GeV-Scale Dark Forces: Motivations and Status

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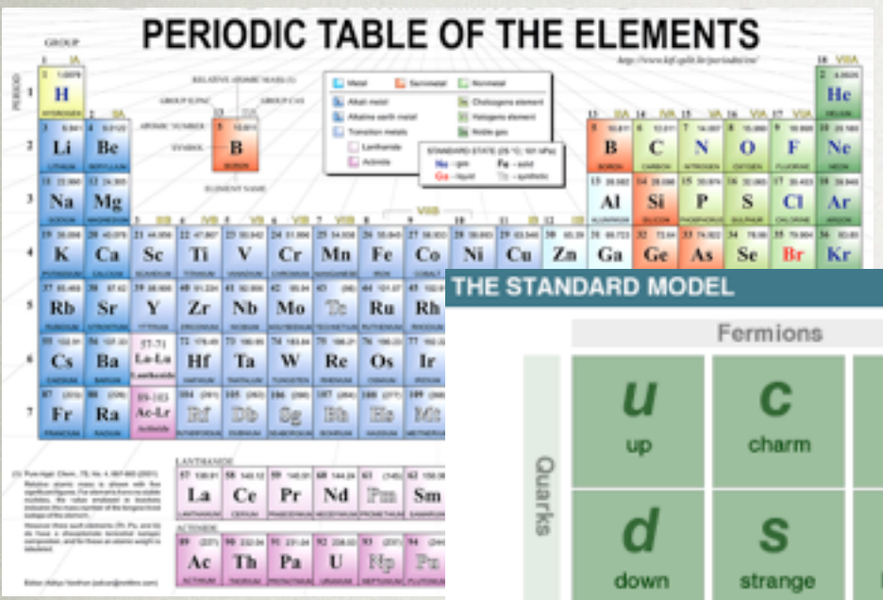
Intensity frontier Meeting
Argonne National Lab
April 26, 2013

Dark Forces Below the Weak Scale

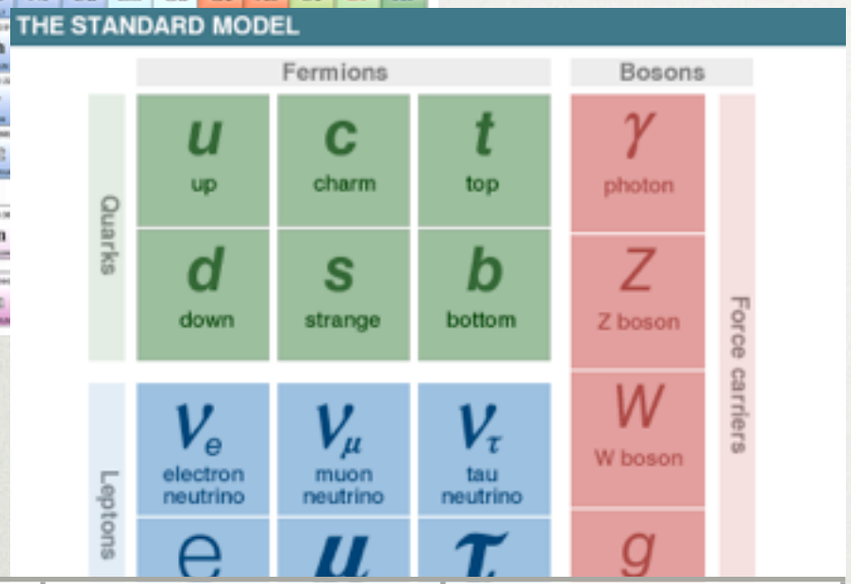
- Theory and Motivation
  - Dark matter [Slatyer] & g-2 [Marciano]
- Direct Search Status
  - High-energy colliders (“lepton jets”)
  - Low-energy colliders
  - Fixed Target (e and p)

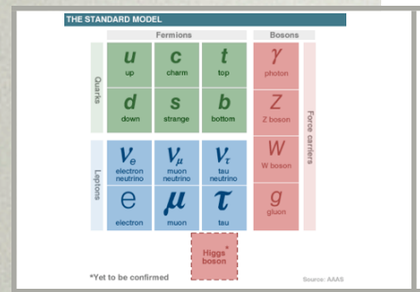
Copernican Particle Physics?

[thanks to Neal Weiner]



p^+, n, e^-





?

...

?

?

?

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

Completely new physics?

How to look for physics FAR beyond the SM?

Most collider searches rely on Standard Model-like interactions ⇒ by definition, SM-neutral new physics is hard to see.

- Interactions invariant under all symmetries tend to involve many fields simultaneously

  ⇒ suppressed by high power of mass-scale of new physics, e.g.

$$(\bar{\psi}_e \psi_e)_{SM} (\bar{\chi}\chi)_{new} / \Lambda^2$$

the few possible exceptions present an opportunity

The "Portals"

Neutrino Portal $\epsilon_\nu \, (hL)\psi$ sterile neutrinos?

Higgs Portal $\epsilon_h \, |h|^2 |\phi|^2$ exotic rare Higgs decays?

Vector Portal (kinetic mixing) $\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$ [Holdom '86]

Generic low-energy remnants of *any* non-SM sector

Only light-vector portal is truly accessible in low-energy production (e & p couplings to h, ν are small)

Vector-Portal Interactions

Consequences of a new mixed U(1):

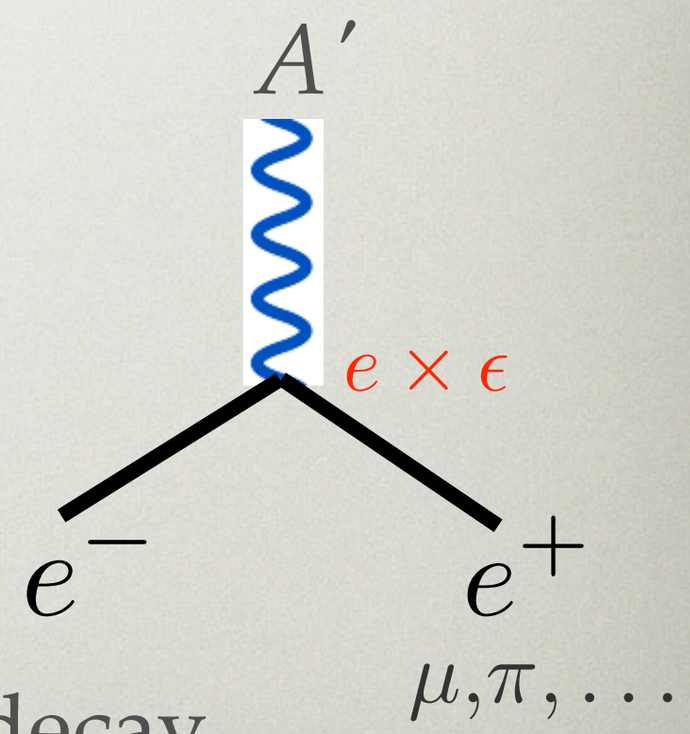
massive

$$\mathcal{L} \supset -\frac{1}{4}F_Y^2 - \frac{1}{4}F'^2 + \frac{\epsilon_Y}{2}F_Y F' + eA_Y J_Y + gA' J' + m^2 A'^2$$

"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



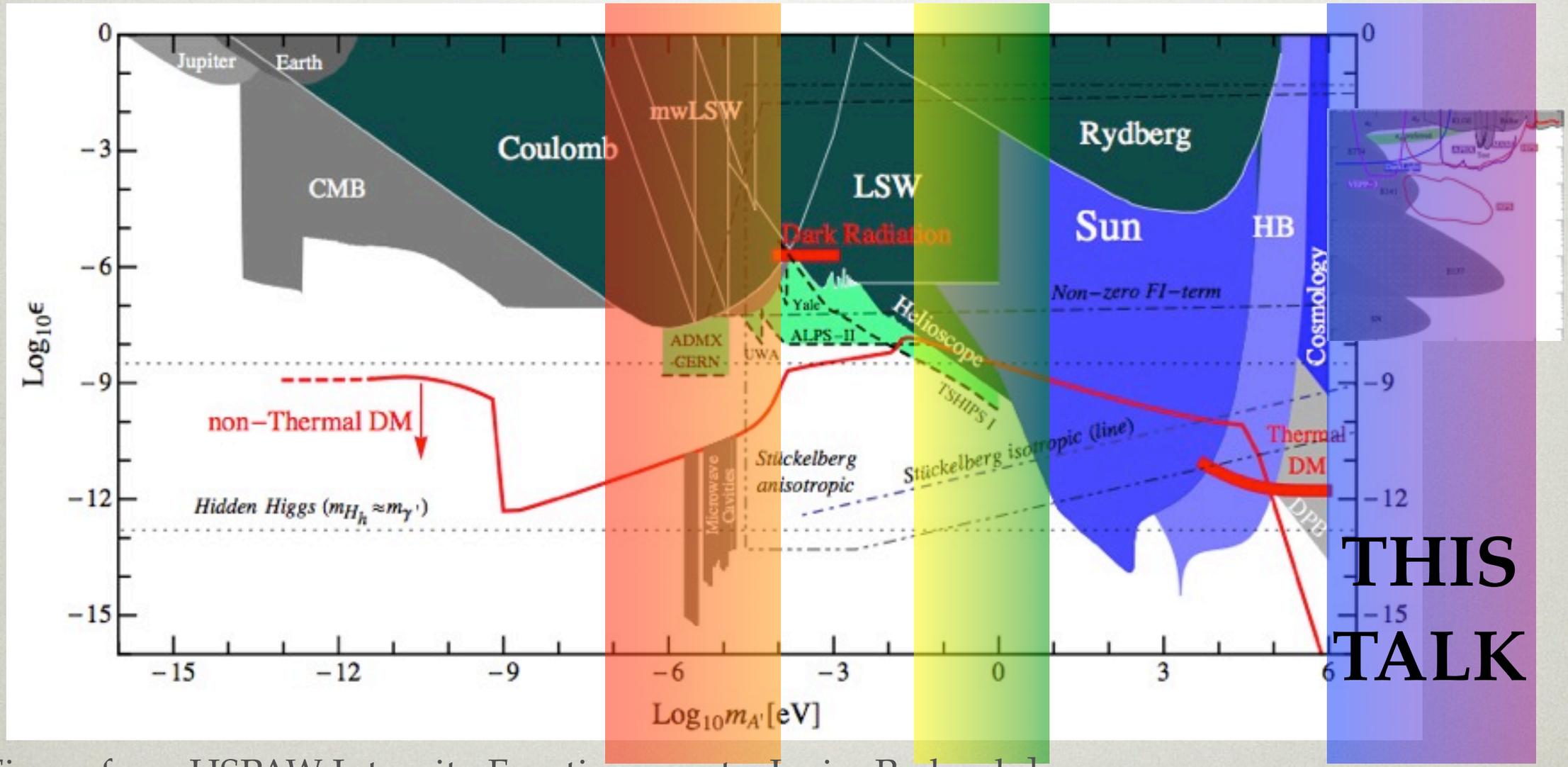
What are reasonable couplings and masses?

