

Muon g-2 & Thermal WIMP DM in $U(1)_{L_\mu - L_\tau}$ Models

Jongkuk Kim
(김종국)

jkkim@kias.re.kr



Based on arXiv: 2204.04889

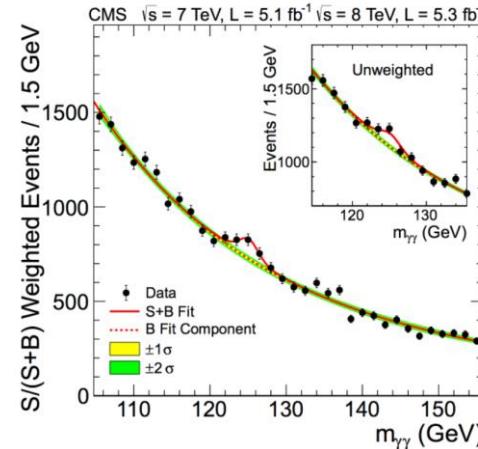
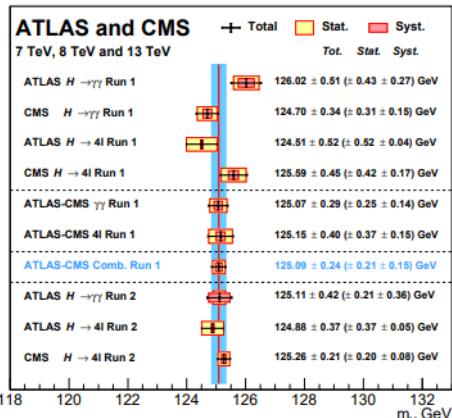
In collaboration with Seungwon Baek (Korea U.), Pyungwon Ko (KIAS)

University of Vienna, Vienna
2023. 8. 29



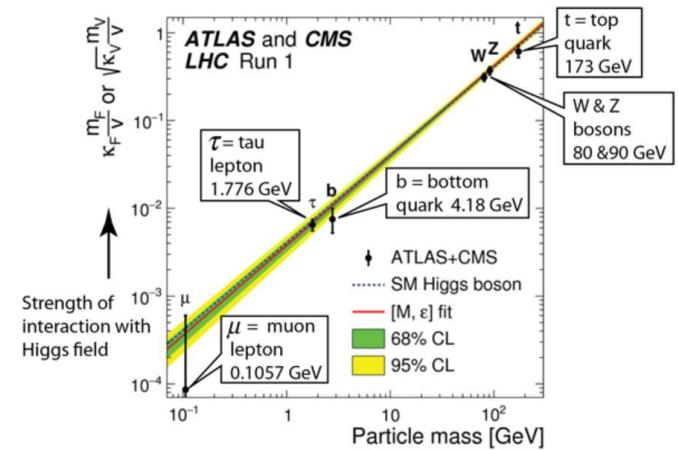
The Standard Model

- The Standard Model is GOOD!
 - The SM predictions are well consistent with experimental data



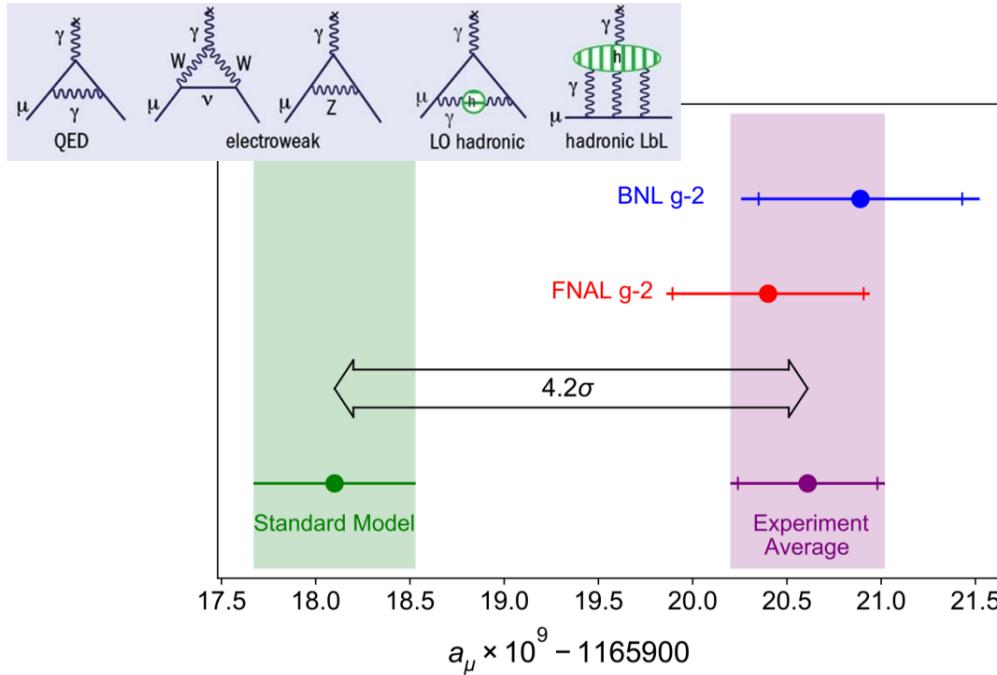
- Evidences to go to BSM theory

- Dark Matter
- Muon g-2 anomaly
- Hubble tension
- Neutrino oscillation
- Baryon asymmetry
- ...



Muon g-2 anomaly

- Muon anomalous dipole magnetic moment (muon g-2)
 - longstanding $\sim 4\sigma$ discrepancy between the measured and predicted values



Muon g-2 collaboration, PRL 2021

$$a_\mu^{BNL} = (11659208.9 \pm 5.4 \pm 3.3) \times 10^{-10}$$

$$a_\mu^{FNAL} = (11659204.0 \pm 5.1 \pm 1.9) \times 10^{-10}$$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.1 \pm 5.9) \times 10^{-10}$$

Combined result (4.2σ deviation)

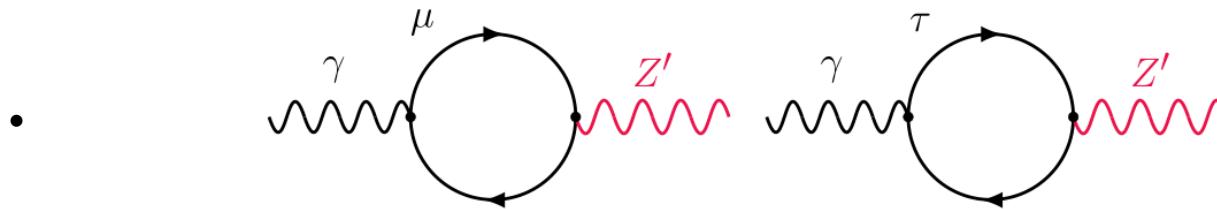
- Hint for new physics

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

- Possible to gauge one of the differences of two lepton-flavor numbers
 - $L_e - L_\mu, L_\mu - L_\tau$: anomaly free without extension of fermion contents
 - Symmetry including L_e is strongly constrained

$$- g_X Z'_\mu (\bar{\ell}_\mu \gamma^\mu \ell_\mu - \bar{\ell}_\tau \gamma^\mu \ell_\tau + \bar{\mu}_R \gamma^\mu \mu_R - \bar{\tau}_R \gamma^\mu \tau_R)$$

- No kinetic mixing between Z' and B @ high-energy
 - Kinetic mixing is generated through

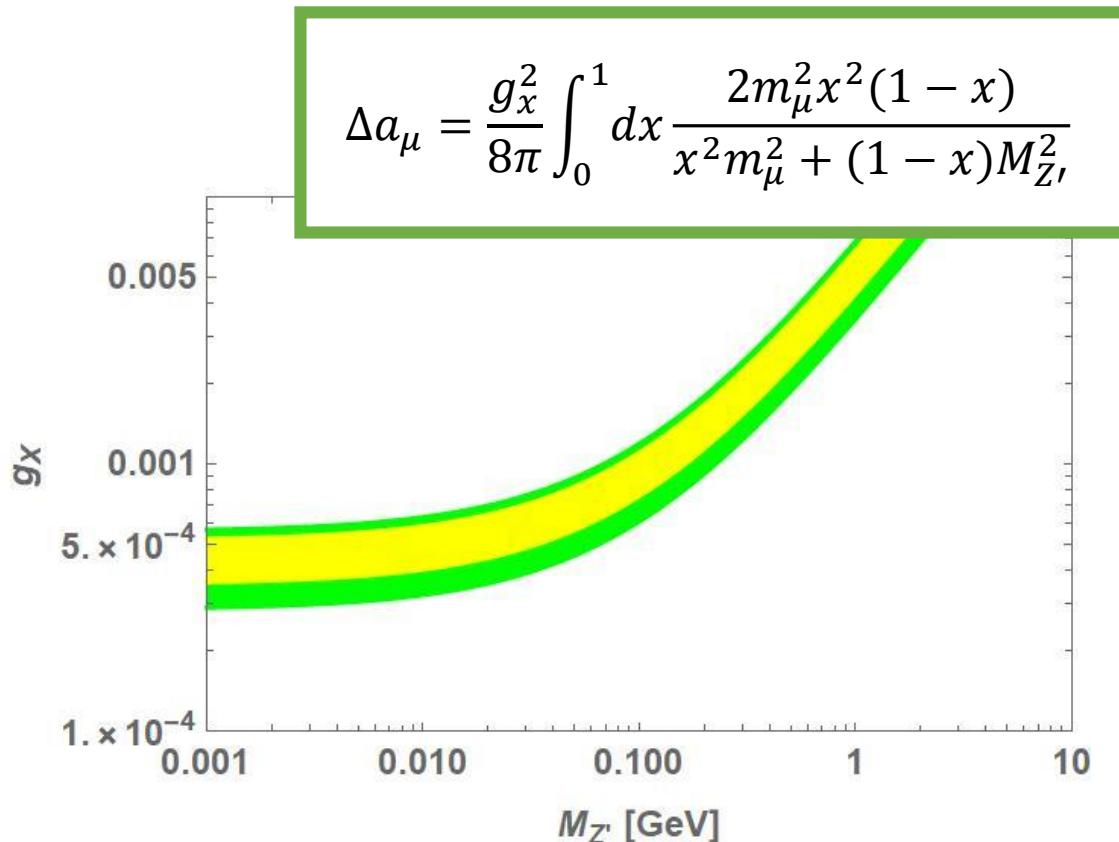


$$\bullet \quad \epsilon = -\frac{eg_{\mu-\tau}}{2\pi^2} \int_0^1 dx x(1-x) \log \left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2} \right] \xrightarrow{m_\mu \gg q} -\frac{eg_{\mu-\tau}}{12\pi^2} \log \frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70}.$$

