Landscape of EW scale dark sector

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“BSM in Particle Physics and Cosmology: 50 Years Later”

Main themes and Key Words:

- Role of dark Higgs boson
- Unitarity, SM + Dark Gauge Invariance
- Stueckelberg vs. (Dark) Higgs for the case of massive dark photon

Contents

- DM Overview
- Particle physics approach based on Quantum Field Theory : global vs. local gauge symmetry for DM stability or longevity
- Key issues: unitarity and renormalizability, gauge invariance (both SM and dark (gauge) symmetries)
- Role of Dark Higgs boson in Particle physics + Cosmology (DR, Higgs Inflation, H_0 , σ_8 , etc.)
- Based on series of works with Seungwon Baek, Wanil Park, Myeonghun Park, Hyun Min Lee, Taeil Hur, Soomin Choi, Alexander Natale, Eibun Senaha, Dongwon Jung, Jinmian Li, Jongkuk Kim, Shu-Yu Ho, Hiroshi Yokoya, Yong Tang, Shu-Yu Ho, Chih-Ting Lu, etc.

SM for particle physics

$$\mathcal{L}_{MSM} = -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu}$$
$$-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R$$
$$+|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i$$
$$+\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2$$
$$-\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right). (1)$$

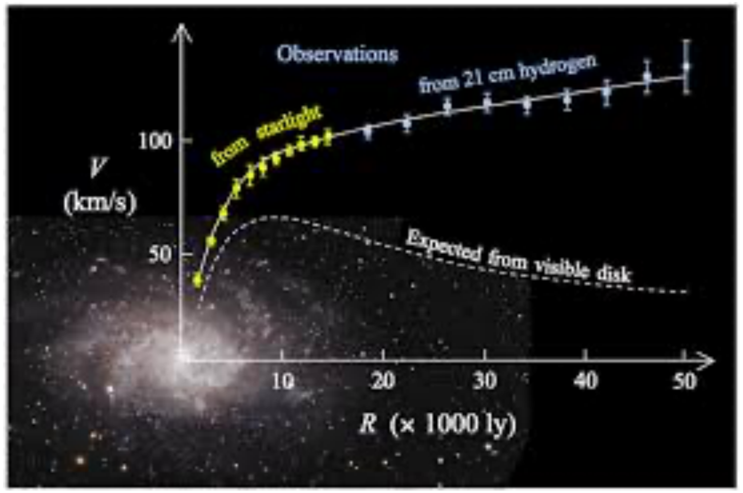
Renormalizable part

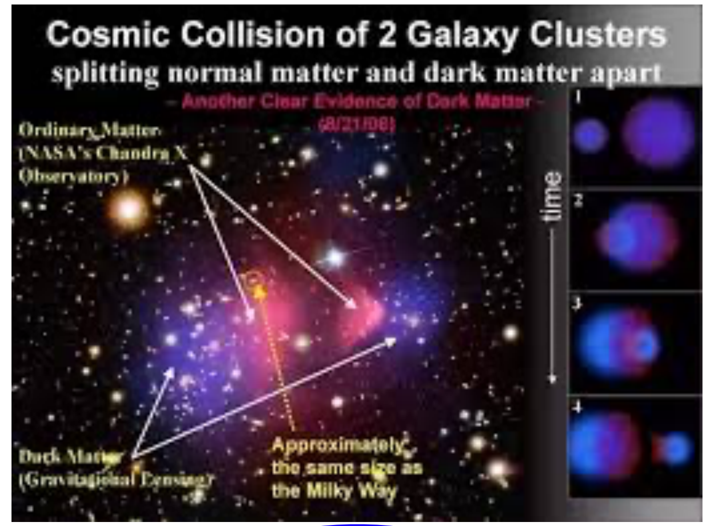
+ ∞ # of higher dim (nonrenormalizable) operators
(why neutrinos are light, proton lives very long)

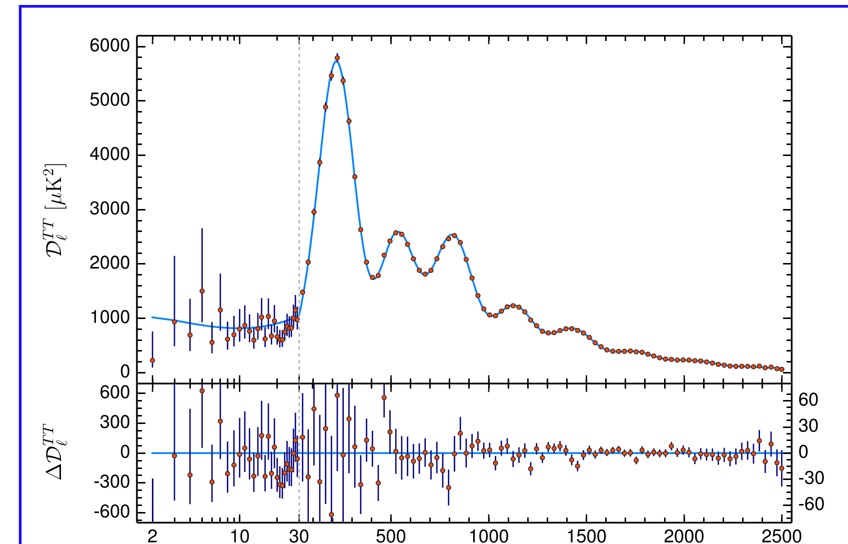
QFT + conservation laws (symmetries):

- $E, \vec{p}, \vec{J}$ + Special Relativity : Poincare sym
- Exact charge conservation : local gauge sym
- No global symmetries imposed : accidental

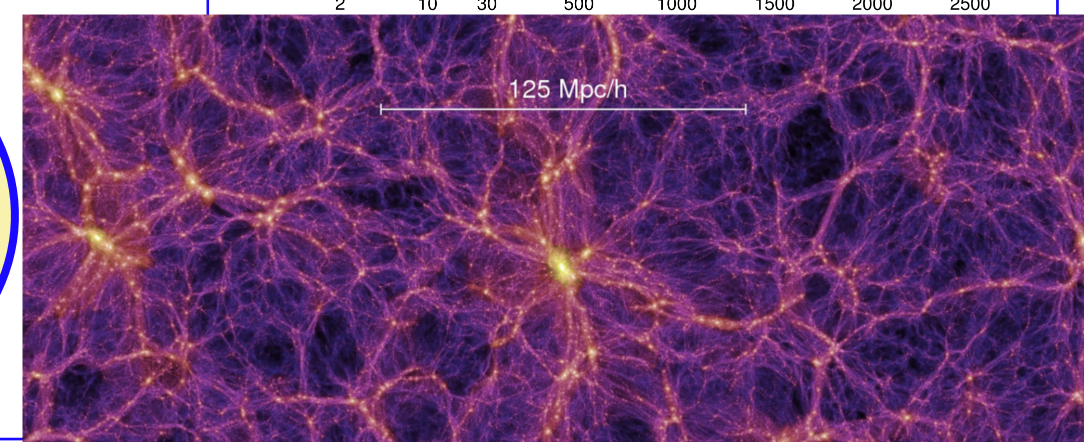
Evidences for DM

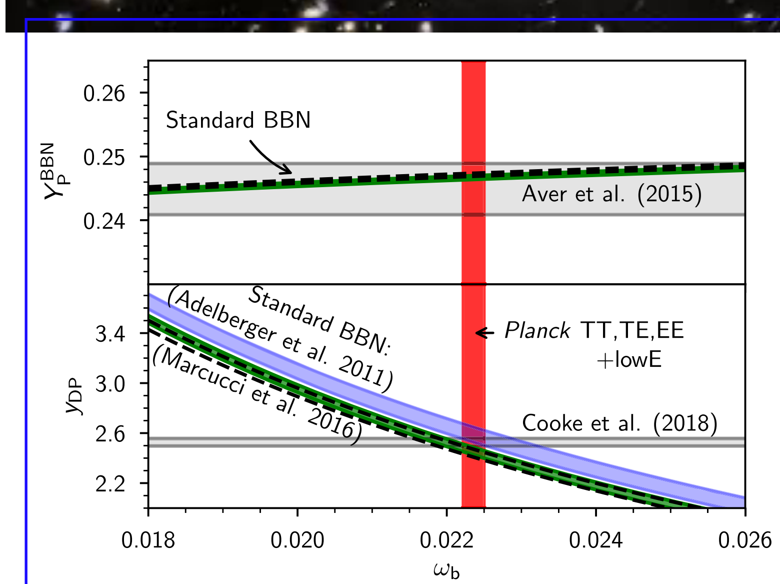


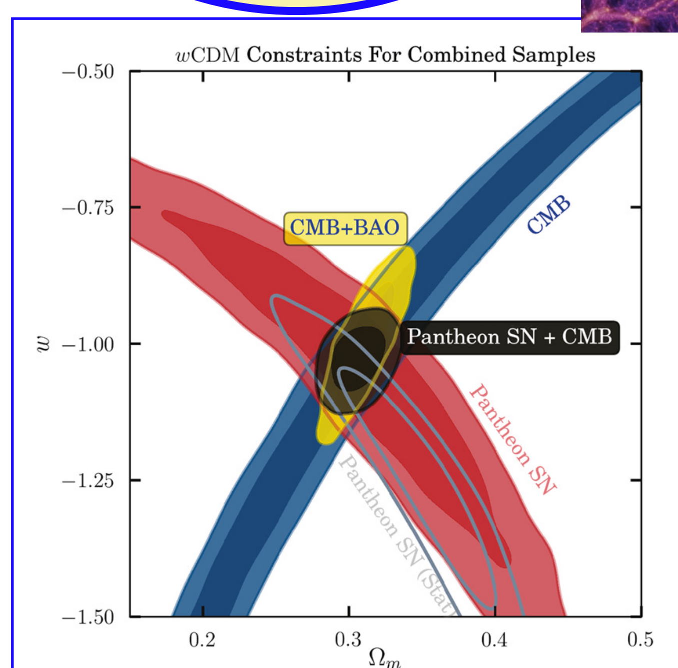


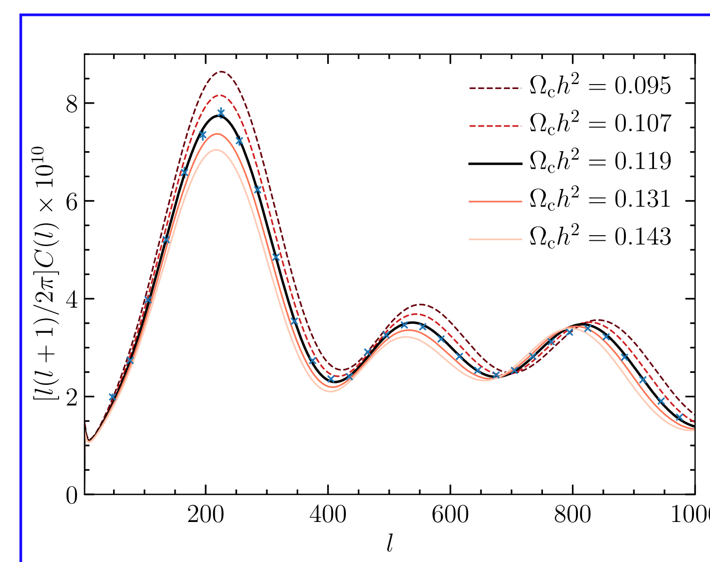


GRAVITY

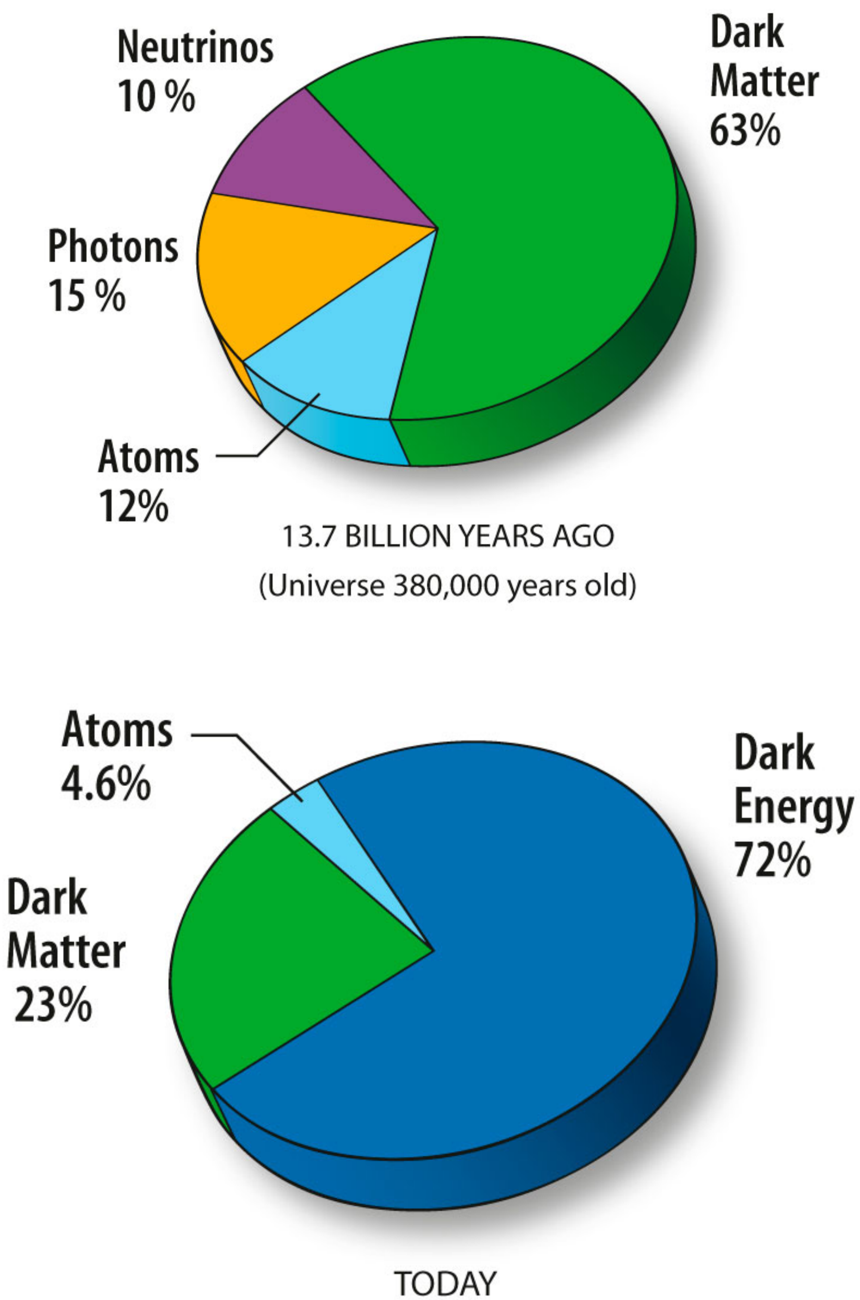


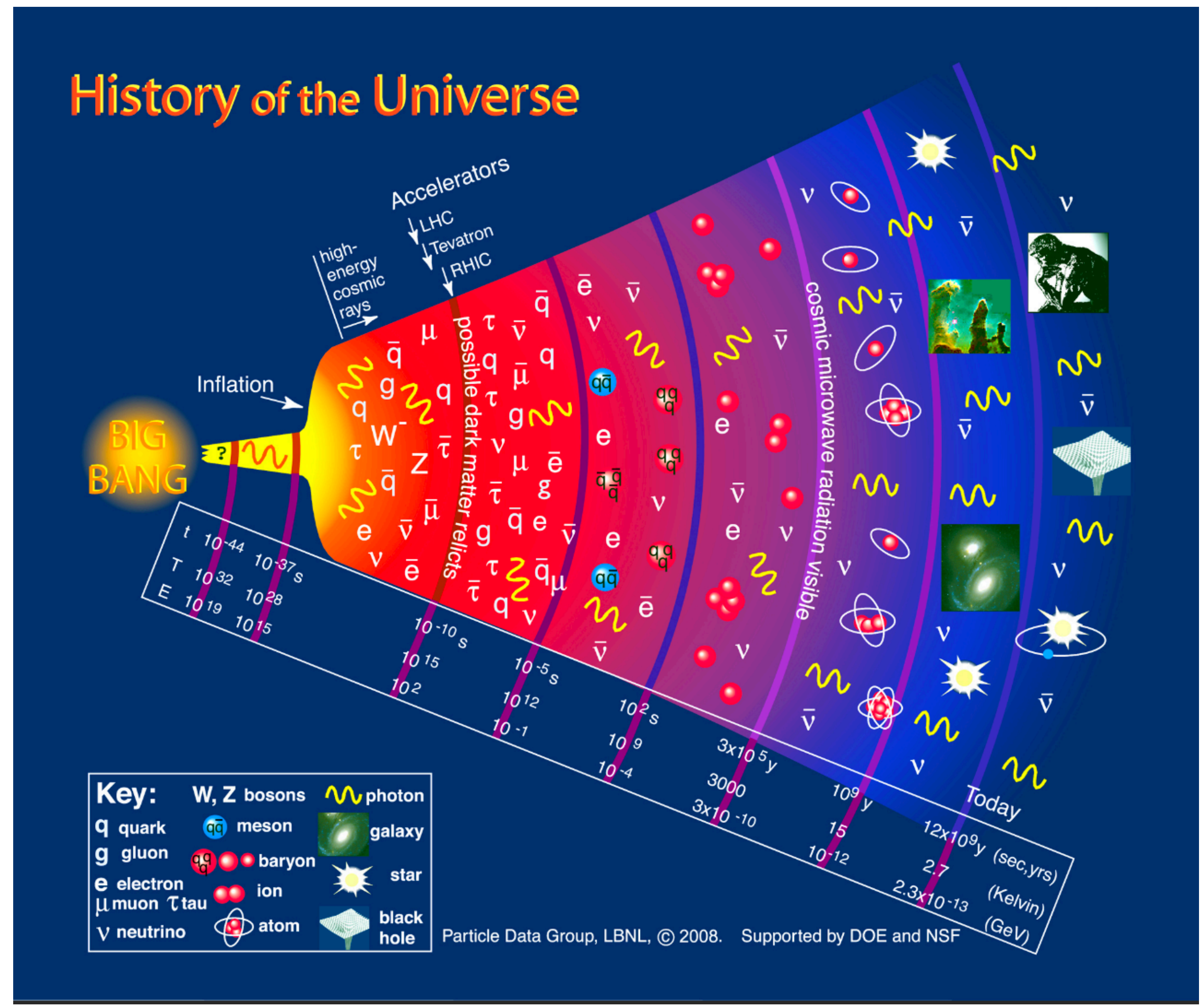






Cos. Concordance Model





KNOWNS

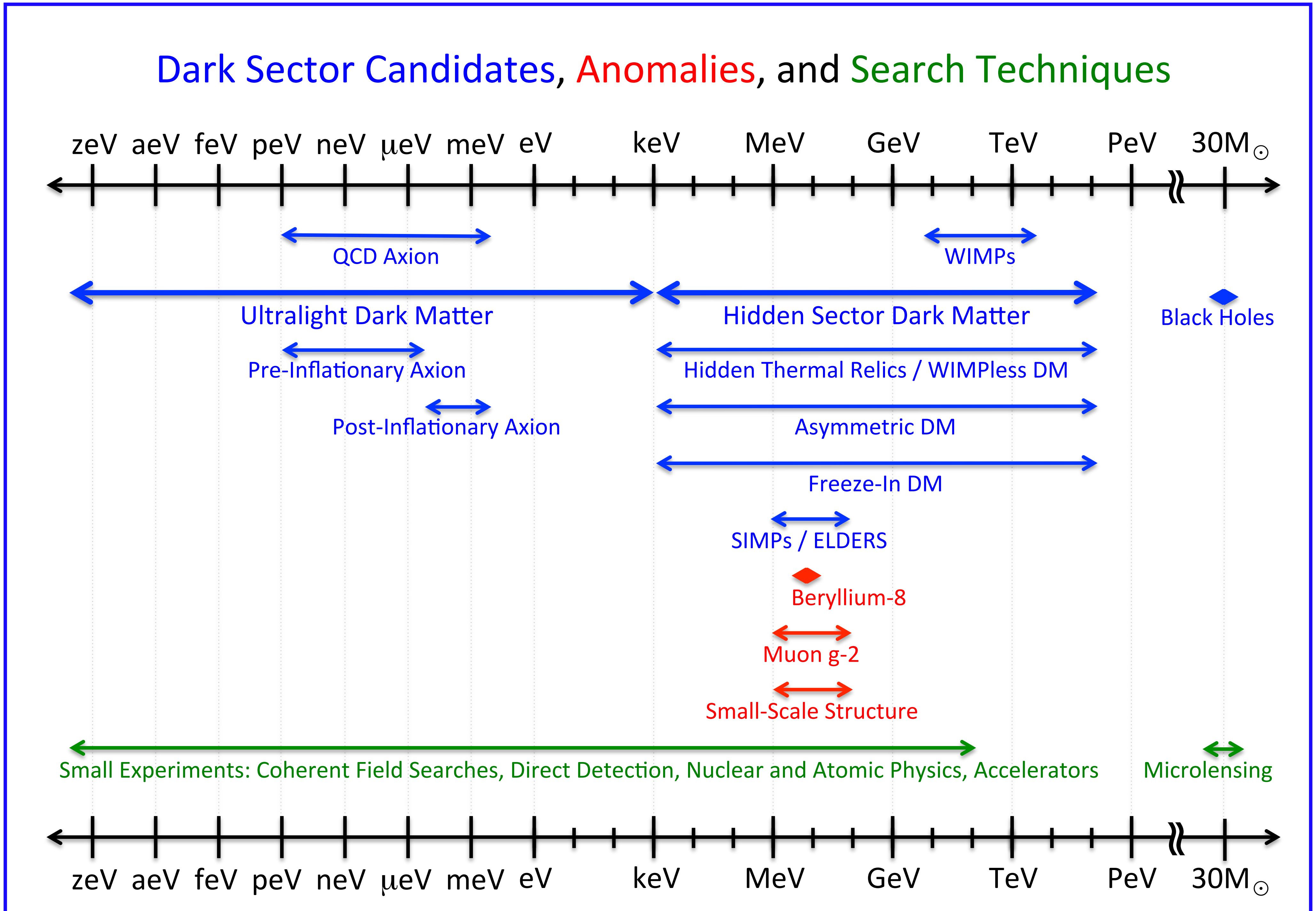
- Feels Gravity > Currently evidences come only thru this
- Its lifetime >> Age of Universe
- $\rho(\simeq m) \gg \ p(\simeq 0)$ (Nonrel.)
- $\Omega_{\rm DM} \sim 5\ \Omega_{\rm Baryon}$
- $\rho_{\rm local} \sim 0.3 {\rm GeV/cm}^3$
- It forms a halo, not a disk

UNKNOWNS

- Mass, Spin ?
- How many species ?
- Any internal quantum #'s ?
- Any internal structures ?
- Interactions w/ SM particles ?
- DM self int. ? ($\sigma_{\chi\chi}/m_\chi \lesssim 1 g/cm^2$)
- Almost nothing known about particle physics nature of DM

Domestic Activities (Th)

[US Cosmic Visions:…., arXiv:1707.04591]



Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
  (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in "local gauge symmetry" without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- "(Chiral) dark gauge theories without any global sym"
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT (I)

- Kinematically long-lived if DM is very light (axion, sterile ν_s ,...) : not considered here
- DM could be absolutely stable due to unbroken local gauge symmetry
  - DM with local Z2 (inelastic), Z3 (semi-annihilation)
  - $SU(3)_D \to SU(2)_D$ (and 2 more works) for H_0, σ_8 (2016)

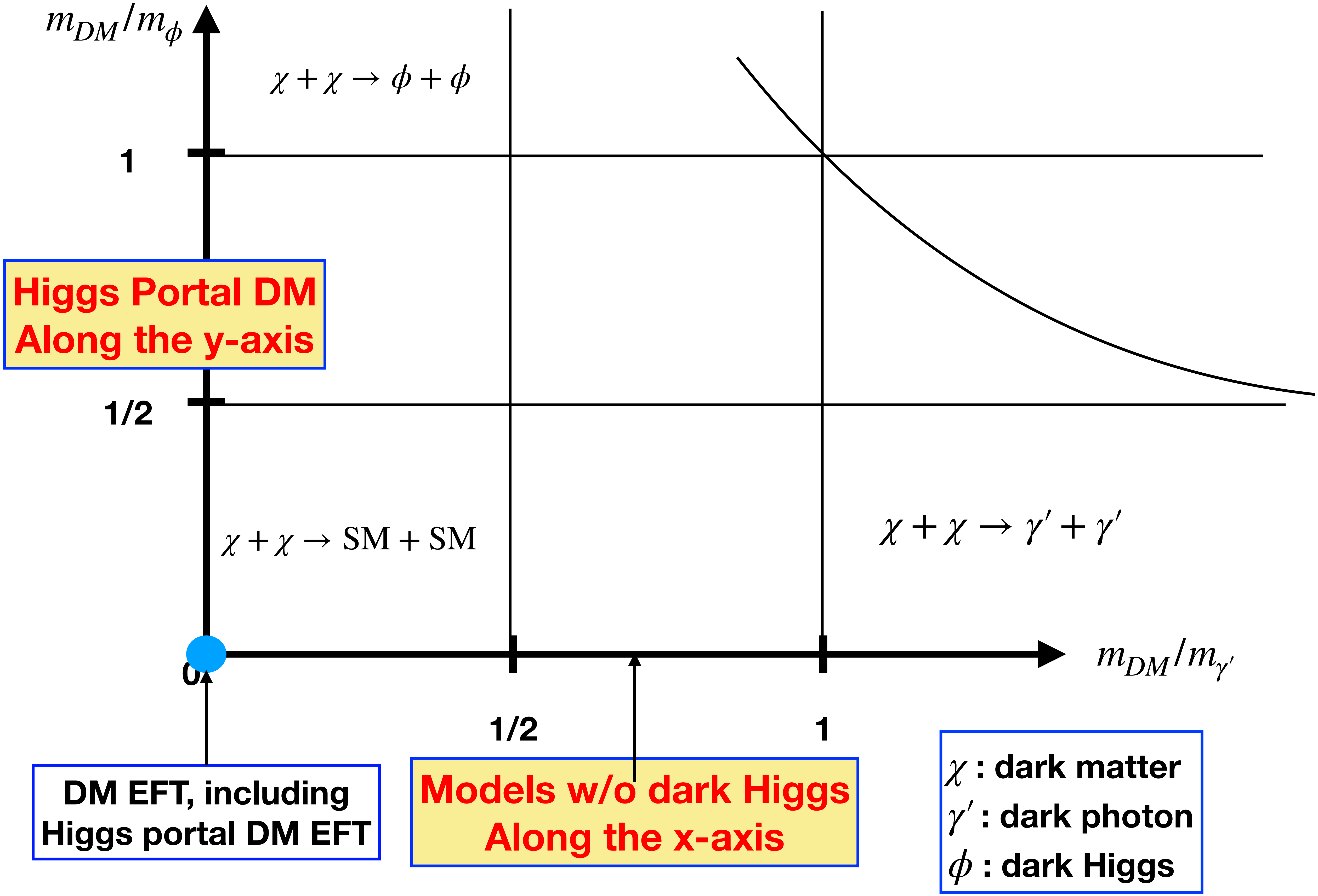
In QFT (II)

- Longevity of DM could be due to some accidental symmetries of unbroken/broken dark gauge symmetries
  - EWSB and CDM from hQCD, and scale invariant extensions : dark pions and dark baryons : Hur, Ko et al (2007)
  - Dark gauge sym completely broken

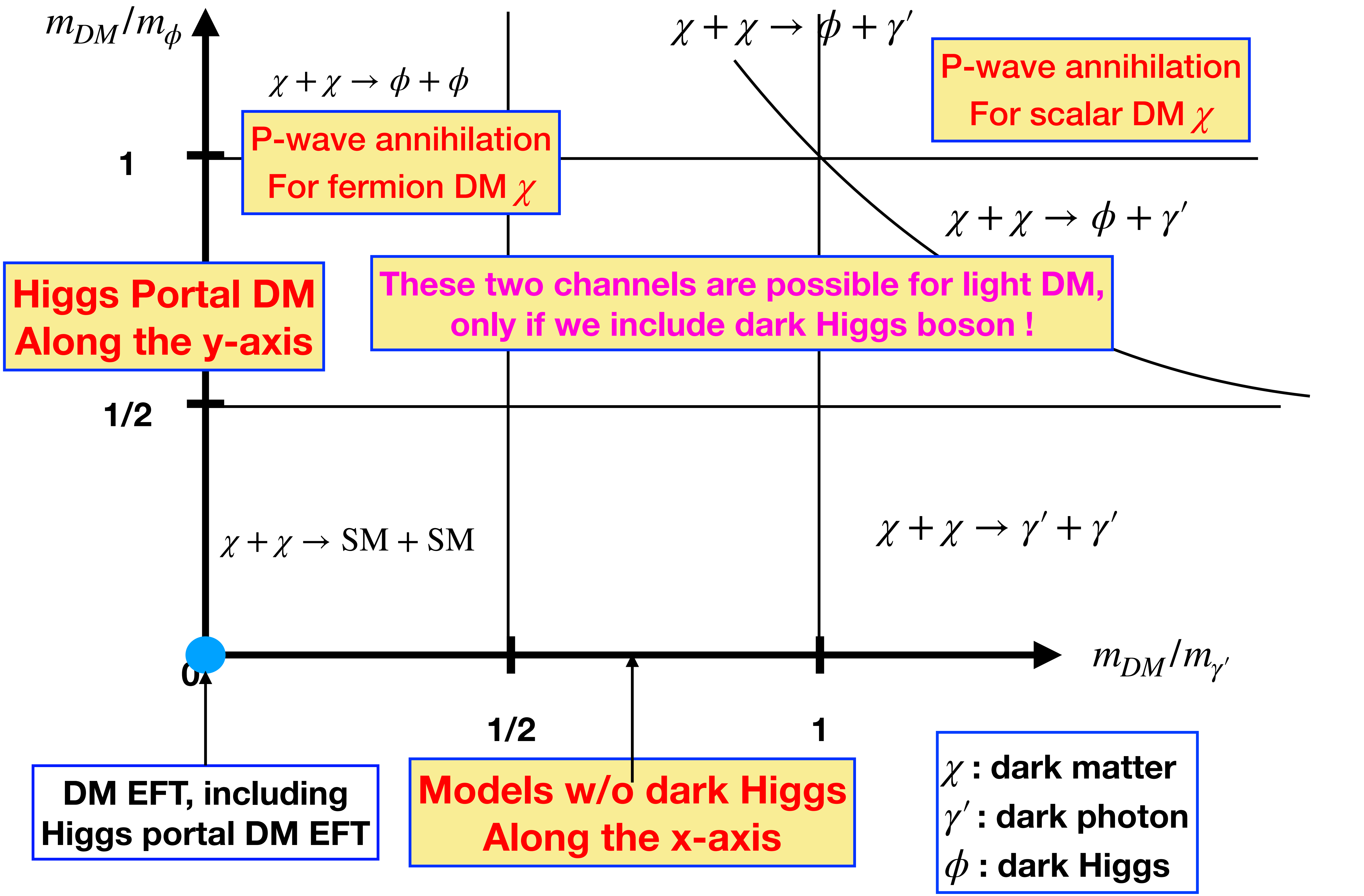
Landscape of dark sector

- DM EFT : DM + SM (unitarity violation in most cases)
- (Improved) Simplified Model for DM : DM + SM + Mediators (without full SM gauge symmetry) Full SM gauge symmetry was imposed by P Ko, A Natale, MH Park, H Yokoya (2016)
- DM stabilized by global symmetry can not protect DM to decay fast from dim-5 operators from gravity : Need to introduce dark gauge symmetry [S Baek, P Ko, WI Park (2013)] : Now called as a "dark sector"
- (Excited) DM, DR, (Light) Mediators with dark gauge symmetry
- Only questions: mass scales and couplings (various mechanisms)

Dark sector parameter space for a fixed m_{DM}



Dark sector parameter space for a fixed m_{DM}



Portals to DM

- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector portal : $\epsilon B_{\mu\nu}X^{\mu\nu}$
- Neutrino portal : $\overline{N_R}(\widetilde{H}l_L + \phi^\dagger\psi)$
- (Dark) Axion portal (HSLee et al)
- So on & on & on …
- <u>Eventually “Portal” is what we observe in the experiments</u>

