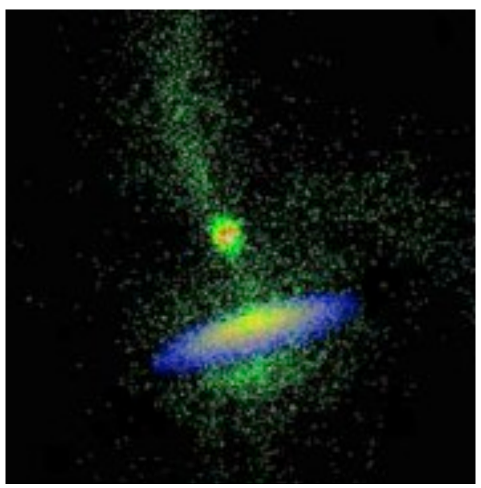
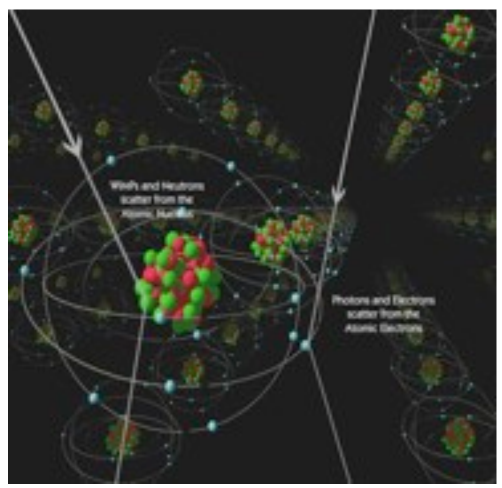
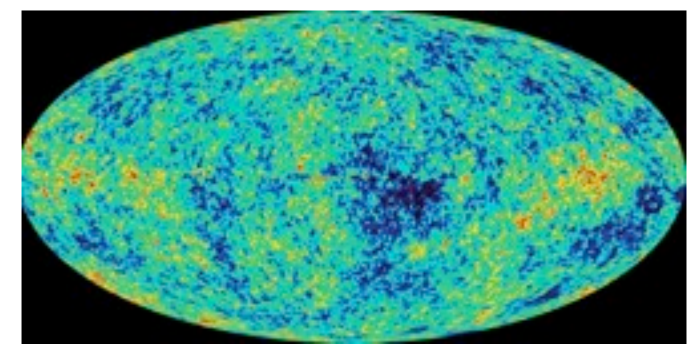
Implications of a Scalar Dark Force for Terrestrial Experiments







Sonny Mantry

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Invisible Universe Conference 2009, Paris, France

arXiv:0807.4363, S.Carroll, S. Mantry, M. Ramsey-Musolf, C. Stubbs (Phys. Rev. Lett. 103, 011301, 2009)
arXiv:0902.4461, S.Carroll, S. Mantry, M.Ramsey-Musolf

The Weak Equivalence Principle

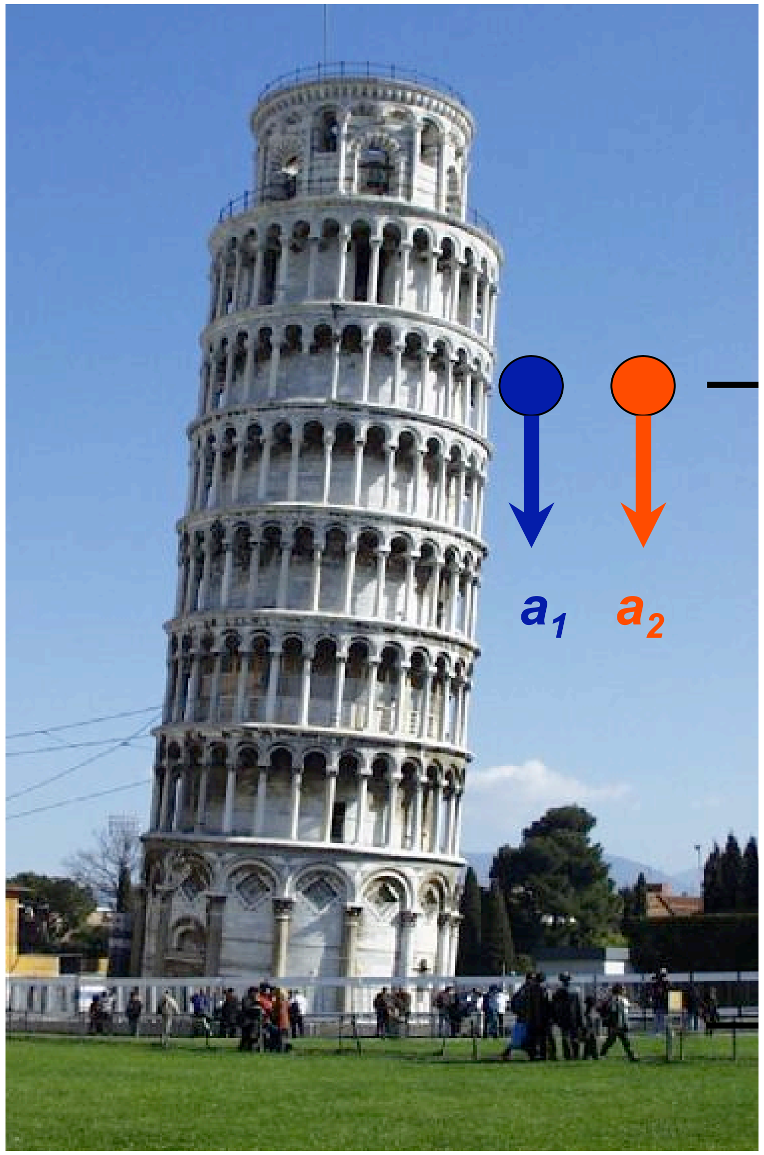
$$\mathbf{F} = m_i\,\mathbf{a}$$

Inertial Mass

$$\mathbf{F}_g = -m_g\,\vec{\nabla}\Phi_g$$

Gravitational Mass

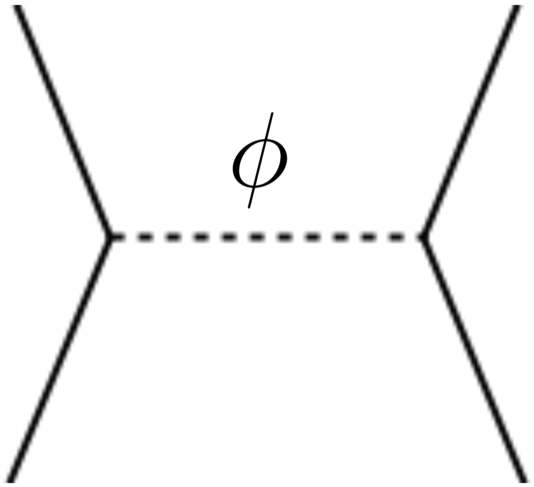
$$\mathbf{a}_i = \frac{\mathbf{F}_g}{m_i} = -\left(\frac{m_g}{m_i}\right)\vec{\nabla}\Phi_g$$



- WEP violation:

$$m_i \neq m_g$$

Fifth Force WEP Violation



- Fifth force mediated by an ultralight scalar can lead to an apparent violation of the WEP.

$$V = -\frac{GM_iM_s}{r}\left(1 + \alpha_{is}e^{-m_\phi r}\right), \qquad \alpha_{is} = \frac{1}{4\pi G}\frac{q_iq_s}{\mu_i\mu_s}$$

WEP violation — Charge to mass ratios

- WEP tightly constrained for ordinary matter. Less constrained for dark matter.

Motivation

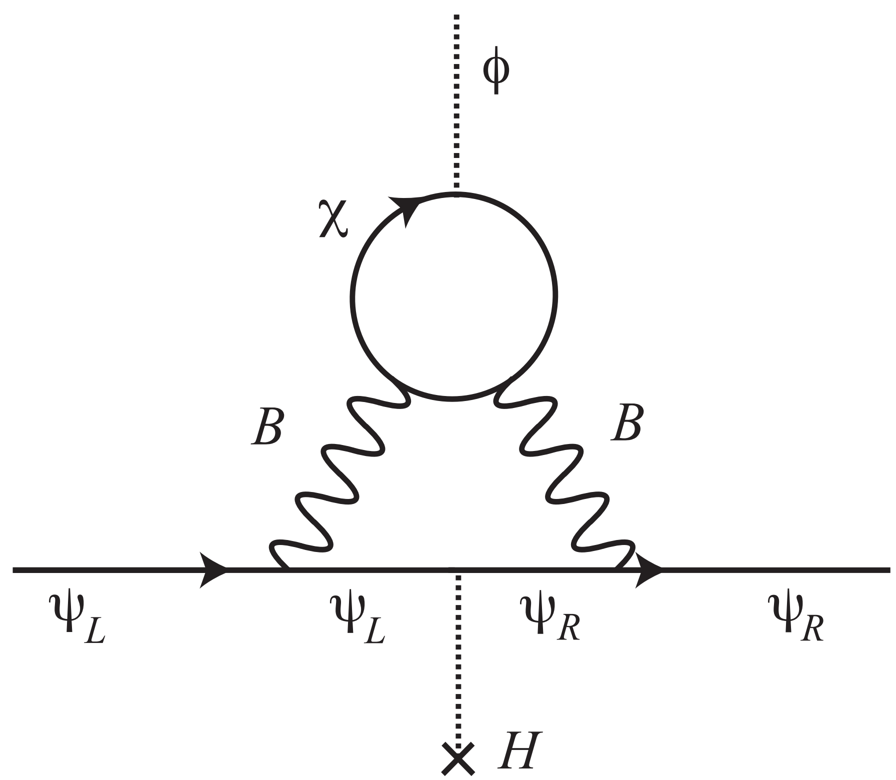
- Laboratory WEP tests do not directly apply to DM. There is a lot more DM in the universe!

- Dark forces arise in cosmological theories with DM-quintessence interactions and in non-universal scalar tensor theories of gravity.
  (Damour, Gibbons, Polyakov, Gundlach; Farrar, Peebles; Amendola; Das, Corasaniti, Khoury; Alimi, Fuzfa; Dent, Stern, Wetterich; Fardon, Nelson, Weiner,...).

