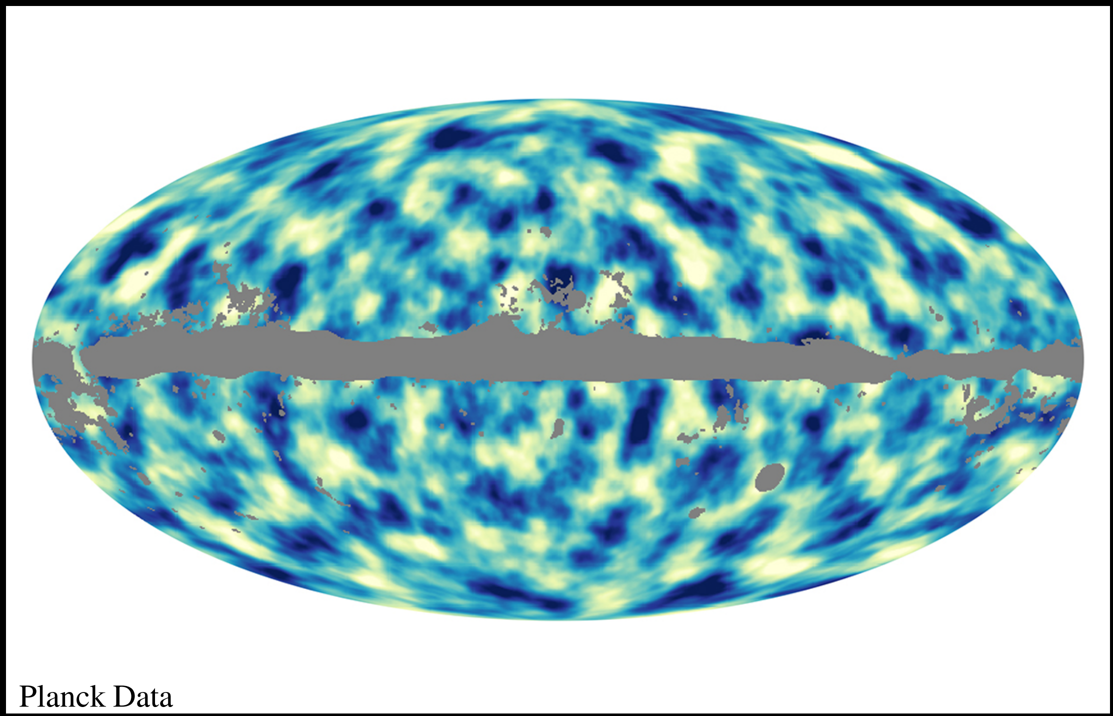
Dark Matter and Dark Forces

Hooman Davoudiasl

Brookhaven National Laboratory

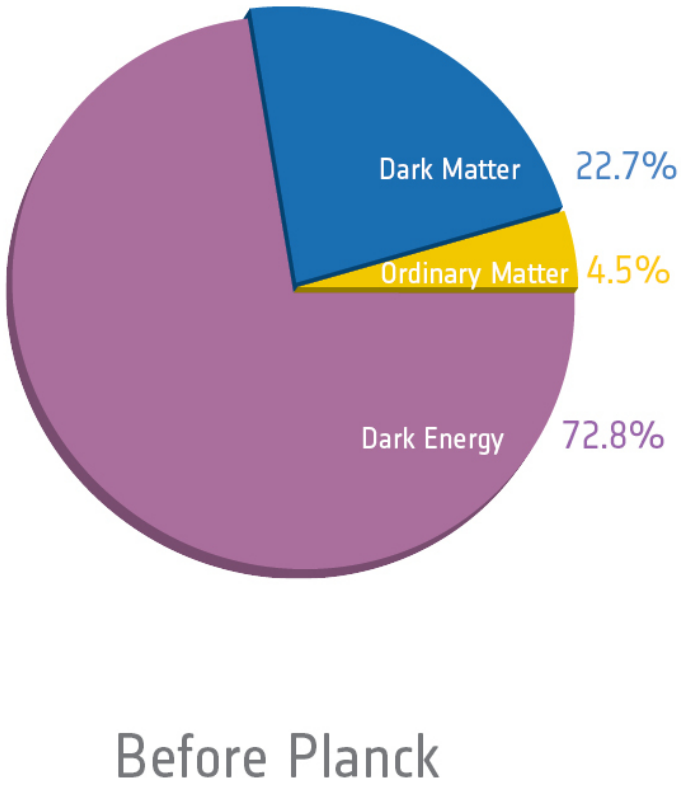


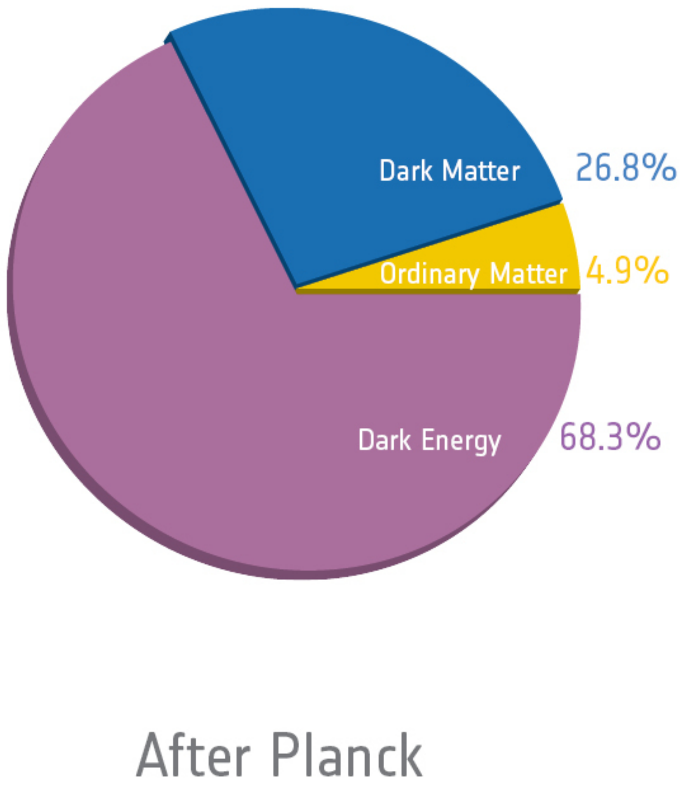
Based on:

H. D., I. Lewis, work in progress

INFO 2013, August 26 - 30, 2013, Santa Fe, NM

Introduction





