Prospects for Low-Energy New Physics Searches

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Beyond the Standard Model

What do we actually know?

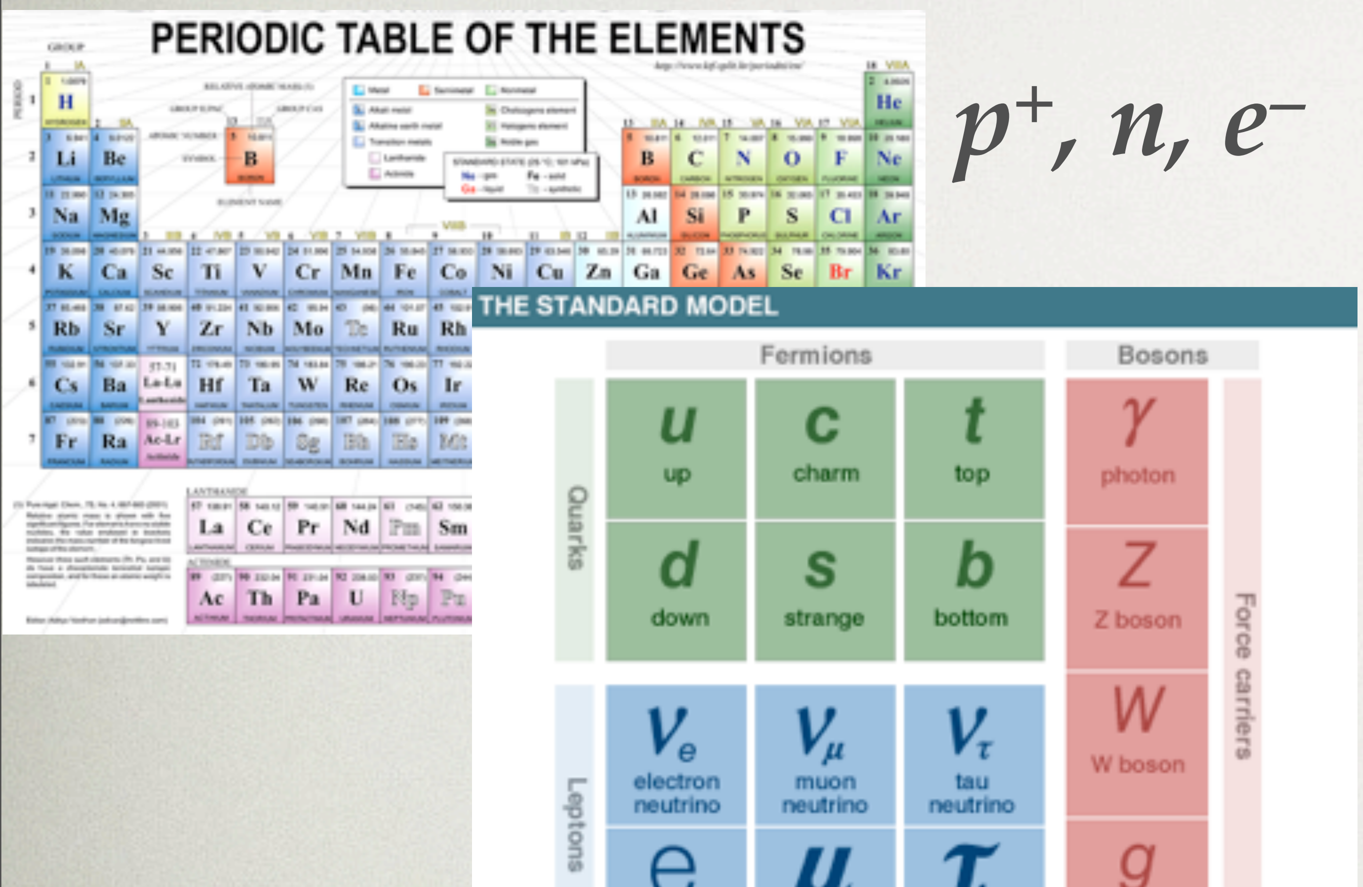
We know there is dark matter (a dark sector).

LHC and dark matter direct detection findings underscore the need to broaden the search for new physics!

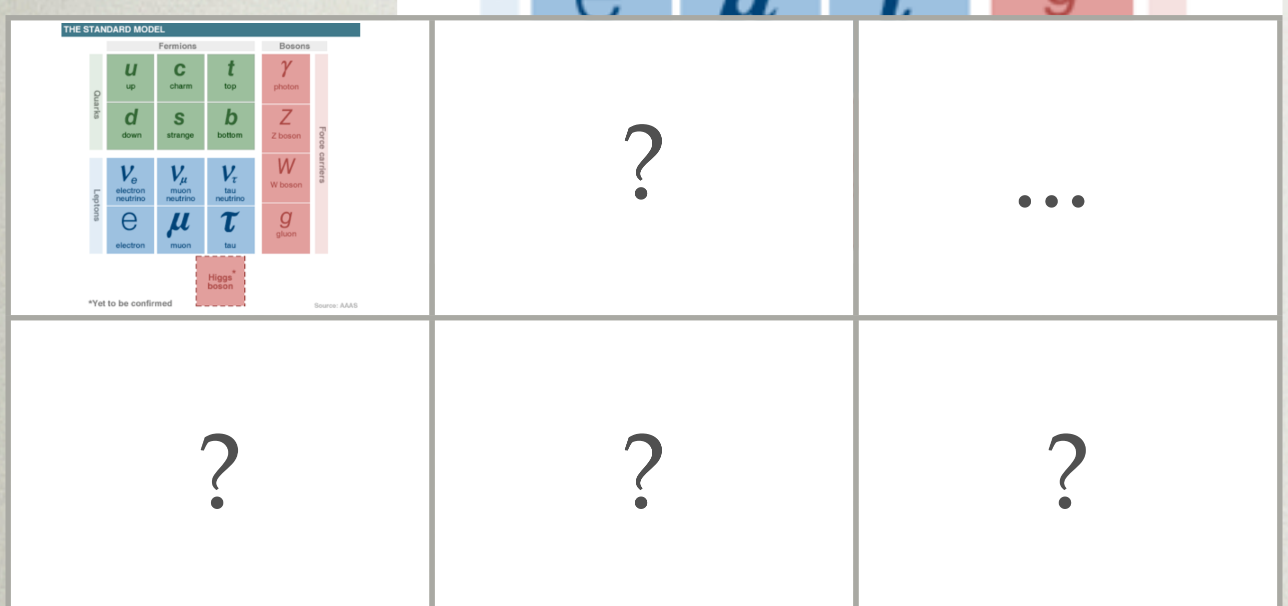
Connection between dark matter and "naturalness" is challenged by LHC results.

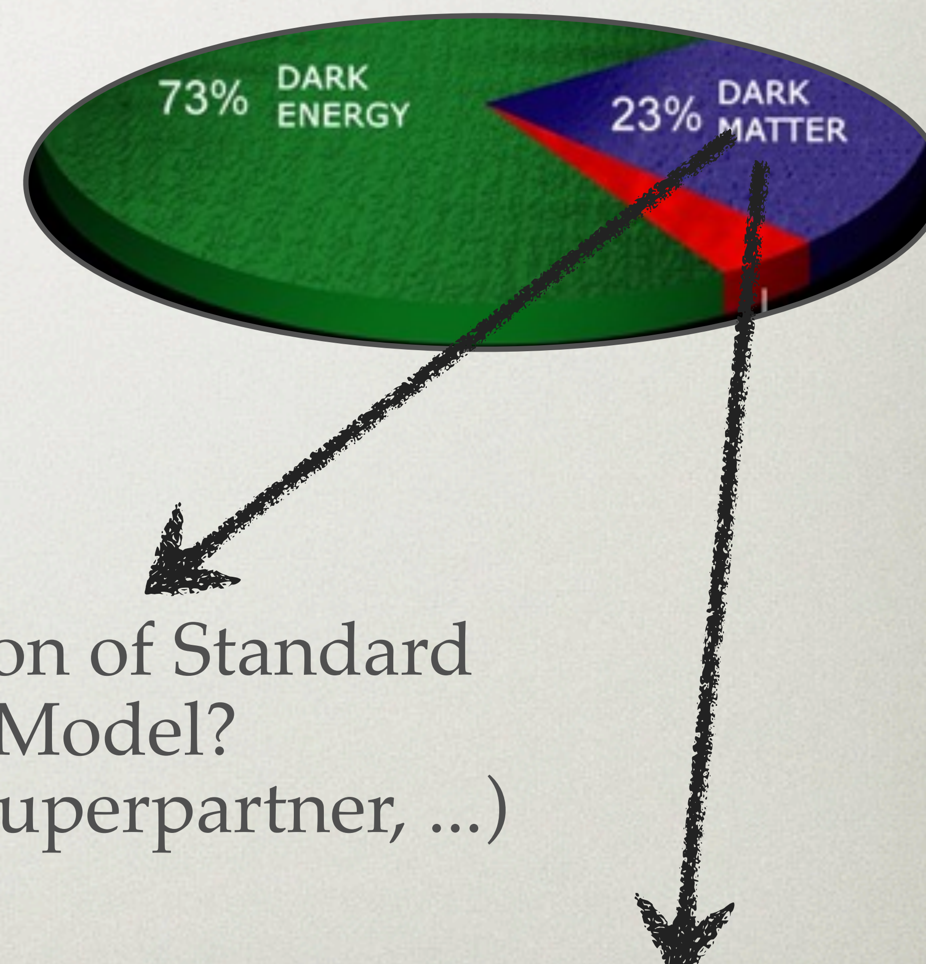
Copernican Particle Physics?

[thanks to Neal Weiner]



p^+, n, e^-





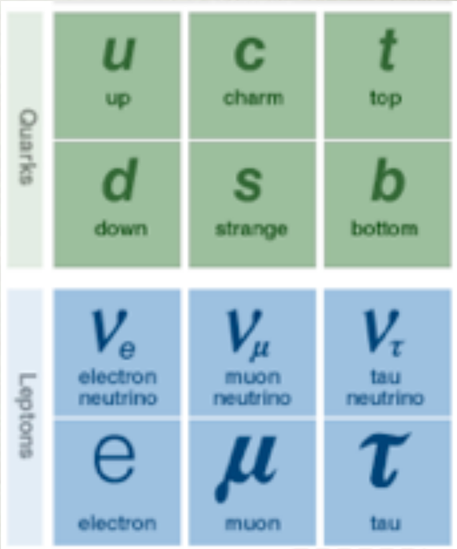
extension of Standard Model?
(axion, superpartner, ...)

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 largely looking for new matter – *but 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 $\epsilon_h \, |h|^2 |\phi|^2$ exotic rare Higgs decays?

Neutrino Portal $\epsilon_\nu \, (hL)\psi$ not-so-sterile neutrinos?

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

Axion Portal (axion-like particles – ALPs) $\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

(Focus of this talk)

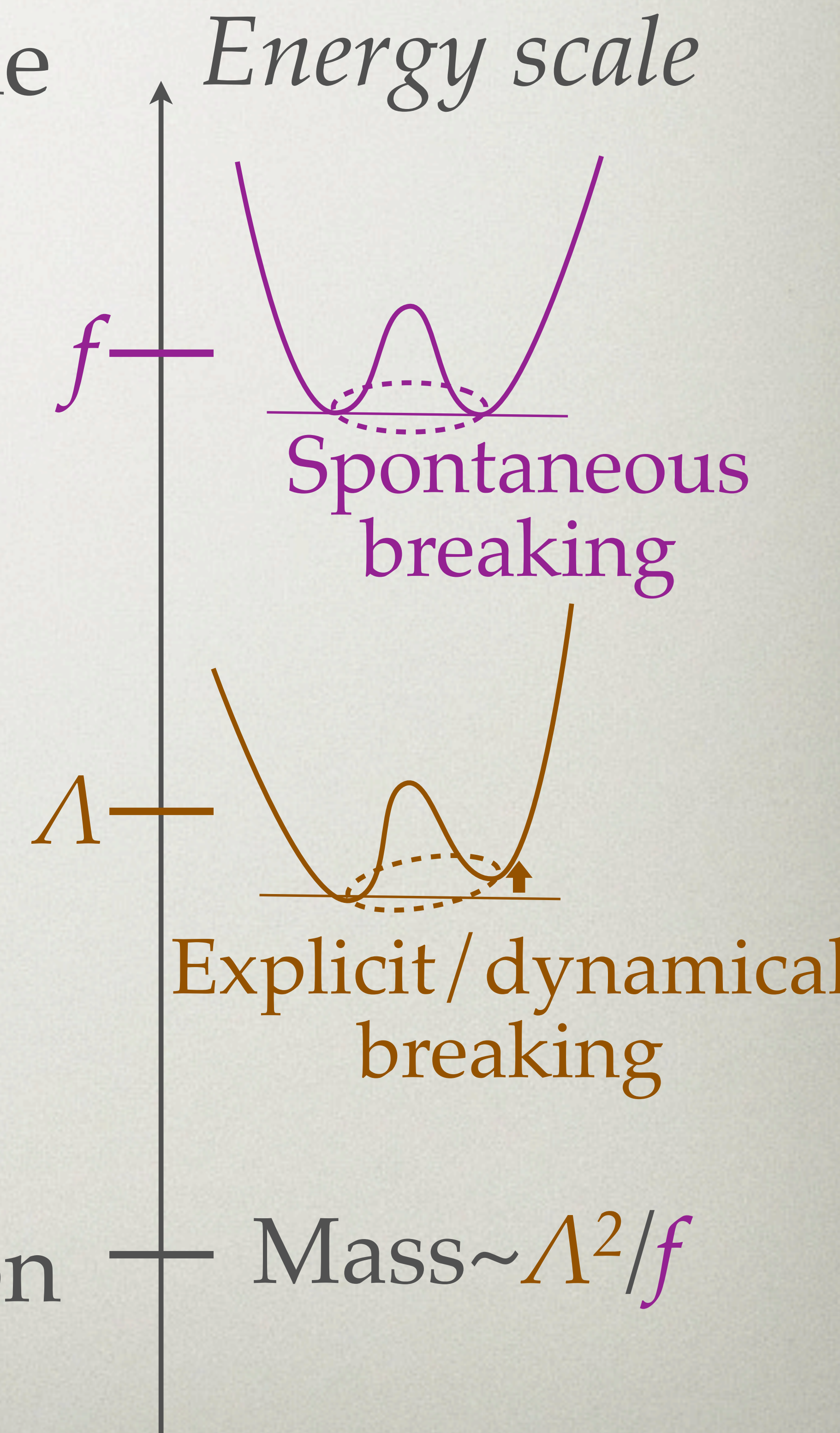
Sources Summarizing Broad Physics Program:

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

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

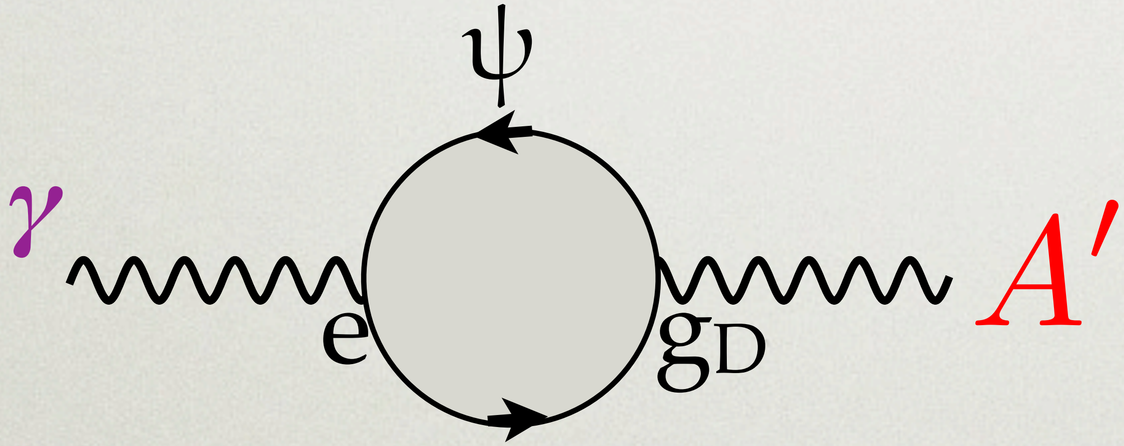
Axion-Like Particles

- A light pseudo-Nambu-Goldstone boson associated with ***spontaneous breaking*** of ***approximate*** global symmetry
  - Mass $\Lambda^2/f \Rightarrow$ can be very light
  - Very weak couplings $\sim 1/f$
- Can couple to gauge bosons without coupling to quarks
- QCD axions (a special case) can explain why CP-violation in strong interactions [e.g. in neutron edm] is small



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

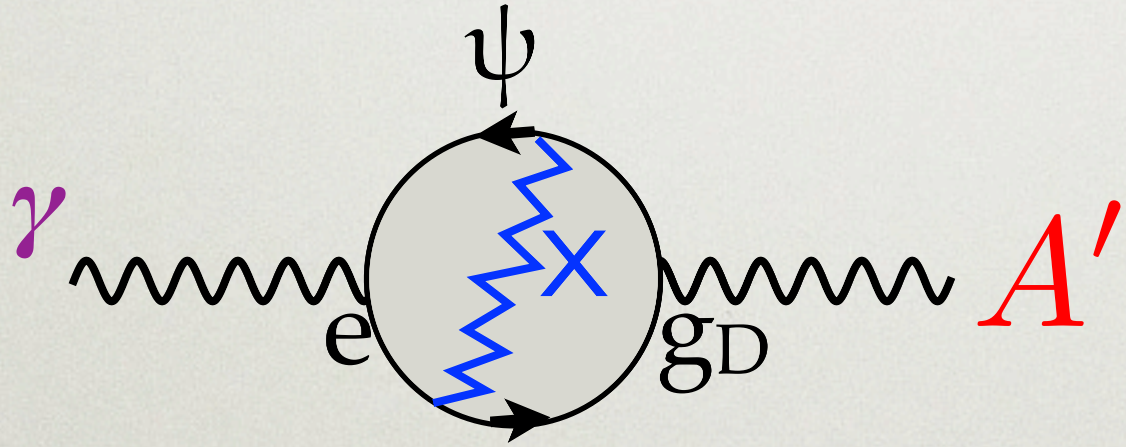
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



