~~New~~ Opportunities for the Study of Baryon-Number Violation at Low-Energy Accelerators

New!

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Based on work in collaboration with Xinshuai Yan (U. Kentucky/CCNU, Wuhan)

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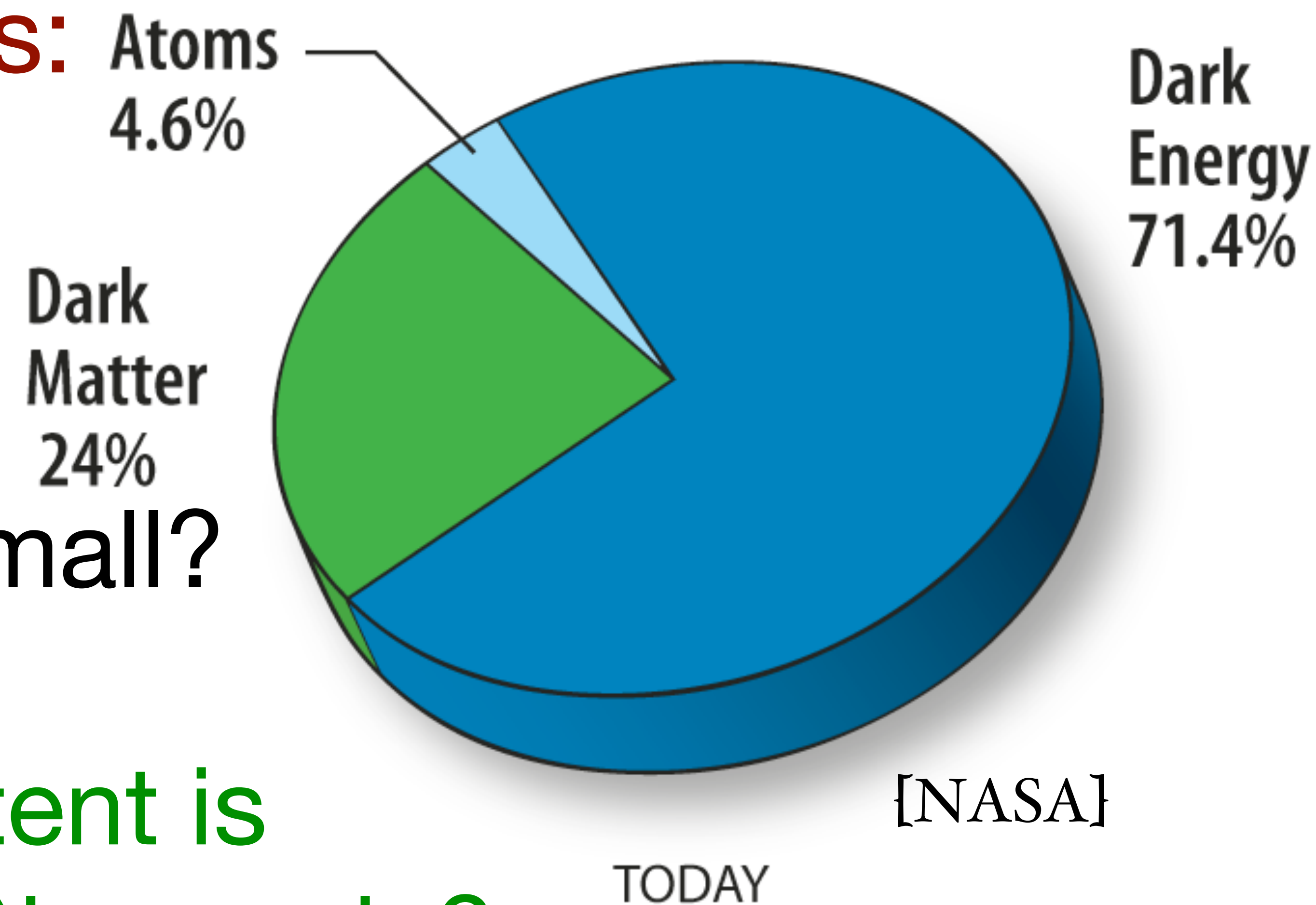
Why Study Baryon Number Violation?

A key thread to interpreting known BSM physics!

Three ***essential*** questions:



[NASA]

How is it that the cosmic energy budget in ordinary matter is so small?

And how is it that its content is overwhelmingly (not *anti*-)baryonic?

How does the neutrino get its mass?

Their answers may be linked, and through observed BNV!

A Cosmic Baryon Asymmetry

From particle physics?

The particle physics of the early universe can explain this asymmetry if B (baryon number), C (particle-antiparticle), and CP (matter-antimatter) violation all exist in a non-equilibrium environment. [Sakharov, 1967]

But what is the mechanism?

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is "special"

Non-equilibrium dynamics? No. (!)

The Higgs particle is of 125 GeV in mass;
lattice simulations reveal the electroweak phase transition is NOT of first-order. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

Thus we must look beyond the (MS?)SM to explain it!

Perspective

Experiment & observation reveal non-zero ν masses, a cosmic BAU, dark matter, dark energy.

Experimental limits on $|\Delta B|=1$ processes are severe, but $|\Delta B|=2$ processes can be of distinct origin & are much less constrained….

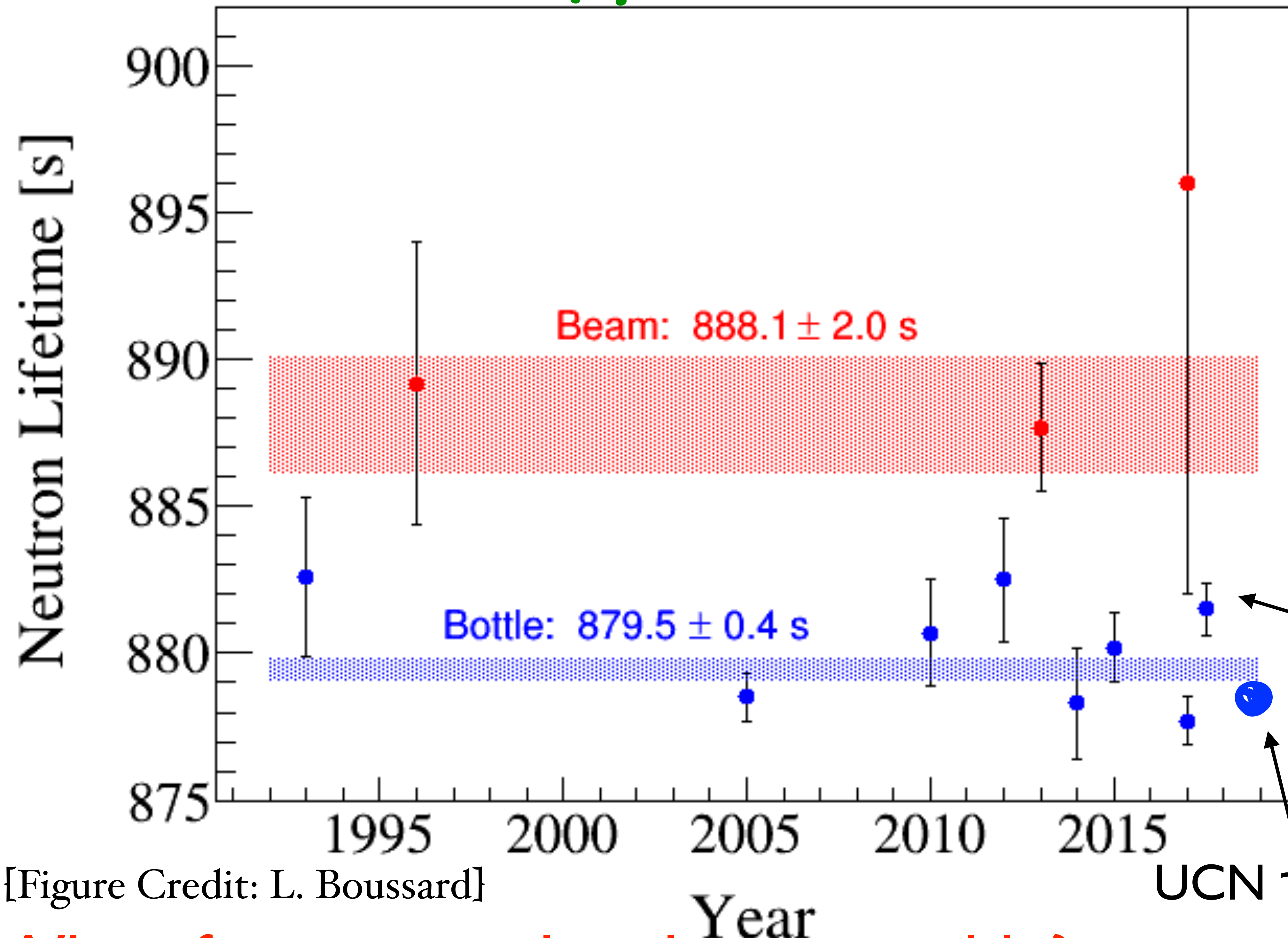
[Marshak and Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013]

$|\Delta B|=2$ &/or $|\Delta L|=2$ interactions (w/ B-L violation) speak to fundamental Majorana dynamics

How does this picture change with the addition of *nearly* hidden (dark) sector?