- Dark Matter: no SM candidate, unknown origin

Generic Models:

- One DM candidate assumed

- Spin-1/2, scalar (matter)

- DM interactions related to SM (Higgs, . . .)

- 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 $e^{\pm}$.

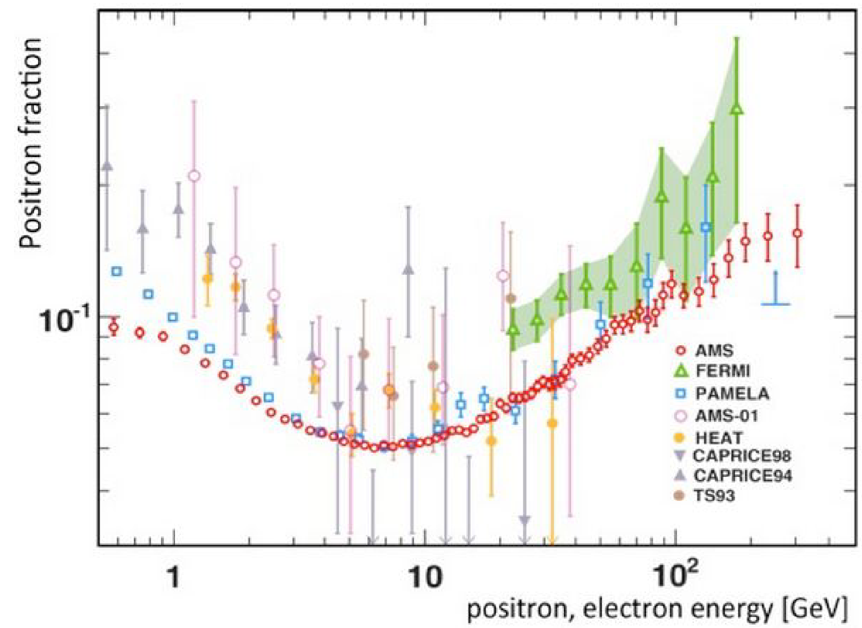
- Multi-component dark sector (like SM)

