Dark Forces and Discovery Opportunities at Intense Electron Beams

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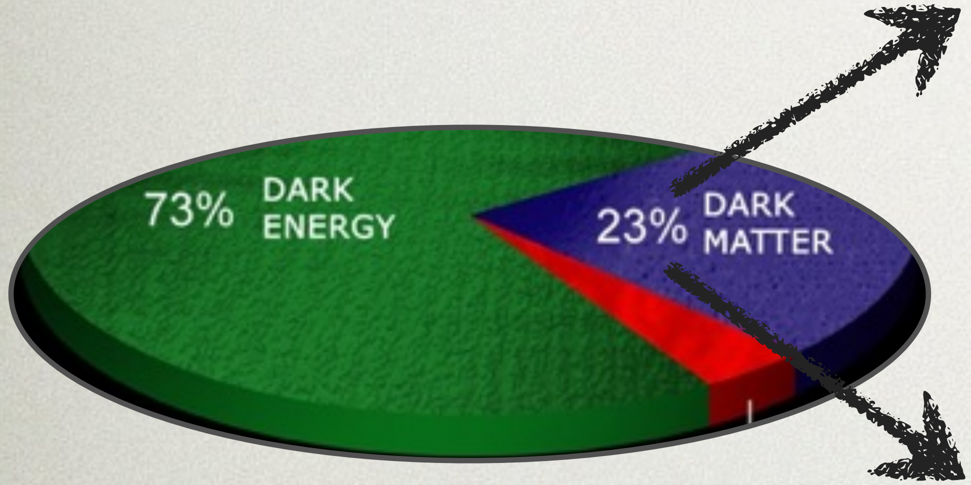
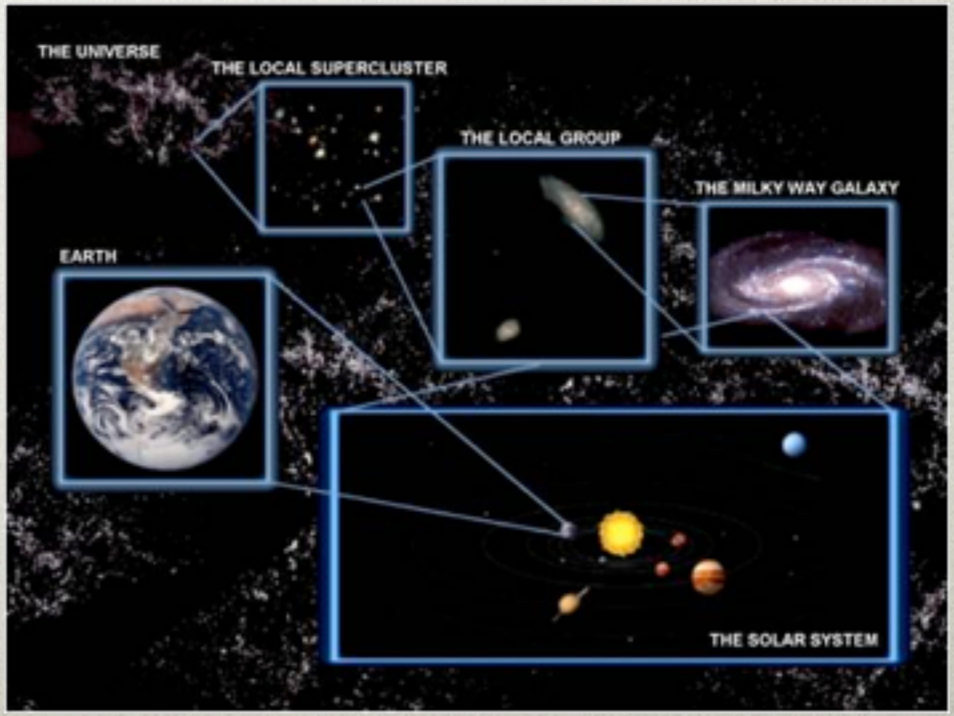
IEB 2015
Cornell University

Copernican Particle Physics?

extension of Standard Model?
(superpartner, new weak multiplet...)



Completely new physics?



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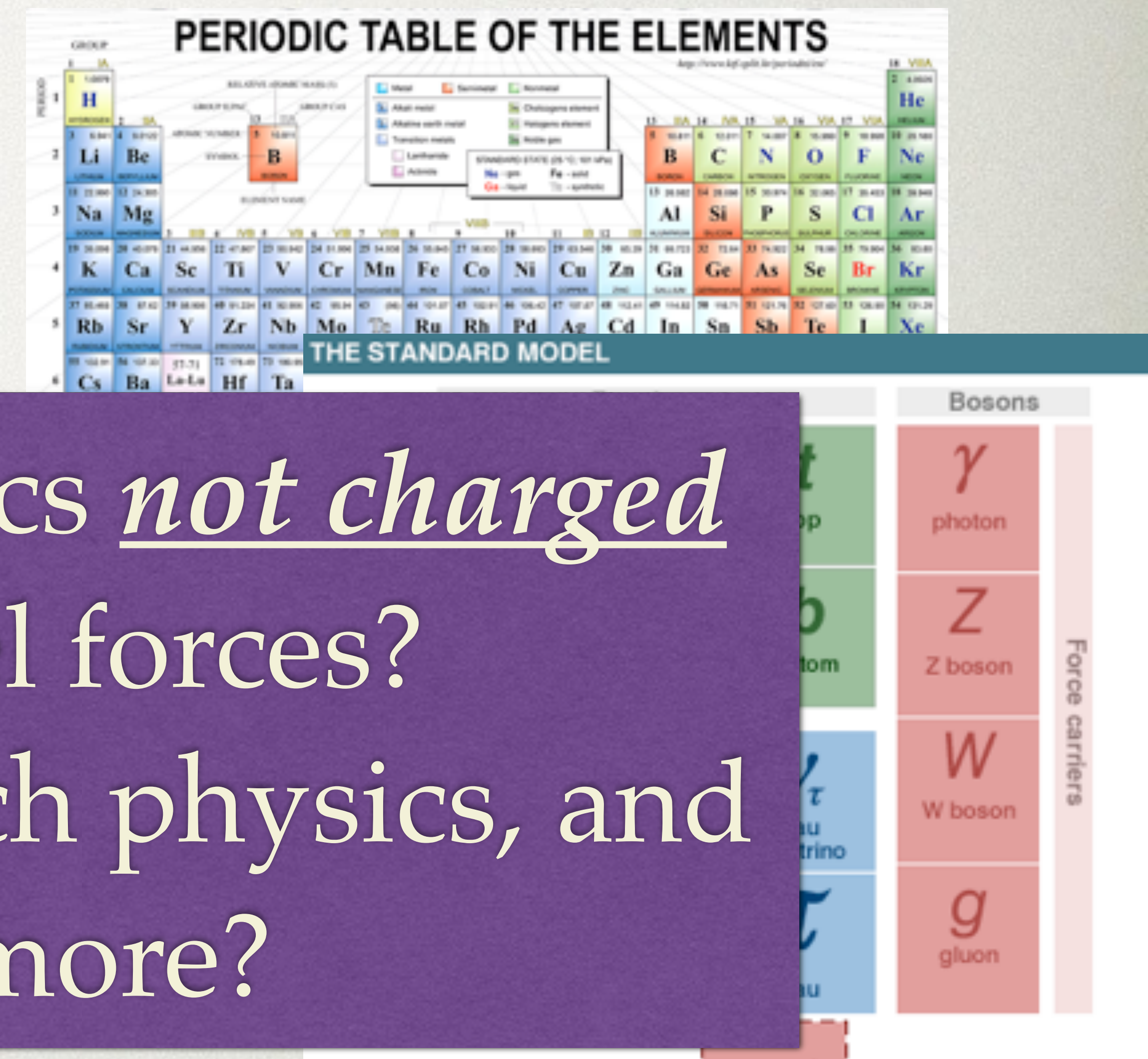
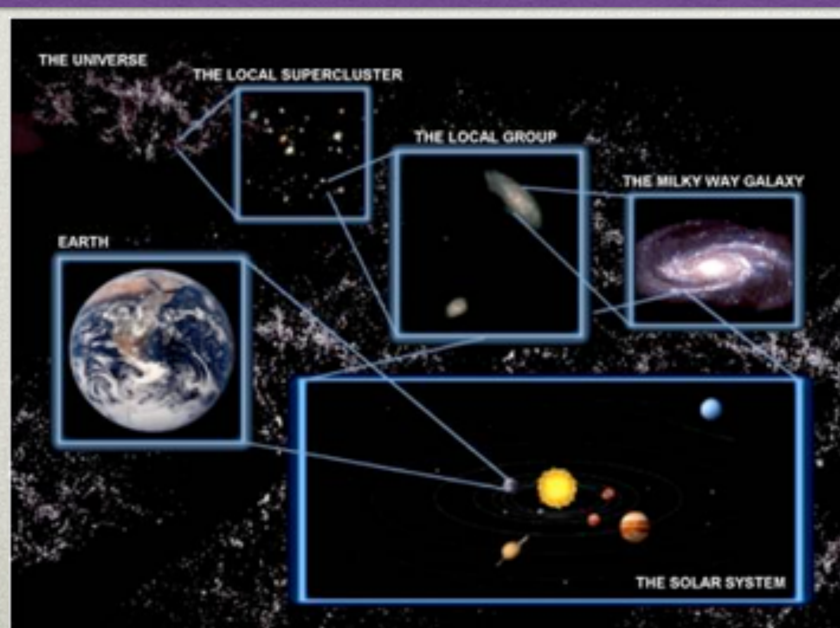
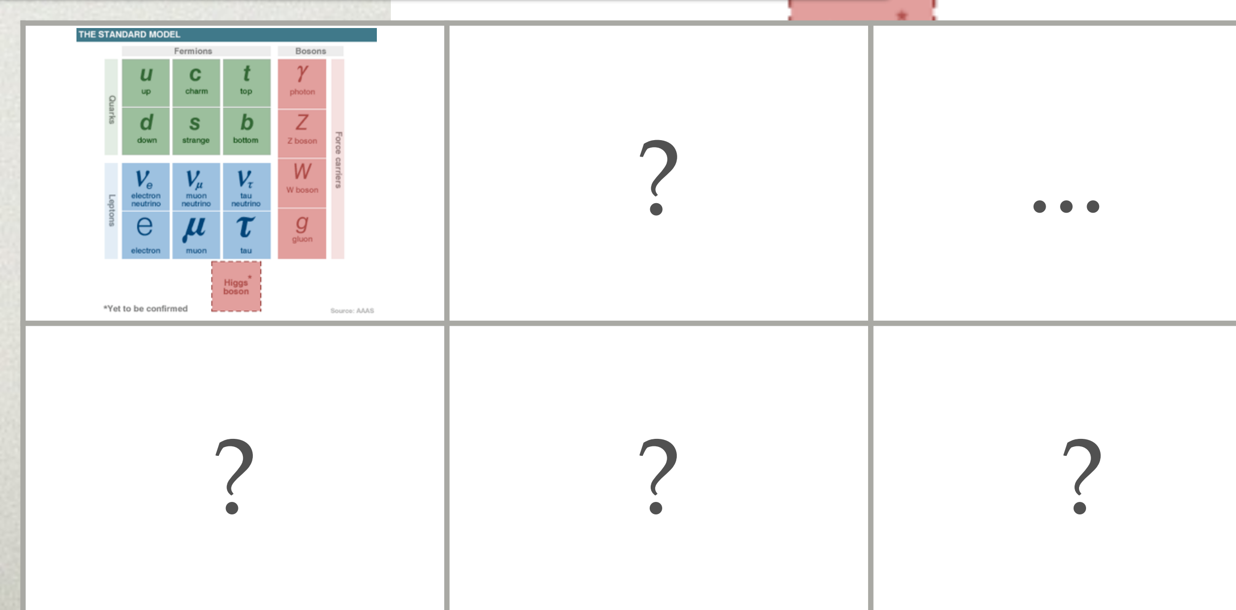


Is there room for new physics ***not charged*** under Standard Model forces?
What do we know about such physics, and how can we learn more?





Searching for Physics "Outside" the Standard Model

- Dark/Hidden Sectors: Mapping out the Possibilities
- Searching for Dark Forces
  - Multi-purpose collider experiments
  - Dedicated fixed-target experiments
- Light Dark Matter
  - An opportunity for very low-energy beams

How to look for physics FAR beyond the SM?

Accessible **mass** isn't enough – need interactions

⇒ suppressed by high power of mass-scale at which interactions are generated

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

[analogous to approximate stability of proton in SM]

Even if χ is light, large $\Lambda \Rightarrow$ unobservable effect.

The few operators with no Λ-suppression* present an opportunity to explore this physics

*gauge-invariant combinations of SM and new fields with dimension < 4

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)

Axions and the Almost-Portals

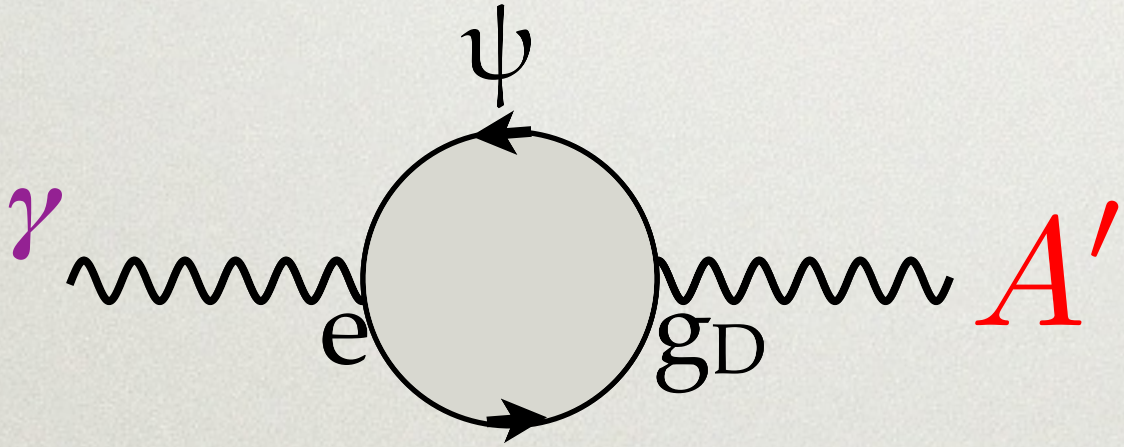
A **pseudo-scalar** boson can have several interactions suppressed by only one power of mass

$$\text{Axion Portal} \begin{cases} \frac{1}{\Lambda} G_{\mu\nu}\tilde{G}^{\mu\nu} a \\ \frac{1}{\Lambda} \bar{f}\gamma^{\mu}\gamma_5 f \partial_{\mu} a \\ \frac{1}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu} a \end{cases}$$

Even for large Λ, coherent-field effects can compensate for weak coupling

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

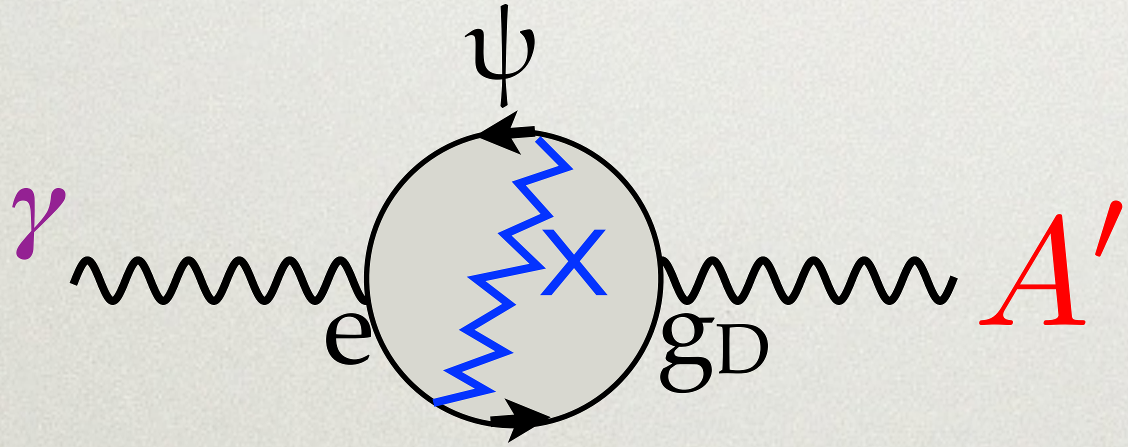
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



