THEORETICAL INTRODUCTION TO POSSIBLE INTERPRETATIONS

Shedding Light on X17

Centro Ricerche Enrico Fermi, Rome

Jonathan Feng, UC Irvine

7 September 2021

NSF
SIMONS FOUNDATION
HEISING-SIMONS FOUNDATION
UC IRVINE

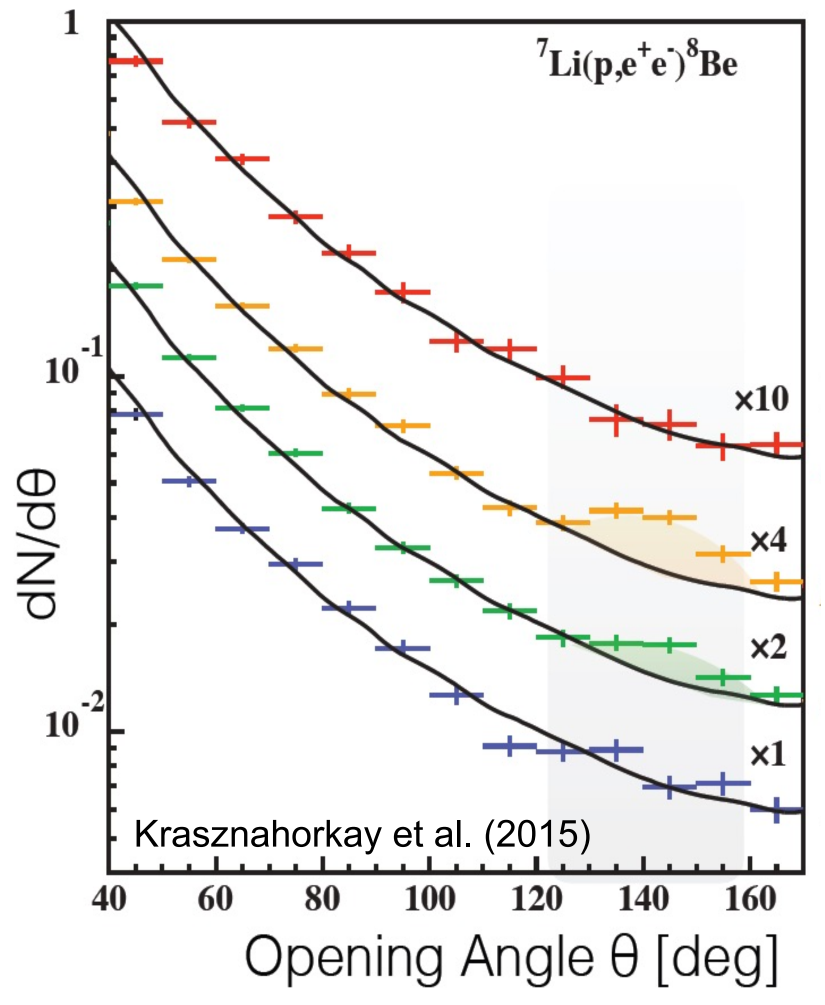
OUTLINE

- Could this be new physics?
- Essential features of the signal
- Explanations that don't work
  - Scalars, dark photons
- Possible solutions
  - vectors, axial vectors, pseudoscalars
- The protophobic gauge boson
- Paths toward a resolution
  - Implications for future experiments

COULD THIS BE NEW PHYSICS?

