THE BERYLLIUM ANOMALY AND NEW PHYSICS

New Physics at the Intensity Frontier

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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], PRD 95, 035017 (2017)


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NEW PHYSICS AT THE INTENSITY FRONTIER

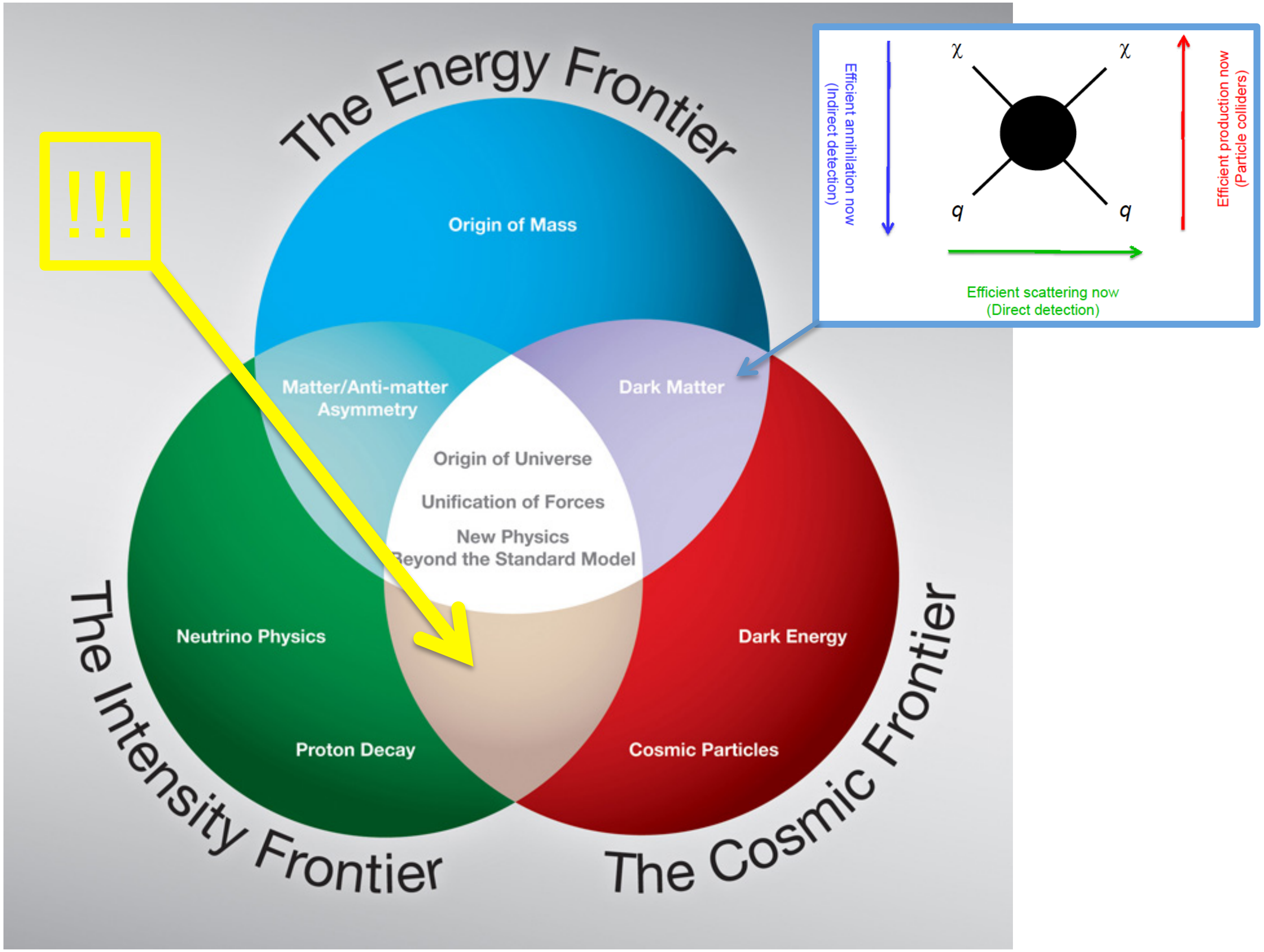
- There are currently many outstanding puzzles: neutrino masses, gauge hierarchy, strong CP, flavor, dark matter, baryogenesis, dark energy,...

- Some of these motivate searches for new particles and forces at high energies: the energy frontier

- But some also motivate searches for new physics that is light, but weakly coupled: the intensity frontier

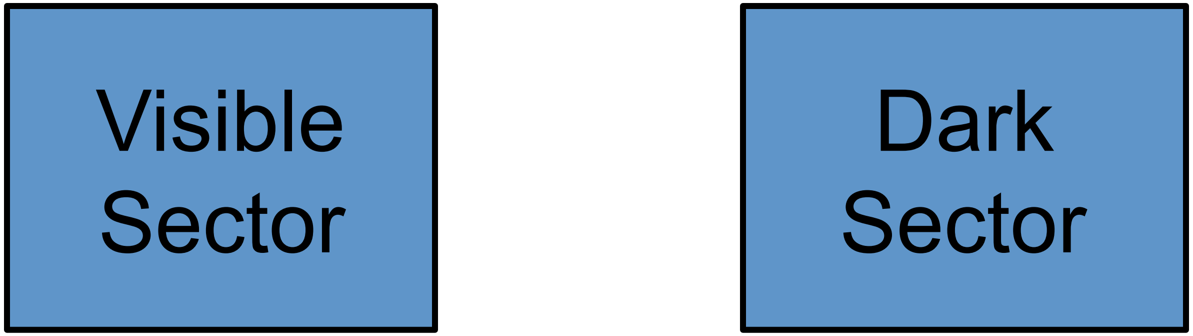
- Of particular interest here are connections to dark matter

DARK MATTER AT THE INTENSITY FRONTIER



DARK SECTORS

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



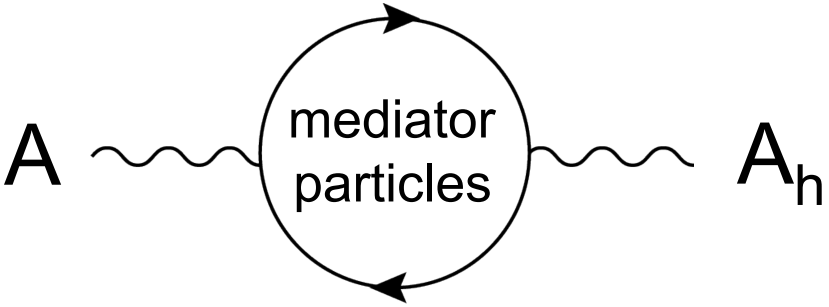
- The dark sector may have a rich structure with matter and forces of its own

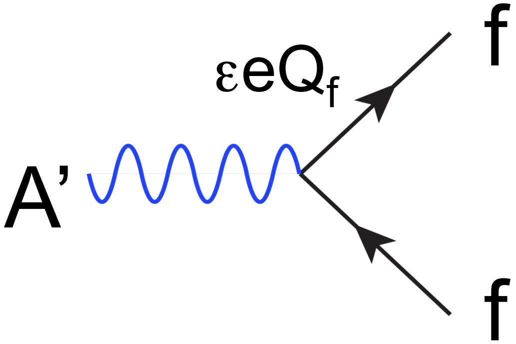
Lee, Yang (1956); Kobsarev, Okun, Pomeranchuk (1966); Blinnikov, Khlopov (1982);
Foot, Lew, Volkas (1991); Hodges (1993); Berezhiani, Dolgov, Mohapatra (1995);
Pospelov, Ritz, Voloshin (2007); Feng, Kumar (2008);...

