Theoretical High Energy Physics Lab

Flux-mediated Dark Matter

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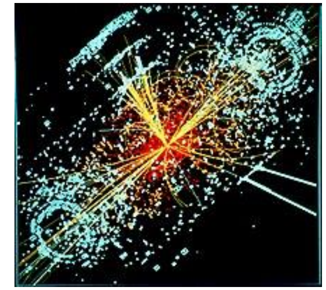
Workshop on particle physics and cosmology 2021

Hierarchy Problems



Higgs Mass

- In SM, all the masses are represented by VEV of the Higgs field
- VEV of the Higgs field is 10^{15} times smaller than the Planck mass

  → Why the Higgs boson is so much lighter than the Planck mass?

Cosmological Constant

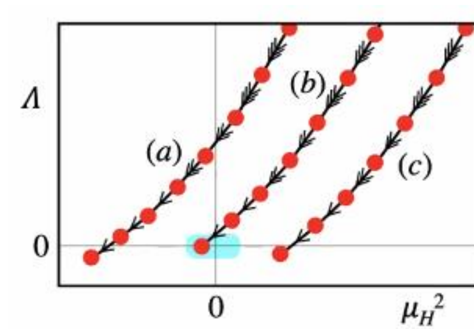
- Theoretically, the value of the cosmological constant can be approximately predicted as a Planck mass
- But measured value of the cosmological constant is 10^{120} times smaller than the Planck mass

  → Why is it so small?

Selfish Higgs

- Dynamical relaxation of Higgs mass and Cosmological constant
- Higgs acts as an anthropic selector for the emergence of a fairly unique non-empty Universe

→ called Selfish Higgs



Giudice et al.

- Selfish Higgs is based on the SM with addition of a single non-dynamical field described by a four-form

Four-Form Flux

- The four-form derives from a three-form

  $A_{\nu\rho\sigma}$: Three-index anti-symmetric tensor field

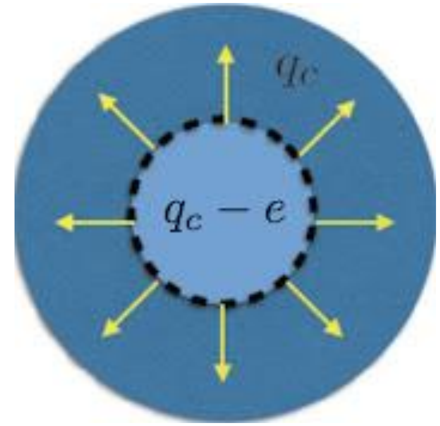
  Four-form field strength : $F_{\mu\nu\rho\sigma} = 4\partial_{[\mu}A_{\nu\rho\sigma]}$

- Assume that the four-form starts with a large flux parameter in the early Universe in a highly excited state

→ excited four-form can reduce its energy by creating membranes

→ four-form undergoes a configuration transition (n → n-1)

Membrane Production



- Flux difference → create membrane
- Membrane production probability

$$P(n+1 \to n) \sim \exp\left(-\frac{24\pi^2 M_P^4}{\Lambda_{n+1}}\right) \quad when \quad \Lambda_{n+1} \ll \frac{T^2}{M_P^2}\ , \quad T: membrane\ tension$$

→ related to tunneling

→ extremely suppressed at the last membrane nucleation

→ flux change stopped.

- After last membrane nucleation,
  the Universe would be empty without reheating

Model for four-form and Dark Matter

We consider pseudo-scalar field (ϕ) for reheating & Dirac fermion dark matter (χ')

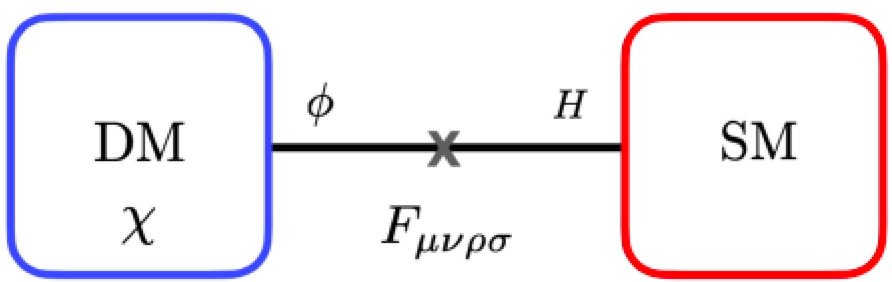
- $\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{relax} + \mathcal{L}_{RH} + \mathcal{L}_{DM} + \mathcal{L}_S + \mathcal{L}_L + \mathcal{L}_{memb}$

