Exploring Dark Sectors

New, Light Weakly-Coupled Particles

Rouven Essig

Yang Institute for Theoretical Physics
Stony Brook University

Co-conveners:
John Jaros (SLAC) & William Wester (Fermilab)

Snowmass 2013, NLWCP colloquium

Welcome to Colloquium

Three talks

- Exploring Dark Sectors (Dark Photons & sub-GeV Dark Matter)
  (Rouven Essig)
- Axions, Axion-like particles, & Chameleons
  (William Wester)
- Why Searches for Dark Sectors are Important
  (Nima Arkani-Hamed)

Panel Discussion

Moderator: *John Jaros*

Nima Arkani-Hamed, Brian Batell, Rouven Essig,
Michael Pivovaroff, Philip Schuster, William Wester

The State of Particle Physics 2013

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It is the result of several decades of
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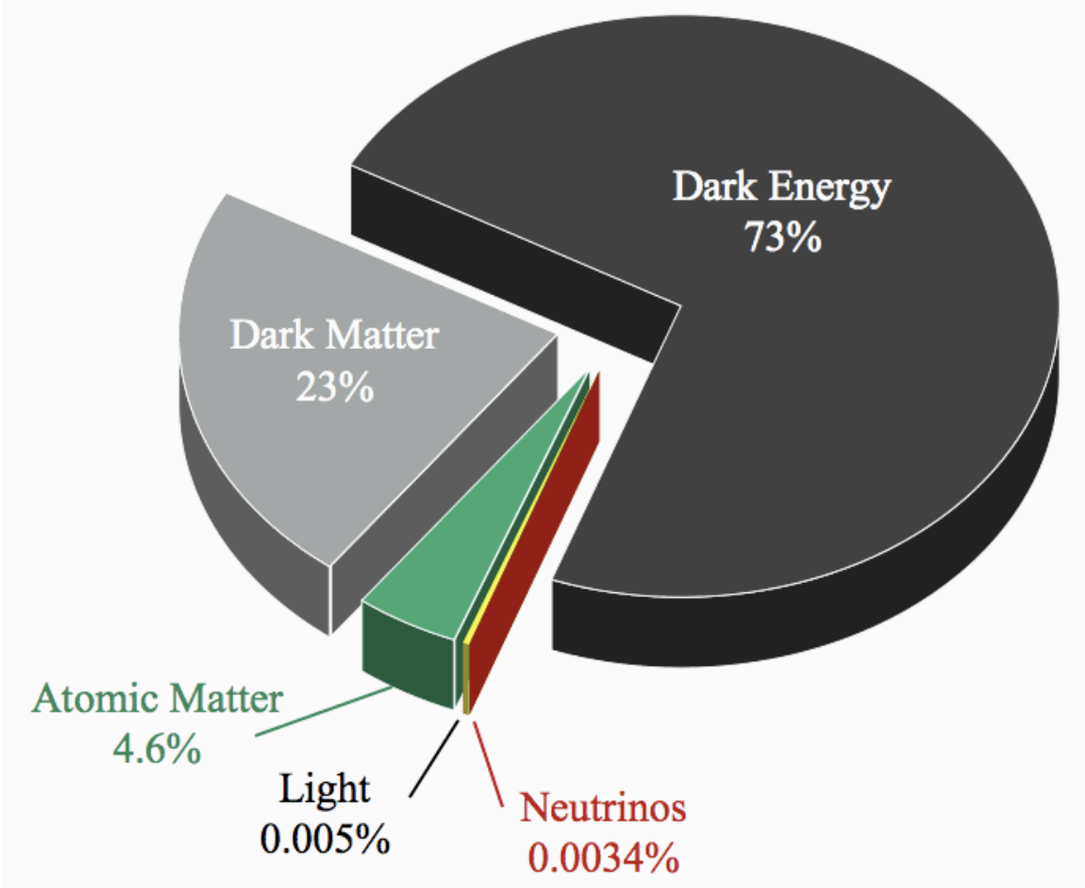
But we are not done!

Standard Model is not satisfactory

Several sharp pieces of evidence for New Physics exist

Dark Matter: powerful evidence for New Physics



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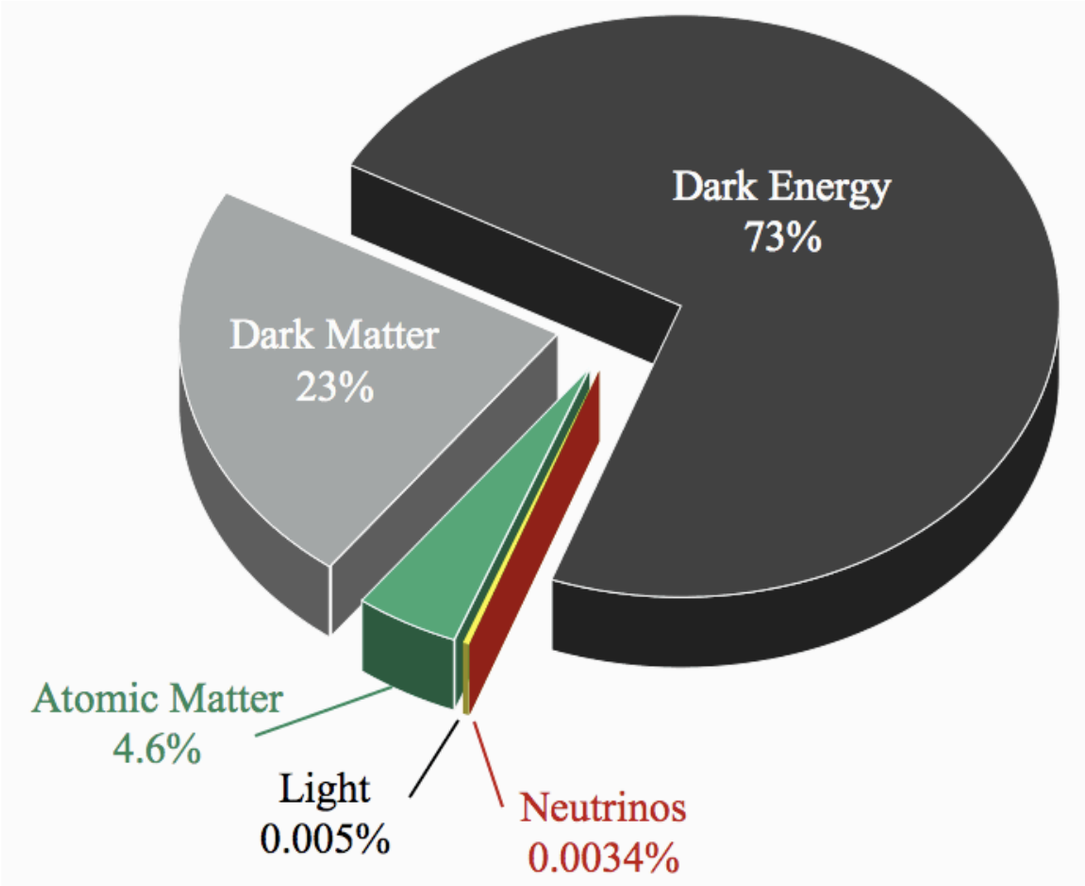

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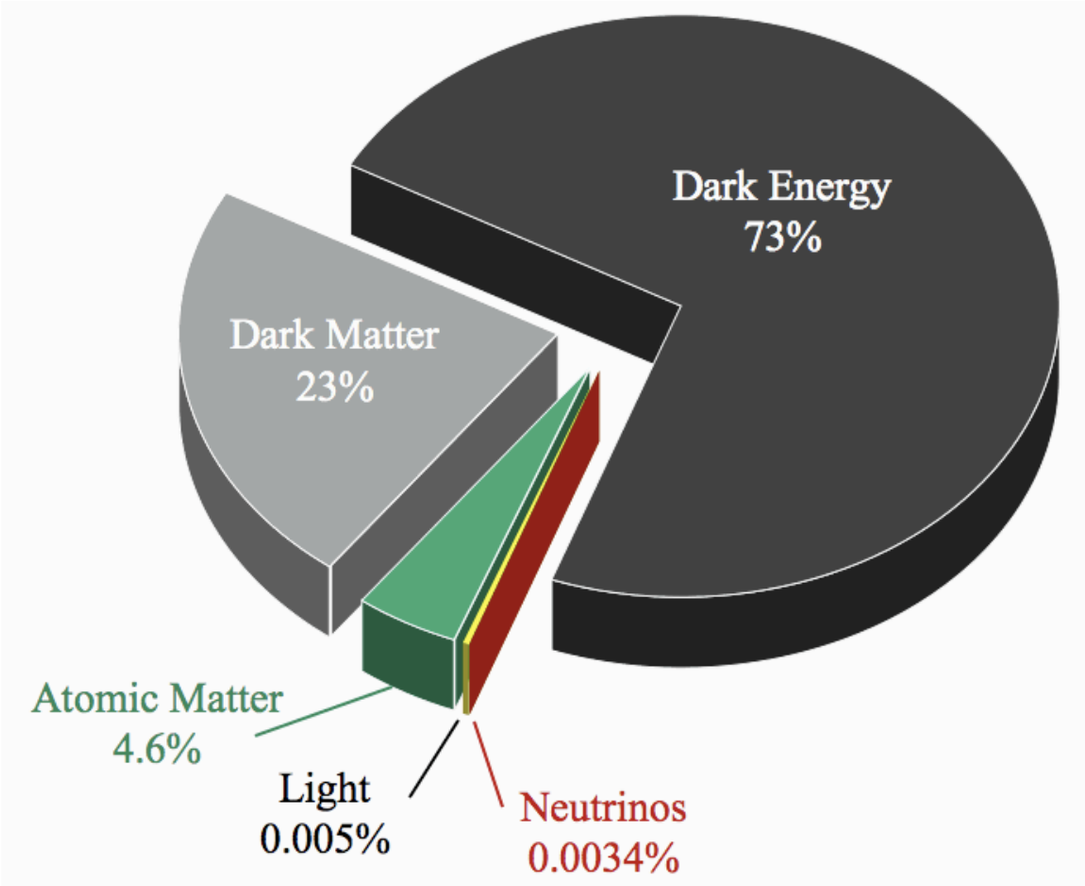

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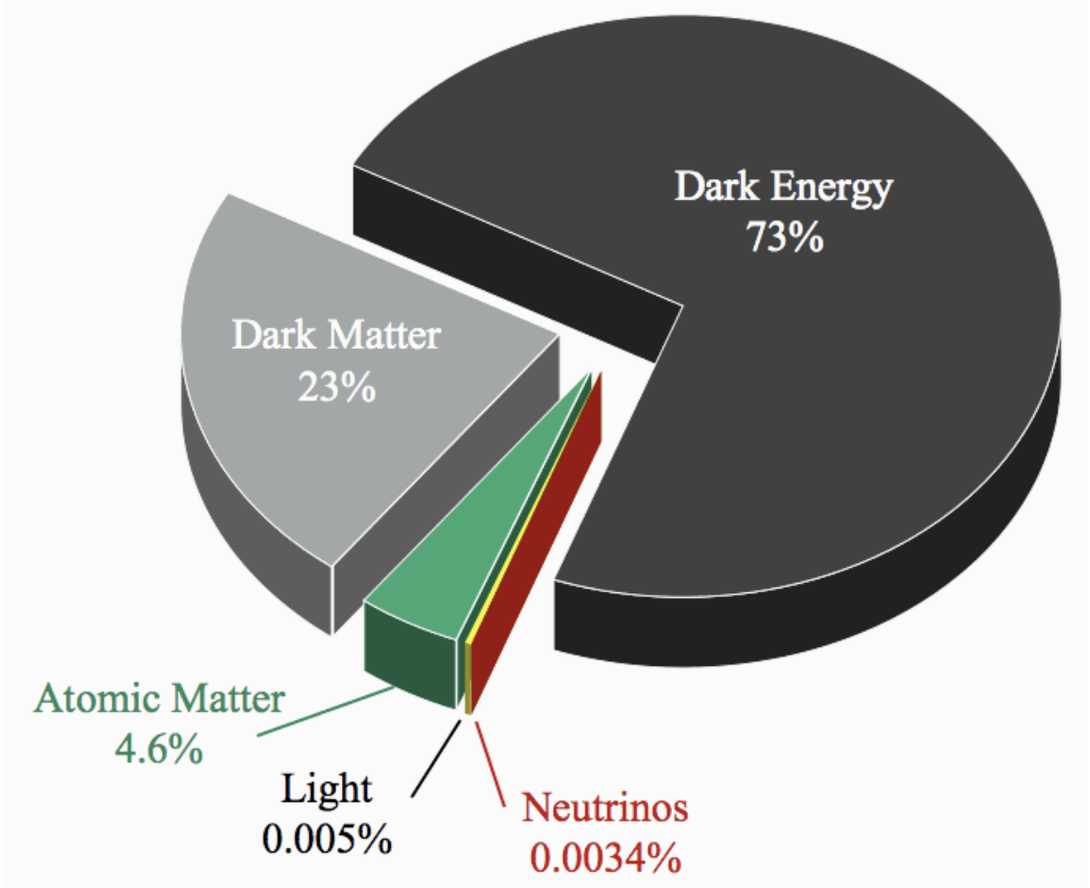

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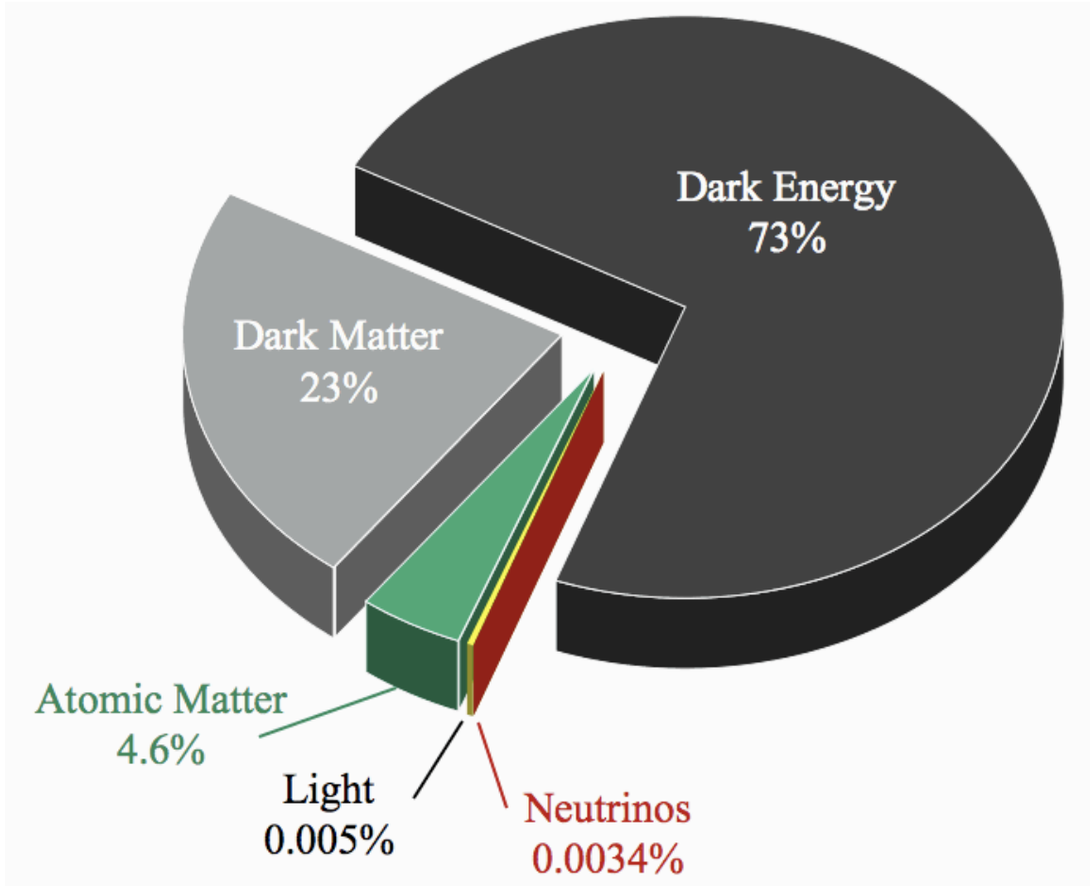
Dark matter suggests the presence of a dark sector,
neutral under all Standard Model forces

Many, rich Dark Sectors?

Why should Standard Model sector be special?



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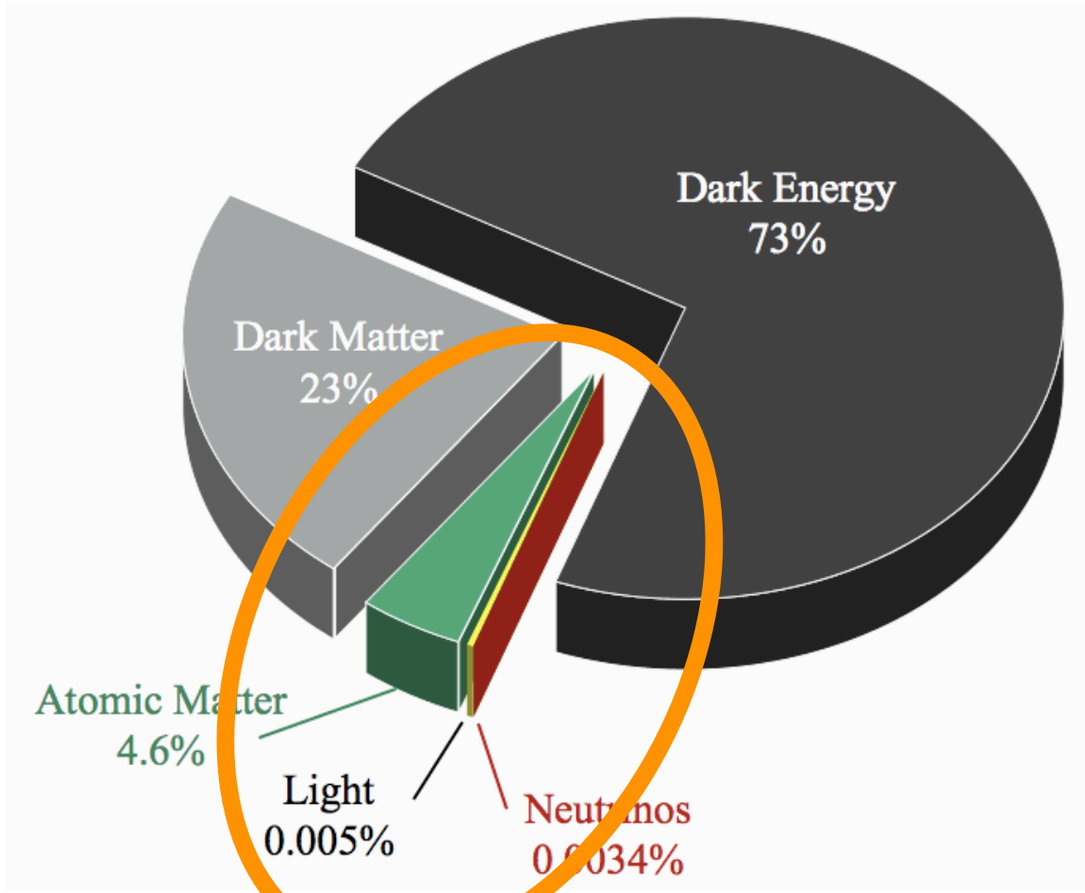

Rich, intricate structure!

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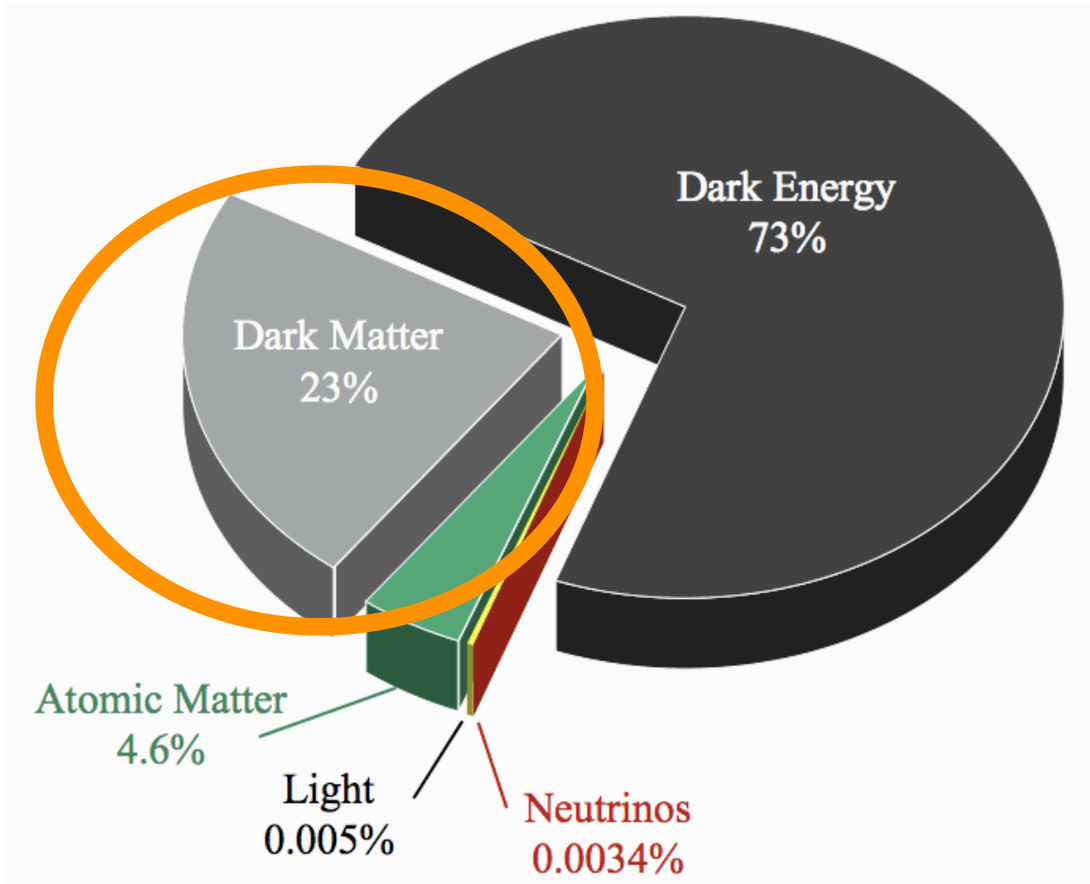

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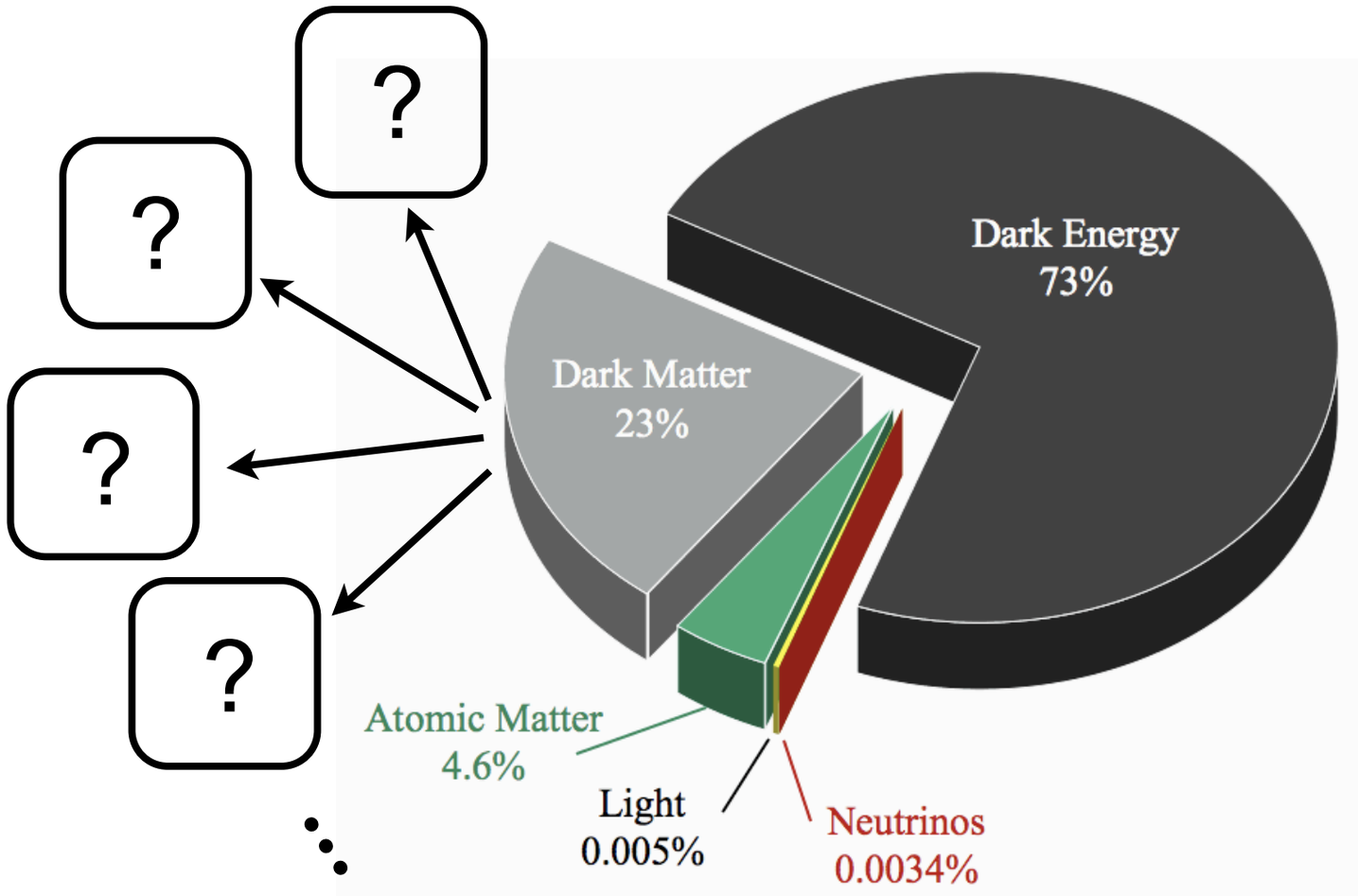

