A decaying dark matter model for 3.5 keV X-ray line

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based on
SB, 1410.1992

Outline

- Zee-Babu neutrino model
- Extended Zee-Babu model including DM
- 3.5keV X-ray line signal in extended Zee-Babu model
- Conclusions

Zee-Babu model for neutrino masses

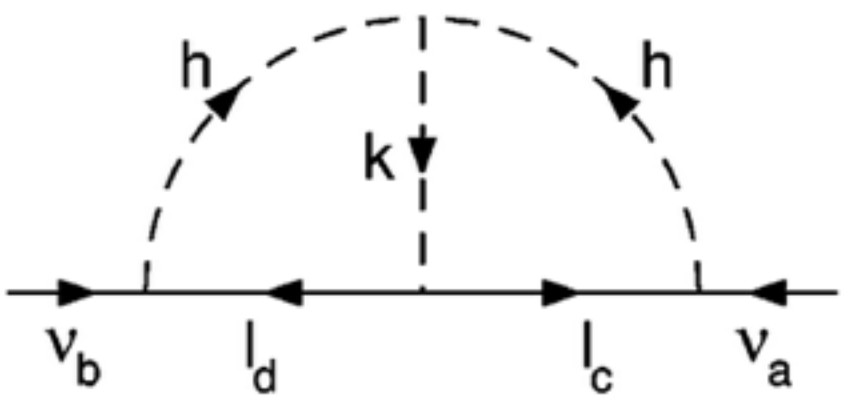
- Zee-Babu model for Majorana neutrinos: two new charged scalars h^+, k^{++} with L=-2 are introduced

$$\mathcal{L}_Y = f_{ab}(\psi_{aL}^{Ti} C \psi_{bL}^{j})\epsilon_{ij} h^+ + h'_{ab}(l_{aR}^T C l_{bR}) k^{++} + \text{H.c.}$$

$$\mathcal{L}_{h-k} = -\mu h^+ h^+ k^{--} + \text{H.c.}$$

L-violating soft term

$$(\mathcal{M}_\nu)_{ab} = 8\mu f_{ac} m_c h_{cd}^* m_d f_{db} I_{cd}$$



- Small neutrino masses are due to loop suppression

- Testable at LHC contrary to seesaw mechanism

- We extend the model to local B-L symmetry and introduce B-L charged DM candidate

The model

$i = 1, 2, 3$

Fields	q_i	ℓ_i	h^+, k^{++}	φ	η	N_{R_i}	ψ_i
$B-L$	$1/3$	-1	2	2	0	-1	$1/3, 7/3, 13/3$
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$\pm$

ψ (Dirac DM) generate transition MD op.

φ $U(1)_{B-L}$ breaking scalar

η Light scalar for relic density & small scale problems

N_R (Majorana) cancel gauge anomaly

The model

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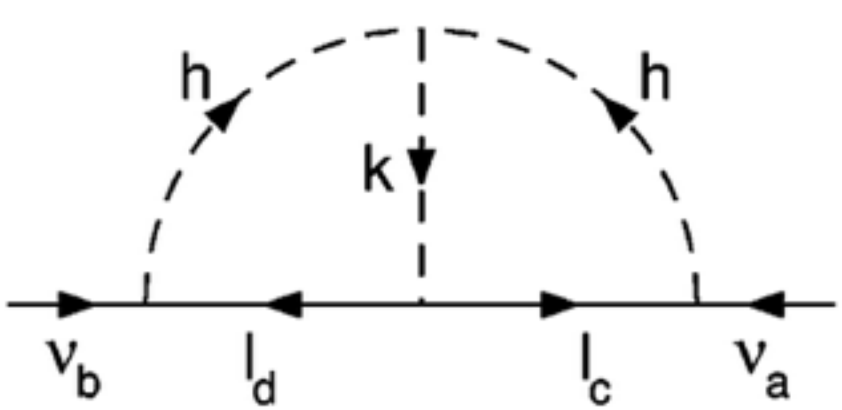
LHN_R forbidden by Z_2

