

Revisiting Minimal Models of Dark Matter

Koichi Hamaguchi (U. of Tokyo)

@PPC 2026, August 31 – September 4, 2026, UNSW.

Based on

[[2604.05326](#)] KH, **Ryoichiro Hayakawa, Hiroki Takahashi**

[[2603.18412](#)] KH, **Atsuya Niki, Kwok Hei To**

[[2507.20659](#)] **Kensuke Akita, KH, Maksym Ovchinnikov**

(Thermal Misalignment DM)

(Coannihilation DM)

(Sterile neutrino DM) cf. [[2509.08175](#)]

PPC 2026

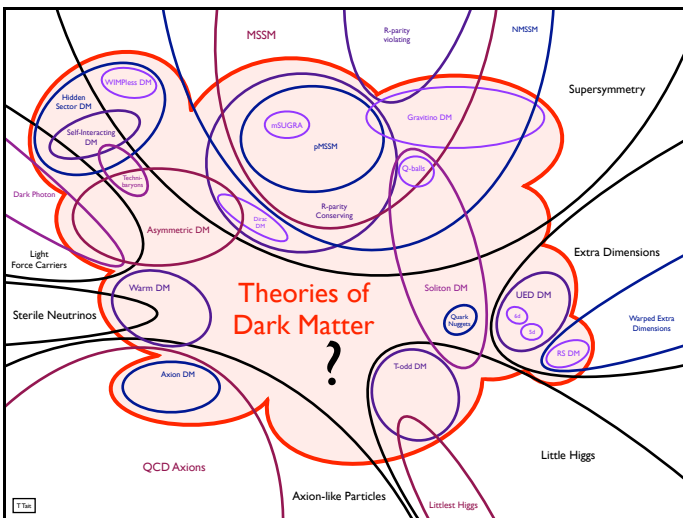


What is Dark Matter?

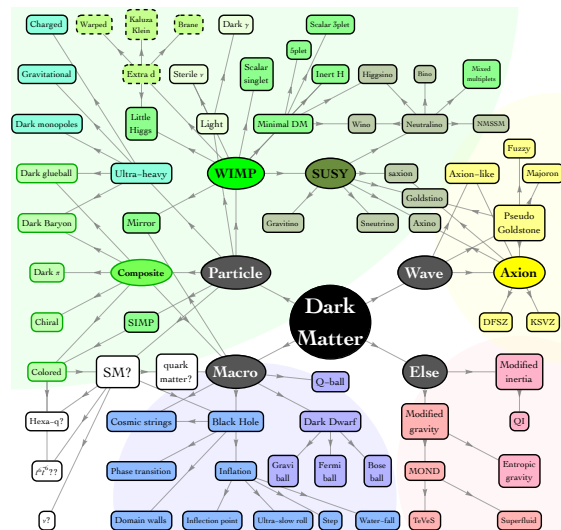
More than 70 orders of magnitude in mass range.

Ultralight DM $\gg$ PBH DM

$\gtrsim 10^{-21} \text{ eV}$ $\sim 10^{22} \text{ g} \sim 10^{54} \text{ eV}$



From talk by Tim Tait,
Snowmass July 2013.



From [[arXiv:2406.01705](https://arxiv.org/abs/2406.01705)]
M. Cirelli, A. Strumia, J. Zupan

What is Dark Matter?

Today:

- Step back and ask: what are the simplest possibilities?
- **Let's revisit minimal models.**

Plan

1. SM + ϕ (singlet scalar) with Z_2
2. SM + ϕ (singlet scalar) without Z_2
3. SM + ψ (singlet fermion) with Z_2
4. SM + ψ (singlet fermion) without Z_2

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1. SM + ϕ (singlet scalar) **with** Z_2

- SM + ϕ (real singlet scalar)
- $Z_2 : \phi \rightarrow -\phi$

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- Most general renormalizable Lagrangian:

$$L = L_{\text{SM}} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda_{\phi H}}{2}\phi^2(H^\dagger H) - \frac{\lambda_\phi}{24}\phi^4$$

Higgs portal DM / Minimal scalar DM

V. Silveira and A. Zee (1985).

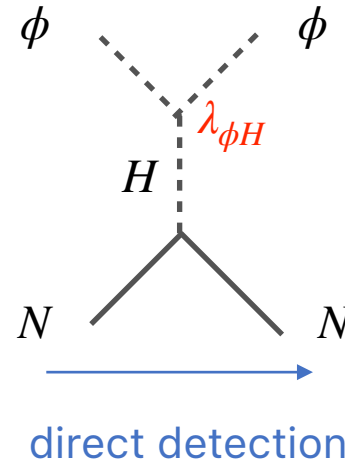
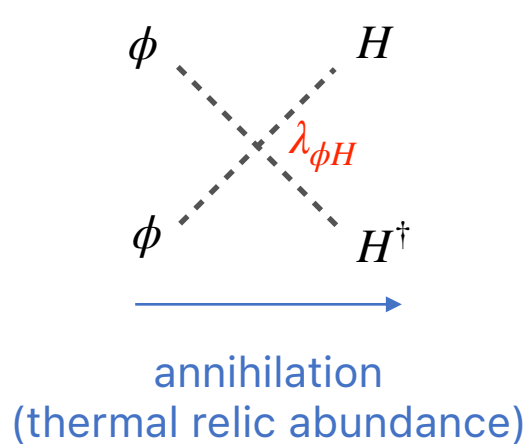
J. McDonald (1994).

C. P. Burgess, M. Pospelov, T. ter Veldhuis (2001).

1. SM + ϕ (singlet scalar) with Z_2

Higgs portal DM / Minimal scalar DM

$$L = L_{\text{SM}} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda_{\phi H}}{2}\phi^2(H^\dagger H) - \frac{\lambda_\phi}{24}\phi^4$$



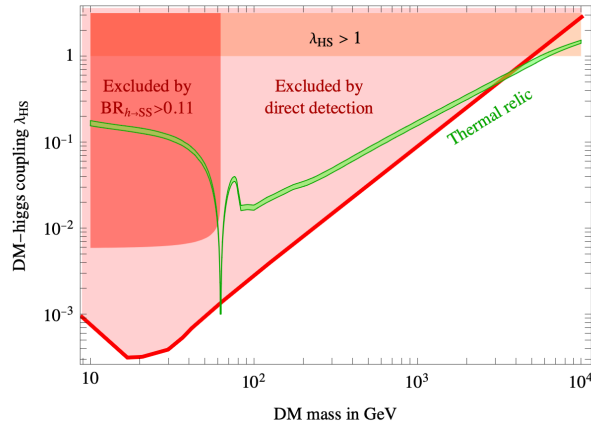
Two parameters
($m_\phi, \lambda_{\phi H}$)

1. SM + ϕ (singlet scalar) with Z_2

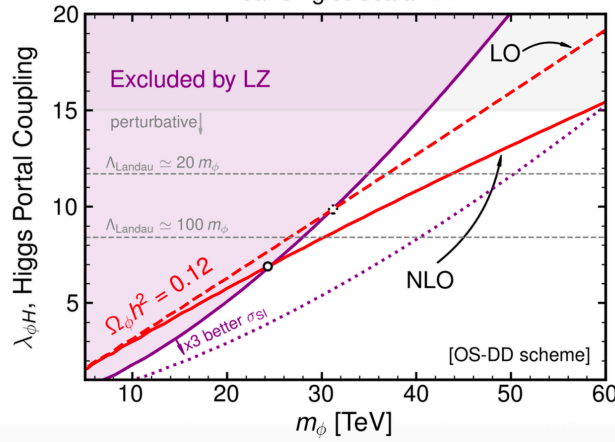
Higgs portal DM / Minimal scalar DM

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Scalar Singlet DM



Real Singlet Scalar DM



→ **Almost entirely excluded.**
(except near the Higgs resonance)

From M. Cirelli, A. Strumia, J. Zupan
[2406.01705]

From M. Escudero Abenza, T. Hambye
[2505.02408]

Plan

1. SM + ϕ (singlet scalar) with Z_2 — Higgs portal DM, **almost excluded**.
2. SM + ϕ (singlet scalar) without Z_2
3. SM + ψ (singlet fermion) with Z_2
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2. SM + ϕ (singlet scalar) **without** Z_2

- SM + ϕ (real singlet scalar) **without** Z_2 :

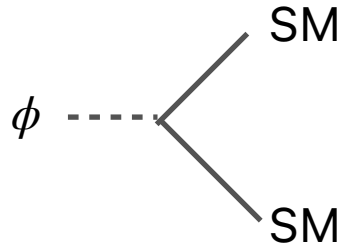
2. SM + ϕ (singlet scalar) **without** Z_2

- SM + ϕ (real singlet scalar) **without** Z_2 :

- General Lagrangian is:

$$L_{\text{int}} \sim \phi \cdot \mathcal{O}_{\text{SM}} + \phi^2 \cdot \mathcal{O}'_{\text{SM}} + \dots$$

- In general, ϕ is **unstable**.



2. SM + ϕ (singlet scalar) **without** Z_2

- To suppress the decay rate, assume a higher-dim operator:

$$L_{\text{int}} = \frac{\phi}{M} \cdot \mathcal{O}_{\text{SM}}$$

$$\text{e.g., } L_{\text{int}} = -\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

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- Then,

$$\Gamma_{\phi} \sim \frac{m_{\phi}^3}{M^2} \quad \rightarrow \quad \tau_{\phi} \gg \tau_{\text{Universe}} \text{ for sufficiently large } M.$$

Later we will focus on $M \gg M_{\text{pl}}$.

※ M is not necessarily a physical threshold; e.g., a heavy charged-fermion loop gives $M \sim M_{\text{heavy}}/(\alpha y)$.

2. SM + ϕ (singlet scalar) **without** Z_2

- Relic abundance ?

$$L_{\text{int}} = \frac{\phi}{M} \cdot \mathcal{O}_{\text{SM}}$$

$$\text{e.g., } L_{\text{int}} = -\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

Can **the same operator** also generate the observed DM abundance?

2. SM + ϕ (singlet scalar) **without** Z_2

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Can **the same operator** also generate the observed DM abundance?

One possibility is (UV-)freeze-in.

Here, let us introduce another mechanism, **thermal misalignment**.

