Exploring New Frontiers:

New, Light Weakly-Coupled Particles (as DM)

Rouven Essig

C.N. Yang Institute for Theoretical Physics
Stony Brook University

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New, light weakly-coupled particles
are motivated by dark matter, theory, strong CP problem, muon g-2, and astrophysics anomalies

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are motivated by dark matter, theory, strong CP problem, muon g-2, and astrophysics anomalies

Topics covered

- axions & axion-like particles
- dark photons
- sub-GeV dark matter

many topics not covered, but for a summary see e.g.
"Fundamental Physics at the Intensity Frontier"
1205.2671

The State of Particle Physics 2013

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The success of the Standard Model is a triumph

But we are in a new era

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Pre-LHC:

discovery of something new at LHC was guaranteed

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discovery of something new at LHC was guaranteed

And now?

We know there is more new physics, but…

no experiment currently running or planned for the future is *guaranteed* to discover a new particle/force

How live in a world without guarantees?

Some of our most-cherished ideas have
not yielded any success (at least, thus far)

e.g. Naturalness of Weak-scale, WIMP miracle

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Should we be worried?

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Should we be worried?

It is of course too early to be worried,
but we shouldn't sit idly by either

How live in a world without guarantees?

In addition to pursuing our "standard"
new-physics targets, we should:

How live in a world without guarantees?

In addition to pursuing our "standard"
new-physics targets, we should:

- expand our experimental & theoretical investigations
  (there are many other motivated ideas for new physics)
- pursue several relatively low-cost & motivated experiments
  (several nice suggestions exist)
- aim to fully exploit existing facilities/technologies, but also
  develop new ones for a few particularly compelling ideas

An Important Example is Dark Matter

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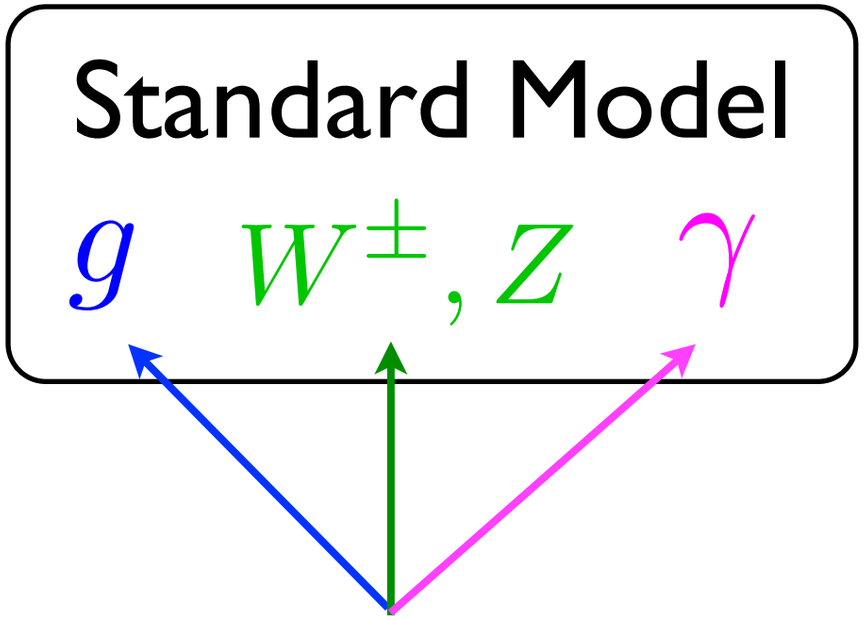
between dark matter and Weak-scale naturalness

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

many possible dark sectors exist
motivated not just by dark matter
emphasizes the need to broaden experimental searches

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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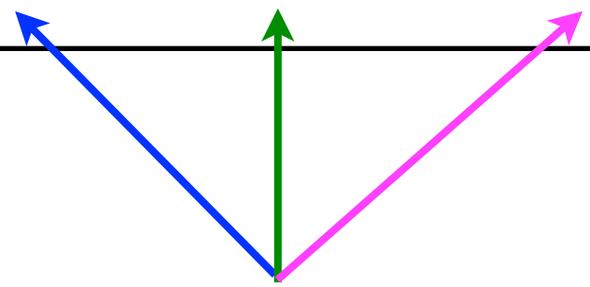
Standard Model

g $W^{\pm}, Z$ γ



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forces + particles

dark matter?

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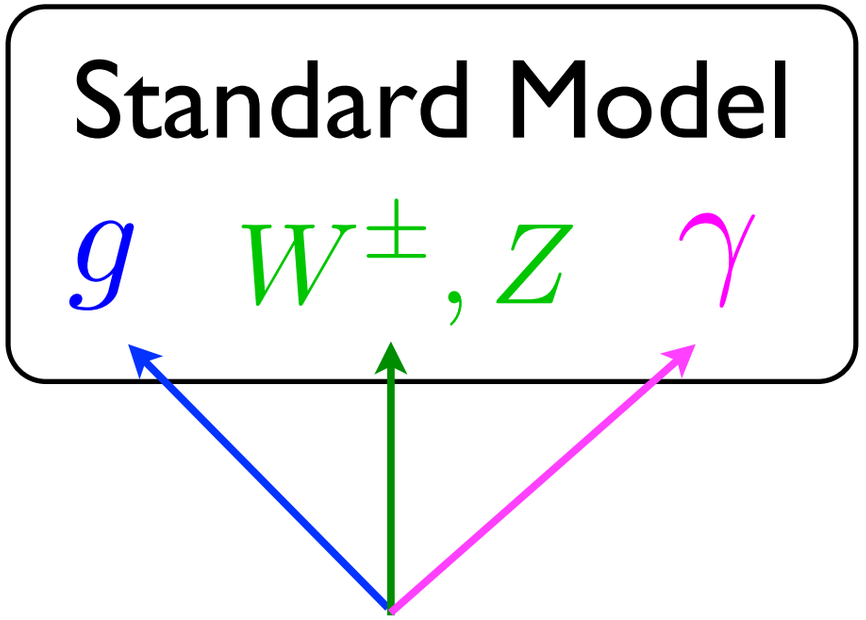
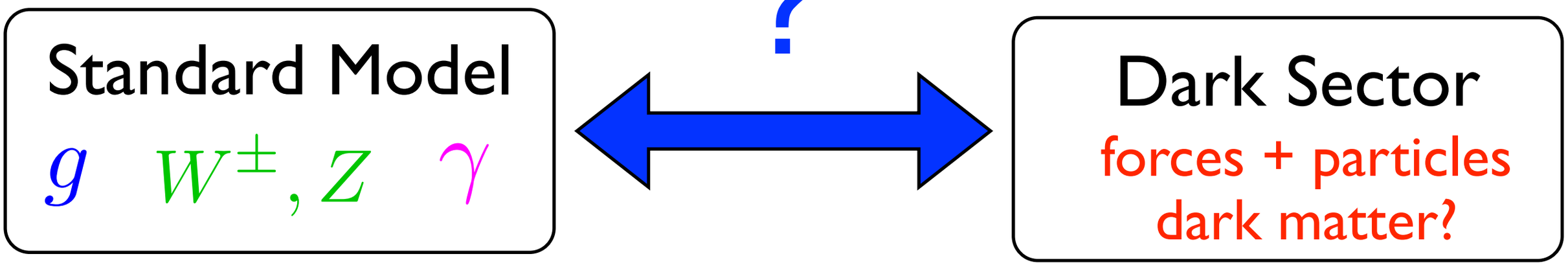


Dark Sector
forces + particles
dark matter?

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

Portals?



only a few important possibilities 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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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

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

naturally light

Axion-Like Particles (ALPs)

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very generally:

breaking of non-PQ approximate global symmetries at high scale can give Axion-Like Particles with small masses

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axions & ALPs are excellent dark matter candidates

Couplings to ordinary matter

axions couple to fermions, photons, gluons

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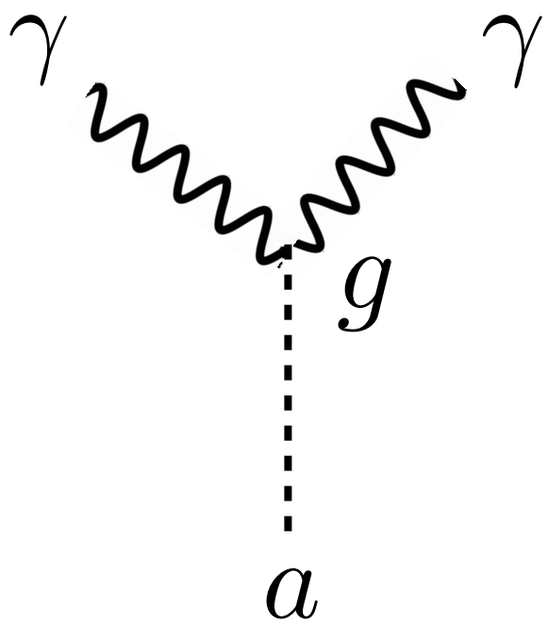


e.g. coupling to photons:

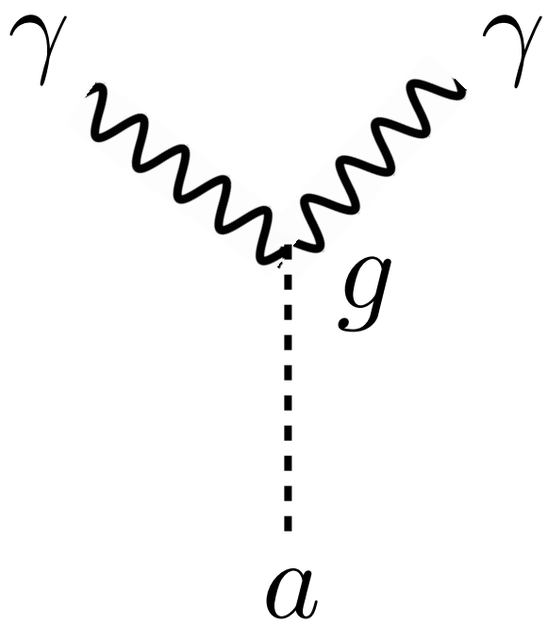
$$g \sim 10^{-13}\,\mathrm{GeV}^{-1} \left(\frac{10^{10}\,\mathrm{GeV}}{\mathrm{f_a}}\right)$$

coupling suppressed by f_a

for ALPs, coupling to photons can be different (even zero)

Couplings to ordinary matter

axions couple to fermions, photons, gluons



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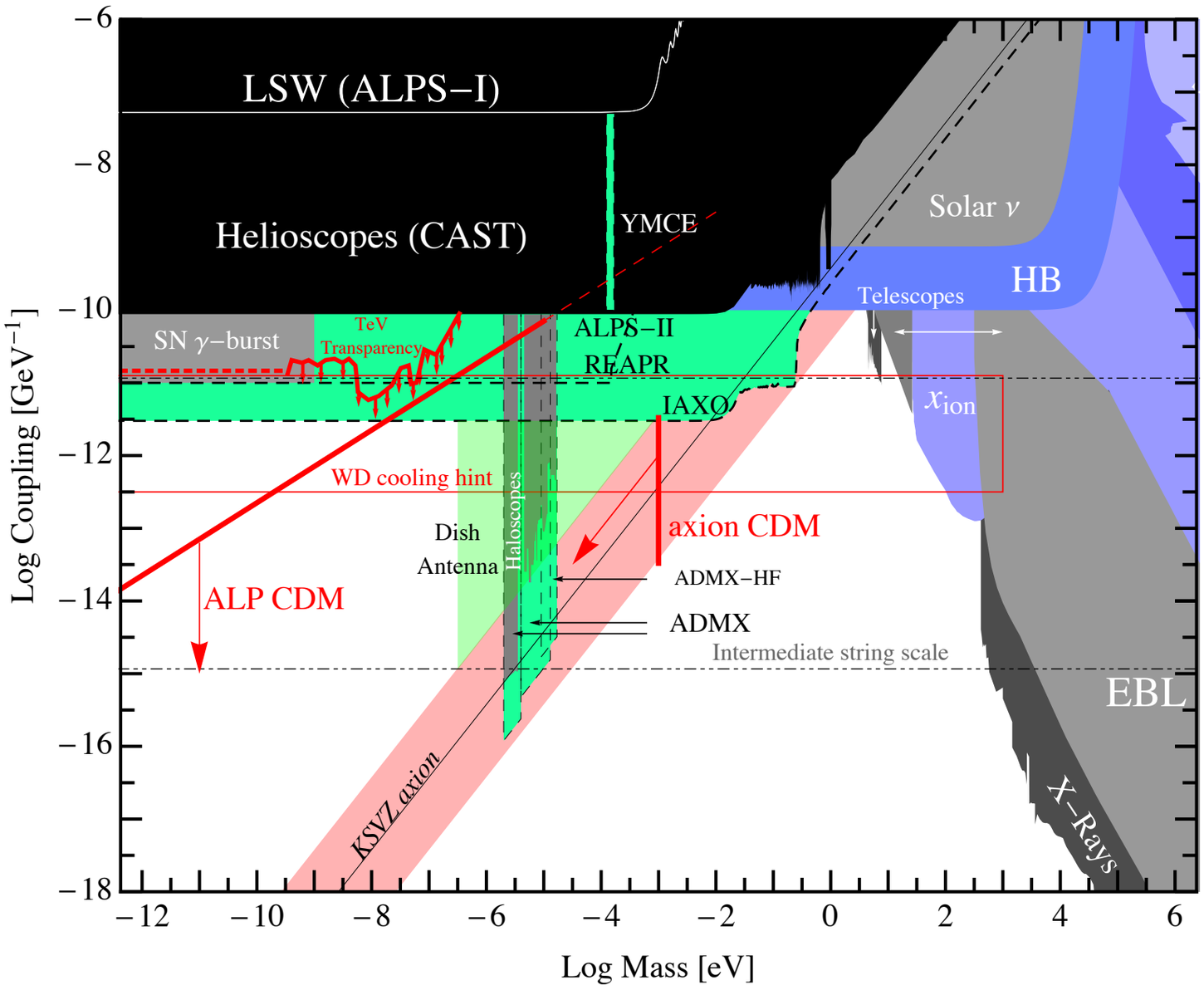
for ALPs, coupling to photons can be different (even zero)