$LH\psi$ forbidden by B-L charge assignment



: dominant contribution for neutrino masses

Local $U(1)_{B-L}$ symmetry

$$+(\lambda_\mu \varphi k^{++} h^- h^- + h.c) \longrightarrow \mu k^{++} h^- h^-$$

dynamically generates LV μ-term

$$\mathcal{L}_\Psi = \overline{\psi_i} i\gamma^\mu D_\mu \psi_i - m_{\psi_i}\overline{\psi_i}\psi_i - f_{12}\left(\overline{\psi_1}\psi_2\varphi^* + \overline{\psi_2}\psi_1\varphi\right) - f_{23}\left(\overline{\psi_2}\psi_3\varphi^* + \overline{\psi_3}\psi_2\varphi\right)$$

ψ's have "flavor" changing Z' and φ interaction
<φ>: $U(1)_{B-L} \rightarrow Z_6$:not broken by quantum gravity->
guarantees absolute stability of DM

$$\mathcal{L}_{N_R} = \overline{N_{R_i}} i\gamma^\mu D_\mu N_{R_i} - \frac{1}{2}\left(\lambda_{N_{ij}}\varphi \overline{N^c_{R_i}} N_{R_j} + h.c.\right)$$

N_R's not DM candidates. Can decay through M_{Pl} suppressed Op.

$$\lambda_{ij}\ell_i H N_{R_j}, \quad \frac{1}{M_{\rm Pl}}\ell_i H N_{R_j}\eta, \quad \frac{1}{M_{\rm Pl}^2}N_{R_i}\ell_j\ell_k\bar{e}_l, \quad \frac{1}{M_{\rm Pl}^2}N_{R_i}\bar{d}_j\bar{d}_k\bar{u}_l,$$

Decaying DM for 3.5 keV X-ray

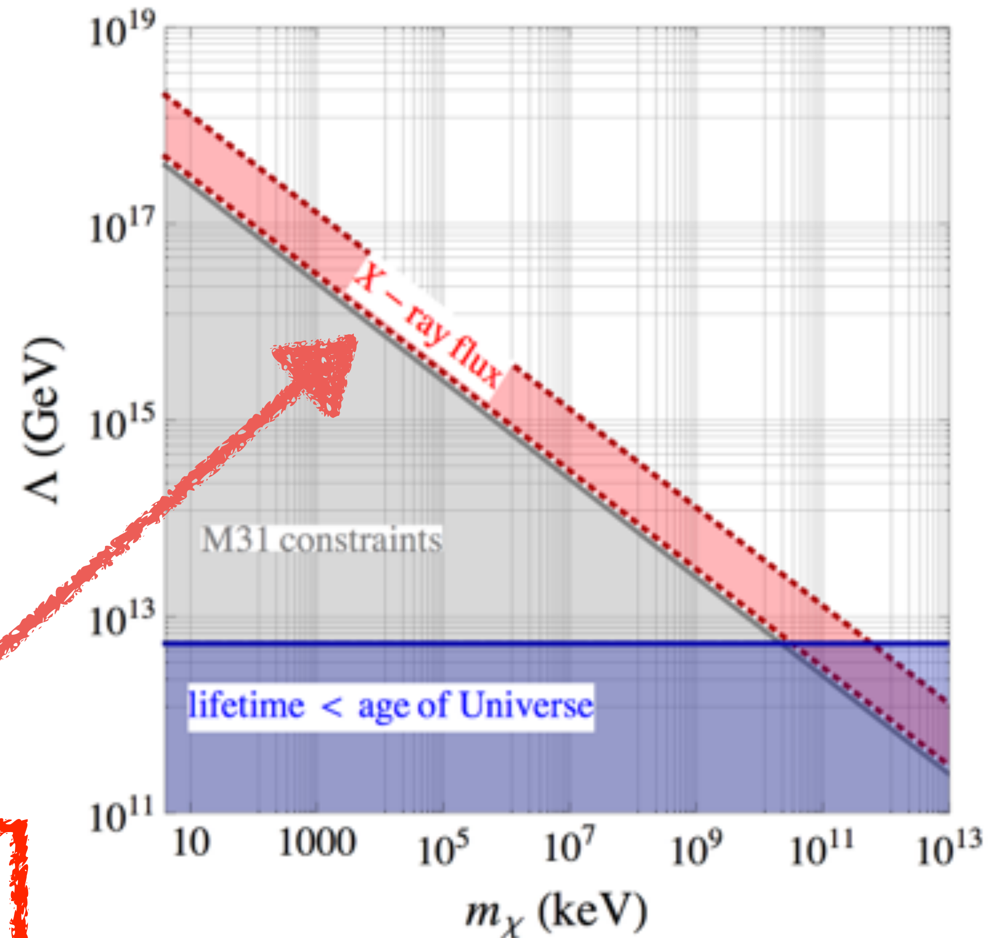
- If the decay can be described by transition dipole moment operator (TMDO)

