MATTER ASYMMETRY GENESIS IN THE Z_3 DM-COMPANION MODEL

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DM AND NEUTRINO FOCUS WEEK AT TDLI/SHANGHAI

2025/08/23

BASED ON THREE WORKS IN COLLABORATION WITH

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

PART 0: BSM——WHO SHOULD YOU REALLY BELIEVE?

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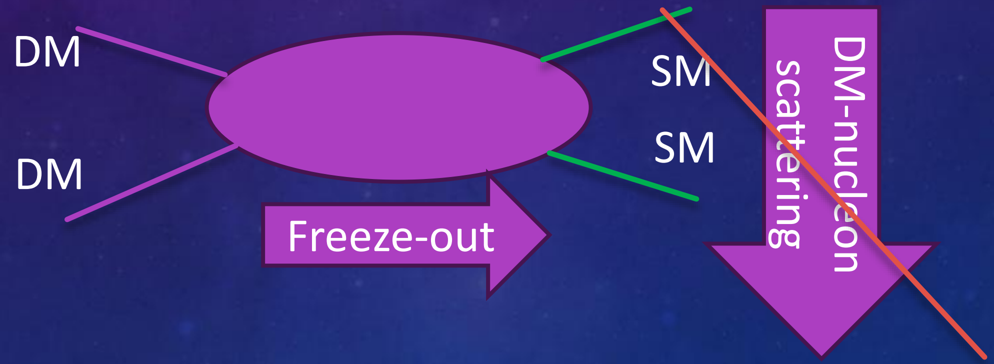
Both neutrino and dark matter are the main theme of new physics beyond the Standard Model of particle physics. The neutrino oscillation is the first new physics supported by various experiments and serves as an inevitable guide for the future study. And the existence of dark matter receives various evidences from astrophysical and cosmological observations. Without dark matter, no galaxy would have enough time to form. Although we are still trying to figure out the identity and properties of dark matter, it is of much great elegence and convenience for particle physics to provide an explanation in the unified framework of quantum field theory. Neutrino and dark matter also share multiple features: both are neutral, produced in the early Universe, having weak interaction with the ordinary matter. They could be understood within a unified picture.

More broadly, the study of neutrino and dark matter is of great importance for understanding the matter world, including both the visible and dark matter worlds, that plays profound roles in the evolution of our Universe. Until now, our human beings can only understand less than 5% of the cosmic energy. Even for this 5%, we still do not know the exact reason for the existence of matter, namely, why there are a lot of matter but almost no anti-matter. In addition, the dark matter world that is more than 5 times abundant than the visible matter. Without understanding the matter worlds, one cannot claim fully understanding the origin and evolution of our Universe.

PART I: WIMP DARK MATTER HIDDEN BEHIND ITS COMPANION



These connections for typical WIMP DM is easily broken for a richer dark sector, for instance, including a mediator Z' to open $\mathrm{DM}+\mathrm{DM}\to Z'Z'$.
Our proposal is based on the variant of semi-annihilating DM

Z_3 SYMMETRIC DM-COMPANION MODEL

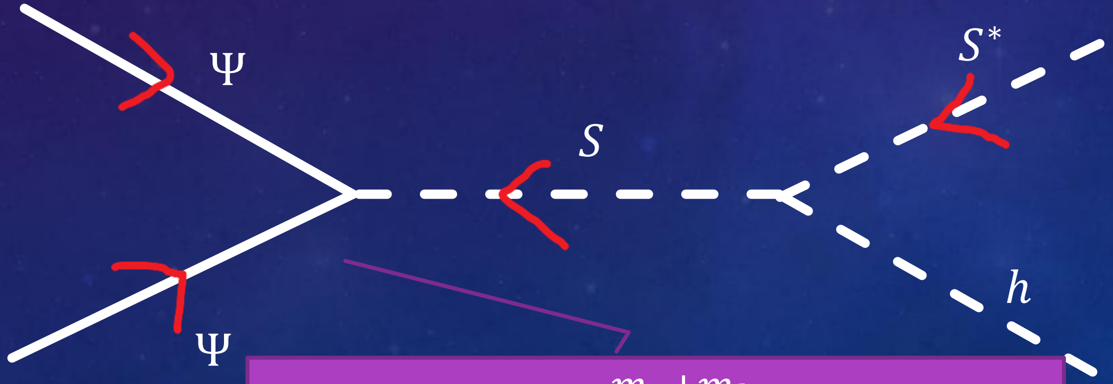
J. Guo, Z. Kang and P. Zhang, PLB (2022)

