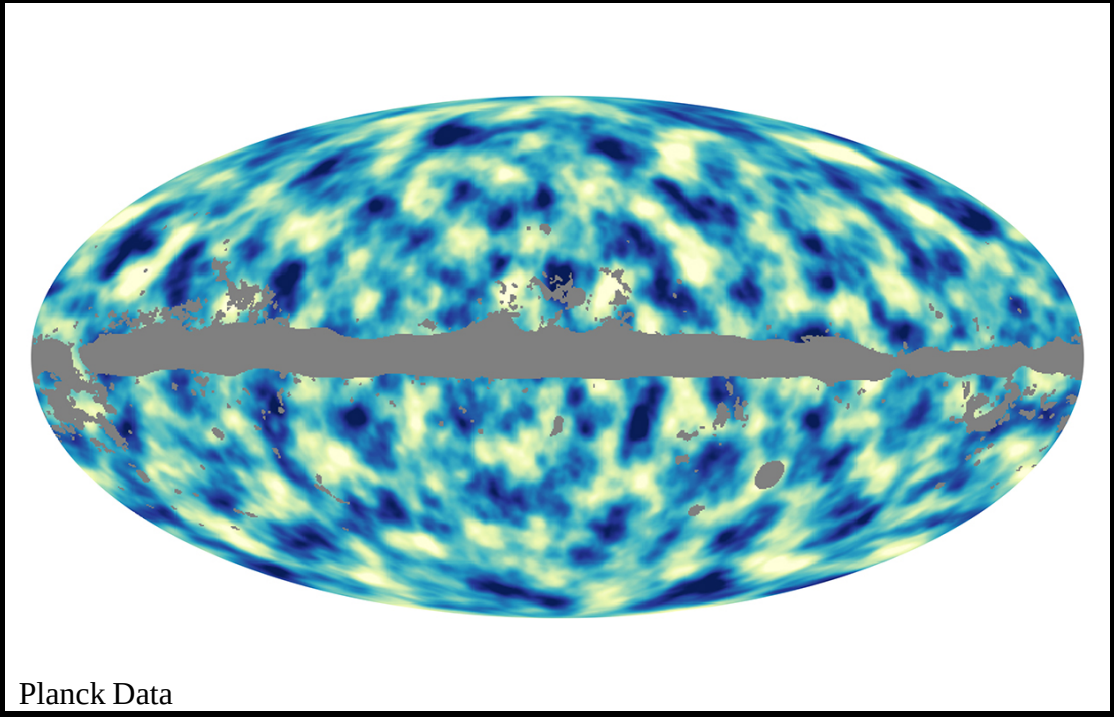
Dark Matter from Hidden Forces

Hooman Davoudiasl

Brookhaven National Laboratory

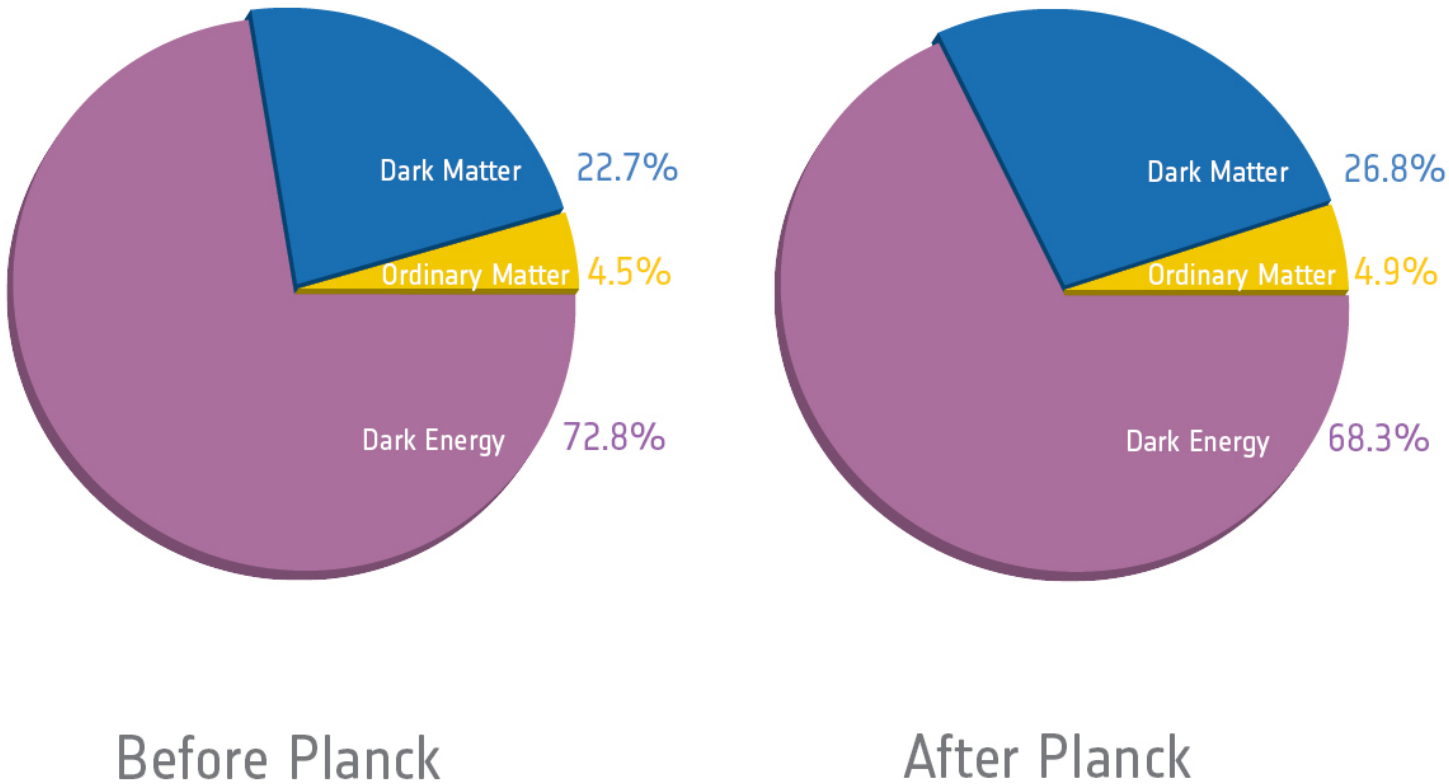


Based on:

H. D., I. Lewis, Phys. Rev. D 89, 055026 (2014) [arXiv:1309.6640 [hep-ph]].

New Perspectives on Dark Matter, Fermilab, April 28-May 2, 2014

Introduction



- Dark Matter: no SM candidate, unknown origin

Generic Models:

- One DM candidate assumed
- Spin-1/2, scalar (matter)
- A $\mathbb{Z}_2$ assumed for DM stability
