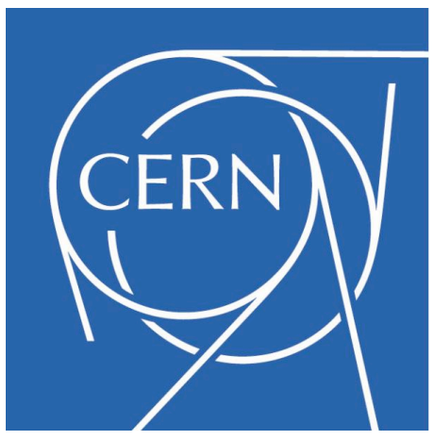
Theoretical Perspectives on Dark Photons

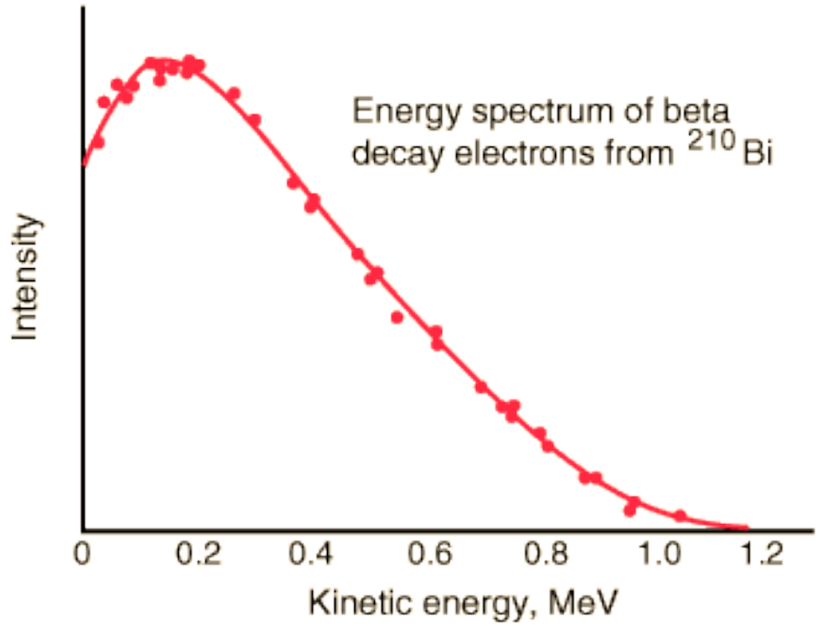
Brian Batell
CERN



PADME Kickoff Meeting
April 20-21, 2015

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons
- Beta decay: $n \to p + e^-$



Continuous spectrum!

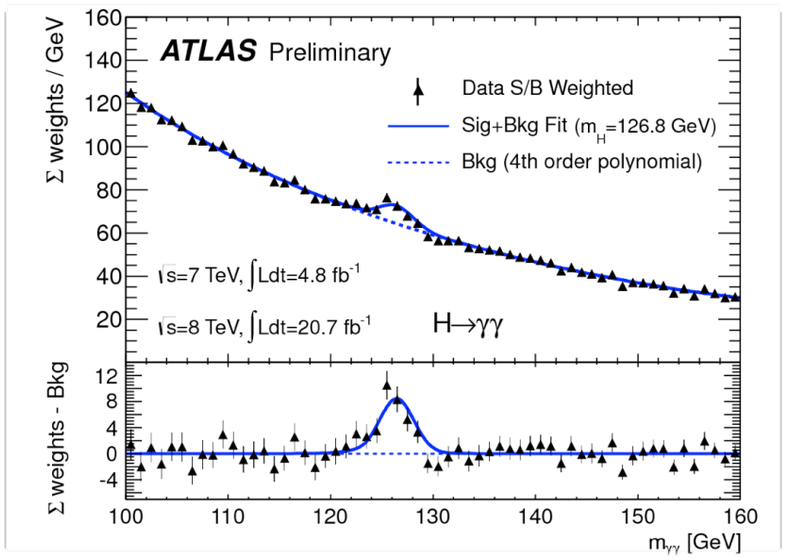
- Pauli proposes a radical solution - the neutrino!

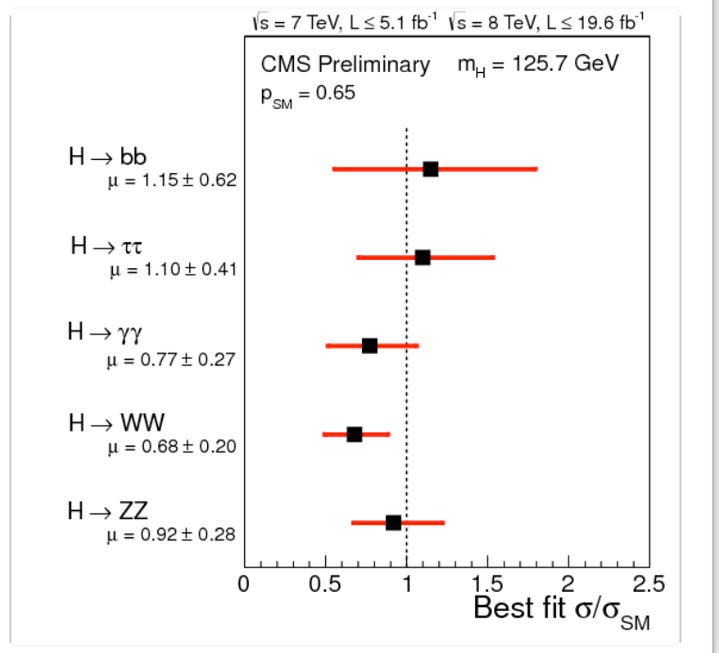
$$n \to p + e^- + \bar{\nu}$$

- Perfect example of a ***hidden sector***!
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Today, 2015 - Where are we?

- Higgs!
- Triumph of the Standard Model!



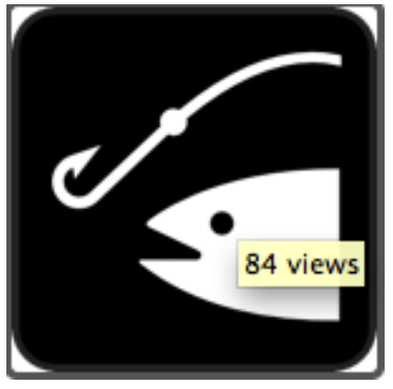


- Still, many reasons to believe there is new physics

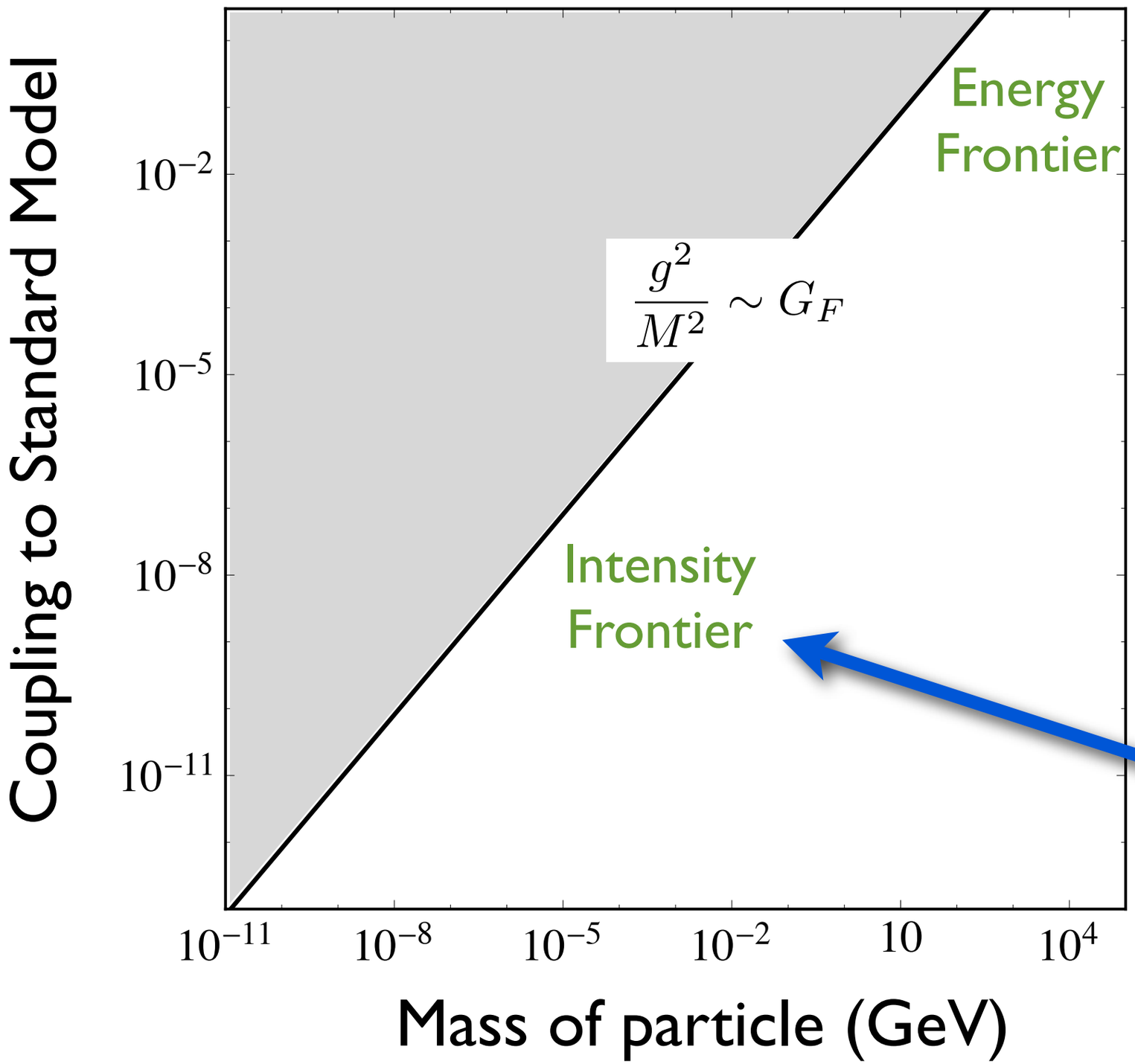
Theoretical: Naturalness (Higgs, CC), Flavor, Strong CP, Unification, Gravity ...

Empirical: Dark Matter, Neutrino Oscillations, Baryon Asymmetry

- Unfortunately, there are no guarantees of discovery
- All searches for new physics are now fishing expeditions



Where is the New Physics?



EWSB, Naturalness
WIMP DM ...

RH neutrinos
Axion
Dark Matter
Hidden sector
...

The Scale of New Physics

Theoretical hints (naturalness) - unambiguously points towards new scale

Hierarchy problem → $v \sim 100\,\mathrm{GeV}$

Cosmological Constant → $\rho_{\mathrm{vac}}^{1/4} \sim 10^{-3}\,\mathrm{eV} \quad (m_\nu \sim 0.1\,\mathrm{eV})$

Empirical hints - no firm prediction for the new physics scale!

Matter-Antimatter Asymmetry → ?

Dark Matter → ?

Neutrino mass → ?

We must search High and Low for New Physics!

Portals

$$LHN \qquad \text{Neutrino portal}$$

$$(\mu S + \lambda S^2) H^\dagger H \qquad \text{Higgs Portal}$$

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu} \qquad \text{Vector Portal}$$

- Only three renormalizable portals - can be generated at a high scale
- Respect approximate symmetries of the Standard Model
  - Flavor, Parity, CP - allows for relatively large couplings to be viable

Portals

LHN Neutrino portal

$(\mu S + \lambda S^2) H^\dagger H$ Higgs Portal

This is what we are here to discuss!

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$ Vector Portal

- Only three … at a high scale
- Respect ap… del
  - Flavor, P… gs to be viable

dictionary

$$V = A' = U = \gamma' = \dots$$

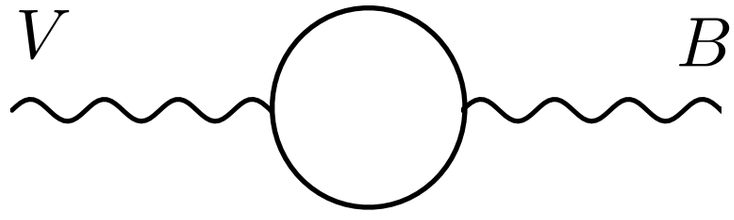
$$\kappa = \epsilon = \sqrt{\alpha'/\alpha} = \chi$$

Vector Portal

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$

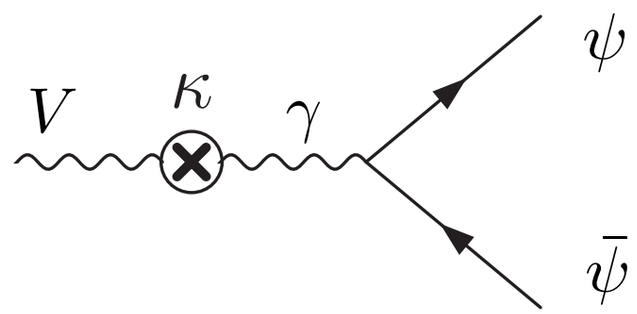
Holdom '86

Mixing parameter can be generated radiatively at one or more loops; expected size ~ 10^{-3} or smaller



$$\kappa \sim \frac{g_Y g_D}{16\pi^2} \log\left(\frac{M}{\mu}\right)$$

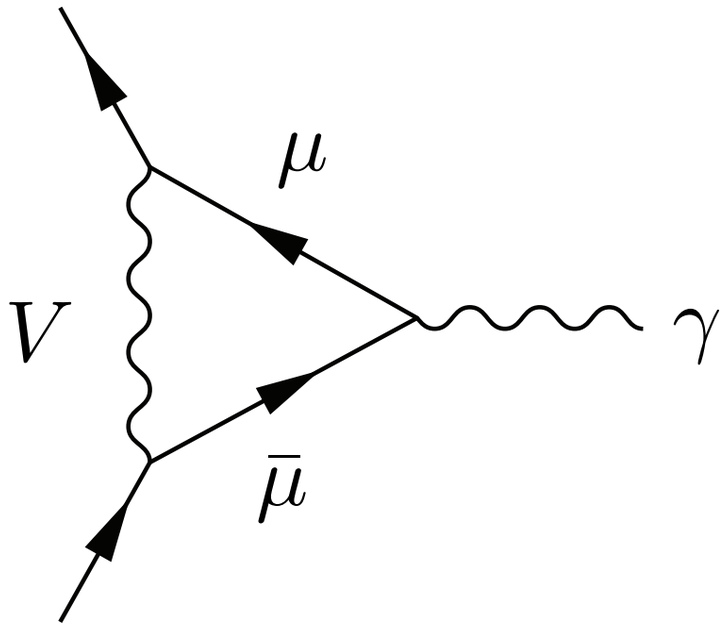
If dark U(1) is broken visible matter picks up a milli-dark charge.

