EVIDENCE FOR A PROTOPHOBIC FIFTH FORCE

Mitchell Workshop on Collider, Dark Matter, and Neutrino Physics
Texas A&M

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Based on 1604.07411, “Evidence for a Protophobic Fifth Force From ^{8}Be Nuclear Transitions,” and work in progress

MOTIVATIONS FOR A FIFTH FORCE

FORCE UNIFICATION

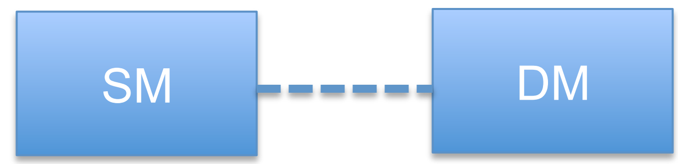
- The quantum numbers of SM matter fields are explained by GUTs:

  SU(3) x SU(2) x U(1) → SU(5), SO(10), E6, E8, …

- SO(10) ... → 5th force

DARK MATTER

- Dark sector: new matter and new forces



- Mediator → weakly-coupled 5^{th} force

These beautiful ideas have focused a great deal attention on the search for a fifth force: Z' bosons, dark photons, dark Z's, and general light, weakly-coupled particles

MAYBE IT'S ALREADY BEEN FOUND

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

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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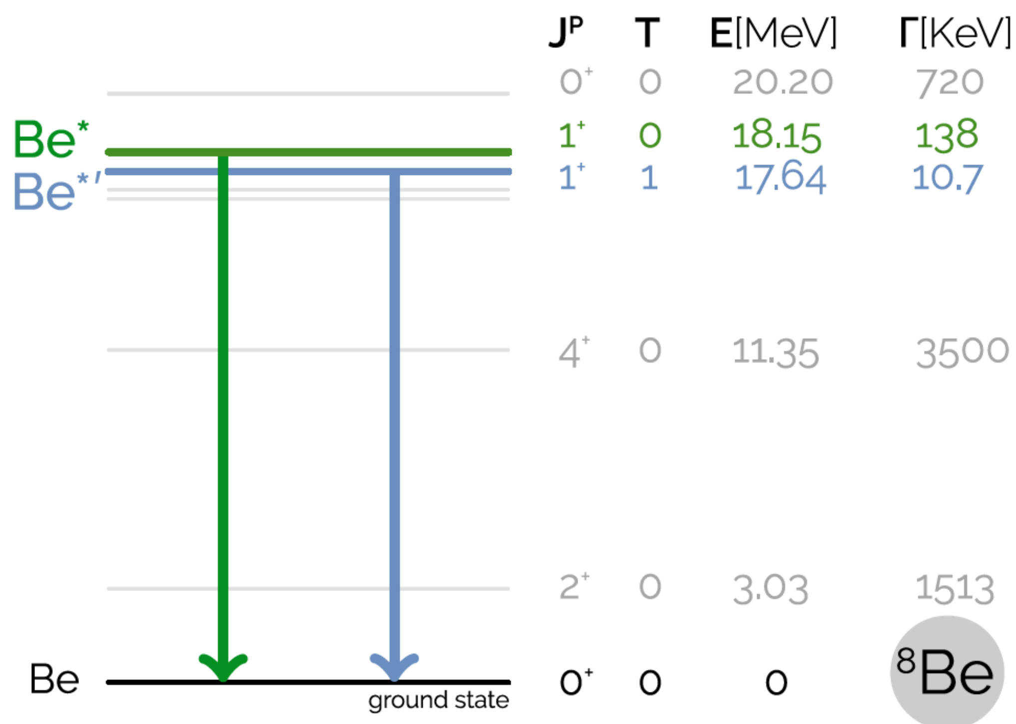
(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.

