
DARK MATTER AND THE SEARCH FOR A FIFTH FORCE

University of Kentucky Colloquium

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FUNDAMENTAL FORCES

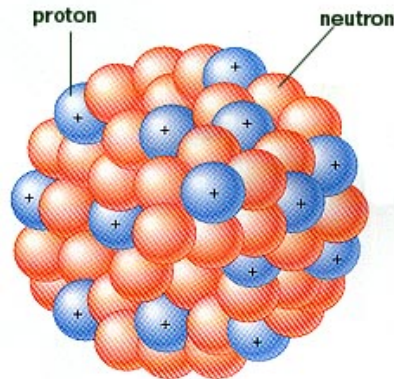
- We know of four fundamental forces



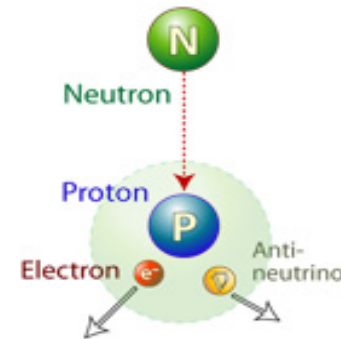
Gravity



Electromagnetism



Strong

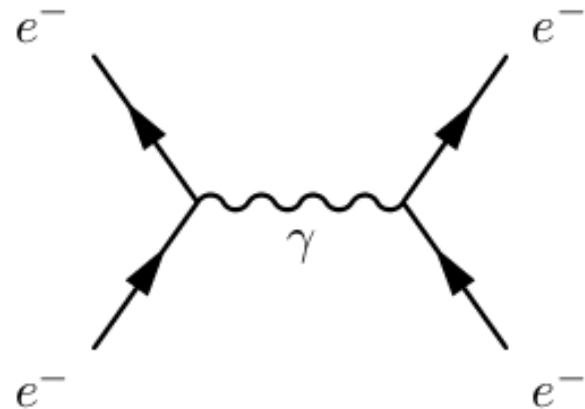


Weak

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

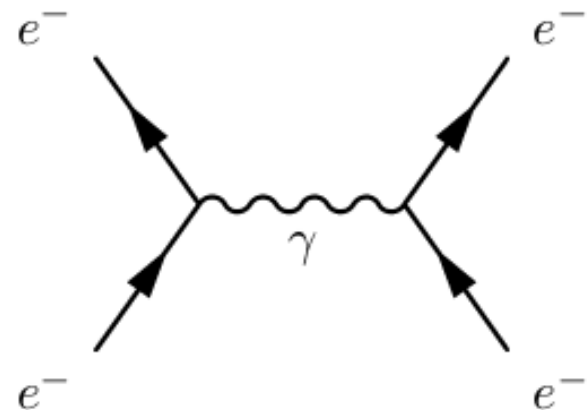
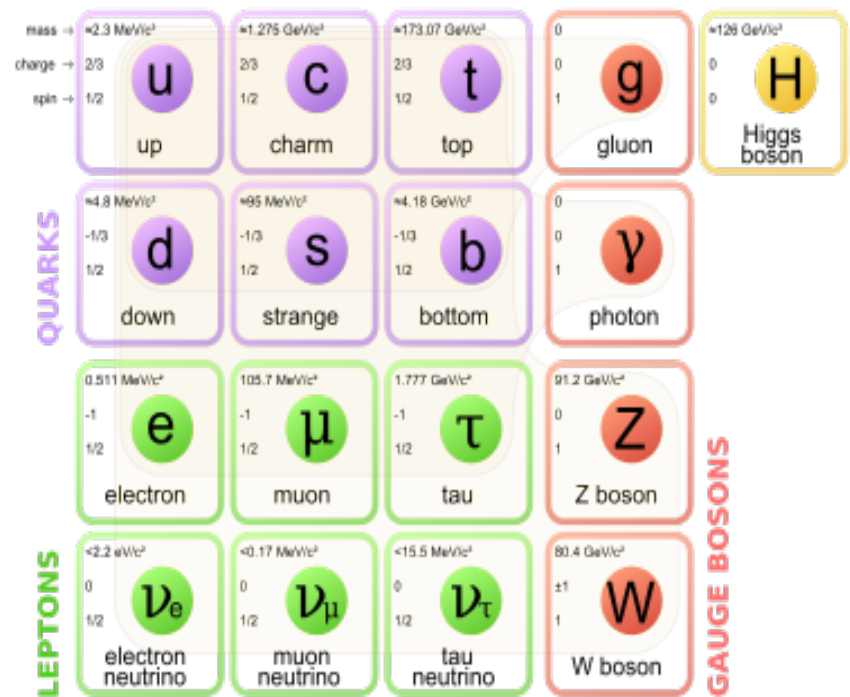
WHAT IS A FUNDAMENTAL FORCE?

- 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

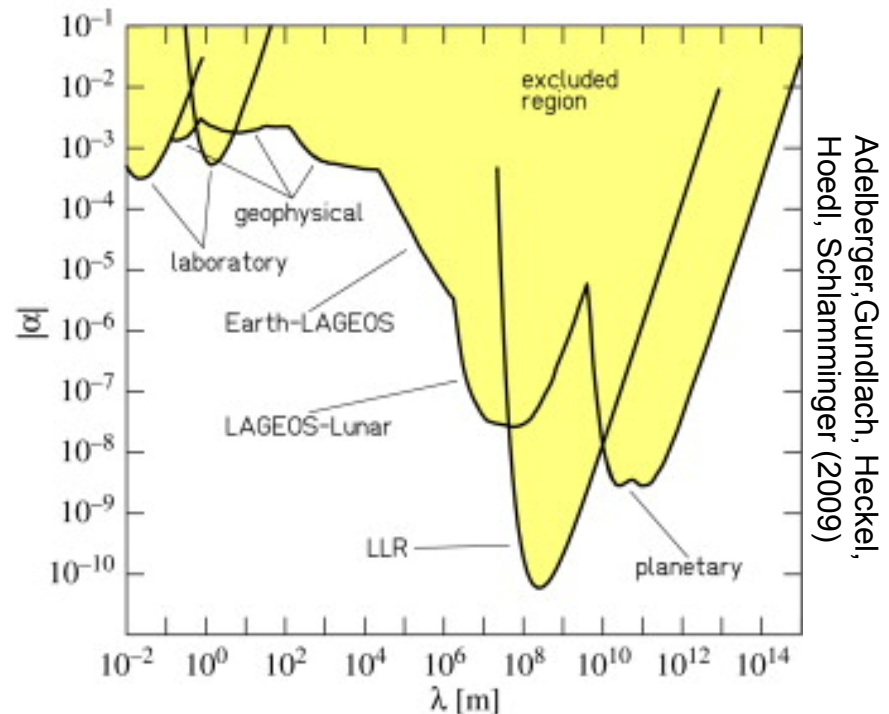
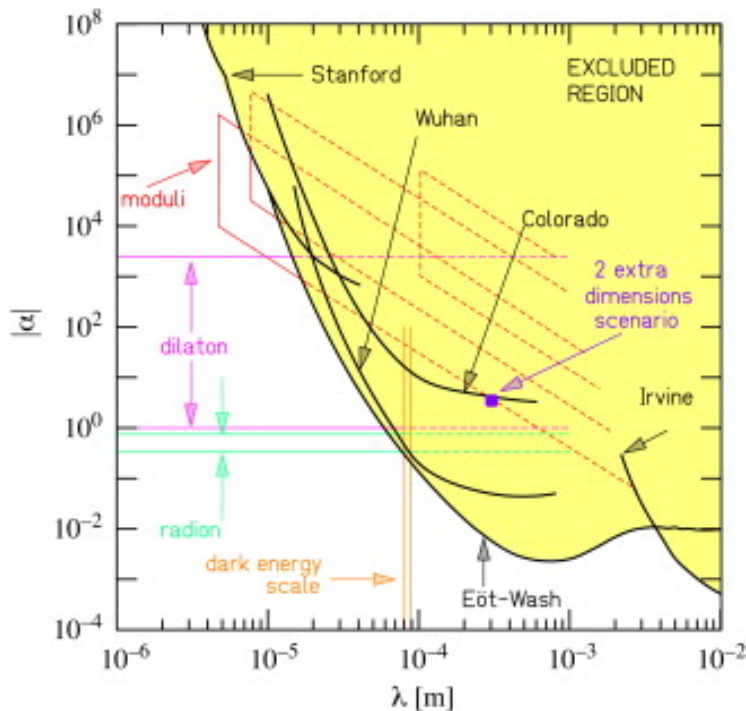


FORCES AND BOSONS

- 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 5th (or 6th) 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, λ 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 5TH FORCE SEARCHES

