MATTER ASYMMETRY GENESIS IN THE Z_3 DM-COMPANION MODEL

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BASED ON THREE WORKS IN COLLABORATION WITH

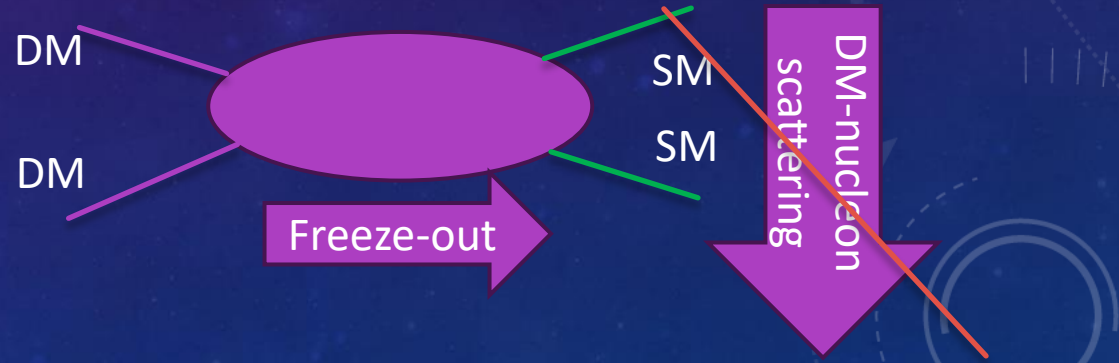
JUN GUO, SHAOLONG CHEN & ZE KUN LIU, PENG ZHANG

OUTLINE

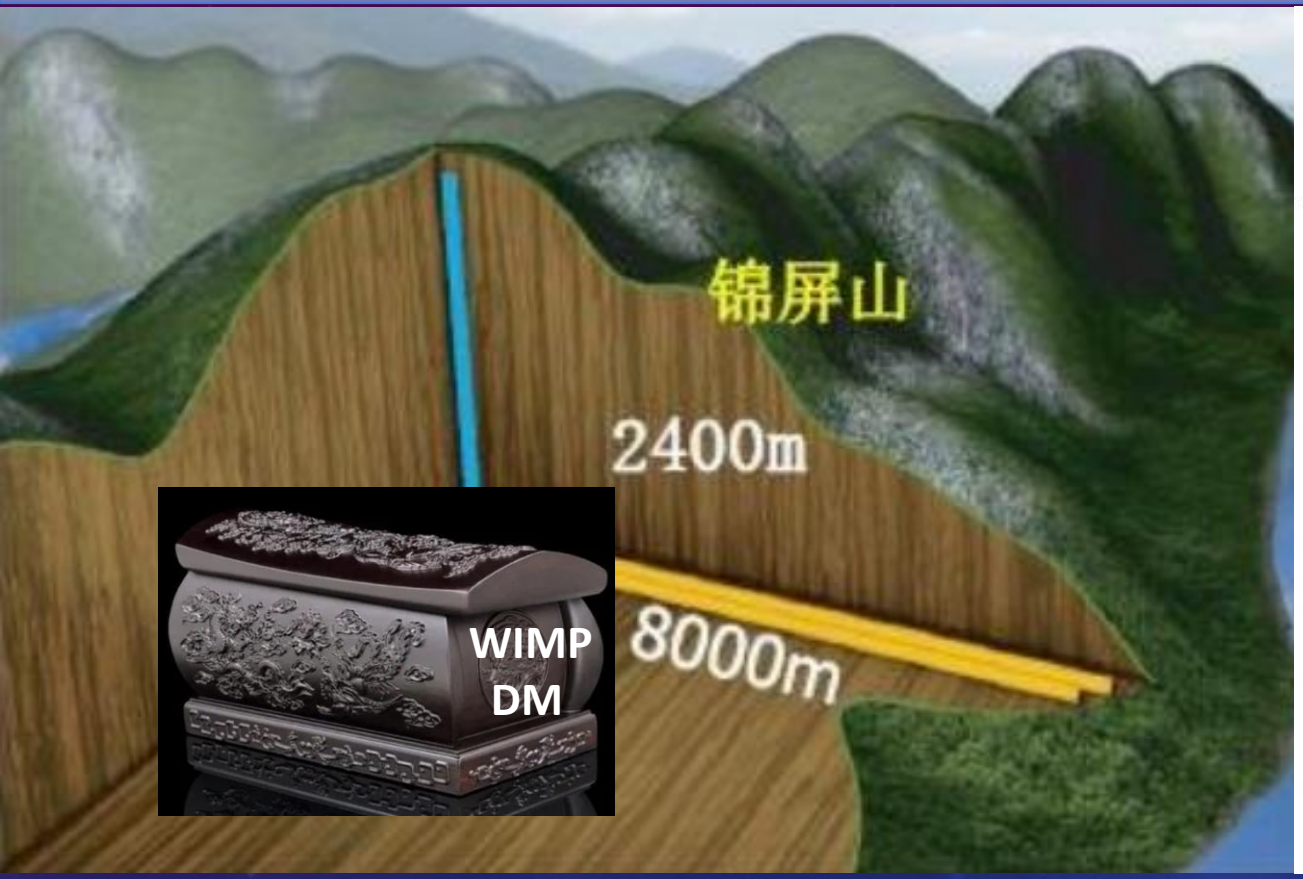
- Z_3 symmetric DM-companion model
- Semi-annihilation DM naturally being asymmetric DM & seeding matter asymmetry
- discussions and outlooks