◆ The simplest DM-companion model is based on Z_3

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

- A Dirac fermion Ψ as DM, with the companion, a complex singlet S,
- DM freeze-out: DM-DM semi-annihilates into the companion plus Higgs boson

They have identical Z_3 charge and the companion opens **a symmetric portal** to SM. In this model, they are both stable, but not in the latter extension



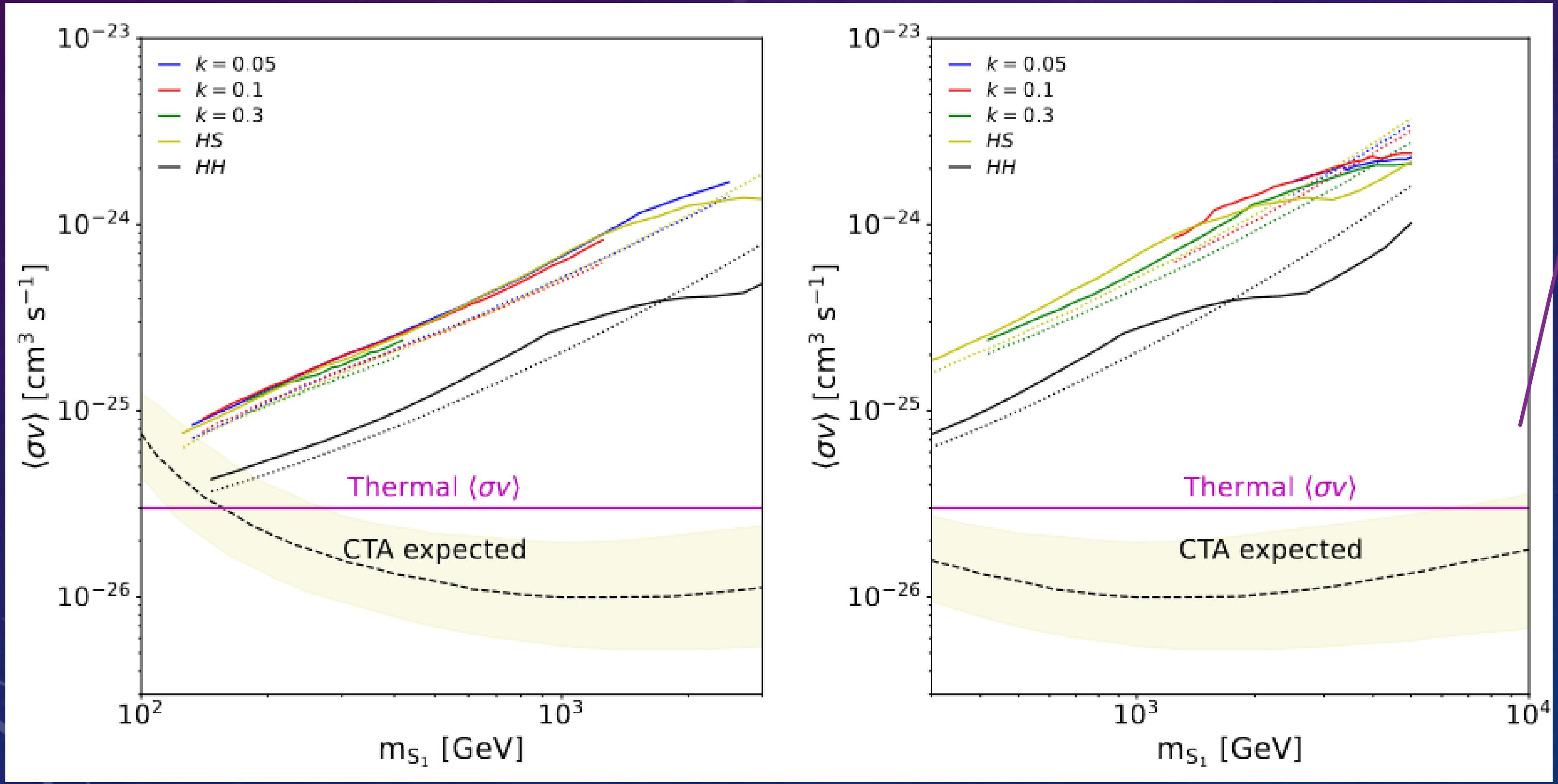
WIMP window: $\frac{m_S+m_h}{2} < m_\Psi < m_S$