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



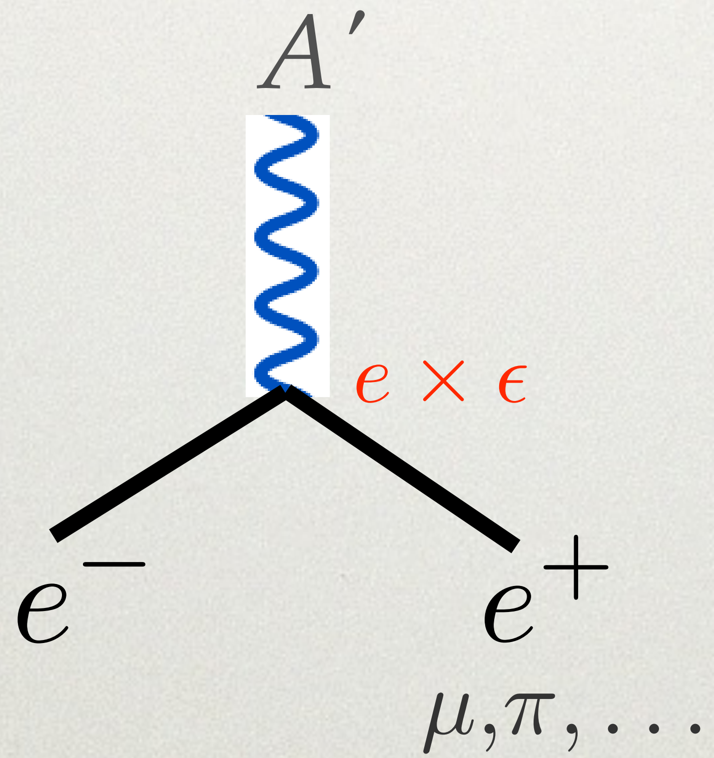
generating $\epsilon \sim 10^{-3} - 10^{-5}$

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

Effects of Kinetic Mixing

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

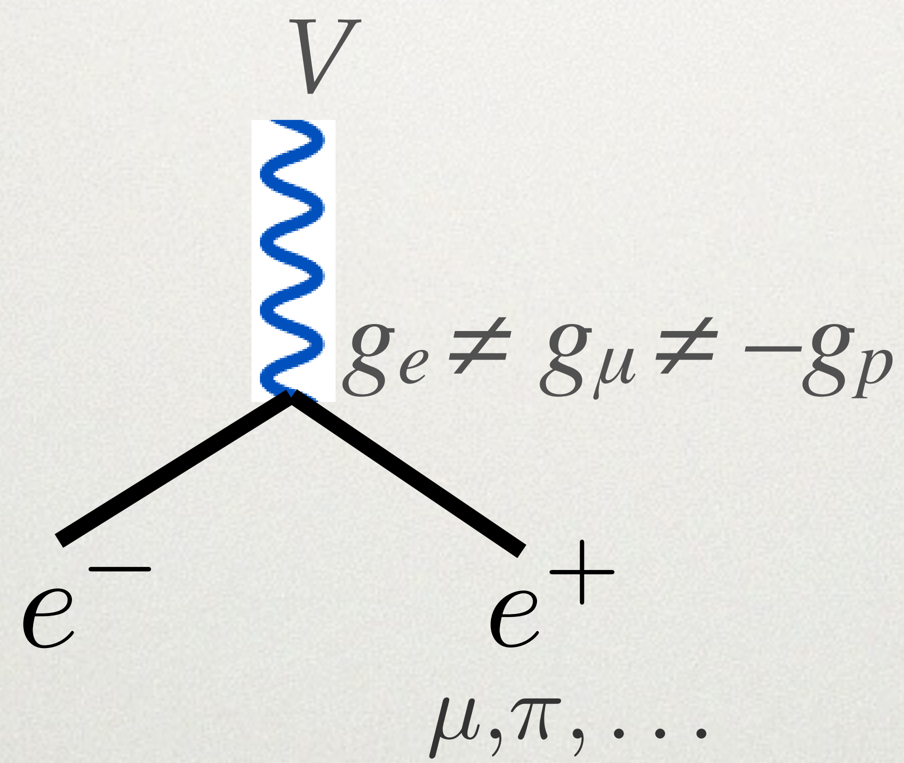
Regardless of where it comes from, **kinetic mixing can always be re-interpreted as (mainly) giving matter of electric charge *qe* an A′ coupling ∝ *qεe***



Dark matter can have an independent coupling g_D to A′

Bycatch

New, weak gauge forces **of** the Standard Model (e.g. to B–L) can be found by the same kinds of searches.

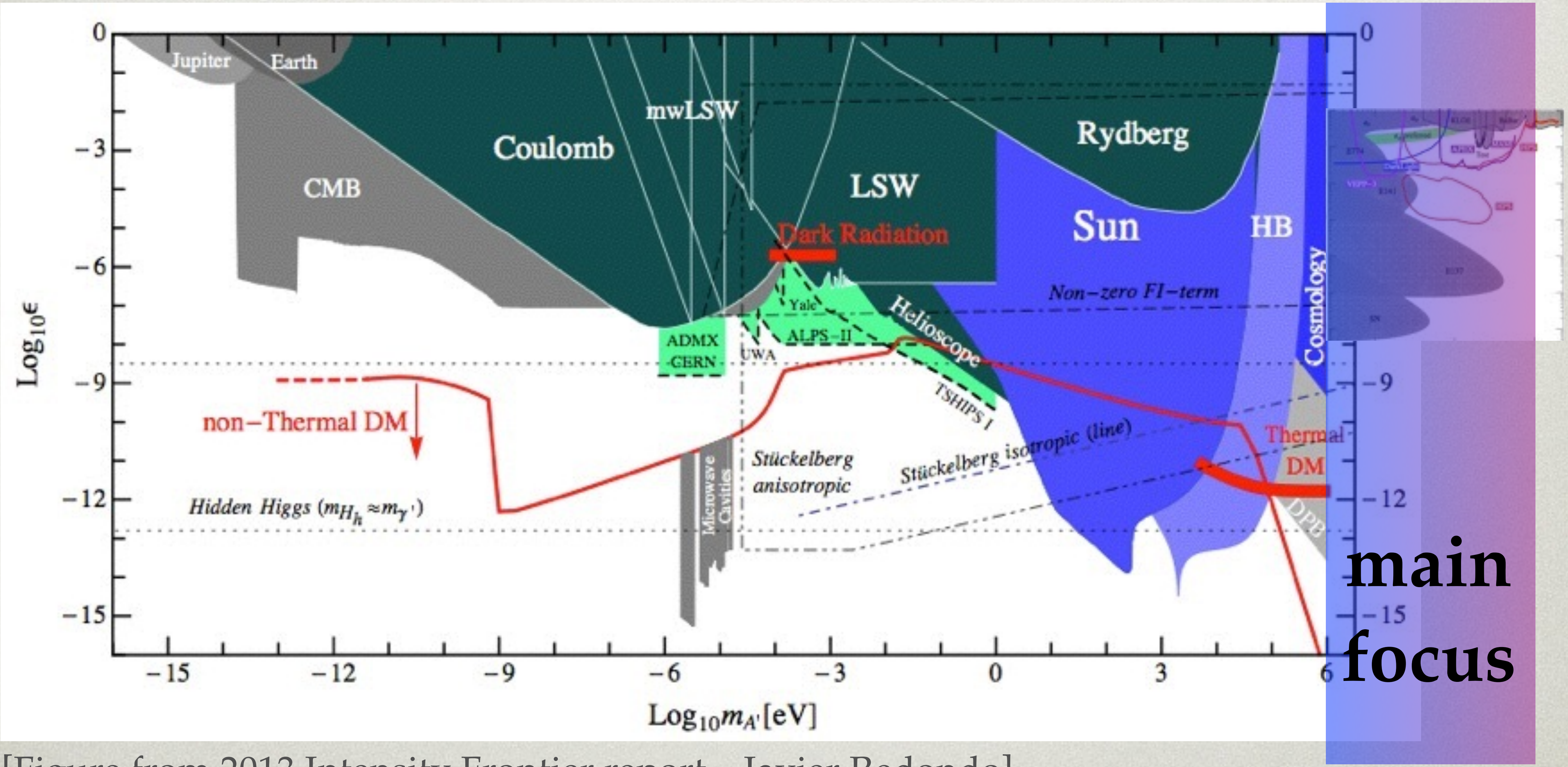


Important to keep this in mind in comparing e.g. *p* to $e^\pm$ beams

May be relevant to e.g. muonic hydrogen anomaly

Wide Parameter Space: Hidden Vectors

Nuclear scale



[Figure from 2013 Intensity Frontier report – Javier Redondo]

new particles

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

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

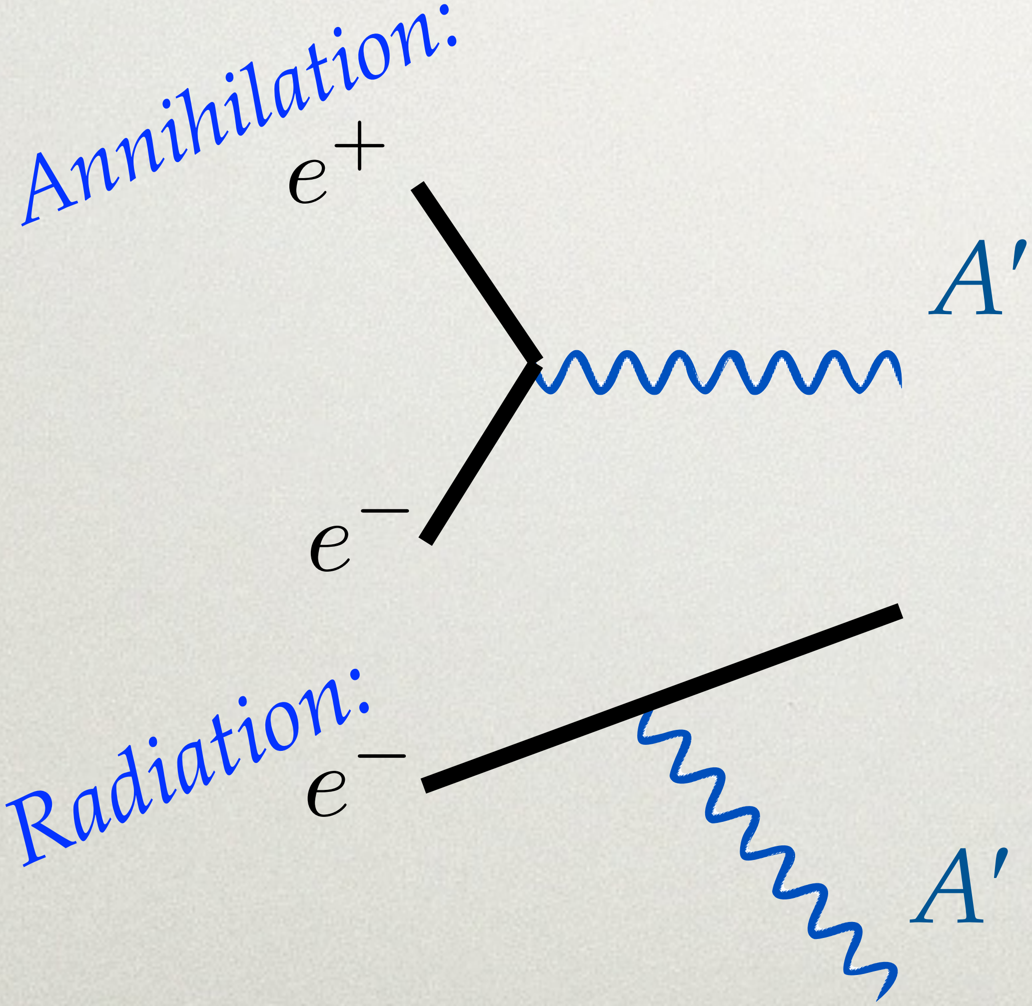
[e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

- motivated by g-2 and dark matter anomalies
- A particularly **relevant** and **accessible** range to explore

A Field Guide to Dark Forces

Production

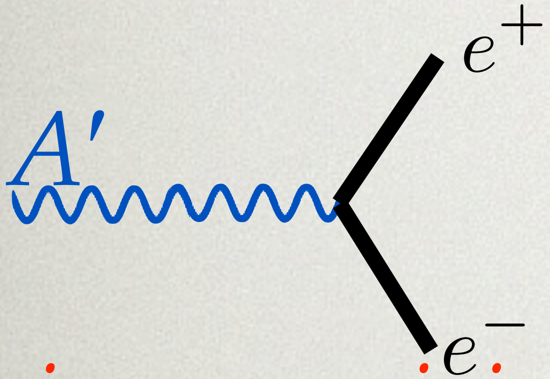
(like ordinary radiation of light, but suppressed by ε)



"Wherever there's a photon, there's a dark photon"

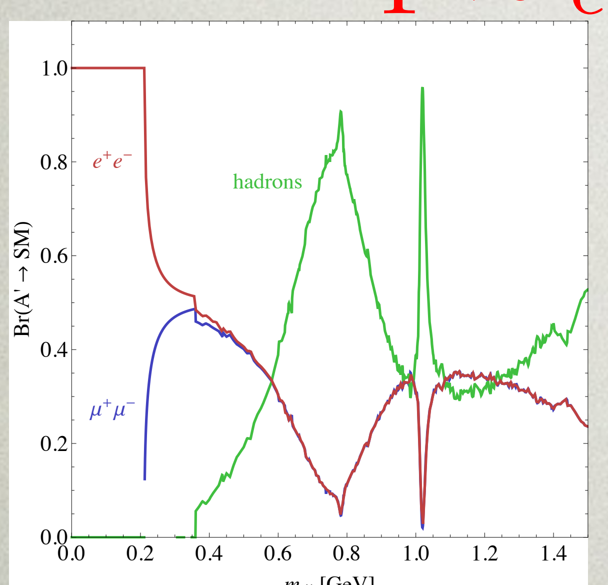
A Field Guide to Dark Forces
Decay

"Minimal" Decay:



via same mixing operator as production ⇒ tiny width

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



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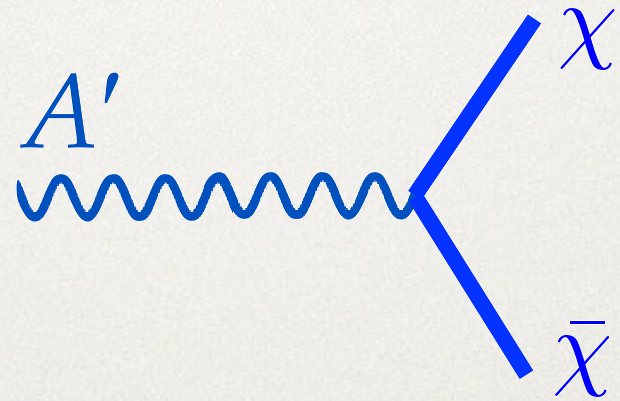


(*not ε-supressed!*)

*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'→ >2 charged particles

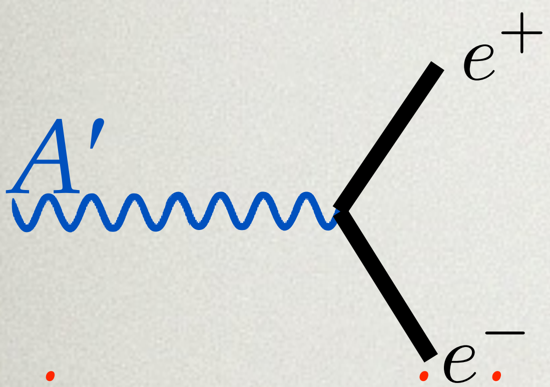
searches at BaBar and KLOE

To test "dark sector" idea, we need to search for both!

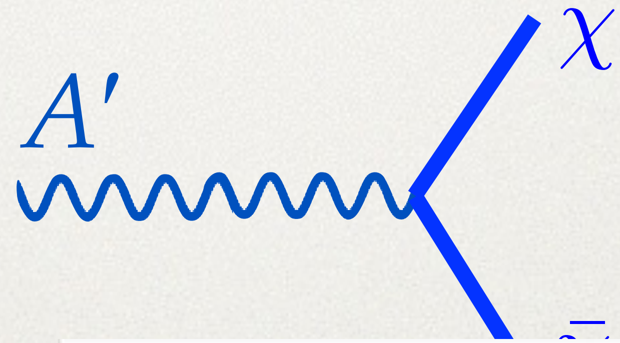
A Field Guide to Dark Forces

Decay

"Minimal" Decay:



"Generic" Decay:



(not ε-supressed!)

*If **any** dark-sector matter χ has ... this ... inates*

Major advances in last 5 years!

Huge upcoming opportunity!

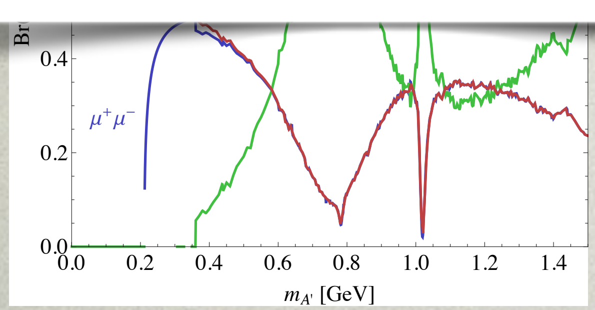
Tw...