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

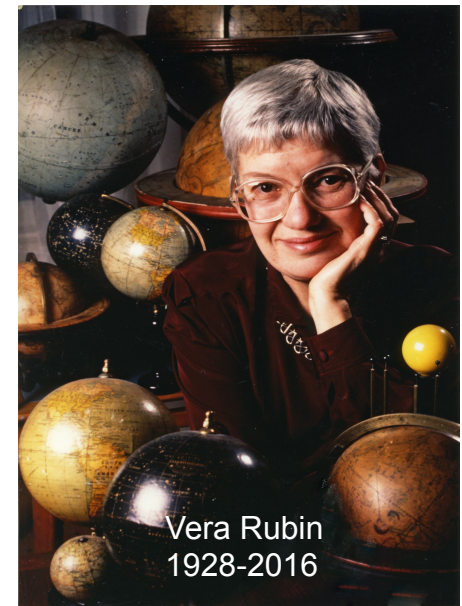
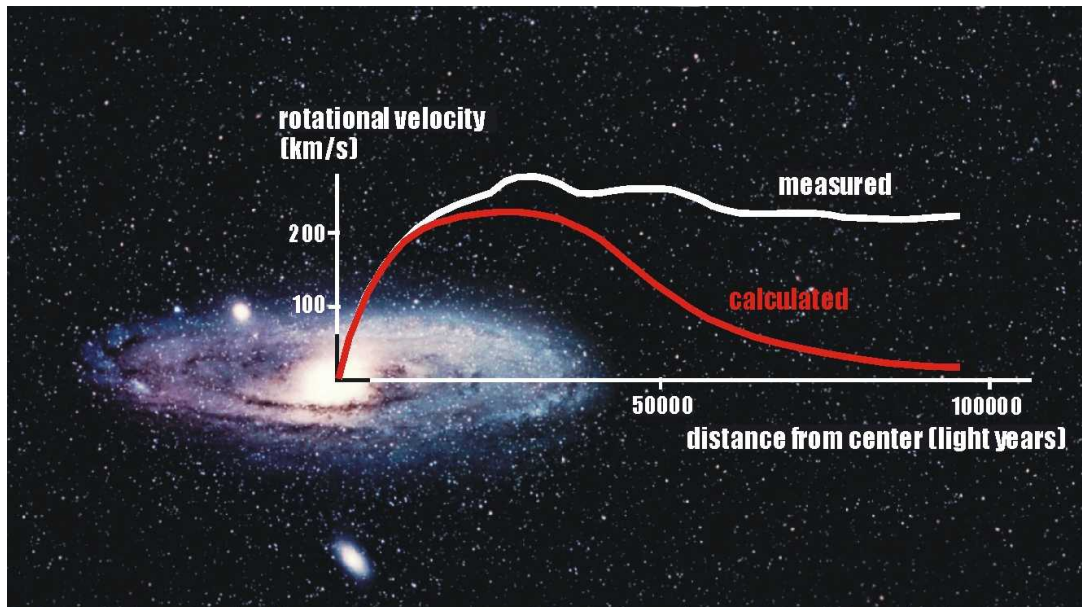


- So far, no such deviations have been found, but the history of 5th force searches is fascinating

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

DARK MATTER

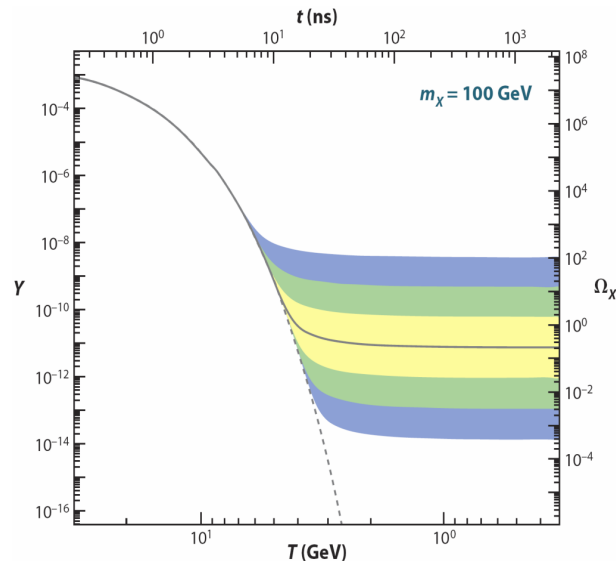
- There is now every indication that the universe includes 6 times as much dark matter as ordinary matter
- Classic evidence: rotation curves



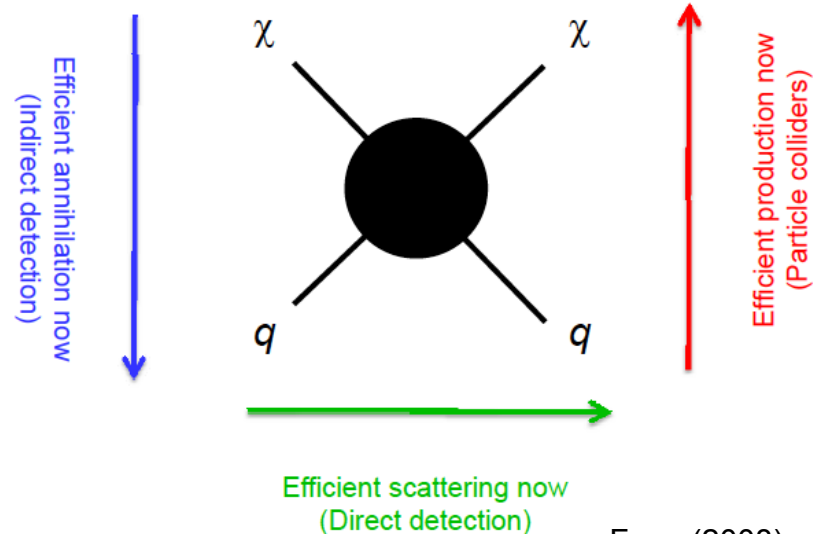
- This evidence has now been supplemented by many other observations, all pointing to the same amount of dark matter

CLASSIC DARK MATTER CANDIDATES

- 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

- 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

- 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

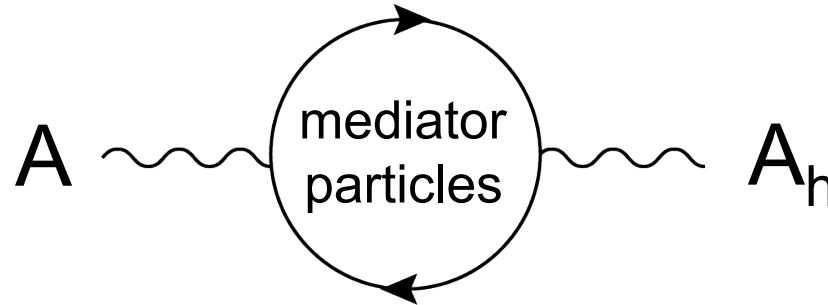
$$F_{\mu\nu} F_h^{\mu\nu}$$

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:

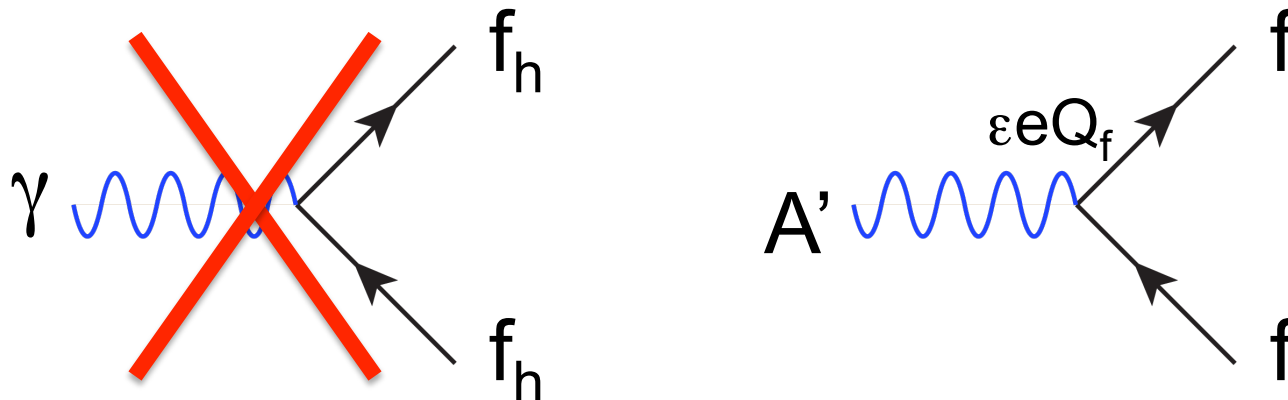


- One might expect this effect to become very small for heavy mediator particles, but it doesn't
- Instead, one gets a vector portal term $\epsilon F_{\mu\nu} F_h^{\mu\nu}$, with $\epsilon \sim 10^{-3} e e_h$, where the 10^{-3} comes from it being a 1-loop effect, and e and e_h are the visible and hidden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

DARK PHOTONS

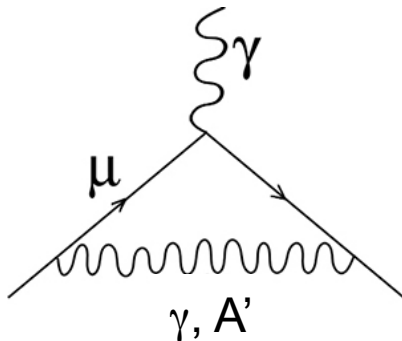
Holdom (1986)

- 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 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 $\epsilon e Q_f$ to visible sector particles: it mediates a 5th force!