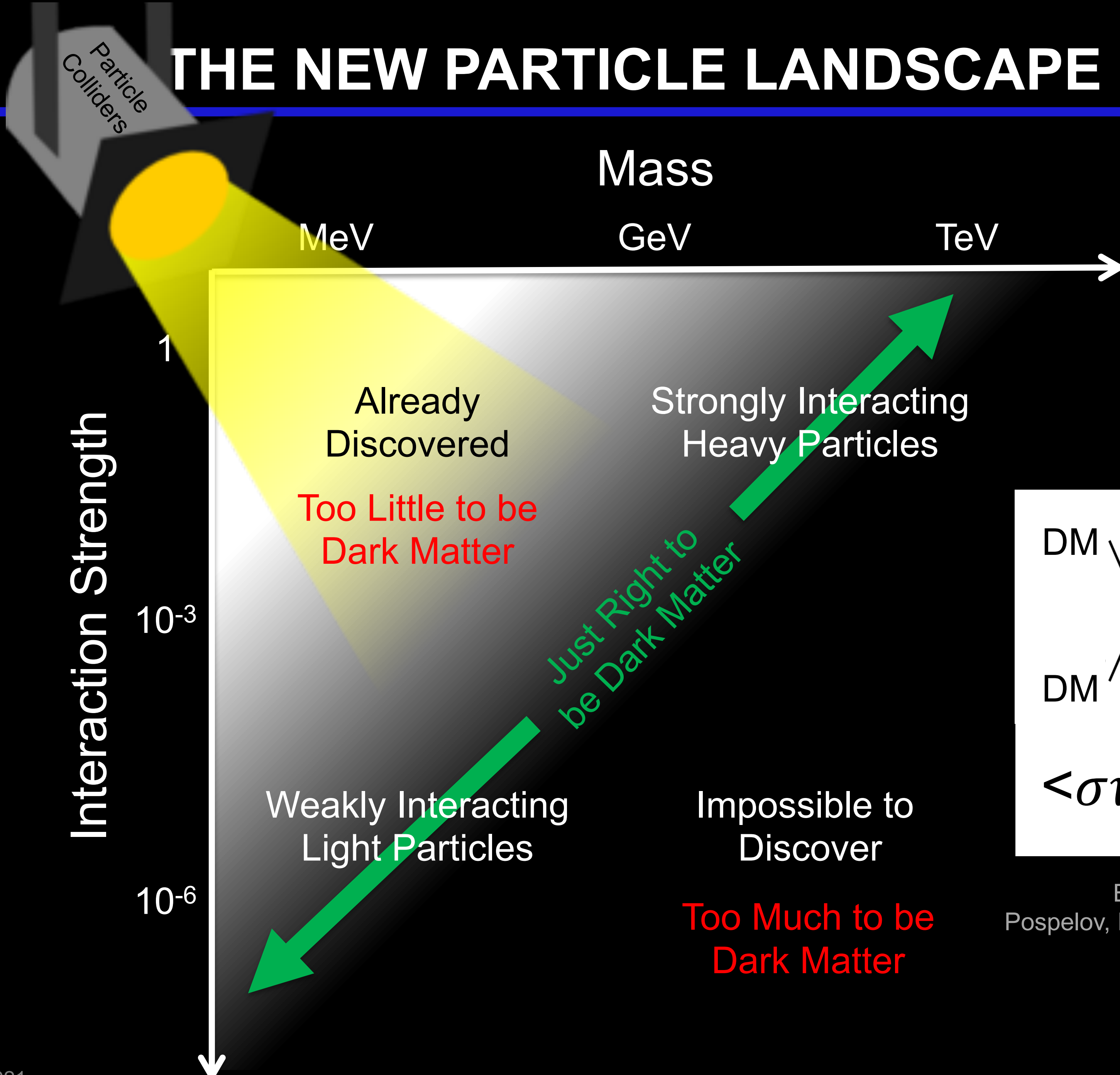
- The ATOMKI ^{8}Be and ^{4}He results are the most interesting anomalies to appear in the last several years.

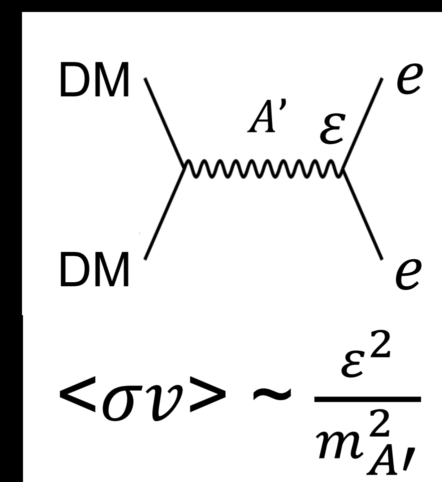
- Key considerations for a BSM theorist
  - 6.8σ statistical significance – not likely to disappear with more data
  - It's a bump, not a general excess
  - Rises and falls as one goes through resonance
  - Fit improves drastically with the introduction of a new particle
  - No compelling SM explanation
    Zhang, Miller (2017); Viviani et al. (2021)
  - No experimental problem identified
  - ^{8}Be and ^{4}He support each other



- And last, in general terms, it fits beautifully with current ideas for BSM physics and cosmology that motivate weakly interacting, light particles.

THE NEW PARTICLE LANDSCAPE





Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)
Feng, Kumar (2008)

REFERENCES

These motivations have led to many works on BSM interpretations. My viewpoint has been informed by these works and collaborators:

- *Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions*, J.L. Feng, B. Fornal, I. Galon, S. Gardner, J. Smolinsky, T. Tait, F. Tanedo, 1604.07411, *Phys. Rev. Lett. 117, 071803 (2016)*

- *Particle Physics Models for the 17 MeV Anomaly in Beryllium Nuclear Decays*, J.L. Feng, B. Fornal, I. Galon, S. Gardner, J. Smolinsky, T. Tait, F. Tanedo, 1608.03591, *Phys. Rev. D 95, 035017 (2017)*

- *Dynamical Evidence for a Fifth Force Explanation of the ATOMKI Nuclear Anomalies*, J.L. Feng, T. Tait, C. Verhaaren, 2006.01151, *Phys. Rev. D 102, 036016 (2020)*


Bart Fornal


Iftah Galon


Susan Gardner


Jordan Smolinsky

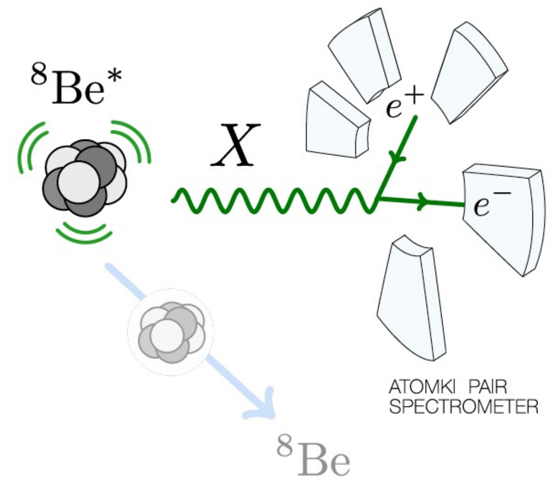

Tim Tait


Flip Tanedo


Chris Verhaaren

ESSENTIAL FEATURES OF THE SIGNAL

- X is produced through nuclear (quark) couplings, decays through electron coupling.

