Fermion dark matter in models with U(1) symmetry

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Work in progress

Higgs portal DM

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

- Minimal models (renormalizable and gauge invariant)
  - Scalar DM
    - Real scalar with Z_2 sym

      J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, 1306.4710 (PRD)], …
    - Complex scalar (Goldstone DM) with softly broken $U(1)$

      C. Gross, O. Lebedev, T. Toma, 1708.02253 (PRL)], …
  - Fermion DM
    - Singlet fermion + Real scalar

      Y. G. Kim, K. Y. Lee and S. Shin, 0803.2932 (JHEP),
      S. Baek, P. Ko and W. I. Park, 1112.1847 (JHEP), …
  - Vector DM
    - Complex scalar with $U(1)_X$
    - [SSB] → Gauge boson: Z_2 sym is needed to avoid the kinetic mixing $B_{\mu\nu} F^{\mu\nu}$

      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 $U(1)$ 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> ($\Psi^2 S^\dagger \rightarrow Z_2$ 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): $m_{\rm DM} < m_{Z'}$

    S. Baek, P. Ko, TM, W.I. Park (**this work**): ε≠0, secluded regime ($m_{\rm DM} \gtrsim m_{Z'}$)
- <u>N = 3 case</u> ($\Psi^3 S^\dagger \rightarrow Z_3$ symmetry)
  - Ψ = scalar [P. Ko, Y. Tang, 1402.6449 (JCAP)]

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

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

  $\Phi^{\rm SM}$, $\mathbb{S} = \frac{1}{\sqrt{2}}(v_S + s + ix^0)$ → (*h*, *H*) w/ mixing angle θ
- Fermion sector: $\mathcal{L}_\psi = -m_\psi\overline{\psi}\psi - \frac{y_\psi}{\sqrt{2}}\overline{\psi^c}\psi\mathbb{S}^\dagger + h.c.$ $\quad \psi_+ = \frac{\psi+\psi^c}{\sqrt{2}} \quad \psi_- = \frac{\psi-\psi^c}{\sqrt{2}i}$
- **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′*.

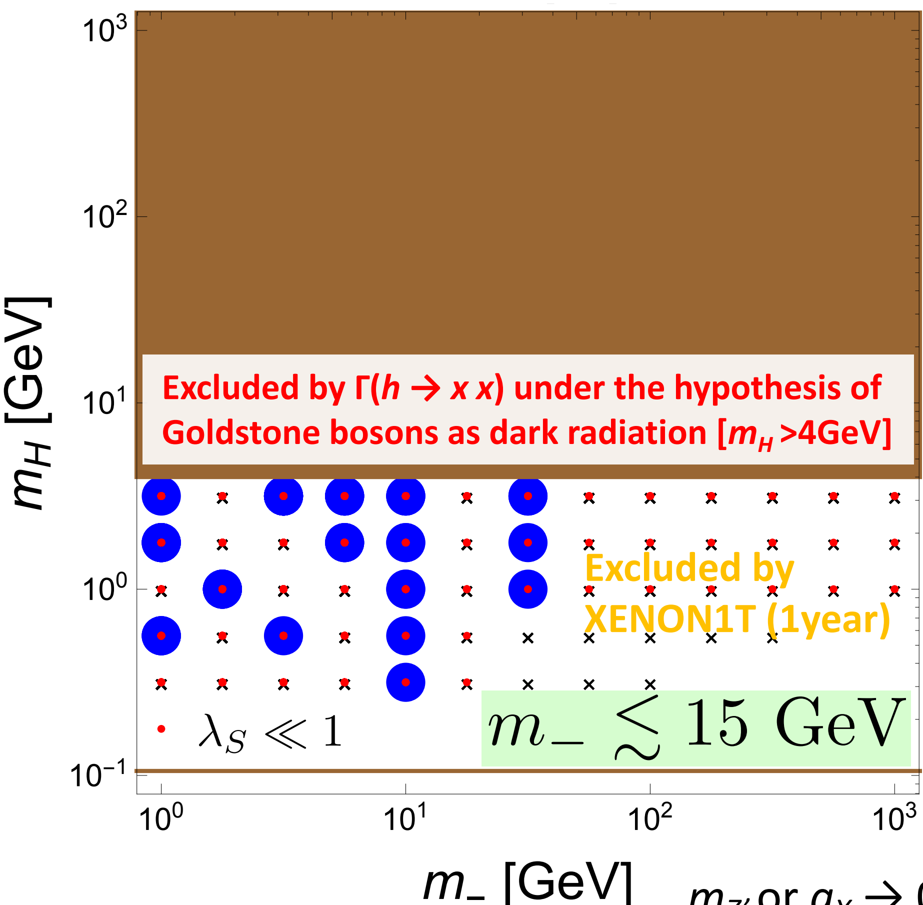
  SSB gives the origin of the *Z′* mass (dark Higgs mechanism).

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

Comparing two models with the DM direct search exclusion

The global model

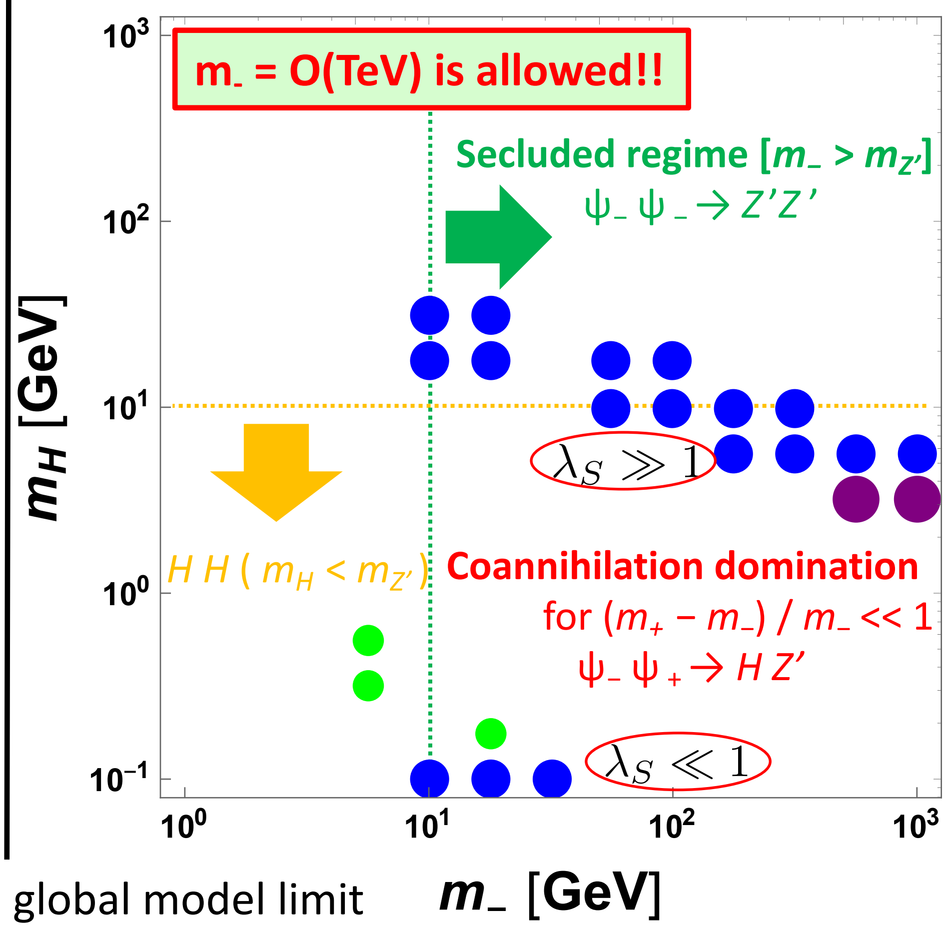
Consistent with [C. G. -Cely, A. Ibarra, E. Molinaro, 1310.6256 (JCAP)]



