FIFTH FORCES

Symmetry Tests in Nuclei and Atoms
KITP, Santa Barbara

Jonathan Feng, UC Irvine

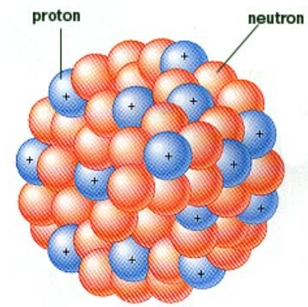
19 September 2016

FUNDAMENTAL FORCES

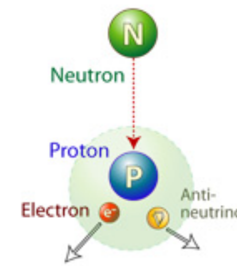
- We know of four fundamental forces

Gravity

Electromagnetism



Strong



Weak

- A fifth one would be a big deal

- Forces can be mediated by a host of particles: pions, Higgs boson, dilaton, towers of KK gravitons,...

- In this talk, "5th force" refers to a force mediated by a new spin-1 gauge boson

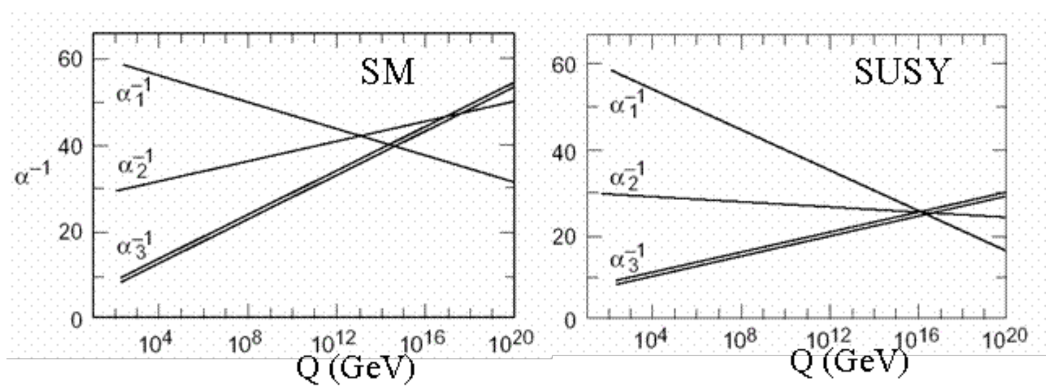
5^{TH} FORCE MOTIVATION: UNIFICATION

- Quantum numbers: e.g., SU(3) x SU(2) x U(1) → SO(10)

ψ	SU (3)c	SU (2)L	Y
q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	−1/3
l_L	1	2	−1/2
e_R	1	1	−1
V_R	1	1	0

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u_r^c : \{+--\ ++\}$	$d_r^c : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u_b^c : \{-+-\ ++\}$	$d_b^c : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u_g^c : \{--+\ ++\}$	$d_g^c : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

- Unification of couplings: at a perturbative value and at a scale below M_{planck} but high enough to satisfy proton decay



- Any GUT group SO(10) or bigger has rank > 4, implies 5^{th} force: $U(1)_{B\text{-}L}$, Z' gauge bosons, etc.

5^{TH} FORCE MOTIVATION: DARK MATTER

- All evidence for dark matter is gravitational. Perhaps its in a hidden sector, composed of particles with no SM gauge interactions (electromagnetic, weak, strong)

- This hidden sector 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); …

DM PORTALS

- Astrophysics is sensitive to DM-DM interactions, but particle and nuclear physics are determined by DM-SM interactions

- There are many ways the hidden particles could couple to us. Use effective operators as 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

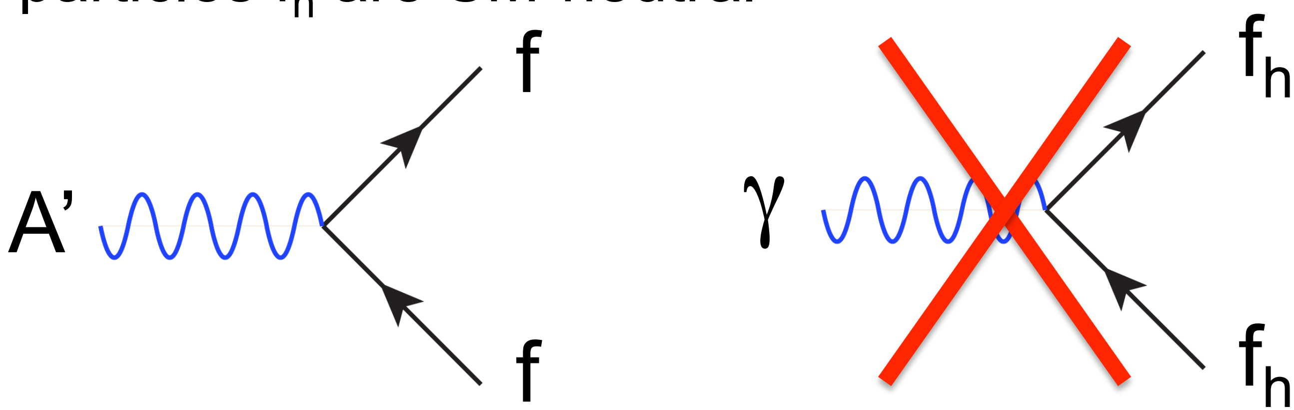
VECTOR PORTAL

Holdom (1986)

- The operator $\epsilon F_{\mu\nu} F_h^{\mu\nu}$ leads to kinetic mixing between the SM photon and the massive hidden photon

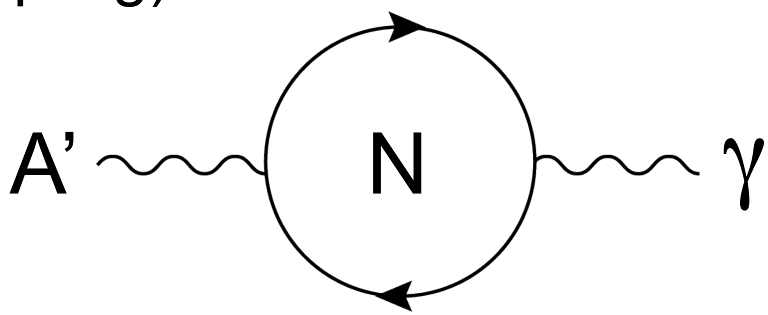
- Diagonalizing, one finds that the physical states are the massless SM photon γ and a massive "dark photon" A'

