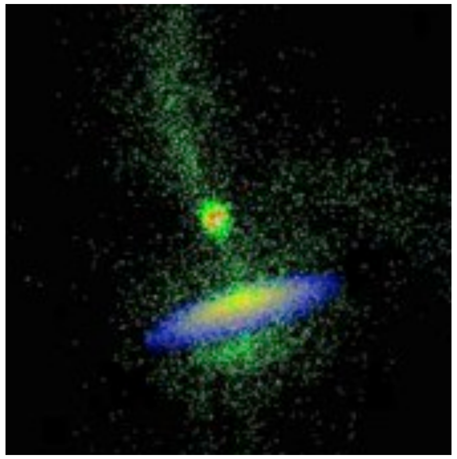
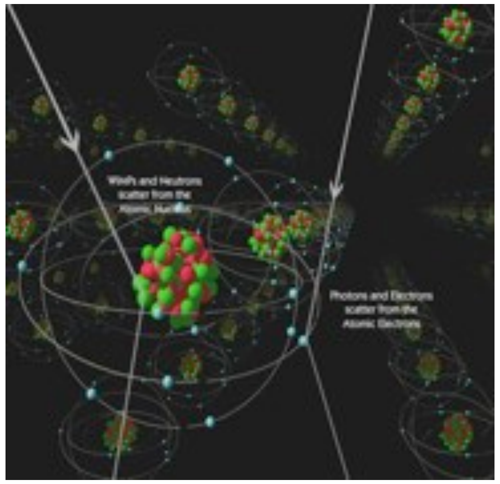
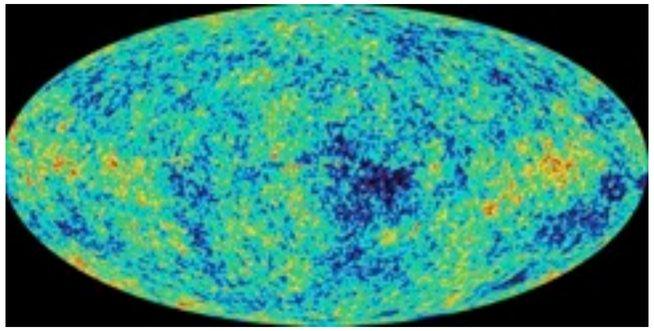
Implications of a Scalar Dark Force for Terrestrial Experiments







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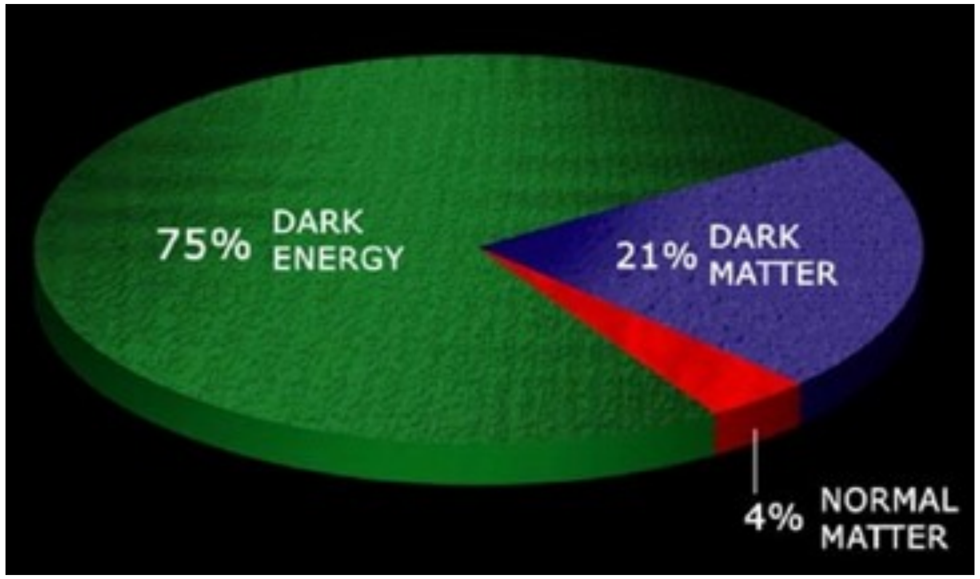
UC Davis, March 16th, 2009

arXiv:0807.4363, S.Carroll, S. Mantry, M. Ramsey-Musolf, C. Stubbs
arXiv:0902.4461, S.Carroll, S. Mantry, M.Ramsey-Musolf

Motivation

- WEP is empirical and must be tested.
- Stringent limits from laboratory experiments exist of WEP violation in ordinary matter.
- However, laboratory tests of WEP violation do not directly apply to the dark sector. There is a lot more dark matter!
- Dark forces have been studied in non-universal scalar tensor theories to explain the origin of dark energy and the coincidence problem. (Alimi, Fuzfa ; Damour, Polyakov)
- Astrophysics and cosmology constrain dark forces.
- Need to connect an observed dark force with microscopic particle physics.



Main Points

- A dark force, via quantum effects, implies WEP violation for ordinary matter.

- For scalar singlet DM, relic density considerations rules out a dark force in large regions of parameter space.

- A dark force implies constraints on the SI DM-direct-detection cross-section via Higgs exchange.

- Depending on the DM model, a dark force can also imply constraints on collider signals.

- The region of parameter space consistent with an observable dark force is quite restricted.

Terrestrial WEP Tests for Ordinary Matter

The Weak Equivalence Principle

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

Inertial Mass

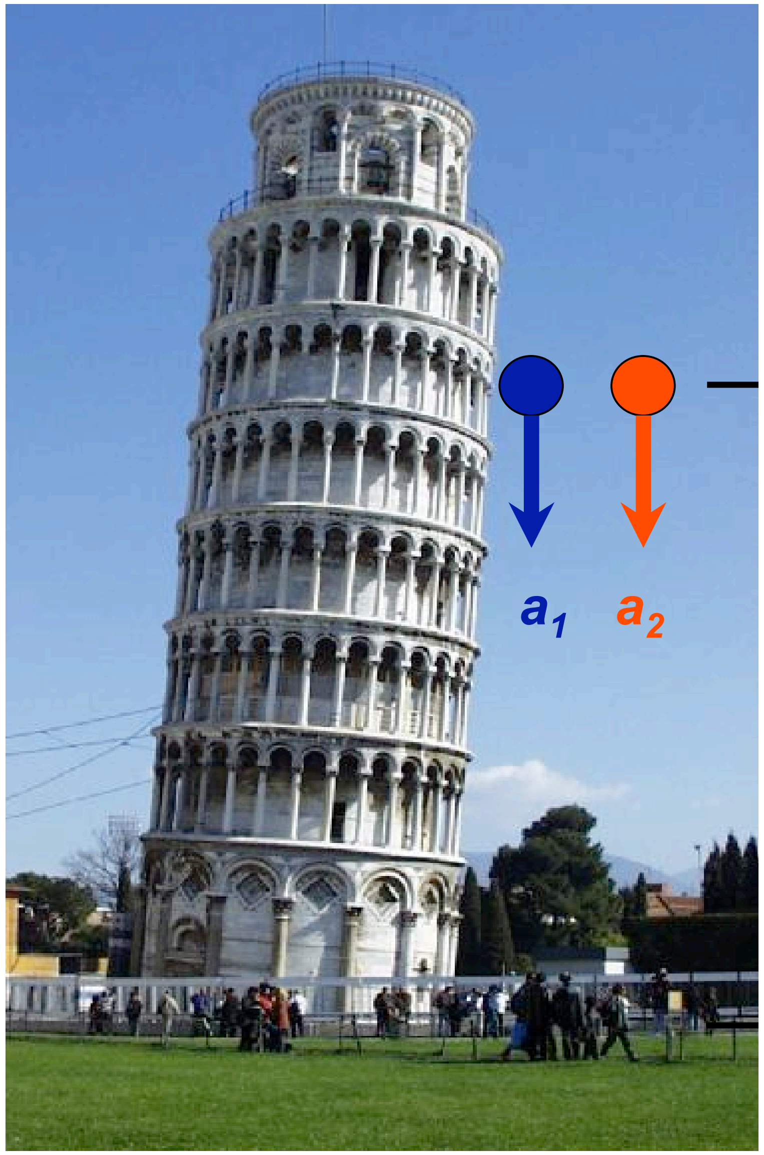
$$\mathbf{F}_g = -m_g \, \vec{\nabla} \Phi_g$$

Gravitational Mass

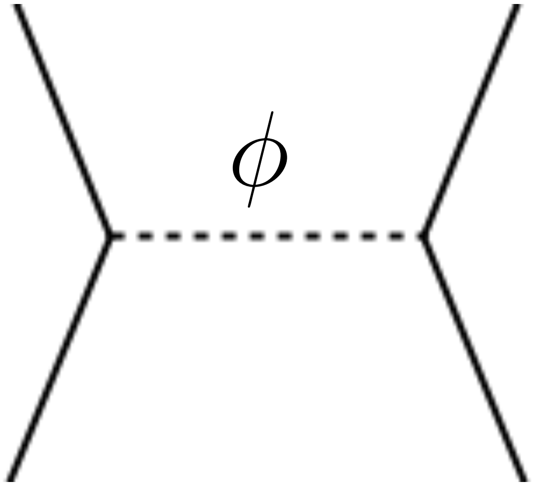
$$\mathbf{a}_i = \frac{\mathbf{F}_g}{m_i} = -\left(\frac{m_g}{m_i}\right) \vec{\nabla} \Phi_g$$

- WEP violation:

$$m_i \neq m_g$$



Fifth Force WEP Violation



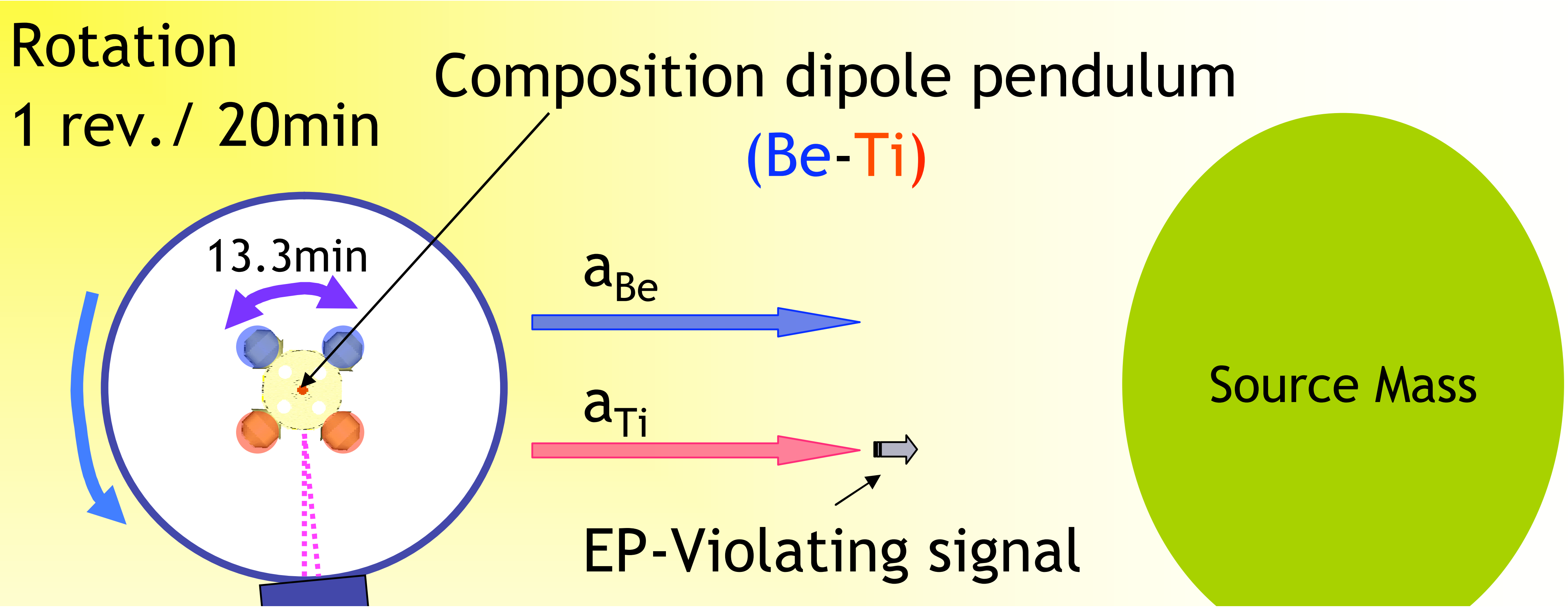
- Fifth force mediated by an ultralight scalar can lead to an apparent violation of the WEP.

