Fermion dark matter in models with $U(1)$ symmetry

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Paper in preparation

Higgs portal DM

Kanemura, Matsumoto, Nabeshima, Okada, 1005.5651 (PRD),
Djouadi, Lebedev, Mambrini, Quevillon, 1112.3299 (PLB), **…**

- Minimal models (renormalizable and gauge invariant)
  - Real scalar
    - **Scalar DM**: Real scalar with a Z_2 symmetry
      J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, 1306.4710 (PRD)], …
    - **Fermion DM**: Real scalar + Singlet fermion
      Y. G. Kim, K. Y. Lee and S. Shin, 0803.2932 (JHEP),
      S. Baek, P. Ko and W. I. Park, 1112.1847 (JHEP), …
  - Complex scalar
    - **Goldstone DM**: Complex scalar with a softly broken global $U(1)$ symmetry
      C. Gross, O. Lebedev, T. Toma, 1708.02253 (PRL)], …
    - **Vector DM**: Complex scalar with a local $U(1)_X$ symmetry
      - The $U(1)_X$ gauge boson gets mass after SSB (Dark Higgs mechanism)
      - The $U(1)_X$ kinetic mixing term $B_{\mu\nu} F^{\mu\nu}$ should be forbidden by a Z_2 symmetry

      S. Baek, P. Ko, W. I. Park and E. Senaha, 1212.2131 (JHEP),
      M. Duch, B. Grzadkowski and M. McGarrie, 1506.08805 (JHEP), …

- **We discuss models with $U(1)_X$ without ad hoc discrete symmetry.**

DM with $U(1)$ symmetry

- <u>Particle contents</u>
  - Complex scalar field S (Dark Higgs) w/ $U(1)_X$ charge $Q_S = 1$
  - $U(1)_X$ gauge field X_μ (Dark Photon) $D_\mu S = (\partial_\mu + i g_X Q_S X_\mu) S$
  - Ψ [= Scalar, Fermion] (Dark Matter) w/ $U(1)_X$ charge $Q_\Psi = 1/N$
- **The stability of DM [Ψ] is guaranteed by residual Z_N symmetry*,** after spontaneous symmetry breaking of U(1) by $\langle S \rangle \neq 0$.

*** Local (gauged) $U(1)$ symmetry protects DM stability even with higher dimensional terms.**

- <u>N = 2 case</u> ($\Psi^2 S^\dagger \to Z_2$ symmetry)
  - Ψ = Scalar [S. Baek, P. Ko, W.I. Park, 1407.6588 (PLB)]
  - Ψ = Fermion

    A. Ahmed, M. Duch, B. Grzadkowski, M. Iglicki, 1710.01853 (EPJC): Multi-comp. DM (ε=0)
    L. Darmé, S. Rao, L. Roszkowski, 1710.08430 (JHEP): $m_{\rm DM} < m_{Z'}$
    M. Pospelov, et al., 0711.4866 (PLB),…: $m_{\rm DM} \gtrsim m_{Z'}$(secluded regime) w/o Dark Higgs mechanism
    S. Baek, P. Ko, TM, W. I. Park (**this work**): We focus on the role of dark Higgs for DM indirect searches.
    P. Ko, TM, Y. L. Tang, 1910.04311 : DM bound state formation (**see Yi-Lei Tang's talk on Tuesday**)

- <u>N = 3 case</u> ($\Psi^3 S^\dagger \to Z_3$ symmetry)
  - Ψ = Scalar [P. Ko, Y. Tang, 1402.6449 (JCAP)]

Global $U(1)$ vs. Local $U(1)$ in fermion DM

- Scalar sector: $V_0(\Phi,\mathbb{S}) = -m_\Phi^2|\Phi|^2 - m_S^2|\mathbb{S}|^2 + \lambda_\Phi|\Phi|^4 + \lambda_S|\mathbb{S}|^4 + \lambda_{\Phi S}|\Phi|^2|\mathbb{S}|^2$

  Φ^{SM}, $\mathbb{S} = \frac{1}{\sqrt{2}}(v_S + s + ix^0)$ → (h, H) w/ mixing angle θ

- Fermion sector: $\mathcal{L}_\psi = -m_\psi\overline{\psi}\psi - \frac{y_\psi}{\sqrt{2}}\overline{\psi^c}\psi\mathbb{S}^\dagger + h.c.$ $\qquad \psi_+ = \frac{\psi+\psi^c}{\sqrt{2}} \qquad \psi_- = \frac{\psi-\psi^c}{\sqrt{2}i}$

- **Global model** $\mathcal{L} = \mathcal{L}_{\rm SM} + |\partial_\mu\mathbb{S}|^2 - V_0(\Phi,\mathbb{S}) + i\overline{\psi}\partial\psi + \mathcal{L}_\psi$

  The NG boson x plays the role of a dark radiation. [S. Weinberg, 1305.1971 (PRL)]

  $T_{\rm dec}\sim m_\mu$ [$\Delta N_{\rm eff}$=0.39] could satisfy the constraint of $N_{\rm eff}$.

- **Local model** $\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}B^{\mu\nu} + |D_\mu\mathbb{S}|^2 - V_0(\Phi,\mathbb{S}) + i\overline{\psi}D\psi + \mathcal{L}_\psi$

  The NG boson x is absorbed by the gauge boson Z'.

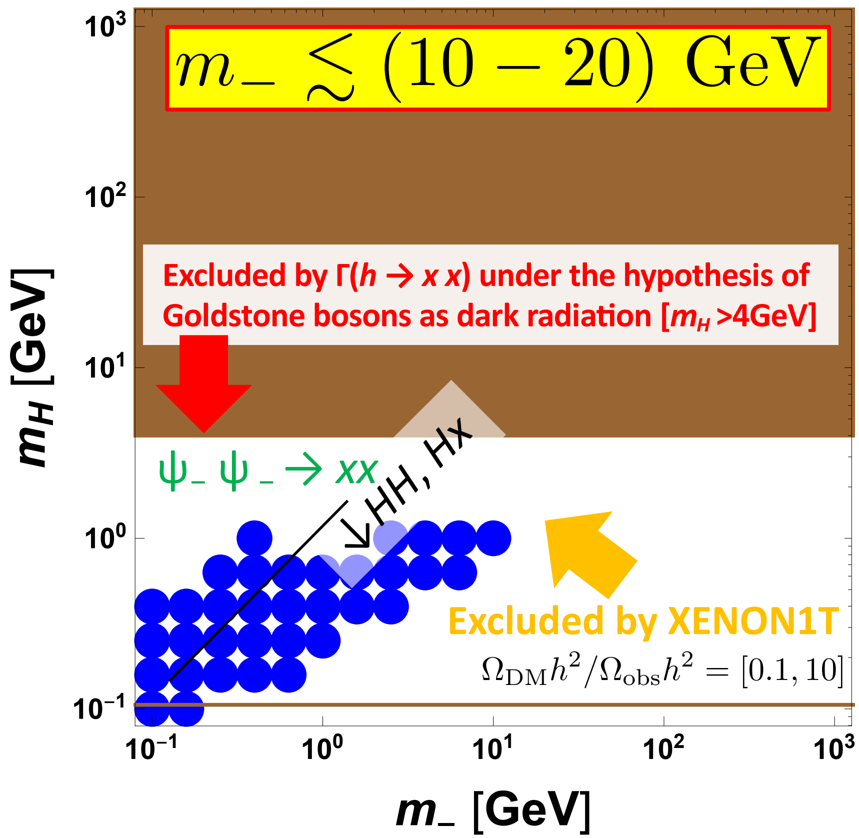
  SSB gives the origin of the Z' mass (Dark Higgs mechanism).