ϕ : Dark Scalars

X_μ : Dark photon

ψ : Dark fermion ~ Sterile ν

Portals to DM

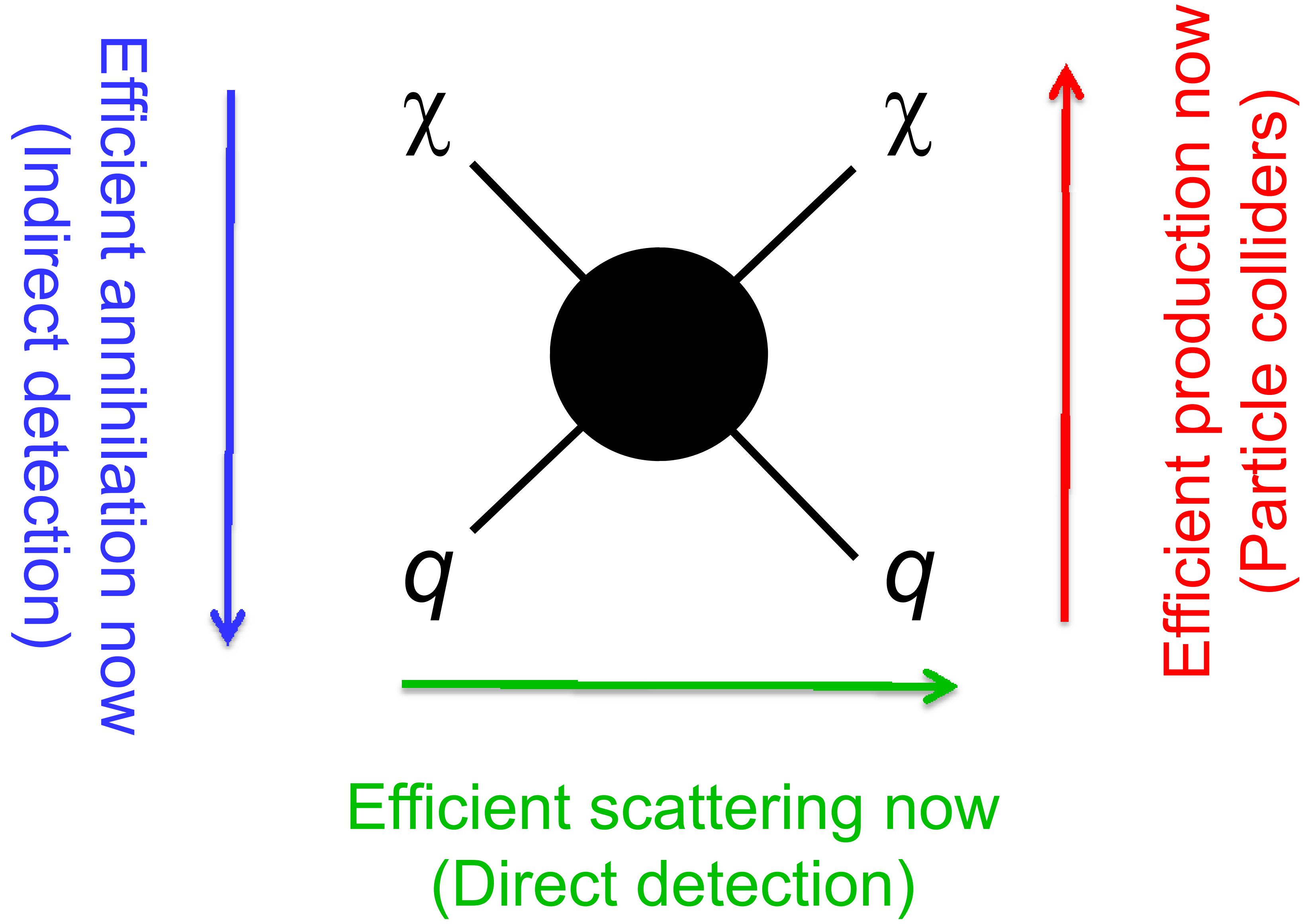
- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector porta
- Neutrino portal : $\overline{N_R}(\widetilde{H} l_L +$
- (Dark) Axion portal (HSLee
- So on, & on & on , …
- Eventually "Portal" is what we observe in experiments

Singlet Portals to Dark sector w/ local dark gauge sym
(Baek, Park, Ko, arXiv:1303.4280 [hep-ph])

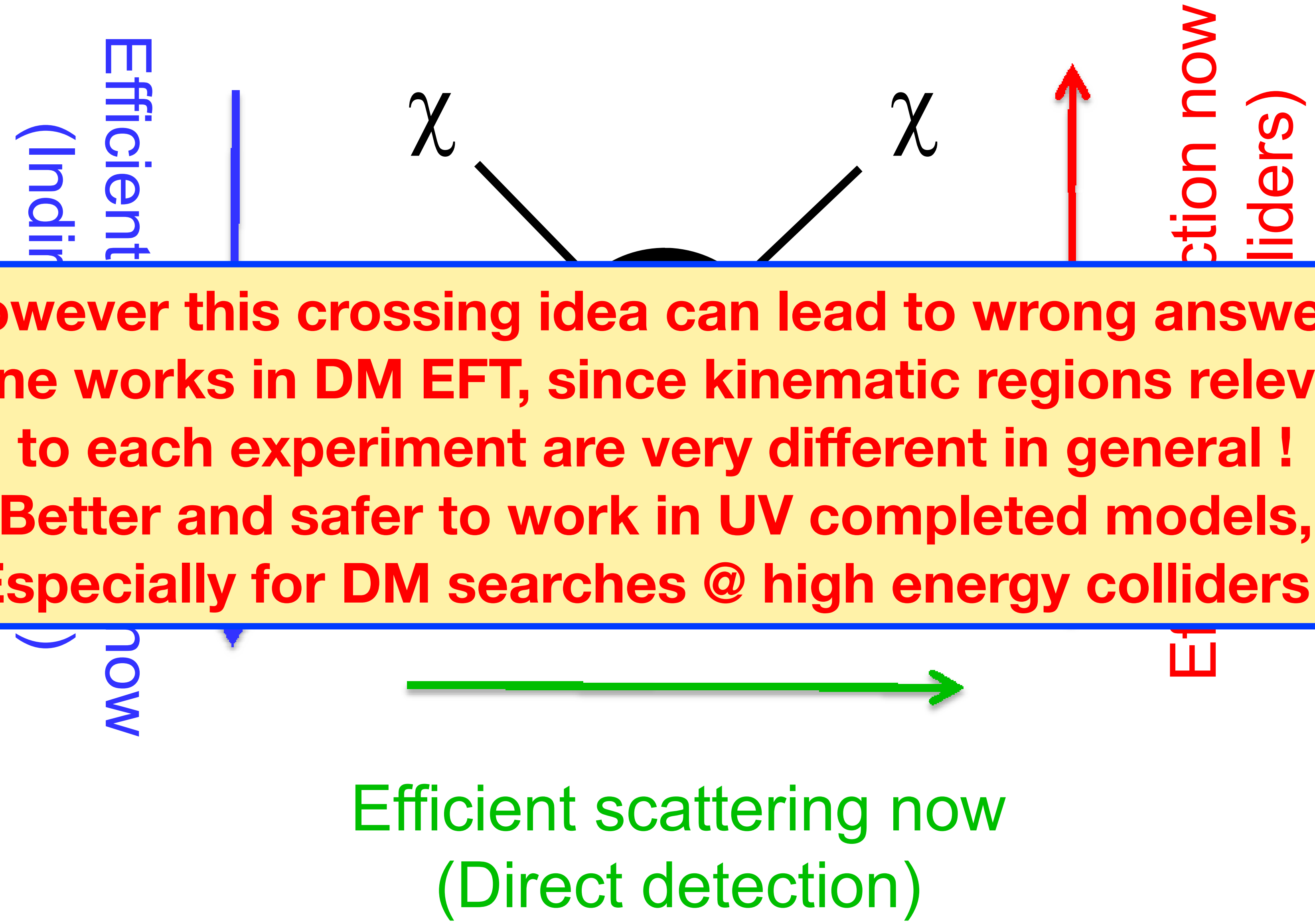
DM stability is guaranteed by
Local gauge symmetry
OR
DM longevity is guaranteed by
accidental global symmetries

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Furthermore one can consider on-shell mediators, dark radiation and inelastic DM, etc..



However this crossing idea can lead to wrong answers if one works in DM EFT, since kinematic regions relevant to each experiment are very different in general !
Better and safer to work in UV completed models, Especially for DM searches @ high energy colliders !

Dark Gauge Symmetry for
DM Stability/Longevity

Z2 real scalar DM

- Simplest DM model with Z2 symmetry : $S \to -S$

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\lambda_{SH}}{2}S^2 H^\dagger H.$$

- Global Z2 could be broken by gravity effects (higher dim operators)

- e.g. consider Z2 breaking dim-5 op : $\frac{1}{M_{\rm Planck}} S O_{\rm SM}^{(4)}$

- Lifetime of EW scale mass “S” is too short to be a DM

- Similarly for singlet fermion DM

Fate of CDM with Z2 sym

(Baek,Ko,Park,arXiv:1303.4280)

Consider Z_2 breaking operators such as

keeping dim-4 SM operators only

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

3 3

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S}{M_{\rm Planck}^2} \sim (\frac{m_S}{100 {\rm GeV}}) 10^{-37} GeV$$

- Global Z2 cannot save EW scale DM from decay with long enough lifetime

The lifetime is too short for ~100 GeV DM

NB: light axion or sterile neutrinos are fine for their long enough lifetime

Fate of CDM with Z2 sym

Spontaneously broken local U(1)x can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$$\phi_X^\dagger X H^\dagger H, \quad \text{and} \quad \phi_X^\dagger X O_{\rm SM}^{(dim-4)}$$

Problematic ! | Perfectly fine !

Higgs is not good for DM stability/longevity

Have to choose dark Higgs charge judiciously
Unless you can be patient with excessive fine tuning

- These arguments will apply to DM models based on ad hoc symmetries (Z_2,Z_3 etc.)

- One way out is to implement Z_2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);

- See a paper by Ko and Tang on local Z_3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local $U(1)_H$

- DM phenomenology richer and DM stability/ longevity on more solid ground

$Q_X(\phi) = 2, \quad Q_X(X) = 1$

arXiv:1407.6588 w/ WIPark and SBaek

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu}B^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger\phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2\phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

Gauge models for excited DM

$$X_R \to X_I\gamma_h^* \text{ followed by } \gamma_h^* \to \gamma \to e^+e^- \quad \text{etc.}$$

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Inelastic DM and XENON1T Excess

We consider Both Scalar and Fermion IDM

arXiv:2006.16876, PLB 810 (2020) 135848
With Seungwon Baek, Jongkuk Kim

Although XENON1T excess has gone, our study still leaves an important lesson for light DM scenarios

Usual Approaches

For example, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \Delta^2\left(\phi^2 + \phi^{*2}\right), \qquad (1)$$

$$\mathcal{L} = g_D A'^{\mu}\left(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1\right) + \epsilon e A'_\mu J^\mu_{\rm EM},$$

Dark photon mass by hand

Similarly for the fermion DM case

$\Delta\ \overline{\psi^C}\psi$: **breaks U(1) explicitly**

Without dark Higgs

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A

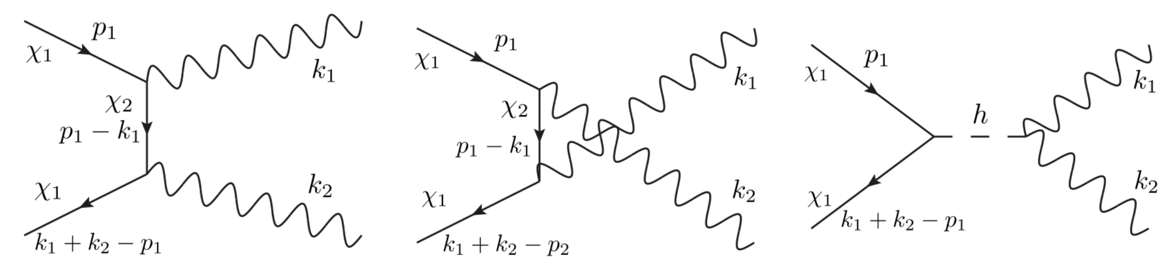


Figure 9: $\chi_1\chi_1 \to \gamma'\gamma'$ diagrams. Compared with the Higgsless soft-breaking model, the third diagram arises in our model

- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$

Z_2 DM models with dark Higgs

- We solve this inconsistency and unitarity issue with Krauss-Wilczek mechanism
- By introducing a dark Higgs, we have many advantages:
  - Dark photon gets massive
  - Mass gap δ is generated by dark Higgs mechanism
  - We can have DM pair annihilation in P-wave involving dark Higgs in the final states, unlike in other works

Relic Density from

$$XX^\dagger \to Z'^* \to f\bar{f}$$

(P-wave annihilation)

For example, arXiv:2006.11938

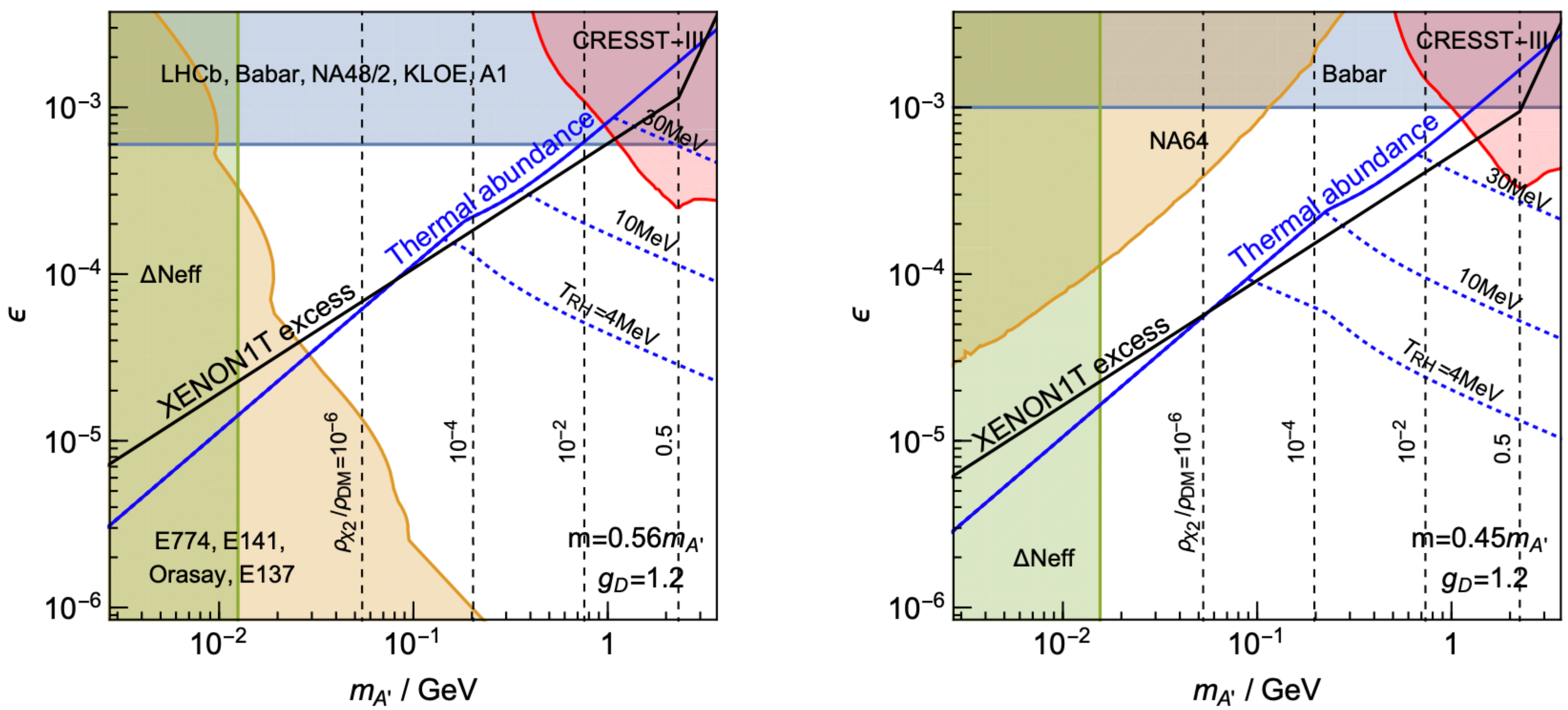


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote the required value of ϵ to obtain the observed DM abundance by the thermal freeze-out process, discussed in Sec. IV. The solid lines correspond to the case without any entropy production. The dashed lines assume freeze-out during a matter dominated era and the subsequent reheating at $T_{\rm RH}$, which suppresses the DM abundance by a factor of $(T_{\rm RH}/T_{\rm FO})^3$. The black dashed lines denote the mass density of χ_2 normalized by the total DM density. The shaded regions show the constraints from dark radiation and various searches for the dark photon A' which are discussed in Sec. V.

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

$$\begin{aligned}\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D^{\mu}\phi^{\dagger}D_{\mu}\phi + D^{\mu}X^{\dagger}D_{\mu}X - m_X^2 X^{\dagger}X + m_{\phi}^2\phi^{\dagger}\phi \\ & -\lambda_{\phi}\left(\phi^{\dagger}\phi\right)^2 - \lambda_X\left(X^{\dagger}X\right)^2 - \lambda_{\phi X}X^{\dagger}X\phi^{\dagger}\phi - \lambda_{\phi H}\phi^{\dagger}\phi H^{\dagger}H - \lambda_{HX}X^{\dagger}XH^{\dagger}H \\ & -\mu\left(X^2\phi^{\dagger} + H.c.\right), \end{aligned} \tag{1}$$

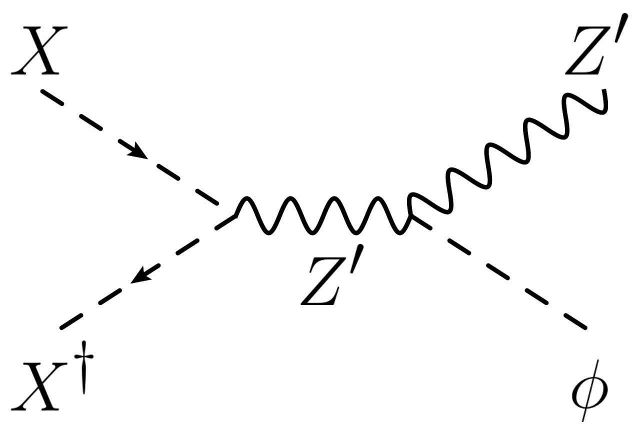
$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + h_\phi),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^\mu (X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \frac{g_Z}{2}Z_\mu \overline{\nu}_L\gamma^\mu\nu_L.$$

$$\mathcal{L} \supset g_X Z'^\mu (X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \epsilon\, e c_W Z'_\mu \overline{e}\gamma^\mu e,$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : X \to -X$



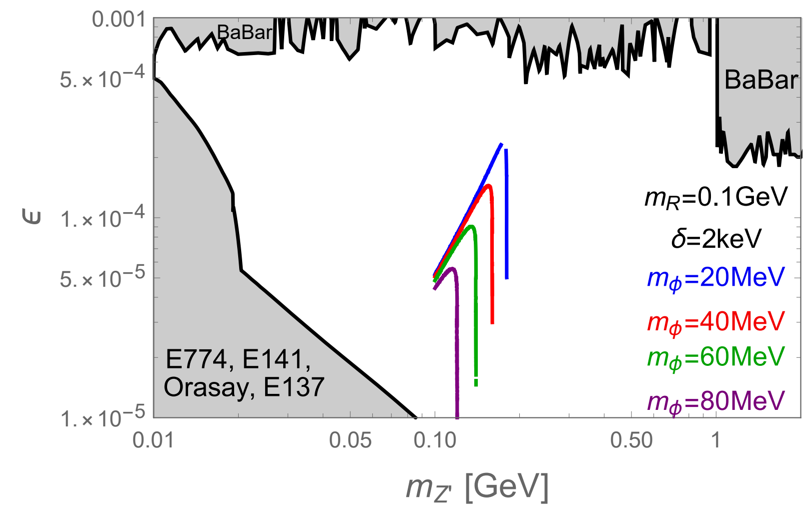


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \to X_R X_I$ is kinematically forbidden.

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4), \qquad (10)$$

Fermion XDM (χ_R & χ_I)

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi$$
$$- \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I),$$
$$\chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I),$$
$$\chi_R^c = \chi_R, \quad \chi_I^c = \chi_I,$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right)$$
$$- \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : \chi \to -\chi$

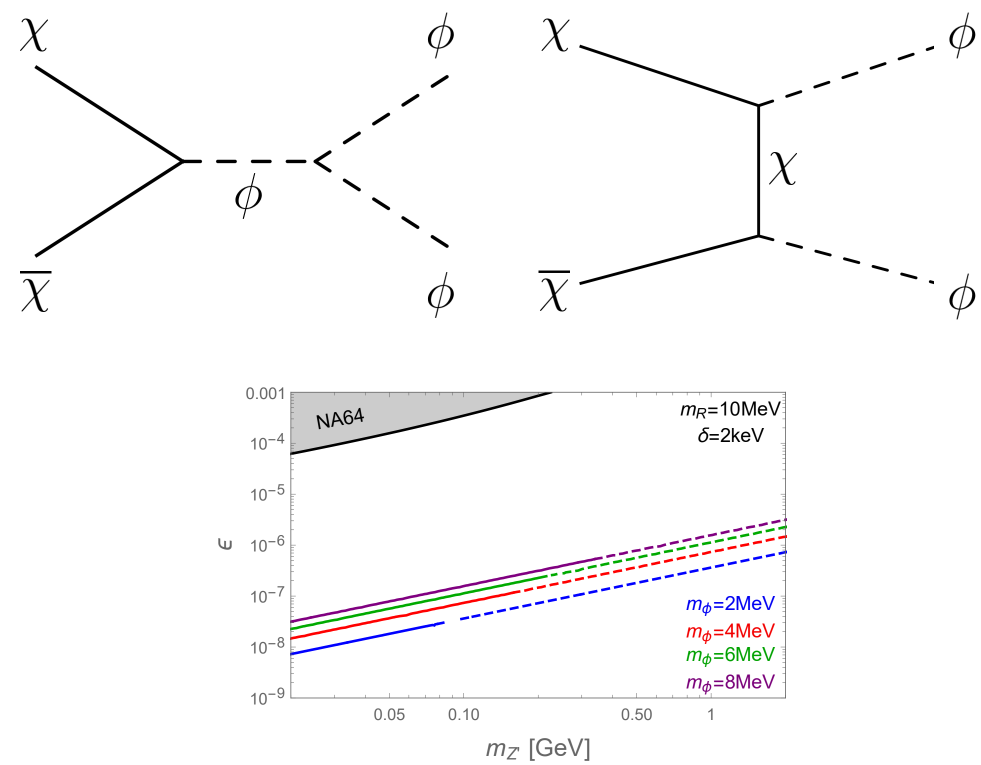


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \to \chi_R \chi_I$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16 m_X^4 + m_{Z'}^4 + m_\phi^4 + 40 m_X^2 m_{Z'}^2 - 8 m_X^2 m_\phi^2 - 2 m_{Z'}^2 m_\phi^2\right) \times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\}\left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\}\right]^{1/2} + \mathcal{O}(v^4), \tag{10}$$

Fermion DM : $\chi\bar{\chi} \to \phi\phi$

$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi} \left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4}\right] + \mathcal{O}(v^4), \tag{28}$$

Crucial to include "dark Higgs" to have DM pair annihilation in P-wave

Higgs Portal DM : EFT vs. UV completions

UNITARITY !

Higgs portal DM models

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H\ \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

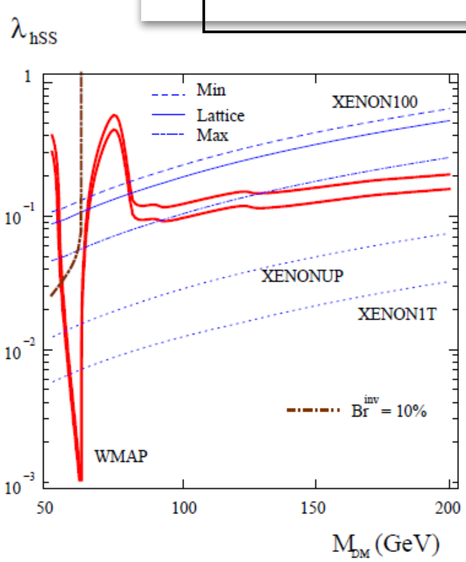


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

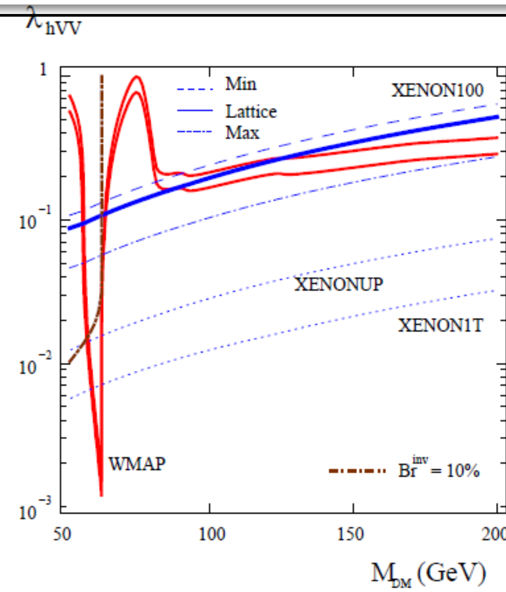


FIG. 2. Same as Fig. 1 for vector DM particles.

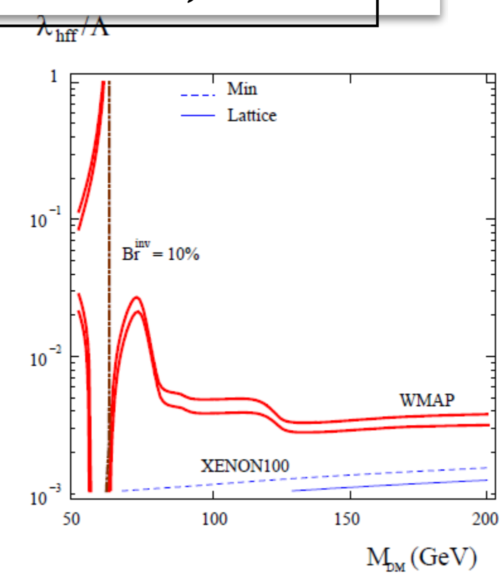


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi \right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc. | And Revived recent papers

We need to include dark Higgs or singlet scalar to get renormalizable/unitary models for Higgs portal singlet fermion or vector DM

[NB: UV Completions : Not unique]

$m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

FIG. 2. Same as Fig. 1 for vector DM particles.

FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV

Models for HP SFDM & VDM

UV Completion of HP Singlet Fermion DM (SFDM)

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
& + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
& + \overline{\psi}(i \not{\partial} - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

UV Completion of HP VDM

$$
\begin{aligned}
\mathcal{L}_{VDM} = & -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 \\
& - \lambda_{H\Phi} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) ,
\end{aligned}
$$

- **The simplest UV completions in terms of # of new d.o.f.**
- **At least, 2 more parameters, (m_ϕ , $\sin\alpha$) for DM physics**

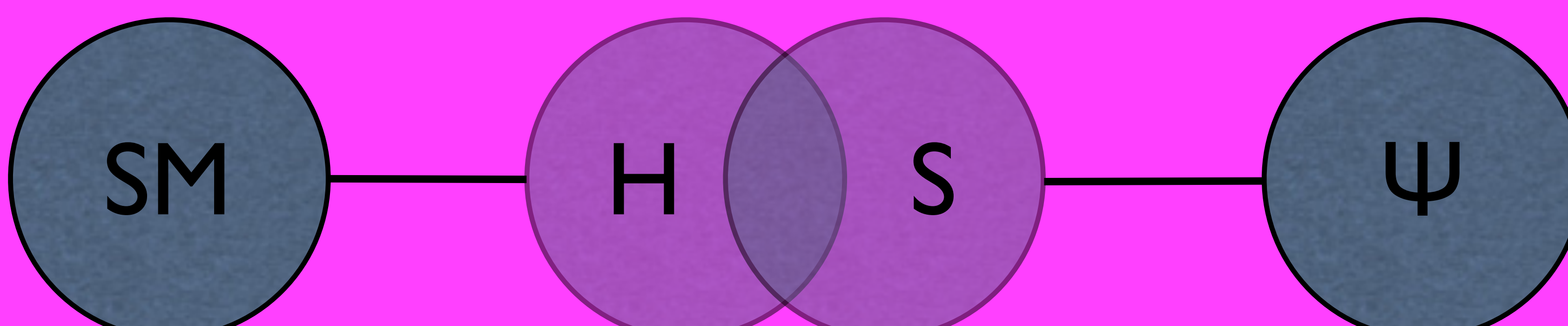
UV Completion for HP FDM

Baek, Ko, Park, arXiv:1112.1847

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
& + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
& + \overline{\psi}(i \not{\partial} - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

Higgs-Singlet Mixing

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$

$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu_S' v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2 v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M_{\text{Higgs}}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$

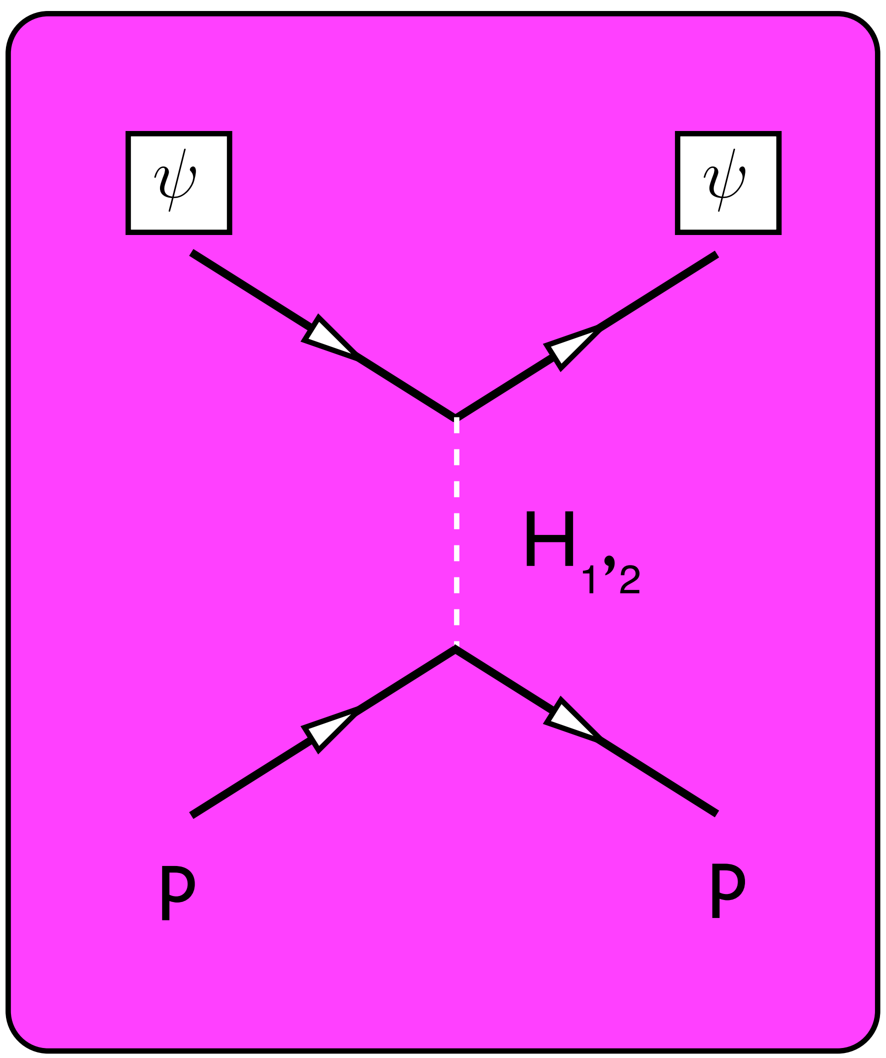
$$H_2 = h\sin\alpha + s\cos\alpha.$$

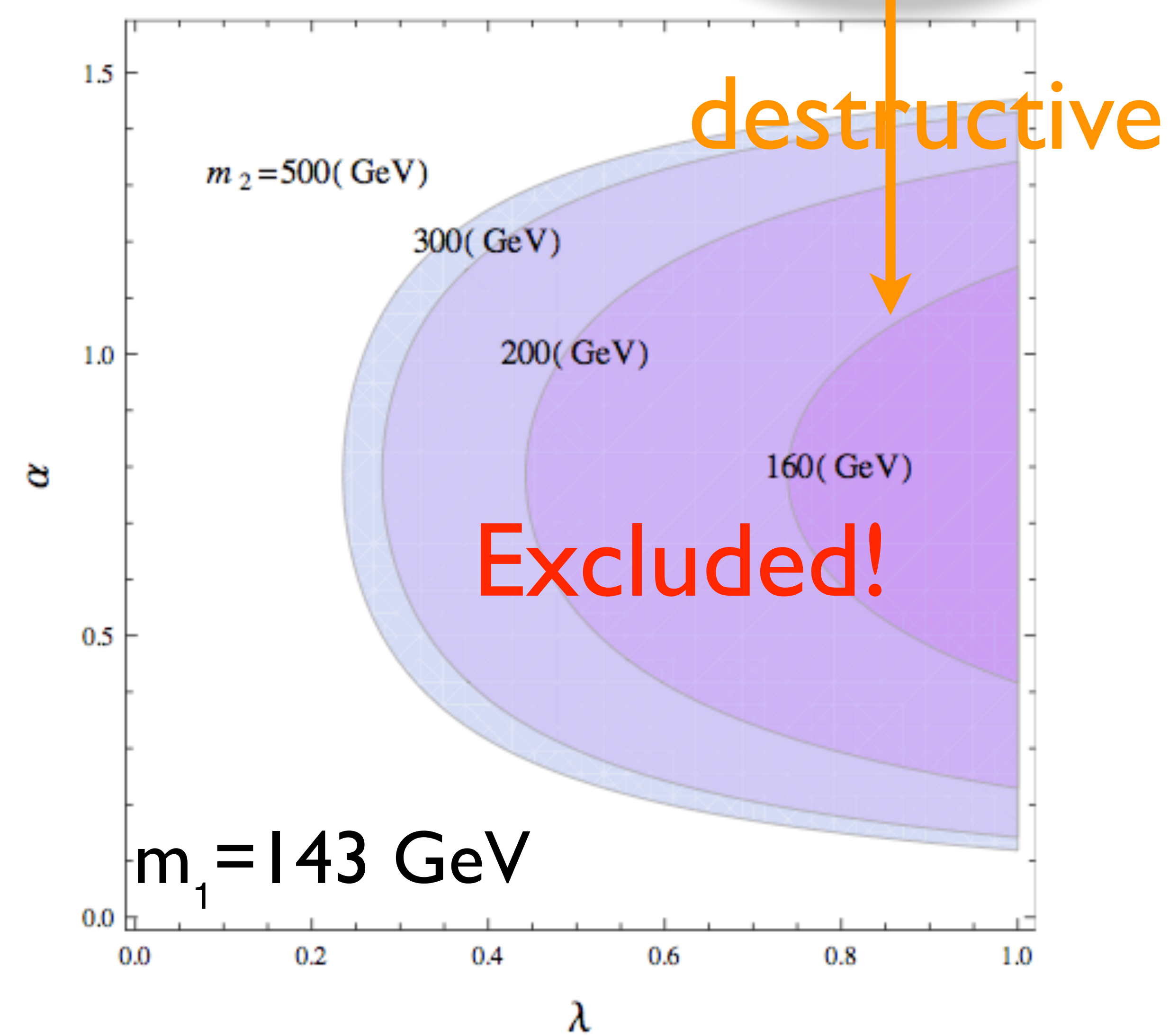
Mixing of Higgs and singlet

Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda \sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





Low energy pheno.