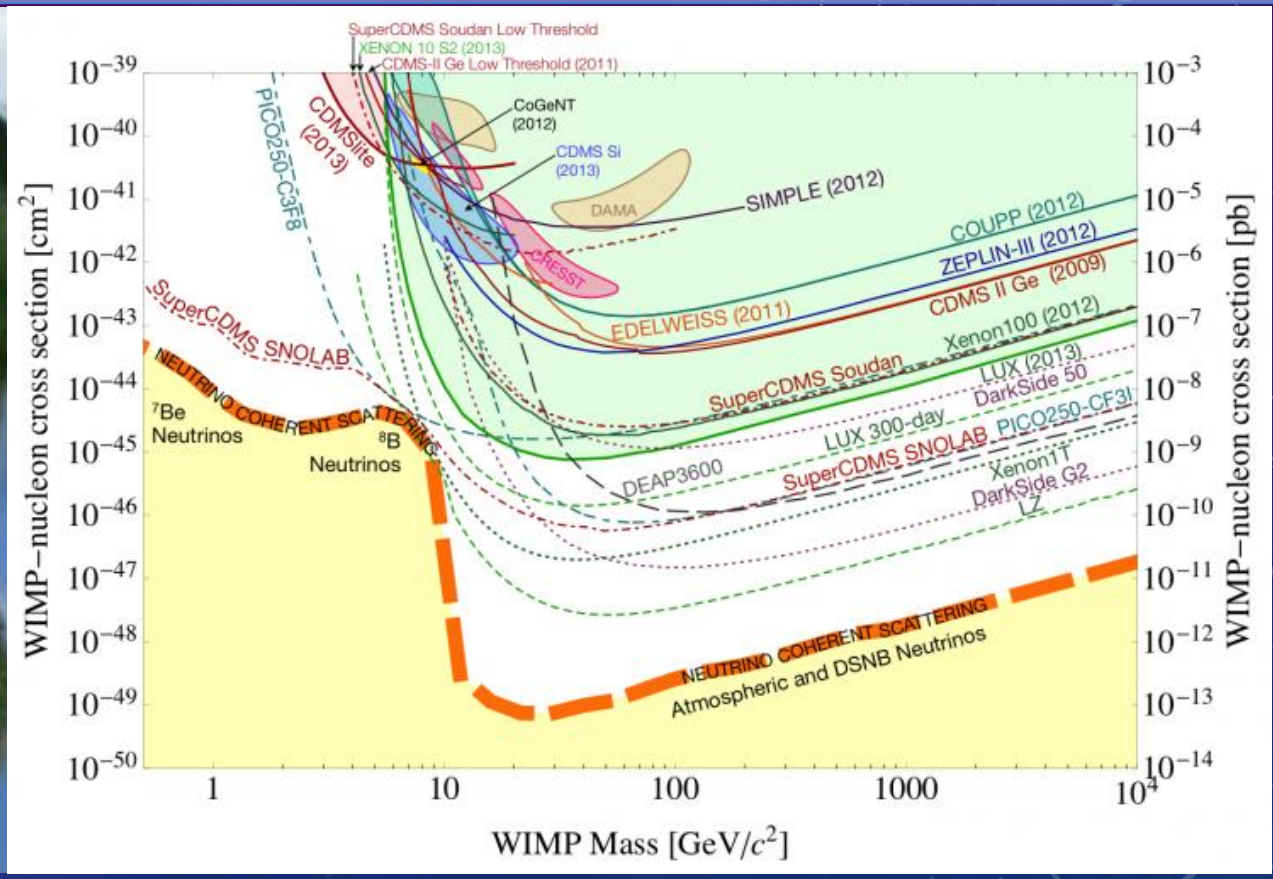
PART I: WIMP DARK MATTER HIDDEN BEHIND ITS COMPANION

Break the typical WIMP DM connections by symmetry：



UNDERGROUND DETECTION: TOMB OF WIMP DM?





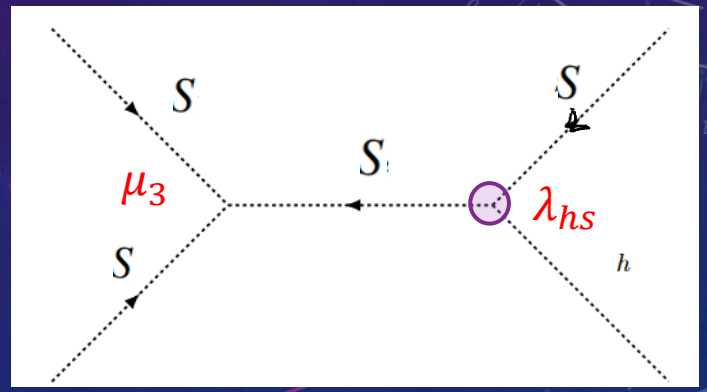
But! WIMP DM is born for its relic density,
not for its scattering with nucleon!

Z_3 SYMMETRIC DM-COMPANION MODEL

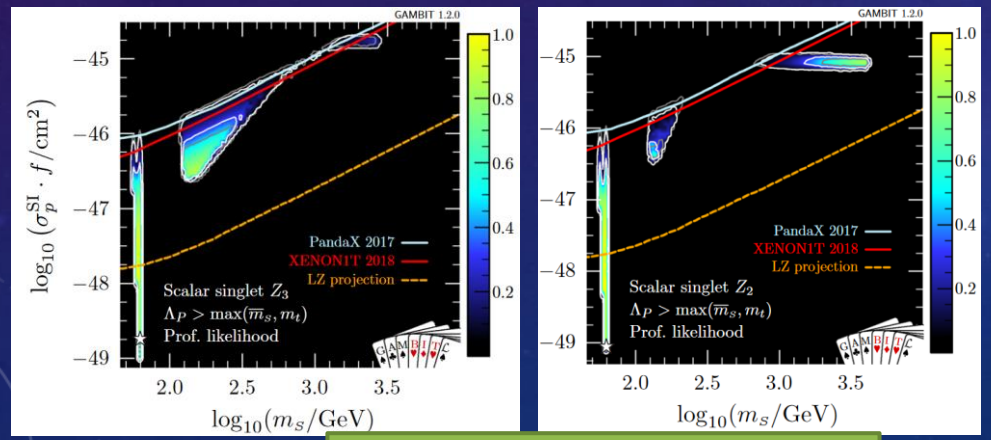
- The simplest Z_3 DM model: a complex scalar DM with Higgs portal

$$V_{\mathbb{Z}_3} = \mu_H^2|H|^2 + \frac{1}{2}\lambda_h|H|^4 + \lambda_{hS}S^\dagger S|H|^2 + \mu_S^2 S^\dagger S + \lambda_S(S^\dagger S)^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3}),$$

$$S \to \exp\left(i\frac{2\pi}{3}\right)S$$



- New-1: Semi-annihilation $SS \to Sh$
- New-2: Alleviate the constraint of DM direct detection, widening the relatively light region



From GAMBIT, EPJC 2018

- The usual Higgs portal is still necessary, but λ_{hs} can be smaller by increasing μ_3

Can we have more fun?E.g., to Improve the embarrassing situation of WIMP DM?