NO DM-nucleon scattering!

FUNS WITH Z_3 DARK MATTER MODELS

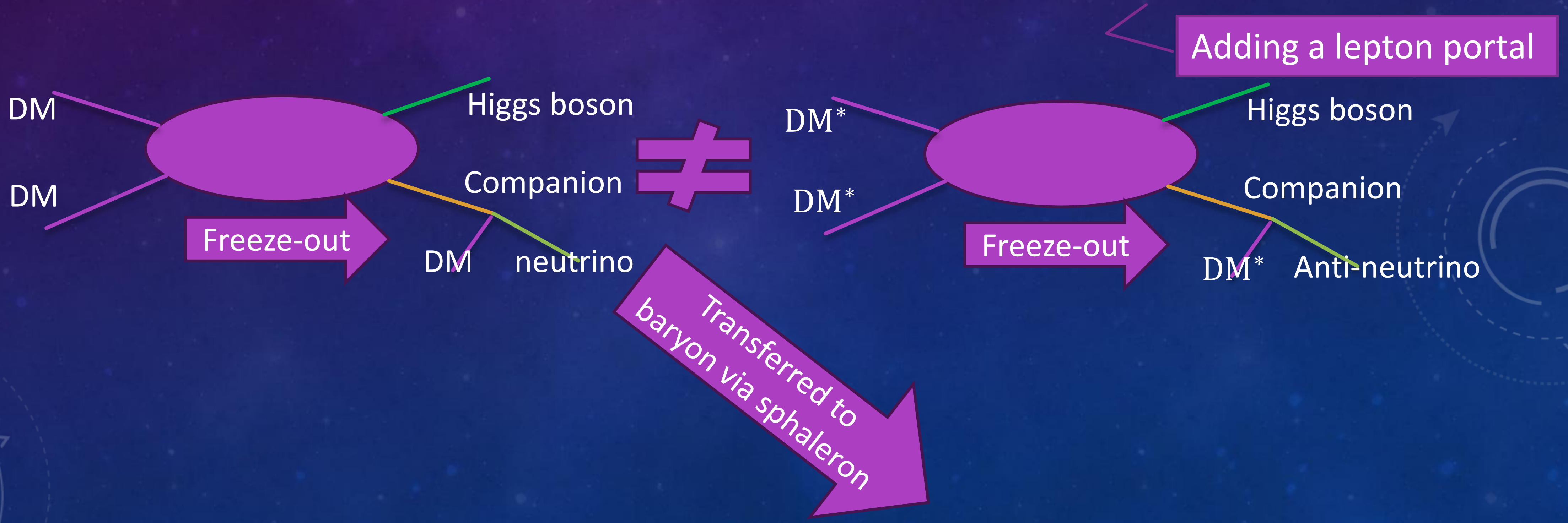
J. Guo, & Z. Kang , 2405.14309, PLB

- Also deeply hidden in the sky? (scalar DM example)
  - 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