BERYLLIUM-8 PRIMER

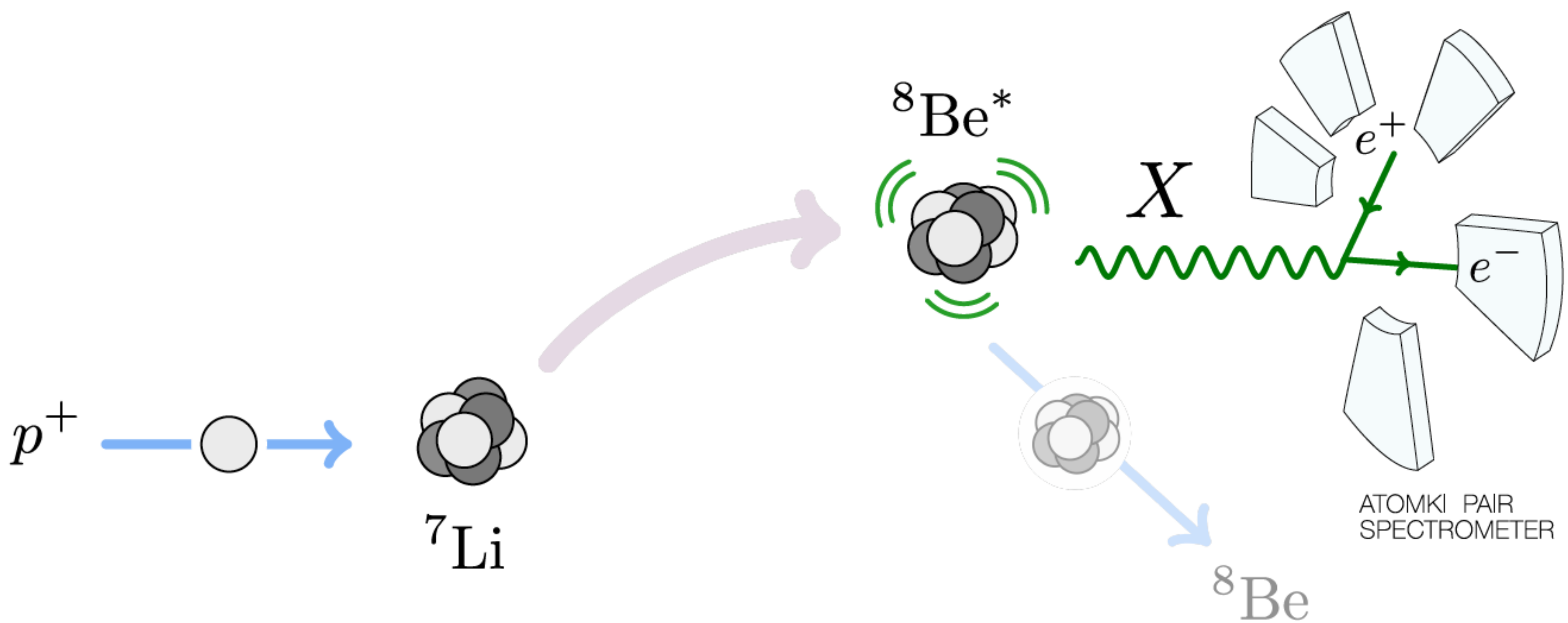
- ^{8}Be: 4 protons + 4 neutrons
- Perhaps best known for its supporting role in $\alpha + \alpha + \alpha \rightarrow {}^{12}$C
- The entire ^{8}Be spectrum is well studied



Tilley et al. (2004); National Nuclear Data Center, http://www.nndc.bnl.gov/nudat2/

THE ^{8}BE EXPERIMENT AT MTA ATOMKI

- 1 μA proton beam hits thin ^{7}Li targets
- E_p = 1.025 MeV → 8Be* resonance, which then decays:
  - Hadronic: B(p ^{7}Li) ≈ 100%
  - Electromagnetic: B(^{8}Be γ) ≈ 1.5 x 10^{-5}
  - Internal Pair Conversion: B(^{8}Be e^+ e^-) ≈ 5.5 x 10^{-8}

