APS DNP Town Meeting - Chicago - September 2014

Light (gauged) hidden sectors
- Theory & Motivation -

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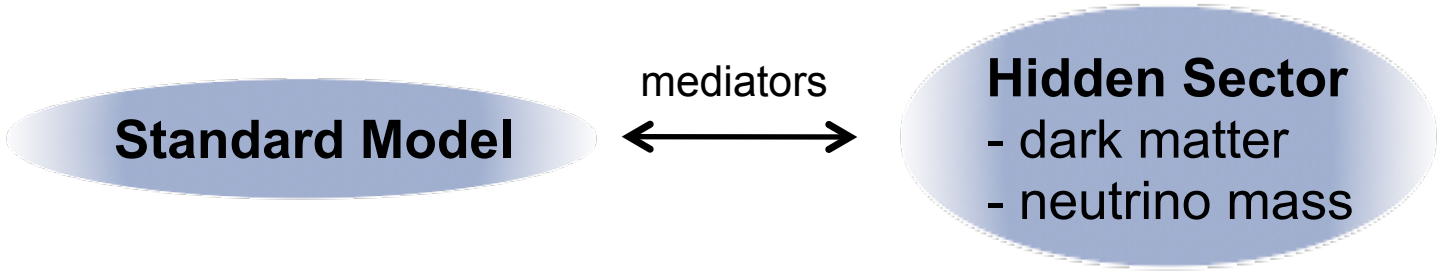
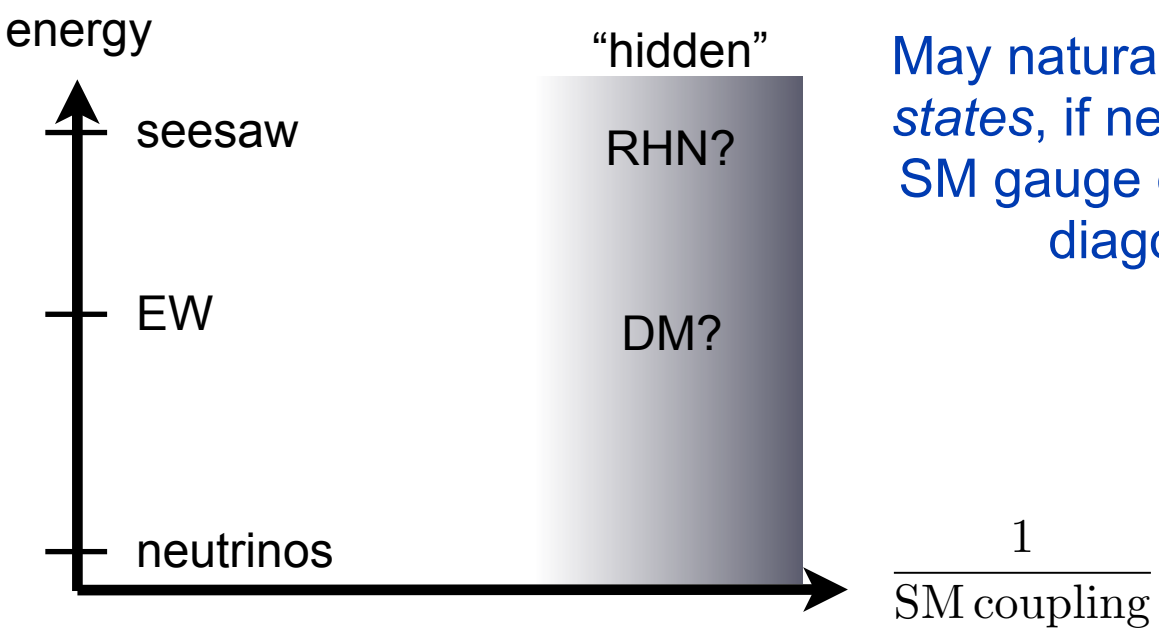
[For a review, see the Snowmass IF5 Report - 1311.0029]

New (dark) physics in a hidden sector

Arguably, most *empirical* evidence for physics beyond the Standard Model does not point to a specific mass scale, but rather to a hidden (or dark) *sector*





May naturally contain *light states*, if neutral under the SM gauge group, flavour-diagonal, etc

EFT for a (neutral) hidden sector

Standard Model $\xleftrightarrow{\text{mediators}}$ **Hidden Sector**

$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal "portals" to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$
- Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

Vector portal model

Standard Model $\xleftrightarrow{\text{mediators}}$ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}F'^{2}_{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{2}_{\mu} + \cdots$$

[Okun, Holdom]

$$\Downarrow$$

$$\mathcal{L}_{\rm int} = -\epsilon e A'_{\mu} J^{\mu}_{\rm em}$$

[Fayet, 1980,81]

A' - couples to the SM via the EM current

- Simple 2D parameter space {ε,$m_{A'}$} (at higher energies the mixing with Z may also be relevant)
- If $m_{A'} > 2m_e$, *A'* decays to leptons, hadrons, Br ~ O(ε^2)
  If $m_{A'} < 2m_e$, A'_μ is long-lived (warm DM) *[focus on higher mass here]*
- A couple of extensions:
  - coupling A'_μ to global U(1) currents J_μ of the SM (e.g. B-L, L_μ - L_τ, etc)
  - adding mass mixing with Z ⇒ P-odd signatures [Fayet; Davoudiasl et al]

Vector portal (DM) model

Standard Model $\xleftrightarrow{\text{mediators}}$ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}F'^{2}_{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{2}_{\mu} + |D_\mu\chi|^2 - m^2_{\rm DM}|\chi|^2 + \cdots$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$\mathcal{L}_{\rm int} = -\epsilon e A'_\mu J^\mu_{\rm em}$$

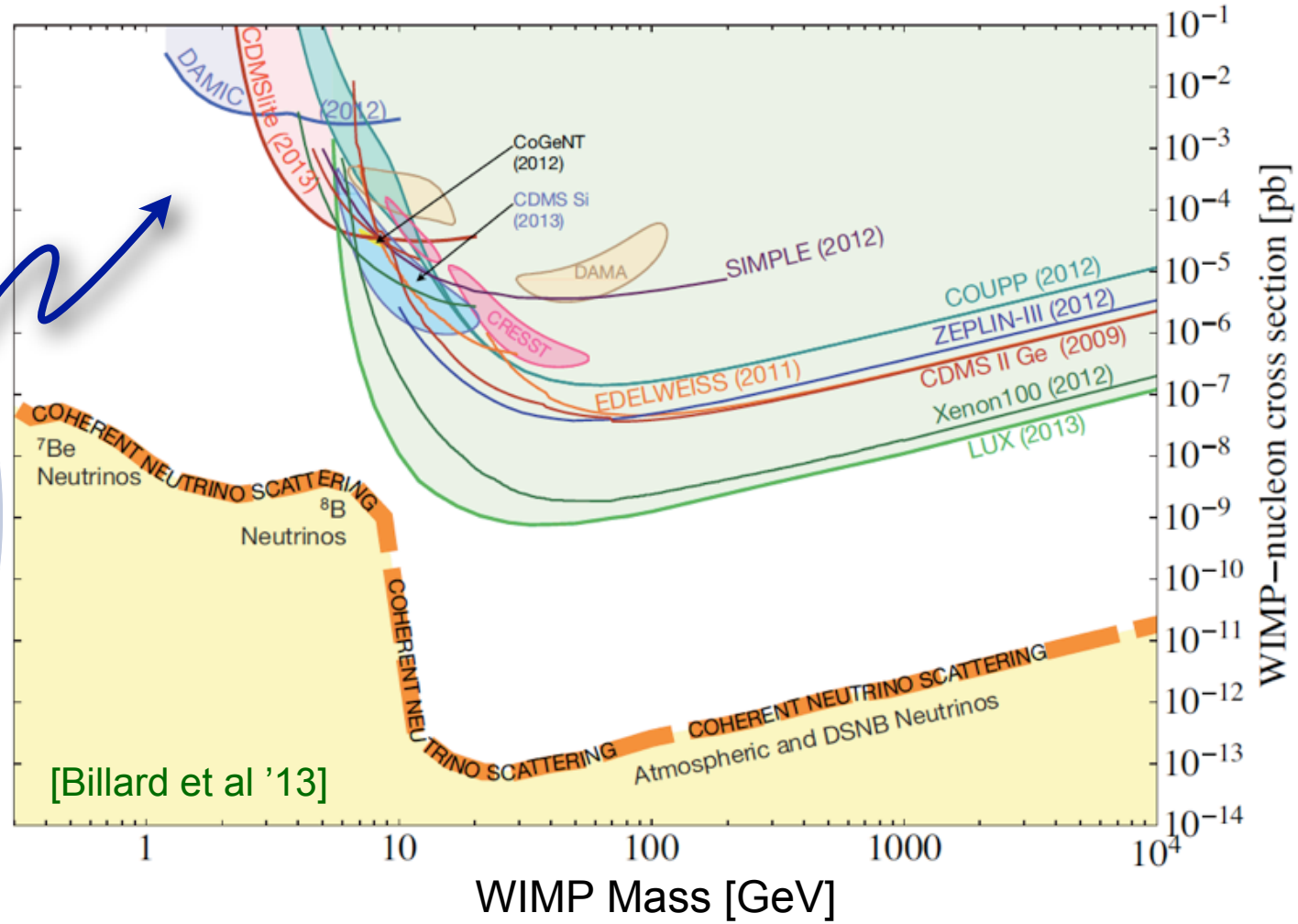
A' - couples to the SM via the EM current

