1604.07411, 1608.03591

17 MEV ANOMALY IN BERYLLIUM-8

NEW PHYSICS IN NUCLEAR TRANSITIONS?

Flip Tanedo

UC Riverside Particle Theory

with

Jonathan Feng, Bart Fornal, Susan Gardner,
Iftah Galon, Jordan Smolinsky, & Tim Tait

7 Dec. 2016: **IBS-CTPU Focus Workshop**

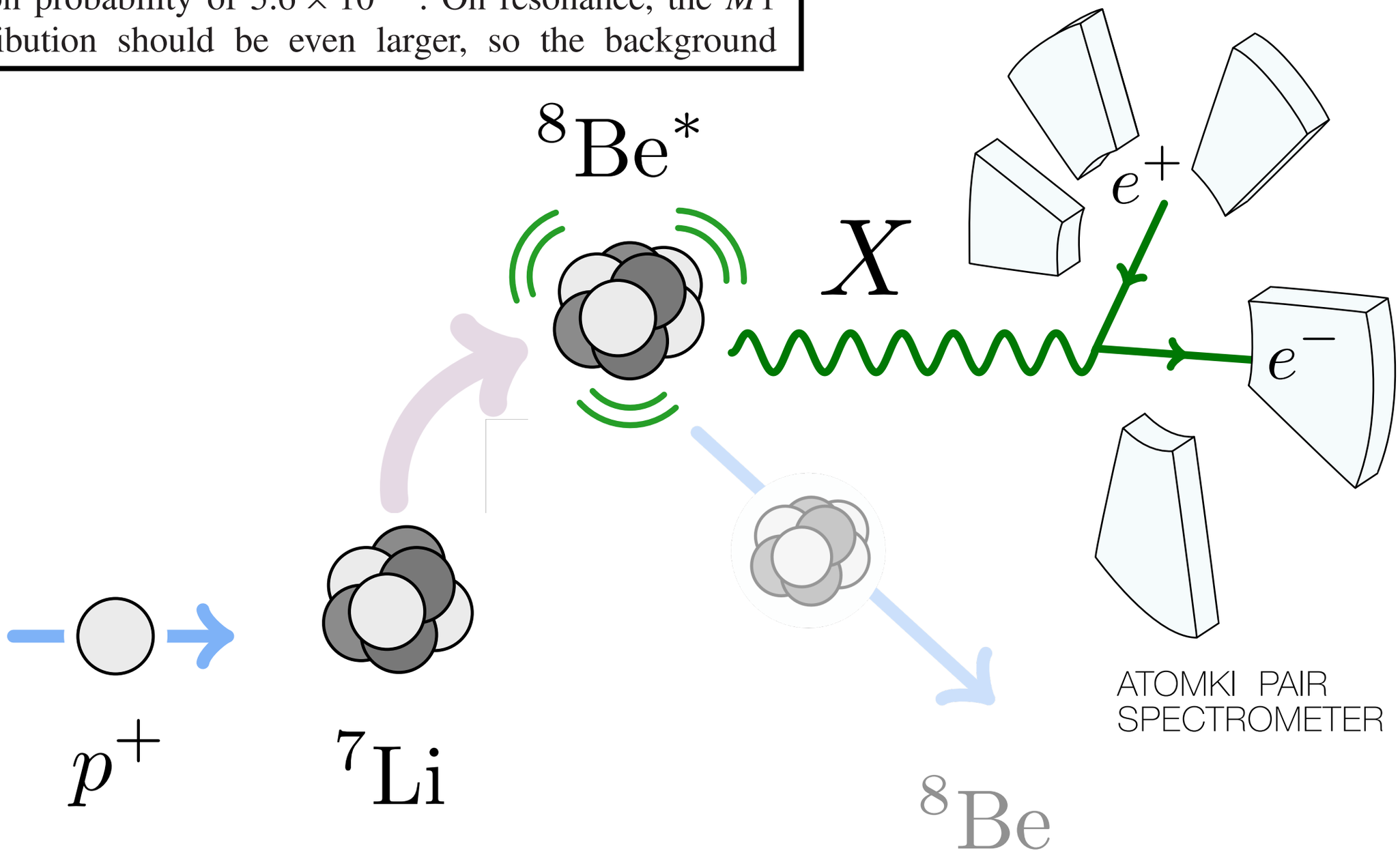
Summary

not have a nuclear physics related origin.

The deviation observed at the bombarding energy of $E_p = 1.10$ MeV and at $\Theta \approx 140°$ has a significance of 6.8 standard deviations, corresponding to a background fluctuation probability of 5.6×10^{-12}. On resonance, the $M1$ contribution should be even larger, so the background

NEW PARTICLE?

$\chi^2/\text{d.o.f.} = 1.07$



UCI IPC 1608.03591

Literature

Observation of Anomalous Internal Pair Creation in 8Be: A Possible Signature of a Light, Neutral Boson
A.J. Krasznahorkay, et al. Phys. Rev. Lett. 116, 042501 (2016); arXiv:1504.01527

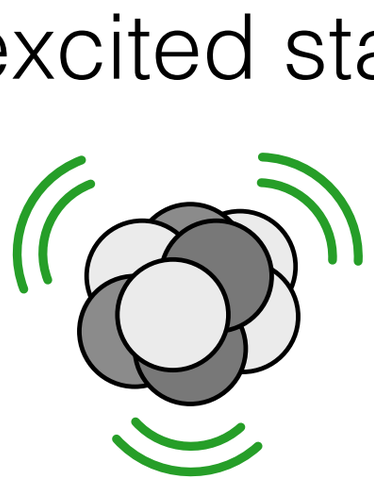
A pair spectrometer for measuring multipolarities of energetic nuclear transitions
J. Gulyás, et al. NIM-A 808, 21 (2016); arXiv:nucl-ex/0311002

Particle Physics Models for the 17 MeV Anomaly in Beryllium Nuclear Decays
arXiv:1608.03591 submitted to PRD

Protophobic Fifth Force Interpretation of the Observed Anomaly in 8Be Nuclear Transitions
arXiv:1604.07411 Phys. Rev. Lett. 117, 071803 (2016)

Science explainer: The Delirium over Beryllium
http://www.particlebites.com/?p=3970

Nuclear Physics vs. New Physics

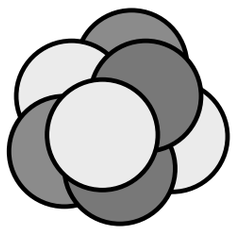


excited state

RESONANT PRODUCTION

Nuclear de-excitation by off-shell photon

DISCRETE TRANSITION



ground state

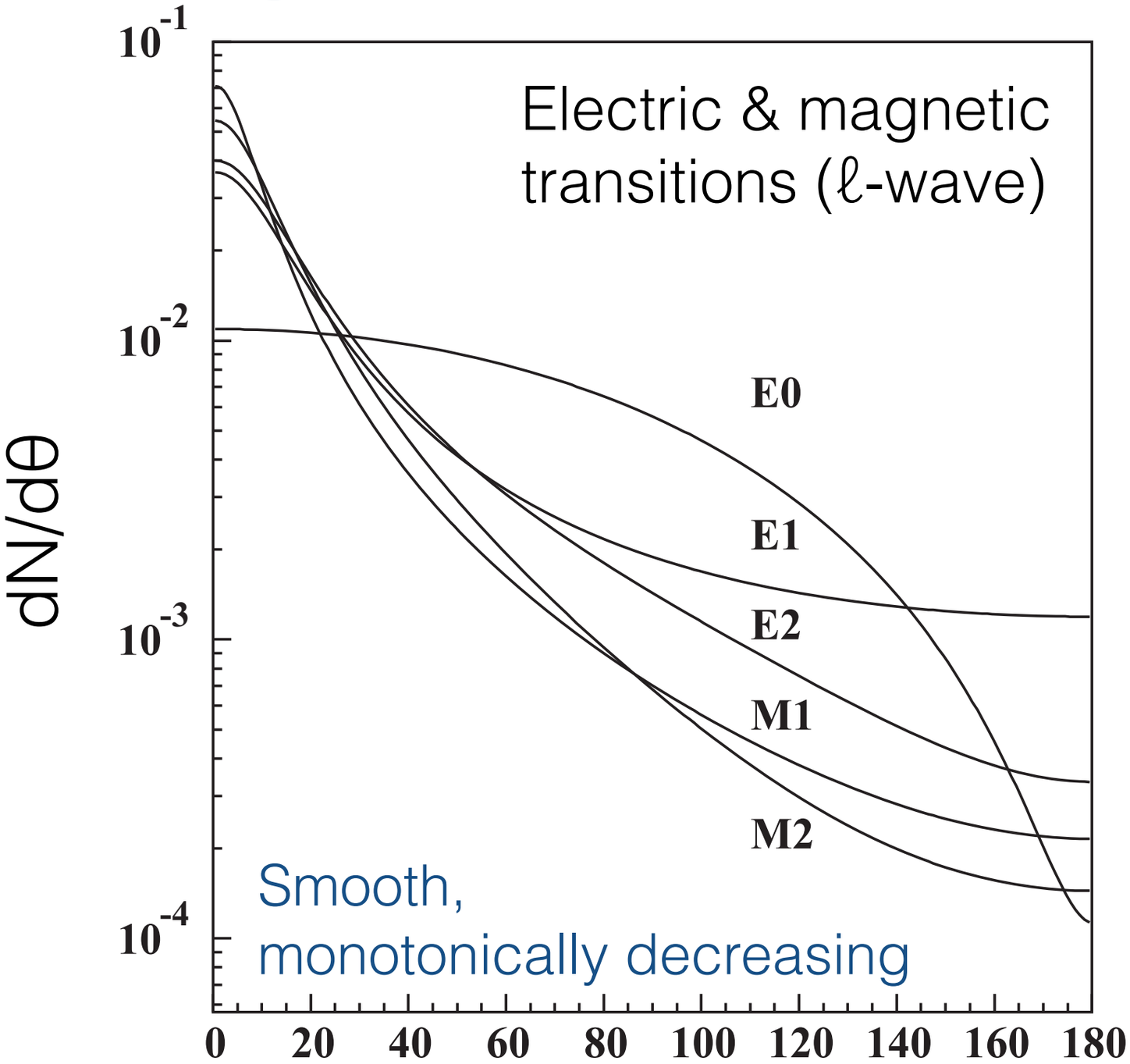
THIS IS GREAT FOR:

weakly coupled, MeV-scale new state

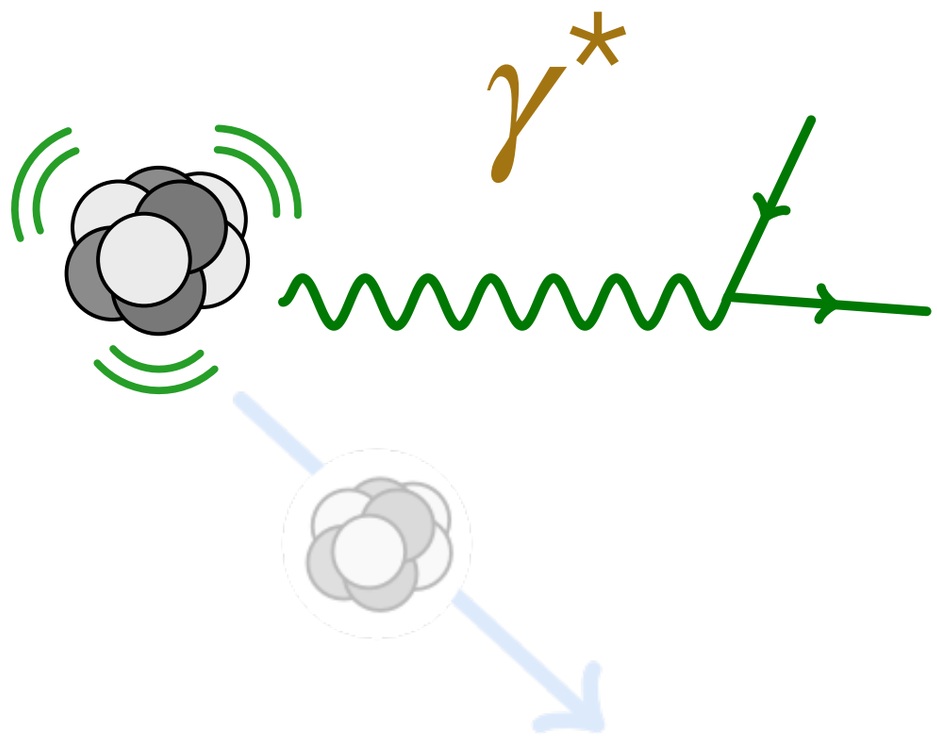
e.g. axions

Treiman & Wilczek, Phys. Lett. B74 ('78), Donnelly et al., Phys. Rev. D18 ('78)