- Constraints on dark forces can translate into constraints on cosmological theories.

Dark-Matter-Induced WEP Violation

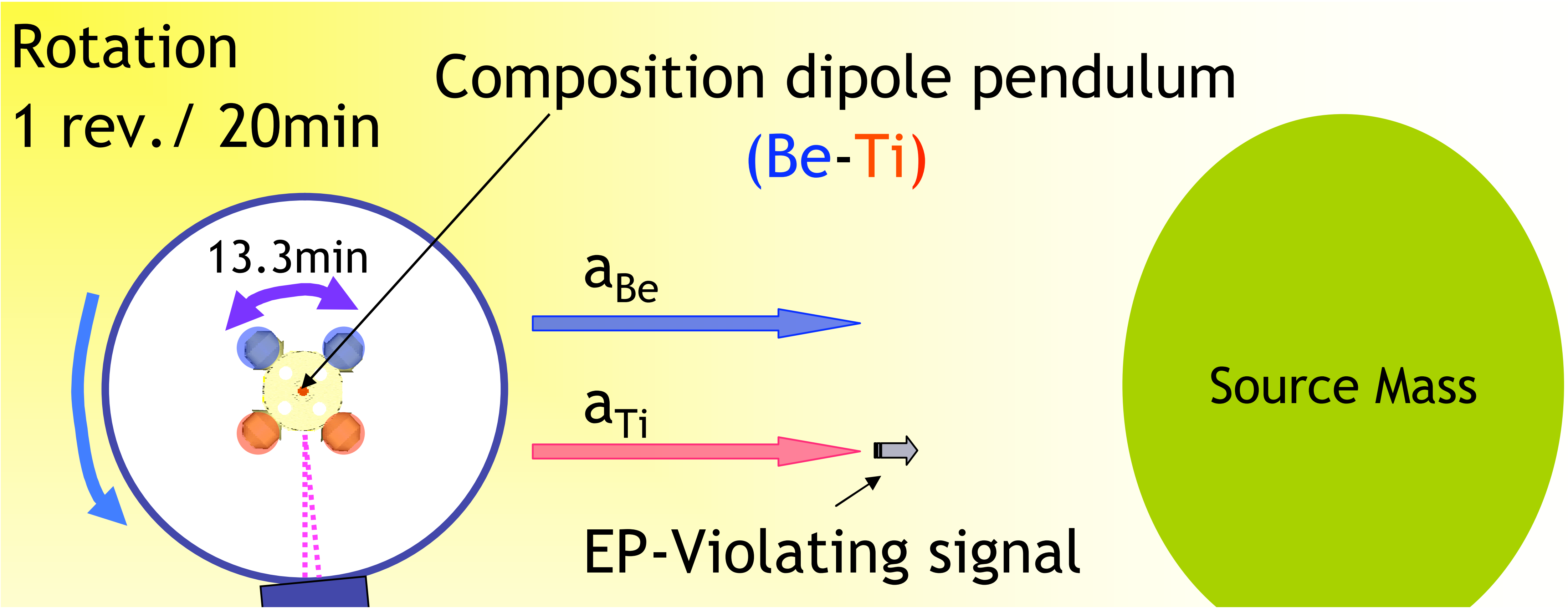
- Dark forces can be communicated to ordinary matter via quantum effects:



- Thus, laboratory WEP tests for ordinary matter can constrain dark forces.

WEP Tests for Ordinary Matter

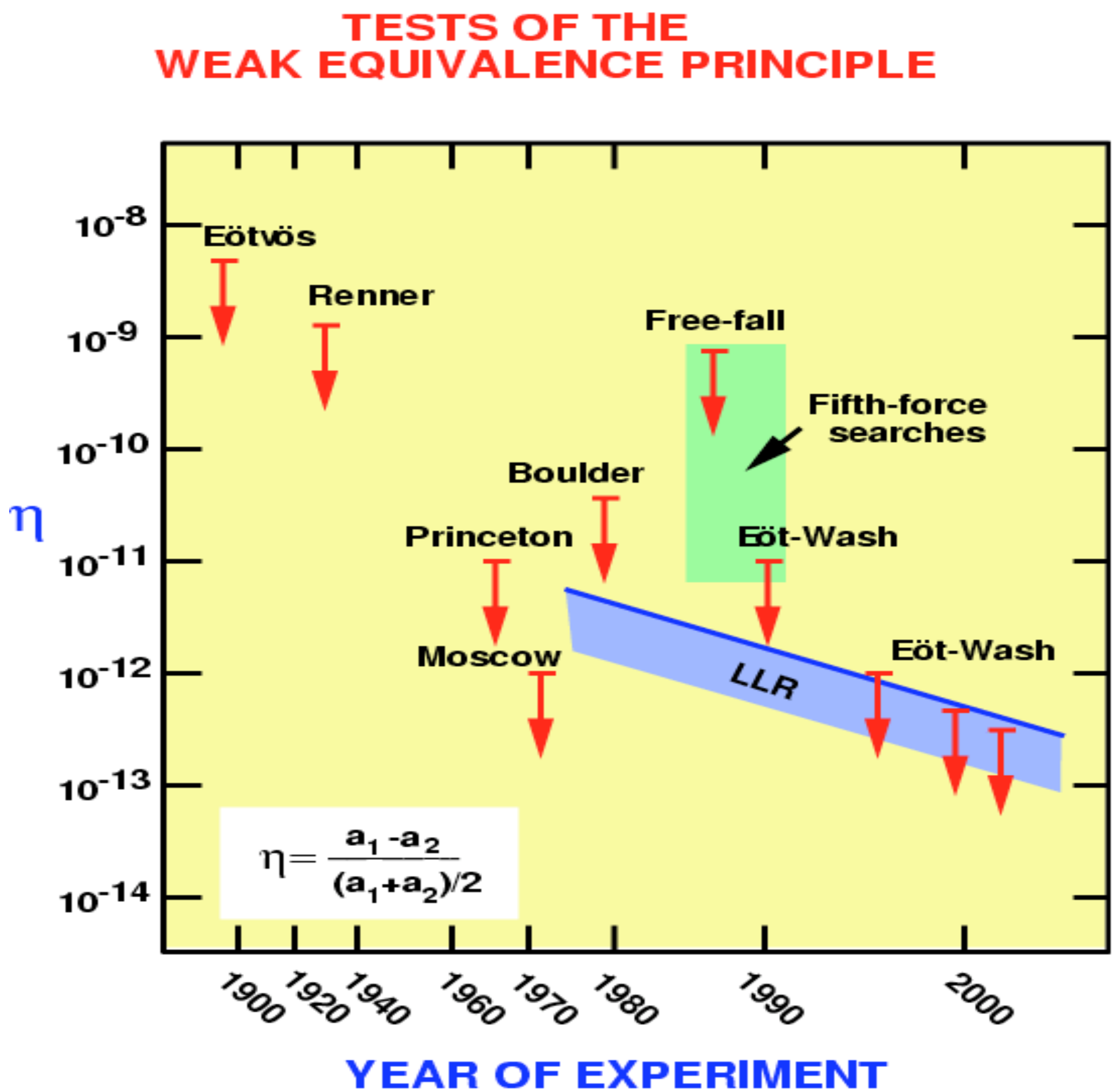
Eotvos Experiments I



- Eotvos Parameter:

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|} \simeq \left|\frac{\Delta a}{a}\right|$$

Eotvos Experiments II



- Current limits:

$$\eta_{\mathrm{E}}^{\mathrm{Be,Ti}} < (0.3 \pm 1.8) \times 10^{-13}$$

(Adelberger, Choi, Gundlach, Schlamminger, Wagner)

Eotvos Experiments III

- Current and future experiments are expected to further improve the sensitivity to WEP violation.

Experiment	Expected Future Sensitivity in η
MiniSTEP[56]	10^{-18}
Microscope[55]	10^{-15}
Apollo (LLR)[61]	10^{-14}

WEP Tests in the Dark Sector

- Tidal tails test of satellite galaxies.

  (Kamionkowski, Kesden; Keselman, Nusser,Peebles)

- Cluster Dynamics.

  (Gradwohl, Frieman ; Farrar, Springel)

- The cosmic microwave background.

  (Gradwohl, Frieman ;Bean, Flanagan,Laszio, Trodden)

- Matter Power Spectrum.

  (Gradwohl, Frieman)

Ultralight Scalar Coupling to Dark Matter

- One can add a coupling of an ultralight scalar to dark matter as a source of WEP violation:

$$\delta\mathcal{L} = \begin{cases} g_\chi \bar{\chi}\chi\phi, & \text{fermionic DM,} \\ g_\chi \chi^\dagger \chi\phi, & \text{scalar DM,} \end{cases}$$

- The following parameter can be constrained from galactic dynamics and structure formation:

$$\beta = \frac{M_P}{\sqrt{4\pi}} \frac{|g_\chi|}{M_\chi} \xi_\chi \quad , \quad \xi_{i,s} = \begin{cases} 1 & \text{for fermionic objects,} \\ \frac{1}{2m_{i,s}} & \text{for scalar objects.} \end{cases}$$

WIMP Dark Matter Coupled to a Dark Force

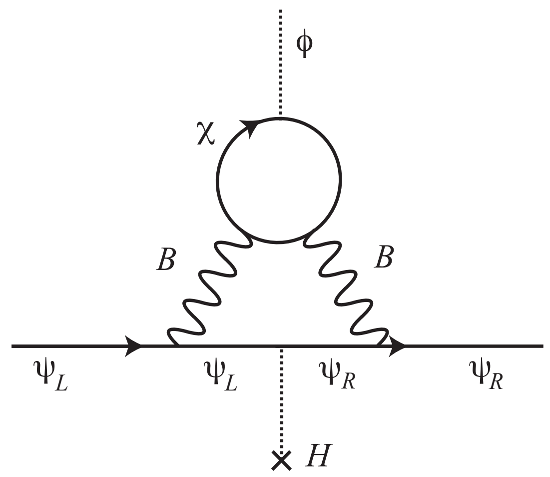
WIMP Dark Matter

- Consider Minimal WIMP models of the type:

$$\mathcal{L} = \begin{cases} \bar{\chi}(i\not{D} + M_0)\chi, & \text{fermionic DM}, \\ c(D_\mu\chi)^\dagger D^\mu\chi - c\, M_0^2\chi^\dagger\chi - V(\chi, H), & \text{scalar DM}, \end{cases}$$

