THE BERYLLIUM ANOMALY AND NEW PHYSICS

Invisibles/Elusives Network

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OUTLINE

A. J. Krasznhorkay *et al.*, "Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson," 1504.01527 [nucl-ex], PRL 116, 042501 (2016)

J. Feng *et al.*, "Protophobic Fifth Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions," 1604.07411 [hep-ph], PRL 117, 071803 (2016)

J. Feng *et al.*, "Particle Physics Models for the 17 MeV Anomaly in Beryllium Nuclear Decays," 1608.03591 [hep-ph]


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LIGHT, WEAKLY-COUPLED PARTICLES

- There are currently many outstanding puzzles: neutrino masses, gauge hierarchy, strong CP, flavor, dark matter, baryogenesis, dark energy,...
- Some of these motivate searches for new particles and forces at high energies
- But some also motivate searches for new physics that is light, but weakly coupled
- For example: neutrino masses, strong CP, and dark matter

AN EXAMPLE: DARK MATTER

- All evidence for dark matter is gravitational. Perhaps it is in a hidden sector, composed of particles with no SM gauge interactions (electromagnetic, weak, strong)

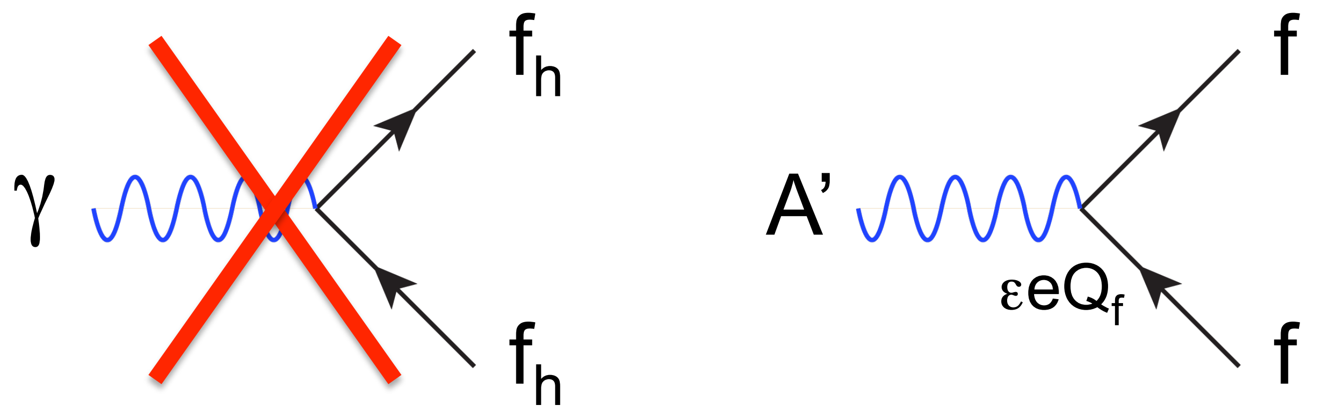
- This hidden sector may have a rich structure with matter and forces of its own

Lee, Yang (1956); Kobsarev, Okun, Pomeranchuk (1966); Blinnikov, Khlopov (1982); Foot, Lew, Volkas (1991); Hodges (1993); Berezhiani, Dolgov, Mohapatra (1995); …

VECTOR PORTAL

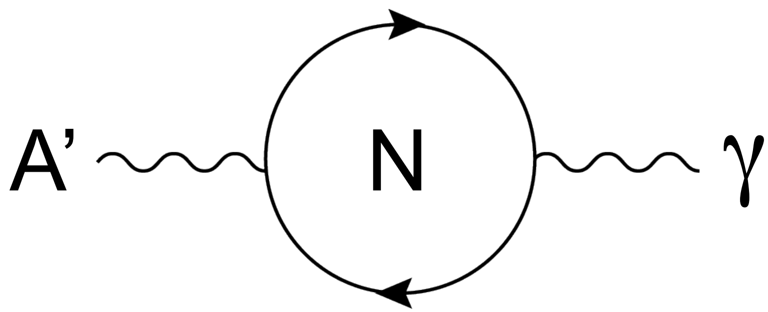
Holdom (1986)

- If the hidden sector has a massive U(1) gauge boson, the operator $\epsilon F_{\mu\nu} F_h^{\mu\nu}$ kinetic mixes the SM photon and the massive hidden photon
- In the mass basis, one finds that the physical states are the massless SM photon γ and a massive "dark photon" A'
- The SM photon does not couple to hidden particles. But the dark photon couples to SM particles with charges proportional to their SM charges



DARK PHOTONS

- The kinetic mixing parameter: $\varepsilon \sim 10^{-3}$ N from 1-loop effects, where N is the number of particles in the loop, even for arbitrarily heavy particles in the loop (non-decoupling)

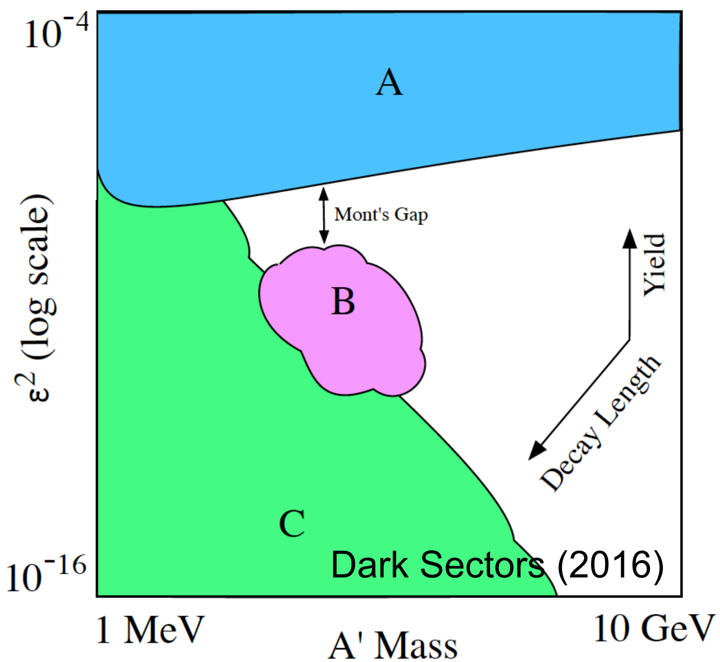


- A dark photon mass $m_{A'} \sim$ 1-100 MeV may induce strong DM self-interactions or (with $\varepsilon \sim 10^{-3}$) resolve the $(g\text{-}2)_\mu$ anomaly

- This motivates searches for dark photons in a vast, unexplored $(m_{A'}, \varepsilon)$ parameter space with, perhaps, a region of special interest with $m_{A'} \sim$ 1-100 MeV and $\varepsilon \sim 10^{-3}$

CURRENT CONSTRAINTS

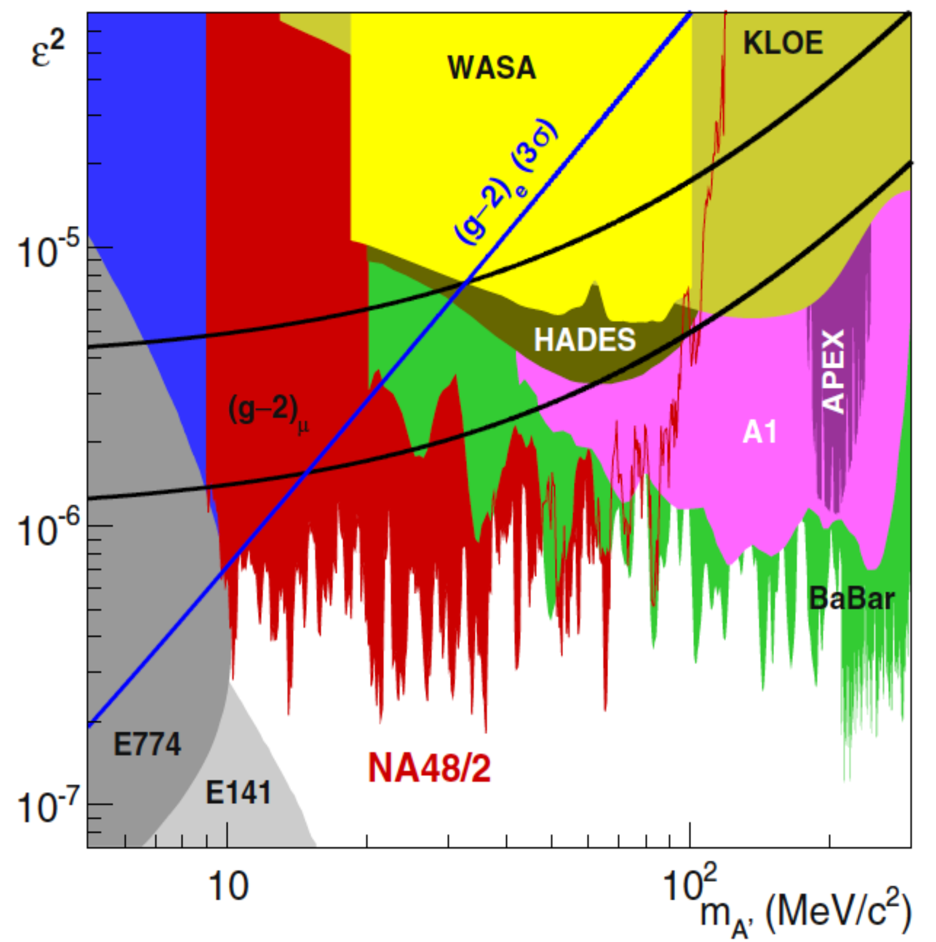
The world-wide program to search for dark photons A'