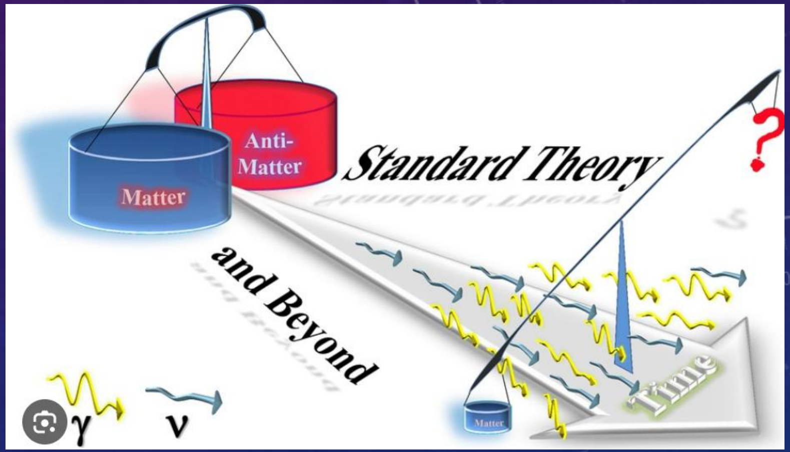


SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

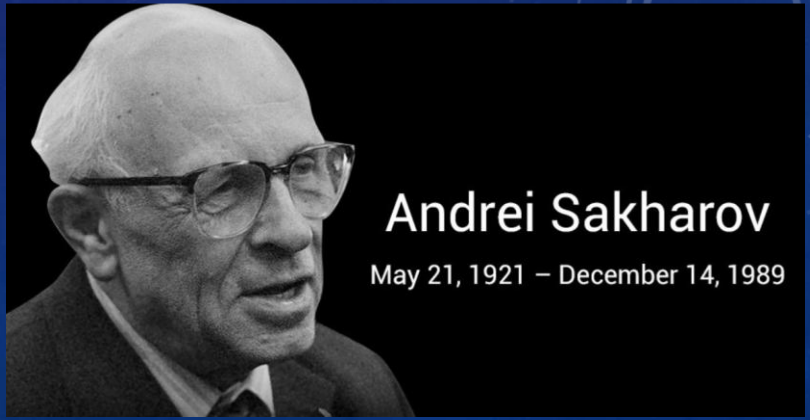
- Maximally asymmetric visible world
  - asymmetry to save the world

    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 $Z_{N\geq3}$) & 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

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

This portal generalizes lepton number to the dark sector

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

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

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

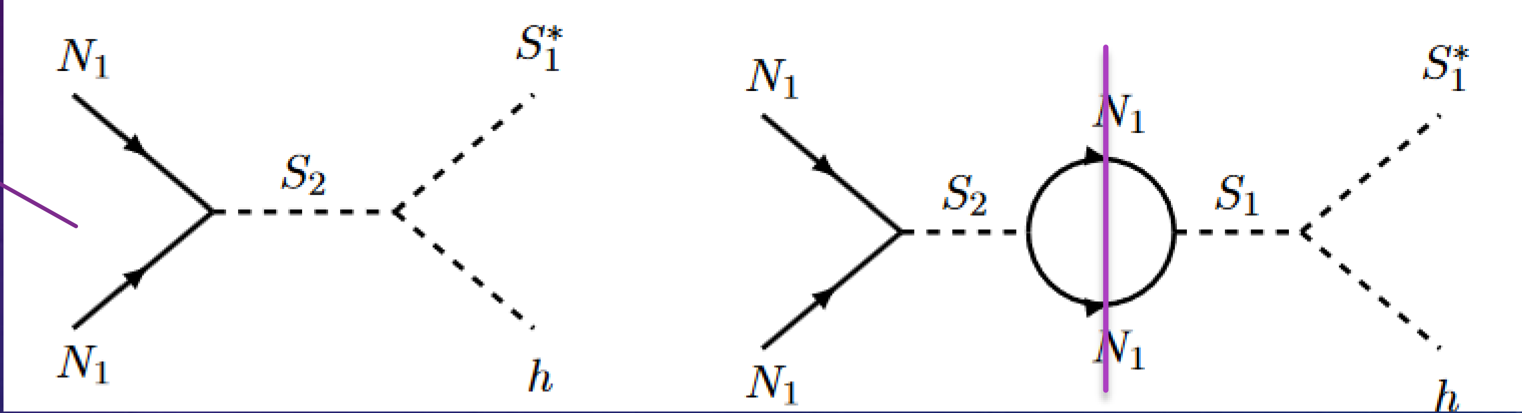
SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

