Dark Forces, Dark Matter, and the GeV-Scale Discovery Frontier

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Perimeter Institute

[with M. Diamond, G. Krnjaic, E. Izaguirre, N. Toro]

HPS Collaboration Meeting
Jefferson National Lab
June 4, 2013

Sources Summarizing Broad Physics Program:

– *Fundamental Physics at the Intensity Frontier* (arXiv:1205.2671)

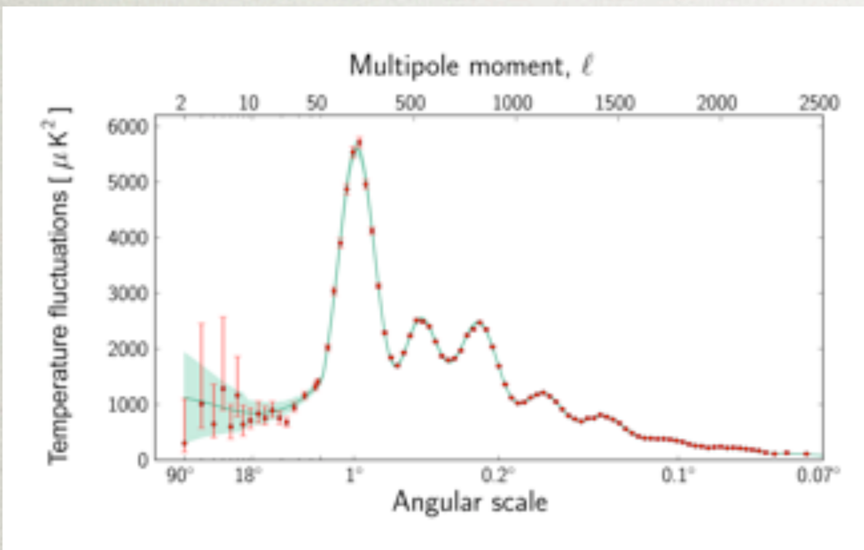
– Intensity Frontier Meeting at Argonne (April 2013) (see posted talks)

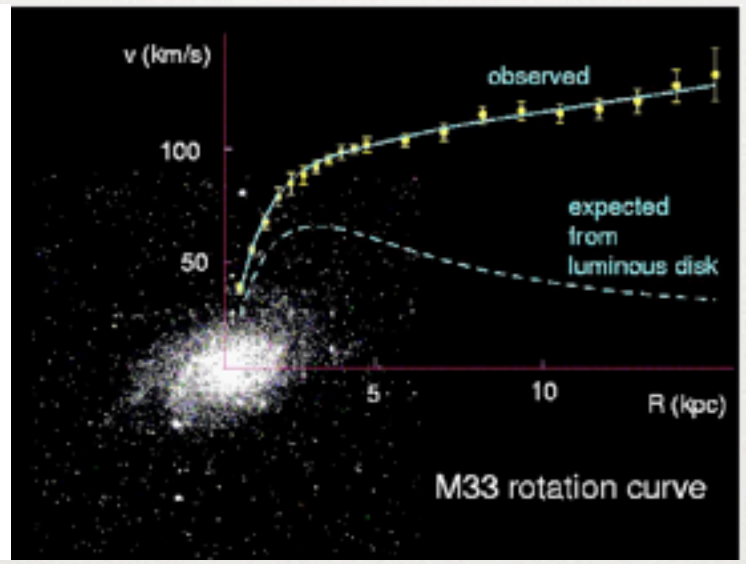
Dark Forces Below the Weak Scale

- Theory and Targets of Opportunity
  - Precision Anomalies
  - Dark matter [Slatyer]
- Direct Search Summary
- Potential for Fixed-Target Dark Matter Searches at JLab (new)

Beyond the Standard Model

We know there is dark matter

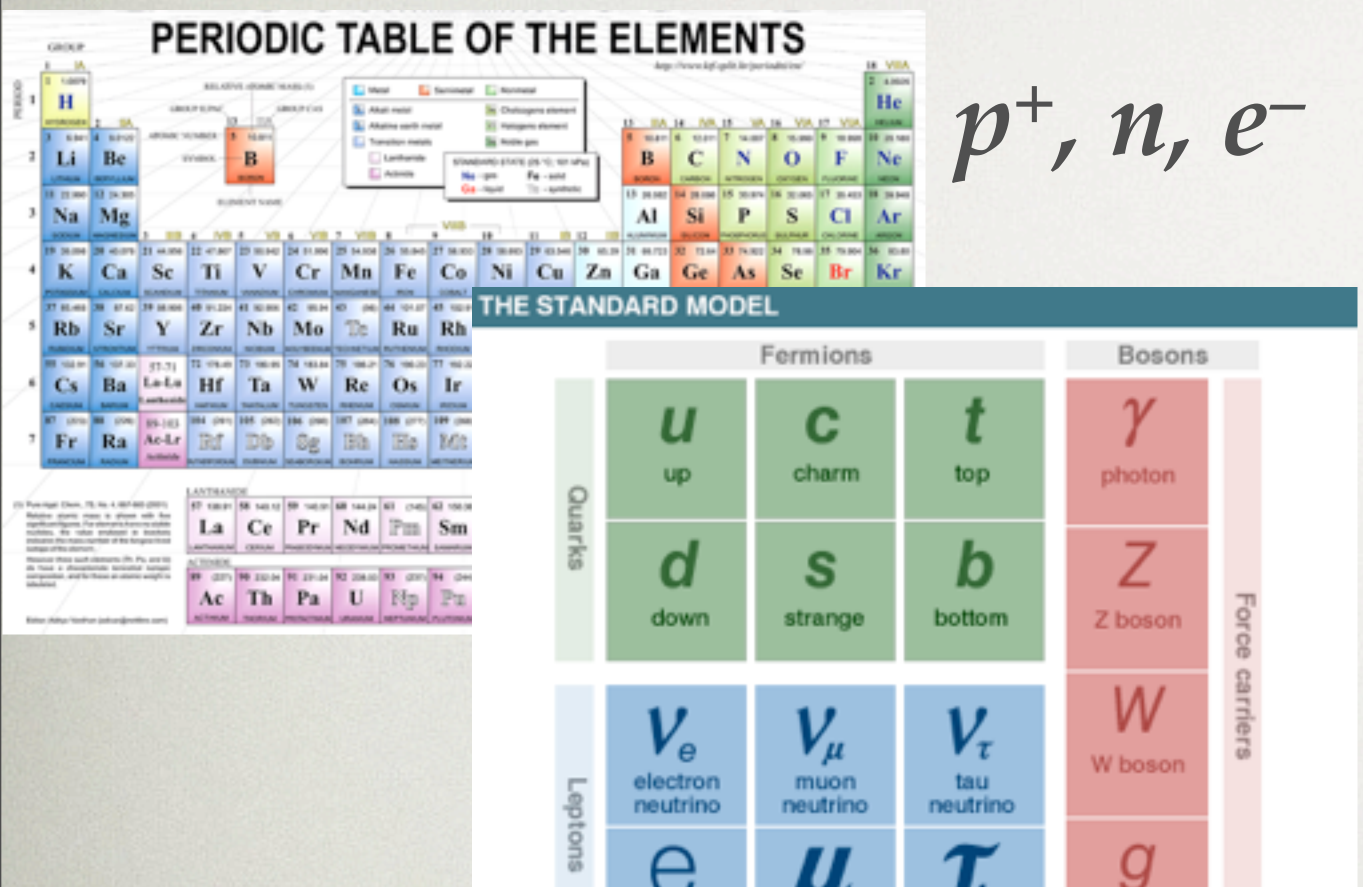




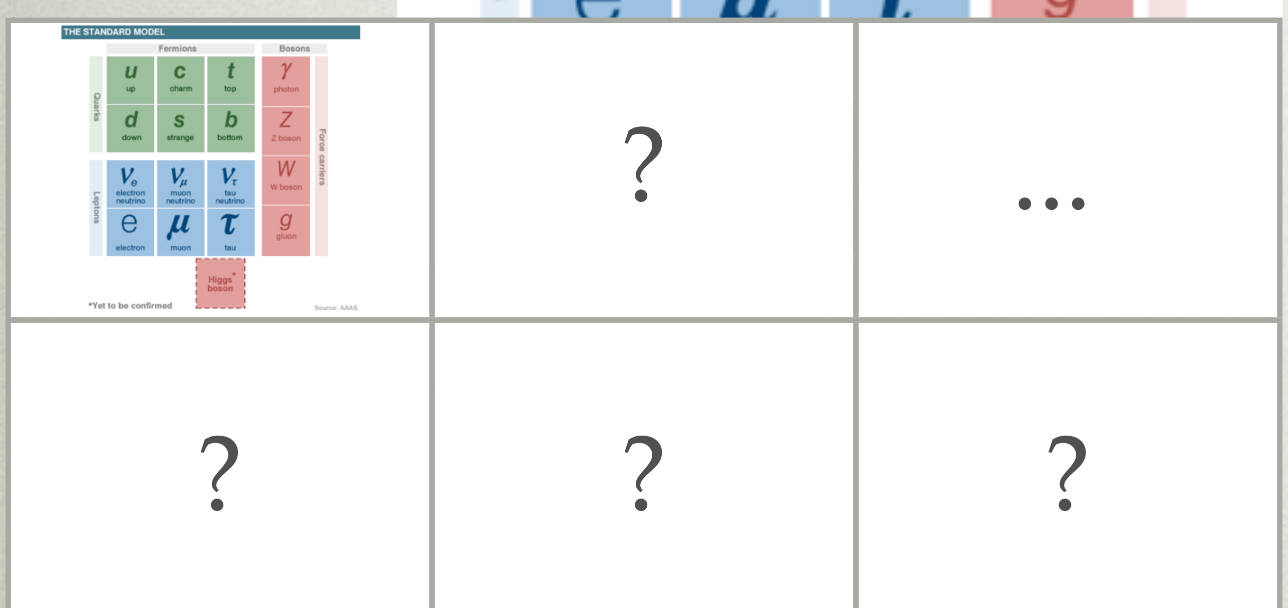
...but what is it?

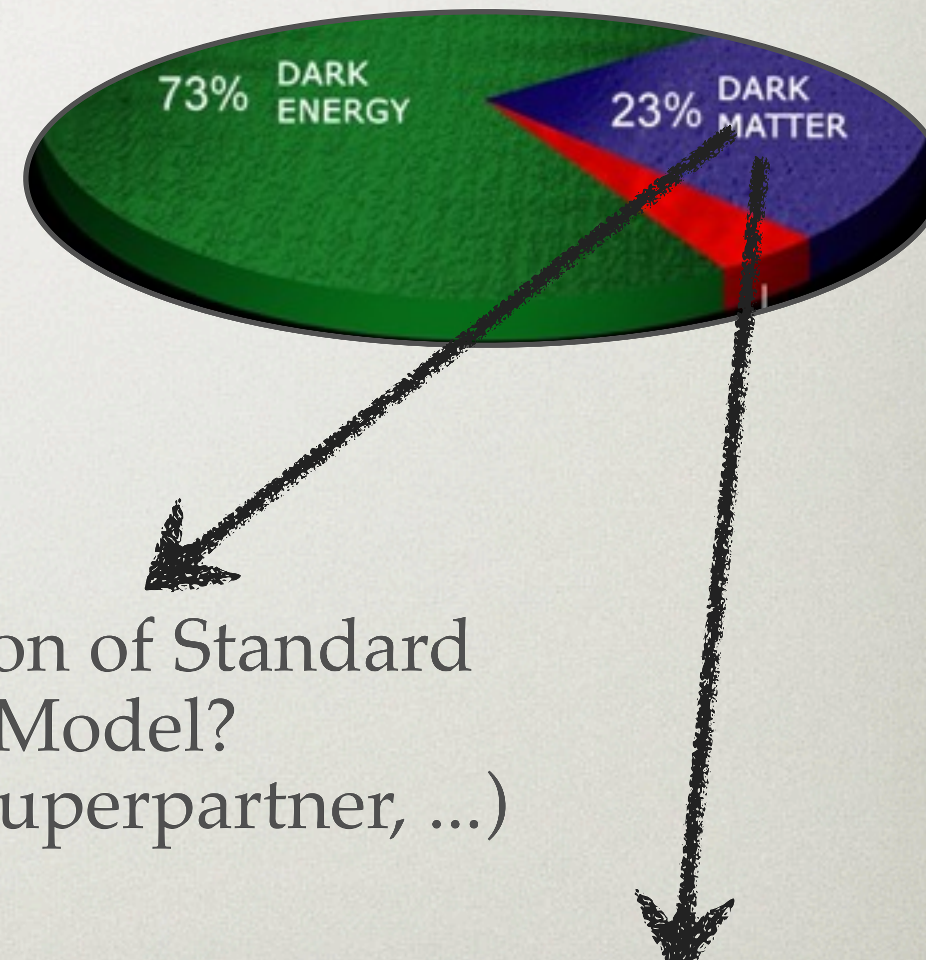
LHC and direct detection results challenge connection of dark matter to "weak-scale naturalness"

Copernican Particle Physics?



p^+, n, e^-





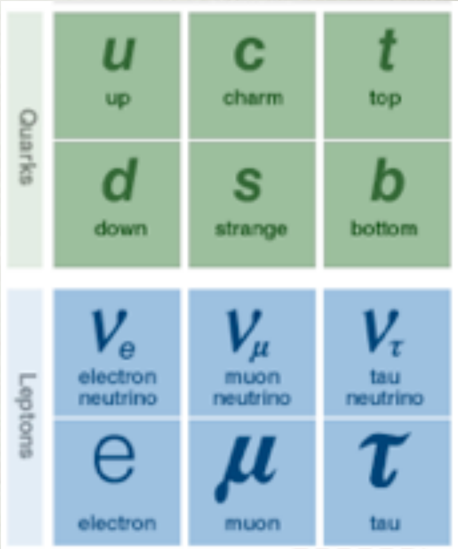
extension of Standard Model?
(axion, superpartner, ...)

