Exploring Dark Sectors

The Search for New, Light, Weakly-coupled Particles

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Invited Session: Dark Matter - Beyond WIMPs

The State of Particle Physics

The success of the Standard Model is a triumph

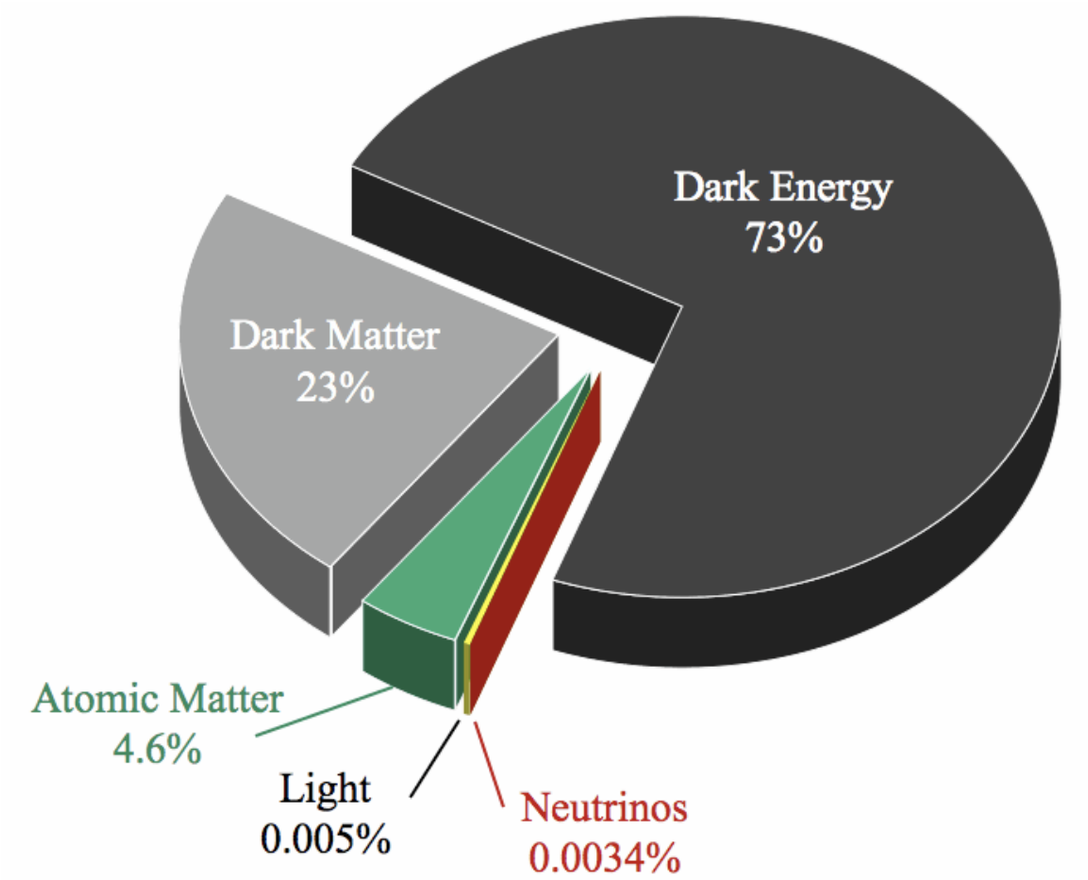
It is the result of several decades of
theoretical & experimental *exploration*, of
pushing at the boundaries of what we knew

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



But what is it?

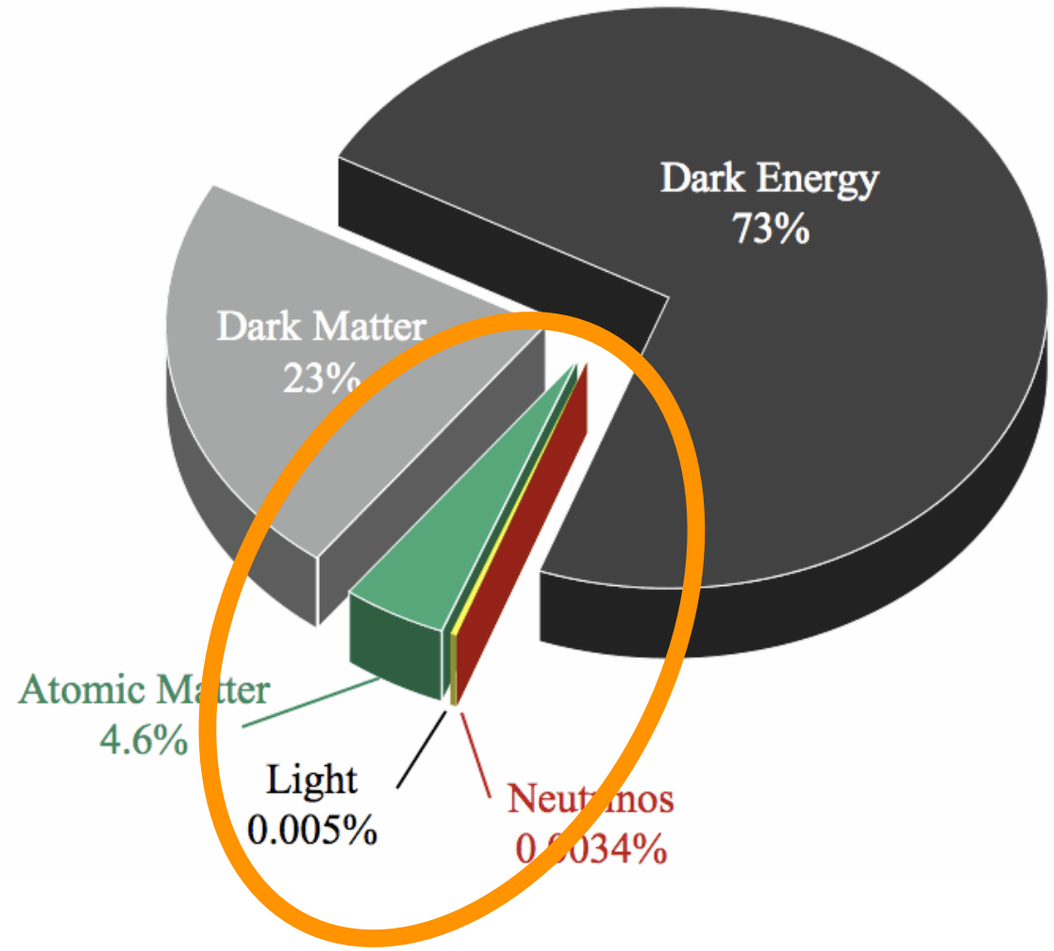
It doesn't have to be a WIMP at the Weak-scale!

LHC results challenge connection between
dark matter and Weak-scale naturalness

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?

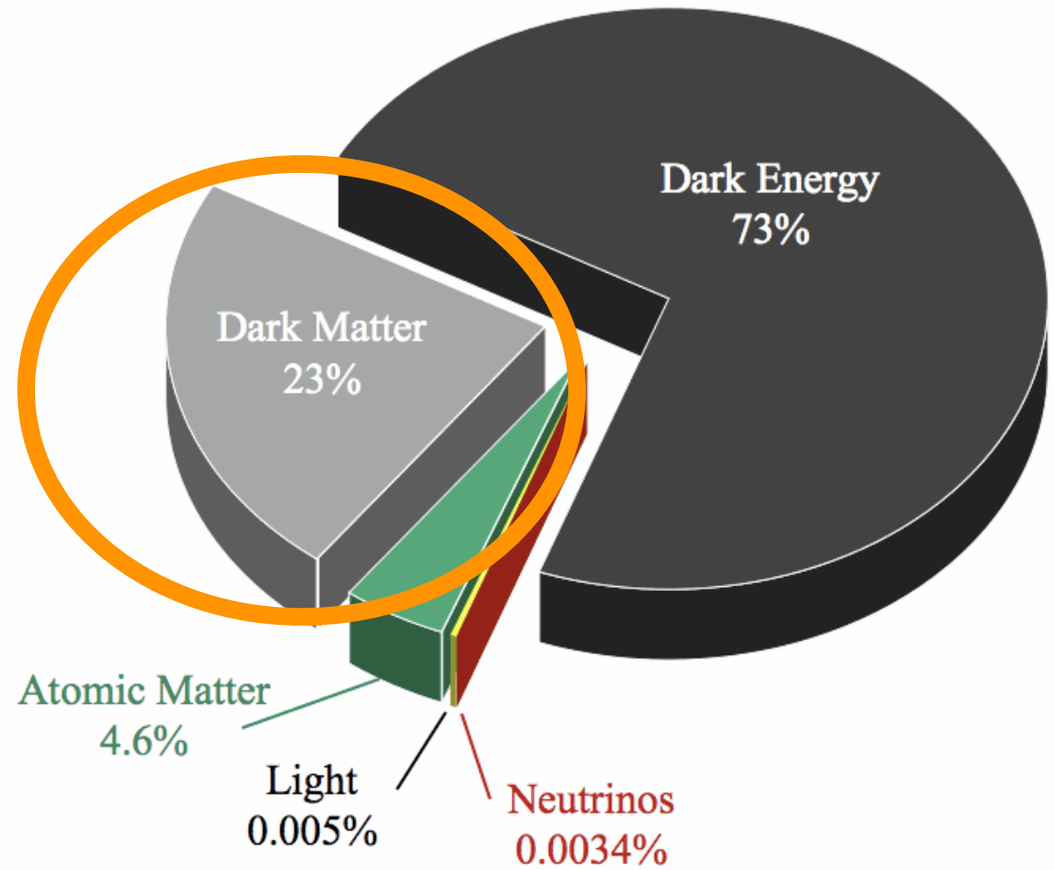


Rich, intricate structure!

Many, rich Dark Sectors?

Why should Standard Model sector be special?

What if Dark Sector
is equally intricate?



Rich, intricate
structure!

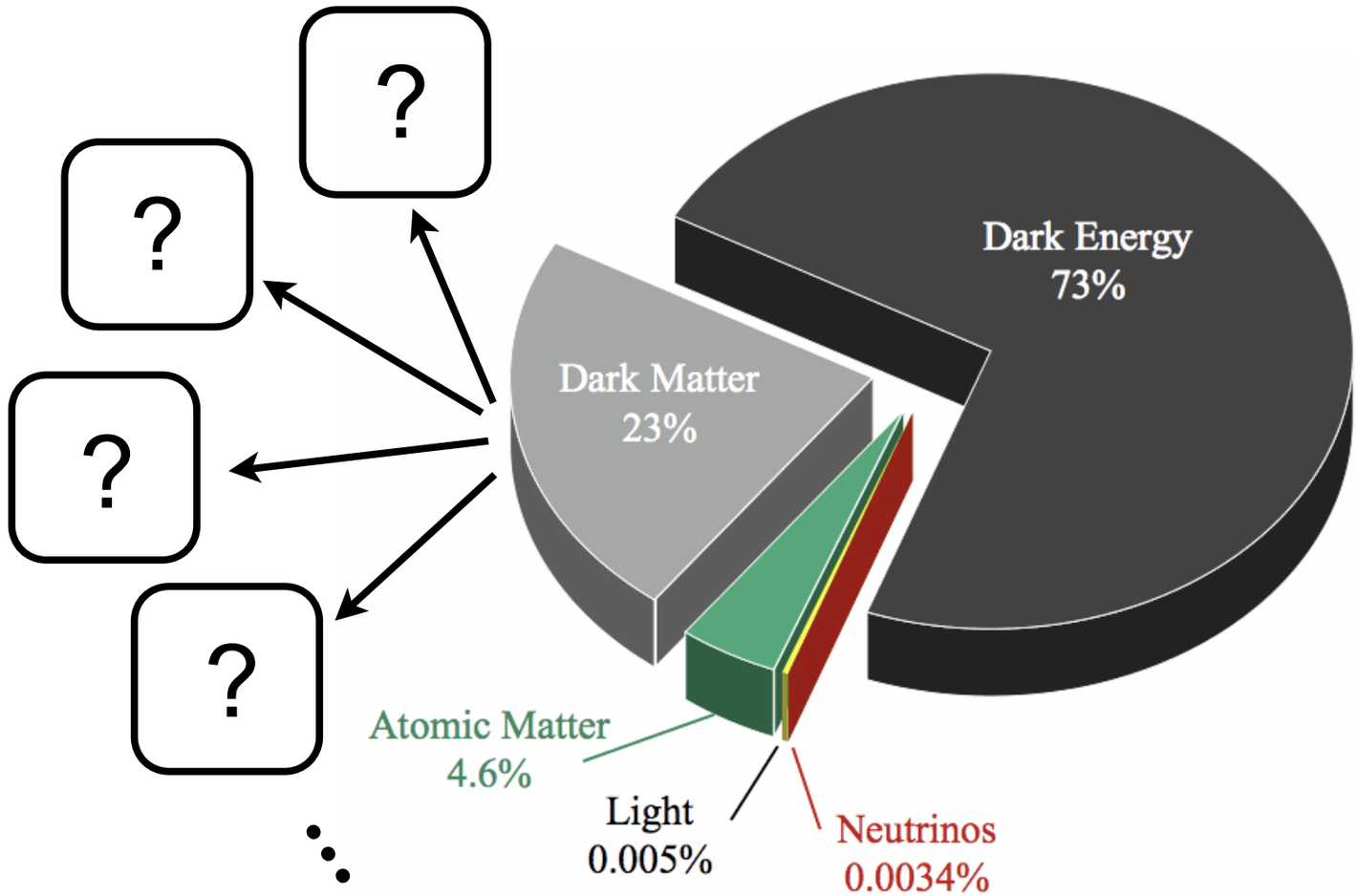
Many, rich Dark Sectors?

Why should Standard Model sector be special?

What if Dark Sector is equally intricate?

What if there are *many* Dark Sectors?

How could we *know?*



Rich, intricate structure!

Dark Sectors

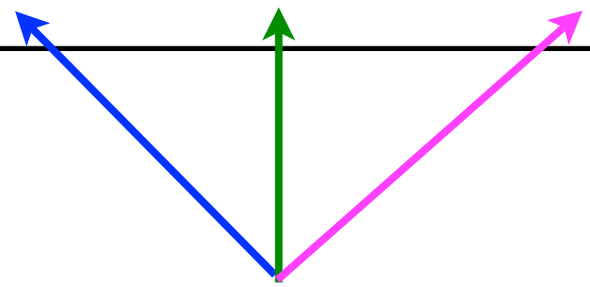
- motivated by dark matter, but also by theory, strong CP, data (e.g. muon g-2 & astrophysics)
- several well-motivated possibilities exist
- probe with a rich, diverse, and relatively inexpensive experimental program, going beyond standard searches
- a discovery would be a game-changer

Dark Sectors

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

Standard Model

g $W^{\pm}, Z$ γ



Known Forces

strong, weak, EM

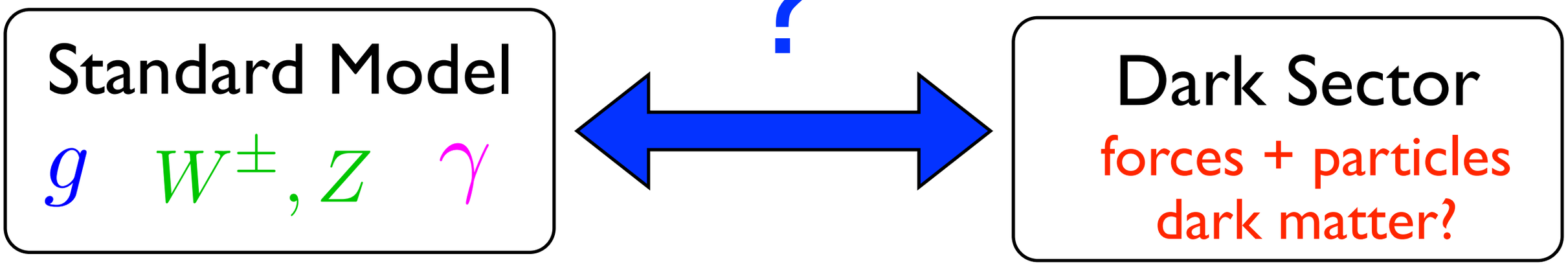
Dark Sector

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?

  see e.g. review 1312.4992
- "Neutrino" $\kappa (H L) N$ sterile neutrinos?

Portals

our focus today

(very brief, since several other talks)

- "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′
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- "Neutrino" $\kappa (HL) N$ — sterile neutrinos?