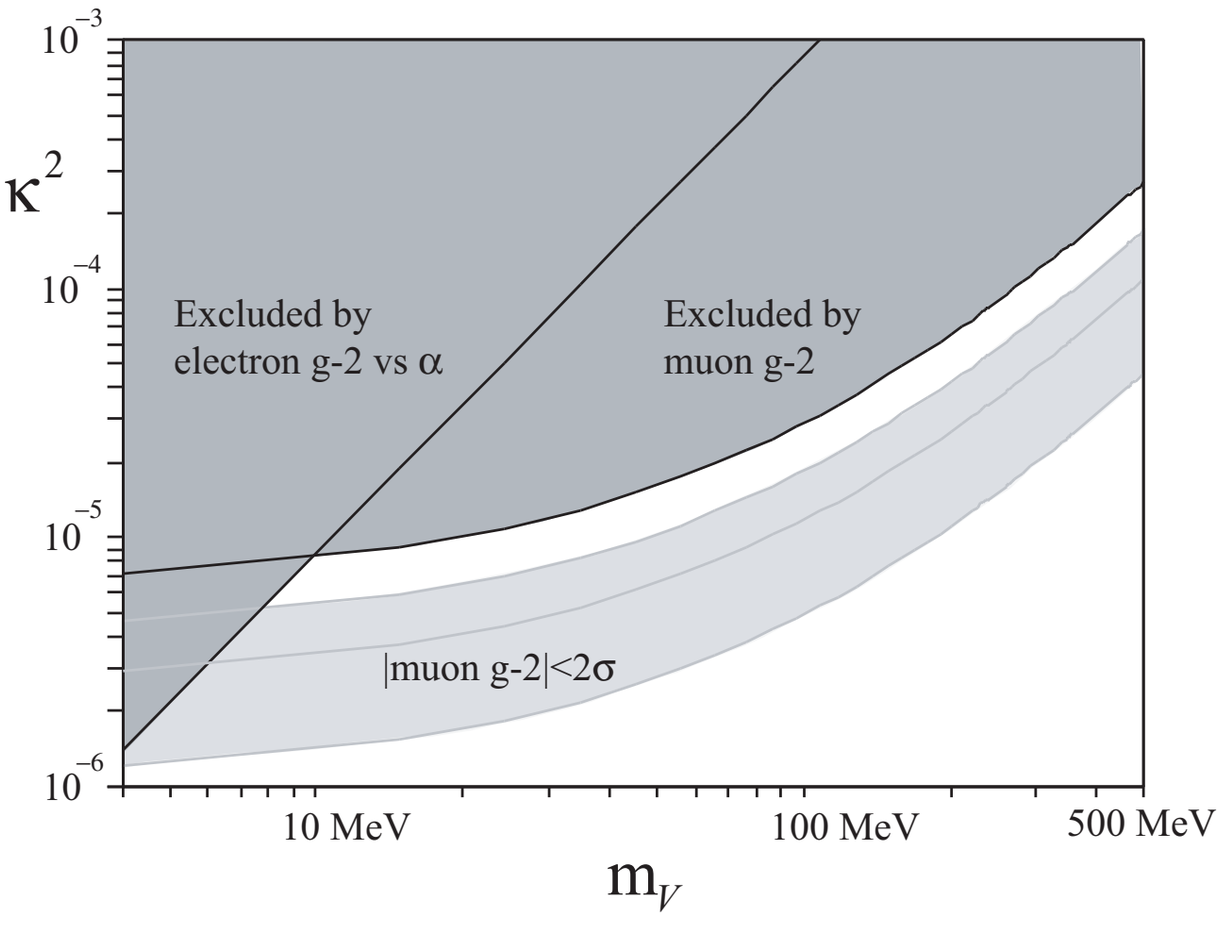


$$\mathcal{L} \supset -\kappa\, e\, V_\mu J^\mu_{\rm EM}$$

Dark photon can address the $(g-2)_\mu$ anomaly $(\sim 3-4\,\sigma)$!

$$\Delta a_\mu = \frac{\kappa^2\alpha}{2\pi} \times \begin{cases} 1 & \text{for} \quad m_\mu \ll m_V \\ \frac{2m_\mu^2}{3m_V^2} & \text{for} \quad m_\mu \ll m_V \end{cases}$$





Pospelov
Bohm, Fayet

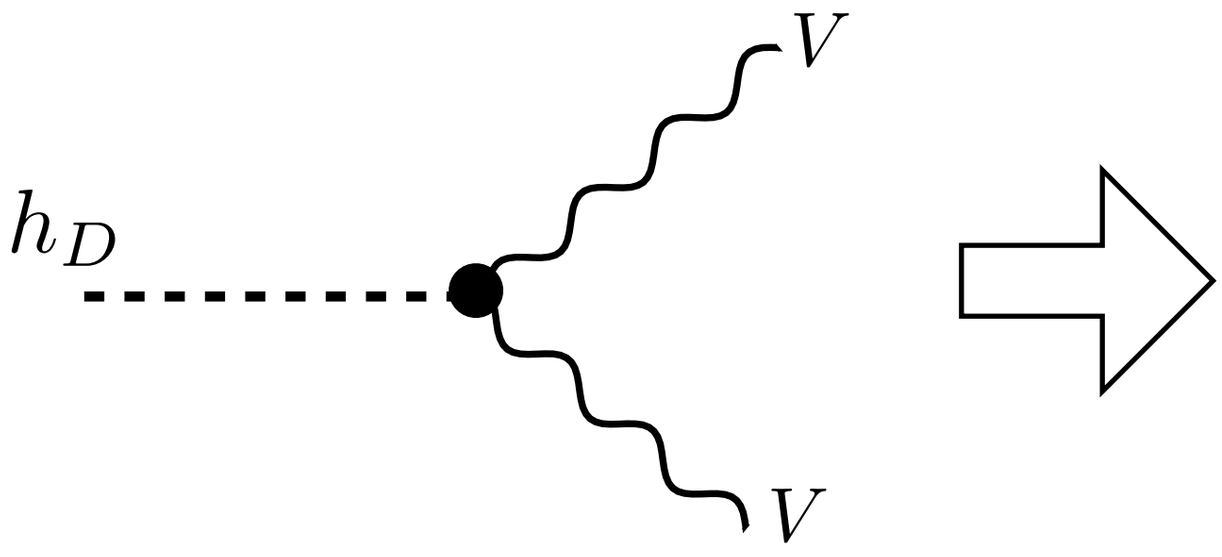
Dark Higgs

BB, Pospelov, Ritz '09

- How is the dark photon mass generated?

$$\mathcal{L} \supset |D_\mu \phi|^2 - V(\phi) \qquad \left(D_\mu = \partial_\mu - i g_D V_\mu \right)$$

$$\rightarrow \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{m_V^2}{v'} h_D V_\mu V^\mu + \dots$$

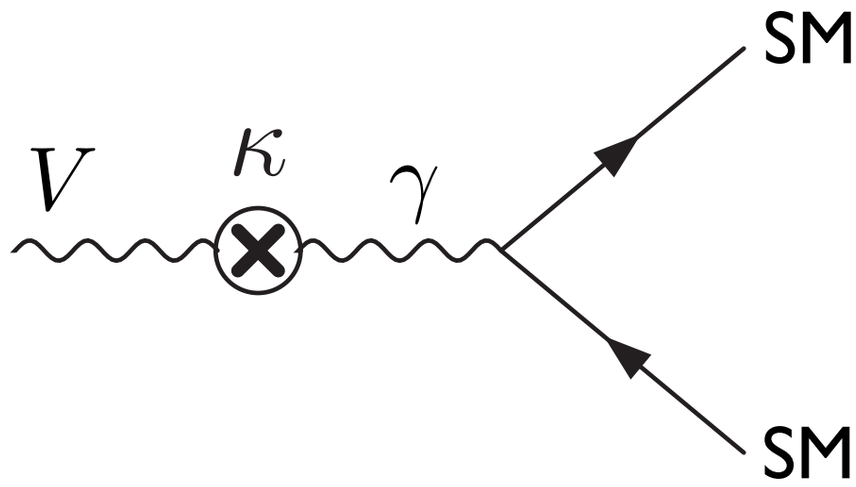


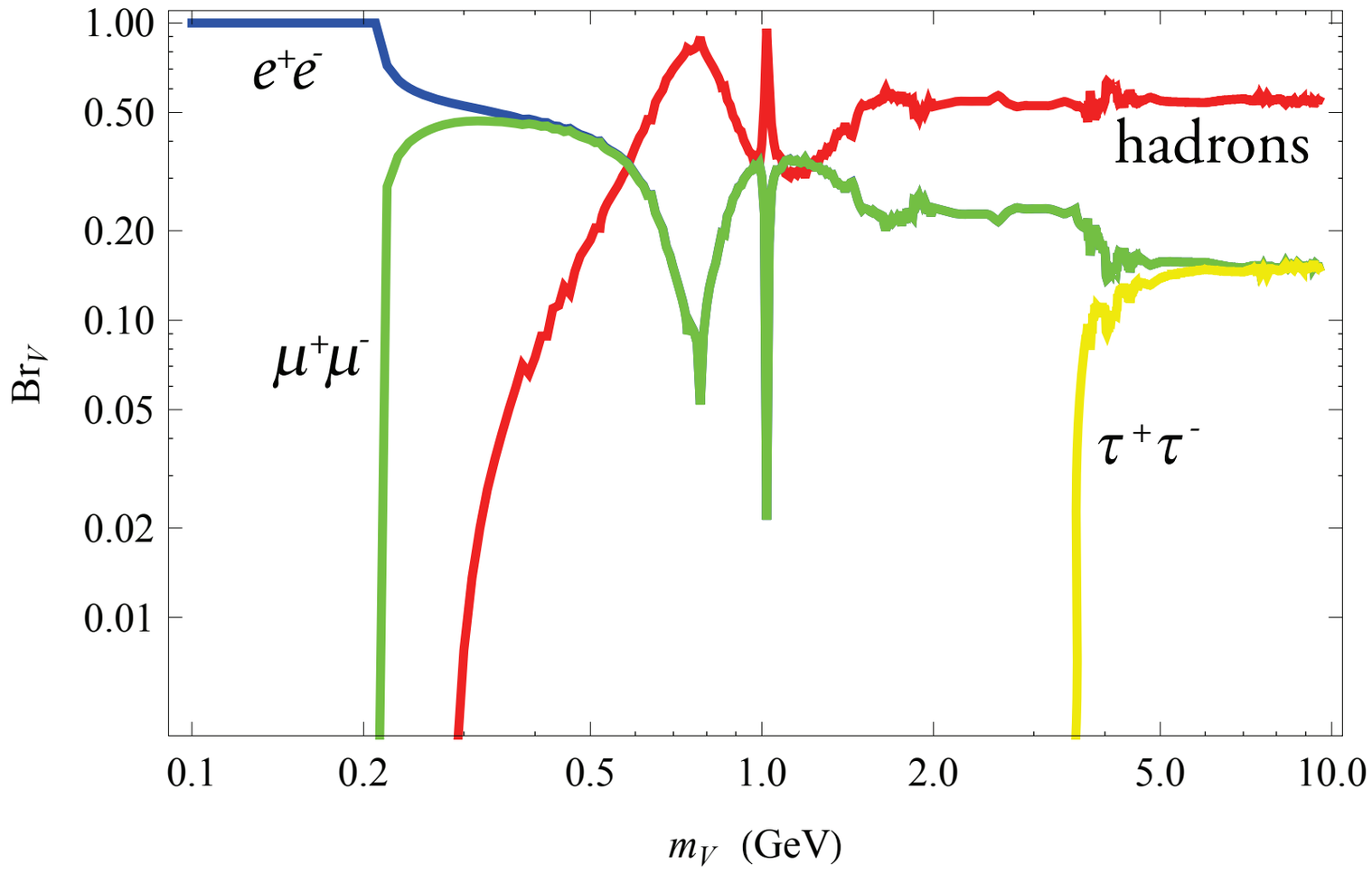
Production and decay of Dark Higgs through vector portal!

