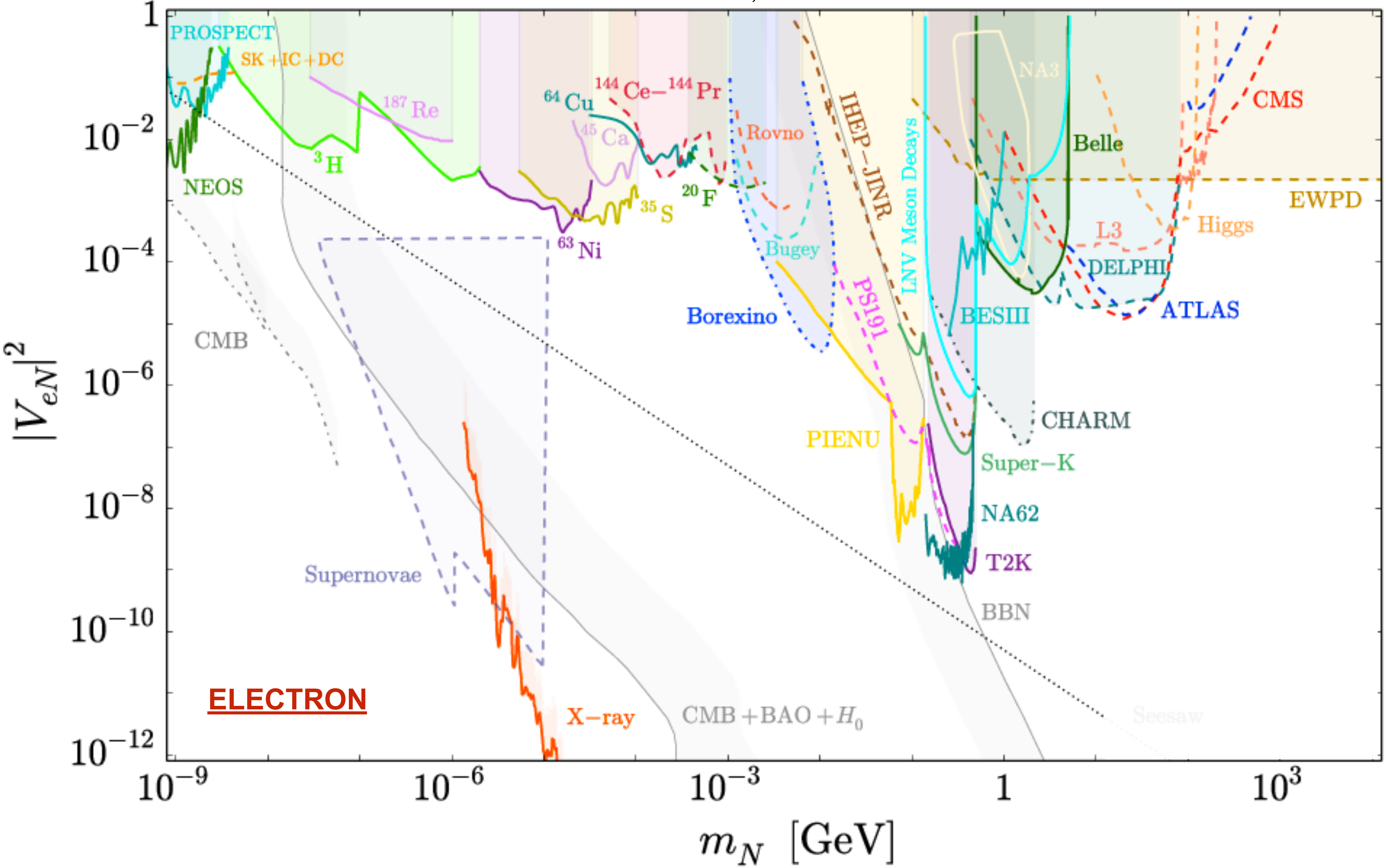

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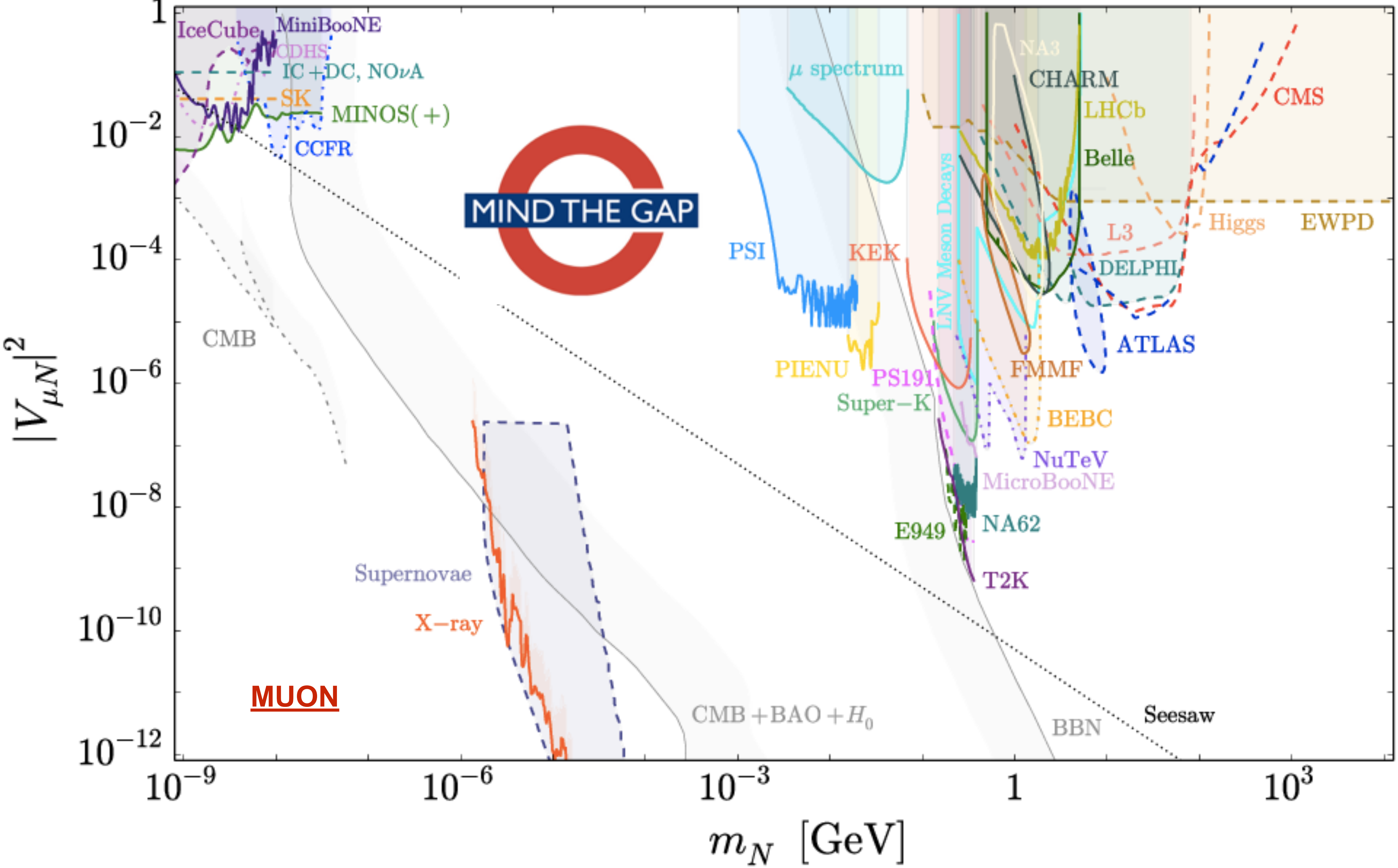

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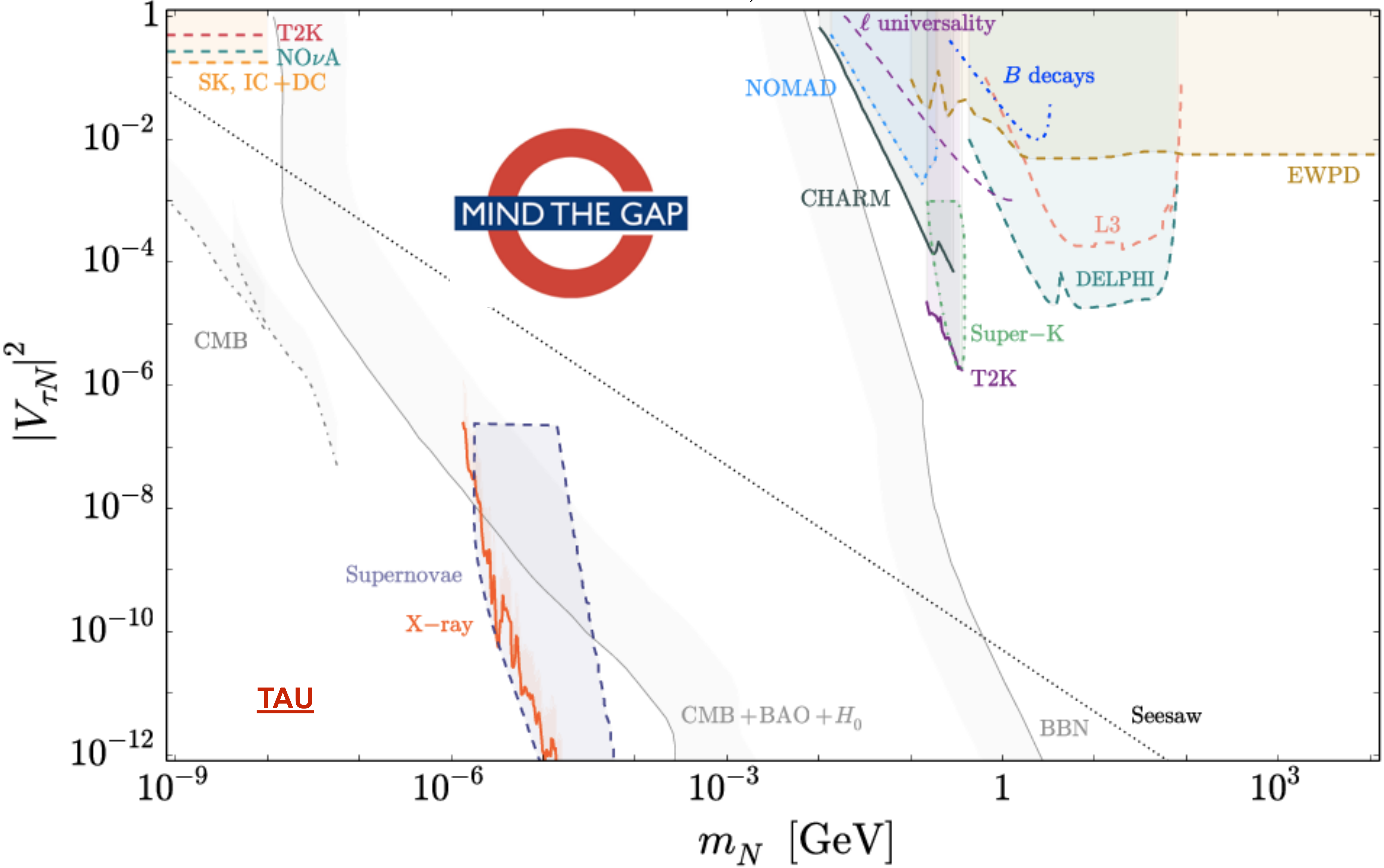

Low Scale Seesaw Variants

Inverse, Extended and Linear seesaws — Adding more HNLs to the picture…

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

HNL 1 (N^c)

HNL 2 (S^c)

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Light neutrino masses are always proportional to **LNV** parameters!

Seesaw limit →

$$m_1 = \frac{\mu m^2 - 2\varepsilon' m\Lambda + \varepsilon'^2\mu'}{\Lambda^2 - \mu\mu'}.$$

Small LNV parameters are technically natural

Smallness of neutrino masses explained due to an approximate **LN conservation.**

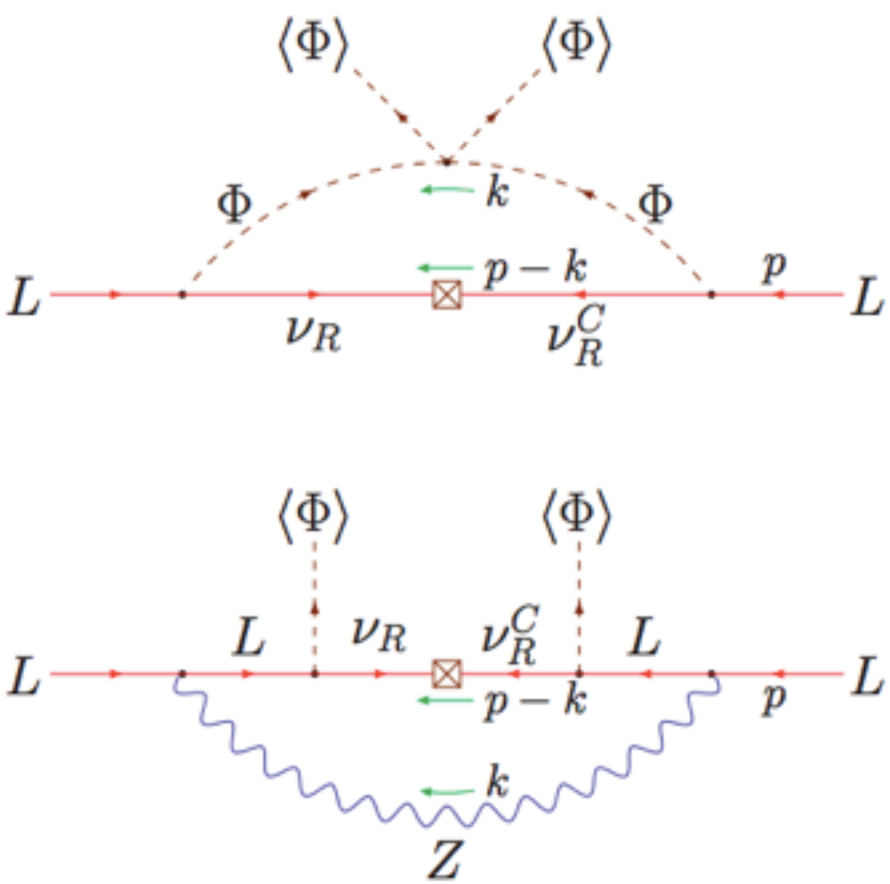
Curious choice of mass matrix texture…

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

Massless neutrinos at tree-level!
— Accidental cancellation —

$$m_1 = 0$$

$$m_{4,5} = \frac{\mu' \mp \sqrt{\mu'^{\,2} + 4(\Lambda^2 + m^2)}}{2}$$



Masses arise from loop-contributions after

SU(2)xU(1)$_Y$ gets broken to U(1)$_{QED}$

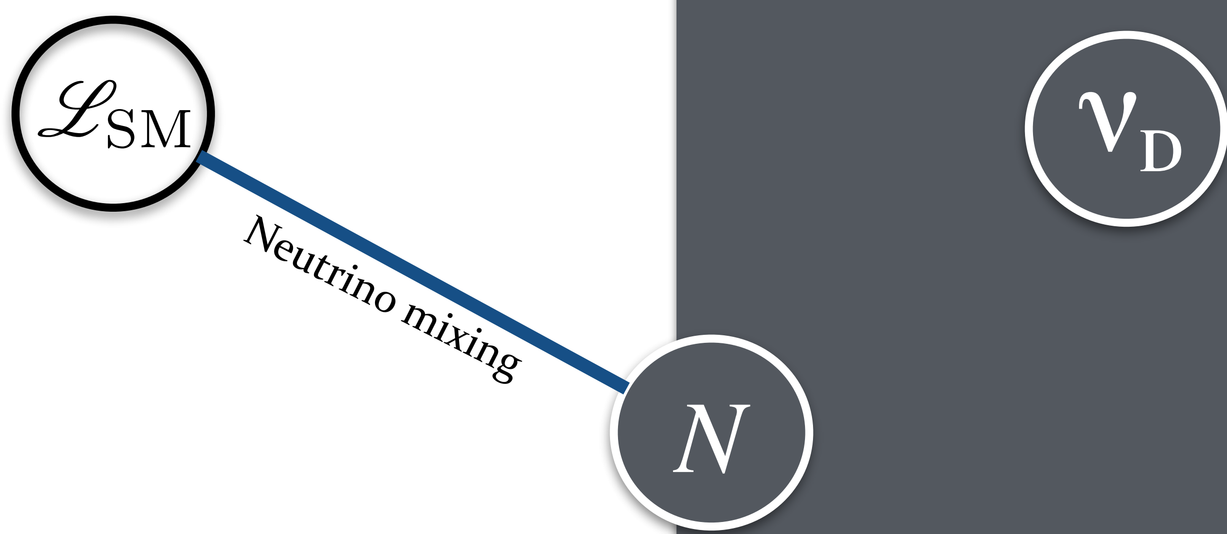
P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342

Let's build a model for that.