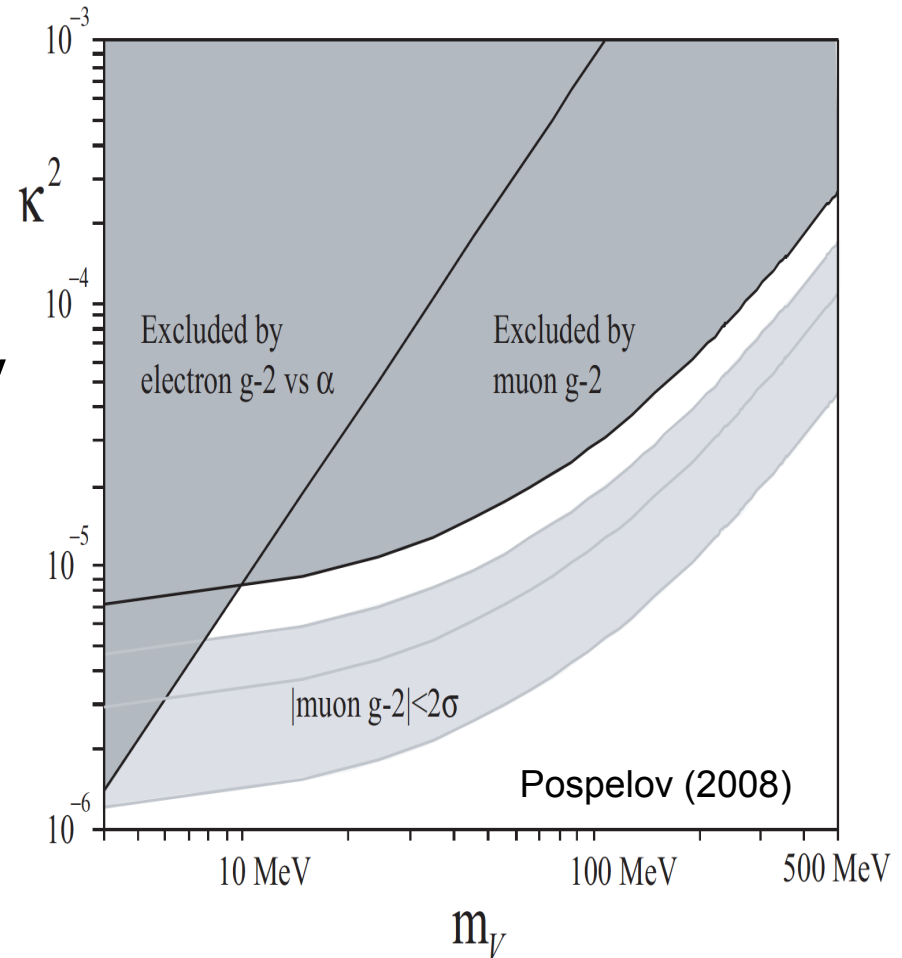


DARK PHOTON SEARCHES

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

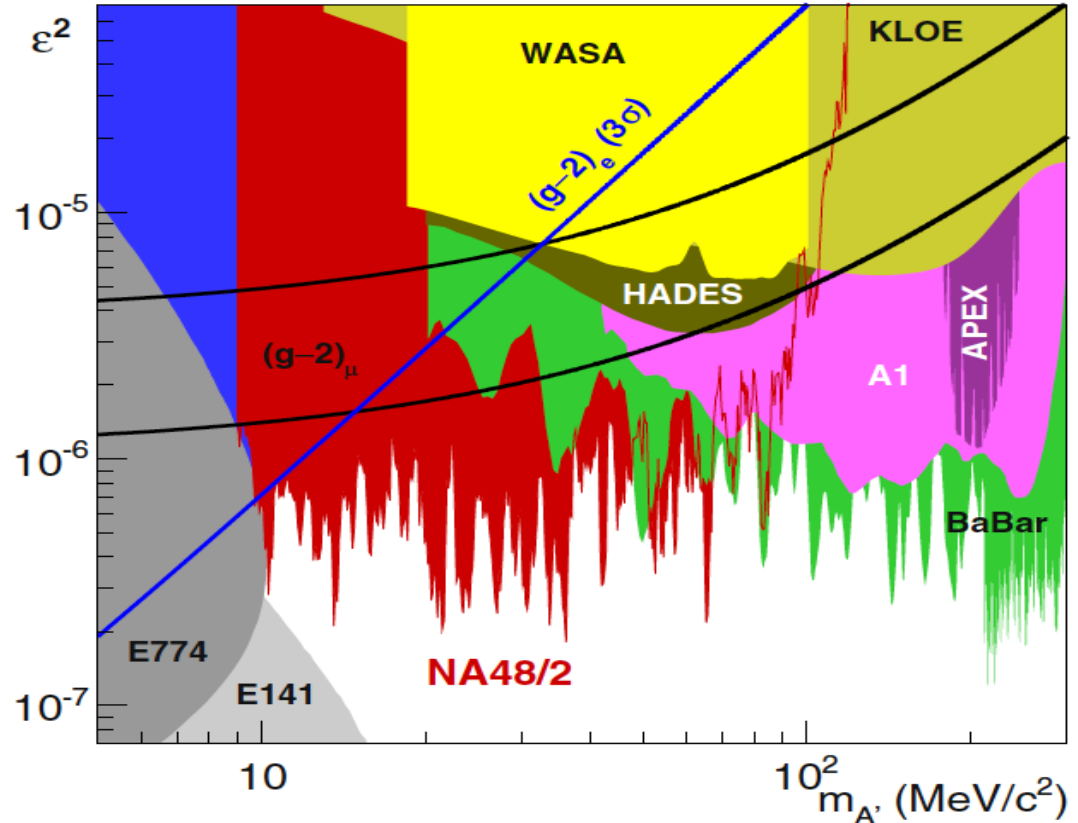


- Lamppost: whatever is not excluded and within reach



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

- The interest in dark matter and 5th 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 ${}^8\text{Be}$ decays

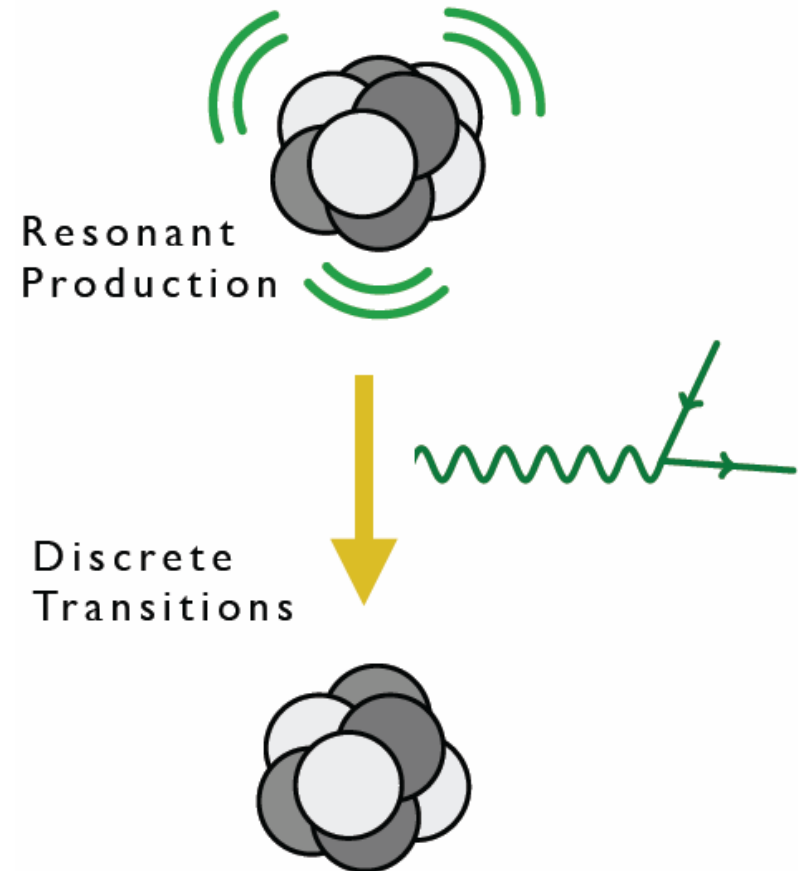
A. J. Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]

- Could these be 5th force gauge bosons?

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

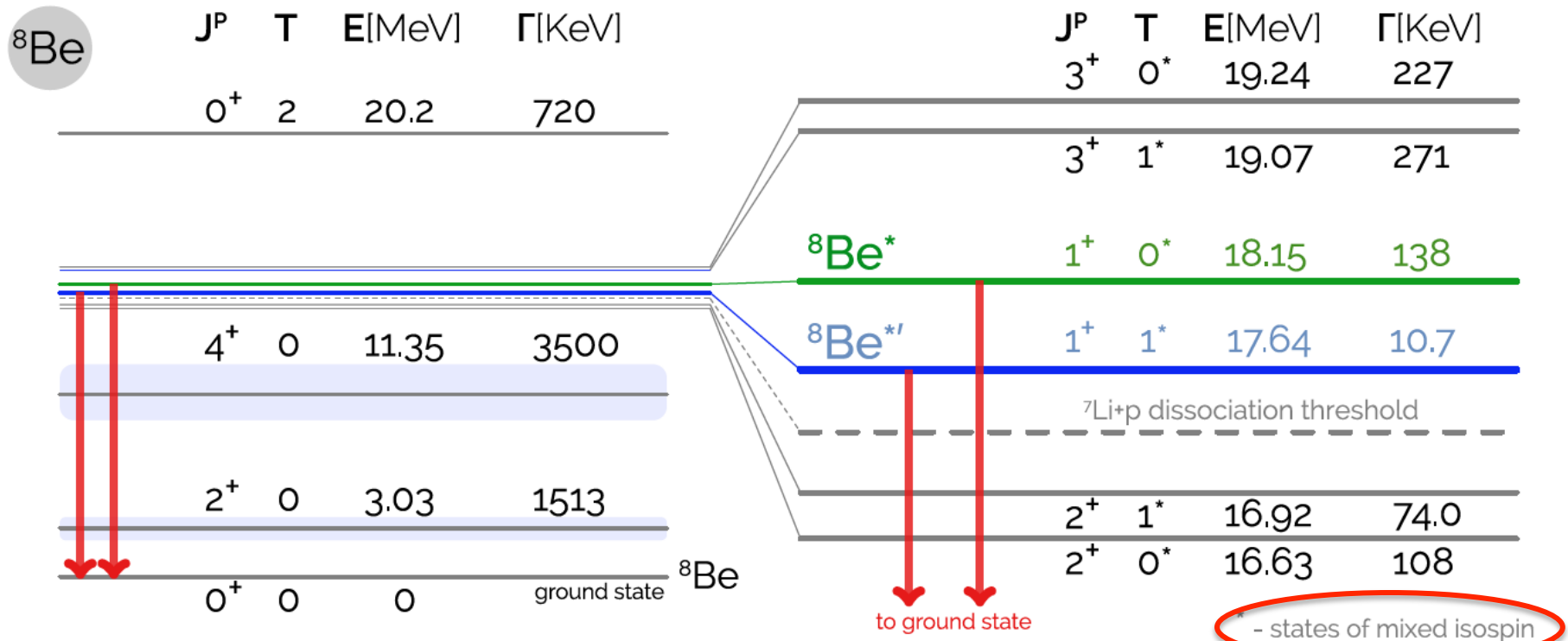
^8Be AS A NEW PHYSICS LAB

- ^8Be 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 (~ 20 MeV)
- ^8Be nuclear transitions then provide interesting probes of light, weakly-coupled particles