“Visible” Dark Photons

Governed by measured EM form factor

Significant branching to leptons

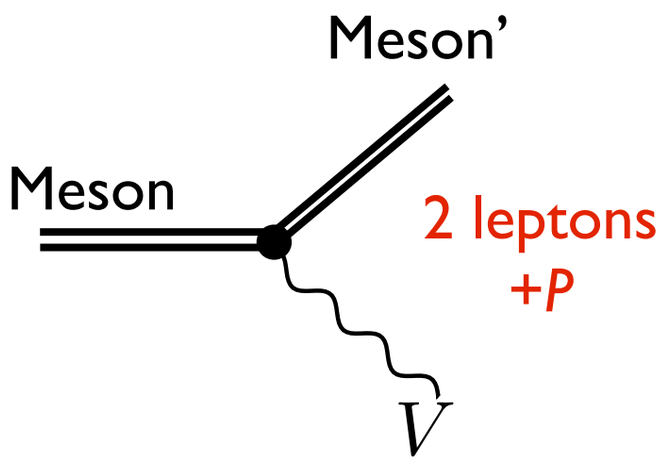




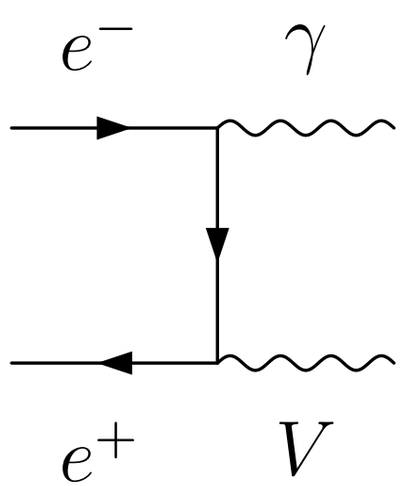
BB, Pospelov, Ritz ’09

Signatures at e^+e^- colliders, meson factories

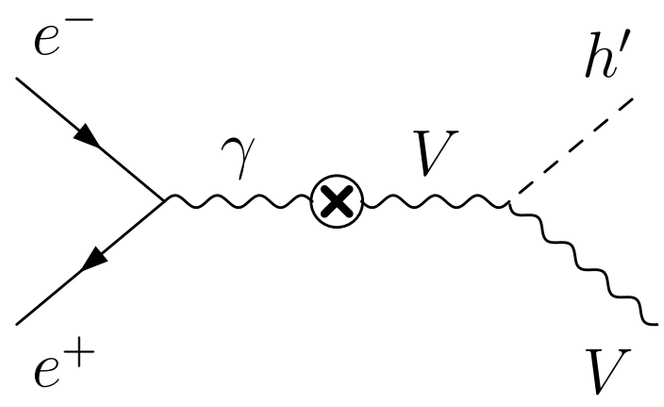
BB, Pospelov, Ritz
Essig, Schuster, Toro
Reece, Wang



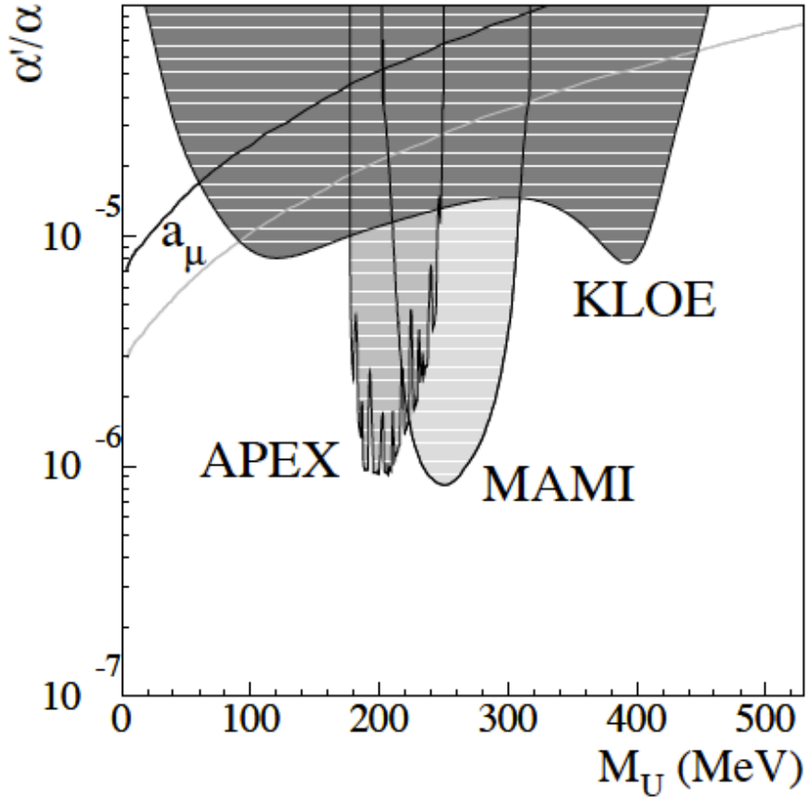
2 leptons
+*P*



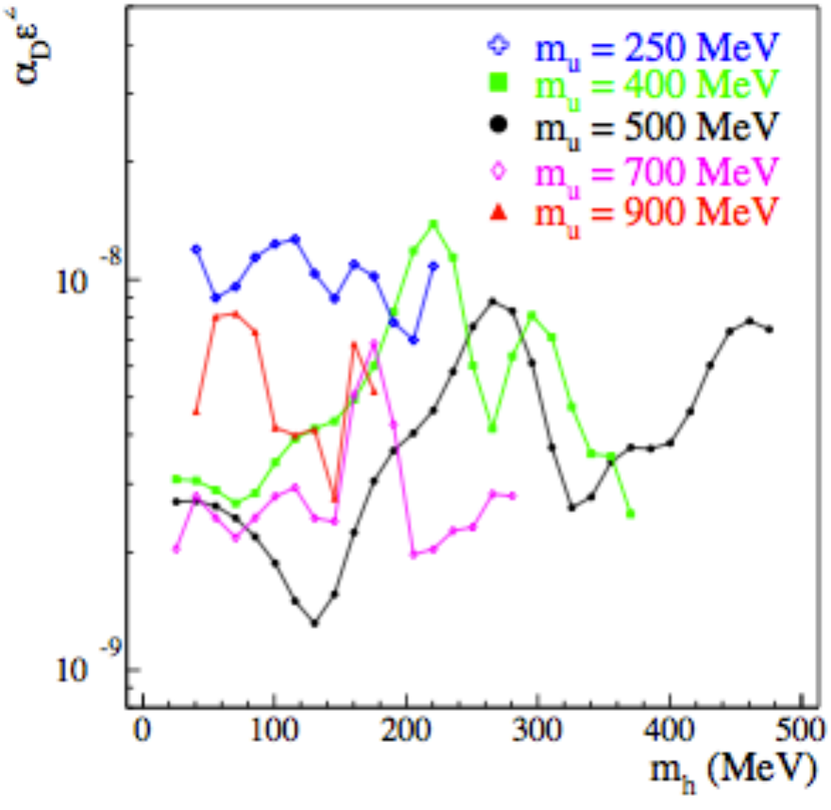
2 leptons
+ photon



6 leptons
or
2 leptons
+ MET



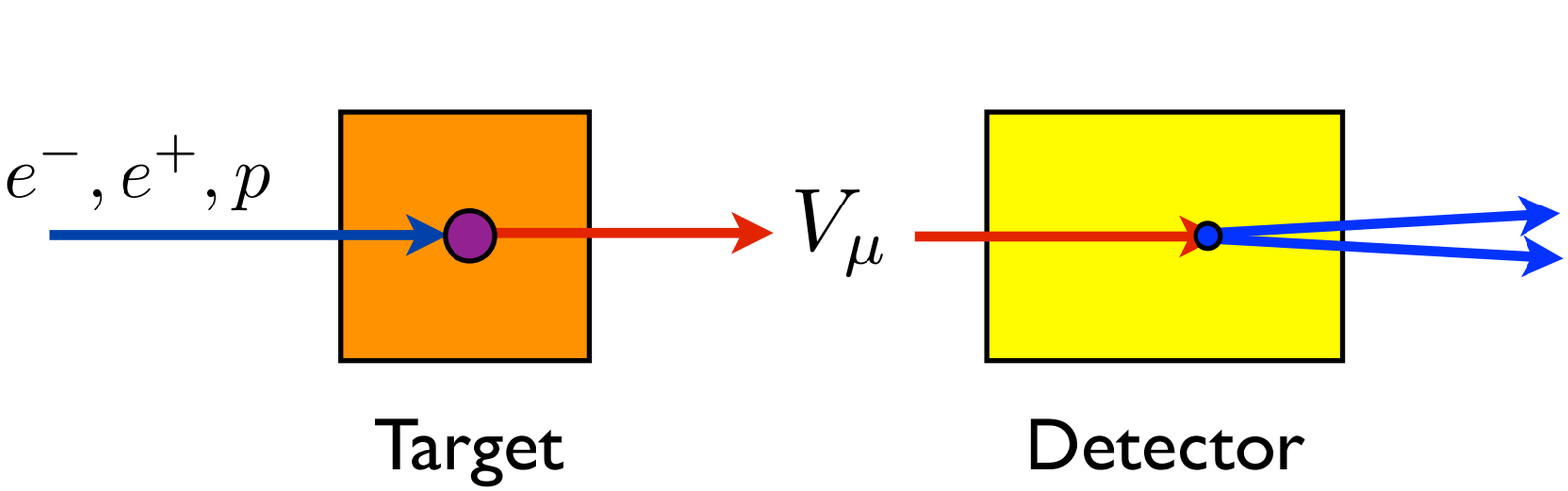
[KLOE-2, arXiv:1110.0411]

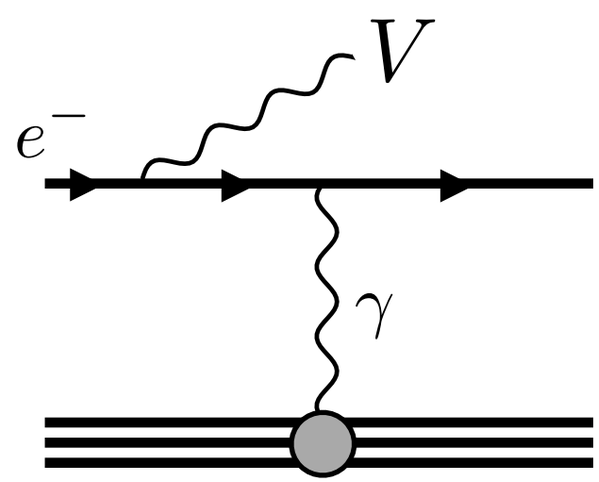


[KLOE-2, arXiv:1501.06795]

Signatures at high intensity fixed target experiments

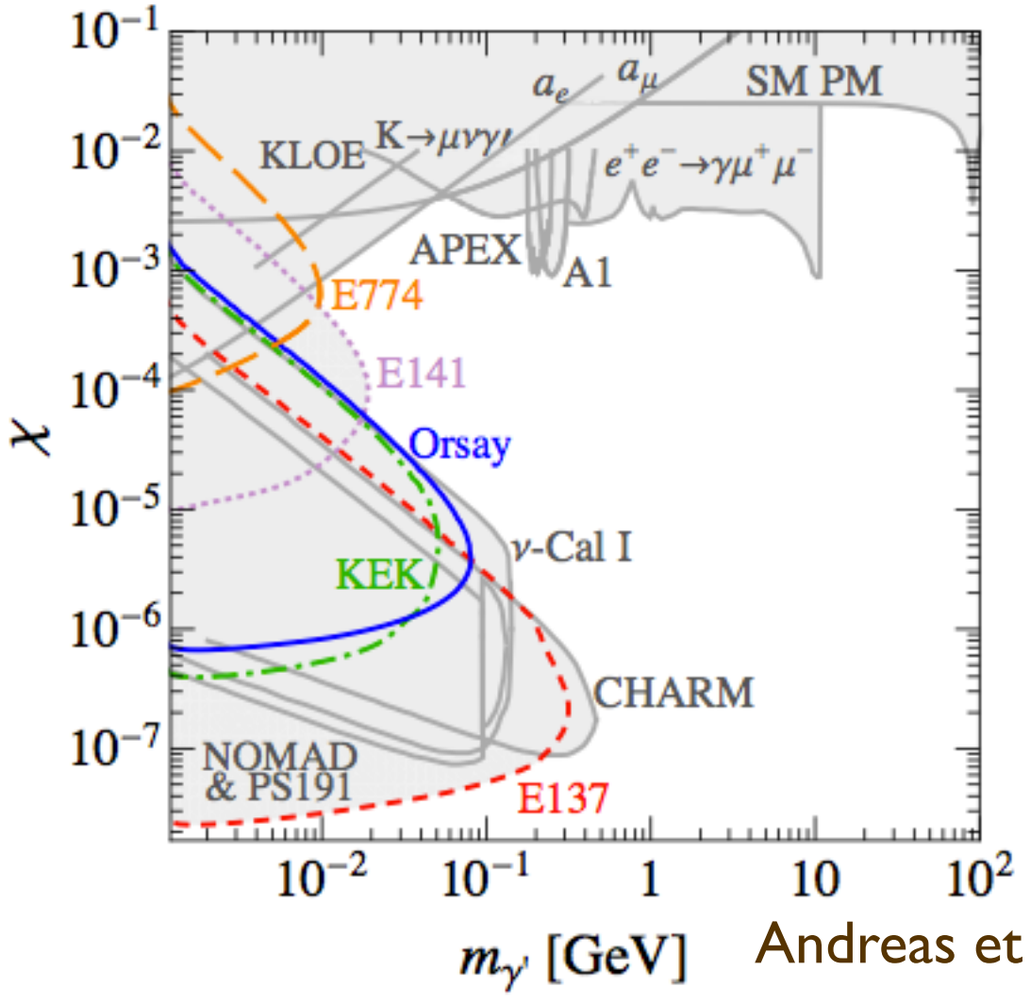
Bjorken, Essig, Schuster, Toro;
Andreas, Niebuhr, Ringwald;
and others...





- Look for a e^+e^- resonance or displaced vertex

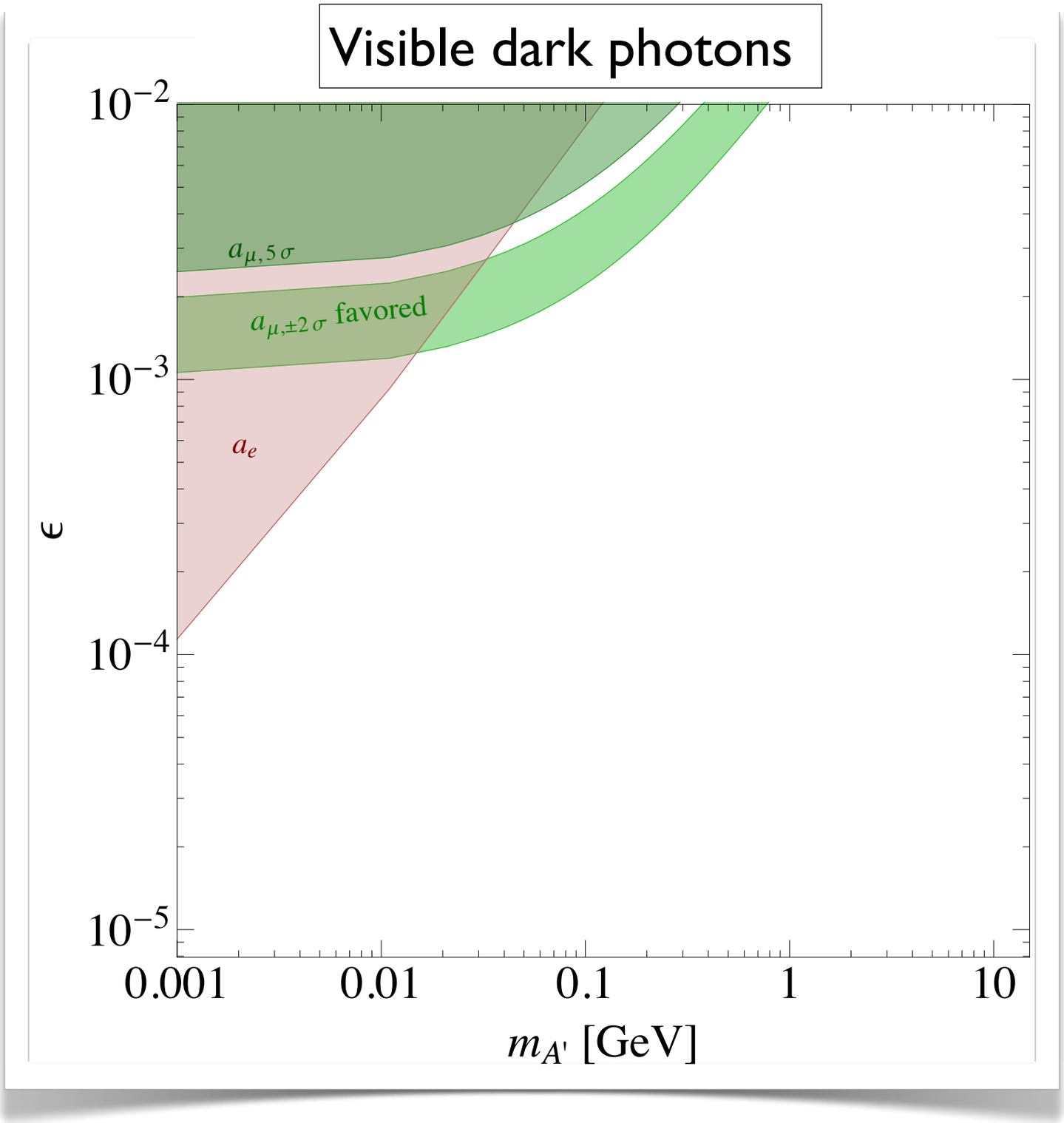
- Current/planned experiments (APEX, HPS, MAMI, DarkLight, VEPP-3, MESA, mu3e, SHiP...) will cover a lot of new ground!