DM candidate, coupled through U(1)', with "fine structure constant" α_D

- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08].
- Weak-scale DM candidates of interest due to Coulomb-enhanced low-v annihilation [Finkbeiner & Weiner, '07; Pospelov, AR, Voloshin '07; Arkani-Hamed et al '08; Pospelov, AR '08].]
- For $m_{DM} < m_{A'}$, the correct relic density fixes a specific relation between $\{\varepsilon, \alpha_D, m_{A'}, m_{DM}\}$ [Pospelov, AR & Voloshin '07]

Motivating the parameter space - light DM

Direct detection sensitivity to halo DM drops for m<*O*(GeV), due to recoil energy thresholds.



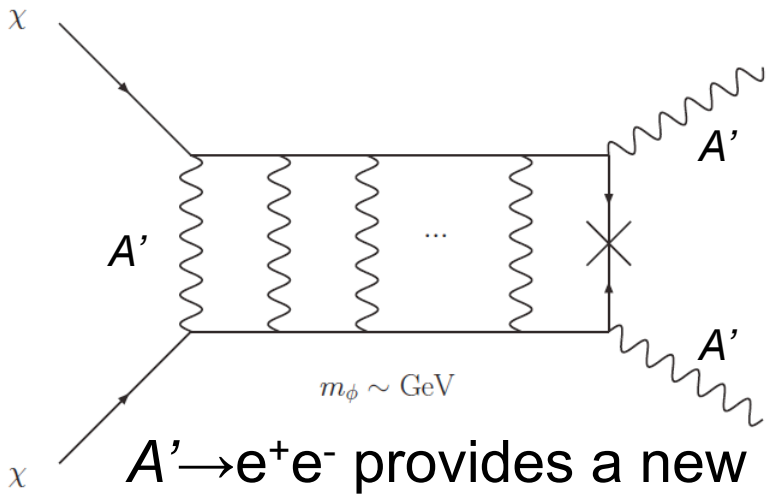
WIMP-like models for light DM also require light force mediators, to ensure sufficient annihilation in the early universe.

$$\sigma_{\rm ann} \propto \frac{m_{\rm DM}^2}{M_{\rm mediator}^4}$$

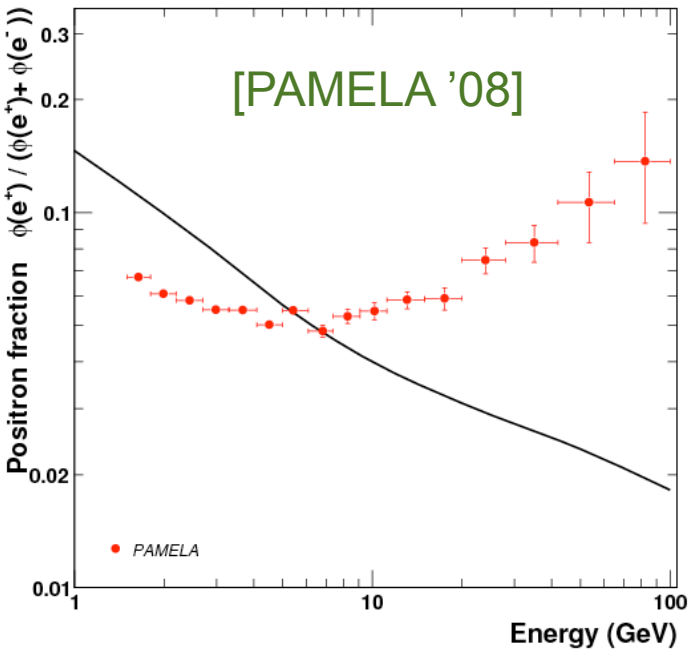
Early DM motivations - from 2008

Light mediator allows for enhanced low velocity DM annihilation rate ($\sim \alpha' m_{DM}/m_{A'}$) in the galactic halo, of interest for enhanced positron (but not antiproton) fraction observed in cosmic rays

[Arkani-Hamed et al '08; Pospelov & Ritz '08; many others]



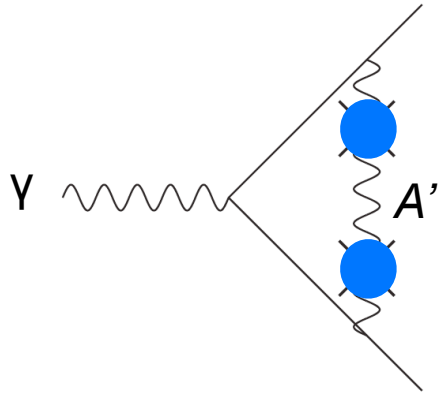
$A' \to e^+e^-$ provides a new primary source of positrons



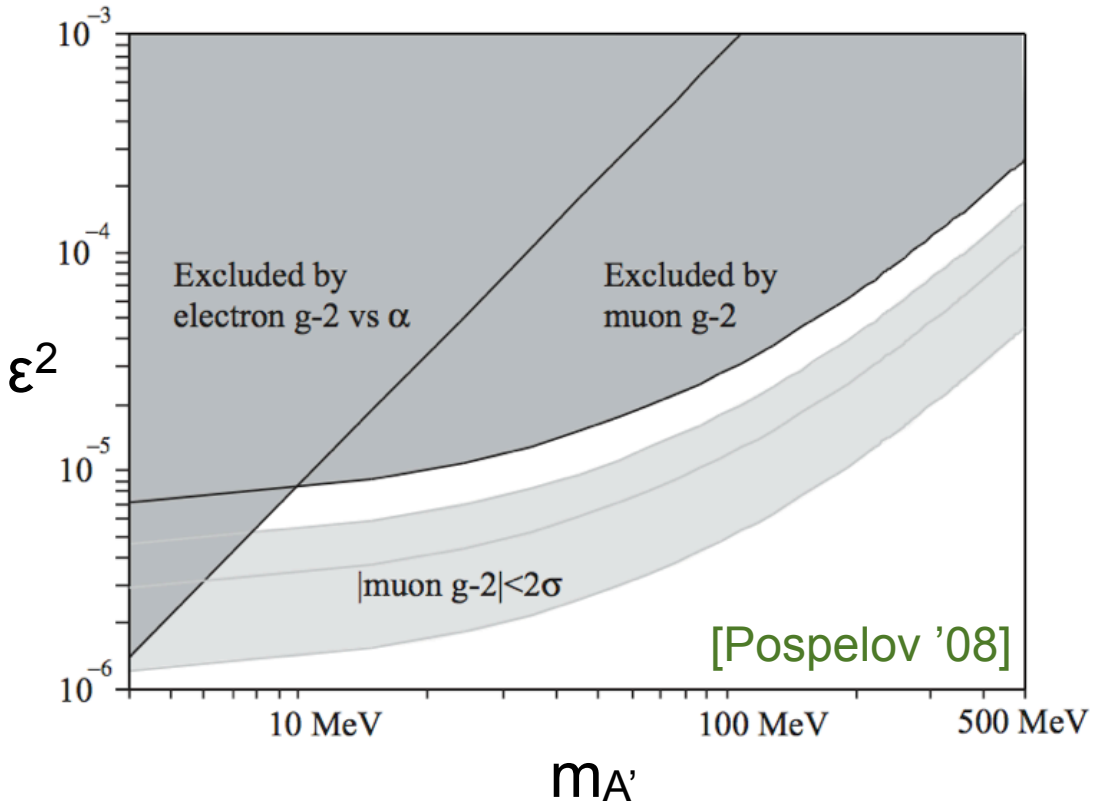
[and subsequently Fermi, AMS-02]

