Spin Probes of Physics Beyond the Standard Model

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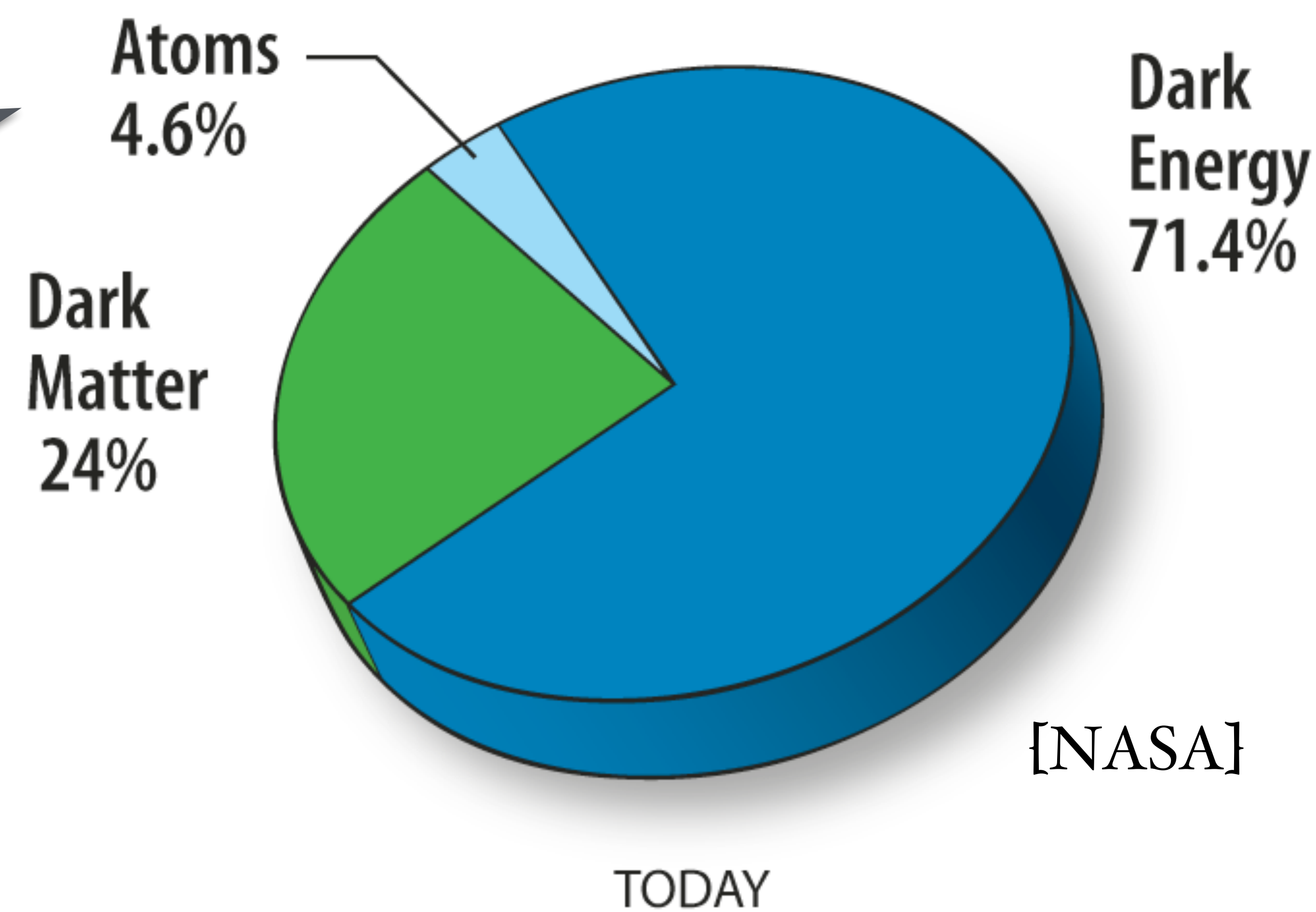
Two Numbers

Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)

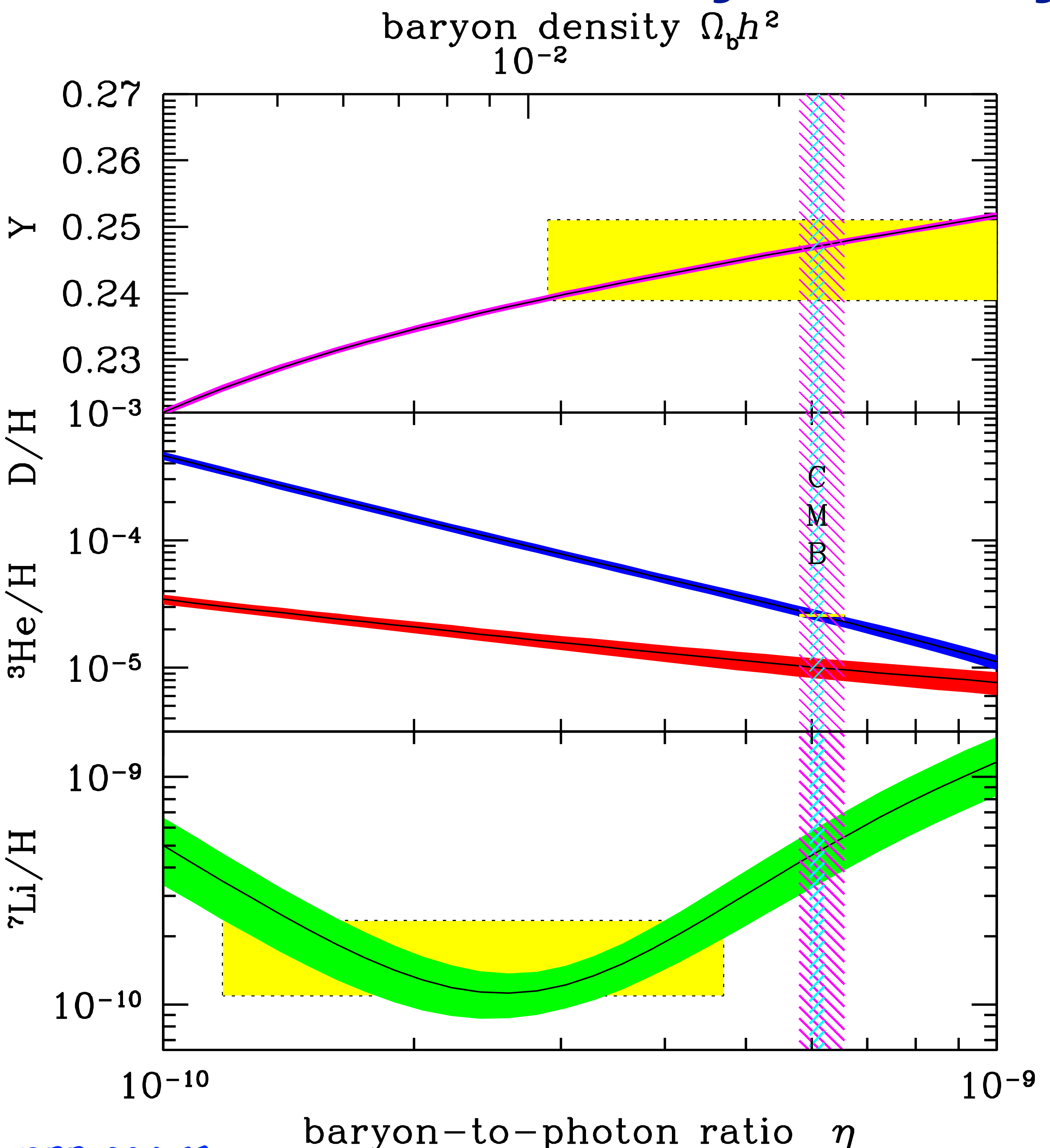


And the cosmic baryon asymmetry

$$\eta = n_{\mathrm{baryon}}/n_{\mathrm{photon}} = (5.96 \pm 0.28) \times 10^{-10}$$

so large? (And how does the neutrino get its mass?)

A Cosmic Baryon Asymmetry



BAU from BBN & observed D/H & ^{4}He/H concordance

BAU from CMB is more precise

[Both @ 95% CL]

[PDG, RPP, 2017]

A Cosmic Baryon Asymmetry

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$

By initial condition?

We interpret the CMB in terms of an inflationary model, so that this seems unlikely. [Krnjaic, PRD 96 (2017)]

From particle physics?

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

Non-equilibrium dynamics are required to avoid "washout" of an asymmetry by back reactions

The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is “special”

Note BAU estimates even with a **light** Higgs are much too small

[Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.] $\eta < 10^{-26}$

Non-equilibrium dynamics? No. (!)

The discovered Higgs particle is of 125 GeV in mass; for this mass lattice simulations reveal there is **no** electroweak phase transition. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

Recipes for a Baryon Asymmetry?

New ν physics might operate!

Perspective

Our dark-dominated universe and its baryon asymmetry speaks to possible **hidden (or visible?!)** particles, interactions, symmetries and more that we may yet discover

Such new physics could arise at either

i) **high energies** with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary

– or –

ii) **low energies** with **very weak** couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!

Symmetry Tests with Spin

"Windows" on New Physics

Some examples…

- Searches for new sources of CP violation: *permanent electric dipole moments (EDMs); time-dependent "EDMs" to probe ultralight (axion-like) dark matter*

Note plenary: F. Rathmann

- Precision measurements of magnetic moments (esp. μ g-2) **and** of $\sin^2\theta_W$ (PVES)

Note plenary: D. Hertzog and G. Smith

- Searches for baryon number violation: *esp. quark probes of Majorana dynamics*

- Searches for BSM physics in beta-decay

Effective Field Theory & New Physics

Enter a "Model Independent" Analysis Framework

Suppose new physics enters at an energy scale E > Λ

Then for E < Λ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \, ,$$

Symmetries guide their construction [Weinberg, 1979]

Here assume SM electroweak symmetry [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

New physics can enter as (i) new operators or as (ii) modifications of c_i for operators in the SM

cf. non-V-A tests with tests of CKM unitarity

Can also break SM symmetries & have new operators only

But what if we introduce new degrees of freedom?

New High or Low Energy Physics?

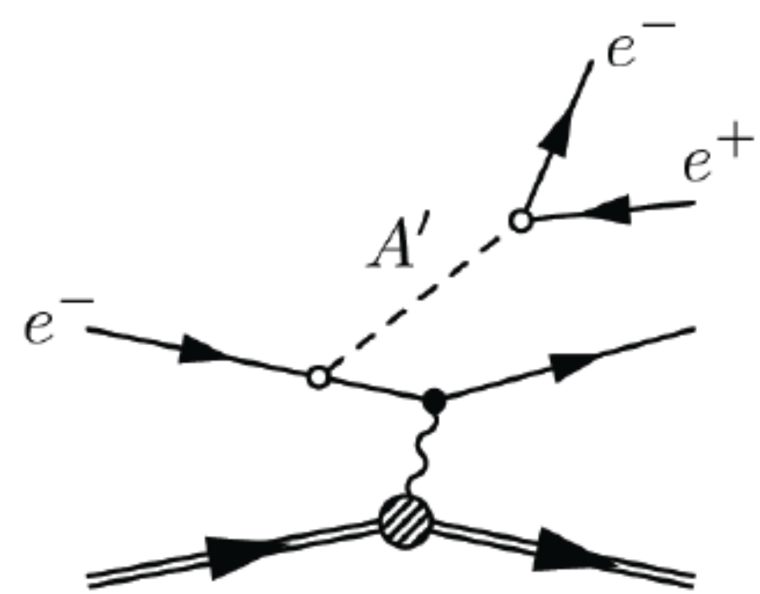
With new low energy degrees of freedom (dof) new dimension 4 operators appear....

