Models for Light New Physics

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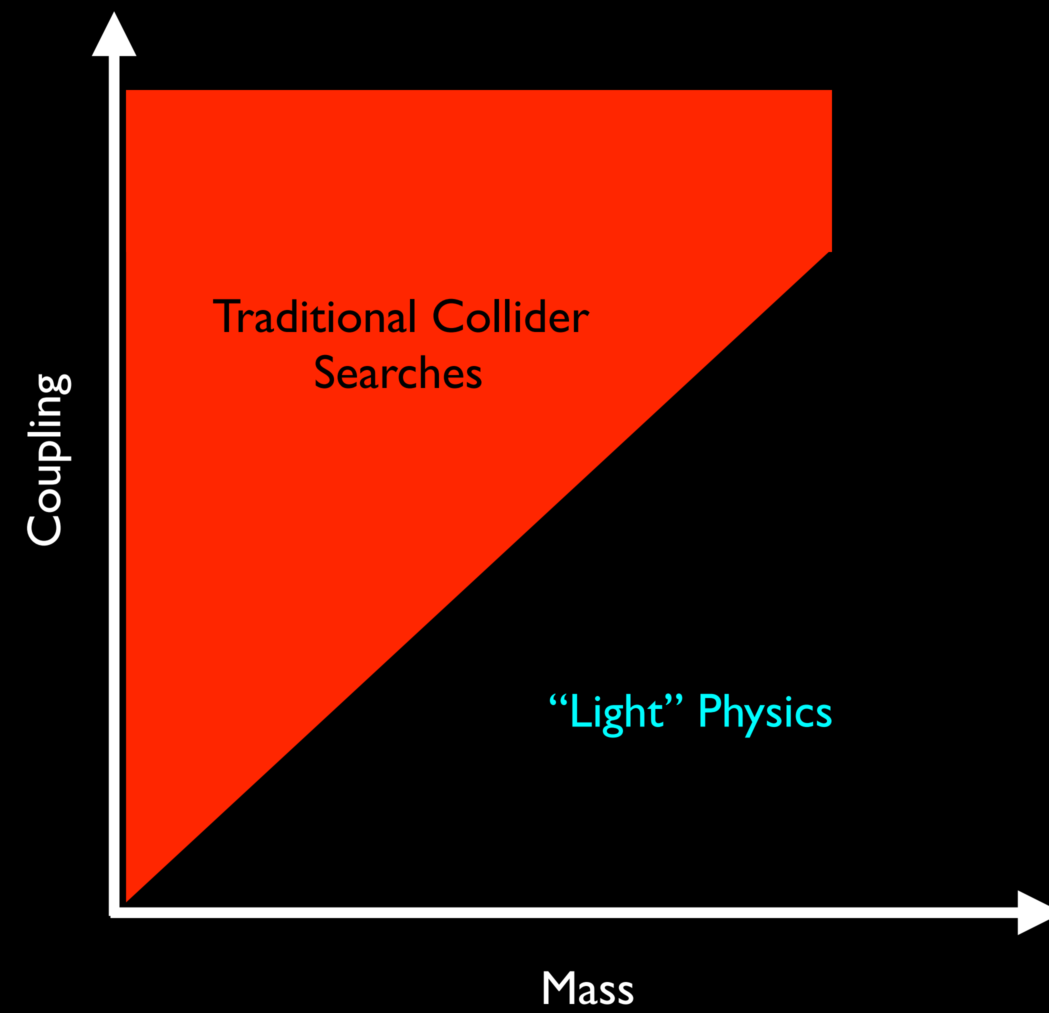
Outline

- Motivations for Light New Physics
  - Searching for the Unknown
  - Dark Matter
  - Experimental Anomalies
- Light Vector Particles
  - Case study: The ATOMKI Be-8 anomaly.
- Open Discussion

Motivations

The Unknown?

- The most basic reason to consider theories with light particles is simply to better understand what experiments tell us is still allowed.
- Light particles must be very weakly coupled to have escaped detection up until this point.
  - "Light" can mean different things to different physicists. For me it means < about GeV.
- We can think of the search for them as complementary to high energy searches such as at the LHC.
- Light physics can *in principle* be produced in existing experiments.



Dark Matter

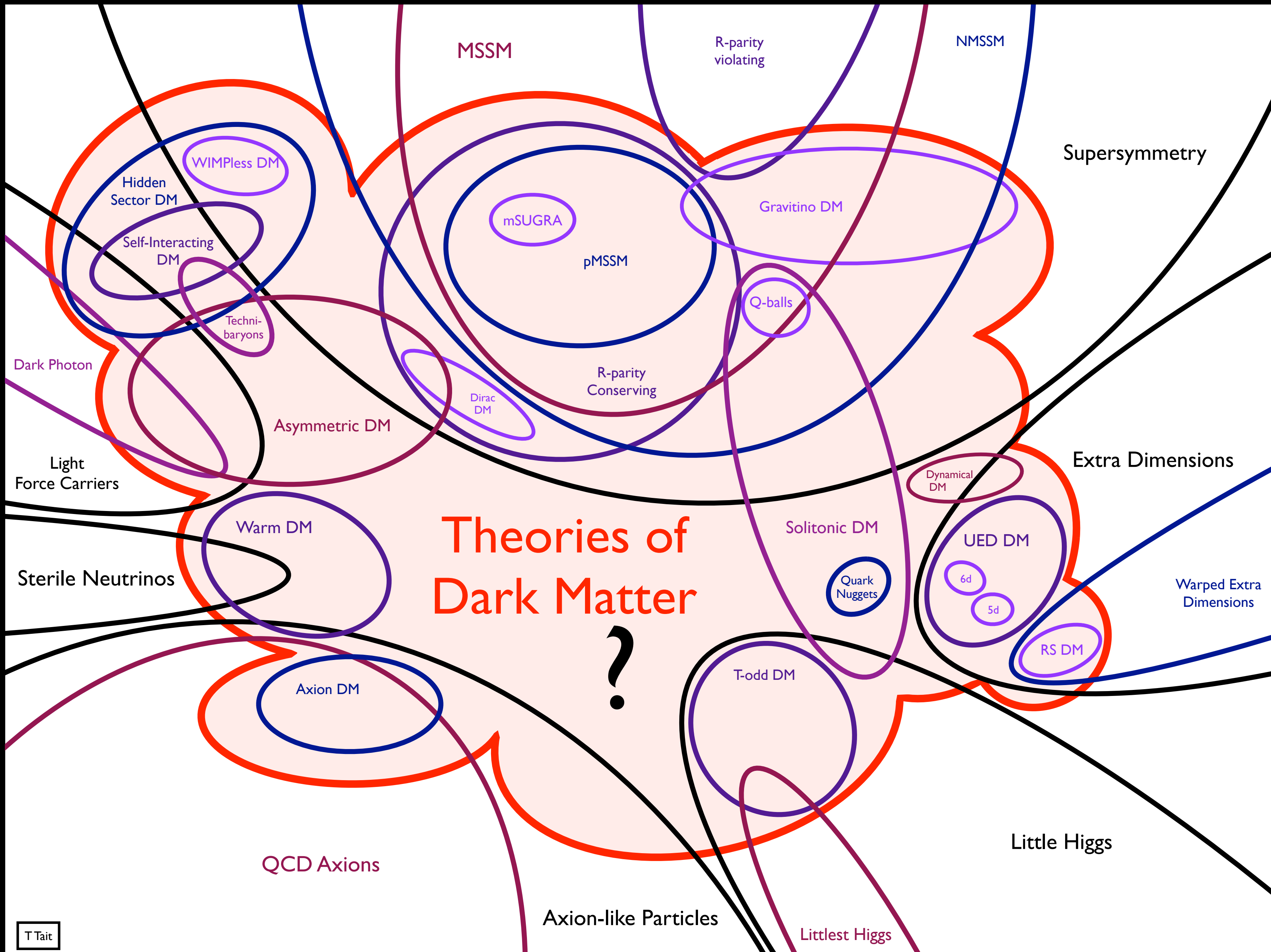
- Since we know essentially nothing about dark matter, it is possible that it is a very light particle.
  - Existing limits from galactic dynamics are around ~eV for fermions, and ~10^{-20} eV for bosons.
  - If the dark matter is produced in the early Universe through freeze-out, evading constraints from the CMB typically requires that there are also light dark forces.

- [ ] Mass
- [ ] Spin
- [ ] Stable?

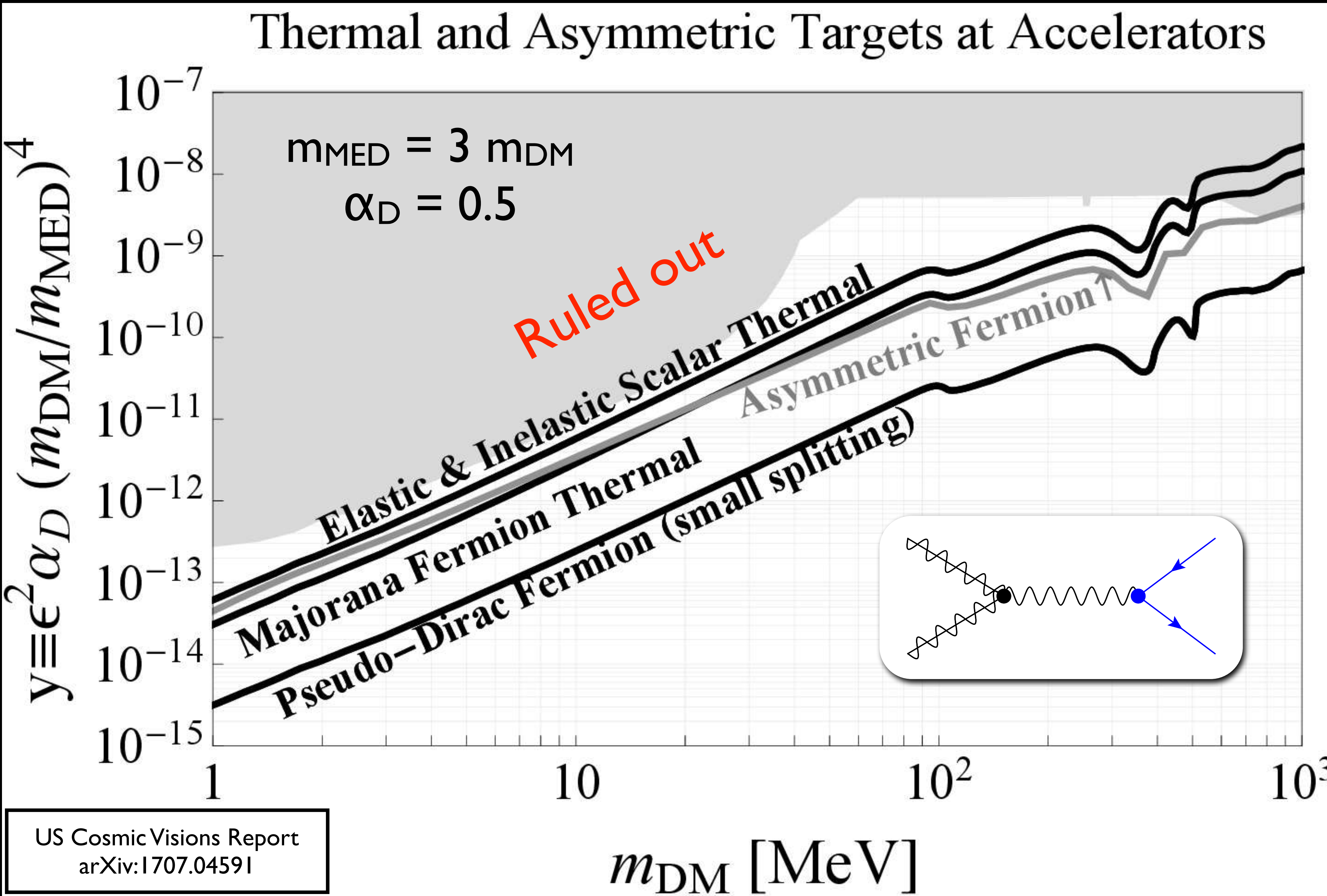
Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

Dark Matter


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter ?
Solitonic DM
UED DM
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Sterile Neutrinos
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

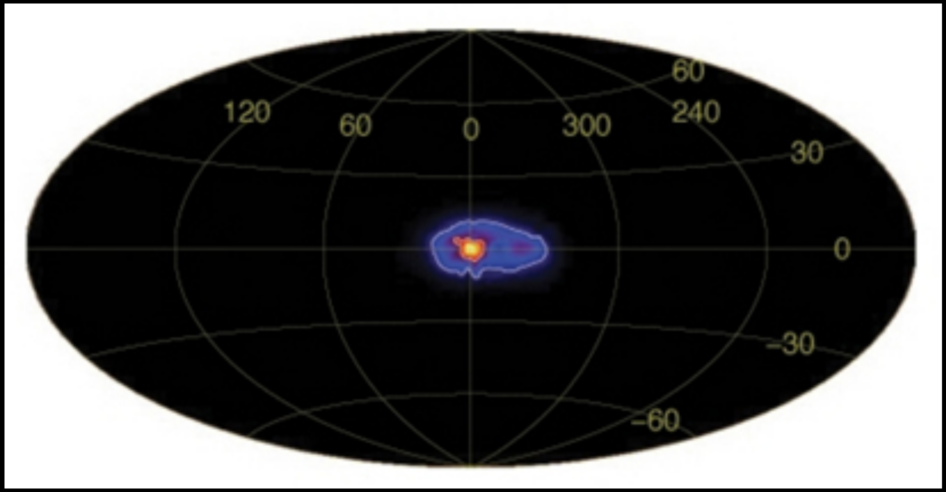
MeV Dark Matter



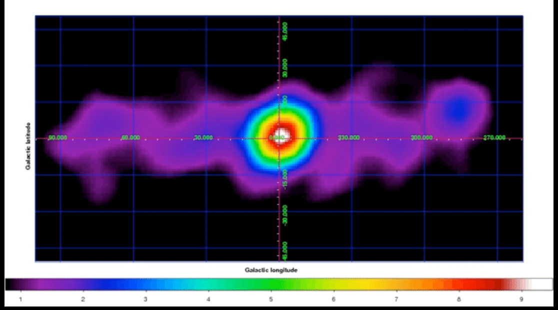
US Cosmic Visions Report
arXiv:1707.04591

MeV Dark Matter

- The Integral satellite measures the sky in hard X-rays. The line at 511 keV from e+e- annihilation tracks production of non-relativistic positrons.



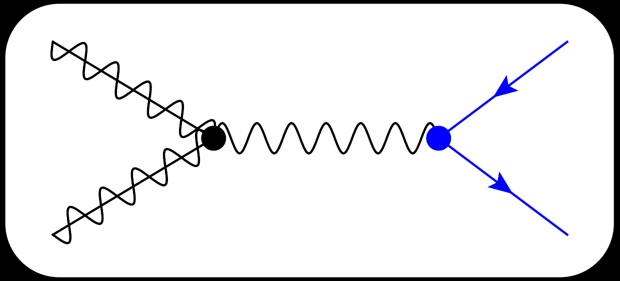
- They see an excess that correlates with the Galactic center, and could be a sign that dark matter annihilates into e+e-.



- (To be fair, it could also be an astrophysical production mechanism).

- To have the e+'s be non-relativistic, the dark matter mass can't be much more than the electron mass.

- Explaining the cross section can work if there is a mediator particle whose mass is also ~ MeV.

