

# The Search for Dark Sectors

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Yang Institute for Theoretical Physics



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# A growing and active field!

summaries:

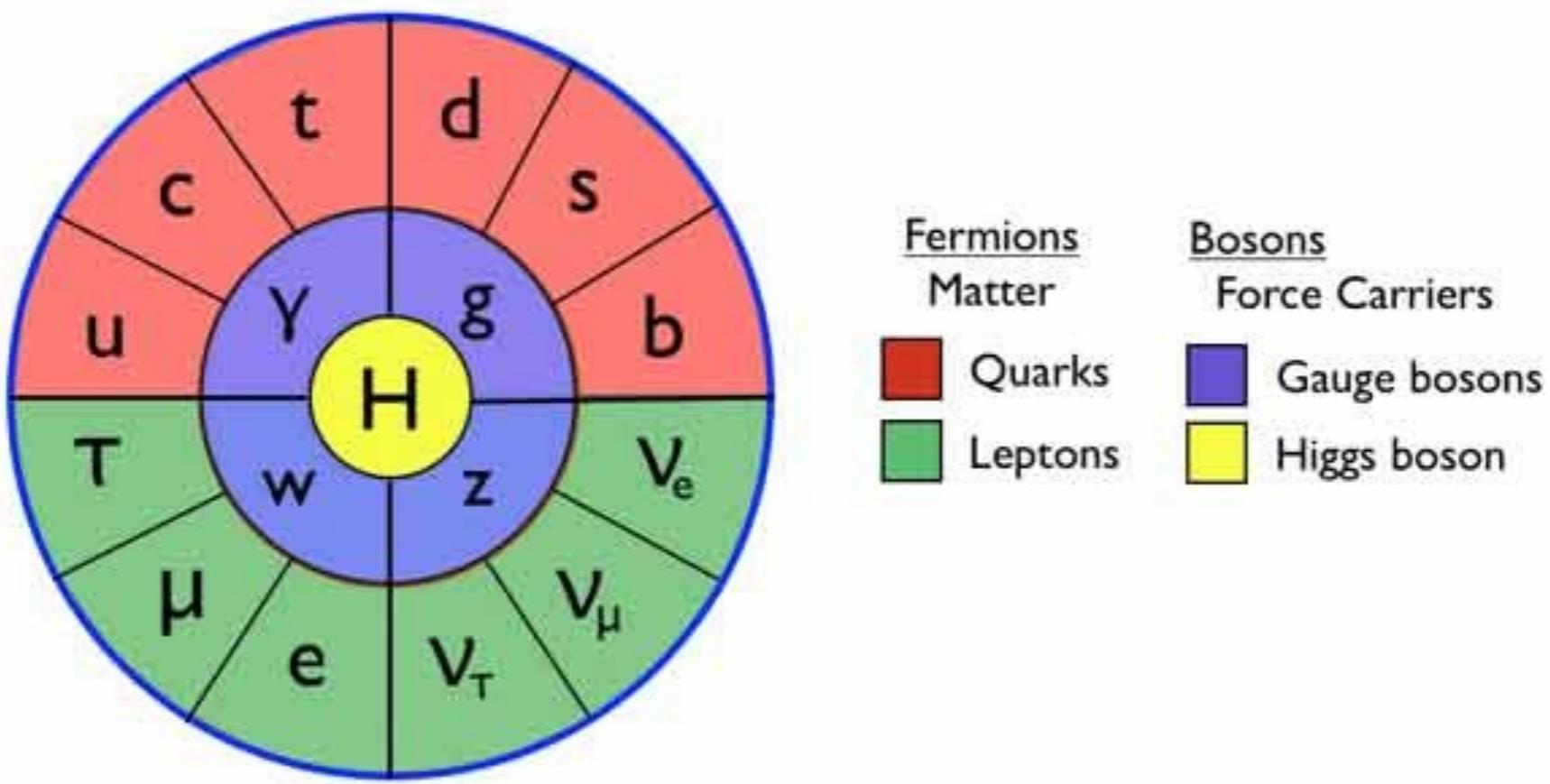
- Low-energy frontier of particle physics 1002.0329
- Fundamental Physics at the Intensity Frontier 1205.2671
- Snowmass 2013 1311.0029
- Dark Sectors 2016 — New! 1608.08632

# Outline

- Introduction
- dark photons (+ dark matter)
- direct detection of  $\text{DM} < 1 \text{ GeV}$

# The Standard Model: a triumph

Murch



but incomplete

# Challenges to the Standard Model

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*Hints from data:*

- gauge coupling unification
- DM self-interactions
- various anomalies (muon g-2, ν,  
astro...)

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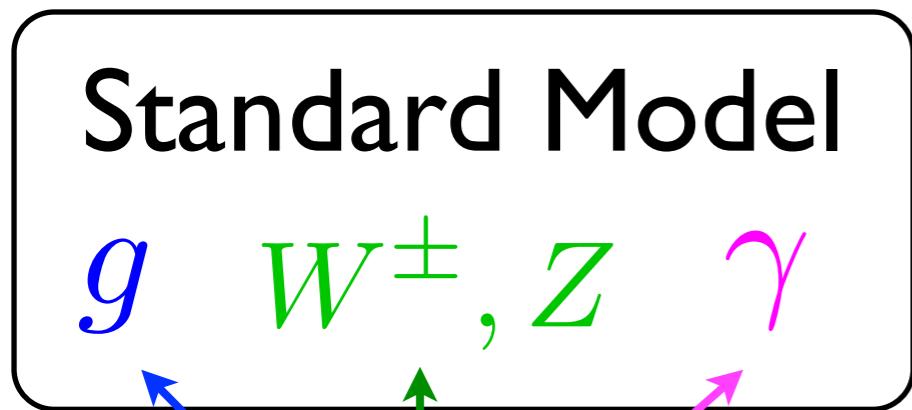
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  - neutral under SM forces
  - can evade constraints from standard searches;  
need high-precision experiments and/or intense beams

# Where search for new physics?

- At Weak scale?
  - LHC, DM direct & indirect detection...
- Above Weak scale?
  - e.g. cosmic-ray detectors; or probe indirectly...
- Below Weak scale?
  - neutral under SM forces → **a dark sector!**
  - can evade constraints from standard searches;  
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# Dark Sectors

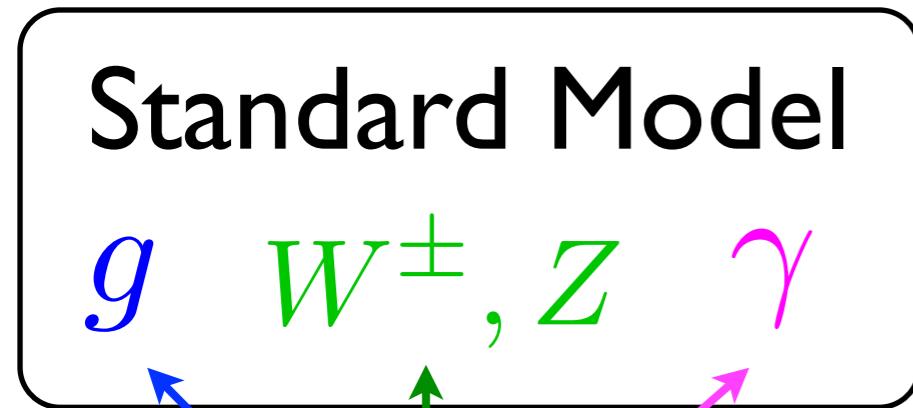
particles not charged directly under the known  
**Strong, Weak, or Electromagnetic forces**



Known Forces  
**strong, weak, EM**

# Dark Sectors

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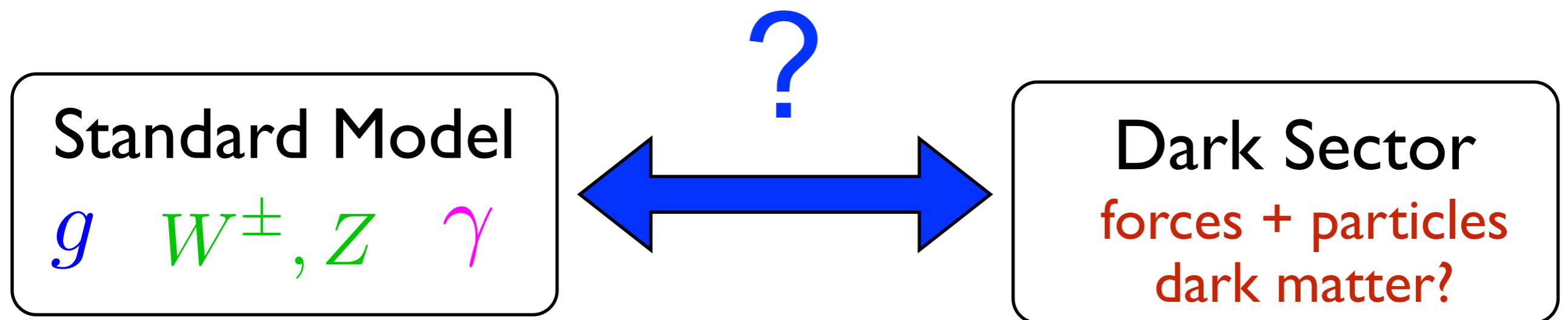
Known Forces

**strong, weak, EM**

Dark Sector  
**forces + particles  
dark matter?**

could have rich,  
intricate structure

# Portals?



Not “anything goes”!

Standard Model symmetries dictate  
most important interactions

# Portals

- “Vector”

$$\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$$

dark photon  $\mathbf{A}'$

- “Higgs”

$$\lambda H^2 S^2 + \mu H^2 S$$

exotic Higgs decays

...

- “Neutrino”

$$\kappa (HL) \mathbf{N}$$

sterile neutrinos

- “Axion”

$$\frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \mathbf{a}$$

axions & axion-like particles (ALPs)

# Challenges possibly addressed by dark sectors

*Strong evidence  
for new physics:*

- ✓ dark matter
- ✓ baryon asymmetry
- ✓ neutrino masses

*Deep theoretical  
problems:*

- Higgs hierarchy problem
- ✓ strong CP problem

*Hints from data:*

- gauge coupling unification
- ✓ DM self-interactions
- ✓ various anomalies (muon g-2, ν,  
astro...)

# For remaining talk, focus on:

- “Vector”

$$\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$$

dark photon  $A'$

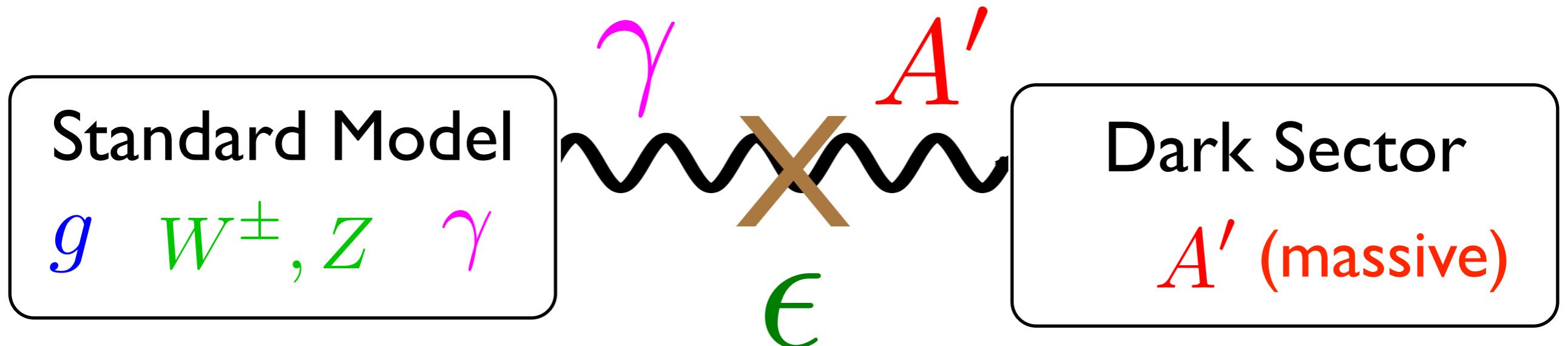
and on MeV-GeV masses\*

many probes

several important experimental targets

\*other mass ranges interesting too!

# Dark Photons

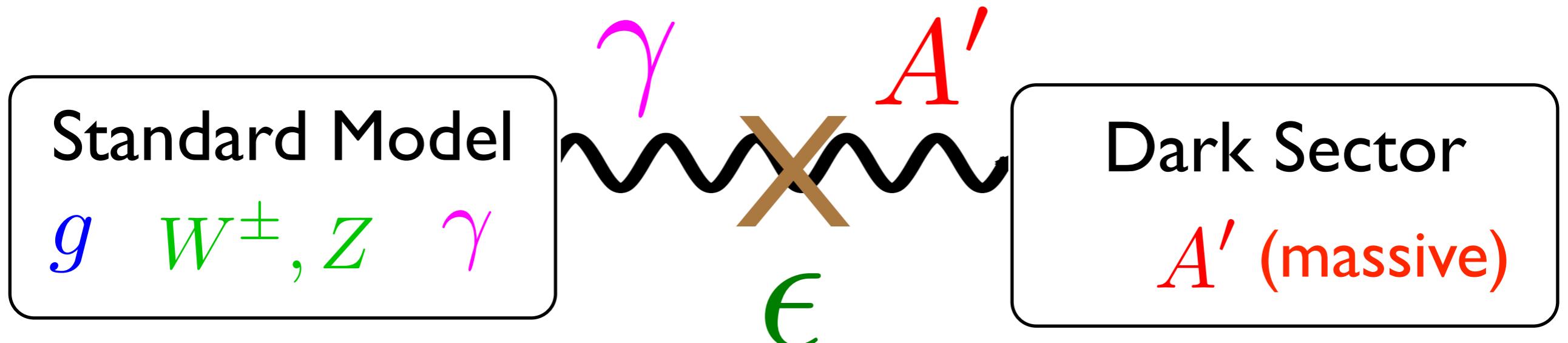


$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

“Kinetic Mixing”

Holdom  
Galison, Manohar

# Dark Photons



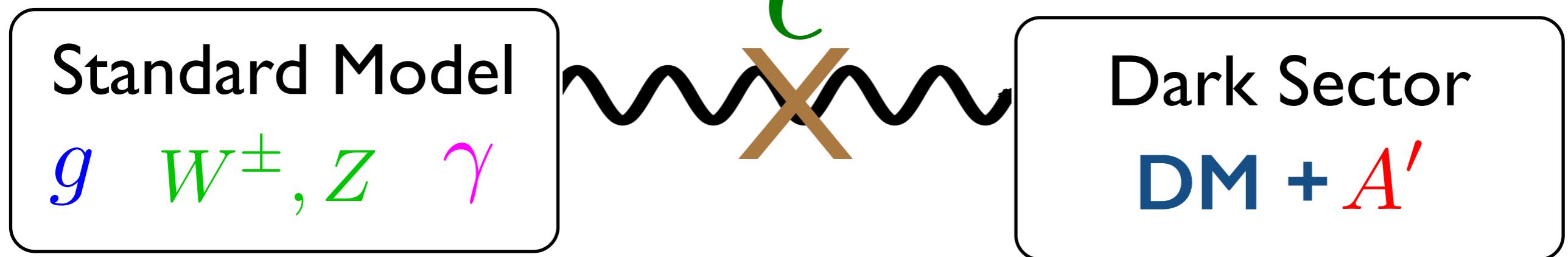
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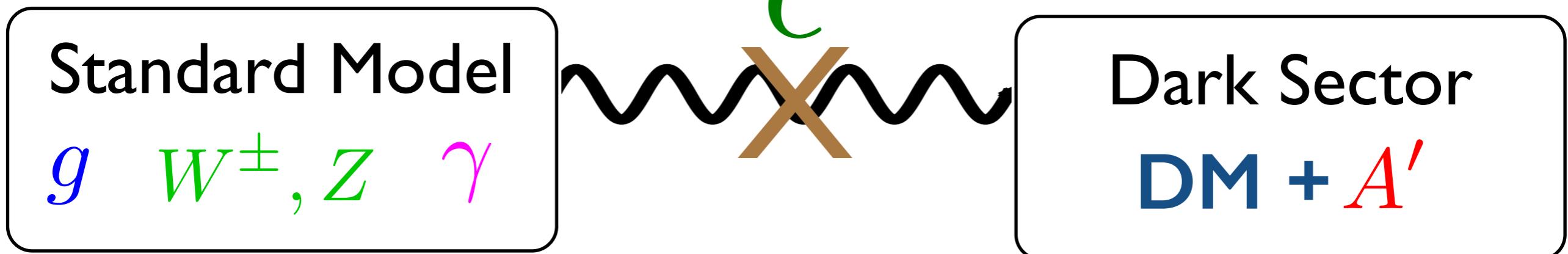
*simplest* dark sector consists of just an  $A'$

# Dark Matter & Dark Photons



allows for simple, viable models of sub-GeV DM  
(of course, many other possibilities exist!)

