Particle Physics Models for the ATOMKI Beryllium-8 Anomaly

Tim M.P. Tait
University of California, Irvine

Work with: J. Feng, B. Fornal, S. Gardner, I. Galon, J. Smolinsky, TMPT, P. Tanedo
arXiv:1604.07411 & PRL;
arXiv:1608.03591 & PRD

Bormio
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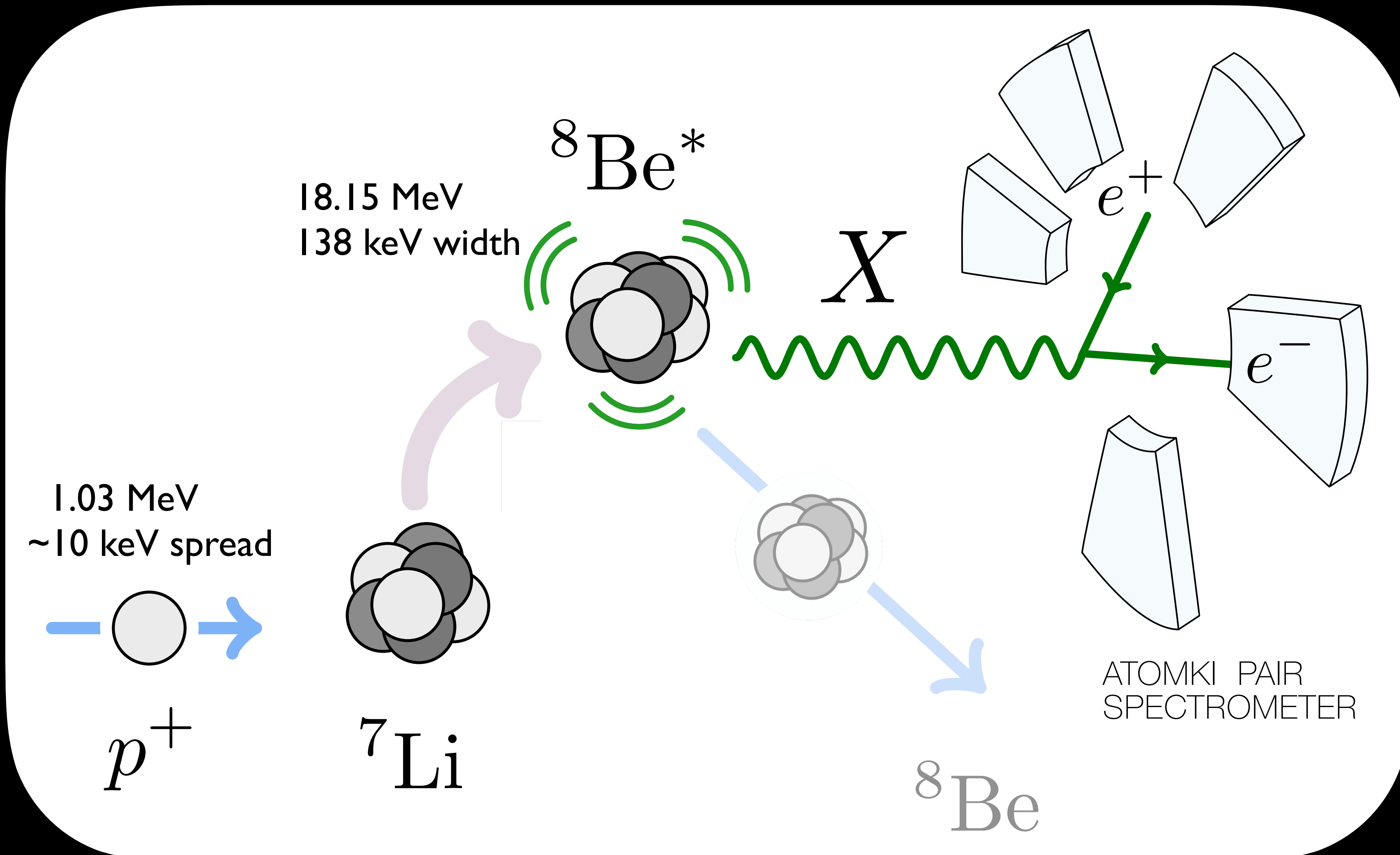
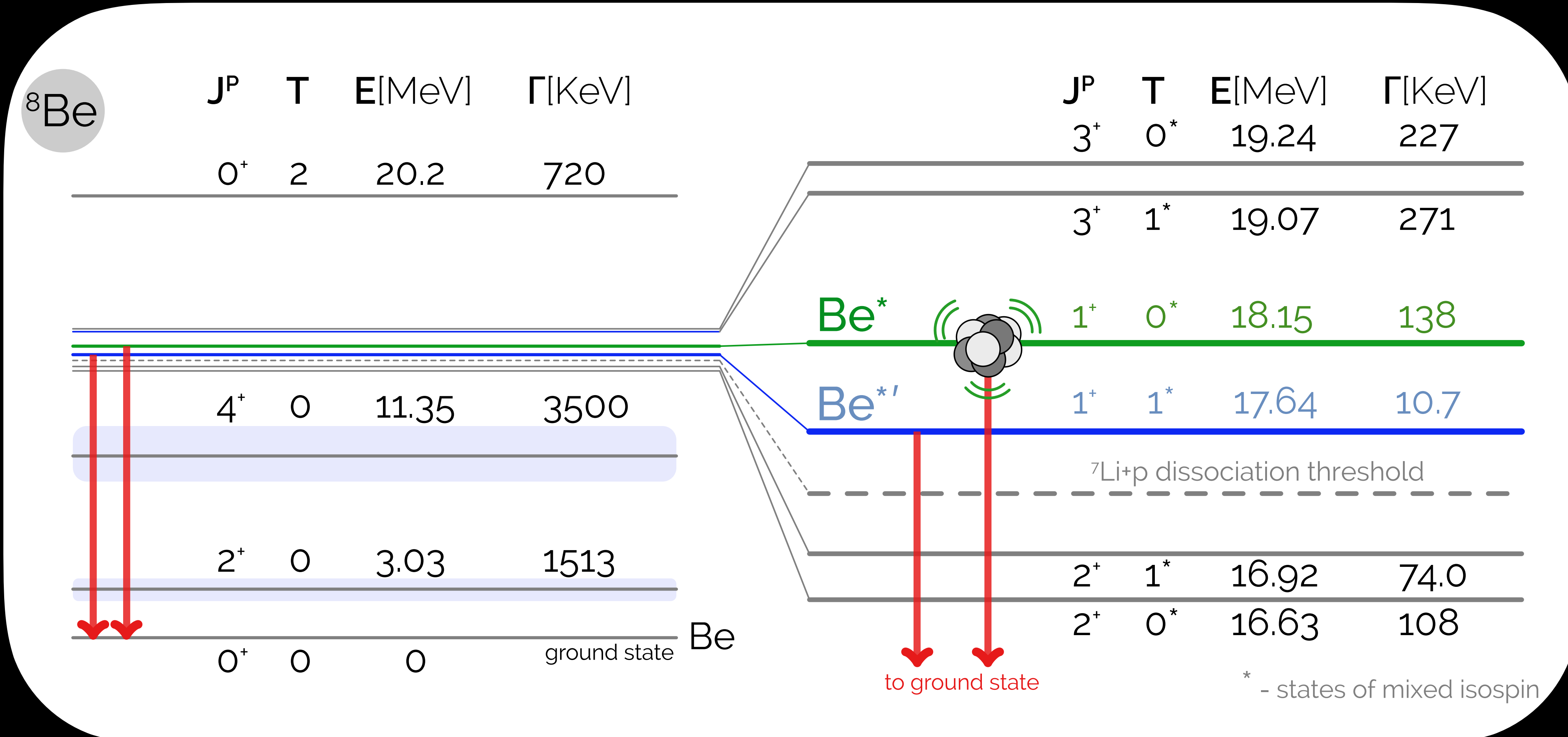
ATOMKI Experiment



- Since Attila already told us about the experiment and results yesterday, I will focus on interpretation.

Be-8 Levels

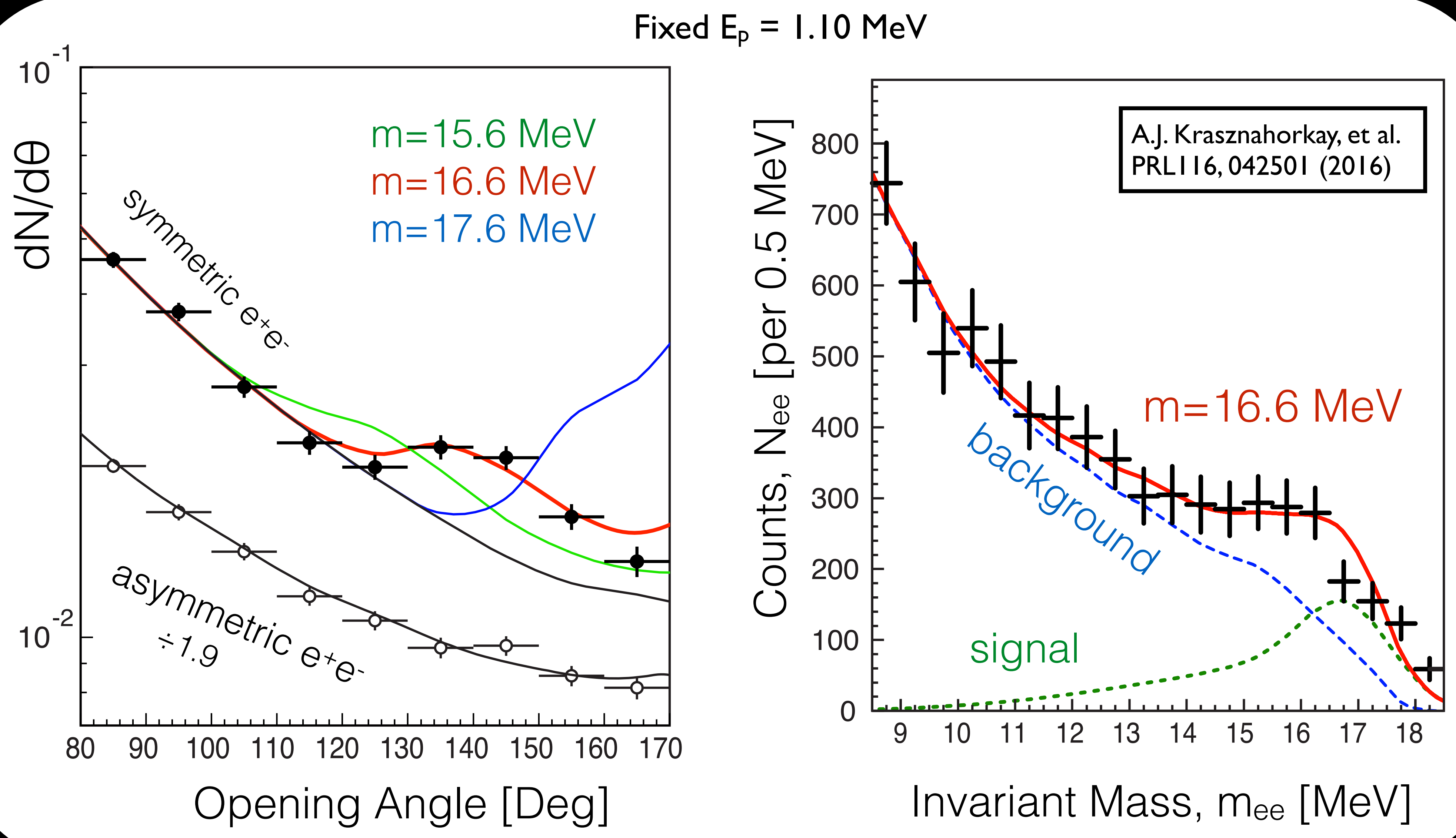


- The Be-8 ground state is a 0^+ isosinglet.
- There are a variety of excited states with different spins and isospins.
- For today, interested in the 1^+ 17.64 Be*' and 18.15 Be* states. There is some evidence that these states are actually admixtures of isotriplet and isosinglet.

arXiv:1608.03591

Pastore et al, PRC90 (2014) [1406.2343]

Experimental Results



- Note that in the bump region ~14 - 18 MeV, the signal is a pretty large fraction of the total number of events (though it is a small fraction of the total integrated over all m_{ee}).