Completely new physics?

What do we actually know about the dark sector?

Beyond the Standard Model

Known matter interacts through three gauge forces (strong, weak, and electromagnetic)



LHC looking for new matter *interacting through the same forces*

...but what about **matter that is not charged under these forces?**

Gauge- & Lorentz-invariance *restrict possible interactions* with such matter to high dimension operators. New sub-GeV matter can be consistent.

The "Portals"

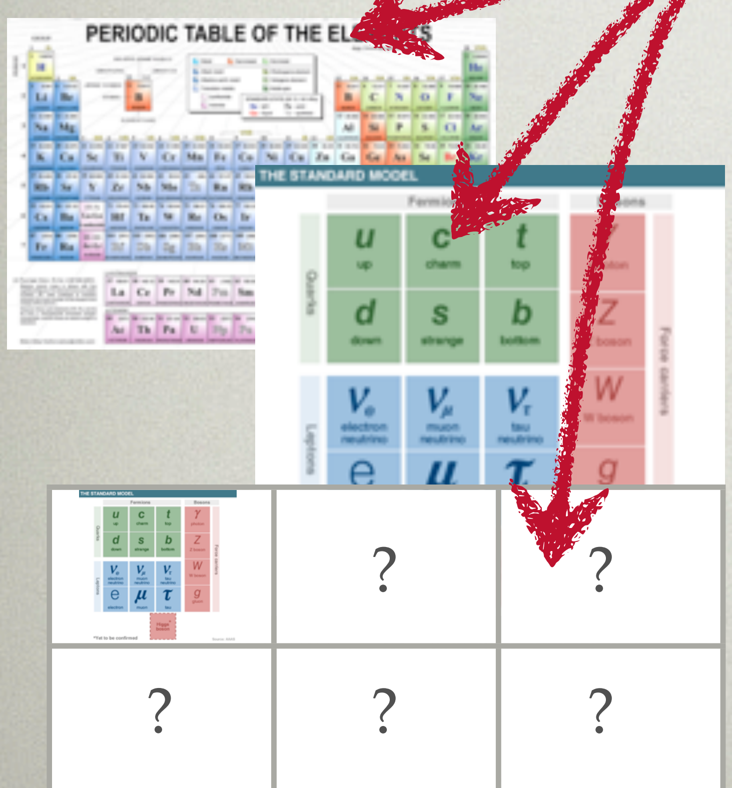
Searches can be organized around a small number of interactions allowed by Standard Model symmetries

Higgs Portal	$\epsilon_h \, \lvert h \rvert^2 \lvert \phi \rvert^2$	exotic rare Higgs decays?
Neutrino Portal	$\epsilon_\nu \, (hL)\psi$	not-so-sterile neutrinos?
Vector Portal (kinetic mixing)	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	(Focus of this talk)
Axion Portal (axion-like particles – ALPs)	$\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	

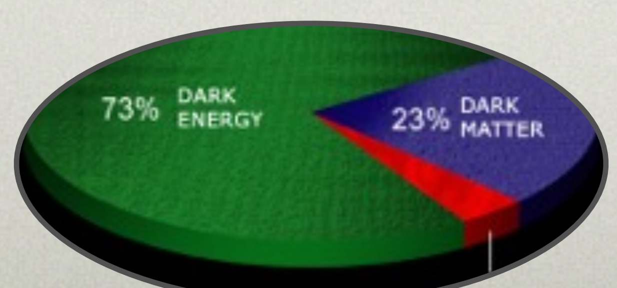
GeV-Scale Discovery Frontier

Experiments at Jefferson Lab will lead the exploration of GeV-Scale dark matter and weakly coupled physics!

Jefferson Lab
EXPLORING THE NATURE OF MATTER



What will we find?



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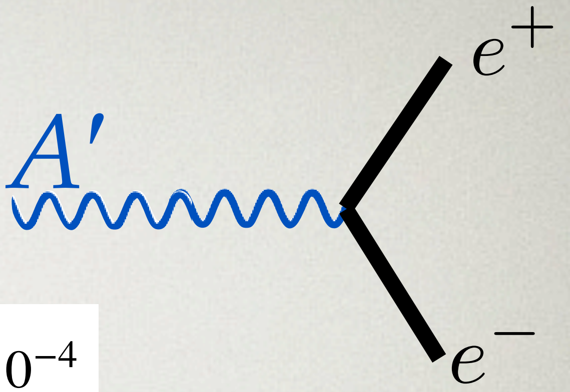
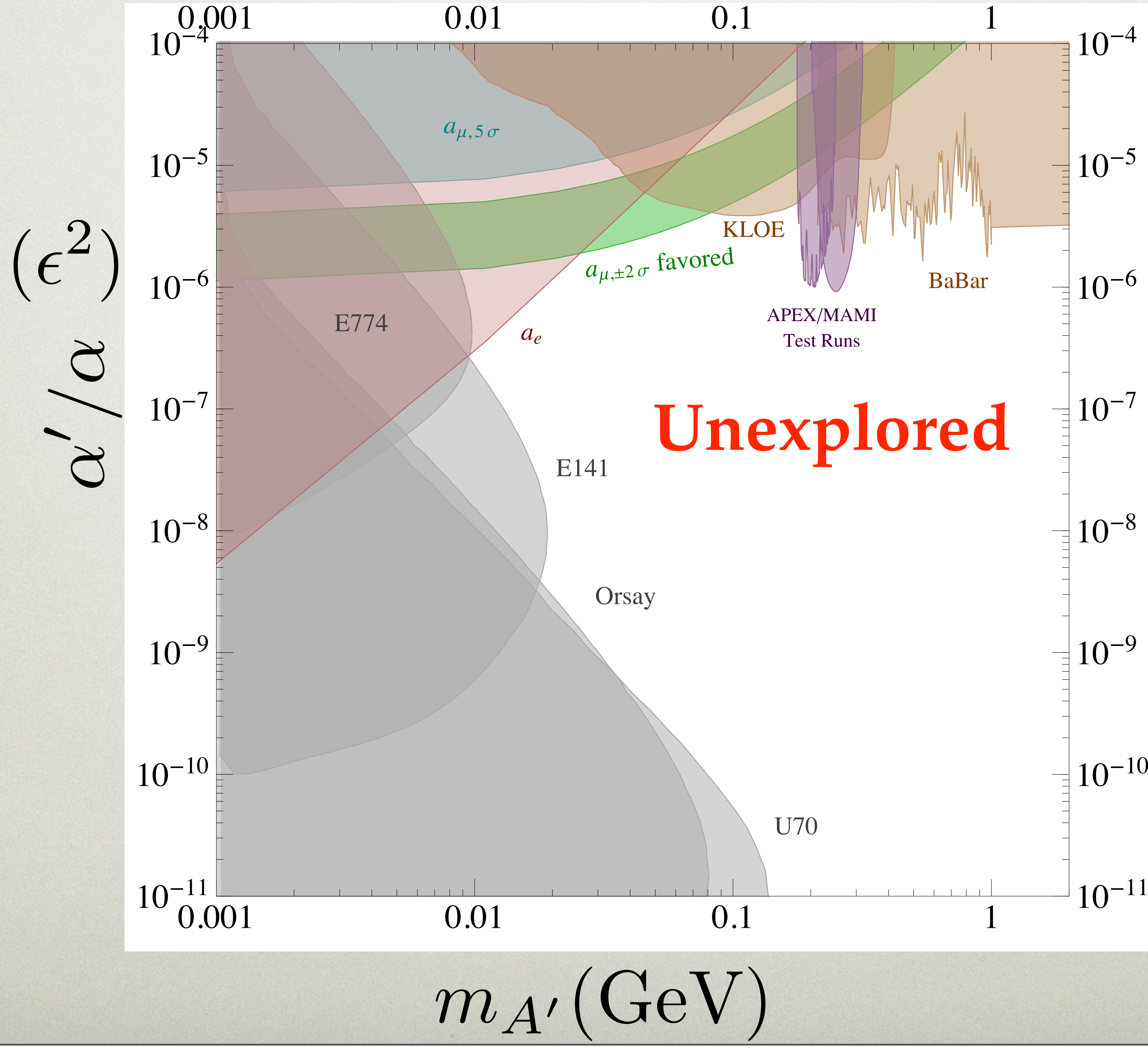
The Territory

(A′ Electron/Muon Decays)





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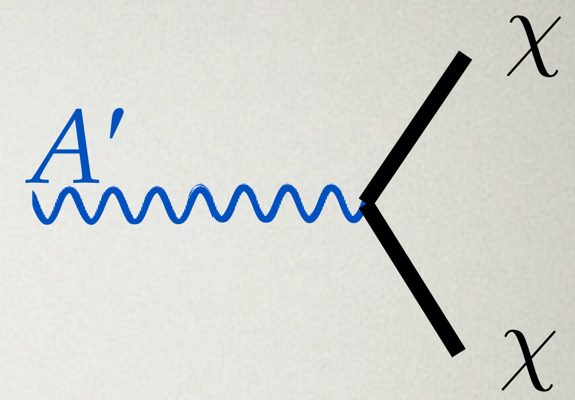
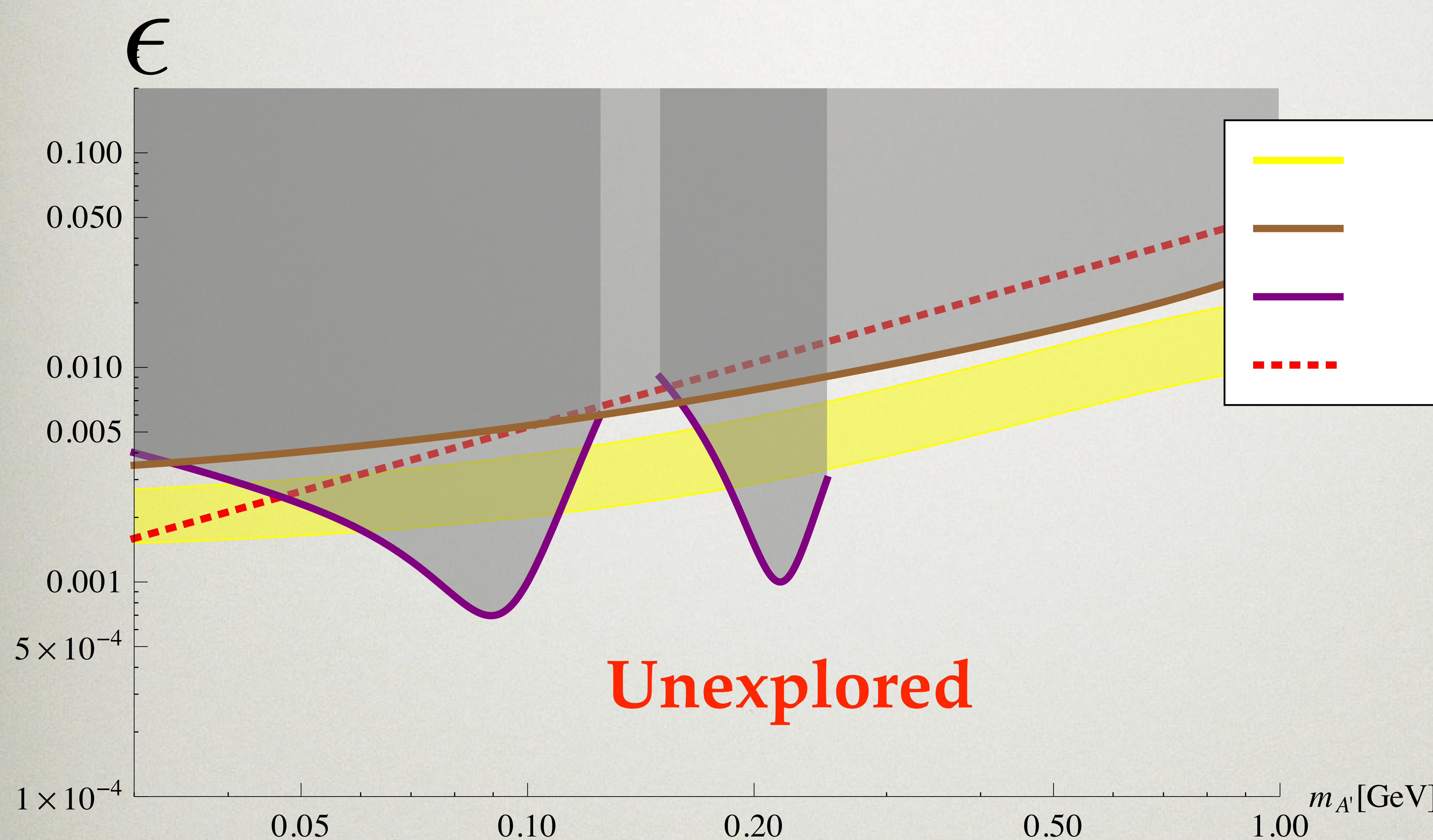
The Territory

(A′ invisible "dark matter" Decays)