$$\frac{1}{\Lambda}\bar{\chi}_e \sigma_{\mu\nu}\chi_g F^{\mu\nu}$$

$$\Gamma = \frac{4(\Delta m)^3}{\pi \Lambda^3}$$

$$\Delta m = 3.5\,\mathrm{keV}$$

$$\Lambda = (6.94\times 10^{14} - 2.75\times 10^{15})\left(\frac{m_\chi}{\mathrm{GeV}}\right)^{-1/2}\,\mathrm{GeV}$$



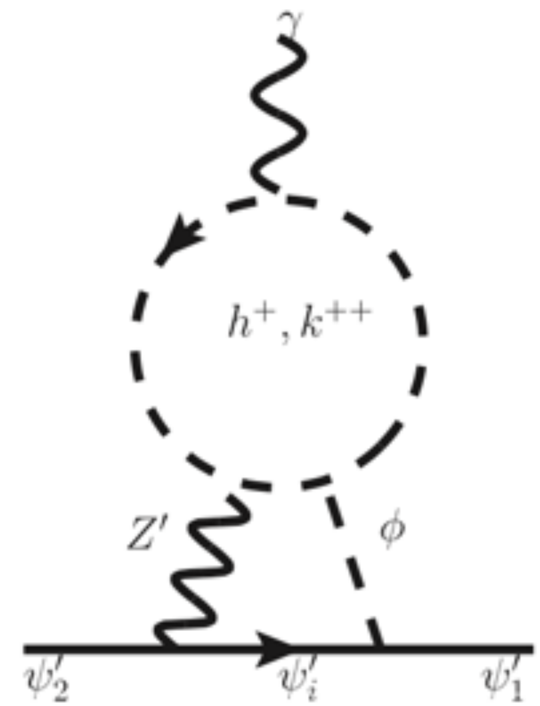
Frandsen, et.al., 1403.1570

Decaying DM in Z-B model

- Through two-loop Barr-Zee

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda}\overline{\psi'_1}\sigma_{\mu\nu}\psi'_2 F^{\mu\nu}$$

is generated



$$\frac{1}{\Lambda} \simeq \sum_{s=h^+,k^{++}} \frac{8eg_{Z'}^2 \Delta Q_\psi Q_s Q'_s \lambda_{\varphi s}\delta^2 \cos 2\theta_{12} s_{13} s_{23}}{(4\pi)^4} \times \int_0^1 dx \int [d\beta] \frac{x\beta_4^2 m_{\psi'_3}^2}{\left(\beta_1 m_{Z'}^2 + \beta_2 m_\phi^2 + \beta_3 m_s^2/(x(1-x)) + \beta_4^2 m_{\psi'_1}^2\right)^2},$$

$$\delta = \Delta m_{31}/m_{\psi'_3}$$

Kinetic mixing

- Z'-γ mixing: $-\sin\chi \hat{Z}'_{\mu\nu}\hat{F}^{\mu\nu}/2$

- Tree-level TMDO? No.

- Canonical kinetic enegy from non-unitary

$$\begin{pmatrix} \hat{A} \\ \hat{Z}' \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & \sec\chi \end{pmatrix} \begin{pmatrix} A \\ Z' \end{pmatrix}$$

$$\Delta\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu,$$

- The transformation is unique for massive Z'

- Covariant derivative

$$\begin{aligned} D_\mu &= \partial_\mu + i\hat{e}Q\hat{A}_\mu + i\hat{g}_{Z'}Q_{Z'}\hat{Z}'_\mu \\ &= \partial_\mu + i\hat{e}QA_\mu + \frac{i}{\cos\chi}(\hat{g}_{Z'}Q_{Z'} - \hat{e}Q\sin\chi)Z'_\mu. \end{aligned}$$

- Photon couples only to EM-charge

Fine-Tuning

- Small parameters in the model: $\Delta m_{12} << m_\psi$
- 't Hooft naturalness criterion "A parameter is **naturally** small if setting it to zero increases the symmetry of the theory"
- Setting Δm_{12} to zero increases the symmetry U(2)-flavor symmetry in (ψ_1, ψ_2) flavor space
- Small Δm_{12} is technically natural