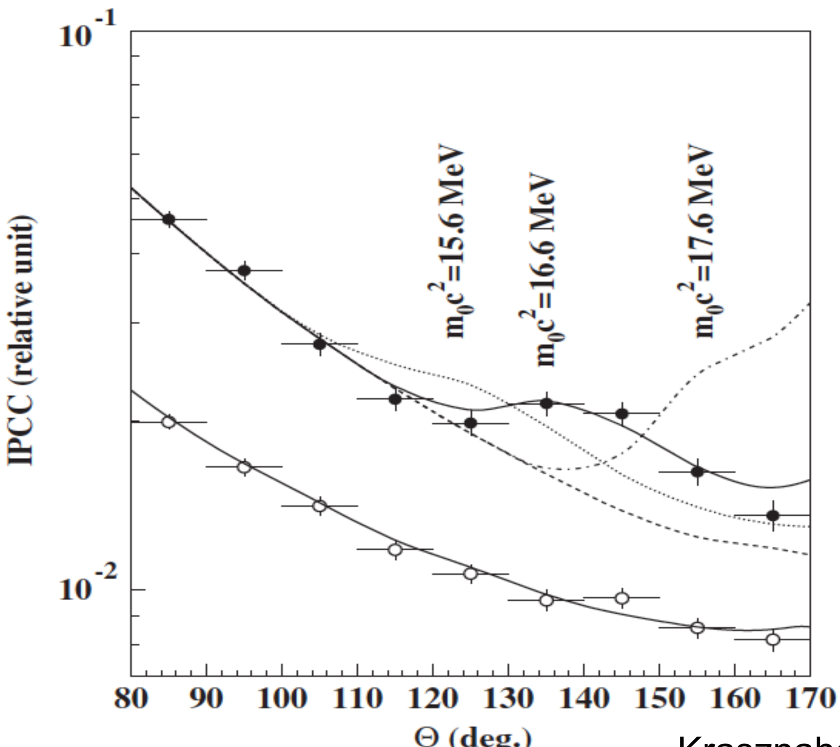


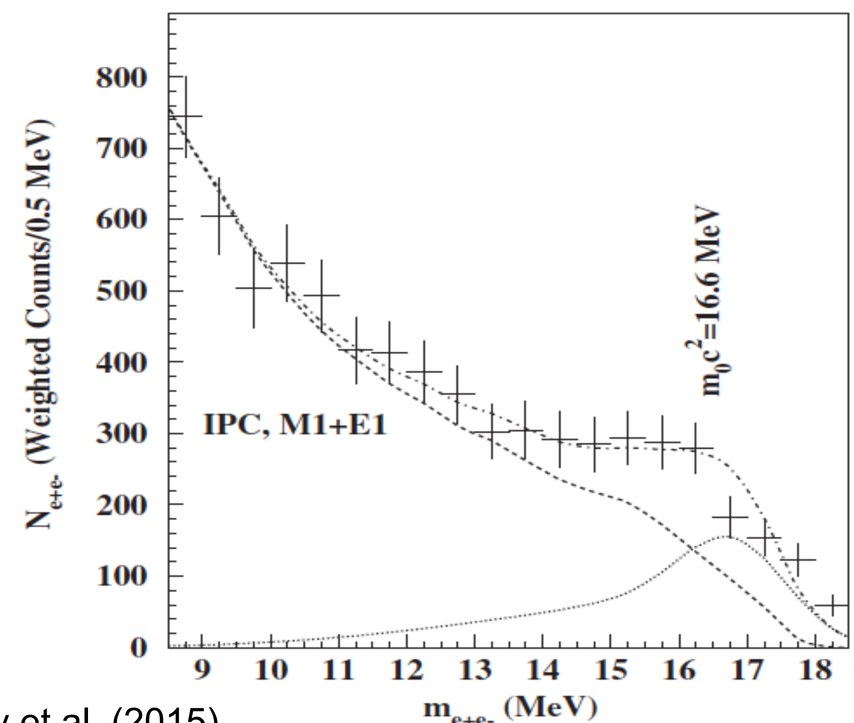
THE ^{8}BE IPC ANOMALY

- Measure the e^+e^- opening angle θ and invariant mass
- Background fluctuation probability: 5.6×10^{-12} (6.8σ)
- Best fit to new particle: χ^2/dof = 1.07

  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)

SIGNAL CHARACTERISTICS

- The excess is not a "last bin" effect: bump, not smooth excess
- In scan through p resonance energy, excess rises and falls
- Peaks in opening angle θ and invariant mass correspond; required for particle interpretation, not for all backgrounds
- LiF_2, LiO_2 target "impurities" understood, do not lead to such energetic photon and IPC events
- Comparable excess not seen for 17.64 MeV state; explainable by phase-space suppression for 17 MeV state
- Completely different from previous claims of excesses: different experiment, different collaboration, different claimed mass, extraordinary statistics, and a bump, not smooth excess