- Universal suppression of collider SM signals

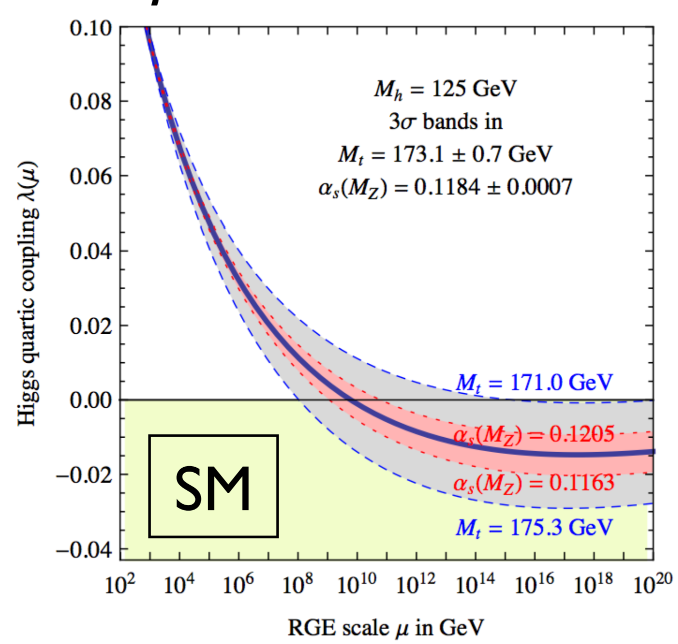
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

- Tree-level shift of $\boldsymbol{\lambda}_{H,SM}$ (& loop correction)

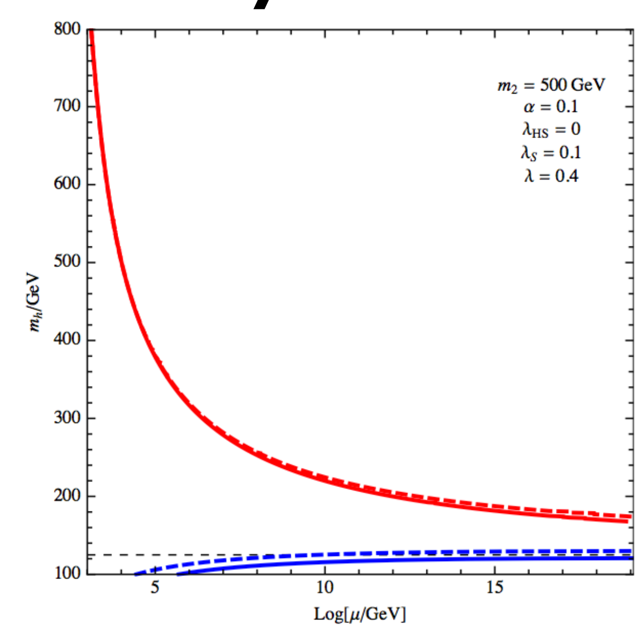
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]

α



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

UV Completion of HP VDM

[S Baek, P Ko, WI Park, E Senaha, arXiv:1212.2131 (JHEP)]

$$\mathcal{L}_{VDM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{H\Phi} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) ,$$

$X_\mu \equiv V_\mu$ here

$$\Phi(x) = (v_\phi + \phi(x))/\sqrt{2}$$

- There appear a new singlet scalar (dark Higgs) $\phi(x)$ from $\Phi(x)$, which mixes with the SM Higgs boson through Higgs portal interaction ($\lambda_{H\Phi}$ term)
- The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge symmetry
- Can accommodate GeV scale gamma ray excess from GC with $VV \to \phi\phi$
- **Can modify the Higgs inflation : No tight correlation with top mass**

Interaction Lagrangians

Scalar DM

$$\mathcal{L}_{\rm SDM}^{\rm int} = -h\left(\frac{2m_W^2}{v_h}W_\mu^+W^{-\mu} + \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) - \lambda_{HS}v_h\; hS^2.$$

Singlet FDM

$$\mathcal{L}_{\rm FDM}^{\rm int} = -\left(H_1\cos\alpha + H_2\sin\alpha\right)\left(\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W_\mu^+W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) + g_\chi\left(H_1\sin\alpha - H_2\cos\alpha\right)\;\bar{\chi}\chi\;.$$

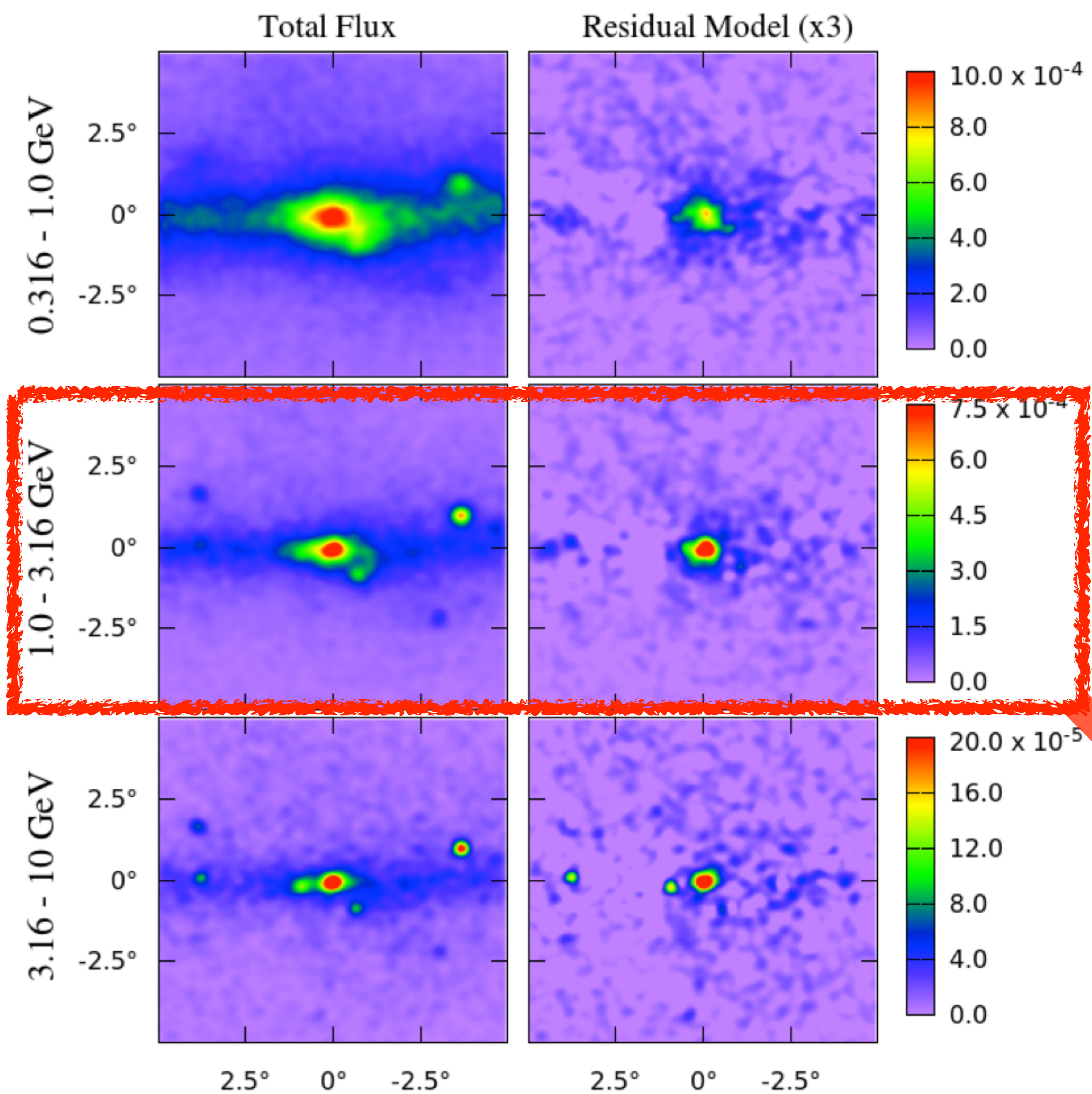
Vector DM

$$\mathcal{L}_{\rm VDM}^{\rm int} = -\left(H_1\cos\alpha + H_2\sin\alpha\right)\left(\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W_\mu^+W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) - \frac{1}{2}g_V m_V\left(H_1\sin\alpha - H_2\cos\alpha\right)\;V_\mu V^\mu\;.$$

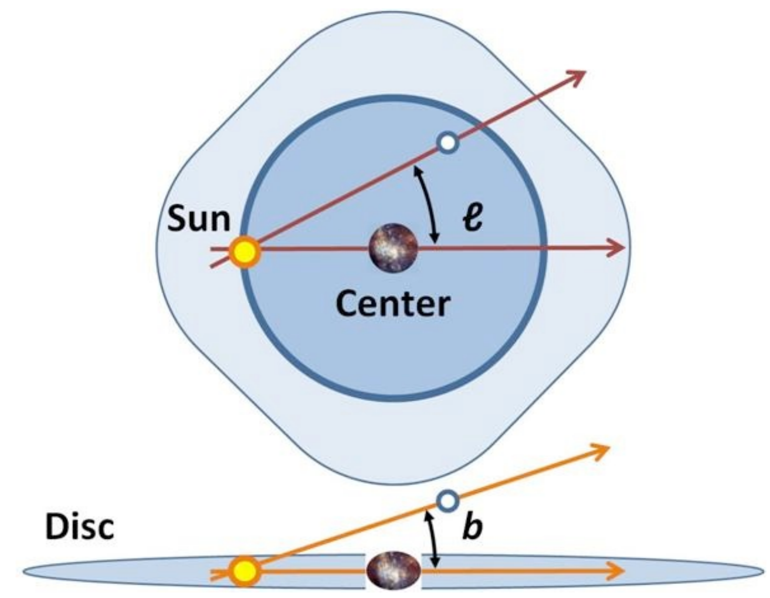
NB: One can not simply ignore 125 GeV Higgs Boson or singlet scalar by hand, since it would violate gauge invariance and unitarity !

Fermi-LAT GC γ-ray

see arXiv:1612.05687 for a recent overview by C.Karwin, S. Murgia, T. Tait, T.A.Porter, P. Tanedo



[1402.6703, T. Daylan et.al.]

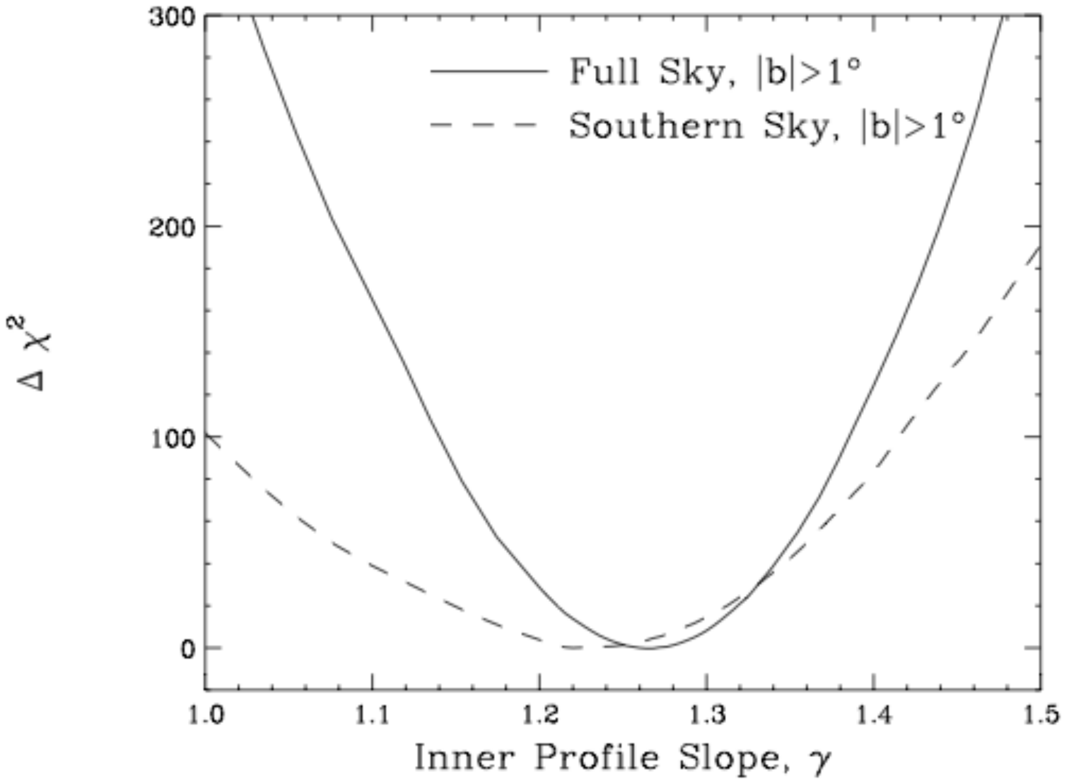


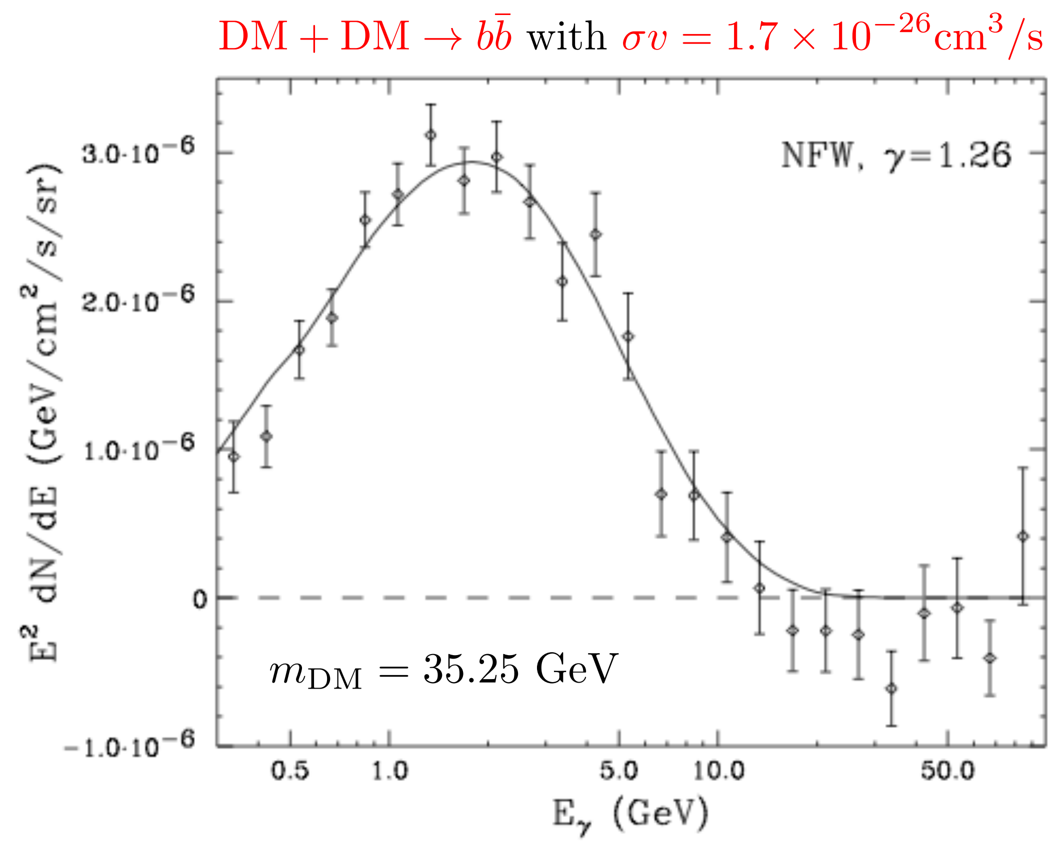
$$\mathrm{GC}: b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

- A DM interpretation





* See "1402.6703, T. Daylan et.al." for other possible channels

- Millisecond Pulars (astrophysical alternative)

It may or may not be the main source, depending on

- luminosity func.
- bulge population
- distribution of bulge population

* See "1404.2318, Q. Yuan & B. Zhang" and "1407.5625, I. Cholis, D. Hooper & T. Linden"

GC gamma ray in HP VDM

P. Ko, WI Park, Y. Tang. arXiv:1404.5257, JCAP

H2 : 125 GeV Higgs
H1 : absent in EFT

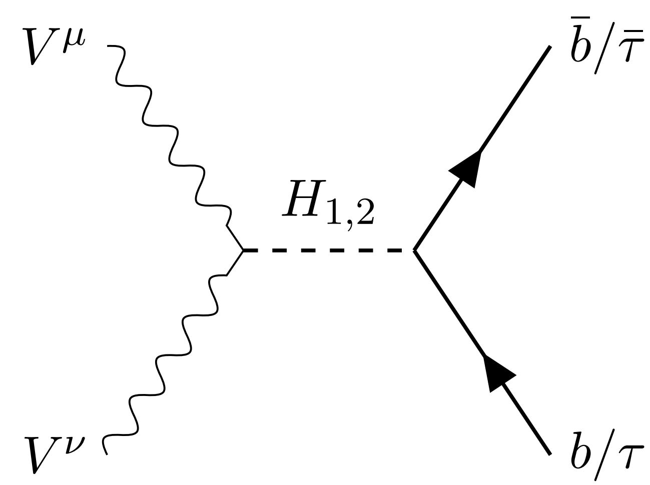


Figure 2. Dominant s channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production

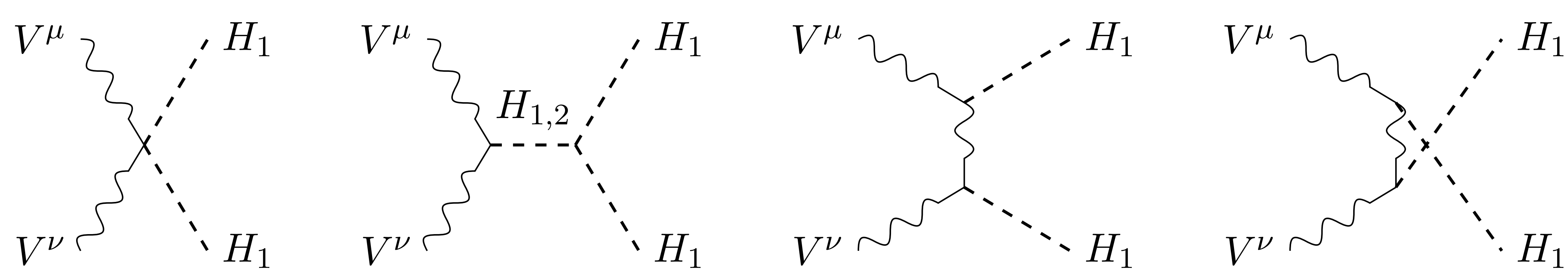


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of HP VDM with Dark Higgs Boson

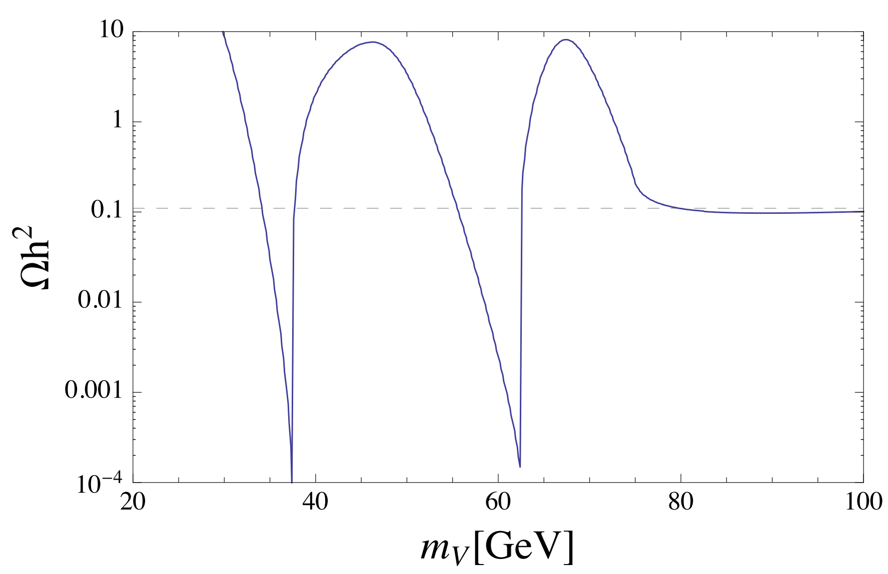


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

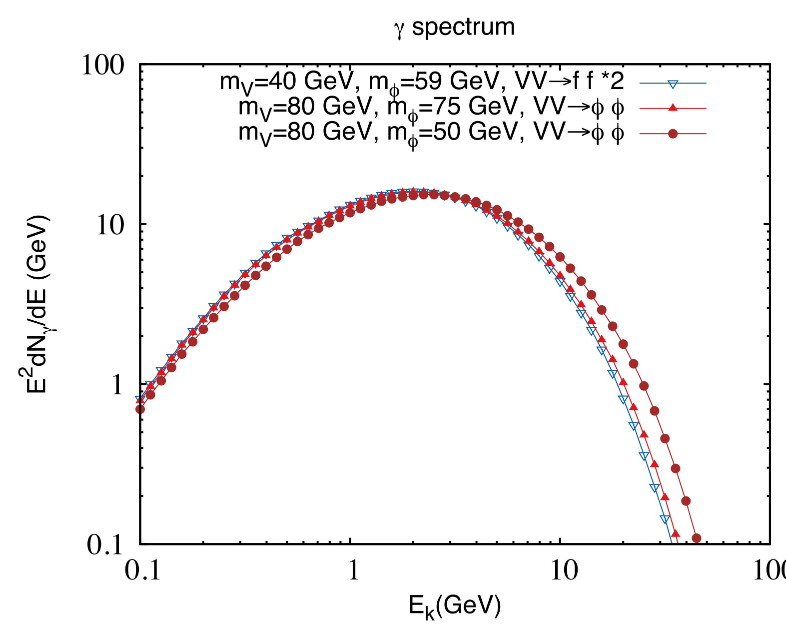


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

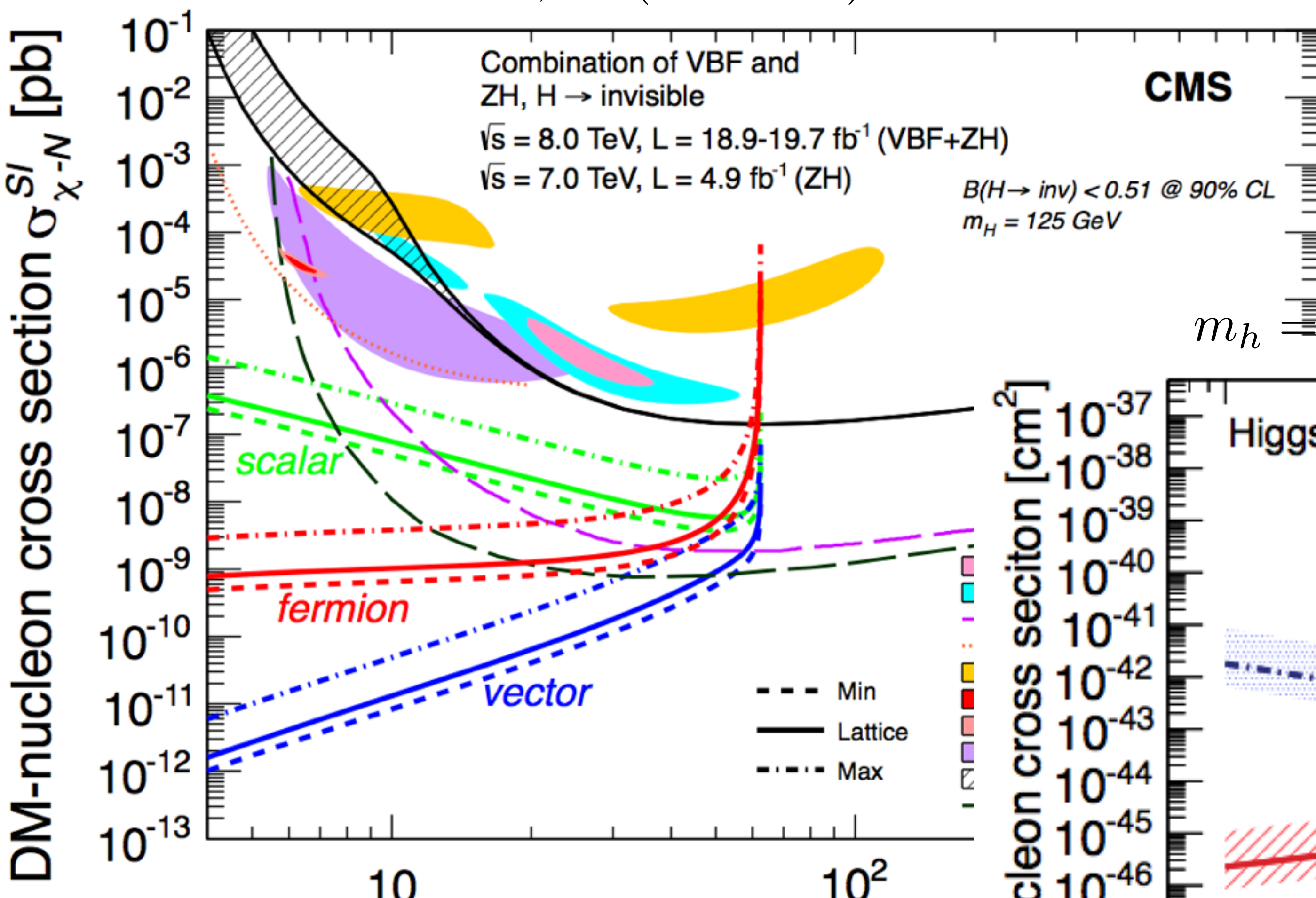
This mass range of VDM would have been impossible in the VDM model (EFT)

And No 2nd neutral scalar (Dark Higgs) in EFT

Collider Implications

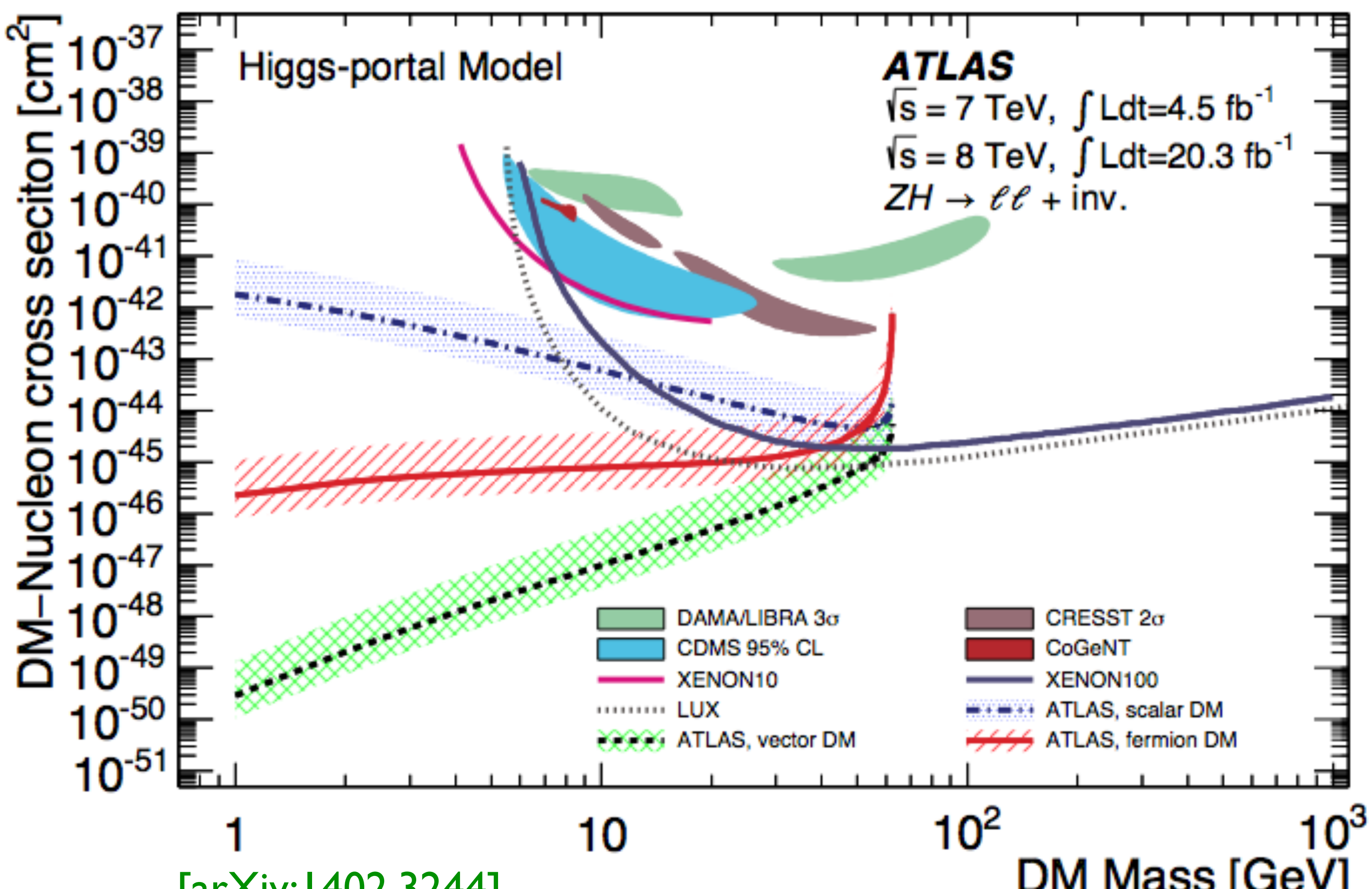
Based on EFTs

$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51$ at 90% CL



[arXiv:1404.1344]

$m_h = 125.5\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.52$ at 90% CL



[arXiv:1402.3244]

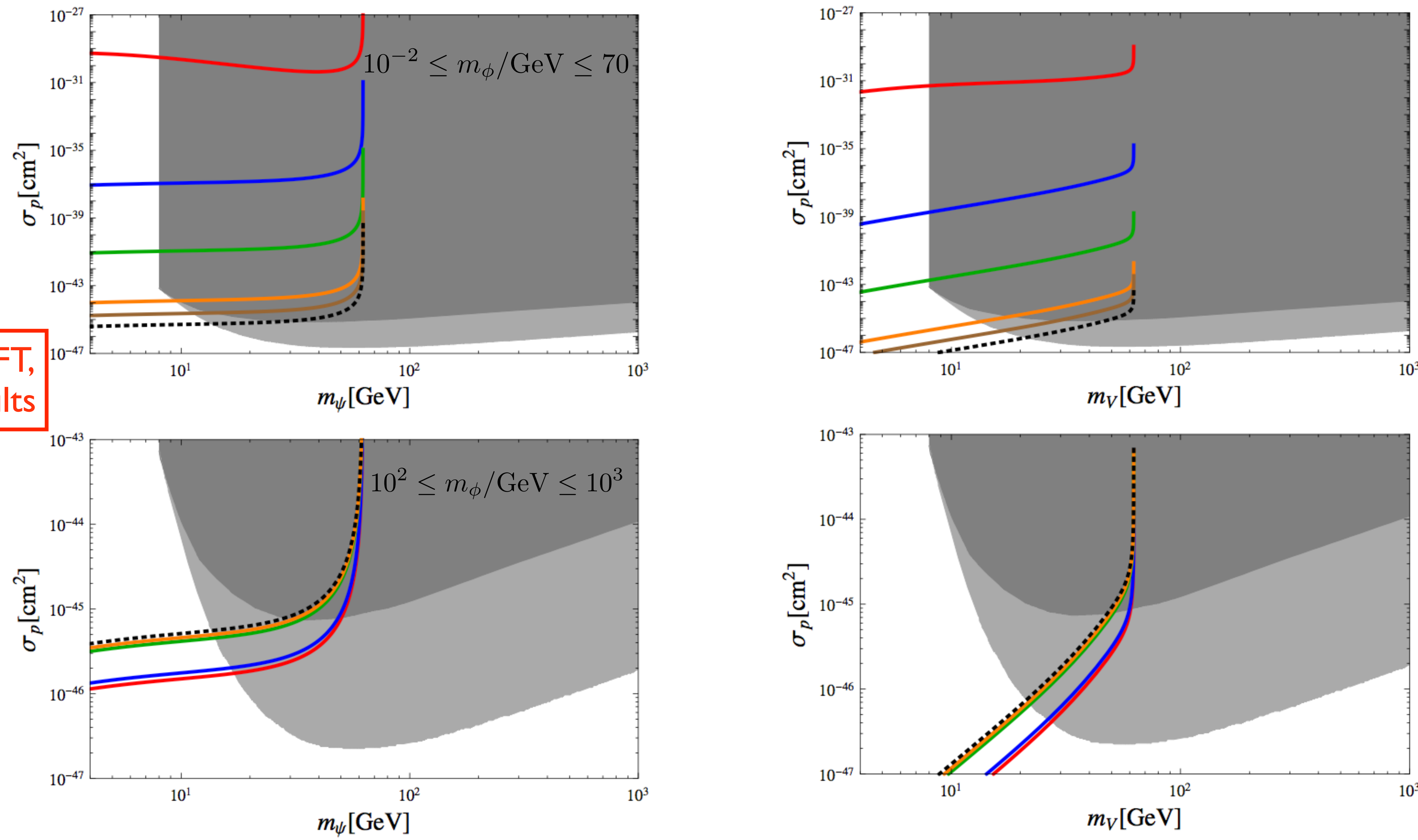
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$



Dashed curves:EFT, ATLAS,CMS results

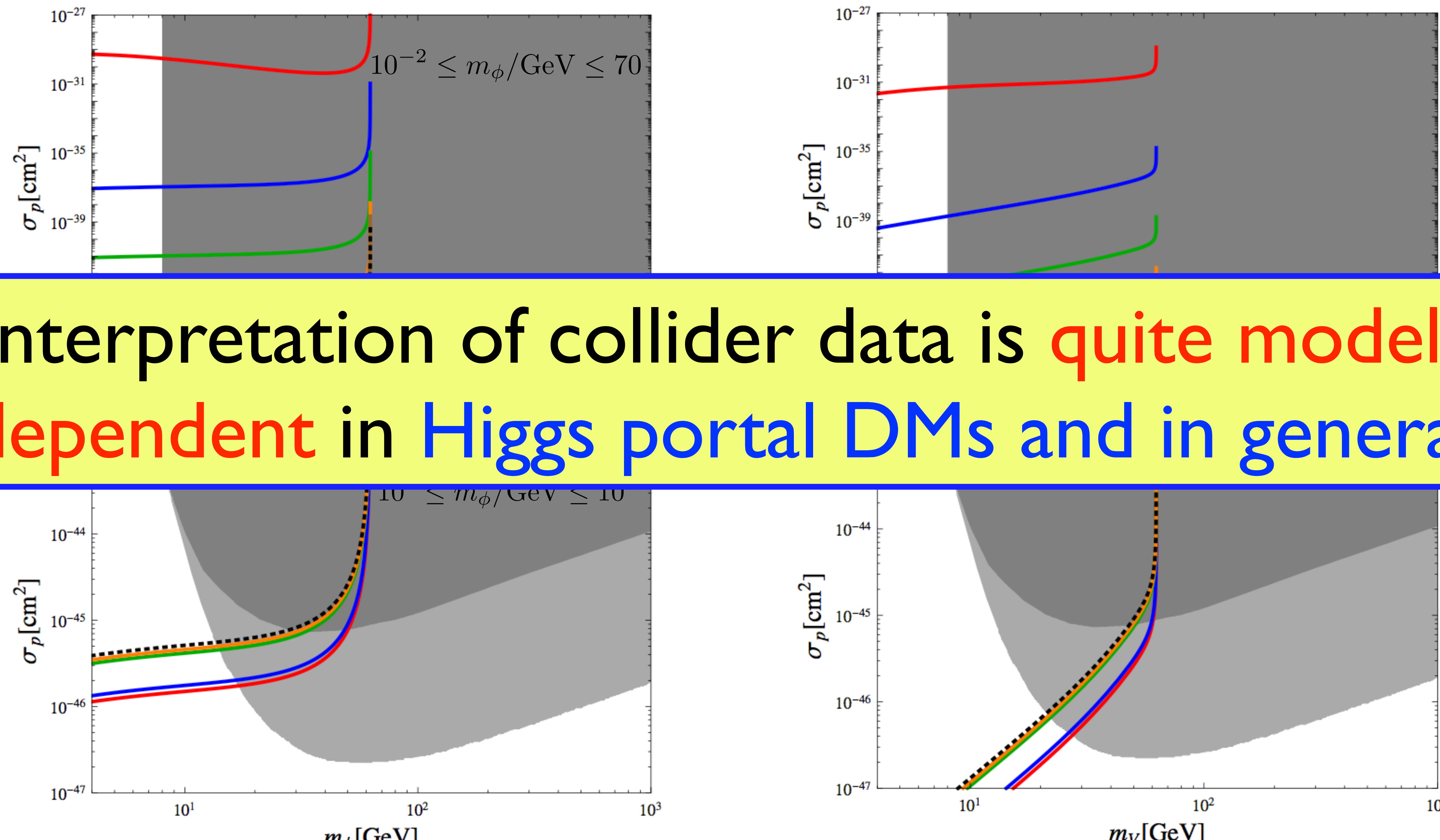
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$



Dashed curv
ATLAS,CMS

Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general

Invisible H decay into a pair of VDM

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{\lambda_{VH}^2}{128\pi}\frac{v_H^2 m_h^3}{m_V^4} \times \left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)\left(1 - \frac{4m_V^2}{m_h^2}\right)^{1/2} \quad (23)$$

Diverge when $m_V \to 0$!!