use this coupling to probe photon to axions/ALP conversions

Current Limits & Prospects

Axions & ALPs



Jaeckel, Redondo, Ringwald, …

Current Limits & Prospects

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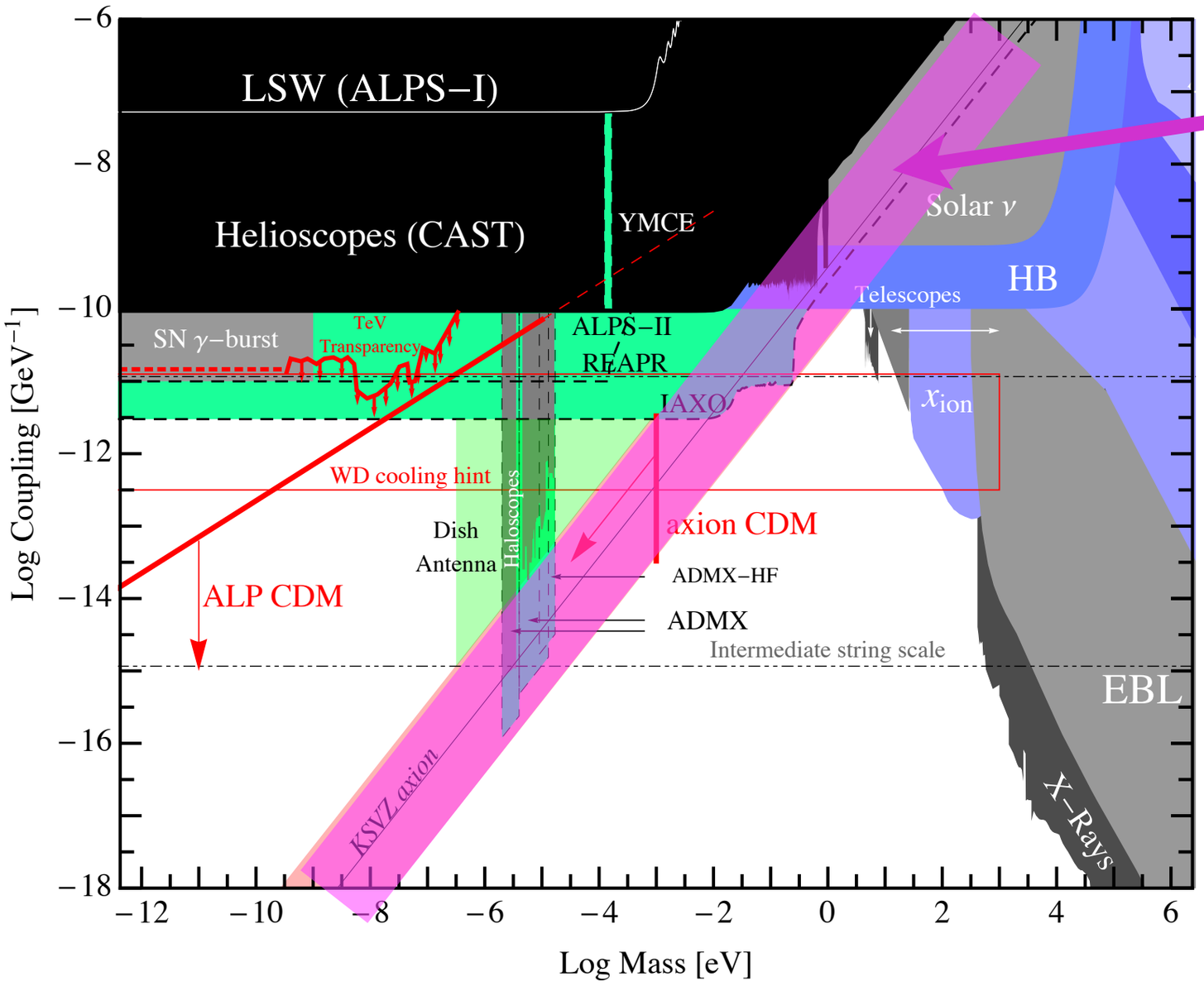
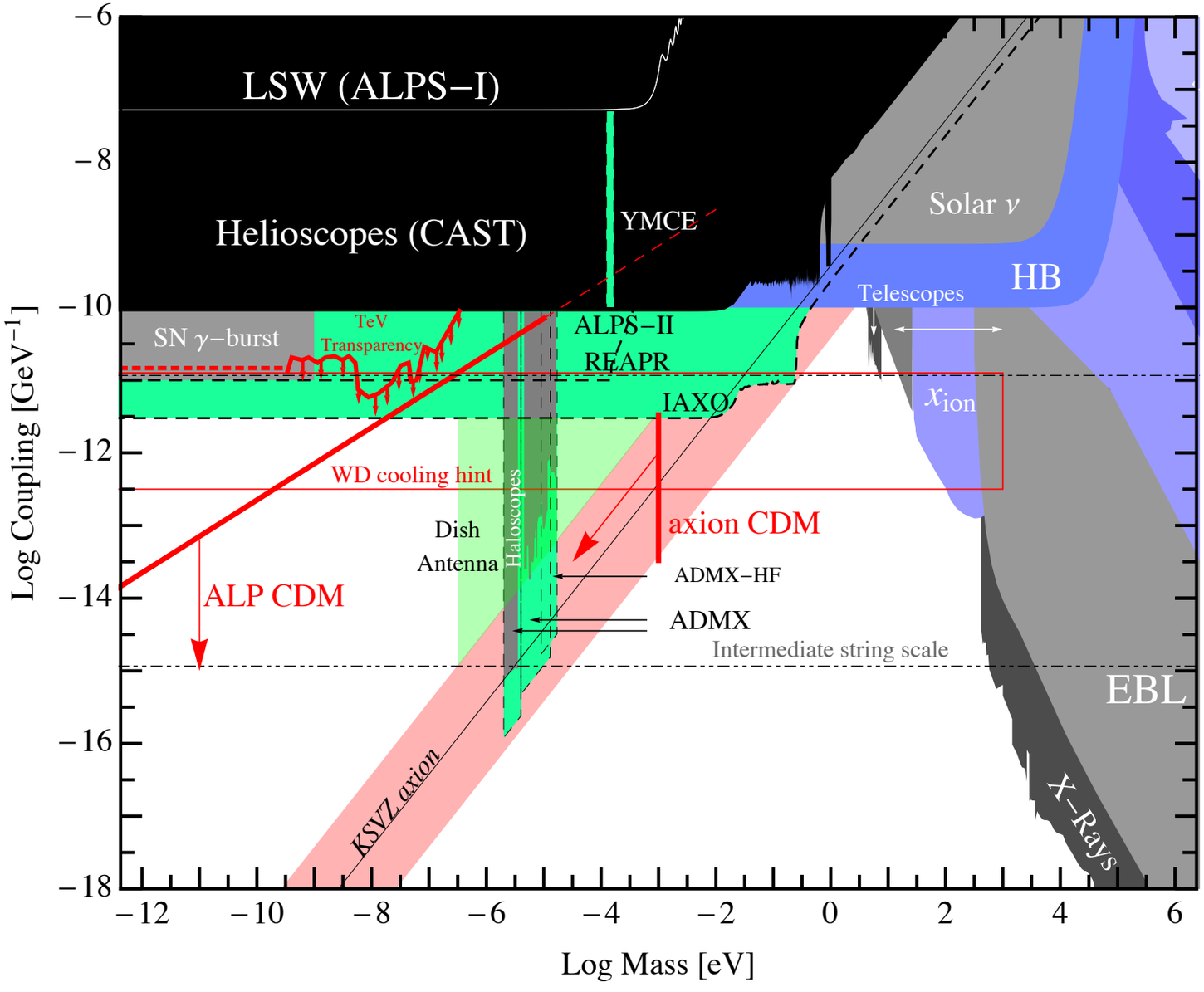


axion band

Jaeckel, Redondo, Ringwald, …

Current Limits & Prospects

Axions & ALPs



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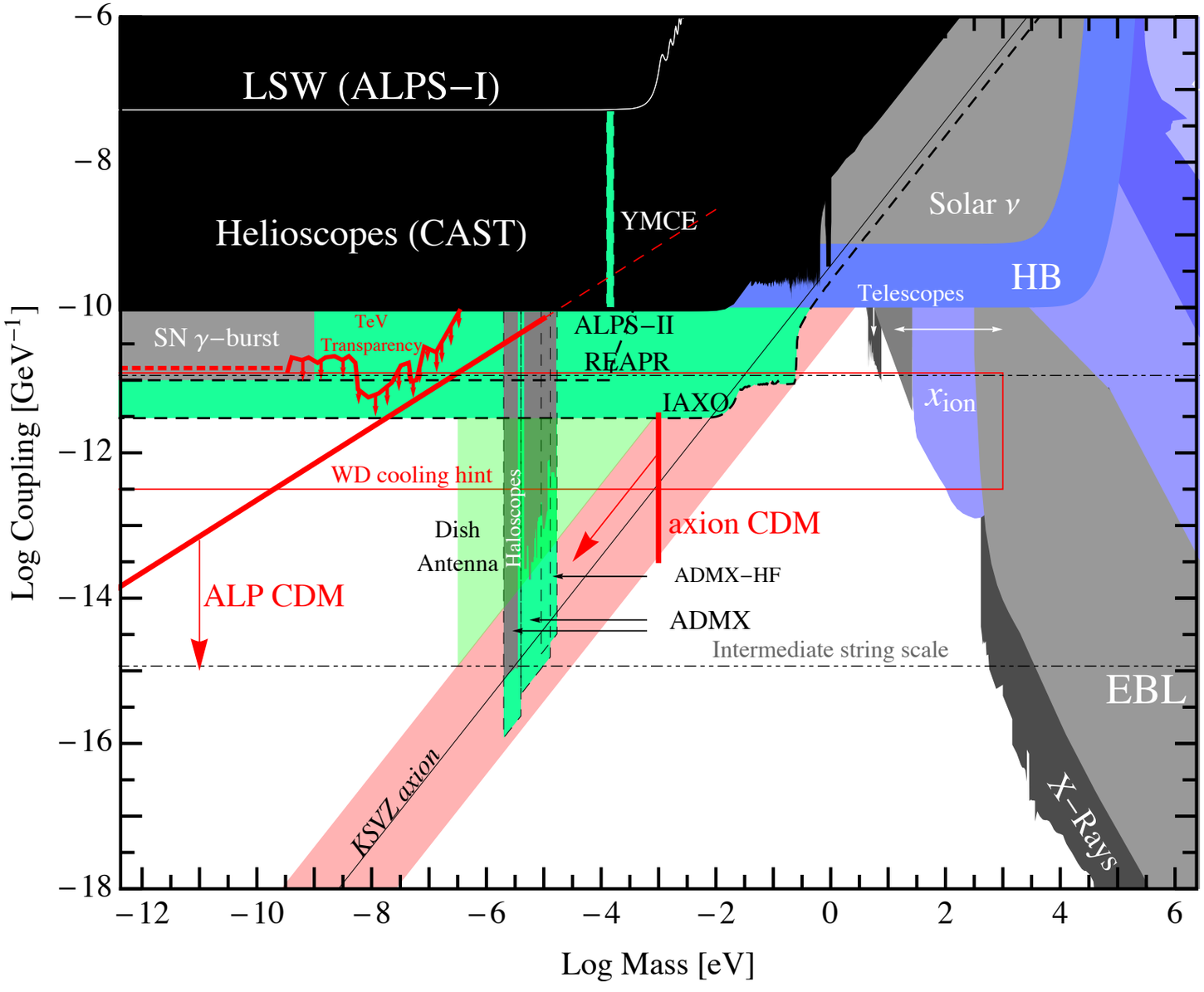
Many experimental opportunities, e.g.

- Light-shining-through-walls
- helioscopes
- haloscopes (e.g. ADMX w/ tunable microwave cavity)

Current Limits & Prospects

Axions & ALPs



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Many experimental opportunities, e.g.

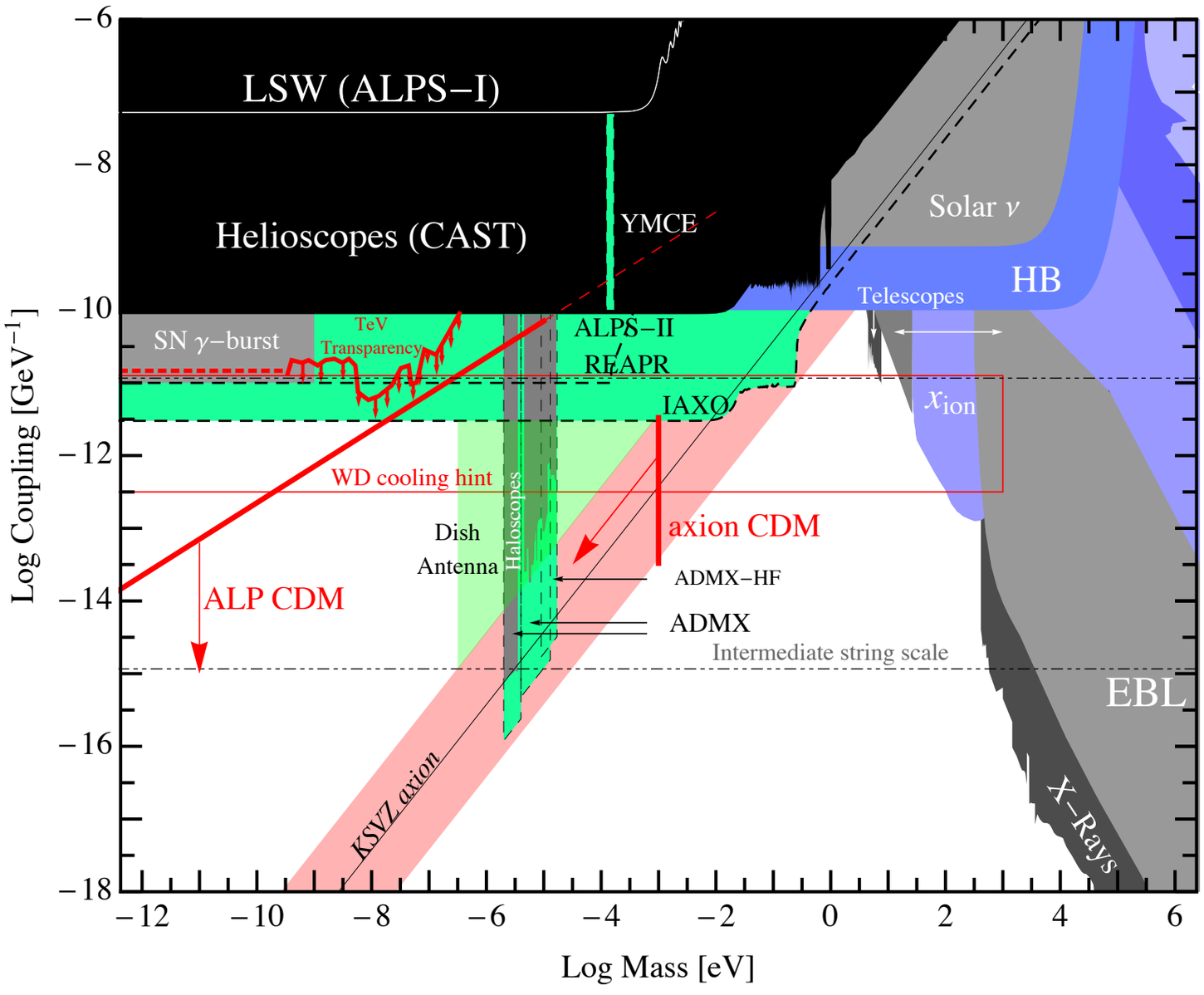
- Light-shining-through-walls
- helioscopes
- haloscopes (e.g. ADMX w/ tunable microwave cavity)

other ideas being developed, e.g. using molecular interferometry or NMR

e.g. Graham, Rajendran et.al.