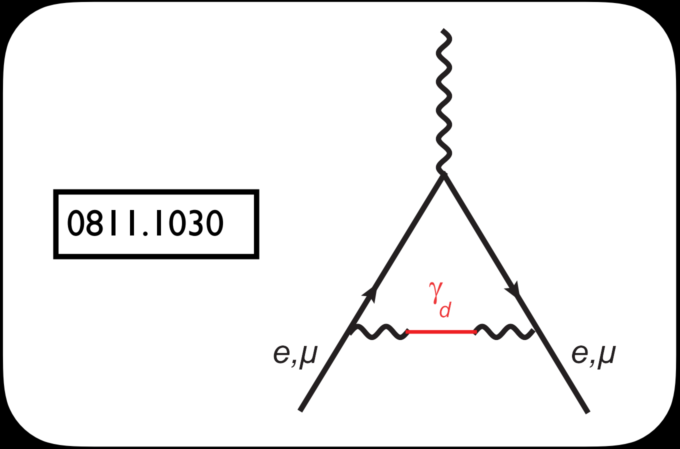


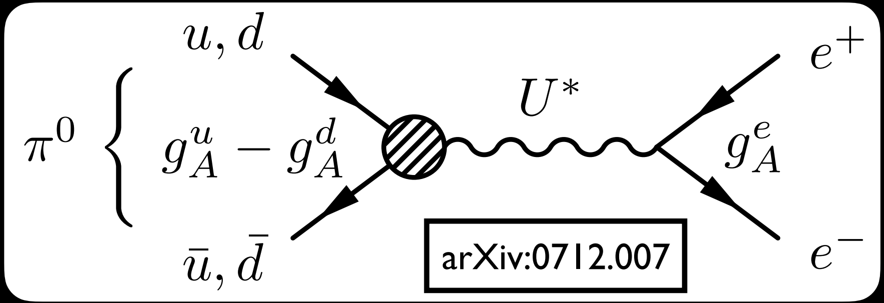
See: astro-ph/030968

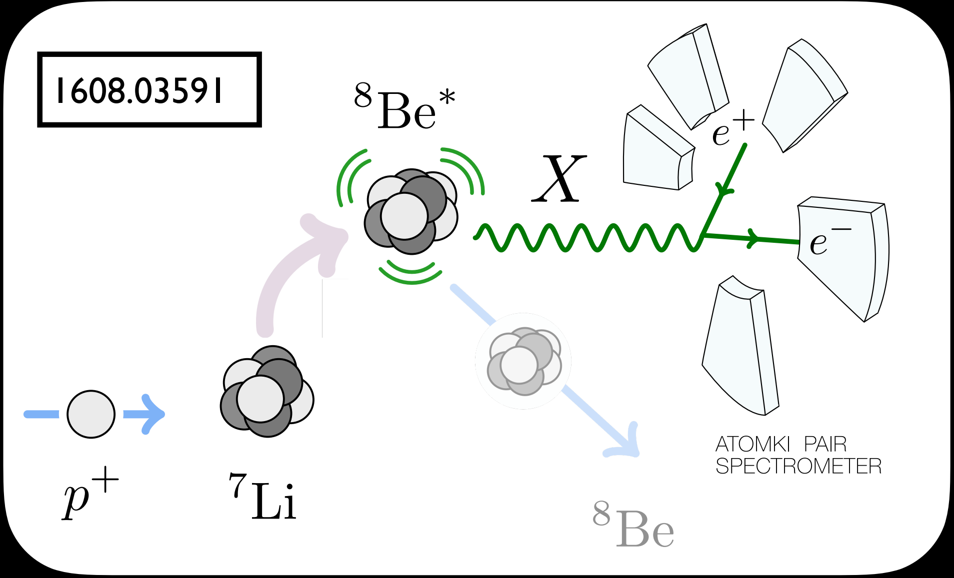
Experimental Anomalies

- While there is no decisive laboratory experimental evidence for light new particles, a few that show some deviation could hint at physics beyond the Standard Model.

- A few examples of puzzling experimental results that could hint at light new physics include:
  - Muon g-2
  - π^0 -> e+ e- (measured by KTeV)
  - ATOMKI Nuclear Transitions in Be-8 and He-4.
  - All three of these hint at ~MeV mass particles with super-weak coupling to the SM.



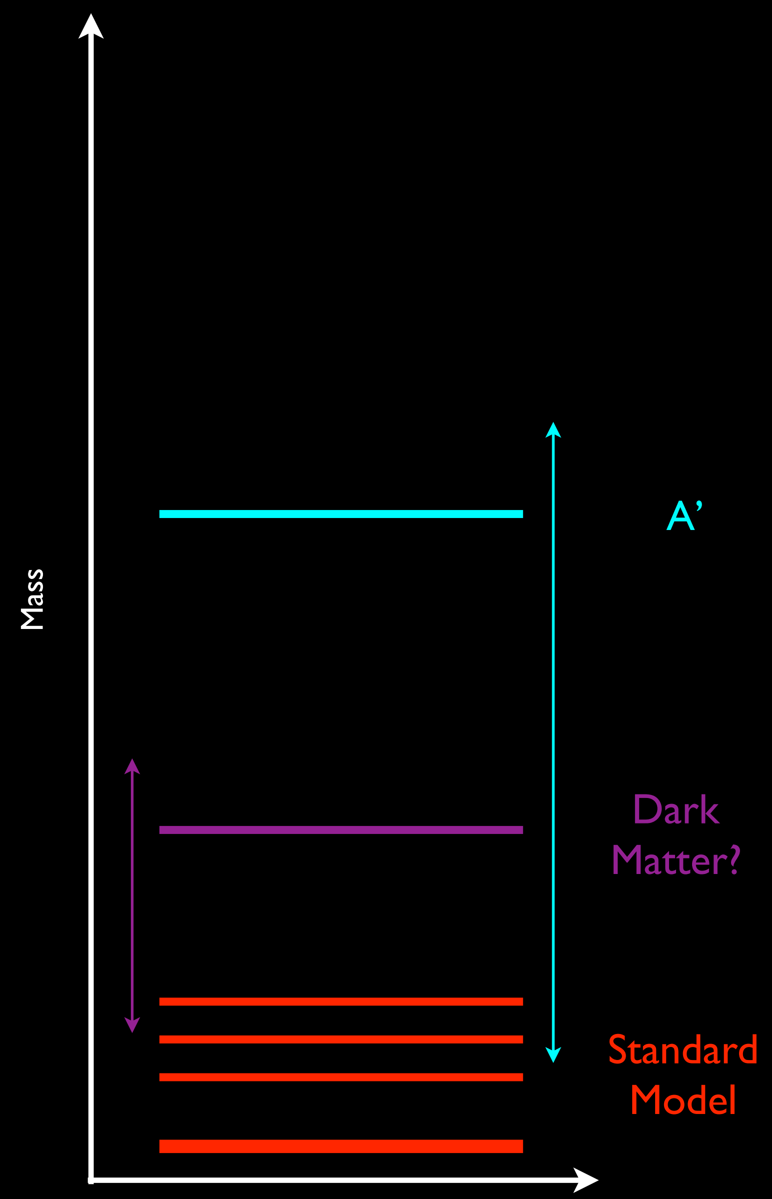




Vector Particles

Vector Simplified Model

- A reasonably simple extension of the SM is to add a light vector particle: A'.
- Quantum field theories of vector particles are a little bit delicate. If we write down interactions indiscriminately, we typically get a theory which is unphysical.
- The usual trick to avoid these problems is to associate the new vector with a gauge symmetry group. [For example a U(1).]
- Including only gauge-invariant terms in the Lagrangian avoids unphysical behavior.
- Then we need to specify how the symmetry acts on SM particles [their charges].



Dark Charge Assignment

- Each SM fermion species (Q, u, d, L, e) [plus right-handed neutrinos if they exist] and the Higgs needs a charge.

$$\{Q_Q, Q_u, Q_d, Q_L, Q_e, Q_H\}$$

- If there is a dark Higgs, we could define its charge as +1.

$$A'_\mu \sum_f \bar{f} \left(c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5 \right) f$$

- To avoid FCNC's, the fermions of each family are typically assigned the same charge. [But that is not essential].

$$c_V^f \equiv \frac{1}{2} g_D \left(Q_{f_L} + Q_{f_R} \right)$$

$$c_A^f \equiv \frac{1}{2} g_D \left(Q_{f_L} - Q_{f_R} \right)$$

- If the charges for Q, u, and d are equal, and L and e are equal, the theory will be vector-like. Otherwise, it will contain axial vector interactions.

$$\mathcal{L}_Y = y_u H Q \bar{u} + y_d H^\dagger Q \bar{d} + y_e H^\dagger L \bar{e}$$

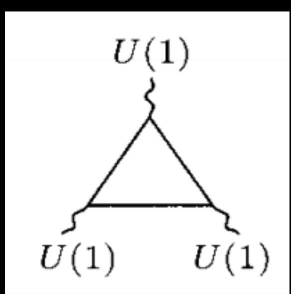
- We need to make sure that we can generate the SM Yukawa interactions.

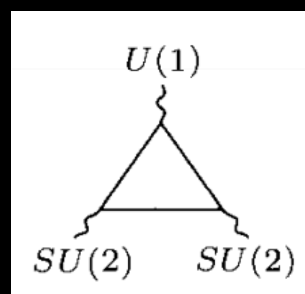
Allowed if, e.g. :

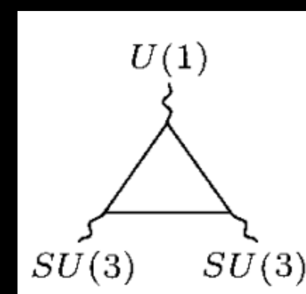
$$Q_H = Q_{f_R} - Q_{f_L}$$

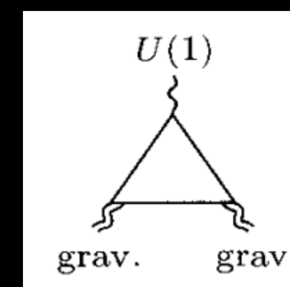
Anomalies

- A Quantum field theory with fermions can violate symmetries which appear to be present in the Lagrangian (e.g. at tree level).
- The dangerous contributions appear as triangle diagrams of fermions with gauge bosons attached to the vertices.





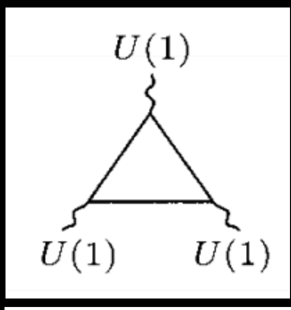




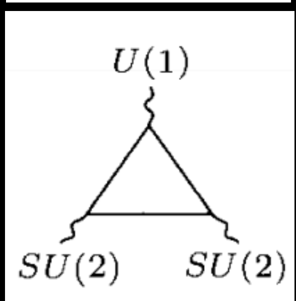
- If this happens for a global symmetry, it means that the Noether current associated with it is not conserved.
- If it happens for a gauge symmetry, that symmetry is violated, and this leads us back to unphysical behavior. So we can't allow that!

Anomalies

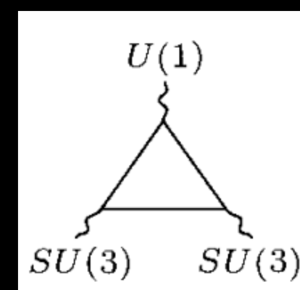
- The cancellation of the anomalies requires that there are relations between the charges of the fermions in the theory:



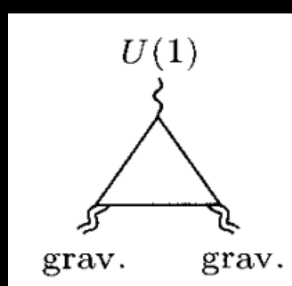
$$\sum_\psi Q_\psi^3 = 0 \qquad \sum_\psi Q_\psi Y_\psi^2 = 0 \qquad \sum_\psi Q_\psi^2 Y_\psi = 0$$



$$\sum_\psi Q_\psi \, T_{R_\psi}^{\mathrm{SU}(2)} = 0$$



$$\sum_\psi Q_\psi \, T_{R_\psi}^{\mathrm{SU}(3)} = 0$$



$$\sum_\psi Q_\psi = 0$$

Exercise: Prove that $U(1)_{B-L}$ is not anomalous if we add 3 RH neutrinos.

If the anomalies don't cancel summing over the SM fermions, additional fermions are necessary to make things cancel. They are often charged under the SM gauge groups (and have color and/or charge as a result). I often call those particles "anomalons".

Mass Mixing

- The dark vector particle could get its mass in part from the SM Higgs, and there are usually other contributions as well.
  - For example a dark Higgs sector.
  - For a U(1), a Stuckelberg mass.
- If Q_H is nonzero, after EWSB, the mass matrix contains mixing terms between the SM Z and the A'.
  - This implies the A' picks up some of the Z boson's interactions, and the Z interactions are modified as well.
  - LEP constraints on the Z boson properties typically require such mixing to be less than about 10^{-3}.

Gauge basis:

$$\begin{bmatrix} \hat{m}_Z^2 & -g_D q_H v \hat{m}_Z \\ -g_D q_H v \hat{m}_Z & g_D^2 q_H^2 v^2 + \hat{m}_{A'}^2 \end{bmatrix}$$

Diagonalized by:

$$\begin{bmatrix} \hat{Z}_\mu \\ \hat{A}'_\mu \end{bmatrix} = \begin{bmatrix} \cos\eta & \sin\eta \\ -\sin\eta & \cos\eta \end{bmatrix} \begin{bmatrix} Z_\mu \\ A'_\mu \end{bmatrix}$$

Gauge Basis — Mass Basis

$$\tan 2\eta = \frac{-2 g_D Q_H v \hat{m}_Z}{(g_D^2 Q_H^2 v^2 + \hat{m}_{A'}^2) - \hat{m}_Z^2}$$

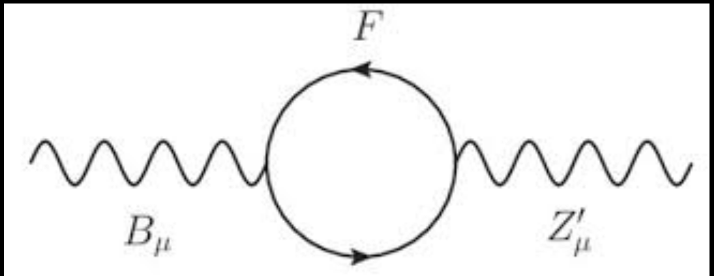
$$\hat{Z}_\mu J^\mu_{\rm NC} \to \left(\cos\eta Z_\mu + \sin\eta A'_\mu\right) J^\mu_{\rm NC}$$

Where: $J^\mu_{\rm NC} = \frac{e}{s_W c_W}\left(T_3 - Q s_W^2\right)$

Kinetic Mixing

- In addition to mass mixing, the A' could also pick up couplings through kinetic mixing.
- If it corresponds to a U(1) gauge symmetry, a kinetic term mixing with the Hypercharge force is gauge invariant, and thus allowed.
- In fact, if there are particles charged under both the dark group and hypercharge, such a term will be induced at the loop level.
- The parameter ε controls the size of the kinetic mixing.
- Going to the mass basis induces a coupling proportional to the photon's interactions.

$$-\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} + \frac{\epsilon}{2c_W}\hat{B}^{\mu\nu}\hat{F}'_{\mu\nu} - \frac{1}{4}\hat{F}'^{\mu\nu}\hat{F}'_{\mu\nu}$$



$$\hat{A}_\mu \to \hat{A}_\mu + \epsilon \hat{A}'_\mu, \quad \hat{Z}_\mu \to \hat{Z}_\mu - \epsilon t_W \hat{A}'_\mu, \quad A'_\mu \to A'_\nu$$

$$e\hat{A}_\mu J^\mu_{\rm EM} \to e\left(\hat{A}_\mu + \epsilon \hat{A}'_\mu\right) J^\mu_{\rm EM}$$

In the limit of purely kinetic mixing, A' is usually called a "dark photon".

A' Coupling Recap

- As a recap, the couplings of the dark gauge boson to the SM fields receive three contributions:
  - Directly from the charges of the SM fields:

$$A'_\mu \sum_f \bar{f} \left(c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5 \right) f$$

  - Through mass-mixing with the Z boson (if Q_H is nonzero):

$$\hat{Z}_\mu J^\mu_{\rm NC} \to \left(\cos\eta Z_\mu + \sin\eta A'_\mu \right) J^\mu_{\rm NC}$$

  - (If the charges allow SM Yukawa couplings, the axial part of these two pieces cancel each other. EXERCISE: Prove this statement!).
  - Through kinetic mixing with the photon (if ε is nonzero):

See: 1609.09072 for more details!

$$e\hat{A}_\mu J^\mu_{\rm EM} \to e \left(\hat{A}_\mu + \epsilon \hat{A}'_\mu \right) J^\mu_{\rm EM}$$

- The physical couplings of the A' are the sum of all three of these.

