# Light thermal Dark Matter Beyond *p*-Wave Annihilation


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**3rd International Joint Workshop on the Standard Model and Beyond**
**11th KIAS Workshop on Particle Physics and Cosmology**

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# Outline

- **A brief introduction to sub-GeV dark matter**

- **minimal dark matter model: one Majorana DM + one new singlet scalar mediator**

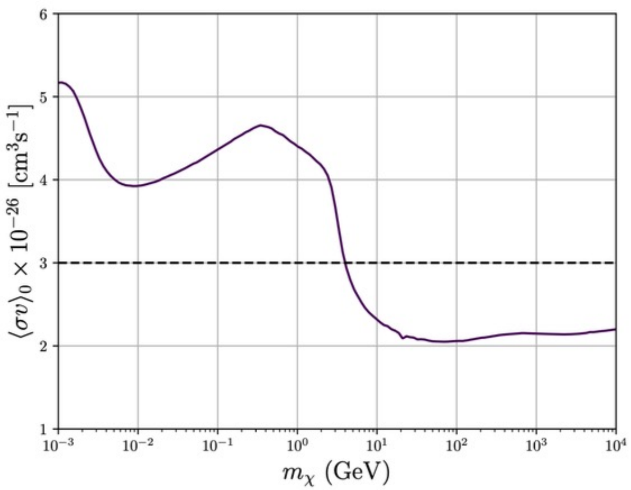
- **Summary**

# WIMPs

## For decades, WIMPs have been the cherish DM candidates

► WIMPs naturally give correct relic density via freeze-out.

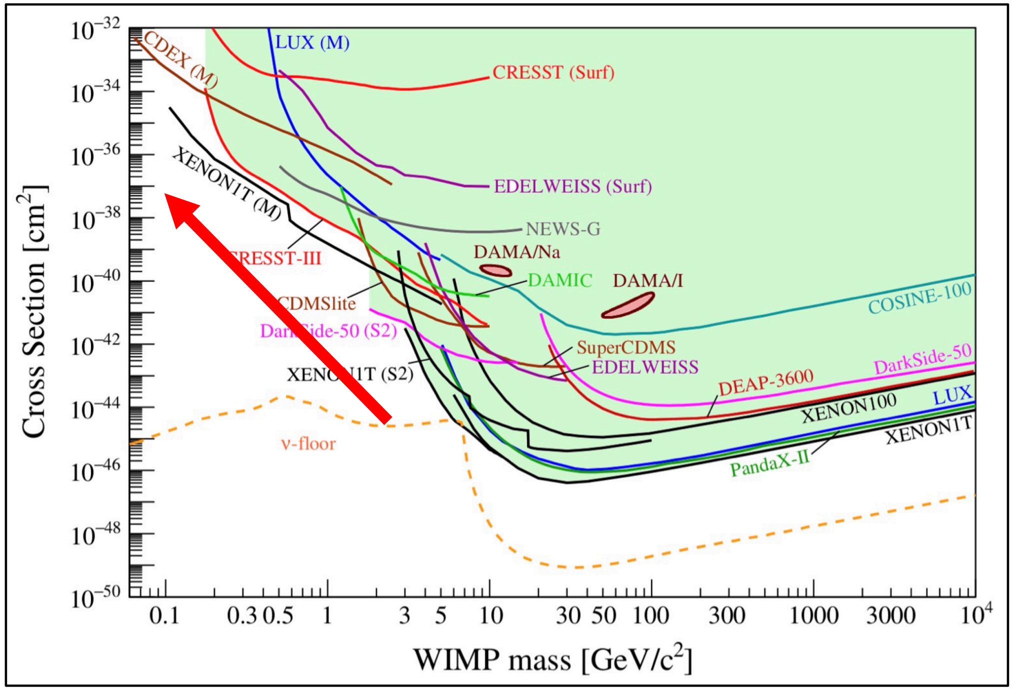
$$\frac{\Omega_\chi h^2}{0.12} \sim \left(\frac{2 \times 10^{-9}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right) \left(\frac{80}{g_\star}\right)^{1/2} \left(\frac{x_f}{23}\right)$$




► Models with NP at EW scale (e.g. Naturalness or Hierarchy Problem) often accommodate a EW scale DM candidate.

# WIMPs Crisis or MeV DM Opportunity?

The answer is : Neutrino floor is coming and No evidence for WIMPs!