Current Limits & Prospects

Axions & ALPs



axion band is well-motivated target and should be pursued

other regions motivated too
(theory+DM+astro hints)

Jaeckel, Redondo, Ringwald, …

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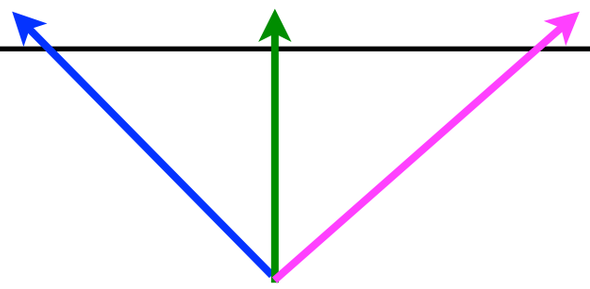
Dark Photons

Standard Model

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



Known Forces

Dark Sector

Dark Photons

consider a very *simple* Dark Sector

Standard Model

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

Known Forces

Dark Sector

A' (massive)

New force: *U(1)*

Dark Photons

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Standard Model

g $W^{\pm}, Z$ γ

Known Forces

Dark Sector

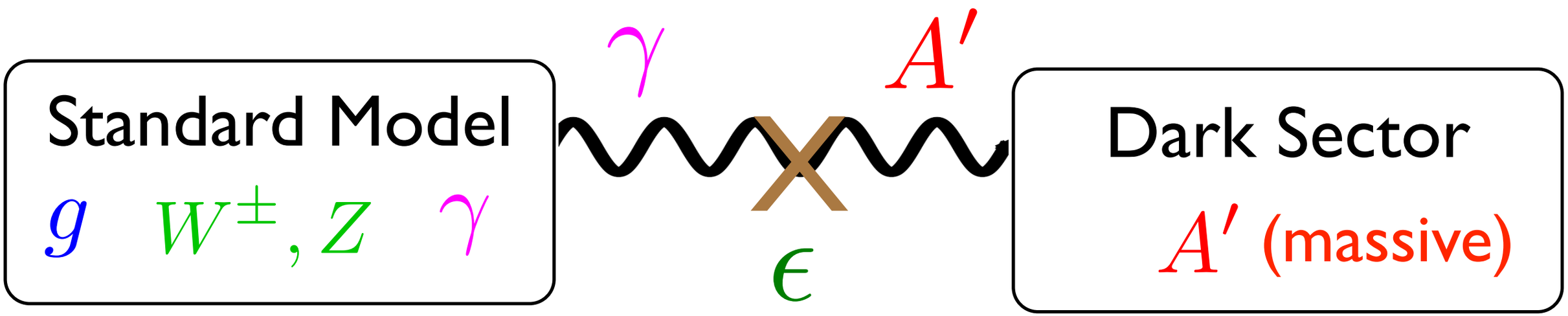
A' (massive)

New force: *U(1)*

(+ possibly dark matter)

Dark Photons

consider a very *simple* Dark Sector



ordinary photon & A′ can mix

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

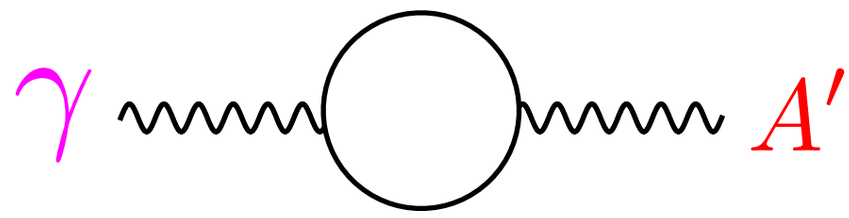
"Kinetic Mixing"

Holdom

Galison, Manohar

Generating Kinetic Mixing

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



$\epsilon \sim 10^{-8} - 10^{-2}$ a motivated target

Mixing with photon allows:

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$A' \leftrightarrow \gamma$ "oscillation"

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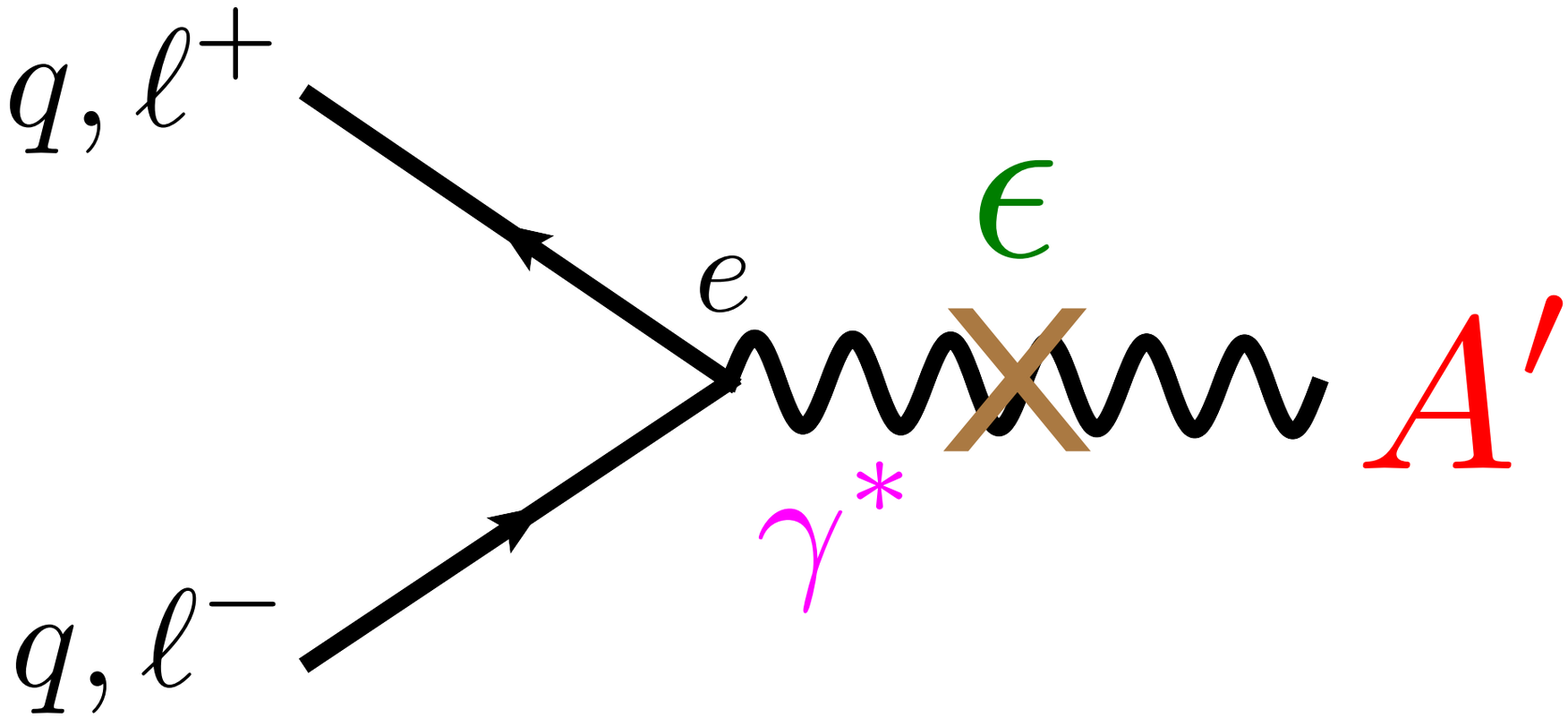
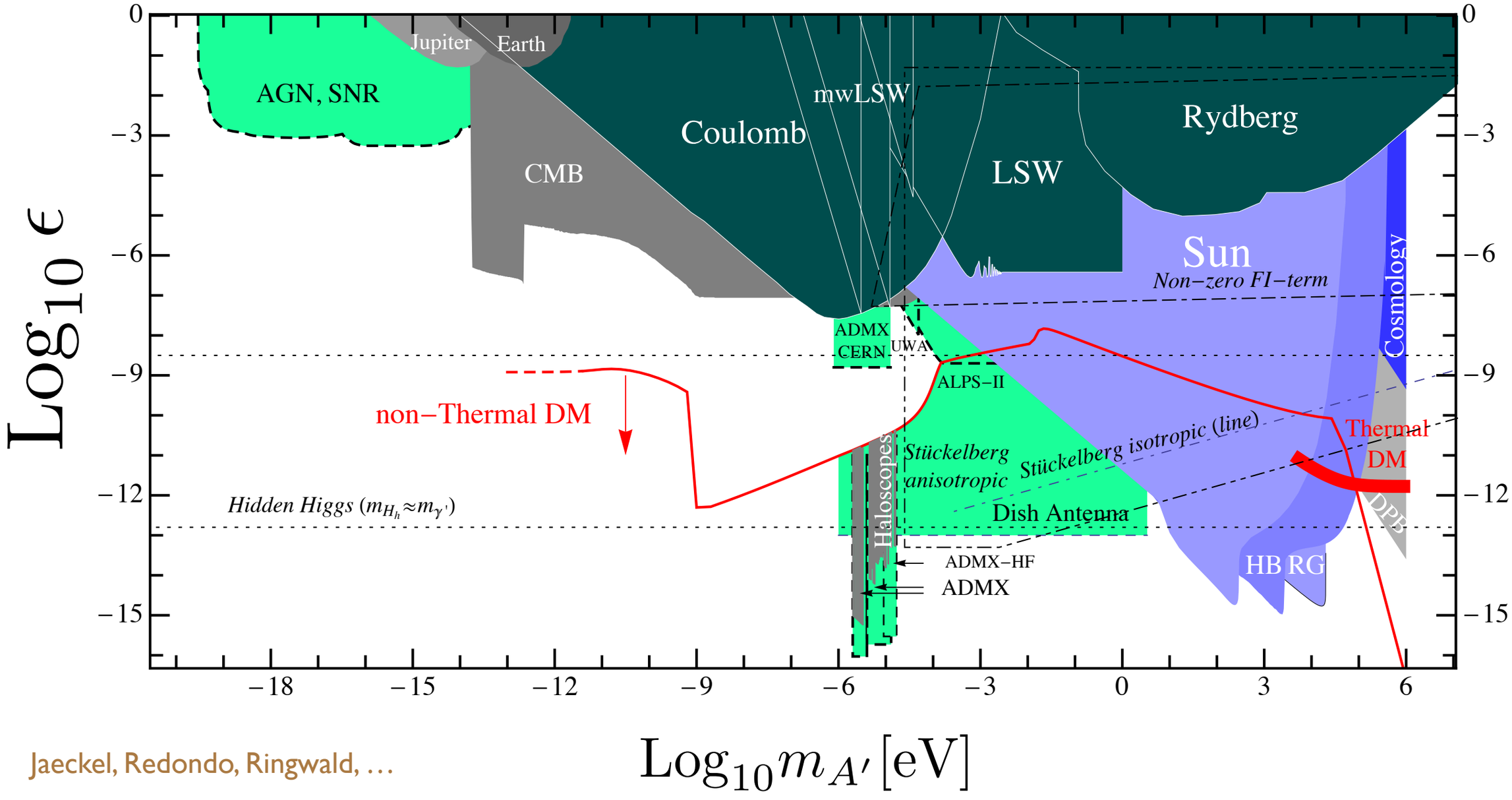
$$A' \leftrightarrow \gamma \text{ “oscillation”}$$

and

A′ coupling to quarks and charged leptons:



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

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- origin of GeV-scale can be naturally related to Weak-scale in some models

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

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

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- A' may explain observed muon g-2 (>3σ discrepancy)

Pospelov
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- Hints of new dark matter interactions from various DM indirect and direct detection anomalies

Arkani-Hamed et.al.; Cholis et.al.;
Pospelov & Ritz; Hooper, Weiner, Xue

How 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.
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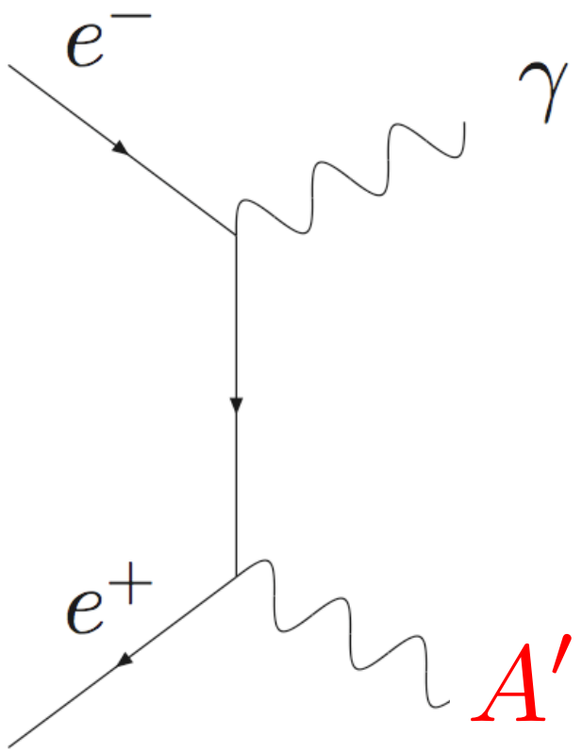

$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$$

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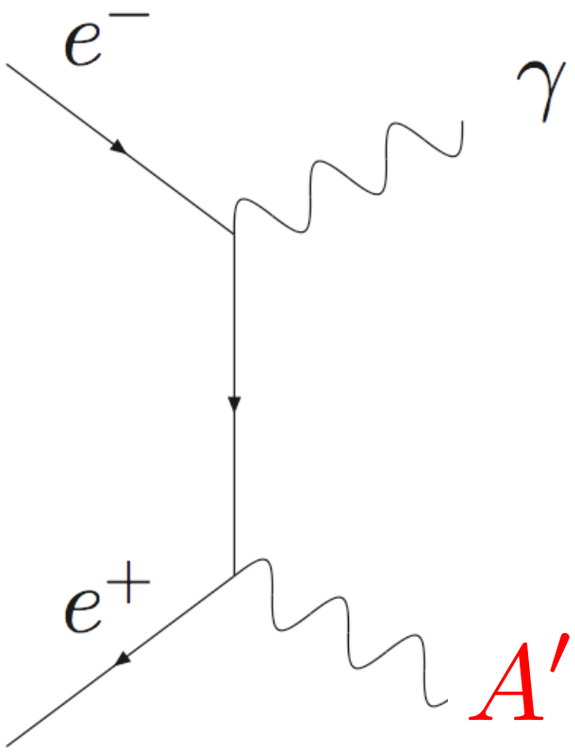

Rare meson decays

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

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

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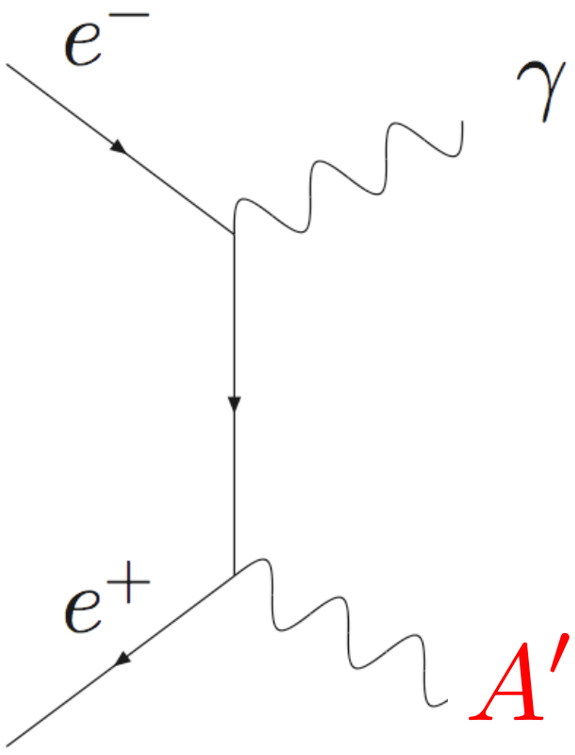

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B-factories, Phi-factories

searches completed/ongoing/planned

How 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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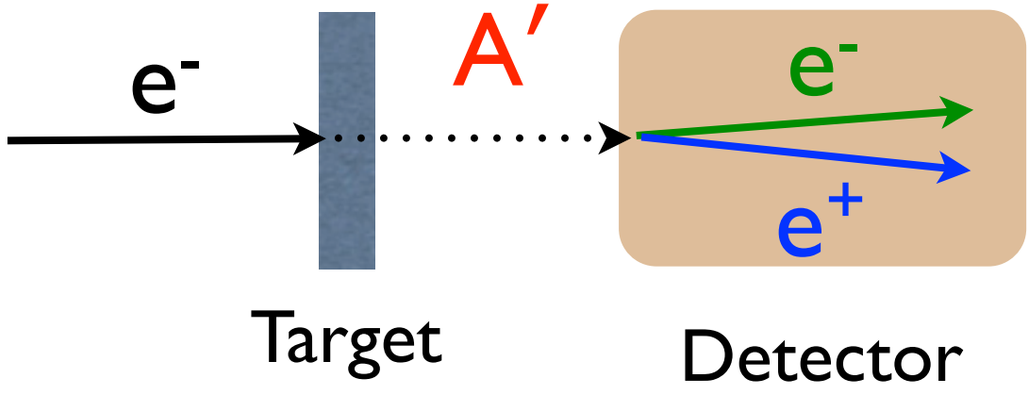

