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

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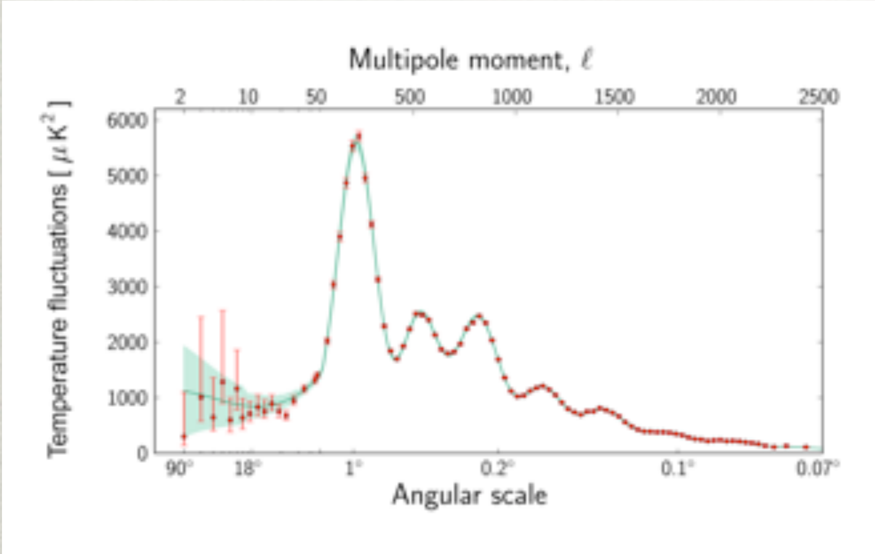
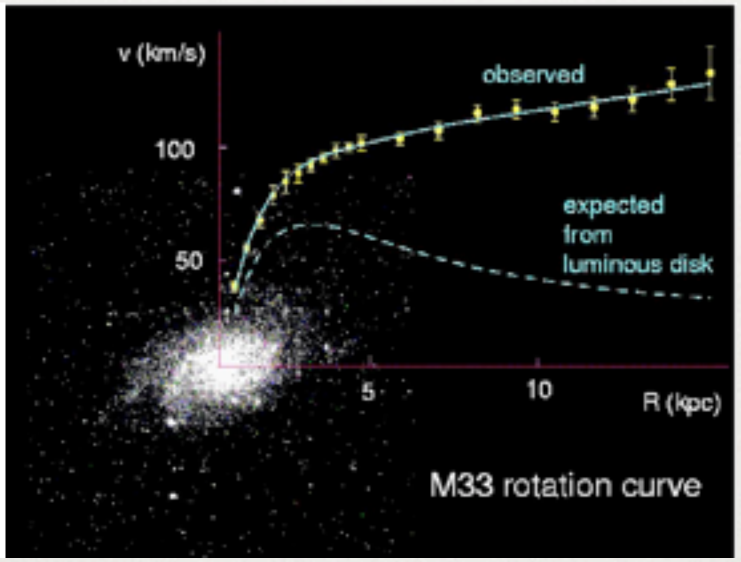
Dark Forces Below the Weak Scale

- Theory, motivation, and goals for new-particle searches at the GeV-scale
- Searching for Dark Forces at colliders
- Fixed-Target Dark Force & Dark Matter Searches

Beyond the Standard Model

We know there is dark matter

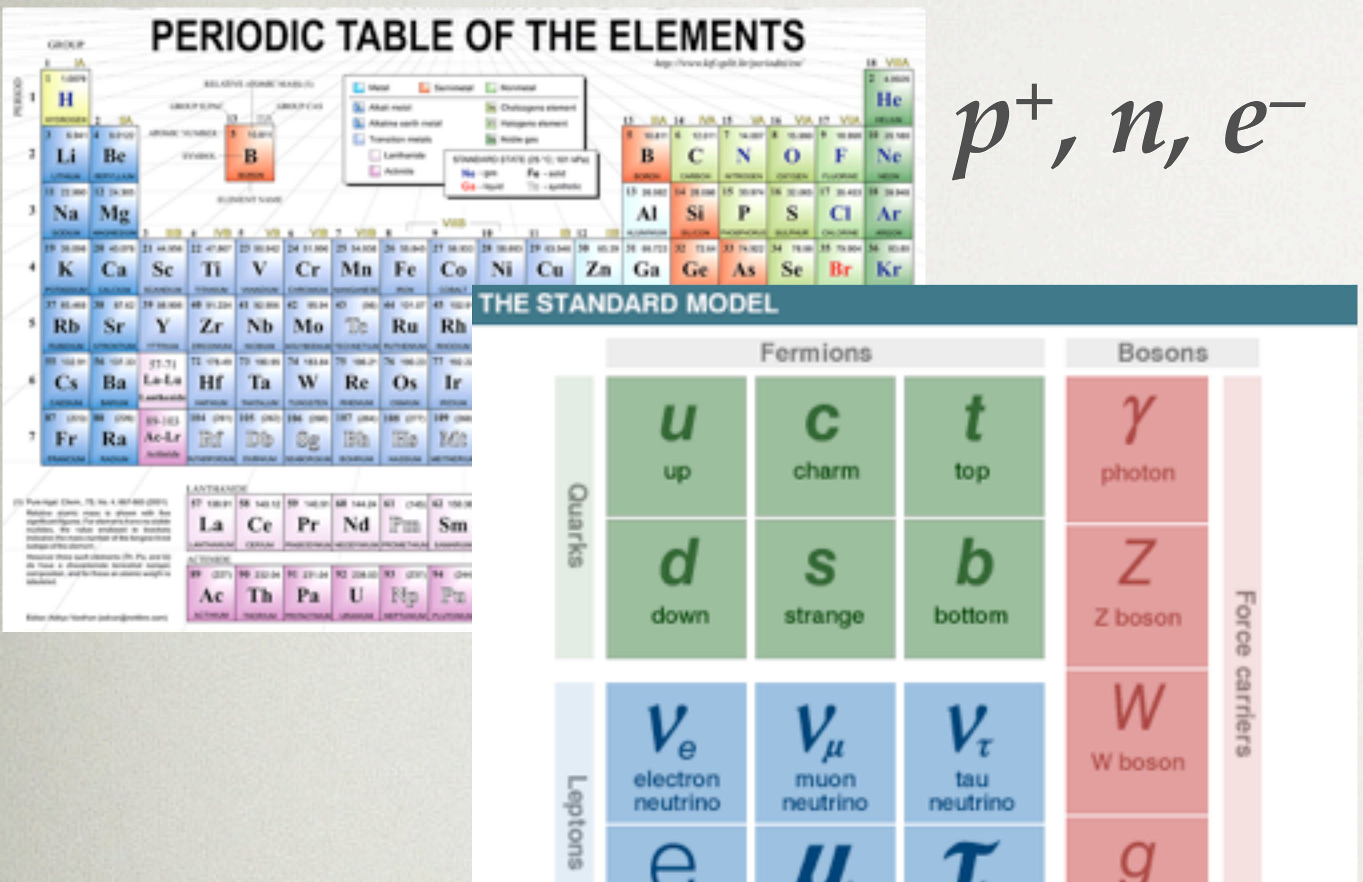




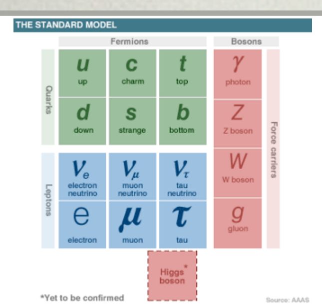
...but what is it?

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

Copernican Particle Physics?



p^+, n, e^-

	?	...
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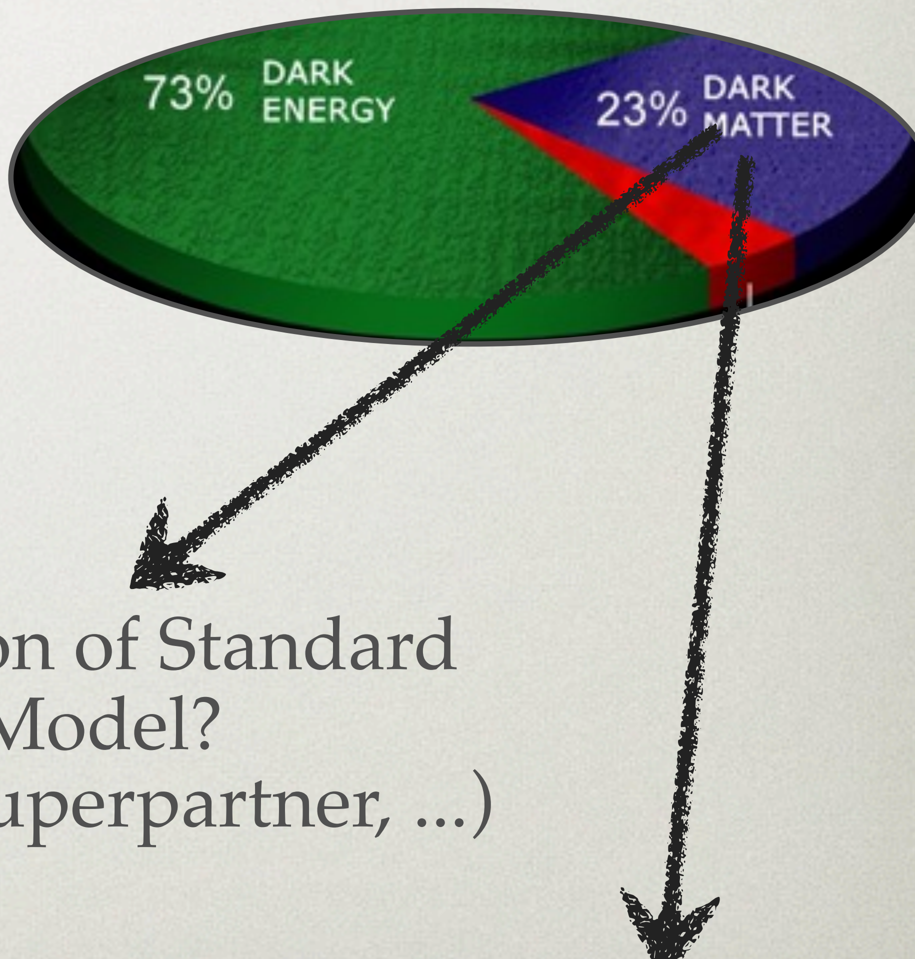


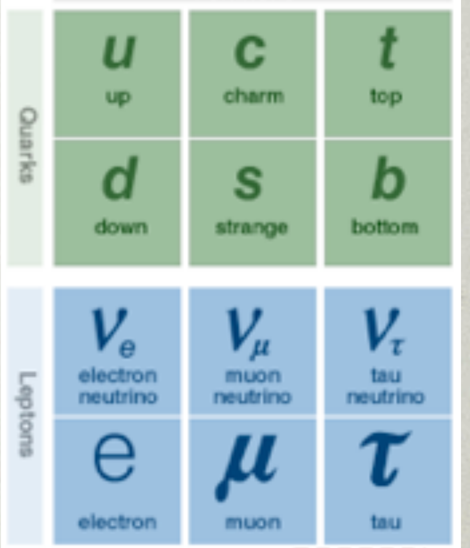
extension of Standard Model?
(axion, superpartner, ...)

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.

Beyond the Standard Model

Dark sector gauge forces provide a simple explanation for why dark sector is "dark" with long-lived dark matter components

Dark Sector ?

$$U(1)_D \times \ldots$$

$$U(1)_Y \times SU(2)_W \times SU(3)_s$$

Look for residual interactions allowed symmetry!

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	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	kinetic mixing?
Axion Portal	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	axion-like particles?

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Vector Portal	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	Focus of this talk
Axion Portal	$\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	axion-like particles?

Vector-Portal Interactions

Consequences of a new mixed U(1): (handwritten insertion: "massive" before U(1))

$$\mathcal{L} \supset -\tfrac{1}{4}F_Y^2 - \tfrac{1}{4}F'^2 + \frac{\epsilon_Y}{2} F_Y F' + e A_Y J_Y + g A' J' + m^2 A'^2$$

"heavy (dark) photon"

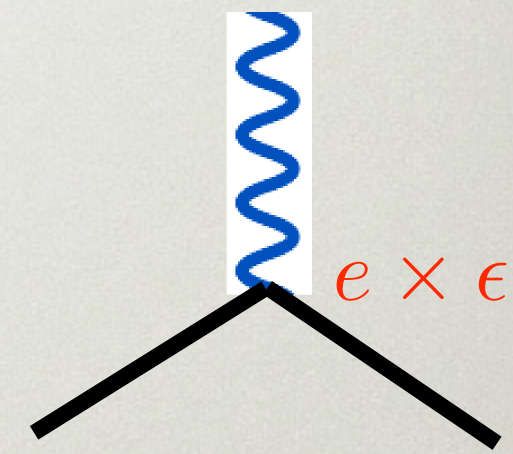
Diagonalize: $A_\mu^Y \to A_\mu^Y - \epsilon_Y A'_\mu$

Induces coupling $\epsilon e A' J_{EM}$

of dark U(1) to EM-charged particles

$(\epsilon = \epsilon_Y \cos\theta_W)$

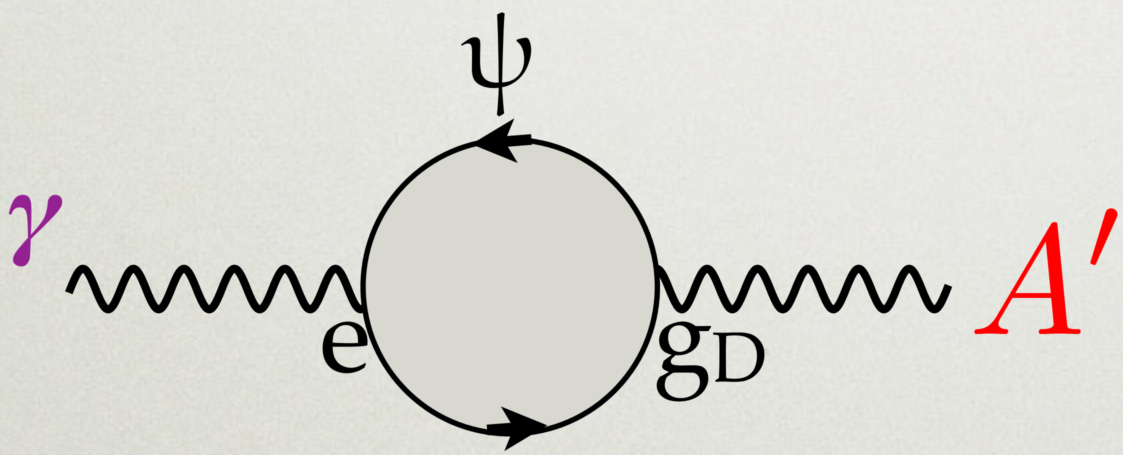
mediates production and (if $m > 2\, m_e$) decay



What are reasonable couplings and masses?