Diving into a HNL Dark Sector

Dark neutrinos

A low scale **SEESAW** mechanism
for neutrino masses



	$SU(2)_L$	$U(1)_Y$
N	$\mathbf{1}$	0
ν_D	$\mathbf{1}$	0

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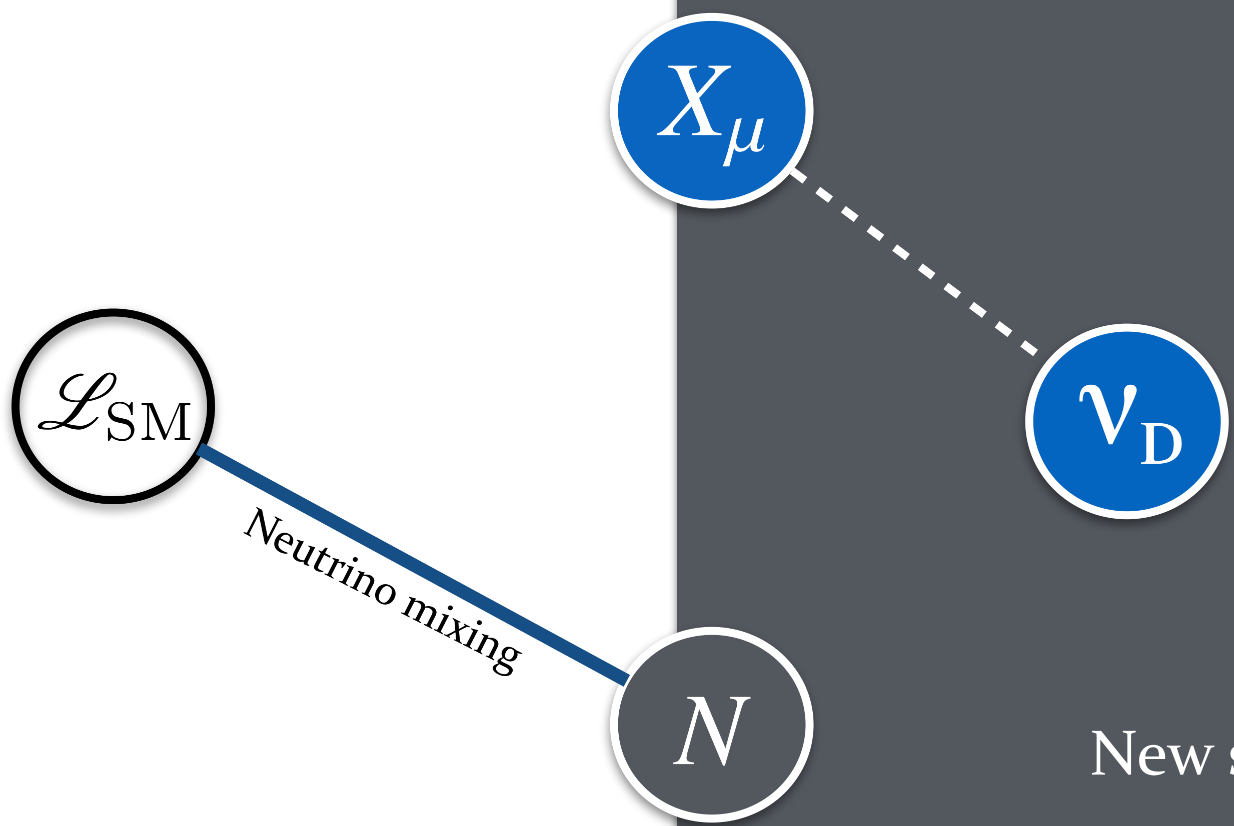

New secluded U(1)' symmetry

	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q

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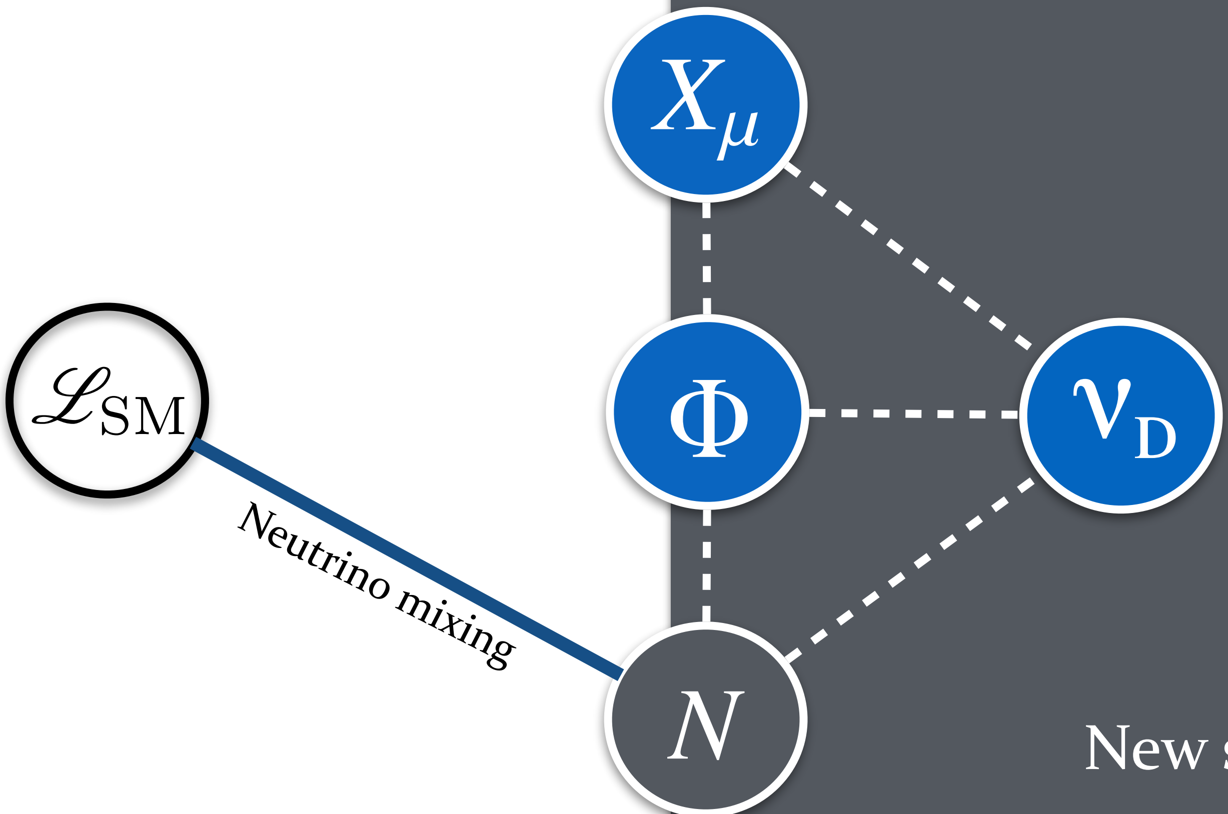

New secluded U(1)' symmetry

spontaneously broken by dark scalar field

	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

$$\begin{aligned}\mathscr{L} =& \mathscr{L}_{SM} + \left(D_\mu\Phi\right)^\dagger (D^\mu\Phi) - V(\Phi, H) \\ &- \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \overline{N}i\partial\!\!\!/ N + \overline{\nu_D}iD\!\!\!\!/\,\nu_D \\ &- \left[y_\nu^\alpha(\overline{L_\alpha}\cdot\widetilde{H})N^c + \frac{\mu'}{2}\overline{N}N^c + y_N\overline{N}\nu_D^c\Phi + \text{h.c.}\right]\end{aligned}$$

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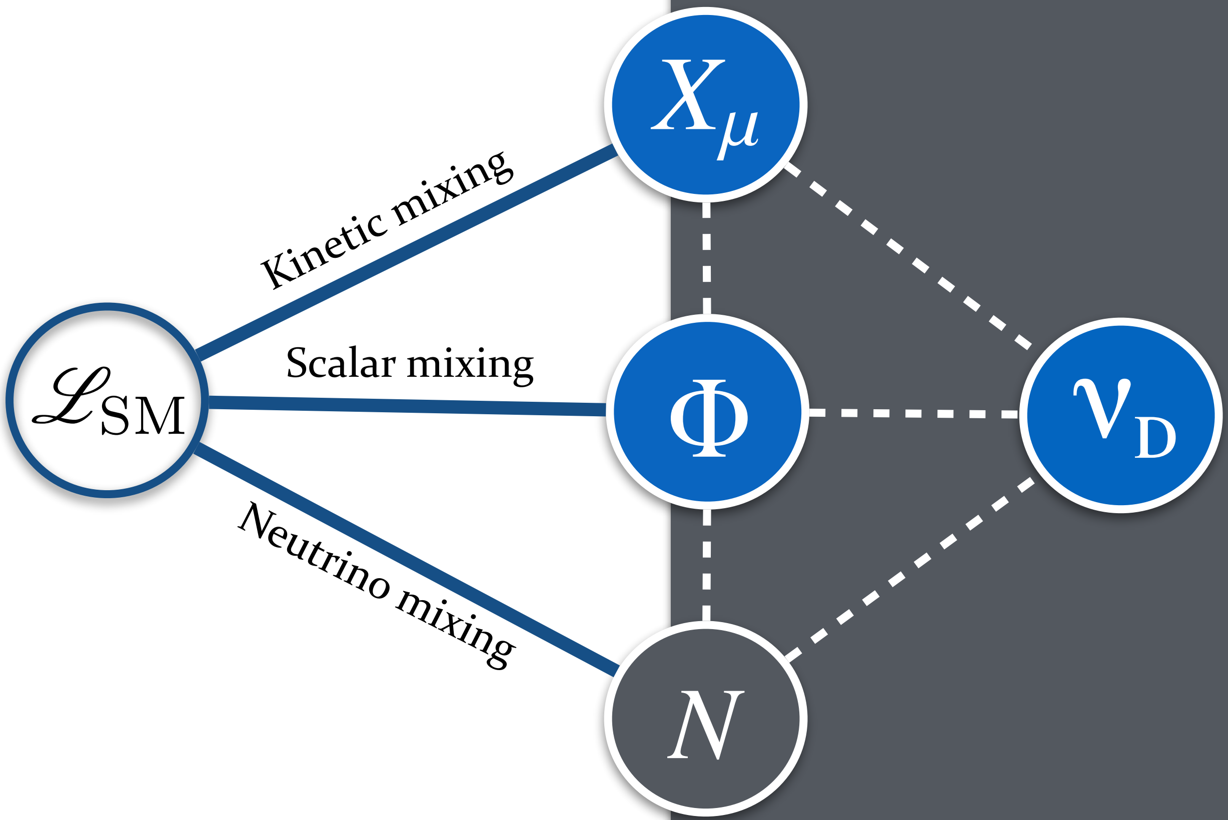


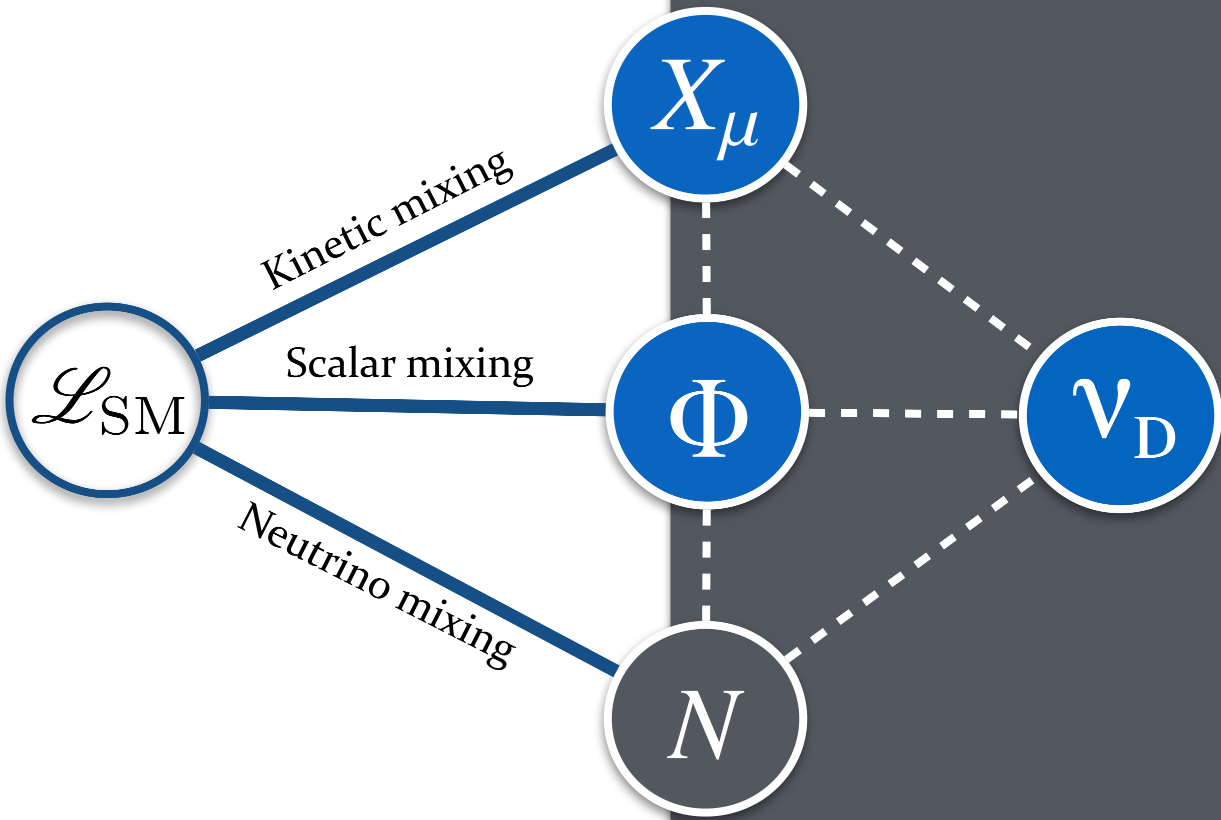
Neutrino mixing $y_\nu \left(\overline{L} \cdot \tilde{H}\right) N^c$

	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	$\mathbf{1}$	0	0
ν_D	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

Not needed for ν mass, but comes for free!

- Kinetic mixing $\frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu}$
- Scalar mixing $\lambda_{\Phi H} H^\dagger H |\Phi|^2$

Dark neutrinos



A low

Gauge anomaly:
Dark Matter particles

χ_L χ_R

	$U(1)'$	$\mathcal{Z}_2$
χ_L	0	-1
χ_R	Q	-1

Neutrino portal DM
Blennow et al, 1903.00006

	$SU(2)_L$	$U(1)_Y$	$U(1)'$
N	**1**	0	0
ν_D	**1**	0	Q
Φ	**1**	0	Q

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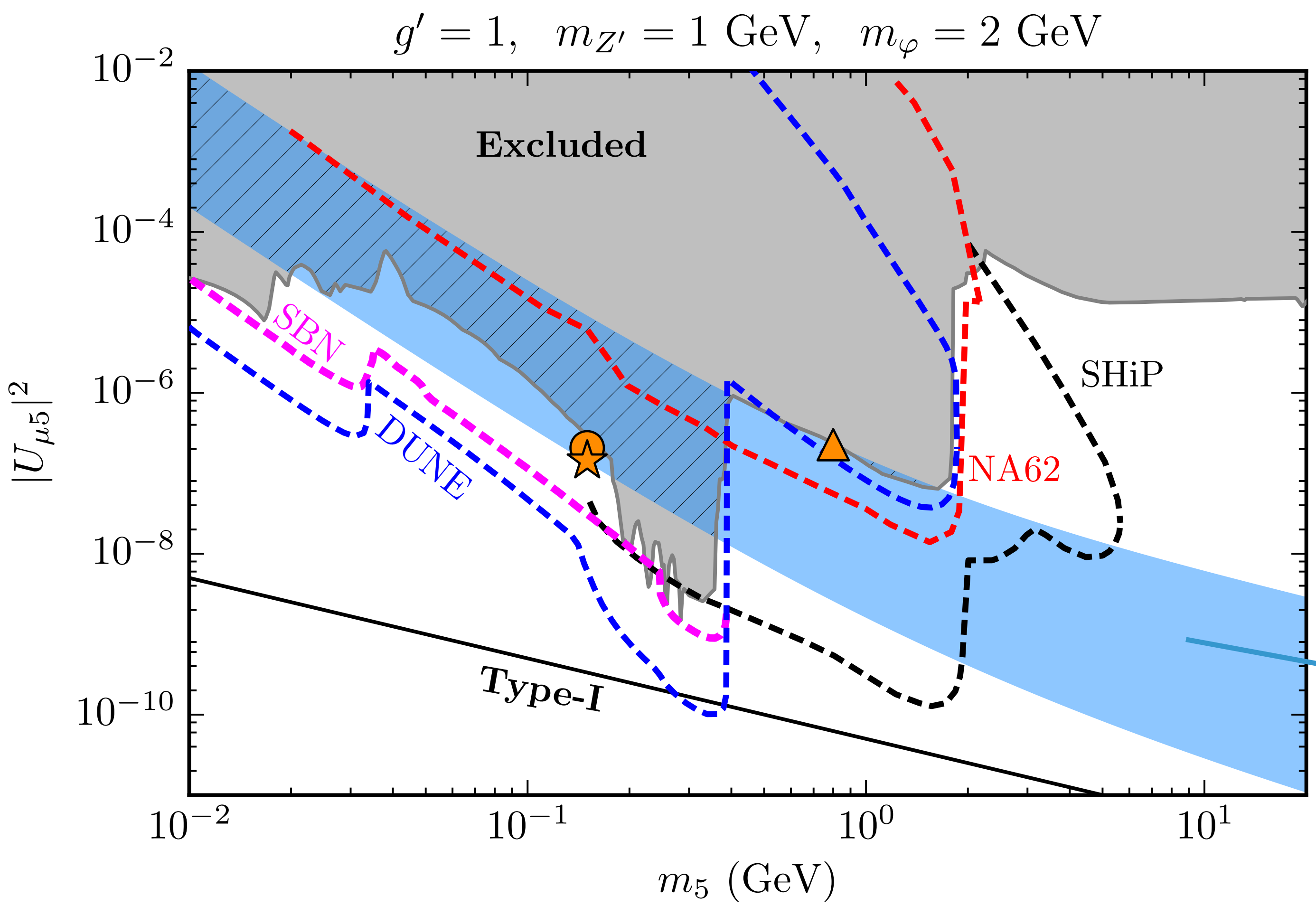
Neutrino masses at one-loop level

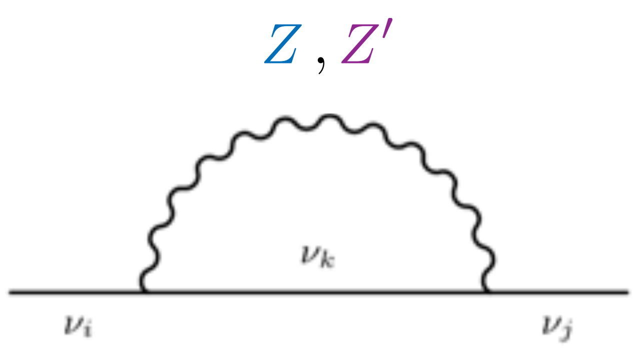
$$\mathcal{L}_{\rm mass} \supset \frac{1}{2}\left(\overline{\nu_\alpha} \quad \overline{N} \quad \overline{\nu_D}\right)\begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}\begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix}$$

LNV

After U(1)' is broken, zeros are no long protected!