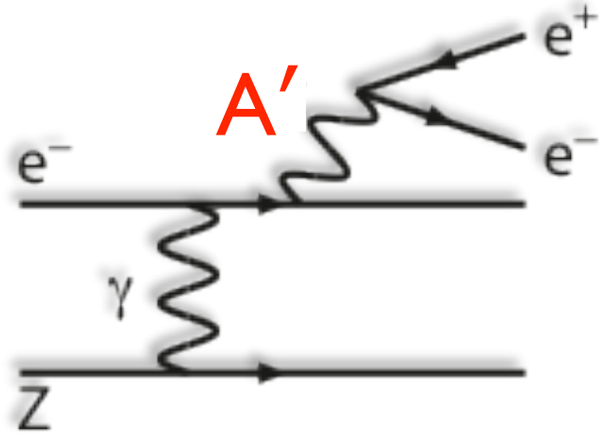

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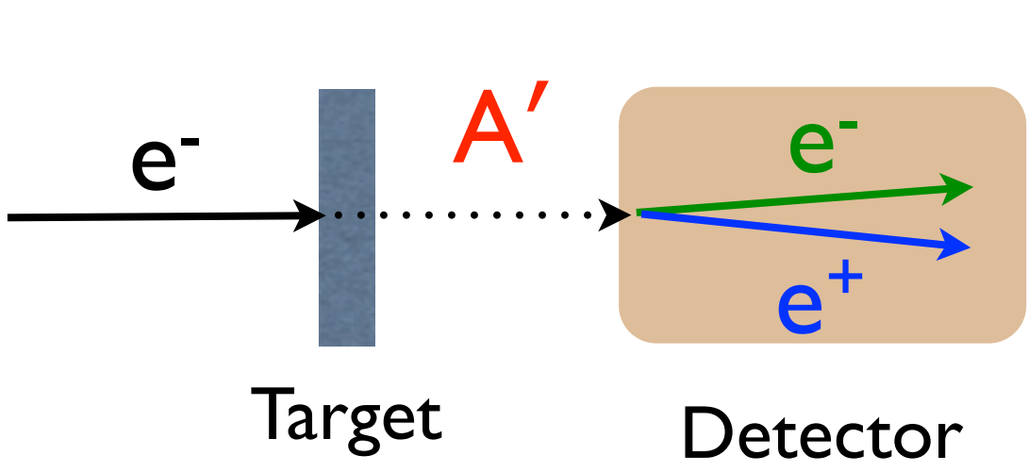

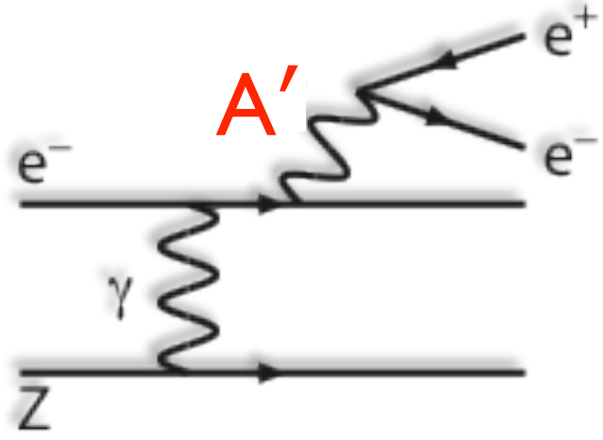

e.g. E137, APEX, HPS, DarkLight, MAMI, VEPP-3, …

How look for A′ with MeV-GeV mass?

Proton-beam fixed target experiments

Batell, Pospelov, Ritz

RE, Harnik, Kaplan, Toro

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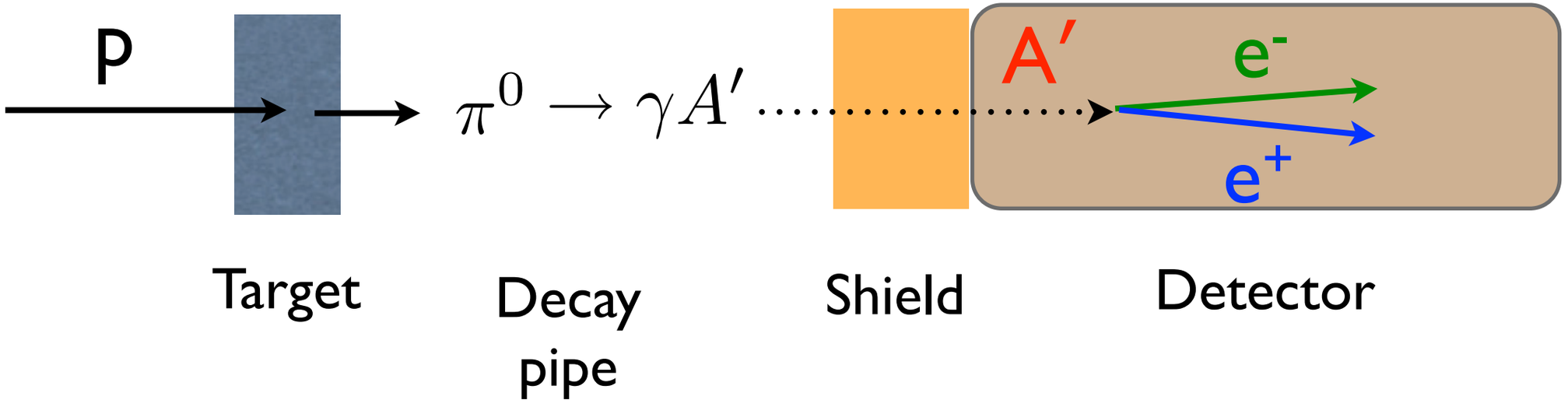
Example: produce A′ from pion decays



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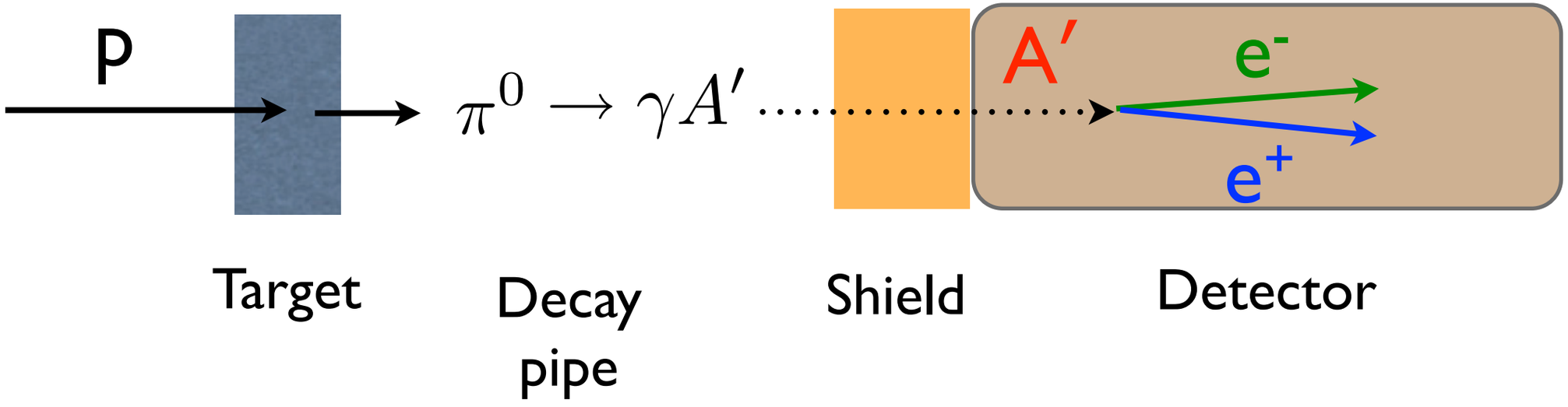
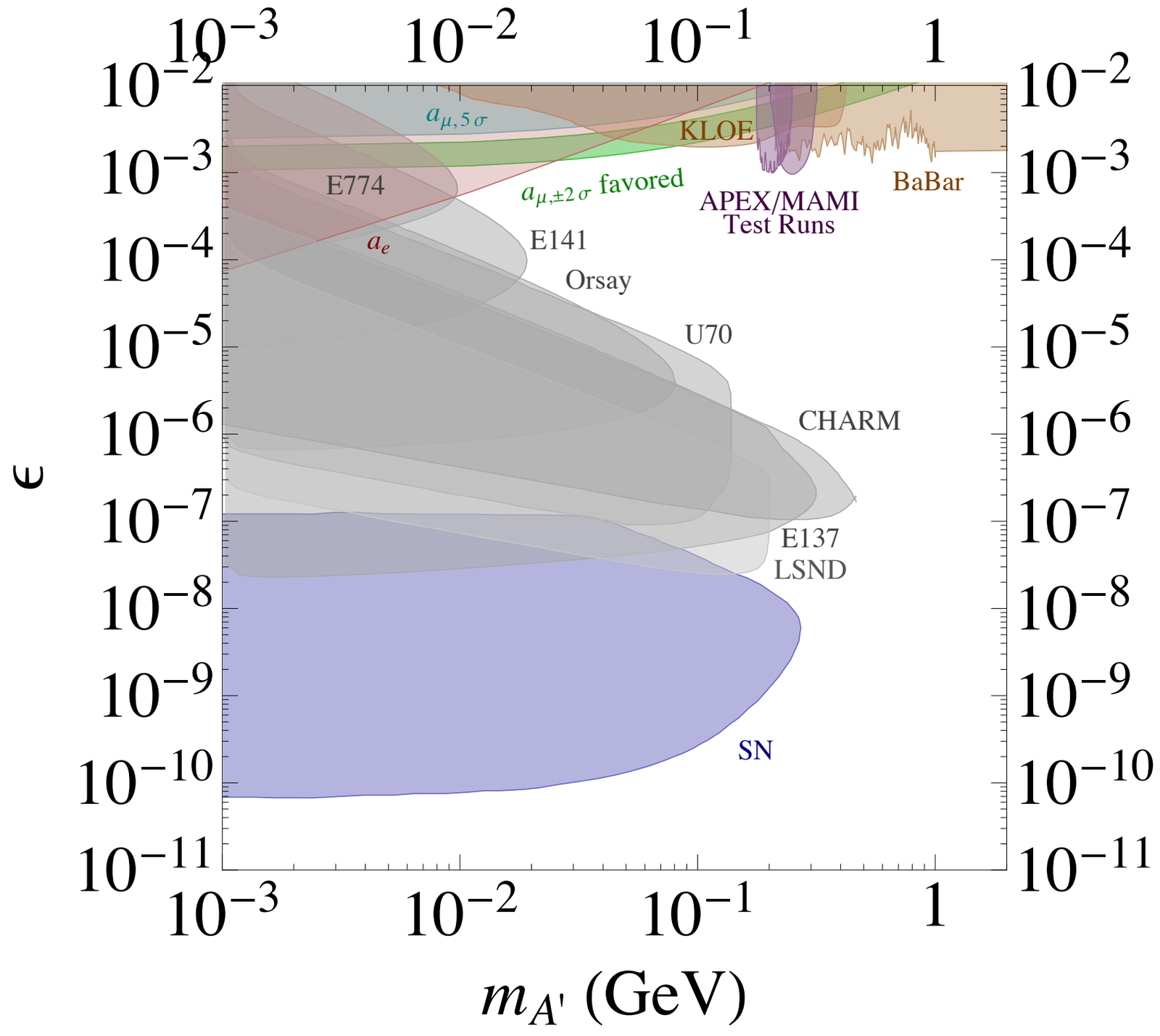