A: Bump hunts

B: Displaced vertices (short decays)

C: Beam dumps (long decays)



More to be done, but experiments already exclude A' as a $(g-2)_\mu$ solution

NEW PHYSICS IN NUCLEAR TRANSITIONS

- Nuclear transitions can be powerful probes of MeV-scale new physics

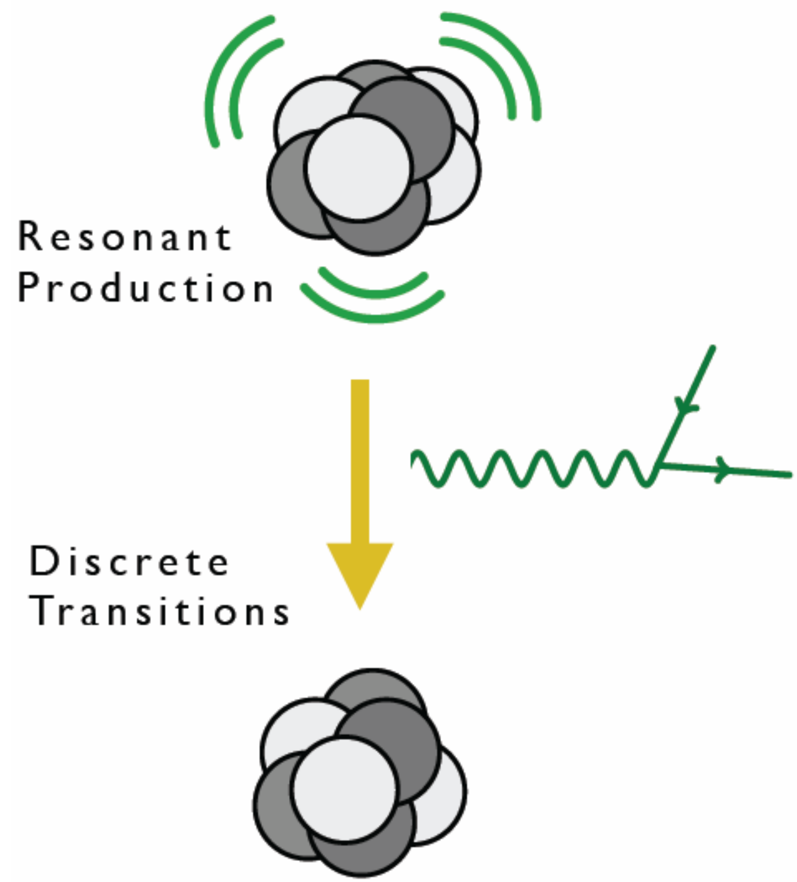
Treiman, Wilczek (1978)
Donnelly, Freedman, Lytel, Peccei, Schwartz (1978)
Savage, McKeown, Filippone, Mitchell (1986)

- A recent 6.8σ experimental anomaly might indicate the production of new particles in excited ^{8}Be decays

A. J. Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]

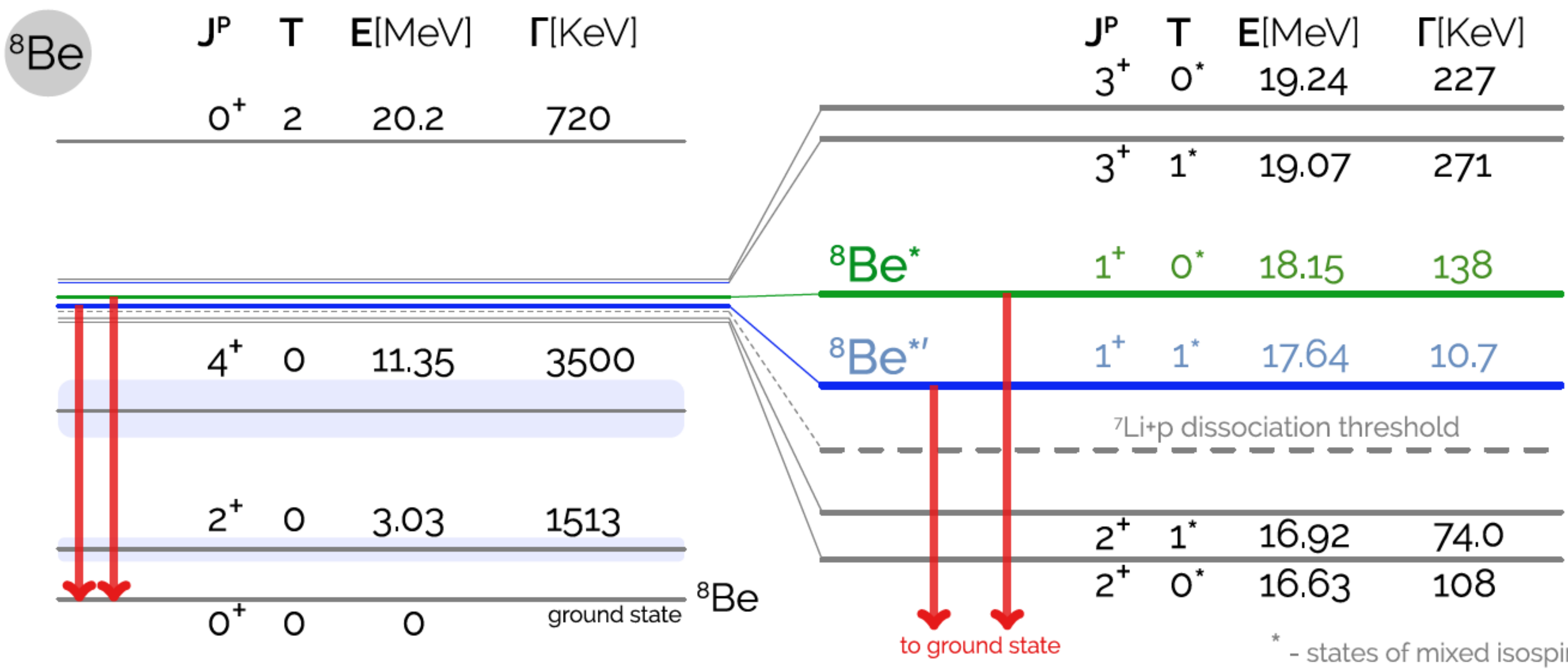
^{8}BE AS A NEW PHYSICS LAB

- ^{8}Be is composed of 4 protons and 4 neutrons
- Excited states can be produced in large numbers through p + ^{7}Li → high statistics “intensity” frontier
- Excited states decay to ground state with relatively large energies (~20 MeV)
- ^{8}Be nuclear transitions then provide interesting probes of light, weakly-coupled particles



^{8}BE SPECTRUM

- Many excited states with different spins and isospins
- Of special interest: the ^{8}Be* (18.15) and ^{8}Be*' (17.64) states

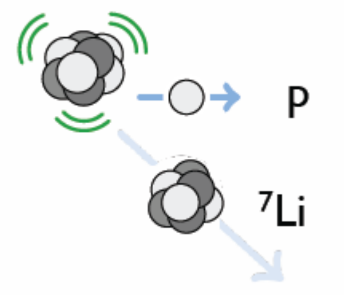


1609.07411; based on Tilley et al. (2004); National Nuclear Data Center, http://www.nndc.bnl.gov/nudat2/