Including SM dof act as "portals" to a hidden sector

$$\mathcal{L}_{\mathrm{dim}\leq 4} = \frac{\kappa}{2} V^{\mu\nu} F'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N$$

[Batell, Pospelov, and Ritz, 2009; Bjorken, Essig, Schuster, Toro, 2009]

- Vector Portal
- Higgs Portal
- Neutrino Portal



Hunting Hidden Forces....

Much focus on the dark photon A′ & the **vector portal**…
note impact on μ g-2 (only simple A′ excluded) [Pospelov, 2009]

Gauge Theories of the Hidden Sector

Dark gauge bosons can also couple directly to fermions

Consider the dark photon...

$$\mathcal{L}_{A'} = \frac{\varepsilon}{2} F^{Y\,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Diagonalization and field definition yields

$$A^{\mu} \longrightarrow A^{\mu} - \varepsilon A'^{\mu} \text{ but } Z - A' \text{ mixing } \mathcal{O}(\varepsilon m^2_{A'}/M^2_Z)$$

[Bjorken, Essig, Schuster, and Toro, 2009...]

Thus the A' couples to SM fermions.

Now w/ an extended Higgs sector…

$$\mathcal{L}_{\mathrm{darkZ}} = -(\varepsilon e J^{\mu}_{\mathrm{em}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\mathrm{NC}}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

BSM Sessions at SPIN 18

Note, too, talks in other sessions

- Searches for new sources of CP violation [Franke, Dietrich, Fierlinger, Franke, Gupta, Kirch, Ruiz Vidal, Yamanaka, Zimmer; Paradisi; Stadnik; Kononov, Nass, Nikolaev]
- Searches for novel spin-dependent interactions [Heil, Rong]
- Measurements of PVES [Gal, Baunack]

Here

- Searches for new S,T degrees of freedom & … in beta-decay
- Searches for baryon number violation: esp. quark probes of Majorana dynamics

Operator Analysis of EDMs

Connecting from high to low scales

A single TeV scale CPV source may give rise to multiple GeV scale sources

Explicit studies of operator mixing & running effects are now available

[Chien et al., arXiv:1510.00725, JHEP 2016; Cirigliano, Dekens, de Vries, Merenghetti, 2016 & 2016]

Lattice QCD studies of single-nucleon matrix elements also exist
Enter isoscalar & isovector tensor charges...

[Bhattacharya et al., 2015 & 2016; Gupta et al., arXiv:1801.03130]

Determining the parameters of the low energy effective Lagrangian experimentally is a distinct problem

Can all the low-energy CPV sources be determined?

★ Need to interpret EDM limits in complex systems: atoms, molecules, and nuclei

Some Thoughts on the Strong CP Problem

The SM has other "fine-tuning" problems

The following term can appear within QCD

$$\mathcal{L}_\theta = \frac{g^2}{32\pi^2}\theta_{\rm QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

as can a similar term from the quark masses, so that

$$\theta_{\rm QCD} \Longrightarrow \bar{\theta} = \theta_{\rm QCD} + \theta_{\rm Yukawa}$$

Neither term needs to be small but
the experimental limit on the n EDM implies

$$\bar{\theta} \ll 10^{-10}$$

Why is "δ" ~ 1?!

Many discussed resolutions… note Peccei-Quinn…

Direct Detection: Ultralight Dark Matter

A new paradigm: axion-like dark matter

The axion originally appears as a solution to the strong CP violation (in QCD) and emerges from spontaneously broken Peccei-Quinn symmetry

[Weinberg 1977, Wilczek 1977]

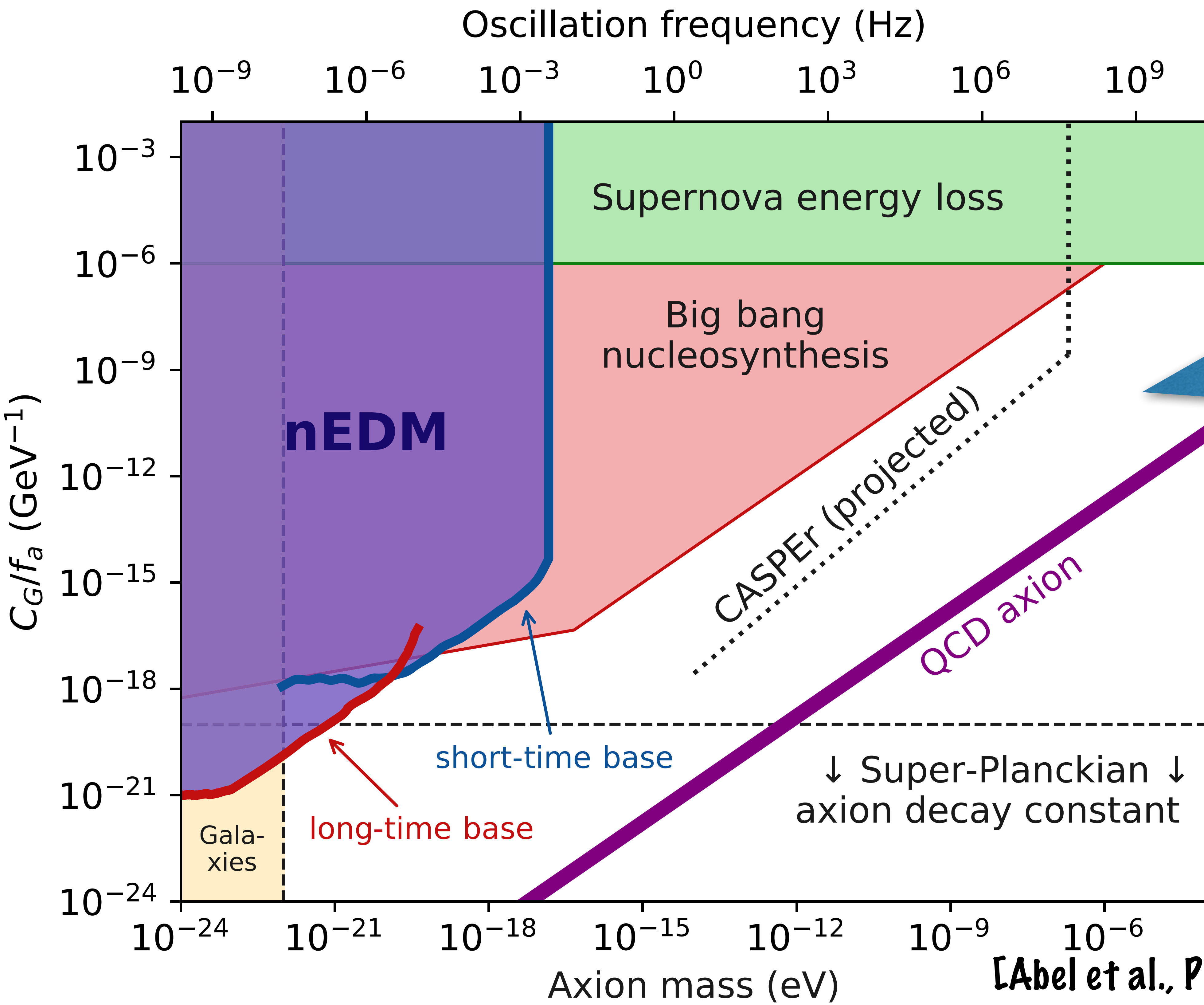
Can consider an axion-like particle which is not tied to that origin

An ultralight axion can induce time-varying T, P odd interactions!

(Axions possess a vast parameter space….)

Note Stadnik talk

Direct Detection: Ultralight Dark Matter



Storage ring EDMs: Rathmann, plenary, this AM! (see ref)

[Abel et al., PRX, 2017]

Theoretical Framework for β Decay

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\text{SM}} + \frac{1}{v^2}\sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i{}^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

Radiative correction*!

$$\begin{aligned}
\mathcal{L}^{\text{eff}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \left(1+\delta_\beta\right) \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_L \, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L \, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_R \, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R \, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ \quad & \epsilon_S \, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \tilde{\epsilon}_S \, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- \quad & \epsilon_P \, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d - \tilde{\epsilon}_P \, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ \quad & \epsilon_T \, \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T \, \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
+ \quad & \text{h.c.} \,.
\end{aligned}$$

[Note Gorchtein talk]

*[Sirlin, 1974, 1978, 1982; Marciano & Sirlin, 1986, 2006; Czarnecki, Marciano, & Sirlin, 2004]

Note right-handed neutrinos appear explicitly

QCD (hadron matrix elements) play a key role!

Theoretical Framework

n,p!

Connecting to Lee and Yang....

$$\mathcal{H}_{int} = (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu - C'_S \bar{\psi}_e \gamma_5 \psi_\nu) + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu - C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu)$$
$$-(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu - C'_A \bar{\psi}_e \gamma^\mu \psi_\nu) + (\bar{\psi}_p \gamma_5 \gamma_\mu \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu - C'_P \bar{\psi}_e \psi_\nu)$$
$$+\frac{1}{2}(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma^{\lambda\mu} \psi_\nu - C'_T \bar{\psi}_e \sigma^{\lambda\mu} \gamma_5 \psi_\nu) + h.c.$$

The terms appear in a one-to-one map....

$$\begin{aligned}
C_i &= \frac{G_F^{(0)}}{\sqrt{2}} V_{ud} \bar{C}_i \\
\bar{C}_V &= g_V \left(1 + \delta_\beta + \epsilon_L + \epsilon_R + \tilde{\epsilon}_L + \tilde{\epsilon}_R\right) \\
\bar{C}'_V &= g_V \left(1 + \delta_\beta + \epsilon_L + \epsilon_R - \tilde{\epsilon}_L - \tilde{\epsilon}_R\right) \\
\bar{C}_A &= -g_A \left(1 + \delta_\beta + \epsilon_L - \epsilon_R - \tilde{\epsilon}_L + \tilde{\epsilon}_R\right) \\
\bar{C}'_A &= -g_A \left(1 + \delta_\beta + \epsilon_L - \epsilon_R + \tilde{\epsilon}_L - \tilde{\epsilon}_R\right) \\
\bar{C}_S &= g_S \left(\epsilon_S + \tilde{\epsilon}_S\right) \\
\bar{C}'_S &= g_S \left(\epsilon_S - \tilde{\epsilon}_S\right) \\
\bar{C}_P &= g_P \left(\epsilon_P - \tilde{\epsilon}_P\right) \\
\bar{C}'_P &= g_P \left(\epsilon_P + \tilde{\epsilon}_P\right) \\
\bar{C}_T &= 4\, g_T \left(\epsilon_T + \tilde{\epsilon}_T\right) \\
\bar{C}'_T &= 4\, g_T \left(\epsilon_T - \tilde{\epsilon}_T\right) \ .
\end{aligned}$$