–

– ...cles,

$A' \to >2$ charged particles

searches at BaBar and KLOE

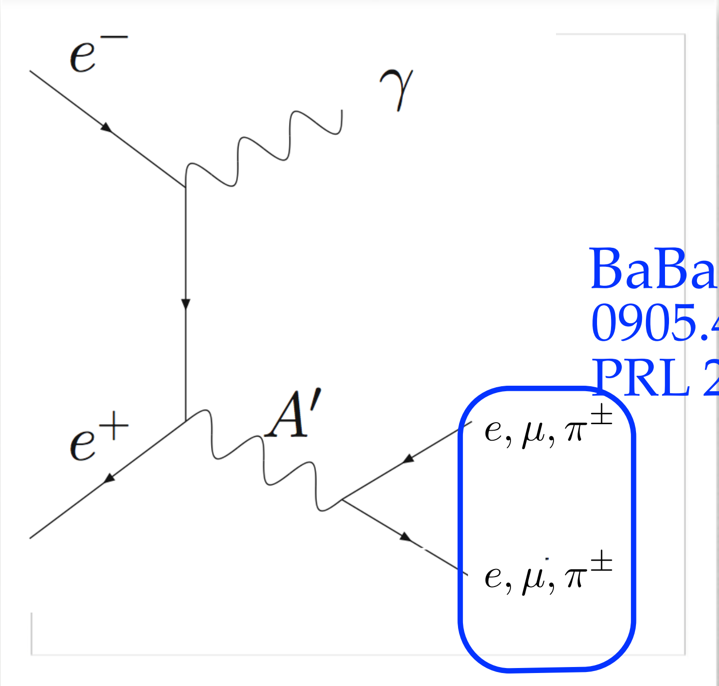


To test "dark sector" idea, we need to search for both!

An Experimental Renaissance

Collider Production

Radiative return

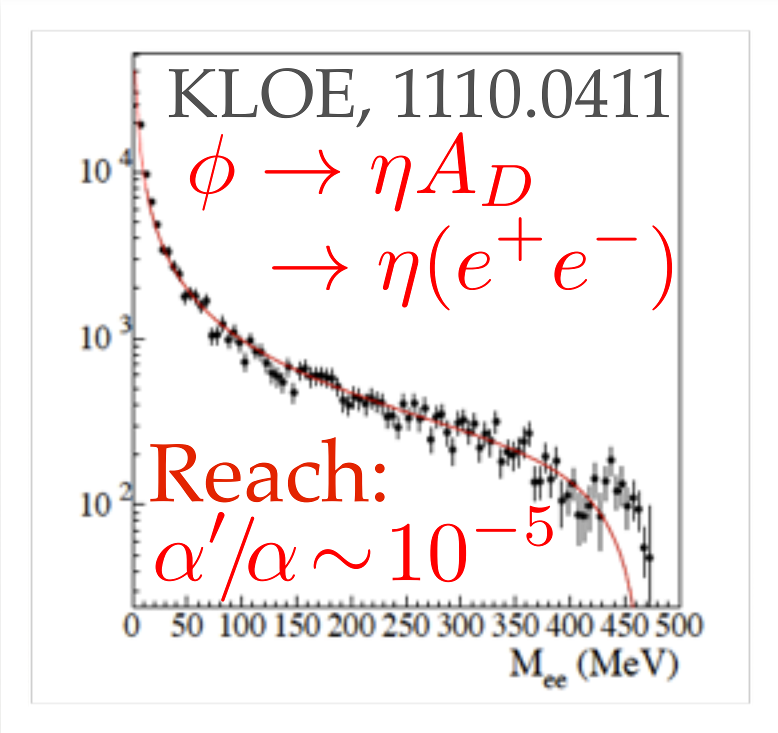


BaBar
0905.4539,
PRL 2009

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}

PLB706 (2012) 251-255

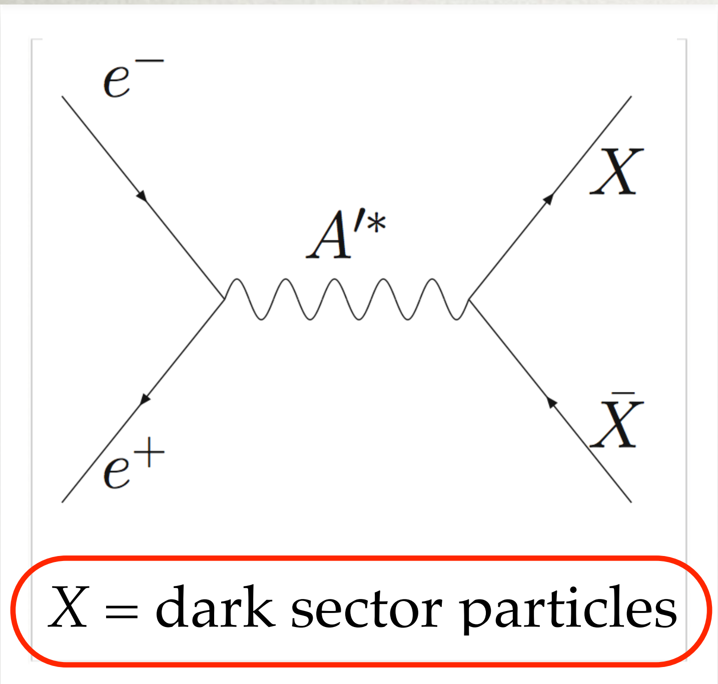


[Reece and Wang 2009]

Wide Breadth of Searches

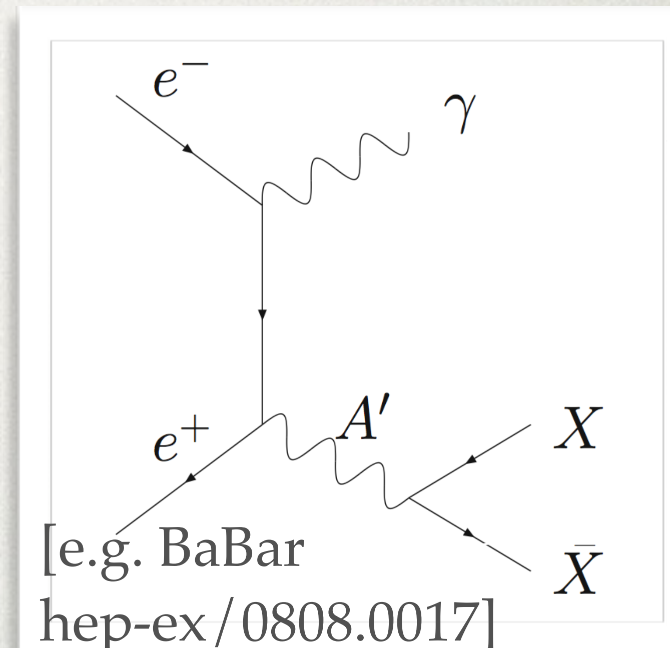
(just a few representative examples)

Off-shell A′ portal

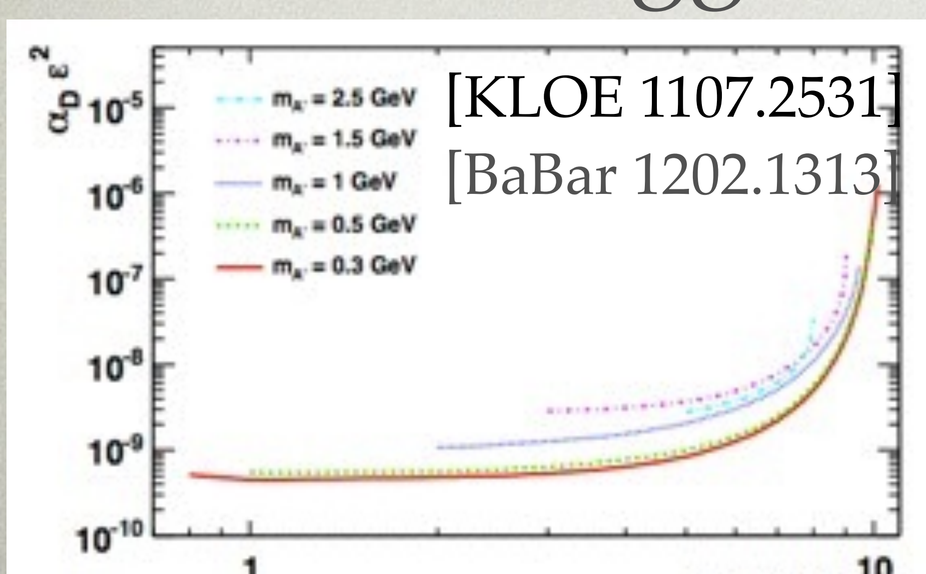


Potential to see rich hidden sectors in complex multi-body final states (searches ongoing at BaBar + several completed)

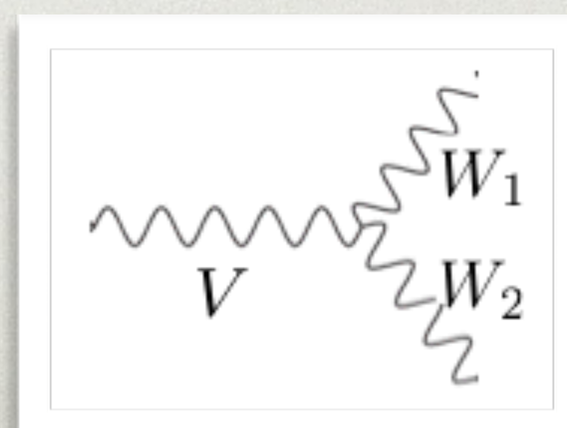
Invisible Decay

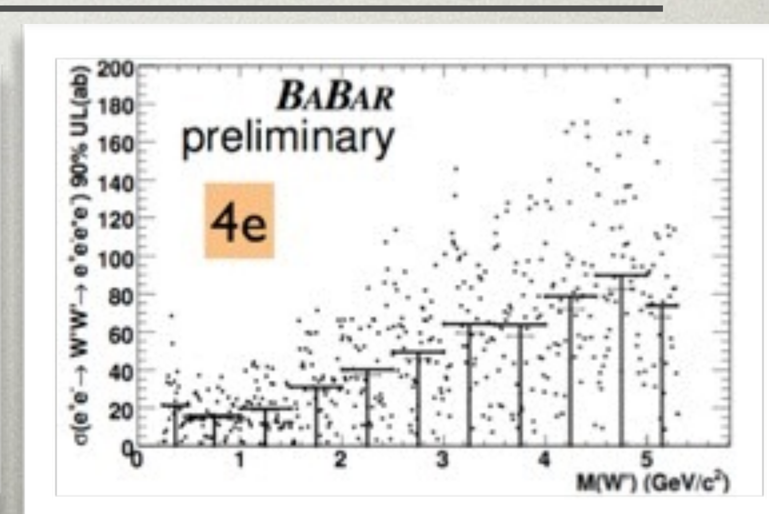


Vector + Higgs:



Non-Abelian Dark Sector



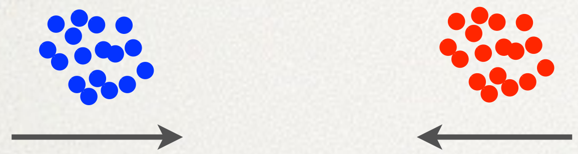


Going Further: Fixed Target

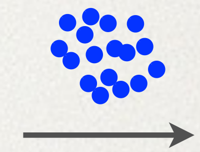
	e^+e^-	Fixed-Target

Luminosity

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



10^{11} e^-



~10^{23} atoms in target

N(hard scatter) ~ 1
per crossing

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

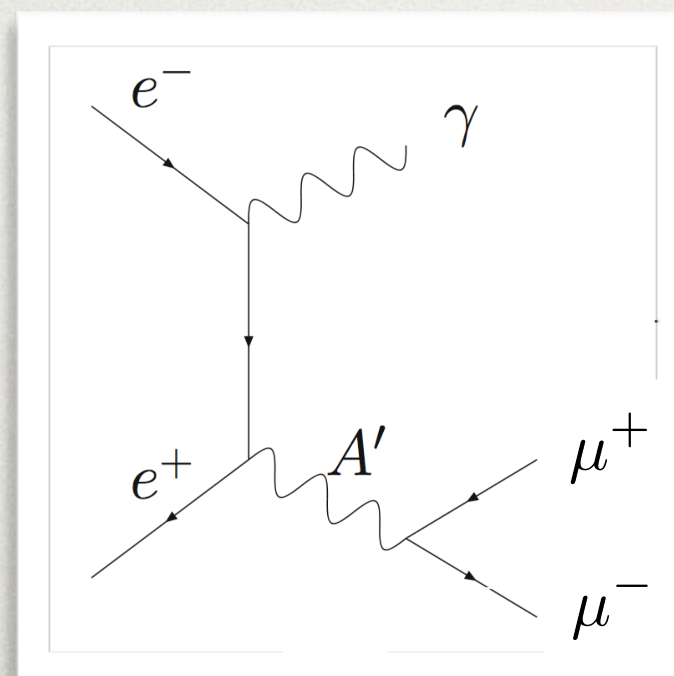
N(hard scatter) ~ 0.01 – 1
per electron

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

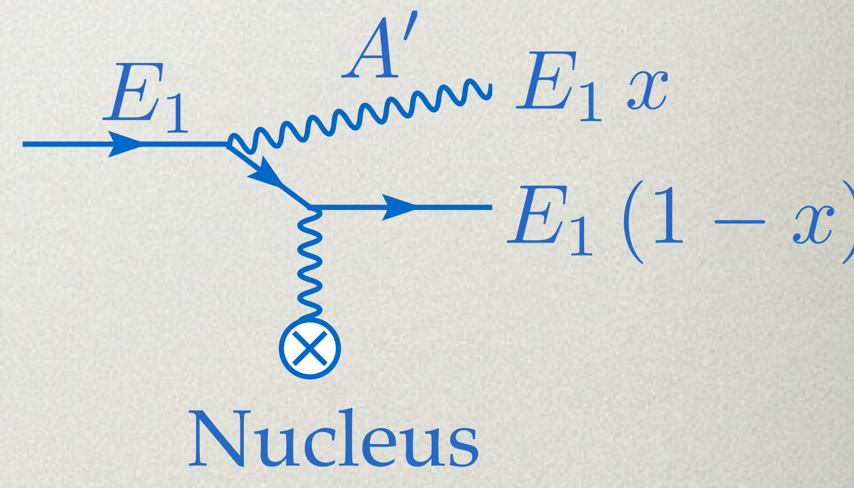
Cross-Section

– Scales as A′ mass, not beam energy

– Coherent scattering from nucleus



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



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

Jefferson Lab Continuous Electron Beam Accelerator Facility

- Delivers beam up to 12 GeV to 4 experimental hall

Halls A,C up to 100 μA
Hall B, D: 1 μA

- 1.5 GHz RF ⇒ each hall gets bunch every 2–4 ns

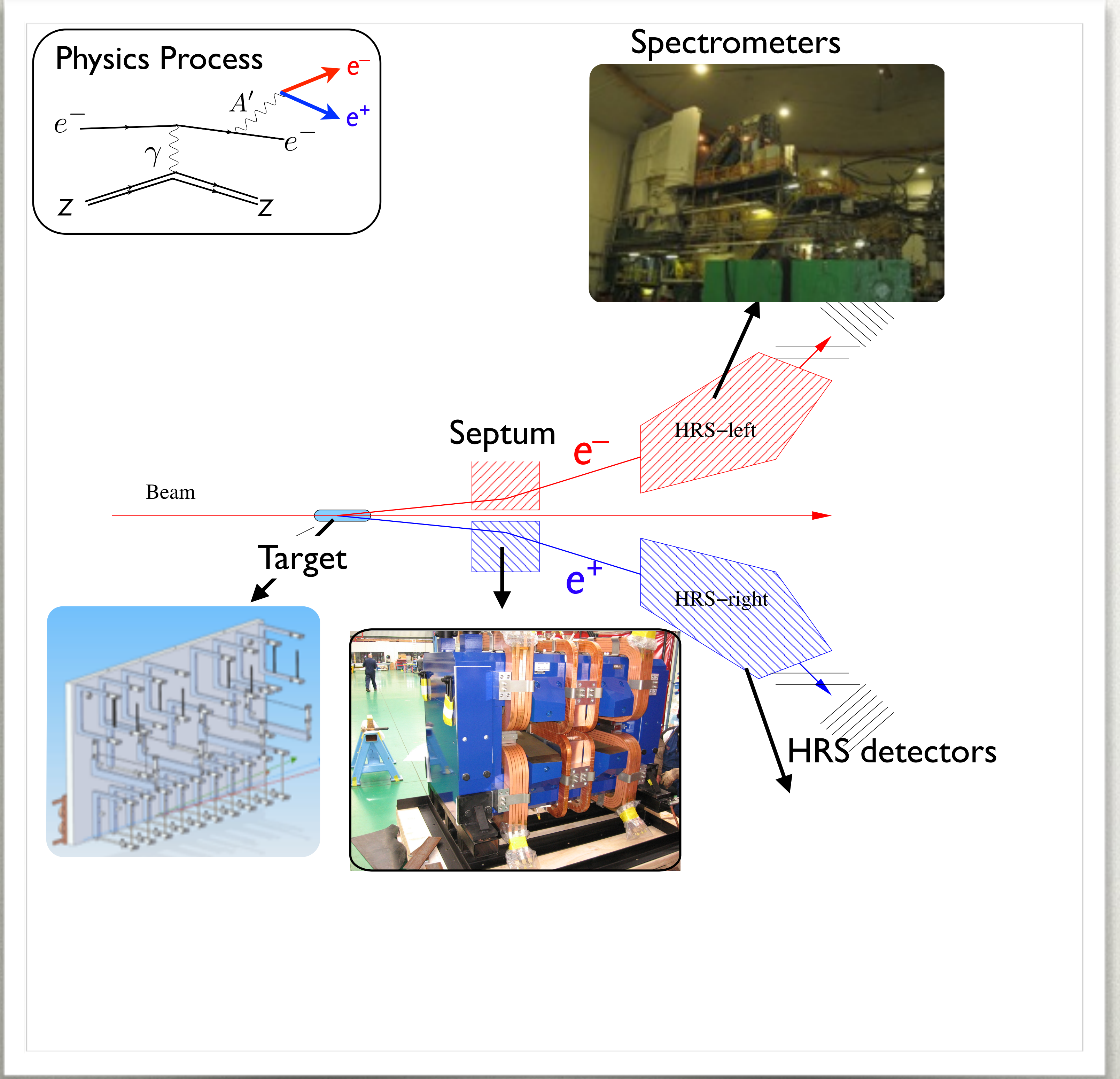
- Commissioning beam to halls after recent energy upgrade & addition of Hall D

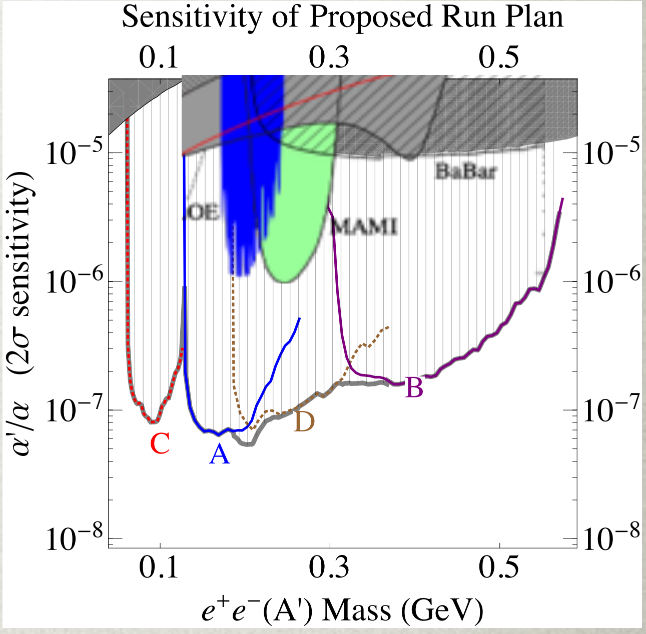
- Only multi-GeV continuous electron beam in the world!