- SM particles f have hidden charge proportional to $\varepsilon e Q_f$, but hidden particles f_h are SM-neutral



DARK FORCE

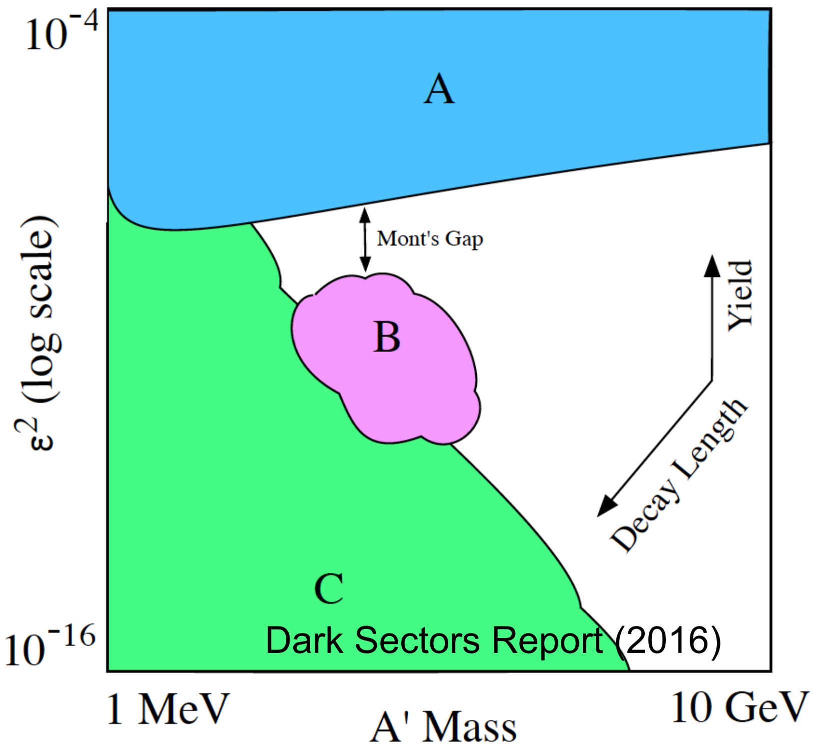
- $\varepsilon \sim 10^{-3}$ N from 1-loop effects, where N is the number of particles in the loop, even for arbitrarily heavy particles in the loop (non-decoupling)

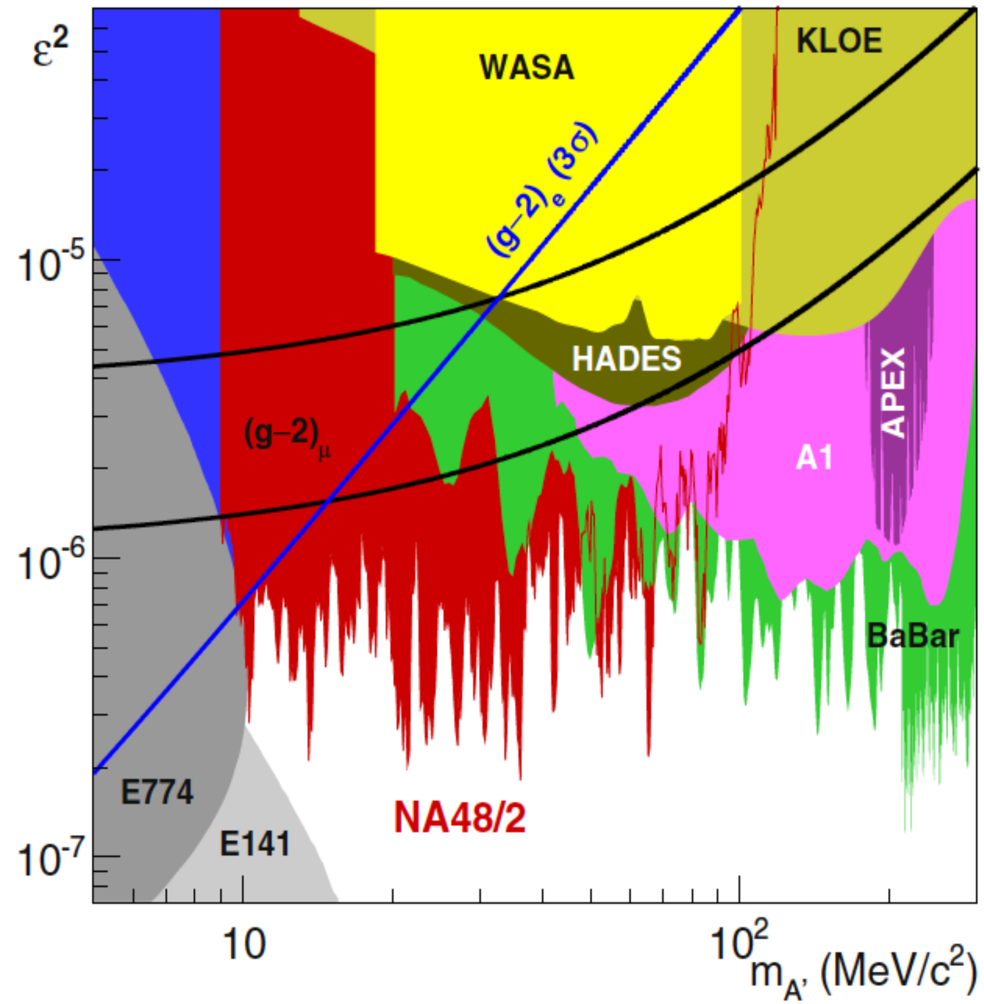


- Dark matter distributions (halo profiles) may indicate strong DM self-interactions with a force carrier of mass ~ 1-100 MeV
- This motivates searches for a "dark force" mediated by dark photons, a 5th force parameterized by $(m_{A'}, \varepsilon)$, with, perhaps, a region of special interest with $m_{A'} \sim$ 1-100 MeV and $\varepsilon \sim 10^{-3}$

CURRENT CONSTRAINTS

This has motivated a world-wide program to search for A'





A: Bump hunts

B: Displaced vertices (short decays)

C: Beam dumps (long decays)

FIFTH FORCE IN NUCLEAR TRANSITIONS

- Nuclear transitions are natural places to look for MeV-scale 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 5th force gauge bosons?