• Perhaps DM extending to the GeV sector

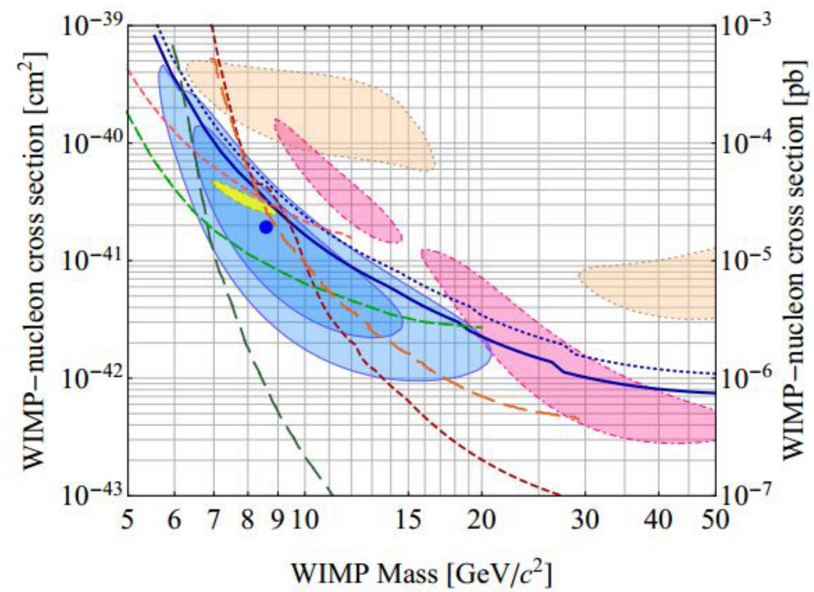
- New vector bosons, scalars, . . .

• Masses $\sim 0.1 - 10$ GeV

• Weak couplings to the SM



AMS Collaboration, 2013



CDMS Collaboration, 2013

This talk:

- Going beyond Abelian DM interactions
- Hidden "electroweak" (hEW) symmetry $SU(2)_h \times U(1)_h$
- Also 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)
- The hEW sector coupled to SM via $U(1)_h$ kinetic mixing with $U(1)_Y$
- Possible hints for a light (~ 10 GeV) DM scale CoGeNT, CDMSII-Si, ...
- 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

Setup H.D. and Lewis, work in progress

- "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

$$W_{h\mu}^\pm = \frac{1}{\sqrt{2}}(W_{h\mu}^1 \pm W_{h\mu}^2)$$

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

$$\cos^2\theta_h = \frac{M_{W_h}^2 - M_{\gamma_h}^2}{M_{Z_h}^2 - M_{\gamma_h}^2} \quad ; \quad \tan\beta \equiv \frac{v_\phi}{v_\Phi}$$

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

- $U(1)_h$ 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

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

(Ignore SM Higgs mixing with Φ and ϕ)