Ignoring kinetic and scalar mixing
(See MiniBooNE discussion)



$$m_\nu \propto \mu'$$

Prediction of the model:

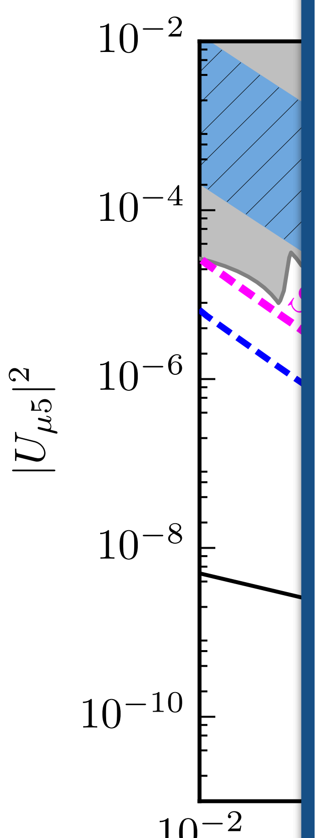
$$R = \frac{m_4}{m_5} = -\frac{U^2_{\alpha 5}}{U^2_{\alpha 4}}$$

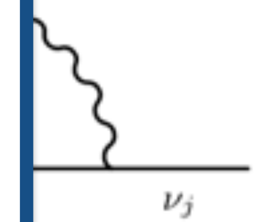
Blue band:

$$m_3 = \sqrt{\Delta m^2_{\rm atm}}$$

$$1\% < R < 99\%$$

Neutrino masses at one-loop level





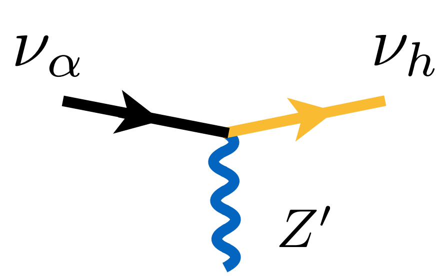
Many other models w/ **MULTIPLE PORTALS:**

C. Diaz, 171205433

Generalized scotogenic, C. Hagedorn et al, 1804.04117

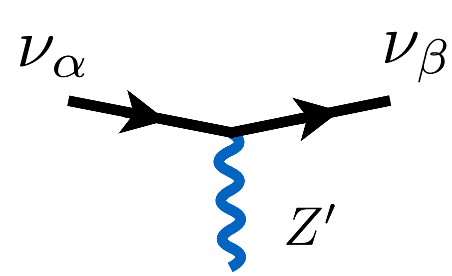
E. Bertuzzo et al, 1808.02500

Very rich interplay between portals:



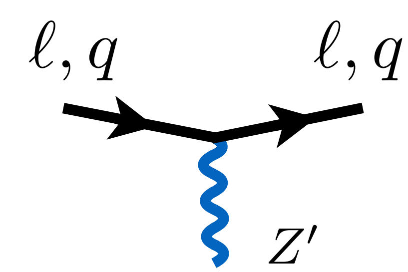
$U^*_{\alpha h} g'$

Mixing x O(1) coupling



$U^*_{\alpha h} U_{\beta h}\, g'$

Doubly suppressed



$e\,\chi\, q_f$

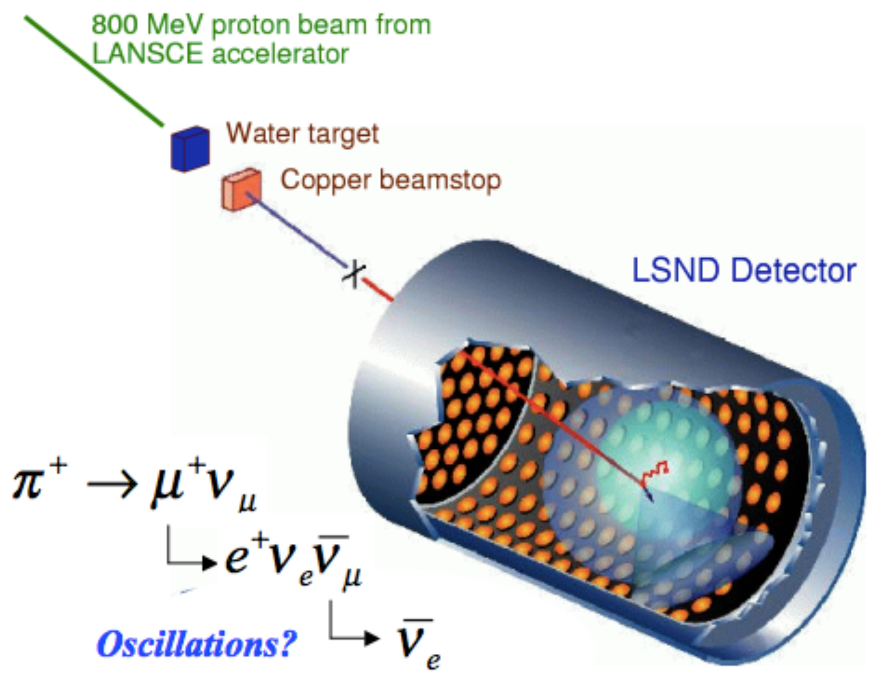
Kinetic mixing

P. Ballett et al, 1903.07589

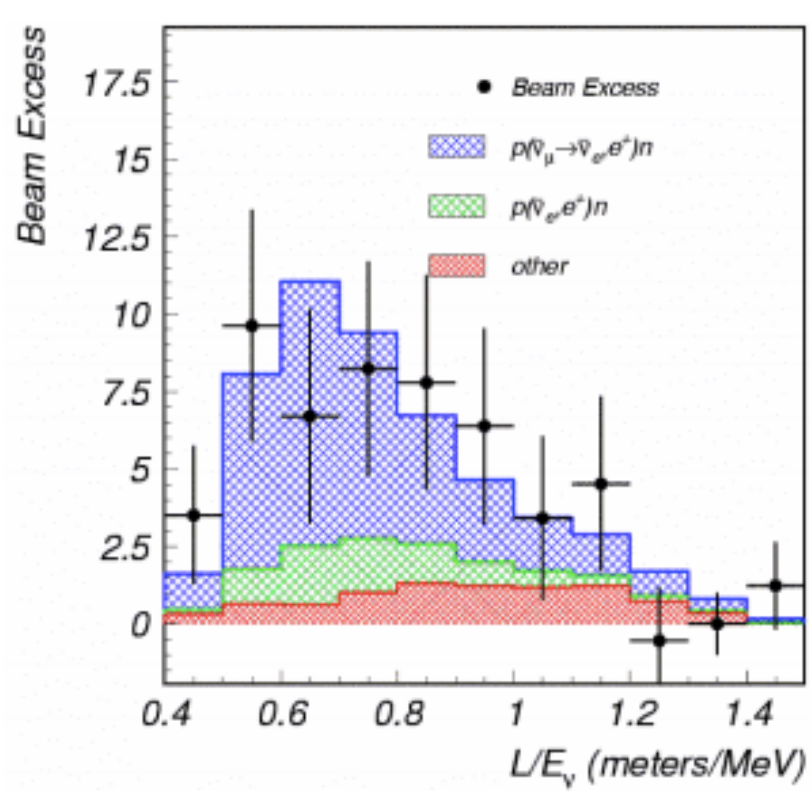
ANY HINTS FROM CURRENT DATA?

LSND & MiniBooNE

Liquid Scintillator Neutrino Detector: 1993 - 1998



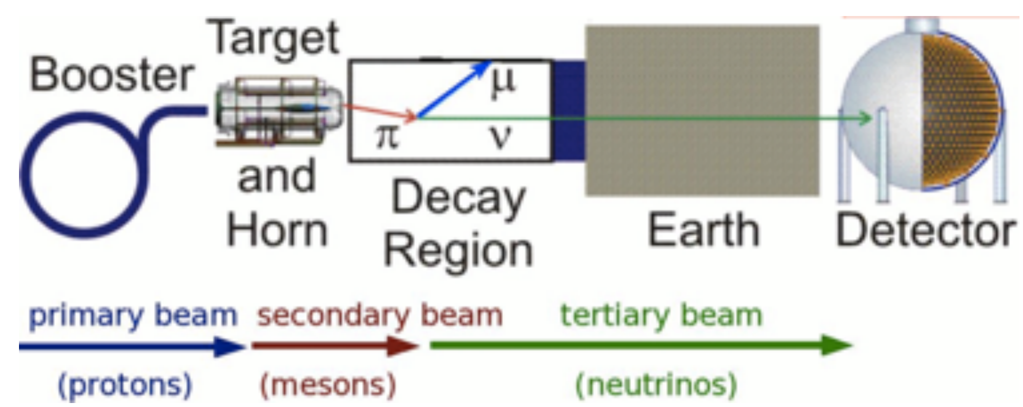
Inverse beta decay events



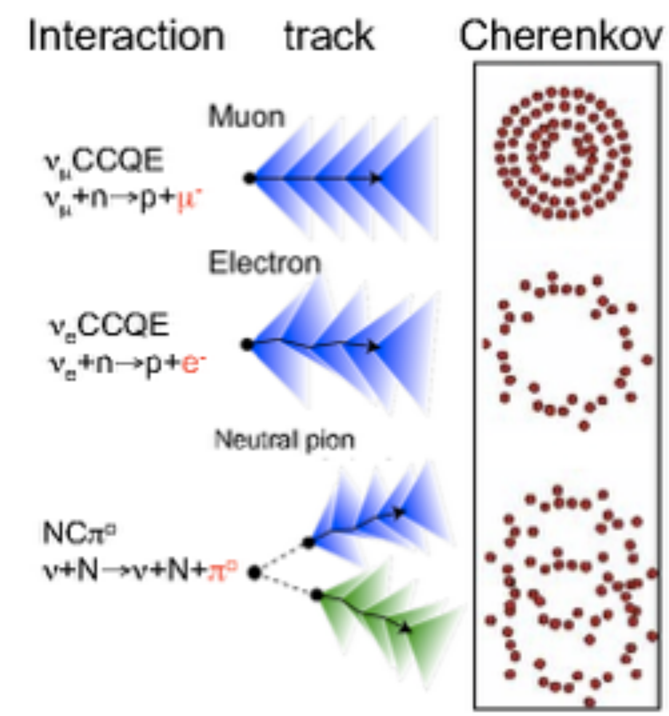
Enu = 52 MeV endpoint — 30 m baseline.

MiniBooNE: 2003 - 2019

818t of CH_2



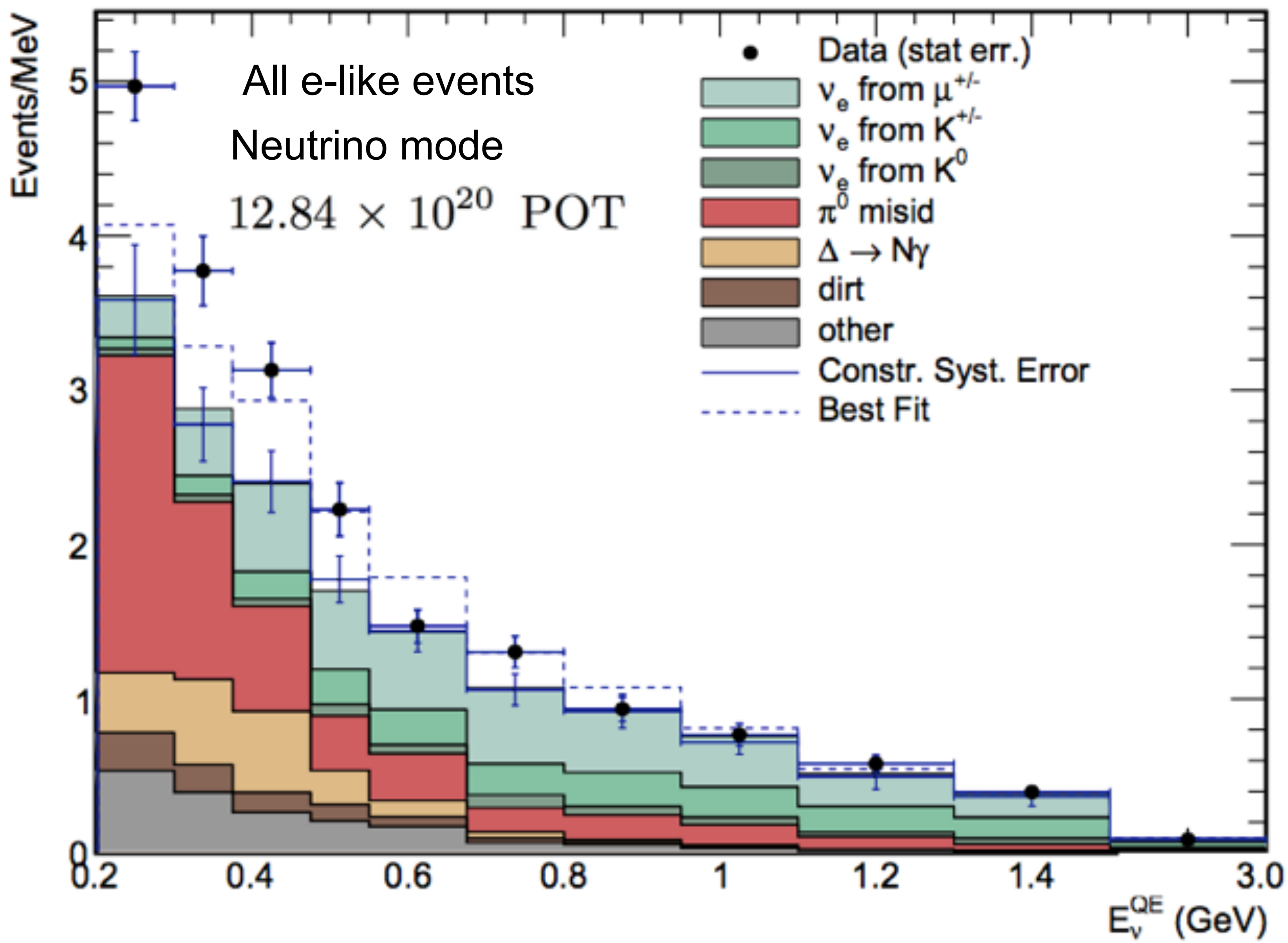
mostly (RES) CCQE



$\langle E_\nu \rangle \approx 800$ MeV — 500 m baseline

4.7σ excess observed in neutrino + antineutrino mode
— data/MC disagreement beyond statistical doubt —

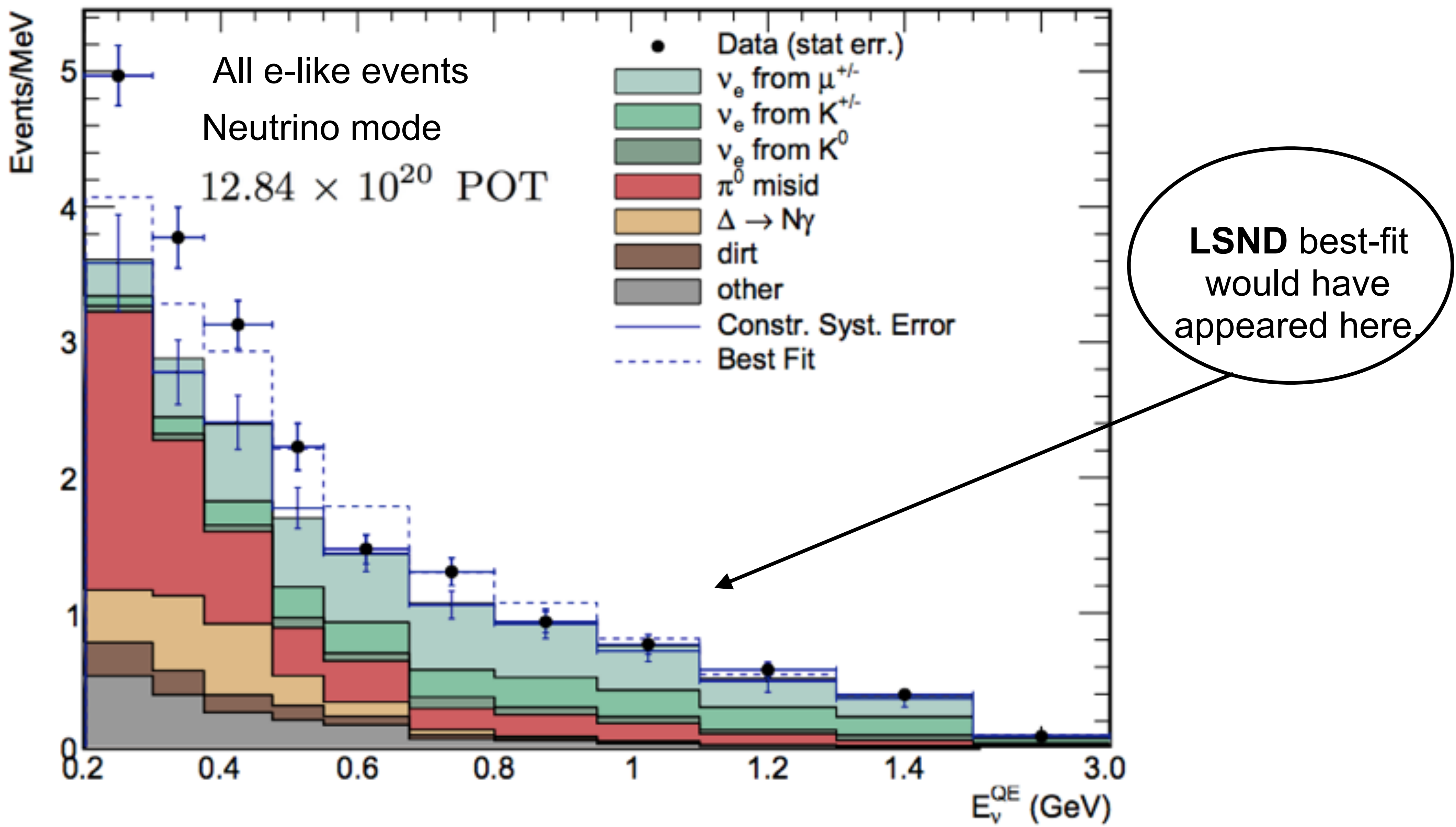
MiniBooNE Collaboration, 1805.12028



The MiniBooNE Low Energy Excess (LEE)

4.7σ excess observed in neutrino + antineutrino mode
— data/MC disagreement beyond statistical doubt —