So What's Going On?

- Obviously, one should be cautious. In the very least we would like to see these results repeated, preferably by a different group.
- Logically, we should consider the possibilities of:
    - Experimental error/Miscalibration/Etc:
        - Nothing is obviously wrong with the experiment: the angles and energies all seem self-consistent and pass the sanity checks;
    - Up until now unknown nuclear physics effect:
        - Nuclear physicists so far haven't come up with an obvious explanation for a bump (but they continue to work on it!) This is crucial;
    - Physics Beyond the Standard Model.
- My attitude here: Let's see what kind of new physics can explain it and see what other constraints/opportunities there are to learn more.

BSM Interpretation

- A BSM interpretation requires a new particle, X.
- The ATOMKI group fits a hypothesis consisting of the expected M1 IPC background (and also allows for a contribution of E1 pollution) plus signal:

$$m_X = 16.7 \pm 0.35\,(\mathrm{stat}) \pm 0.5\,(\mathrm{sys})\ \mathrm{MeV}$$
$$\frac{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\,X)}{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\,\gamma)}\,\mathrm{Br}(X \to e^+e^-) = 5.8 \times 10^{-6}$$

- A few things are clear:
  - It must be a boson coupled to leptons in order to decay into e+e-
  - It must couple to quarks and/or gluons so that it can appear in beryllium transitions.
  - It has a short life-time such that it decays within about 1 cm so that its decay is prompt compared to the detector geometry.

Effective Field Theory

- We can capture the essential features of the decay in terms of a low energy effective field theory.
- The deBroglie wavelength of the emitted particle is $\lambda \sim 1/\ (6\ \text{MeV})$, whereas the size of the nucleus is $r \sim 1/(100\ \text{MeV})$.
  - We can treat the nucleus as point-like, expanding in $r\ /\ \lambda \sim 1\ /\ 20$.
- We assume parity conservation to avoid getting bogged down with strong APV constraints, but this assumption can be relaxed.

arXiv:1604.07411 and arXiv:1608.03591

$$\mathcal{L}_V = \frac{g_V}{\Lambda_V} \mathrm{Be}\, G_{\mu\nu} F^{(V)}_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

$$\mathcal{L}_S = \frac{g_S}{\Lambda_S^2} (\partial_\mu s)(\partial_\nu \mathrm{Be}) G_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

$$\mathcal{L}_A = \frac{g_A}{\Lambda_A} \mathrm{Be}\, G^{\mu\nu} F^{(A)}_{\mu\nu} + \frac{m_A^2}{g_A \Lambda'_A} \mathrm{Be}\, A_\mu\, \mathrm{Be}^{*\mu}$$

$$\mathcal{L}_P = g_P\, \mathrm{Be}\ (\partial_\mu a)\, \mathrm{Be}^{*\mu}\ .$$

$$G_{\mu\nu} \equiv \partial_\mu Be^*_\nu - \partial_\nu Be^*_\mu$$

The leading operators are dimension-four (pseudo-scalar), -five (vector and axial-vector), and -six (scalar).

The scalar 0^+ operator vanishes upon applying the equation of motion.

0^+ Scalar Particle

We expect our finding for the scalar operator is more general.

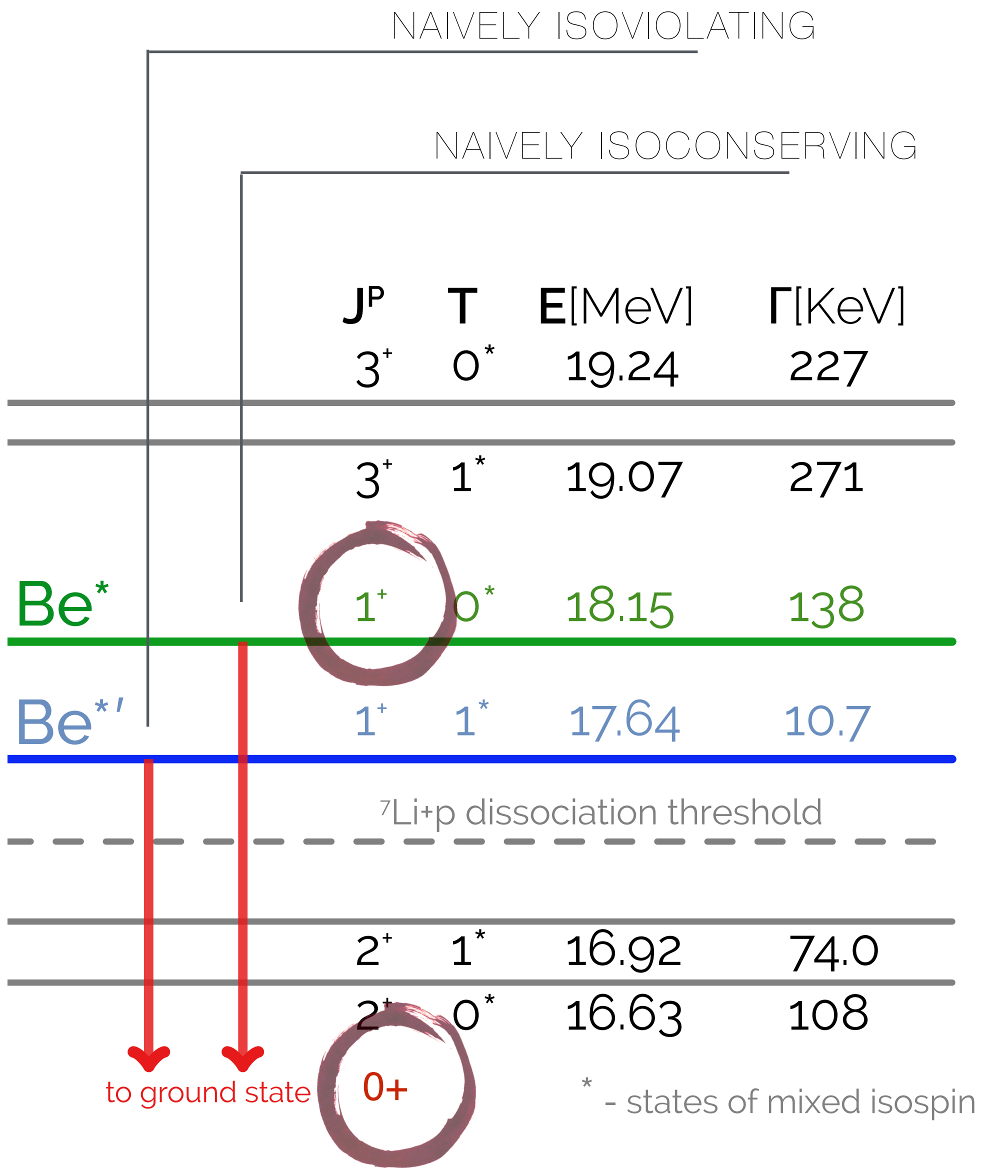
ANGULAR MOMENTUM

$$\ell = 1$$

PARITY

$$P = \underset{-}{(-)^{\ell}} \, \underset{+}{P_{\mathrm{Be}}} \, \underset{+}{P_X}$$

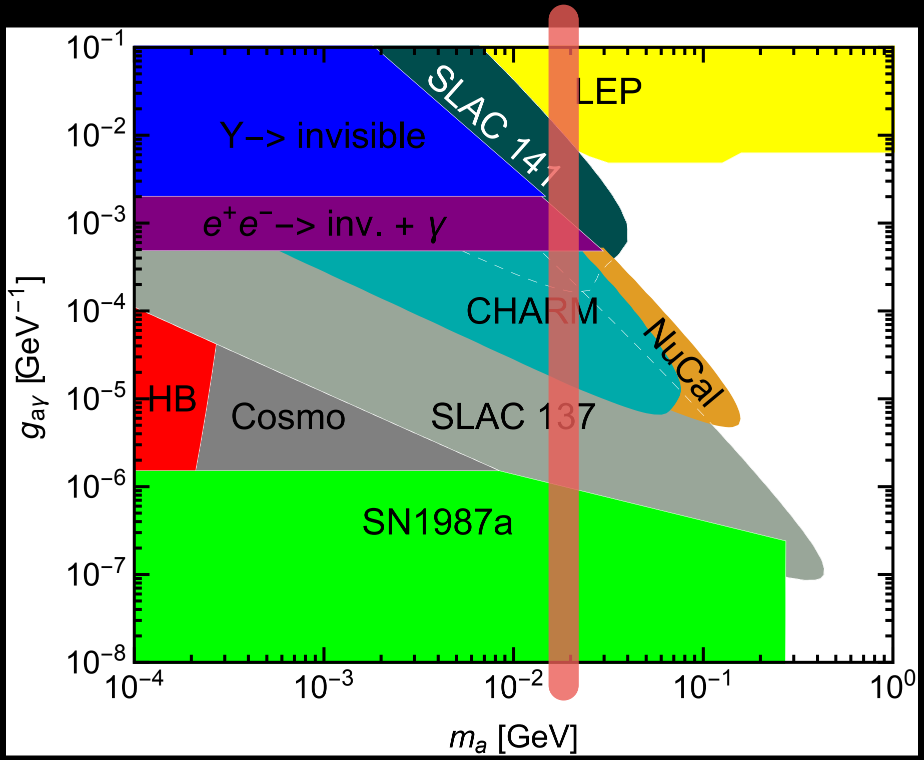
The decay is **forbidden** if parity is conserved.