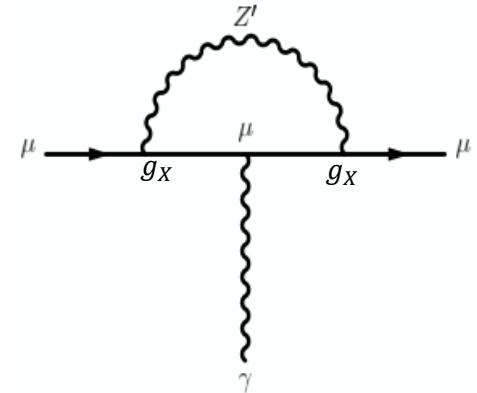
$U(1)_{L_\mu - L_\tau}$ model

- **Muon $g-2$ anomaly**

- $g_X \sim (3 - 8) \times 10^{-4}$ & $M_{Z'} \sim O(10)$ MeV when $M_{Z'} < M_\mu$



S. Baek, Deshpande, He, P. Ko, 2001
S. Beak, P. Ko, 2008
...

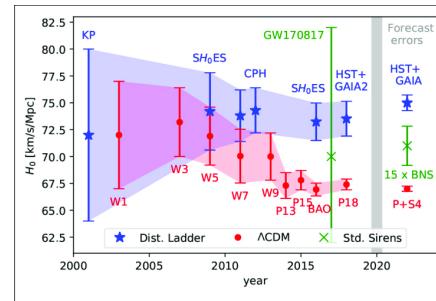


$U(1)_{L_\mu - L_\tau}$ model

- **Hubble tension**

P. Shah et al, AAR 2021

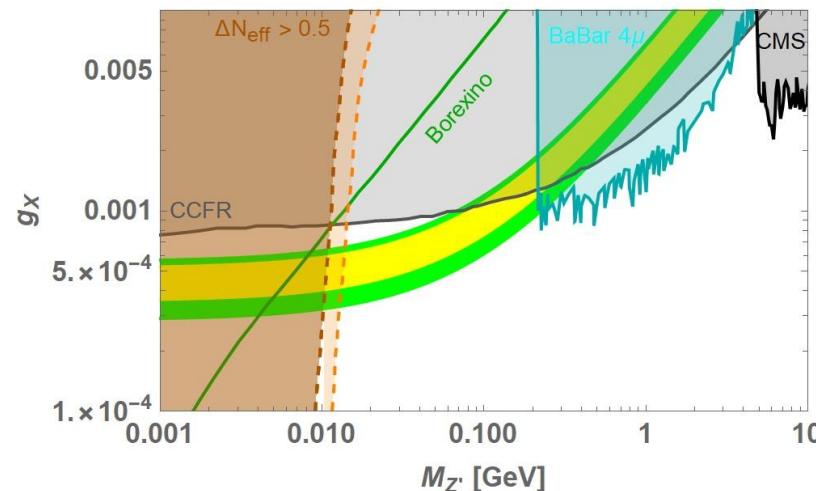
- Large difference between early and late H_0 measurement
 - $H_0 = 73.2 \pm 1.3 \text{ kms}^{-1}\text{Mpc}^{-1}$
 - $H_0 = 67.4 \pm 0.5 \text{ kms}^{-1}\text{Mpc}^{-1}$



- $U(1)_{L_\mu - L_\tau}$ Z' gauge boson

M. Escudero et al, JHEP 2019

- 10 – 20 MeV Z' reached thermal equilibrium in the early Universe & decay → Heating the neutrino population and **delaying the process of neutrino decoupling**
- $0.2 < \Delta N_{\text{eff}} < 0.5$



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

- Lagrangian (Here χ : fermion DM, Z' : Dark photon)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - g_X (\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau + \bar{\nu}_{L\mu}\gamma^\mu\nu_{L\mu} - \bar{\nu}_{L\tau}\gamma^\mu\nu_{L\tau}) Z'_\mu$$

$$- \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

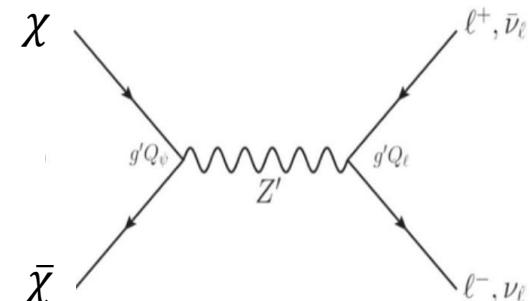
$$+ \bar{\chi} (i\partial_\mu \gamma^\mu - m_\chi) \chi - Q_\chi g_X Z'^\mu \bar{\chi} \gamma_\mu \chi$$

- Dominant annihilation channels:

- $\chi\bar{\chi} \rightarrow Z'^* \rightarrow \nu\bar{\nu}$
- $\chi\bar{\chi} \rightarrow Z'^* \rightarrow l\bar{l}$ when $m_l < m_\chi$
- $\chi\bar{\chi} \rightarrow Z'Z'$ when $m_{Z'} < m_\chi$

- Complex scalar DM

- Annihilation cross section is p-wave
- DM mass should be ~10MeV to explain both Hubble tension and muon g-2 anomaly at the same time



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

- Lagrangian (Here χ : fermion DM, Z' : Dark photon)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + g_X (\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau + \bar{\nu}_{L\mu}\gamma^\mu\nu_{L\mu} - \bar{\nu}_{L\tau}\gamma^\mu\nu_{L\tau}) Z'_\mu$$

$$- \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

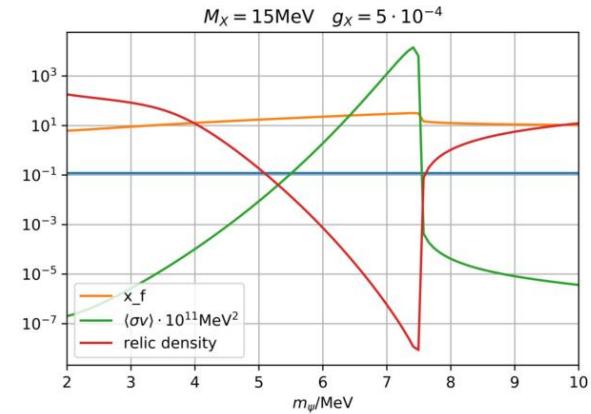
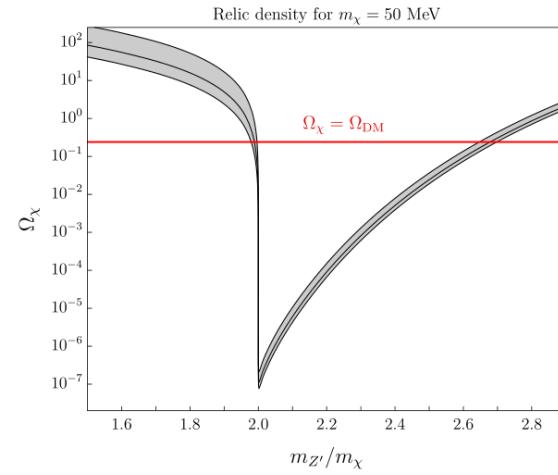
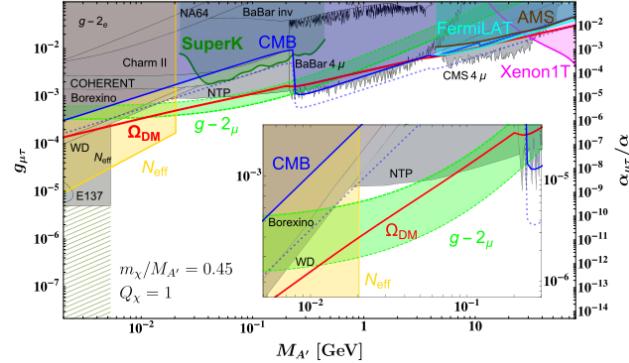
$$+ \bar{\chi} (i\partial_\mu\gamma^\mu - m_\chi) \chi - Q_\chi g_X Z'^\mu \bar{\chi} \gamma_\mu \chi$$