MiniBooNE Collaboration,1805.12028



The MiniBooNE Low Energy Excess (LEE)

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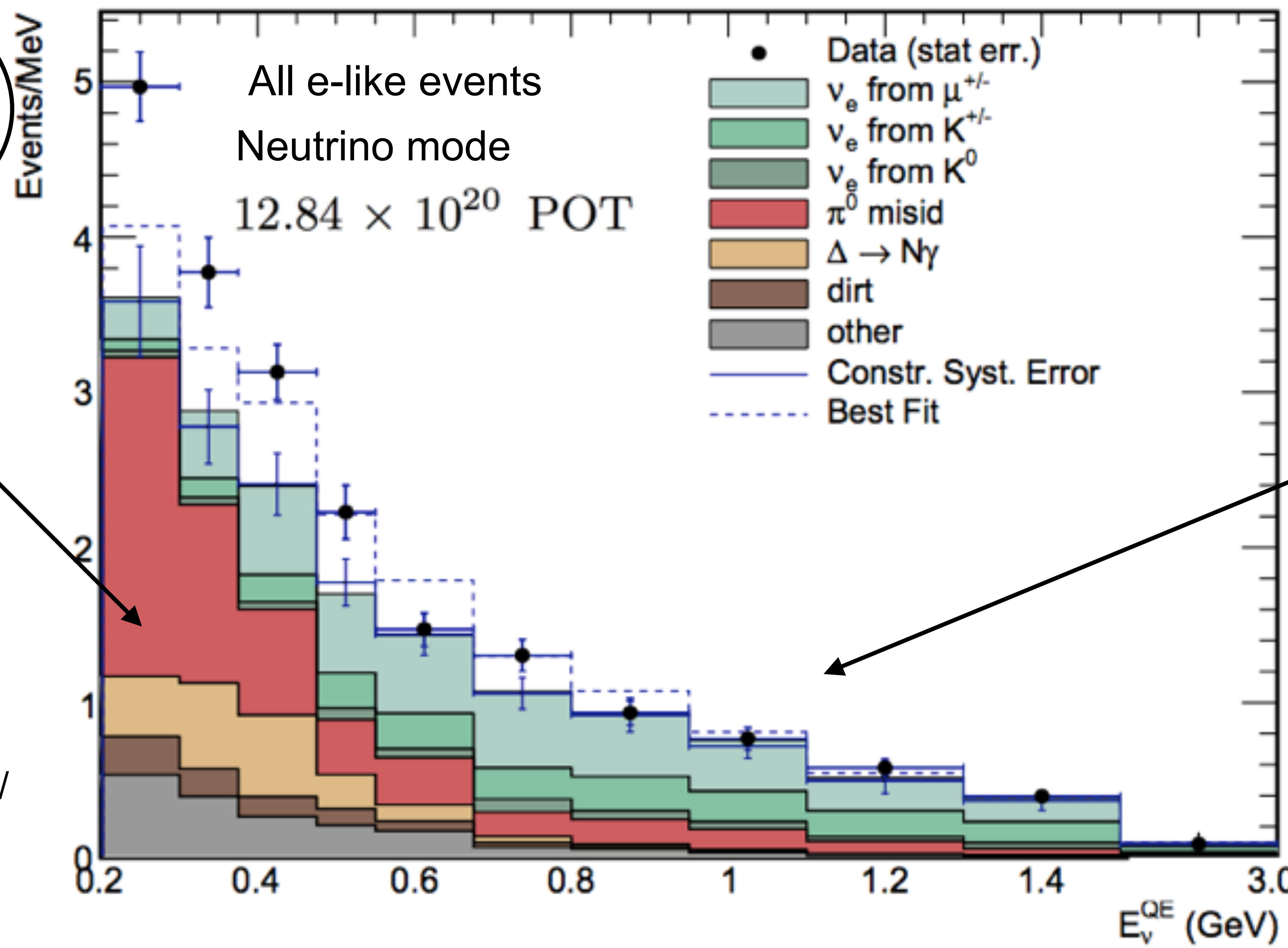
MiniBooNE Collaboration,1805.12028

Single-photon and other **mis-ID** backgrounds accumulate here

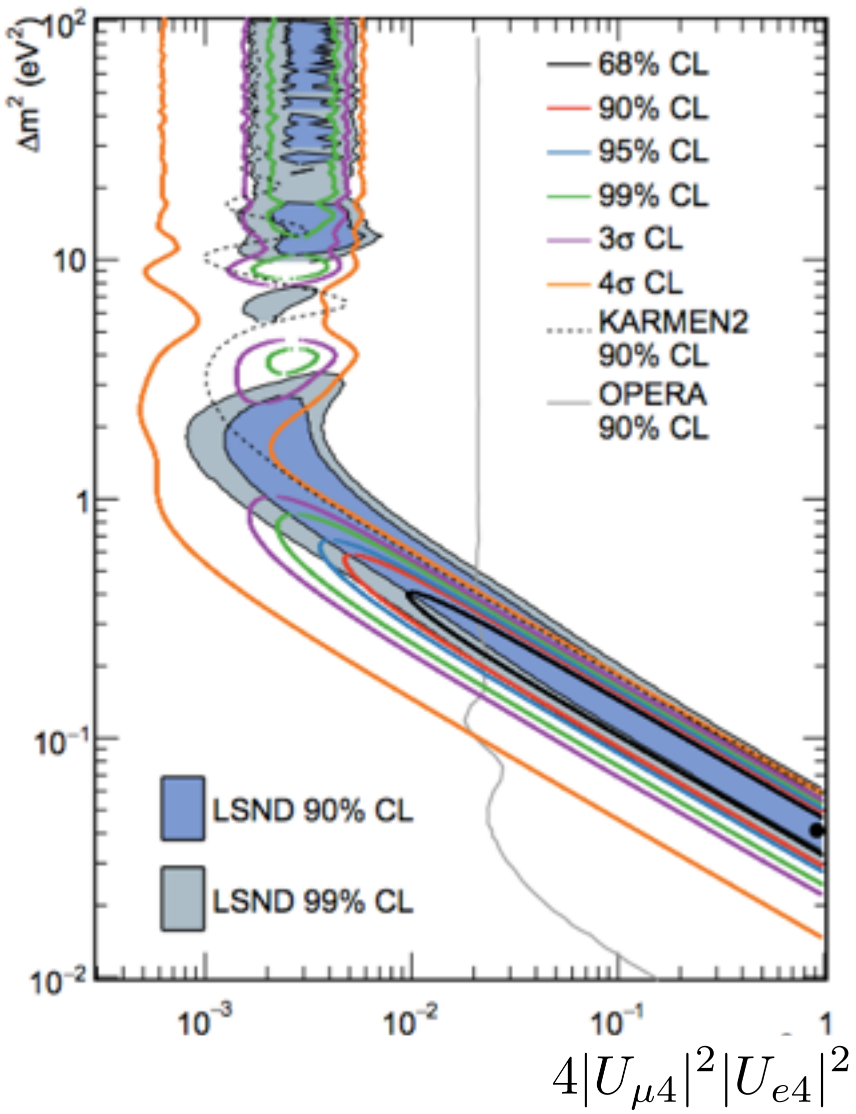


LSND best-fit would have appeared here.

For a nice discussion of backgrounds, see:

T. Katori talk at CERN
https://indico.cern.ch/event/791940/

MiniBooNE Collaboration, 1805.12028

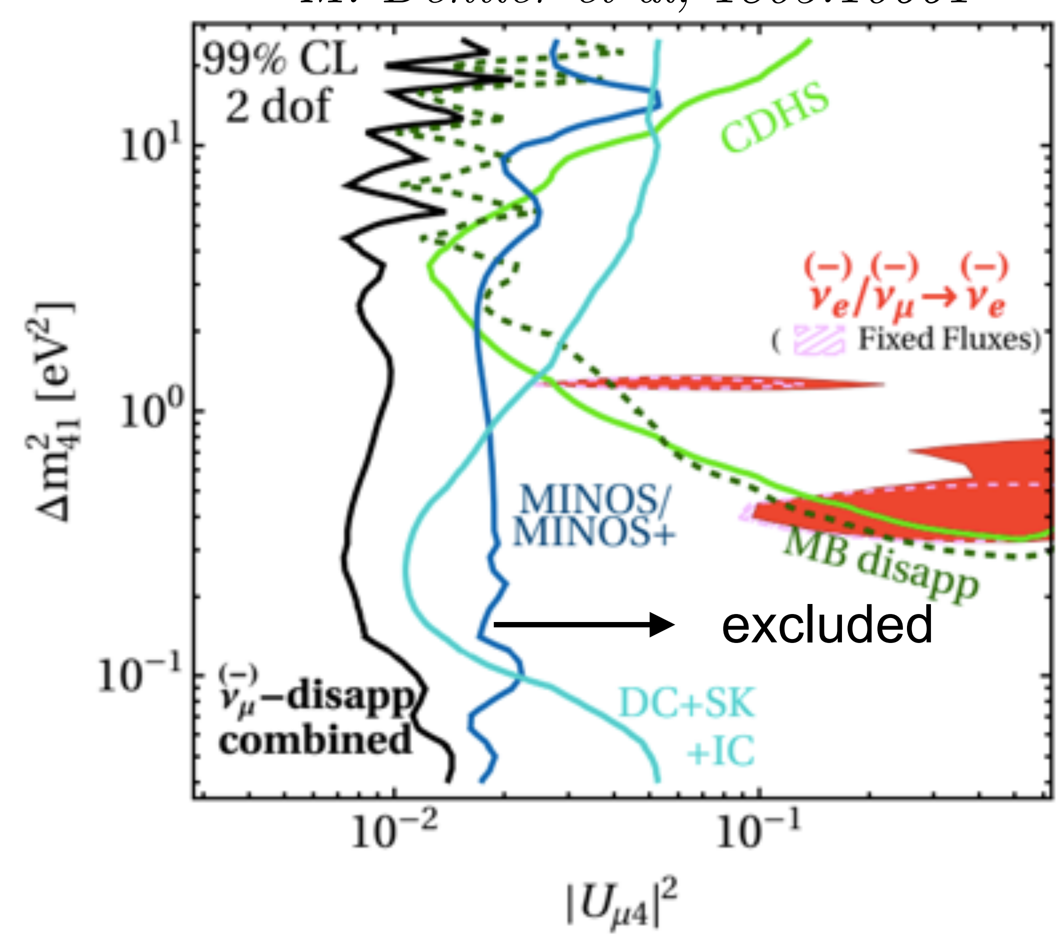


Appearance and disappearance probs.

$$P^{3+1}_{\nu_\mu\to\nu_e} = 4|U_{\mu4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P^{3+1}_{\nu_\mu\to\nu_\mu} = 1 - 4\,|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

M. Dentler et al, 1803.10661

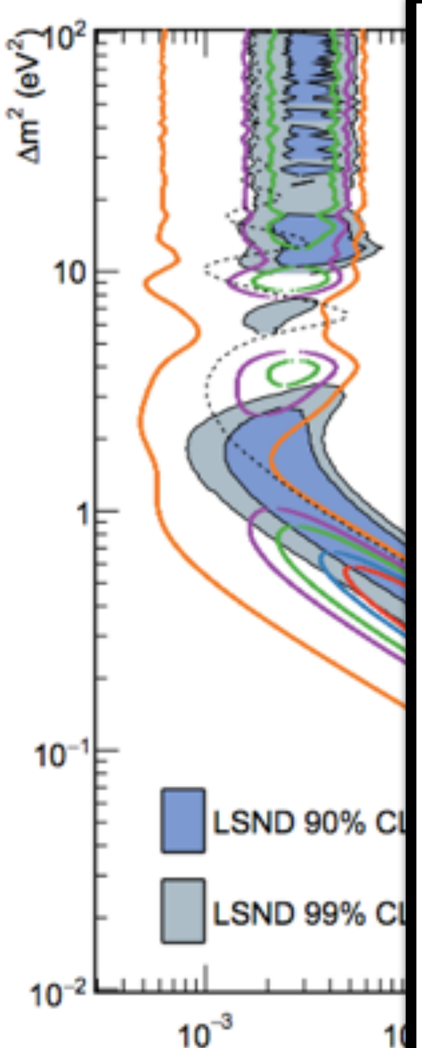


An **appearance** signal implies electron- **and muon-flavour disappearance**

Large tension between datasets.

eV sterile oscillations

MiniBooNE Collaboration,1805.12028



earance probs.

$\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

$U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

IF we are seeing sterile neutrinos,

they are probably more **exotic** than we thought…

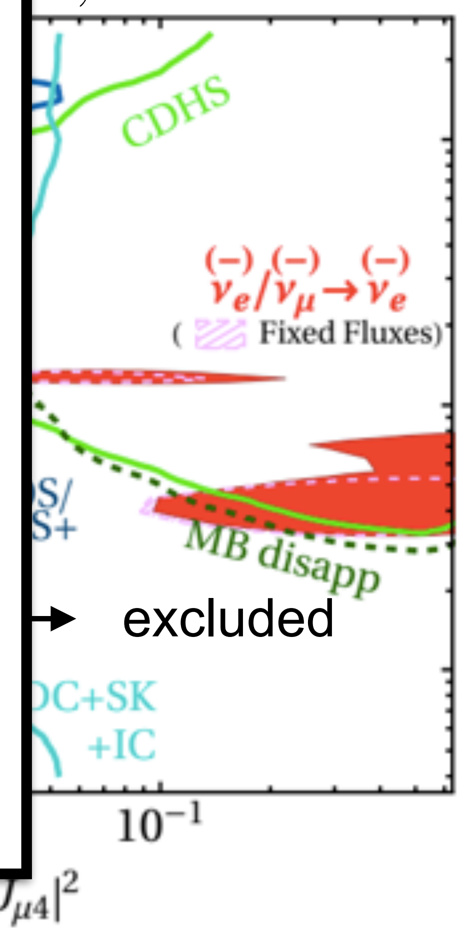
1) sterile in upscattering?

2) decaying steriles?
Dentler et al, 1911.01427
de Gouvea et al, 1911.01447
Palomares-Ruiz et al, 0505216

3) steriles w/ new matter effects?
J. Bramante, 1110.4871
J. Asaadi et al., 1712.08019
D. Doring H. Päs, 1808.07734