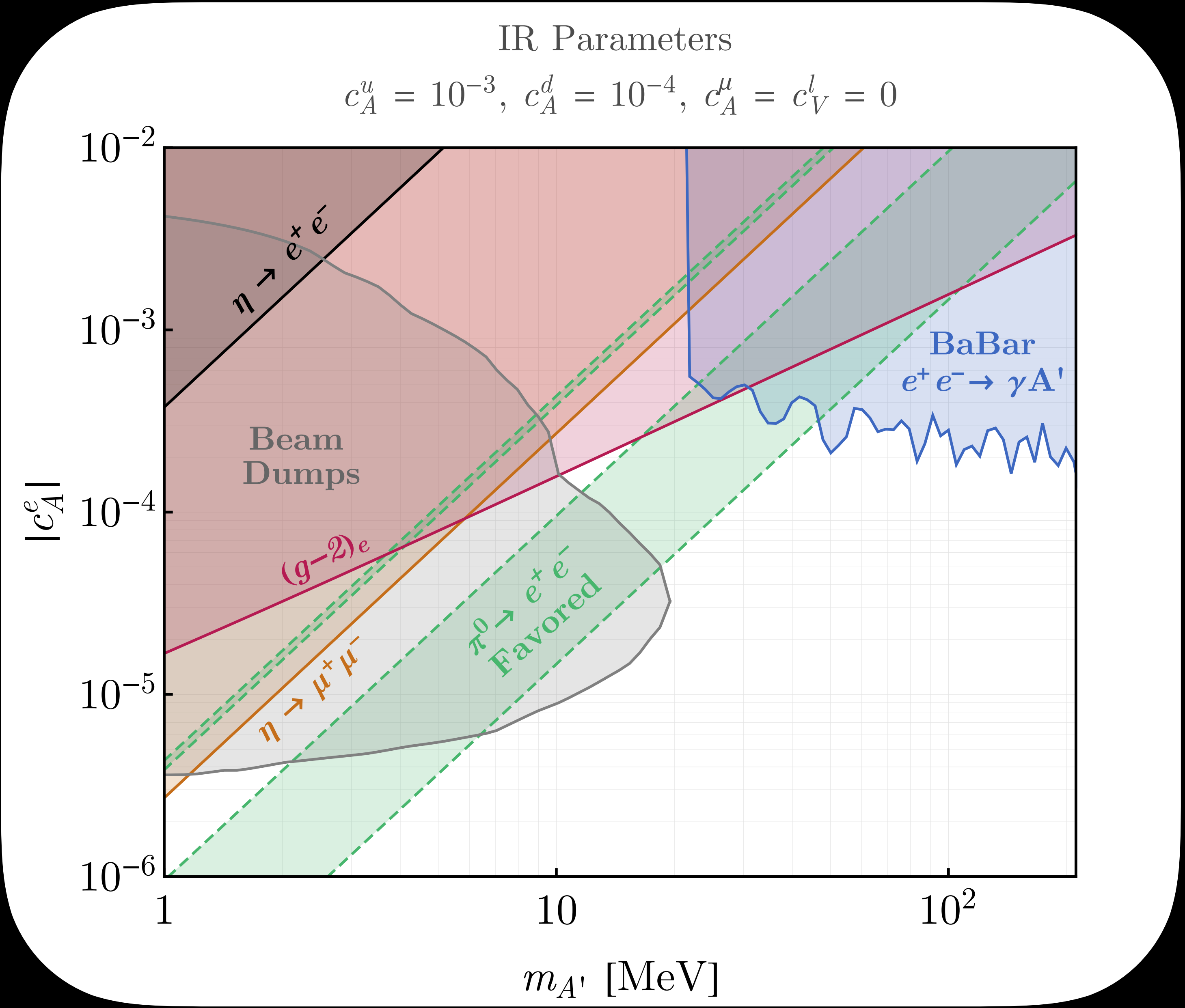
Experimental Constraints

- There is a wealth of data informing the parameter choices for light vector particles. Some of the important ones include:
  - $(g-2)_e$ and $(g-2)_\mu$, which is famously high by about 3.5σ and thus could be suggestive of target regions of parameter space in muon couplings.
  - Atomic Parity Violation (APV) in cesium at $Q^2 \sim (30\ \text{MeV})^2$ which constrains products of $c^q_V \times c^e_A$.
  - Parity violation in Moller scattering by E158 at SLAC at $Q^2 \sim (100\ \text{MeV})^2$ which constrains the product $c^e_V \times c^e_A$.
  - Neutrino-Electron scattering by Borexino and TEXONO at $Q^2 \sim (\text{MeV})^2$ which constrains the product $c^e_V \times c^\nu$, through interference with the SM process.
  - Meson decays, such as searches for $\pi 0 \to \gamma A'$ by NA48/2, which puts strong constraints on a combination of c^u_V and c^d_V, but much milder constraints on the axial vector interactions.

Experimental Constraints

- Meson decay π^0 -> e+ e- as measured by KTeV. Since they see a ~2.5σ discrepancy with the SM, this favors specific choices of the couplings (c^u_A - c^d_A) x c^e_A and mass of the A'. (Also: there are constraints from η decays into e+e- and μ+μ-).
- The annihilation process e+e- -> γ A' at high intensity colliders (such as B-factories) puts a constraint on ($c^e{}_V{}^2 + c^e{}_A{}^2$).
- Similarly, fixed target experiments can use the process e p -> e p A' through bremsstrahlung to also put a constraint on ($c^e{}_V{}^2 + c^e{}_A{}^2$).
- If $m_{A'} > 2\ m_\mu$, the A' can decay visibly into dimuons, which could be visible in decays of heavy vector mesons such as ψ or Υ -> γ A'. These put constraints on the c_A couplings for the heavy quarks, c and b.
- Conversely, for $m_{A'} < 2\ m_e$, the A' has only very suppressed decays to neutrinos or to 3 γ's. Generally there are strong constraints from stellar cooling bounds.

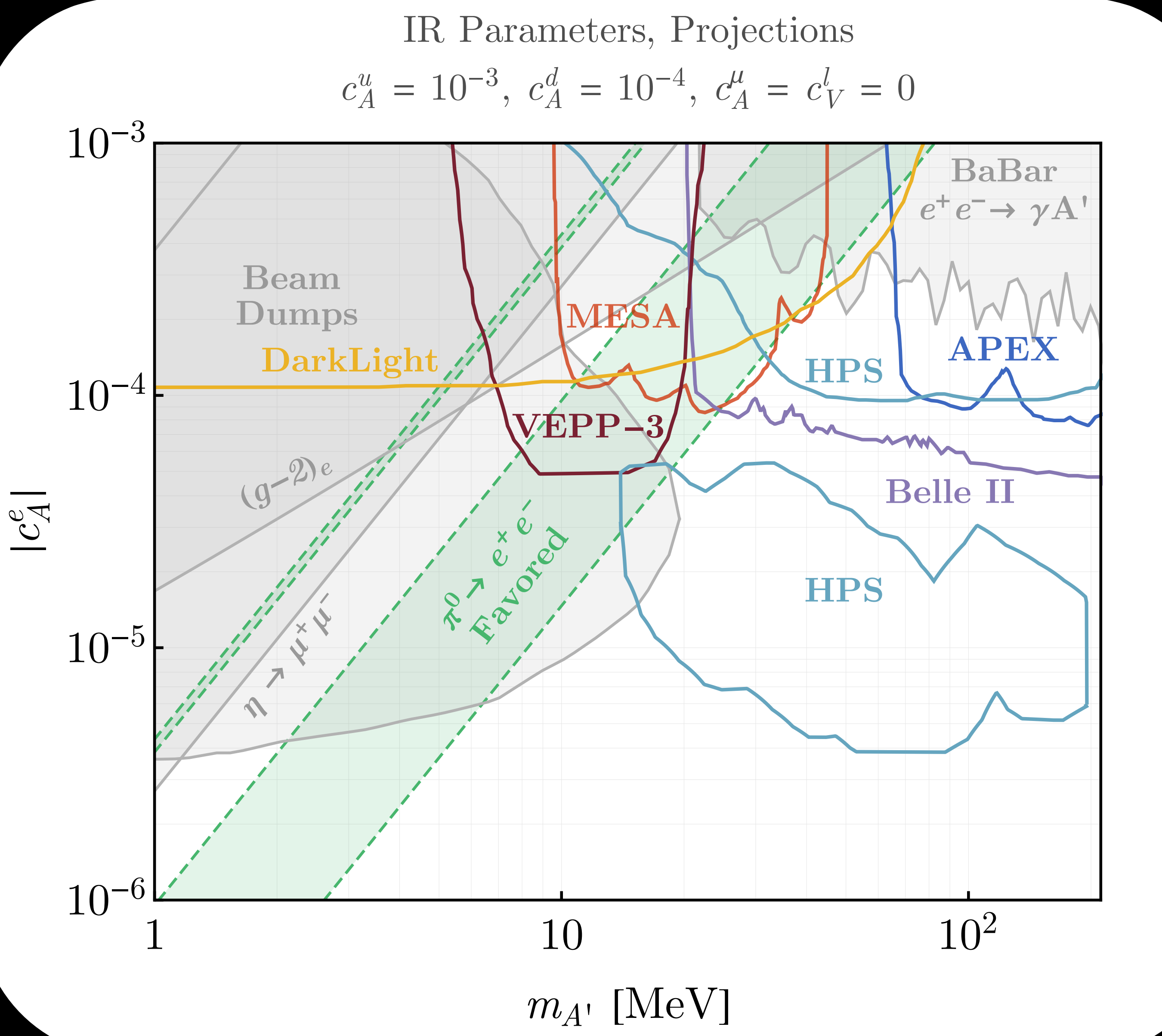
IR Benchmark #1



All other couplings assumed to vanish.

1609.09072

Future Projections



All other couplings assumed to vanish.

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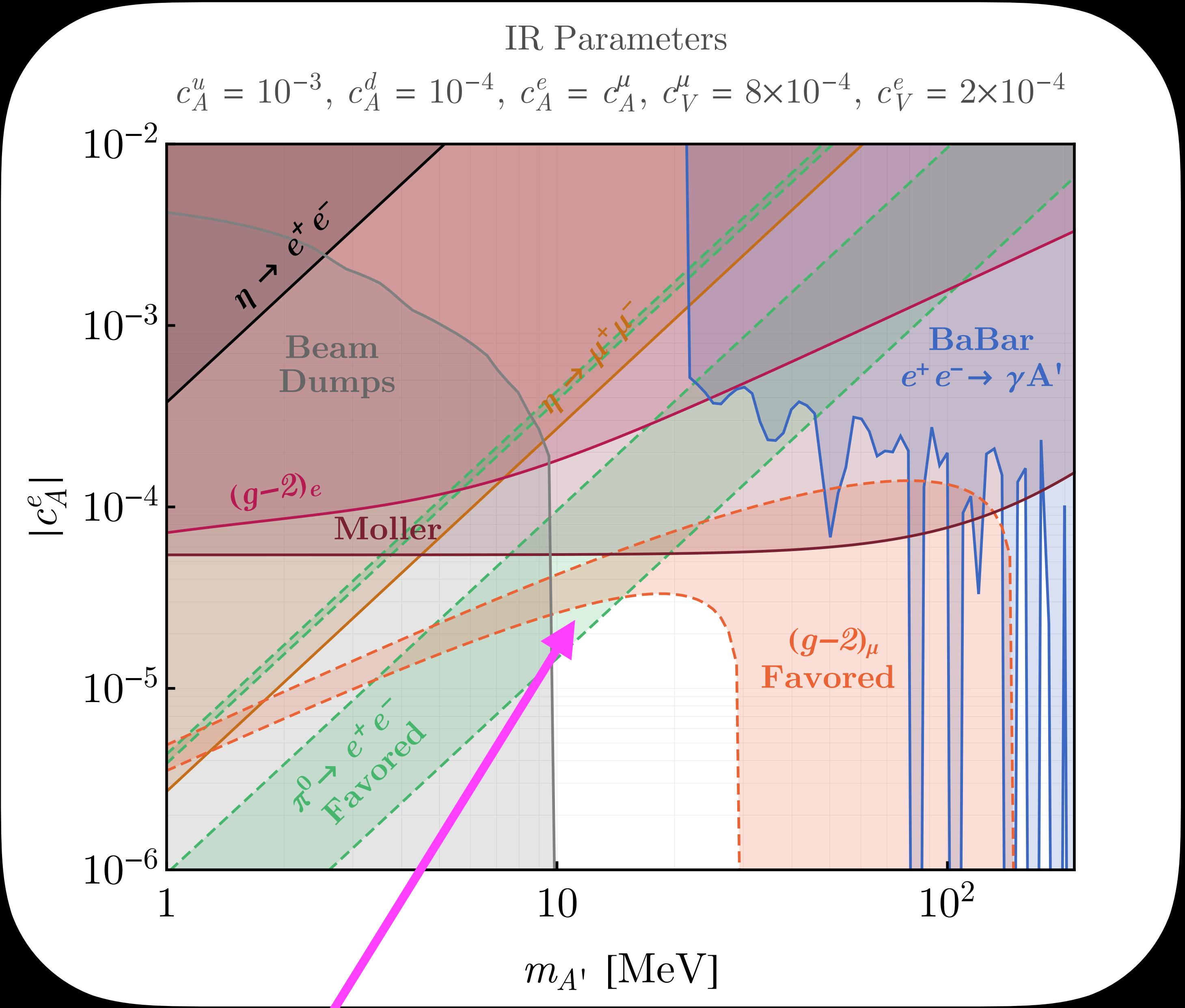
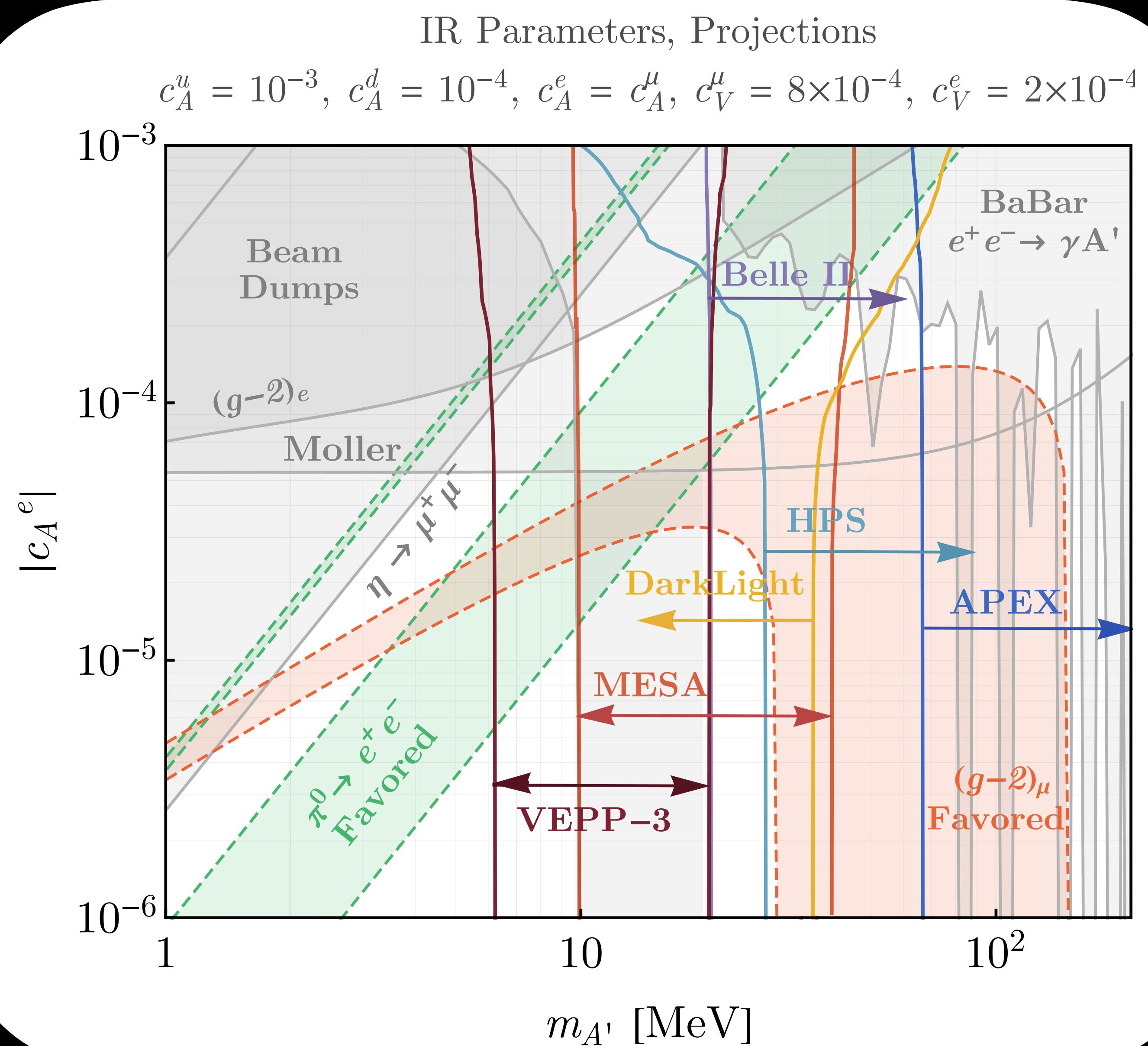
IR Benchmark #2



Possible to fit g-2 and KTeV.