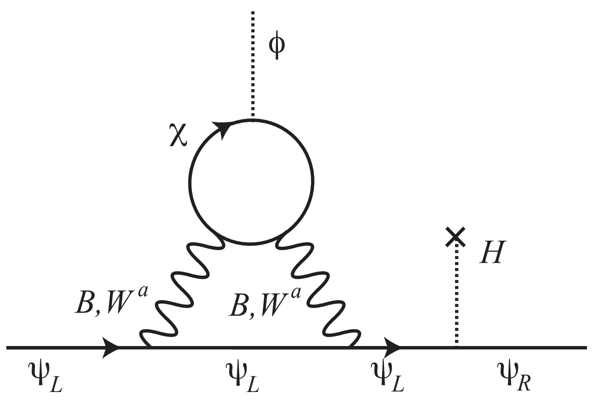
- Two loop diagrams can induce dimension five operators like:

$$\mathcal{O}_u^H \;=\; S\,\bar{Q}_L\,\epsilon H^\dagger\, C_u^H\, u_R + \text{h.c.}$$

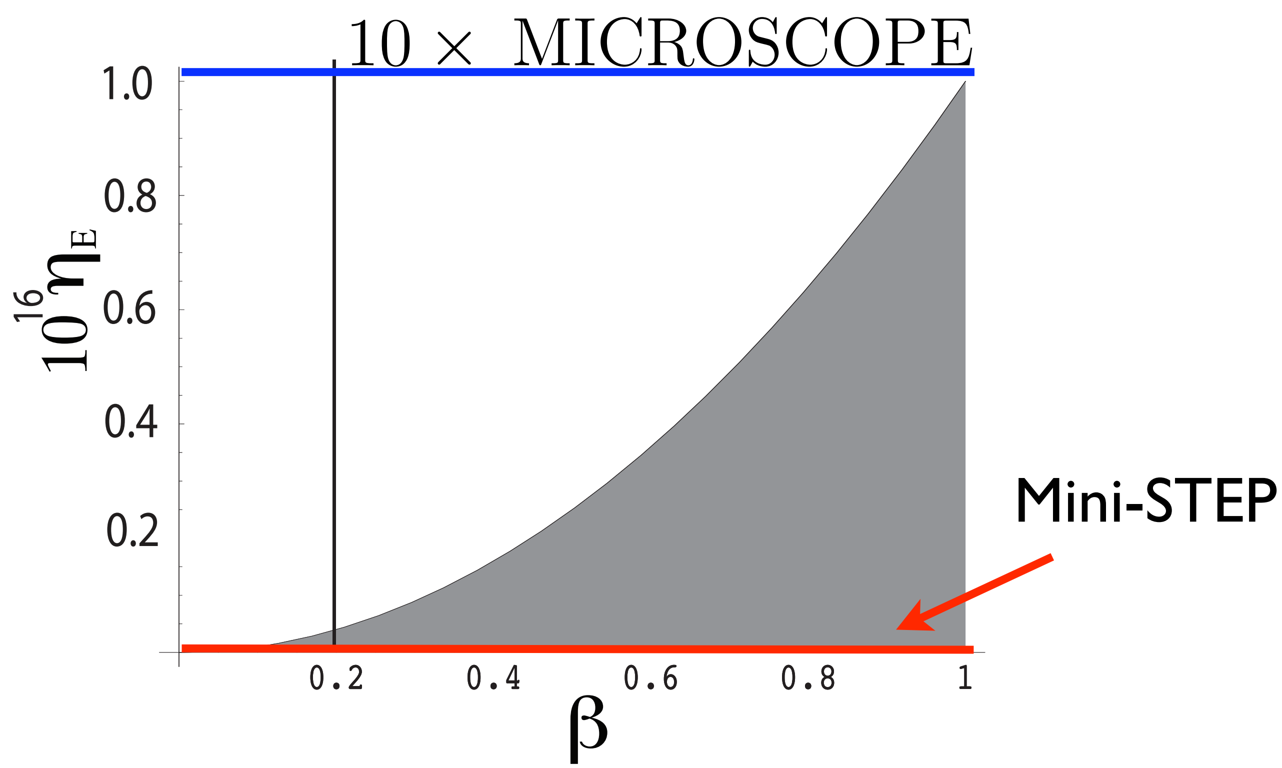


- After EWSB the coupling to fermions is given by:

$$g_f = C_N\left(\frac{\alpha_{em}}{\pi}\right)^2 \frac{m_p}{M_\chi} g_\chi\xi_\chi + C_Y Y^2\left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{m_p}{M_\chi} g_\chi\xi_\chi - \sin\theta\frac{m_p}{v}$$



Expectation for Eotvos Experiments



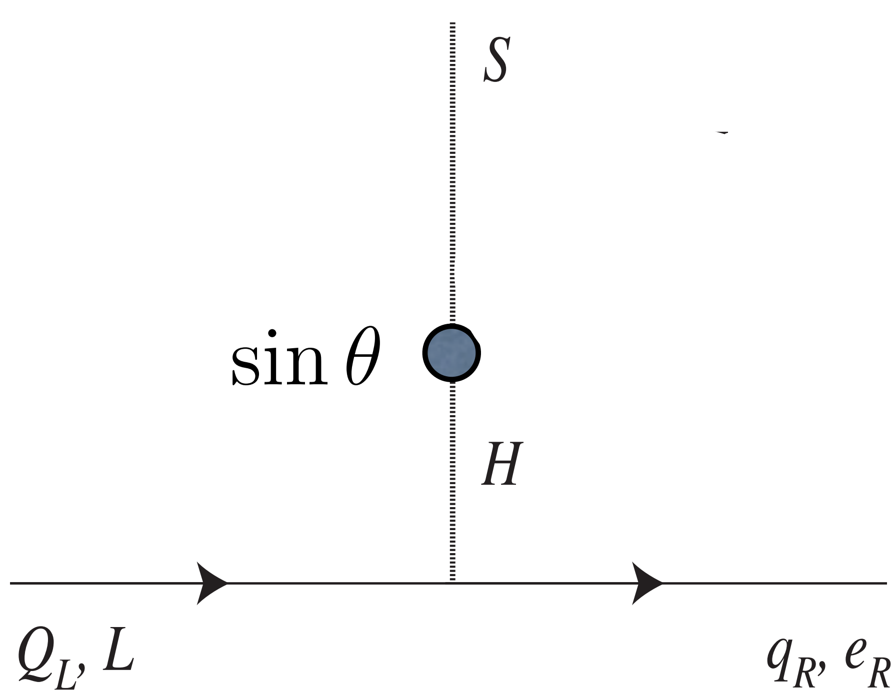
$$g_f = C_N \left(\frac{\alpha_{em}}{\pi}\right)^2 \frac{m_p}{M_\chi} g_\chi \xi_\chi + C_Y Y^2 \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{m_p}{M_\chi} g_\chi \xi_\chi - \sin\theta \frac{m_p}{v}$$

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

$$\beta = \frac{M_P}{\sqrt{4\pi}} \frac{|g_\chi|}{M_\chi} \xi_\chi$$

- Minimal WIMP models are out of reach of MICROSCOPE but could be probed by Mini-STEP.

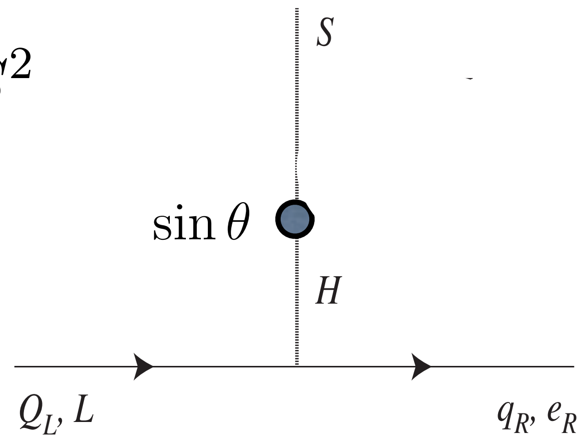
Dark Force Mediation via Mixing



Ultralight-Scalar Higgs Mixing

- Recall the potential before EWSB:

$$V(H,S) = -\mu_h^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H S + \frac{\delta_2}{2} H^\dagger H S^2 - \left(\frac{\delta_1 \mu_h^2}{\lambda}\right) S + \frac{\kappa_2}{2} S^2 + \frac{\kappa_3}{3} S^3 + \frac{\kappa_4}{4} S^4.$$



- The mixing mass term after EWSB is given by:

$$\sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2} \quad , \quad \mu_{hS}^2 = \delta_1 v$$

Mixing from renormalizable coupling.

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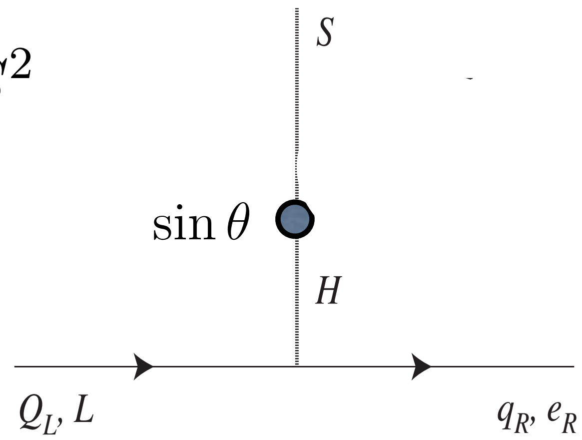

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Mixing from renormalizable coupling.

- If we add a dimension five operator:

$$\delta V(H,S) = C_2 \left(H^\dagger H\right) \left(H^\dagger H\right) S$$

Higher dimension operator will contribute to mixing.