$m_V \propto g_x Q_\Phi v_\Phi$

$$\frac{g_X^2}{m_V^2} = \frac{g_X^2}{g_X^2 Q_\Phi^2 v_\Phi^2} \to \frac{1}{v_\Phi^2} = \text{finite}$$

VS.

$$\Gamma_i^{\rm inv} = \frac{g_X^2}{32\pi}\frac{m_i^3}{m_V^2}\left(1 - \frac{4m_V^2}{m_i^2} + 12\frac{m_V^4}{m_i^4}\right)\left(1 - \frac{4m_V^2}{m_i^2}\right)^{1/2}\sin^2\alpha \quad (22)$$

Invisible H decay width : finite for small mV in unitary/renormalizable model

Two Limits for $m_V \to 0$

Also see the addendum:
by S Baek, P Ko, WI Park

- $m_V = g_X Q_\Phi v_\Phi$ in the UV completion with dark Higgs boson

- Case I : $g_X \to 0$ with finite $v_\Phi \neq 0$

$$\frac{g_X^2 Q_\Phi^2}{m_V^2} = \frac{g_X^2 Q_\Phi^2}{g_X^2 Q_\Phi^2 v_\Phi^2} = \frac{1}{v_\Phi^2} = \text{finite.}$$

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} = \frac{1}{32\pi}\frac{m_h^3}{v_\Phi^2}\sin^2\alpha = \Gamma(h \to a_\Phi a_\Phi)$$

with a_Φ being the NG boson for spontaneously broken global $U(1)_X$

- Case II : $v_\Phi \to 0$ with finite $g_X \neq 0$

$$\alpha \xrightarrow{v_\Phi \to 0^+} \frac{2\lambda_{H\Phi} v_\Phi}{\lambda_H v_H}$$

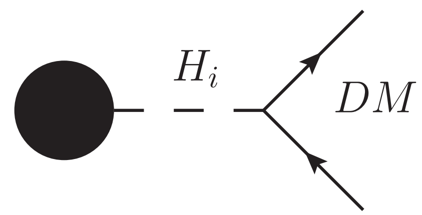
$$\frac{g_X^2 Q_\Phi^2}{m_V^2}\sin^2\alpha \xrightarrow{v_\Phi \to 0^+} \frac{4\lambda_{H\Phi}^2}{\lambda_H^2 v_H^2} = \frac{2\lambda_{H\Phi}^2}{\lambda_H m_h^2} = \text{finite,}$$

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} \xrightarrow{v_\Phi \to 0^+} \frac{1}{16\pi}\frac{\lambda_{H\Phi}^2 m_h}{\lambda_H}$$

Therefore $\Gamma(h \to VV)$ is finite when $m_V \to 0$ in the UV completions

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



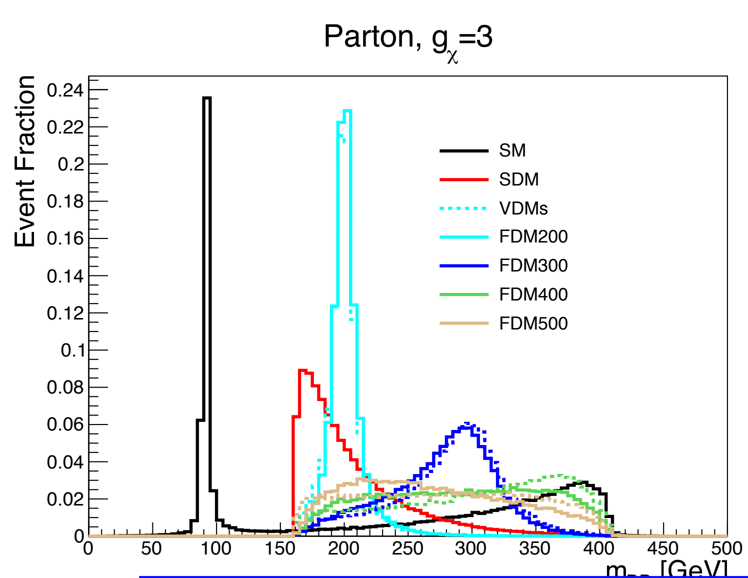
, $\quad t \equiv m_{DD}^2$

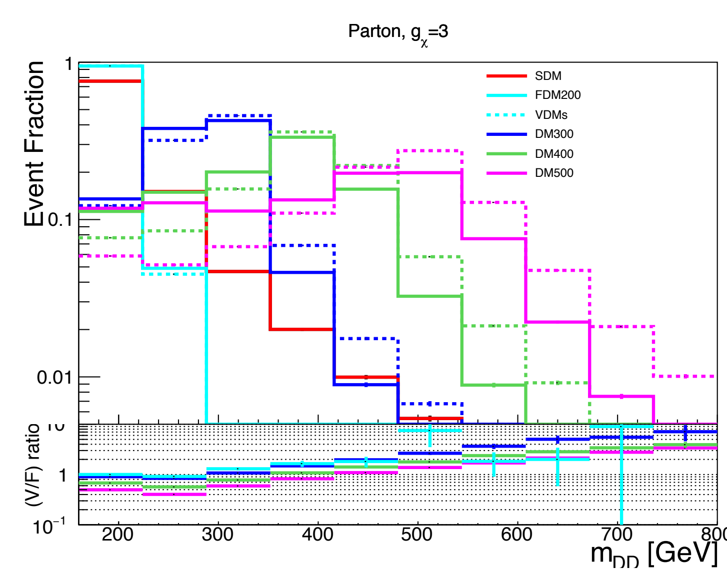
We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$

$$\frac{d\sigma_{\rm SDM}}{dt} \propto \sigma^{h^*}_{\rm SDM} \times \left|\frac{1}{t - m_h^2 + i m_h \Gamma_h}\right|^2,$$

$$\frac{d\sigma_{\rm FDM}}{dt} \propto \sigma^{h^*}_{\rm FDM} \times \left|\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}\right|^2 \cdot \left(2t - 8m_\chi^2\right),$$

$$\frac{d\sigma_{\rm VDM}}{dt} \propto \sigma^{h^*}_{\rm VDM} \times \left|\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}\right|^2 \cdot \left(2 + \frac{(t - 2m_D^2)^2}{4m_V^4}\right).$$





Fix DM mass = 80 GeV, sin(alpha) = 0.3, and vary H2 mass (200,300,400,500) GeV

Asymptotic behavior in the full theory ($t \equiv m_{\chi\chi}^2$)

$$\text{ScalarDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \tag{5.7}$$

$$\text{SFDM}: \quad G(t) \sim \left| \frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2} \right|^2 \left(t-4m_\chi^2\right) \tag{5.8}$$

$$\to |\frac{1}{t^2}|^2 \times t \sim \frac{1}{t^3} \text{ (as } t \to \infty) \tag{5.9}$$

$$\text{VDM}: \quad G(t) \sim \left| \frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2} \right|^2 \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right] \tag{5.10}$$

$$\to |\frac{1}{t^2}|^2 \times t^2 \sim \frac{1}{t^2} \text{ (as } t \to \infty) \tag{5.11}$$

Asymptotic behavior w/o the 2nd Higgs (EFT)

$$\text{SFDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left(t-4m_\chi^2\right)$$

$$\to \frac{1}{t} \text{ (as } t \to \infty)$$

$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right]$$

$$\to \text{constant (as } t \to \infty)$$

Unitarity is violated in EFT!

S. Baek, P. Ko, M. Park, WIPark, C.Yu, arXiv:1506.06556, PLB (2016)

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of
  $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator
  $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

$$\frac{d\sigma_i}{dm_{\chi\chi}} \propto \left|\frac{\sin 2\alpha\ g_\chi}{m_{\chi\chi}^2 - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{\sin 2\alpha\ g_\chi}{m_{\chi\chi}^2 - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}\right|^2$$

$$\text{H.P.} \xrightarrow[m_{H_2}^2 \gg \hat{s}]{} \text{H.M.},$$

$$\text{S.M.} \xrightarrow[m_S^2 \gg \hat{s}]{} \text{EFT},$$

$$\text{H.M.} \neq \text{EFT}\,.$$

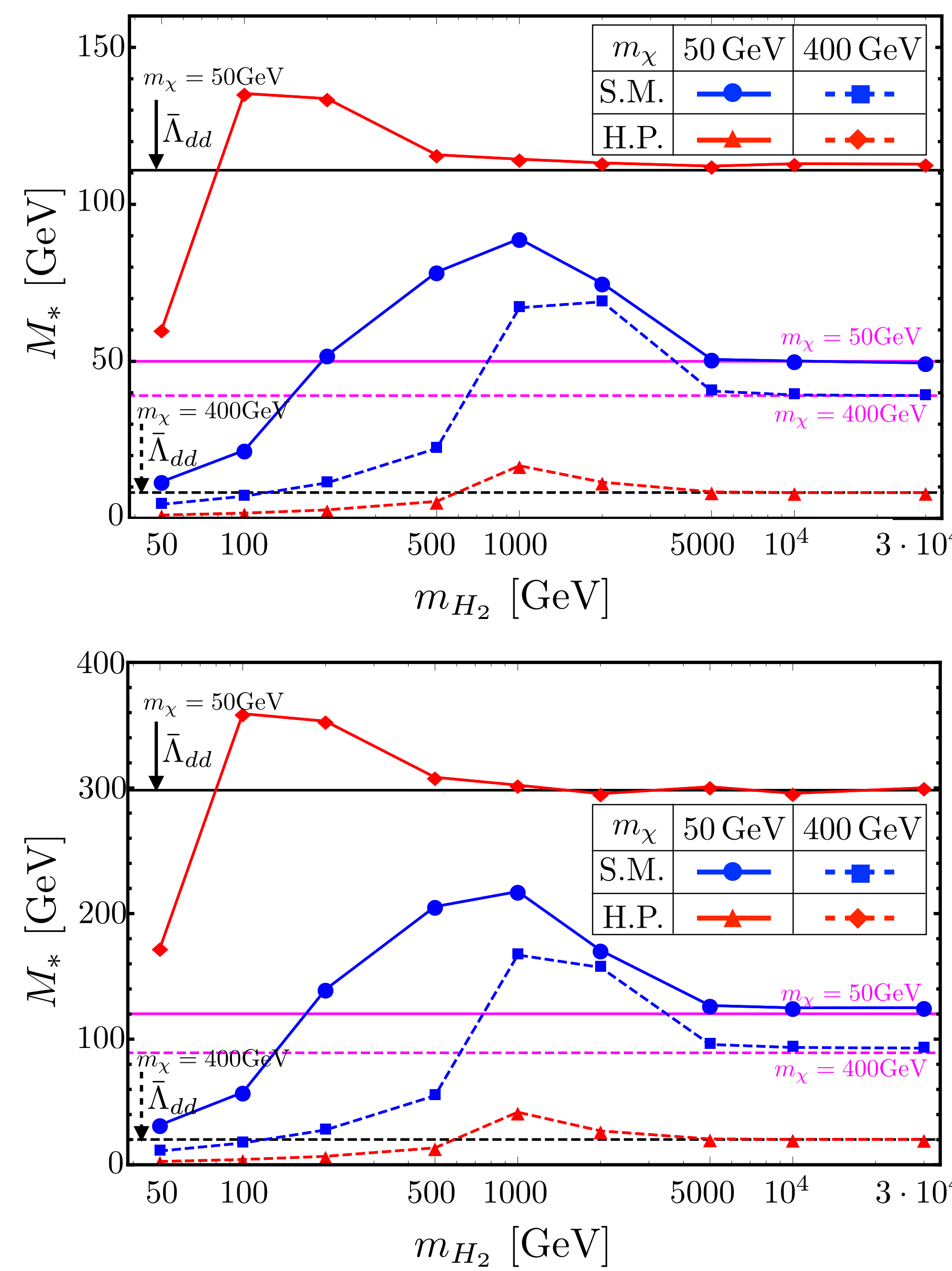


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass M_* through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.

Summary

- Phenomenology of HP VDM and Singlet FDM presented within EFT vs. UV completed models

- EFT approach has a number of drawbacks : non-renormalizable, unitarity violation at high energy colliders, and it applies only if $m_{DM}, m_{\rm SM} \ll m_\phi$ [But we don't know mass scales of dark particles !]

- In particular, one has $\Gamma_{\rm EFT}(H_{125} \rightarrow VV) \rightarrow \infty$, as $m_V \rightarrow 0$, whereas it is finite in UV completed models [Importance of gauge invariance, unitarity and renormalizability]

- The dark Higgs ϕ can play crucial roles in interpreting the DM signatures at colliders, explaining the GC γ-ray excess ($VV \rightarrow \phi\phi$), improving vacuum stability up to Planck scale, modifying the Higgs inflation [ϕ should be actively searched for !]

Hidden Sector Monopole, Stable VDM and Dark Radiation

$SU(2)_h \rightarrow U(1)_h$

+

Higgs portal

[S. Baek, P. Ko & WIP, arXiv:1311.1035]

The Model

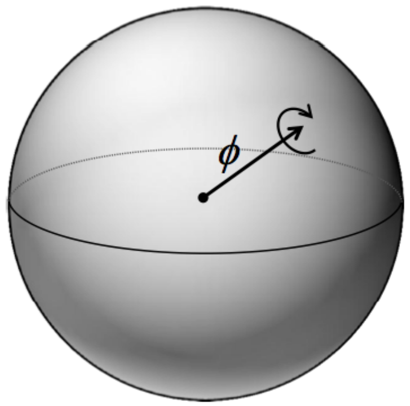
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V^a_{\mu\nu}V^{a\mu\nu} + \frac{1}{2}D_\mu\vec{\phi}\cdot D^\mu\vec{\phi} - \frac{\lambda_\phi}{4}\left(\vec{\phi}\cdot\vec{\phi} - v_\phi^2\right)^2 - \frac{\lambda_{\phi H}}{2}\vec{\phi}\cdot\vec{\phi}H^\dagger H$$

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \to U(1)$$



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}}(V_1 \mp iV_2),\ \gamma' \equiv V_3,\ H_1,\ H_2\right)$
  - VDM: $m_V = g_X v_\phi$
  - Monopole: $m_M = m_V/\alpha_X$
  - Higgses: $m_{1,2} = \frac{1}{2}\left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{\left(m_{hh}^2 - m_{\phi\phi}^2\right)^2 + 4m_{\phi h}^4}\right]$

Stable due to topology and U(1)

Main Results

- h-Monopole is stable due to topological conservation
- h-VDM is stable due to the unbroken U(1) subgroup, even if we consider higher dim nonrenormalizable operators
- Massless h-photon contributes to the dark radiation at the level of 0.08-0.11
- Higgs portal plays an important role

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture

Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2) + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

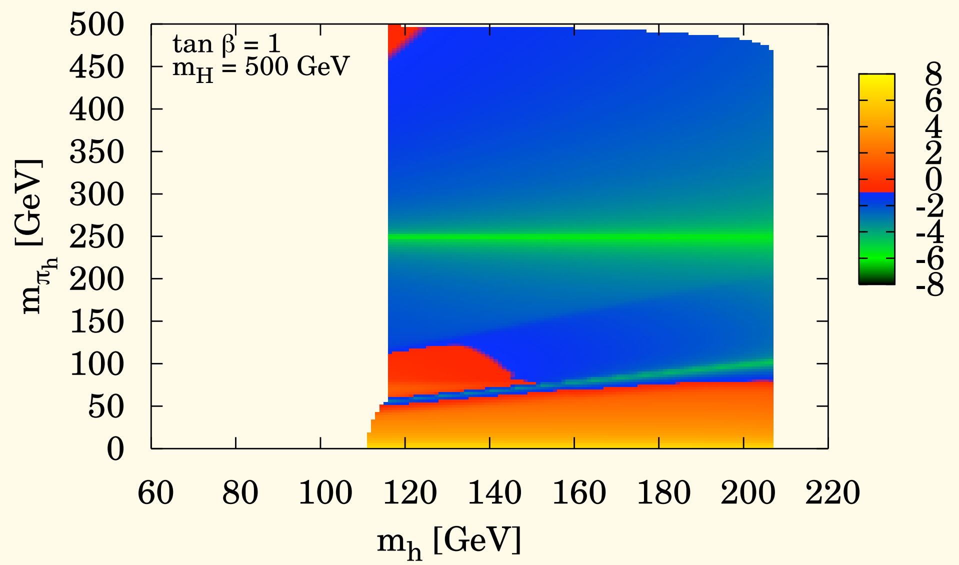
Not present in the two-Higgs Doublet model

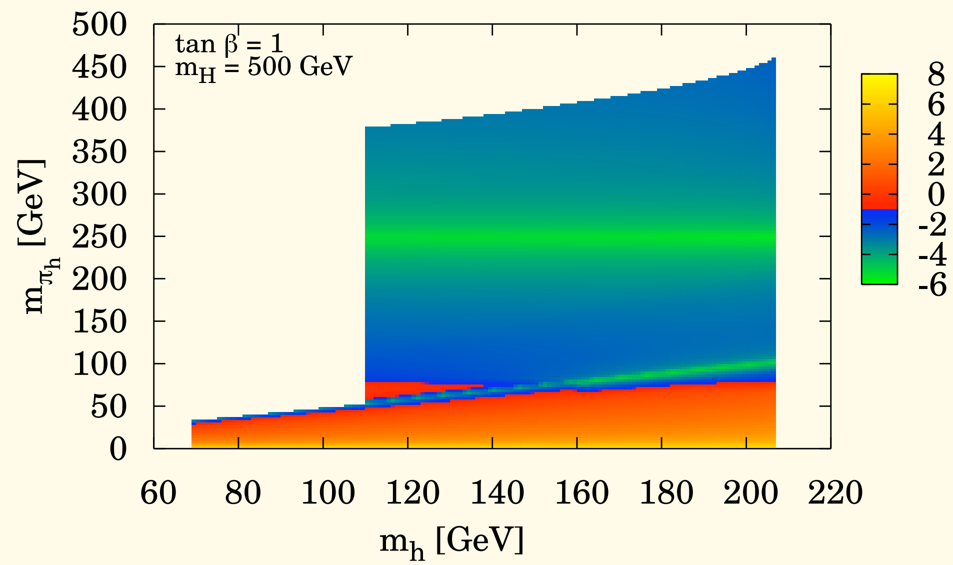
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

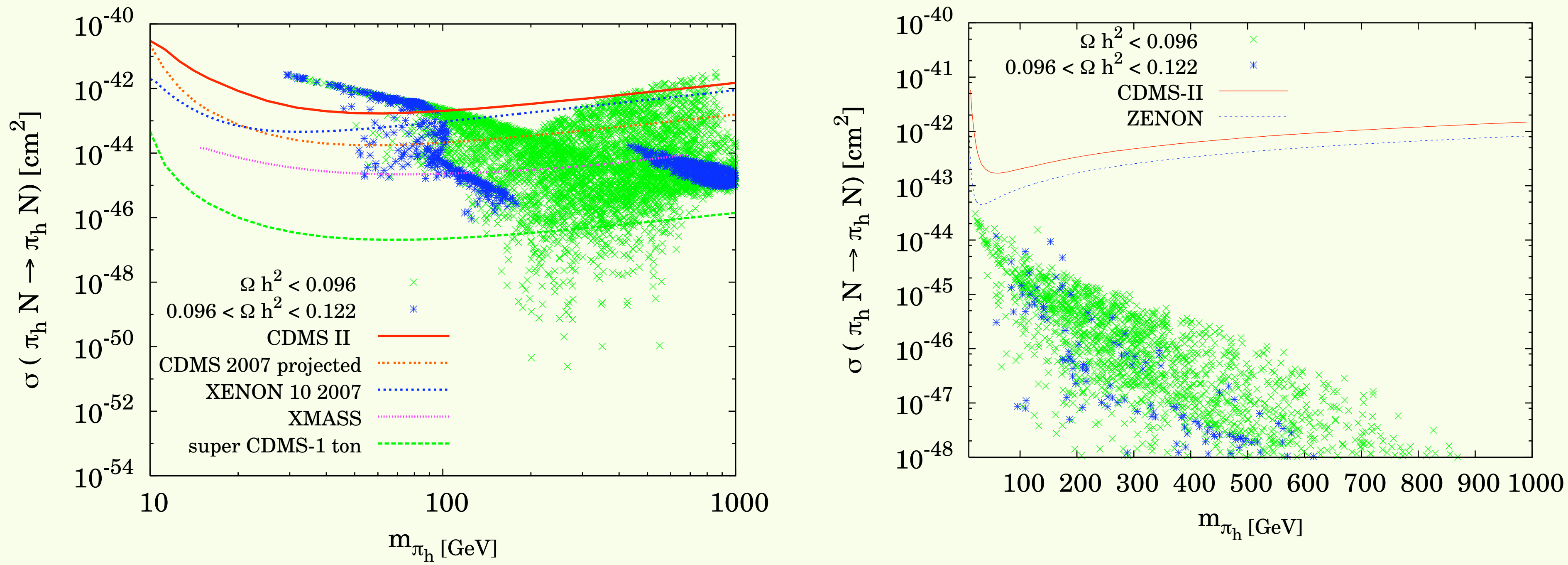
Relic Density





- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

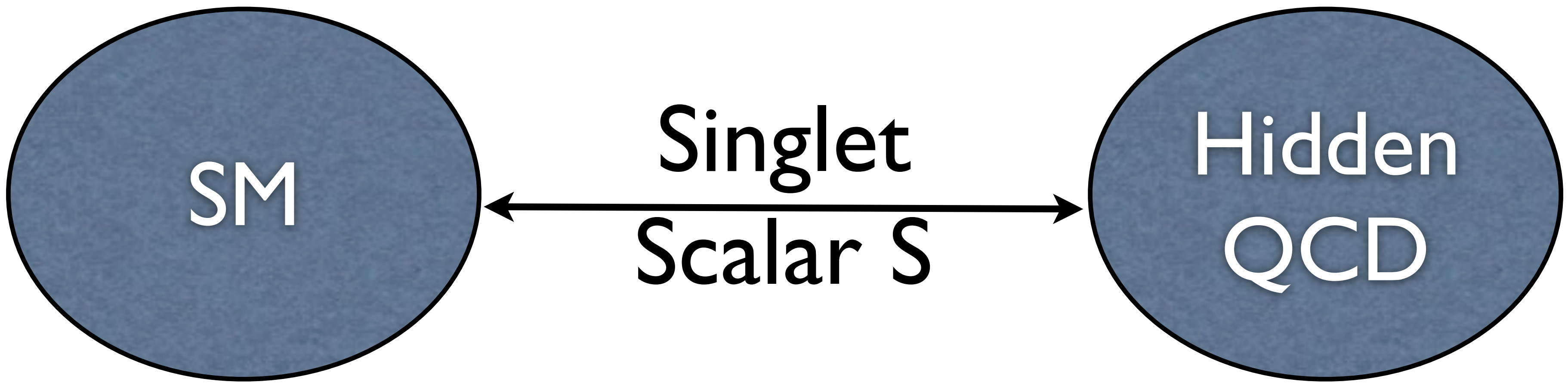
Direct detection rate



- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\ &+ \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

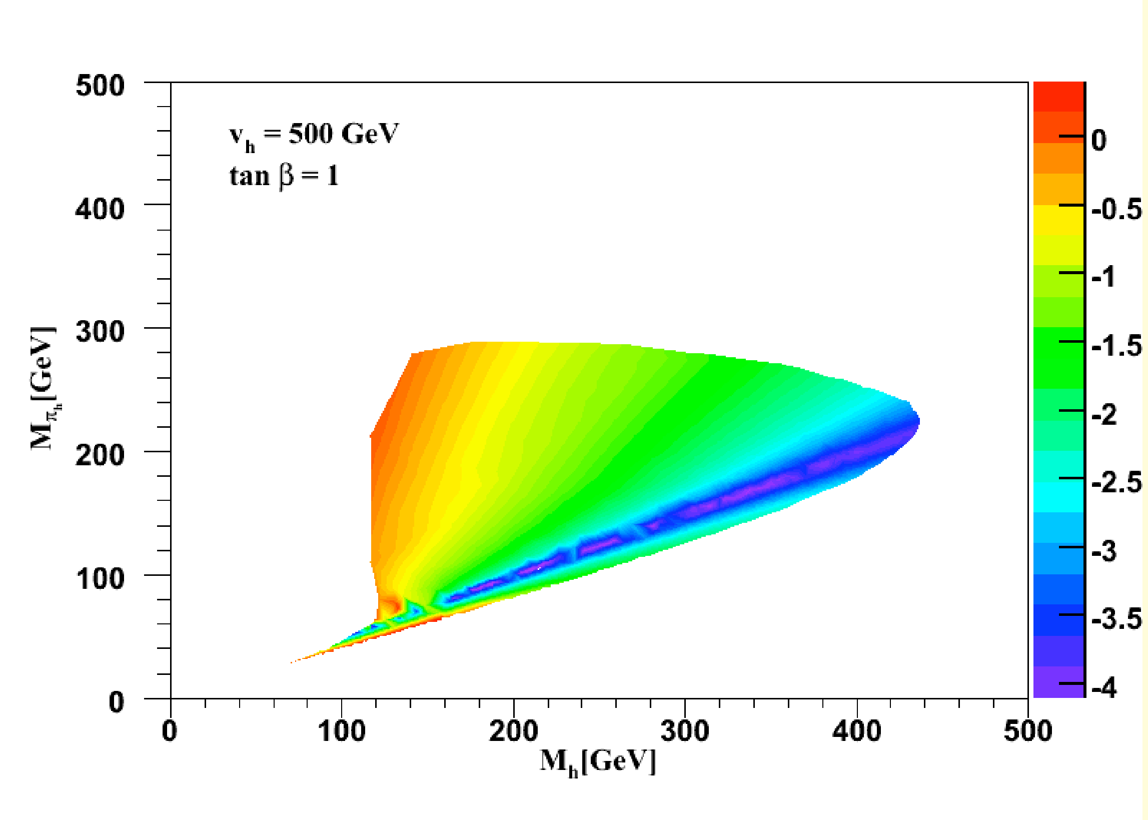
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

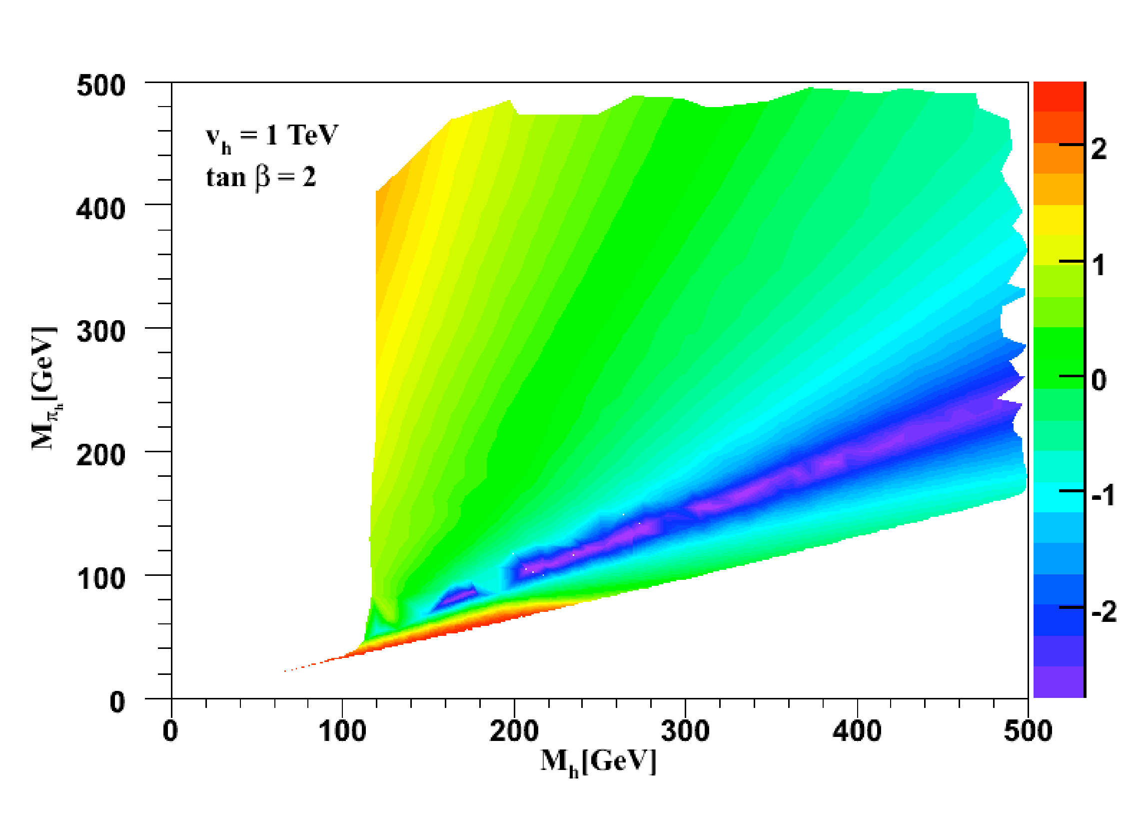
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density



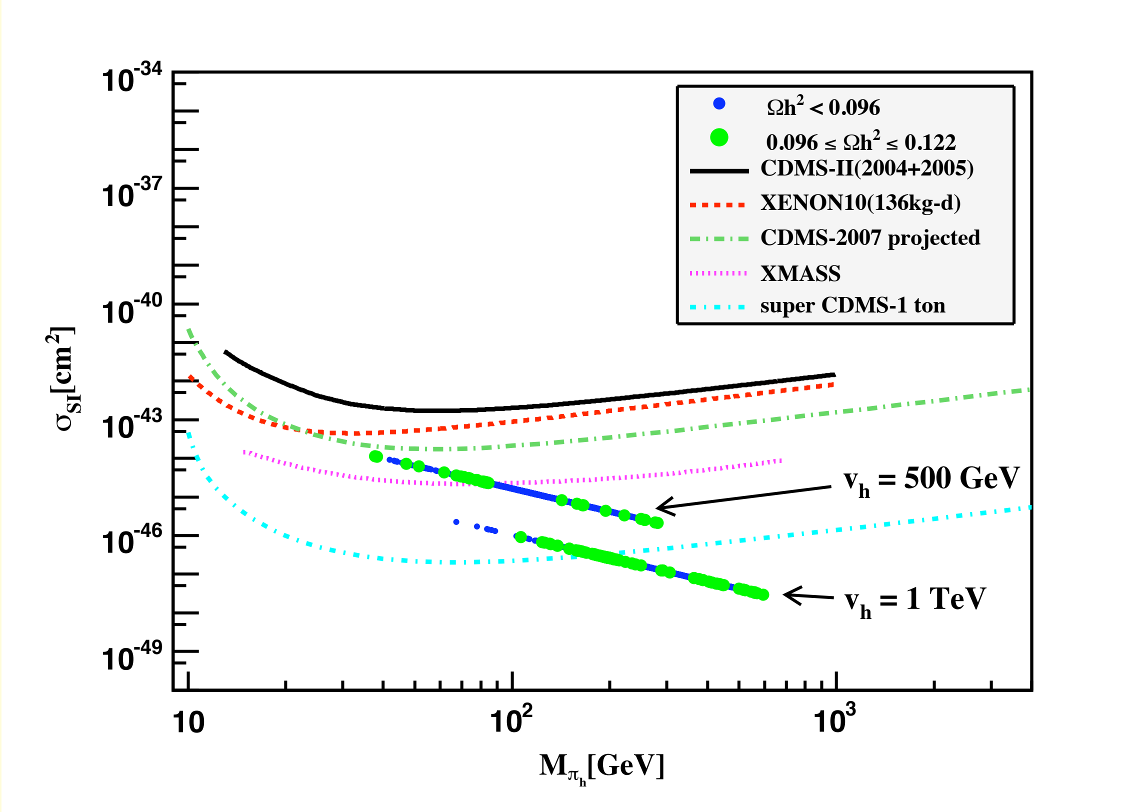


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Low energy pheno.