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

THE EXPERIMENTAL RESULT

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

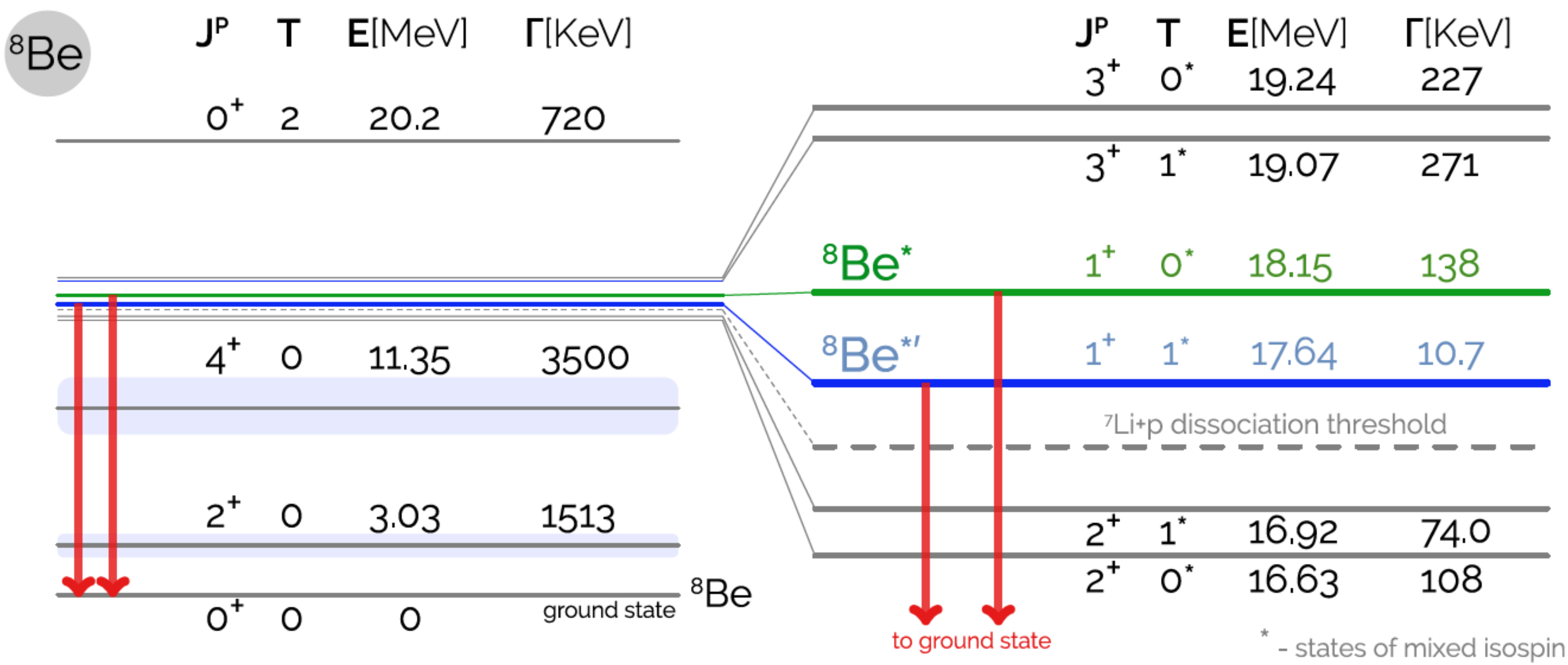
A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(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 $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})\ \text{MeV}/c^2$ and $J^\pi = 1^+$ was created.

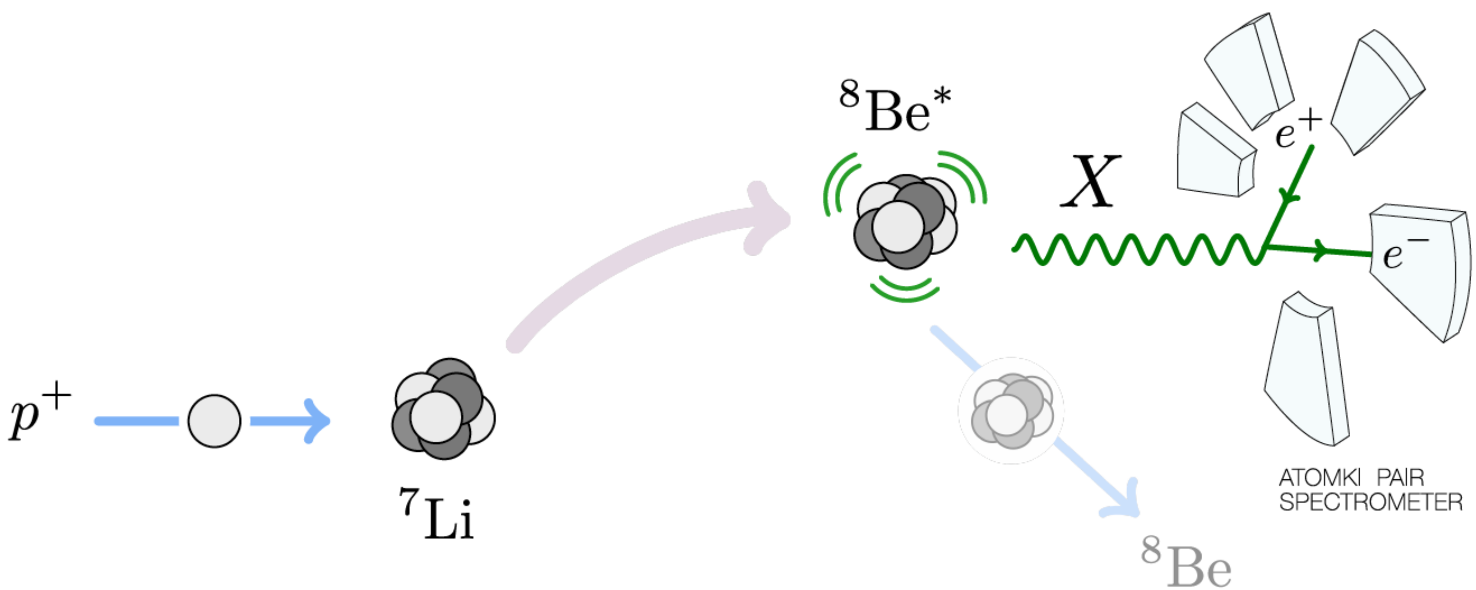
^{8}BE SPECTRUM



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 = 1.03 MeV → ^{8}Be* 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}