# Dark Matter & Dark Photons

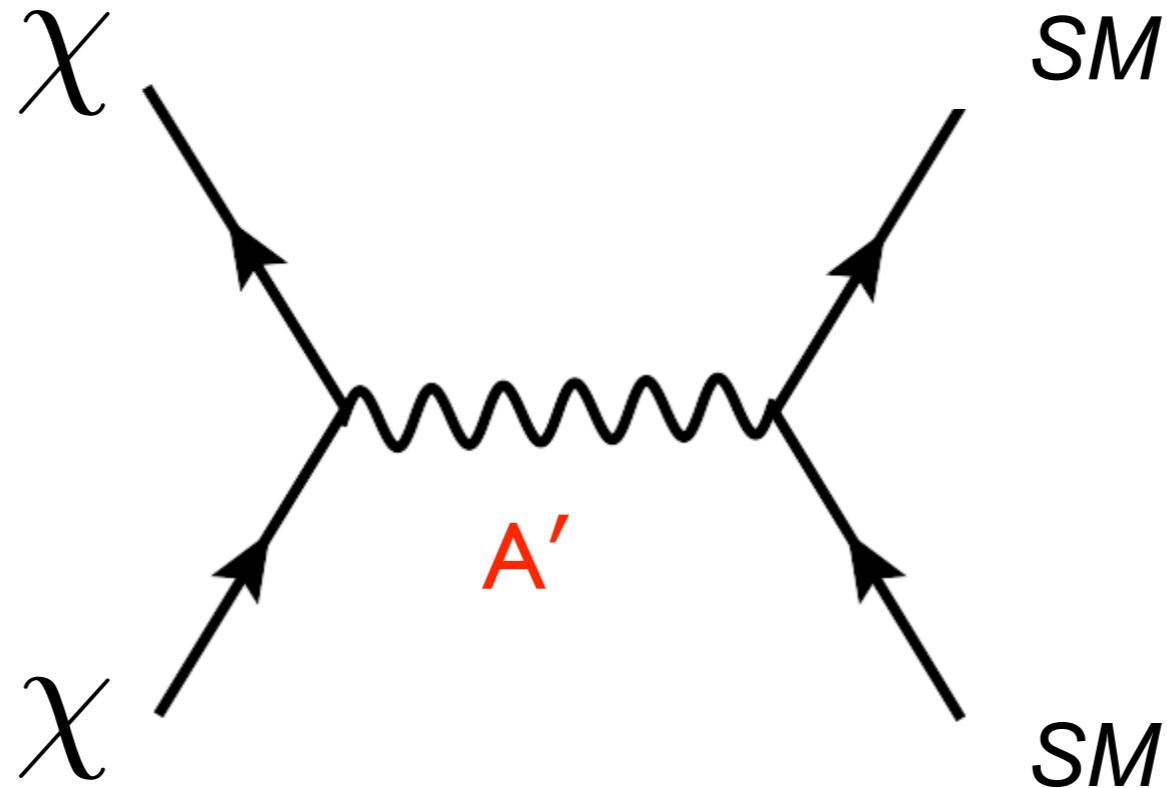


allows for simple, viable models of sub-GeV DM  
(of course, many other possibilities exist!)

very rich  
phenomenology

- direct detection
- fixed-target
- colliders
- indirect detection

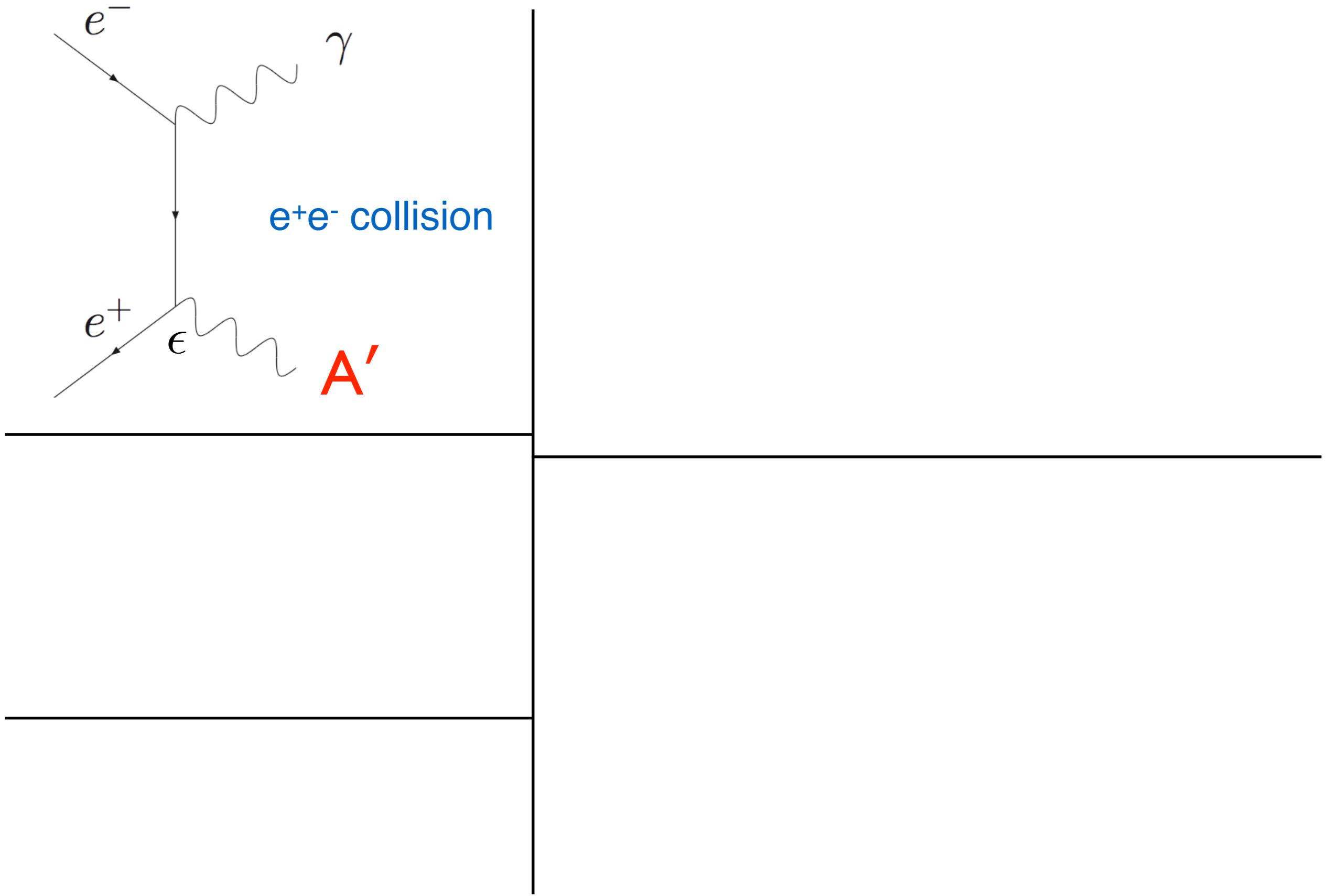
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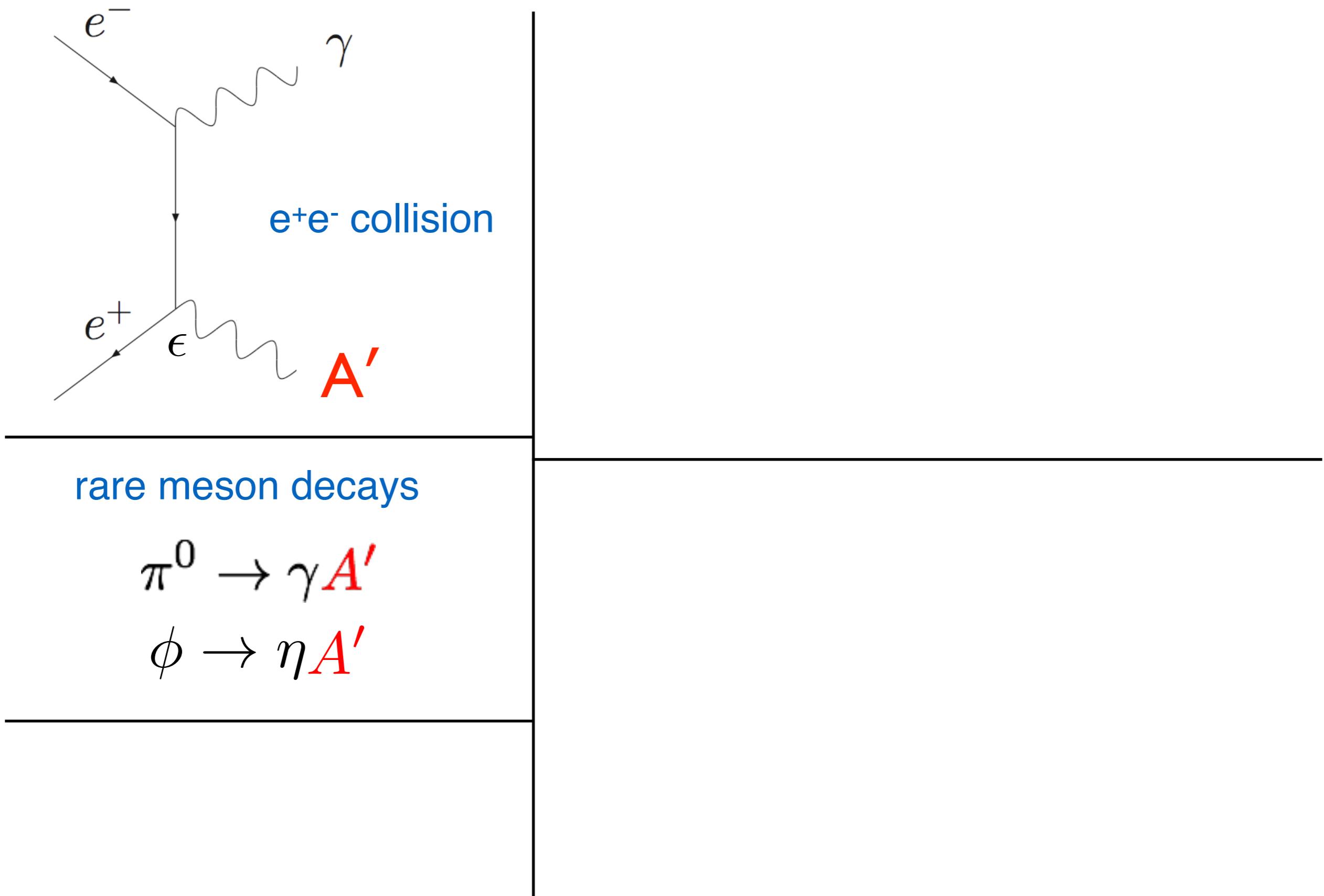
can obtain observed relic abundance via freeze-out,  
freeze-in, or assume an initial asymmetry

+ can have sufficient DM self-interactions

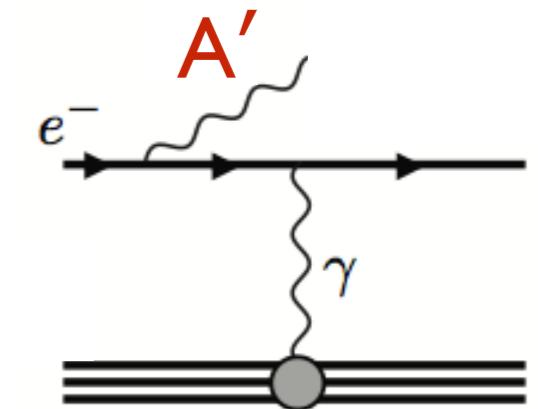
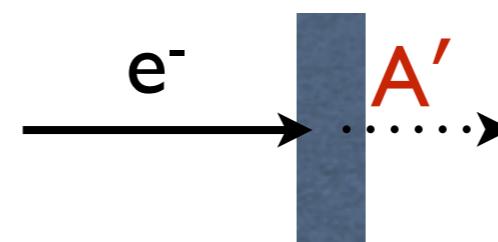
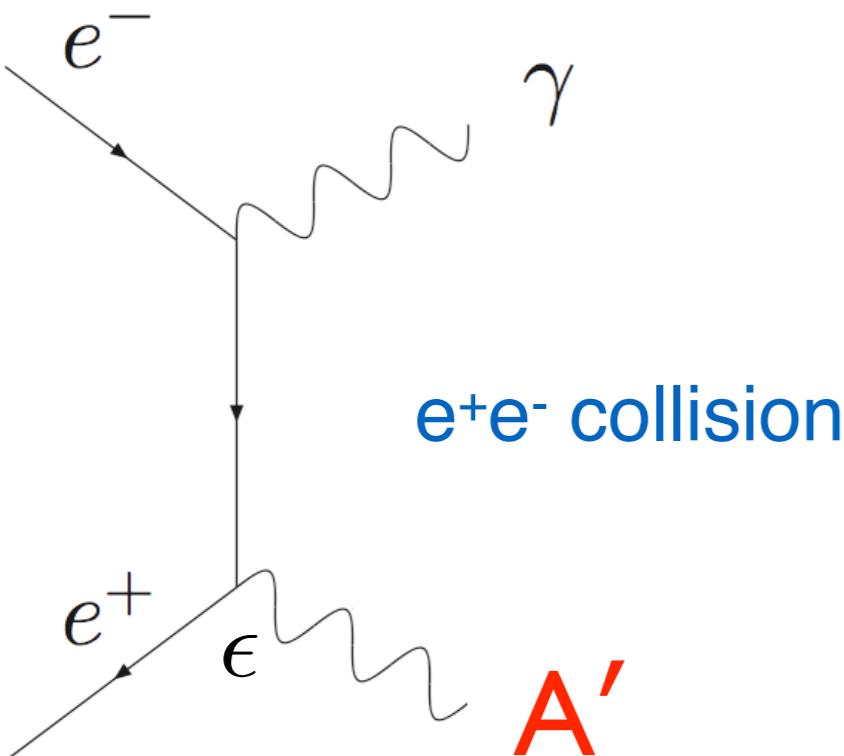
# Examples of A' Production