OPEN QUESTIONS

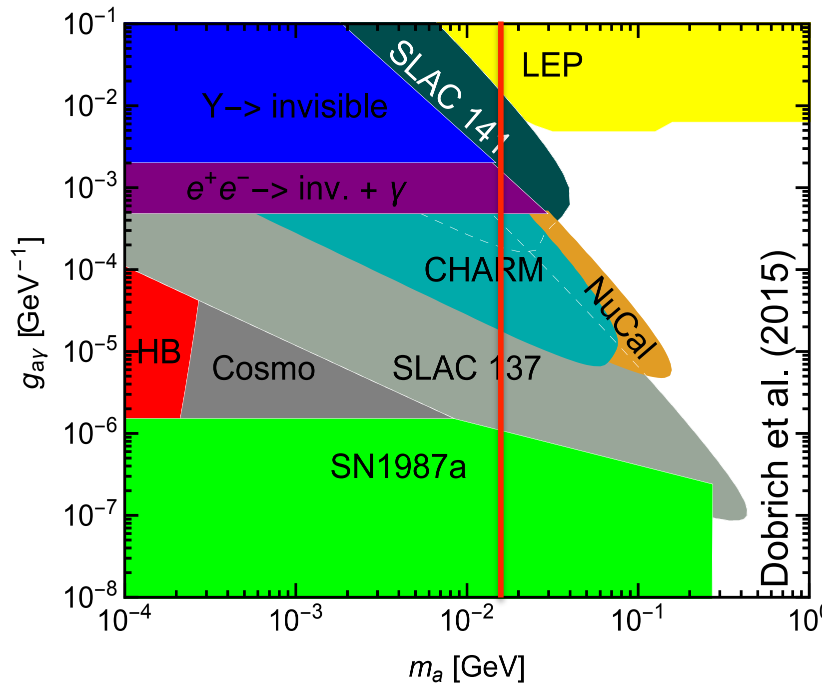
- What kinds of neutral bosons are possible?
- What are the required parton-level couplings?
- Is this consistent with all other experiments?
- Is there a UV-complete model that predicts this?
- What other experiments can check this?

SPIN 0 NEUTRAL BOSONS

SCALARS "DARK HIGGS"

- J^P Assignments: $1^+ \rightarrow 0^+ \, 0^+$
- L Conservation:
  L = 1
- Parity Conservation:
  $P = (-1)^L = 1$
- Forbidden in parity-conserving theories

PSEUDOSCALARS "AXION-LIKE PARTICLES"



- Forbidden for large range of aγγ couplings

VECTORS: 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

$$\frac{1}{\Lambda}\epsilon^{\mu\nu\alpha\beta}\left(\partial_\mu {}^8\mathrm{Be}^*_\nu - \partial_\nu {}^8\mathrm{Be}^*_\mu\right) X_{\alpha\beta} {}^8\mathrm{Be}$$

- The width is

$$\Gamma({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X) = \frac{(e/2)^2(\varepsilon_p+\varepsilon_n)^2}{3\pi\Lambda^2}\underbrace{|\mathcal{M}|^2}_{\langle {}^8\mathrm{Be}|(\bar{p}\gamma_\mu p + \bar{n}\gamma_\mu n)|{}^8\mathrm{Be}^*\rangle}|\vec{p}_X|^3$$

- The nuclear matrix elements and Λ cancel in the ratio

$$\frac{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X)}{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma)} = (\varepsilon_p+\varepsilon_n)^2\frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.6\times10^{-6}$$

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)