The local model

g_X = [10^{-2},10^{-1}) [10^{-1},10^{0}) [10^{0},√4π]

$m_{Z'}$=10GeV,($m_+ - m_-/m_-$,s_ϵ,s_θ)=(10^{-2},10^{-4},10^{-6})



$m_{Z'}$ or $g_X \to 0$: global model limit

DM indirect searches for local model

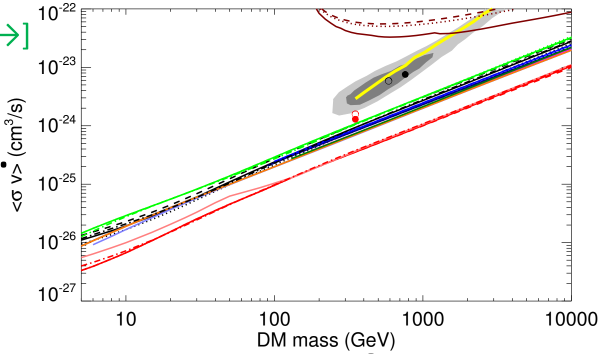
- A unified model which explains PAMELA/Fermi, WMAP, INTEGRAL and DAMA simultaneously was proposed.

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)
  - $\langle \sigma v \rangle \sim O(10^{-23})\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ A. Lopez, C. Savage, D. Spolyar and D. Q. Adams, arXiv:1501.01618 (JCAP)
- However,
  - CMB bound on *s*-wave DM 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.

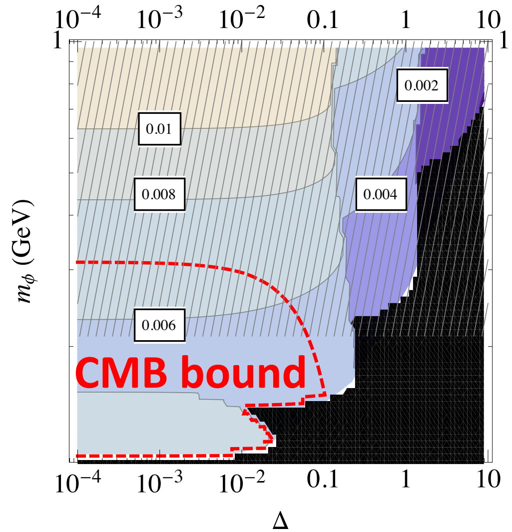


DM indirect searches for local model

- 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 $\Delta \gtrsim O(0.1)$



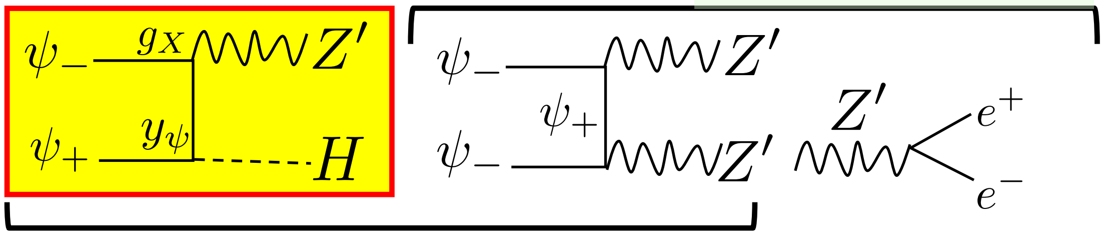
A case for 1000GeV DM with 7 × 10^-4 GeV mass splitting

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

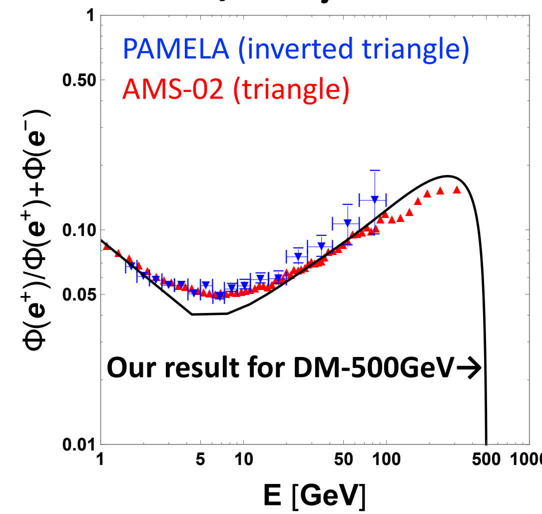
Positron excess (PAMELA, Fermi, AMS-02, …)

- Annihilation process:

Positron excess→



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



- 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

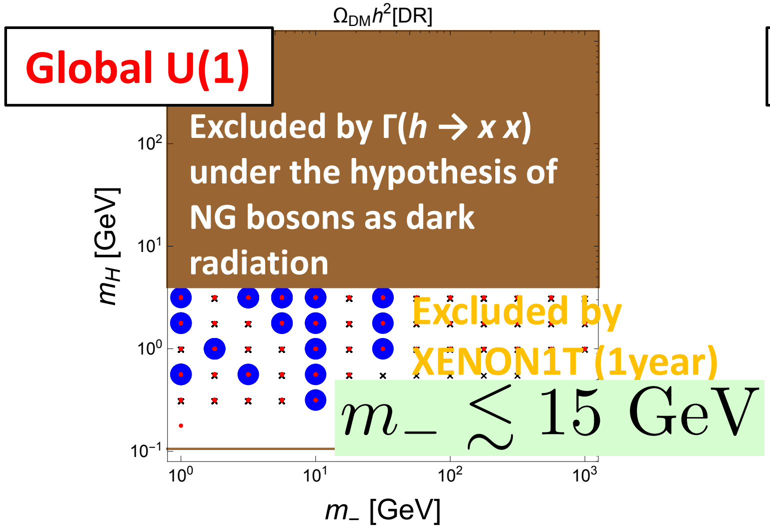
DM direct searches & perturbativity give upper bound