We compare the local $U(1)$ model and the global $U(1)$ model.

Comparing two models with the DM direct search exclusion

The global U(1) model

$(m_+/m_- - 1, s_\theta, \lambda_S) = (10^{-3}, 10^{-4}, 1)$

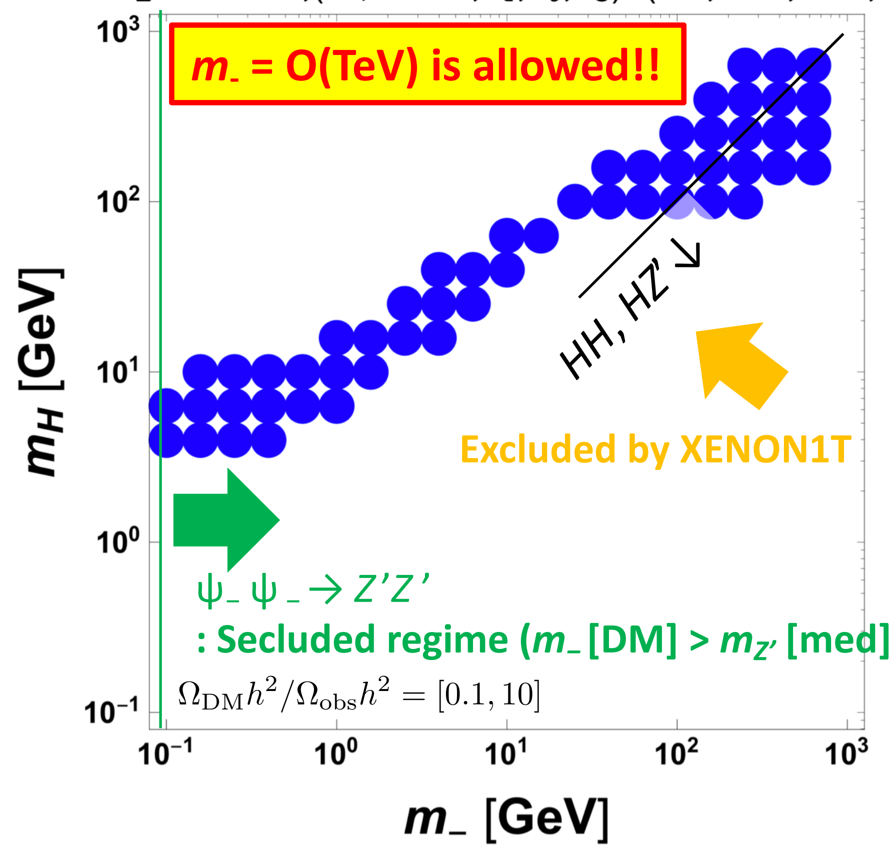


Consistent with [C. G. -Cely, A. Ibarra, E. Molinaro, 1310.6256 (JCAP)]

The global model limit for $m_{Z'}$ or $g_X \to 0$ in the local model

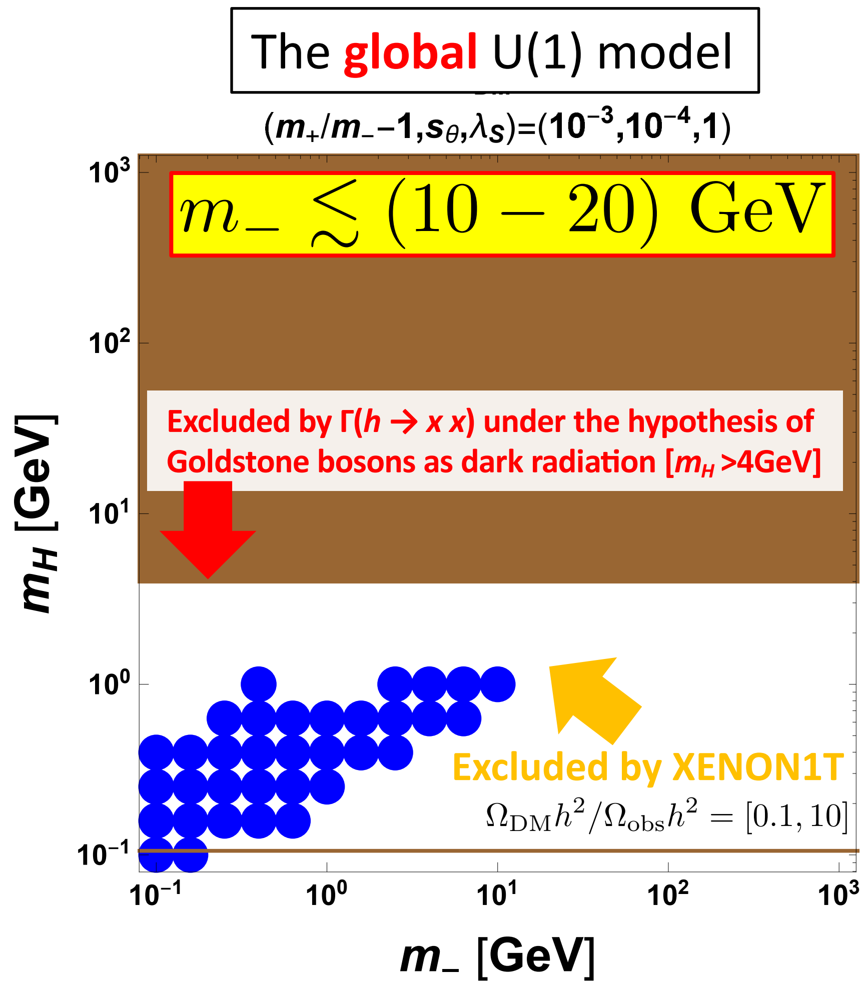
The local U(1) model

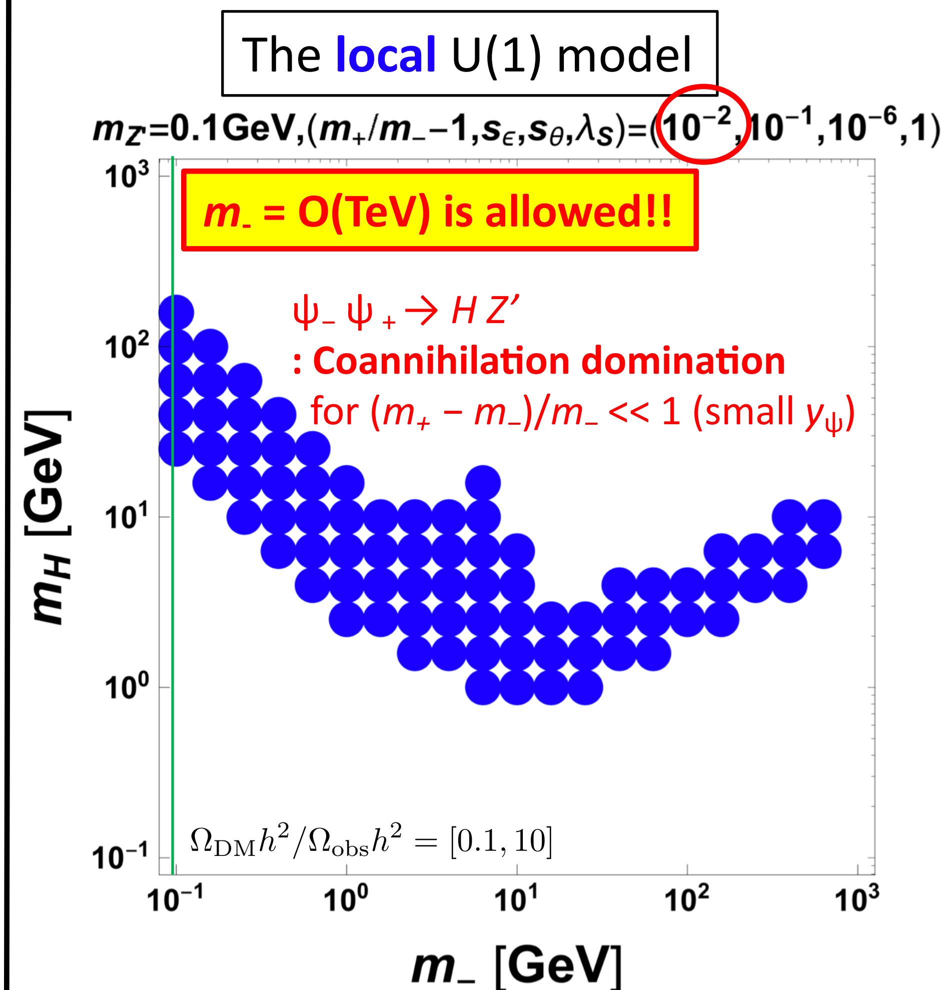
$m_{Z'}$=0.1GeV, $(m_+/m_- - 1, s_\epsilon, s_\theta, \lambda_S) = (0.5, 10^{-1}, 10^{-6}, 1)$