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

WEP violation

Charge to mass ratios

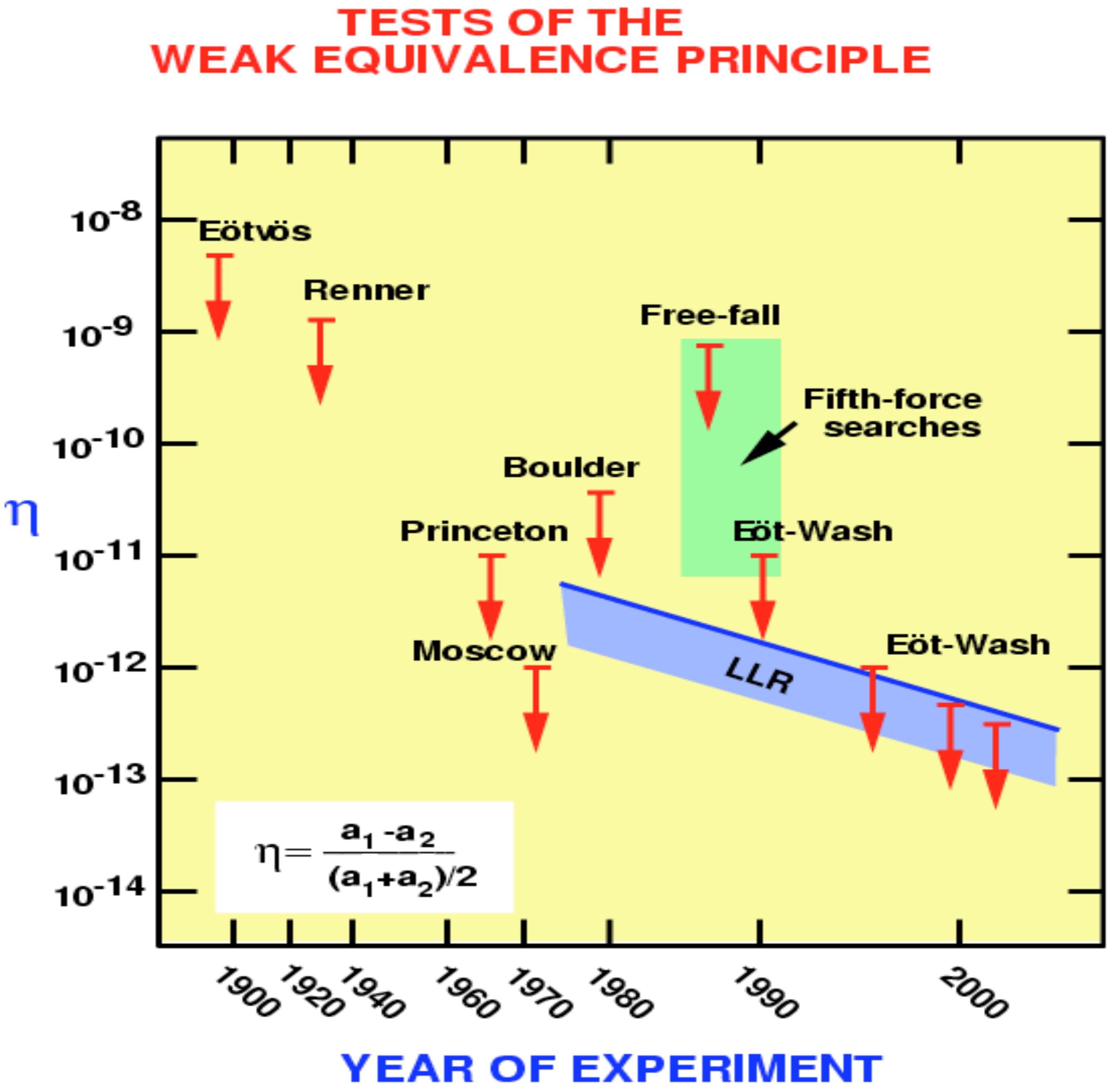
Eotvos Experiments I



- 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:

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

$$\eta_{\rm DM}^{\rm Be,Ti} < (4 \pm 7) \times 10^{-5}$$

(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

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:

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

WEP Tests in the Dark Sector

- Tidal tails test of satellite galaxies.

(Kamionkowski, Kesden; Keselman, Nusser,Peebles)

- The cosmic microwave background.

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

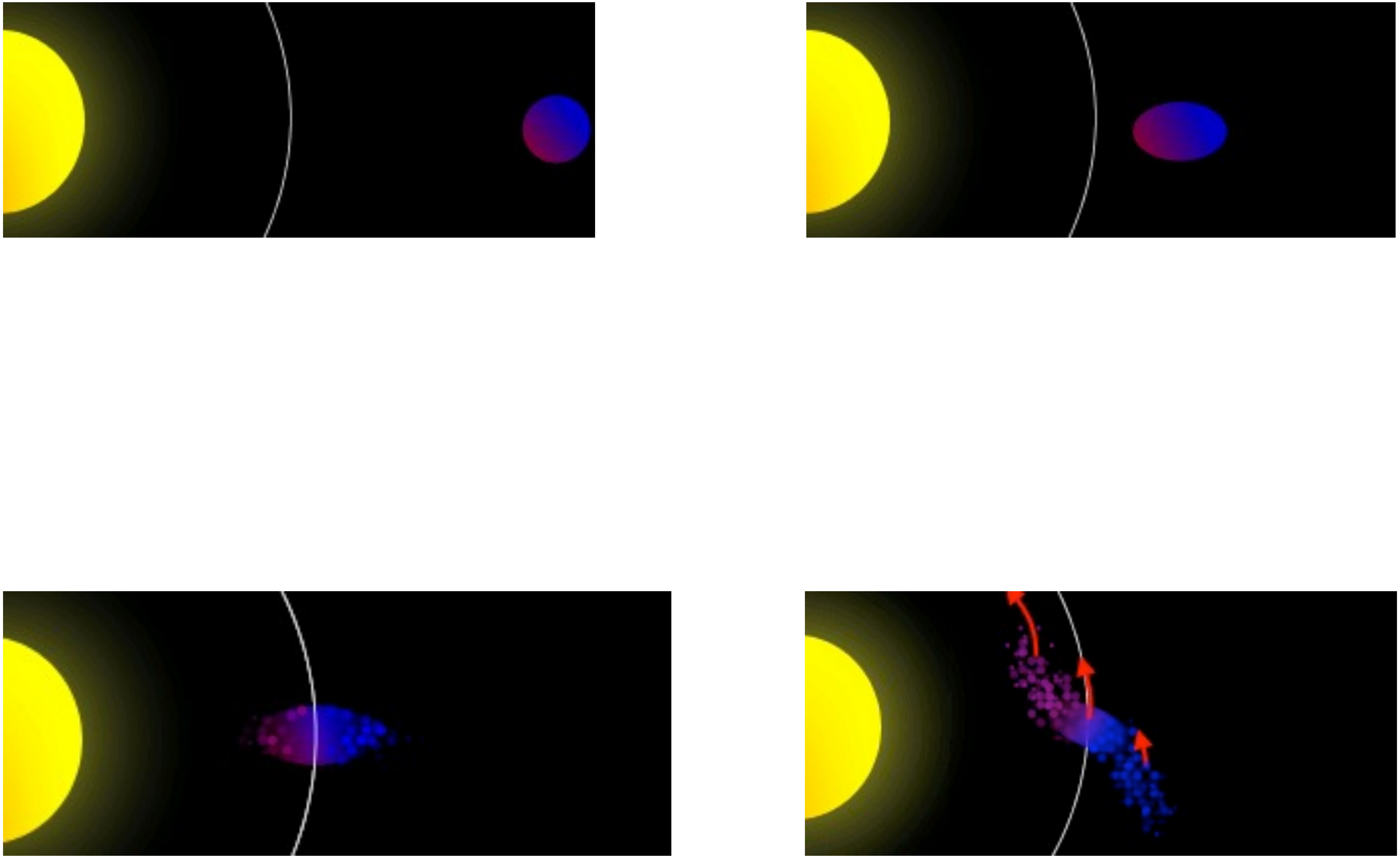
- Matter Power Spectrum.

(Gradwohl, Frieman)

- Cluster Dynamics.

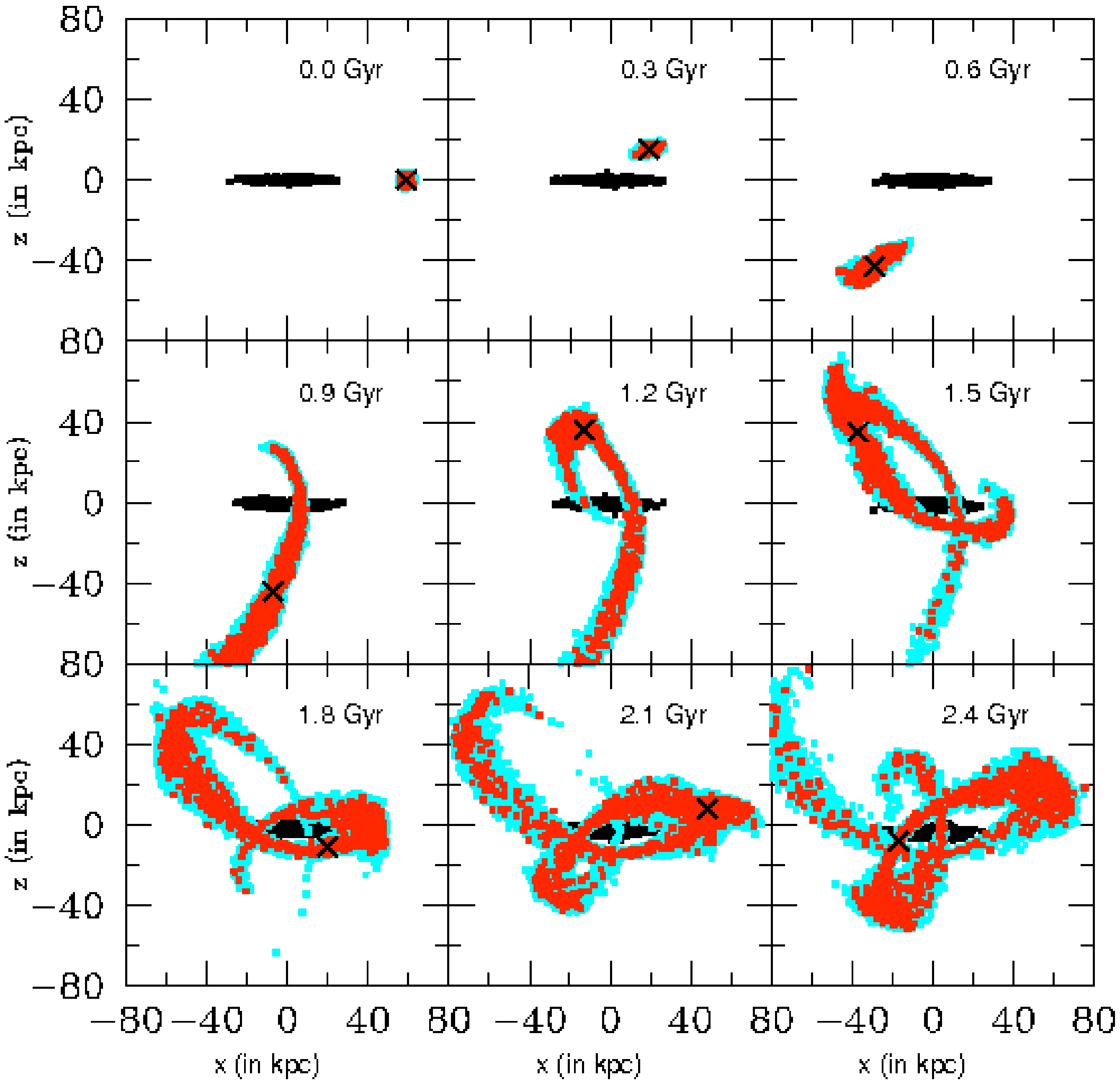
(Gradwohl, Frieman ; Farrar, Springel)

Tidal Disruption



(Wikipedia)

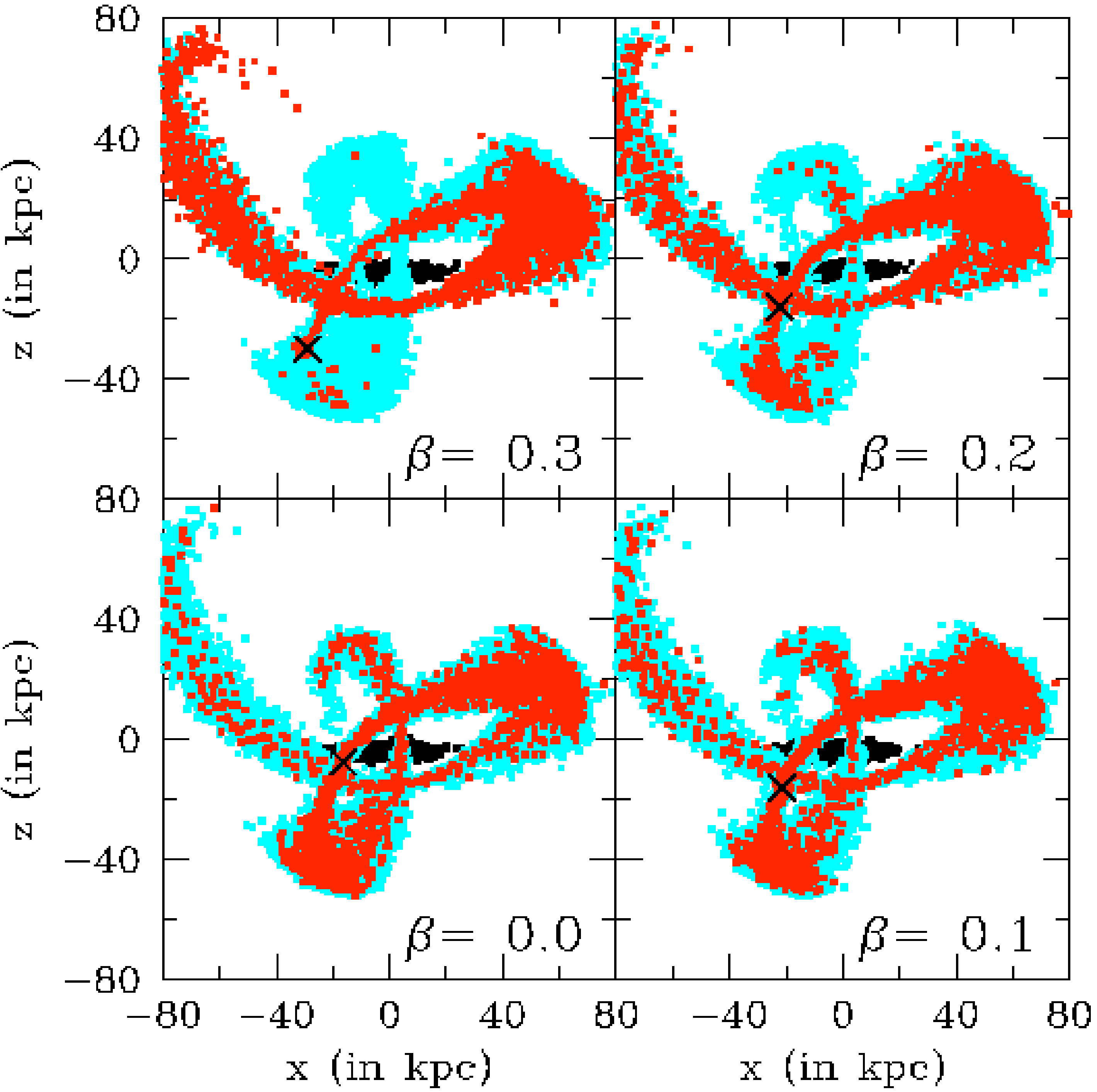
Tidal Tails Test of the WEP



(Kamionkowski, Kesden)

- A satellite galaxy orbiting the Milky Way experiences tidal disruption.
- The disruption forms leading and trailing tidal streams of stars
- A dark force would lead to an enchanced trailing stream.