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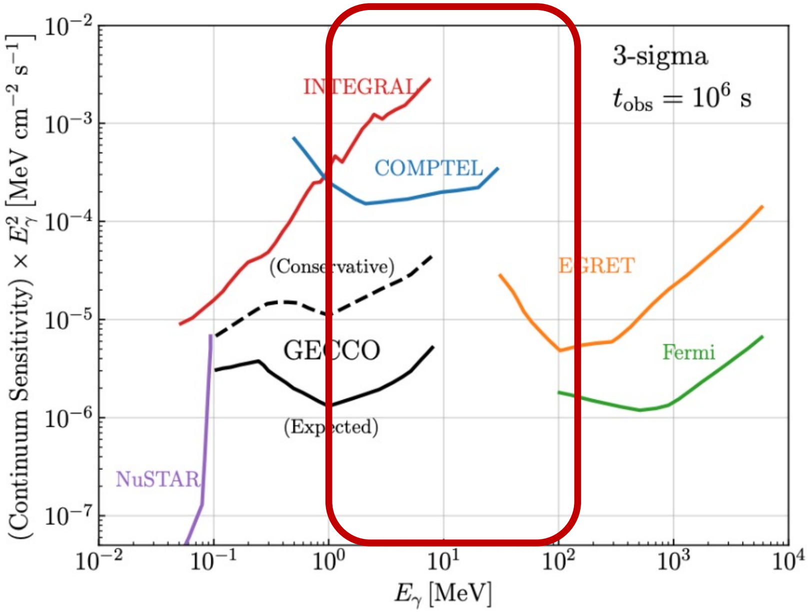
- DM mass region above GeV is highly constrained by direct detection ;
- Sub-GeV DM still has a large parameter space;
- The search for sub-GeV DM is turning to indirect detection.

# Future Indirect Detection : Great opportunity to explore MeV dark matter

GECCO (2112.07190)



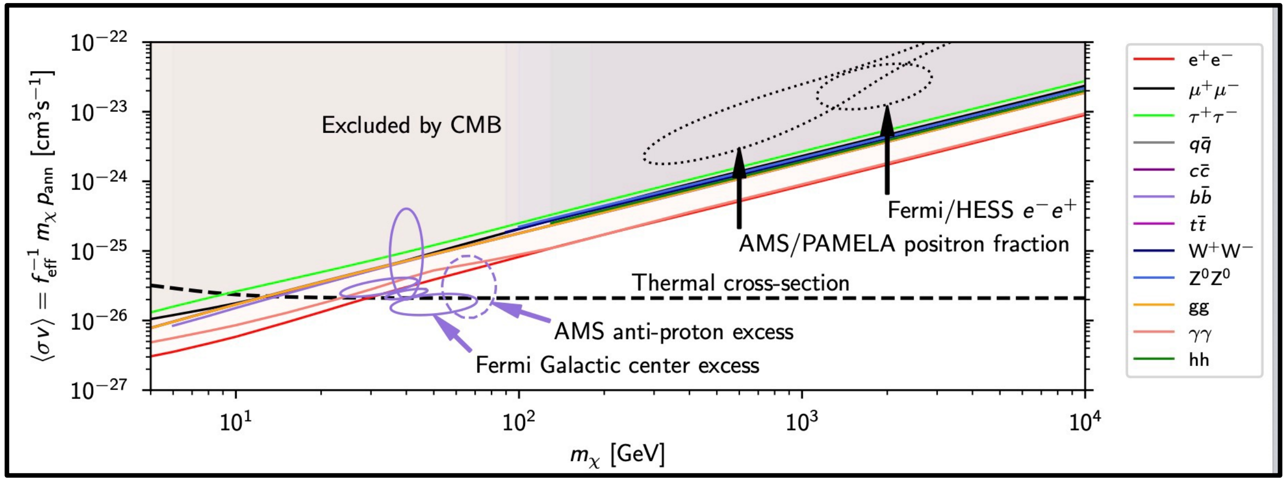

| Telescope | Status | Energy Range | Reference |
|---|---|---|---|
| *INTEGRAL* | On 2002 October 17 | 15 keV to 10 MeV | 0801.2086<br>1107.0200 |
| e–ASTROGAM | 2029 | 0.3 MeV to 3 GeV | 1711.01265 |
| COSI | 2025 | 0.2 MeV to 5 MeV | 2109.10403 |
| GECCO | ? | 0.1 MeV to 8 MeV | 2112.07190 |
| AMEGO | ? | 0.2 MeV to 10 GeV | 1907.07558 |
| VLAST | ? | 100 MeV to 20 TeV | chinaXiv:202203.00033V2 |

- In the past few decades, there have been no good telescopes focused on the **MeV Gap**
- Fortunately, many new MeV telescopes have been proposed in recent years.