If y_ψ is large, $\psi_- \psi_- \to H\,H$ is possible at $m_H < m_-$.
→ Large m_- is allowed for the local $U(1)$ model.

Comparing two models with the DM direct search exclusion



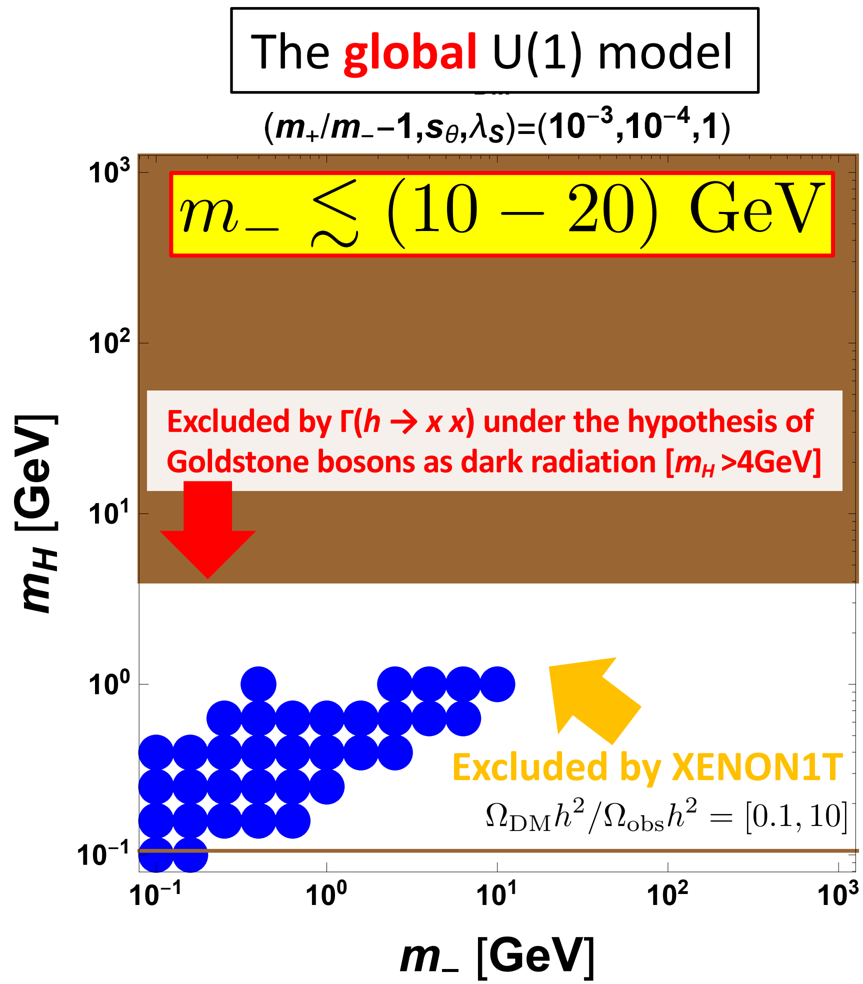


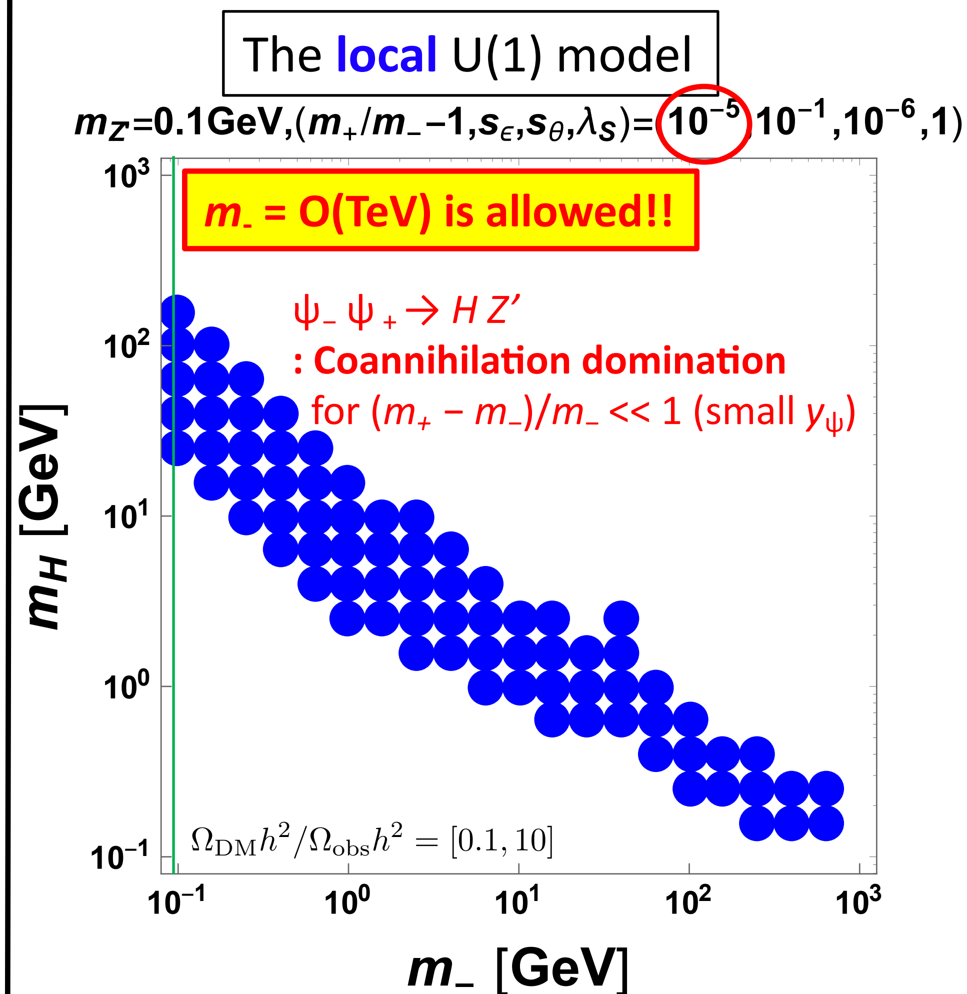
Consistent with [C. G. -Cely, A. Ibarra, E. Molinaro, 1310.6256 (JCAP)]

The global model limit for $m_{Z'}$ or $g_X \to 0$ in the local model

Coannihilation process gives significant deviation with large g_X for the local model.