Tidal Tails with a Dark Force



(Kamionkowski, Kesden)

- Enhanced trailing tidal stream is seen in simulations for a non-zero dark force.
- Leading and trailing streams of the Sagittarius dwarf galaxy have been studied by SDSS and 2MASS collaborations.
- Current limit on a dark force from the tidal tails test is

$$\beta < 0.2$$

Evolution of density perturbations

- A dark force leads to a modified gravitational constant in the dark sector. Correspondingly, there is a modification of the evolution equations of density perturbations

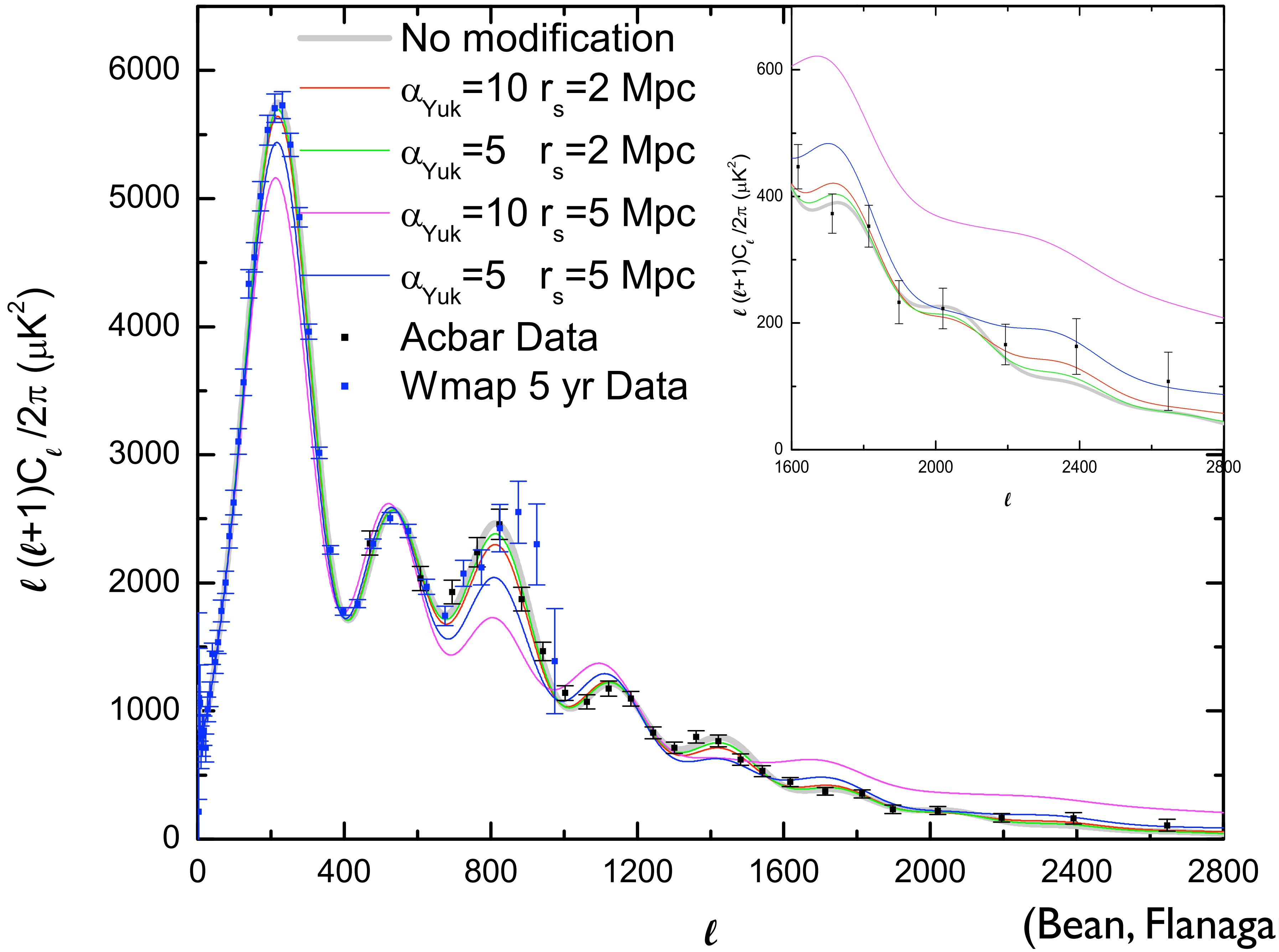
$$\ddot{\delta}_c \ + \ \mathcal{H}\dot{\delta}_c - 4\pi G a^2 \left[\frac{G_c(k)}{G}\rho_c\delta_c + \rho_b\delta_b + 2\rho_\gamma\delta_\gamma\right] = 0$$

- Modified gravitational coupling in the dark sector

$$G_c(k) \ = \ G\left[1 + \frac{\alpha_{\mathrm{Yuk}}}{1+(kr_s)^{-2}}\right], \qquad \alpha_{YUK} = 8\pi\beta^2$$

- A dark force can be constrained from the evolution of matter density perturbations and their effect on the CMB and large scale structure power spectrum.

Cosmic Microwave Background



(Bean, Flanagan, Laszio, Trodden)

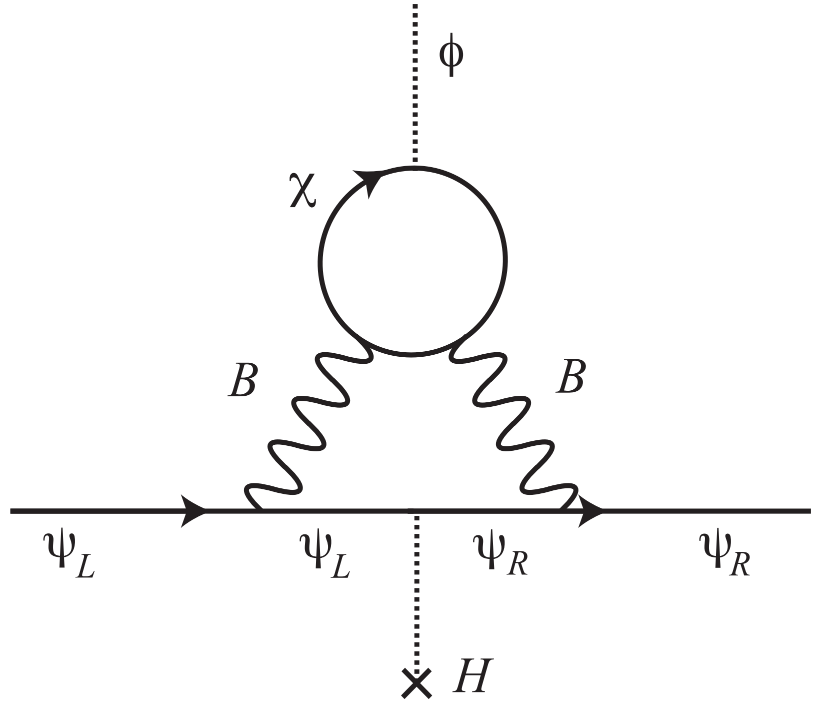
- Effects of a dark force on the CMB power spectrum. From WMAP and ACBAR data one can constrain dark forces from the CMB.

Dark Force and Eotvos Experiments

Dark Force Implies WEP Violation for Ordinary Matter

- WEP violation in the dark sector will be communicated to ordinary matter via quantum effects as long as the dark matter is not sterile.

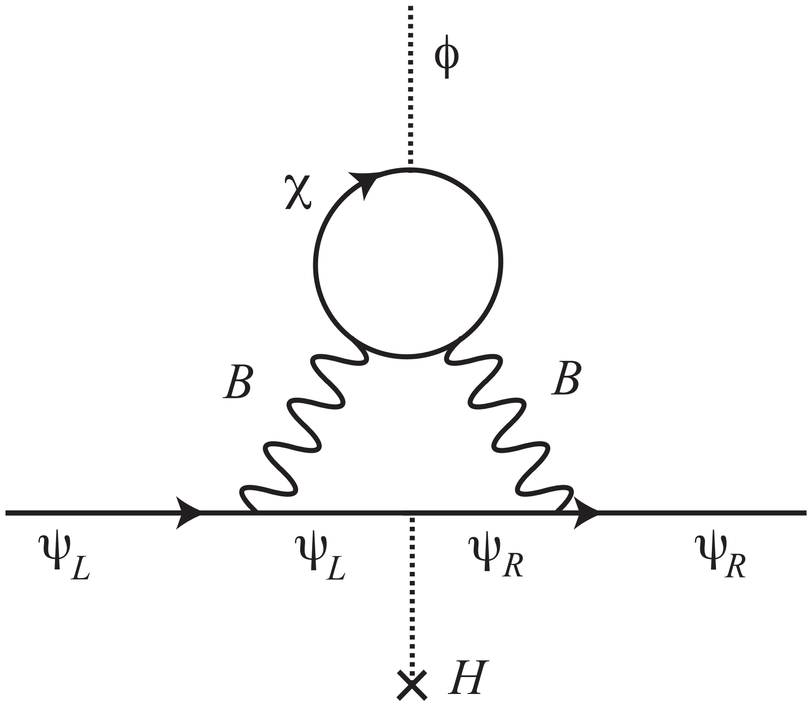
- This implies a connection between laboratory tests of the WEP for ordinary matter and the observation of a dark force in astrophysics or cosmology.



Ultralight Scalar Couplings

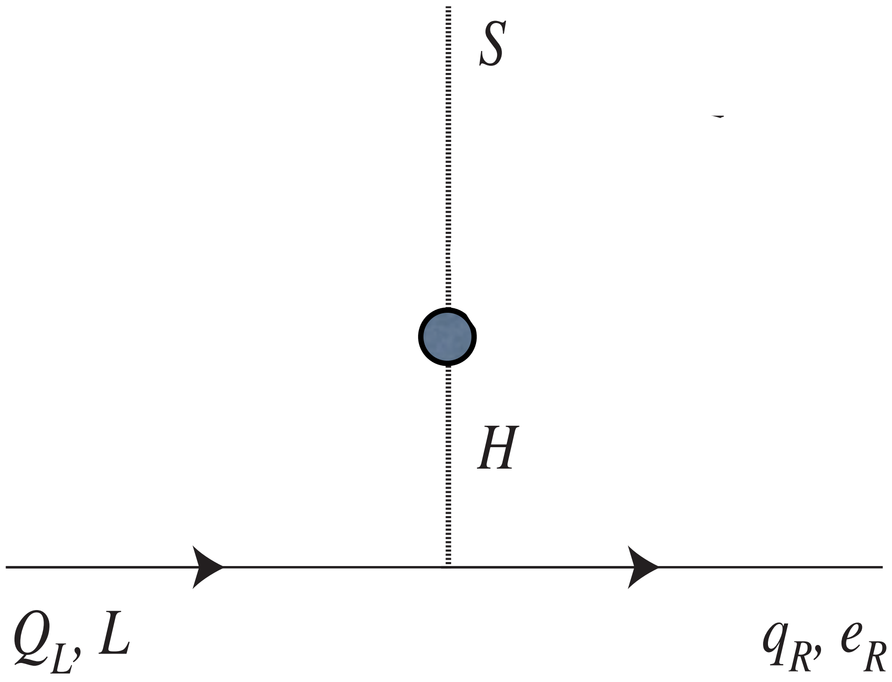
- In general, the ultralight scalar can couple to the SM in two ways:

Higher dimension operators



$$\delta\mathcal{L} = \frac{m_f}{m_p} g_f \bar{f} f$$

Mixing with the Higgs



$$g_f \simeq \frac{m_p}{m_f}\frac{v}{\sqrt{2}}\tilde{c}_f - \sin\theta\frac{m_p}{v}$$

- From the coupling to SM fermions one can deduce the Eotvos parameter:

$$g_f \simeq \frac{m_p}{m_f}\frac{v}{\sqrt{2}}\tilde{c}_f - \sin\theta\frac{m_p}{v} \qquad \longrightarrow \qquad \eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|} \simeq \left|\frac{\Delta a}{a}\right|$$

- The Eotvos parameter is determined by the charge to mass ratios of the test and source objects:

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|} \simeq \left|\frac{\Delta a}{a}\right| , \qquad \eta_s^{1,2} = \frac{1}{4\pi G}\left|\frac{q_1\hat{\xi}_1}{\mu_1} - \frac{q_2\hat{\xi}_2}{\mu_2}\right|\left|\frac{q_s\hat{\xi}_s}{\mu_s}\right|$$

- One can estimate the Eotvos parameter as

$$\eta_S^{\rm univ} \simeq \bar{g}\left(\frac{M_P^2}{4\pi m_N^2}\right)\left(\frac{7}{9}\right)\left|\hat{\xi}_S\left(\frac{q}{\mu}\right)_S\right|\,\left|\left(\frac{Z_1}{A_1}-\frac{Z_2}{A_2}\right)\left\{m_e+\sum_q m_q\left(x_{q,p}-x_{q,n}\right)\right\}\right|$$

$$g_f \equiv \bar{g}, \qquad x_{q,p} = \langle p|\bar{q}q|p\rangle, \qquad x_{q,n} = \langle n|\bar{q}q|n\rangle$$

Known nuclear
matrix elements

- The charge to mass ratio for Earth as a source object is:

$$\hat{\xi}_E\left(\frac{q}{\mu}\right)_E\Bigg|_{\rm univ} \simeq \bar{g}\left(\frac{v}{m_N^2}\right)\frac{g_h(N_p+N_n)+(m_e/v)N_e}{(N_p+N_n)+(m_e/m_N)N_e} \simeq 0.0017\,\bar{g}\left(\frac{v}{m_N^2}\right)$$

- These expressions will receive corrections from binding energy effects which we neglect for order of magnitude estimates.