  - SM guide: Gauge, Lorentz invariance $\oplus$ Renormalizability.
- DM interactions related to SM (Higgs portal, . . .)
- Weak scale, $\mathscr{O}(100\ \mathrm{GeV})$, states (WIMP miracle)
  - Possible relation to the hierarchy problem

Potential Hints, Speculations

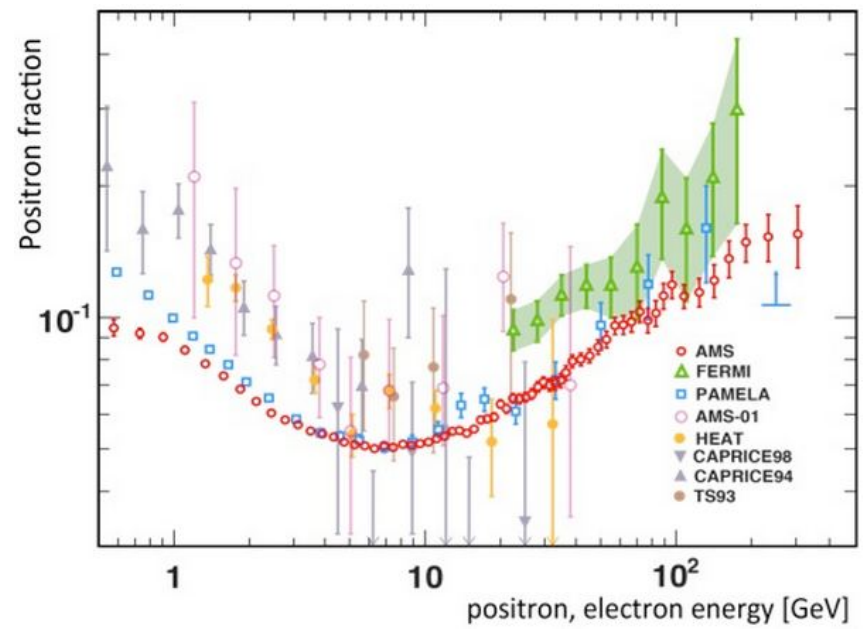
- Heavy DM annihilation signals
- New interactions in the dark sector

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

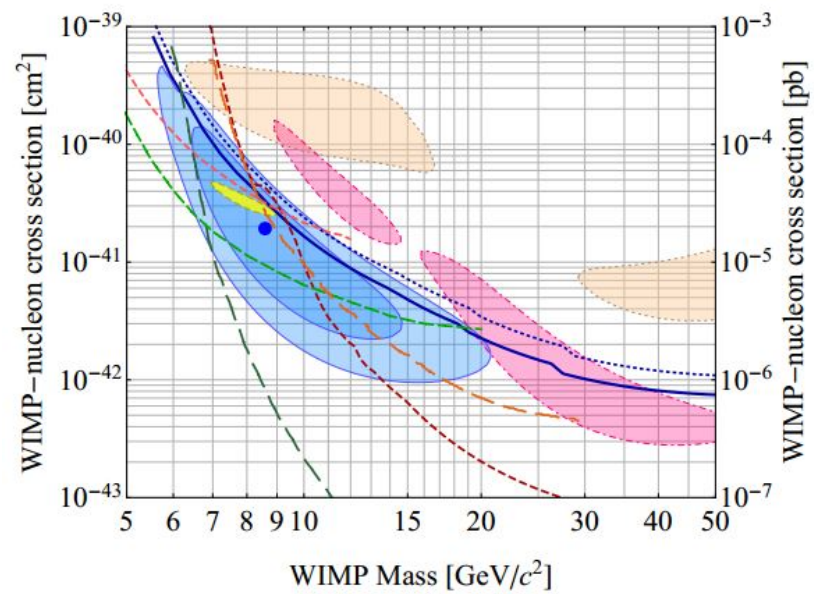
- "Dark photon," kinetic mixing
- Dark photon: contribution to lepton $g-2$