Wide Parameter Space: Hidden Vectors

Macro-scopic

AMO scale

Nuclear scale

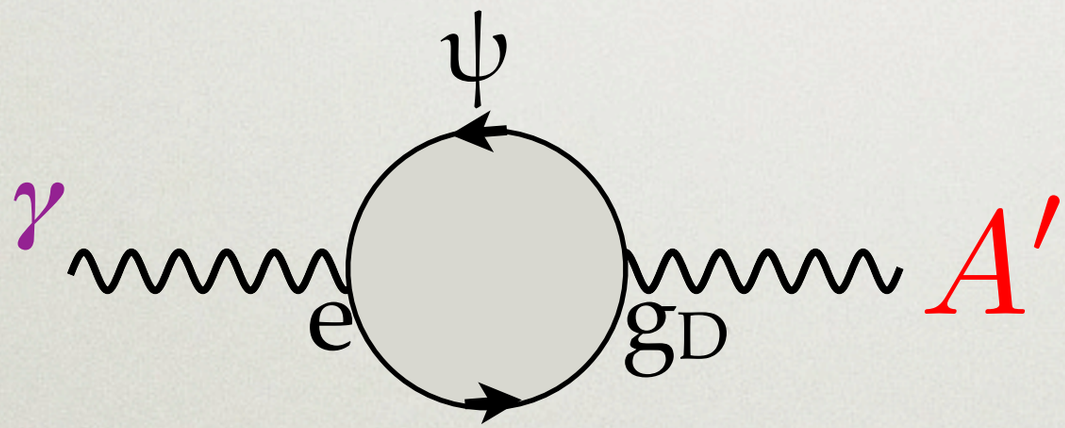


[Figure from HSPAW Intensity Frontier report – Javier Redondo]

new forces *light* *new particles*

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

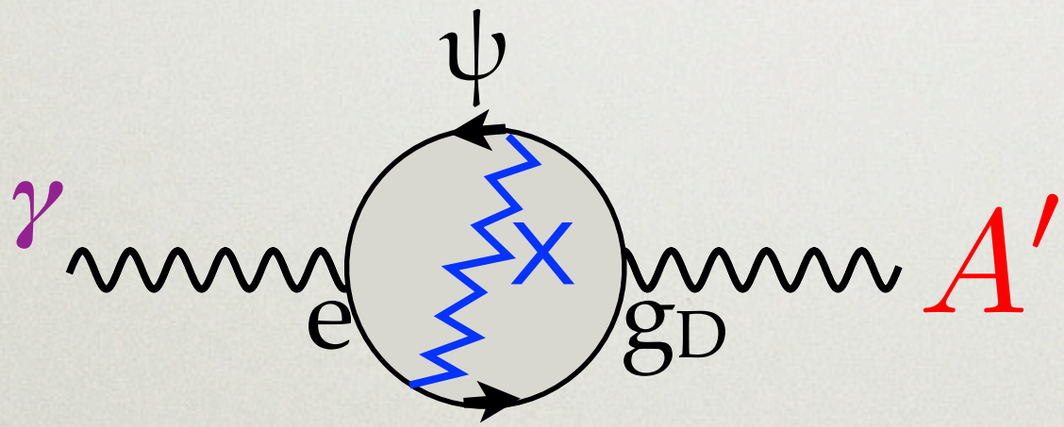
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



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

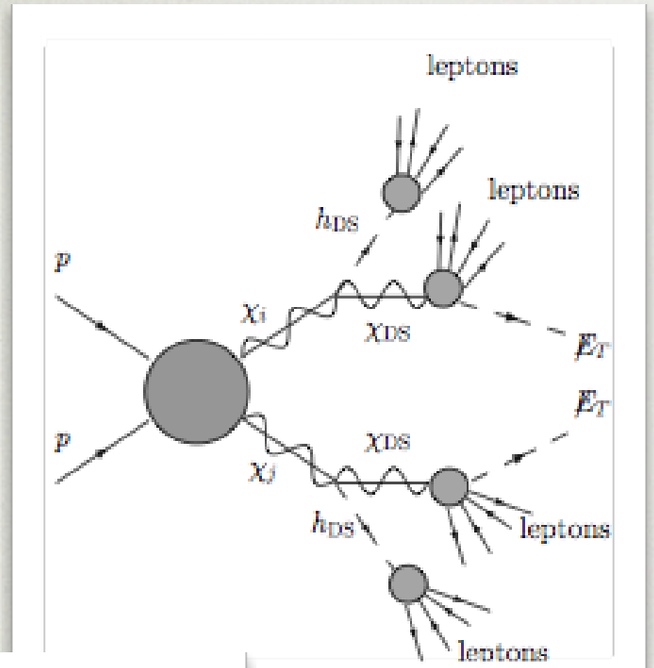
- MeV-to-GeV is
  - **allowed** at couplings $>10^{-7}$
  - motivated by g-2 and dark matter anomalies
- Possible origin: related to M_Z by small parameter
  - e.g. supersymmetry+kinetic mixing ⇒ scalar coupling to SM Higgs, giving

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

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

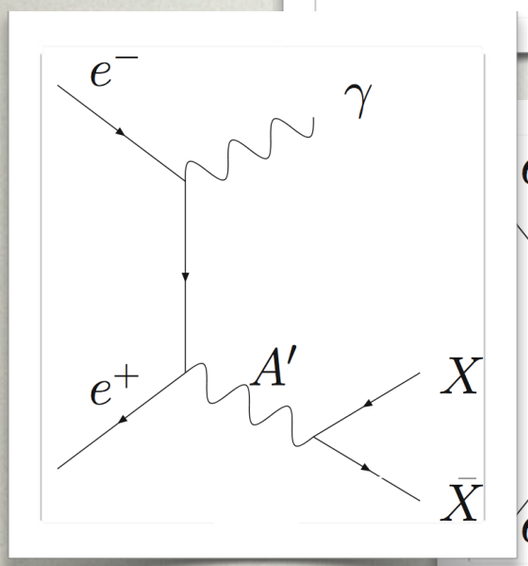
a motivated target of opportunity

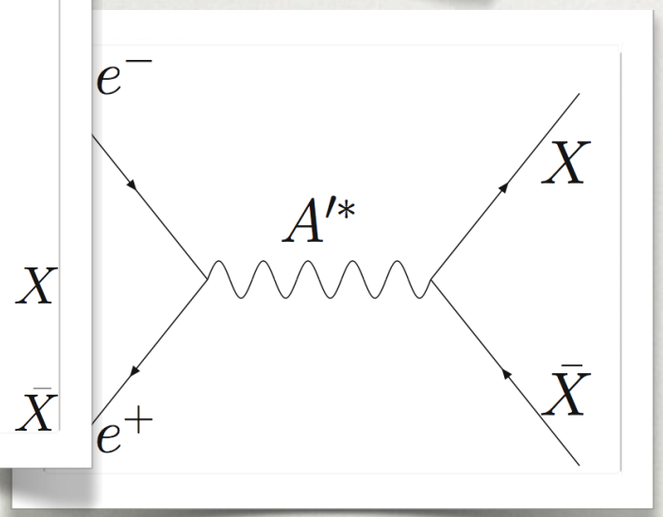
Broad Array of Searches! (done, ongoing, planned)



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

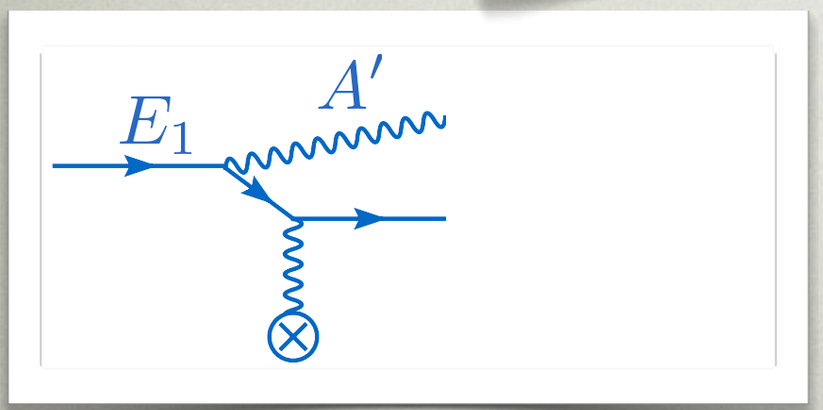
(ATLAS, CMS, CDF & D0)





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

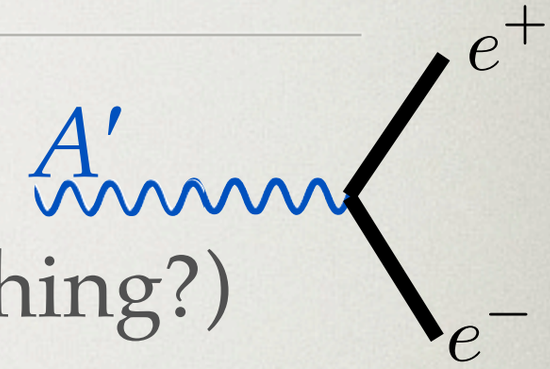
(BaBar, BELLE, BES-III, CLEO, KLOE)



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

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

Goals for Heavy-Photon Searches



- Minimal decay
  - (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
- Inclusive searches
  - Off-shell effects, e.g. (g-2): ε^2 in interference
  - ε^2-suppressed minimal decay
  - Recoiling electron + X

Searches are Broader than Motivations

- Kinetic mixing ⇒ A′ coupling ∝ q_{EM}

But by no means the only option!

Using different production/decay modes in different searches is valuable!

The parameter space is too big for one ε vs. *m* plot

Rates and Things

- Notational interlude

  Mixing/coupling strength: $\varepsilon^2 = \kappa^2 = \alpha'/\alpha$

  U=A′ = Heavy/dark photon = **any** weakly coupled heavy vector boson (not necessarily kinetically mixed)

- Production: $\sigma \sim \epsilon^2/E^2$ or $\sigma \sim \epsilon^2/m^2$
- Lifetime (assuming 100% to Standard Model):

  $$\tau^{-1} \sim \epsilon^2 m N_{eff}$$

  where N_{eff} is weighted number of species available for decay (2+R above muon threshold)

  $1/N_{eff} = e^+e^-$ or $\mu^+\mu^-$ branching fraction

Rest of this talk:

– Basic strategies for heavy-photon searches

– Relative strengths of each approach

context for today's talks and for thinking about new opportunities

09:00
Current Status on Dark Matter Motivation for Heavy Photons — *Tracy SLATYER*
Bldg. 360, Rm. A-224 — 09:00 - 09:25

New Electron Beam Dump Searches — *Sarah ANDREAS*
Bldg. 360, Rm. A-224 — 09:30 - 09:50

10:00
Searches for Hidden Sector Particles in KLOE-2 — *Francesca CURCIARELLO*
Bldg. 360, Rm. A-224 — 09:55 - 10:10

BaBar Searches for Hidden Sector Particles — *Bertrand ECHENARD*
Bldg. 360, Rm. A-224 — 10:15 - 10:30

Coffee Break
Auditorium Lobby Area — 10:30 - 11:00

11:00
Hidden Sector Particles at the LHC — *Andrew HAAS*
Bldg. 360, Rm. A-224 — 11:00 - 11:15

Searches for Hidden Sector Photons at Mainz — *Tobias BERANEK*
Bldg. 360, Rm. A-224 — 11:20 - 11:35