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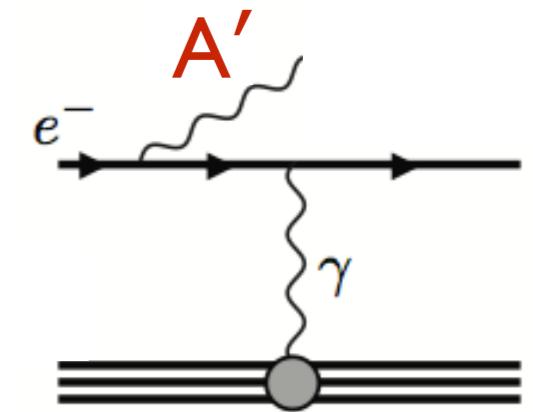
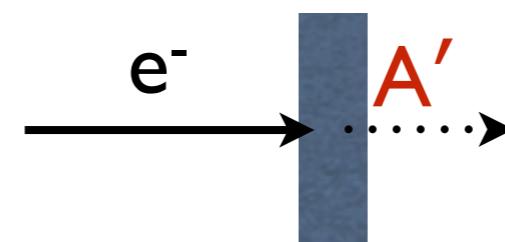
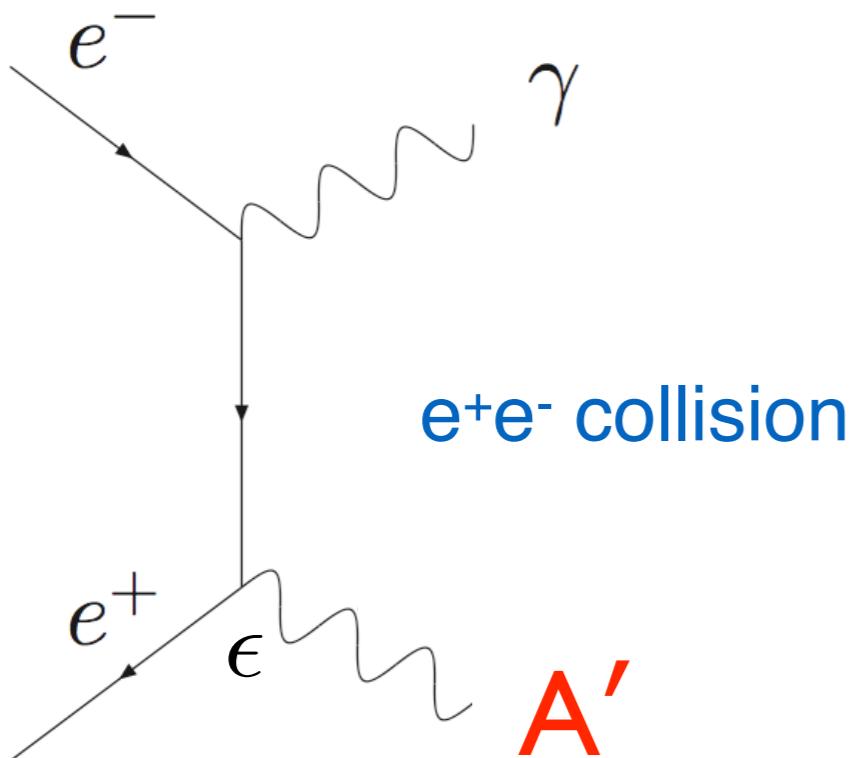


rare meson decays

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

$$\phi \rightarrow \eta A'$$

# Examples of A' Production



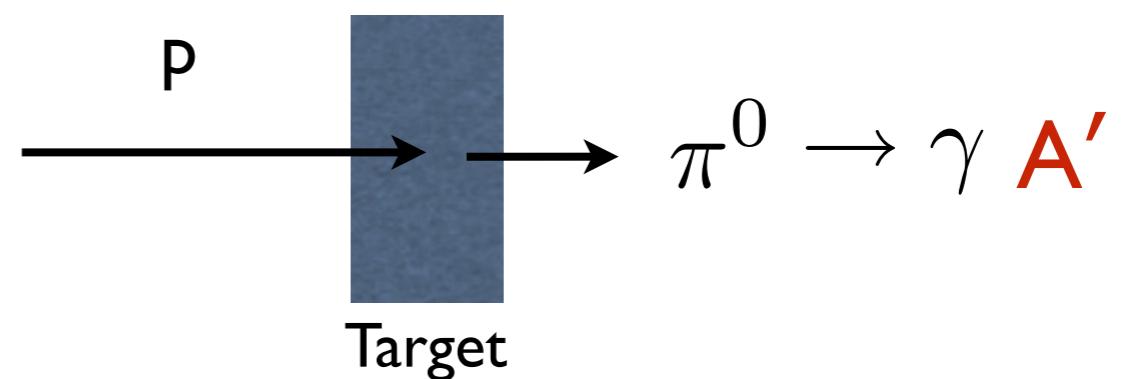
Target

electron-beam fixed target

rare meson decays

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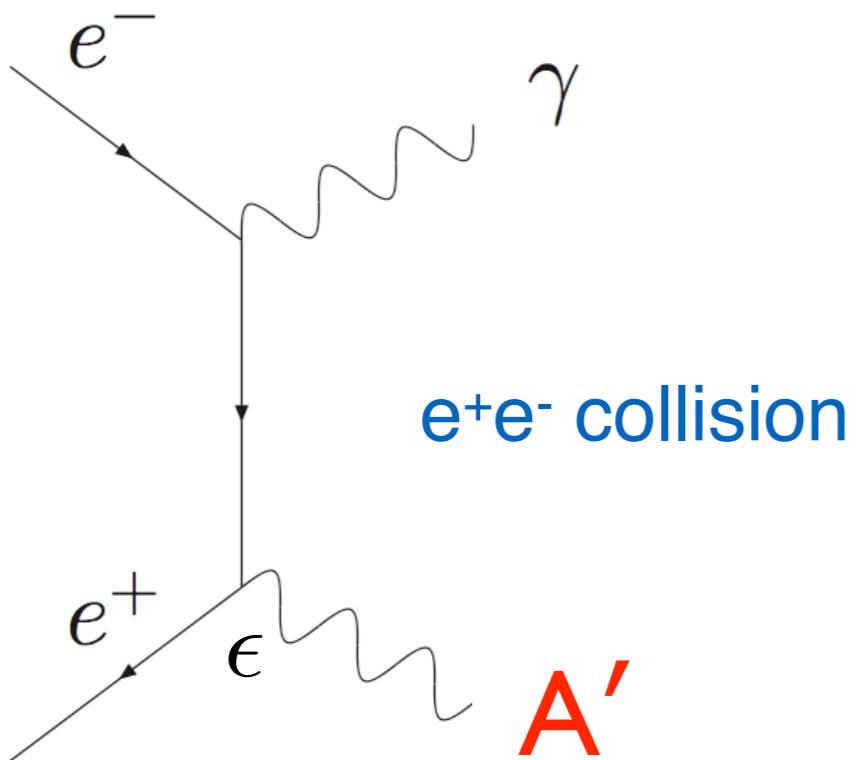
$$\phi \rightarrow \eta A'$$



Target

proton-beam fixed target

# Examples of A' Production



$e^+e^-$  collision

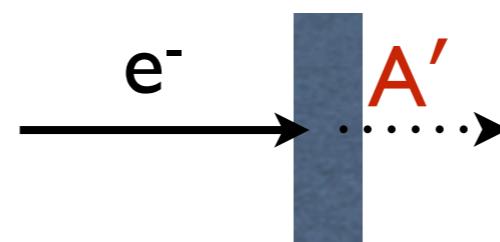
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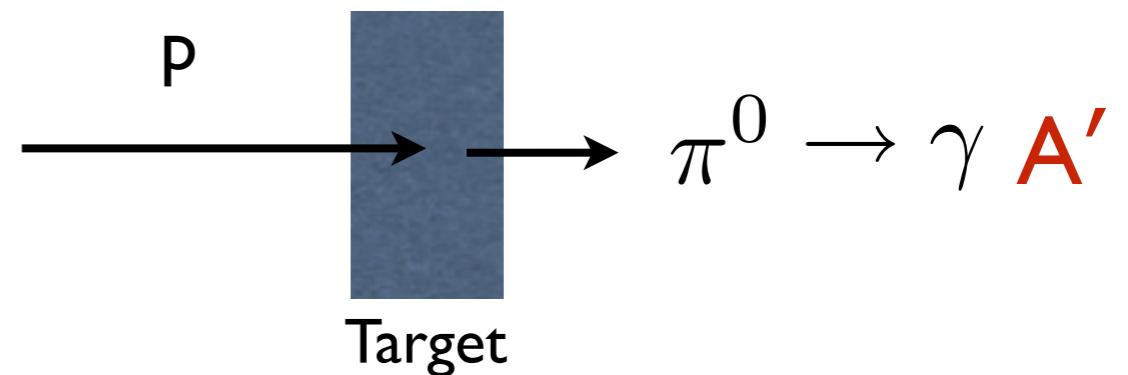
rare Higgs decays at LHC

$$h \rightarrow Z A'$$



Target

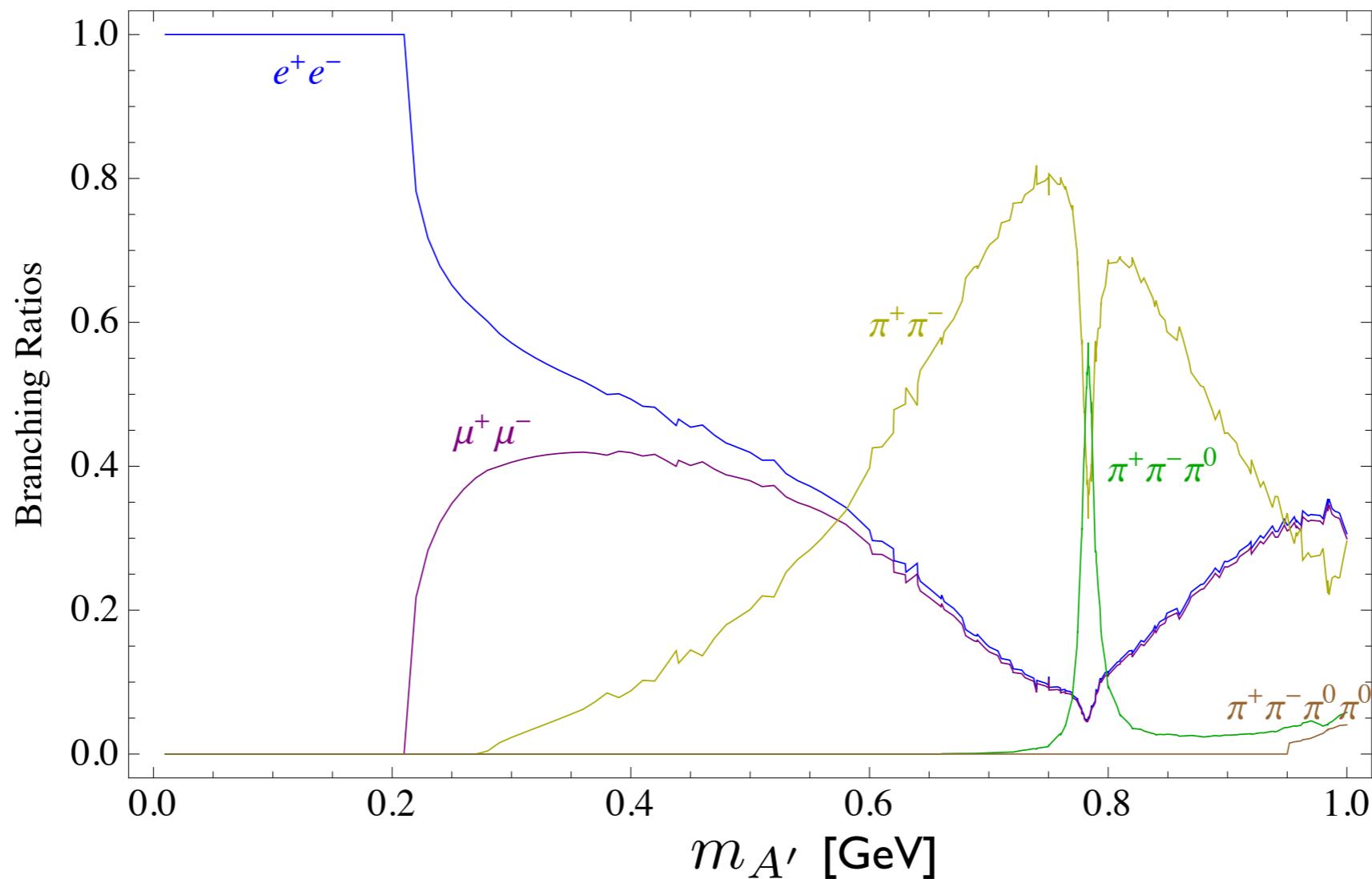
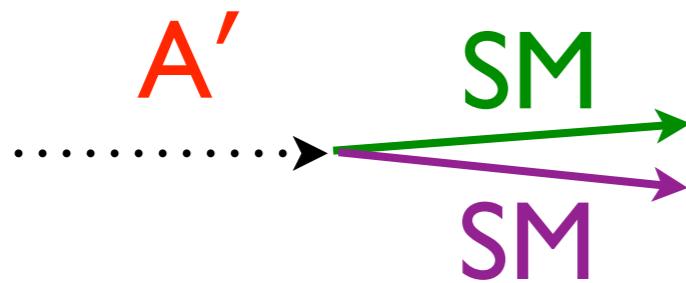
electron-beam fixed target



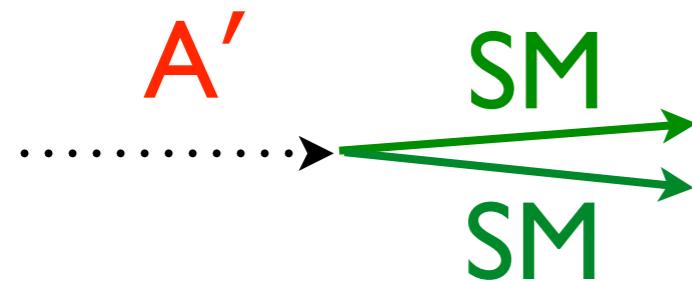
Target

proton-beam fixed target

# “visible” A' decays

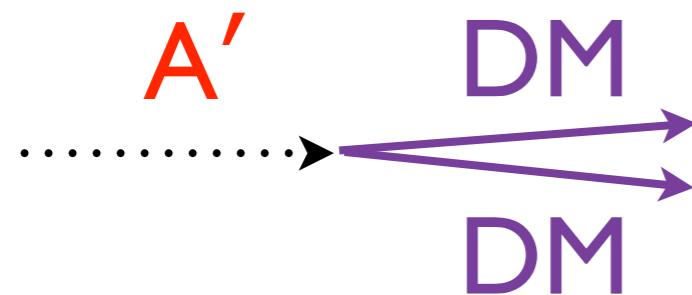


# “visible” $A'$ decays



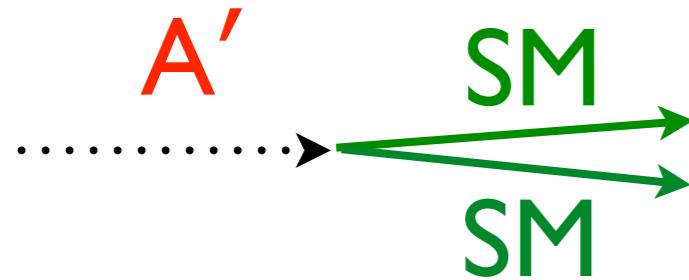
detect e.g.  $e^+e^-$  pairs

# “invisible” $A'$ decays



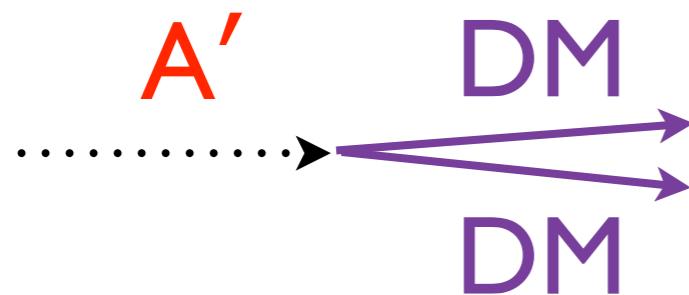
1. “missing mass/momenta”
2. DM can re-scatter in a detector down-stream