The "QCD parts" are now clearly identified; note, e.g., in n decay

$$\langle p(p_p) |\, \bar{u}\, d \,| n(p_n) \rangle \;=\; g_S(q^2)\ \bar{u}_p(p_p)\, u_n(p_n)$$

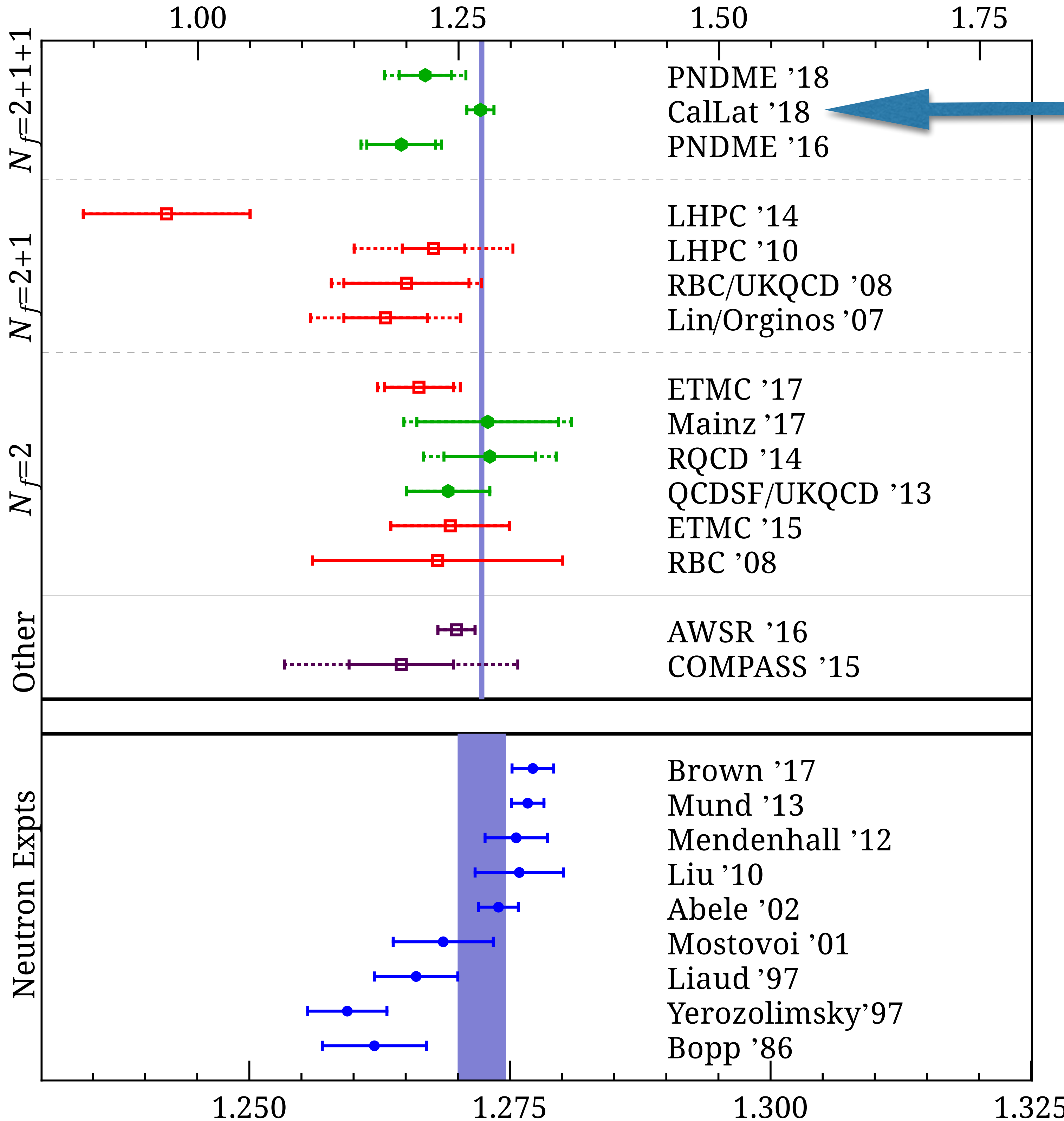
★ **Enter lattice QCD....**

[Bhattacharya et al., 2012]

Summary Snapshot

Nucleon axial isovector charge

g_A [Gupta et al. [PNDME '18], 1806.09006]



!!

[Chang et al. [CalLat], Nature 558, 91 (2018), 1805.12130]

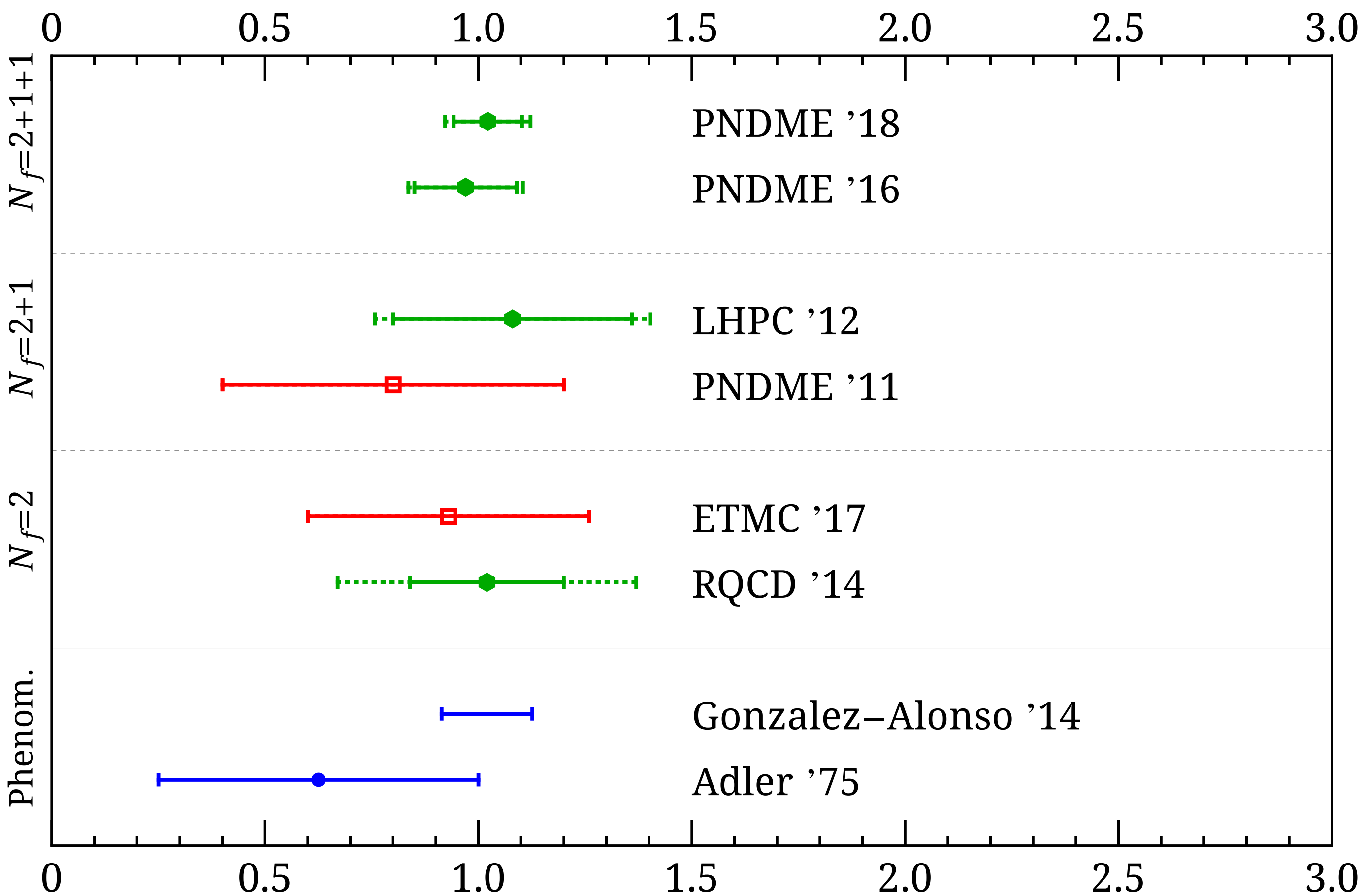
Recent g_A result of 1% precision in agreement w/ expt!

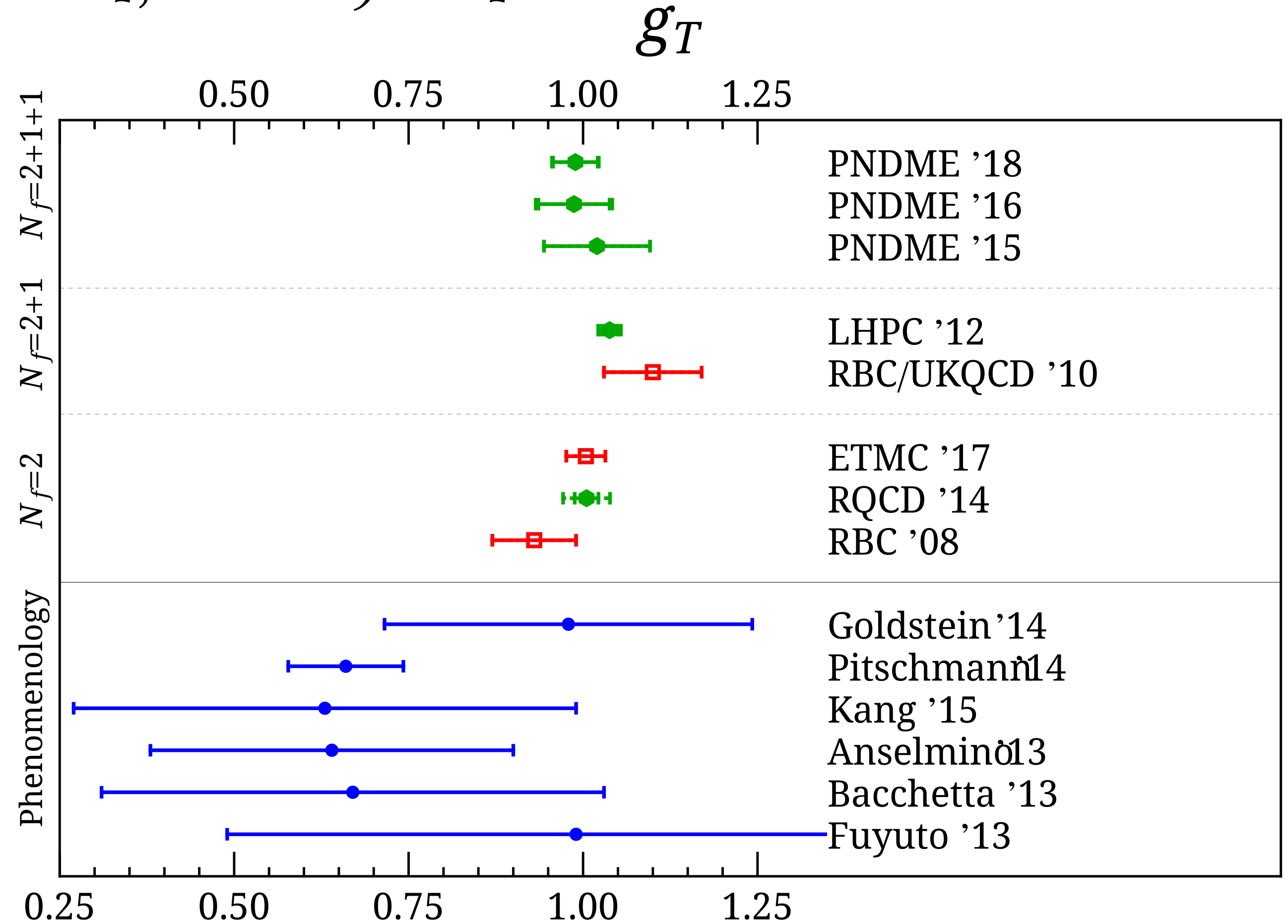
"Deep dive" by PNDME '18 reveals no serious disagreements