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

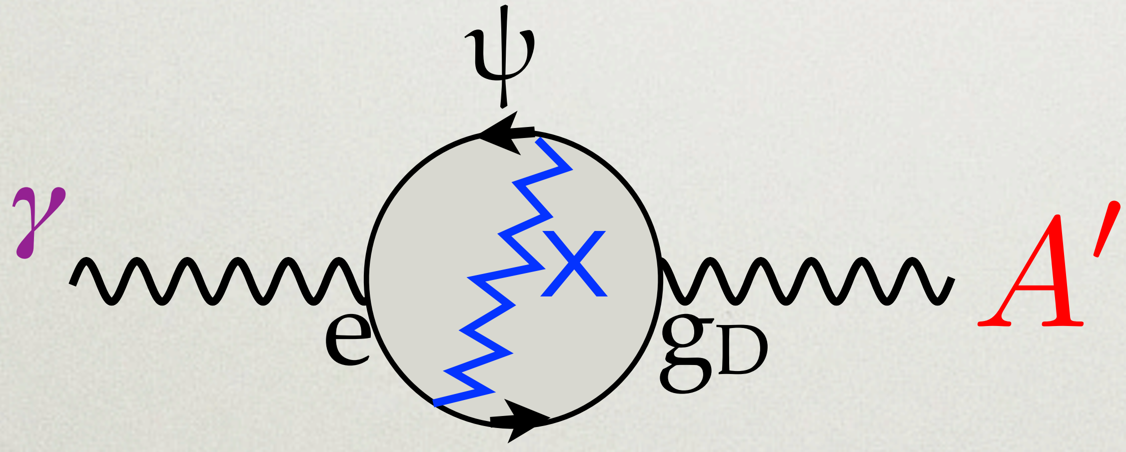
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



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

- MeV-to-GeV is **allowed** at couplings >10^{-7}
- Possible origin: related to M_Z by small parameter
  - e.g. supersymmetry+kinetic mixing ⇒ scalar coupling to SM Higgs, giving

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

[e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

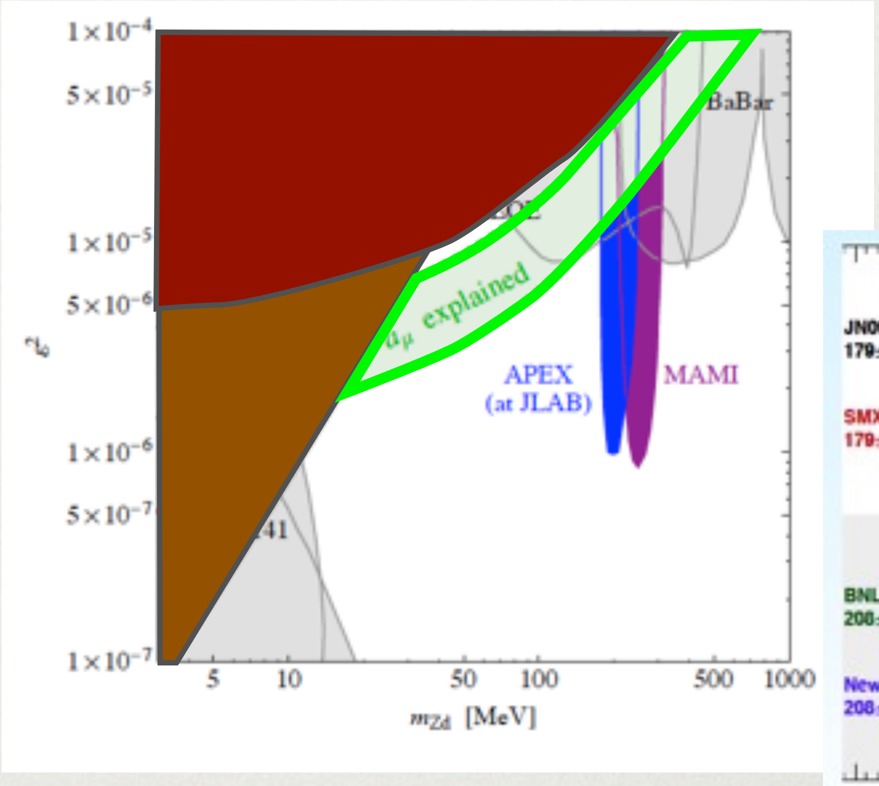
- motivated by g-2 and dark matter anomalies

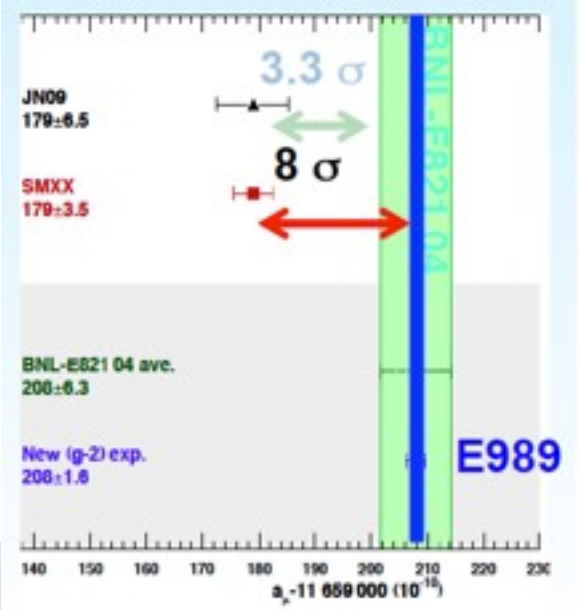
a motivated target of opportunity

Target of Interest? 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**

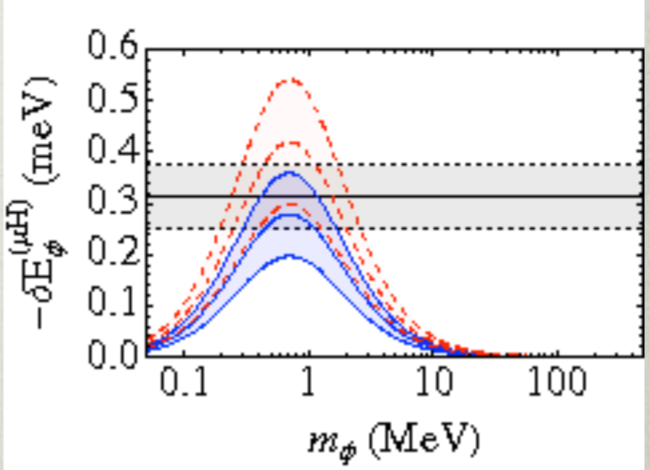




Muonic hydrogen

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)

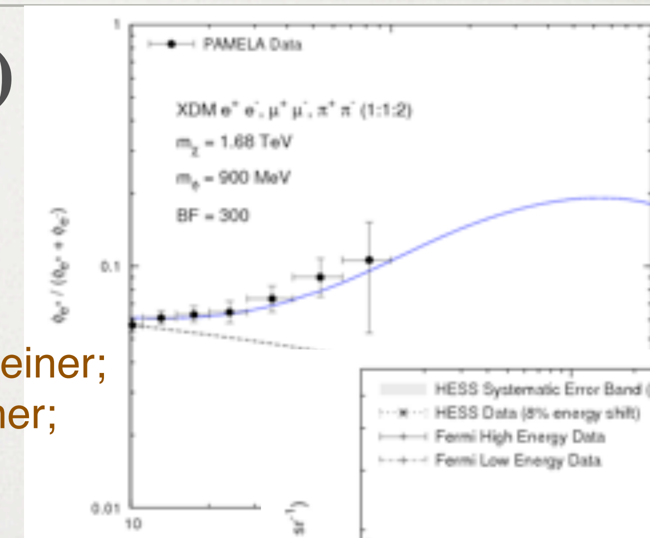


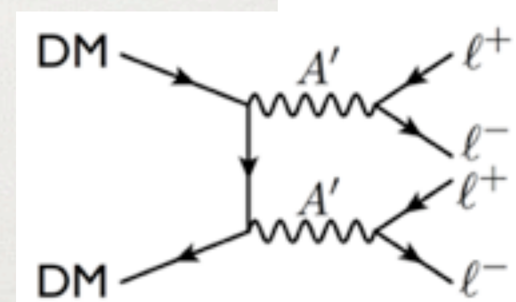
[Tucker-Smith & Yavin, 1011.4922]

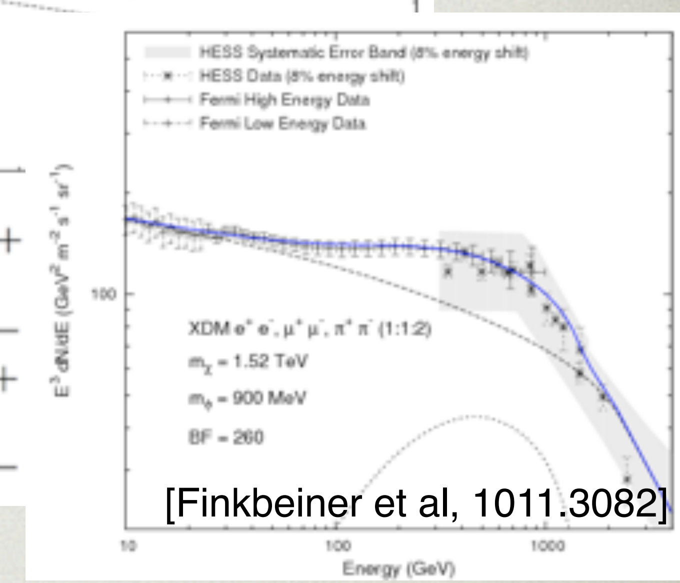
Target of Interest? Dark Matter Interactions

High-energy cosmic e^+/e^- (PAMELA, FERMI, AMS)

Thermal DM charged under $U(1)_D$ can have large local annihilation rate (Sommerfeld enhancement) and hard, lepton-rich decays [Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]







[Finkbeiner et al, 1011.3082]

No signals in other probes of DM annihilation

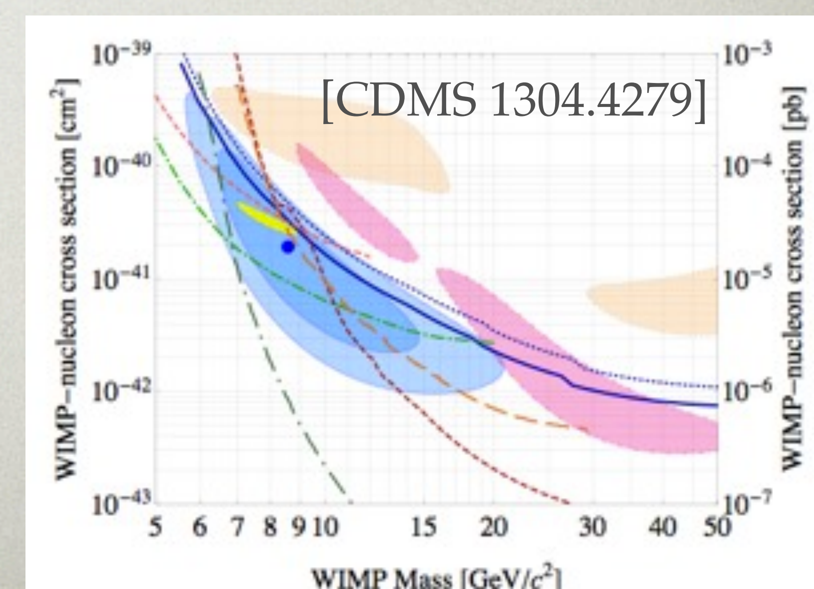
– constrained but not excluded

– interesting ways out of constraints

Light dark matter hints (DAMA, CoGeNT, CRESST, CDMS-Si)

Many instrumental challenges & constraints…

A dark force easily reconciles ≲10 GeV DM with Standard-Model-like decays of Z and h



[CDMS 1304.4279]

GeV-Scale Discovery Frontier

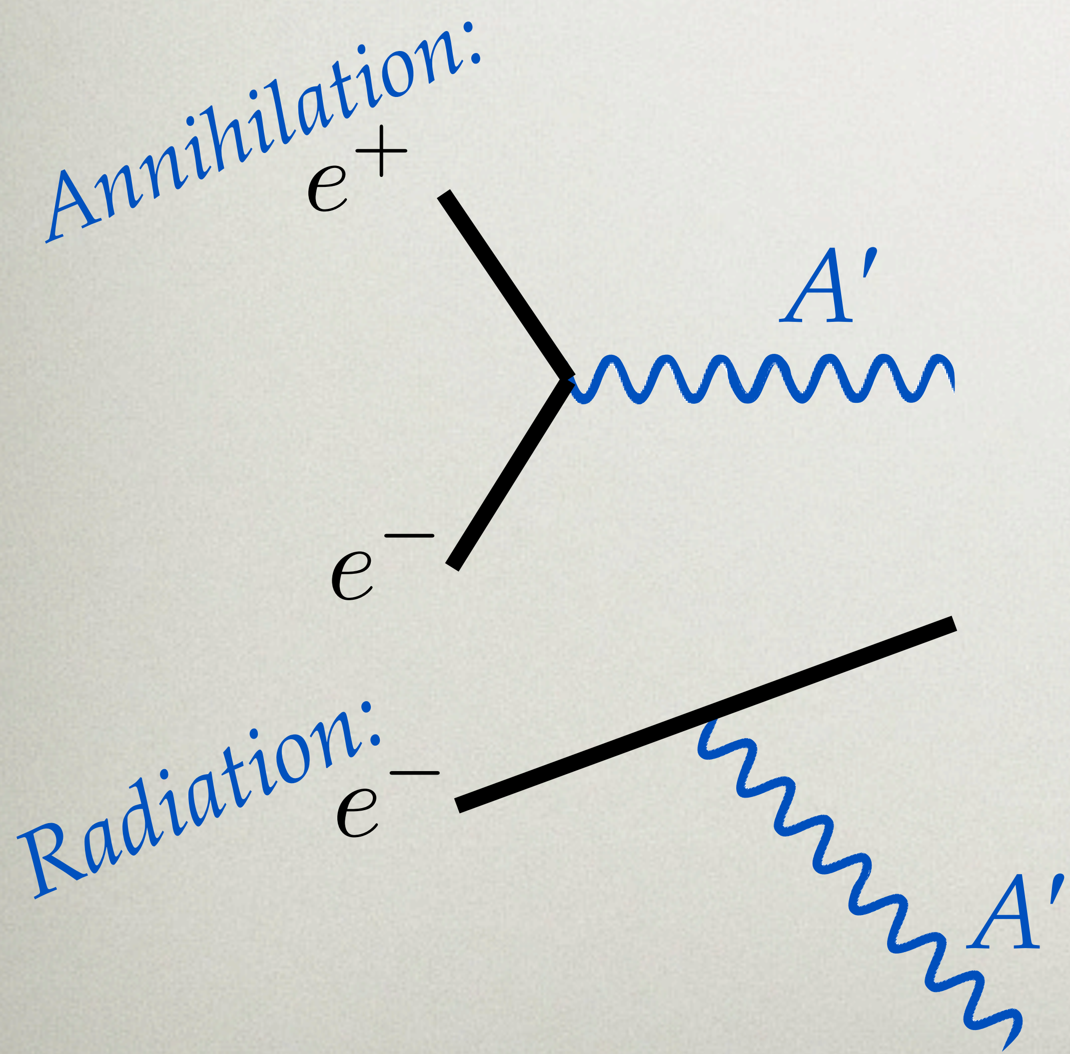
Tremendous opportunity to explore GeV-Scale dark matter and weakly coupled physics with novel small-scale experiments!

What will we find?

Searching For MeV-GeV Dark Forces: Production

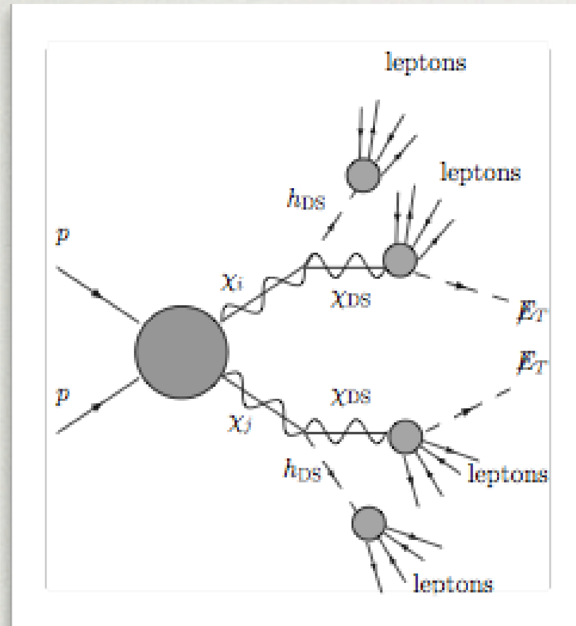
$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu} \;\; \longrightarrow \;\; \epsilon e A' J_{EM}$ $\Rightarrow$ Particles of EM charge q get ***effective*** $U(1)'$ charge $\boldsymbol{\epsilon q}$

Production



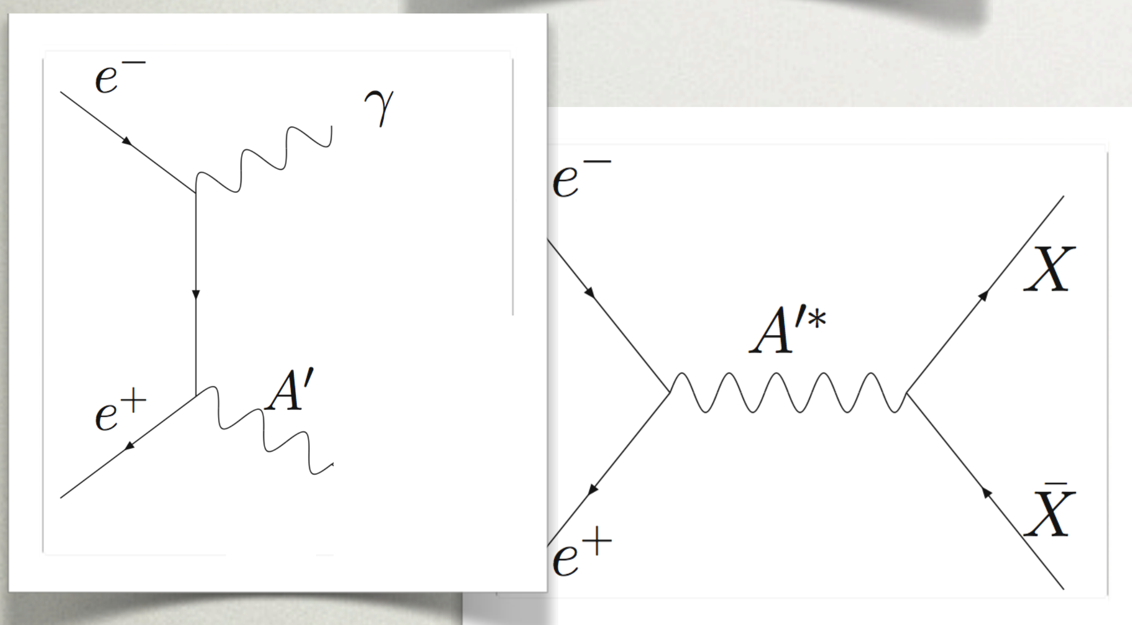
Requires high luminosity – ***not*** high energy!