Comparing two models with the DM direct search exclusion





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The global model limit for $m_{Z'}$ or $g_X \to 0$ in the local model

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DM indirect searches for local model

- Secluded regime is difficult to detect at colliders or direct searches, but indirect signatures will be important prove.

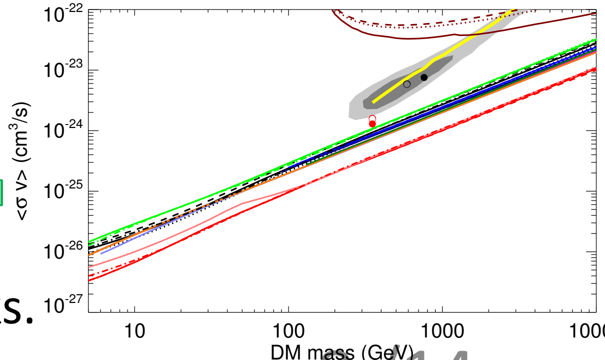
M. Pospelov, A. Ritz a, M. Voloshin, 0711.4866 (PLB)

- A unified model which explains PAMELA/Fermi, WMAP, INTEGRAL and DAMA simultaneously was proposed.

N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, 0810.0713 (PRD)

- Cosmic ray spectra require a WIMP with
  - $m_{\rm DM}$ ~ 0.5-1 TeV N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, 0810.0713 (PRD)
  - $\langle \sigma v \rangle \sim O(10^{-23})$ cm^3 s^{-1} A. Lopez, C. Savage, D. Spolyar and D. Q. Adams, arXiv:1501.01618 (JCAP)

- However,
  - CMB bound on s-wave annihilation excludes $\langle\sigma v\rangle \gtrsim O(10^{-24}) \mathrm{cm}^3 \mathrm{s}^{-1}$ T. R. Slatyer, 1506.03811 (PRD) [Fig →]
  - Dark Higgs mechanism (the origin of $m_{Z'}$ or $m_{\rm DM}$) was not considered in the previous works.

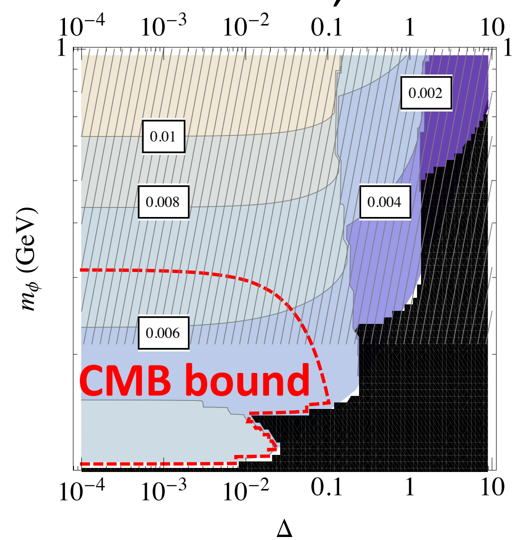


DM indirect searches for local model

- In order to avoid the CMB constraint, we consider presence of local substructure with Sommerfeld enhancement.

$$S_{\rm eff} \simeq S_{v(r)} + S_{v\to 0}\Delta(r)$$ T. R. Slatyer, N. Toro and N. Weiner, 1107.3546 (PRD)

  - S_v is the Sommerfeld enhancement factor at velocity v
  - $1+\Delta(r) \equiv \frac{\langle \rho^2(r)\rangle}{\langle \rho(r)\rangle^2}$ is substructure boost factor were r = Galactocentric radius
  - In the substructure-dominated case, the CMB bound allows for $\Delta \gtrsim O(0.1)$

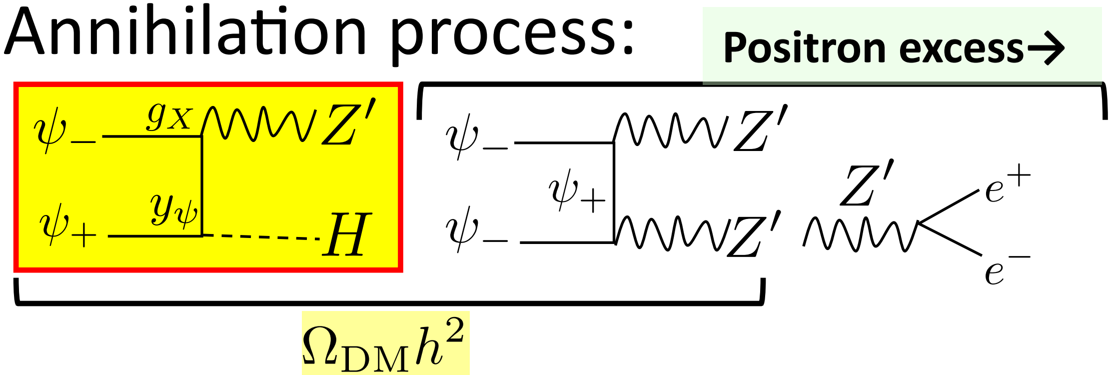


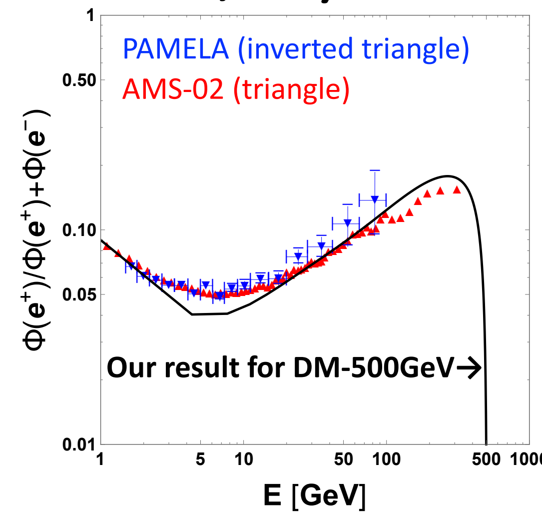
A case for 1000GeV DM with 7 × 10^{-4} GeV mass splitting

$$\frac{1}{2}\frac{y_\psi}{\Lambda}\left(\bar{\psi}^C\psi S^* S^* + h.c\right)$$

Positron excess (PAMELA, Fermi, AMS-02, …)

- Annihilation process:





- Benchmark point in our model:

BM	m_-	$\delta \equiv m_+ - m_-$	g_X	$m_{Z'}$	$\sin\epsilon$	m_H	$\sin\theta$
DM(500GeV)	500 GeV	0.005 GeV	0.79	100 MeV	10^{-4}	200 MeV	10^{-6}