Decaying DM in Z-B model

- To explain 3.5 keV X-ray line, we need

$$\Lambda = (6.94 \times 10^{14} - 2.95 \times 10^{15}) \left(\frac{m_{\psi'_2}}{\mathrm{GeV}} \right)^{-1/2} \mathrm{GeV}.$$

- In our case it is obtained not by heavy particle but by loop suppression

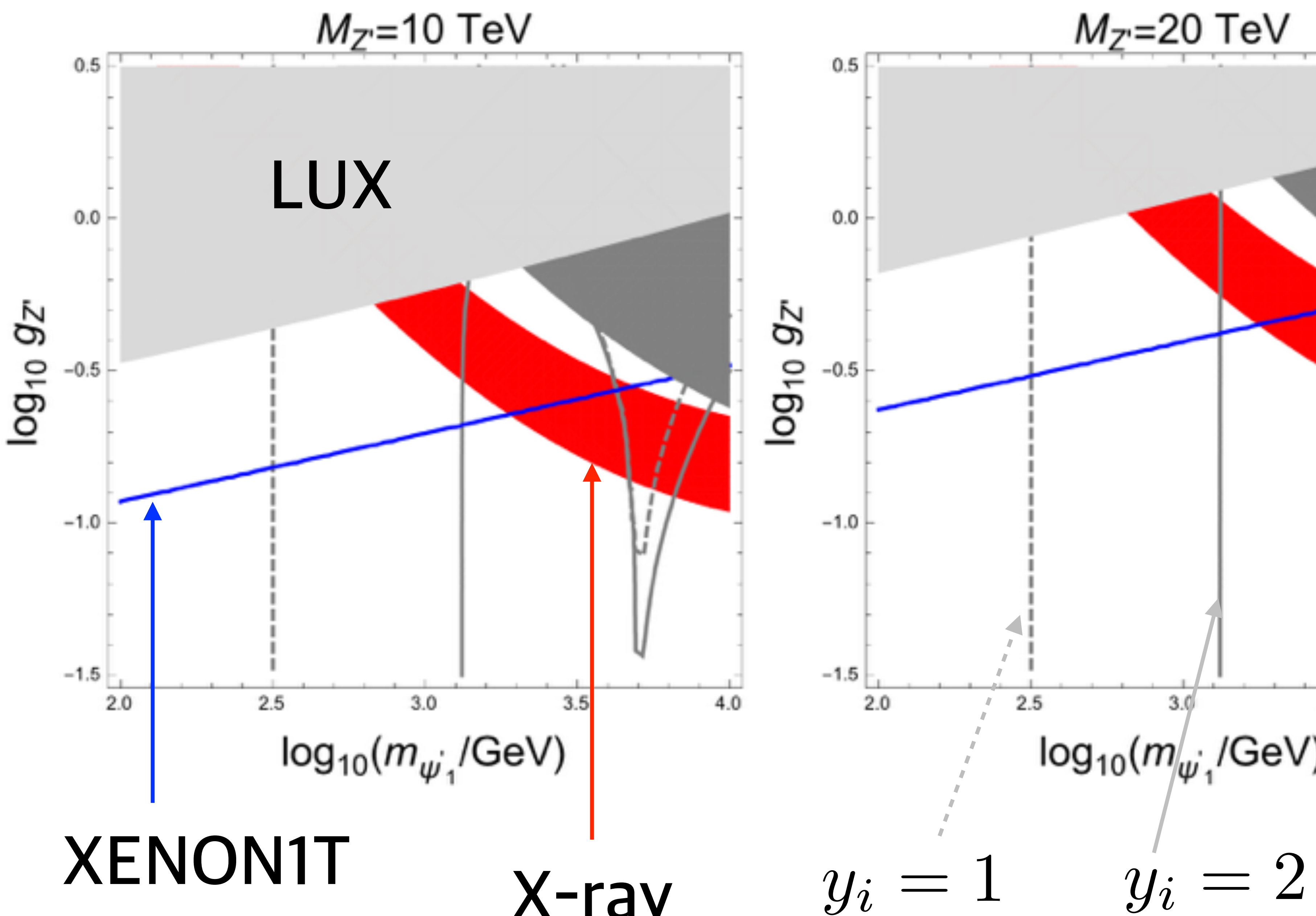
- Benchmark point

$$\delta = 0.2,\ \theta_{12} = \theta_{23} = 0.2,\ m_\phi = m_{h^+} = m_{k^{++}} = 1\ \mathrm{TeV}$$

$$\lambda_{\varphi h} = \lambda_{\varphi k} = 1. \qquad m_\eta = 1\,\mathrm{MeV}$$