Andreas et al;

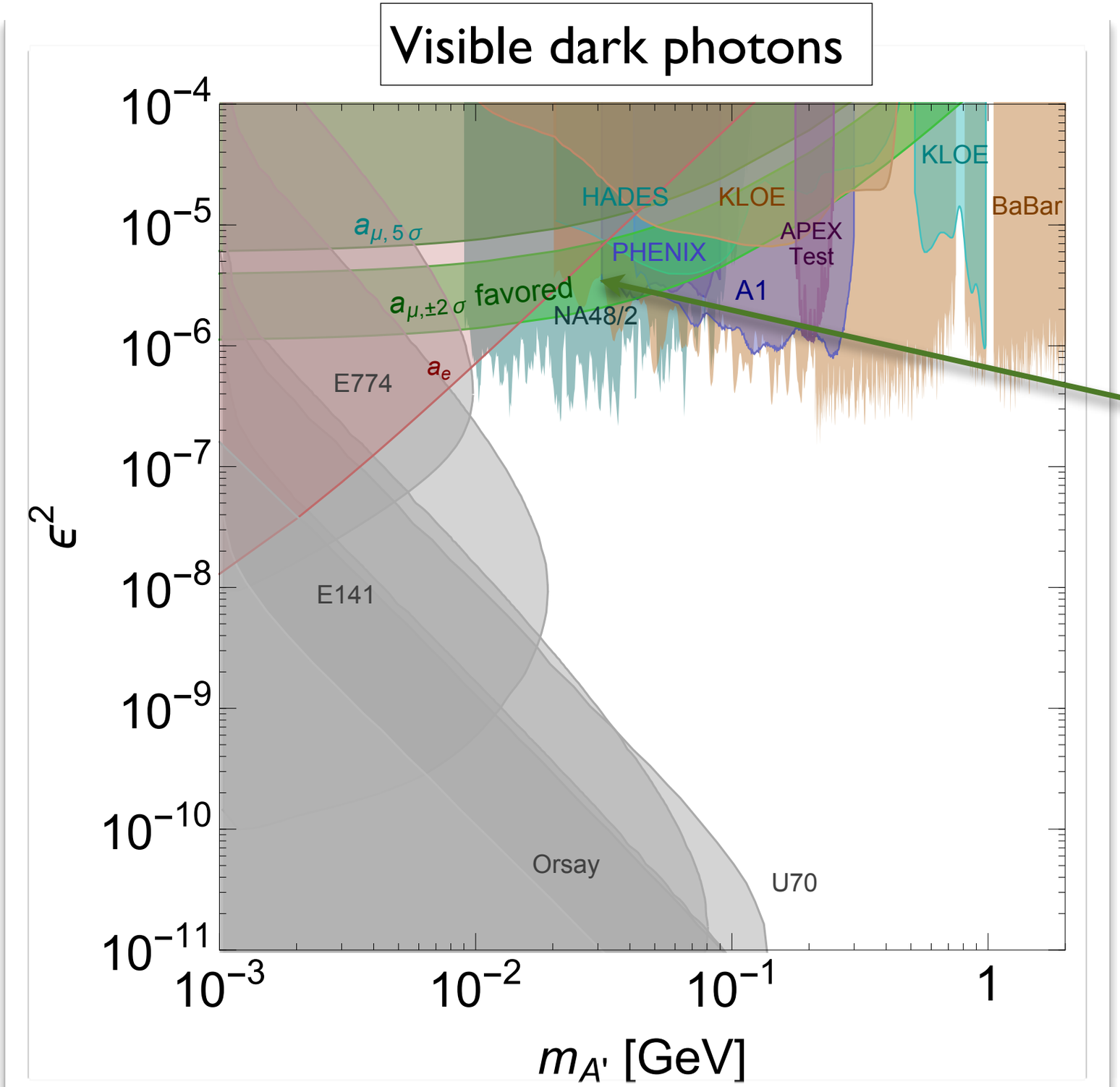
Where we started

Thanks to R. Essig for the plots!



Where we stand today

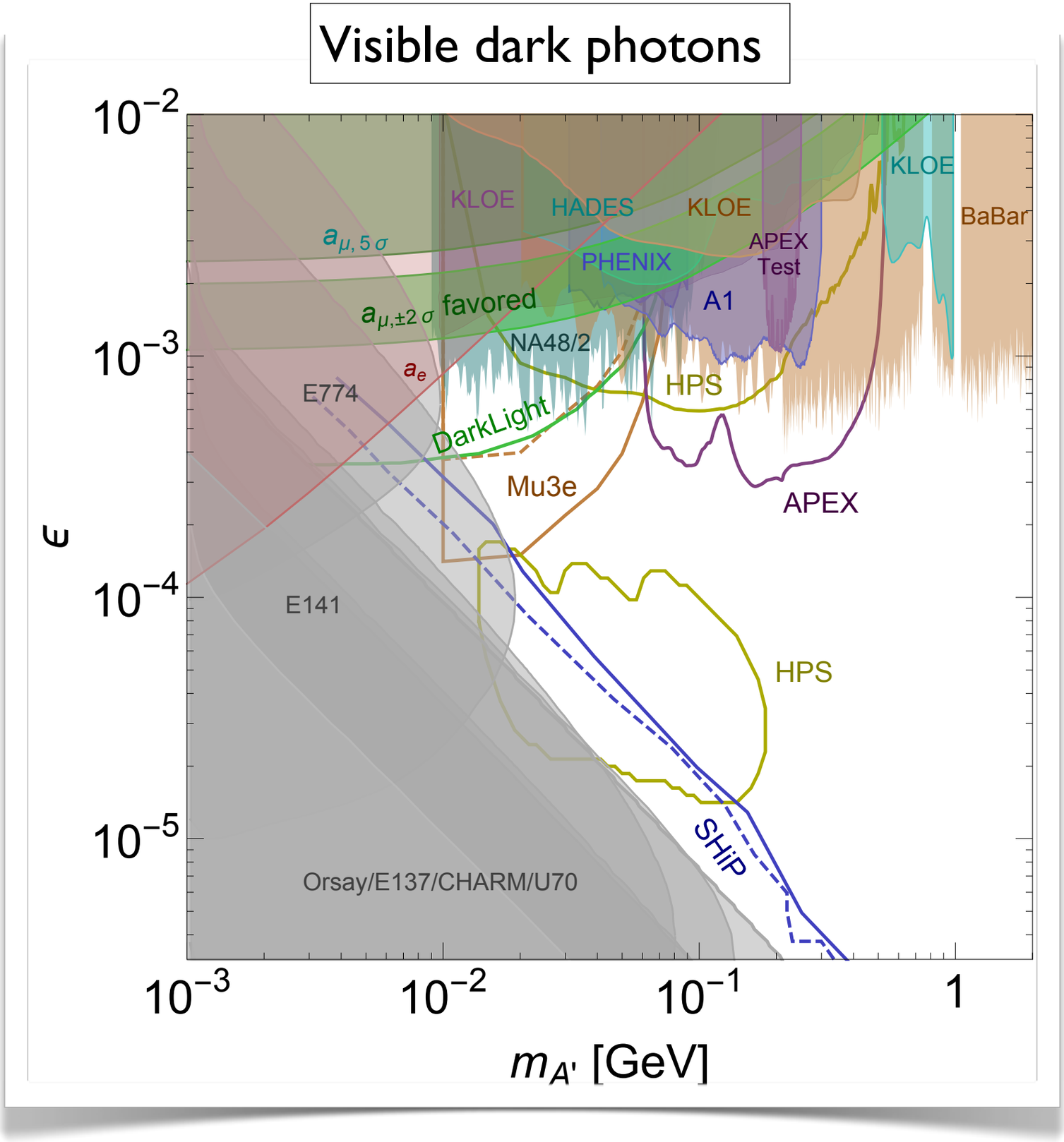
Thanks to R. Essig for the plots!



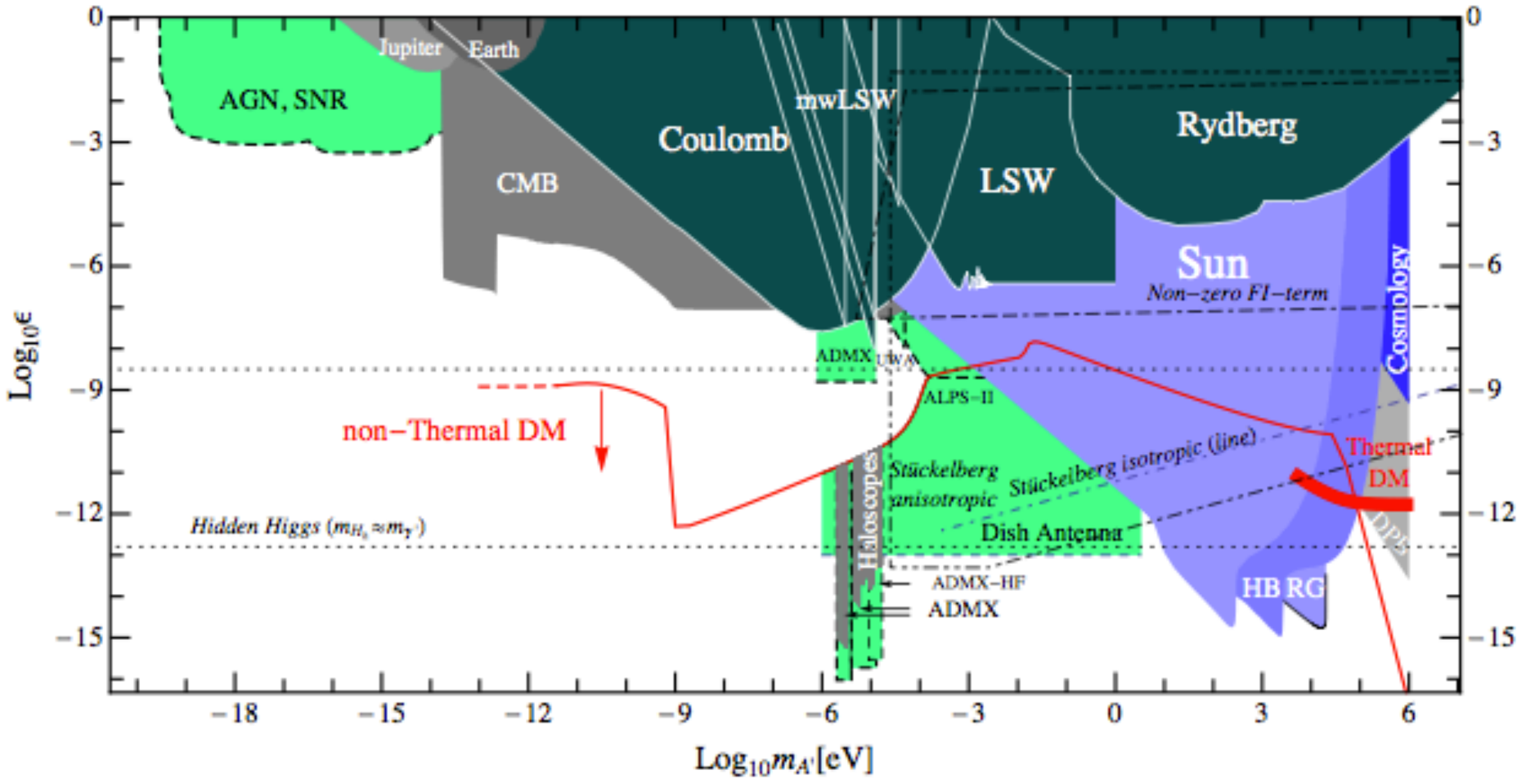
$(g-2)_\mu$ region excluded for visible decays!

Where we are headed

Thanks to R. Essig for the plots!