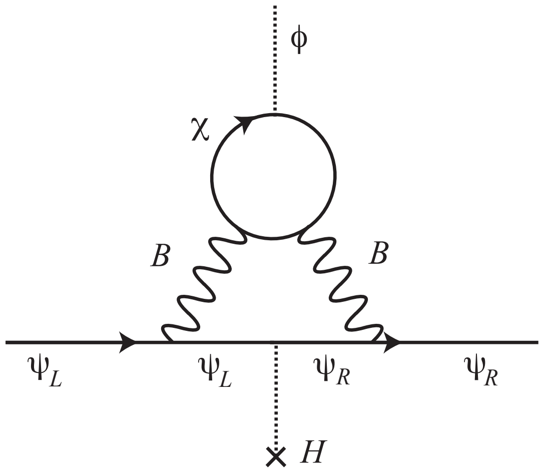
WIMP Dark Matter Coupled to a Dark Force

WIMP Dark Matter

- Consider Minimal WIMP models of the type:

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

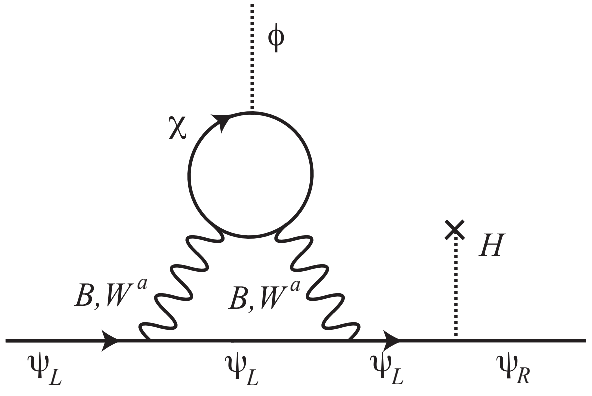
- Two loop diagrams can induce dimension five operators like:



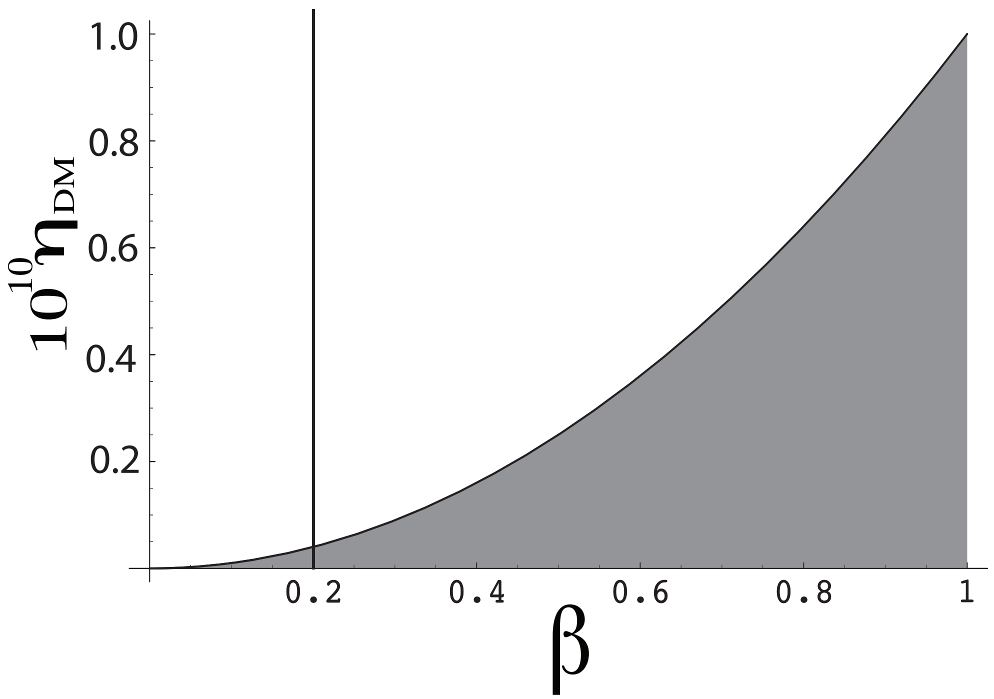
$$\mathcal{O}_u^H \; = \; S\,\bar{Q}_L\,\epsilon H^\dagger\,C_u^H\;u_R + \text{h.c.}$$

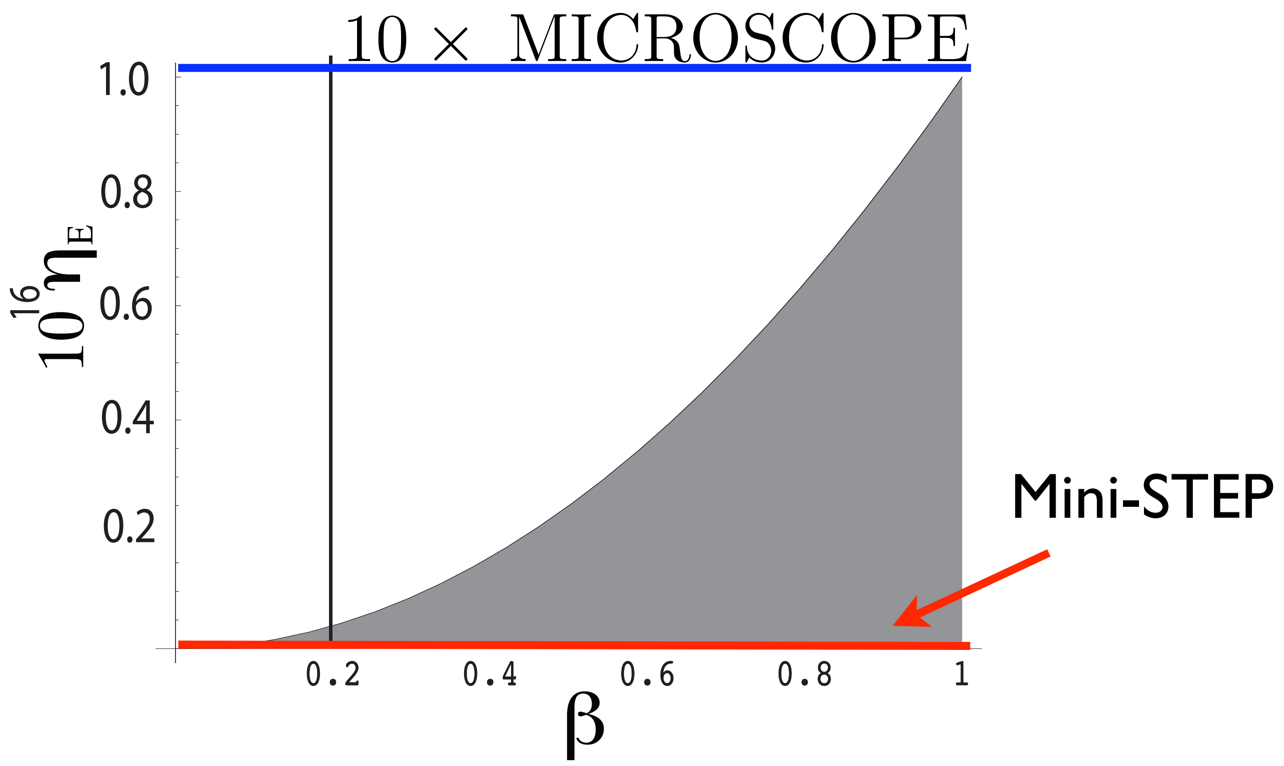
- After EWSB the coupling to fermions is given by:

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



Expectation for Eotvos Experiments



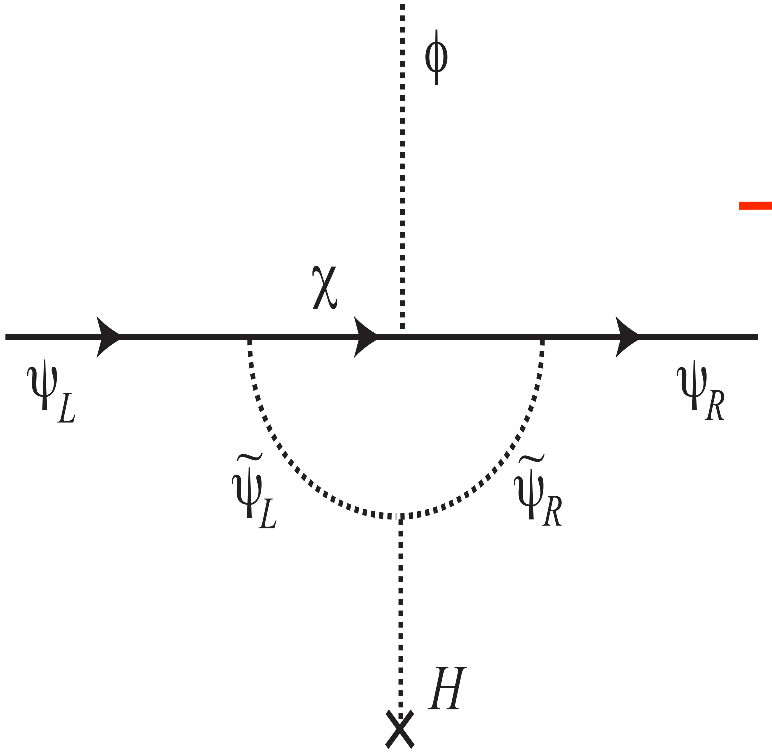


$$g_f = C_N\left(\frac{\alpha_{em}}{\pi}\right)^2\frac{m_p}{M_\chi}g_\chi\xi_\chi + C_Y Y^2\left(\frac{\alpha_{em}}{4\pi}\right)^2\frac{m_p}{M_\chi}g_\chi\xi_\chi - \sin\theta\frac{m_p}{v}$$

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

- If a much larger effect is seen in Eotvos experiments, it would indicate the possibility of a non-minimal DM model or a large mixing ultralight-scalar-Higgs mixing.

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



could give bigger effects

- One loop induced WEP violating coupling in a non-minmal DM model.

Dark Force Mediation via Mixing

Ultralight-Scalar-Higgs Mixing I

- All renormalizable interactions of the light scalar with the SM is given by

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - V(H,S)$$

- The potential is given by

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

Ultralight-Scalar-Higgs Mixing II

- After EWSB, the quadratic terms in the potential are:

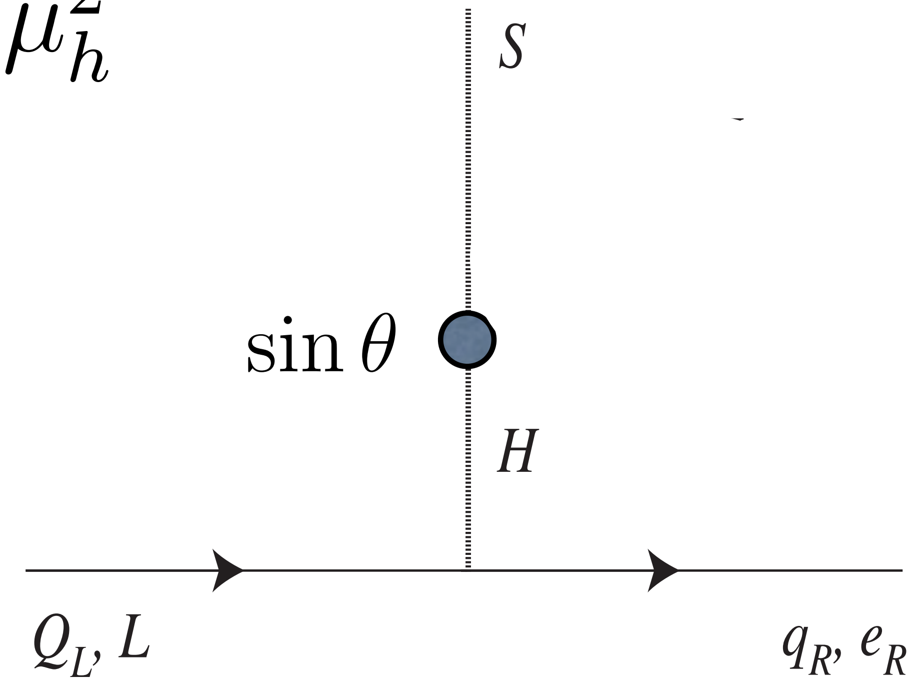
$$V_{\rm mass} = \frac{1}{2}(\mu_h^2\, h^2 + \mu_S^2\, S^2 + \mu_{hS}^2\, hS),$$

- After diagonalizing the mass matrix the ultralight scalar is

$$\phi = S\cos\theta - h\sin\theta\ , \qquad \sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2} \ll 1$$

- The ultralight scalar mass is given by

$$m_\phi^2 \simeq \mu_S^2 - \frac{\mu_{hS}^4}{4m_h^2}$$



Dark Force Parameter Space

- The ultralight scalar is very light:

$$m_\phi < 10^{-25}\ \mathrm{eV}$$

- Parameter space for observable dark force is restricted:

$$m_\phi^2 \simeq \mu_S^2 - \frac{\mu_{hS}^4}{4m_h^2}$$

Must be restricted in
parameter space to
maintain small mass

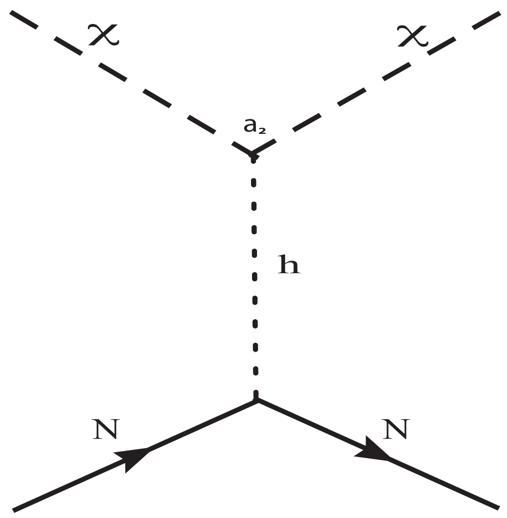
Has to be large enough
to give an observable
dark force

- In other regions of parameter space there will be no observable dark force.