Axion

explains why CP violation in strong force is so small

i.e. solves strong CP problem

axion is associated with spontaneous breaking at a scale f_a

of an approximate global Peccei-Quinn (PQ) symmetry

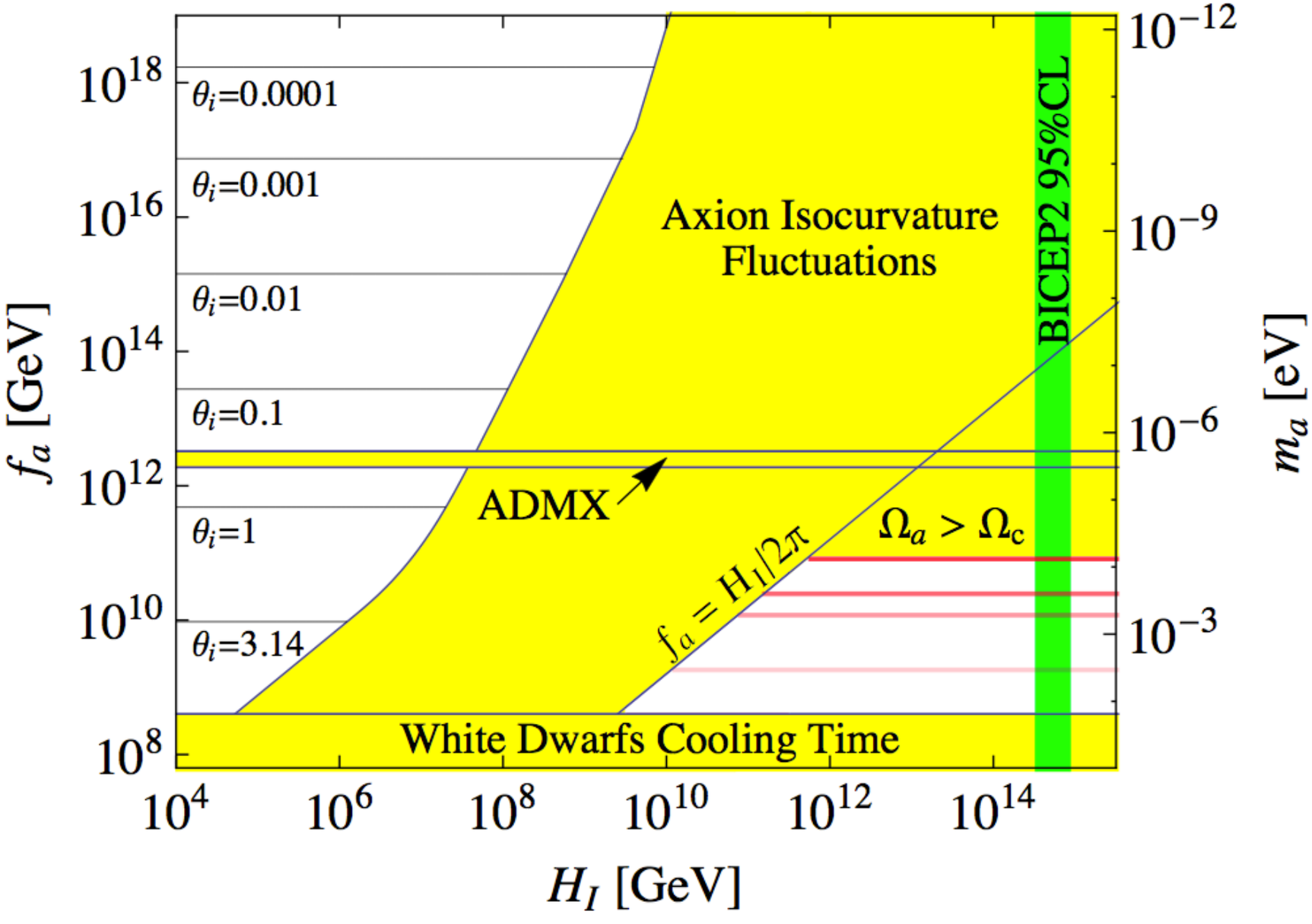
$$m_a \sim \frac{{\Lambda_{\rm QCD}}^2}{f_a} \simeq 0.6 \text{ meV } \frac{10^{10}\,\text{GeV}}{\rm f_a}$$

naturally light

can be generalized to axion-like particles or "ALPs"

axions & ALPs are excellent dark matter candidates

If Axions are all of Dark Matter…

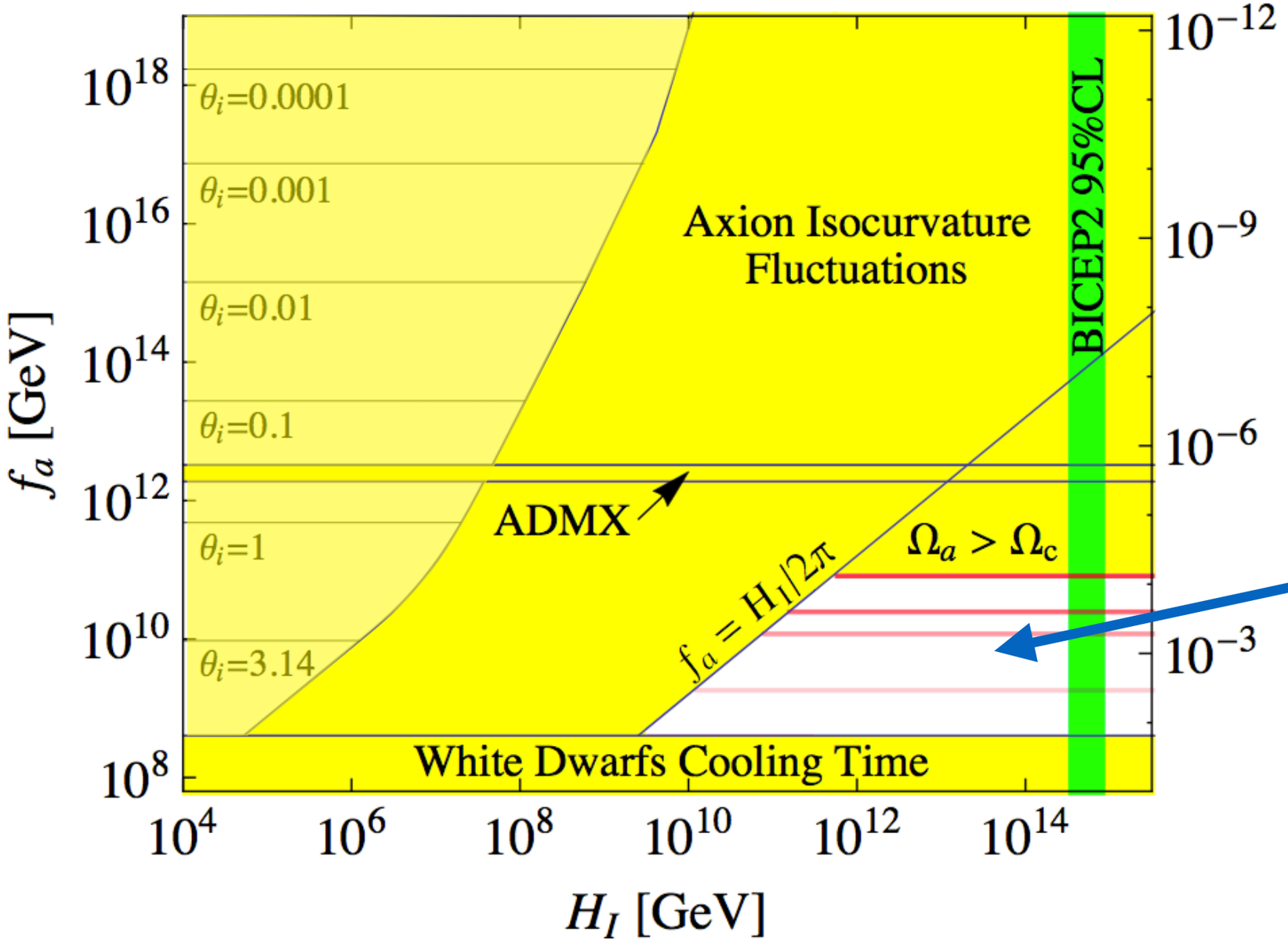


Visinelli, Gondolo

(Turner & Wilczek; see also Marsh et.al., Higaki et.al.)

if $f_a > H_I$, then get large isocurvature perturbations (disfavored by WMAP/Planck)

If Axions are all of Dark Matter…



Visinelli, Gondolo

(Turner & Wilczek; see also Marsh et.al., Higaki et.al.)

favored axion DM region (assuming standard ΛCDM cosmology

(but caveats exist!!)

if $f_a > H_I$, then get large isocurvature perturbations (disfavored by WMAP/Planck)

$\Longrightarrow$ BICEP2 disfavors axion DM for large f_a

Portals

our focus today

- "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?

see e.g. review 1312.4992

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

Dark Photons

dark matter?

Standard Model

g $W^{\pm}, Z$ γ

Known Forces

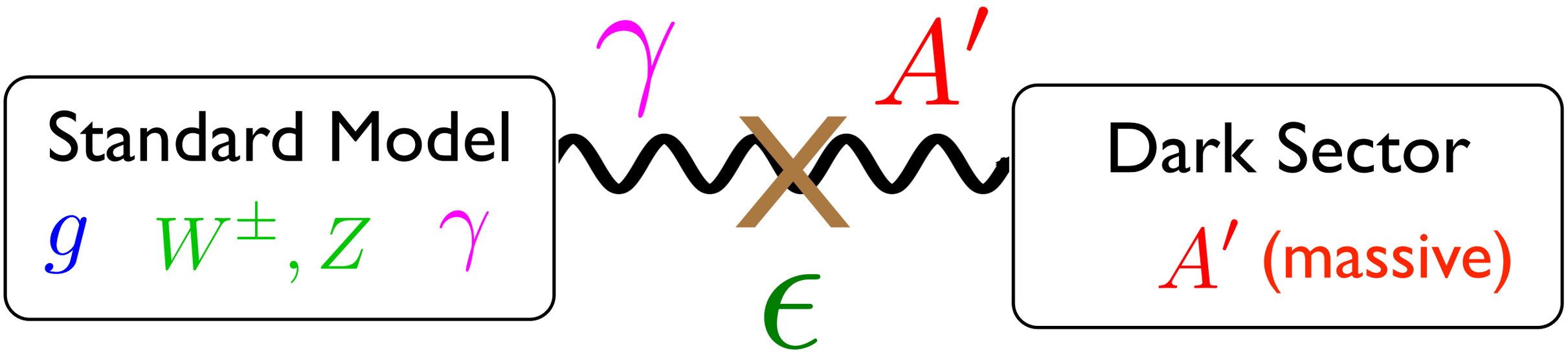
Dark Sector

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"

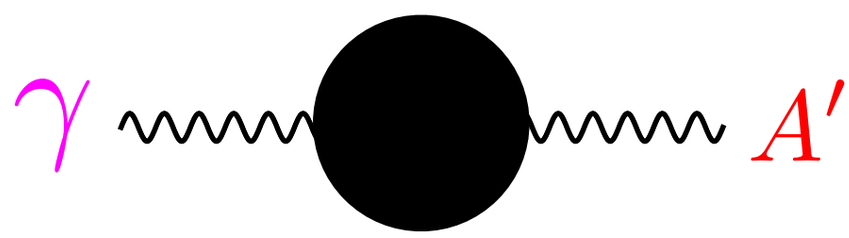
Holdom

Galison, Manohar

simplest Dark Sector consists of just an A′

Generating Kinetic Mixing

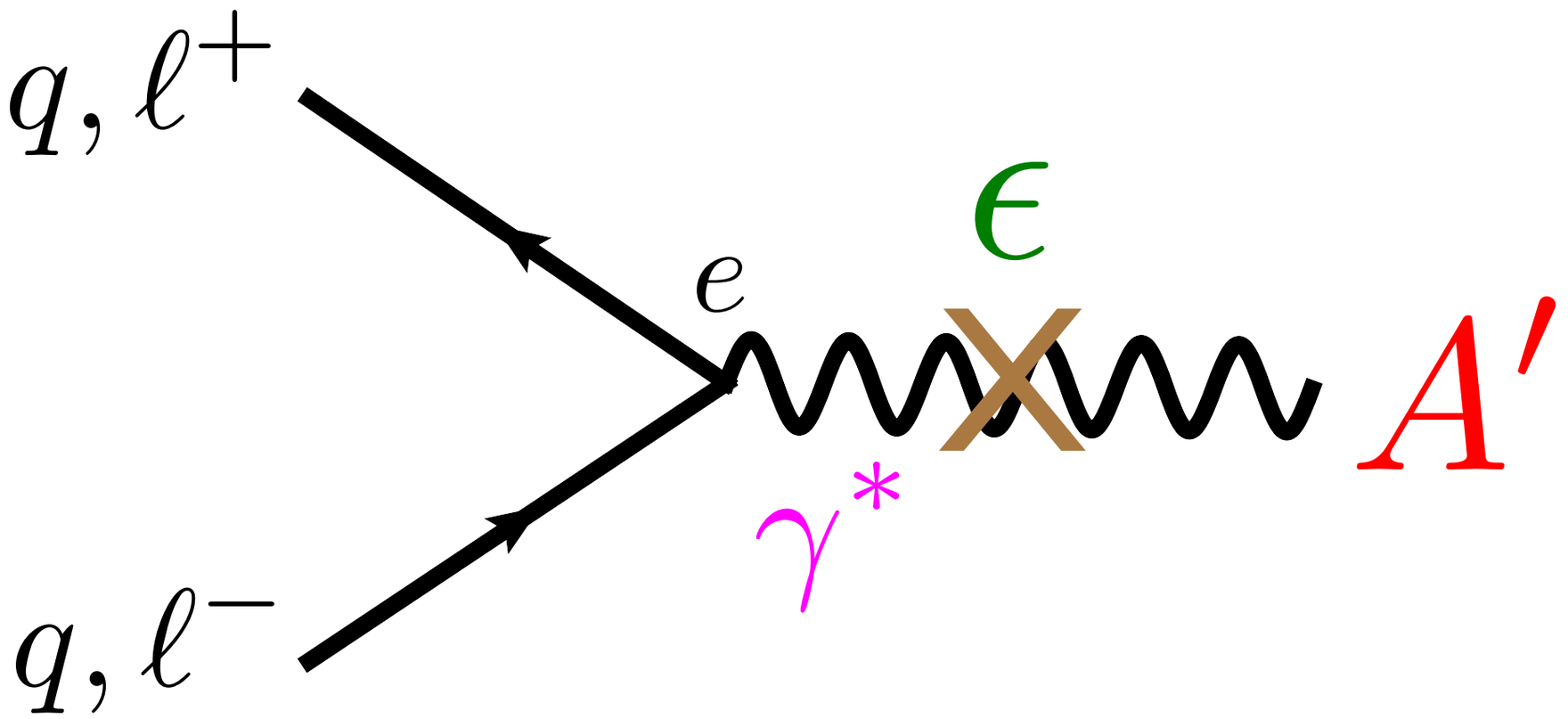
e.g. loops of heavy particles charged under photon and A'



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

Mixing with photon allows:

A′ coupling to quarks and charged leptons:

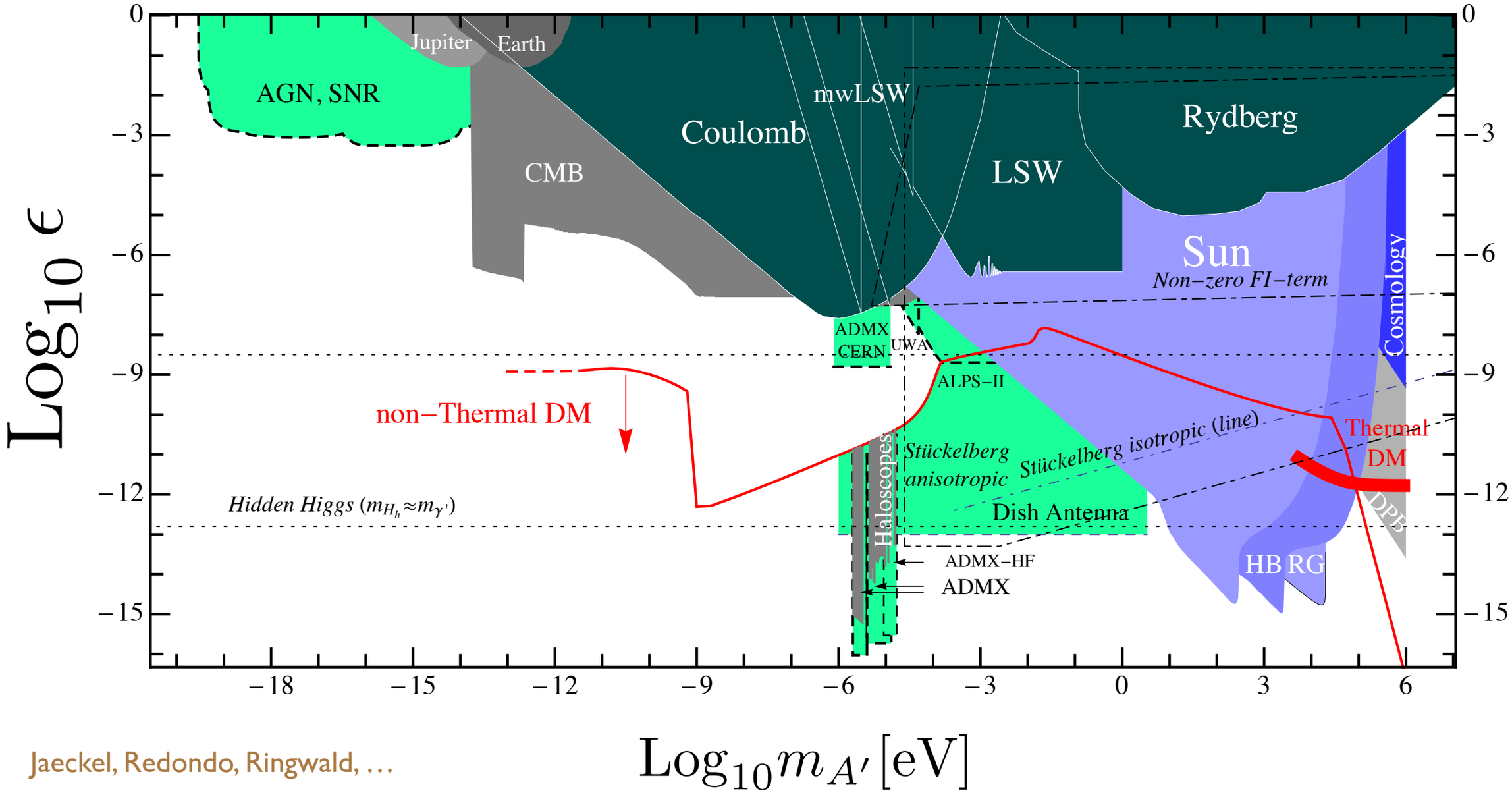


and

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

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

- mass scale appears naturally in some models

e.g. Arkani-Hamed & Weiner; Cheung et.al.; Morrissey etl.al.

- much excitement generated in 2008 from various cosmic-ray and terrestrial "anomalies" suggesting dark matter interacts with A'

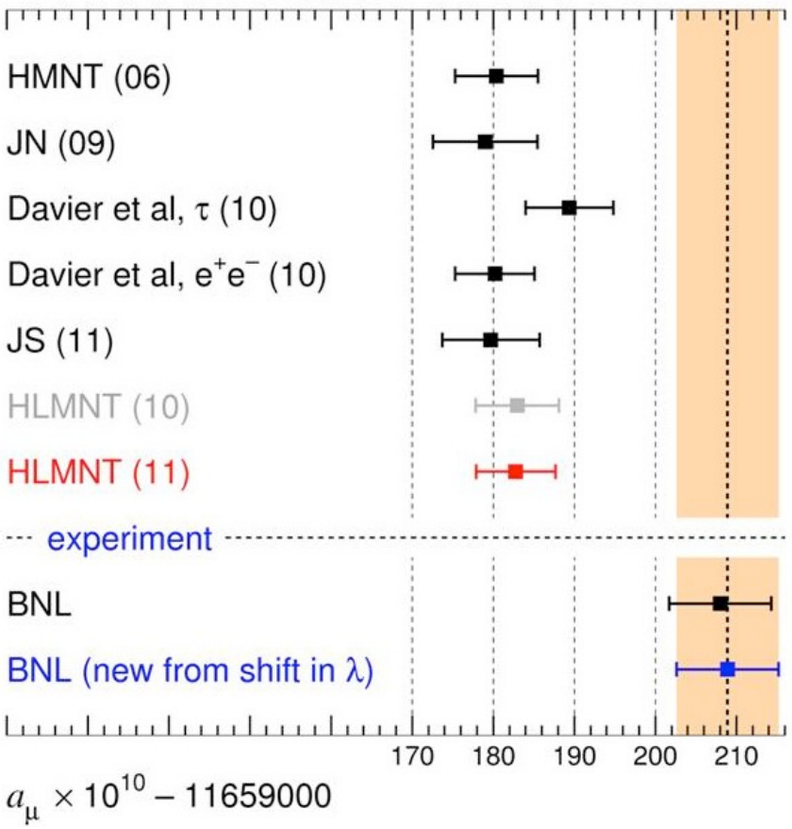
Arkani-Hamed et.al.; Cholis et.al.; Pospelov & Ritz

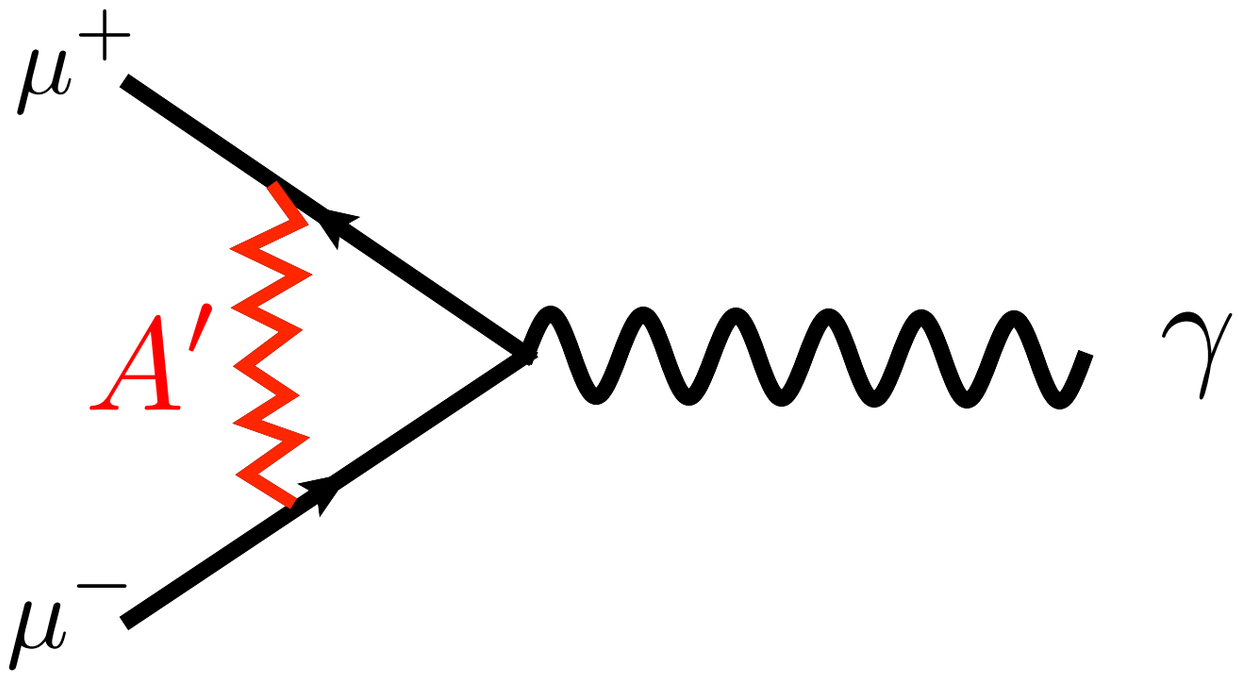
while speculative, it made us realize
amazing possibilities at GeV-scale!

Hints for A′ with MeV-GeV mass?

anomalous muon g-2 ?

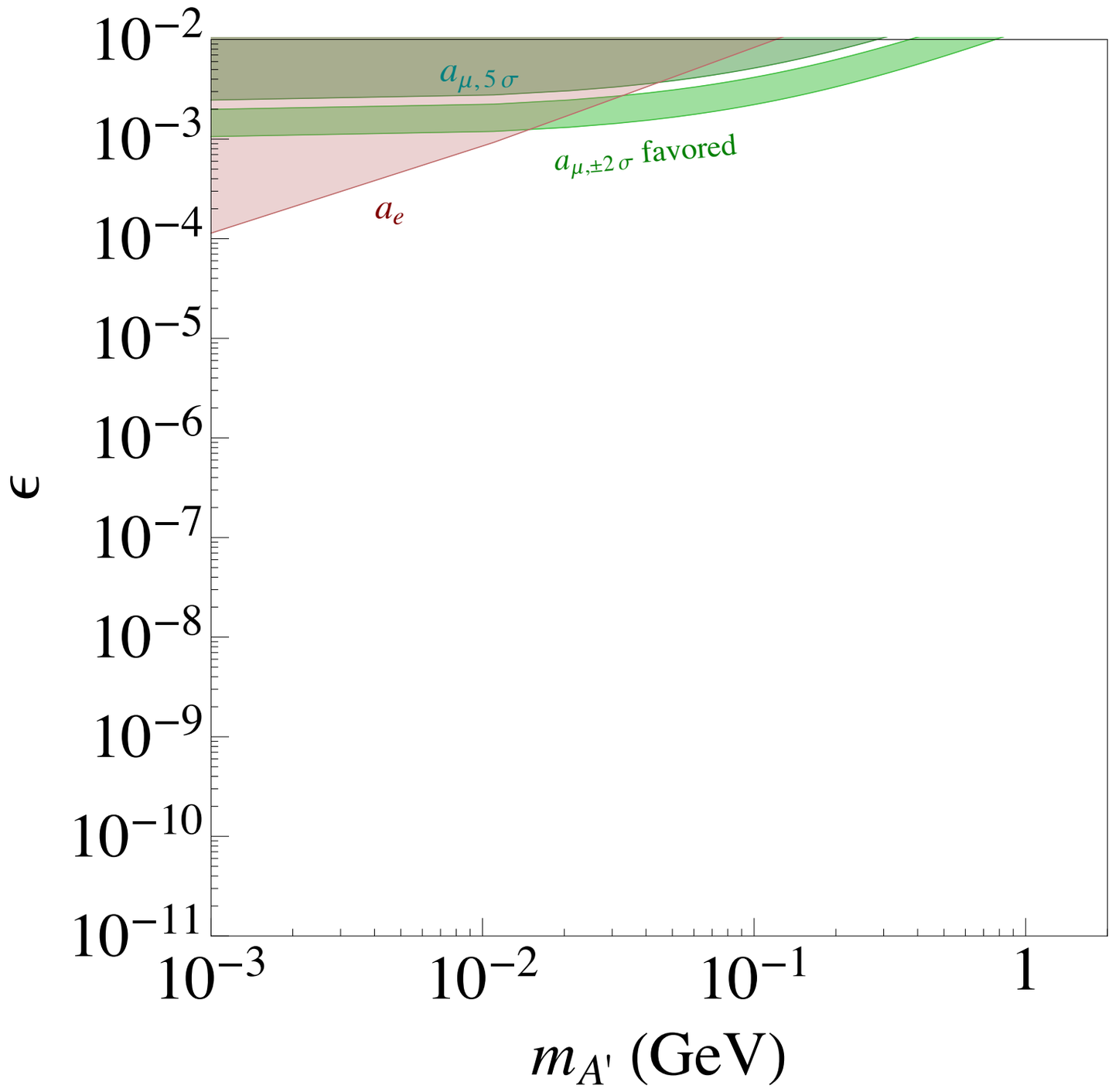
Pospelov
Boehm, Fayet





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

Known constraints ~2008

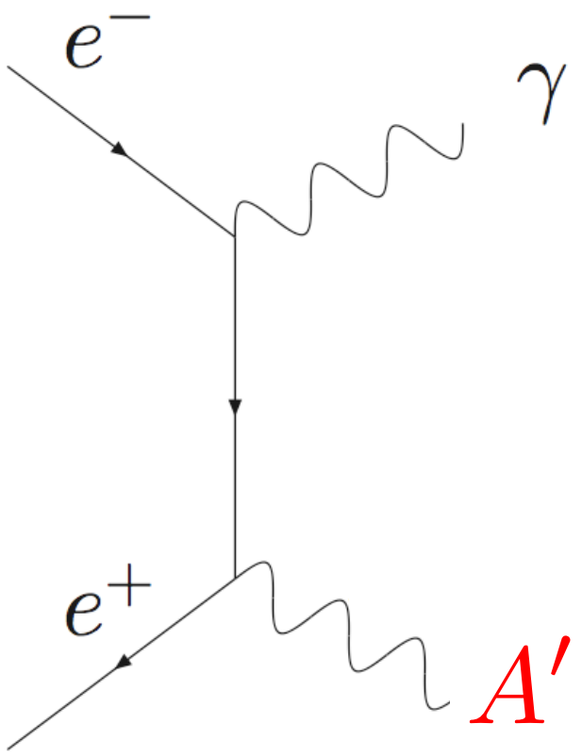


Pospelov; Fayet;

How to look for A′ with MeV-GeV mass?

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

e^+e^- colliders



Rare meson decays

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

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

or A′ → Dark Matter (see later)

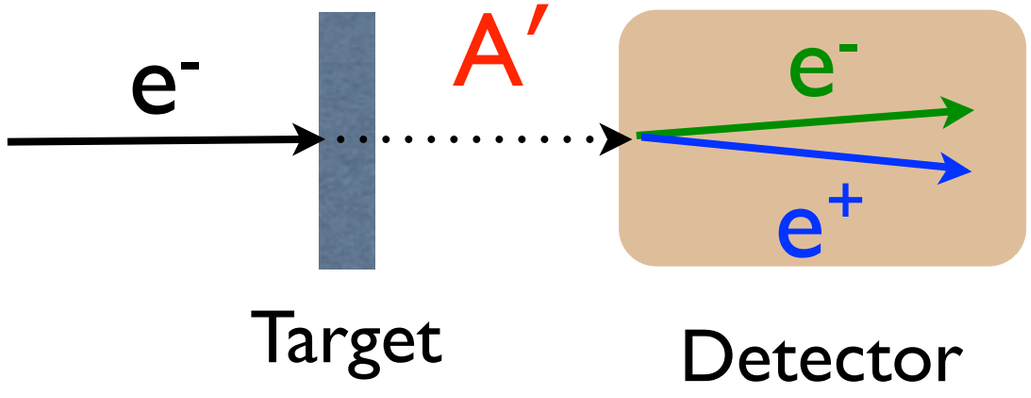
B-factories, Phi-factories

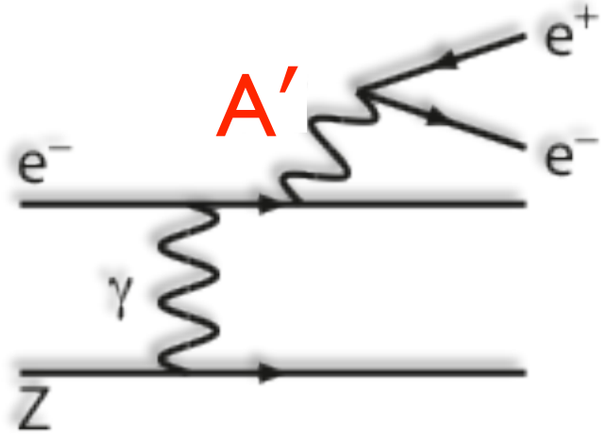
searches completed/ongoing/planned

How to look for A′ with MeV-GeV mass?