$$\mathcal{L}_0 = \sqrt{-g}\left[\frac{1}{2}R - \Lambda - \frac{1}{48}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma} - \left|D_\mu H\right|^2 - M^2|H|^2 + \lambda_H|H|^4\right]$$

$$\mathcal{L}_{relax} = \frac{c_H}{24}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}|H|^2$$ Higgs mass scanning

$$\mathcal{L}_{RH} = -\frac{1}{2}\left(\partial_\mu\phi\right)^2 - \frac{1}{2}m_\phi^2(\phi-\alpha)^2 + \frac{\mu}{24}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\phi$$ reheating

$$\mathcal{L}_{DM} = i\bar{\chi}'\gamma^\mu\partial_\mu\chi' - m_\chi'\bar{\chi}'\chi' + i\frac{m_\chi'}{f}\phi\bar{\chi}'\gamma^5\chi'$$ Dark matter



The Relaxation Mechanism with Four-Form Flux

- Using equation of motion for $F_{\mu\nu\rho\sigma}$

$$\rightarrow \ \mathcal{L} = \sqrt{-g}\left[\frac{1}{2}R - \Lambda - \left|D_\mu H\right|^2 + M^2|H|^2 - \lambda_H|H|^4\right]$$

$$-\frac{1}{2}\left(\partial_\mu\phi\right)^2 - \frac{1}{2}m_\phi^2(\phi-\alpha)^2 - \frac{1}{2}(\mu\phi + c_H|H|^2 + q)^2 + \mathcal{L}_{DM} + \mathcal{L}_{nucl}$$

- Flux parameter q is quantized in units of e as $q = en$ (n : integer)

- Nucleate a membrane : $q = en \ \rightarrow \ e(n-1) \ \rightarrow \ e(n-2) \ \rightarrow \ \cdots$

- Flux change stops at $q = q_c - e$ with $q_c \equiv M^2/c_H - \mu\langle\phi\rangle$

$\Rightarrow$
$$M_{eff}^2(q) = M^2 - c_H(q + \mu\langle\phi\rangle) \ \Rightarrow \ c_H e \sim (100GeV)^2$$
$$\Lambda_{\text{eff}}(q) = \Lambda + \frac{1}{2}\text{q}^2 + V(\langle\phi\rangle) + V(\langle H\rangle) \ \Rightarrow \ \sim 0$$

} relaxed

G. F. Giudice et al. arXiv:1907.05370

Four-form coupling induced Higgs mixing

- SM Higgs & pseudo-scalar are expanded around the vacuum :

$$\langle H\rangle = \frac{(0, v_H(q)+h)^T}{\sqrt{2}} \quad \& \quad \langle \phi\rangle = v_\phi + \varphi$$

$$v_H(q) = \sqrt{\left(M^2 - c_H\left(q + \mu v_\phi\right)\right) \,/\, \left(\lambda_H + \frac{1}{2} c_H^2\right)}$$

$$v_\phi(q) = \frac{m_\phi^2}{\mu^2 + m_\phi^2}\left[\alpha - \frac{\mu}{m_\phi^2}\left(\frac{1}{2} c_H v_H^2 + q\right)\right]$$

- Transformation to the mass eigenstates (h_1, h_2)

$$\rightarrow \; m_{h_{1,2}}^2 = \frac{1}{2}\left(m_\varphi^2 + m_h^2\right) \mp \frac{1}{2}\sqrt{\left(m_\varphi^2 - m_h^2\right)^2 + 4 c_H^2 \mu^2 v_H^2(q)} \quad \& \quad tan2\theta(q) = \frac{2 c_H \mu v_H(q)}{m_\varphi^2 - m_h^2}$$

- Electroweak symmetry is broken at $q = q_c - e$

$$v^2 = \frac{m_\phi^2}{\mu^2 + m_\phi^2}\left(\frac{c_H e}{\lambda_{H,eff} - \frac{1}{2}\frac{c_H^2 \mu^2}{\mu^2 + m_\phi^2}}\right)$$