Fayet, 2007; Pospelov, 2008

- Dark matter stability
- Gauge charges, analogous to $e^{\pm}$.
- Multi-component dark sector (like SM)
- Perhaps DM extending to the GeV sector
- New vector bosons, scalars, . . .
- Masses $\sim 0.1-10$ GeV, weak couplings SM



AMS Collaboration, 2013

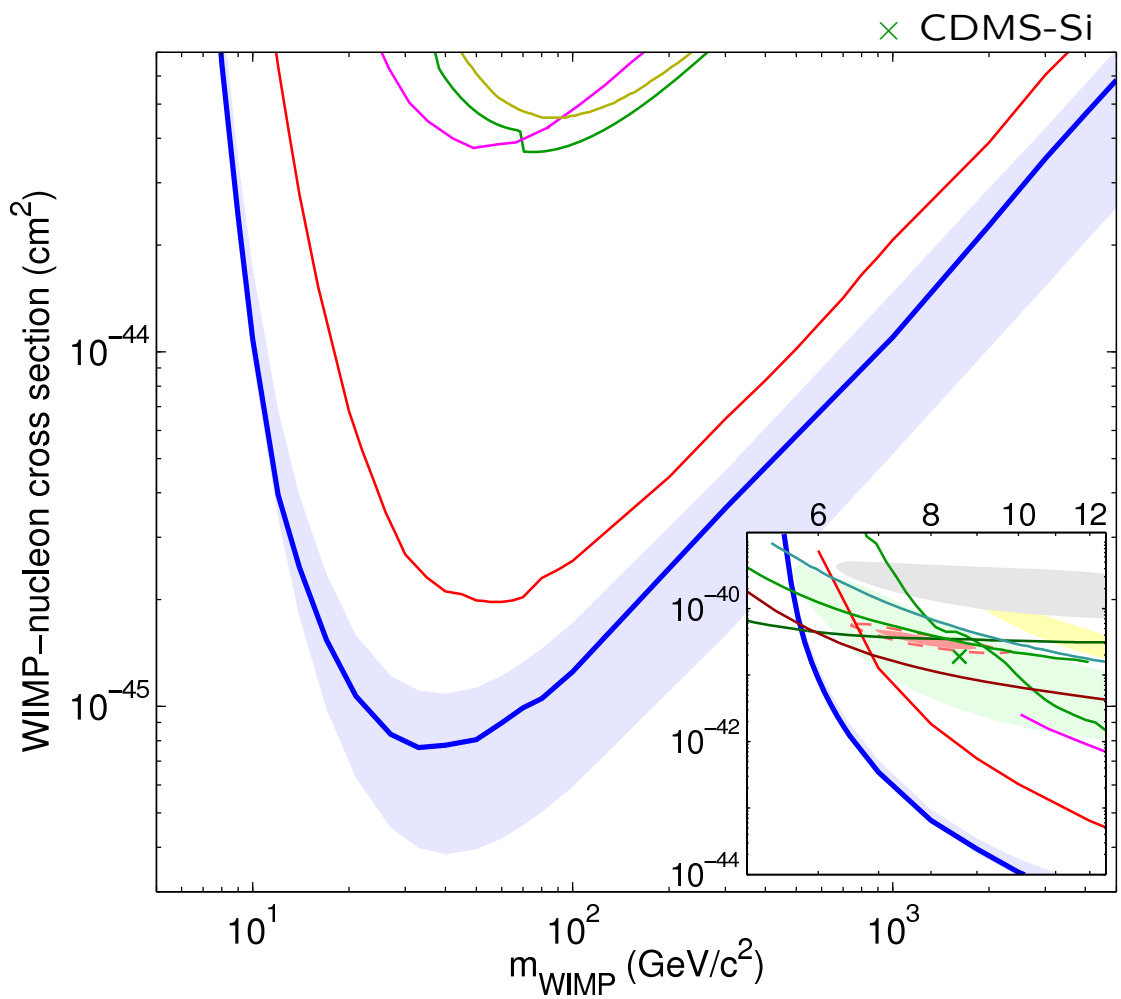


CDMS Collaboration, 2013

- Recent input from LUX
- Light DM signals may require further support.
  - Challenging, could hide surprises.
- We do not know what DM may be, so keep options open.
  - GeV-scale γ-rays from Galactic center?

Daylan et al., 2014

Agrawal, Batell, Hooper, Lin, 2014



This talk:

- Going beyond Abelian DM interactions
- Hidden "electroweak" (hEW) symmetry $SU(2)_h \times U(1)_h$
- The hEW sector coupled to SM via $U(1)_h$ kinetic mixing with $U(1)_Y$
- Hidden Higgs sector to break hEW: no massless invisible states
- Minimal assumption: "Dark Force" = "Dark Matter"
- DM is then made of a spin-1 population (hidden W)
- Stability: gauge/Lorentz invariance (dim-4 operators)
- Direct detection, other experimental probes

Prior work in this direction includes: Hambye, 2008; Hambye and Tytgat, 2009; Diaz-Cruz and Ma, 2010; Chiang, Nomura, and Tandean, 2013; Ko, Park, and Tang, 2014

Setup

H.D. and Lewis, Phys. Rev. D **89**, 055026 (2014) [arXiv:1309.6640 [hep-ph]]