PAMELA↑ co-annihilation↑

$\Omega_{\rm DM}h^2$

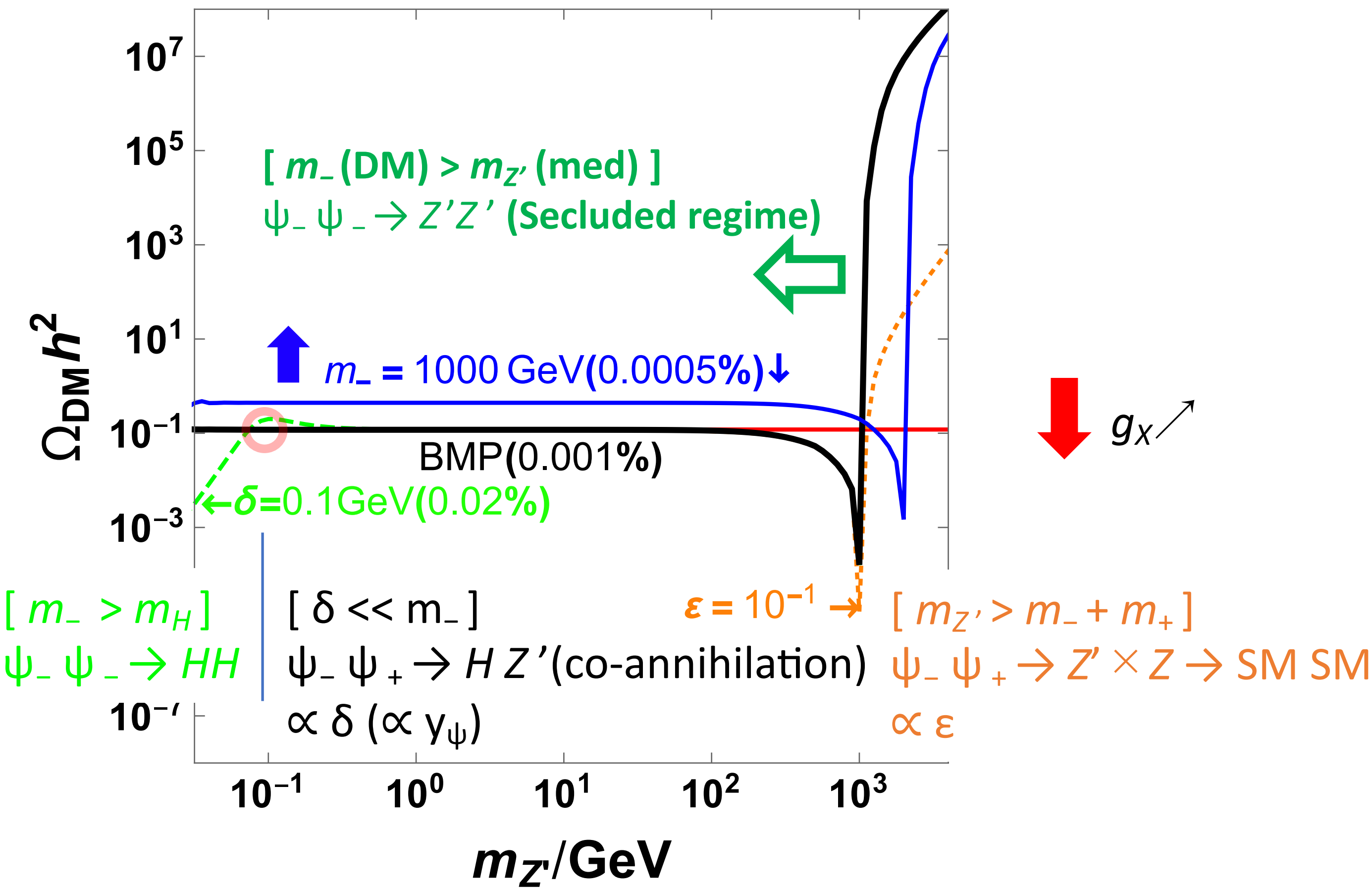
Constrained by dark photon searches

DM direct searches & perturbativity give upper bound

If $m_{Z'} > 2m_\mu$, the relic density does not change, but the final state may become more complicated.

- We find the contribution of dark Higgs is important!

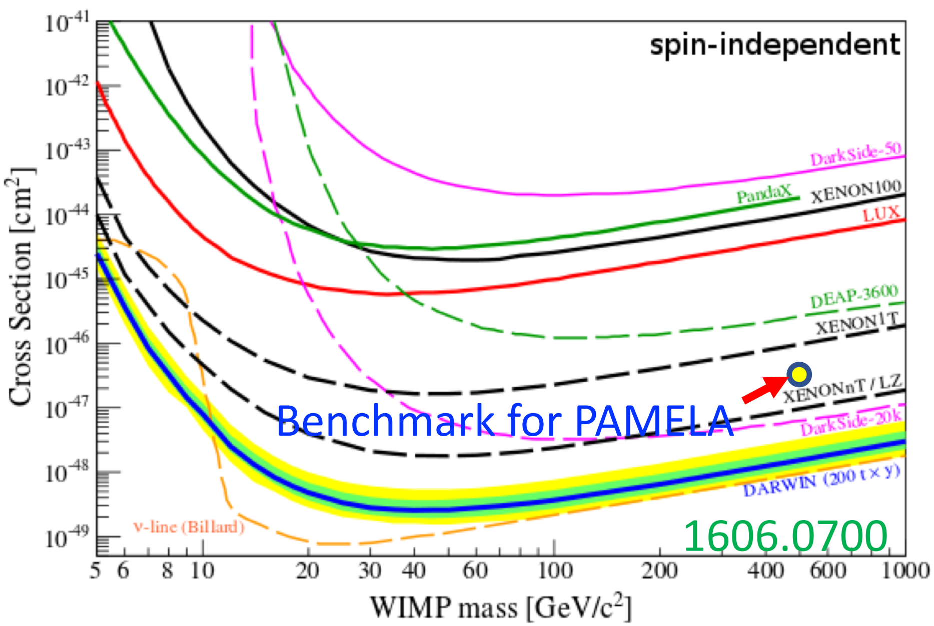
DM relic density (Parameter dependence)

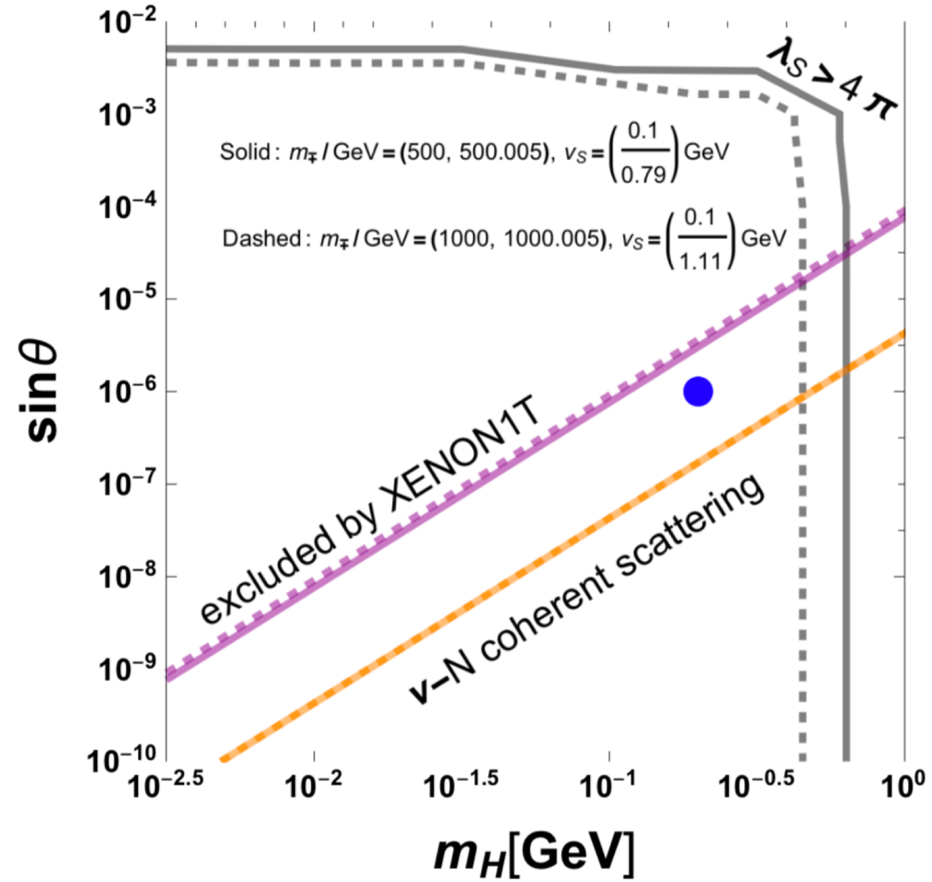


Dominant processes:

BM	m_-	$\delta \equiv m_+ - m_-$	g_X	$m_{Z'}$	$\sin\epsilon$	m_H	$\sin\theta$
DM(500GeV)	500 GeV	0.005 GeV	0.79	100 MeV	10^{-4}	200 MeV	10^{-6}

DM direct searches

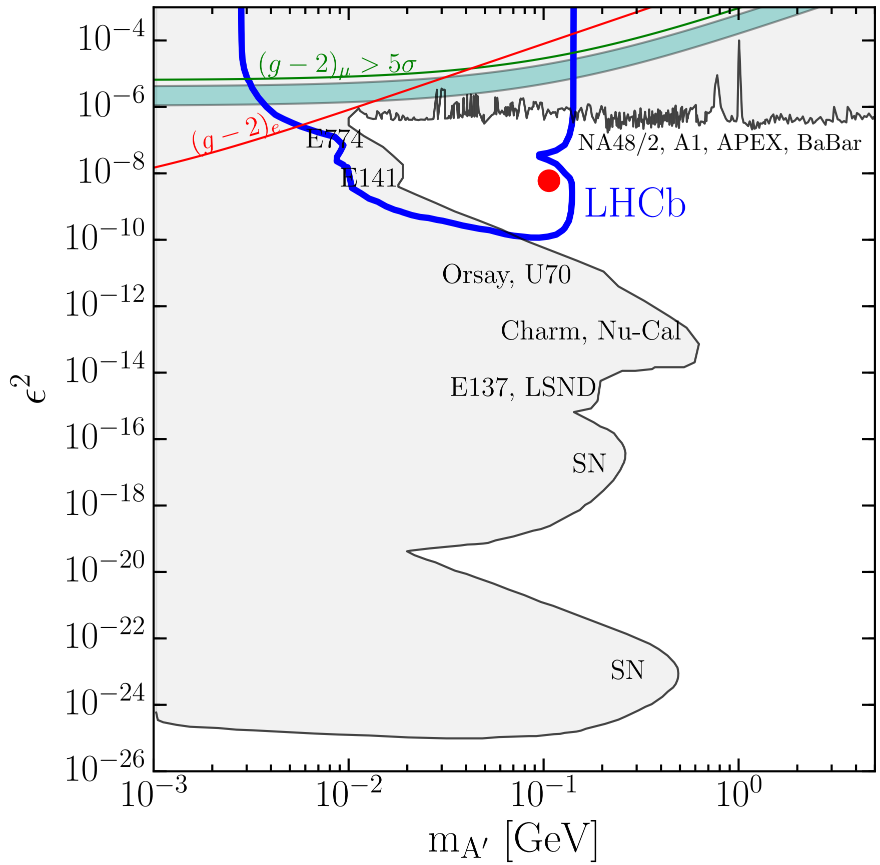




Perturbativity: $\lambda_S = \frac{g_X^2}{2m_{Z'}^2}(m_h^2 \sin^2\theta + m_H^2 \cos^2\theta) < 4\pi$

Dark photon searches

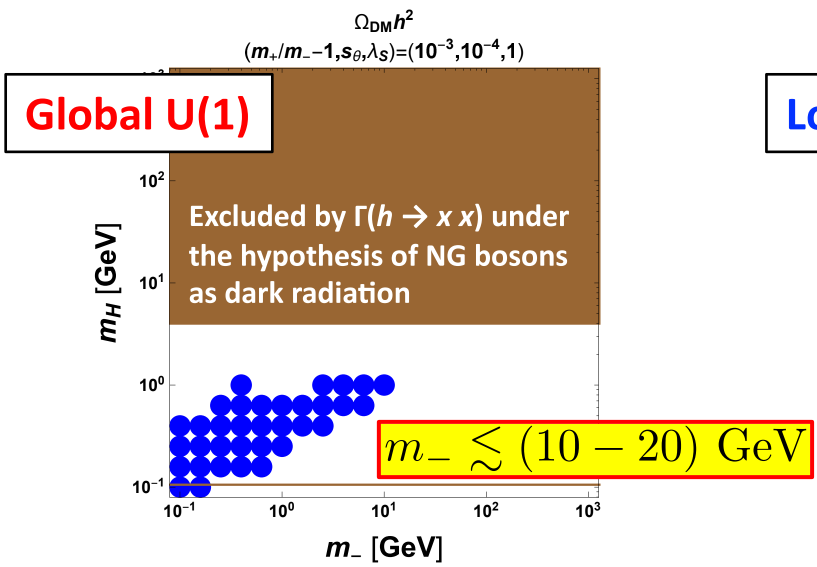
P. Ilten, J. Thaler, M. Williams and W. Xue, arXiv:1509.06765 (PRD)

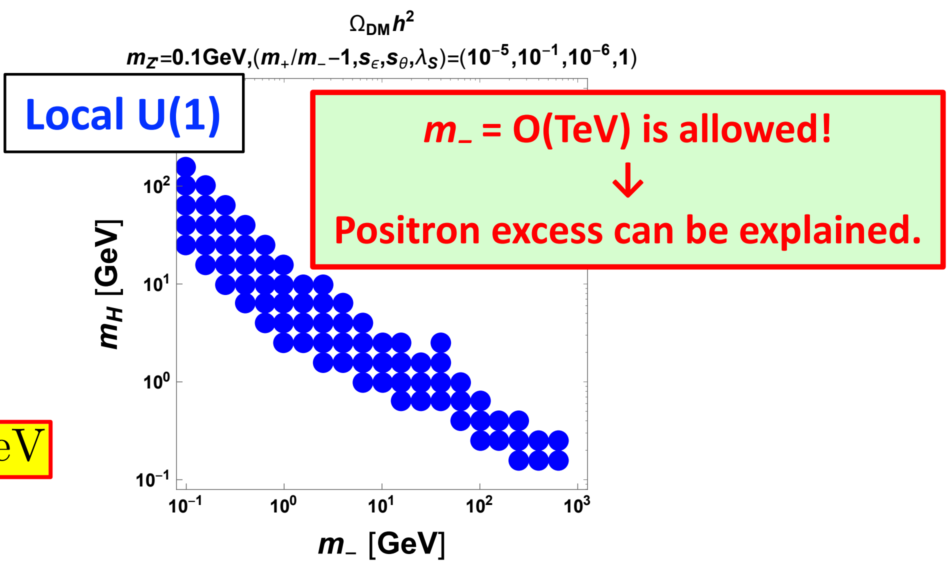


Our BMP will be explored by APEX/Belle-II/HPS/LHCb/SeaQuest/SHiP.

Conclusions

- "**SSB of $U(1)_X$**" → DM is stabilized by a residual discrete symmetry.
- We have focused on a case for **the fermion DM**.
- We have shown that the deviation from the global $U(1)_X$ case is significant by the coannihilation *HZ'* for the secluded regime ($m_{Z'} << m_-$) in the local $U(1)_X$ case.