e.g. LSND, MINOS, MiniBooNE, Project X

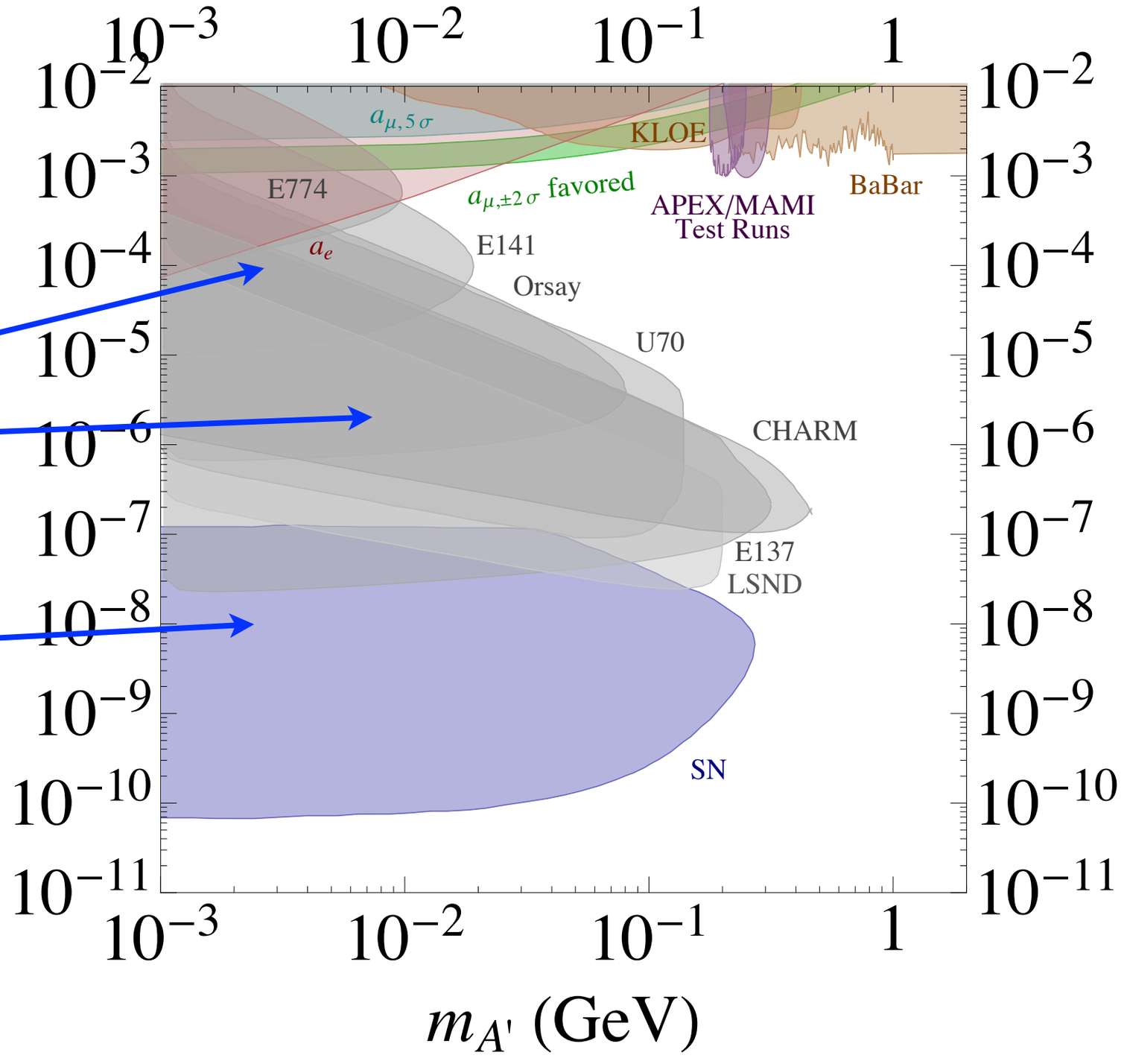
Current constraints



Current constraints

past
electron + proton
beam dumps

supernova



Bjorken, RE, Schuster, Toro

Andreas, Niebuhr, Ringwald

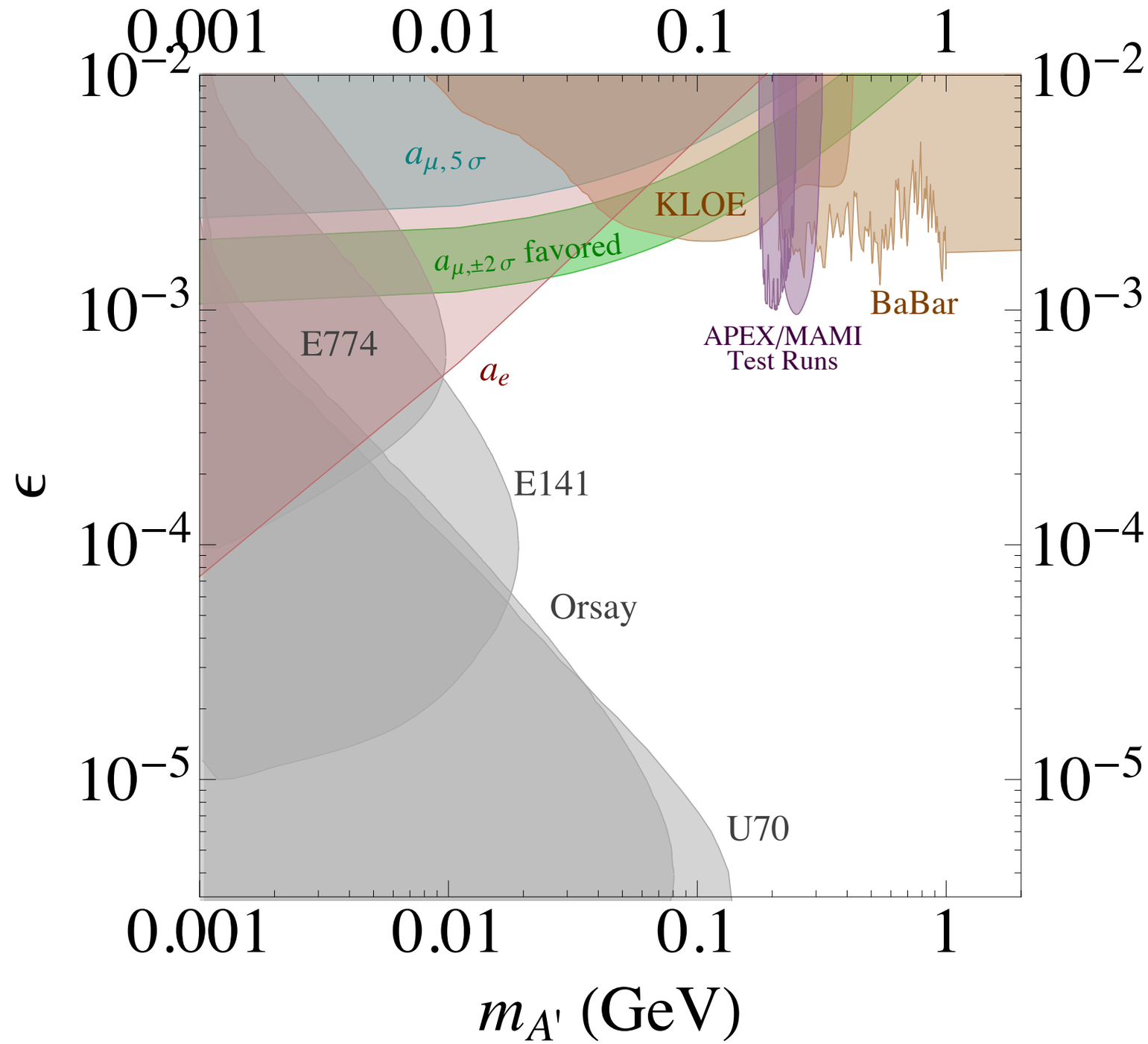
Batell, Pospelov, Ritz

RE, Harnik, Kaplan, Toro

Blumlein, Brunner

Dent, Ferrer, Krauss

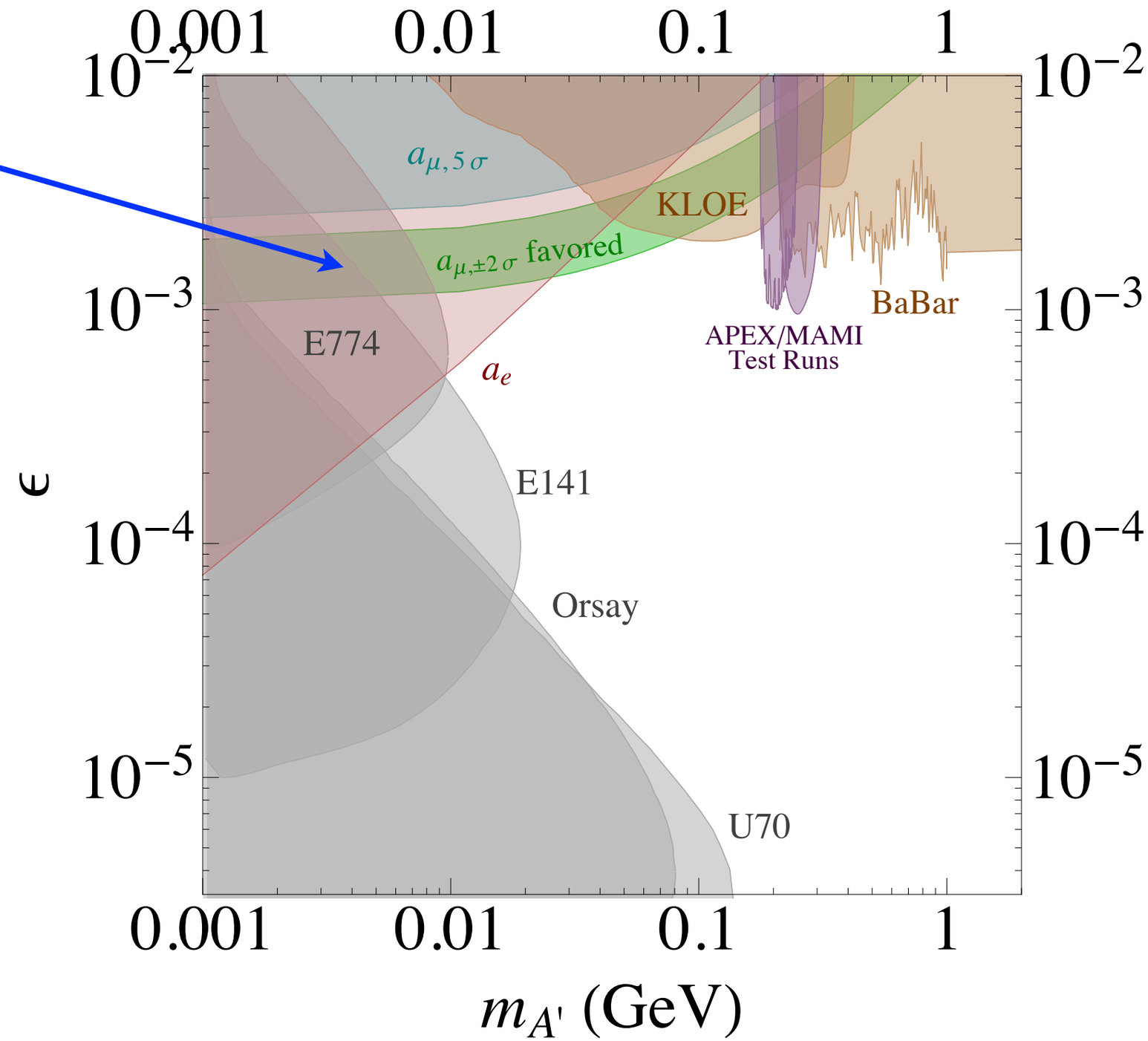
Current constraints (zoomed in)



Pospelov
Bjorken, RE, Schuster, Toro
RE, Schuster, Toro, Wojtsekhowski
KLOE Collaboration
APEX Collaboration
MAMI/A1 Collaboration

Current constraints (zoomed in)

g-2 of e^-, μ^-



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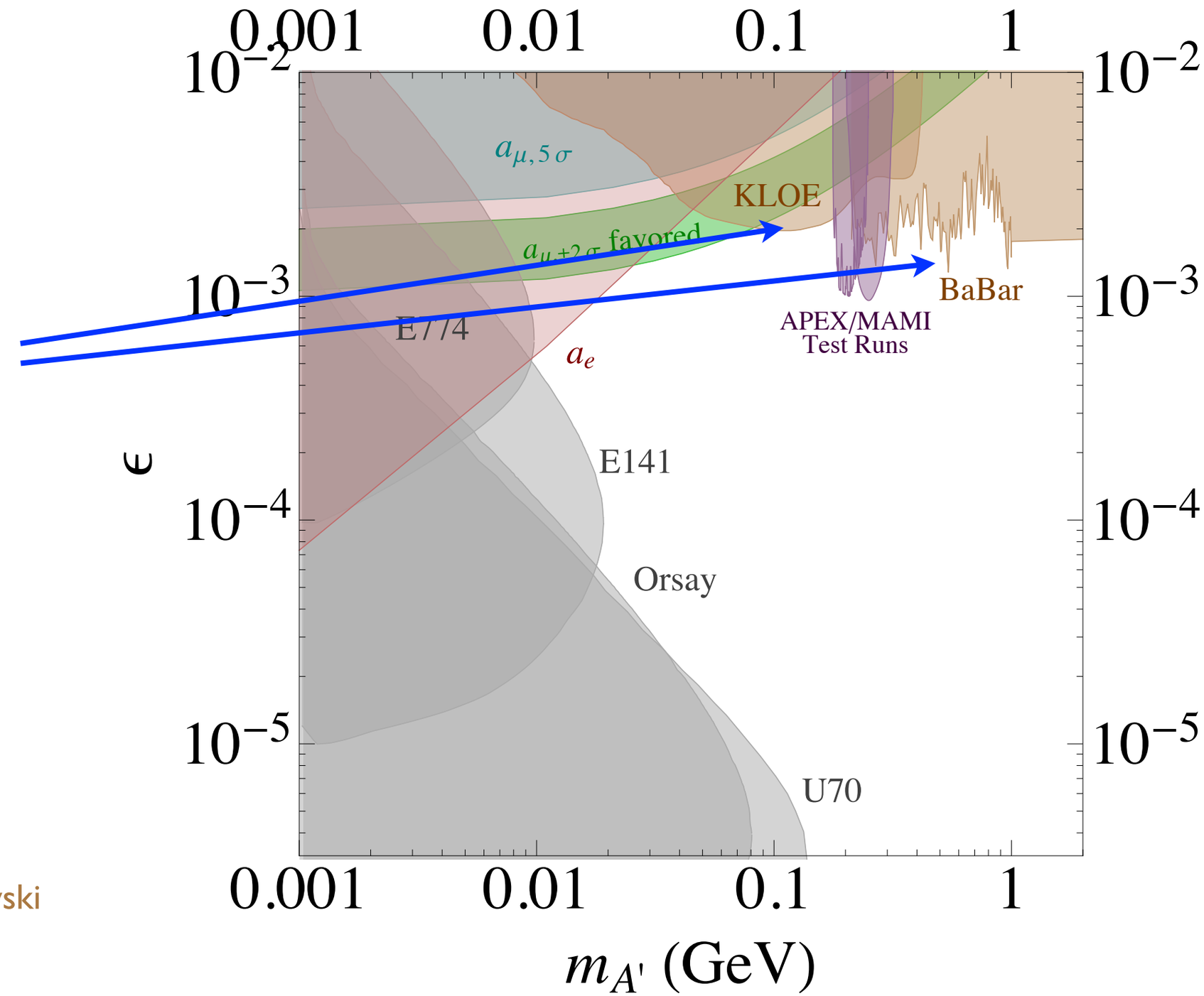
B/Phi-factory searches



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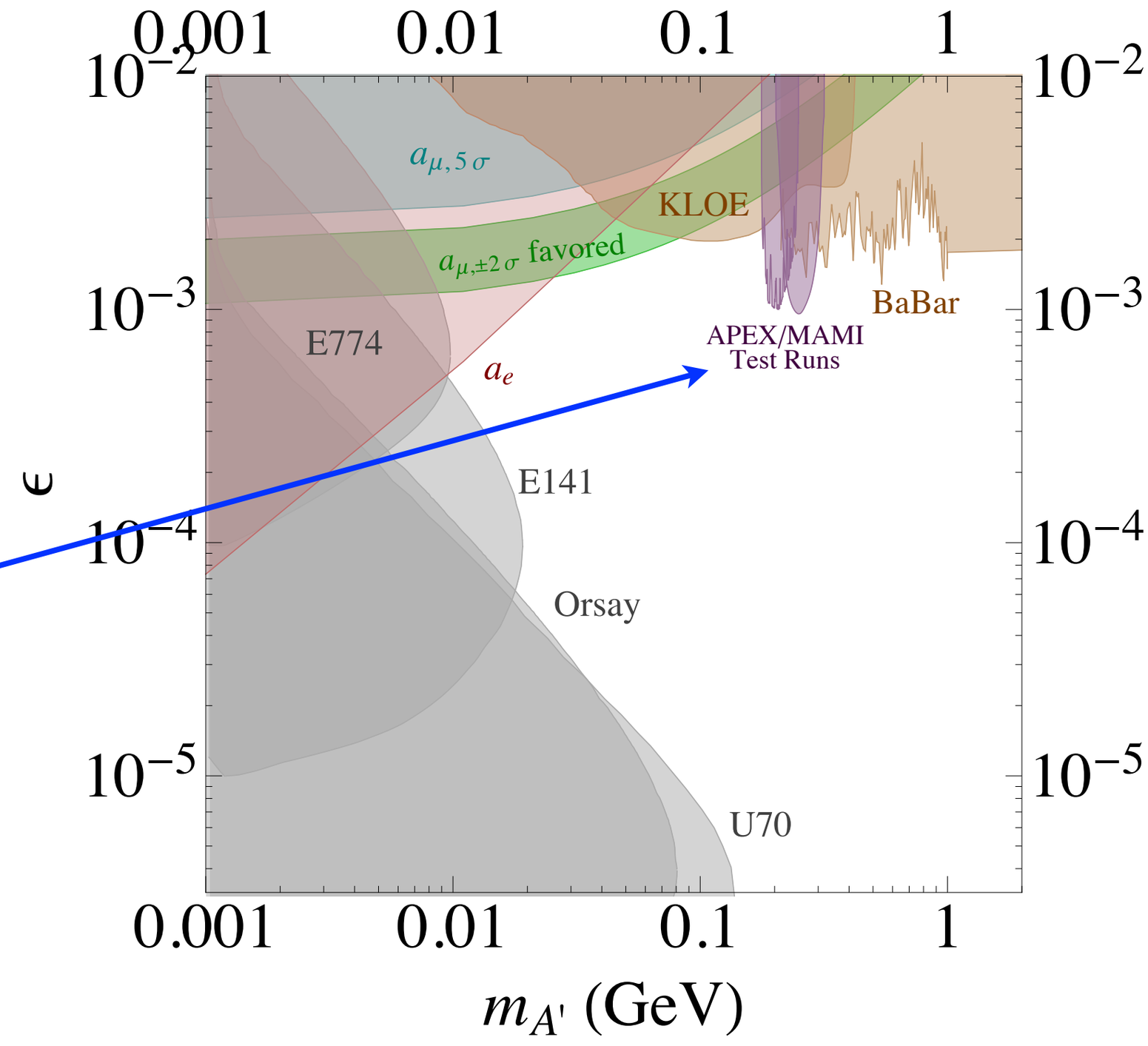
B/Phi-factory searches

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

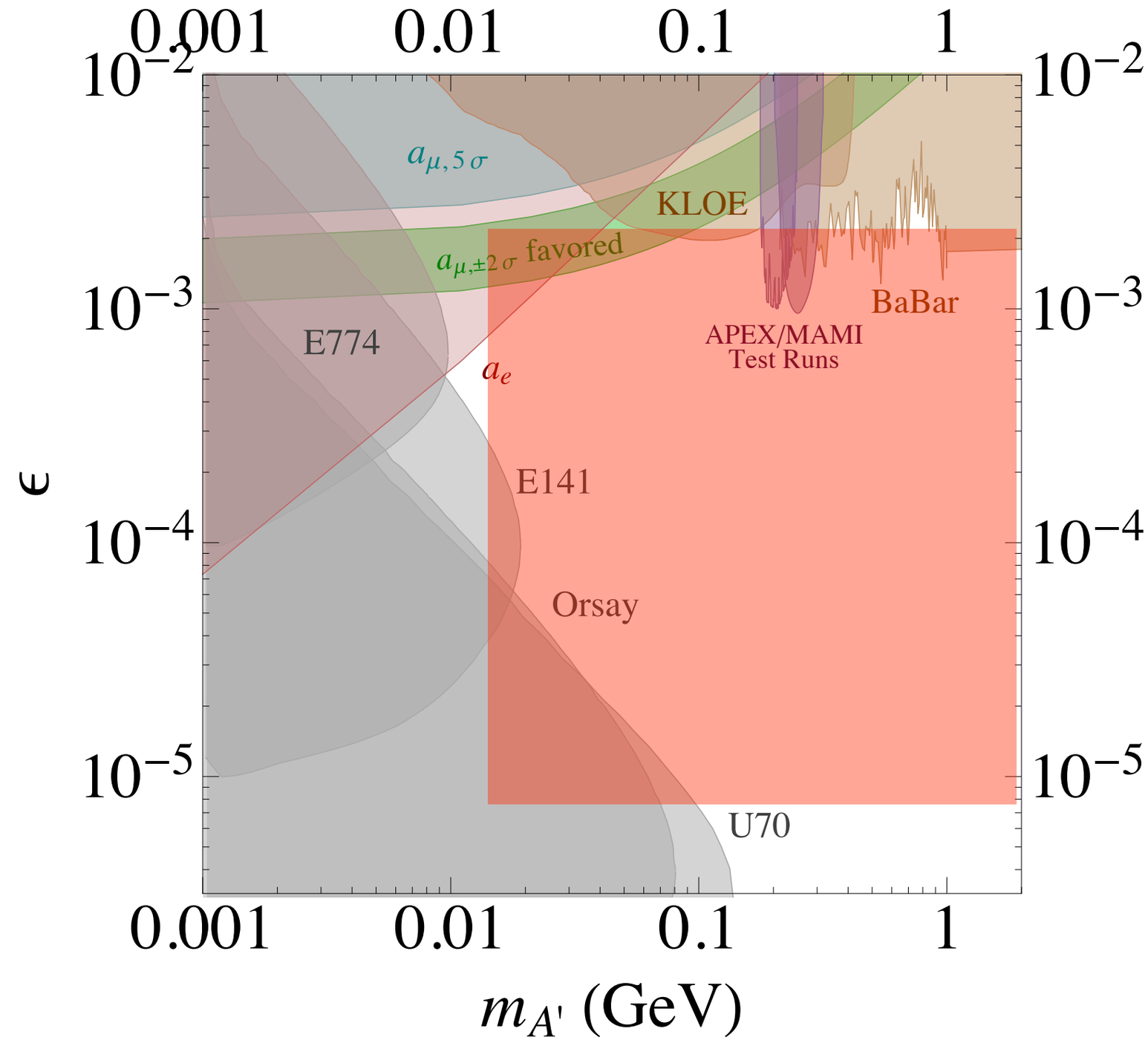


Pospelov
Bjorken, RE, Schuster, Toro
RE, Schuster, Toro, Wojtsekhowski
KLOE Collaboration
APEX Collaboration
MAMI/A1 Collaboration