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

New & old e^- fixed target experiments





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

e.g. SLAC, JLab, MAMI, …

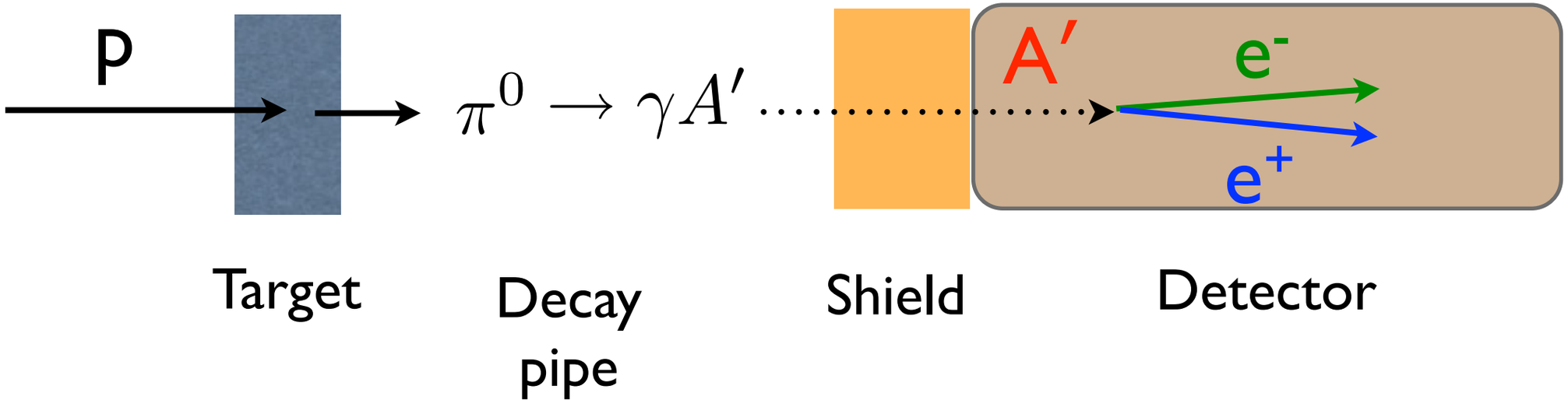
How to look for A′ with MeV-GeV mass?

Proton-beam fixed target experiments

Batell, Pospelov, Ritz

RE, Harnik, Kaplan, Toro

Example: produce A′ from pion decays

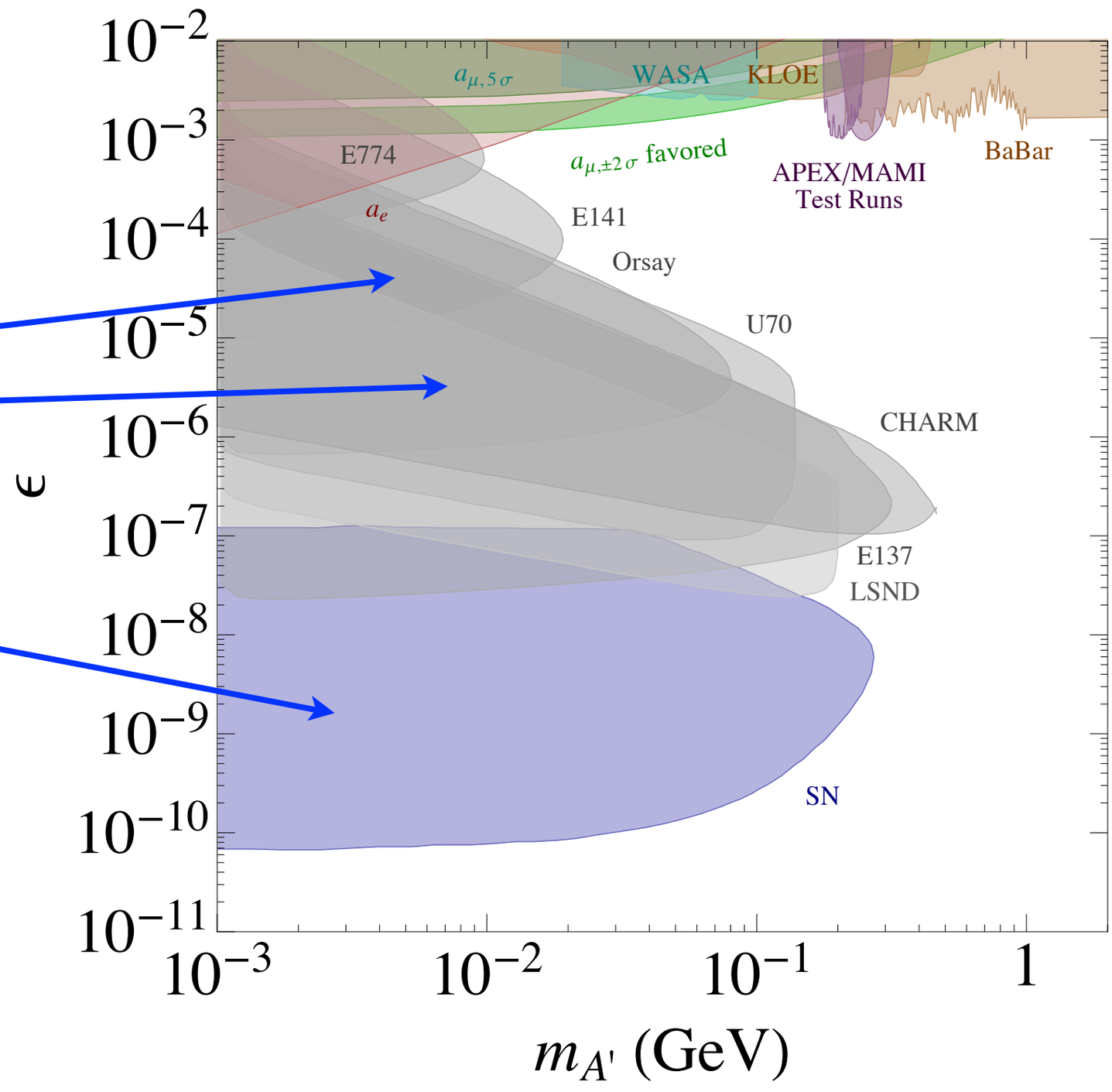


LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …

Current constraints

past
electron + proton
beam dumps

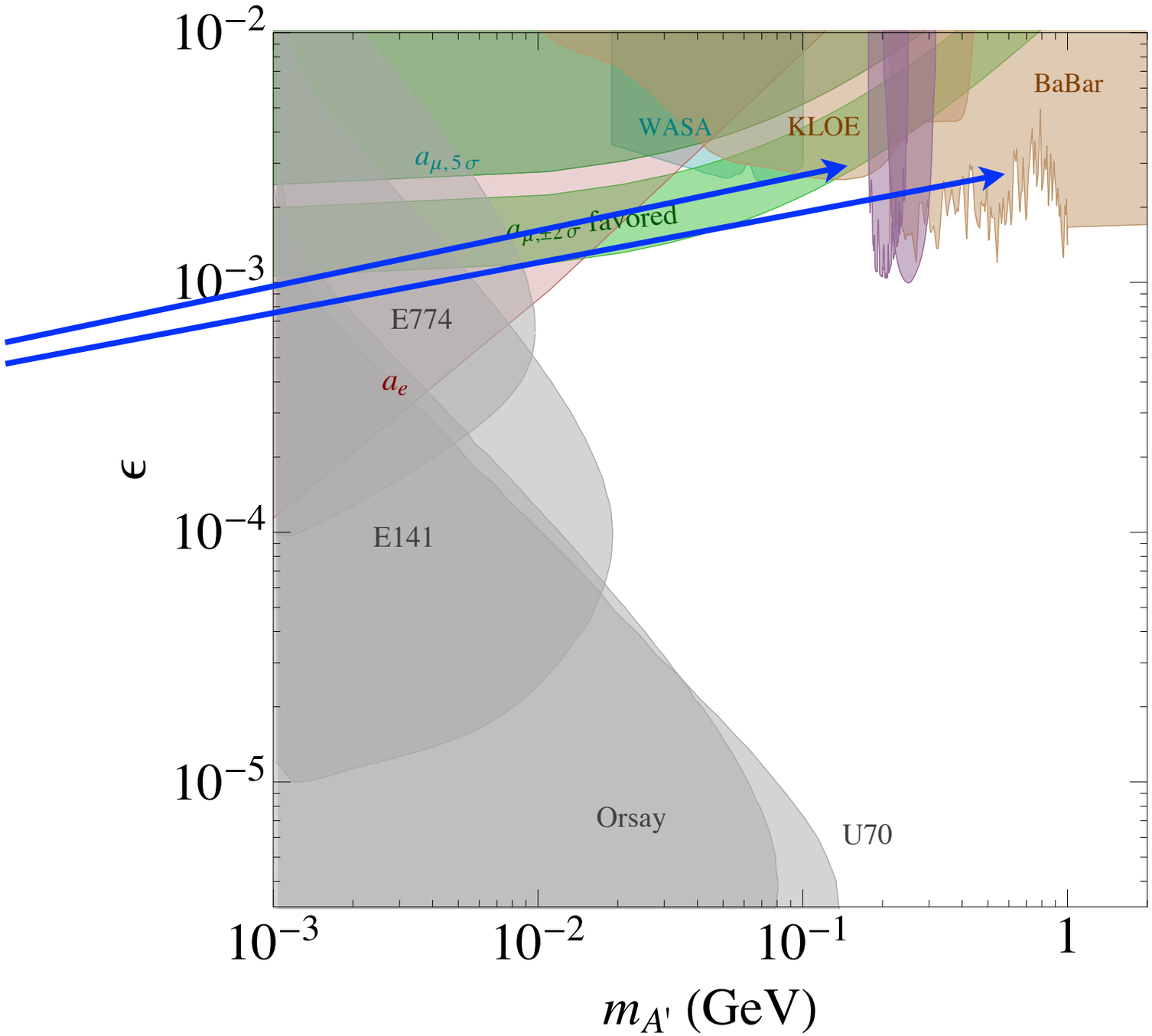
supernova



Pospelov; Fayet;
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 (zoomed in)

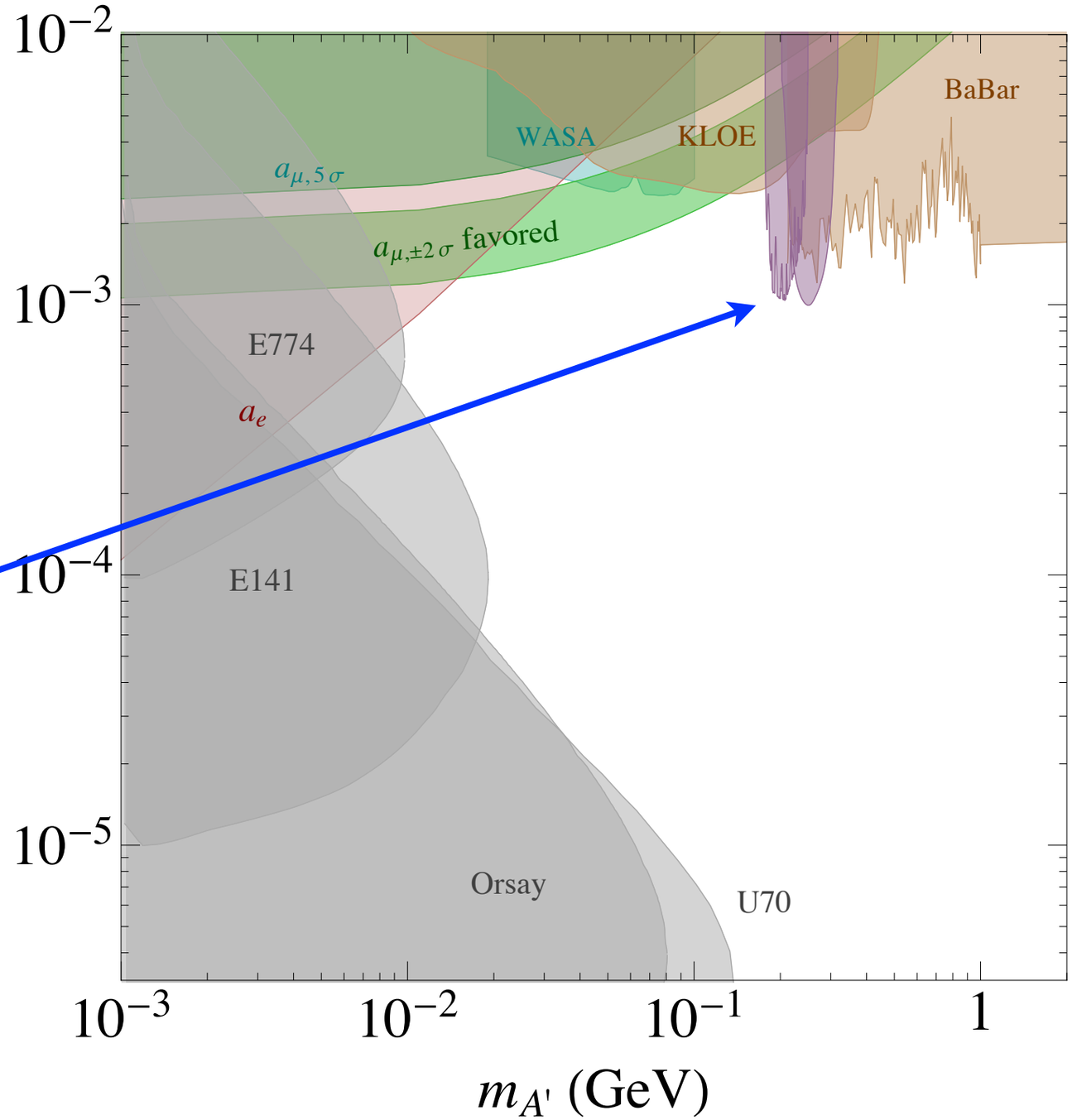
B/Phi-factory searches



Current constraints (zoomed in)

B/Phi-factory searches

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



Constraints expected this year

Phenix @ RHIC
(preliminary)

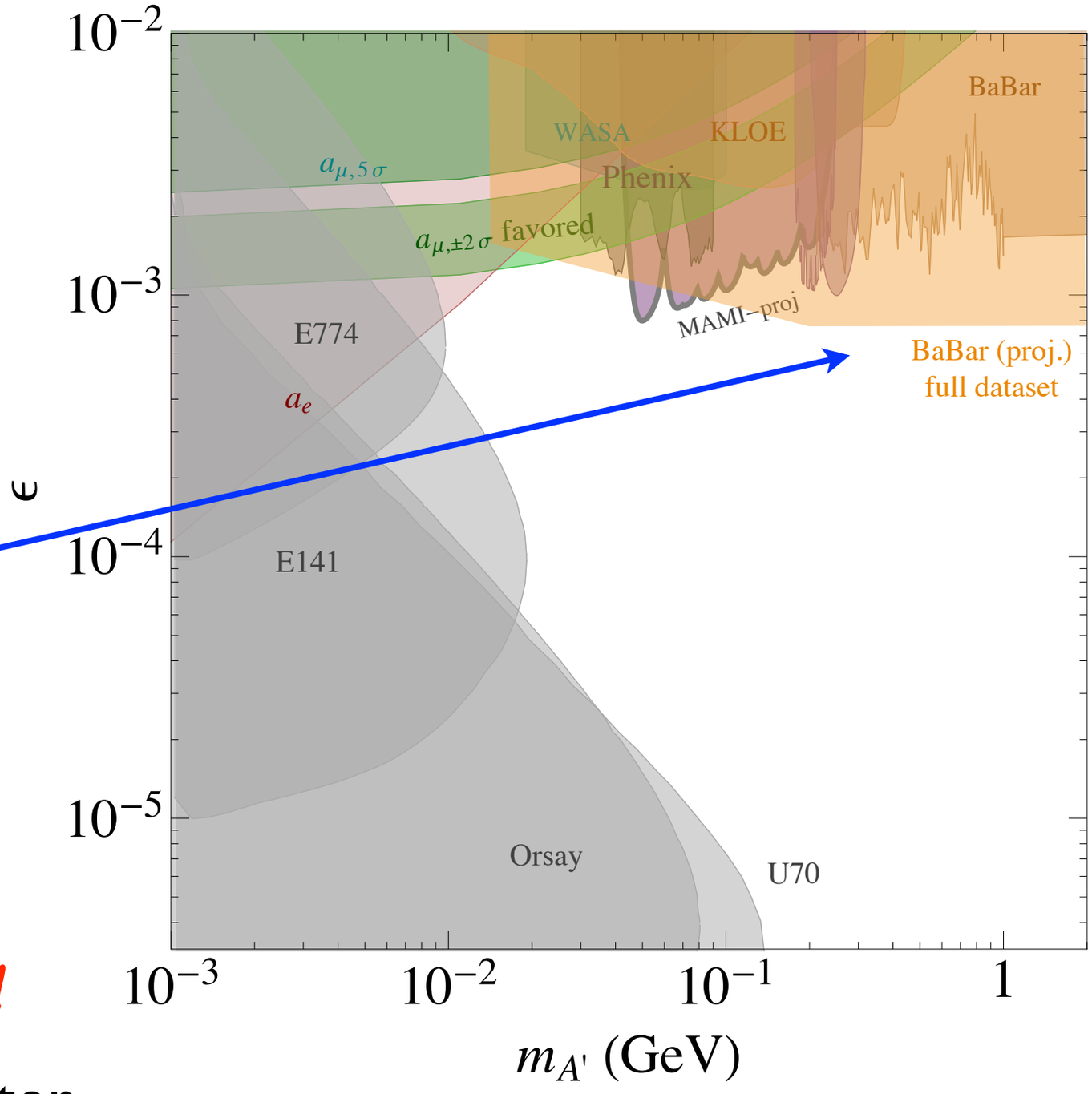
MAMI?