The Neutron Lifetime Puzzle

A darkly provocative result?



(8.6 s, (>)4σ)

Count **protons** that appear

Serebrov

Count **neutrons** that persist

UCN τ_n

Gonzalez et al.,2021

[Figure Credit: L. Boussard]

What if neutrons also decay invisibly?

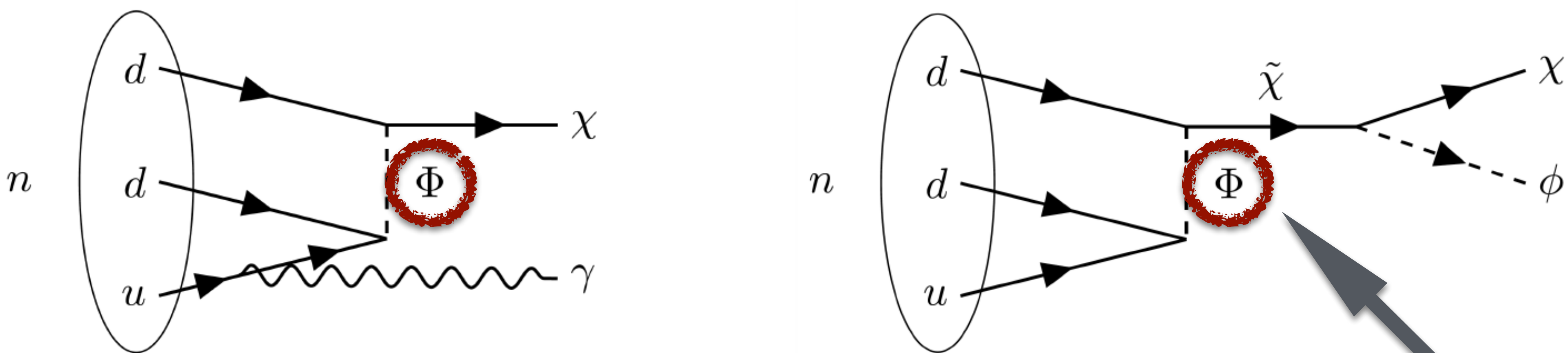
[Recall early suggestion: Z. Berezhiani & "mirror neutrons" & 2019; note Broussard et al., 2022!]

Neutron Dark Decays

Modeled to solve the n lifetime puzzle

[Fornal & Grinstein, 2018]

★ Enter $n \to \chi\gamma$; also $n \to \chi(\phi \to e^+e^-)$



$\phi \to e^+e^-$

B-carrying scalar!

At low E: $$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

Select χ mass window to avoid **proton decay** ($|\Delta B| = 1$)

& nuclear constraints: $937.900\,\text{MeV} < m_\chi < 938.783\,\text{MeV}$

Thus $\tau_n^{\text{beam}} = \tau_n^{\text{bottle}}$ / Br(n→p + anything)

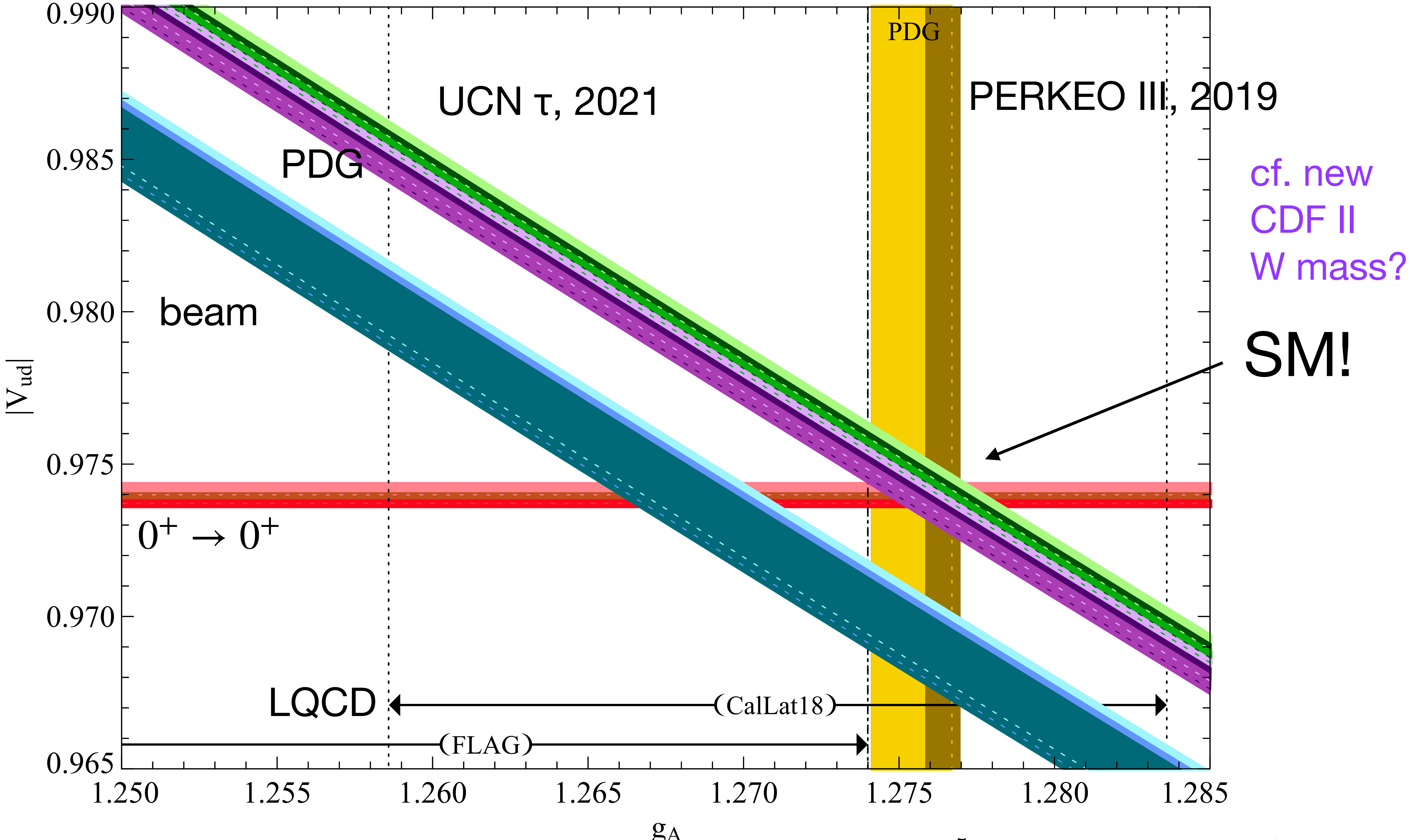
Many constraints! But $\Gamma_{n\,\text{dark}} \gg \Gamma_{|\Delta B|=1}$ still possible!

β Decay in the SM

[Czarnecki, Marciano, Sirlin, 2018]

Constrains n dark decays

$$|V_{ud}|^2 \tau_n (1 + 3g_A^2) = \frac{2\pi^3}{G_F^2 m_e^5 (1 + \delta_{RC}) f}$$