Current constraints (zoomed in)

need new experiments to probe this region

Bjorken, RE, Schuster, Toro



New Experiments

@JLab (USA):

APEX, HPS,

DarkLight

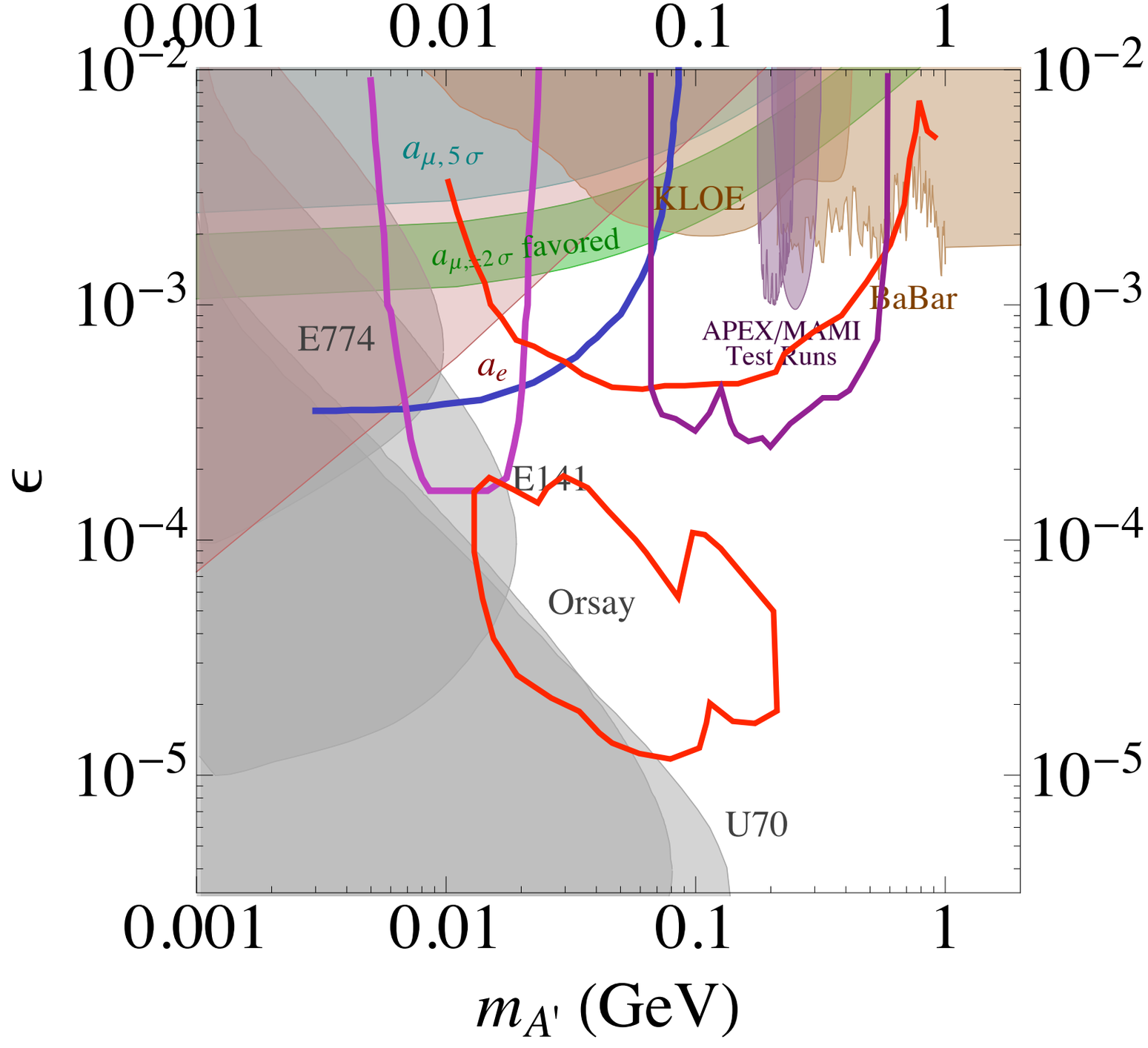
in Russia:

VEPP-3

in Germany:

Mainz (not shown)

look for A′ → e^+e^- resonance or displaced vertex (unique to HPS)



How look for A′ with MeV-GeV mass?

No time to discuss other searches,
e.g. Dark Sector ("Hidden Valley") explorations at Tevatron/LHC

Strassler, Zurek

Arkani-Hamed, Weiner

Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

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)

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

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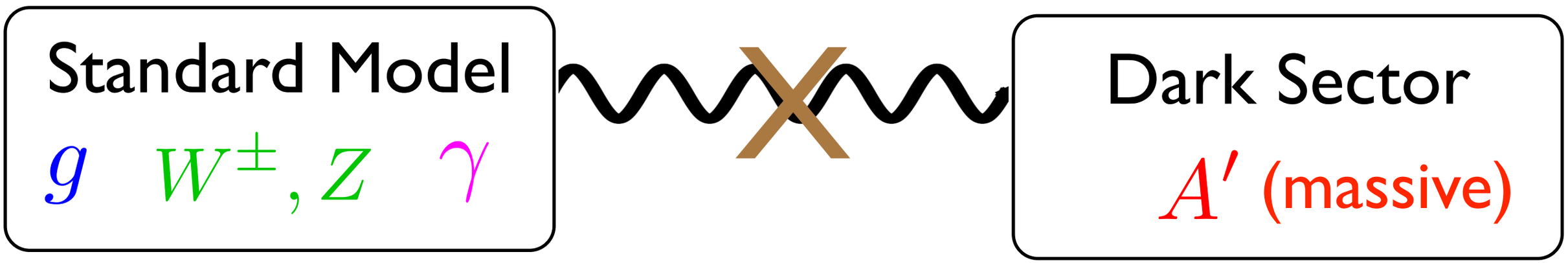


Dark Sector can easily be more complicated,
so must look for other signals too

Example: sub-GeV Dark Matter + A′

sub-GeV Dark Matter

very rich phenomenology

(much of it still under active investigation)

Can probe in various ways:

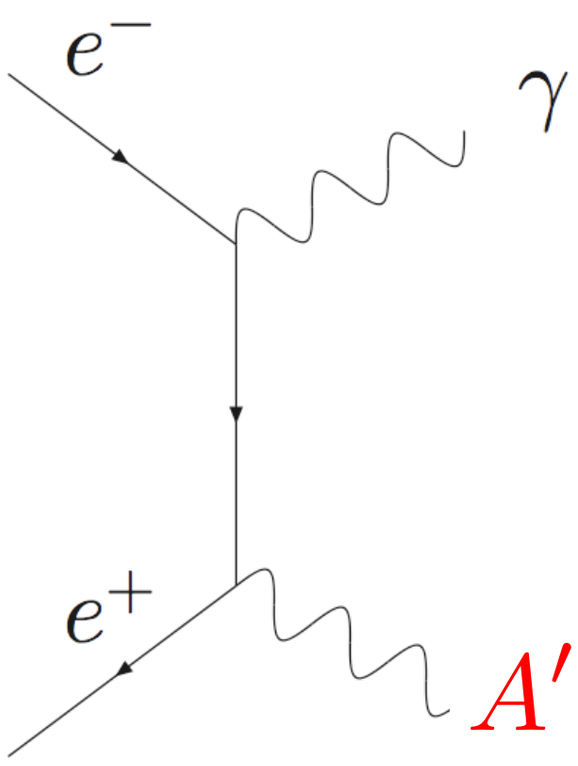
- colliders
- fixed-target (p & e^-)
- direct detection
- indirect detection

Low-energy e^+e^- colliders

RE, Mardon, Papucci, Volansky, Zhong

(to appear)

Example:



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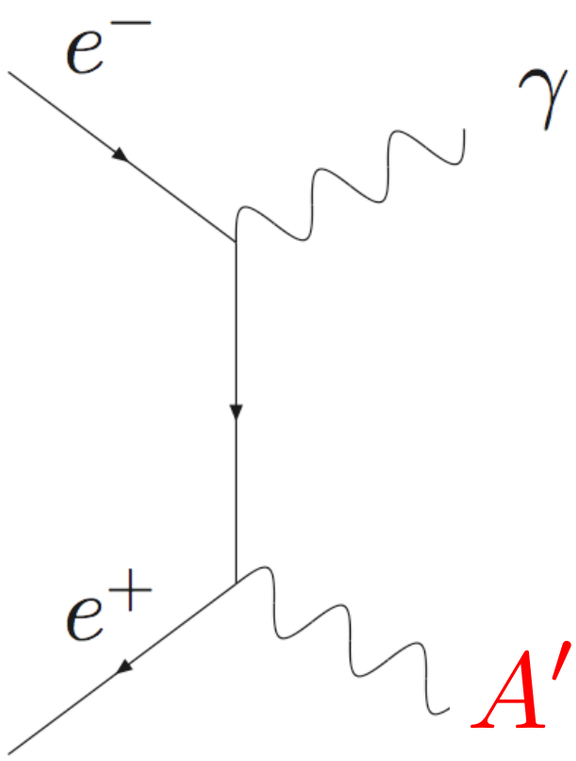

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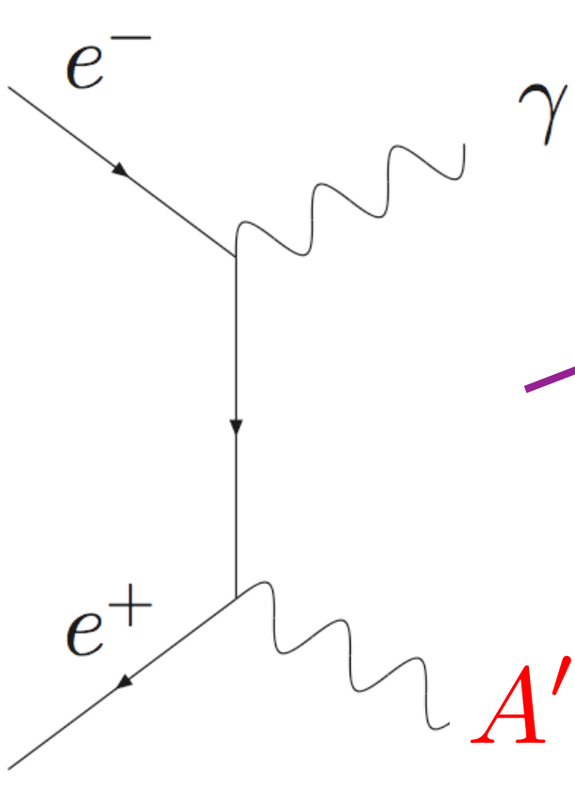
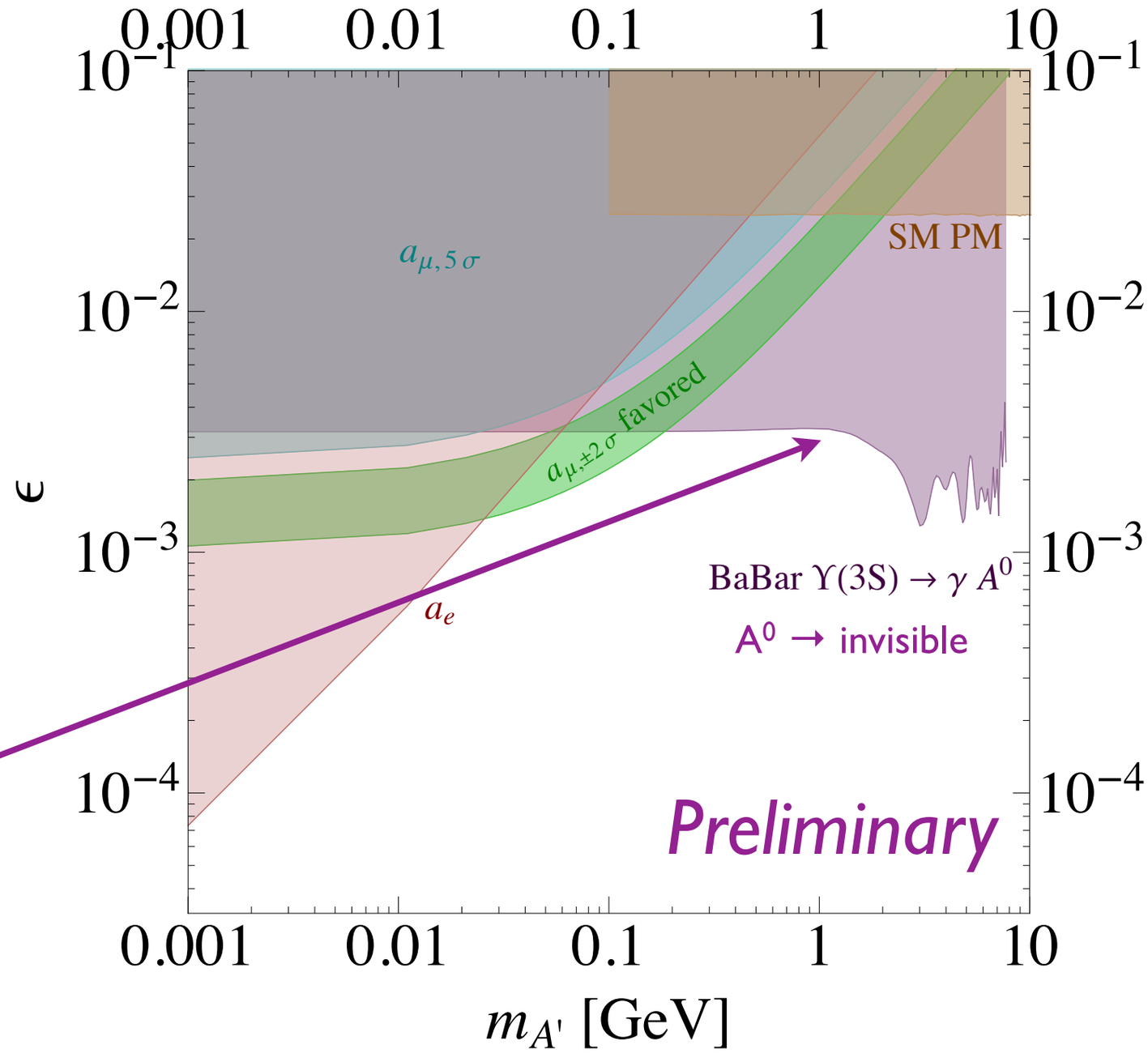


$A' \to \mathrm{DM} + \mathrm{DM}$
(invisible!)