Summary Snapshots

Nucleon scalar and tensor isovector charges

[Gupta et al. [PNDME], 1806.09006]





Act to sharpen constraints on non-V-A currents from decay correlation measurements (esp. b)

Phenom Forecasts (g_T; SoLID) have much higher precision

[Ye et al. , PLB 2017 arXiv: 1609.02449]

Decay Correlations

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \frac{\vec{J}}{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e\,E_\nu} \right] + \dots \right\}$$

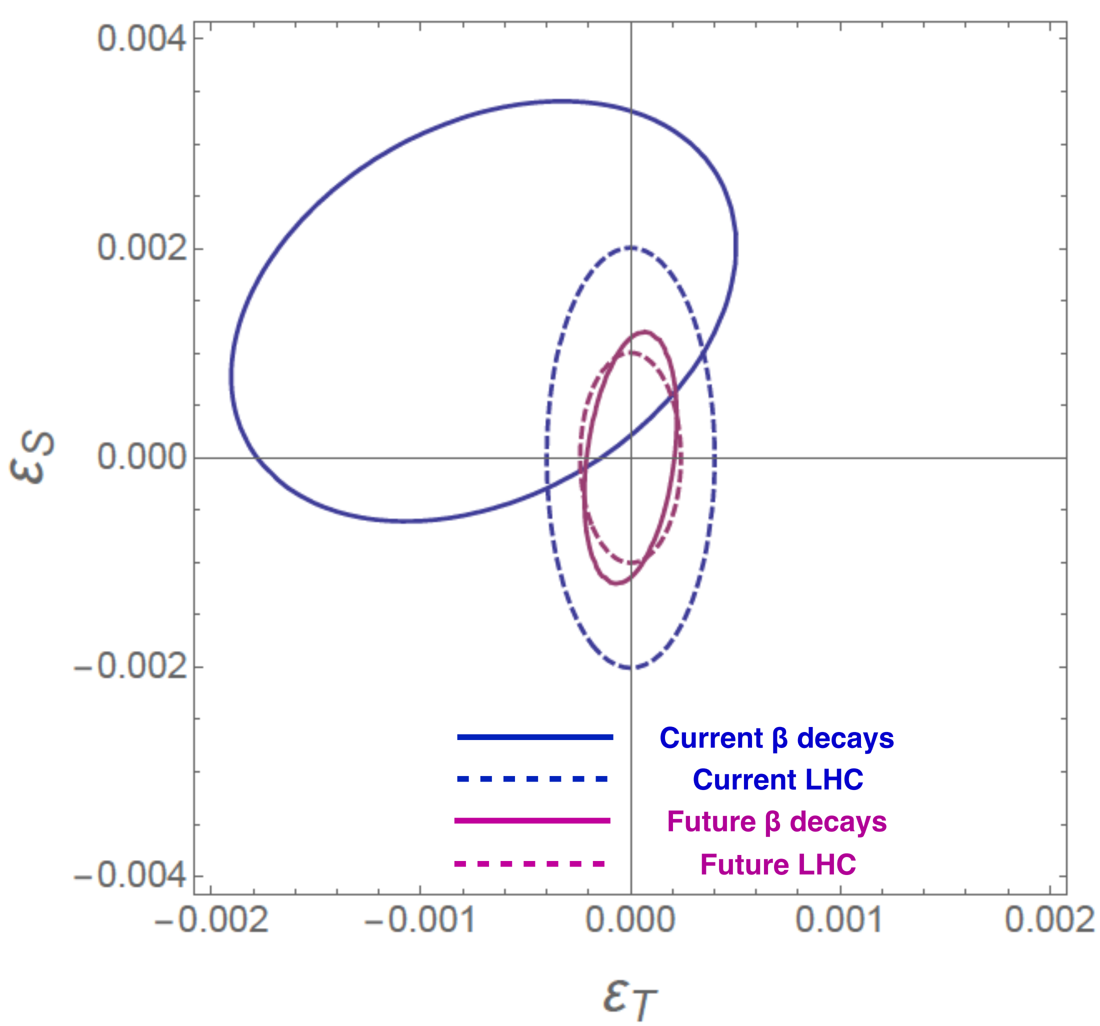
[Jackson, Treiman, Wyld, 1957]

If $J \neq 1/2$

$$b = \frac{2\gamma}{1+3\lambda^2} \left[g_S\,\mathrm{Re}(\epsilon_S) - 12\lambda\, g_T\,\mathrm{Re}(\epsilon_T) \right] ,$$

$$b_\nu = \frac{-2\gamma}{1+3\lambda^2} \left[g_S\,\mathrm{Re}(\epsilon_S)\,\lambda - 4 g_T\,\mathrm{Re}(\epsilon_T)\,(1-2\lambda) \right]$$

$$B(E_e) = B_0 + b_\nu m_e / E_e$$

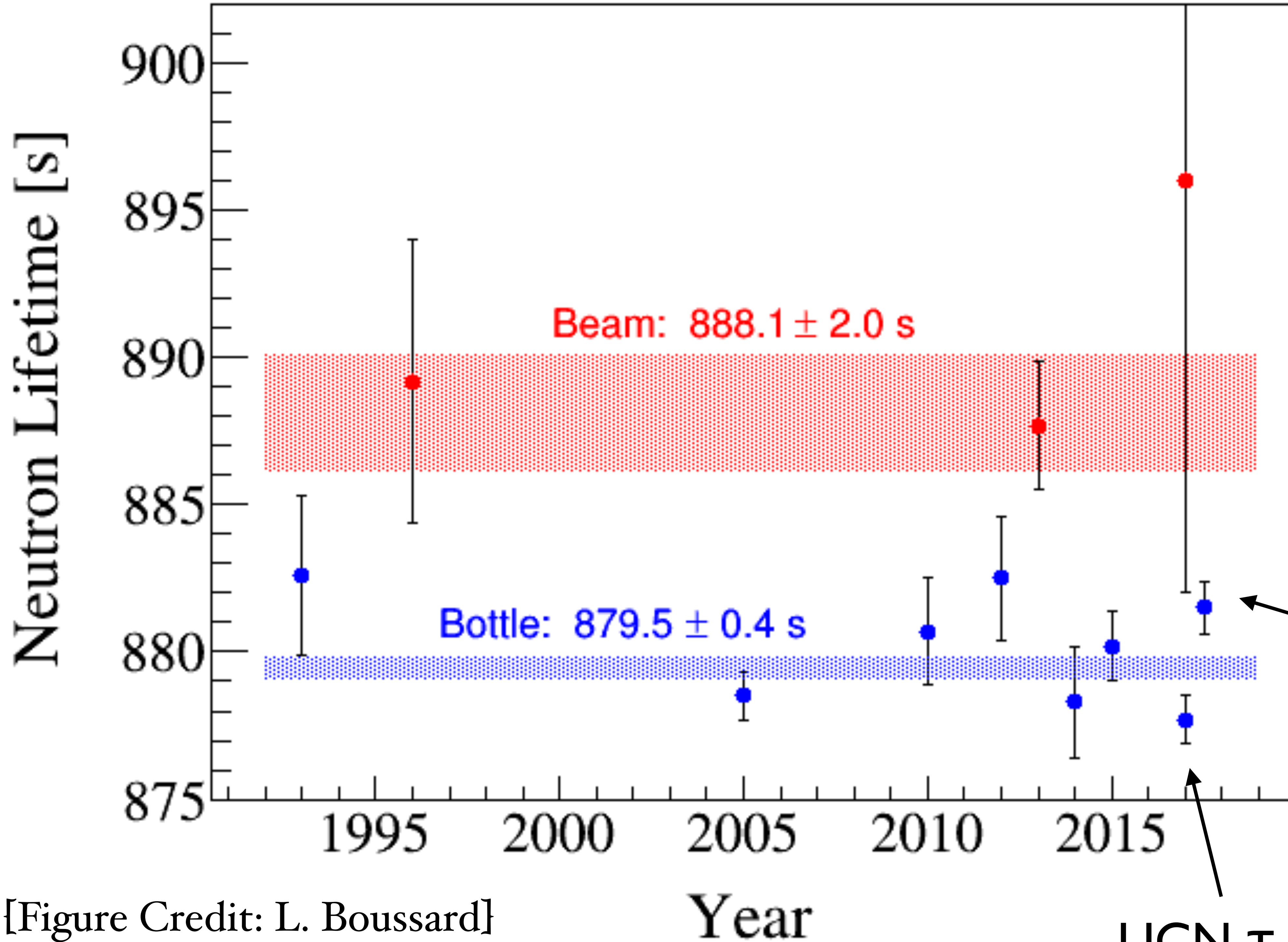


Comparison assumes Λ_{BSM} > 13 TeV

[Gupta et al. [PNDME], 1806.09006; current β decay from Gonzalez-Alonso et al, 1803.08752]

Analysis & forecast neglect second class currents [SG & Plaster, 2013]

The Neutron Lifetime Puzzle



(8.6 s, 4σ)

Count **protons** that appear

Serebrov

Count **neutrons** that persist

UCN τ_n

[Figure Credit: L. Boussard]

What if neutrons also decay invisibly?