# “visible” $A'$ decays



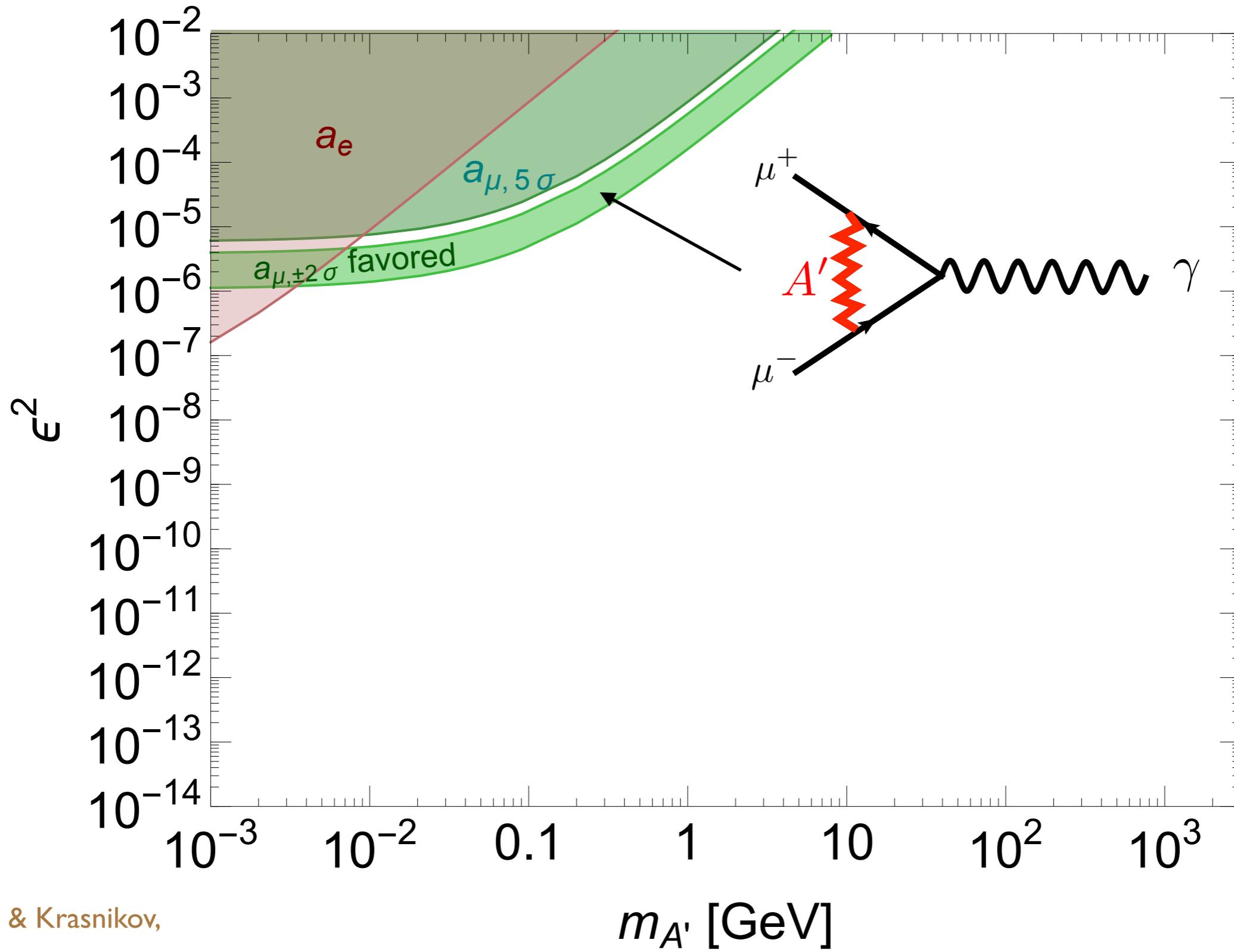
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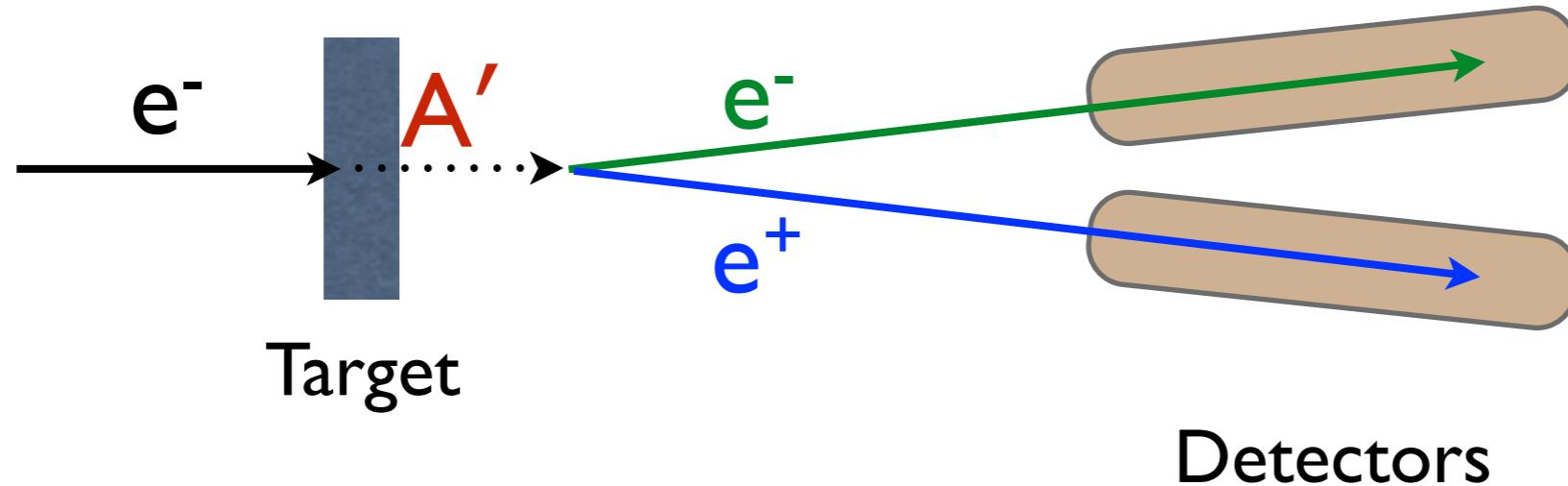
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# A' Status 2008



# Electron-Beam Fixed-Target Experiments

Bjorken, RE, Schuster, Toro (2009)

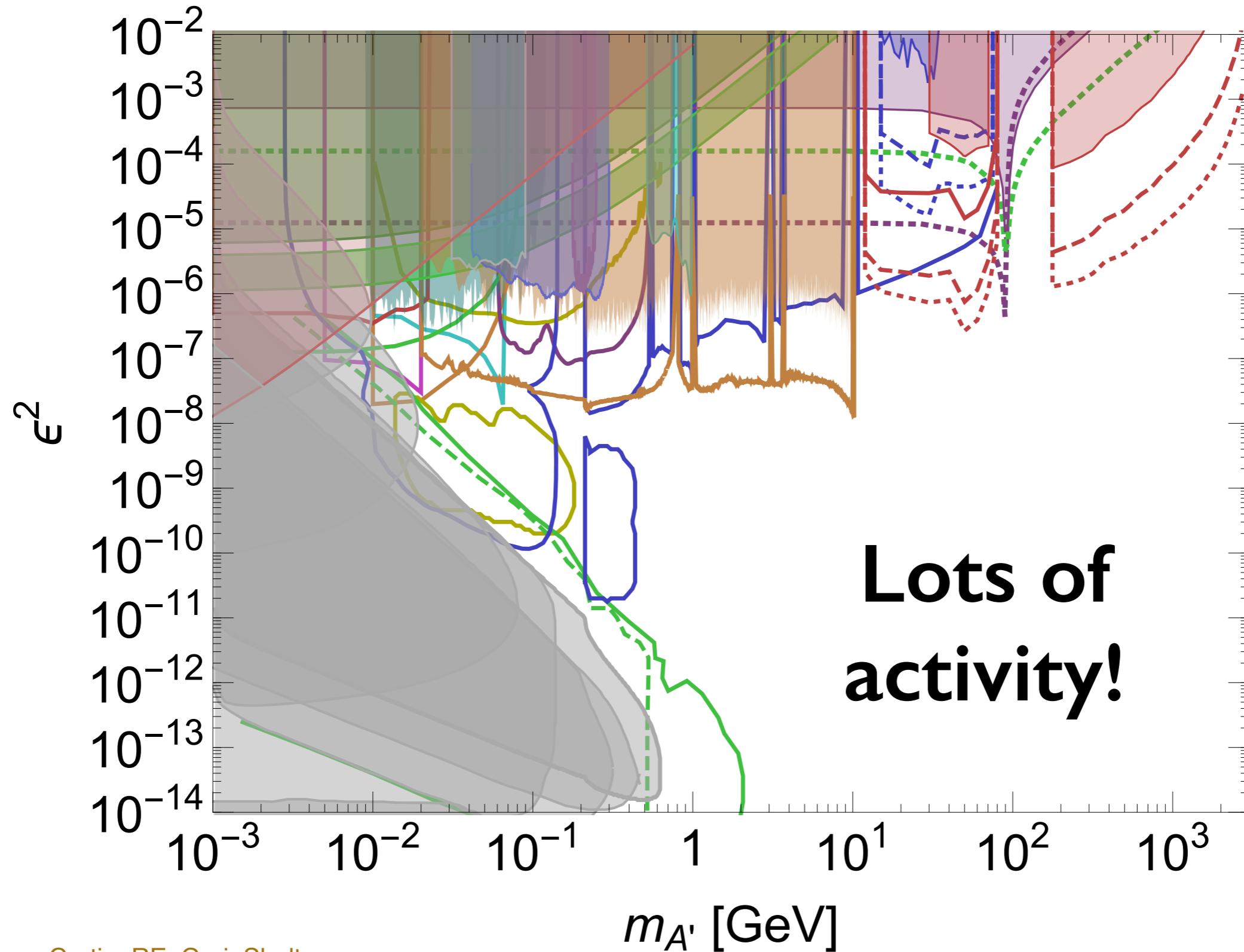


look for  $A' \rightarrow e^+e^-$   
resonance (“bump hunt”) or displaced vertex

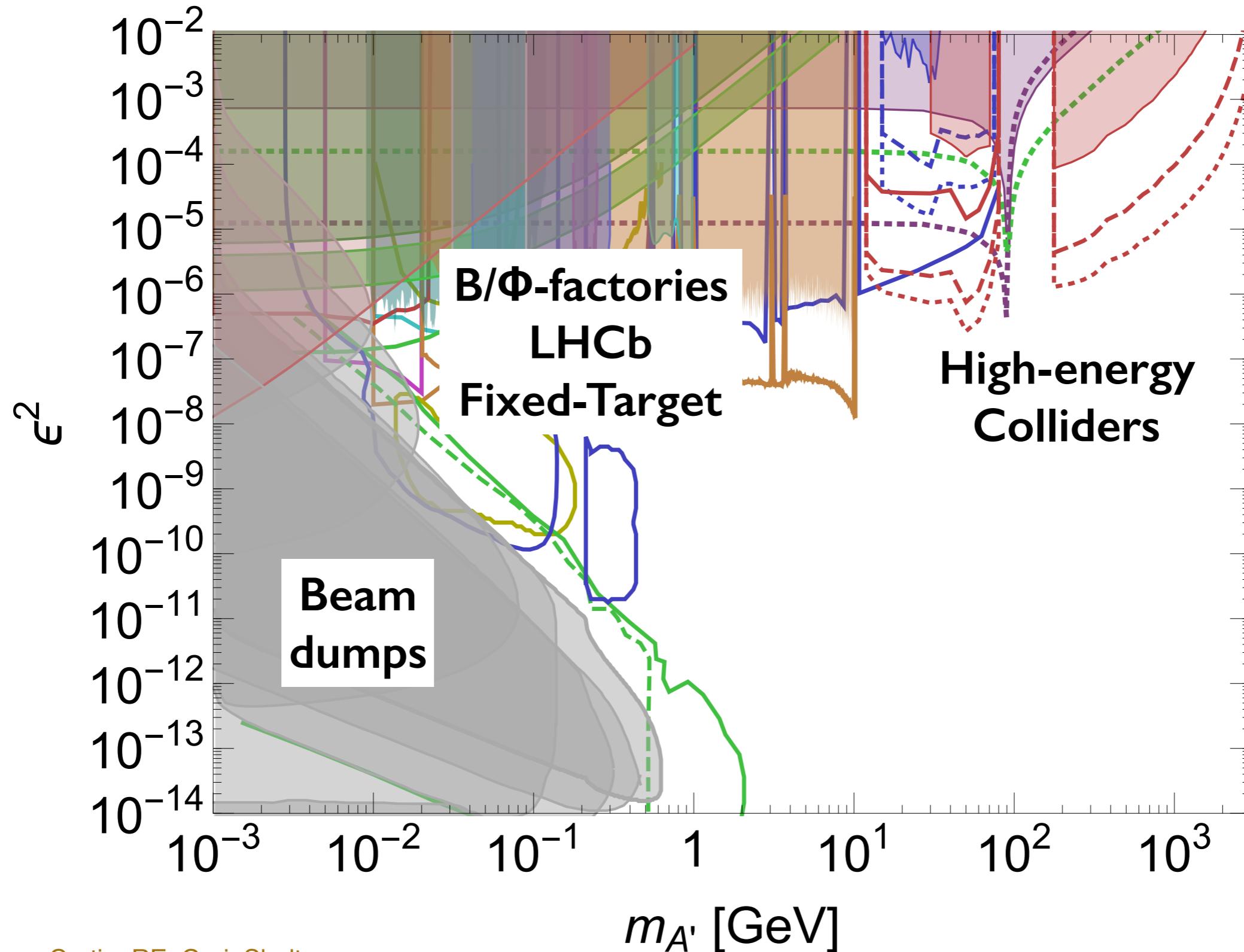
various (beam dump) constraints & new strategies