Axion-like Particle

- The EFT dictates that a pseudo scalar particle can couple Be* to the ground state.
- We initially discarded this possibility because of strong ALP constraints on this mass range.
- However, these bounds are relaxed because of the prompt decay to e+e-.
- Ellwanger and Moretti followed this up in 1609.01669.
  - They use a nuclear shell model to estimate transition matrix elements.
  - They conclude that it works provided O(10%) cancellations in some FCNCs.

$$\mathcal{L}_P = g_P \,\mathrm{Be}\, (\partial_\mu a)\, \mathrm{Be}^{*\mu}$$



$$g_P = \sum_f \xi_f \frac{m_f}{v}$$

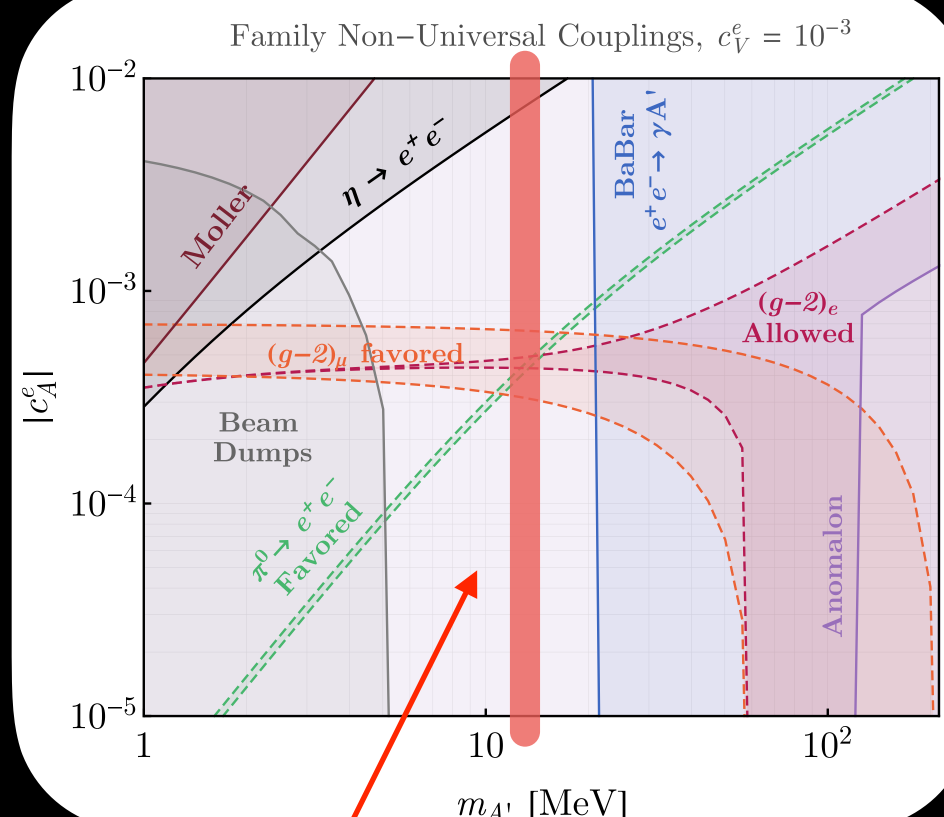
$\xi_q \sim 0.7$ $\xi_\ell \sim 4$

Spin One

- For a vector particle, the EFT corresponds to a dimension-5 operator (two operators for axial-vectors).
- For a massless vector, this EFT also describes EM transitions, and the dimension 5 nature of the operator reflects the fact that this is an M1 transition.
- For axial-vector couplings, the nuclear matrix elements only have recently been computed. Kozaczuk, Morrissey, Stroberg arXiv:1612.01525
  - The results seem promising to fit the signal and evade constraints.
  - There is a wider menu of constraints and UV worries such as anomalies.

$$\mathcal{L}_V = \frac{g_V}{\Lambda_V} \mathrm{Be}\, G_{\mu\nu} F^{(V)}_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

$$\mathcal{L}_A = \frac{g_A}{\Lambda_A} \mathrm{Be}\, G^{\mu\nu} F^{(A)}_{\mu\nu} + \frac{m_A^2}{g_A \Lambda'_A} \mathrm{Be}\, A_\mu\, \mathrm{Be}^{*\mu}$$



Kahn, Krnjaic, Mishra-Sharma, TMPT arXiv:1609.09072

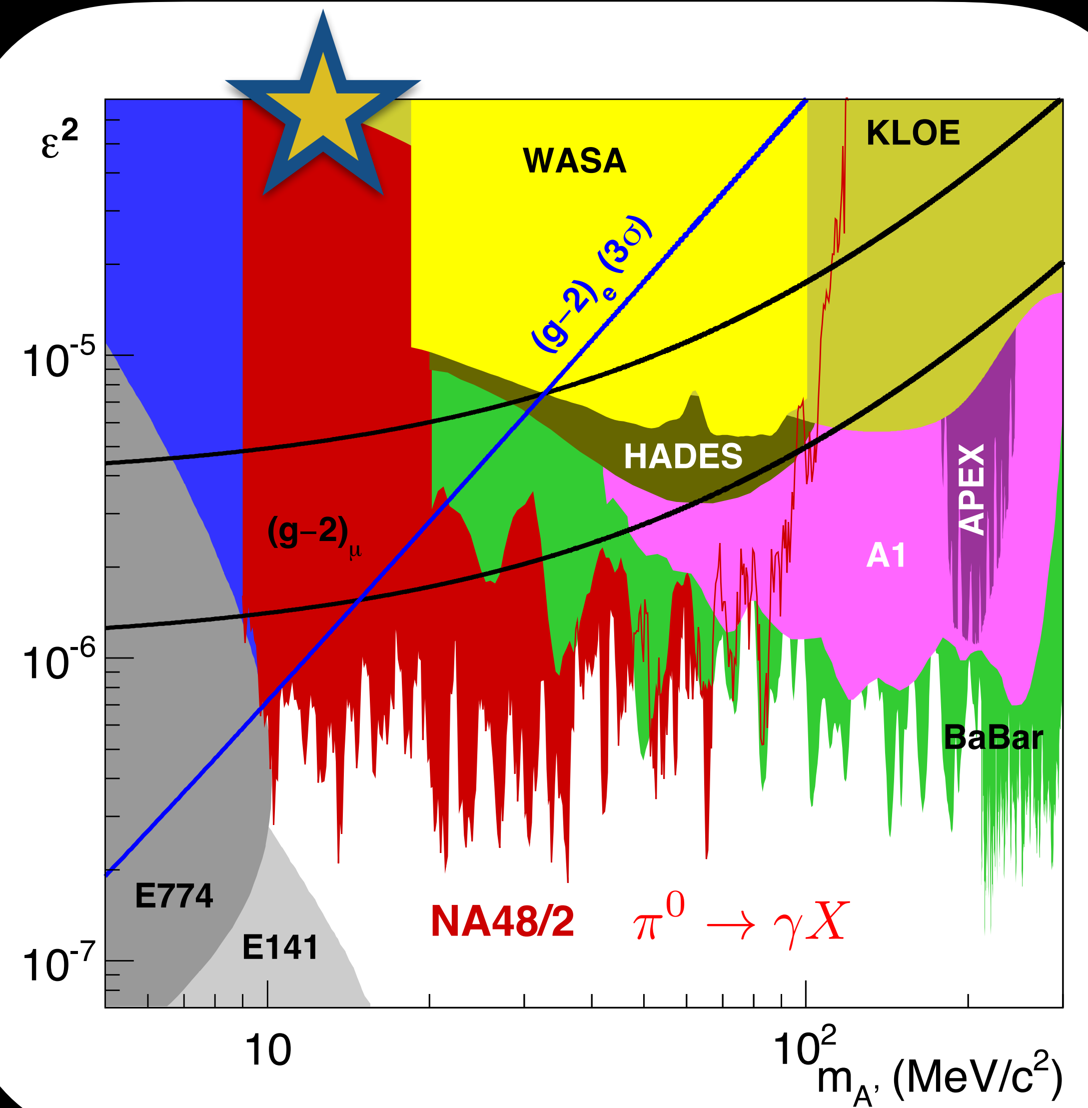
17 MeV is an interesting hole in the low energy constraints, but naively probed by UV physics at the LHC!

Dark Photon

- For a dark photon, the nuclear physics is identical to the usual EM transition, and cancels out of the ratio of partial widths.

$$\frac{Br({}^8\mathrm{Be}^* \to X)}{Br({}^8\mathrm{Be}^* \to \gamma)} \sim \varepsilon^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3}$$

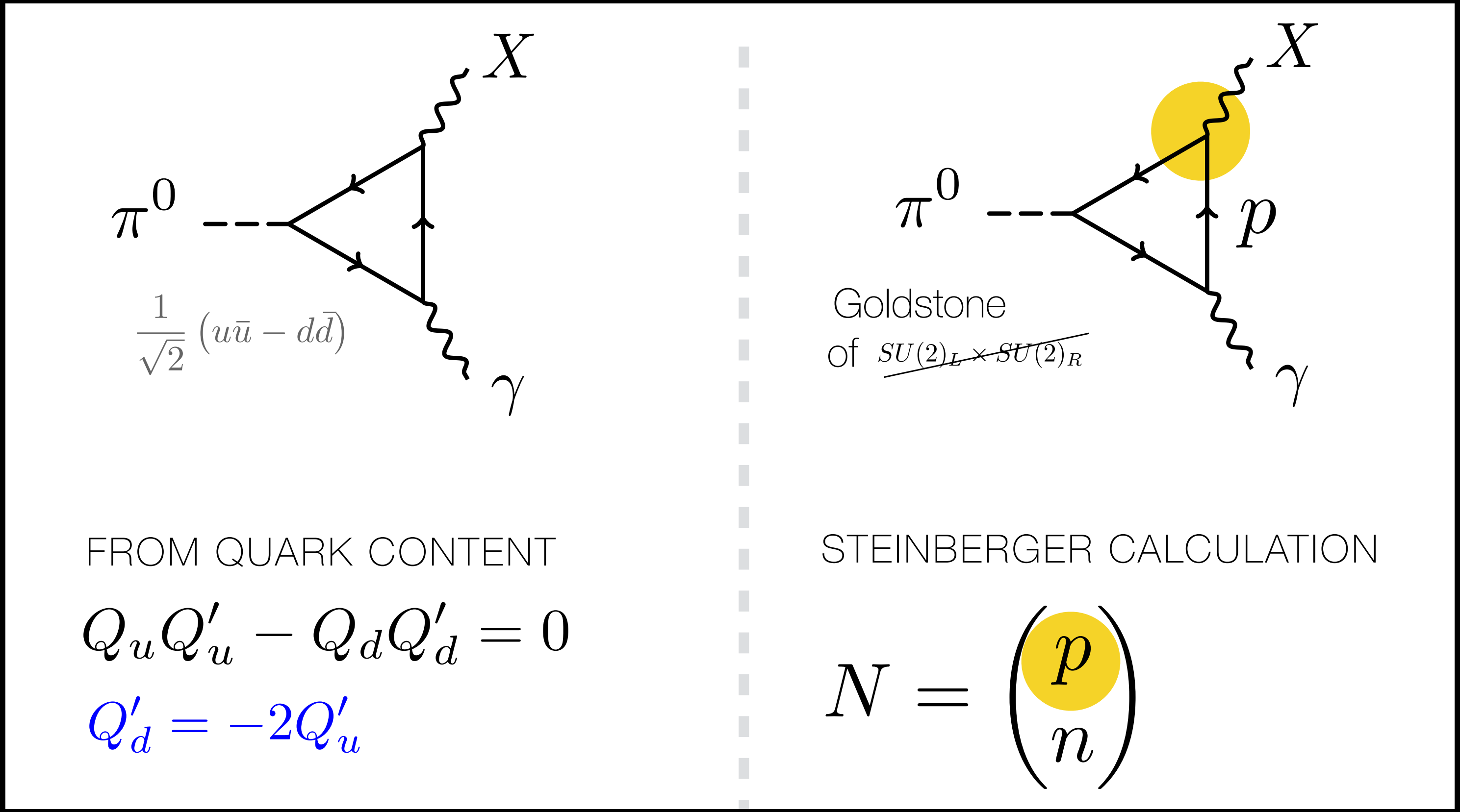
- Fitting the size of the signal requires ε~ 0.1, which is ruled out by NA48/2's search for $\pi^0 \to \gamma X$.