- "Hidden" gauge group: $SU(2)_h \times U(1)_h$ Gauge couplings: g_h and g'_h
- No Fermions, but two hidden Higgs fields: $\Phi_{(2,\frac{1}{2})}$ and $\phi_{\frac{1}{2}}$
- No massless degrees of freedom: $\langle \Phi \rangle = v_\Phi/\sqrt{2}$ and $\langle \phi \rangle = v_\phi/\sqrt{2}$
- Massive Z_h, $W_h^\pm$, and γ_h

$$W^\pm_{h\mu} = \frac{1}{\sqrt{2}}(W^1_{h\mu} \pm i W^2_{h\mu})$$

$$Z_{h\mu} = \cos\theta_h W^3_{h\mu} - \sin\theta_h B_{h\mu} \quad ; \quad \gamma_{h\mu} = \sin\theta_h W^3_{h\mu} + \cos\theta_h B_{h\mu}$$

$$\cos^2\theta_h = \frac{M^2_{W_h} - M^2_{\gamma_h}}{M^2_{Z_h} - M^2_{\gamma_h}} \quad ; \quad \eta \equiv \frac{v_\phi}{v_\Phi}$$

- $M_{W_h} \leq M_{Z_h}$ and we assume $M_{\gamma_h} \ll M_{W_h}$; $\eta \ll 1$

- $U(1)_h$ *kinetically mixed* with $U(1)_Y$: $\frac{\varepsilon}{2\cos\theta_W} B_{h\mu\nu} B^{\mu\nu}$

- With our assumptions, two "dark photon" states: γ_h and Z_h

- Couplings to SM electromagnetic current

$$\mathscr{L}_{\rm h}^{\rm em} = -\varepsilon e \left[\cos\theta_h \gamma_{h\mu} - \sin\theta_h Z_{h\mu}\right] J_{\rm em}^{\mu}$$

(Ignore SM Higgs mixing with Φ and ϕ)

- A remnant $\mathbb{Z}_2$ after hEW symmetry breaking

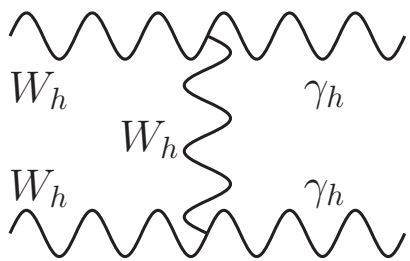
- Without light hidden fermions, W_h is stable, dark matter candidate

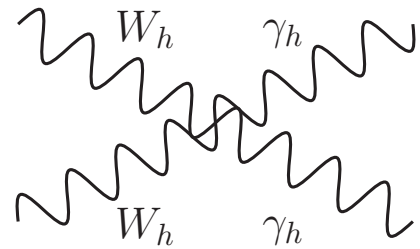
- $(\phi D_\mu \phi)^*(\Phi D^\mu \Phi)/\Lambda^2$ can mix $W_h^\pm$ with $B_h \Rightarrow$ decays of $W_h^\pm$ to SM fermions.
- DM $W_h^\pm$: lifetime $\gtrsim 10^{27}$ s $\Rightarrow \Lambda \gtrsim 10^{12}$ GeV.

- Direct DM detection through $\mathscr{L}_{\rm h}^{\rm em}$ and $W_h W_h \gamma_h$ coupling

Early Universe

- $\sigma_{\rm ann} v_{\rm rel} = a + b\, v_{\rm rel}^2$ for s- and p-wave contributions
- $\langle \sigma_{\rm ann} v_{\rm rel} \rangle = a + 6b/x$ with $x \equiv M_{W_h}/T$
- Cosmic relic density: $\Omega_h \simeq 1.04 \times 10^9 \frac{x_f\, {\rm GeV}^{-1}}{\sqrt{g_*} M_{\rm Pl}\, (a + 3b/x_f)}$
- $x_f \simeq \ln[0.038\, (\kappa/\sqrt{x_f g_*})\, M_{\rm Pl} M_{W_h} \langle \sigma_{\rm ann} v_{\rm rel} \rangle]$; $x_f \simeq 20$
- g_* is the relativistic d.o.f at T_f; $\kappa = 3$ for a massive vector
- Simplifying assumptions: M_{Z_h}, $M_\Phi > 2M_{W_h}$ and $\eta \ll 1$
- Φ-ϕ mixing angle $\sim \eta$
- Thermal relic density set by $W_h W_h \to \gamma_h \gamma_h$





- Other $2 \to 2$ processes forbidden or suppressed by η
- Example: s-channel $W_h W_h \to \gamma_h \gamma_h$ via Φ-ϕ mixing

$$\boxed{\langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq \frac{19\,(g_h \sin\theta_h)^4}{72\pi M_{W_h}^2}} \qquad (M_{\gamma_h} \ll M_{W_h})$$

- s- and p-wave contributions included for numerical results

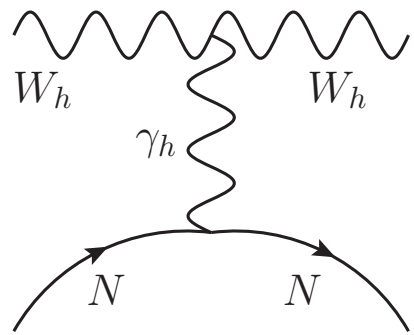
$$(g_h \sin\theta_h)^2 \simeq \frac{M_{W_h}}{10\ \text{GeV}} \begin{cases} 2.2 \times 10^{-3}; & T_f \lesssim \Lambda_{QCD} \\ 1.5 \times 10^{-3}; & T_f \gtrsim \Lambda_{QCD} \end{cases}$$