Background: Internal Pair Creation

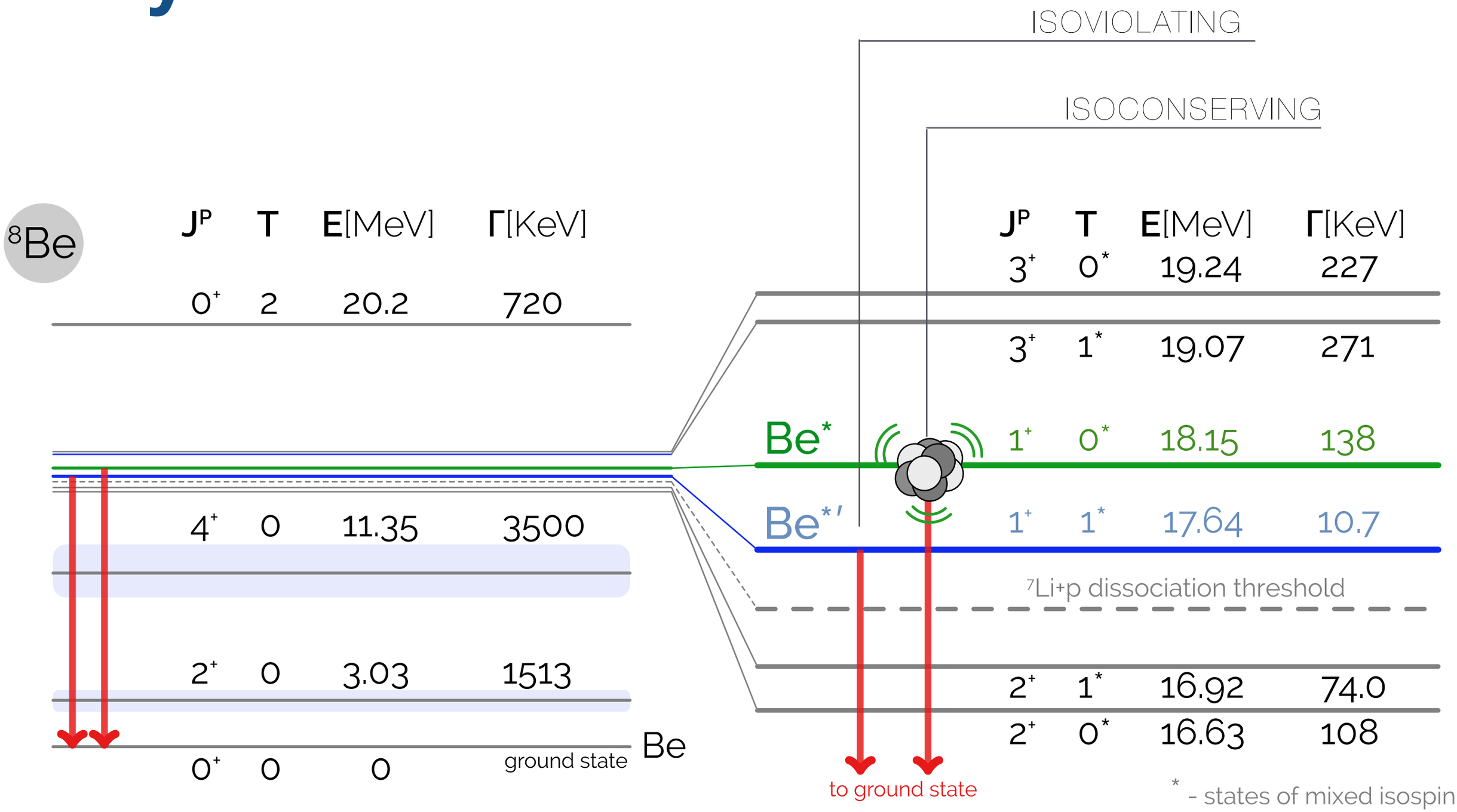


Nuclear de-excitation by off-shell photon



Gulyás et al. NIM 1504.00489

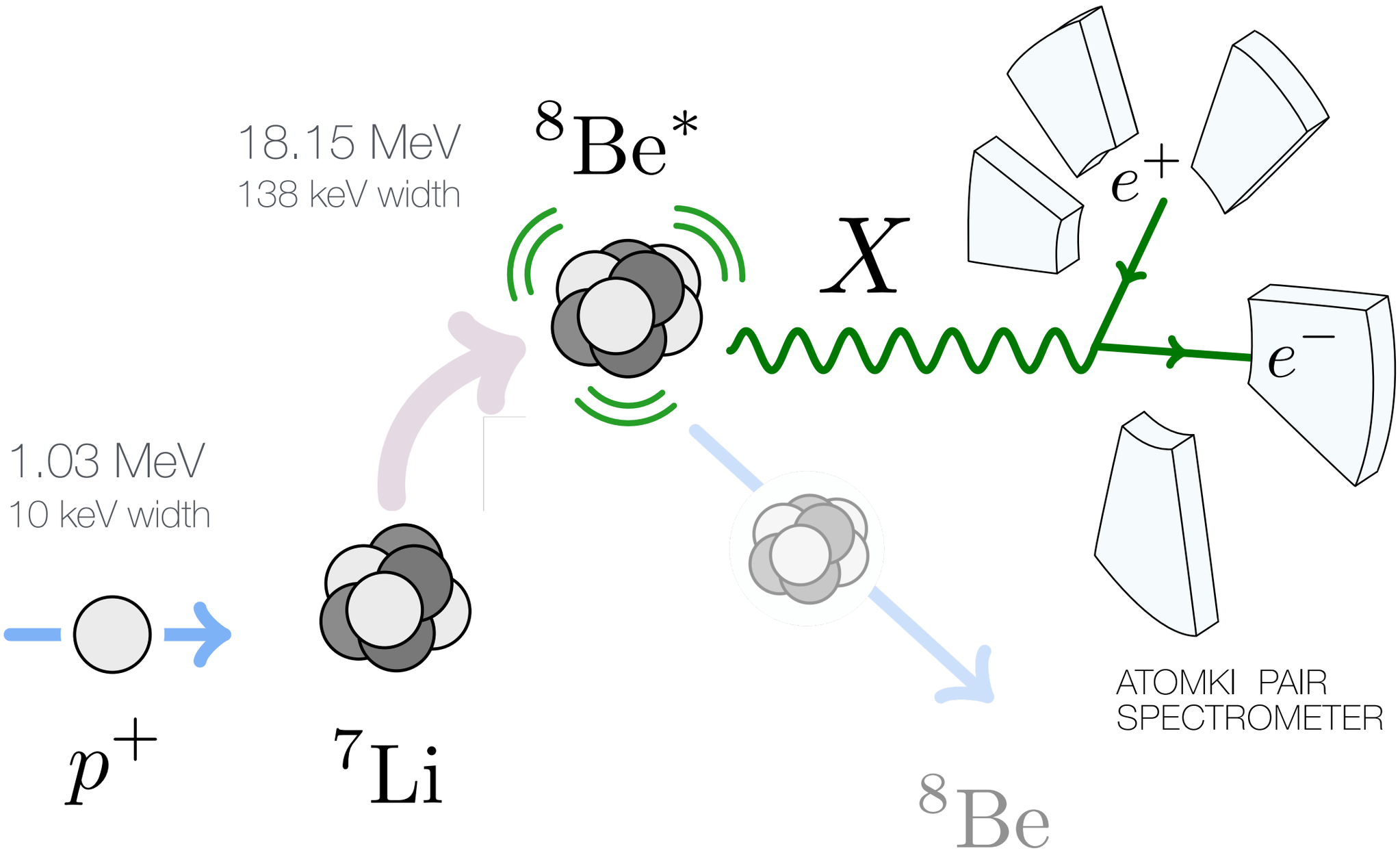
Beryllium-8 Levels



Hint: Isospin conservation is a red herring!

Based on Pastore et al. Phys. Rev. C 90 (2014) [1406.2343]

Experiment & interpretation



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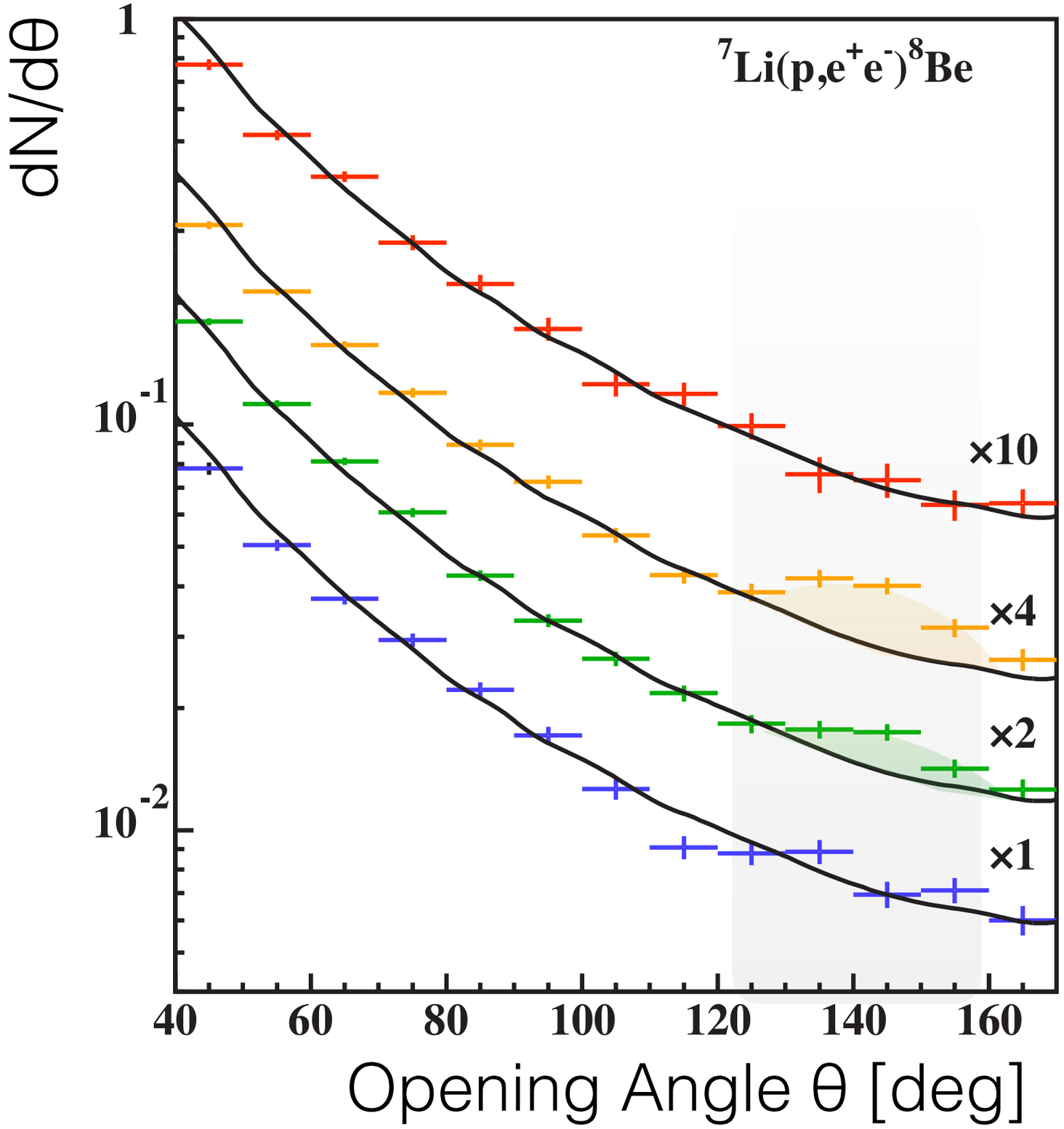
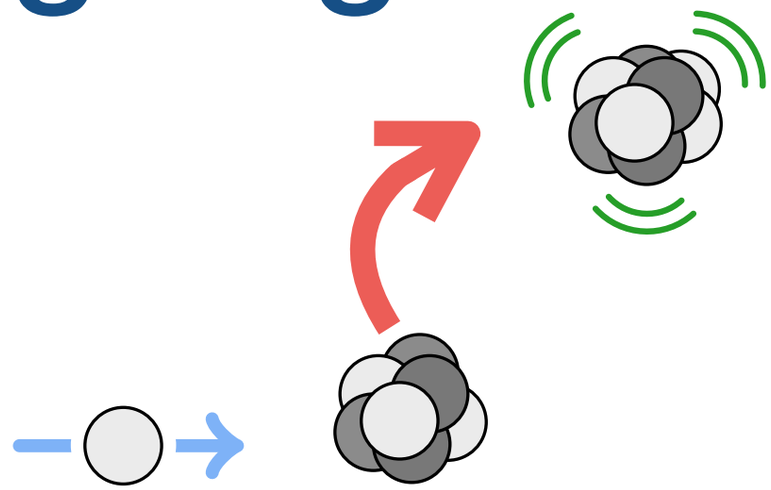
A 6.8σ anomaly: opening angle