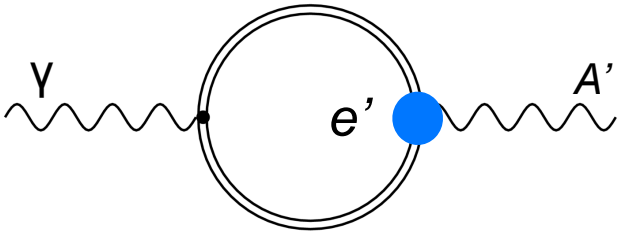
- now there is some tension with Fermi γ-ray spectra, and CMB
- astrophysical explanation possible (e.g. pulsars)

Motivating the parameter space - muon g-2



- 1-loop correction can shift muon g-2 into line with BNL measurement
- The muon g-2 anomaly also provides a sensitivity benchmark, comparable to new EW-scale physics.



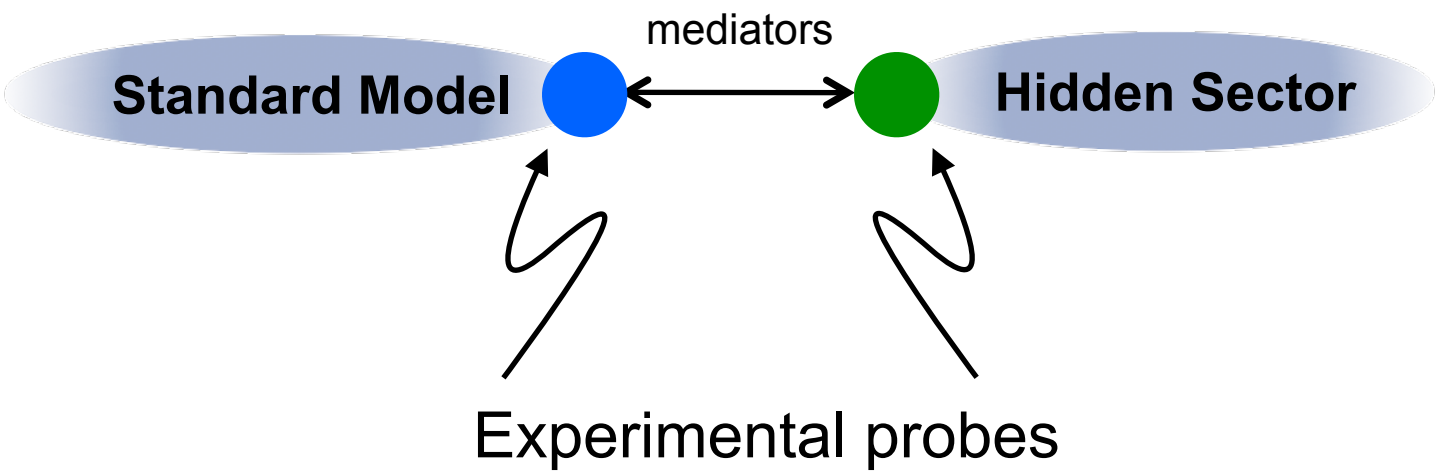


$$\epsilon_{(1-\mathrm{loop})} \sim \frac{ee'}{12\pi^2} \ln\left(\frac{\Lambda_{\mathrm{UV}}}{\Lambda}\right)$$