Beranek et.al.

BaBar?

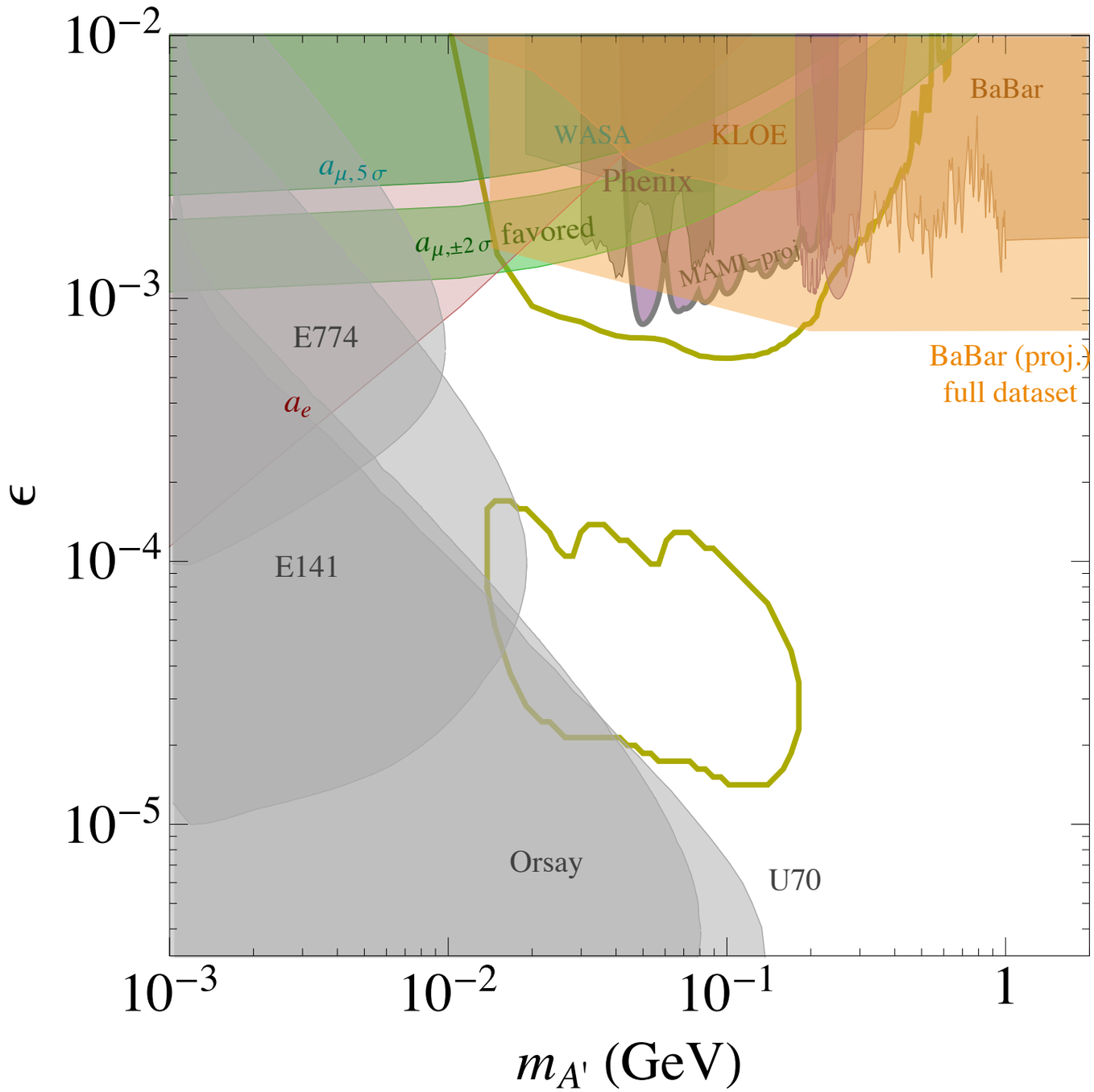
most of g-2 region
covered soon, *assuming*
Br(A′ → visible) = 100% !

for invisible decay see later



New searches (~few years)

2015:
HPS
(vertexing!)



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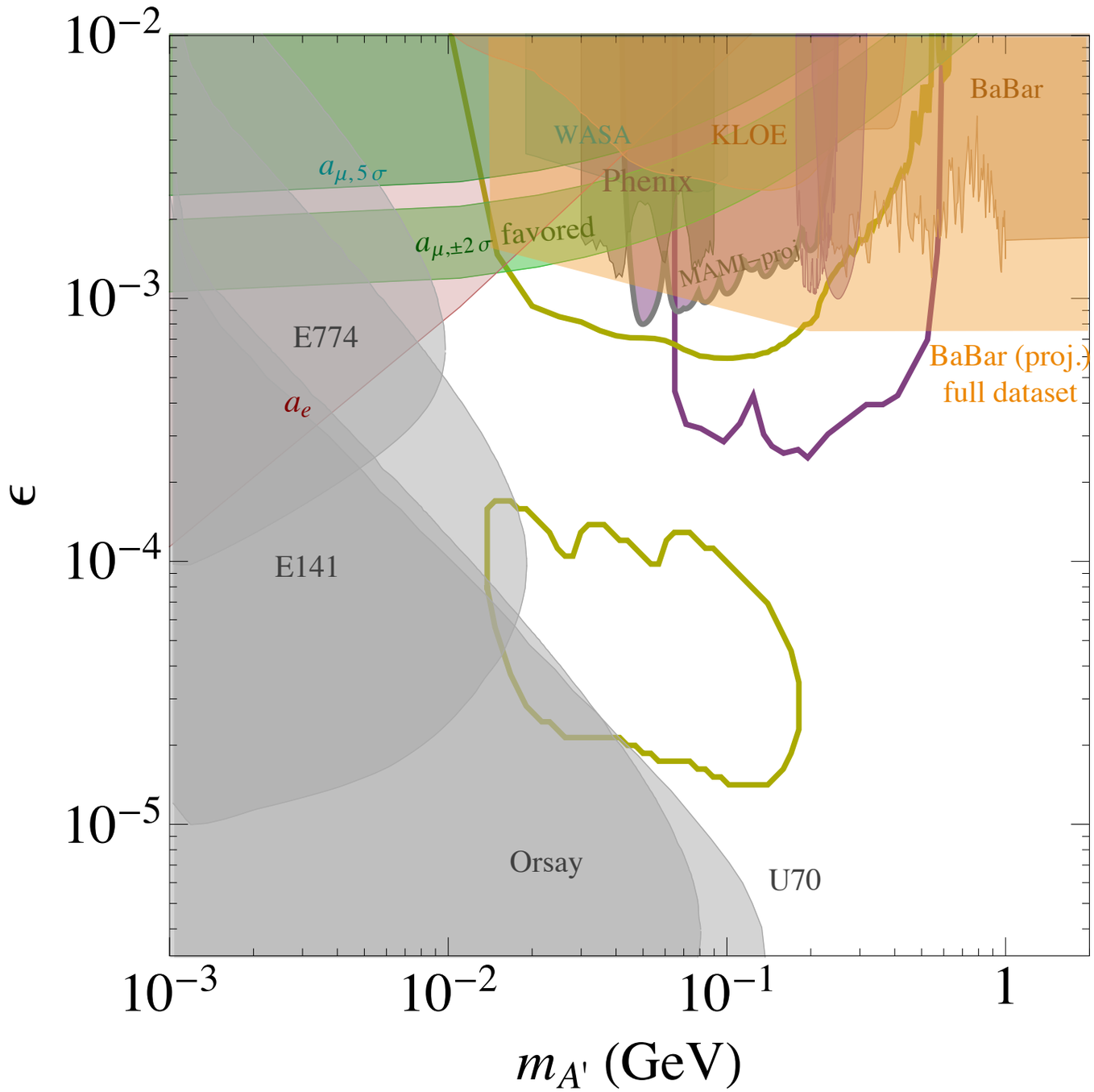
~2016/17:
APEX



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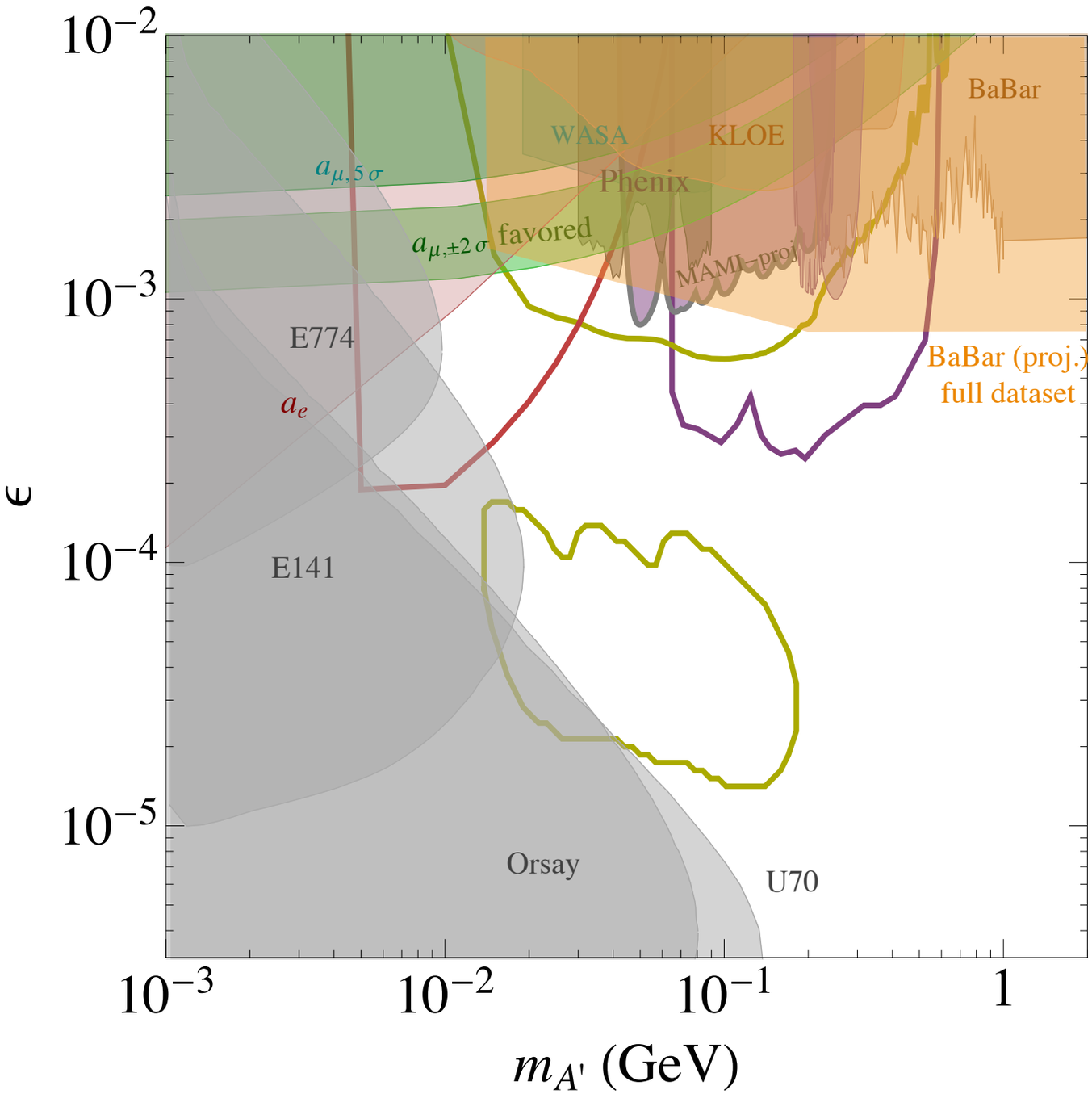
Mu3e (Echenard, RE, Zhong)



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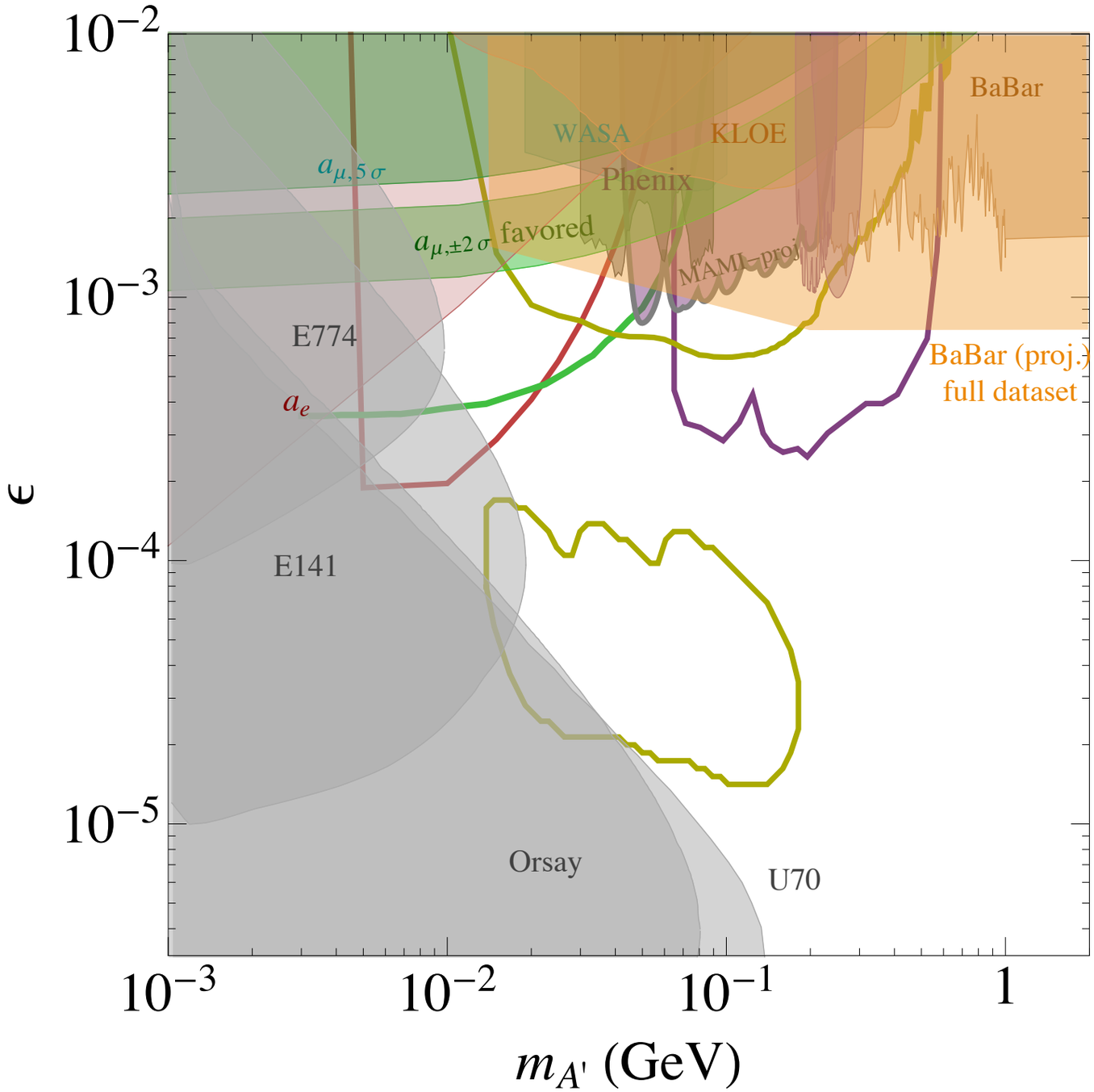