PROTON ENERGY

E_p = 1.20 MeV

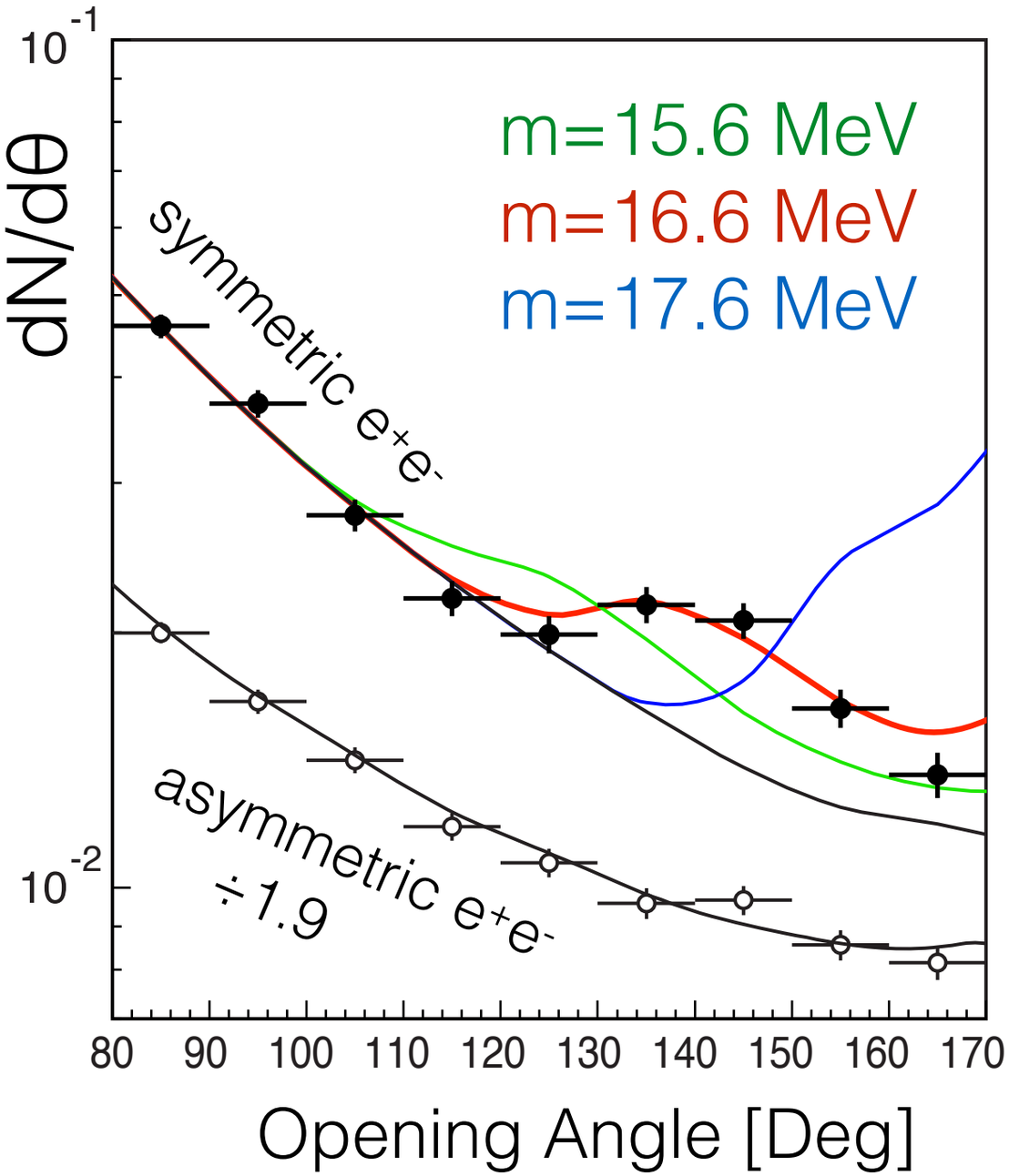
E_p = 1.10 MeV

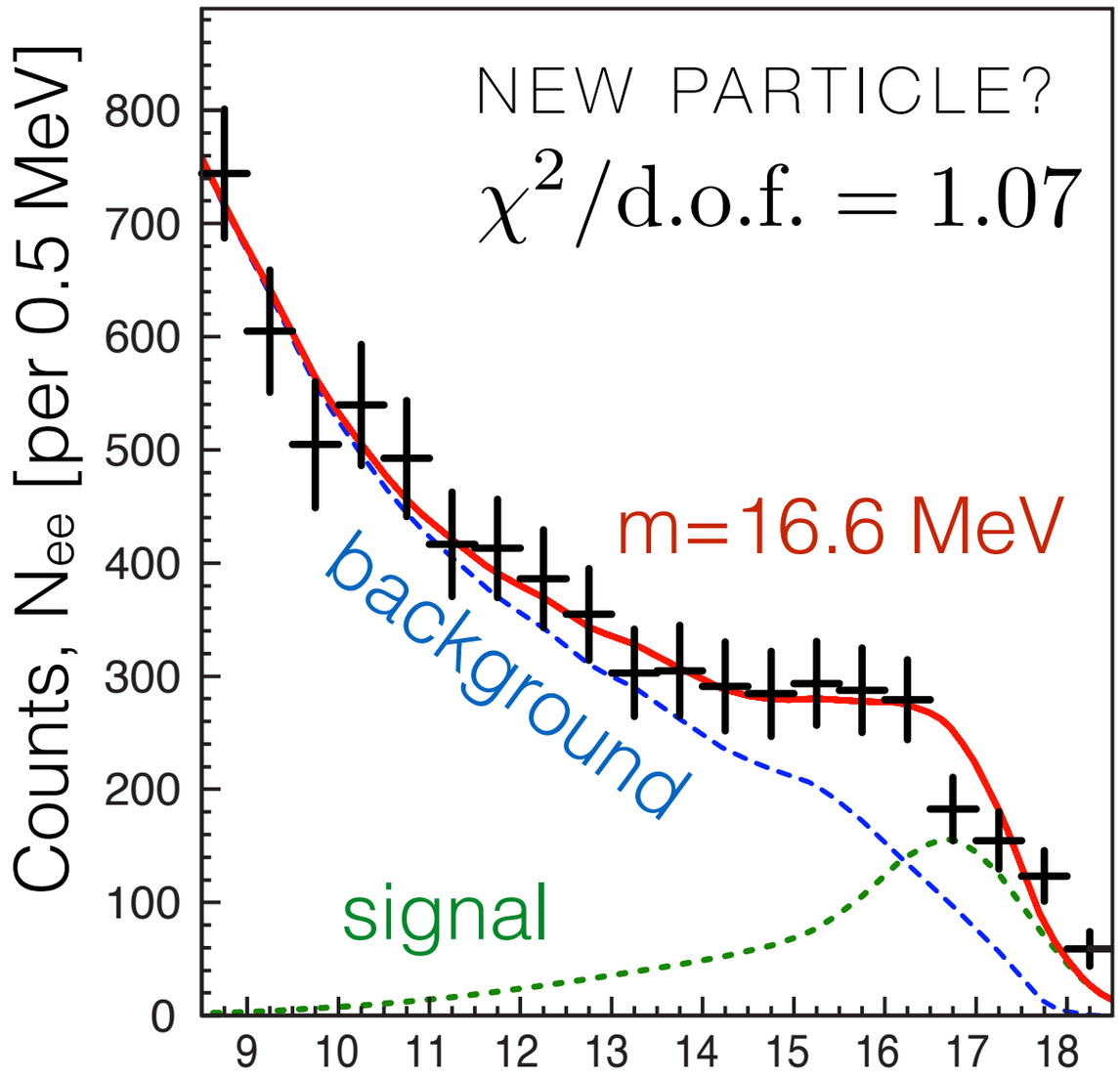
E_p = 1.04 MeV

E_p = 0.80 MeV

Krasznahorkay et al. Phys. Rev. Lett 116 (2016) 042501

A 6.8σ anomaly: two measurements





Krasznahorkay et al. Phys. Rev. Lett 116 (2016) 042501

Sanity Checks

1. Bump, not monotonically decreasing background

2. Opening angle and invariant mass agree (17 MeV)

3. Bump disappears off resonance
   not from interference with other decays

4. Bump disappears for asymmetric energies
   consistent with kinematics for on-shell particle

5. Large transition, wouldn't see it in other nuclei

New Particle?

Not a dark Higgs ($j^{\pi} = 0^{+}$)

ANGULAR MOMENTUM

$$\ell = 1$$

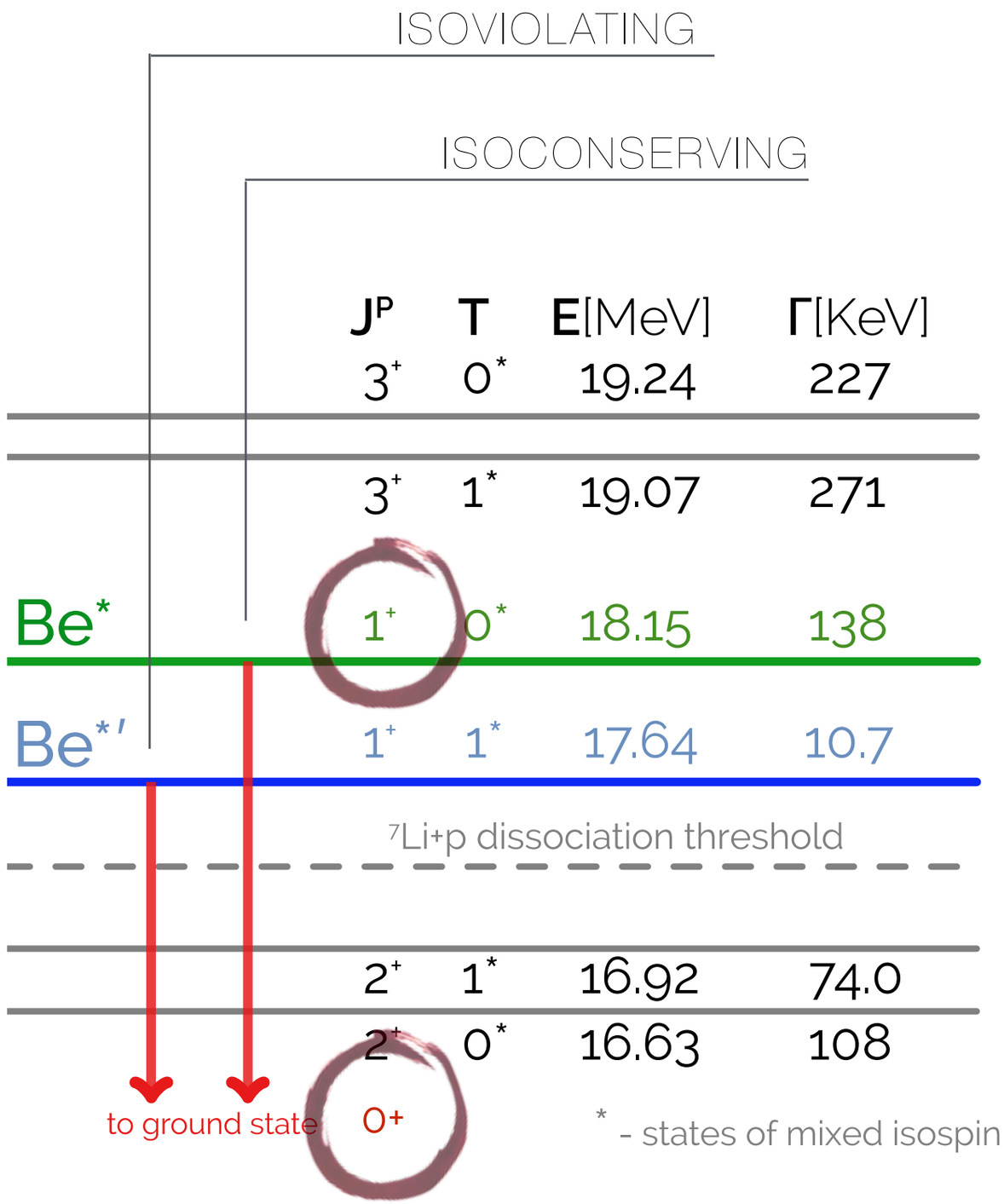
PARITY

$$P = (-)^{\ell} P_{\mathrm{Be}}\, P_X$$

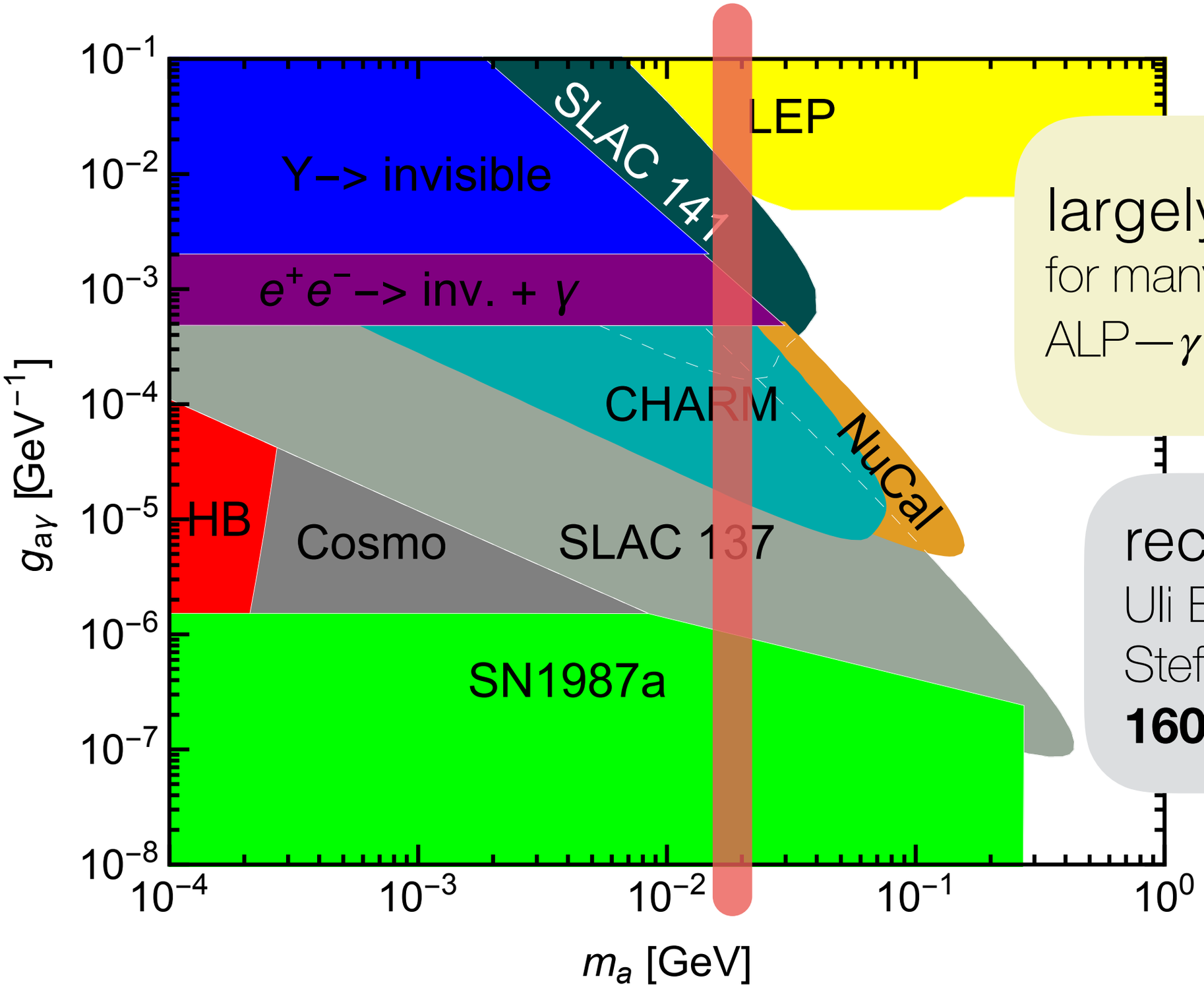
$$-\quad +\quad +$$

Decay is **forbidden**

up to parity violation



Not an axion-like particle ($j^p = 0^+$)