- Universal suppression of collider SM signals

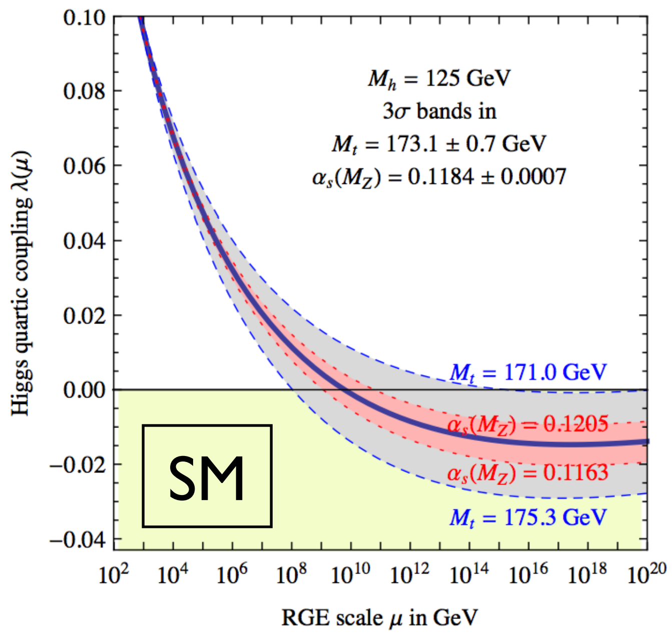
  [See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

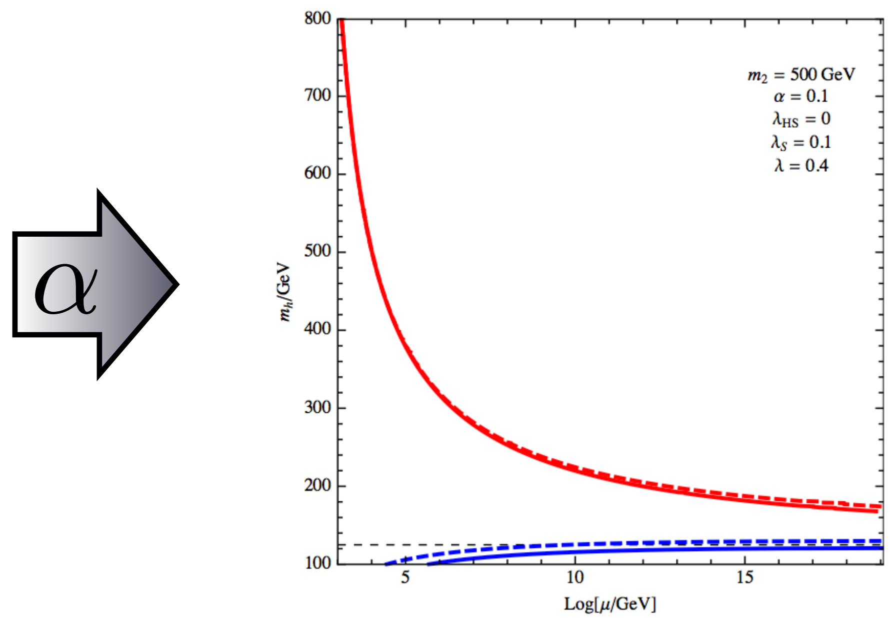
- Tree-level shift of $\boldsymbol{\lambda}_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2 \alpha \right] \lambda_H^{\rm SM}$$

➡ If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long-lived because of accidental flavor symmetry), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without fine tuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- “S” helps the Higgs inflation [Higgs-portal assisted Higgs inflation, Kim,Ko,Park, arXiv:1405.1635]
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Wess-Zumino term: 3 > 2 possible (e.g. Hochberg, Kuflik, Murayam, Volansky, Wacker for Sp(N) case)
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H.Hatanaka, D.W.Jung@KIAS)

SIMP Scenario in Dark QCD

SIMP paradigm

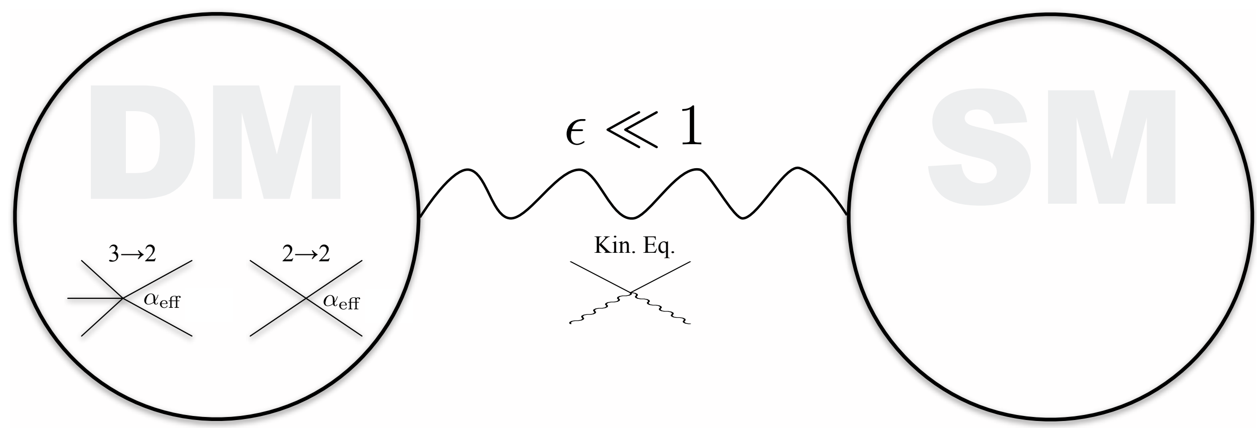


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions are naturally predicted to explain small scale structure anomalies while the couplings to the visible sector predict measurable consequences.

Hochberg, Kuflik, Tolansky, Wacker, arXiv:1402.5143
Phys. Rev. Lett. 113, 171301 (2014)

SIMP Conditions

Freeze-out :

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2} \sim H(T_F)$$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

$$\alpha_{\rm eff} = 1 - 30 \to m_{\rm DM} \sim 10{\rm MeV} - 1{\rm GeV}$$

2->2 Self scattering :

$$\frac{\sigma_{\rm scatter}}{m_{\rm DM}} = \frac{a^2 \alpha_{\rm eff}^2}{m_{\rm DM}^3}$$

with a~O(1)

$$\frac{\sigma_{\rm scatter}}{m_{\rm DM}} \lesssim 1\ {\rm cm}^2/{\rm g}$$

Dark QCD + WZW

- Dark flavor symmetry G=SU(N_f)$_L$ x SU(N_f)$_R$ is SSB into diagonal H=SU(N_f)$_V$ by dark QCD condensation

- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for π_5 (G/H) = Z (Nf > 2)

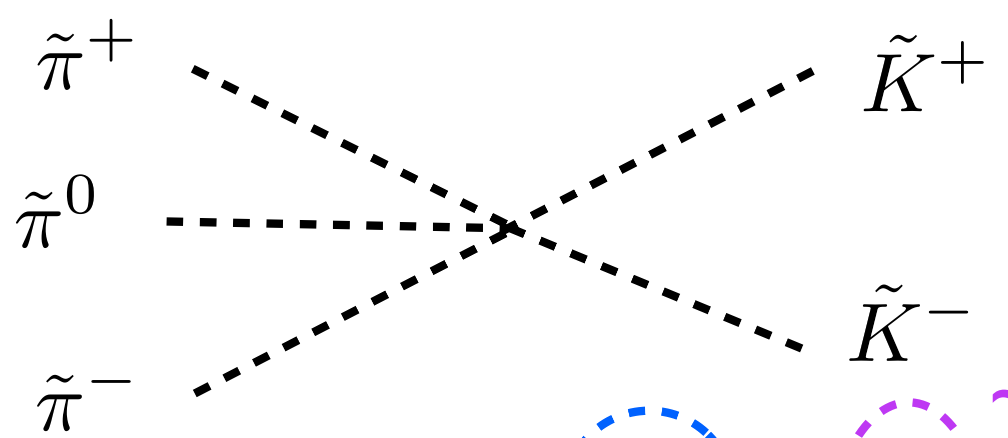
$$\Gamma_{\rm WZ} = C \int_{M^5} d^5x \; {\rm Tr}(\alpha^5) \qquad {\rm with} \quad \alpha = dUU^\dagger .$$

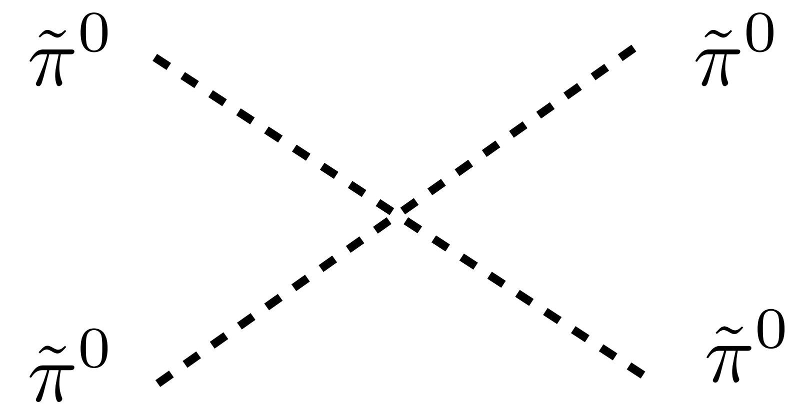
$$U = e^{2i\pi/F}$$

$$C = -i \frac{N_c}{240\pi^2}$$

in the absence of external gauge fields

SIMP Dark Mesons





~const

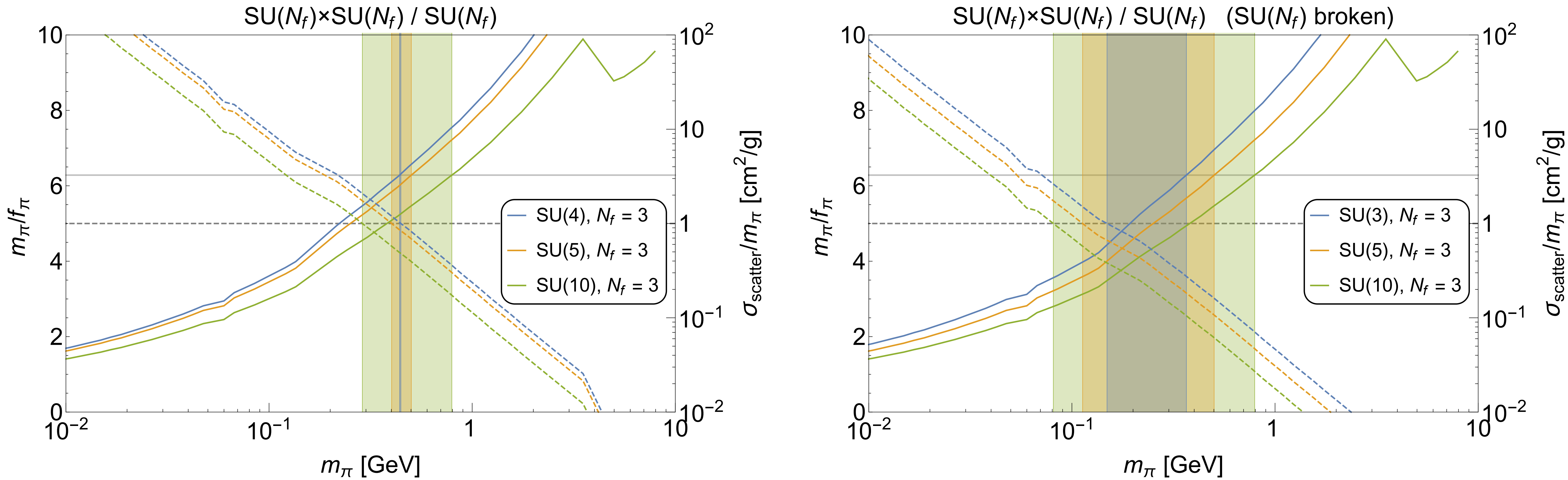
~const

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5} N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi}\right)^2, \qquad \sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$SU(N_c)$	$\frac{SU(N_f)\times SU(N_f)}{SU(N_f)}$ $(N_f \geq 3)$	$N_f^2 - 1$	$\frac{4}{3} N_f (N_f^2 - 1)(N_f^2 - 4)$	$8(N_f - 1)(N_f + 1)(3N_f^4 - 2N_f^2 + 6)$
$SO(N_c)$	$SU(N_f)/SO(N_f)$ $(N_f \geq 3)$	$\frac{1}{2}(N_f + 2)(N_f - 1)$	$\frac{1}{12} N_f (N_f^2 - 1)(N_f^2 - 4)$	$(N_f - 1)(N_f + 2)(3N_f^4 + 7N_f^3 - 2N_f^2 - 12N_f + 24)$
$Sp(N_c)$	$SU(2N_f)/Sp(2N_f)$ $(N_f \geq 2)$	$(2N_f + 1)(N_f - 1)$	$\frac{2}{3} N_f (N_f^2 - 1)(4N_f^2 - 1)$	$4(N_f - 1)(2N_f + 1)(6N_f^4 - 7N_f^3 - N_f^2 + 3N_f + 3)$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL (2015)]

SIMP Parameter Space



Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

- DM self scattering : $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Large Nc > 3

- Validity of ChPT : $m_\pi/f_\pi < 2\pi$

More serious in NNLO ChPT
Sannino et al, 1507.01590

Issues in the SIMP w/ hQCD

- Dark flavor sym is not good enough to stabilize dark pion (We have to assume dim-5 operator is highly suppressed)
- Dark baryons can make additional contribution to DM of the universe (It could produce additional diagrams for SIMP)
- Validity region of ChPT : need to include resonances (dark rho meson, dark sigma meson, etc.)
- How to achieve Kinetic equilibrium with the SM ? (Dark sigma meson or adding singlet scalar S may help. Or lifting the mass degeneracy of dark pions can help.)

SIMP + VDM

With Soo Min Choi, Hyun Min Lee, Alexander Natale,
arXiv:1801.07726, PRD (2018)

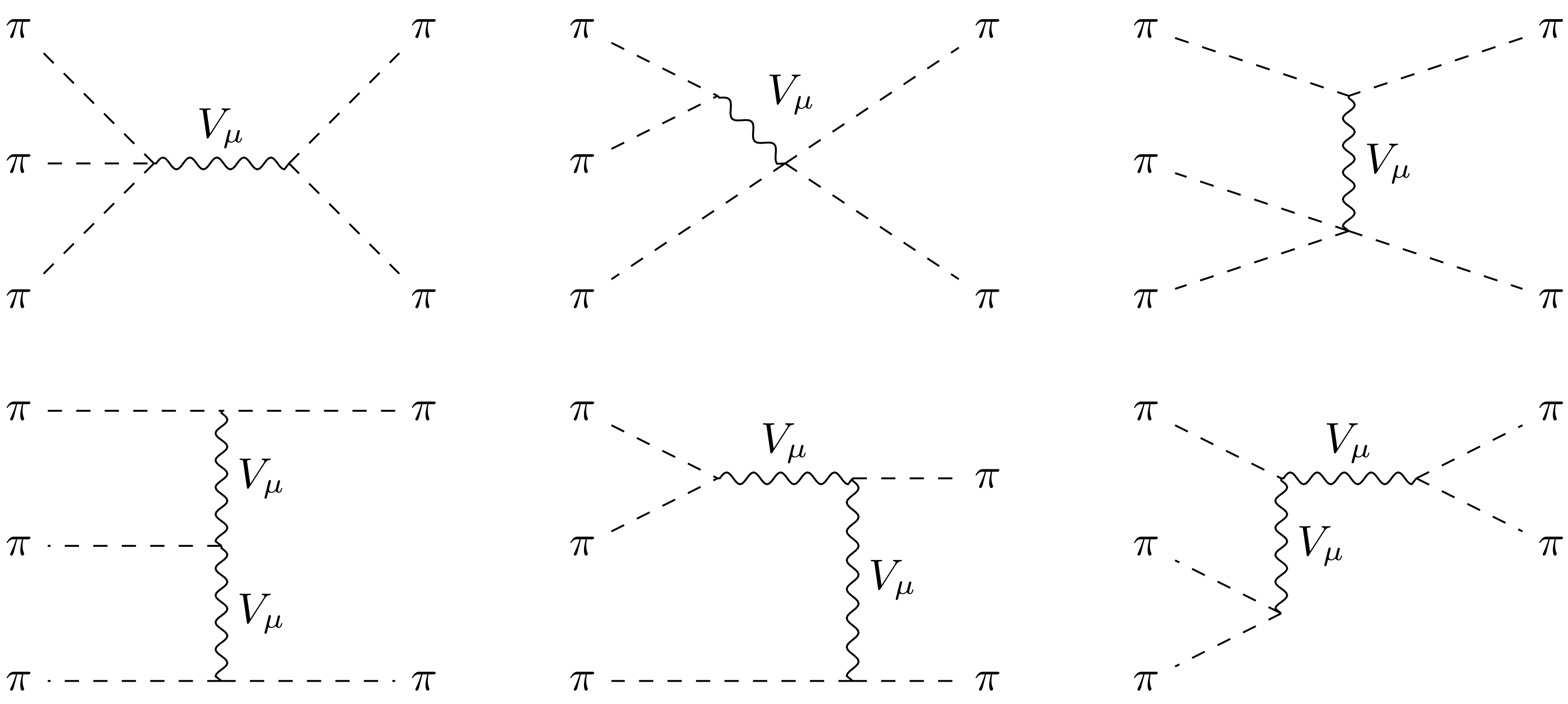


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involving dark vector mesons

$$\pi^+\pi^-\pi^0 \to \omega \to K^+K^-(K^0\overline{K^0})$$

$$\gamma = \frac{m_V\Gamma}{9m_\pi^2}, \text{ and } \epsilon = \frac{m_V^2 - 9m_\pi^2}{9m_\pi^2}$$ **(for 3 pi resonance case)**

We choose a small epsilon [say, 0.1 (near resonance)]
and a small gamma (NWA)

Results

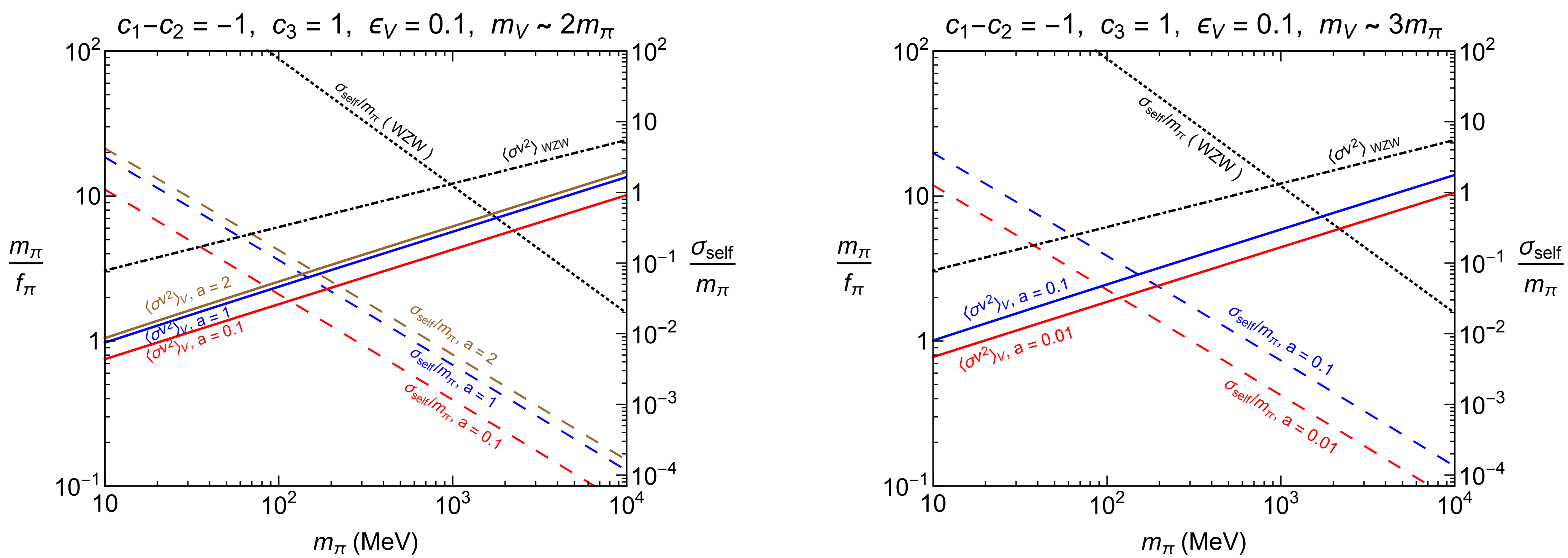


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V = 2(3)m_\pi\sqrt{1+\epsilon_V}$ on left(right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken.

- The allowed parameter space is in a better shape now, especially for 2 pi resonance case

Conclusion

- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB, (C)DM
- WIMP scenario is still viable, and will be tested to some extent by precise measurements of the Higgs signal strength and by discovery of the singlet scalar, which is however a formidable task unless we are very lucky
- SIMP scenario using 3->2 scattering via WZW term is interesting, but there are a few issues which ask for further study (dark resonance could play an important role for thermal relic and kinetic contact with the SM sector)

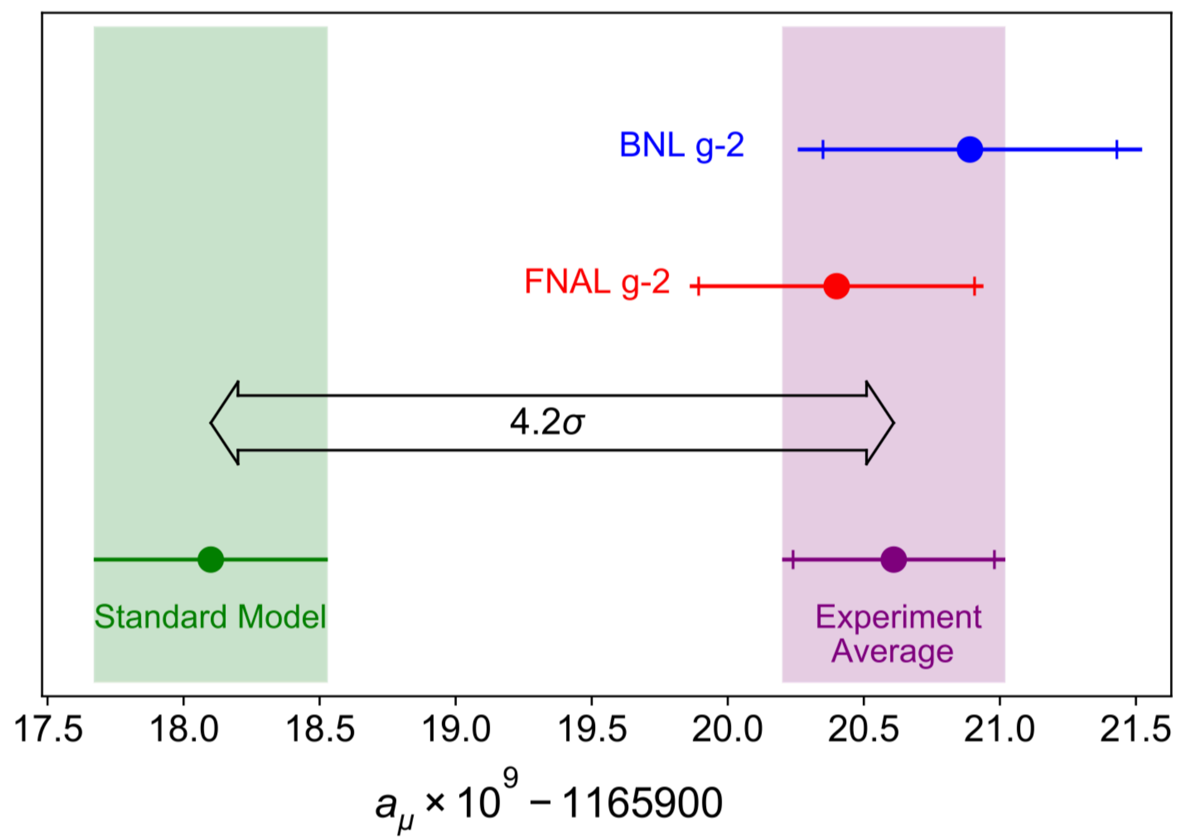
$U(1)_{L_\mu - L_\tau}$ -charged DM
: Z' only vs. $Z' + \phi$

arXiv:2204.04889 [hep-ph]
With Seungwon Baek, Jongkuk Kim

SM+$U(1)_{L_\mu - L_\tau}$ gauge sym

- He, Josh, Lew, Volkas, PRD 43, 22; PRD 44, 2118 (1991)
- One of the anomaly free gauge groups without extension of fermion contents
- The simplest anomaly free U(1) extensions that couple to the SM fermions directly
- Can affect the muon g-2, PAMELA e^+ excess, (and B anomalies with extra fermions : Not covered in this talk)

Muon g-2



The Muon g-2 Collaboration, 2104.03281

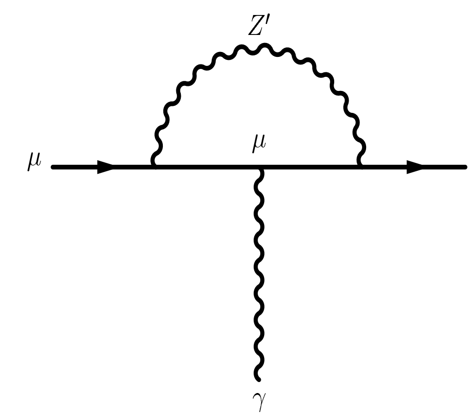
Excellent example for graduate students

- Relativistic E&M (spinning particle in EM fields)
- Special relativity (time dilation)
- (V-A) structure of charged weak interaction

Muon (g-2) in $U(1)_{\mu-\tau}$ Model

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$\begin{array}{llll} L_L^e: & (1,2,-1)(0) & e_R: & (1,1,-2)(0) \\ L_L^\mu: & (1,2,-1)(2a) & \mu_R: & (1,1,-2)(2a) \\ L_L^\tau: & (1,2,-1)(-2a) & \mu_R: & (1,1,-2)(-2a). \end{array}$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_\mu^2}{3M_{Z'}^2}$$

$$Z' \to \mu^+\mu^-, \tau^+\tau^-, \nu_\alpha\bar{\nu}_\alpha \text{ (with } \alpha = \mu \text{ or } \tau), \ \psi_D\overline{\psi}_D$$

$$\Gamma(Z' \to \mu^+\mu^-) = \Gamma(Z' \to \tau^+\tau^-) = 2\Gamma(Z' \to \nu_\mu\bar{\nu}_\mu) = 2\Gamma(Z' \to \nu_\tau\bar{\nu}_\tau) = \Gamma(Z' \to \psi_D\bar{\psi}_D)$$

if $M_{Z'} \gg m_\mu, m_\tau, M_{\rm DM}$. The total decay rate of Z' is approximately given by

$$\Gamma_{\rm tot}(Z') = \frac{\alpha'}{3} M_{Z'} \times 4(3) \approx \frac{4(\text{or } 3)}{3} \text{ GeV} \left(\frac{\alpha'}{10^{-2}}\right) \left(\frac{M_{Z'}}{100\text{GeV}}\right)$$

$$q\bar{q} \text{ (or } e^+e^-) \to \gamma^*, Z^* \to \mu^+\mu^- Z', \tau^+\tau^- Z' \\ \to Z^* \to \nu_\mu\bar{\nu}_\mu Z', \nu_\tau\bar{\nu}_\tau Z'$$

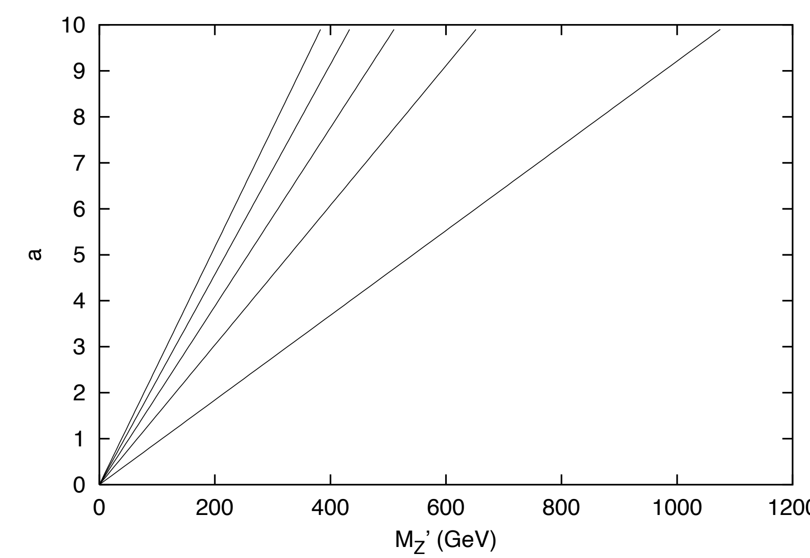


FIG. 2. Δa_μ on the a vs. $m_{Z'}$ plane in case b). The lines from left to right are for Δa_μ away from its central value at $+2\sigma, +1\sigma, 0, -1\sigma$ and -2σ, respectively.