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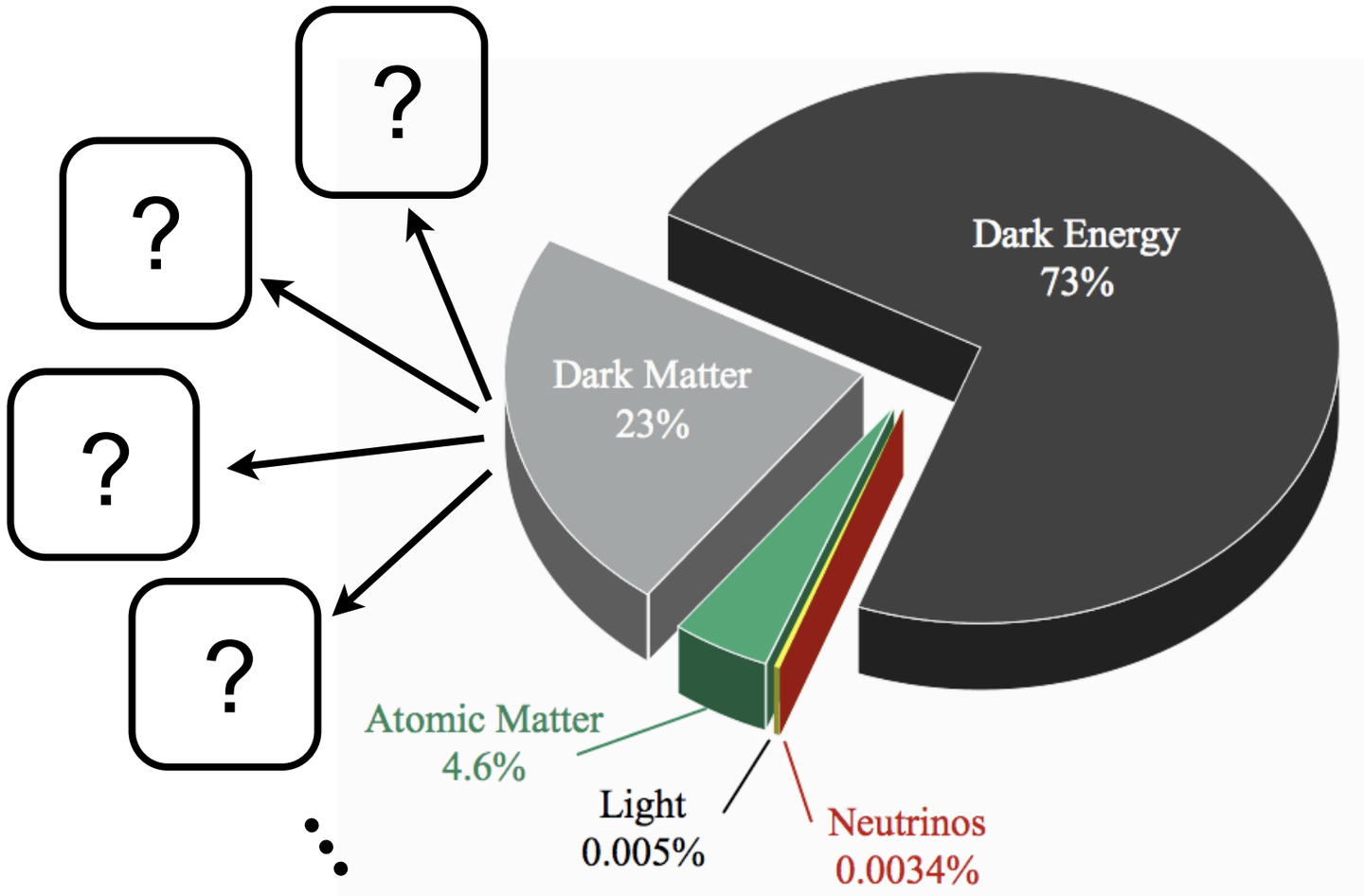
How could we *know?*



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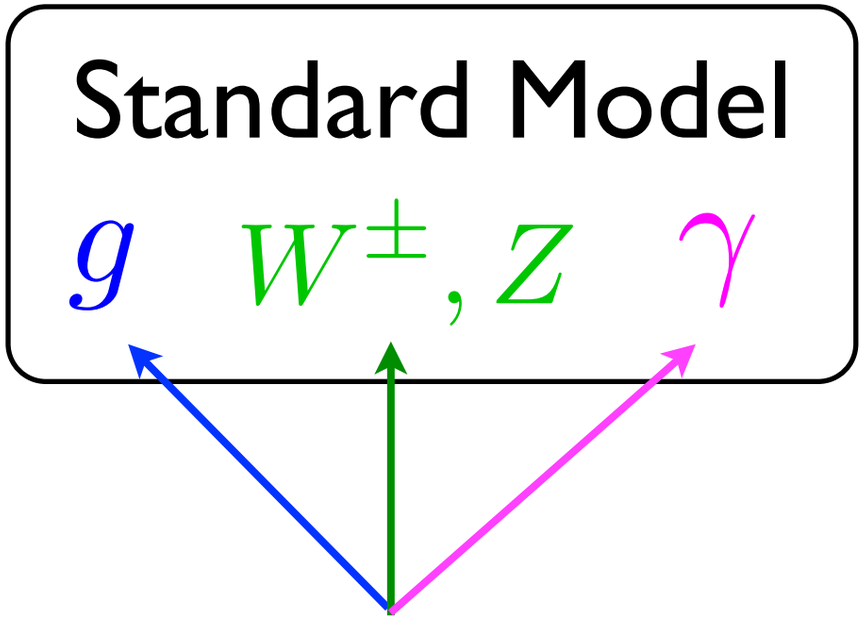
A discovery would be a game-changer

Dark Sectors

A dark sector consists of particles that do not interact with known forces



Known Forces

strong, weak, EM

Dark Sectors

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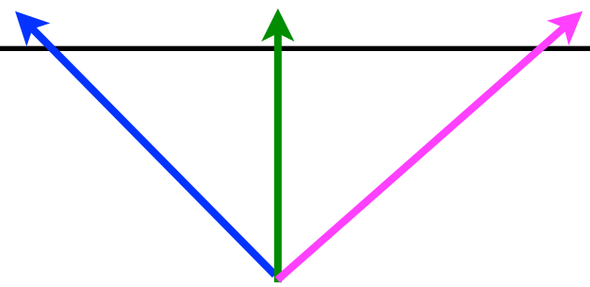
Standard Model

g $W^{\pm}, Z$ γ



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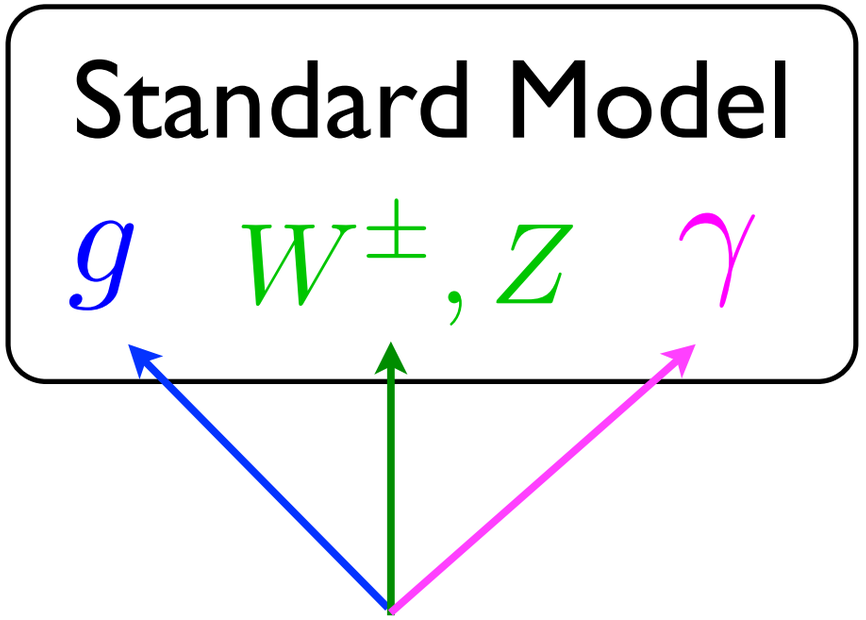
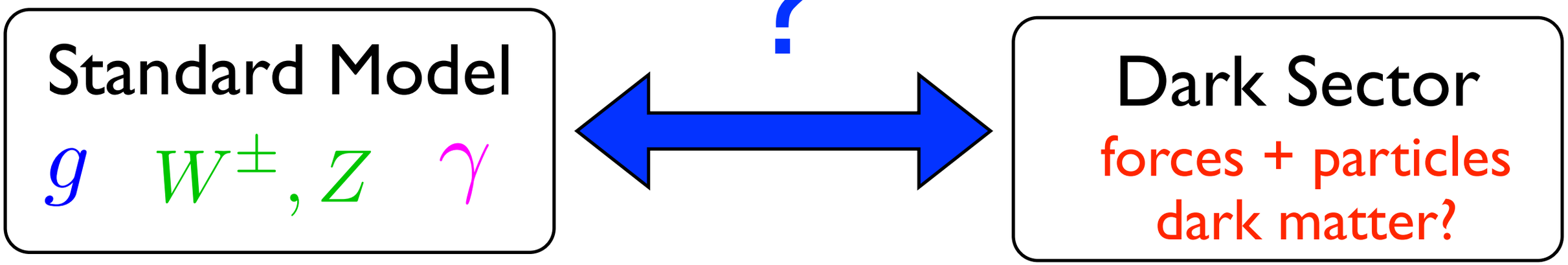


Dark Sector
forces + particles
dark matter?

unlike matter that interacts with known forces, dark sector particles can be *well below Weak-scale*

Portals?



only a few important interactions exist that are allowed by Standard Model symmetries

Portals

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

- "Vector" $\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$ dark photon A′

- "Higgs" $\lambda H^2 S^2 + \mu H^2 S$ exotic Higgs decays?

- "Neutrino" $\kappa (H L) N$ sterile neutrinos?

Portals

our focus today

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see William Wester's talk next

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Dark Photons

dark matter?

Standard Model

g $W^{\pm}, Z$ γ

Known Forces

Dark Sector

Dark Photons

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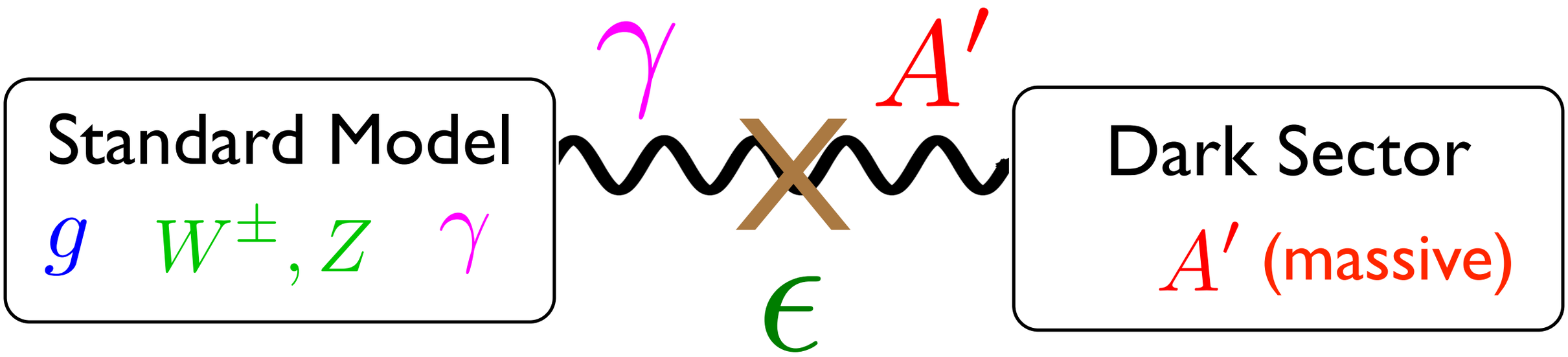
Dark Sector

A' (massive)

New force: *U(1)*

Dark Photons

ordinary photon & A' can mix



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing"

Holdom

Galison, Manohar

Dark Photons

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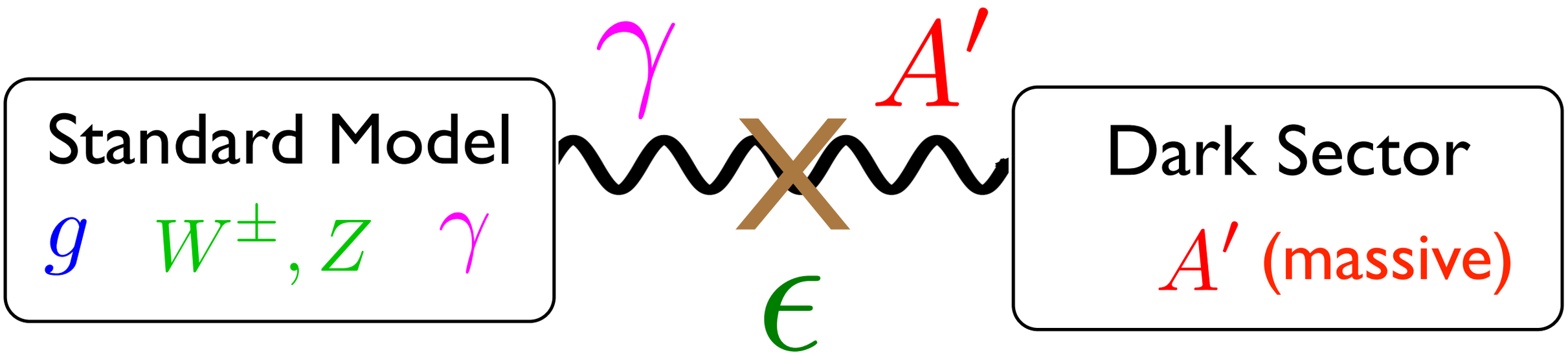

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"Kinetic Mixing"

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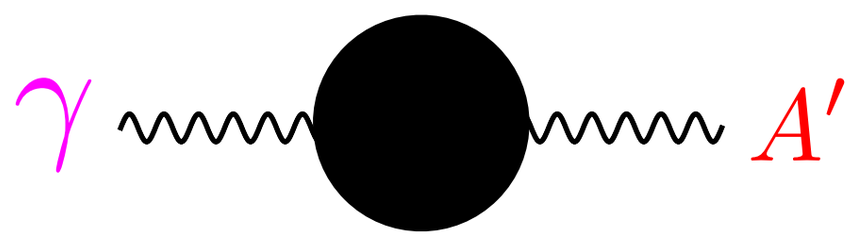
simplest Dark Sector consists of just an A′

Generating Kinetic Mixing

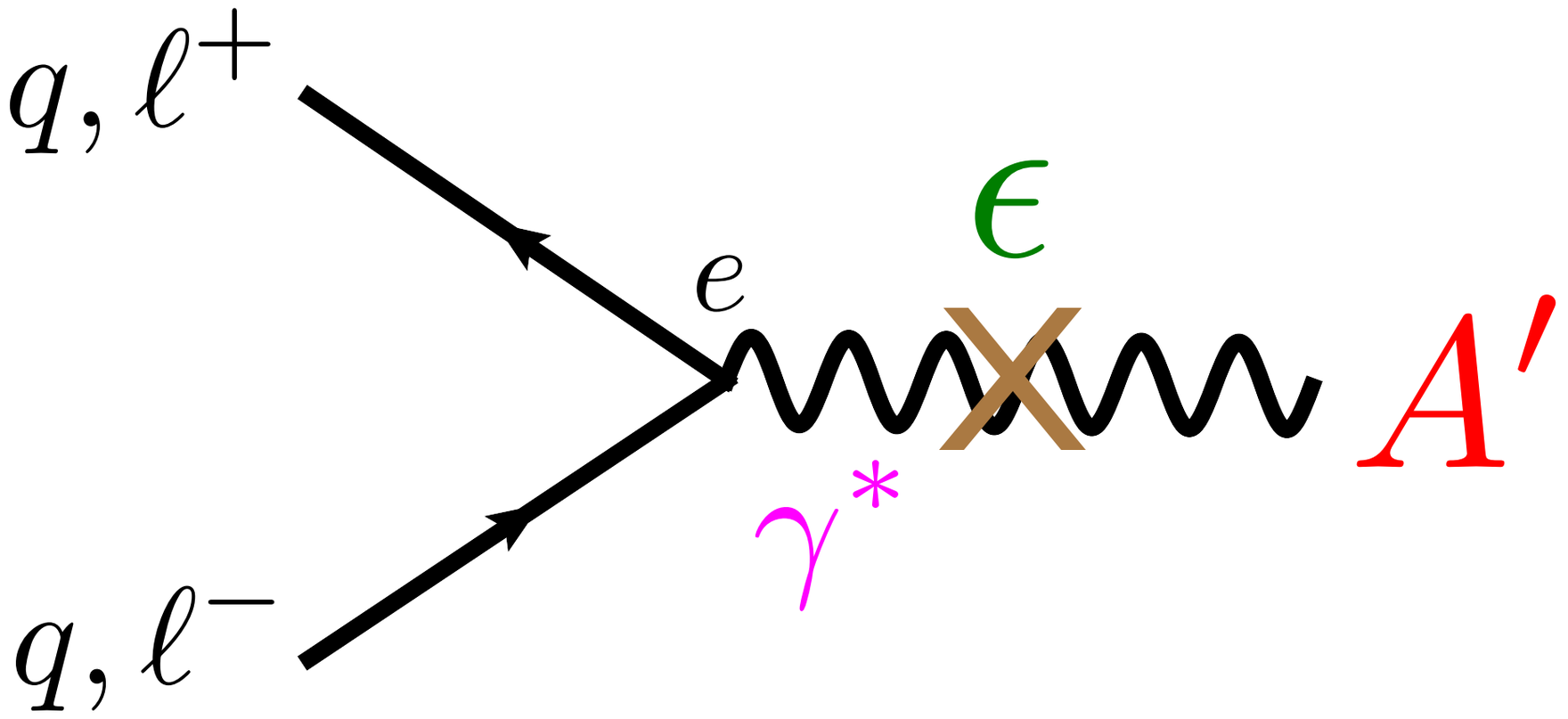
e.g. loops of heavy particles
charged under photon and A'



$\epsilon \sim 10^{-5} - 10^{-2}$ a motivated target

Mixing with photon allows:

A′ coupling to quarks and charged leptons:



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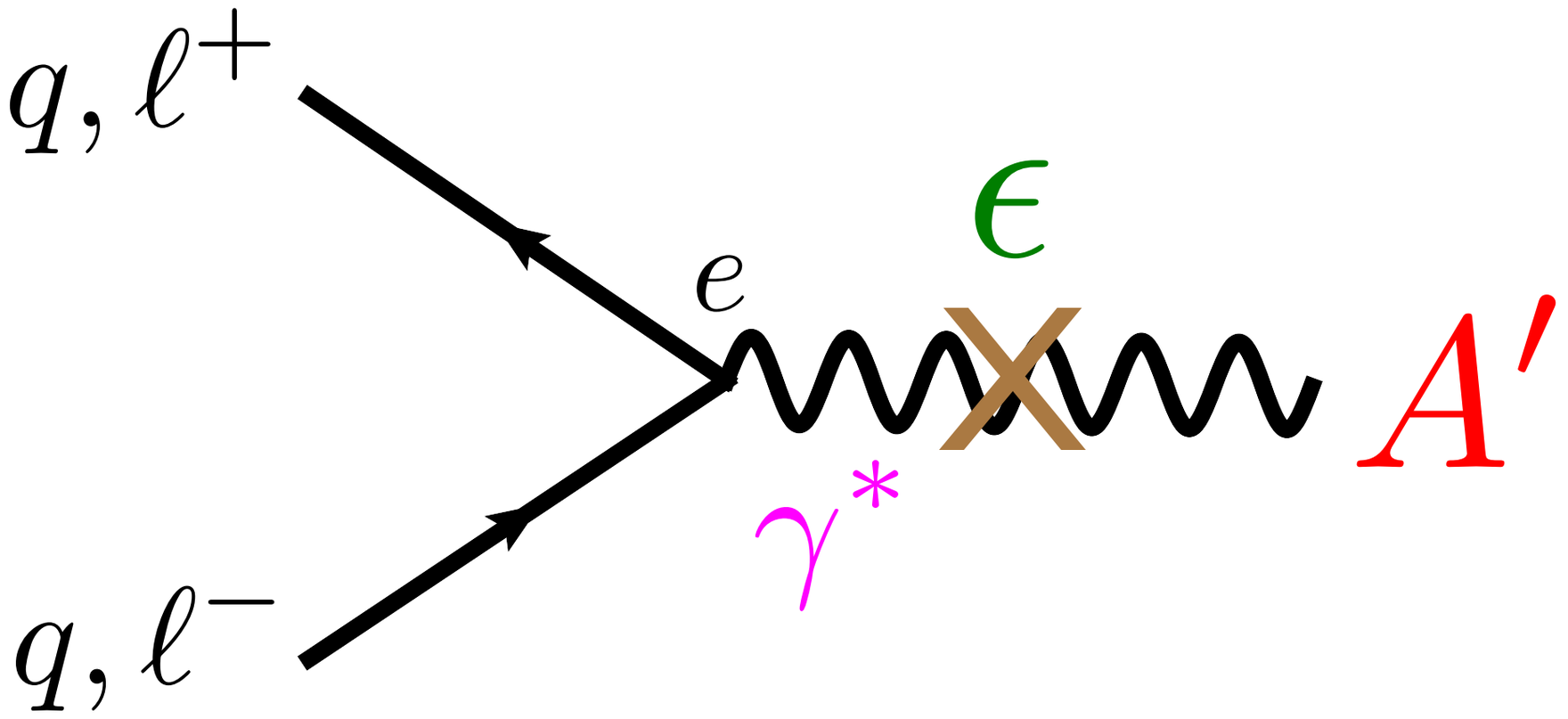
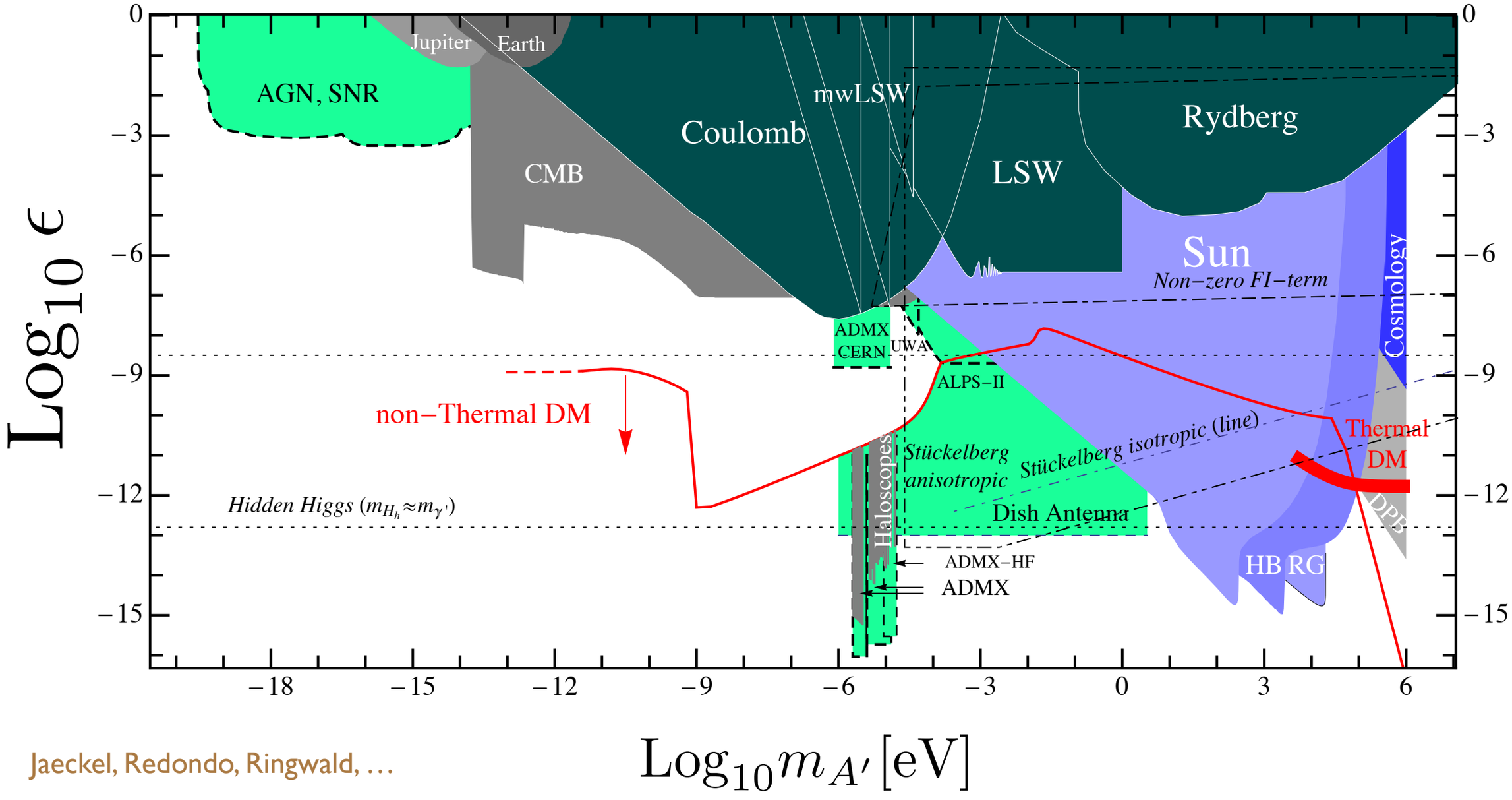


and

for low A′ masses, can also get

$A' \leftrightarrow \gamma$ "oscillation" (like ν's)

low-mass (< MeV) A′ parameter space



Jaeckel, Redondo, Ringwald, …

Experimental techniques often similar to axion/ALP searches, but $A' \leftrightarrow \gamma$ conversion doesn't require magnets

Another well-motivated target: $m_{A'} \sim$ MeV-GeV

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origin of this scale can be naturally related to Weak-scale by a small parameter

e.g. in some models

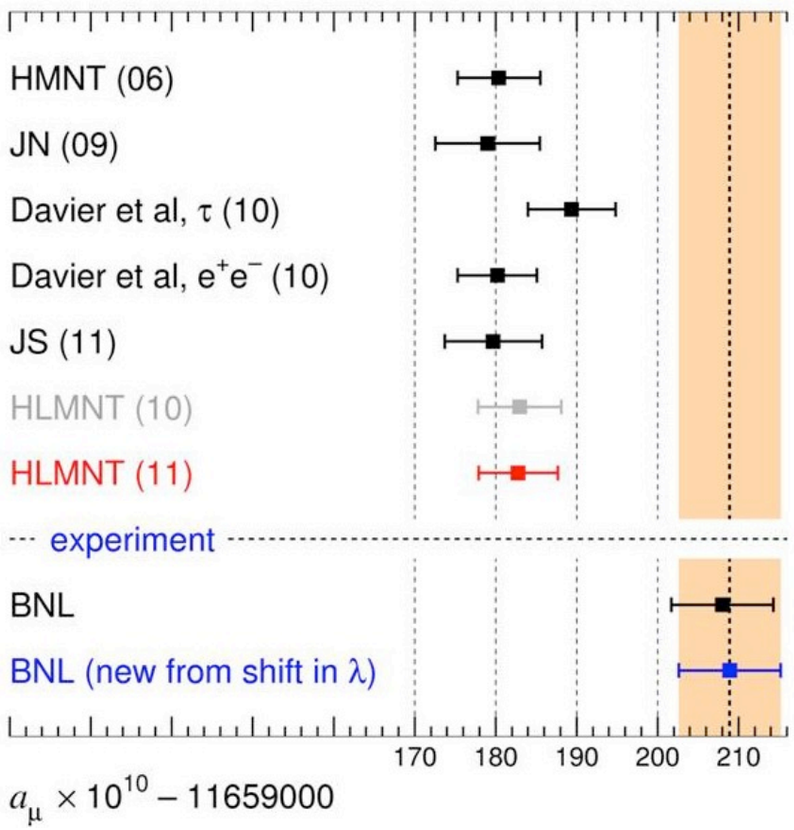
$$m_{A'} \sim \sqrt{\epsilon} M_Z \lesssim 1 \text{ GeV}$$

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;

Hints for A′ with MeV-GeV mass?

anomalous muon g-2 ?