2. SM + ϕ (singlet scalar) without Z_2

- At finite temperature,

$$L_{\text{int}} = \frac{\phi}{M} \cdot \mathcal{O}_{\text{SM}} \quad \rightarrow \quad \delta V_T(\phi) = c \frac{\phi}{M} T^4$$

temperature-dependent
linear potential.

e.g., $L_{\text{int}} = -\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$

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e.g., $L_{\text{int}} = -\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$

→ Combined with $-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$, this leads to $L = -\frac{1}{4} \left(1 + \frac{\phi}{4M}\right) F_{\mu\nu} F^{\mu\nu}$

→ gauge coupling: $g^2(\phi) = g^2 \left(1 + \frac{\phi}{4M}\right)^{-1} \simeq g^2 \left(1 - \frac{\phi}{4M}\right)$ for $\phi \ll M$

→ Free energy at two loop: $F_2 \simeq c_2 g^2(\phi) T^4 \rightarrow \underline{\delta V_T(\phi) = -c_2 g^2 \frac{\phi}{M} T^4}$

cf. W. Buchmuller, KH, M. Ratz, [hep-ph/0307181]

W. Buchmuller, KH, O. Lebedev, M. Ratz, [hep-th/0404168, 0411109]

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Note:

Axion-type couplings $\phi F_{\mu\nu} \widetilde{F}^{\mu\nu}$ do **not** induce such a term.

$$F_{\mu\nu} \widetilde{F}^{\mu\nu} \text{ is parity-odd} \quad \rightarrow \quad \langle F_{\mu\nu} \widetilde{F}^{\mu\nu} \rangle_T = 0.$$

Thermal misalignment DM

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Thermal misalignment DM

B. Batell and A. Ghalsasi [2109.04476].

E. J. Chun [2109.07423].

B. Batell, A. Ghalsasi, and M. Rai, [2211.09132].

A. Alachkar, M. Fairbairn, and D. J. E. Marsh [2406.06395].

D. Cyncynates and O. Simon [2408.16816, 2410.22409].

KH, R. Hayakawa, H. Takahashi [2604.05326]

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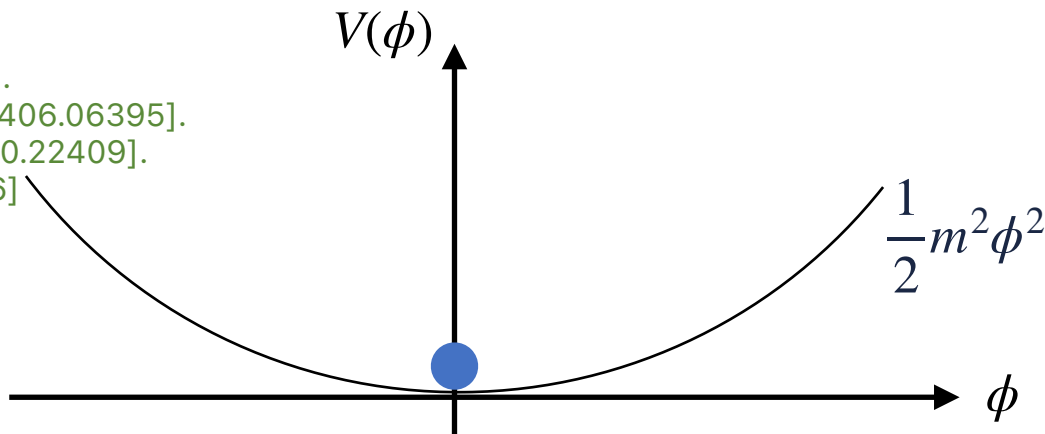
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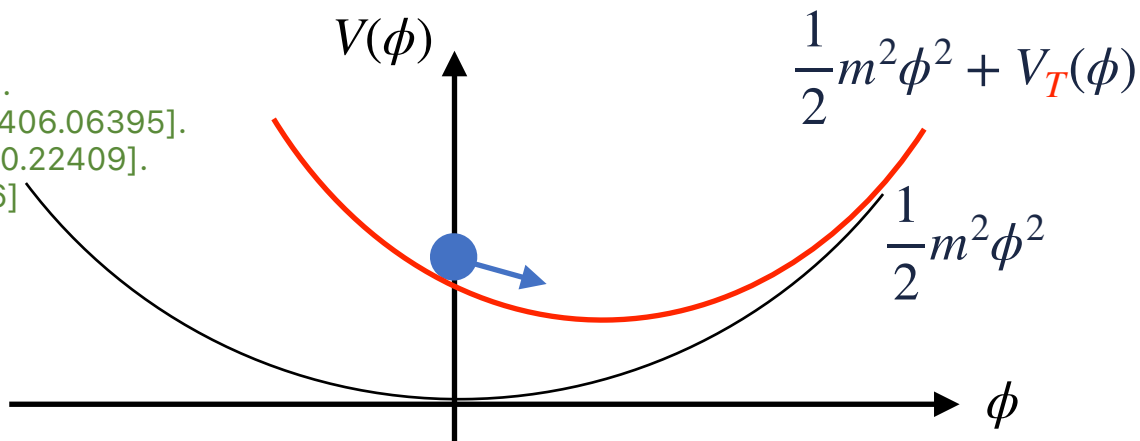
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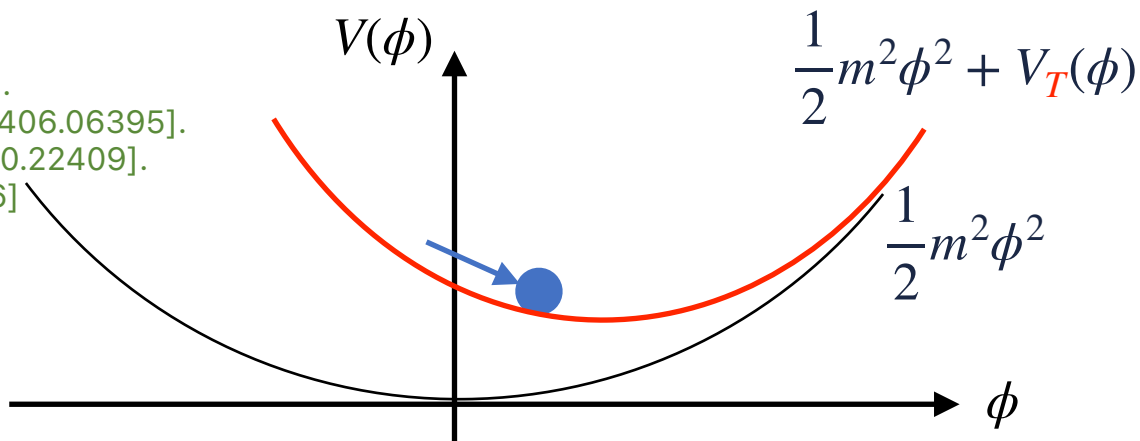
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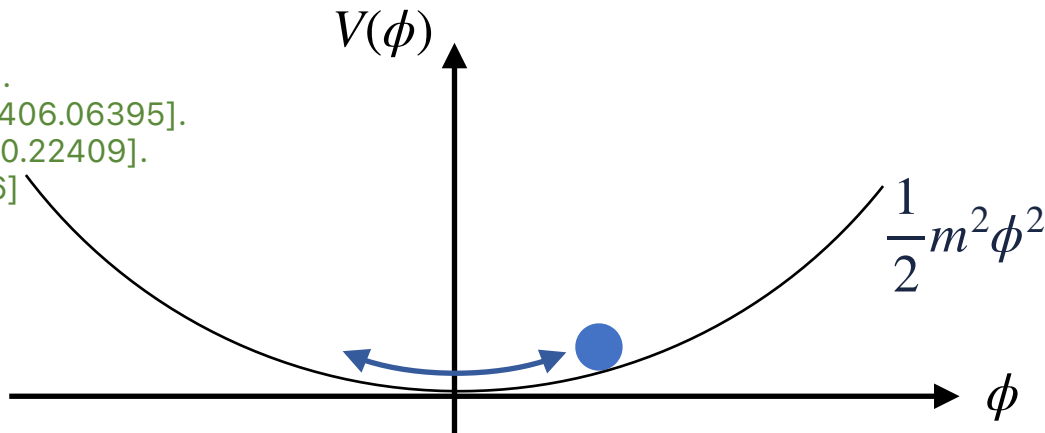
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Thermal misalignment DM

KH, R. Hayakawa, H. Takahashi [[2604.05326](#)] see also; D. Cyncynates and O. Simon [[2408.16816](#)]

We considered

$$L = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + L_{\text{int}}, \quad L_{\text{int}} = -\frac{\phi}{M}F_{\mu\nu}F^{\mu\nu} \quad (F^{\mu\nu}: \text{QED})$$

EW embedding

$$L_{\text{int}} = -\frac{\xi}{\cos^2\theta_W}\frac{\phi}{M}B^{\mu\nu}B_{\mu\nu} - \frac{1-\xi}{\sin^2\theta_W}\frac{\phi}{M}W^{a\mu\nu}W_{\mu\nu}^a \quad \begin{cases} B^{\mu\nu} : U(1)_Y \\ W^{\mu\nu} : SU(2)_L \end{cases}$$

parameters:
(M, m, ξ)

Thermal potential

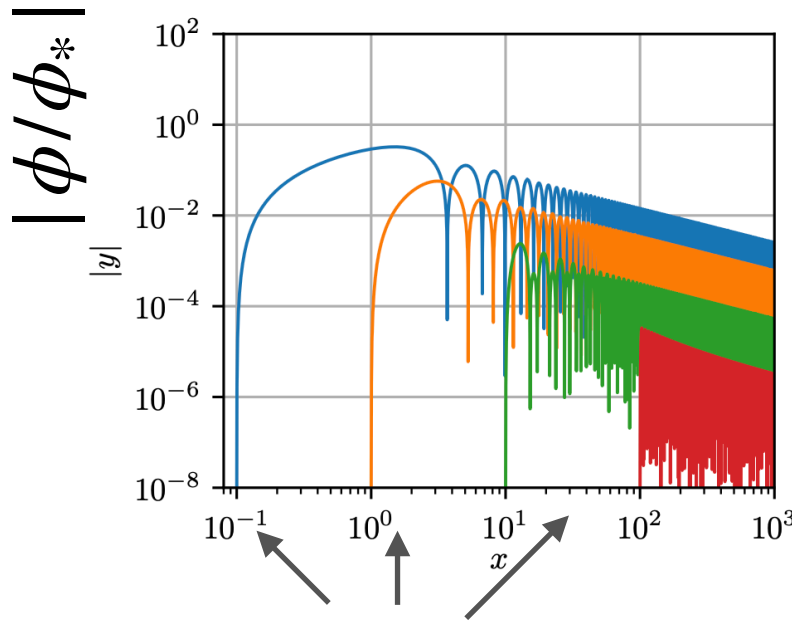
$$V_T(\phi) \simeq -\left(\frac{55}{144}\frac{\xi}{\cos^2\theta_W}g_Y^2 + \frac{43}{48}\frac{1-\xi}{\sin^2\theta_W}g_2^2\right)\frac{\phi}{M}T^4 \quad (T > T_{\text{EW}})$$

EOM

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_{\text{eff}}(\phi)}{\partial\phi} = 0, \quad V_{\text{eff}}(\phi) = \frac{1}{2}m^2\phi^2 + V_T(\phi).$$

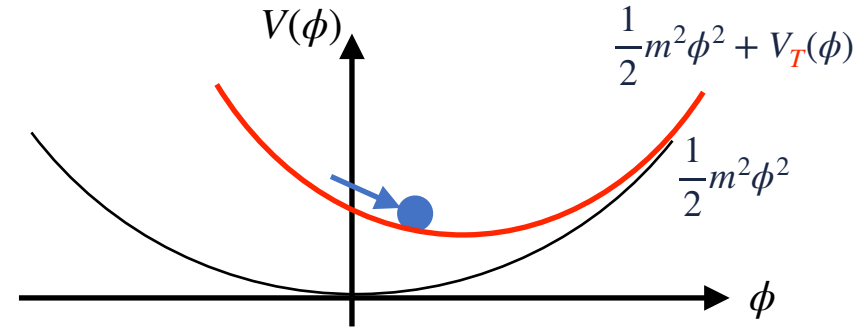
Thermal misalignment DM

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mt

Different initial time corresponds to
different reheating temperature.
(We assume instantaneous reheating, for simplicity.)