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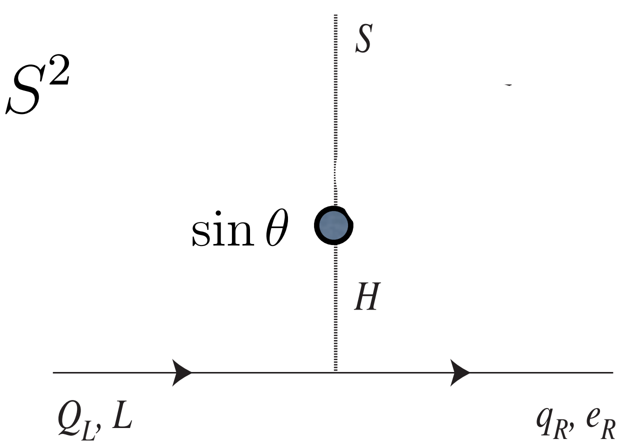

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Higher dimension operator will contribute to mixing.

- The mixing angle receives an additional contribution.

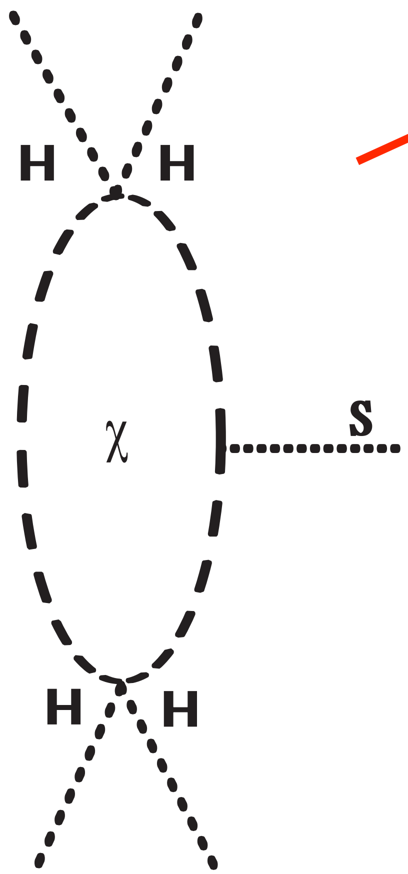
$$\sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2} \quad , \quad \mu_{hS}^2 = 2C_2 v^3 + \delta_1 v$$

$$a_2 H^\dagger H \chi^2$$

DM-Higgs interaction

$$\mu_{hS}^2 = 2C_2 v^3 + \delta_1 v$$

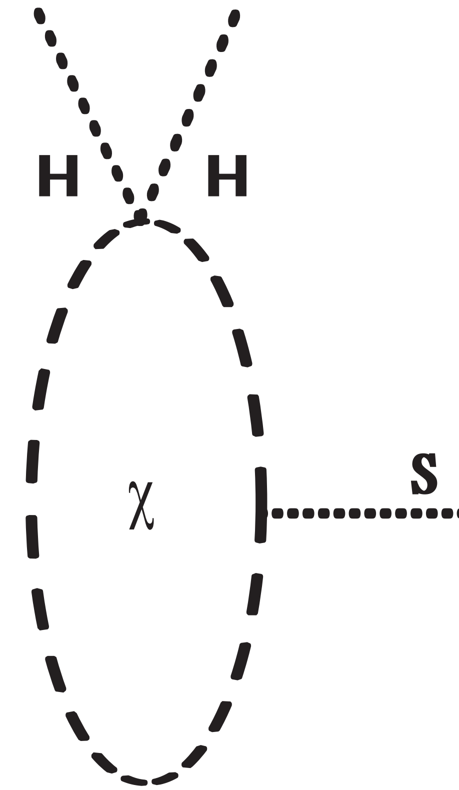
$$\sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2}$$



$$\delta V(H,S) = C_2 \left(H^\dagger H\right)\left(H^\dagger H\right) S$$

finite contribution

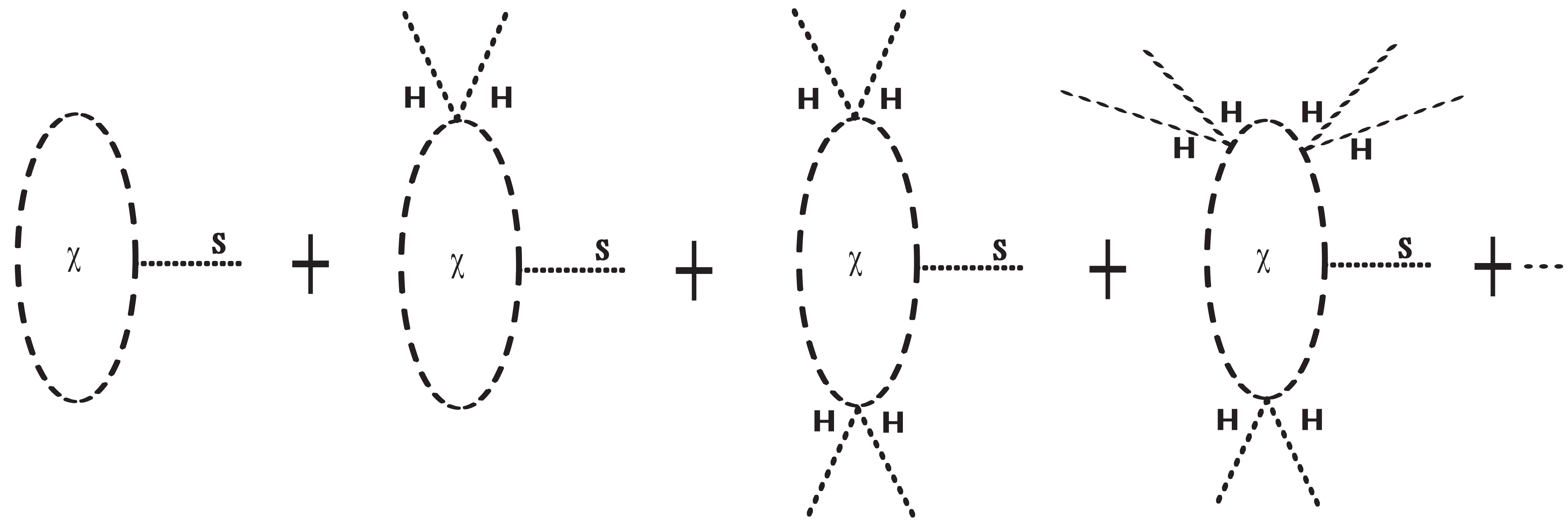
$$C_2 = \kappa \frac{a_2^2}{8\pi^2} \frac{g_\chi}{M_0^2}$$



$$\frac{\delta_1}{2} H^\dagger H S$$

divergent contribution just renormalizes δ_1

Ultralight-Scalar Higgs Mixing IV



$$-\,iV^S_{\rm eff}(S,h) \;=\; -i\kappa g_\chi S \int_E \frac{d^dk}{(2\pi)^d} \sum_{n=0}^{\infty} \frac{(a_2\, h^2)^n}{(k^2+M_0^2)^{n+1}}$$

$$\mu^2_{hS} \;=\; 2\frac{\partial^2 \mathcal{V}_{\rm eff}(h,S)}{\partial S \partial h}\Big|_{h=v,S=0} = \; v\left[\hat{\delta}_1(\mu) + \kappa \frac{g_\chi a_2}{4\pi^2}\left(\ln \frac{M_\chi^2}{\mu^2} - 1\right)\right] + \kappa \frac{a_2^2}{4\pi}\frac{g_\chi v^3}{M_\chi^2}$$

↓ $\delta_1^{\rm ren}$

↓ finite contribution from resummed higher dim ops

Ultralight-Scalar Higgs Mixing V

$$\sin\theta \simeq \kappa \frac{a_2^2}{4\pi^2} \frac{g_\chi v^3}{M_\chi^2 m_h^2} + \frac{\delta_1^{\mathrm{ren}} v}{m_h^2} = \kappa \frac{a_2^2}{\pi^{3/2}} \frac{v^3}{M_P m_h^2} \beta + \frac{\delta_1^{\mathrm{ren}} v}{m_h^2}$$

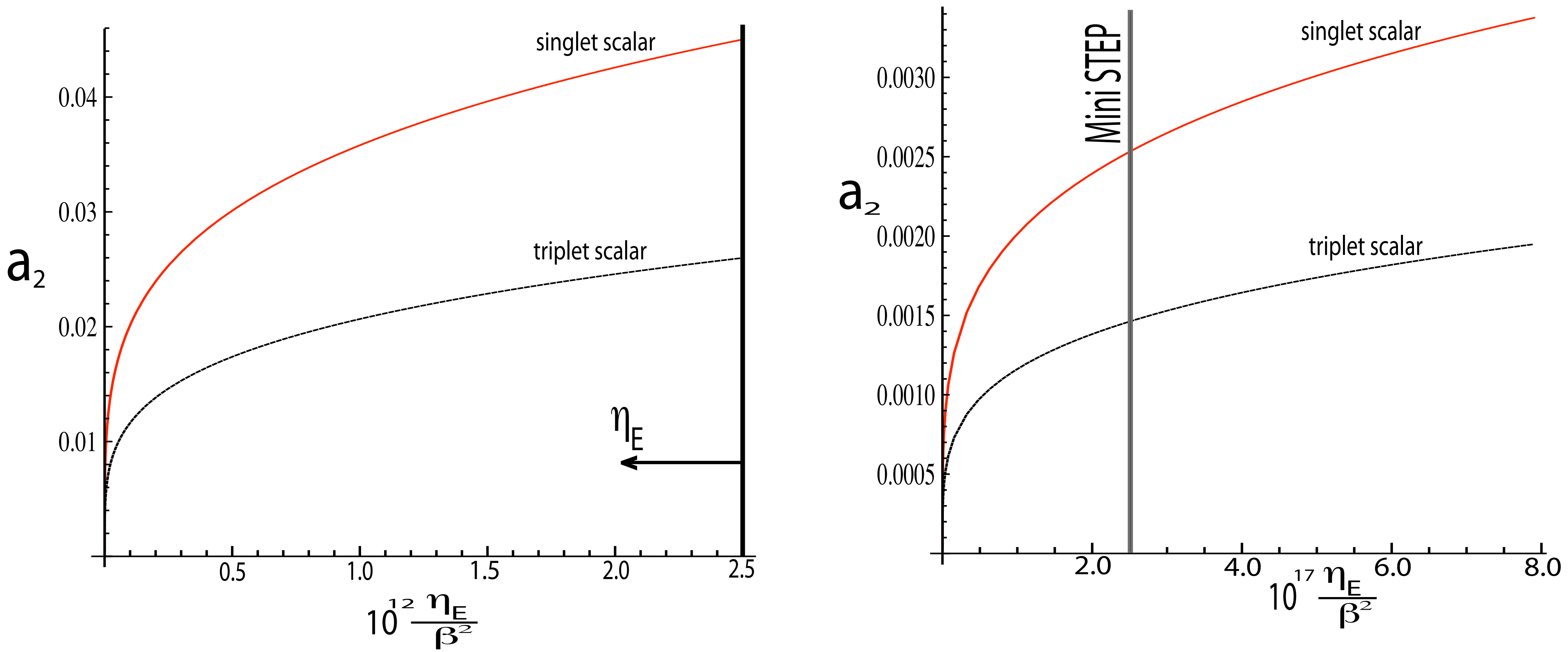
Constrained by WEP tests

Constrained by cosmology and astrophysics

Implies constraint on a2

- Eotvos experiments and observation in cosmology and astrophysics implies constraints on a2.