THE REQUIRED PARTON-LEVEL COUPLINGS

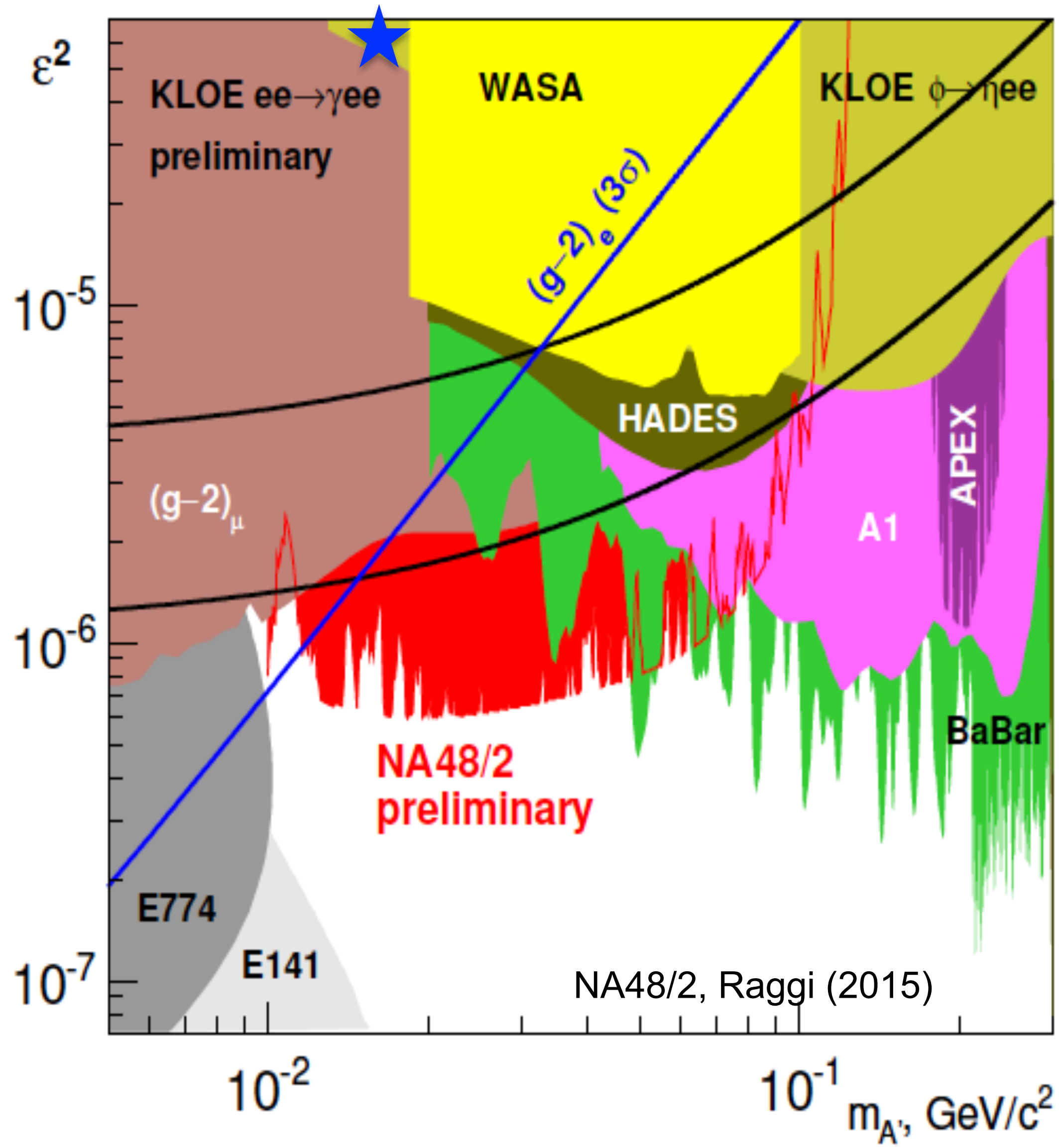
- To get the right signal strength:

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

- To decay within 1 cm:

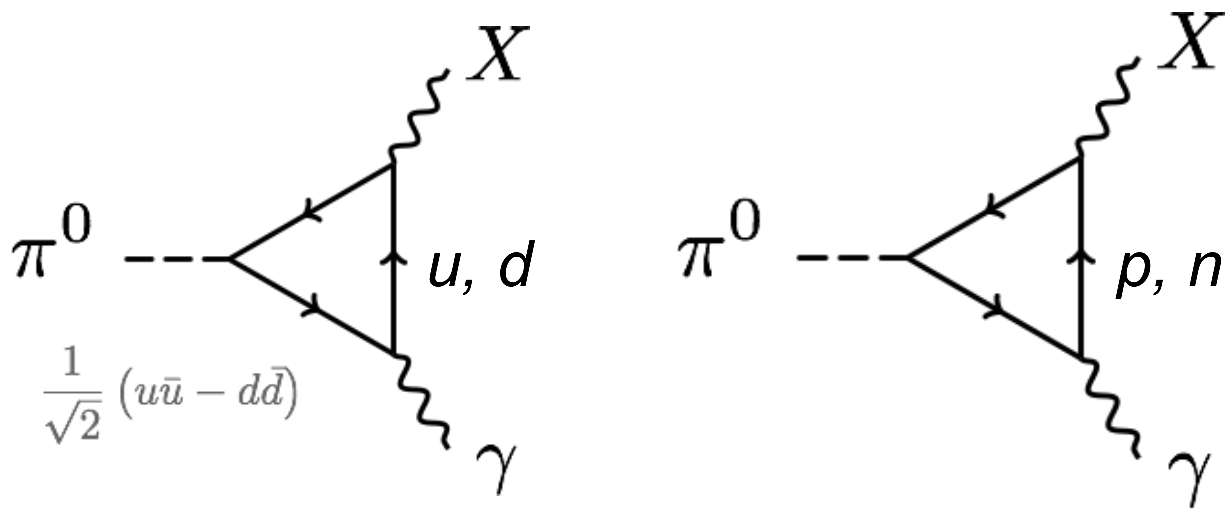
$$|\varepsilon_e| \gtrsim 1.3 \times 10^{-5}$$