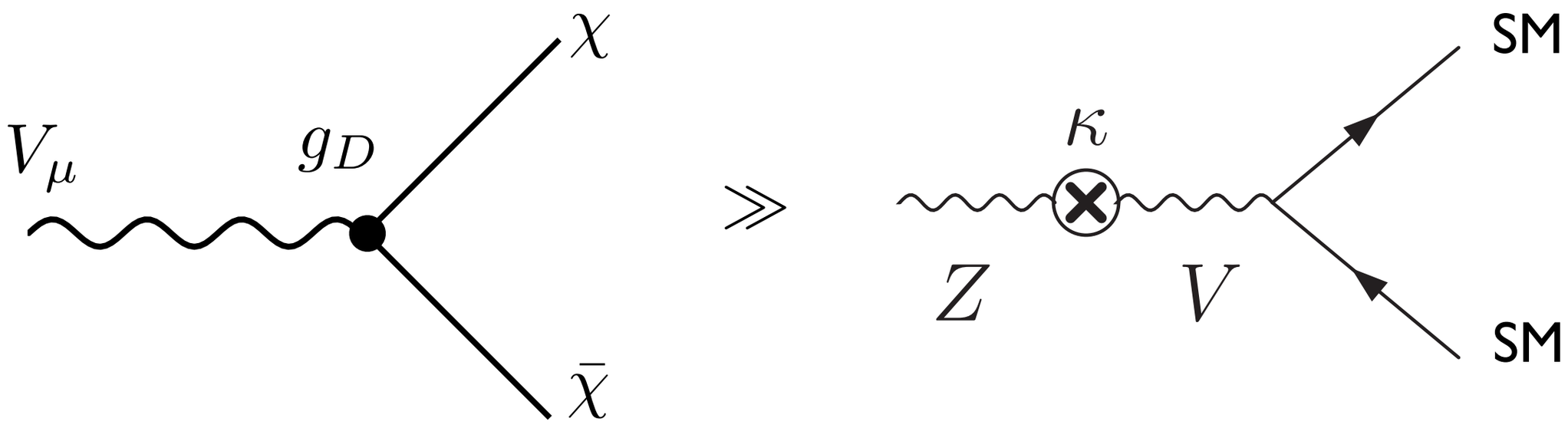
The Big Picture



Jaeckel, Ringwald, Redondo...

Invisible dark photons

- Suppose there are new matter fields, χ , chared under U(1)D, with mass $m_\chi < m_V/2$

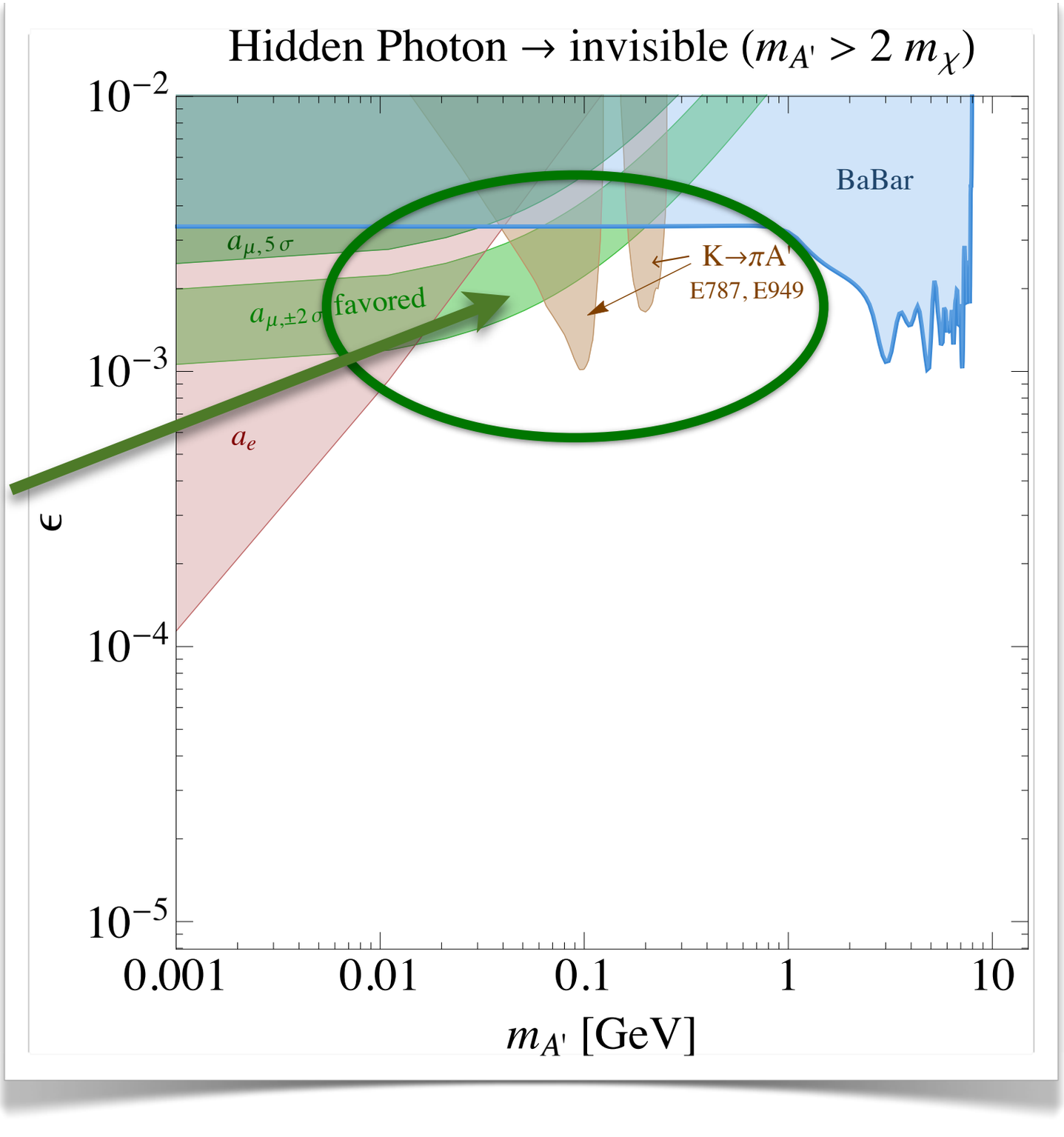


All of the previous limits that rely on the dark photon decaying to leptons do not apply!

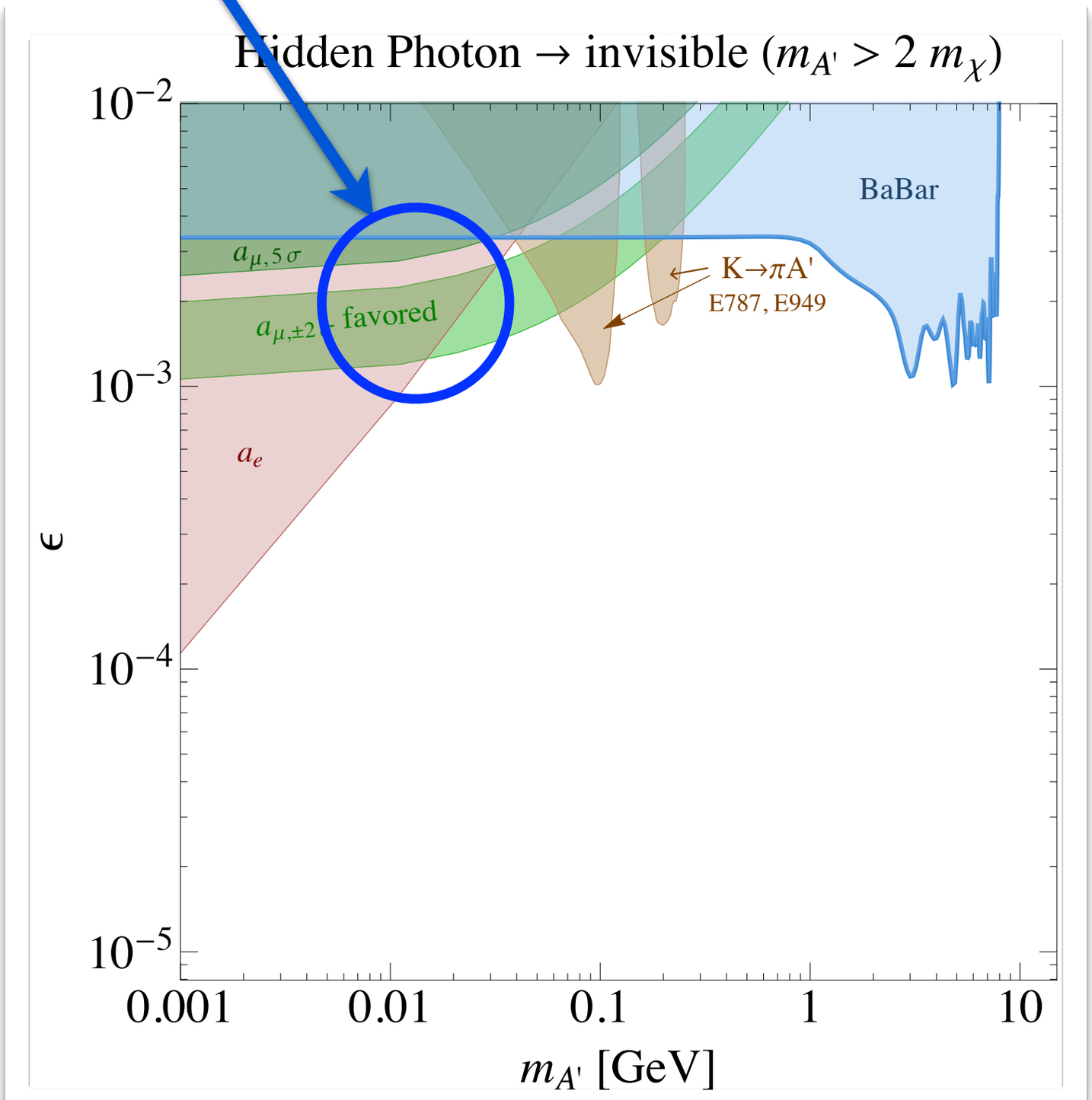
Where we stand today

Thanks to R. Essig for the plots!

$(g-2)_\mu$ explanation still possible for invisible decays!



PADME can look here!



Caution with $(g-2)_e$ constraint

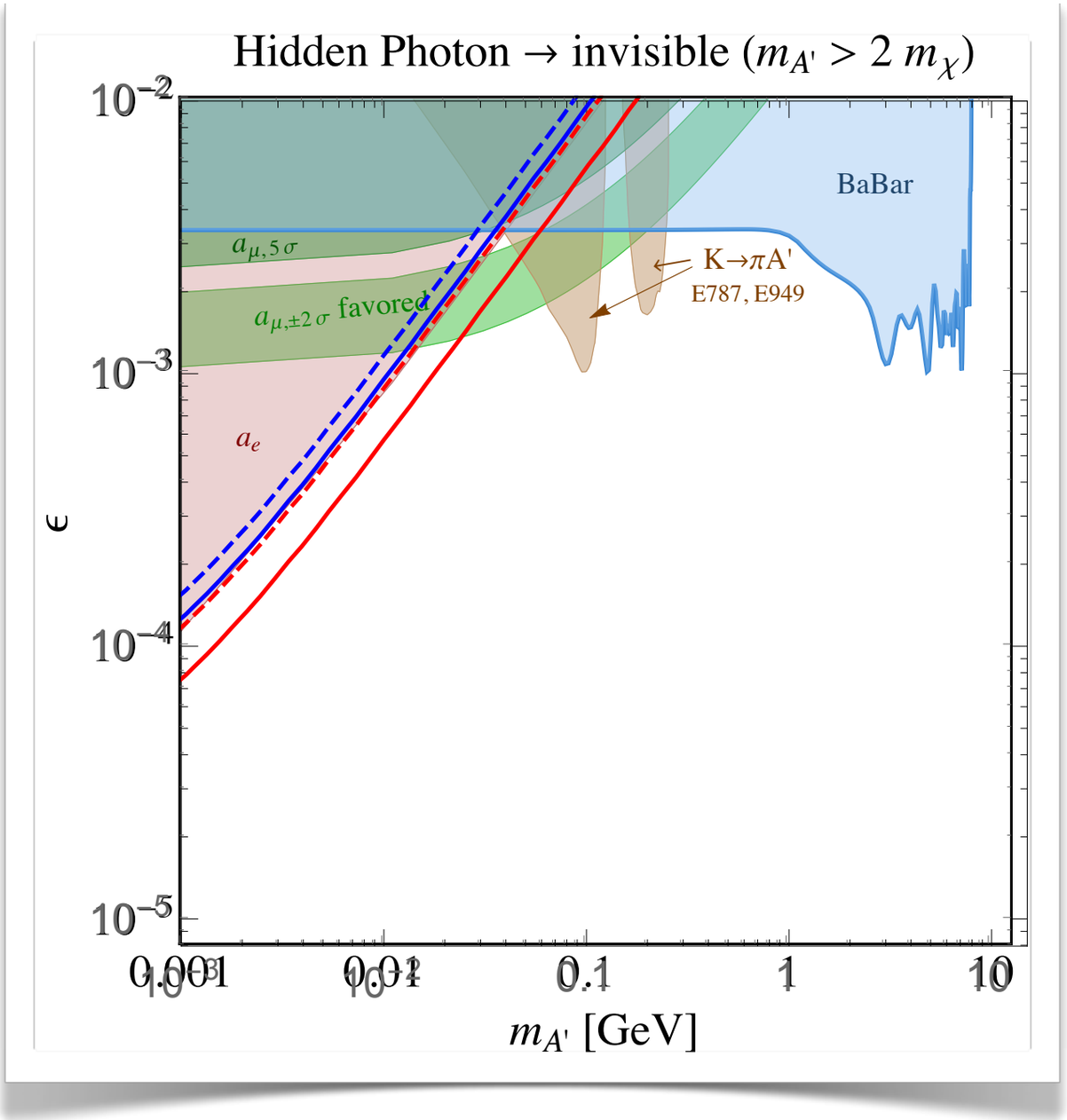
- The two most precise determinations of fine structure constant disagree at 1.5σ level
- One can reasonably argue for a more conservative constraint