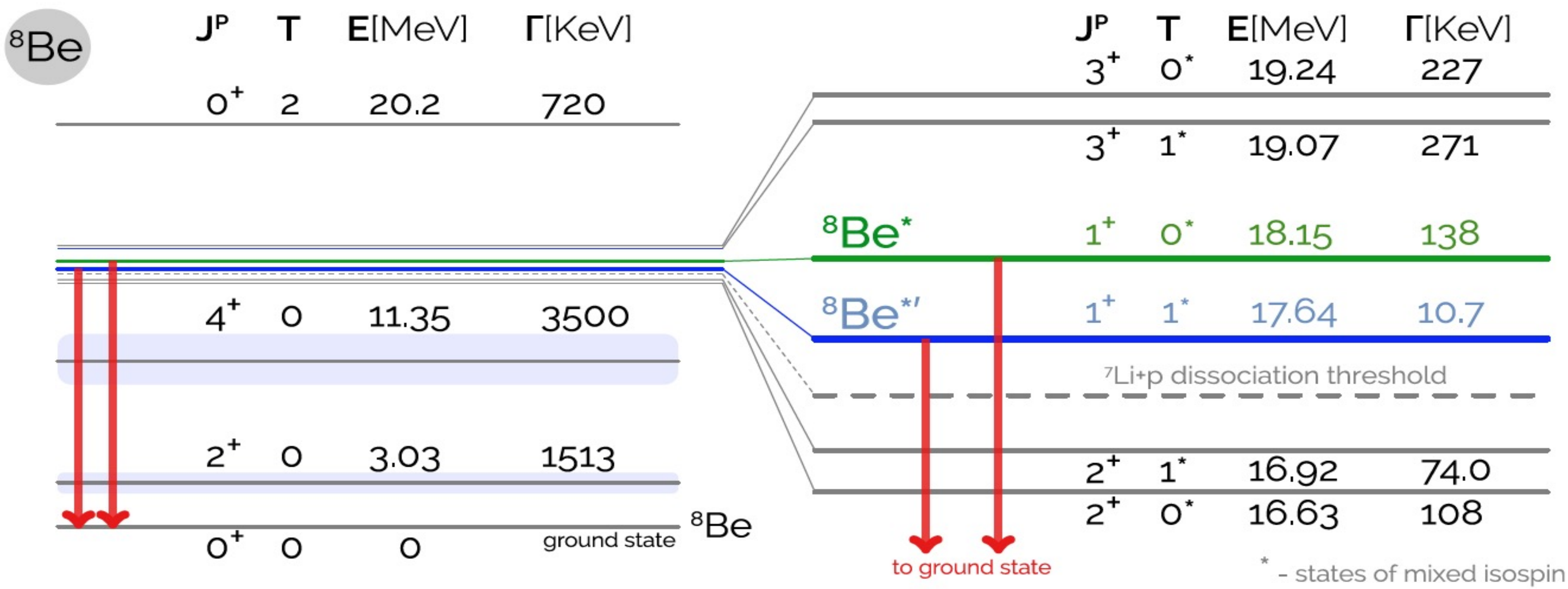


- Bump at 140°: 2-body final state, $m_X \approx$ 17 MeV.
- X must be a 17 MeV, neutral boson. It therefore implies a new force with a range of 12 fm.
- Signal rate is determined by $\sigma(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X)$ $\mathrm{BR}(X \to e^+e^-)$.
- Other decay modes possible ($X \to \nu\bar{\nu}$, DM, ...), but these imply larger nuclear couplings to maintain signal rate; assume $\mathrm{BR}(X \to e^+e^-) = 1$.
- Nuclear couplings: determined by signal rate.
- Electron coupling: X cannot travel too far → lower bound.
- Symmetries provide additional constraints, as well as all expts probing the 10 MeV scale since the early days of nuclear and particle physics.

EXPLANATIONS THAT DON'T WORK: SCALARS

- Can X be a spin-0 boson (dark Higgs boson) with $J^P = 0^+$?
- The decay would then have J^P assignments: $1^+ \rightarrow 0^+ \, 0^+$.
- L Conservation: L = 1, Parity Conservation: $P = (-1)^L = 1$, so this is forbidden in parity-conserving theories.
- A scalar is not a viable explanation of the ^{8}Be results.

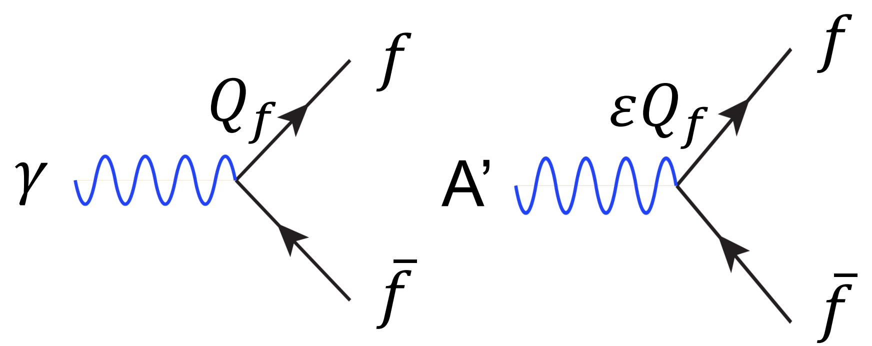
Feng et al. (2016)



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

EXPL. THAT DON'T WORK: DARK PHOTONS

- The dark photon A' is a specific new spin-1 gauge boson: it's couplings are identical to the photon's, but suppressed by a small parameter ε.