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

$$m_{A'} \sim \epsilon e' m_Z$$

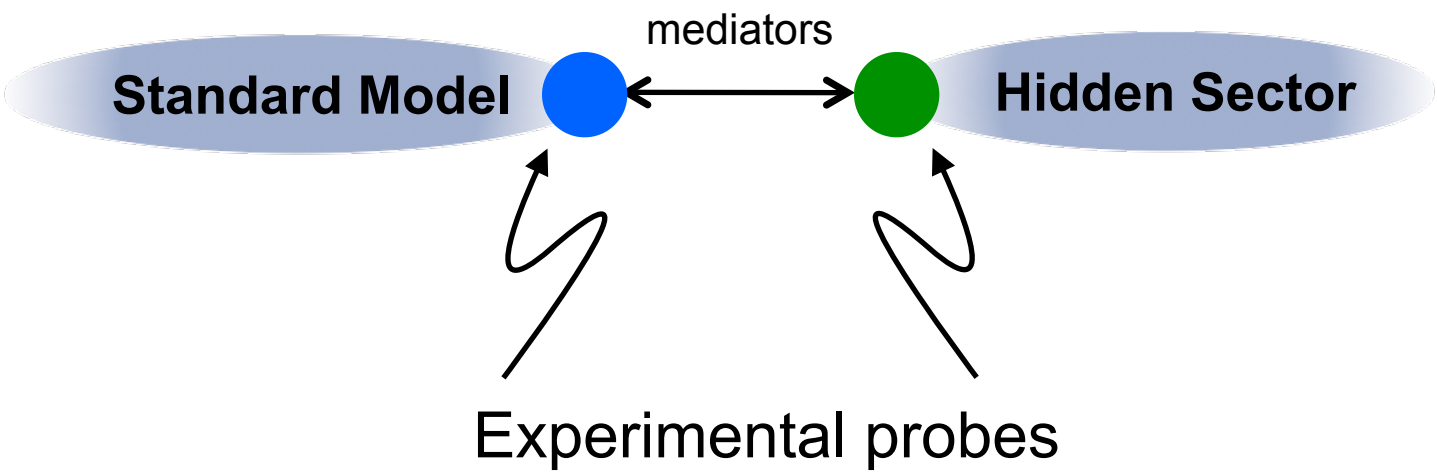
Probing the vector portal



- Precision corrections
- rare (visible) decays

- rare (invisible) decays
- anomalous NC-like scattering

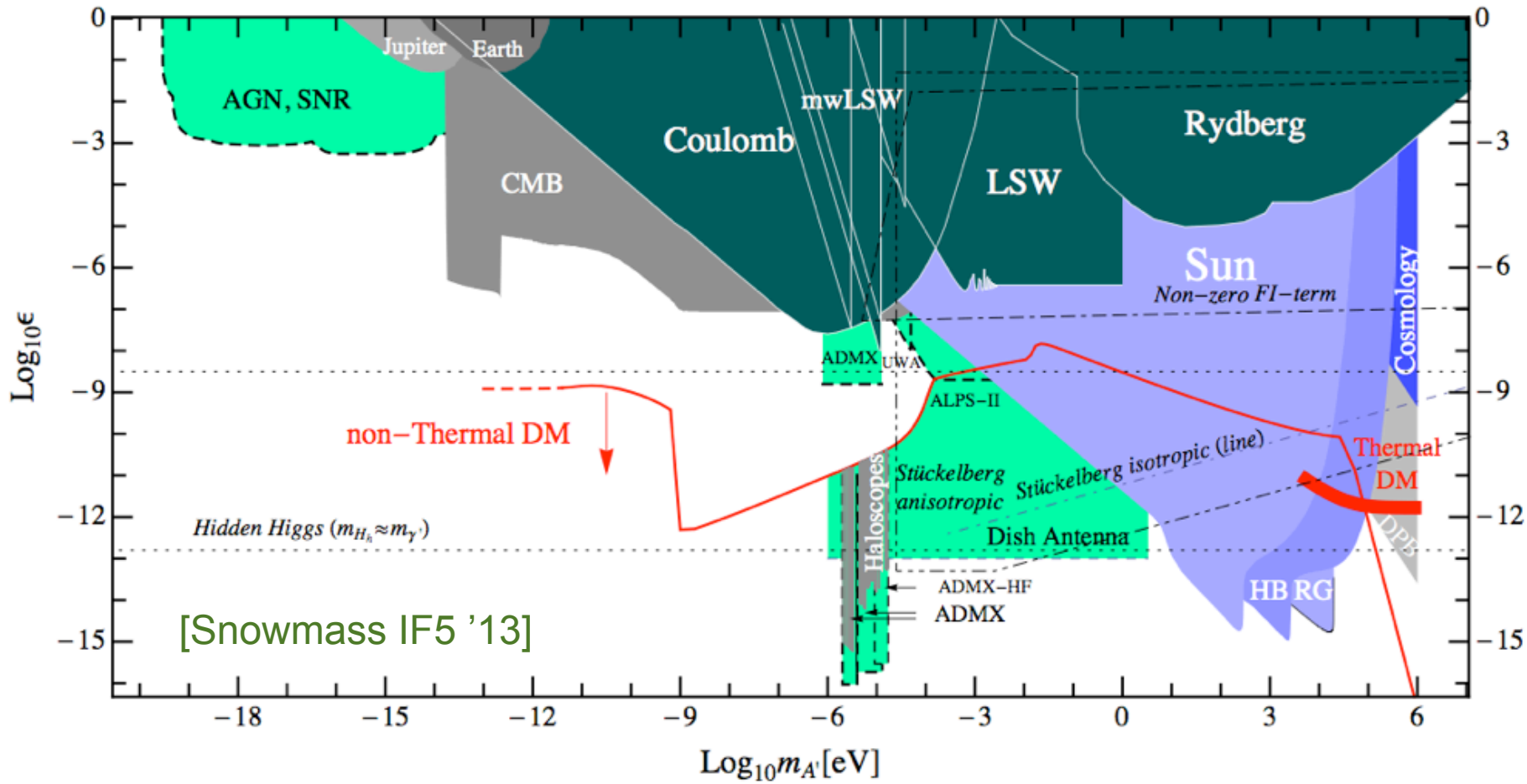
Probing the vector portal



- corrections to lepton g-2
- collider/fixed target production plus e.g. leptonic A' decays, $O(\varepsilon^2)$ x Br(SM)

- collider production plus missing energy in decays and scattering, $O(\varepsilon^2)$ x Br(Hid)
- Fixed target production plus anomalous NC-like scattering, $O(\varepsilon^2 \times \varepsilon^2\alpha_D)$

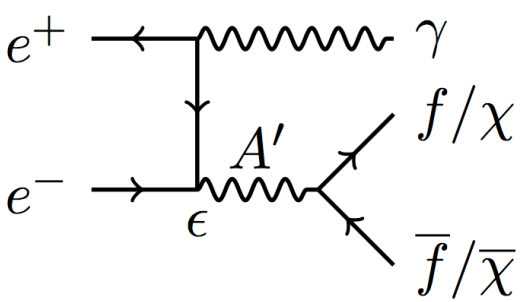
Very low mass - multiple probes

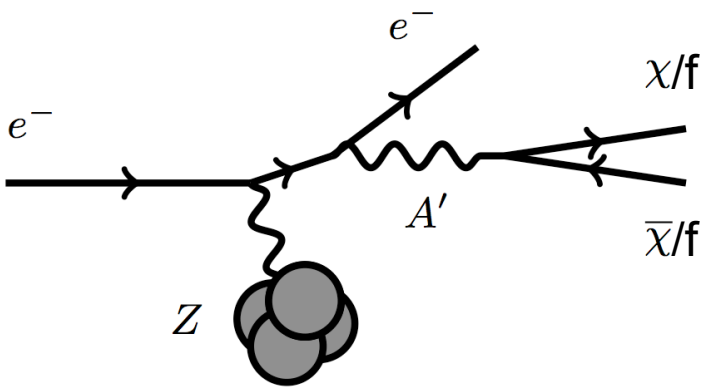


For m < O(MeV), other techniques including astrophysics provide strong sensitivity. [➠ talk by Josh Long]

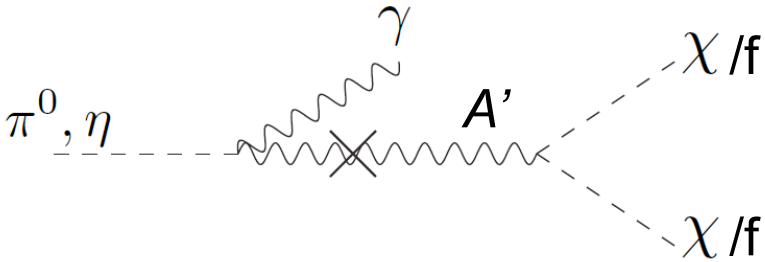
Production and Detection Channels

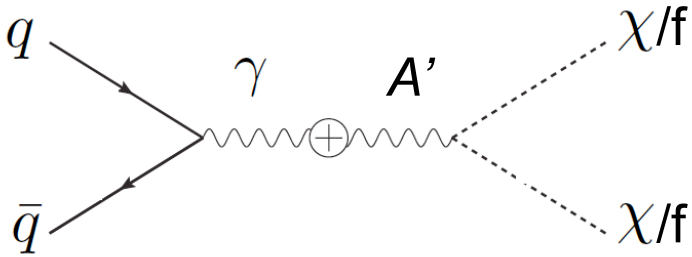
- Production - (low E) electron colliders/fixed targets





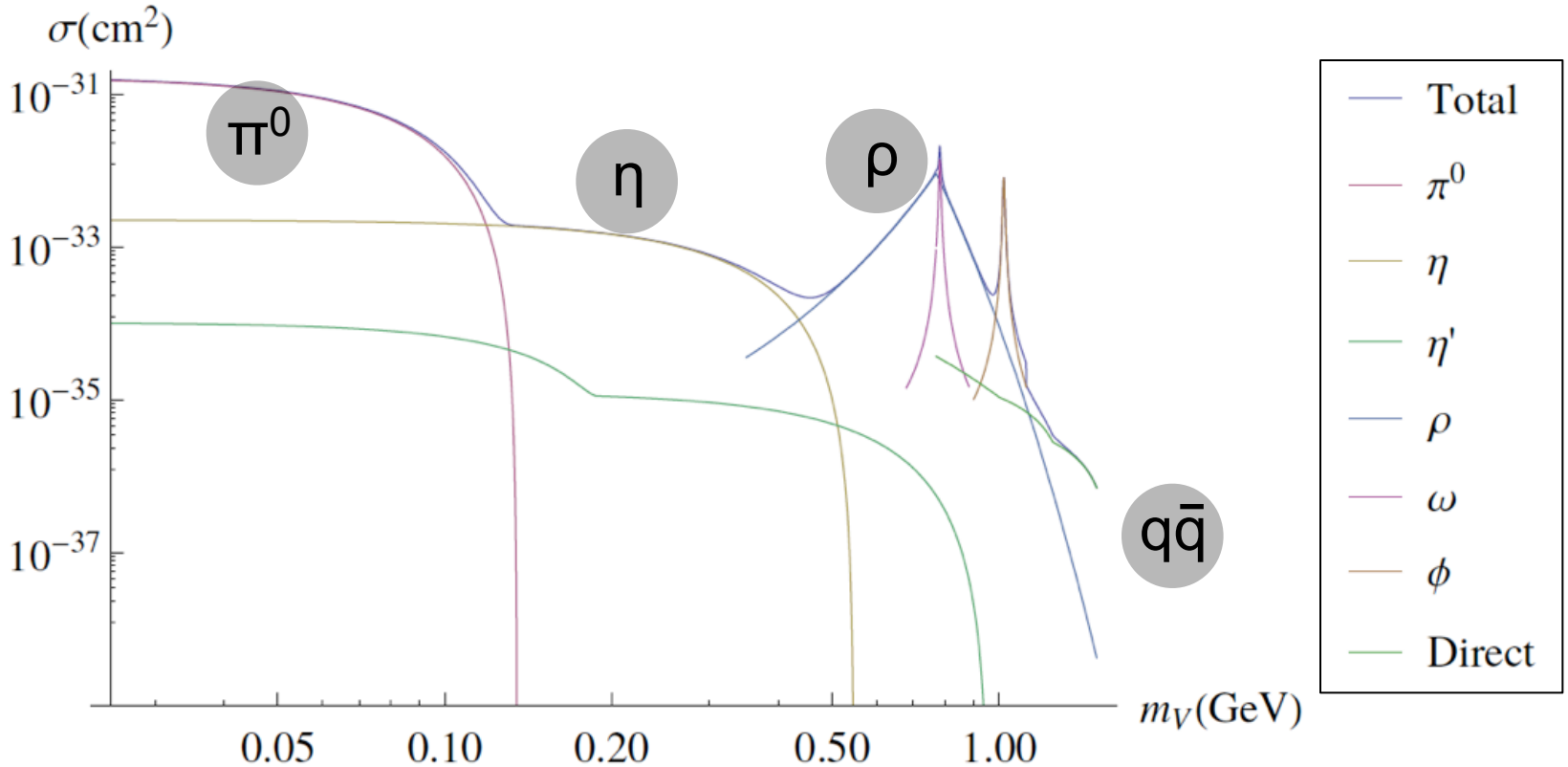
- Production - proton colliders/fixed targets (neutrino facilities)