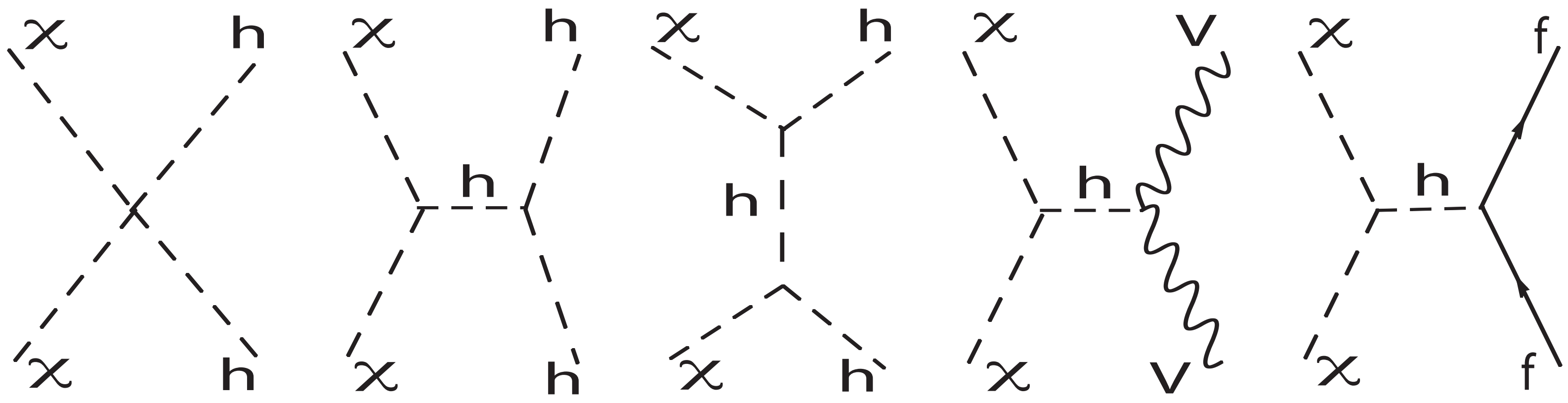
Scalar Singlet DM Coupled to a dark force

Scalar Singlet DM I

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



SI direct detection cross-section

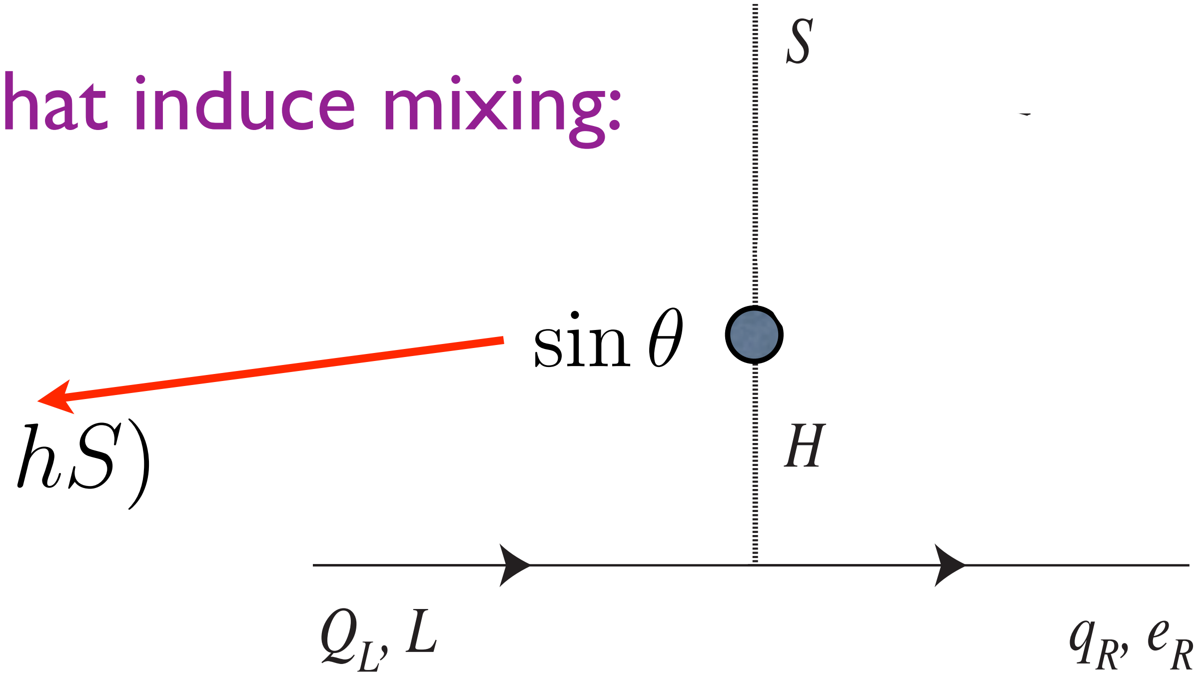


Annihilation diagrams

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

Ultralight-Scalar Higgs Mixing I

- Recall quadratic terms in potential that induce mixing:



$$V_{\rm mass} = \frac{1}{2}(\mu_h^2\, h^2 + \mu_S^2\, S^2 + \mu_{hS}^2\, hS)$$

- Recall quadratic terms in potential that induce mixing:

$$\phi = S\cos\theta - h\sin\theta\ , \quad \sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2}$$

- The size of this mixing angle is constrained by WEP tests.
- A dark force will give contributions to this mixing angle which will also be constrained.

Ultralight-Scalar Higgs Mixing II

- Recall the potential before EWSB:

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

- The mixing mass term after EWSB is given by:

$$\mu_{hS}^2 = \delta_1 v$$

- If we add a dimension five operator:

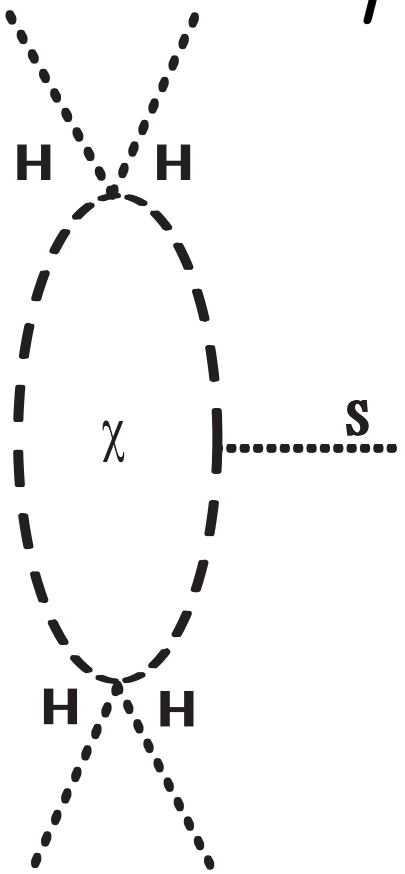
$$\delta V(H,S) = C_2 \left(H^\dagger H\right) \left(H^\dagger H\right) S$$

- The mixing angle receives an additional contribution.

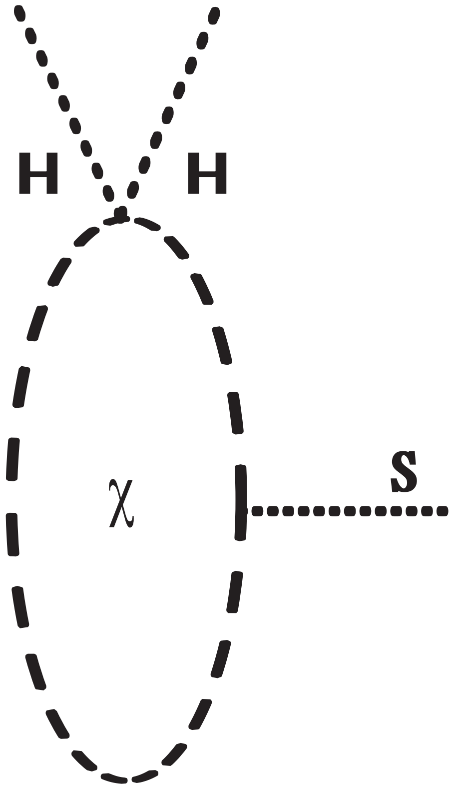
$$\mu_{hS}^2 = 2C_2 v^3 + \delta_1 v \qquad \sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2}$$