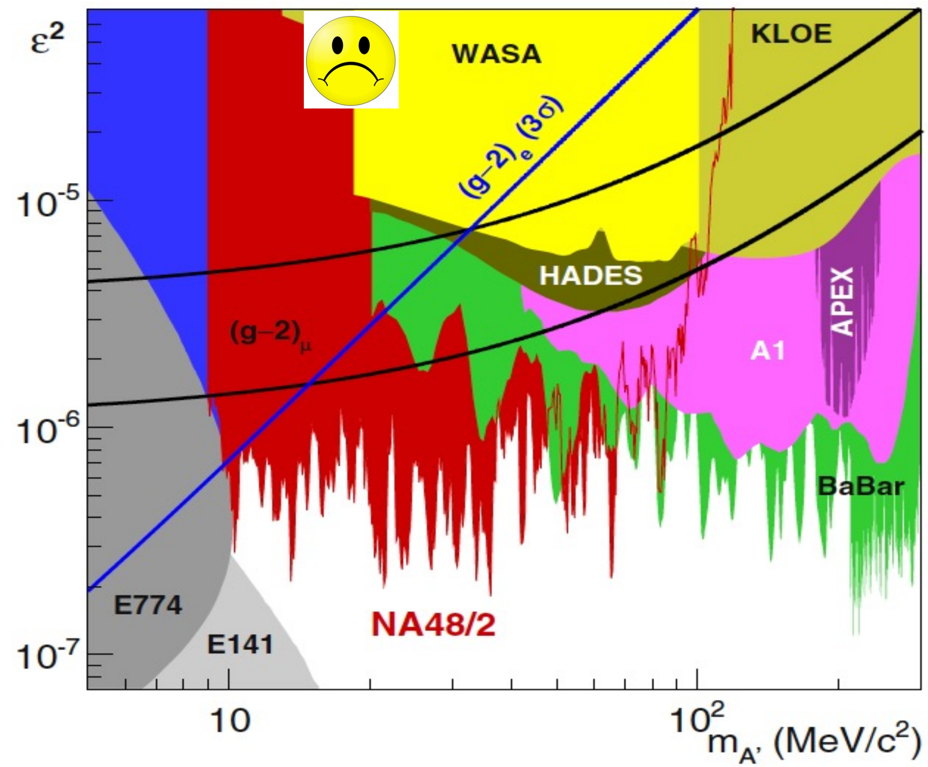


- To get the right signal strength, need

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

- Given the dark photon's couplings $\varepsilon_f = \varepsilon Q_f$, this implies $\varepsilon \sim 0.01$, which is excluded by experiments.

- The dark photon is not a viable explanation of the ^{8}Be results.



Feng et al. (2016)

POSSIBLE SOLUTIONS

- One must then turn to other possible candidates.

- Vectors (spin-1 gauge bosons) that are not dark photons
  - Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo (1604.07411, 1608.03591); Gu, He (1606.05171); Jia, Li (1608.05443); Chen, Lin, Lin, Xu (1609.07198); Kitahara, Yamamoto (1609.01605); Delle Rose, Khalil, Moretti (1704.03436); …

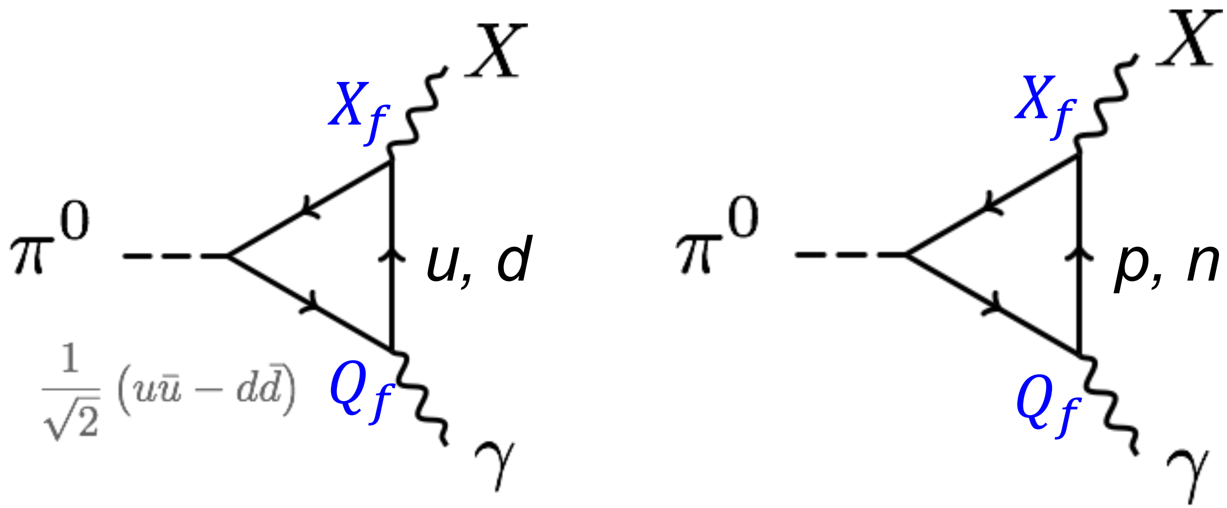
- Axial vectors
  - Kahn, Krjaic, Mishra-Sharma, Tait (1609.09072); Kozaczuk, Morrissey, Stroberg (1612.01525); …

- Pseudo-scalars
  - Ellwanger, Moretti (1609.01669); Alves, Weiner (1710.03764); …

- …and others. See the talks of Delle Rose, Tait, Zhang, Alves, and Wong at this meeting, and also the review of Fornal (1707.09749).