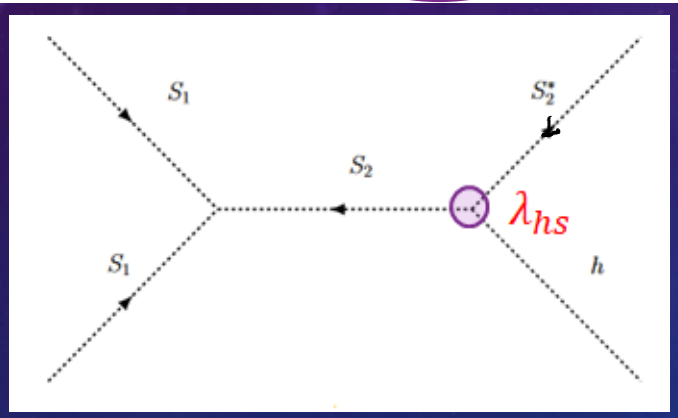
Z_3 SYMMETRIC DM-COMPANION MODEL

J. Guo, Z. Kang and P. Zhang, PLB (2022)

A new way to untie WIMP DM freeze-out & DM-nucleon scatter

- DM with a Z_3-symmetric companion

$$-\mathcal{L}_{Z_3} \supset m_1^2 S_1 S_1^* + m_2^2 S_2 S_2^* + \lambda_{1h}|S_1|^2|H|^2 + \lambda_{2h}|S_2|^2|H|^2 + \left(\frac{A_1 S_1^3}{3} + \frac{A_2 S_2^3}{3} + \frac{1}{2}A_{12} S_1^2 S_2 + \frac{1}{2}A_{21} S_1 S_2^2 + c.c\right),$$



- Fermionic Z_3 DM ***has no*** DM Higgs portal!

$$-\mathcal{L}_{Z_3} \supset + m_S^2|S|^2 + M_\Psi \bar{\Psi}\Psi + \lambda_{sh}|S|^2|H|^2 + \left(\frac{A_s}{3}S^3 + \lambda_L \overline{\Psi^C} P_L \Psi S + \lambda_R \overline{\Psi^C} P_R \Psi S + c.c.\right),$$

- If extend the original model by one more copy of DM S_1, then this DM companion S_2 furnishes the symmetric portal to SM
- Now the Higgs portal for DM can/should be turned off, by hand
- To allow DM semi-annihilate away, we require **the window: $m_{S_2} + m_h < 2m_{S_1} < 2m_{S_2}$**

The idea can be implemented in any Z_N model for $N > 2$

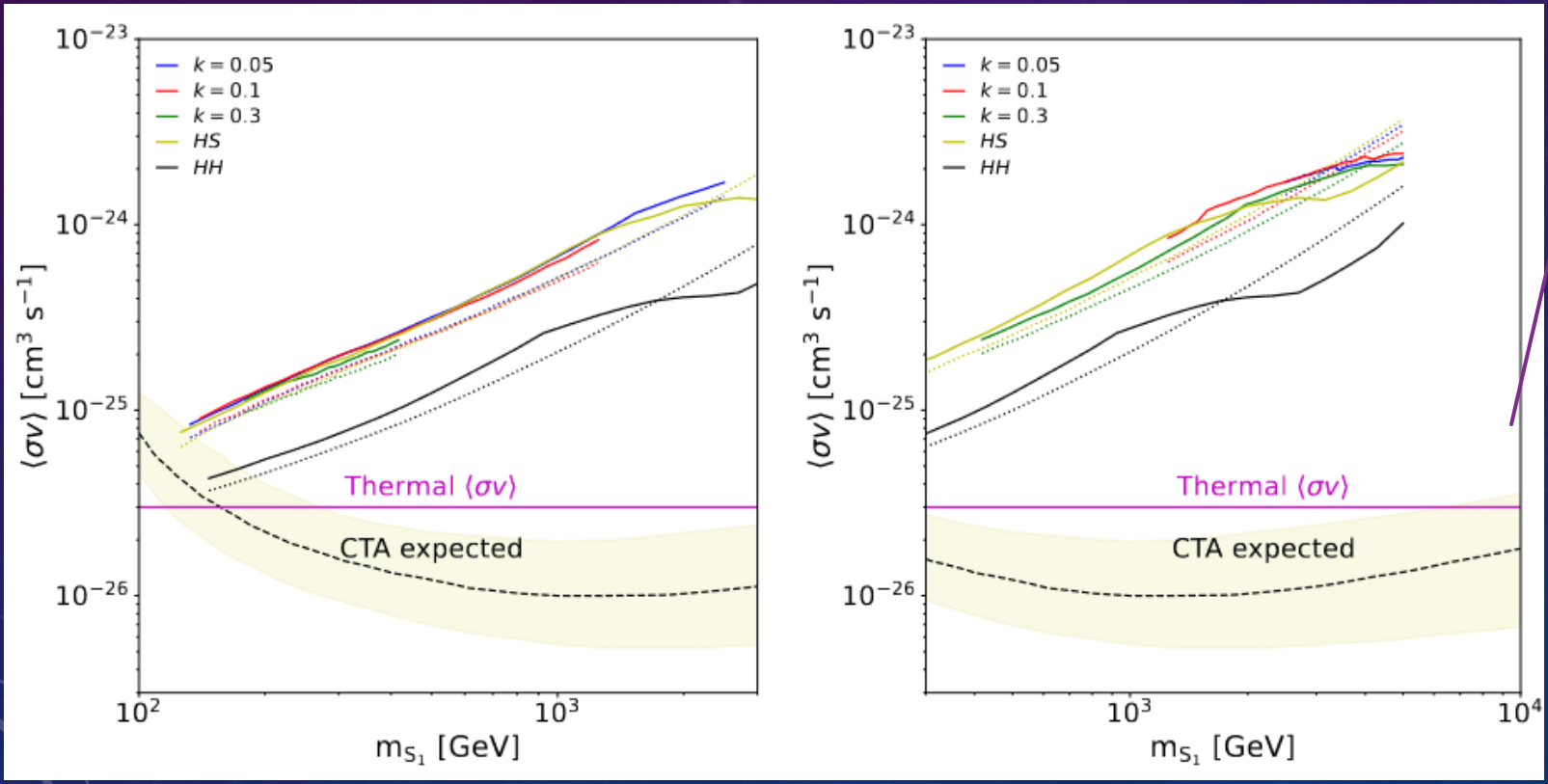
Due to the accidental Z_2 for fermion, companion is also stable in this model