[Recall early suggestion: Z. Berezhiani & "mirror neutrons"]

Possible Dark Decays

Modeled to solve the n lifetime puzzle

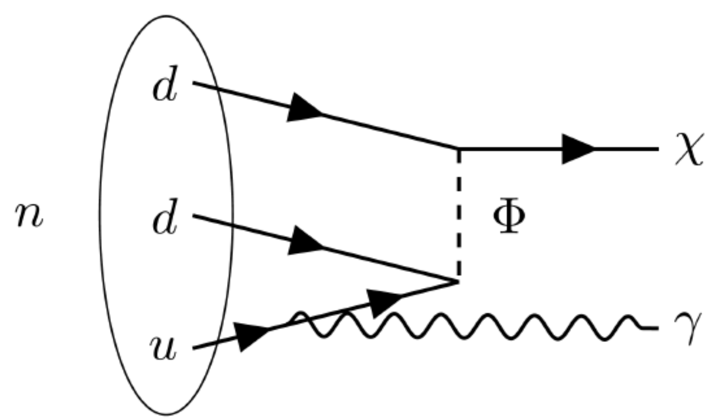
[Fornal & Grinstein, PRL, 2018]

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

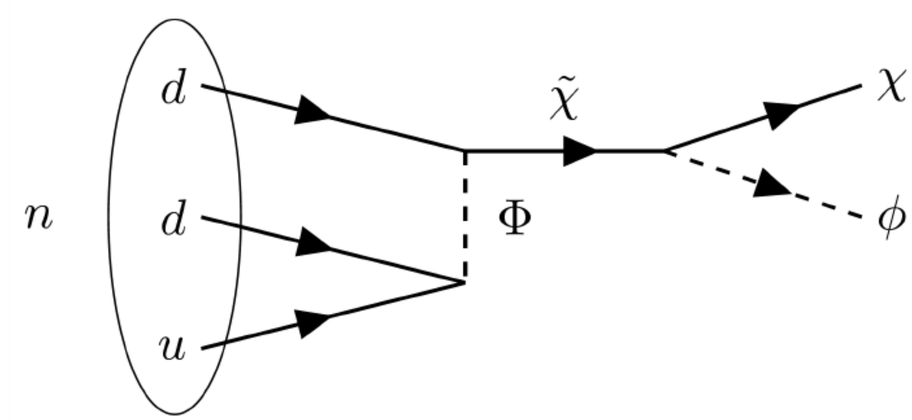
~99%

★Visible

$$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\not{\partial} - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}(i\not{\partial} - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$



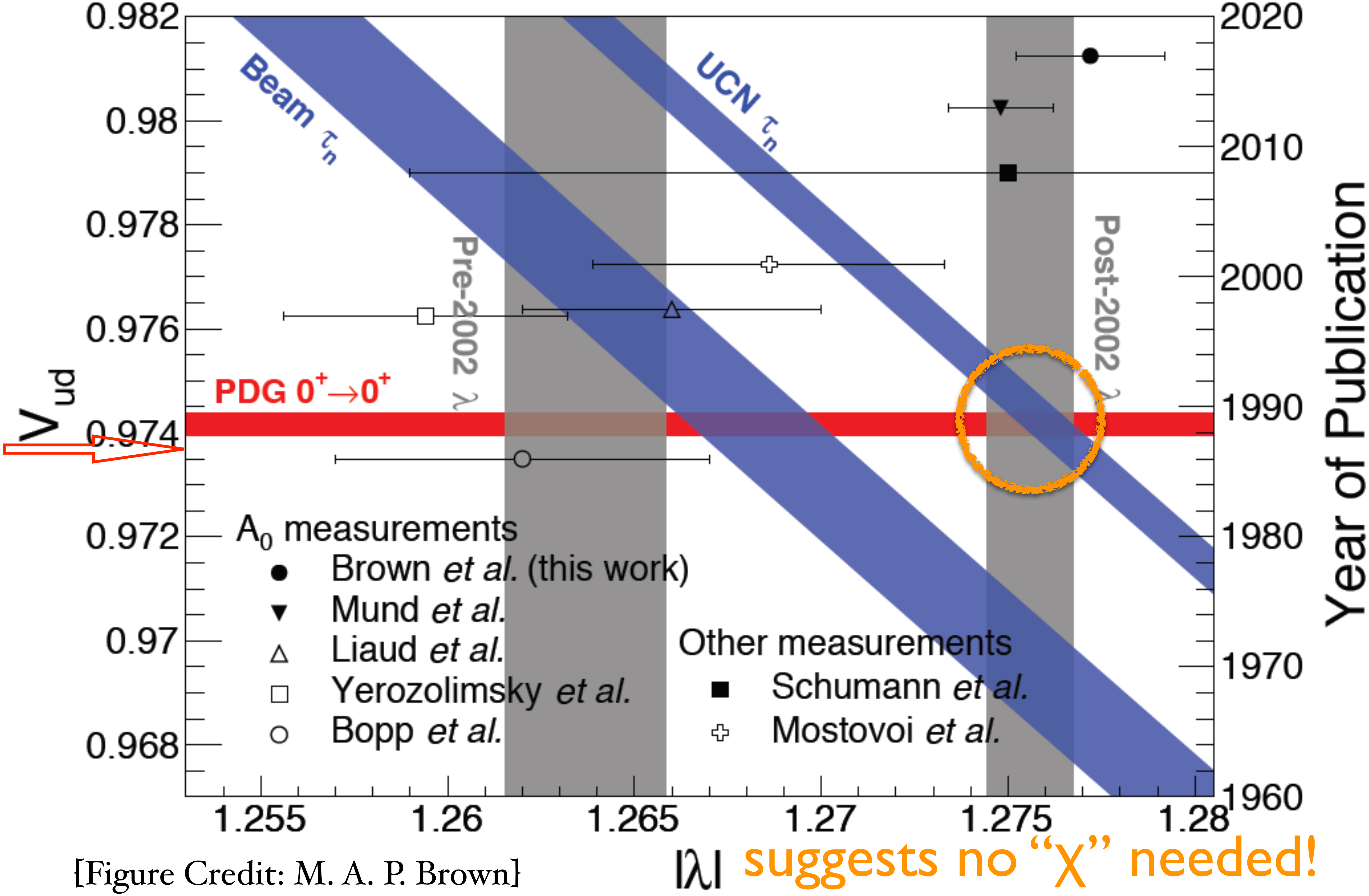
Invisible



Enter Φ = (3, 1, -1/3) and χ a SM singlet

Select χ mass window to avoid **proton decay** & nuclear constraints

Status of V_{ud}



[Figure Credit: M. A. P. Brown]

[Czarnecki, Marciano, Sirlin, PRL 2018]

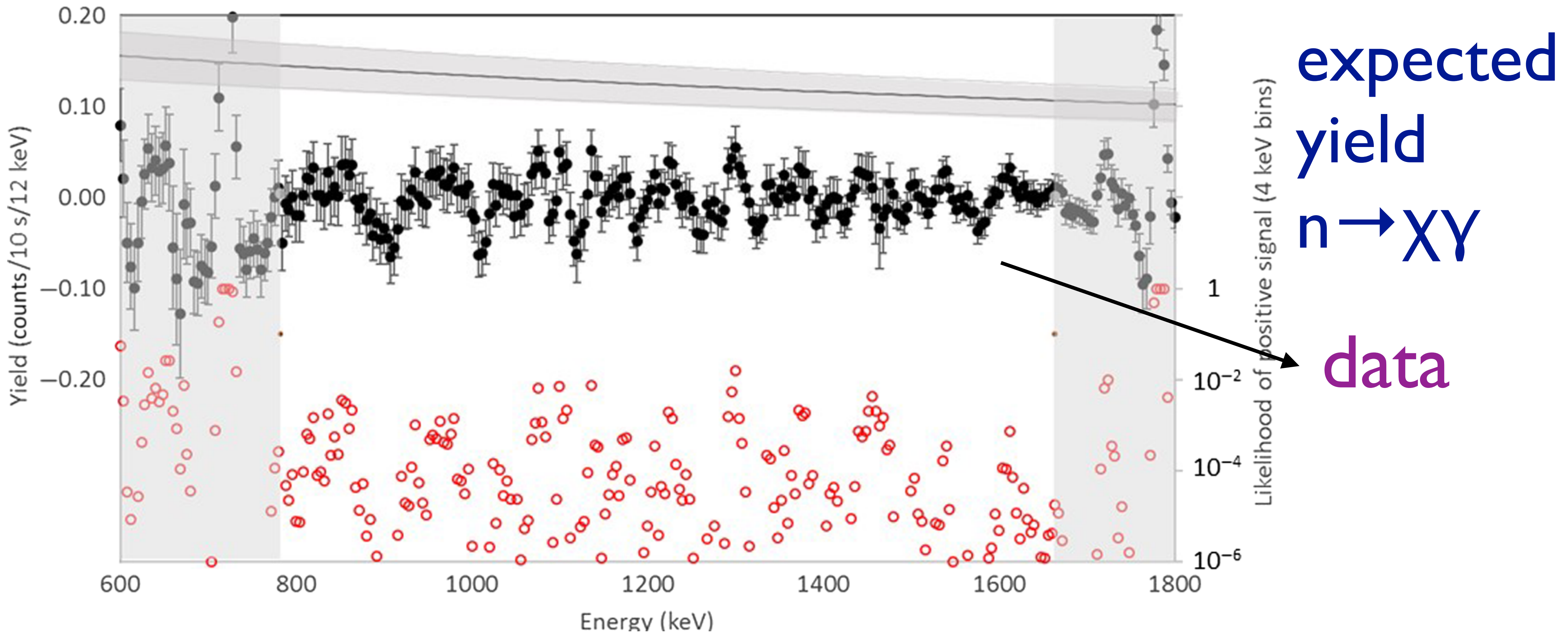
suggests no "X" needed!

But note most recent bottle τ_n

Dark Aftermaths?

Particular models are now excluded

as explanations of the **entire** anomaly



[Tang et al., PRL, 2018]

These models 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]

B-L Violation with Quarks

in collaboration with Xinshuai Yan

Origins of the Neutrino Mass

The Majorana mass and 0 ν ββ decay

A neutrino can have a Majorana mass
if B-L symmetry is broken

(Enter the Weinberg operator $(v_{\underline{weak}}{}^2/\Lambda_{new})\ \nu_L{}^T C\ \nu_L$)

→ Or (and) the neutrino could have a Dirac mass

(Enter the right-handed neutrino & the Higgs mechanism)

But only B-L violation permits 0 ν ββ decay

However, 0 ν ββ decay need not mediated by the exchange of a light Majorana ν (other sources could act); though its observation would show it effectively exists

[Schechter & Valle, 1982]

Mechanisms of 0ν ββ decay

Why the energy scale of B-L violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \lambda v_{\rm weak}^2/\Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\rm weak}$, then naturally $m_\nu \ll m_f$! N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that m_ν is small just because $d \gg 4$ and Λ need not be so large.

[EFTs: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

Can we establish the scale of $\mathcal{B} - \mathcal{L}$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension ("short range") operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider B-L violation in the quark sector:
via n-$\bar{\text{n}}$ transitions

Neutron-Antineutron 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)
- neutron-antineutron conversion (NEW!)

[SG & Xinshuai Yan, arXiv:1710.09292, PRD 2018 (also arXiv:1602.00693, PRD 2016)]

Patterns of |ΔB|=2 Violation?

Minimal scalar-fermion models give connections

[SG & Xinshuai Yan, arXiv: 1808.05288]

Note such models of $n \to \bar{n}$ oscillation without p decay

[Arnold, Fornal, Wise, PRD, 2013]

Enter new scalars X_i that respect SM gauge symmetry and interactions $X_i X_j X_k$ or $X_i X_j X_k X_l$
— cf. "hidden sector" searches: possible masses are limited by experiment

Here products of different new scalars give $n \to \bar{n}$ oscillation and $n\bar{n}$ conversion ($e^- p \to e^+ \bar{p}$, ...), and thus can predict $\pi^- \pi^- \to e^- e^-$!

New Scalars in SM EFT?

Eliminating p decay gives severe constraints!

Scalar-fermion couplings

TABLE I. Scalar particle representations in the $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM that carry nonzero B and/or L but permit no proton decay at tree level, after Ref. [4]. We indicate the possible interactions between the scalar X and SM fermions schematically. Note that the indices a, b run over three generations, that the symmetry of the associated coupling g_i^{ab} under $a \leftrightarrow b$ exchange is noted in brackets, and finally that our convention for Y is $Q_{\rm em} = T_3 + Y$. Please refer to the text for further discussion.