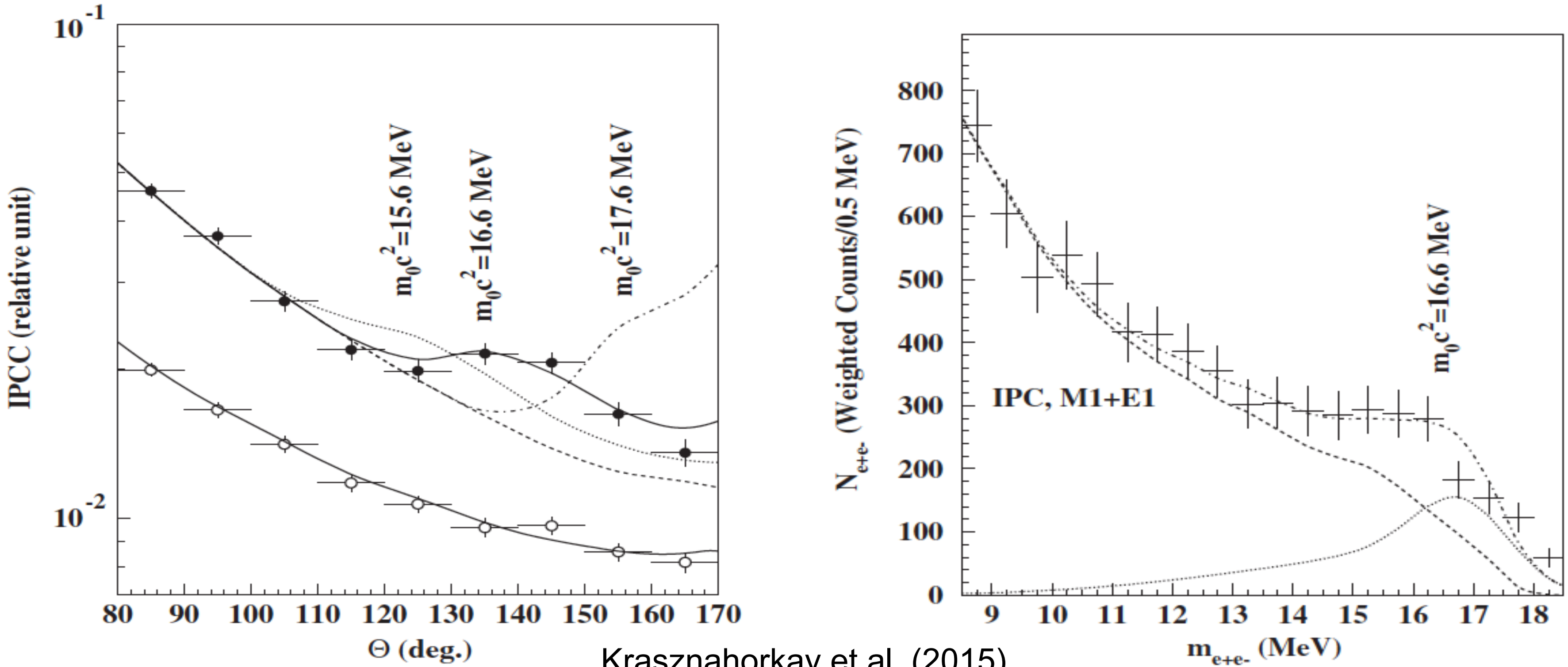


THE ^{8}BE IPC ANOMALY

- 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

$m = 16.7 \pm 0.35$ (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)

SIGNAL CHARACTERISTICS

- The excess consists of hundreds of events in each bin; this is not a statistical fluctuation, clearly all possible explanations (nuclear physics, experimental setup, particle physics) should be explored
- The excess is not a “last bin” effect: bump, not smooth excess
- In scan through p resonance energy, excess rises and falls
- Excess is seen in the expected event subsamples: events with symmetric e^- and e^+ energies, events passing the 18 MeV gate
- Peaks in opening angle θ and invariant mass correspond; required for particle interpretation, not for all backgrounds
- Comparable excess not seen for 17.64 MeV state; explainable by phase-space suppression for > 17 MeV particle

INTERESTING QUESTIONS

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

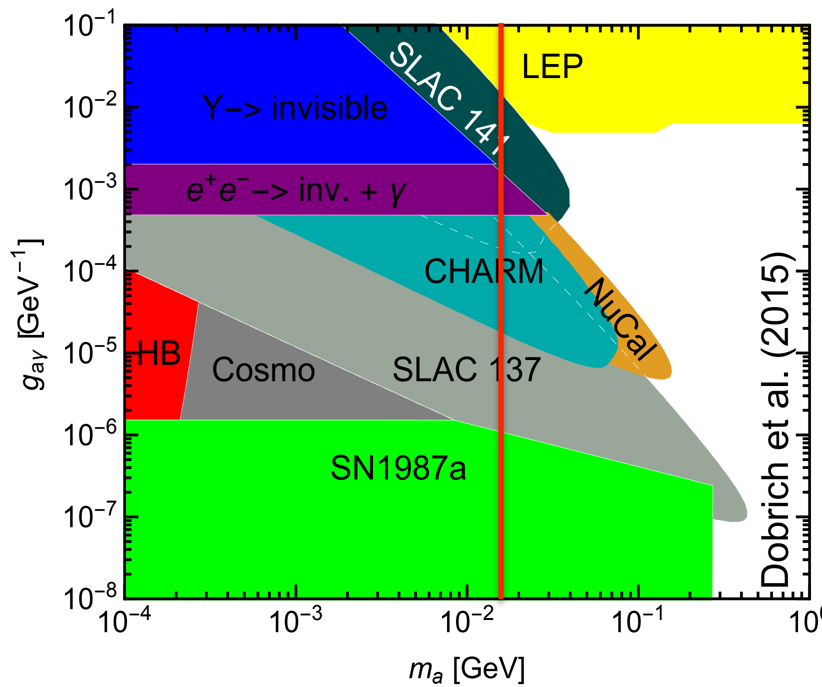
Feng, Fornal, Galon Gardner, Smolinsky, Tait, Tanedo (2016) Gu, He (2016);
Chen, Liang, Qiao (2016); Jia, Li (2016); Kitahara, Yamamoto (2016); Ellwanger, Moretti (2016)