Reheating

- Just after the last membrane nucleation, pseudo-scalar VEV is shifted by four-form flux

$$\Delta v_\phi = v_{\phi,c} - v_{\phi,0} = \frac{\lambda_H}{c_H}\frac{v^2\mu}{m_\phi^2}$$

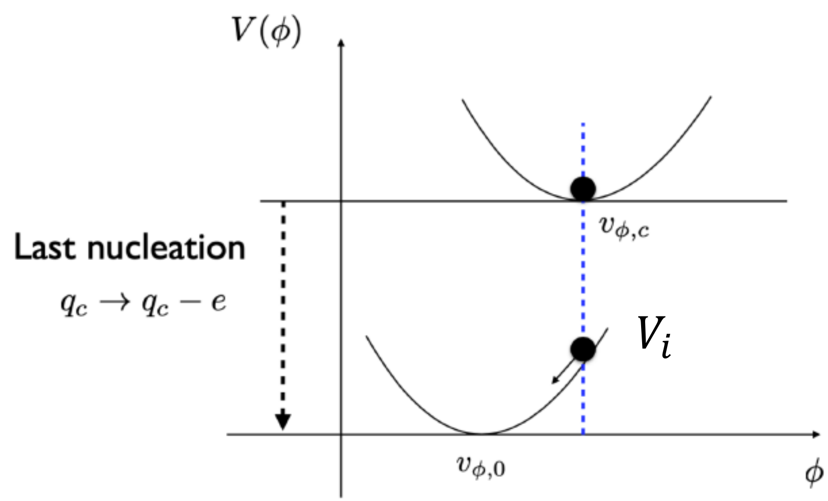
- The initial vacuum energy for reheating : $V_i = \frac{1}{2}\left(\frac{\lambda_H}{c_H}\frac{\mu^2}{m_\phi^2} - \frac{1}{2}c_H\right)^2 v^4$

→ The maximum temperature of the Universe during the reheating :

$$T_{max} \cong 40\mathrm{GeV}\left(\frac{V_i^{1/4}}{100\mathrm{GeV}}\right)\left(\frac{100}{g_*}\right)^{1/4}$$

- Choose $\sqrt{e} \sim 100\mathrm{GeV} - 10\mathrm{TeV}$ for $\frac{m_\phi}{|\mu|} \sim 0.01 - 1$

→ $T_{max} \sim 40\mathrm{GeV} - 4\mathrm{TeV}$



- For $m_\chi < T_{max}$, DM starts being relativistic and in equilibrium

Dark Matter Interactions

- Mass term for dark matter(DM) shifted ($\because$ VEV of the pseudo-scalar field)

$$\mathcal{L}_{\chi,mass} = -m'_\chi \bar{\chi}'\chi' + \frac{i m'_\chi v_\phi}{f}\bar{\chi}'\gamma^5\chi' \quad \text{where} \quad m_\chi = m'_\chi\sqrt{1+\frac{v_\phi^2}{f^2}} \quad \& \quad \chi = (\chi_1, \chi'_2)^T$$

$$= -m_\chi\,\bar{\chi}\,\chi \quad \text{with} \quad \chi_1 = e^{-i\beta}\chi'_1 \quad \& \quad \tan\beta = \frac{v_\phi}{f}$$

Redefined DM

- Interaction terms for dark matter :

$$\mathcal{L}_{\chi,int} = \frac{i m_\chi}{f} e^{-i\beta}(cos\theta(q)h_1 + sin\theta(q)h_2)\bar{\chi}P_R\chi - \frac{i m_\chi}{f} e^{-i\beta}(cos\theta(q)h_1 + sin\theta(q)h_2)\bar{\chi}P_L\chi$$

$$\equiv -\textstyle\sum_{i=1,2} h_i\bar{\chi}\left(v_{\chi,i} + i a_{\chi,i}\gamma^5\right)\chi$$

$$v_{\chi,1} = \frac{m_\chi}{f} sin\beta cos\theta(q) \quad , \quad a_{\chi,1} = -\frac{m_\chi}{f} cos\beta cos\theta(q)$$

$$v_{\chi,2} = \frac{m_\chi}{f} sin\beta sin\theta(q) \quad , \quad a_{\chi,2} = -\frac{m_\chi}{f} cos\beta sin\theta(q)$$