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

Possible SM gauge invariant models

TABLE II. Minimal interactions that break B and/or L from scalars X_i that do not permit $|\Delta B| = 1$ interactions at tree level, indicated schematically, with the Hermitian conjugate implied. Interactions labelled M1-M9 appear in models 1-9 of Ref. [4]. Interactions A-G possess $|\Delta L| = 2$, $|\Delta B| = 0$. M19, M20, and M21 follow from M8, M17, and M18 under $X_7 \to X_6$, respectively, but they do not involve first-generation fermions only.

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	$X_4X_7X_7X_3^\dagger$

[SG & Xinshuai Yan, arXiv: 1808.05288]

Patterns of |ΔB|=2 Violation

Discovery implications for 0ν ββ decay

TABLE IV. Possible patterns of $|\Delta \mathrm{B}| = 2$ discovery and their interpretation in minimal scalar-fermion models. Note that only $n - \bar{n}$ oscillations and $e^- n \to e^- \bar{n}$ break B-L symmetry and that the pertinent conversion processes can be probed through electron-deuteron scattering. The latter are distinguished by the electric charge of the final-state lepton accompanying nucleon-antinucleon annihilation. Note that the $0\nu\beta\beta$ query refers specifically to the existence of $\pi^-\pi^- \to e^-e^-$ from new, short-distance physics. Note that we can possibly establish model D and $|\Delta \mathrm{L}| = 2$ violation, but that model does not give rise to $\pi^-\pi^- \to e^-e^-$. In contrast we cannot establish X_8 alone and thus cannot establish model C.

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?]

Note high-intensity, low energy PVES experiments (P2, e.g.) can be used to broader purpose

[SG & Xinshuai Yan, arXiv: 1808.05288]

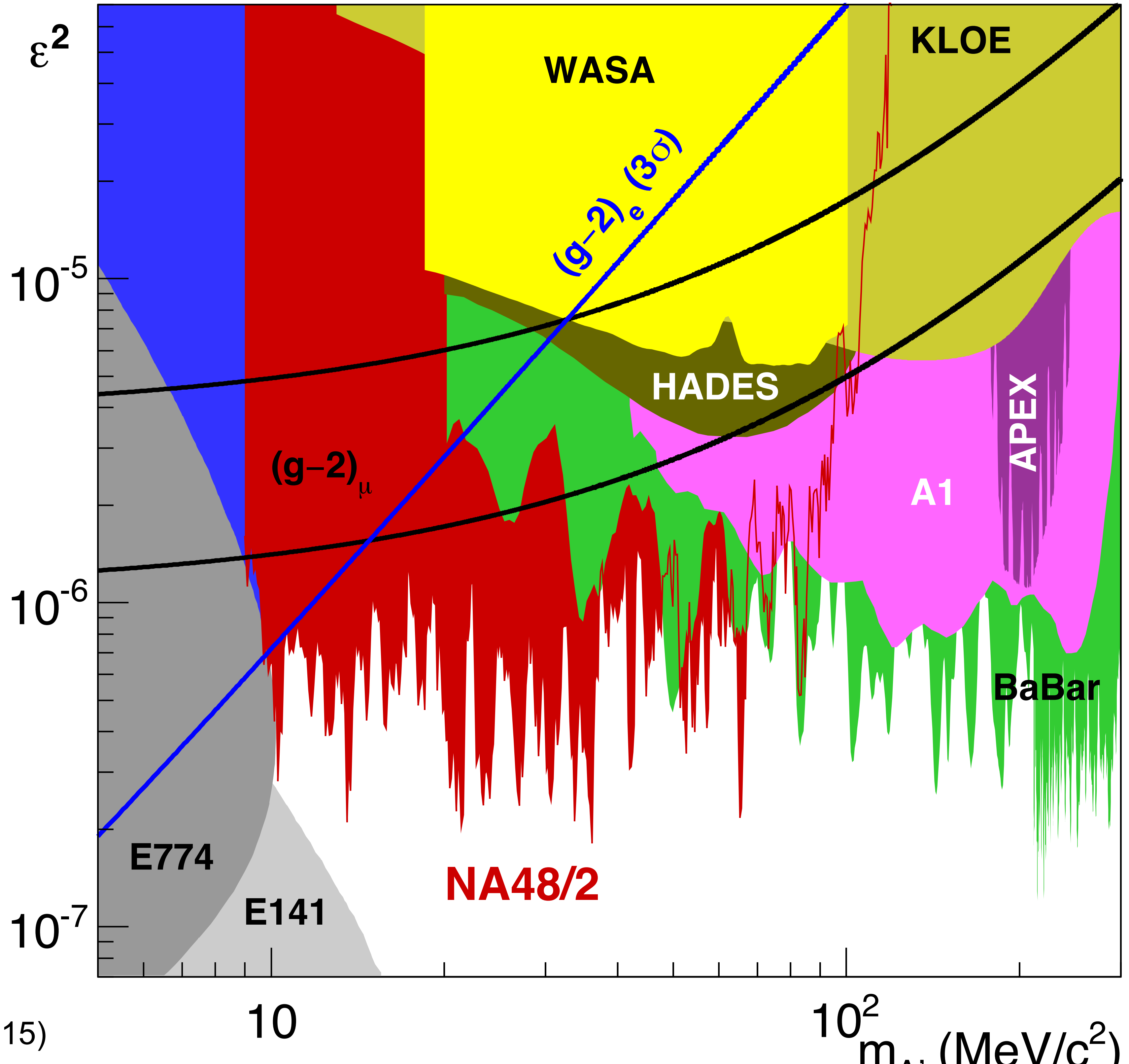
Summary

- The long-standing g_A problem in LQCD appears to have been finally solved!
- The possibility of light, dark physics in neutron decay has generated intense interest — with no end as yet!
- The energy scale of B-L violation speaks to different explanations as to why the neutrino is light (A "TeV scale" mechanism could also generate B-L violation in the quark sector)
- We have noted neutron-antineutron conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering)
- Experiments with intense low-energy electron beams, e.g., can also be used to search for B-L violation & help solve the ν mass puzzle

Backup Slides

Dark Photon Constraints

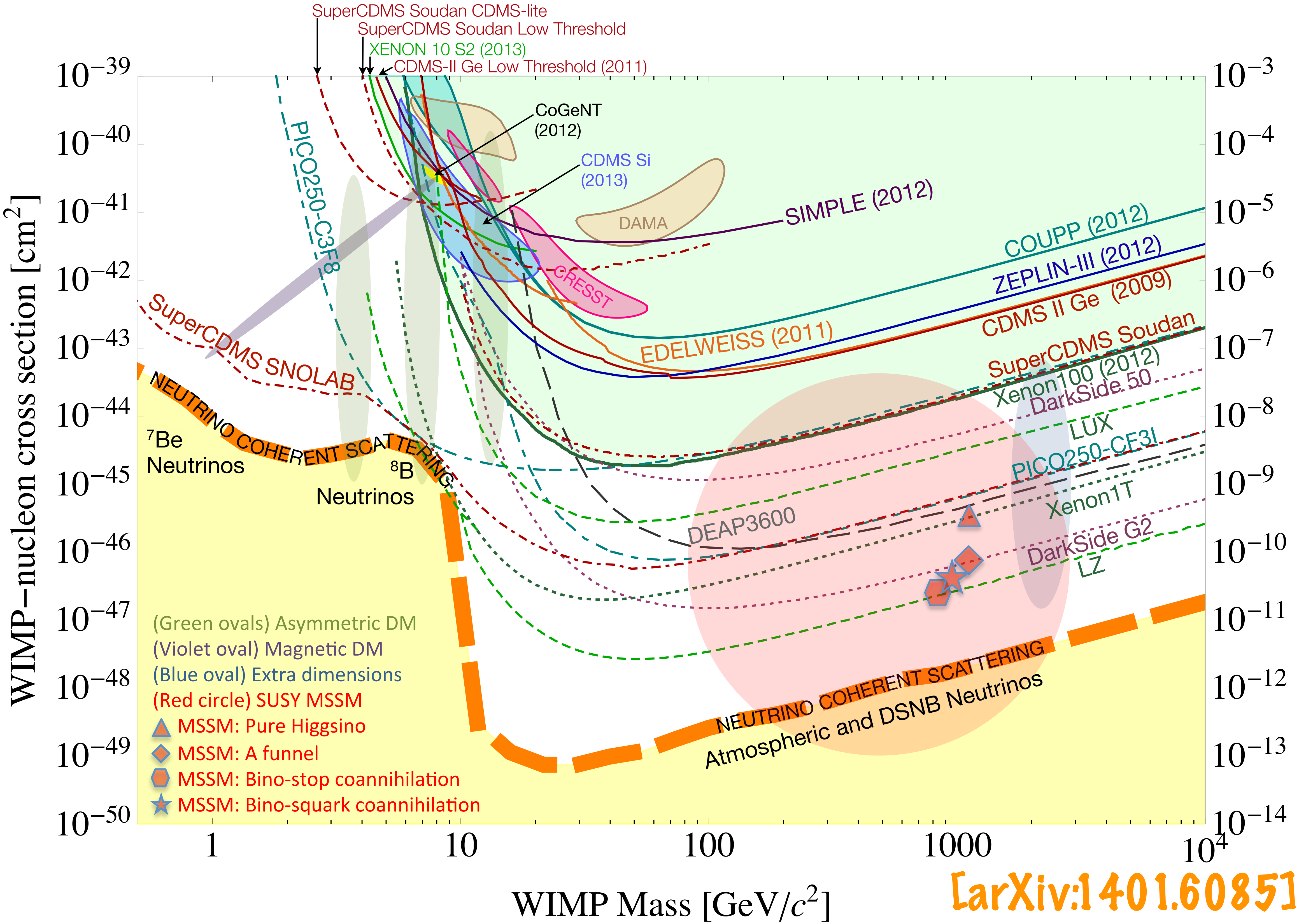
Assuming A' does not decay to the hidden sector



[NA 48/2, Raggi (2015)

Direct Detection: Dark Matter “WIMPs”

Limits rely on local DM density and velocity distribution



[arXiv:1401.6085]

Dark Matter & the CMB

Opening the axion window....