$$\Delta a_e = (-1.05 \pm 0.82) \times 10^{-12}$$

Aoyama et al. 1205.5368

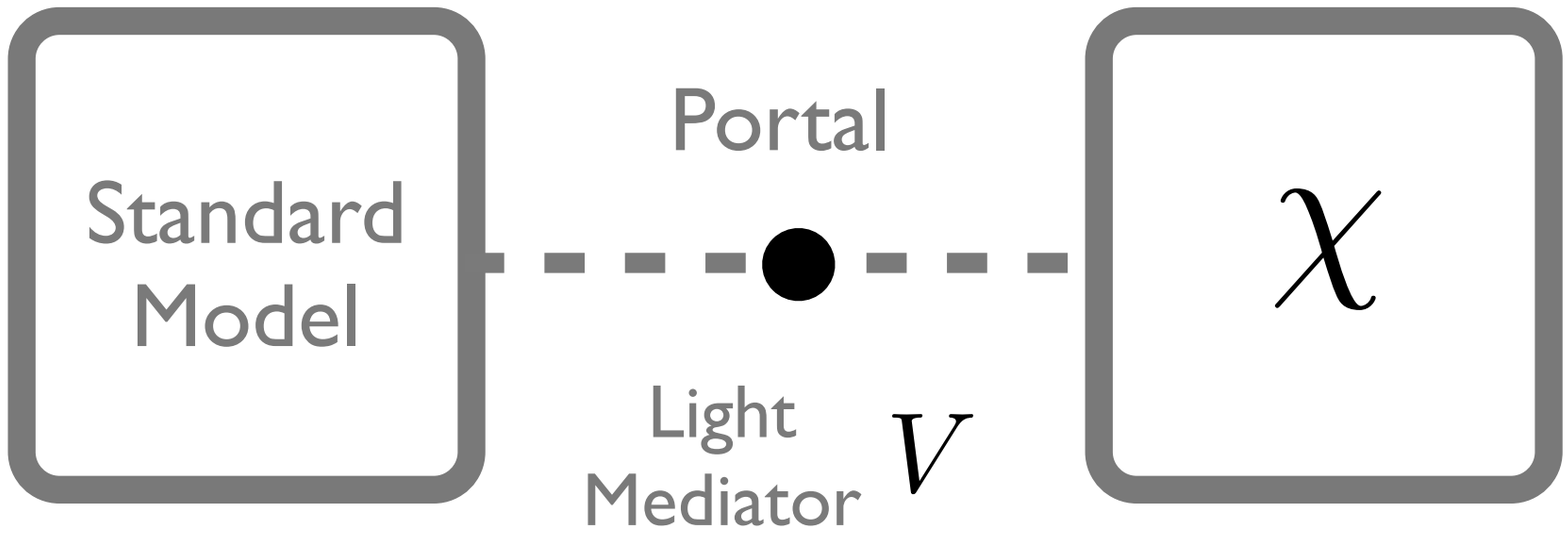
Or just using error

$$\Delta a_e = \pm 0.82 \times 10^{-12}$$

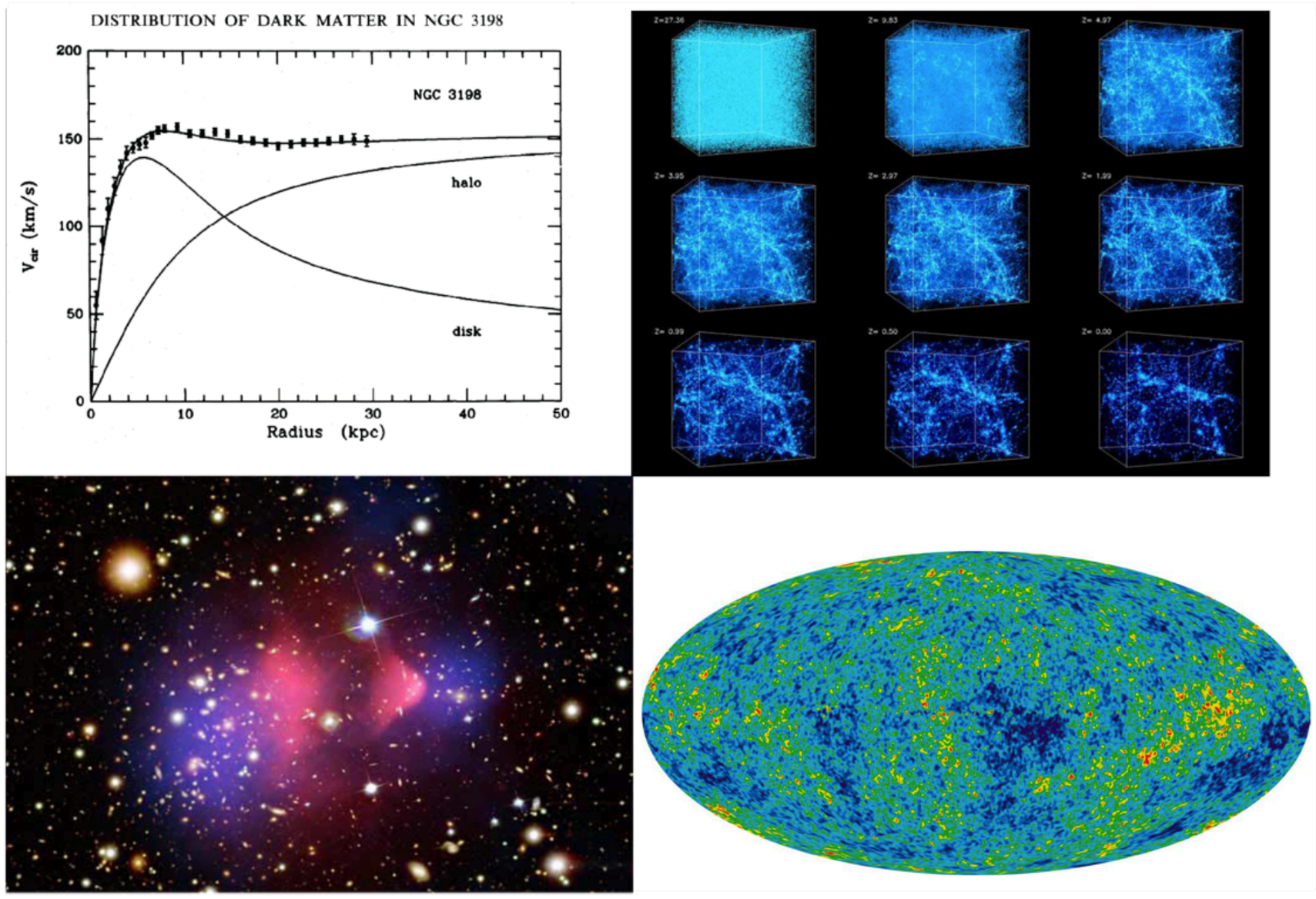


Important to also have a direct probe of this region of parameter space!

Portal to Dark Matter

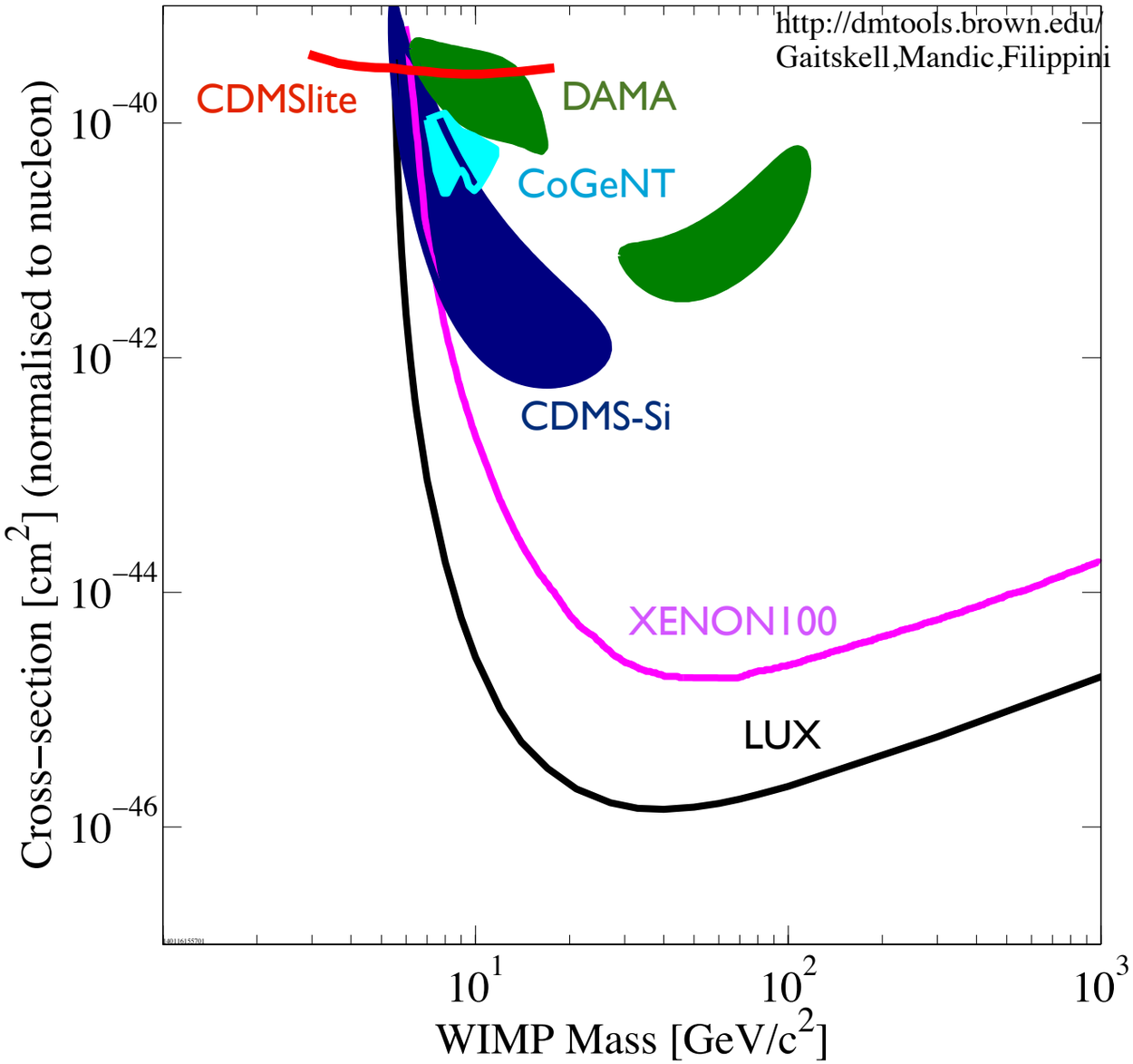


Dark Matter



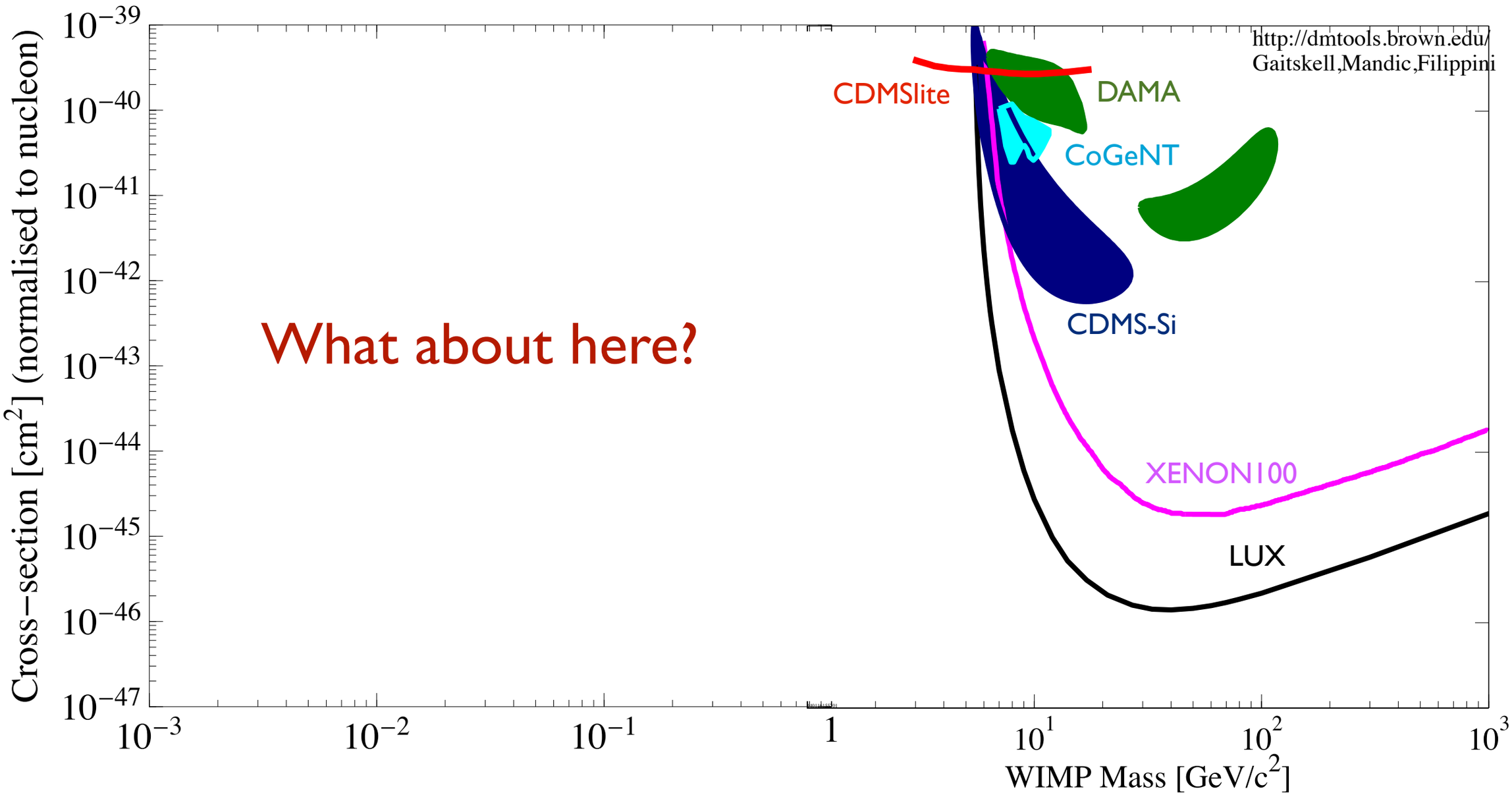
- One of the few *empirical* hints of new physics
- Detecting non-gravitational interactions of DM is a top-priority

Direct Detection



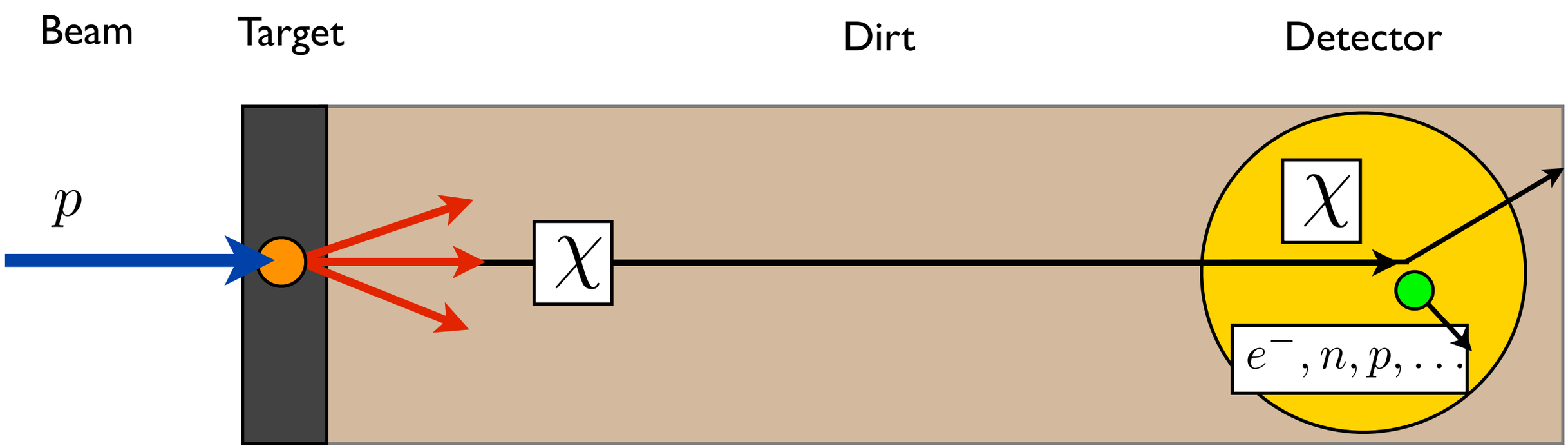
- Enormous progress over past two decades
- Probe DM masses above ~ few GeV

Direct Detection



- Nuclear recoil too weak - $v_{\rm DM} \sim 10^{-3}$
- Can we find a relativistic source of Dark Matter?