largely ruled out
for many decades in
ALP—γ couplings

recent work:
Uli Ellwanger &
Stefano Moretti
1609.01669

Döbrich et al. "ALPtraum," 1512.03069; see also Intensity Frontier 1205.2671

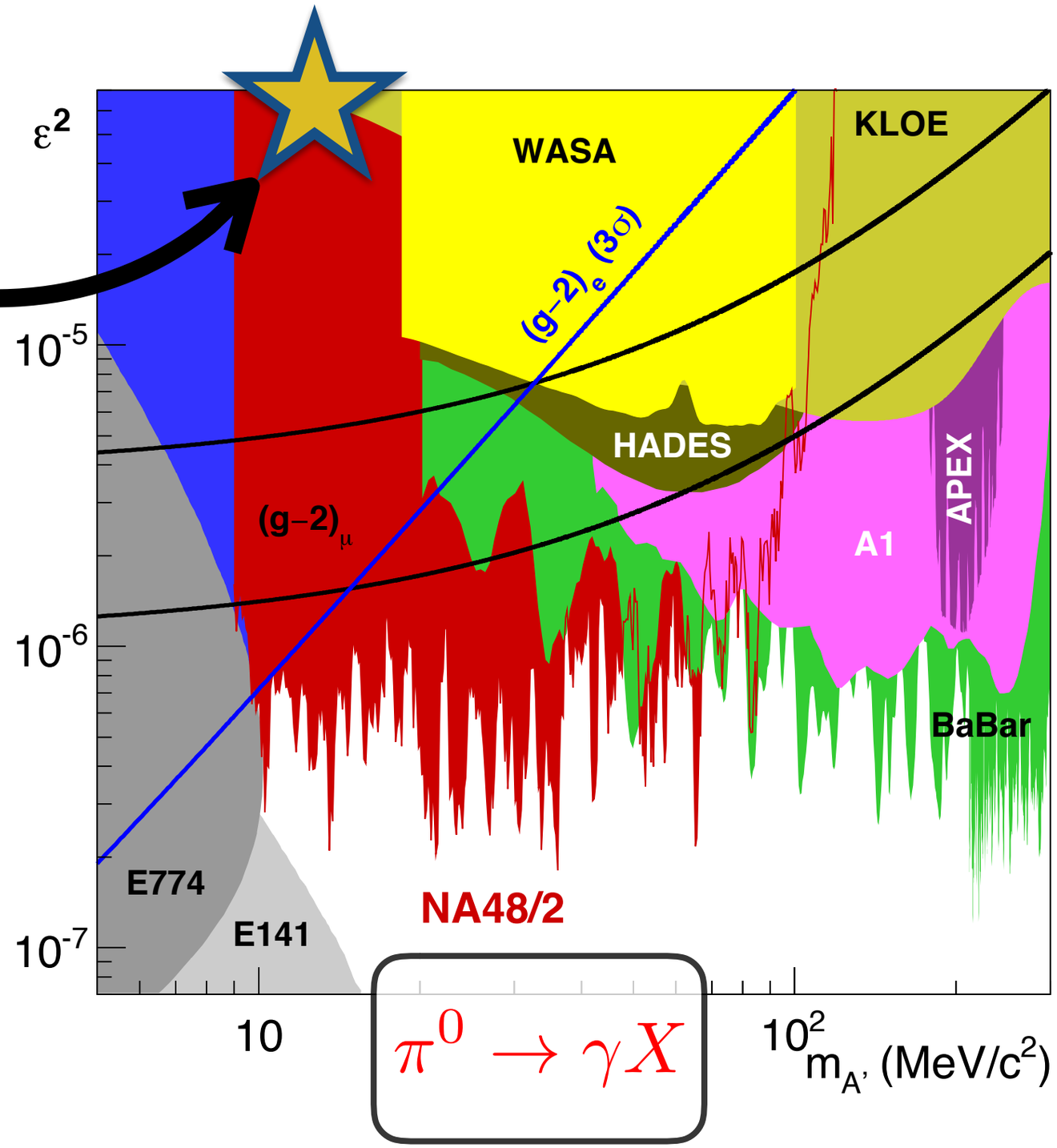
Not a dark photon

$$\varepsilon \approx 0.011$$

Similarly, dark Z tension
w/ atomic parity violation

Proposal: separate
u, *d* and *e* couplings

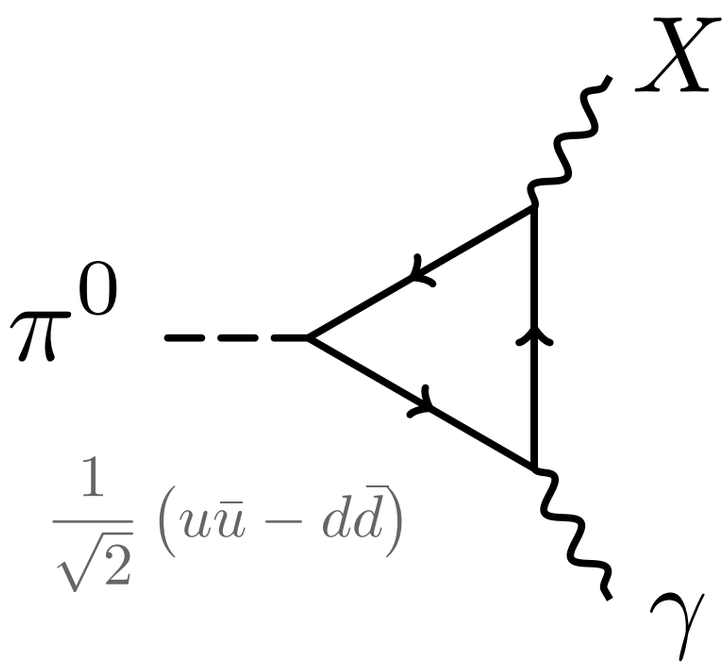
Phenomenological model
to diagnose what is required
for a new physics interpretation

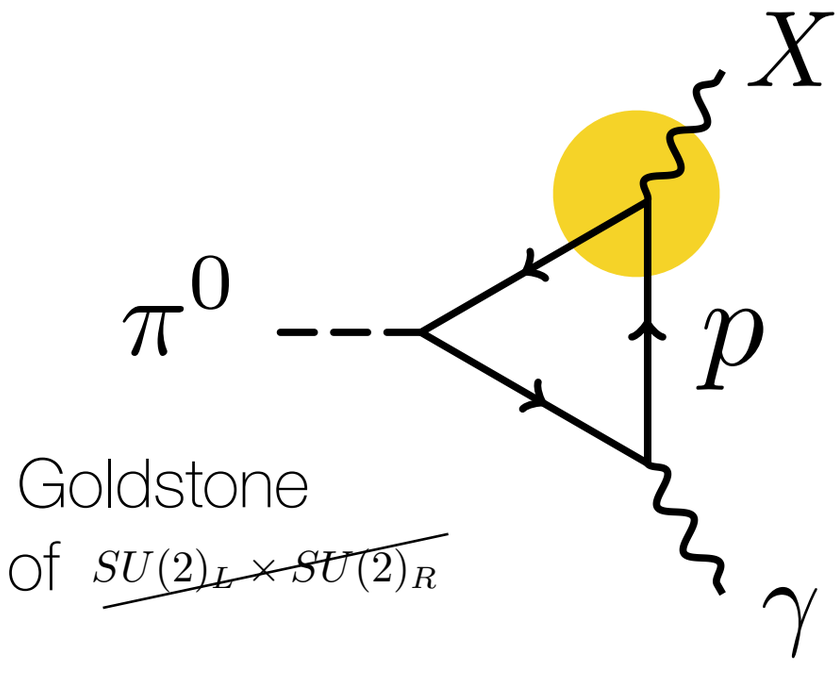


NA46/2 1504.00607

π^0-phobia = p^+-phobia

To avoid NA46/2, prohibit π^0 decay to Xγ





FROM QUARK CONTENT

$$Q_u Q'_u - Q_d Q'_d = 0$$

$$Q'_d = -2Q'_u$$

STEINBERGER CALCULATION

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

For spin-1[-] see Georgi, *Weak Interactions, 2nd ed.*

Beryllium + new particle EFT

EFT: use parity, Lorentz

$$\mathcal{L}_V = \frac{g_V}{\Lambda_V} \mathrm{Be}\, G_{\mu\nu} F^{(V)}_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

$$G_{\mu\nu} = \partial_{[\mu} \mathrm{Be}^* \partial_{\nu]}$$

~~$$\mathcal{L}_S = \frac{g_S}{\Lambda_S^2} (\partial_\mu s)(\partial_\nu \mathrm{Be}) G_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$~~

VANISHES, e.g. INTEG. BY PARTS + BIANCHI

$$\mathcal{L}_A = \frac{g_A}{\Lambda_A} \mathrm{Be}\, G^{\mu\nu} F^{(A)}_{\mu\nu} + \frac{m_A^2}{g_A \Lambda'_A} \mathrm{Be}\, A_\mu\, \mathrm{Be}^{*\mu}$$

TRIUMF COLLAB. 1612.01525

$$\mathcal{L}_P = g_P\, \mathrm{Be}\, (\partial_\mu a)\, \mathrm{Be}^{*\mu}$$

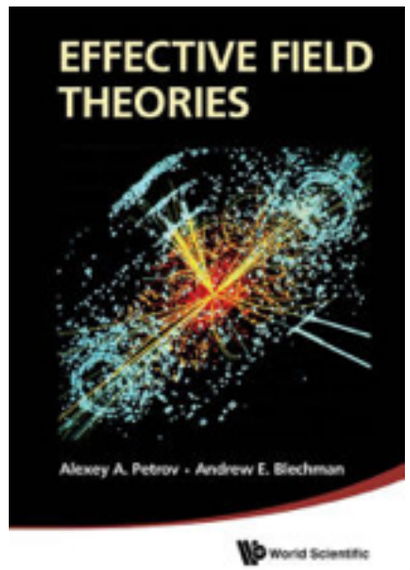
matrix elements?