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

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

a motivated target of opportunity

Potential Implications

- Connection to long-standing problems
  - Dark Matter
  - Strong CP Problem

- Indirect probe of **very** high-energy physics

Dark Forces Below the Weak Scale

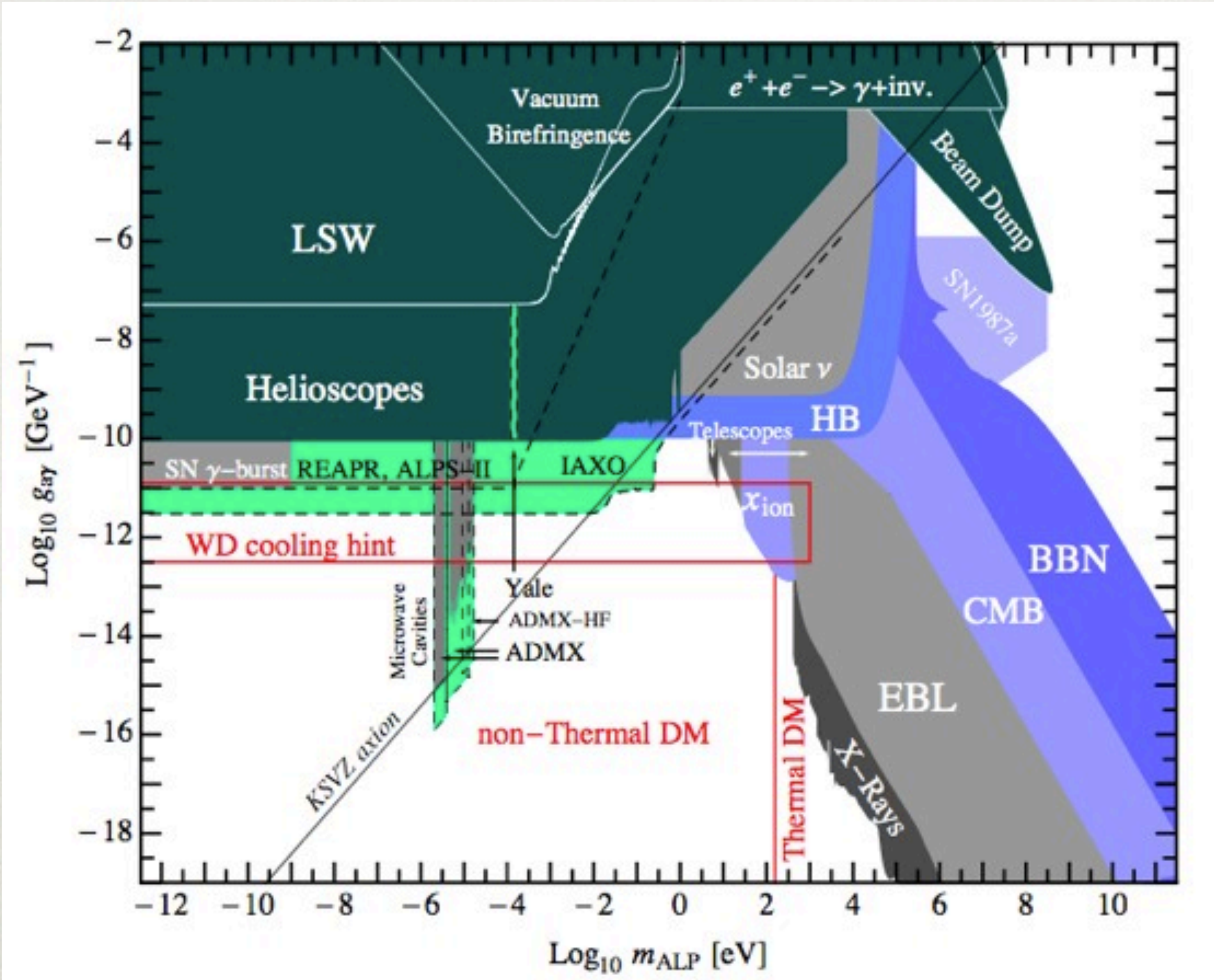
Motivation and Outlook

- Why look for dark forces?
- What can they teach us?

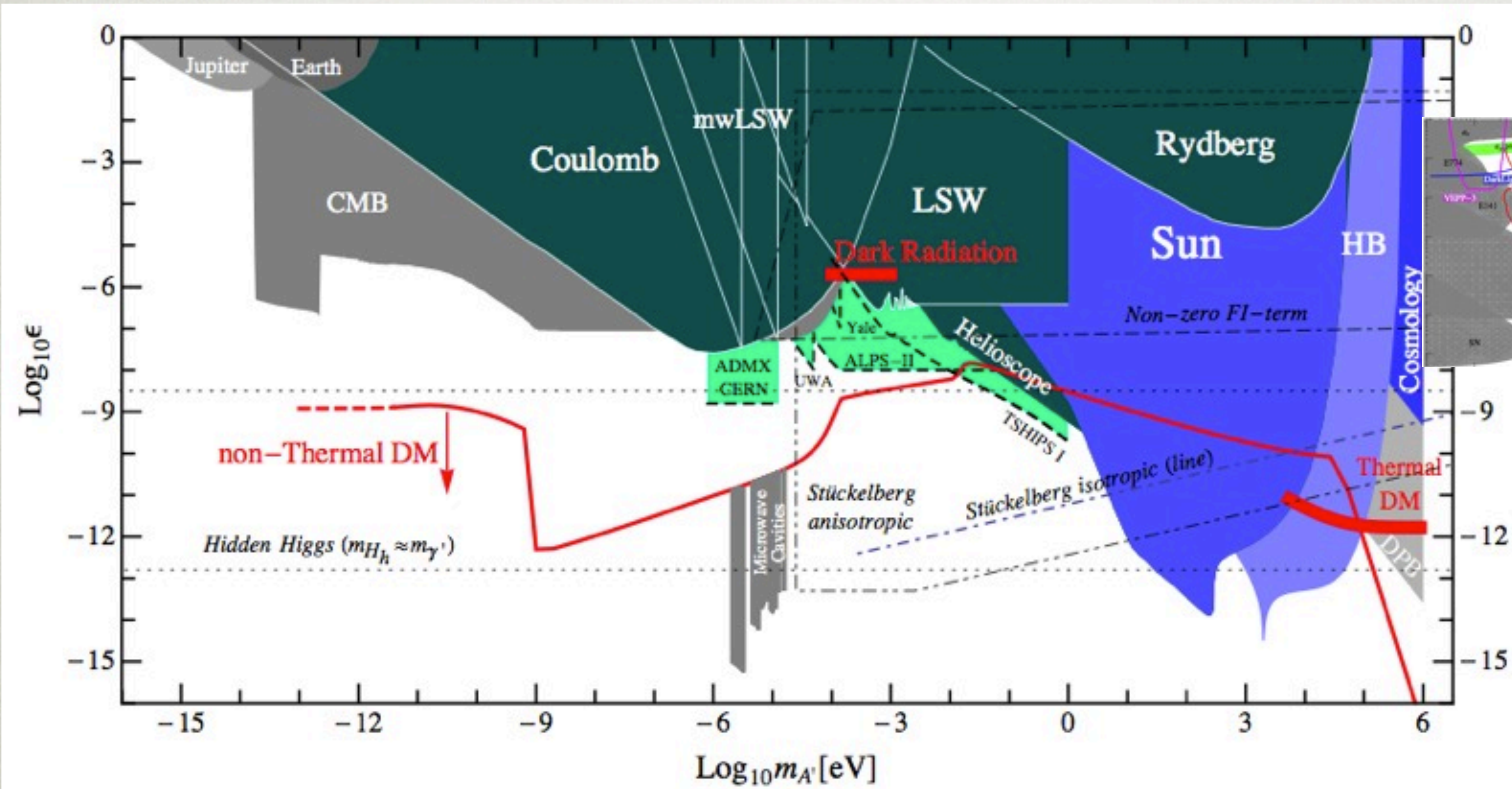
Three Experimental Windows

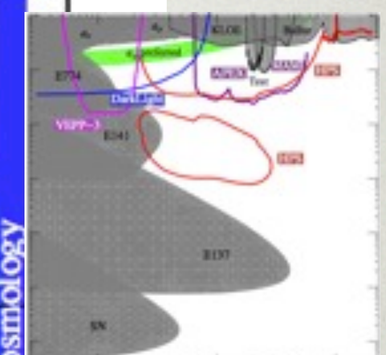
- Macroscopic
- AMO-Range
- Nuclear-Range (main focus of this talk)

Wide Parameter Space: axion-like particles

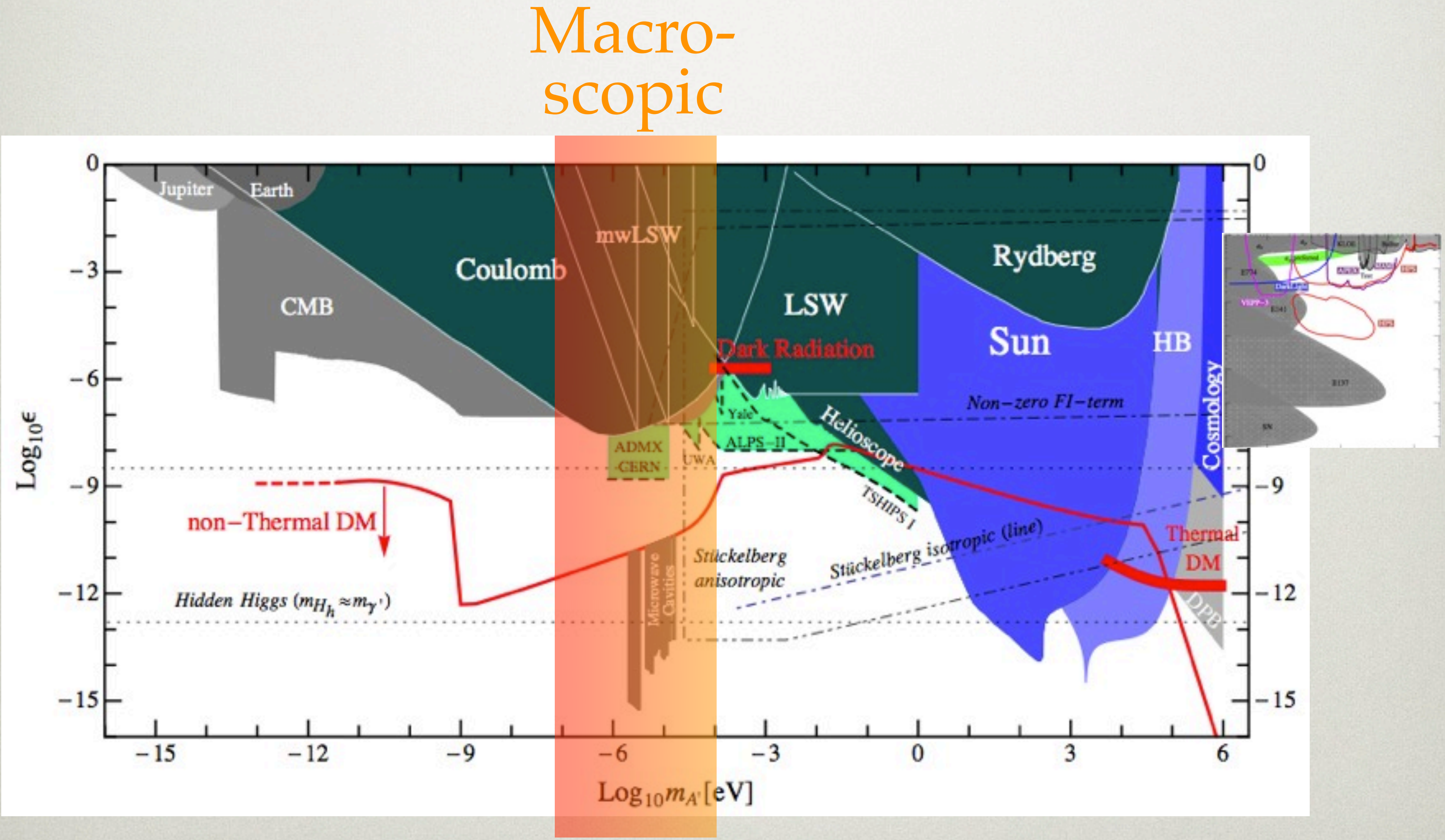


Wide Parameter Space: Hidden Vectors





Wide Parameter Space: Hidden Vectors

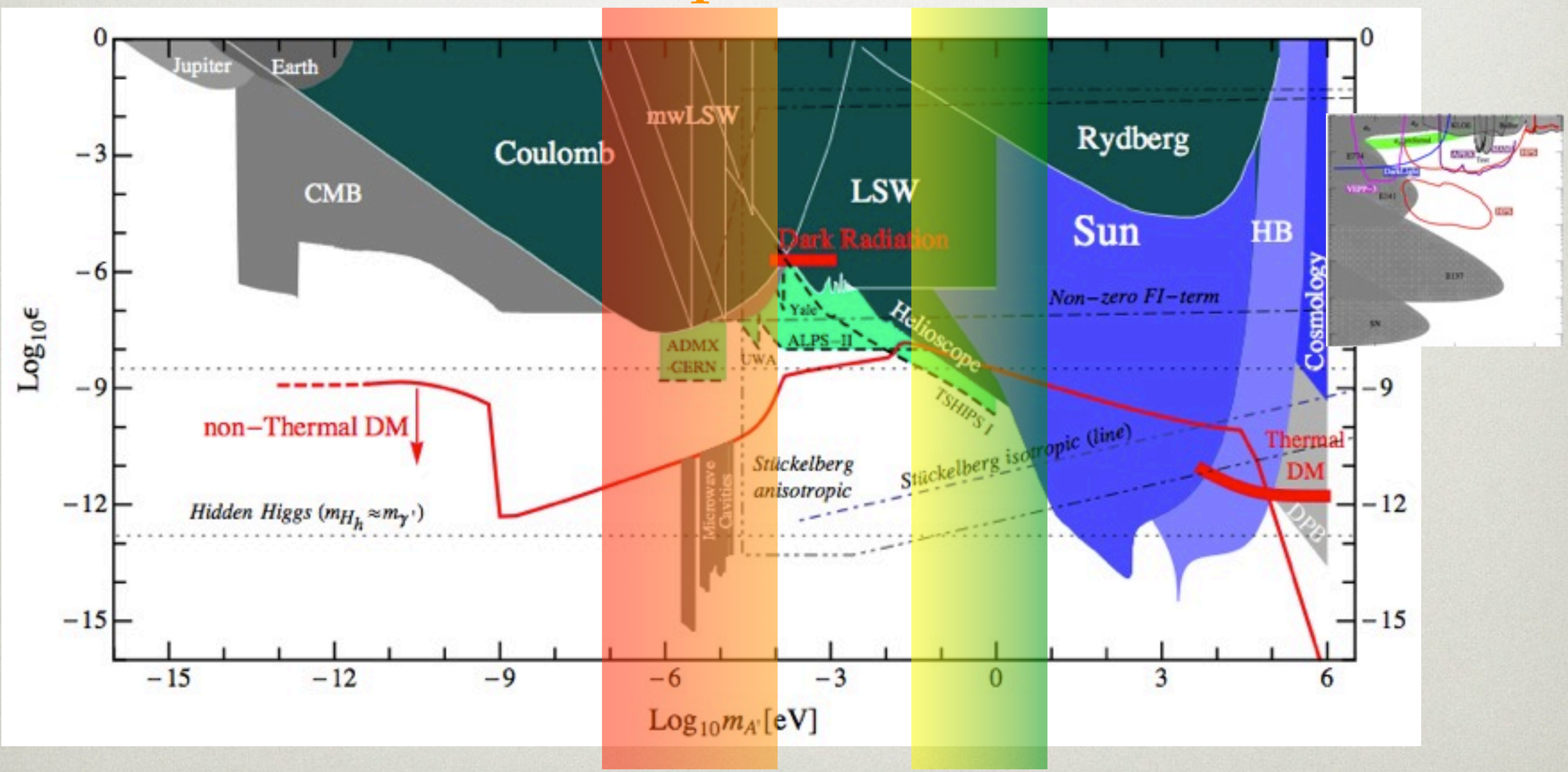


new forces

Wide Parameter Space: Hidden Vectors

Macro-
scopic

AMO
scale

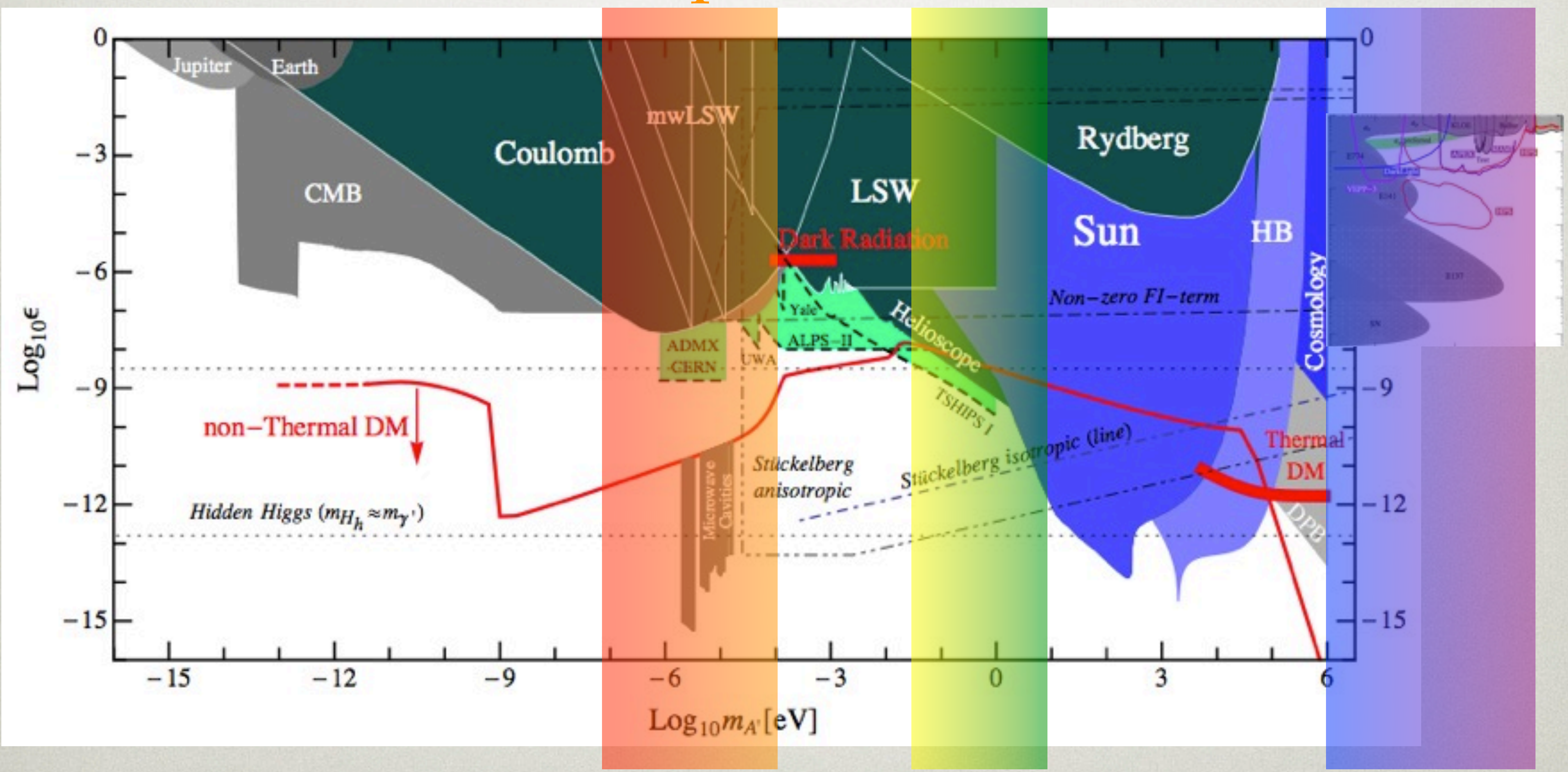


new forces

light

Wide Parameter Space: Hidden Vectors

Macro-scopic | AMO scale | Nuclear scale



new forces | *light* | *new particles*

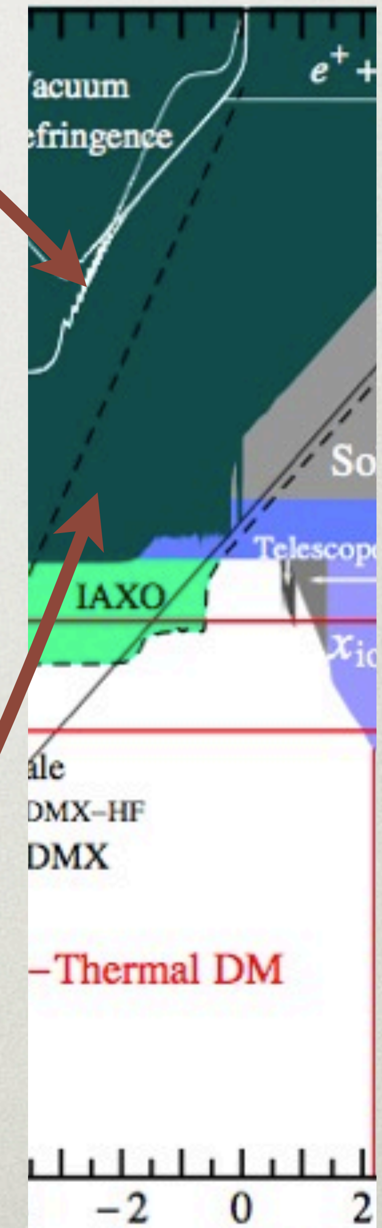
AMO-Range Dark Forces

Hidden Vector

Axion-Like

Light Shining Through Walls

[PVLAS,ALPS,LIPPS,ALPS-II,REAPR...]