Pospelov
Boehm, Fayet



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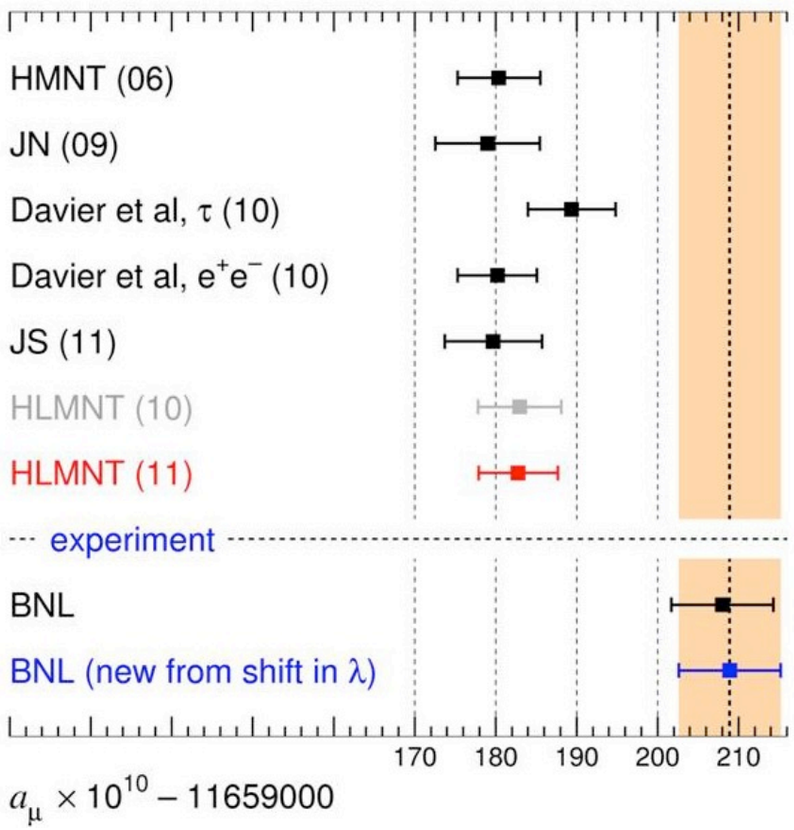

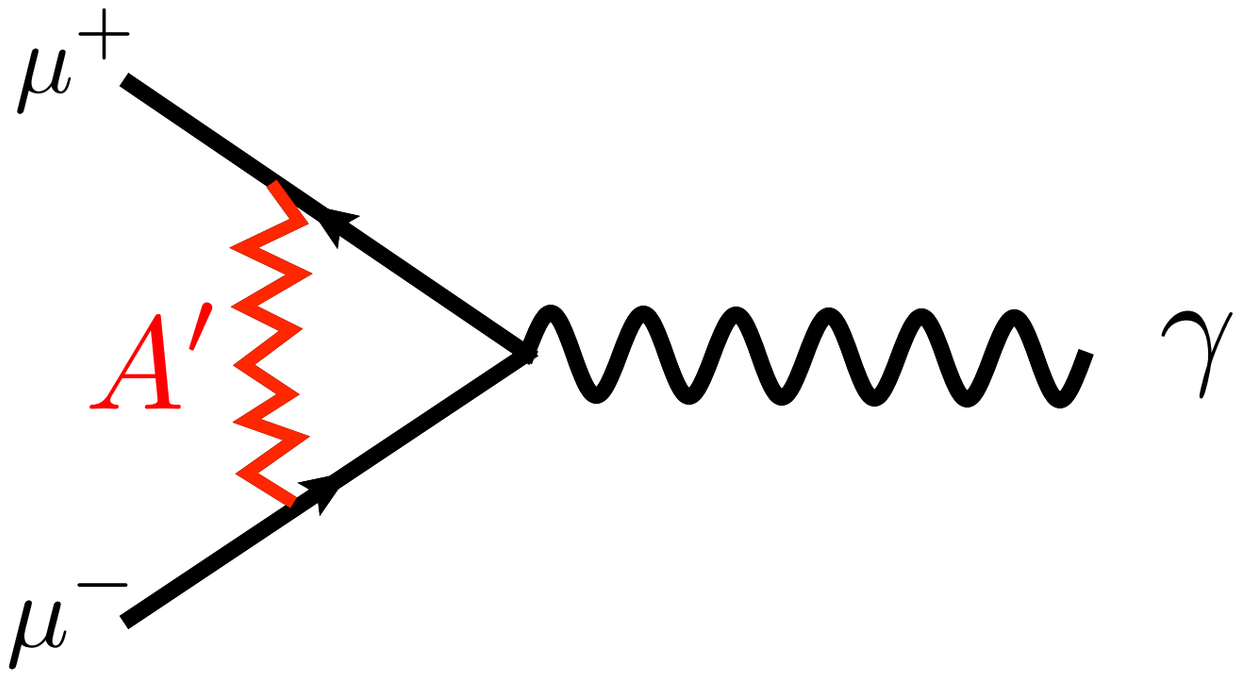

A′ may explain observed $(g_s - 2)_\mu$

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New dark matter interactions?

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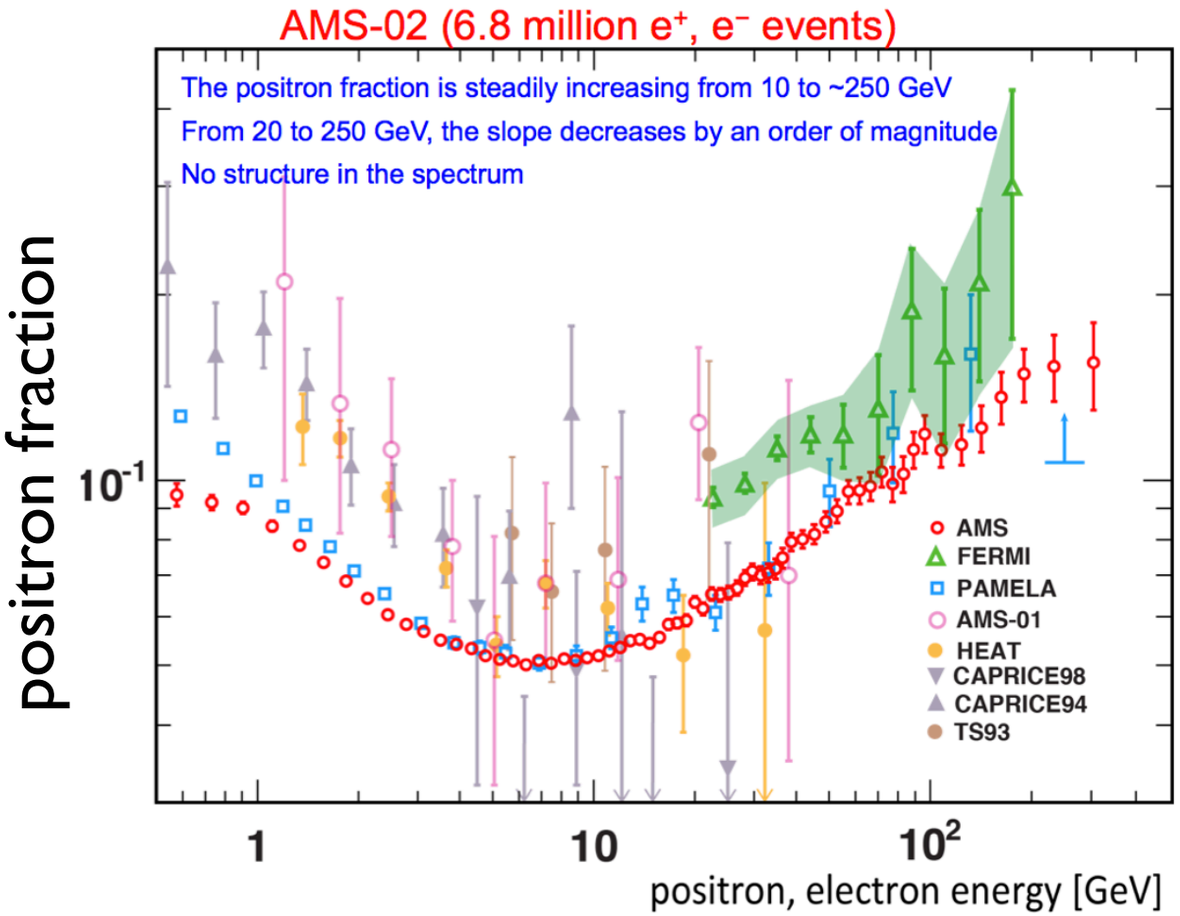

cosmic-ray e^+, e^- excesses?

PAMELA, Fermi, AMS2…

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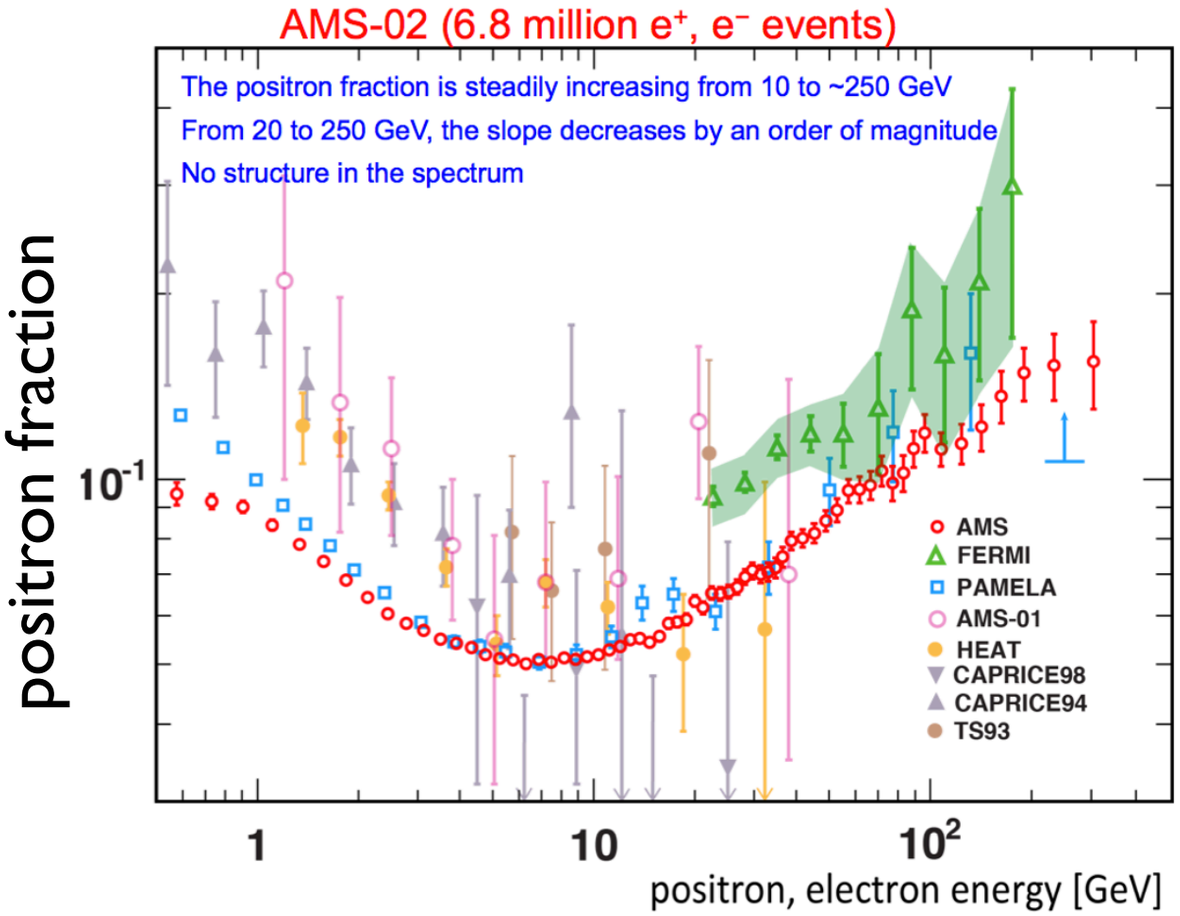
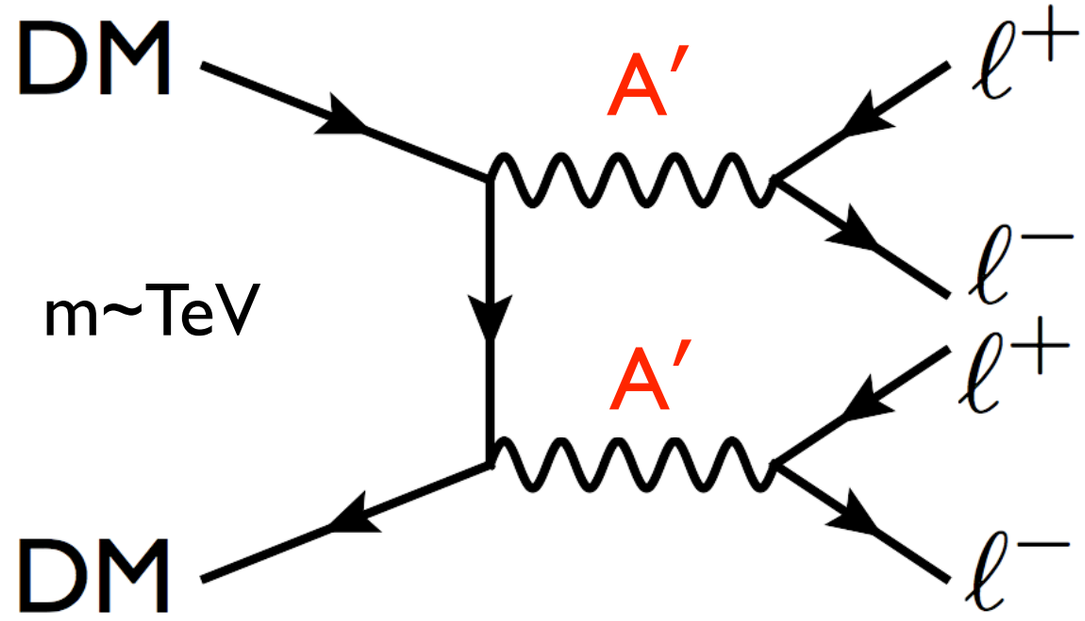
Arkani-Hamed et.al.; Cholis et.al.; Pospelov & Ritz





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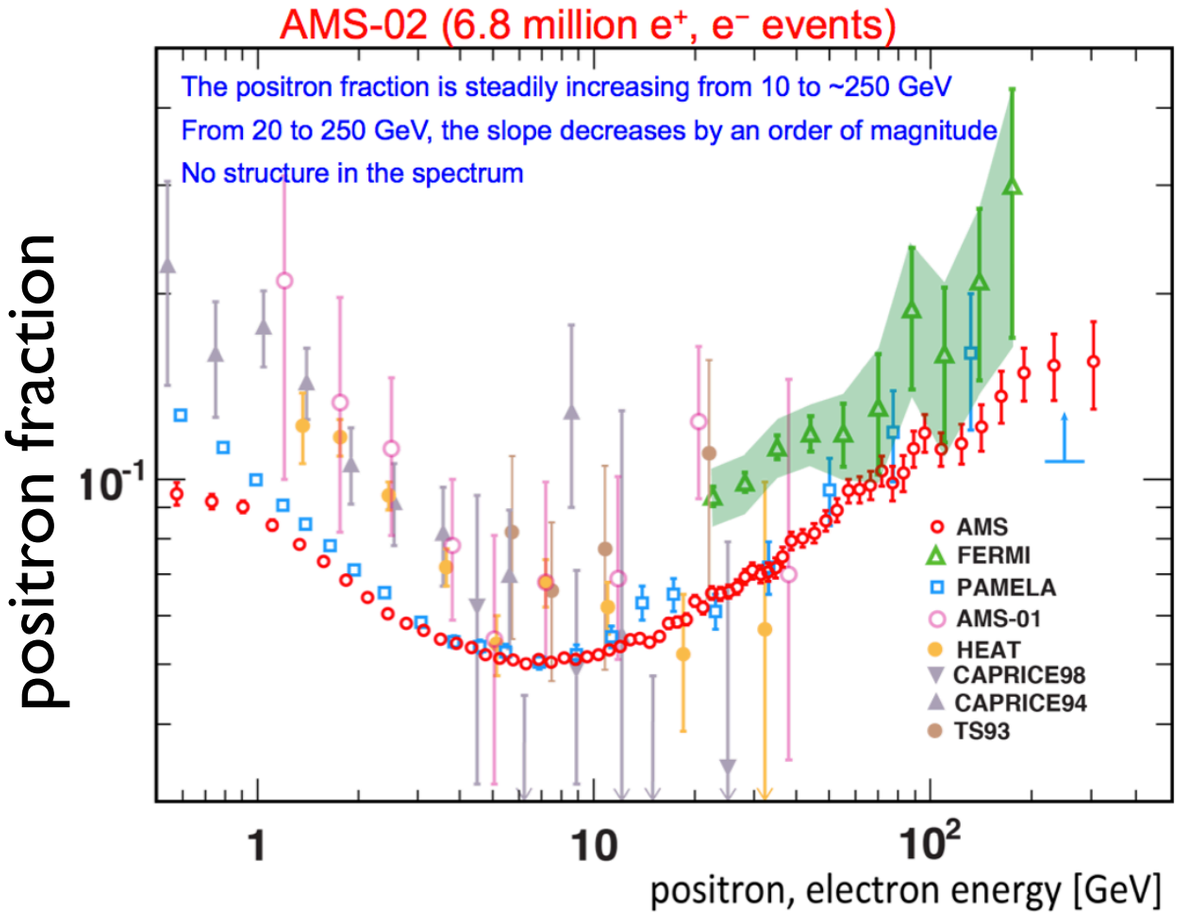

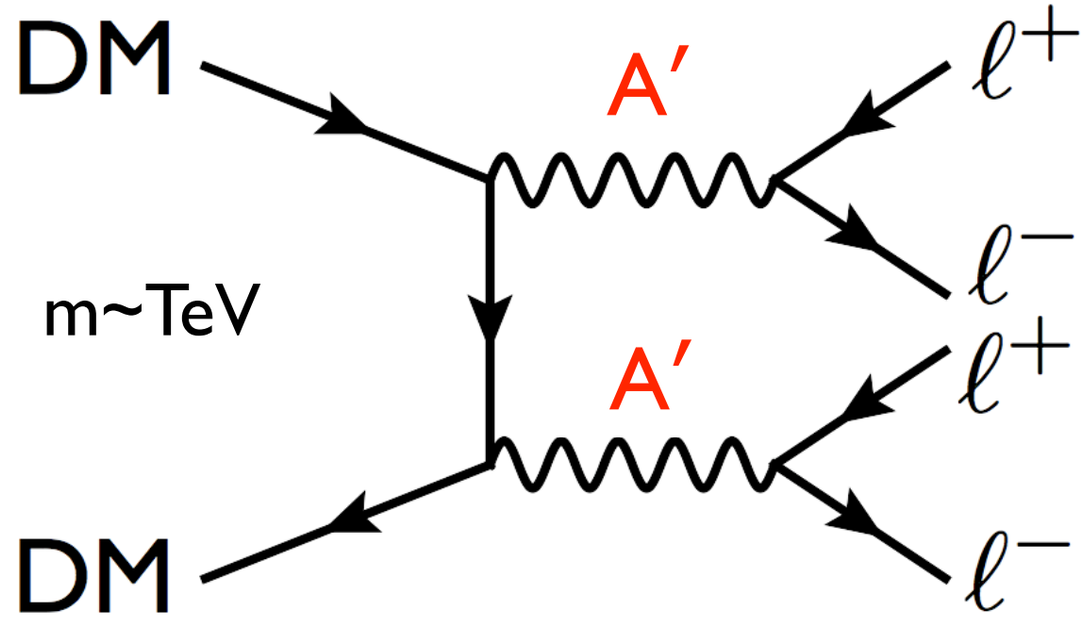

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Viability is actively debated, large systematic uncertainties

it made us realize amazing possibilities at GeV-scale!

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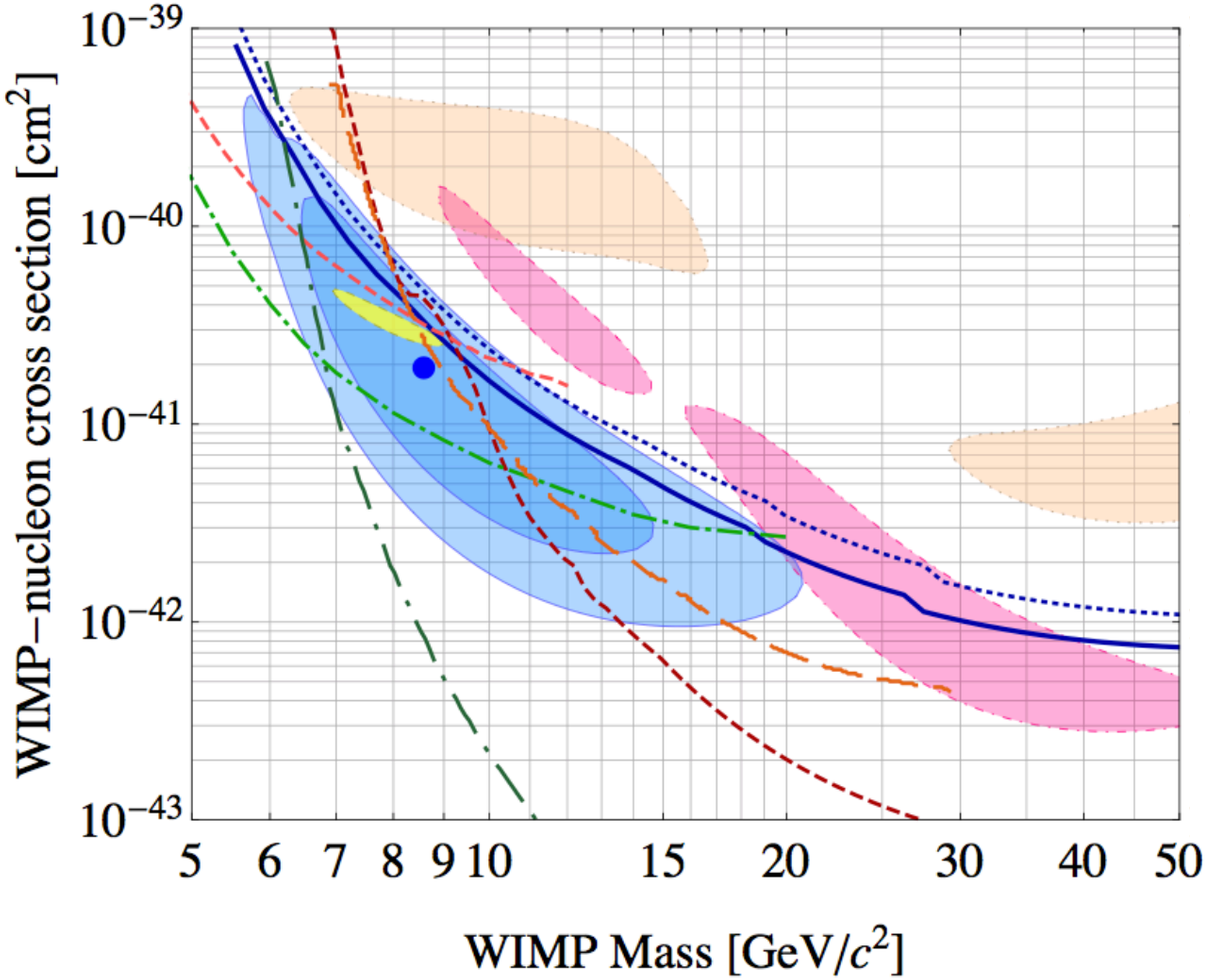

direct detection hints?