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



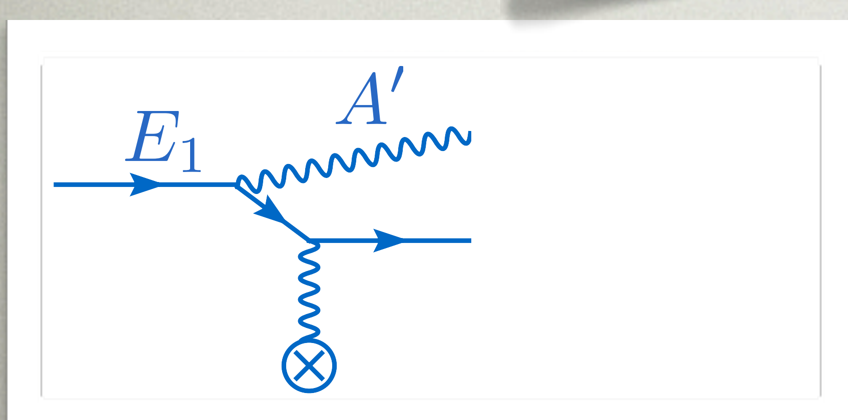
High Energy Hadron Colliders (indirect) – New heavy particles can decay into dark sector "lepton jets"

(ATLAS, CMS, CDF & D0)



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

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

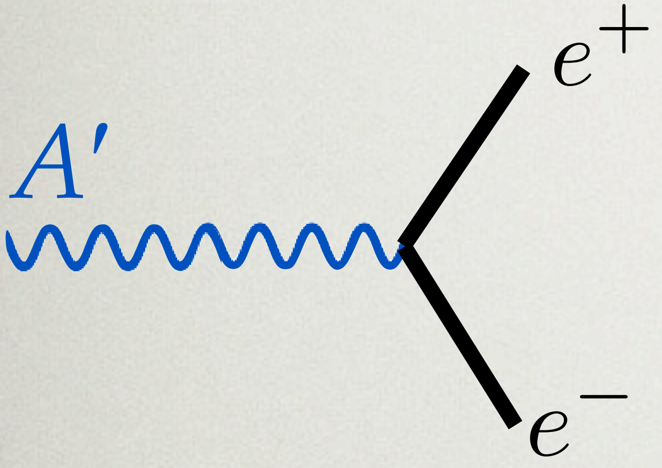


Fixed-Target: Electron or Proton collisions, A′ decays to di-lepton, pions, invisible

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

Searching For MeV-GeV Dark Forces: Decay

"Minimal" Decay:



(also $\mu^+\mu^-$, $\pi^+\pi^-$, …)

via same mixing operator as production ⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$

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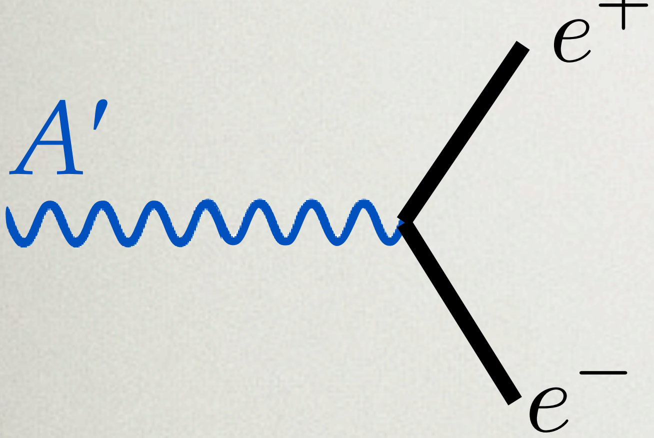

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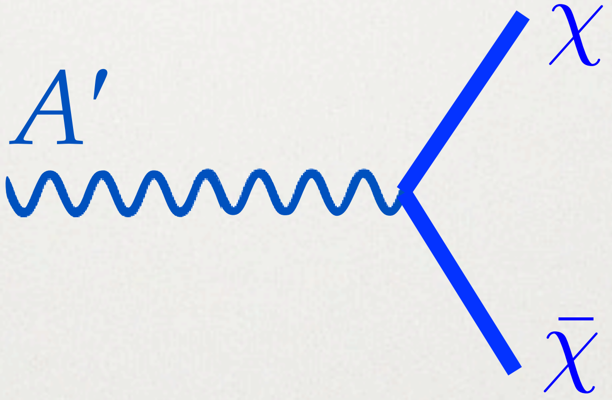


(*not ε-supressed!*)

*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:

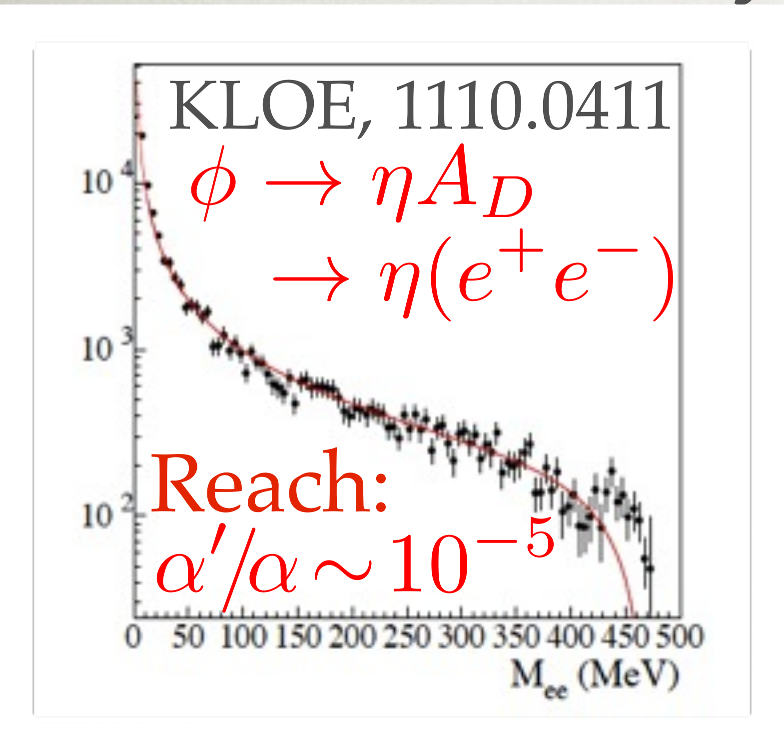
- χ stable & invisible
- χ decays into SM particles, $A' \to$ >2 charged particles

Important! Testing the idea of dark sectors requires a collection of searches sensitive to **all** possible A′ decays, visible & invisible.

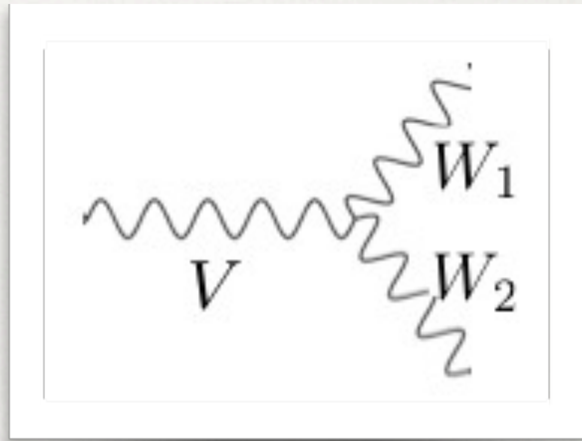
Wide Breadth of Searches

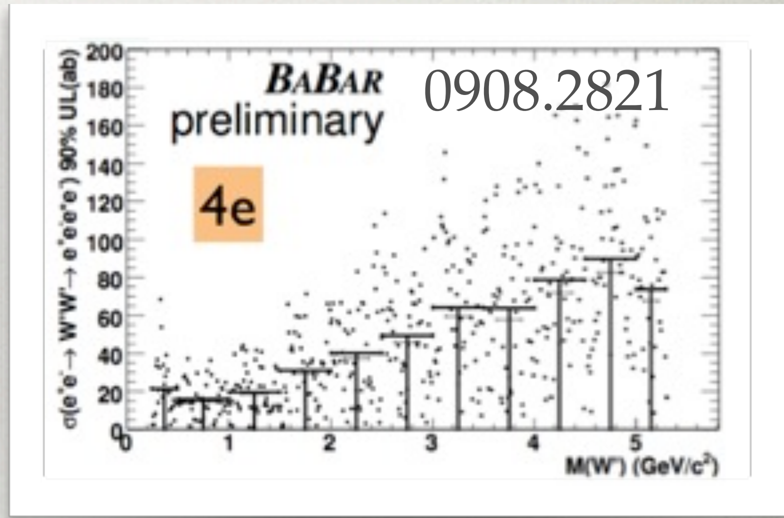
(just a few representative examples)

Minimal Decay

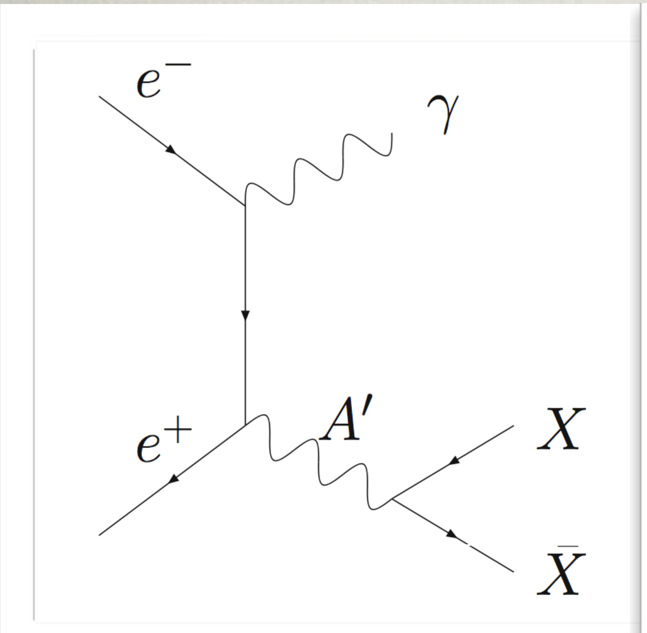


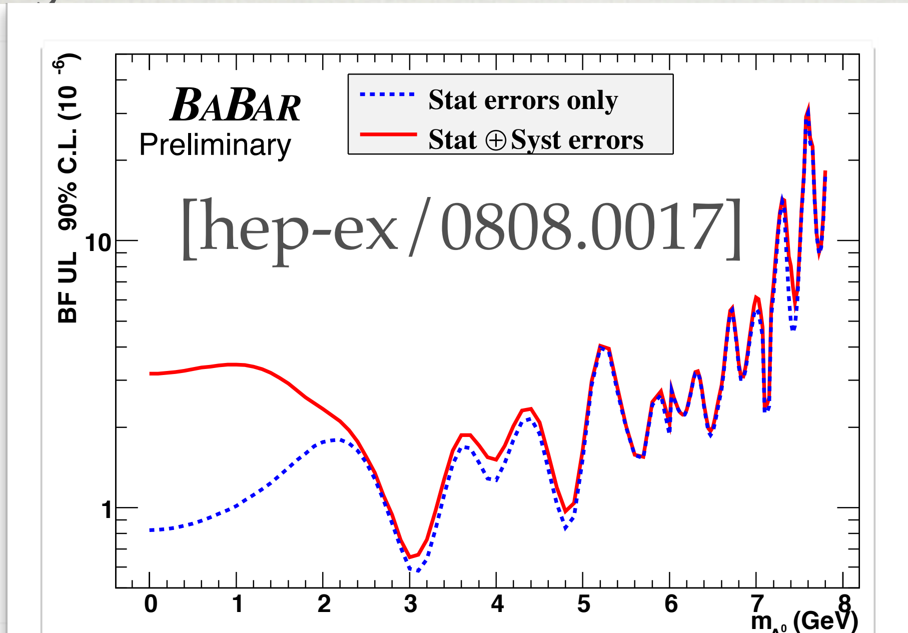
Non-Abelian Dark Sector



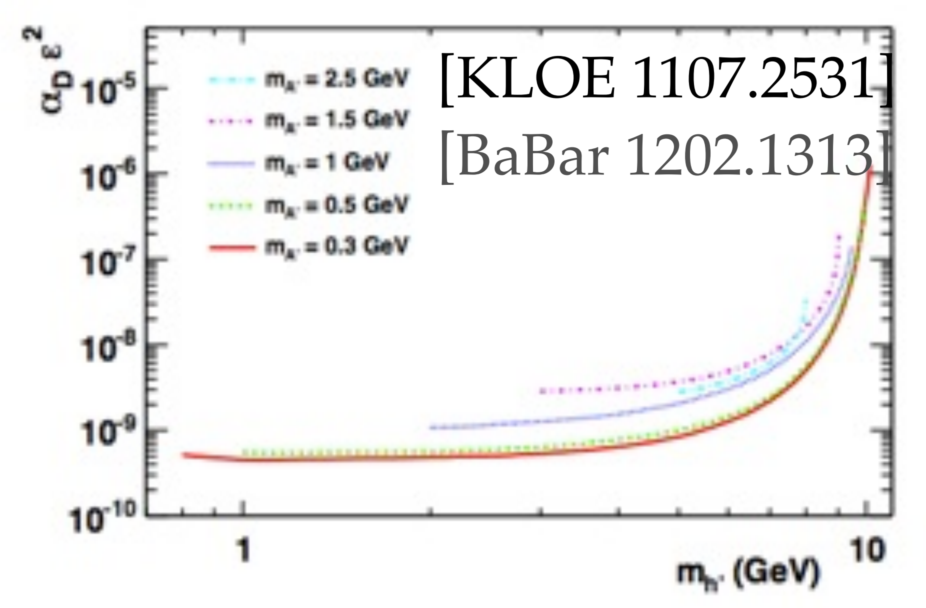


Invisible Decay





Vector + Higgs:

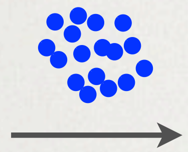


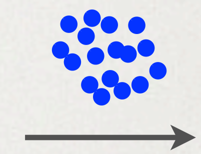
Advantages of Flavor Factories

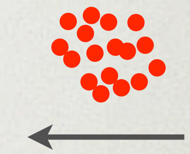
- Highest collider *(Lumi.)*/(E_{CM})^2 in the world
- 4π detectors & clean reconstruction
  - **Broadest** possible search program: $A' \to l^+ l^-$, invisible A′, multi-body cascade decays
- Large dataset "in the bank"
  - Many searches viable using standard triggers
  - Some decays (e.g. γ+invisible A′) require ***and motivate*** new, non-standard trigger

Fixed-Target Advantages

	Fixed-Target	e^+e^-
Luminosity	10^{11} e^- → ; ~10^{23} atoms in target	10^{11} e^- → ; ← 10^{11} e^+
	N(hard scatter) ~ 0.01 – 1 *per electron*	N(hard scatter) ~ 1 *per crossing*
	$\mathrm{O(few)}\ ab^{-1}$ per day	$\mathrm{O(few)}\ ab^{-1}$ per decade