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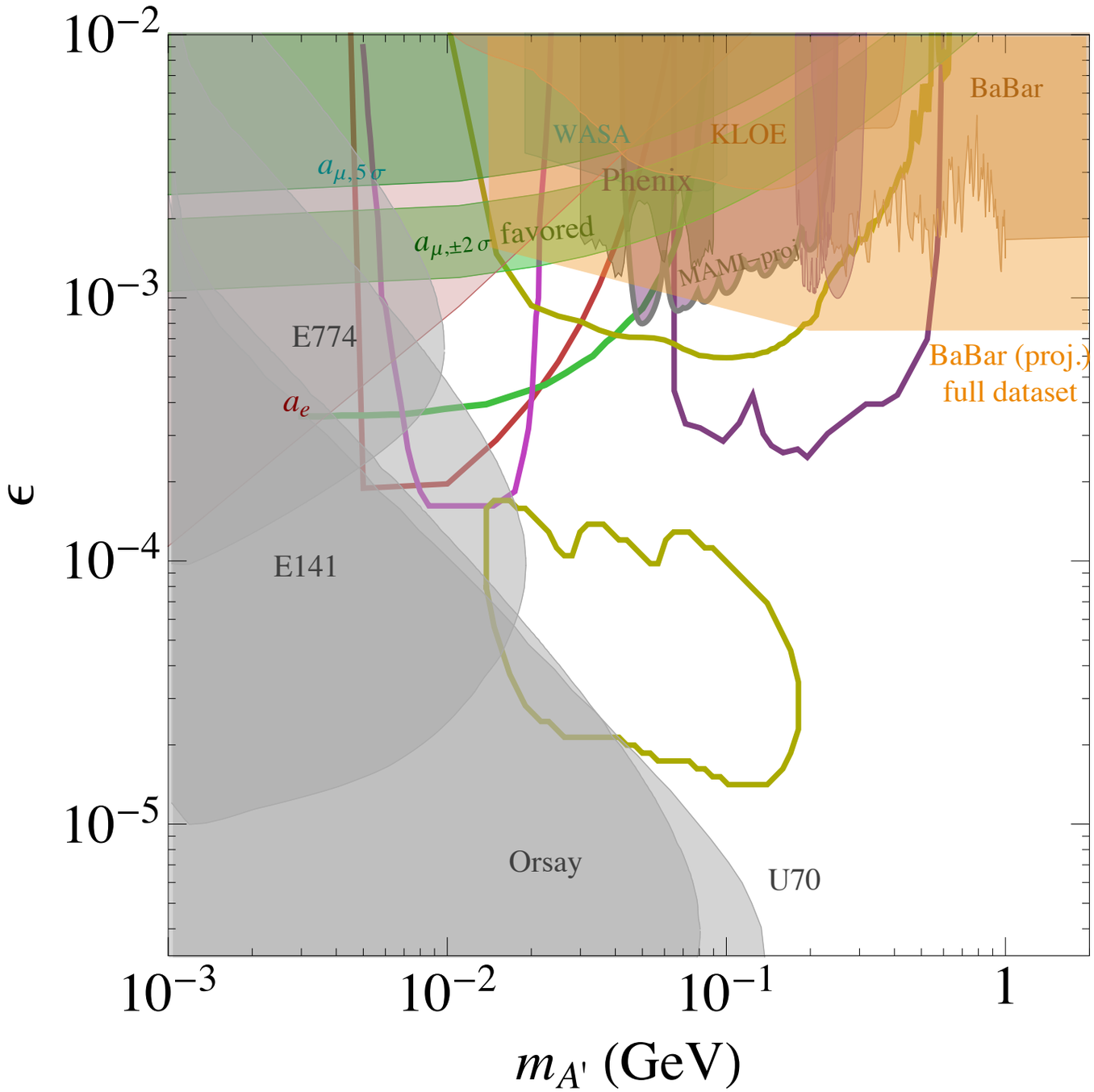
APEX
Mu3e (Echenard, RE, Zhong)
DarkLight
VEPP-3



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(vertexing!)

~2016/17:

APEX

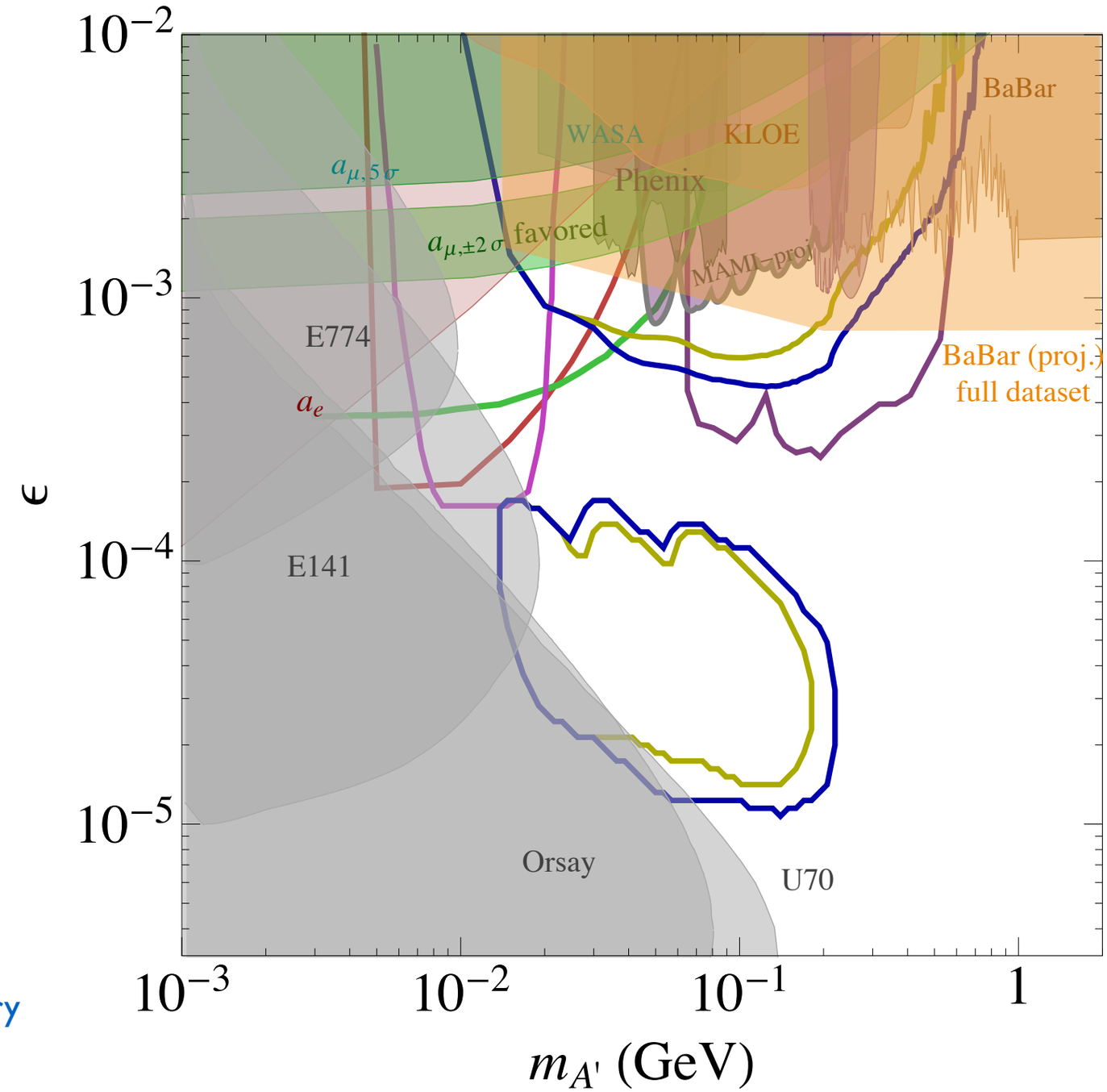
Mu3e (Echenard, RE, Zhong)

DarkLight

VEPP-3

HPS

w/ possible
True Muonium discovery



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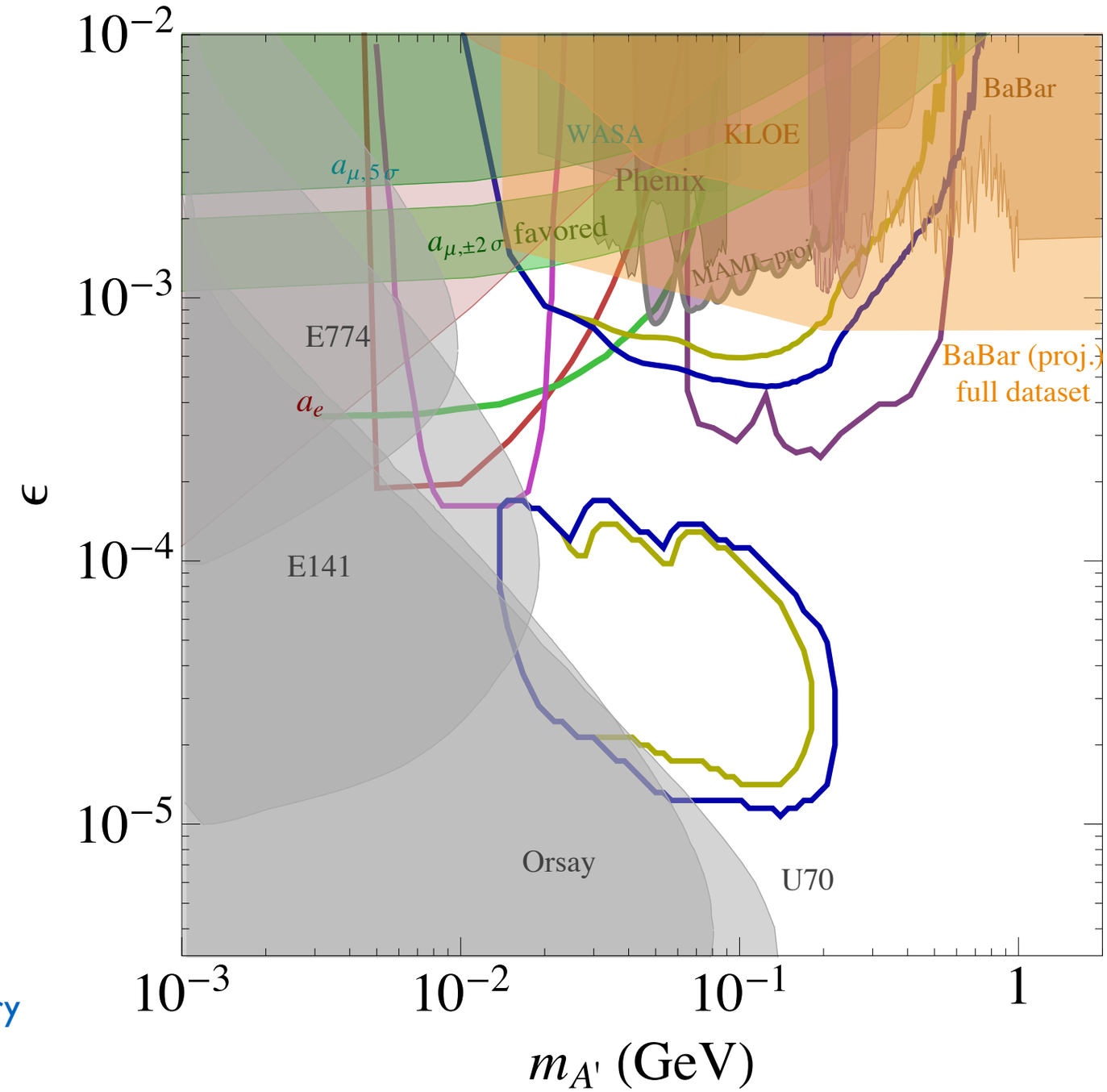
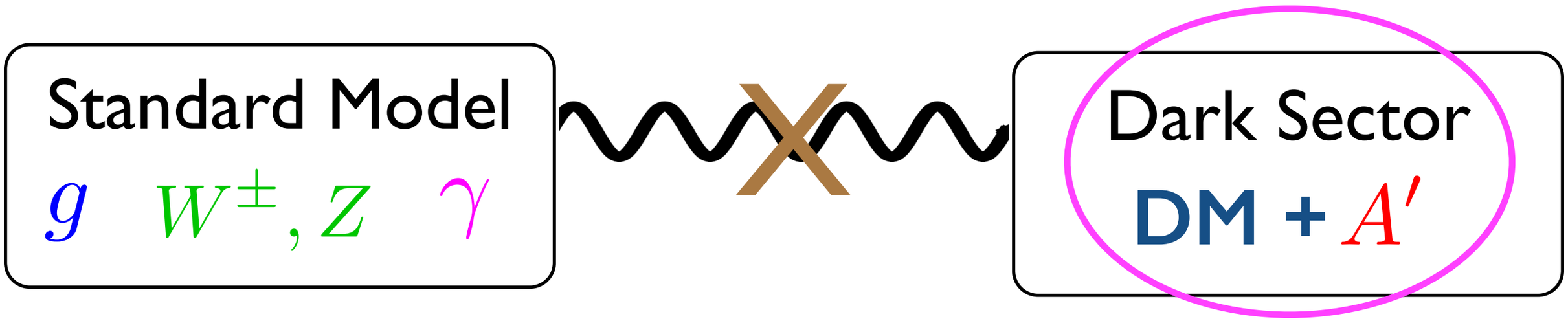
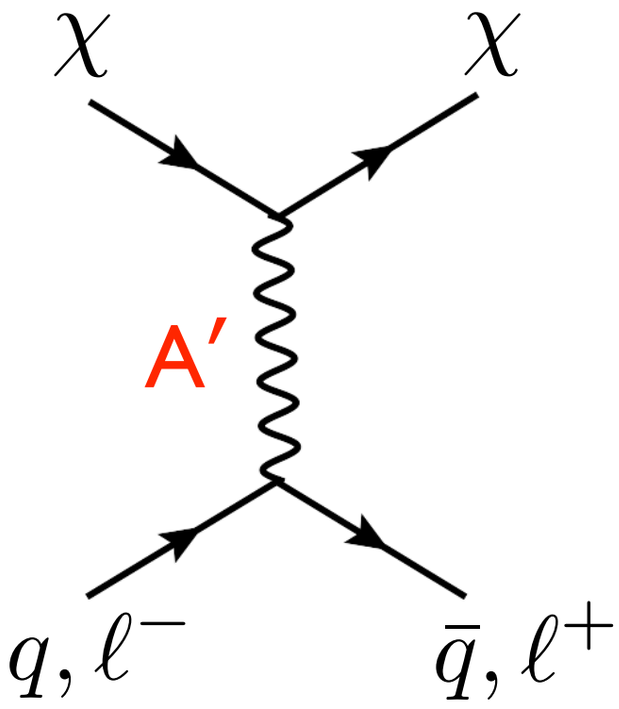