DAMA, CoGeNT, CRESST, CDMS-Si

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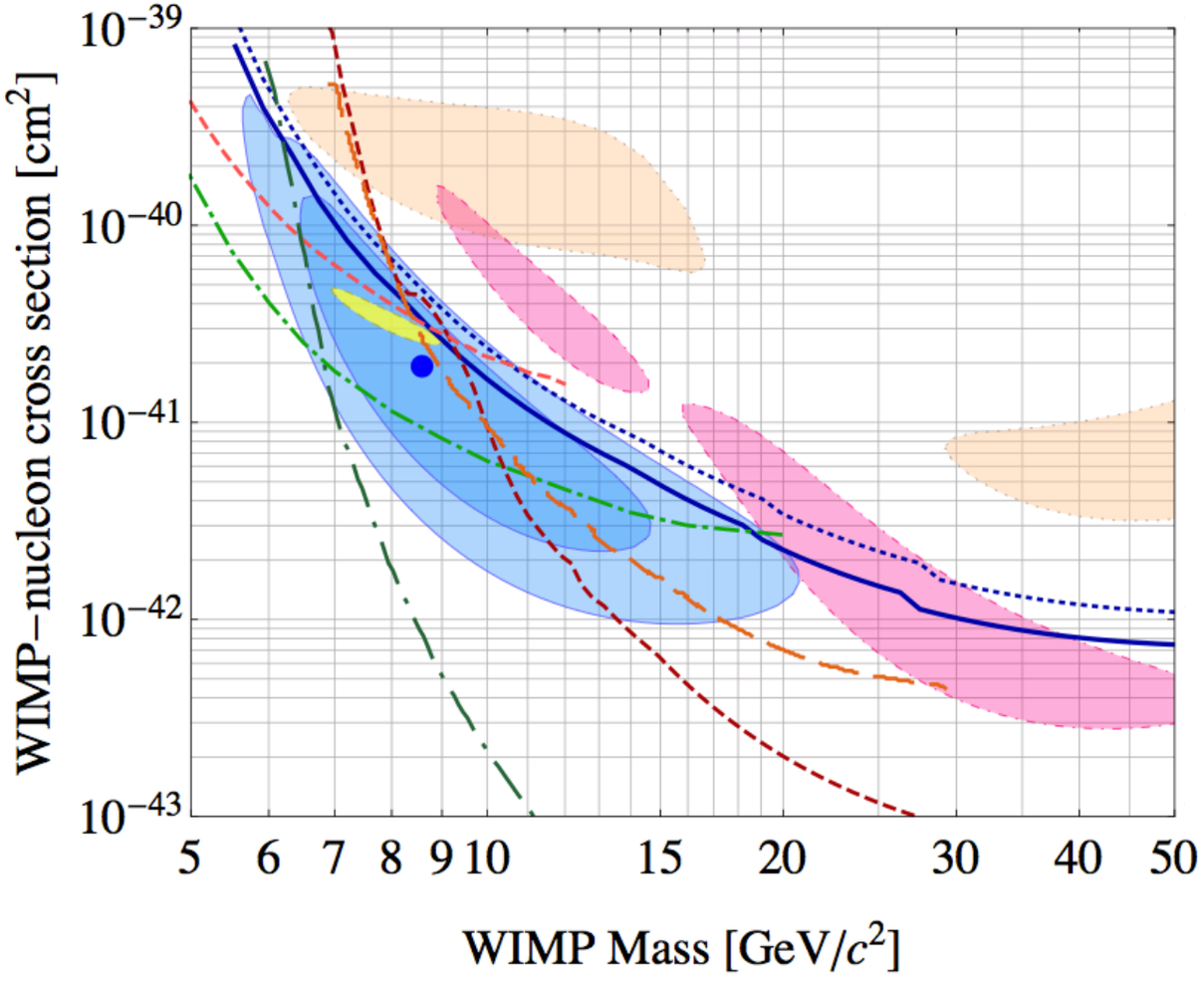

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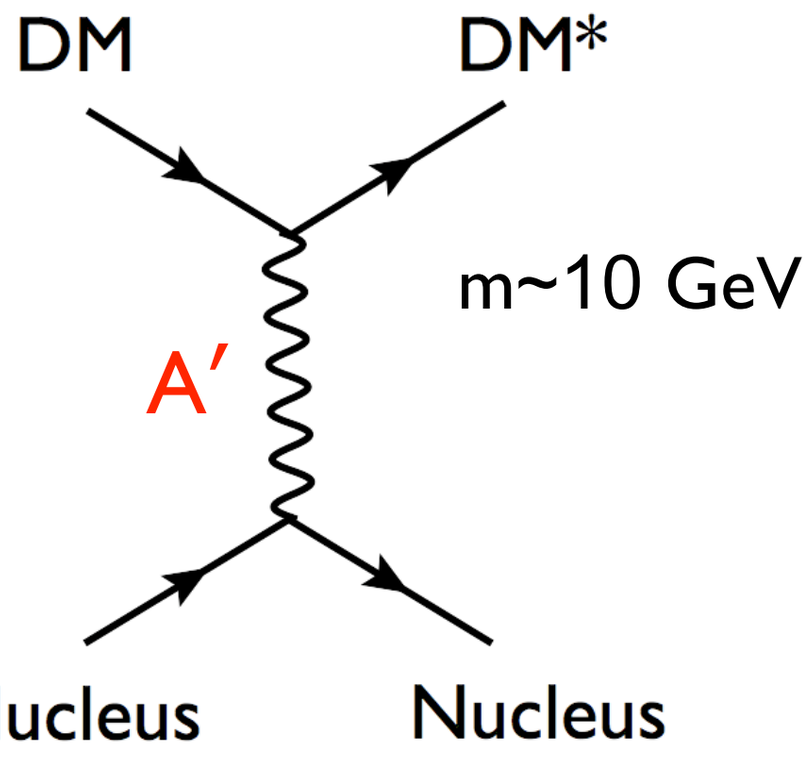

hard for Standard Model mediators, easier for light mediators

Hints for A′ with MeV-GeV mass?

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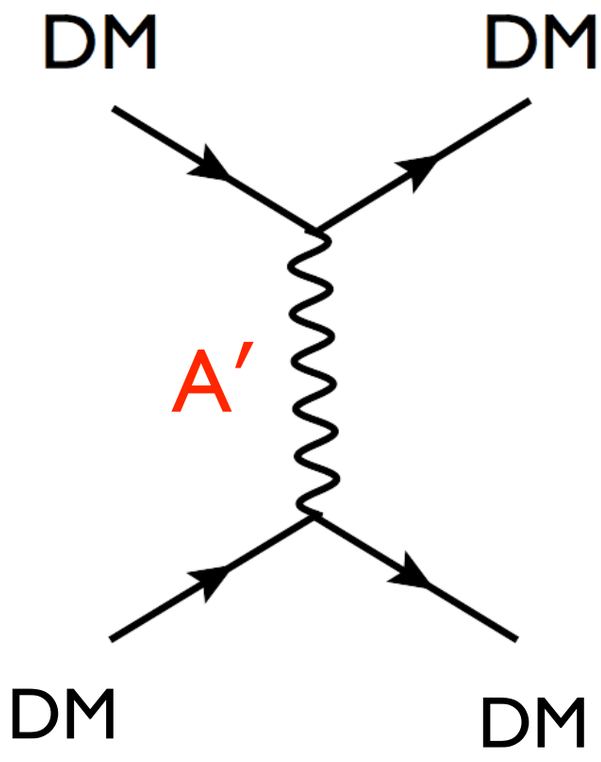
New dark matter interactions?

Dark matter self-interactions?

e.g. Spergel & Steinhardt; Loeb & Weiner; Kaplinghat, Tulin, Yu



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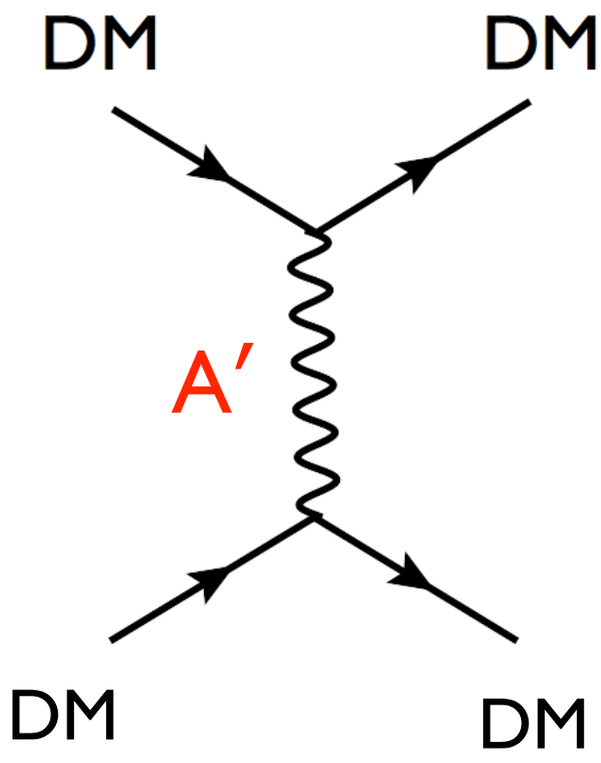

new, light mediators have implications for wide range of actively studied phenomena

How to look for A′ with MeV-GeV mass?

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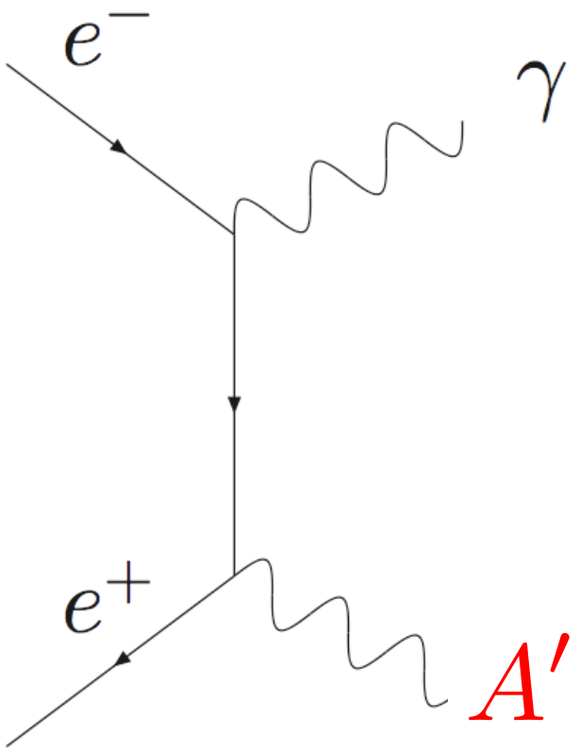
e^+e^- colliders

RE, Schuster, Toro
Batell, Pospelov, Ritz
Reece, Wang
Borodatchenkova et.al.
Fayet



$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$$

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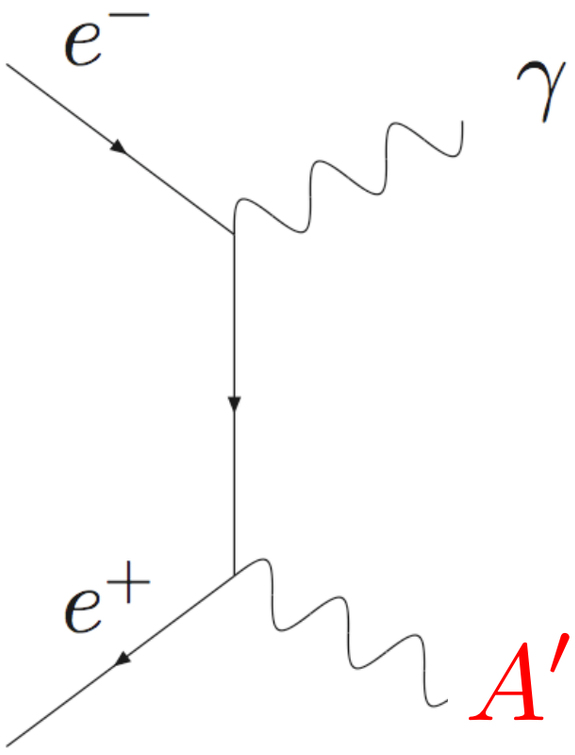

Rare meson decays

$$\phi \to \eta A'$$

$$\pi^0 \to \gamma A'$$

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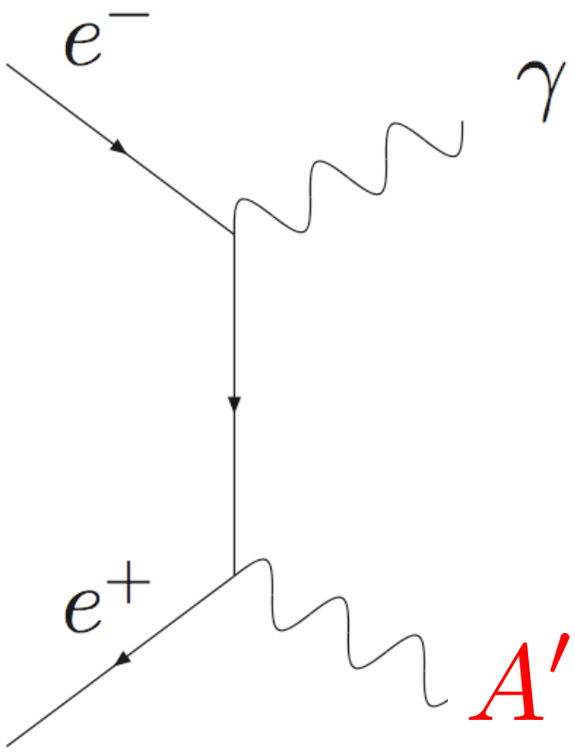

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$$\phi \to \eta A'$$

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B-factories, Phi-factories

searches completed/ongoing/planned

How to look for A′ with MeV-GeV mass?

Bjorken, RE, Schuster, Toro
Freytsis, Ovanesyan, Thaler
Reece & Wang

New & old e^- fixed target experiments

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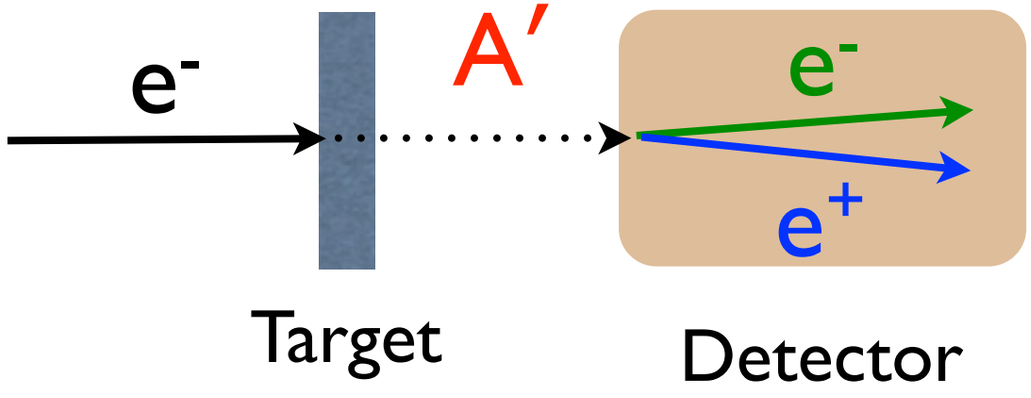
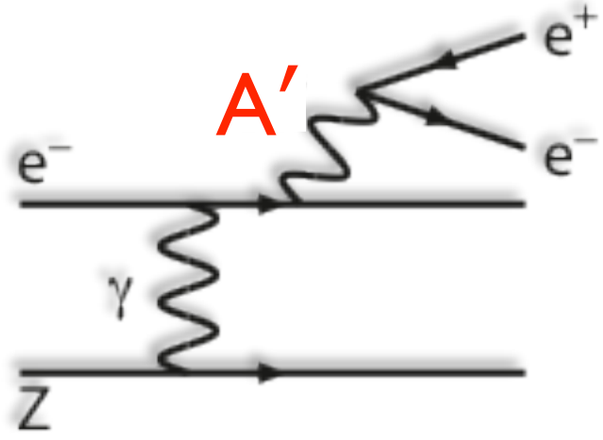


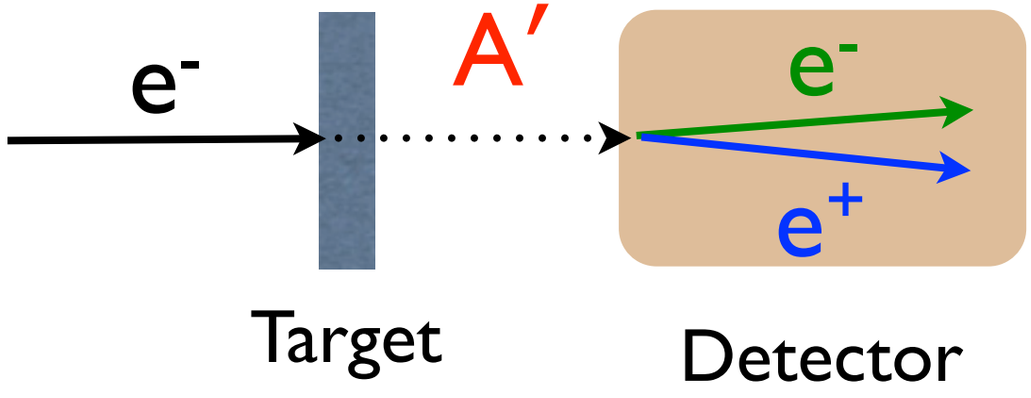


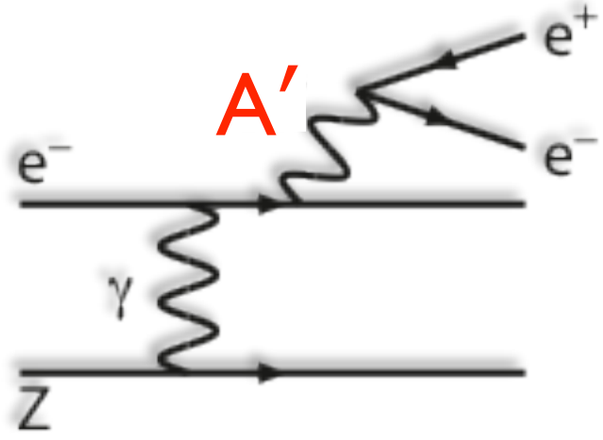
look for $A' \rightarrow e^+e^-$
resonance or
displaced vertex

How to look for A′ with MeV-GeV mass?

Bjorken, RE, Schuster, Toro
Freytsis, Ovanesyan, Thaler
Reece & Wang

New & old e^- fixed target experiments





look for A′ → e^+e^-
resonance or
displaced vertex

e.g. SLAC, JLab, MAMI, …

How to look for A′ with MeV-GeV mass?

Proton-beam fixed target experiments

Batell, Pospelov, Ritz

RE, Harnik, Kaplan, Toro

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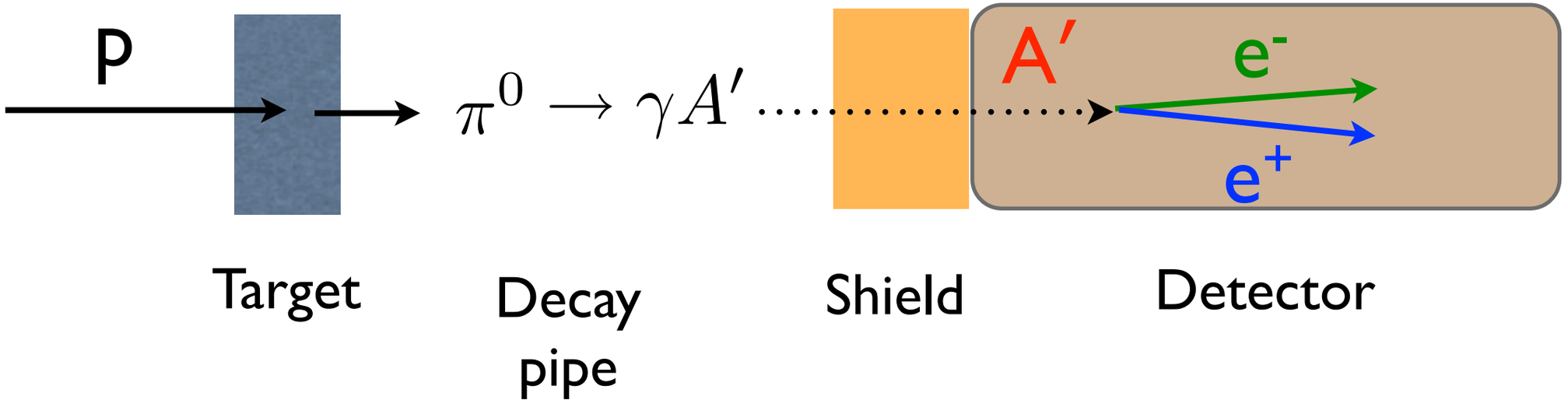

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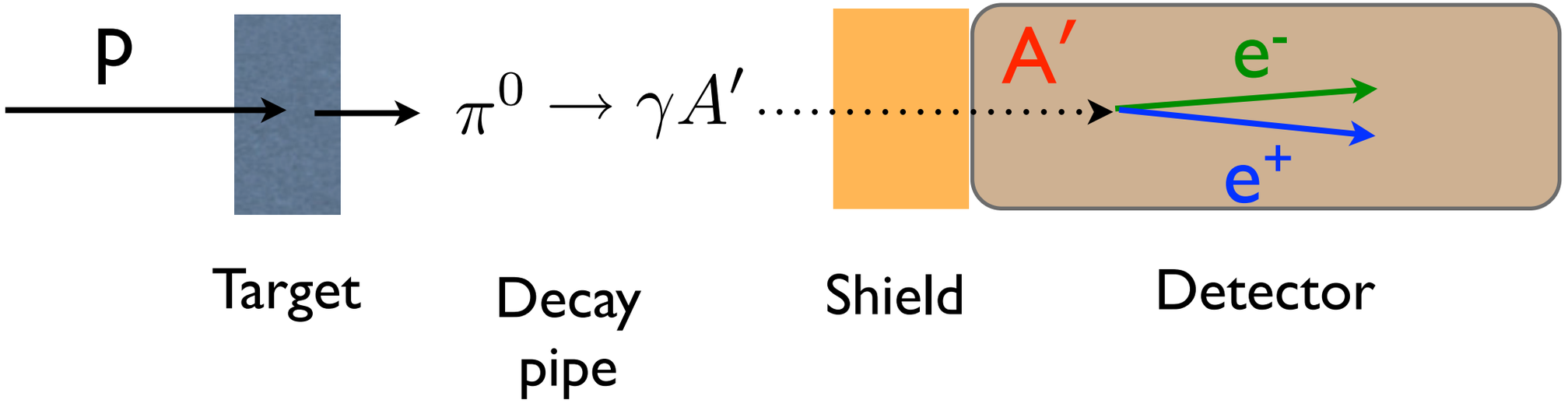
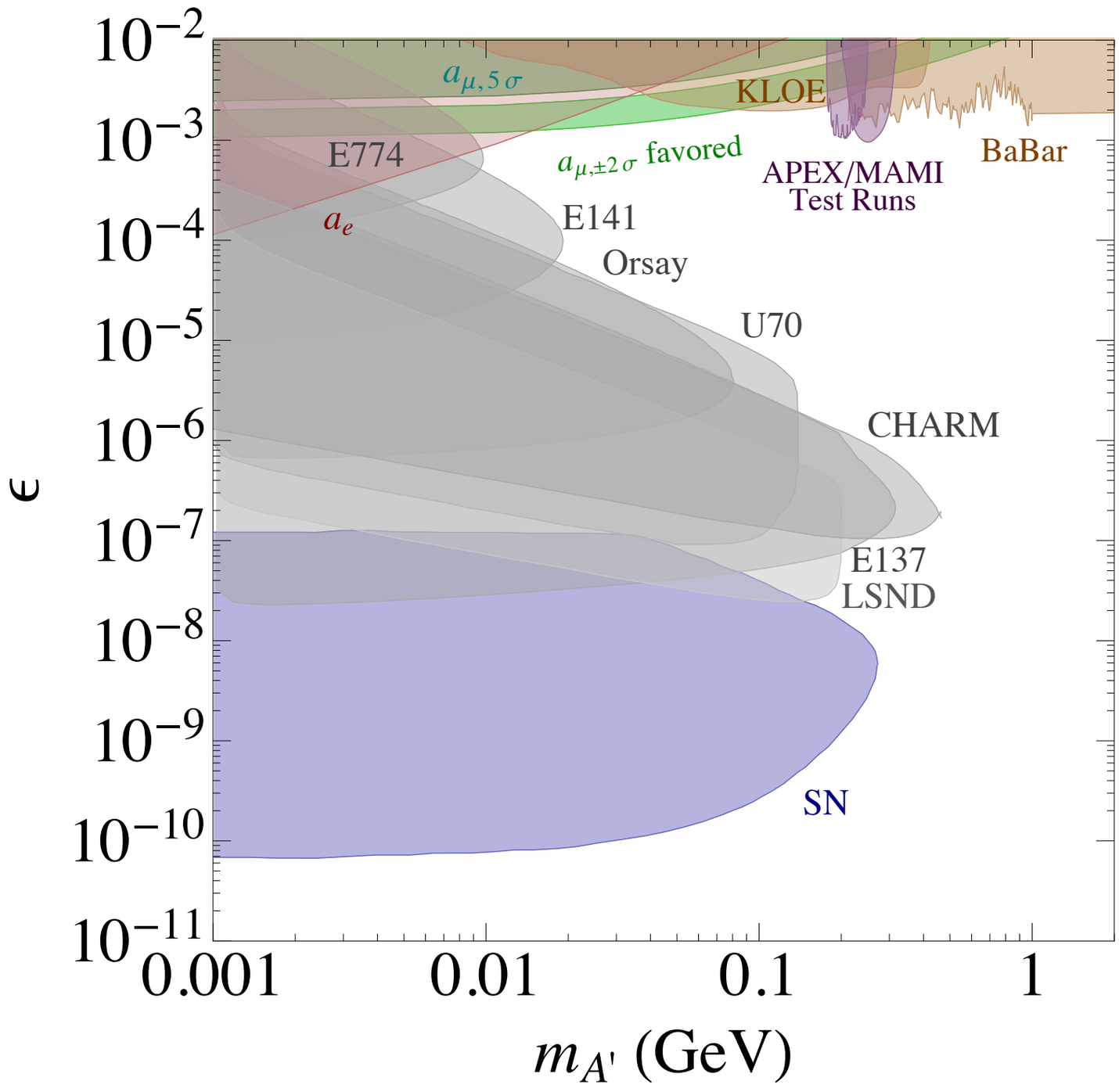


LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …

Current constraints (A′ → visible)

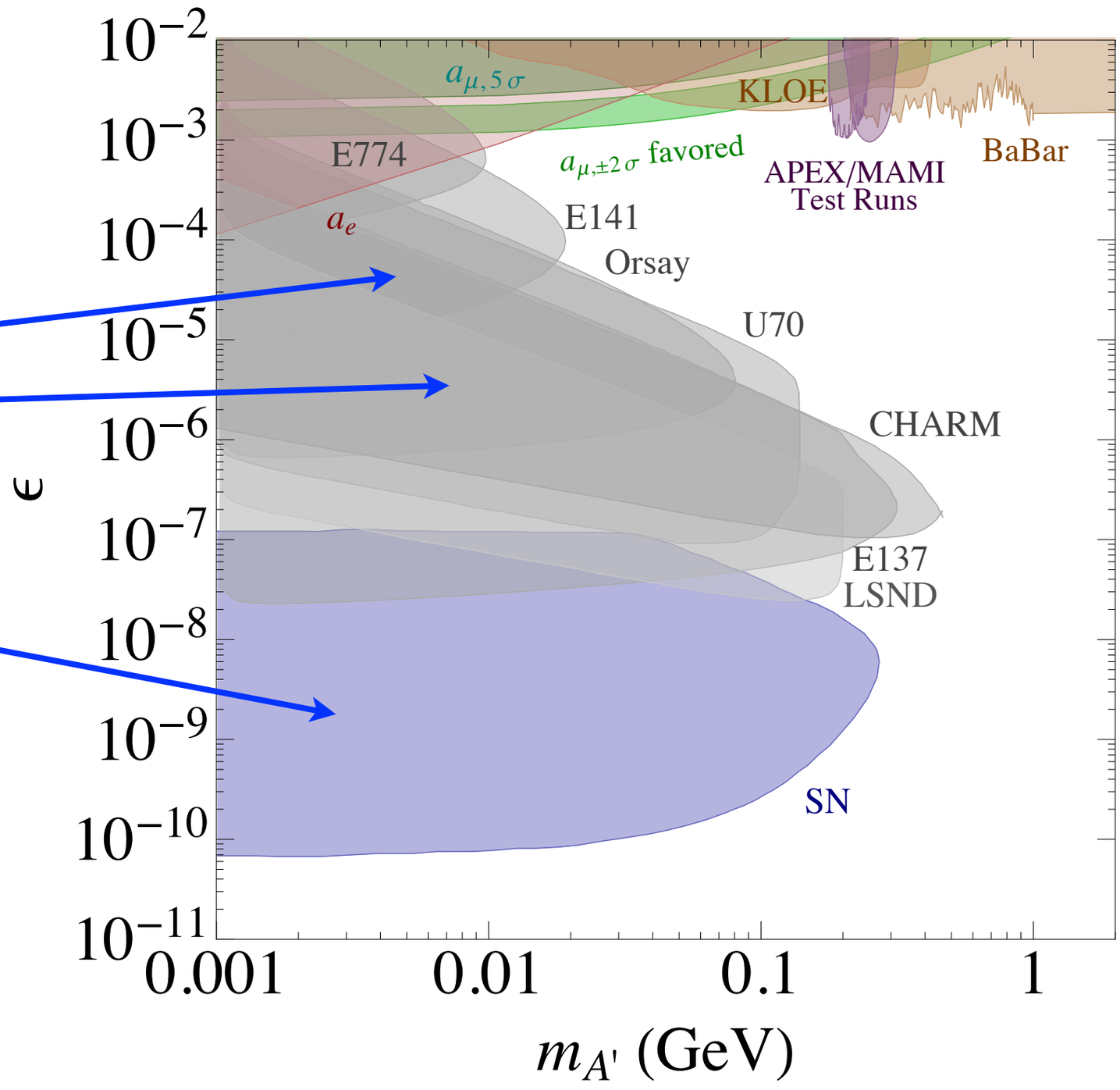


Pospelov;
Bjorken, RE, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
RE, Harnik, Kaplan, Toro
Blumlein, Brunner;
Dent, Ferrer, Krauss
RE, Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collaborations
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