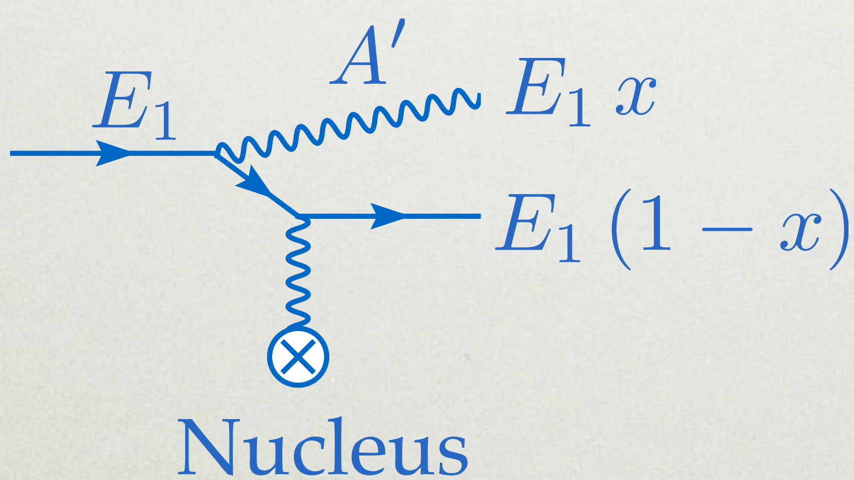


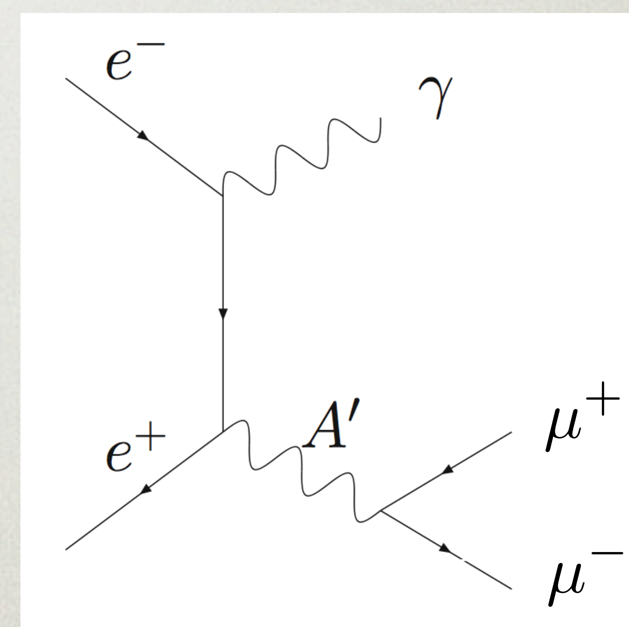




Cross-Section

- Scales as A′ mass, not beam energy
- Coherent scattering from nucleus

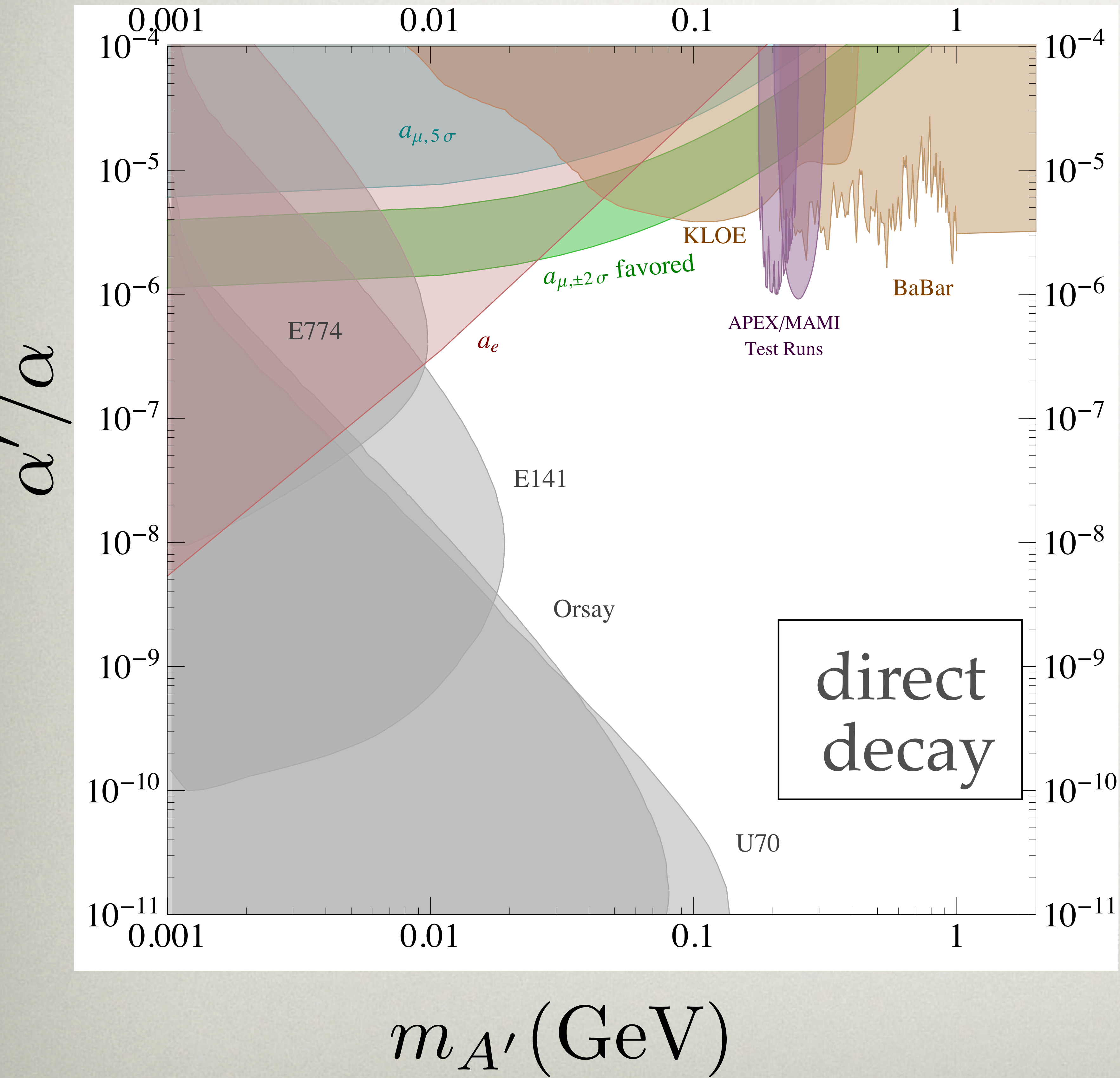




$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

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

Fixed-Target Territory: "Minimal" visible decay (l^+l^-)

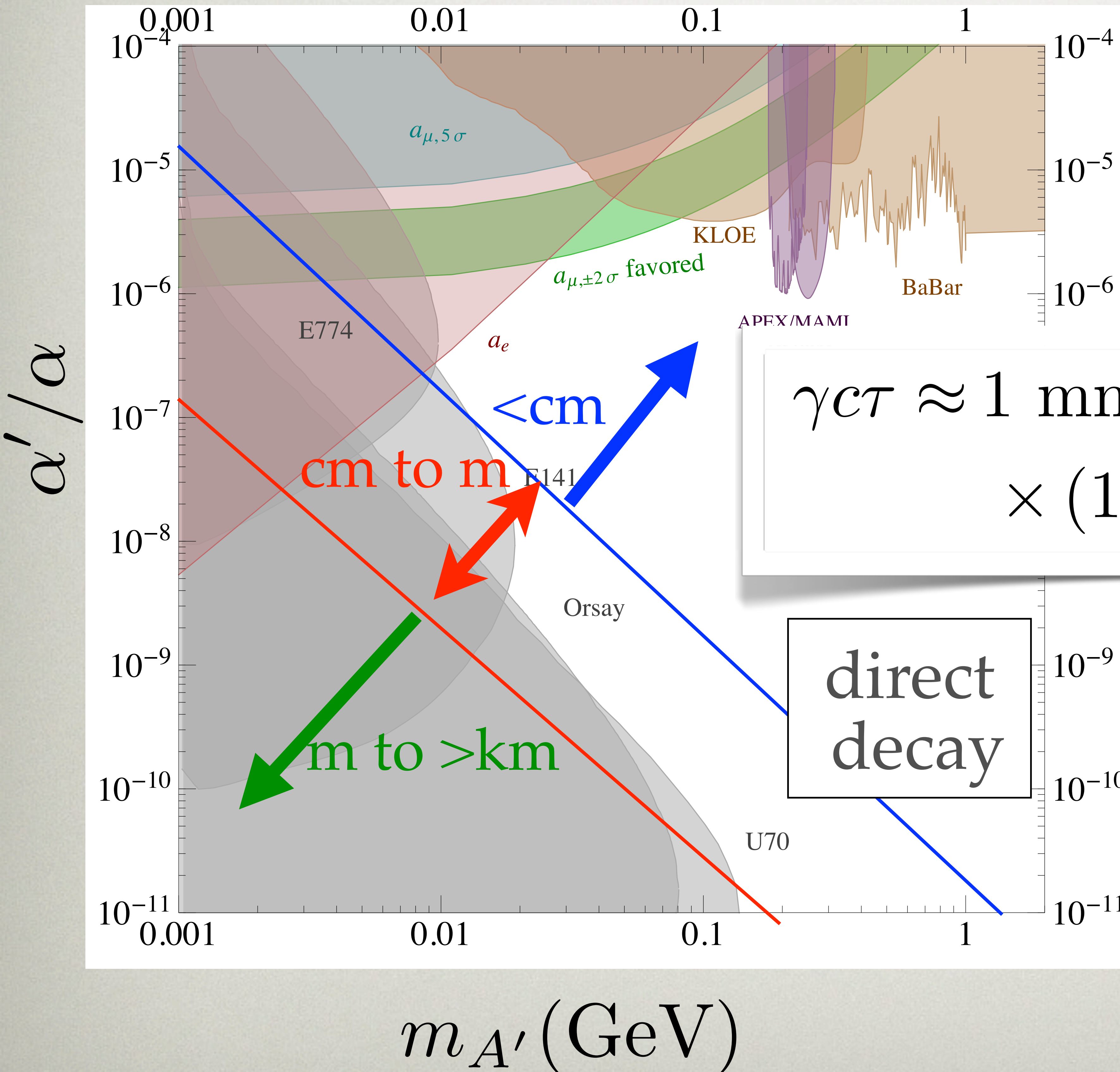


one-loop

two-loop
(GUT)

three-
loop

Fixed-Target Territory:
"Minimal" visible decay (l^+l^-)

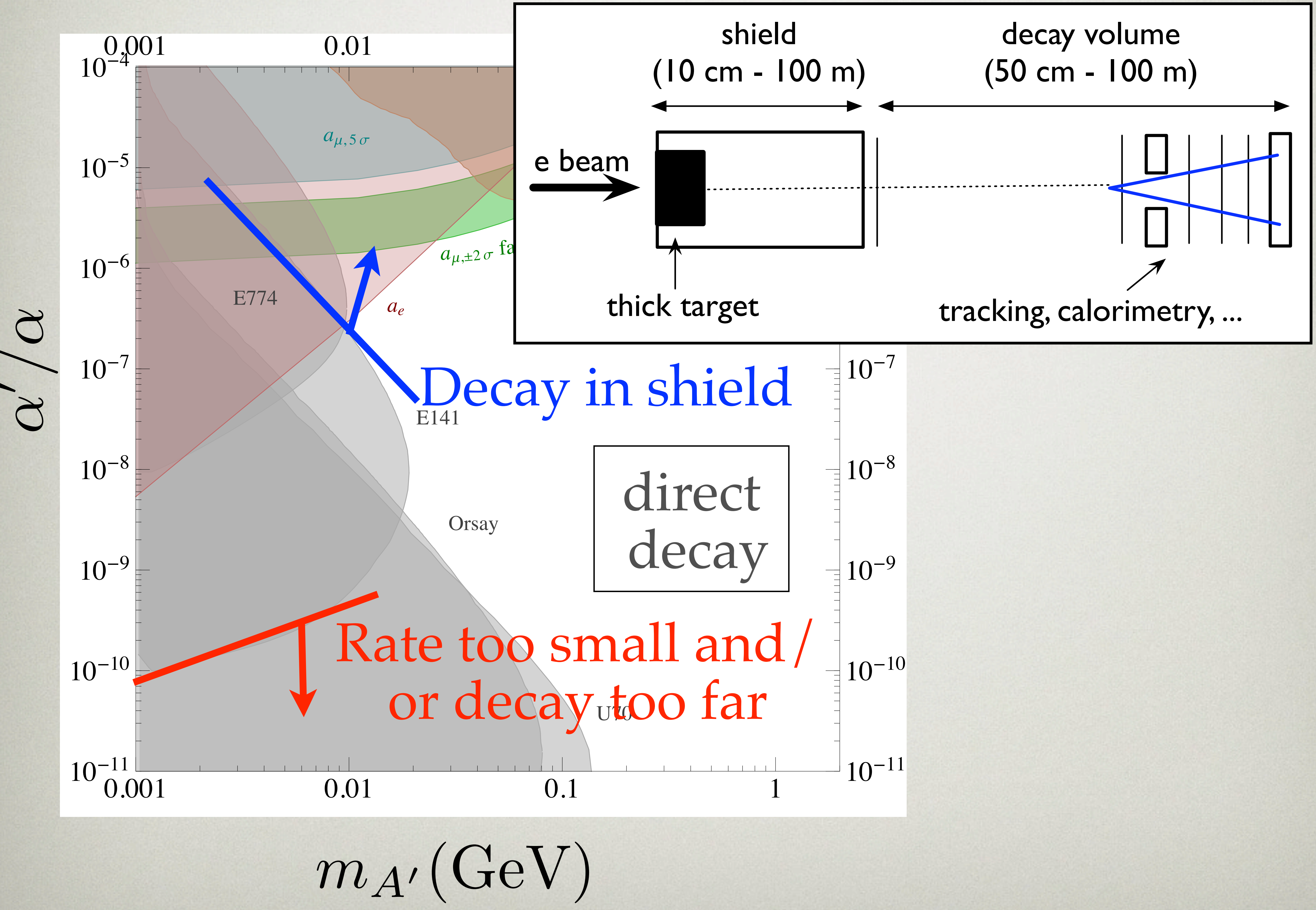


$$\gamma c\tau \approx 1\ \text{mm}\,(\gamma/10)\left(10^{-8}\alpha/\alpha'\right) \times (100\ \text{MeV}/m_{A'})$$

one-loop

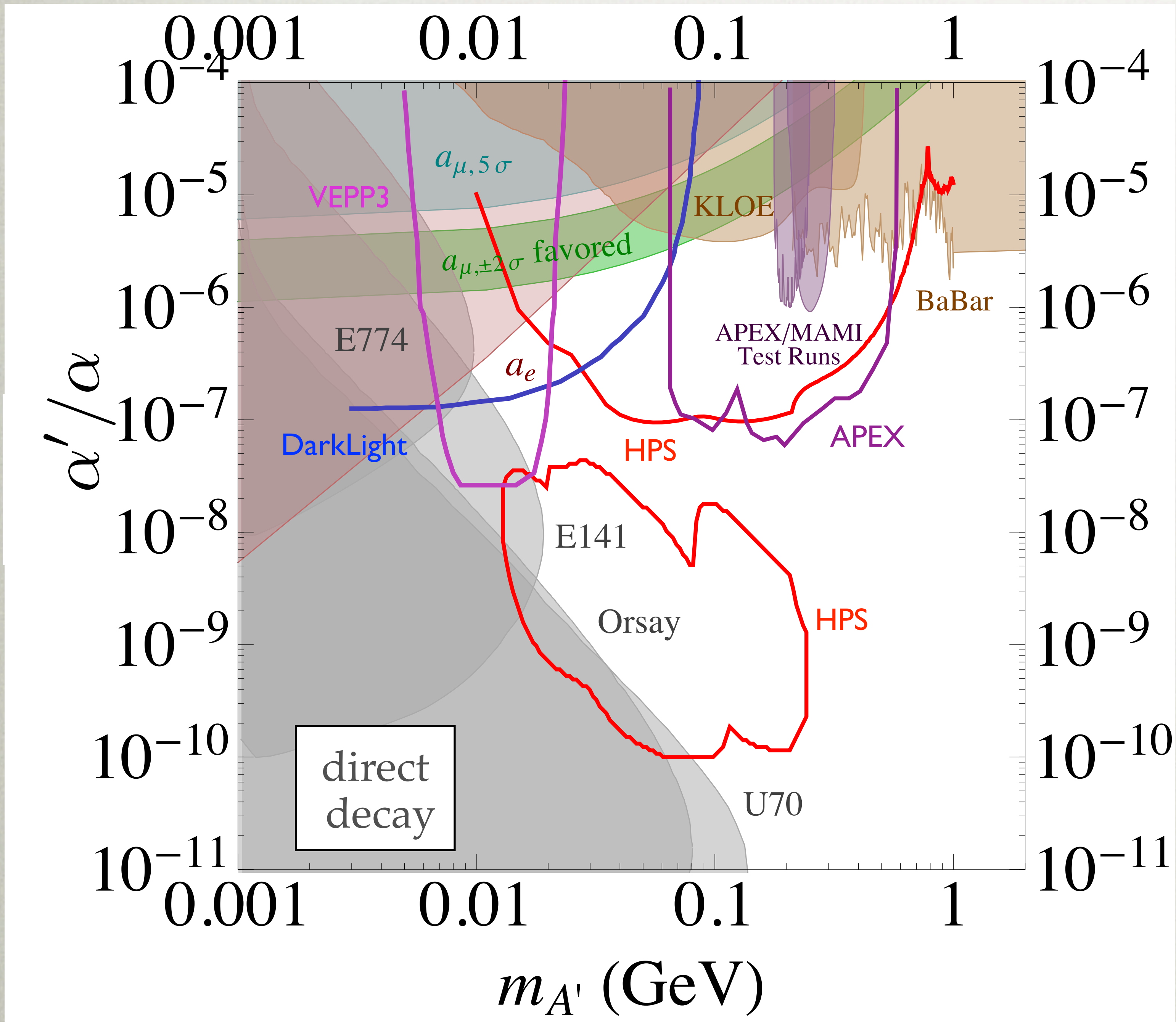
three-loop

Beam-Dump Limits



Electron Beam Sensitivity

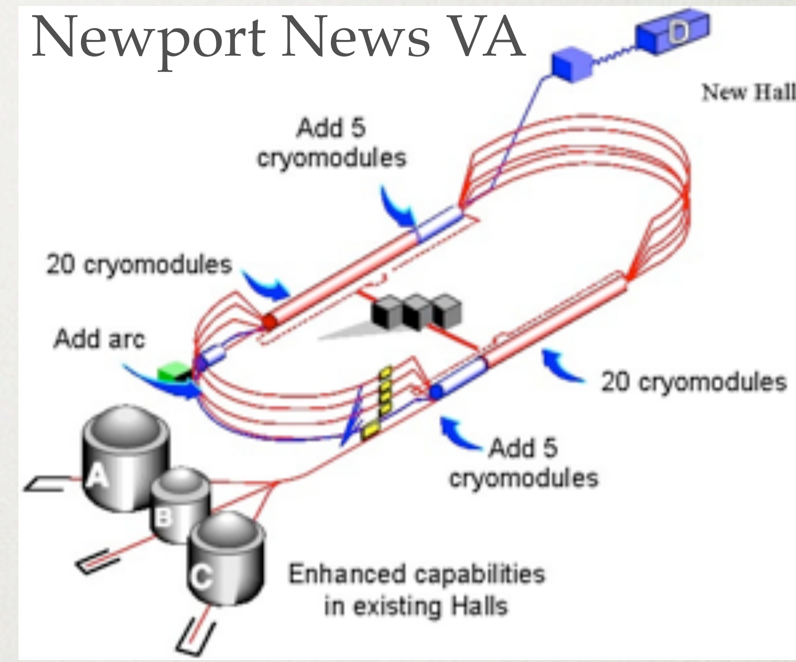
Approved and funded experiments will explore much of the parameter space below 300 MeV in next few years