Baek and Ko, arXiv:0811.1646, for PAMELA e^+ excess

$$\mathcal{L}_{\rm Model} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm New}$$

$$\mathcal{L}_{\rm New} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi_D} i D \cdot \gamma \psi_D - M_{\psi_D} \overline{\psi_D} \psi_D + D_\mu \phi^* D^\mu \phi$$
$$-\lambda_\phi (\phi^* \phi)^2 - \mu_\phi^2 \phi^* \phi - \lambda_{H\phi} \phi^* \phi H^\dagger H.$$

Here we ignored kinetic mixing for simplicity

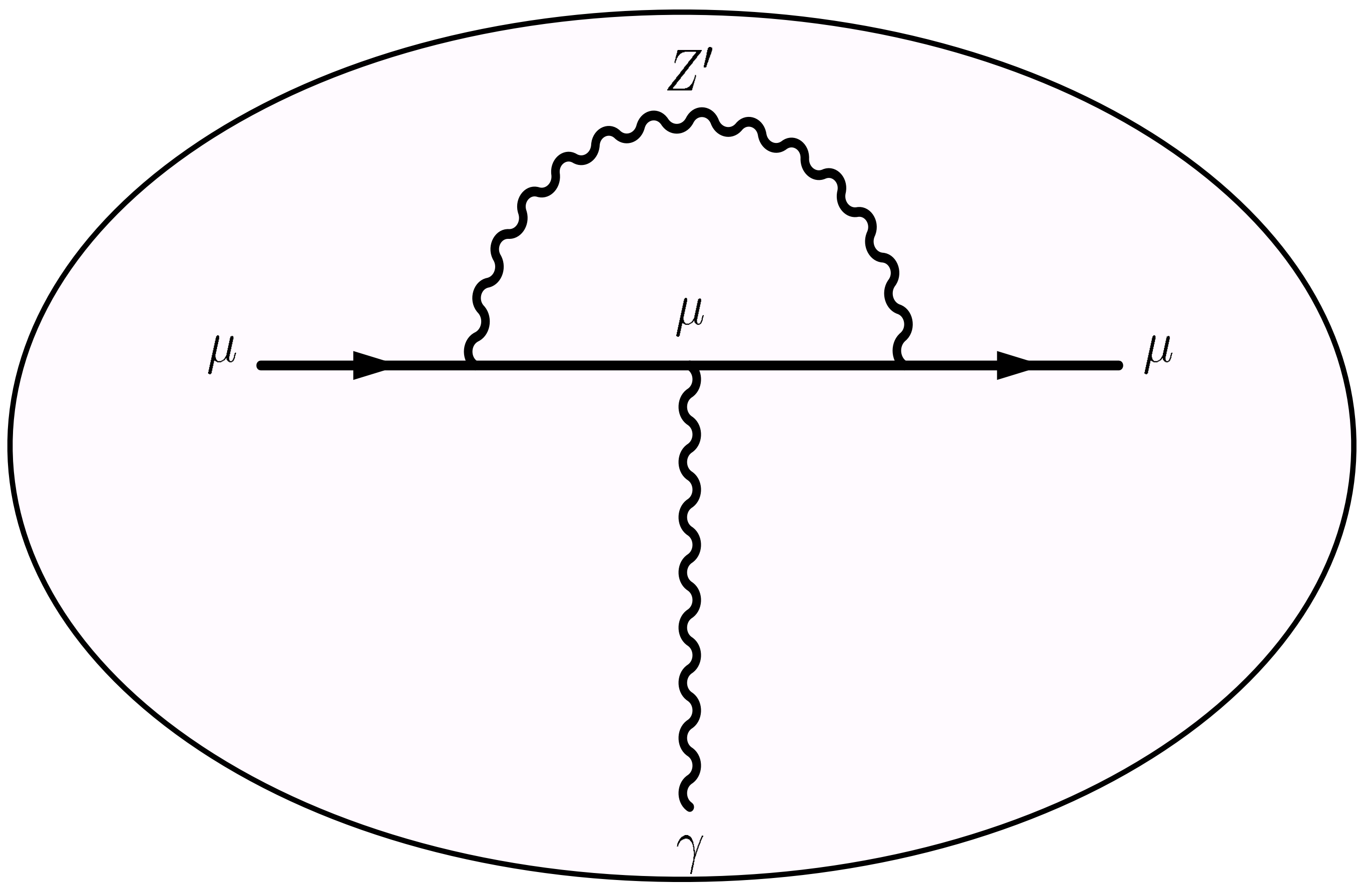
$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{e}{s_W c_S}(I_3 - s_W^2 Q) Z_\mu + ig' Y' Z'_\mu$$

muon g-2, Leptophilc DM, Collider Signature

Muon (g-2)

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (302 \pm 88) \times 10^{-11}.$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_\mu^2}{3M_{Z'}^2}$$

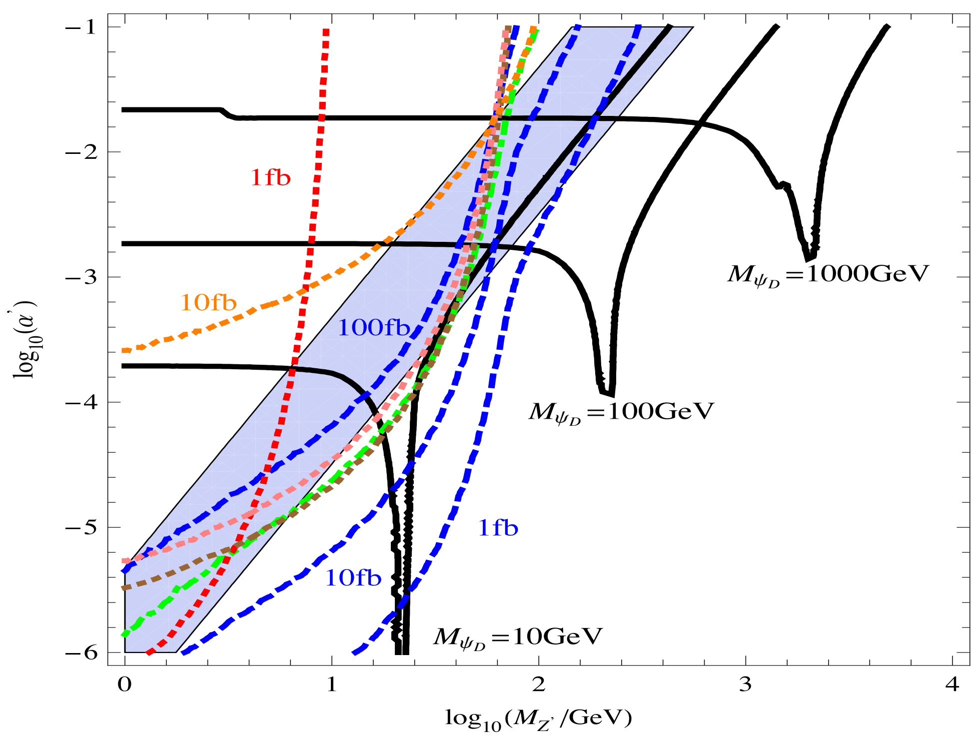


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5×10^{-6} GeV, brown dotted) in the $(\log_{10}\alpha', \log_{10} M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88) \times 10^{-11}$ within 3 σ.

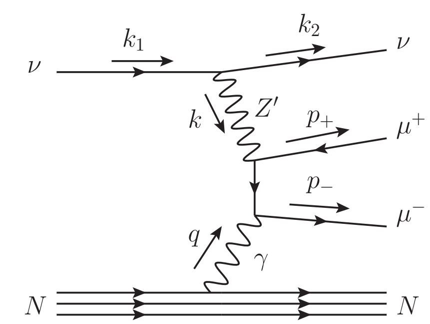


FIG. 1. The leading order contribution of the Z′ to neutrino trident production (another diagram with μ^+ and μ^- reversed
i … in g'

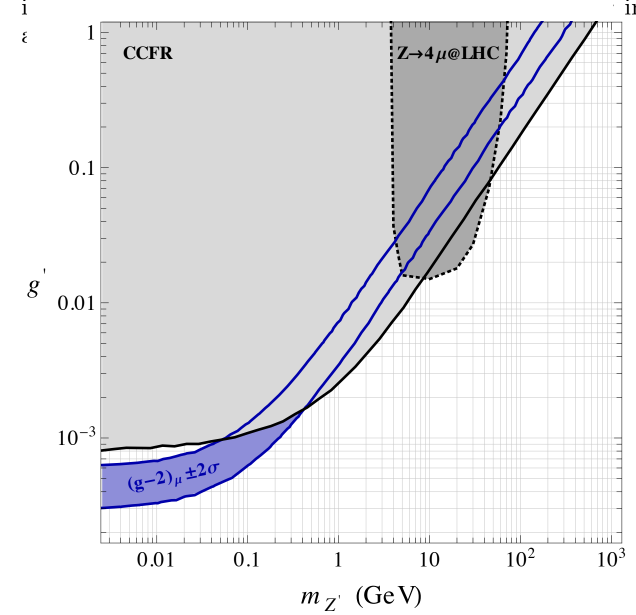


FIG. 2. Parameter space for the Z′ gauge boson. The light-grey area is excluded at 95% C.L. by the CCFR measurement of the neutrino trident cross-section. The grey region with the dotted contour is excluded by measurements of the SM

Seungwon Baek, Pyungwon Ko, arXiv:0811.1646, JCAP(2009) about PAMELA e^+ excess

Altmannshofer et al. arXiv:1406.2332 [hep-ph]

Neutrino trident puts strong constraints on this model

One can evade the neutrino trident constraint, if one introduces New fermions and generate muon g-2 at loop level w/ new fermions !

Z' Only

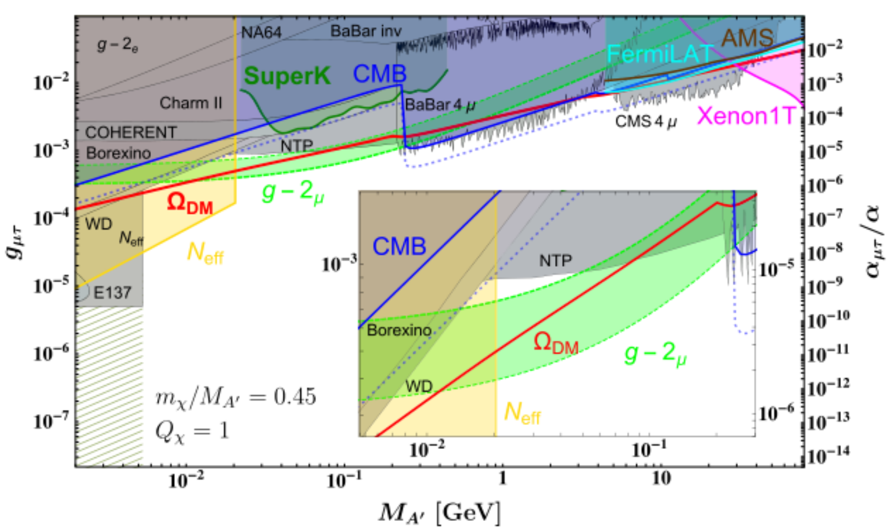
- Consider light Z' and $g_X \sim (\text{a few}) \times 10^{-4}$ for the muon g-2. Then
- $\chi\bar{\chi} \to Z'^{*} \to f_{\rm SM}\bar{f}_{\rm SM}$: dominant annihilation channel
- $g_X \sim 10^{-4}$ is too small for $\chi\bar{\chi} \to Z'Z'$ to be effective for $\Omega_\chi h^2$
- $m_{Z'} \sim 2m_{\rm DM}$ with the s-channel Z' resonance for the correct relic density
- Many recent studies on this case:

- Asai, Okawa, Tsumura, 2011.03165
- Holst, Hooper, Krnjaic, 2107.09067
- Drees and Zhao, arXiv:2107.14528
- And some earlier papers

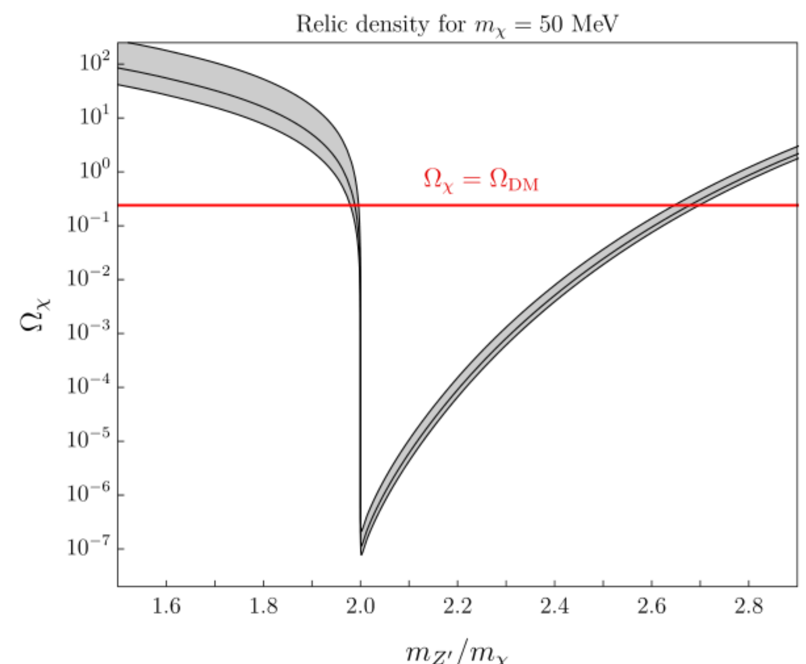
Leptophilic Z' model + DM

- $\chi\bar{\chi}(X\bar{X}) \to Z'^* \to \nu\bar{\nu}$: dominant annihilation channels
  - $M_{Z'} \sim 2M_\chi$ with the **s-channel Z' resonance** only gives the correct relic density

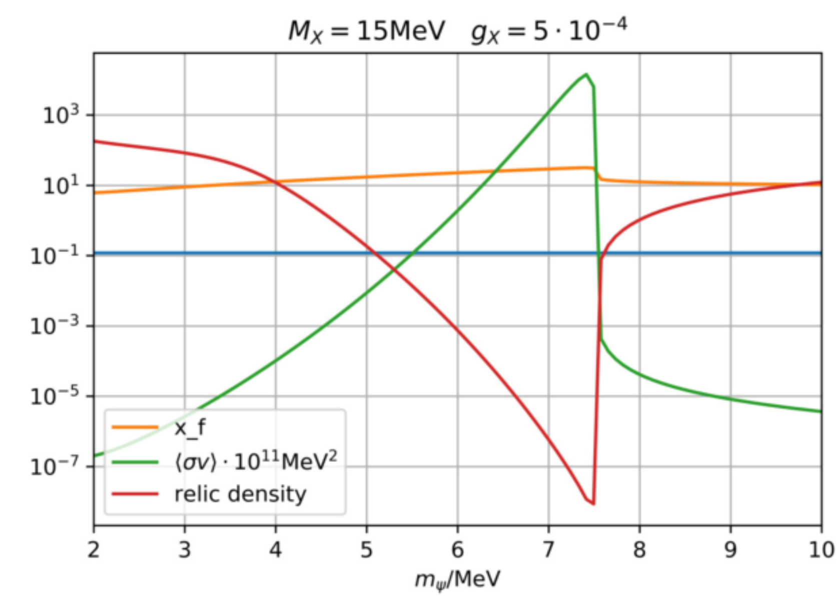
P. Foldenauer, PRD 2019



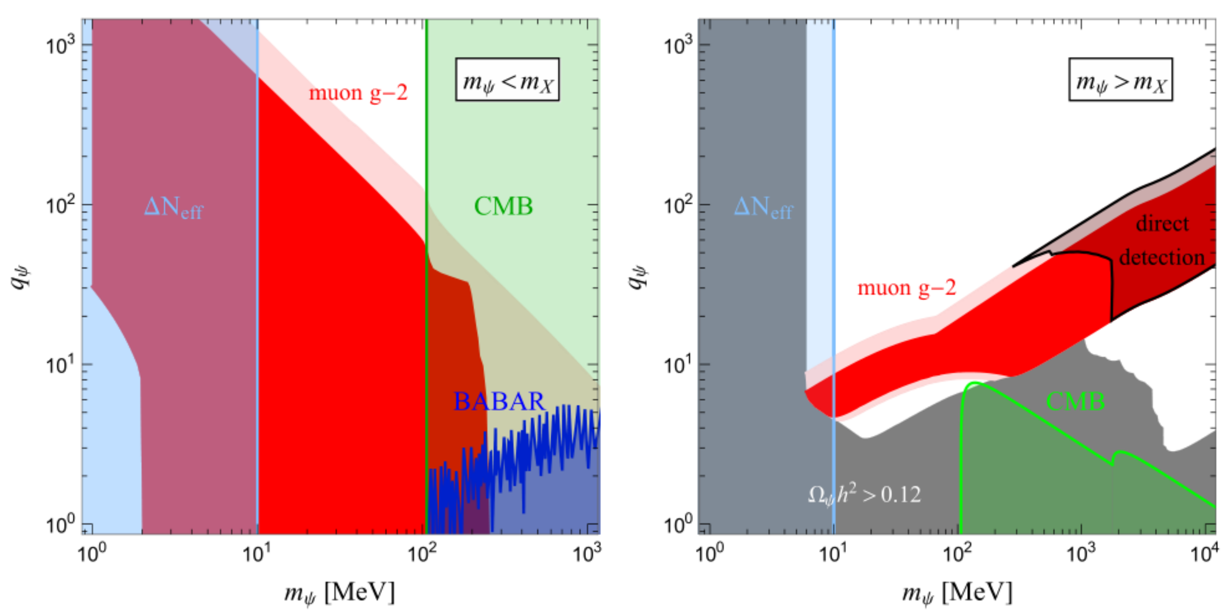
I. Holst. D. Hooper, G. Krnjaic, PRL 2022

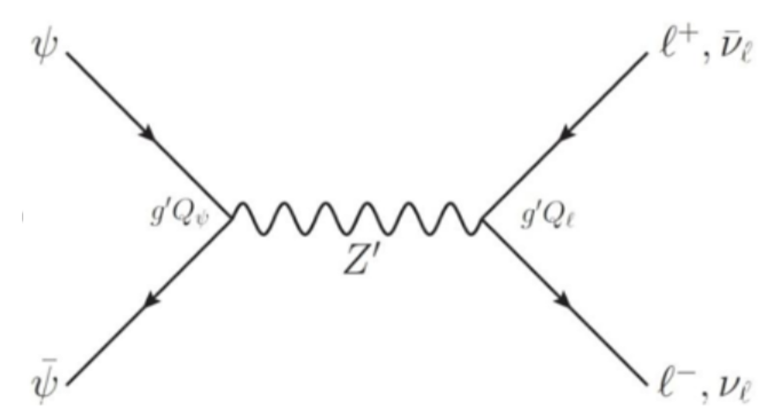


M. Drees, W. Zhao, PLB 2022



Asai, Okawa, Tsumura, JHEP 2021





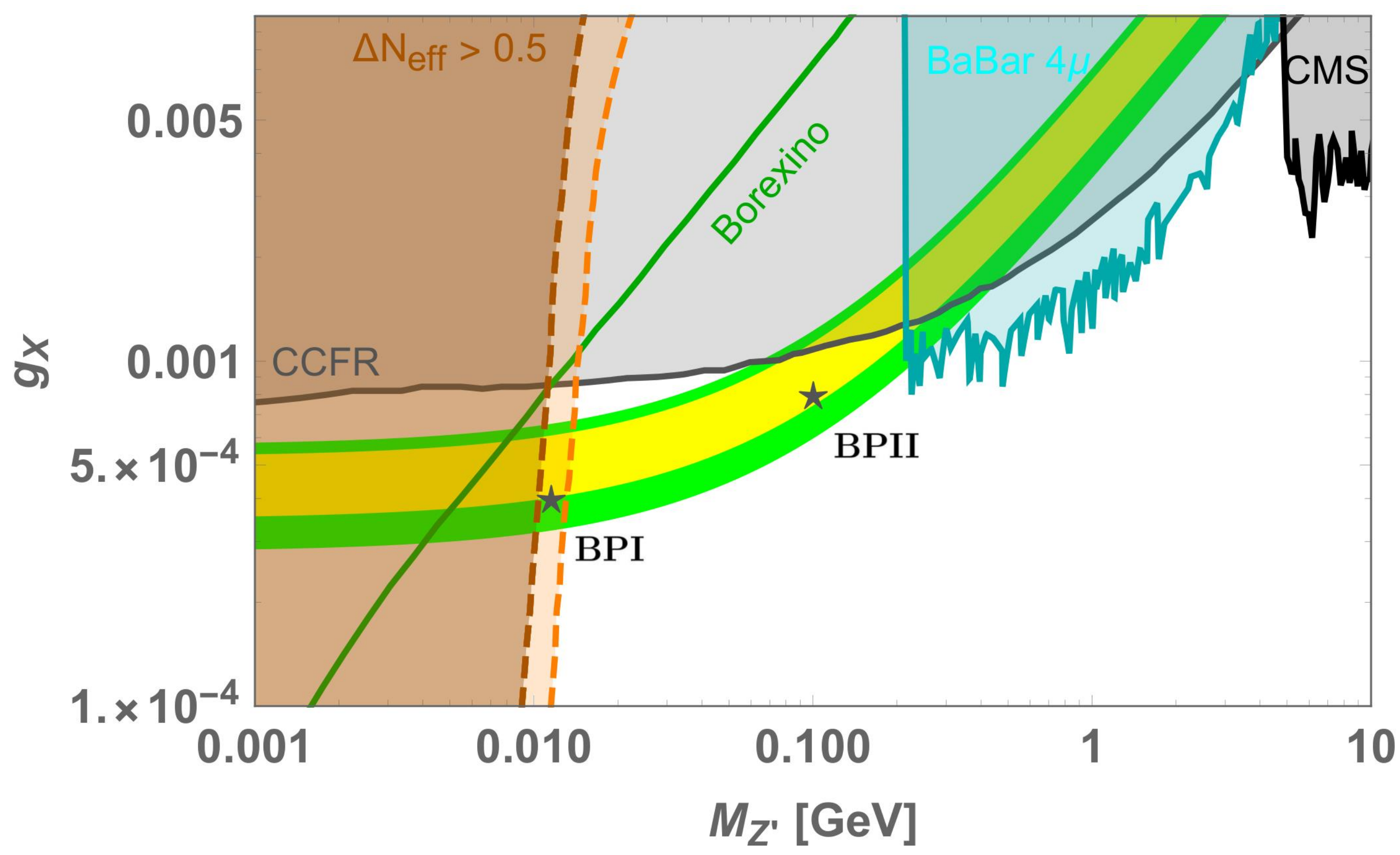


FIG. 1. Regions inside the yellow and Green shaded areas by the Δa_μ are allowed at 1σ and 2σ C.L.. Cyan, black, and orange regions are excluded by other experimental bounds. Above green solid line is ruled out by the Borexino experiment. Region inside the orange area can resolve the Hubble tension. We take two Benchmark Points (BP) $(M_{Z'}, g_X)$ as **BPI** $=(11.5\,\mathrm{MeV}, 4\times 10^{-4})$ and **BPII** $= (100\,\mathrm{MeV}, 8\times 10^{-4})$.

$U(1)_{L_\mu - L_\tau}$ -charged DM

: Z' only vs. $Z' + \phi$

cf: Let me call Z' , $U(1)_{L_\mu - L_\tau}$ gauge boson,
"dark photon", since it couples to DM

Models with Φ

TABLE I: $U(1)$ charge assignments of newly introduced particles and SM particles. The other SM particles are singlet.

Field	Z'_μ	$X(\chi)$	Φ	$L_\mu = (\nu_{L\mu}, \mu_L), \mu_R$	$L_\tau = (\nu_{L\tau}, \tau_L), \tau_R$
spin	1	0 (1/2)	0	1/2	1/2
$U(1)$ charge	0	$Q_X(Q_\chi)$	Q_Φ	+1	-1

We Consider Both Complex Scalar (X) and Dirac Fermion DM (χ)

- Physics depends on Q_Φ , Q_X and Q_χ
- $Q_\Phi = 2Q_{X(\chi)}$ and $3Q_X$ need special cares, since there are extra gauge invariant op's that break $U(1) \to Z_2$, Z_3 after $U(1)$ is spontaneously broken by nonzero VEV of Φ

Complex Scalar DM (generic with $Q_\Phi \neq Q_X, etc$)

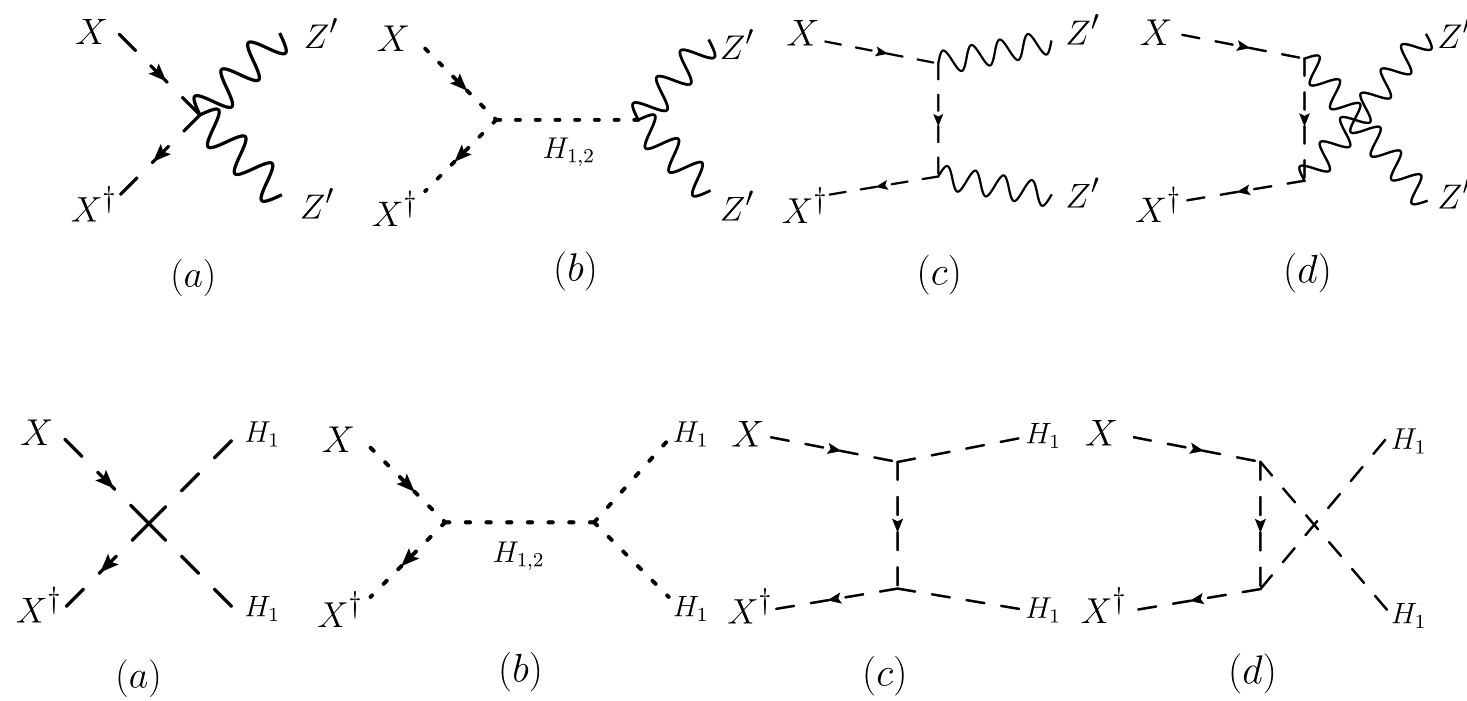


FIG. 2. (*Top*) Feynman diagrams for Complex scalar DM annihilating to a pair of Z' bosons. (*Bottom*) Feynman diagrams for Complex scalar DM annihilating to a pair of H_1 bosons.

$H_2 \simeq H_{125}$ and $H_1 \simeq \phi$ (dark Higgs)

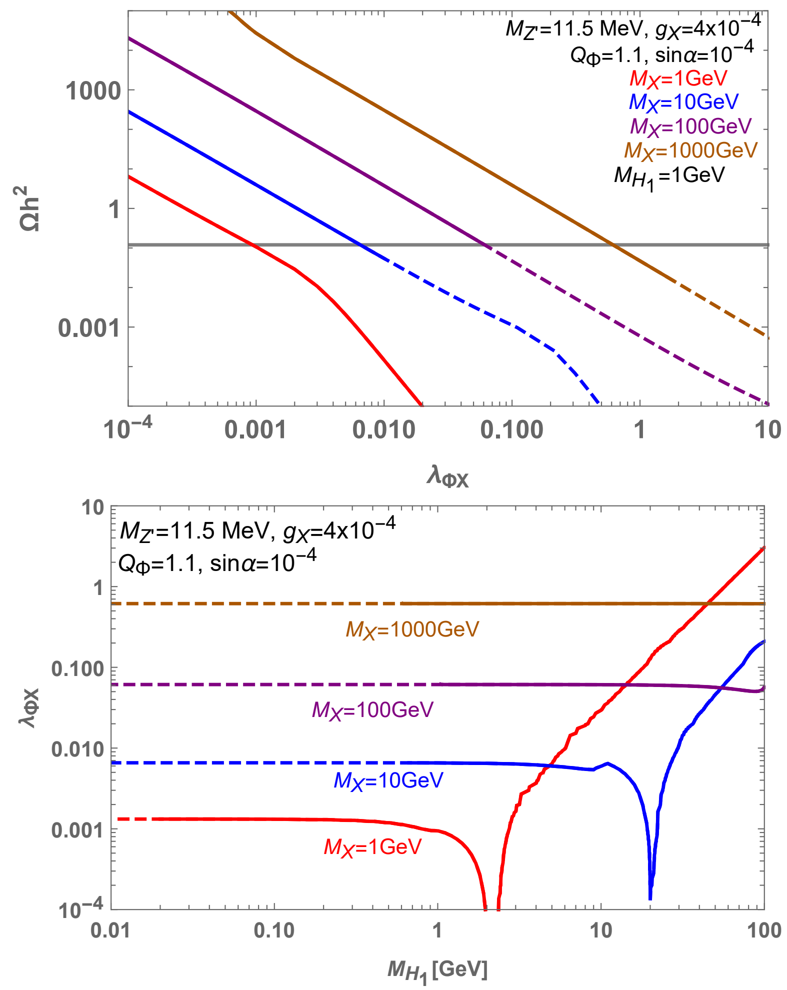


FIG. 3. *Top*: relic abundance of complex scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] for $M_X = 1,\ 10, 100,\ 1000$GeV, respectively. We assumed $Q_\Phi = 1.1$, $M_{H_1} = 1$GeV, and $\sin\alpha = 10^{-4}$. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$.

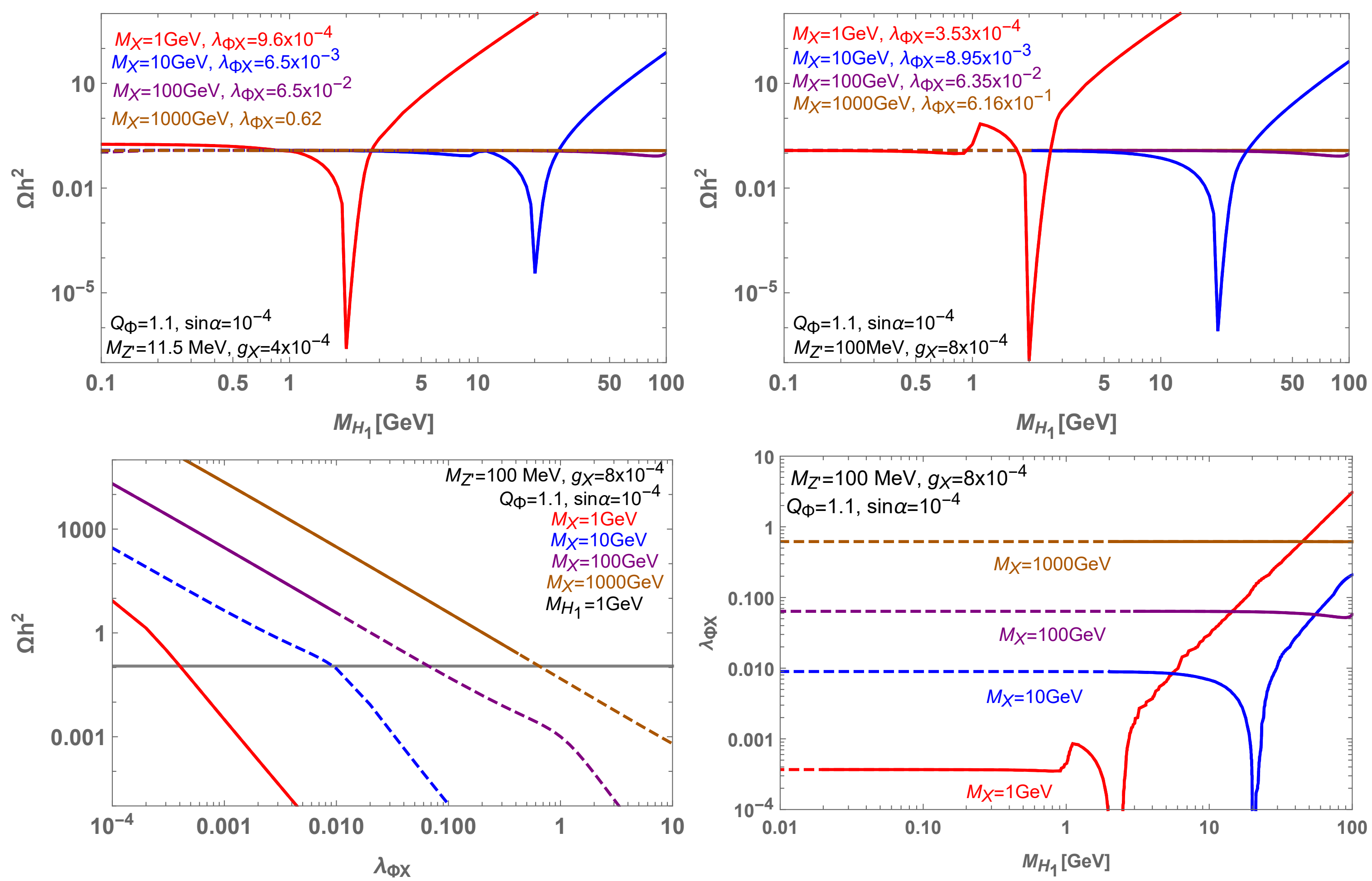


FIG. 7. The (*Top*) plots show the relic abundance of complex scalar DM for $Q_\Phi = 1.1$ as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*). The (*Bottom*) plots show the relic density as functions of $\lambda_{\Phi X}$ (*Left*) and the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$ (*Right*) for [**BPII**] . We take four different DM masses, $M_X = 1,\ 10, 100,\ 1000$GeV, respectively. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$
due to dark Higgs boson contributions

Complex Scalar DM: $U(1)_{L_\mu - L_\tau} \to Z_2 \; (Q_\Phi = 2Q_X)$

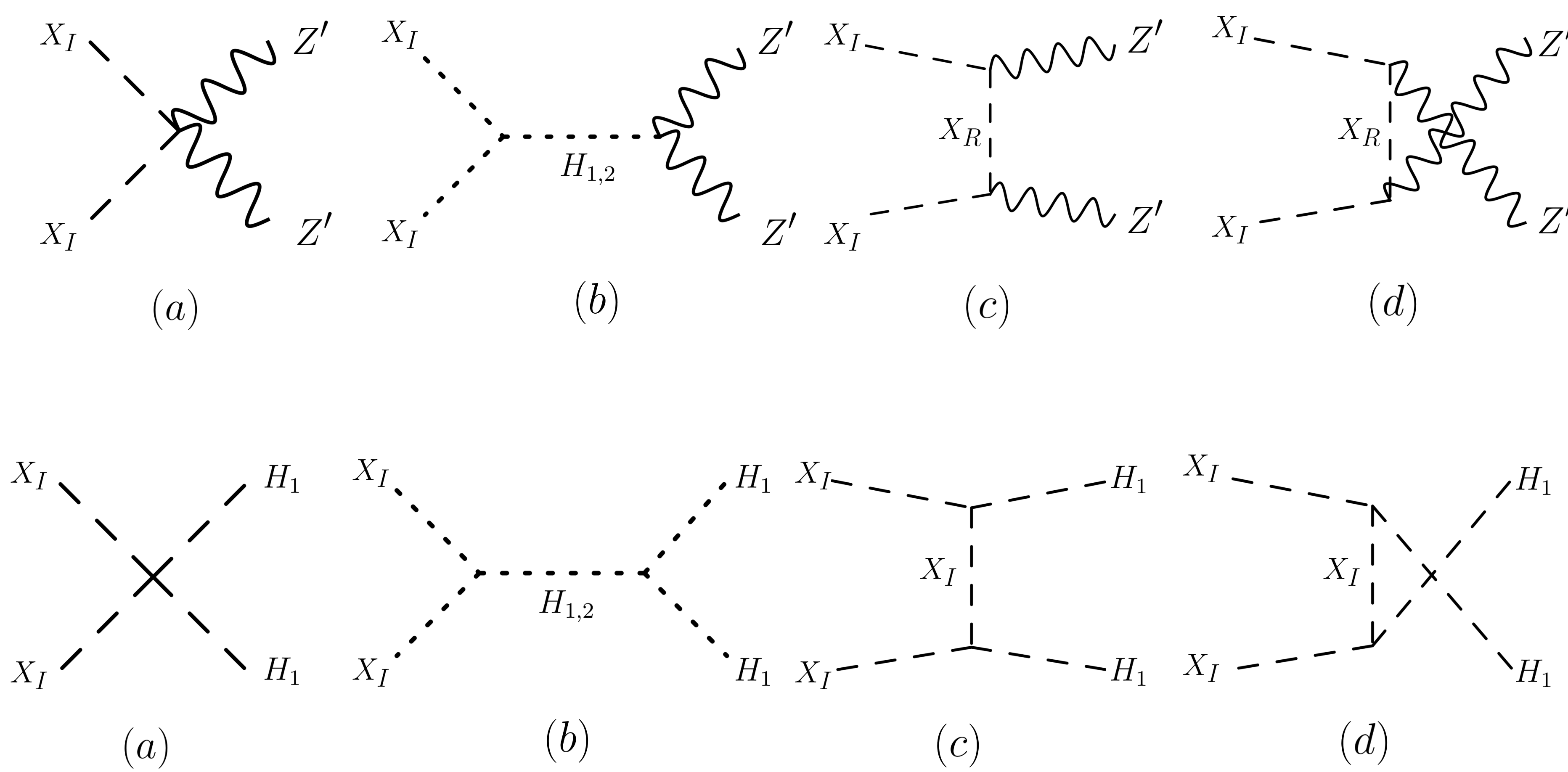


FIG. 8. (*Top*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of Z' bosons. (*Bottom*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of H_1 bosons, which is mostly dark Higgs-like.