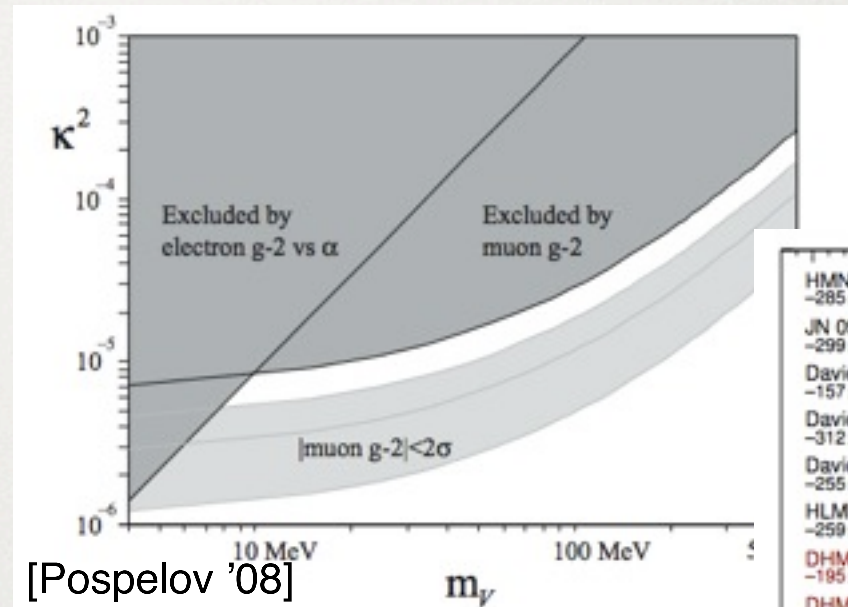
$m_{A'}$ (GeV)

(from M. Diamond)

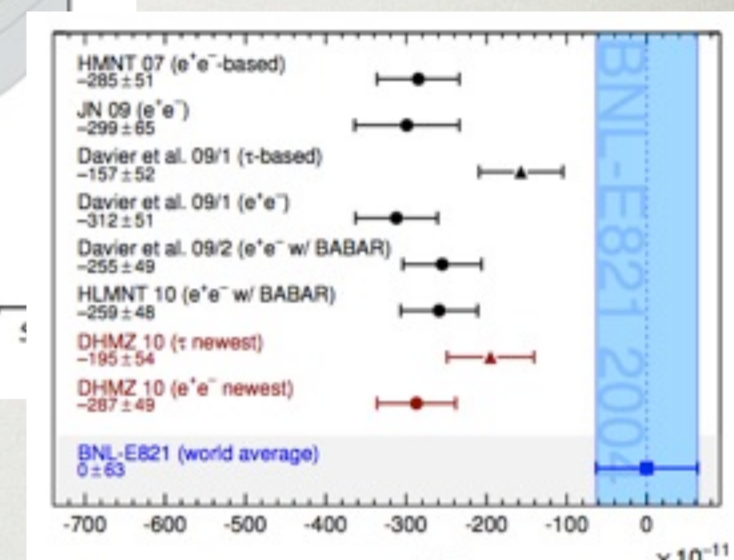
Target of Opportunity? Precision Anomalies

Muon g-2

$U(1)_D$ coupling modifies $(g-2)_\mu$, with correct sign. $\varepsilon \sim 1\text{-}3\ 10^{-3}$ can explain discrepancy with Standard Model



[Pospelov '08]

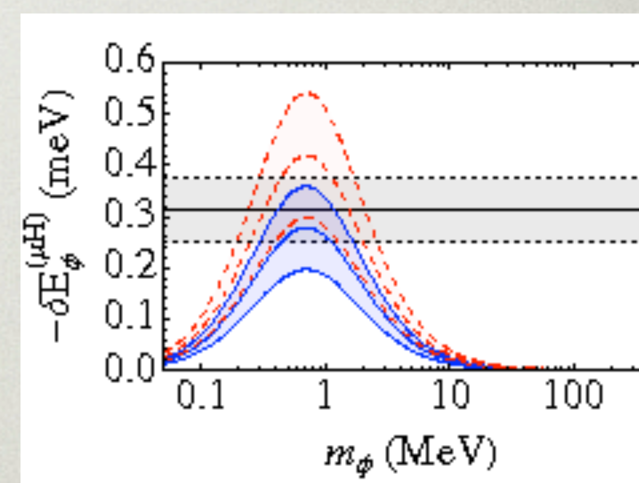


[Hoeker '10]

Muonic hydrogen

MeV-scale force carriers can explain the discrepancy between (μ^-,p) Lamb shift [Pohl et al. 2010] and other measurements of proton charge radius.

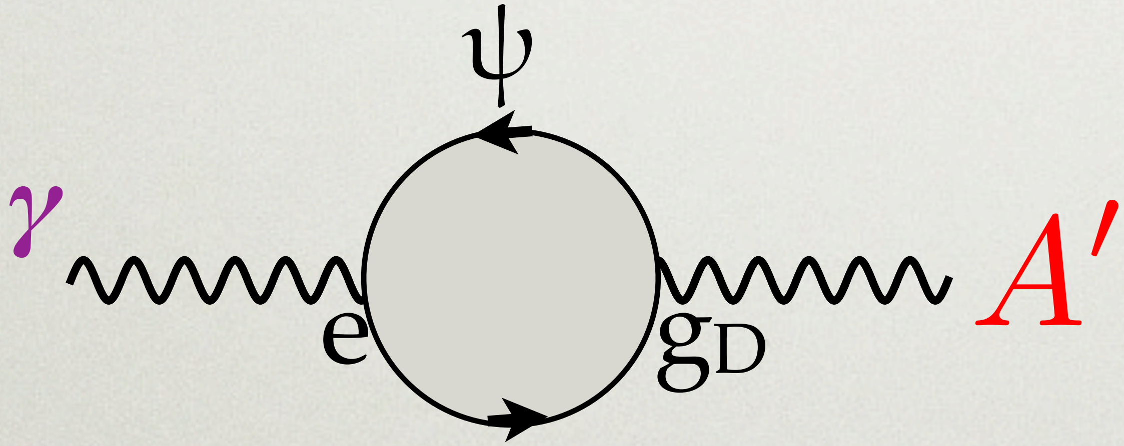
Requires couplings *beyond* kinetic mixing (lepton flavor-violating component)



[Tucker-Smith & Yavin, 1011.4922]

Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$

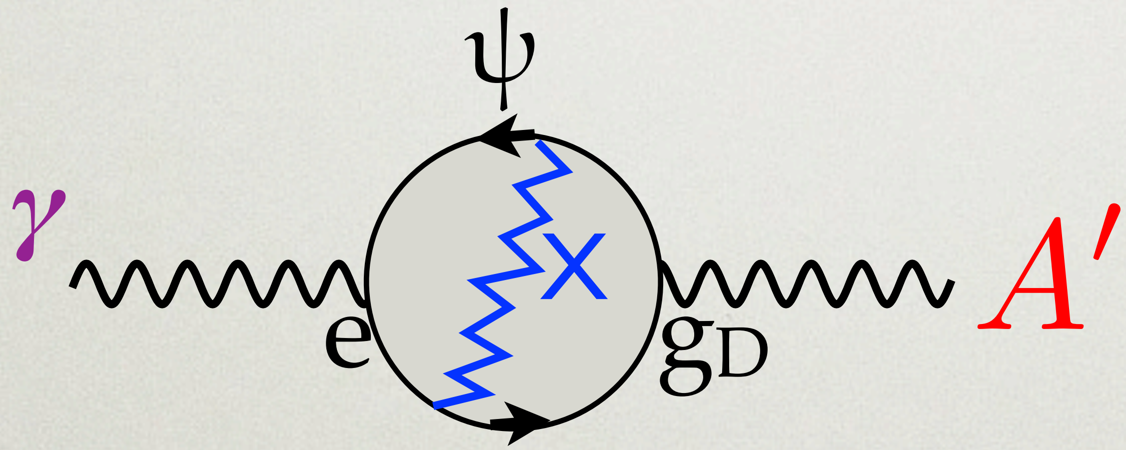
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



generates $\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$

Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu} F'^{\mu\nu}$

- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - In Grand Unified Theory, symmetry forbids tree-level & 1-loop mechanisms. GUT-breaking enters at 2 loops



generating $\epsilon \sim 10^{-3} - 10^{-5}$

($\rightarrow 10^{-7}$ if both U(1)'s are in unified groups)

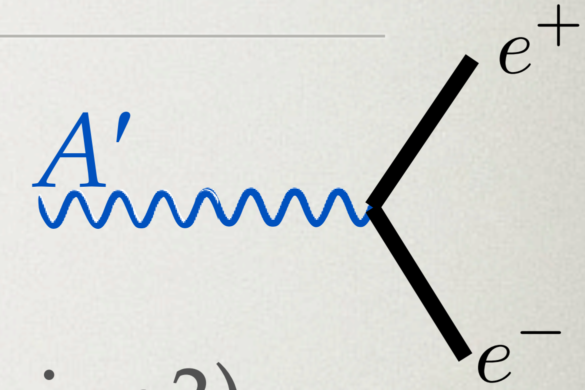
Sources and Sizes of Mass Term

- sub-MeV: non-perturbative physics (like Λ_{QCD})
- MeV-to-GeV is motivated by g-2 and dark matter anomalies
- Possible origin: related to M_Z by small parameter
  - e.g. supersymmetry+kinetic mixing ⇒ scalar coupling to SM Higgs, giving

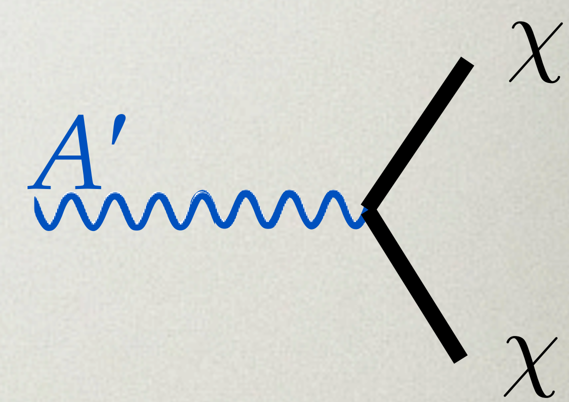
$$m_{A'} \sim \sqrt{\epsilon}\, M_Z \lesssim 1\text{GeV}$$

a motivated target of opportunity

Goals for "Heavy-Photon" Searches

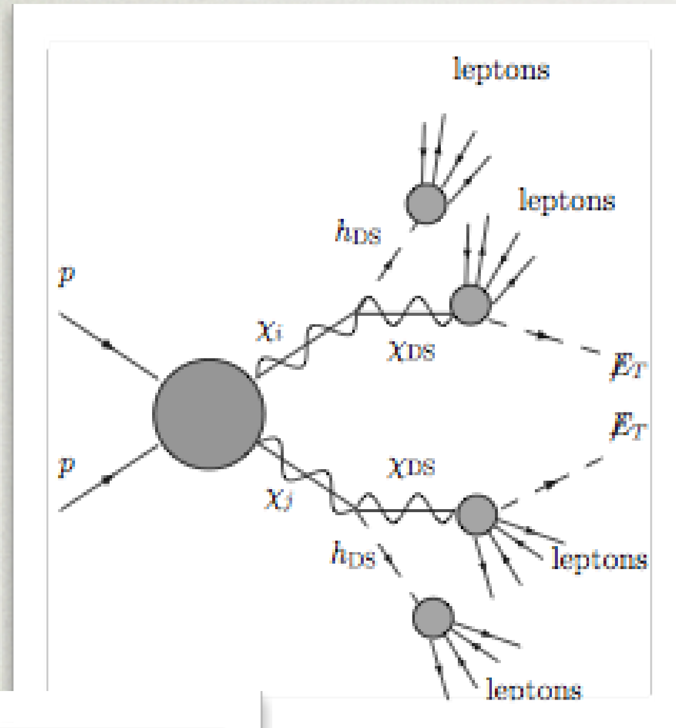


- Lepton Decays
  - (g_μ-2)–motivated region (<100% branching?)
  - Full perturbative coupling range ($\varepsilon \gtrsim 10^{-8}$) over widest mass range possible



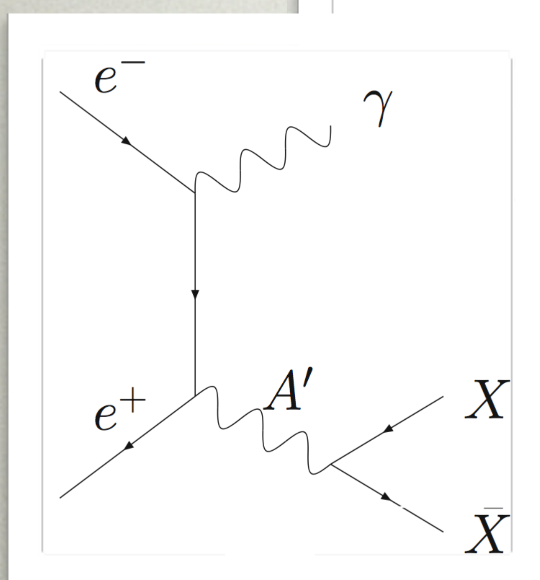
- Dark-Sector decays
  - $A' \rightarrow \chi\chi$ (χ = collider-invisible, maybe dark matter)
  - $A' \rightarrow XX \rightarrow$ multi-body SM final states