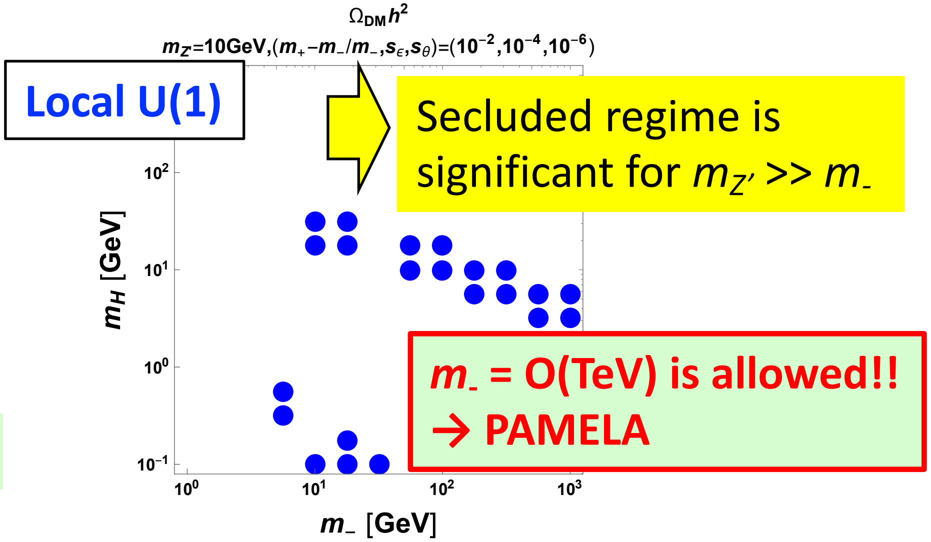
If $m_{Z'} > 2m_\mu$, the relic density does not change, but the final state may become more complicated.

- We find the contribution of dark Higgs is important!

Conclusions

- "**SSB of U(1)$_X$**" → DM is stabilized by <u>a residual discrete symmetry</u>.
- We have focused on a case for **the fermion DM**.
- 1. We have compared models with the global U(1)$_X$ and the local U(1)$_X$.





- 2. Local model can explain excess of DM indirect searches (PAMELA, Fermi, AMS-02) and will be explored by direct searches of DM and dark photon.
- **We have shown that the contribution of the dark Higgs is important.**

Back Up

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 $N_{\rm eff}$

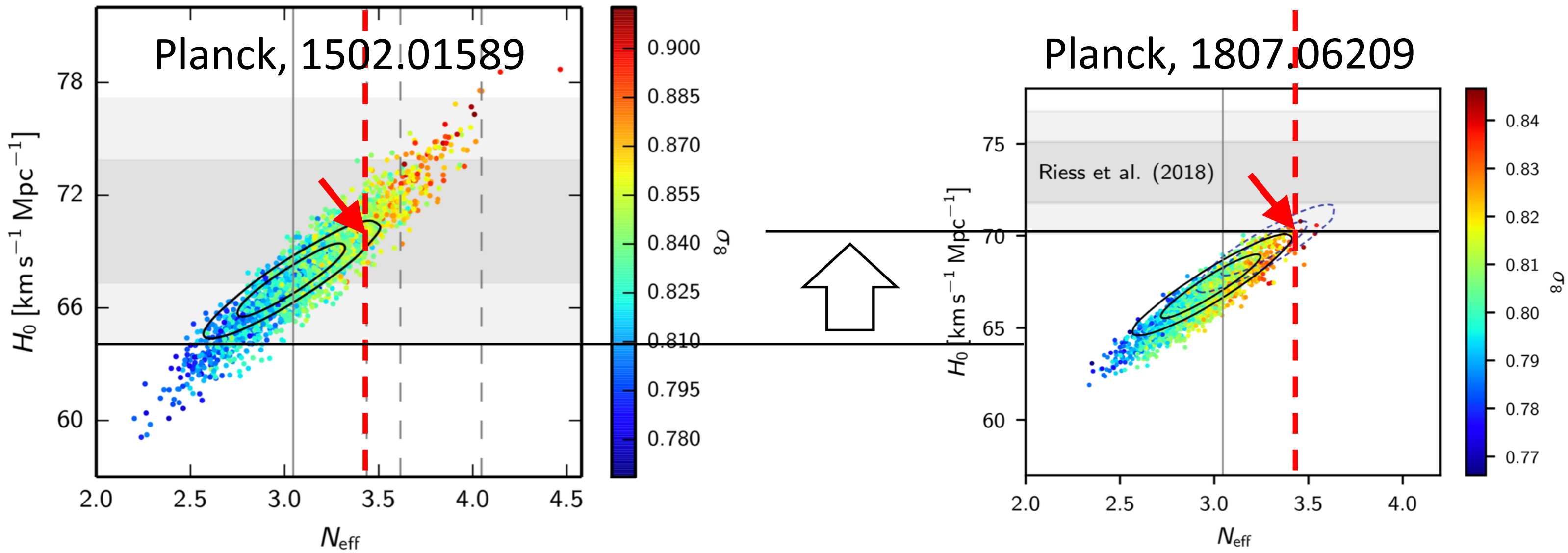


Fig. 31. Samples from *Planck* TT+lowP chains in the $N_{\rm eff}$–H_0 plane, colour-coded by σ_8. The grey bands show the constraint $H_0 = (70.6 \pm 3.3)$ km s^{-1}Mpc^{-1} of Eq. (30). Notice that higher $N_{\rm eff}$ brings H_0 into better consistency with direct measurements, but increases σ_8. Solid black contours show the constraints from *Planck* TT,TE,EE+lowP+BAO. Models with $N_{\rm eff} < 3.046$ (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 ($\Delta N_{\rm eff} \approx 0.57$), or before muon annihilation ($\Delta N_{\rm eff} \approx 0.39$), or an additional sterile neutrino that decoupled around the same time as the active neutrinos ($\Delta N_{\rm eff} \approx 1$).

Fig. 35. Samples from *Planck* TT,TE,EE+lowE chains in the $N_{\rm eff}$–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 $N_{\rm eff} < 3.046$ (left of the solid vertical line) require photon heating after neutrino decoupling or incomplete thermalization.