APEX, HPS, Mainz strategies following scenarios discussed in Phys.Rev. D80 (2009) 075018 (Bjorken, Essig, Schuster, NT)

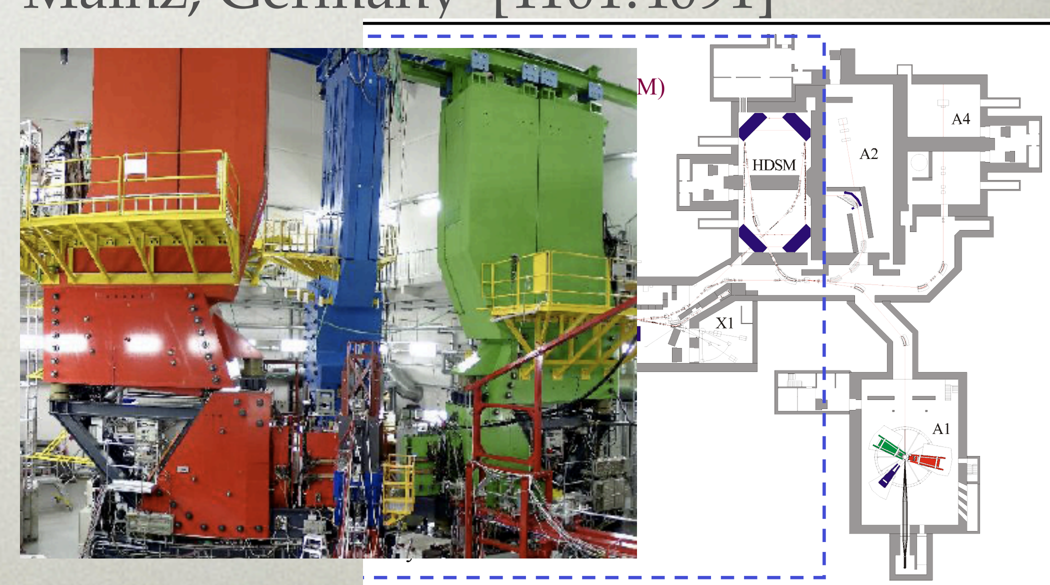
JLAB CEBAF

Newport News VA



MAMI/A1 (sensitivity not shown)

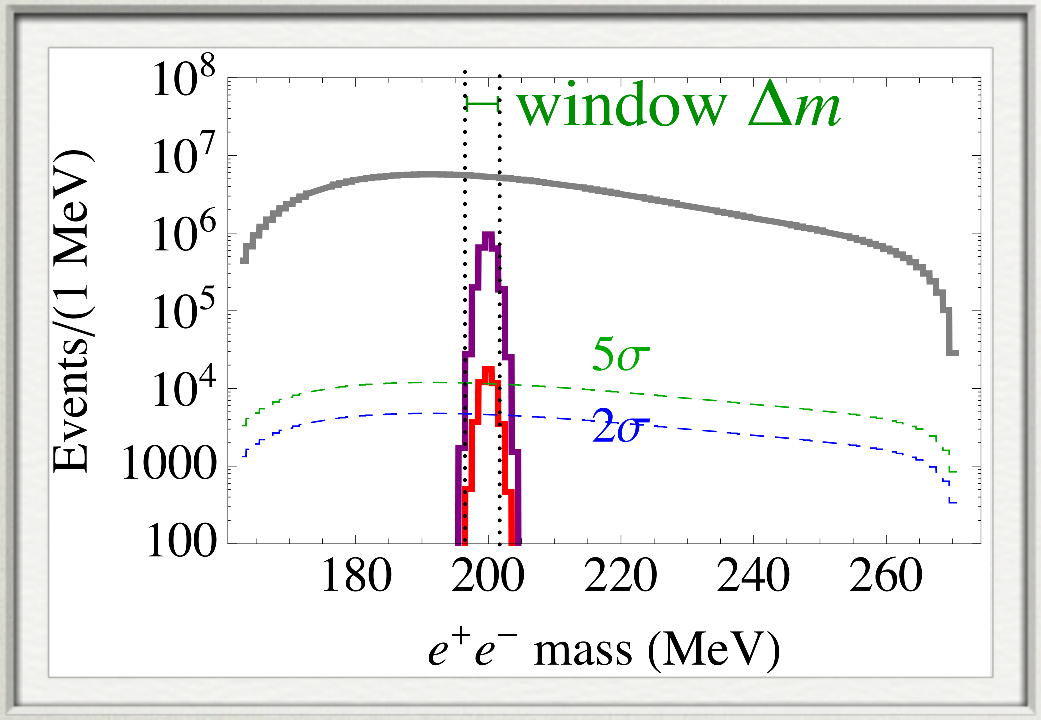
Mainz, Germany [1101.4091]



Two Search Strategies

High-Statistics Resonance Search

(MAMI, APEX, HPS, DarkLight)



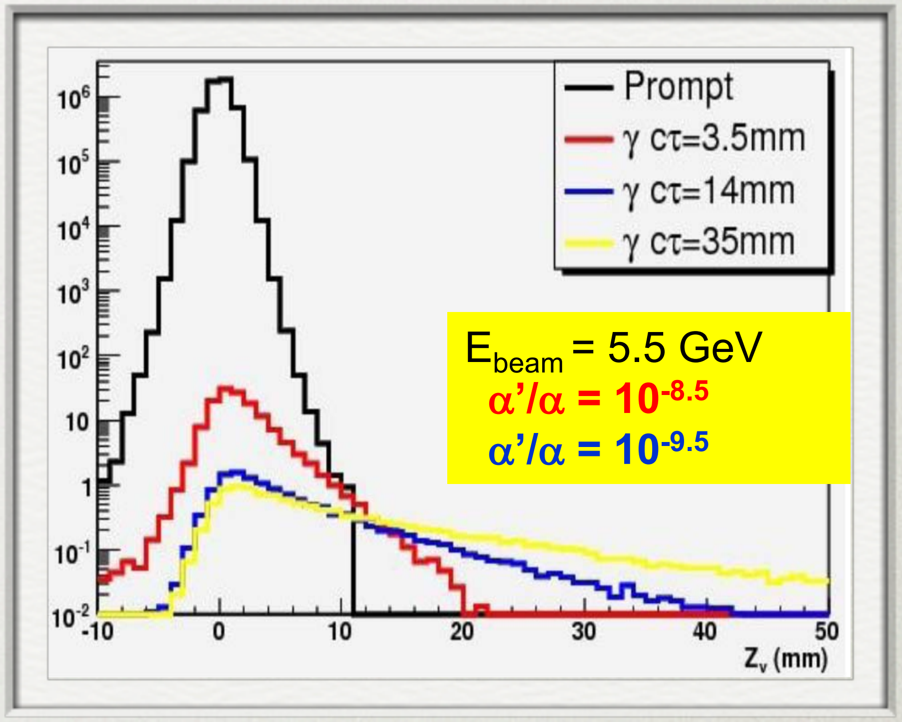
Demands high data-taking rate, background suppression and excellent mass resolution

Demonstrated in test runs: Mainz (1101.4091) and APEX (1108.2750)

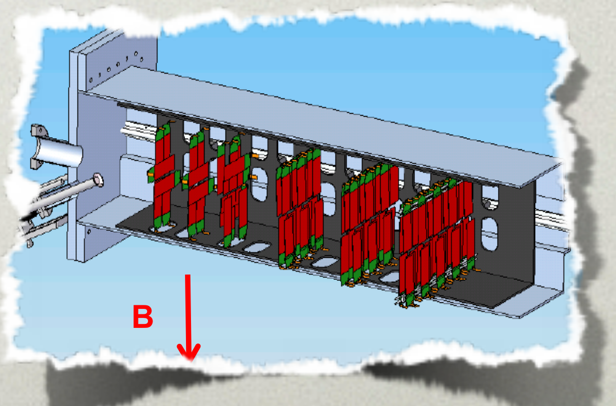
DarkLight: full reconstruction of recoil → sensitive to invisible A′ decays

Displaced Resonance search

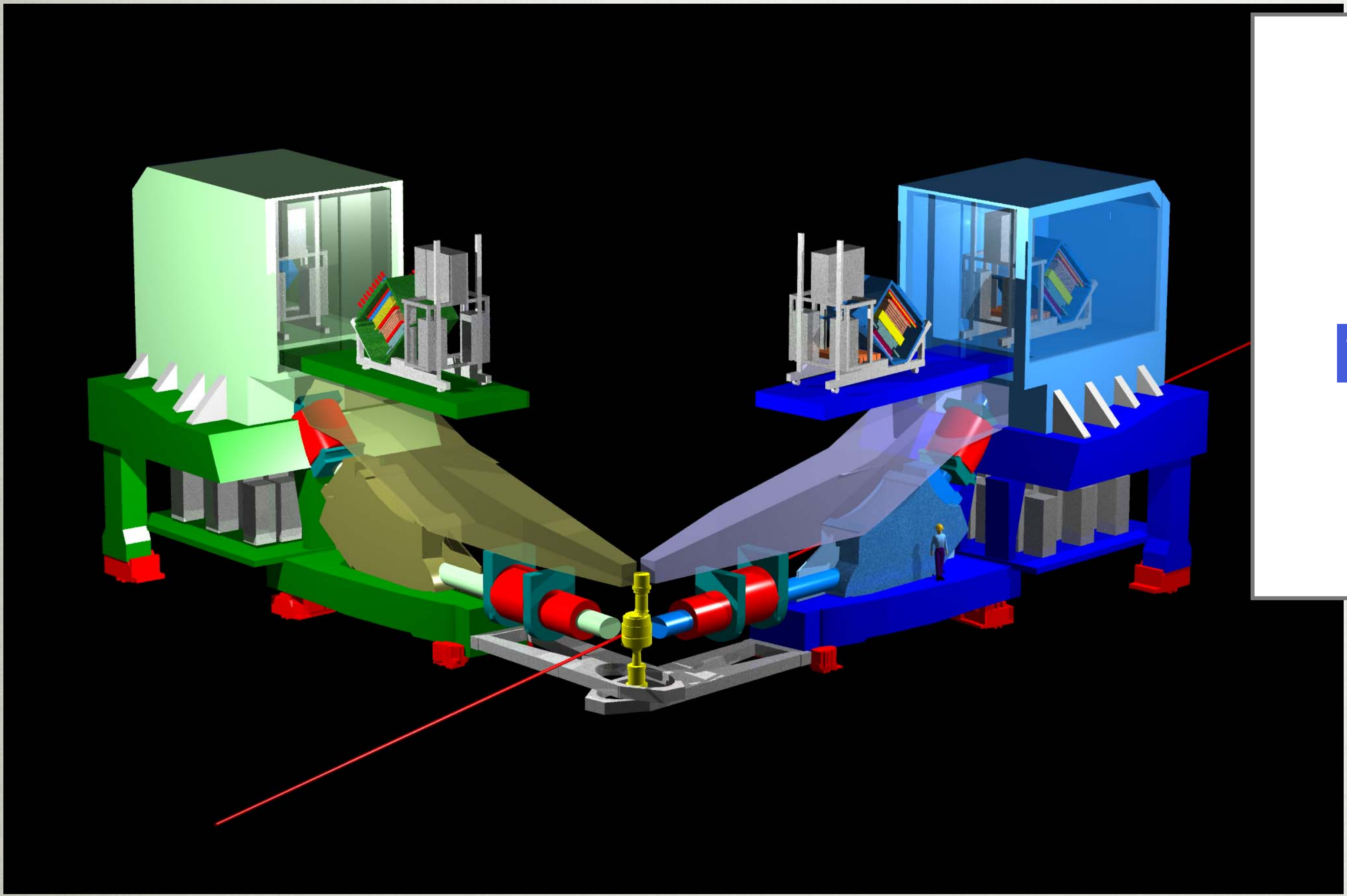
(HPS)

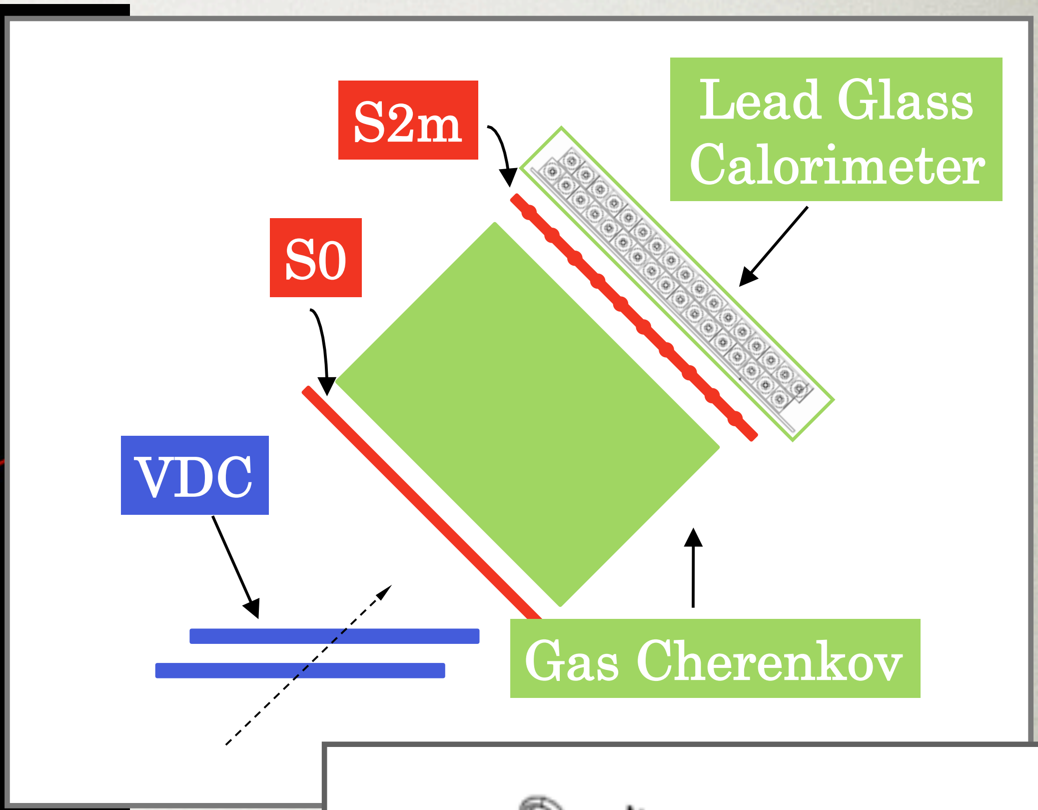


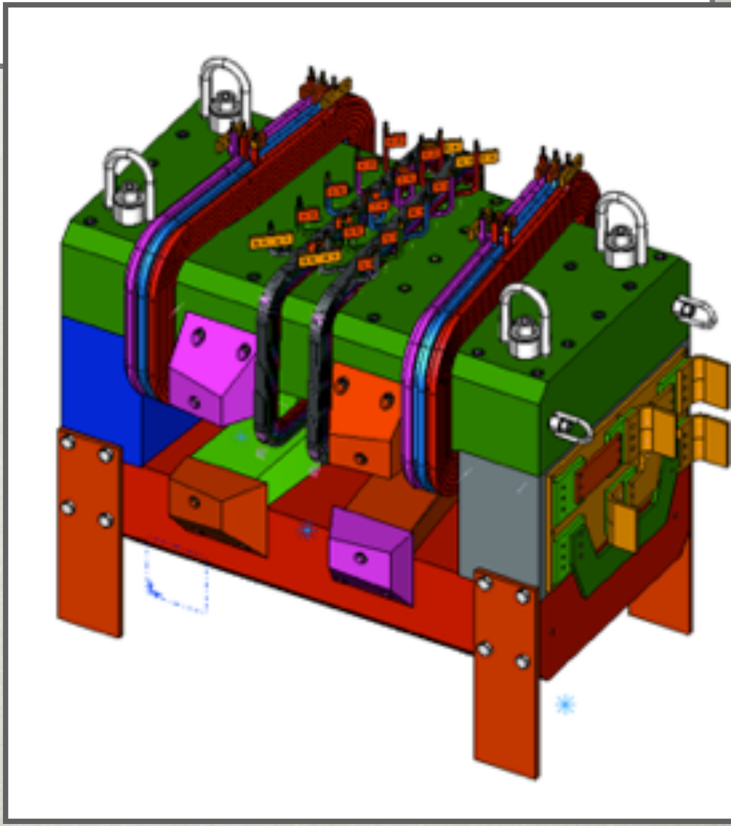
...and forward vertex resolution (well-controlled tails)