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

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

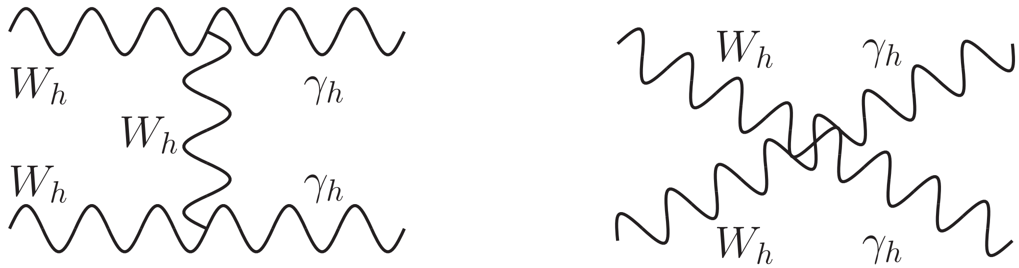
- Direct DM detection possibility through $\mathscr{L}_{\rm h}^{\rm em}$ and $W_h W_h \gamma_h$ coupling

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: $\Omega_h \simeq 1.07 \times 10^9 \dfrac{x_f \, {\rm GeV}^{-1}}{\sqrt{g_*} M_{\rm Pl} \, (a + 3b/x_f)}$
- $x_f \simeq \ln[0.038\, c(c+2)(g/\sqrt{x_f g_*}) M_{\rm Pl} M_{W_h} \langle \sigma_{\rm ann} v_{\rm rel} \rangle]$
- Typically $x_f \simeq 20$ and $c \approx 1/2$; g_* is the relativistic d.o.f at T_f
- $g = 3$ for a massive vector

- *Simplifying assumptions:* M_{Z_h}, $M_\Phi > 2M_{W_h}$ and $\tan\beta \ll 1$

- Thermal relic density set by $W_h W_h \to \gamma_h \gamma_h$



- Other $2 \to 2$ processes forbidden or suppressed by $\tan\beta$

- Example: s-channel $W_h W_h \to \gamma_h \gamma_h$ via Φ-ϕ mixing

- Φ-ϕ mixing angle $\sim \tan\beta$

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

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

Dark Higgs Interactions

- Hidden Higgs scalars can decay fast if not too light:

- $\Phi \to W_h W_h,\, Z_h Z_h,\, Z_h \gamma_h,\, \gamma_h \gamma_h$

- $\Phi \to Z_h \gamma_h,\, \gamma_h \gamma_h$ rates suppressed by $\tan^4 \beta$ and $\tan^8 \beta$

- $M_\Phi > 2M_{W_h}$: $\Gamma_\Phi \gg H(T_f)$ (Assumed before)

- $H(T_f) \lesssim 10^{-18}$ GeV

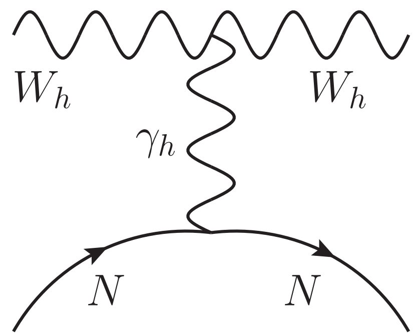
- $\phi \to \gamma_h \gamma_h,\, Z_h \gamma_h,\, Z_h Z_h$

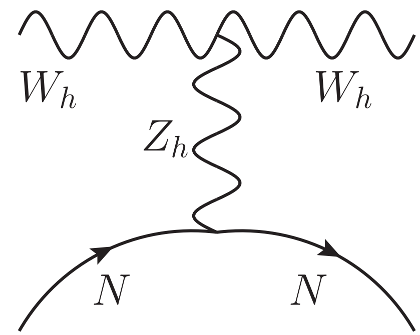
- As long as $M_\phi > 2M_{\gamma_h}$: $\Gamma_\phi \gg H(T_f)$ (γ_h the lightest state)

- Z_h and γ_h promptly decay: $\Gamma_V \sim \varepsilon^2 \alpha M_V \gg (1\ \mathrm{s})^{-1}$ (BBN)