VECTOR PORTAL

Holdom (1986)

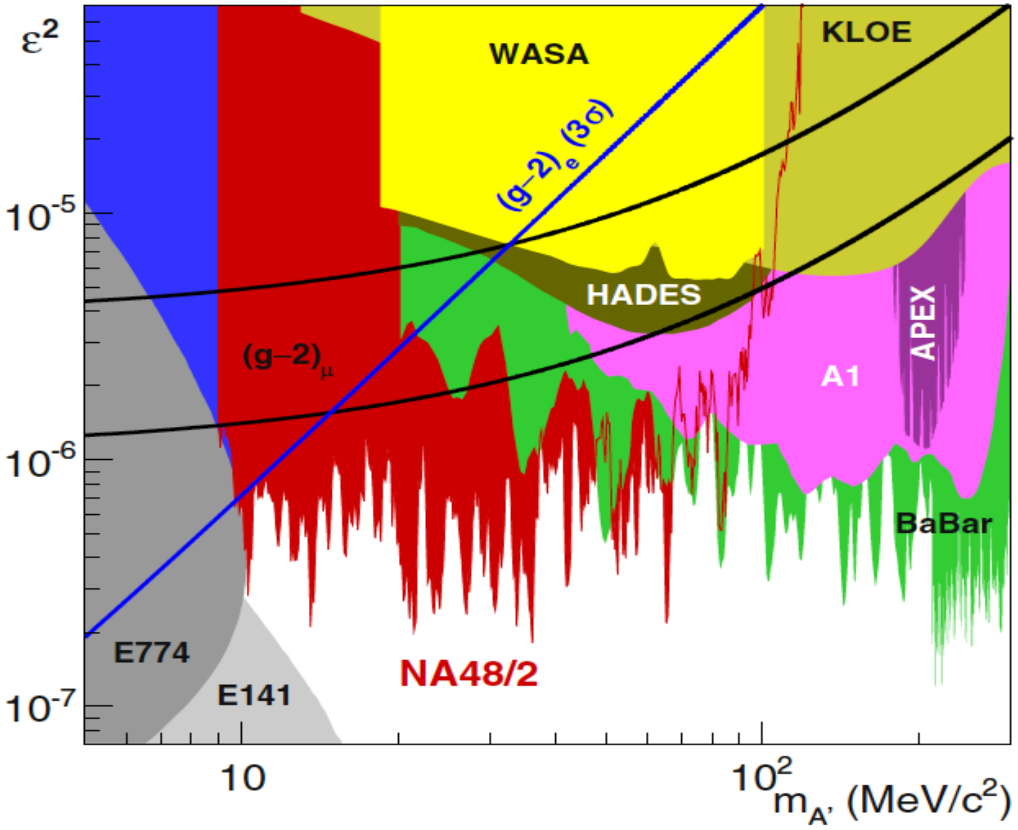
- To detect a dark sector, we must know how it interacts with us
- Suppose there are mediator particles with both dark sector and visible sector charges. This induces a kinetic mixing term $\epsilon F_{\mu\nu} F_h^{\mu\nu}$, with $\varepsilon \sim 10^{-3}\, e\, e_h$, where the 10^{-3} comes from it being a 1-loop effect, and e and e_h are the visible and hidden sector charges
- The physical state is a massive dark photon A' with the same couplings as the SM photon, but suppressed by ε





CURRENT CONSTRAINTS

- In recent years, this has motivated a host of searches in the (mass, coupling) plane, with special interest around $\varepsilon \sim 10^{-3}$ and $m_{A'} \sim$ MeV – GeV, where experiments can probe and muon g-2 can be resolved



Pospelov (2008)

- The dark photon resolution to the muon g-2 anomaly is now disfavored, but there is still a lot of parameter space to explore and many proposed experiments

DARK FORCES IN NUCLEAR PHYSICS

- The interest in new, light gauge bosons opens up new connections to other branches of physics

- In particular, for the MeV scale, nuclear physics becomes a relevant probe of new particles

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

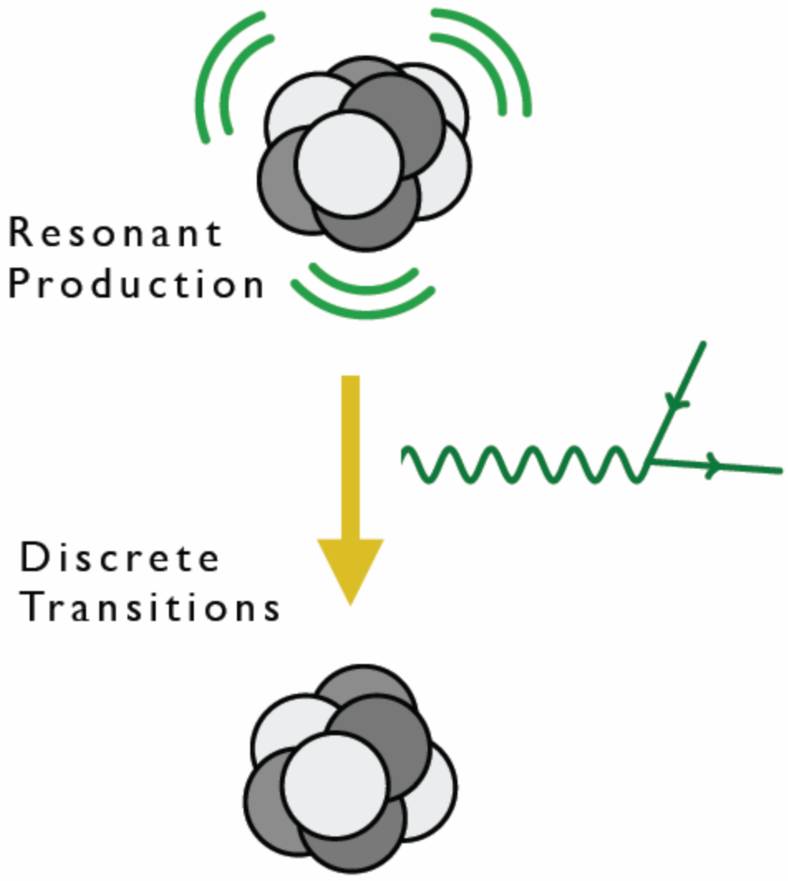
A. J. Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]

- Could these be new gauge bosons?

Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo,
PRL, 1604.07411 [hep-ph]; PRD, 1608.03591 [hep-ph]

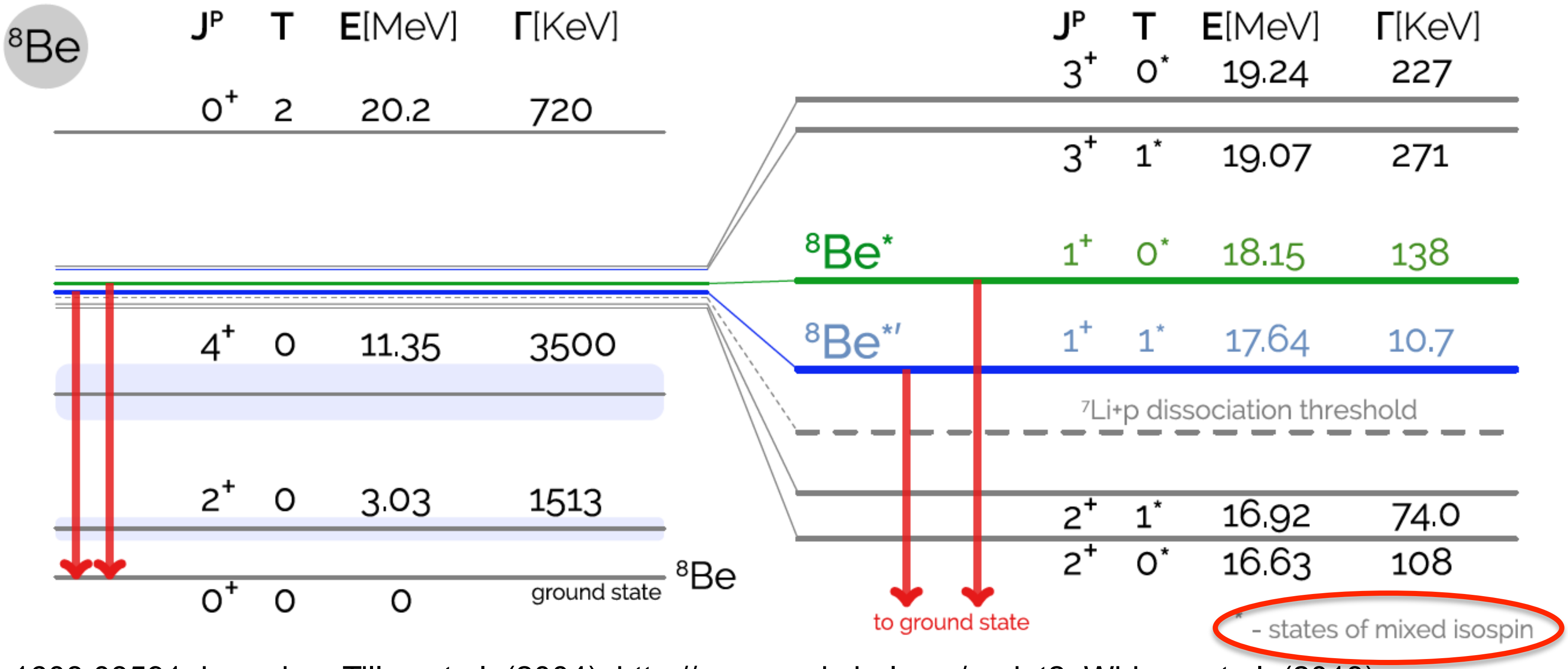
^{8}BE AS A NEW PHYSICS LAB

- ^{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



^{8}Be

J^P	T	E[MeV]	Γ[KeV]
0^+	2	20.2	720
4^+	0	11.35	3500
2^+	0	3.03	1513
0^+	0	0	

^{8}Be ground state

	J^P	T	E[MeV]	Γ[KeV]
	3^+	0^*	19.24	227
	3^+	1^*	19.07	271
^{8}Be*	1^+	0^*	18.15	138
^{8}Be*′	1^+	1^*	17.64	10.7
	2^+	1^*	16.92	74.0
	2^+	0^*	16.63	108