Current constraints (A′ → visible)

past
electron + proton
beam dumps

supernova



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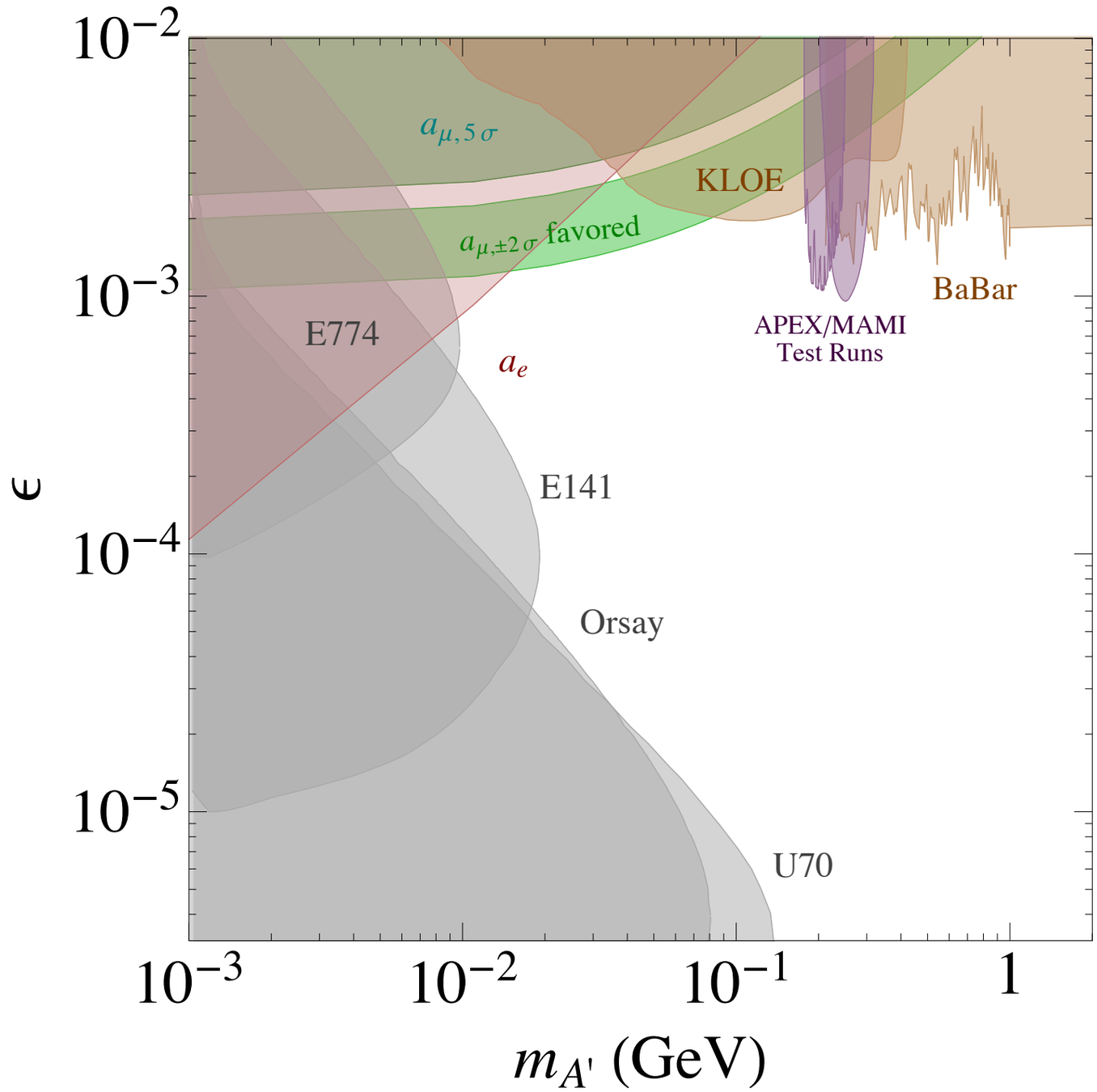
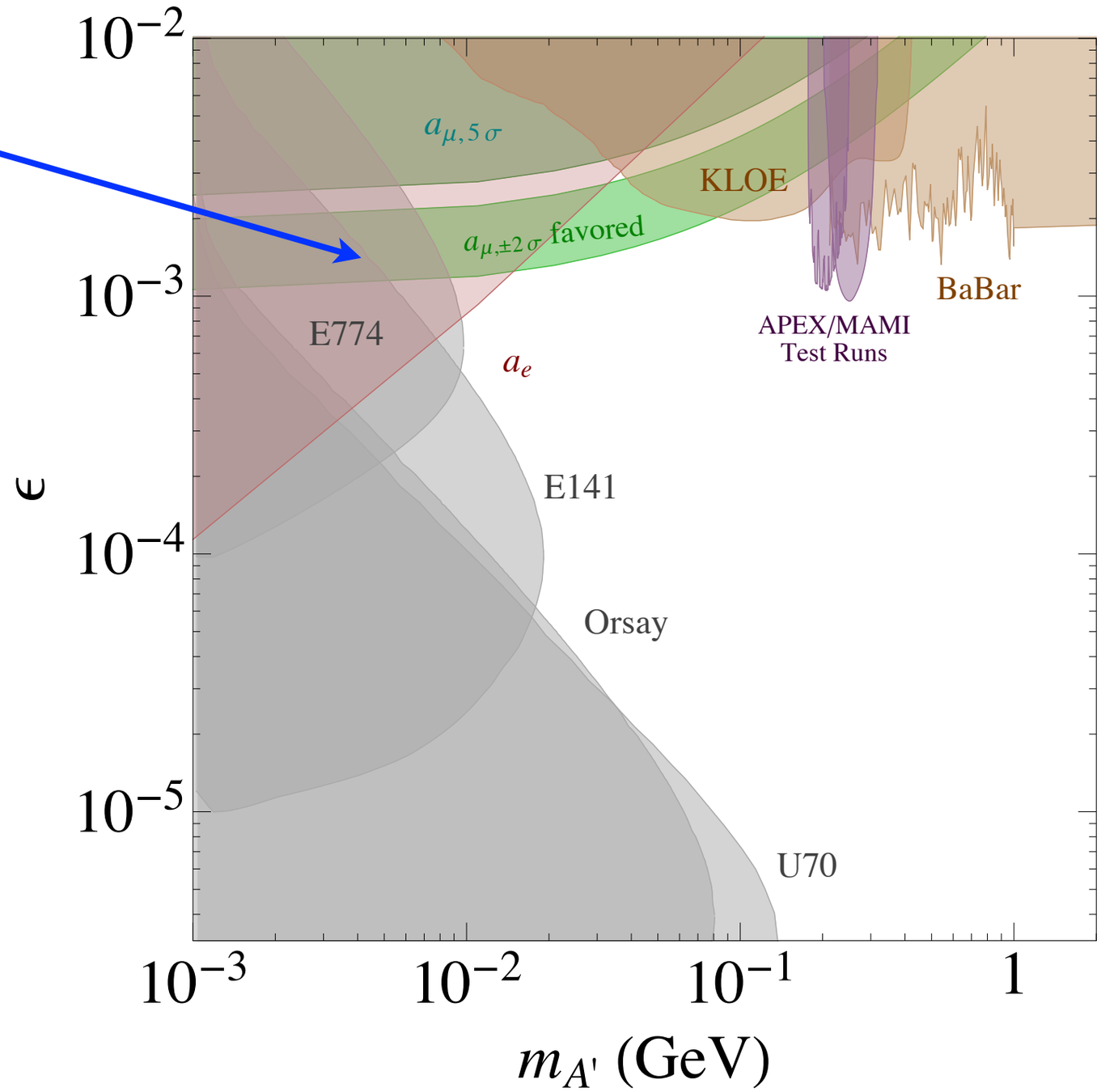
Current constraints (zoomed in)



Current constraints (zoomed in)

g-2 of e^-, μ^-



Current constraints (zoomed in)

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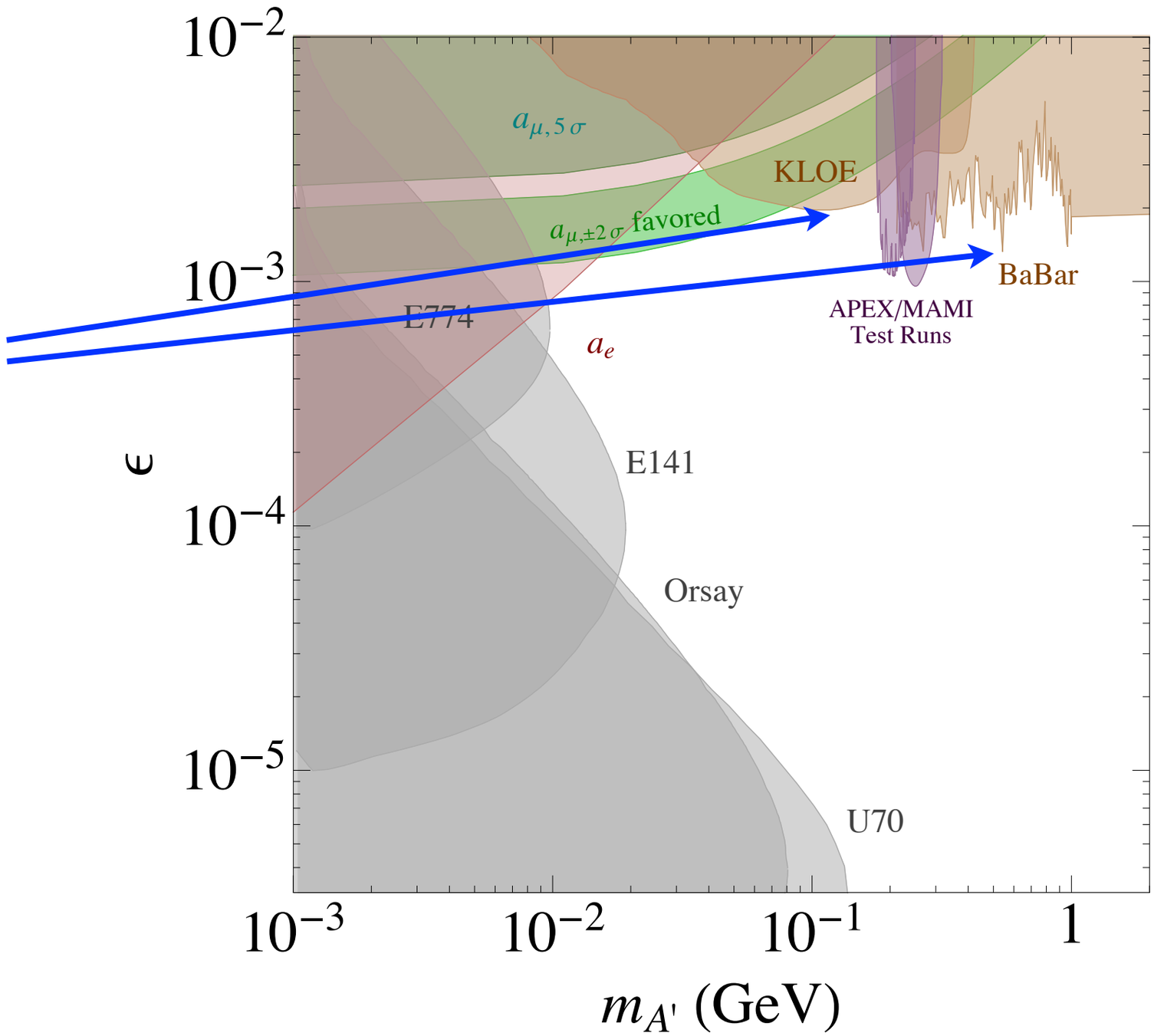
B/Phi-factory searches

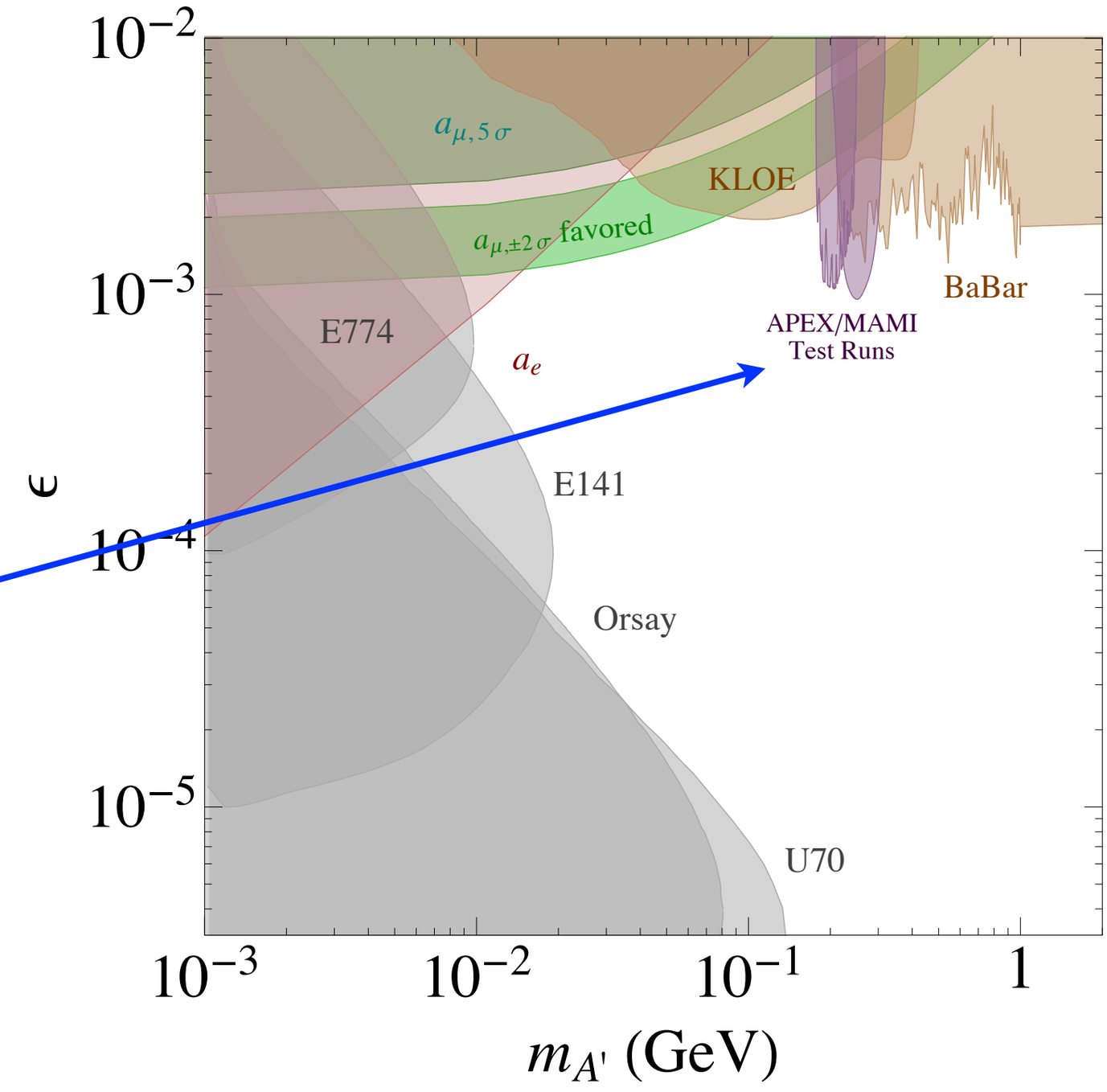


Current constraints (zoomed in)

g-2 of e^-, μ^-

B/Phi-factory searches

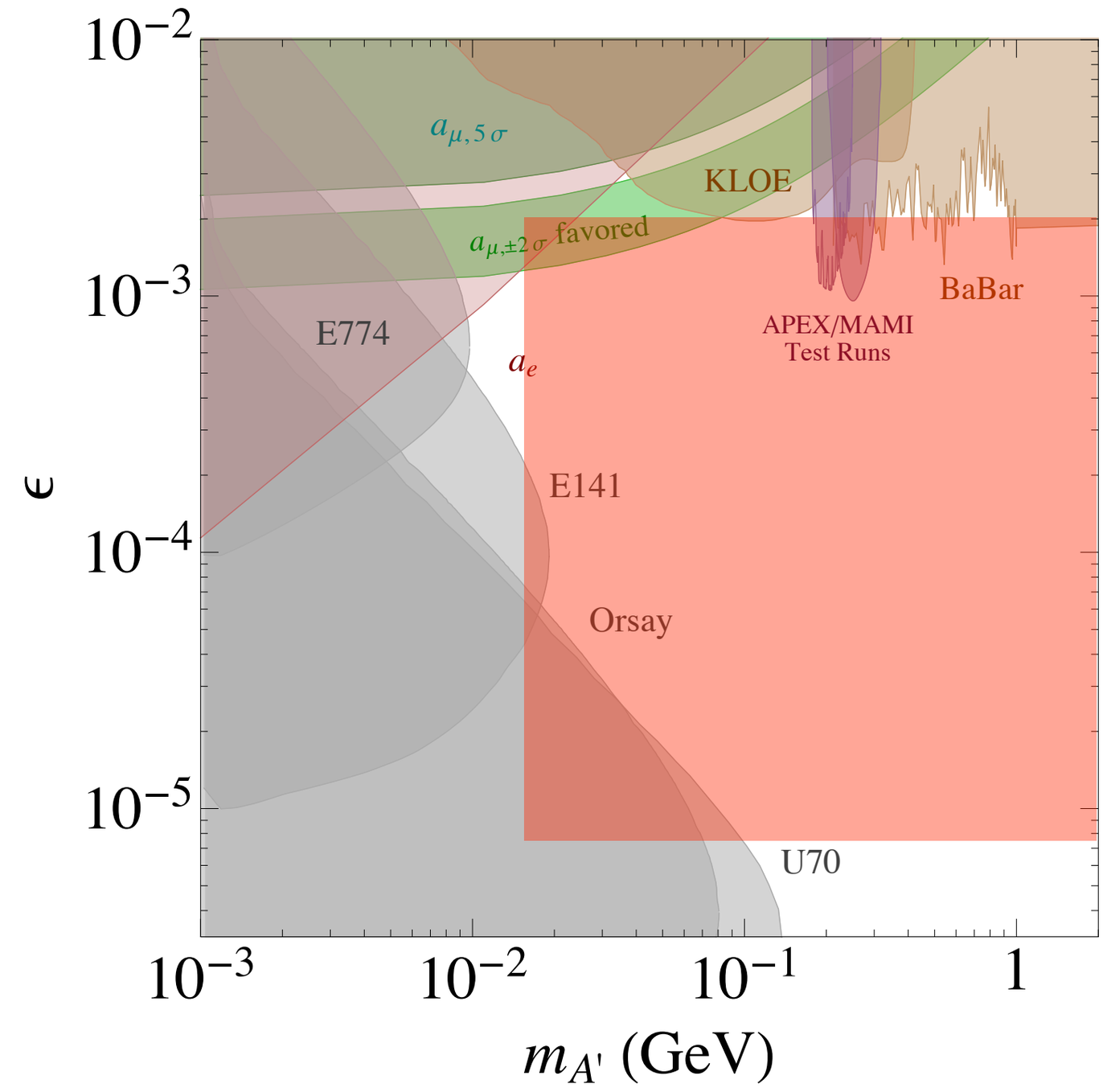
Test runs of new e^--FT experiments @ JLab/Mainz



Current constraints (zoomed in)

large unexplored region!

Region motivated by theory, g-2, direct detection, astrophysics, …



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need new experiments

Bjorken, RE, Schuster, Toro
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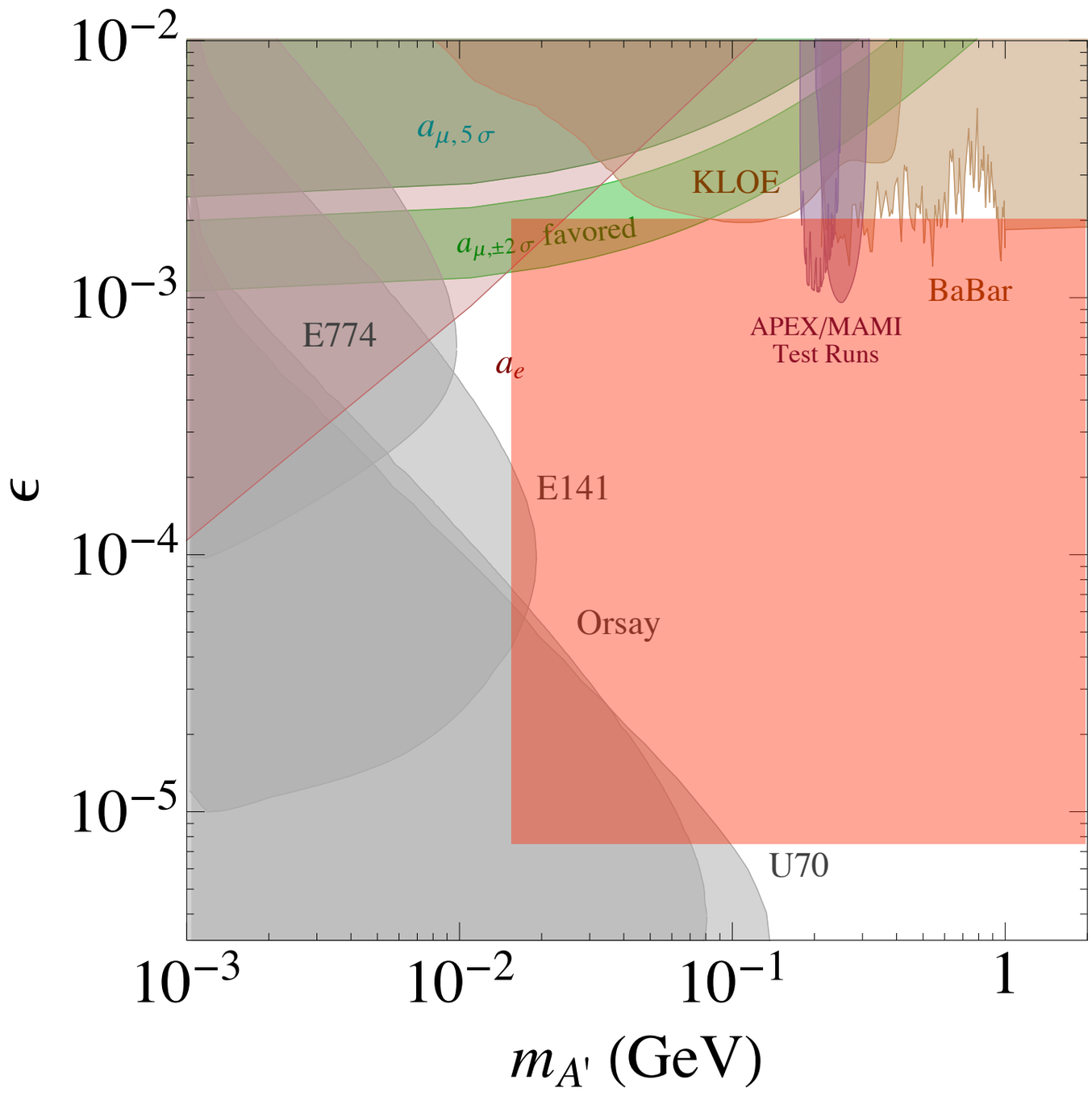
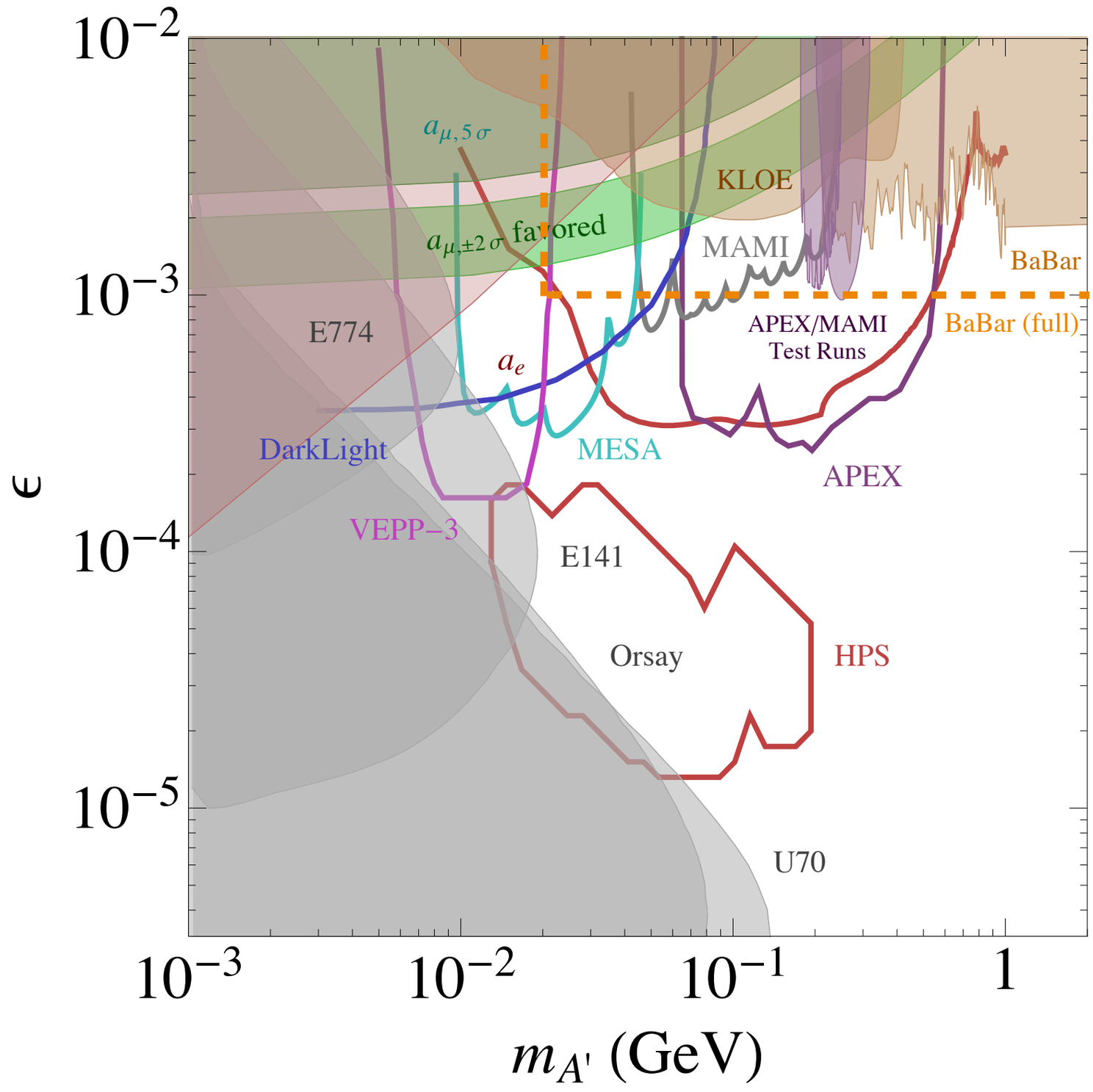