APEX A′→ e^+e^- resonance search using Hall A high-resolution spectrometers and septa magnet

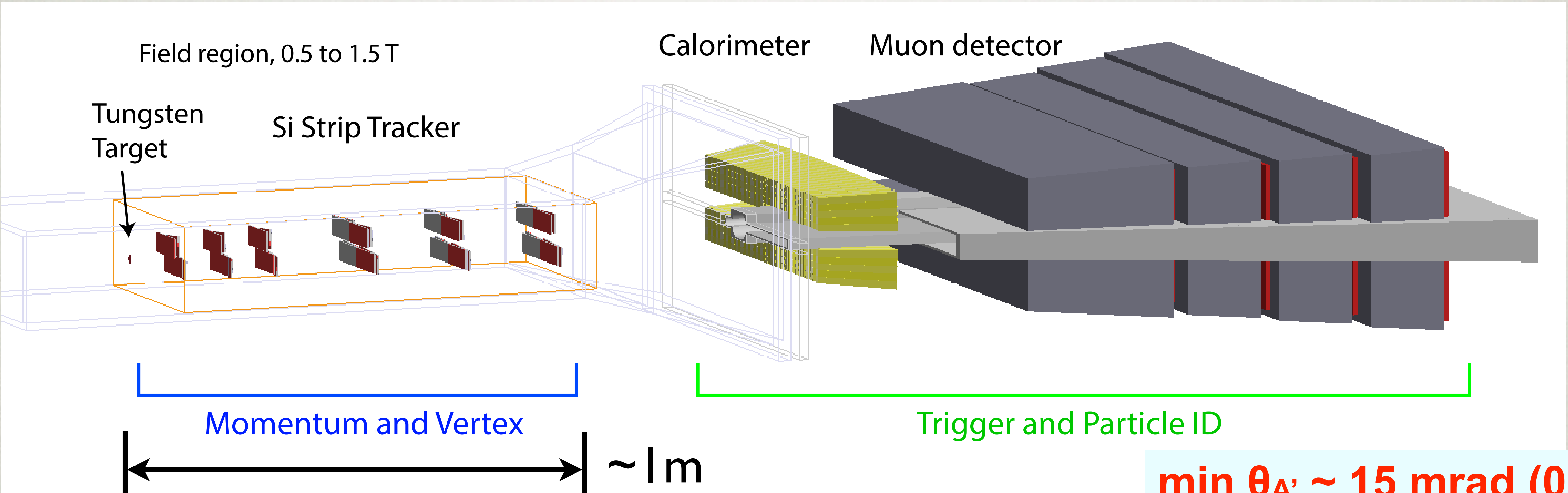






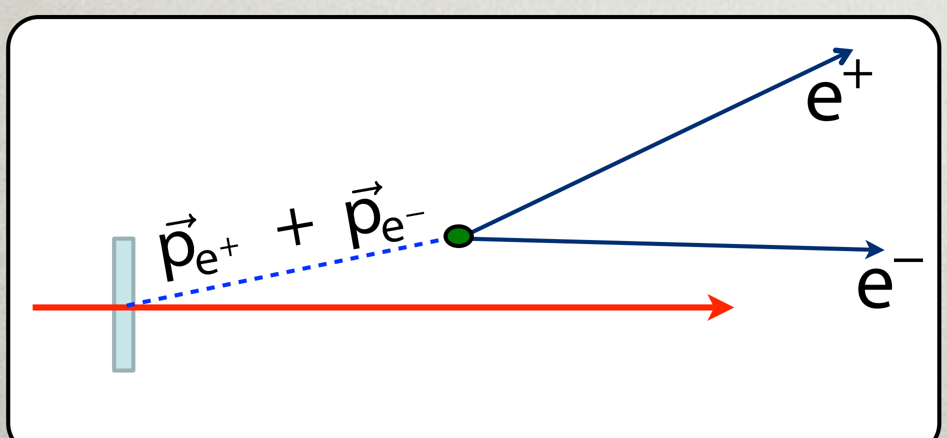
Range	Acceptance	Resolution
$0.3<p<4.0$ GeV/c	$-4.5\%<\Delta p/p<4.5\%$	$\delta p/p \leq 2\ 10^{-4}$
$12.5^o<\theta_0<150^o$	6msr	$\delta\phi=0.5$ mrad (H)
($\theta_0=5^o$ and 4.5 msr at with septum)		$\delta\theta=1$ mrad (V)

HPS: Resonance + Vertex Searches

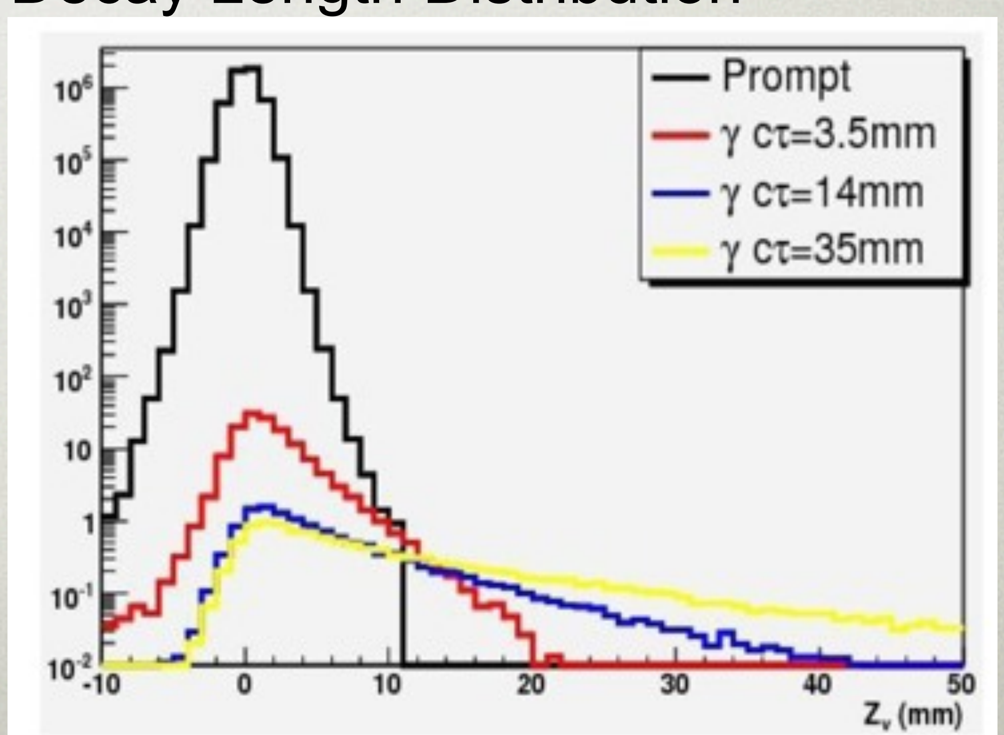


min $\theta_{A'}$ ~ 15 mrad (0.85°)
$\Delta m/m$ ~ 1% (bump hunt)
Δz ~ 1mm (vertexing)

Vertexing allows sensitivity to weakly coupled A′ that produce only ~25 events!