NA46/2 1504.00607

Proto-phobic Vectors

- We choose to focus from here on at vector (rather than axial vector) interactions.
- We'd like to engineer away the bounds from NA48/2 without turning off couplings to first generation quarks altogether, which drives us to ``proto-phobic'' couplings:



- Note that axial vectors will naturally evade NA48/2, since their couplings to π^0 do not go through the anomaly, and are thus suppressed by the small quark masses.

Isospin Violation

- To identify the target region for generalized up and down quark charges, we need to address the evidence for isospin mixing in the Be* and Be*' states.

Pastore, et al. Phys. Rev. C 90 [1406.2343]; Phys. Rev. C 88 [1308.5670]

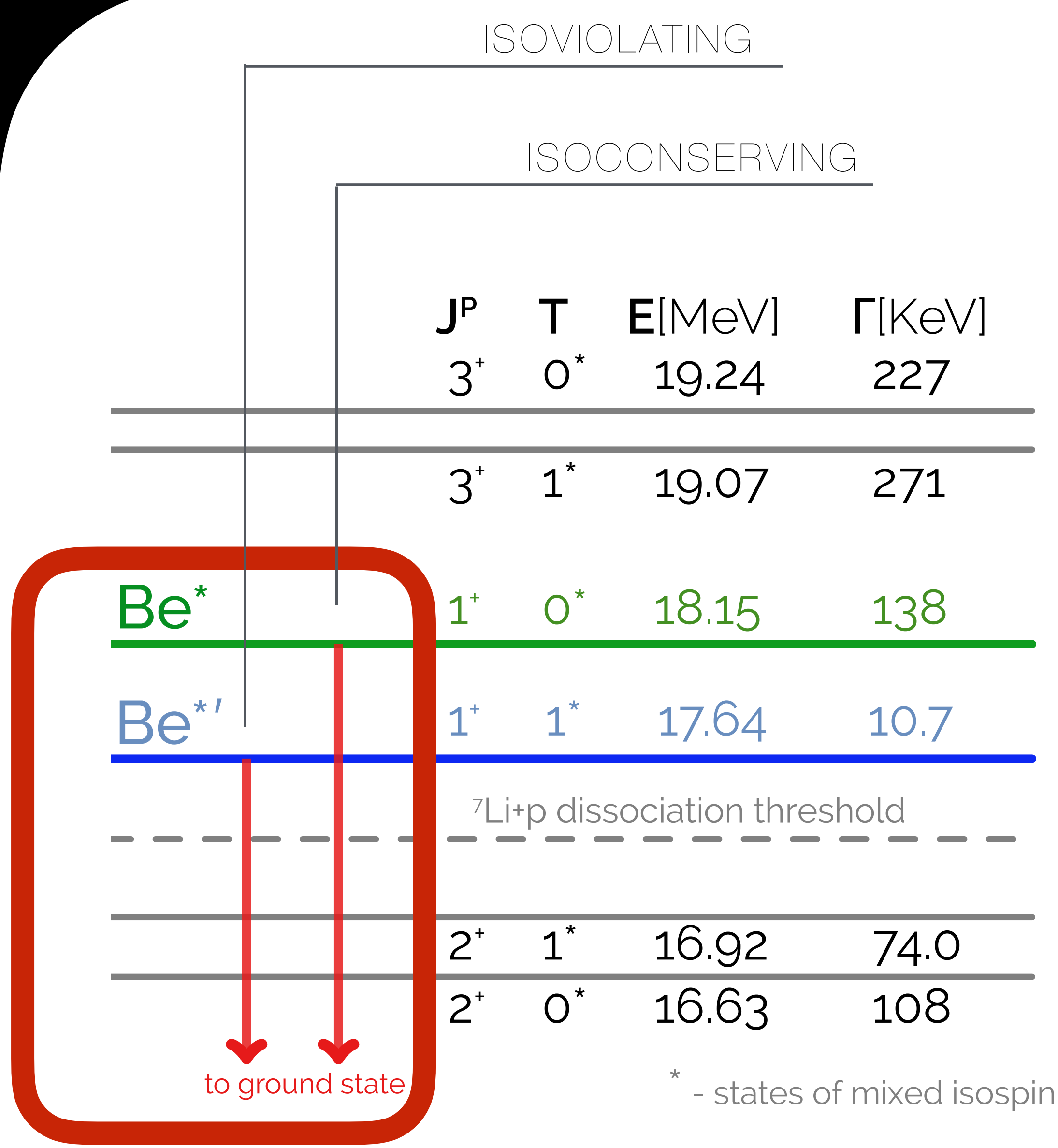
- Pastore et al infer that these states are mixed by looking at their hadronic decays, which find that the physical states {a,b} are related to eigenstates of isospin by:

$$\Psi^a = \alpha_1 \Psi_{T=0} + \beta_1 \Psi_{T=1}$$

$$\Psi^b = \beta_1 \Psi_{T=0} - \alpha_1 \Psi_{T=1}$$

- with mixing parameters:

$$\alpha_1 \sim 0.21(3) \qquad \beta_1 \sim 0.98(1)$$



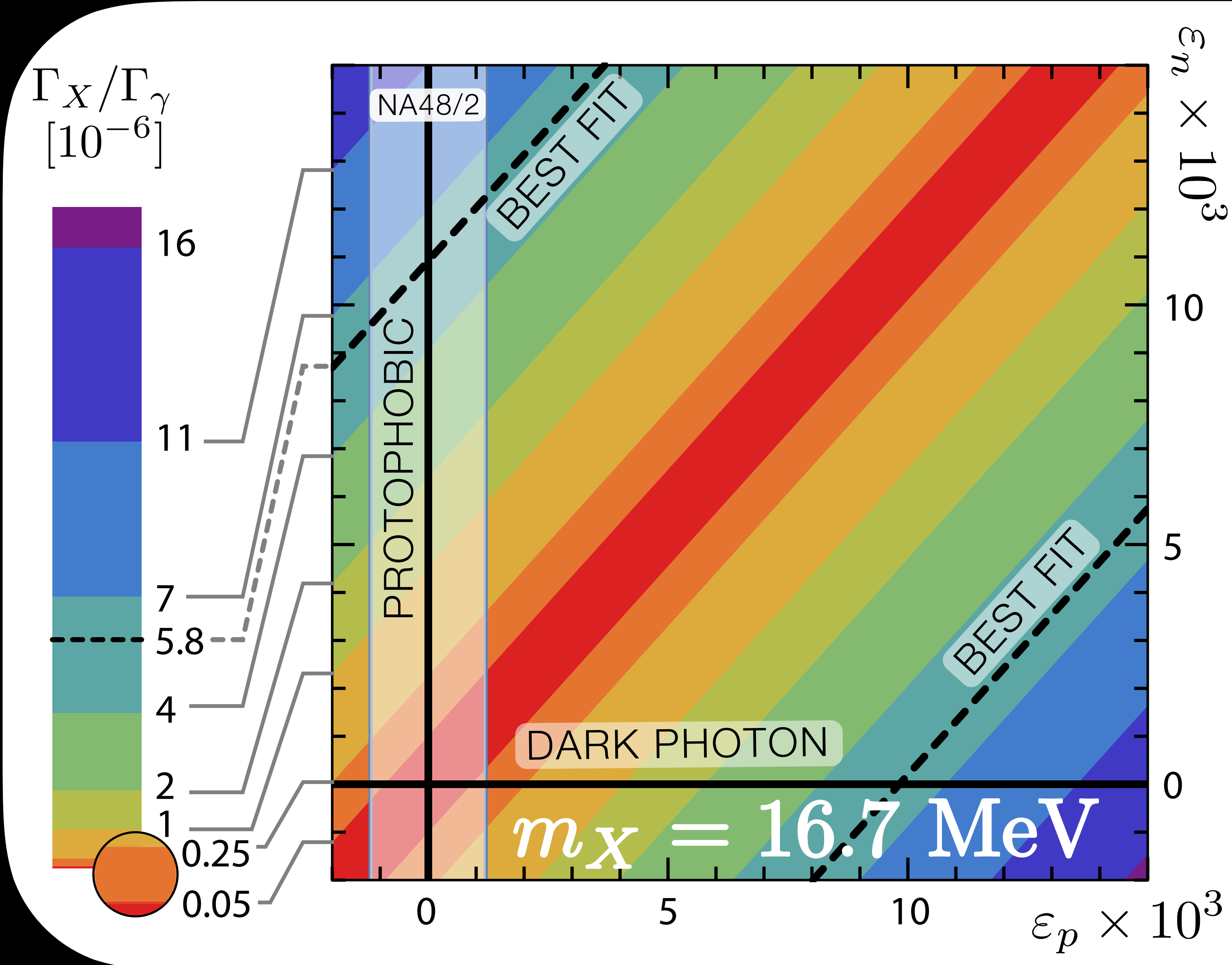
Results

$$\frac{\Gamma_X}{\Gamma_\gamma} = \frac{|(\varepsilon_p + \varepsilon_n)\beta_1 M1_{1,T=0} + (\varepsilon_p - \varepsilon_n)(-\alpha_1 M1_{1,T=1} + \beta_1 \kappa M1_{1,T=1})|^2}{|\beta_1 M1_{1,T=0} - \alpha_1 M1_{1,T=1} + \beta_1 \kappa M1_{1,T=1}|^2} \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