^8Be 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

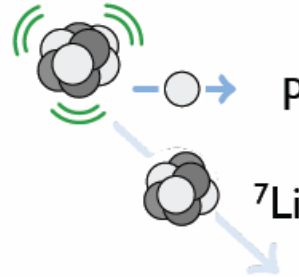


1608.03591; based on Tilley et al. (2004), <http://www.nndc.bnl.gov/nudat2>, Wiringa et al. (2013)

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

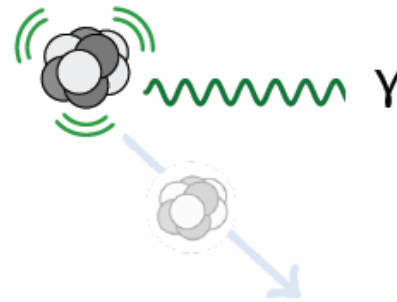
- Hadronic

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



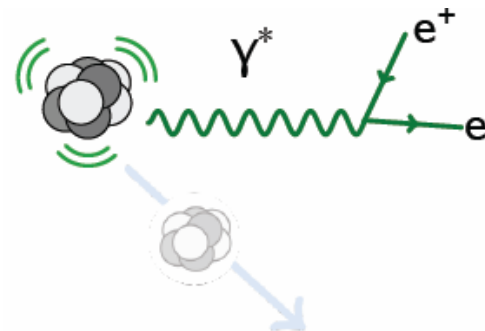
- Electromagnetic

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



- Internal Pair Creation

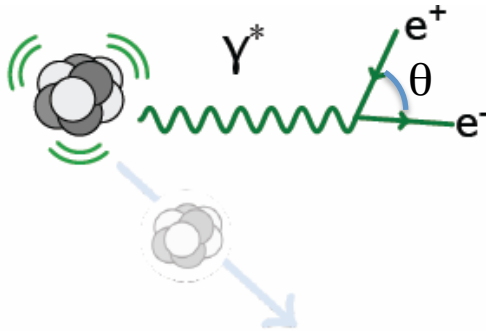
$$B(^8\text{Be} \ e^+ e^-) \approx 5.5 \times 10^{-8}$$



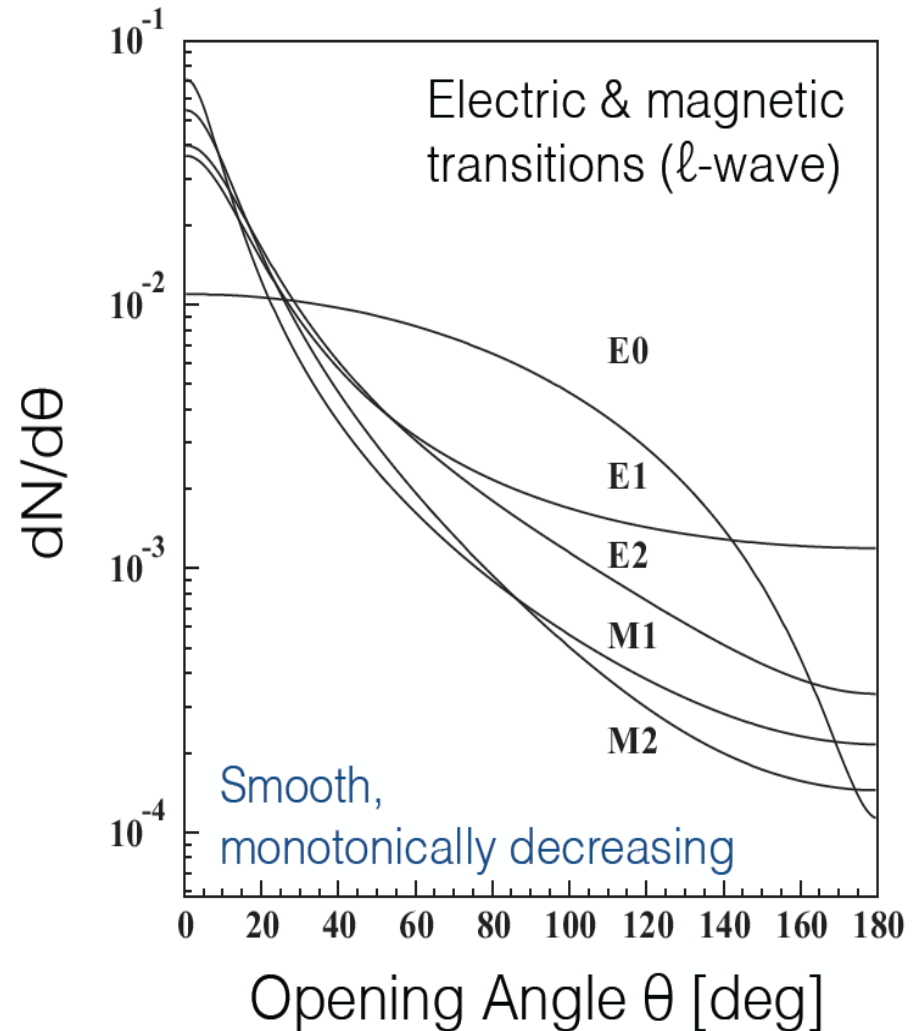
INTERNAL PAIR CREATION KINEMATICS

- Internal Pair Creation

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



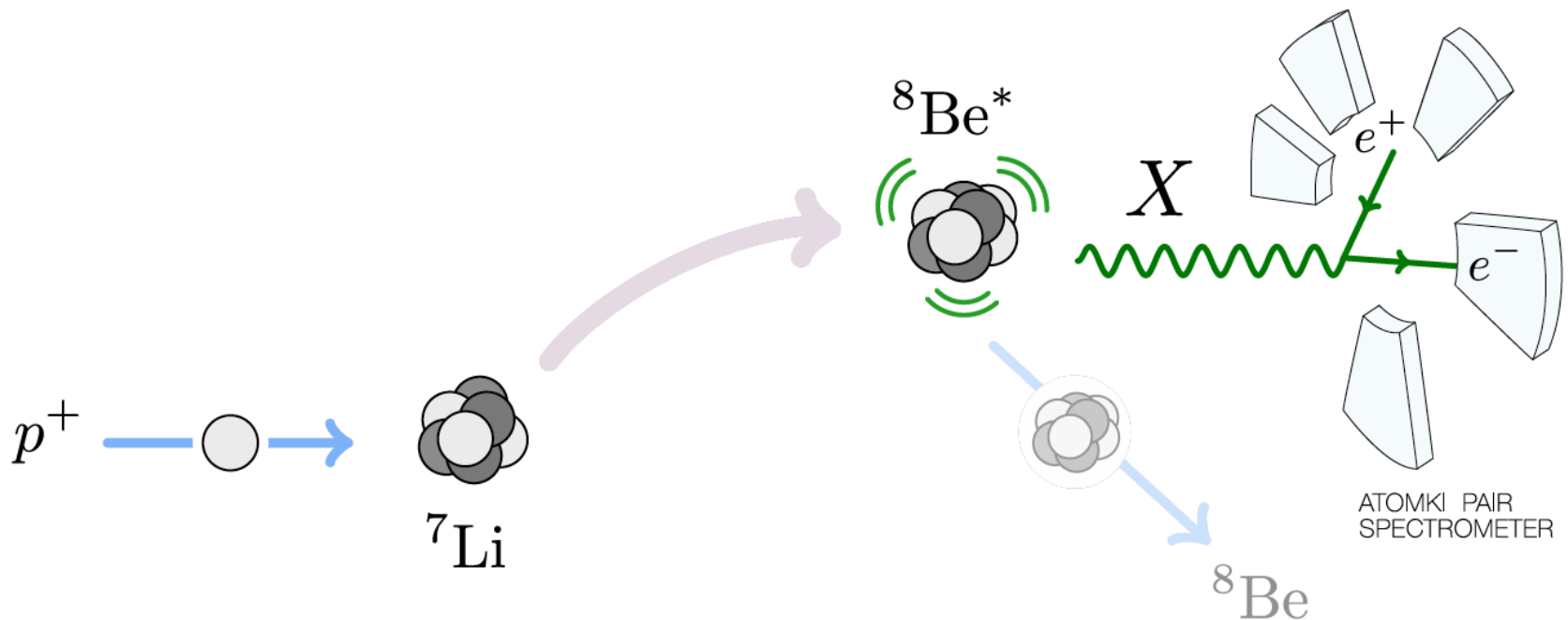
For e^+e^- produced by a virtual photon, $dN/d\theta$ is sharply peaked at low opening angle θ and is expected to be a monotonically decreasing function of θ