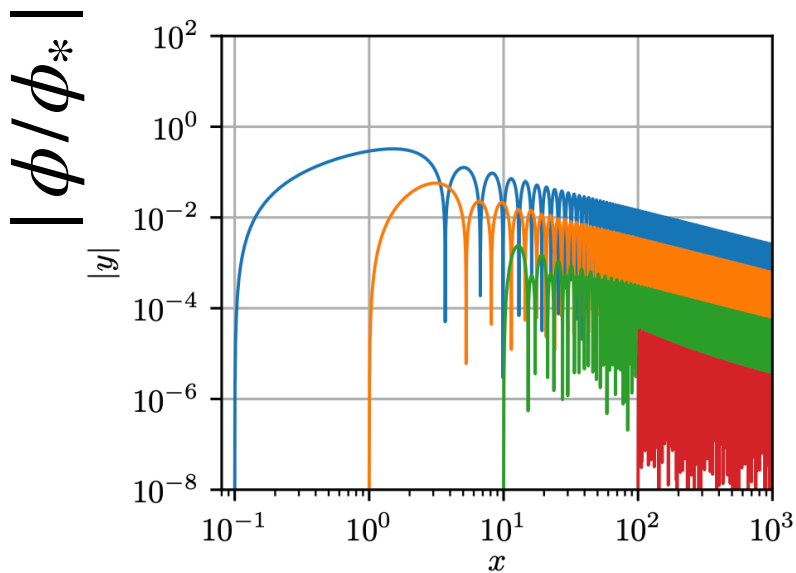


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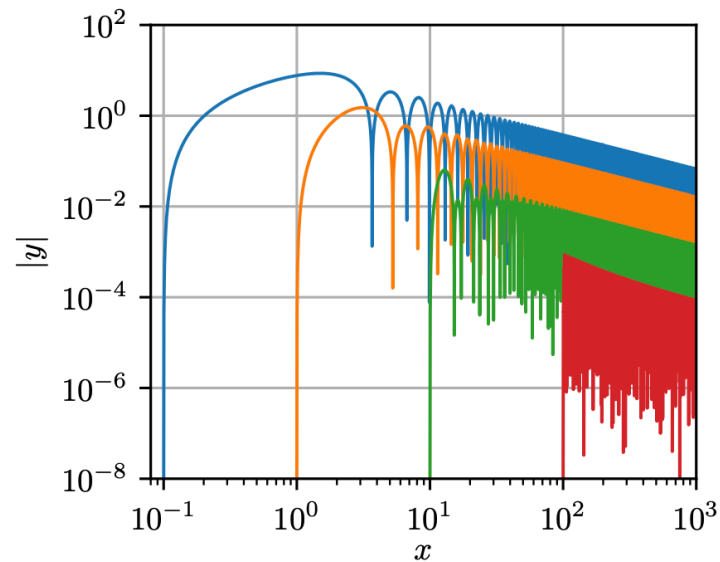
$$\phi_* = \frac{\alpha M_{\text{P}}^2}{M}$$

Thermal misalignment DM

KH, R. Hayakawa, H. Takahashi [[2604.05326](#)] see also; D. Cyncynates and O. Simon [[2408.16816](#)]



$\xi = 1 : U(1)_Y$ dominant



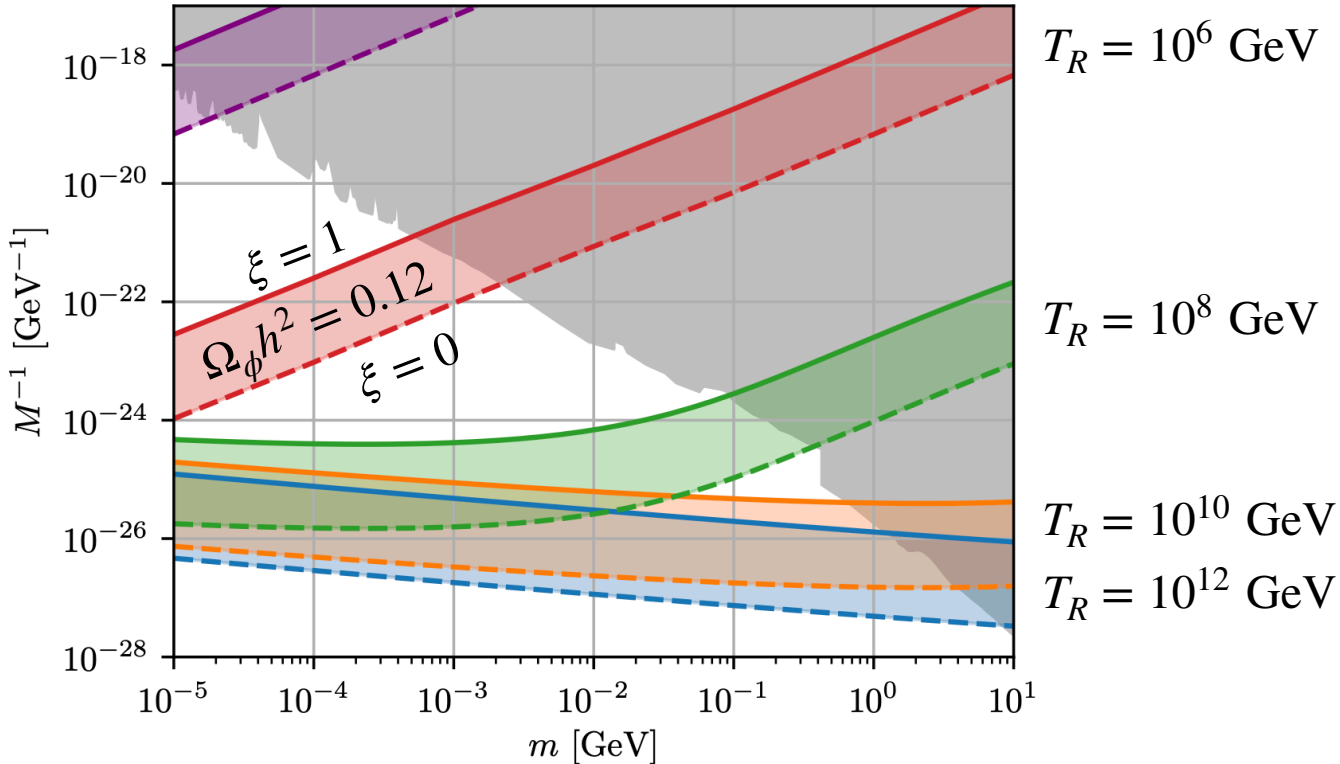
$\xi = 0 : SU(2)_L$ dominant

mt

$$L_{\text{int}} = -\frac{\xi}{\cos^2 \theta_W} \frac{\phi}{M} B^{\mu\nu} B_{\mu\nu} - \frac{1-\xi}{\sin^2 \theta_W} \frac{\phi}{M} W^{a\mu\nu} W_{\mu\nu}^a \quad \begin{cases} B^{\mu\nu} : U(1)_Y \\ W^{\mu\nu} : SU(2)_L \end{cases}$$

Thermal misalignment DM

KH, R. Hayakawa, H. Takahashi [[2604.05326](#)] see also; D. Cyncynates and O. Simon [[2408.16816](#)]



Thermal misalignment DM

KH, R. Hayakawa, H. Takahashi [[2604.05326](#)] see also; D. Cyncynates and O. Simon [[2408.16816](#)]

- Any signals / constraints?

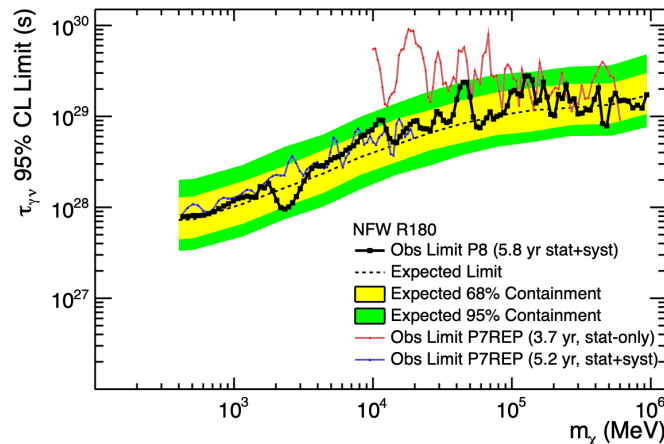
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- The **same operator** induces $\phi \rightarrow \gamma\gamma$.
(ϕ is a decaying DM.)

$$\gamma\text{-ray signal: } \Gamma(\phi \rightarrow \gamma\gamma) = \frac{m^3}{4\pi M^2}.$$