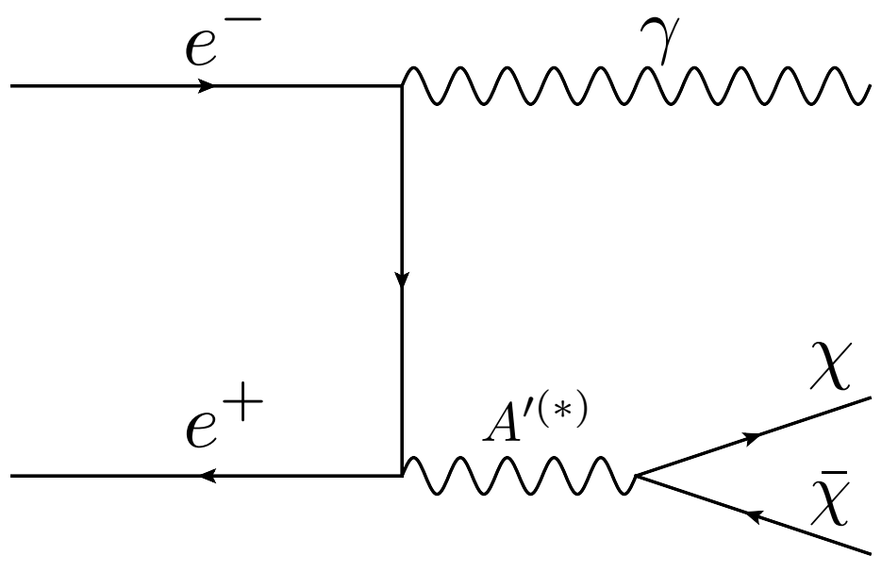
+MAMI, Phenix, WASA, HPS2019, … (not shown)

sub-GeV DM & Dark Photons



Examples





Direct Detection

RE, Mardon, Volansky

see also Graham et.al., Va'vra

probe DM in our halo scattering off

e.g. *electrons* in detector

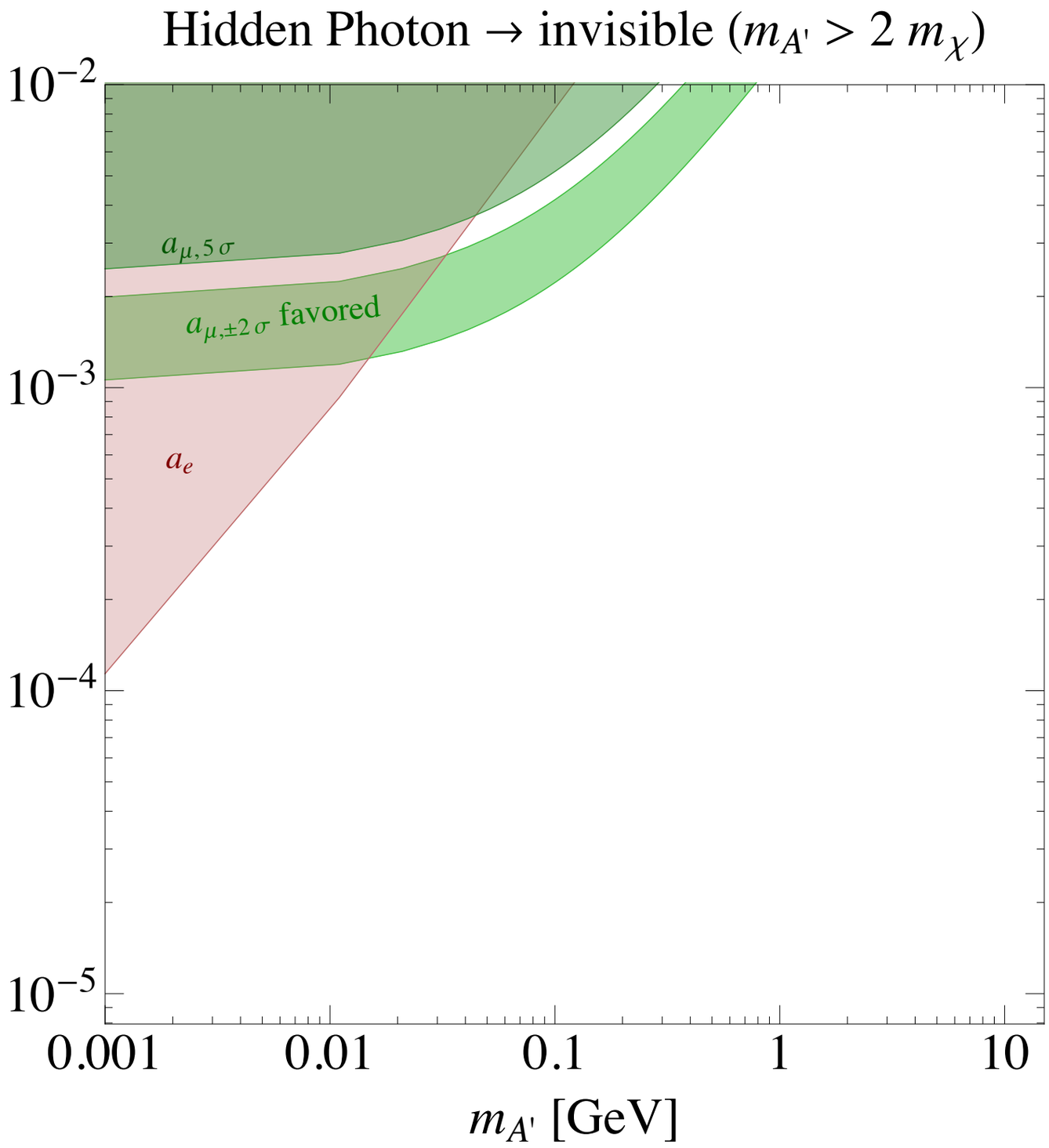
lots of potential for current & new experiments!

(XENON100, LUX, Darkside, Super-CDMS, …)