- Yukawa couplings between the SM Higgs & SM fermions f :

$$\mathcal{L}_Y = -\frac{m_f}{v} h\bar{f}f$$

$$\equiv -\textstyle\sum_{i=1,2} v_{f,i} h_i \bar{f}f$$

$$v_{f,1} = -\frac{m_f}{v} sin\theta(q)$$

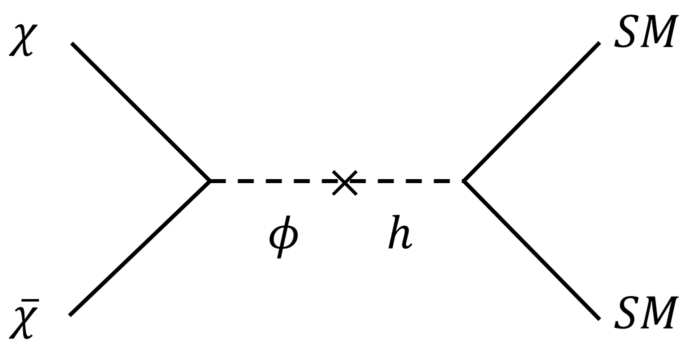
$$v_{f,2} = \frac{m_f}{v} cos\theta(q)$$

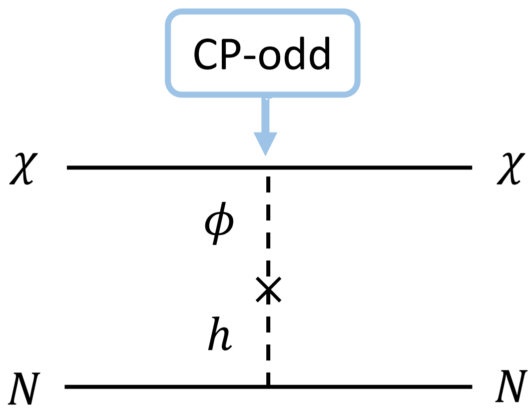
Dark Matter Interactions

- CP Violation

  Four-form coupling to pseudo scalar field : CP-odd

  Four-form coupling to Higgs field : CP-even

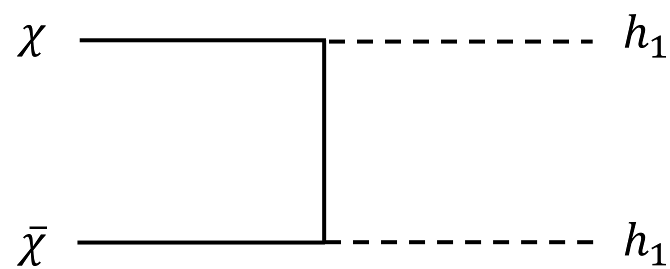




- Direct Detection ➡ Suppressed

- Mixing induced by four-form flux

  ➡ leads DM → SM annihilation



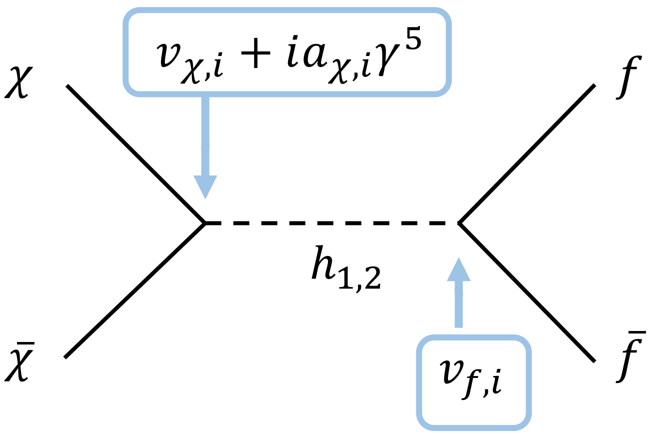
- DM annihilation

  ➡ Unsuppressed annihilation exists

H. M. Lee et al. arXiv:1205.4675

DM annihilation

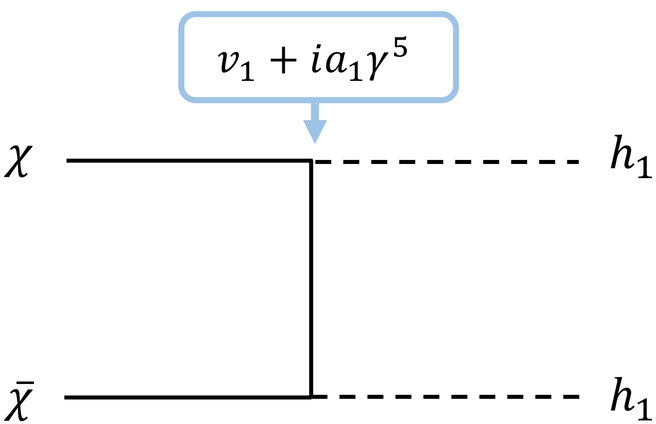
- We consider $m_\chi \le T_{max}$
- DM can pair annihilate into a pair of the SM fermions ($\chi\bar{\chi} \rightarrow f\bar{f}$)