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"



- Requires re-analysis of constraints on aγγ couplings

Ellwanger, Moretti (2016)

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

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

- Neglecting isospin mixing,

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

- The nuclear matrix elements and Λ cancel in the ratio

$$\frac{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X)}{B({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.6 \times 10^{-6}$$

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)

EFFECT OF ISOSPIN MIXING

- There are strong indications that the ^{8}Be 1$^+$ states are isospin-mixed

$$\Psi_J^a = \alpha_J \Psi_{J,T=0} + \beta_J \Psi_{J,T=1} \qquad \alpha_1 = 0.21(3)$$
$$\Psi_J^b = \beta_J \Psi_{J,T=0} - \alpha_J \Psi_{J,T=1} \qquad \beta_1 = 0.98(1)$$

Barker (1966); Oothoudt, Garvey (1977); Pastore, Wiringa, Pieper, Schiavilla (2014)

- In general, this can have a large effect on the width, changing

$$\frac{\Gamma({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X)}{\Gamma({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

to

$$\frac{\Gamma_X}{\Gamma_\gamma} = |-0.09\,(\varepsilon_p + \varepsilon_n) + 1.09\,(\varepsilon_p - \varepsilon_n)|^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

- In the protophobic limit, however, the effect is O(10%)

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

THE REQUIRED PARTON-LEVEL COUPLINGS

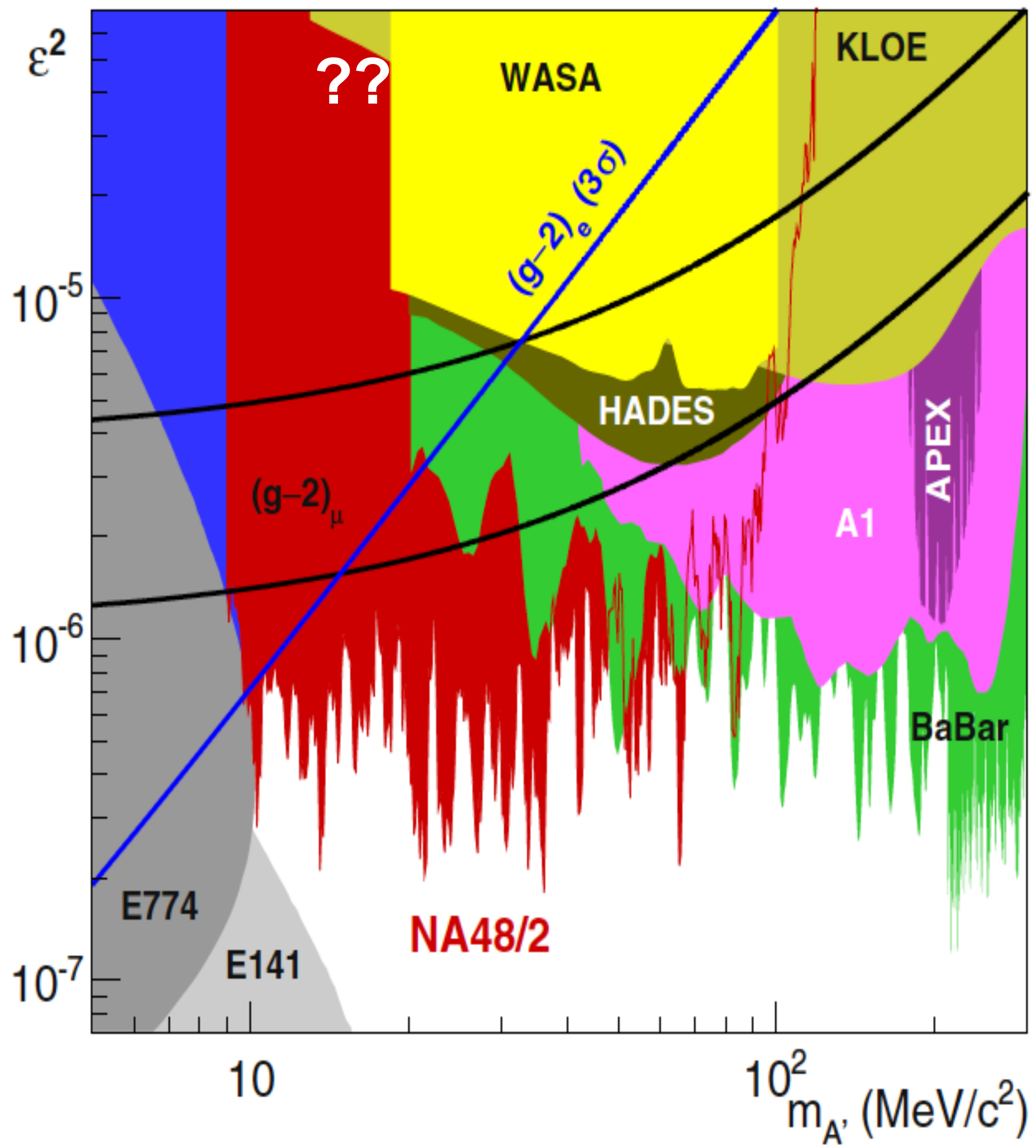
- To get the right signal strength:

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

- The observed width is completely dominated by experimental effects, but the decay must happen within ~ 1 cm:

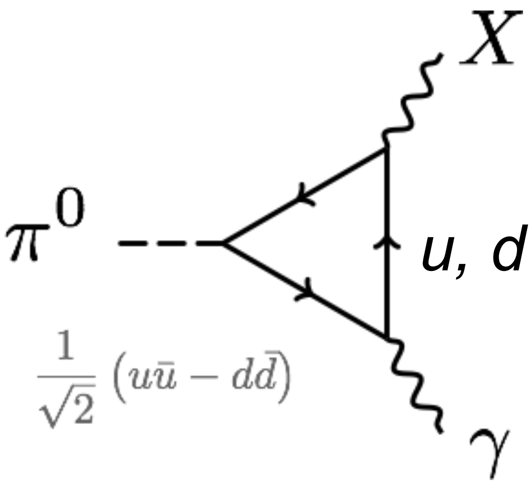
$$|\varepsilon_e| \gtrsim 1.3 \times 10^{-5}$$

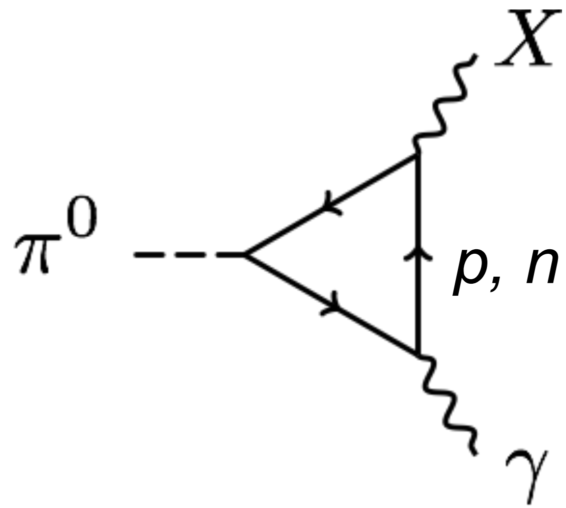
- This cannot be a dark photon



PROTOPHOBIA

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

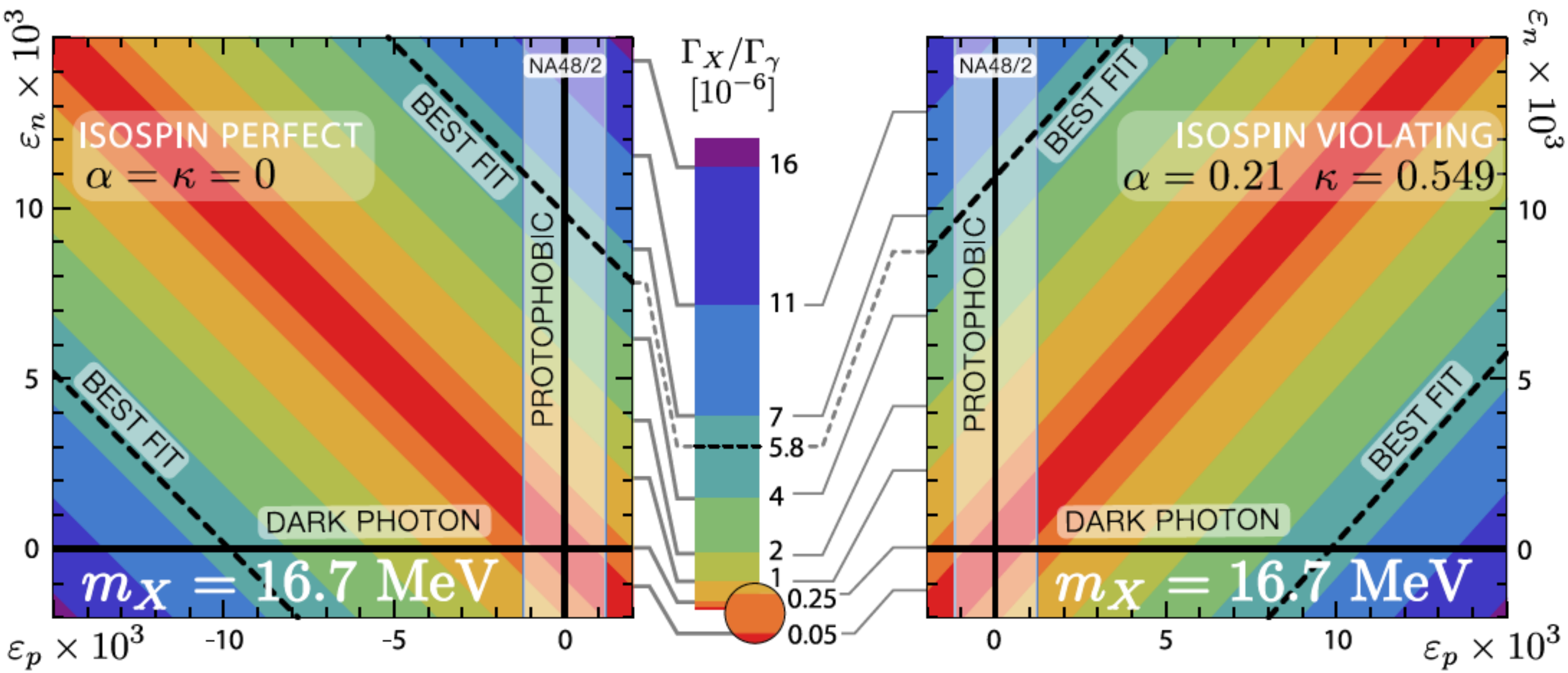




- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

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

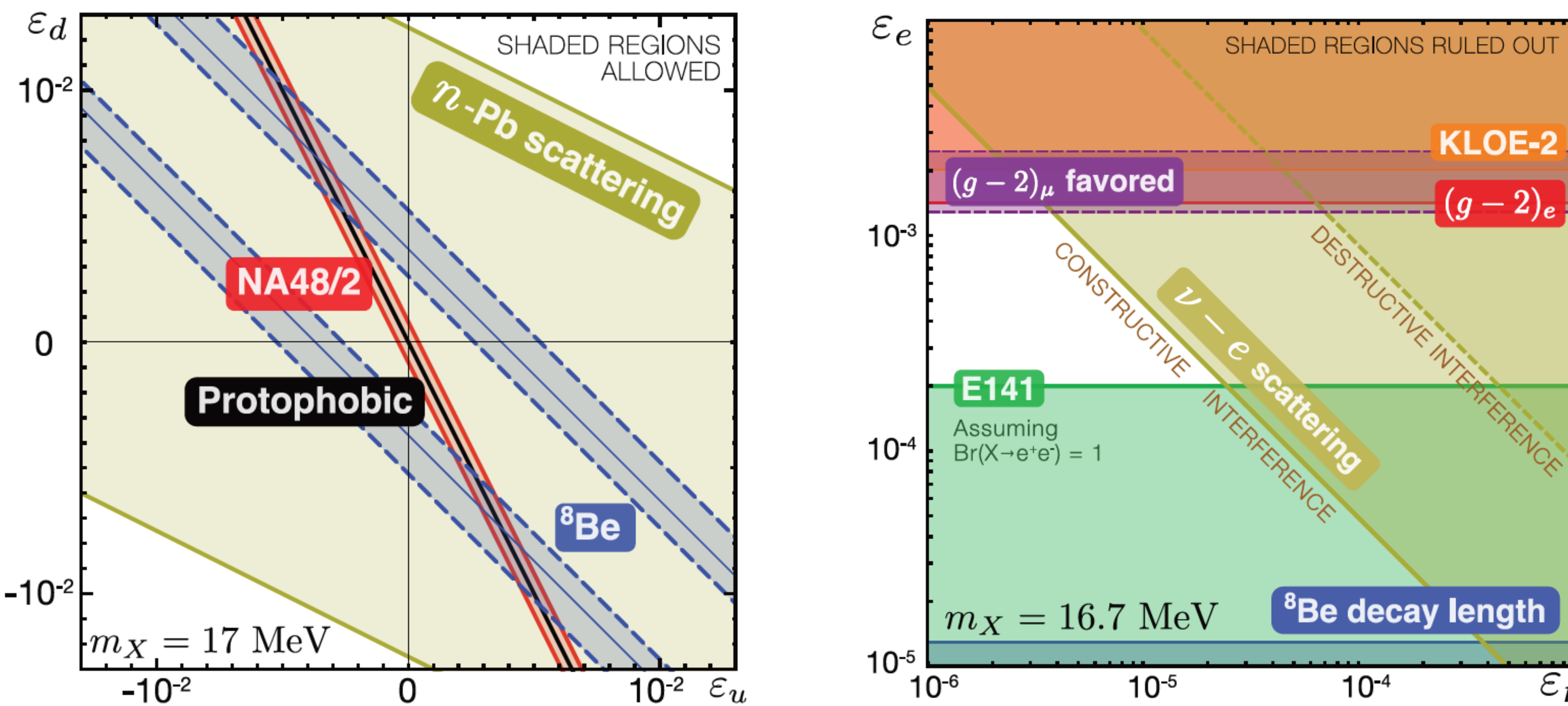