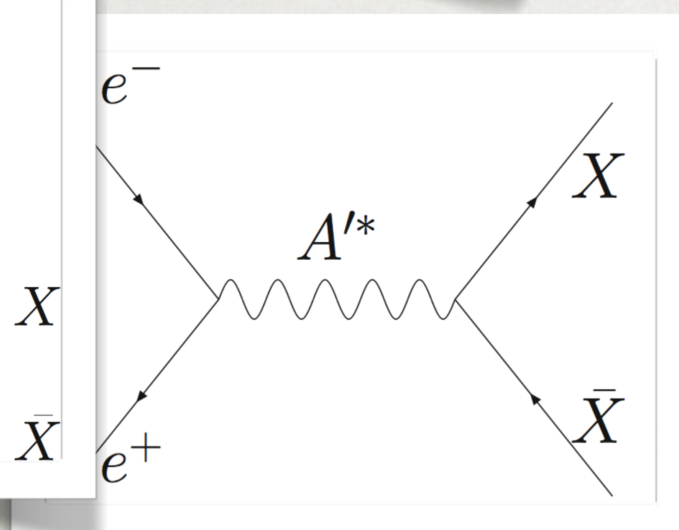
Broad Array of Searches! (done, ongoing, planned)



High Energy Hadron Colliders: New heavy particles decaying into dark sector (lepton jets)

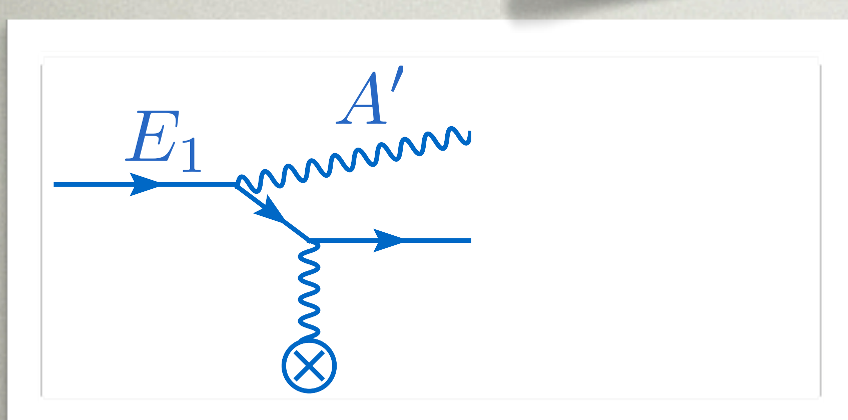
(ATLAS, CMS, CDF & D0)





Colliding e+e-: On- or Off- shell A', X=dark sector or leptons & pions

(BaBar, BELLE, BES-III, CLEO, KLOE)



Fixed-Target: Electron or Proton collisions, A' decays to di-lepton, pions, multiple channels

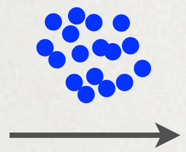
(FNAL, JLAB (Hall A & B & FEL), MAMI (Mainz), WASA@COSY ...)

Fixed-Target Searches

Luminosity

Fixed-Target

10^{11} e$^-$



~10^{23} atoms in target

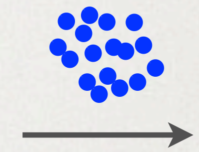
N(hard scatter) ~ 0.01 – 1

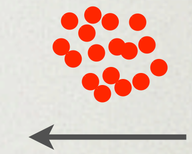
per electron

O(few) ab^{-1} per day

e$^+$e$^-$

10^{11} e$^-$ 10^{11} e$^+$





N(hard scatter) ~ 1

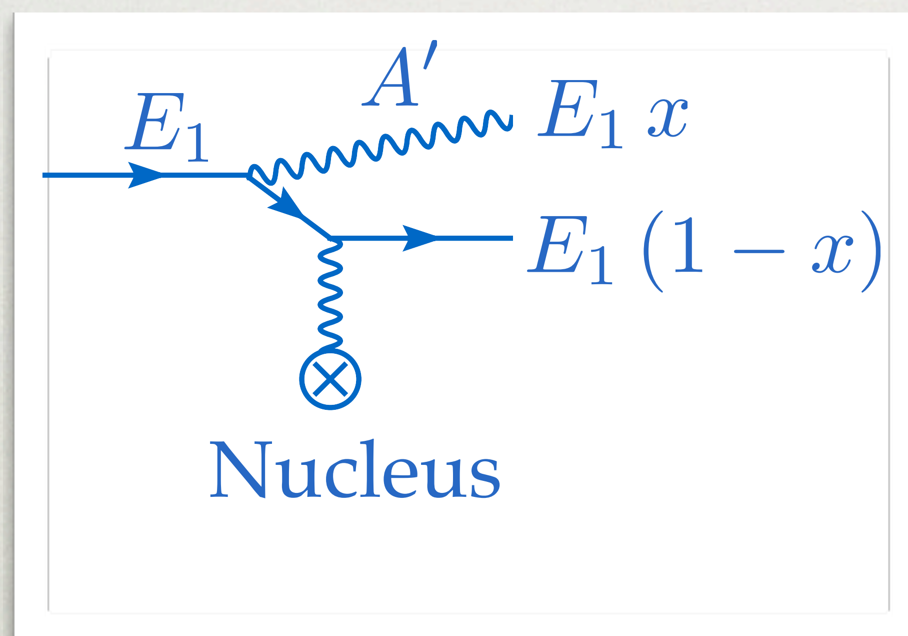
per crossing

O(few) ab^{-1} per decade

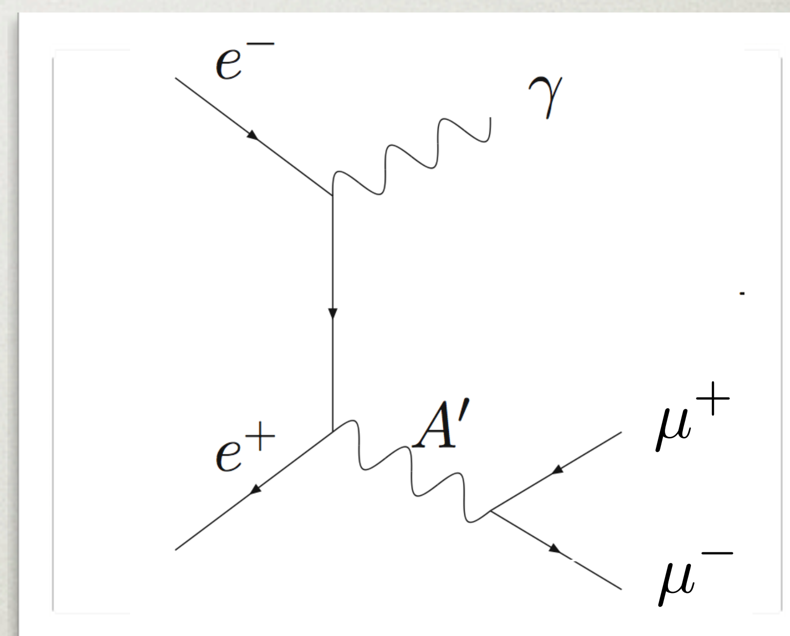
Cross-Section

– Scales as A′ mass, not beam energy

– Coherent scattering from nucleus



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$



$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

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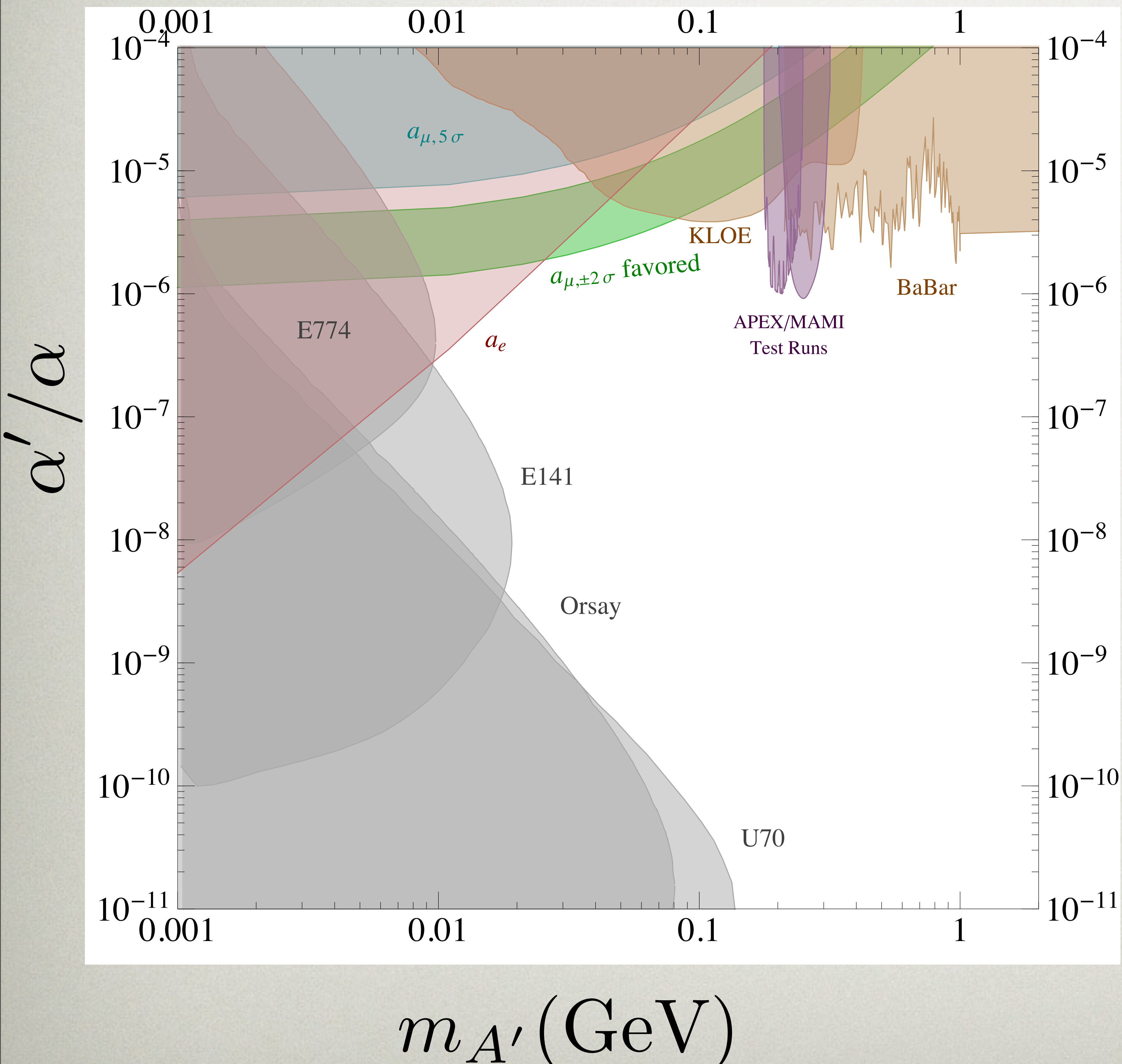
Fixed-Target Territory

(Lepton Decays)



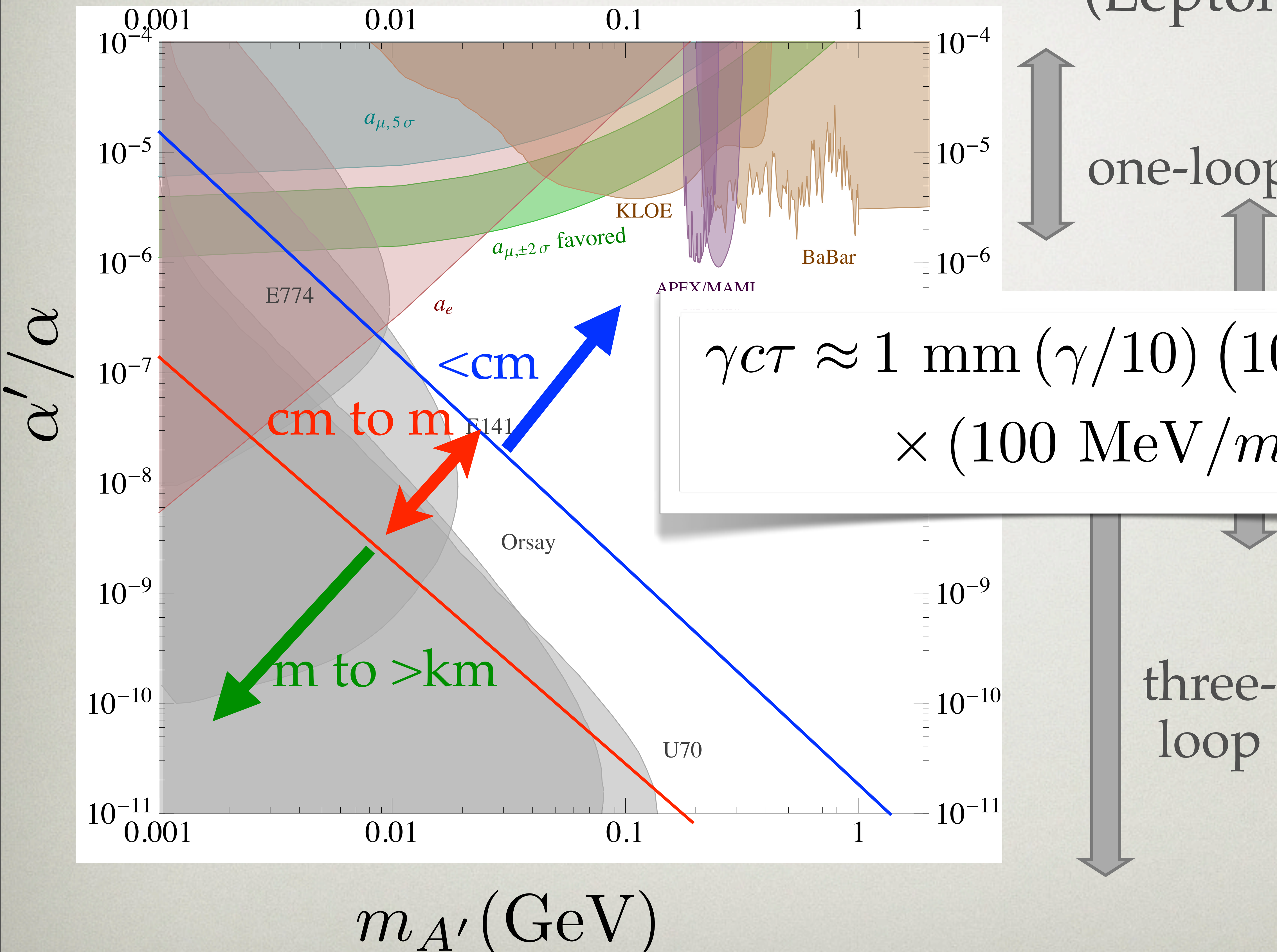
one-loop

two-loop
(GUT)