Direct Detection

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





  - $M_{\gamma_h} \to M_{Z_h}$, 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

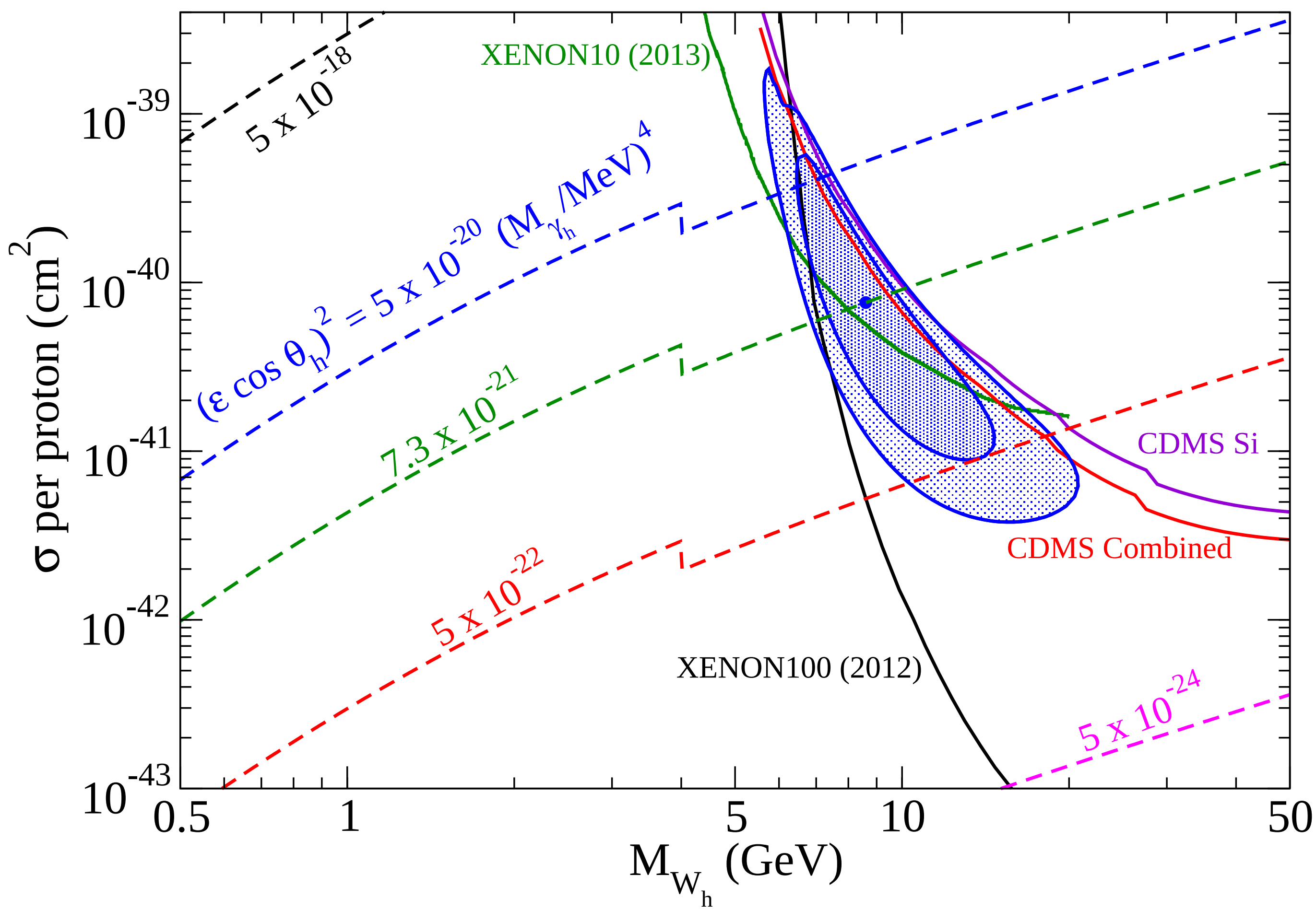
- Cross section per nucleon: $\boxed{\sigma_n \simeq \left(\dfrac{Z^2}{A^2}\right) \dfrac{e^2 \varepsilon^2 \sin^2(2\theta_h) g_h^2 \mu_{\rm r}^2(W_h,n)}{4\pi M_{\gamma_h}^4}}$