- Muon g-2 + DM relic density

P. Foldenauer, PRD 2019

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

M. Drees, W. Zhao, PLB 2022



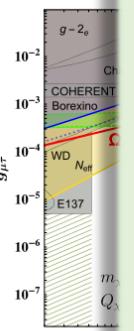
$U(1)_{L_\mu - L_\tau}$ -charged DM

- Lagrangian (Here w/o fermion DM χ : Dark photon)

- $g_X \sim 10^{-4}$ is **too small** to get $\Omega h^2 = 0.12$
- $M_{Z'} \sim 2M_\chi$ with the **s-channel Z' resonance**
- Only consider sub-GeV **Fermion DM**
- **No direct detection bound**

Tight correlation between
DM mass and Z' mass

P. Fox et al., arXiv:2207.03321 [hep-ph], 2022

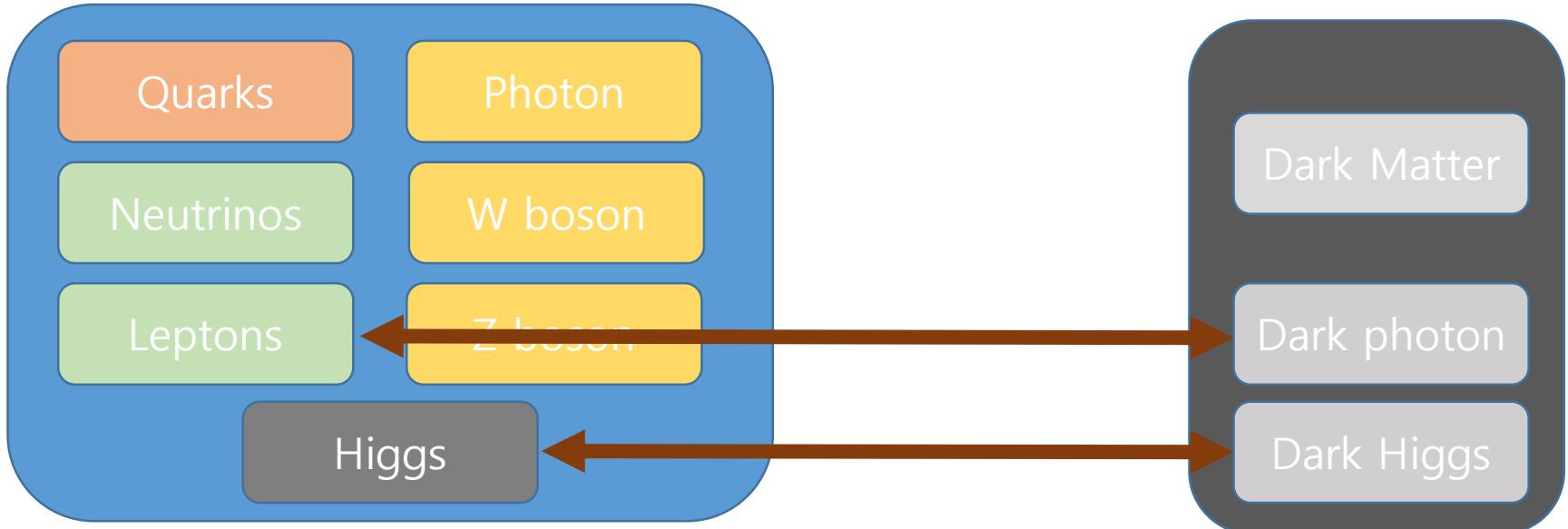


$$M_{Z'} \sim 2M_{\text{DM}}$$

$m_{Z'}/m_\chi$

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

- $U(1)_{dark} \equiv U(1)_{L_\mu-L_\tau}$
 - Let's call Z' , $U(1)_{L_\mu-L_\tau}$ gauge boson, **dark photon** since it couple to DM



- **UV complete** $U(1)_{L_\mu-L_\tau}$ -charged **scalar/fermion** DM model
- Dark photon Z' gets massive through $U(1)_{L_\mu-L_\tau}$ breaking
- A new singlet scalar (Dark Higgs), which mixes with the SM Higgs

DM physics with dark Higgs

- Scalar potential

$$V = \lambda_H \left(H^\dagger H - \frac{v_H^2}{2} \right)^2 + \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 + \boxed{\lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi}{2} \right) \left(H^\dagger H - \frac{v_\Phi}{2} \right)}$$

- If dark symmetry is spontaneously broken, $\Phi(x) = \frac{1}{\sqrt{2}} (v_\Phi + \phi(x))$
- Dark photon Z' gets massive: $M_{Z'} = g_X |Q_\Phi| v_\Phi$
- Two CP-even neutral scalar bosons

- $\begin{pmatrix} \phi \\ h \end{pmatrix} = O \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$ $\tan 2\alpha = \frac{\lambda_{\Phi H} v_\Phi v_H}{\lambda_H v_H^2 - \lambda_\Phi v_\Phi^2}$

- $\begin{pmatrix} 2\lambda_\Phi v_\Phi^2 & \lambda_{\Phi H} v_\Phi v_H \\ \lambda_{\Phi H} v_\Phi v_H & 2\lambda_H v_H^2 \end{pmatrix} = \begin{pmatrix} M_{H_1}^2 c_\alpha^2 + M_{H_2}^2 s_\alpha^2 & (M_{H_2}^2 - M_{H_1}^2) c_\alpha s_\alpha \\ (M_{H_2}^2 - M_{H_1}^2) c_\alpha s_\alpha & M_{H_1}^2 s_\alpha^2 + M_{H_2}^2 c_\alpha^2 \end{pmatrix}$

- 3 independent parameters: M_{H_1} , M_{H_2} , $\sin\alpha$



Local symmetry in Dark Sector

- The required longevity of DM can be guaranteed by a symmetry
 - If the symmetry is global, it can be broken by gravitational effects

S. Beak, P. Ko, W.I. Park, JHEP 2013

$$-\mathcal{L}_{\text{decay}} = \begin{cases} \frac{\lambda_{X,\text{non}}}{M_P} X F_{\mu\nu} F^{\mu\nu} & \text{for bosonic DM } X \\ \frac{\lambda_{\psi,\text{non}}}{M_P} \bar{\psi} (\not{D} \ell_{Li}) H^\dagger & \text{for fermionic DM } \psi \end{cases}$$

M. Ackermann et al, PRD 86, 2012

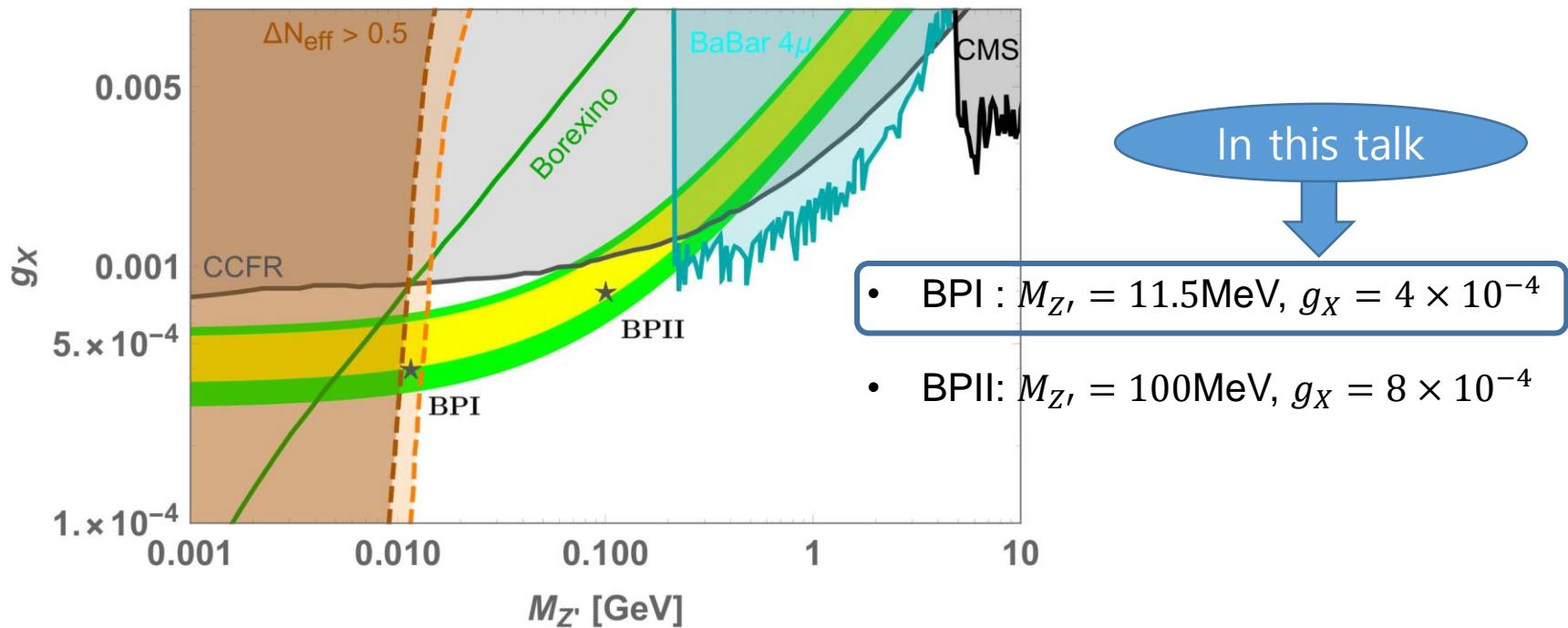
- $\tau_{DM} \geq 10^{26-30} \text{sec} \rightarrow \begin{cases} m_{DM} \leq O(10) \text{keV} & \text{(Scalar)} \\ m_{DM} \leq O(1) \text{GeV} & \text{(Fermion)} \end{cases}$