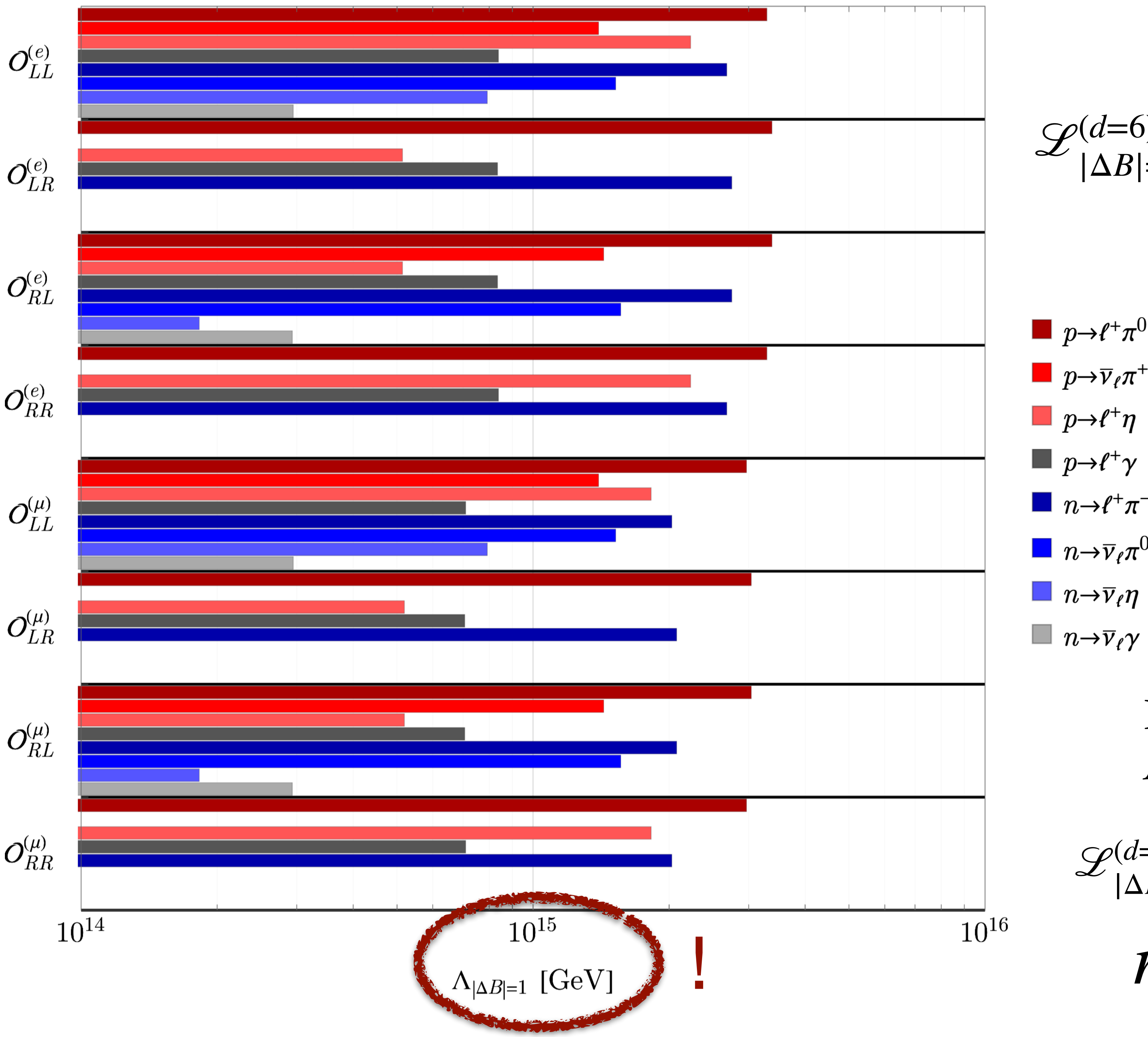


[Berryman, SG, & Zakeri, 2022]

Limits on $|\Delta B| = 1$ Decays

Mediated by mass dimension 6 operators in SMEFT

[Berryman, SG, & Zakeri, 2022]



$$\mathscr{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}} (qqq\ell)_i + \text{h.c.}$$

But the origin of $|\Delta B| = 2$ processes can be distinct!

[Marshak & Mohapatra, 1980;
Babu & Mohapartra, 2001 & 2012;
Arnold, Fornal, & Wise, 2013....]

$$\mathscr{L}^{(d=9)}_{|\Delta B|=2} \supset \sum_i \frac{c_i}{\Lambda^5_{|\Delta B|=2}} (qqqqqq)_i + \text{h.c.}$$

$n\bar{n}$ expt'l limit yields

$$\Gamma_{|\Delta B|=2} \gtrsim 10^{5.5}\ \text{GeV}$$

Fundamental Majorana Dynamics

Can exist for electrically neutral massive fermions: either leptons (ν's) or combinations of quarks (n's)

Lorentz invariance allows

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi - \frac{1}{2} m (\psi^T C \psi + \bar{\psi} C \bar{\psi}^T)$$

[Majorana, 1937]

where m is the Majorana mass.

A "Majorana neutron" is an entangled n and $\bar{n}$ state, but a Majorana neutrino can be a two-component field

Bibliography:
S.G. & Xinshuai Yan, Phys. Rev. D93, 096008 (2016) [arXiv:1602.00693];
S.G. & Xinshuai Yan, Phys. Rev. D97, 056008 (2018) [arXiv:1710.09292];
S.G. & Xinshuai Yan, Phys. Lett. B790 (2019) 421 [arXiv:1808.05288];
and on ongoing work in collaboration with Xinshuai Yan

Nucleon-Antinucleon Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n's & in nuclei)

"spontaneous"
& thus **sensitive** to
environment

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

$$P_{n\to\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2}\left[1 - \cos(2\mu_n B t)\right]$$

- dinucleon decay (in nuclei)

(limited by finite nuclear density)

- (low E) nucleon-antinucleon conversion

(mediated by external interactions)

Today!

$\bar{N}$ id proceeds from detection of ~5π's after annihilation

low E: "prompt" ann. & low bkgd [D. Phillips II et al., Phys.Rep., 2016]]

Modeling |ΔB|=2 Processes

Enter minimal scalar models without proton decay

[Arnold, Fornal, and Wise, 2013; Dev & Mohapatra, 2015]

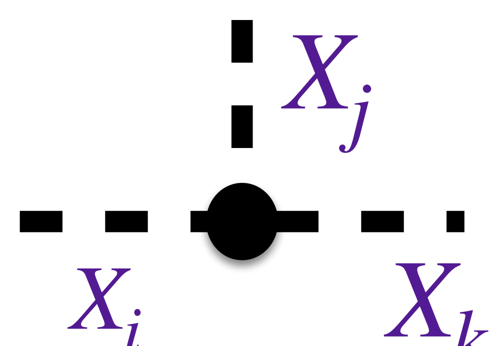
Already used for $n \to \bar{n}$ oscillation without p decay

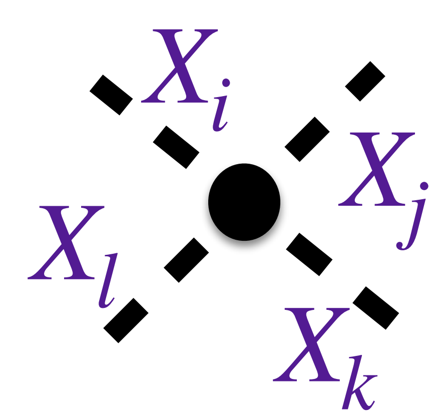
[Arnold, Fornal, Wise, 2013]

Add new scalars X_i that do not give N decay at tree level

Also choose X_i that respect SM gauge symmetry and also under interactions $X_iX_jX_k$ or $X_iX_jX_kX_l$ — cf. "hidden sector" searches: possible masses are limited by experiment

With this a much richer set of B and L violating processes emerge!

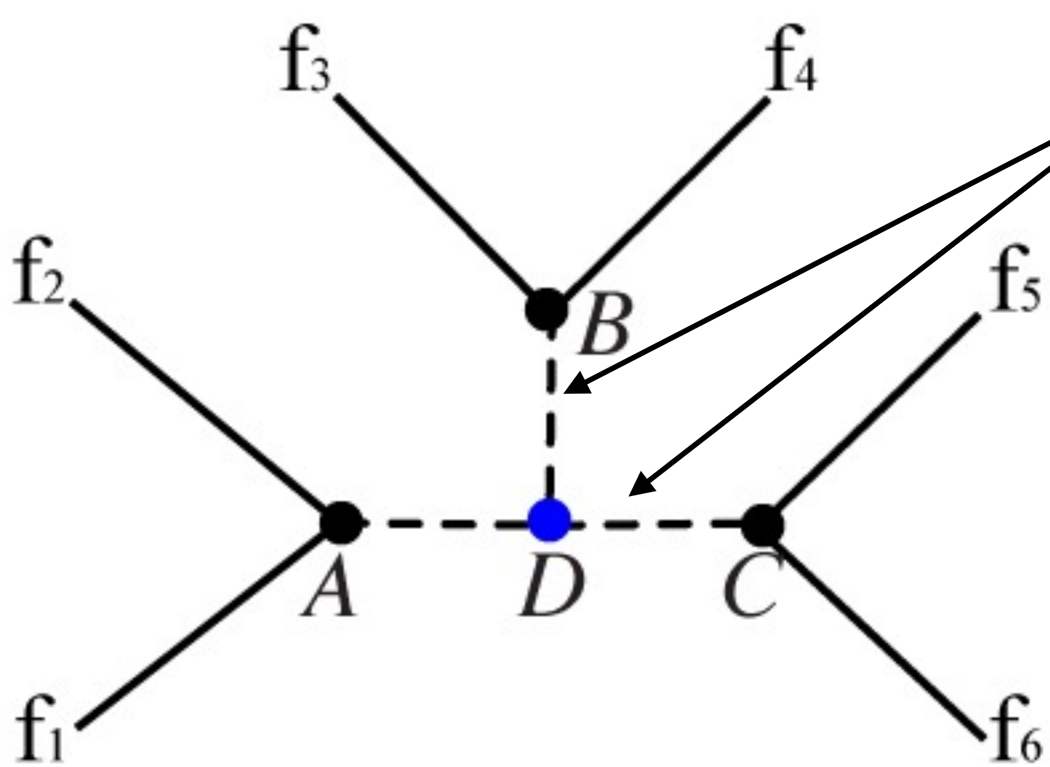




Context: 0ν ββ Decay in Nuclei

Can be mediated by "short-" or "long"-range mechanisms

The "short-range" mechanism involves new B-L violating dynamics; e.g.,



S or V that carries B or L

For choices of fermions f_i this decay topology can yield n-$\bar{n}$ or 0ν ββ decay