## The challenge to MeV Dark matter: CMB

***Planck*** **2018 constraints on DM mass and annihilation cross section**

$$\langle \sigma v \rangle \simeq a + b v^2$$




### *s*-wave $(b = 0)$

- *s*-wave dark matter annihilations with masses less than 1GeV would be difficult to escape CMB limits

### *p*-wave $(a = 0)$

- *p*-wave dark matter annihilation can satisfy the CMB but the cross section at the present time is too small to be observed.

**Can we find a sub-GeV DM signal in future telescope but also escape from CMB limits ?**

# Basic and minimum Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi, H),$$

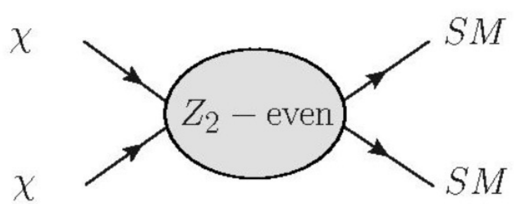
Majorana DM

SM singlet scalar

Scalar interaction (p-wave)

Pseudo-scalar interaction (s/p-wave )

Mixing between New scalar and SM Higgs




**s-channel annihilation**

*A minimum setup:*

**one singlet Majorana DM + one SM singlet scalar mediator.**

**Cosmological and astrophysical constraints**

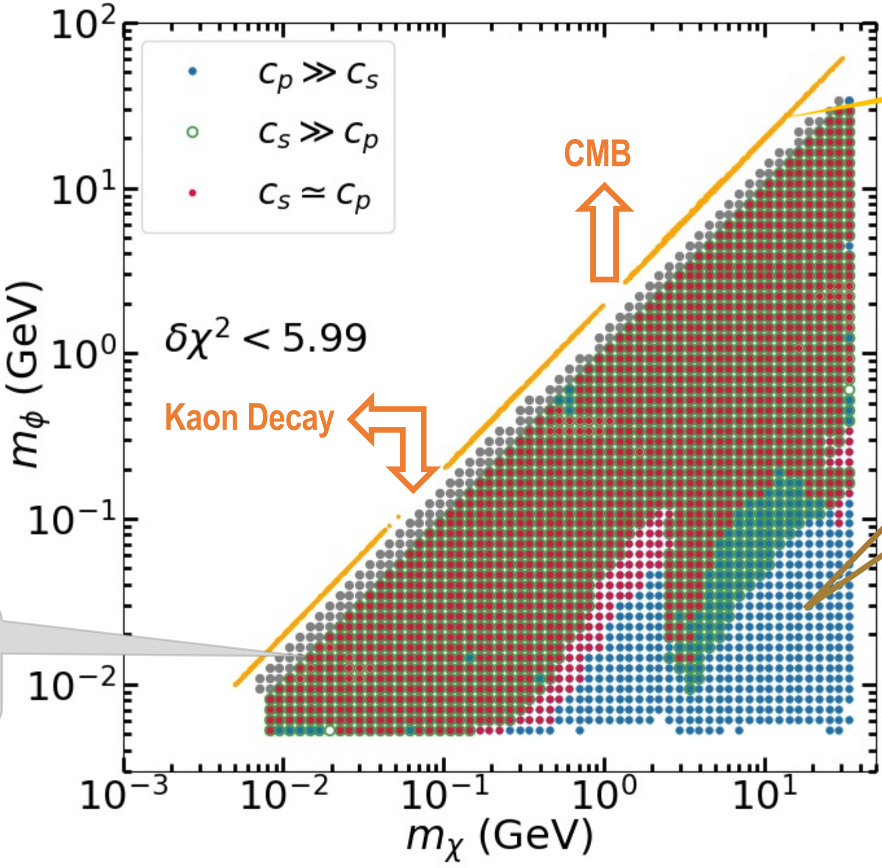
| | Likelihood | Constraints |
|---|---|---|
| Relic abundance | Gaussian | $\Omega_\chi^{\rm exp}h^2 = 0.1193 \pm 0.0014$ [10]; $\sigma_{\rm sys} = 10\% \times \Omega_\chi^{\rm th}h^2$. |
| Equilibrium | Conditions | either $(\Gamma^{\rm FO}_{\chi {\rm SM}} \geq H_{\rm FO})$, or $(\Gamma^{\rm FO}_{\chi {\rm SM}} \geq H_{\rm FO}$ and $\Gamma^{\rm FO}_{\chi\phi} \geq H_{\rm FO})$ |
| DM direct detection | Half Gaussian | $9\,{\rm GeV} < m_\phi < 10\,{\rm TeV}$ (LZ [12]), $3.5\,{\rm GeV} < m_\phi < 9\,{\rm GeV}$ (PANDAX-4T [13]), $60\,{\rm MeV} < m_\phi < 5\,{\rm GeV}$ (DarkSide [11]). |
| $\triangle N_{\rm eff}$ | Half Gaussian | $\triangle N_{\rm eff} < 0.17$ for 95% C.L. [10] |
| BBN | Conditions | if $(m_\phi \geq 2m_\pi)$ then $\tau_\phi \leq 1$ s [15], if $(m_\phi \leq 2m_\pi)$ then $\tau_\phi \leq 10^5$ s [16]. |