- **WIMP DM is unlikely to be stable**
- **Consider a gauge symmetry in dark sector, too**

- Local $U(1)_{L_\mu - L_\tau}$ symmetry is broken into its subgroup: **Local Z_2**

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

- **Muon g-2 (+ Hubble tension)**
 - We take two benchmark points in $(M_{Z'}, g_X)$ space
- **Generic scalar DM, Local Z_2 scalar/fermion DM**
 - DM mass range become much wider from GeV to O(a few) TeV via opening new channels for DM pair annihilations into the final states involving dark Higgs boson



Local Z_2 scalar DM

- DM Lagrangian at renormalizable level

$$\mathcal{L}_{\text{DM}} = |D_\mu X|^2 - m_X^2 |X|^2 - \lambda_{HX} |X|^2 \left(|H|^2 - \frac{v_H^2}{2} \right) - \underline{\lambda_{\Phi X} |X|^2 \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right)}$$

- Taking $2Q_\chi = Q_\Phi = 2$, one more gauge invariant operator

$$-\mu(X^2\Phi^\dagger + H.c.) \quad \xrightarrow{\hspace{1cm}} \quad \mu(X^2\phi^\dagger + H.c.) = \frac{1}{\sqrt{2}}\mu v_\Phi(X_R^2 - X_I^2) \left(1 + \frac{\phi}{v_\Phi} \right)$$

- DM & XDM masses: $M_R^2 = M_X^2 + \sqrt{2}\mu v_\Phi$, $M_I^2 = M_X^2 - \sqrt{2}\mu v_\Phi$.

- Off-diagonal interaction

$$\mathcal{L} \supset g_X Z'^\mu (X_R \partial_\mu X_I - X_I \partial_\mu X_R)$$

- Dominant DM annihilation channels

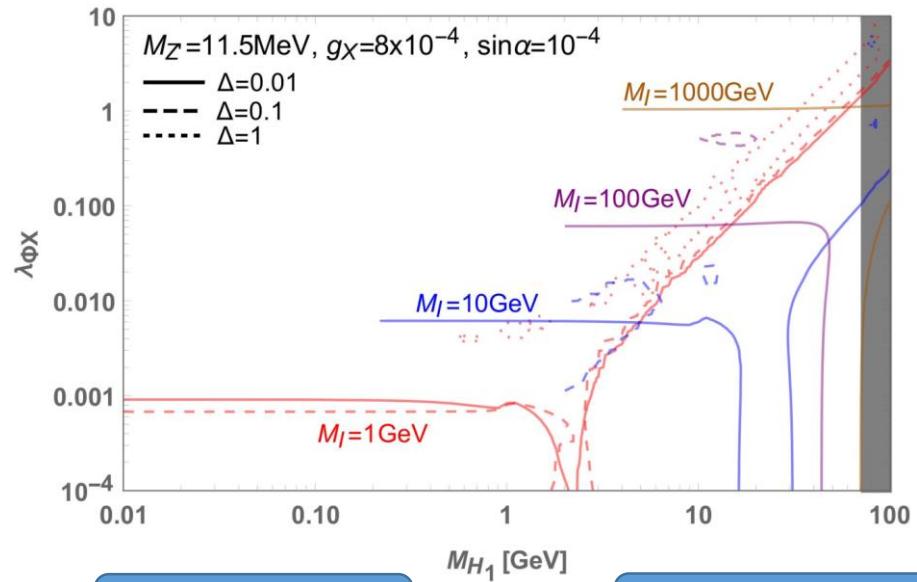
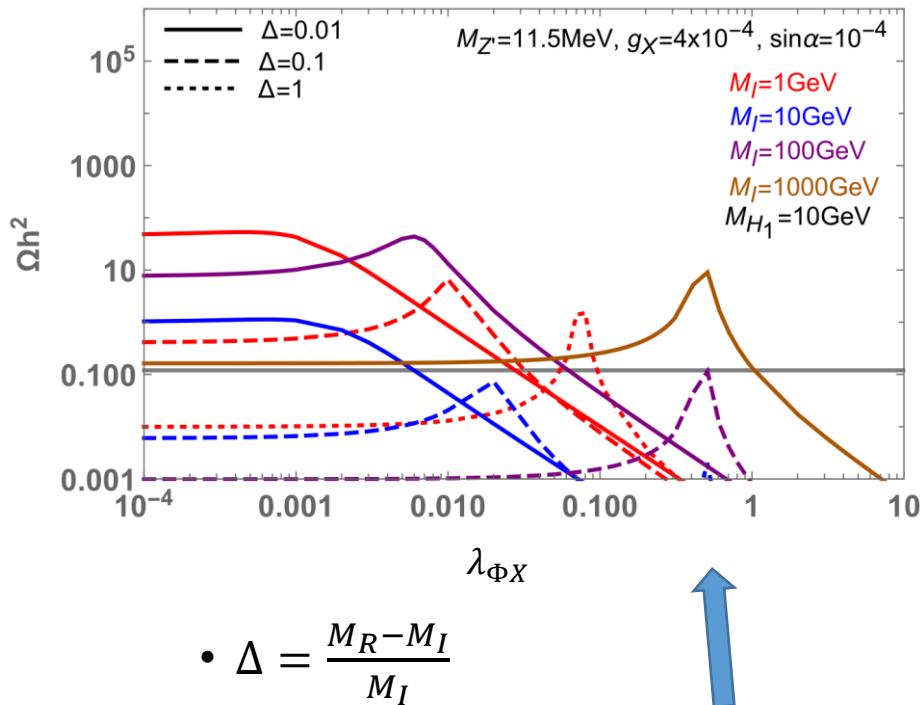
- $X_I X_I^\dagger \rightarrow H_1 H_1, Z' Z'$
- $X_R X_R^\dagger \rightarrow H_1 H_1, Z' Z'$

$$m_{H_1}, m_{Z'} < m_{\chi_I}$$

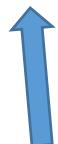
Local Z_2 scalar DM

- Higgs-mediated elastic scattering

$$\sigma_{\text{SI}} = \frac{\mu_N^2}{4\pi} \left(\frac{M_N}{M_I} \right)^2 \frac{c_\alpha^4}{M_{H_1}^4} f_N^2 \left[\left(\lambda_{\Phi X} - \frac{\sqrt{2}\mu}{v_\Phi} \right) \frac{v_\Phi}{v_H} t_\alpha \left(1 - \frac{M_{H_1}^2}{M_{H_2}^2} \right) - \lambda_{HX} \left(t_\alpha^2 + \frac{M_{H_1}^2}{M_{H_2}^2} \right) \right]^2$$



$$\bullet \Delta = \frac{M_R - M_I}{M_I}$$



$$\lambda_1 = (\lambda_{\Phi X} v_\Phi - \sqrt{2}\mu) c_\alpha - \lambda_{HX} v_H s_\alpha \text{ and } \lambda_2 = (\lambda_{\Phi X} v_\Phi - \sqrt{2}\mu) s_\alpha + \lambda_{HX} v_H c_\alpha.$$

$X_I X_I \rightarrow H_1 H_1$

$X_I X_I \rightarrow Z' Z'$

Local Z_2 fermion DM

- Taking $2Q_\chi = Q_\Phi = 2$

$$\mathcal{L}_{\text{DM}} = \bar{\chi}(iD - m_\chi)\chi - \left(y_\Phi \overline{\chi^C} \chi \Phi^\dagger + H.c.\right).$$

- After symmetry breaking $U(1)_X \rightarrow Z_2$
 - Nonzero $y_\Phi \rightarrow$ Dirac fermion χ is decomposed into two Majorana fermion (χ_R, χ_I)
 - Mass gap between XDM and DM: $\delta \equiv M_R - M_I = 2y_\Phi v_\Phi$
 - χ_I : DM & χ_R : XDM
- DM Lagrangian after Dark SSB

$$\mathcal{L}_{\text{DM}} = \frac{1}{2} \sum_{i=R,I} \bar{\chi}_i (i\partial_\mu \gamma^\mu - M_i) \chi_i - i \frac{g_X}{2} Z'_\mu (\bar{\chi}_R \gamma^\mu \chi_I - \bar{\chi}_I \gamma^\mu \chi_R) - \underline{\frac{1}{2} y_\Phi (c_\alpha H_1 + s_\alpha H_2) (\bar{\chi}_R \chi_R - \bar{\chi}_I \chi_I)}.$$