1609.09072

Future Projections

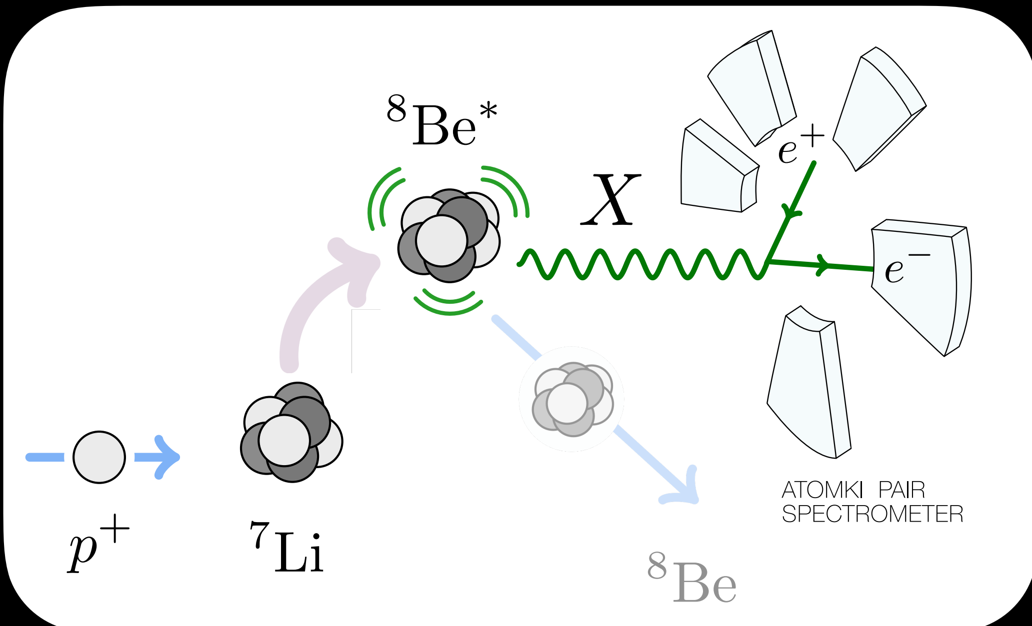


1609.09072

Case Study: ATOMKI X17

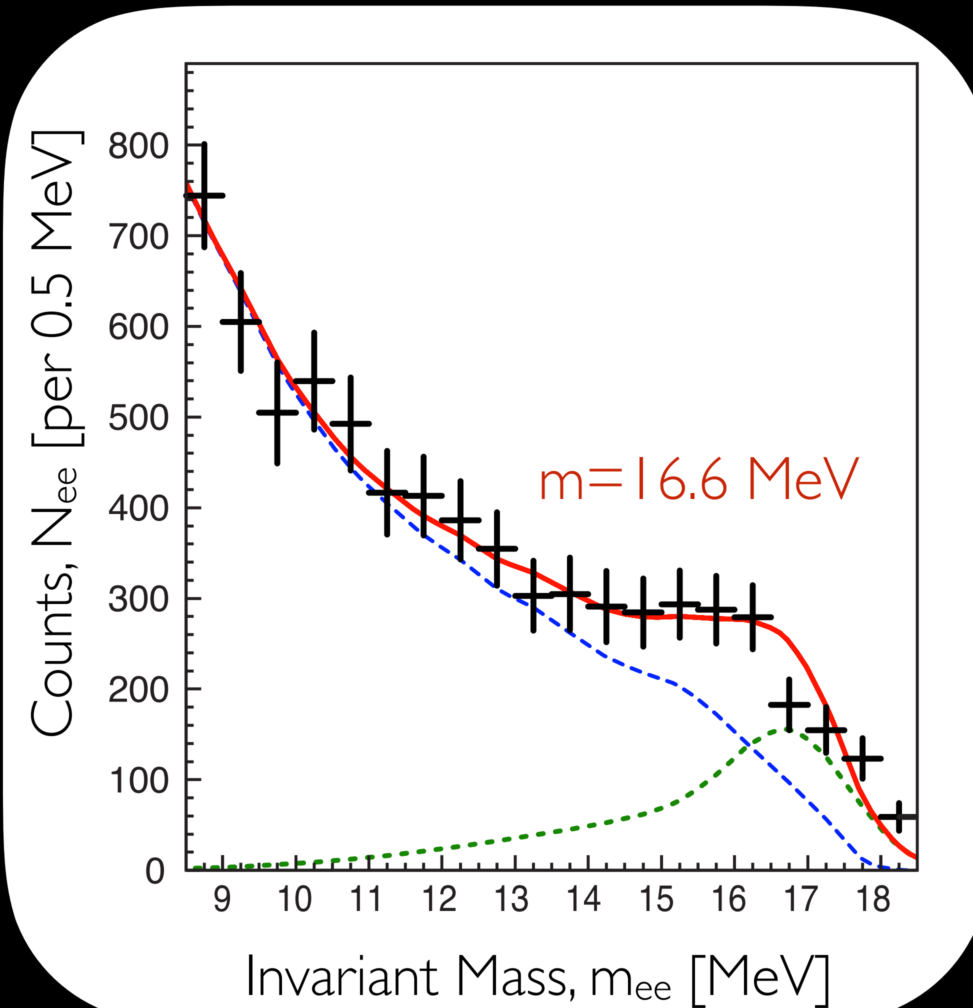
Observation of Anomalous Internal Pair Creation in 8Be: A Possible Signature of a Light, Neutral Boson

A.J. Krasznahorkay, et al. PRL 116, 042501(2016); arXiv:1504.01527



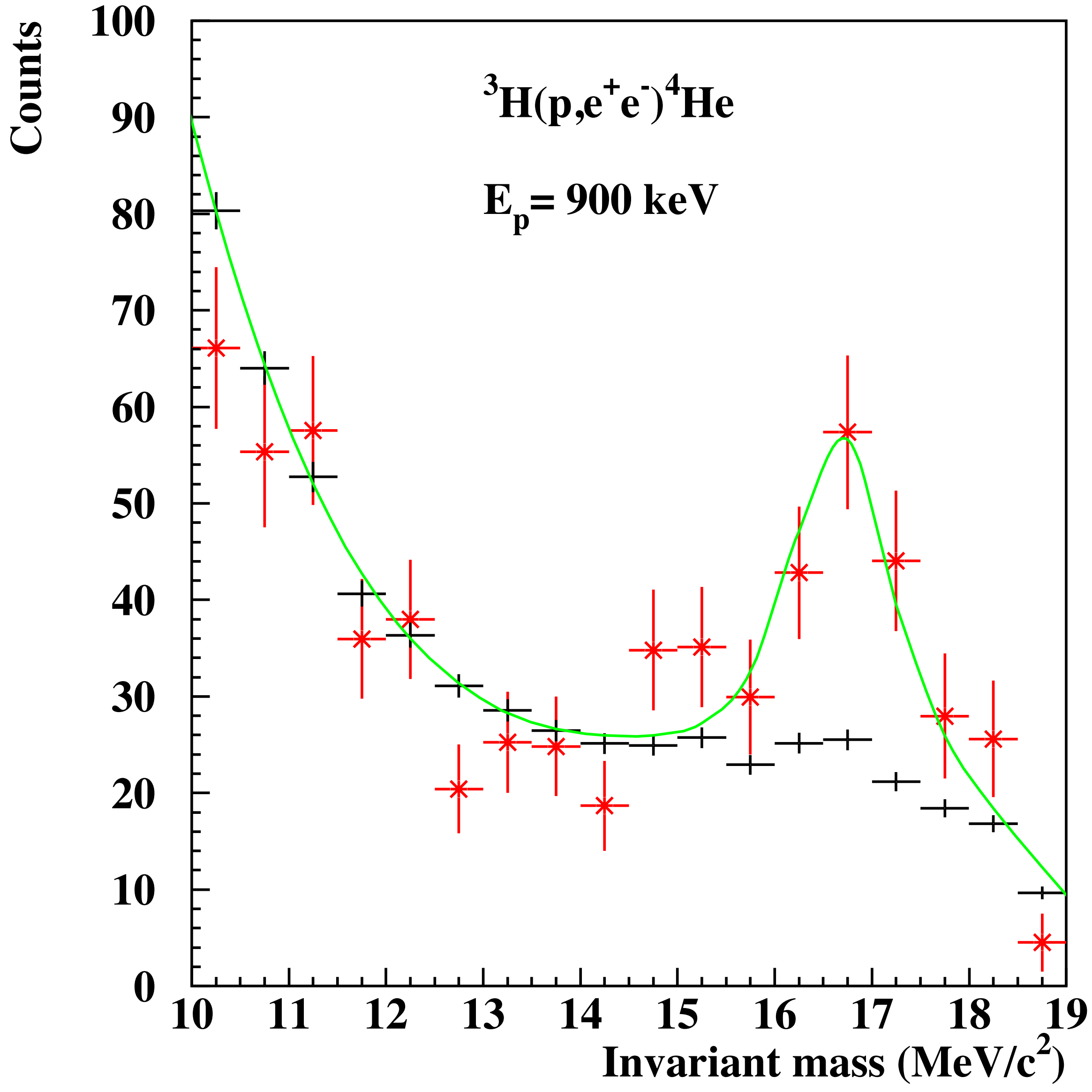
$$m_X = 16.7 \pm 0.35\,(\mathrm{stat}) \pm 0.5\,(\mathrm{sys})\ \mathrm{MeV}$$

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X)}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma)}\,\mathrm{Br}(X \to e^+e^-) = 5.8 \times 10^{-6}$$



I'll explore a light spin-1 particle with vector couplings as the X particle. Of course, this result needs experimental confirmation, and to rule out nuclear physics explanations.

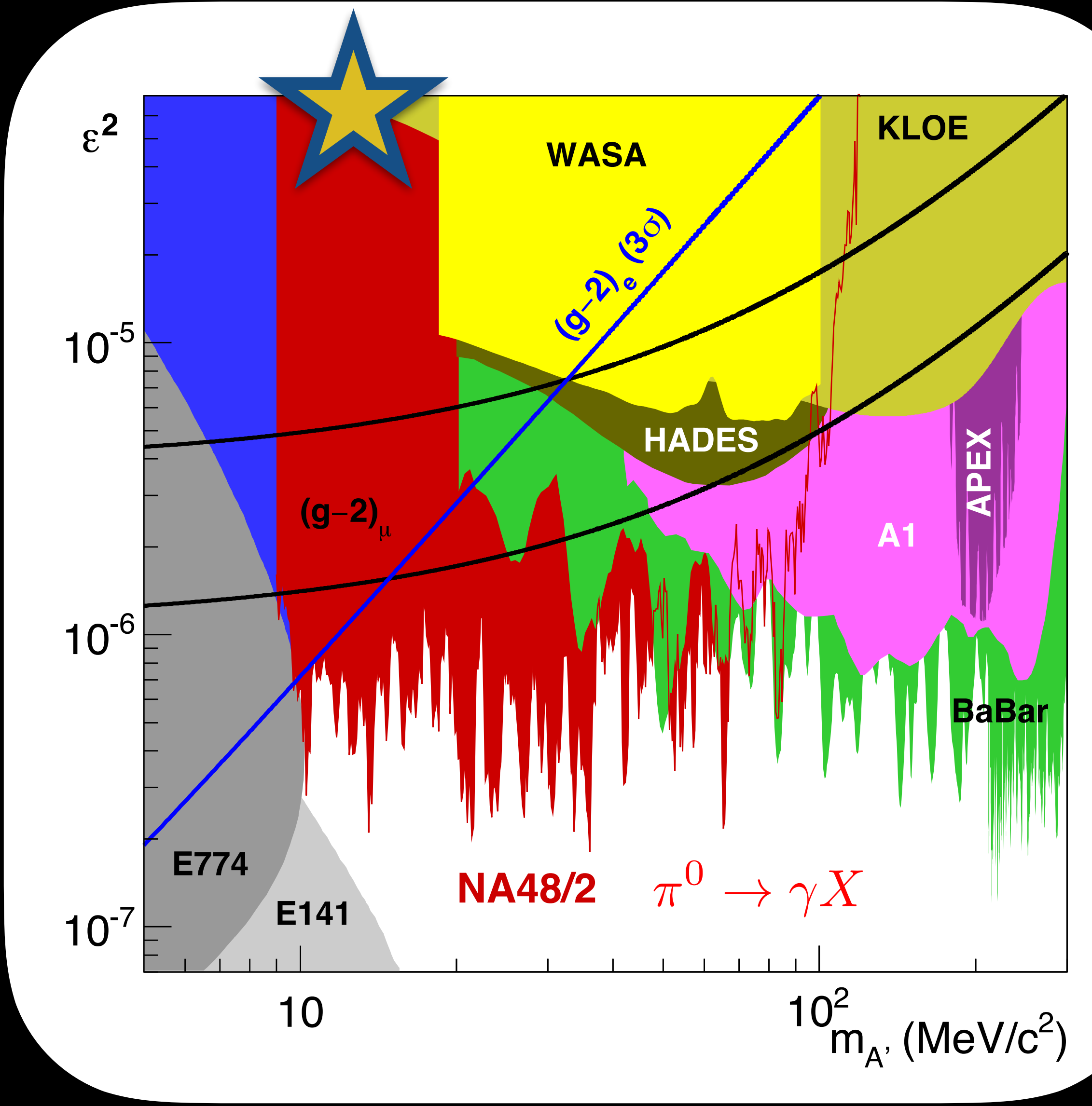
He-4



In 1910.10459, they report evidence of a similar excess in a transition of He-4 for essentially the same mass of ~17 MeV.

Dark Photon

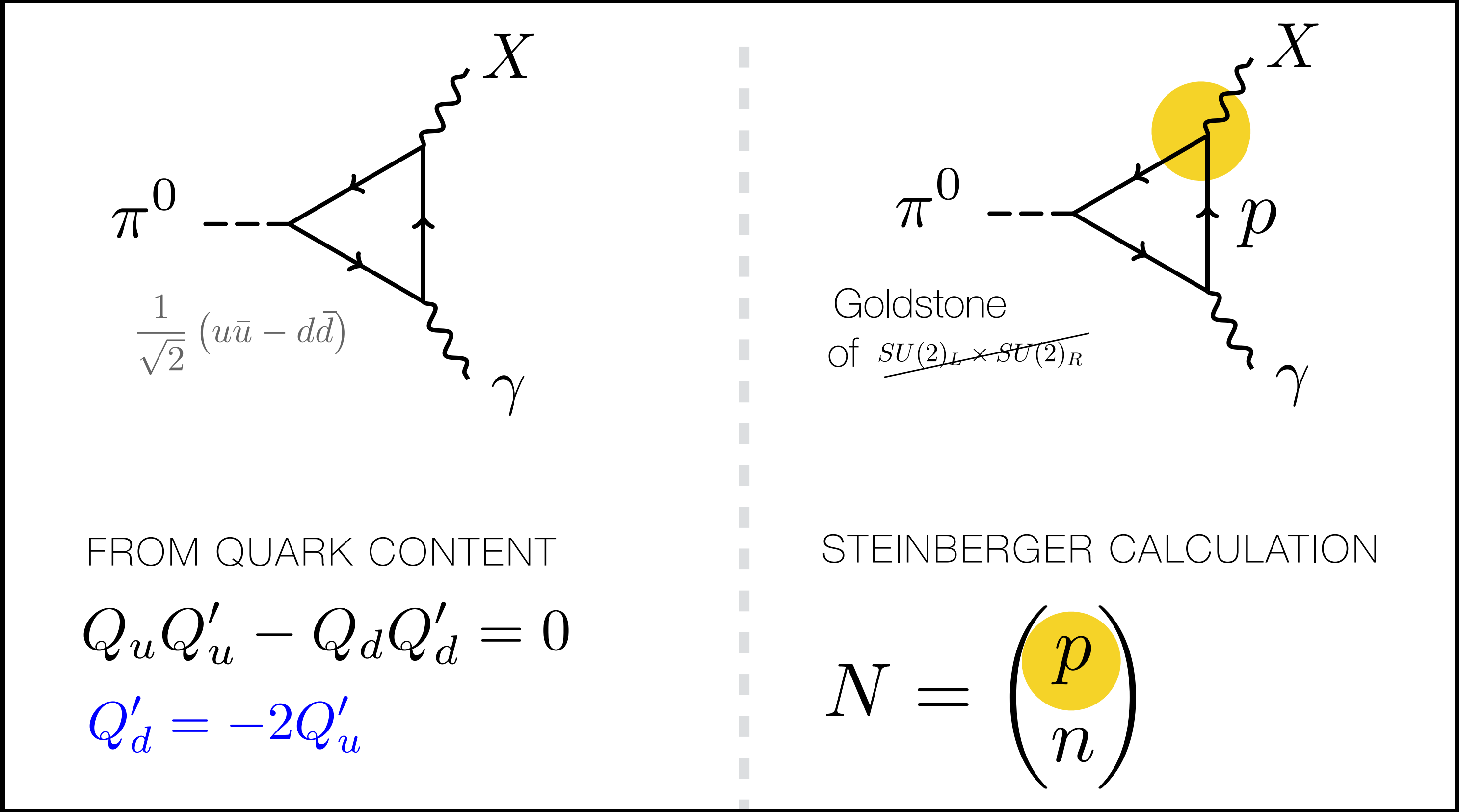
- I decided (somewhat arbitrarily) to look at models with vector couplings.
- As we already saw, a simple model with vector couplings is the dark photon limit, where all of the SM charges are zero, and there is no mass mixing.
- There can still be kinetic mixing, and the entire parameter space in that case is the A' mass and ε.
- However, this is strongly ruled out by NA48/2 for couplings big enough to explain ATOMKI results.