$v_{\chi,i} \ll a_{\chi,i} \quad for \quad sin\beta \ll 1$

$$(\sigma v_{rel})_{\chi\bar{\chi}\to f\bar{f}} = \frac{m_f^2 m_\chi^4}{8\pi v^2 f^2}\cos^4\beta\,\sin^2 2\theta \times \left(\frac{1}{4m_\chi^2 - m_{h_1}^2} - \frac{1}{4m_\chi^2 - m_{h_2}^2}\right)^2 \left(1 - \frac{m_f^2}{m_\chi^2}\right)^{3/2}$$

- For $m_\chi \ge m_{h_1}, m_{h_2}$



$\chi\bar{\chi} \rightarrow h_1 h_1$: s-wave → suppressed

p-wave → unsuppressed

$\chi\bar{\chi} \rightarrow h_2 h_2$: suppressed

$\chi\bar{\chi} \rightarrow h_1 h_2$: suppressed

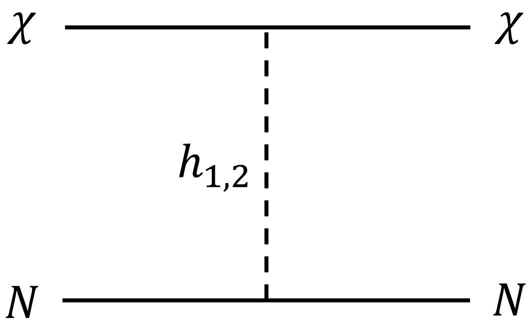
By Higgs mixing angle

$\theta \ll 1$

DM Direct Detection

- $\mathcal{L}_{DD} = \Sigma_{\mathrm{f}} \lambda_f \Sigma_{i=1,2} \frac{\widetilde{v}_i}{m_{h_i}^2} \left[\bar{\chi}\left(v_{\chi,i} + i a_{\chi,i} \gamma^5\right)\chi\right] \bar{f} f$

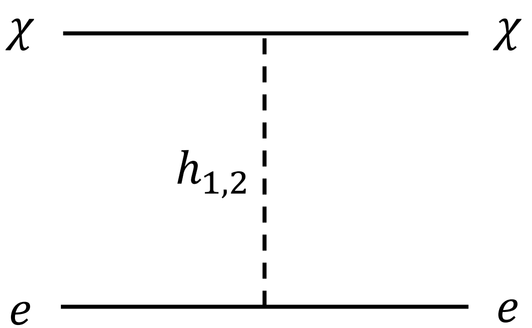
- Elastic scattering between DM & nucleons



$$\sigma_{\chi-N} \simeq \frac{\mu_{\chi N}^2 m_\chi^2}{4\pi v^2 f^2 A^2} (\sin 2\theta)^2 \sin^2\beta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2 \left(Z f_p + (A-Z) f_n\right)^2$$