Status of APEX — *Philip SCHUSTER*
Bldg. 360, Rm. A-224 — 11:40 - 11:55

12:00
DarkLight — *Ross CORLISS*
Bldg. 360, Rm. A-224 — 12:00 - 12:15

14:00
Searches for Hidden Sector Particles with HPS — *Stepan STEPANYAN*
Bldg. 360, Rm. A-224 — 14:00 - 14:15

VEPP3 — *Bogdan WOJTSEKHOWSKI*
Bldg. 360, Rm. A-224 — 14:20 - 14:35

Muon Anomaly and Dark Bosons — *William MARCIANO*
Bldg. 360, Rm. A-224 — 14:40 - 15:00

15:00
Future Searches at Protons Accelerators for New Particles — *Brian BATELL*
Bldg. 360, Rm. A-224 — 15:05 - 15:25

Coffee Break
Auditorium Lobby Area — 15:30 - 16:00

16:00
New Particle Searches at Neutrino Beams — *Dr. Richard VAN DE WATER*
Bldg. 360, Rm. A-224 — 16:00 - 16:15

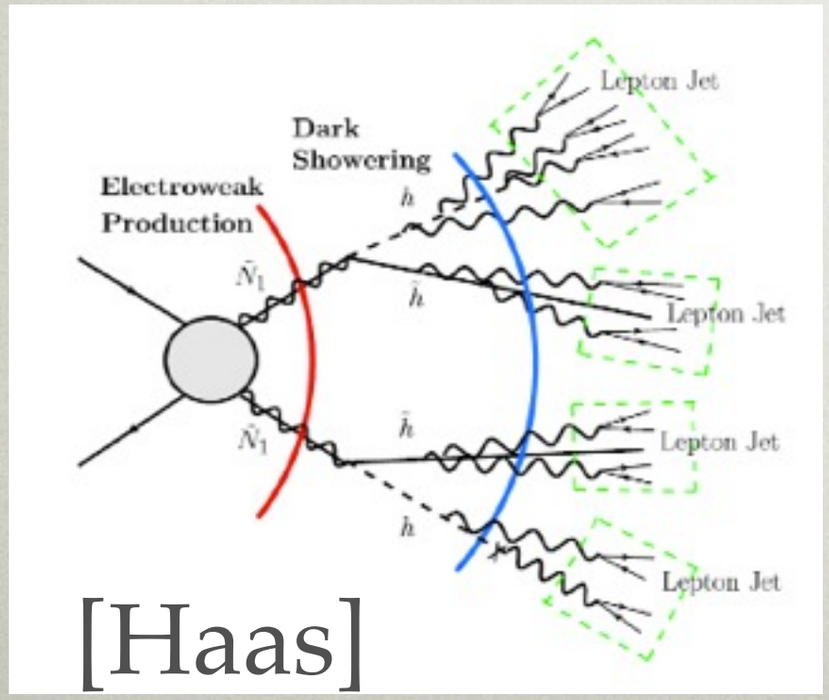
Detectors for proton beam dump experiments — *Athanasios HATZIKOUTELLS*
Bldg. 360, Rm. A-224 — 16:20 - 16:35

Preparations for Minneapolis
Bldg. 360, Rm. A-224 — 16:40 - 16:55

"Lepton Jets" from Heavy Photons

Though LHC not especially favorable for **direct** A′ production, may offer unique opportunity for indirect production

Any new, otherwise stable particle can **only** decay into A′ ⇒ no ε^2 suppression in production rate.



[Haas]

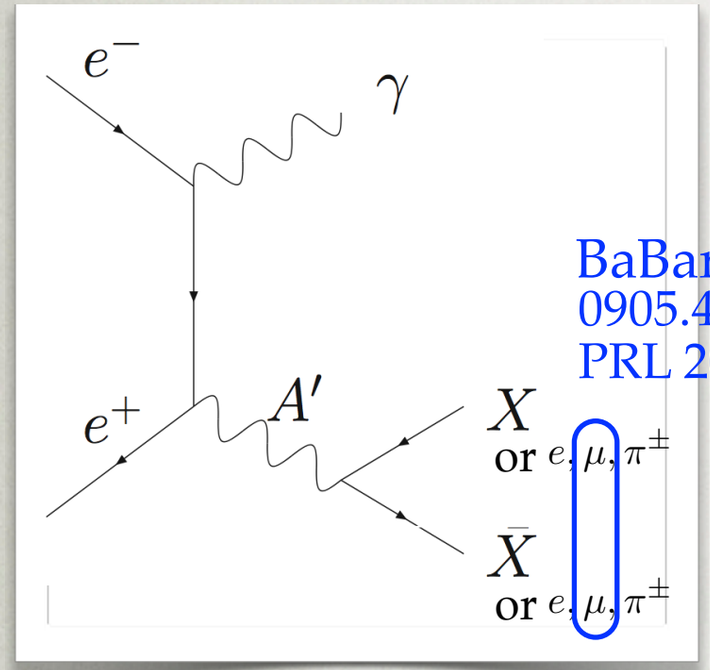
Large boost ⇒ highly collimated decay products "lepton jets"

LHC Search Advantages

- Unsuppressed (but lucky) production⇒ sensitivity to smaller couplings
- Inclusive strategies possible
- New frontier: Higgs → Dark Sector
  - We know the Higgs is there
  - Rate ***is*** ε-suppressed, but higgs width small to begin with

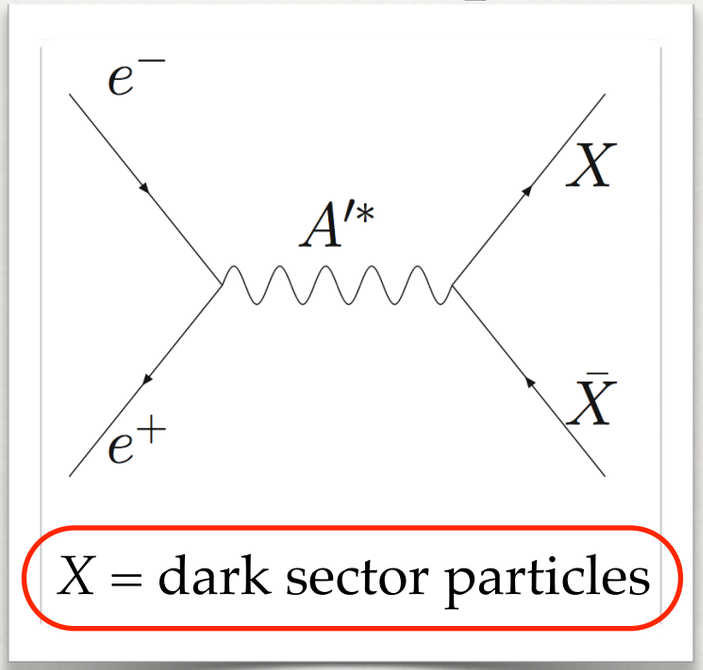
Collider Production

Radiative return



BaBar
0905.4539,
PRL 2009

Off-shell A′ portal



Potential to see rich hidden sectors in complex multi-body final states (searches ongoing at BaBar + several completed)

Rare meson decays

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

[Reece and Wang 2009]

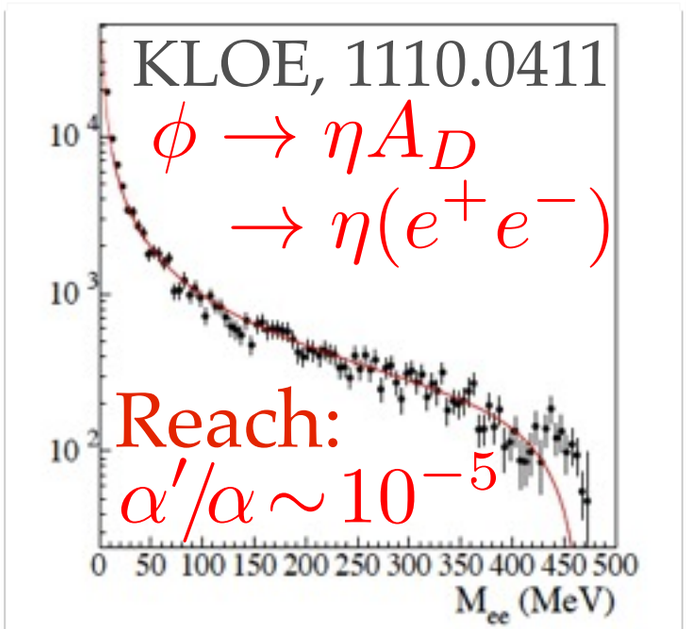
KLOE

PLB706 (2012) 251-255

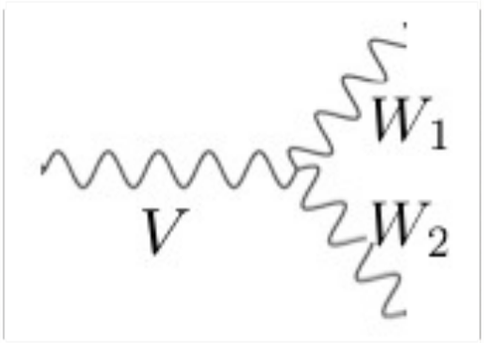
Wide Breadth of Searches

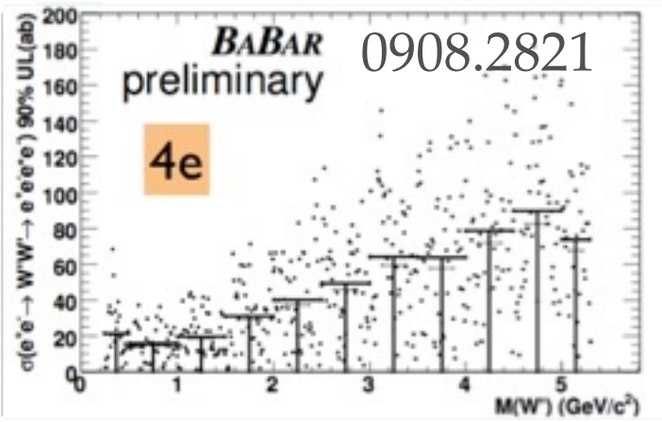
(just a few representative examples)