- Possible hint from CDMSII-Si: 3 events, background 0.7 event

arXiv:1304.4279 [hep-ex], CDMS Collaboration

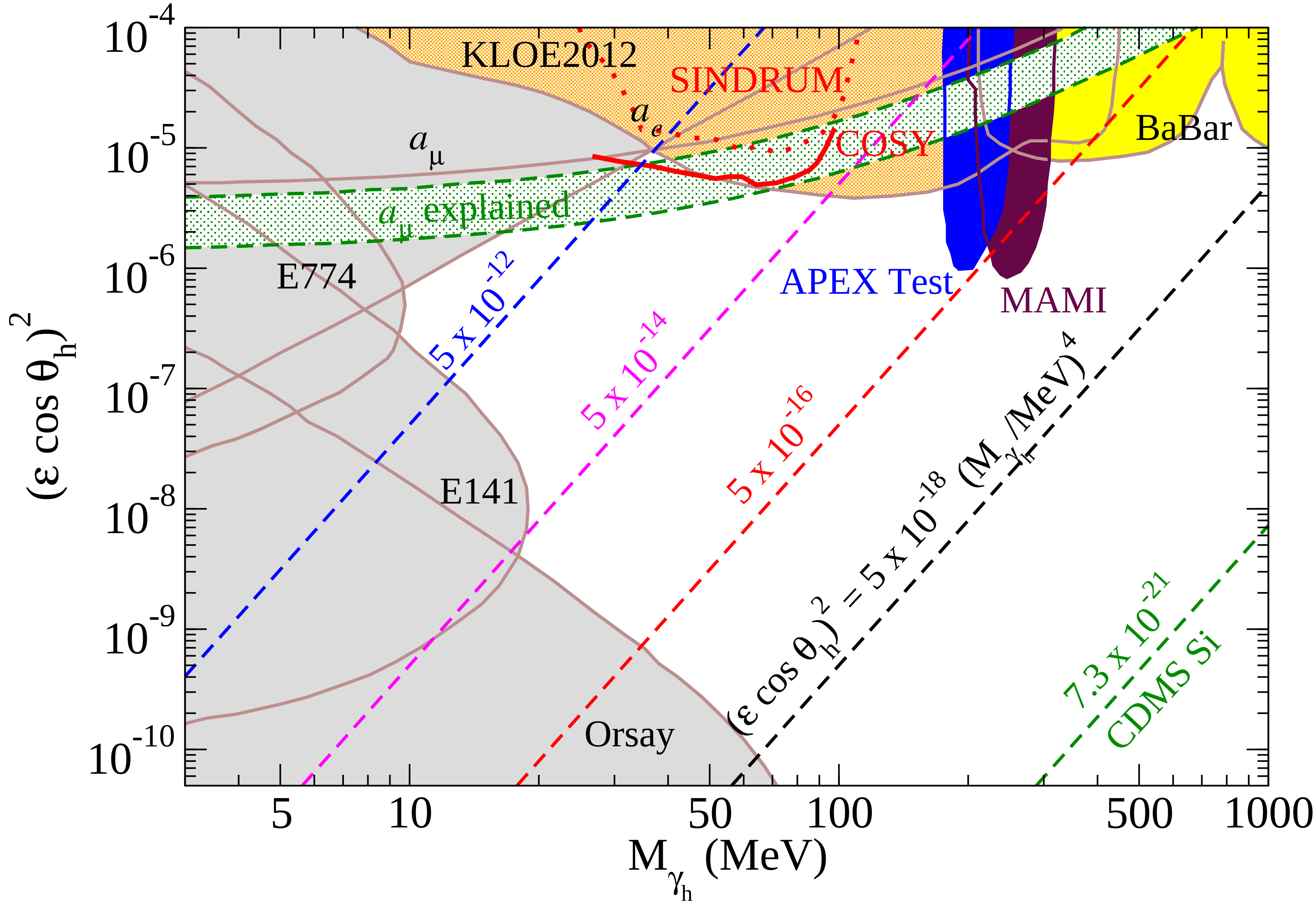
- Highest likelihood: $m_{\rm WIMP} = 8.6$ GeV and $\sigma_n^{\rm CDMS} = 1.9 \times 10^{-41}$ cm^2