Tension between $N_{\rm eff}$ and H_0

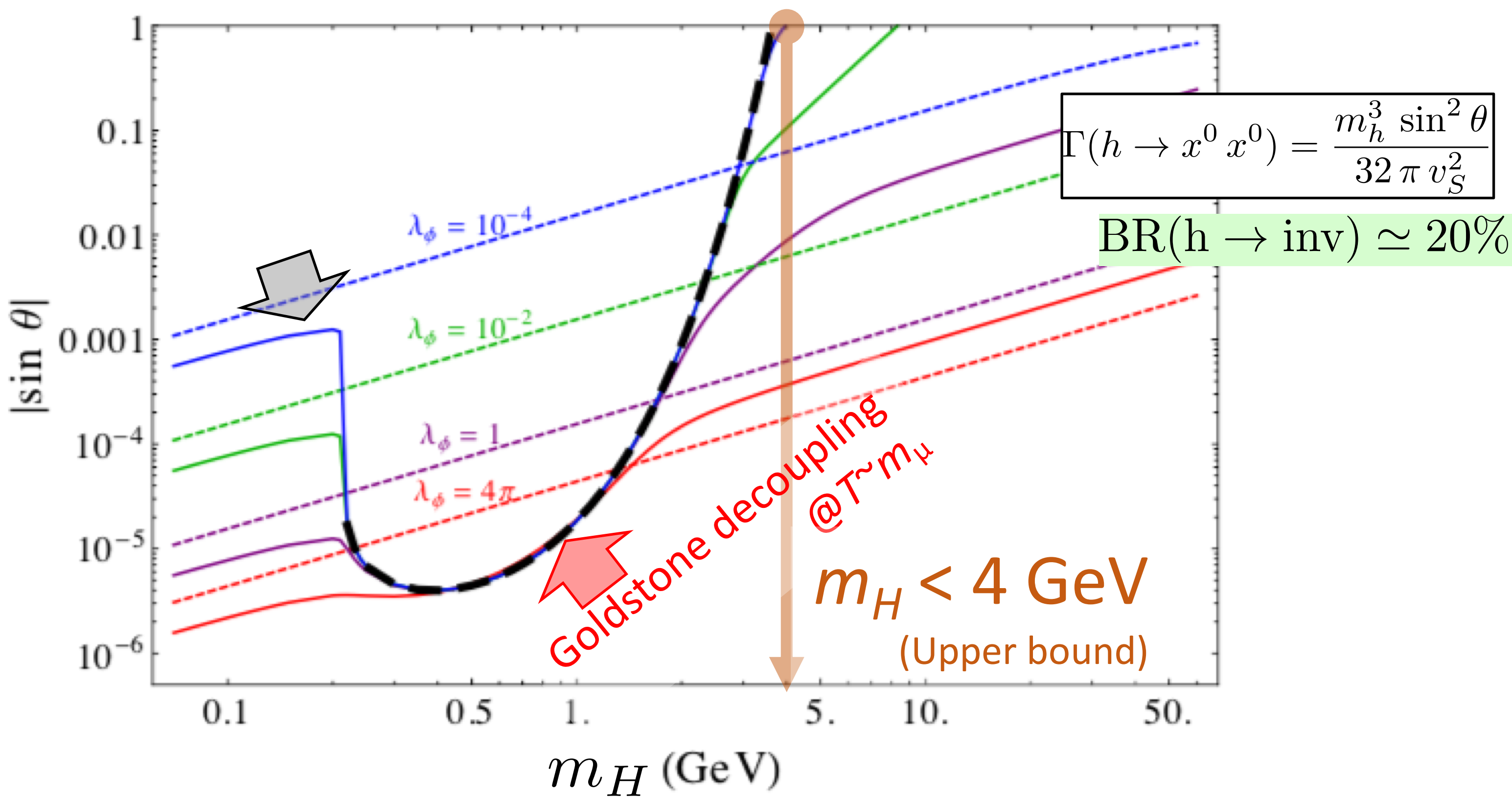
→ The global model w/ $T_{\rm dec} < m_\mu$ is allowed for the joint constraint (1σ).

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*)