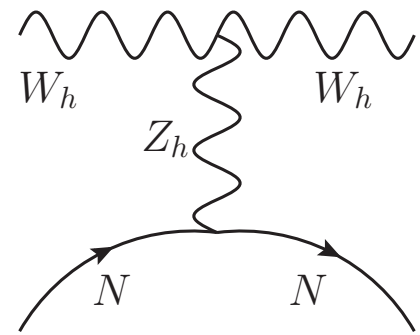
- γ_h in thermal equilibrium at T_f: $\frac{M_{\gamma_h}}{T_f} \Gamma_{\gamma_h} \gtrsim H(T_f) \qquad (M_{\gamma_h} < T_f)$

$$\Rightarrow\ (\varepsilon \cos\theta_h)^2 \left(\frac{M_{\gamma_h}}{\text{MeV}}\right)^2 \gtrsim 10^{-12} g_\star^{1/2} \left(\frac{M_{W_h}}{10\ \text{GeV}}\right)^3 \qquad (T_f = M_{W_h}/20)$$

Direct Detection

- $\sigma_{\rm el} \simeq \dfrac{4Z^2\alpha\,(\varepsilon\cos\theta_h)^2(g_h\sin\theta_h)^2\,\mu_{\rm r}^2(W_h,N)}{M_{\gamma_h}^4}$



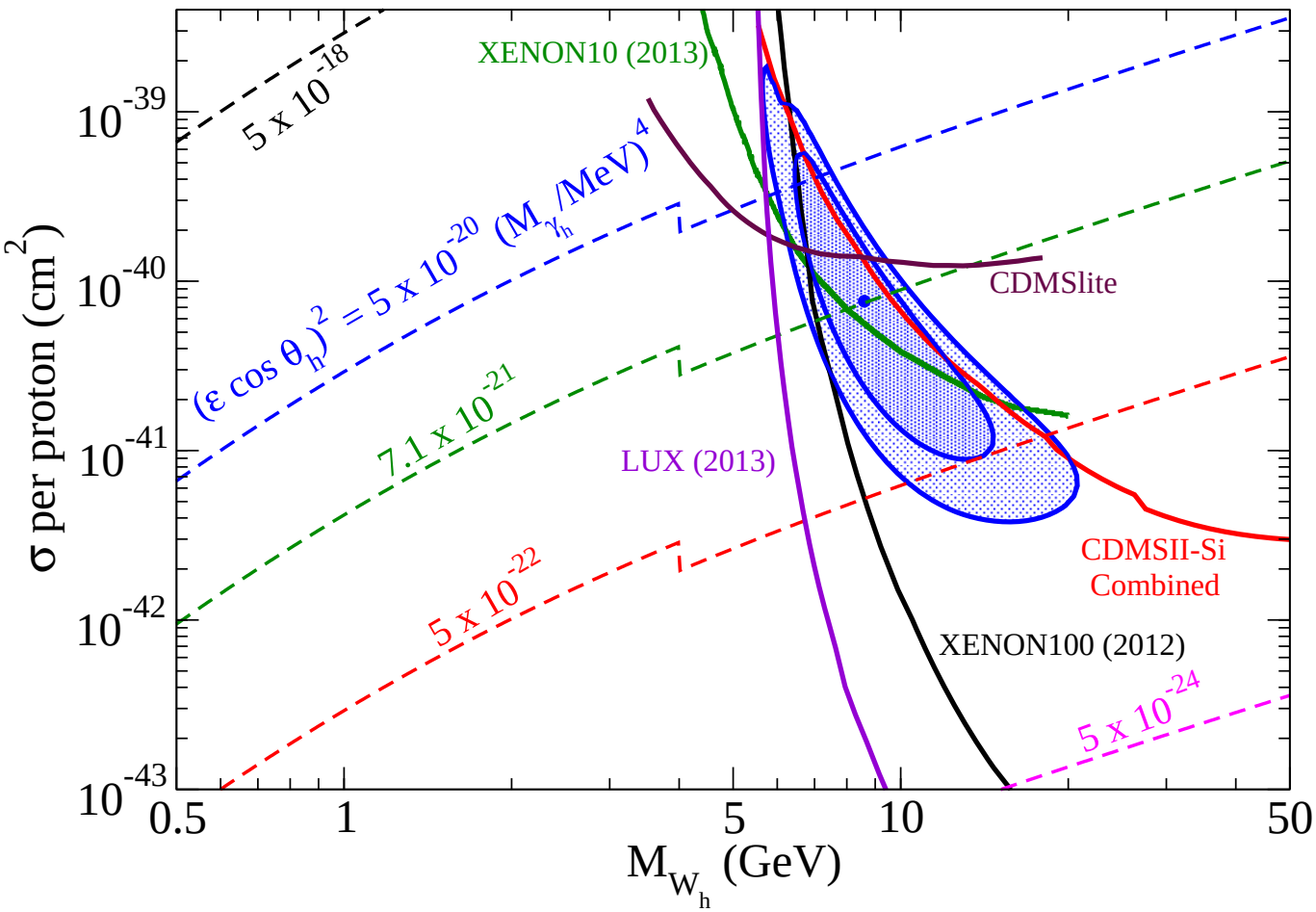


  - $M_{\gamma_h} \to M_{Z_h}$, for Z_h
  - γ_h dominates for $M_{Z_h} \gg M_{\gamma_h}$
  - Reduced mass $\mu_{\rm r}(X,Y) = M_X M_Y/(M_X+M_Y)$
  - Nucleus (A,Z): $M_N \simeq A m_n$; $m_n \simeq 938$ MeV