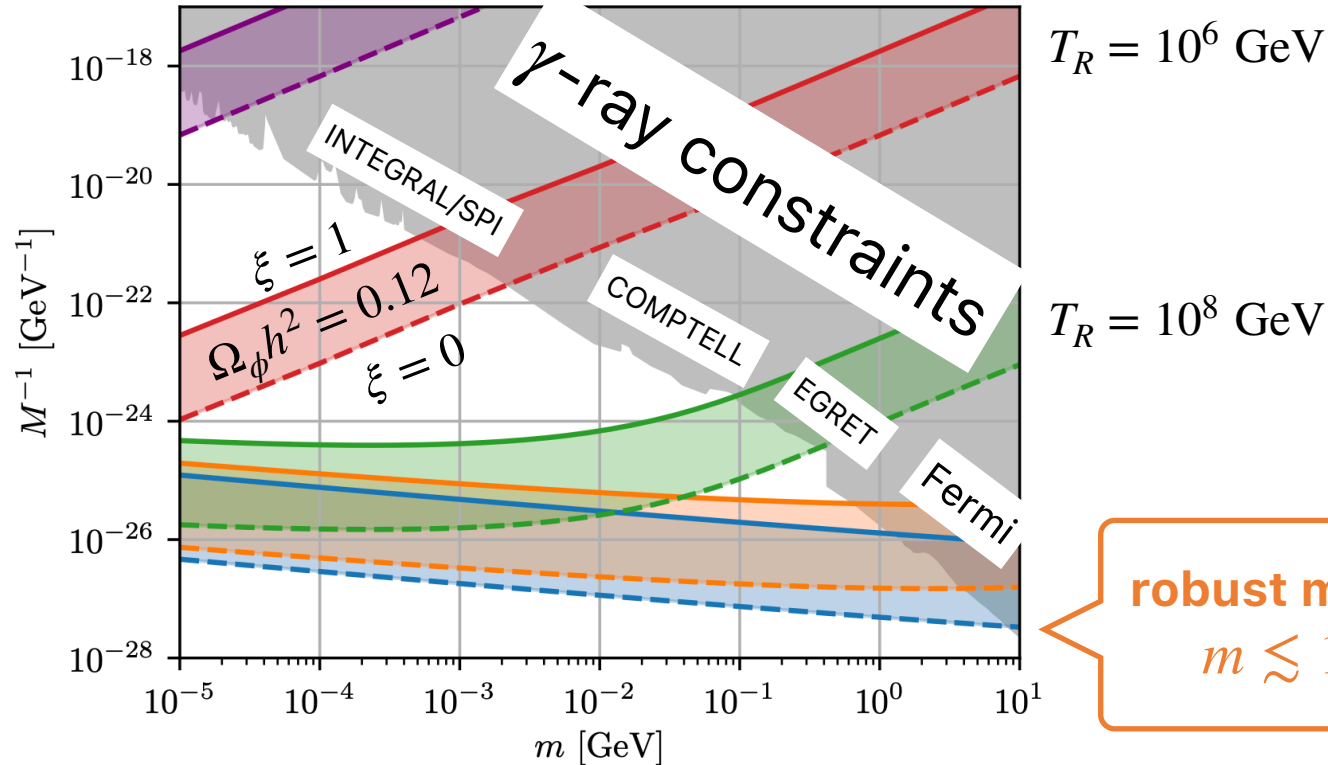
See D. Cyncynates and O. Simon [[2408.16816](#)]
for other constraints / signals.

Example:
constraint from Fermi-LAT (2015)



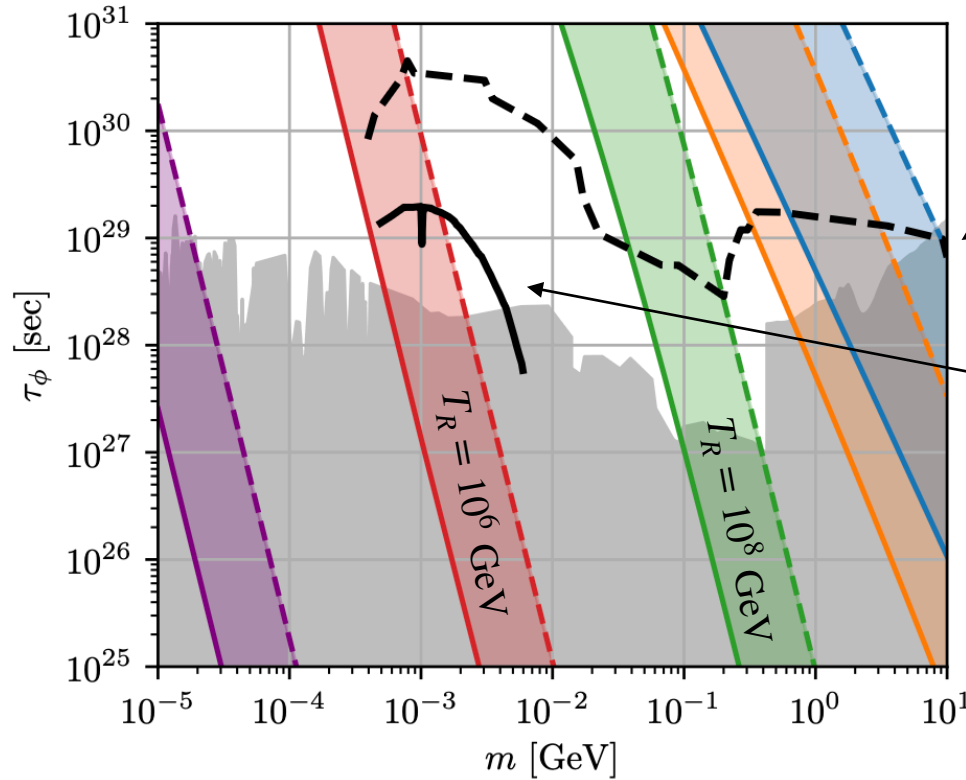
Gamma-Ray signatures of Thermal misalignment DM

KH, R. Hayakawa, H. Takahashi [[2604.05326](#)]



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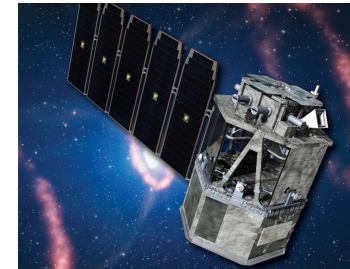
KH, R. Hayakawa, H. Takahashi [[2604.05326](#)]



Future sensitivities

K. E. O'Donnell, T. R. Slatyer [[2411.00087](#)]
GECCO, e-ASTROGAM, AMEGO, MAST,
AdEPT, PANGU, GRAMS

COSI [[2308.12362](#), [2210.09310](#)]
launch: 2027~



from Wikipedia

Plan

1. SM + ϕ (singlet scalar) with Z_2 — Higgs portal DM, **almost excluded**.
2. SM + ϕ (singlet scalar) without Z_2
— thermal misalignment DM, **γ -ray signals**
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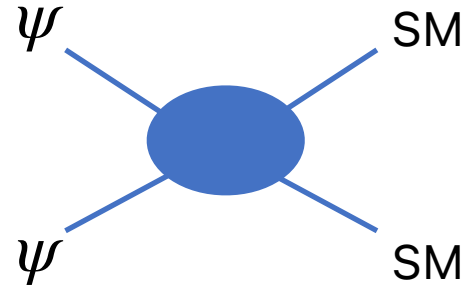
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3. SM + ψ (singlet fermion) **with** Z_2

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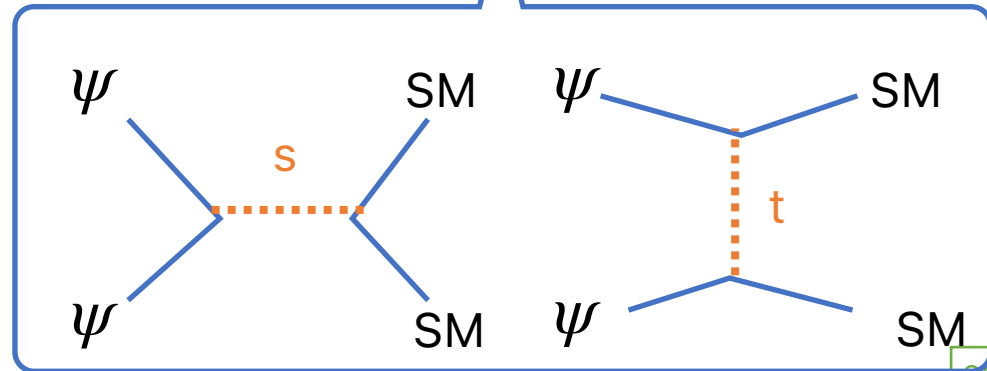
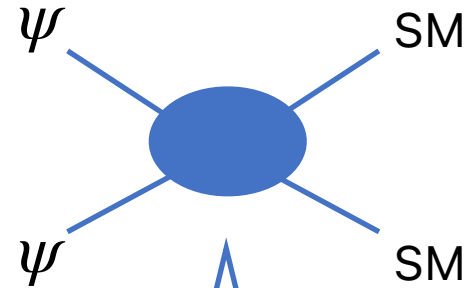
- At renormalizable level, ψ cannot have a direct coupling to SM.



3. SM + ψ (singlet fermion) **with** Z_2

- SM + ψ (singlet fermion)
- $Z_2 : \psi \rightarrow -\psi$

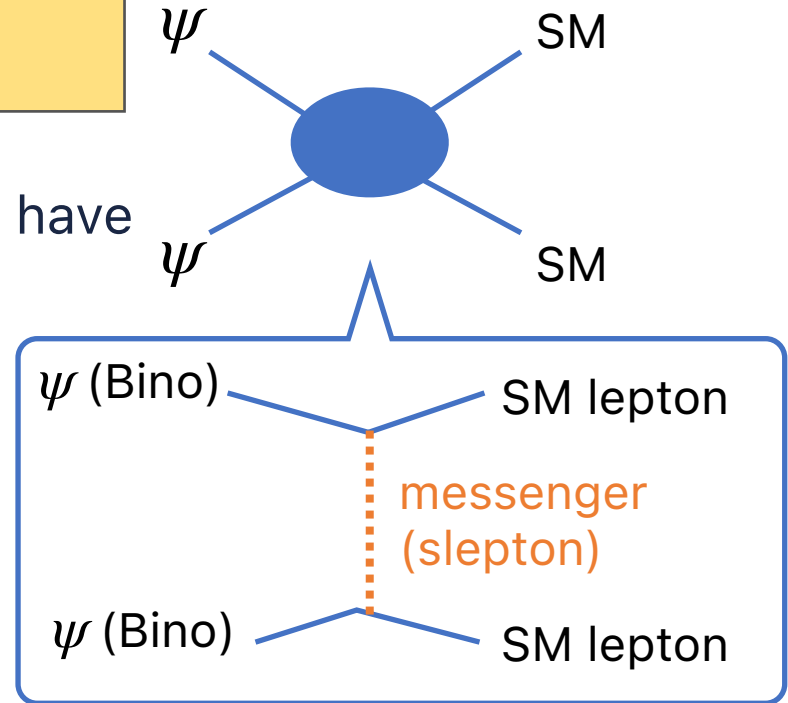
- At renormalizable level, ψ cannot have a direct coupling to SM.
- A **messenger** is needed.
- Many options: s/t-channel, quark/lepton coupling, ...