[Bonnet, Hirsch, Ota, & Winter, 2013; Berezhiani, 2013]

The possibilities can be related in a data-driven way

[SG & Xinshuai Yan, 2019]

Cf. connection via |ΔB|=1 process
[Babu & Mohapatra, 2015]

On Neutrinoless Double Beta (0ν ββ) decay

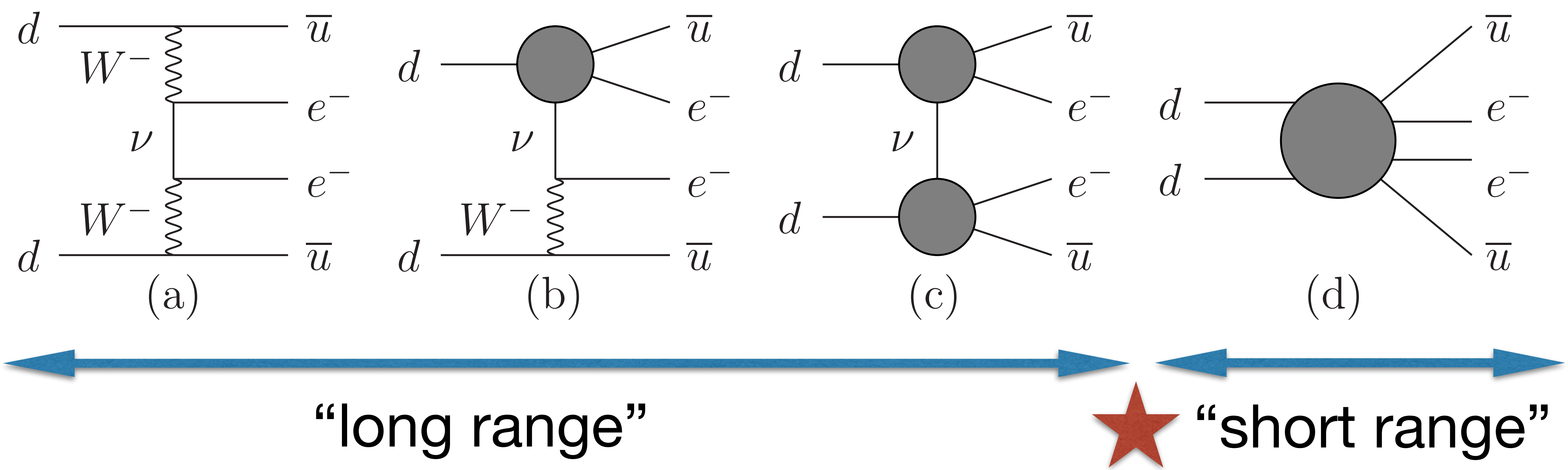
If observed, the ν has a Majorana mass

[Schechter & Valle, 1982]

0ν ββ mediated by a dimension 9 operator:

$\mathcal{O} \propto \bar{u}\bar{u}dd\bar{e}\bar{e}$ (or $\pi^- \pi^- \rightarrow e^- e^-$)

"mass mechanism"



[Bonnet, Hirsch, Ota, & Winter, 2013]

mediated by B-L breaking!

Scalars without Proton Decay

That also carry B or L charge

Scalar-fermion couplings

$Q_{em} = T_3 + Y$

Scalar	SM Representation	B	L	Operator(s)	$[g_i^{ab}?]$
X_1	$(1,1,2)$	0	-2	$Xe^a e^b$	[S]
X_2	$(1,1,1)$	0	-2	$XL^a L^b$	[A]
X_3	$(1,3,1)$	0	-2	$XL^a L^b$	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	$XQ^a Q^b$	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	$XQ^a Q^b, Xu^a d^b$	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	$Xd^a d^b$	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	$Xd^a d^b$	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	$Xu^a u^b$	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^a e^b, XL^a \bar{u}^b$	[–,–]

Note SU(3) rep'ns

$SU(3) \times SU(2)_L \times U(1)_Y$

chiral

[?: a⟷b symmetry]

cf. n dark decay: $(3,1,-1/3)$

A Sample Model

$$\mathcal{L}_{10} \supset -g_1^{ab} X_1 (e^a e^b) - g_7^{ab} X_7^{\alpha\beta} (d_\alpha^a d_\beta^b) - g_8^{ab} X_8^{\alpha\beta} (u_\alpha^a u_\beta^b)$$
$$-\lambda_{10} X_7^{\alpha\alpha'} X_8^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'} + \mathrm{H.c.}$$

Each term has mass dimension ≤ 4

But can generate a mass-dimension 12 operator at low energies to realize $e^- p \rightarrow e^+ \bar{p}$

There are several possible models.

Patterns of |ΔB|=2 Violation?

Note possible SM gauge invariant scalar models

[H.c. implied.]

[SG & Xinshuai Yan, 2019]

Model		Model		Model	
M1	$X_5X_5X_7$	A	$X_1X_8X_7^\dagger$	M10	$X_7X_8X_8X_1$
M2	$X_4X_4X_7$	B	$X_3X_4X_7^\dagger$	M11	$X_5X_5X_4X_3$
M3	$X_7X_7X_8$	C	$X_3X_8X_4^\dagger$	M12	$X_5X_5X_8X_1$
M4	$X_6X_6X_8$	D	$X_5X_2X_7^\dagger$	M13	$X_4X_4X_5X_2$
M5	$X_5X_5X_5X_2$	E	$X_8X_2X_5^\dagger$	M14	$X_4X_4X_5X_3$
M6	$X_4X_4X_4X_2$	F	$X_2X_2X_1^\dagger$	M15	$X_4X_4X_8X_1$
M7	$X_4X_4X_4X_3$	G	$X_3X_3X_1^\dagger$	M16	$X_4X_7X_8X_3$
M8	$X_7X_7X_7X_1^\dagger$			M17	$X_5X_7X_7X_2^\dagger$
M9	$X_6X_6X_6X_1^\dagger$			M18	$X_4X_7X_7X_3^\dagger$

"4 X" models can yield

$e^-p \to e^+\bar{p}$

$e^-p \to \bar{\nu}\bar{n}$

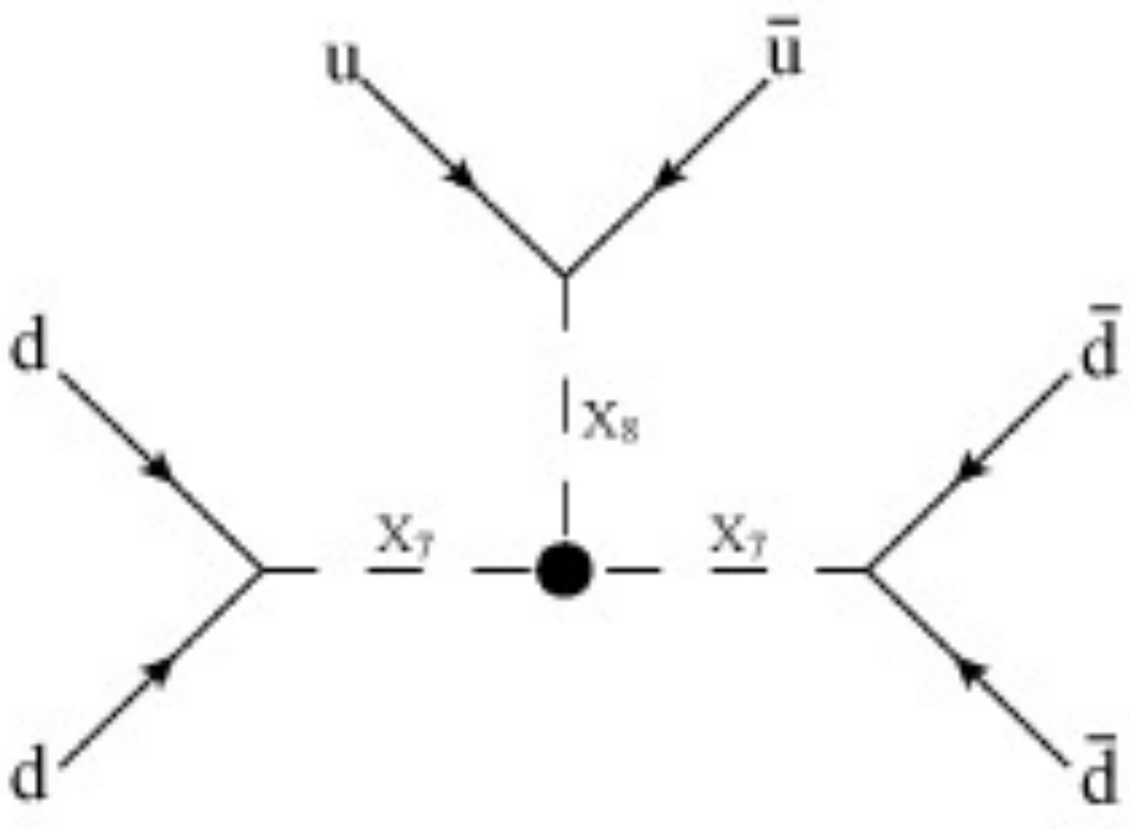
and more!