Minimal Decay

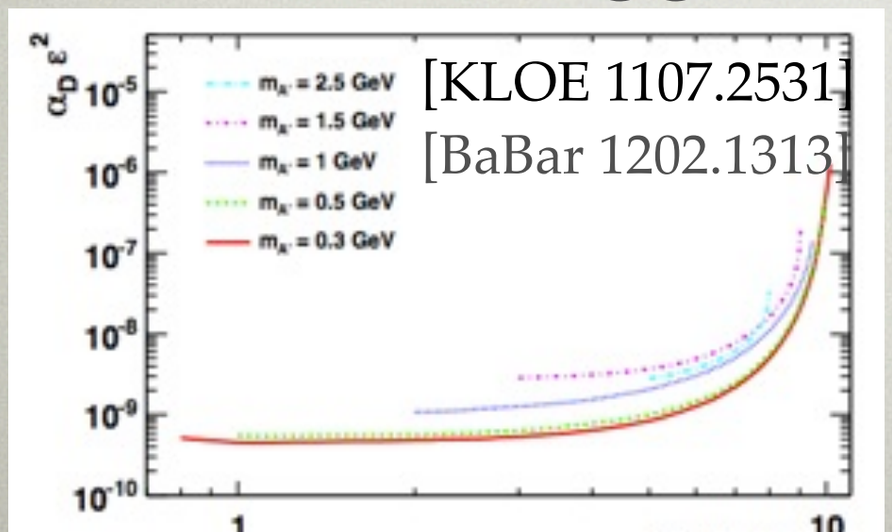


Non-Abelian Dark Sector

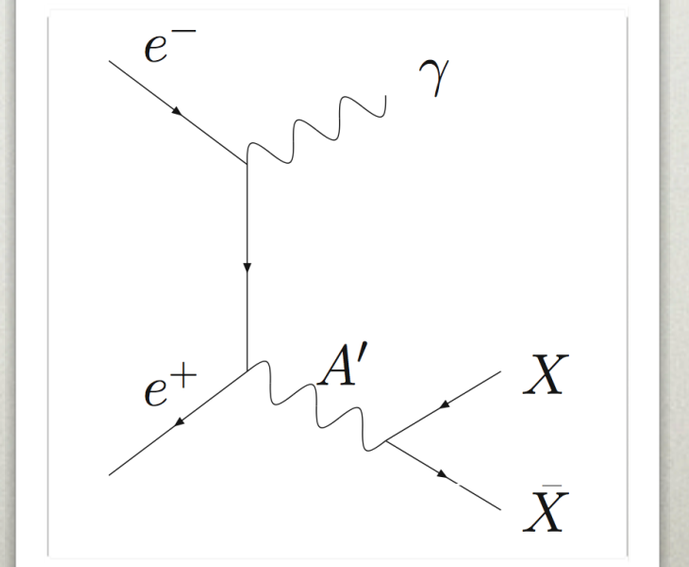




Vector + Higgs:



Invisible Decay

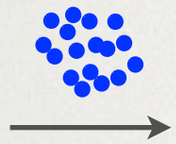
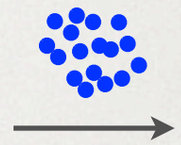
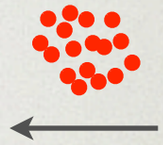


[e.g. BaBar hep-ex/0808.0017]

Flavor Factory Advantages

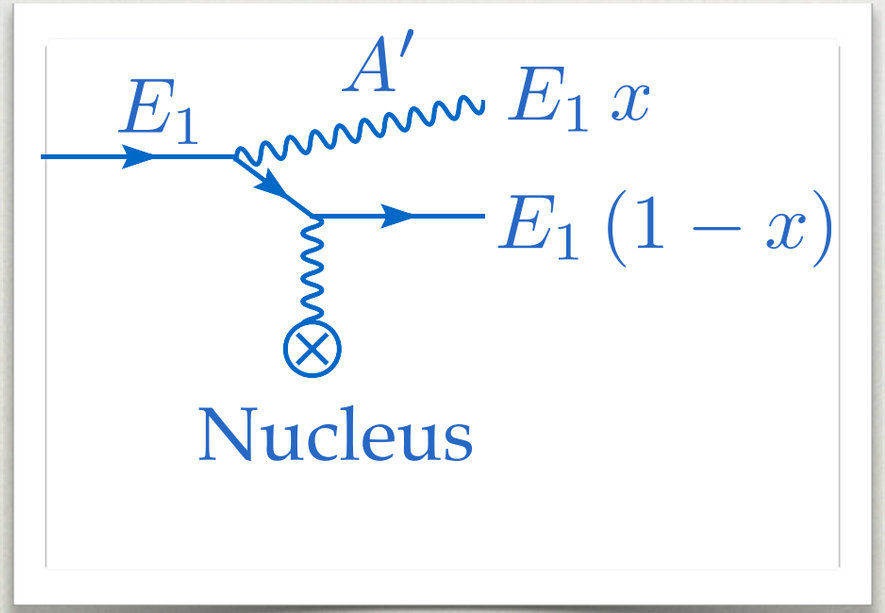
- Highest collider $(Lumi.)/(E_{CM})^2$ in the world
- 4π detectors, clean reconstruction, less boosted
- Large dataset "in the bank" (+ SuperB?)
  - Many searches can use standard triggers
  - **Extremely broad** search program ongoing; can be even more extensive

Fixed-Target Advantages

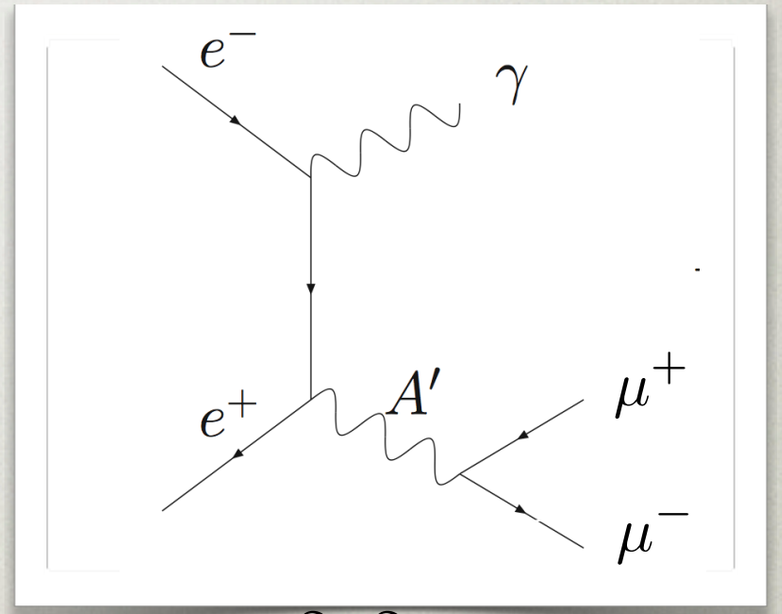
	Fixed-Target	e^+e^-
Luminosity	10^{11} e^-  ~10^{23} atoms in target	10^{11} e^-  10^{11} e^+ 
	N(hard scatter) ~ 0.01 – 1 *per electron*	N(hard scatter) ~ 1 *per crossing*
	O(few) ab^{-1} per day	O(few) ab^{-1} per decade