three-
loop

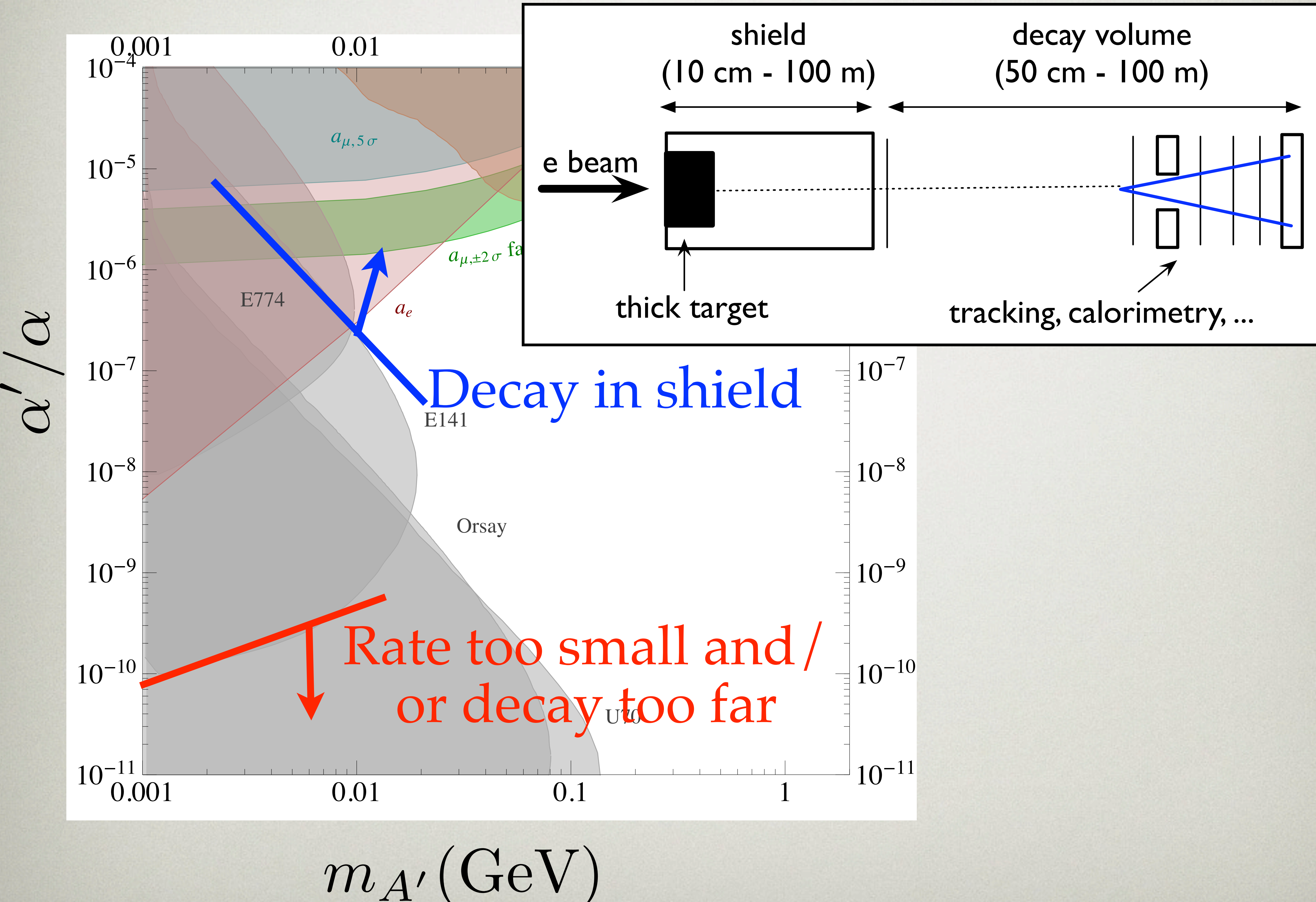
Fixed-Target Territory

(Lepton Decays)



$$\gamma c\tau \approx 1 \text{ mm} \, (\gamma/10) \left(10^{-8}\alpha/\alpha'\right) \times (100 \text{ MeV}/m_{A'})$$

Beam-Dump Limits



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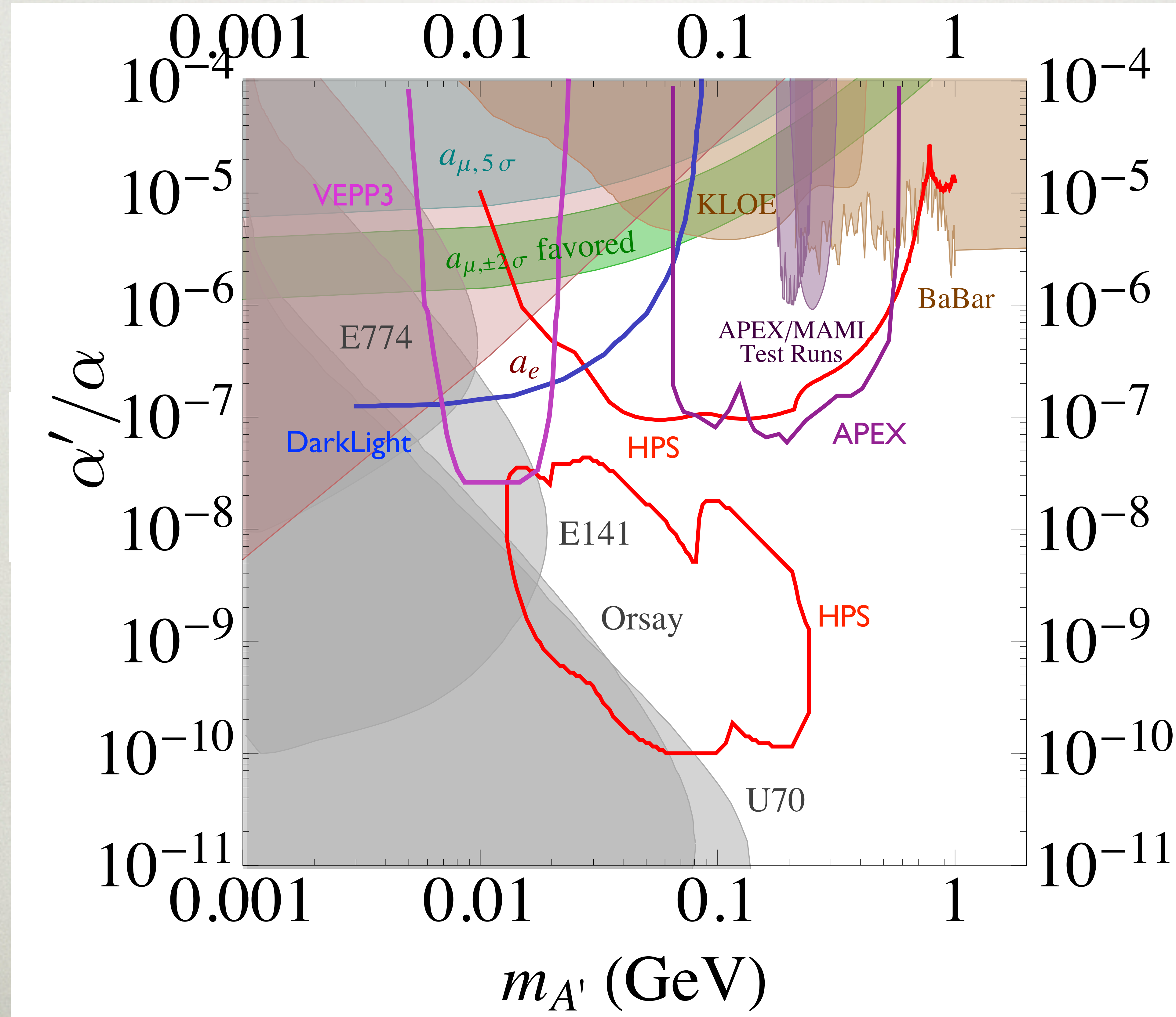
Electron F.T. Proposals

(JLab only; similar @ Mainz)



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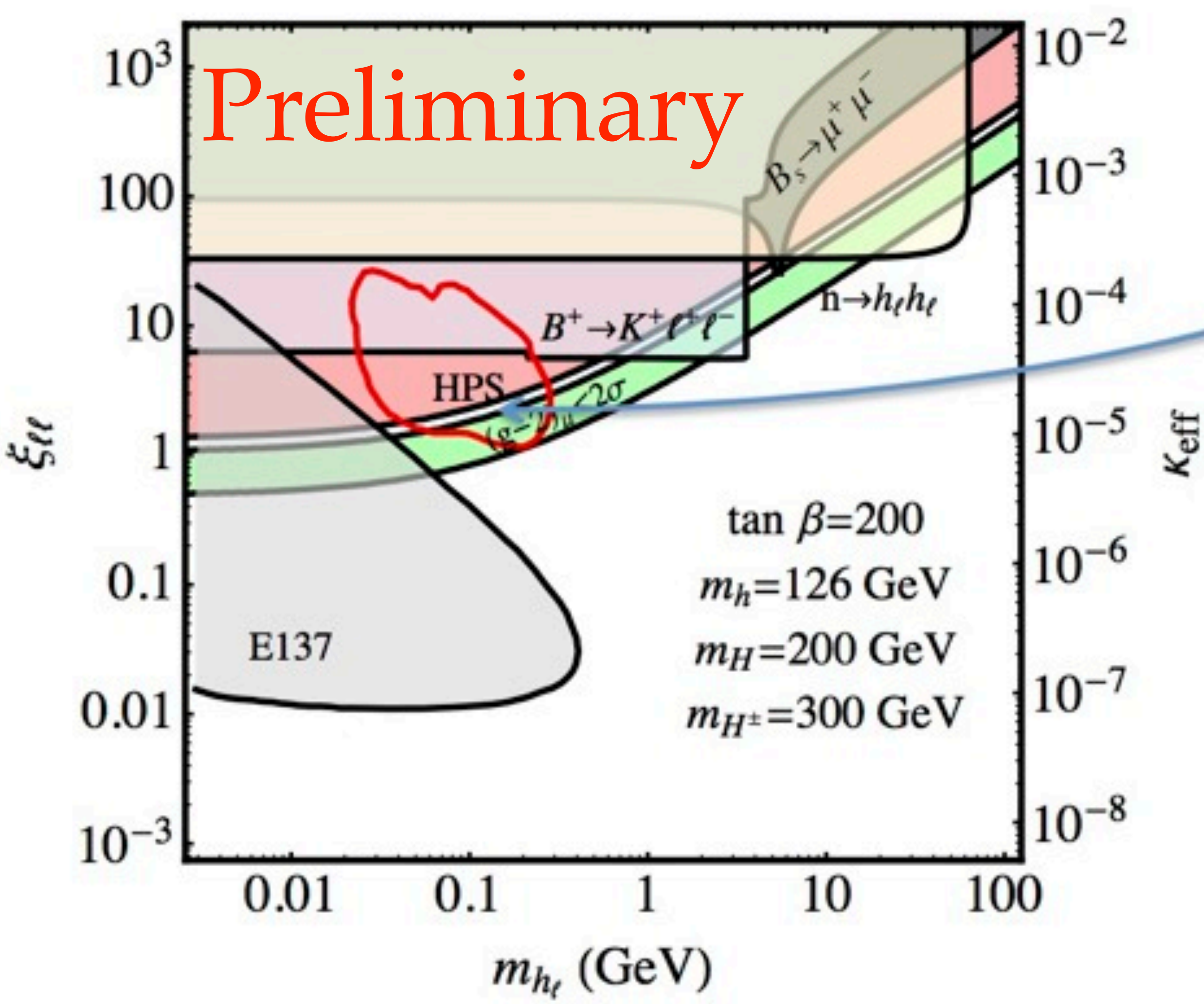
HPS Sensitivity to Extended SM Higgs Sectors

2 Higgs doublet model coupled to a dark sector singlet

$$\mathcal{L}_{\text{Yuk}} = \frac{m_\ell}{v c_\beta}\rho_1 \bar{\ell}\ell + \frac{m_q}{v s_\beta}\rho_2 \bar{q} q$$
$$\equiv \frac{m_\ell}{v}\left(\xi_{h\ell\ell} h + \xi_{H\ell\ell} H + \xi_{\ell\ell} h_\ell\right)\bar{\ell}\ell + \frac{m_q}{v}\left(\xi_{hqq} h + \xi_{Hqq} H + \xi_{qq} h_\ell\right)\bar{q} q$$



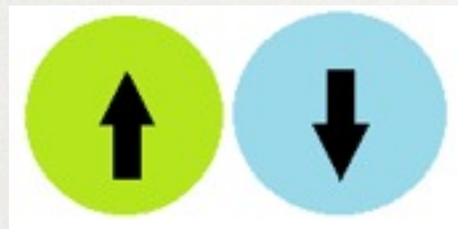
Only HPS has sensitivity in this region!