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

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

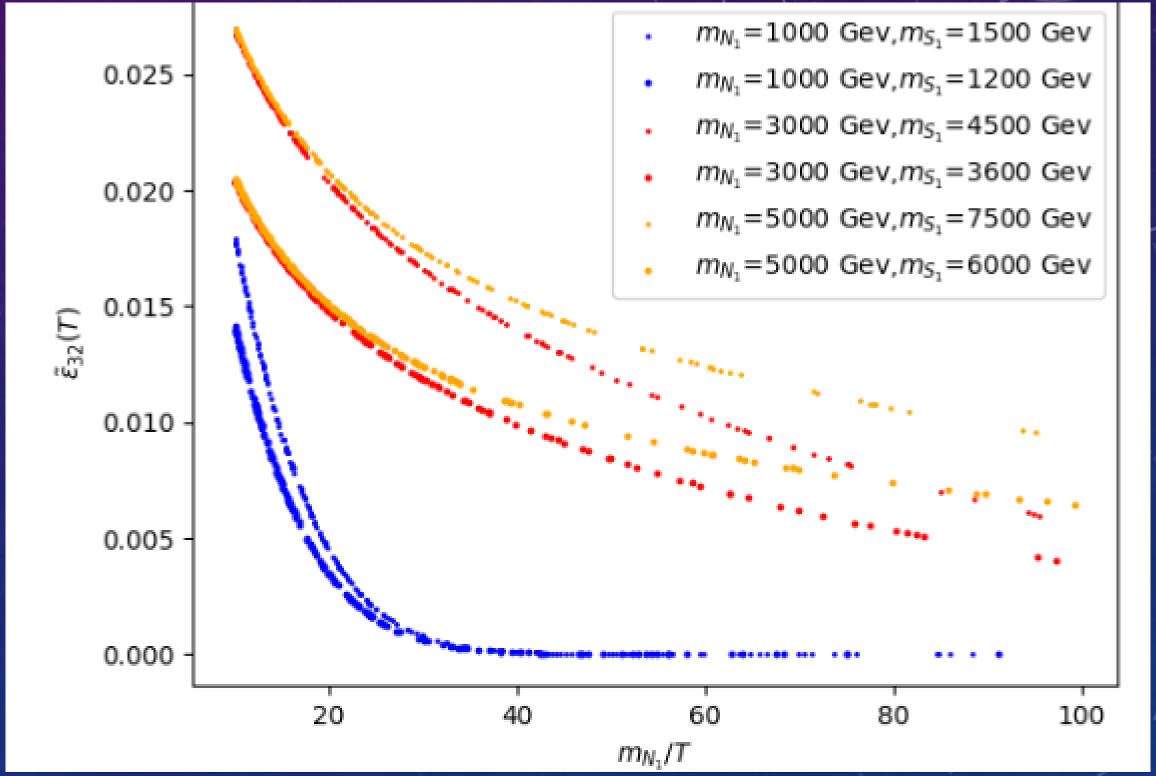
SEMI & ASYMMETRIC-ANNIHILATING DARK MATTER