arXiv:1609.07411

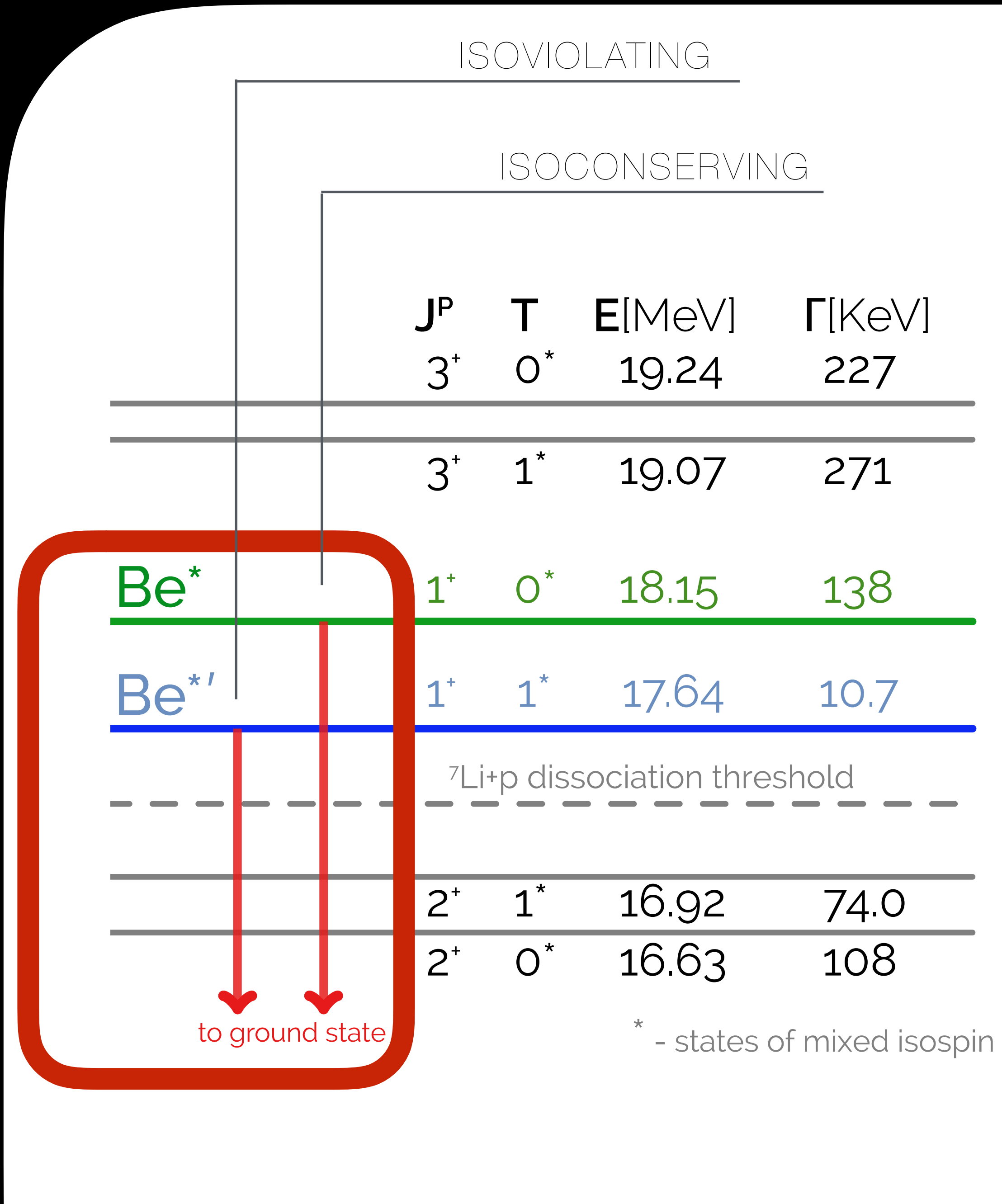
$$g_i \equiv e \times \varepsilon_i$$

To explain the ATOMKI results, one would like a coupling ε to neutrons of order 10^{-2} and one to protons < about 10^{-3}.



Why nothing from 17.64 ?

- The large isospin mixing between the 17.64 and 18.15 MeV states argues that it is difficult to use iso-spin structure to explain why no signal is seen in the Be*’ state.
- Of course, this possibility was also closed because protophobic couplings imply an equal admixture of isosinglet and isotriplet currents.
- Thus, the best prospect to explain why the new boson is produced in Be* but not Be*’ decays is the fact that the phase space is close to saturated.
- That said, the kinematics and isospin structure is such that eventually this decay must happen in any reasonable particle physics explanation.



Electron Couplings

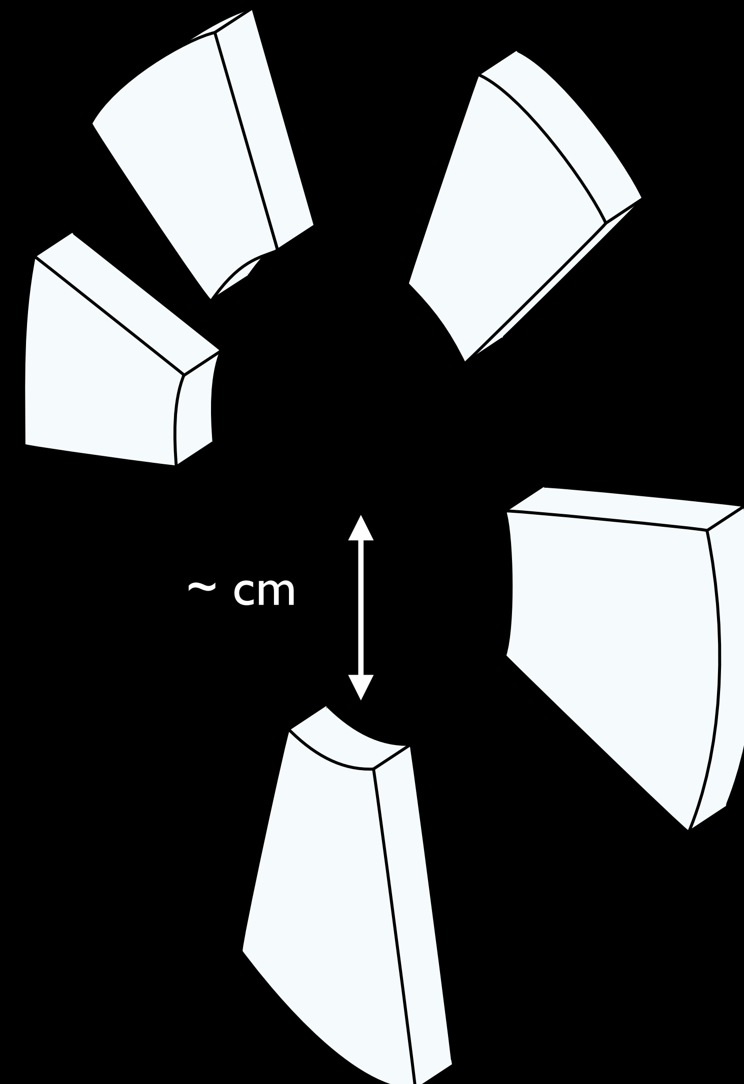
- The electron couplings are bounded from below by the need to decay promptly before the ATOMKI detectors, ~ cm from the target.

$$\Gamma(X \to e^+e^-) = \varepsilon_e^2 \alpha \frac{m_X^2 + 2m_e^2}{3m_X} \sqrt{1 - 4m_e^2/m_X^2}$$

- This requirement places the mild constraint that the electron couplings be:

$$\varepsilon_e \gtrsim 1.4 \times 10^{-5}$$

- It doesn't particularly care whether these couplings are vector or axial, but we choose vector couplings to avoid running into APV and other parity-odd observable constraints.

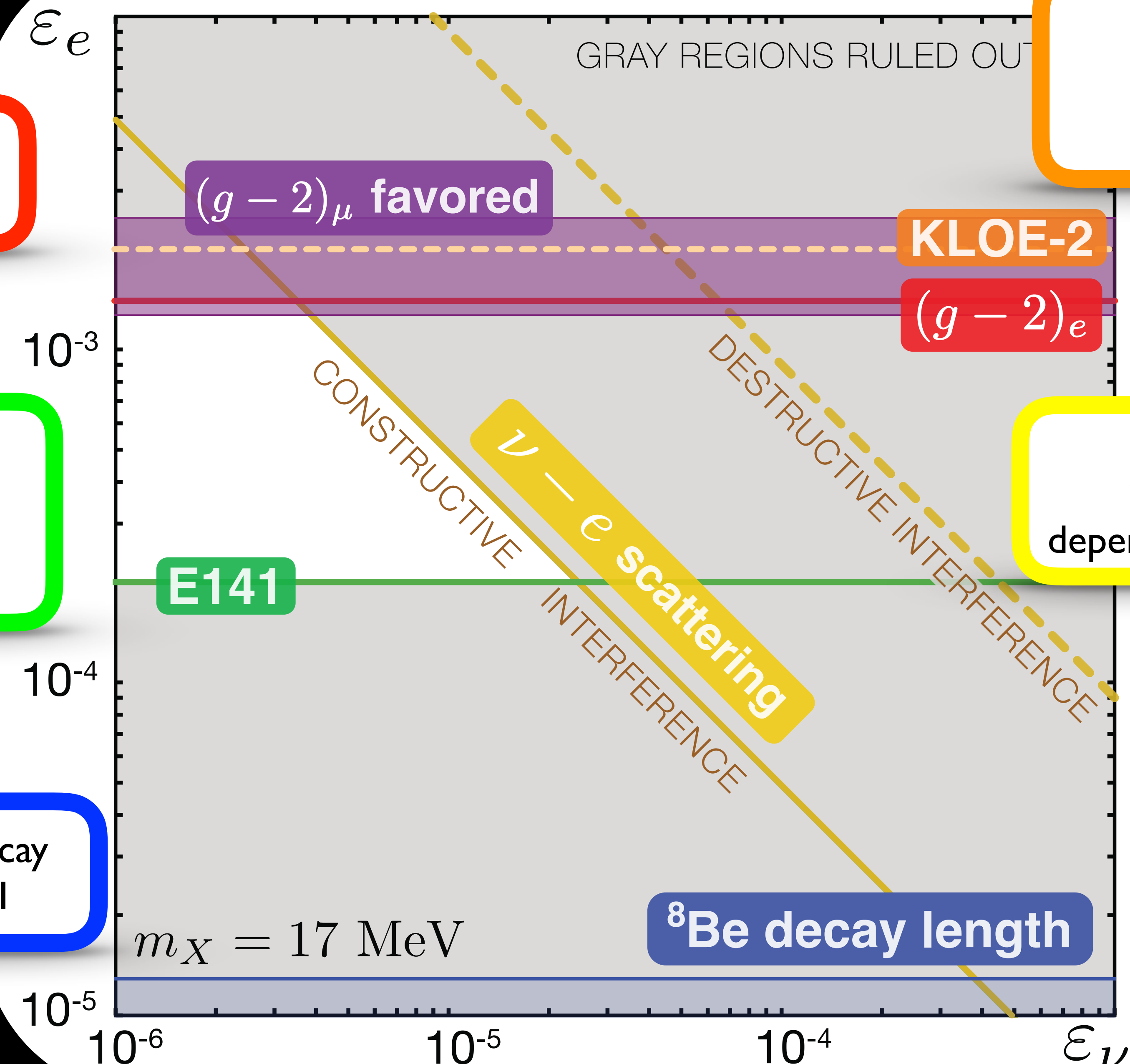


Lepton Couplings

(g-2)e

E141:
Lower bound so
X decays inside
the beam dump

Prompt X decay
at ATOMKI



KLOE-2:
e+e- → γX

TEXONO:
ν-e scattering;
depends on interference

arXiv:1608.03591

Summary of IR Parameters

$$\varepsilon_u = -\frac{1}{3}\varepsilon_n \approx \pm 3.7 \times 10^{-3}$$

$$\varepsilon_d = \frac{2}{3}\varepsilon_n \approx \mp 7.4 \times 10^{-3}$$

Protophobic to ~10%

$$2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

E141 and $(g-2)_e$

$$|\varepsilon_\nu \varepsilon_e|^{1/2} \lesssim 7 \times 10^{-5}$$

TEXONO

arXiv:1608.03591

Protophobic Challenge

- It is a model-building challenge to get protophobic couplings to the quarks, because they do not commute with SU(2) x U(1).
- Engineering them requires electroweak symmetry breaking. There are two simple options:
  - Mass mixing (through a Higgs charged under SU(2) x $U(1)_Y$ x $U(1)_X$):
    - A small fraction ($< 10^{-3}$) of the SM Z appears in the mass eigenstate.

$$\varepsilon_f = g_X X_f + \theta_Z g_f^Z$$

  - Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}\widetilde{F}_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}\widetilde{X}_{\mu\nu}\widetilde{X}^{\mu\nu} + \frac{\epsilon}{2}\widetilde{F}_{\mu\nu}\widetilde{X}^{\mu\nu} + \frac{1}{2}m_{\widetilde{X}}^2\widetilde{X}_\mu\widetilde{X}^\mu + \sum_f \bar{f}i\not{D}f$$

$$\varepsilon_f = g_X X_f + \epsilon Q_f$$

- Since mass mixing generically leads to axial couplings, we choose to follow the kinetic mixing path from here on.