- This cannot be a dark photon



PROTOPHOBIA

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

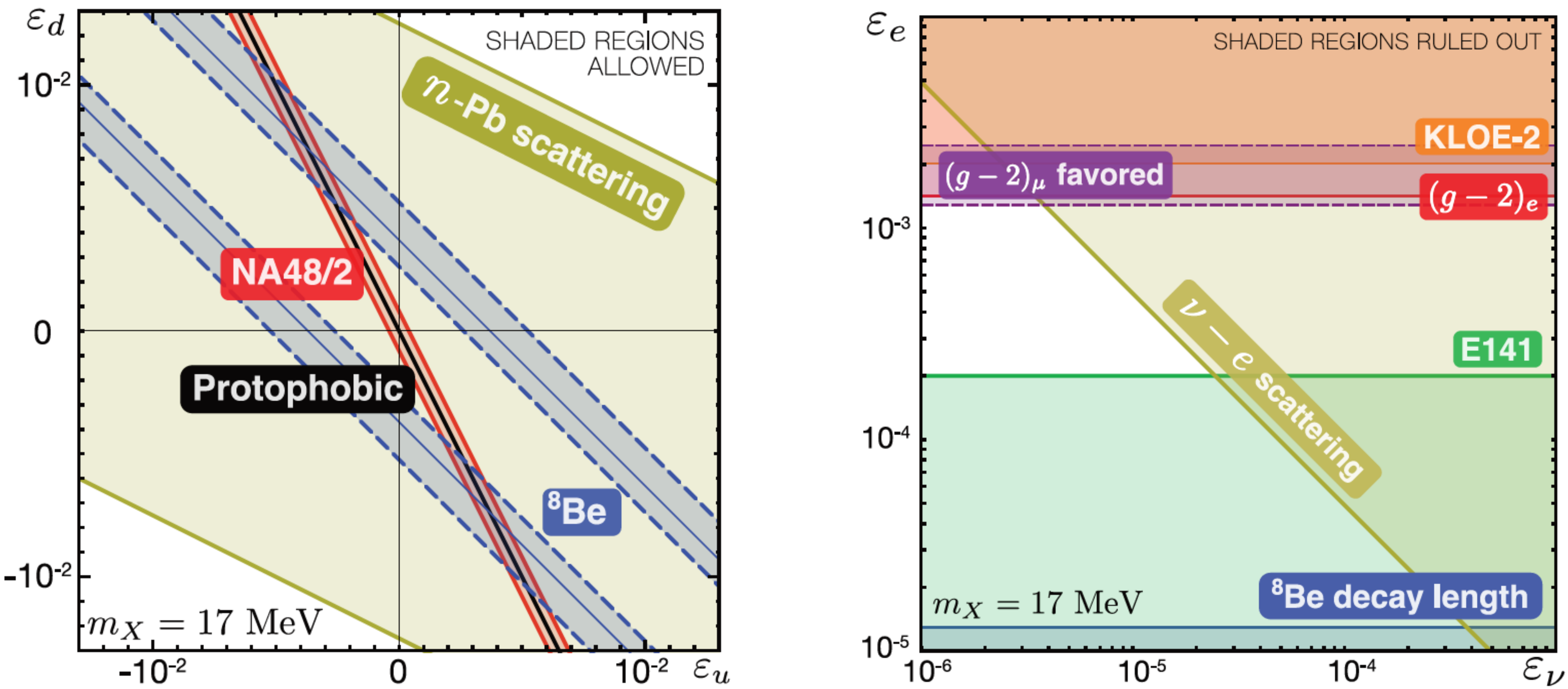


- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

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

COUPLING CONSTRAINTS

- Consider all constraints and also the region favored by $(g-2)\mu$
- In the end, require ε_u, $\varepsilon_d \sim$ few 10^{-3} with ~10% cancelation 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)

AN ANOMALY-FREE, UV-COMPLETE MODEL

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

- 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 mixes with the photon:

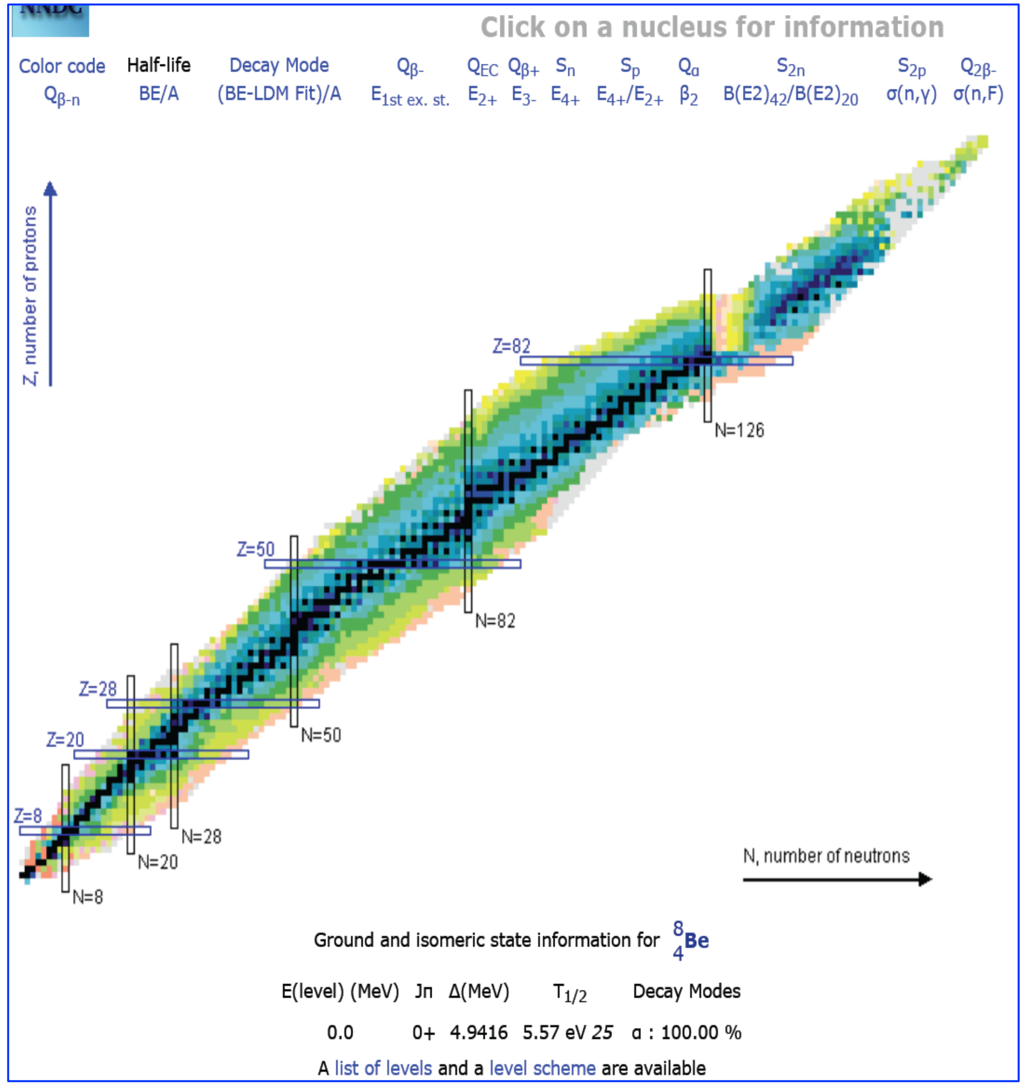
$$\varepsilon_u : \quad \frac{2}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad \varepsilon_\nu : \quad -\varepsilon_{B-L}$$

$$\varepsilon_d : \quad -\frac{1}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad \varepsilon_e : \quad -\varepsilon - \varepsilon_{B-L} \ ,$$