PROTOPHOBIA

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

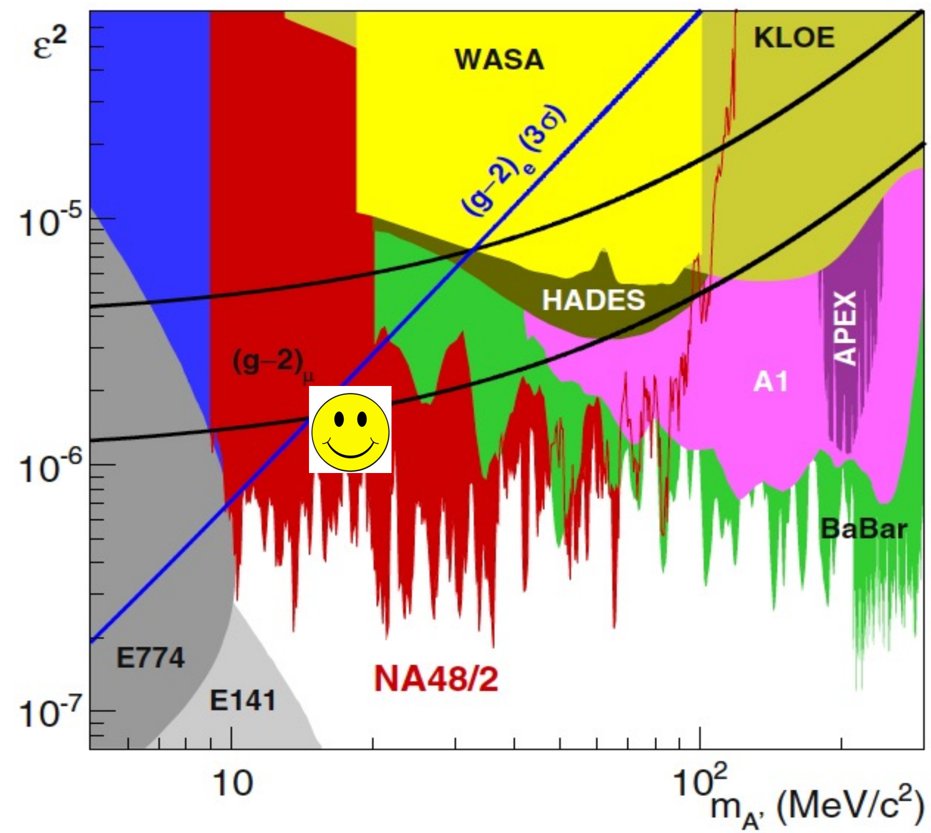


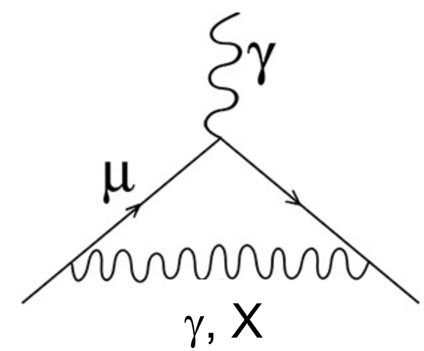
- This is eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$.

- 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

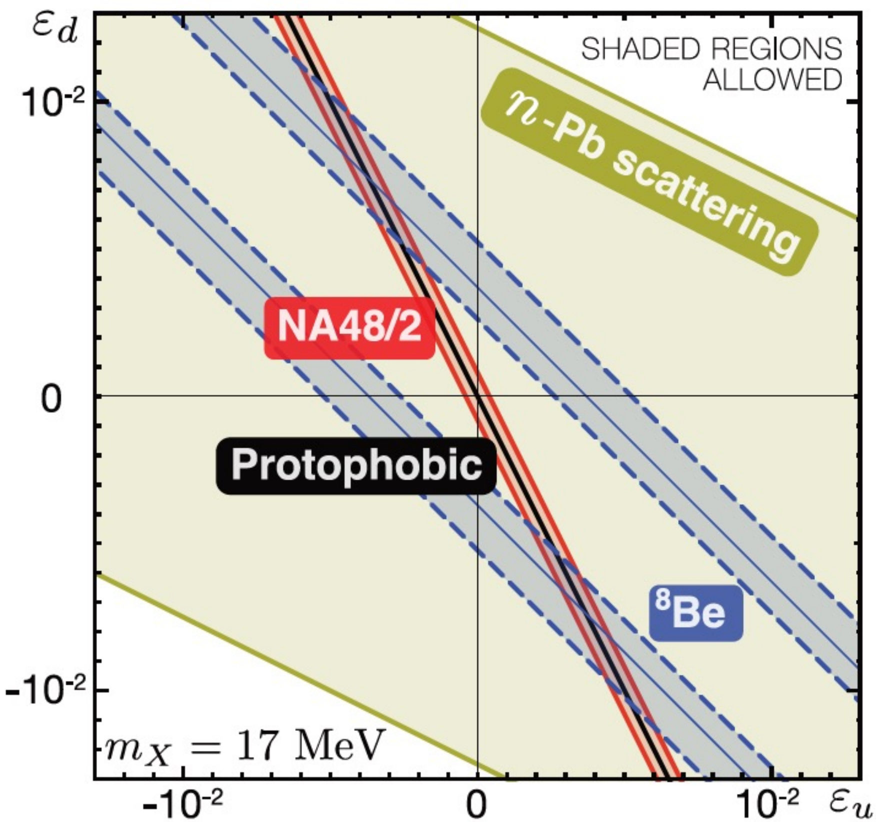
- For a protophobic gauge boson, the NA48/2 "quark" constraints are weakened.
- One can, then, take up and down quark couplings around 10^{-3}. Such couplings are allowed by all constraints.
- A protophobic gauge boson can explain the ^{8}Be results, and simultaneously reduce the muon g-2 anomaly from ~4σ to 2σ.
- Examples of protophobic gauge bosons: the Z at low energies, B-Q, and B-L-Q.