ELLWANGER & MORETTI 1609.01669

EXPANSION PARAMETER

$$\frac{\text{size of nucleus}}{\text{de Broglie } \lambda} = \frac{(100\ \mathrm{MeV})^{-1}}{(6\ \mathrm{MeV})^{-1}}$$

as seen in PETROV & BLECHMANN



UCI-IPC

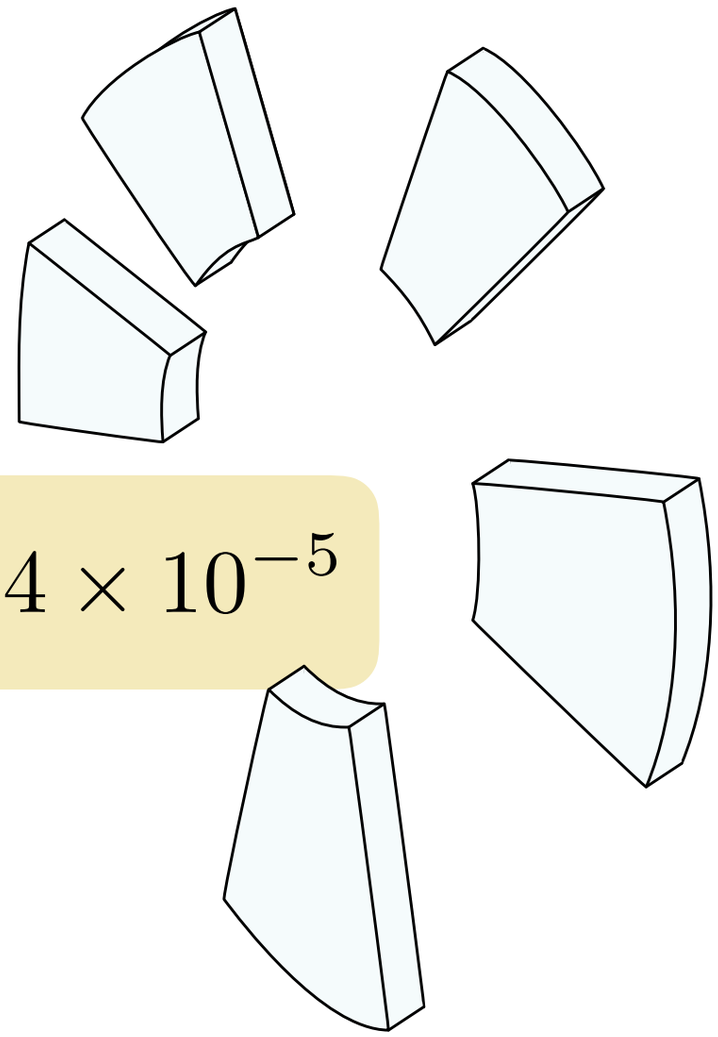
Rate

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

PRODUCTION

$$\frac{g}{\Lambda} \mathrm{Be}\, \partial_{[\mu} \mathrm{Be}^*_{\nu]}\, F_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$$

HADRONIC MATRIX ELEMENTS
CANCEL IN THIS RATIO



DECAY

$$\varepsilon_e \gtrsim 1.4 \times 10^{-5}$$

$$g_i \equiv \varepsilon_i e$$

Beryllium-8 Levels

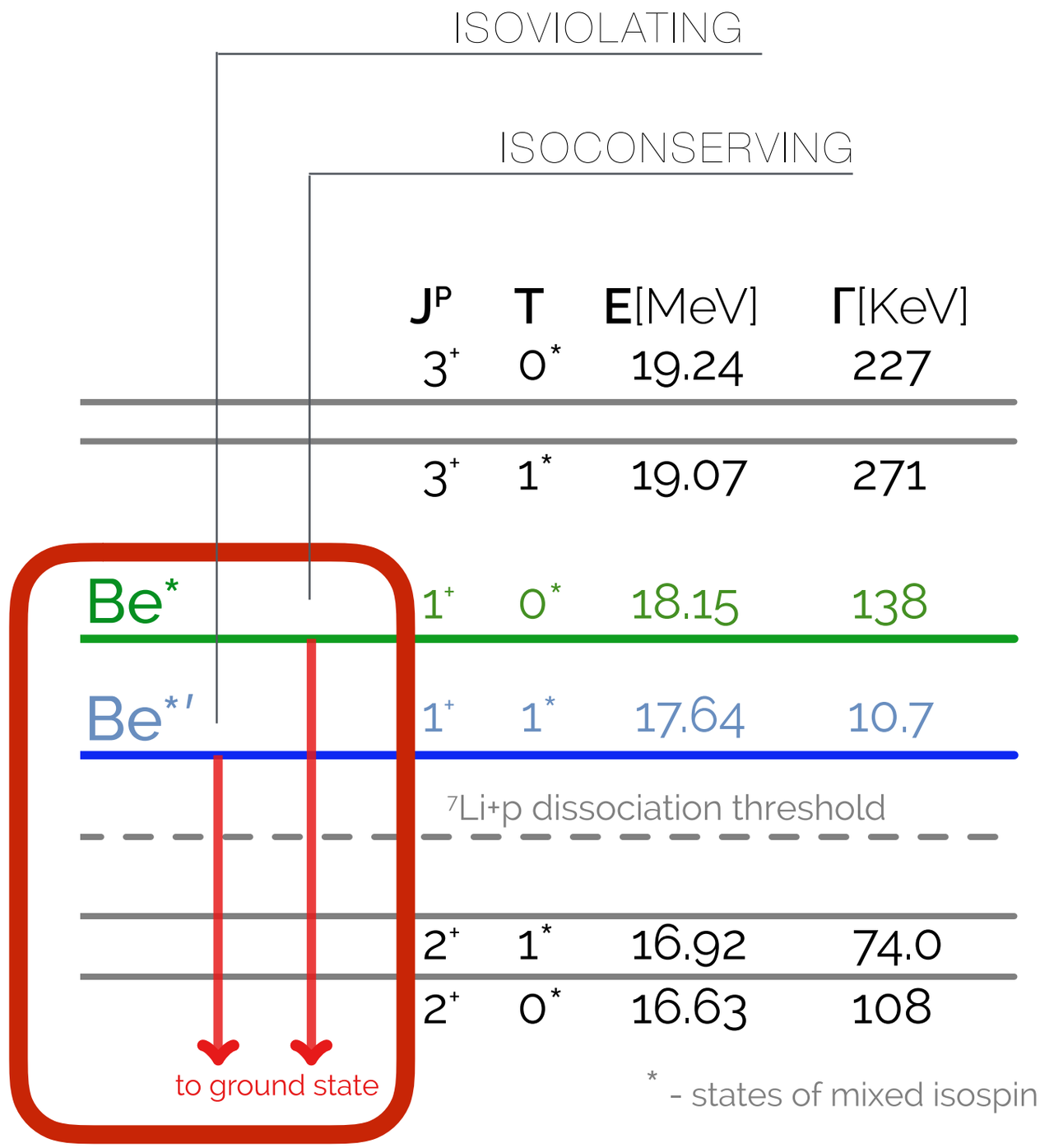
What about iso-violating 17.6 MeV transition?

PHASE SPACE SUPPRESSION (~5)

$$\frac{\mathrm{Br}(^8\mathrm{Be}^* \to X)}{\mathrm{Br}(^8\mathrm{Be}^* \to \gamma)} \sim \varepsilon^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3}$$

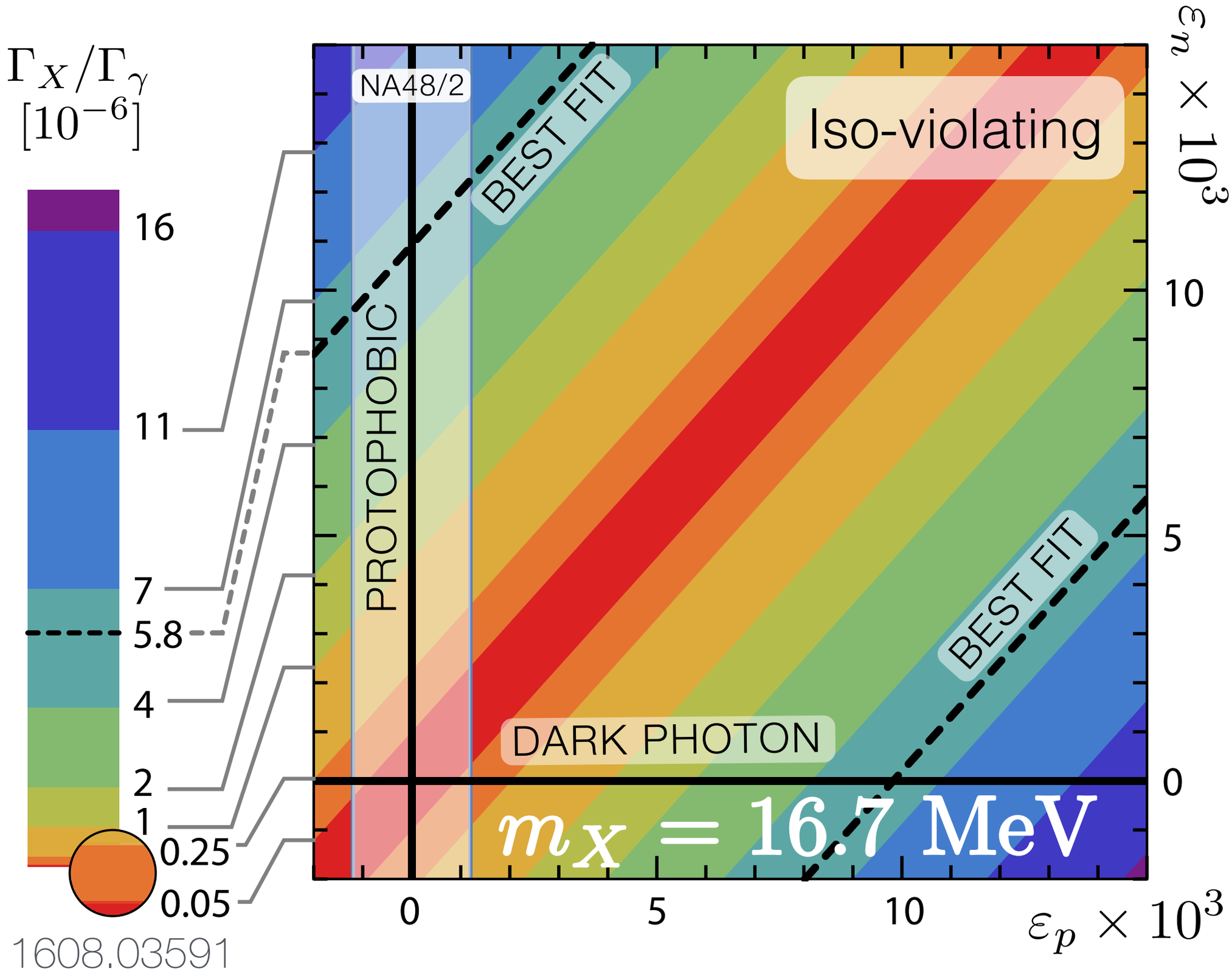
This is a robust prediction

ANALOGOUS TO $\gamma\gamma$ AND $Z\gamma$ FOR INDIRECT DETECTION OF DARK MATTER



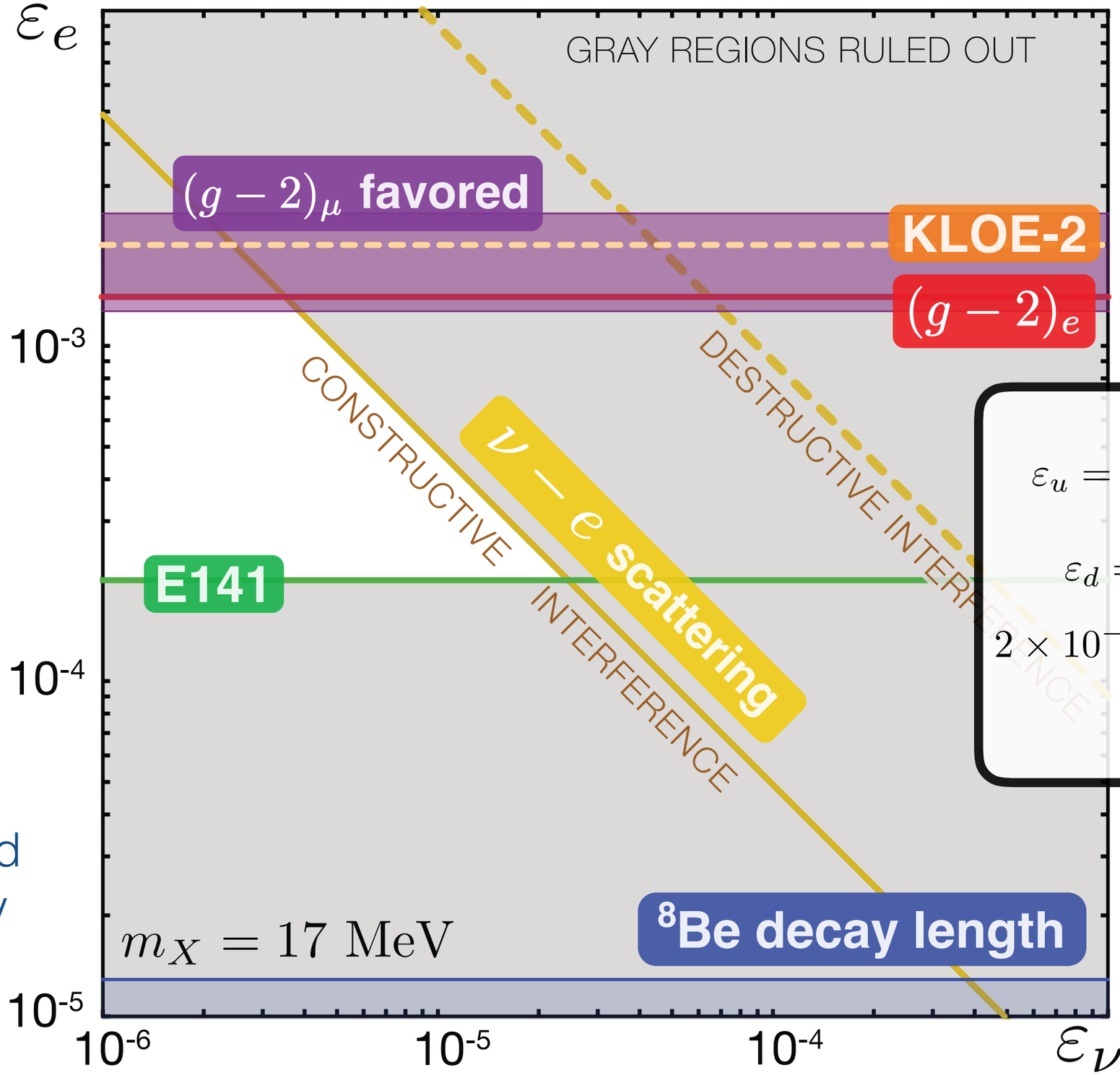
Based on Pastore et al. Phys. Rev. C 90 (2014) [1406.2343]

Production (quark) couplings



UCI-IPC: 1608.03591

Decay (lepton) couplings



KLOE-2

$e^+e^- \to \gamma X$

E141

Lower bound on ε_e: decay inside dump

^{8}Be

Lower bound on ε_e: decay in detector

PROTOPHOBIA

$$\varepsilon_u = -\frac{1}{3}\varepsilon_n \approx \pm 3.7 \times 10^{-3}$$

$$\varepsilon_d = \frac{2}{3}\varepsilon_n \approx \mp 7.4 \times 10^{-3}$$

$$2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

$$|\varepsilon_\nu \varepsilon_e|^{1/2} \lesssim 7 \times 10^{-5}$$

UCI IPC 1608.03591

UV completions of protophobia?