^{7}Li+p dissociation threshold

to ground state

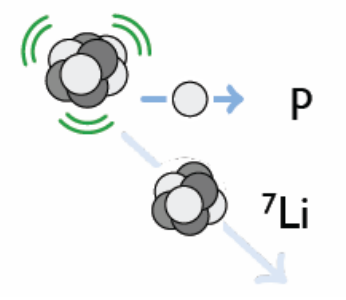
* - states of mixed isospin

1608.03591; based on Tilley et al. (2004), http://www.nndc.bnl.gov/nudat2, Wiringa et al. (2013)

^{8}BE* DECAY

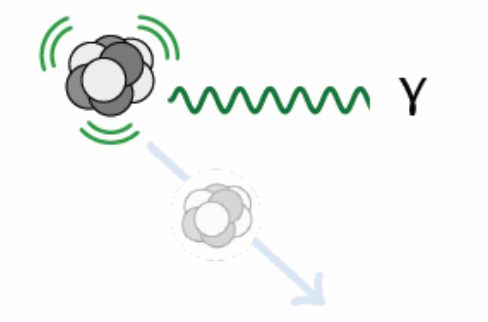
- Hadronic

  B(p ^{7}Li) ≈ 100%



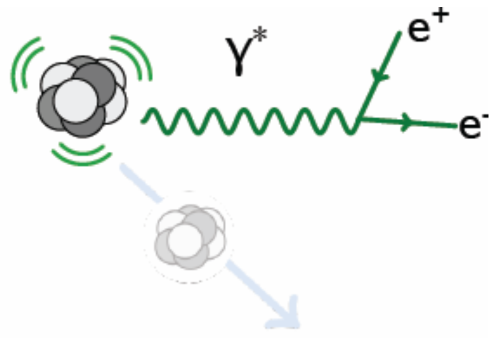
- Electromagnetic

  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

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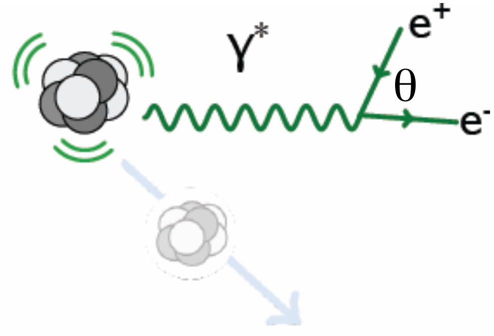
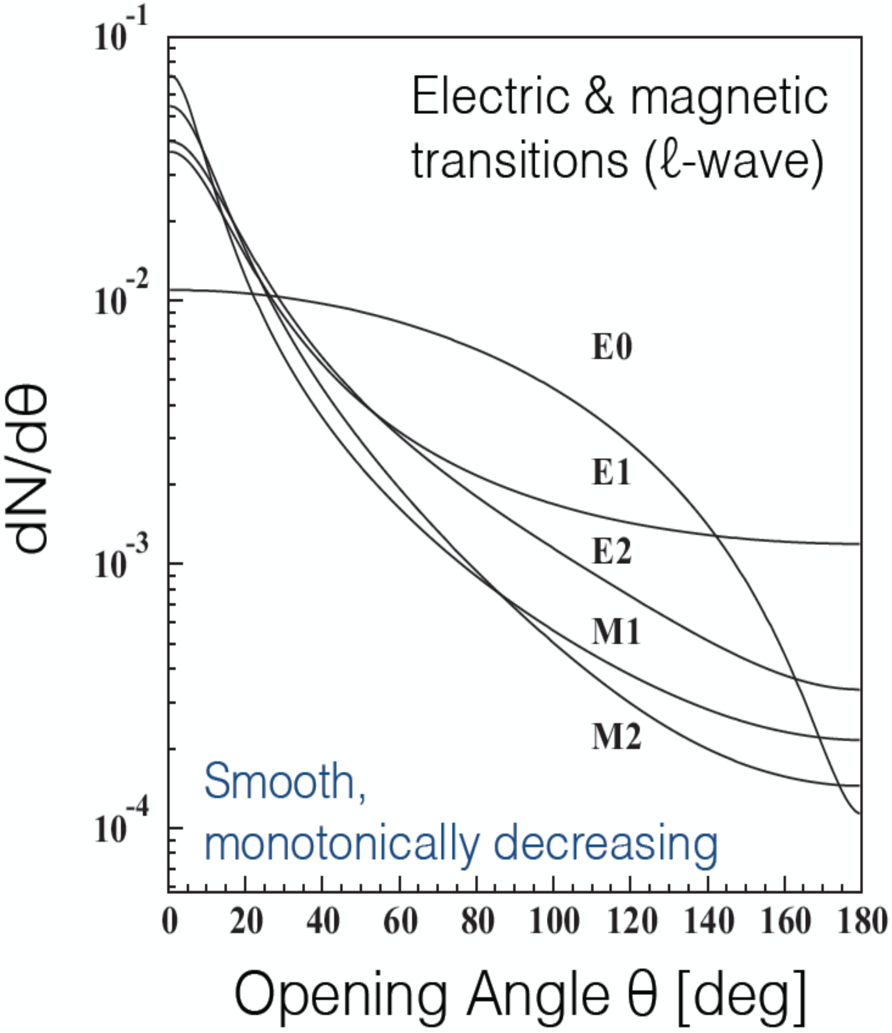


For e^+e^- produced by a virtual photon, $dN/d\theta$ is sharply peaked at low θ and is expected to be a monotonically decreasing function of θ

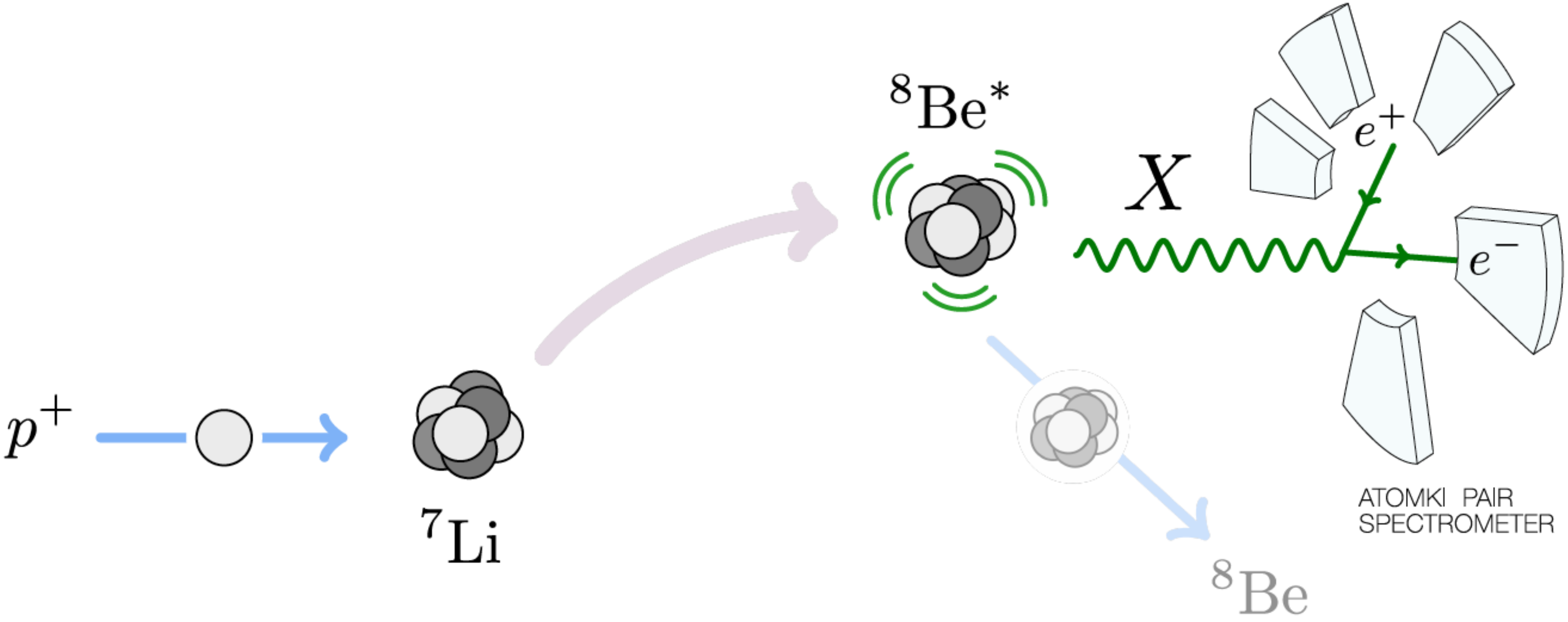


Gulyas et al. (2015); Rose (1949)