Based on previous work: JHEP 07(2019)050
(Red indicates update limits)

**Collider experiments constraints**

| | $\phi$ signature | Constraints |
|---|---|---|
| Higgs decay | Prompt* | See the upper limits of ${\rm BR}(h \to \phi\phi){\rm BR}(\phi \to ll)^2$ from Fig. 12 of Ref. [19] and Fig. 7 of Ref. [23]. |
| | Displaced* | See Ref. [20, 21] |
| | Long-lived* | ${\rm BR}(h \to {\rm inv.})_{BSM} \leq 0.145$ [24] |
| $B$ decay | Prompt | ${\rm BR}(B^\pm \to K^\pm\mu^-\mu^+) \lesssim 3 \times 10^{-7}$ [31] |
| | Displaced | (1) $\sin^2\theta \gtrsim 2 \times 10^{-8}$ for the region $0.5 < m_\phi/{\rm GeV} < 1.5$ and $1 < c\tau_\phi/{\rm cm} < 20$ [34] (2) See Fig. 5 of Ref. [33] for details. |
| | Long-lived | $P_p$ ${\rm BR}(B^\pm \to K^\pm\nu\bar\nu) \leq 2.4 \times 10^{-5}$ [35] |
| Kaon decay | Prompt | (1) ${\rm BR}(K^+ \to \pi^+\mu^-\mu^+) \leq 4 \times 10^{-8}$ [36] (2) ${\rm BR}(K_L \to \pi^0 e^- e^+) \leq 2.8 \times 10^{-10}$ [37] (3) ${\rm BR}(K_L \to \pi^0\mu^-\mu^+) \leq 3 \times 10^{-10}$ [38] |
| | Displaced | CHARM detected events $\gtrsim 2.3$ [43] |
| | Long-lived* | (1) ${\rm BR}(K_L \to \pi^0\nu\bar\nu) \leq 3.0 \times 10^{-9}$[25] (2) See ${\rm BR}(K^+ \to \pi^+\nu\bar\nu)$ limits from Fig. 18 of Ref. [39] and Fig. 4 of Ref. [18] for details. |

# Preliminary Result: $(m_\chi, m_\phi)$




**Resonance state ($m_\phi \approx 2m_\chi$)**

**($m_\chi > m_\phi$) Direct Detection Constraint**

**Forbidden DM ($m_\phi \gtrsim m_\chi$)**

**Elastic scattering between DM and nuclei**

$$\sigma_{\chi N} \approx \frac{\mu_{\chi N}^2}{\pi m_H^4}\left[Z f_p + (A-Z) f_n\right]^2 \left[\lambda_{\chi s}^2 + \lambda_{\chi p}^2 \frac{q^2}{4m_\chi^2}\right],$$