Constraint on a2 from WEP tests

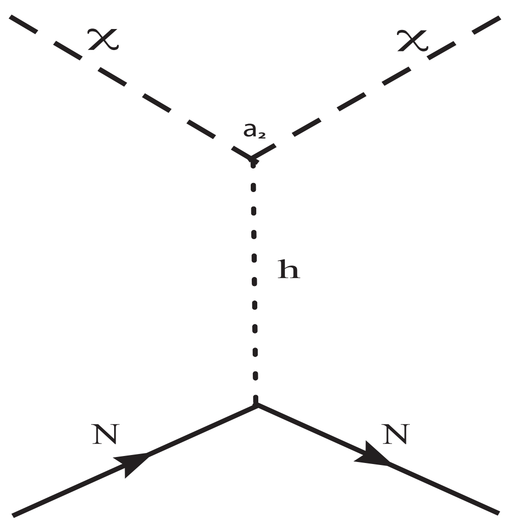


- WEP constraints on a2 in the presence of a dark force.

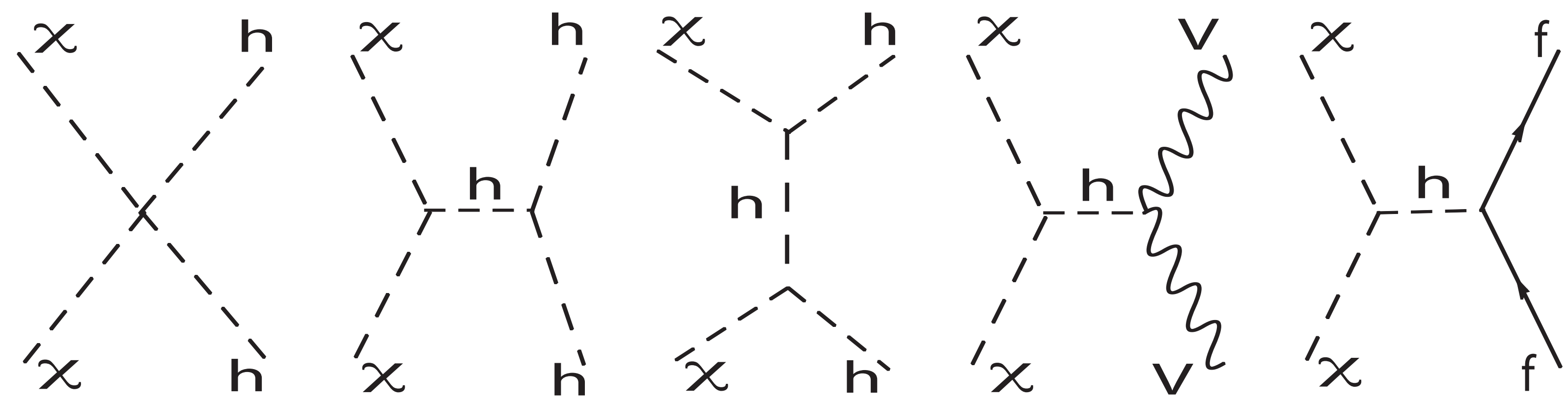
Scalar singlet DM coupled to a dark force

Scalar Singlet DM

$$V(H,S,\chi) \;=\; V(H,S) + \frac{1}{2}M_0^2\chi^2 + \frac{\lambda_\chi}{4}\chi^4 + a_2 H^\dagger H\chi^2 + g_\chi\chi^2 S + \lambda_{\chi s}\chi^2 S^2$$



SI direct detection cross-section



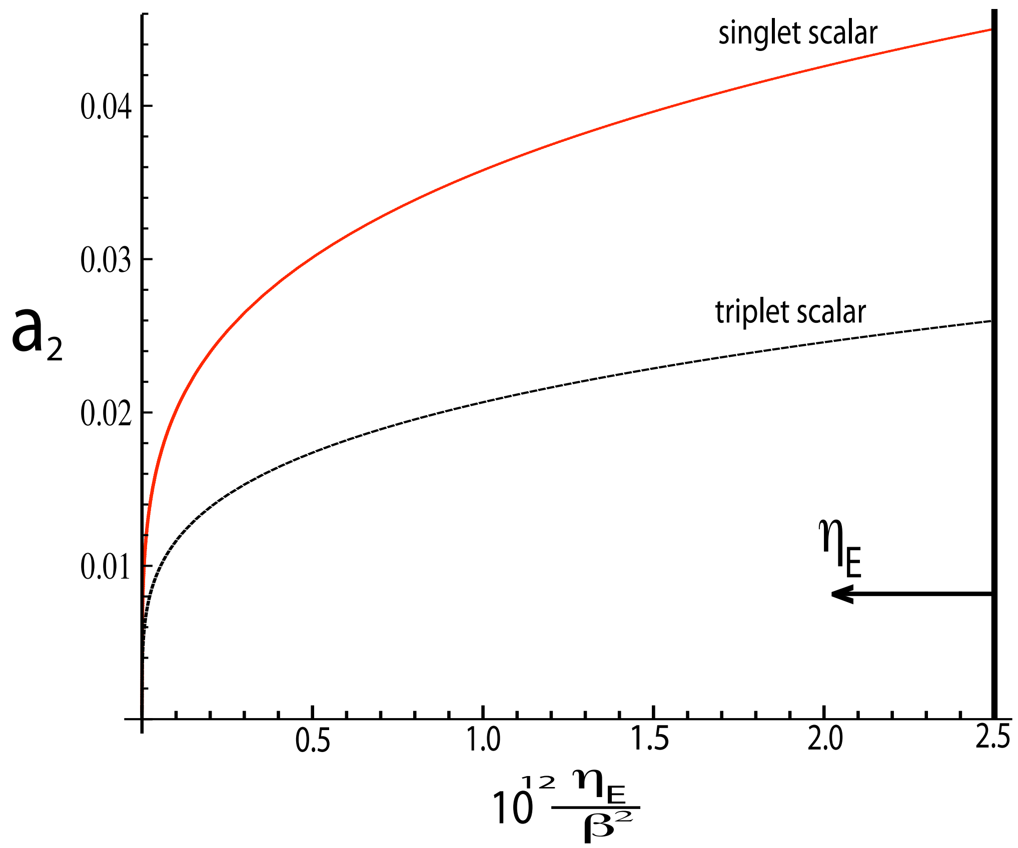
Annihilation diagrams

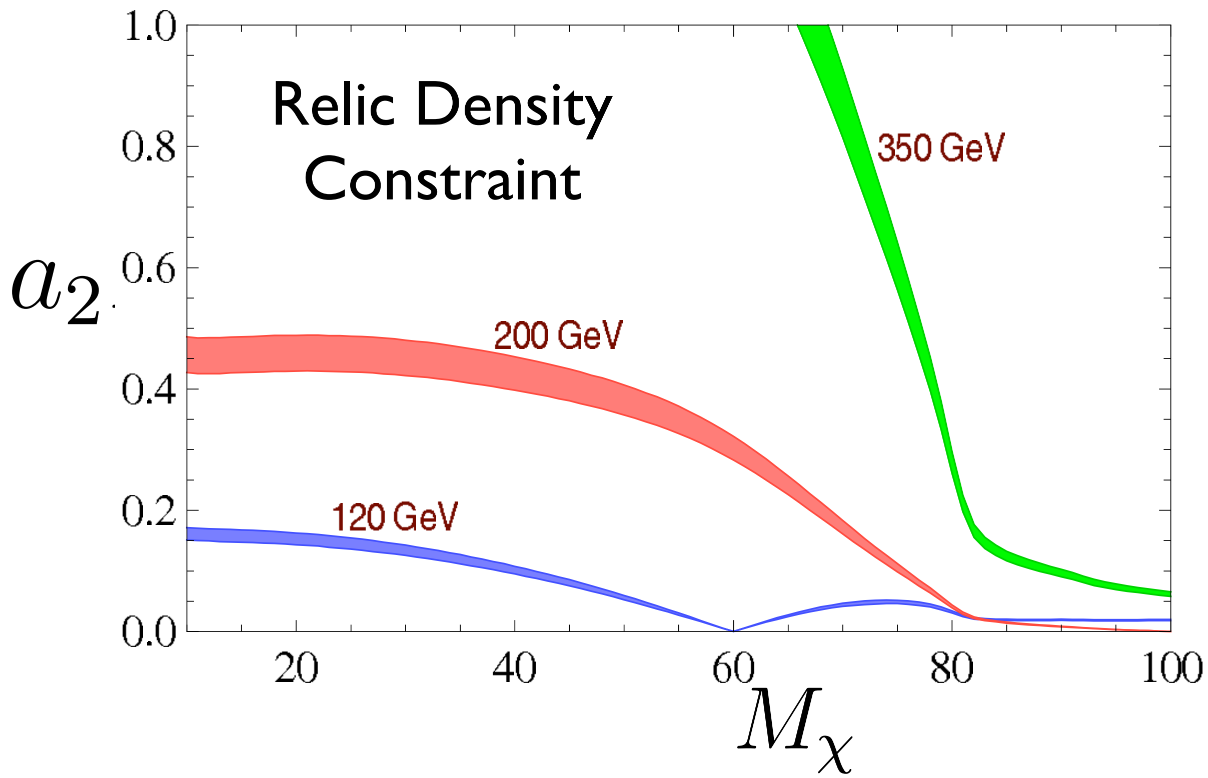
- Parameter a2 determines the direct detection cross-section and the relic density.