FUNS WITH Z_3 DARK MATTER MODELS

J. Guo, & Z. Kang , 2405.14309, PLB

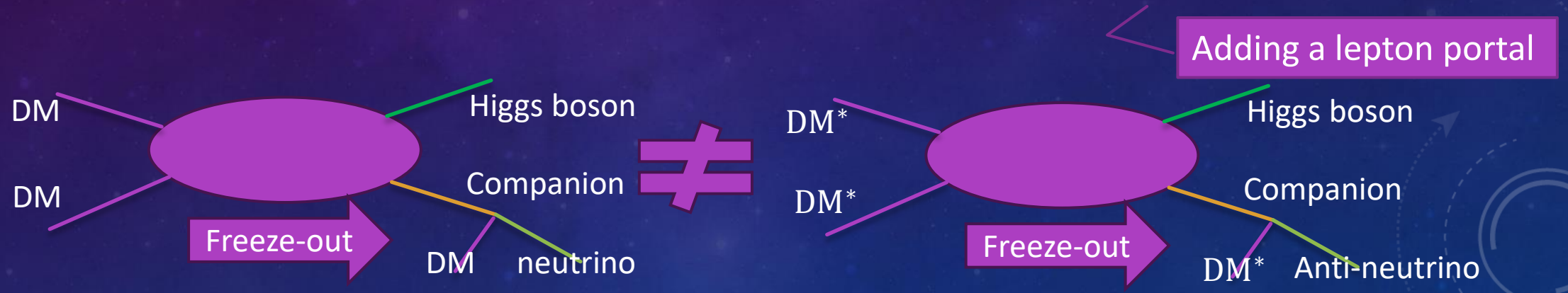
Highly hidden in the sky?

- Cosmic ray signal via on/off shell Higgs bosons: $S_1 S_1 \to S_2(\to S_1 h) + h$

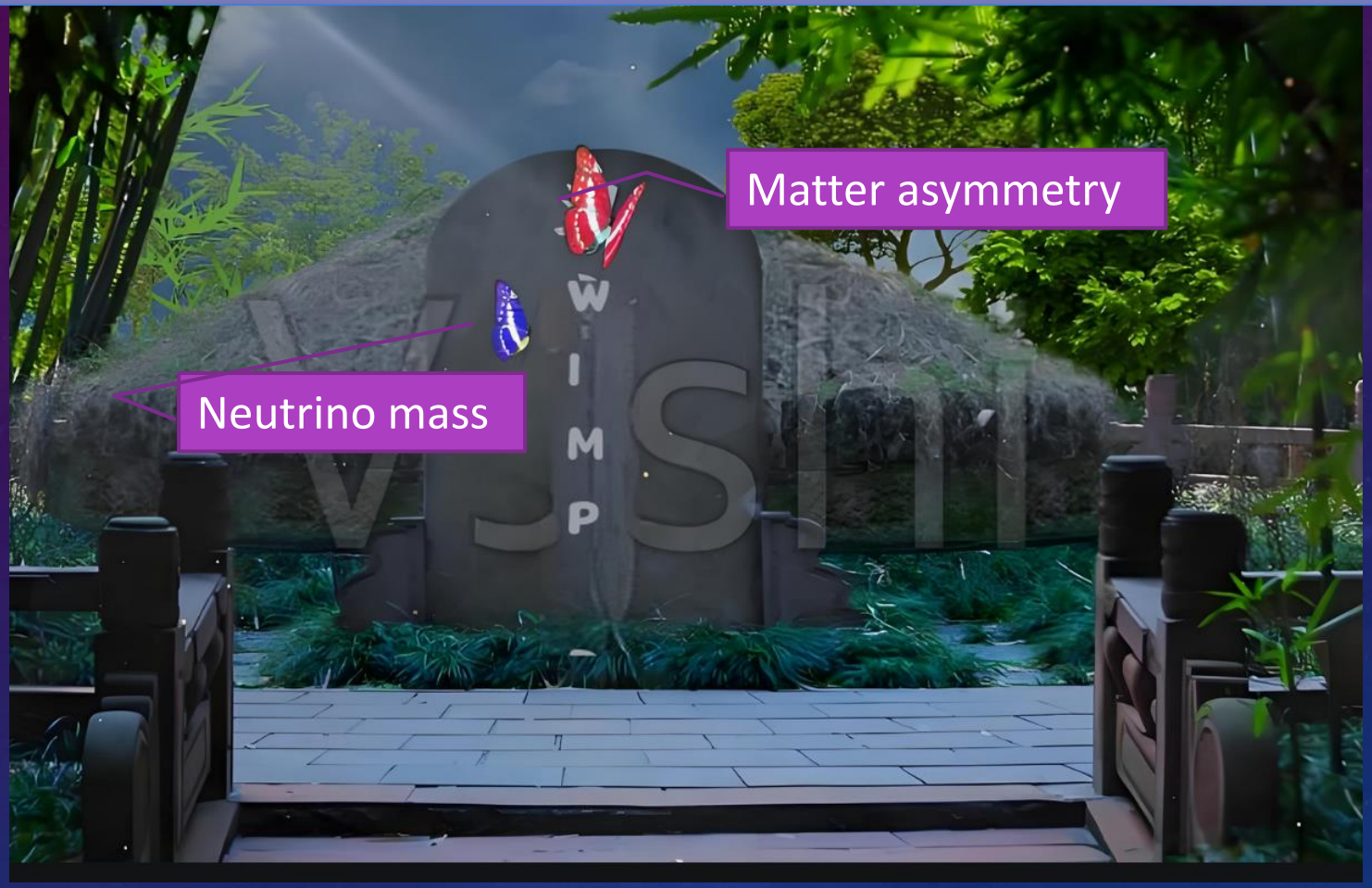


- Similar to the single Higgs signal from the conventional semi-annihilation model
- The 14&6-year FRMI-LAT data cannot yield meaningful constraint in the heavy region
- CTA can cover the whole space
- in the deep coannihilation region, this signal rate may be highly suppressed