3. SM + ψ (singlet fermion) with Z_2

- SM + ψ (singlet fermion)
- $Z_2 : \psi \rightarrow -\psi$

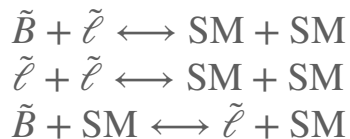
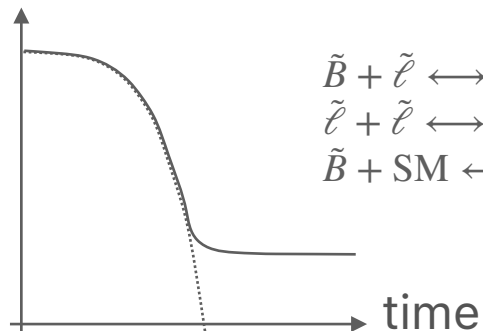
- At renormalizable level, ψ cannot have a direct coupling to SM.
- Here, we focus on **t-channel leptophilic messenger** — specifically, **bino-slepton coannihilation DM in SUSY**.



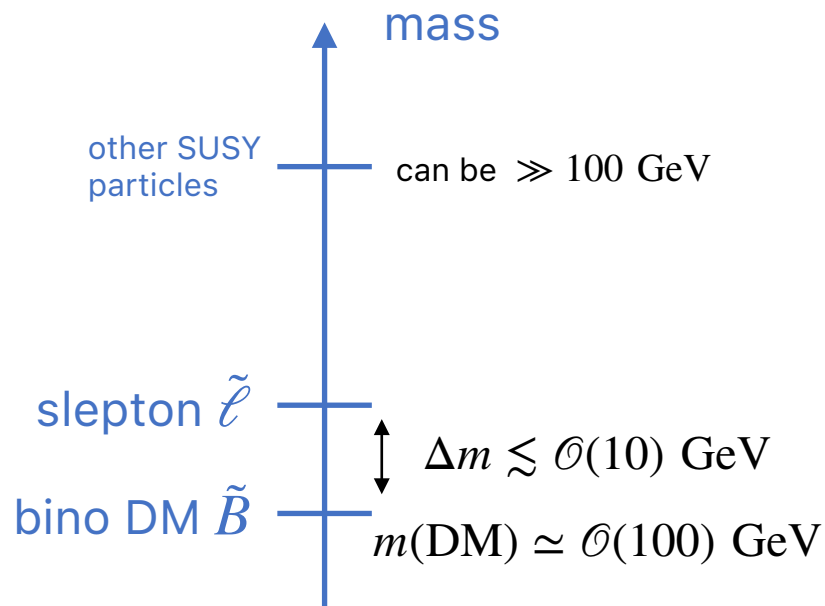
Bino-slepton coannihilation DM

- A simple thermal relic scenario.

abundance

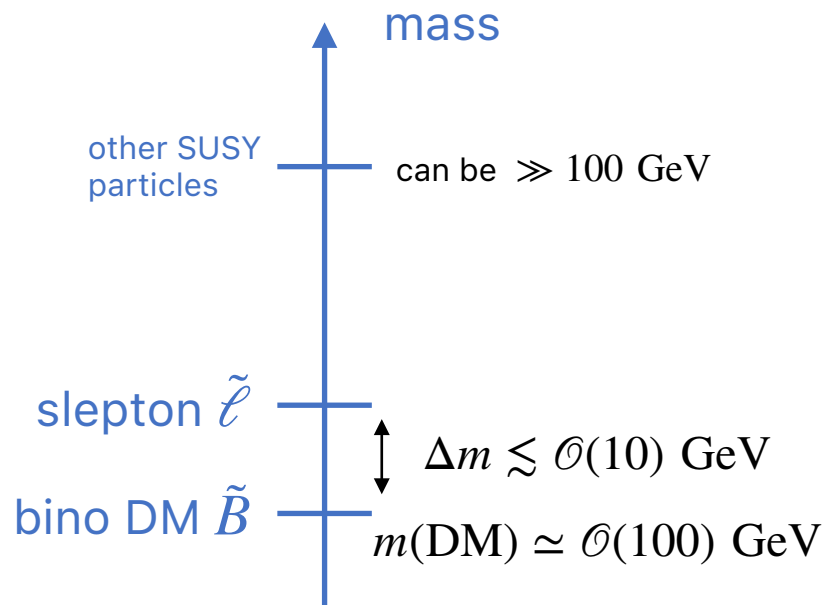


Charged partner helps to reduce the DM abundance. K. Griest and D. Seckel (1991)



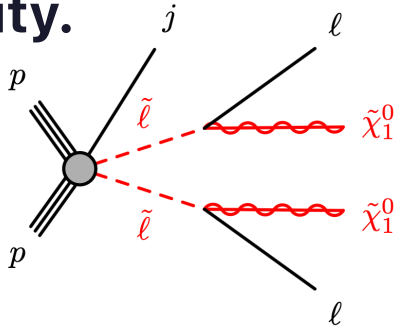
Bino-slepton coannihilation DM

- A simple thermal relic scenario.
- Very **difficult to probe**.
 - Degenerate spectrum
→ difficult to probe at **LHC**.
 - **Direct** detection rate is too small.
 - **Indirect** signal is also too small.

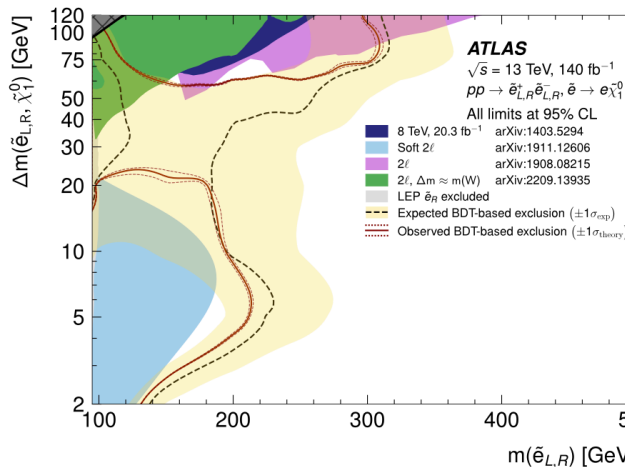


Bino-slepton coannihilation DM

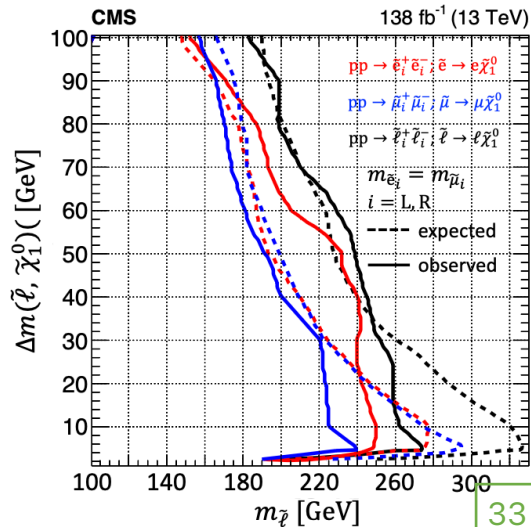
- A simple thermal relic scenario.
- Very difficult to probe.
- But recent (2025) LHC soft-lepton searches have significantly improved the sensitivity.



ATLAS [[2503.17186](#)]



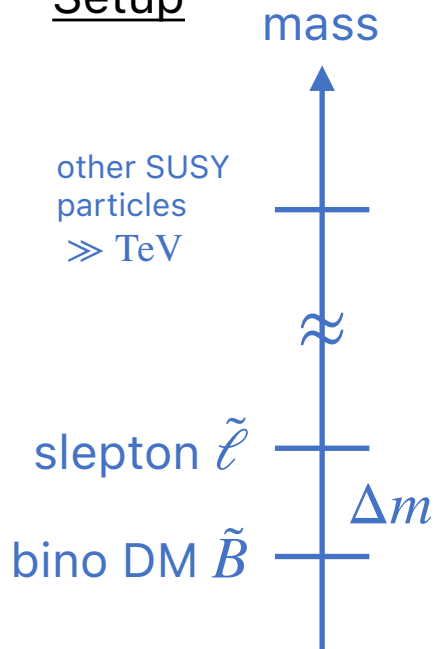
CMS [[2508.13900](#)]



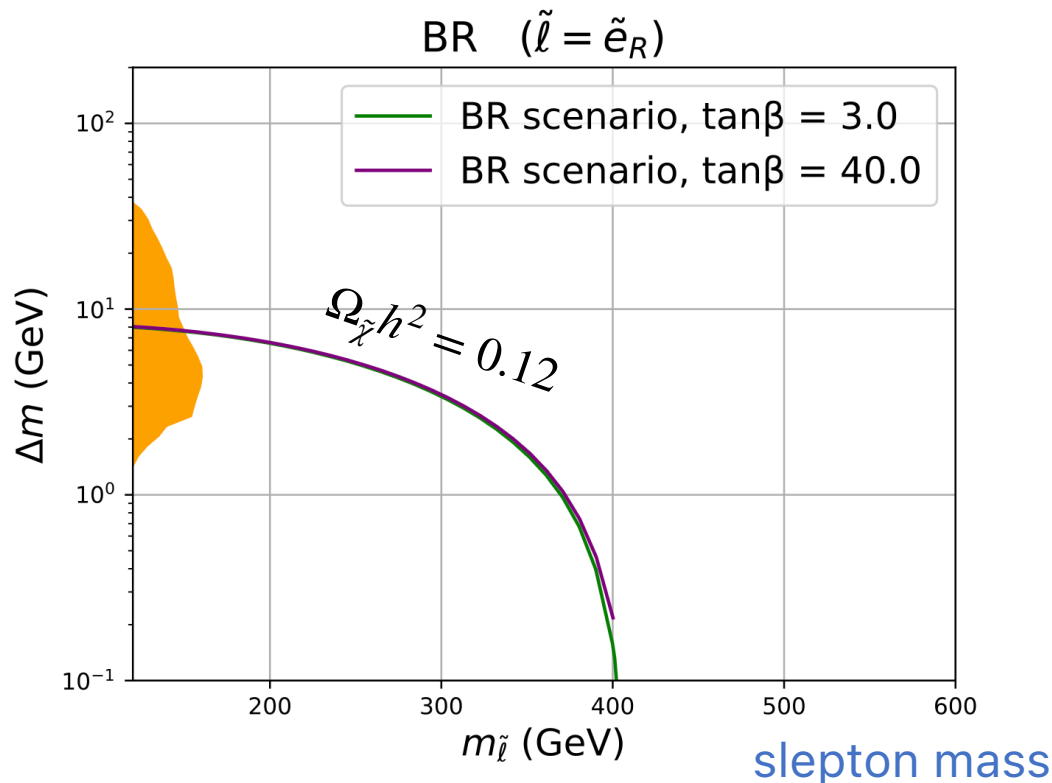
Revisiting bino-slepton coannihilation DM