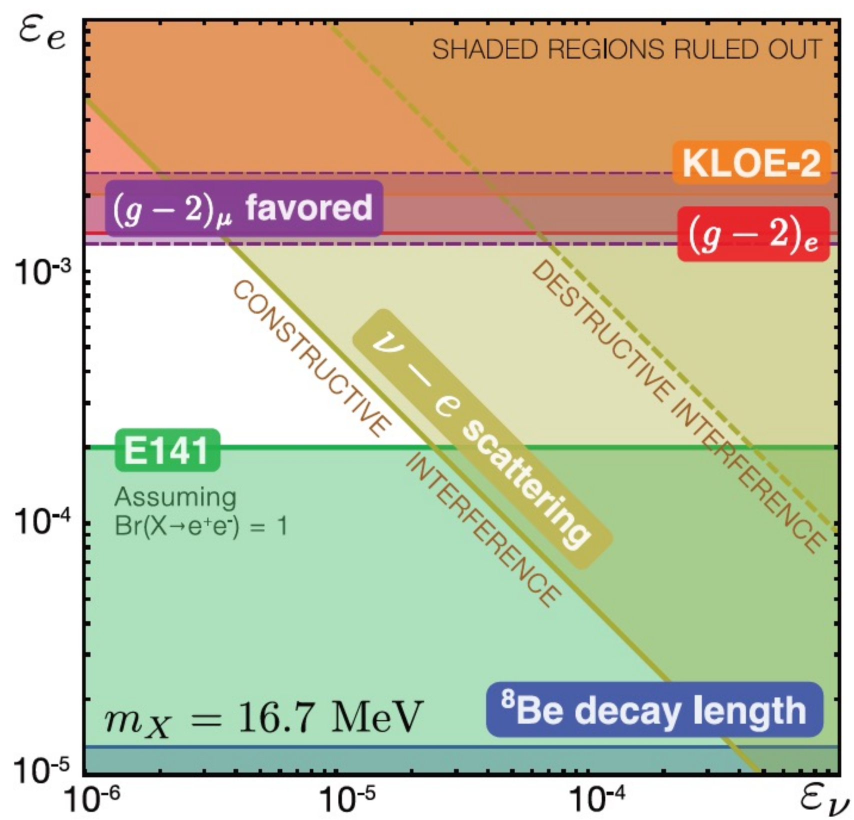




COUPLING CONSTRAINTS

- Considering all constraints, the ^{8}Be results can be explained with
  - ε_u, ε_d ~ few 10^{-3} with ~10% cancelation for protophobia (exact protophobia not needed).
  - $10^{-5} < \varepsilon_e$ from requiring X decay length < 1 cm. Other experiments require $10^{-4} < \varepsilon_e < 10^{-3}$, although the $10^{-4} < \varepsilon_e$ bound is very sensitive to m_X.

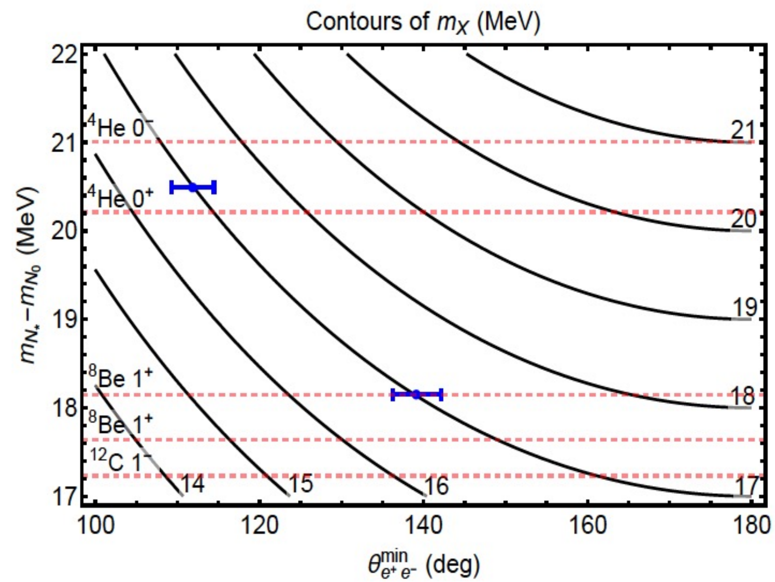




Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo (2016)

CONSISTENCY WITH THE ^{4}HE ATOMKI RESULTS

- In 2019, THE ATOMKI group found evidence of another 7σ signal in ^{4}He nuclei. The excess is at a different opening angle (110°), but the implied mass is the same: 17 MeV.