Dark Force, WEP Test, and Relic Density

Dark Force, WEP Test, and Relic Density

(Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy; He, T. Li, X. Li, Tandean, Tsai)





(He, T. Li, X. Li, Tandean, Tsai)

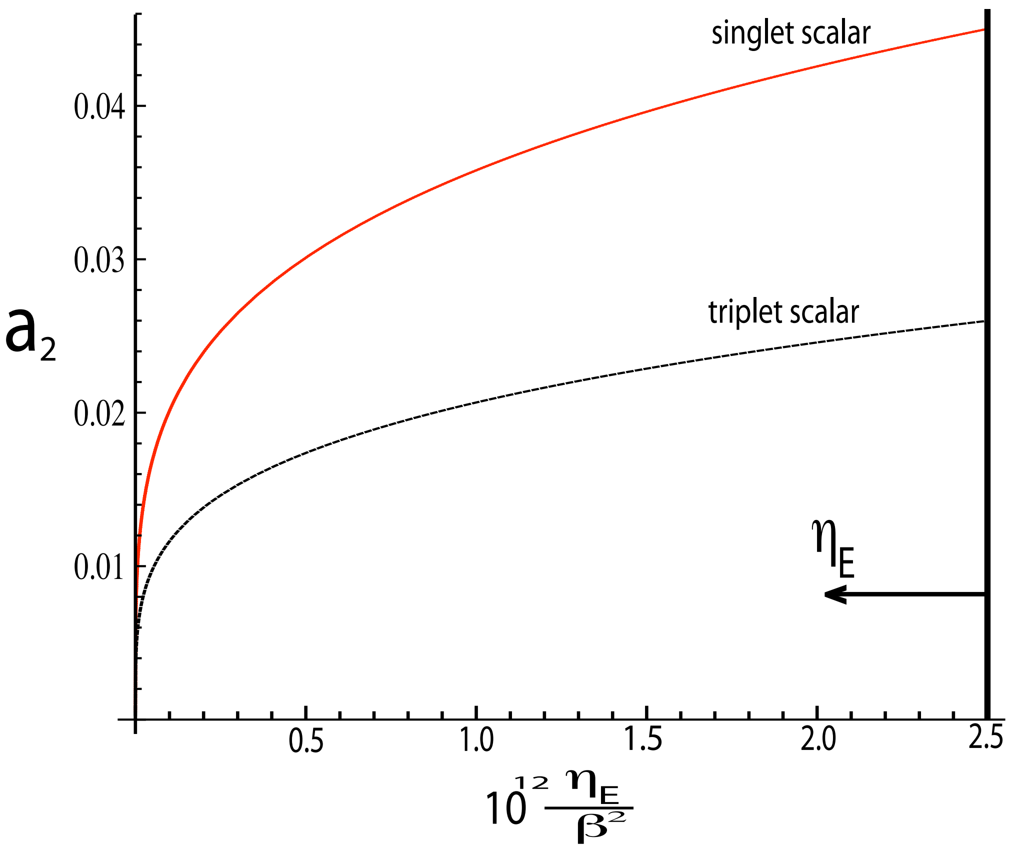
$a_{2\mathrm{relic}}$	M_χ(GeV)	Expectation for $\frac{\eta_E}{\beta^2}$	$\beta = 0.2$
0.15	20	4×10^{-10}	Excluded
0.10	40	7×10^{-11}	Excluded
0.02	100	1×10^{-13}	Allowed

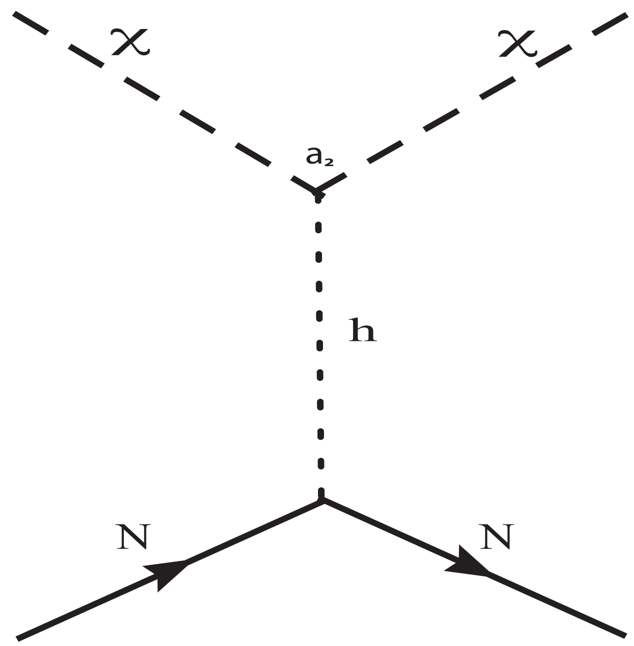
- Large regions in the parameter space of scalar singlet DM models with a dark force are ruled out by relic density requirements

Dark Force, WEP Test, and Direct Detection

Dark Force, WEP Test, and Direct Detection

(Bovy, Farrar)
(Carroll, Mantry, Ramsey-Musolf)

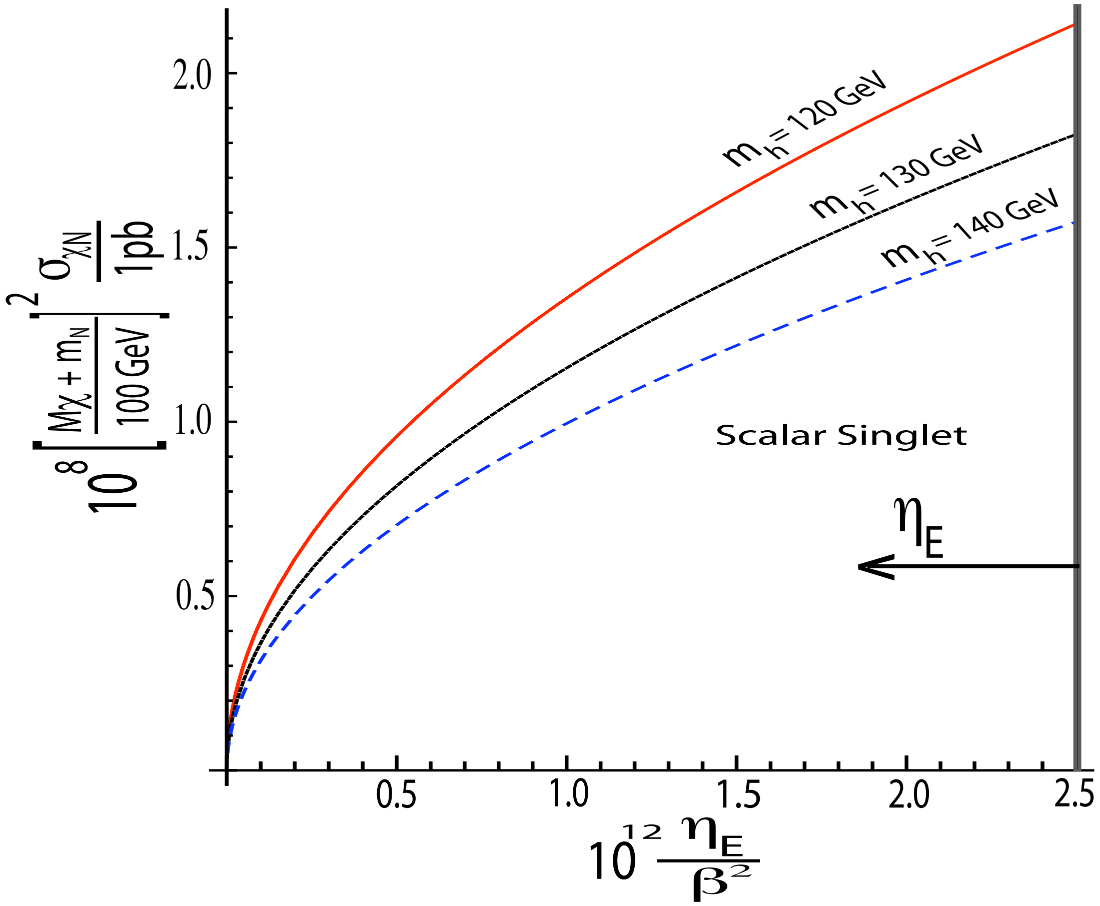


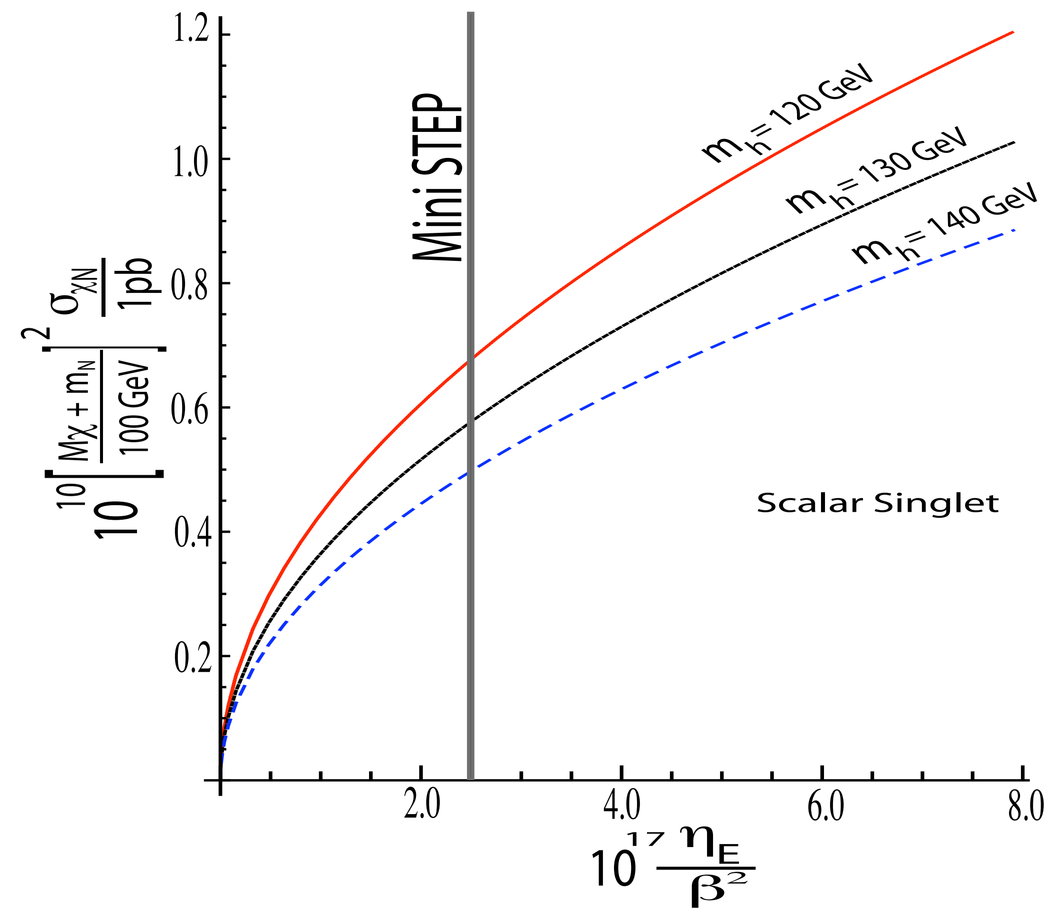


$$\sigma_{\chi N} \simeq \frac{a_2^2 g_h^2 v^2 m_N^2}{\pi (M_\chi + m_N)^2 m_h^4}$$