KH, A Niki, K. H. To [[2603.18412](#)]

Setup



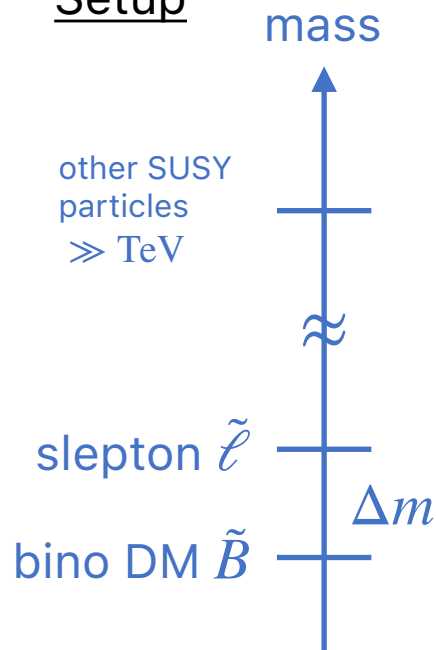
mass difference



Revisiting bino-slepton coannihilation DM

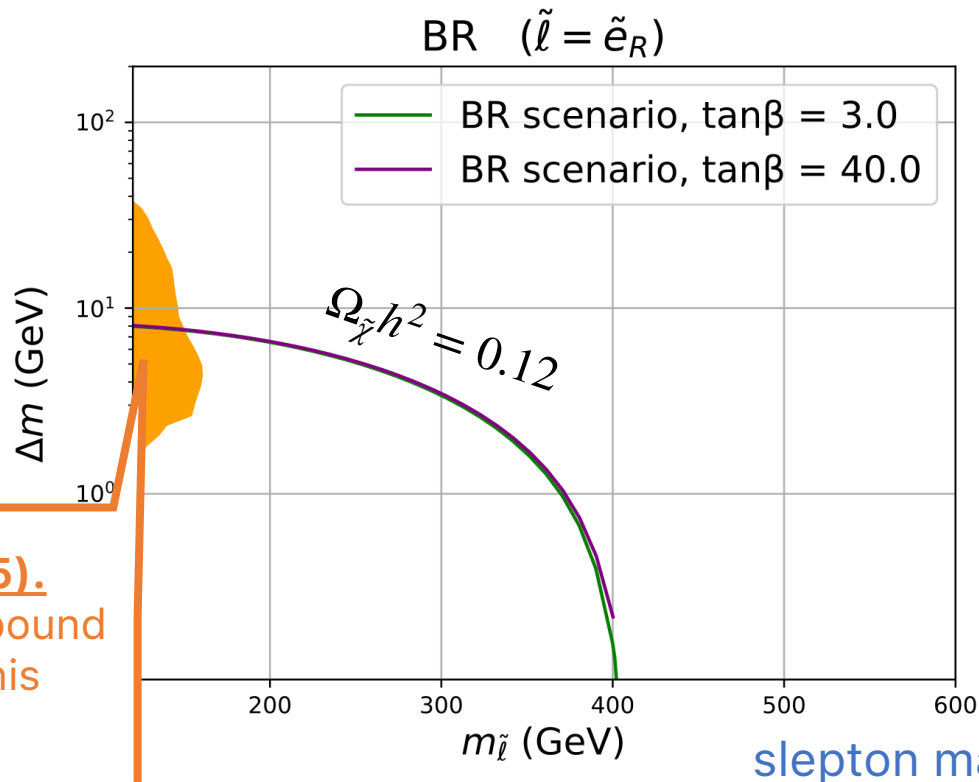
KH, A Niki, K. H. To [[2603.18412](#)]

Setup



mass difference

From LHC (2025).
First LHC lower bound
on DM mass in this
scenario



Revisiting bino-slepton coannihilation DM

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Setup

mass

other SUSY
particles
 $\gg \text{TeV}$

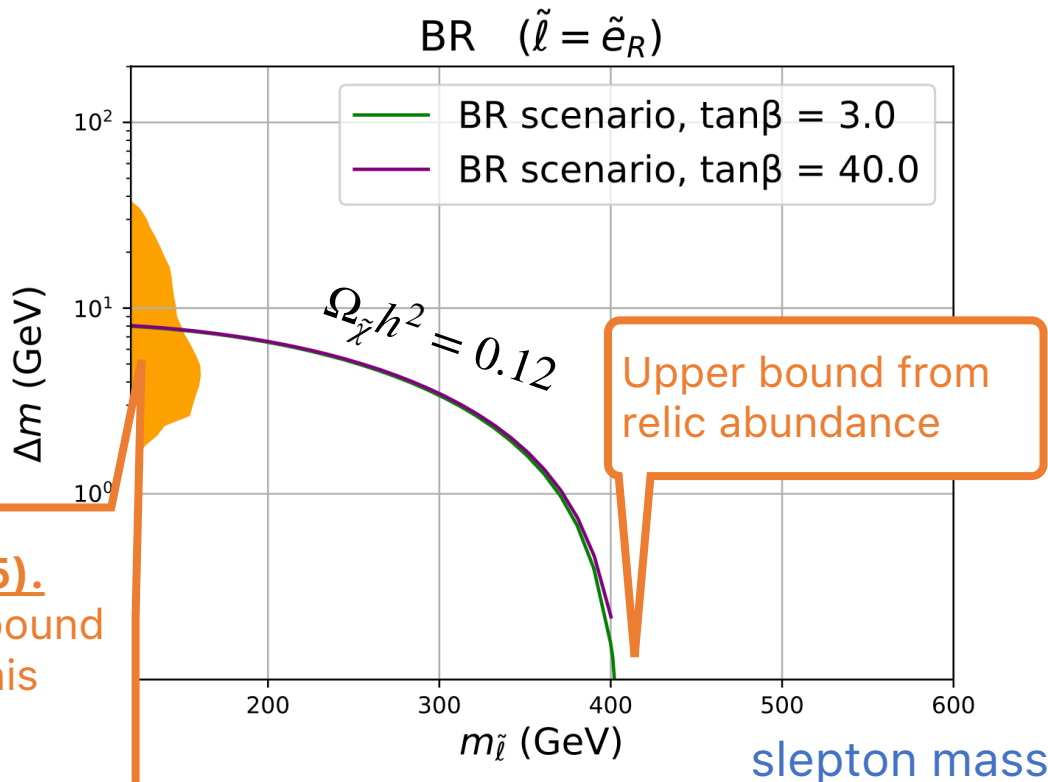
$\tilde{z}$

slepton $\tilde{\ell}$

Δm

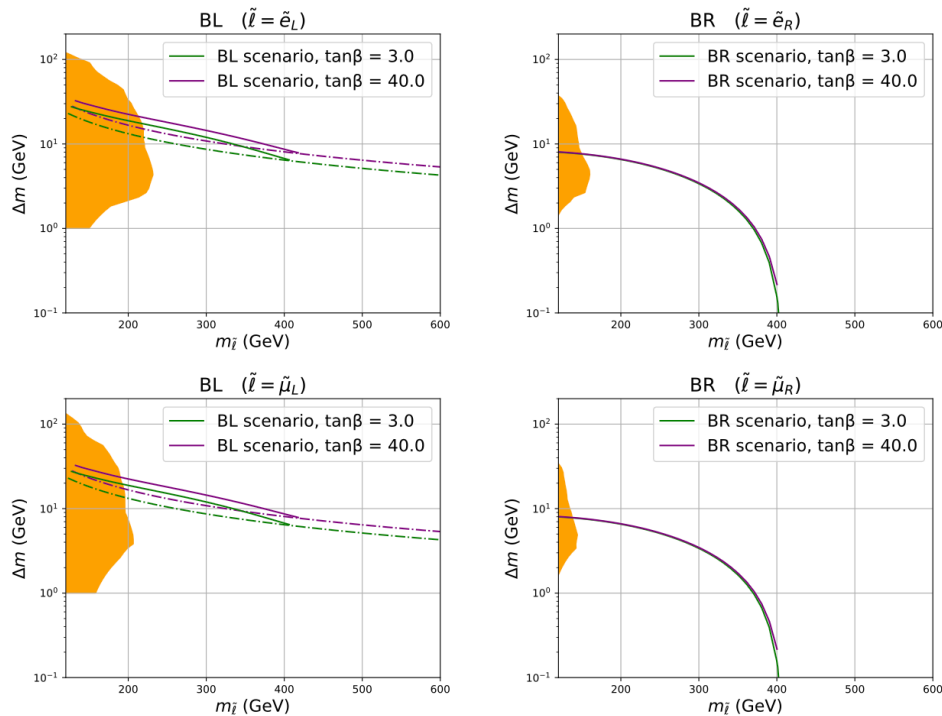
bino DM $\tilde{B}$

mass difference



Revisiting bino-slepton coannihilation DM

KH, A Niki, K. H. To [[2603.18412](#)]



Bino-DM + **left**-handed slepton:

- $m_{\text{DM}} \simeq 170 - 420 \text{ GeV}$
- $m_{\tilde{\ell}_L} \simeq 190 - 430 \text{ GeV}$

Bino-DM + **right**-handed slepton:

- $m_{\text{DM}} \simeq 130 - 430 \text{ GeV}$
- $m_{\tilde{\ell}_R} \simeq 140 - 430 \text{ GeV}$

The viable mass range is narrowing.

See [[2603.18412](#)] for flavor universal case.

Plan

1. SM + ϕ (singlet scalar) with Z_2 — Higgs portal DM, **almost excluded**.
2. SM + ϕ (singlet scalar) without Z_2
— thermal misalignment DM, **γ -ray signals**
3. SM + ψ (singlet fermion) with Z_2
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- At renormalizable level, the only allowed interaction is:

$$L_{\text{int}} = y \bar{\psi} \ell H + \text{h.c.} \quad \begin{cases} \ell : \text{SM lepton} \\ H : \text{SM Higgs} \end{cases}$$

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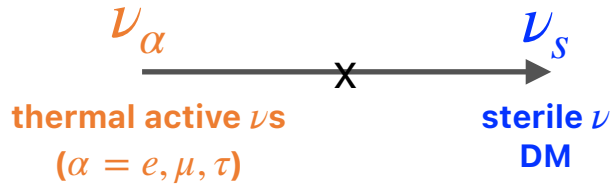
- SM + ψ (singlet fermion) **without** Z_2

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- For ψ to be DM (sufficiently stable), it must be **light** and/or have **small mixing** with active neutrinos.
- This is nothing but the **sterile neutrino DM**. — let's revisit it.