NA48/2 1504.00607

Proto-phobic Vectors

- We'd like to engineer away the bounds from NA48/2 without turning off couplings to first generation quarks altogether, which drives us to ``proto-phobic'' couplings:



- (Also note that axial vectors will naturally evade NA48/2, since their couplings to π^0 do not go through the anomaly, and are thus suppressed by the small quark masses.)

Fit to ATOMKI

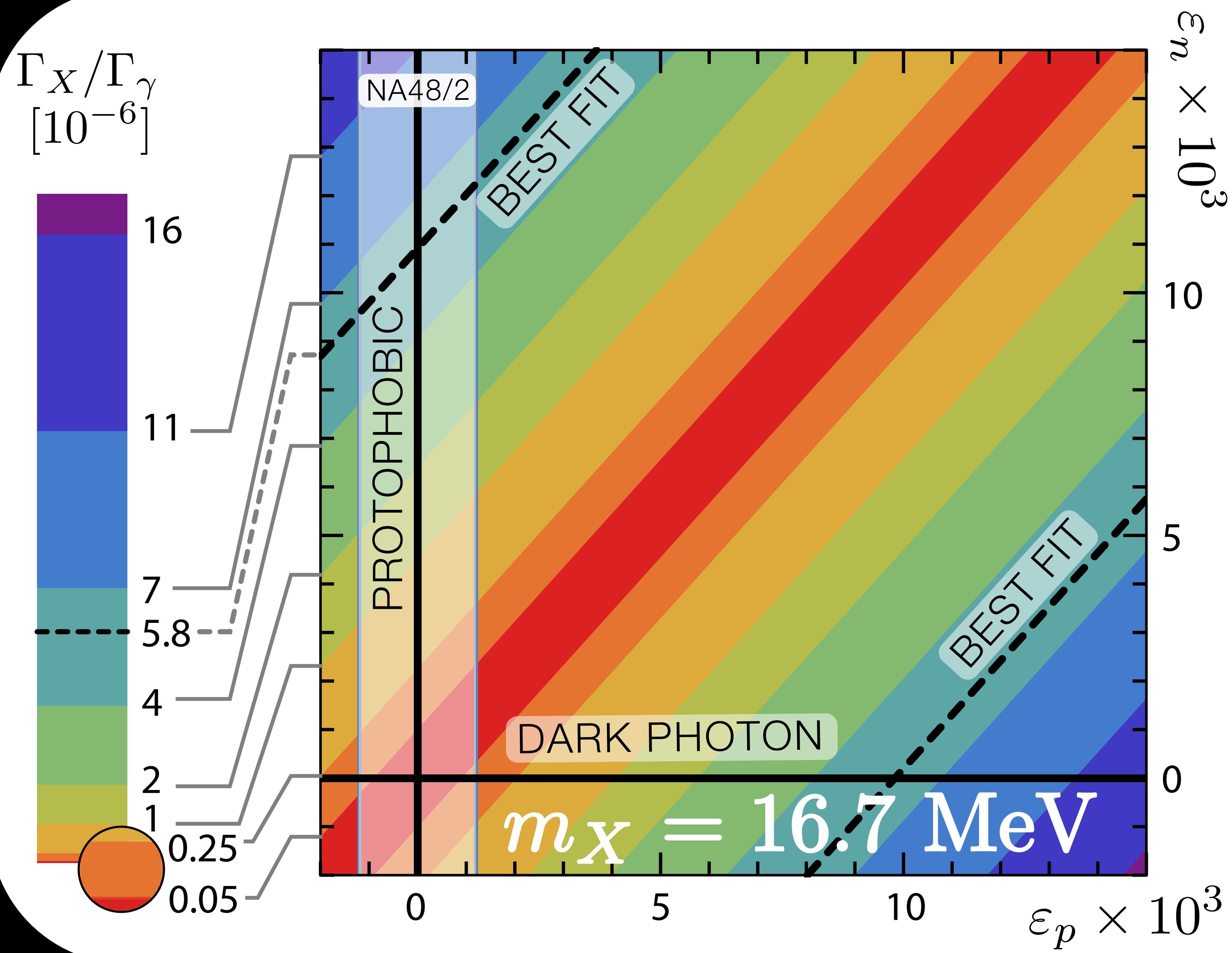
$$\frac{\Gamma_X}{\Gamma_\gamma} = \frac{|(\varepsilon_p+\varepsilon_n)\beta_1 M1_{1,T=0} + (\varepsilon_p-\varepsilon_n)(-\alpha_1 M1_{1,T=1}+\beta_1\kappa M1_{1,T=1})|^2}{|\beta_1 M1_{1,T=0} - \alpha_1 M1_{1,T=1} + \beta_1\kappa M1_{1,T=1}|^2}\frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3}$$

arXiv:1609.07411

Nuclear Physics…

$$g_i \equiv e \times \varepsilon_i$$

To explain the ATOMKI results, one would like a coupling ε to neutrons of order 10^{-2} and one to protons < about 10^{-3}.

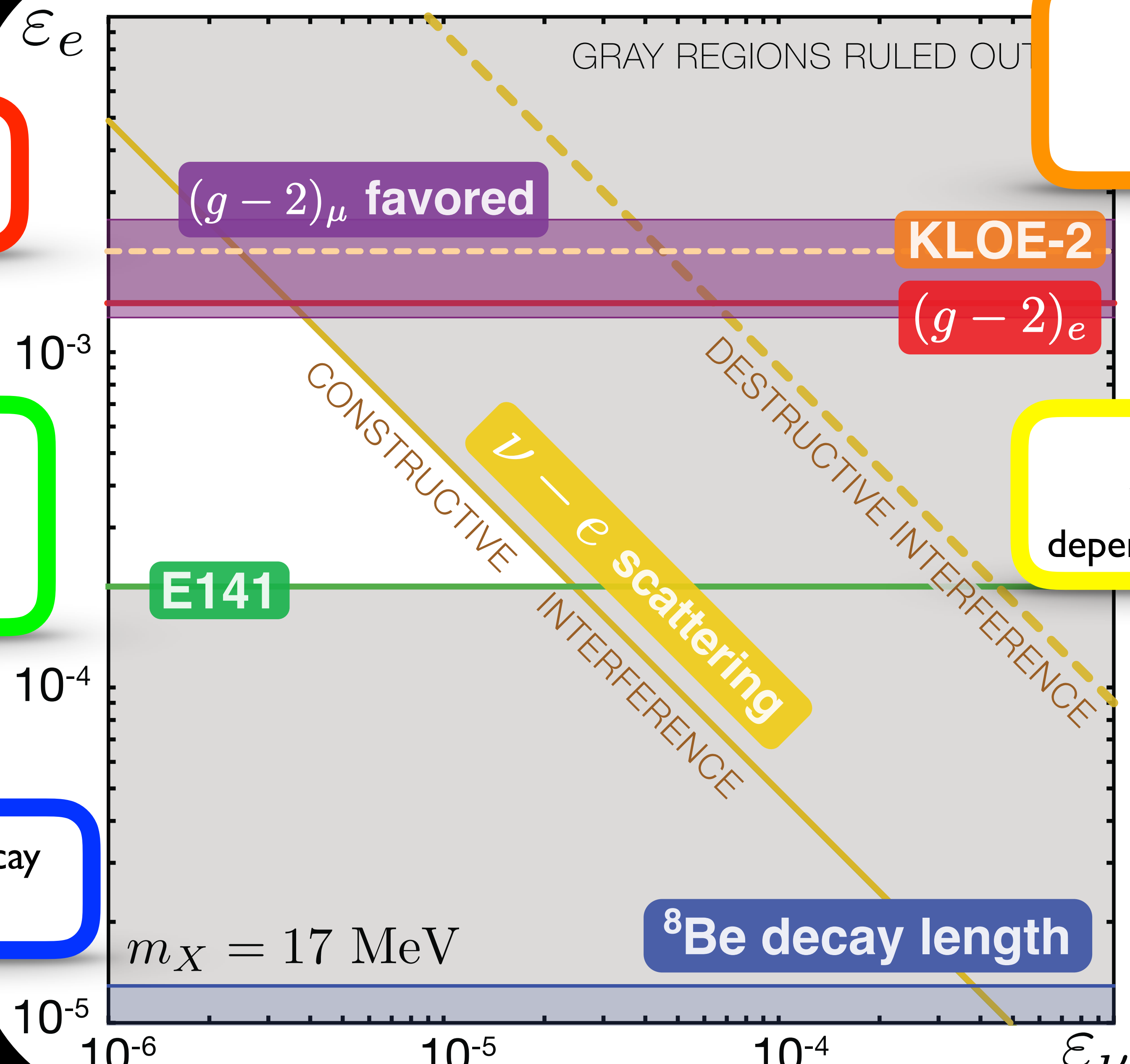


Lepton Couplings

(g-2)$_e$

E141:
Lower bound so
X decays inside
the beam dump

Prompt X decay
at ATOMKI



KLOE-2:
e+e- → γX

TEXONO:
ν-e scattering;
depends on interference

arXiv:1609.07411

Summary of IR Parameters

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

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

Protophobic to ~10%

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

E141 and $(g\text{-}2)_e$

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

TEXONO

arXiv:1609.07411

Future Outlook

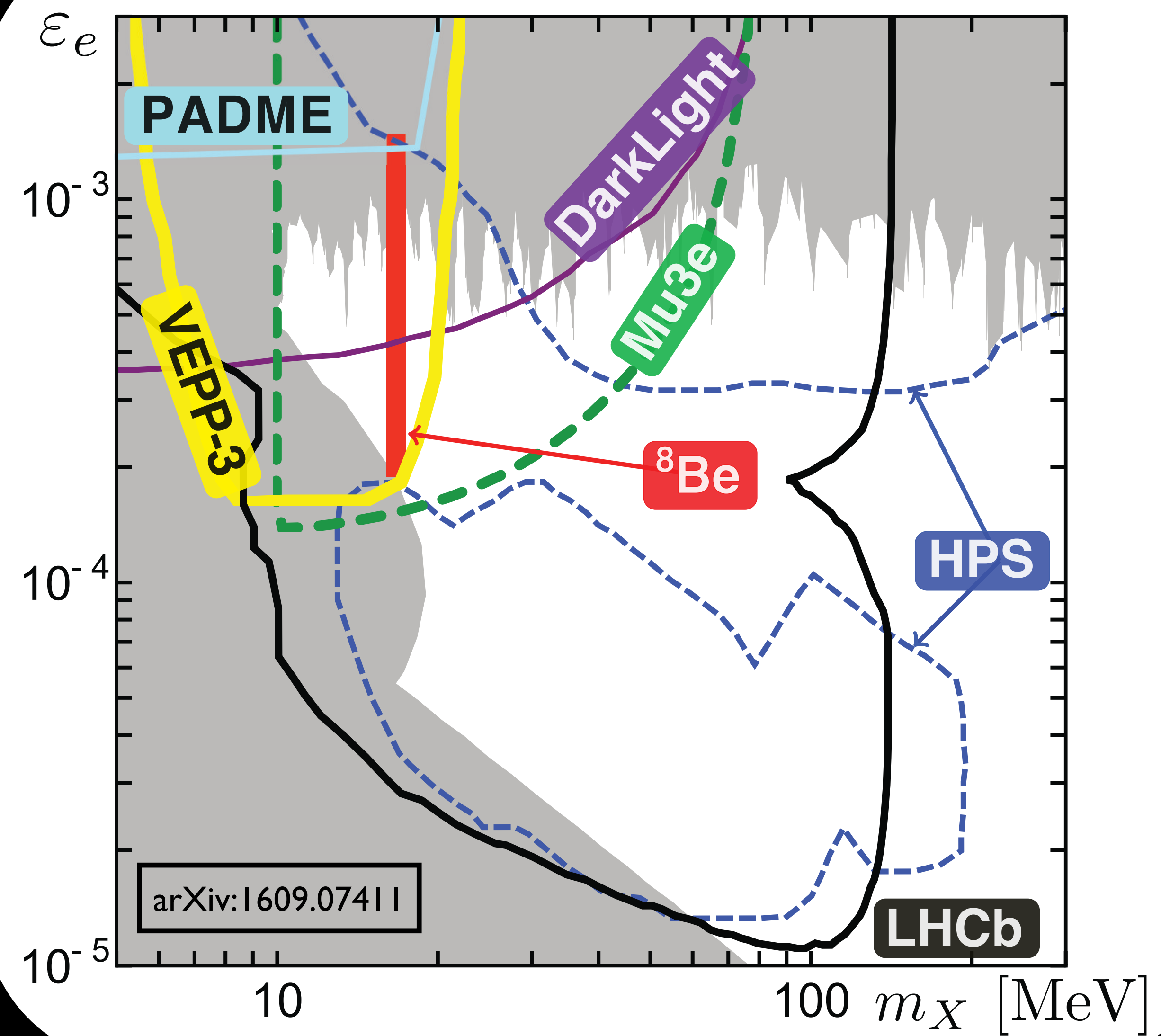
- Upcoming low energy experiments can probe the relevant parameter space…

Mu3e, phase 2
(starting 018)

LHCb, run 3
(2021-2023)

Darklight
e+e- ⟶ γX
(a few years?)

VEPP-3 (proposed)
e+e-⟶γX



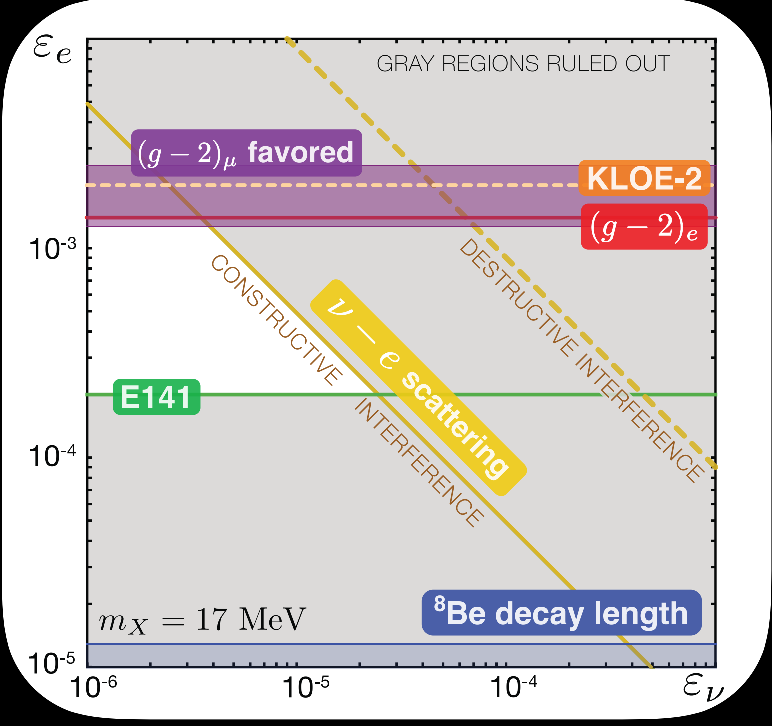
UV Model: U(1) Baryon

- To begin with, take $U(1)_B$.
- By itself, this results in equal couplings to proton and neutron. The proton is neutralized if we tune the kinetic mixing parameter $\varepsilon = - g_B$.
  - This tuning is O(10%) to successfully evade NA48/2.
- The electron couplings tend to be generically a bit too big.
  - (However, the muon couplings are in the ballpark needed to address $(g - 2)_\mu$!)
- Neutrino couplings are naturally zero.

$$\begin{aligned}
\varepsilon_u &= \frac{1}{3}\varepsilon_B + \frac{2}{3}\varepsilon \\
\varepsilon_d &= \frac{1}{3}\varepsilon_B - \frac{1}{3}\varepsilon \\
\varepsilon_\nu &= 0 \\
\varepsilon_e &= -\varepsilon \ .
\end{aligned}$$

$$\epsilon = -g_B + \delta$$

$$\begin{aligned}
\varepsilon_u &= -\frac{1}{3}\varepsilon_B + \frac{2}{3}\delta \\
\varepsilon_d &= \frac{2}{3}\varepsilon_B - \frac{1}{3}\delta \\
\varepsilon_\nu &= 0 \\
\varepsilon_e &= \varepsilon_B - \delta \ ,
\end{aligned}$$



U(1) Baryon Anomalons

- Cancelling anomalies requires us to add more fermions.
- A set of fermions which look like a chiral family of leptons (but carrying baryon number) will do the trick.
- The U(1)B - breaking Higgs VEV is too small to give them big enough masses, so they get the bulk of their masses from the SM Higgs.