…

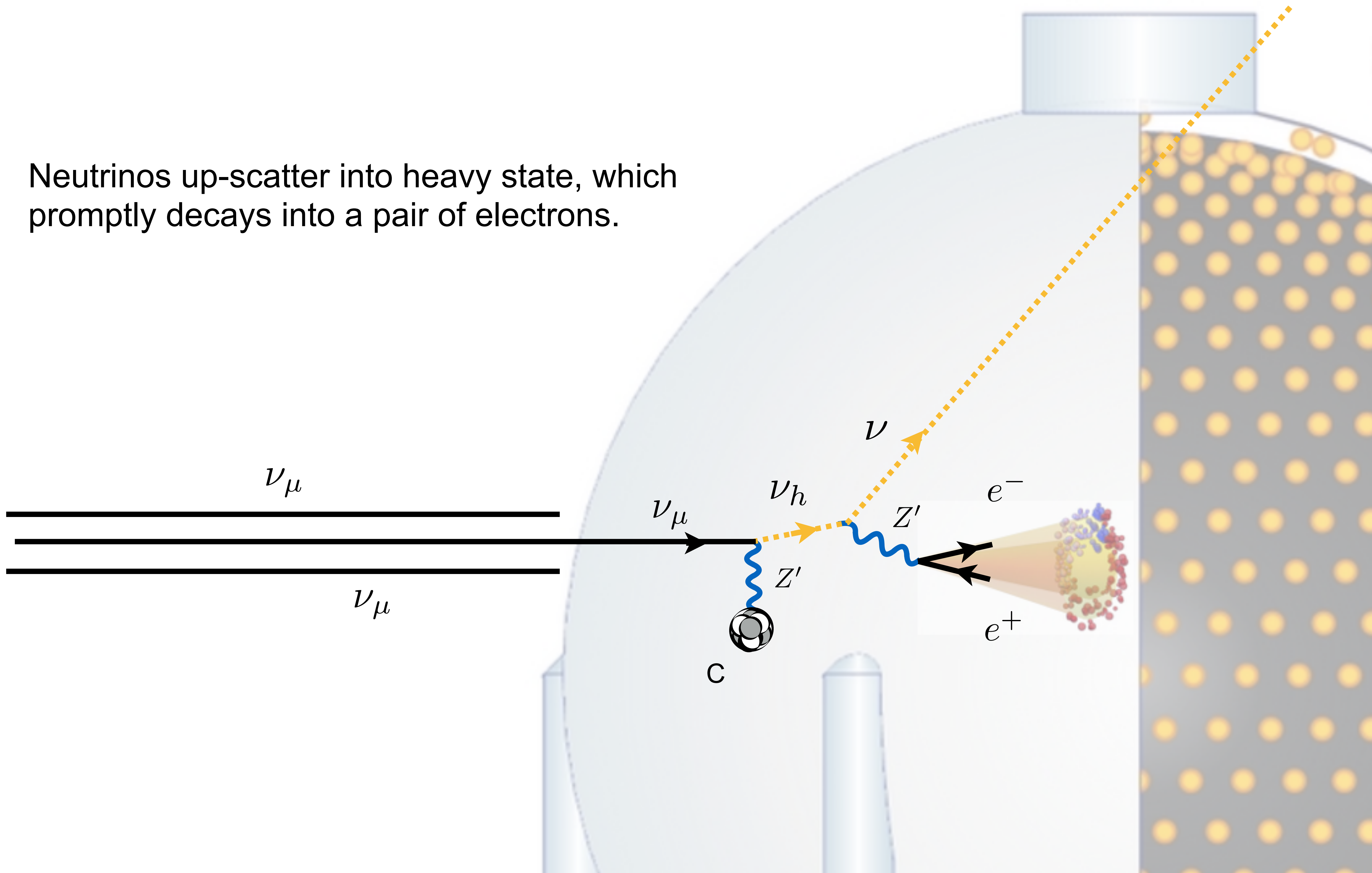
al, 1803.10661

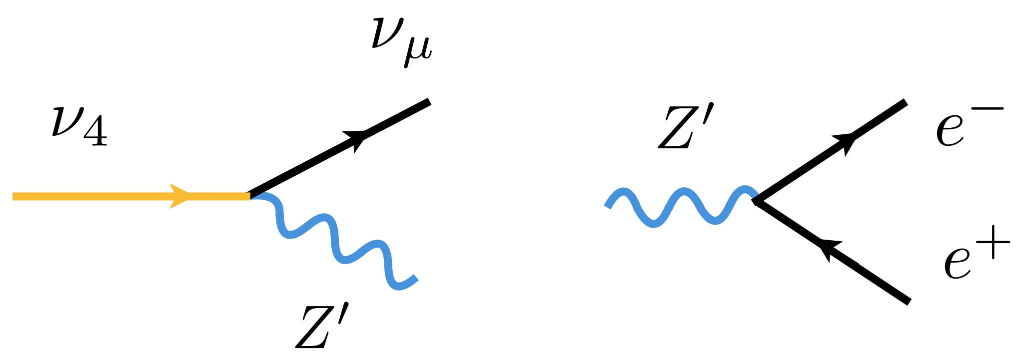


An **appearanc**
electron- **and muon-f**

Large tension b

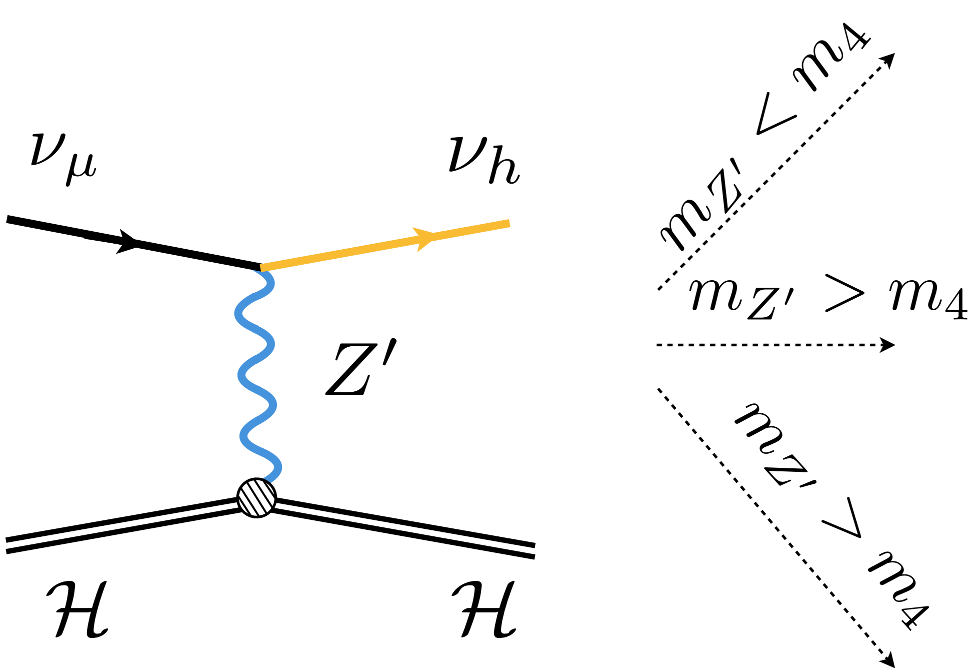
Neutrinos up-scatter into heavy state, which promptly decays into a pair of electrons.

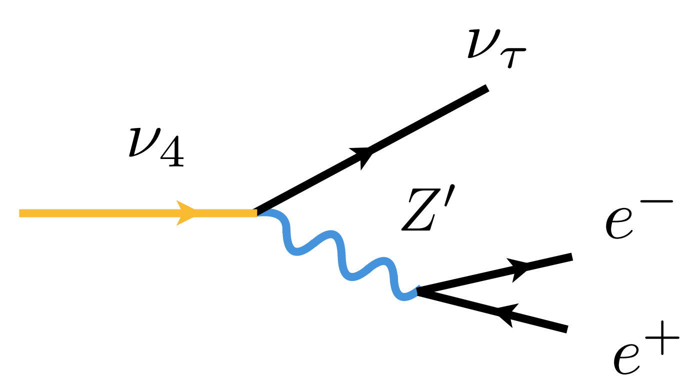




E. Bertuzzo et al.,1807.09877

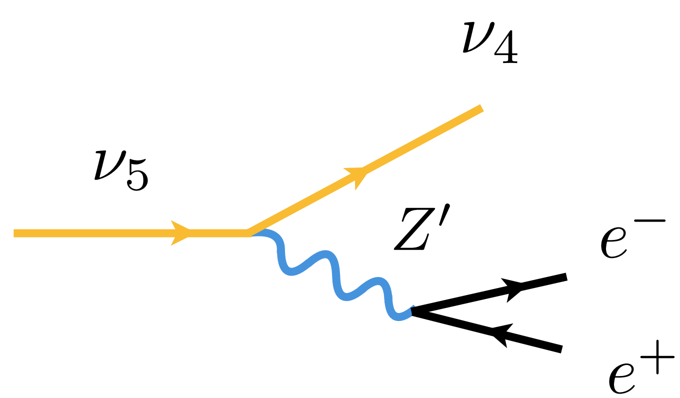
Coherent scattering overlapping ee pairs





P. Ballett et al., 1808.02915

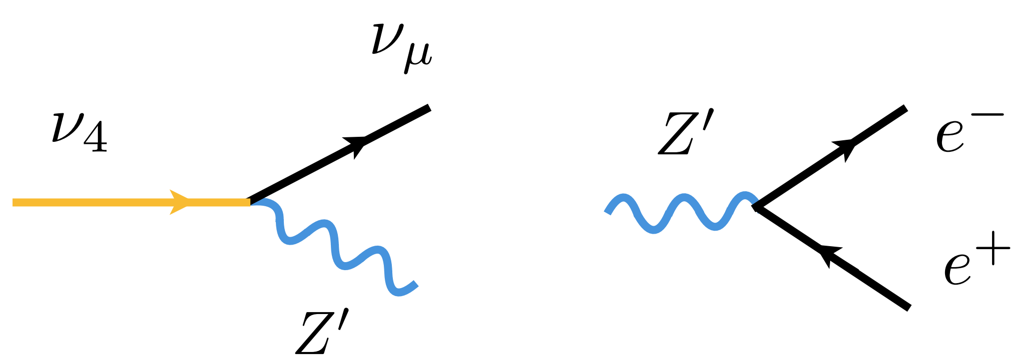
Proton elastic signal
Isotropic signal



P. Ballett et al., 1903.07589

Fast decays
Proton elastic signal
Isotropic signal

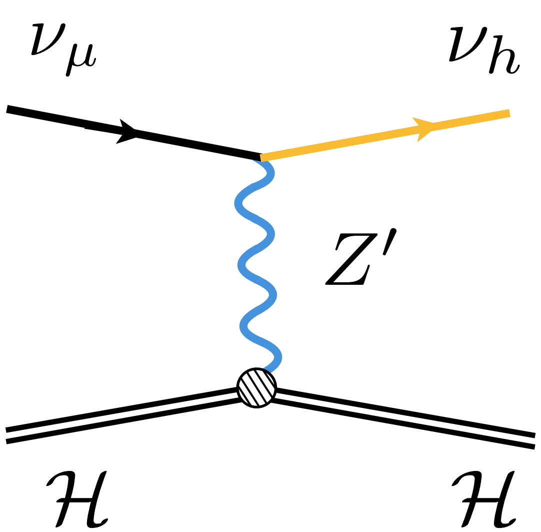
Dark neutrinos @ MiniBoonE

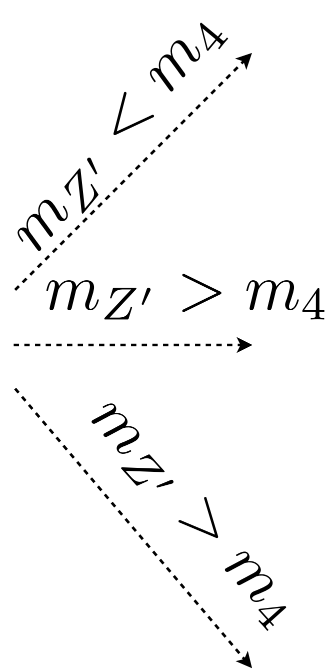


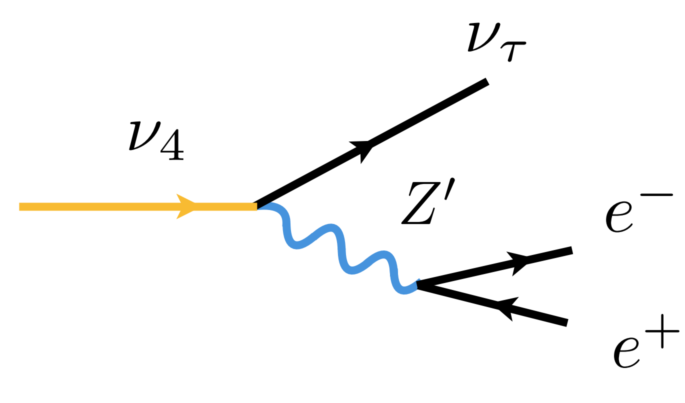
E. Bertuzzo et al.,1807.09877

Cannot reconcile nu-e scattering data with angular distribution at MB.

C. Arguelles et al, 1812.08768

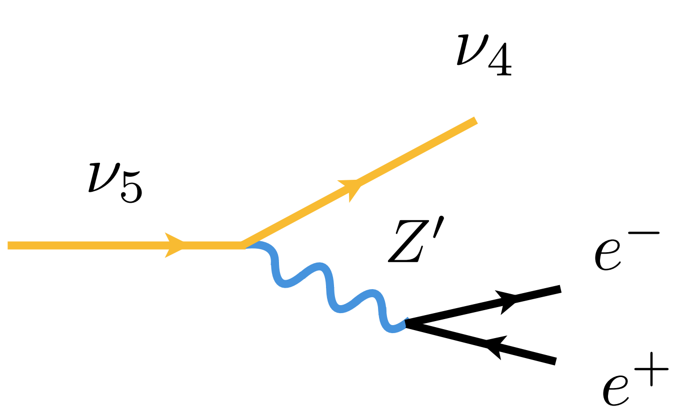






P. Ballett et al., 1808.02915

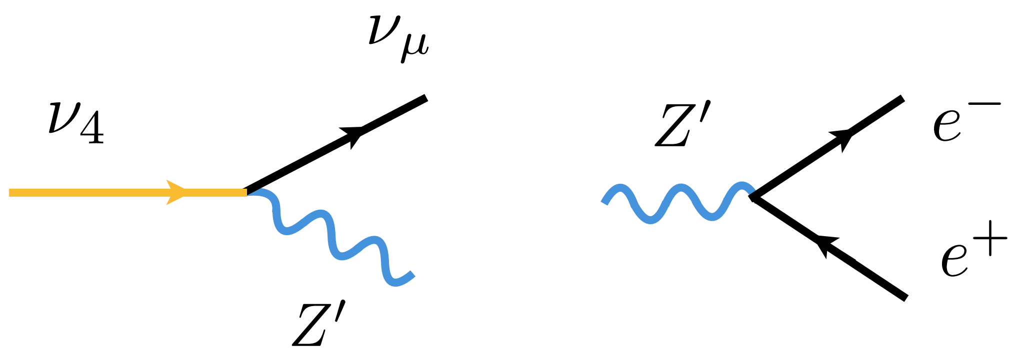
Mixing with tau is too large.



P. Ballett et al., 1903.07589

More contrived.

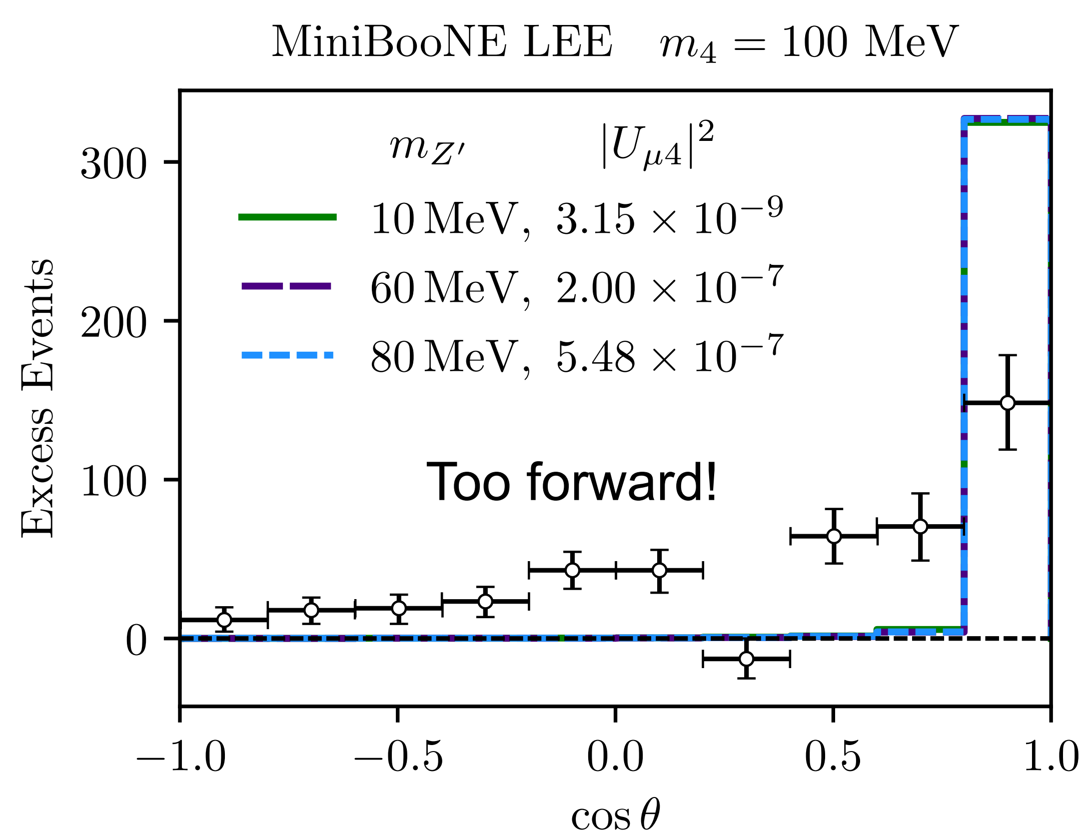
MiniBooNE — Light dark photon — revisited



E. Bertuzzo et al.,1807.09877

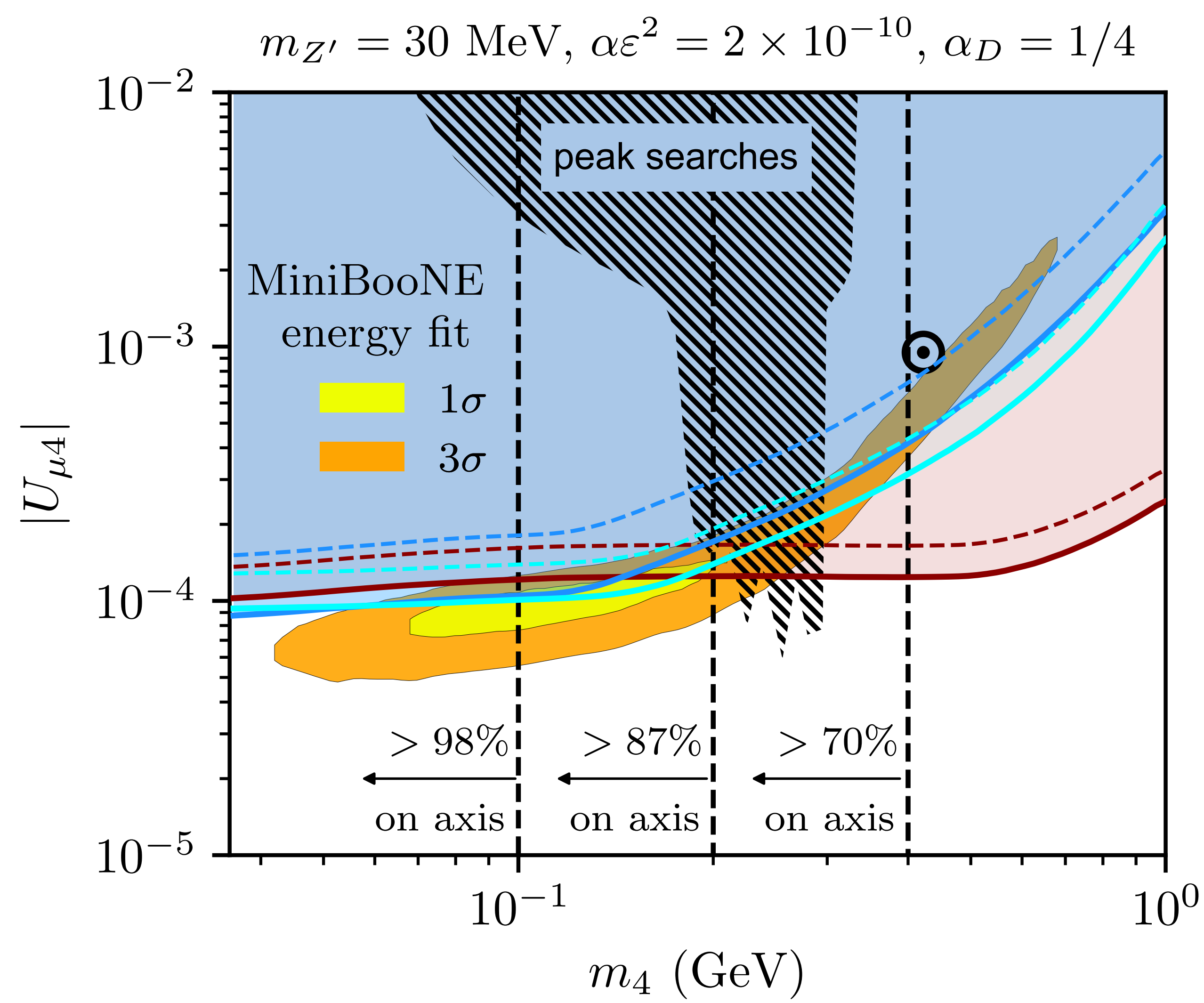
We revisit this MiniBooNE explanation using a better signal definition:

"Single photons" in **nu-e** scattering



Cannot reconcile angular dist. w/ nu-e data!