Helioscopes

[CAST, IAXO]

Interactions with Photons

Hidden Vectors: $\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$

Mixed kinetic term ⇒ virtual photon can turn into hidden-vector, and vice versa

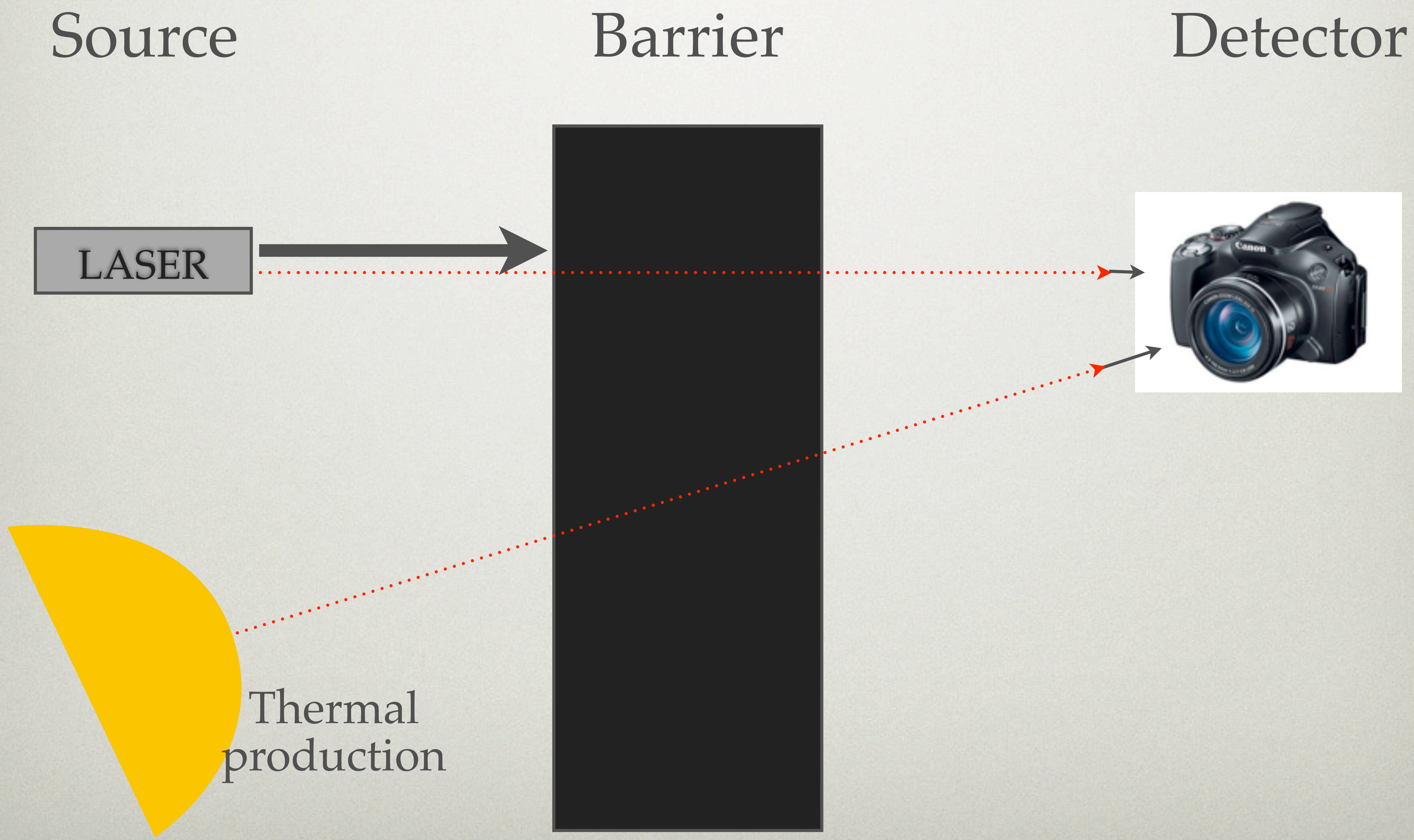
A source of sufficiently energetic EM waves will also be a (weak) source of hidden-vectors

Axion-Like: $\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{1}{f_a} a \vec{E}.\vec{B}$

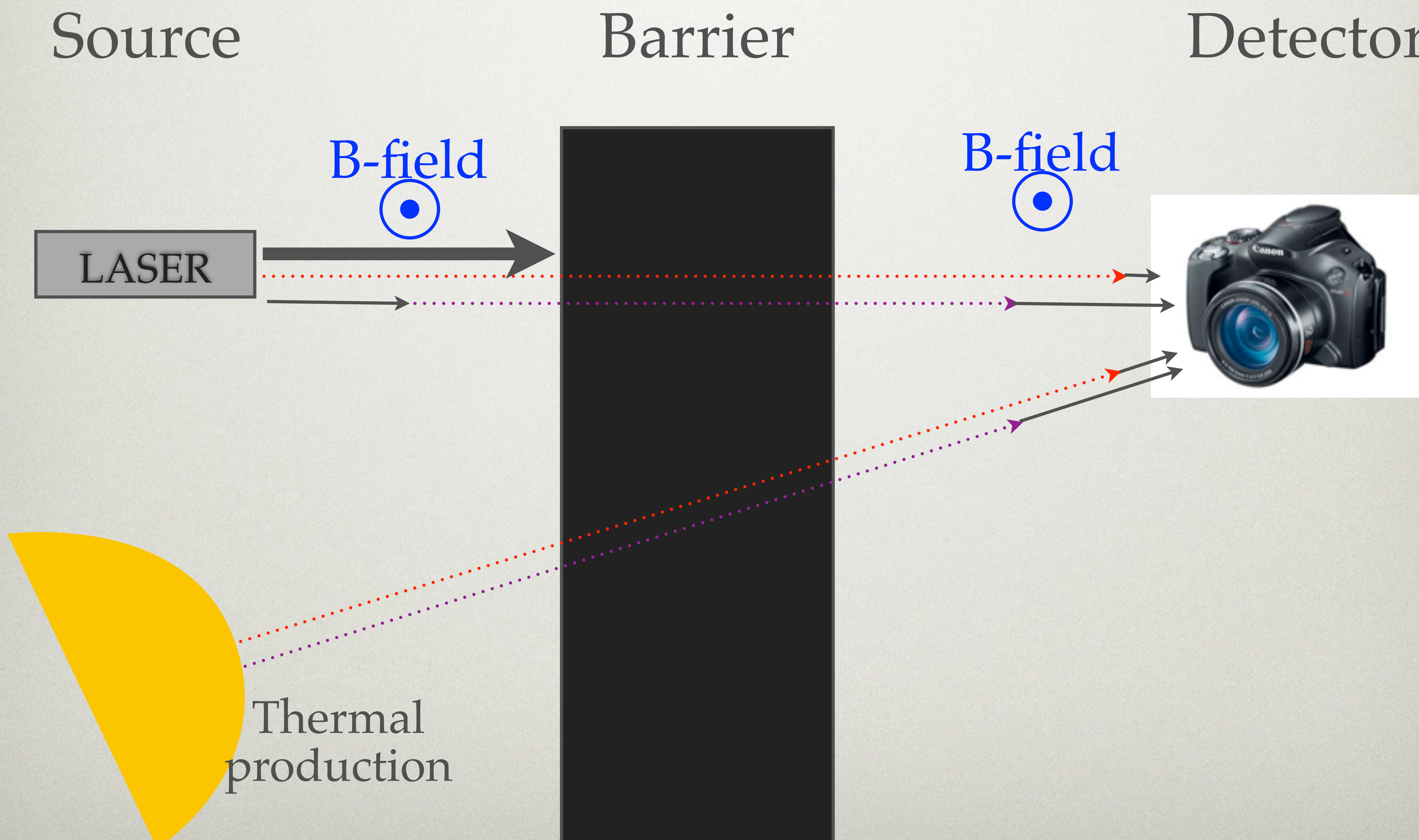
In presence of a background *B*-field, *a* mixes with photons

Mixed propagators are **massive** ⇒ finite-range forces

AMO-Range Dark Forces

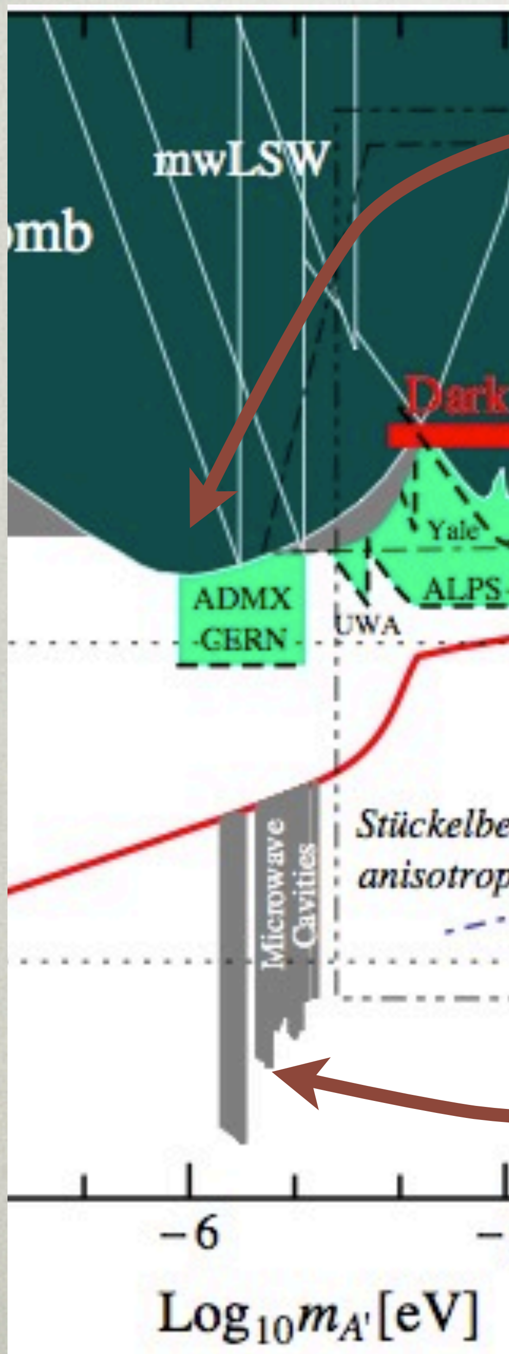


AMO-Range Dark Forces



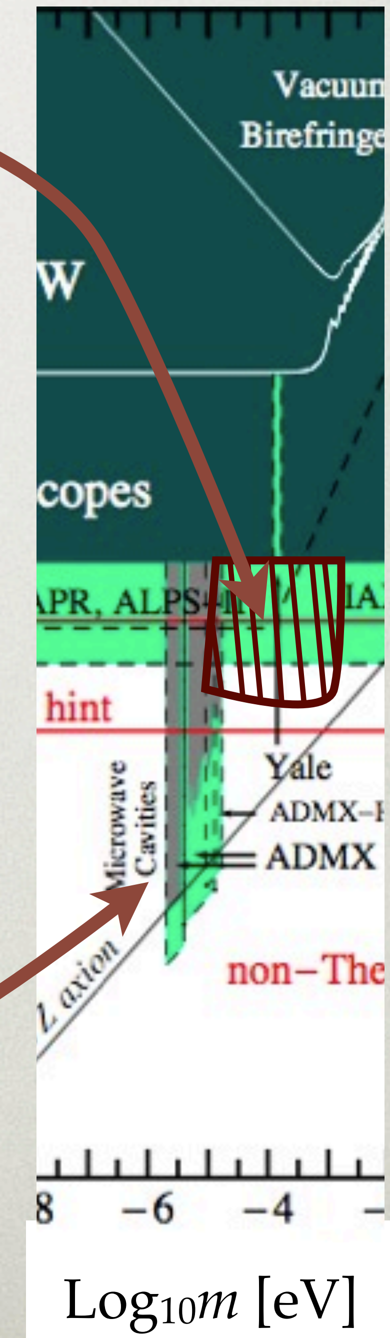
Macroscopic Dark Forces

Hidden Vector



m mm

Axion-Like



Eöt-Wash

New-Force Searches

Hidden vector:
Coulomb's law

Axion-like:
probes independent coupling to matter
[e.g. Eöt-Wash]

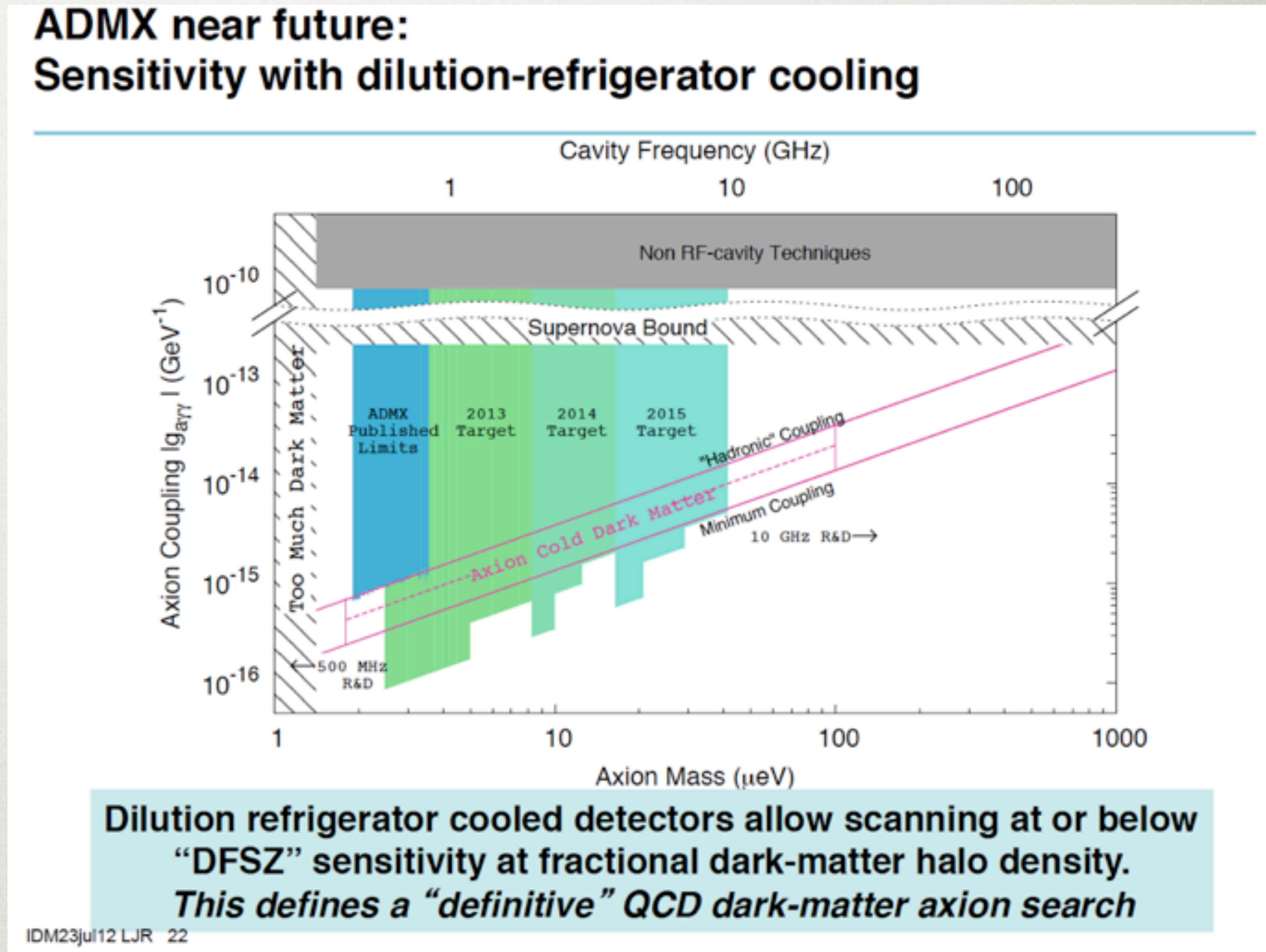
Microwave Cavities
[e.g. ADMX]

Microwave Resonant Cavities

Exploit Dark Matter axion density:

Static *B*-field in a cavity of resonant frequency $\omega \approx m_a$ converts dark matter axions into microwaves.