Cross-Section

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

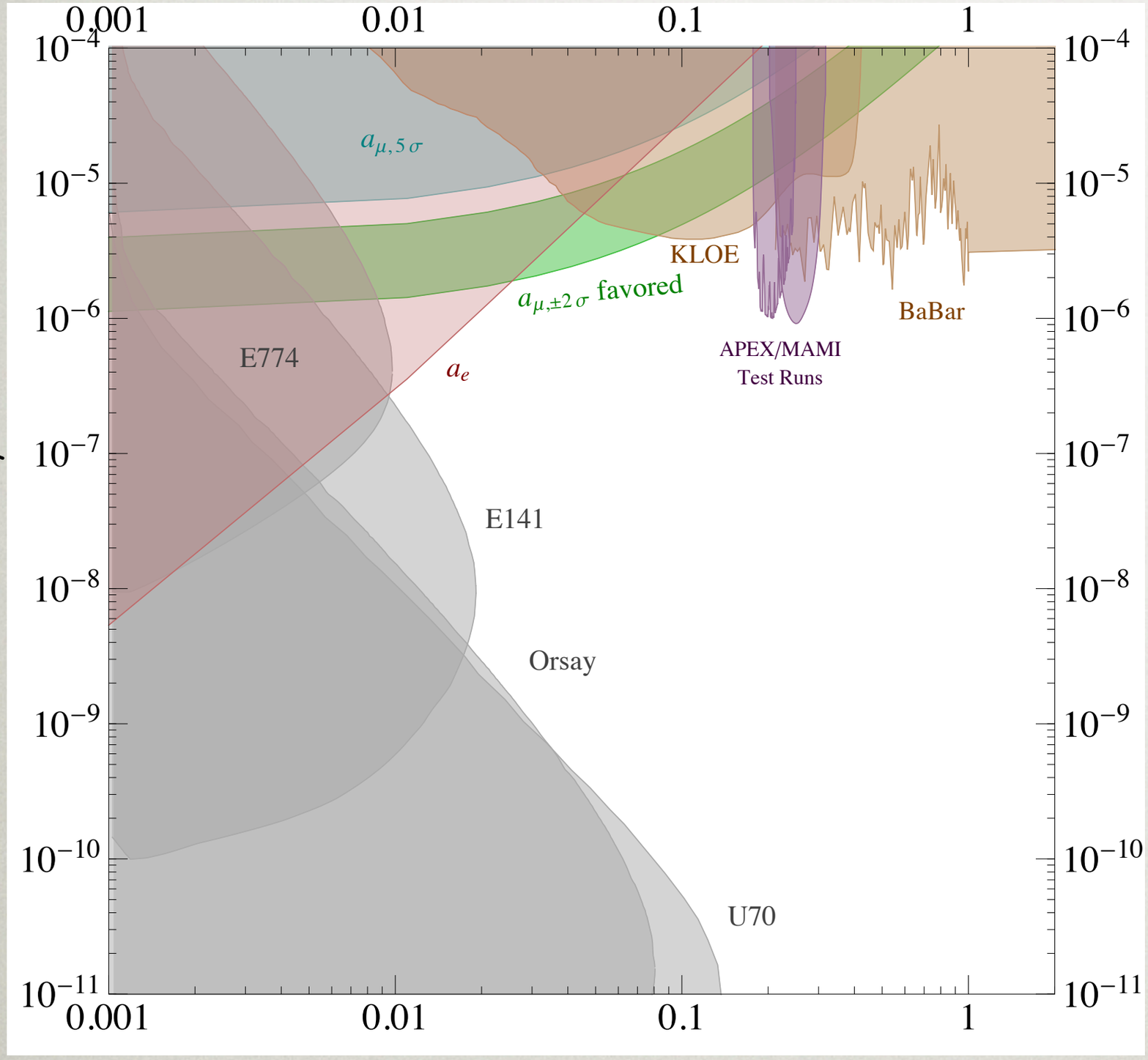


$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$



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

Fixed-Target Territory



α'/α

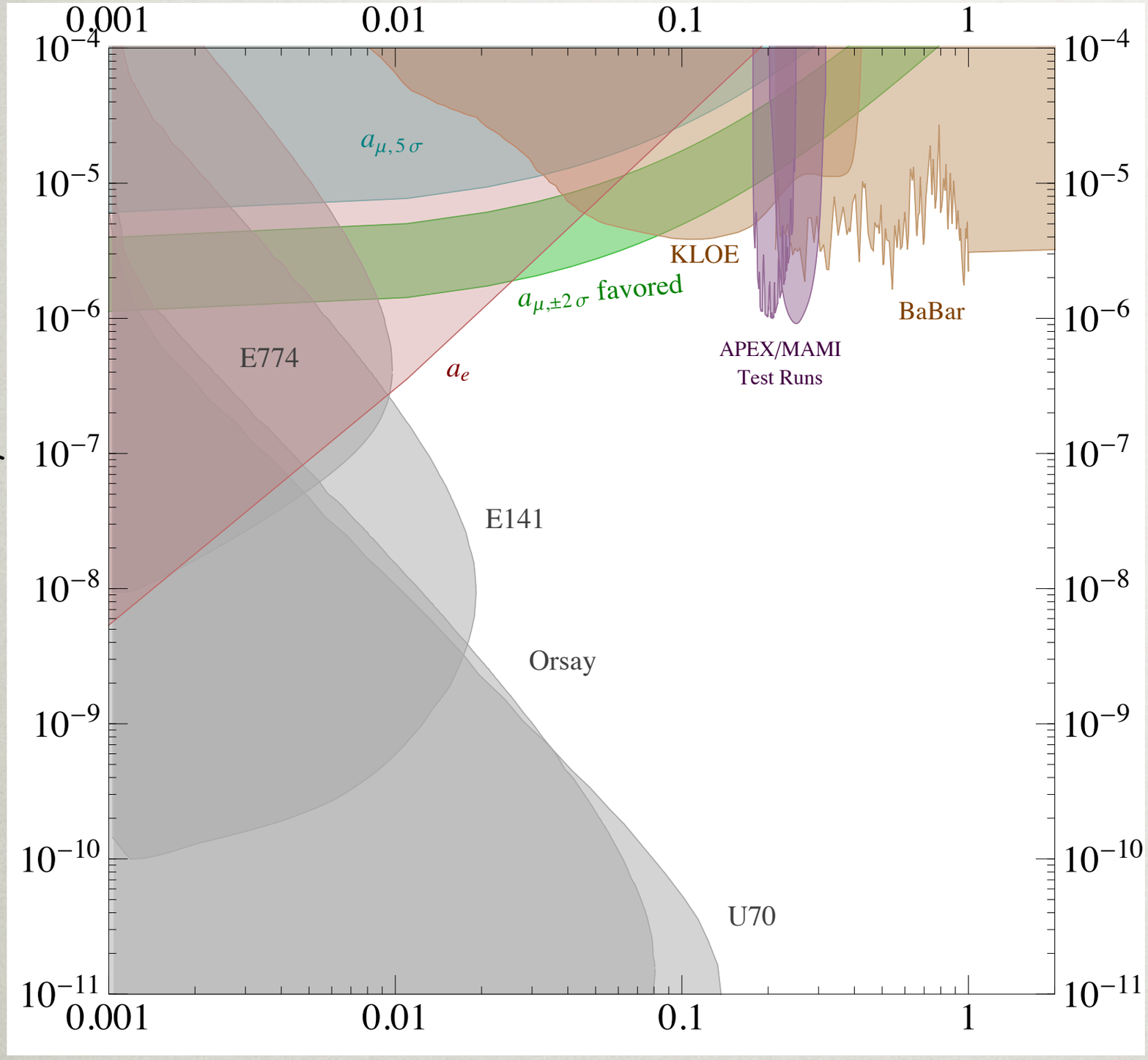
$m_{A'}(\mathrm{GeV})$

one-loop

two-loop (GUT)

three-loop

Fixed-Target Territory



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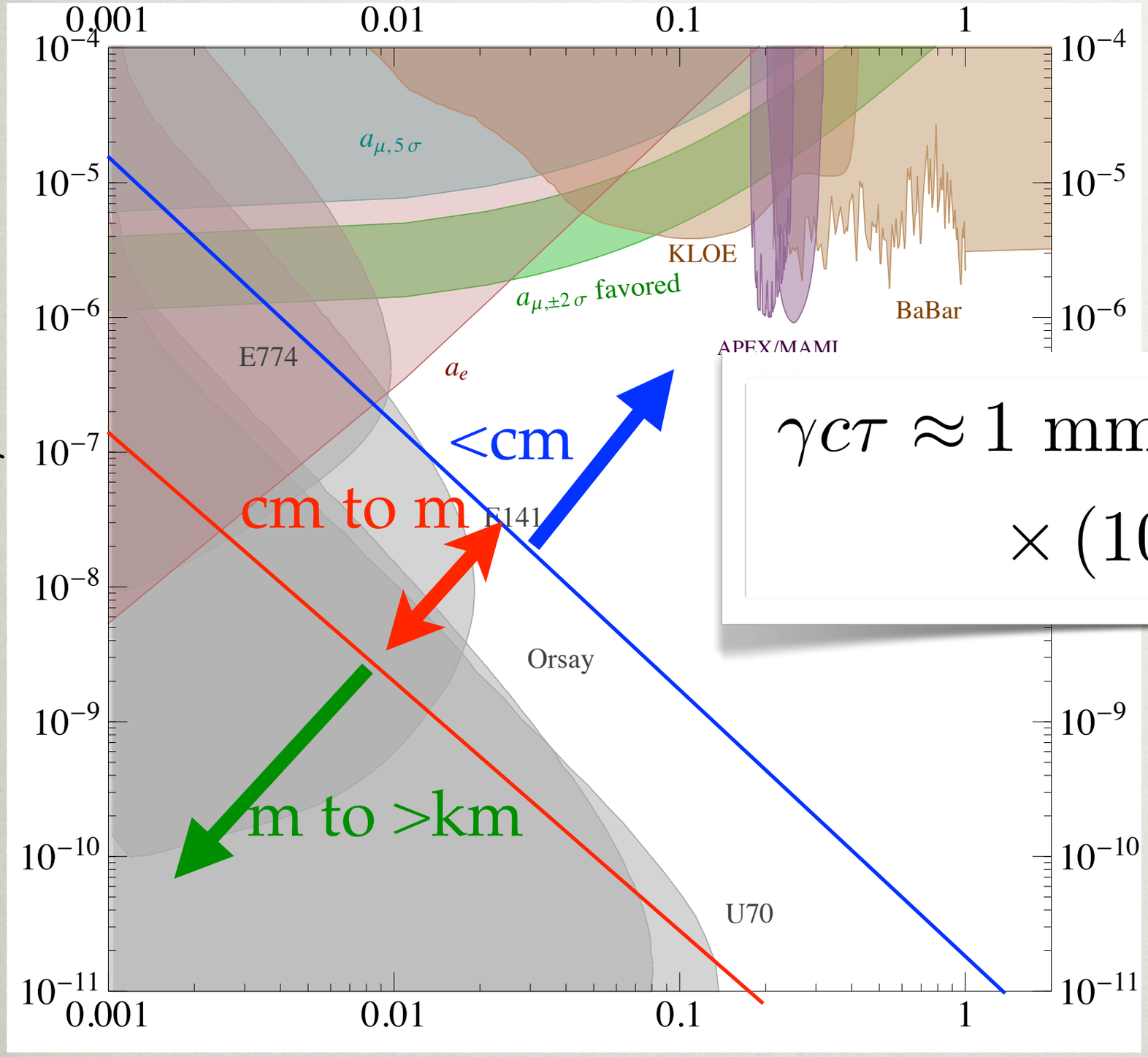
Fixed-Target Territory