5^{TH} FORCE EXPLANATIONS OF ^{8}BE



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

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 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)

ANOMALY-FREE MODELS

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

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

- Example: 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 kinetically mixes with the photon:

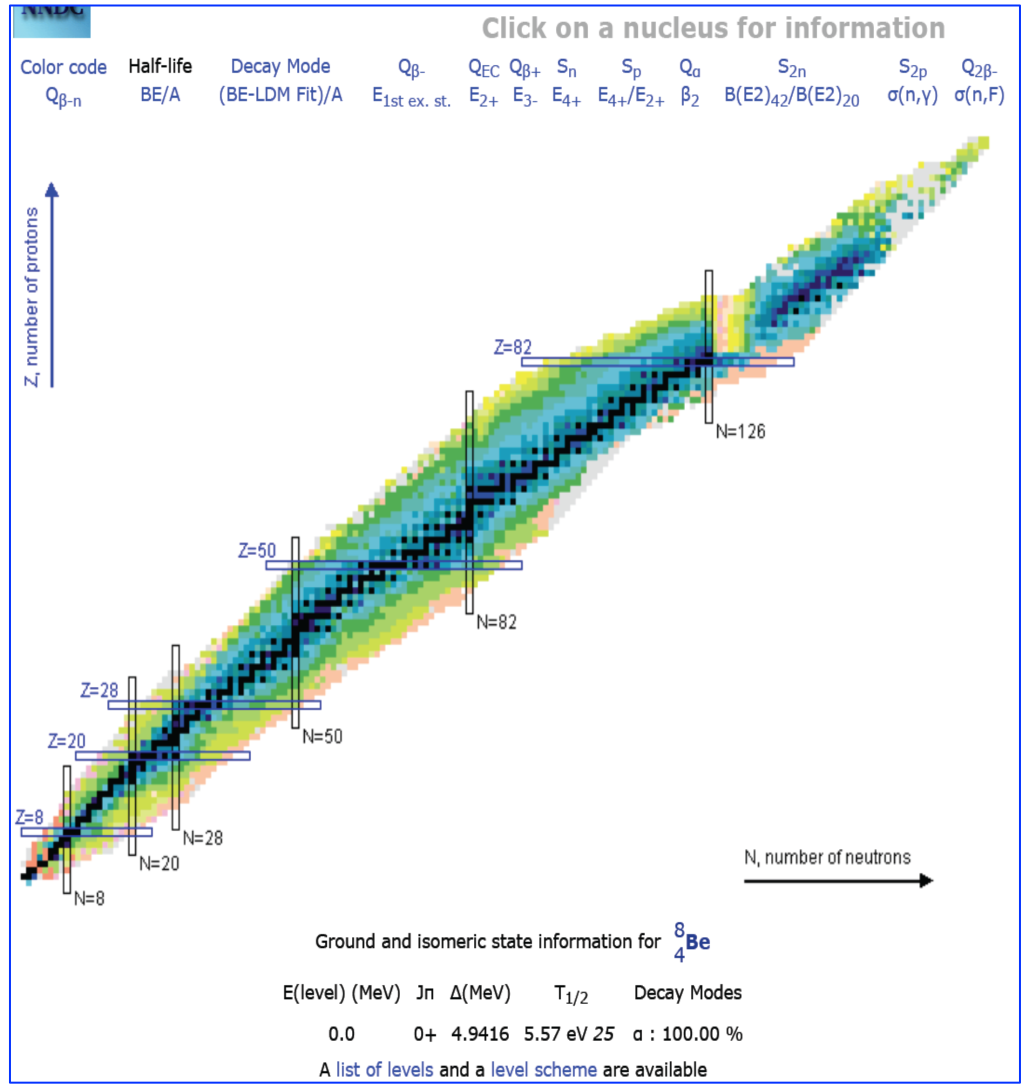
$$\varepsilon_u = \frac{1}{3}\varepsilon_{B-L} + \frac{2}{3}\varepsilon \qquad \varepsilon_\nu = -\varepsilon_{B-L}$$