Production and Detection Channels

Production in proton fixed targets (e.g. MiniBooNE)



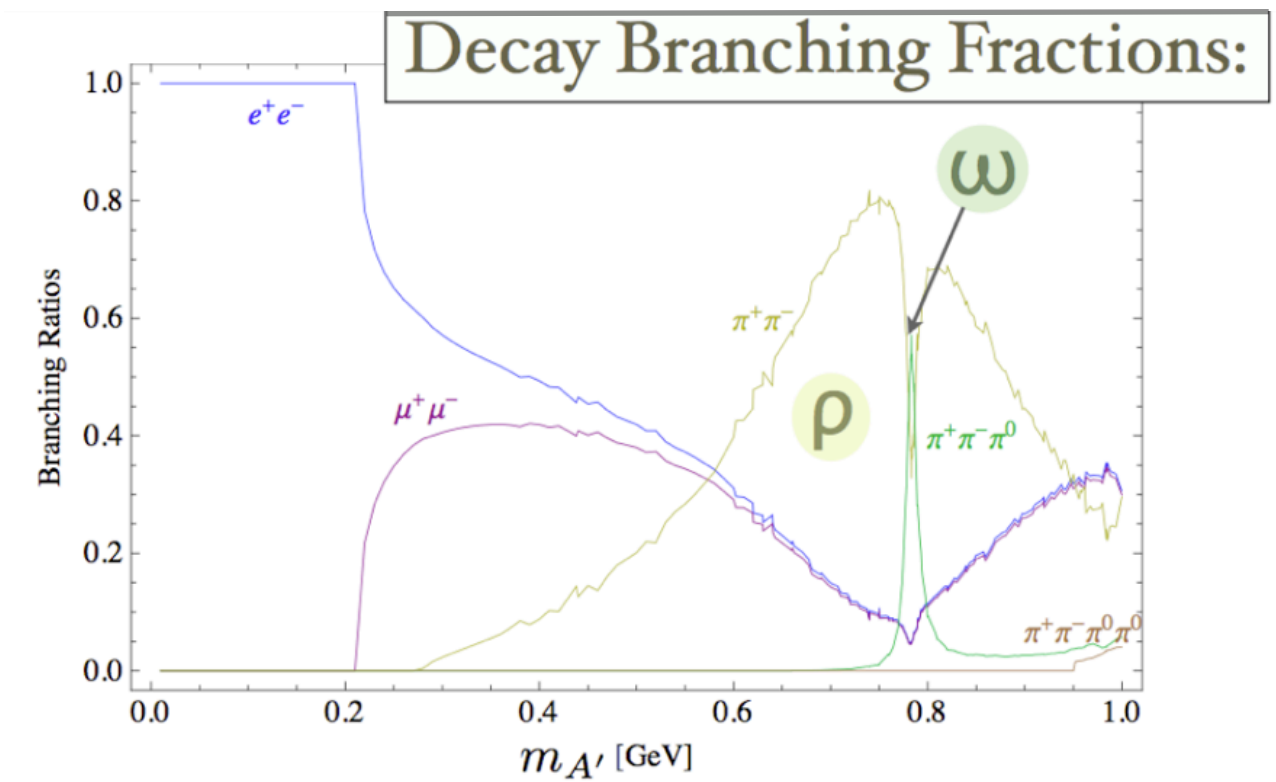
[9 GeV beam, Ge target]

Production and Detection Channels

- Decays
  - EM shower (or Missing E)

    Assuming no hidden sector decays, BR's fixed by $m_{A'}$

$$c\tau(A' \to l^+l^-) \sim 10\mu m \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{A'}}\right)$$



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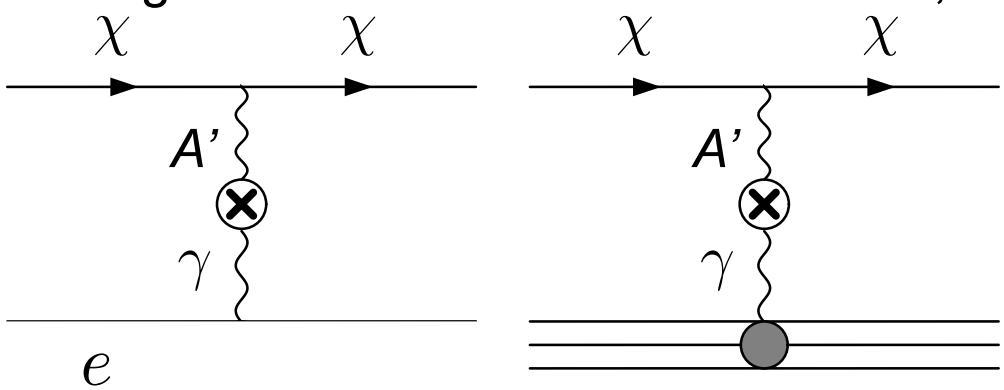
- Elastic Scattering
  - for decays to long-lived states in the hidden sector, e.g. light DM



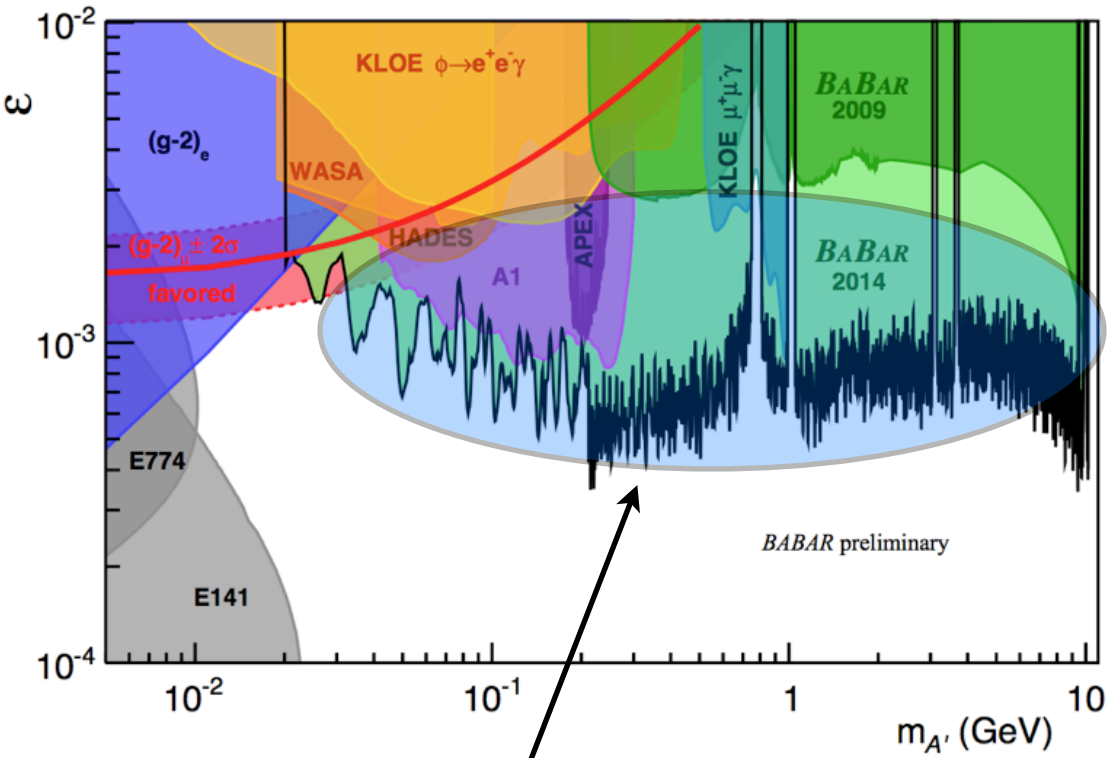
(possibly coherent)