+ plenty of other searches and new analyses since then

# visible A' Status Today

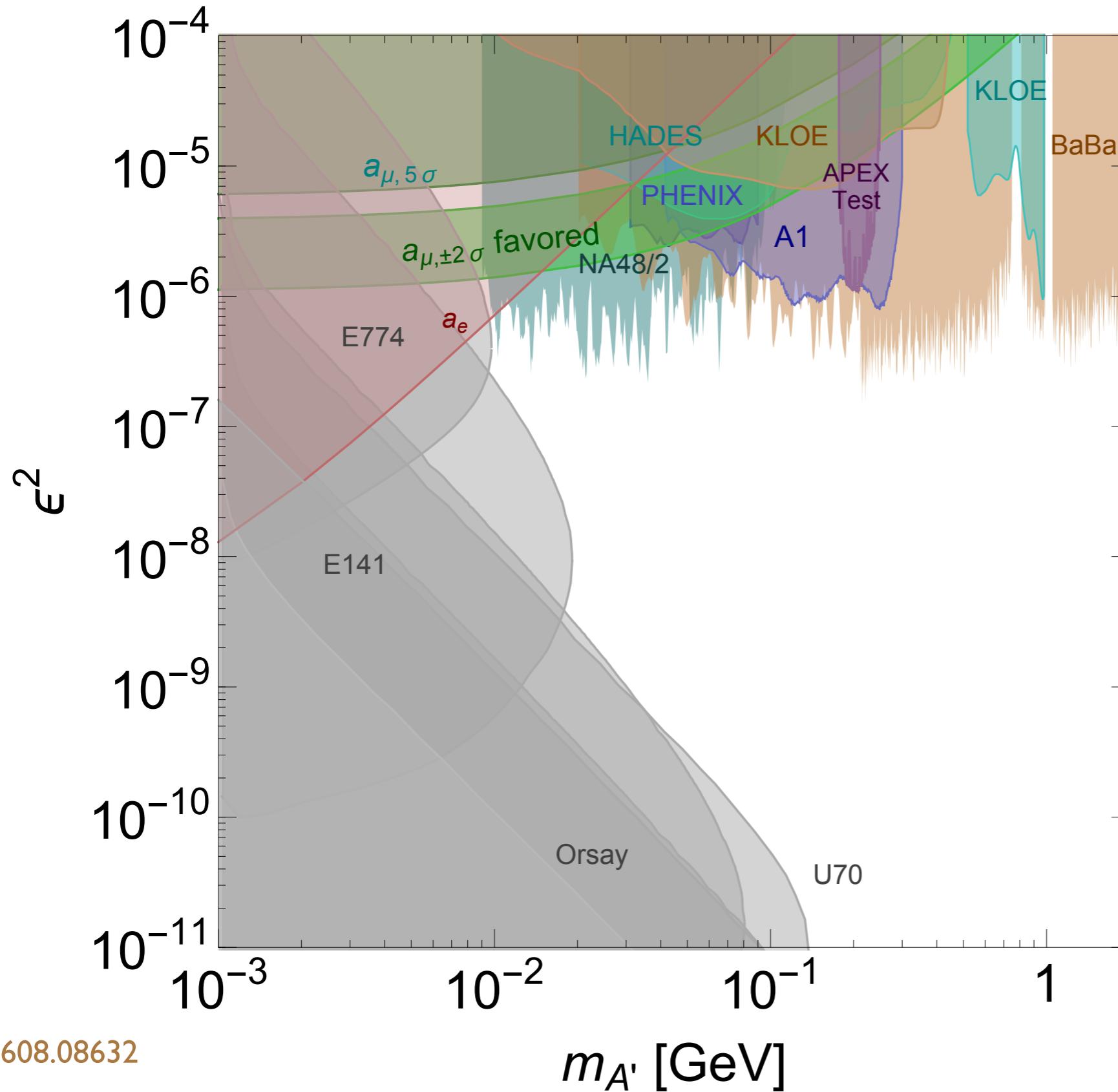


# visible A' Status Today

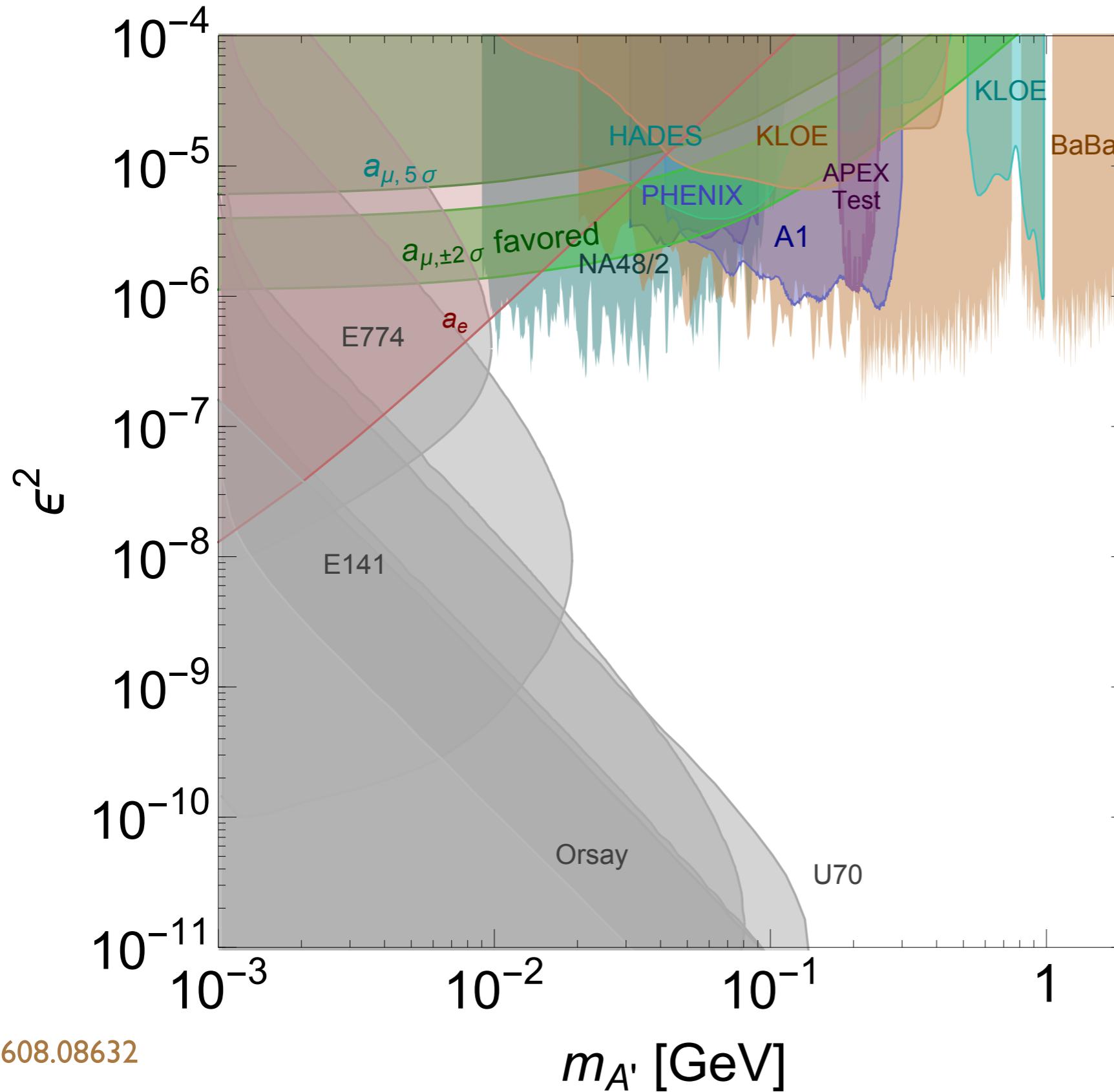


adapted from Curtin, RE, Gori, Shelton

# visible A' Status Today: MeV-GeV

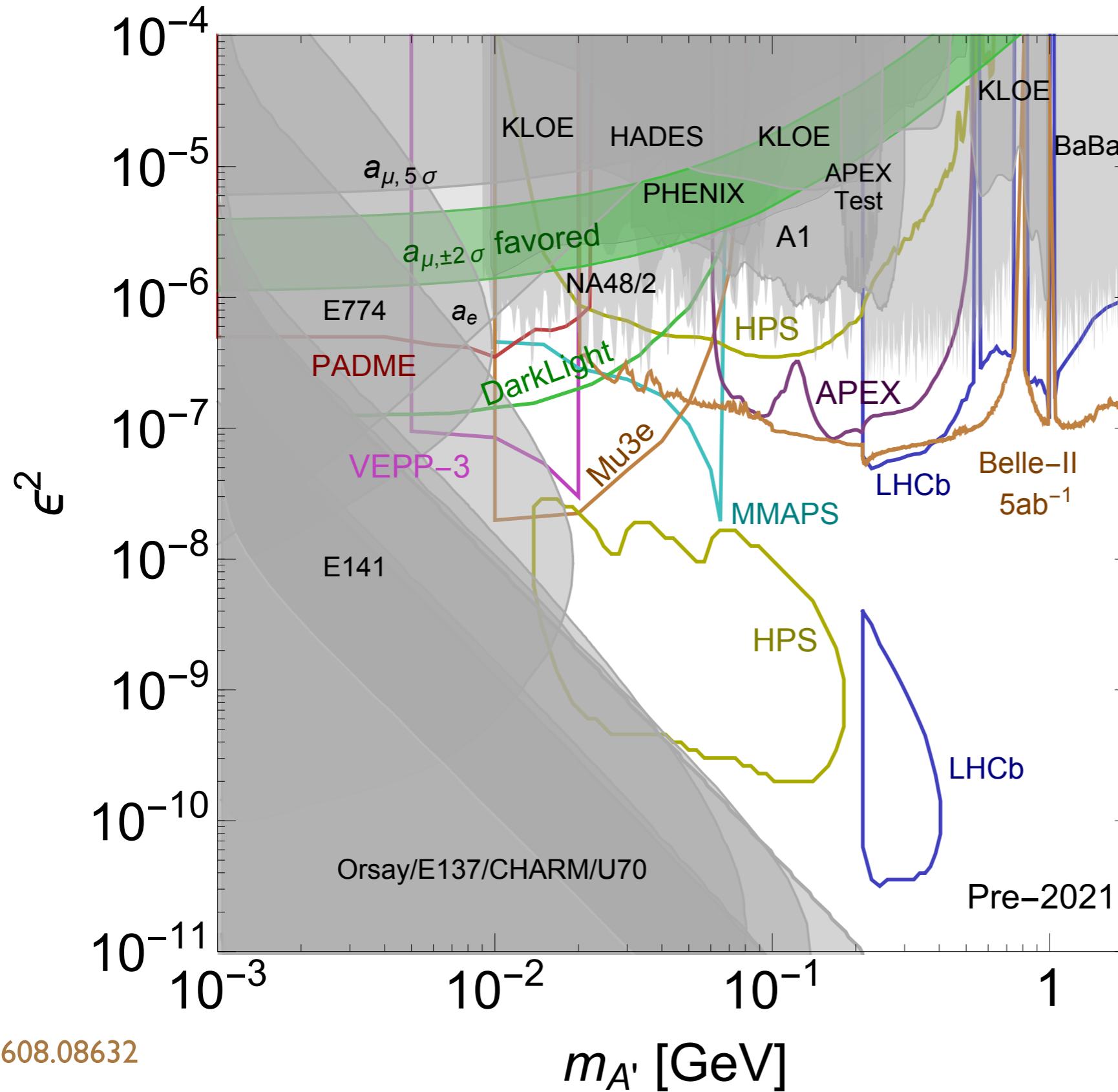


# visible A' Status Today: MeV-GeV



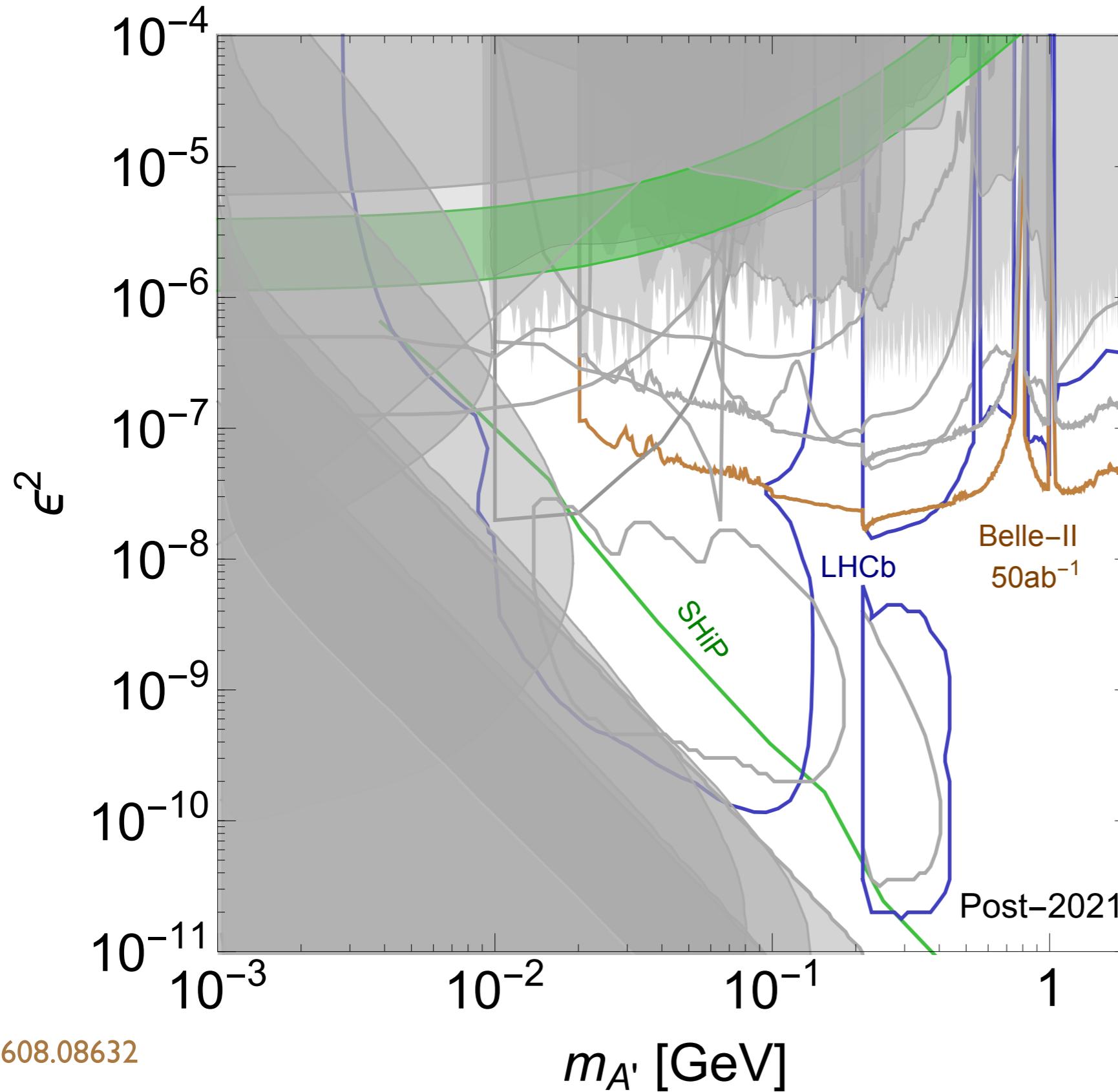
muon g-2 region  
disfavored, for A'  
decaying 100% to  
Standard Model

# visible A' Status Today: MeV-GeV



prospects in  
next 5 years  
(<2021)

# visible A' Status Today: MeV-GeV

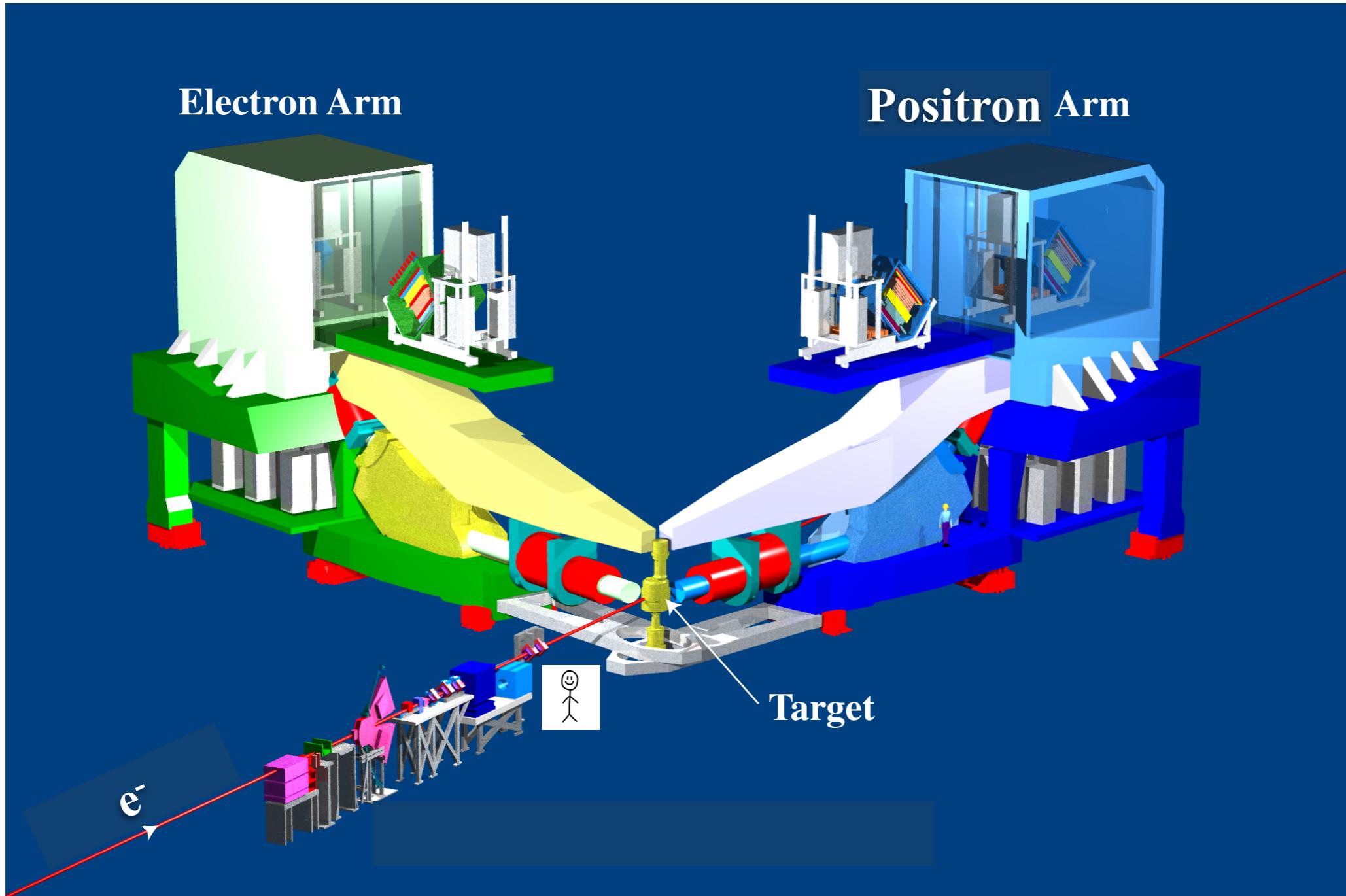


prospects beyond  
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# The A' Experiment & Heavy Photon Search (APEX & HPS)