- $\chi_I \chi_I \rightarrow Z' Z'$, $H_1 H_1$ annihilation & $\chi_I \chi_R \rightarrow H_1 Z'$

$$m_{H_1}, m_{Z'} < m_{\chi_I}$$

$$m_{H_1} + m_{Z'} < m_{\chi_I} + m_{\chi_R}$$

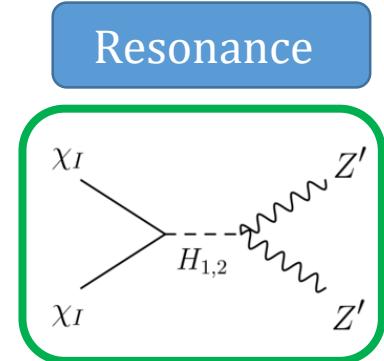
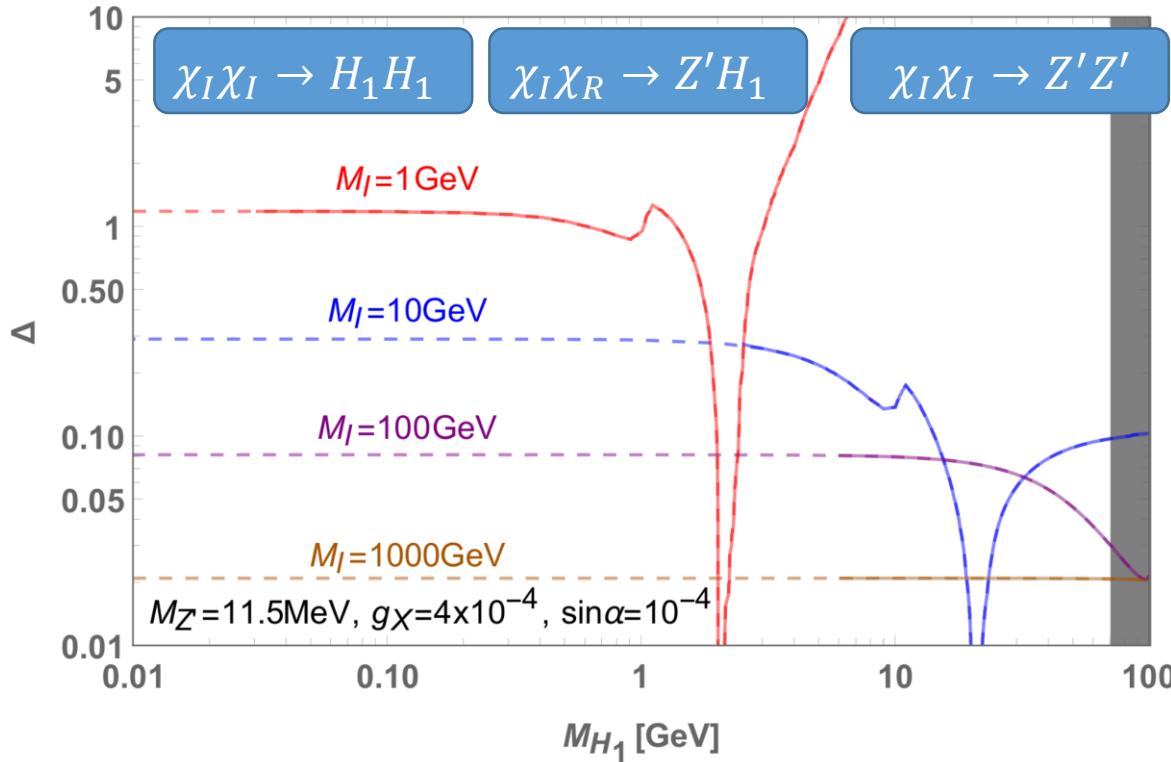
Local Z_2 fermion DM

- Higgs-mediated elastic scattering

P. Ko et al, JHEP 2020
 S. Baek, JKK, P.Ko, PLB 2020

$$\bullet \quad \sigma_{\text{SI}} = \frac{\mu_N^2}{\pi} \Delta^2 \left(\frac{M_I M_N}{v_H v_\Phi} \right)^2 f_N^2 s_\alpha^2 c_\alpha^2 \left(\frac{1}{M_{H_1}^2} - \frac{1}{M_{H_2}^2} \right)^2$$

$$\Delta = \frac{M_R - M_I}{M_I}$$



Conclusions

- We need new physics beyond the Standard Model to resolve DM and anomalies reported by experiments
- DM physics with massive dark photon cannot be complete without including dark gauge symmetry breaking mechanism which have been largely ignored by DM community
- Muon g-2 example shows the importance of the dark Higgs in DM phenomenology