[ADMX: Asztalos et al, 2010]



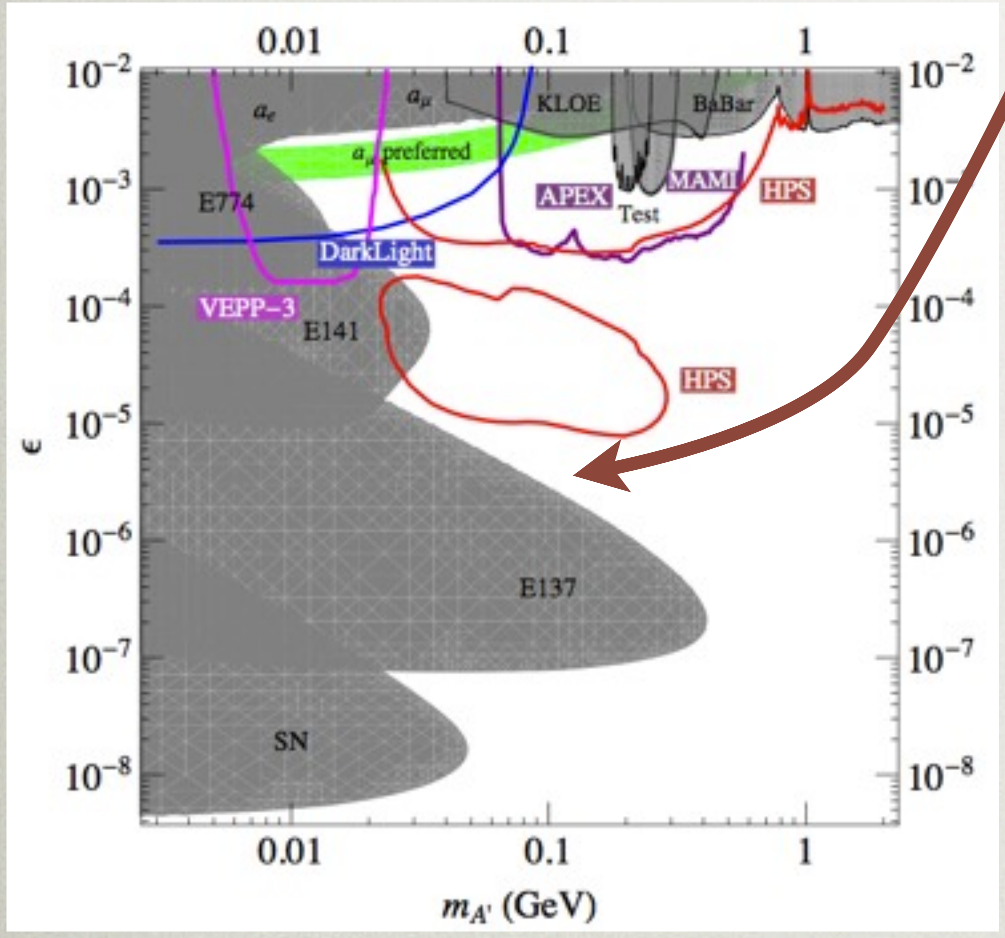
Two-cavity searches (emitter & detector) sensitive to hidden photons with mixing $\varepsilon \gtrsim 10^{-8}$

[ADMX: Wagner et al, 2010]

Nuclear-Range Dark Forces

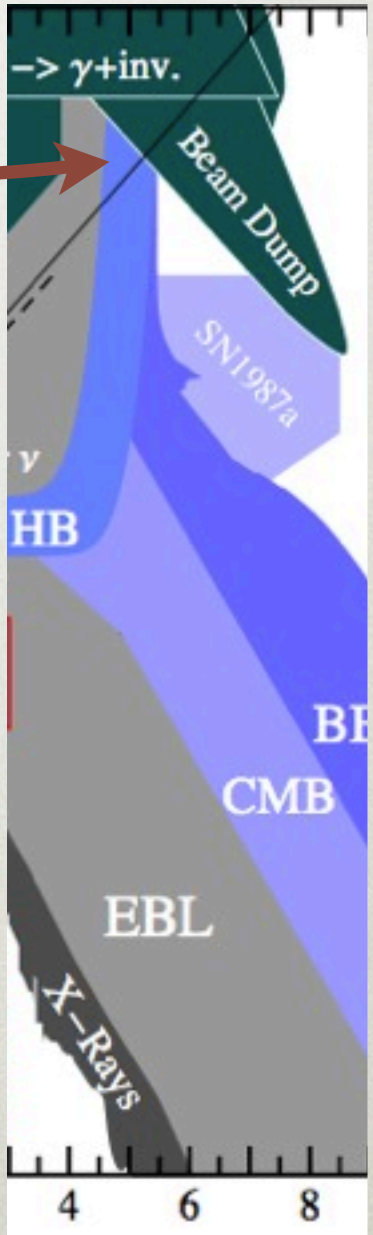
Hidden Vector

Axion-Like



New-Particle Searches

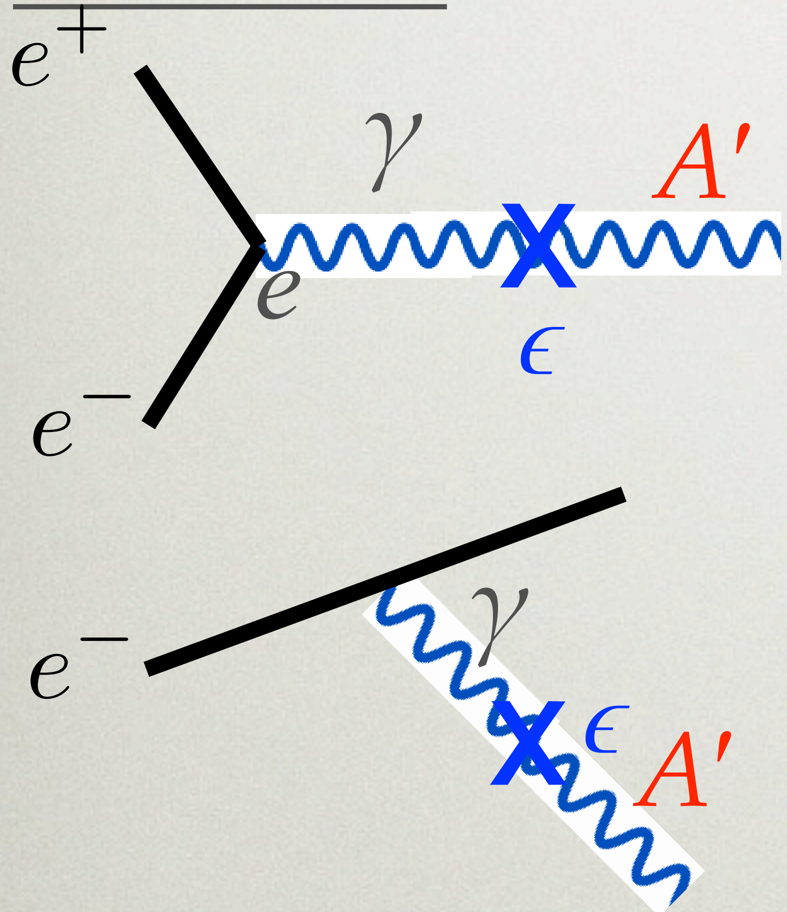
[MAMI, APEX, HPS, DarkLight]



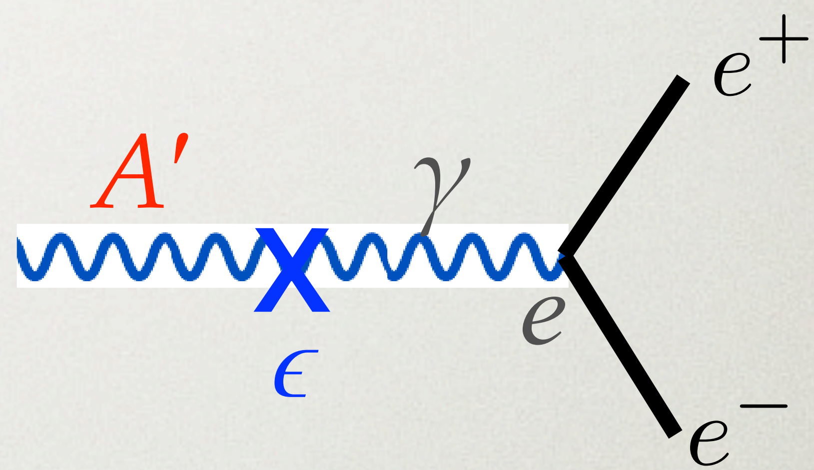
Kinetic Mixing
for MeV-GeV Hidden Vectors

$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$ leads to processes:

Production

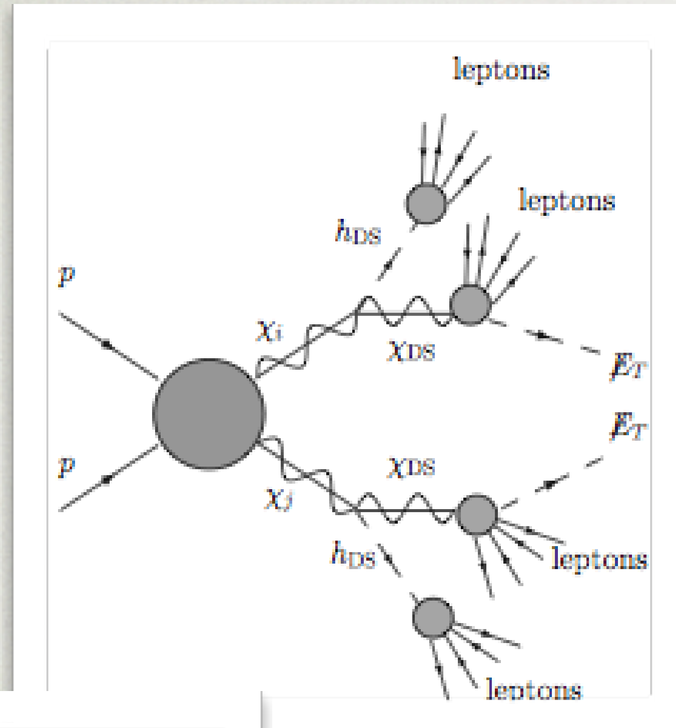


Decay



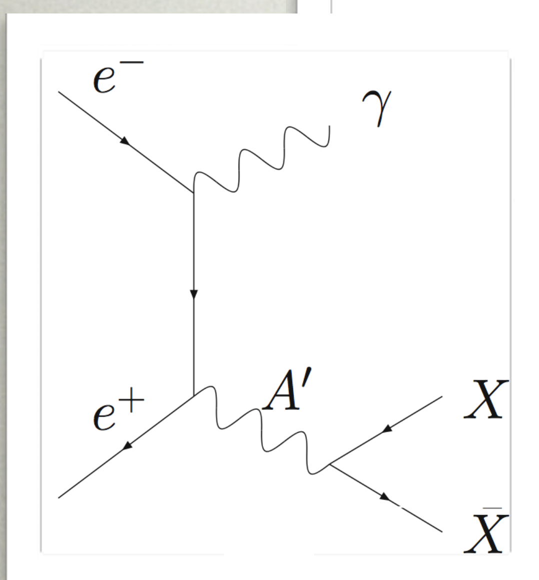
Particles of EM charge q get ***effective*** *U(1)′* charge $\boldsymbol{\epsilon q}$

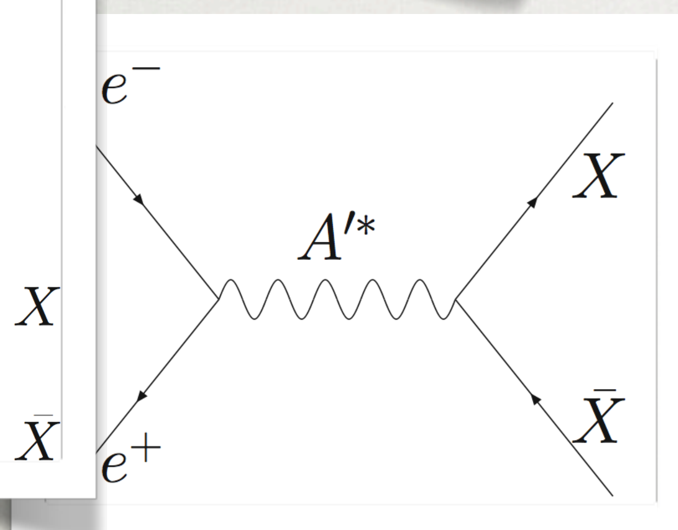
Broad Array of Searches! (done, ongoing, planned)



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

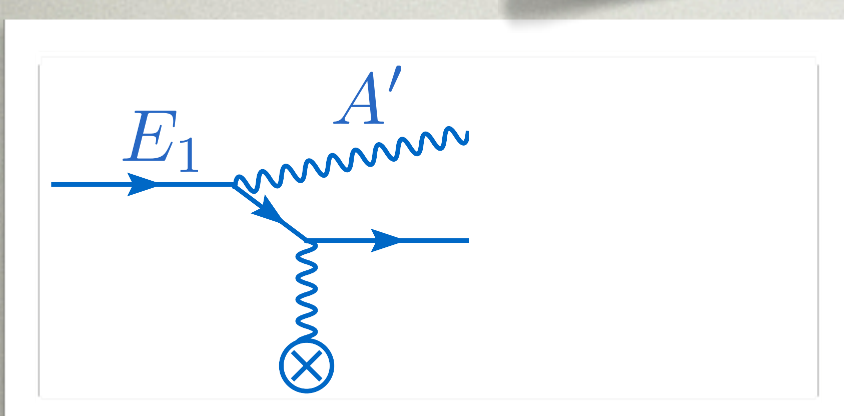
(ATLAS, CMS, CDF & D0)





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 ...)

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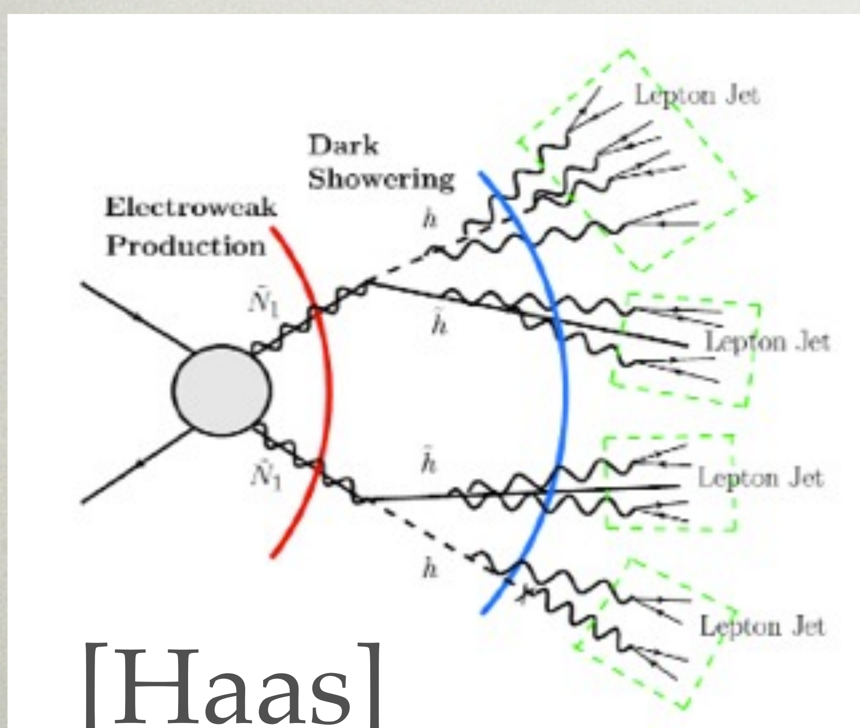
"Lepton Jets" from Heavy Photons

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]

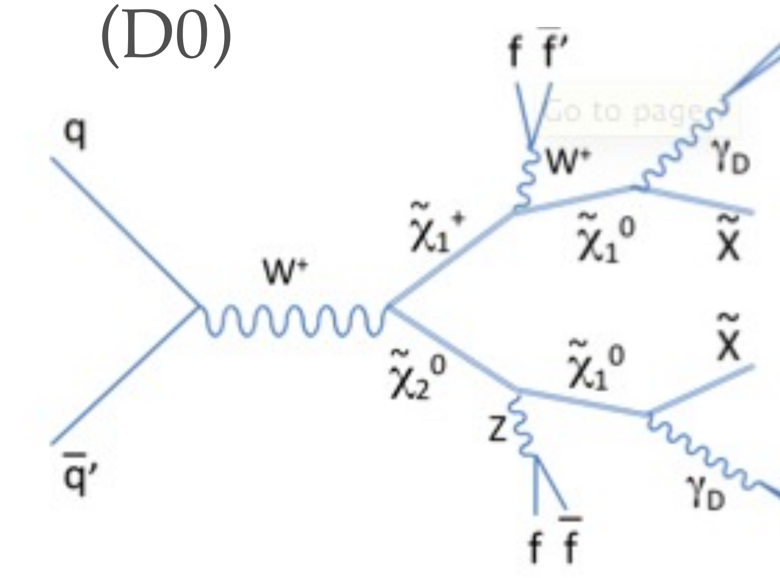
Large boost ⇒ highly collimated decay products "lepton jets"

A Sampling of Tevatron and LHC Results

Search for dark photons from supersymmetric hidden valleys [0905.1478]

Search for events with leptonic jets and missing transverse energy in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [1008.3356]

(D0)