PART II: MATTER ASYMMETRY COME FROM THE DM-COMPANION SECTOR



BORN AFTER ``DEATH”



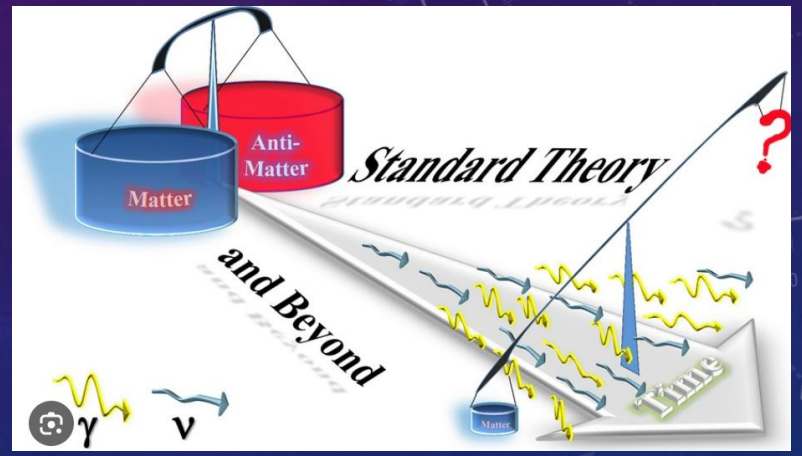
WIMP DM is closely related to the visible world, and it may shed light on other clouds

SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

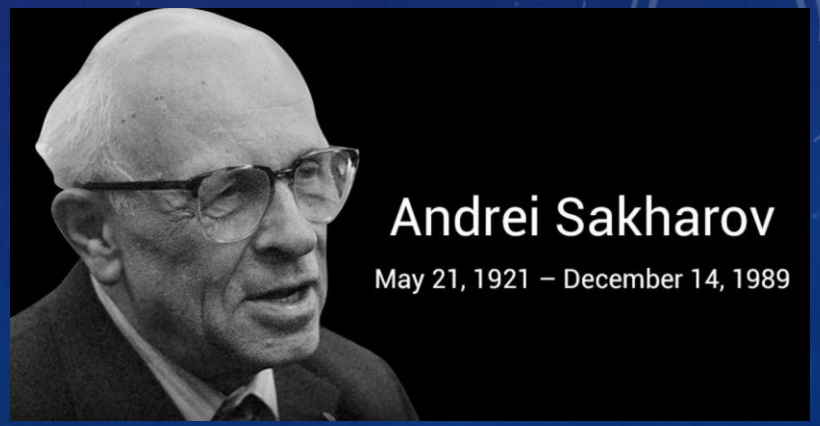
- Maximally asymmetric visible world
  - asymmetry to save the world

    Were in a symmetric early universe, the nucleon-antinucleon large annihilation rate would lead to negligible matter fraction

  - a tiny asymmetry at $T \gtrsim 38\ \mathrm{MeV}$ to prevent over-annihilation: $\frac{n_q - n_{\bar{q}}}{n_\gamma} \sim 10^{-10}$



- Origin of asymmetry in BSM & Sakharov's 3 conditions (1967)
  - B violation
  - C &CP violation
  - out-of-equilibrium (decay, freeze-out, first order phase transition)



SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

Connect to dark matter?
idea traced back to
asymmetric dark matter

- Asymmetry first generated in the dark matter, carrying generalized B/L number
- Translated to the visible sector via proper operators, e.g., DM^2
- Related to but different than the models where DM directly annihilates into L/B to produce matter asymmetry

Natural dark Sakharov's 3 conditions in semi-annihilation models

- dark matter number (not self-conjugate by $Z_{N\geq 3}$) & its violation (S^3 term)
- CP violation: readily & safely present in the dark sector
- WIMP freeze out from the plasma departures from equilibrium

TRANSFER TO THE VISIBLE SECTOR

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

- A lepton portal extension to the DM-companion model
  - an extra doublet scalar companion η

$$-\mathcal{L}_{extra} \supset + y_{ij}\overline{L_{Li}}\tilde{\eta}\Psi_{Rj} + \lambda_\eta H^\dagger H \eta^\dagger \eta + g\eta^\dagger H S + m_\eta^2 \eta^\dagger \eta,$$

The portal generalize lepton number to dark sector

A ``derivation" to the two-loop neutrino mass model by E. Ma

Fileds	$SU(2)$	$U(1)_Y$	$\mathcal{Z}_3$
H	2	1/2	1
L_L	2	-1/2	1
$\Psi^i_{R,L}$	1	0	w
$\eta = \begin{pmatrix} \eta^\dagger \\ \eta^0 \end{pmatrix}$	2	1/2	w
S	1	0	w

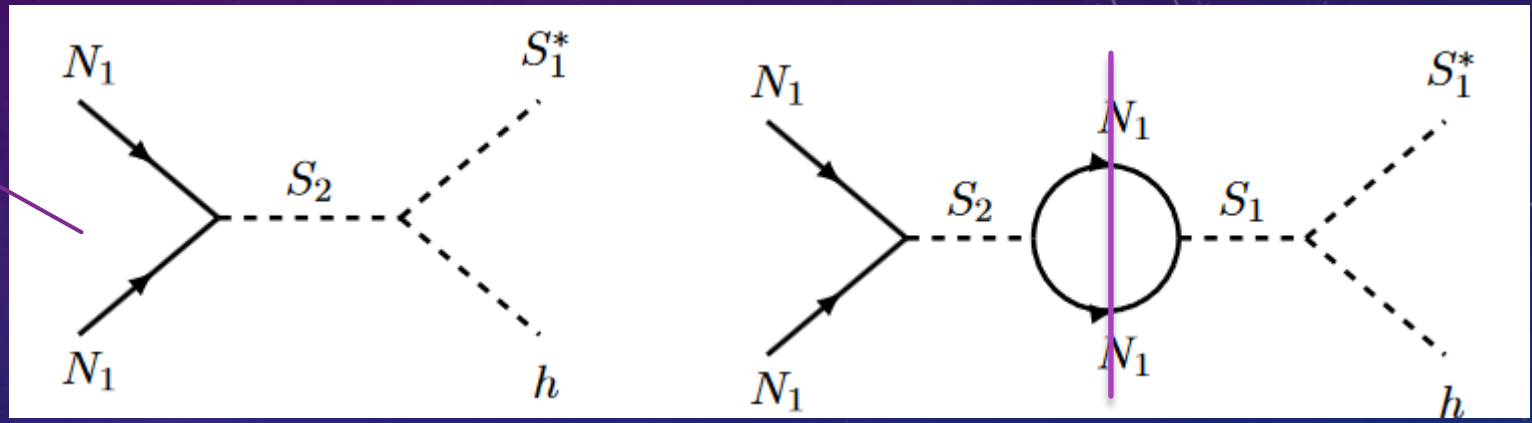
  - $S - \eta^0$ mixture→neutrino+DM, transferring DM asymmetry to leptons
  - Further transfers to baryon asymmetry? Depends on DM! see later

SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

- Non-zero CP-violation parameter thanks to thermal motion
  - tree-loop interference

A resonant pole is needed for multi-TeV scale DM



  - Zero CP violation in the static limit: initial & loop particles are the same

$$\epsilon = \frac{|M|^2_{N_1N_1\to S_1^*h} - |M|^2_{\overline{N_1N_1}\to S_1h}}{|M|^2_{N_1N_1\to S_1^*h} + |M|^2_{\overline{N_1N_1}\to S_1h}} = -\frac{Im[\lambda_0^*\lambda_1]}{4\pi|\lambda_0|^2}\frac{\sqrt{s(s-4m_{N1}^2)}(s-2m_{N1}^2)}{(s-m_{S_2}^2)m_{N_1}^2}$$

  - way out: Thermal average consistently defined below

$$\epsilon_T \equiv \langle\epsilon(s)\rangle = \frac{4m_{N_1}^2}{n_a^{eq}n_b^{eq}}\int d\Pi_a f_a^{eq} d\Pi_b f_b^{eq}\epsilon(a+b\to i+j).$$

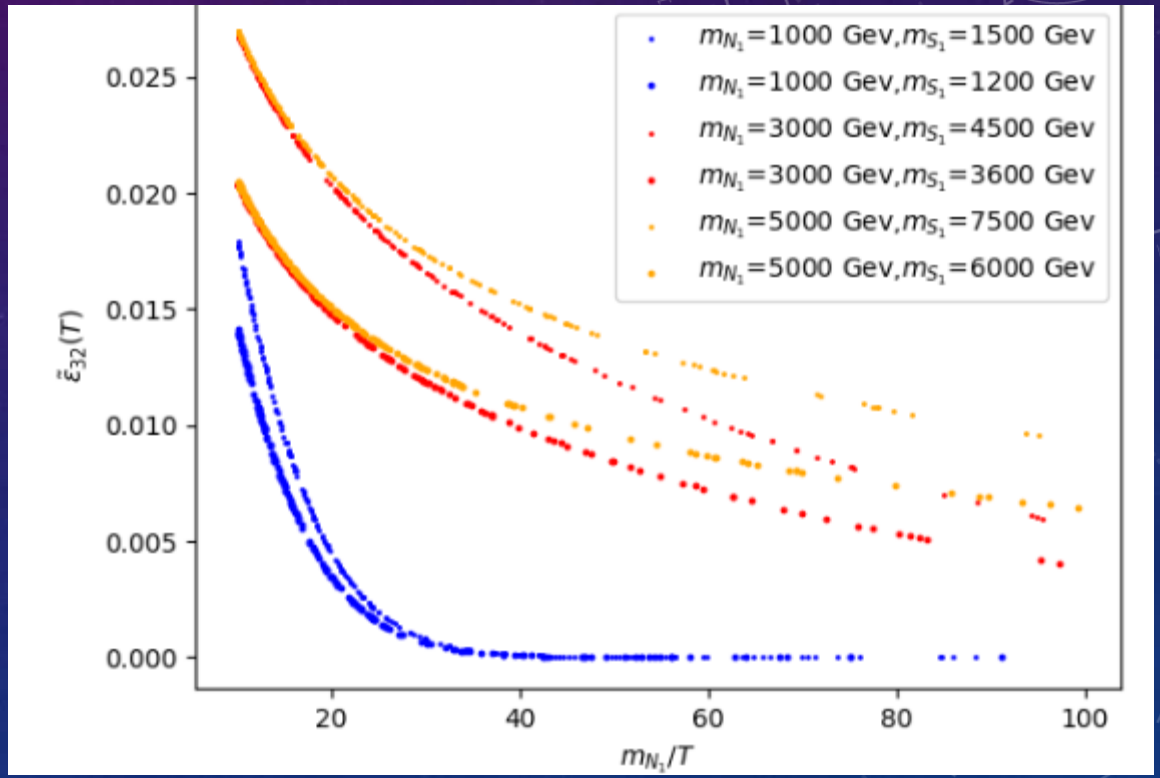
SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

Non-zero CP-violation parameter thanks to thermal motion

- nonrelativistic suppression is mild, $\sim\mathcal{O}(0.001)-\mathcal{O}(0.01)$

$$\langle\tilde{\epsilon}_{32}(T)\rangle \approx \frac{e^{2z}}{8g_N^2(15/8+z)^2 z\pi\sqrt{\frac{\pi}{2}}} \int_{2z}\sqrt{x}e^{-x}\sqrt{x^2-4z^2}\frac{x\sqrt{(x^2-4z^2)(x^2-2z^2)}}{(x^2-y^2)}dx$$



- Resonant enhancement $\sim\mathcal{O}(10)$ from the coupling part is reasonable

$$\frac{\mathrm{Im}[\lambda_0^*\lambda_1]}{|\lambda_0|^2} = \frac{\mathrm{Im}[\lambda_{R2}^*\lambda_{sh12}\lambda_{R2}\lambda_{R2}\lambda_{R1}^*\lambda_{sh1}^*]}{|\lambda_{R1}\lambda_{sh12}^*|^2} \to \frac{|\lambda_{R1}||\lambda_{R2}||\lambda_{sh1}|}{|\lambda_{sh12}|}e^{i\beta}$$