$$\varepsilon_d = \frac{1}{3}\varepsilon_{B-L} - \frac{1}{3}\varepsilon \qquad \varepsilon_e = -\varepsilon_{B-L} - \varepsilon$$

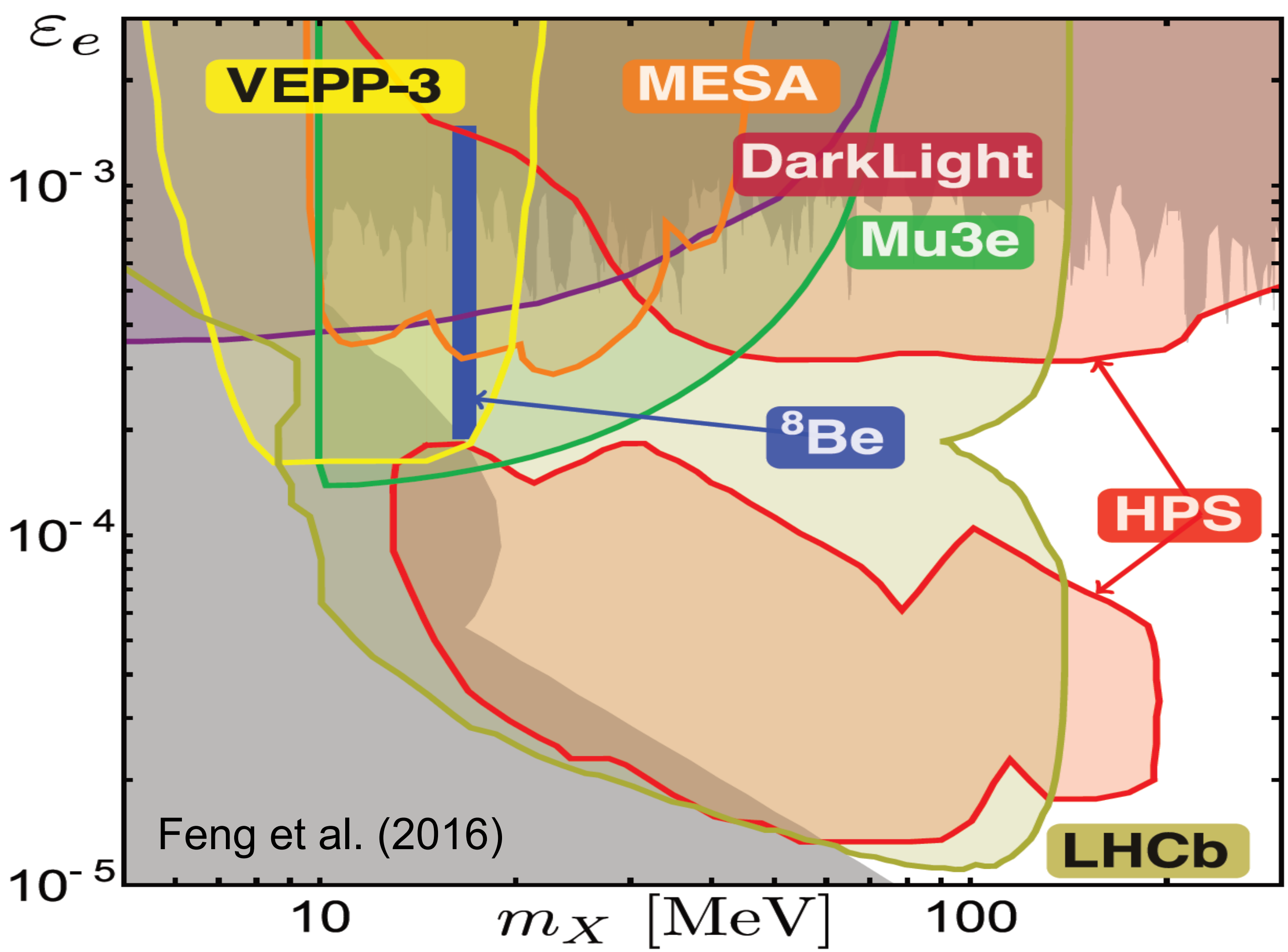
- For $\varepsilon \approx -\varepsilon_{B-L}$, we get B-L-Q charges: $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e \ll \varepsilon_{u,d}$. The neutrino X-charge can be suppressed by mixing with vector-like leptons

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 among the largest known with discrete gamma rays
- Are others possible? E.g., ^{10}B (19.3), ^{10}Be (17.8)



FUTURE TESTS: “DARK PHOTON” EXPTS



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

CONCLUSIONS

- 5^{th} forces are motivated by unification and dark matter and may be probed in "intensity frontier" experiments and nuclear decays
- There is currently a 6.8σ anomaly in ^{8}Be* IPC decays. A particle interpretation yields a χ^2/dof = 1.07 best fit with

  $m = 16.7 \pm 0.35 \text{ (stat)} \pm 0.5 \text{ (sys) MeV}$

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

- The data are consistent with a protophobic gauge boson that mediates a 5^{th} force and explains $(g-2)_\mu$
- In simple SM extensions, the gauge boson is a $U(1)_{B-L}$ or $U(1)_B$ gauge boson that kinetically mixes with the photon
- Many opportunities for near future experimental tests