Relativistic Dark Matter Beam!



BB, Pospelov Ritz '09

Superior sensitivity to light dark matter + light mediator

Provides a strong new physics motivation for intense proton and electron sources

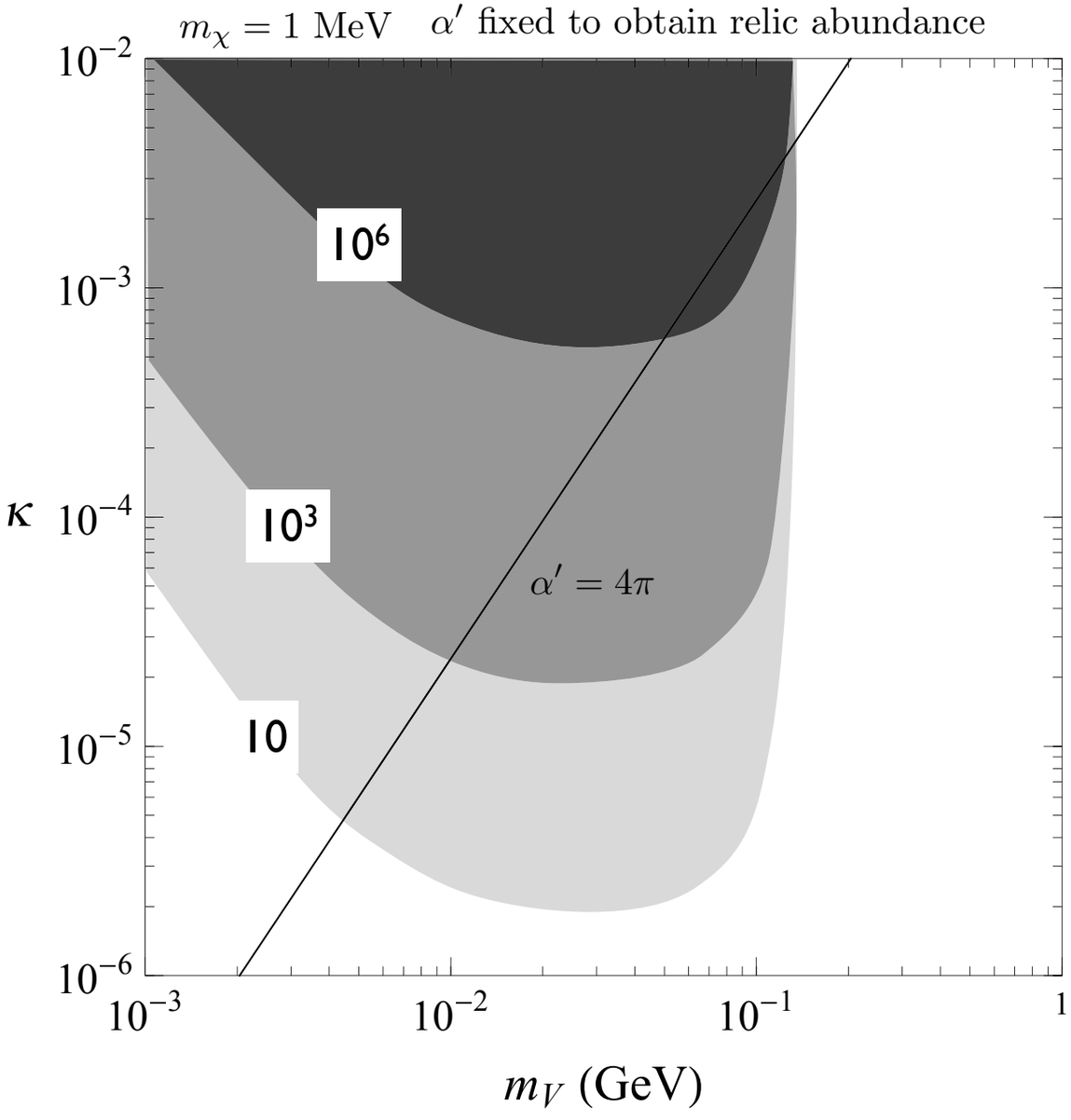
LSND

Production: $\pi^0 \to \gamma V \to \gamma \chi \bar{\chi}$

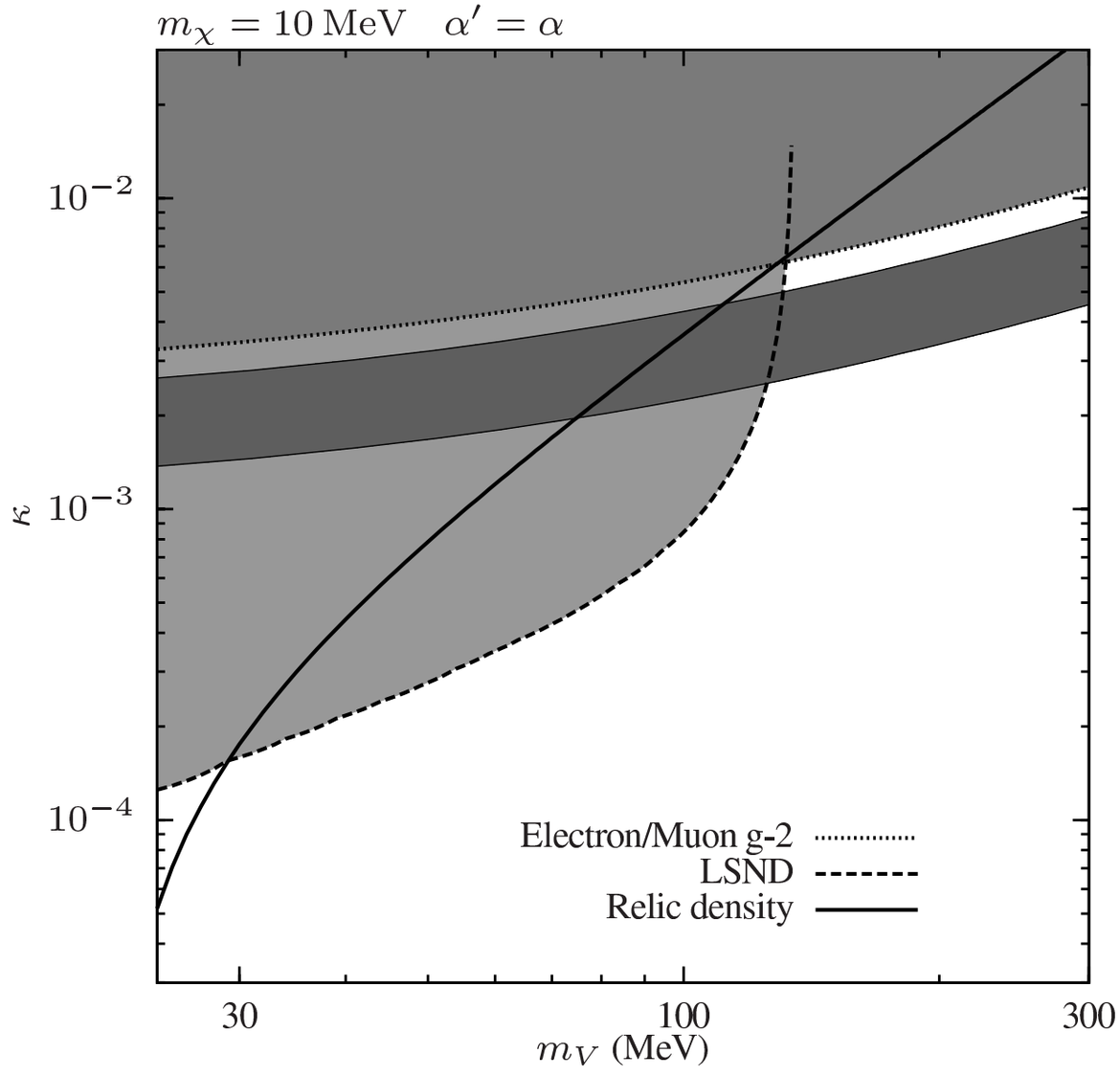
Sensitivity to $\chi e \to \chi e$

[Auerbach et al. (LSND Collaboration), '01]

- LAMPF, 800 MeV protons, ~ 10^{23} POT
- water / high Z target
- detector: 30m off axis from target, cylindrical, 170 tons mineral oil



BB, Pospelov, Ritz



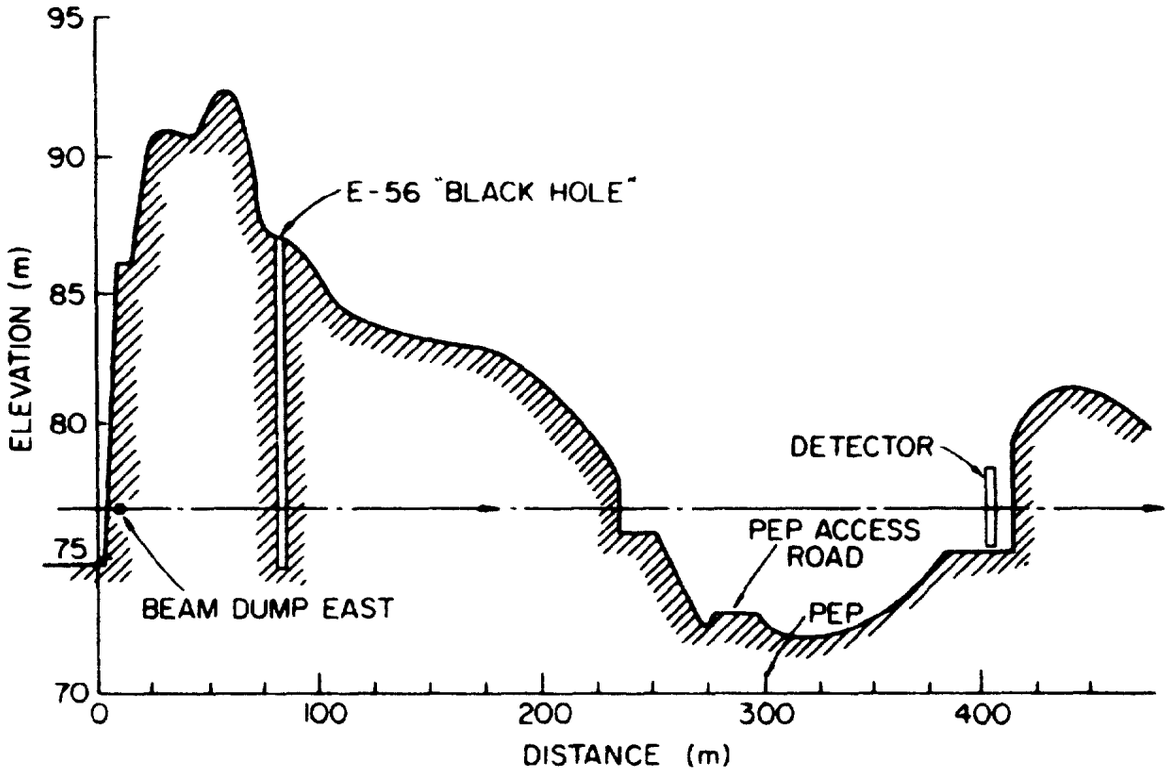
deNiverville, Pospelov, Ritz

SLAC E137

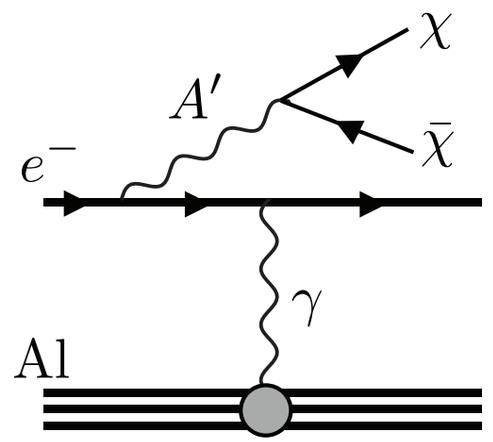
BB, Essig, Surujon

[Bjorken et al., (E137 Collaboration) '88]

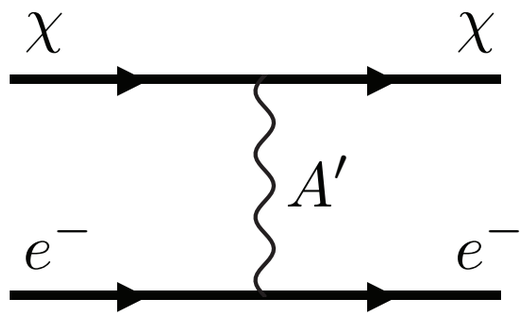
- 20 GeV electron beam; 30 C dumped;
- Aluminum target
- Shower calorimeter detector, 400m from dump