^{8}BE* DECAY

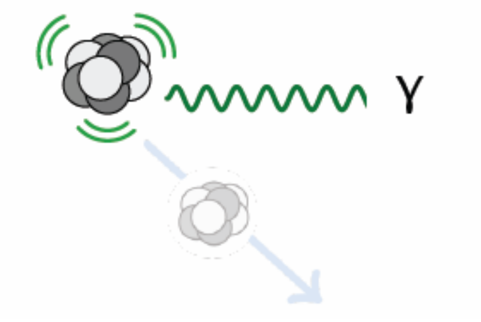
- Hadronic

  B(p ^{7}Li) ≈ 100%



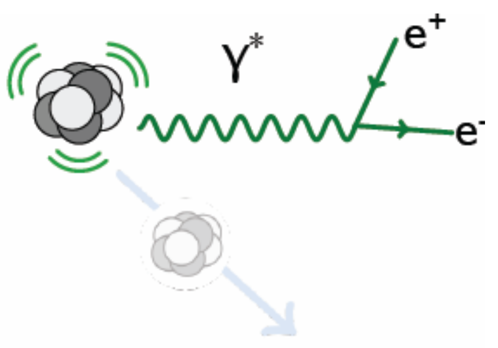
- Electromagnetic

  B(^{8}Be γ) ≈ 1.5 x 10^{-5}



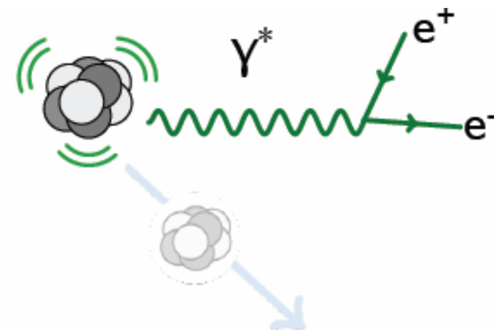
- Internal Pair Creation

  B(^{8}Be e^+ e^-) ≈ 5.5 x 10^{-8}

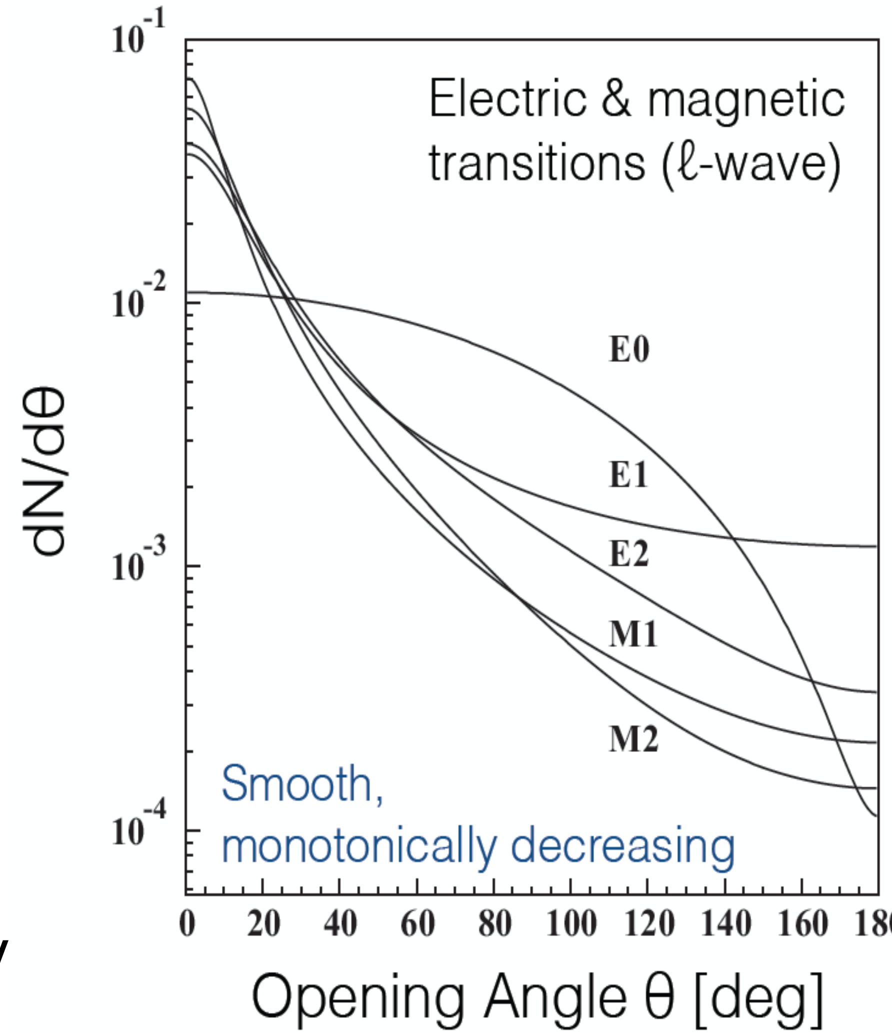


^{8}BE* DECAY

- Internal Pair Creation
  $B(^8\text{Be}\ e^+\ e^-) \approx 5.5 \times 10^{-8}$



Given the photon propagator, $dN/d\theta$ is sharply peaked at low e^+e^- opening angle θ and is expected to be a monotonically decreasing function of θ

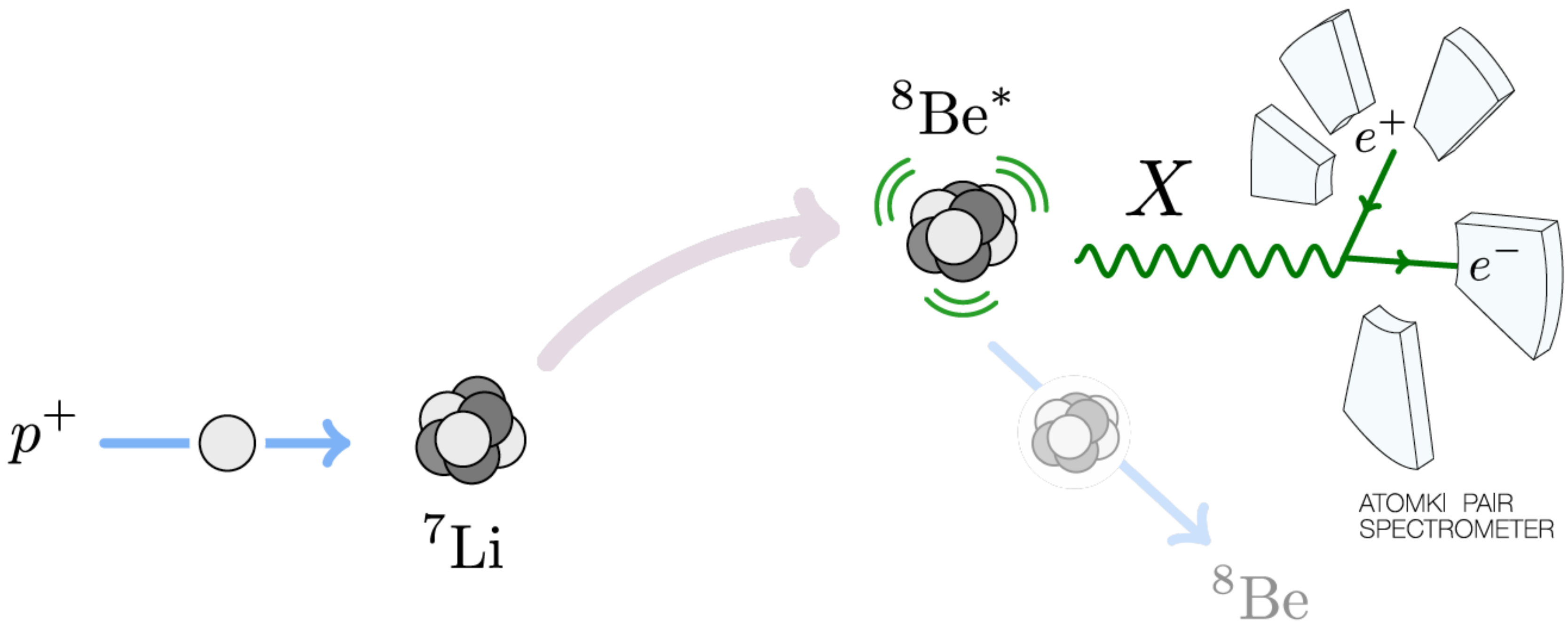


Gulyas et al. (2015); Rose (1949)