n-$\bar{n}$ $\pi^-\pi^- \to e^-e^-$

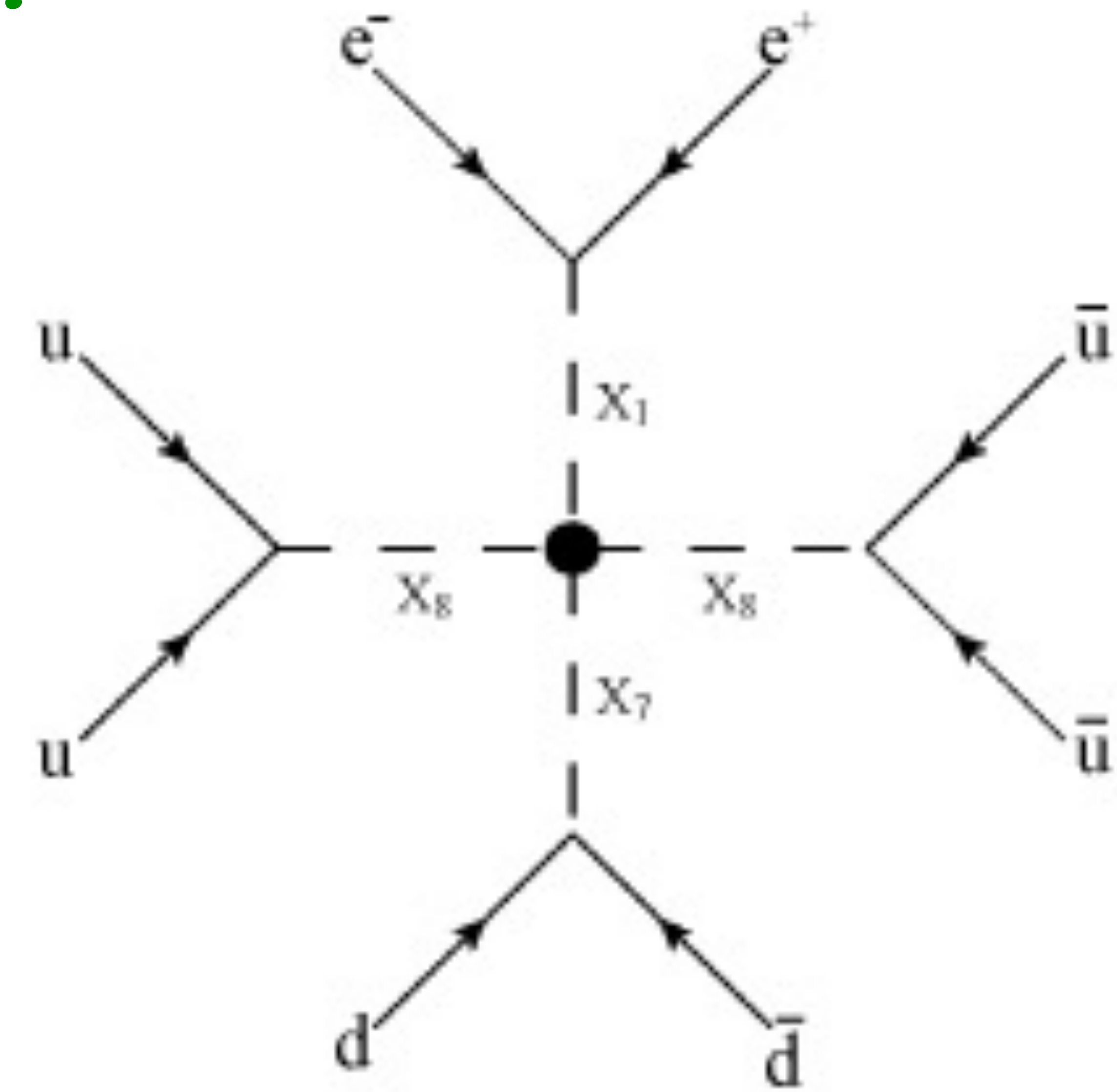
[Models with |ΔL|=2 always involve 3 different scalars.]

Connecting |ΔB|=2 to |ΔL|=2…

An example...



“M3” (a)



“M10” (b)

n-$\bar{n}$

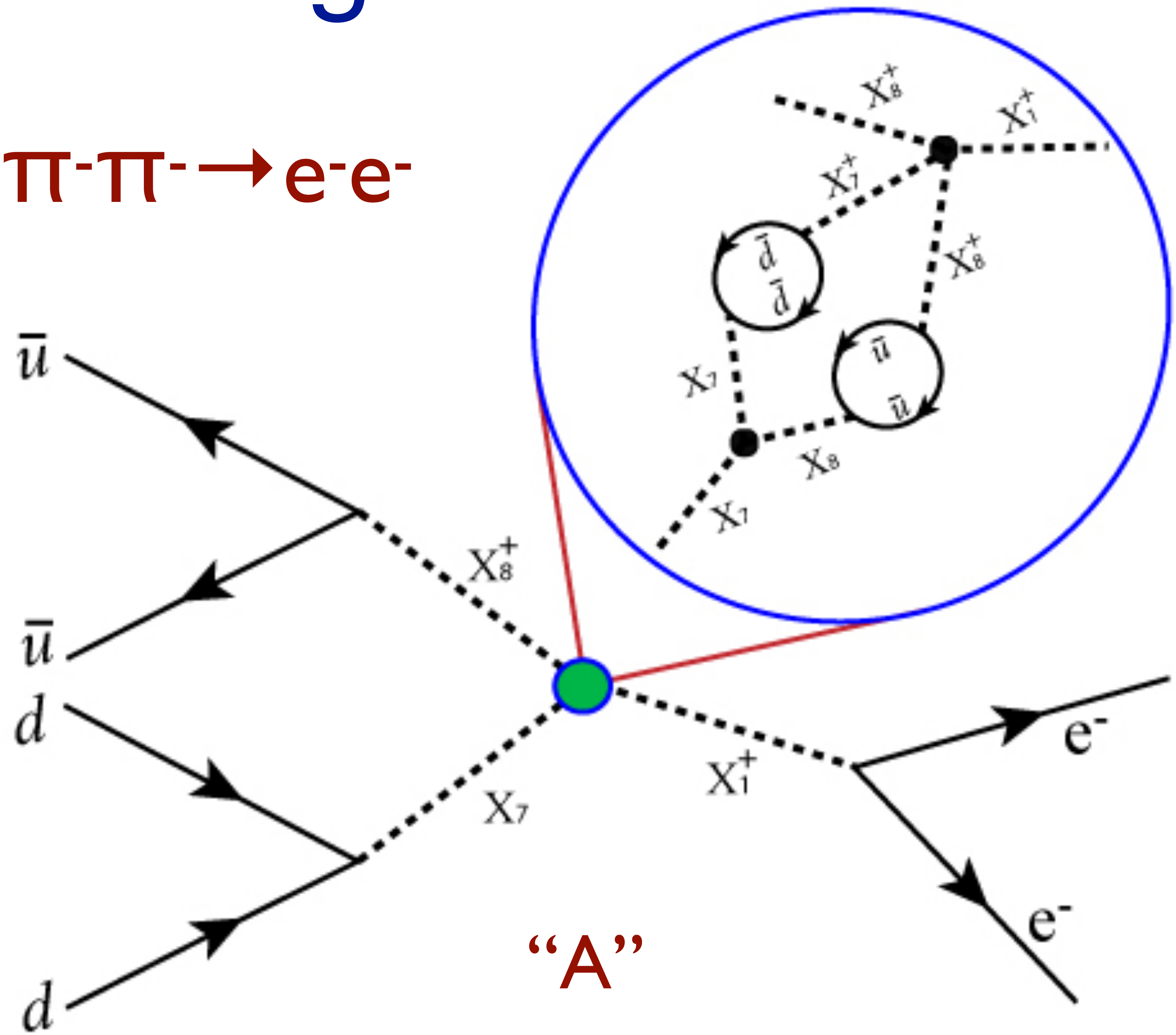
B-L violating

$e^- p \rightarrow e^+ \bar{p}$

B-L conserving

Connecting |ΔB|=2 to |ΔL|=2…

$\pi^- \pi^- \rightarrow e^- e^-$



"Everything not forbidden is compulsory" [M. Gell-Mann, after T.H. White]

Patterns of |ΔB|=2 Violation

Discovery implications for 0ν ββ decay

S.G. & Xinshuai Yan, 2018

Model	$n\bar{n}$?	$e^- n \to e^- \bar{n}$?	$e^- p \to \bar{\nu}_X \bar{n}$?	$e^- p \to e^+ \bar{p}$?	$0\nu\beta\beta$?
M3	Y	N	N	Y	Y [A]
M2	Y	Y	Y	Y	Y [B]
M1	Y	Y	Y	N	? [D]
–	N	N	Y	Y	? [C?]