Feng, Tait, Verhaaren (2020)

- In 2020, Tait, Verhaaren, and I showed that, for the protophobic gauge boson, the required couplings are also similar:

$$\text{Protophobic vector boson: } \Gamma(^4\text{He}(20.21) \to {}^4\text{He}\, X) = (0.3 - 3.6) \times 10^{-5}\ \text{eV}$$
$$\text{ATOMKI Experiment [33, 34]: } \Gamma(^4\text{He}(20.21) \to {}^4\text{He}\, X) = (2.8 - 5.2) \times 10^{-5}\ \text{eV}$$

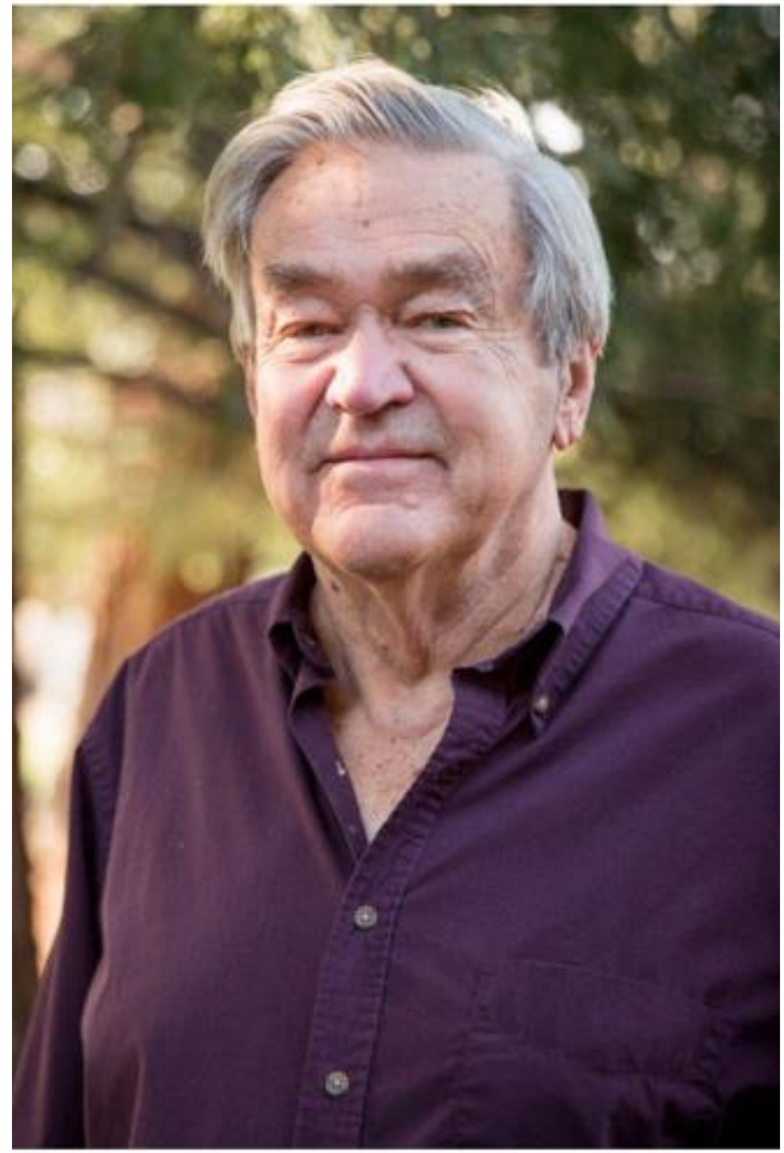
- The ^{4}He rate, as well as the kinematics, therefore supports the protophobic gauge boson; this is highly non-trivial and is not the case for other candidates. (But see upcoming talks.)

PATHS TOWARD A RESOLUTION

- When the protophobic explanation was announced in April 2016, it and the ATOMKI anomaly itself elicited a large range of reactions.

- The most interesting to me was from James Bjorken: “All this is to say that our scenario is a longshot, but it need not be demoted further by theoretical arguments.”

- His point: what is needed is further experimental data. What are the other implications? How can it be tested?

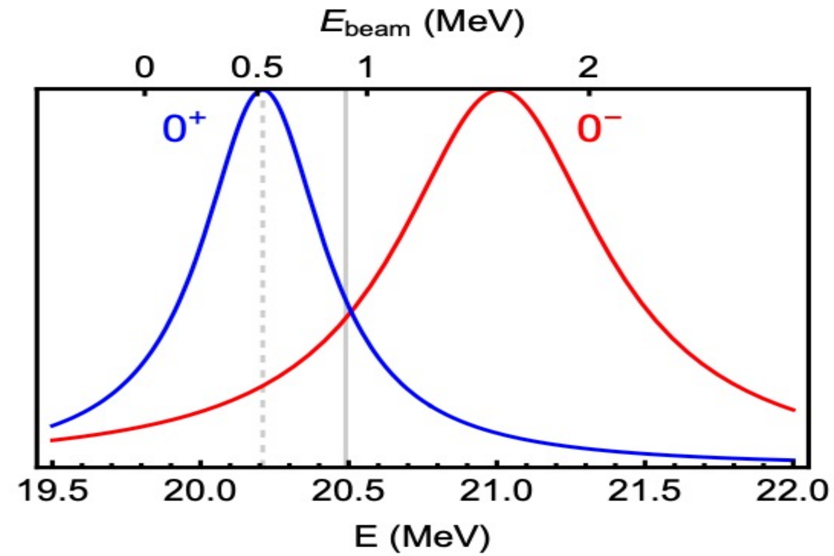


NUCLEAR EXPERIMENTS

- Clearly it would be good for other groups to examine the decays of ^{8}Be* (18.15) and ^{4}He (20.49).