THE ATOMKI ^{8}BE EXPERIMENT

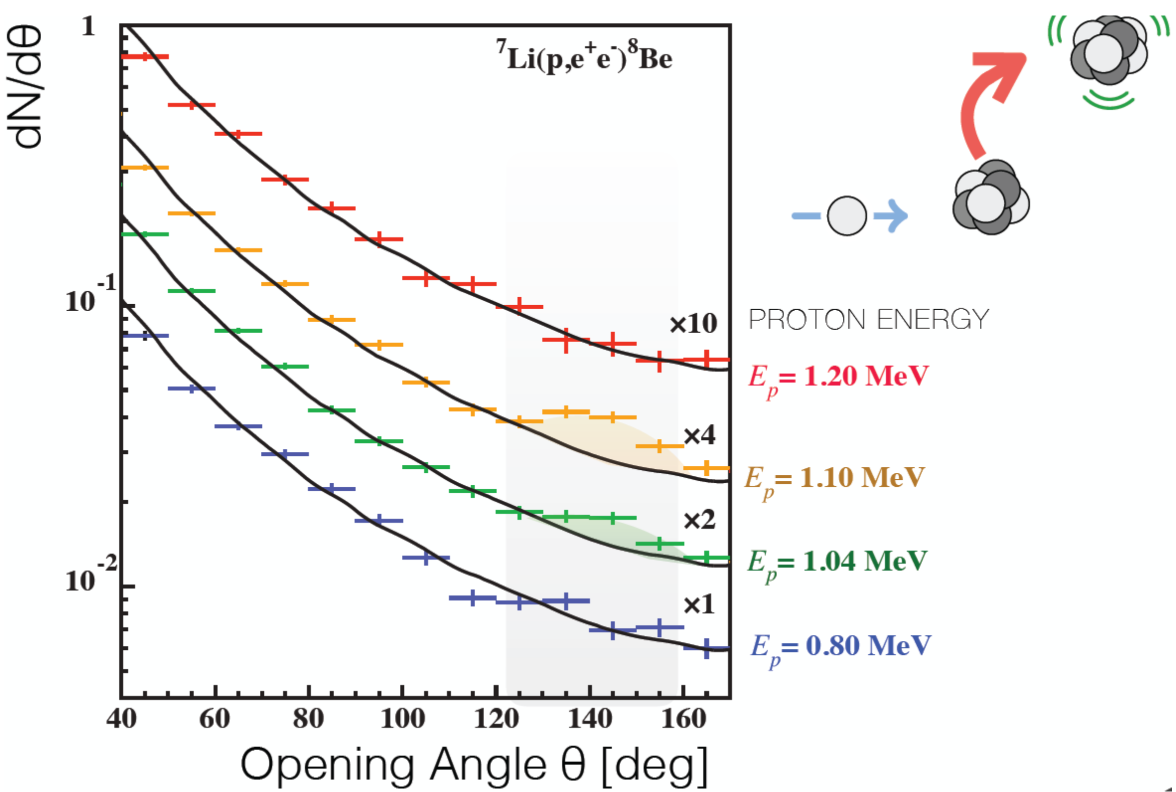
THE ATOMKI ^{8}BE EXPERIMENT

A 1 μA p beam with ΔE_p ~ 10 keV strikes a thin ^{7}Li foil target. The beam energy can be adjusted to select various ^{8}Be excited state resonances.



THE ATOMKI ANOMALY

- A bump at ~140 degrees is observed as one passes through the $^8Be^*$ resonance
- Background fluctuation probability: 5.6×10^{-12} (6.8σ)



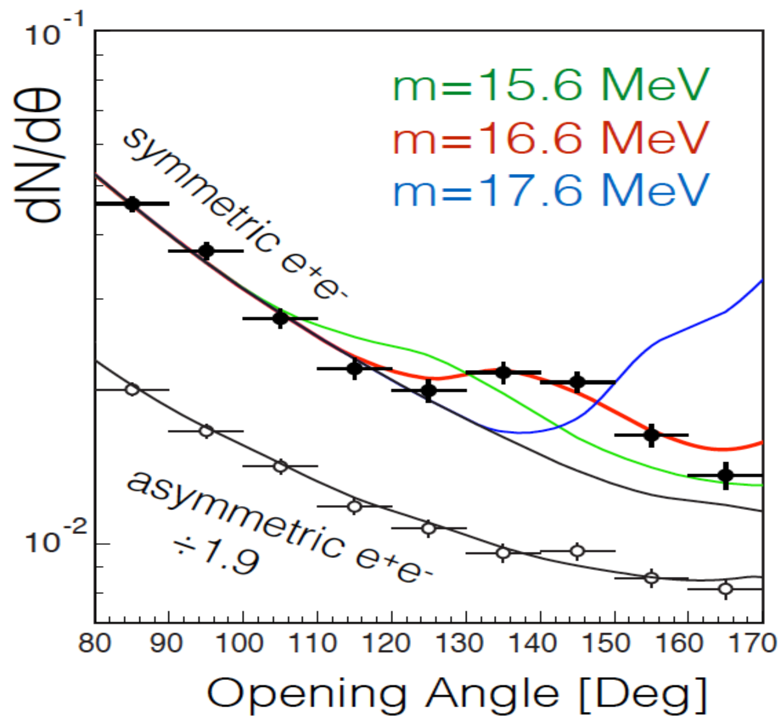
Krasznahorkay et al. (2015)

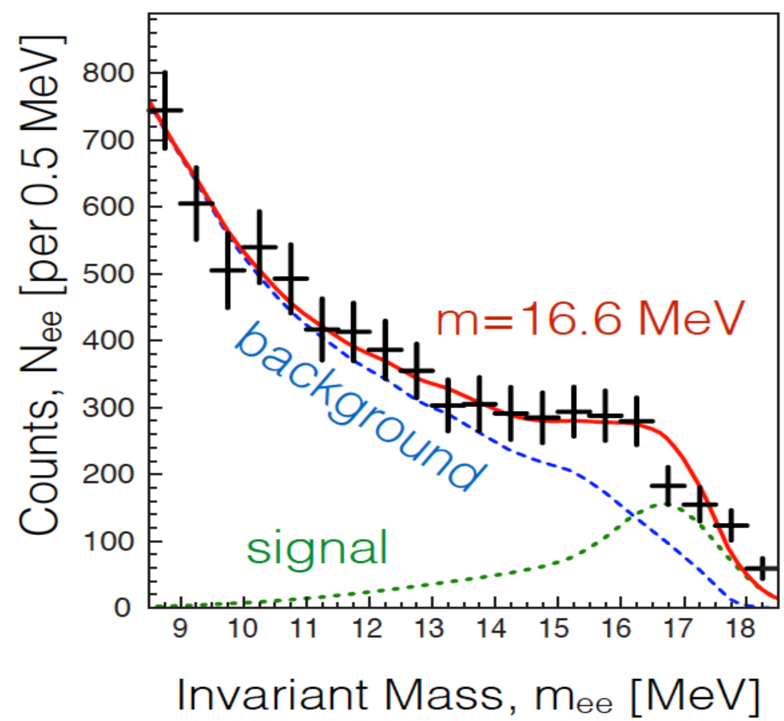
THE ATOMKI ANOMALY

- The e^+e^- opening angle θ (and invariant mass) distributions are well fit to a new particle: $\chi^2/\text{dof} = 1.07$

$$m = 16.7 \pm 0.35\ (\text{stat}) \pm 0.5\ (\text{sys})\ \text{MeV}$$

$$B(^8\text{Be}^* \rightarrow {}^8\text{Be}\ X) / B(^8\text{Be}^* \rightarrow {}^8\text{Be}\ \gamma) = 5.6 \times 10^{-6}$$

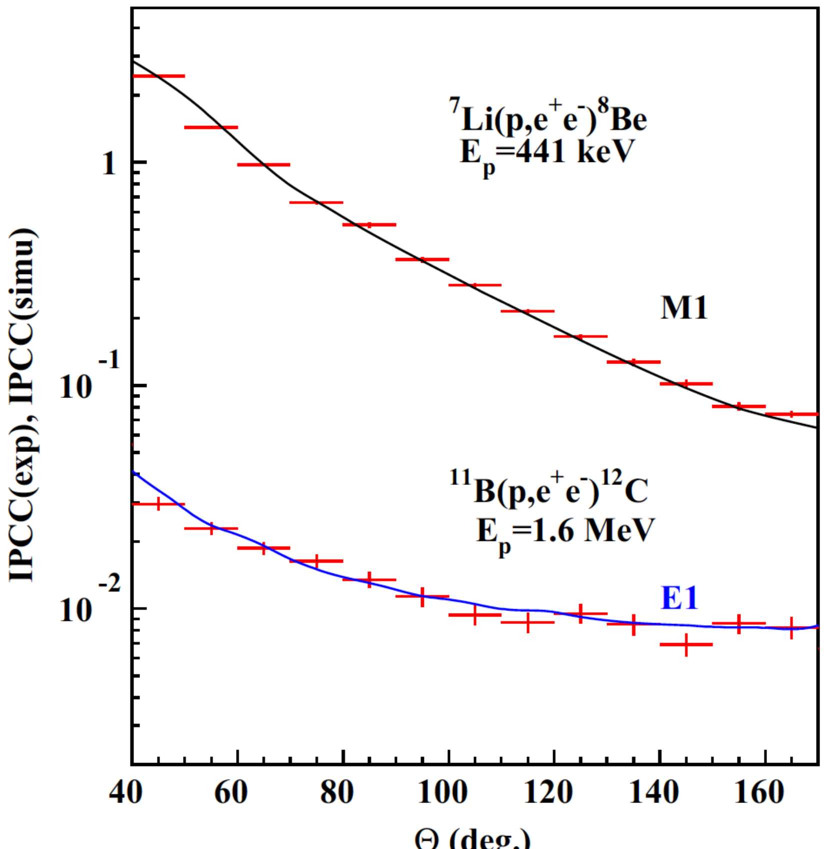




Krasznahorkay et al. (2015)