Conclusions

- We r
DM a

Thank you
very much
for listening

to

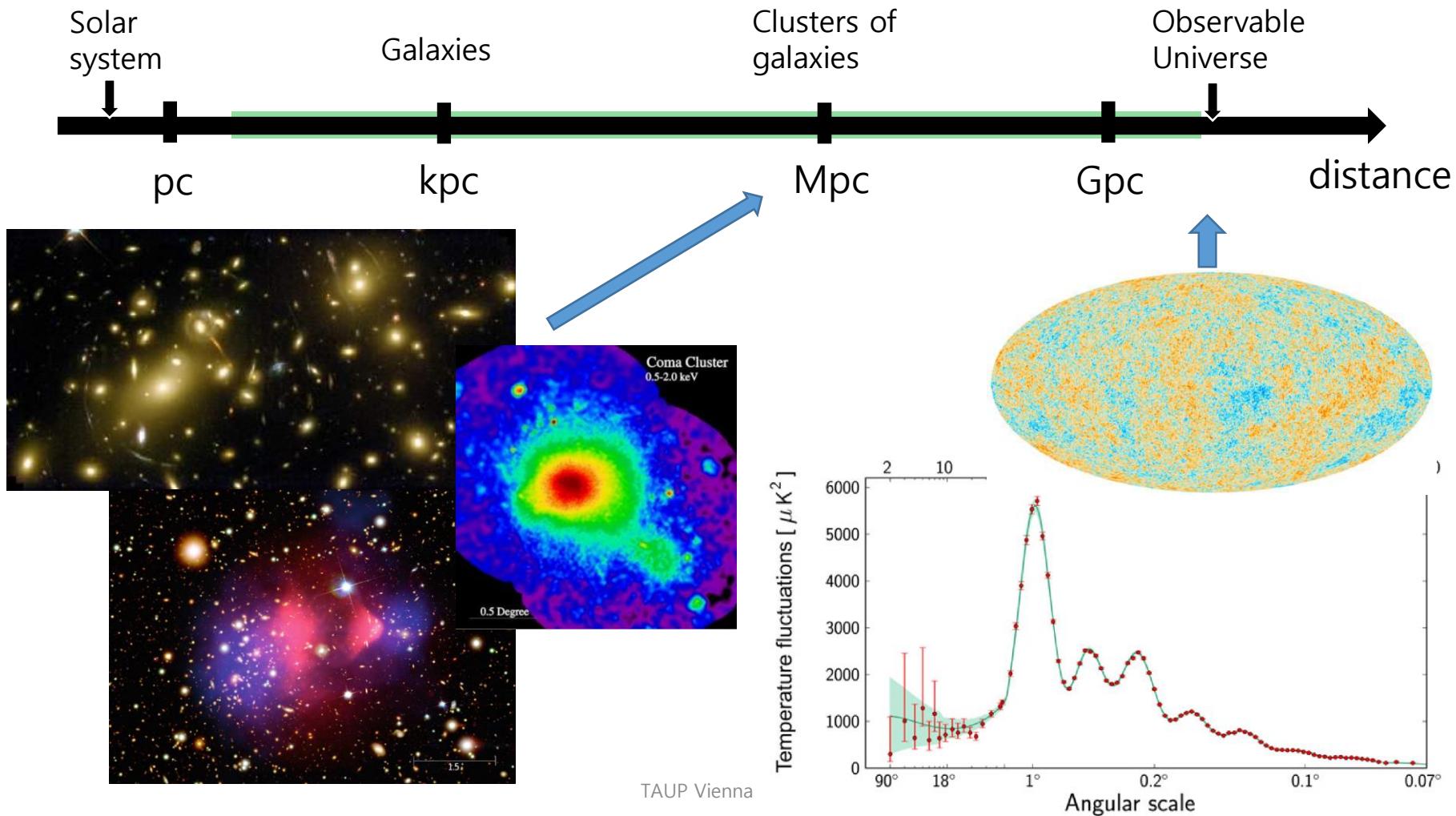
my presentation

- Muo
DM I

Back up

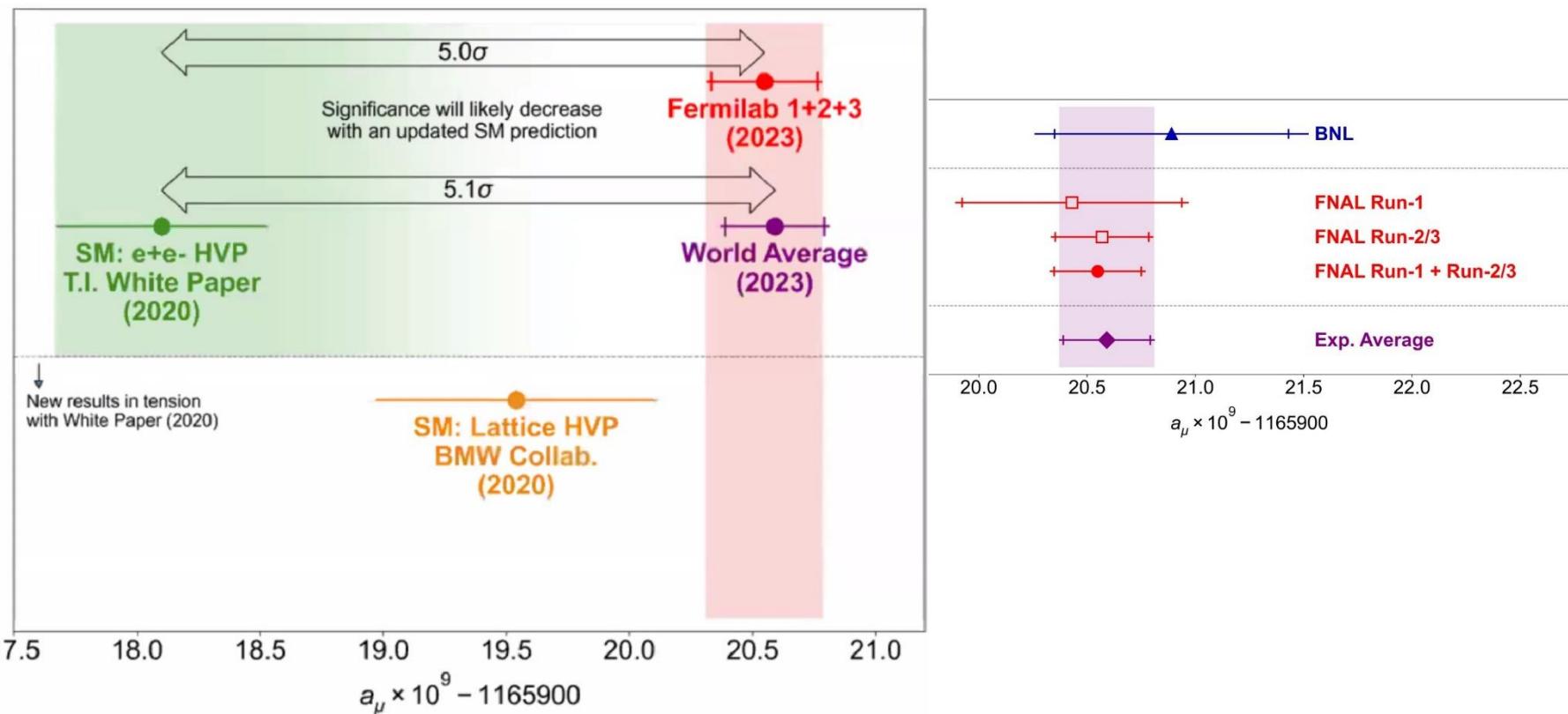
Evidences – Dark Matter

- There are undeniable evidences for dark matter in a wide range of distance scales



Muon g-2 anomaly

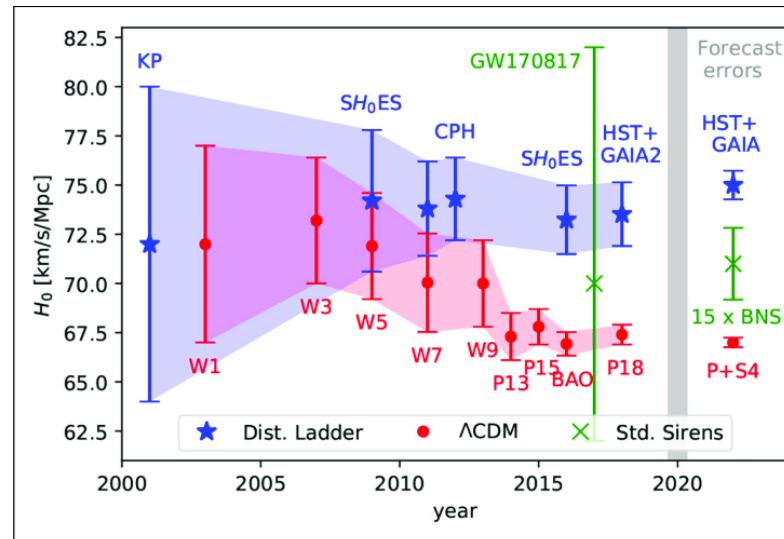
- Muon g-2 experiment improves the precision of their previous result by a factor of 2
- *New result*



Hubble tension

- Large difference between early and late H_0 measurement
 - $H_0 = 73.2 \pm 1.3 \text{ kms}^{-1}\text{Mpc}^{-1}$
 - $H_0 = 67.4 \pm 0.5 \text{ kms}^{-1}\text{Mpc}^{-1}$
- The discrepancy either arises because
 - Our distance measurements are incorrect
 - Cosmological model we use to fit all those distances is incorrect

• ΔG_N vs ΔN_{eff}



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

- **Neutrino trident production**

W. Altmannshofer et al, PRL 2014

- Production of a muon pair from the scattering of a muon neutrino with heavy nuclei
- $R_{CCFR} \equiv \frac{\sigma_{CCFR}}{\sigma_{SM}} = 0.82 \pm 0.28.$

- **BaBar 4 μ channels**

BarBar Collaboration, PRD 2016

- $e^+ e^- \rightarrow \mu^+ \mu^- Z'$, $Z' \rightarrow \mu^+ \mu^-$, $\nu \bar{\nu}$
- Upper limit on g_X for $200\text{MeV} \leq M_{Z'} \leq 10\text{GeV}$

- ΔN_{eff}

M. Escudero et al, JHEP 2019

- Z' will reheat the neutrino gas, resulting in a higher expansion rate
- Increase the effective number of neutrinos N_{eff}

- **Borexino**

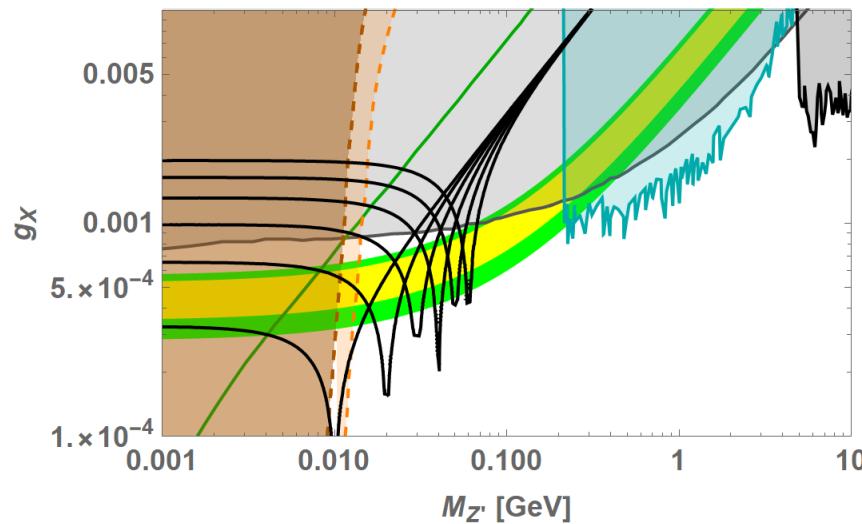
R. Harnik et al, JCAP 2012

- a liquid scintillator experiment measuring solar neutrino scattering off electron ($\nu - e$ scattering)

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

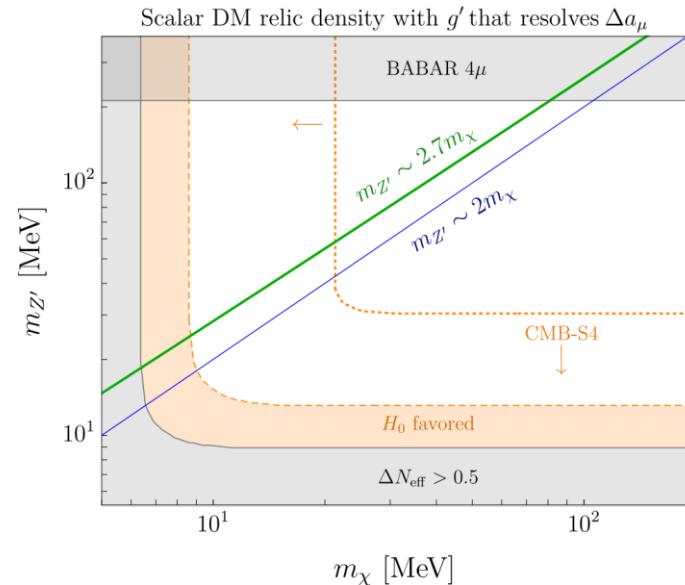
- Complex scalar DM (Here X : complex scalar DM)
 - Annihilation cross section is **p-wave**
 - Annihilation during the CMB era is velocity suppressed

$$\bullet XX \rightarrow f\bar{f}: \sigma(s) = \sum_f \frac{k_f g'^4}{12\pi s} \beta_f \beta_X \left[\frac{(s + 2m_f^2)}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \right]$$



- $m_X = 5, 10, 15, 20, 25, 30 \text{ MeV}$

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



Dark Higgs constraints

- After spontaneous symmetry breakings
 - Additional interactions with the dark Higgs

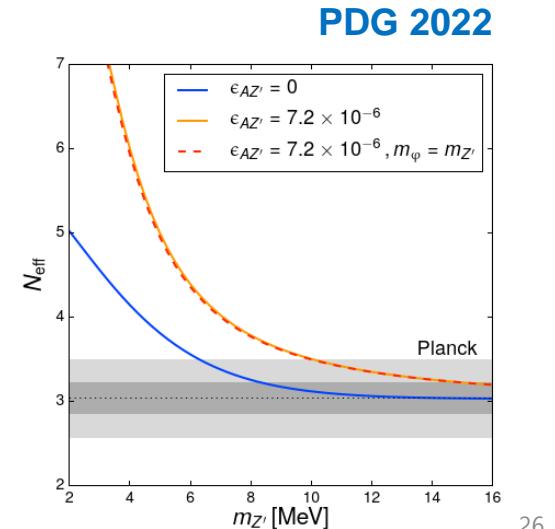
$$\mathcal{L}_\phi \supset \frac{1}{2}g_X^2 Q_\Phi^2 Z'^\mu Z'_\mu \phi^2 + g_X^2 Q_\Phi^2 v_\Phi Z'^\mu Z'_\mu \phi - \lambda_\Phi v_\Phi \phi^3 - \lambda_H v_H h^3 - \frac{\lambda_{\Phi H}}{2} v_\Phi \phi h^2 - \frac{\lambda_{\Phi H}}{2} v_H \phi^2 h$$