@ Jefferson Lab, Virginia, USA

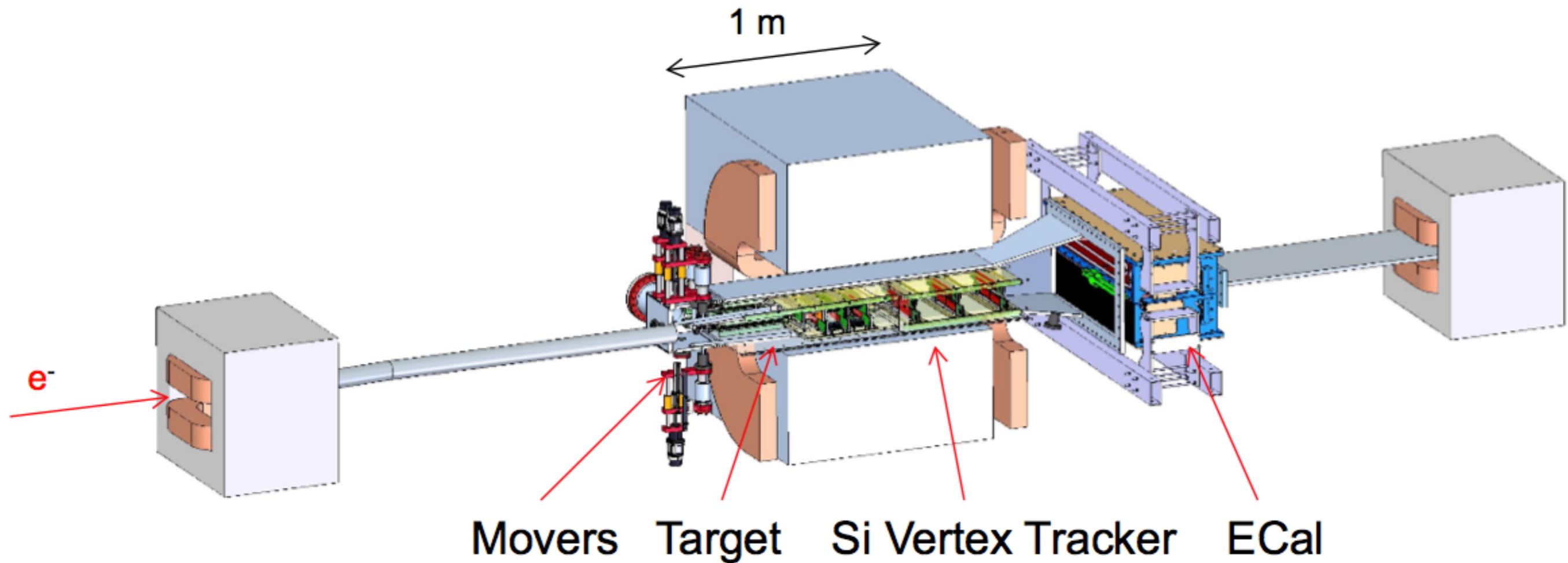
# APEX Experimental Setup\*



mostly existing equipment  
bump hunt

\*septum magnet not shown

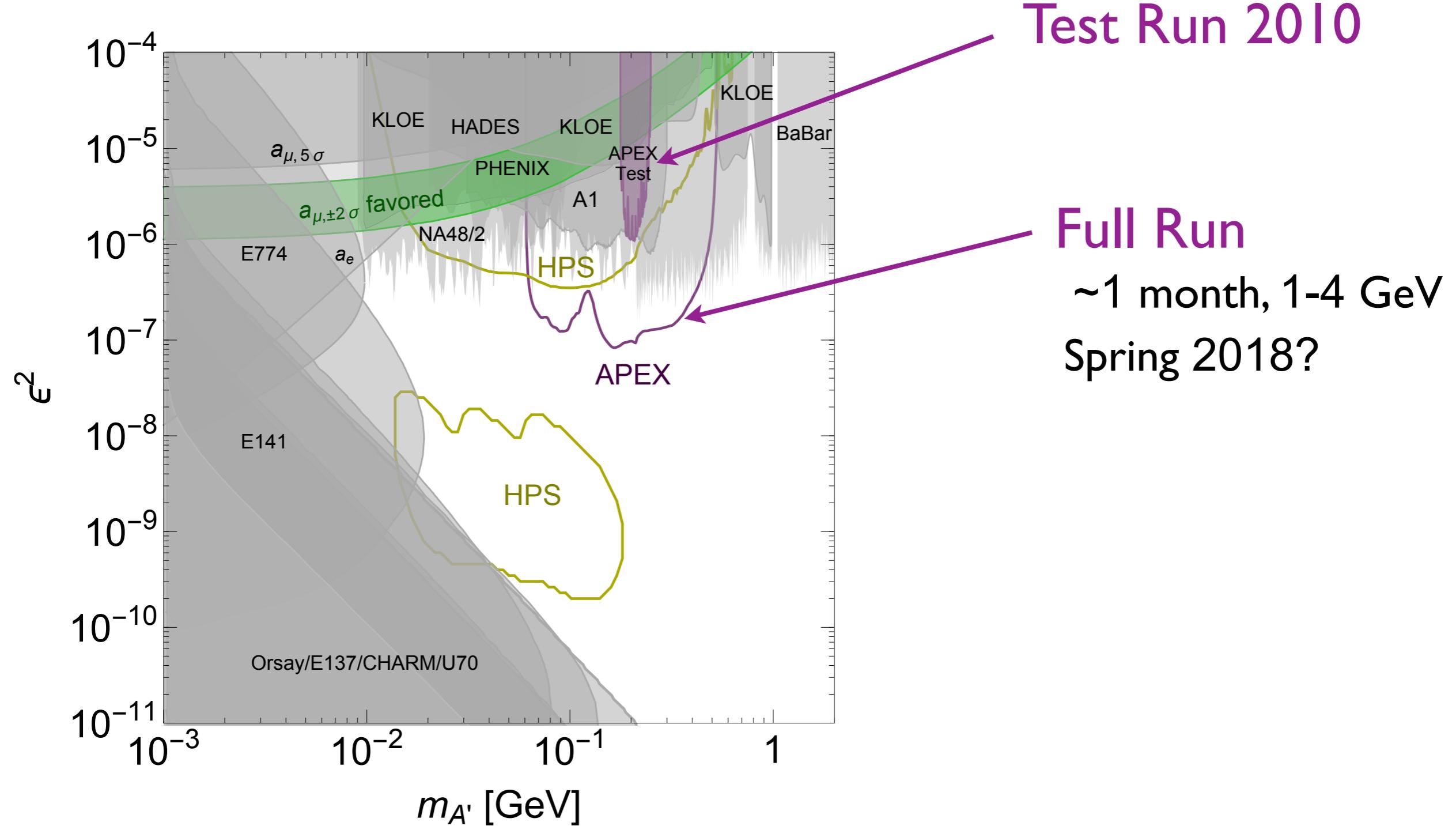
# HPS Experimental Setup



dedicated equipment

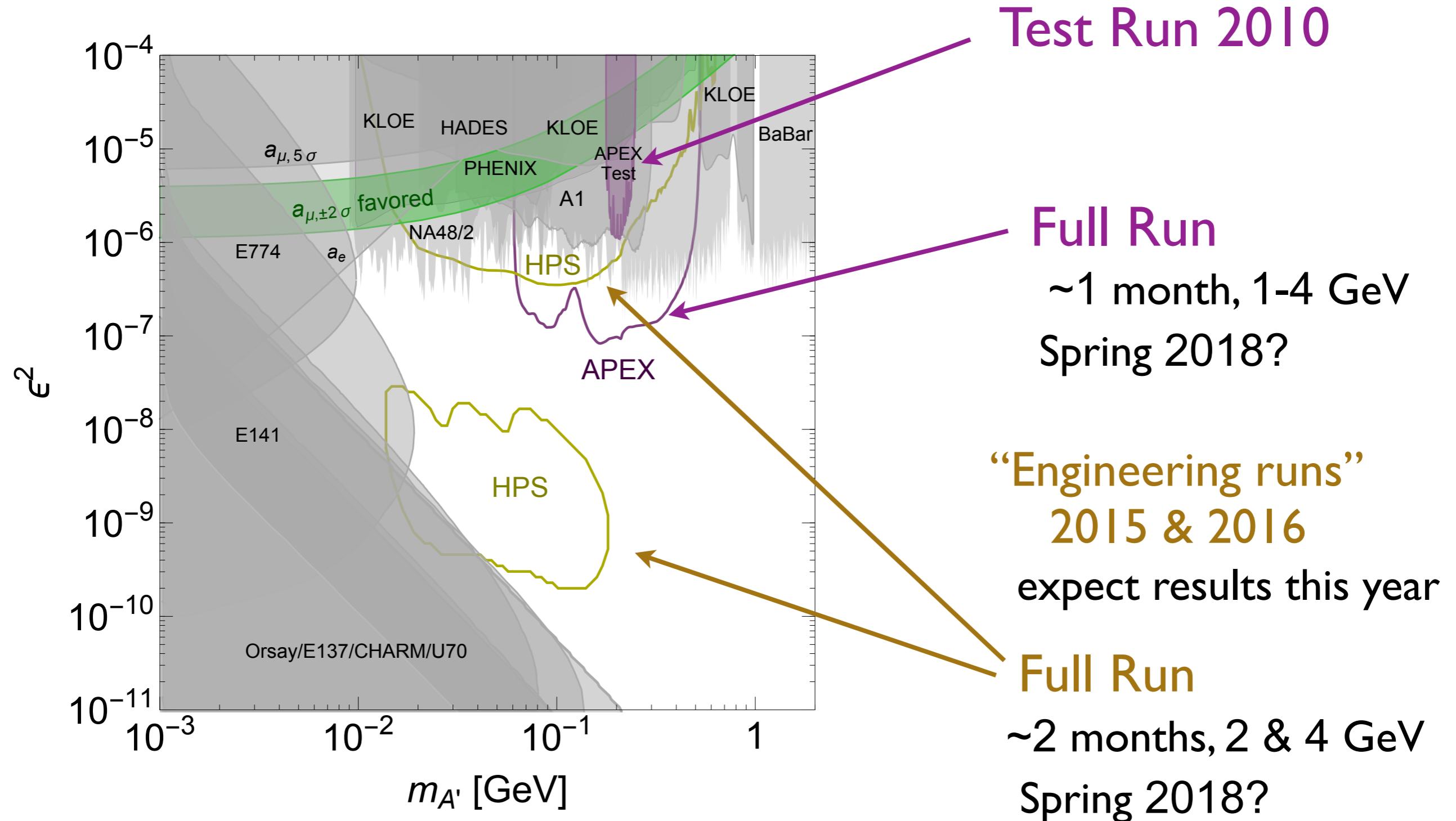
bump hunt + displaced vertex

# APEX



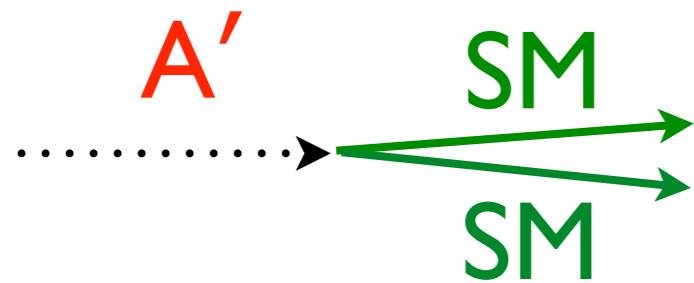
spokespeople: RE, Schuster, Toro, Wojtsekhowski (APEX);  
Holtrop, Jaros, Stepanyan (HPS)

# APEX and HPS



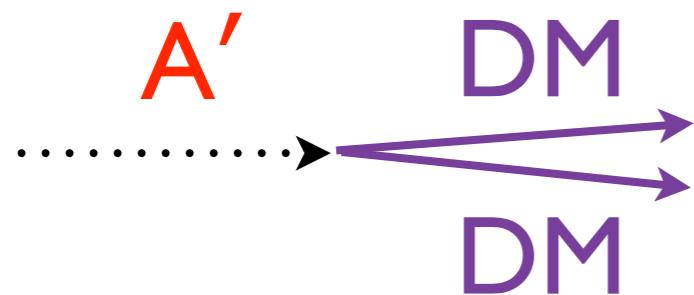
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# “visible” A' decays