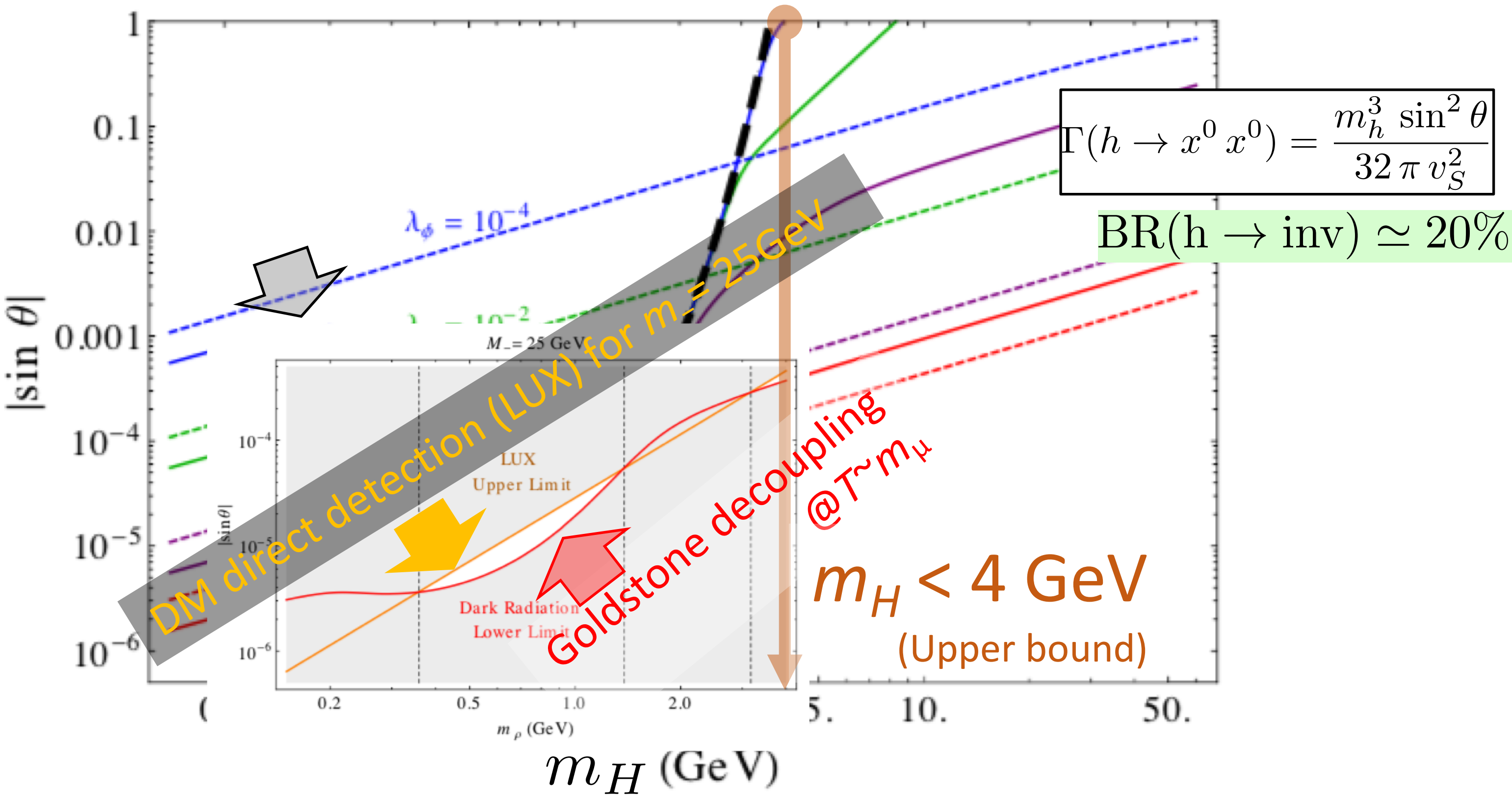


The global model

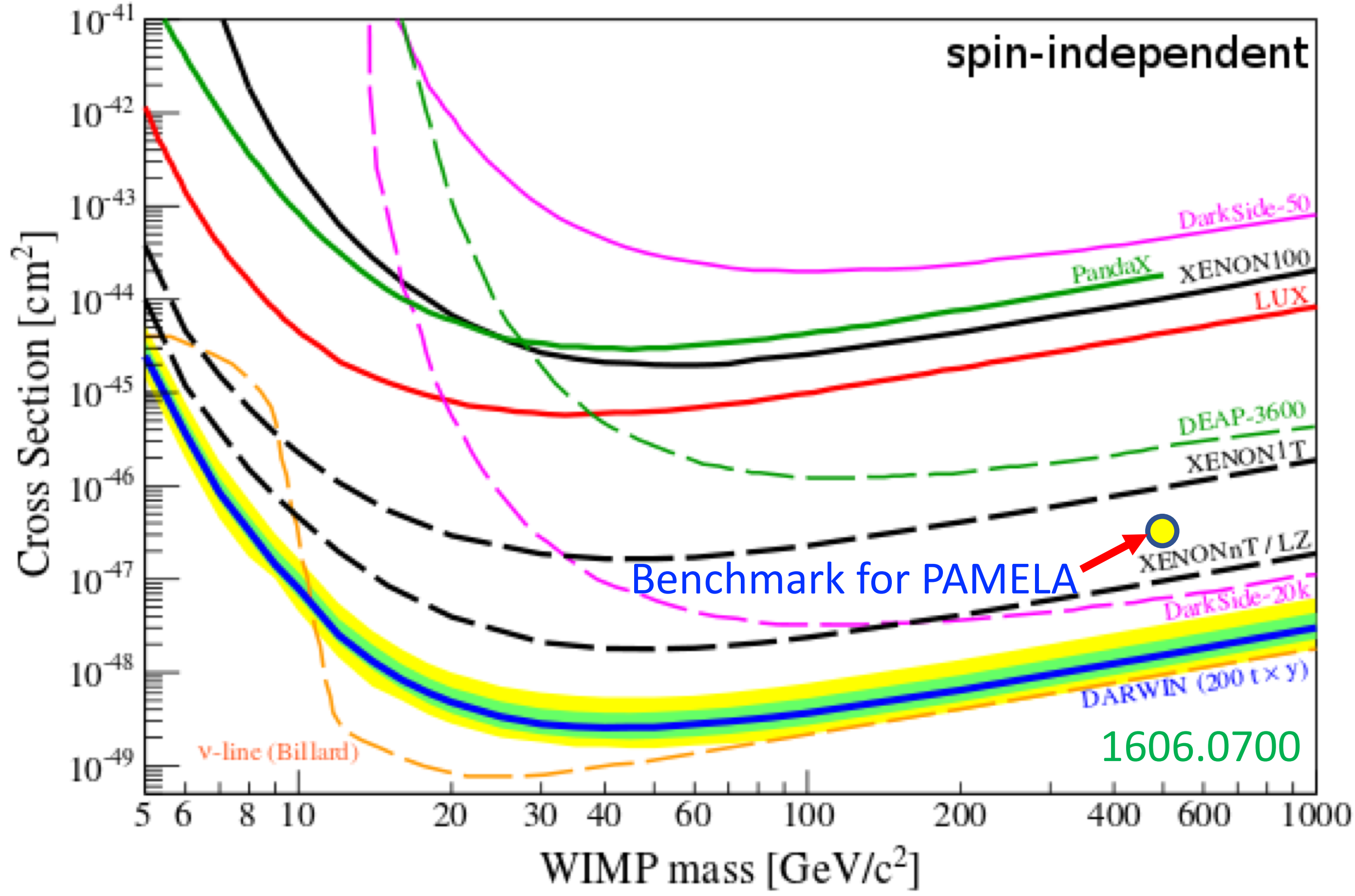
Constraints

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

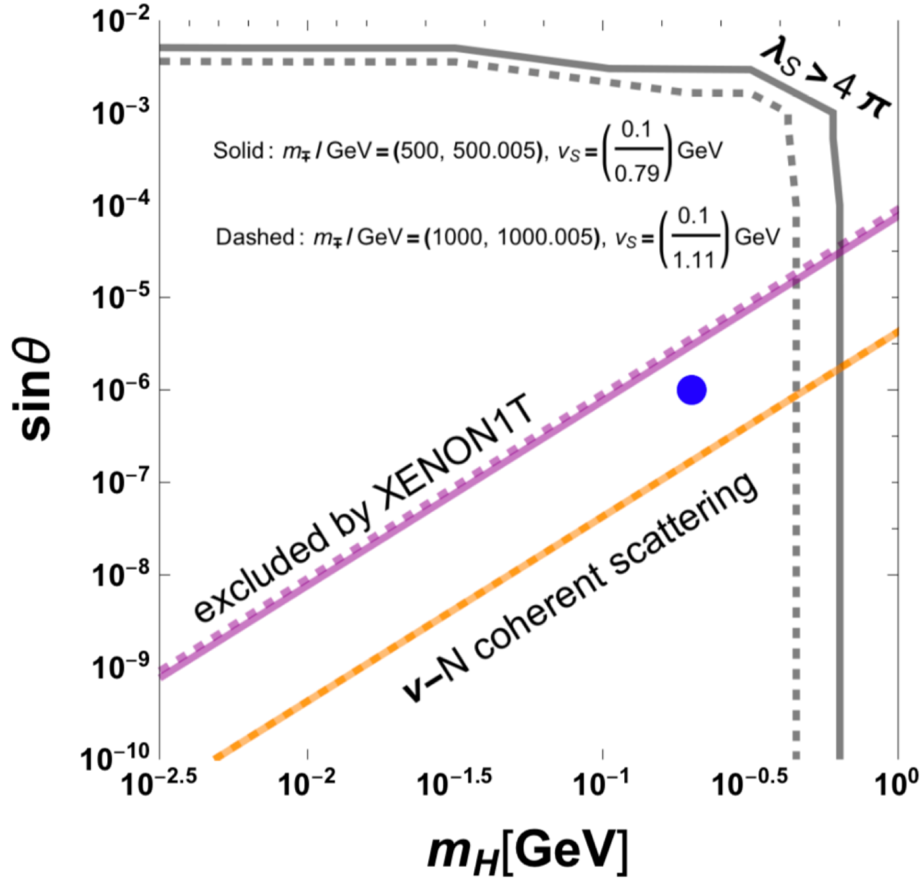
- Lower bound of sinθ ← Goldstone boson can play the role of a dark radiation
- Upper bound of sinθ ← Decay rate: Γ(h→xx) and DM direct detection