Proton-beam fixed target experiments

Batell, Pospelov, Ritz
Deniverville, Pospelov, Ritz
Aguilar-Arevalo et.al. (MiniBooNE proposal)

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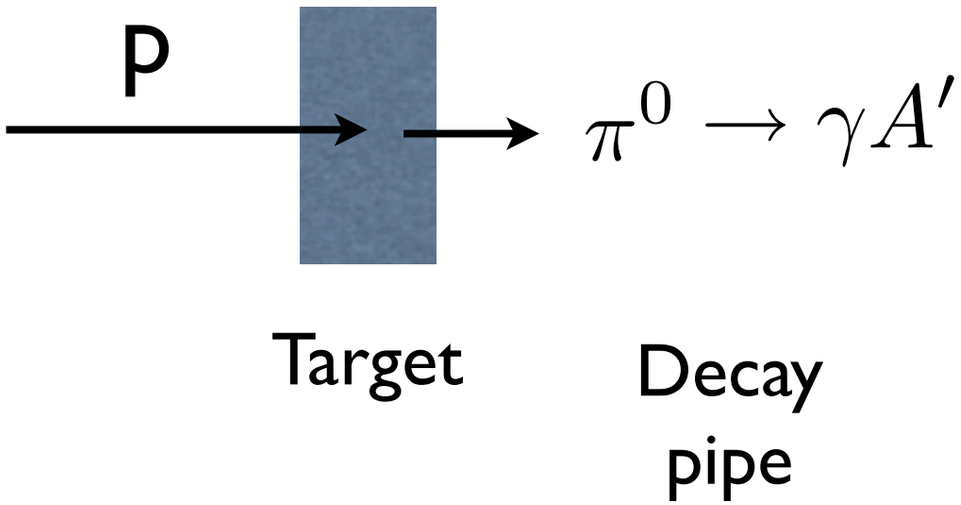

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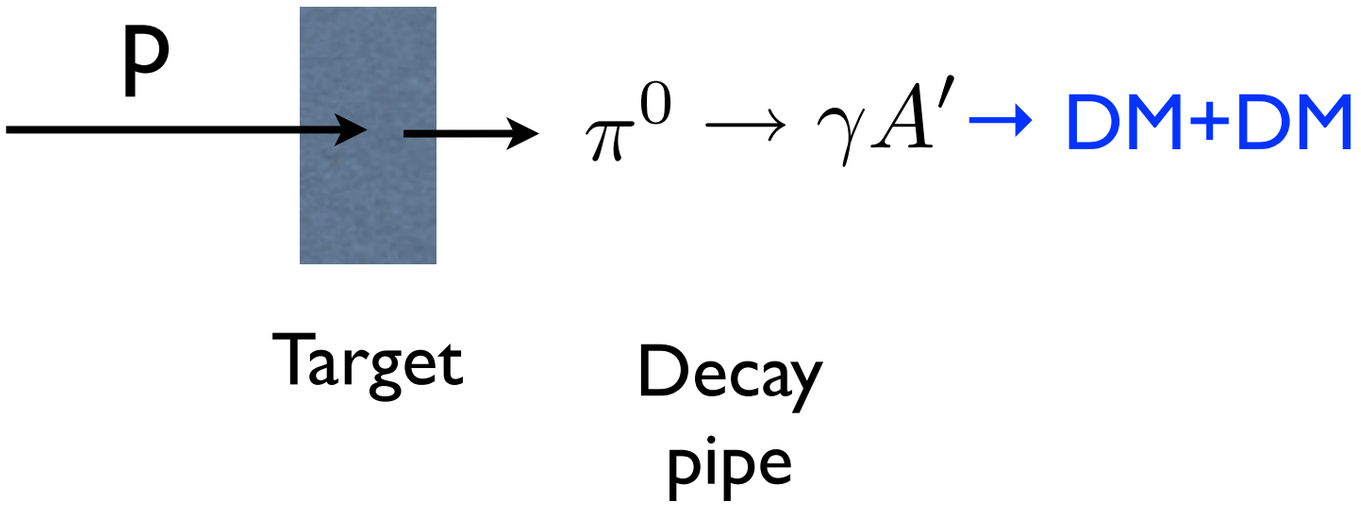
$A' \rightarrow$ DM+DM



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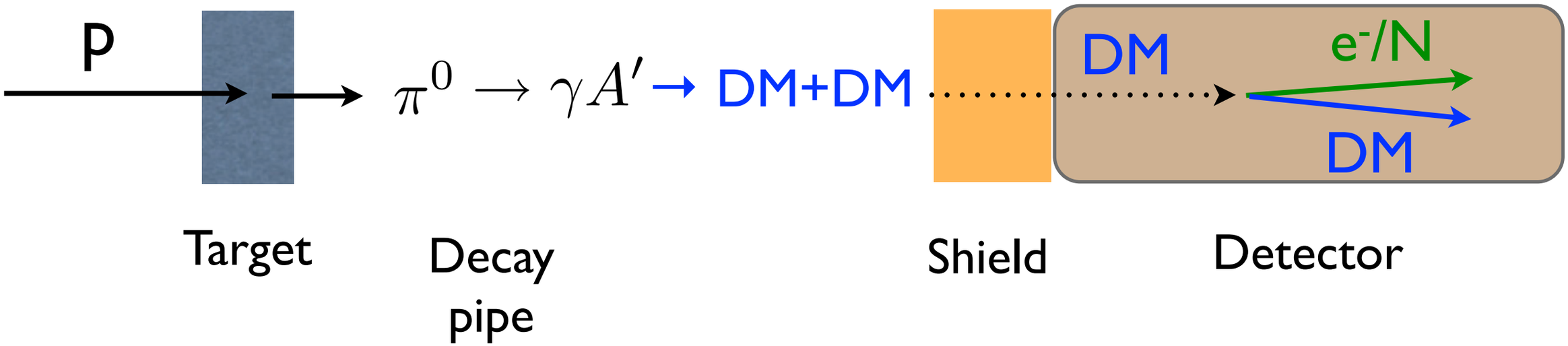

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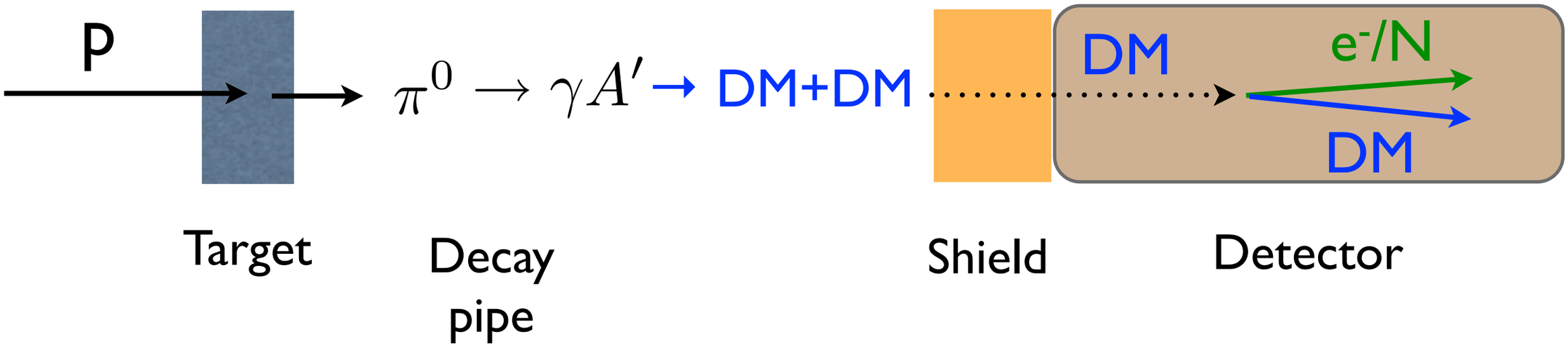


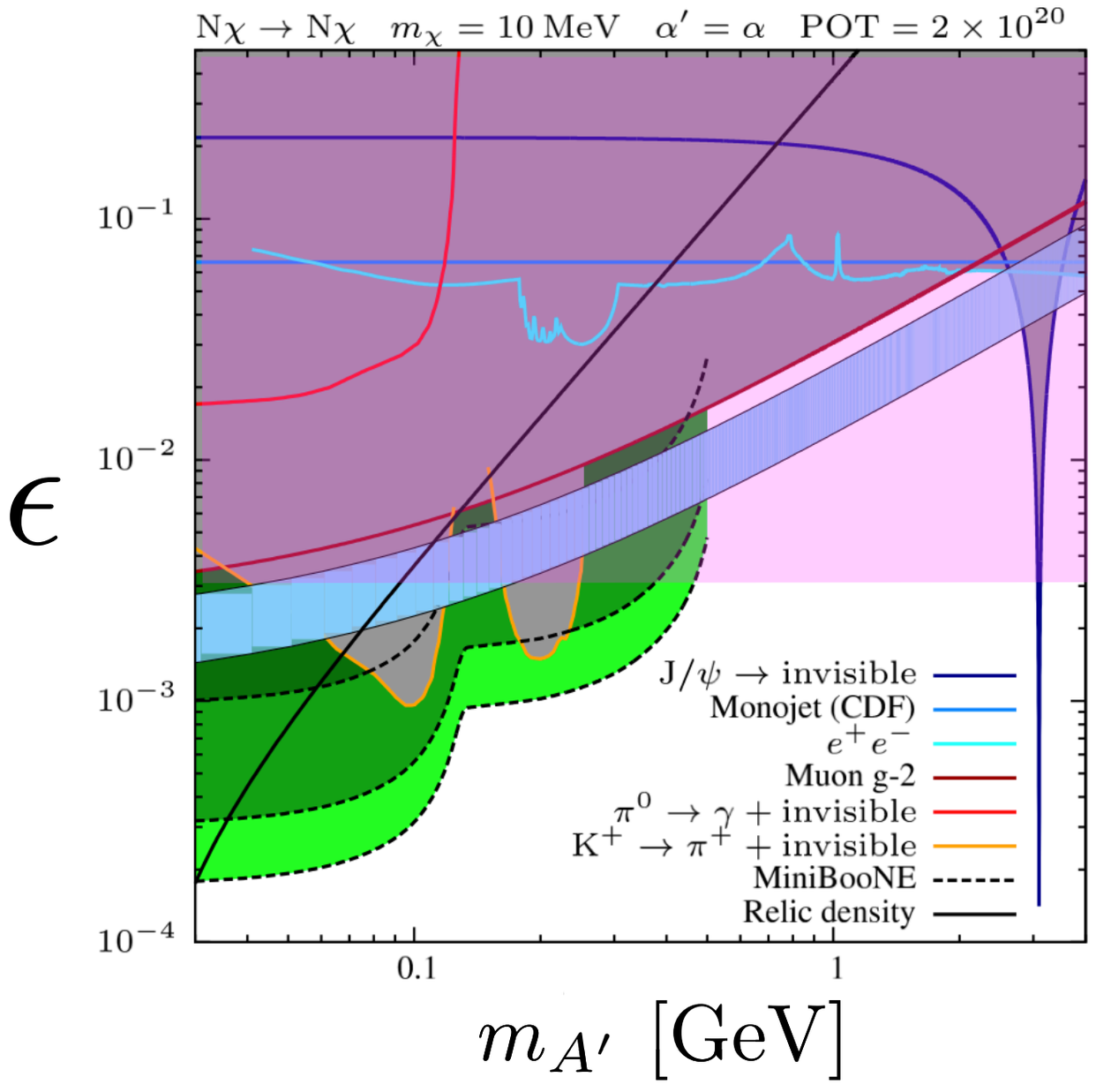
plenty of room for exploration

e.g. LSND, MINOS, MiniBooNE, Project X

Proton-beam fixed target experiments

Proposal for more MiniBooNE running

Aguilar-Arevalo et.al. (MiniBooNE proposal)

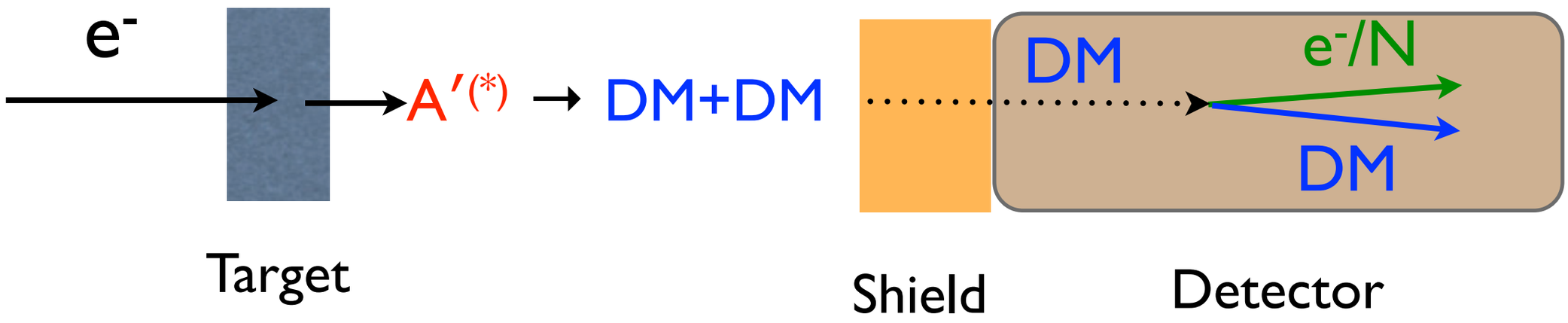


Electron-beam fixed target experiments

to appear: Diamond, Schuster; Krnjaic, Izaguirre, Schuster, Toro

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

DM recoils of e^-/nucleon in detector



plenty of room for future experiments

e.g. JLab, Mainz, …

Direct Detection

RE, Mardon, Volansky

probe DM in our halo scattering off

e.g. electrons in detector

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RE, Mardon, Volansky

probe DM in our halo scattering off

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first direct detection limits

on sub-GeV DM, using

published XENON10 data

RE, Manalaysay, Mardon,
Sorensen, Volansky

O *MeV !*

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probe DM in our halo scattering off

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Sorensen, Volansky

lots of potential
for current & new
experiments!

see also Graham et.al.