Observations of the CMB power spectrum constrain the ratio of tensor (gravitational wave) to scalar (density fluctuations) power r

$r < 0.07$ at 95% C.L. [Ade et al., PRL 116 (2016) 031302] (BICEP2 + Keck + Planck)]

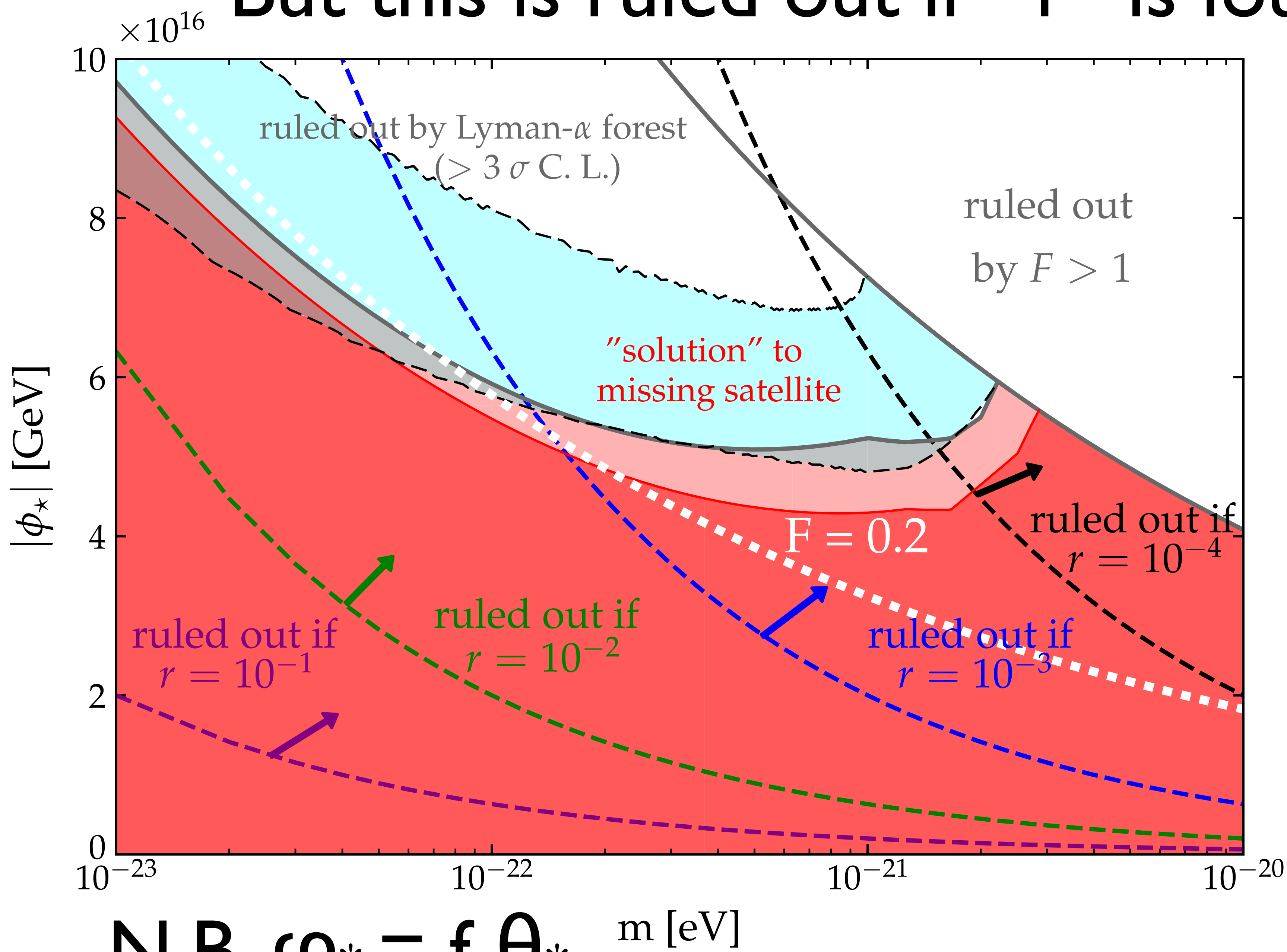
This quantity has not been detected making ultralight (axion-like) dark matter ($m_a \sim 10^{-22}$ eV) "fuzzy (quantum wave) dark matter" possible....

[Hu, Barkana, Gruzinov, PRL 85 (2000) 1158;
Schive, Chiueh, Broadhurst, Nat. Phys. 10 (2014) 496...;
Graham & Rajendran, PRD 84 (2011) 055013,... for direct detection prospects]

Ultralight Axion Window

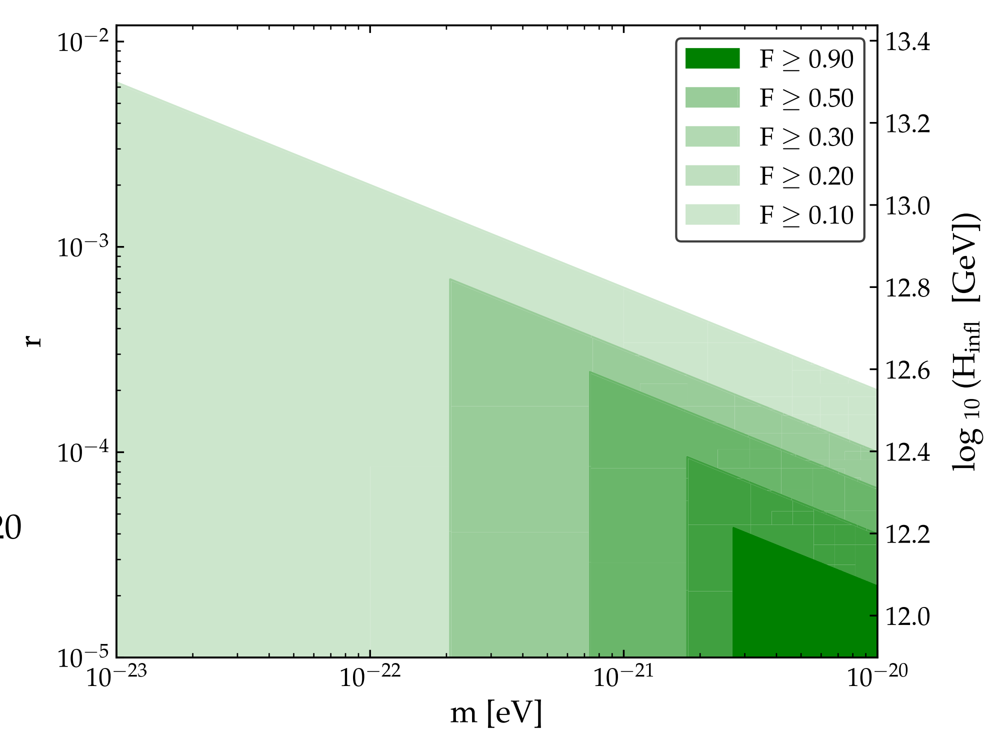
A new pseudoscalar boson (not connected to QCD) can explain the "dark matter"!

But this is ruled out if "r" is found to be too big!



N.B. $\varphi_* = f_a\theta_*$

Kobayashi et al., PRD 96 (2017) 123514



Electric & Magnetic Dipole Moments

Taken relativistically for fermion f with charge -e

$$\mathcal{H} = e\bar{\psi}_f \gamma^\mu \psi_f A_\mu + a_f \frac{1}{4} \bar{\psi}_f \sigma^{\mu\nu} \psi_f F_{\mu\nu} + d_f \frac{i}{2} \bar{\psi}_f \sigma^{\mu\nu} \gamma_5 \psi_f F_{\mu\nu}$$

photon field A_μ $\qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\mu_f = g_f \frac{e}{2m_f} \qquad g_f = 2 + 2a_f$$

a_f is an anomalous magnetic moment

For an elementary fermion a_f and d_f can only be generated through loop corrections (N.B. D>4)

EDMs & Sensitivity to New Physics

The electric and (anomalous) magnetic moments change chirality

$$\bar{\psi}\sigma^{\mu\nu}\psi = (\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\psi_L)$$

$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi = (\bar{\psi}_L\sigma^{\mu\nu}\gamma_5\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\gamma_5\psi_L)$$

By dimensional analysis we infer the scaling

New Physics Scale

$$d_f \sim e\frac{\alpha}{4\pi}\frac{m_f}{\Lambda^2}\sin\phi_{\rm CP}$$

$$d_{d\,\rm quark} \sim 10^{-3} e\frac{m_d({\rm MeV})}{\Lambda({\rm TeV})^2} \sim 10^{-25}\frac{1}{\Lambda({\rm TeV})^2}e - {\rm cm}$$

Note ILL limit on neutron EDM:

$d_n < 3\text{x}10^{-26}$ e-cm @ 90%CL [Pendlebury et al., 2015]

EDM experiments have (at least) TeV scale sensitivity

EDMs in the SM

The contribution from the CKM matrix first appears in three-loop order!

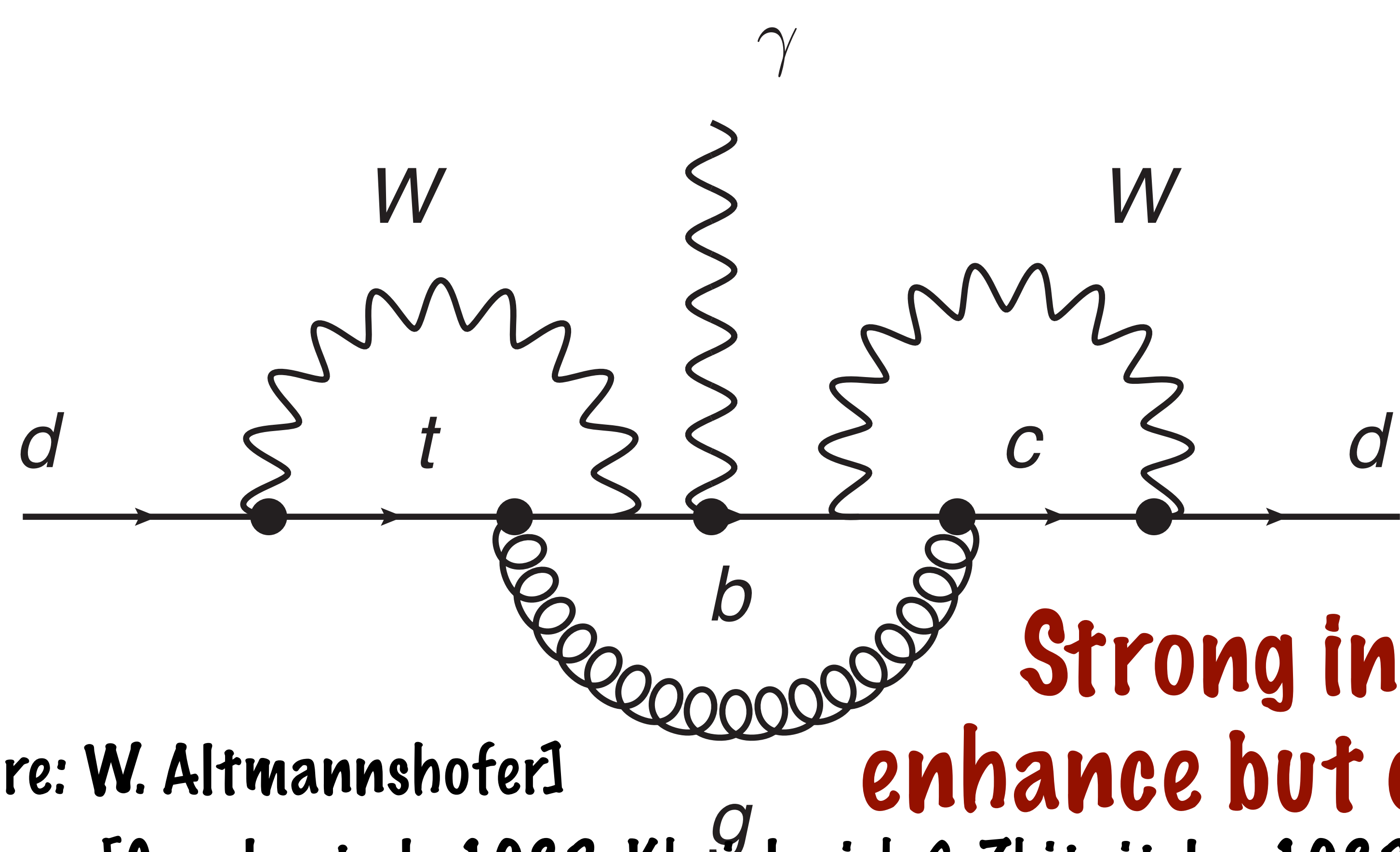
The EDM is flavor diagonal, so that…

at one-loop order no "Im V…" piece survives

at two-loop order the "Im V…" piece vanishes [Shabalin, 1978]

at three-loop order the gluon-mediated terms dominate

[Khriplovich, 1986]



$|d_d| \sim 10^{-34}$ e-cm

[Czarnecki & Krause, 1997]

Inaccessibly small!