- ***N_{eff}* @ *T*~a few MeV**

- If light dark Higgs masses are lighter than $T_{dec}^\nu \sim 1 \text{ MeV}$, the light dark Higgs mainly decays into $e^\pm \rightarrow \Delta N_{eff} \neq 0$
- The dark Higgs decay before 1sec

- **Higgs invisible decay @ LHC**

- $\text{Br}(H_2 \rightarrow \text{inv.}) = \frac{\Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}}{\Gamma_{H_2}^{SM} + \Gamma_{H_2}^{inv} + \Gamma_{H_2}^{H_1 H_1}} < 11\%$
- $\sin\alpha$ should be small (BPI: $\sin\alpha \leq 10^{-3}$)
- Take $\sin\alpha = 10^{-4} \rightarrow \phi \cong H_1, h \cong H_2$



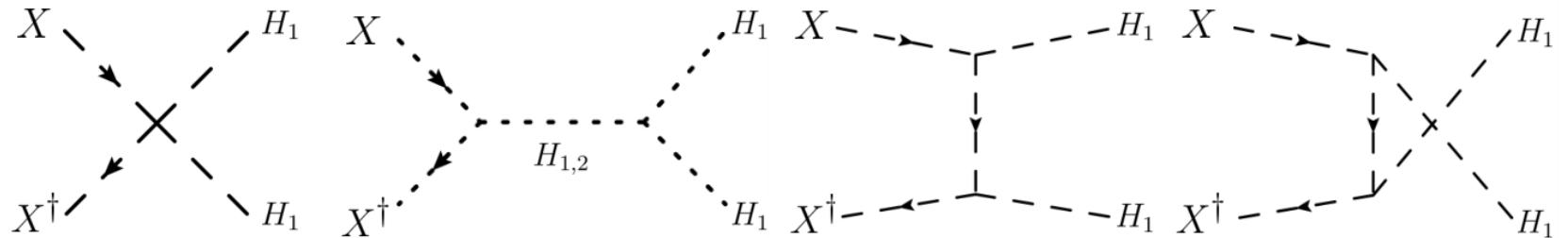
Scalar DM: $Q_X/Q_\Phi \neq \pm 1, \pm 1/2, \pm 1/3$, etc

- Consider complex scalar DM with a generic Q_X/Q_Φ

- Gauge invariant & renormalizable Lagrangian

$$\mathcal{L}_{\text{DM}} = |D_\mu X|^2 - m_X^2 |X|^2 - \lambda_{HX} |X|^2 \left(|H|^2 - \frac{v_H^2}{2} \right) - \lambda_{\Phi X} |X|^2 \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right)$$

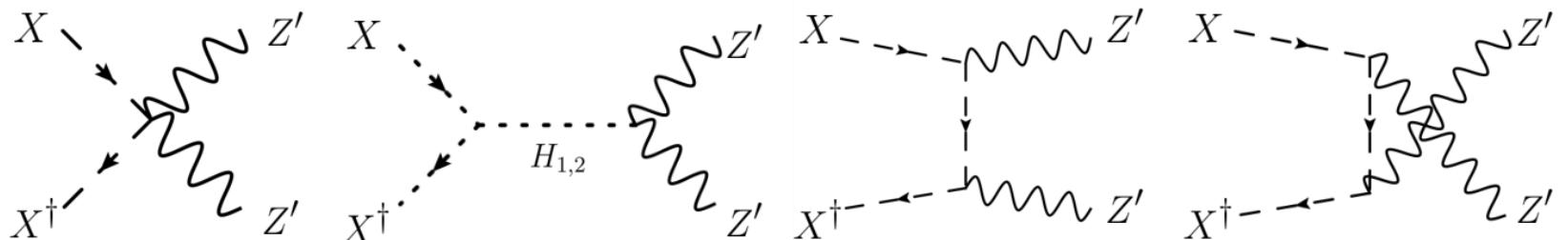
- $D_\mu X = (\partial_\mu + ig_X Q_X Z'_\mu) X$ ($Q_X = 1$)
- $XX^\dagger \rightarrow H_1 H_1$ annihilation channel



- $\langle \sigma v_{\text{rel}}(XX^\dagger \rightarrow H_1 H_1) \rangle \simeq \frac{\mathcal{S}}{16\pi s} (\lambda_{\Phi X} c_\alpha^2 + \lambda_{HX} s_\alpha^2)^2 \left(1 - \frac{4M_S^2}{s}\right)^{1/2}$

Scalar DM: $Q_X/Q_\Phi \neq \pm 1, \pm 1/2, \pm 1/3$, etc

- $XX^\dagger \rightarrow Z'Z'$ annihilation channels



$$\overline{|\mathcal{M}|^2} \simeq \frac{s^2}{4M_{Z'}^4} (\lambda_{\Phi X} v_\Phi)^2 \left| \left(\frac{c_\alpha \kappa_1}{s - M_{H_1}^2 + i\Gamma_{H_1} M_{H_1}} + \frac{s_\alpha \kappa_2}{s - M_{H_2}^2 + i\Gamma_{H_2} M_{H_2}} \right) \right|^2,$$

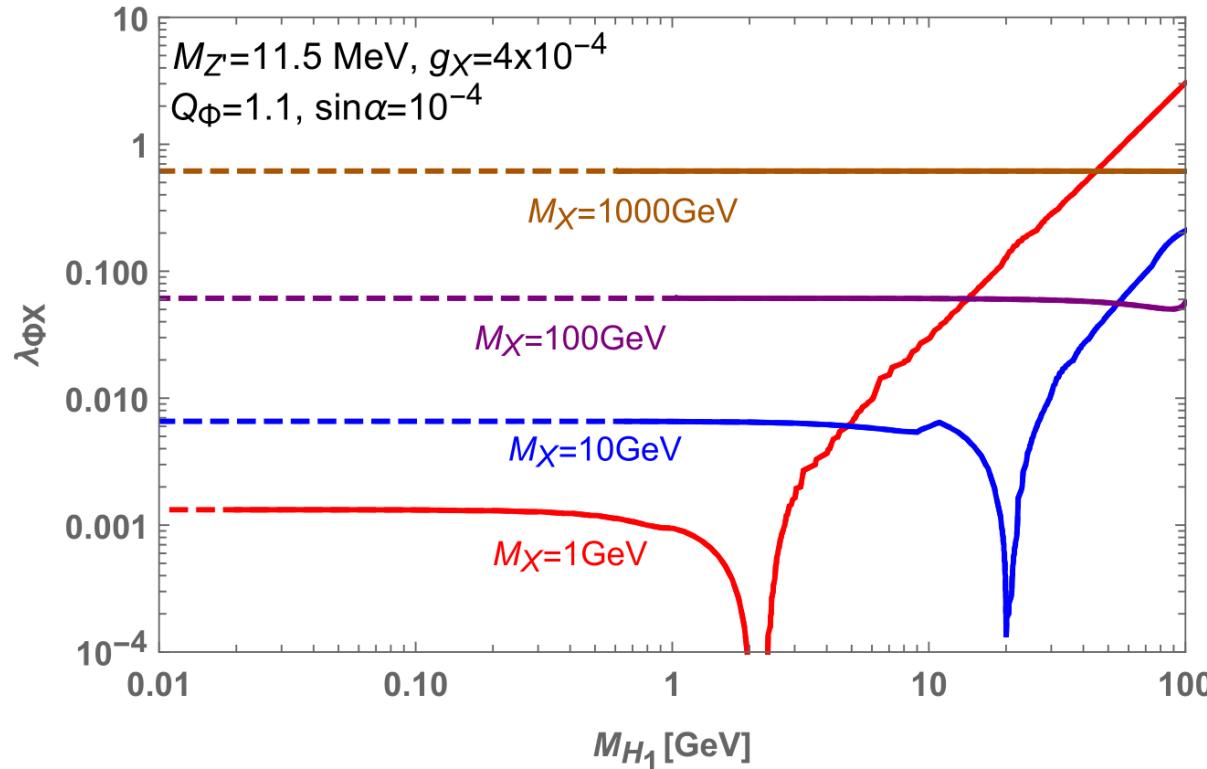
$$\begin{aligned} \kappa_1 &= 6\lambda_H v_H s_\alpha^3 - 6\lambda_\Phi v_\Phi c_\alpha^3 + 3\lambda_\Phi v_H s_\alpha c_\alpha^2 - 3\lambda_\Phi v_\Phi c_\alpha s_\alpha^2, \\ \kappa_2 &= -6\lambda_\Phi v_\Phi c_\alpha^2 s_\alpha - 6\lambda_H v_H s_\alpha^2 c_\alpha + \lambda_\Phi v_H (2c_\alpha^2 s_\alpha - s_\alpha^3) - \lambda_\Phi v_\Phi (c_\alpha^3 - 2c_\alpha s_\alpha^2). \end{aligned}$$

$$\langle \sigma v_{\text{rel}}(XX^\dagger \rightarrow Z'Z') \rangle = \frac{1}{32\pi s} \overline{|\mathcal{M}|^2} \left(1 - \frac{4M_{Z'}^2}{s} \right)^{1/2}.$$