$Q - B$

e.g. gauged *B* with tuned kinetic mixing to *Q*
but: *e* coupling too **big**, anomalous (need new matter)

$Q - (B - L)$

good: manifestly anomaly-free
bad: *e* coupling too **small**, stuck with **v** couplings
ugly: need separate module to cancel **v** couplings

NON-PROTOPHOBIC

Axial vector?
TRIUMF GROUP
1612.01525

Pseudoscalar?
ELLWANGER & MORETTI
1609.01669

UCI-IPC

Matrix element uncertainty?

Future experiments

Next Step: Independent Verification

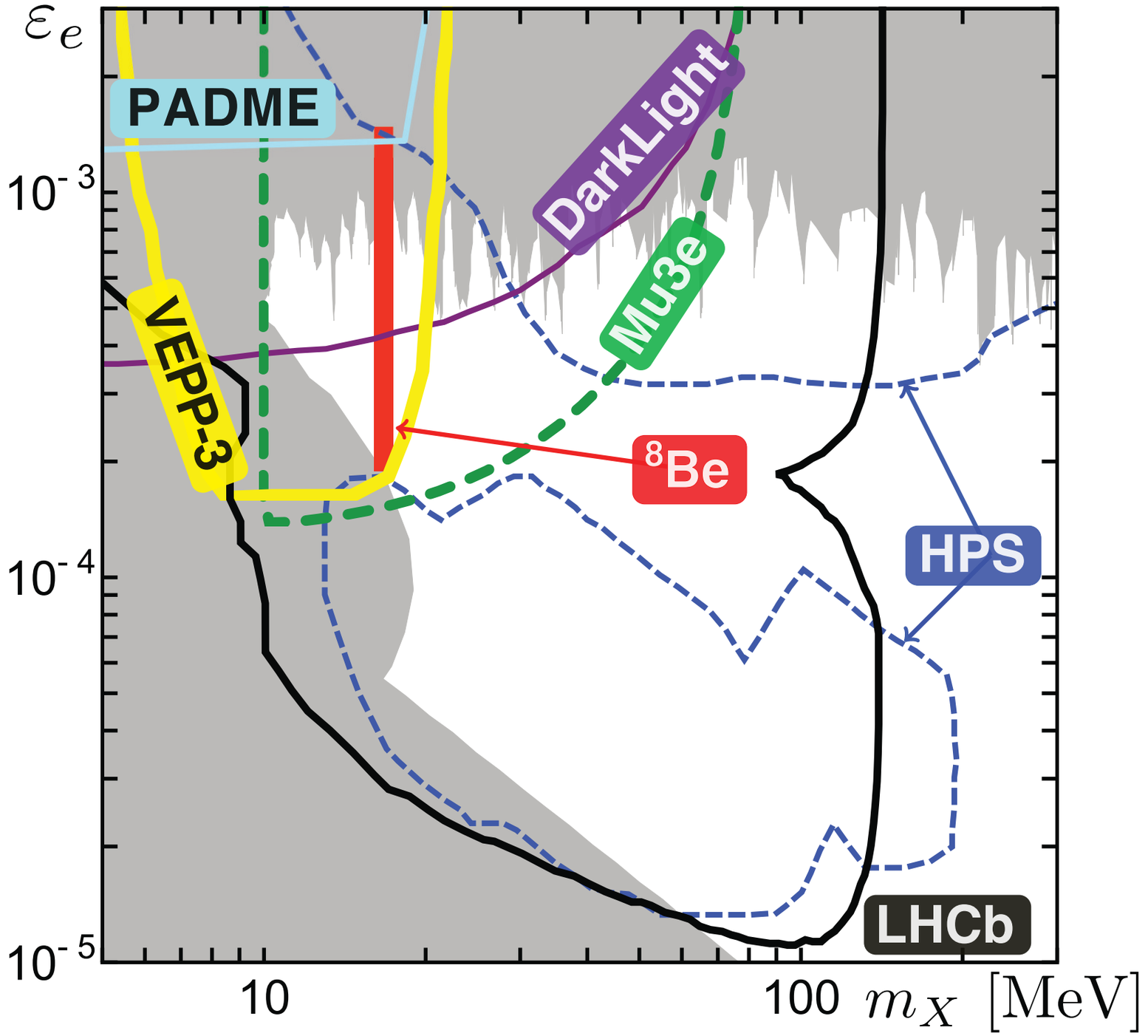
COMPLEMENTARY SEARCH

Mu3e, phase 2
Starting 2018

LHCb, Run III
2021 - 2023

POSSIBLE DIRECT CHECKS

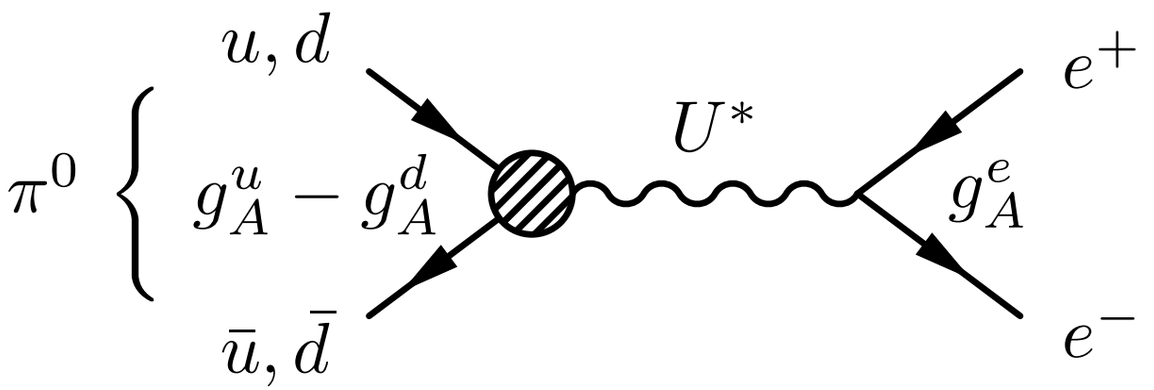
TUNL: $\gamma N \rightarrow ee$
UK: VdG acc.
Others?



UCI IPC 1608.03591

Other $\mathcal{O}$(10 MeV) Anomalies?

- $(g\text{-}2)_\mu$ may be in the same ballpark
  Would likely require invisible modes
- proton radius problem?
  Difficult to build models even without ^{8}Be
- Self-interacting dark matter?
  Conflicts with direct detection; attempt: 1609.01605
- $\pi \to e^+e^-$ KTeV anomaly?
  depends on axial couplings, same ballpark



$$(g_A^u - g_A^d) g_A^e \left(\frac{20\ \text{MeV}}{m_X}\right)^2 \approx 1.6 \times 10^{-7}$$

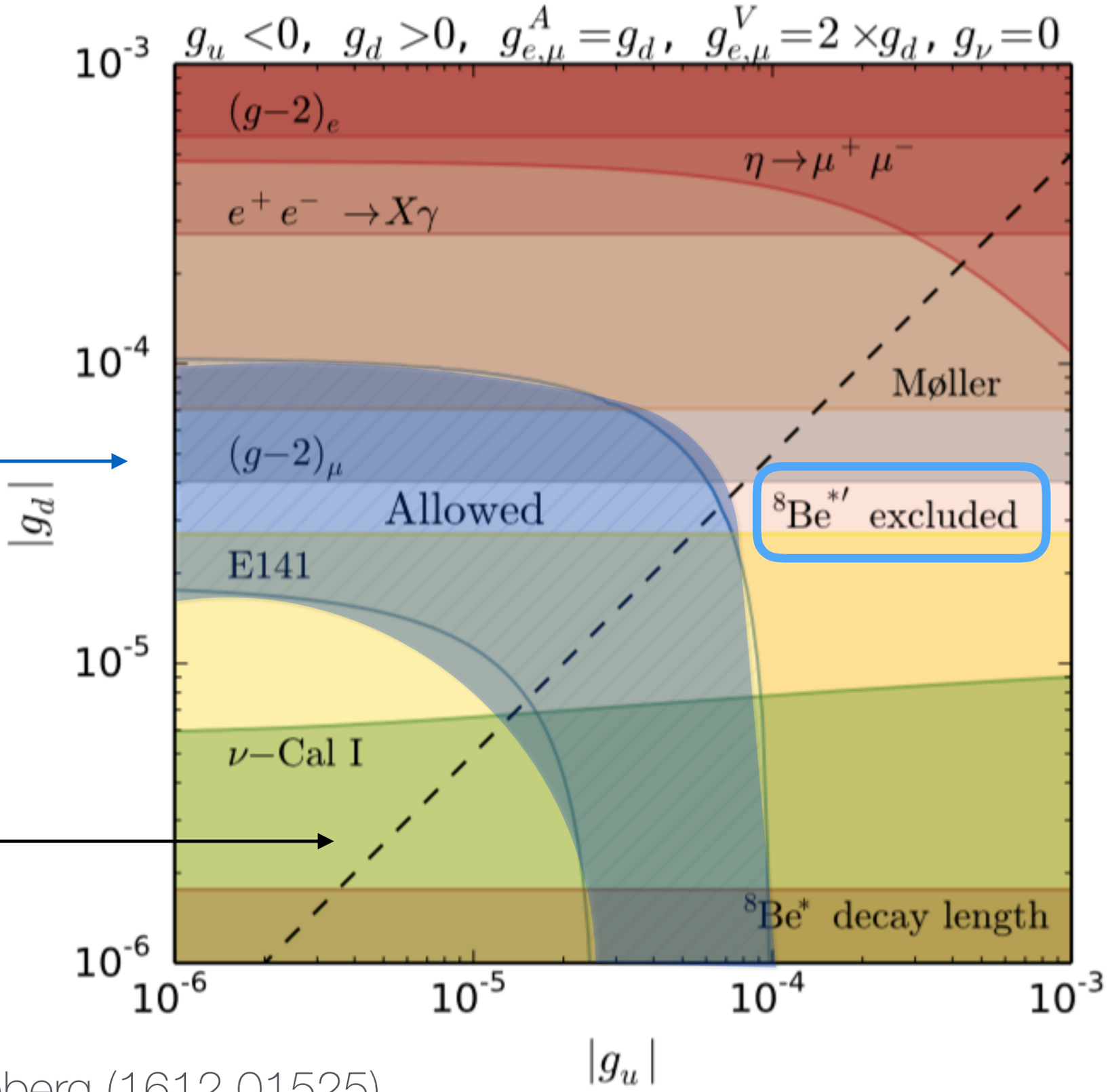
Kahn, Schmitt, Tait (0712.0007) and Kahn, Krnjaic, Tait (1609.09072)

Axial Vector (new from TRIUMF)

FEATURE: ISOVECTOR TRANSITION SUPPRESSED VS. VECTOR CASE.

^{8}Be* preferred →

explicit model (UV complete) →



Kozaczuk, Morrissey, Stroberg (1612.01525)

Thanks! 감사합니다!