From: Batell, McKeen, Pospelov, Ritz, *work in progress*.

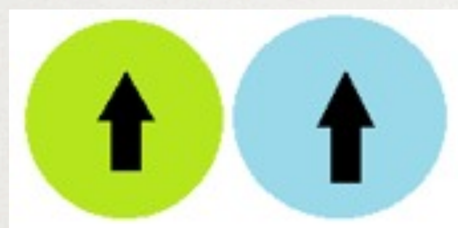
HPS Target of Opportunity: Discover and Study True Muonium

True Muonium is a bound state of a $\mu^+\mu^-$ pair, it has **never been observed.**

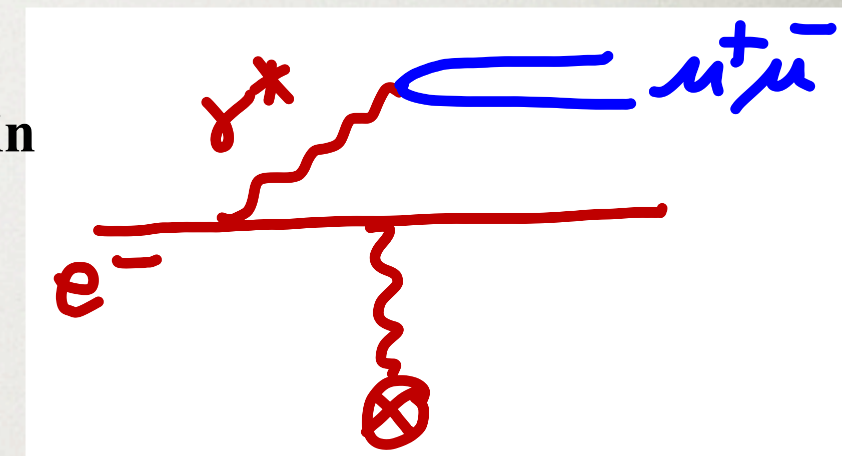
➔ Singlet – Paradimuonium: decays to $\gamma\ \gamma$, $c\tau \sim 0.181$ mm (n=1)



➔ Triplet – Orthodimuonium: decays to e^+e^-, $c\tau \sim 0.543$ mm (n=1)



We're interested in this one;



Interesting properties that could be observed:

- Lifetimes of 1S, 2S, 2P (sensitive to physics that couples to leptonic currents)
- Dissociation cross-sections as a function of energy;

Brodsky and Lebed, Phys. Rev. Lett. 102, 213401 (2009)

Brodsky, True Muonium at Jlab, SLAC, Jan 24, 2012 Talk

➔ QED as perturbative laboratory for QCD bound states;

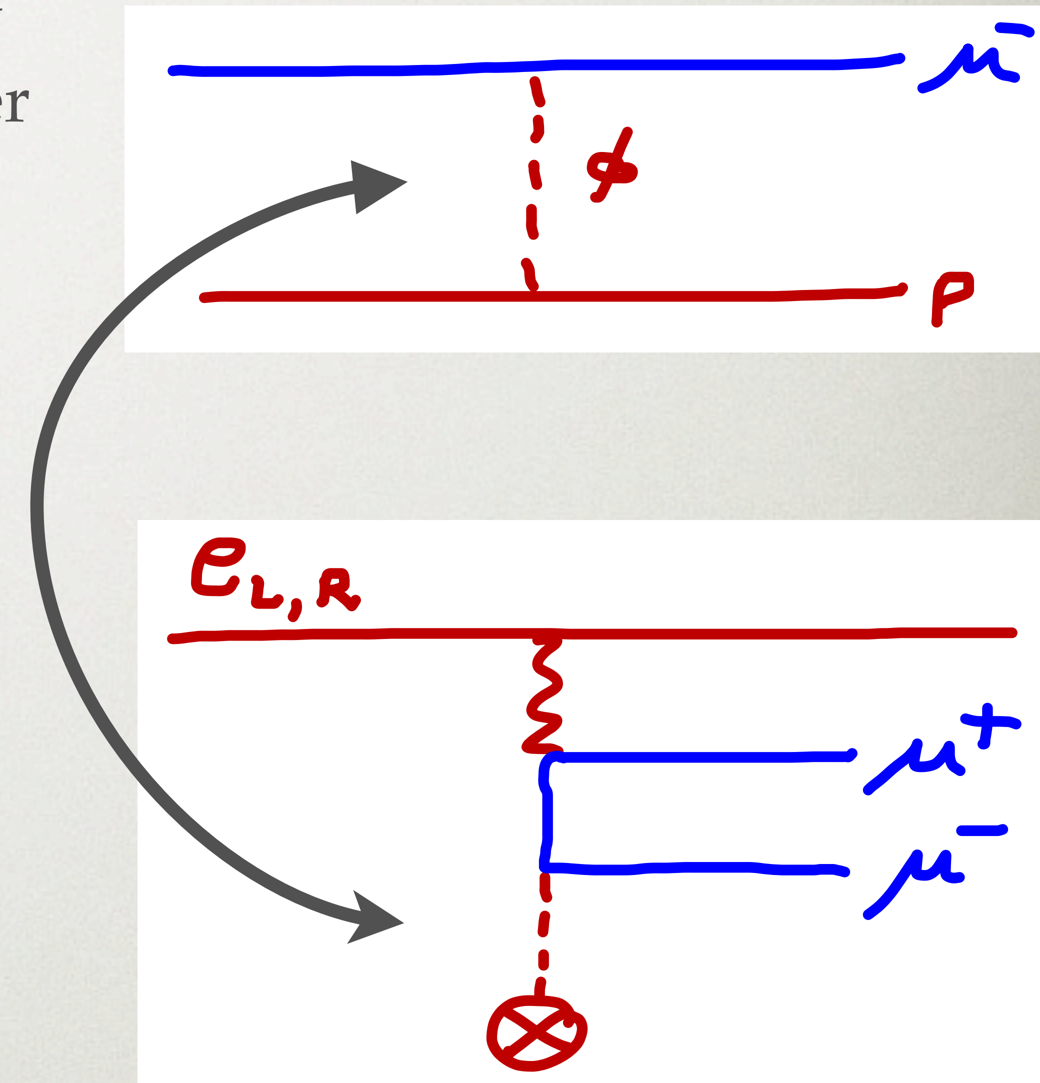
Yield with vertex displacement >1.5 cm ~200–300 events; even 10-20% efficiency gives sizeable sample.

HPS Target of Opportunity: Muonic Hydrogen Anomaly

Muonic hydrogen

MeV-scale force carriers can explain the discrepancy between (μ^-,p) Lamb shift [Pohl et al. 2010] and other measurements of proton charge radius.

Requires couplings *beyond* kinetic mixing (lepton flavor-violating component)



Light mediator can induce electron polarization dependent correction to muon trident rate

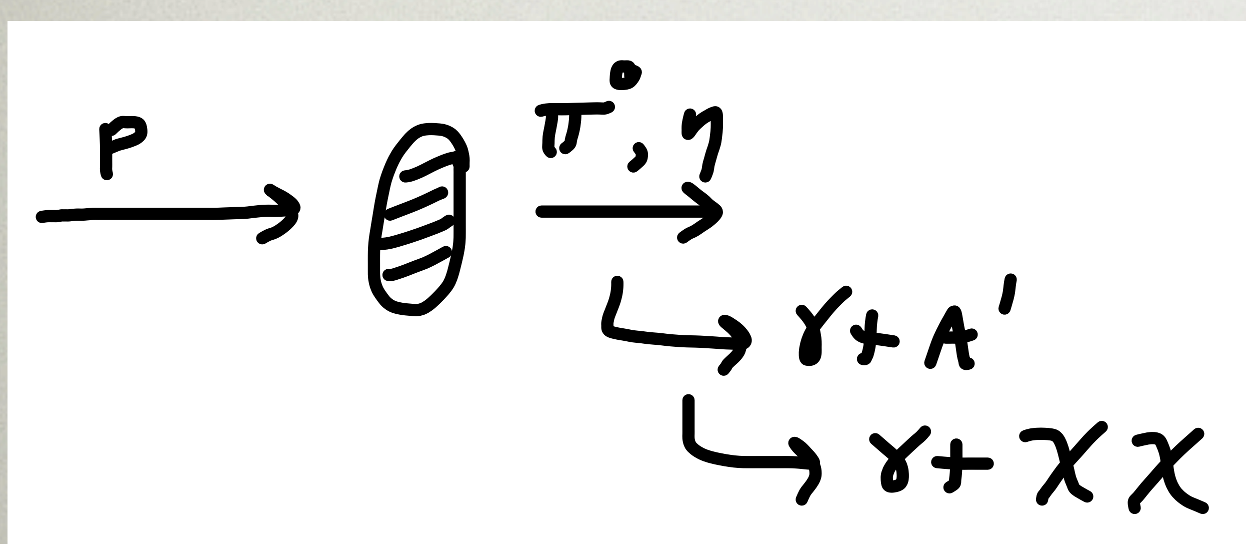
$$\delta = \frac{A_L(\mu^+\mu^-) - A_R(\mu^+\mu^-)}{A_L(\mu^+\mu^-) + A_R(\mu^+\mu^-)} \sim 10^{-3} - 10^{-4}$$ would be interesting!

M. Pospelov

Fixed-Target Dark Matter Searches

So far, only proton beams and large scale neutrino detectors have been considered for fixed-target dark matter searches

Production of Dark Matter: Initiated by meson production, followed by A′ decay



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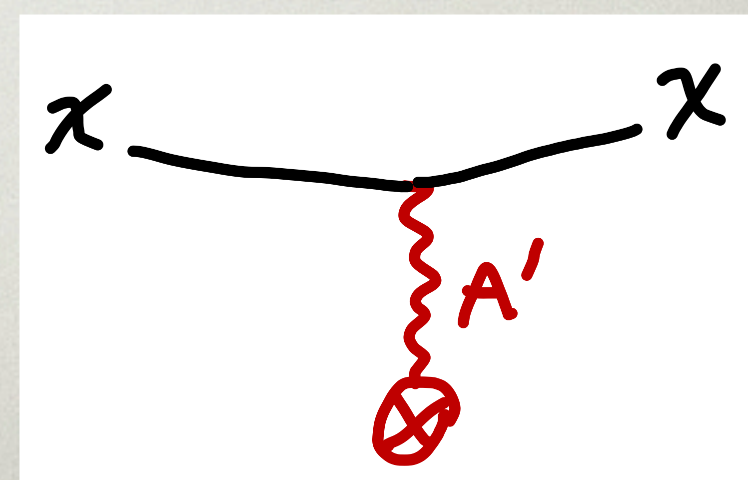
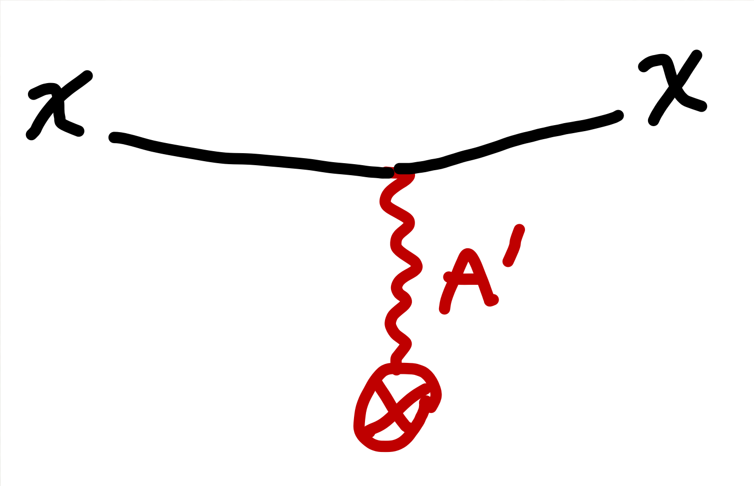
Look for neutral current scattering



Fixed-Target Dark Matter Searches

Look for neutral current -like scattering of long-lived dark sector states or dark matter off of nuclei and/or electrons