APEX

http://hallaweb.jlab.org/experiment/APEX/

Search for new gauge boson *A'* using Hall A high-resolution spectrometers (HRS)





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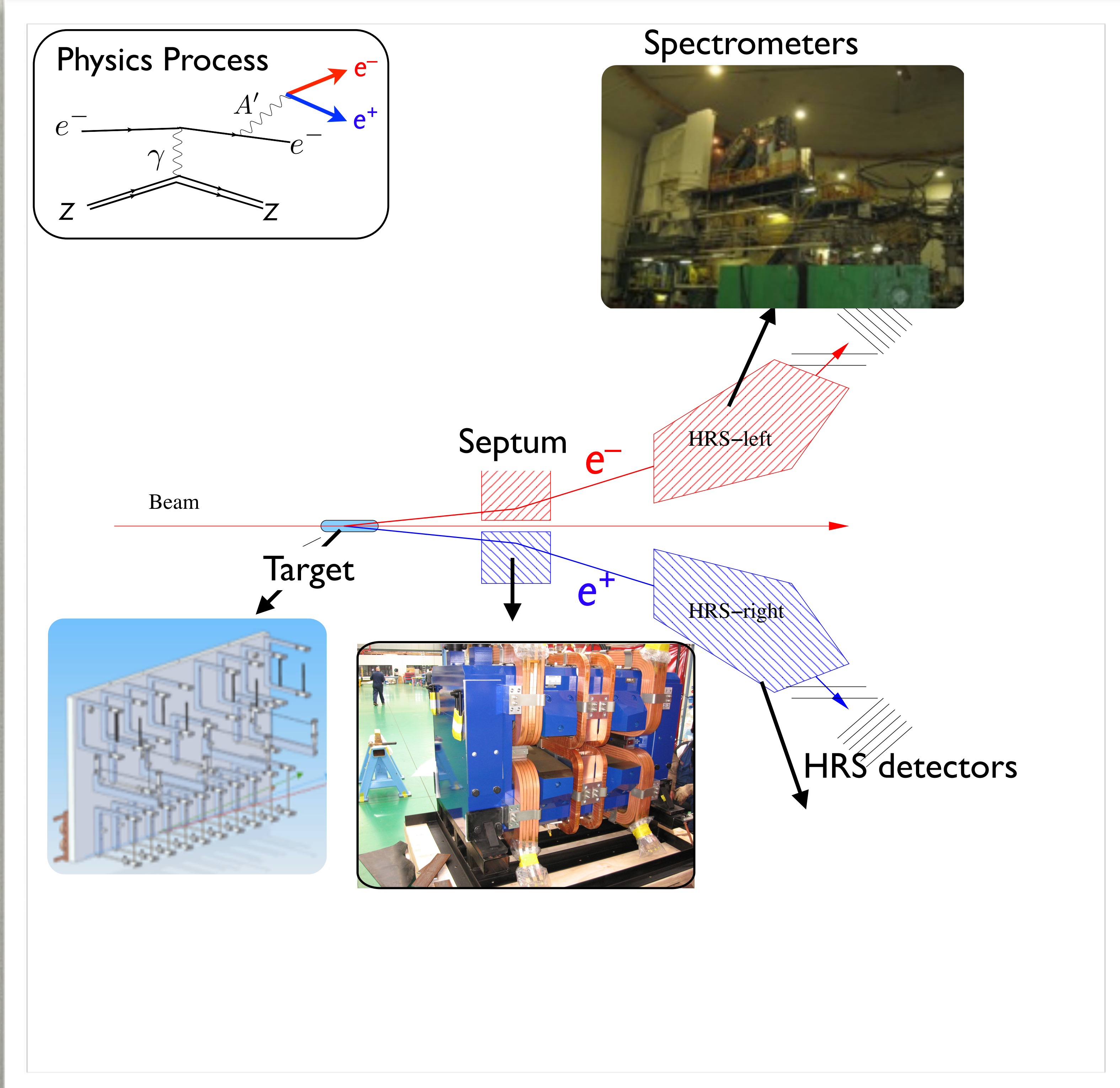
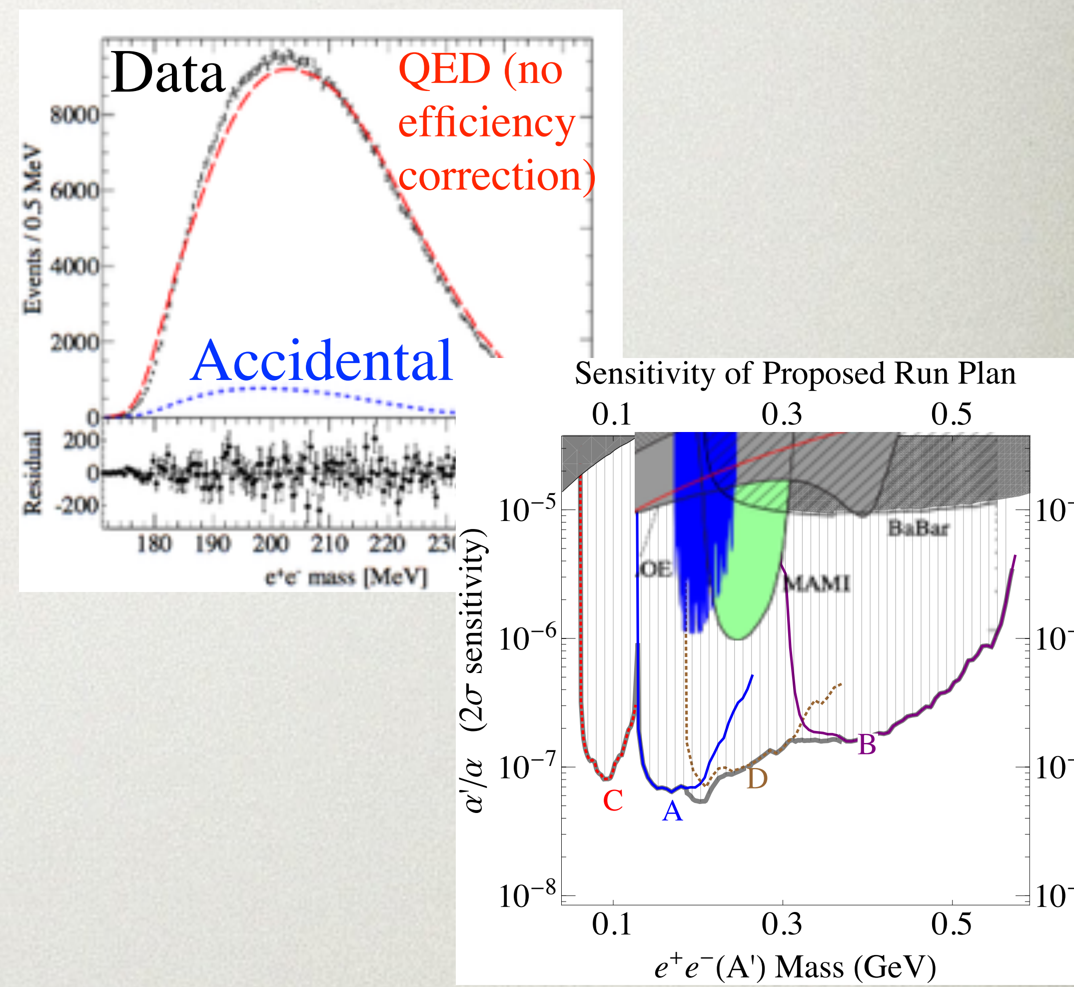


Status

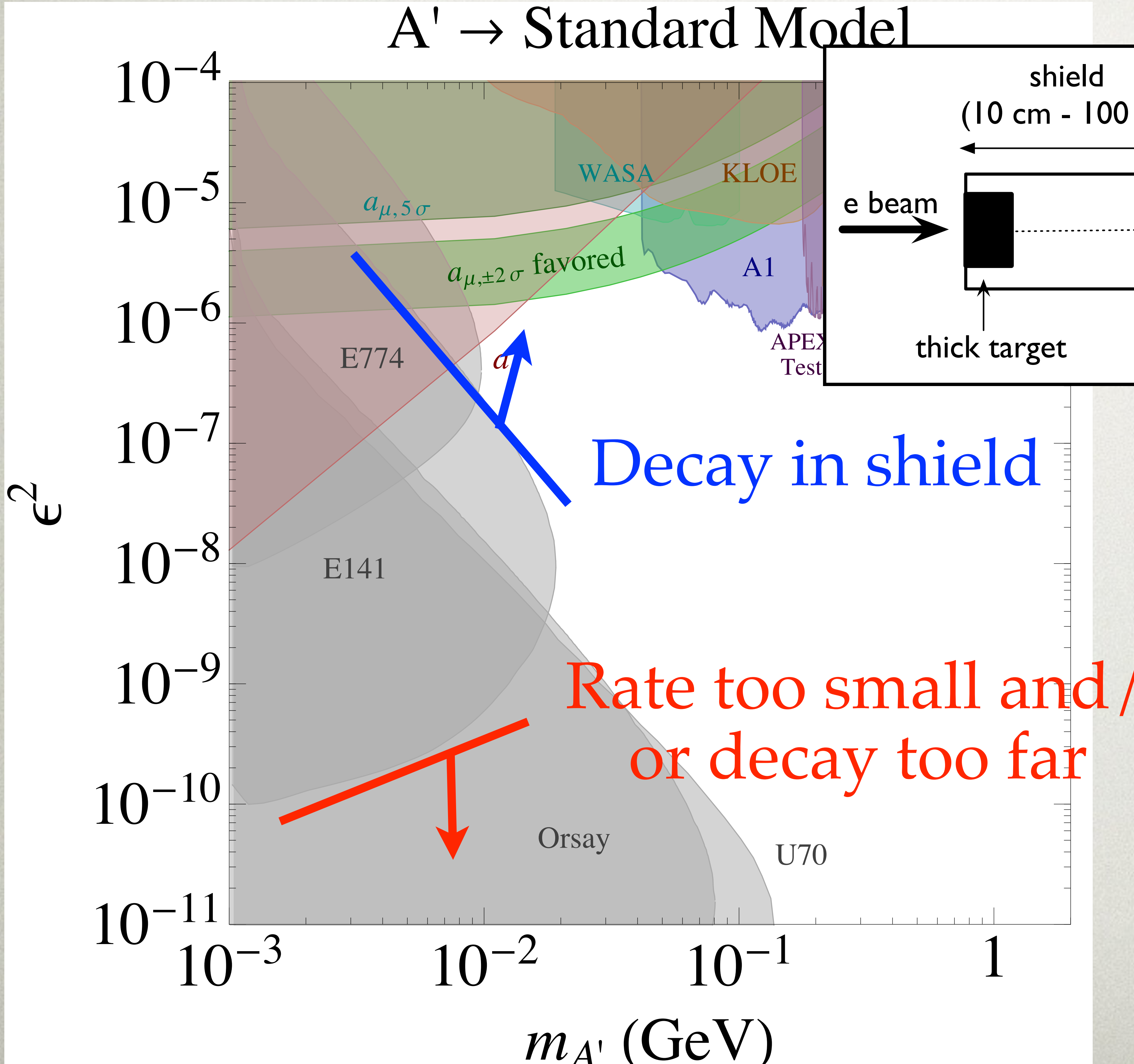
Test run (2010): concept & technical demonstration; weekend run achieved world-record sensitivity

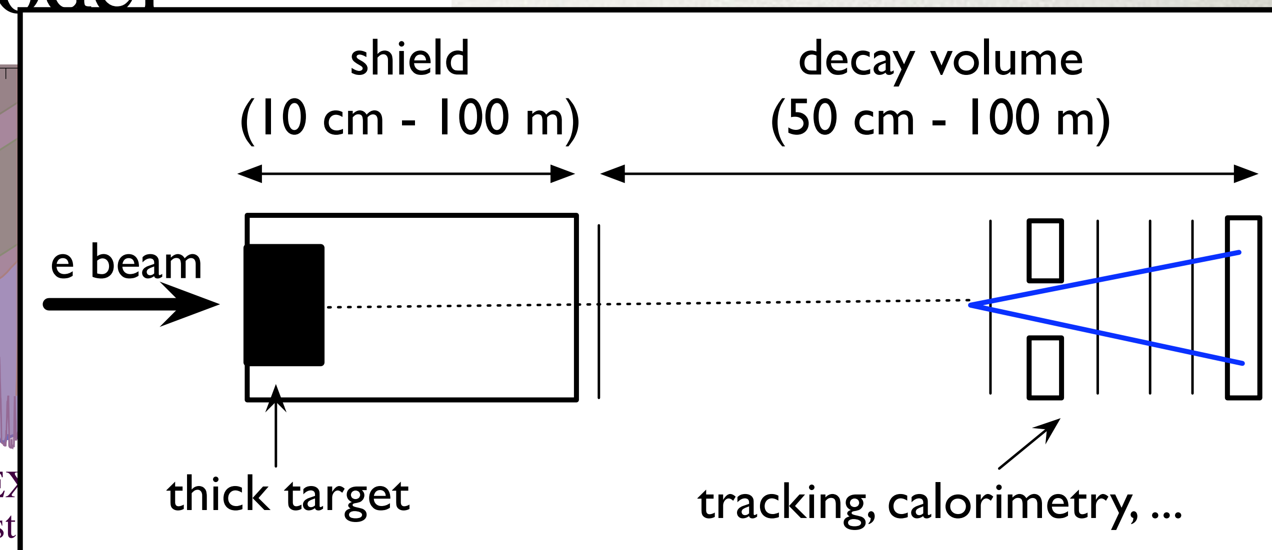


Full run: Prioritized by JLab, funded, projected to run 2017

- Optimized septa magnet constructed
- Smaller beam line items funded
- HRS detectors ready to go