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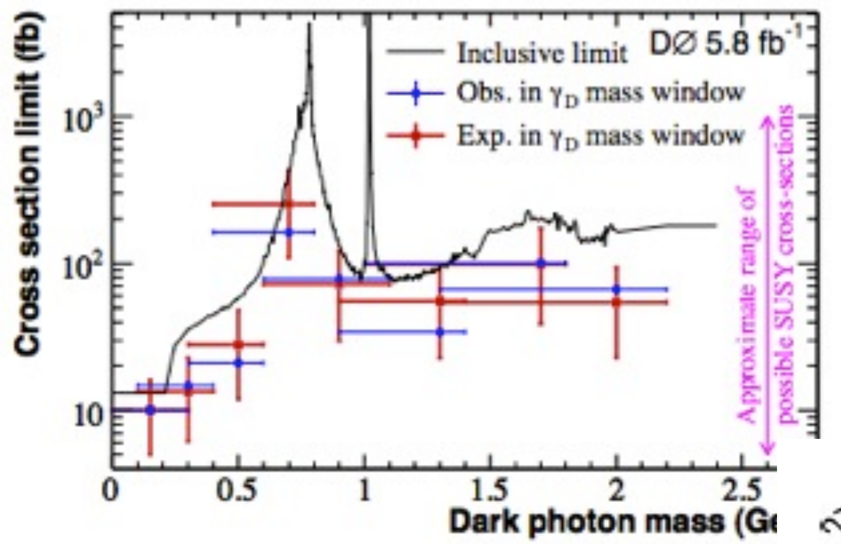
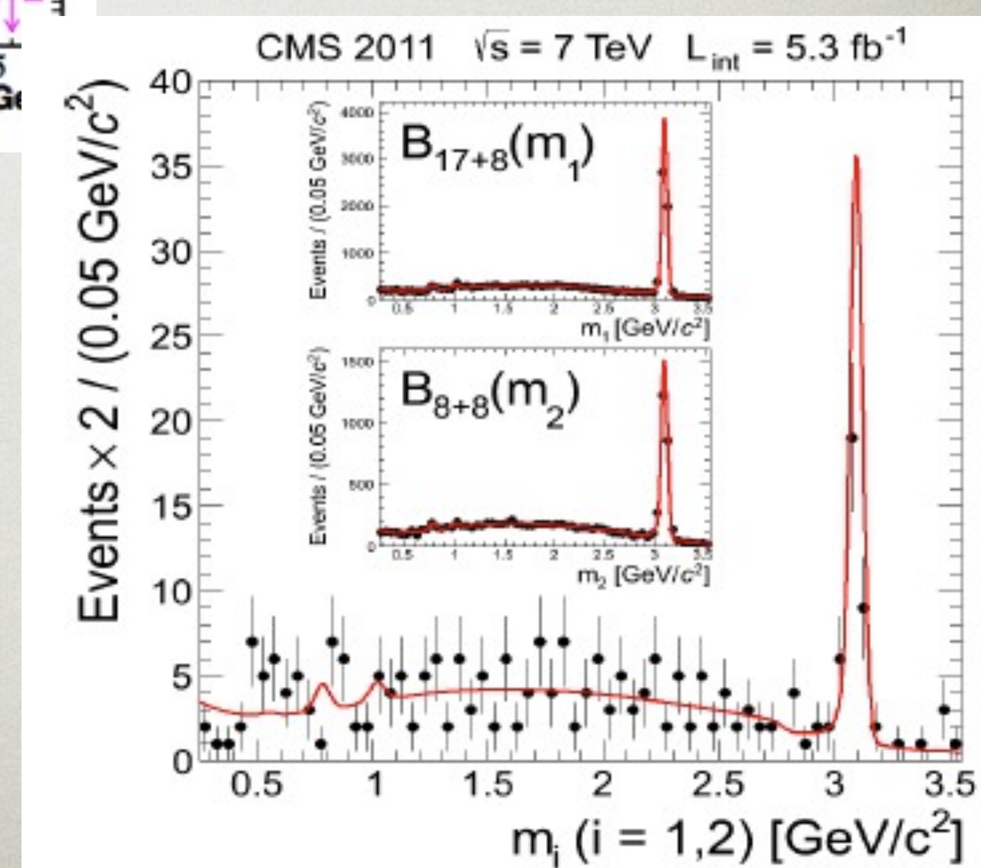
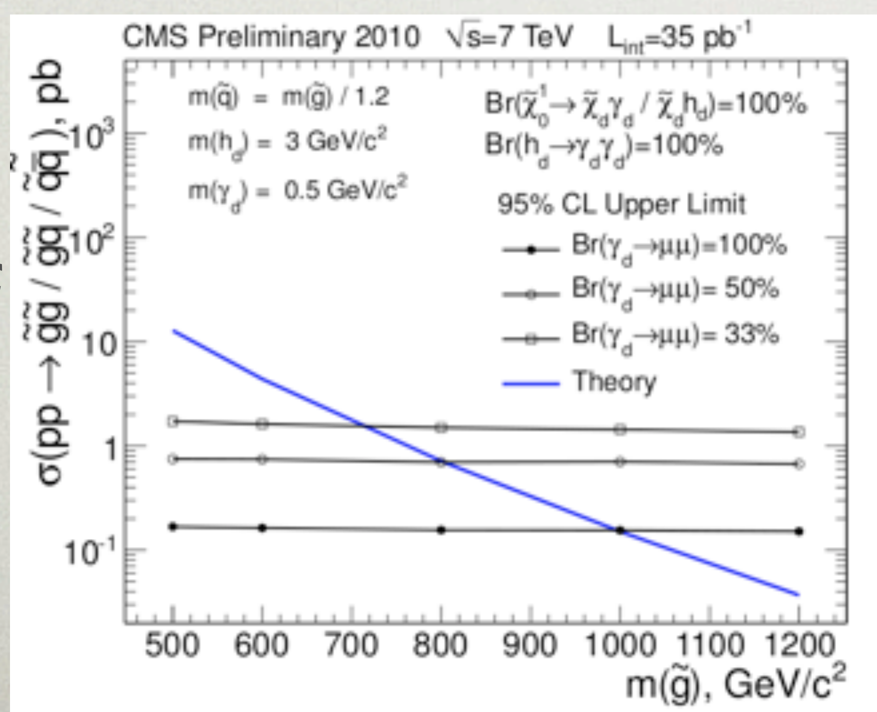


“Higgs to muon lepton Jets” (CMS EXO-12-012)

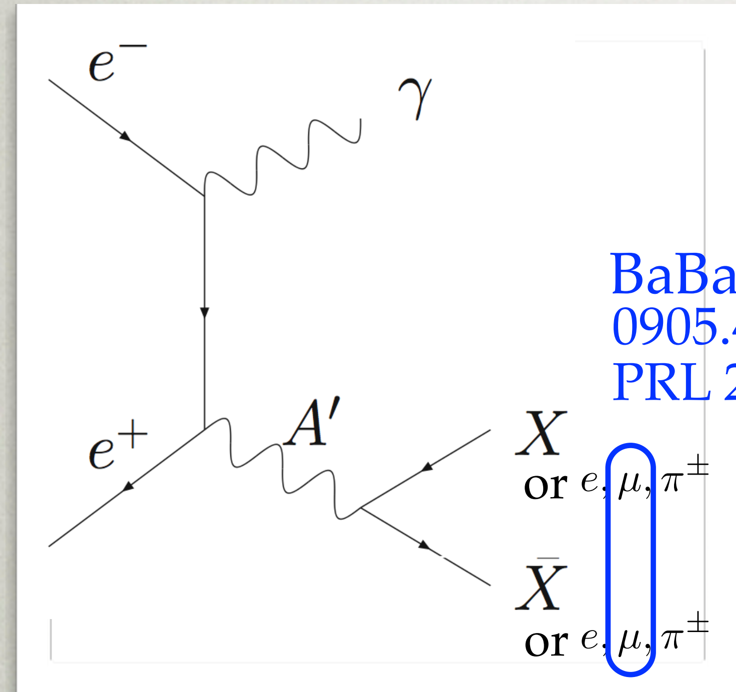


“Search for Resonant Production of Lepton Jets” (CMS EXO-11-013)



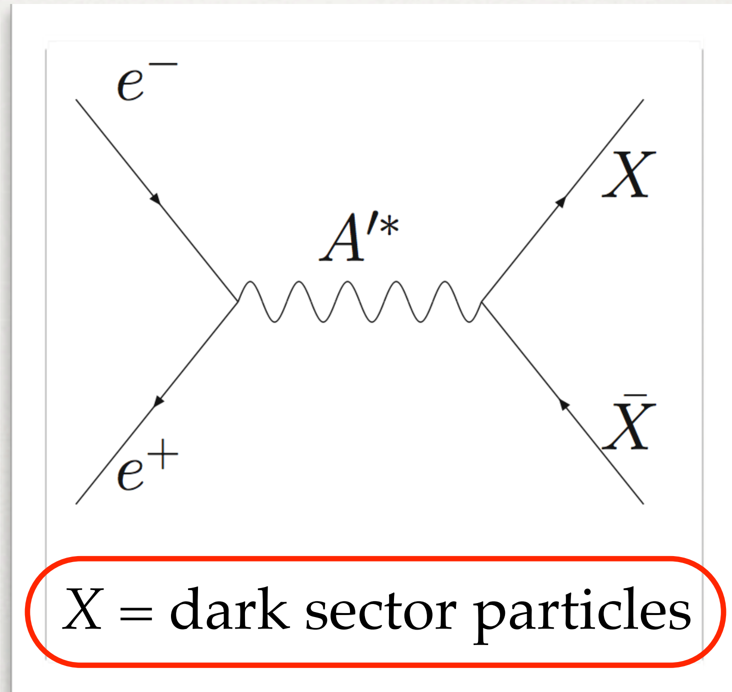
Collider Production

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)	$\mathrm{BR}(X \to Y + \gamma)$	$\mathrm{BR}(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	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}

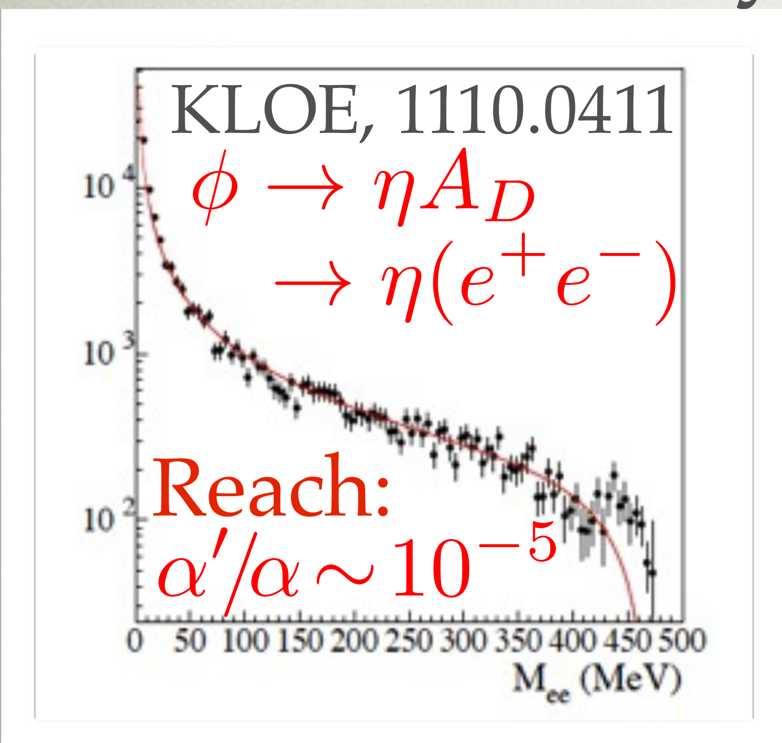
[Reece and Wang 2009]

KLOE
PLB706 (2012) 251-255

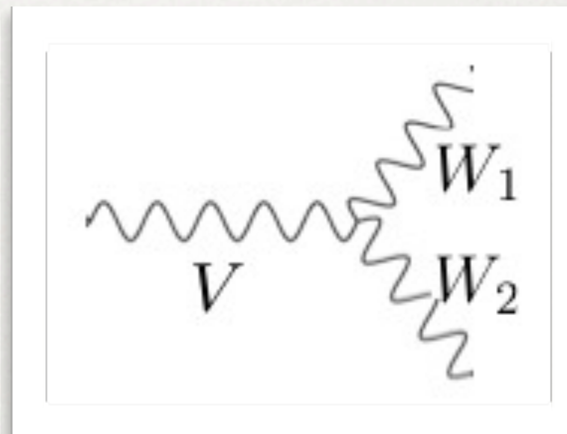
Wide Breadth of Searches

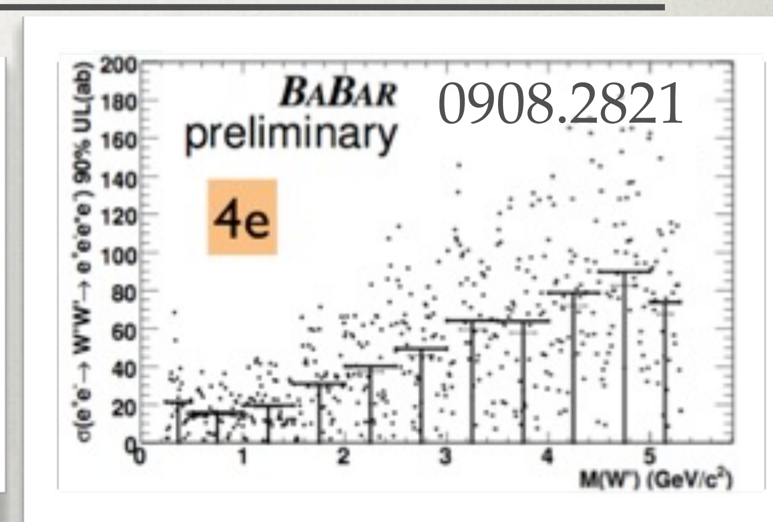
(just a few representative examples)

Minimal Decay

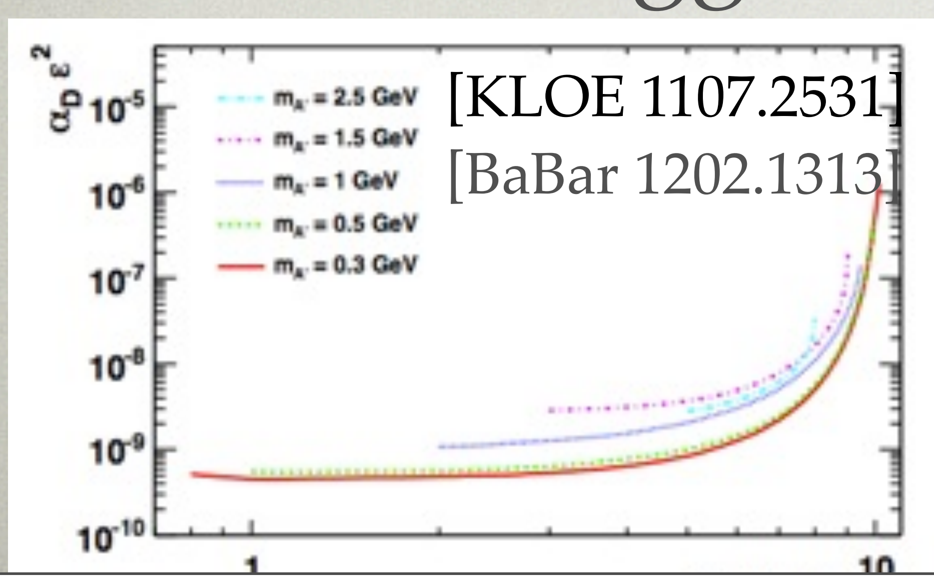


Non-Abelian Dark Sector

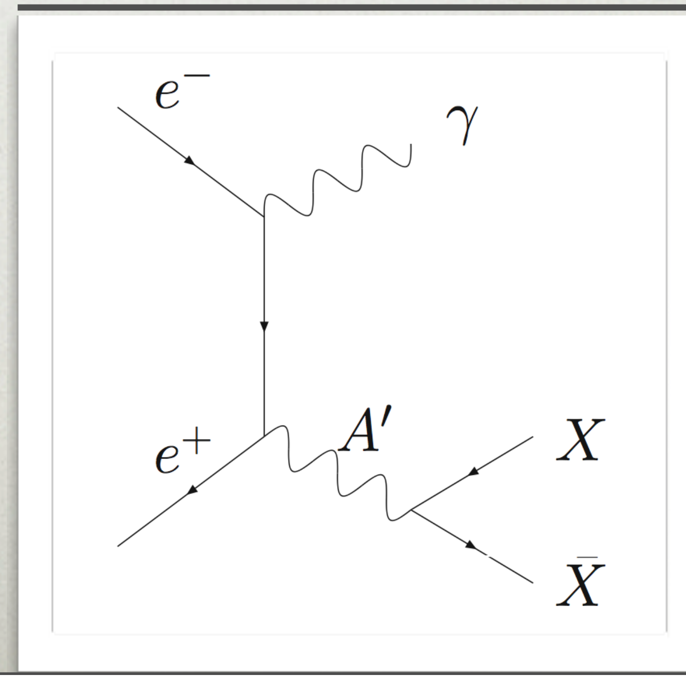




Vector + Higgs:



Invisible Decay



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

Flavor Factory Advantages

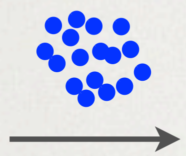
- Highest collider $(Lumi.)/(E_{CM})^2$ in the world
- 4π detectors, clean reconstruction, less boosted
- Large dataset "in the bank"
  - Many searches can use standard triggers
  - **Extremely broad** search program ongoing; can be even more extensive

