DARK MATTER AND THE SEARCH FOR A FIFTH FORCE

TRIUMF Colloquium

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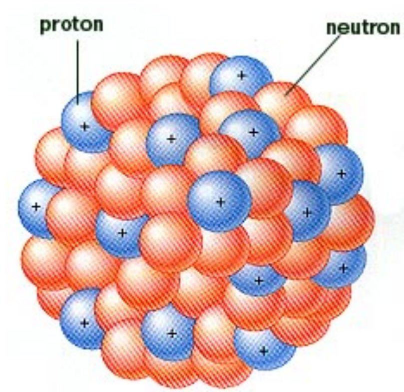
9 February 2017

FUNDAMENTAL FORCES

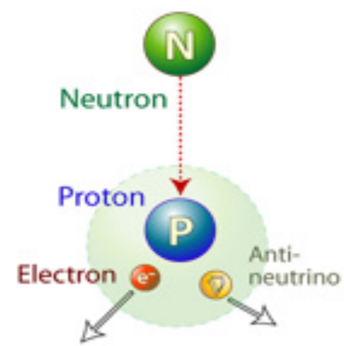
- We know of four fundamental forces

Gravity

Electromagnetism



Strong



Weak

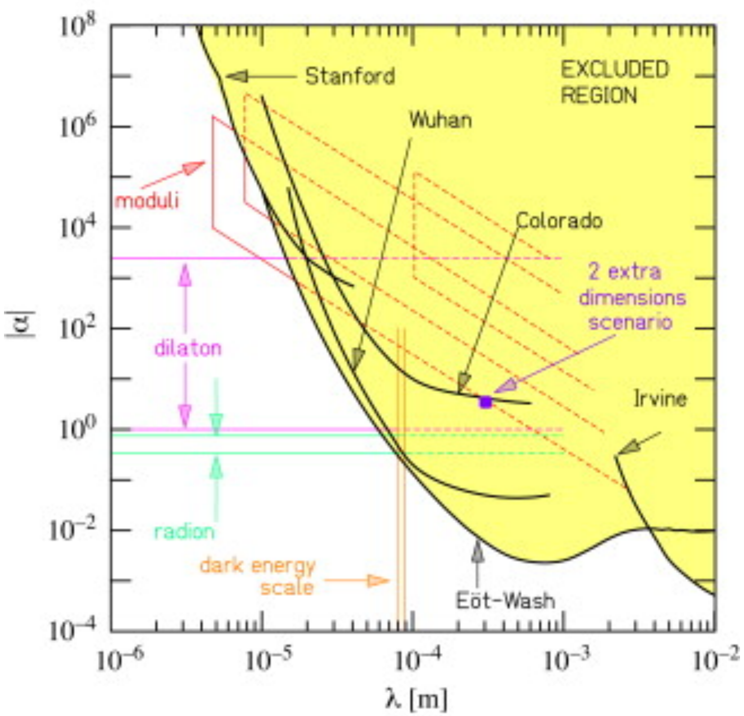
- Are there more? Is there a fifth fundamental force?

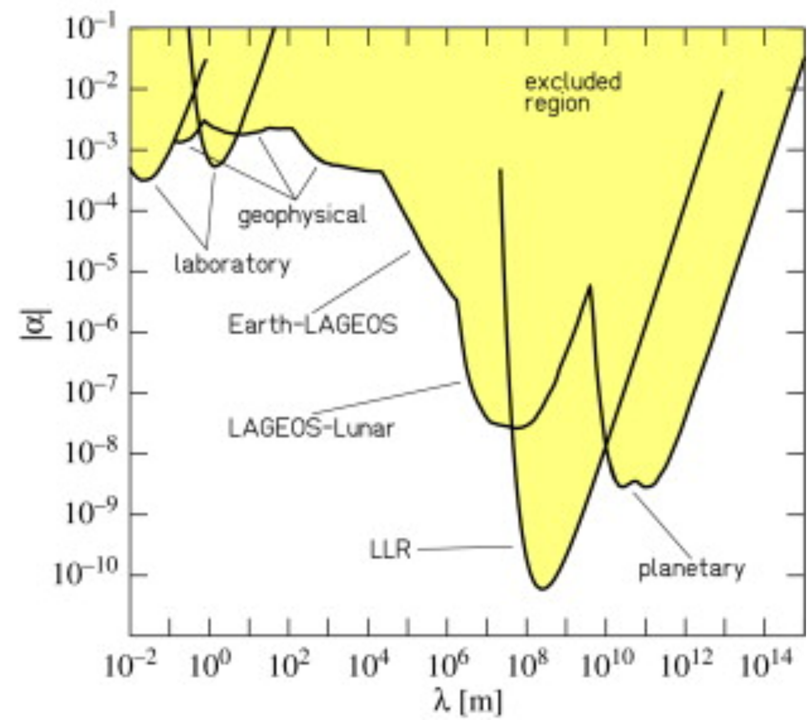
FORCES AND PARTICLES

- In this talk, discovering a new fundamental force means discovering a new boson; primarily, I have in mind spin 1 gauge bosons, like the photon, W, Z, and gluon, but other bosons qualify as well
- With this definition, 5th forces can be mediated by a host of hypothetical particles: Z' gauge bosons, A' dark photons, dilatons, Kaluza-Klein gravitons, ...
- The force's range is inversely proportional to the force-mediating particle's mass: range $\lambda \sim m^{-1}$
- The "force" language is perhaps most natural when m is small, λ is large. E.g.,
  - $m_{Z'} \sim$ TeV, $\lambda \sim 2 \times 10^{-19}$ m is a particle
  - $m_{A'} \sim$ MeV, $\lambda \sim 200$ fm starts to look like a force

PAST 5TH FORCE SEARCHES

- There have been many searches for 5th forces; for example, deviations from gravity: $V(r) = -G_\infty \frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$





Adelberger, Gundlach, Heckel, Hoedl, Schlamminger (2009)

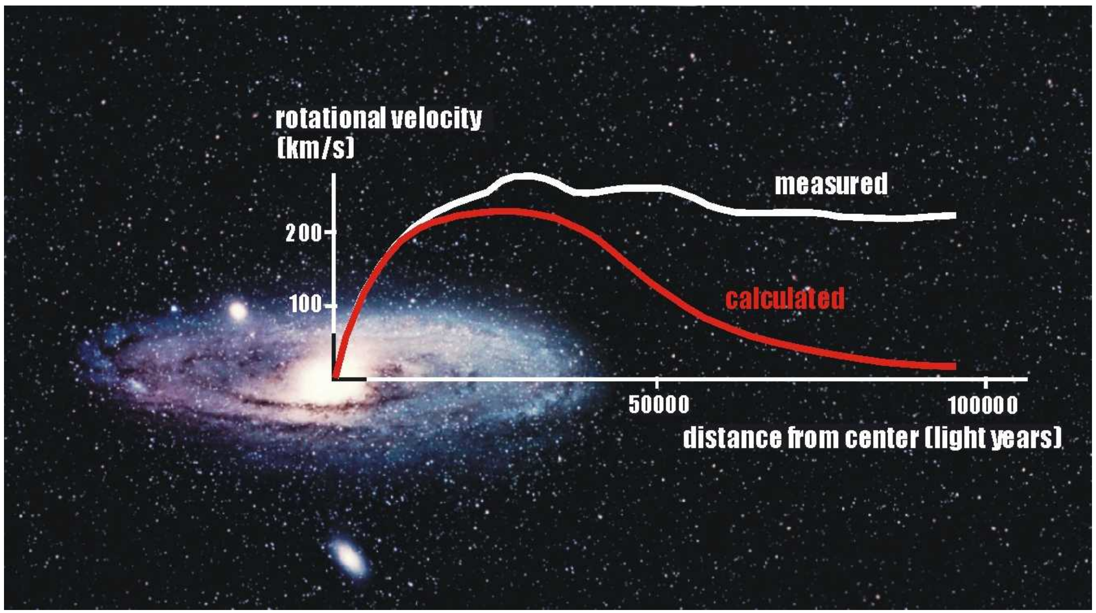
- So far, no such deviations have been found, but the history of 5th force searches is fascinating

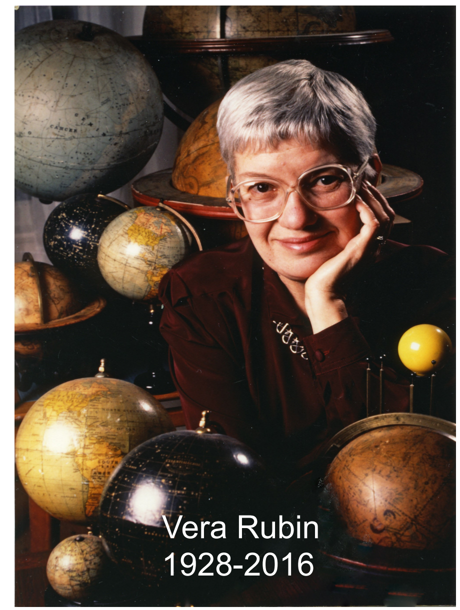
See, e.g., Fischbach, "The 5th Force: A Personal History" (2015)

DARK MATTER

- There is now every indication that the universe includes 6 times as much dark matter as ordinary matter

- Classic evidence: rotation curves



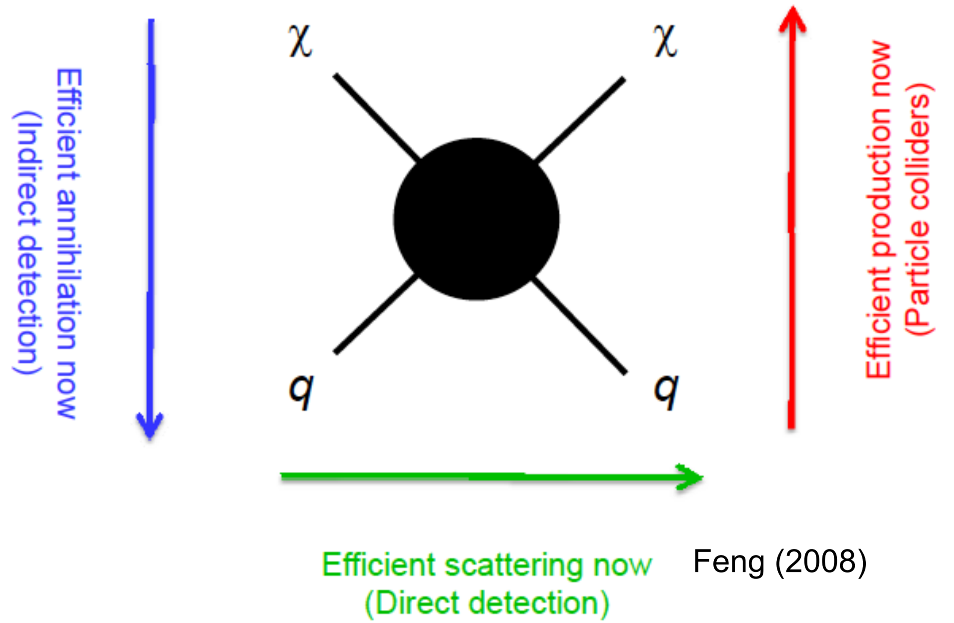


- This evidence has now been supplemented by many other observations, all pointing to the same amount of dark matter

CLASSIC DARK MATTER CANDIDATES

- Along with the classic evidence for dark matter, there are classic candidates: axions, sterile neutrinos, and weakly-interacting massive particles (WIMPs)

- For many years, we have been exploring how to find these candidates: e.g., WIMPs at colliders, direct/indirect detection

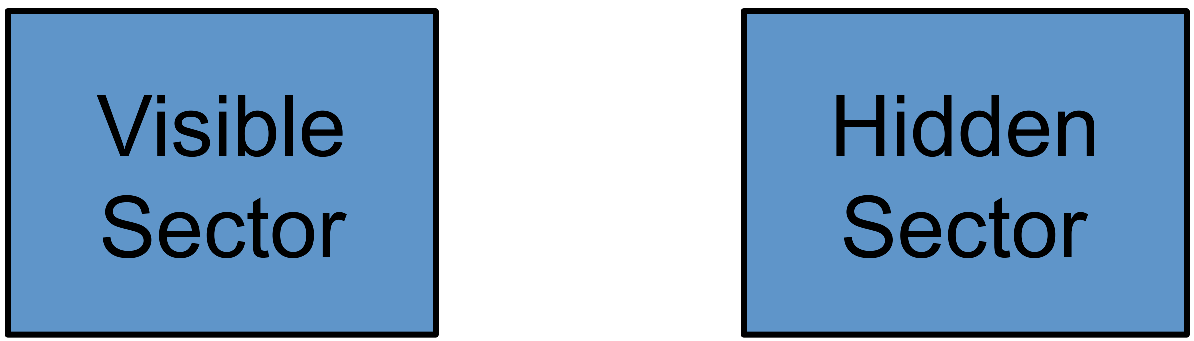


Feng (2008)

- So far none of them has been found

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)



- A hidden sector with dark matter in it is a "dark sector," and it 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);...

DARK MATTER PORTALS

- If we are to detect it, we need to know how the hidden sector interacts with us

- Seemingly a Pandora's box of possibilities, but effective operators provide an organizing principle:

$$\mathcal{L} = \mathcal{O}_4 + \frac{1}{M}\mathcal{O}_5 + \frac{1}{M^2}\mathcal{O}_6 + \ldots$$

  where the operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [$F_{\mu\nu}$] = 2

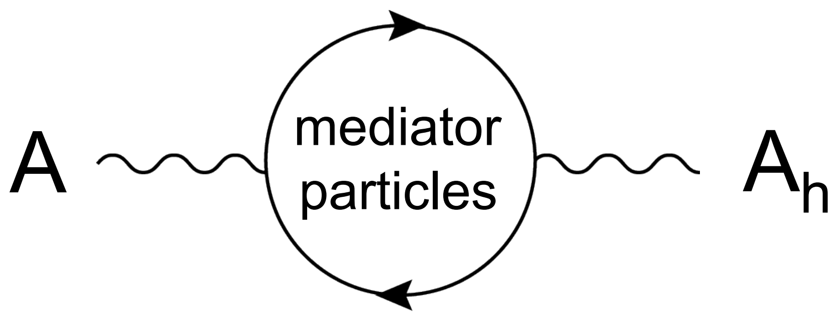
- *M* is a (presumably) large "mediator mass," so start with dimension 4 operators. Some of the few possibilities:

hLN	$h^\dagger h \phi_h^\dagger \phi_h$	$F_{\mu\nu} F_h^{\mu\nu}$
Neutrino portal	Higgs portal	Vector portal

VECTOR PORTAL

Holdom (1986)

- Suppose there are mediator particles with both hidden sector and visible sector charges. These will induce a coupling between the visible and hidden gauge fields:



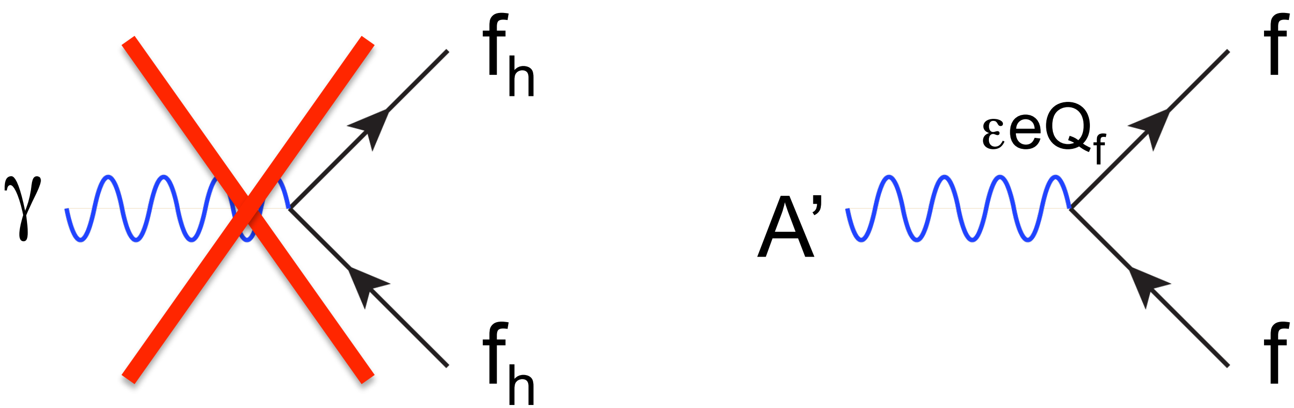
- One might expect this effect to become very small for heavy mediator particles, but it doesn't

- Instead, one gets a vector portal 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

DARK PHOTONS

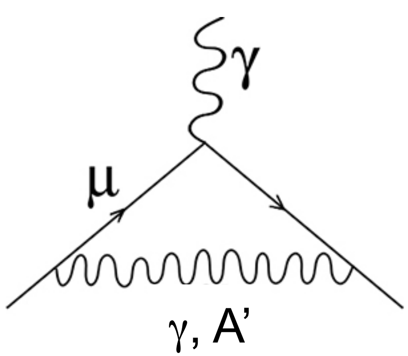
Holdom (1986)

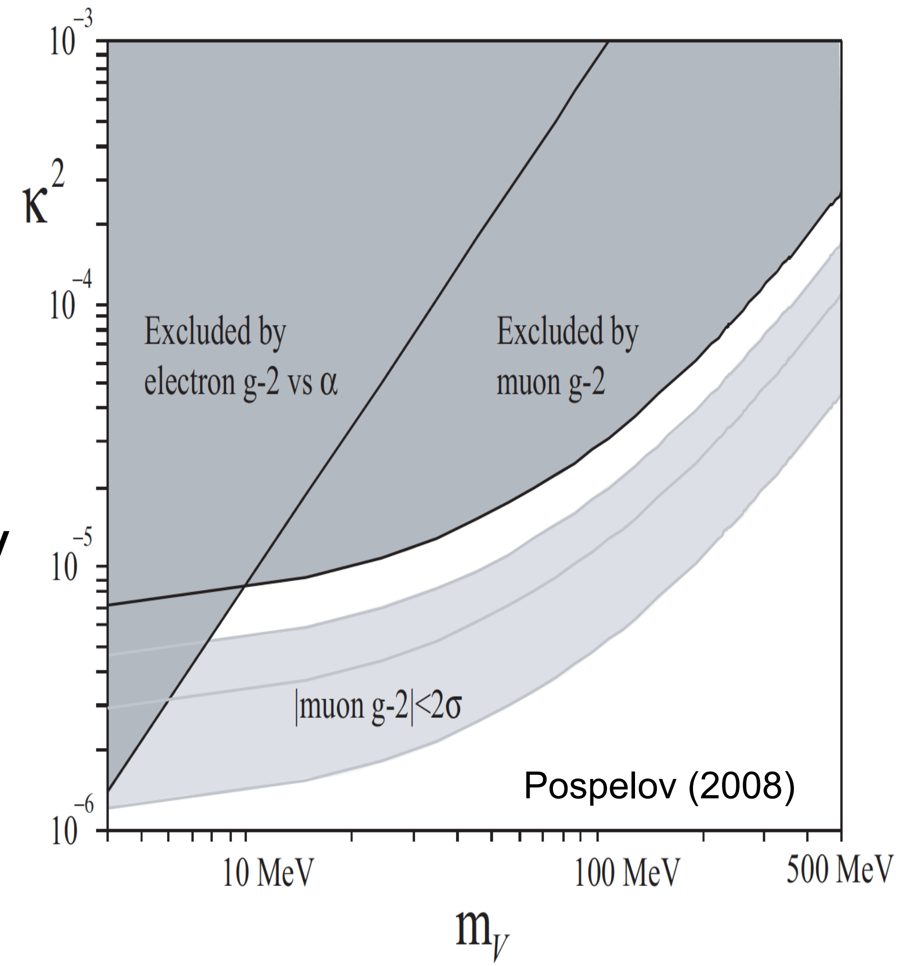
- The operator $\epsilon F_{\mu\nu} F_h^{\mu\nu}$ mixes the visible and hidden force carriers. Diagonalizing to eliminate this mixing term, one finds that the physical states are
  - a massless force carrier: the SM photon γ
  - a massive force carrier: the "dark photon" A'
- The SM photon doesn't couple to hidden sector particles, but the dark photon couples with charge $\varepsilon e Q_f$ to visible sector particles: it mediates a 5th force!



DARK PHOTON SEARCHES

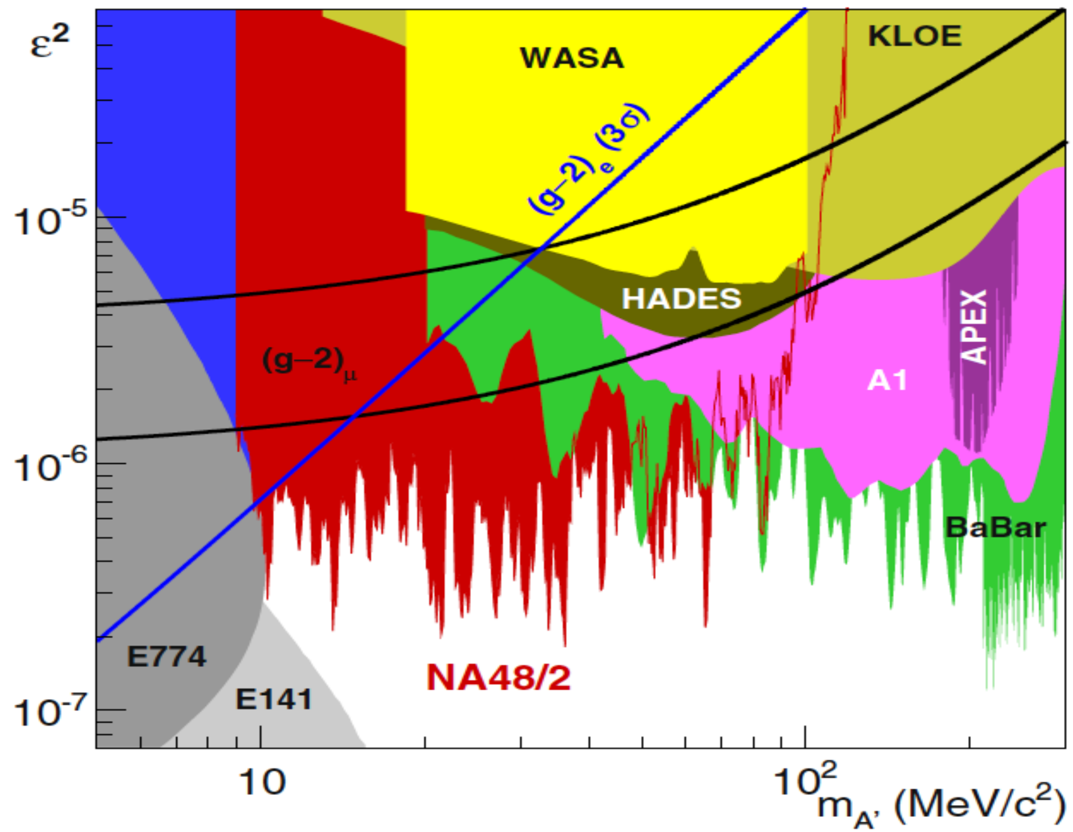
- This has motivated a world-wide hunt for dark photons throughout the (mass, coupling) parameter space
- What parameters are interesting?
  - Lamppost: whatever is not excluded and within reach
  - $\varepsilon \sim 10^{-3}$
  - Anomalies: muon g-2, currently a 3.5σ discrepancy





CURRENT CONSTRAINTS

- In just 8 years, a large number of analyses have started constraining the parameter space by analyzing archived and current data and by doing new experiments



- 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

FIFTH FORCE IN NUCLEAR PHYSICS

- The interest in dark matter and 5^{th} forces at low energy scales 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

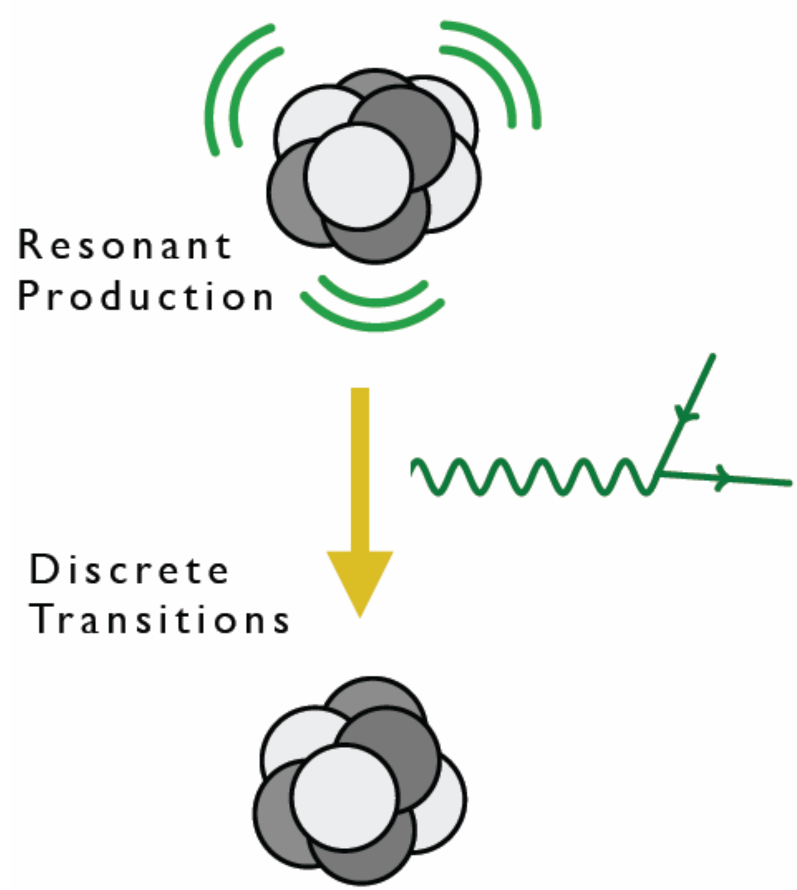
A. J. Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]

- Could these be 5^{th} force gauge bosons?

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

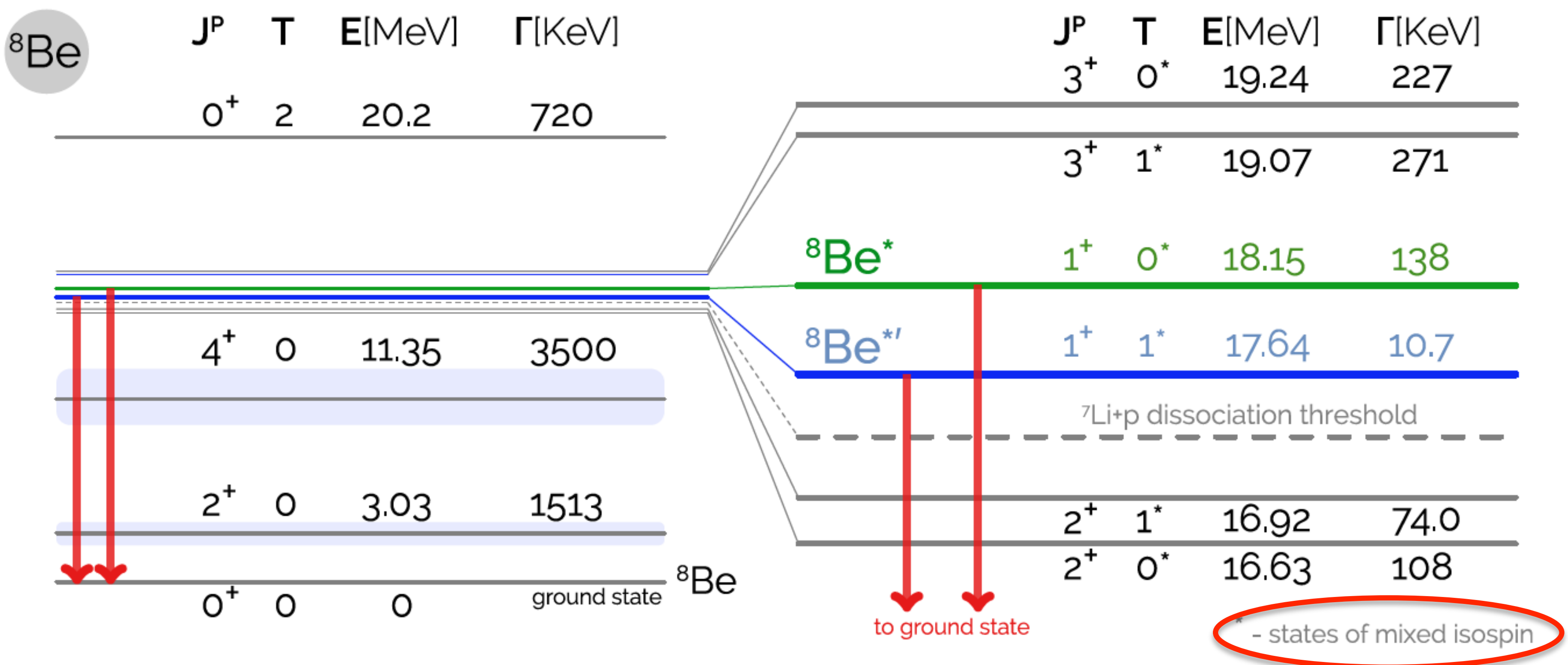
^{8}BE AS A NEW PHYSICS LAB

- ^{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

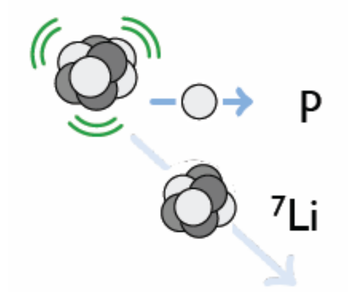
- Many excited states with different spins and isospins
- Of special interest: the ^{8}Be* (18.15) and ^{8}Be*' (17.64) states



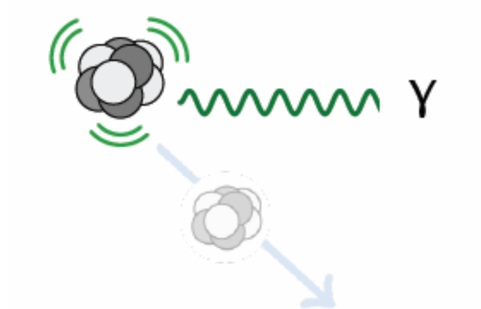
1608.03591; based on Tilley et al. (2004), http://www.nndc.bnl.gov/nudat2, Wiringa et al. (2013)

^{8}BE* DECAY

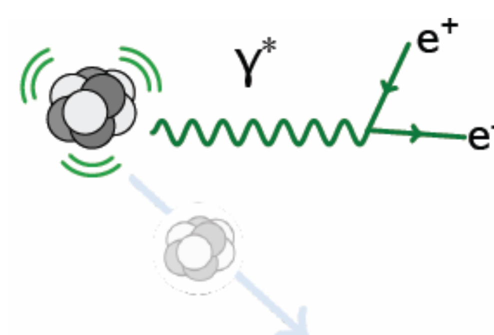
- Hadronic
  B(p ^{7}Li) ≈ 100%



- Electromagnetic
  B(^{8}Be γ) ≈ 1.5 x 10^{-5}



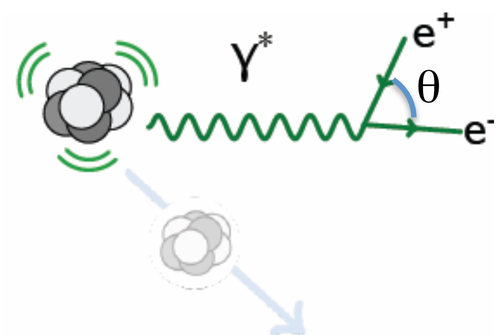
- Internal Pair Creation
  B(^{8}Be e^+ e^-) ≈ 5.5 x 10^{-8}



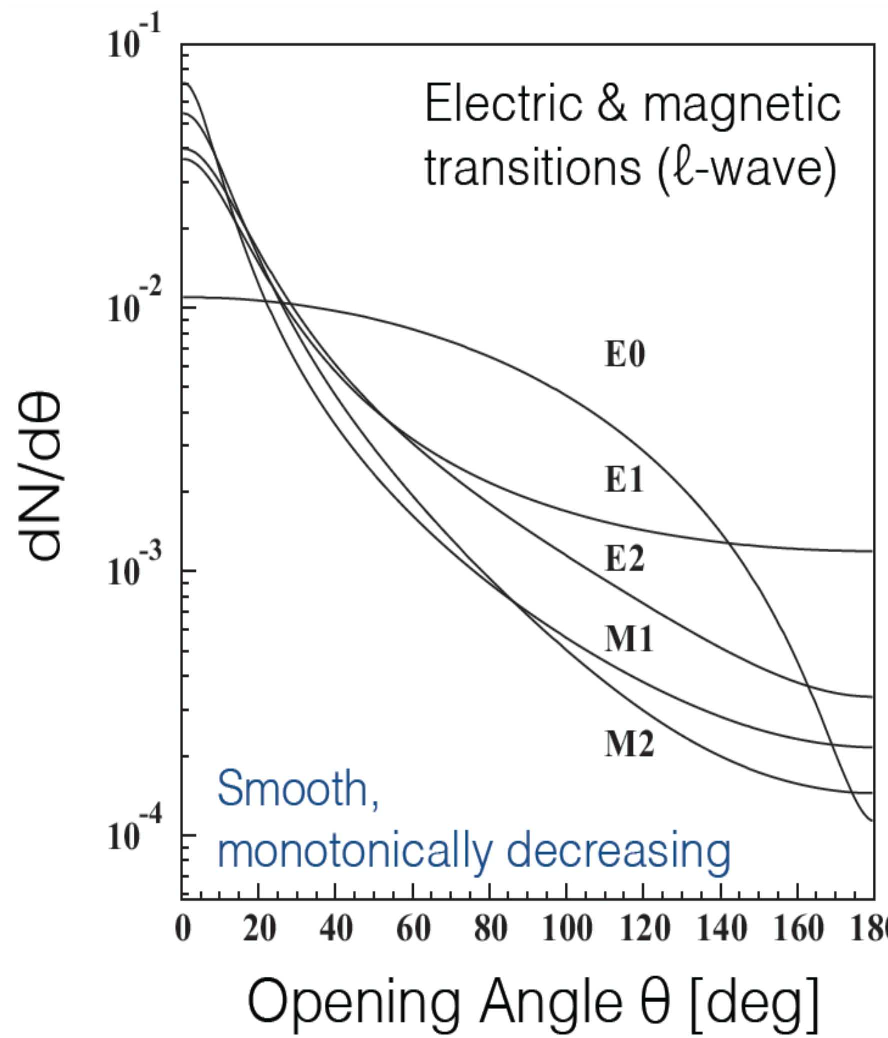
^{8}BE* DECAY

- Internal Pair Creation

  B(^{8}Be $e^+ e^-$) ≈ 5.5 x 10^{-8}



For e^+e^- produced by a virtual photon, dN/dθ is sharply peaked at low opening angle θ and is expected to be a monotonically decreasing function of θ

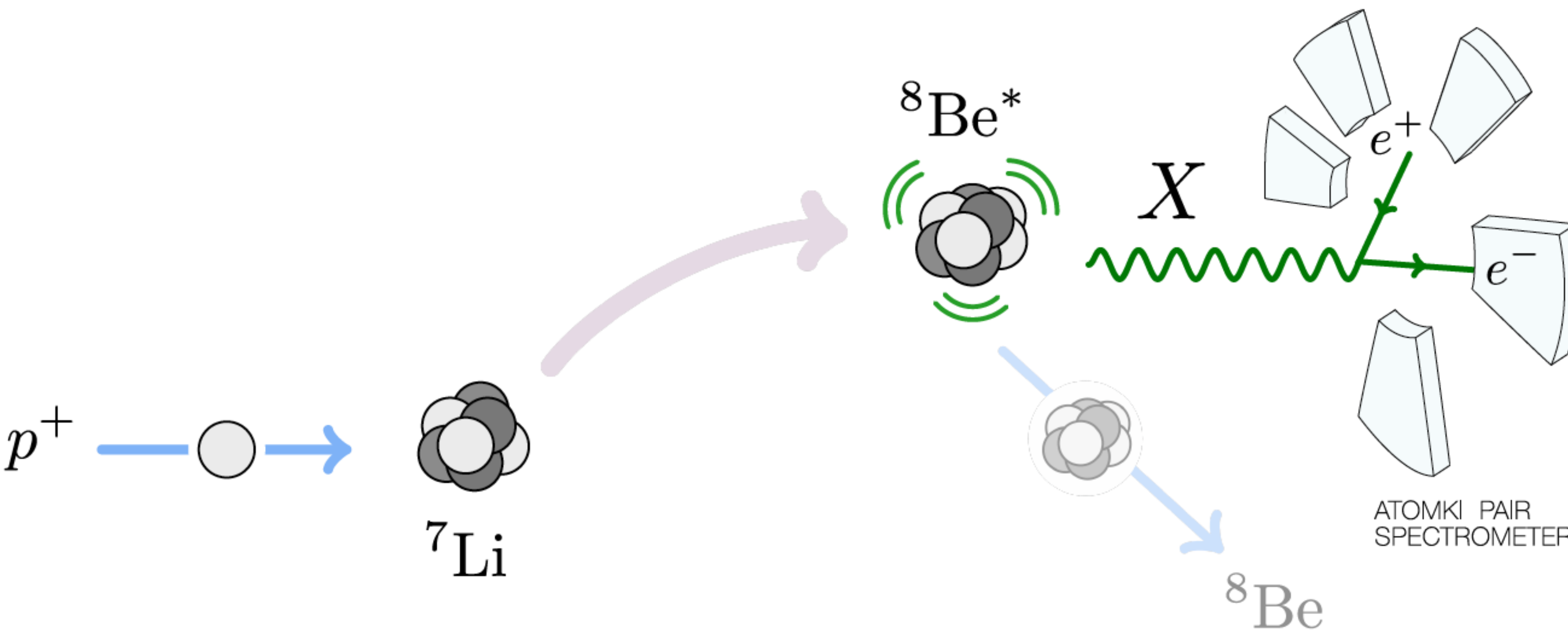


Gulyas et al. (2015); Rose (1949)

THE ATOMKI ^{8}BE EXPERIMENT

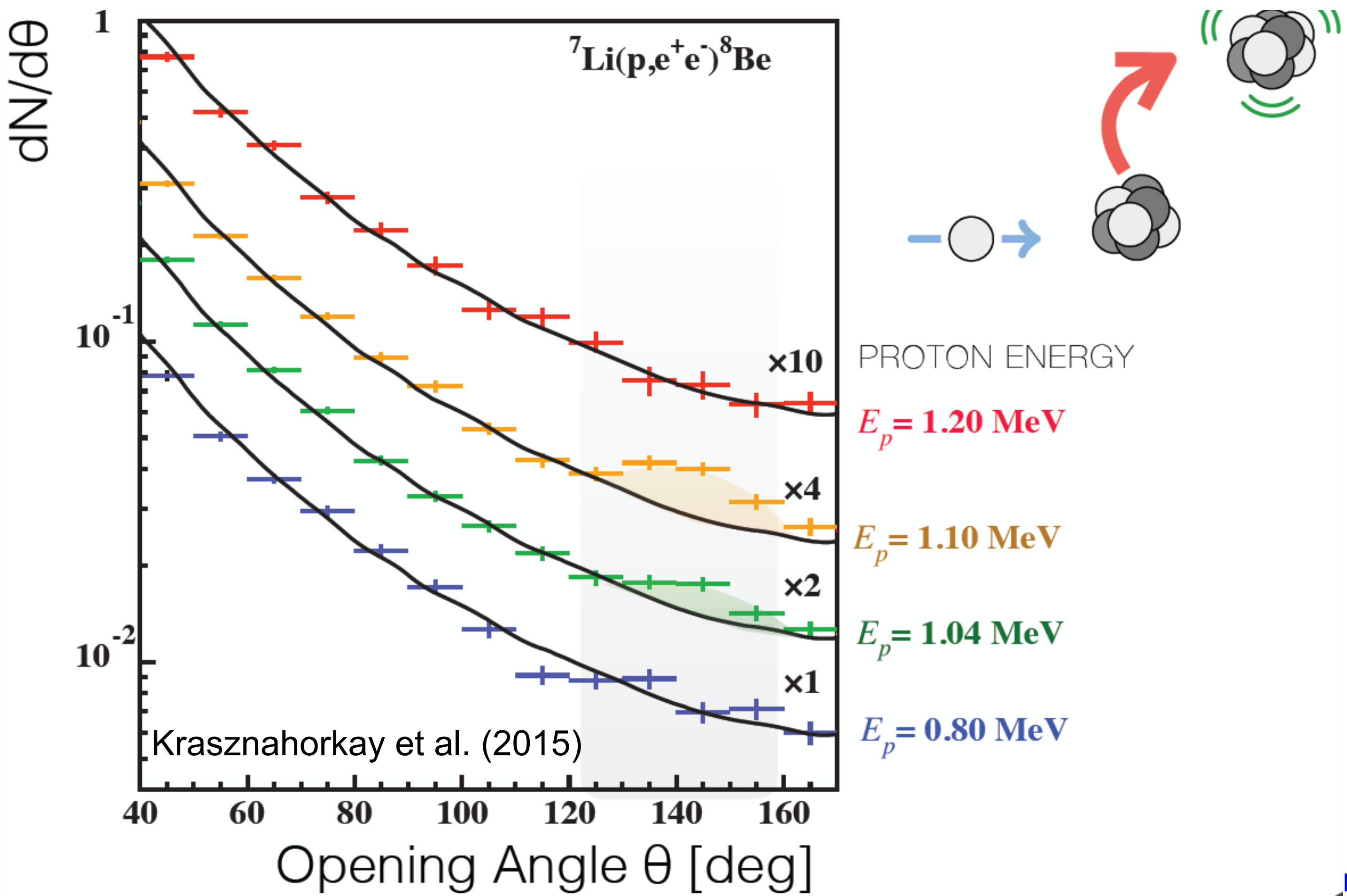
THE ATOMKI ^{8}BE EXPERIMENT

A 1 μA p beam with $\Delta E_p \sim 10$ 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

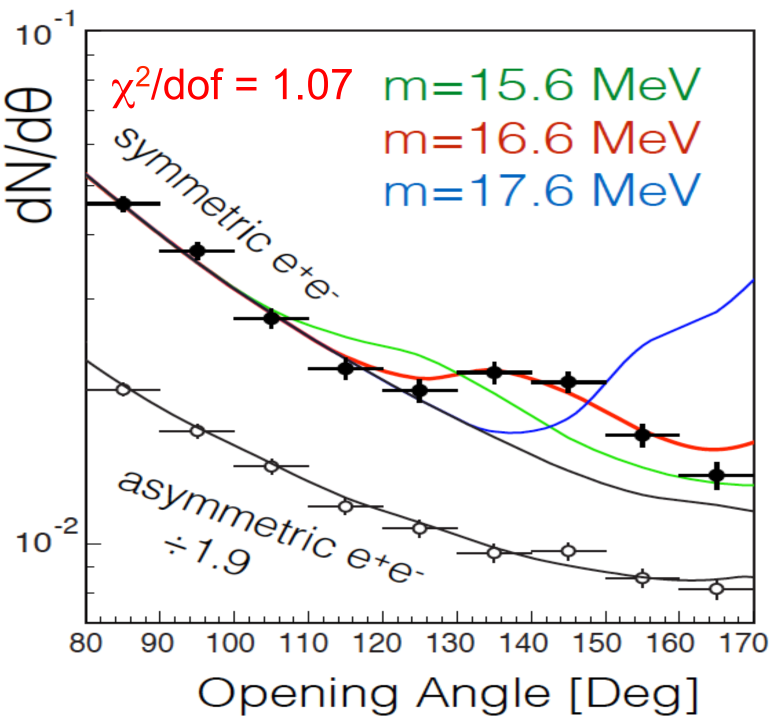
- A bump at ~140 degrees is observed as one passes through the $^8Be^*$ resonance
- Background fluctuation probability: 5.6 x 10^{-12} (6.8σ)

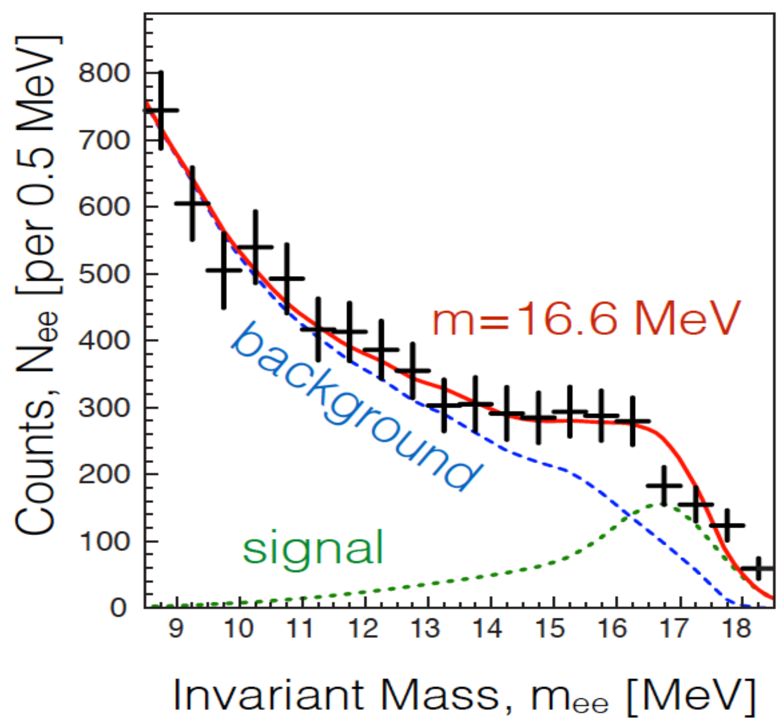


THE ATOMKI ANOMALY

- The θ (and m_{ee}) distributions can be explained by postulating a new particle and 2-step decay: $^8Be^* \rightarrow {}^8Be\ X,\ X \rightarrow e^+e^-$
- The best fit parameters: m = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV

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

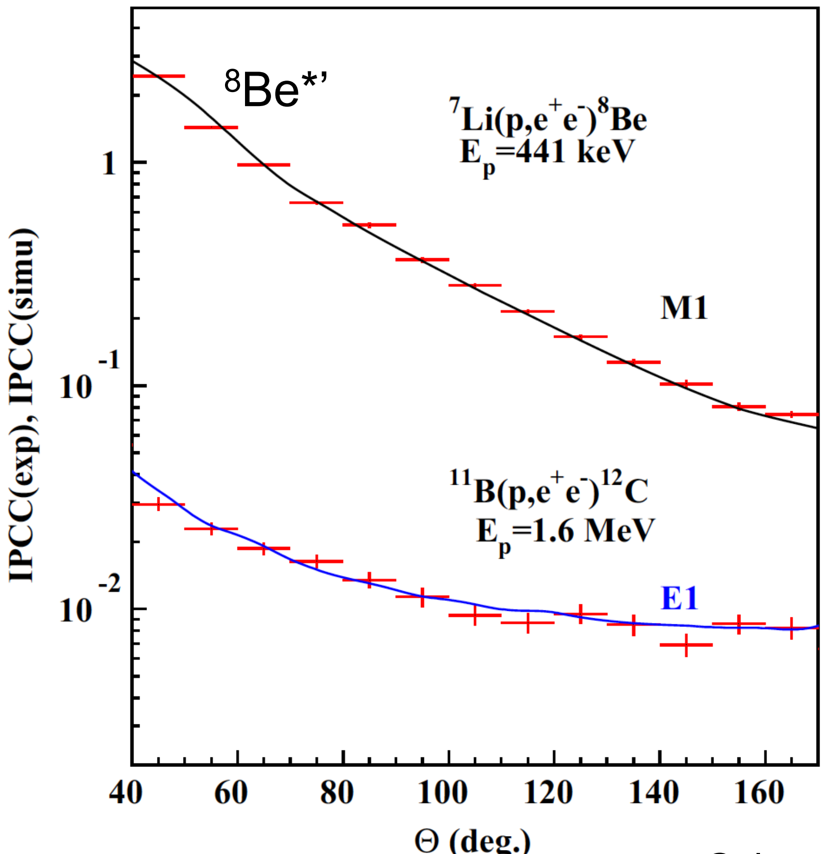




Krasznahorkay et al. (2015)

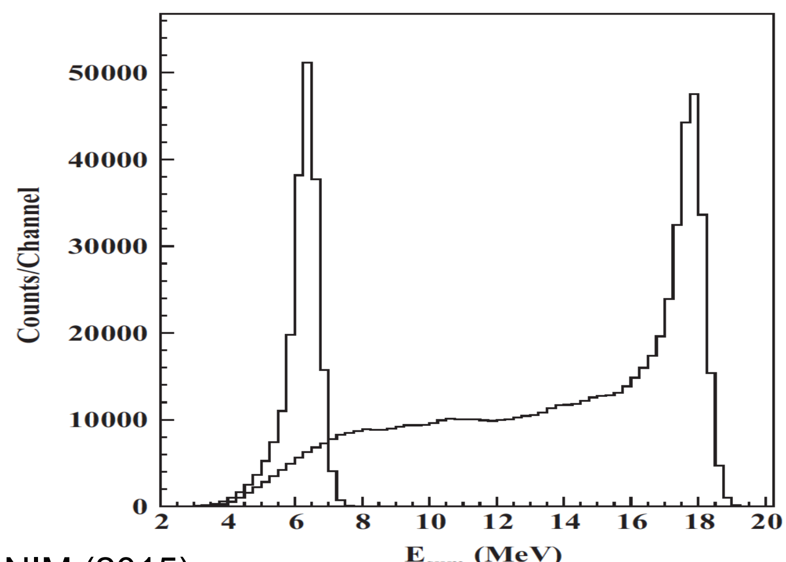
CROSS CHECKS

- 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, 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 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
- Comparable excess not seen for 17.64 MeV states; explainable by phase-space suppression for 17 MeV particle
- Reports of conflicts with previous results of this collaboration are highly misleading / exaggerated
- the excellent fit to a new particle interpretation is purely coincidental
- Hungarian group is now collection 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 data
- Must simultaneously explain lack of similarly-sized bump in (isospin-mixed) 17.64 data
- the excellent fit to a new particle interpretation is purely coincidental
- Preliminary results investigating interference effects reported at APS meeting in January by Zhang and Miller
- Further work would be of great interest

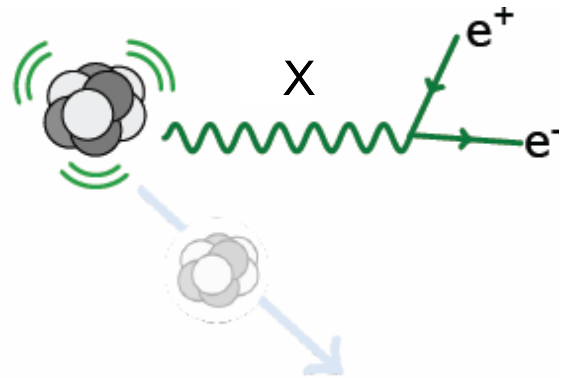
(3) Particle Physics

- 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 – a 5th force

Not everything works

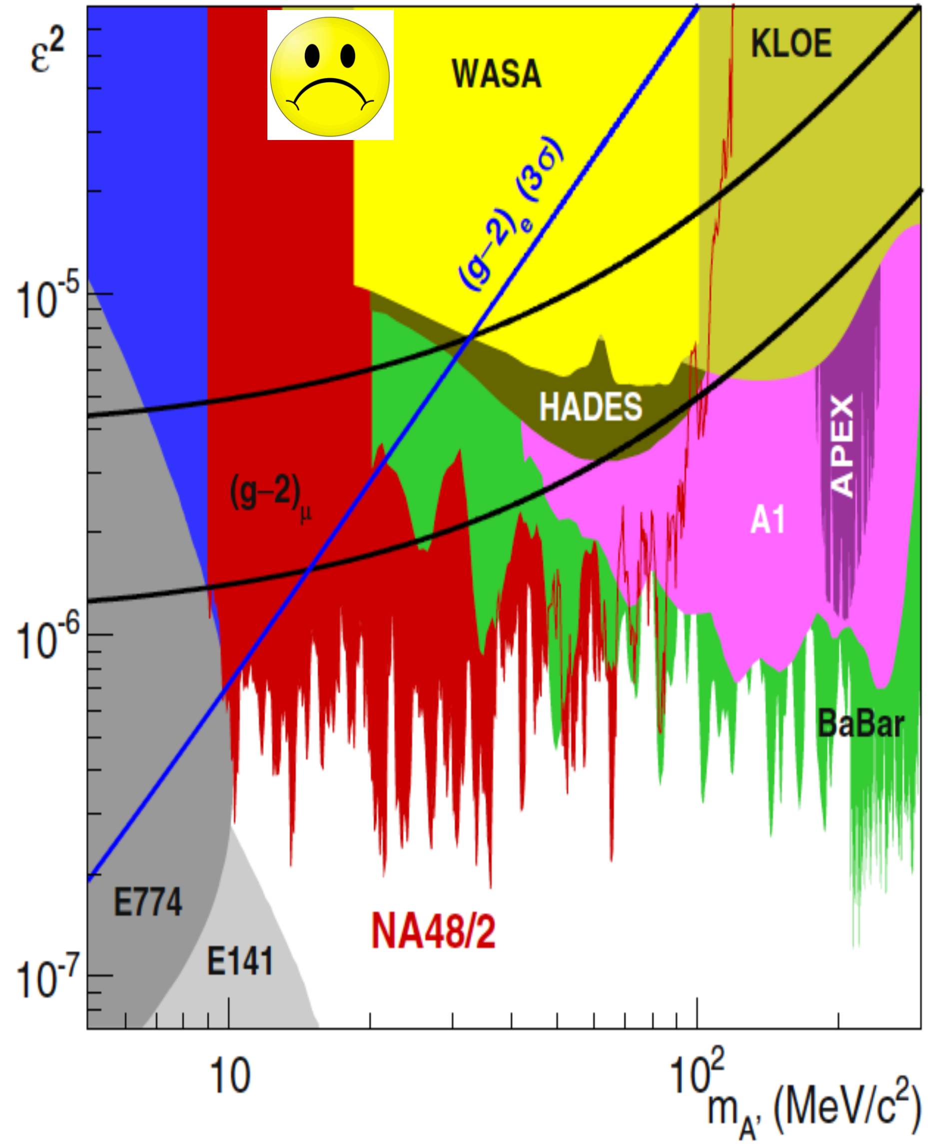
- For example: a spin 0 boson ("dark Higgs boson")
- J^P Assignments: $1^+ \rightarrow 0^+ \, 0^+$
- L Conservation: L = 1
- Parity Cons.: $P = (-1)^L = 1$
- Forbidden in parity-conserving theories

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

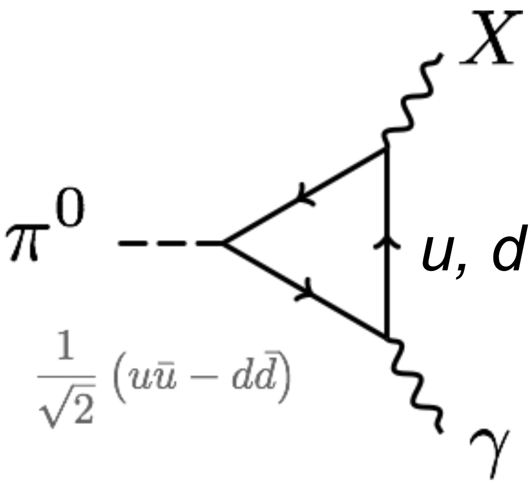
$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$$

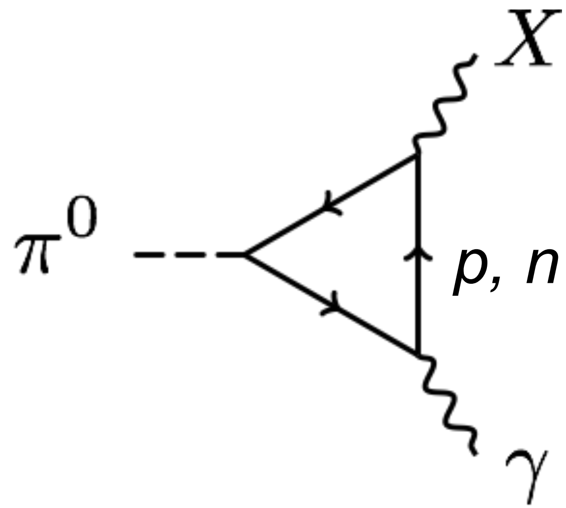
- For the special case of a dark photon with $\varepsilon_f = \varepsilon Q_f$, this implies kinetic mixing parameter $\varepsilon \sim 0.01$, which is excluded
- This is not a dark photon



PROTOPHOBIA

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



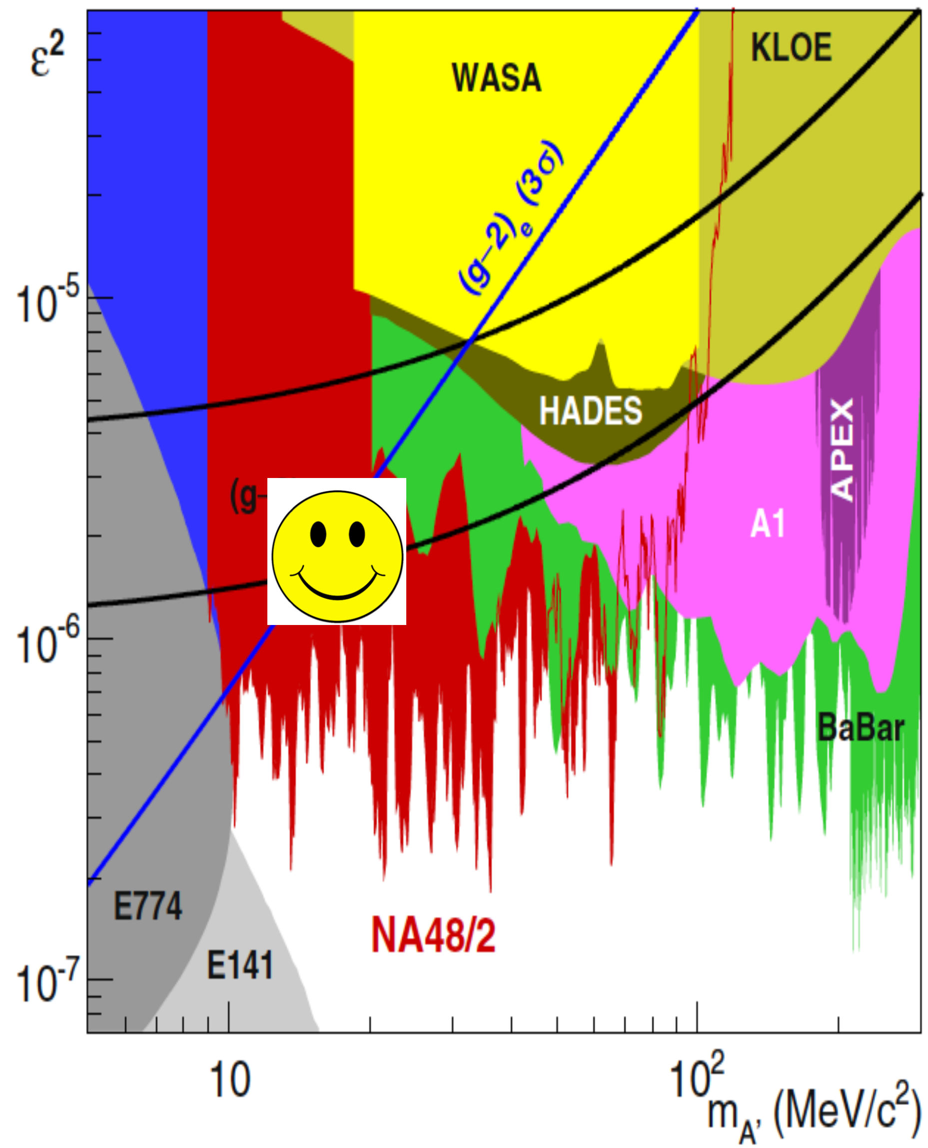


- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

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

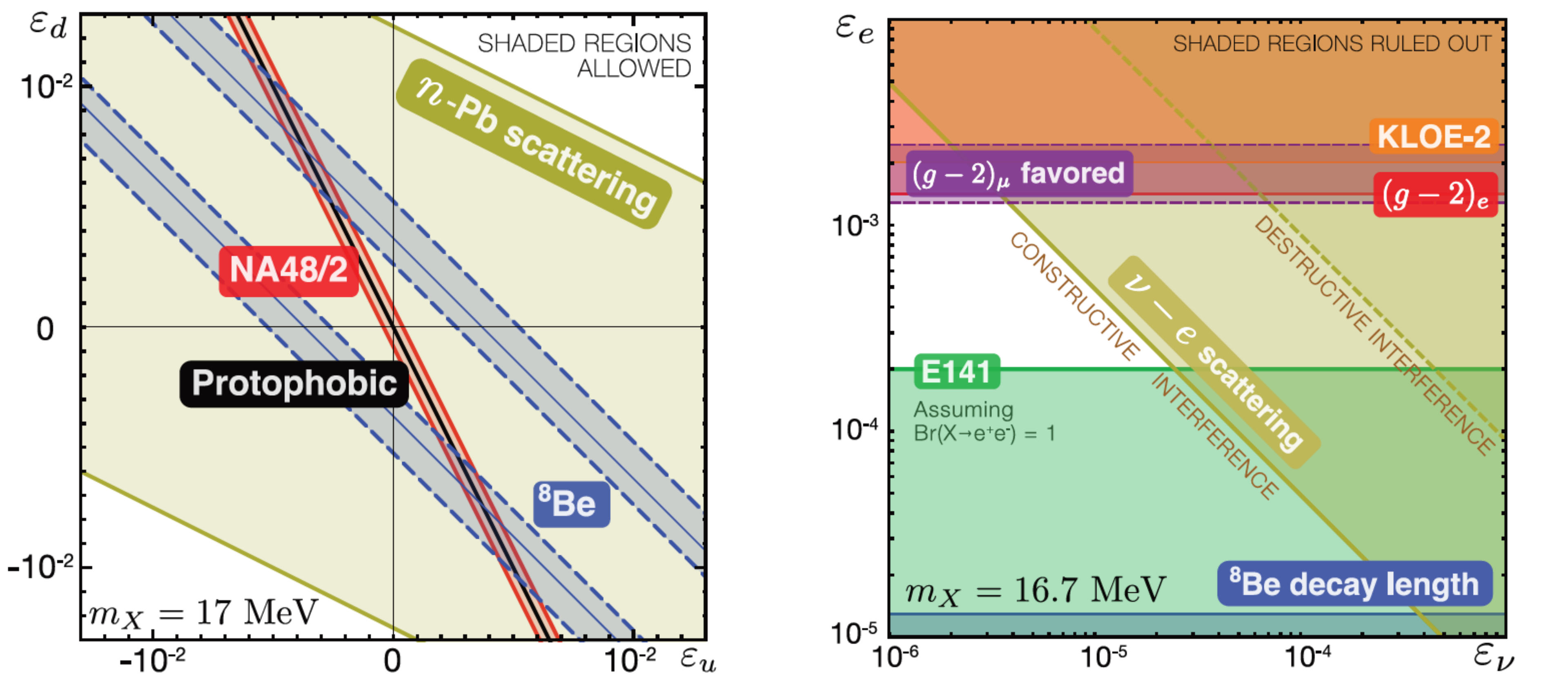
PROTOPHOBIC GAUGE BOSON

- For a protophobic gauge boson, the NA48/2 "quark" constraints are weakened
- One can, then, take electron and muon couplings around 10^{-3}. Such couplings are allowed by all constraints
- A protophobic gauge boson can resolve both the ^{8}Be and muon g-2 anomalies
- Implies a milli-charged 5th force with range ~ 12 fm



COUPLING CONSTRAINTS

- Considering all constraints, require ε_u, $\varepsilon_d \sim$ few 10^{-3} with cancelation to ~10% for protophobia, $10^{-4} < \varepsilon_e < 10^{-3}$, and $|\varepsilon_e \varepsilon_\nu|^{1/2} < 3 \times 10^{-4}$



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

PARTICLE MODELS

- 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. After kinetic mixing with the photon, the new boson’s couplings can be B-L-Q or B-Q.

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

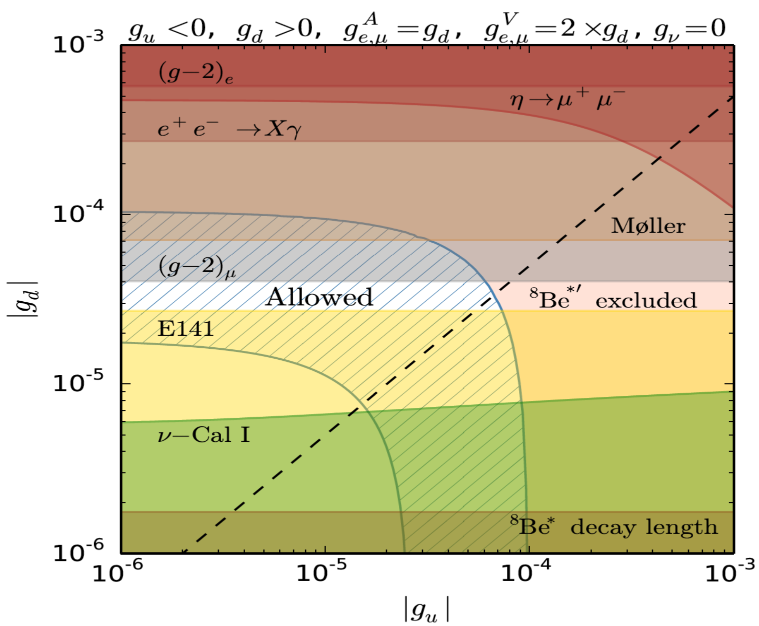
- Pseudoscalars have also been explored and are also possible

Ellwanger, Moretti (2016)

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

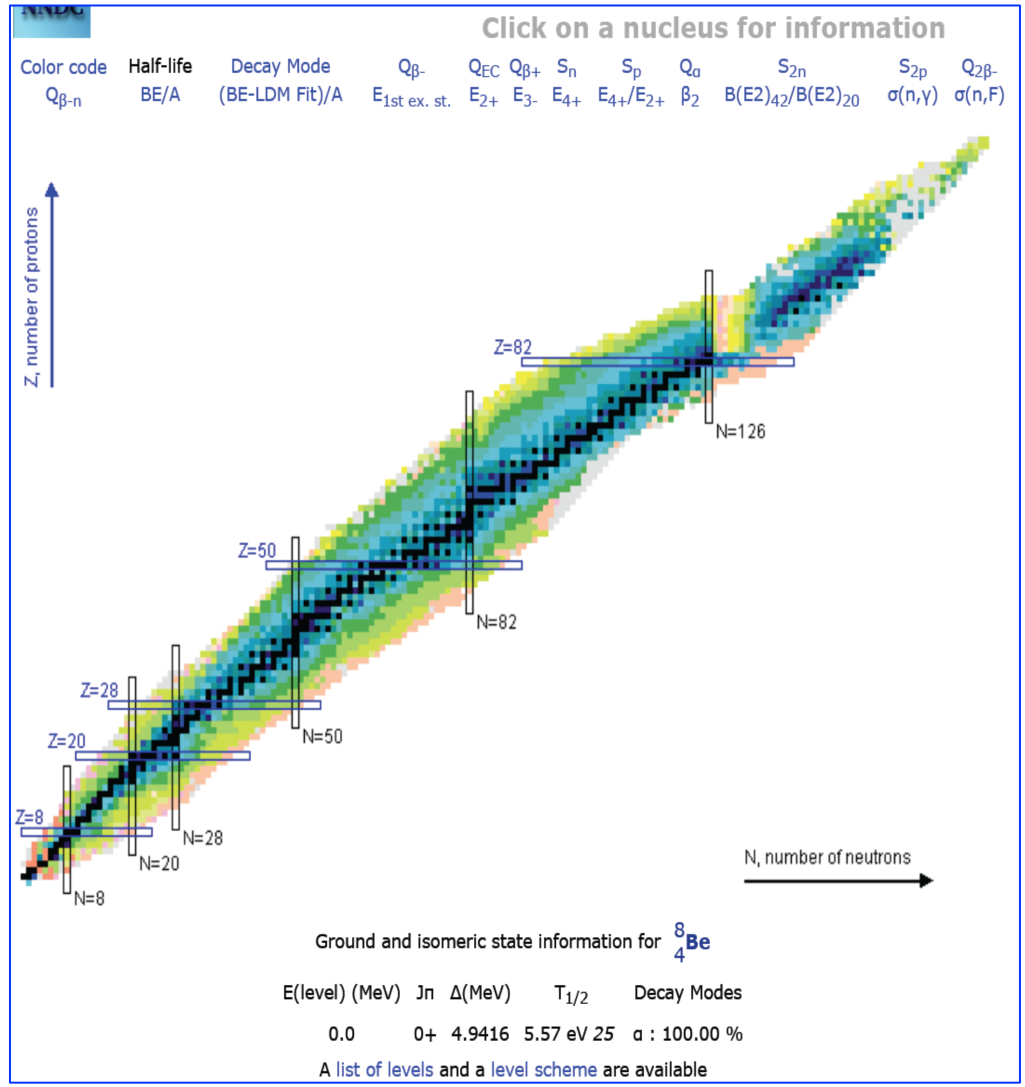
Kozaczuk, Morrissey, Stroberg (2016)

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



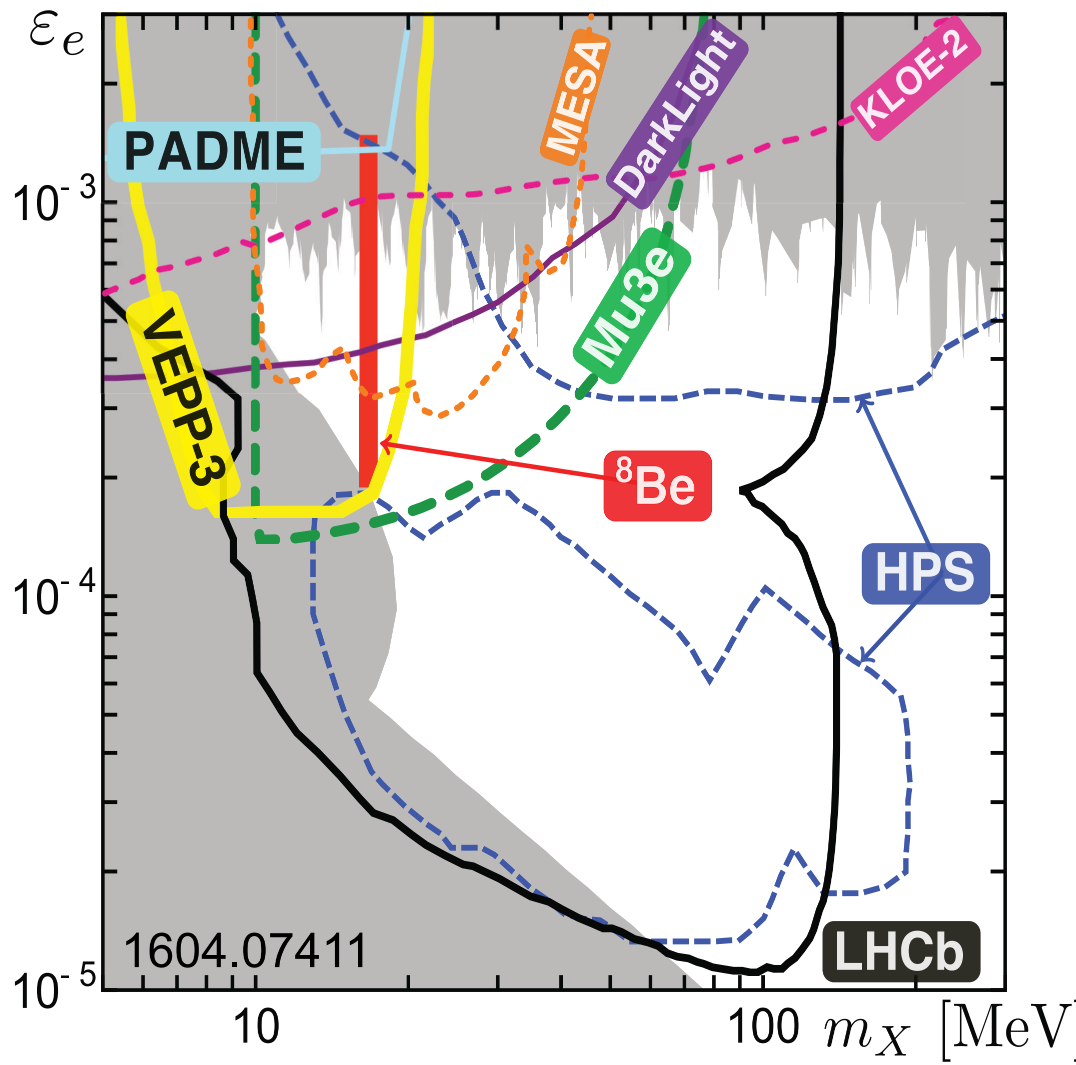
FUTURE TESTS: NUCLEAR PHYSICS

- 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 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: 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
- Generally they look for $e^+e^- \rightarrow \gamma X$, posibly followed by $X \rightarrow e^+e^-$
- See "Advances in Dark Matter and Particle Physics 2016," Messina, Italy, October 2016



CONCLUSIONS

- A 5th force is an open and exciting possibility
- Dark matter provides new motivation to look for light, weakly-coupled particles that may mediate a 5th force
- There is currently a 6.8σ anomaly in ^{8}Be* nuclear decays
- The data are consistent with new particle explanations, including a protophobic gauge boson that mediates a 5th force and simultaneously explains the muon g-2 anomaly
- The result, if true, has spectacular implications for dark matter, force unification, etc.
- Further work is needed and there are many interesting upcoming experiments