- Considering DM local substructure, the local $U(1)_X$ can explain positron excess of DM indirect searches and will be explored by direct searches for DM (ψ_-) & DP (Z').
- **We have shown that the contribution of the dark Higgs is important.**

Back Up

Benchmark points

BM	m_-	$\delta \equiv m_+ - m_-$	g_X	$m_{Z'}$	$\sin\epsilon$	m_H	$\sin\theta$
DM(500GeV)	500 GeV	0.005 GeV	0.79	100 MeV	10^{-4}	200 MeV	10^{-6}

Ωh^2	$\langle\sigma v\rangle$ [cm^{3}sec^{-1}]	$\tau_{Z'}$ [sec]	τ_{ψ_+} [sec]	τ_H [sec]	$\sigma^{\rm SI}$ [cm^2]
0.1187	2.3×10^{-26}	1.2×10^{-13}	3.9×10^{-4}	7.3×10^{-3}	3.4×10^{-47}
$\psi_-\psi_+ \xrightarrow{48\%} Z'H$ $\psi_-\psi_- \xrightarrow{26\%} Z'Z'$ $\psi_+\psi_+ \xrightarrow{26\%} Z'Z'$	$\psi_-\psi_- \xrightarrow{100\%} Z'Z'$	$Z' \xrightarrow{50\%} \bar{u}u$ $Z' \xrightarrow{38\%} e^-e^+$ $Z' \xrightarrow{12\%} \bar{d}d$	$\psi_+ \xrightarrow{99\%} \psi_-e^-e^+$ $\psi_+ \xrightarrow{1\%} \psi_-\bar{u}u$	$H \xrightarrow{88\%} \bar{s}s$ $H \xrightarrow{10\%} \bar{d}d$ $H \xrightarrow{2\%} \bar{u}u$	

The global model

Goldstone boson as dark radiation

[S. Weinberg, 1305.1971 (PRL)]

- Radiation = relativistic particle
- Effective number of neutrino species ($N_{\rm eff}$)
  - SM @$T < m_e$ (γ, $\nu_{i=1,2,3}$): $N_{\rm eff}^{\rm SM}$ ($\equiv g_\nu/g_\gamma$) = 3.046

[Mangano, Miele, Pastor, Pinto, Pisanti, Serpico, 0506164 (NPB)]

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu = \left(1 + \left(\frac{g_\nu}{g_\gamma}\right)\left(\frac{7}{8}\right)\left(\frac{T_\nu}{T_\gamma}\right)^4\right)\rho_\gamma \qquad \frac{(T_\nu)_{\rm after}}{(T_\gamma)_{\rm before}} = \left(\frac{2}{11/2}\right)^{1/3}$$

- Existence of dark radiation: $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$
  - Goldstone decoupling @$T_{\rm dec} < m_\mu$ (γ, $\nu_{i=1,2,3}$, e): $\Delta N_{\rm eff}$ =0.39

Assumption

$$\rho_x = \frac{1}{2}\left(\frac{T_x}{T_\gamma}\right)^4 \rho_\gamma = \left(\frac{1}{2}\frac{8}{7}\left(\frac{T_x}{T_\nu}\right)^4\right)\left(\frac{7}{8}\right)\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma \qquad \frac{(T_x)_{\rm before}}{(T_\nu)_{\rm after}} = \left(\frac{57/4}{43/4}\right)^{1/3}$$

The global model: Constraint of N_{eff}

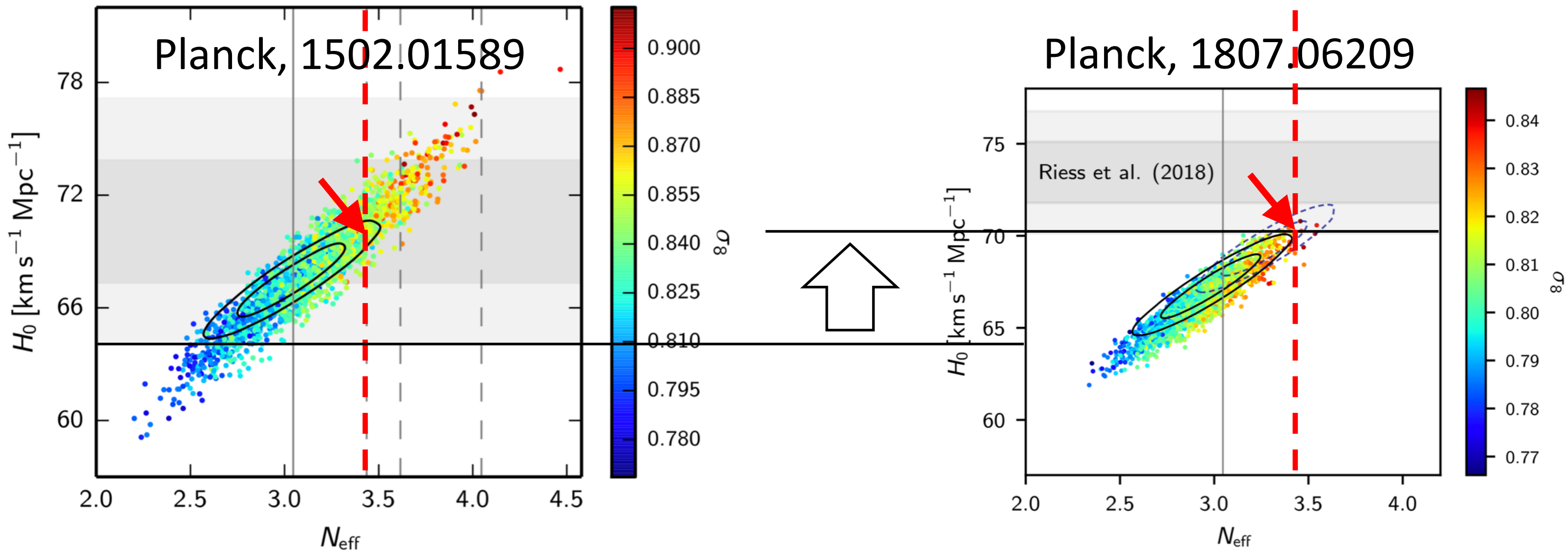


Fig. 31. Samples from *Planck* TT+lowP chains in the N_{eff}–H_0 plane, colour-coded by σ_8. The grey bands show the constraint $H_0 = (70.6 \pm 3.3)$ km s^{-1}Mpc^{-1} of Eq. (30). Notice that higher N_{eff} brings H_0 into better consistency with direct measurements, but increases σ_8. Solid black contours show the constraints from *Planck* TT,TE,EE+lowP+BAO. Models with $N_{\mathrm{eff}} < 3.046$ (left of the solid vertical line) require photon heating after neutrino decoupling or incomplete thermalization. Dashed vertical lines correspond to specific fully-thermalized particle models, for example one additional massless boson that decoupled around the same time as the neutrinos ($\Delta N_{\mathrm{eff}} \approx 0.57$), or before muon annihilation ($\Delta N_{\mathrm{eff}} \approx 0.39$), or an additional sterile neutrino that decoupled around the same time as the active neutrinos ($\Delta N_{\mathrm{eff}} \approx 1$).

Fig. 35. Samples from *Planck* TT,TE,EE+lowE chains in the N_{eff}–H_0 plane, colour-coded by σ_8. The grey bands show the local Hubble parameter measurement $H_0 = (73.45 \pm 1.66)$ km s^{-1}Mpc^{-1} from Riess et al. (2018a). Solid black contours show the constraints from *Planck* TT,TE,EE +lowE+lensing+BAO, while dashed lines the joint constraint also including Riess et al. (2018a). Models with $N_{\mathrm{eff}} < 3.046$ (left of the solid vertical line) require photon heating after neutrino decoupling or incomplete thermalization.