Patterns of observation can distinguish the possibilities.

First try to see if any "XXXX" processes can be visible!

$n\bar{n}$ limits are severe! $\tau_{n\bar{n}} > 2.7 \times 10^8$ s @ 90 % CL

[SuperK: Abe et al., 2015]

Phenomenology of New Scalars

Constraints from many sources — Focus on first generation

i) n-$\bar{n}$ (But some models do not produce it)

ii) Collider constraints

CMS: $\ell^+\ell^+$ search; cannot look at invariant masses below 8 GeV

[CMS 2012, 2014, 2016]

iii) $(g-2)_e$ [Babu & Macesanu, 2003]

Use latest exp't! [Hanneke, Fogwell, Gabrielse, 2008]

Limit: $M_1/g_1^{11} \geq 80$ GeV

[superseded by Møller expt, save for light masses] [SG & Xinshuai Yan, 2020]

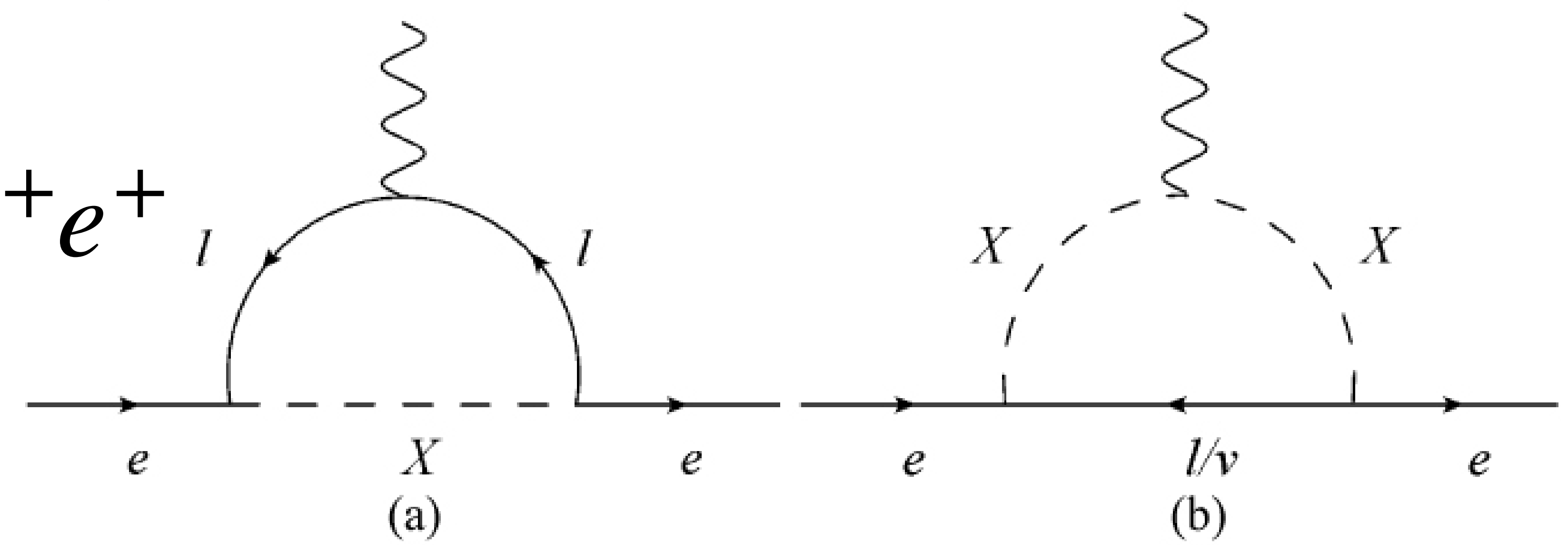
$M_{X_{1,3}}/g_{1,3}^{11} \geq 2.7\,\mathrm{TeV}\,@\,90\,\%\,\mathrm{CL}$ [E158] (if "heavy")

iii) Nuclear stability

SuperK $^{16}\mathrm{O}:\ pp \to e^+e^+$

[Bramante, Kumar, & Learned, 2015]

But note short-distance repulsion!



iv) H$\overline{\mathrm{H}}$ annihilation

[Grossman, Ng, & Ray, 2018]

But beware galactic magnetic fields!