Ultralight-Scalar Higgs Mixing III

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



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



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

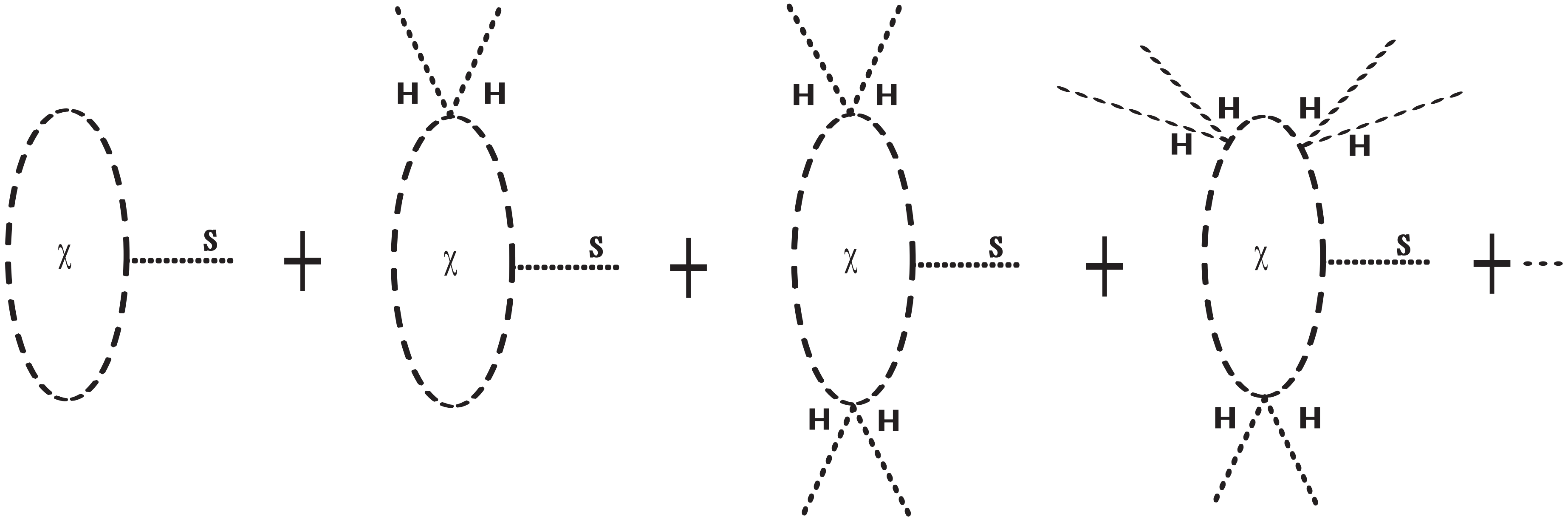
$$\frac{\delta_1}{2} H^\dagger H S$$

finite contribution

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

divergent contribution
just renormalizes δ_1

Ultralight-Scalar Higgs Mixing IV



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

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

$\downarrow$ $\delta_1^{\rm ren}$

$\downarrow$ finite contribution from resummed higher dim ops

Ultralight-Scalar Higgs Mixing V

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

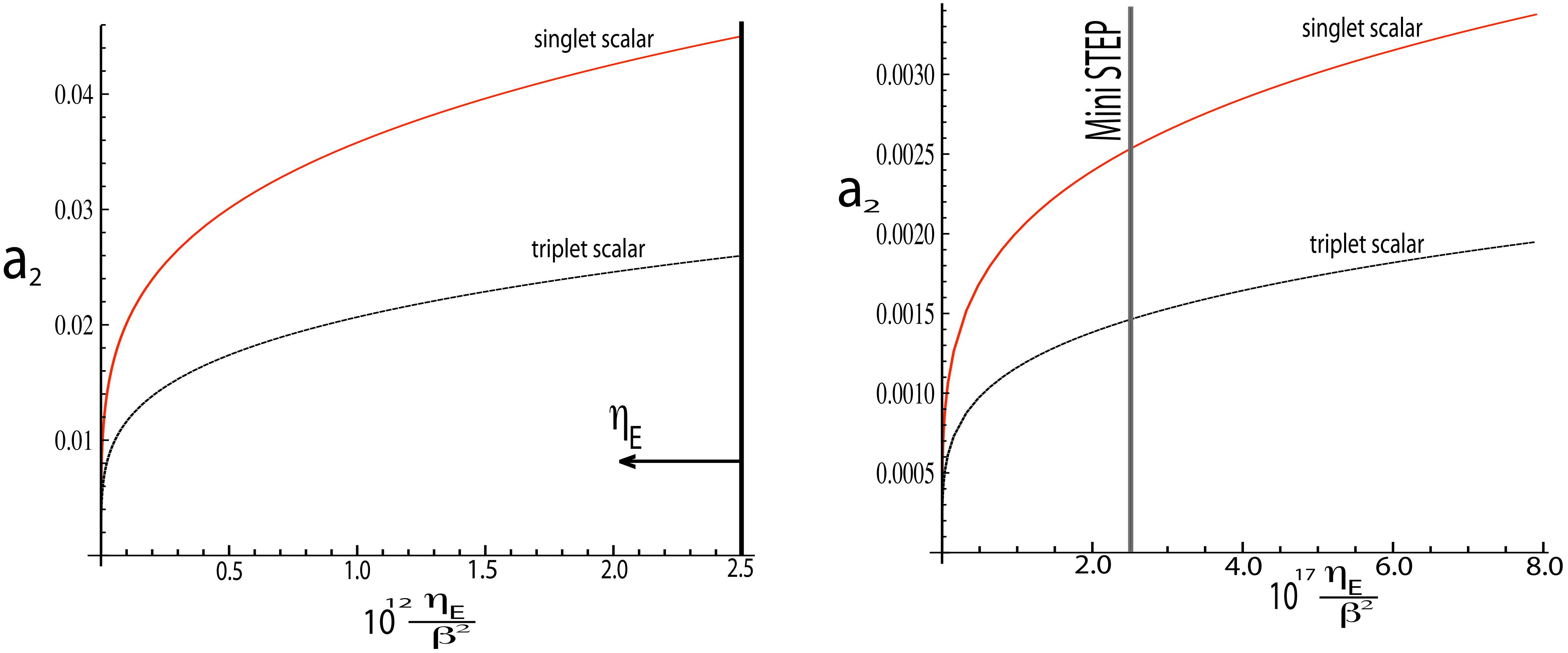
Constrained by WEP tests

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

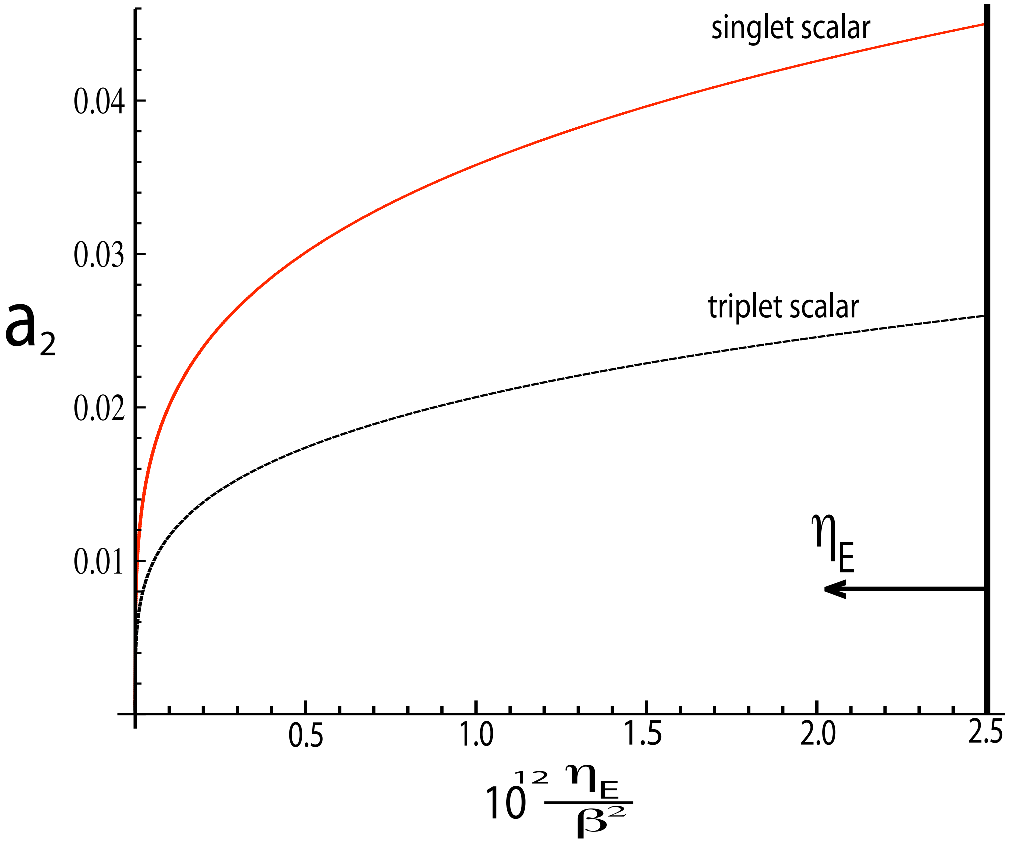


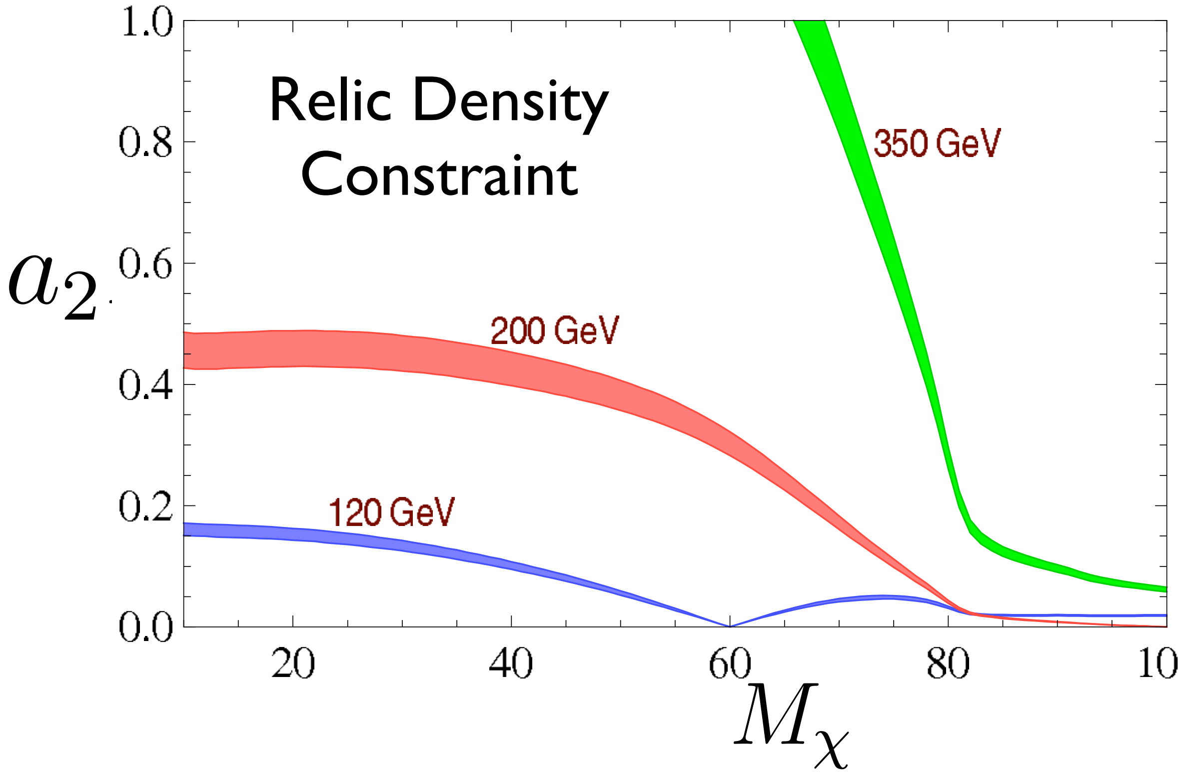
- WEP constraints on a2 in the presence of a dark force.

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)

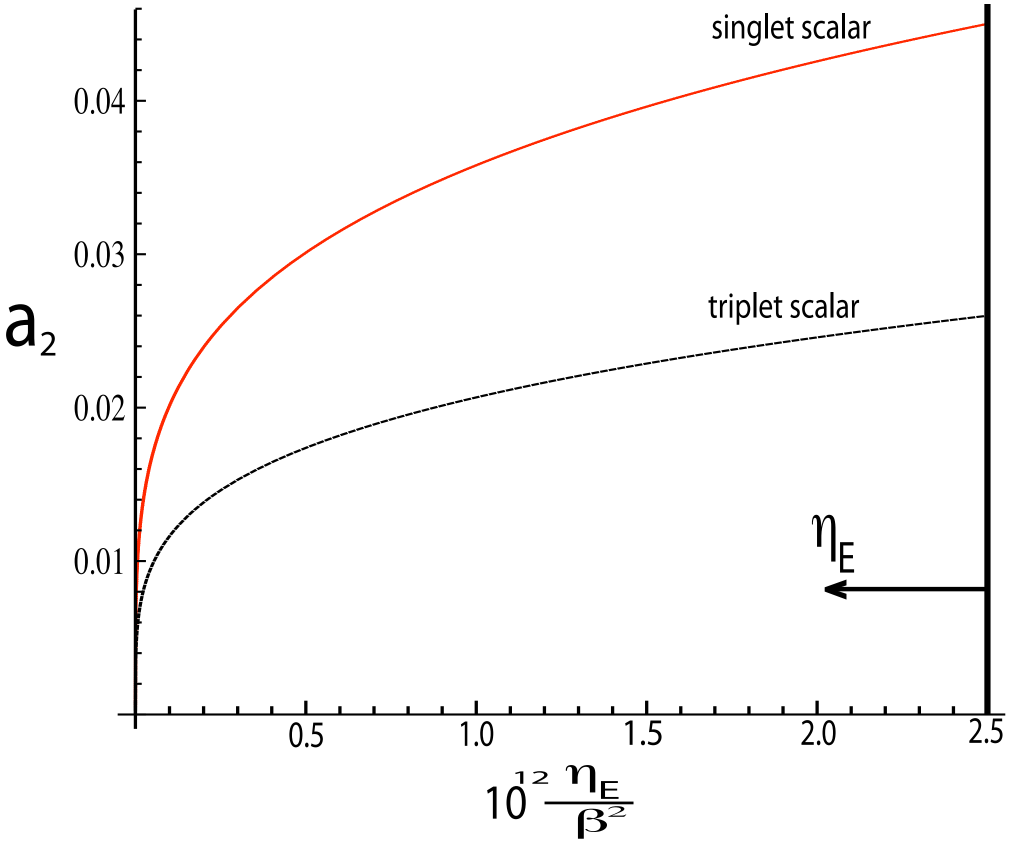
$a_{2\text{relic}}$	$M_\chi(\text{GeV})$	Expectation for $\frac{\eta_E}{\beta^2}$	$\beta = 0.2$
0.15	20	4×10^{-10}	Excluded
0.10	40	7×10^{-11}	Excluded
0.02	100	1×10^{-13}	Allowed

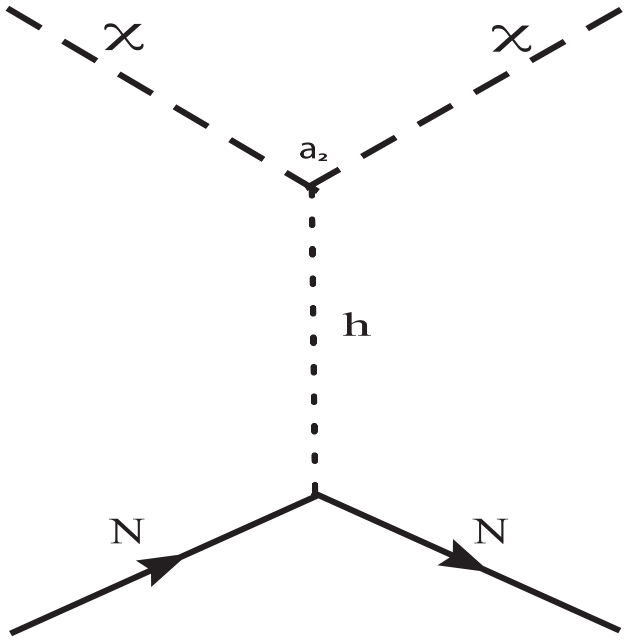
- Large regions in the parameter space of scalar singlet DM models with a dark force are ruled out by relic density requirements