- Constraints: LUX DM direct search, perturbativity, DM relic abundance, LFV, $\frac{M_{Z'}}{g_{Z'}} > 7\,\mathrm{TeV}$

Decaying DM in Z-B model



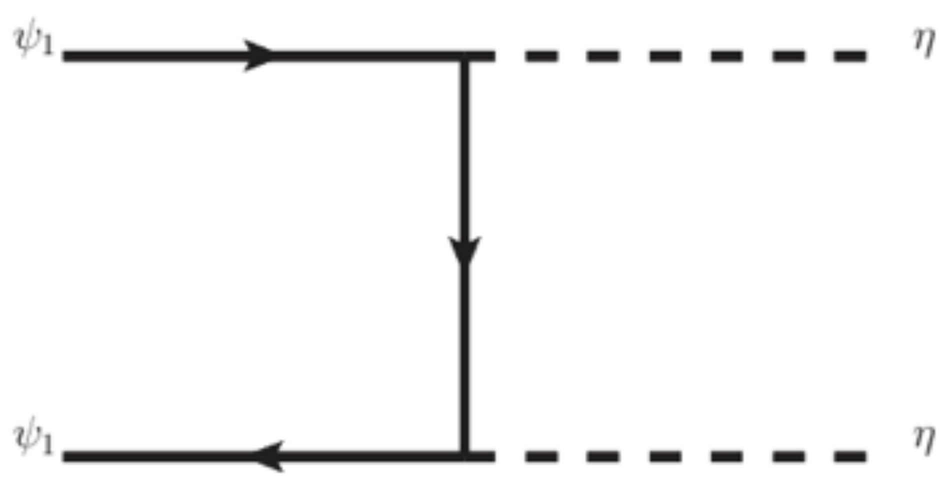
$-\eta(y_1\overline{\psi_1}\psi_1 + y_2\overline{\psi_2}\psi_2 + y_3\overline{\psi_3}\psi_3)$

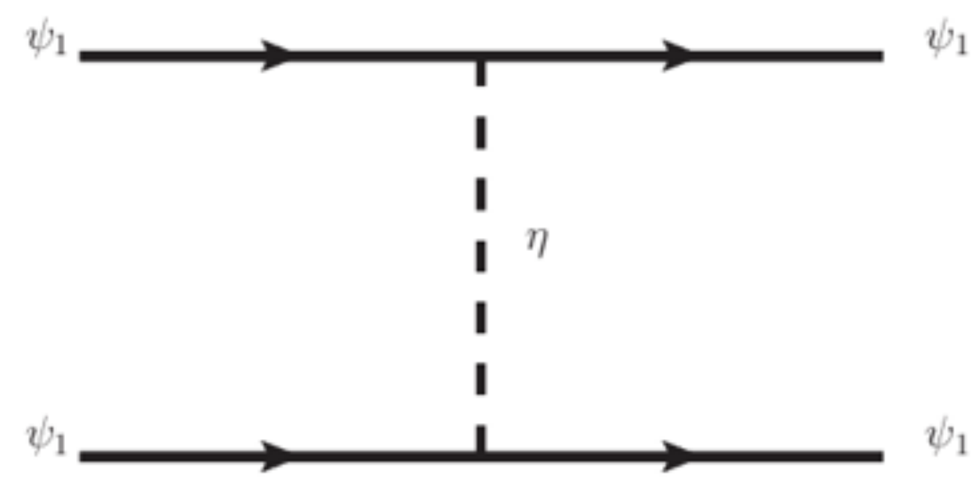
relic density $\Omega_\psi h^2 = 0.1199 \pm 0.0027$

The role of η

- η gives the correct relic abundance
- Light m_η (1—10 MeV) can enhance $\psi'_{1(2)}, \psi'_{1(2)} \to \psi'_{1(2)}, \psi'_{1(2)}$ and can explain small scale structure problems, core-vs-cusp and too-big-to-fail problems, if

$$\sigma_T/m_{\psi'_1} \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g},$$