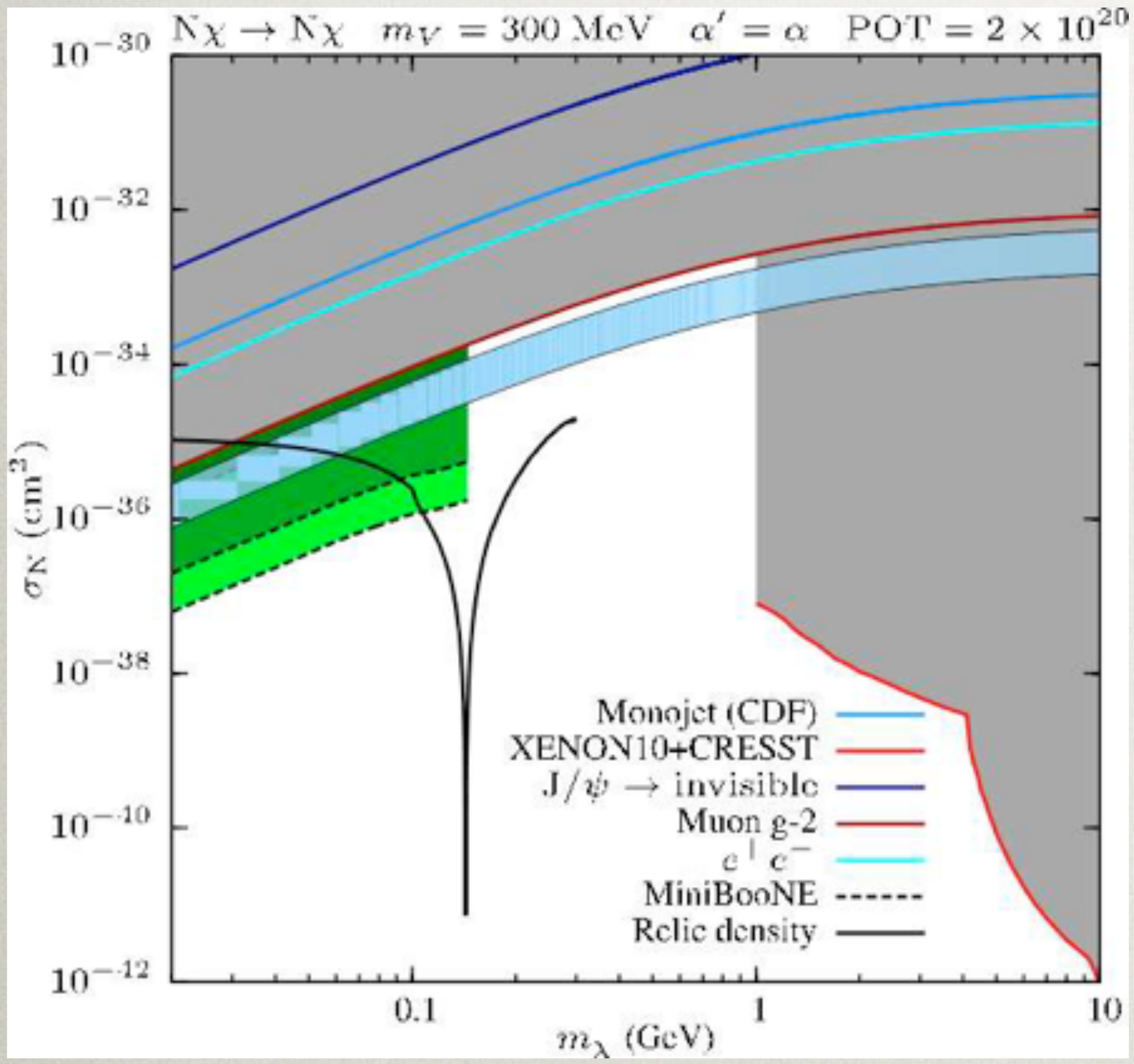


This process can be O(100,000) times larger than neutrino scattering at the same energy for much of the muon g-2 region of interest!

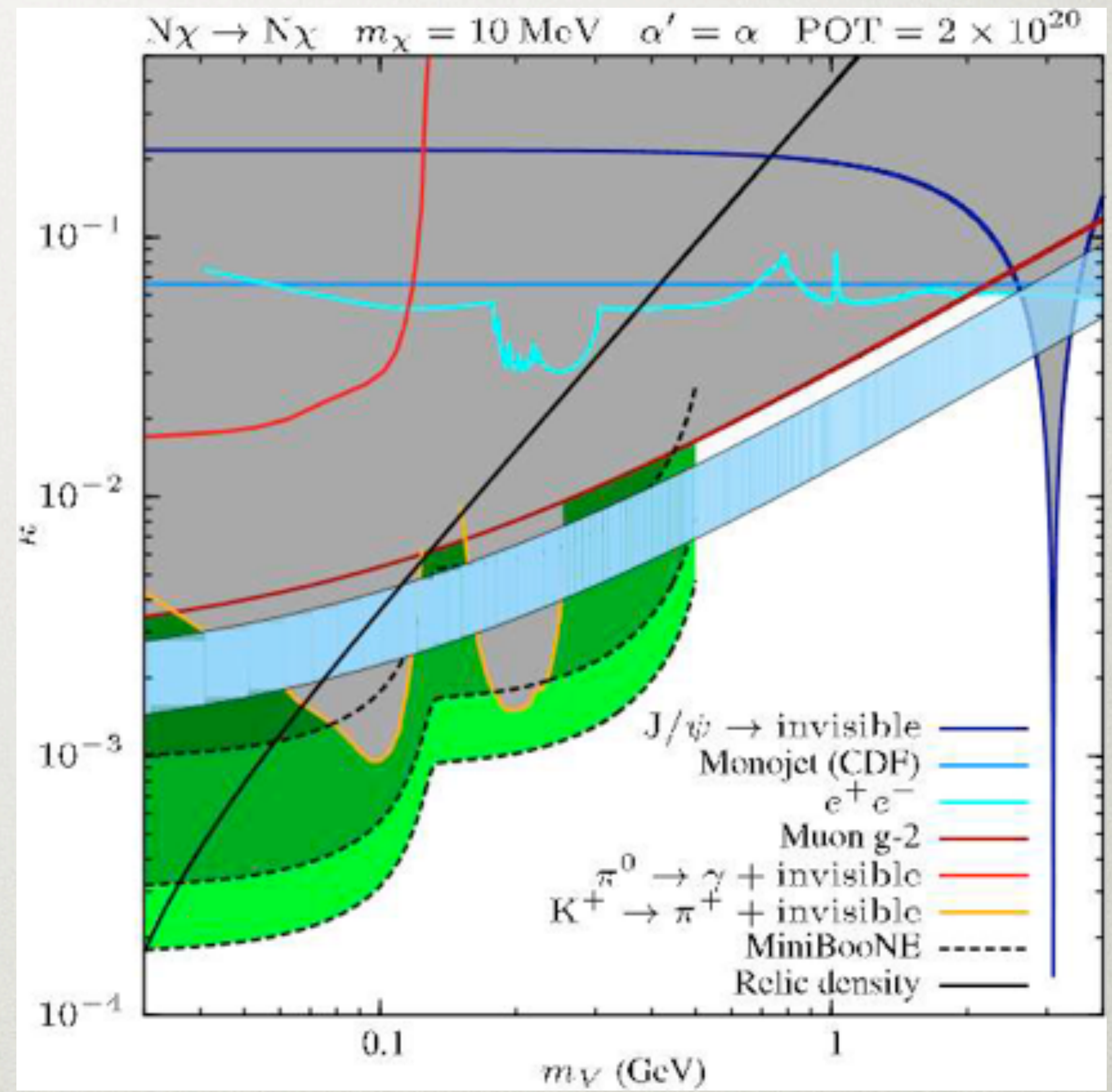
Proton Beams

sub- 500 MeV WIMP search using MiniBooNE

Fix m_V, vary m_χ



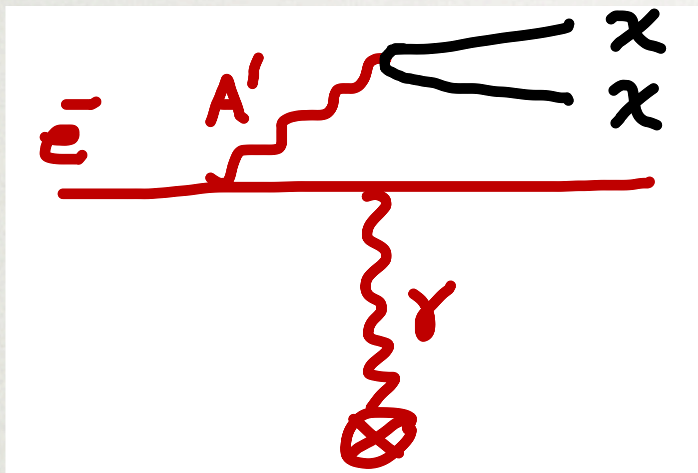
Fix m_χ, vary m_V



(see: arXiv:1211.2258 for proposal)

Electron Beams

dark matter production



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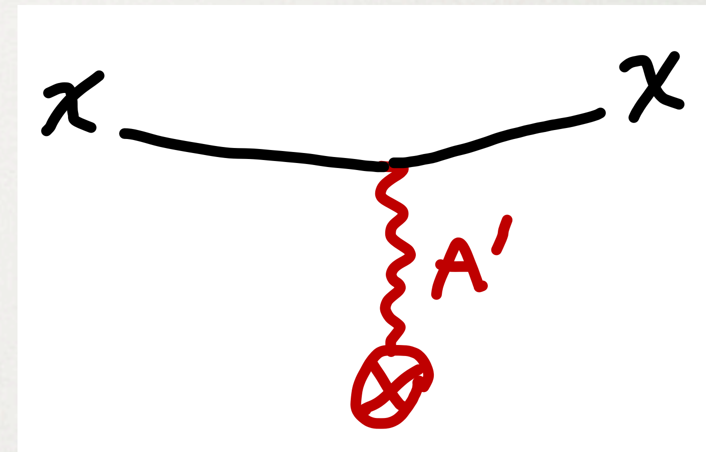
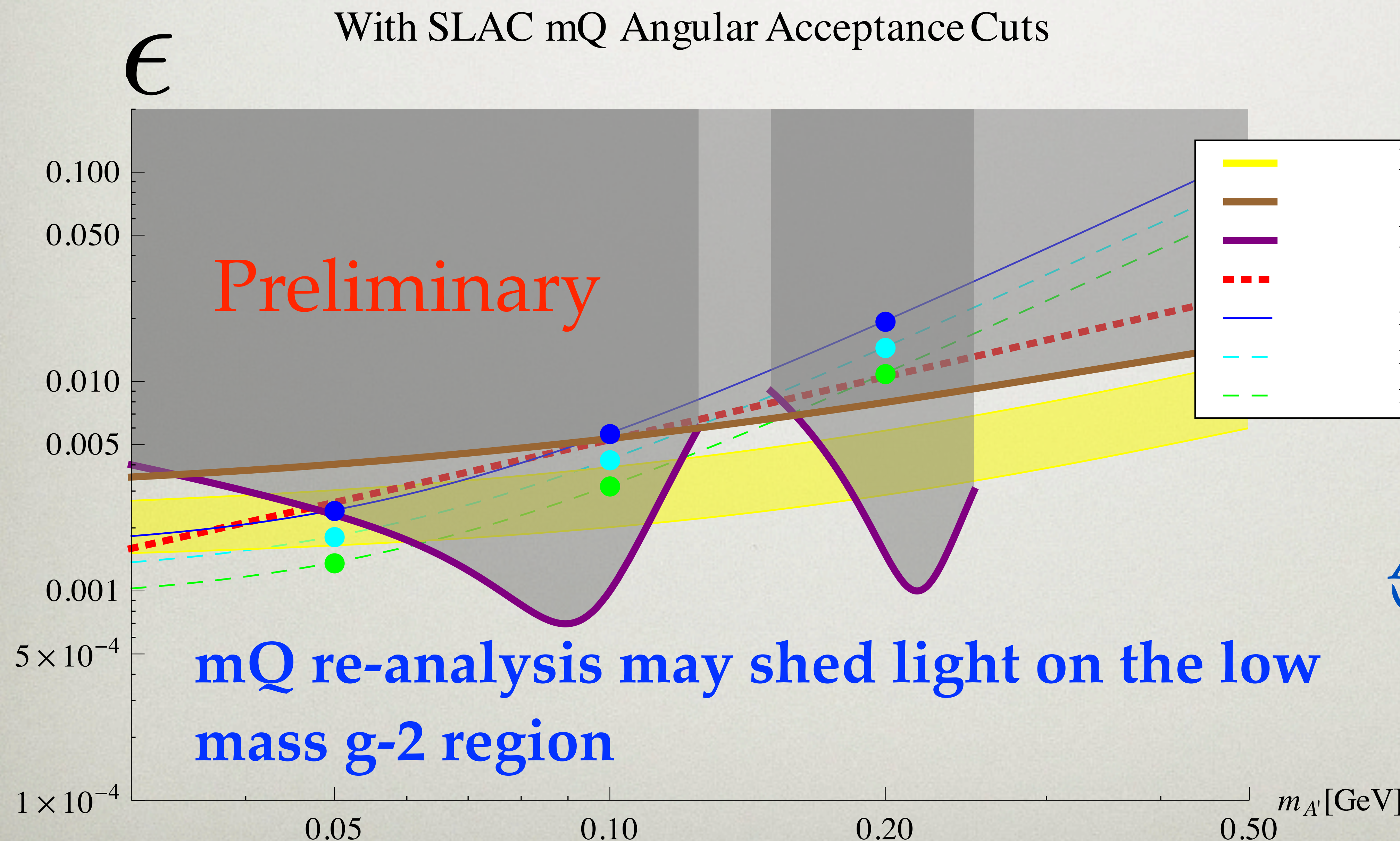