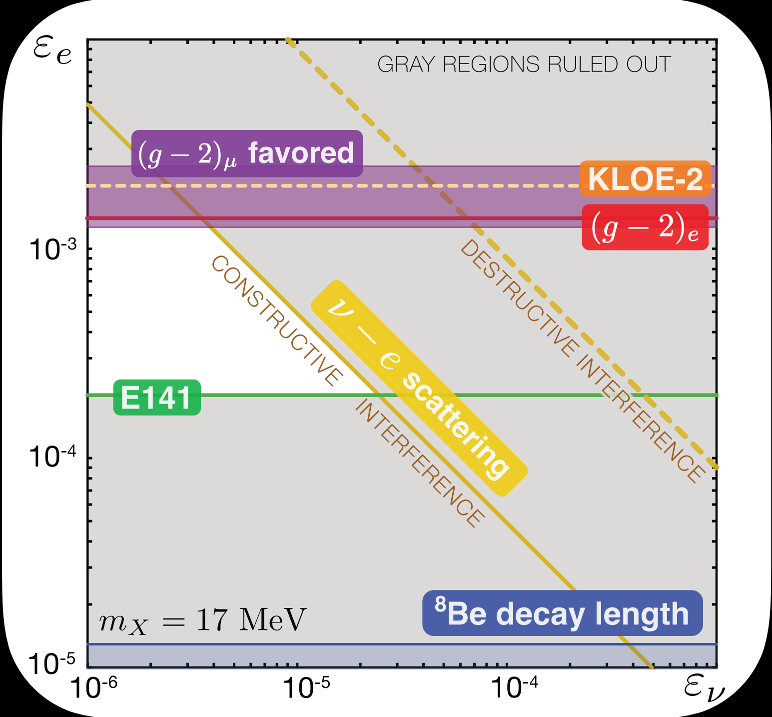
U(1) Baryon

- To begin with, take $U(1)_B$.
- By itself, this results in equal couplings to proton and neutron. The proton is neutralized if we tune the kinetic mixing parameter $\varepsilon = - g_B$.
  - This tuning is O(10%) to successfully evade NA48/2.
- The electron couplings tend to be generically a bit too big.
  - (However, the muon couplings are in the ballpark needed to address $(g - 2)_\mu$!)
- Neutrino couplings are naturally zero.

$$\begin{aligned} \varepsilon_u &= \frac{1}{3}\varepsilon_B + \frac{2}{3}\varepsilon \\ \varepsilon_d &= \frac{1}{3}\varepsilon_B - \frac{1}{3}\varepsilon \\ \varepsilon_\nu &= 0 \\ \varepsilon_e &= -\varepsilon \ . \end{aligned}$$

$$\epsilon = -g_B + \delta$$

$$\begin{aligned} \varepsilon_u &= -\frac{1}{3}\varepsilon_B + \frac{2}{3}\delta \\ \varepsilon_d &= \frac{2}{3}\varepsilon_B - \frac{1}{3}\delta \\ \varepsilon_\nu &= 0 \\ \varepsilon_e &= \varepsilon_B - \delta \ , \end{aligned}$$



U(1) Baryon Anomalons

- Cancelling anomalies requires us to add more fermions.
- A set of fermions which look like a chiral family of leptons (but carrying baryon number) will do the trick.
- The U(1)B - breaking Higgs VEV is too small to give them big enough masses, so they get the bulk of their masses from the SM Higgs.

Field	Isospin I	Hypercharge Y	B
S_B	0	0	3
Ψ_L	$\frac{1}{2}$	$-\frac{1}{2}$	B_1
Ψ_R	$\frac{1}{2}$	$-\frac{1}{2}$	B_2
η_R	0	-1	B_1
η_L	0	-1	B_2
χ_R	0	0	B_1
χ_L	0	0	B_2

$$B_2 - B_1 = 3$$

$$\begin{aligned}\mathcal{L}_Y = & -y_1 \overline{\Psi}_L h_{\mathrm{SM}} \eta_R - y_2 \overline{\Psi}_L \widetilde{h}_{\mathrm{SM}} \chi_R - y_3 \overline{\Psi}_R h_{\mathrm{SM}} \eta_L - y_4 \overline{\Psi}_R \widetilde{h}_{\mathrm{SM}} \chi_L \\ & -\lambda_\Psi S_B \overline{\Psi}_L \Psi_R - \lambda_\eta S_B \overline{\eta}_R \eta_L - \lambda_\chi S_B \overline{\chi}_R \chi_L + \mathrm{h.c.}\end{aligned}$$

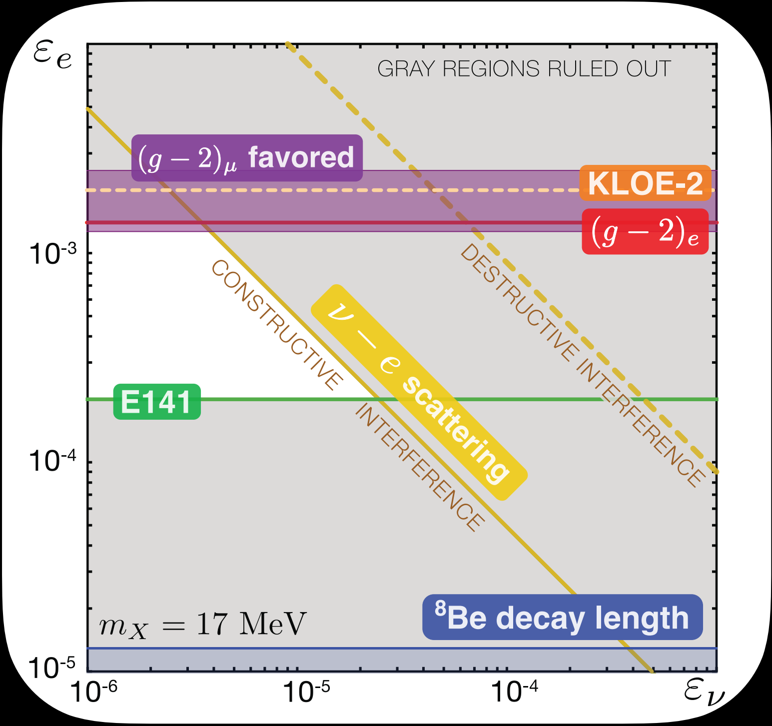
- Contributions to precision electroweak S and T parameters are acceptable for $\Delta M \sim 50$ GeV.
- LHC bounds require M > about 500 GeV.

These new fermions look something like charginos and neutralinos in the MSSM.

U(1) B-L

- An intrinsically anomaly free option is $U(1)_{B\text{-}L}$.
- This still results in equal couplings to proton and neutron, so again we neutralize the proton by O(10%) tuning of the kinetic mixing parameter to $\varepsilon = - g_{B\text{-}L}$.
- Now the electron couplings are naturally smaller than the quark couplings, as desired.
- The price to pay is that the neutrino couplings are not only non-zero, but roughly the size of the neutron coupling; too big!
    - We can dial these away by mixing with vector-like leptons. This still requires large Yukawa interactions, and generically produces chiral lepton couplings.

$$\begin{aligned}
\varepsilon_u &= -\frac{1}{3}\varepsilon_{B-L} + \frac{2}{3}\delta \\
\varepsilon_d &= \frac{2}{3}\varepsilon_{B-L} - \frac{1}{3}\delta \\
\varepsilon_\nu &= -\varepsilon_{B-L} \\
\varepsilon_e &= -\delta \ .
\end{aligned}$$



Outlook

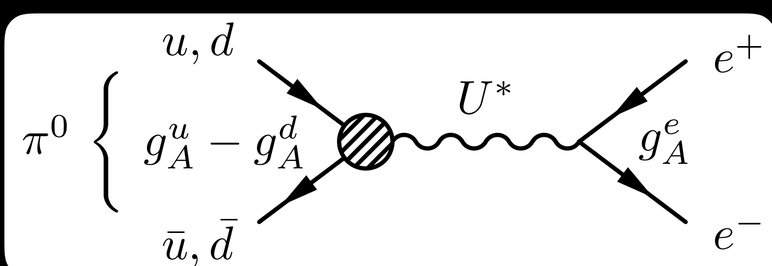
- A bump in the e+e- invariant mass spectrum of a rare decay of ^{8}Be* to the ^{8}Be ground state motivates a new particle whose mass is ~ 17 MeV.
    - Statistically, the signal is ~6.8σ. In my mind, the main question is the modeling of nuclear background processes.
    - Requires ~ 10^{-3} couplings to quarks, and should not appear in π^0 decays. For a vector, this happens for protophobic couplings.
- There could be connections to other mysteries at the MeV scale:
    - $(g - 2)_\mu$?
        - Couplings are in the correct ballpark.
    - Proton radius?
        - Difficult to build models.

Outlook

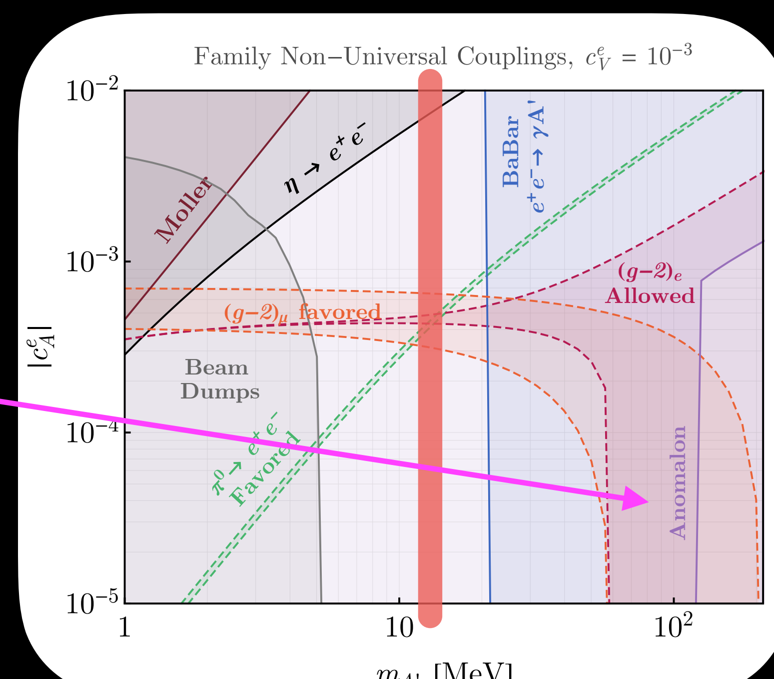
- There could be connections to other mysteries at the MeV scale:
  - Self-interacting dark matter?
    - Attempted in 1609.01605.
    - Problems with direct detection?
  - $\pi^0 \rightarrow$ e+e- as measured by KTev?
    - Longstanding 2-3σ discrepancy; requires axial couplings.