DM direct search



DM direct search

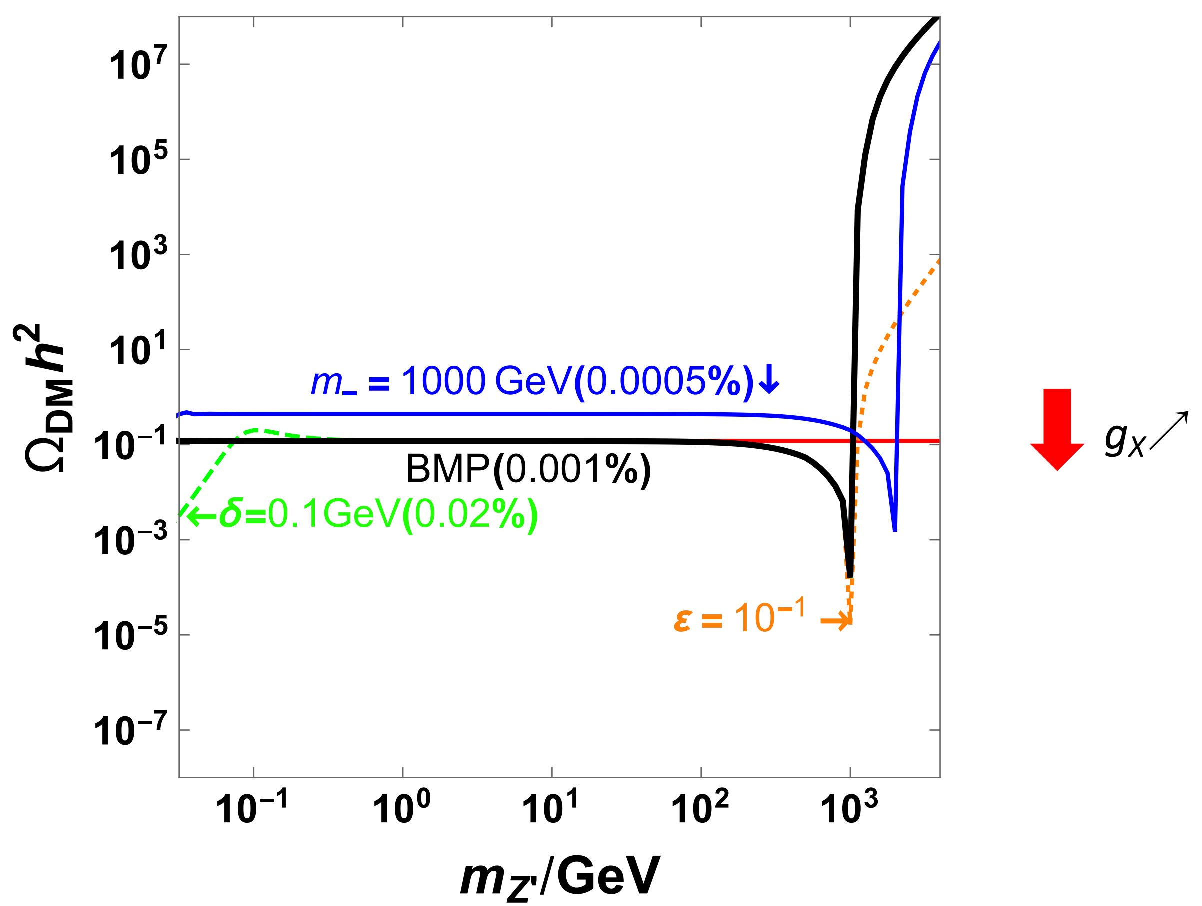


perturbativity.

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

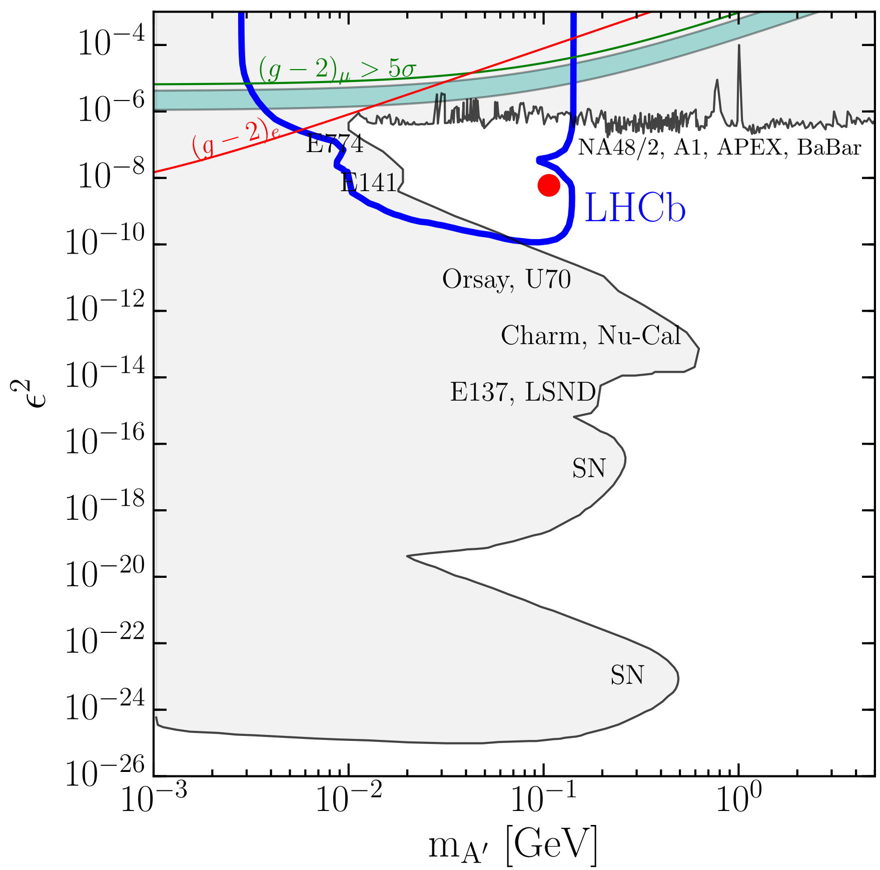
$m_{Z'}$ < O(GeV) → m_H should be MeV scale.

Parameter dependence



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.