Tree level

Loop level

arXiv:1609.09079

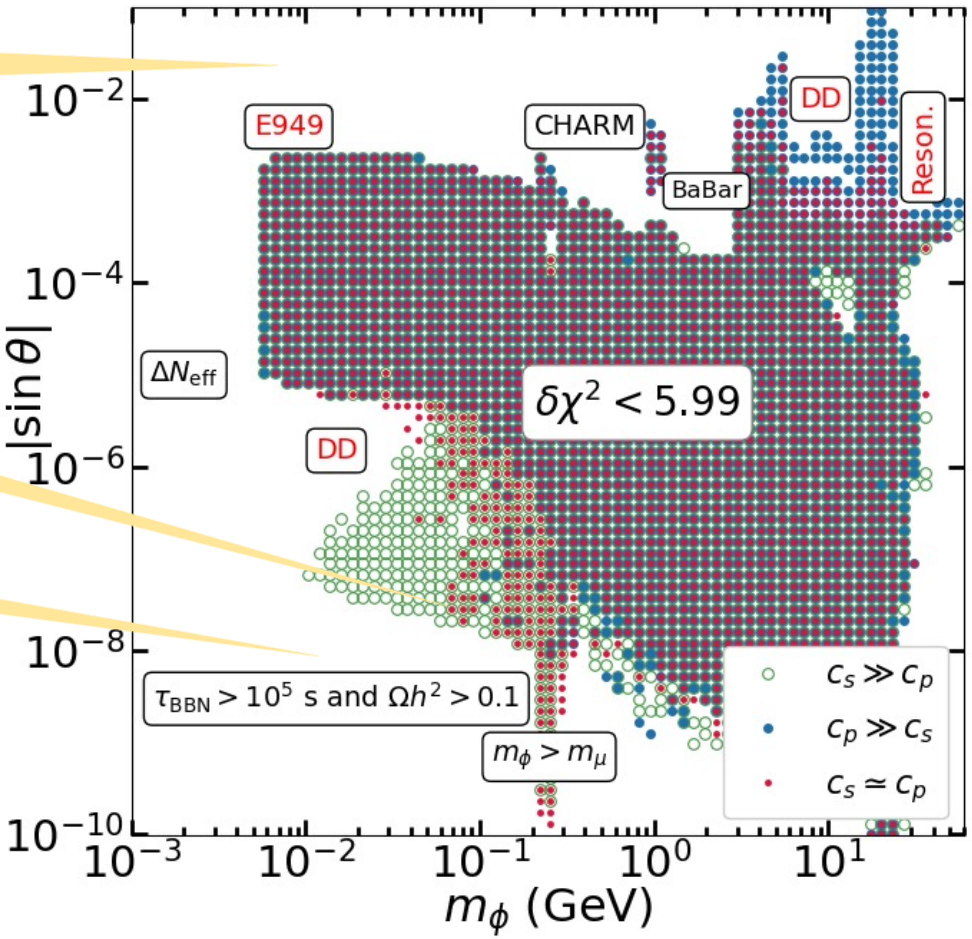
# Preliminary Result: $(m_\phi, |\sin\theta|)$