Kitahara, Yamamoto
[1609.01606]

Kahn, Krnjaic, Mishra-Sharma, TMPT
arXiv:1609.09072



Requires careful understanding of UV physics canceling anomalies.



Kahn, Schmitt, TMPT
arXiv:0712.007 & PRD

$$(g_A^u - g_A^d)g_A^e \left(\frac{20\ \text{MeV}}{m_X}\right)^2 \approx 1.6 \times 10^{-7}$$

Outlook

- The next step is obviously to get experimental confirmation.
  - ATOMKI is running with new detectors.
  - TUNL?
  - Purdue?
  - …
- Upcoming low energy experiments can probe the relevant parameter space…

Outlook

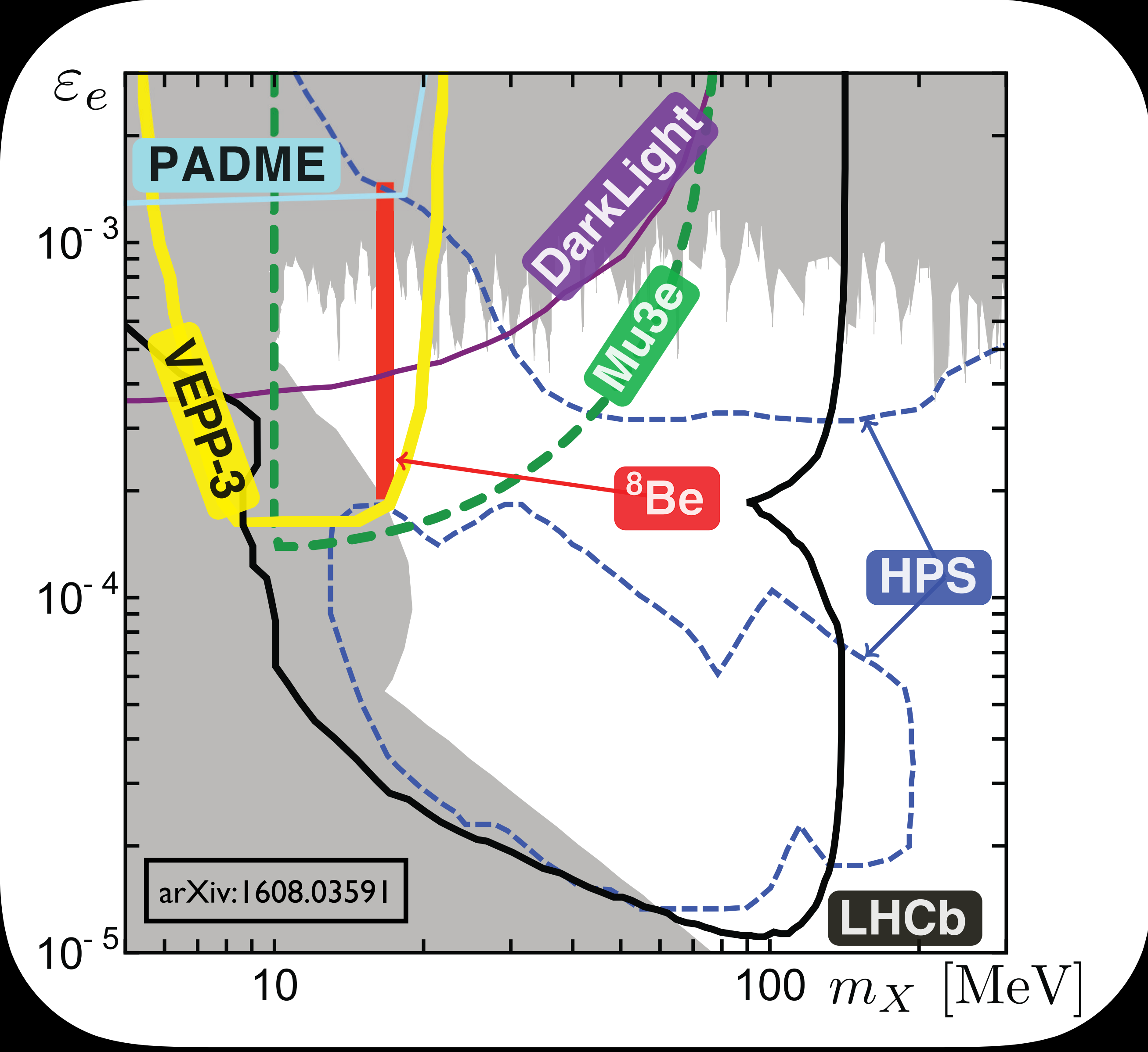
- Upcoming low energy experiments can probe the relevant parameter space…

Mu3e, phase 2
(starting 018)

LHCb, run 3
(2021-2023)

Darklight II
e+e- ⟶ γX
(a few years?)

VEPP-3 (proposed)
e+e- ⟶ γX



Grazie!

Bonus Slides

Considered Constraints

(Lifted directly from arXiv:1609.07411)

A. Quark Coupling Constraints

The production of the X boson in $^8\text{Be}^*$ decays is completely governed by its couplings to hadronic matter. The most stringent bound on these couplings in the $m_X \approx 17$ MeV mass range is the decay of neutral pions into $X\gamma$. For completeness, we also list the leading subdominant constraints on ε_q, for $q = u, d$.

1. *Neutral pion decay, $\pi^0 \to X\gamma$*

The primary constraint on new gauge boson couplings to quarks comes from the NA48/2 experiment, which performs a search for rare pion decays $\pi^0 \to \gamma(X \to e^+e^-)$ [58]. The bound scales like the anomaly trace factor $N_\pi \equiv (\varepsilon_u q_u - \varepsilon_d q_d)^2$. Translating the dark photon bound $N_\pi < \varepsilon_{\text{max}}^2/9$ to limits on the new gauge boson couplings gives

$$|2\varepsilon_u + \varepsilon_d| \;=\; |\varepsilon_p| \;\lesssim\; \frac{(0.8 - 1.2) \times 10^{-3}}{\sqrt{\text{Br}(X \to e^+e^-)}} \;, \tag{34}$$

where the range comes from the rapid fluctuations in the NA48/2 limit for masses near 17 MeV. In Ref. [7], we observed that the left-hand side becomes small when the X boson is protophobic—that is, when its couplings to protons are suppressed relative to neutrons.

2. *Neutron–lead scattering*

A subdominant bound is set from measurements of neutron-nucleus scattering. The Yukawa potential acting on the neutron is $V(r) = -(\varepsilon_n e)^2 A e^{-m_X r}/(4\pi r)$, where A is the atomic mass number. Observations of the angular dependence of neutron–lead scattering constrain new, weakly-coupled forces [59], leading to the constraint

$$\frac{(\varepsilon_n e)^2}{4\pi} < 3.4 \times 10^{-11} \left(\frac{m_X}{\text{MeV}}\right)^4 . \tag{35}$$

3. *Proton fixed target experiments*

The ν-Cal I experiment at the U70 accelerator at IHEP sets bounds from X-bremsstrahlung off the initial proton beam [60] and $\pi^0 \to X\gamma$ decays [61]. Both of these processes are suppressed in the protophobic scenario so that these bounds are automatically satisfied when Eq. (34) is satisfied.

4. *Charged kaon and ϕ decays*

There are also bounds on second generation couplings. The NA48/2 experiment places limits on $K^+ \to \pi^+(X \to e^+e^-)$ [43]. For $m_X \approx 17$ MeV, the bound on ε_n is much weaker than the one from π^0 decays in Eq. (34) [56, 62]. The KLOE-2 experiment searches for $\phi \to \eta(X \to e^+e^-)$ and restricts [63]

$$|\varepsilon_s| \lesssim \frac{1.0 \times 10^{-2}}{\sqrt{\text{Br}(X \to e^+e^-)}} . \tag{36}$$

In principle ε_s is independent and need not be related to the $^8\text{Be}^*$ coupling. However, in the limit of minimal flavor violation, one assumes $\varepsilon_d = \varepsilon_s$.

5. *Other meson and baryon decays*

The WASA-at-COSY experiment also sets limits on quark couplings based on neutral pion decays. It is both weaker than the NA48/2 bound and only applicable for masses heavier than 20 MeV [64]. The HADES experiment searches for dark photons in π^0, η, and Δ decays and restricts the kinetic mixing parameter to $\varepsilon \lesssim 3 \times 10^{-3}$ but only for masses heavier than 20 MeV [65]. HADES is able to set bounds on gauge bosons around 17 MeV in the $\pi^0 \to XX \to e^+e^-e^+e^-$ decay channel. This, however, is suppressed by ε_n^4 and is thus insensitive to $|\varepsilon_n| \lesssim 10^{-2}$. Similar considerations suppress X contributions to other decays, such as $\pi^+ \to \mu^+\nu_\mu e^+e^-$, to undetectable levels.

6. *W and Z decays*

The X boson can be produced as final state-radiation in W and Z decays into SM fermions. When the X then decays into an electron–positron pair, this gives a contribution to $\Gamma(Z \to 4e)$ that is suppressed by $\mathcal{O}(\varepsilon_e^2)$. For the electron couplings $\varepsilon_e \lesssim 10^{-3}$ required here, the impact on the inclusive widths is negligible compared to the order per mille experimental uncertainties on their measurement [66]. The specific decay $Z \to 4\ell$ has been measured to lie within 10% of the SM expectation by ATLAS and CMS [67, 68] and is consistent with the couplings of interest here.

B. Electron Coupling Constraints

The X boson is required to couple to electrons to contribute to IPC events. In Eq. (30) we gave a lower limit on ε_e in order for X to decay within 1 cm of its production in the Atomki apparatus. In this section we review other bounds on this coupling.

1. *Beam dump experiments*

Electron beam dump experiments, such SLAC E141 [69, 70], search for dark photons bremsstrahlung from electrons that scatter off target nuclei. For $m_X = 17$ MeV, these experiments restrict $|\varepsilon_e|$ to live in one of two regimes: either it is small enough to avoid production, or large enough that the X decay products are caught in the dump [71], leading to

$$|\varepsilon_e| < 10^{-8} \qquad \text{or} \qquad \frac{|\varepsilon_e|}{\sqrt{\mathrm{Br}(X \to e^+e^-)}} \gtrsim 2 \times 10^{-4} \,. \tag{37}$$

The region $|\varepsilon_e| < 10^{-8}$ is excluded since the new boson would not decay inside the Atomki apparatus. This leads to the conclusion that X must decay inside the beam dump. Less stringent bounds come from Orsay [72] and the SLAC E137 [73] experiment. The E774 experiment at Fermilab is only sensitive to $m_X < 10$ MeV [74].

2. *Magnetic moment of the electron*

The upper limit on $|\varepsilon_e|$ can be mapped from dark photon searches that depend only on leptonic couplings. The strongest bound for $m_X = 17$ MeV is set by the anomalous magnetic moment of the electron, $(g-2)_e$, which constrains the coupling of the new boson to be [62]

$$|\varepsilon_e| < 1.4 \times 10^{-3} \,. \tag{38}$$

3. *Electron–positron annihilation into X and a photon, $e^+e^- \to X\gamma$*

A similar bound arises from the KLOE-2 experiment, which looks for $e^+e^- \to X\gamma$ followed by $X \to e^+e^-$, and finds $|\varepsilon_e|\sqrt{\mathrm{Br}(X \to e^+e^-)} < 2\times 10^{-3}$ [75]. An analogous search at BaBar is limited to $m_X > 20$ MeV [76].