THE ATOMKI ^{8}BE EXPERIMENT

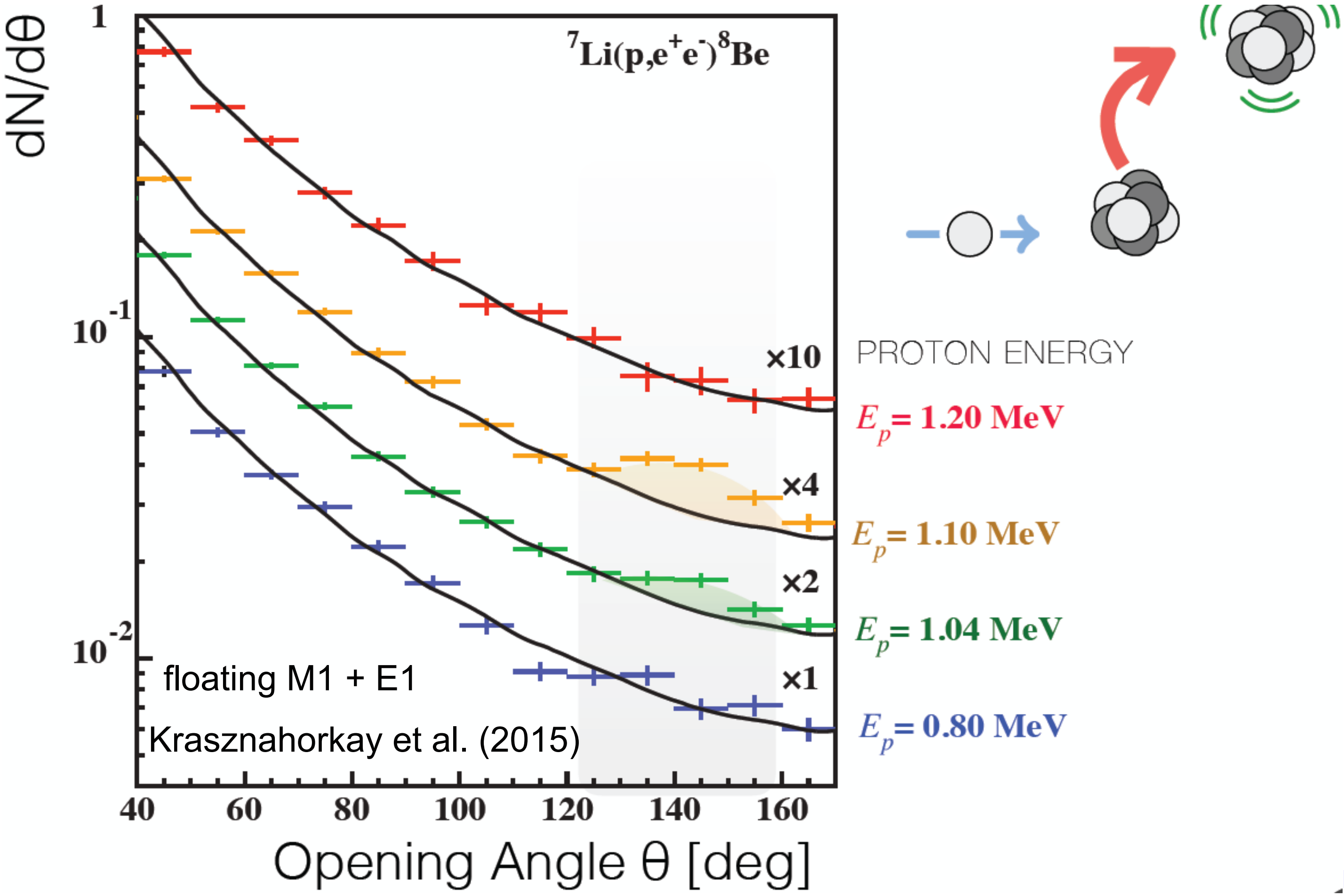
THE ATOMKI ^{8}BE EXPERIMENT

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. Typical run time is ~ a week at each proton energy.



THE ATOMKI ANOMALY

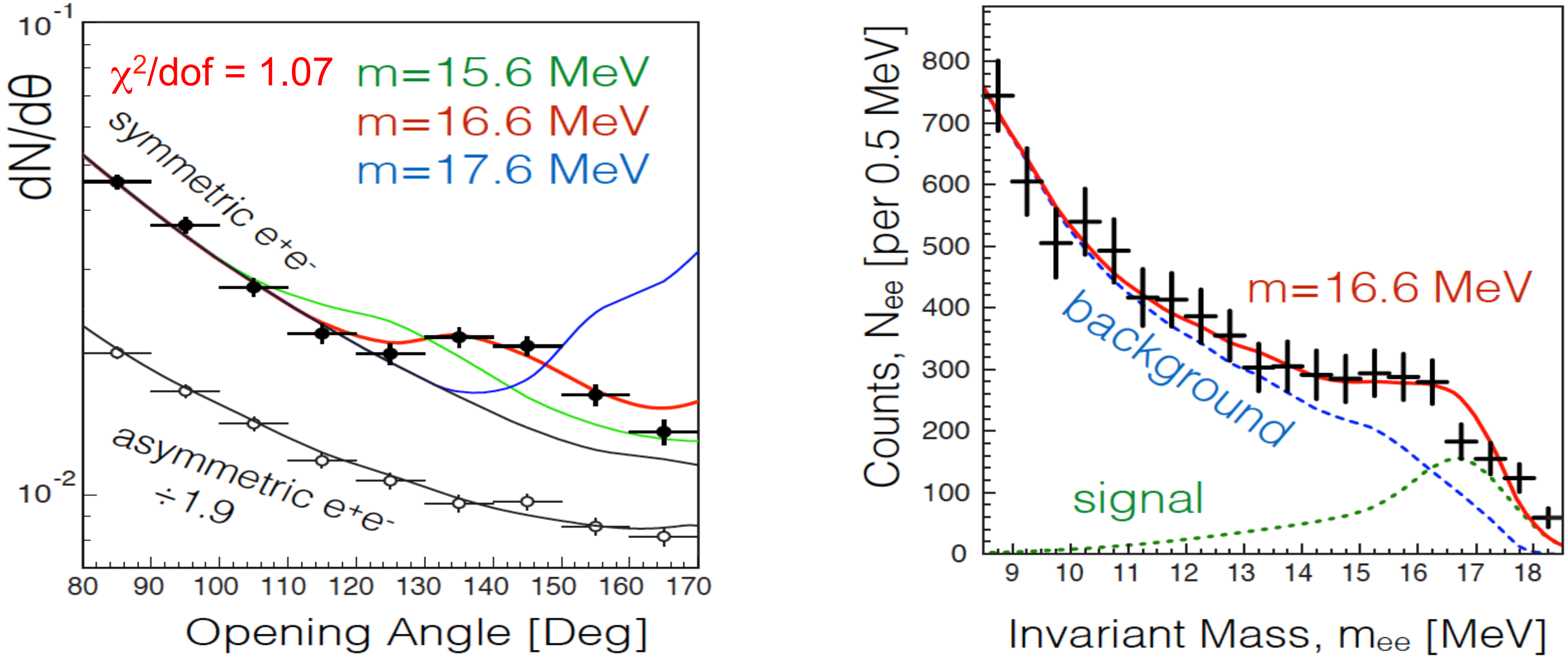
- A bump at ~140 degrees is observed as one passes through the ^{8}Be* resonance
- Background fluctuation probability: 5.6 x 10^{-12} (6.8σ)



THE ATOMKI ANOMALY

- The θ (and m_{ee}) distributions can be explained by postulating a new particle and the decay ^{8}Be* → ^{8}Be X, followed by X → e^+e^-
- Best fit parameters: m = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV

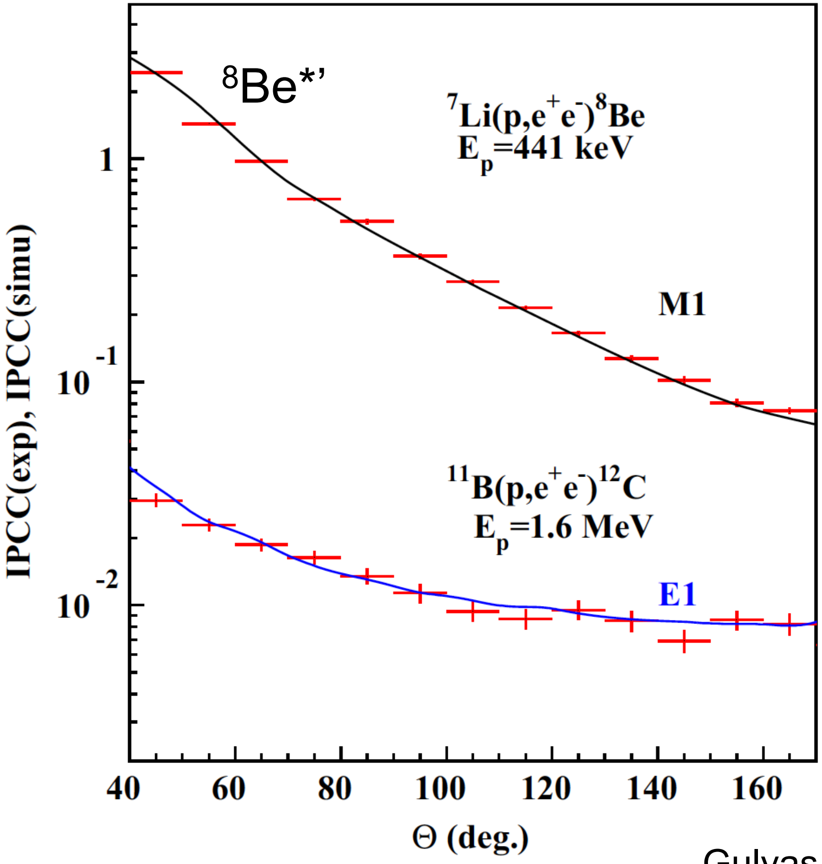
$$B(^{8}\mathrm{Be}^* \rightarrow {}^{8}\mathrm{Be}\,X) / B(^{8}\mathrm{Be}^* \rightarrow {}^{8}\mathrm{Be}\,\gamma) = 5.6 \times 10^{-6}$$



Krasznahorkay et al. (2015)

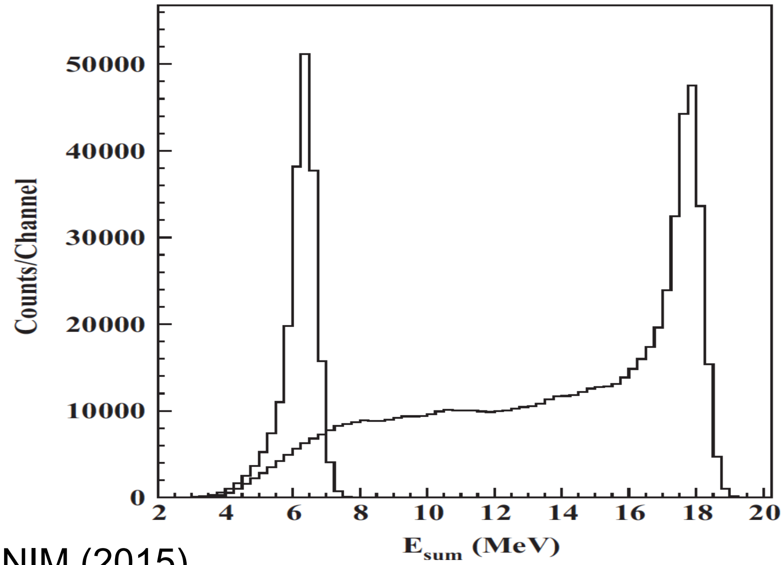
CROSS CHECKS

- 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_{sum} > 18 MeV, as expected for a new particle interpretation

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



Gulyas et al. NIM (2015)

POSSIBLE EXPLANATIONS

Three possibilities:

(1) an as-yet-unidentified nuclear experimental problem
(2) an as-yet-unidentified nuclear theory effect
(3) new particle physics

(1) Nuclear Experiment

- 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
- Reports of conflicts with previous results of this collaboration have in some cases been highly exaggerated
- If resolved by nuclear experiment, the excellent fit to a new particle interpretation is purely coincidental
- Comparable bump not seen for 17.64 MeV state: explainable by phase-space suppression for 17 MeV particle, but smaller excess should eventually appear
- Hungarian group is now collecting data with improved detector, continues to see bump
- Similar experiments by other groups would be of great interest

POSSIBLE EXPLANATIONS

(2) Nuclear Theory

- Must explain bump in 18.15 IPC decays
- Must simultaneously explain lack of similarly-sized bump in (isospin-mixed) 17.64 IPC decays
- If resolved by nuclear theory, the excellent fit to a new particle interpretation is purely coincidental
- Preliminary results investigating interference effects reported at American Physical Society meeting in January by Zhang and Miller
- Further work would be of great interest

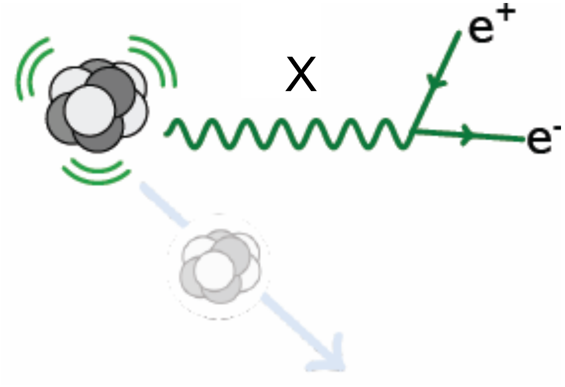
(3) Particle Physics

- If it's new physics, what kind of new particle can it be?
- Is it consistent with all other experiments?
- Are there complete particle physics models that can incorporate this new particle?
- What other experiments can confirm or exclude 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) ; Kozaczuk, Morrissey, Stroberg (2016); ...

WHAT KIND OF NEW PARTICLE CAN IT BE?

Some Quick Observations



- Must couple to both quarks and electrons
- Must be neutral
- Must be a boson

Not everything works

- For example: a spin 0 boson ("dark Higgs boson")
- J^P Assignments: $1^+ \rightarrow 0^+ \, 0^+$
- L Conservation: L = 1
- Parity Cons.: $P = (-1)^L = 1$
- Forbidden in parity-conserving theories

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

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

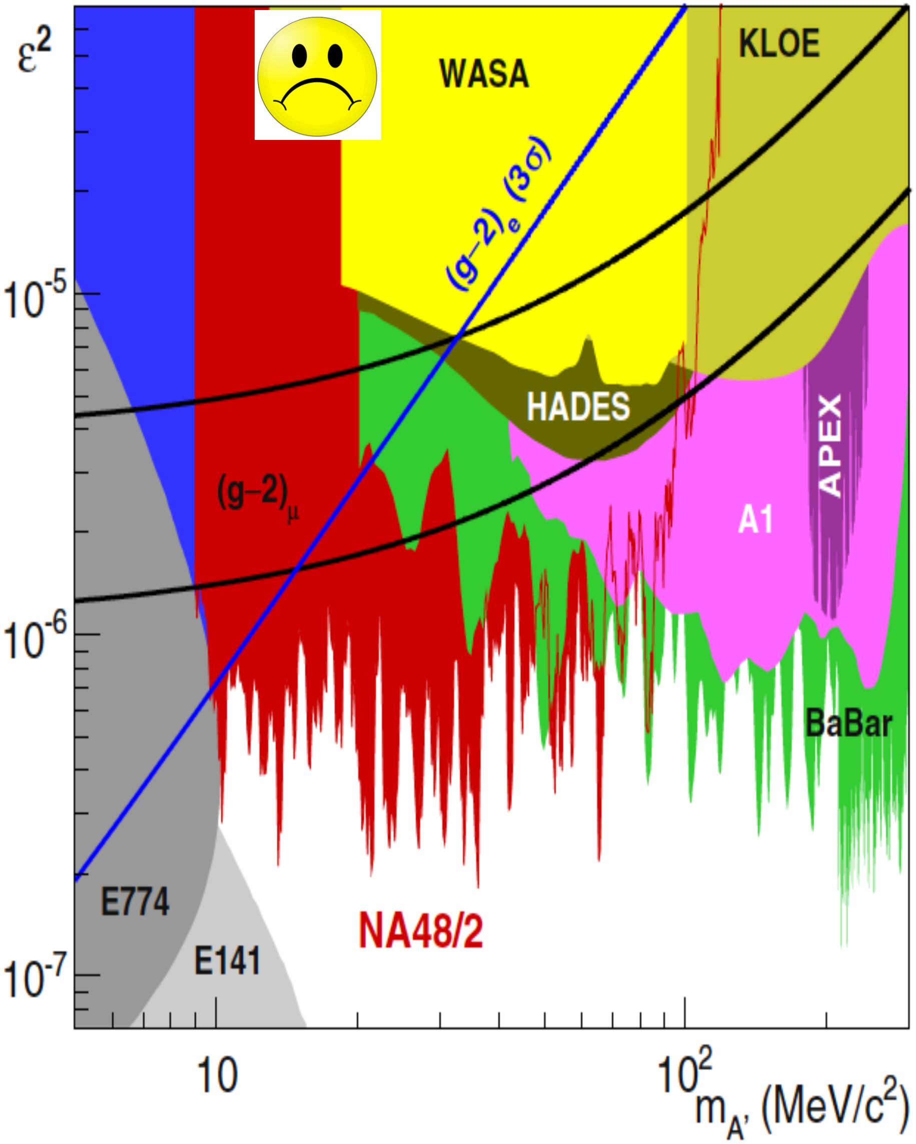
where $\varepsilon_p = 2\varepsilon_u+\varepsilon_d$ and $\varepsilon_n = \varepsilon_u+2\varepsilon_d$ are the nucleon X-charges (in units of e)

DARK PHOTON?