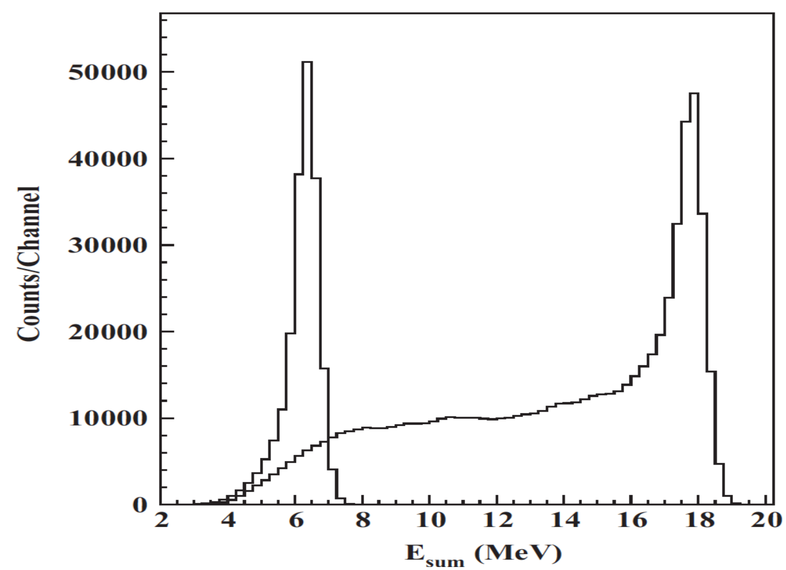
CROSS CHECKS

- For example: other (lower energy) decays fit theoretical expectations well



- The excess is confined to events with symmetric energies, |y| < 0.5 and large summed energies E > 18 MeV

$$E \equiv E_{e^+} + E_{e^-} \qquad y \equiv \frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}$$



Gulyas et al. NIM (2015)

SIGNAL CHARACTERISTICS

- The excess consists of hundreds of events in each bin and is comparable to the background; this is not a statistical fluctuation
- The excess is not a "last bin" effect: bump, not smooth excess
- Comparable excess not seen for 17.64 MeV and other states; explainable by phase-space suppression for > 17 MeV particle
- Explanations of the signal: (1) an as-yet-unidentified experimental problem, (2) an as-yet-unidentified nuclear theory effect, (3) new particle physics. In the first two cases, the excellent fit to a new particle interpretation is purely coincidental.
- Clearly all explanations should be considered (and they are being considered!). Here focus on new particle interpretations.

NEW PHYSICS QUESTIONS

- What kinds of neutral bosons are possible?
- What are the required parton-level couplings?
- Are these consistent with all other experiments?
- Is there an anomaly-free model that predicts this?
- What other experiments can check this?

Feng, Fornal, Galon Gardner, Smolinsky, Tait, Tanedo (2016); Gu, He (2016);
Chen, Liang, Qiao (2016); Jia, Li (2016); Kitahara, Yamamoto (2016); Ellwanger, Moretti (2016) ; ...

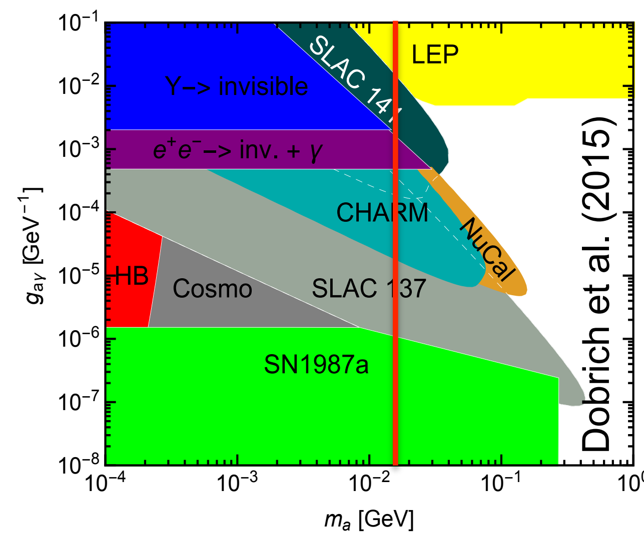
SPIN 0 NEUTRAL BOSONS

SCALARS
"DARK HIGGS"

- J^P Assignments: $1^+ \rightarrow 0^+ \, 0^+$
- L Conservation: L = 1
- Parity Conservation: $P = (-1)^L = 1$
- Forbidden in parity-conserving theories

PSEUDOSCALARS
"AXION-LIKE PARTICLES"

- We noted that the $a\gamma\gamma$ couplings are highly constrained at 17 MeV



- But Ellwanger and Moretti (2016) noted that these constraints are modified by the required $a \rightarrow e^+e^-$ decays and found phenomenologically viable parameters

SPIN-1 GAUGE BOSONS

- What quark-, nucleon-level couplings are required? In general requires calculating nuclear matrix elements

- But for 1[-] vector, in the EFT, there is only 1 operator

$$\frac{1}{\Lambda}\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu{}^8\mathrm{Be}^*_\nu - \partial_\nu{}^8\mathrm{Be}^*_\mu\right) X_{\alpha\beta}{}^8\mathrm{Be}$$

- Neglecting isospin mixing,

$$\Gamma({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X) = \frac{(e/2)^2(\varepsilon_p+\varepsilon_n)^2}{3\pi\Lambda^2}\underbrace{|\mathcal{M}|^2}_{\langle{}^8\mathrm{Be}|(\bar{p}\gamma_\mu p+\bar{n}\gamma_\mu n)|{}^8\mathrm{Be}^*\rangle}|\vec{p}_X|^3$$

- The nuclear matrix elements and Λ cancel in the ratio

$$\frac{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X)}{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma)} = (\varepsilon_p+\varepsilon_n)^2\frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.6\times 10^{-6}$$

where $\varepsilon_p = 2\varepsilon_u + \varepsilon_d$ and $\varepsilon_n = \varepsilon_u + 2\varepsilon_d$ are the nucleon X-charges (in units of e)

THE REQUIRED PARTON-LEVEL COUPLINGS

- To get the right signal strength:

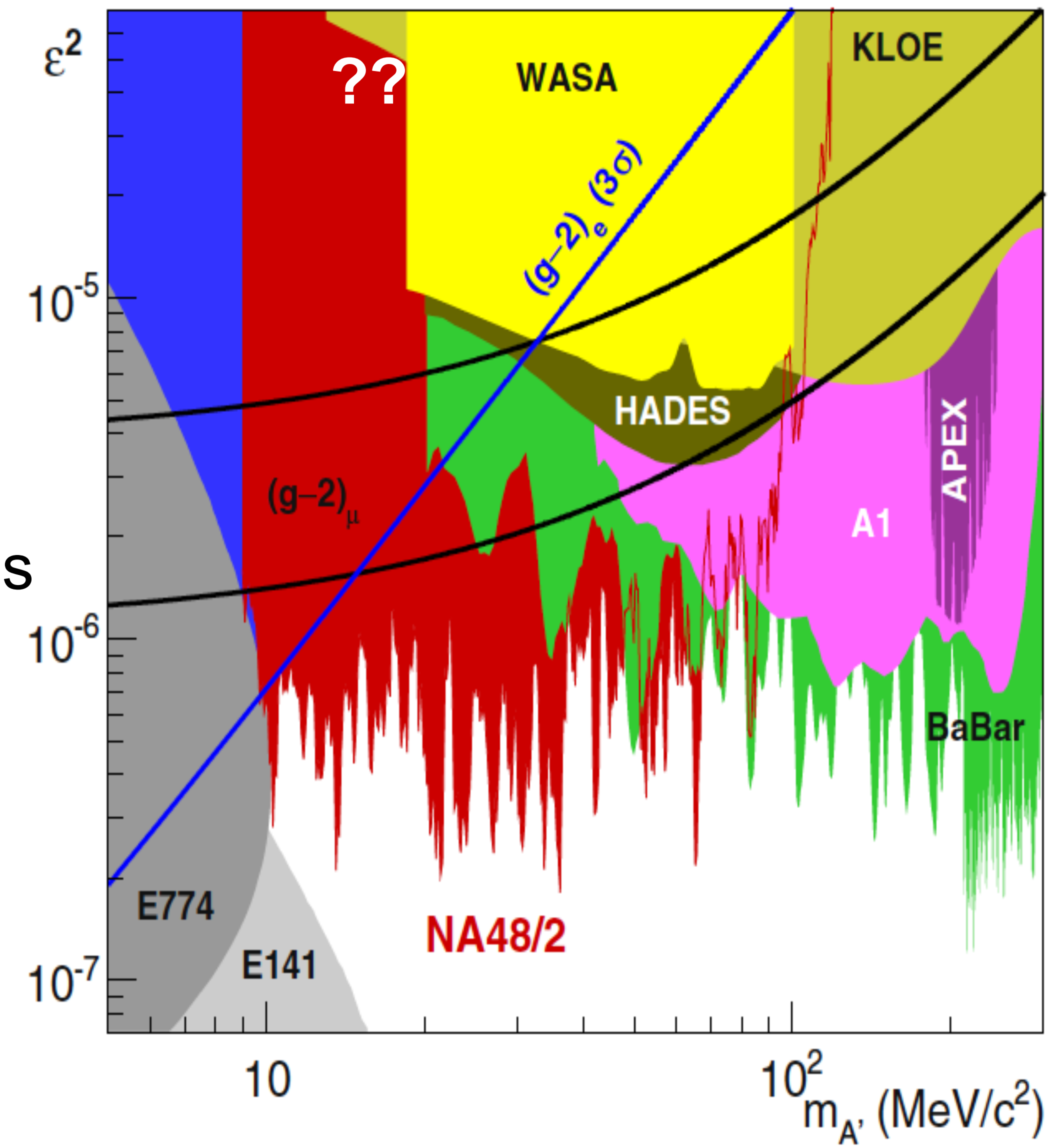
$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$$