Fixed-Target Advantages

	Fixed-Target	e^+e^-

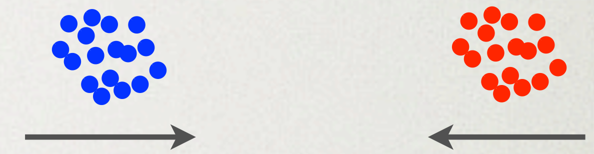
Luminosity

Fixed-Target: 10^{11} e^-



$\sim 10^{23}$ atoms in target

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



N(hard scatter) ~ 0.01 – 1 *per electron*

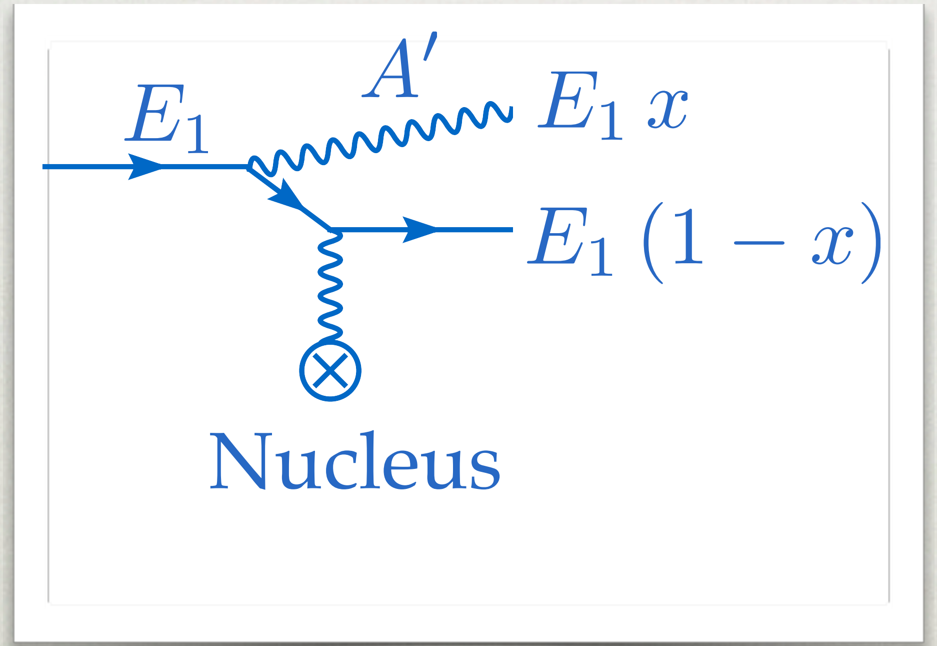
$\mathrm{O(few)}\ ab^{-1}$ per day

N(hard scatter) ~ 1 *per crossing*

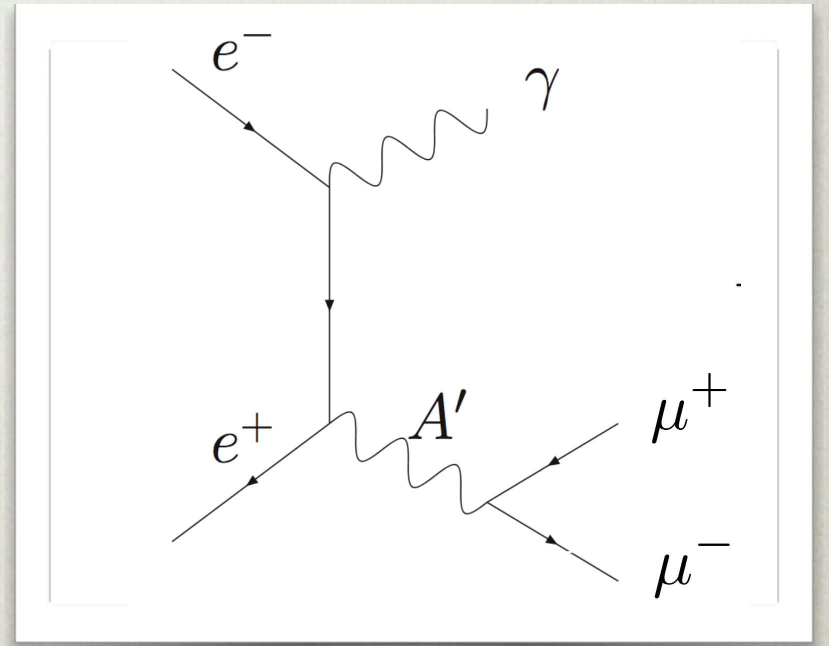
$\mathrm{O(few)}\ ab^{-1}$ per decade

Cross-Section

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



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



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

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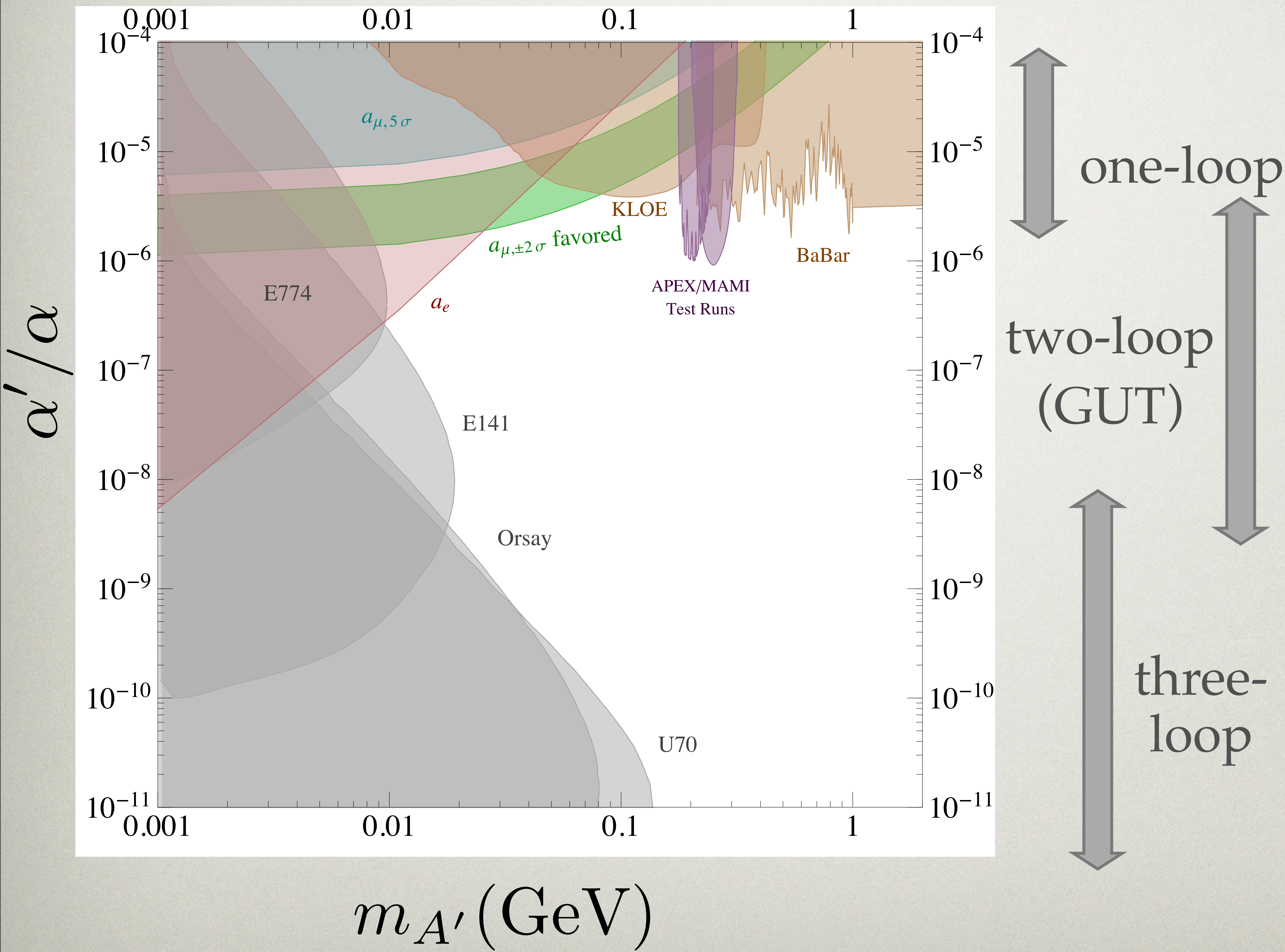
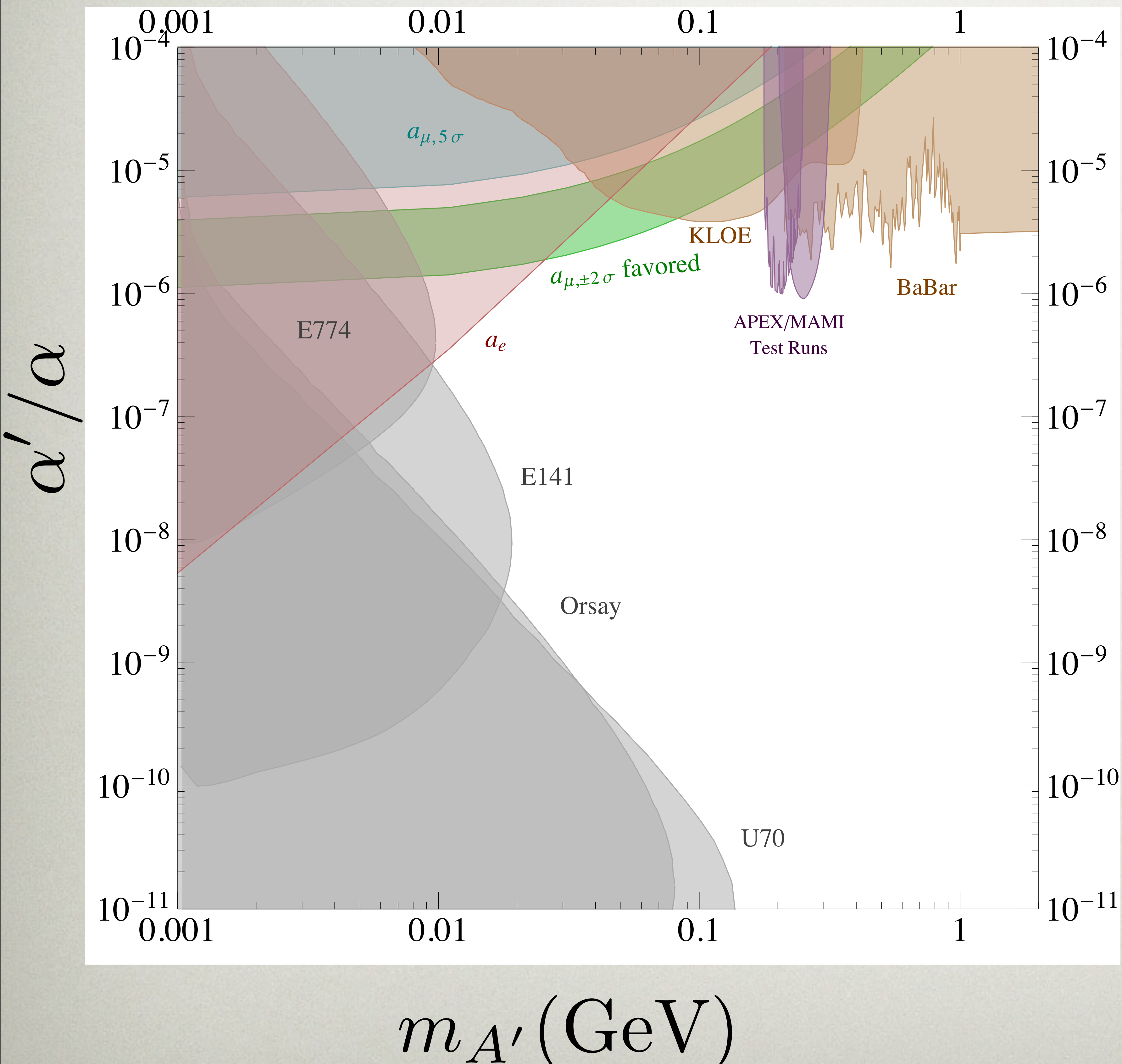
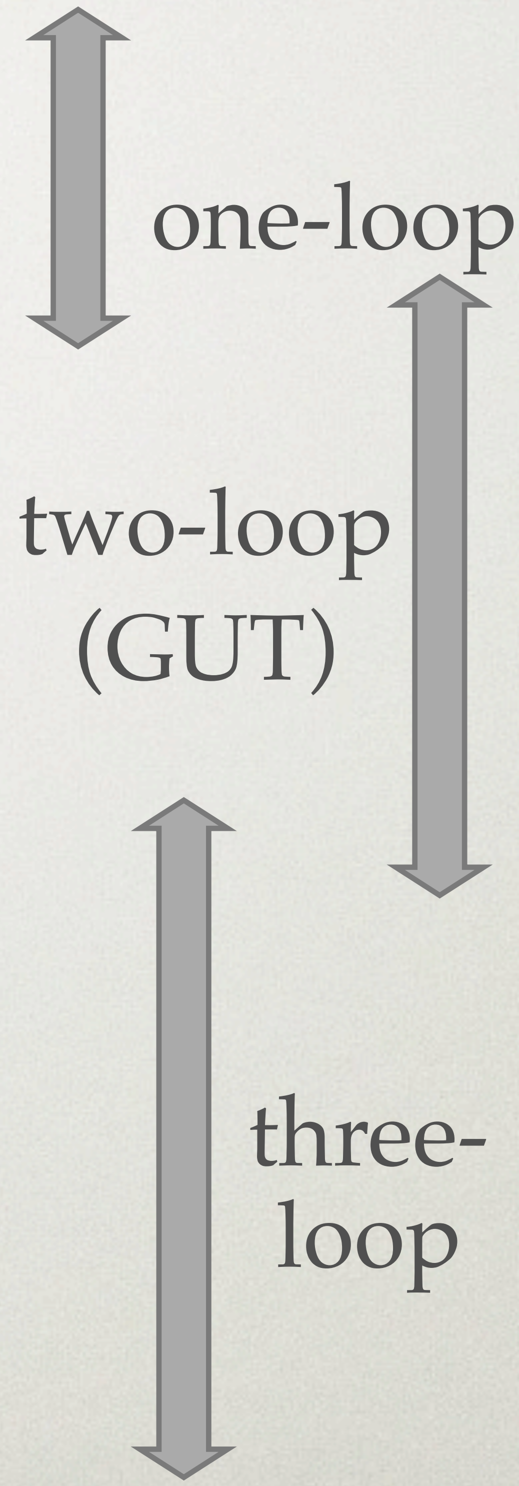
Fixed-Target Territory