Strong interaction effects can enhance but only by $10^{2 \text{ or } 3}$ in neutron

[figure: W. Altmannshofer]

[Gavela et al., 1982: Khriplovich & Zhitnitsky, 1982; Mannel & Uraltsev, 2012;... Seng, 2015]

Lepton EDMs in the SM

The contribution from the CKM matrix first appears in four-loop order!

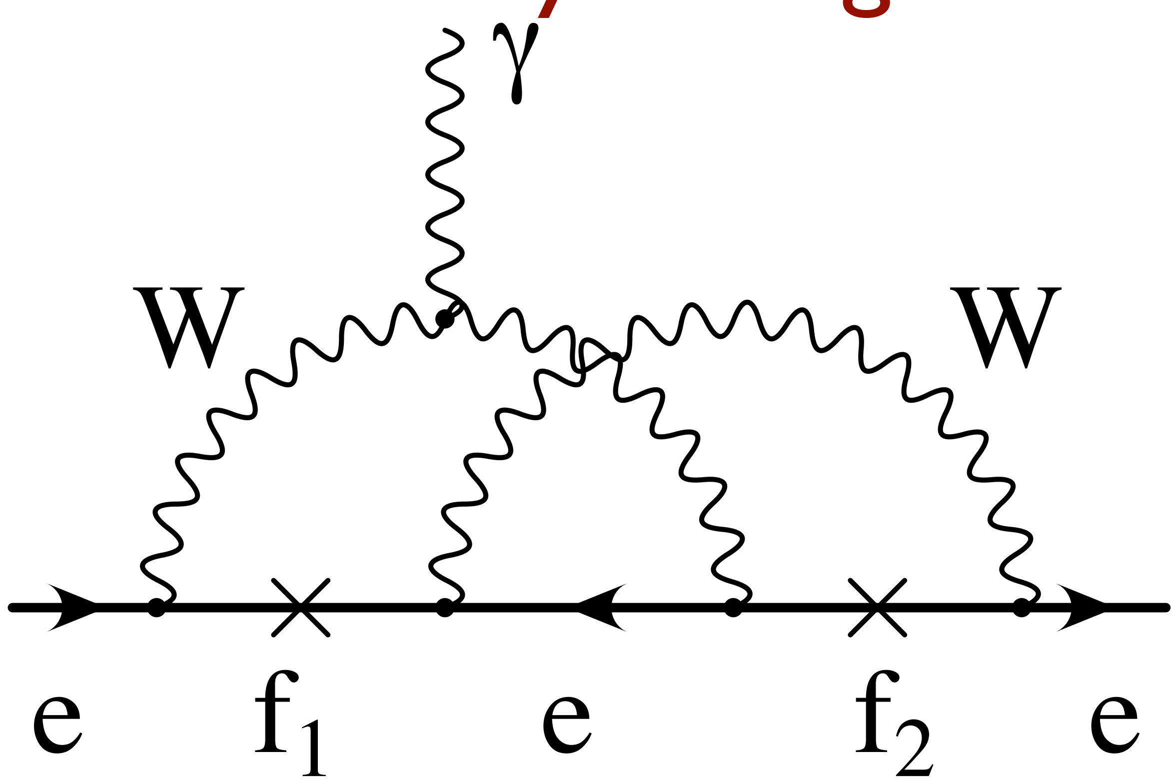
cf. d_e^{eff} *from CPV e-N*
[Pospelov & Ritz, 2013]

$d_e \sim 10^{-44}$ e-cm [Khriplovich & Pospelov, 1991]

Majorana neutrinos can enhance a lepton EDM

[Ng & Ng, 1996]

but not nearly enough to make it "visible"



For "fine tuned" parameters

$d_e \lesssim 10^{-33}$ e-cm

[Archambault, Czarnecki, & Pospelov, 2004]

Look to CPV in ν oscillations to probe leptogenesis!

Permanent EDMs in Complex Systems

A fundamental EDM points along the particle's spin, breaking both T and P

$$\mathcal{H} = -d\vec{E} \cdot \frac{\vec{S}}{S} - \mu\vec{B} \cdot \frac{\vec{S}}{S}$$

Applied electric fields can be enormously enhanced in atoms and molecules [Purcell and Ramsey, 1950]

Searches in different systems:

paramagnetic & diamagnetic & the neutron

ACME (ThO) [Baron et al., 2014]

YbF [Hudson et al., 2011]

[Fr] Tl [Regan et al., 2002]

Hg [Graner et al., 2016]

Xe [Rosenberry & Chupp, 2001]

Ra [Bishof et al., 2016]

n [Pendlebury et al., 2015]

with many more (& more methods) under development!

[Pospelov & Ritz, 2005; Engel, Ramsey-Musolf, & van Kolck, 2013; Jung, 2013; Chupp et al., 2017]

Theoretical Framework

Fixing the Fermi constant

$$G_F^{(0)}/\sqrt{2} = g^2/8M_W^2$$ is fixed from muon decay

$$\mathcal{L}_{\mu\to e\bar{\nu}_e\nu_\mu} = -4\,G_F^{(0)}\left(1+\delta_\mu+\epsilon_\mu\right)\ \bar{e}_L\gamma_\mu\nu_{eL}\cdot\bar{\nu}_{\mu L}\gamma^\mu\mu_L\ +\ \text{h.c.}$$

[van Ritbergen & Stuart, 2000]

[N.B. MuLan expt, Chitwood, 2007]

$$G_\mu \equiv G_F^{(0)}(1+\delta_\mu+\epsilon_\mu)$$

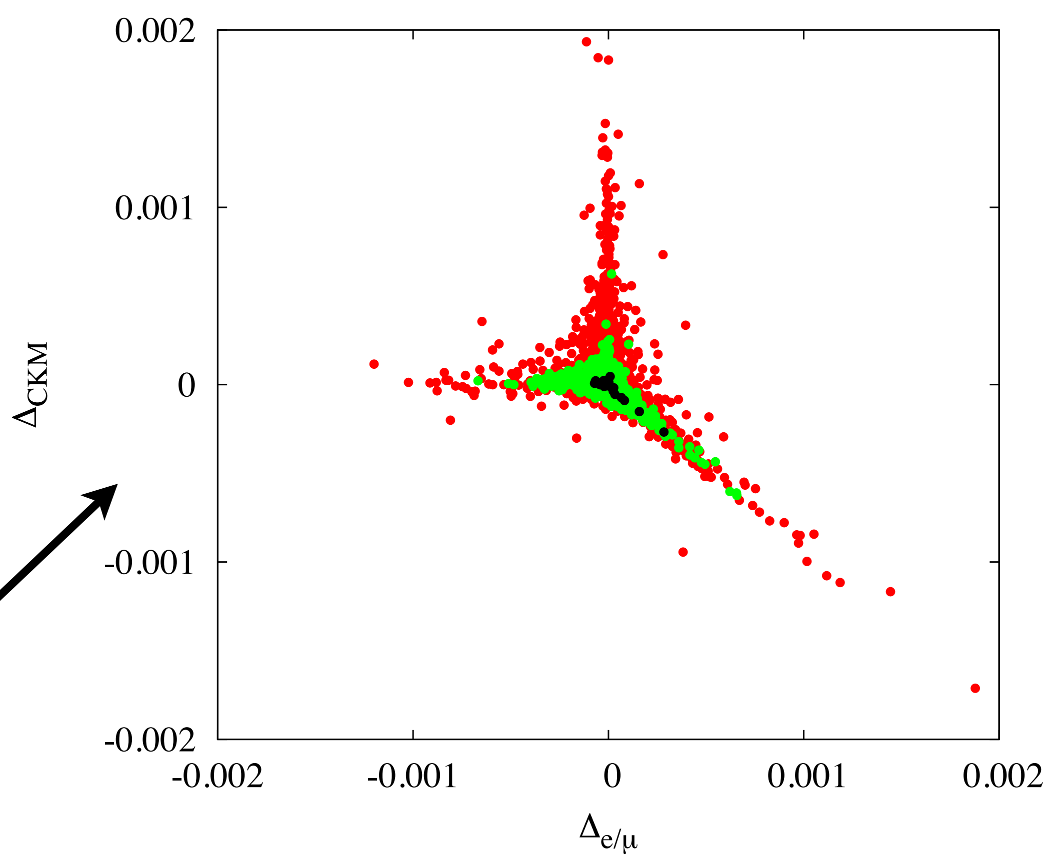
New physics!

Thus testing CKM unitarity probes weak universality!

Also each extracted V_{ij} can contain BSM effects

N.B. explicit studies in the MSSM...

[Kurylov & Ramsey-Musolf, 2002; Bauman, Erler, Ramsey-Musolf, 2012]



n - n̄ Transitions & Spin

Spin can play a role in a "mediated" process

A neutron-antineutron **oscillation** is a spontaneous process & thus the spin does not ever flip

However,

$$\mathcal{O}_4 = \psi^T C\gamma^\mu\gamma_5\psi\,\partial^\nu F_{\mu\nu} + \mathrm{h.c.}$$

$n(+) \to \bar{n}(-)$ occurs directly because the interaction with the current flips the spin.

This is concomitant with $n(p_1, s_1) + n(p_2, s_2) \to \gamma^*(k)$, for which only $L = 1$ and $S = 1$ is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here $e + n \to \bar{n} + e$, e.g., so that the experimental concept for "$n\bar{n}$ conversion" would be completely different.

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
  → Then the neutron-level conversion operators could also be different

Note studies of scattering matrix elements of Majorana dark matter [Kumar & Marfatia, PRD, 2013]

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

$n \to \bar{n}$

"spontaneous" → oscillation

$n \to \bar{n}$

conversion

[SG & Xinshuai Yan, arXiv: 1710.09292, PRD 18]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion (here $e^- n \to e^- \bar{n}$)

Theoretical Framework

On non "V-A" currents

$$\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[\Big(1+\delta_\beta\Big)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+ \quad \epsilon_L\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\ \ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+ \quad \epsilon_R\ \ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d\ +\ \tilde{\epsilon}_R\ \ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+ \quad \epsilon_S\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d\ +\ \tilde{\epsilon}_S\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d$$
$$- \quad \epsilon_P\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$
$$+ \quad \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\ +\ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d$$
$$+ \quad \text{h.c.}\ .$$

$\epsilon_L + \epsilon_R$	CKM unitarity
$\epsilon_L - \epsilon_R,\quad \epsilon_P,\quad \tilde{\epsilon}_P$	R_π
ϵ_S	$b,\ \ B\ \ [a,\ \ A]$
ϵ_T	$b,\ \ B\ \ [a,\ \ A],\quad \pi \to e\nu\gamma$
$\tilde{\epsilon}_{\alpha\neq P}$	R_π

ϵ_S , ϵ_T enter

in linear order!

"most visible"

$$R_\pi \equiv \Gamma(\pi \to e\nu[\gamma])/\Gamma(\pi \to \mu\nu[\gamma]).$$