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

THE ATOMKI ^8Be EXPERIMENT

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

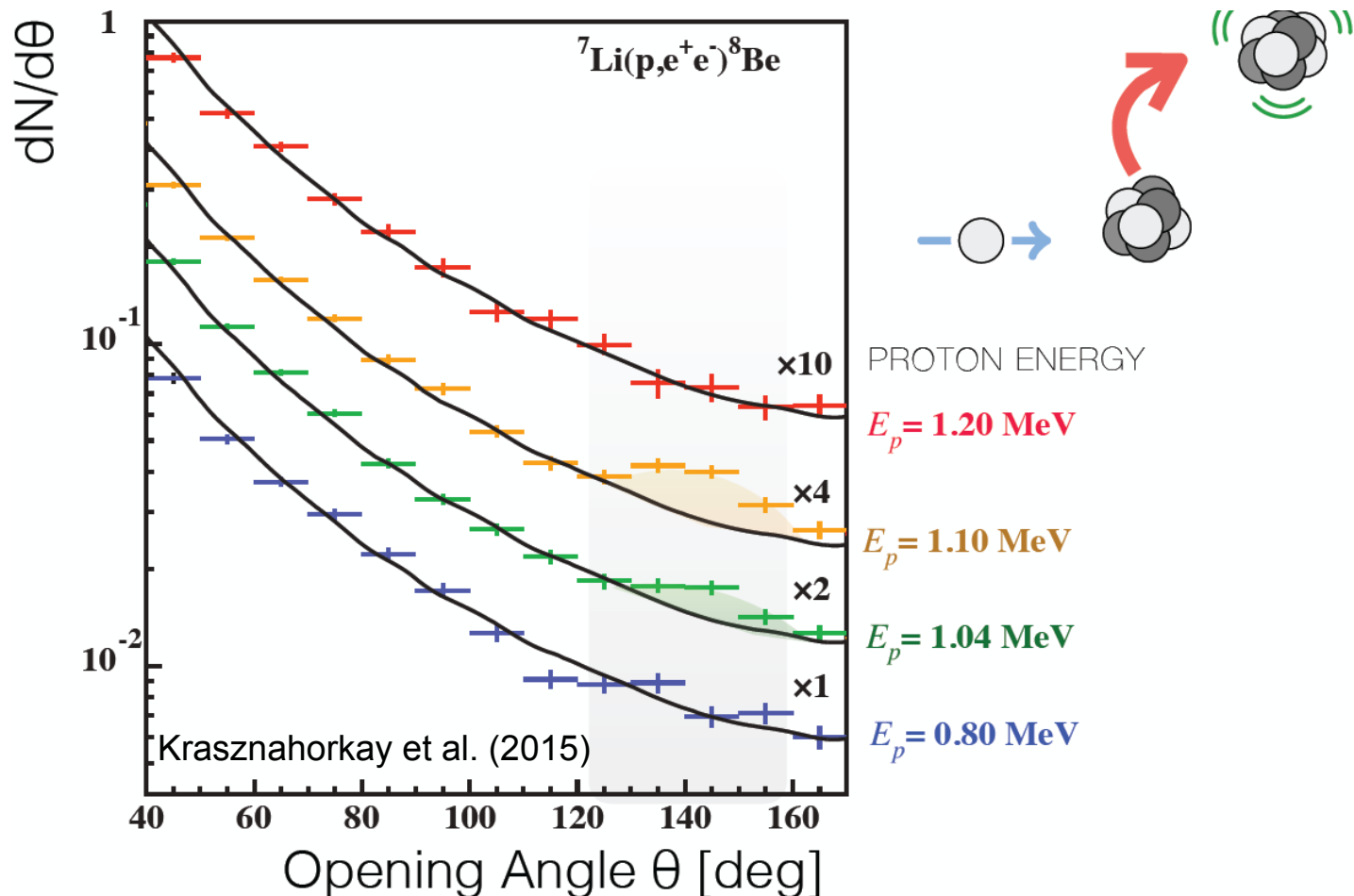


THE ATOMKI ^8Be EXPERIMENT



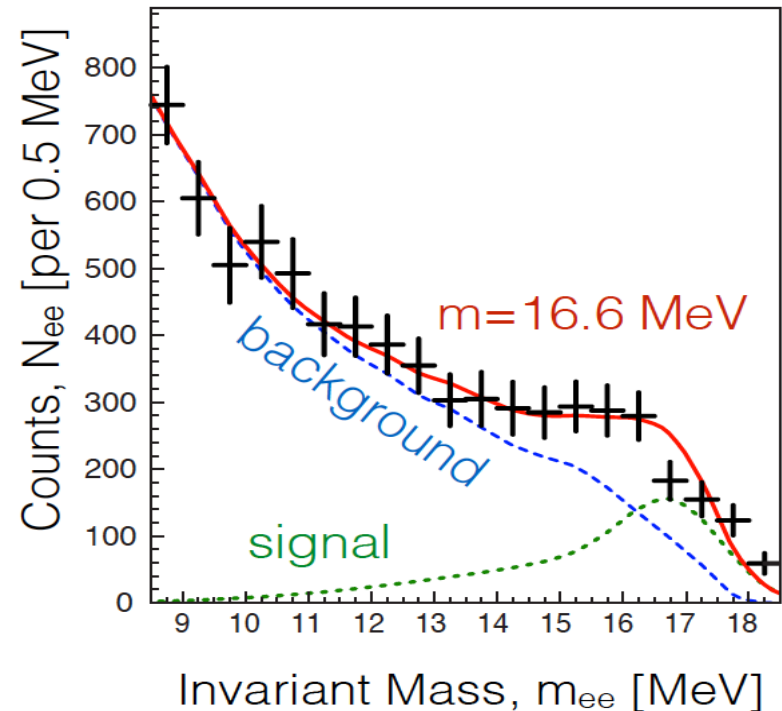
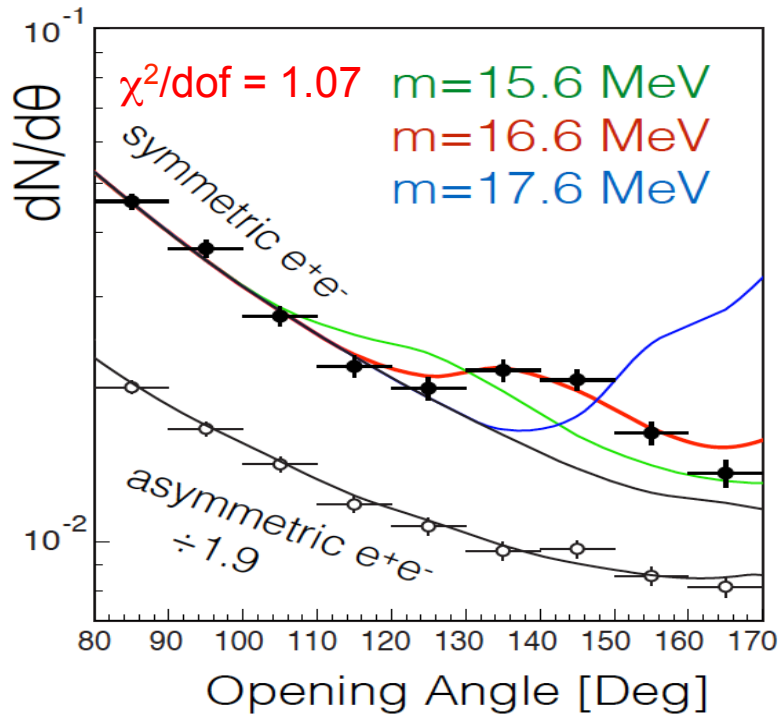
THE ATOMKI ANOMALY

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



THE ATOMKI ANOMALY

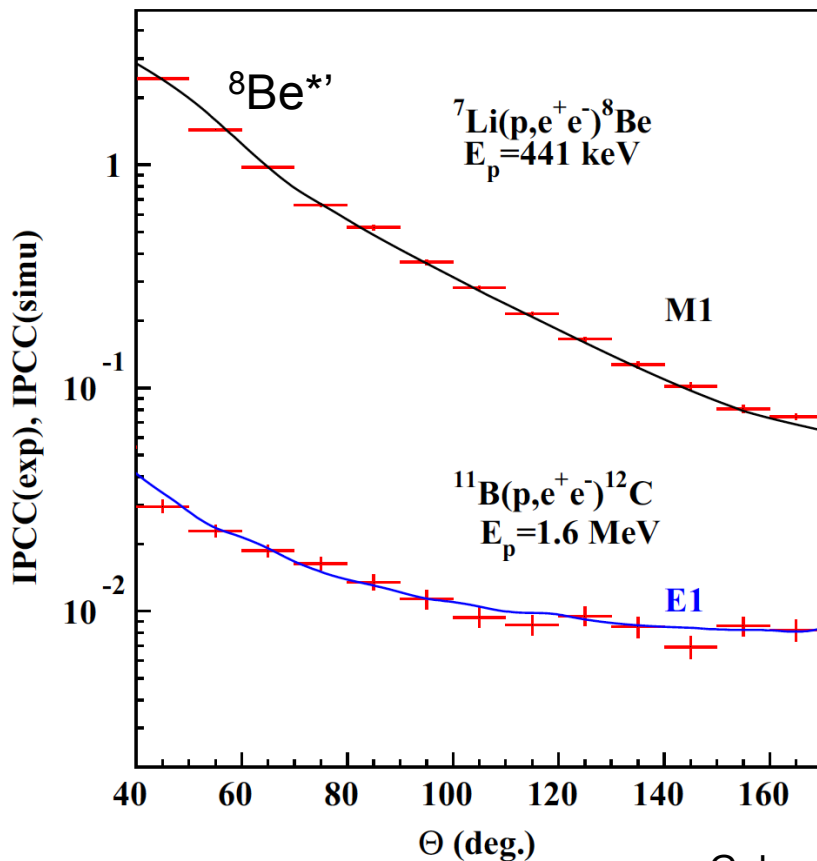
- The θ (and m_{ee}) distributions can be explained by postulating a new particle and 2-step decay: ${}^8\text{Be}^* \rightarrow {}^8\text{Be} X, X \rightarrow e^+e^-$
- The best fit parameters: $m = 16.7 \pm 0.35$ (stat) ± 0.5 (sys) MeV
 $B({}^8\text{Be}^* \rightarrow {}^8\text{Be} X) / B({}^8\text{Be}^*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