Turning Weakness Into Strength

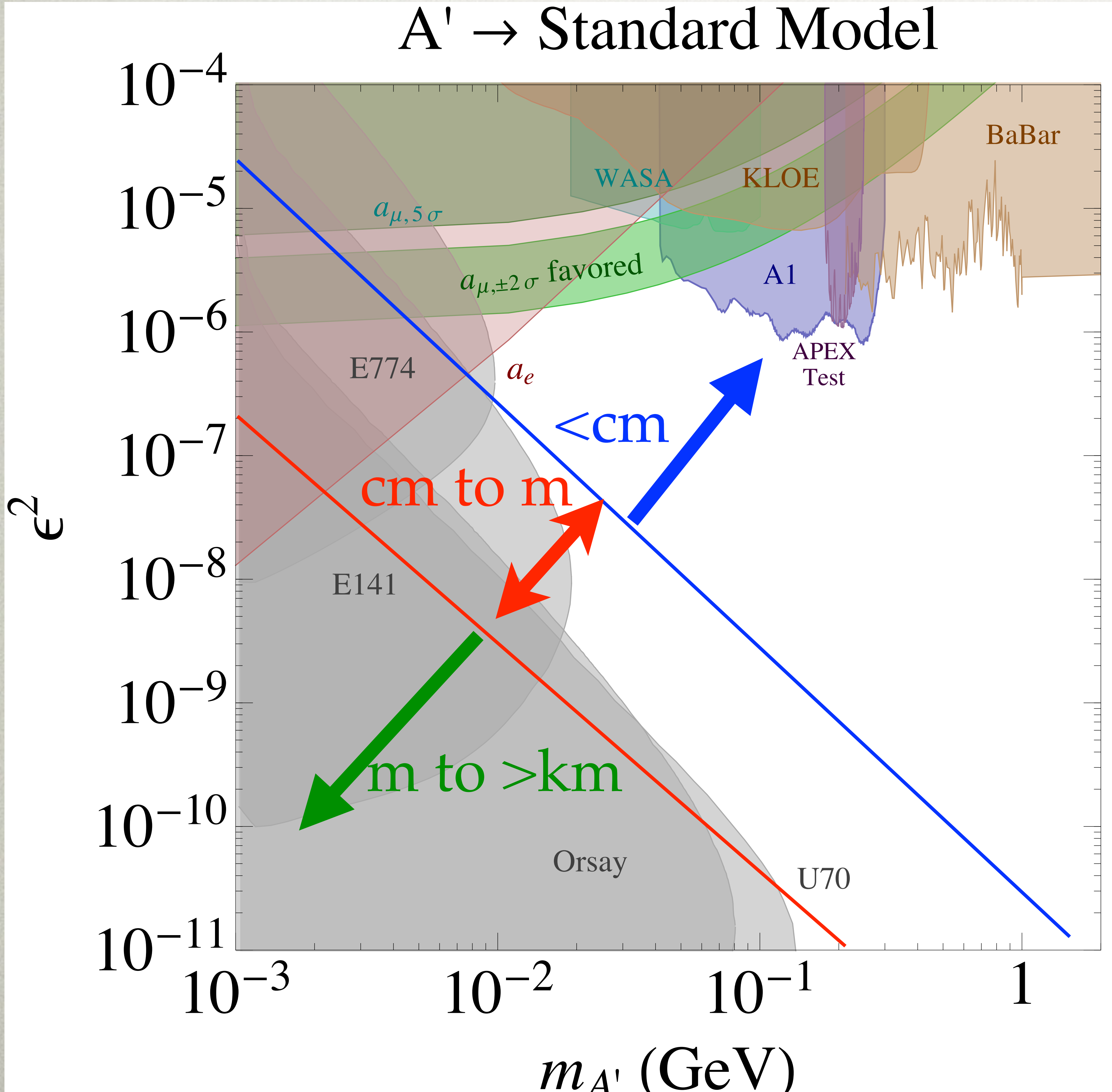




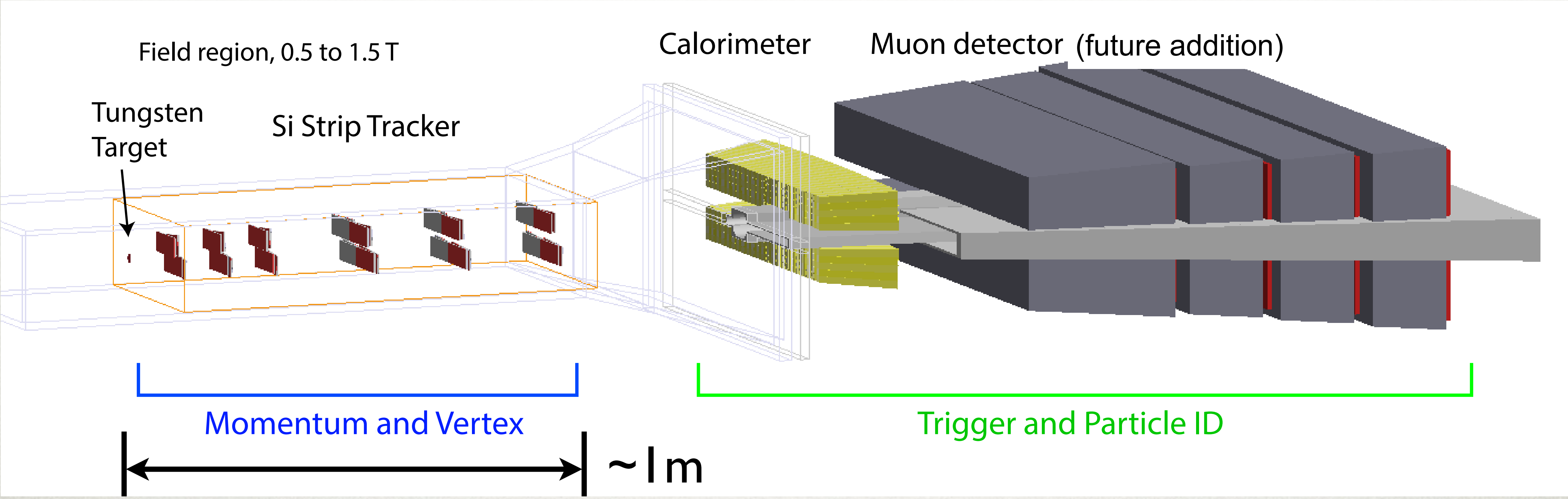
Lab-frame lifetime

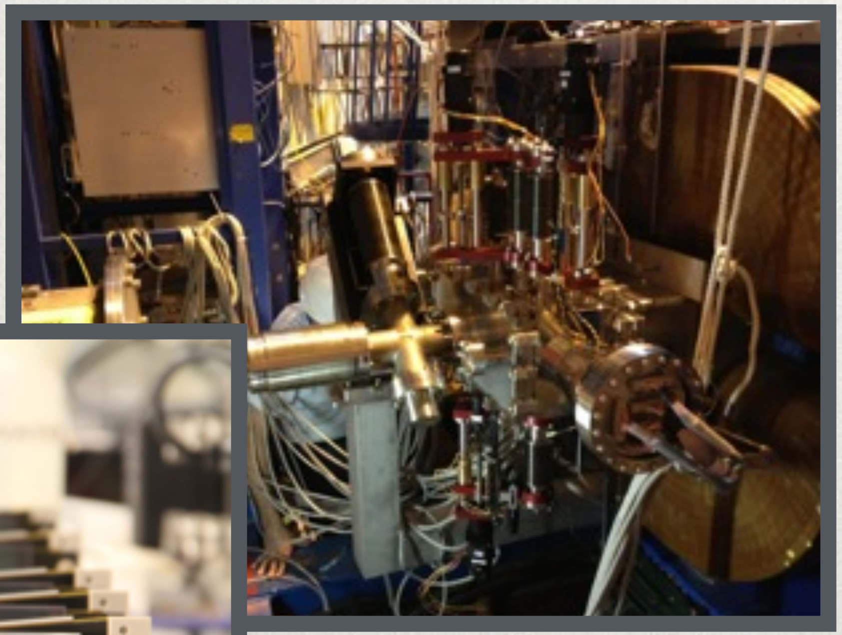
$$\propto \frac{E}{m_{A'}^2 \epsilon^2}$$

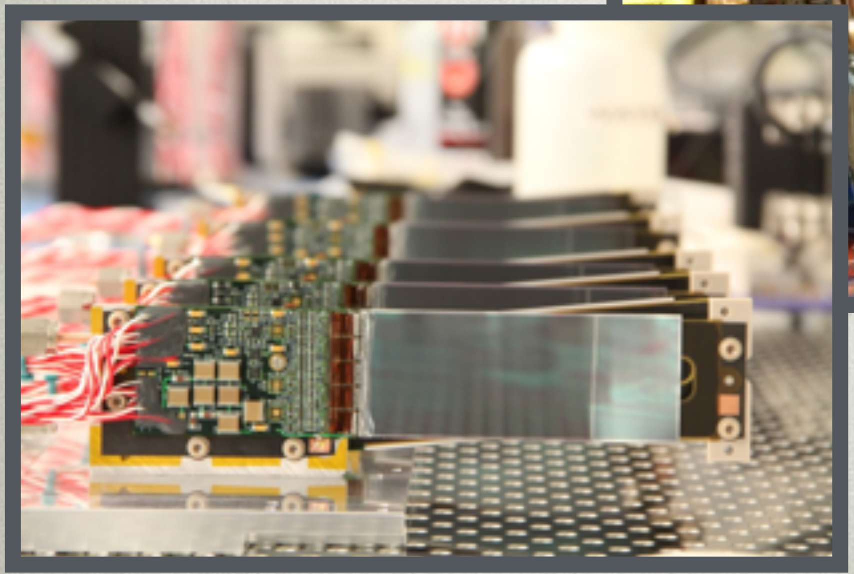
Turning Weakness Into Strength



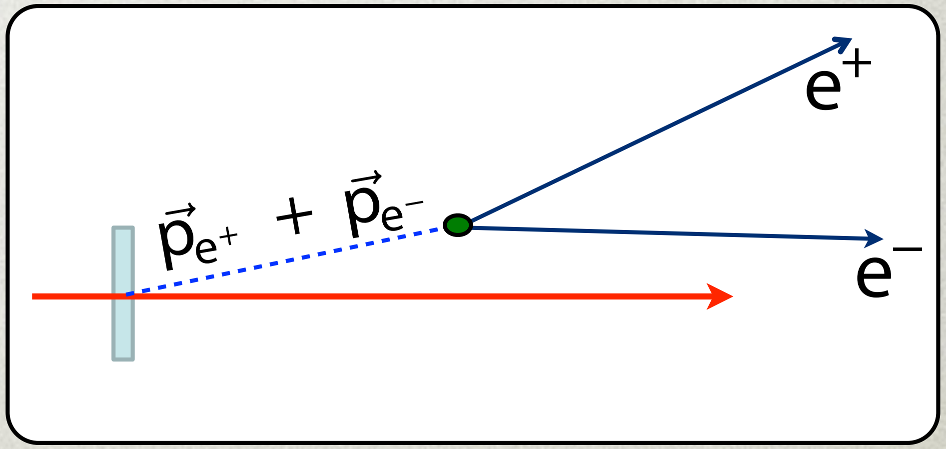
HPS: Resonance + Vertex Searches







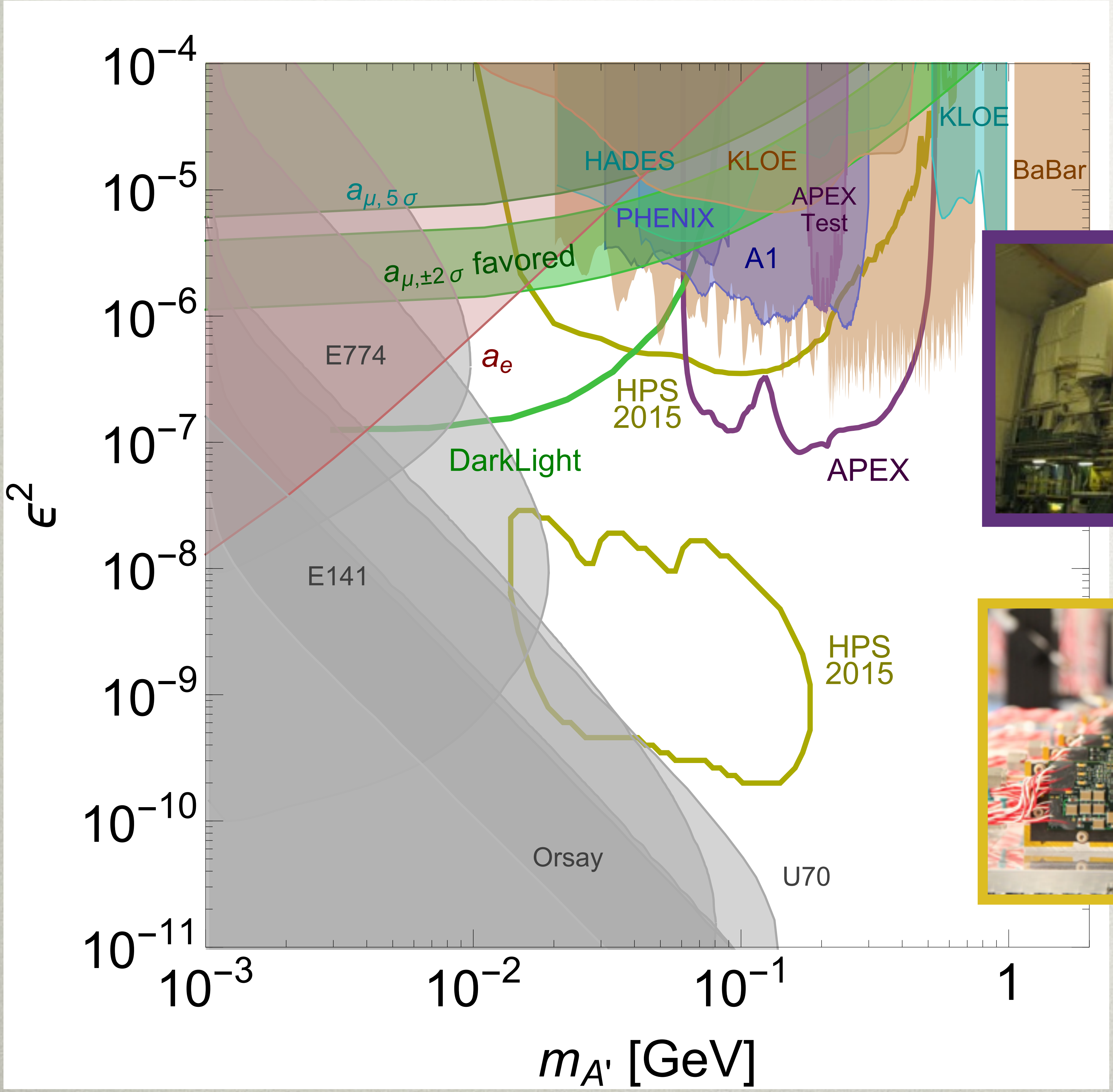
Allows sensitivity to very weak couplings with ~cm decay vertex

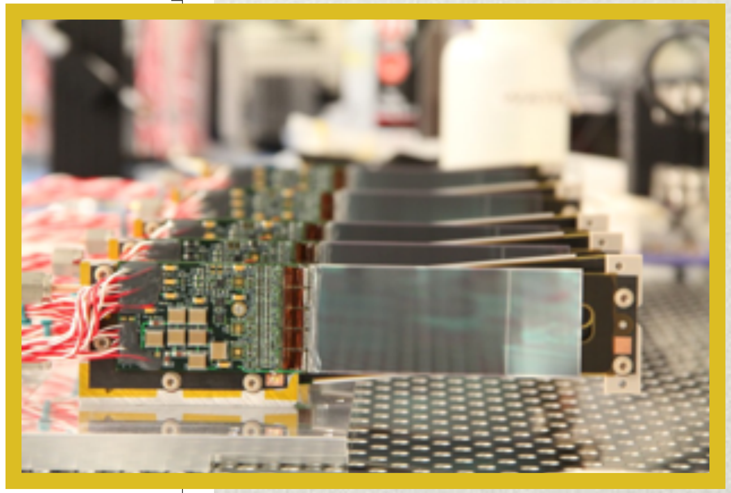


Engineering run this spring!