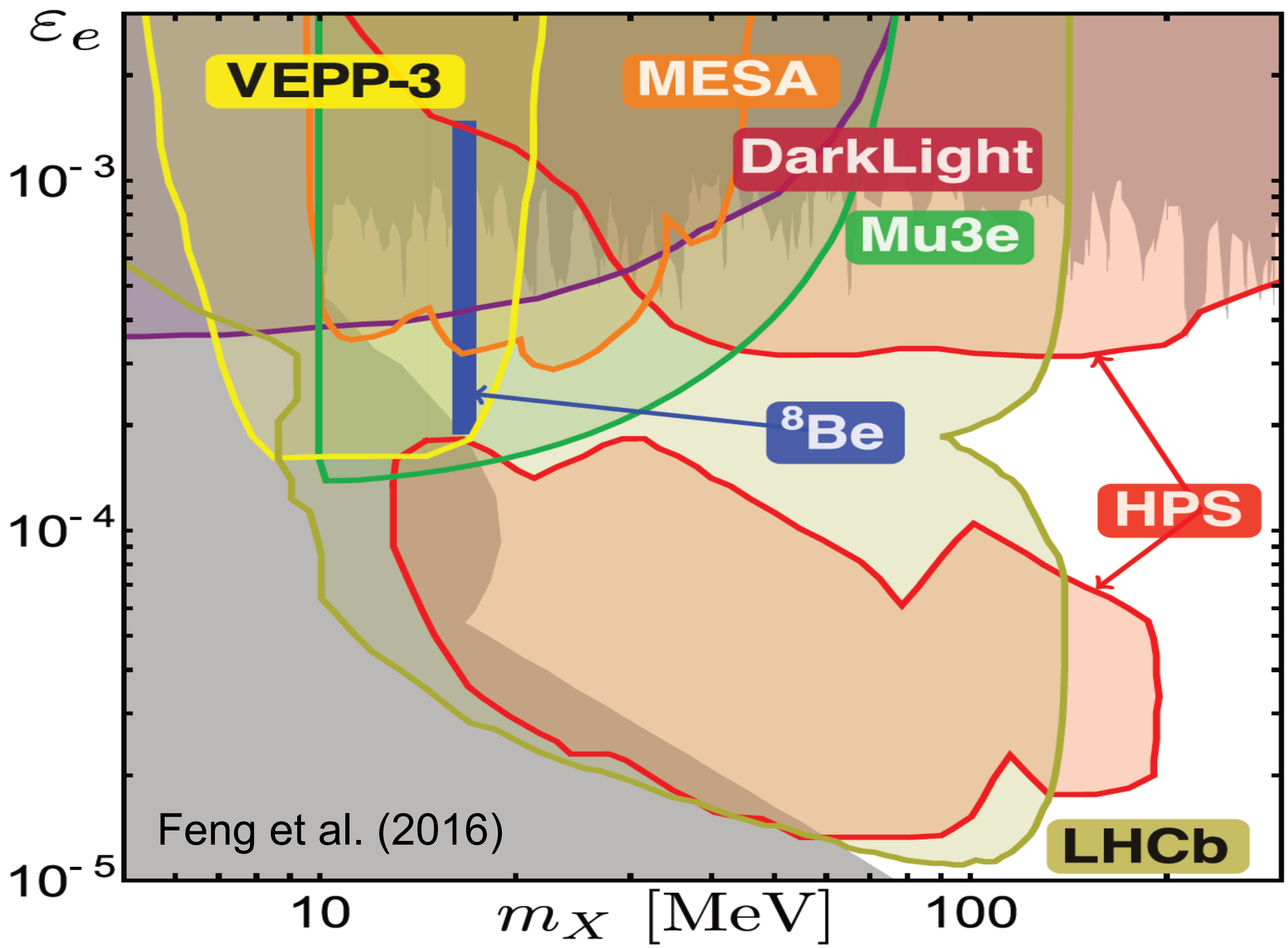
- For $\varepsilon + \varepsilon_{B-L} \approx 0$, we get both $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e << \varepsilon_{u,d}$!
- The neutrino X-charge can be suppressed in a number of ways, e.g., by mixing with X-charged sterile neutrinos

FUTURE TESTS: NUCLEAR PHYSICS

- The most direct test would be to look for other nuclear IPC transitions
- The ^{8}Be 18.15 and 17.64 transitions are the largest known with discrete gamma rays
- Would likely need to re-examine the ^{8}Be 18.15 transition



FUTURE TESTS: "DARK PHOTON" EXPTS



- Also KLOE-2, SHiP, SeaQuest, PADME, …

CONCLUSIONS

- The 6.8σ ^{8}Be IPC signal currently has no known experimental or nuclear physics explanations
- Particle interpretation yields a χ^2/dof = 1.07 best fit with

  m = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV

  $B(^8Be^* \rightarrow {}^8Be\ X) / B(^8Be^* \rightarrow {}^8Be\ \gamma) = 5.6 \times 10^{-6}$
- The data are consistent with a protophobic gauge boson that mediates a 5th force with range 12 fm, milli-charged couplings to quarks and leptons, and explains $(g-2)_\mu$
- A UV-complete, anomaly-free model: B-L gauge boson that kinetically mixes with the photon, with active ν mixing with X-charged sterile neutrinos
- Many upcoming experimental tests