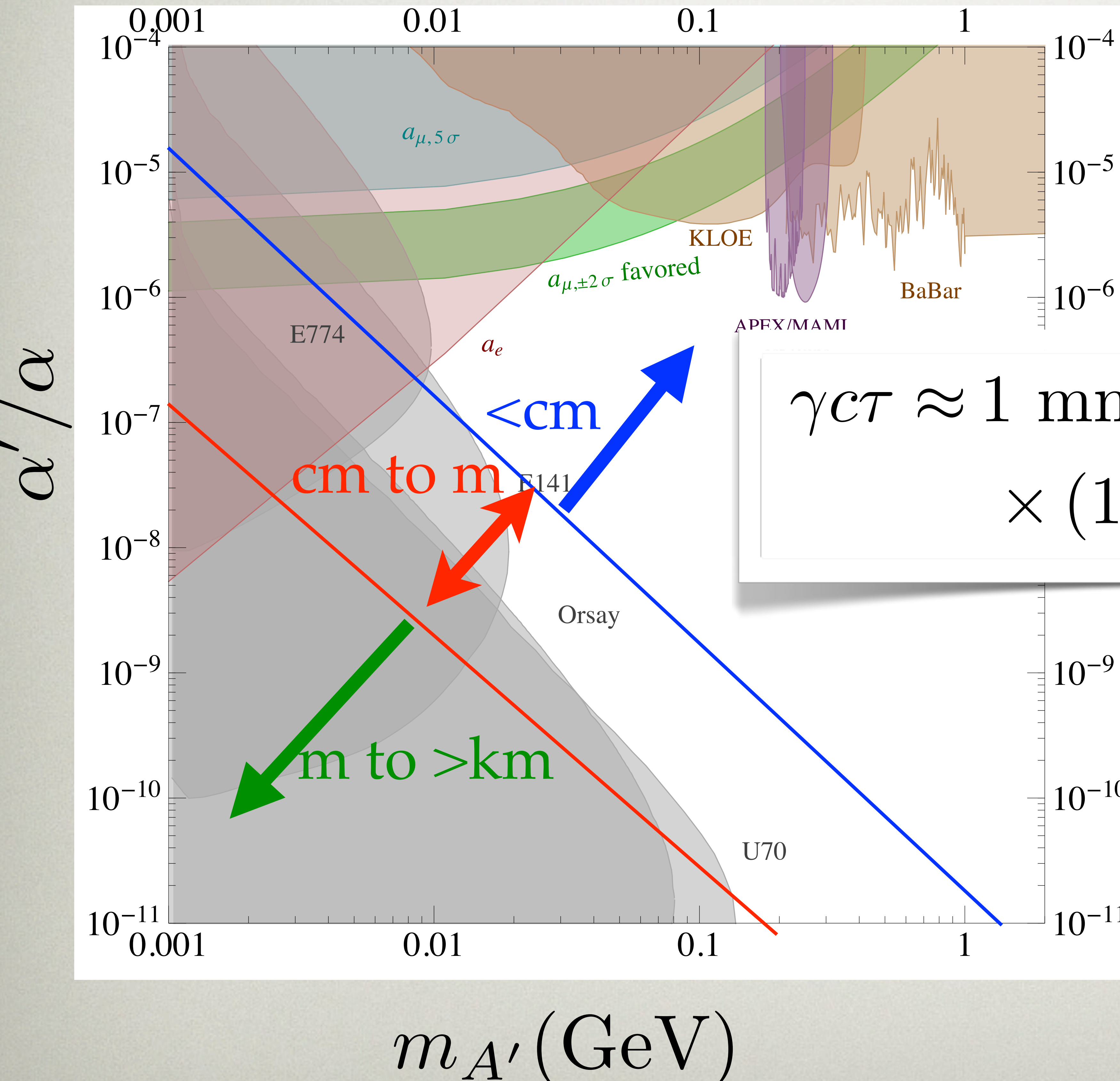
Thursday, 2 May, 13

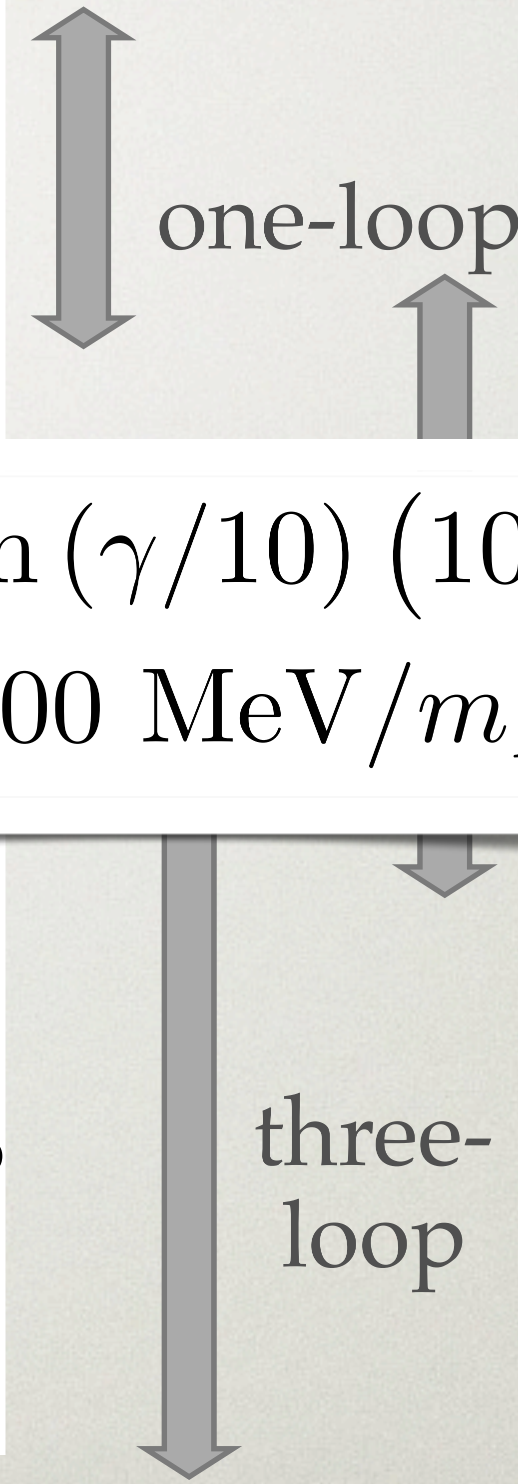
Fixed-Target Territory





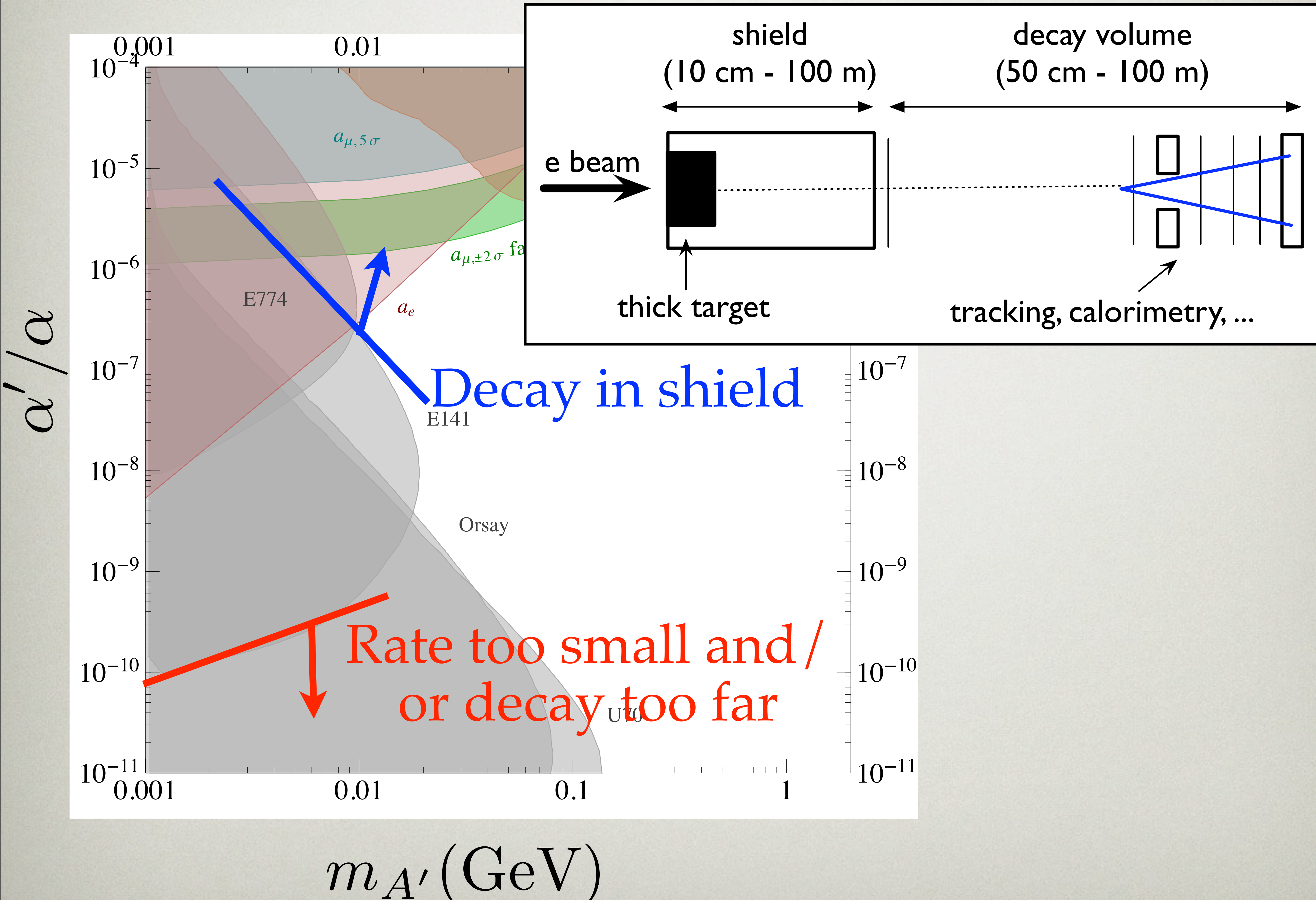
Fixed-Target Territory





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

Beam-Dump Limits



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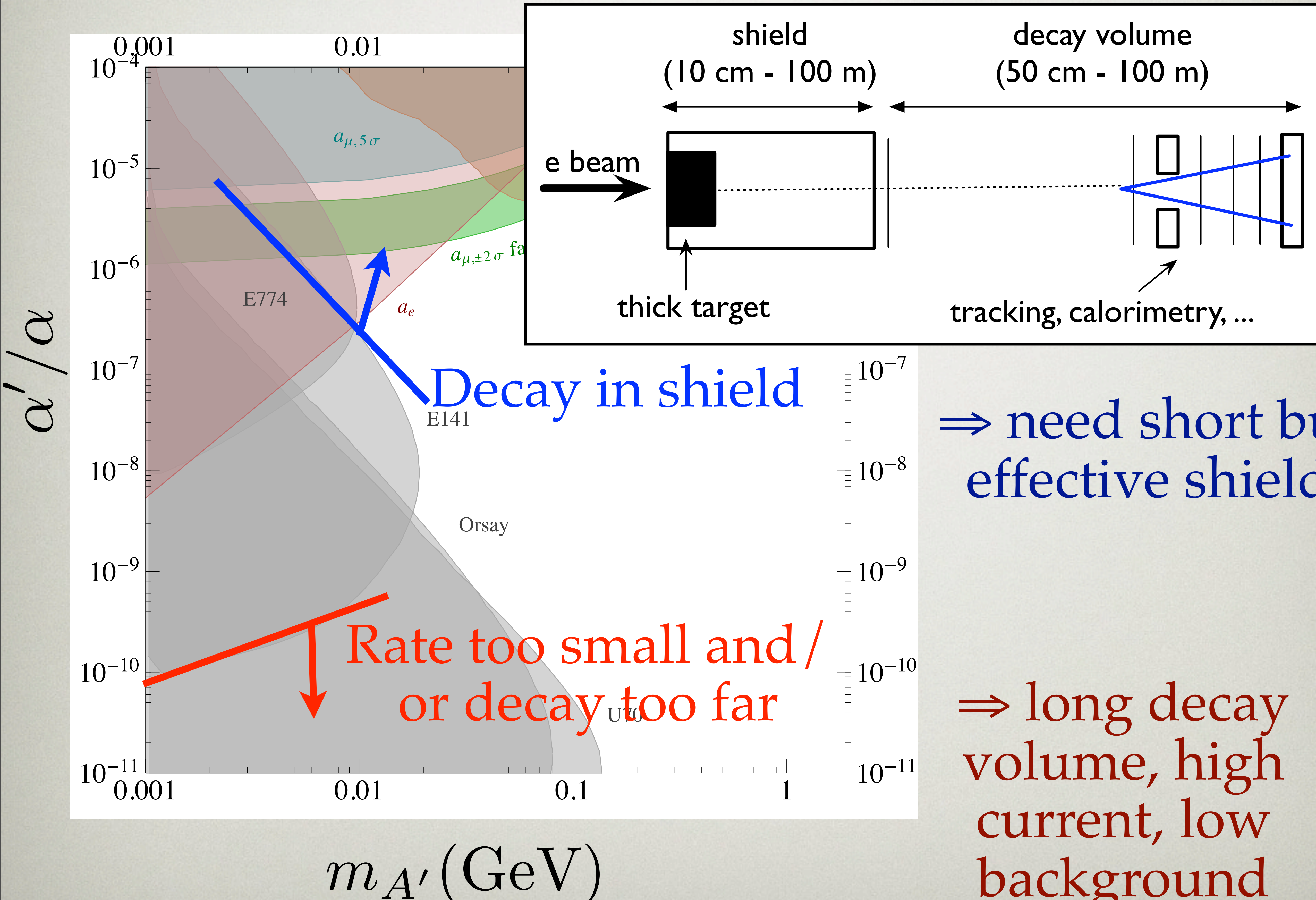
Beam-Dump Limits

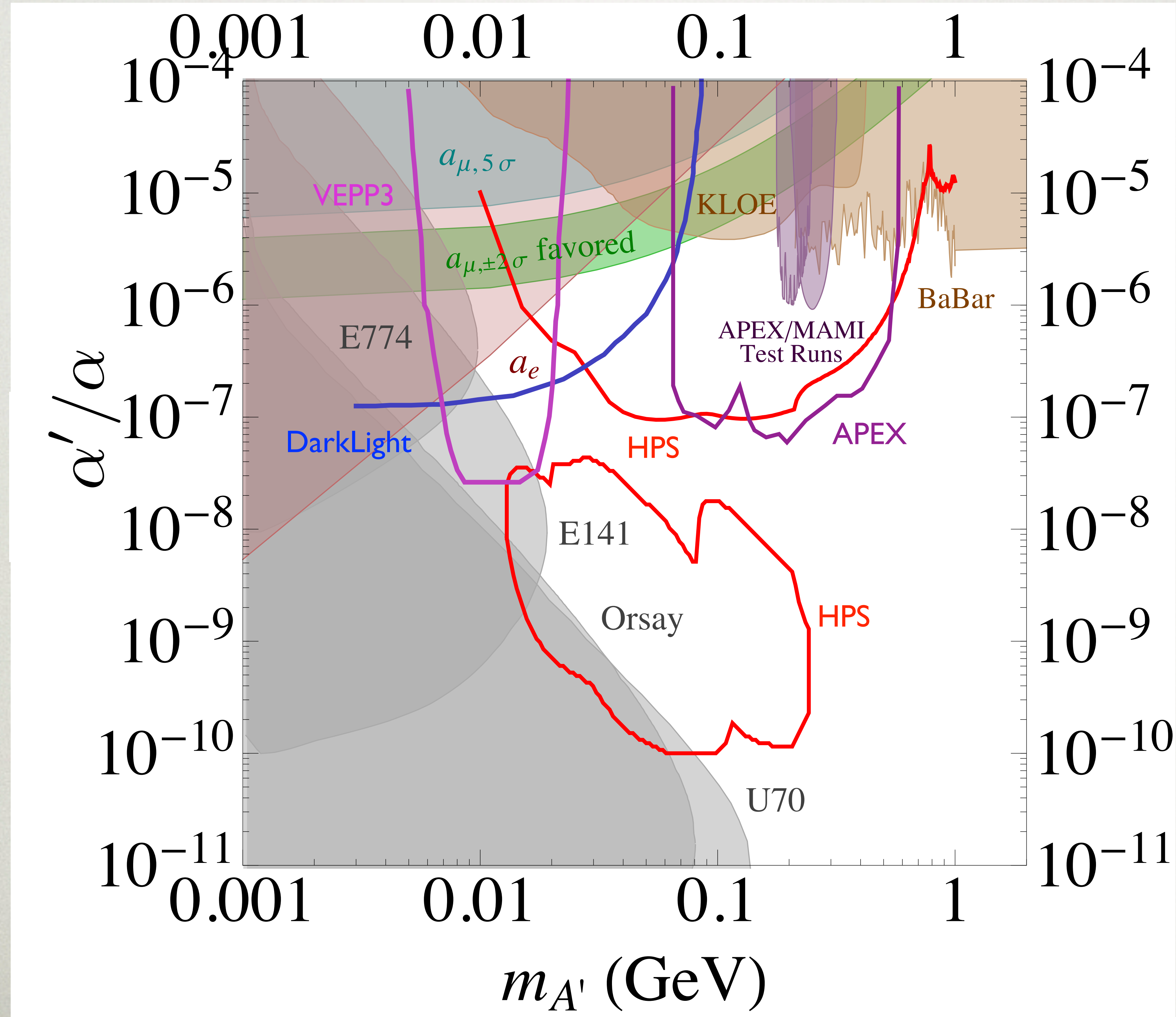


⇒ need short but effective shield

⇒ long decay volume, high current, low background

Electron F.T. Proposals

(JLab only; similar @ Mainz)



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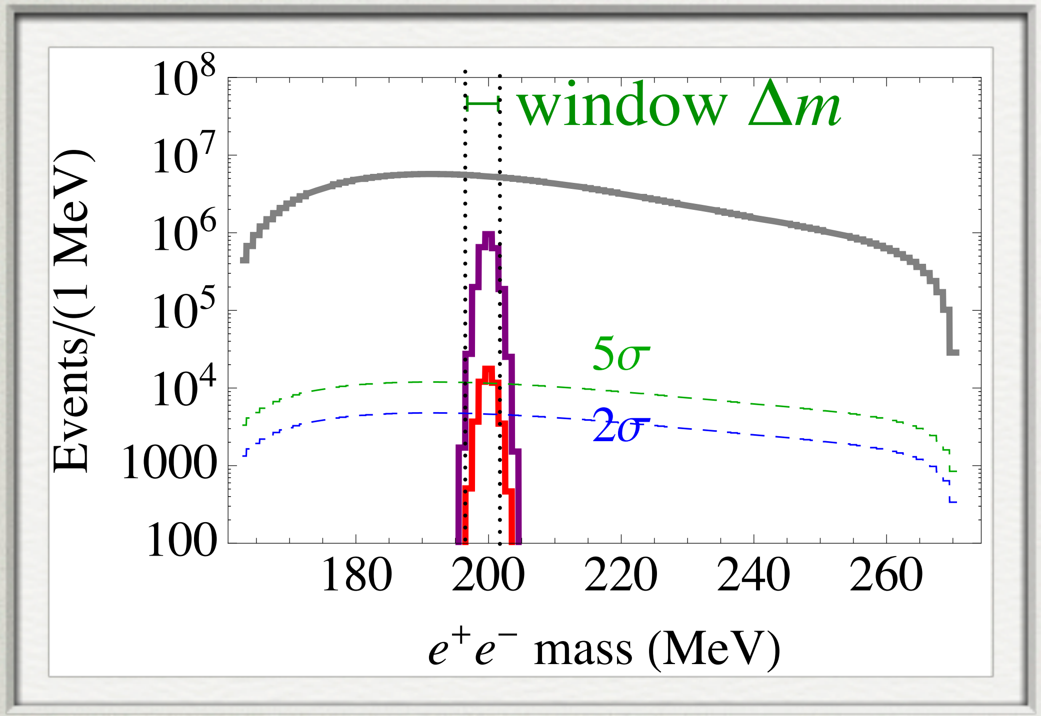
Two Search Strategies

High-Statistics Resonance Search

(MAMI, APEX, HPS, DarkLight)



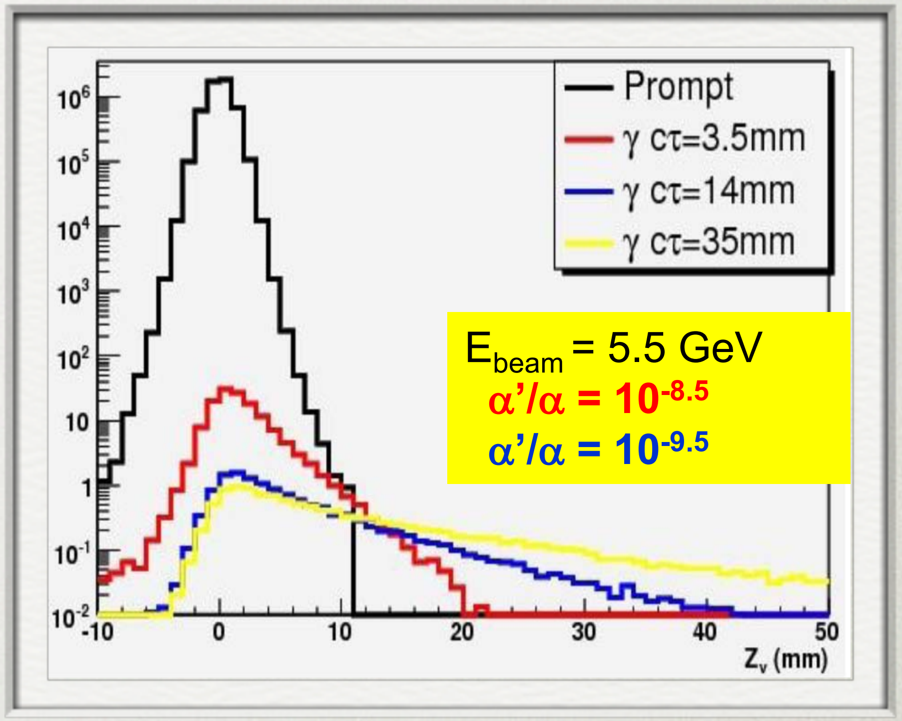
Demands high data-taking rate, background suppression and excellent mass resolution

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

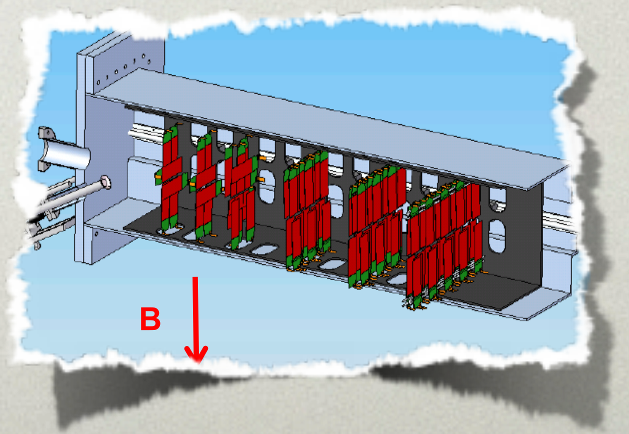
DarkLight: full reconstruction of recoil → sensitive to invisible A′ decays

Displaced Resonance search

(HPS)



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



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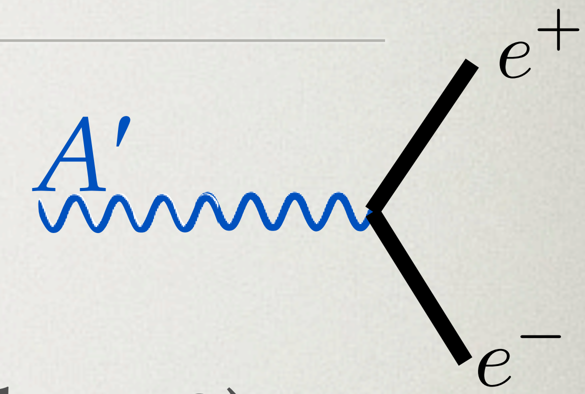
Goals for Heavy-Photon Searches