- Consider the *general* case of a spin-1 gauge boson with couplings $\varepsilon_f e$ to particle f
- To get the right signal strength, need

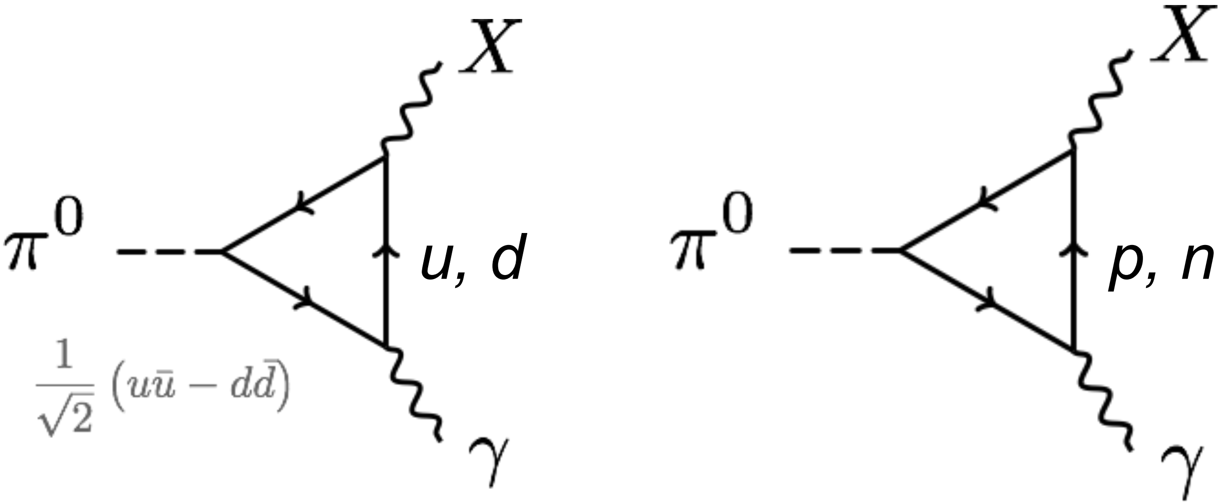
$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$$

- For the special case of a dark photon with $\varepsilon_f = \varepsilon Q_f$, this implies kinetic mixing parameter $\varepsilon \sim 0.01$, which is excluded
- This is not a dark photon



PROTOPHOBIA

- At 17 MeV, the dominant constraints are null results from searches for exotic pion decays $\pi^0 \rightarrow X\gamma \rightarrow e^+ e^- \gamma$

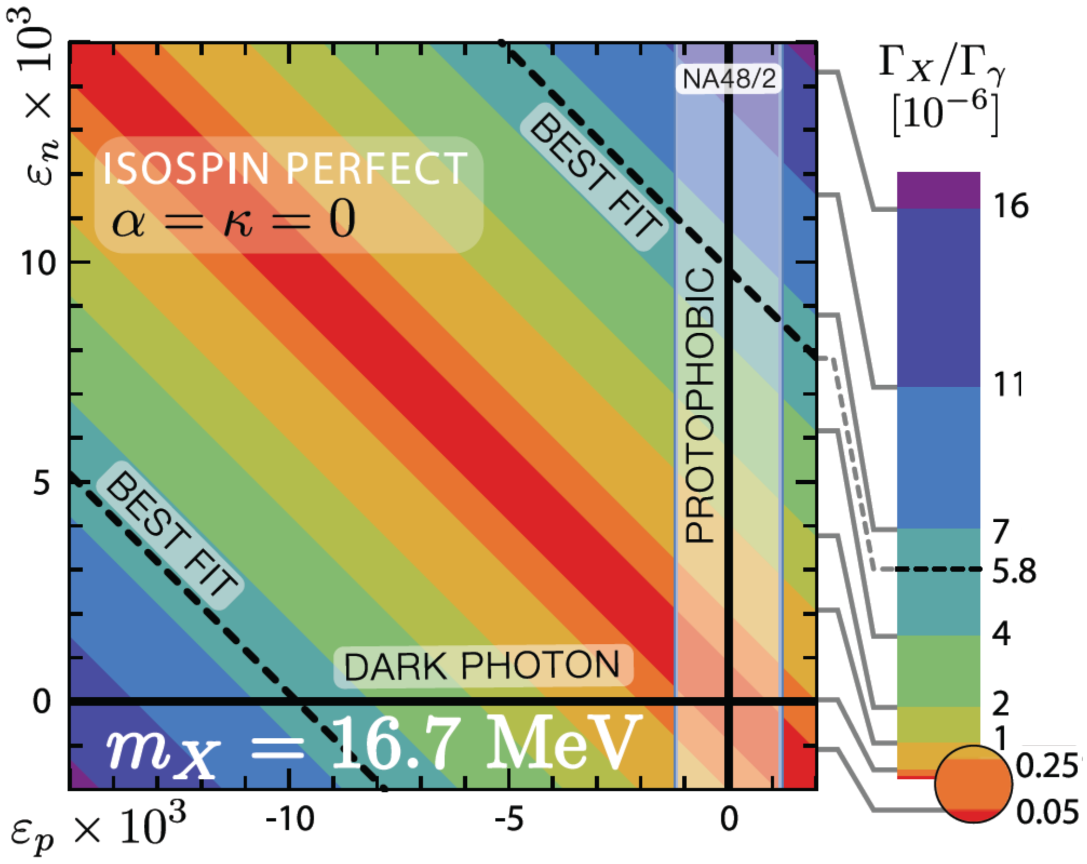


- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

- 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

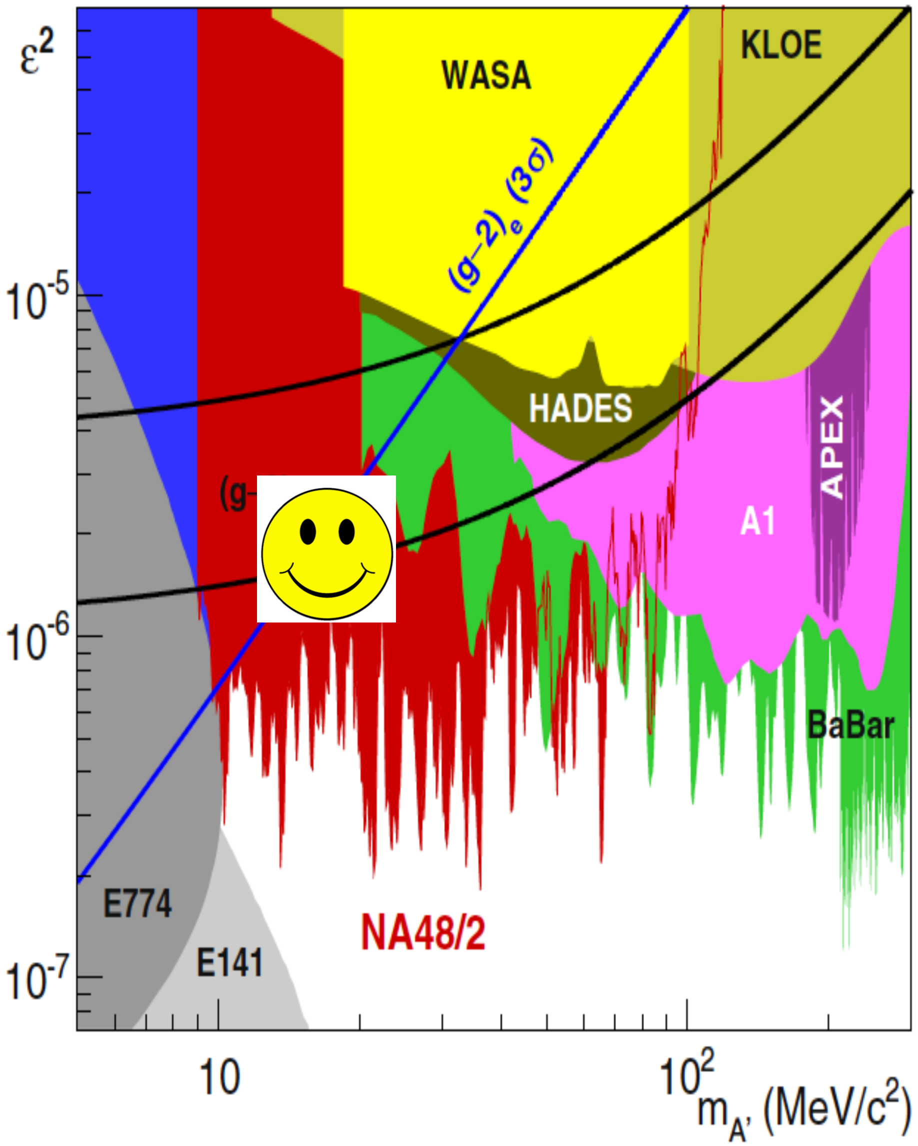
- The ^{8}Be anomaly can be explained by a protophobic gauge boson with $\varepsilon_n \sim 10^{-2}$ and $\varepsilon_p < 10^{-3}$