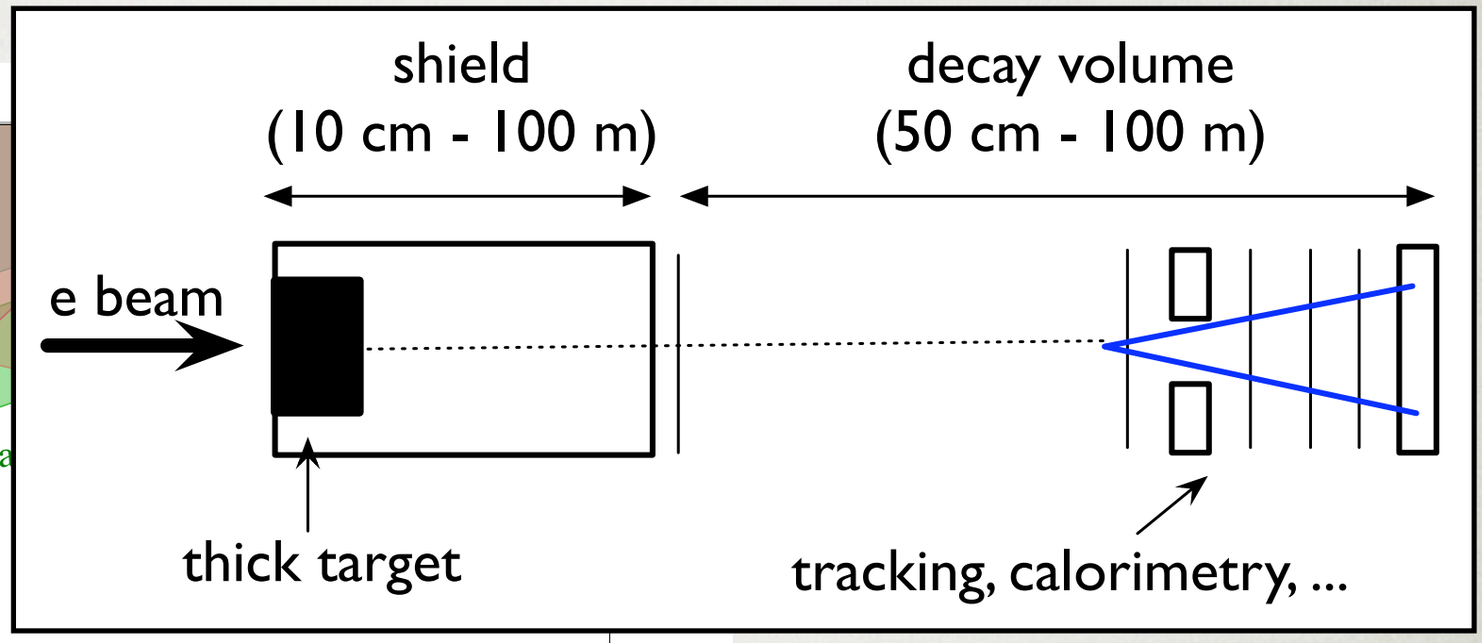


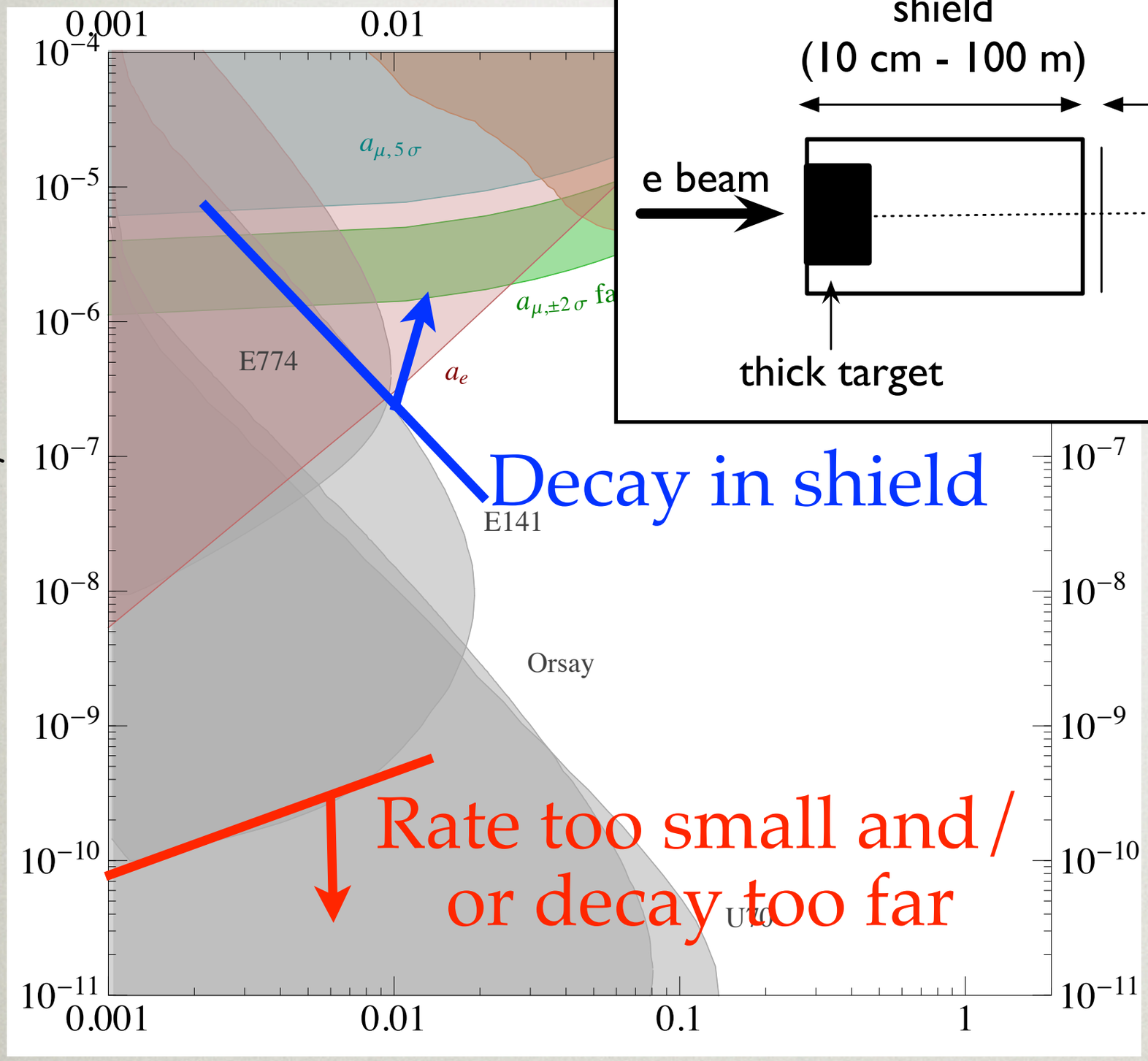
one-loop

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

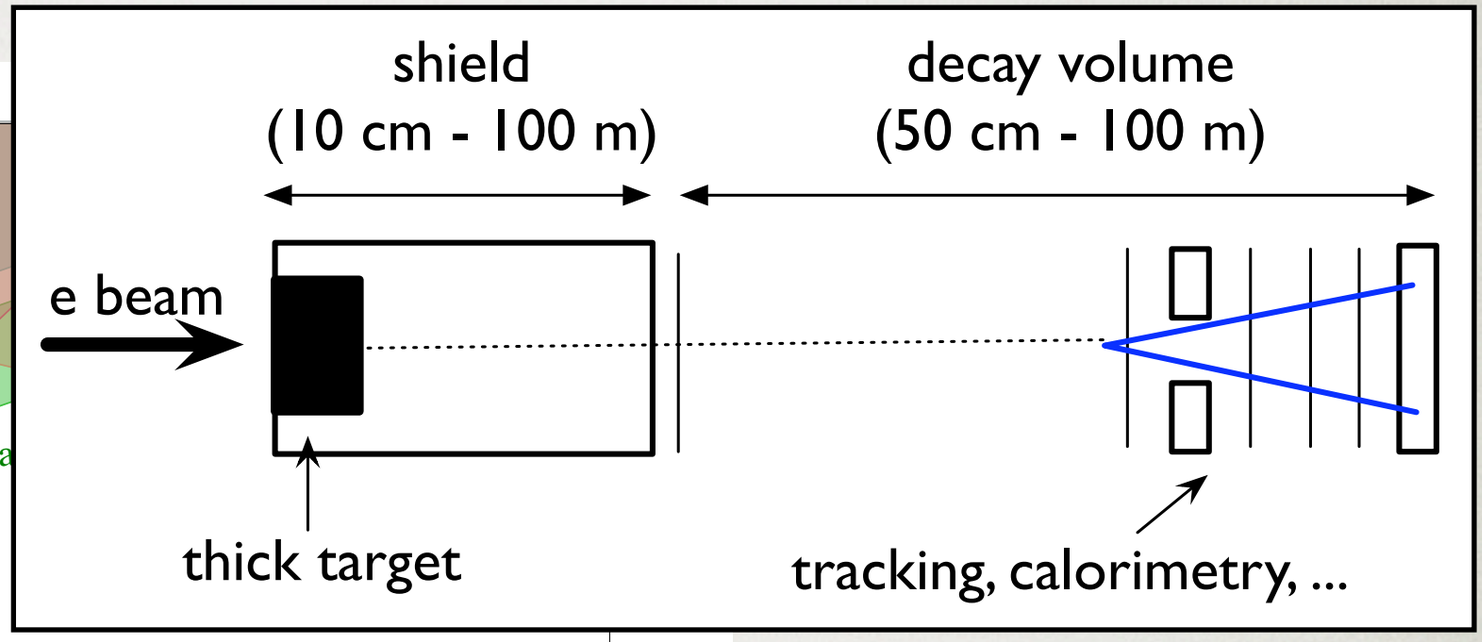
three-loop

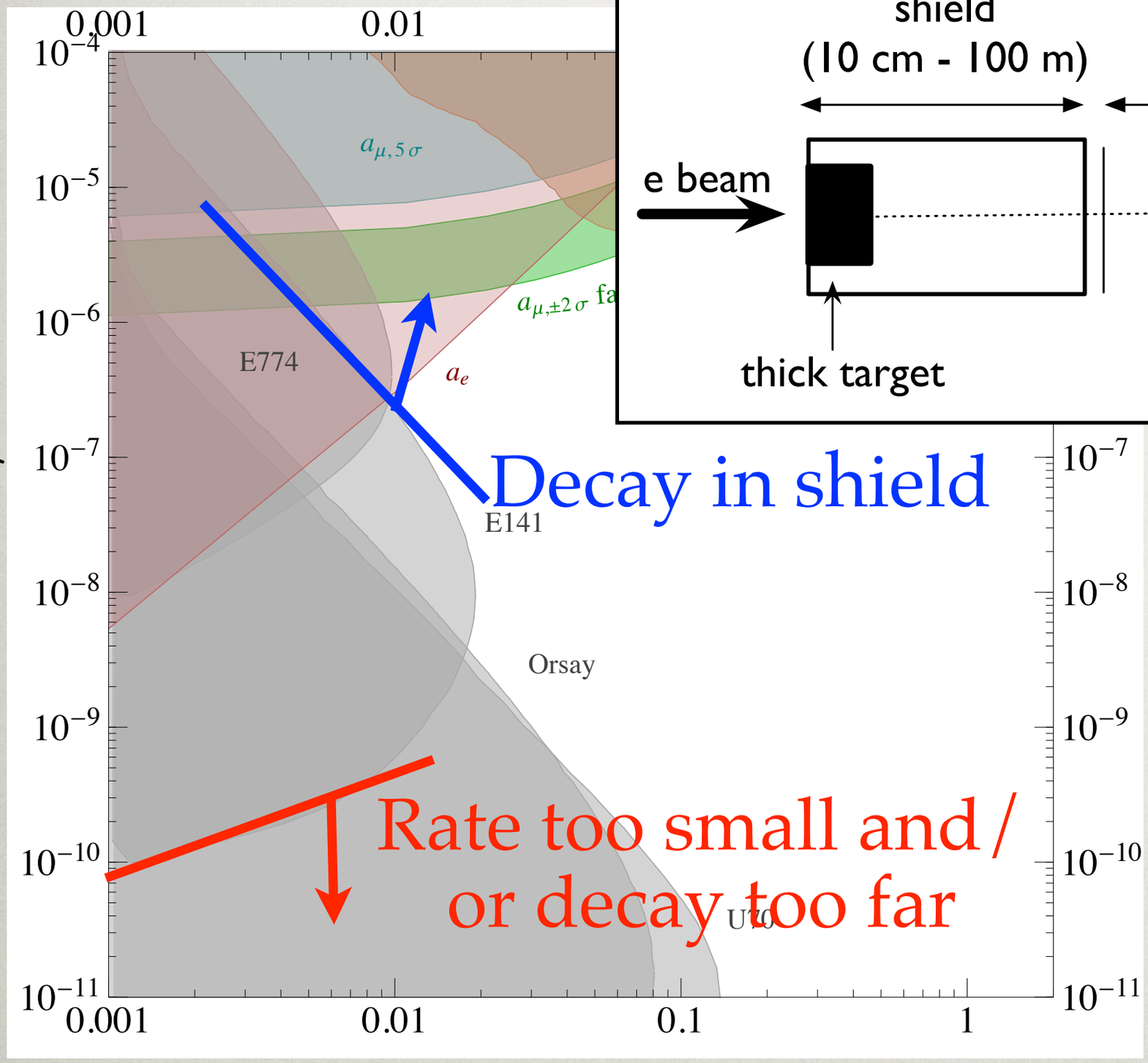
Beam-Dump Limits





Beam-Dump Limits





Decay in shield

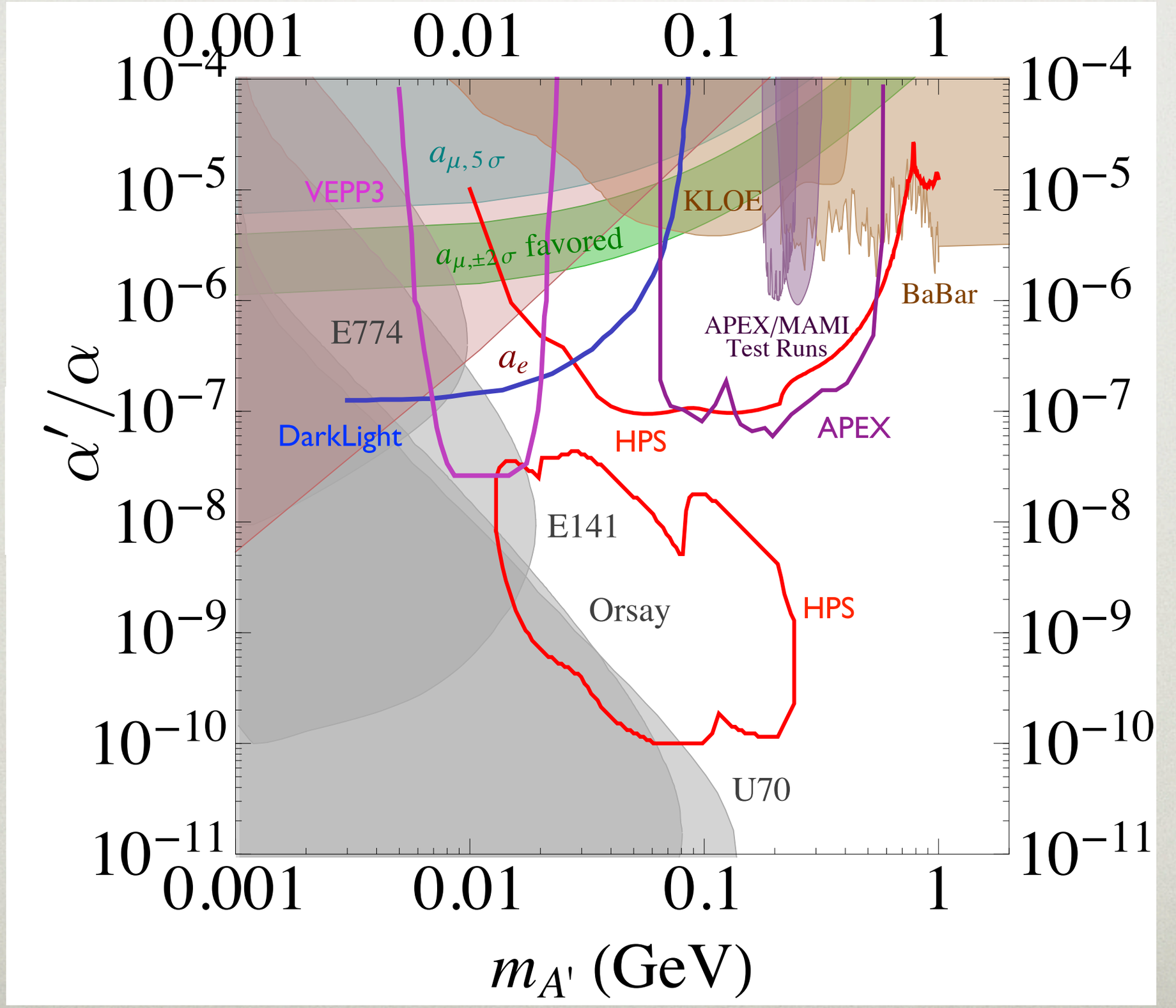
Rate too small and / or decay too far

⇒ need short but effective shield

⇒ long decay volume, high current, low background

Electron F.T. Proposals

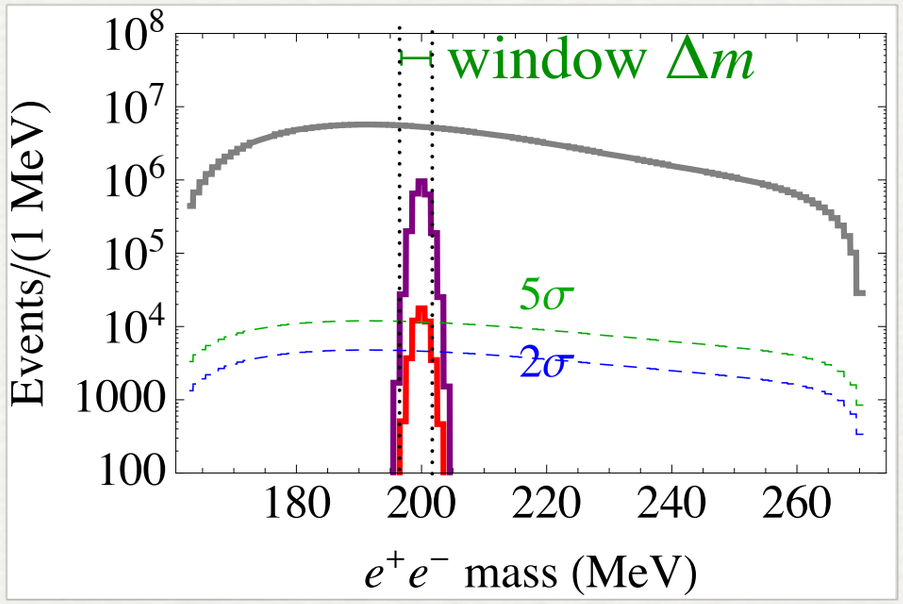