C. Arguelles et al, 1812.08768



MINERvA LE, **MINERvA ME**, **CHARM-II**

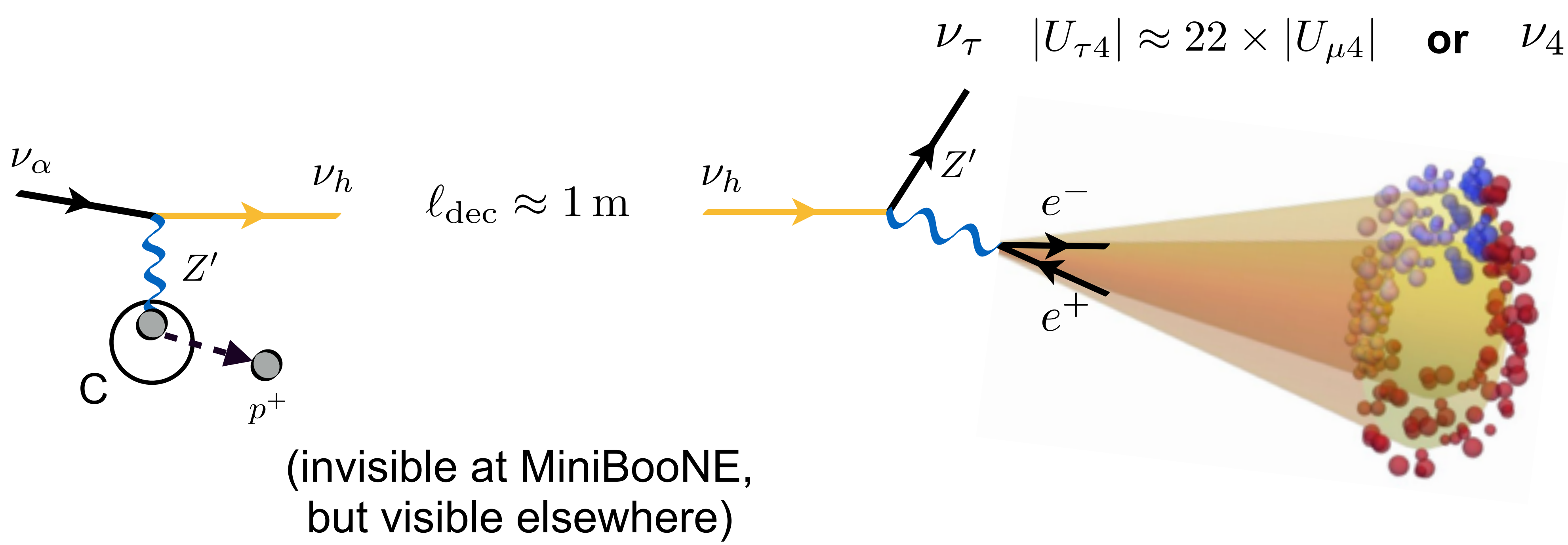
Heavy dark photon case

$m_{Z'} > m_4$

Signal: Proton + shower(s)

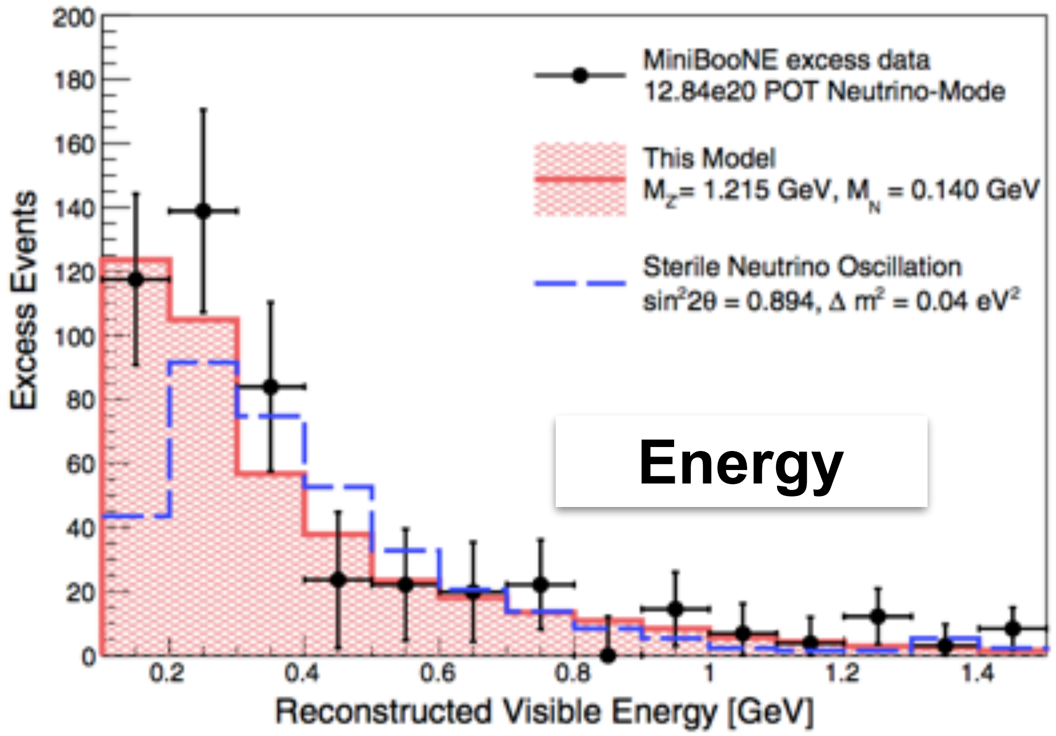
P. Ballett et al, 1808.02915
P. Ballett et al, 1903.07589

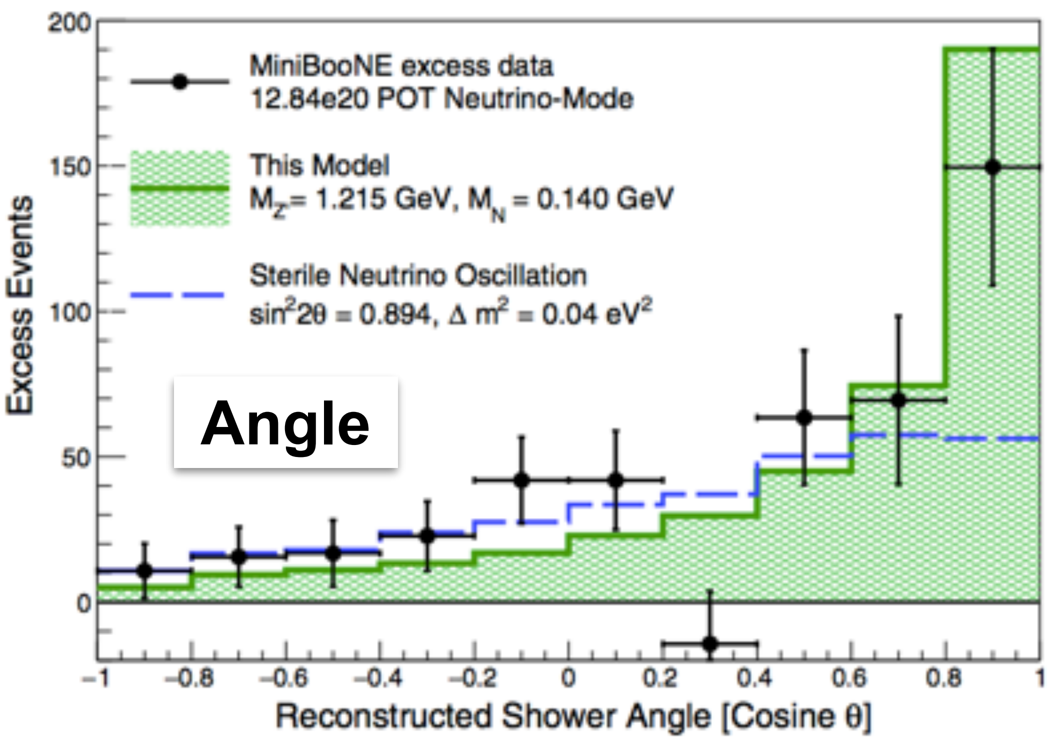
— single EM shower + some hadronic activity —



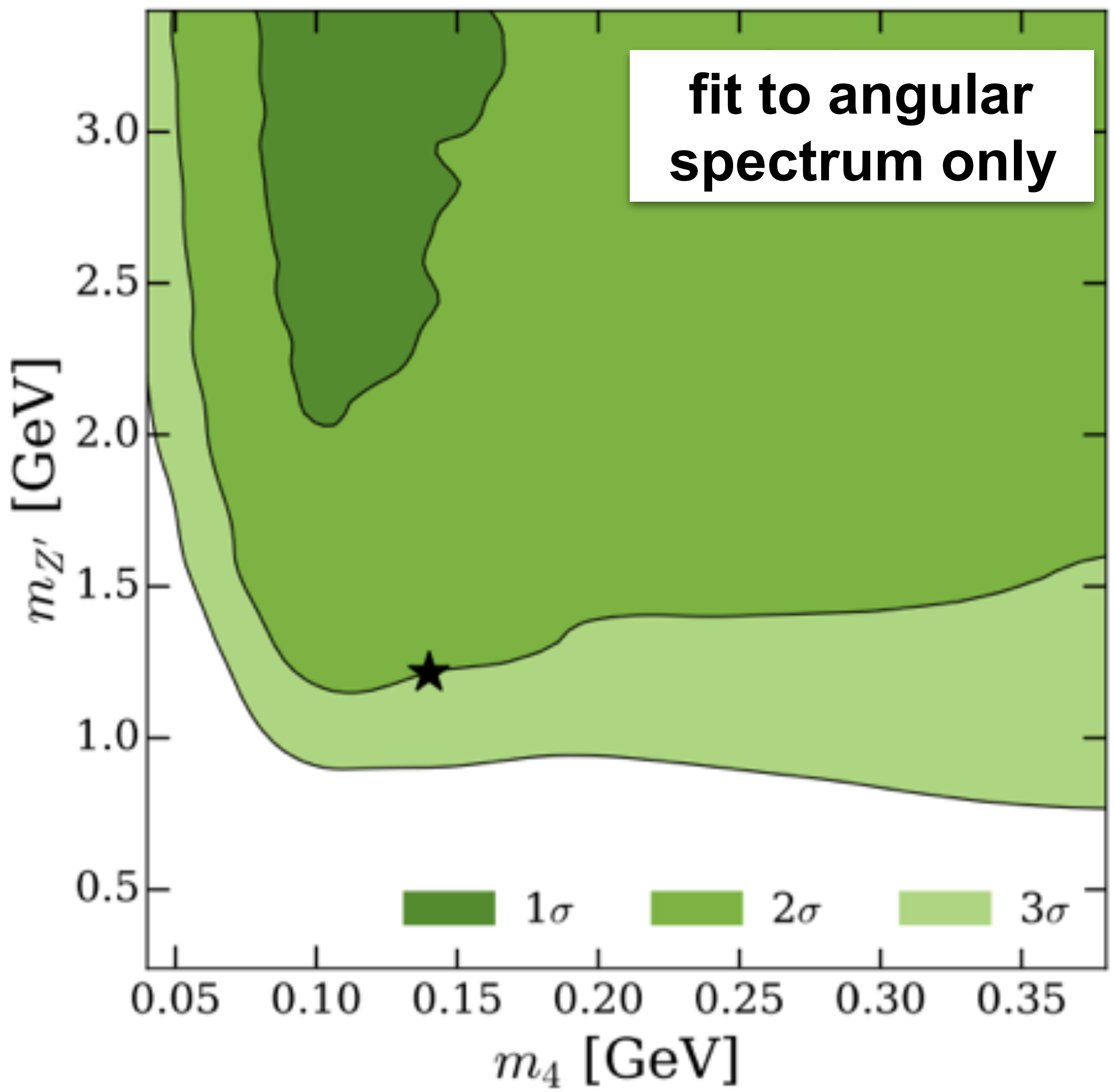
Does not show up in nu-e scattering due to hadronic activity!

Decay length is much smaller in 3+2 model and **~ free parameter!**





See *P. Ballett et al, PRD.99.071701*



Much better angular fit!

Sterile Neutrino Decays

$$-\mathcal{L}_{\rm int} = g\bar{\nu}_s \nu_s \phi$$

Palomares-Ruiz et al, 0505216

Sterile Neutrino Decays

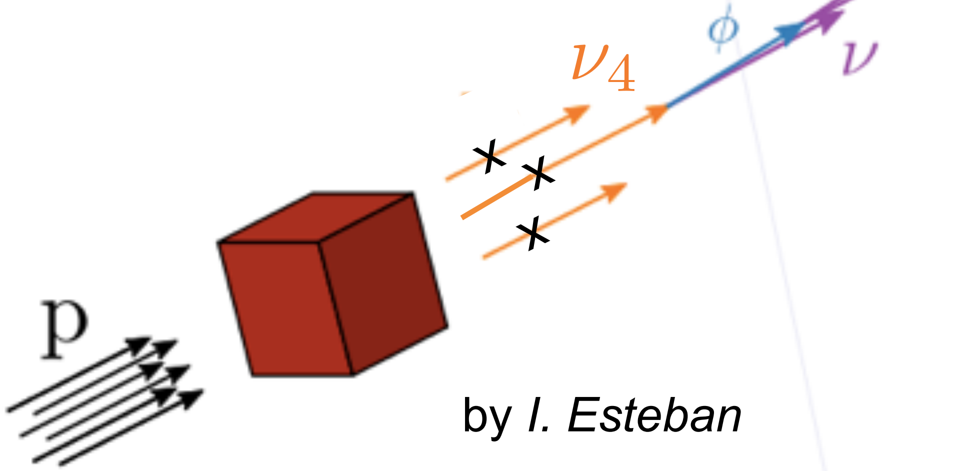
Dentler et al, 1911.01427
de Gouvea et al, 1911.01447

$$-\mathcal{L}_{\rm int} = g\bar{\nu}_s\nu_s\phi \supset gU^*_{s4}\,\bar{\nu}_4\left(\sum_{i=1}^{3} U_{si}\nu_i\right)\phi + g\left(\sum_{i=1}^{3} U^*_{si}\bar{\nu}_i\right)\left(\sum_{i=1}^{3} U_{si}\nu_i\right)\phi$$

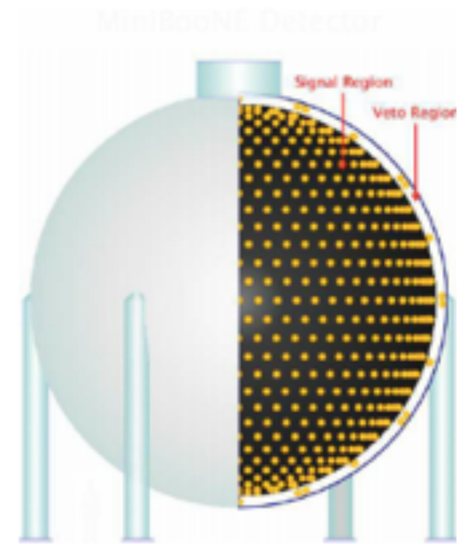
See I. Esteban talk at CERN 10.5281/zenodo.3509890.

$$\nu_4 \longrightarrow \phi + \nu_F$$
$$\hookrightarrow \nu_F + \bar{\nu}_F$$

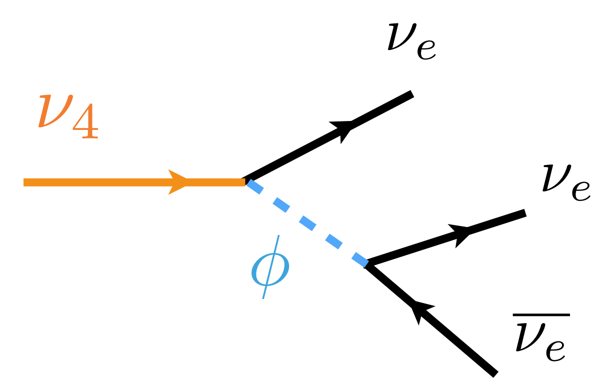
At MB sterile is produced through muon-mixing.



by *I. Esteban*



At least one sterile state and one "neutrinophilic" scalar



MB LEE prefers a **massive scalar** that decays on-shell.

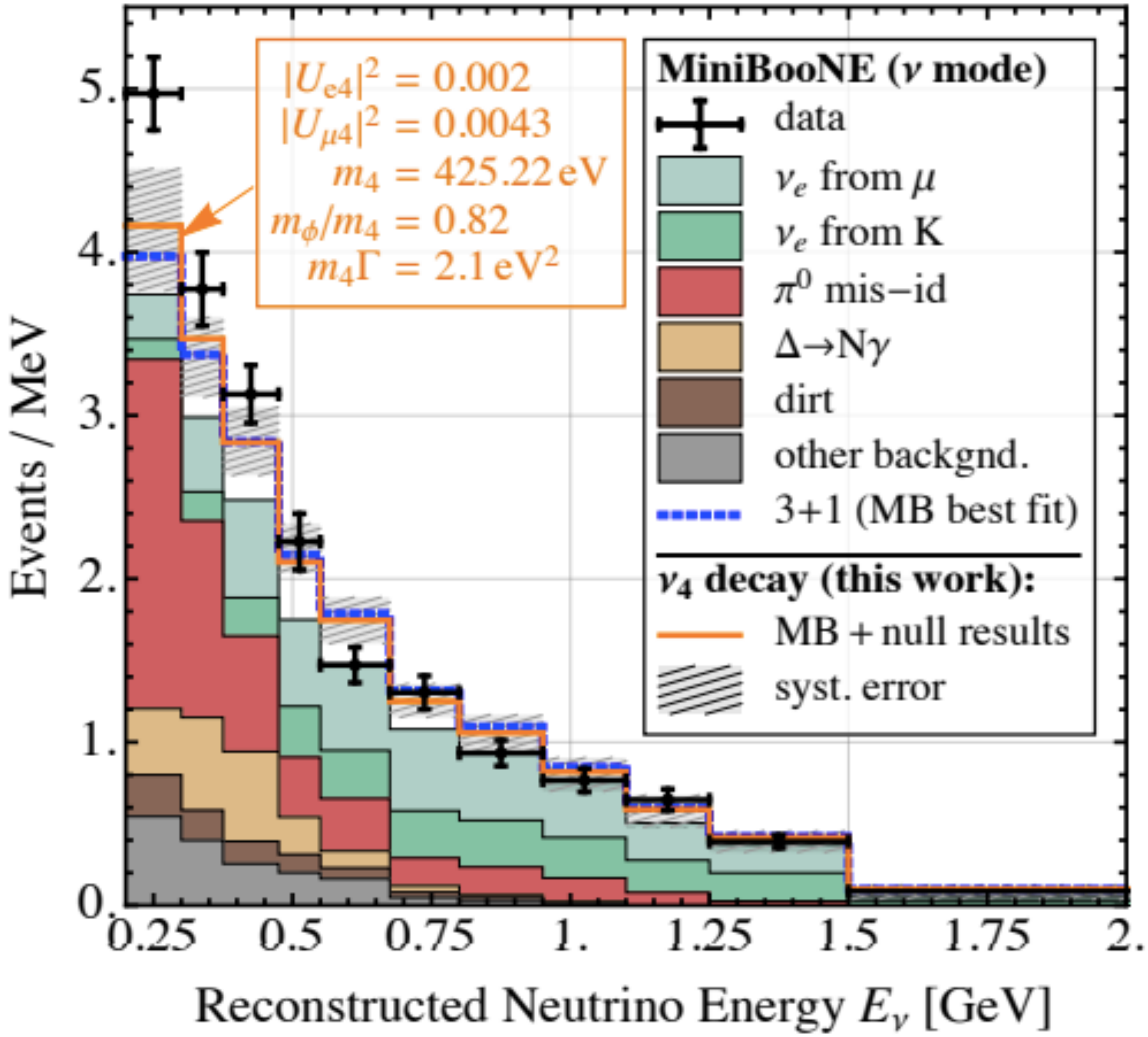
Muon disappearance signal is small.