Field	Isospin I	Hypercharge Y	B
S_B	0	0	3
Ψ_L	$\frac{1}{2}$	$-\frac{1}{2}$	B_1
Ψ_R	$\frac{1}{2}$	$-\frac{1}{2}$	B_2
η_R	0	-1	B_1
η_L	0	-1	B_2
χ_R	0	0	B_1
χ_L	0	0	B_2

$$B_2 - B_1 = 3$$

$$\mathcal{L}_Y = -y_1 \overline{\Psi}_L h_{\rm SM} \eta_R - y_2 \overline{\Psi}_L \widetilde{h}_{\rm SM} \chi_R - y_3 \overline{\Psi}_R h_{\rm SM} \eta_L - y_4 \overline{\Psi}_R \widetilde{h}_{\rm SM} \chi_L$$
$$-\lambda_\Psi S_B \overline{\Psi}_L \Psi_R - \lambda_\eta S_B \overline{\eta}_R \eta_L - \lambda_\chi S_B \overline{\chi}_R \chi_L + \text{h.c.}$$

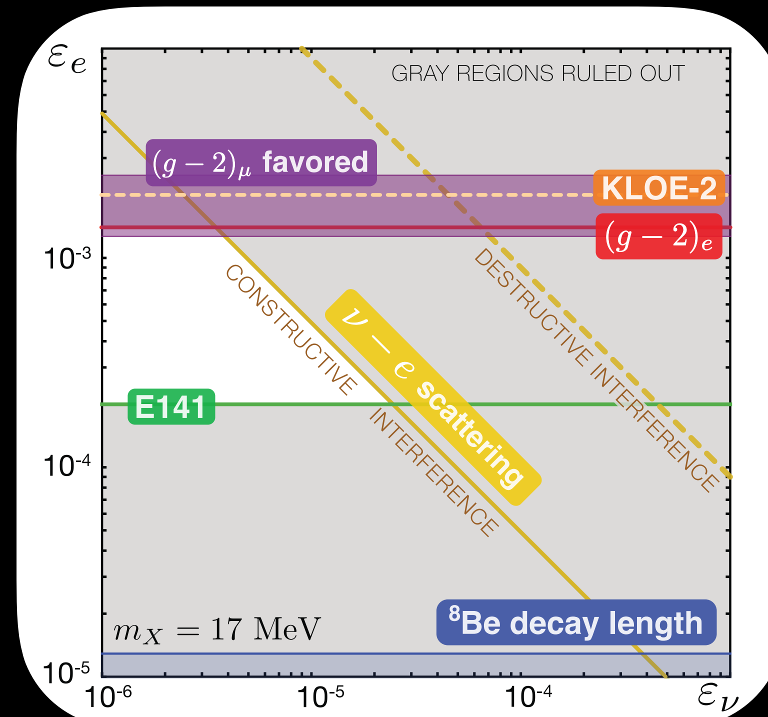
- Contributions to precision electroweak S and T parameters are acceptable for ΔM ~ 50 GeV.
- LHC bounds require M > about 500 GeV.

These new fermions look something like charginos and neutralinos in the MSSM.

UV Model: U(1) B-L

- An intrinsically anomaly free option is $U(1)_{B-L}$.
- This still results in equal couplings to proton and neutron, so again we neutralize the proton by O(10%) tuning of the kinetic mixing parameter to $\varepsilon = -g_{B-L}$.
- Now the electron couplings are naturally smaller than the quark couplings, as desired.
- The price to pay is that the neutrino couplings are not only non-zero, but roughly the size of the neutron coupling; too big!
  - There are ways to fix that…

$$\varepsilon_u = -\frac{1}{3}\varepsilon_{B-L} + \frac{2}{3}\delta$$
$$\varepsilon_d = \frac{2}{3}\varepsilon_{B-L} - \frac{1}{3}\delta$$
$$\varepsilon_\nu = -\varepsilon_{B-L}$$
$$\varepsilon_e = -\delta \ .$$



Outlook

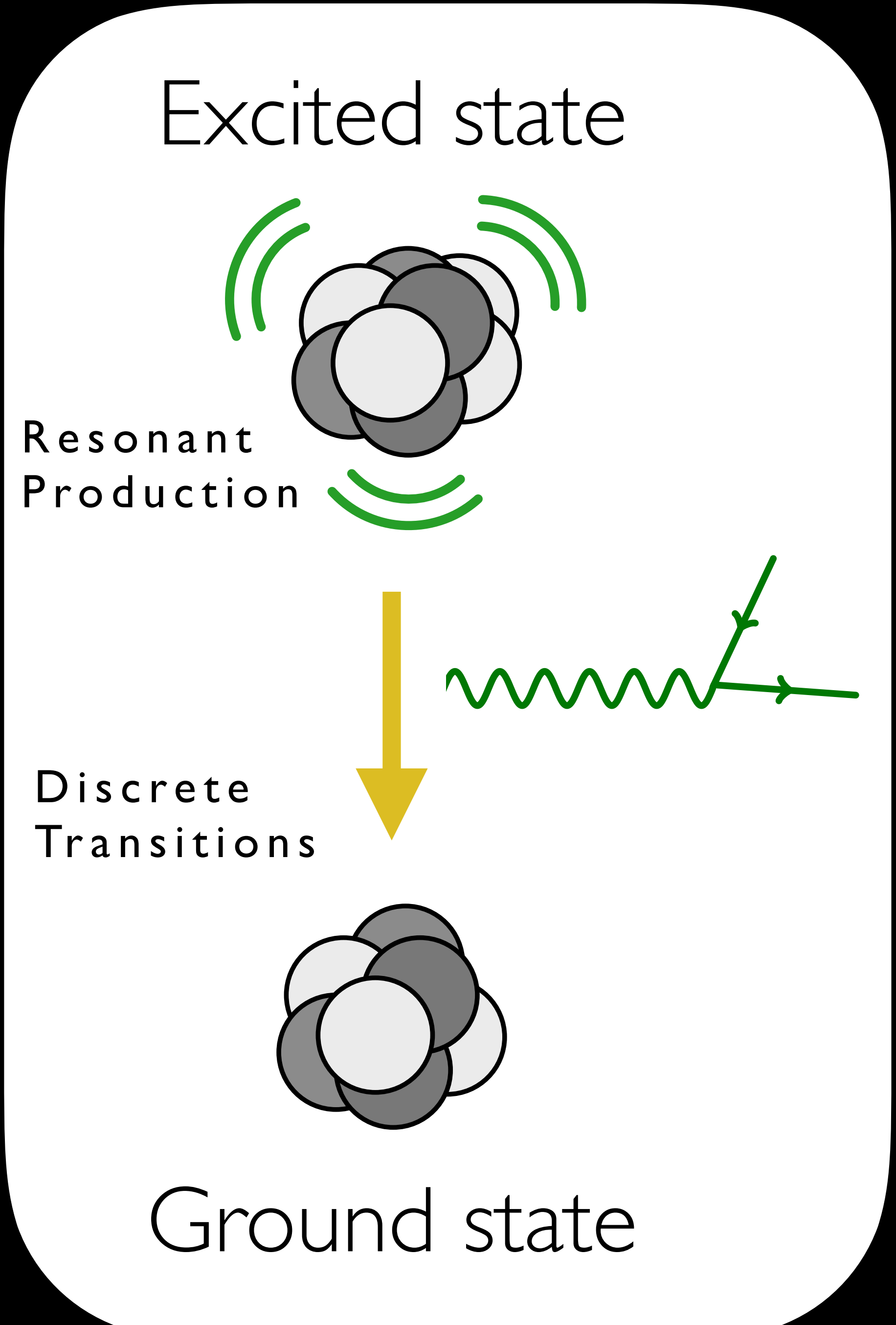
- Light new physics is an important ingredient in physics beyond the SM.
- I discussed some of the issues related to MeV — GeV theories containing vector particles, and used the ATOMKI anomaly as an example to show how model-building can work.
- There are still a lot of issues I didn't have time to cover:
  - More systematic exploration of UV theories
  - Connection to Dark Matter
  - Phenomenology of light dark Higgses.
- Nature may still contain secrets for us to discover below the GeV scale…

Bonus Slides

Beryllium-8

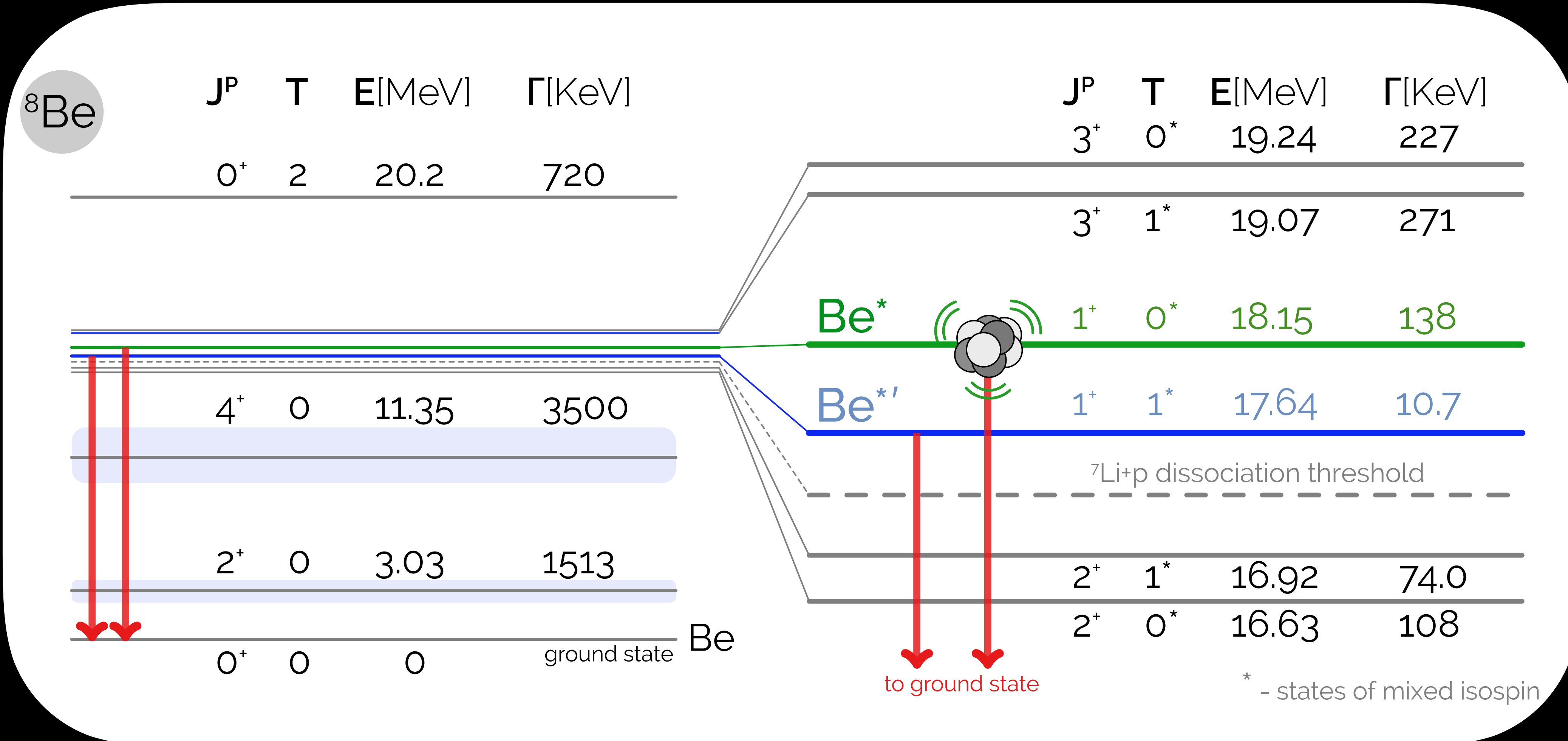
Be-8 As a New Physics Lab

- Beryllium-8 is composed of four protons and four neutrons.
- Its ground state decays into two alpha particles.
- It is a somewhat unusual nucleus:
  - It has large excitations (~20 MeV) with reasonably long lifetimes.
  - Relatively easy to make in the lab from p + ^{7}Li.
- Transitions from excited to ground states probe MeV-scale weakly coupled physics, such as an axion.



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

Be-8 Levels



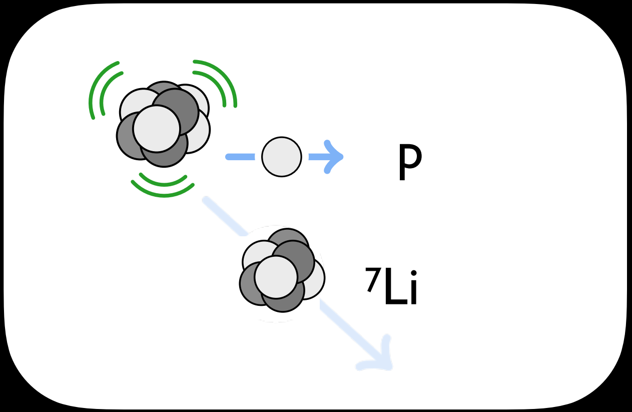
- The Be-8 ground state is a 0^+ isosinglet.
- There are a variety of excited states with different spins and isospins.
- For today, interested in the 1^+ 17.64 Be*' and 18.15 Be* states. There is some evidence that these states are actually admixtures of isotriplet and isosinglet.

arXiv:1609.07411

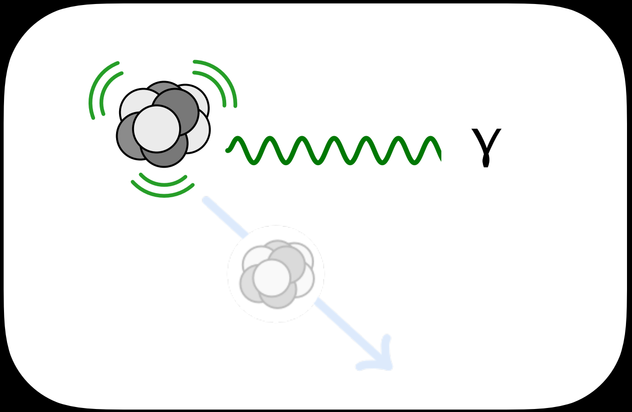
Pastore et al, PRC90 (2014) [1406.2343]

Be* Decays

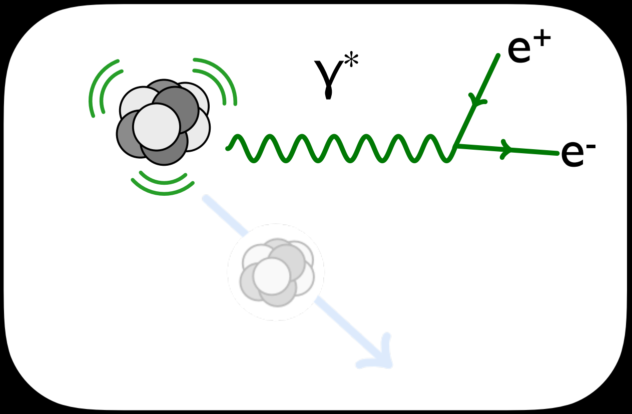
- Be* decays are dominantly a hadronic transition into ^{7}Li + p.



- There are also rare M1 electromagnetic transitions into a gamma ray and the ^{8}Be ground state.

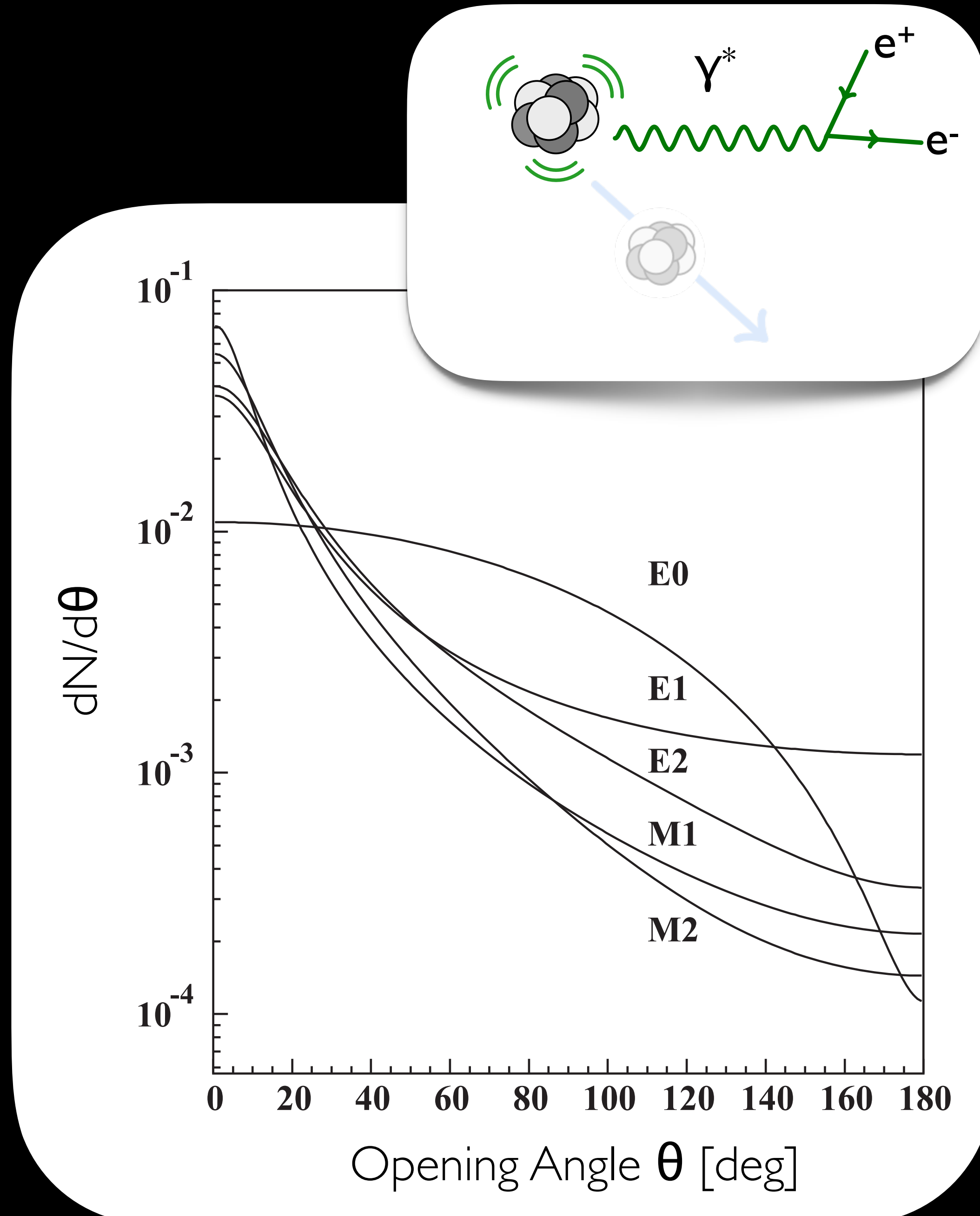


- Even rarer still is through an off-shell photon (still M1), leading to a final state of e+e- plus the ^{8}Be ground state.
  - This process is often referred to as ``internal pair creation” (IPC).