: doubly suppressed

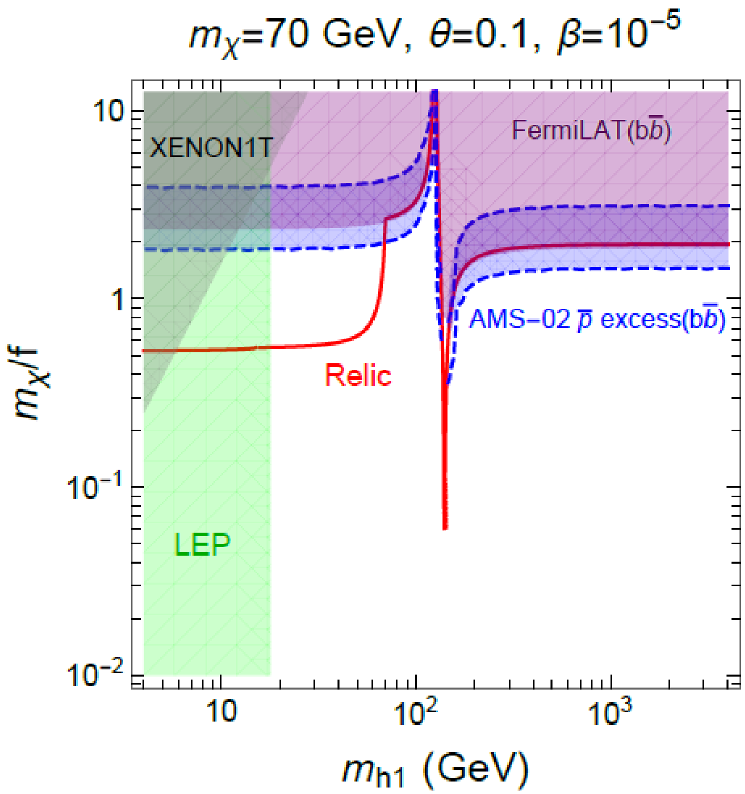
- Elastic scattering between DM & electron

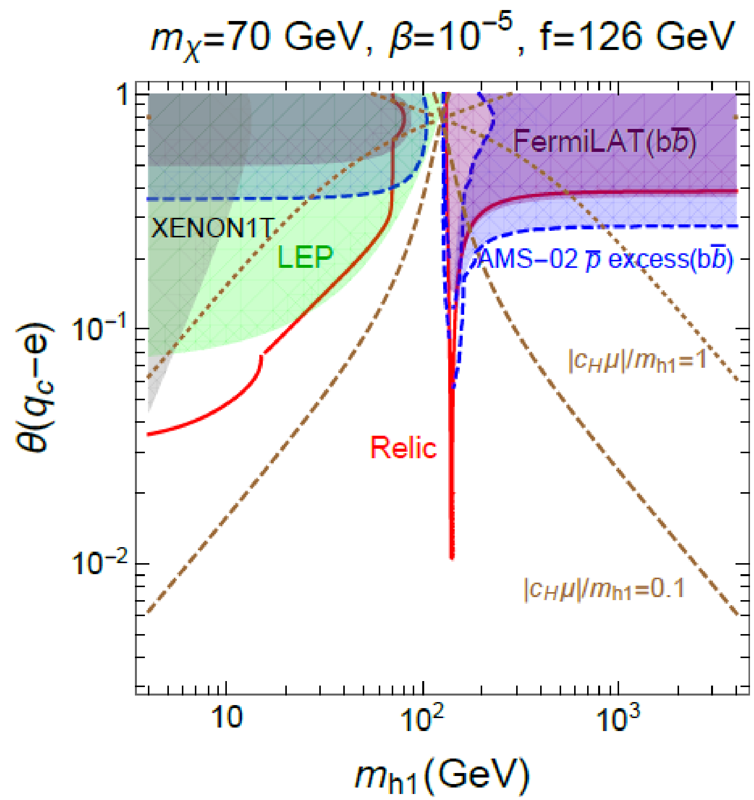


$$\sigma_{\chi-e} \simeq \frac{\mu_{\chi e}^2 m_e^2 m_\chi^2}{4\pi v^2 f^2} (\sin 2\theta)^2 \sin^2\beta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2$$