- For a dark photon with couplings proportional to SM couplings, this implies kinetic mixing parameter

  $\varepsilon \sim 0.01$

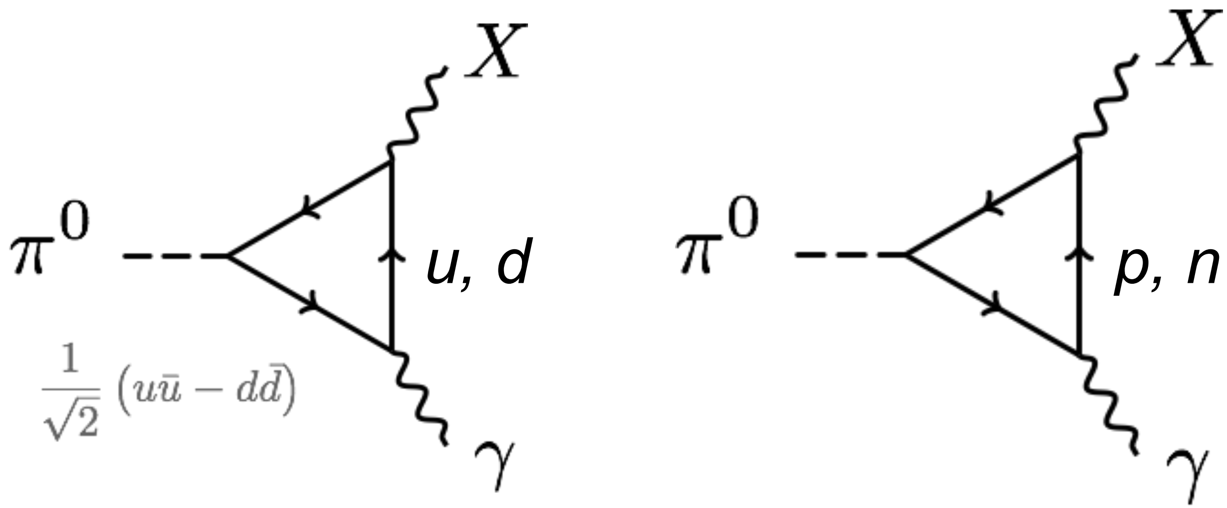
  which is excluded

- This cannot be a dark photon



PROTOPHOBIA

- The dominant constraints are null results from searches for $\pi^0 \rightarrow X\,\gamma \rightarrow e^+\,e^-\,\gamma$

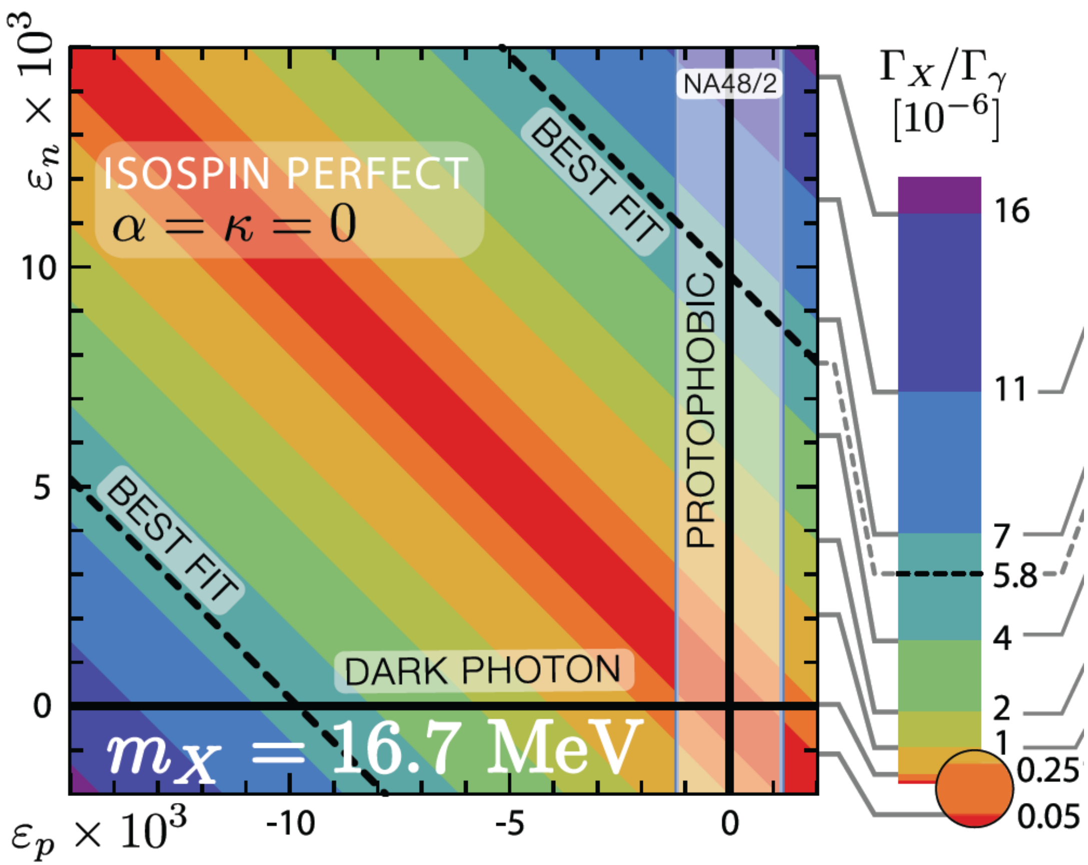


- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

- A protophobic gauge boson with couplings to neutrons, but suppressed couplings to protons, can explain the ^{8}Be signal without violating other constraints

PROTOPHOBIC GAUGE BOSON

- The ^{8}Be anomaly can be explained by a protophobic gauge boson with $\varepsilon_n \sim 10^{-2}$ and $\varepsilon_p < 10^{-3}$



Feng, Fornal, Galon Gardner, Smolinsky, Tait, Tanedo (2016)

EFFECT OF ISOSPIN MIXING

- There are strong indications that the ^{8}Be 1^+ states are isospin-mixed

$$\Psi_J^a = \alpha_J \Psi_{J,T=0} + \beta_J \Psi_{J,T=1} \qquad \alpha_1 = 0.21(3)$$

$$\Psi_J^b = \beta_J \Psi_{J,T=0} - \alpha_J \Psi_{J,T=1} \qquad \beta_1 = 0.98(1)$$

Barker (1966); Oothoudt, Garvey (1977); Pastore, Wiringa, Pieper, Schiavilla (2014)