- Astrophysics/cosmology
  - stars, SN (low mass) [Bjorken et al, Dreiner et al]
  - impact on BBN, CMB [Pospelov & Pradler, Batell et al '14]

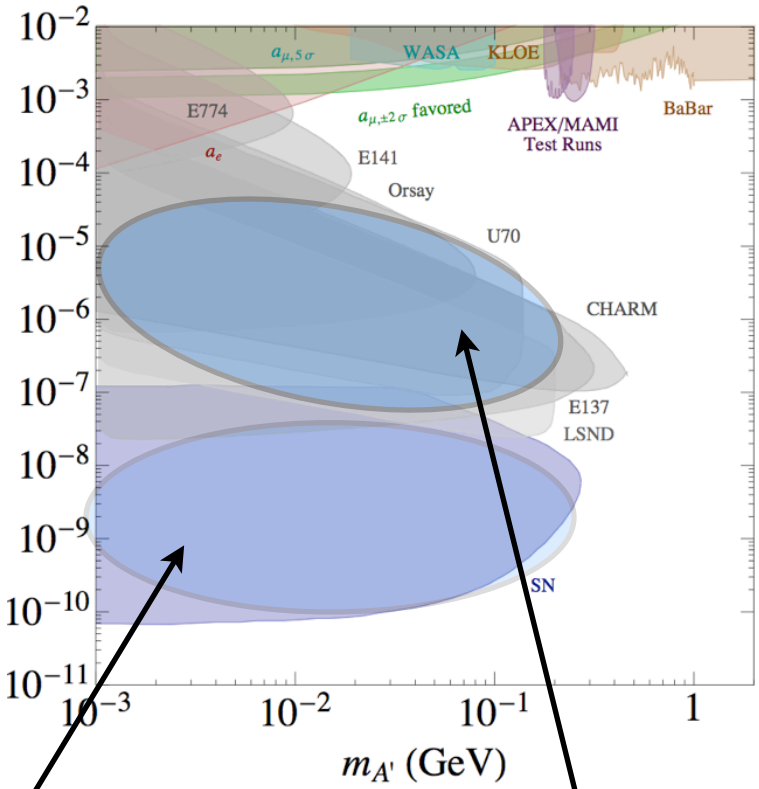
Current Sensitivity - Br(SM)~O(1)

Large (and growing) experimental program to explore these channels

[BaBar '14]



[Essig et al, Snowmass IF5 '13]



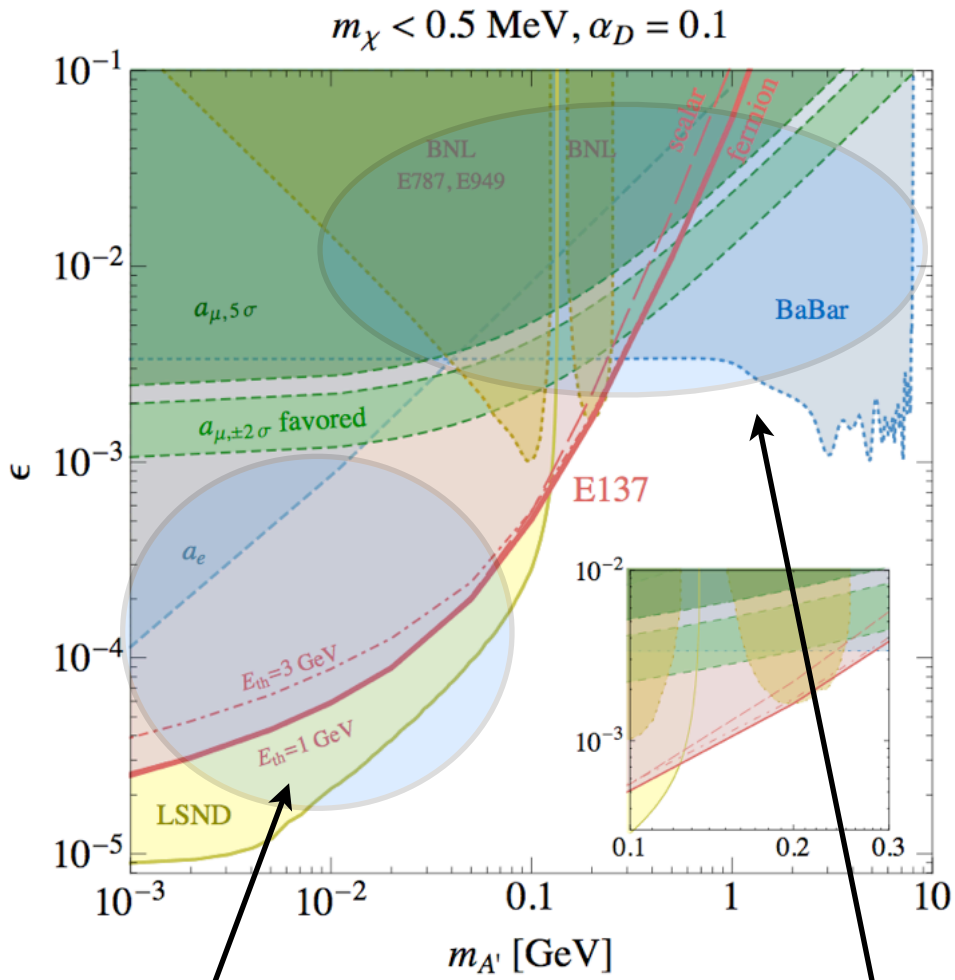
$e^+e^- \to l^+l^- \gamma$

stellar energy loss

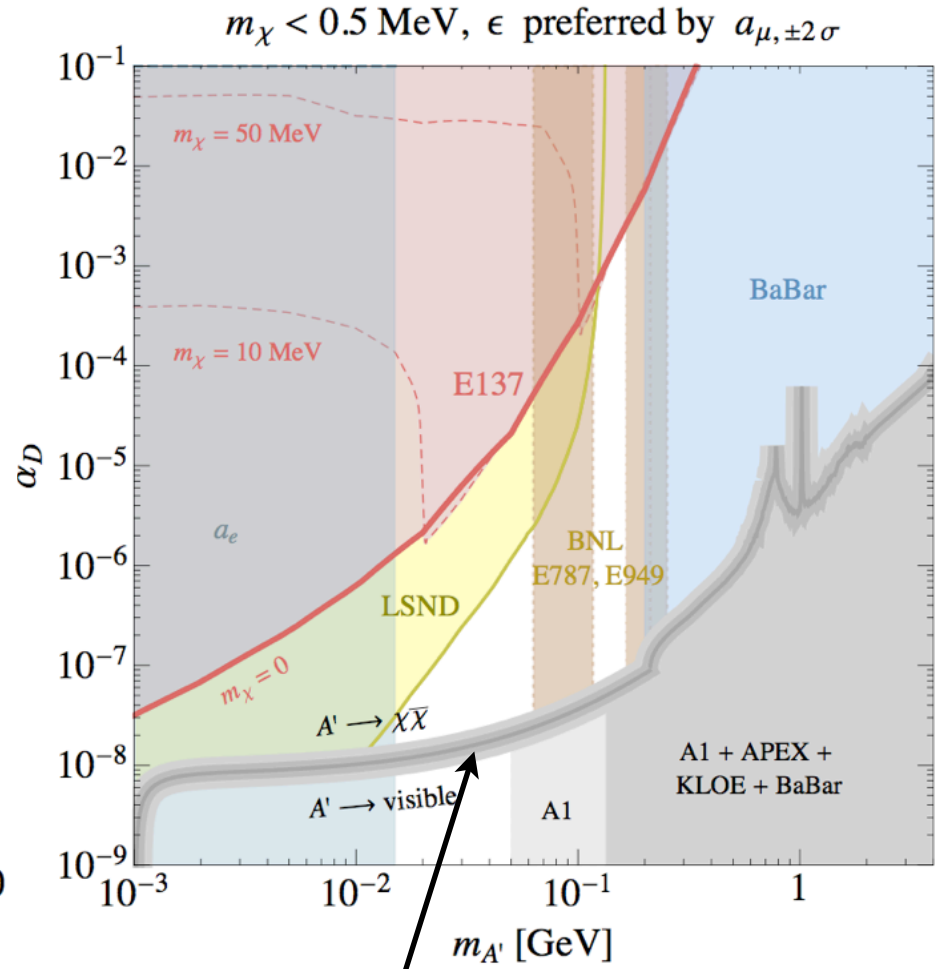
metastable, with EM shower from decay

Current Sensitivity - Br(Hid)~O(1)