Dark Force, WEP Test, and Direct Detection

Dark Force, WEP Test, and Direct Detection

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

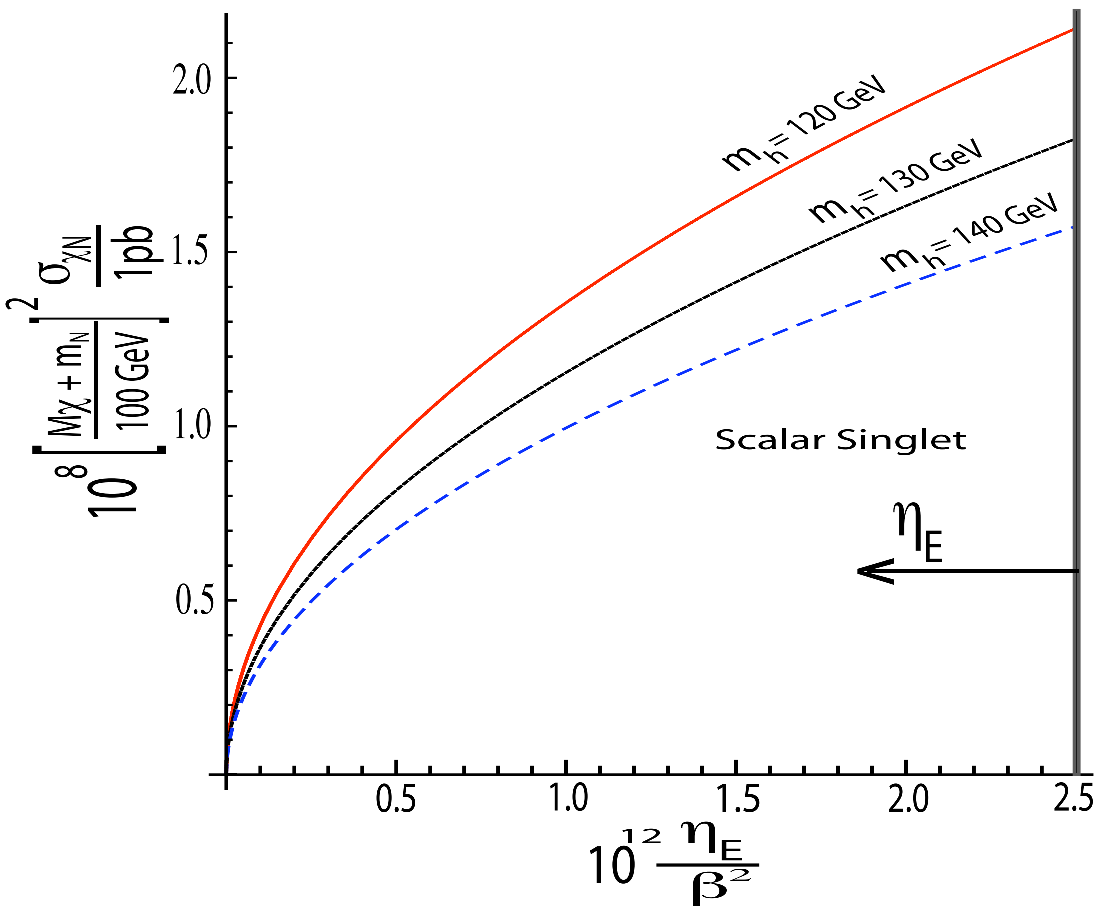


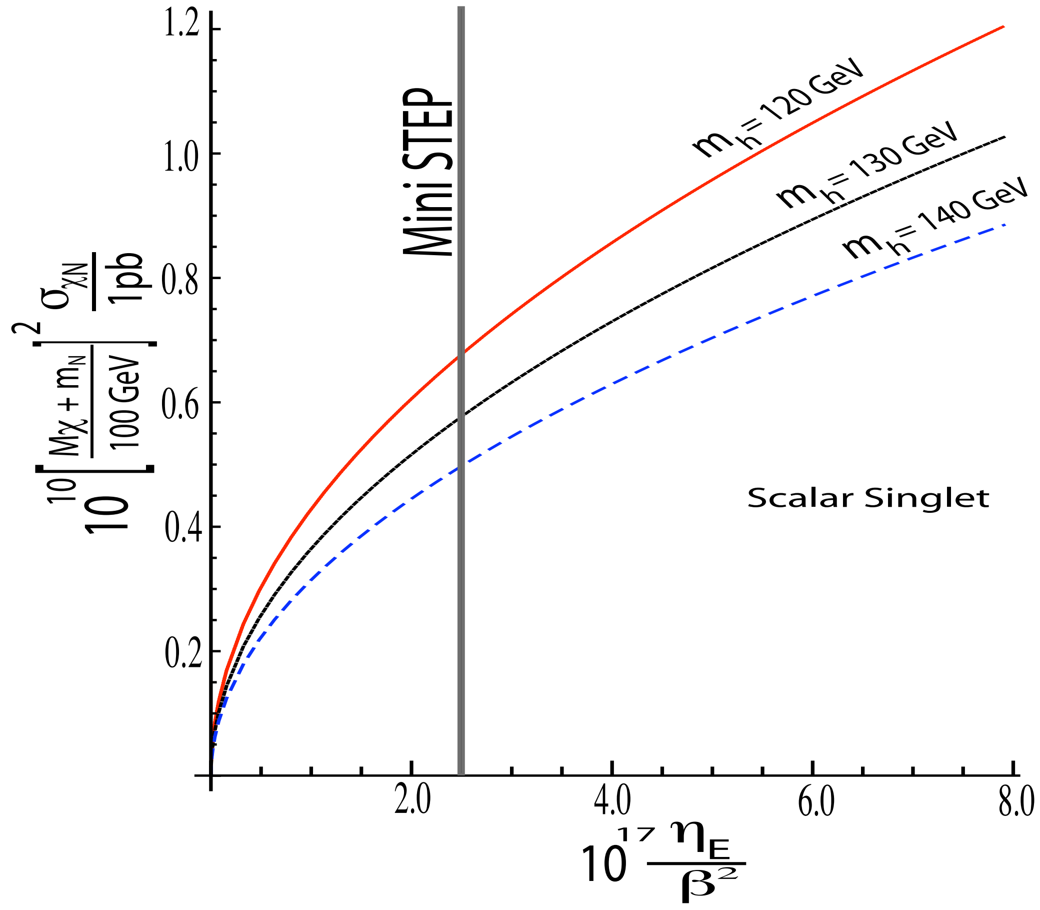


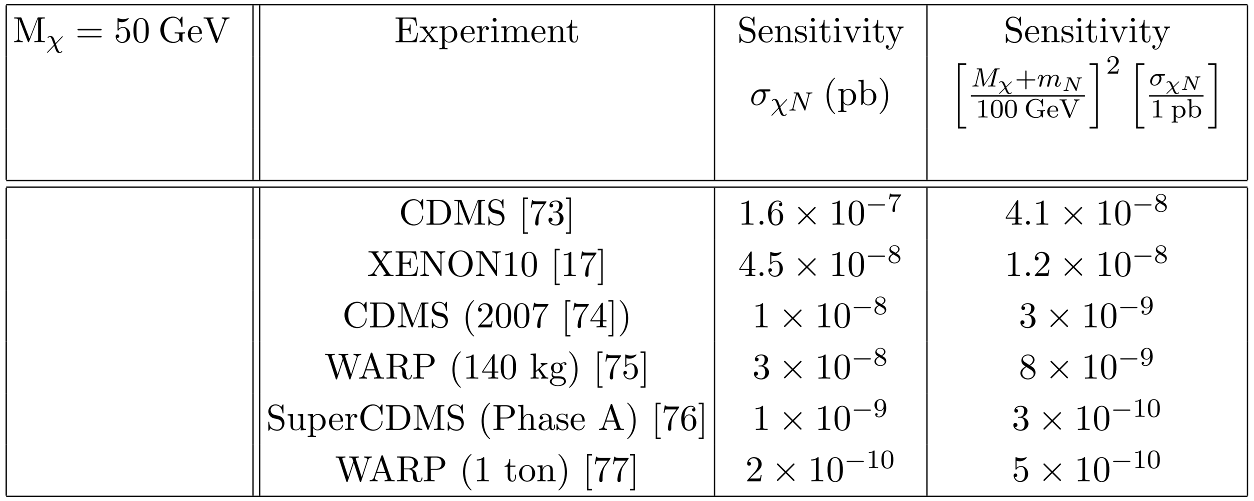
$$\sigma_{\chi N} \simeq \frac{\enclose{circle}{a_2^2} g_h^2 v^2 m_N^2}{\pi (M_\chi + m_N)^2 m_h^4}$$

- 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



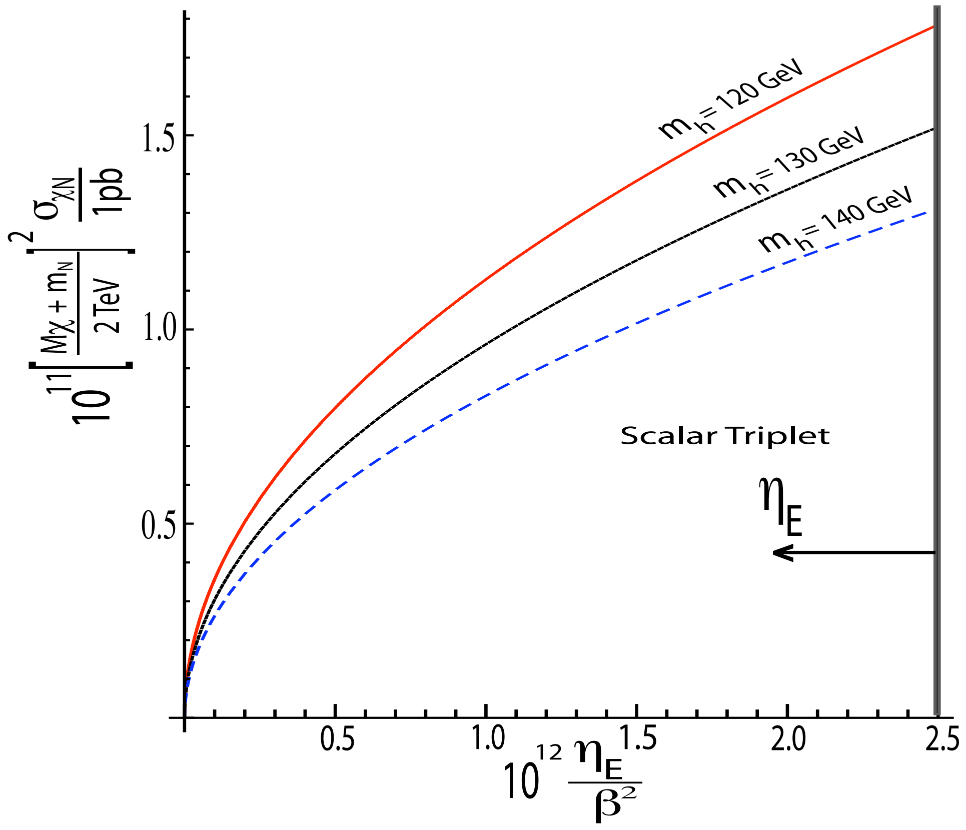


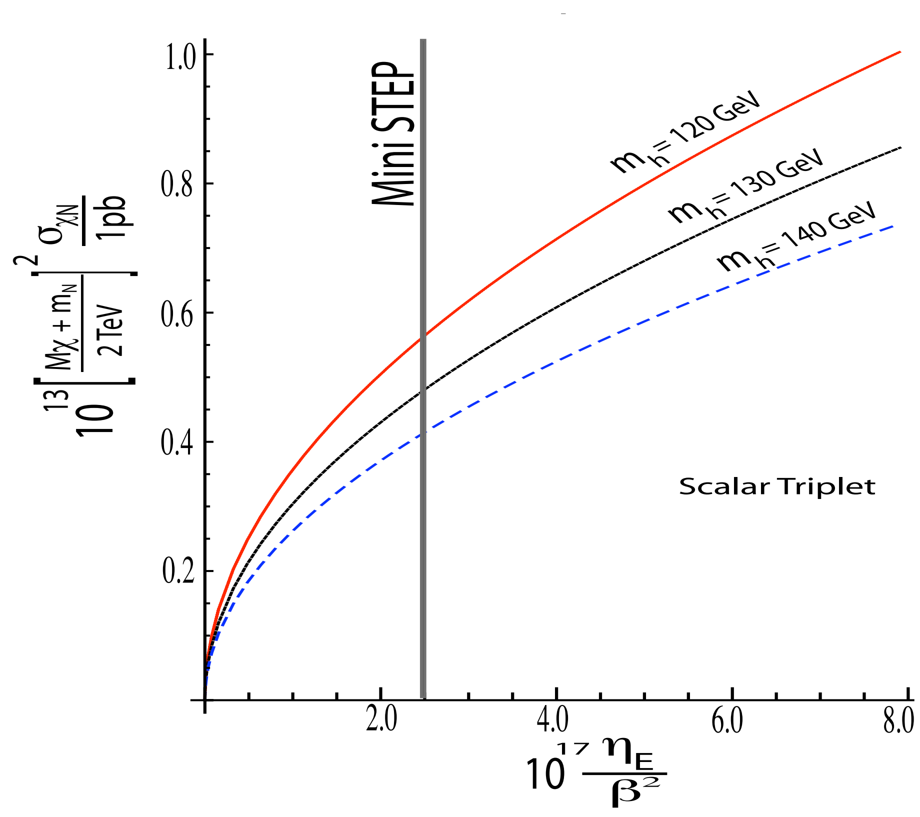


$M_\chi = 50$ GeV	Experiment	Sensitivity $\sigma_{\chi N}$ (pb)	Sensitivity $\left[\frac{M_\chi+m_N}{100\text{ GeV}}\right]^2\left[\frac{\sigma_{\chi N}}{1\text{ pb}}\right]$
	CDMS [73]	1.6×10^{-7}	4.1×10^{-8}
	XENON10 [17]	4.5×10^{-8}	1.2×10^{-8}
	CDMS (2007 [74])	1×10^{-8}	3×10^{-9}
	WARP (140 kg)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

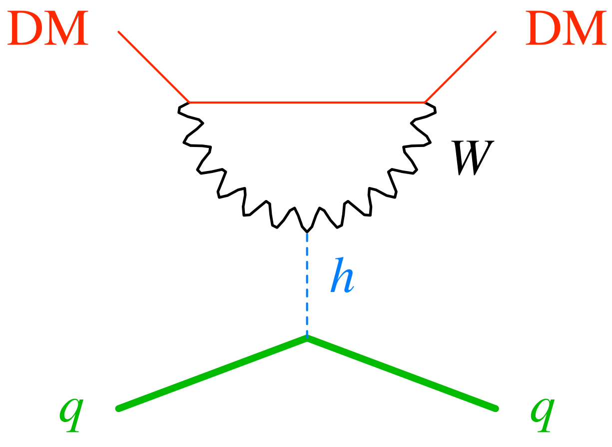
- Direct detection bounds can be probed by current or future direct detection experiments.

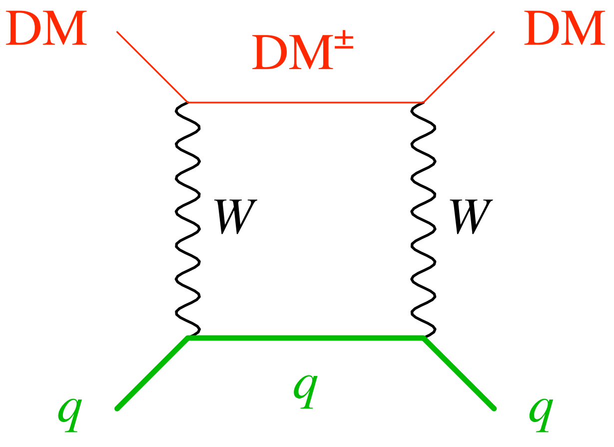
Bound on Tree Level DM-Nucleus Cross-Section for Real Scalar Triplet Dark Matter

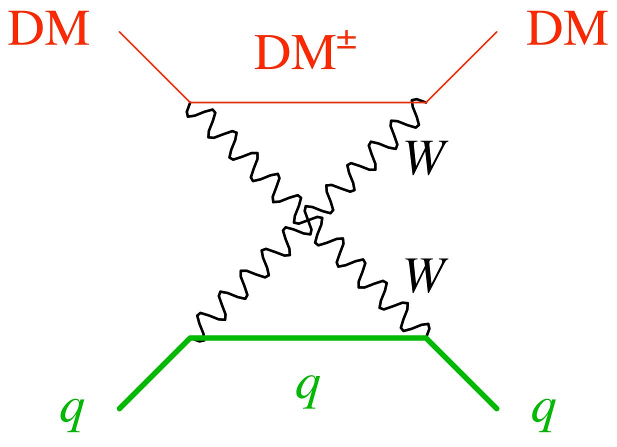




- The WEP constraint on tree level DM-Nucleus cross-section implies that typically direct detection will be given dominated by one loop contributions which begin at about 10^(-9) pb.