Scalar DM: $Q_X/Q_\Phi \neq \pm 1, \pm 1/2, \pm 1/3$, etc

- Higgs-mediated elastic scattering

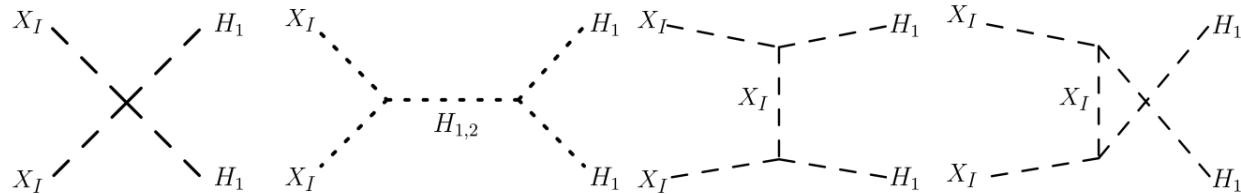
$$\bullet \sigma_{\text{SI}} = \frac{\mu_N^2}{4\pi} \left(\frac{M_N}{M_X} \right)^2 \frac{c_\alpha^4}{M_{H_1}^4} f_N^2 \left[\lambda_{\Phi X} \frac{v_\Phi}{v_H} t_\alpha \left(1 - \frac{M_{H_1}^2}{M_{H_2}^2} \right) - \lambda_{HX} \left(t_\alpha^2 + \frac{M_{H_1}^2}{M_{H_2}^2} \right) \right]^2$$



Local Z_2 scalar DM

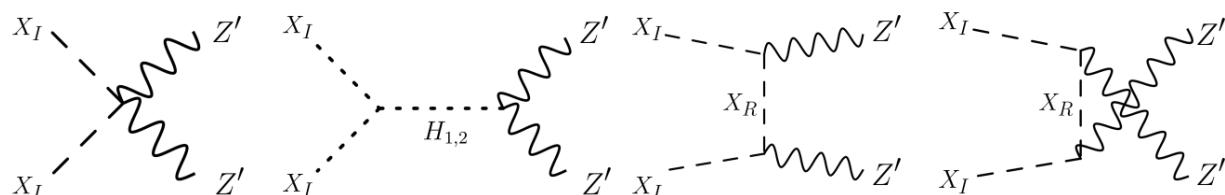
- Dominant DM annihilation channels

- $X_I X_I^\dagger \rightarrow H_1 H_1$



$$\langle \sigma v_{\text{rel}}(X_I X_I \rightarrow H_1 H_1) \rangle \approx \frac{1}{32\pi s} (\lambda_{\Phi X} c_\alpha^2 + \lambda_{HX} s_\alpha^2)^2 \sqrt{1 - \frac{4M_{H_1}^2}{s}}$$

- $X_I X_I^\dagger \rightarrow Z' Z'$



$$\langle \sigma v_{\text{rel}}(X_I X_I \rightarrow Z' Z') \rangle \approx \frac{1}{8\pi} \frac{M_I^2}{v_\Phi^2} \left| \frac{\lambda_1 c_\alpha}{s - M_{H_1}^2 + i\Gamma_{H_1} M_{H_1}} + \frac{\lambda_2 s_\alpha}{s - M_{H_2}^2 + i\Gamma_{H_2} M_{H_2}} \right|^2.$$

Local Z_3 scalar DM

- Take $3Q_X = Q_\Phi = 3$

P. Ko et al, JCAP 2014
P. Ko et al, PLB 2020

- Relevant Lagrangian

$$\mathcal{L}_{\text{DM}} = D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X - \lambda_{HX} X^\dagger X \left(H^\dagger H - \frac{v_H^2}{2} \right) - \lambda_{\Phi X} X^\dagger X \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) + \lambda_3 (X^3 \phi^\dagger + H.c.)$$

- Usual annihilation channel

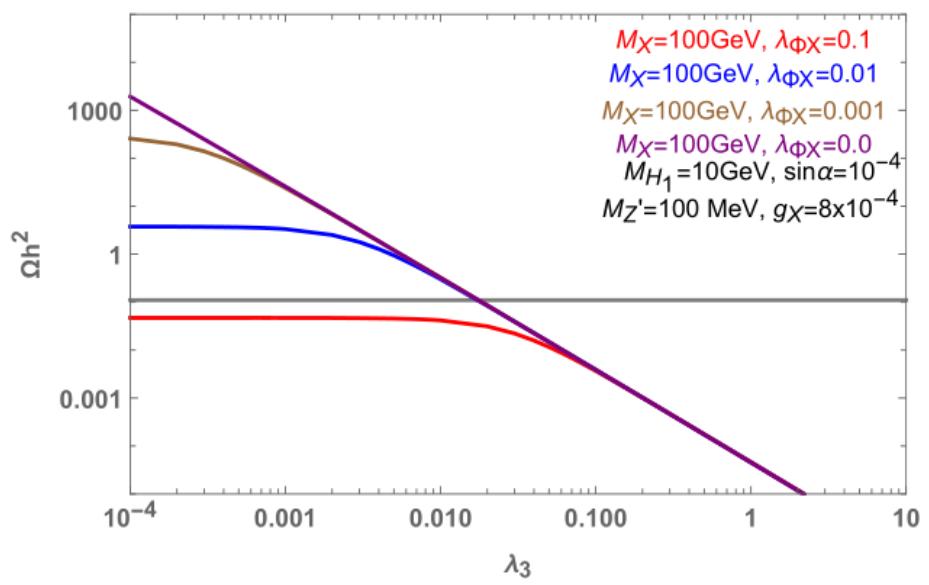
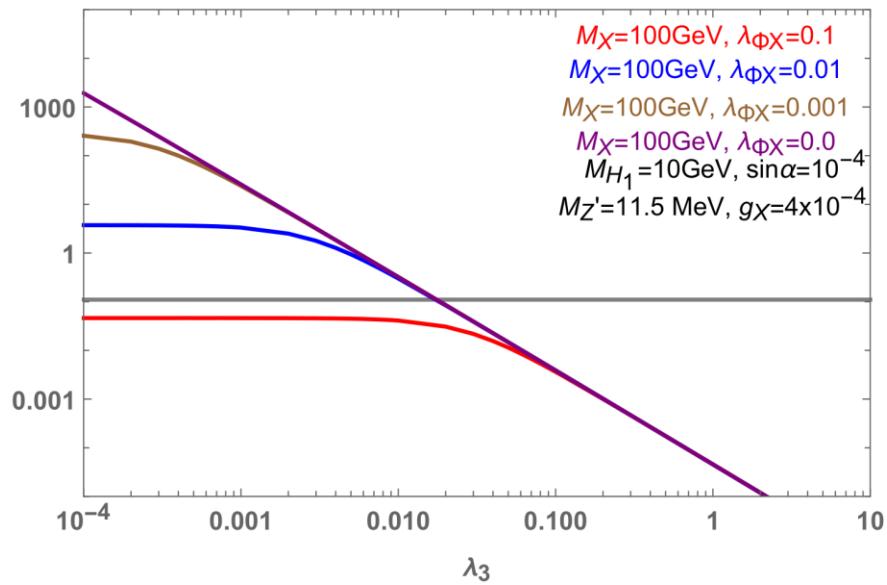
- $XX^\dagger \rightarrow Z'(H_1, H_2) \rightarrow (\text{SM particles})$

- New mechanism: semi-annihilations

- $XX \rightarrow X^\dagger H_1, X^\dagger Z'$
- $g_X \sim O(10^{-4}) \rightarrow XX \rightarrow X^\dagger Z'$ is not important

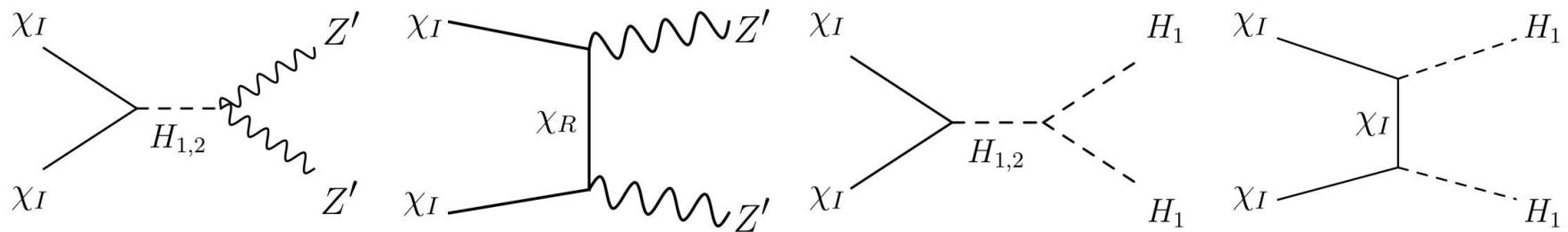
Local Z_3 scalar DM

- Relic abundance of Z_3 scalar DM



Local Z_2 fermion DM

- $\chi_I \chi_I \rightarrow Z' Z', H_1 H_1$



- $\chi_I \chi_R \rightarrow H_1 Z'$