This coupling can be very small due to DM annihilation with resonant enhancement

TRANSFER TO THE VISIBLE SECTOR

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

Boltzmann equations

- evolutions of number density of the (anti)DM-(anti)companion system

$$\begin{aligned}\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z_N} = \frac{m_N^3}{z_N^2 H(m_N)}[&2Y_{S_1^*}Y_h\langle\sigma_a v\rangle - 2Y_{N_1}Y_{N_1}\langle\sigma_b v\rangle + Y_{S_1}\frac{z_N^3}{m_N^3}\Gamma_D - Y_{v_1}e^{-\frac{z_N\Delta m}{m_N}}\frac{z_N^3}{m_N^3}\Gamma_D \\ &+ Y_{S_1}Y_h\langle\sigma_c v\rangle - Y_{N_1}Y_{\overline{v_1}}\langle\sigma_c v\rangle + 2Y_{S_2^*}Y_h\langle\sigma_a v\rangle - 2Y_{N_1}Y_{N_1}\langle\sigma_b v\rangle \\ &+ Y_{S_2}\frac{z_N^3}{m_N^3}\Gamma_D - Y_{v_1}e^{-\frac{z_N\Delta m}{m_1}}\frac{z_N^3}{m_N^3}\Gamma_D + Y_{S_2}Y_h\langle\sigma_c v\rangle - Y_{N_1}Y_{\overline{v_1}}\langle\sigma_c v\rangle],\end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}Y_{S_1^*}}{\mathrm{d}z_1} = \frac{m_1^3}{z_1^2 H(m_1)}[&Y_{N_1}Y_{N_1}\langle\sigma_b v\rangle - Y_{S_1^*}Y_h\langle\sigma_a v\rangle + Y_{v_1}e^{-\frac{z_1\Delta m}{m_1}}\frac{z_1^3}{m_1^3}\Gamma_D - Y_{S_1}\frac{z_1^3}{m_1^3}\Gamma_D \\ &+ Y_{N_1}Y_{\overline{v_1}}\langle\sigma_c v\rangle - Y_{S_1}Y_h\langle\sigma_c v\rangle],\end{aligned}$$

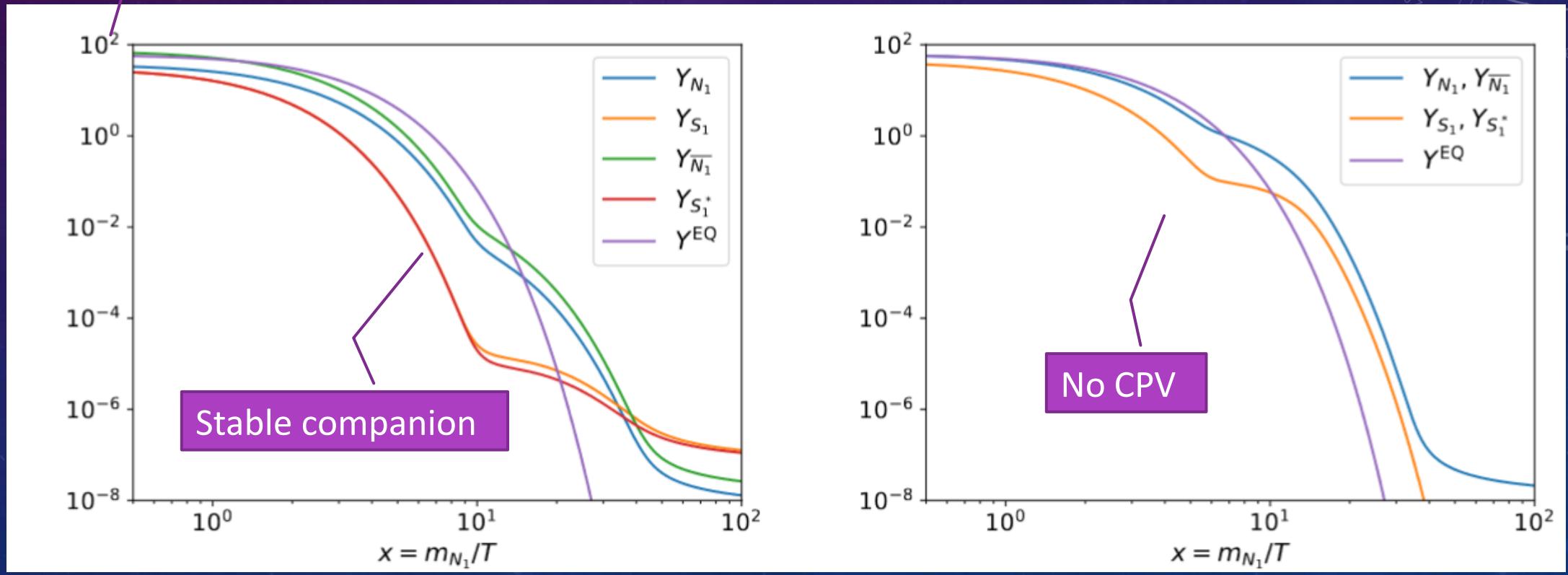
The only accessible channel of asymmetric companion decay is into neutrino, **without washing-out**