Sterile neutrino DM



- Dodelson-Widrow (1993)
 - ... but excluded by X-ray + Lyman- α

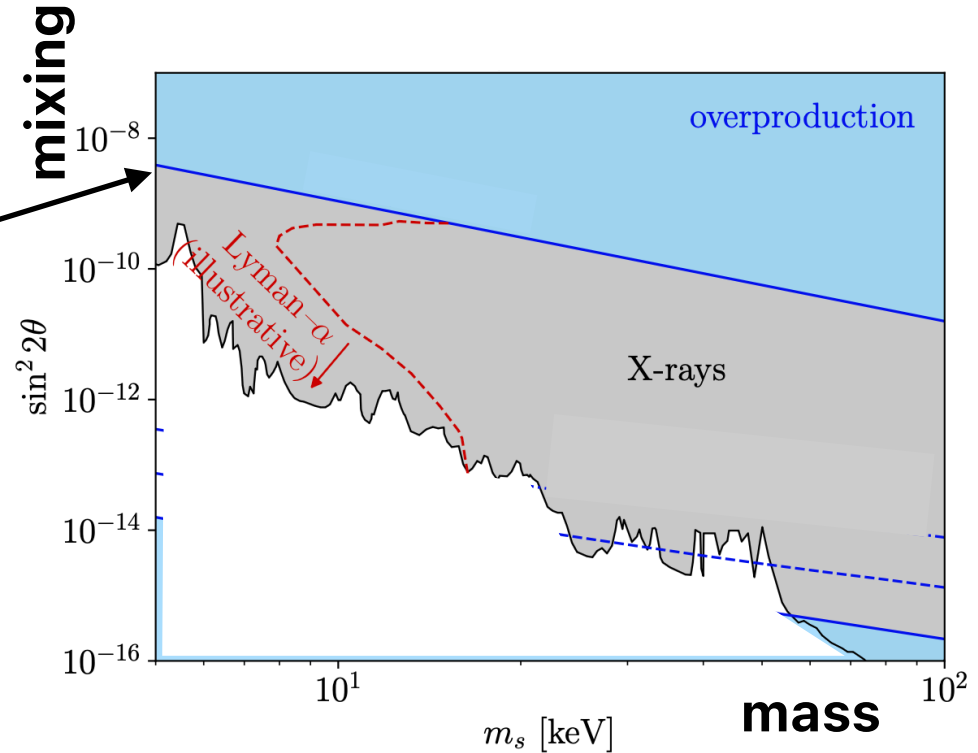
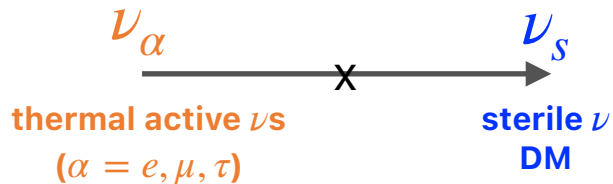


Fig. from K. Akita, KH, M. Ovchinnikov [[2507.20659](#)]

Sterile neutrino DM



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- Shi-Fuller (1998)
 - **Large lepton asymmetry** $L_\alpha = \Delta n_\alpha / s$
 $\rightarrow$ resonant enhancement of the mixing.
 - ... but almost excluded.
 - BBN and CMB disfavor $|L_\alpha| \gtrsim 10^{-3}$.

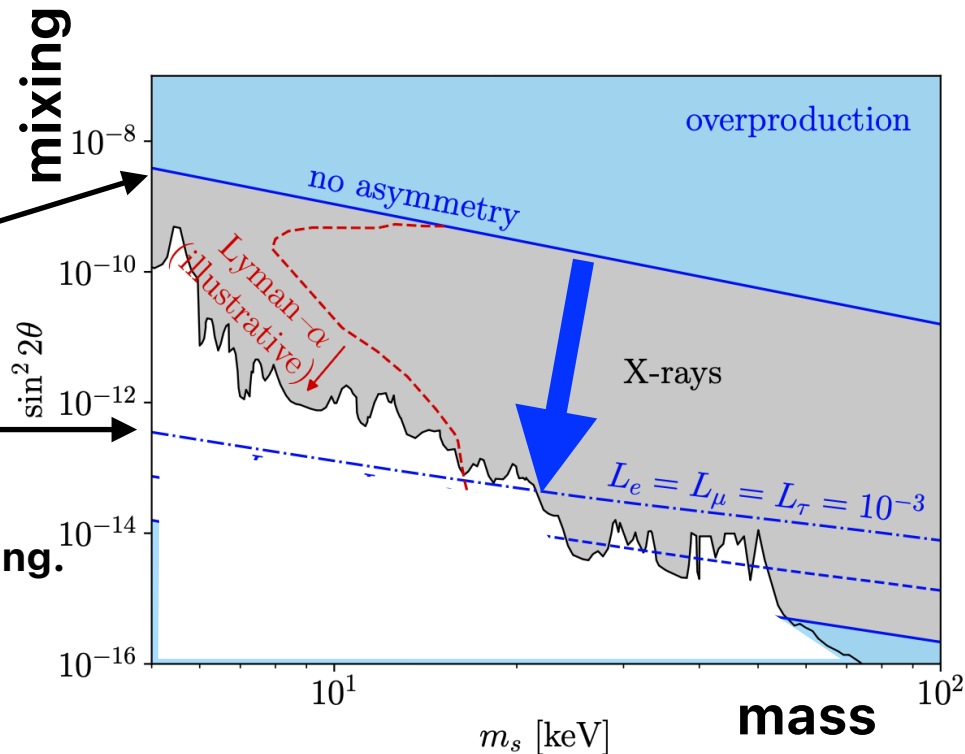
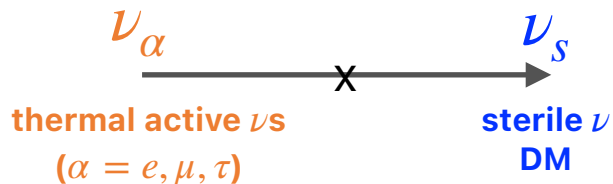


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Our work

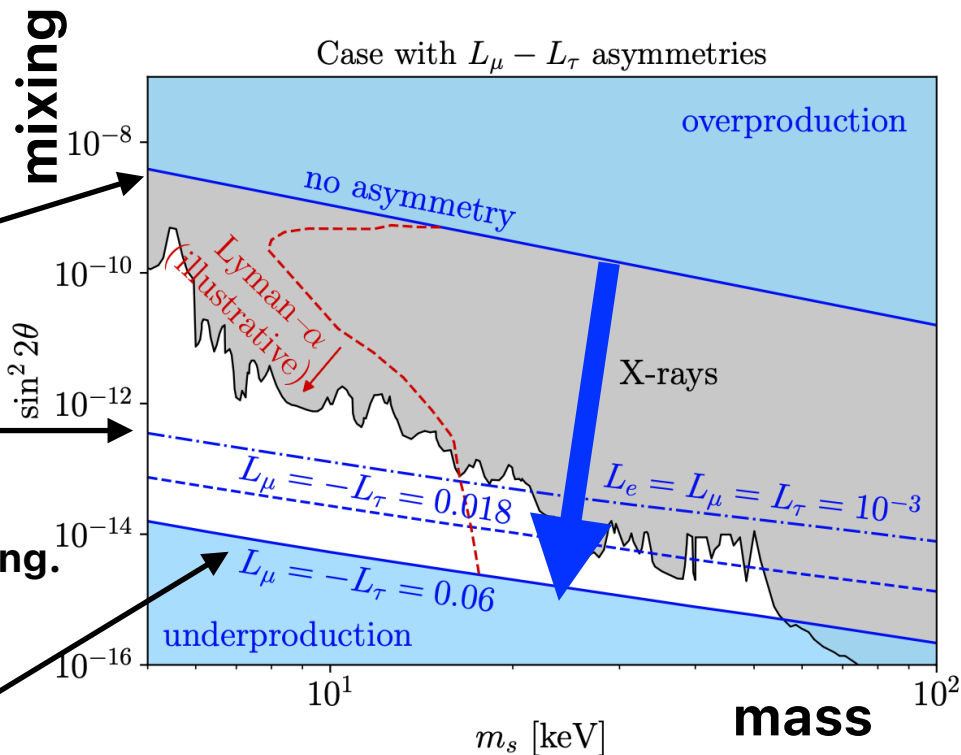


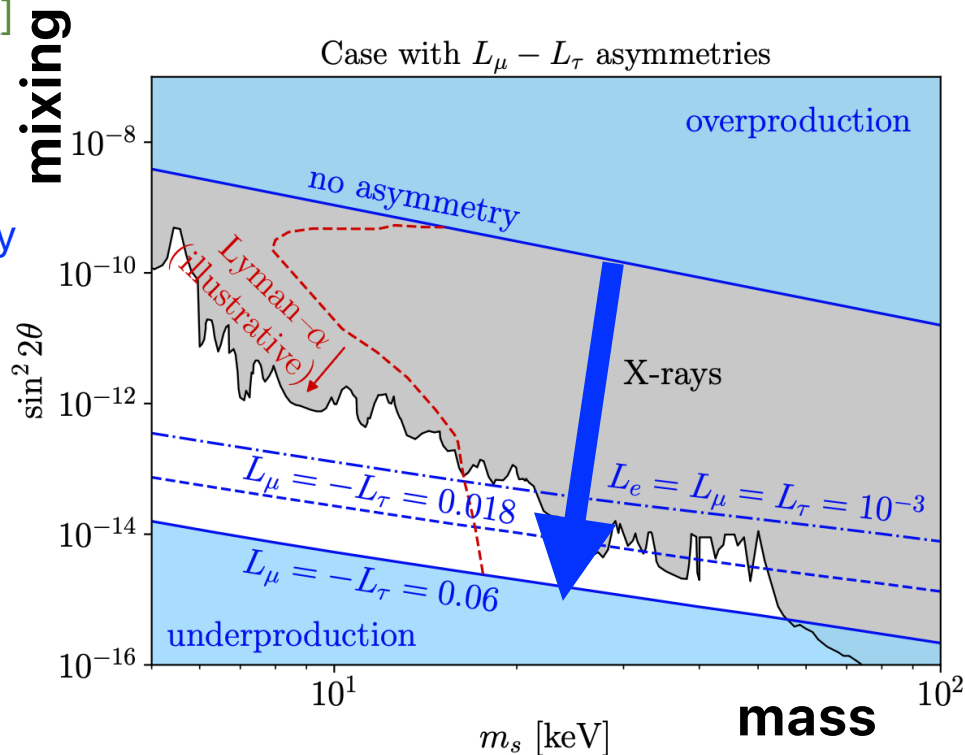
Fig. from K. Akita, KH, M. Ovchinnikov [2507.20659]

Sterile neutrino DM with large lepton flavor asymmetry

K. Akita, KH, M. Ovchinnikov [[2507.20659](#)]

We showed:

- large lepton flavor asymmetries with vanishing total lepton asymmetry (e.g., $L_\mu = -L_\tau \simeq \mathcal{O}(0.01)$) open up a new parameter space.
...with a detailed analysis with a Semi-classical Boltzmann eq. and quantum kinetic eqs.