- In general, this can have a large effect on the width, changing

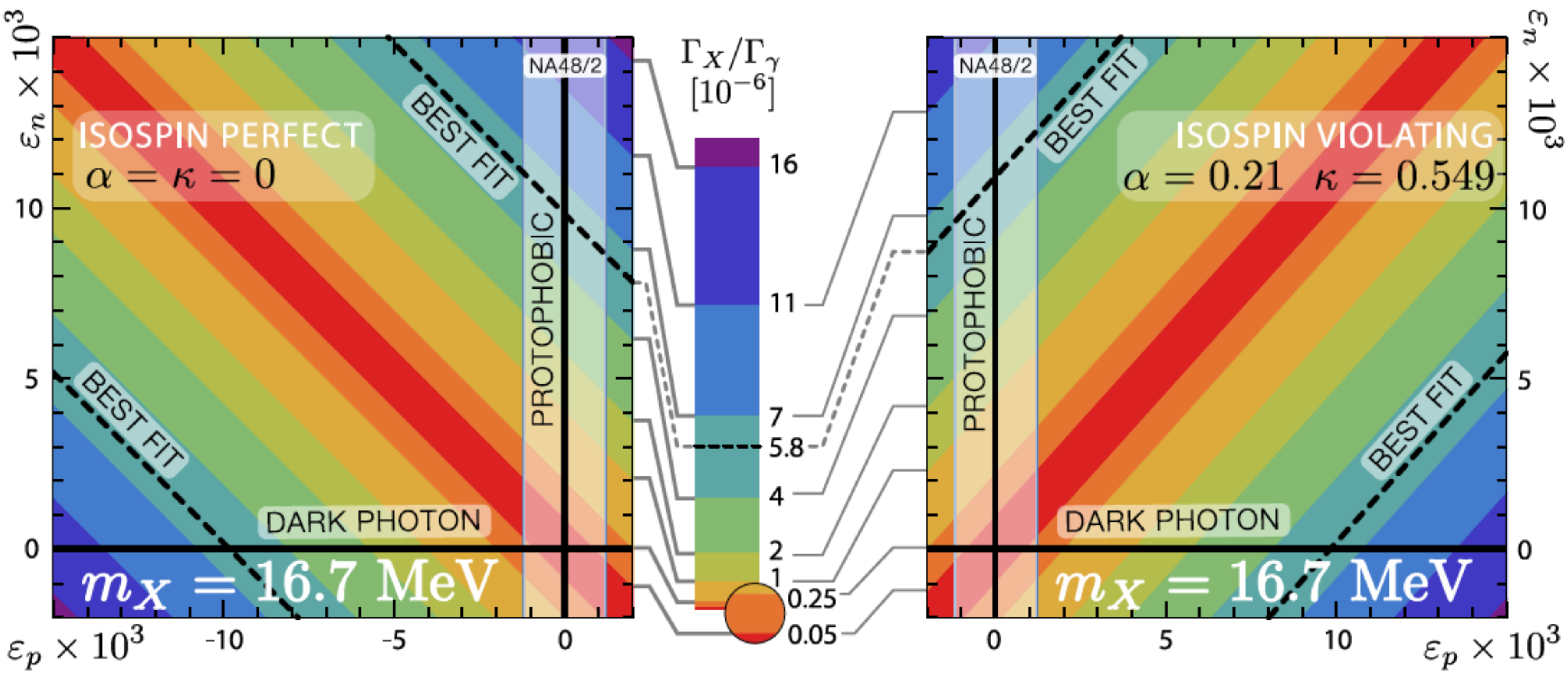
$$\frac{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\,X)}{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\,\gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

to

$$\frac{\Gamma_X}{\Gamma_\gamma} = |-0.09\,(\varepsilon_p + \varepsilon_n) + 1.09\,(\varepsilon_p - \varepsilon_n)|^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

- In the protophobic limit, however, the effect is O(10%)

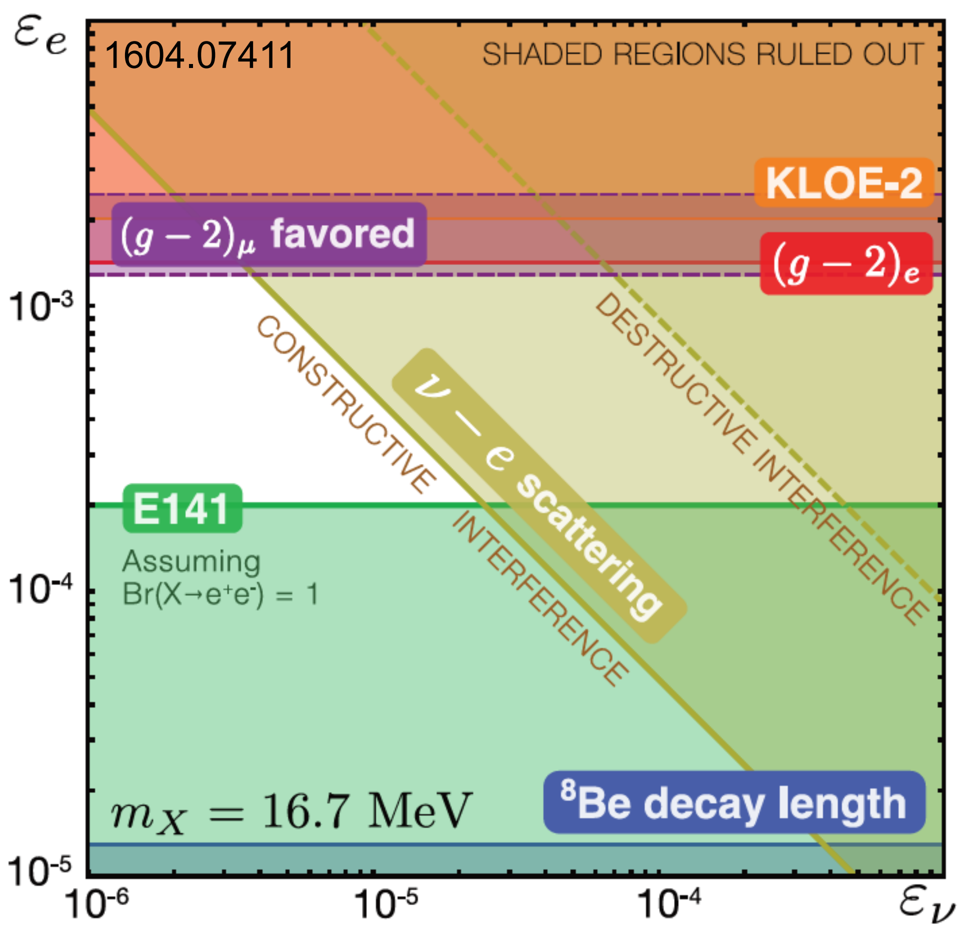
EFFECTS OF ISOSPIN MIXING



Feng, Fornal, Galon Gardner, Smolinsky, Tait, Tanedo (2016)

LEPTON COUPLING CONSTRAINTS

- Consider all constraints and also the region favored by $(g\text{-}2)_\mu$
- In the end, require $10^{-4} < \varepsilon_e < 10^{-3}$, and $|\varepsilon_e \varepsilon_\nu|^{1/2} < 3 \times 10^{-4}$



ANOMALY-FREE MODELS

Feng, Fornal, Galon Gardner, Smolinsky, Tait, Tanedo (2016)

- How strange is protophobia? The Z boson is protophobic at low energies, as is a gauge boson coupling to B-L-Q or B-Q

- The latter observation suggests a model-building strategy: consider a model with a light B-L or B gauge boson. It will generically kinetically mix with the photon:

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

- In the mass basis, the SM photon couplings to SM fermions are unchanged, but the B-L or B gauge boson's couplings to SM fermions will be shifted by Q.

A B-L PROTOPHOBIC MODEL

- Gauge the $U(1)_{B-L}$ global symmetry of the SM. This is anomaly-free with the addition of 3 sterile neutrinos.
- Generically the B-L boson kinetically mixes with the photon:

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

$$\varepsilon \equiv -\varepsilon_{B-L} + \delta$$

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

- For $\varepsilon \approx -\varepsilon_{B-L}$ to O(10%) (small δ), we get B-L-Q charges:

  $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e << \varepsilon_{u,d}$. The neutrino X-charge is, however, generically too big.

A B-L PROTOPHOBIC MODEL

- The neutrino charges can be neutralized by mixing with new, vector-like "4th generation" leptons with opposite B-L charge.

Field	Isospin I	Hypercharge Y	$B-L$
$h_{\rm SM}$	$\frac{1}{2}$	$\frac{1}{2}$	0
$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	$-\frac{1}{2}$	-1
e_R	0	-1	-1
ν_R	0	0	-1
h_X	0	0	2
$L_{i_L} = \begin{pmatrix} \nu_{i_L} \\ e_{i_L} \end{pmatrix}$	$\frac{1}{2}$	$-\frac{1}{2}$	1
$L_{i_R} = \begin{pmatrix} \nu_{i_R} \\ e_{i_R} \end{pmatrix}$	$\frac{1}{2}$	$-\frac{1}{2}$	1
E_{i_L}	0	-1	1
E_{i_R}	0	-1	1

- When the B-L Higgs boson gets a ~10 GeV vev, it
  - gives a 17 MeV mass to the B-L gauge boson
  - Mixes the SM and new neutrino fields, neutralizing the neutrinos
  - Generates a Majorana mass for the SM neutrinos → see-saw

- Implies ~100 GeV 4th generation leptons

A U(1)$_B$ PROTOPHOBIC MODEL

- Alternatively, can gauge the U(1)$_B$ global symmetry of the SM. After kinetic mixing,