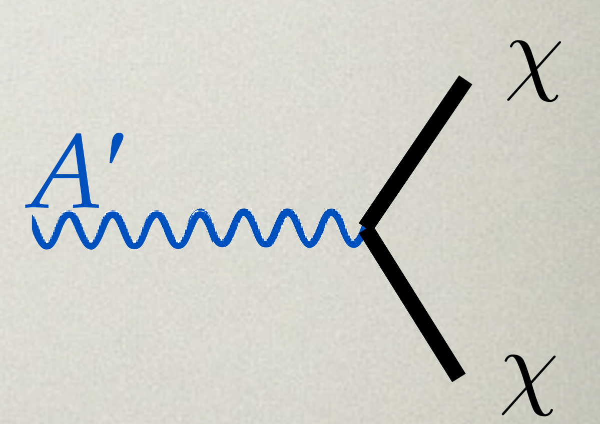
- Several advantages to using electron beams
  - Production does not require $m_{A'} < m_{\pi^0}$ or $2m_\chi < m_{A'}$
  - Very small (zero) neutrino background
  - Can be parasitic (large luminosity without dedicated beam time)
  - Very forward peaked production and lower beam backgrounds permit very small detector (i.e. meter scale or smaller)

Electron Beams

A′ Invisible Decays in the SLAC milli-charge Experiment (mQ)

1.3 C of electrons on target, looking for small scintillation signal in time with beam bunches (primary aim was to detect milli-charge particles)





[M. Diamond, PS to appear] 28

Electron Beams

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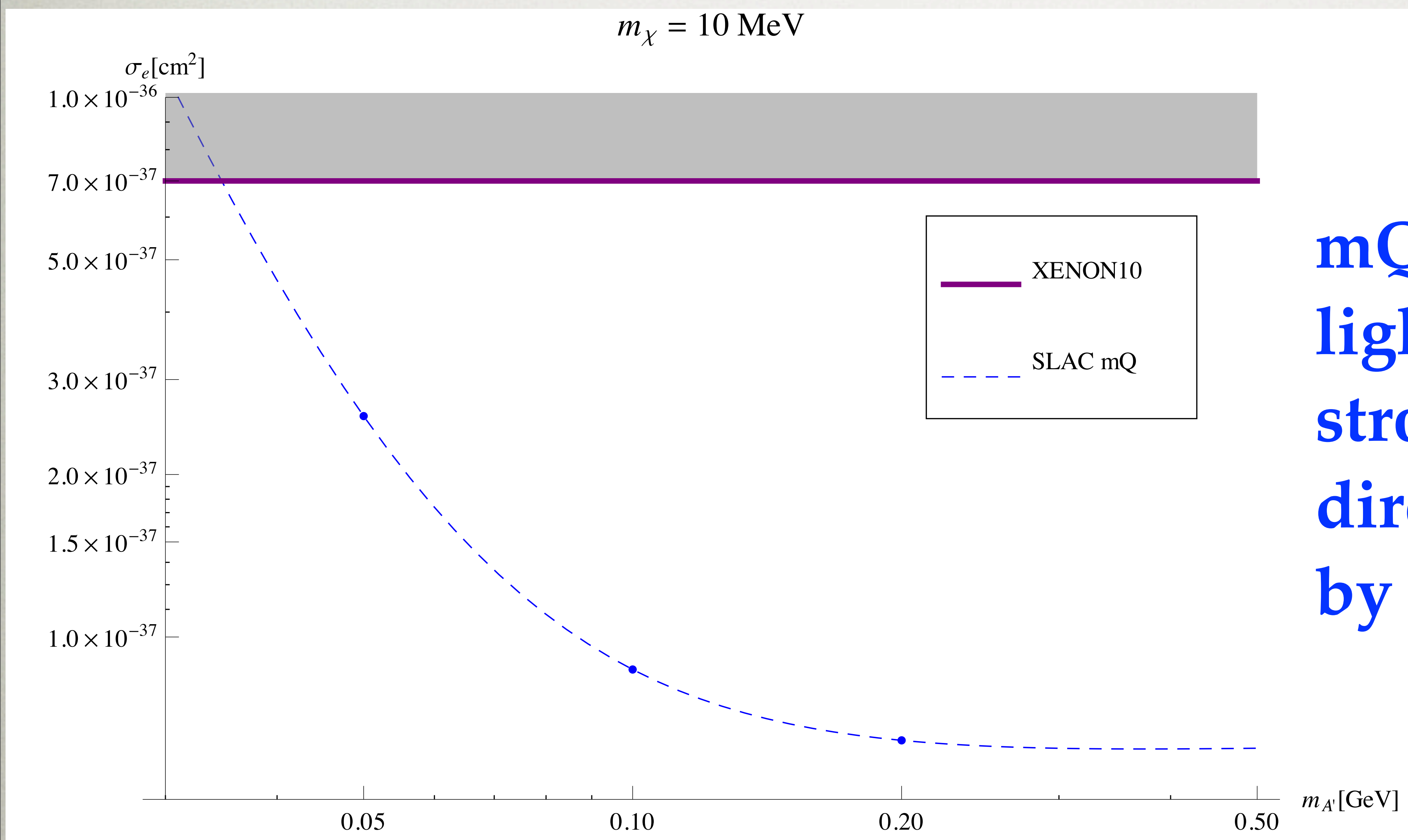
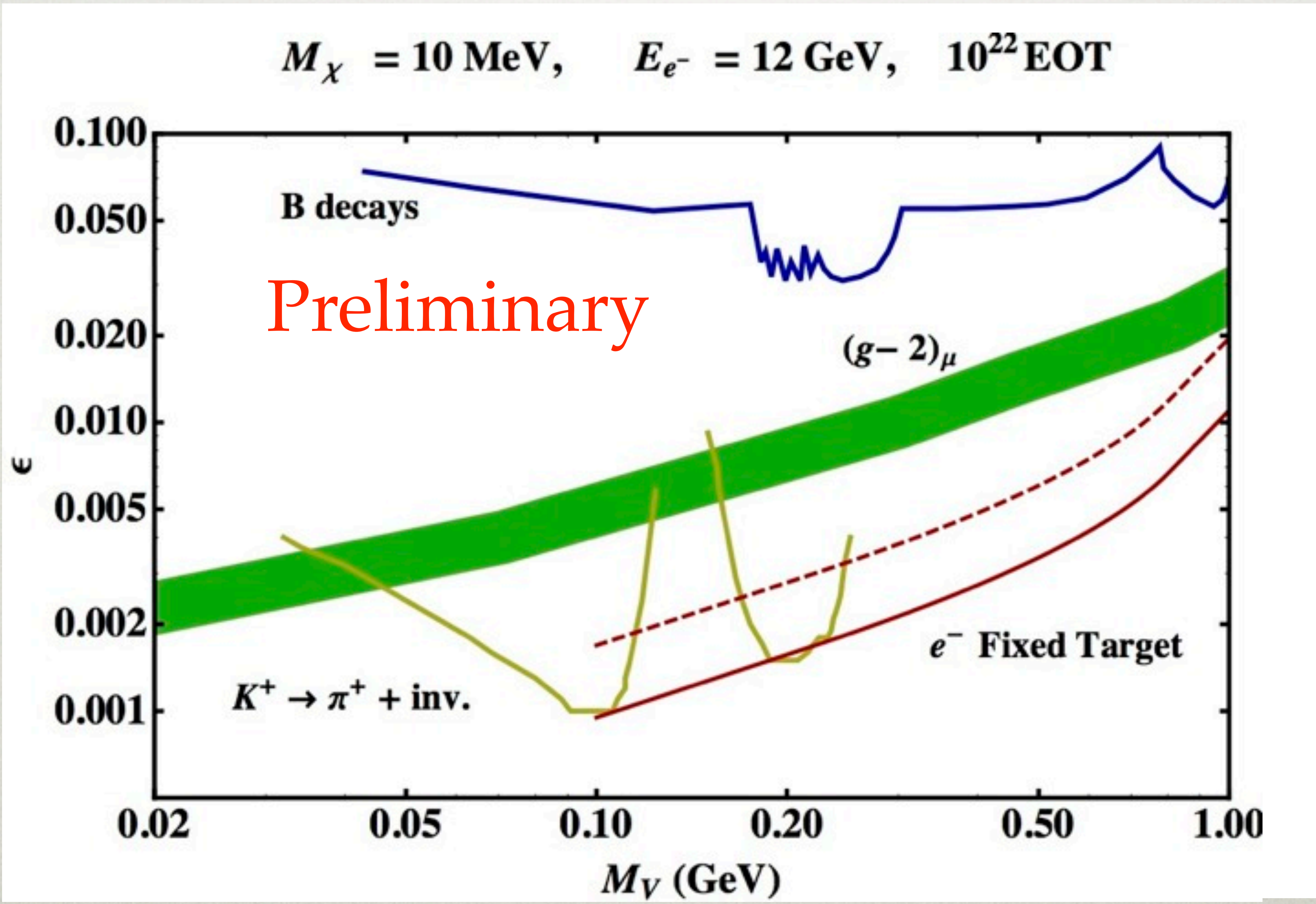


mQ constraints on light dark matter stronger than best direct detection limits by more than O(10)!

[M. Diamond, PS to appear]

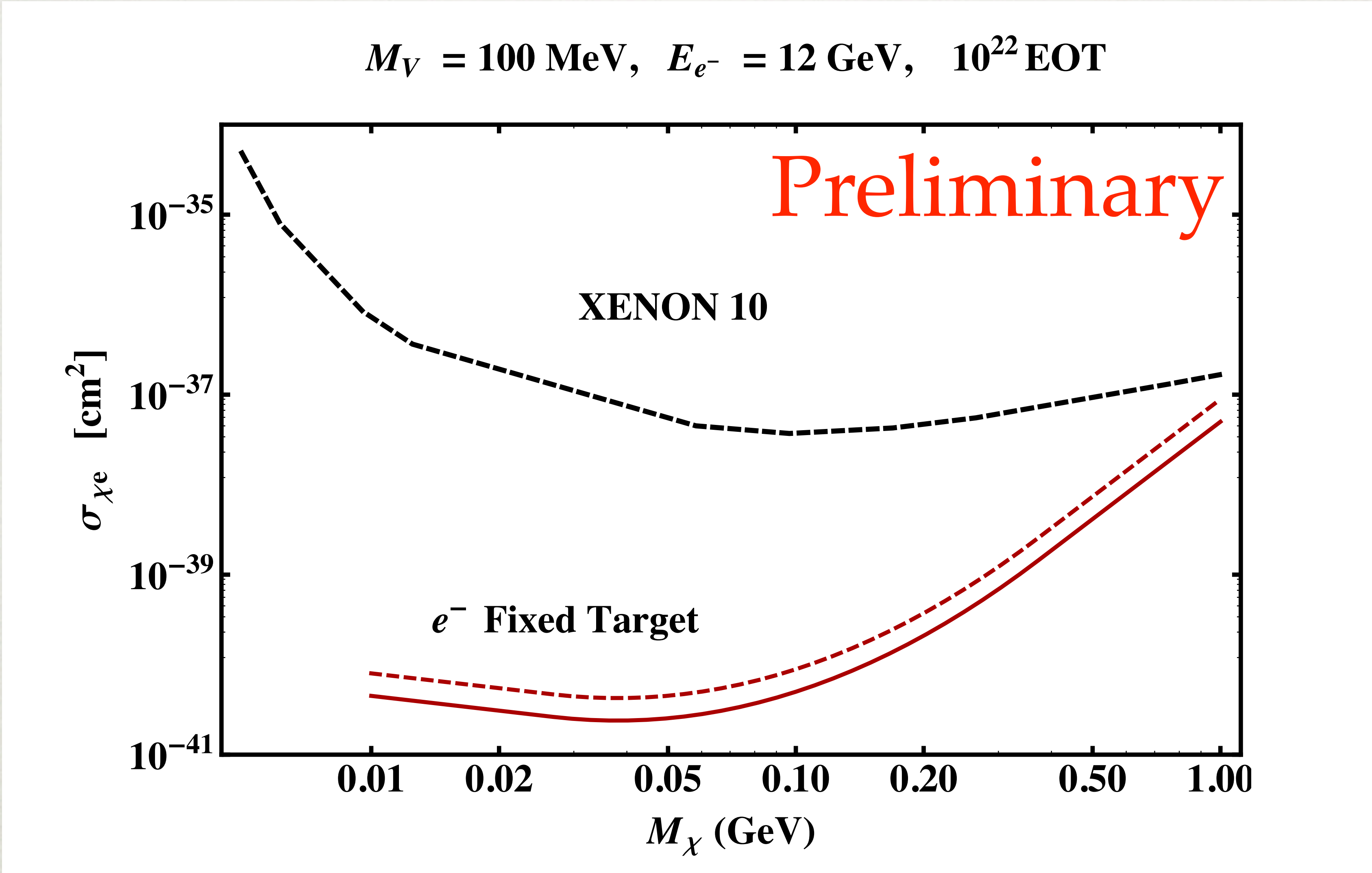
What about JLab CW Beams, behind the dumps?

Meter-scale (MiniBooNE style) detector, 10 meters from the dump, estimating bkg from measured beam un-related bkg for MiniBooNE (re-scaled)



[G. Krnjaic, E. Izaguirre, PS, N. Toro work in progress]

Electron Beams vs Direct Detection



- Meter-scale neutral current detector behind a JLab dump might have unparalleled sensitivity to light dark matter.
  - **A smaller test detector may still cover the g-2 region!**

[G. Krnjaic, E. Izaguirre, PS, N. Toro work in progress]

Conclusions

- Dark Forces are an exciting window into physics **far beyond** the Standard Model
  - Possible connections to dark matter, muon g-2, and physics at very high energies
- Jefferson Laboratory experiments are pioneering the exploration of this physics
  - Will explore large new physics territory for direct A' production and decay and discover rare SM physics
- Potential opportunities at JLab to directly produce dark matter and search for invisible A' decays with detection sensitivity far surpassing existing dark matter searches

Thanks!