Direct Detection Cross Section per Proton (Preliminary)



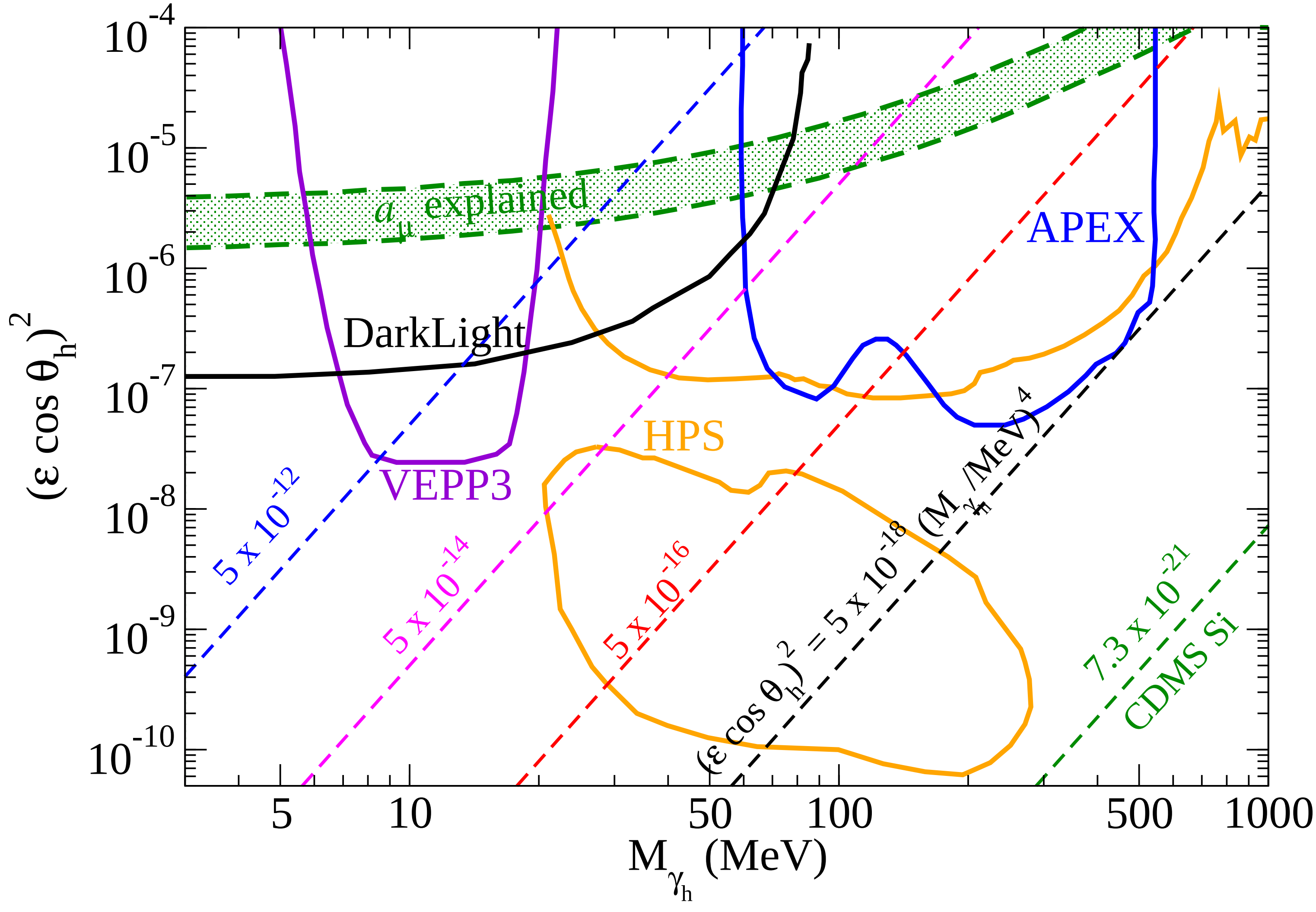
- For Si($Z = 14$, $A = 28$): $\sigma_p^{\text{CDMS}} = (A^2/Z^2)\sigma_n^{\text{CDMS}} = 7.4 \times 10^{-41}$ cm^2 in our setup.
- $\Lambda_{\text{QCD}} \approx 200$ MeV (change in g_* for $x_f \approx 20$)