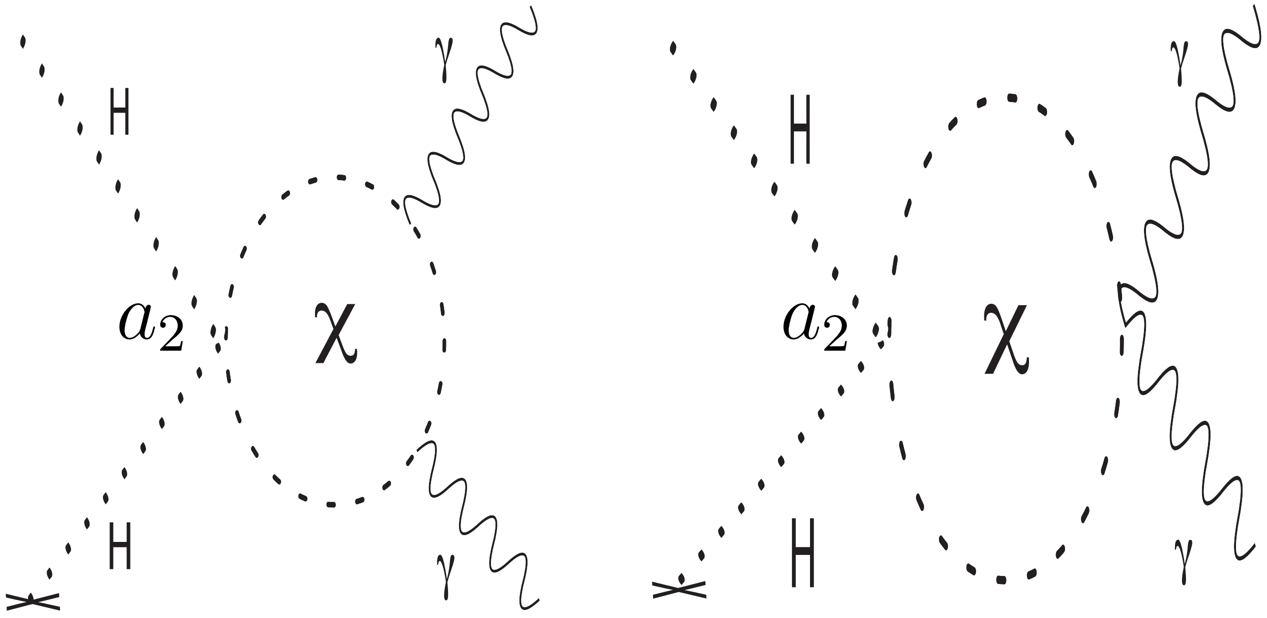


(Cirelli,Fornengo,Strumia)

Dark Force, WEP Test, and Colliders

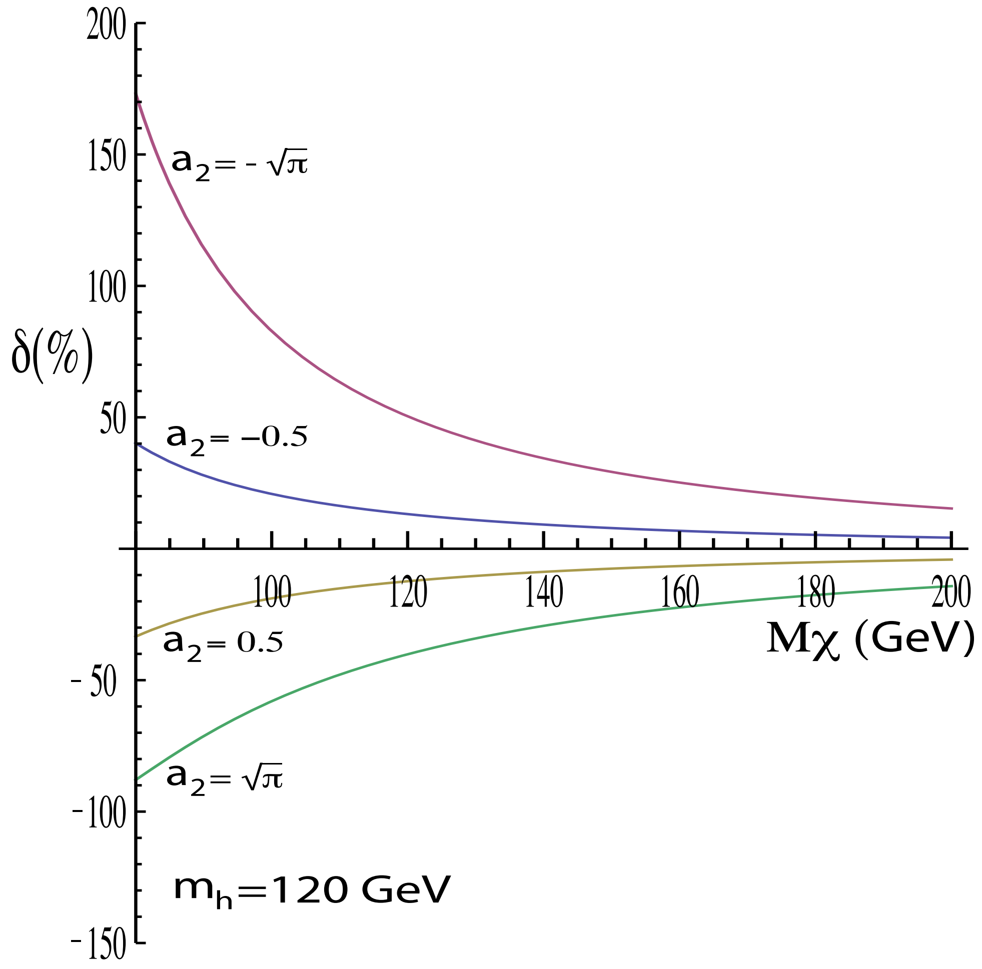
Dark Force, WEP Test, and Higgs Decay

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

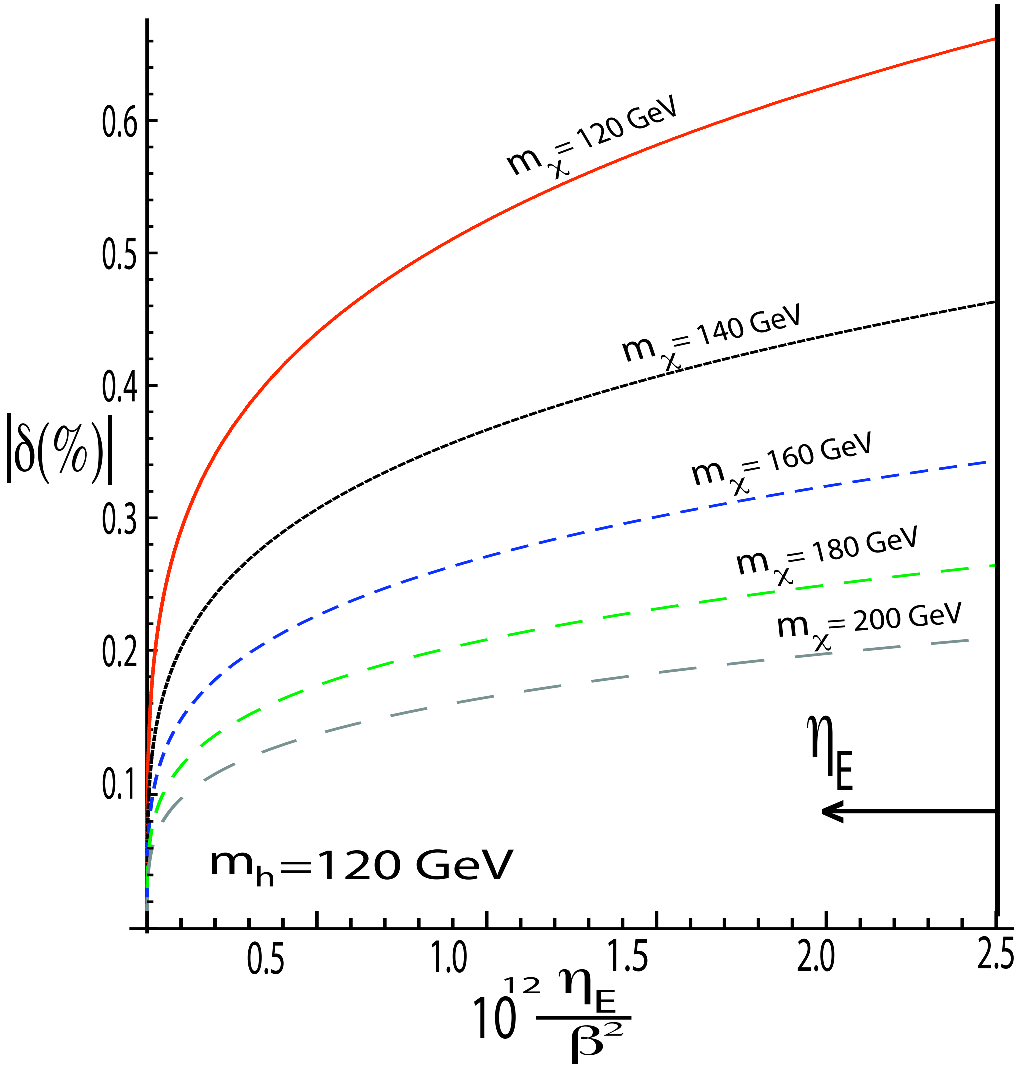


- One can parameterize the size of these graphs via the shift

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



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



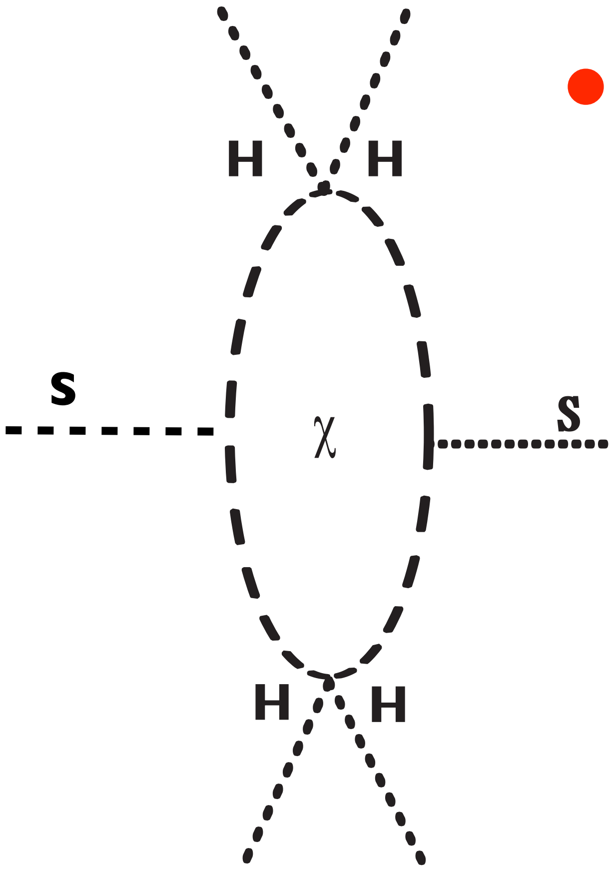
- The LHC or future colliders are likely to be sensitive to shifts in Higgs decay to two photons for triplet masses less than 200 GeV.
- Such light DM will be only a tiny fraction of the relic density in minimal models. A dark force in this case would have unobservable effects in astrophysics or cosmology.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

Dark Force Parameter Space

$$m_\phi^2 \simeq \mu_S^2 - \frac{\mu_{hS}^4}{4m_h^2} \quad , \quad m_\phi < 10^{-25}\mathrm{eV}$$

Also receives finite contributions from higher dim ops

$$\mu_S^2 = \kappa_2 + \text{higher dim ops}$$



- Dimension six operator which contributes to diagonal S^2 mass term after EWSB.

$$D_2\, H^\dagger H H^\dagger H S^2 , \qquad D_2 \sim \frac{a_2^2}{\pi M_P^2}\beta^2$$

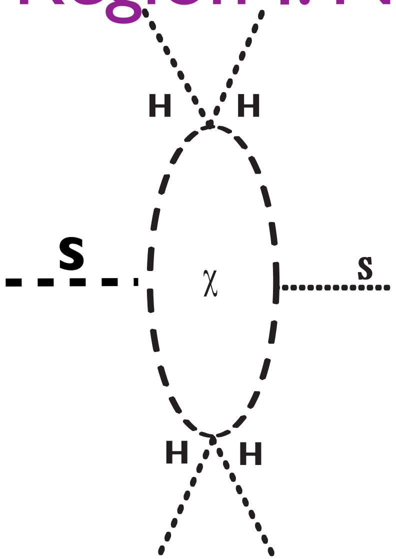
EWSB

$$m_\phi^2 \simeq \mu_S^2 - \frac{\mu_{hS}^4}{4m_h^2}$$

Three Types of Regions in Parameter Space

$$m_\phi^2 \simeq \mu_S^2 - \frac{\mu_{hS}^4}{4m_h^2}\,, \quad m_\phi < 10^{-25}\mathrm{eV}$$

- Region I: No intricate cancellations between any parameters



$$a_2^2 < \frac{4\pi}{\beta^2}\frac{M_P^2}{v^2}\frac{m_\phi^2}{v^2} < \frac{3\times 10^{-39}}{\beta^2}.$$

→ No dark force. Ruled out by relic density.

- Region II: No intricate cancellations between in mixing angle:

$$\sin\theta \simeq \frac{\mu_{hS}^2}{\mu_h^2} = \kappa\frac{a_2^2}{\pi^{3/2}}\frac{v^3}{M_P m_h^2}\beta + \frac{\delta_1^{\mathrm{ren}} v}{m_h^2}$$

→ Interesting constraints

- Region III: Intricate cancellations in mixing angle:

→ No interesting implications in this slice of parameter space.

Conclusions

- A dark force, via quantum effects, implies a non-zero effect in laboratory tests of the WEP as long as the DM is not sterile.
- For scalar singlet DM, relic density considerations combined with laboratory 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.
- Depending on the DM model, a dark force can also imply constraints on collider signals.
- Dark force parameter space is quite restricted.
- Future planned WEP tests will improve precision by several orders of magnitude allowing one to severely constrain dark forces.