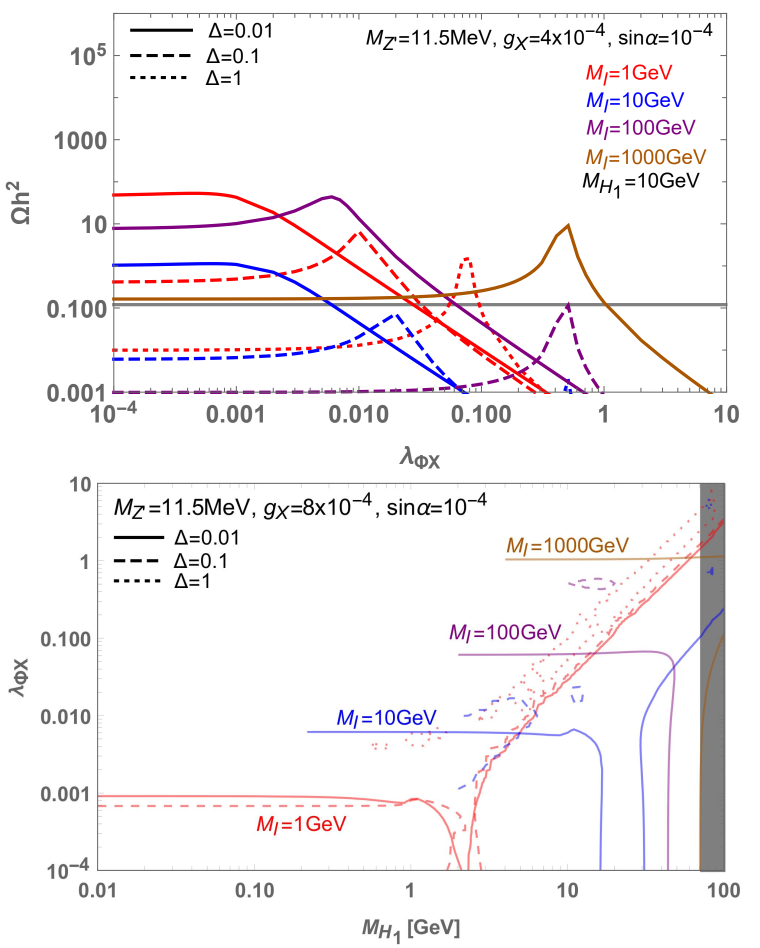


FIG. 4. *Top*: Relic abundance of local Z_2 scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] and different values of mass splittings (Δ). We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the curves satisfy the DM direct detection bound. *Bottom*: The preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for different values of Δ. The gray area is excluded by the perturbative condition.

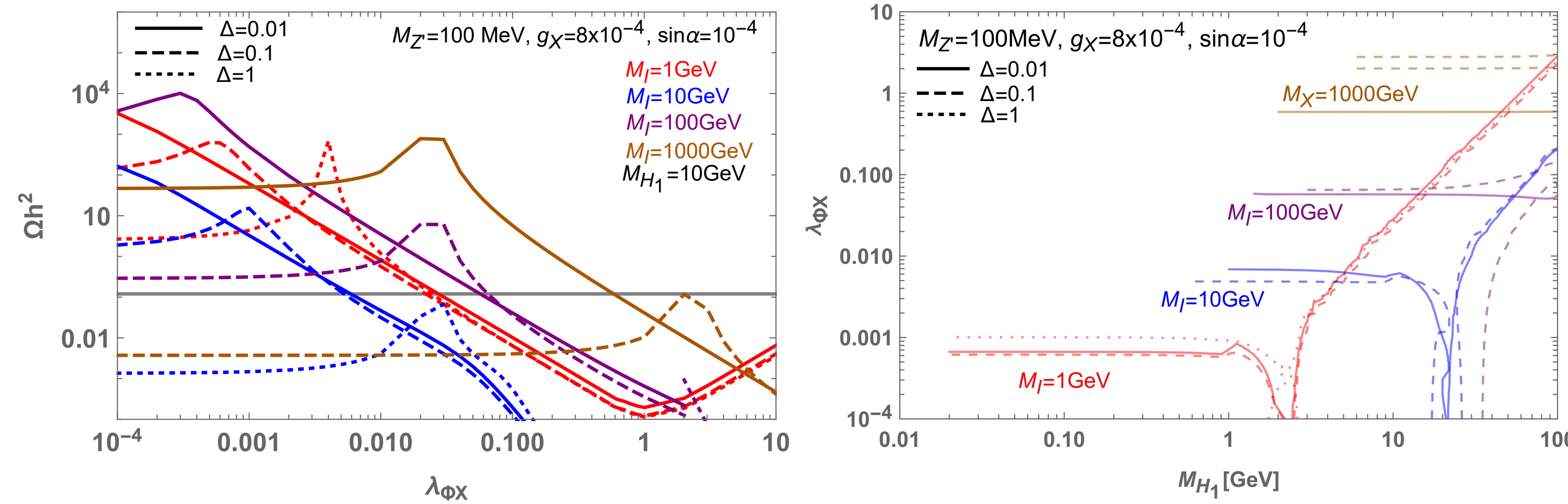


FIG. 9. (*Left*) Relic abundance of local Z_2 scalar DM in case of [**BPII**]. We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the lines satisfy the DM direct detection bound. (*Right*) Relic abundance of local Z_2 scalar DM in the $(M_{H_1}, \lambda_{\Phi X})$ plane.

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$ due to dark Higgs boson contributions

Dirac fermion DM: $U(1)_{L_\mu - L_\tau} \to Z_2$ $(Q_\Phi = 2Q_\chi)$

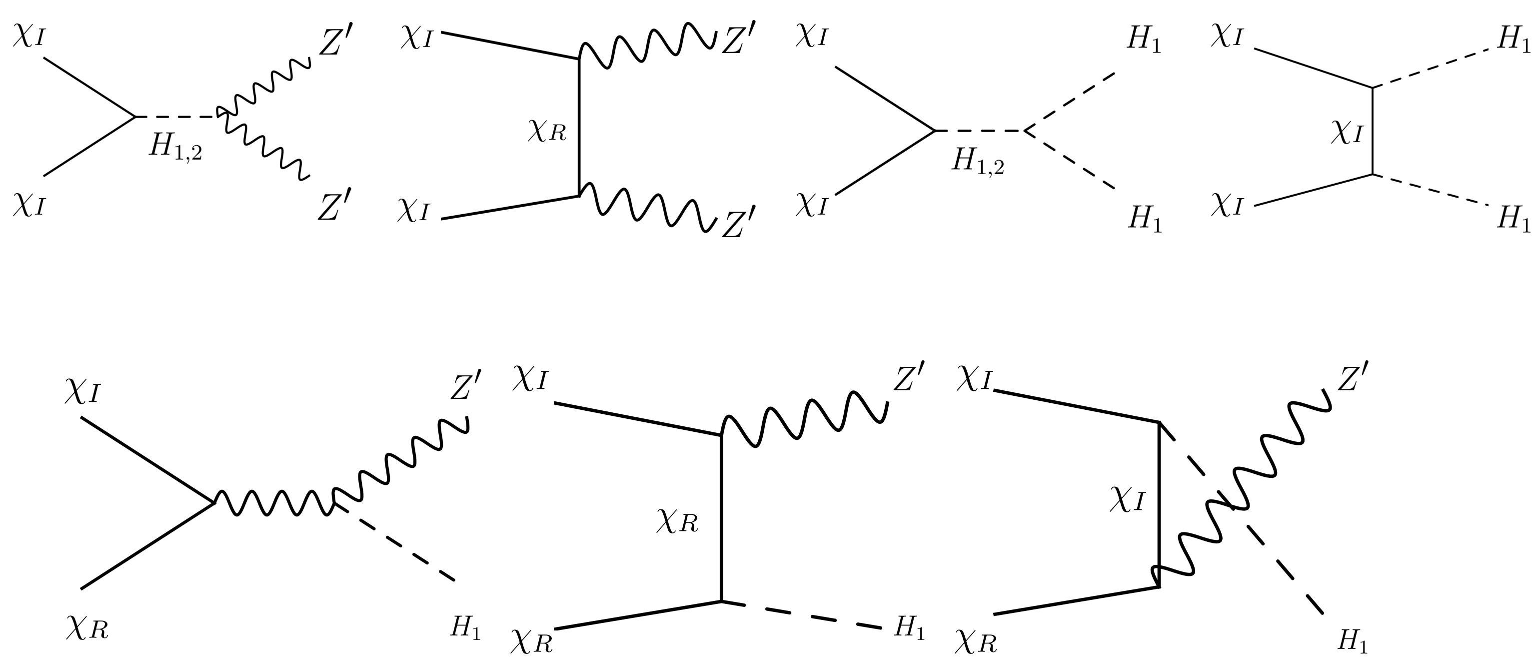


FIG. 5. Feynman diagrams of local Z_2 fermion DM (co-)annihilating into a pair of Z' bosons and H_1 bosons (*Top*), and $Z' + H_1$ (*Bottom*).

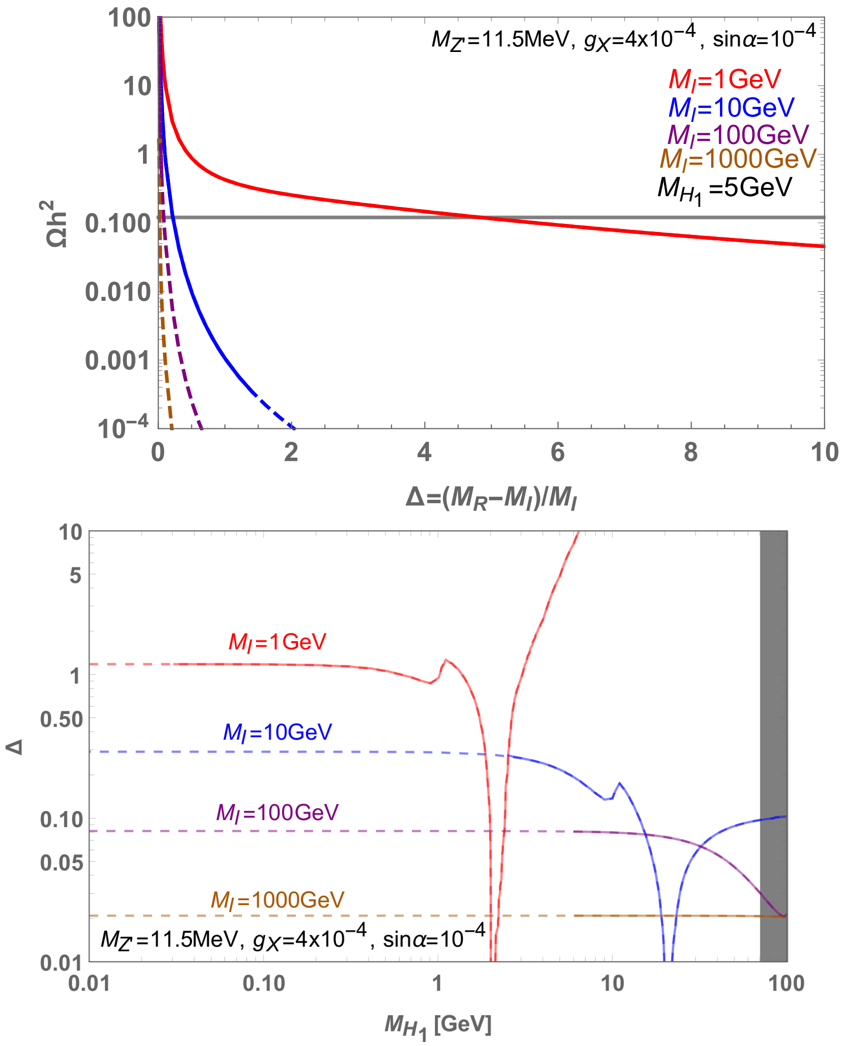


FIG. 6. *Top*: Dark matter relic density as functions of mass splitting Δ for [**BPI**] and for different values of DM mass, $M_I = 1, 10, 100, 1000$GeV. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: Preferred parameter space in the (M_{H_1}, Δ) plane for different DM masses. The gray region is ruled out by the perturbativity condition on λ_Φ.

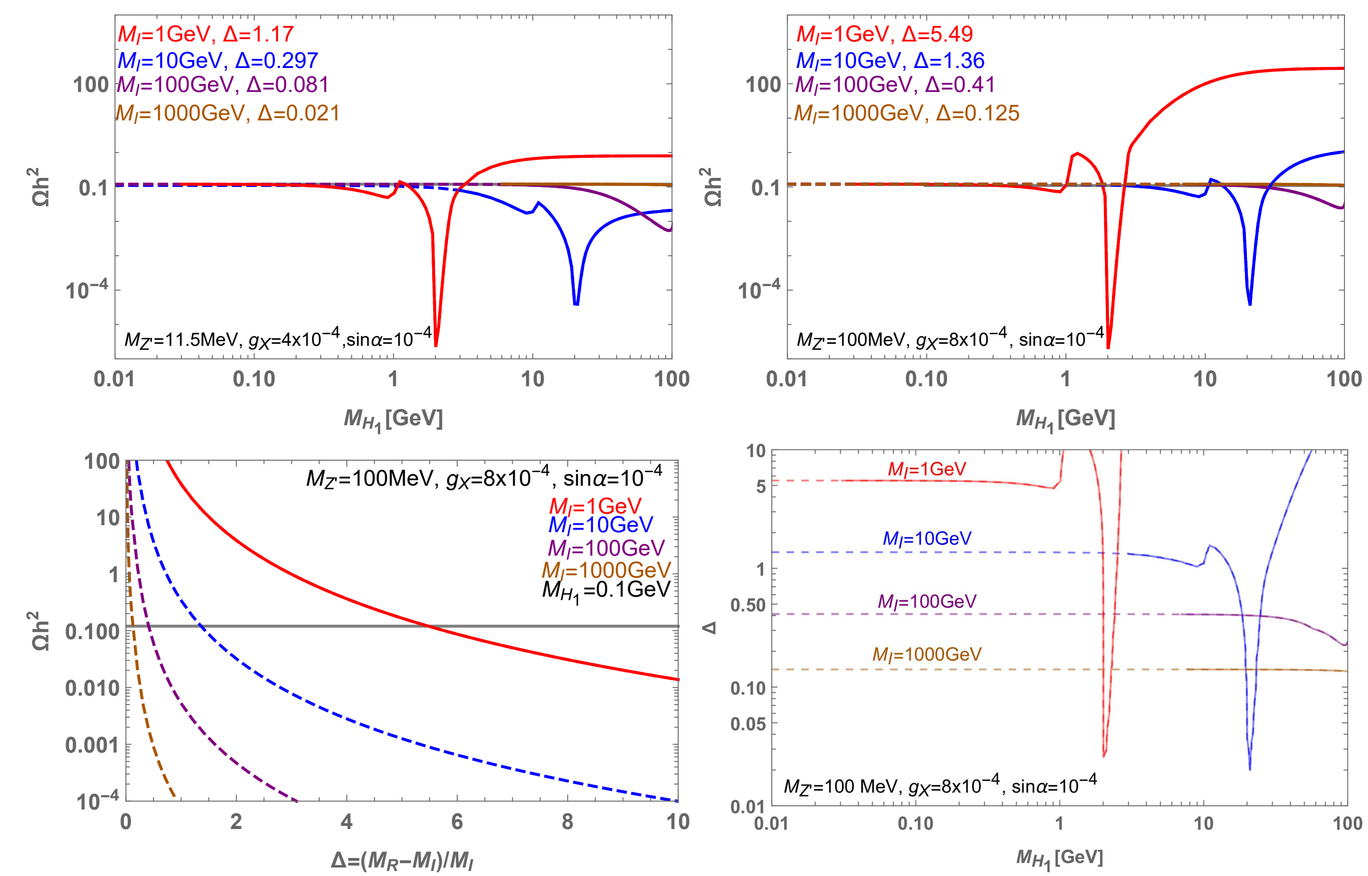


FIG. 11. (*Top*) Dark matter relic density as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*) (*Bottom-Left*) Dark matter relic density as functions of Δ for [**BPII**], and *(Bottom-right)* Preferred parameter region in the (Δ, M_{H_1}) plane. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$ due to dark Higgs boson contributions

Conclusion

- DM physics with massive dark photon can not be complete without including dark gauge symmetry breaking mechanism, e.g. dark Higgs field ϕ, which have been largely ignored by DM community (or some ways other than dark Higgs to provide dark photon mass)

- Many examples show the importance of ϕ in DM phenomenology, astroparticle physics and cosmology

- Once ϕ is included, can accommodate the muon g-2 and thermal DM without the s-channel resonance condition $m_{Z'} \sim 2m_{\rm DM}$

- $m_{\rm DM}$: essentially free, whereas $m_{Z'} \sim O(10-100)$ MeV and $g_X \sim O(10^{-4})$ can explain the muon (g-2)

On Recent Belle II data on $B^+ \to K^+\nu\bar{\nu}$

Work in preparation
With Shu-Yu Ho, Jongkuk Kim

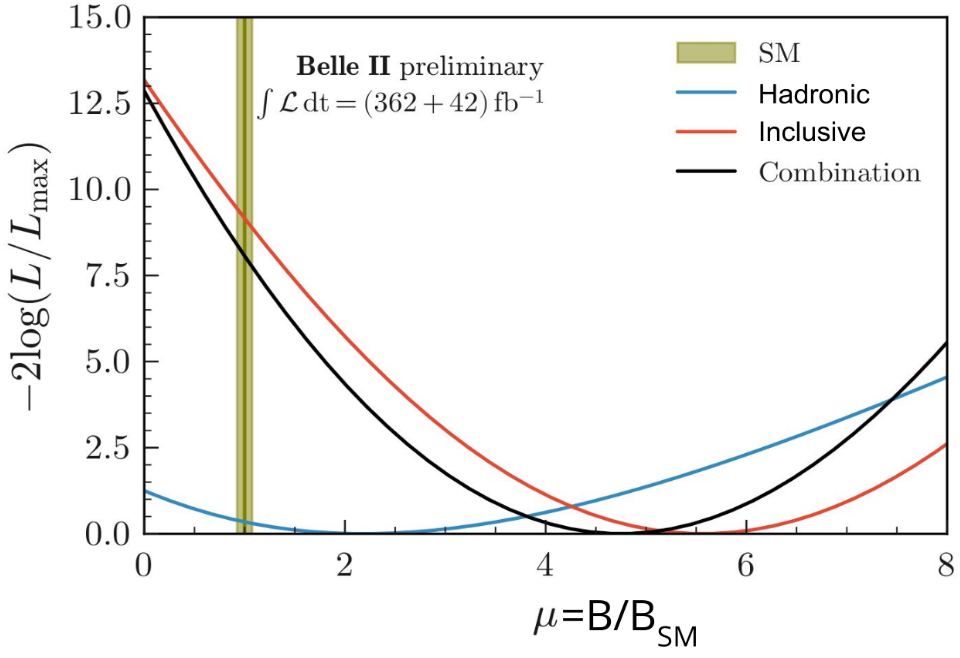
Measurement of $B^+ \to K^+ \nu\bar{\nu}$

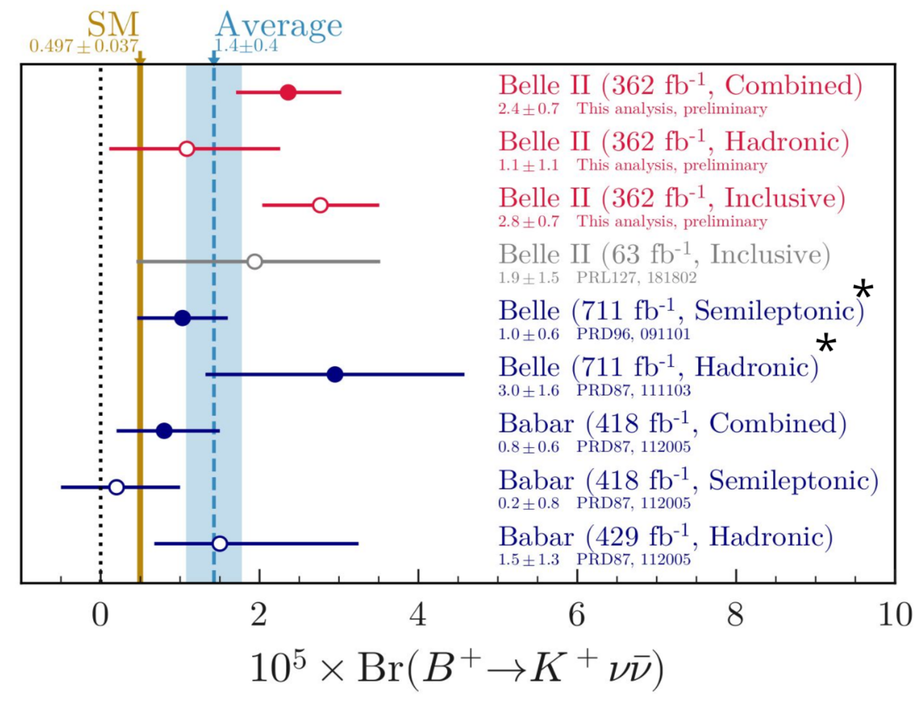
- Challenges in reconstructing the events
  - Searches for $B \to K^{(*)}\nu\bar{\nu}$ have only been performed at the B factories Belle and BaBar

- Using the same techniques in Belle, BaBar
  - Semileptonic tagged analyses
  - Hadronic-tagged analyses

- Inclusive tag analysis (Belle & BelleII)
  - Allow one to reconstruct inclusively the decay $B^+ \to K^+\nu\bar{\nu}$ from the charged kaon

Measurement of $B^+ \to K^+\nu\bar{\nu}$





- $Br(B^+ \to K^+\nu\bar{\nu}) = (2.4 \pm 0.7) \times 10^{-5}$
  - Significance of observation is 3.6σ
  - 2.8σ tension with the SM prediction
- $Br(B^+ \to K^+E_{\text{miss}})_{NP} = (1.9 \pm 0.7) \times 10^{-5}$
- Indicate not only the presence of NP in the $b \to s\nu\bar{\nu}$ transitions but even the presence of new light states (particles in dark sector?)

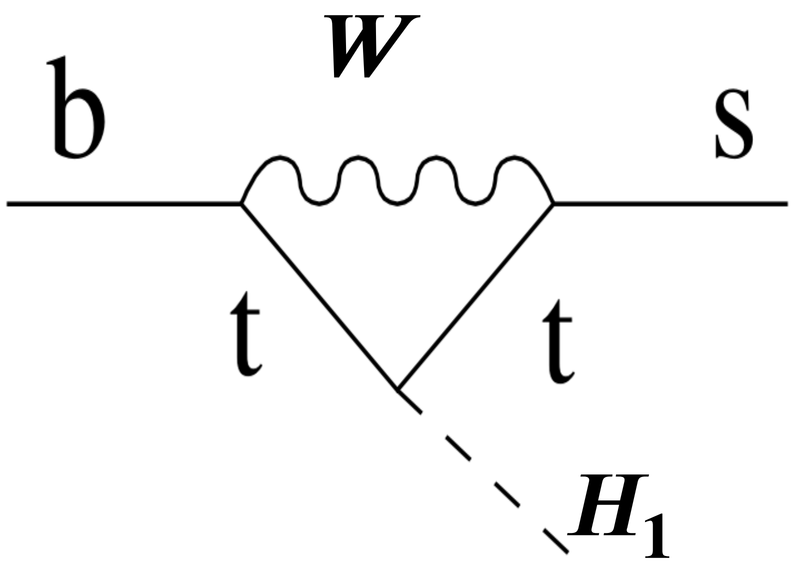
CMB constraints

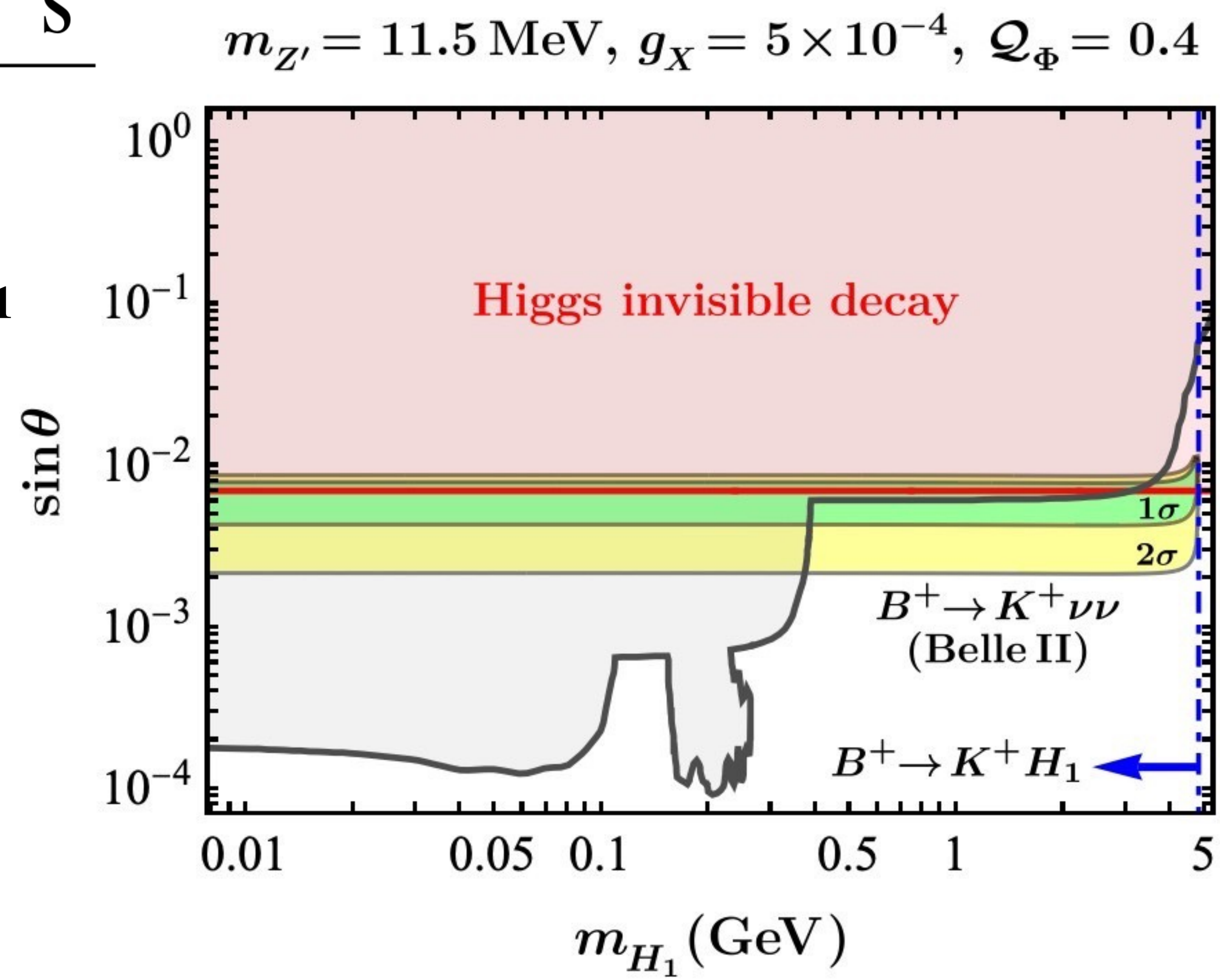
- Dominant DM annihilation channel
  - Before resonance, $XX^* \to Z'Z', h_1 h_1$
  - Near resonance, $XX^* \to Z'h_1$
  - After resonance, $XX^* \to Z'Z'$
- h_1 dominantly decays into a pair of either Z' or DM (kinematically open when $m_{h_1} > 2m_X$)

- We can avoid the stringent CMB bound thanks to invisible decay of both h_1 and Z'

BelleII anomaly: two-body decay

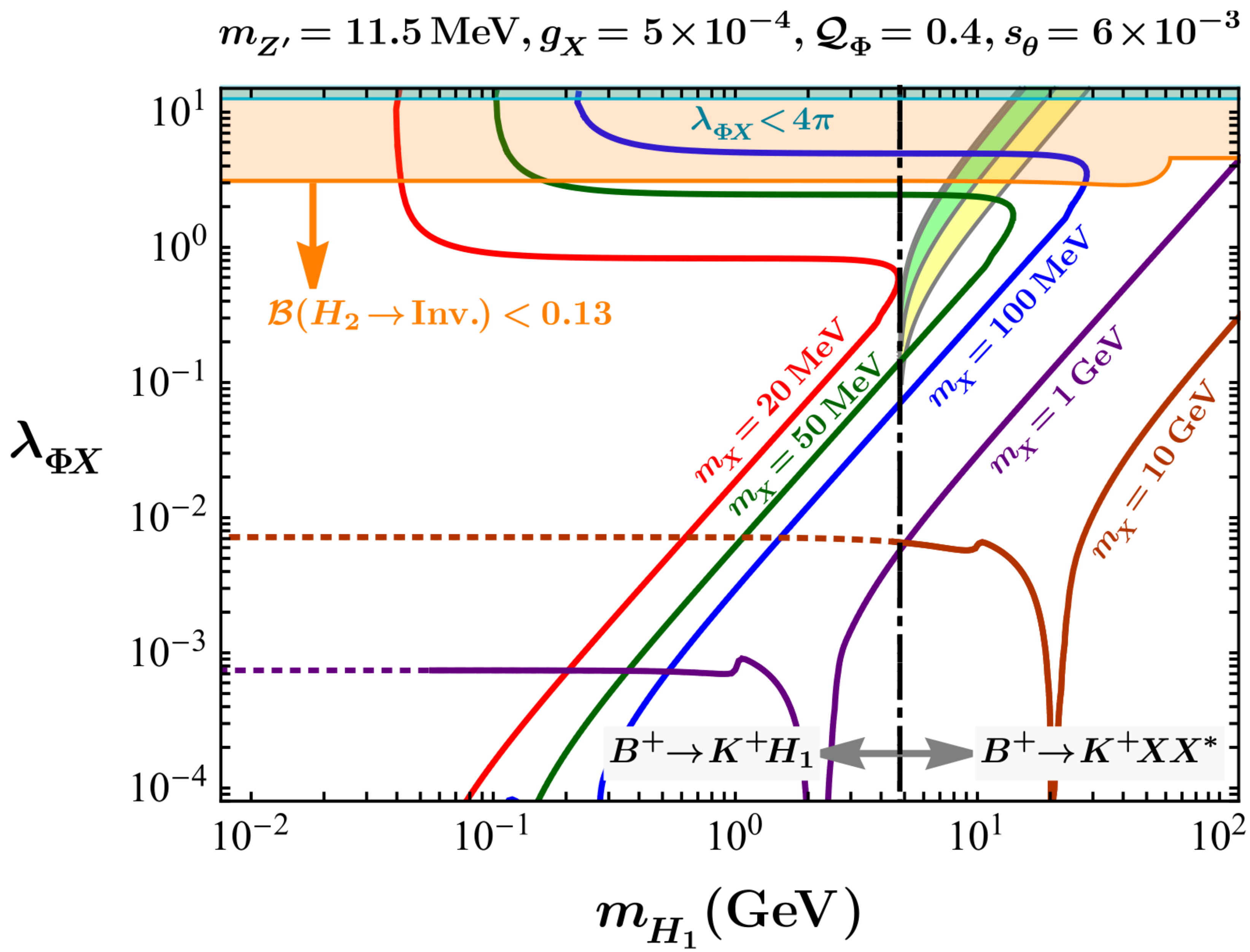
- When $m_{H_1} < m_B - m_K$, two-body decay
-





BelleII anomaly: three-body decay

- When $m_{H_1} > m_B - m_K$, H_2 is off-shell → three-body decay
  - Two-body decay: $m_X \lesssim 6.5\text{GeV}$ $(m_{H_1} = 2\text{GeV})$
  - Three-body decay: $20\text{MeV} < m_X \lesssim 60\text{MeV}$ $(m_{H_1} > m_B - m_K)$