P. Ko, TM, Y.L Tang

Bound state formation

- The wave functions overlap between “scattering” and “bound state”:

  $\phi^{\rm SC}\,[\psi_- \psi_+ \rightleftarrows \psi_- \psi_+] \to \phi^{\rm BS}\,[\psi_- \psi_- \rightleftarrows \psi_+ \psi_+]$ $(n^{2s+1}\, l_J = 1^1\, S_0)$ + Z' <Main process>

- Ward identity ($p^\mu_{Z'}\mathcal{M}_\mu = 0$) in the previous work [Petraki, Postma and Vries, 1611.01394 (JHEP)] should be modified with the Goldstone boson contribution:

$$p^\mu_{Z'}\mathcal{M}_\mu = \Delta m \mathcal{M}_{\rm GS}$$

[Solutions from the Schroedinger equations]

$$\vec{\mathcal{J}}^{\{\pm\}}_{\rm d\to s+DP} = \int d^3\vec{r}\left(i\vec{\nabla}\phi^{\rm BS}_{{\rm s},nlm}(\vec{r})\right)\left\{\begin{array}{c} i\sigma^2 \\ \sigma^3 \end{array}\right\}\phi^{\rm SC}_{\rm d}(\vec{r})e^{-i\vec{p}_{Z'}\cdot\vec{r}/2}$$

$$\mathcal{I}^{\{\pm\}}_{\rm d\to s+GS} = \int d^3\vec{r}(\phi^{\rm BS}_{{\rm s},nlm}(\vec{r}))^*\left\{\begin{array}{c} \sigma^1 \\ \sigma^0 \end{array}\right\}\phi^{\rm SC}_{\rm d}(\vec{r})e^{-i\vec{p}_{Z'}\cdot\vec{r}/2}$$

$$v_{\rm rel}\frac{d\sigma_{\rm BSF}}{d\Omega} = \frac{|\vec{p}_{Z'}|}{64\pi^2 M^2 \mu_r}|\mathcal{M}|^2$$

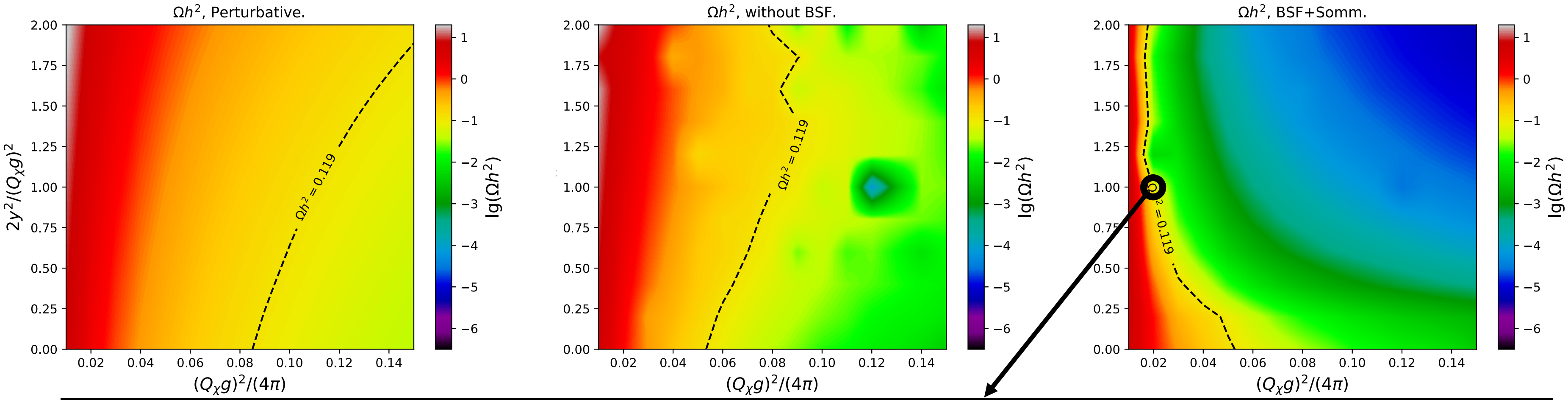
- We find that a significant re-annihilation process arise to reduce the dark matter relic abundance!