- Cross section per nucleon: $\sigma_n = (Z^2/A^2)\sigma_p$ with

$$\boxed{\sigma_p \simeq \frac{4\alpha\,(\varepsilon\cos\theta_h)^2(g_h\sin\theta_h)^2\,\mu_{\rm r}^2(W_h,n)}{M_{\gamma_h}^4}}$$

Direct Detection Cross Section per Proton



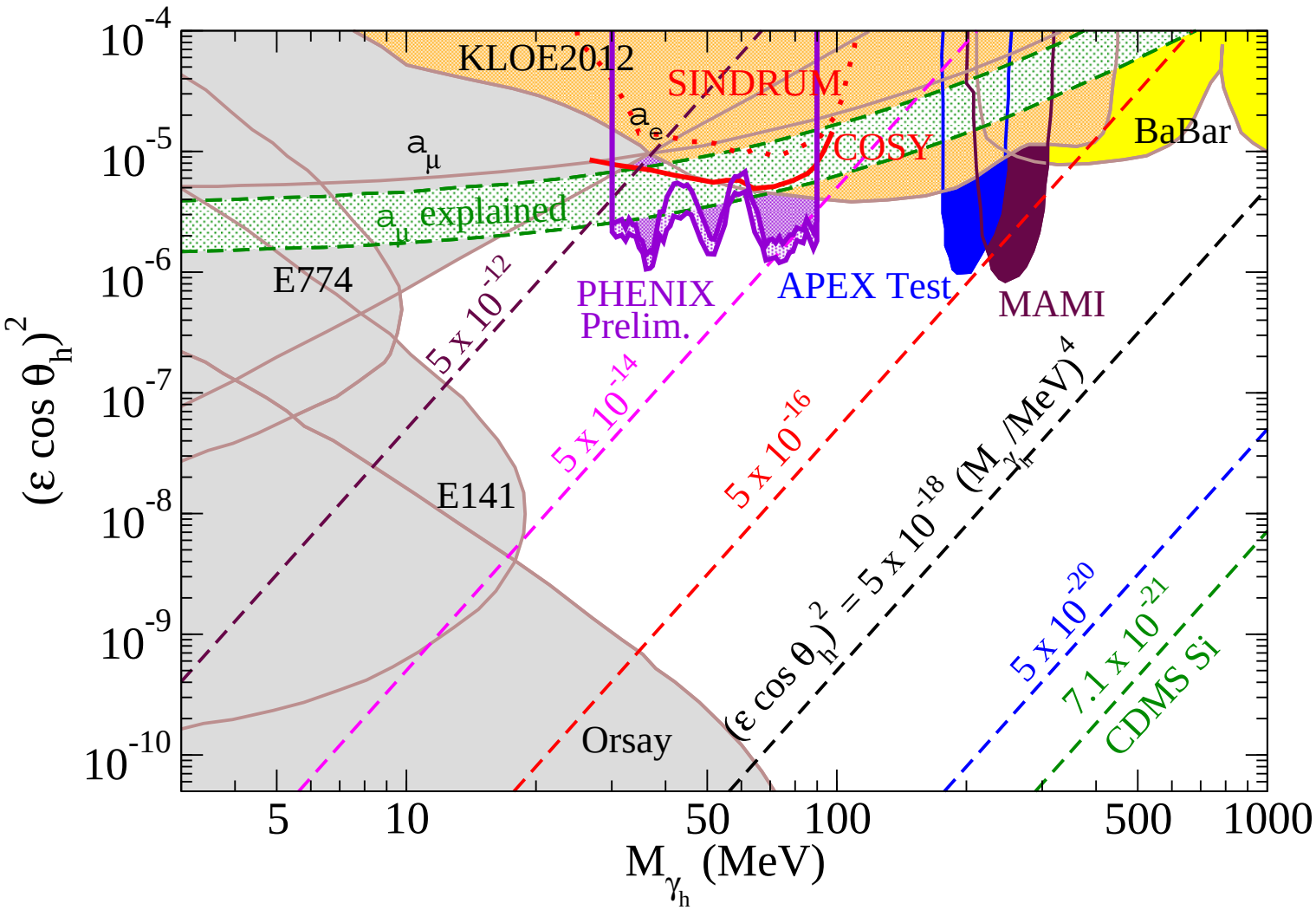
- $\Lambda_{\rm QCD} \approx 200$ MeV (change in g_* for $x_f \approx 20$)

"Dark" Photon and "Invisible" Photon

- Our setup has two "dark photons": Z_h and γ_h.
  - Only one kinetic mixing term
- For some range of parameters, $M_{Z_h} > 2M_{W_h}$
  - Assumed for relic abundance calculation
- For $M_{\gamma_h} \ll M_{W_h}$ then $\cos\theta_h \lesssim 1/2$ ("typical" γ_h coupling to $J^\mu_{\rm em}$)
- $M_{Z_h} > 2M_{W_h} \Rightarrow Z_h \to W_h W_h$ dominates (suppressed SM coupling)
  - Z_h essentially invisible
- $\mathcal{O}(1)$ branching fractions for $\gamma_h \to e^+e^-, \ldots$
  - γ_h is the the oft invoked "dark photon" with well-studied phenomenology