TRANSFER TO THE VISIBLE SECTOR

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEP

- BEs, beyond the coannihilation region
  - Asymmetry evolution samples

Asymmetry ~DM yield

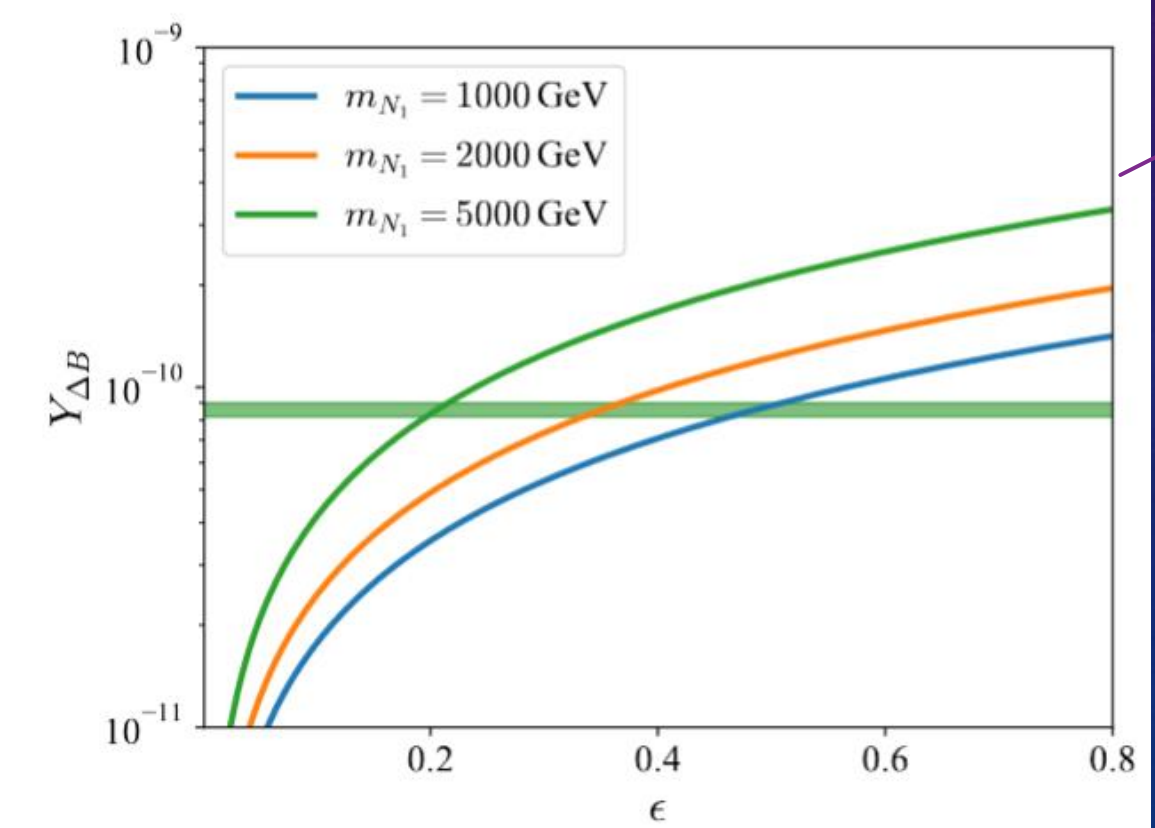


TRANSFER TO THE VISIBLE SECTOR

SL Chen, ZK Liu, Z. Kang and P. Zhang, 2405.05694 JHEPing

Results

- matter asymmetry versus thermally averaged CP violation parameter

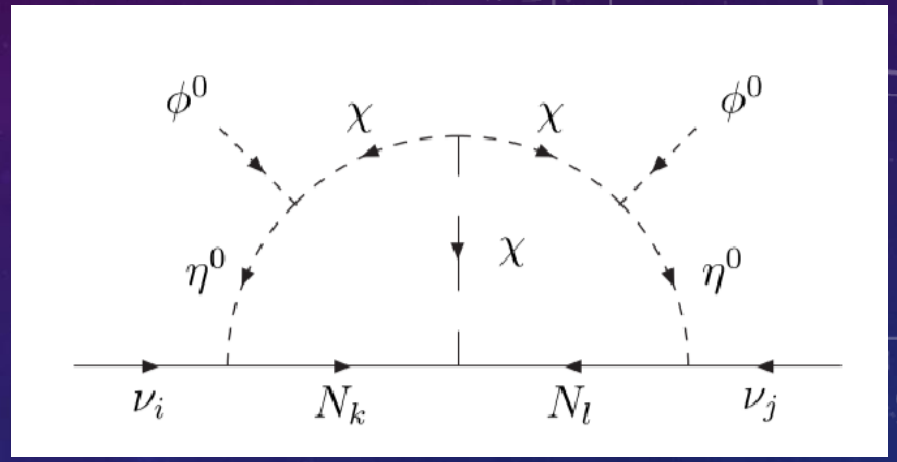


For the interesting multi-TeV scale DM, $\epsilon \sim 0.1$ works

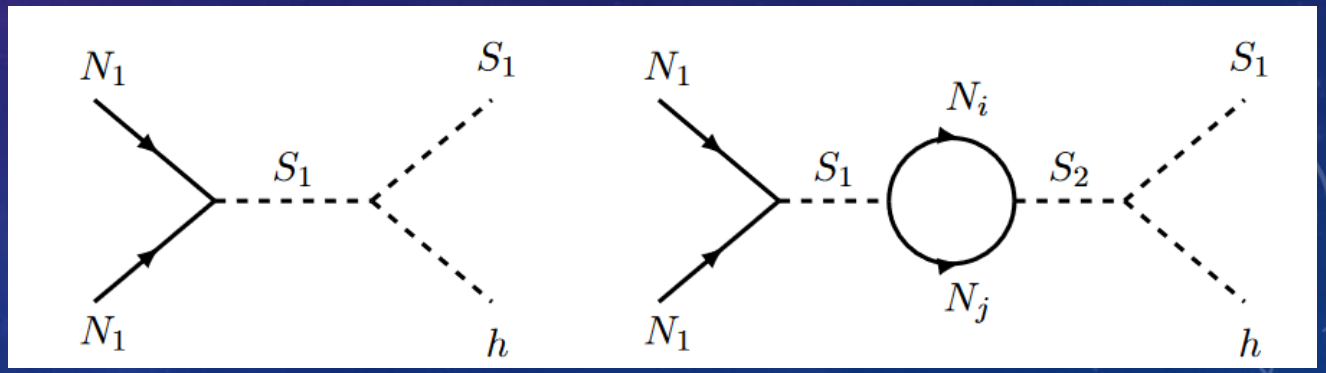
Thank you for your attention!

FUTURE WORK (WISH LIST LAST YEAR)

- Neutrino & matter asymmetry
  - a part of two-loop neutrino model
  - ingredients for matter asymmetry



- $\mathrm{DM}-\mathrm{DM}$ not DM-anti-DM annihilation (dark number violation)
- CP violation in the dark sector or from the neutrino sector
- Departure from equilibrium during DM freeze-out
- transforming DM asymmetry to matter via leptons



Thank you for your attention!