(JLab only; similar @ Mainz)



Two Search Strategies

High-Statistics Resonance Search

(MAMI, APEX, HPS, DarkLight)



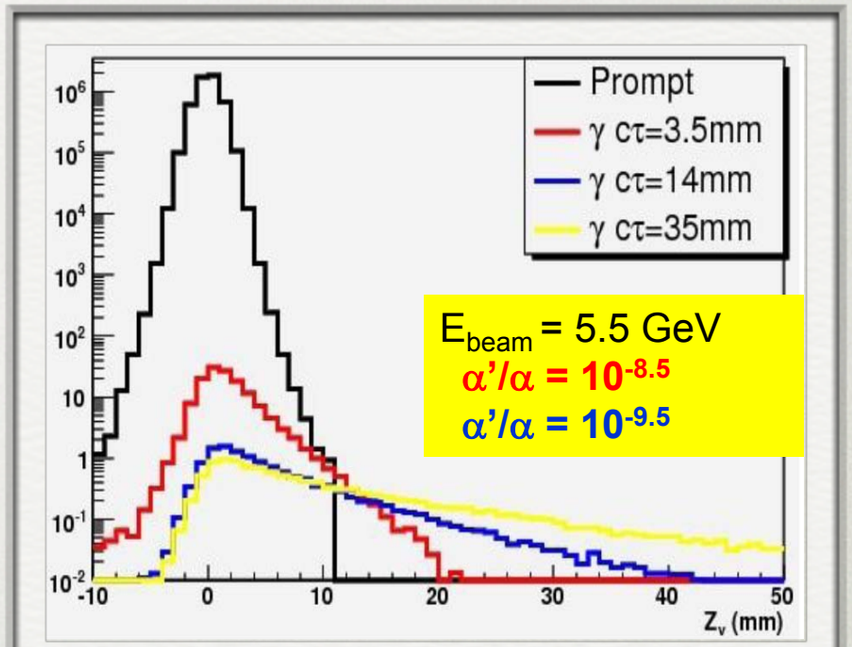
Demands high data-taking rate, background suppression and excellent mass resolution

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

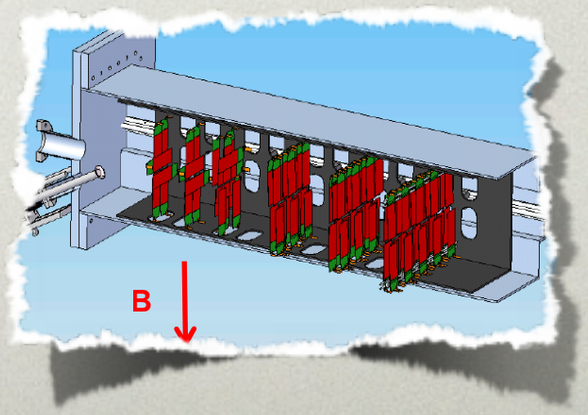
DarkLight: full reconstruction of recoil → sensitive to invisible A′ decays

Displaced Resonance search

(HPS)



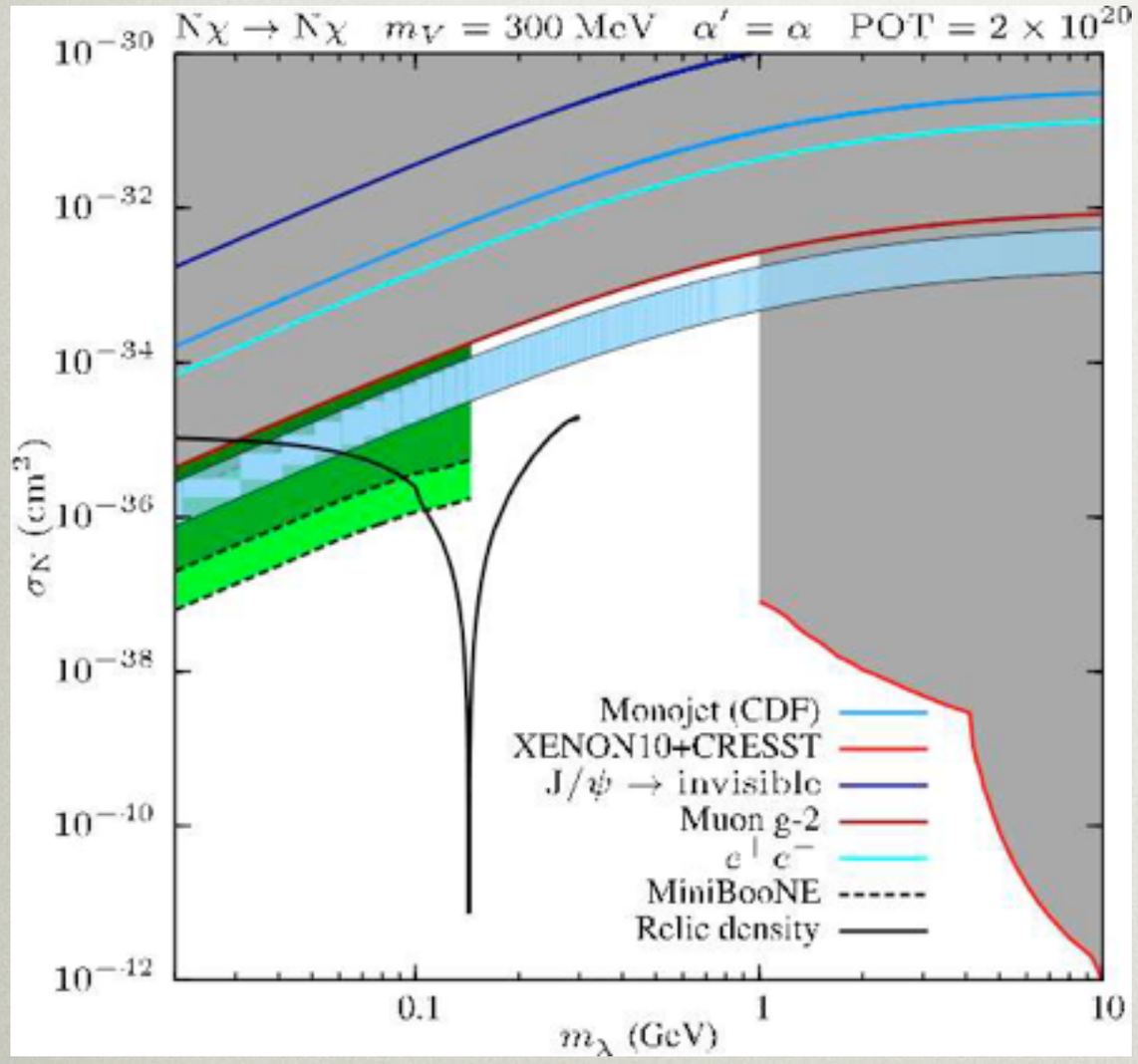
...and forward vertex resolution (well-controlled tails)