New Experiments (A′ → visible)

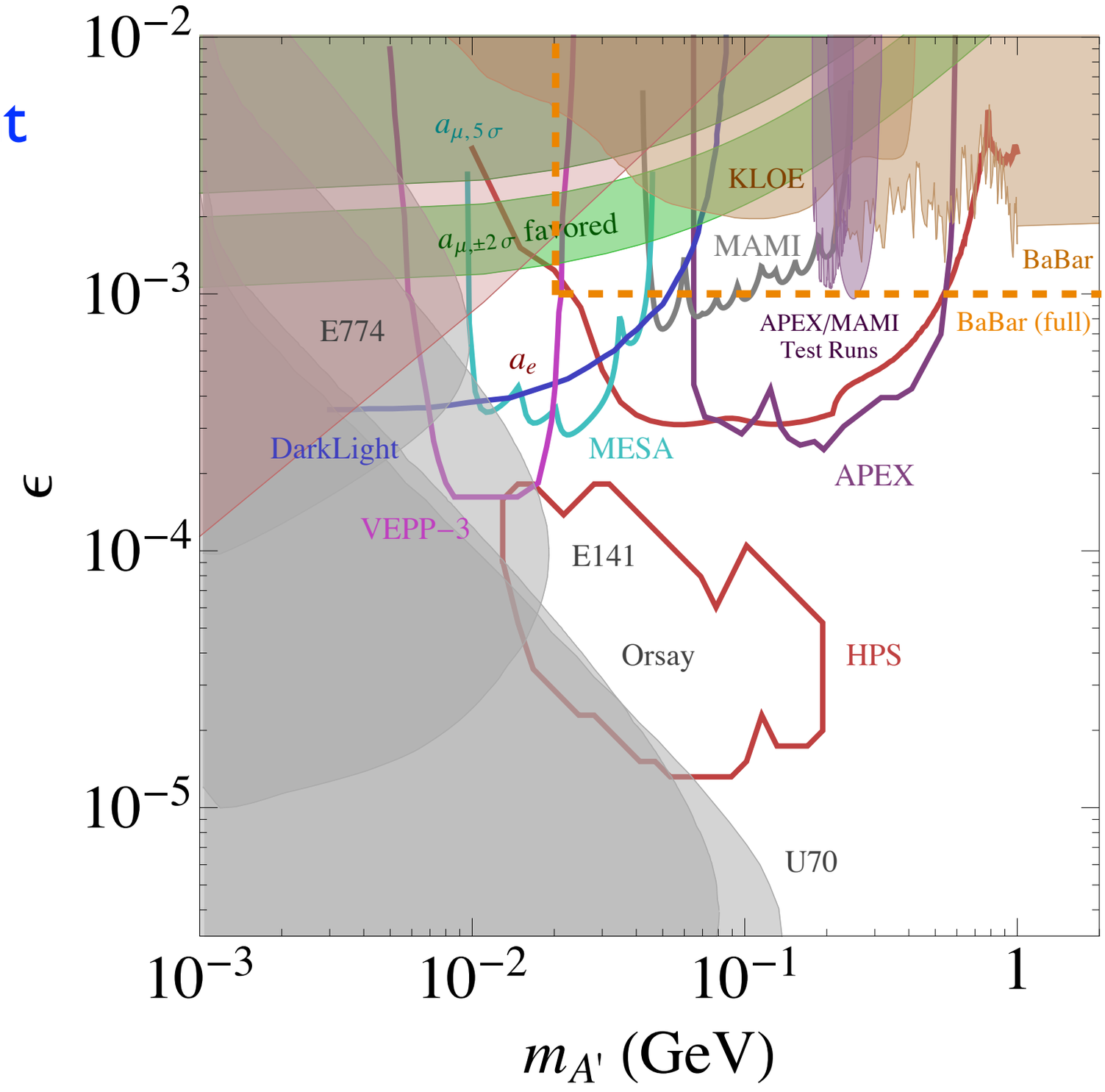


~5-year timescale

New Experiments (A′ → visible)

APEX, HPS, DarkLight

(JLab)



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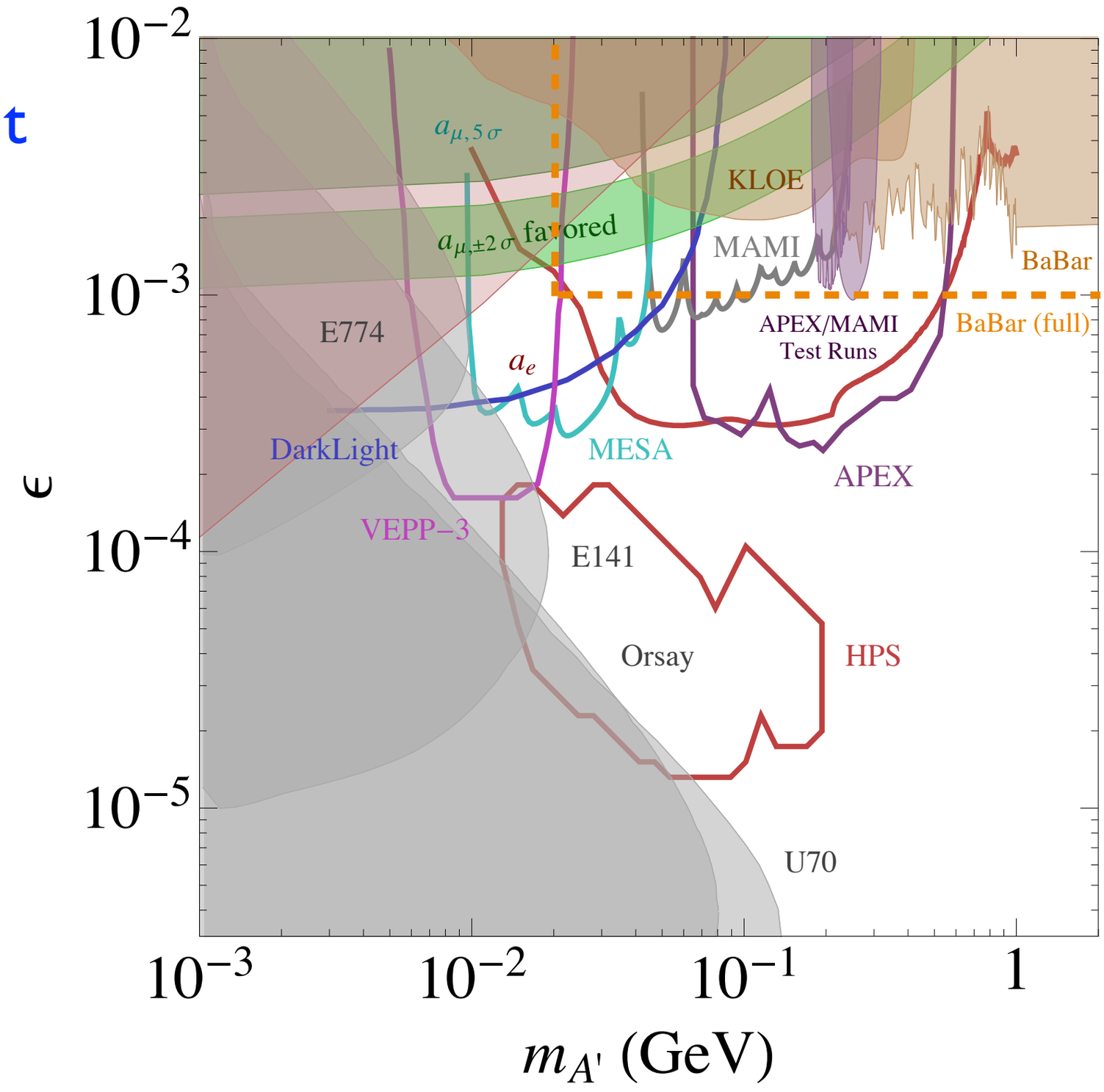
cost: ~$100k, $2M



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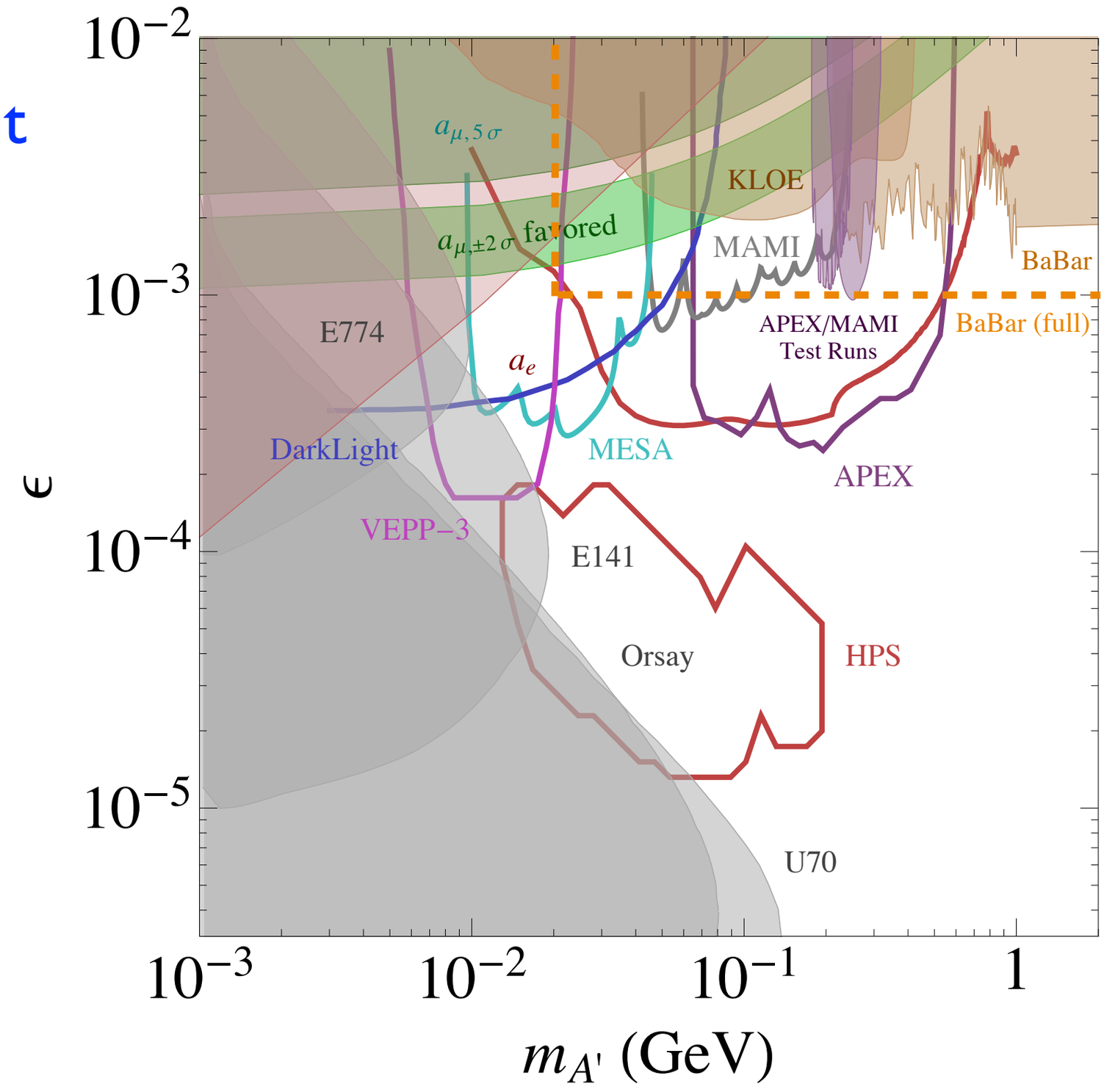

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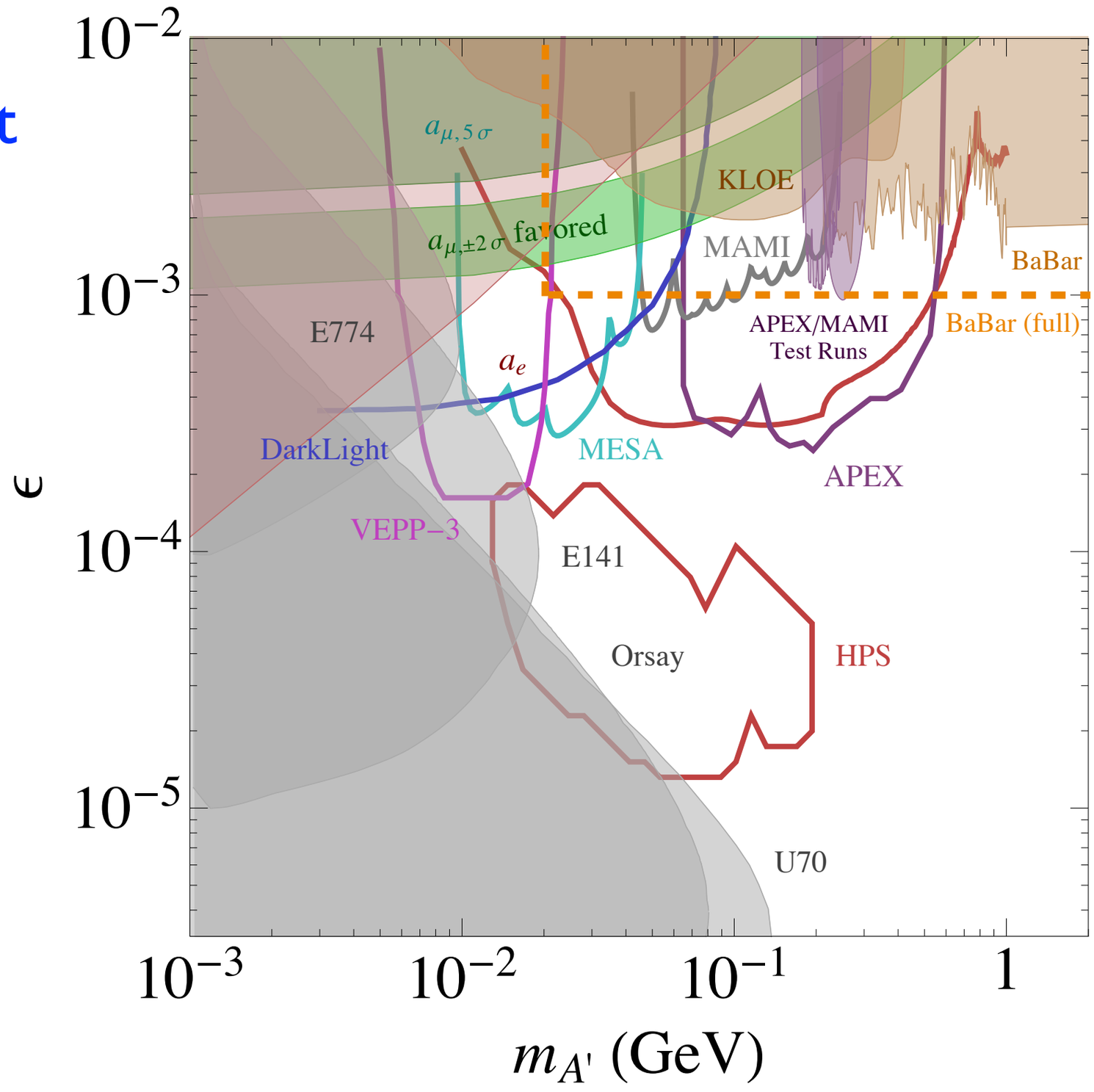
VEPP-3 (Russia)

MAMI/MESA (Germany)



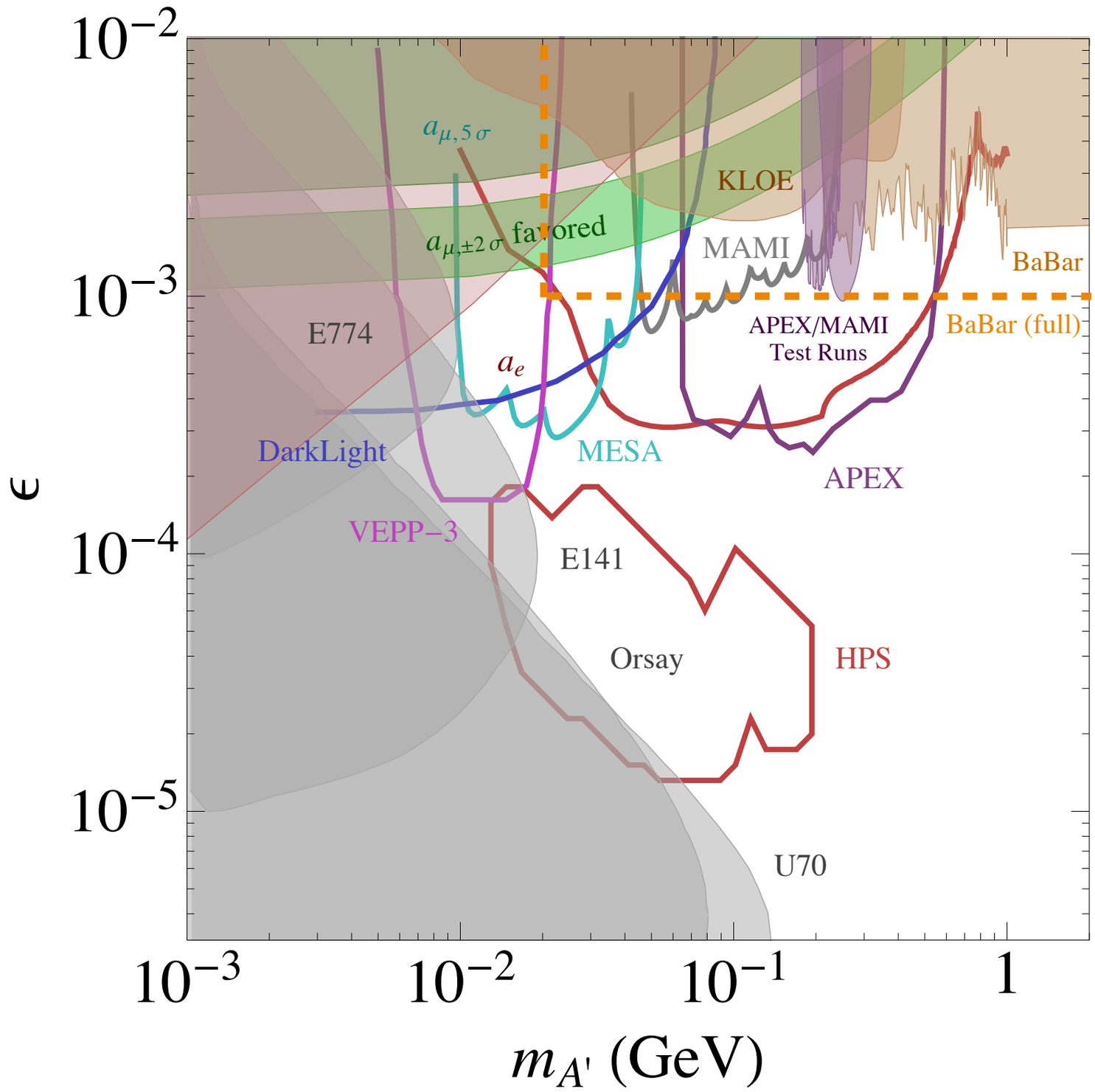
~5-year timescale

Future? (~10-20 year timescale)

Rest of space is also motivated!

We need to:

- close gaps
- higher $m_{A'}$
- lower ε



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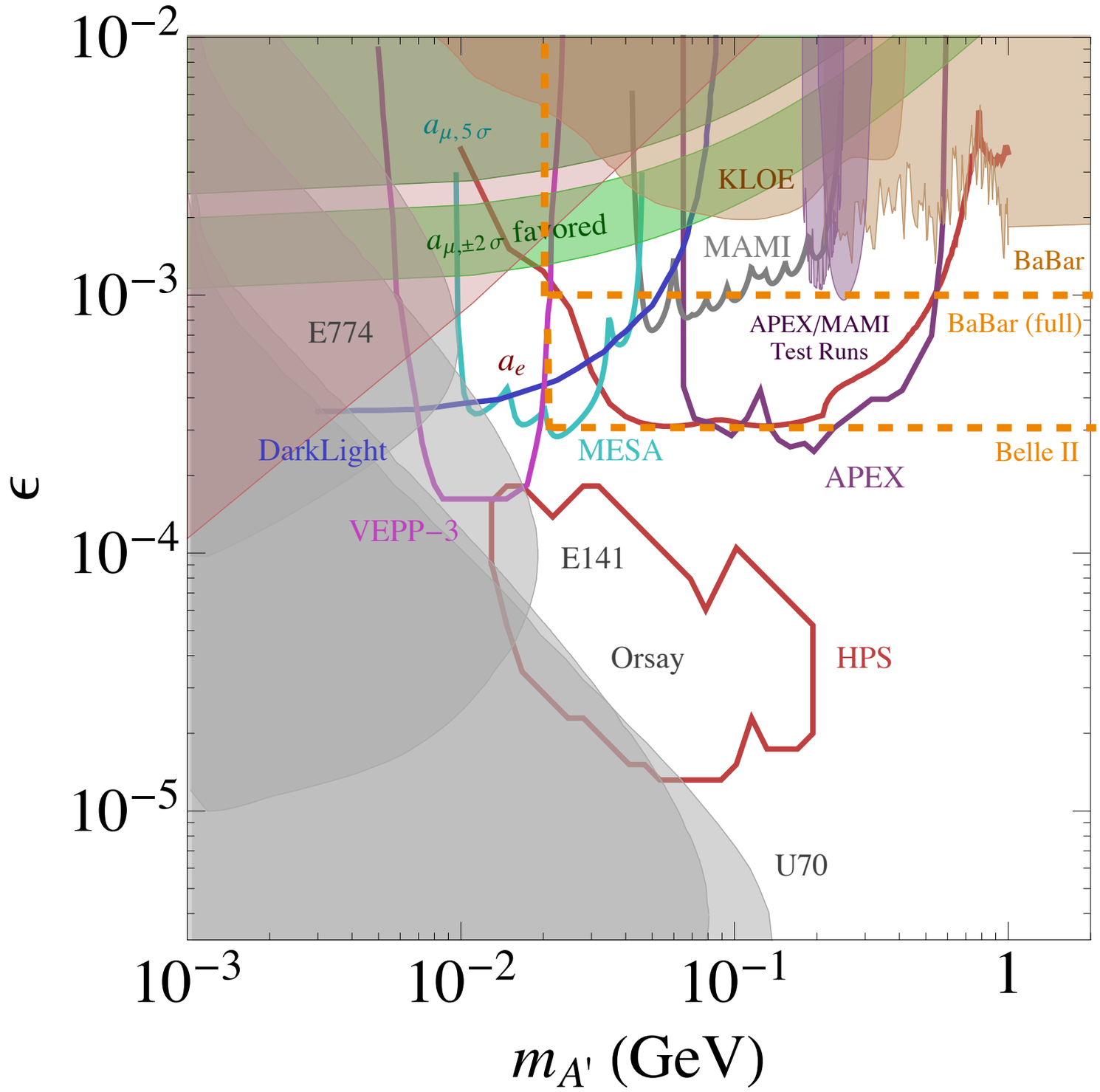
Belle II



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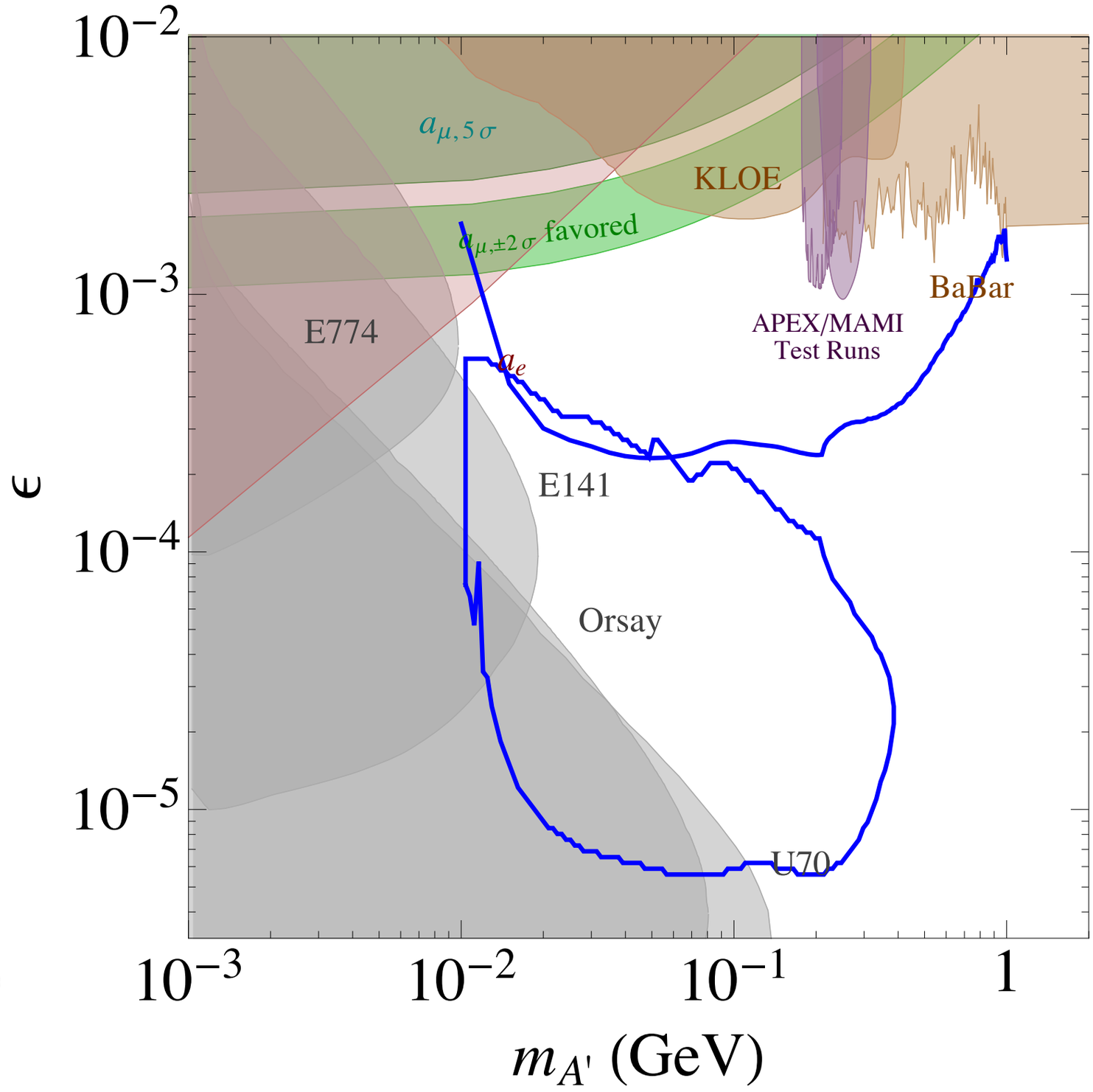
Belle II

e.g.
upgraded "HPS-like"
(24x luminosity, 2x vertex resolution)
Graham & Nelson

many other possibilities!