O *MeV !*

Conclusions

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- Dark matter points to a Dark Sector

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- New, light weakly-coupled particles are well-motivated
  - axions, ALPs, dark photons, …
  - motivated by DM, strong CP, muon g-2, astro anomalies, theory…

Conclusions

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Conclusions

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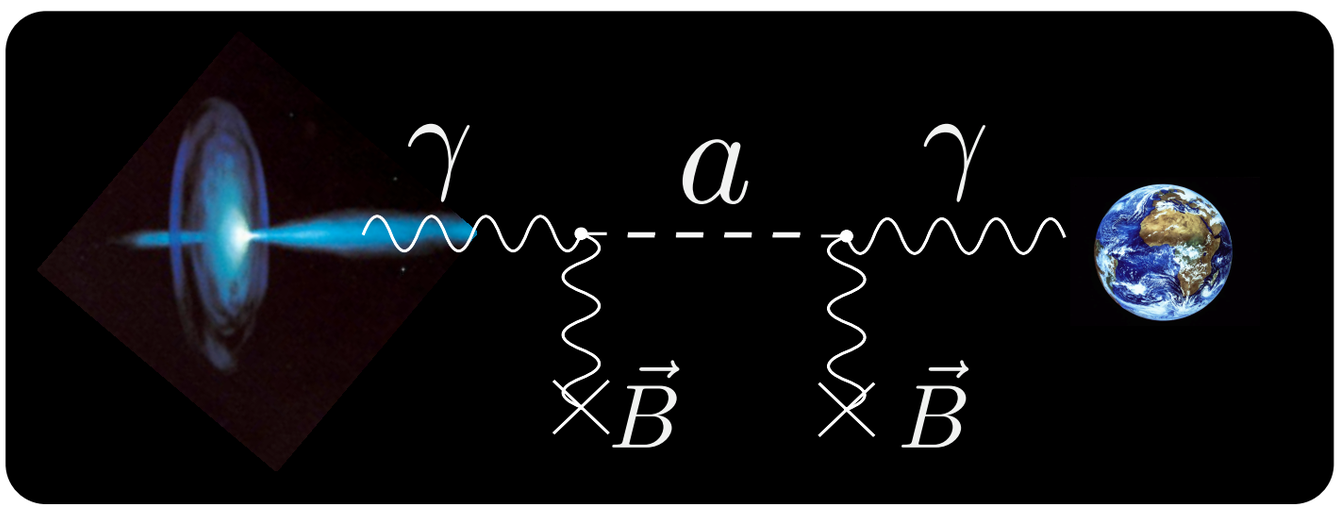
- experiments use intense beams & sensitive detectors
  - often make use of existing facilities/technologies (i.e. ~inexpensive)
  - could benefit from further technological developments
- support for these explorations is crucial
  - we don't know which guiding principle for finding new physics is reliable; must explore all motivated possibilities

Backup

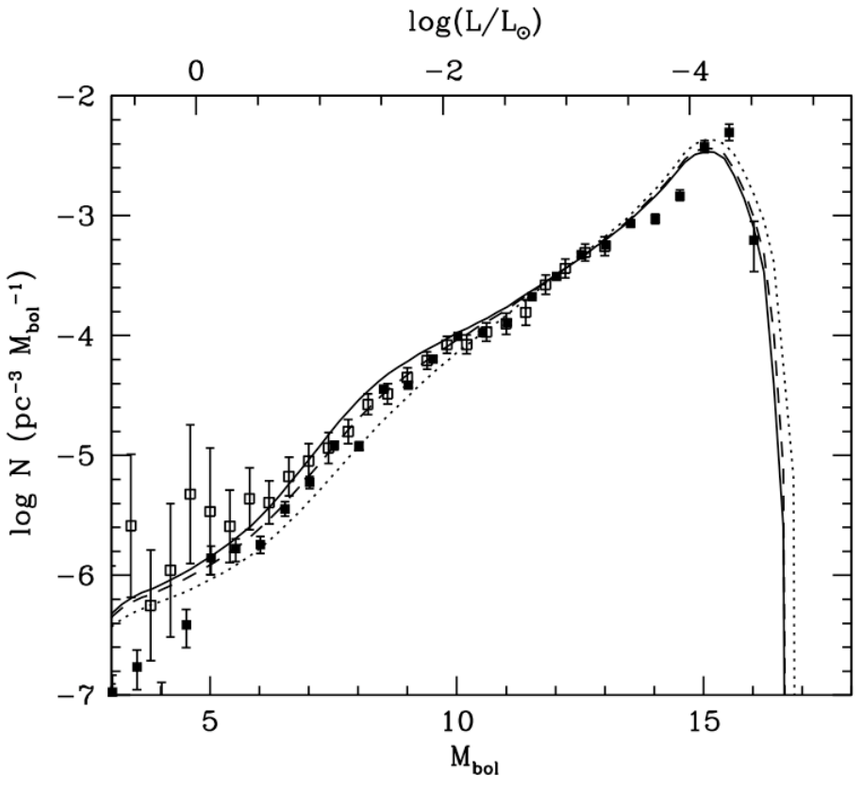
Axion/ALPs: hints from astro puzzles?



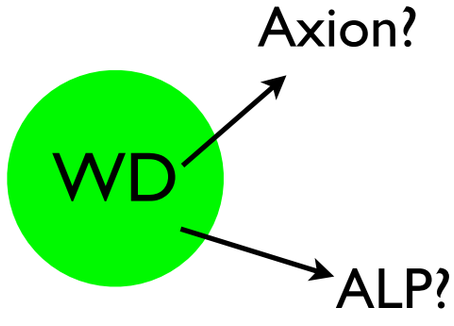
Roncadelli, de Angelis, …

Is universe more transparent than expected to high energy γ-rays?

γ-ALP conversion?



Isern, Garcia–Berro, Torres, Catalan



Do white dwarf stars cool faster than expected?

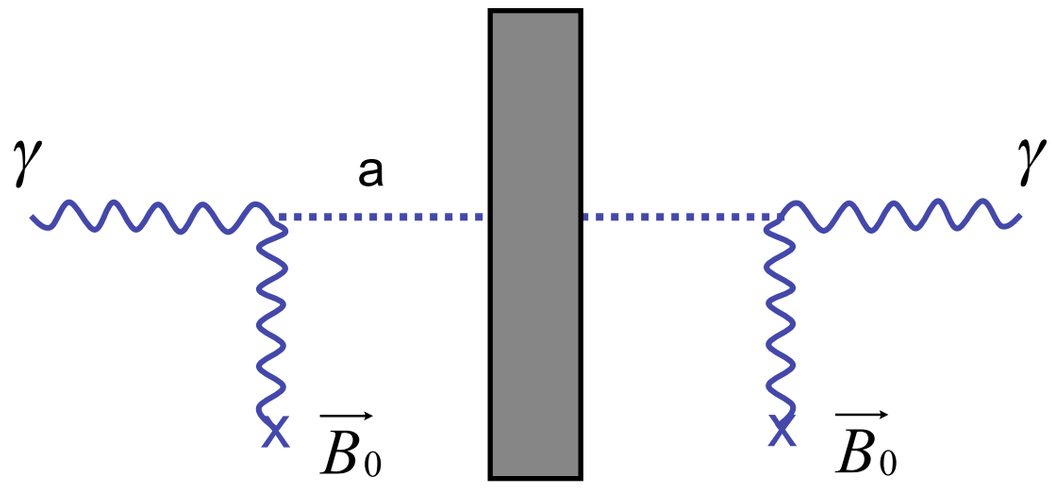
cooling enhanced by axion/ALP radiation?

How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

"Light-shining-through-walls"

Okun; Sikivie; Anselm; van Bibber;



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

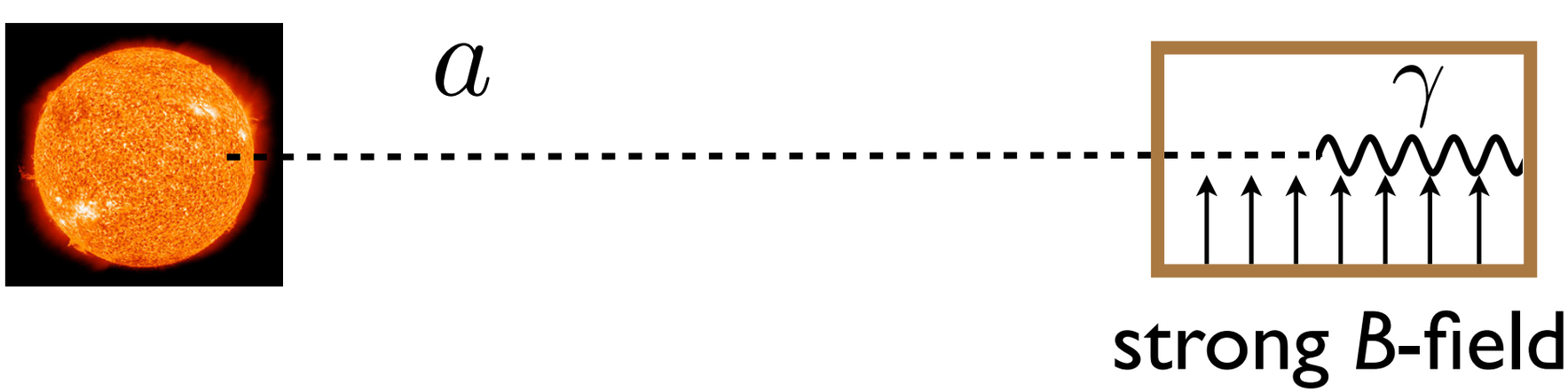
Need large magnets, powerful lasers, optical cavities

How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

Helioscopes: stare at the sun

Sikivie; ….



SHIPS, CAST, SUMICO, IAXO, …

Need large magnets, sensitive detectors

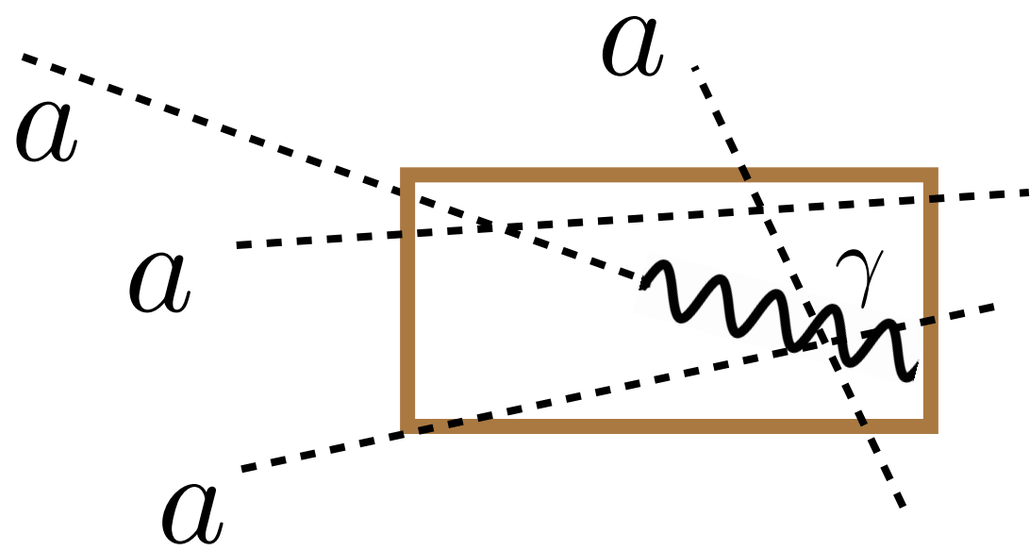
How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

Resonant Cavities with Large Magnetic Field

Sikivie; ….

assume axions are dark matter

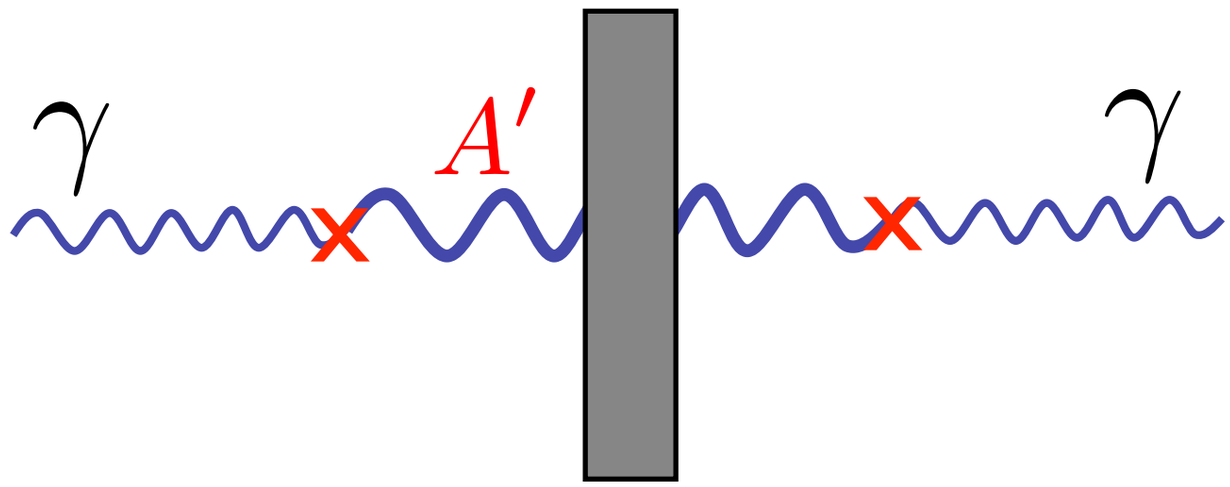


tunable Resonant Cavity

ADMX, ADMX-HF, …

How look for low-mass A′?

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



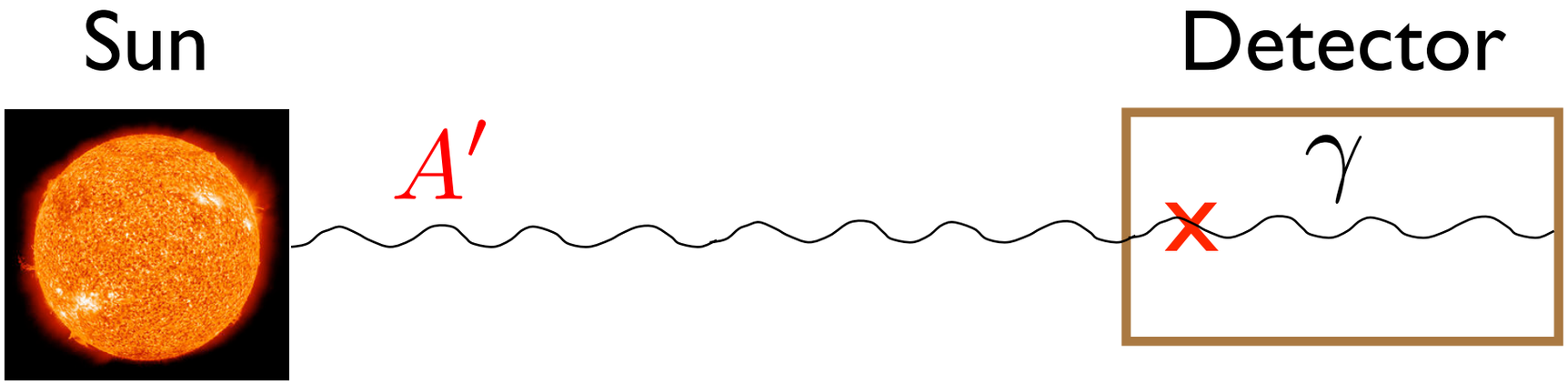
LIPSS (Jlab) , BFRT (BNL), BMV (LULI), GammeV (Fermilab),
ALPS (DESY), OSQAR (CERN), PVLAS (INFN), ...

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:

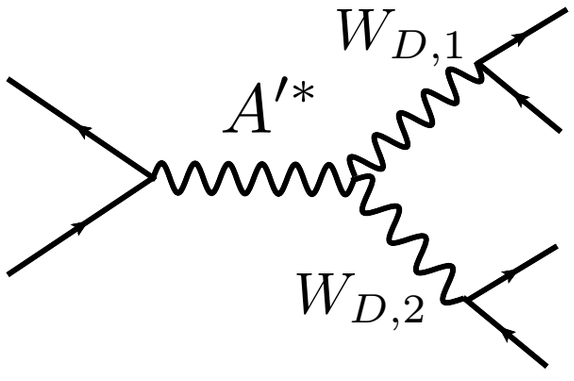
simplest Dark Sector consists of just an A'

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

Example 2: non-Abelian or dark-higgs

Several searches done/ongoing/planned

Examples only:



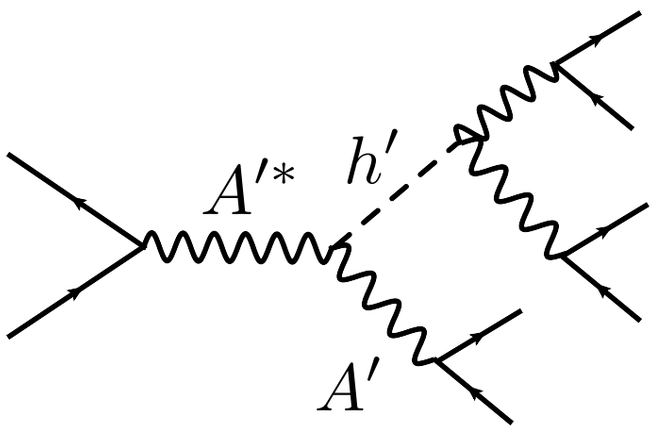
Done

$4e, 4\mu, 2e + 2\mu$

BaBar

[Graham & Roodman]

non-Abelian hidden sectors
(many gauge bosons)



light hidden-sector
Higgs boson

6ℓ Done

arXiv:1202.1313
[Echenard]

2ℓ In progress

Higgs′-strahlung

[Batell, Pospelov,Ritz]