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, $\sim\mathcal{O}(0.001) - \mathcal{O}(0.01)$

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



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

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

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
  - evolution of companion asymmetry $\Delta_{S_1} = Y_{S_1} - Y_{S_1^*}$

$$\frac{d\Delta_{S_1}}{dz_1} = \frac{m_1^3}{z_1^2 H(m_1)}\Big[Y_{N_1}^2\left(1-\left(\frac{Y_{N_1}^{eq}}{Y_{N_1}}\right)^2\frac{Y_{S_1^*}}{Y_{S_1^*}^{eq}}\right)\epsilon$$
$$-\langle\sigma_b v\rangle\Sigma_{N_1}\Delta_{N_1} - \langle\sigma_b v\rangle\frac{(Y_{N_1}^{eq})^2}{Y_{S_1^{eq}}}\Delta_{S_1} - \Delta_{S_1}\frac{z_1^3}{m_1^3}\Gamma_{D_1} + \frac{z_1^3}{m_1^3}\Gamma_{D_1}Y_{S_1}^{eq}\left(\Delta_{N_1} - \Delta_\nu\frac{Y_{N_1}^{eq}}{Y_{N_1}}\right)$$

Source term from CP-violating $\overline{N_1 N_1} \to S_1 + h$

Wash-out from inverse scattering

Wash-out from inverse decay of $S_1 \to N_1 + \bar{\nu}$, and one can suppress this one by a small decay width, **producing lepton asymmetry maximally at the same time**

$$y_1^2 \lesssim 4\pi g_*^{1/2}\left(\frac{4\pi^3}{45}\right)^{1/2}\frac{m_{S_1}}{M_P}\left(\frac{T_{ID}}{\Delta m}\right)^2 e^{\Delta m/T_{ID}} \approx 4.6\times 10^{-11}\times\frac{m_{S_1}}{1\mathrm{TeV}}\left(\frac{T_{ID}/\Delta m}{0.1}\right)^2$$

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◆ Asymmetry evolution samples