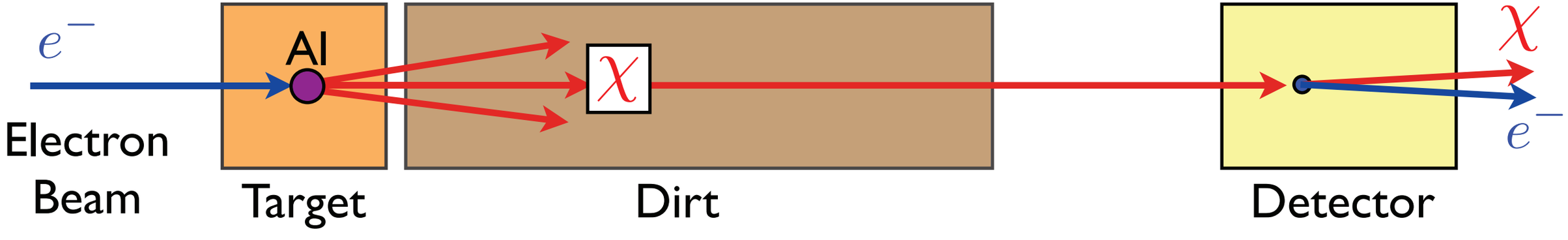


Production



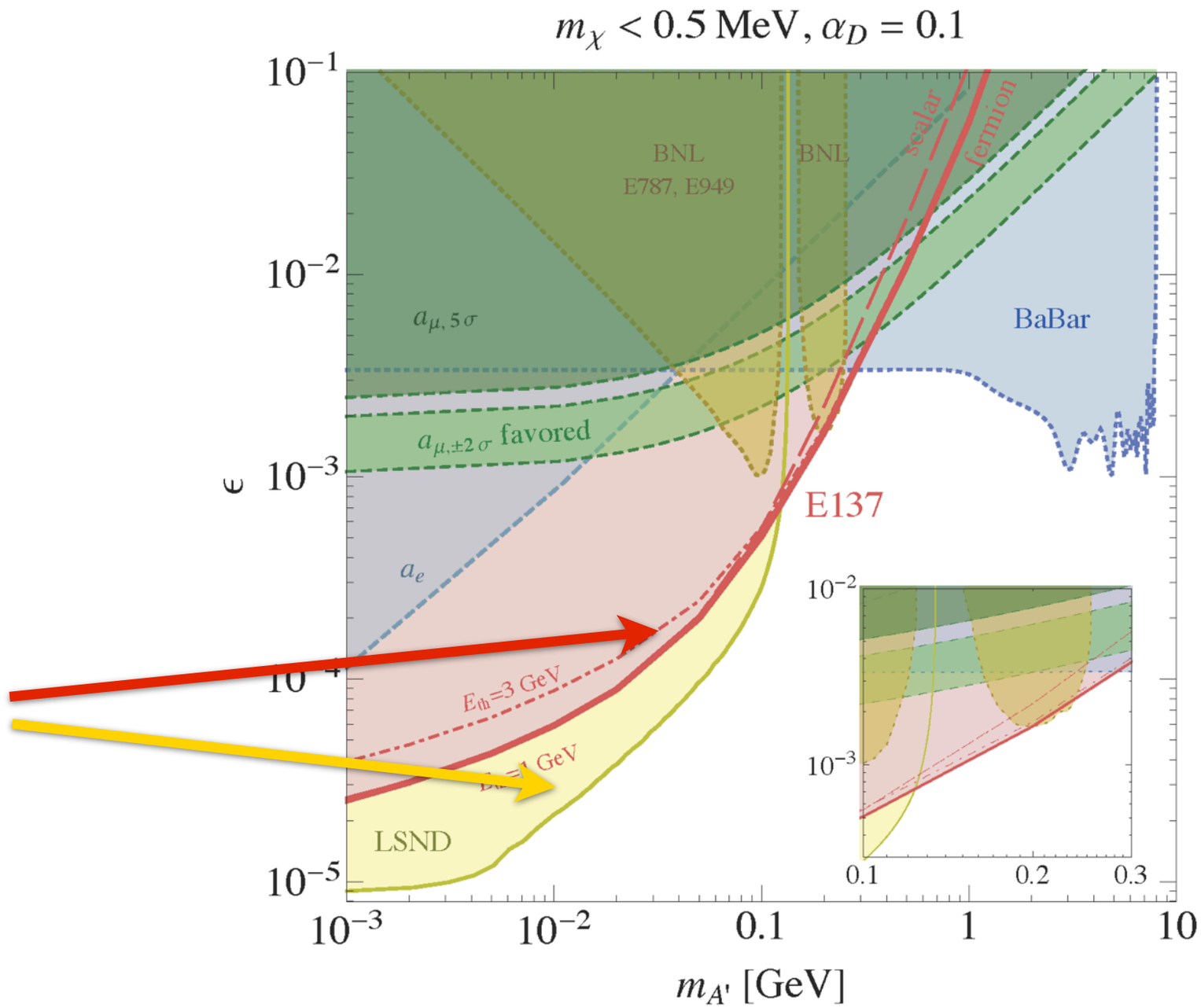
Scattering





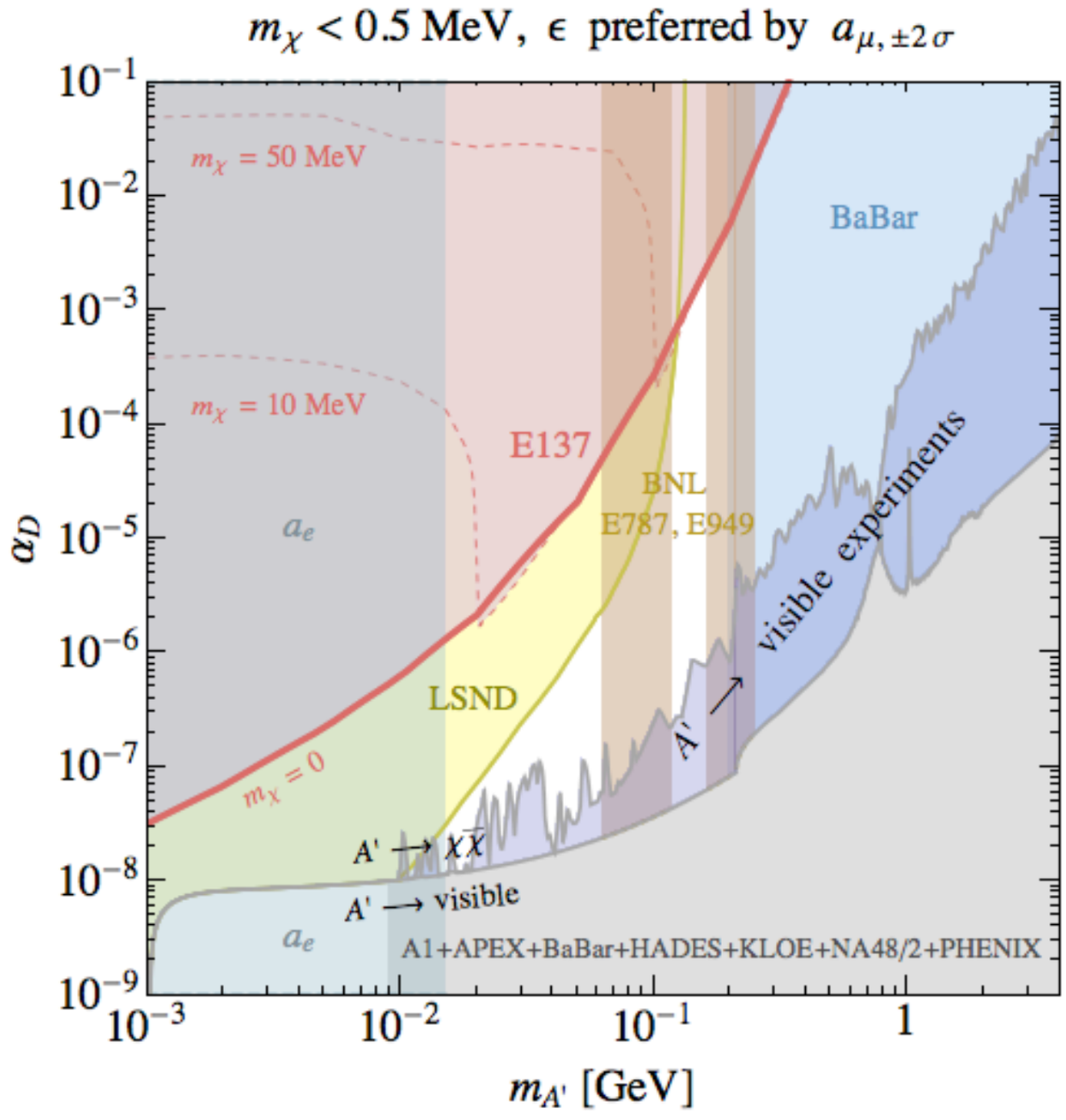
Current constraints on vector portal DM

LSND and E137 constraints depend on α_D



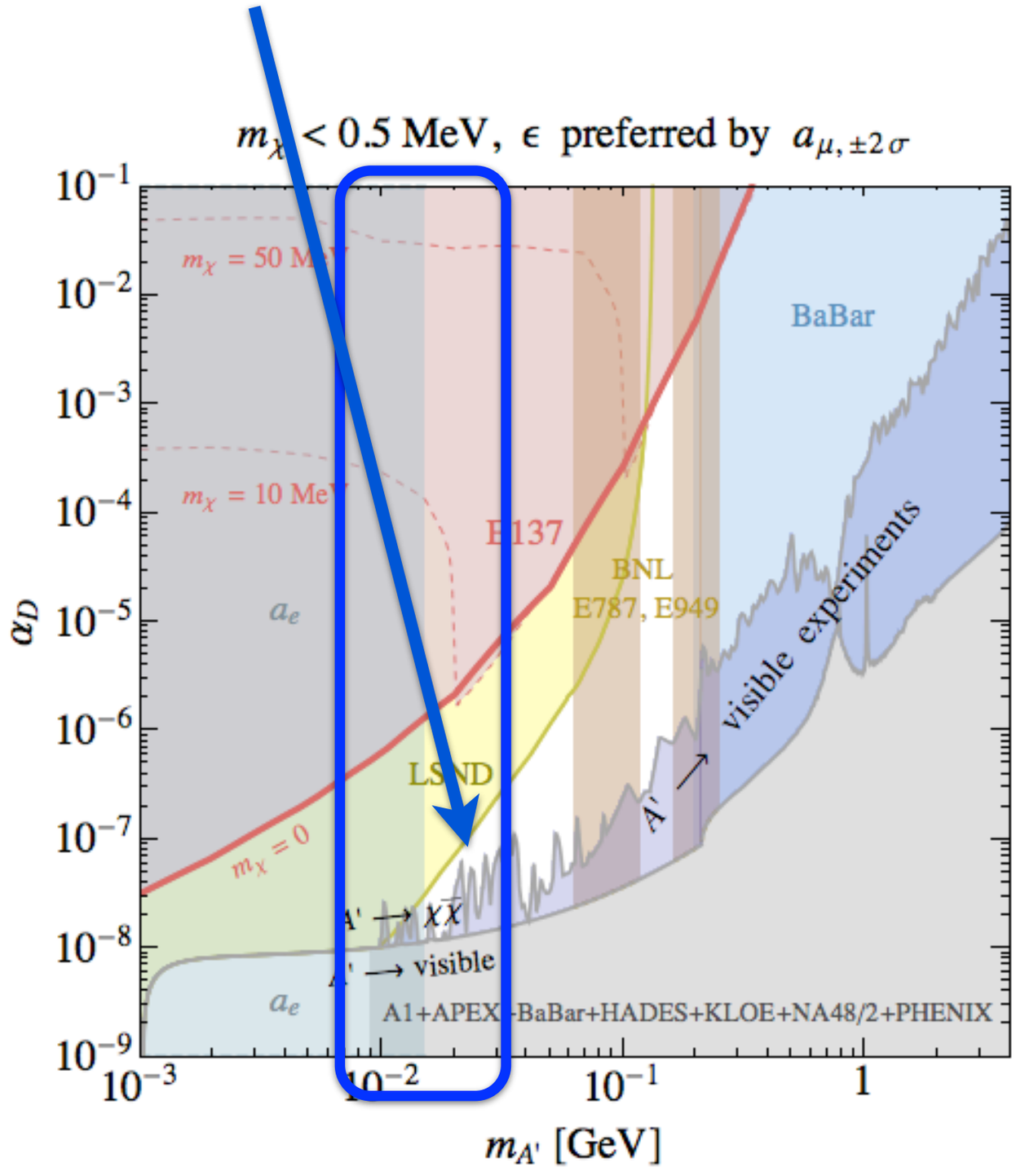
BB, Essig, Surujon '14

Current constraints on vector portal DM



BB, Essig, Surujon '14

PADME can look here!



Many promising proposals to probe Sub-GeV Dark Matter

(see Marco's talk next)

- MiniBooNE Beam Dump search for DM — R. Dharmapalan et al. 1211.2258
- Direct detection via scattering with electrons — Essig, Mardon, Volansky
- Electron Beam fixed target - scattering experiments
  - BDX (Beam Dump eXperiment) — Izaguirre, Krnjaic, Schuster, Toro; Battaglieri et al. 1406.3028
- Fixed target - missing momentum experiments
  - SPS Proposal P348 http://p-348.web.cern.ch/

    Andreas et al. 1312.3309

    (See also Kahn, Thaler; Izaguirre, Krnjaic, Schuster, Toro)
- Neutrino factories, e.g., DAEdULUS — Kahn et al.

Outlook

- There is a strong physics case to search for dark photons
  - General effective field theory arguments - portals
  - New light forces may be associated with dark matter, neutrino masses, baryon asymmetry, and new priniciples such as SUSY
  - Explain experimental/observational anomalies, e.g. $(g-2)_\mu$
- There is a robust and diverse experimental program underway to search for dark photons and light dark matter (see Marco's talk next)
- Important to cover both visible and invisible decays

PADME can contribute to this exciting effort!