: doubly suppressed

Results



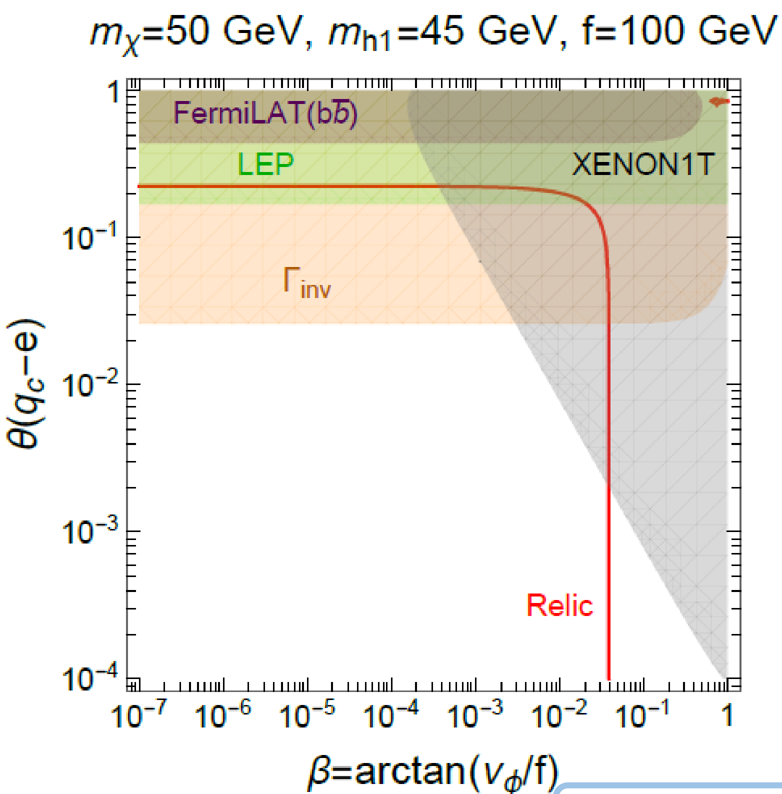


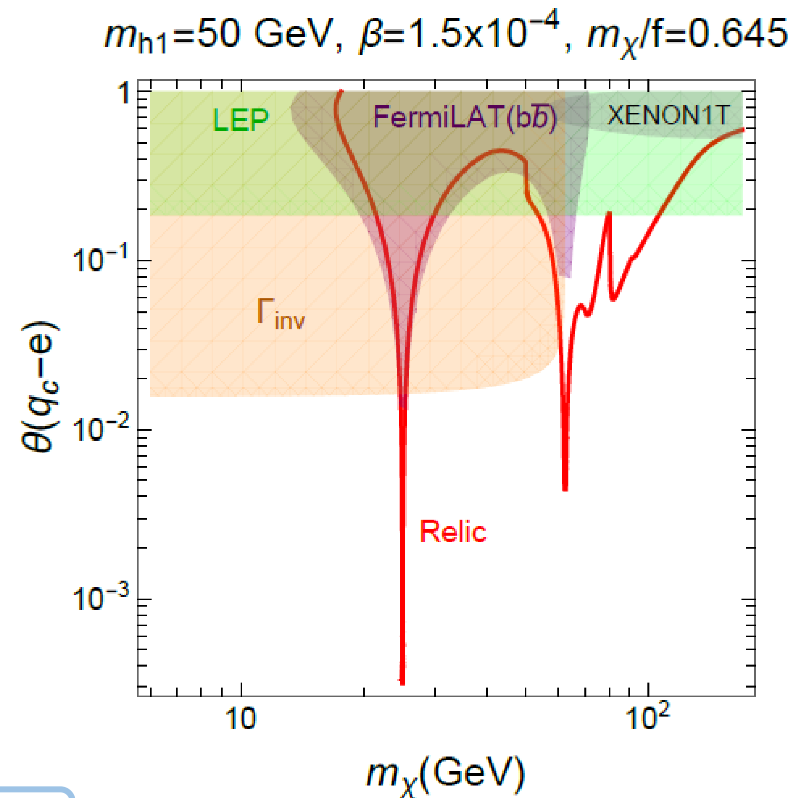
DM & Nucleon scattering

$h_1 \to b\bar{b}$

- Red line : Relic density
- Gray & Green : excluded by XENON1T and LEP , respectively
- Purple : disfavored by diffuse gamma-rays from Fermi-LAT dwarf galaxies
- Blue : favored by AMS-02 anti-proton excess

Results





DM & Nucleon scattering

$h_1 \rightarrow b\bar{b}$

- Red line : Relic density
- Gray & Green : excluded by XENON1T and LEP , respectively
- Purple : disfavored by diffuse gamma-rays from Fermi-LAT dwarf galaxies
- Orange : disfavored by Higgs invisible decay

Summary

- In four-form flux model , a simultaneous relaxation of the Higgs mass and cosmological constant is possible.

→ $M^2_{eff}(q)$ & $\Lambda_{\rm eff}(q)$ depend on one flux parameter ‘q’

- We consider pseudo-scalar field to explain the reheating process.

- In this scenario, we introduce Dirac fermion DM with pseudo-scalar coupling.

→ Flux portals lead to mixing between pseudo-scalar and Higgs

→ Direct Detection : suppressed

Indirect Detection : unsuppressed signatures for cosmic rays