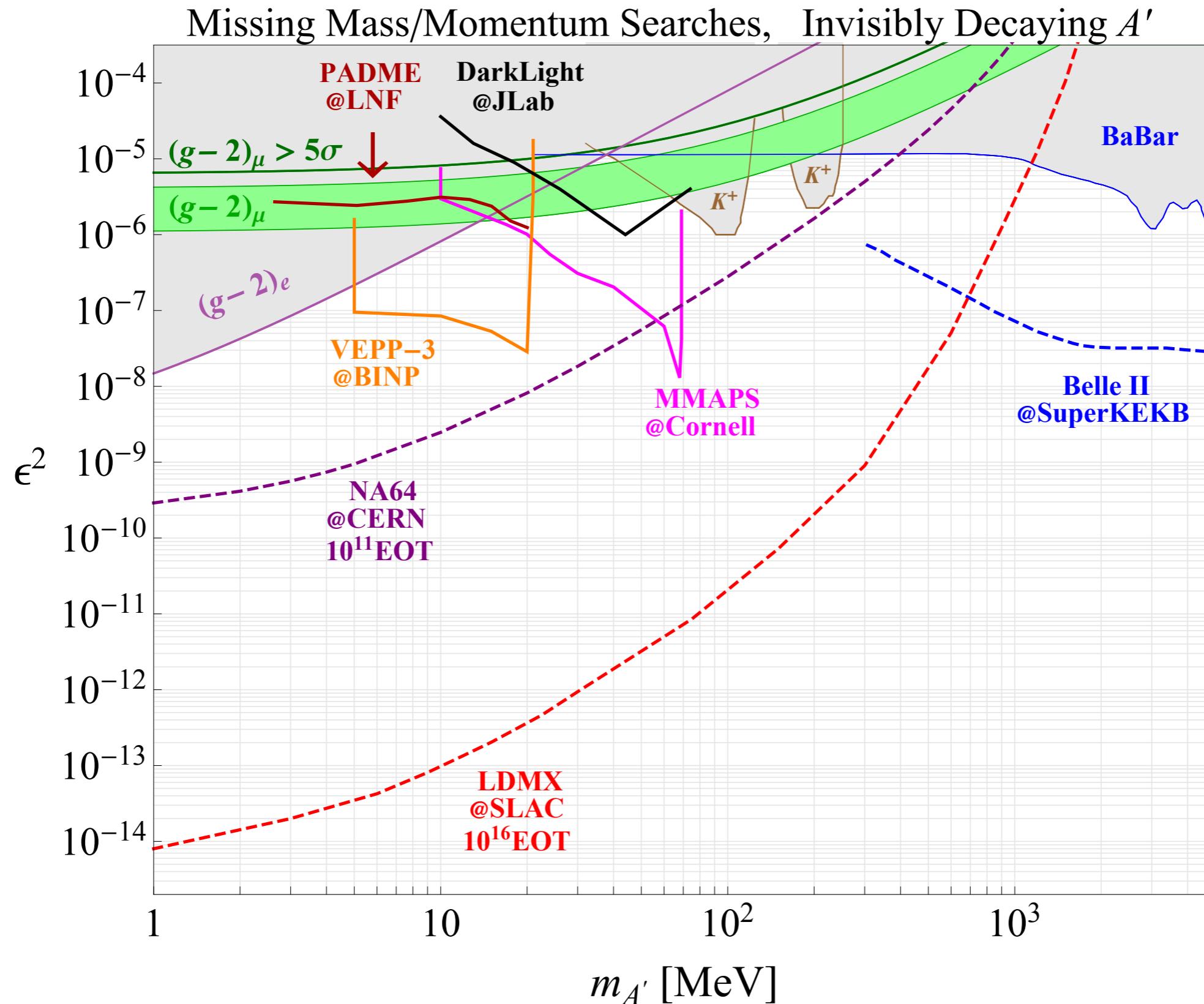
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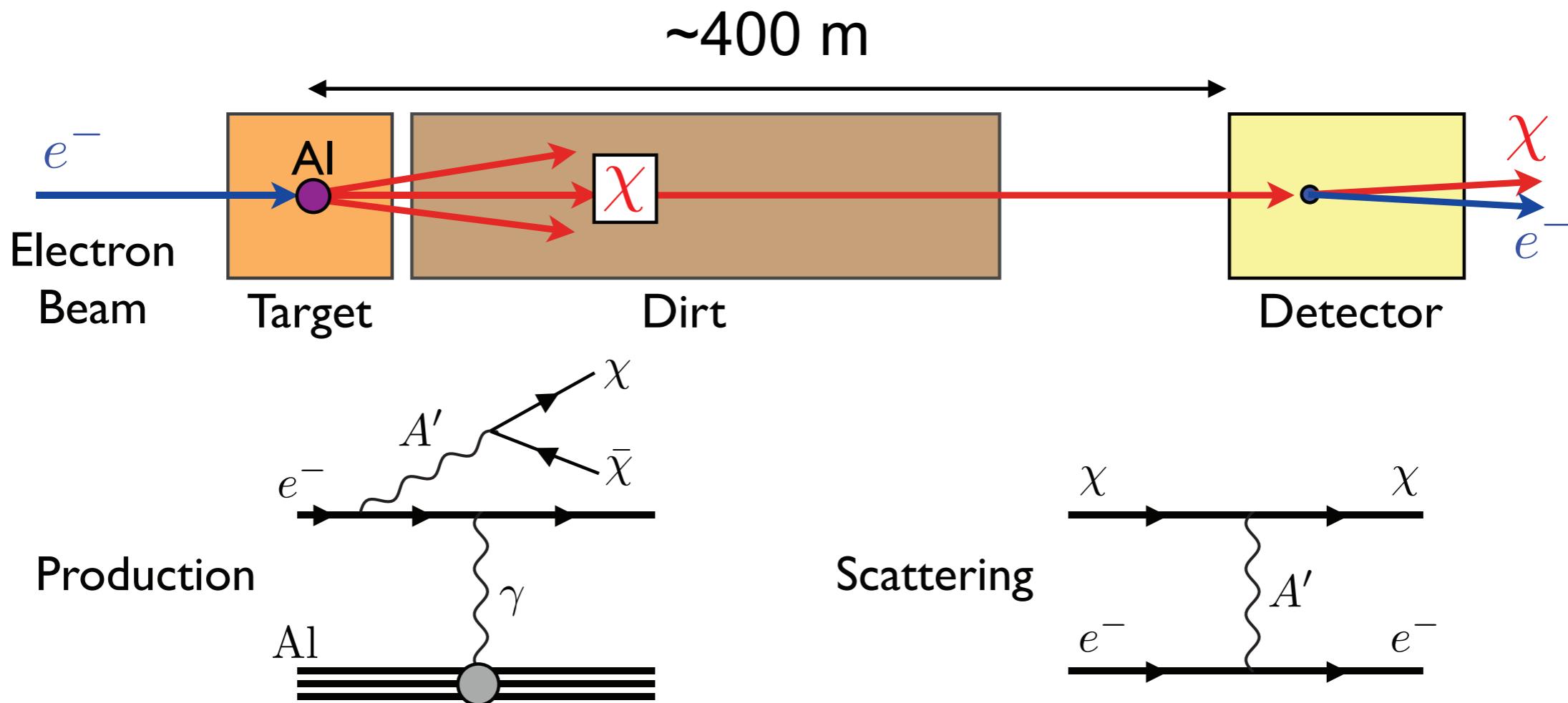
# 1. Missing mass/momentum, invisible $A'$



## 2. sub-GeV DM scatters in a detector down-stream

e.g. at SLAC's E137

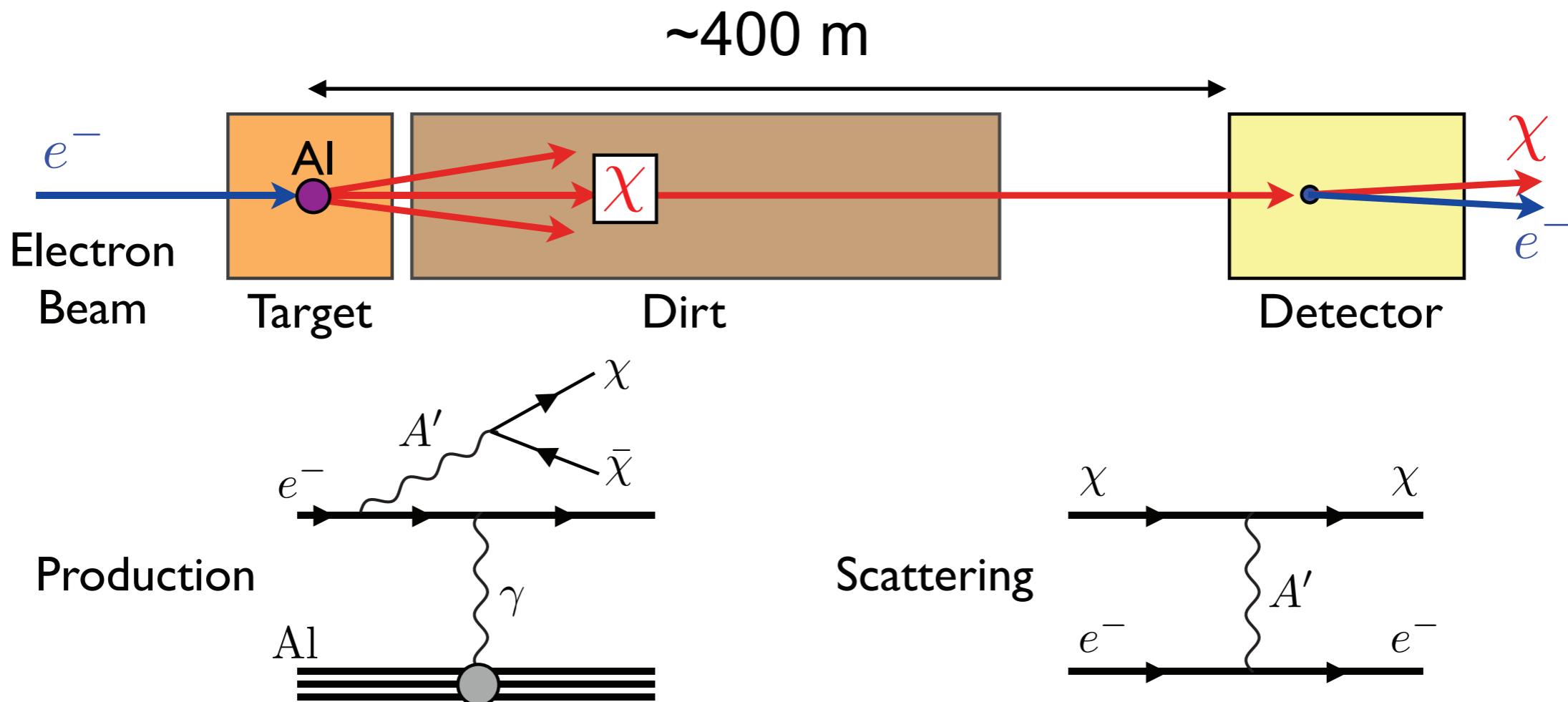
Bjorken et.al.  
Batell, RE, Surujon



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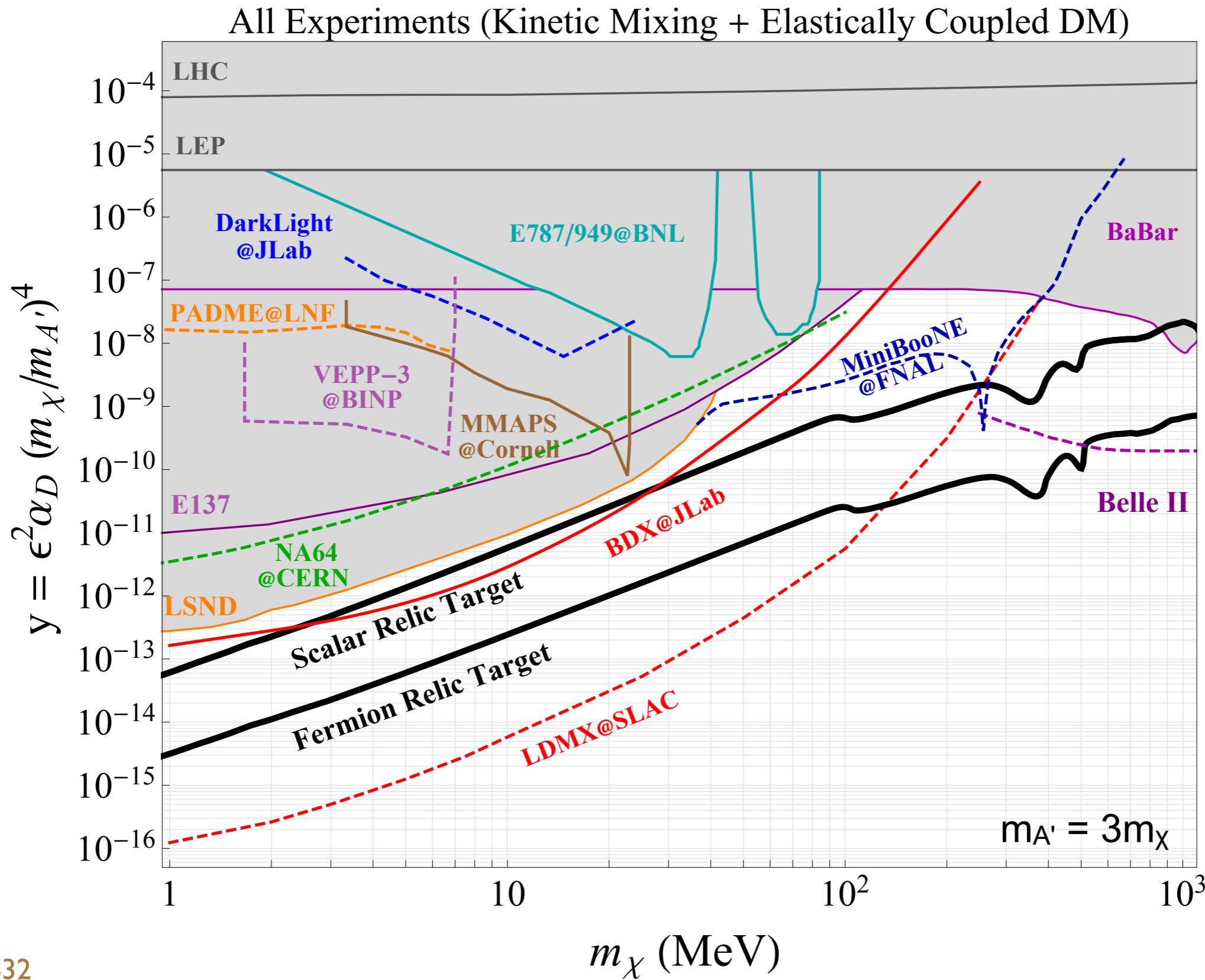
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much room for future exploration, also with proton beam dumps

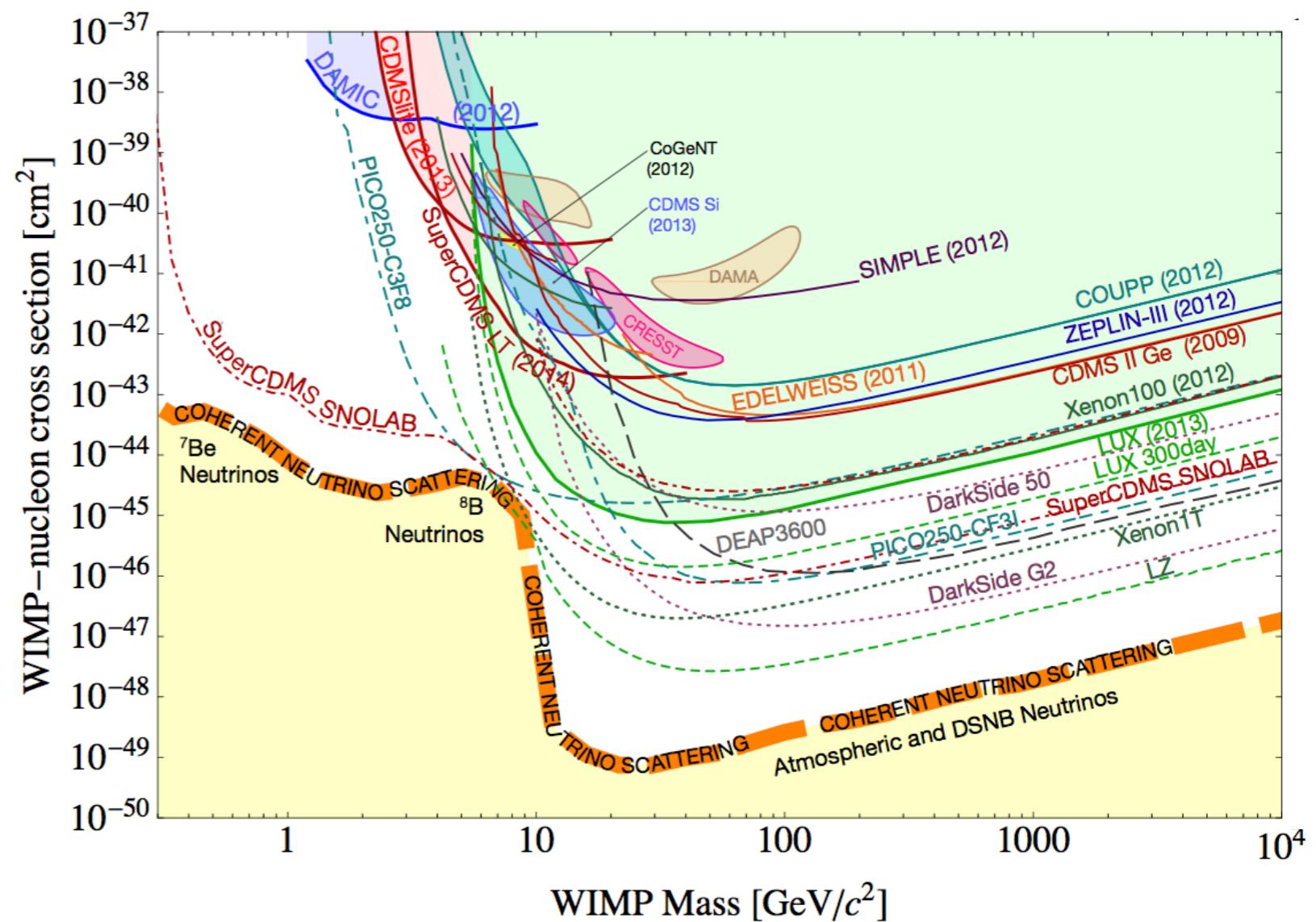
see also e.g. Batell, Pospelov, Ritz; Deniverville, Pospelov, Ritz; Deniverville, McKeen, Ritz;  
Aguilar-Arevalo et.al.; Krnjaic, Izaguirre, Schuster, Toro (several); Diamond, Schuster;  
RE, Mardon, Papucci, Volansky, Zhong; etc.