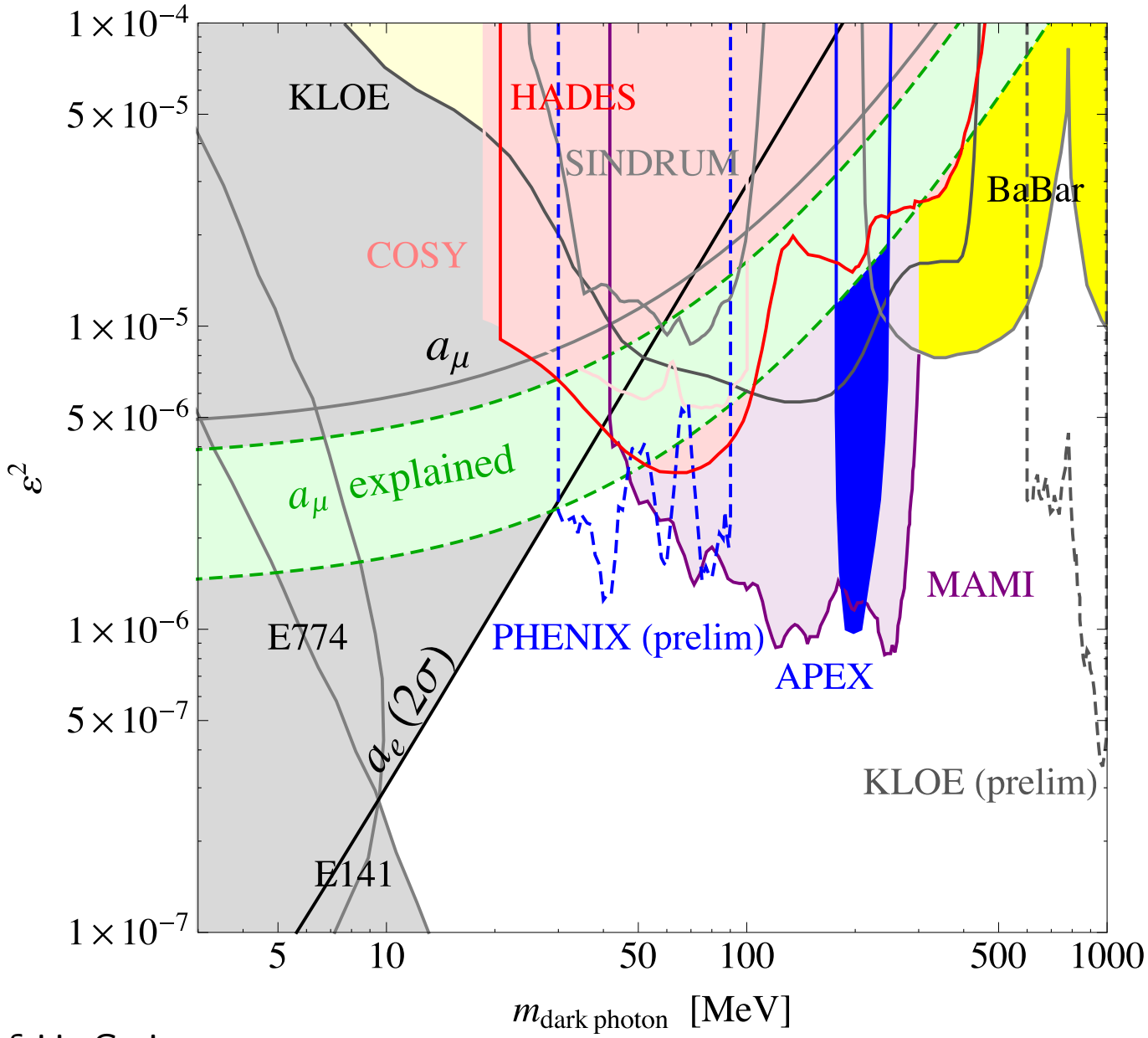
Experimentally probed at BNL, Fermilab (dark beam), JLAB, Mainz, COSY,...