Tension between N_{eff} and H_0

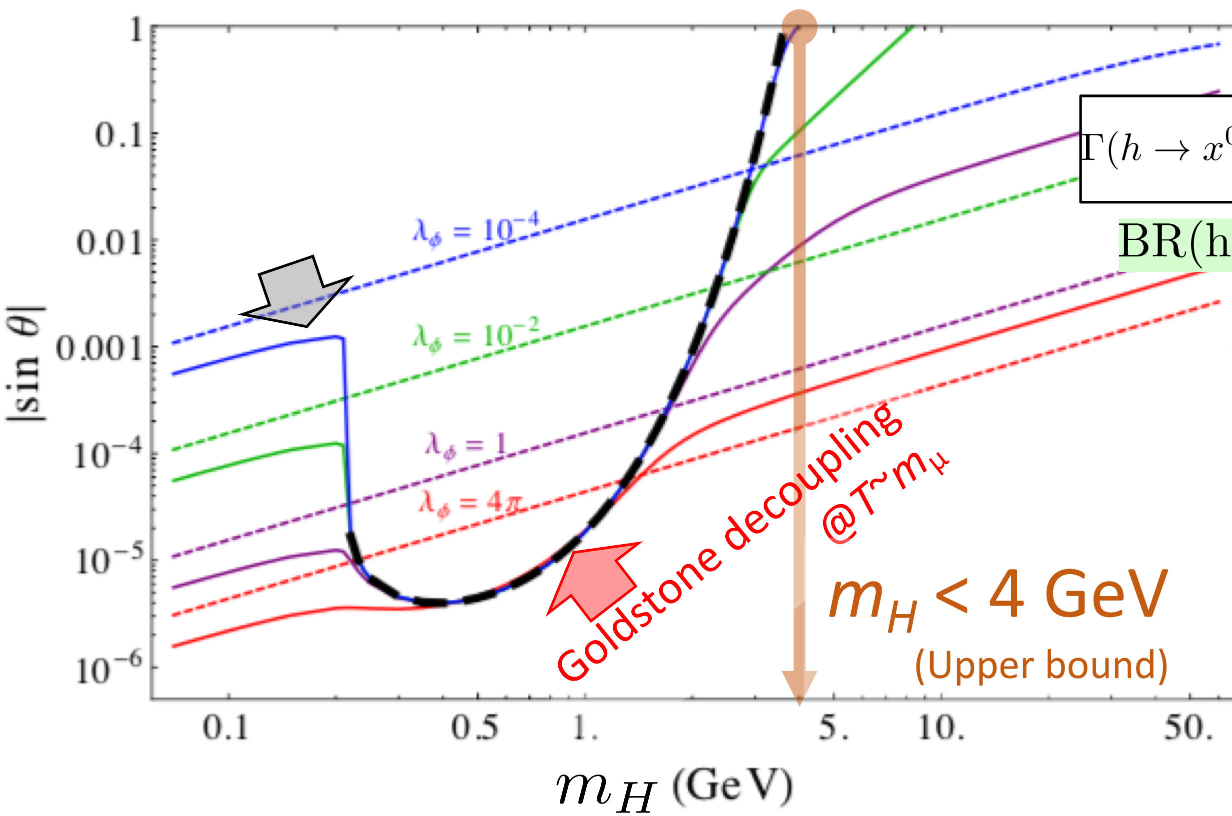
→ The global model w/ $T_{\mathrm{dec}} < m_\mu$ is allowed for the joint constraint (1σ).

The global model

Constraints

[C. G. -Cely, A. Ibarra, E. Molinaro, 1310.6256 (JCAP)]

- Lower bound of sinθ ← Goldstone boson can play the role of a dark radiation
- Upper bound of sinθ ← Decay rate: Γ(*h*→*xx*)



$$\Gamma(h \to x^0 x^0) = \frac{m_h^3 \sin^2\theta}{32\pi v_S^2}$$

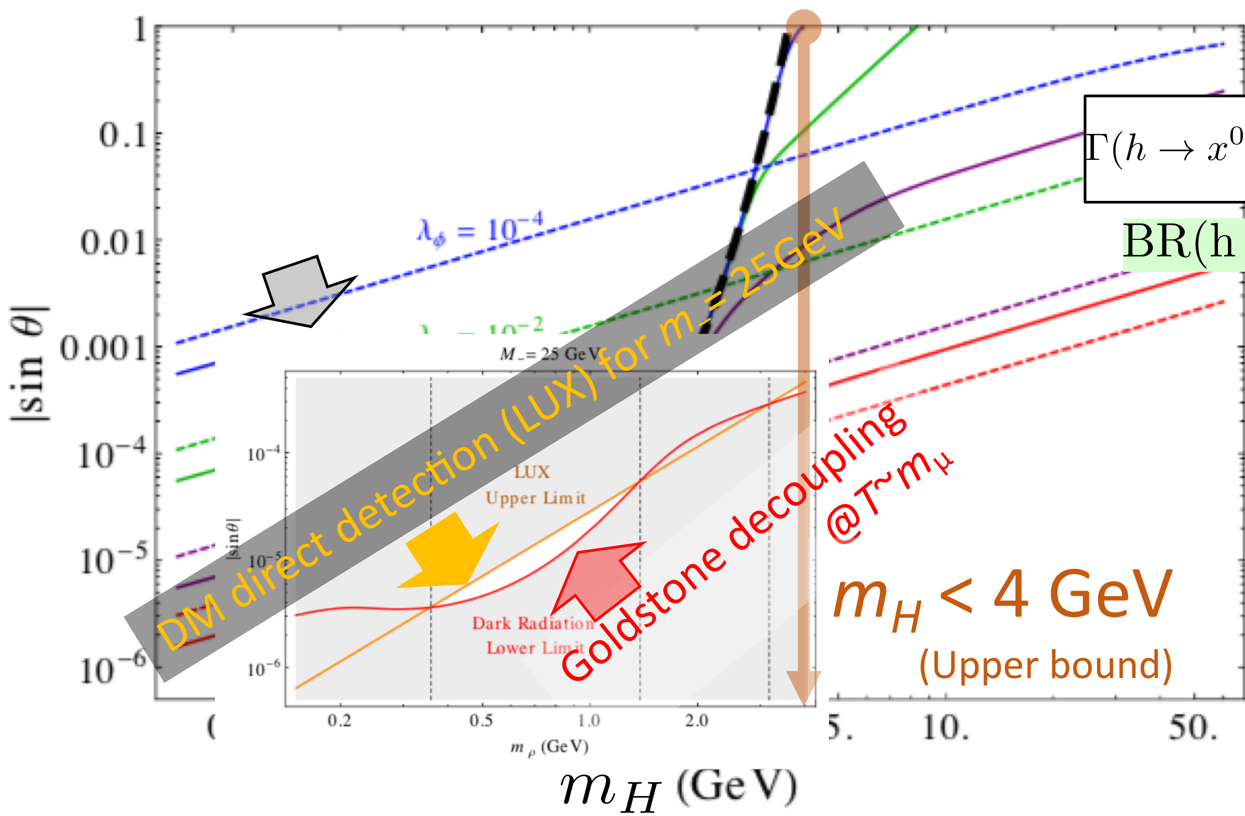
$$\mathrm{BR}(\mathrm{h} \to \mathrm{inv}) \simeq 20\%$$

The global model

Constraints

[C. G. -Cely, A. Ibarra, E. Molinaro, 1310.6256 (JCAP)]

- Lower bound of sinθ ← Goldstone boson can play the role of a dark radiation
- Upper bound of sinθ ← Decay rate: Γ(*h*→*xx*) and DM direct detection



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