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

$$\varepsilon \equiv -\varepsilon_B + \delta$$

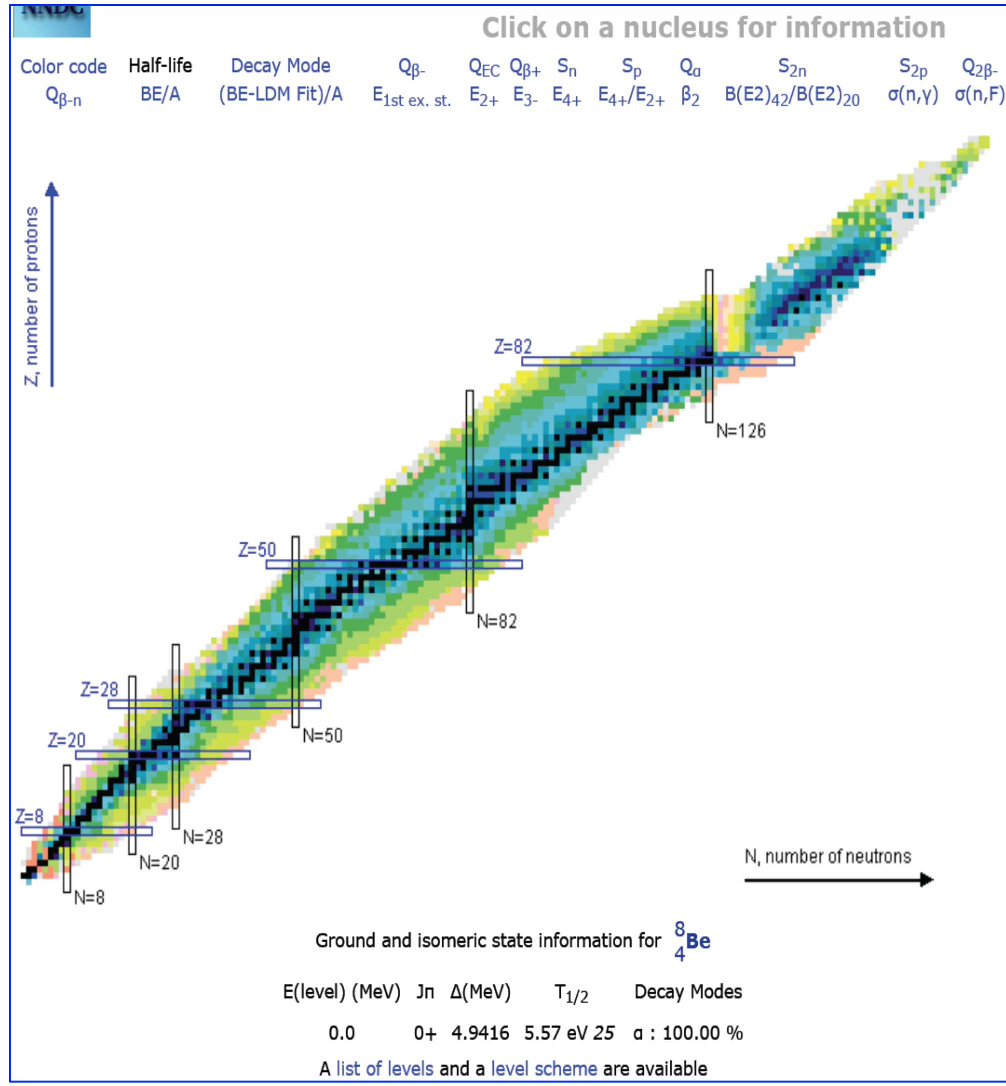
$$\varepsilon_u = -\frac{1}{3}\varepsilon_B + \frac{2}{3}\delta \quad \varepsilon_d = \frac{2}{3}\varepsilon_B - \frac{1}{3}\delta \quad \varepsilon_\nu = 0 \quad \varepsilon_e = \varepsilon_B - \delta \ ,$$

- Now the neutrino is automatically neutral, but we need new fields to cancel anomalies. One of these can be dark matter, and the X boson is then a dark force carrier.

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

FUTURE TESTS: NUCLEAR PHYSICS

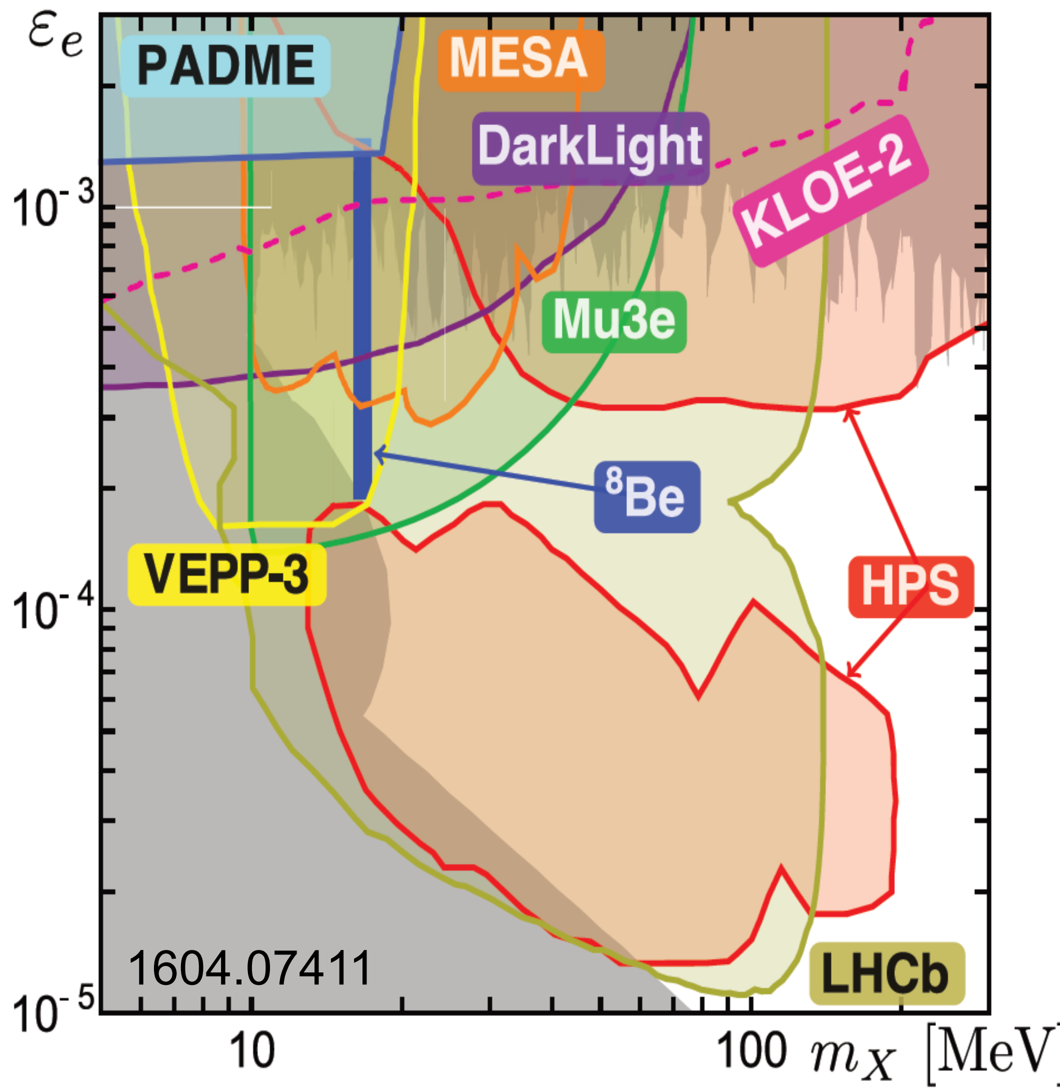
- The most direct follow-up tests are to look again at nuclear IPC transitions
- The ATOMKI group has new preliminary results with improved detectors for the 18.15 and 17.64 transitions
- Other groups may be able to duplicate this in nuclear labs or at particle experiments where ^{8}Be transitions are used as a calibration source of high-energy photons
- Are other transitions possible? E.g., ^{10}B (19.3), ^{10}Be (17.8)



FUTURE TESTS: "DARK PHOTON" EXPTS

- Also SHiP, SeaQuest, … There are a host of experiments that have long been planned for dark photon searches, and may now be sensitive to the 17 MeV range.

- See "Advances in Dark Matter and Particle Physics 2016," Messina, Italy, October 2016



CONCLUSIONS

- There is currently a 6.8σ anomaly in ^{8}Be* IPC decays. A particle interpretation yields a χ^2/dof = 1.07 best fit with

  $m = 16.7 \pm 0.35$ (stat) ± 0.5 (sys) MeV

  $B(^8Be^* \rightarrow {}^8Be\, X) / B(^8Be^* \rightarrow {}^8Be\, \gamma) = 5.6 \times 10^{-6}$

- The data are consistent with a protophobic gauge boson that simultaneously resolves (to within 2σ) the discrepancy in $(g-2)_\mu$

- In simple SM extensions, the protophobic gauge boson is realized by a $U(1)_{B-L}$ or $U(1)_B$ gauge boson that kinetically mixes with the photon

- Many opportunities for near future experimental tests