4. *Proton fixed target experiments*

The CHARM experiment at CERN also bounds X couplings through its searches for $\eta, \eta' \to \gamma(X \to e^+e^-)$ [77]. The production of the X boson in the CHARM experiment is governed by its hadronic couplings. The couplings required by the anomalous IPC events, Eq. (31), are large enough that the X boson would necessarily be produced in CHARM. Given the lower bound from decay in the Atomki spectrometer, Eq. (30), the only way to avoid the CHARM constraint for $m_X = 17$ MeV is if the decay length is short enough that the X decay products do not reach the CHARM detector. The dark photon limit on ε applies to ε_e and yields

$$\frac{|\varepsilon_e|}{\sqrt{\mathrm{Br}(X \to e^+e^-)}} > 2 \times 10^{-5} \; . \tag{39}$$

This is weaker than the analogous lower bound on $|\varepsilon_e|$ from beam dump experiments. LSND data imposes an even weaker constraint [78–80].

C. Neutrino Coupling Constraints

The interaction of a light gauge boson with neutrinos is constrained in multiple ways, depending on the SM currents to which the boson couples; see Refs. [81, 82]. The neutrino coupling is relevant for the ^{8}Be anomaly because $SU(2)_L$ gauge invariance relates the electron and neutrino couplings. Because neutrinos are lighter than electrons, this generically opens additional X decay channels and reduces $\mathrm{Br}(X \to e^+e^-)$. This, in turn, reduces the lower bound on ε_e in Eq. (30) and alleviates many of the experimental constraints above at the cost of introducing new constraints from X–neutrino interactions.

1. *Neutrino–electron scattering*

Neutrino–electron scattering stringently constrains the X boson's leptonic couplings. In the mass range $m_X \approx 17$ MeV, the most stringent constraints are from the TEXONO experiment, where $\bar{\nu}_e$ reactor neutrinos with average energy $\langle E_\nu \rangle = 1 - 2$ MeV travel 28 meters and scatter off electrons. The resulting electron recoil spectrum is measured. The path length is short, so the neutrinos remain in nearly pure ν_e flavor eigenstates. In the SM, $\bar{\nu}_e e \to \bar{\nu}_e e$ scattering is mediated by both s- and t-channel diagrams. A new neutral gauge boson that couples to both neutrinos and electrons induces an additional t-channel contribution.

Because constraints from $\bar{\nu}_e e$ scattering are sensitive to the interference of SM and new physics, they depend on the signs of the new gauge couplings, unlike all of the other constraints discussed above. The importance of the interference term has been highlighted in Ref. [48] in the context of a $B - L$ gauge boson model. In that model, the neutrino and electron couplings have the same sign, and the interference was found to be always constructive.

Assuming that the experimental bound is determined by the total cross section and not the shape of the recoil spectrum, one may use the results of Ref. [48] to determine the bounds in our more general case, where the couplings can be of opposite sign and the interference may be either constructive or destructive. Define the quantity $g \equiv |\varepsilon_e \varepsilon_\nu|^{1/2}$. Let $\Delta\sigma$ be the maximal allowed deviation from the SM cross section and $g_\pm$ (g_0) be the values of g that realize $\Delta\sigma$ in the case of constructive/destructive (negligible) interference,

$$\Delta\sigma = \quad g_0^4 \sigma_X \tag{40}$$

$$\Delta\sigma = \quad g_+^2 \sigma_{\rm int} + g_+^4 \sigma_X \tag{41}$$

$$\Delta\sigma = -g_-^2 \sigma_{\rm int} + g_-^4 \sigma_X \ , \tag{42}$$

where $g^4\sigma_X$ is the purely X-mediated contribution to the cross section and $g^2\sigma_{\rm int}$ is the absolute value of the interference term. Solving these equations for the g's yields the simple relation

$$g_- g_+ = g_0^2 \ . \tag{43}$$

The authors of Ref. [48] found that for $m_X = 17$ MeV, the maximal allowed $B-L$ gauge boson coupling, g_{B-L}, is 2×10^{-5} and 4×10^{-5} in the cases of constructive interference and no interference, respectively. From this, including the factor of e difference between the definitions of g_{B-L} and our ε's, we find

$$\sqrt{|\varepsilon_e \varepsilon_\nu|} < 7 \times 10^{-5} \qquad \text{for} \quad \varepsilon_e \varepsilon_\nu > 0 \quad \text{(constructive interference)} \tag{44}$$

$$\sqrt{|\varepsilon_e \varepsilon_\nu|} < 3 \times 10^{-4} \qquad \text{for} \quad \varepsilon_e \varepsilon_\nu < 0 \quad \text{(destructive interference)} \ . \tag{45}$$

The relative sign of the couplings thus has a significant effect. For a fixed value of ε_e, the bound on $|\varepsilon_\nu|$ is 16 times weaker for the sign that produces destructive interference than for the sign that produces constructive interference.

In addition to its well-known motivations of providing interesting measurements of $\sin\theta_W$ and bounds on heavy Z' boson [83, 84], coherent neutrino–nucleus scattering, may also provide leading constraints on light, weakly-coupled particles [85, 86]. Although ν–N scattering has not yet been observed, it is the target of a number of upcoming experiments that use reactors as sources. In addition, the process can also be probed using current and next-generation dark matter direct detection experiments by searching for solar neutrino scattering events [87]. For a $B-L$ gauge boson, this sensitivity has been estimated in Ref. [88] for SuperCDMS, CDMSlite, and LUX, with the latter providing the most stringent constraint of $g_{B-L} \lesssim 1.5 \times 10^{-4}$. Rescaling this result to the case of a boson with couplings $\varepsilon_\nu e$ and $\varepsilon_{p,n} e$ to nucleons yields

$$\varepsilon_\nu \varepsilon_n \left[(A-Z) + Z \frac{\varepsilon_p}{\varepsilon_n} \right] < \frac{A}{4\pi\alpha} \left(1.5 \times 10^{-4}\right)^2 \ , \tag{46}$$

where we approximate the LUX detector volume to be composed of a single xenon isotope. Since the NA48/2 bounds on $\pi^0 \to X\gamma$ imply the protophobic limit where $\varepsilon_p \ll \varepsilon_n$, the second term on the left-hand side may be ignored. Taking $A = 131$ and $Z = 54$ then yields $|\varepsilon_\nu \varepsilon_n|^{1/2} < 6 \times 10^{-4}$ or

$$\varepsilon_\nu < 2 \times 10^{-4} \left(\frac{0.002}{\varepsilon_n} \right) \ . \tag{47}$$

This bound is weaker than the ν–e scattering bound with constructive interference and comparable to the ν–e bound with destructive interference. As the ν–N bounds are estimated sensitivities, we use the ν–e bounds in the discussion below.

Future Probes

(Lifted directly from arXiv:1609.07411)

Other Large Energy Nuclear Transitions. The ^{8}Be* and ^{8}Be$^{*\prime}$ states are quite special in that they decay electromagnetically to discrete final states with an energy release in excess of 17 MeV. Other large-energy gamma transitions have been observed [122], such as the 19.3 MeV transition in ^{10}B to its ground state [123] and the 17.79 MeV transition in ^{10}Be to its ground state [124]. Of course, what is required is large production cross sections and branching fractions so that many IPC events can be observed. It would certainly be interesting to identify other large energy nuclear transitions with these properties to test the new particle interpretation of the ^{8}Be anomaly.

LHCb. A search for dark photons A' at LHCb experiment during Run 3 (scheduled for the years 2021 – 2023) has been proposed [125] using the charm meson decay $D^*(2007)^0 \to D^0 A'$ with subsequent $A' \to e^+e^-$. It takes advantage of the LHCb excellent vertex and invariant mass resolution. For dark photon masses below about 100 MeV, the experiment can explore nearly all of the remaining parameter space in ε_e between the existing prompt-A' and beam-dump limits. In particular, it can probe the entire region relevant for the X gauge boson explaining the ^{8}Be anomaly.

Mu3e. The Mu3e experiment will look at the muon decay channel $\mu^+ \to e^+\nu_e\bar{\nu}_\mu(A' \to e^+e^-)$ and will be sensitive to dark photon masses in the range $10 \text{ MeV} \lesssim m_{A'} \lesssim 80 \text{ MeV}$ [126]. The first phase (2015 – 2016) will probe the region $\varepsilon_e \gtrsim 4 \times 10^{-3}$, while phase II (2018 and beyond) will extend this reach almost down to $\varepsilon_e \sim 10^{-4}$, which will include the whole region of interest for the protophobic gauge boson X.

VEPP-3. A proposal for a new gauge boson search at the VEPP-3 facility was made [127]. The experiment will consist of a positron beam incident on a gas hydrogen target and will look for missing mass spectra in $e^+e^- \to A'\gamma$. The search will be independent of the A' decay modes and lifetime. Its region of sensitivity in ε_e extends down into the beam dump bounds, i.e., below $\varepsilon_e \sim 2 \times 10^{-4}$, and includes the entire region relevant for X. Once accepted, the experiment will take 3 – 4 years.

KLOE-2. As mentioned above, the KLOE-2 experiment, looking for $e^+e^- \to \gamma(X \to e^+e^-)$, is running and improving its current bound of $|\varepsilon_e| < 2 \times 10^{-3}$ [75] for $m_X \approx 17$ MeV. With the increased DAϕNE-2 delivered luminosity and the new detectors, KLOE-2 is expected to improve this limit by a factor of two within two years [128].

MESA. The MESA experiment will use an electron beam incident on a gaseous target to produce dark photons of masses between $\sim 10-40$ MeV with electron coupling as low as $\varepsilon_e \sim 3 \times 10^{-4}$, which would probe most of the available X boson parameter space [129]. The commissioning is scheduled for 2020.

DarkLight. The DarkLight experiment, similarly to VEPP-3 and MESA, will use electrons scattering off a gas hydrogen target to produce on-shell dark photons, which later decay to e^+e^- pairs [130]. It is sensitive to masses in the range $10-100$ MeV and ε_e down to 4×10^{-4}, covering the majority of the allowed protophobic X parameter space. Phase I of the experiment is expected to take data in the next 18 months, whereas phase II could run within two years after phase I.

HPS. The Heavy Photon Search experiment is using a high-luminosity electron beam incident on a tungsten target to produce dark photons and search for both $A' \to e^+e^-$ and $A' \to \mu^+\mu^-$ decays [131]. Its region of sensitivity is split into two disconnected pieces (see Fig. 6) based on the analyses used: the upper region is probed solely by a bump hunt search, whereas the lower region also includes a displaced vertex search. HPS is expected to complete its dataset by 2020.

PADME. The PADME experiment will look for new light gauge bosons resonantly produced in collisions of a positron beam with a diamond target, mainly through the process $e^+e^- \to X\gamma$ [132]. The collaboration aims to complete the detector assembly by the end of 2017 and accumulate 10^{13} positrons on target by the end of 2018. The expected sensitivity after one year of running is $\varepsilon_e \sim 10^{-3}$, with plans to get as low as 10^{-4} [133, 134].

BES III. Current and future e^+e^- colliders, may also search for $e^+e^- \to X\gamma$. A recent study has explored the possibility of using BES III and BaBar to probe the 17 MeV protophobic gauge boson [13].