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

LEPTON COUPLINGS AND MUON g-2

- For a protophobic gauge boson, the NA48/2 "quark" constraints are weakened
- Relaxing the dark photon restrictions, one can, then, take electron and muon couplings around 10^{-3}
- A protophobic gauge boson with such couplings can resolve both the ^{8}Be and muon g-2 anomalies
- Implies a milli-charged 5th force with range ~ 12 fm

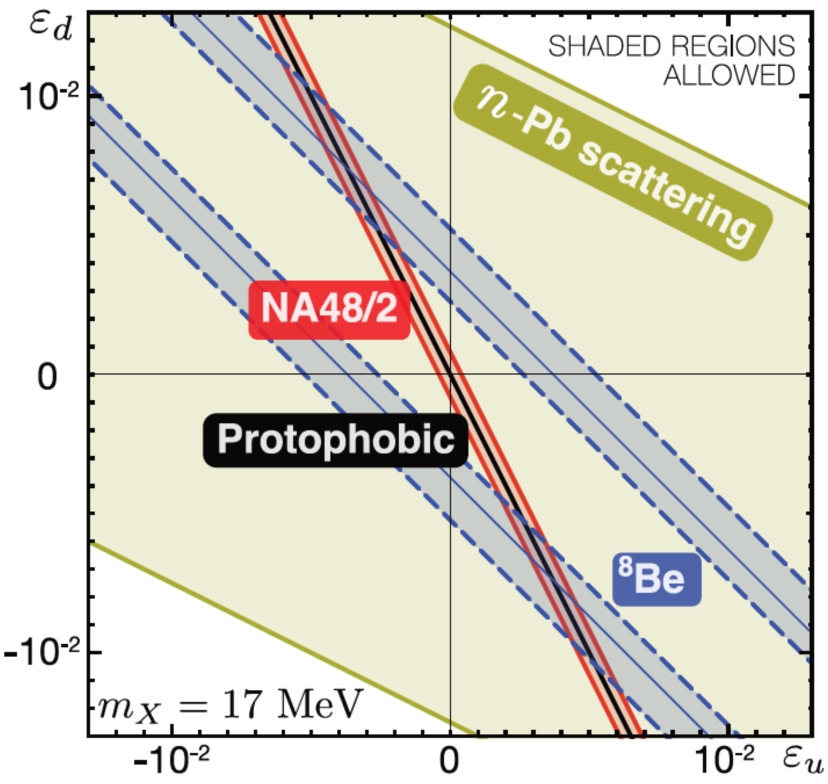


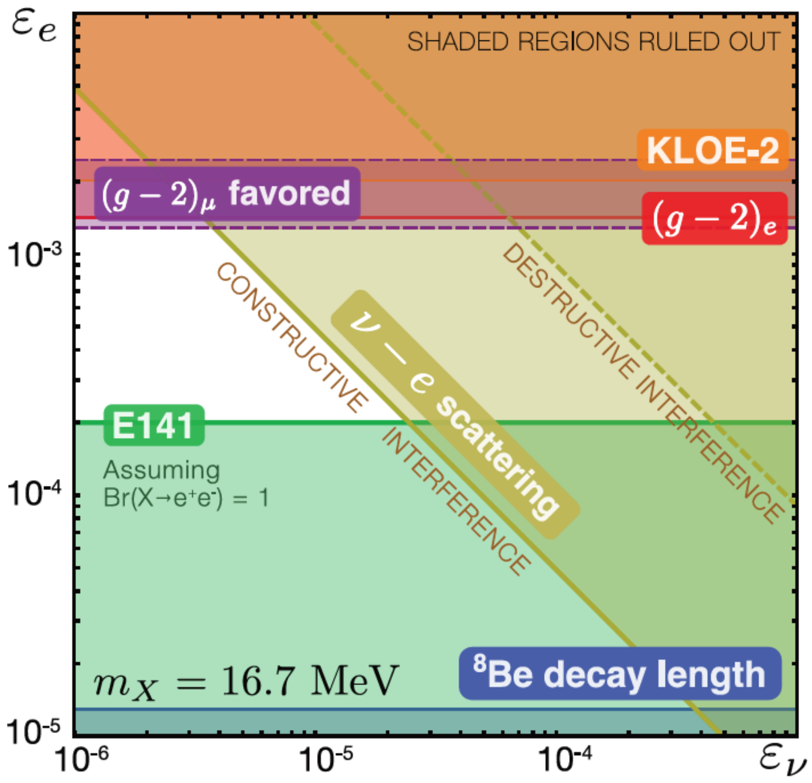
COUPLING CONSTRAINTS IN DETAIL

$$\begin{aligned}
|\varepsilon_n| &= (2-10)\times 10^{-3}\\
|\varepsilon_p| &\lesssim 1.2\times 10^{-3}\\
|\varepsilon_e| &= (0.2-1.4)\times 10^{-3}\\
\sqrt{|\varepsilon_e\varepsilon_\nu|} &\lesssim 3\times 10^{-4}\,.
\end{aligned}$$

In the exact protophobic limit:

$$\begin{aligned}
\varepsilon_u &= -\frac{1}{3}\varepsilon_n\\
\varepsilon_d &= \frac{2}{3}\varepsilon_n
\end{aligned}$$





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%)

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

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:

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

- 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:

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

- For $\varepsilon \approx -\varepsilon_{B-L}$, we get B-L-Q charges:

  $\varepsilon_u \approx \varepsilon/3$, $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e << \varepsilon_{u,d}$ (nice!)

  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_{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,

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

- 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

OTHER J^P MODELS

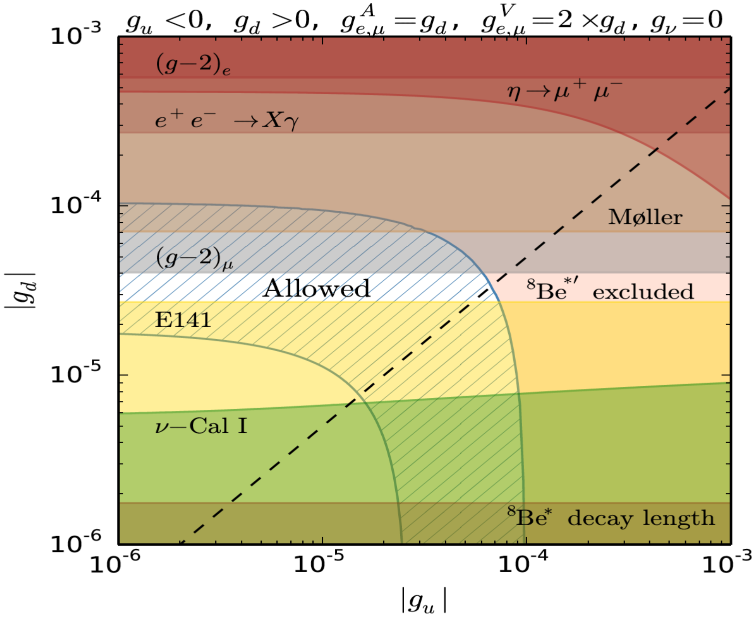
- Pseudoscalars have also been explored and are also possible

Ellwanger, Moretti (2016)

- Axial vectors, which automatically decouple from pion decays, have been analyzed and are also possible

Kozaczuk, Morrissey, Stroberg (2016)

$$-\mathscr{L} \supset X_\mu \sum g_q \bar{q} \gamma^\mu \gamma^5 q$$



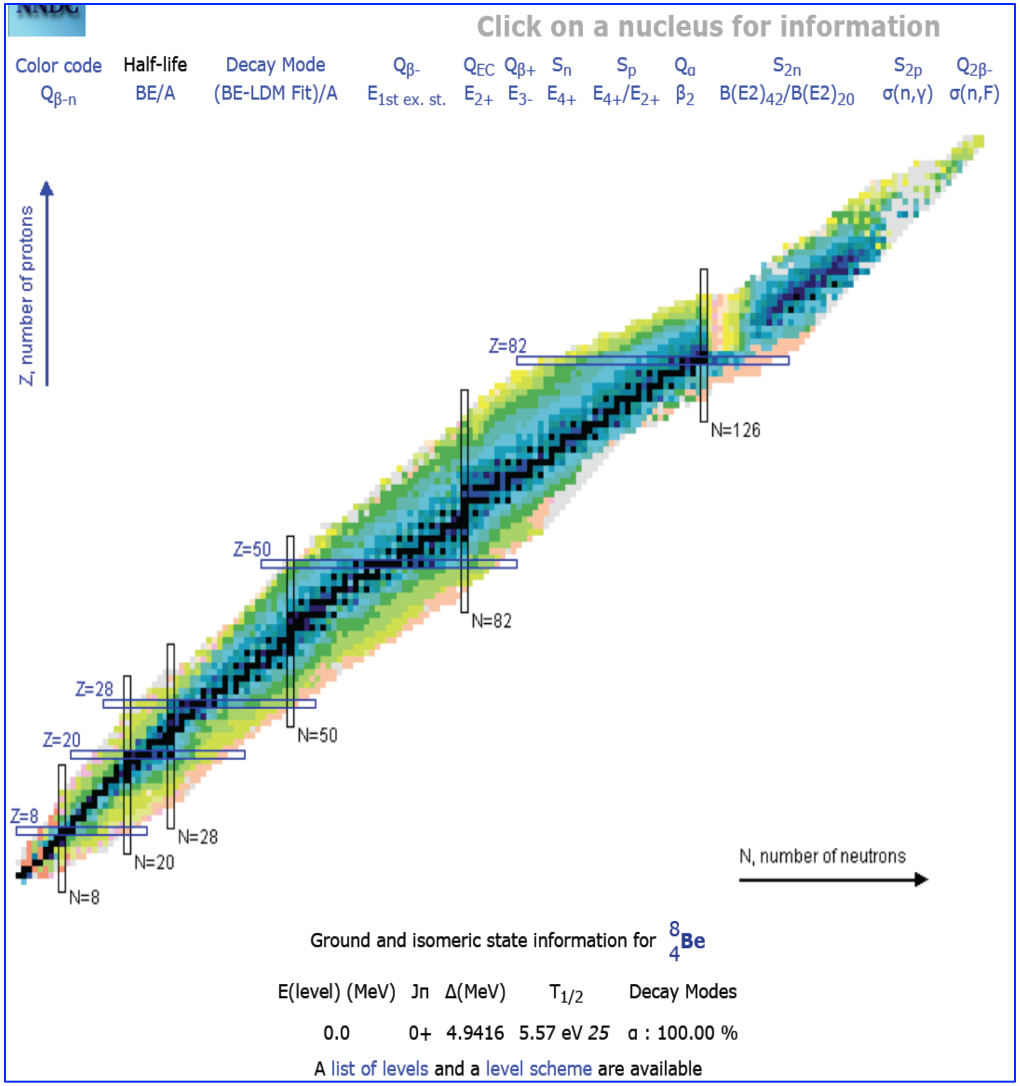
FUTURE TESTS: NUCLEAR PHYSICS

- 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 can 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)



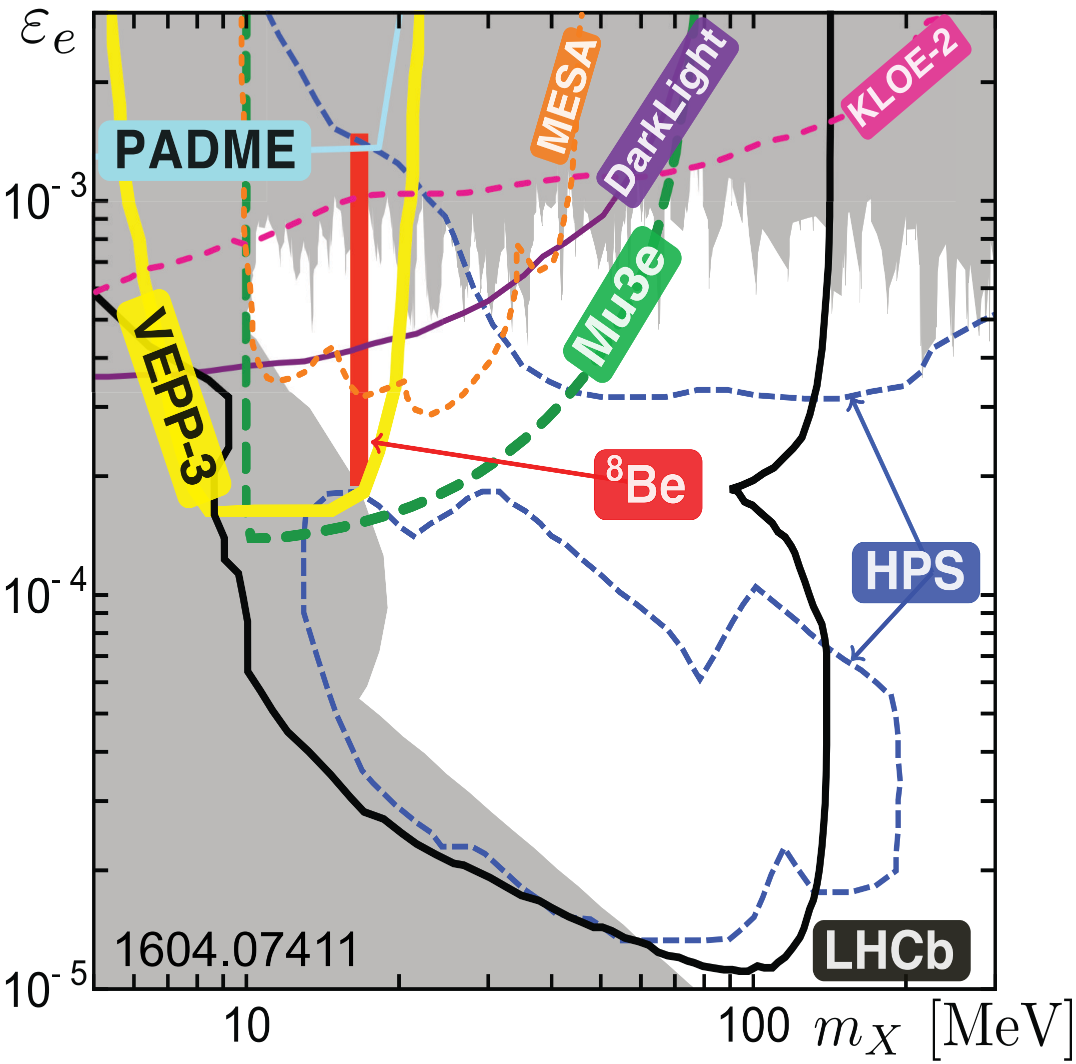
Ground and isomeric state information for $^8_4$**Be**

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	4.9416	5.57 eV *25*	α : 100.00 %

A list of levels and a level scheme are available

FUTURE TESTS: PARTICLE PHYSICS

- There are a host of collider experiments that have been planned for dark photon searches, and may now be sensitive to the 17 MeV range and electron couplings of the desired size
- Generally they look for $e^+e^- \rightarrow \gamma X$, possibly followed by $X \rightarrow e^+e^-$
- See “Advances in Dark Matter and Particle Physics 2016,” Messina, Italy, October 2016



CONCLUSIONS

- There is currently a 6.8σ anomaly in ^{8}Be* nuclear decays; the data are beautifully fit with χ^2/dof = 1.07 by a new particle interpretation

- A possible new physics explanation, consistent with all other constraints, is a protophobic gauge boson that also explains the muon g-2 anomaly

- Is it new physics? All the possible resolutions appear non-trivial at present; further work is needed in nuclear and particle experiment and theory

- Nuclear physics: bump in 17.64 8Be*' is phase-space suppressed, but should eventually appear

- Particle physics: the parameters $m_X \sim 17$ MeV, $\varepsilon_n \sim (2\text{-}10)\ 10^{-3}$, $\varepsilon_e \sim (2\text{-}14)\ 10^{-4}$ provide an interesting target for future experiments

- A future ^{8}Be null result would disfavor new physics, but a confirmation would still be subject to nuclear theory uncertainties; good ideas for complementary probes are welcome

- The protophobic gauge boson is a reminder that variants on the standard light boson candidates are easily imagined and may be quite interesting