- Anomaly in the ^{8}Be (18.15 MeV) transition
- 6.8σ bump; χ^2/d.o.f.= 1.07
- More exotic than a dark photon

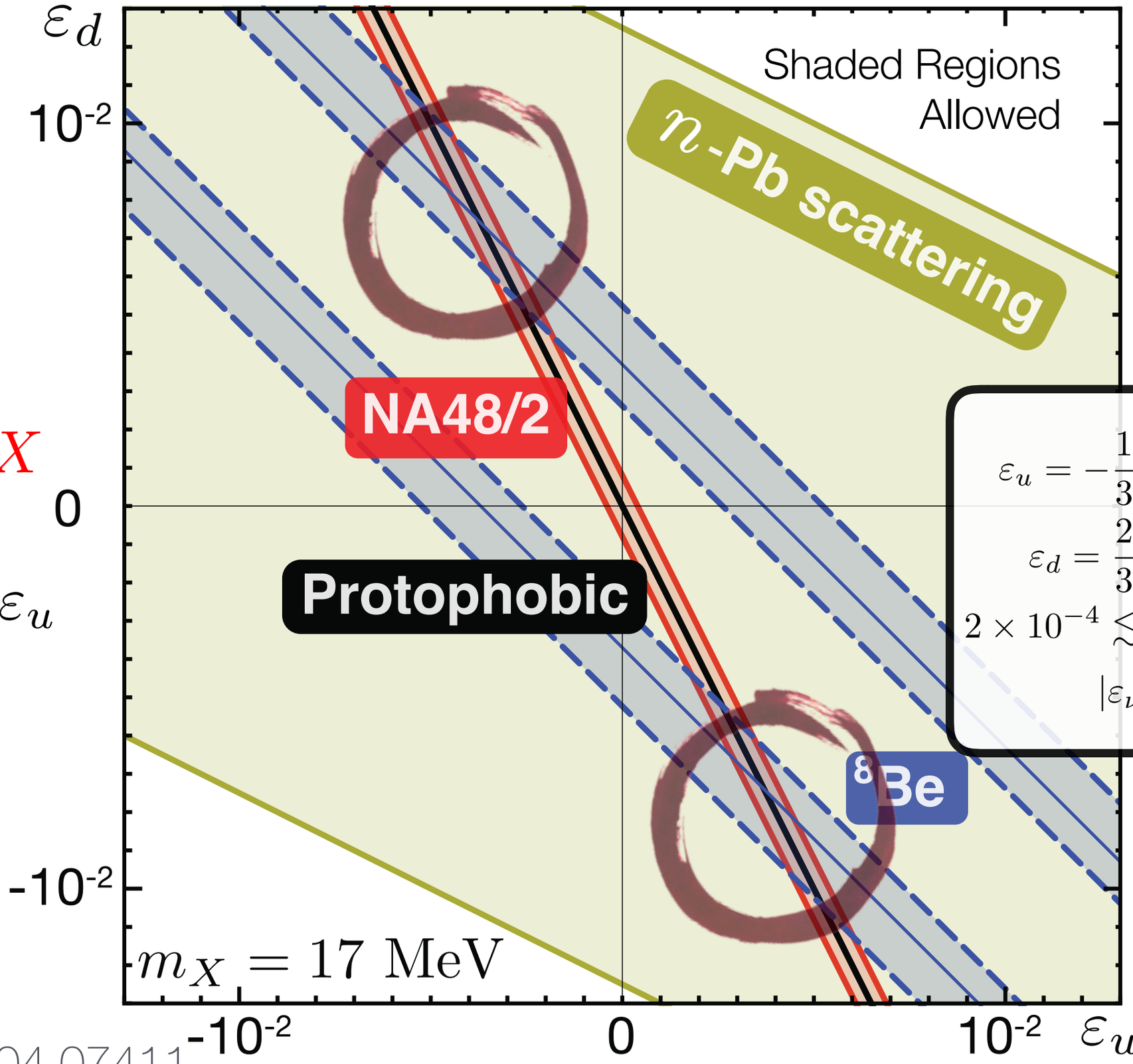
  UV realization of protophobia?
  Axial vector / axion-like particle?
- Nearby anomalies may be relevant
- Next step is experimental: confirm or kill

Extra Slides

Production (quark) couplings

$\pi^0 \to \gamma X$

$\varepsilon_d = -2\varepsilon_u$



Barbieri Ericson
Phys. Lett B57 (1975)

PROTOPHOBIA

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$$2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

$$|\varepsilon_\nu \varepsilon_e|^{1/2} \lesssim 7 \times 10^{-5}$$

$g_i \equiv \varepsilon_i e$

UCI IPC 1604.07411

Normalizing with γ decay

$$J^\mu_{T=0} = \bar{N}\gamma^\mu N \qquad J^\mu_{T=1} = \bar{N}\gamma^\mu T^3 N \qquad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

ISOSINGLET ISOVECTOR

X—NUCLEON CURRENT

$$J^\mu_N = e\varepsilon_p \underbrace{\frac{1}{2}\left(J^\mu_{T=0} + J^\mu_{T=1}\right)}_{J^\mu_p} + e\varepsilon_n \underbrace{\frac{1}{2}\left(J^\mu_{T=0} - J^\mu_{T=1}\right)}_{J^\mu_n}$$

$$\langle {}^8\mathrm{Be}|J^\mu_{T=1}|{}^8\mathrm{Be}^*\rangle = 0$$

NOT REALLY: BUT RESULT UNCHANGED

$$\langle {}^8\mathrm{Be}|J^\mu_N|{}^8\mathrm{Be}^*\rangle = \frac{e}{2}(\varepsilon_p + \varepsilon_n)\langle {}^8\mathrm{Be}|J^\mu_{T=0}|{}^8\mathrm{Be}^*\rangle$$

$$\langle {}^8\mathrm{Be}|J^\mu_{\mathrm{EM}}|{}^8\mathrm{Be}^*\rangle = \frac{e}{2}\langle {}^8\mathrm{Be}|J^\mu_{T=0}|{}^8\mathrm{Be}^*\rangle$$

MATRIX ELEMENTS CANCEL

UCI-IPC; see also Pastore et al. Phys. Rev. C90 (2014)

What about isospin violation?

Pastore *et al.*: large isospin mixing in these states.

Nuclear physics here may not be fully understood, but effect is unlikely to be able to help.

"CARTOON" EXPLANATION

$$\frac{\Gamma(\mathrm{Be}^* \to \mathrm{Be}\, X)}{\Gamma(\mathrm{Be}^* \to \mathrm{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \left[1 - \left(\frac{m_X}{18.15\ \mathrm{MeV}}\right)^2\right]^{3/2} \left(1 - \frac{2\varepsilon_n}{\varepsilon_p + \varepsilon_n} \frac{\langle \mathrm{Be}|J_1^\mu|\mathrm{Be}^*\rangle}{\langle \mathrm{Be}|J_0^\mu|\mathrm{Be}^*\rangle + \langle \mathrm{Be}|J_1^\mu|\mathrm{Be}^*\rangle}\right)^2$$

ISOSPIN VIOLATING PIECE

Hope: denominator is small due to cancelation; nuclear calculations do not corroborate this.

$(\ldots)^2$ ends up $\lesssim 1$

FOR DETAILS:

Pastore, Wiringa et al. Phys. Rev. C 90 [1406.2343], Phys. Rev. C 88 [1308.5670]

Isospin Violation

ISOSINGLET TRANSITION

$$M1_{1,T=0} = 0.014(1)\,\mu_N$$

ISOVECTOR TRANSITION

$$M1_{1,T=1} = 0.767(9)\,\mu_N$$

PHYSICAL STATES

$$\langle \Psi_{0,0} || M1 || \Psi_1^a \rangle = \alpha_1 M1_{1,T=0} + \beta_1 M1_{1,T=1} + \alpha_1 \kappa M1_{1,T=1}\,,$$

$$\langle \Psi_{0,0} || M1 || \Psi_1^b \rangle = \beta_1 M1_{1,T=0} - \alpha_1 M1_{1,T=1} + \beta_1 \kappa M1_{1,T=1}\,.$$

ISOSPIN VIOLATION

$$\kappa = 0.549$$

NEW IN 1608.03591

$$\alpha_1 = 0.21(3) \qquad \beta_1 = 0.98(1)$$

ISOSPIN MIXING ANGLES

Pastore, Wiringa et al. Phys. Rev. C 90 [1406.2343], Phys. Rev. C 88 [1308.5670]

What about the X-dipole moment?

These are already included in the full isospin treatment by Pastore *et al*.

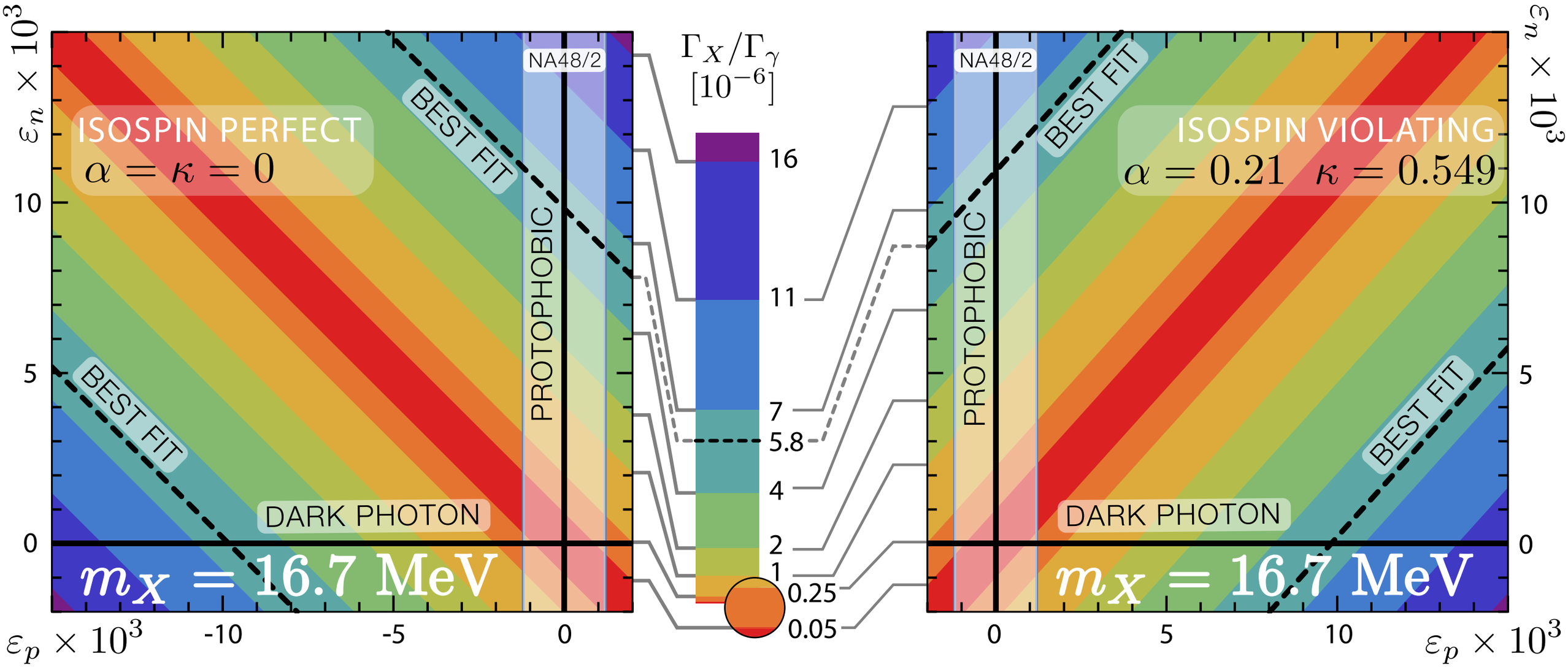
Quark's tiny electric charge gives a tiny quark magnetic dipole. Neutron dipole comes from QCD, and is isospin conserving.

Pastore formalism (isospin basis) includes electric dipoles in the *M1* matrix elements.

We also use the isospin basis and the Pastore *M1* matrix elements, rescaled by the appropriate *X*-charges.

Pastore, Wiringa et al. Phys. Rev. C 90 [1406.2343], Phys. Rev. C 88 [1308.5670]

Production (quark) couplings

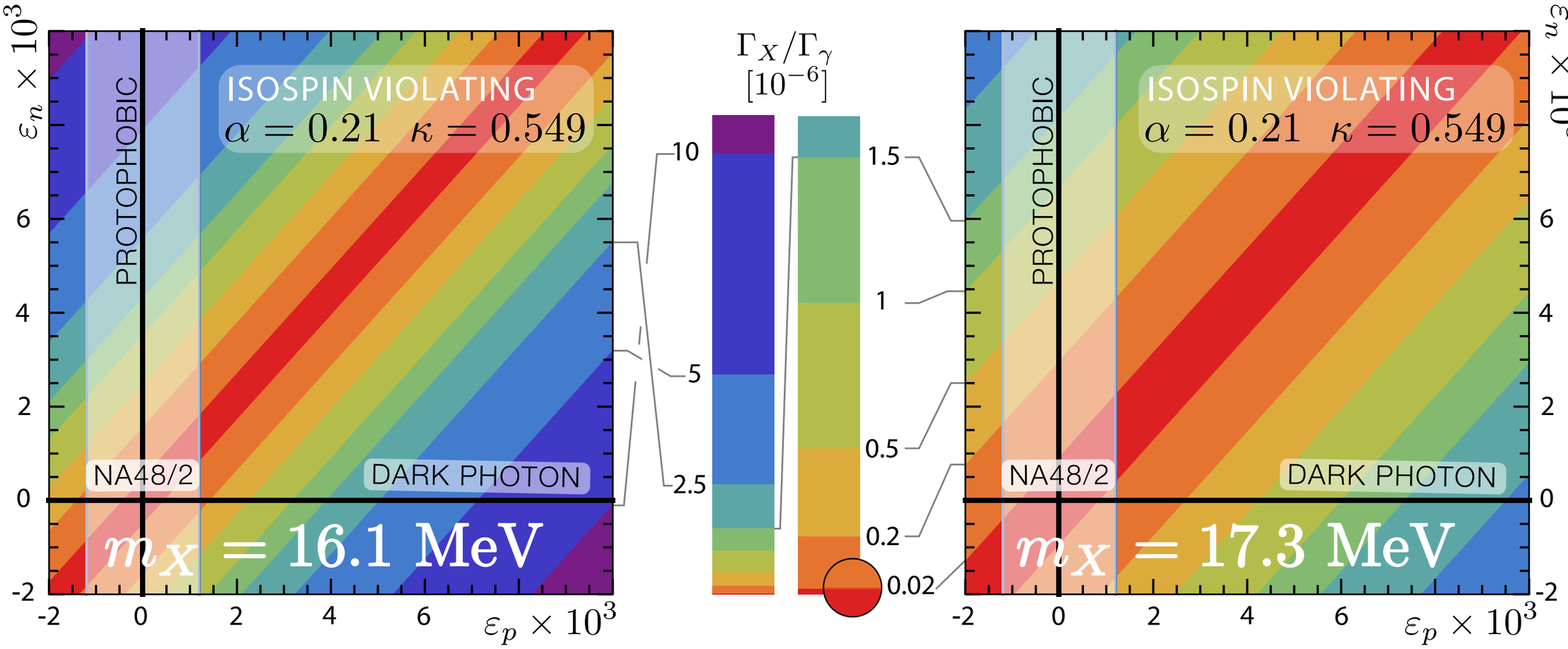


$$\frac{\Gamma_X}{\Gamma_\gamma} = |-0.09\,(\varepsilon_p + \varepsilon_n) + 1.09\,(\varepsilon_p - \varepsilon_n)|^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

$$\frac{\Gamma_X}{\Gamma_\gamma} = |\quad 0.05\,(\varepsilon_p + \varepsilon_n) + 0.95\,(\varepsilon_p - \varepsilon_n)|^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