# Prospects



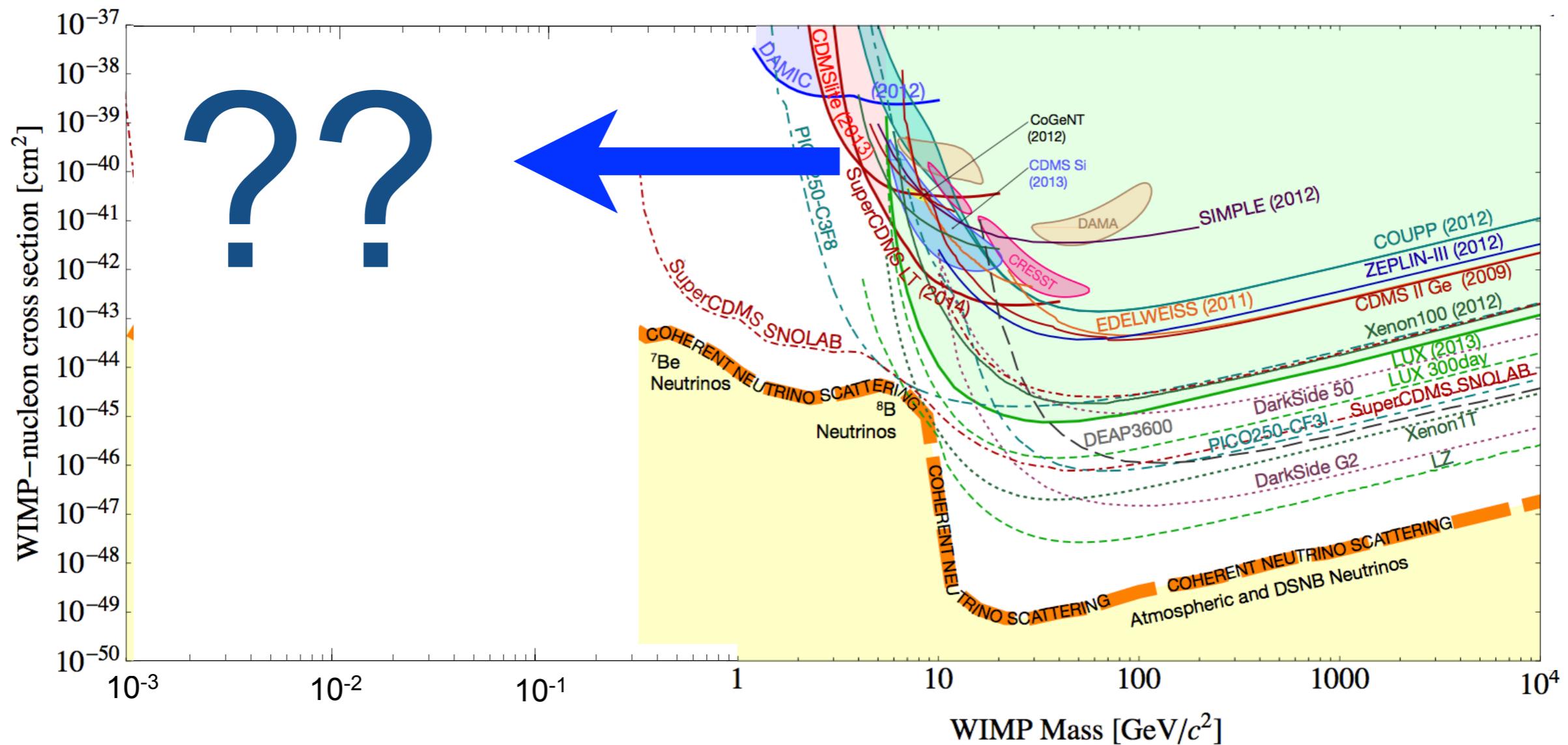
# Direct Detection below 1 GeV?

Not with standard technique!  
(i.e. DM-nucleus elastic scattering)



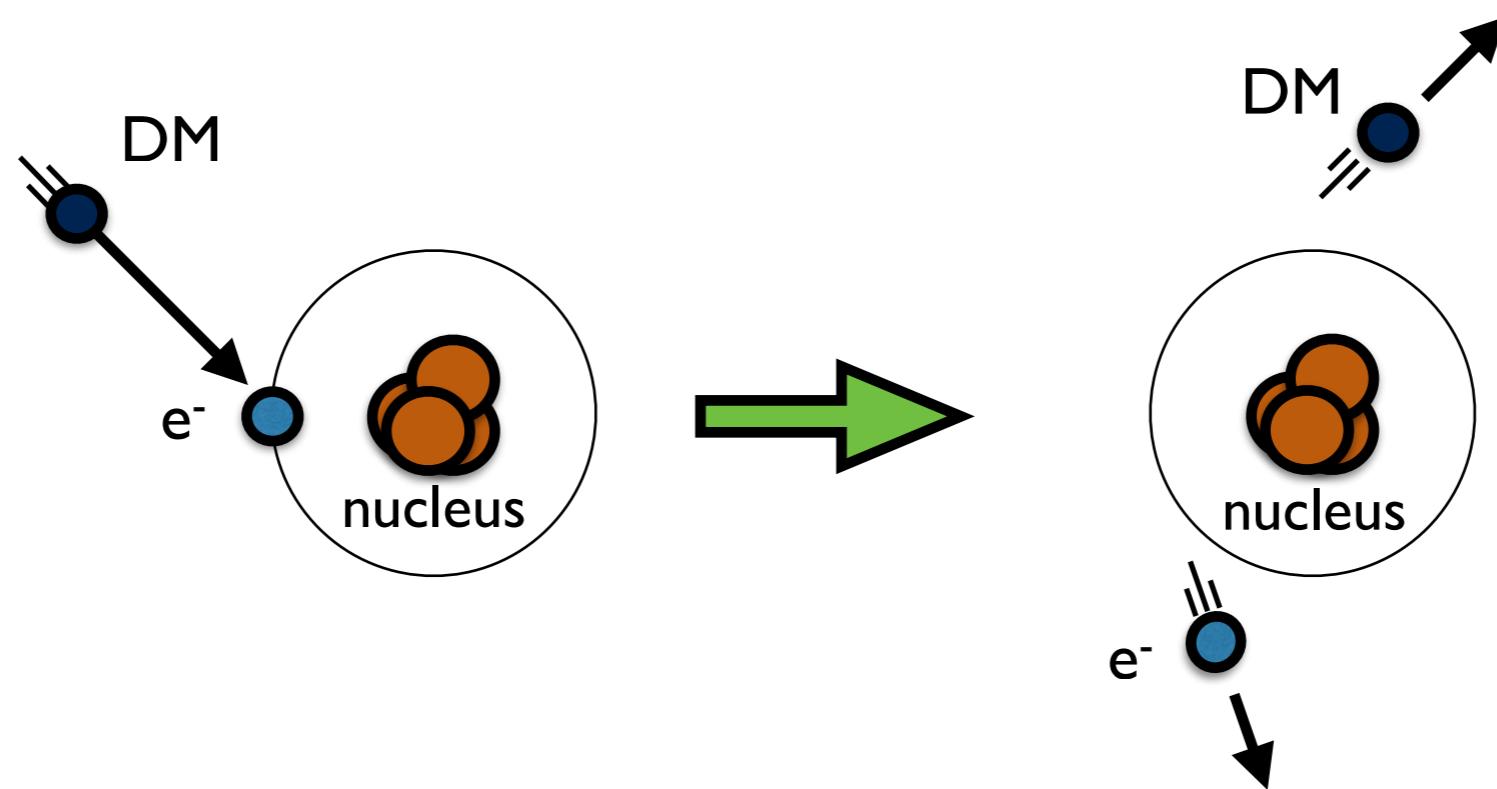
# Direct Detection below 1 GeV?

But other approaches can probe to  
~1 MeV and perhaps even lower!



# Fruitful approach: DM-electron scattering

RE, Mardon, Volansky



Signal depends on material & detector setup

# First Direct Detection Limits down to a few MeV

RE, Manalaysay, Mardon, Sorensen, Volansky (2012)

using published XENON10 data

# Direct Detection below 1 GeV

recent explosion of new ideas, using various possible target materials

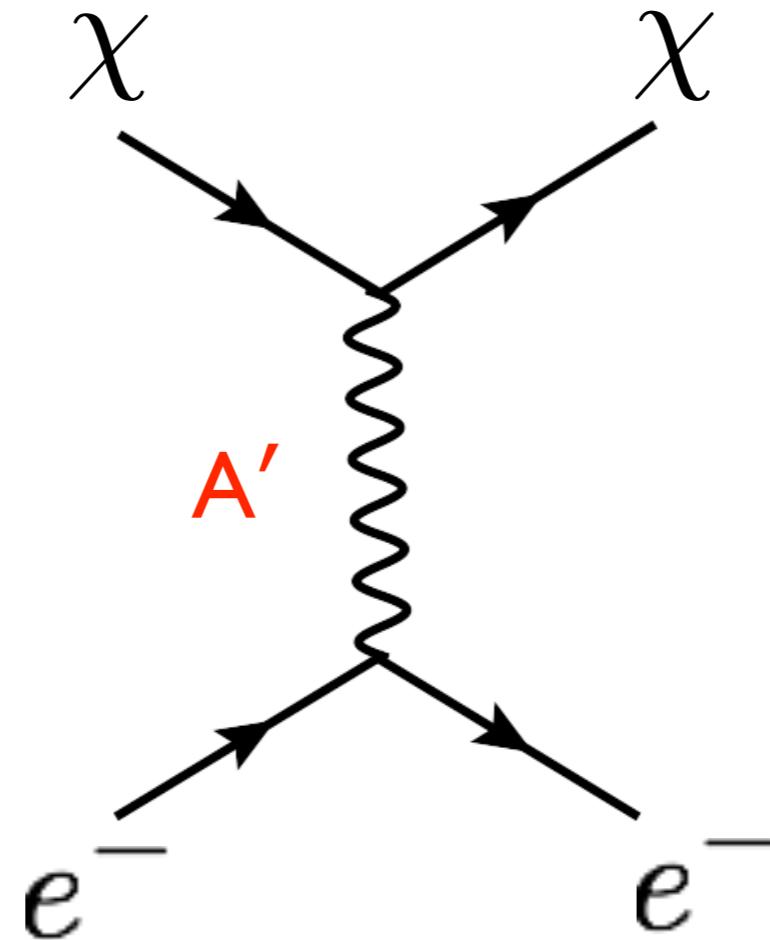
noble liquids, semiconductors, scintillators, graphene, helium, superconductors...

great potential for current, planned, and new experiments!

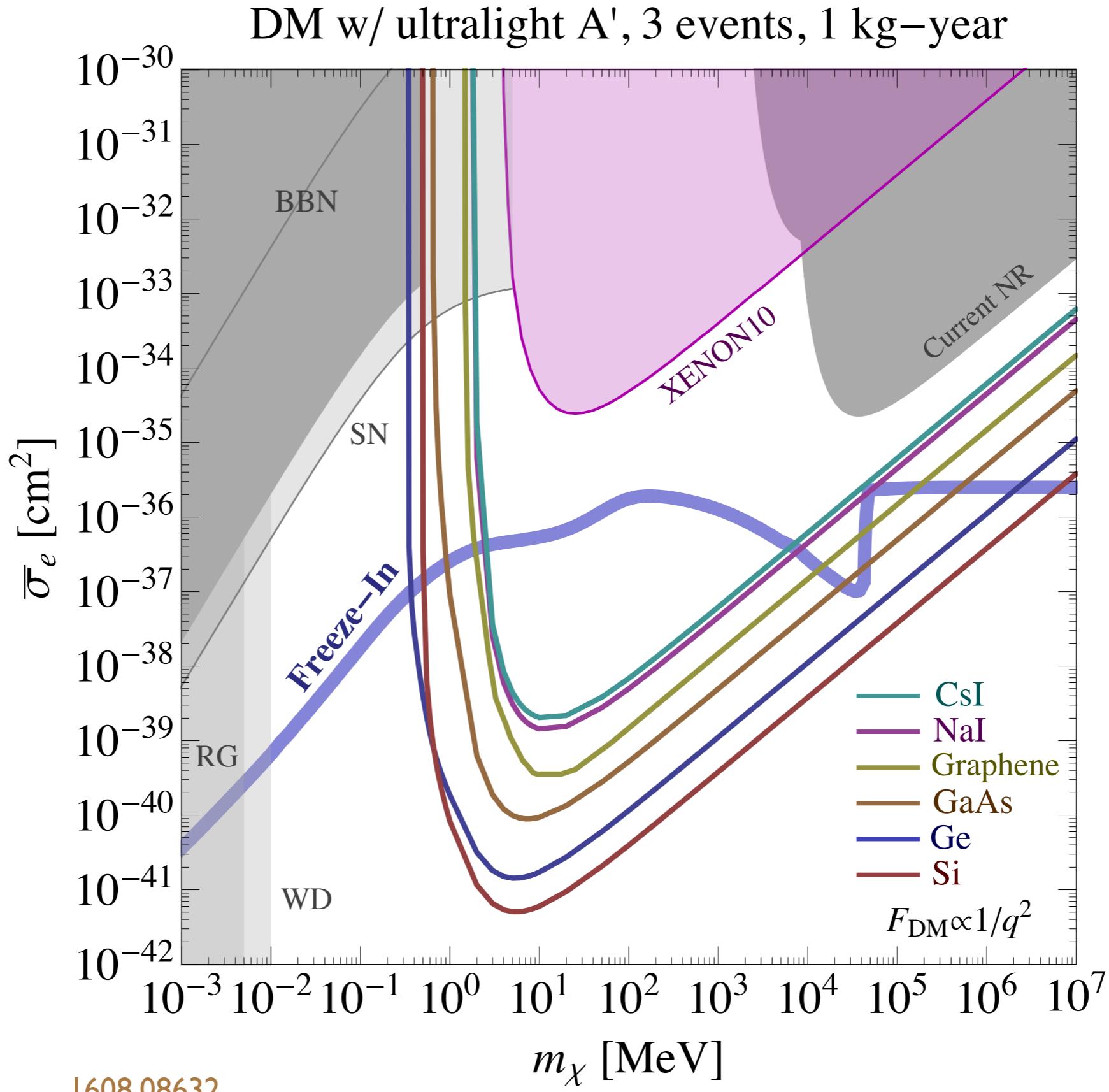
XENON100, LUX, DAMIC, SuperCDMS... + new experiments!

RE, Mardon, Volansky; Graham, Kaplan, Rajendran, Walters; RE, Manalaysay, Mardon, Sorensen, Volansky; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu ; Lee, Lisanti, Mishra-Sharma, Safdi; Derenzo, RE, Massari, Soto, Yu; Hochberg, Zhao, Zurek; Hochberg, Pyle, Zhao, Zurek; Hochberg, Kahn, Lisanti, Tully, Zurek; Schutz, Zurek; RE, Mardon, Slone, Volansky; RE, Mardon, Volansky, Yu (to appear); An, Pospelov, Pradler, Ritz; Hochberg, Lin, Zurek; Bloch, RE, Tobioka, Volansky, Yu; ...

# Example: DM + A'



# Direct Detection Prospects: Example



# Conclusions

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- Dark photons:
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- Dark sectors: well-motivated by dark matter, theory, strong CP, muon g-2, various anomalies, ...
- Dark photons:
  - much recent progress from several experiments
  - small-scale, inexpensive experiments like APEX and HPS will expand sensitivity further
- MeV-to-GeV mass dark matter:
  - lots of potential for upcoming & new direct detection experiments, as well as beam-dumps and colliders