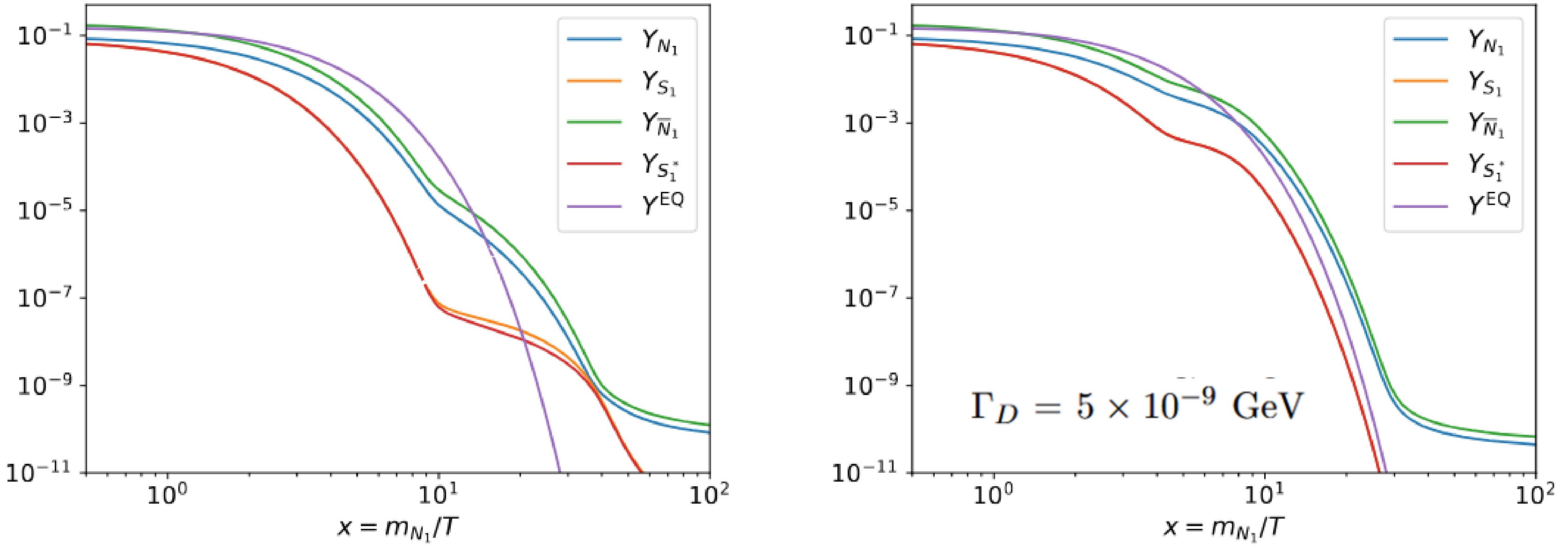


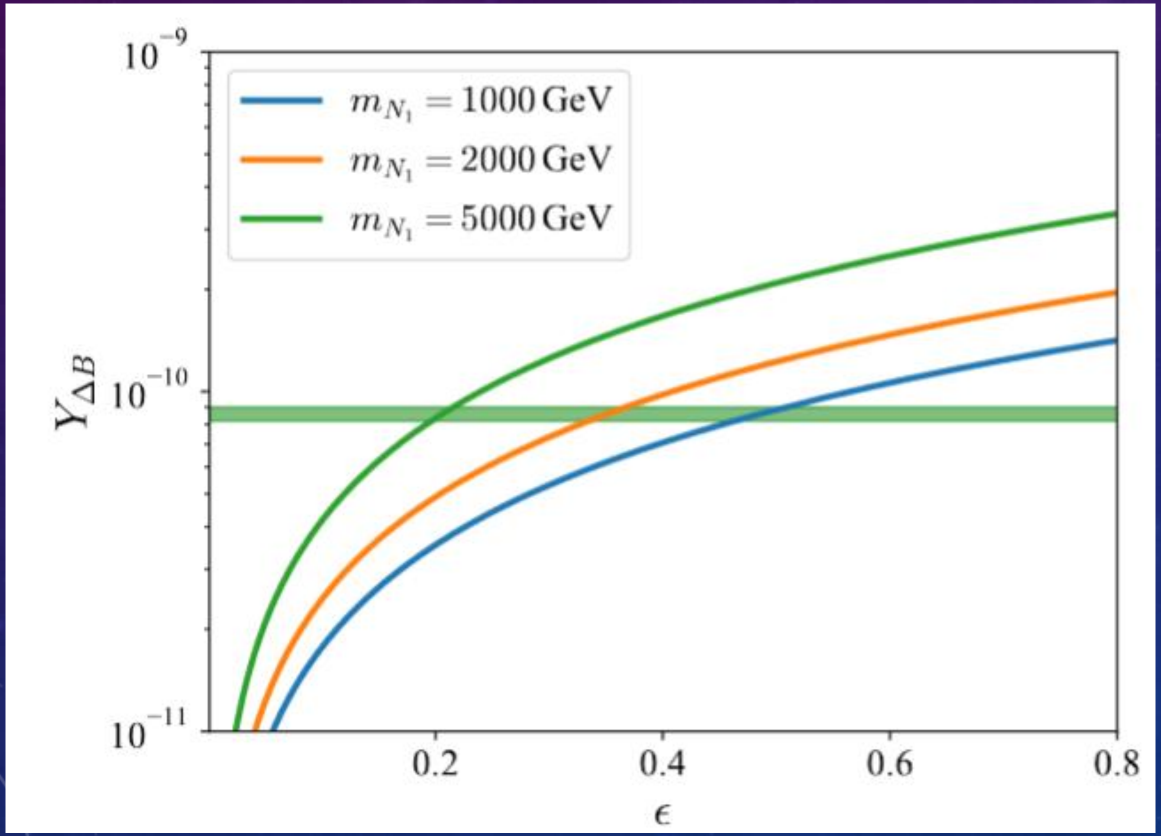
FIG. 3. Demonstration of the evolution of particle abundances. We fix dark matter mass $m_{N_1} = 500$ GeV, CP-violation parameter $\epsilon = 0.25$ and $\langle \sigma_{N_1 N_1 \to S_1^* h} v \rangle = 5 \times 10^{-12}$ GeV^{-2} and $\langle \sigma_{S_1 S_1^* \to hh} v \rangle = 5 \times 10^{-10}$ GeV^{-2}. For other parameters, we set: $m_{S_1}/m_{N_1} = 1.6$ and S_1 decay width $\Gamma_D = 10^{-15}$ GeV (left panel), $m_{S_1}/m_{N_1} = 1.9$ and $\Gamma_D = 5 \times 10^{-9}$ GeV (right panel). The change of Y_{S_1} at $x = 10$ for both S_1 and N_1 corresponds to the freeze-out of S_1. For $x > 30$, Y_{S_1} decreases sharply, it corresponds to the decay $S_1^* \to N_1 \nu$(in the left). In the right plot, the kinks around $x = 4$ correspond to the freeze-out of S_1.