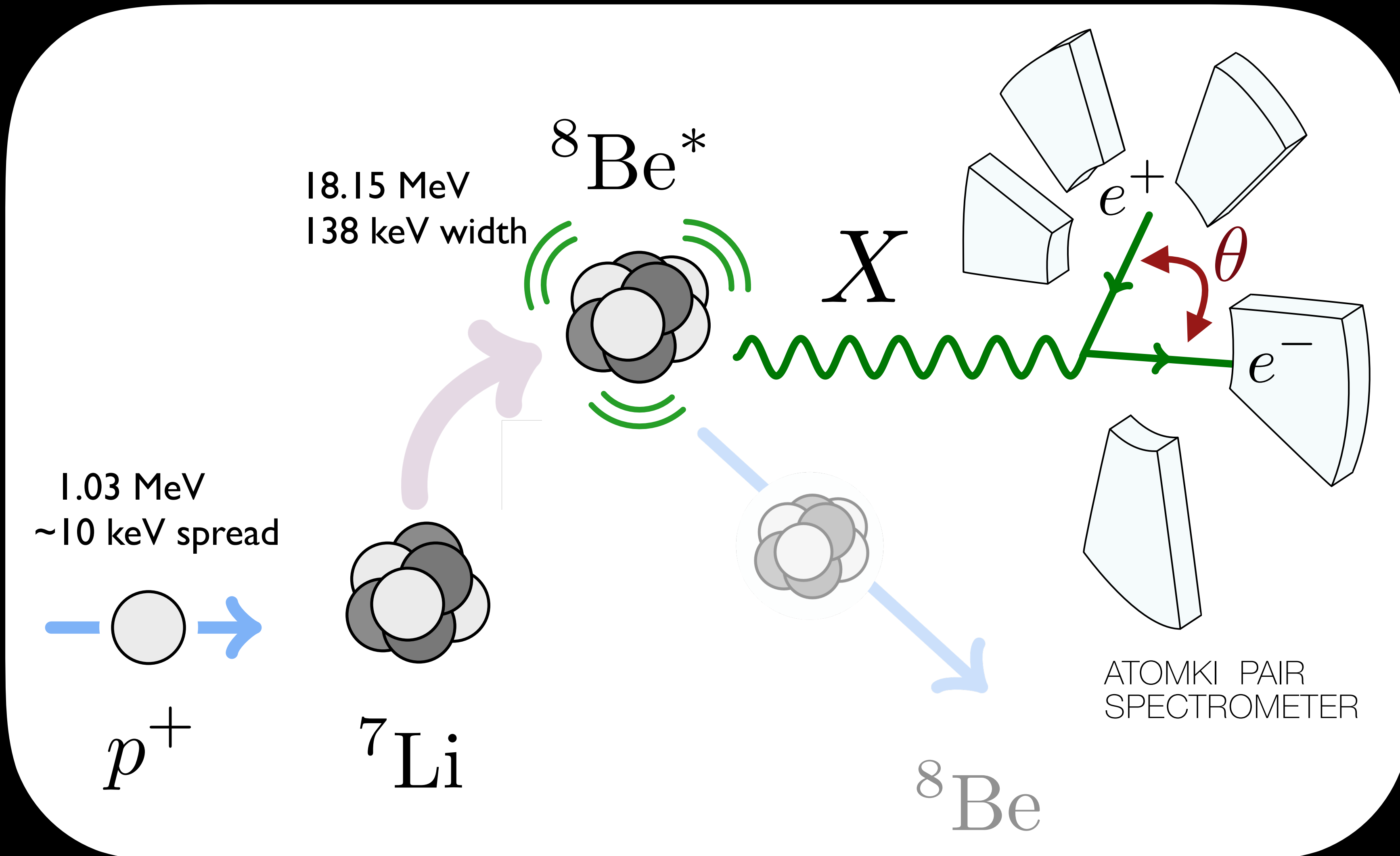
Internal Pair Creation

- Internal pair creation is observed for a variety of nuclear transitions.
- It is generally well-described analogously to atomic transitions.
  - They can be classified as E or M and the angular momentum l = 0, 1, 2, …
- The photon propagator leads to an invariant mass of the e+e- which falls with rising m_{ee}.
  - All of these transitions are monotonically falling and expected to be pretty smooth.



The ATOMKI Experiment

ATOMKI Experiment



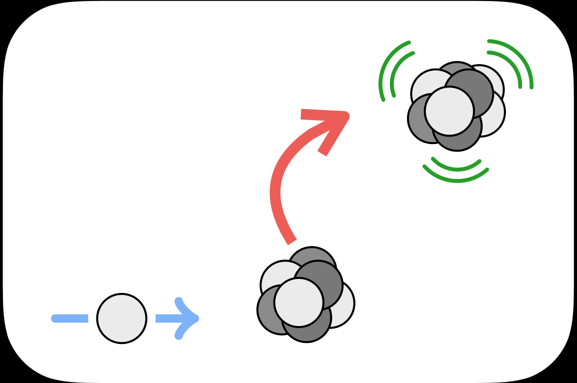
- The ATOMKI experiment produces a beam of protons with well-calibrated energy which strike a thin lithium foil, producing excited states of ^{8}Be. Particular excited states can be selected by adjusting the energy of the protons in the beam.
- Detectors measure the e+e- opening angle and their energies.

ATOMKI Experiment

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

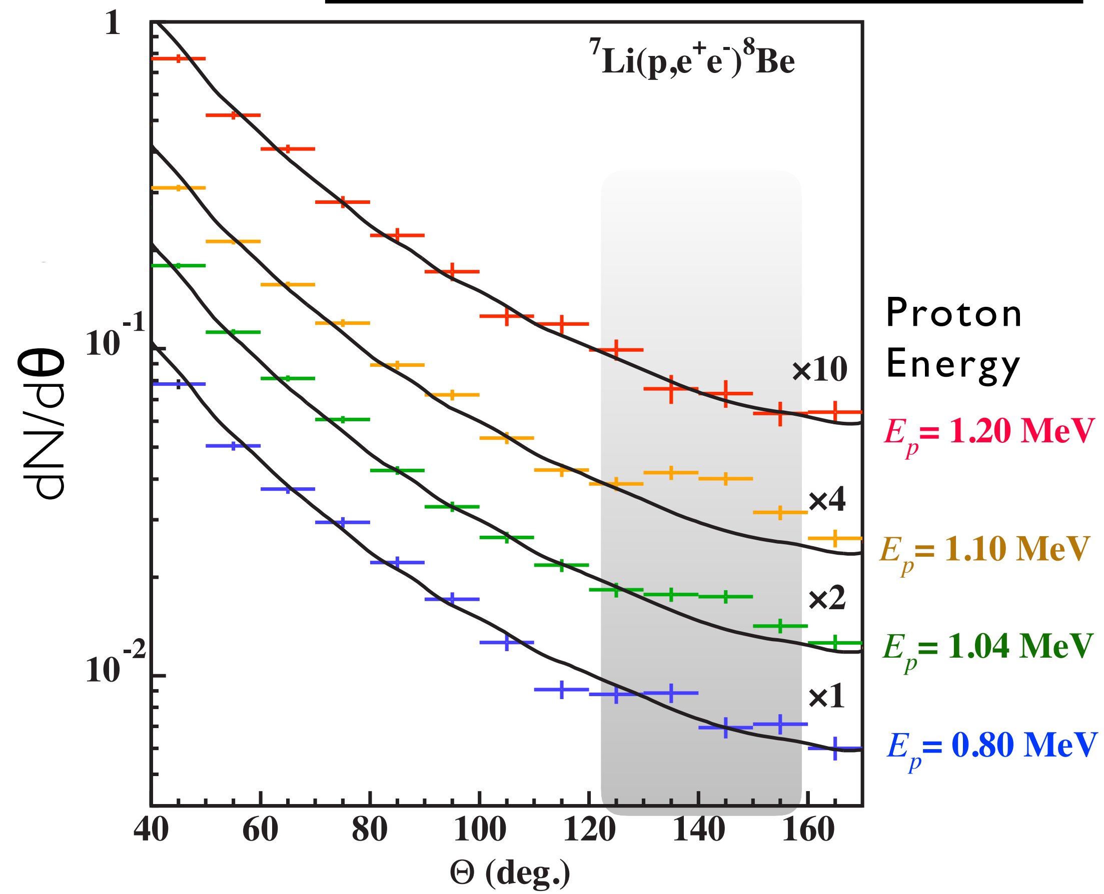
A pair spectrometer for measuring multipolarities of energetic nuclear transitions
J. Gulyás, et al. NIM-A 808, 21 (2016);
arXiv:nucl-ex/0311002

Energy Scan



- The ATOMKI experiment observes a bump-like structure in opening angles around 140 degrees when they scan through the Be* resonance.
- Off-resonance runs, both above and below the Be* state seem to match the naive expectations of an M1 IPC transition.
    - In particular, the 17.64 MeV Be*' state does not see the same enhancement.
- The (local) statistical significance of the bump structure is ~ 6.8σ above background.

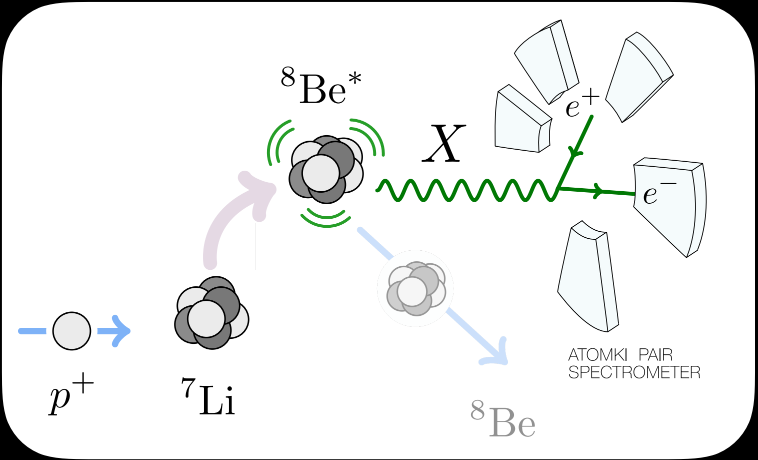
A.J. Krasznahorkay, et al. PRL116, 042501 (2016)



(Curves are artificially scaled for readability)

Event Selection

- A resonant structure in the opening angle is suggestive of a peak in the e+e- invariant mass.
  - Maybe Be* can decay into a new state of some kind (which itself decays into e+e-) and the ground state?



- Given the intriguing result, the ATOMKI analysis examines some of the characteristics of the resonance-like signal, based on measurements of the e+ and e- energies.

The Be* is produced with v ~ 0.02, very close to at rest.

- The invariant mass of the e+e- defines the mass of the hypothetical new state. It should be produced with a definite boost, and so the opening angle should correlate with that mass appropriately.

$$m_{ee}^2 = 2E_{e^+}E_{e^-} - 2\sqrt{E_{e^+}^2 - m_e^2}\sqrt{E_{e^-}^2 - m_e^2}\cos\theta + 2m_e^2$$

  - The opening angle observable is correlated, but distinct from the invariant mass.

Event Selection 2

- They also define the ``symetric-ness" of the e+e- pair, y.
  - A two body decay of Be* into the ground state and a new particle should have roughly equal energies for the e+ and the e-.
  - They divide their data into events with $y < 0.5$ and $y > 0.5$.
- To avoid the possibility of decay into a lower level excited state (rather than directly to the ground state), they apply a cut on the sum of the e+ and e- energies.

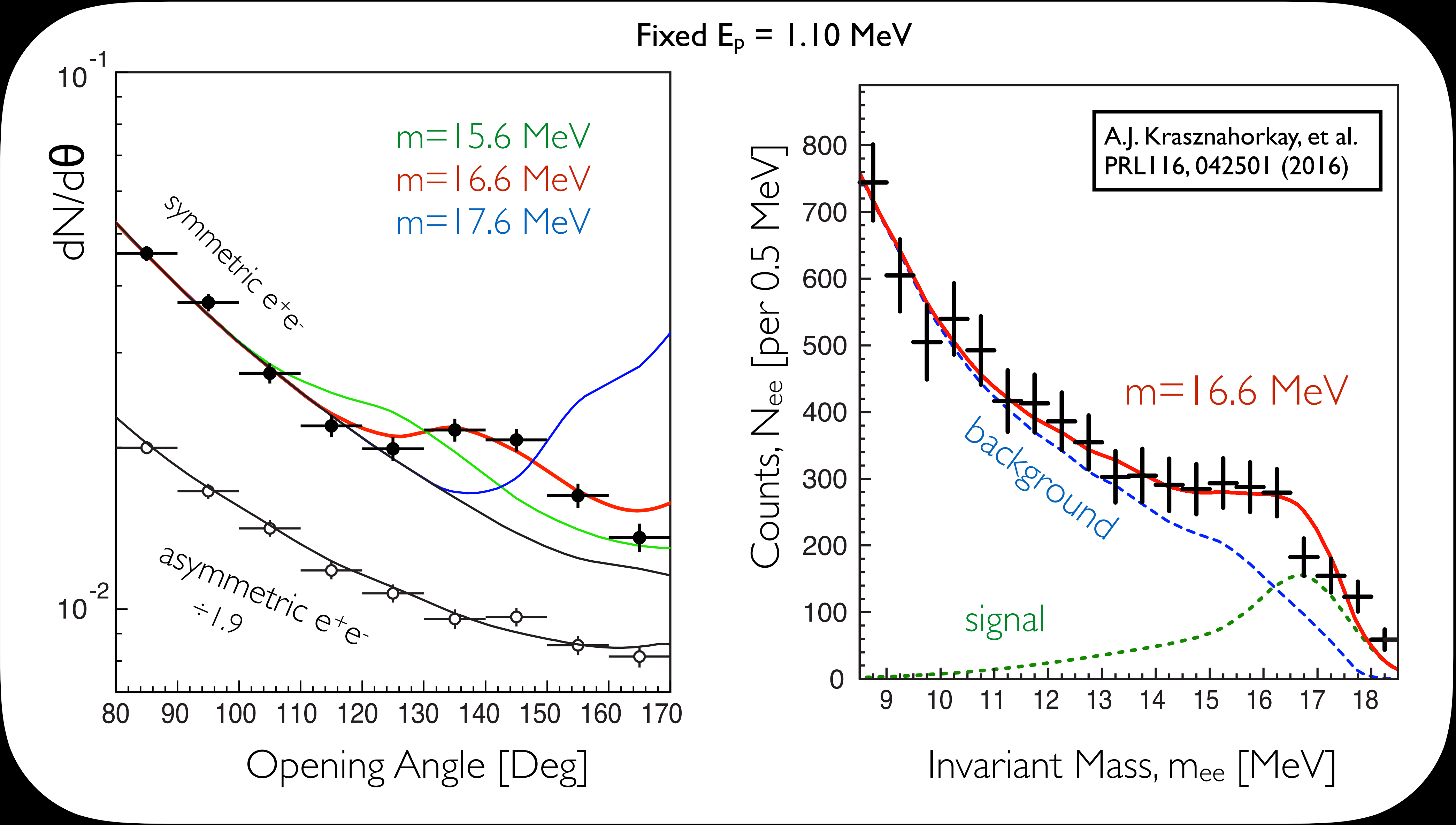
$$y \equiv \frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}$$

$$\begin{aligned} m_{ee}^2 &= 2E_{e^+}E_{e^-} - 2\sqrt{E_{e^+}^2 - m_e^2}\sqrt{E_{e^-}^2 - m_e^2}\cos\theta + 2m_e^2 \\ &= (1-y^2)E^2\sin^2\frac{\theta}{2} + 2m_e^2\left(1 + \frac{1+y^2}{1-y^2}\cos\theta\right) + \mathcal{O}(m_e^4) \end{aligned}$$