[Batell, Essig, Surujon '14]



[Batell, Essig, Surujon '14]



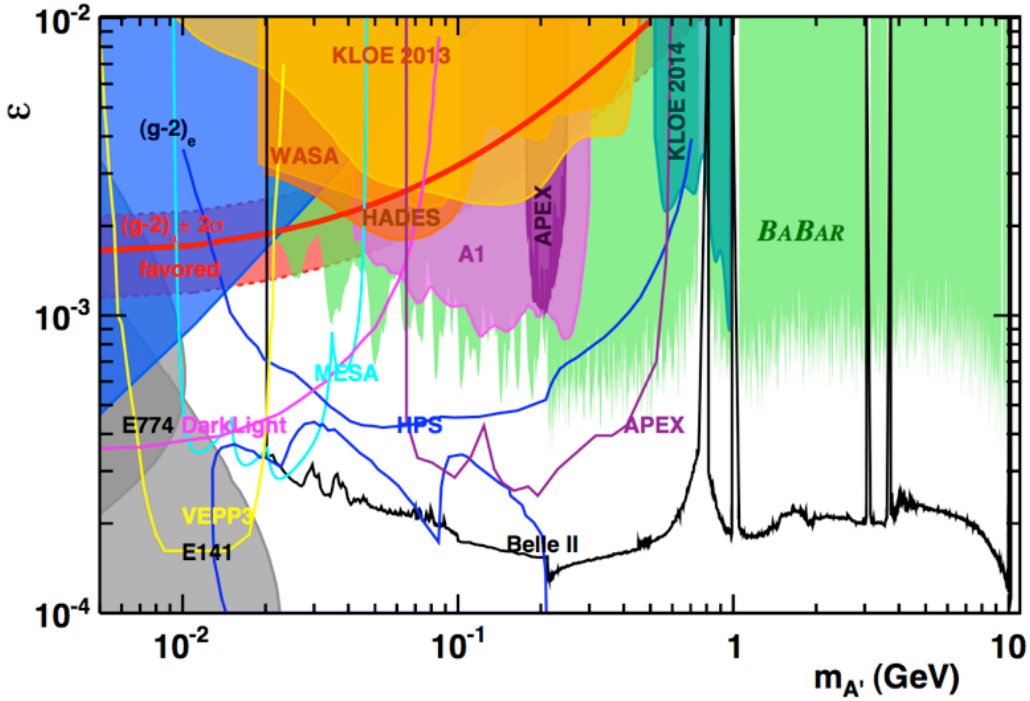
NC-like scattering ~ α_D

invisible decays

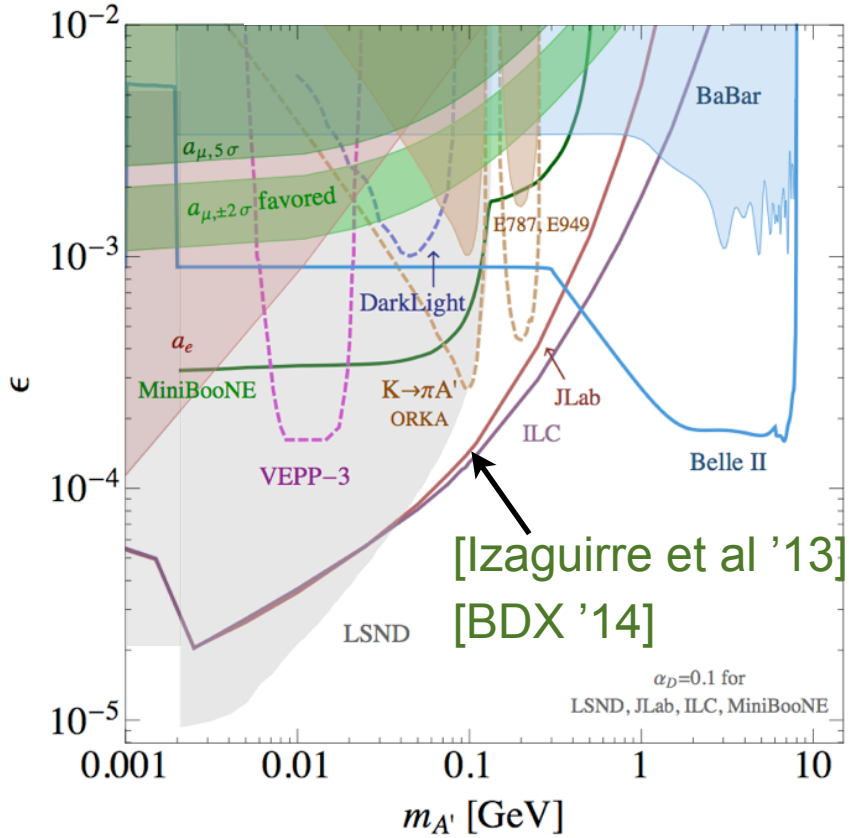
α_D controls ratio of hidden/visible decays

Future Sensitivity

[BaBar '14]



[Essig et al, Snowmass IF5 '13]



[Izaguirre et al '13]
[BDX '14]

Br(A'→SM)~O(1)

Br(A'→Hid)~O(1)

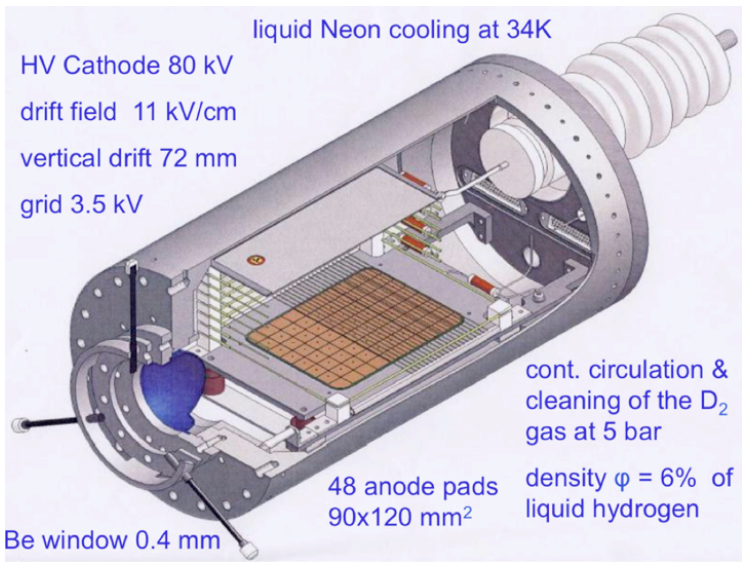
[➠ talk by Richard Milner]

(Ideas for) additional signatures

Missing E in π/μ capture

$$\pi^- + {}^3He \to A' + t$$

High sensitivity missing E search possible for $m_{A'}$ < ~100 MeV at PSI (MuSun Cryo TPC)