- The WEP constraint on a2 in the presence of a dark force implies a constraint on the direct detection cross-section.

Bound on Direct Detection Cross-Section

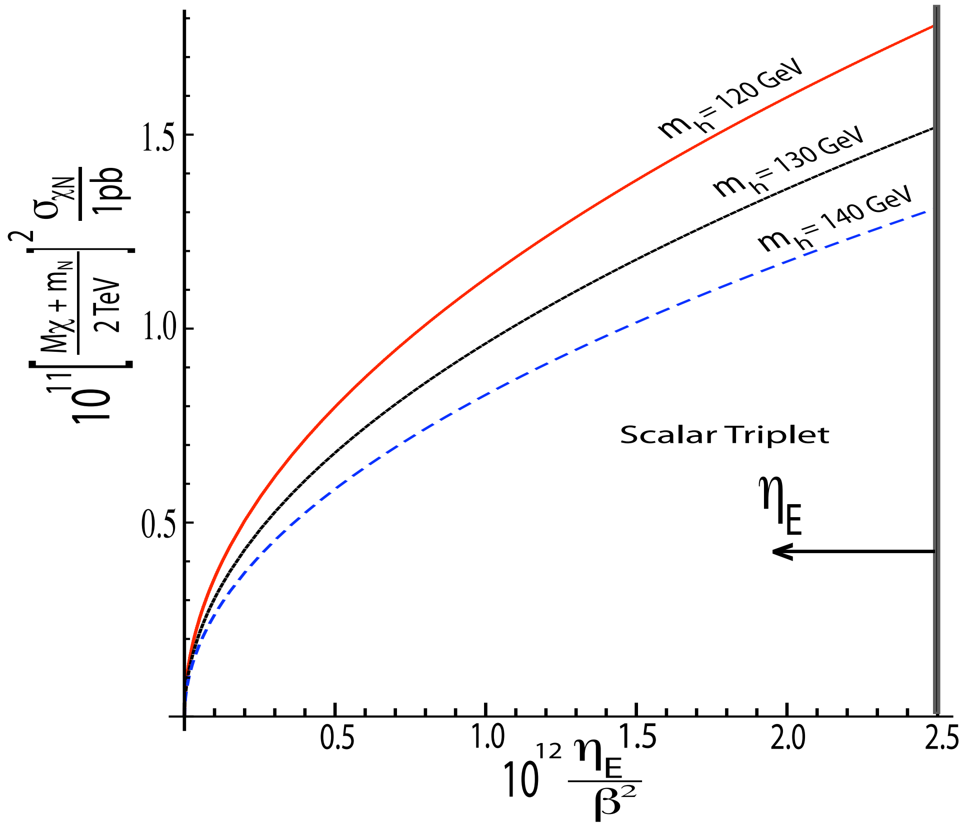


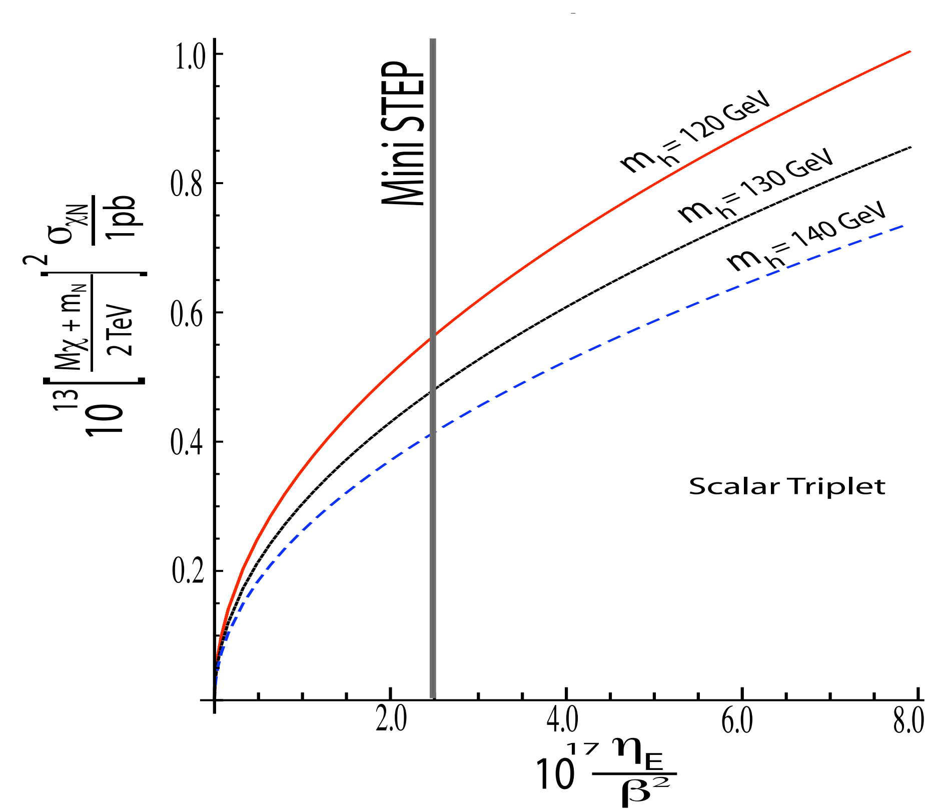


$M_\chi = 50$ GeV	Experiment	Sensitivity $\sigma_{\chi N}$ (pb)	Sensitivity $\left[\frac{M_\chi+m_N}{100\,\text{GeV}}\right]^2\left[\frac{\sigma_{\chi N}}{1\,\text{pb}}\right]$
	CDMS [73]	1.6×10^{-7}	4.1×10^{-8}
	XENON10 [17]	4.5×10^{-8}	1.2×10^{-8}
	CDMS (2007 [74])	1×10^{-8}	3×10^{-9}
	WARP (140 kg) [75]	3×10^{-8}	8×10^{-9}
	SuperCDMS (Phase A) [76]	1×10^{-9}	3×10^{-10}
	WARP (1 ton) [77]	2×10^{-10}	5×10^{-10}

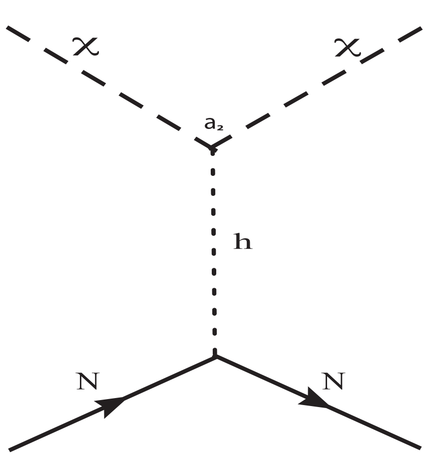
- Direct detection bounds can be probed by current or future direct detection experiments.

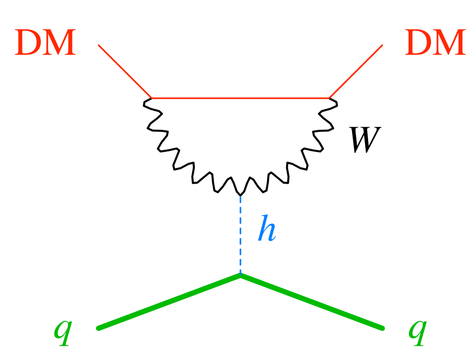
Bound on Tree Level DM-Nucleus Cross-Section for Real Scalar Triplet Dark Matter

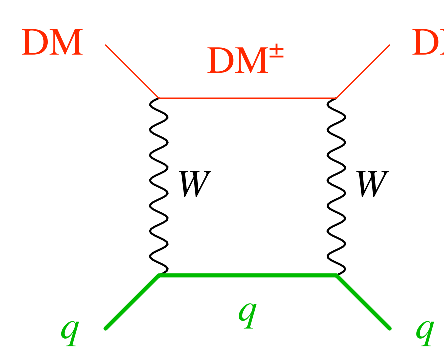


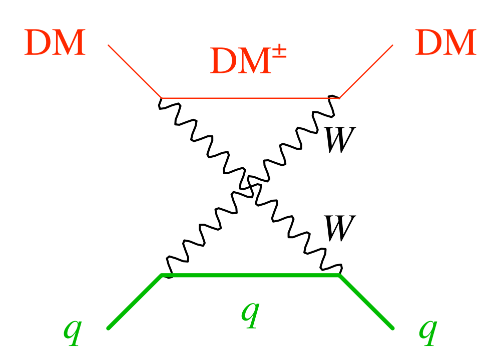


- The WEP constraint on tree level DM-Nucleus cross-section implies that typically direct detection will be given dominated by one loop contributions which begin at about 10^(-9) pb.