``Symmetric": $y < 0.5$
``Asymmetric": $y > 0.5$

$$E \equiv E_{e^+} + E_{e^-} > 18 \text{ MeV}$$

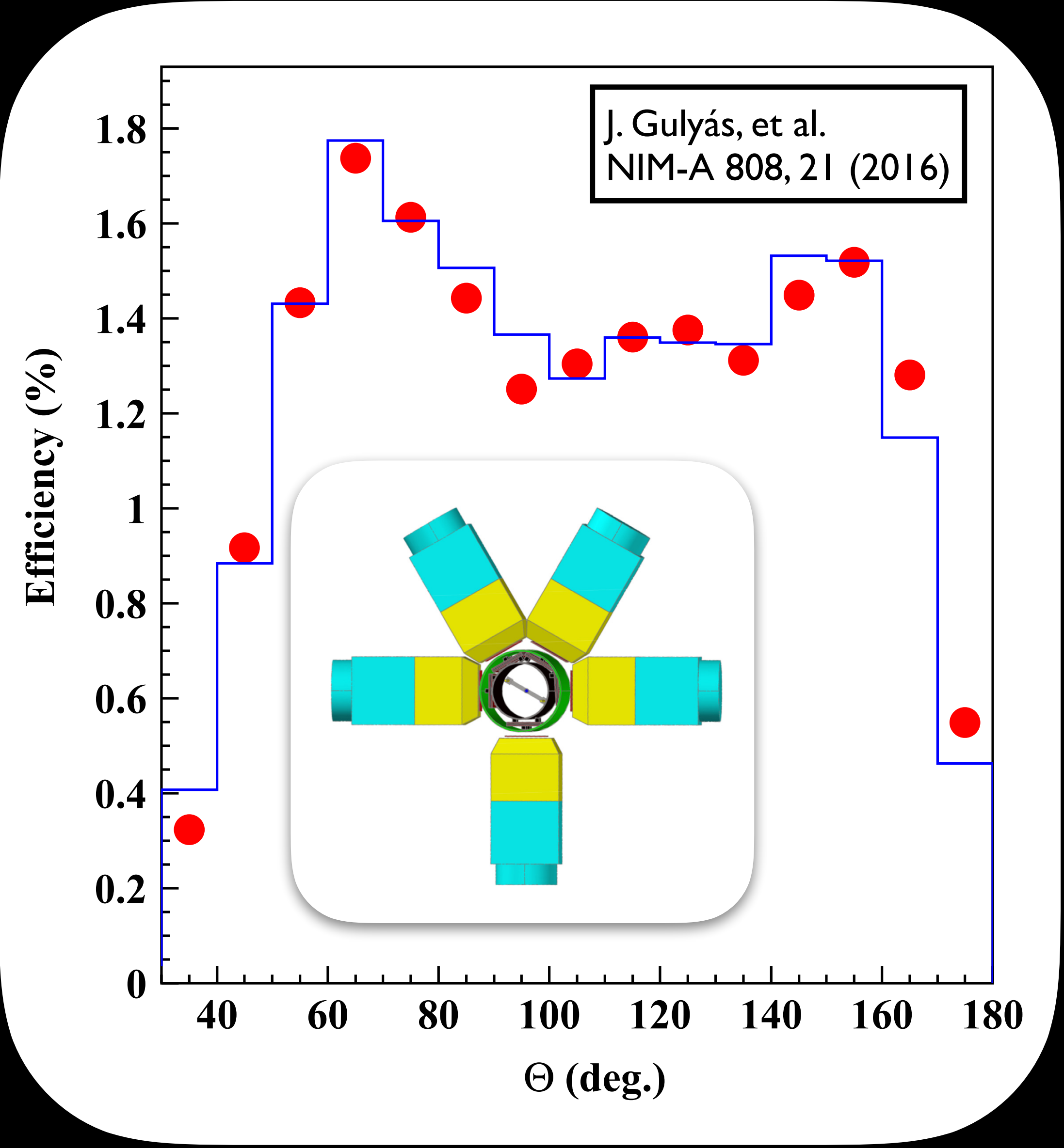
Event Selection 2



- Note that in the bump region ~14 - 18 MeV, the signal is a pretty large fraction of the total number of events (though it is a small fraction of the total integrated over all m_{ee}).

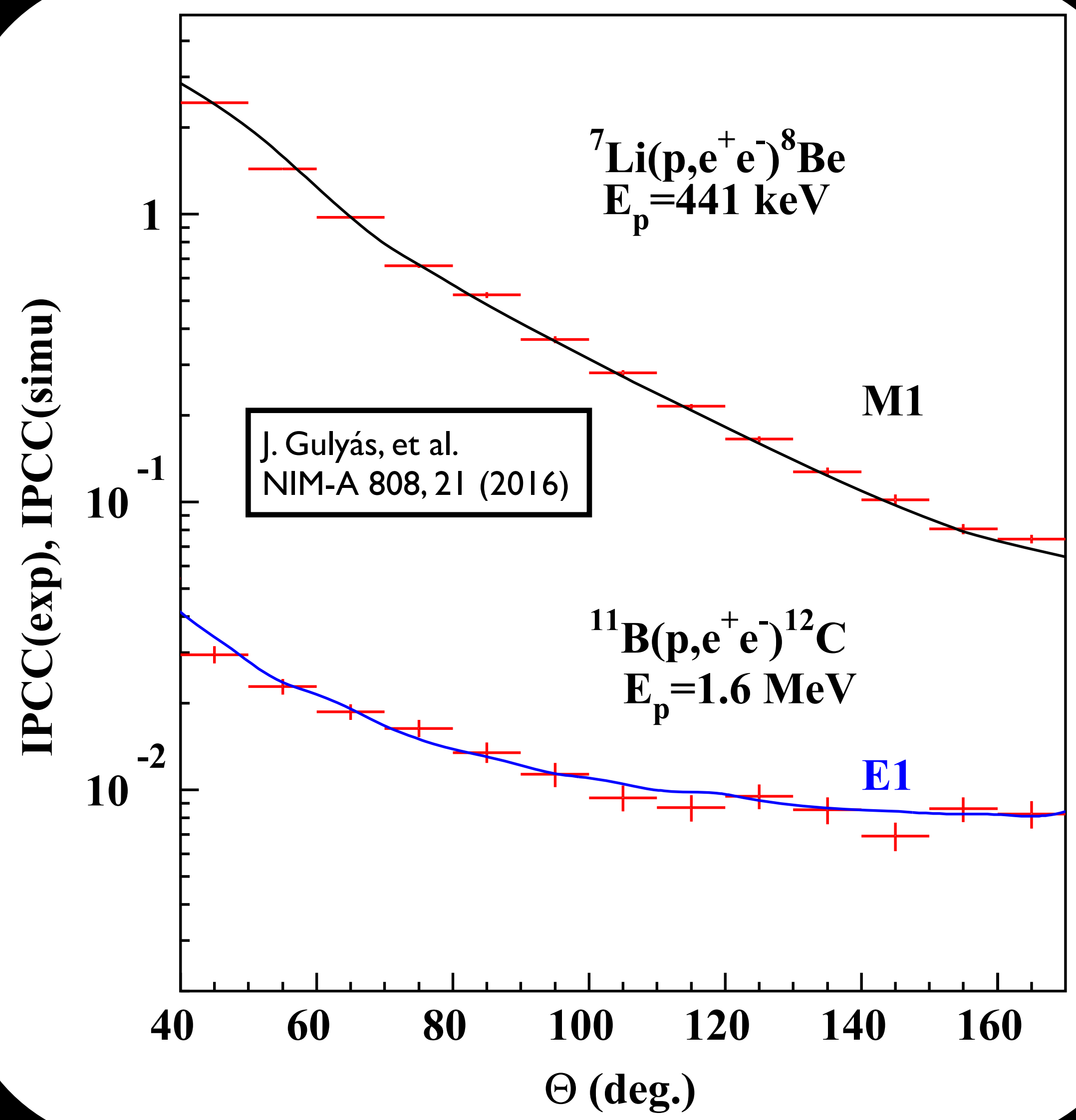
Detector Resolution

- ATOMKI detector geometry does have some impact on the acceptance in terms of the opening angle between the e+ and e-.
- However, based on simulations (blue histogram), and confirmed by calibration data (red dots), they do not expect a sharp feature at ~140 degrees.
- There is some structure in the response, but at a much smaller level, more like ~20%. It is hard to see how this should produce an artificial signal as large as the background itself.



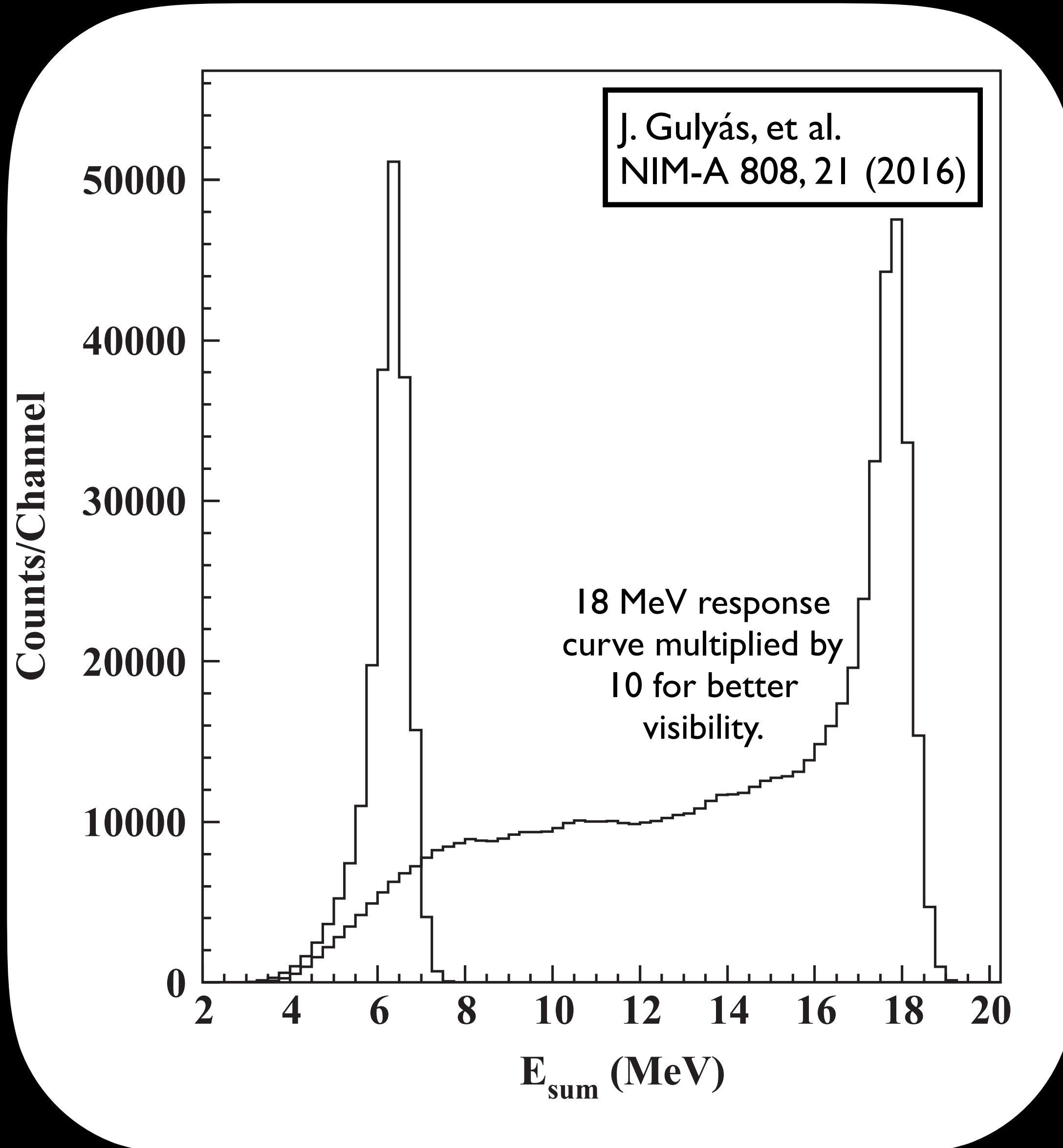
Detector Resolution

- Both at similar (for an ^{11}B target) and lower (for the ^{7}Li target) proton energies, the reconstructed angular distribution agrees well with the expectations from simulation of either an E1 or an M1 transition.
- They also consider a variety of other targets, including O, Si, etc, and find no hint of a signal from any of them.



Detector Resolution 2

- ATOMKI simulated the expected reconstructed peak shapes for a narrow particle decaying into e+e-.
- They consider both a low mass (6 MeV) and high mass (18 MeV) example.
- At high masses, there is a fairly long tail down to lower energies.
  - But note that their cut on E essentially removes sensitivity to those energies anyway.
  - The response on the high end is pretty narrow, with a ~MeV energy resolution.



Sanity Checks

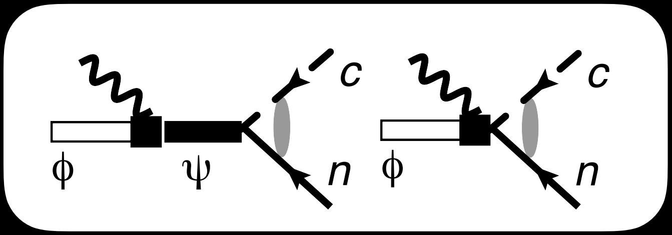
- The excess is a bump on top of what is expected to be a smooth monotonically decreasing background.
  - It's not on the edge of sensitivity, and thus not a ``last bin" effect.
- The opening angle and invariant mass are consistent with a two body decay from Be* to a state with rest energy around 16.5 MeV and the ground state.
- The e+ and e- have symmetric energies, consistent with a sequence of two-body decays:
  - Be* $\longrightarrow$ X(16.5 MeV) + Be (ground state)
  - X $\longrightarrow$ e+ e-
- The bump disappears for off-shell proton energies, perhaps arguing against some kind of nuclear interference effect.
- There are a handful of known nuclear transitions at such large energies, and none we have found have been very well-studied in IPC transitions.

So What's Going On?

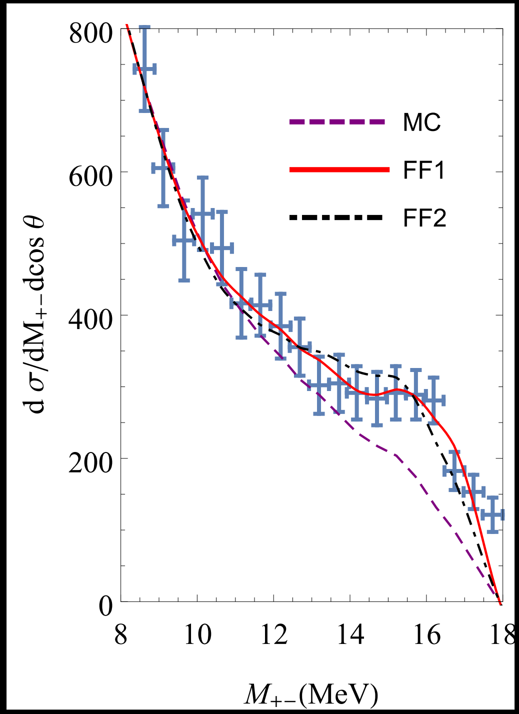
- Obviously, one should be cautious. In the very least we would like to see these results repeated, preferably by a different group.
- Logically, we should consider the possibilities of:
  - Experimental error/miscalibration/etc:
    - Nothing is obviously wrong with the experiment: the angles and energies seem self-consistent and pass the sanity checks;

So What's Going On?

- Up until now unknown nuclear physics effect:
  - Nuclear physicists so far haven't come up with an obvious explanation for a bump (but they continue to work on it!) This is crucial;



Zhang, Miller 1703.04588



They examine interference, considering both production and de-excitation.

Conclude that a FF would have to be unreasonably large to play a role.

Conclude interference can be important to interpret a signal, but doesn't explain the observations…

  - It would be very helpful to see it in a different nuclear system (maybe ^{4}He?).

- My attitude here: Let's see what kind of new physics can explain it and see what other constraints/opportunities there are to learn more.