Bounds on Dark Photons



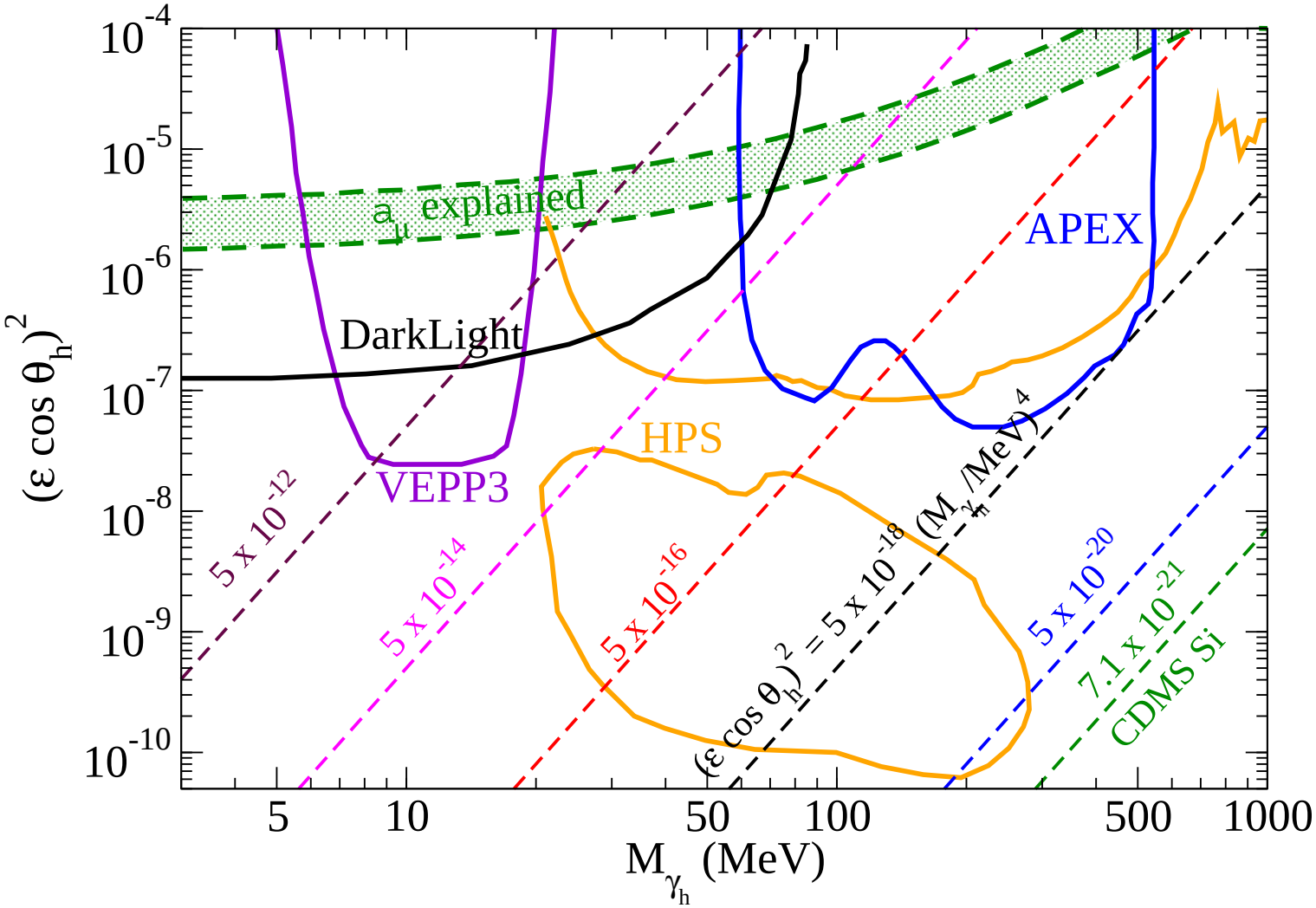
Adapted from HD, Lee, Lewis, Marciano, arXiv:1304.4935 [hep-ph]

Recent results from MAMI (arXiv:1404.5502 [hep-ex])



Courtesy of H.-S. Lee

Dark Photon Experimental Prospects



Adapted from HD, Lee, Lewis, Marciano, arXiv:1304.4935 [hep-ph]

Dark Matter Beams at Fixed Target Experiments

Batell, Pospelov, Ritz, 2009; deNiverville, Pospelov, Ritz, 2011; deNiverville, McKeen, Ritz, 2012; Dharmapalan *et al.* [MiniBooNE Collaboration], 2012; Izaguirre, Krnjaic, Schuster, Toro, 2013

In a $U(1)_d$ model:

- Light DM produced in decays of "invisible" dark photon
- Detection through exchange of the same dark photon

In our $SU(2)_h \times U(1)_h$ model:

- Production of Z_h from SM states (meson decays, . . .); coupling $\varepsilon e \sin\theta_h$
- For $M_{Z_h} > 2M_{W_h}$, Z_h decays into W_h (spin-1 DM) *beam*
- Detection of W_h via exchange of Z_h and γ_h with couplings $\varepsilon e \sin\theta_h$ and $\varepsilon e \cos\theta_h$

- Dominated by γ_h exchange with our assumptions: $M_{\gamma_h} \ll M_{Z_h}$

- Production and detection governed by <u>different</u> couplings

- DM below $\sim$few GeV subject to CMB constraints (for s-wave annihilation).

- $M_{W_h} \gtrsim 1$ GeV in our framework.

Madhavacheril, Sehgal, Slatyer, 1310.3815

Conclusions

- We considered a hidden gauge group $SU(2)_h \times U(1)_h$.
- The model can yield a viable W_h dark matter candidate.
- In such a setup: "Dark Force" = "Dark Matter."
- Connection with SM via kinetic mixing of $U(1)_Y$ and $U(1)_h$.
- After complete symmetry breaking, two massive "dark photons": Z_h and γ_h.
- Relevant for various current and planned low energy experiments.
- Under simplifying assumptions:

- Relic density controlled by $W_h W_h \gamma_h$ coupling.

- Direct detection dominated by γ_h exchange with protons (EM charges).

- "Dark matter beam" experiments via emission of $Z_h (\to W_h W_h)$.

- Detection dominated by γ_h, typical "dark photon" coupling.

- γ_h can be probed via its visible decays in various experiments.

- DM may be a manifestation of <u>hidden</u> <u>gauge dynamics</u>.