RE, Manalaysay, Mardon, Sorensen, Volansky

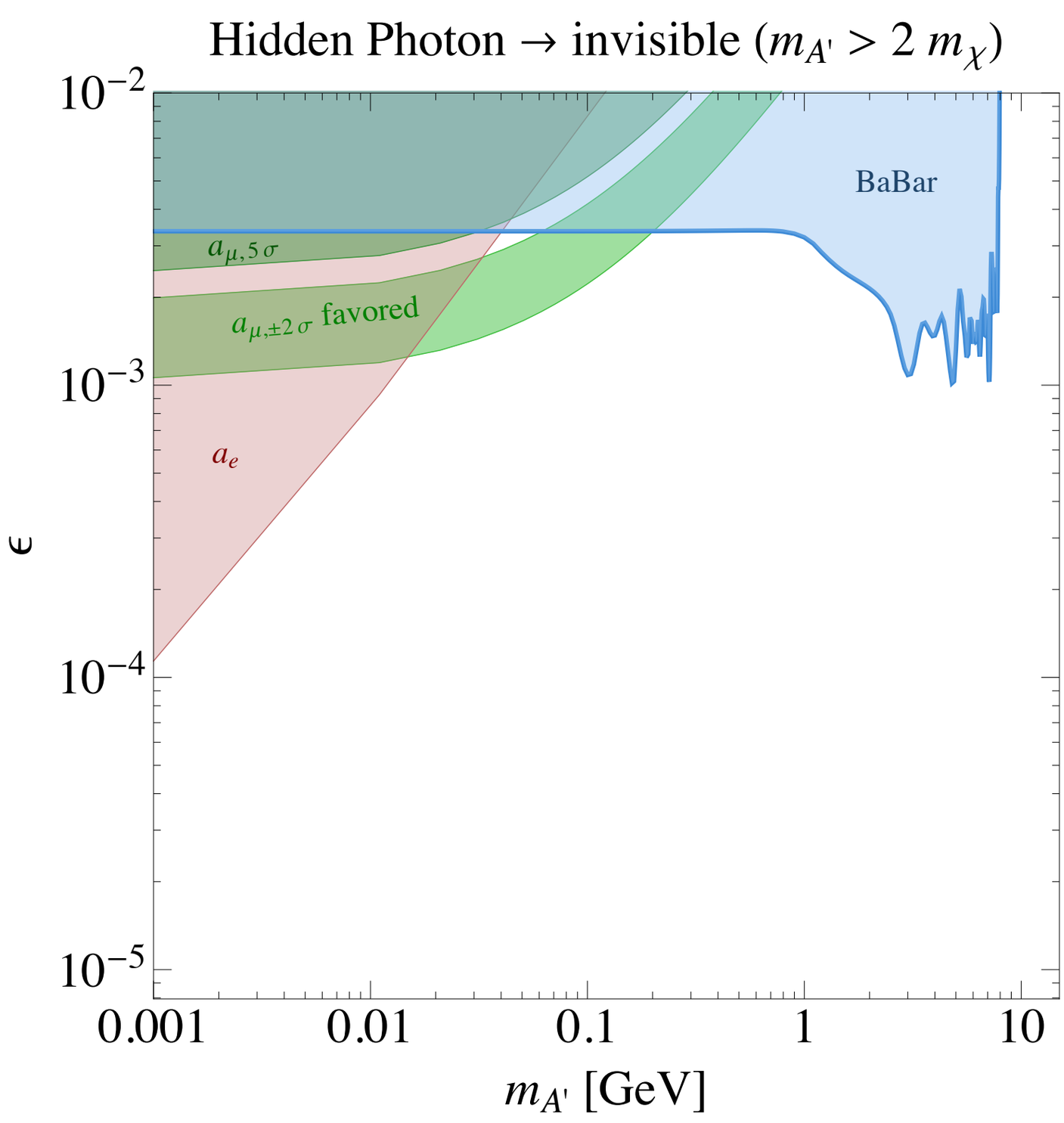
O *MeV !*

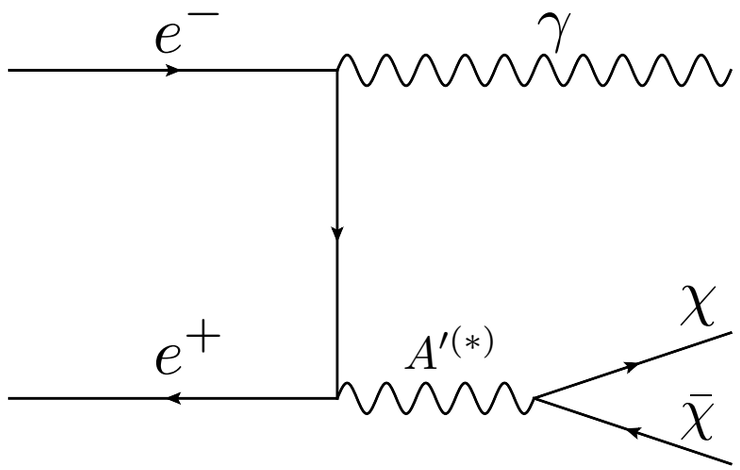
Invisible A′ decays



Pospelov

Invisible A′ decays

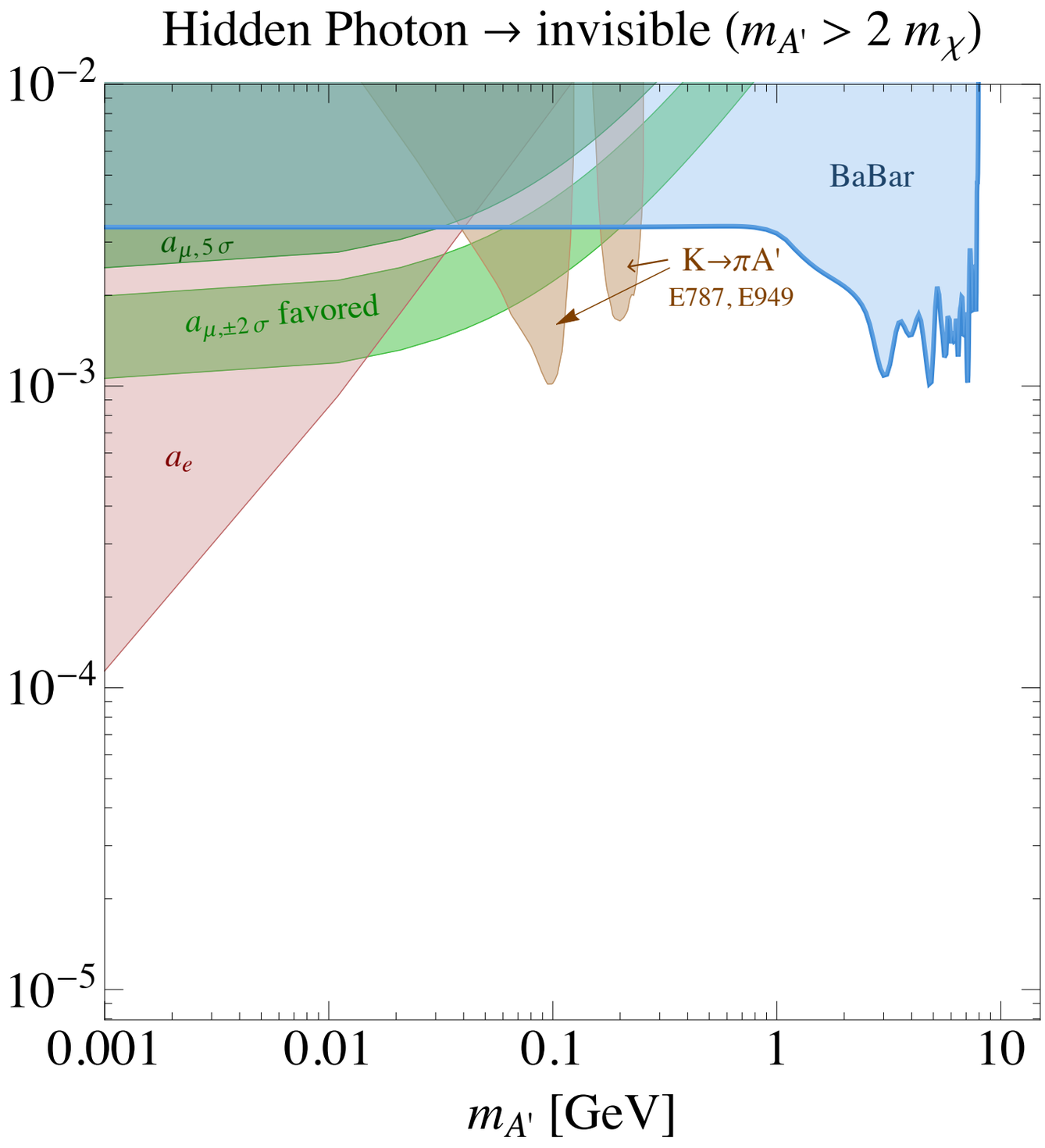




Pospelov

RE, Mardon, Papucci, Volansky, Zhong;
Izaguirre, Krnjaic, Schuster, Toro

Invisible A′ decays

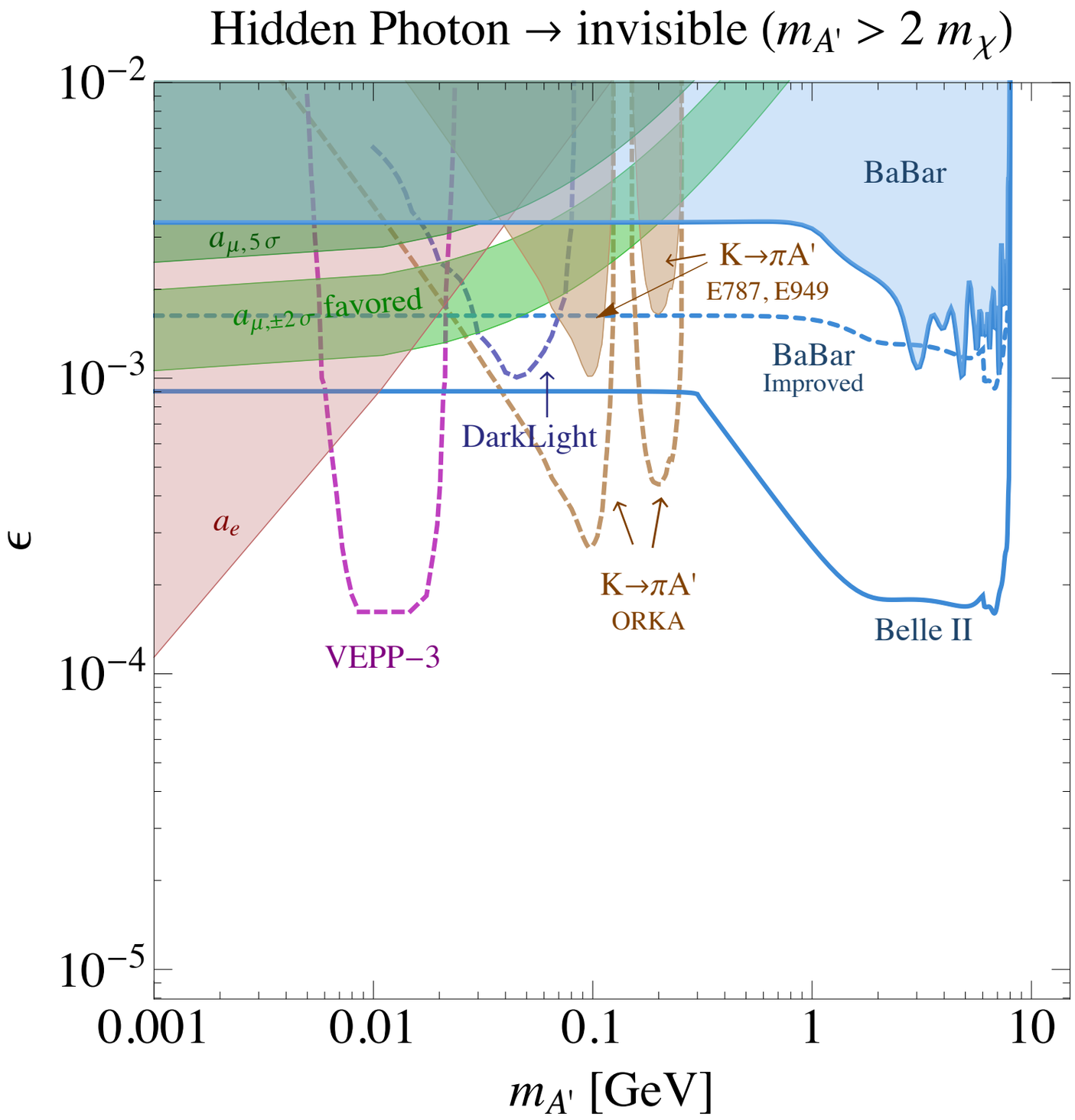


Pospelov

RE, Mardon, Papucci, Volansky, Zhong; Izaguirre, Krnjaic, Schuster, Toro

deNiverville, Pospelov, Ritz

Invisible A′ decays



Pospelov

RE, Mardon, Papucci, Volansky, Zhong; Izaguirre, Krnjaic, Schuster, Toro

deNiverville, Pospelov, Ritz

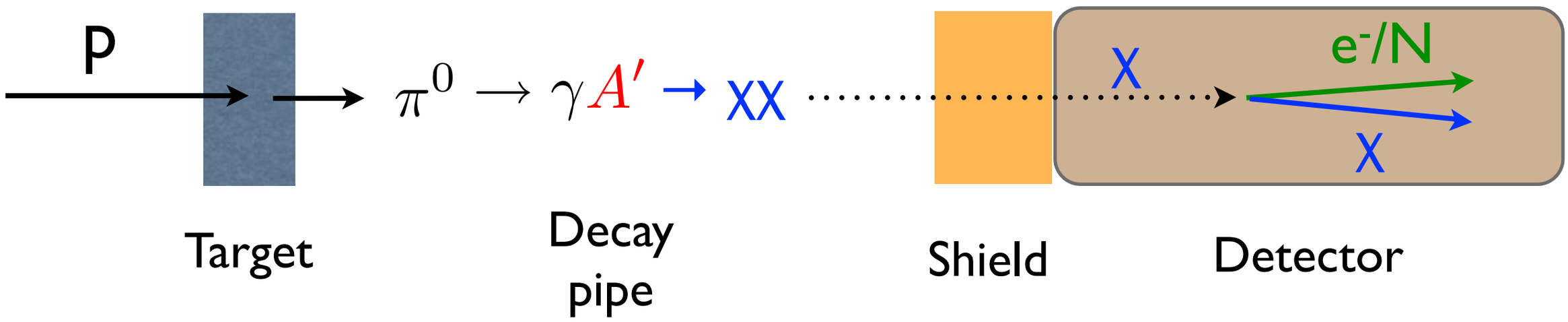
Kahn, Thaler

Wojtsekhowski, Nikolenko, Rachek

Proton-beam fixed target experiments

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

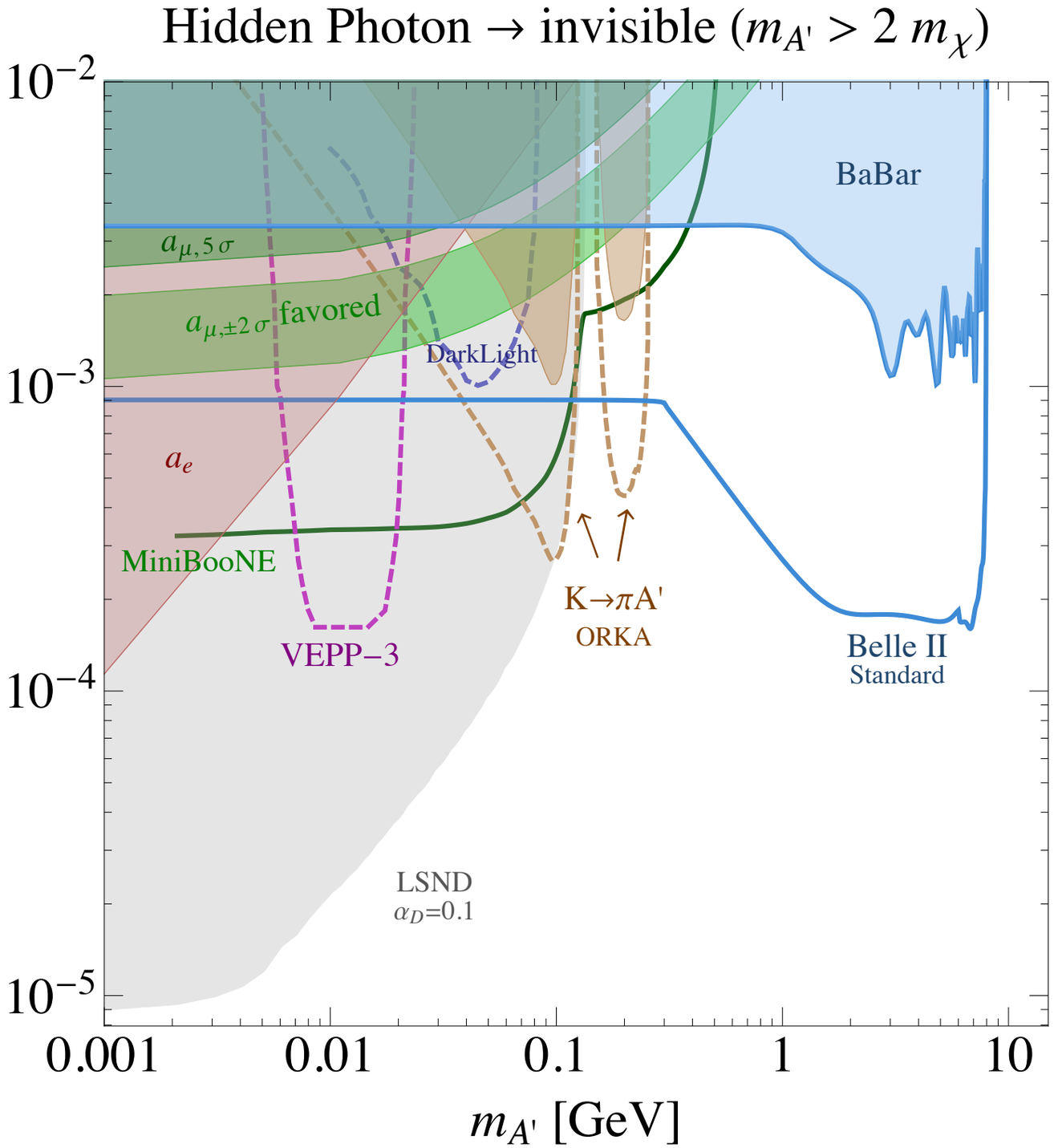
e.g. neutrino facilities



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

LSND sets powerful constraints

Batell, deNiverville, Pospelov, Ritz, …



MiniBooNE
currently taking data

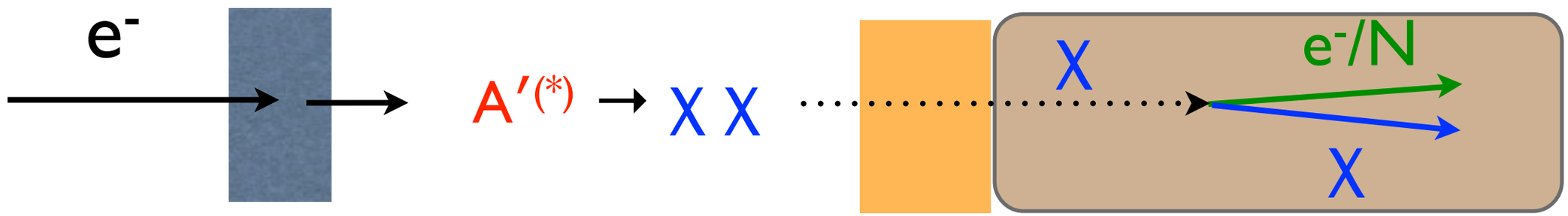
Aguilar-Arevalo et.al.

Note:
Constraints are model-dependent!

Electron-beam fixed target experiments

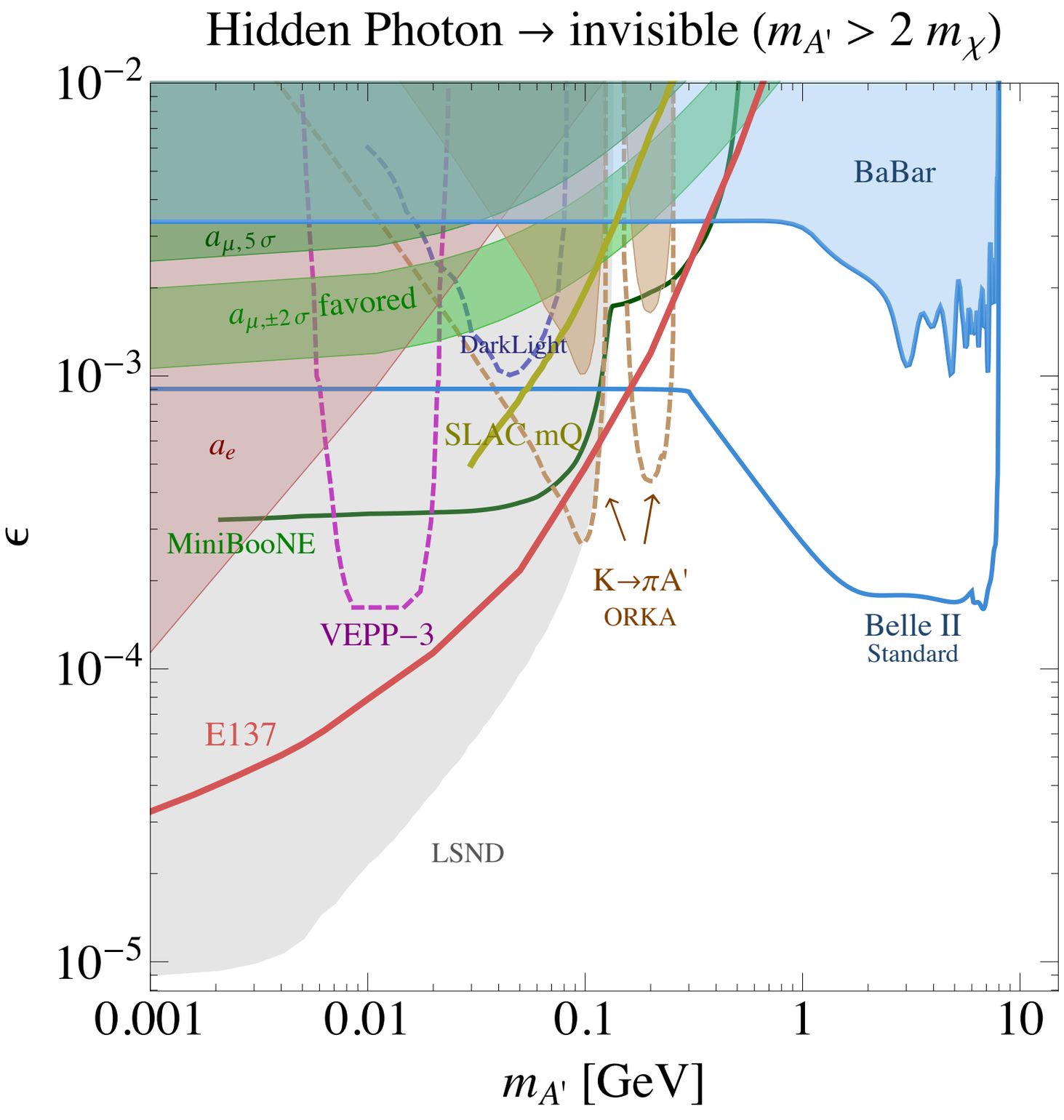
Krnjaic, Izaguirre, Schuster, Toro

Diamond, Schuster



new parasitic experiments possible at
e.g. JLab, Mainz, SLAC, SuperKEK, ILC, …

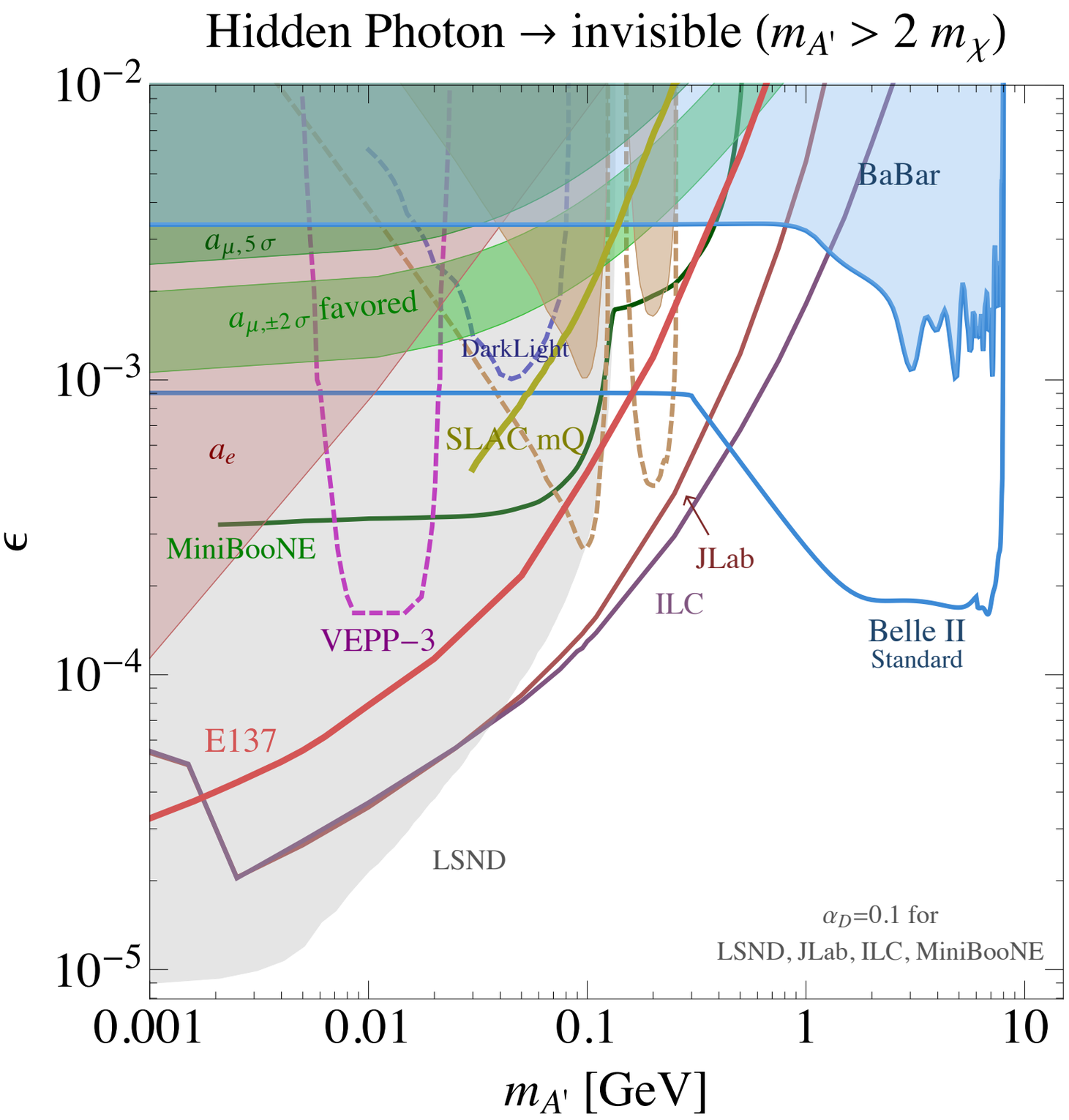
Constraints from past beam dumps



E137 — Batell, RE, Surujon (to appear)

SLAC mQ — Diamond, Schuster

Constraints from past beam dumps



E137 — Batell, RE, Surujon (to appear)

SLAC mQ — Diamond, Schuster

+exciting prospects for future experiments!

Note: g-2 region is strongly constrained for simplest invisible decays

Conclusions

- Dark sectors are well-motivated by theory, DM, strong CP, muon g-2, astrophysics, …
- experiments use intense beams & sensitive detectors
- small-scale, inexpensive, uses existing facilities/ technologies

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