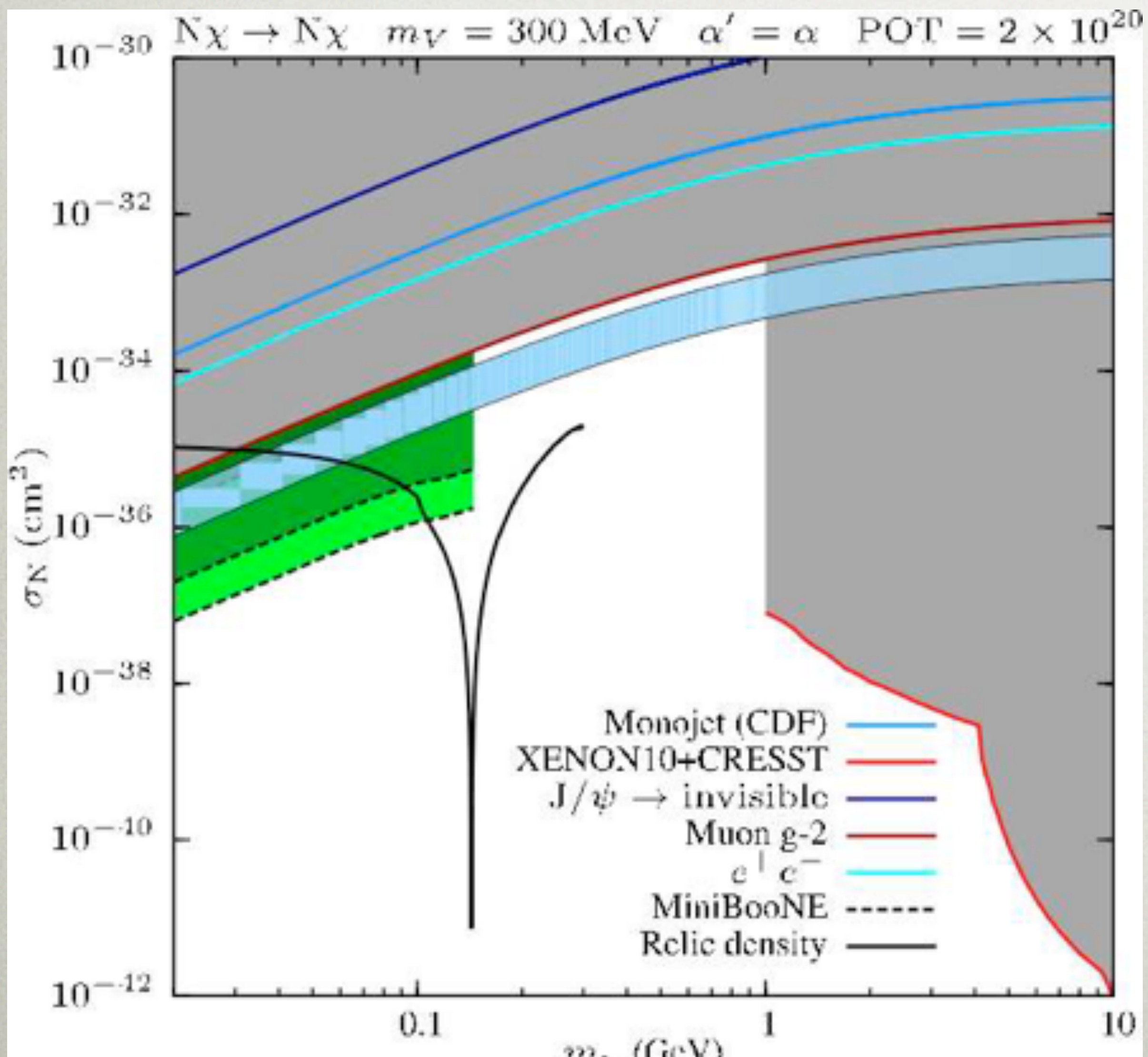
- Minimal decay
  - (g_μ-2)–motivated region (<100% branching?)
  - Full perturbative coupling range ($\varepsilon \gtrsim 10^{-8}$) over widest mass range possible
- Dark-sector decays
  - $A' \rightarrow \chi\chi$ (χ = collider-invisible, maybe dark matter)
  - $A' \rightarrow XX \rightarrow$ multi-body SM final states

Proton Beams

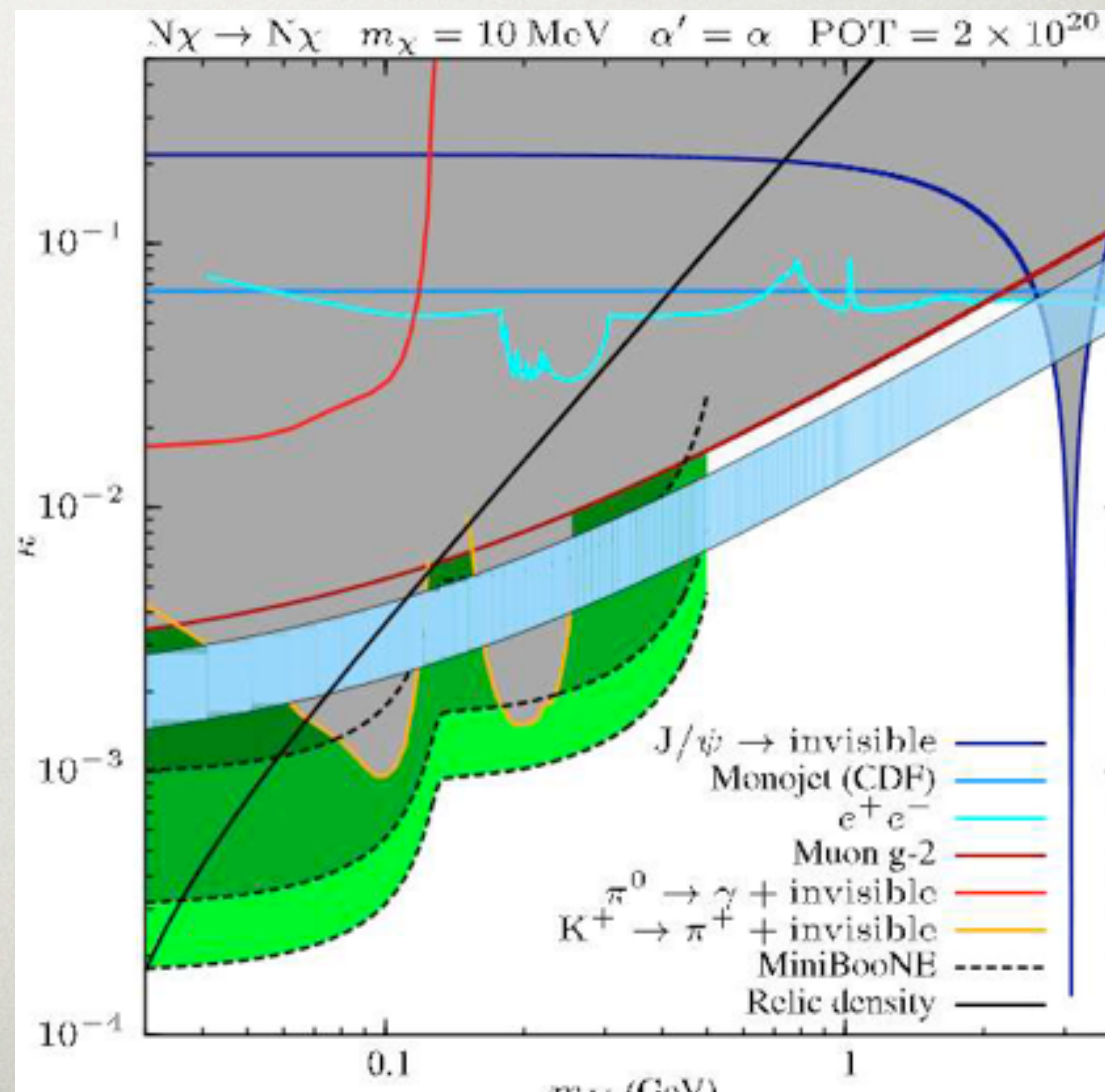
Can look for light dark matter produced in fixed-target collisions

New light-WIMP search at MiniBoone:

Fix m_V, vary m_χ

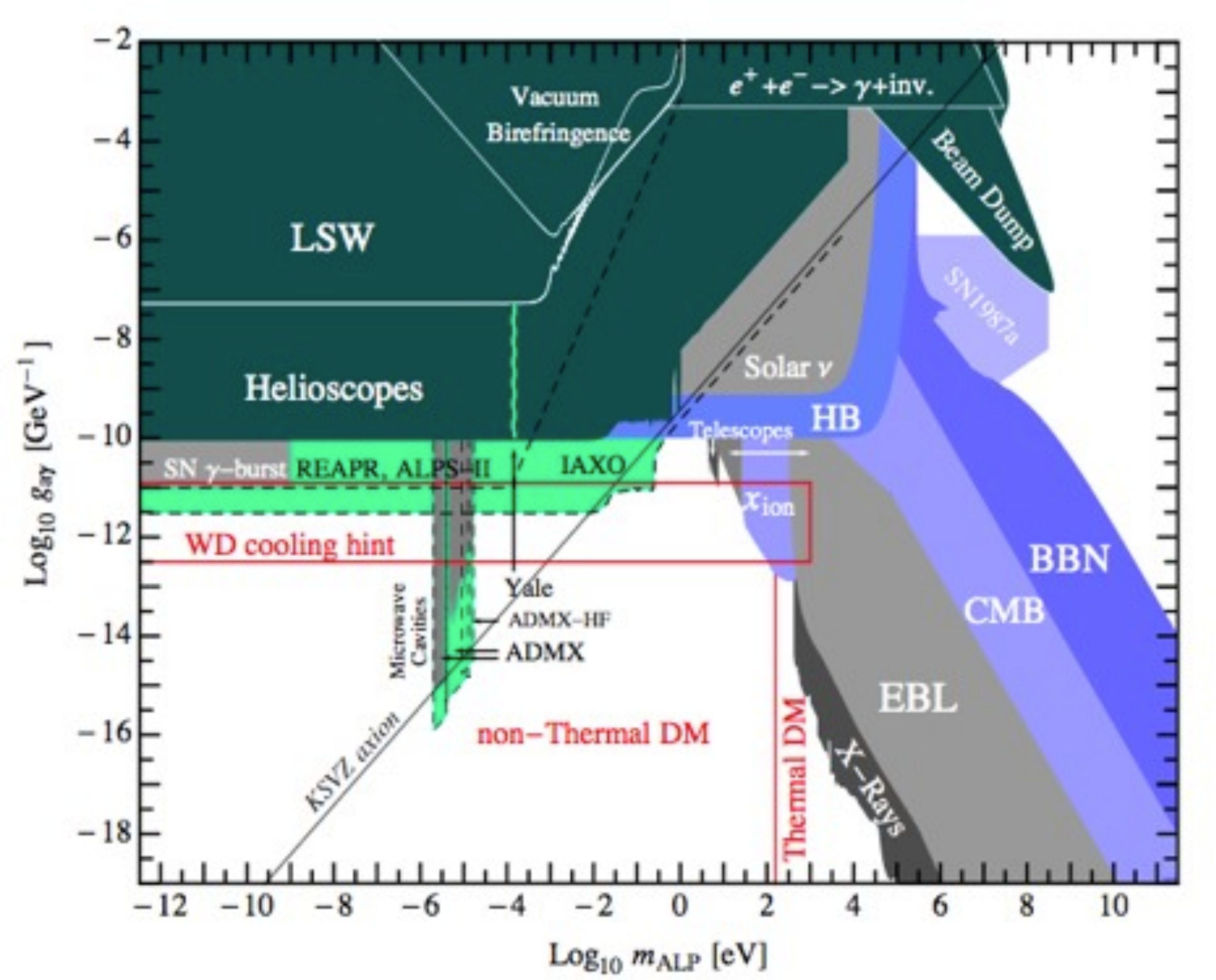


Fix m_χ, vary m_V

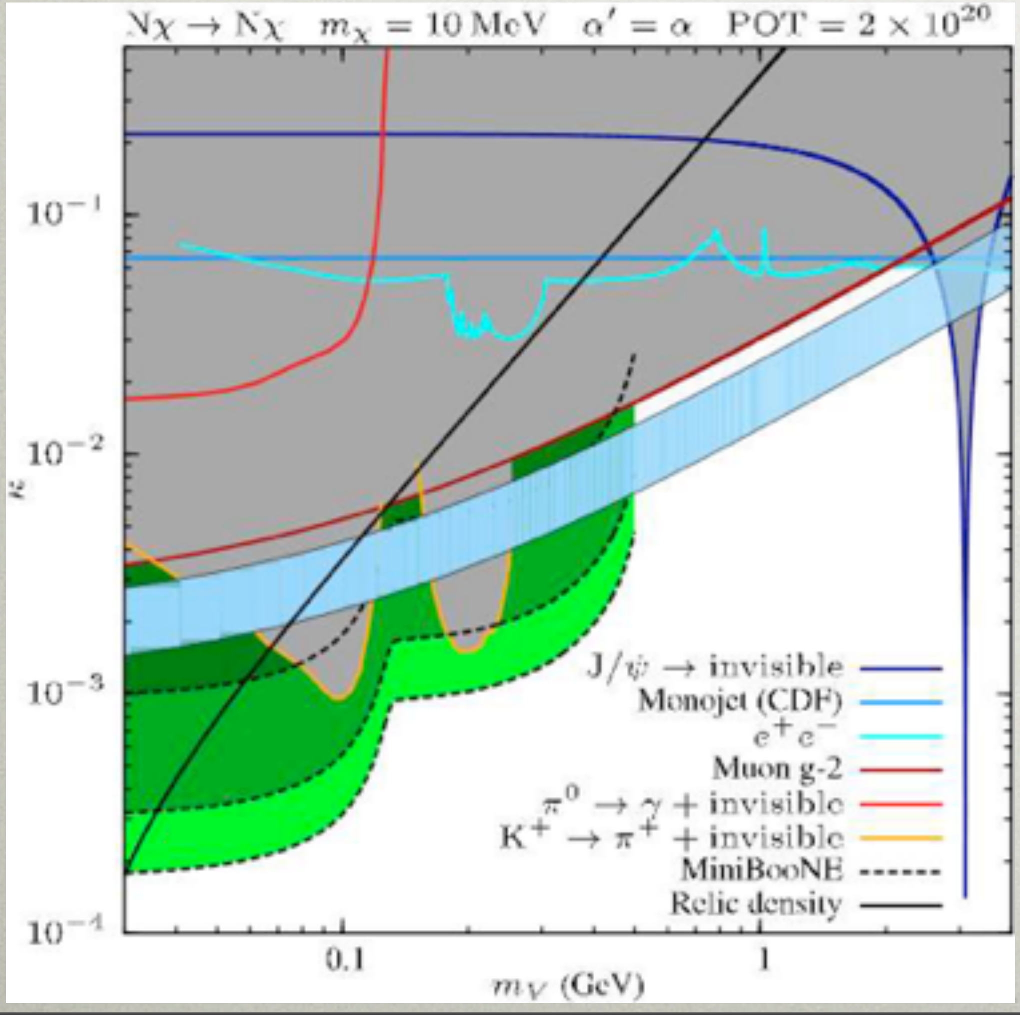


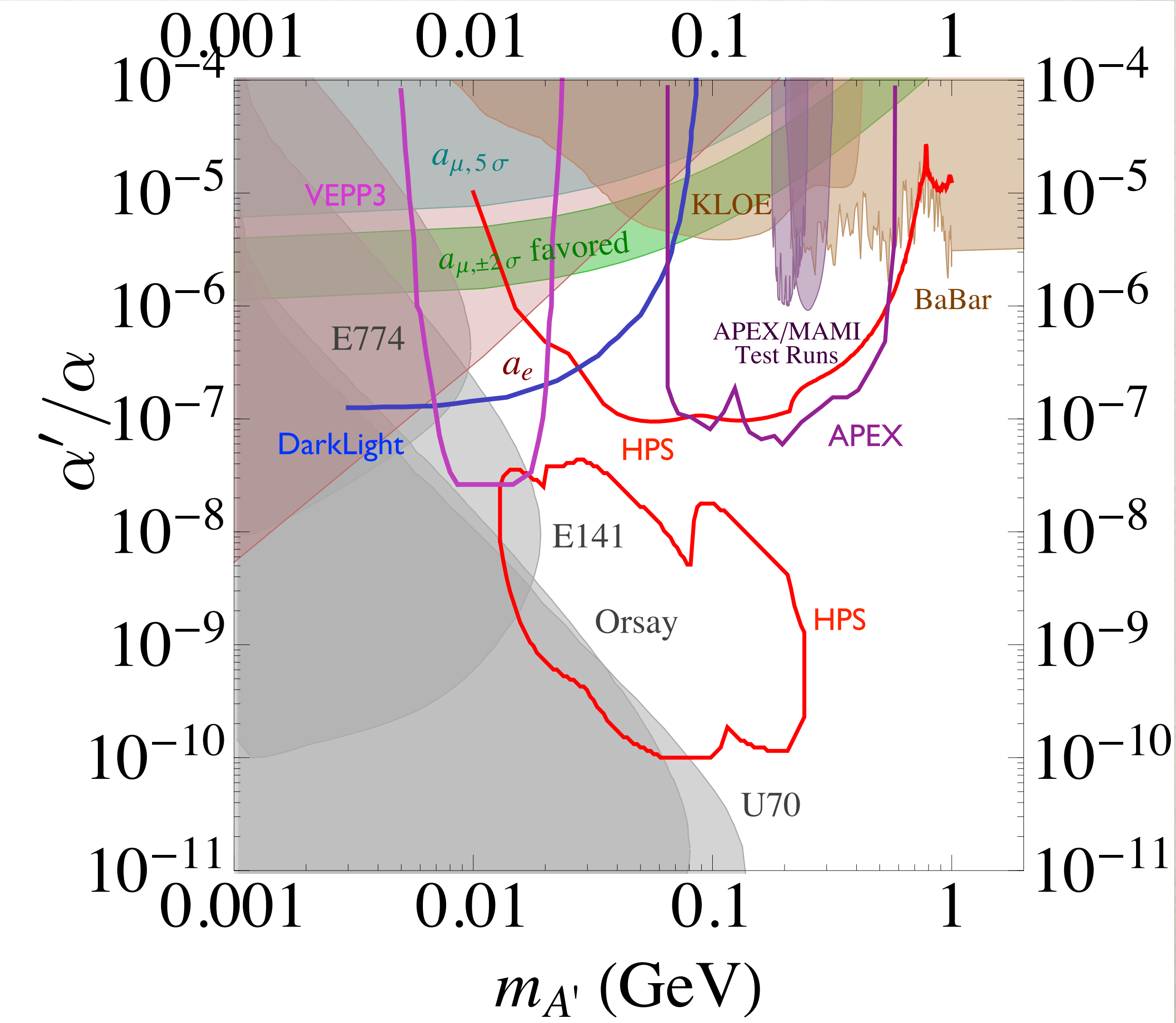
Conclusions

- 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 forces, microwave cavities & light shining through walls
  - New-particle production in B-factories and dedicated fixed-target experiments
- A lot of uncharted territory: opportunities for further exploration – and discovery – abound!


Vacuum
Birefringence
$e^+ + e^- \to \gamma$+inv.
Beam Dump
LSW
SN1987a
Helioscopes
Solar ν
HB
Telescopes
SN γ-burst
REAPR, ALPS-II
IAXO
χ_{ion}
WD cooling hint
BBN
CMB
Yale
ADMX-HF
ADMX
Microwave Cavities
EBL
non-Thermal DM
Thermal DM
X-Rays
KSVZ axion
$\mathrm{Log}_{10}\, g_{a\gamma}$ [GeV^{-1}]
$\mathrm{Log}_{10}\, m_{ALP}$ [eV]

Thanks!


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


$a_{\mu,5\sigma}$
VEPP3
KLOE
$a_{\mu,\pm 2\sigma}$ favored
BaBar
E774
APEX/MAMI
Test Runs
a_e
DarkLight
HPS
APEX
E141
Orsay
HPS
U70
α'/α
$m_{A'}$ (GeV)