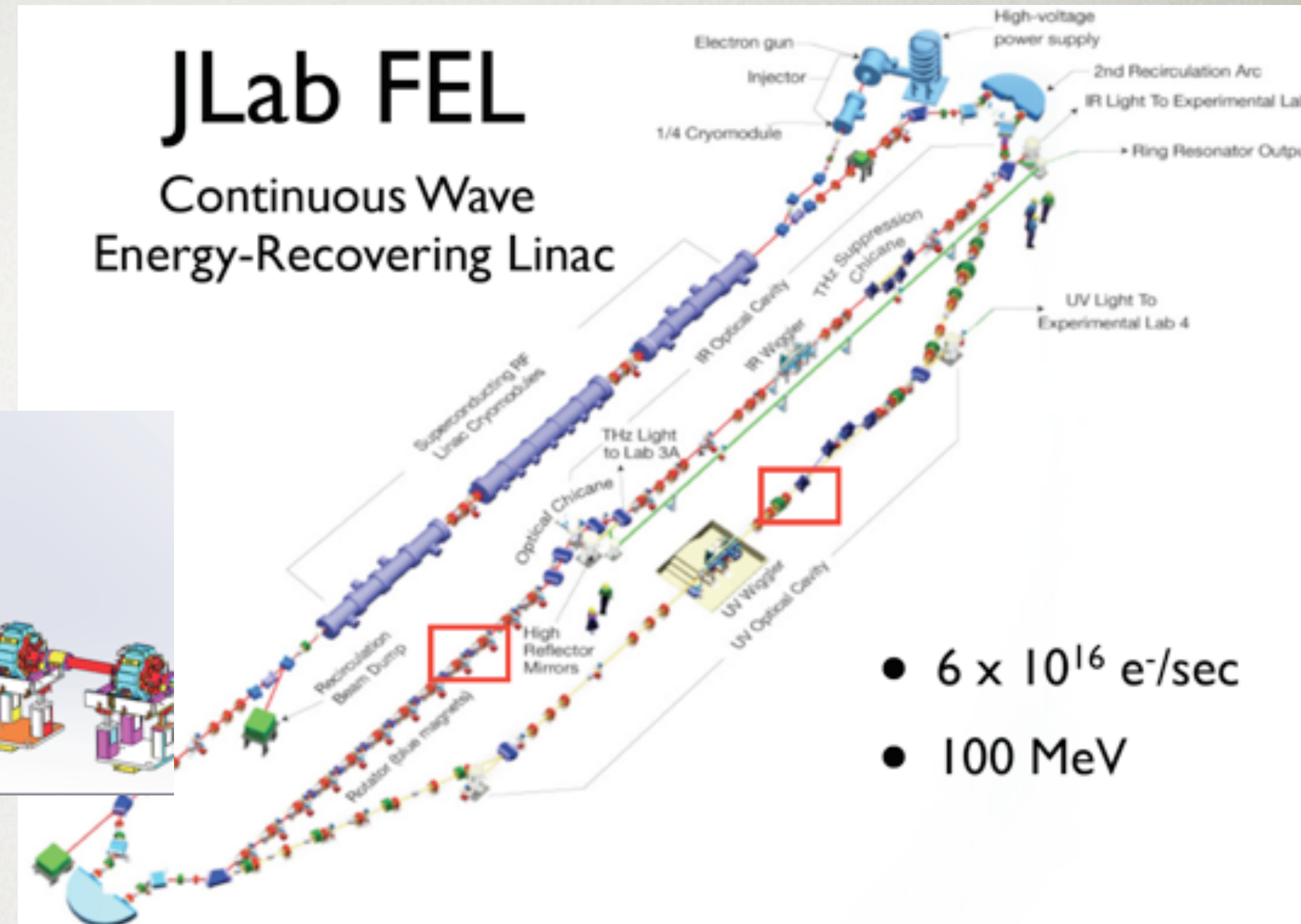
Decay Length Distribution



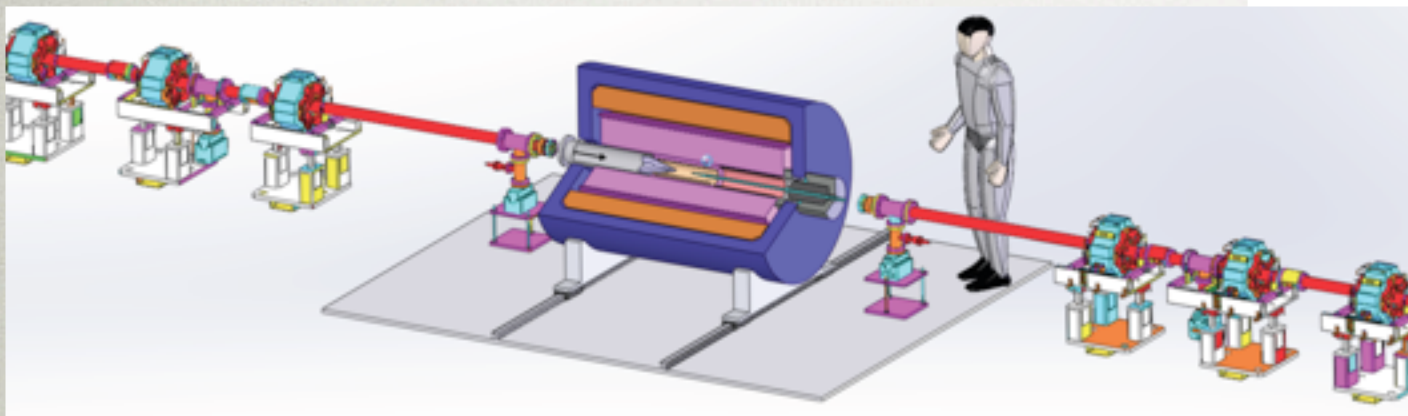
DARKLIGHT

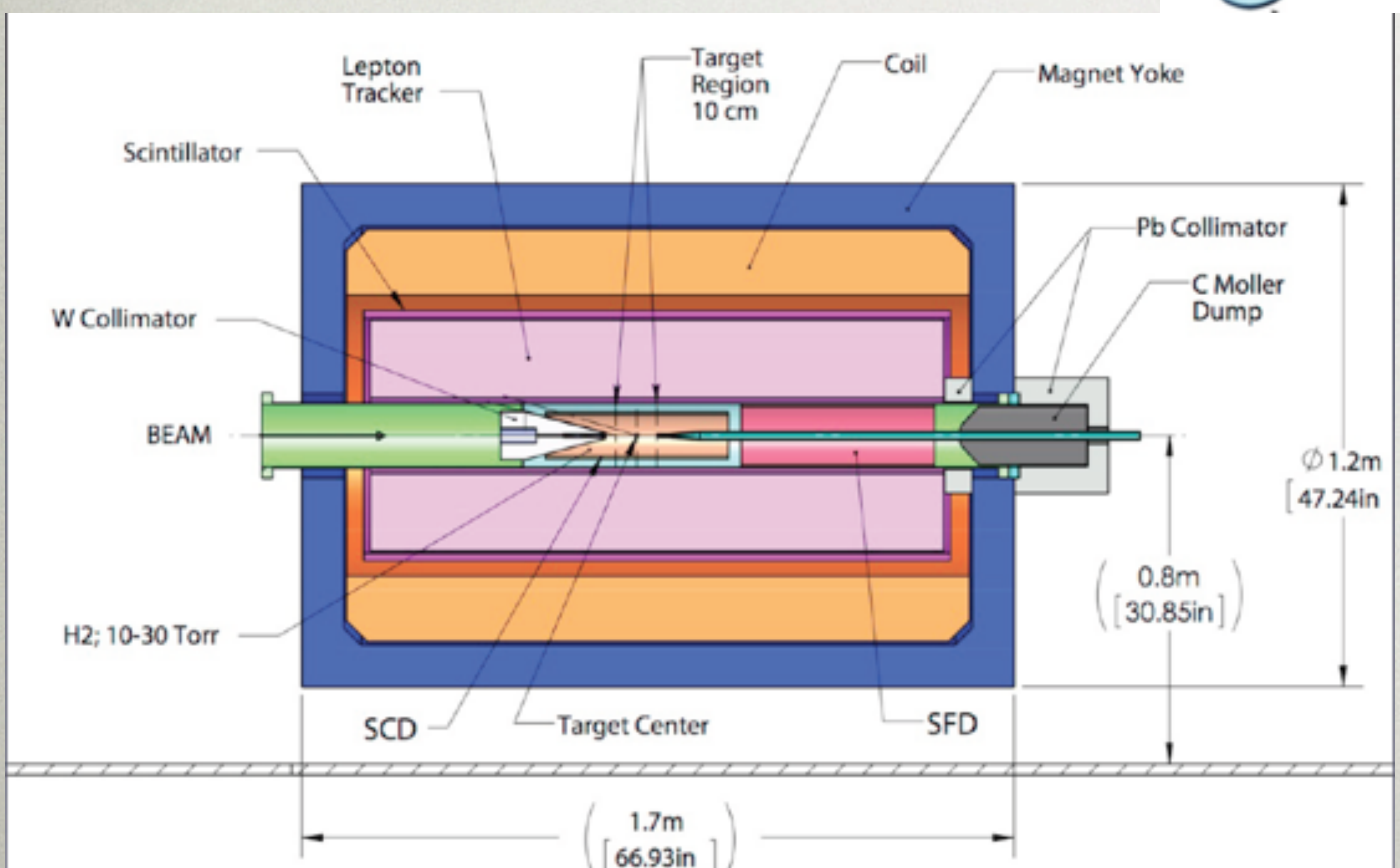
JLab FEL

Continuous Wave Energy-Recovering Linac



- 6×10^{16} e^-/sec
- 100 MeV

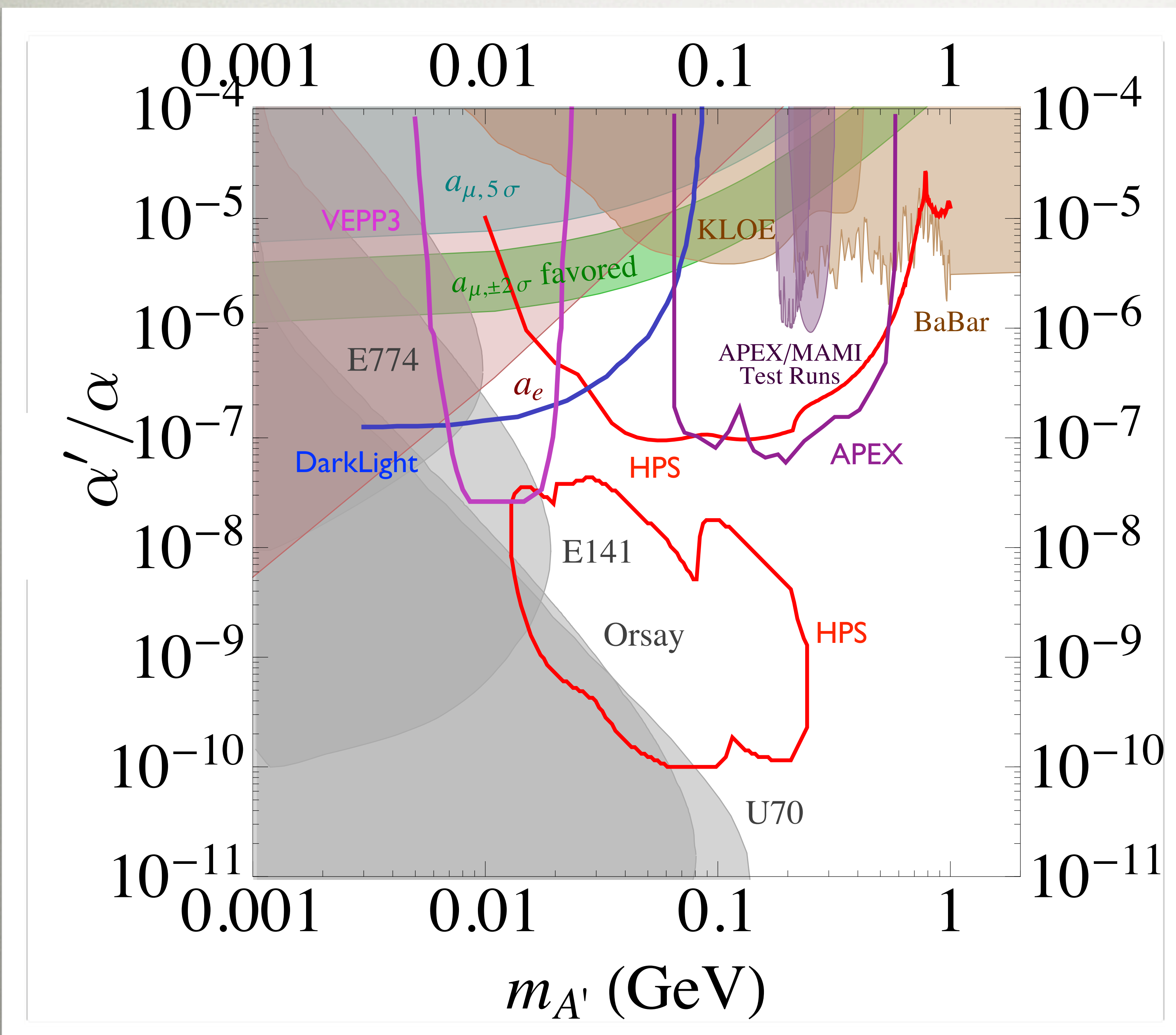




~10^{19}cm^{-2} gas target, 10mA beam

Searches for visible and invisible A′ decay

Fixed-Target Summary: Direct Decay Case



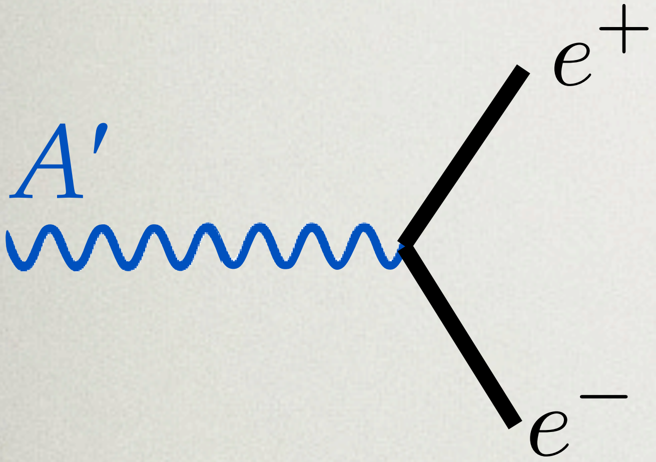
Complementary approaches:

- beam dump (~1980s)
- vertex search (HPS)
- resonance search (Mainz, APEX, DarkLight,HPS)

First-generation vertex and resonance searches will cover a lot of new ground, in theoretically interesting parameter region, $m_{A'} \lesssim 200\text{-}800$ MeV

Searching For MeV-GeV Dark Forces: Decay

"Minimal" Decay:

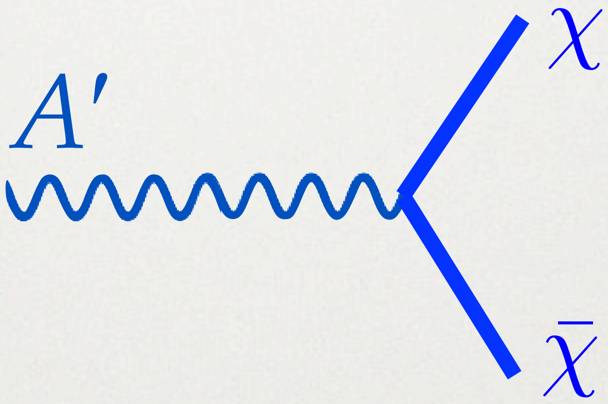


(also $\mu^+\mu^-$, $\pi^+\pi^-$, …)

via same mixing operator as production ⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$

"Generic" Decay:



(*not ε-supressed!*)

*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:

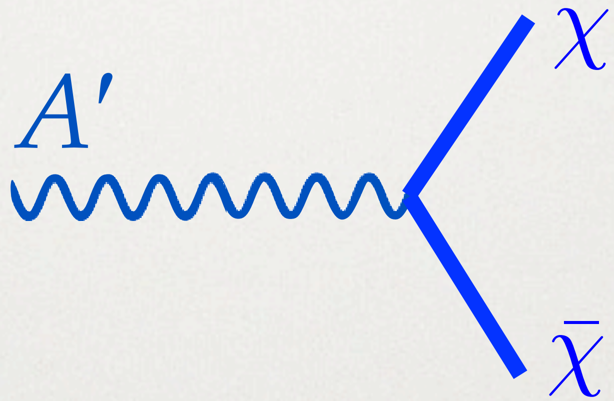
– χ stable & invisible

– χ decays into SM particles, $A' \rightarrow$ >2 charged particles

Important! Testing the idea of dark sectors requires a collection of searches sensitive to **all** possible A′ decays, visible & invisible.

Searching For MeV-GeV Dark Forces: Decay

"Generic" Decay:



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If ***any*** *dark-sector matter* χ *has* $m_\chi < 2m_{A'}$*, this decay dominates*

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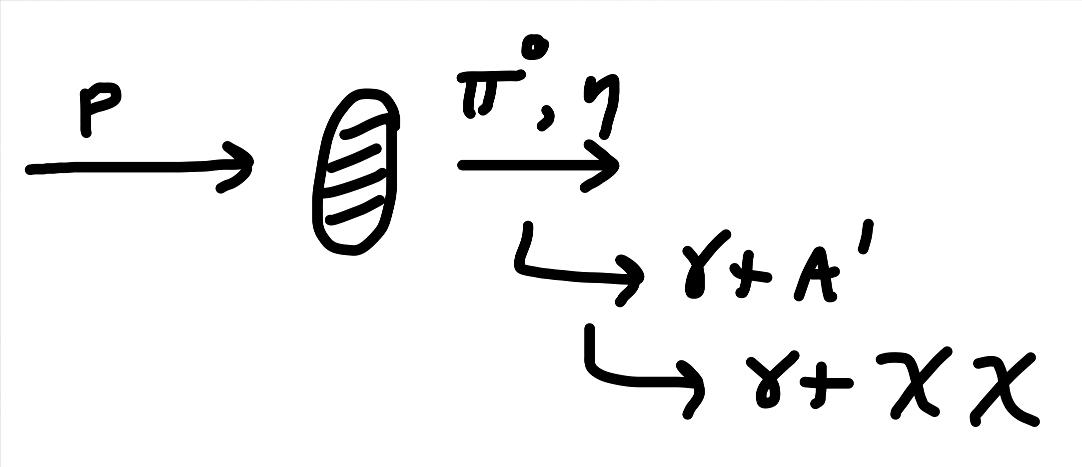
– χ decays into SM particles, $A' \rightarrow$ >2 charged particles

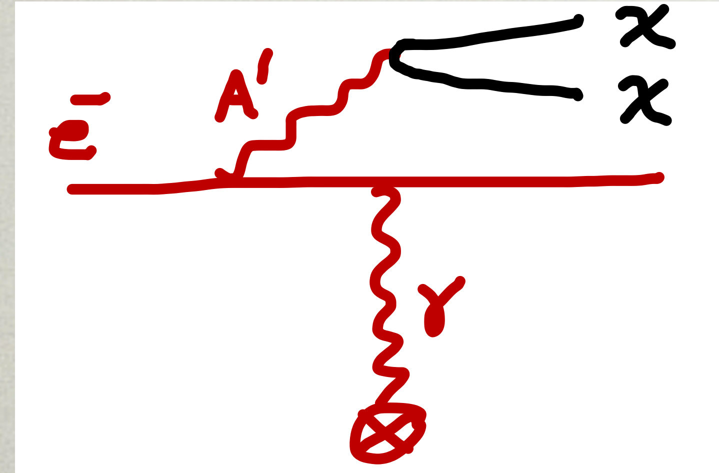
hard at fixed-target (pileup, <4π coverage), but HPS and DarkLight may have a shot

What if the dark photon doesn't come back?

Collider: look for photon recoiling off invisible A′ resonance

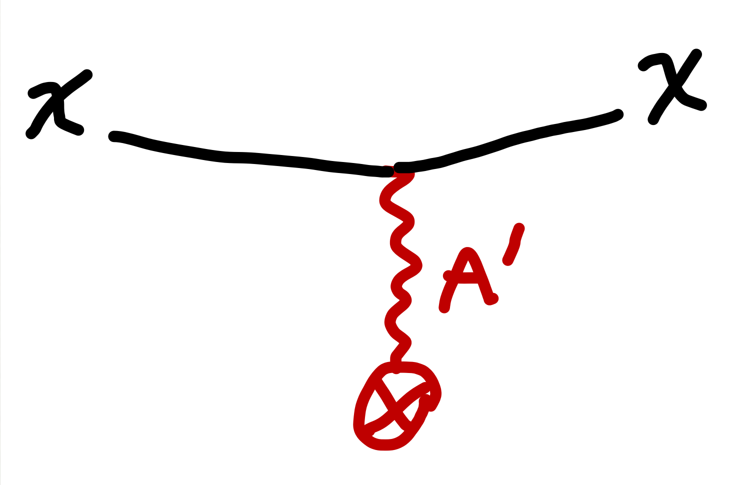
Fixed-target: A′ is produced, then decays to invisible χ (dark matter?):





+

Look for neutral current scattering of χ



PROTON & ELECTRON BEAMS

Proton beams:

– Use existing accelerator ν detectors

– Large ν-scattering backgrounds, almost irreducible

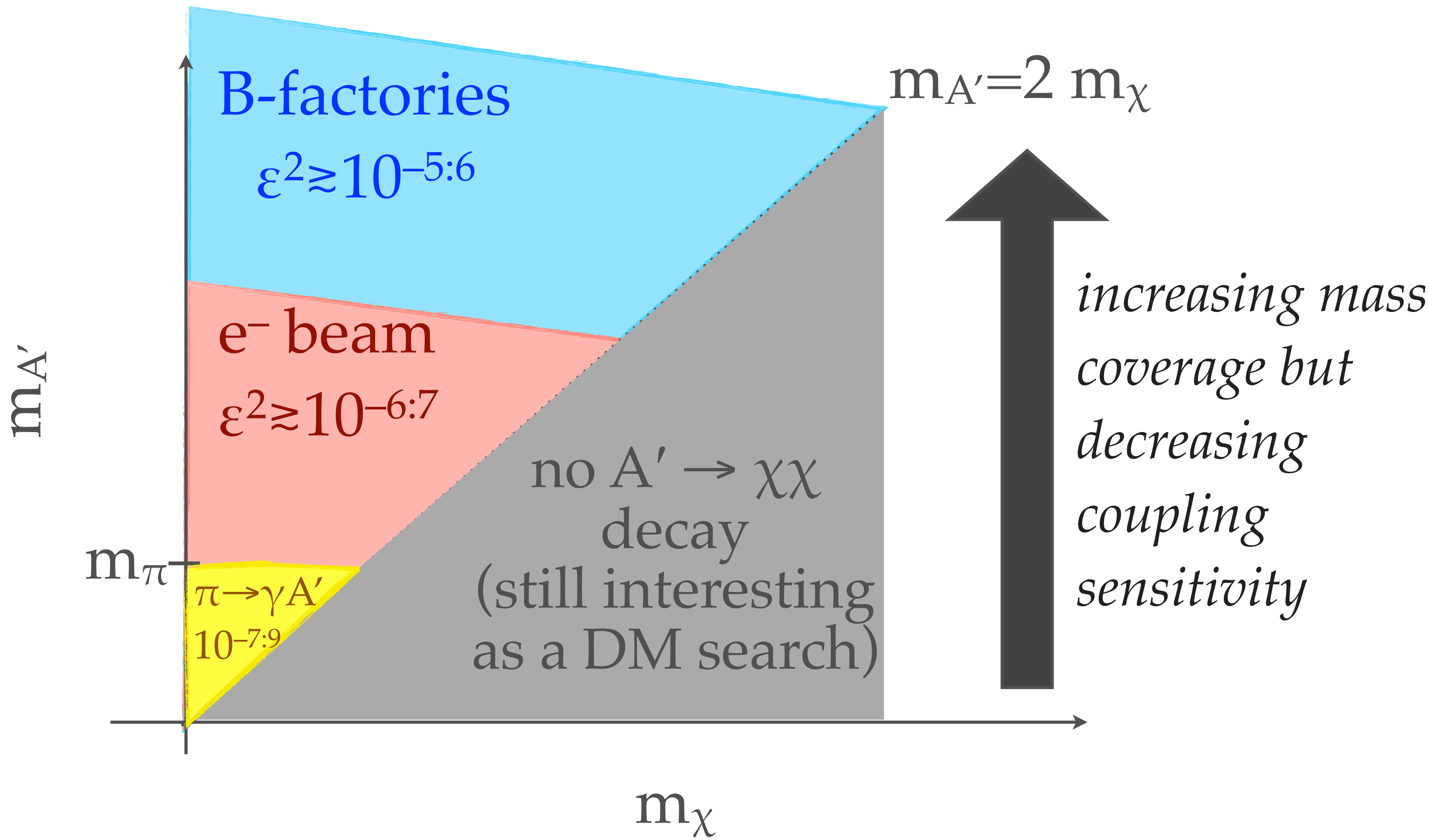
Electron beams:

– Need new detector behind dump
(but forward production ⇒ can be small)

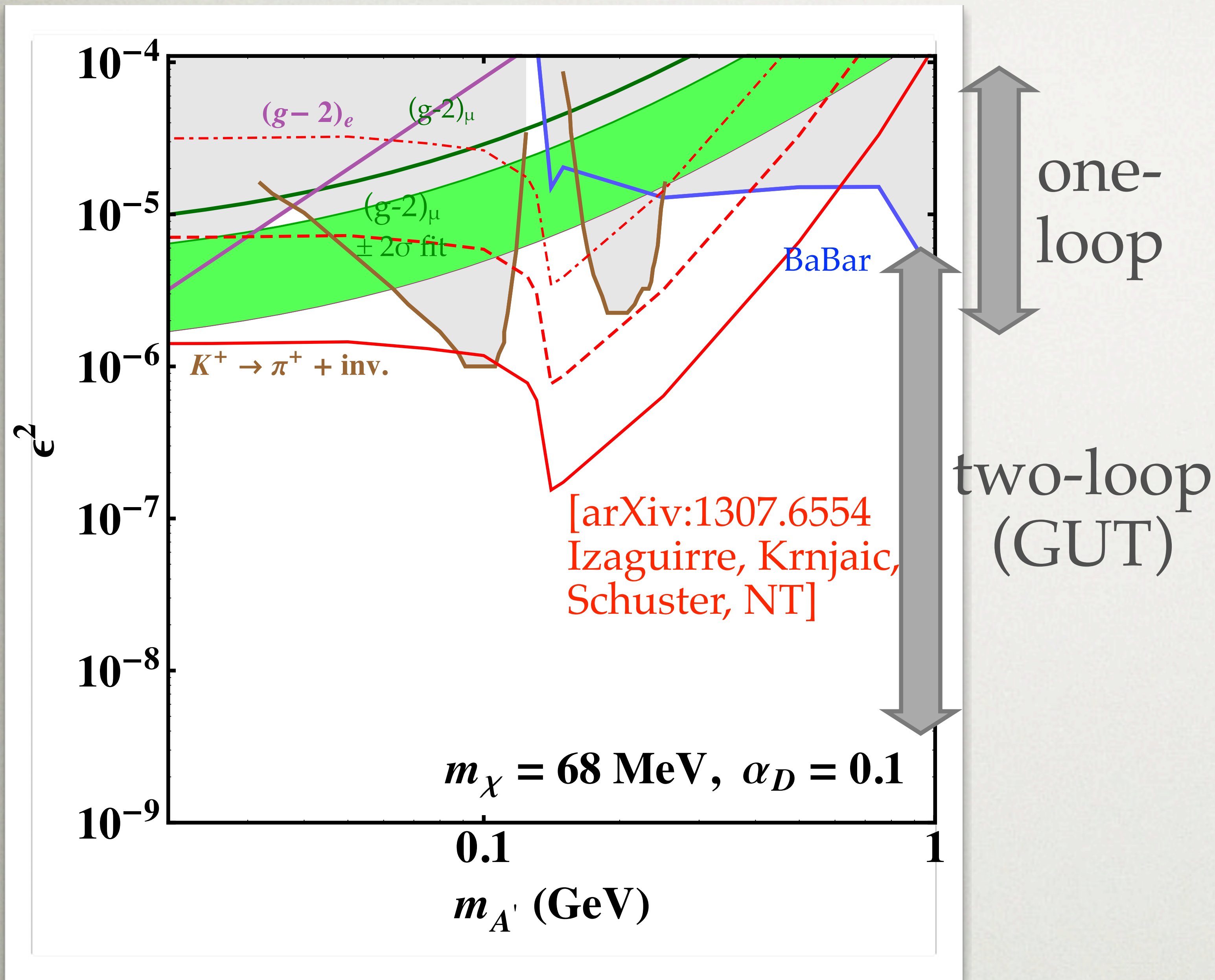
– Minimal beam-related backgrounds but using CW
e^- beam ⇒ limited by cosmogenic bkg

relative merits & complementarity of different scattering signals not thoroughly explored in either case

Prospects vs. Mass



Status and Prospects



Harder than visible A′ searches!

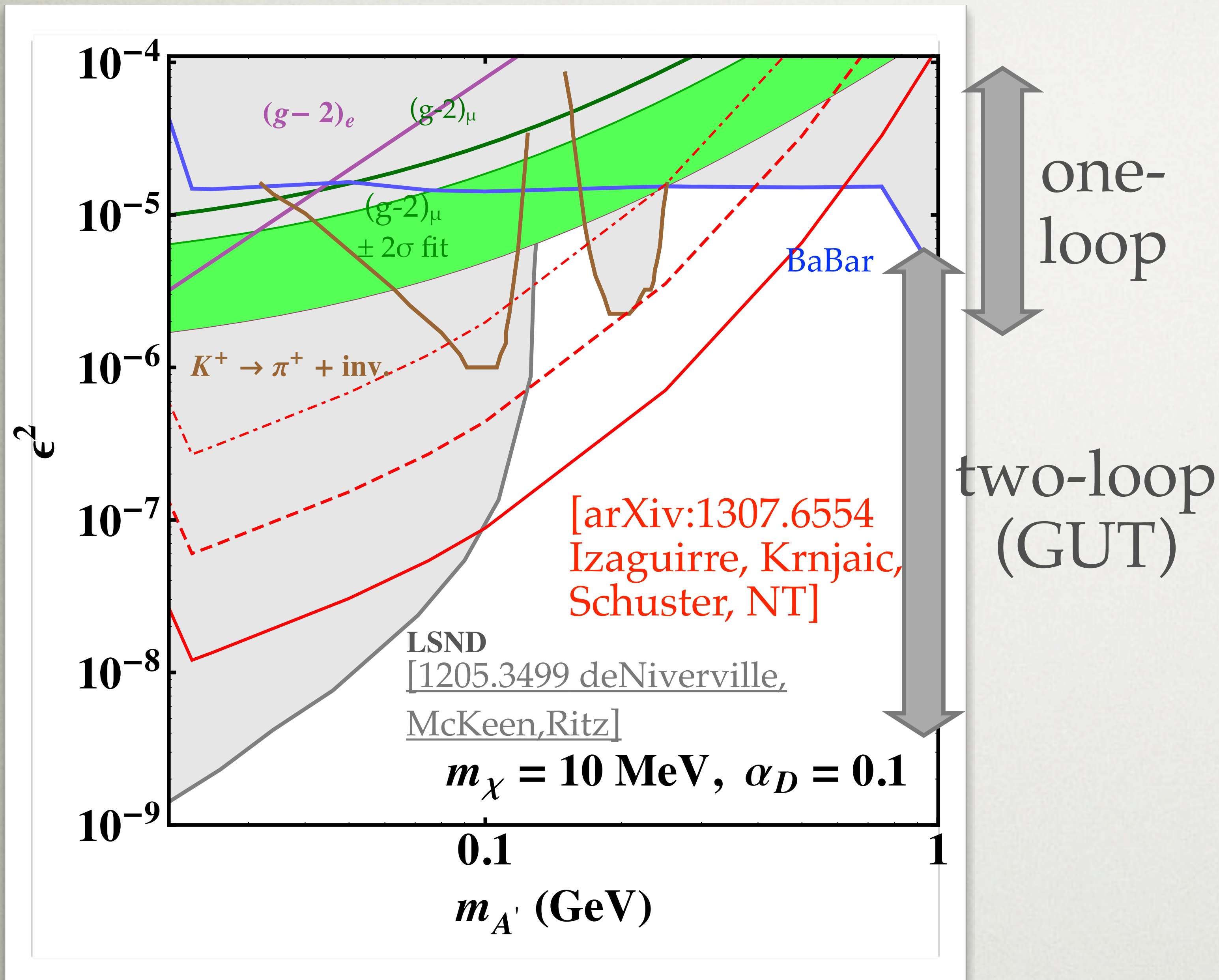
– signal $\propto \varepsilon^4$ not ε^2

But important parameter range

– $(g\text{-}2)_\mu$ preferred region
– motivated ε^2 range
– generic possibility of light dark-sector matter
– χ dark matter not constrained by direct detection or LHC

Red lines = quasi-elastic scattering behind JLab-like beam dump, with (top to bottom) no neutron bg rejection, **1/20 rejection**, 10^{-3} rejection
Dedicated MiniBoone run sensitivity comparable to middle line [arXiv:1211.2258]; see also [arXiv:1309.5084 Essig et al] for impact of aggressive analysis with new triggers at Belle 2

Status and Prospects



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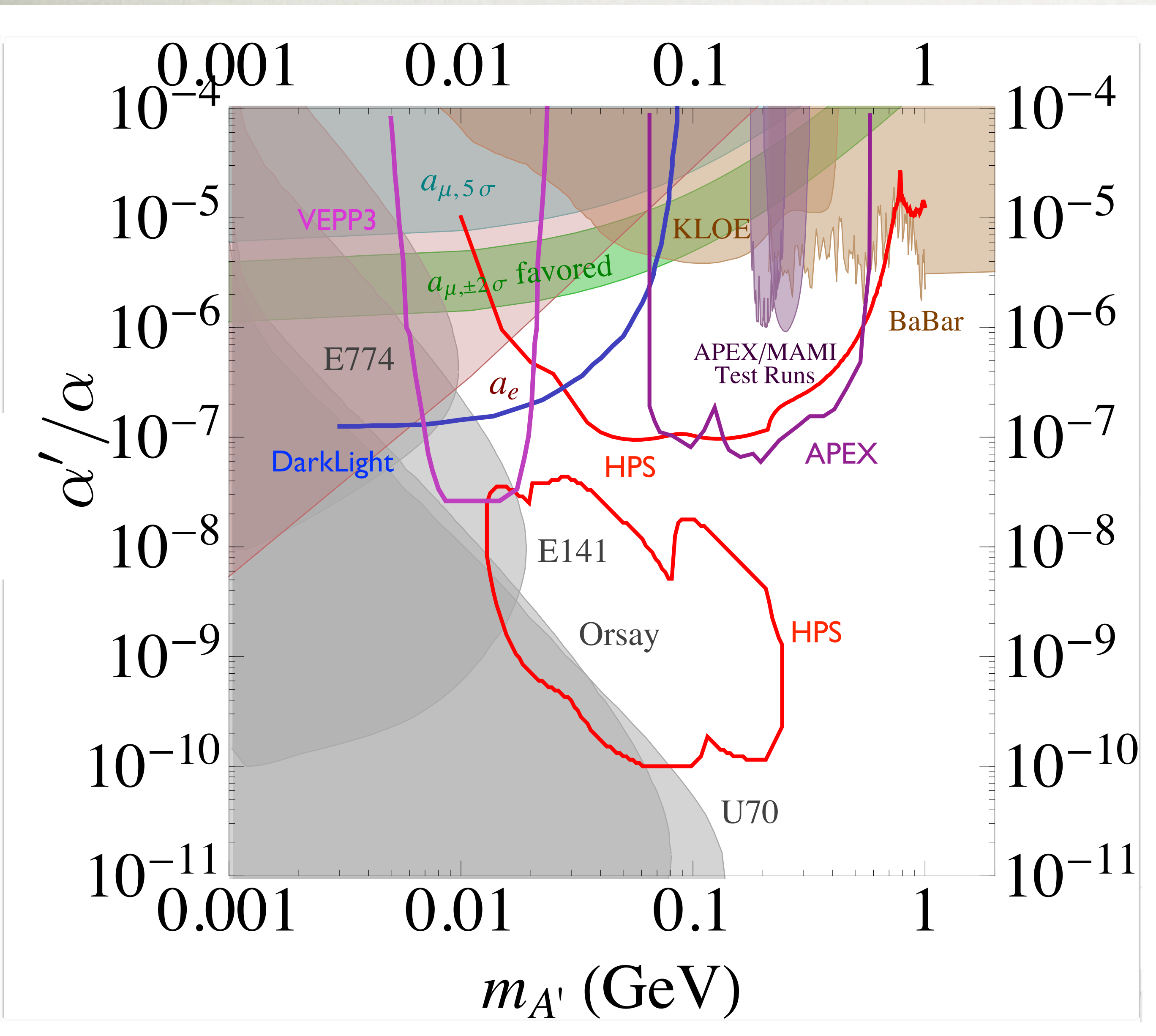
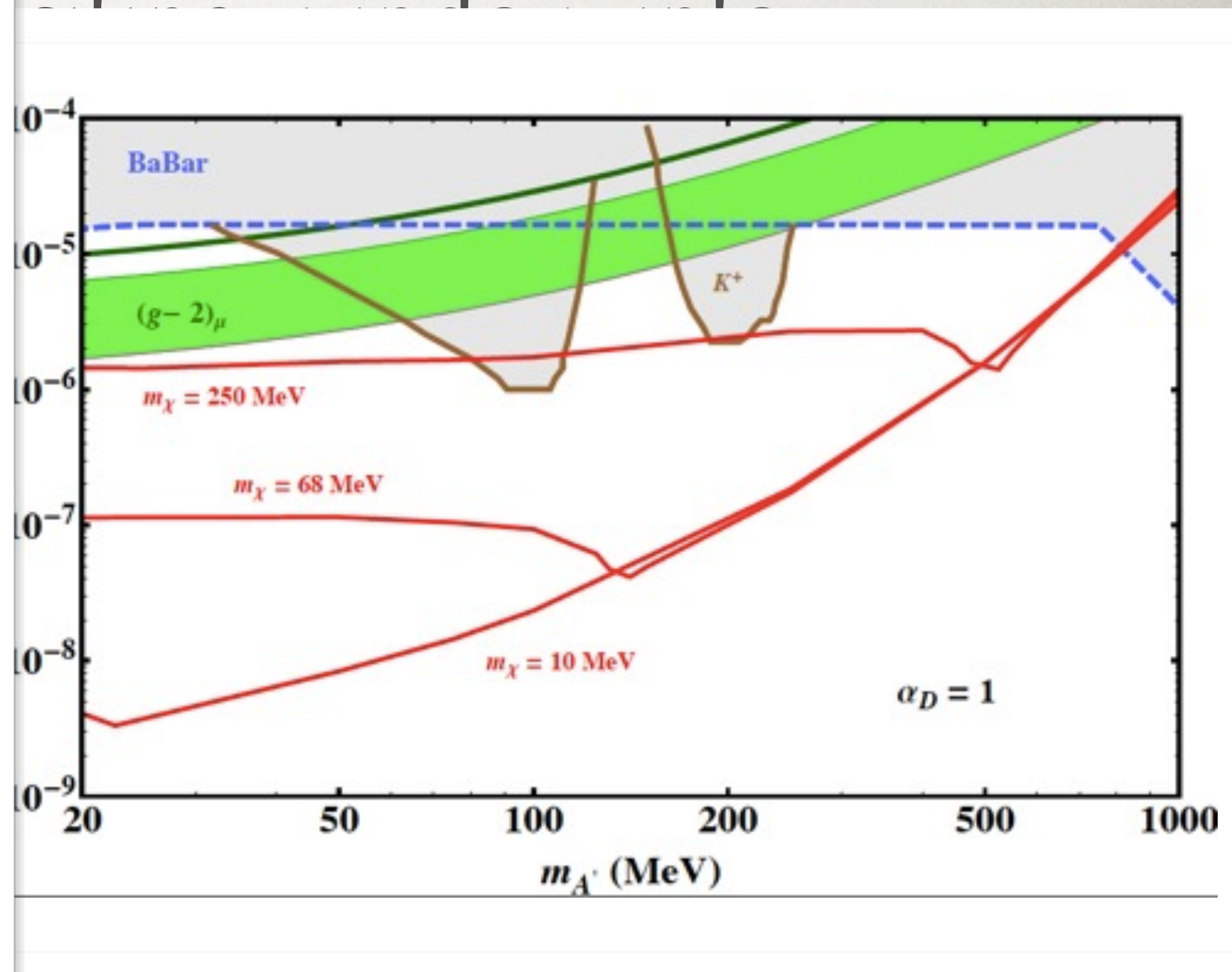
Conclusions

- Dark Forces are an exciting window into physics far beyond the Standard Model
  - Possible connections to dark matter and physics at very high scales
- Several mass ranges are testable in moderate-scale experiments
  - New-particle searches in B-factories – many results already, continuing to extend
  - Dedicated fixed-target experiments are extending range to much lower couplings
  - Many recent developments in searches for **invisible** A' decays
- A lot of uncharted territory: opportunities for further exploration – and maybe discovery – abound!

Conclusions





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- A lot of uncharted territory: opportunities for further exploration – and maybe discovery – abound!