- ^{8}Be*' (17.64) decay to X17 is also generically present (although phase space suppressed). Given identical J^P and isospin mixing, this is typically there, although suppressed.

- For ^{4}He, the current data are from running between the 0^+ and 0^- resonances. Different states are produced in 0^- decays vs. 0^+ decays, so a scan through these resonances would be very informative.



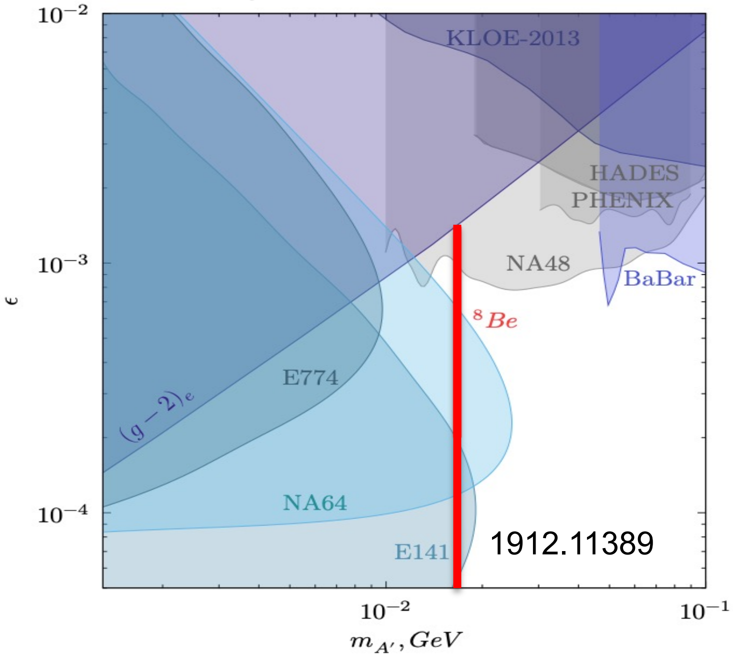
- The decays of the $J^P = 1^-$ state ^{12}C (17.23) also help discriminate. For X17:

$$\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C}\, X) = (1-5) \times 10^{-5}\, \Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C}\, \gamma)$$

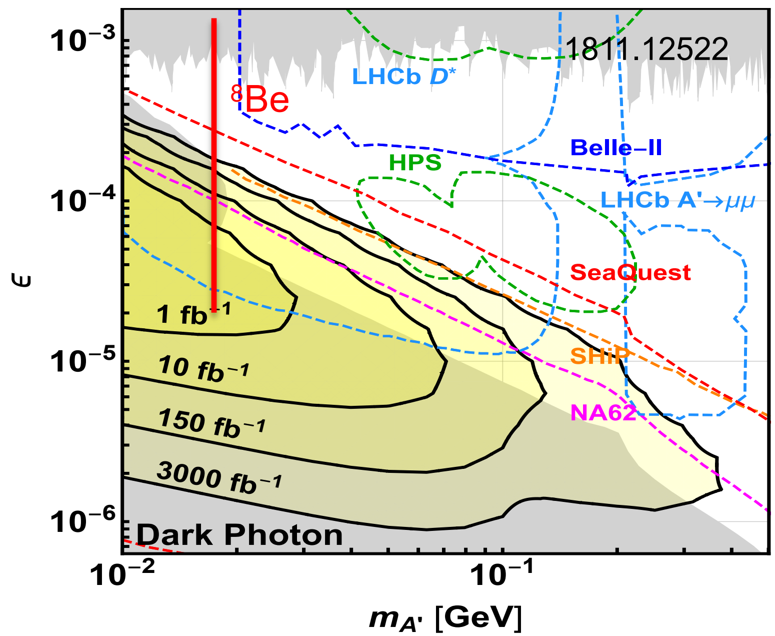
PARTICLE EXPERIMENTS

- Particle experiments can test the ATOMKI anomalies by exploiting the fact that the new 17 MeV particle must couple to electrons and positrons.

NA64 @ CERN, Current bounds



FASER @ CERN, Projected Sensitivity



- In the next few years, NA64 and FASER will be able to discover or exclude an X(17) particle for the remaining electron couplings in the range $\varepsilon \sim 10^{-5} - 10^{-3}$.

- Also prospects for PADME, many other LLP experiments.

SUMMARY

- The ^{8}Be results have been tantalizing for 6 years now, and are now supplemented by ^{4}He results.

- New physics explanations require a new weakly-interacting, light particle, with connections to beautiful ideas in particle physics, cosmology, and dark matter.

- There are many interesting explanations, and these strongly motivate a diverse set of nuclear and particle experiments.