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



ISSUE: DM freeze-out typically at $T_D \sim \frac{m_{\mathrm{DM}}}{30} > T_{\mathrm{sphaleron}} \sim 100\mathrm{GeV} \Rightarrow m_{\mathrm{DM}} > 3\mathrm{TeV}$

Relic density is problematic, and we are trying to relax this issue by more careful analysis on the role of companion

DM & MATTER ASYMMETRY: NOT NEW

- WIMPy baryogenesis for conventional WIMP

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- Not-conventional DM freeze-out, e.g., conversion-driven freeze-out, freeze-in

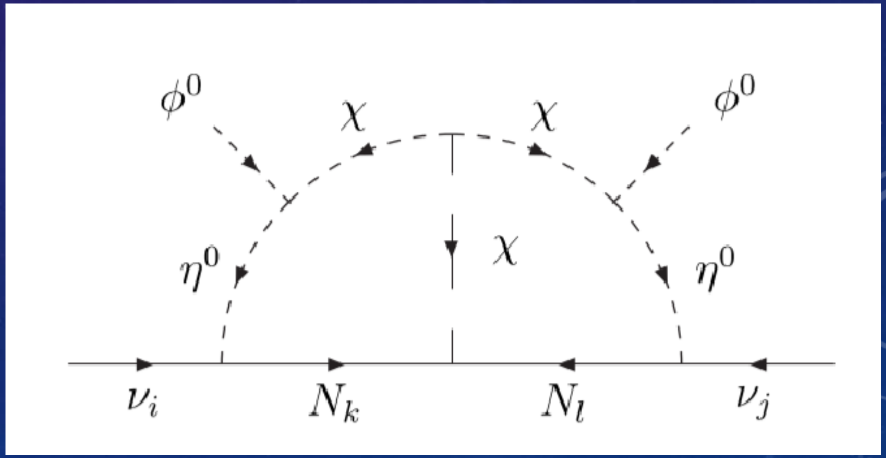
Conversion-Driven Leptogenesis: A Testable Theory of Dark Matter and Baryogenesis at the Electroweak Scale

Jan Heisig (RWTH Aachen U. and Virginia U.) (Apr 18, 2024)

Published in: *Phys.Rev.Lett.* 133 (2024) 19, 19 • e-Print: 2404.12428 [hep-ph]

CONCLUSION & OUTLOOK

- DM having a companion both under $Z_{N\geq 3}$ can maintain the WIMP miracle without giving rise to large DM-nucleon scattering
- Semi-annihilation DM naturally being asymmetric DM & seeding matter asymmetry
- a part of two-loop neutrino model, and we are working to reproduce neutrino mass & mixing



Thank you for your attention!