Krasznahorkay et al. (2015)

CROSS CHECKS

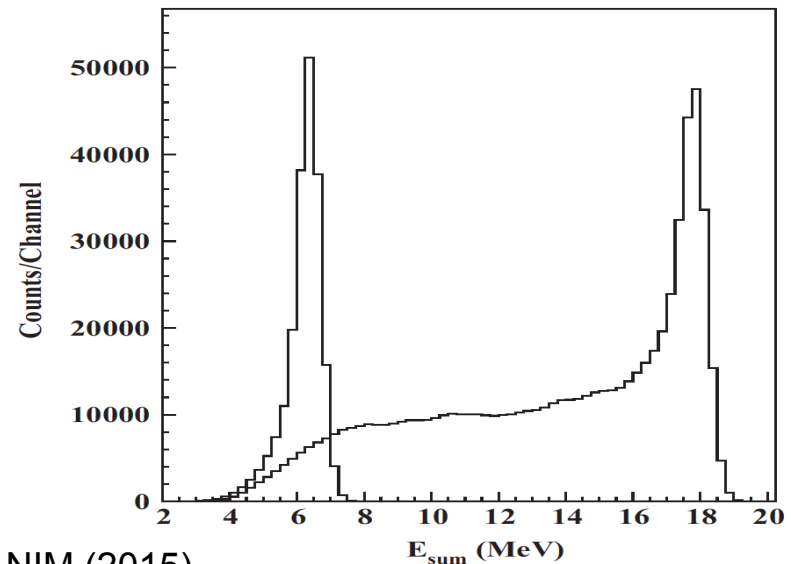
- For example: other decays (all with lower energy), fit theoretical expectations well



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

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

(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)

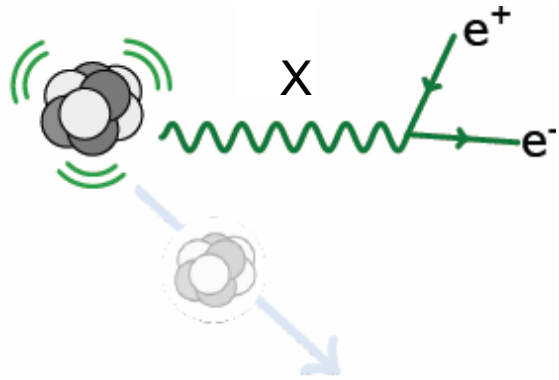
(3) Particle Physics

- 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 5th force

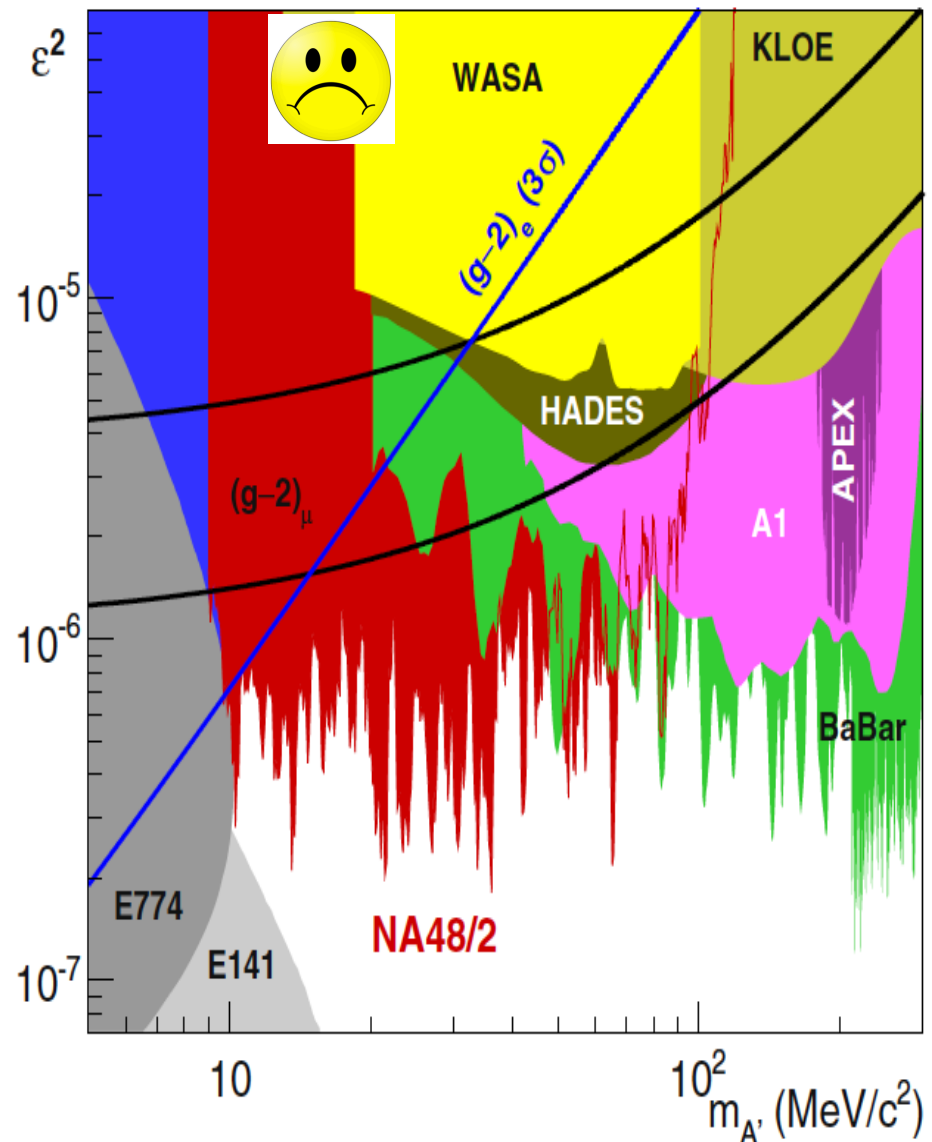
Not everything works

- 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?

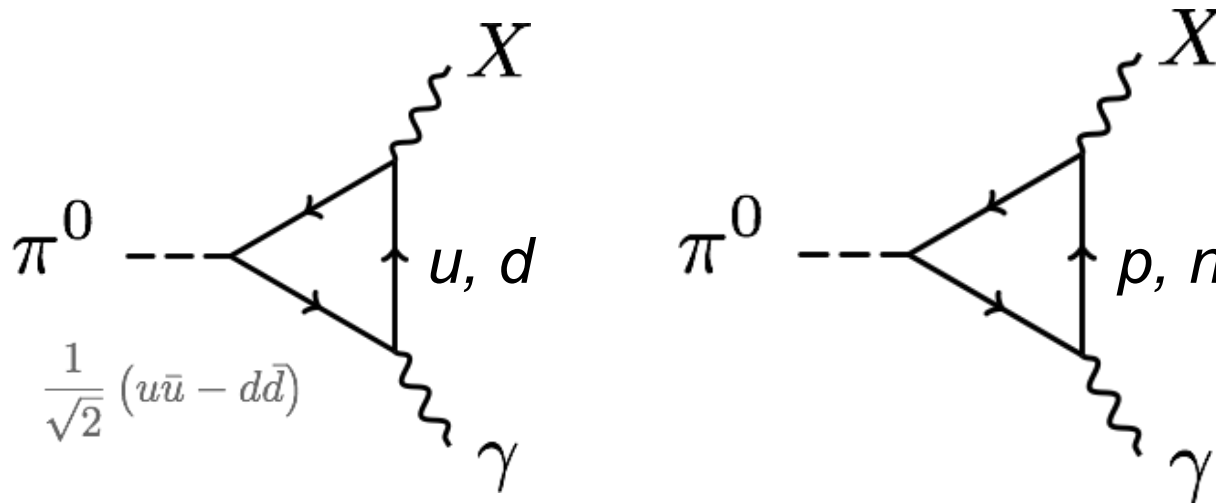
- Consider the case of a spin 1 gauge boson with general couplings $\varepsilon_f e$ to particle f
- To get the right signal strength, need