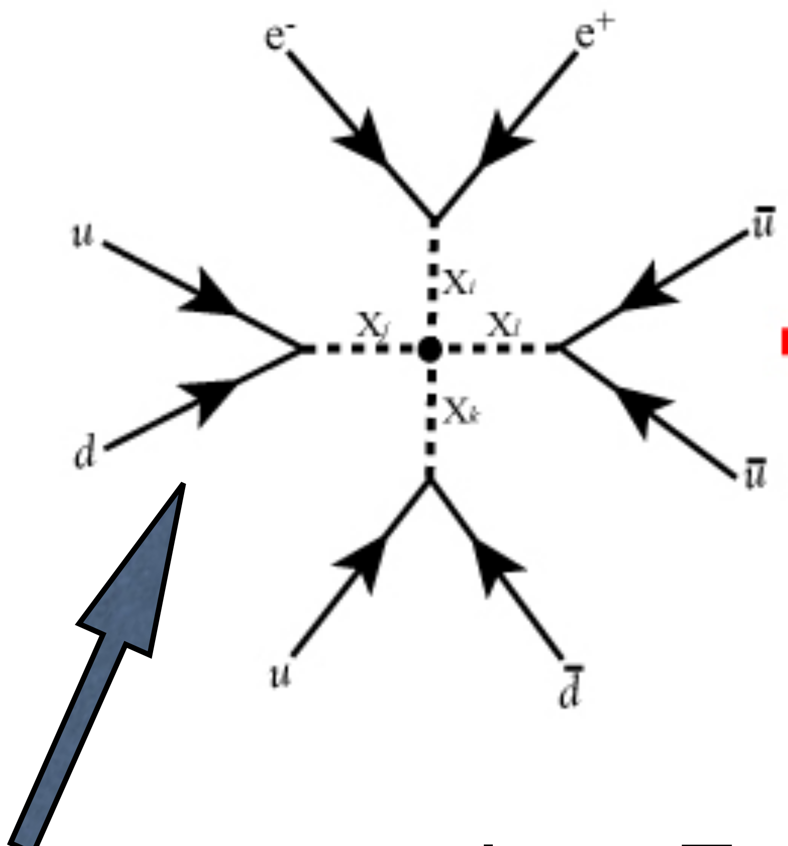
Few GeV mass window possible

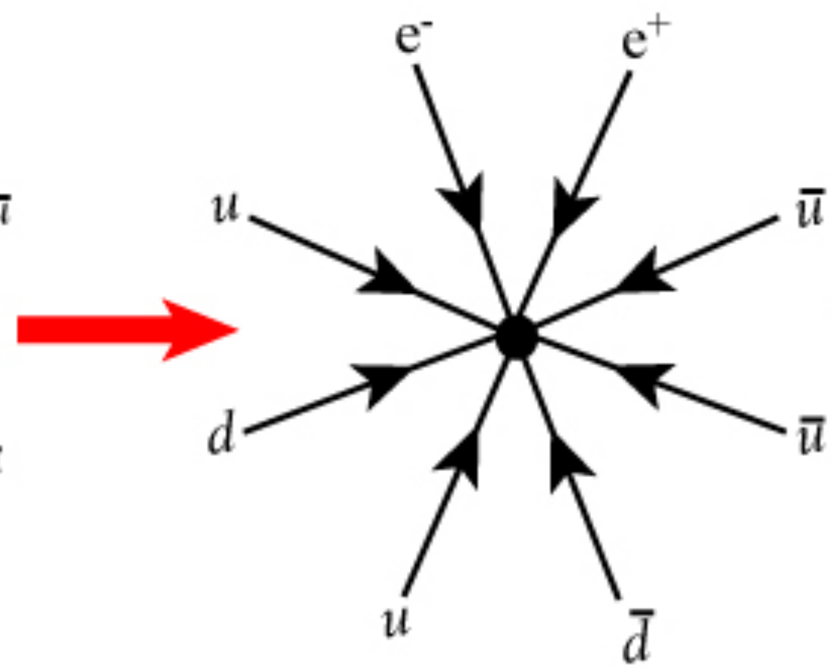
Rate Estimates

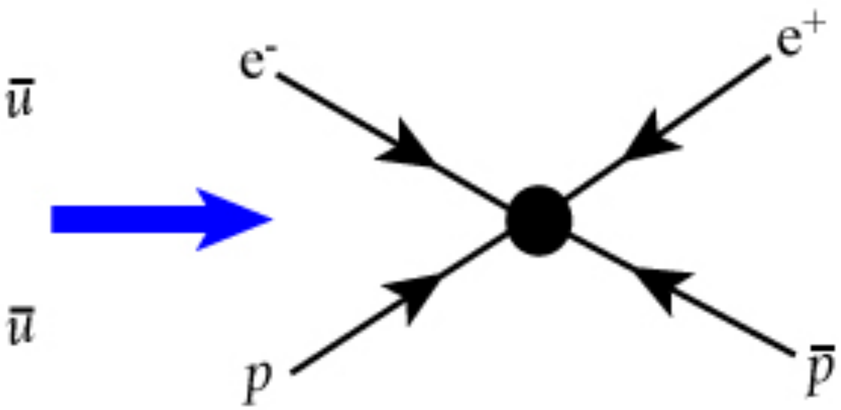
For $e^- p \to e^+ \bar{p}$ at a low energy electron accelerator

as the electron energy decreases…

Assume $M_{X_i}^2 \gg Q^2$







e.g.

low-E σ depends on
$g_i^2 / M_{X_i}^2$

Match to hadron
effective theory
at tree level; compute
matrix elements in
MIT bag model

Low-Energy Electron Facilities

Note illustrative parameter choices

[Hydrogen]

Facility	Beam		Target		Luminosity (cm^{-2})
	Energy(MeV)	Current (mA)	Length (cm)	Density (g/cm^3)	
💡 CBETA [14]	150	40	60	0.55×10^{-6}	2.48×10^{36}
💫 MESA [15]	100	10	60	0.55×10^{-6}	6.21×10^{35}
💥 ARIEL [16]	50	10	100	0.09×10^{-3}	1.69×10^{38}
			* 0.2	71.3×10^{-3}	2.68×10^{38}
🎉 FAST [17]	150	28.8	100	0.09×10^{-3}	4.88×10^{38}
			* 0.1	71.3×10^{-3}	3.87×10^{38}

*Liquid

- 💡 = proposed, ERL (internal target)
- 💫 = ERL (e.g.)
- 💥 = Linac (external target)
- 🎉 = Linac, ILC test accelerator

Use E=40 MeV for estimates.

Event Rates

Select particular scalar masses/couplings for reference

$\lambda_i=1$ $M_{Xi}/g_i^{1/2}=30$ GeV for i=1,2,3 else 1GeV

Rates in #/yr

$e^- p \to e^+ p$:

Facility	M7	M10	M11	M12	M14	M15	M16
CBETA [18]	1.12	0.18	0.01	0.00	0	2.24	0.45
MESA [19]	0.28	0.05	0.00	0.00	0	0.56	0.11
ARIEL [20]	76.41	12.59	0.41	0.20	0	152.69	30.68
	121.06	19.95	0.65	0.31	0	241.93	48.62
FAST [21]	220.05	36.27	1.18	0.56	0	439.75	88.37
	174.33	28.73	0.93	0.45	0	348.38	70.00

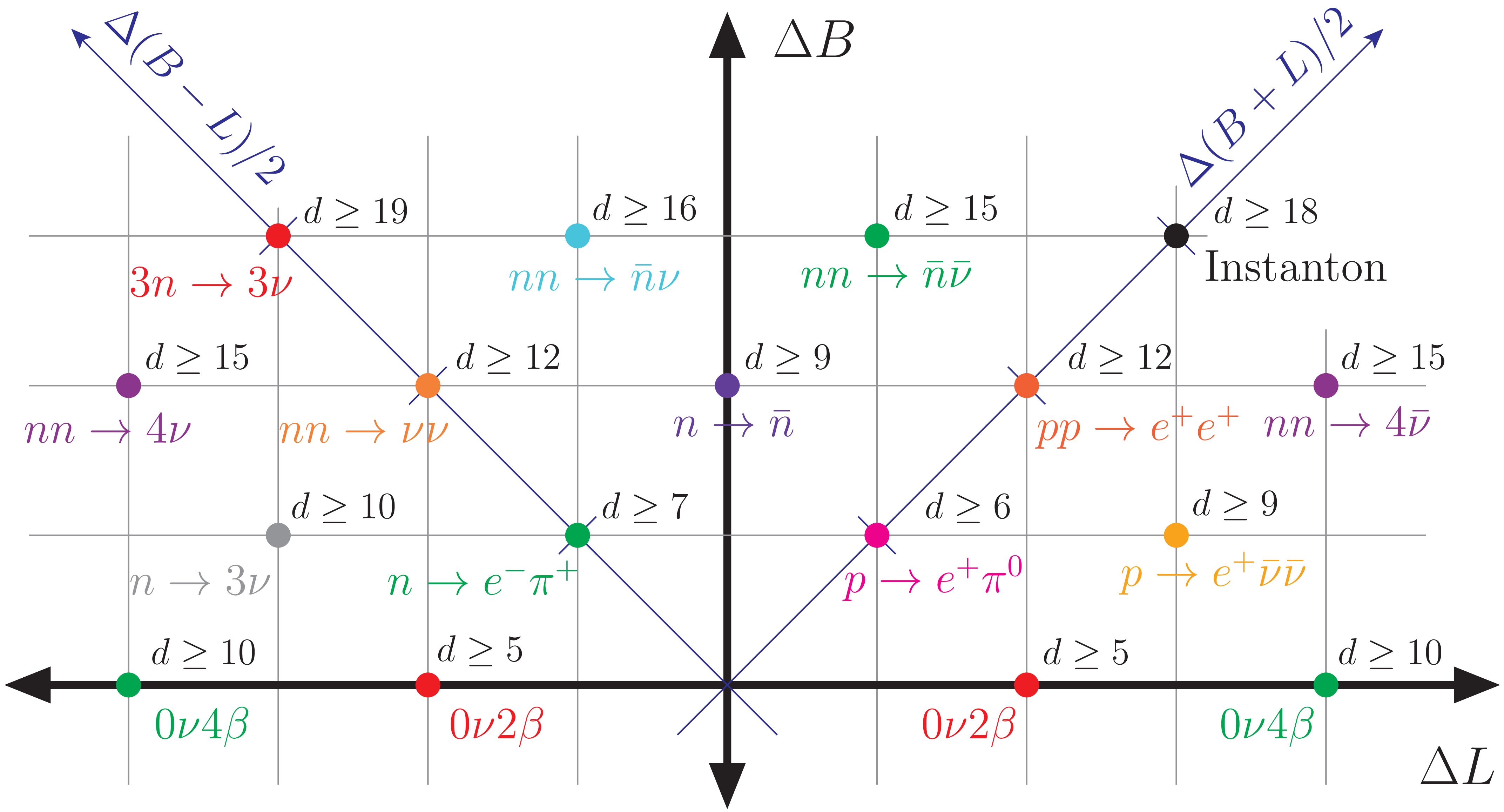
$e^- p \to \overline{\nu}_e \overline{n}$

Facility	M5	M6	M7	M11	M13	M14	M16
CBETA [18]	0.00	0	0.08	0.00	0.14	0	0.02
MESA [19]	0.00	0	0.02	0.00	0.03	0	0.01
ARIEL [20]	0.03	0	5.17	0.24	9.45	0	1.59
	0.04	0	8.19	0.38	14.97	0	2.51
FAST [21]	0.08	0	14.88	0.70	27.20	0	4.57
	0.06	0	11.79	0.55	21.55	0	3.62

[S.G. & Xinshuai Yan, **in preparation**]

Still Broader Possibilities

Different channels connected by vector addition



[Heeck & Takhistov, 2020]

Summary

—New, possible avenues for B (& L) NV (by 2 units & more) have been largely overlooked

—These studies may provide new insights into the nature of the neutrino mass

—Light hidden sectors that could help mediate mass rare processes associated with dim ≥ 9 operators are not excluded by existing experiments