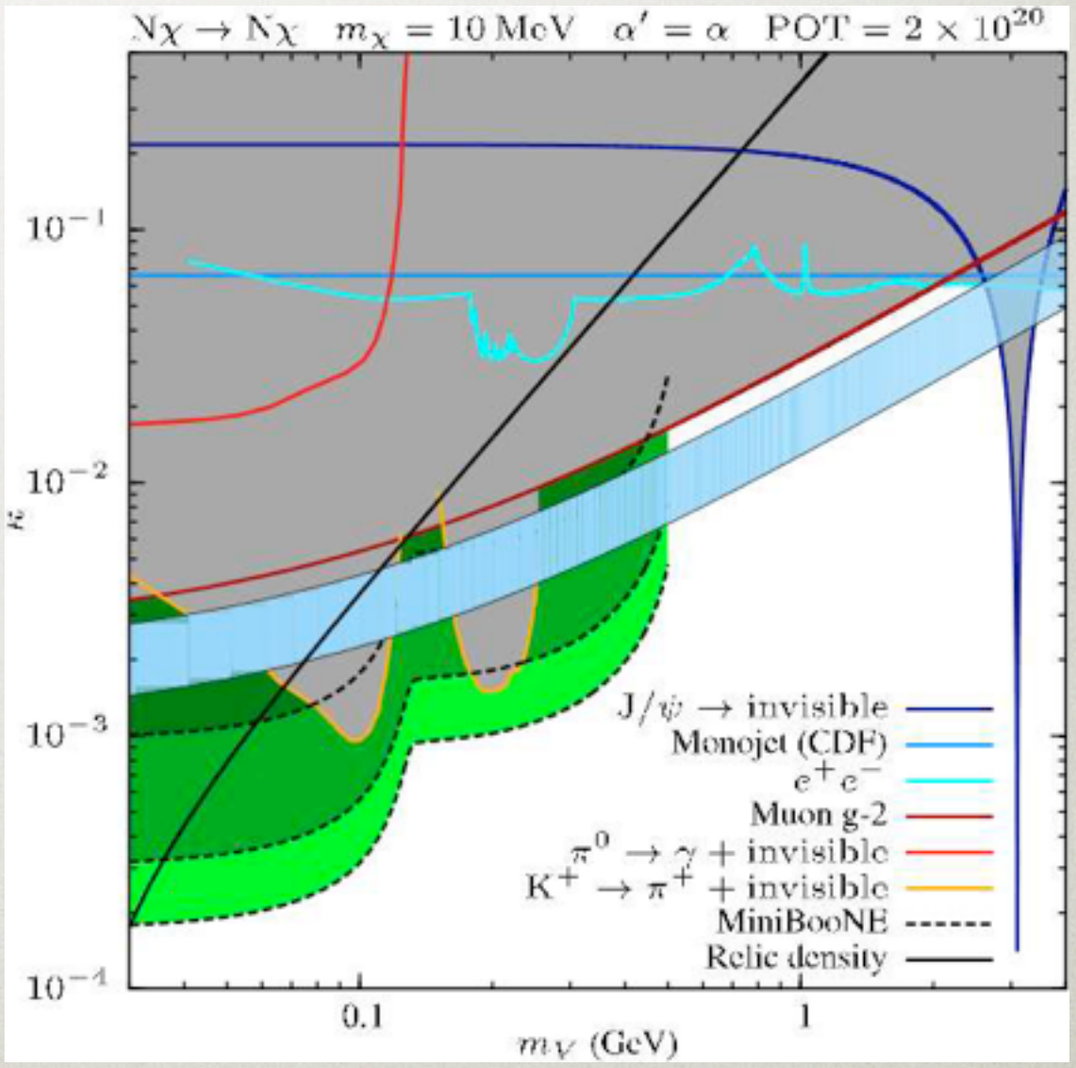
Proton Beams

New light-WIMP search at MiniBoone
(from M. Pospelov)

Fix m_V, vary m_χ



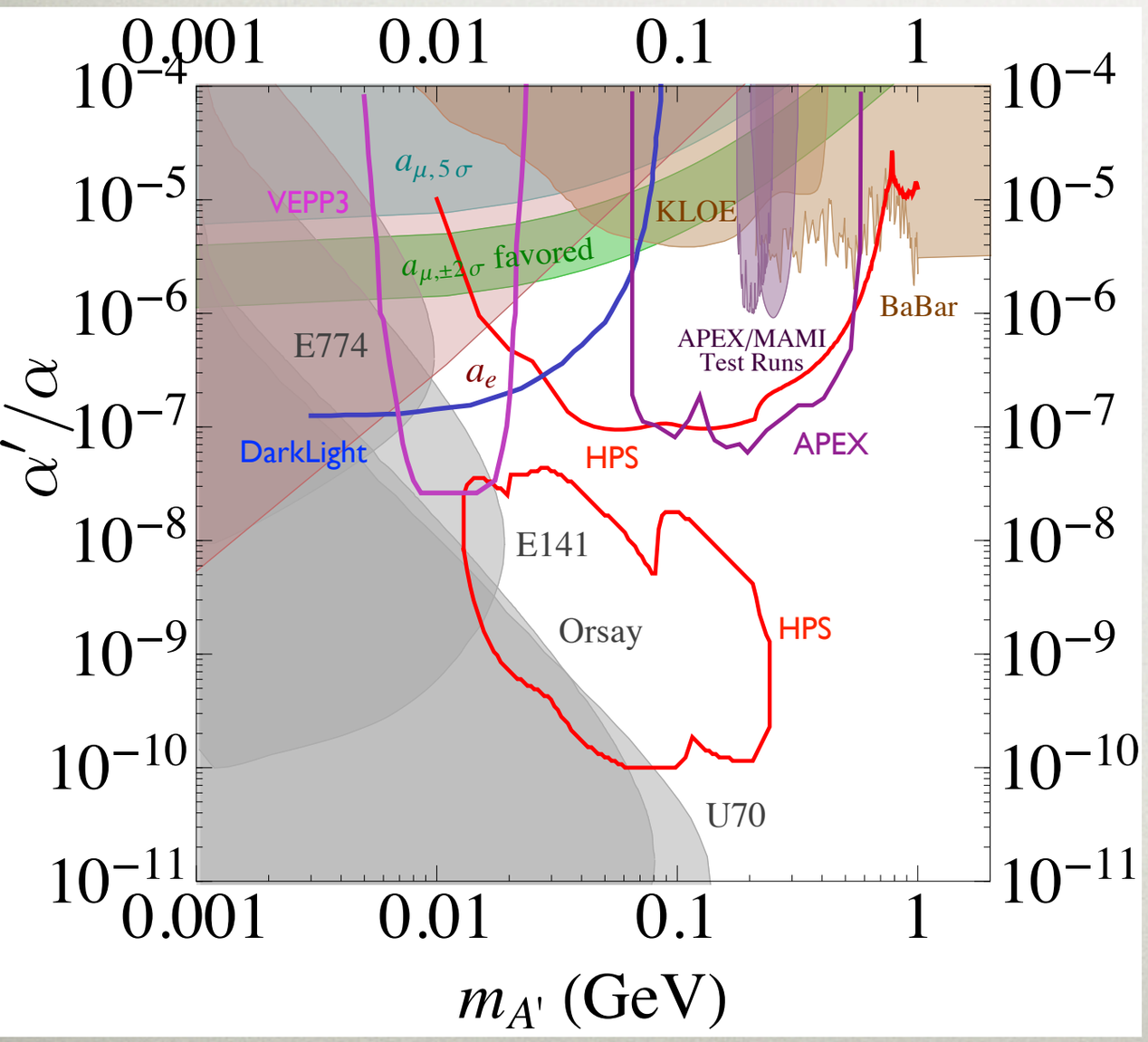
Fix m_χ, vary m_V

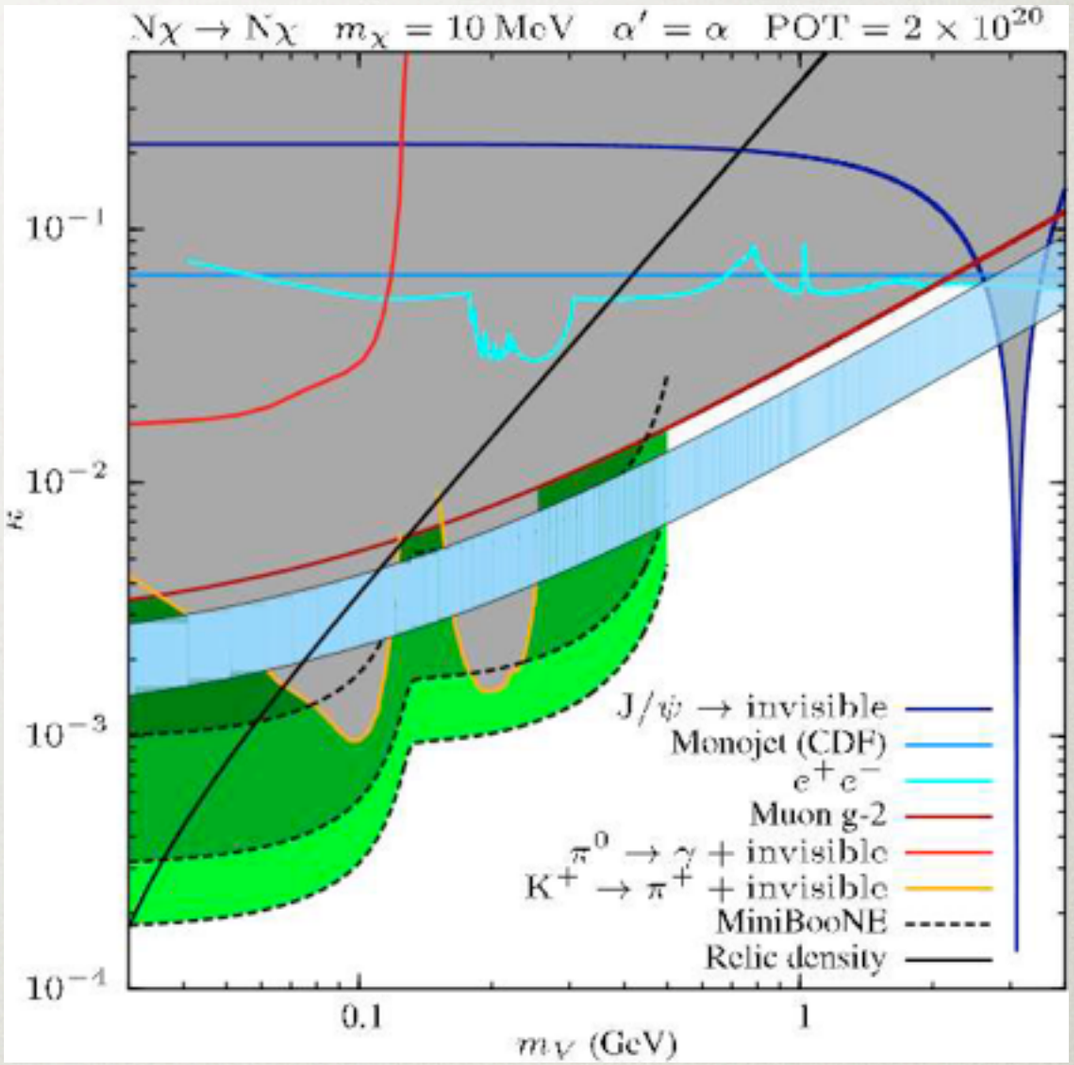


Conclusions

- 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
- Several mass ranges are testable in moderate-scale experiments
  - Rich program of LHC Searches
  - New-particle searches in B-factories – many results already, continuing to extend
  - Dedicated fixed-target experiments are extending range to much lower couplings
- A lot of uncharted territory: opportunities for further exploration – and discovery – abound!

Thanks!


0.001
0.01
0.1
1
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
α'/α
$m_{A'}$ (GeV)
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favored
a_e
VEPP3
KLOE
BaBar
APEX/MAMI
Test Runs
APEX
HPS
HPS
E774
DarkLight
E141
Orsay
U70


$N\chi \to N\chi$ $m_\chi = 10\,\mathrm{MeV}$ $\alpha' = \alpha$ $\mathrm{POT} = 2 \times 10^{20}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ϵ^2
0.1
1
m_V (GeV)
$J/\psi \to$ invisible
Monojet (CDF)
e^+e^-
Muon g-2
$\pi^0 \to \gamma +$ invisible
$K^+ \to \pi^+ +$ invisible
MiniBooNE
Relic density