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

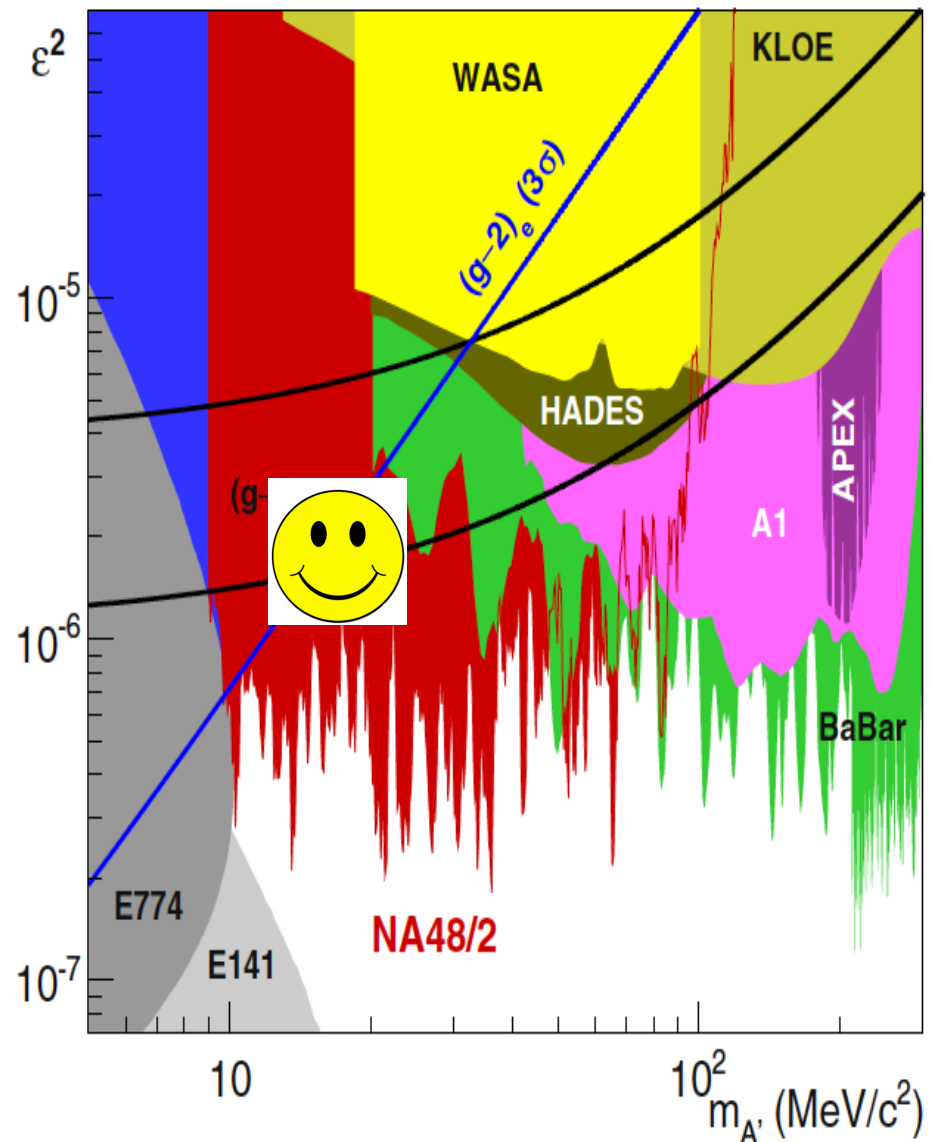
- The dominant constraints are null results from searches for exotic pion decays $\pi^0 \rightarrow X \gamma \rightarrow e^+ e^- \gamma$



- 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

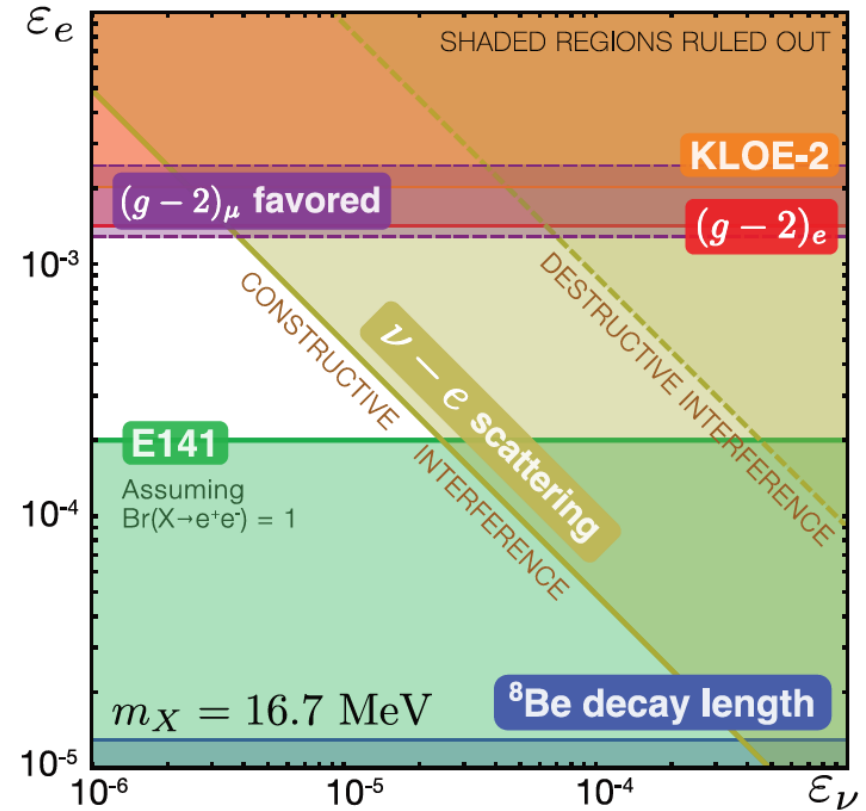
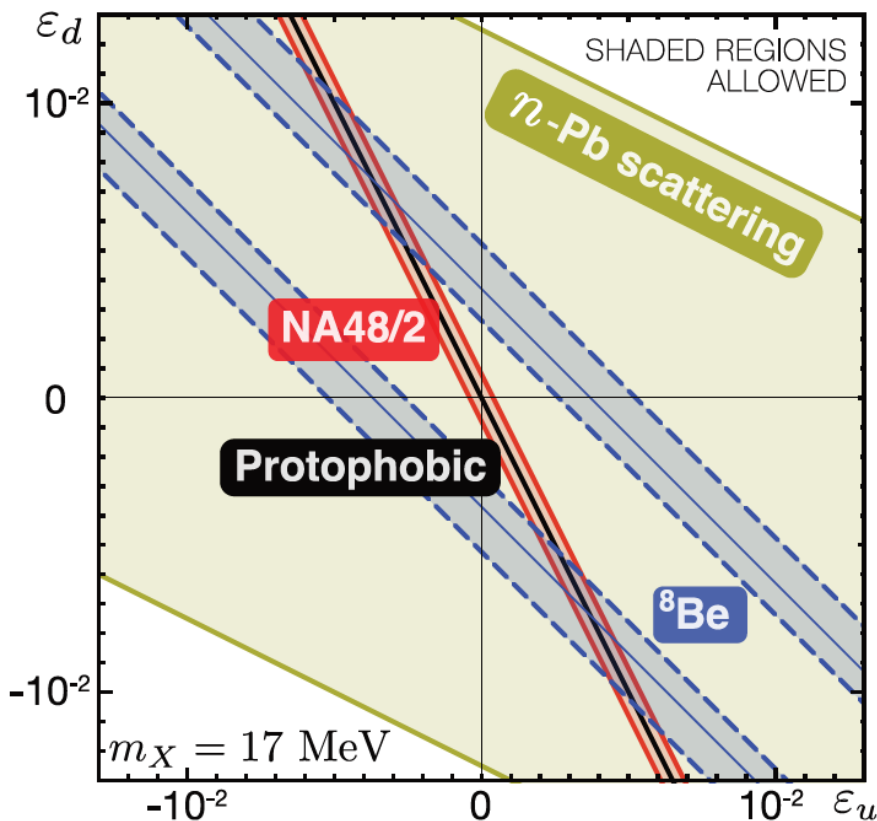
PROTOPHOBIC GAUGE BOSON

- 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 5th force with range ~ 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)

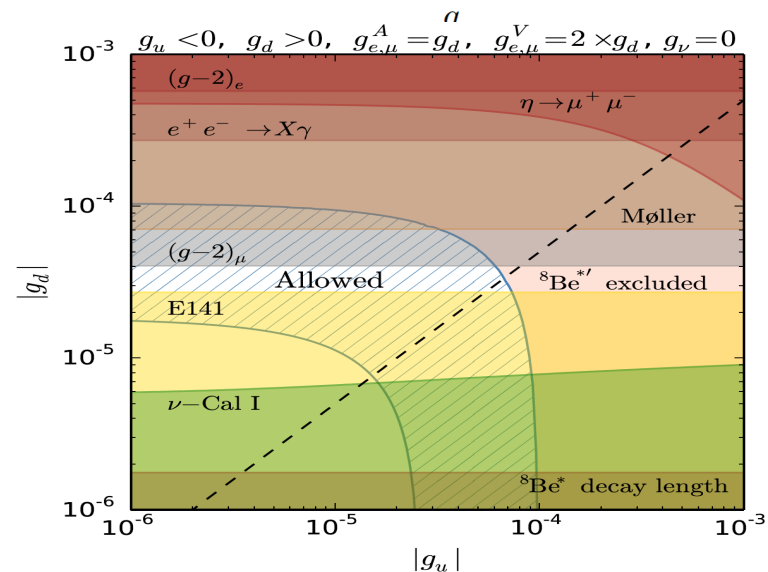
- Pseudoscalars have also been explored and are also possible

Ellwanger, Moretti (2016)