* Non-trivial cosmology but no dedicated analysis performed so far.

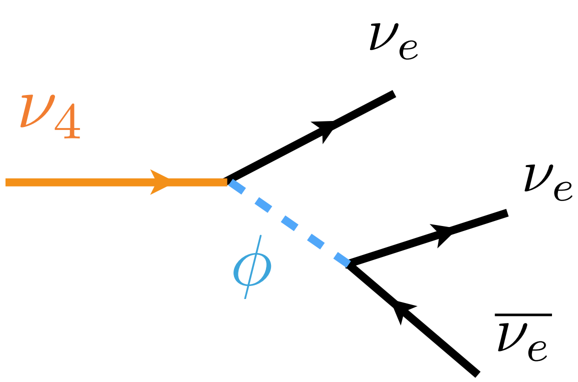
Sterile Neutrino Decays

$$-\mathcal{L}_{\rm int} = g\bar{\nu}_s\nu_s\phi \supset gU^*_{s4}\,\bar{\nu}_4\left(\sum_{i=1}^{3} U_{si}\nu_i\right)\phi + g\left(\sum_{i=1}^{3} U^*_{si}\bar{\nu}_i\right)\left(\sum_{i=1}^{3} U_{si}\nu_i\right)\phi$$

Dentler et al. 2019



At least one sterile state and one "neutrinophilic" scalar



MB LEE prefers a **massive scalar** that decays on-shell.

Conclusions

We have learned a lot about HNLs — in particular, what they **are not!**

Exciting new prospects w/ advent of large scale neutrino detectors and intense beams.

Dark sectors and HNL's go *hand in hand*
— plethora of possibilities for "**secret**/**dark**/**hidden**" neutrino physics —

Renewed interest in MiniBooNE
— many new models and fresh ideas with **non-minimal** sectors —

Thank you!

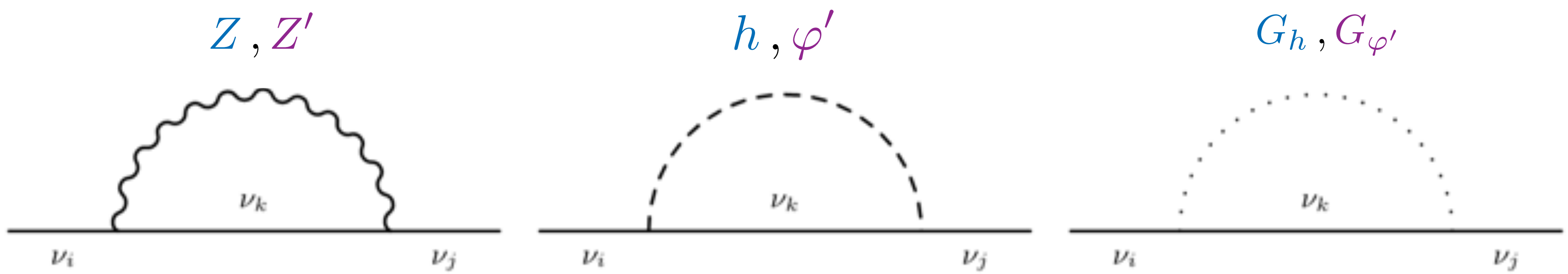
APPENDIX

$$\mathcal{L}_{\text{mass}} \supset \frac{1}{2}\left(\overline{\nu}_\alpha \quad \overline{N} \quad \overline{\nu_D}\right)\begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}\begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix}$$

LNV

U(1)' protected

After U(1)' is broken, zeros are no long protected!



$$m_{ij} = \frac{1}{4\pi^2}\sum_{k=4}^{5}\left[C_{ik}C_{jk}\frac{m_k^3}{m_Z^2}F(m_k^2, m_Z^2, m_h^2) + D_{ik}D_{jk}\frac{m_k^3}{m_{Z'}^2}F(m_k^2, m_{Z'}^2, m_{\varphi'}^2)\right],$$

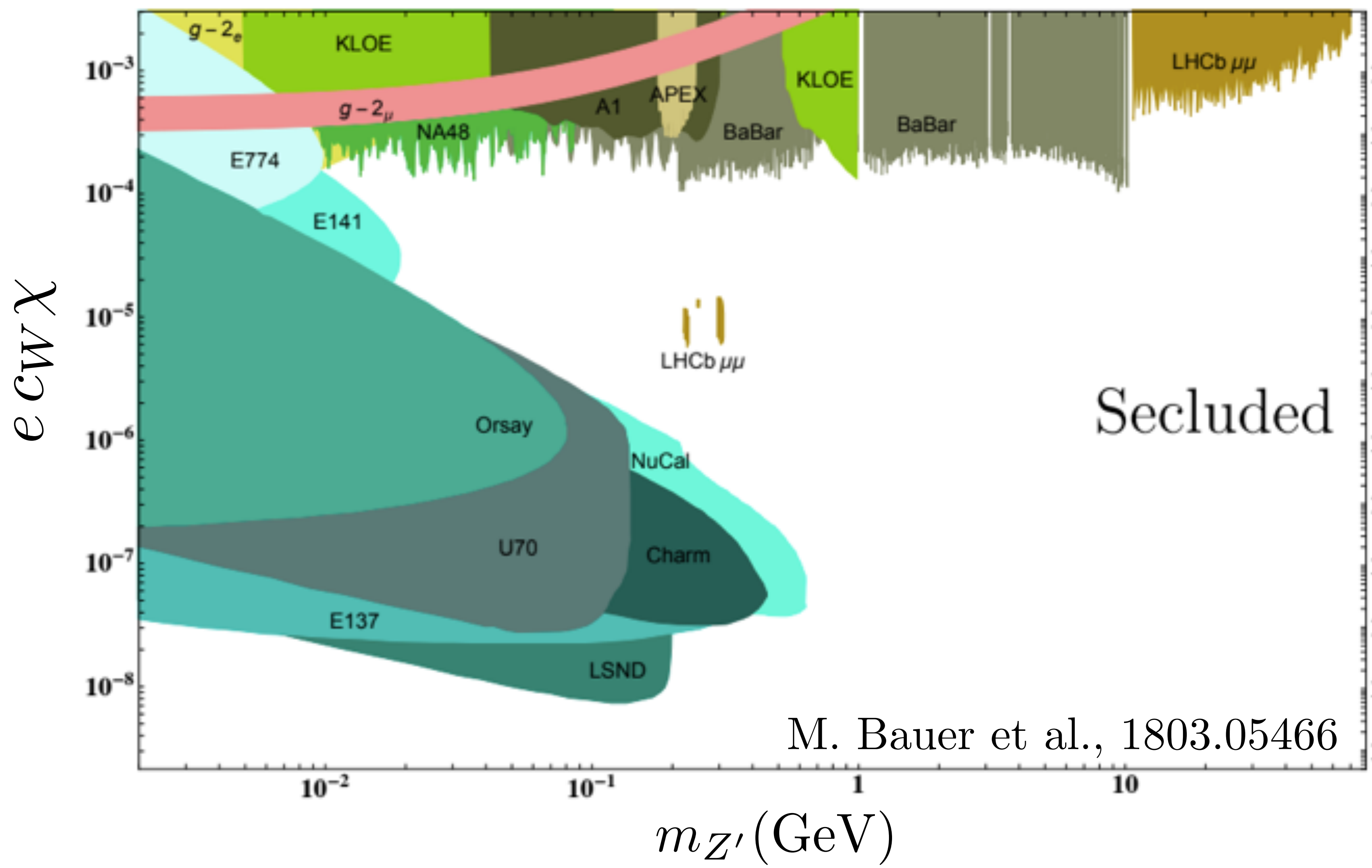
SM $\quad C_{ik} \equiv \frac{g}{4c_W}\sum_{\alpha=e}^{\tau} U_{\alpha i}^* U_{\alpha k} \qquad D_{ik} \equiv \frac{g'}{2}U_{Di}^* U_{Dk}.$ BSM

In general, both contributions are important, but if NP is light, it dominates.

If both are large => two massive neutrinos $\quad m_\nu \propto \mu'$

$$\frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu}$$

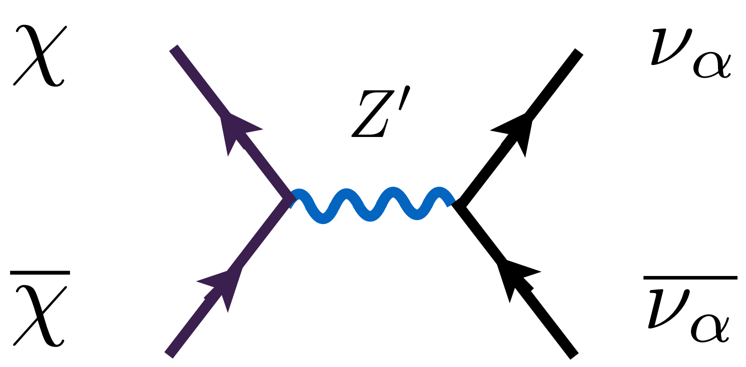
For a light boson —> couples only to electric charge (dark photon).



Neutrino portal DM — growing literature, see, *e.g.*,

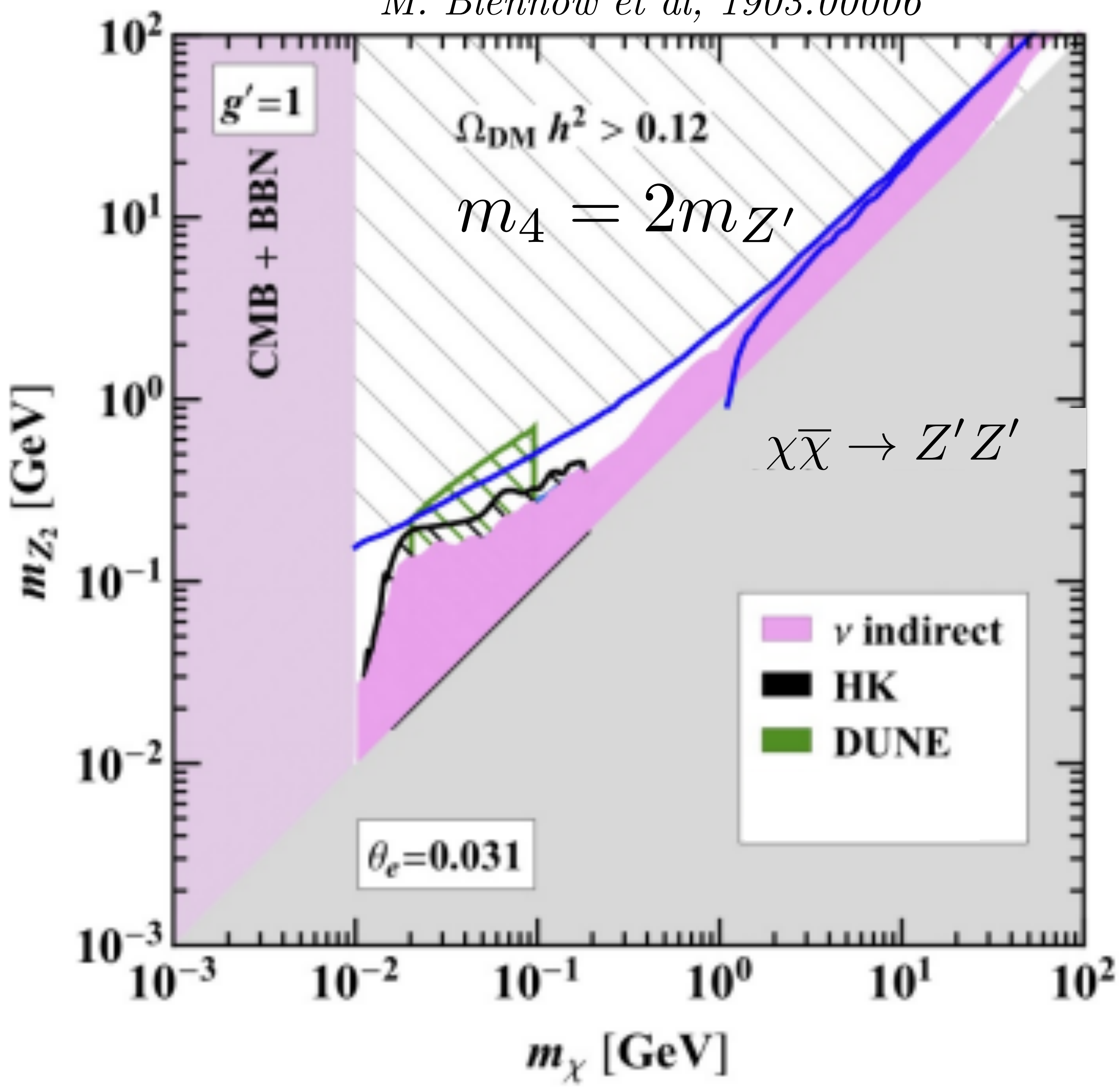
B. Bertoni et al, 1412.3113
B. Batell et al, 1709.07001
M. Blennow et al, 1903.00006

$$\langle \sigma v_r \rangle \approx \frac{g'}{8\pi} |U_{\alpha 4}|^4 \frac{m_\chi^2}{\left(4m_\chi^2 - m_{Z'}^2\right)^2}$$



Monochromatic neutrinos from the Galaxy can be searched for in large volume detectors.

M. Blennow et al, 1903.00006

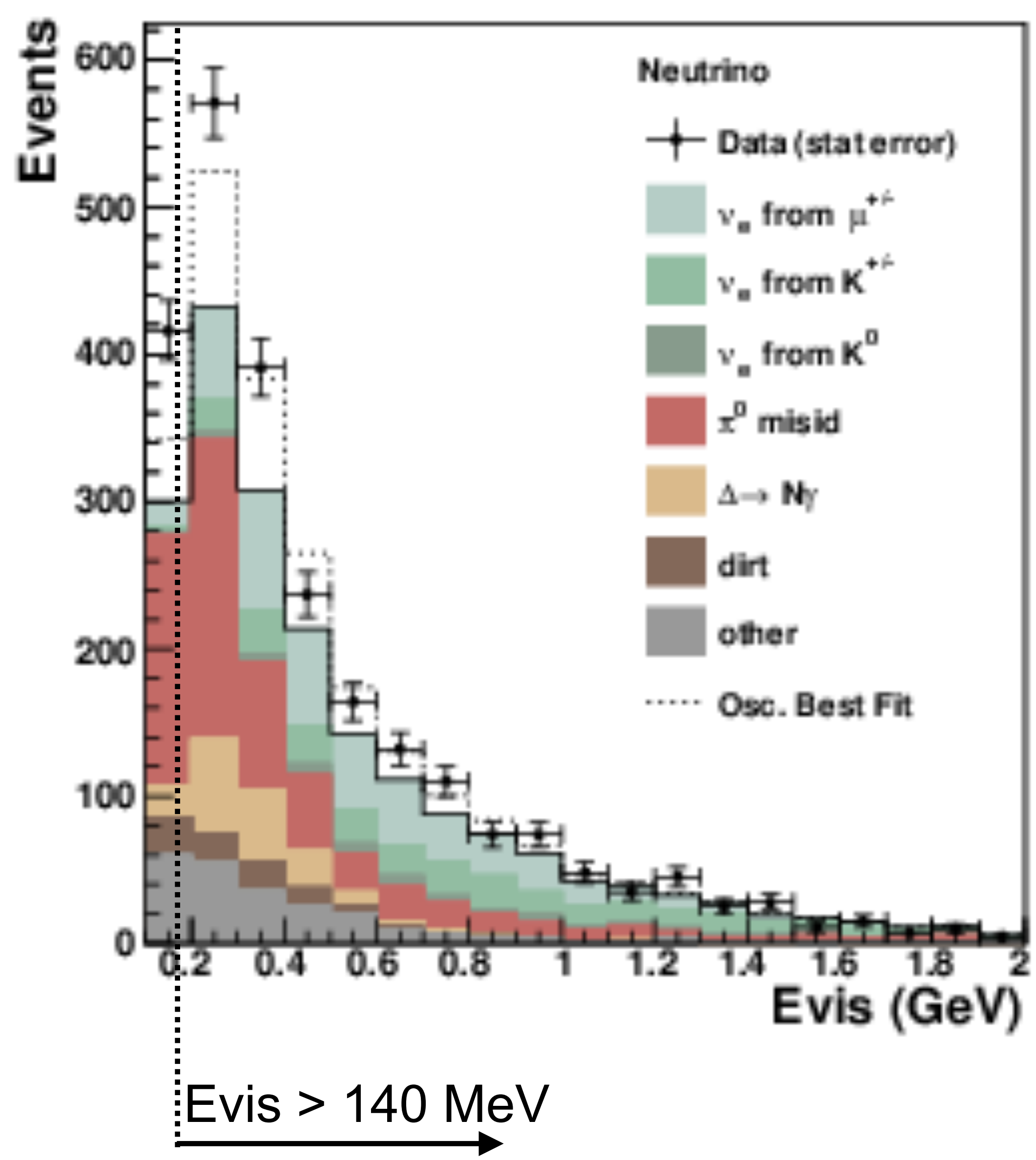


The MiniBooNE Low Energy Excess (LEE)