**Collider constraints**
$(\sin\theta < 10^{-2})$

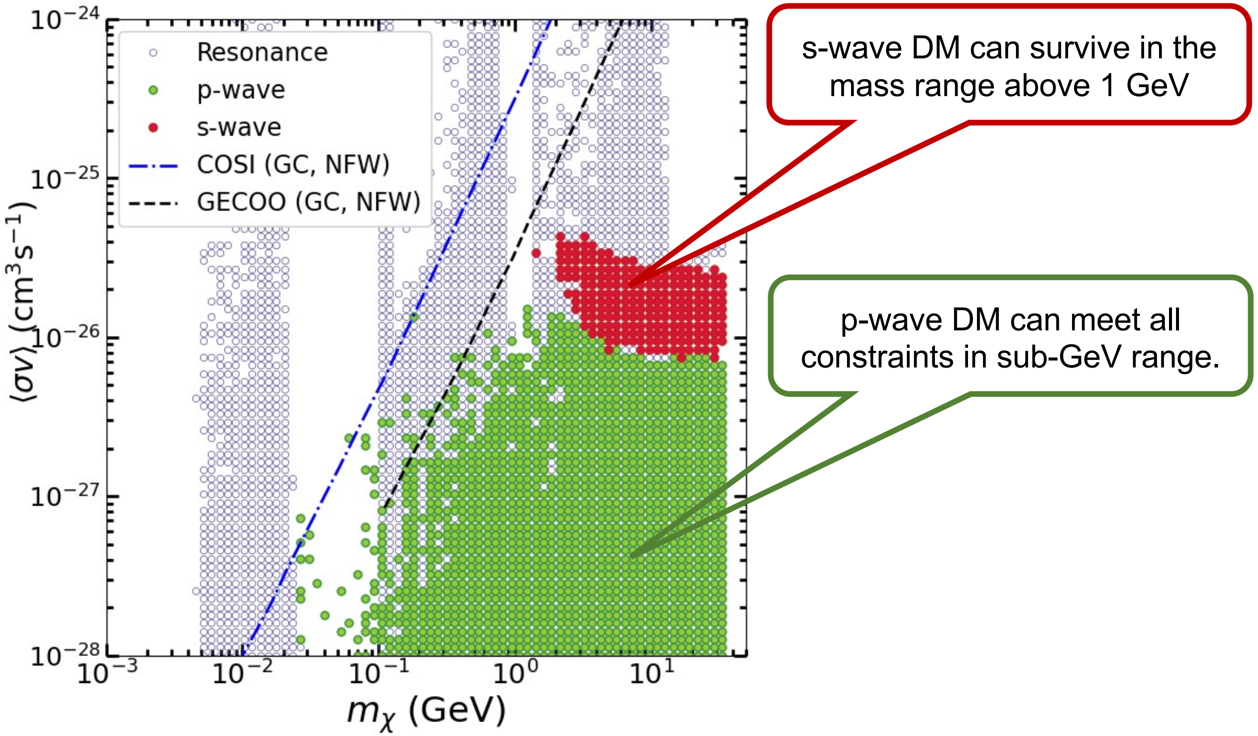
**CMB constrain**

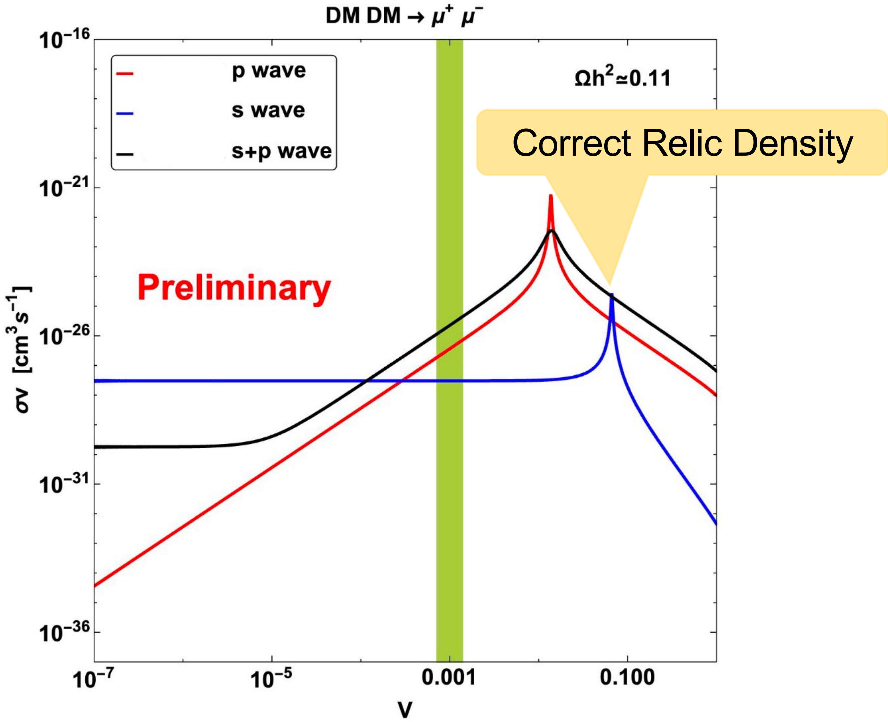
**BBN constrain**
$(\sin\theta > 10^{-8})$

$$\Gamma(\phi \to e^+e^-) = \sin^2\theta \times \frac{m_e^2 m_\phi}{8\pi v_H^2}\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{3/2}$$



# Preliminary Result: Indirect Detection




Only resonant state can be observed in future indirect detection experiments!

# SUMMARY

- We investigate a minimal dark matter model that incorporates a light Majorana dark matter and a new scalar mediator;
- Our comprehensive likelihood analysis considers constraints from direct detection experiments, collider searches, cosmological and astrophysical observations;
- We find that light dark matter through p-wave can escape CMB constraint, but only the resonance state can offer a promising prospect in the future indirect detection.

**THANK YOU !**

감사합니다 !