See also:

- D. Gorbunov, D. Kalashnikov, G. Krugan [[2502.17374](#)]
- C. M. Vogel, H. Garcia Escudero, J. Froustey, K. N. Abazajian [[2507.18752](#)]

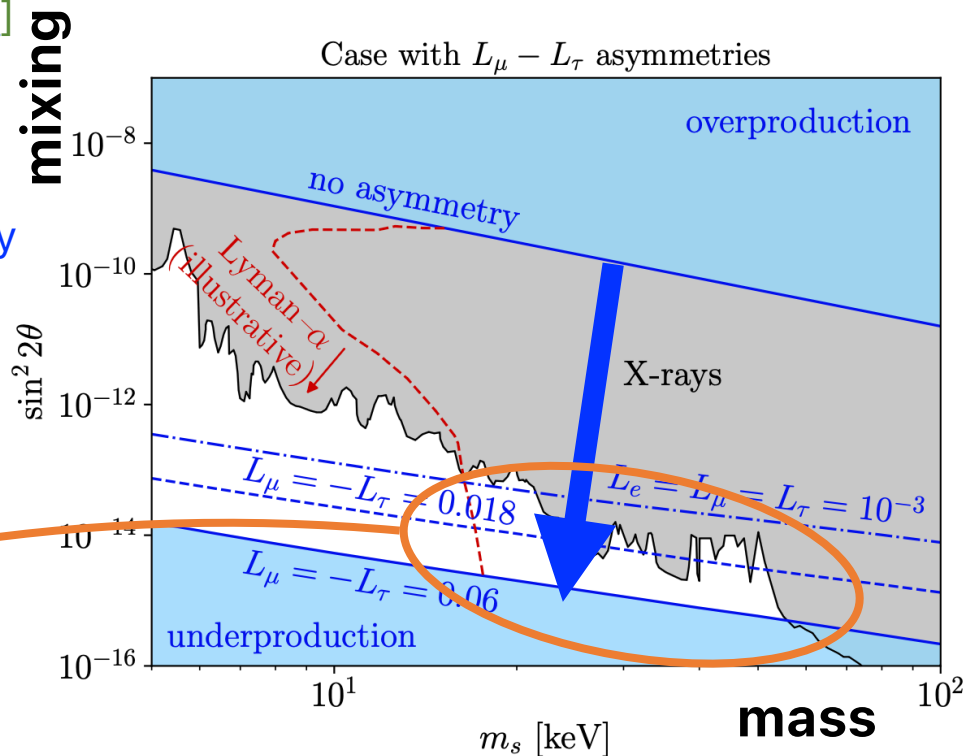
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...with a detailed analysis with a Semi-classical Boltzmann eq. and quantum kinetic eqs.
- Newly opened space is testable by future X-ray, structure formation, and CMB searches.



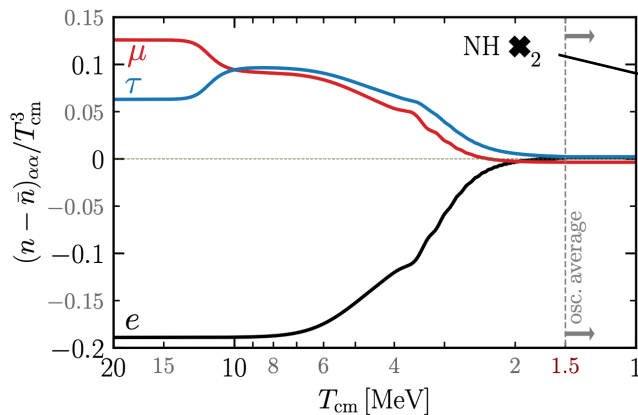
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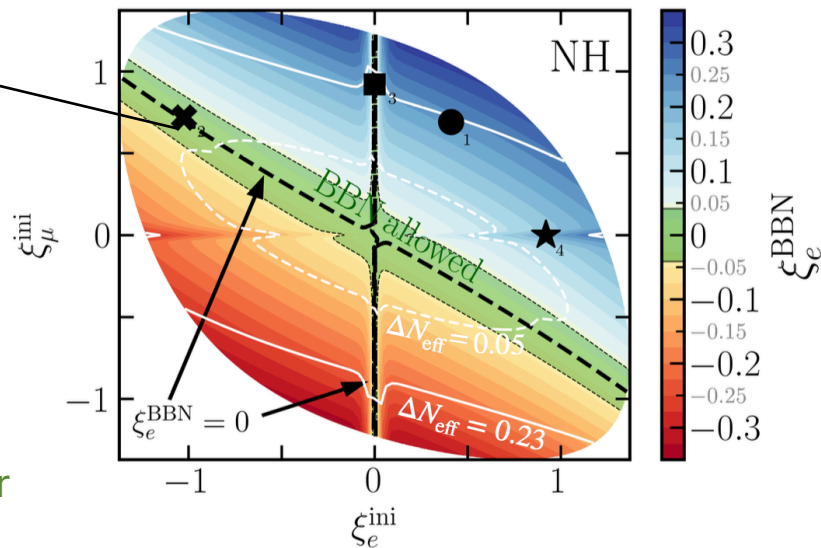
Fig. from K. Akita, KH, M. Ovchinnikov [[2507.20659](#)]

Sterile neutrino DM with large lepton flavor asymmetry

Such large lepton flavor asymmetries with vanishing total lepton asymmetry
(e.g., $L_\mu = -L_\tau \simeq \mathcal{O}(0.01)$)
are consistent with BBN/CMB.



V. Domcke, M. Escudero,
M. Fernandez Navarro, S. Sandner
[arXiv:2502.14960]



Sterile neutrino DM with large lepton flavor asymmetry

Such large lepton flavor asymmetries with vanishing total lepton asymmetry
(e.g., $L_\mu = -L_\tau \simeq \mathcal{O}(0.01)$)

can be naturally generated by Affleck-Dine mechanism along $Q\bar{u}L\bar{e}$ flat direction
with Q-ball formation.

K. Akita, KH, M. Ovchinnikov [[2509.08175](#)]

L -conserving but
lepton-flavor-violating.

👉 cf. talk at Busan workshop
in Nov. 2025.

Affleck-Dine Leptoflavorgenesis

Koichi Hamaguchi (Tokyo U.)

@2025 CERN-CKC joint workshop with the 13th KIAS Workshop
on Particle Physics and Cosmology, November 16–21, Busan.

Based on
[arXiv:2509.08175], "Affleck-Dine Leptoflavorgenesis"
Kensuke Akita, KH, Maksym Ovchinnikov.

See also
[arXiv:2507.20659], "Maximal parameter space of sterile neutrino dark matter with lepton asymmetries"
Kensuke Akita, KH, Maksym Ovchinnikov.

Summary

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4. SM + ψ (singlet fermion) without Z_2 — Sterile ν DM, **flavor asymmetry opens new windows**.

**Minimal models are not exhausted,
and the targets are getting clearer.**

backup

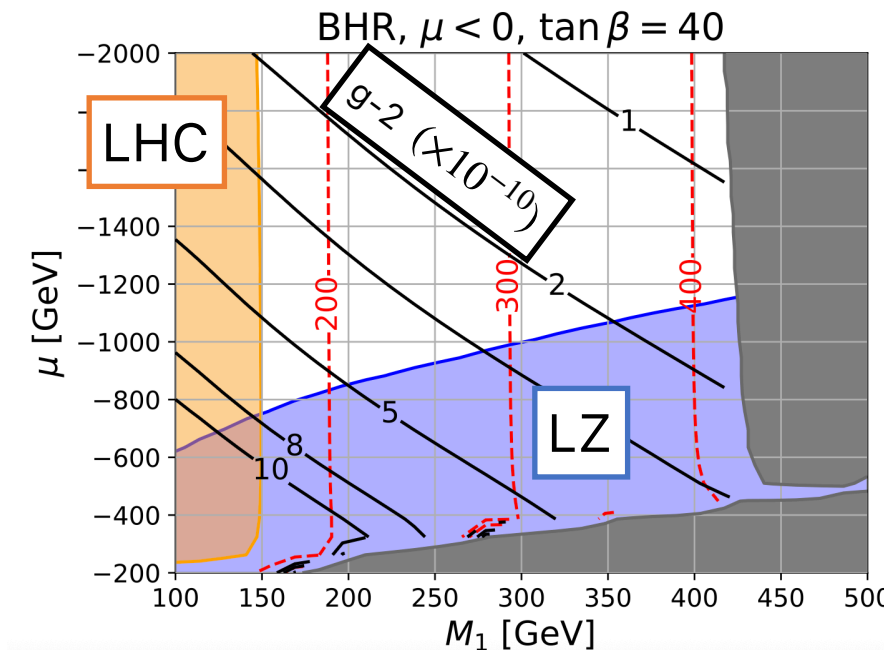
Revisiting bino-slepton coannihilation DM

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Side remark

Light Higgsino and Muon g-2

- So far, only $(\tilde{B}, \tilde{\ell}_L)$ or $(\tilde{B}, \tilde{\ell}_R)$ are light.
- What if **Higgsino** is also light?
- LHC + LZ (direct detection) constraints.
- Implication for muon g-2:
 $|\Delta a_\mu^{\text{SUSY}}| \lesssim 8 \times 10^{-10}$.
in the so-called **BHL/BHR** scenarios.
(see [[2603.18412](#)] for BLR case.)
- It is consistent with the latest g-2 theory/experiment results (2025), $\Delta a_\mu = (3.8 \pm 6.3) \times 10^{-10}$.



Slepton mass is adjusted
to reproduce $\Omega_{\tilde{\chi}} h^2 = 0.12$.