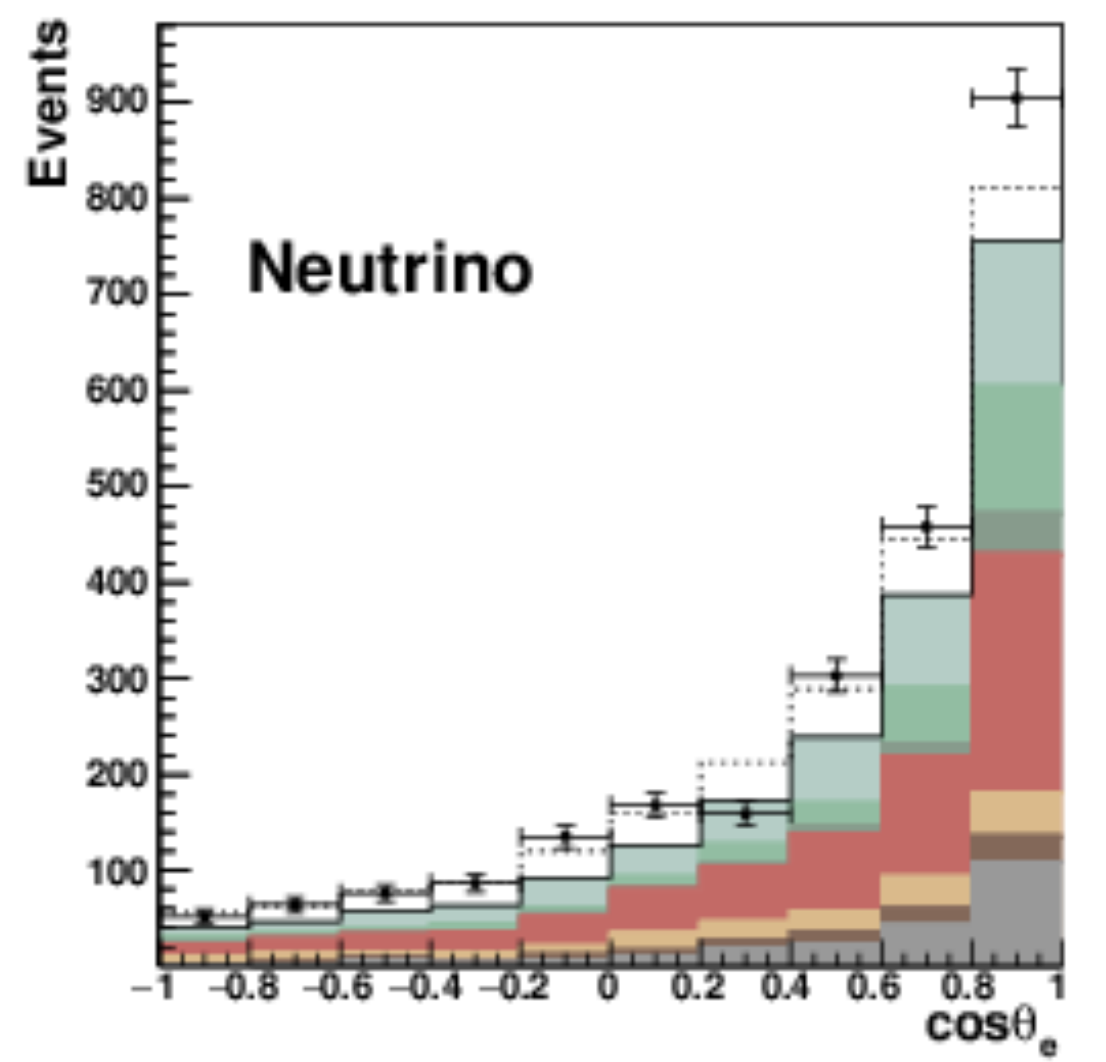
4.7σ excess observed in neutrino + antineutrino mode

— data/MC disagreement beyond statistical doubt —

MiniBooNE Collaboration, 1805.12028

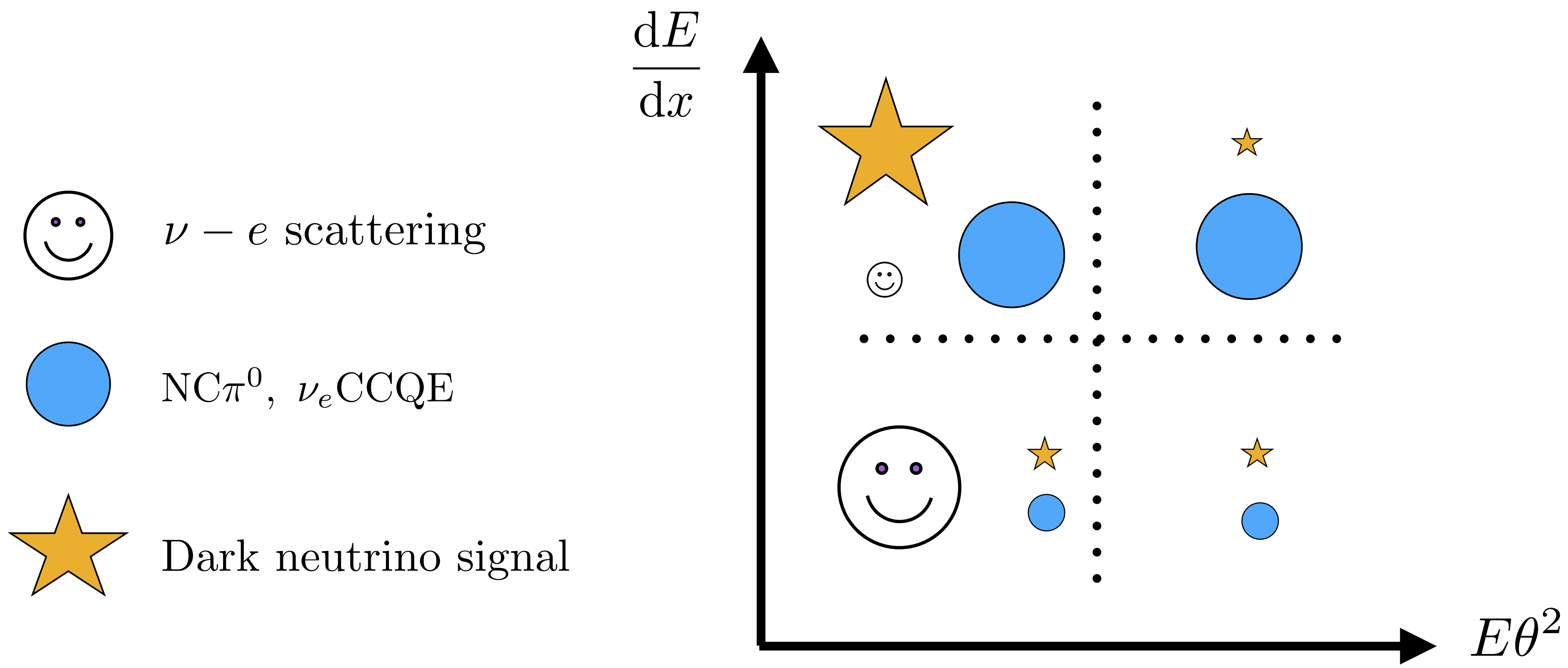


MiniBooNE Collaboration, 1805.12028



Dark neutrino signature

Data usually shown in one of 2 variables
— angle w.r.t. the beam or dE/dx (energy deposition) —



New physics shows up in sideband — would benefit from full dataset

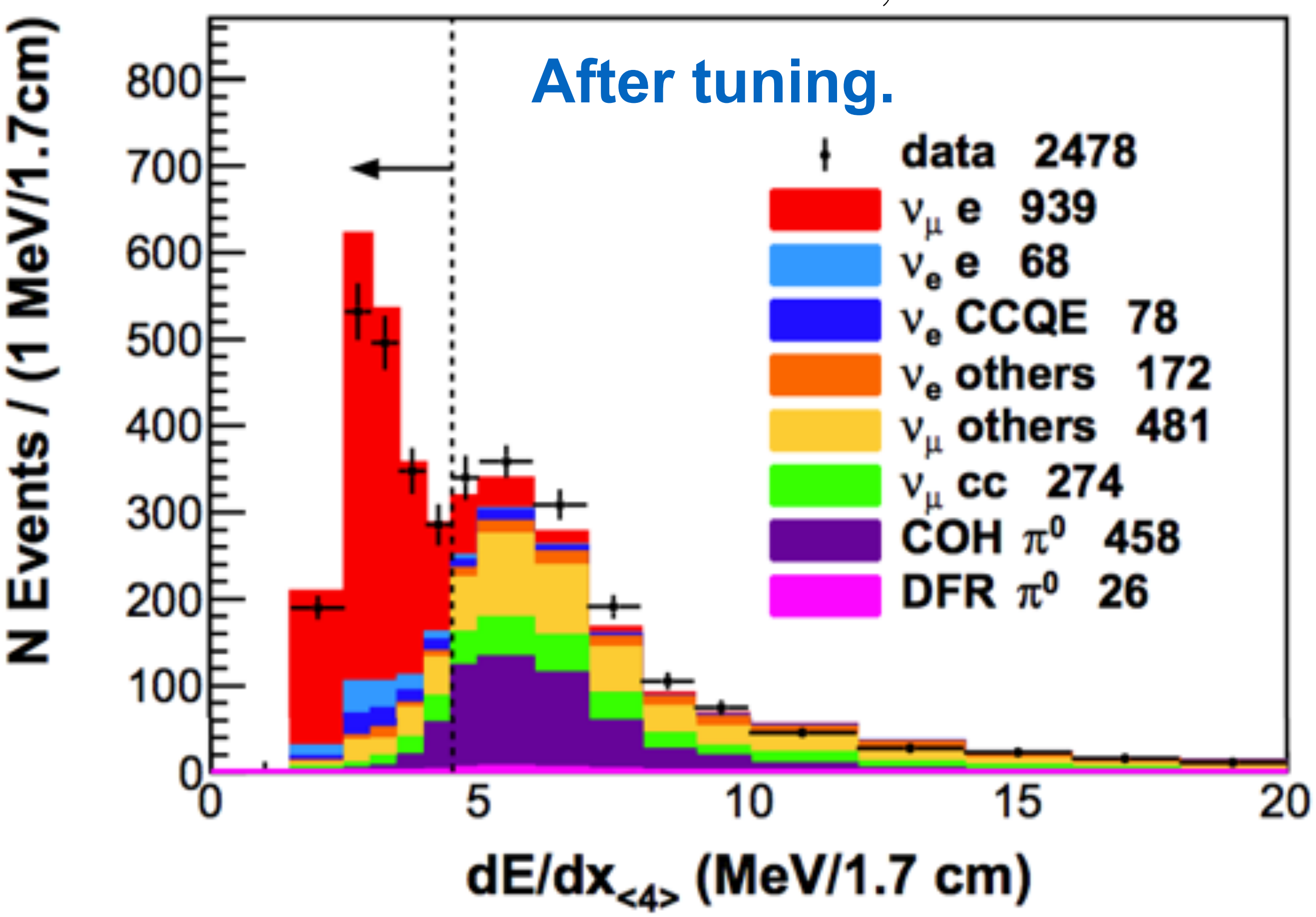
See Carlos Argüelles talk at PONDD: 10.5281/zenodo.2642413

MINERvA Medium Energy results

BUT! MINERvA actually sees an excess at large dE/dx!

… and tunes it away to measure the neutrino flux.

MINERvA Collaboration, 1906.00111



MINERvA Collaboration, 1906.00111

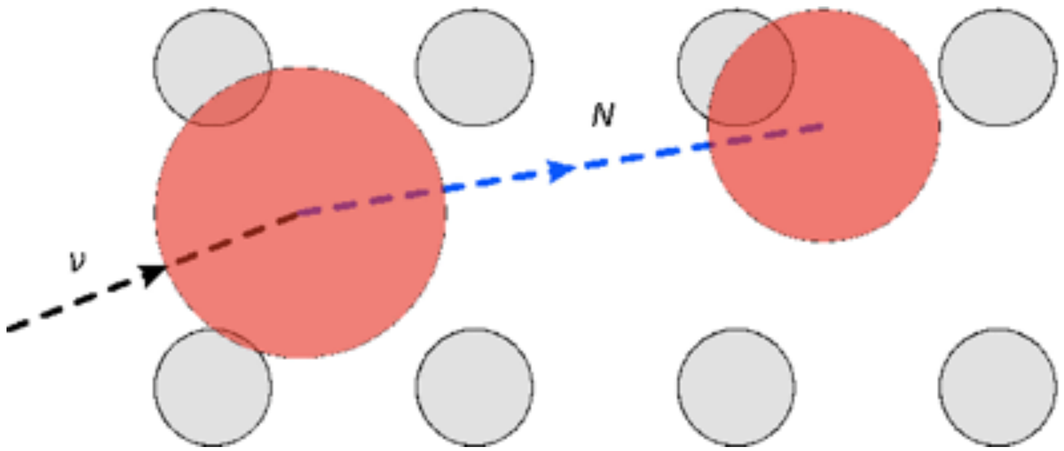
Process	Normalization
ν_e	0.87 ± 0.03
ν_μ CC	1.08 ± 0.04
ν_μ NC	0.86 ± 0.04
NC COH $0.8 < E_e < 2.0$ GeV	0.9 ± 0.2
NC COH $2.0 < E_e < 3.0$ GeV	1.0 ± 0.3
NC COH $3.0 < E_e < 5.0$ GeV	1.3 ± 0.2
NC COH $5.0 < E_e < 7.0$ GeV	1.5 ± 0.3
NC COH $7.0 < E_e < 9.0$ GeV	1.7 ± 0.8
NC COH $9.0 < E_e$	3.0 ± 0.9

TABLE I. Background normalization scale factors extracted from the fits to kinematic sidebands, with statistical uncertainties.

Excess attributed to coherent π0 events — grows with energy.

— disagreement with GENIE prediction claimed both in **NC and CC channels** —

Double Bangs at IceCube

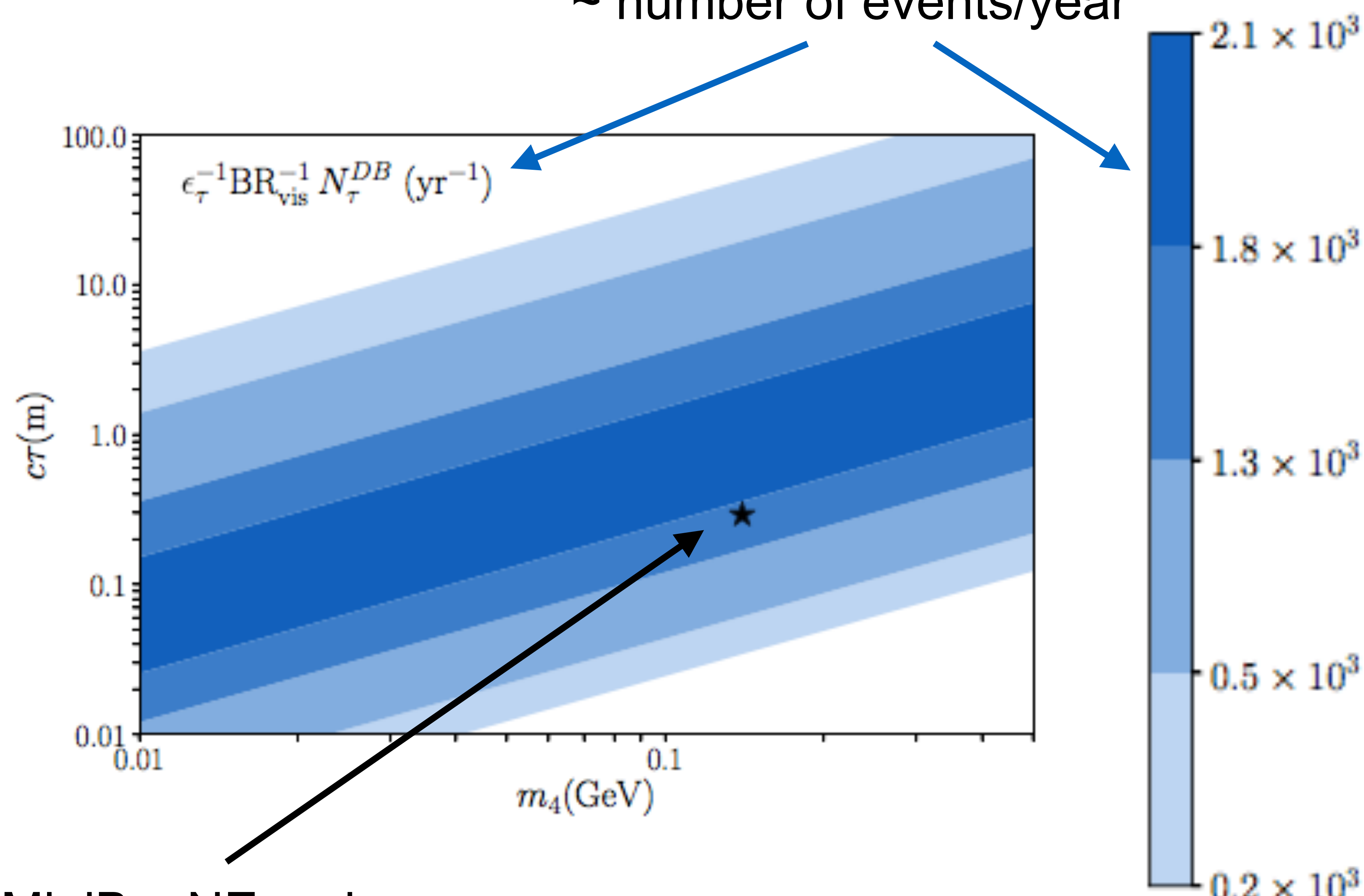


Prediction: **Double-bang events at IceCube**.

Large rate for large tau mixing (3+1),
but smaller rate for muon mixing only (3+2).

P. Coloma, 1906.02106

~ number of events/year



MiniBooNE r.o.i.