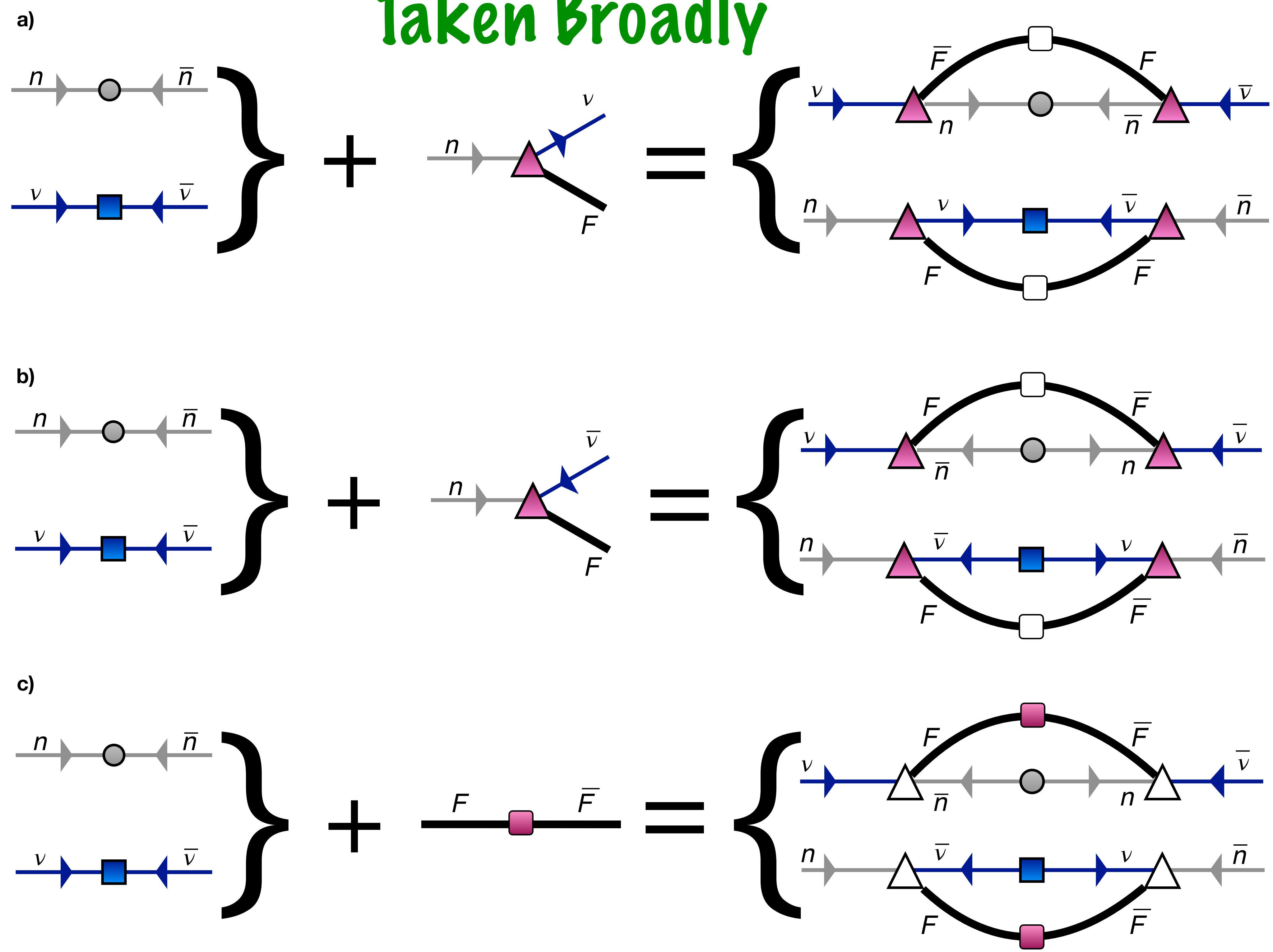
— We have noted the existing constraints & the discovery potential of some possible new experiments

—These possibilities could be explored at intense, low E electron accelerator facilities & strengthen interest in $|\Delta B| = 2$ experiments of increased sensitivity!

Backup Slides

Connecting Majorana Masses

Taken Broadly



[Berryman, SG, & Zakeri, 2022]

Patterns of |ΔB|=2 Violation?

Note possible BNV processes

[SG & Xinshuai Yan, 2019]

$n\bar{n}$	$\pi^-\pi^- \to e^-e^-$	$e^-p \to \bar{\nu}_{\mu,\tau}\bar{n}$	$e^-p \to \bar{\nu}_e\bar{n}/e^+\bar{p}$	$e^-p \to e^+\bar{p}$
M1	A	M5	M7	M10
M2	$B^{(*)}$	M6	M11	M12
M3	$C^{(*)}$	M13	M14	M15
			M16	

Also support $nn \to \bar{\nu}\bar{\nu}$

Dark Aftermaths?

Particular models are excluded

➡ as explanations of the **entire** anomaly

Direct search: $n \to \chi\gamma$ [Tang et al., PRL, 2018]

$n \to \chi e^+ e^-$ [Sun et al., 2018; Klopf et al., PRL, 2019]

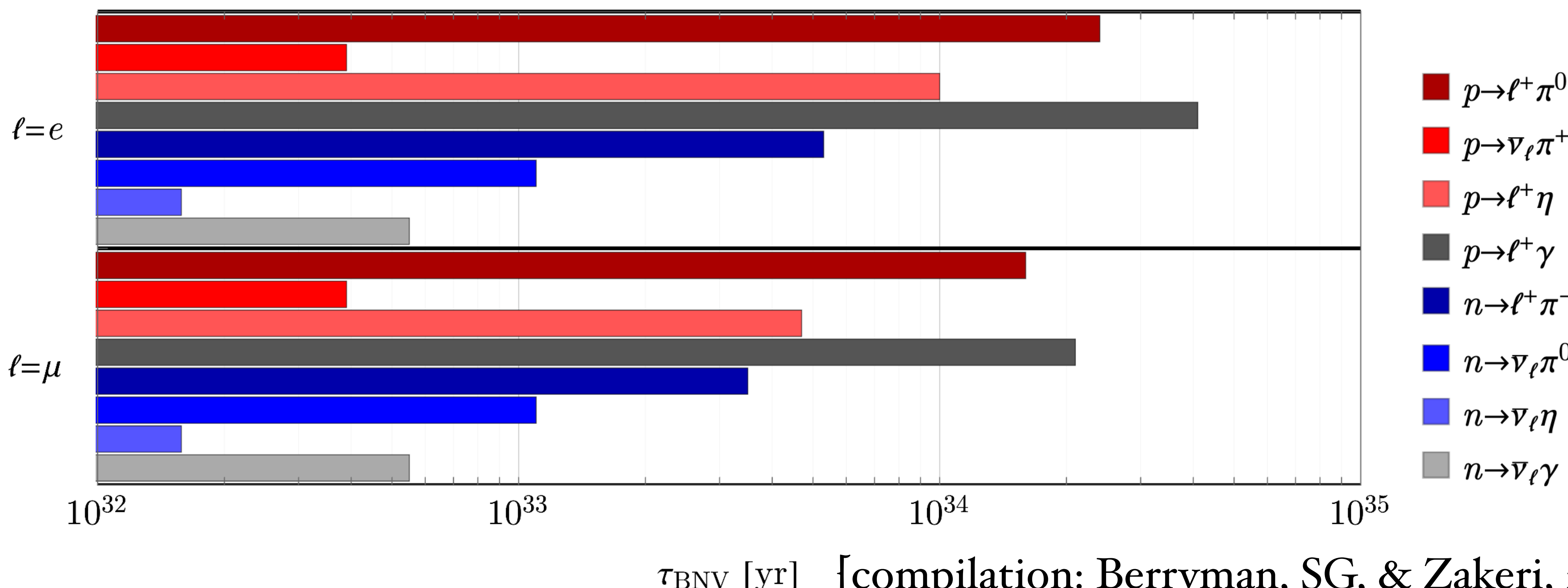
These models (to explain the entire anomaly) also run afoul of the existence of 2 $M_\odot$ neutron stars (unless χ is self-interacting or heavy)

[McKeen et al., 2018; Baym et al., 2018, Motta et al., 2018]

Using measured n decay "A" (PERKEO III, UCNA) & the SM & UCNτ also leaves little room for dark decay $\mathrm{Br}_\chi < 0.28\,\%$ (95 % CL) [Dubbers et al., 2019]

Limits on Nucleon ($|\Delta B| = 1$) Partial Lifetimes

90% C.L. upper limits



[compilation: Berryman, SG, & Zakeri, 2022]

Neutron-Antineutron Conversion

Different mechanisms are possible

- * $n\text{-}\bar{n}$ conversion and oscillation could share the same "TeV" scale BSM sources

  → Then the quark-level conversion operators can be derived noting the quarks carry electric charge

- * $n\text{-}\bar{n}$ conversion and oscillation could come from different BSM sources

  → Indeed different $|\Delta B|=2$ processes could appear (e.g., $e^- p \rightarrow e^+ \bar{p}$)

$N\bar{N}$ conversion

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{2}\mu_n \bar{n}\sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.}$$

$[\; Qej^\nu = \partial_\mu F^{\mu\nu} \;]$

magnetic moment

"spontaneous" → $n \to \bar{n}$ oscillation

$n \to \bar{n}$ conversion

[SG & Xinshuai Yan, arXiv: 1710.09292]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion