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# **DARK MATTER AND THE SEARCH FOR A FIFTH FORCE**

*University of Kentucky Colloquium*

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14 April 2017

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# FUNDAMENTAL FORCES

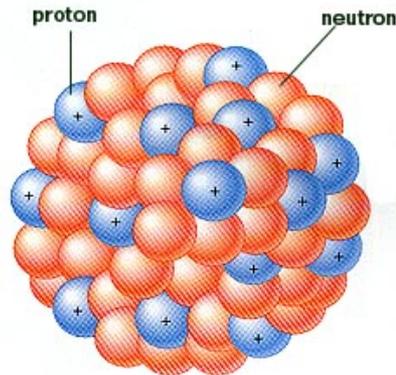
- We know of four fundamental forces



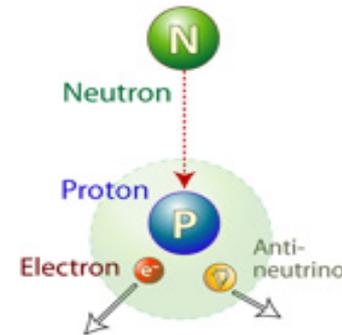
Gravity



Electromagnetism



Strong



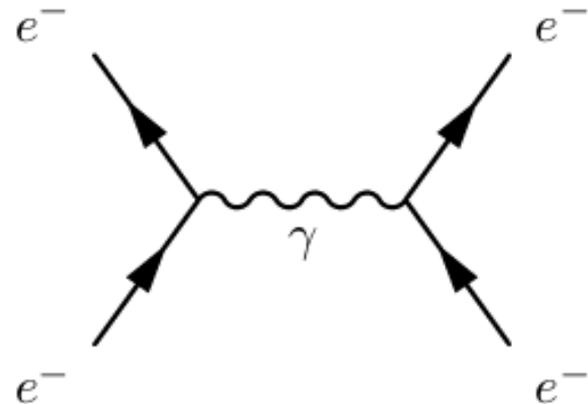
Weak

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

# WHAT IS A FUNDAMENTAL FORCE?

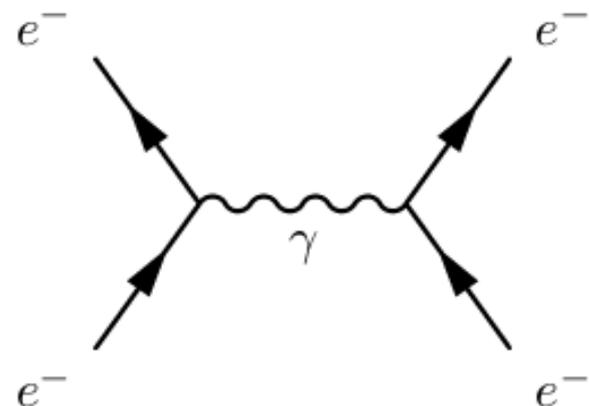
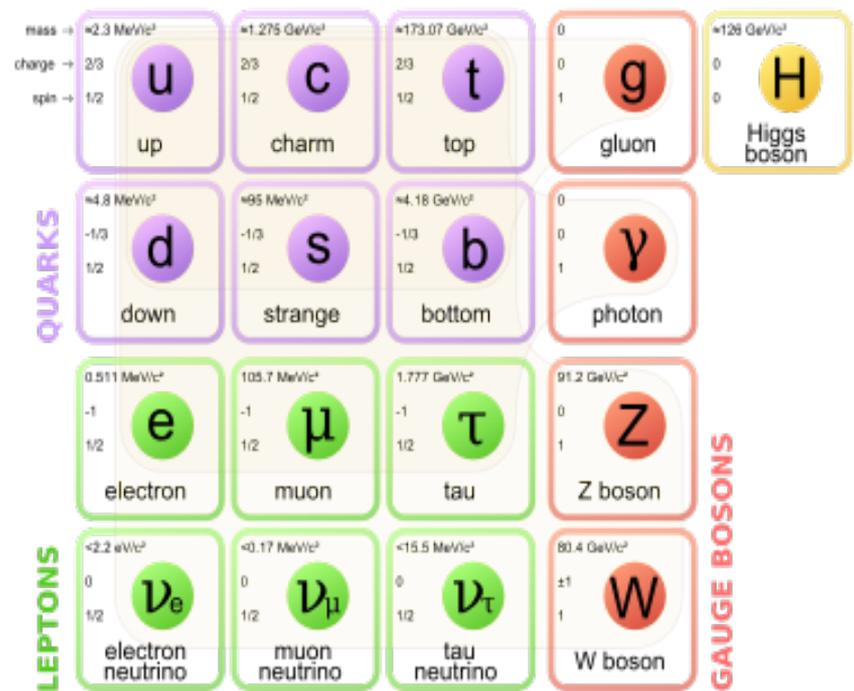
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- There are many kinds of forces: gravitational forces, contact forces, friction forces, tension forces, Coulomb forces, magnetic forces...
- How do we decide which of these are fundamental?
- At the most basic level, forces are mediated by the exchange of particles
- Fundamental forces are, then, those mediated by the exchange of fundamental particles



# FORCES AND PARTICLES

- The known particles can be divided into 2 groups
  - Bosons (integer spin)
  - Fermions (half-integer spin)
- Lorentz invariance implies that all interactions involve an even number of fermions
- Particles can therefore emit a boson, but not a fermion
- We therefore identify
  - Bosons = force-mediating particles
  - Fermions = matter particles



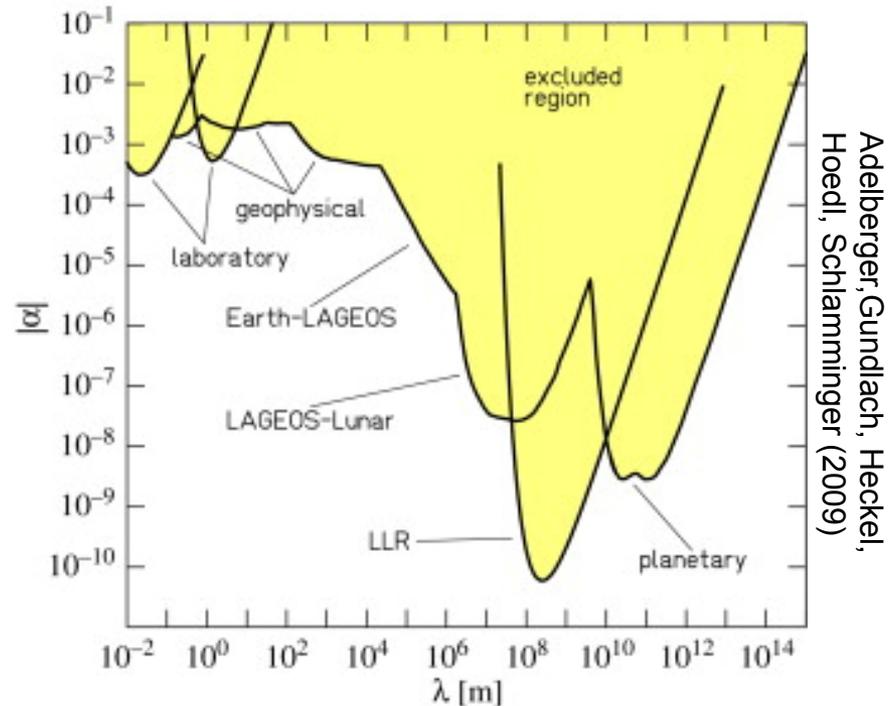
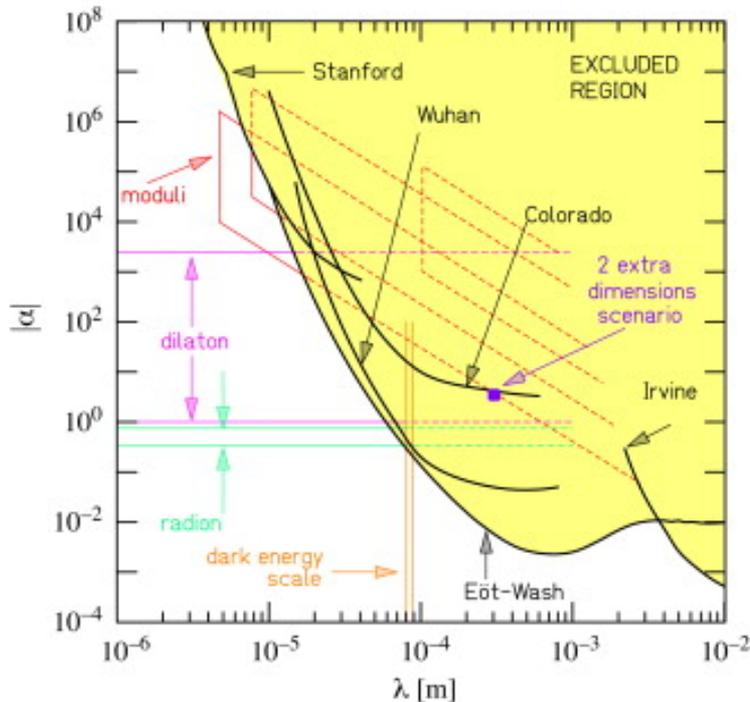
# FORCES AND BOSONS

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- At present the known fundamental bosons are
  - Photons (electromagnetism)
  - Gluons (strong force)
  - Gravitons (gravity)
  - W and Z bosons (weak force)
  - and probably the Higgs boson (Higgs force)
- Discovering a 5<sup>th</sup> (or 6<sup>th</sup>) fundamental force means discovering a new fundamental boson. Many proposed: dilatons, radions, Z' gauge bosons, A' dark photons, Kaluza-Klein gravitons, ...
- The particle's mass determines the force's range and potential:
$$\lambda \sim m^{-1} \quad V(r) \sim \frac{1}{r} e^{-r/\lambda}$$
- “Force” language is most natural when  $m$  is small,  $\lambda$  is large
  - If  $m \sim \text{TeV}$ ,  $\lambda \sim 2 \times 10^{-19} \text{ m}$ , this looks like a new particle
  - If  $m \sim \text{MeV}$ ,  $\lambda \sim 200 \text{ fm}$ , this looks like a new force

# PAST 5<sup>TH</sup> FORCE SEARCHES

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



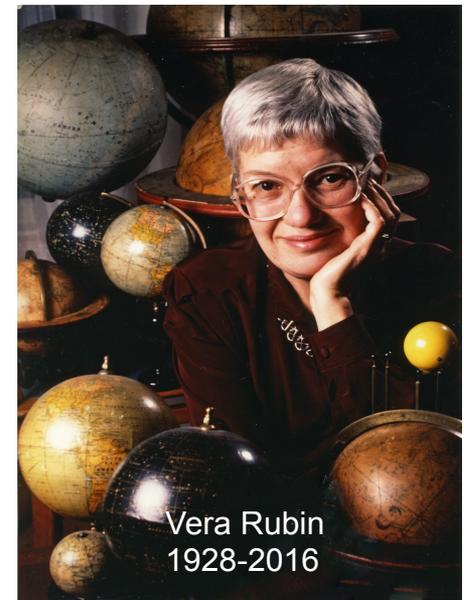
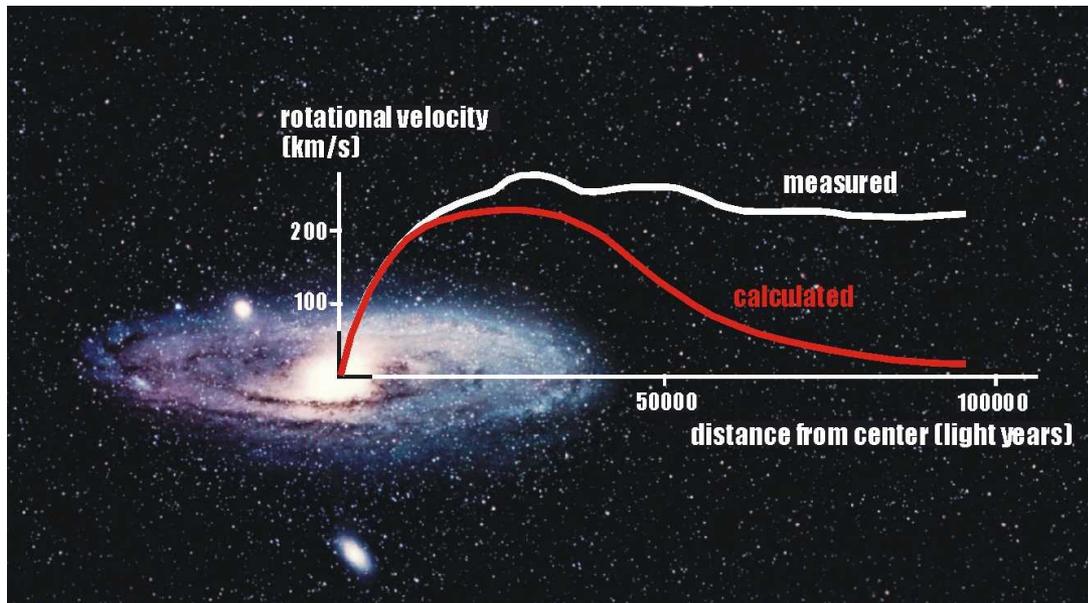
Adelberger, Gundlach, Heckel, Hoedl, Schlamminger (2009)

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

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

# DARK MATTER

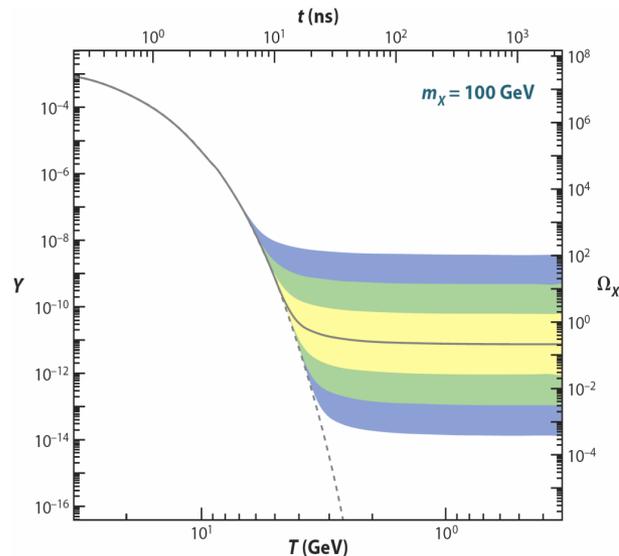
- There is now every indication that the universe includes 6 times as much dark matter as ordinary matter
- Classic evidence: rotation curves



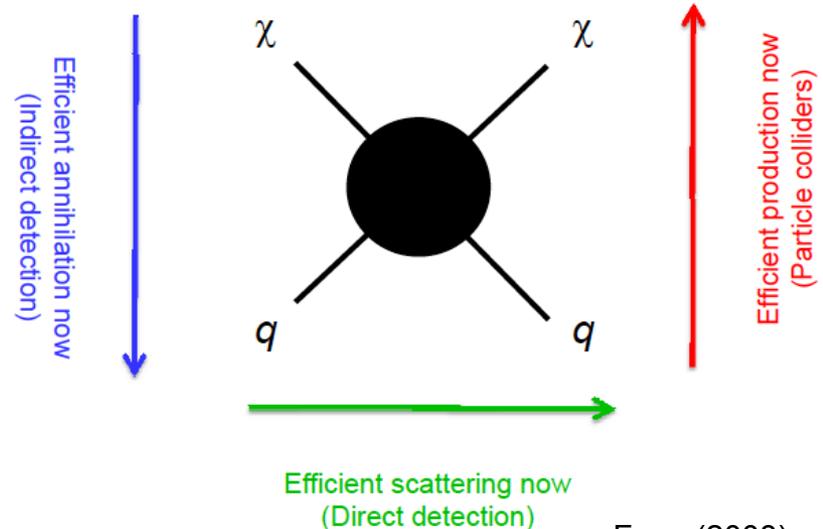
- This evidence has now been supplemented by many other observations, all pointing to the same amount of dark matter

# CLASSIC DARK MATTER CANDIDATES

- There are classic, well-motivated candidates: axions, sterile neutrinos, and weakly-interacting massive particles (WIMPs)
- E.g., WIMPs, particles interacting through the weak force, naturally have the right relic density, can be discovered at colliders and through direct and indirect detection



Zeldovich (1965); Scherrer, Turner (1985); ...



Feng (2008)

- So far none of them has been found

# DARK SECTORS

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- All evidence for dark matter is gravitational. Let's choose a different starting point: perhaps it is in a hidden sector, with no electromagnetic, strong, or weak interactions



- 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

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- But if we are to detect it non-gravitationally, it must have some (very weak) interactions with us. What are they?
- Seemingly a Pandora's box of possibilities, but effective operators provide an organizing principle:

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

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:

$$hLN$$

Neutrino portal

$$h^\dagger h \phi_h^\dagger \phi_h$$

Higgs portal

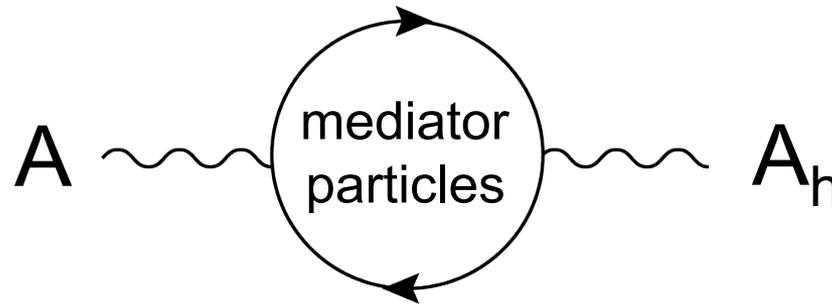
$$F_{\mu\nu} F_h^{\mu\nu}$$

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:

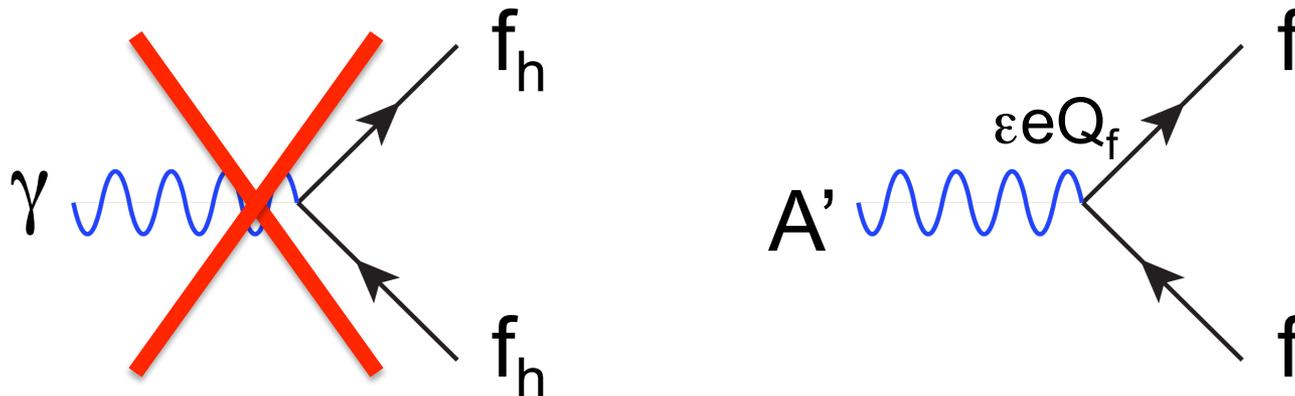


- One might expect this effect to become very small for heavy mediator particles, but it doesn't
- Instead, one gets a vector portal term  $\epsilon F_{\mu\nu} F_h^{\mu\nu}$ , with  $\epsilon \sim 10^{-3} e e_h$ , where the  $10^{-3}$  comes from it being a 1-loop effect, and  $e$  and  $e_h$  are the visible and hidden sector charges

# DARK PHOTONS

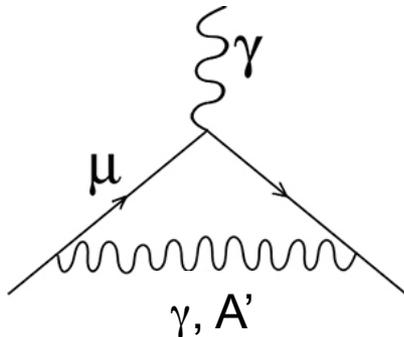
Holdom (1986)

- 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  $\gamma$
  - 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  $\epsilon e Q_f$  to visible sector particles: it mediates a 5<sup>th</sup> force!

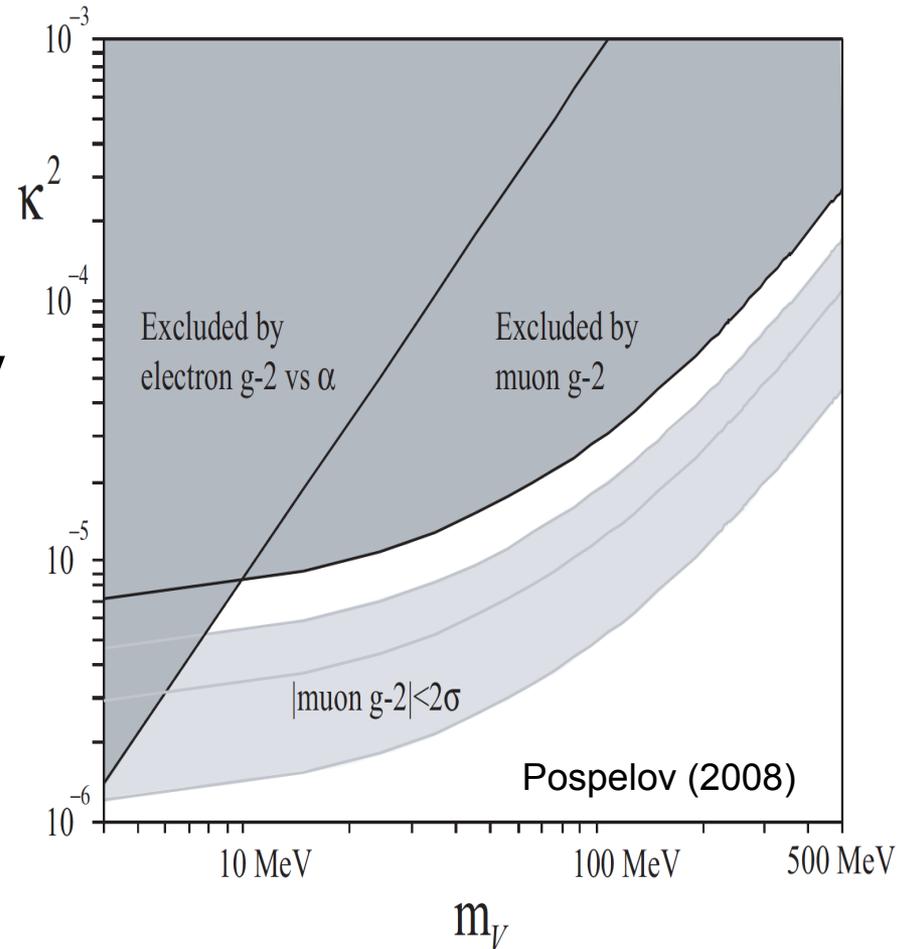


# DARK PHOTON SEARCHES

- This has motivated a world-wide hunt for dark photons throughout the (mass, coupling) parameter space
- What parameters are interesting?
  - $\epsilon \sim 10^{-3}$
  - Anomalies: muon g-2, currently a  $3.5\sigma$  discrepancy

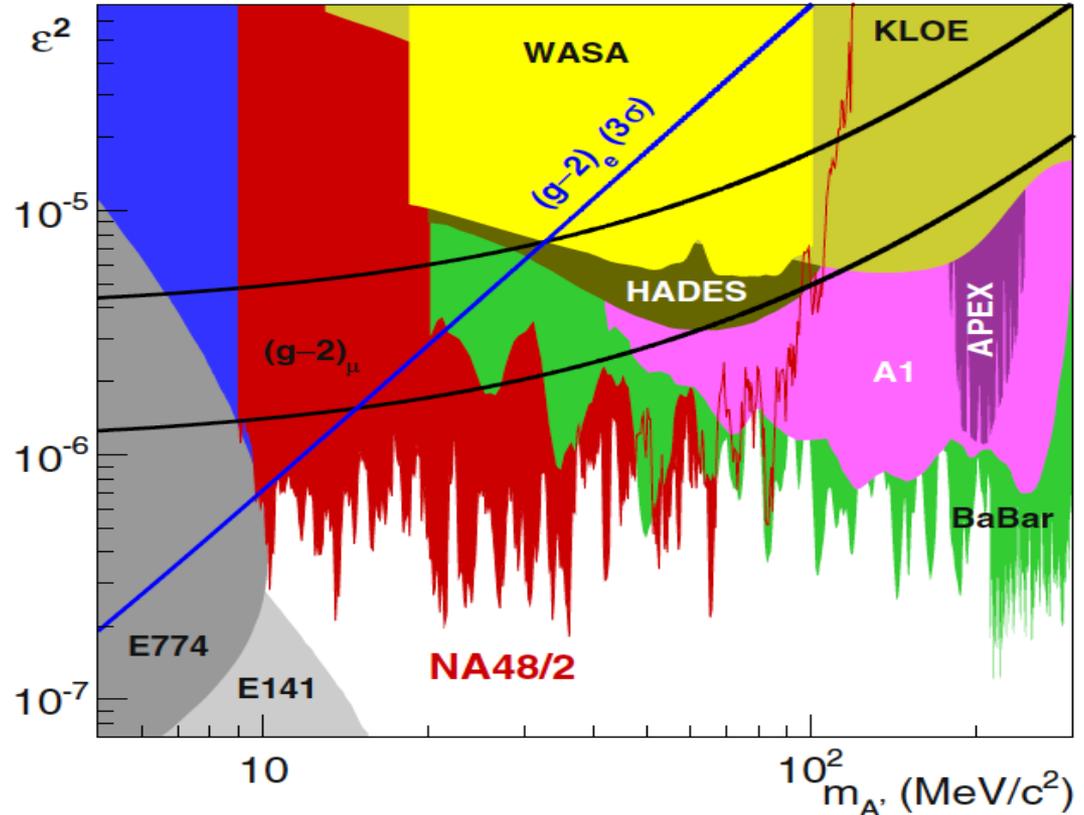


- Lamppost: whatever is not excluded and within reach



# 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 excluded, but there is still a lot of parameter space to explore and many proposed experiments

# FIFTH FORCE IN NUCLEAR PHYSICS

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- The interest in dark matter and 5<sup>th</sup> 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  $6.8\sigma$  experimental anomaly might indicate the production of new particles in excited  $^8\text{Be}$  decays

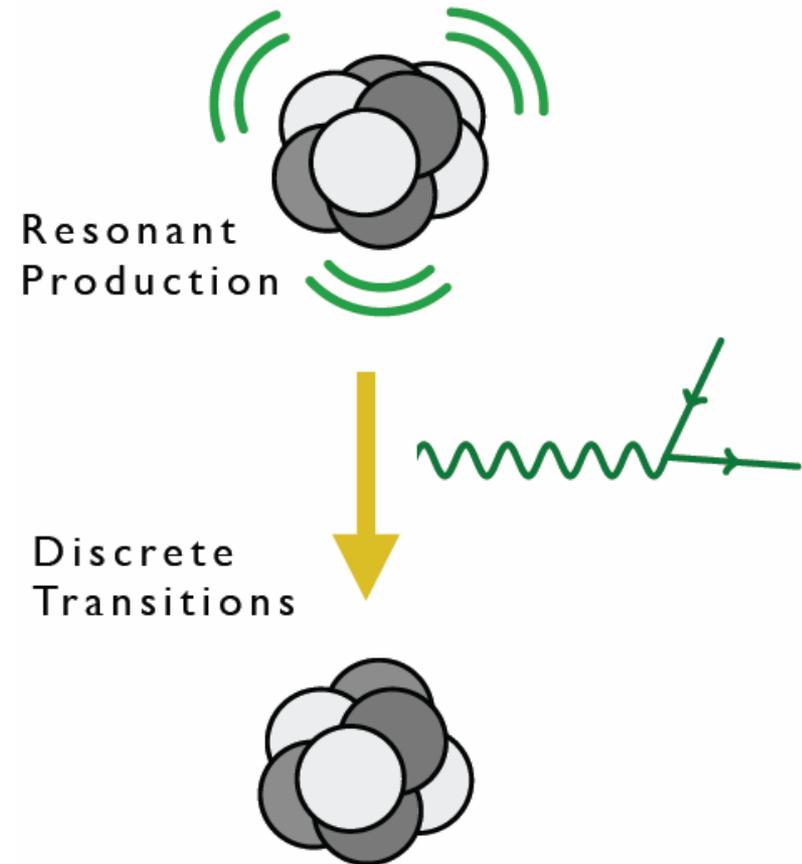
A. J. Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]

- Could these be 5<sup>th</sup> force gauge bosons?

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

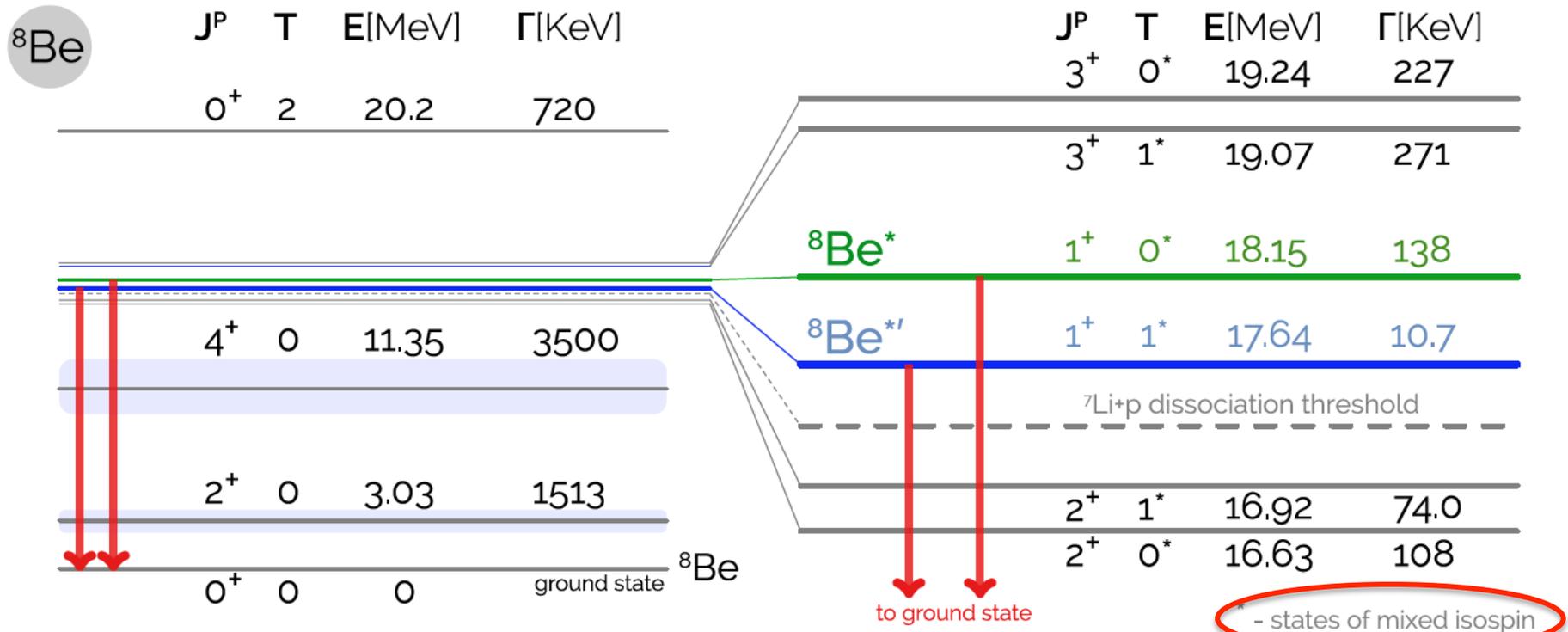
# $^8\text{Be}$ AS A NEW PHYSICS LAB

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



# $^8\text{Be}$ SPECTRUM

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

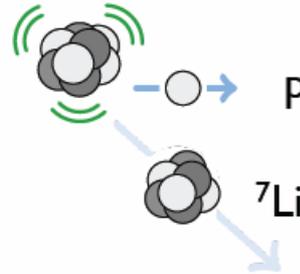


1608.03591; based on Tilley et al. (2004), <http://www.nndc.bnl.gov/nudat2>, Wiringa et al. (2013)

# $^8\text{Be}^*$ DECAY

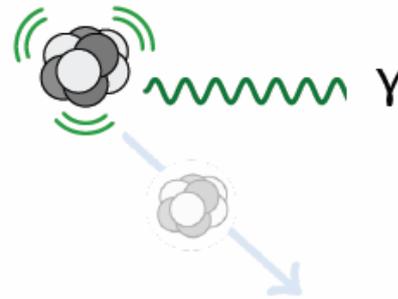
- Hadronic

$$B(p \ ^7\text{Li}) \approx 100\%$$



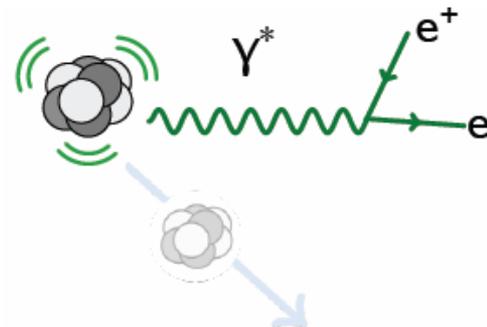
- Electromagnetic

$$B(^8\text{Be} \ \gamma) \approx 1.5 \times 10^{-5}$$



- Internal Pair Creation

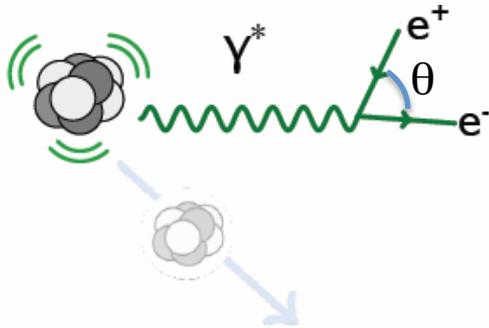
$$B(^8\text{Be} \ e^+ \ e^-) \approx 5.5 \times 10^{-8}$$



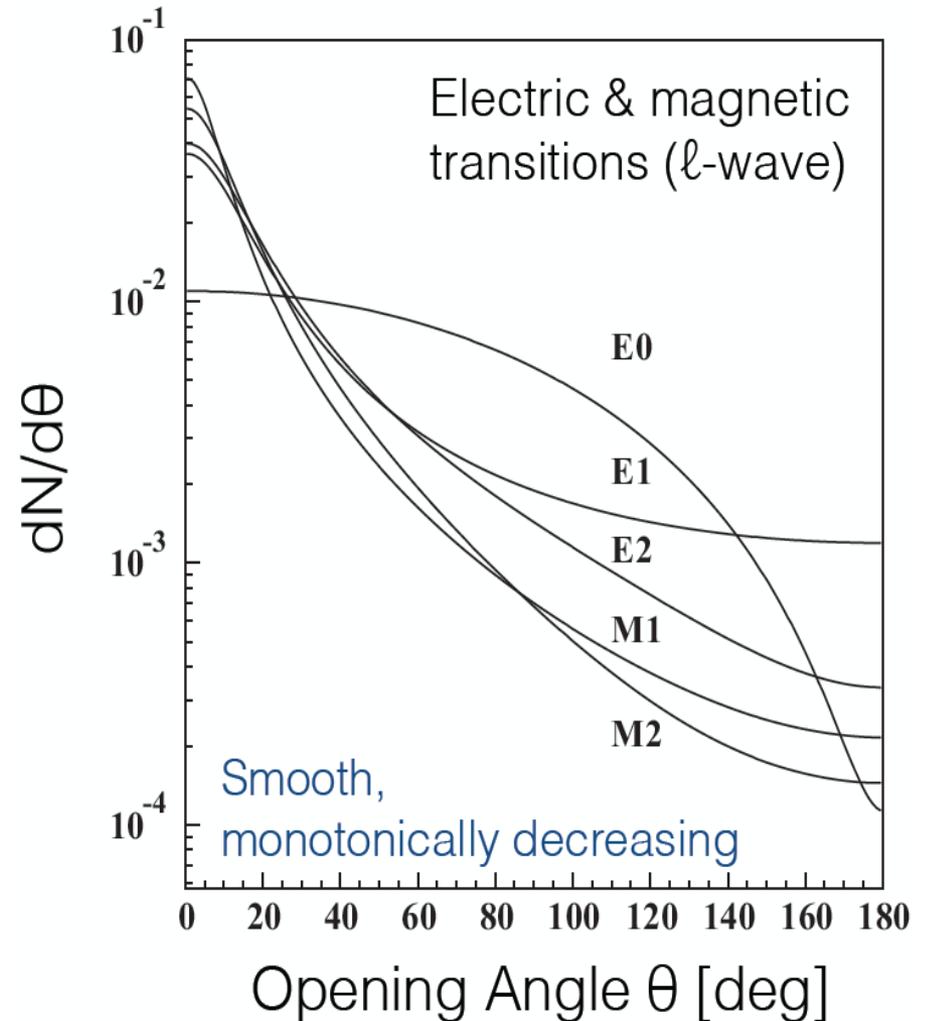
# INTERNAL PAIR CREATION KINEMATICS

- Internal Pair Creation

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



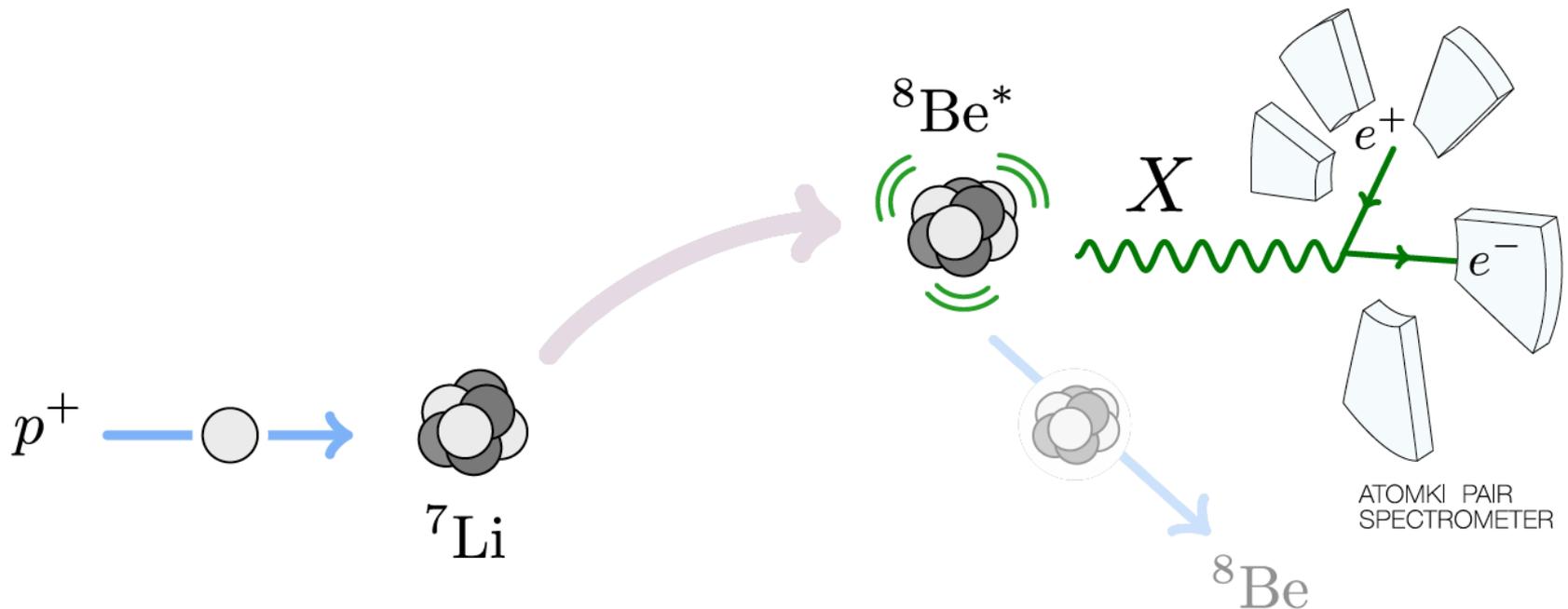
For  $e^+e^-$  produced by a virtual photon,  $dN/d\theta$  is sharply peaked at low opening angle  $\theta$  and is expected to be a monotonically decreasing function of  $\theta$



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

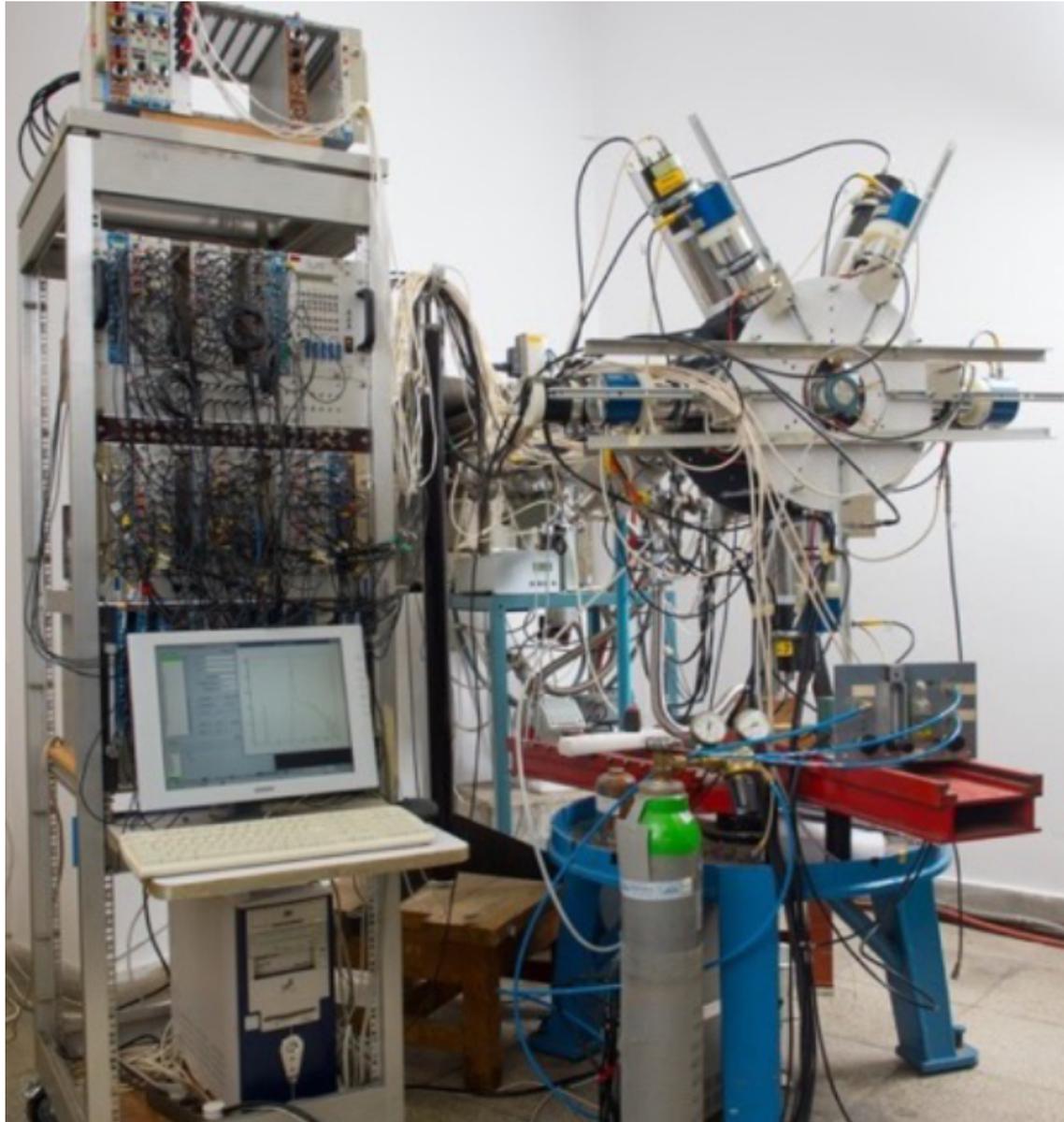
# THE ATOMKI $^8\text{Be}$ EXPERIMENT

A  $1\ \mu\text{A}$   $p$  beam with  $\Delta E_p \sim 10\ \text{keV}$  strikes a thin  $^7\text{Li}$  foil target. The beam energy can be adjusted to select various  $^8\text{Be}$  excited state resonances.



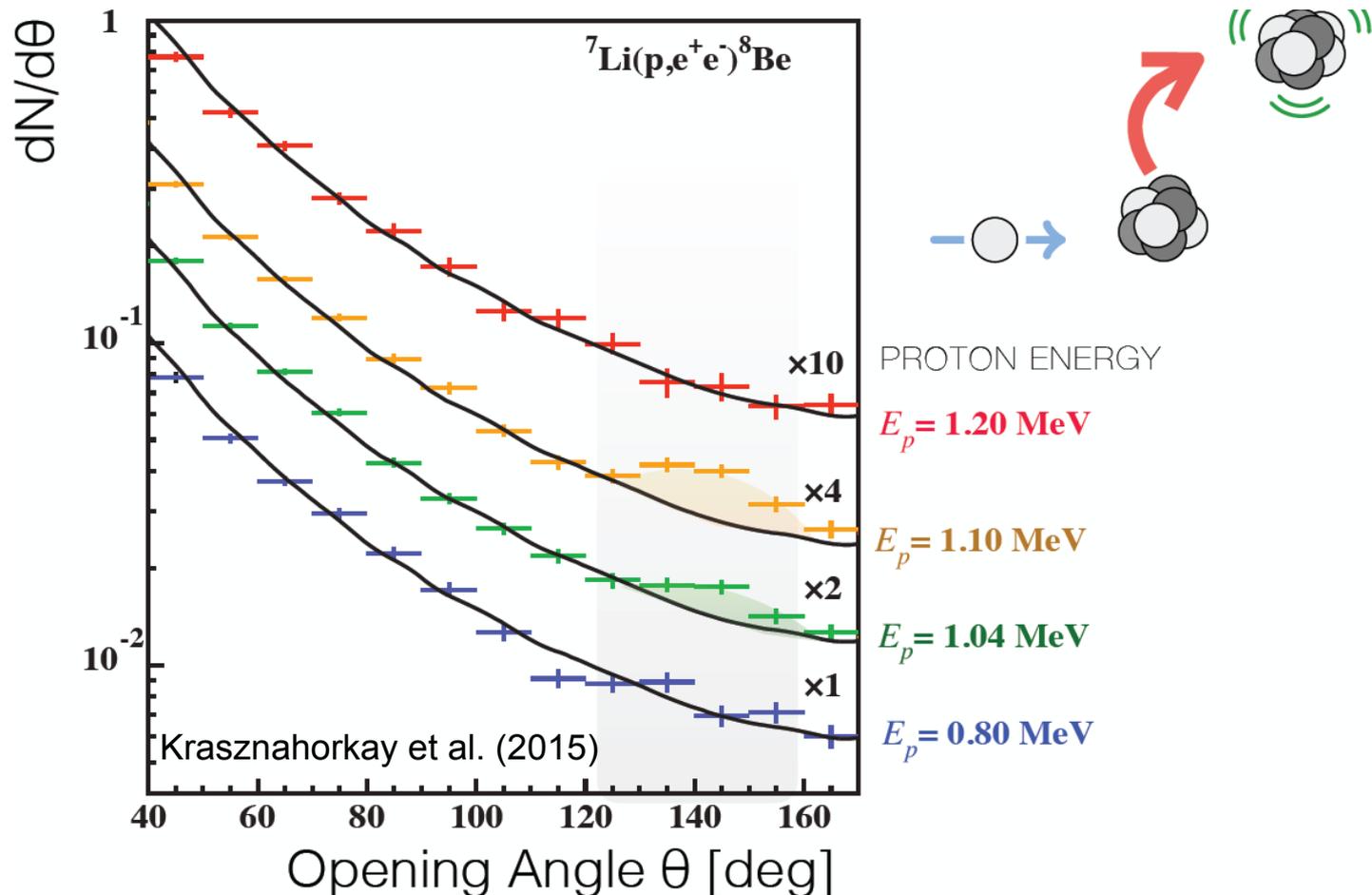
# THE ATOMKI $^8\text{Be}$ EXPERIMENT

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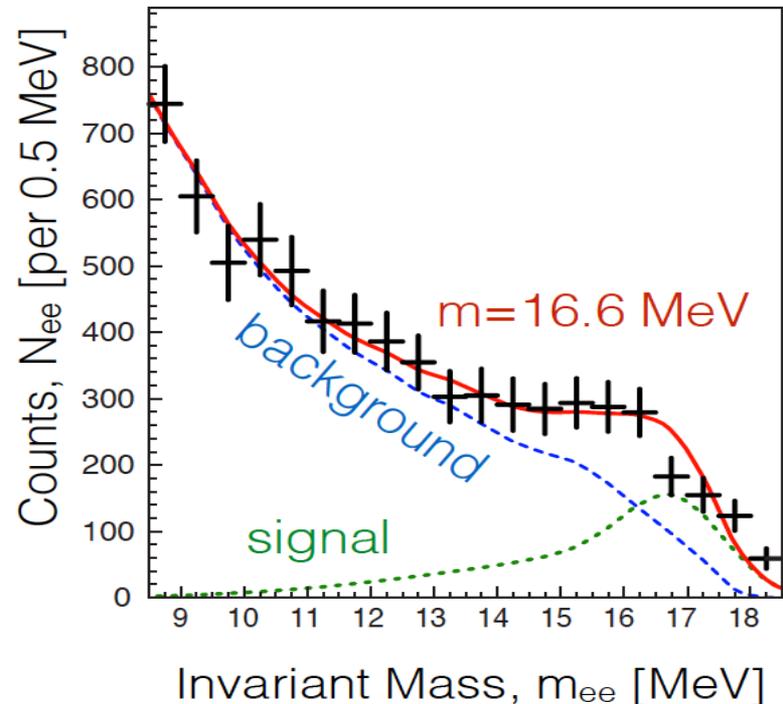
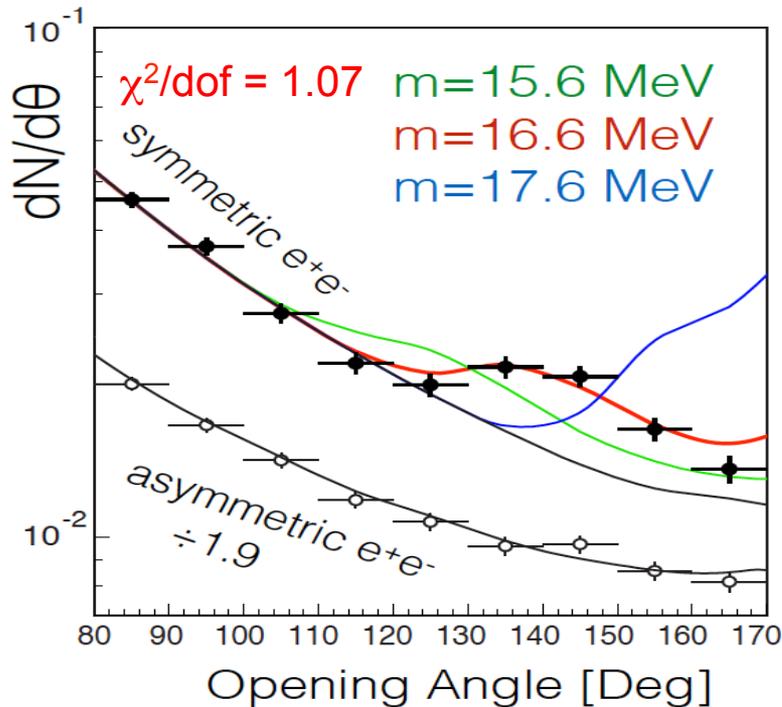
# THE ATOMKI ANOMALY

- A bump at  $\sim 140$  degrees is observed as one passes through the  ${}^8\text{Be}^*$  resonance
- Background fluctuation probability:  $5.6 \times 10^{-12}$  ( $6.8\sigma$ )



# THE ATOMKI ANOMALY

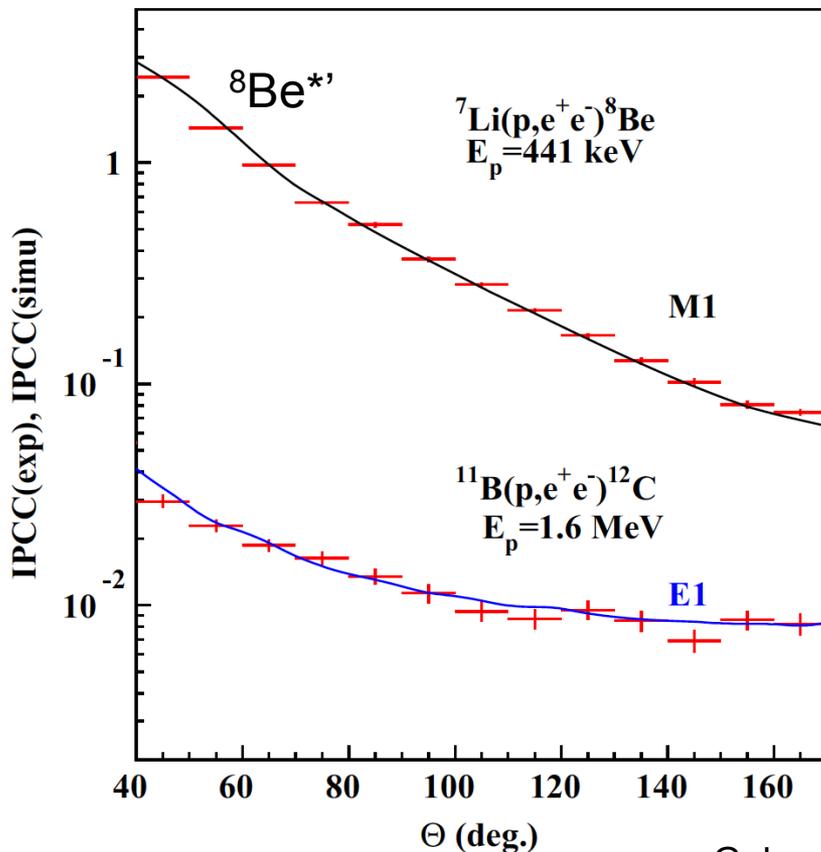
- The  $\theta$  (and  $m_{ee}$ ) distributions can be explained by postulating a new particle and 2-step decay:  ${}^8\text{Be}^* \rightarrow {}^8\text{Be} X, X \rightarrow e^+e^-$
- The best fit parameters:  $m = 16.7 \pm 0.35$  (stat)  $\pm 0.5$  (sys) MeV  
 $B({}^8\text{Be}^* \rightarrow {}^8\text{Be} X) / B({}^8\text{Be}^* \rightarrow {}^8\text{Be} \gamma) = 5.6 \times 10^{-6}$



Krasznahorkay et al. (2015)

# CROSS CHECKS

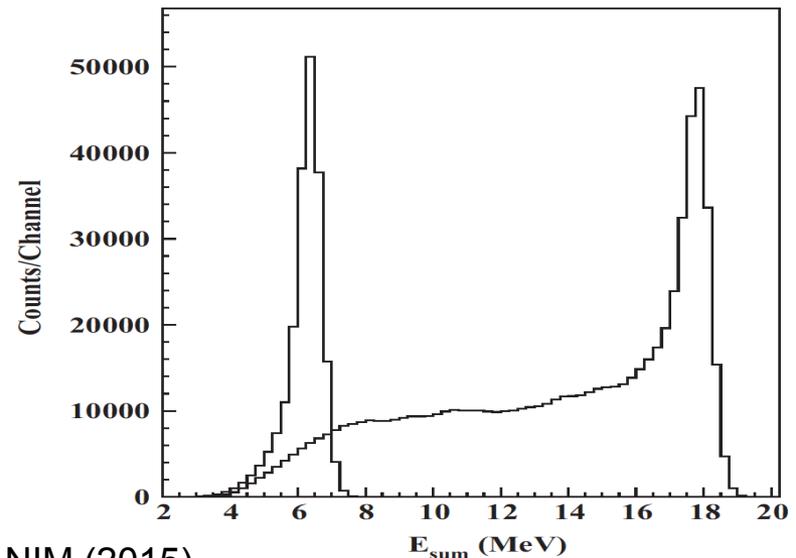
- For example: other decays (all with lower energy), fit theoretical expectations well



Gulyas et al. NIM (2015)

- The excess is confined to events with symmetric energies,  $|y| < 0.5$  and large summed energies  $E > 18 \text{ MeV}$ , as expected for a new particle interpretation

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



# POSSIBLE EXPLANATIONS

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Three possibilities:

- (1) an as-yet-unidentified **nuclear experiment** 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; not likely to disappear with more data
- The excess is not a “last bin” effect: bump, not smooth excess
- If a nuclear experimental problem, why does it only affect the decay with the largest energy? (Easily explained if we are producing a 17 MeV particle)
- If a nuclear experimental problem, the excellent fit to a new particle interpretation is purely coincidental
- Hungarian group is now collecting data with an improved detector, continues to see bump
- Followup experiments by others are being proposed (see below)

# POSSIBLE EXPLANATIONS

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## (2) Nuclear Theory

- Must explain bump in 18.15 data and no (similarly-sized) bump in 17.64 data
- If a nuclear theory explanation, the excellent fit to a new particle interpretation is purely coincidental
- A detailed analysis of nuclear theory effects finds no reasonable explanation for the bump

Zhang, Miller (2017)

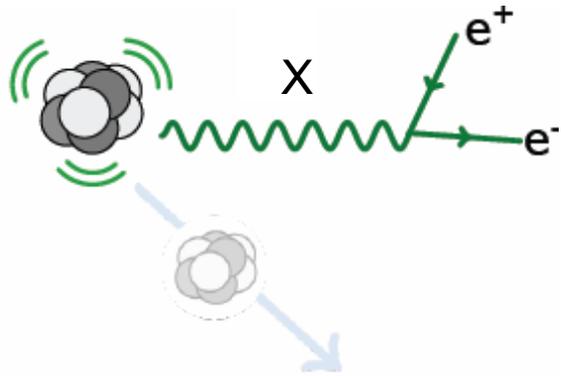
## (3) Particle Physics

- 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 5<sup>th</sup> force

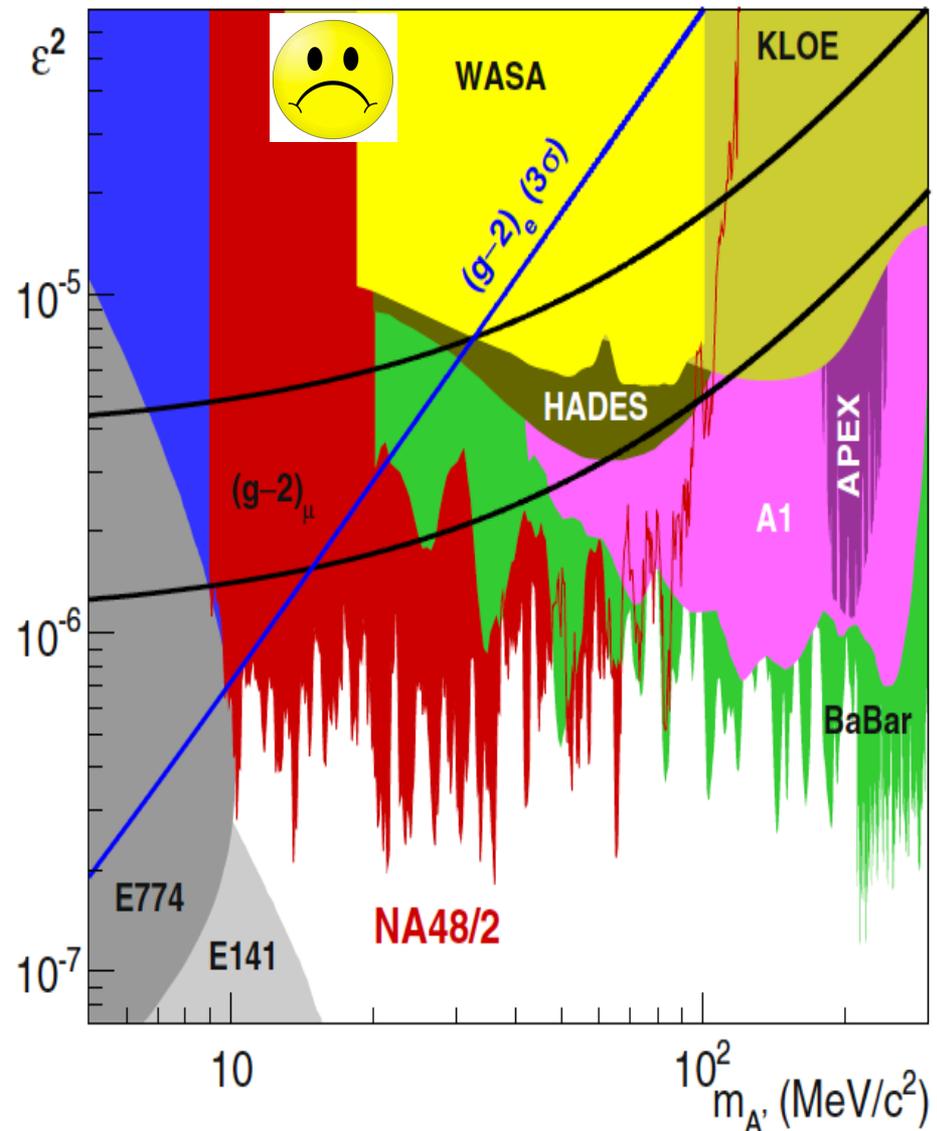
## Not everything works

- 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?

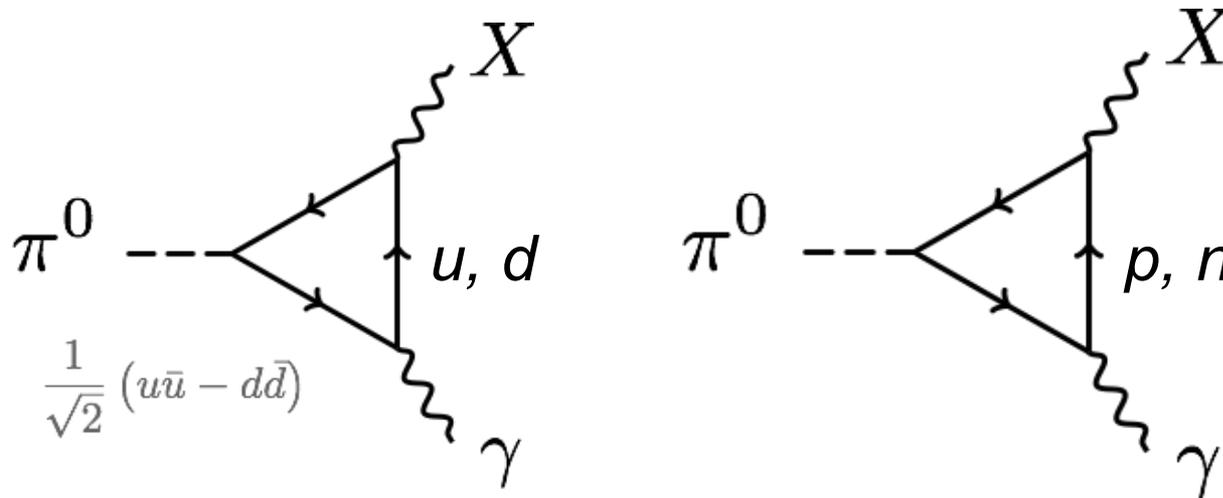
- Consider the case of a spin 1 gauge boson with general couplings  $\varepsilon_f e$  to particle  $f$
- To get the right signal strength, need  

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

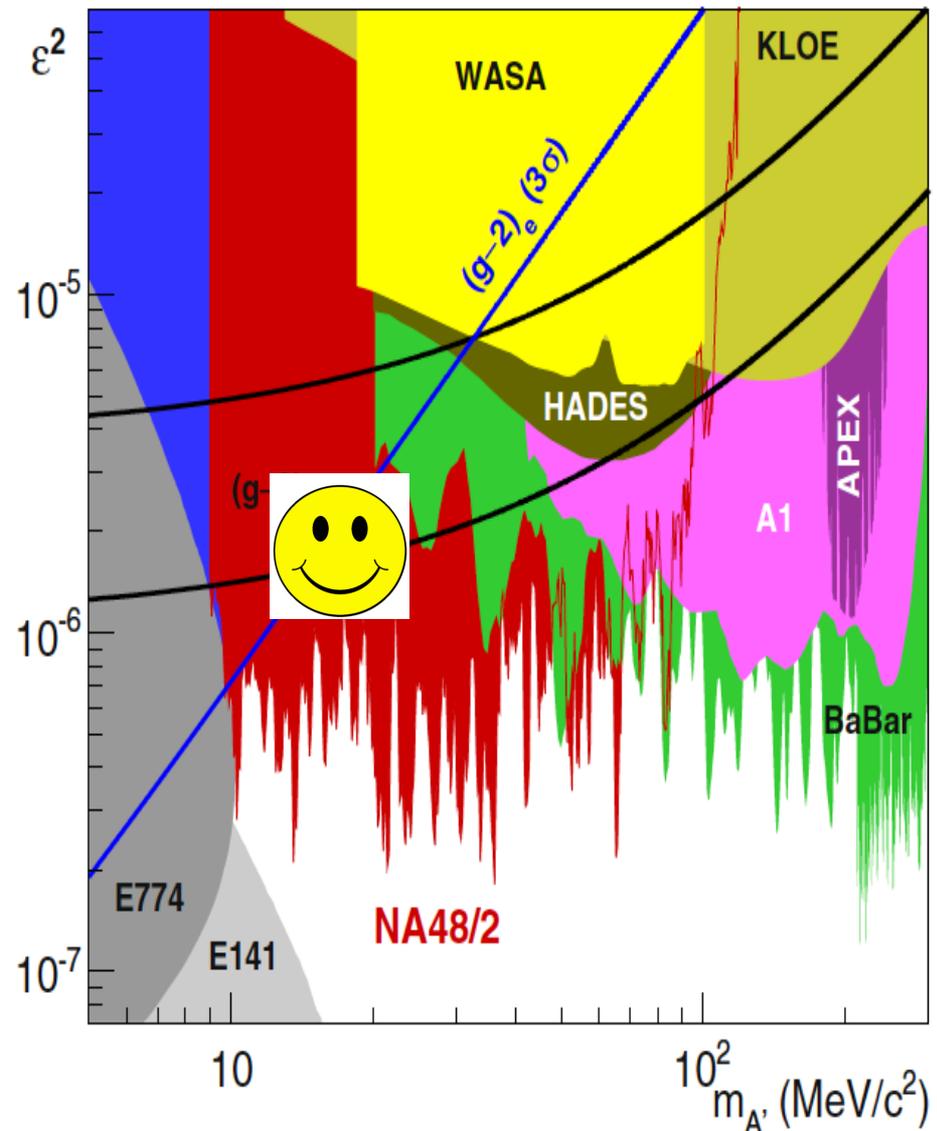
- The dominant constraints are null results from searches for exotic pion decays  $\pi^0 \rightarrow X \gamma \rightarrow e^+ e^- \gamma$



- 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  ${}^8\text{Be}$  signal without violating other constraints

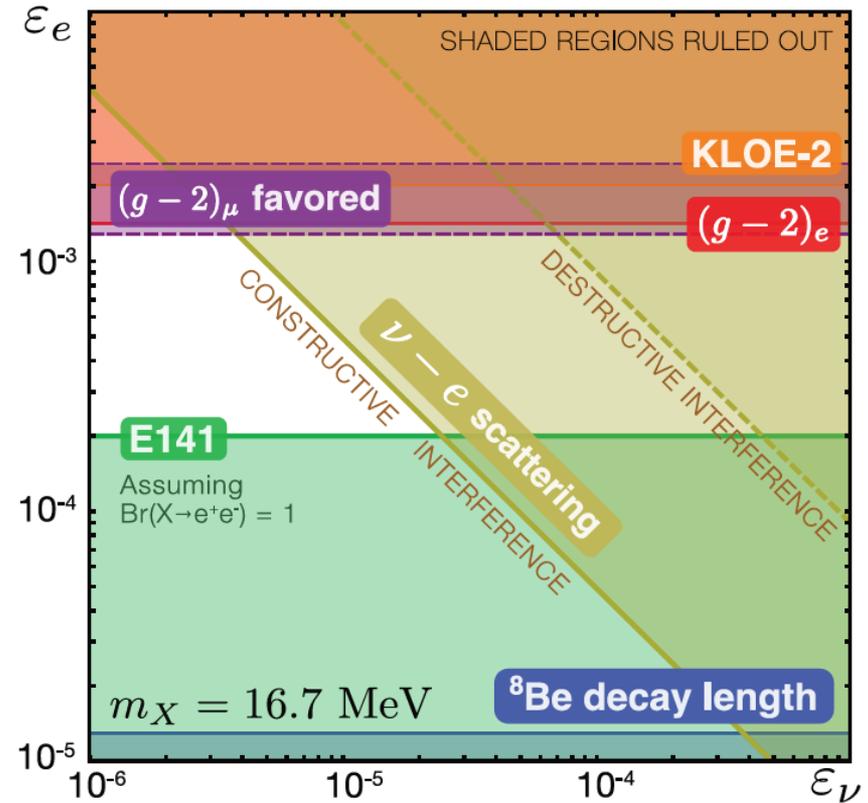
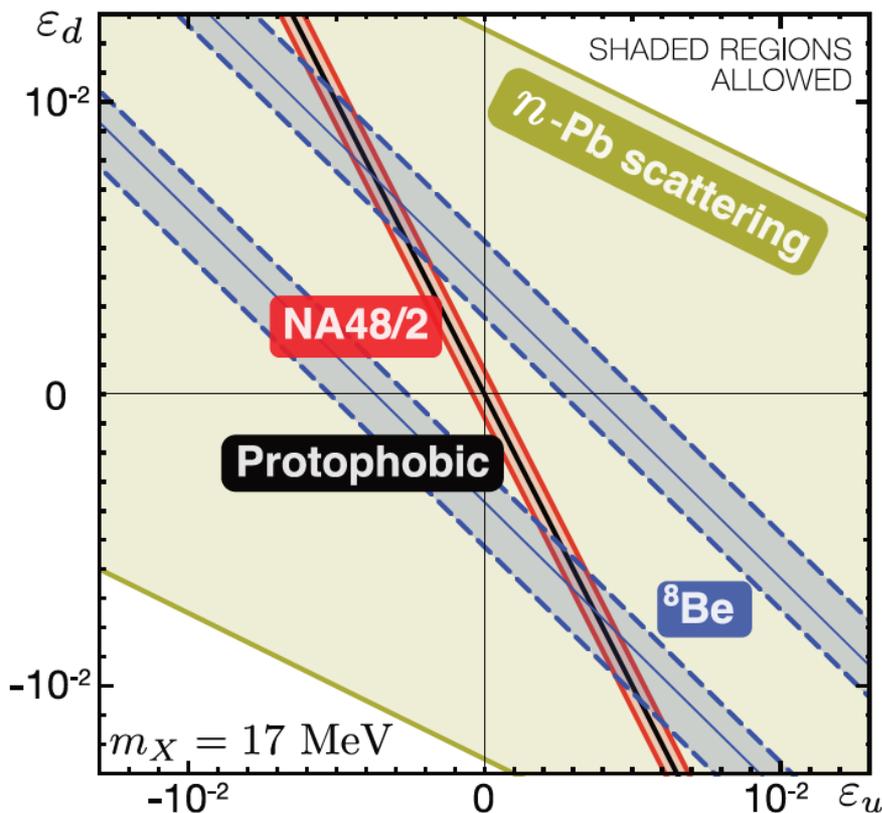
# PROTOPHOBIC GAUGE BOSON

- 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  $^8\text{Be}$  and muon  $g-2$  anomalies
- Implies a milli-charged 5<sup>th</sup> force with range  $\sim 11$  fm



# COUPLING CONSTRAINTS

- Considering all constraints, require  $\epsilon_u, \epsilon_d \sim \text{few } 10^{-3}$  with cancelation to  $\sim 10\%$  for protophobia,  $10^{-4} < \epsilon_e < 10^{-3}$ , and  $|\epsilon_e \epsilon_\nu|^{1/2} < 3 \times 10^{-4}$



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

# PARTICLE MODELS

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

Particle	Q	B	L	B-Q	B-L-Q
e	-1	0	1	1	0
p	1	1	0	0	0
n	0	1	0	1	1

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

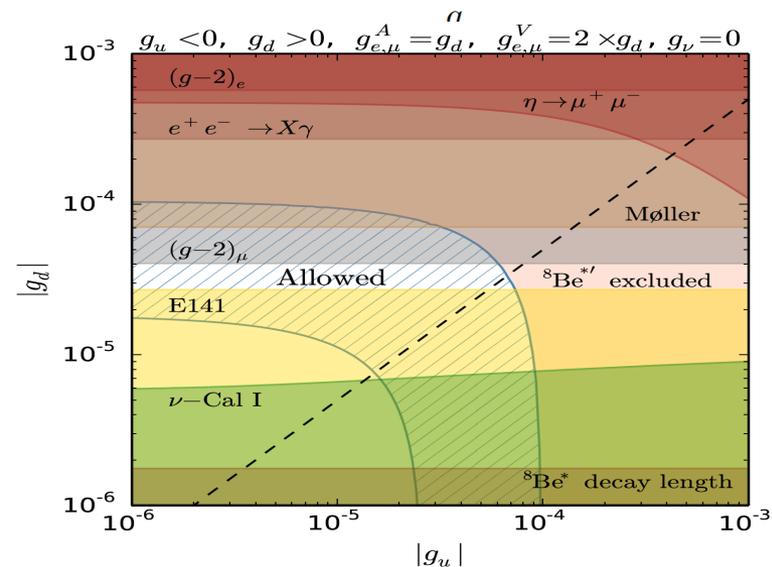
- Pseudoscalars have also been explored and are also possible

Ellwanger, Moretti (2016)

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

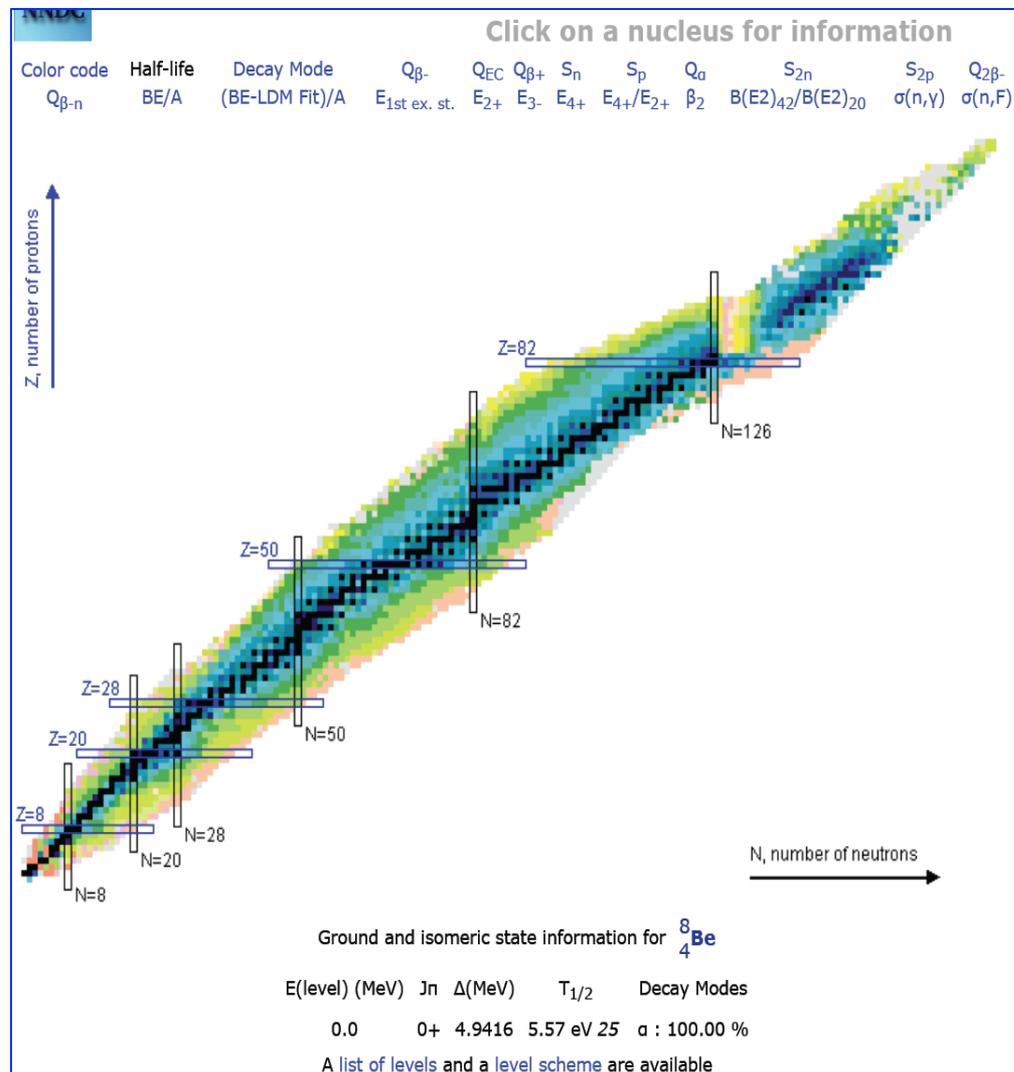
Kozaczuk, Morrissey, Stroberg (2016)

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



# 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  $^8\text{Be}$  transitions are used as a calibration source of high-energy photons
- Are other transitions possible? E.g.,  $^4\text{He}$  (21.0),  $^{10}\text{Be}$  (17.8)



# PROPOSED $^8\text{Be}$ EXPERIMENTS

## Purdue

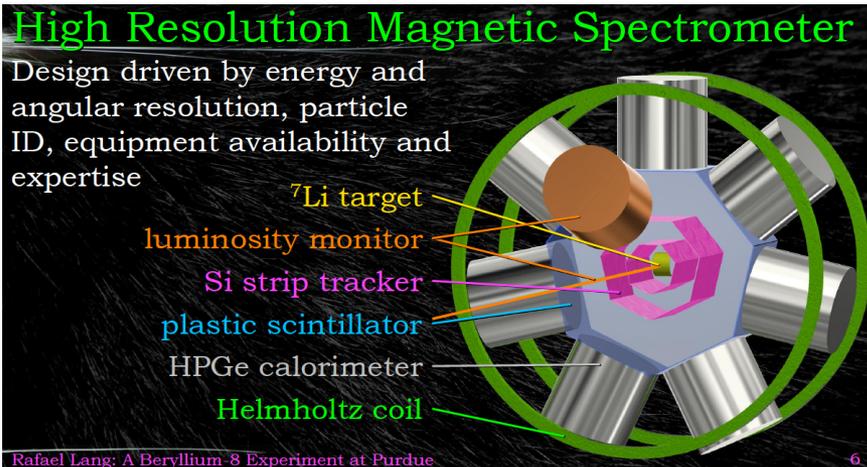


**$8\text{BeP}$ : A  $^8\text{Be}$  Experiment at Purdue**

Rafael F. Lang, Marc Caffee, David Koltick,  
Matthew Jones, Brijesh Srivastava, Thomas Ward  
Department of Physics and Astronomy, Purdue University  
New Ideas in Dark Matter, College Park, March 2017

**High Resolution Magnetic Spectrometer**

Design driven by energy and angular resolution, particle ID, equipment availability and expertise



- $^7\text{Li}$  target
- luminosity monitor
- Si strip tracker
- plastic scintillator
- HPGe calorimeter
- Helmholtz coil

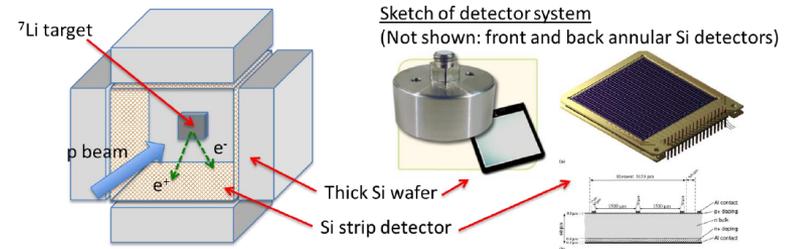
Rafael Lang: A Beryllium-8 Experiment at Purdue

## Notre Dame

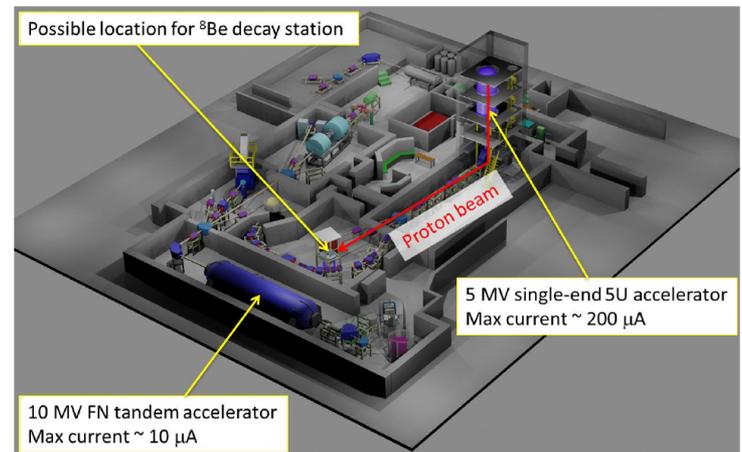


### A $^8\text{Be}$ IPC Decay Measurement at the Notre Dame-NSL

M. Brodeur (U. Notre Dame) and K.G. Leach (Colorado School of Mines)



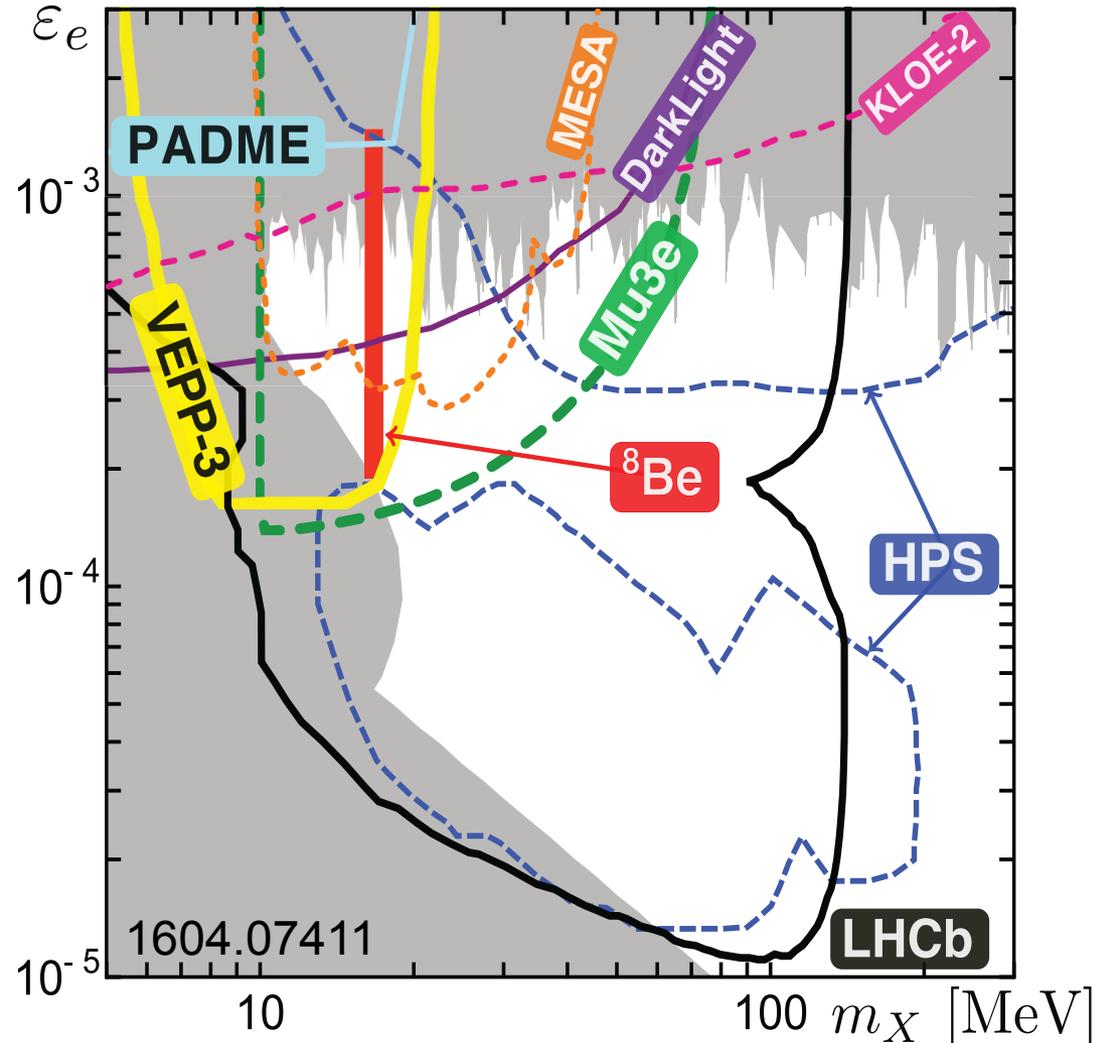
The Nuclear Science Laboratory of the University of Notre Dame



Timescale: 1-2 years, Total cost:  $\sim$  \$750K

# FUTURE TESTS: PARTICLE PHYSICS

- There are a host of accelerator experiments that have been planned for dark photon searches, and may also be sensitive to a 17 MeV X boson
- Generally they look for  $e^+e^- \rightarrow \gamma A'$ , possibly followed by  $A' \rightarrow e^+e^-$
- The  $^8\text{Be}$  results provide an interesting target for new accelerator searches for light, weakly-coupled particles



# CONCLUSIONS

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- A 5<sup>th</sup> force is an open and exciting possibility
- Dark matter provides new motivation to look for light, weakly-coupled particles that may mediate a 5<sup>th</sup> force
- There is currently a  $6.8\sigma$  anomaly in  ${}^8\text{Be}^*$  nuclear decays
- The data are consistent with new particle explanations, including a protophobic gauge boson that mediates a 5<sup>th</sup> force and simultaneously explains the muon  $g-2$  anomaly
- The result, if true, has spectacular implications for all of basic science, but particular for particle physics and astrophysics (dark matter, force unification, etc.)
- Much work remains, but relatively quick and inexpensive follow-up experiments are in the works