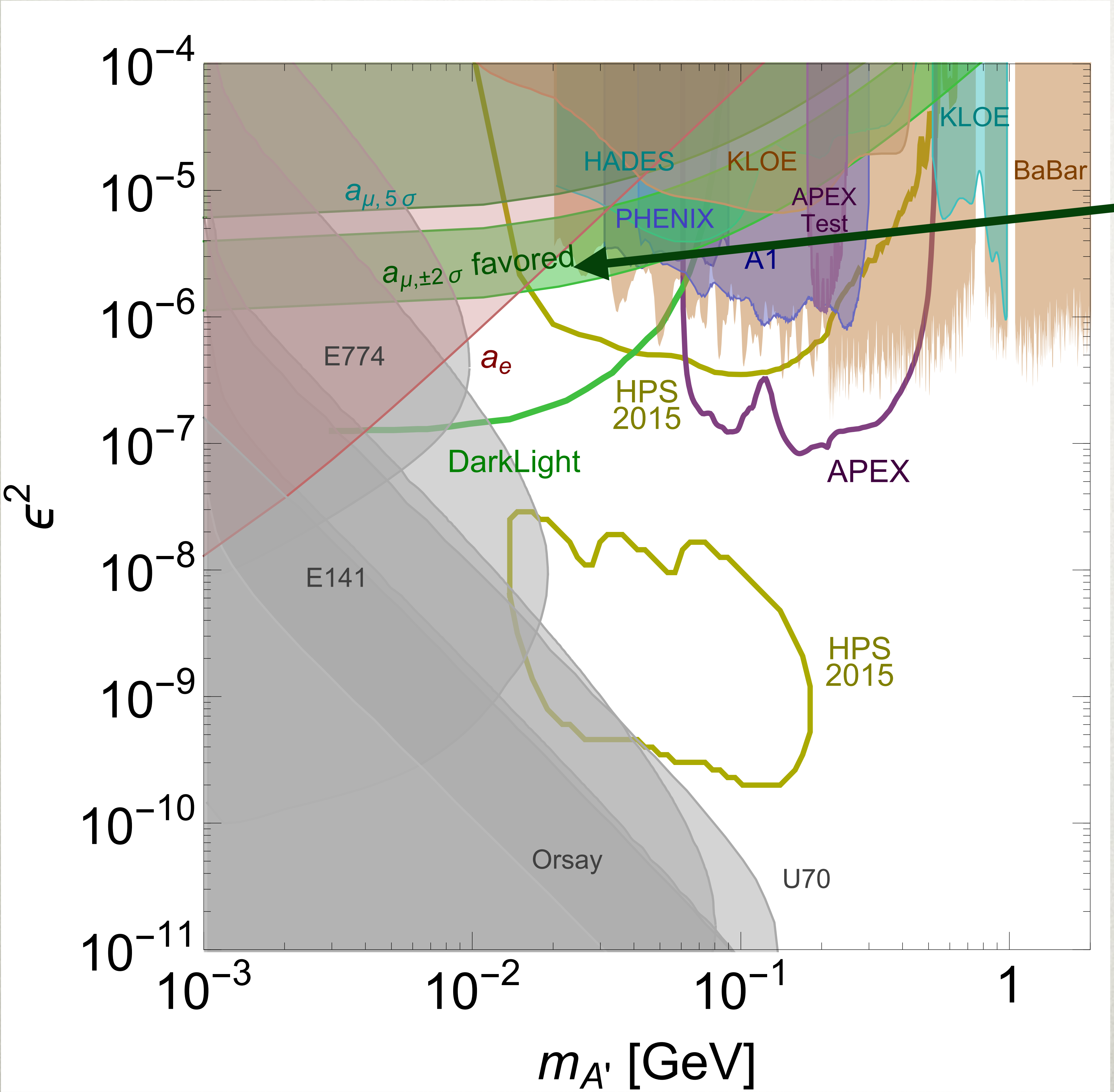
https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment

Projections for 2015-17



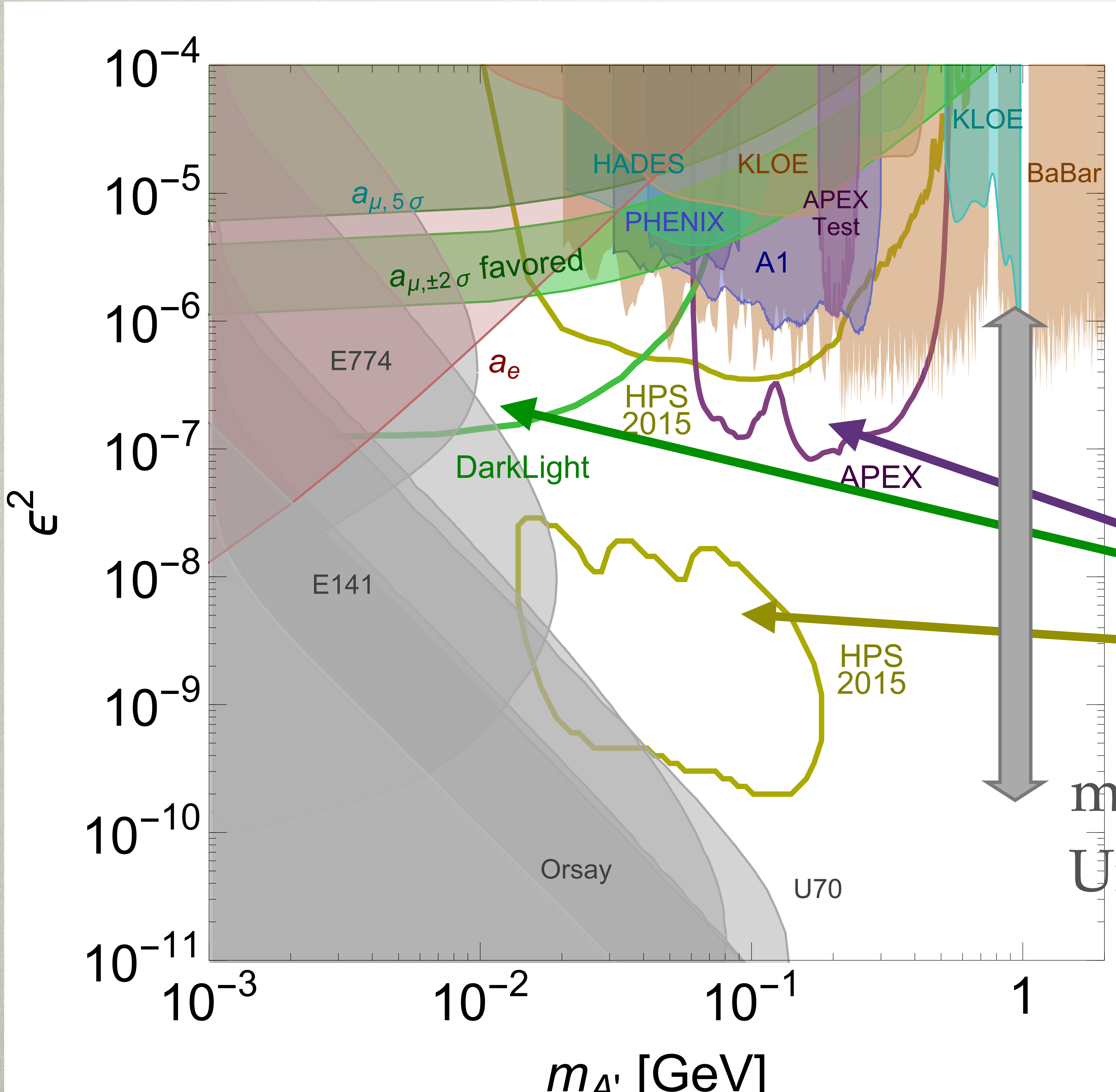


Projections for 2015-17



Tested this interpretation of muon magnetic moment anomaly!

Projections for 2015-17

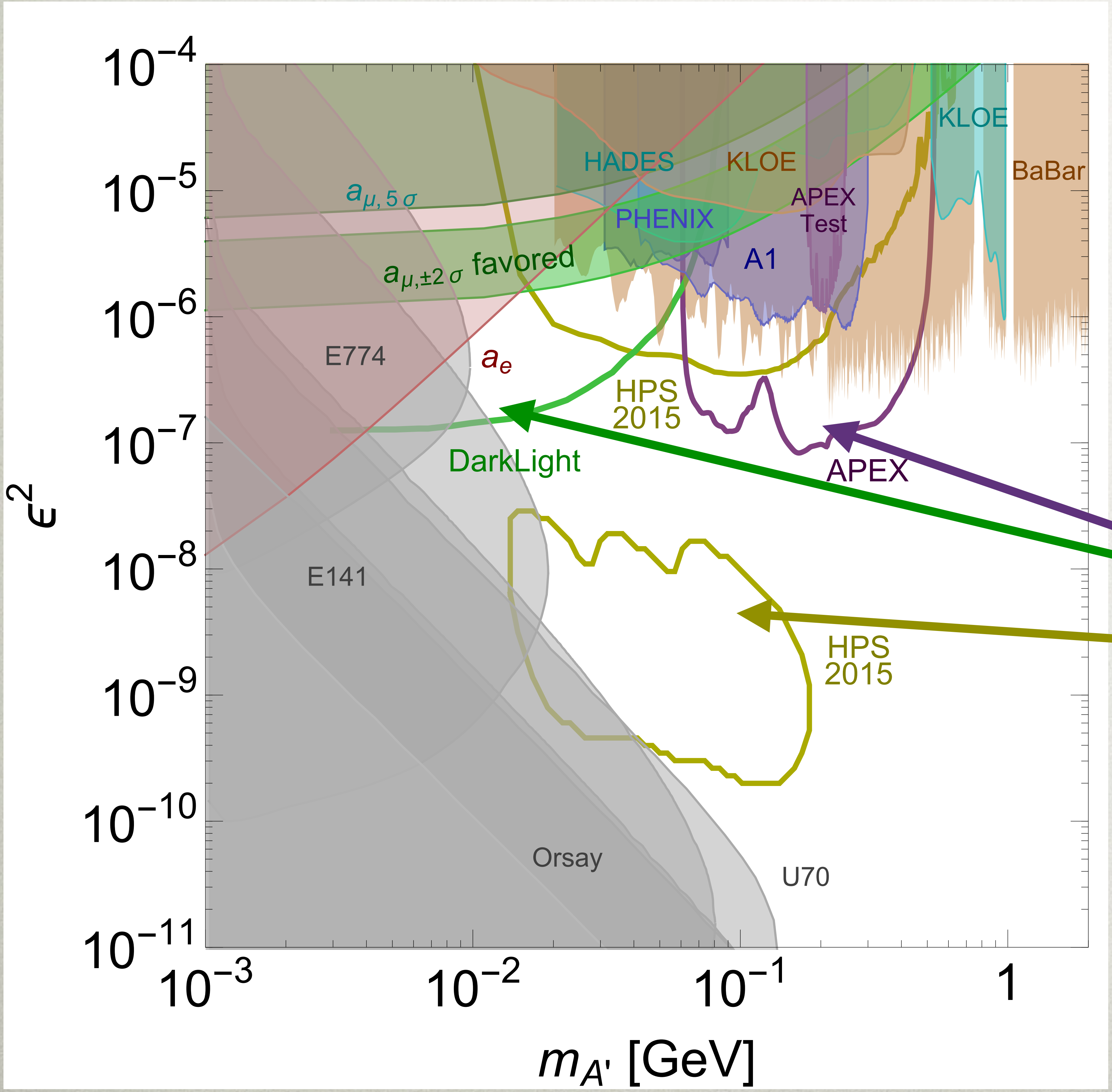


Upcoming experiments explore this region from above: APEX, DarkLight

and below: HPS

mixing in Grand Unified Theories

Projections for 2015-17

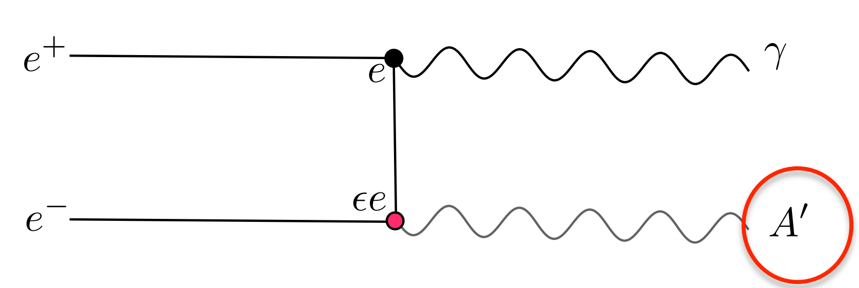


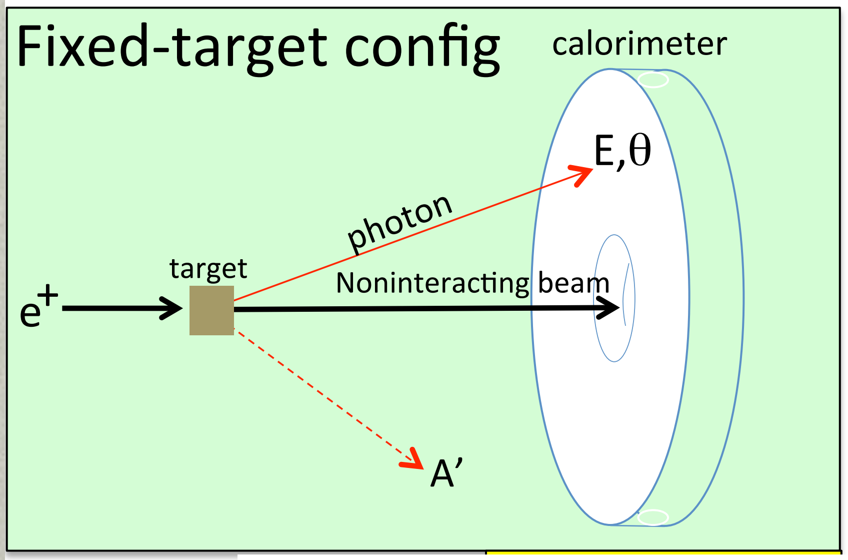
Also interesting mass range for dark matter interactions

Dark Photons at Cornell

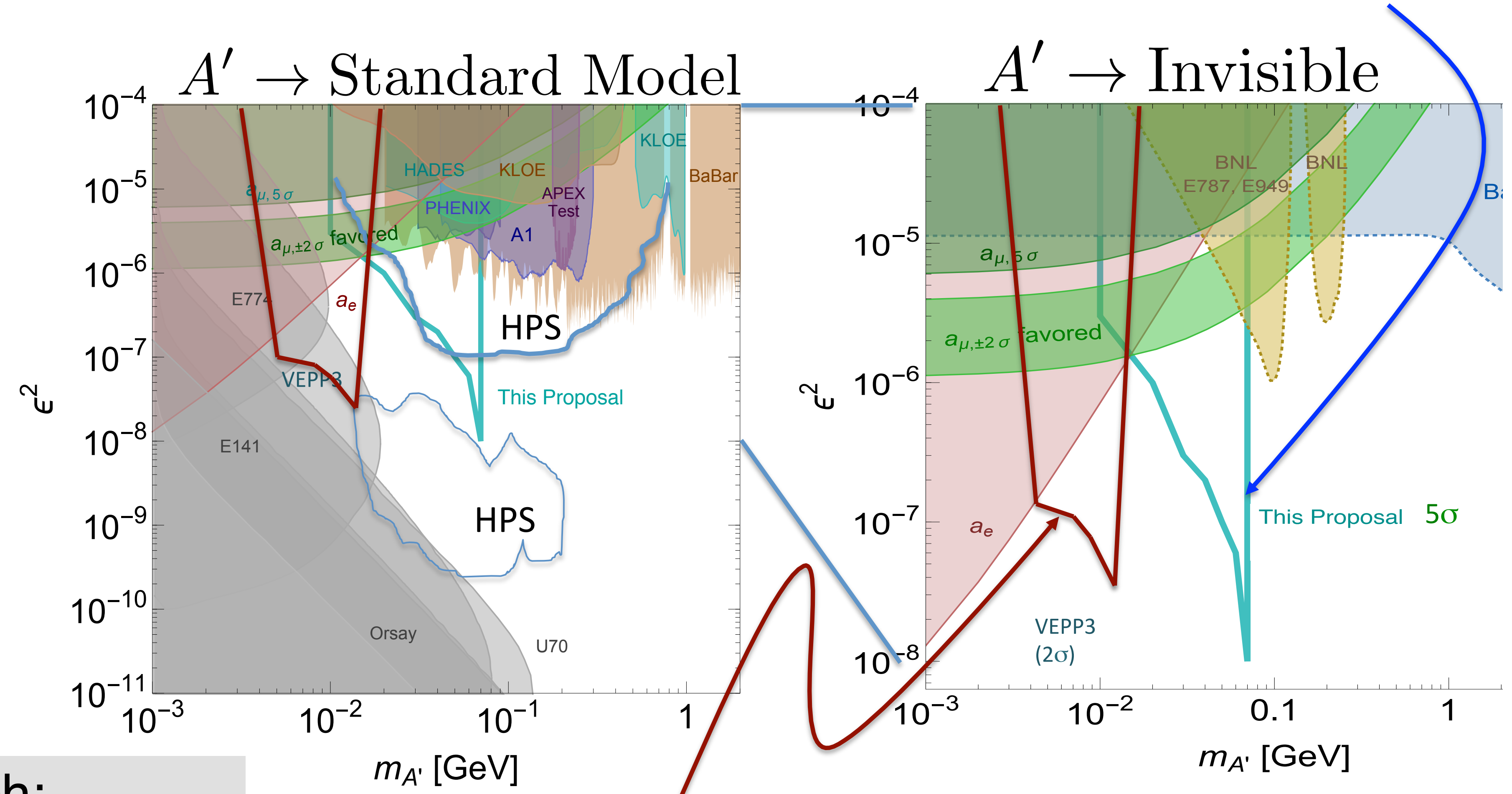
(figures from J. Alexander's talk to APEX collab. mtg, April 2015)

Dark Model





E_{beam}=5.3GeV, I^{avg}_{beam}=2.3nA, Lumi = 1.0x10^{34}, T = 10^{7}sec, 5-sigma excl



"Sister experiment" at Novosibirsk (proposed)

- *Missing mass* search:
  - Independent of A' decay mechanism
  - Bump hunt
  - Limited by sqrt(s)

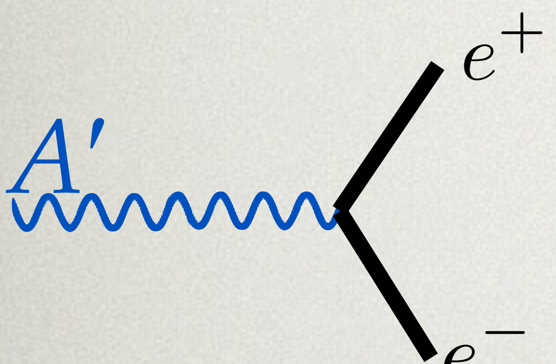
    $M'_A < \frac{1}{2}\sqrt{s} \approx \sqrt{m_e E_{beam}/2}$
  - 5 GeV beam: $M_{A'}$ < 71 MeV
- Need positrons
- *This is the basic idea for the A' search at Cornell.*

Complementary in mass-coupling space and independent of A′ decay mode

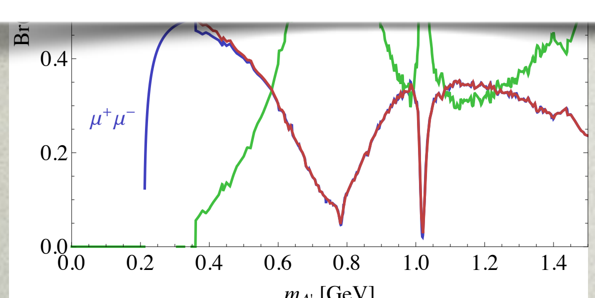
A Field Guide to Dark Forces

Decay

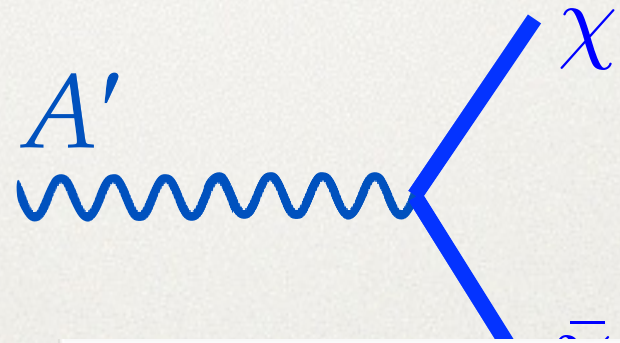
<u>"Minimal" Decay:</u>



Major advances in last 5 years!