Dark Photons

Recall:

simplest Dark Sector consists of just an A' at low energies

Standard Model

$g \quad W^{\pm}, Z \quad \gamma$

Dark Sector

A' (massive)

Dark Photons

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Dark Sector can easily be richer,
so must look for other signals too

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$g \quad W^{\pm}, Z \quad \gamma$

Dark Sector

A' (massive)

Dark Sector can easily be richer,
so must look for other signals too

Example: sub-GeV Dark Matter + A′

sub-GeV Dark Matter

Dark matter does not have
to be at the Weak-scale!

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sub-GeV dark matter *is* allowed

(an old idea, e.g. Boehm, Fayet, …)

sub-GeV Dark Matter

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to be at the Weak-scale!

sub-GeV dark matter *is* allowed

(an old idea, e.g. Boehm, Fayet, …)

Constraints from e.g. Cosmic Microwave Background disfavor thermal WIMPs annihilating to charged matter below ~10 GeV…

not applicable to other models

(asymmetric, WIMPless, freeze-in, sub-dominant, …)

sub-GeV Dark Matter

very rich phenomenology

(much of it still under active investigation)

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Can probe in similar ways to Weak-scale DM

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Can probe in similar ways to Weak-scale DM

- colliders
- fixed-target (p & e^-)
- direct detection
- indirect detection

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Can probe in similar ways to Weak-scale DM

focus on this now

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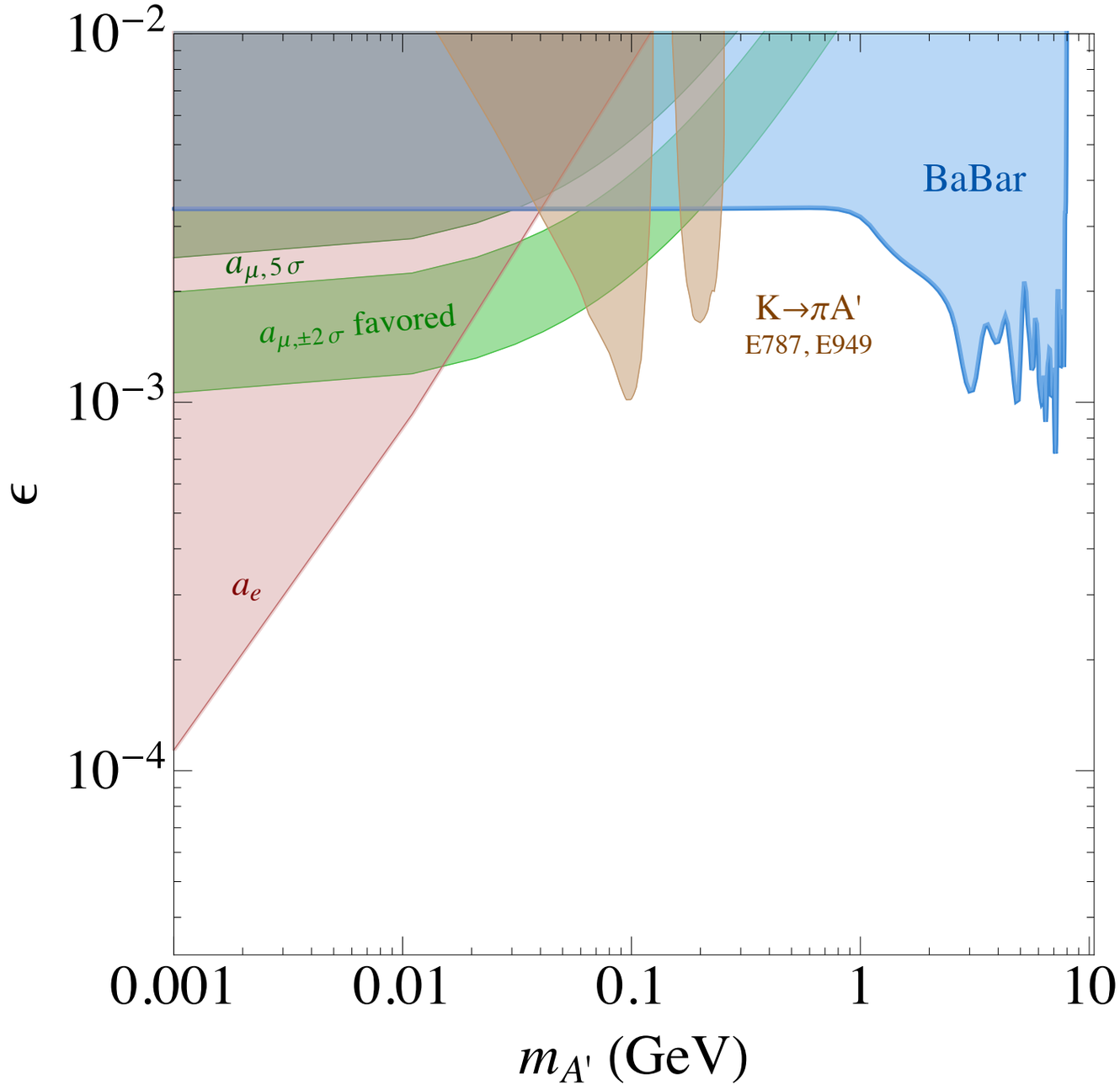
Constraints for A′ → invisible

Produce A′ directly

$A' \to \mathrm{DM} + \mathrm{DM}$



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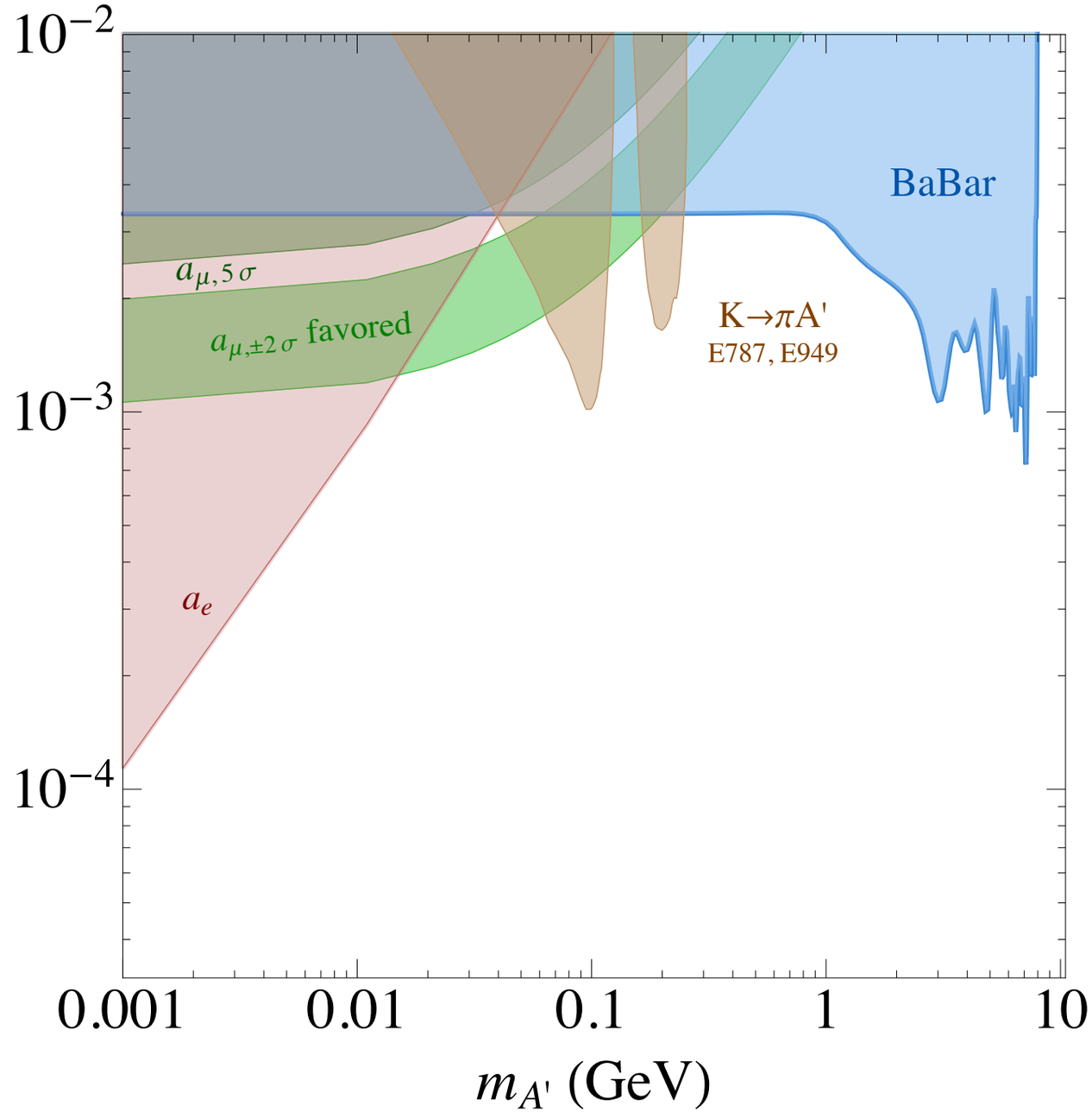

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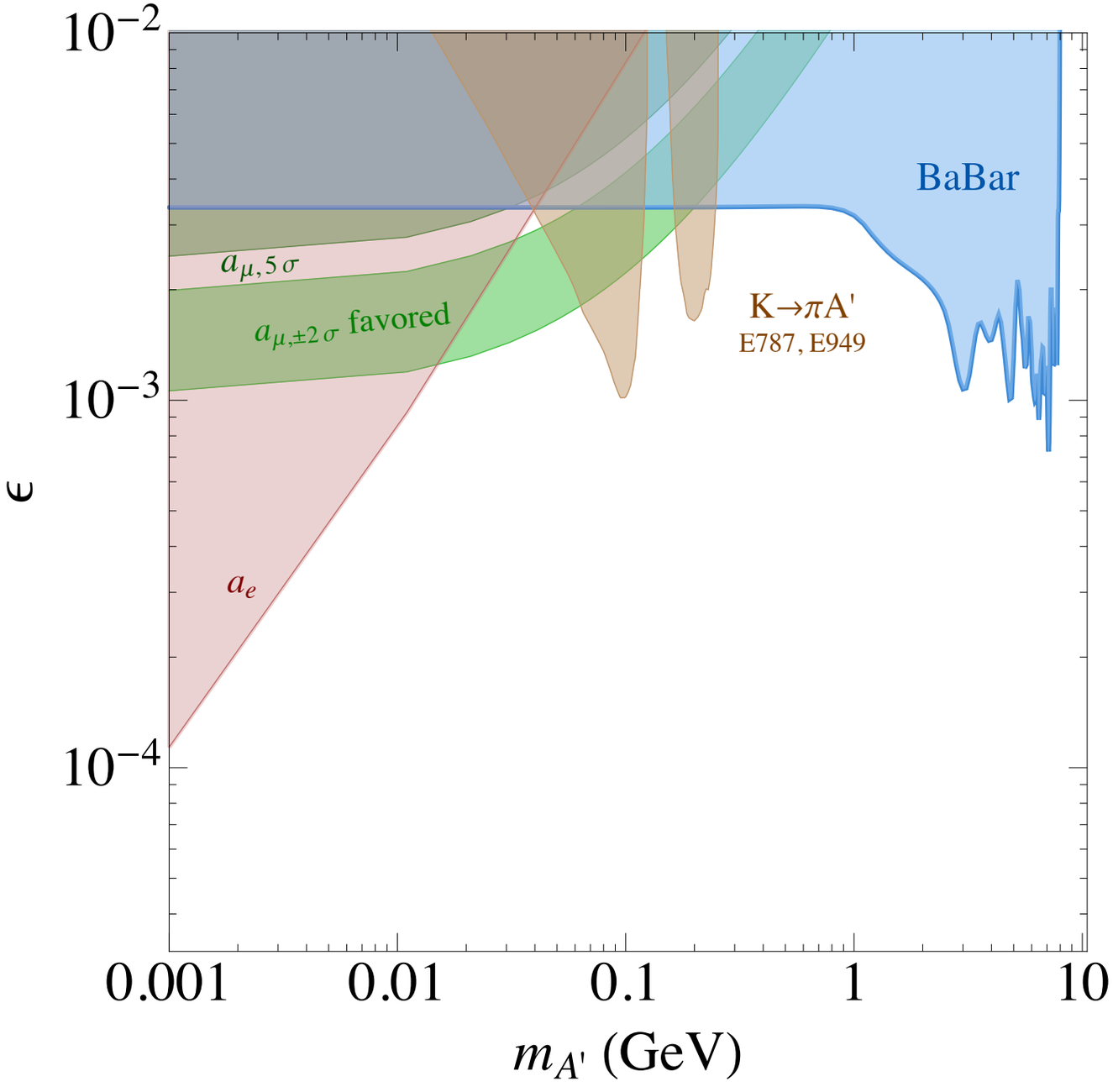
Batell, Pospelov, Ritz



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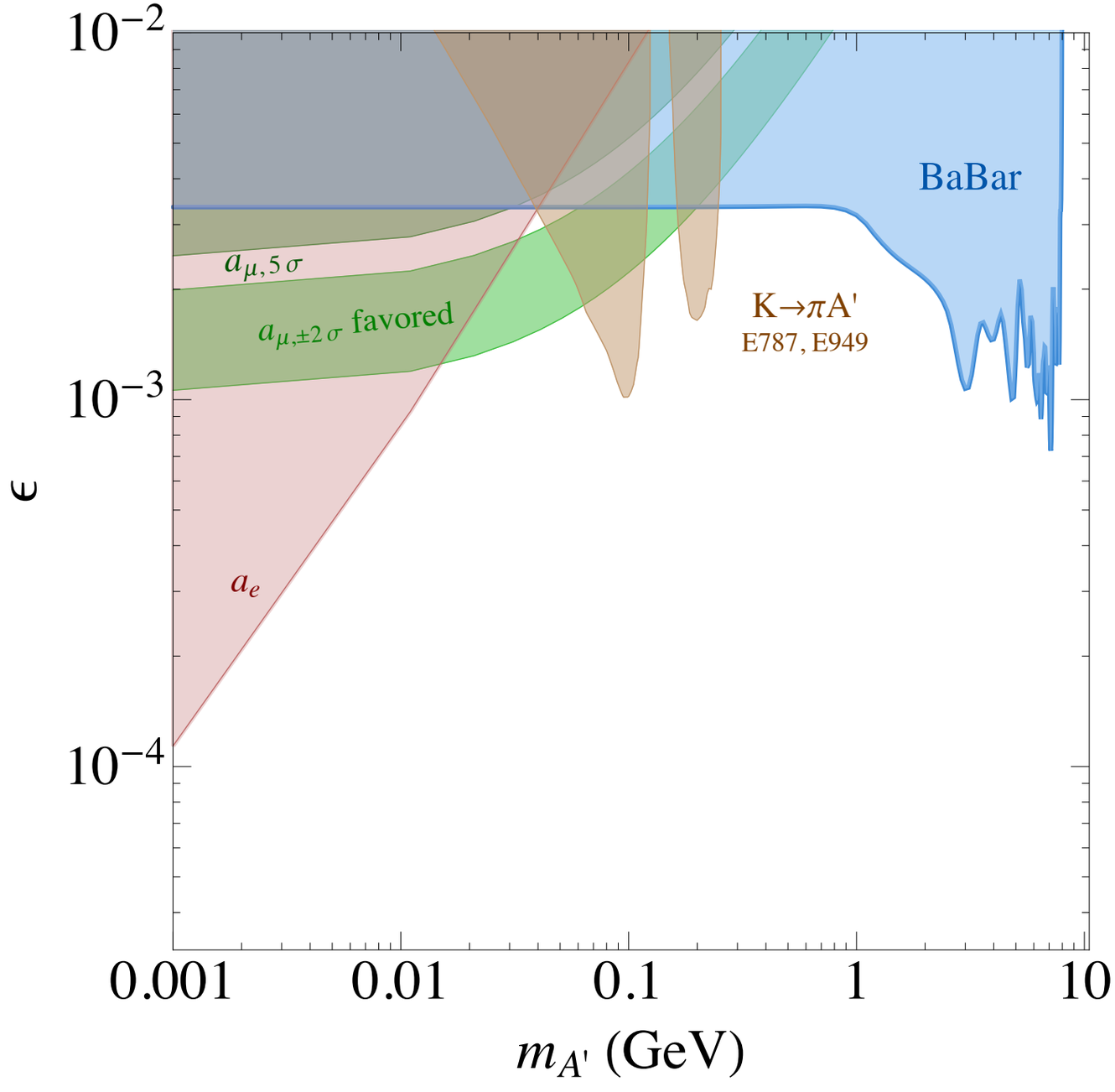
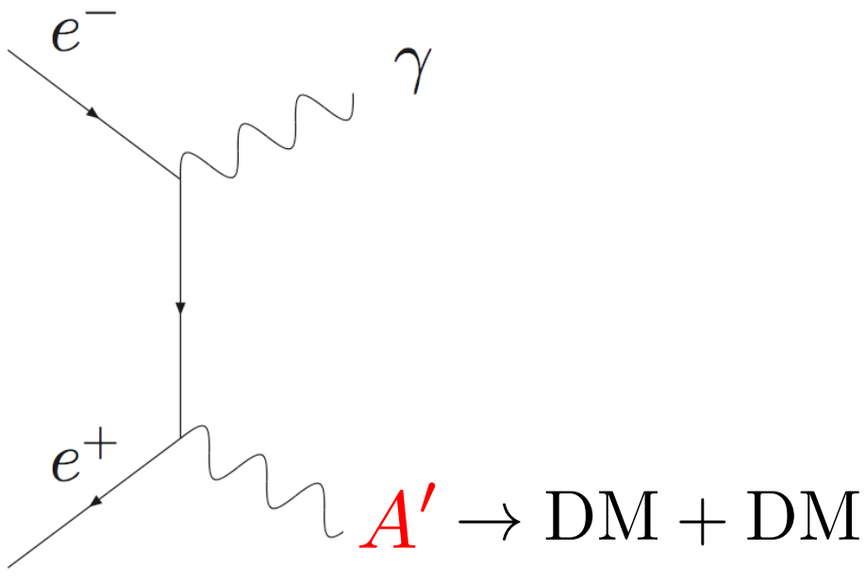


BaBar



based on BaBar search for $\Upsilon(3S) \to \gamma A^0$

RE, Mardon, Papucci, Volansky, Zhong
Krnjaic, Izaguirre, Schuster, Toro
Fayet
Borodatchenkova, Choudhury, Drees

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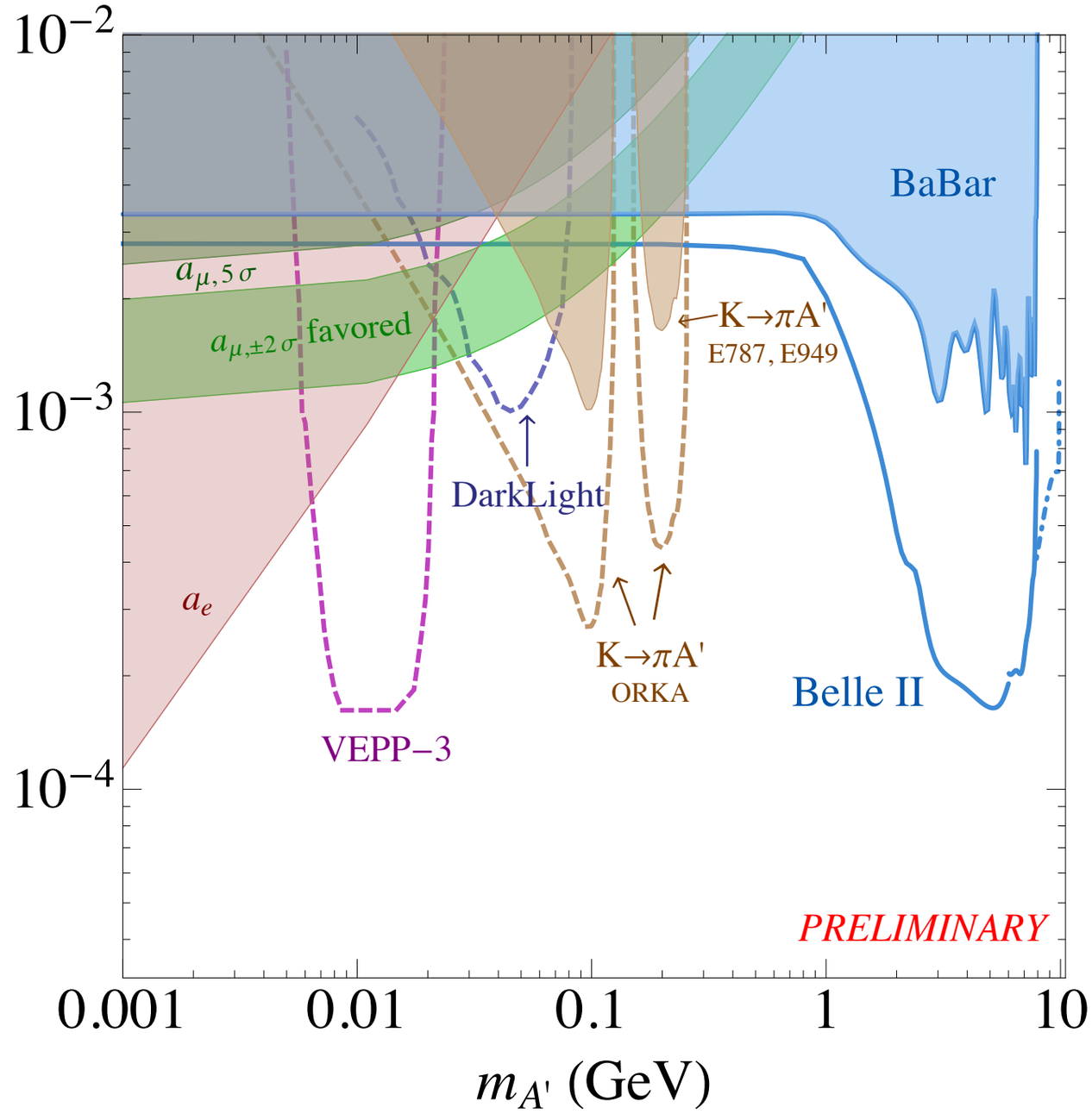

RE, Mardon, Papucci, Volansky, Zhong
VEPP-3, DarkLight

Major improvements possible with
ORKA, Belle II, DarkLight, VEPP-3

Constraints for A′ → invisible

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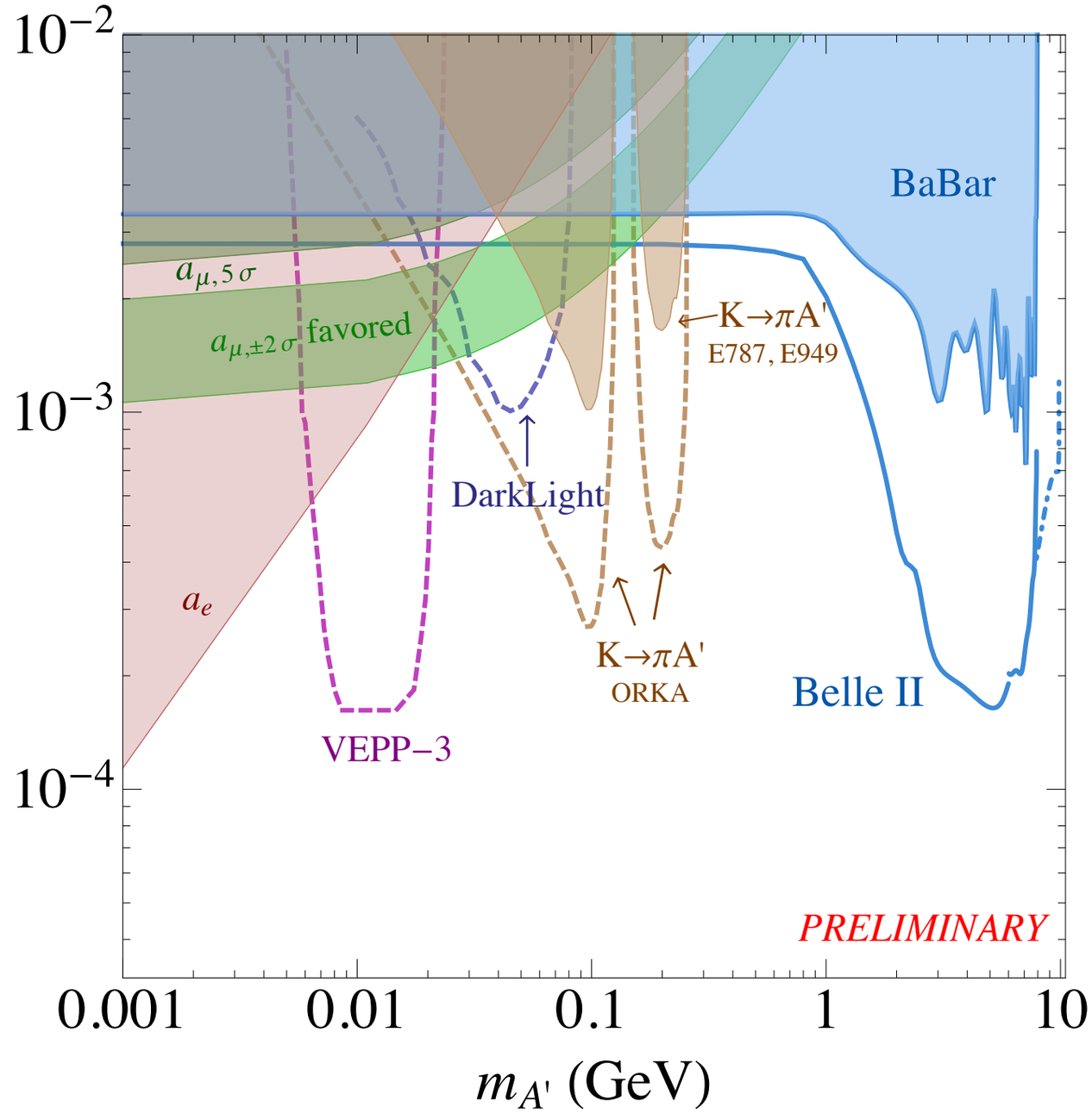

+ several new beam dump searches possible too!