Current Bounds on Dark Photons (Preliminary)



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

Dark Photon Experimental Prospects (Preliminary)



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

“Dark” Photon and “Invisible” Photon

- Our setup has two “dark photons”: Z_h and γ_h.

- For some range of parameters, $M_{Z_h} > 2M_{W_h}$

  - For $M_{\gamma_h} \ll M_{W_h}$ this means $\cos\theta_h \lesssim 1/2$

  - In this case, $Z_h \to W_h W_h$ dominates (SM coupling $\propto \varepsilon \ll 1$)

  - Z_h essentially invisible

  - $\mathscr{O}(1)$ branching fractions for $\gamma_h \to e^+ e^-, \ldots$

  - γ_h is the oft-invoked dark photon with well-studied phenomenology

Experiments at JLAB, Mainz, COSY,. . .

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:

- Bremsstrahlung of Z_h from charged SM states; coupling $\varepsilon e \sin\theta_h$
- For $M_{Z_h} > 2M_{W_h}$, Z_h decays into W_h (DM) *beam*
- Detection of W_h from exchange of Z_h and γ_h with coupling $\varepsilon e \cos\theta_h$

- Dominated by γ_h exchange, with our assumption of $M_{\gamma_h} \ll M_{W_h}$

Potential (Indirect) Implications

- Kinetic mixing: fermion F charged under both $U(1)_Y$ and $U(1)_h$.

- $O_F = \frac{H^\dagger H \bar{F} F}{\Lambda}$ allowed for vector-like F.

- For $\Lambda \gtrsim m_F \sim 100$ GeV, loops of F can mediate new Higgs decays:

$H \to Z_h \gamma, \gamma_h \gamma, \ldots$ H.D., Lee, Marciano, 2012; H.D., Lee, Lewis, Marciano, 2013

- For example, CDMSII-Si implies $\varepsilon \cos\theta_h \sim 10^{-10} (M_{\gamma_h}/\mathrm{MeV})^2$

- With $M_{\gamma_h} \sim 3$ GeV ($\tan\beta$ not too small) one could have $\varepsilon \cos\theta_h \sim 10^{-3}$

- Loop induced kinetic mixing $\varepsilon \sim g' g'_h/(16\pi^2)$, then $g'_h \sim g'$

- F loops could then potentially yield "dark decays" of $H(126)$ near observable levels

  [Analogy with other loop-mediated $H(126)$ decays in SM]

- Speculation: F from a sector with a weak scale DM candidate (indirect signals?)

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 $Z_h (\rightarrow W_h W_h)$.

\- Detection dominated by γ_h.

\- Emission of γ_h typically unsuppressed, can be probed via its visible decays.

- DM signals may be a manifestation of hidden gauge dynamics.