<u>"Generic" Decay:</u>



(not ε-supressed!)

*If **any** dark-sector matter χ has* ... *this* ... *inates*

Huge upcoming opportunity!

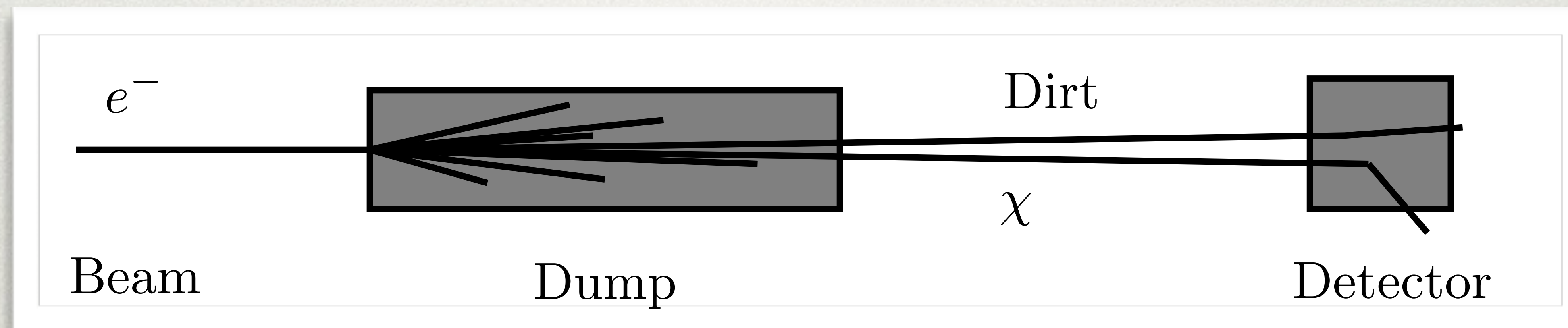
$A' \to$ >2 charged particles

searches at BaBar and KLOE

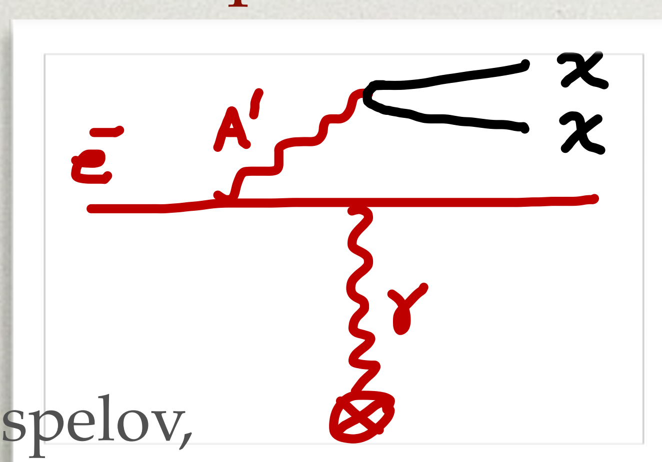
To test "dark sector" idea, we need to search for both!

Dark Matter from the Dark Sector

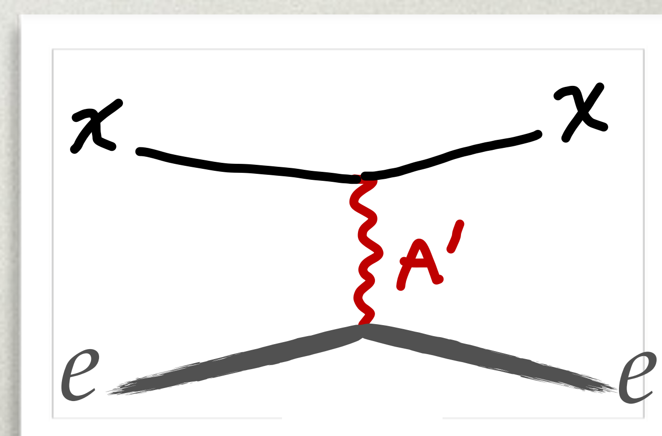
The **same interaction** that produces dark matter in the early Universe can also lead to production and detection in laboratory experiments!



Produce DM through the portal…



…detect its scattering downstream



Izaguirre, Krnjaic, Schuster & NT PRD.88.114015 and 1403.6826

Proton beams: Batell, deNiverville, Ritz, Pospelov, McKeen, Dharmapalan, …

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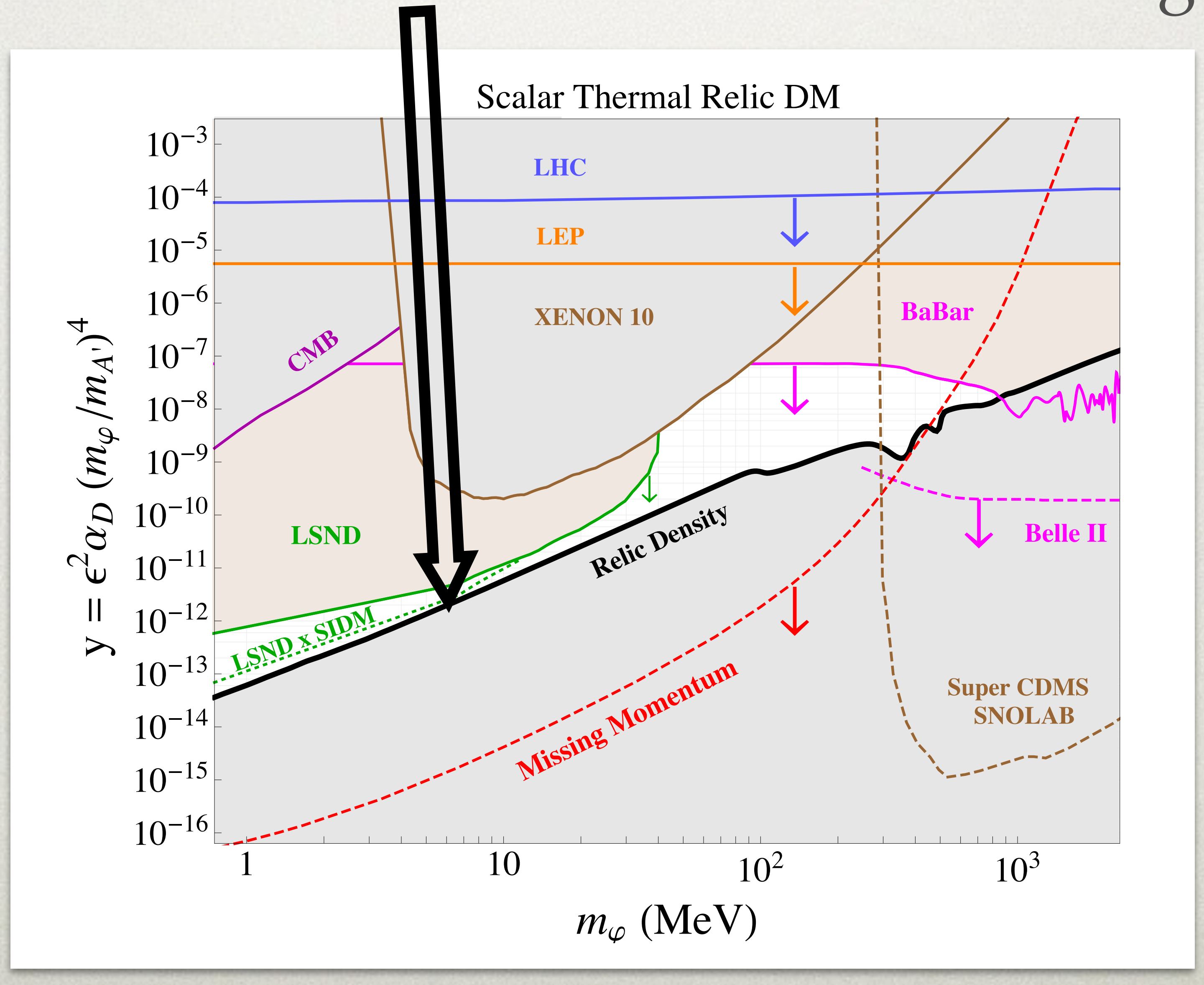
(thermal abundance ⇒ **minimum** interaction strength)



Izaguirre, Krnjaic, Schuster, NT 1505.00011

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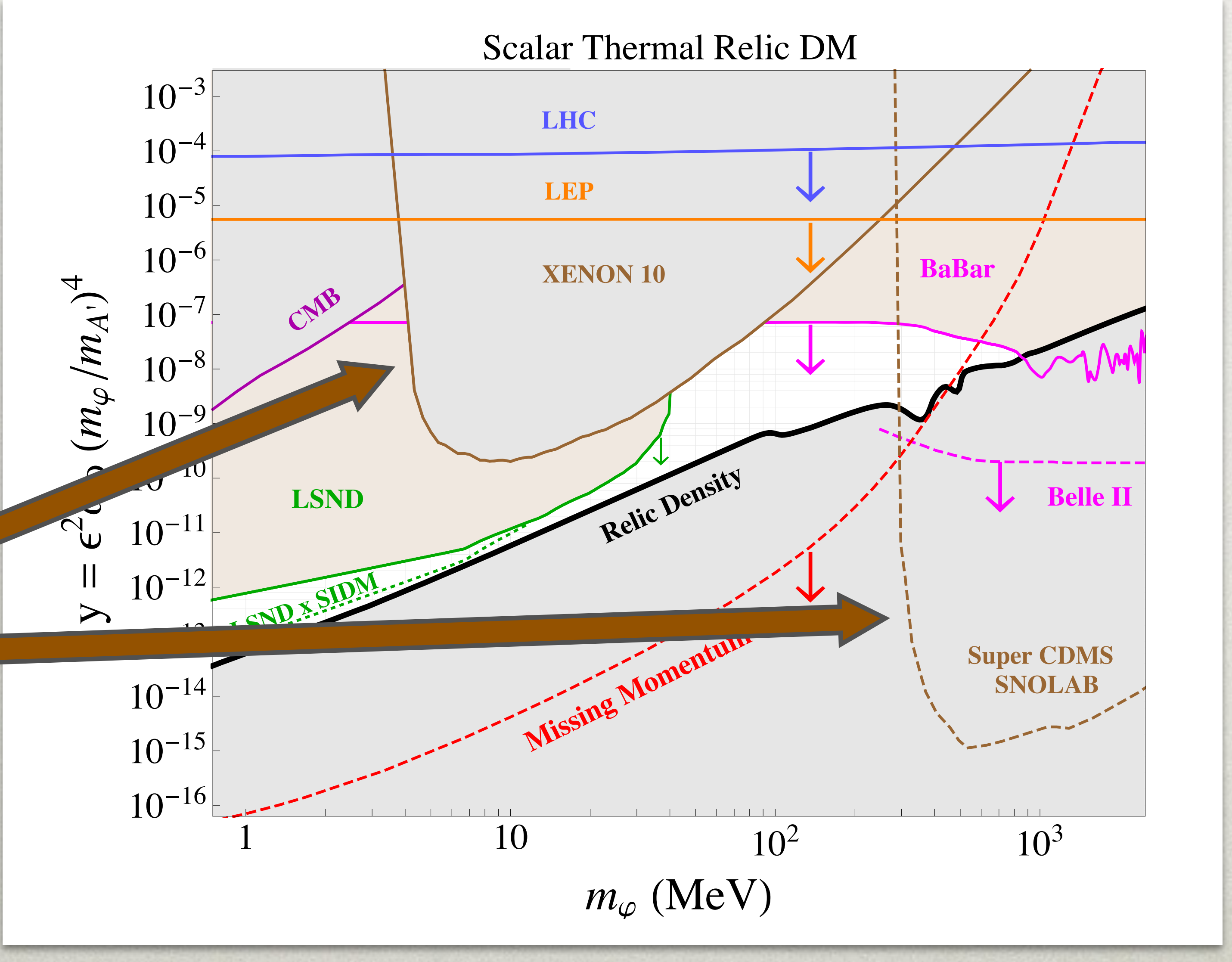

Izaguirre, Krnjaic, Schuster, NT 1505.00011

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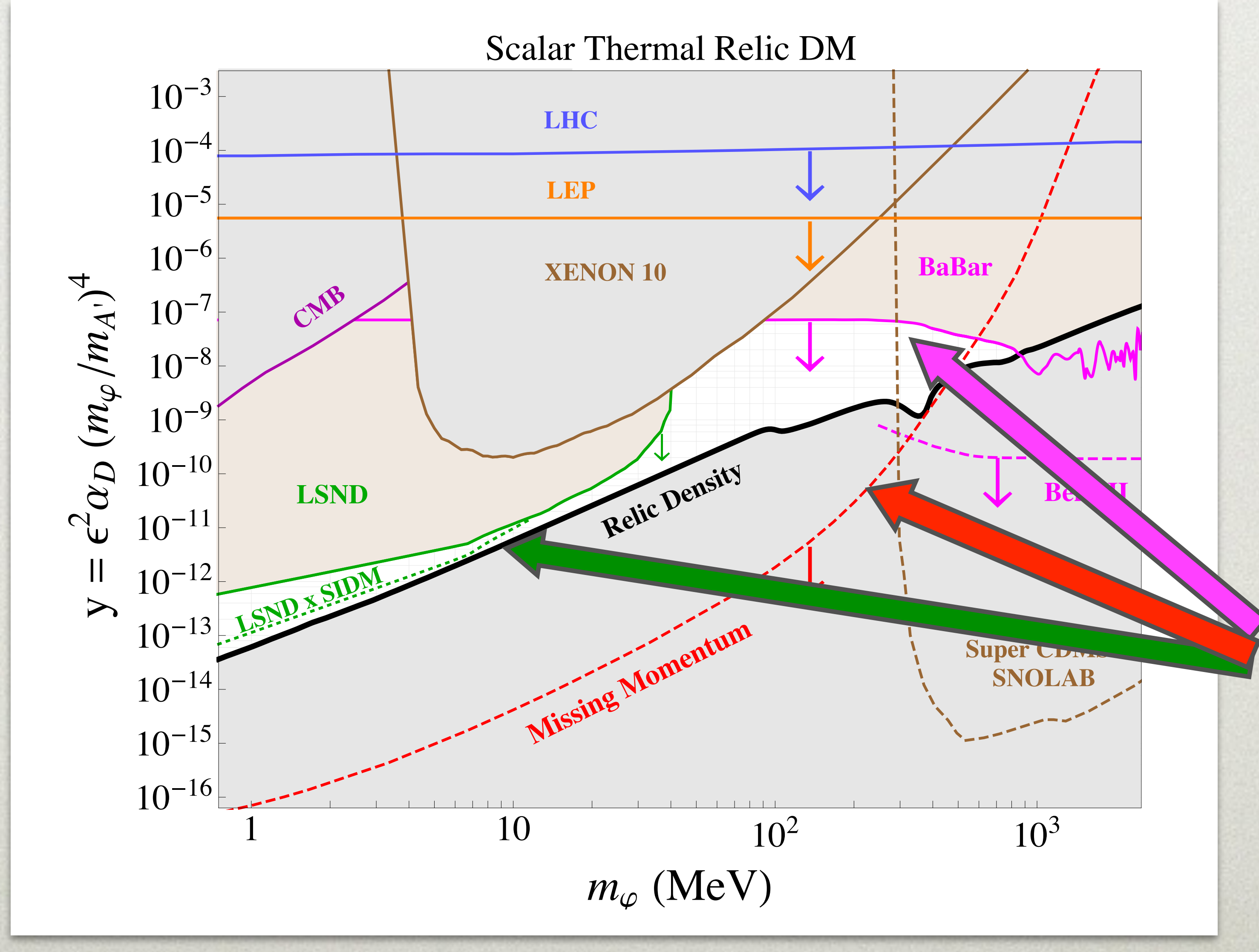
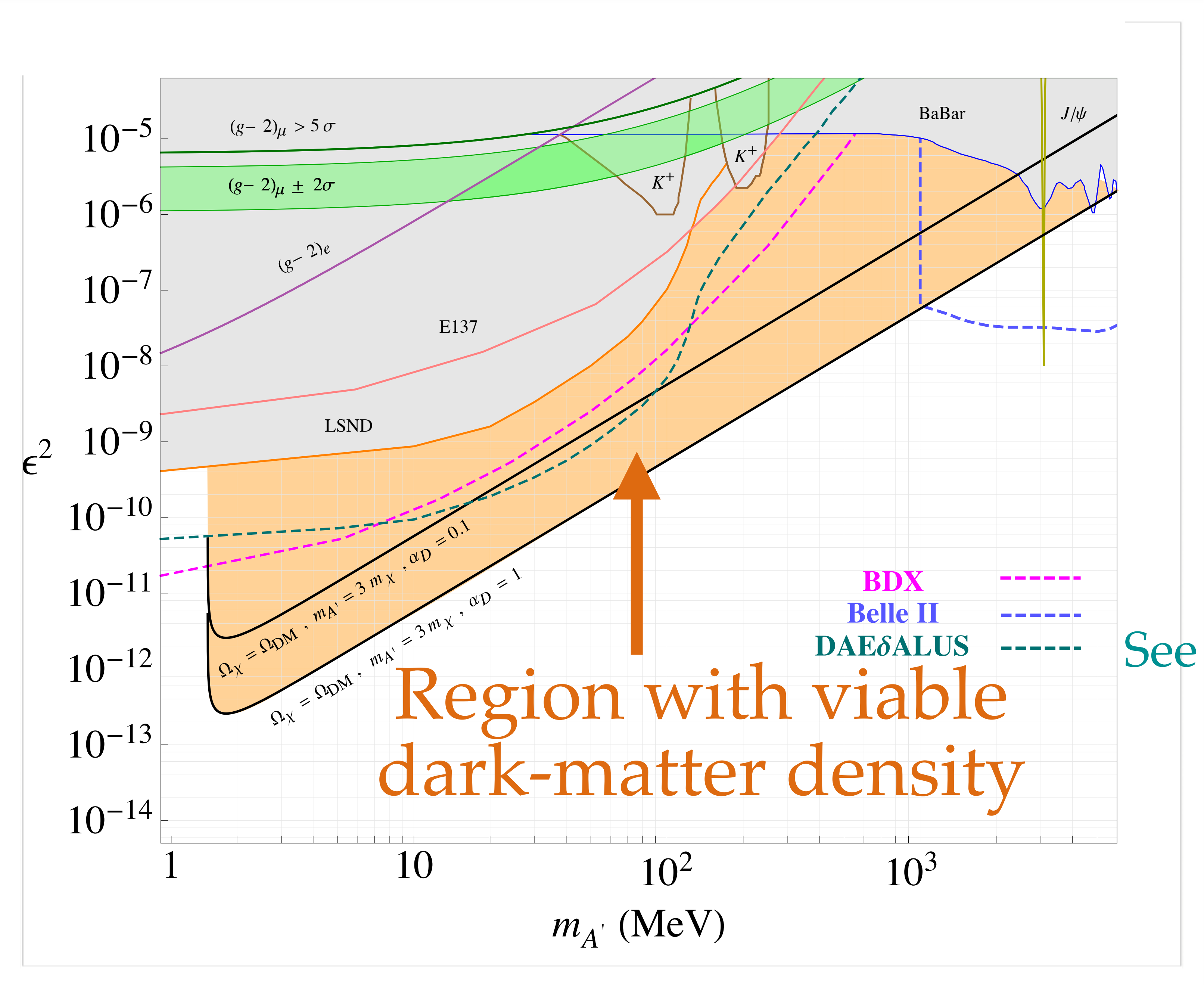