Proton-beam fixed target experiments

Batell, Pospelov, Ritz
Deniverville, Pospelov, Ritz
Deniverville, McKeen, Ritz
Aguilar-Arevalo et.al.

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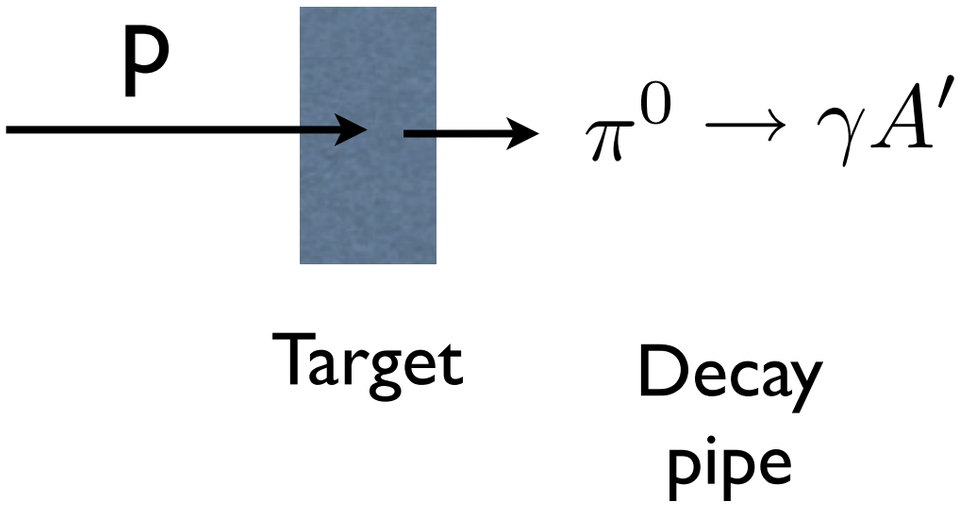

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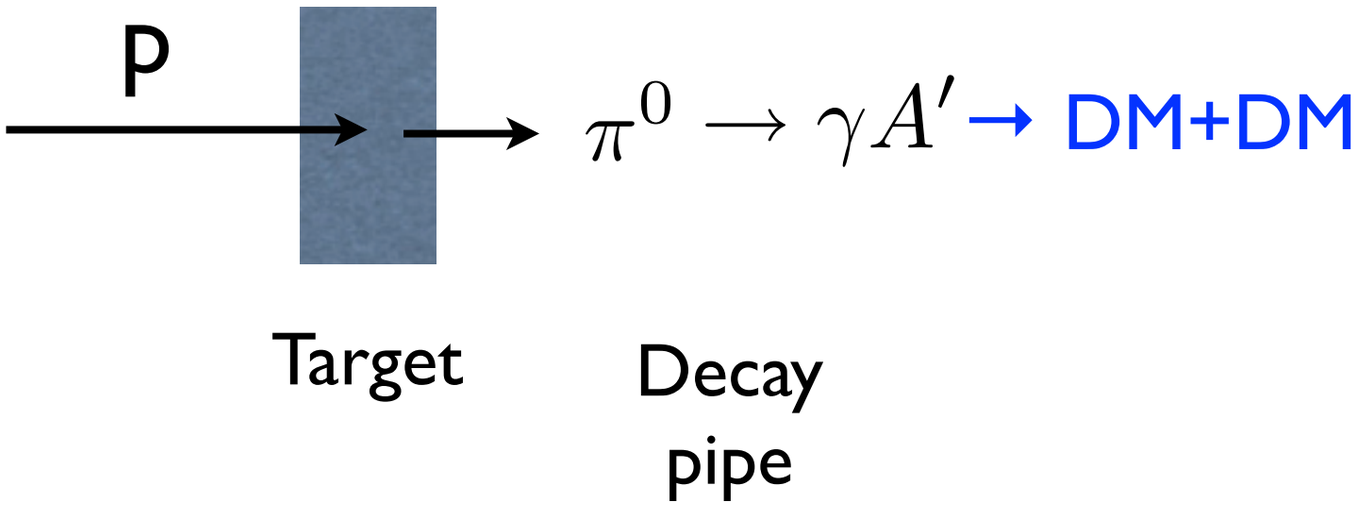
Example: produce A' from pion decays

$A' \rightarrow$ DM+DM



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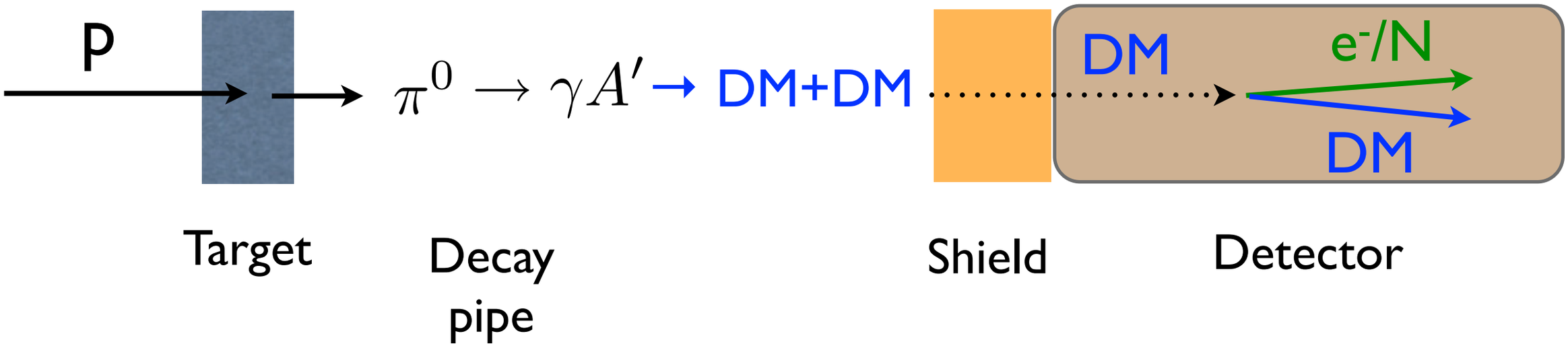

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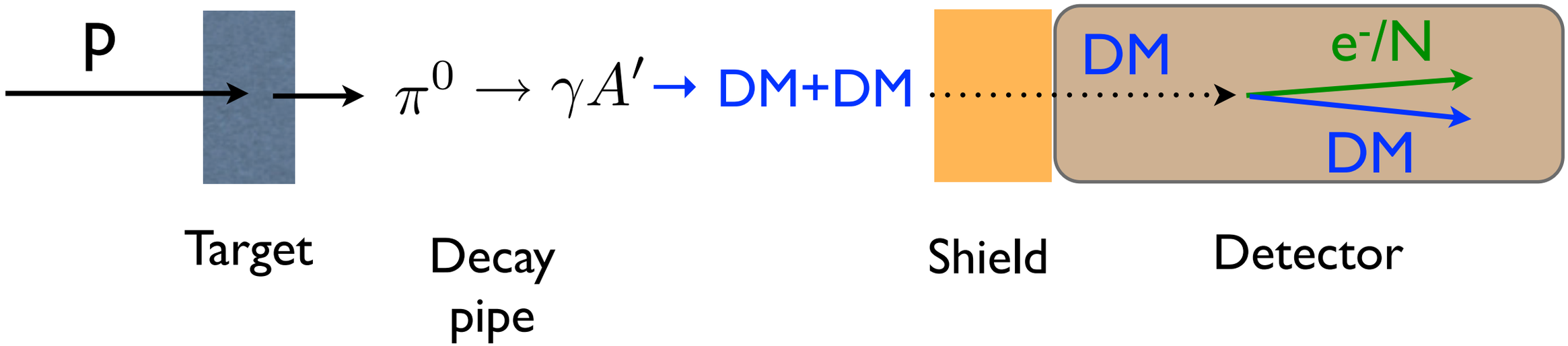


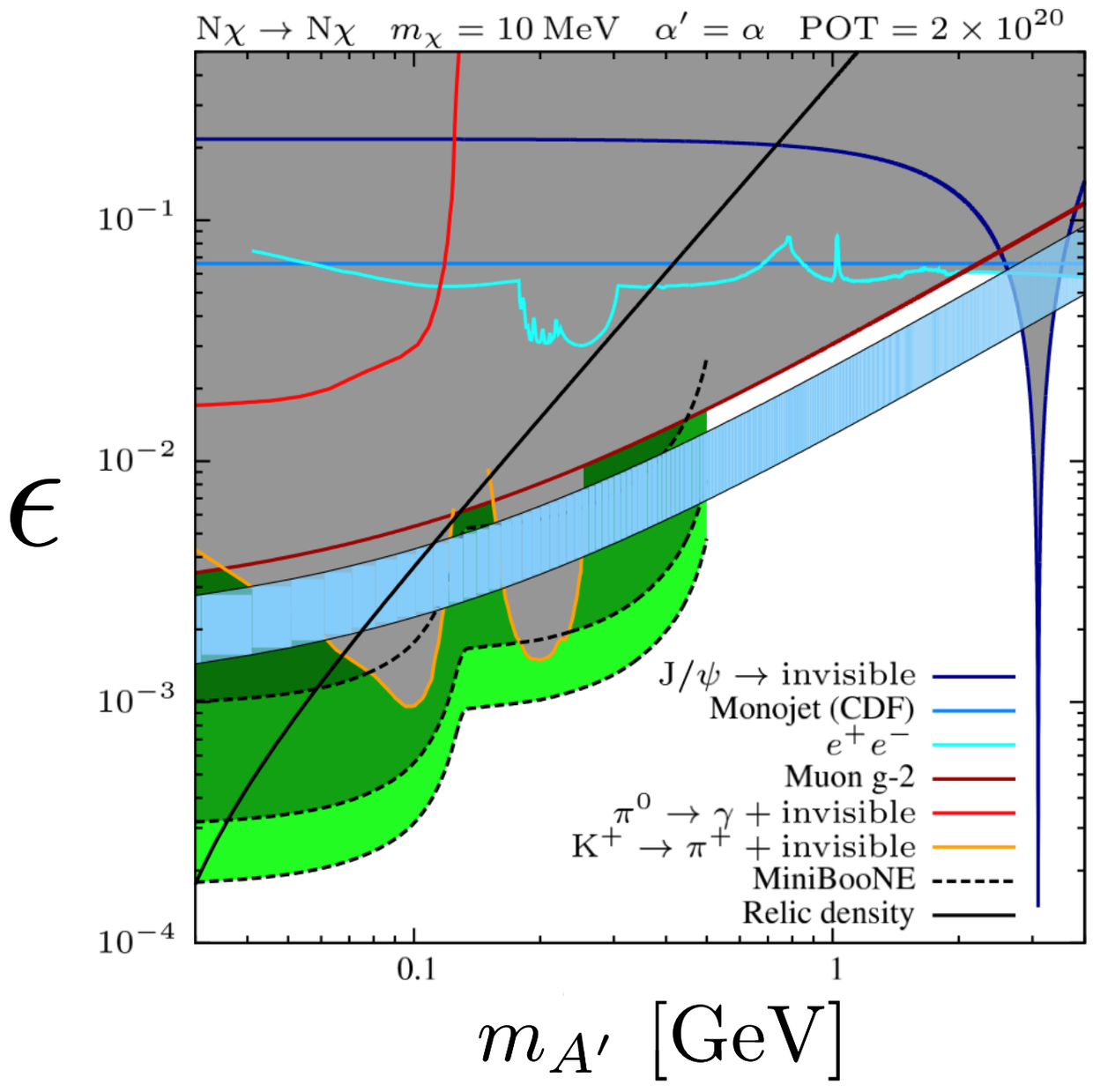
plenty of room for future exploration at neutrino facilities, e.g.

LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …

Proton-beam fixed target experiments

MiniBooNE proposal for sub-GeV DM search

Aguilar-Arevalo et.al. (MiniBooNE proposal)



e.g. $m_{\mathrm{DM}} = 10\ \mathrm{MeV}$

pioneering search for sub-GeV dark matter using a neutrino factory

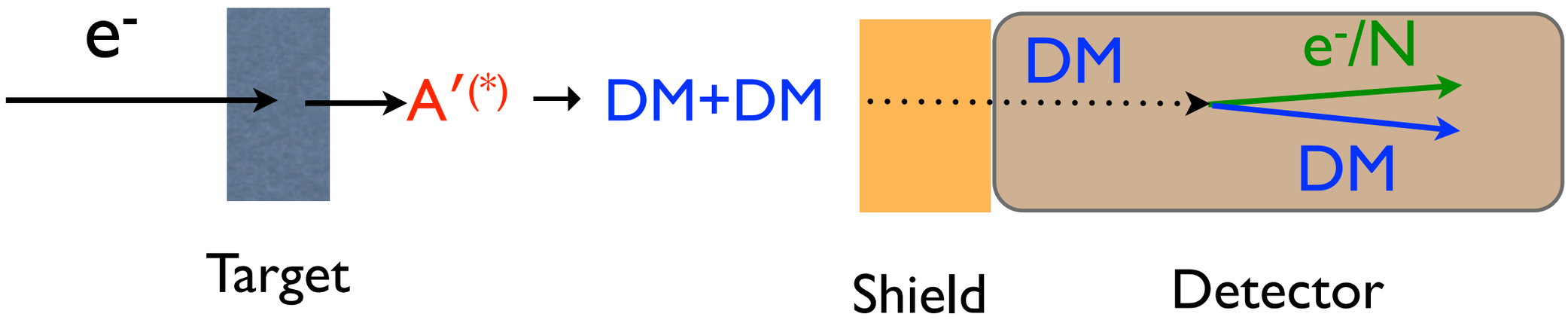
relatively inexpensive, no new facility

Electron-beam fixed target experiments

Krnjaic, Izaguirre, Schuster, Toro
Diamond, Schuster

Example: produce DM directly from on/off-shell A'

DM recoils of e^-/nucleon in detector



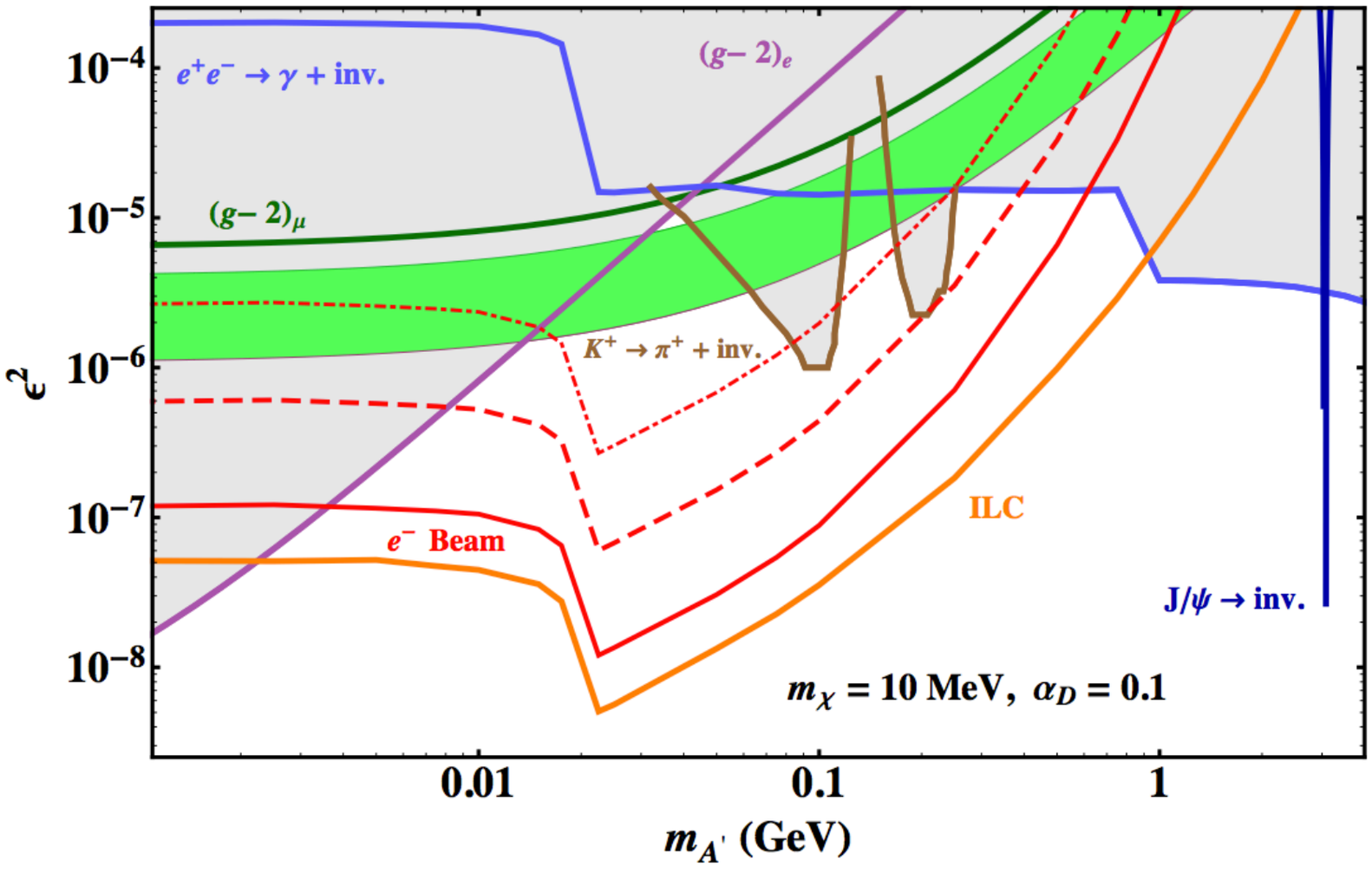
no beam-related background, small detector, favorable kinematics

Electron-beam fixed target experiments

Krnjaic, Izaguirre, Schuster, Toro
Diamond, Schuster

new parasitic experiments can cover large parameter space robustly

e.g. JLab, Mainz, SLAC, SuperKEK, …



can also take advantage of linear collider beam dump

Conclusions

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- Dark sectors (new, light weakly-coupled particles) are well-motivated by theory, DM, strong CP, muon g-2, astrophysics, …

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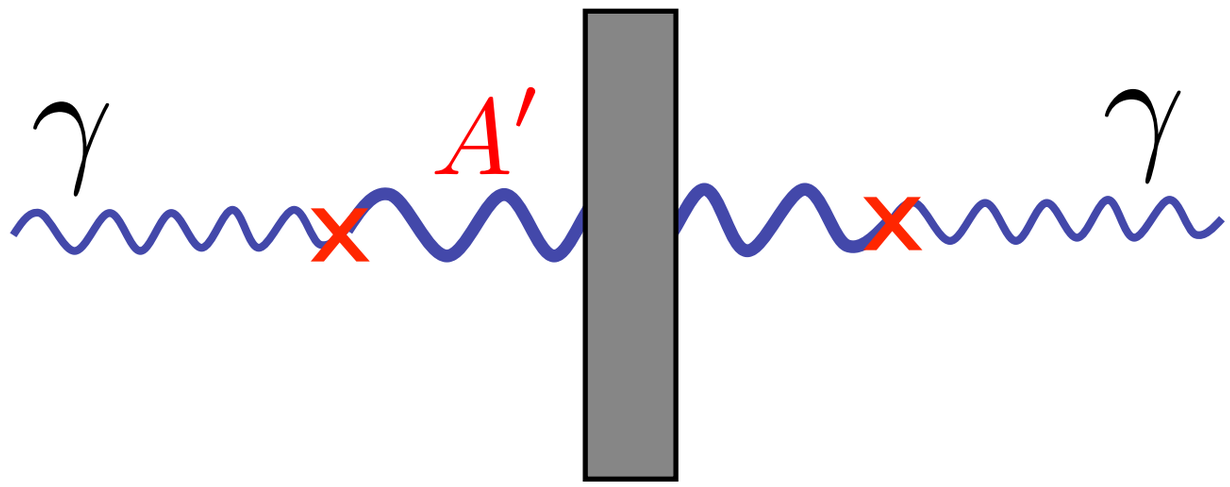
we don't know which guiding principle for finding new physics is reliable; must explore all motivated possibilities

Possible game-changing discovery for low-cost

Backup

How look for low-mass A′?

"Light-shining-through-walls" (cf. axions)



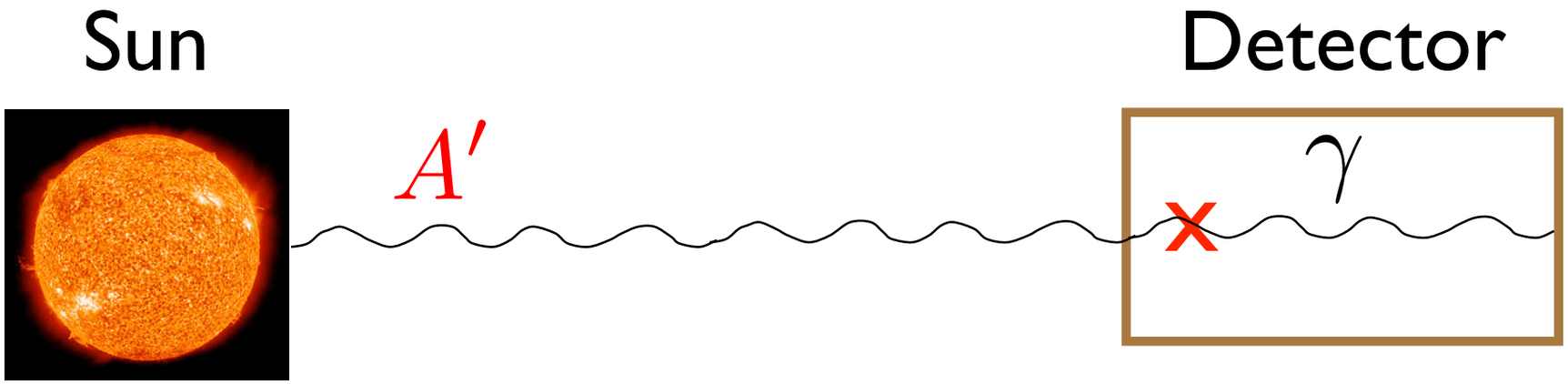
LIPSS (Jlab) , BFRT (BNL), BMV (LULI), GammeV (Fermilab),
ALPS (DESY), OSQAR (CERN), PVLAS (INFN), ...

Need powerful lasers but no magnets

How look for low-mass A′?

Helioscopes: stare at the sun (cf. axions)

Okun, …

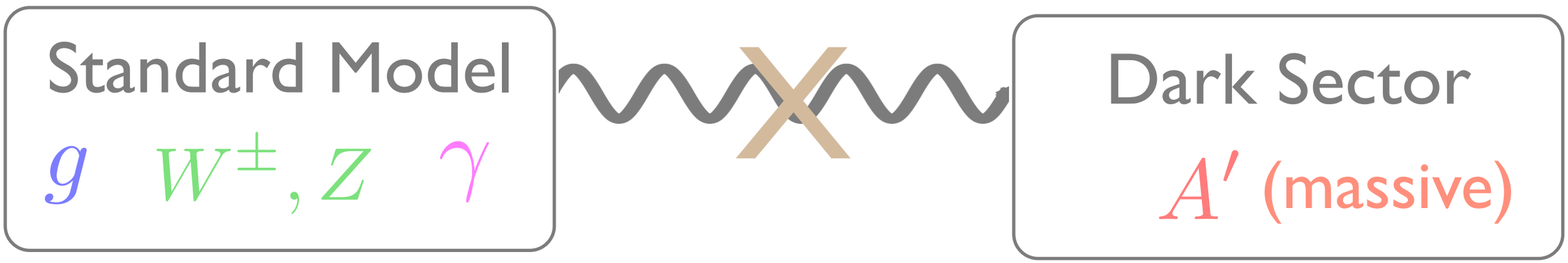


TSHIPS, CAST, SUMICO, IAXO, …

Dark Photons

Recall:

simplest Dark Sector consists of just an A'



Dark Sector can easily be richer,
so must look for other signals too

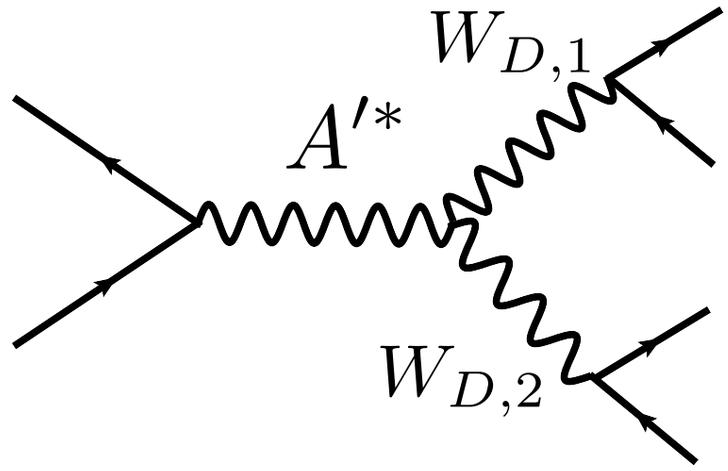
Example 2: non-Abelian or dark Higgs

Several searches done/ongoing/planned

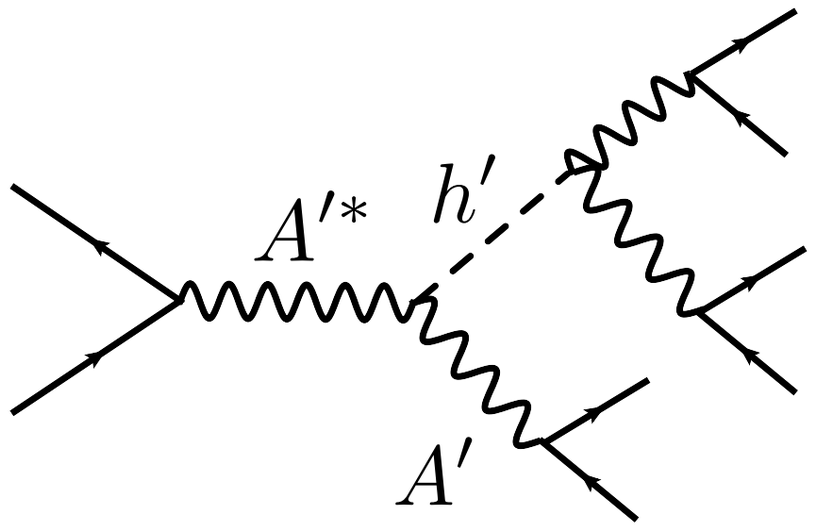
e.g. BaBar

Examples:

non-Abelian
(many gauge bosons)



Dark Higgs boson



Direct Detection

RE, Mardon, Volansky

probe DM in our halo scattering off

e.g. electrons in detector

first direct detection limits

on sub-GeV DM, using

published XENON10 data

RE, Manalaysay, Mardon,
Sorensen, Volansky

lots of potential
for current & new
experiments!

see also Graham et.al.

O *MeV !*