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

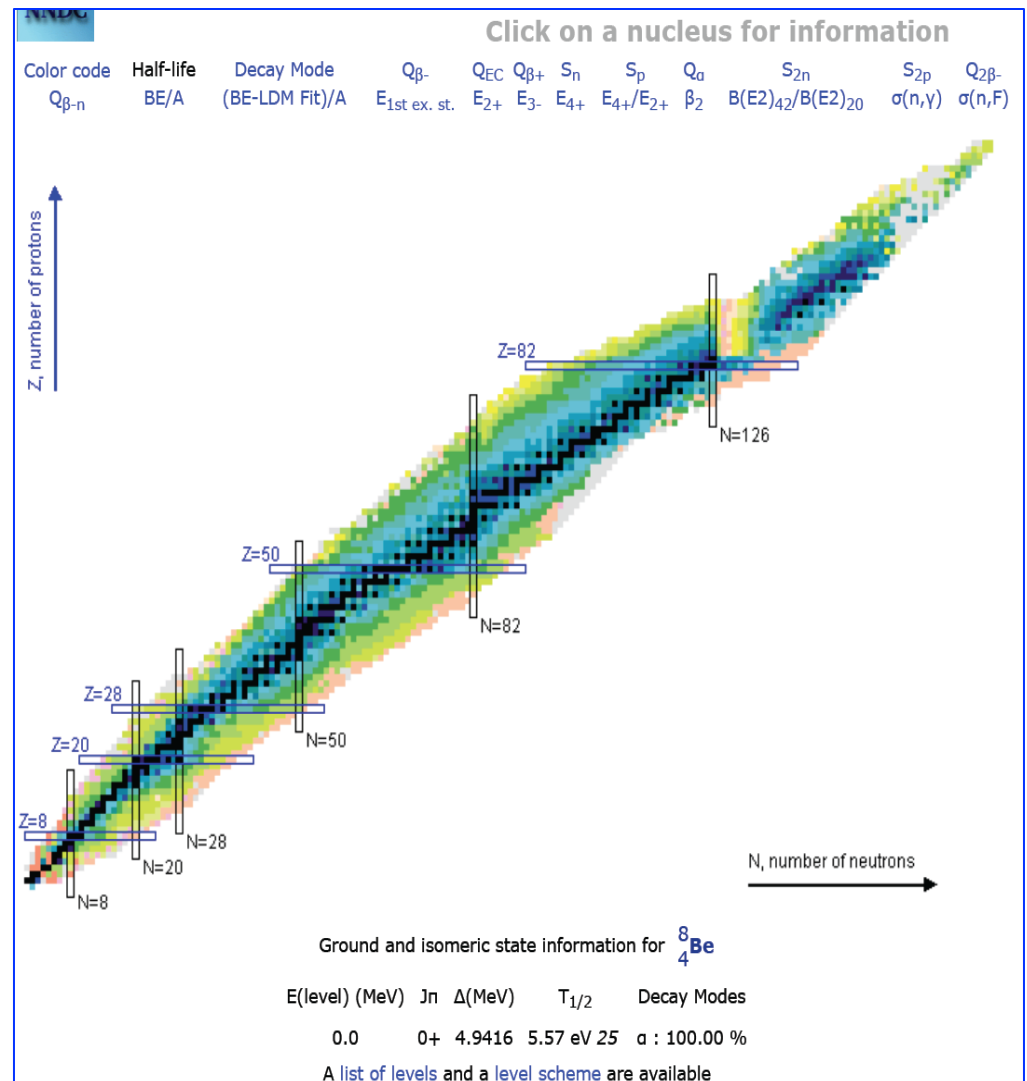
Kozaczuk, Morrissey, Stroberg (2016)

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



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



PROPOSED ^8Be EXPERIMENTS

Purdue

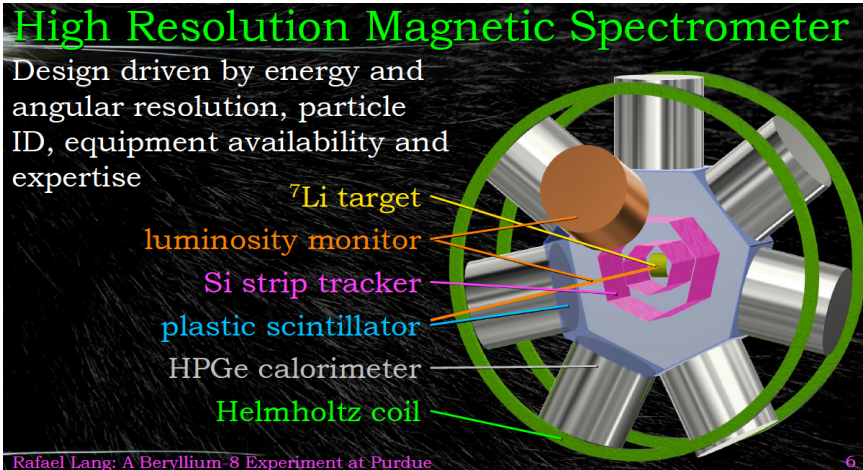


8BeP : A ^8Be Experiment at Purdue

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



- ^7Li target
- luminosity monitor
- Si strip tracker
- plastic scintillator
- HPGe calorimeter
- Helmholtz coil

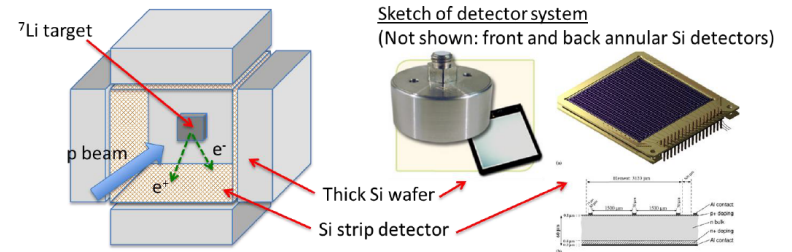
Rafael Lang: A Beryllium-8 Experiment at Purdue

Notre Dame

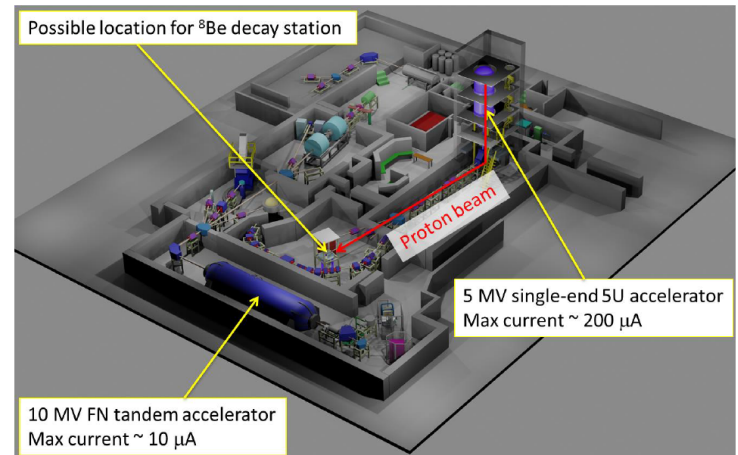


A ^8Be IPC Decay Measurement at the Notre Dame-NSL

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



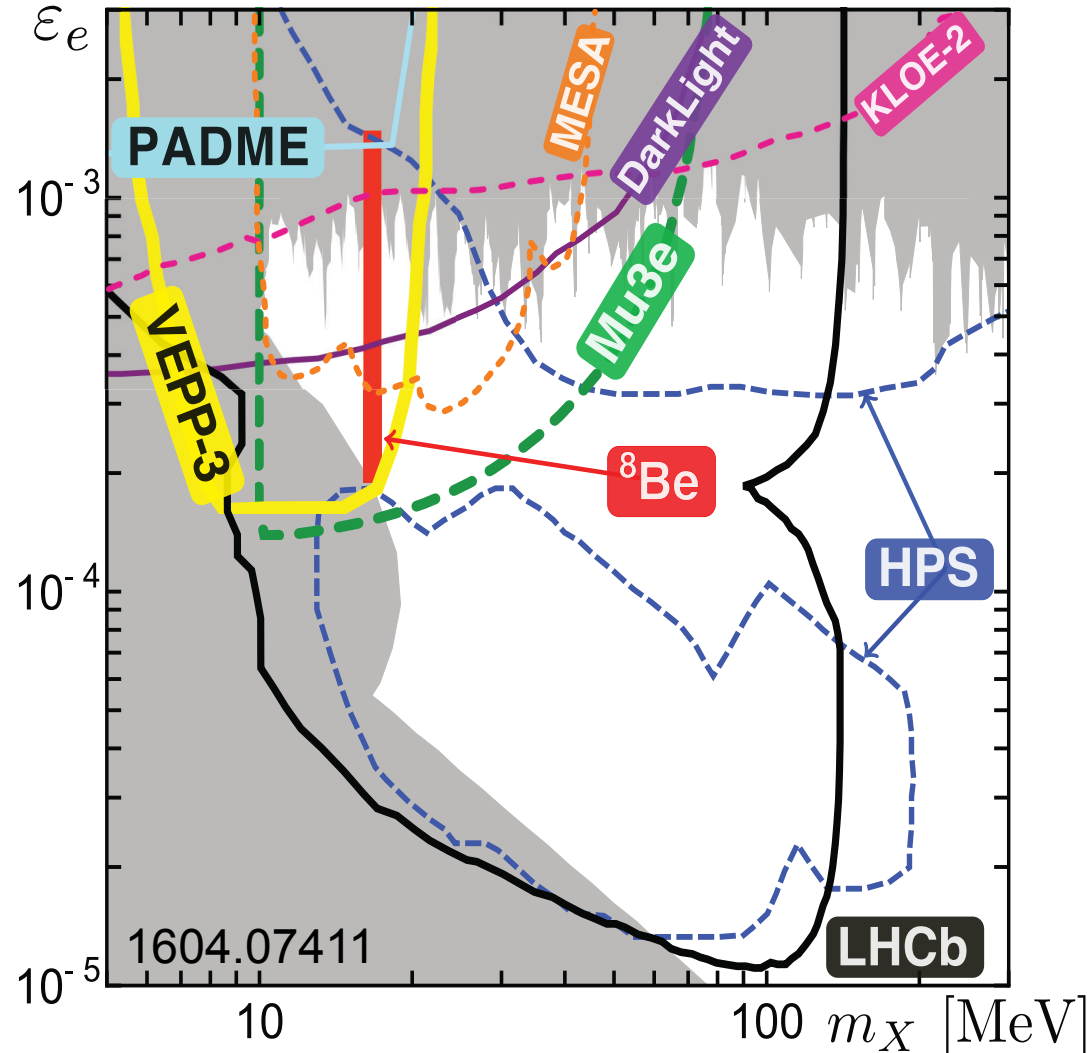
The Nuclear Science Laboratory of the University of Notre Dame



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

- 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 ${}^8\text{Be}^*$ 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 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