UCI IPC 1608.03591

Mass Dependence



UCI IPC 1608.03591

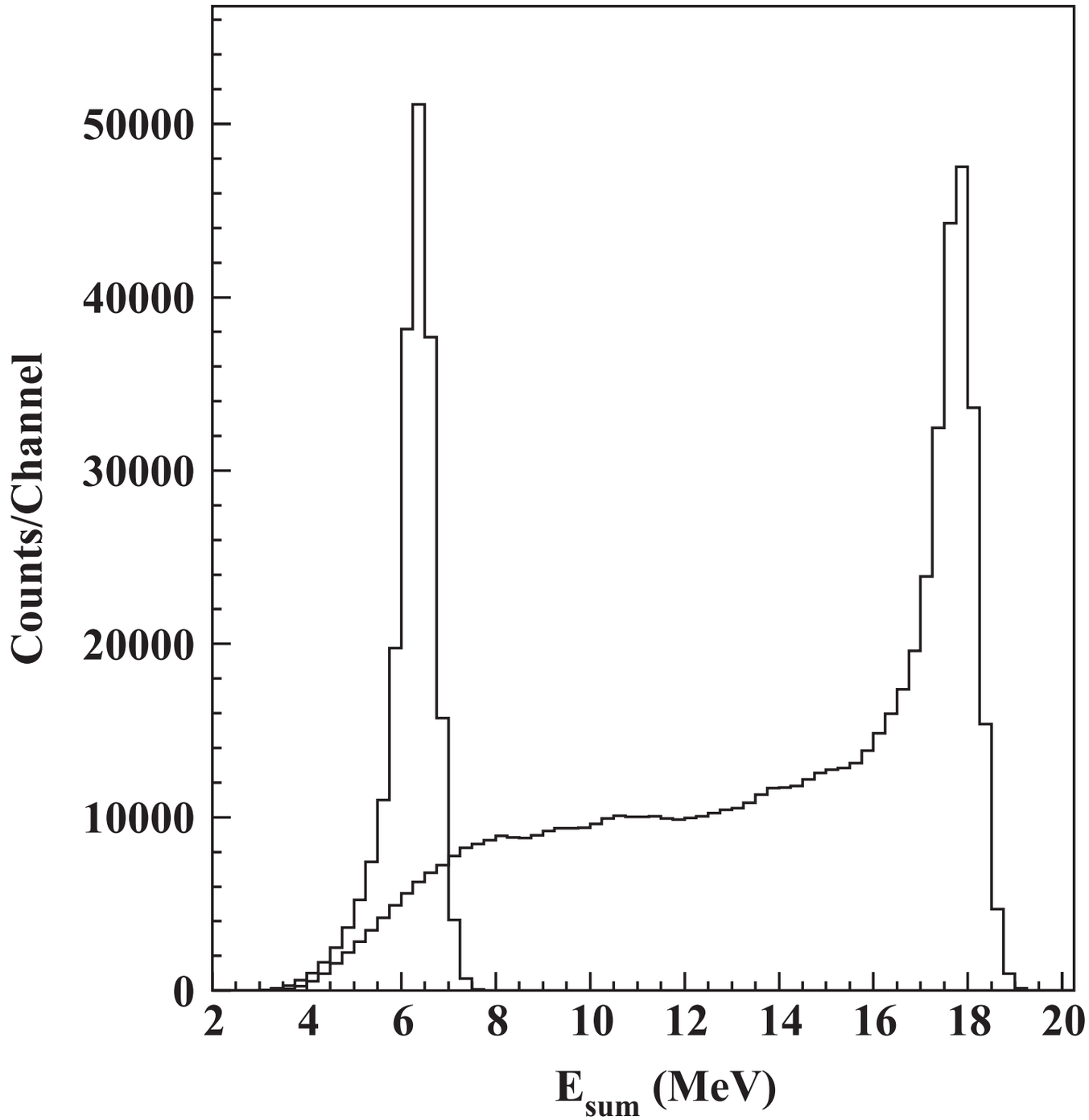
ATOMKI Pair Spectrometer

from A.J. Krasznahorkay; slideplayer.com/slide/6112261/

Detector Resolution

Simulated peak shapes for the spectrometer at 6 and 18 MeV using 10 million events for both energies.

The response function for 18 MeV is multiplied by 10 for better visibility.



Gulyás et al. NIM 1504.00489

The Beryllium that Cried ‘Wolf’?

A pre history of Beryllium anomalies

Pre-History, the *de Boeron*

A deviation in internal pair conversion

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Abstract

The E1 e^+e^- decay of the 17.2 MeV level in ^{12}C, and the M1 e^+e^- decay of the 17.6 MeV level in ^{8}Be have been studied in a search for possible signals of short-lived neutral bosons with masses between 5 and 15 MeV/c^2. Whereas for the E1 decay at large correlation angles no deviation is found from internal pair conversion (IPC), surprisingly the M1 angular correlation deviates from IPC at the 4.5σ level.

No gates, no resolution to see bump (… no bump)

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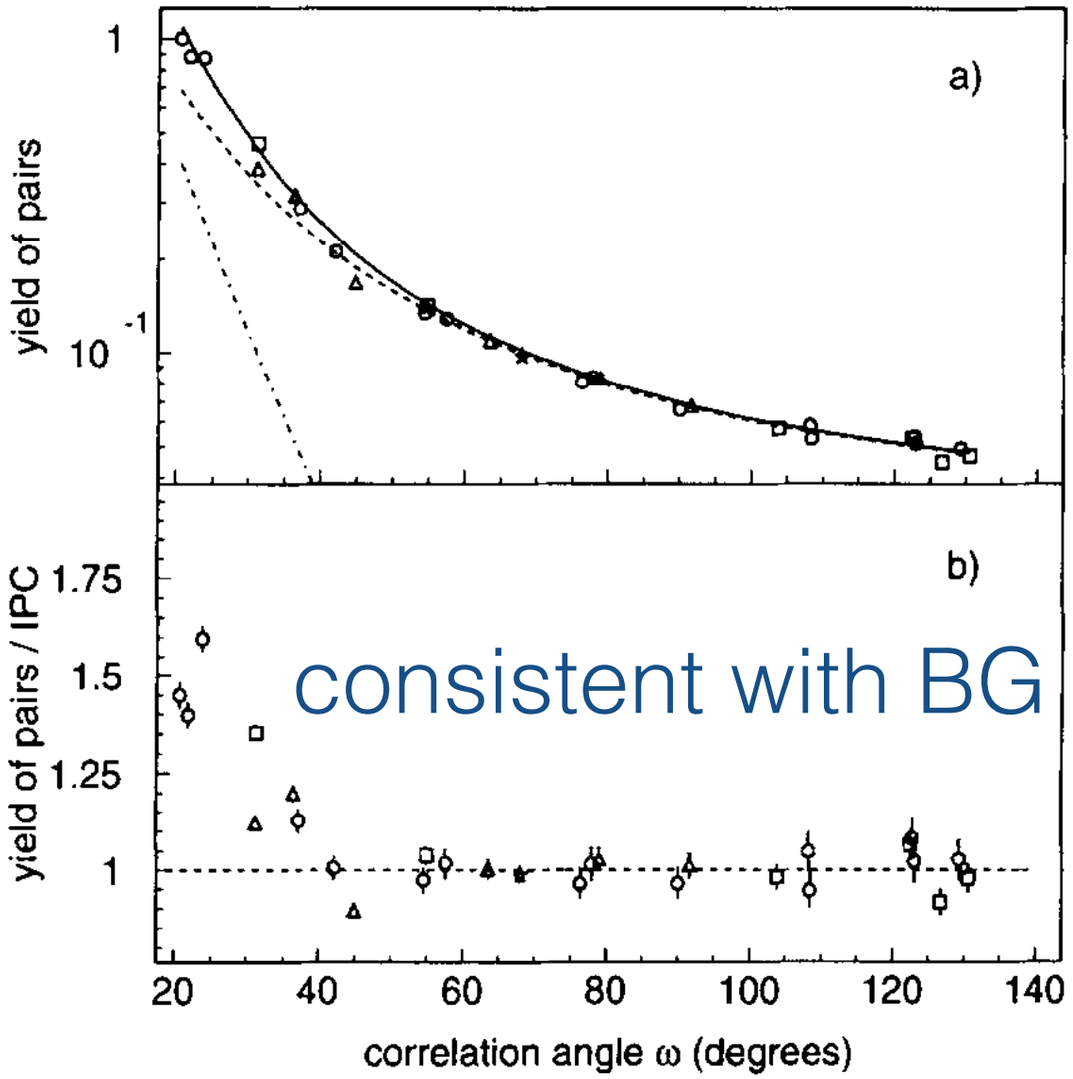
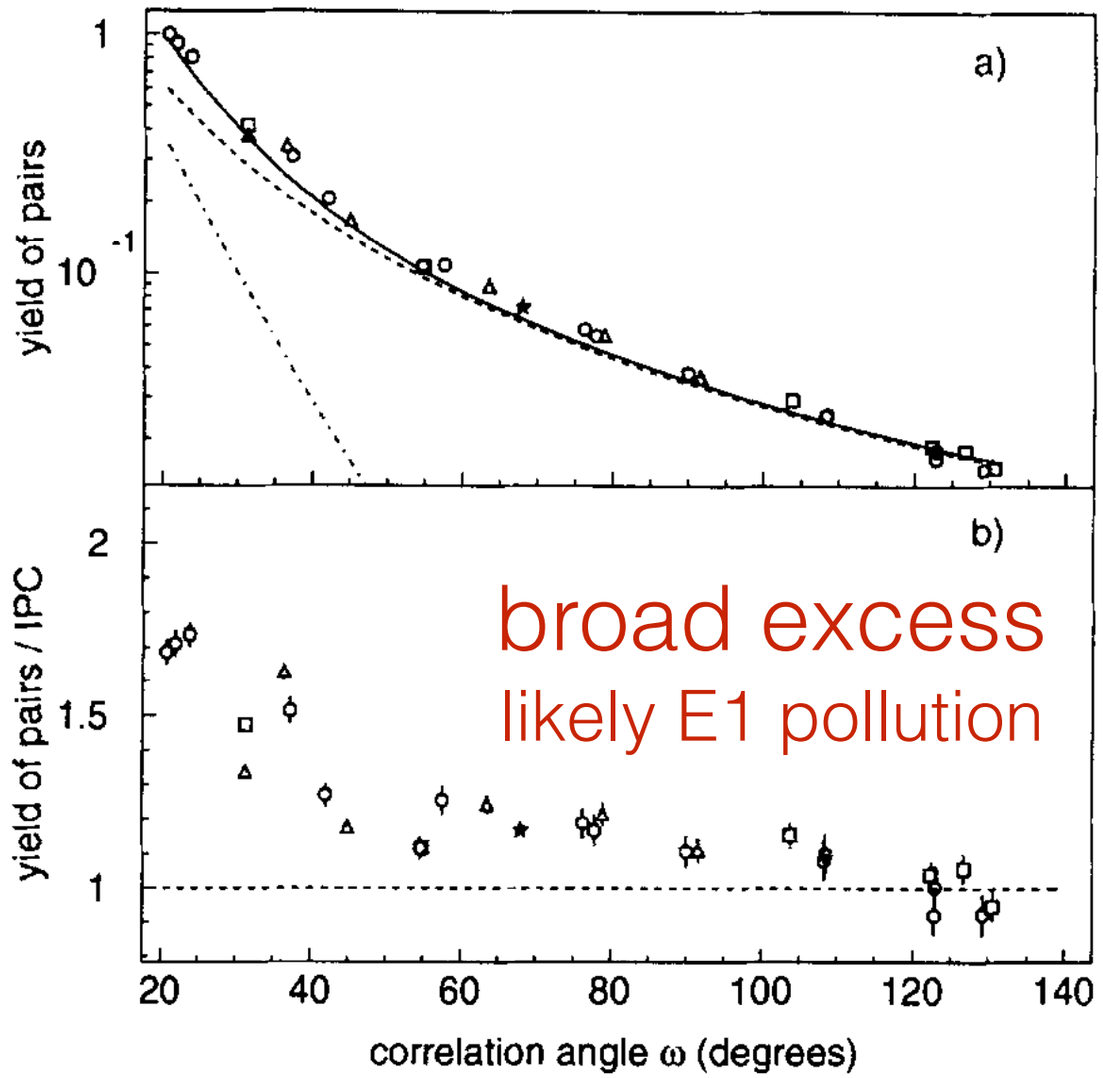
Is Beryllium Crying Wolf?

The 1996 “de Boer-on” is ruled out



^{12}C E1 transition



^{8}Be (17.6 MeV) M1 transition

excluded by ATOMKI study

ATOMKI: 2% E1 removes excess

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