More robustly tested by GeV-scale accelerator experiments

Izaguirre, Krnjaic, Schuster, NT 1505.00011

Dark Matter from the Dark Sector

Directly in terms of the mixing ϵ^2…focus on low masses

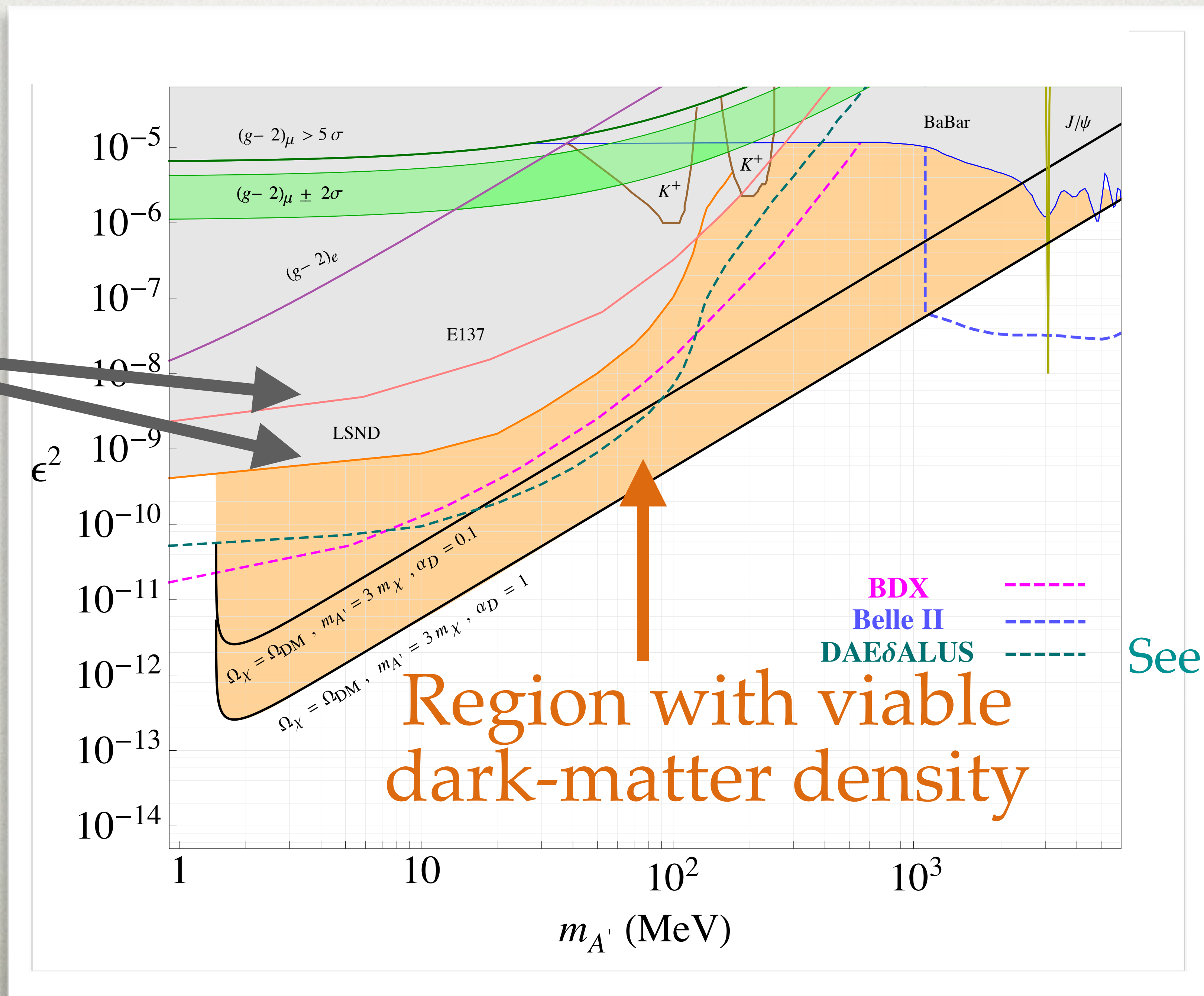


See Kahn, Krnjaic, Thaler, Toups 1411.1055

Dark Matter from the Dark Sector

Directly in terms of the mixing ϵ²…focus on low masses

Constraints from past e^- and p beam-dump experiments

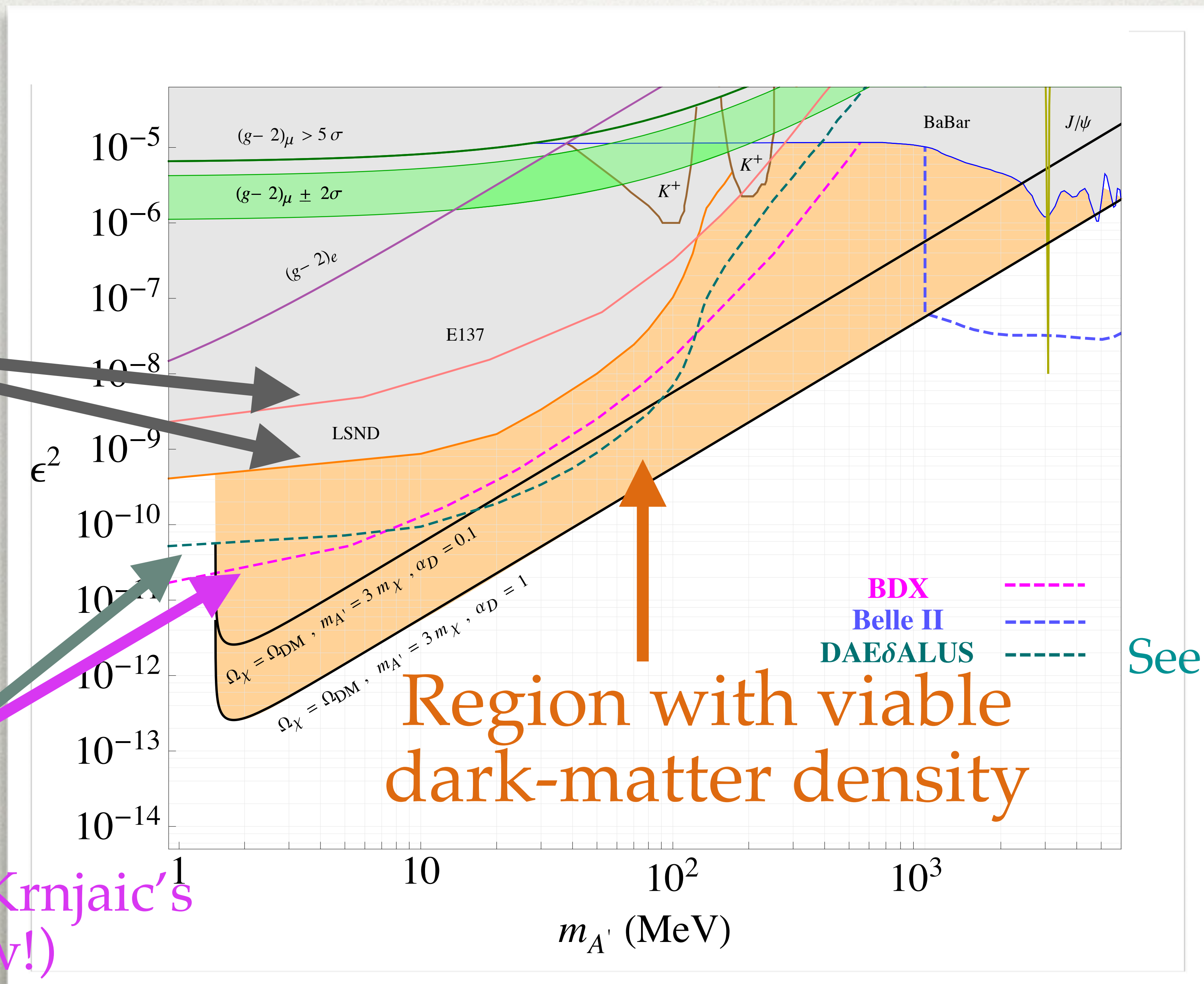


See Kahn, Krnjaic, Thaler, Toups 1411.1055

Dark Matter from the Dark Sector

Directly in terms of the mixing ϵ^2…focus on low masses

Constraints from past e^- and p beam-dump experiments



Future prospects (see Gordan Krnjaic's talk tomorrow!)

See Kahn, Krnjaic, Thaler, Toups 1411.1055

Dark Matter from the Dark Sector

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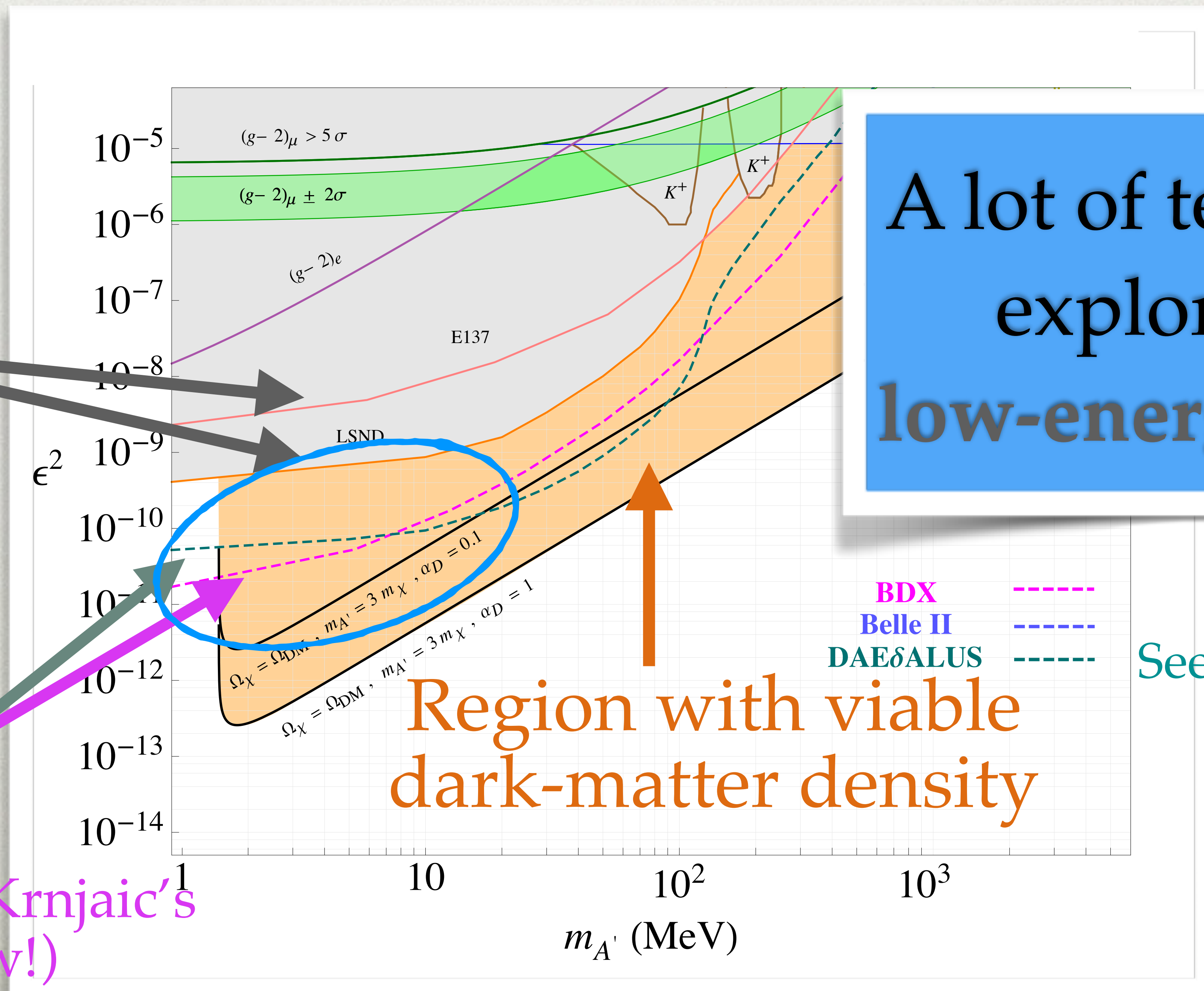

See Kahn, Krnjaic, Thaler, Toups 1411.1055

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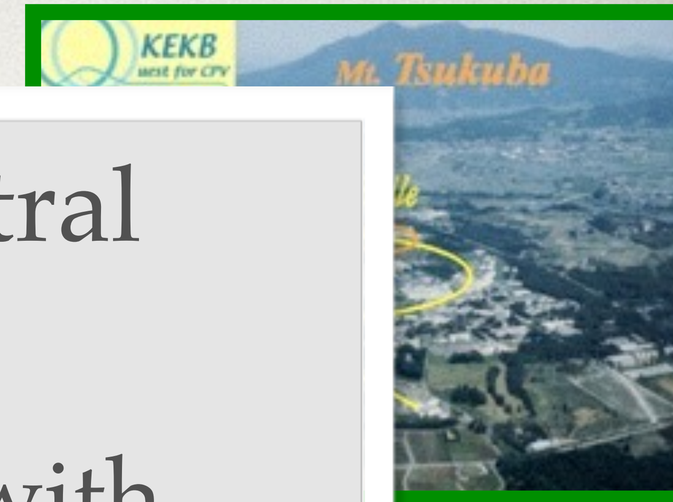
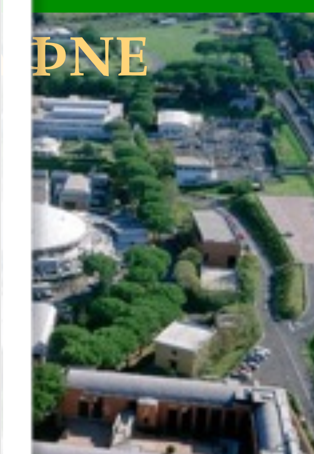
The Future Ahead





- Portals to explore physics neutral under Standard Model
  - Organize around **interaction** with ordinary matter, and visible vs. dark-sector decay
- Powerful sensitivity from current, planned, and ongoing experiments
- A lot of uncharted territory: opportunities abound for further exploration – and discovery – with intense electron beams!