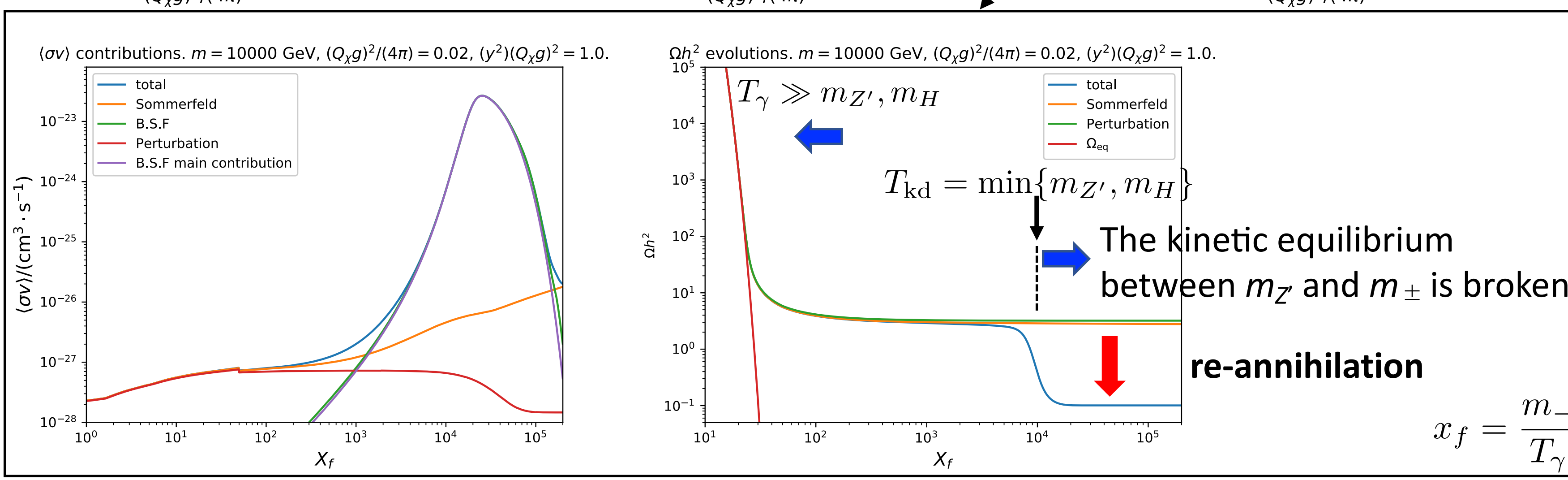
Numerical results

P. Ko, TM, Y.L Tang

$m_{\rm DM}$ = 10TeV, $m_{Z'}$=1GeV, m_H=7GeV

Tree-level perturbative results | + Sommerfeld results | + bound state formation



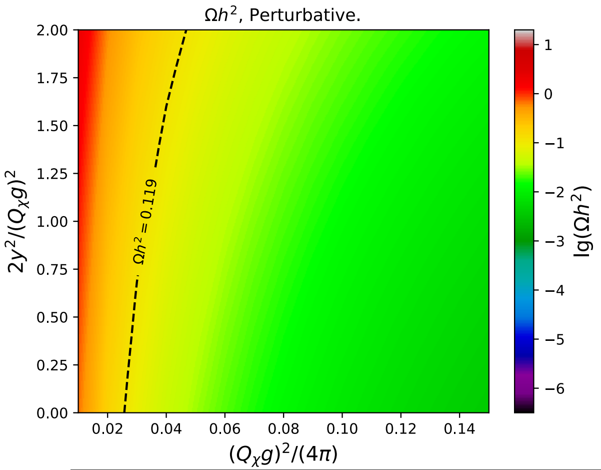


Numerical results

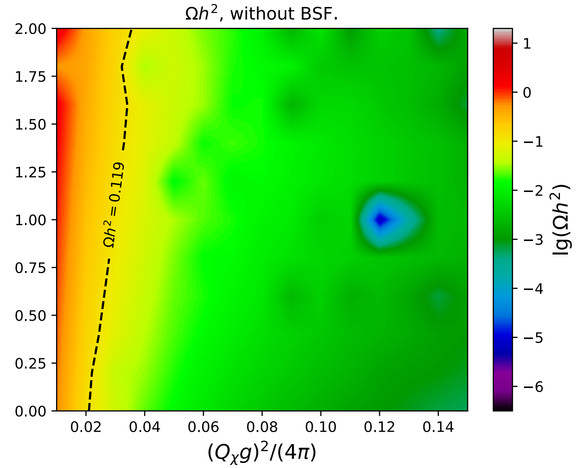
P. Ko, TM, Y.L Tang

$m_{\rm DM}$ = 3TeV, $m_{Z'}$=0.3GeV, m_H=2GeV

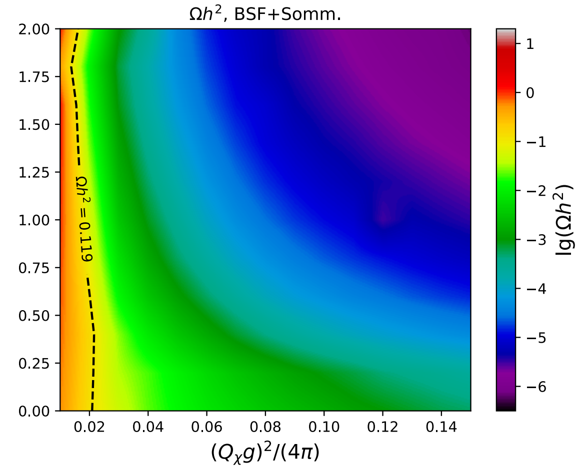
Tree-level perturbative results

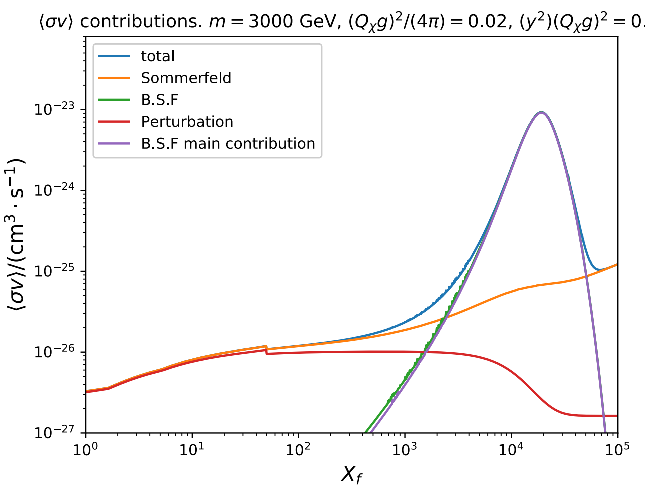


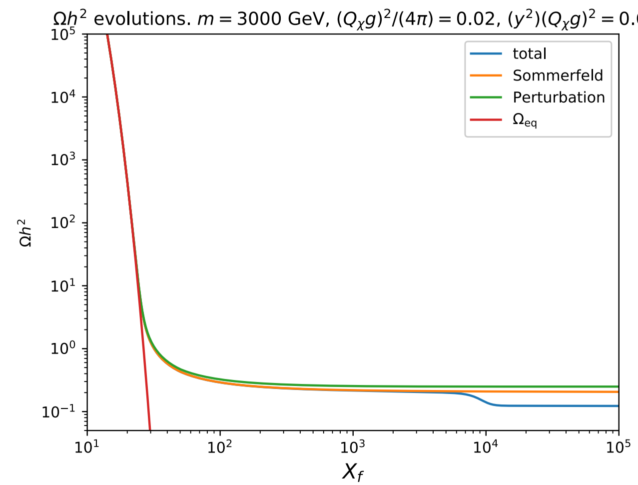
+ Sommerfeld results



+ bound state formation







Some comments on bound stats

- The effect of the bound stats formation is important at the region $m_{DM} >> O(1)$ TeV.
- Unitary bound on the DM K. Griest and M. Kamionkowski, PRL64, 615 (1990) is 30 TeV for freeze-out case.
- In order to avoid some troubles in constraints from the DM indirect detection as well as the recombination epoch, we forbid the dark Higgs (H) emission.

Benchmark points

- PAMELA

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}
$\psi_-\psi_+ \xrightarrow{48\%} Z'H$ $\psi_-\psi_- \xrightarrow{26\%} Z'Z'$ $\psi_+\psi_+ \xrightarrow{26\%} Z'Z'$	$\psi_-\psi_- \xrightarrow{100\%} Z'Z'$	$Z' \xrightarrow{50\%} \bar{u}u$ $Z' \xrightarrow{38\%} e^-e^+$ $Z' \xrightarrow{12\%} \bar{d}d$	$\psi_+ \xrightarrow{99\%} \psi_- e^- e^+$ $\psi_+ \xrightarrow{1\%} \psi_- \bar{u}u$	$H \xrightarrow{88\%} \bar{s}s$ $H \xrightarrow{10\%} \bar{d}d$ $H \xrightarrow{2\%} \bar{u}u$	

- BS

BM	m_-	$\delta \equiv m_- - m_-$	g_X	$m_{Z'}$	$\sin\varepsilon$	m_H	$\sin\theta$
DM (BS)	3.0 TeV	0.33 GeV	0.50	0.30 GeV	0	2.00 GeV	0

BM	m_-	$\delta \equiv m_- - m_-$	g_X	$m_{Z'}$	$\sin\varepsilon$	m_H	$\sin\theta$
DM (BS)	10.0 TeV	1.41 GeV	0.50	1.00 GeV	0	6.67 GeV	0