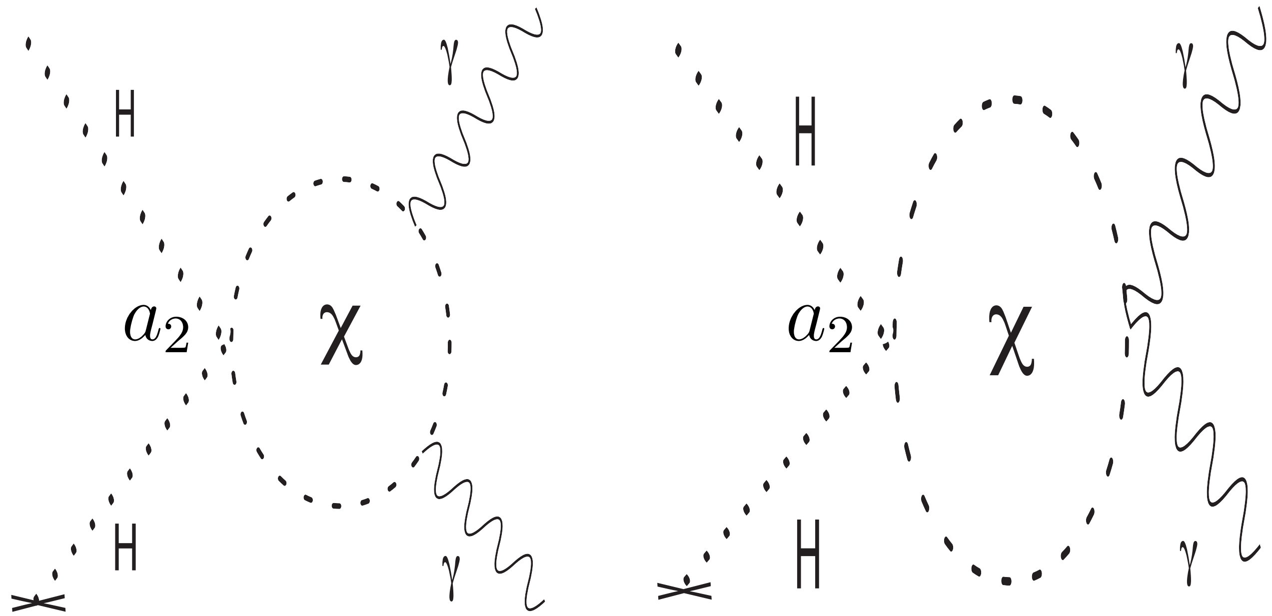




(Cirelli,Fornengo,Strumia)

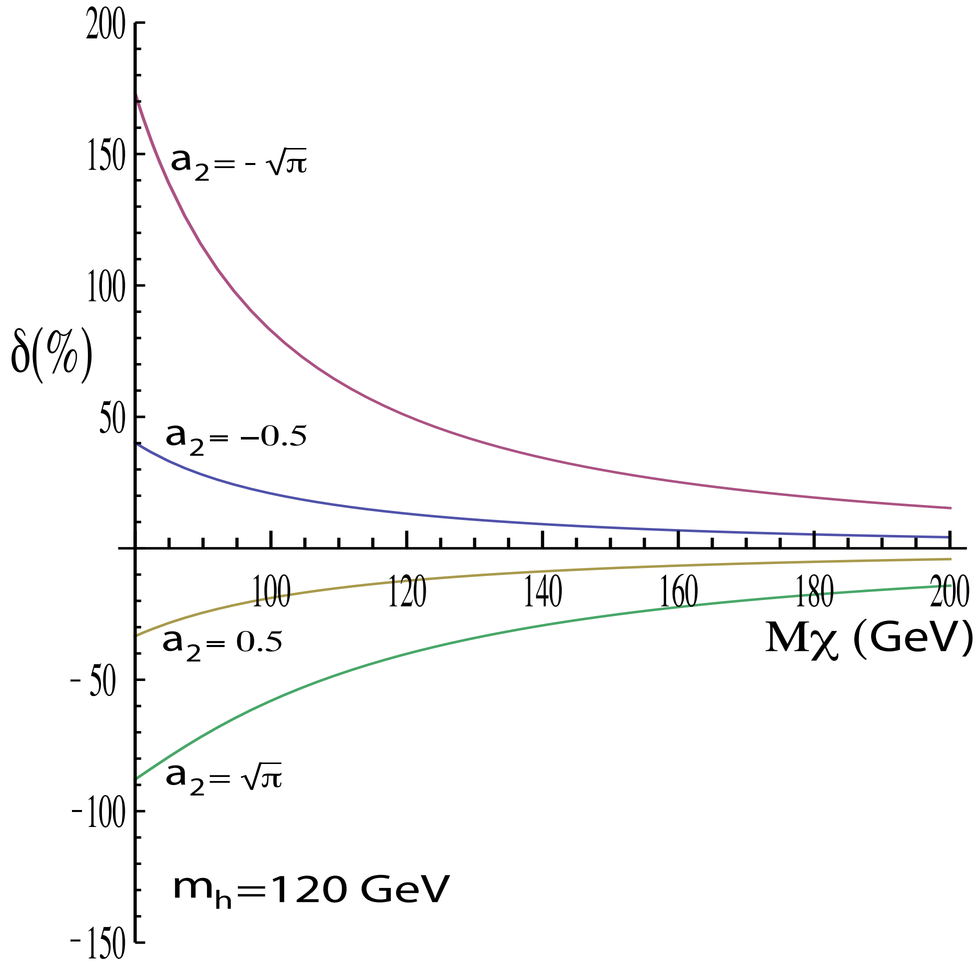
Dark Force, WEP Test, and Higgs Decay

- WEP constraints on a2 imply constraints on the size of the following one loop graphs which contribute to the Higgs decay to two photons

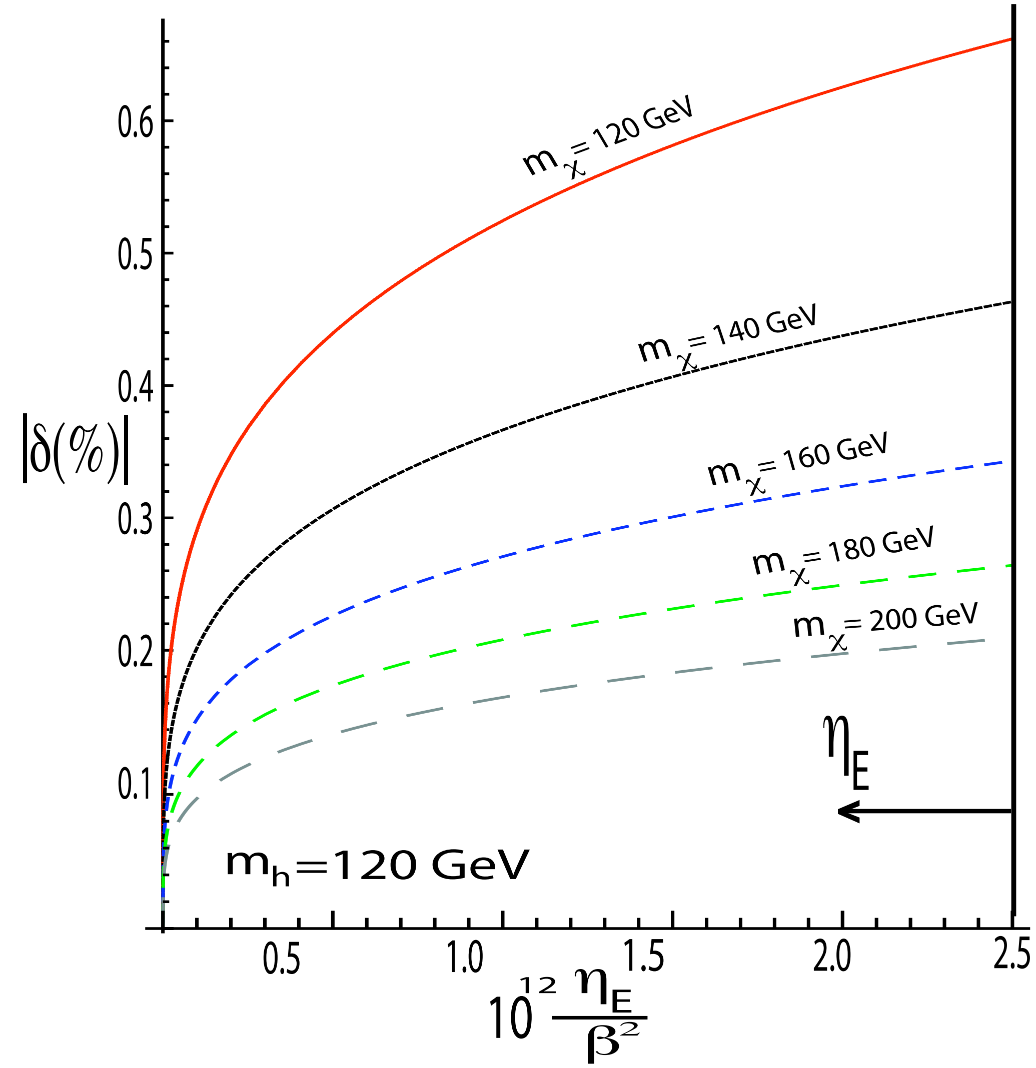


- One can parameterize the size of these graphs via the shift

$$\delta(\%) \equiv 100 \times \frac{\Gamma(h \to \gamma\gamma) - \Gamma^{SM}(h \to \gamma\gamma)}{\Gamma^{SM}(h \to \gamma\gamma)}$$



(Filevez Perez, Patel,Ramsey-Musolf,Wang)



- The LHC or future colliders are likely to be sensitive to shifts in Higgs decay to two photons for triplet masses less than 200 GeV.
- Such light DM will be only a tiny fraction of the relic density in minimal models. A dark force in this case would have unobservable effects in astrophysics or cosmology. Colliders can still probe these dark forces.

Conclusions

- A dark force implies a non-zero effect in laboratory WEP tests via quantum effects.
- For scalar singlet DM, relic density and WEP tests rule out a dark force in large region of parameter space.
- A dark force implies constraints on the SI DM-direct-detection cross-section via Higgs exchange.
- A dark force can also imply constraints on collider signals.
- Terrestrial Experiments can probe incredibly feeble forces, weaker than gravity, confined to the dark sector.