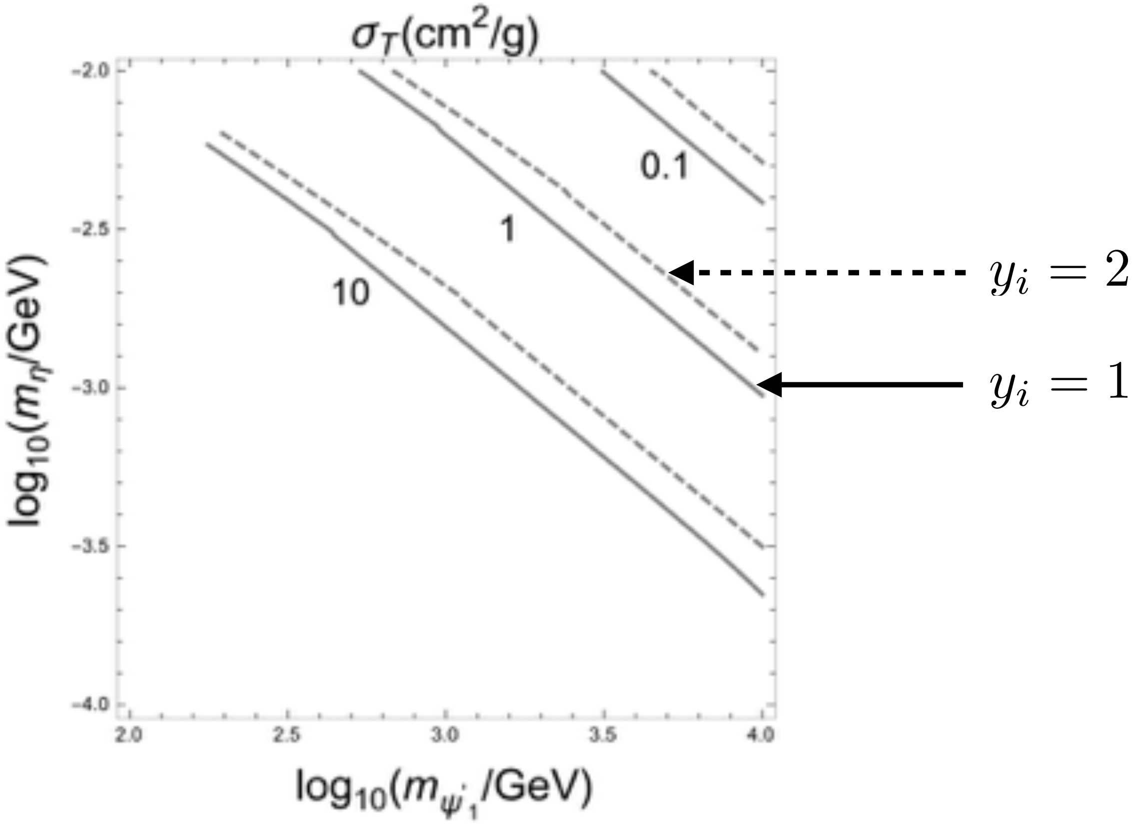
Decaying DM in Z-B model

- For $y_i \sim \mathcal{O}(1)$, the self-interaction occurs in the non-perturbative $(\alpha_y m_{\psi'}/m_\eta \gtrsim 1 \text{ with } \alpha_y \equiv y^2/4\pi)$ and classical $(m_{\psi'} v_{\rm rel}/m_\eta \gg 1)$ regime

$$\sigma_T = \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega} = \begin{cases} \frac{4\pi}{m_\eta^2}\beta^2\ln(1+\beta^{-1}) & \text{for } \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\eta^2}\beta^2/(1+1.5\beta^{1.65}) & \text{for } 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\eta^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \text{for } \beta \gtrsim 10^3, \end{cases}$$

$$\beta \equiv 2\alpha_y m_\eta/(m_\psi v_{\rm rel}^2)$$

S. Tulin, et.al., 1302.3898



Conclusions

- 3.5keV X-ray line signal can be explained in extended Zee-Babu model with DM
- Some parameter region is sensitive to the next generation DM direct search
- Light η achieves the correct relic abundance and also solves the small scale structure problems, core-vs-cusp and too-big-to-fail problem
- h^+, k^{++} may be discovered at LHC