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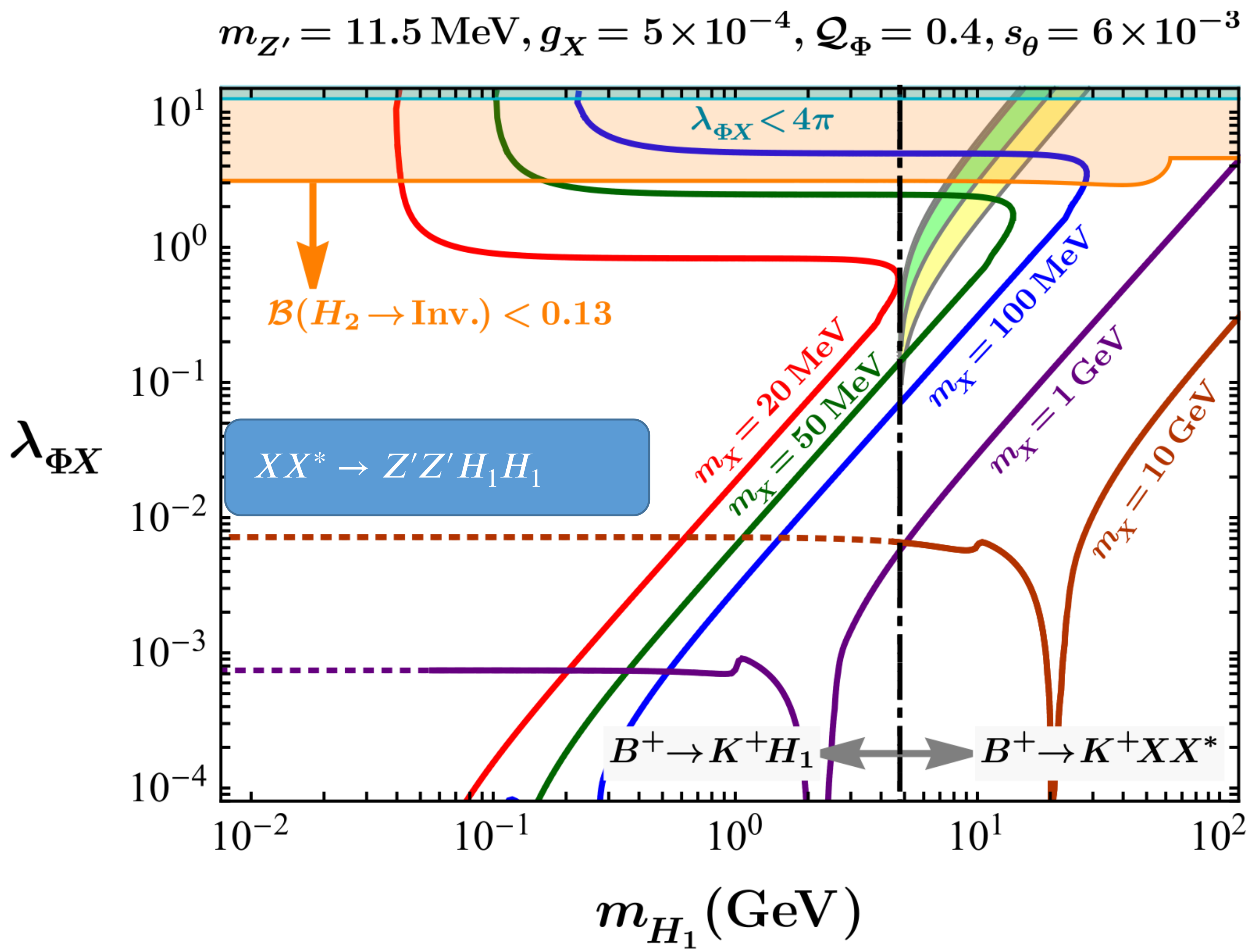

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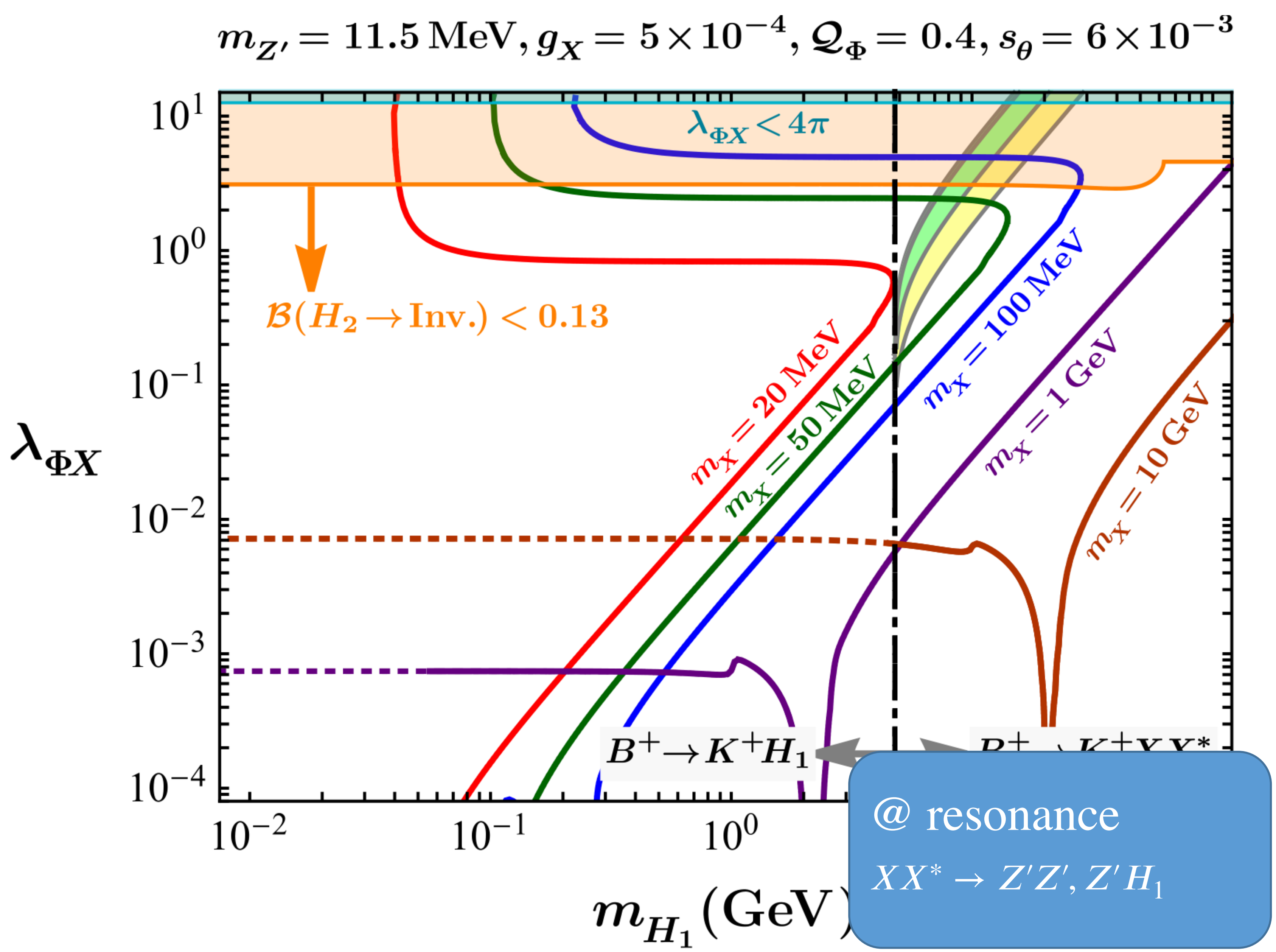

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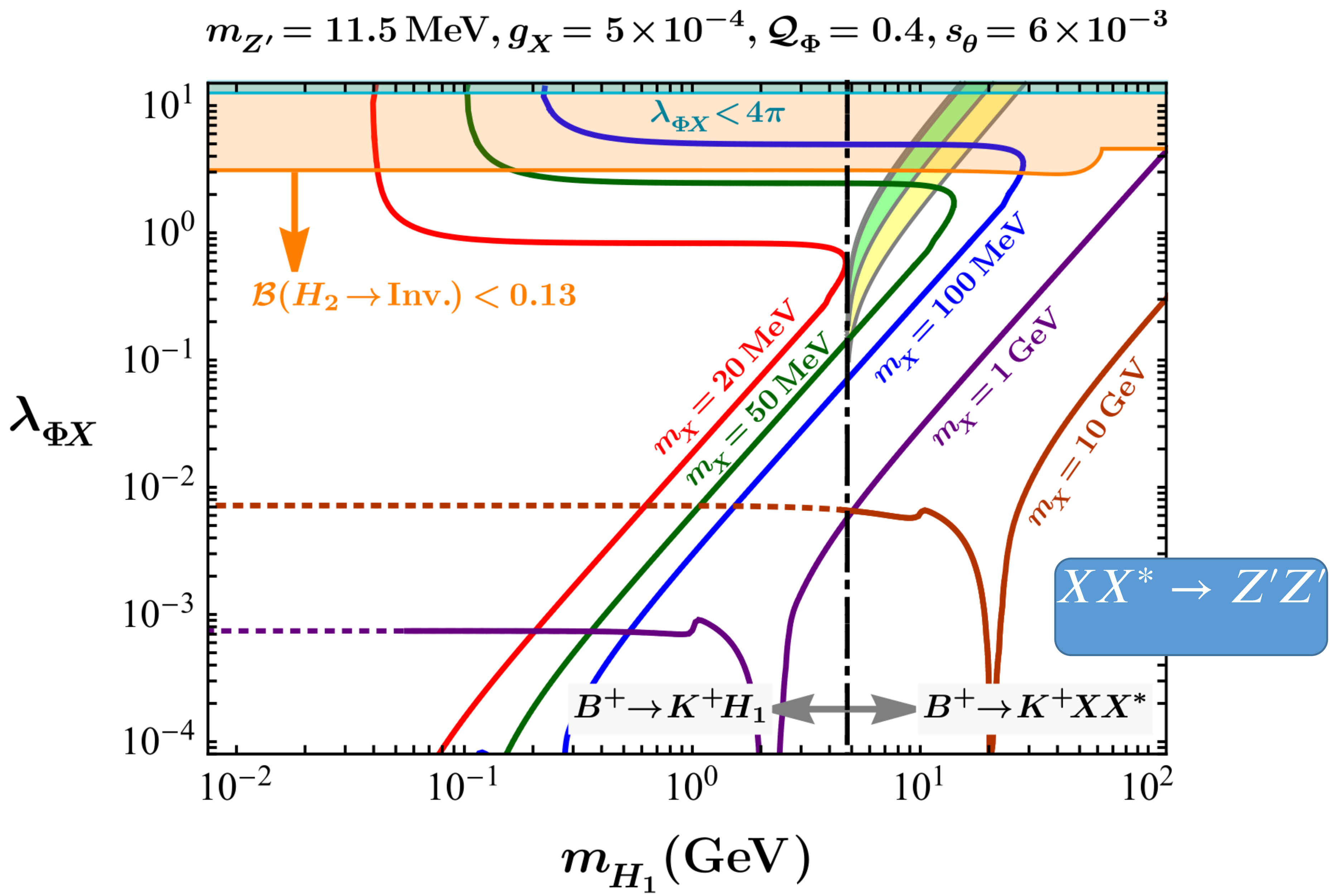
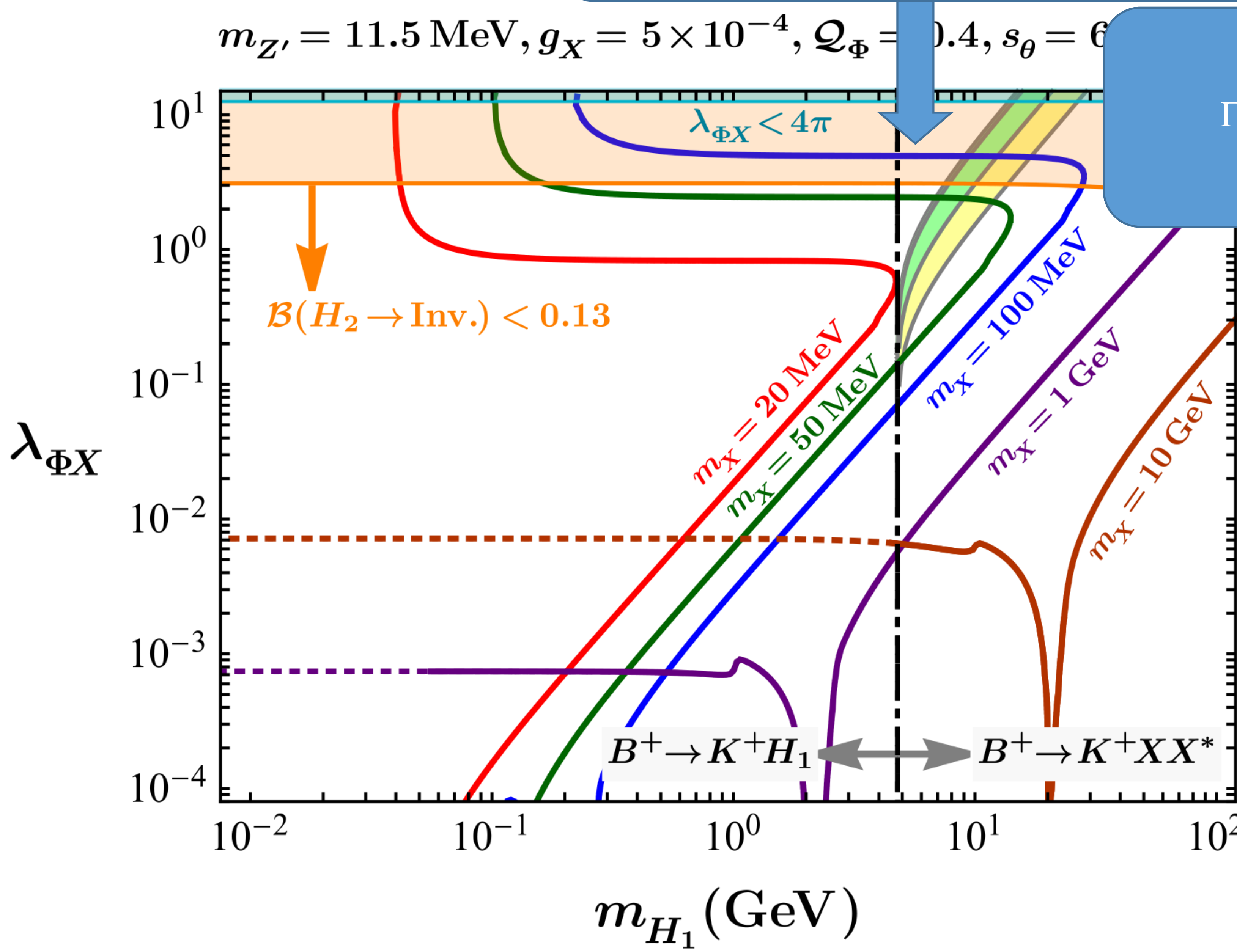


BelleII anomaly: three-body decay

- When $m_{H_1} > m_B - m_K$, H_2 is off-
  - Two-body decay: $m_X \lesssim 6.5\text{GeV}$ (
  - Three-body decay: $20\text{MeV} < m_X$

$$\sigma v \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2}\frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(4m_X^2 - m_{H_1}^2)^2 + m_{H_1}^2\Gamma_{H_1}^2}\sqrt{1-\frac{m_{Z'}^2}{m_X^2}}$$

$$\Gamma_{H_1} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}}\sqrt{1-\frac{4m_X^2}{m_{H_1}^2}}$$



BelleII anomaly: three-body decay

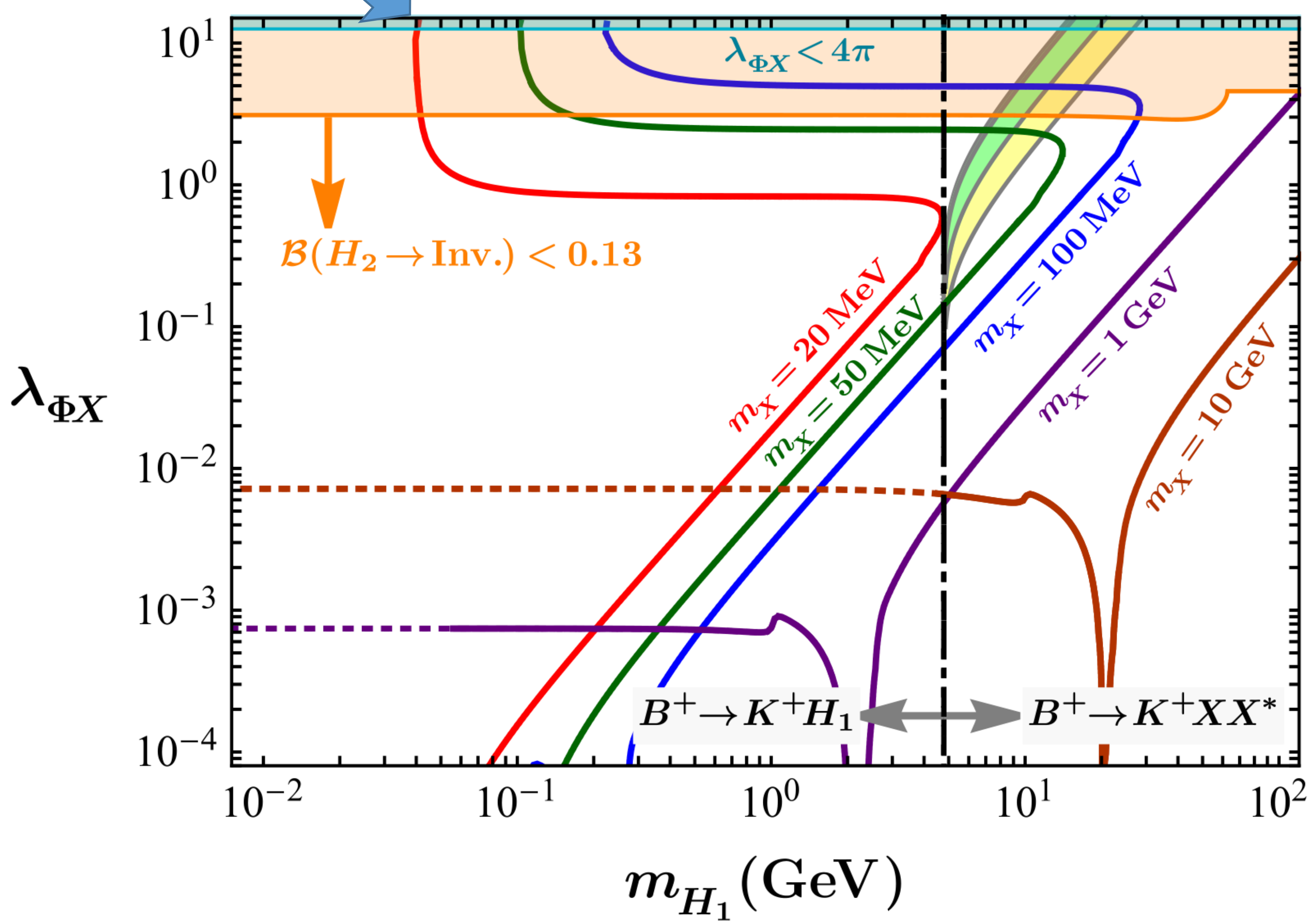
$$\Gamma_{H_1} = \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi\, m_{H_1}} \sqrt{1 - \frac{4m_X^2}{m_{H_1}^2}} \qquad \sigma v \propto \frac{\lambda_{\Phi X}^2}{m_{H_1}^2 \Gamma_{H_1}^2}$$

Phase-space suppression

ee-body decay

$_B - m_K)$

$m_{Z'}$ ... 1.5 MeV, $g_X = 5\times 10$ ..., $Q_\Phi = 0.4$, $s_\theta = 6\times 10^{-3}$



Interplay btw Higgs Inflation and DM

- Jinsu Kim, Sarif Khan, PK, arXiv:2309.07839

Basics

- Higgs-portal Assisted Higgs Inflation: 2 scalars, H, ϕ
- Dark Higgs contributes to λ_H (positive contribution)
- Nonminimal couplings: $\xi_h H^\dagger H + \xi_\phi \Phi^\dagger \Phi$
- Generalized Higgs Inflation with two scalar fields and R^2 (Starobinsky)
- No more tight correlation with top quark mass

Model

- SM + Dark sector with $U(1)_D$ charges : $\psi(n_\psi), \phi_D(1)$, and dark photon W_D ($1 \leq n_\psi \leq 100$, $M_{W_D} < M_\psi$)

- Adding dark fermion to the Higgs portal VDM model

- DM candidates: W_D, ψ (assume kinetic mixing = 0)

- Dark photon mass given by dark Higgs mechanism, and new channels for dark photon pair annihilations into a pair of (dark) Higgs boson. [In Stueckelberg, no dark Higgs and the model is not viable, since DM is overproduced.]

Feynman Diagrams

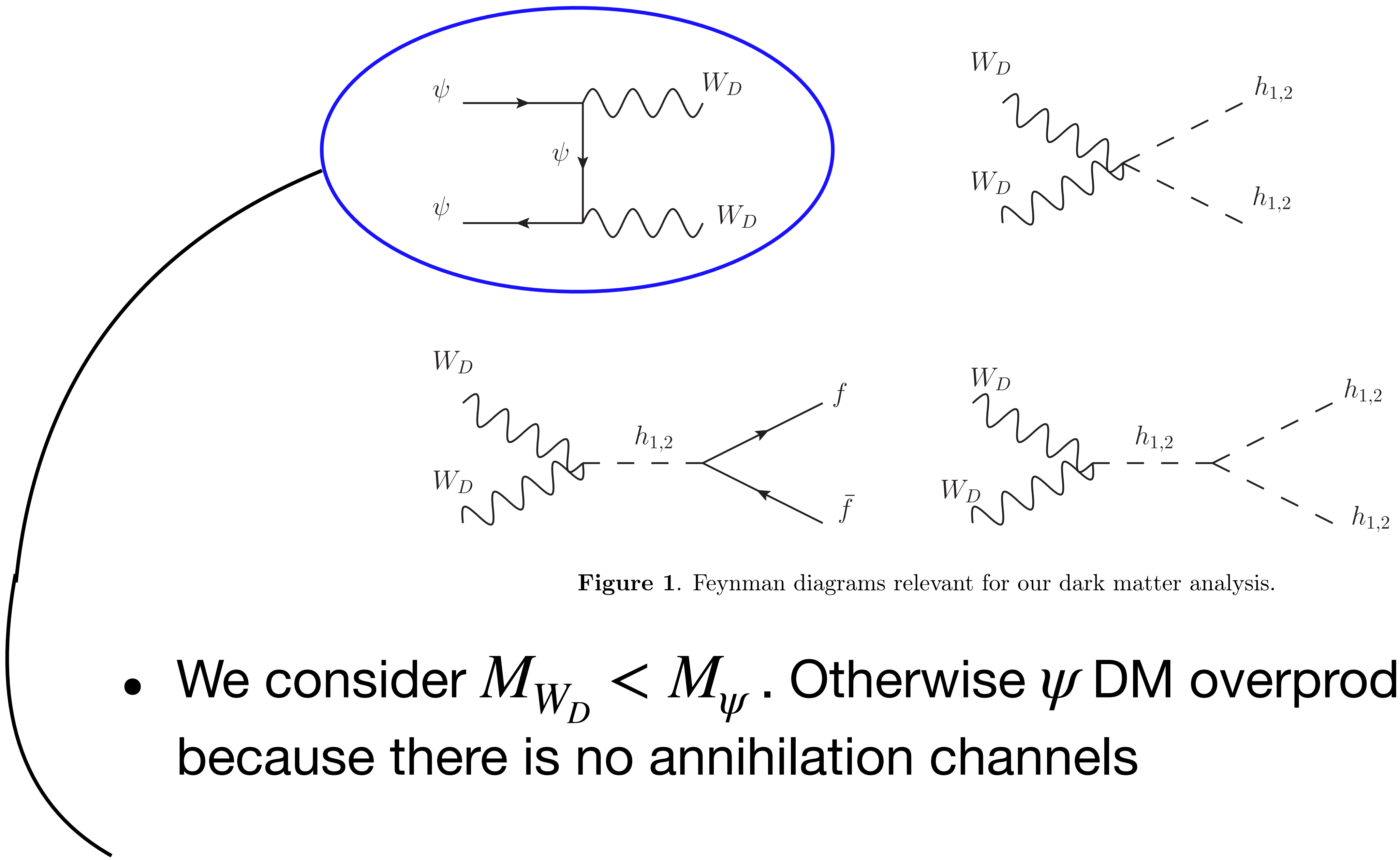


Figure 1. Feynman diagrams relevant for our dark matter analysis.

- We consider $M_{W_D} < M_{\psi}$. Otherwise ψ DM overproduced because there is no annihilation channels
- Only diagram for ψ DM pair annihilation

(In)Direct Detections

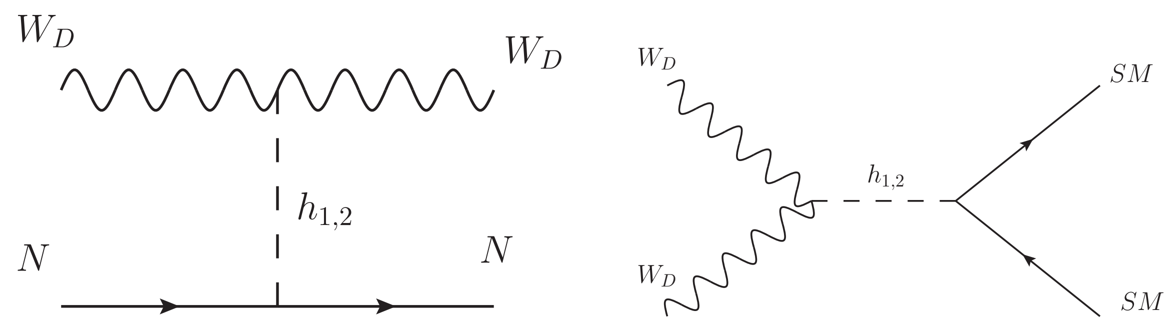
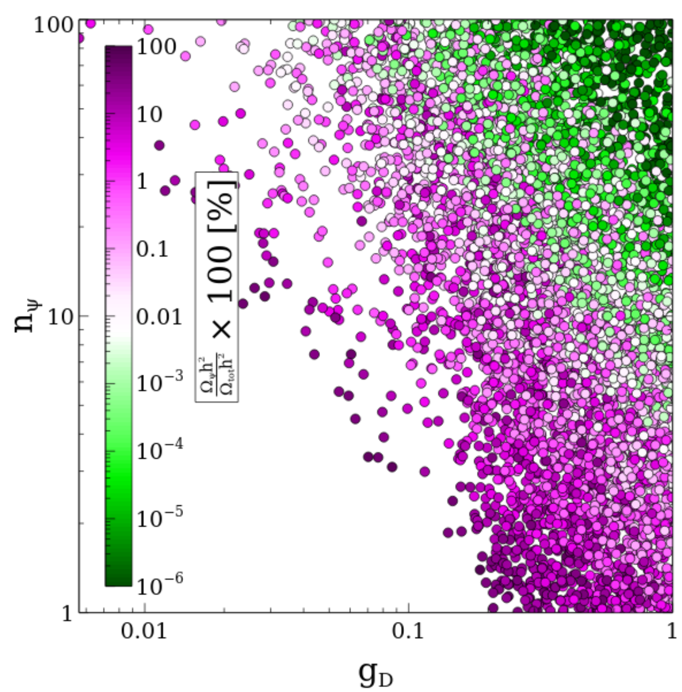


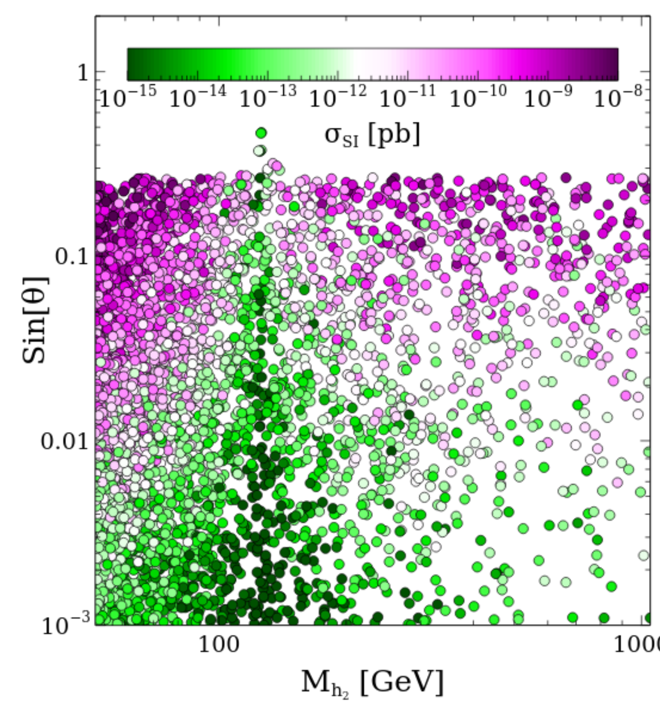
Figure 2. Relevant Feynman diagrams for the direct detection (left) and indirect detection (right) prospects.

- ψ DM : Not sensitive to direct detection experiments
- (In)direct detection signals : controlled by (dark) Higgs
- Cancellation mechanism for direct detection of W_D DM (Ko et al, 2012, etc): $\sigma_{\rm SI} \propto (1/m_{H_1}^2 - 1/m_{H_2}^2)^2$

Allowed Ranges

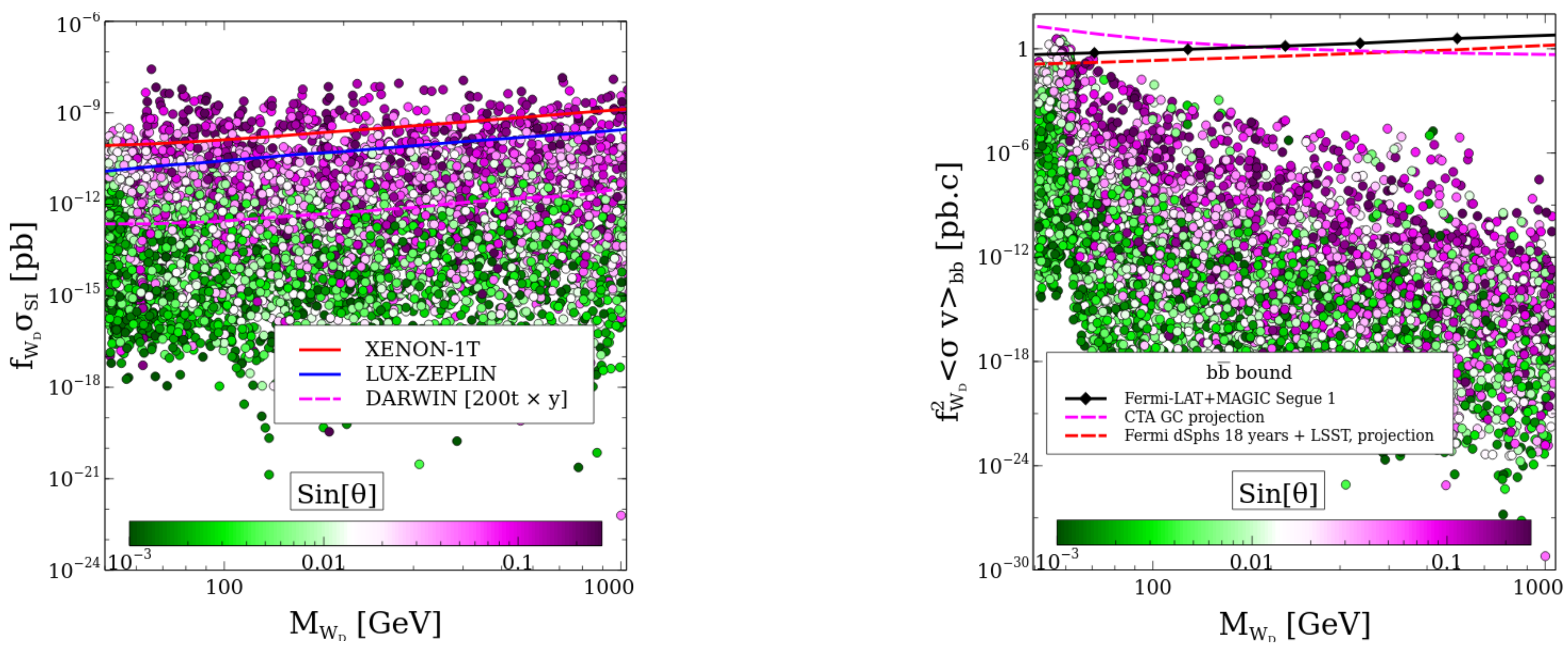
$$50 \leq M_{h_2}\,[\mathrm{GeV}] \leq 1050\,, \quad 50 \leq M_{W_D}\,[\mathrm{GeV}] \leq 1050\,, \quad 1 \leq (M_\psi - M_{W_D})\ [\mathrm{GeV}] \leq 100\,,$$
$$10^{-3} \leq g_D \leq 1\,, \quad 10^{-3} \leq \sin\theta \leq 0.5\,, \quad 1 \leq n_\psi \leq 100\,. \tag{3.7}$$





- Anti—correlation between n_ψ & g_D
- Cancellation between two Higgs boson in σ_{SI}

Detection Prospects



$$f_{W_D} \equiv \Omega_{W_D}/\Omega_{\rm DM}$$

- Detection strength is suppressed by f_{W_D} (fraction of W_D)
- Although DM is WIMP type, a large portion of parameter space will be accessed in the future

Summary

- Minimal model for weak scale DM : DM + Dark gauge symmetry $\rightarrow$ dark photon, dark Higgs, DR

- The only relevant pheno questions: particle contents, mass scales of these particles and coupling strengths

- Then one can interpret (in)direct DM detection, DM@colliders, and cosmological effects in a consistent way. Otherwise one can have wrong/misleading results

- Sometimes it is crucial to consider both particle physics and cosmological data simultaneously

Conclusions

- I discussed different types of stable or long-lived DM models with built-in (light) mediators because of the underlying local dark gauge symmetry (standard QFT)
- Dynamics (interaction between DM and SM particles and DM self interactions) is completely fixed by local gauge symmetry
- Dark Higgs important for Unitarity and gauge invariance, and light DM scenarios

- Natural Ground for Light Mediators that solve (some) CDM puzzles
- Invisible Higgs decay into a pair of DM, or
- Non Standard Higgs decays into a pair of light dark Higgs bosons, or dark gauge bosons, etc.
- Additional singlet-like scalar "S" : generic, can play important roles in DM phenomenology, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio (also strong 1st order ph tr)>> Should be actively searched for