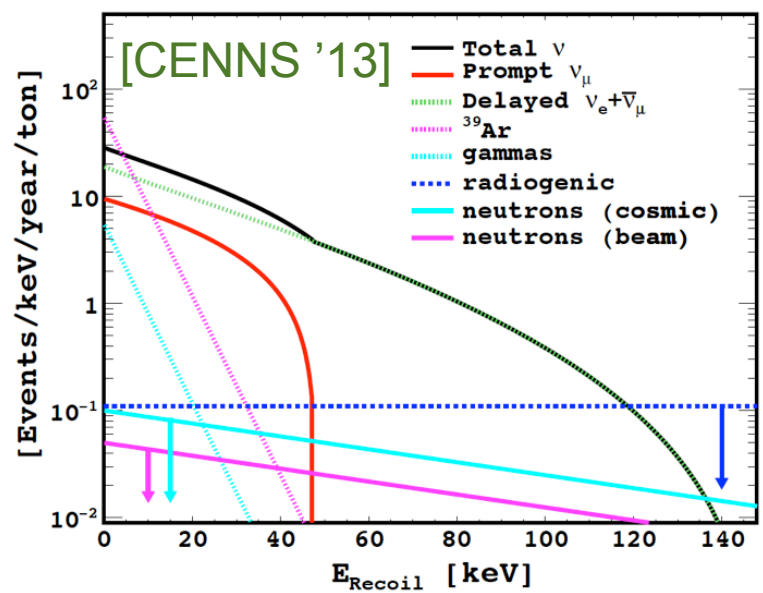


[Kammel & Pospelov]

Coherent ν scattering

$$\pi^- + p \to A' + n$$
$$\to \chi + \chi^\dagger + n$$

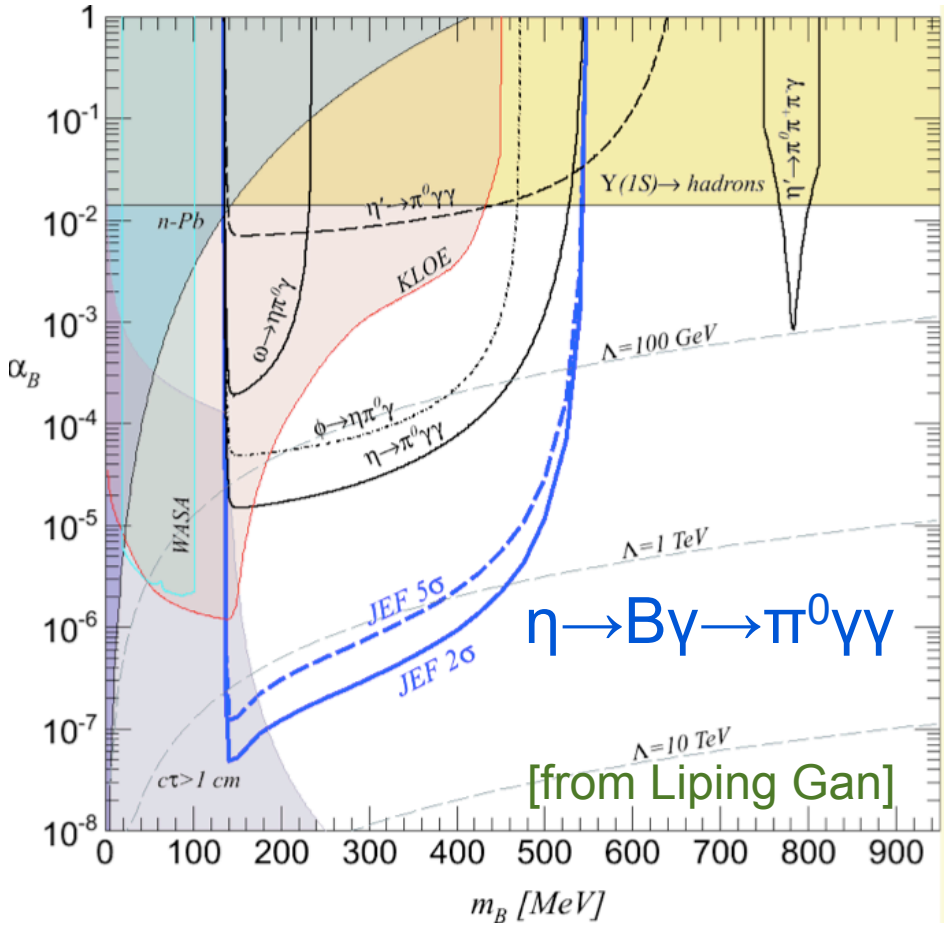
Isotropic fixed target production allows for significant DM scattering (e.g. coherent DM-nucleus scattering) in experiments designed to search for coherent ν scattering, e.g. COHERENT, CENNS (also OscSNS)



Probing other currents (e.g. leptophobic)

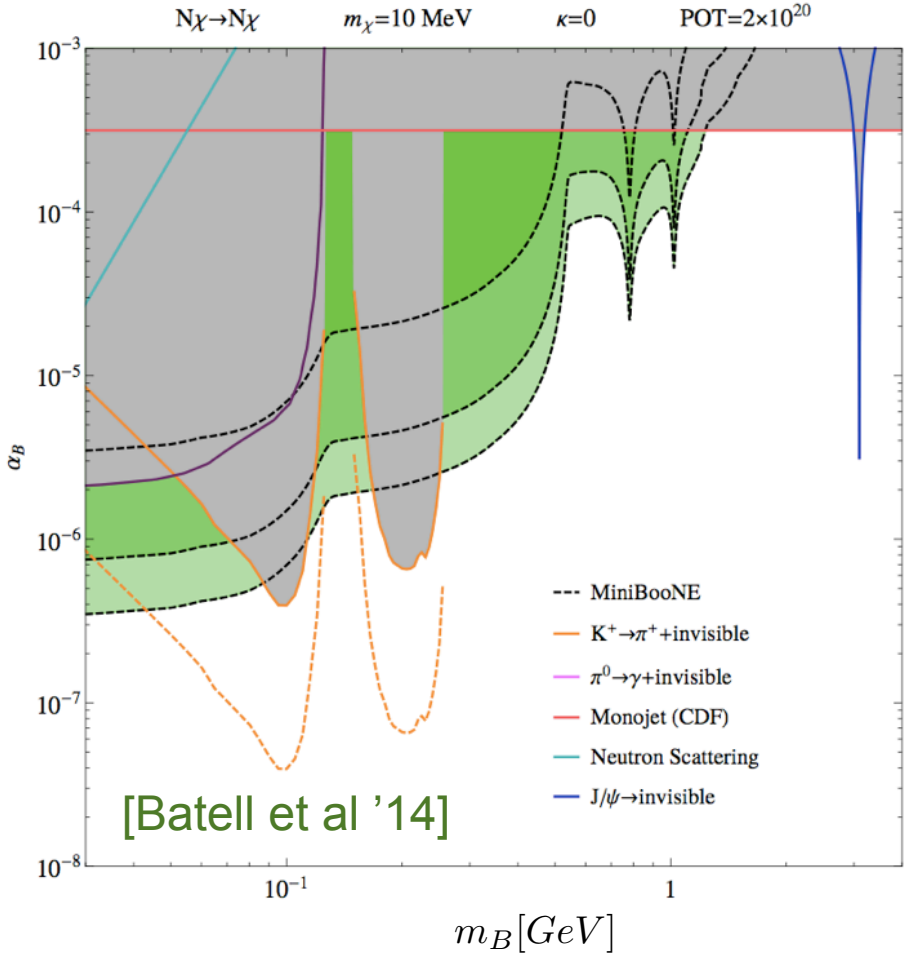
$$\mathcal{L} = g_B A_{B\mu} J_B^\mu$$

JEF (JLab)



Br(A_B →SM)~O(1)

MiniBooNE



Br(A_B →Hid)~O(1)

Summary

- Hidden sectors provide a generic resolution to several empirical pieces of evidence for new physics
  - EFT focusses attention on a small number of generic UV-complete interaction channels, un-suppressed by (possibly) heavy new physics scales
  - E.g. vector portal provides a light, technically natural, model with varied (testable) phenomenology

- Expanding experimental program to explore the primary interaction channels
  - *Parasitic operation* - Importantly, experimental sensitivity is available with small additions to experiments measuring SM rates (neutrino expts, new beam dumps for collider storage rings, FELs, and others) [➠ talk by Richard Milner]