Light thermal Dark Matter Beyond *p*-Wave Annihilation

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Outline

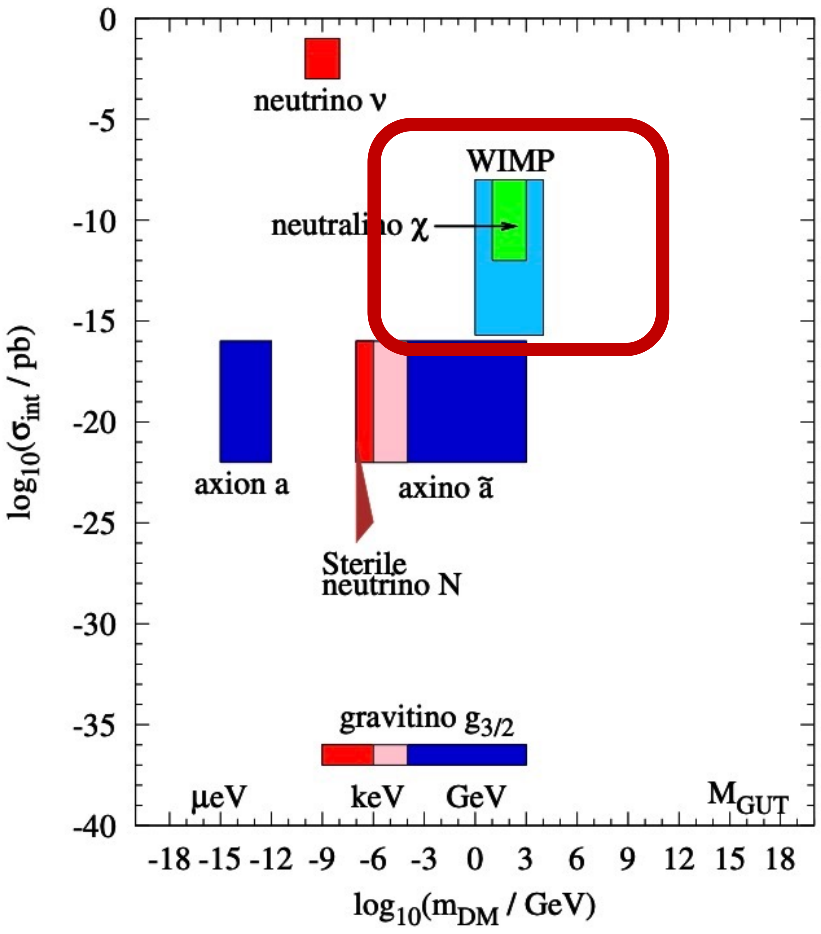
- **A brief introduction to sub-GeV dark matter**

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

- **Summary**

WIMPs

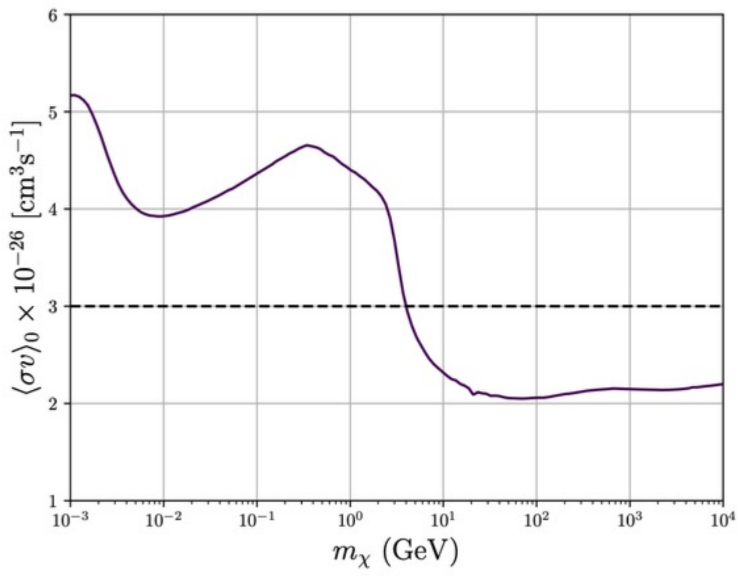
For decades, WIMPs have been the preferred DM candidates



Rept.Prog.Phys. 81 (2018) 6, 066201

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

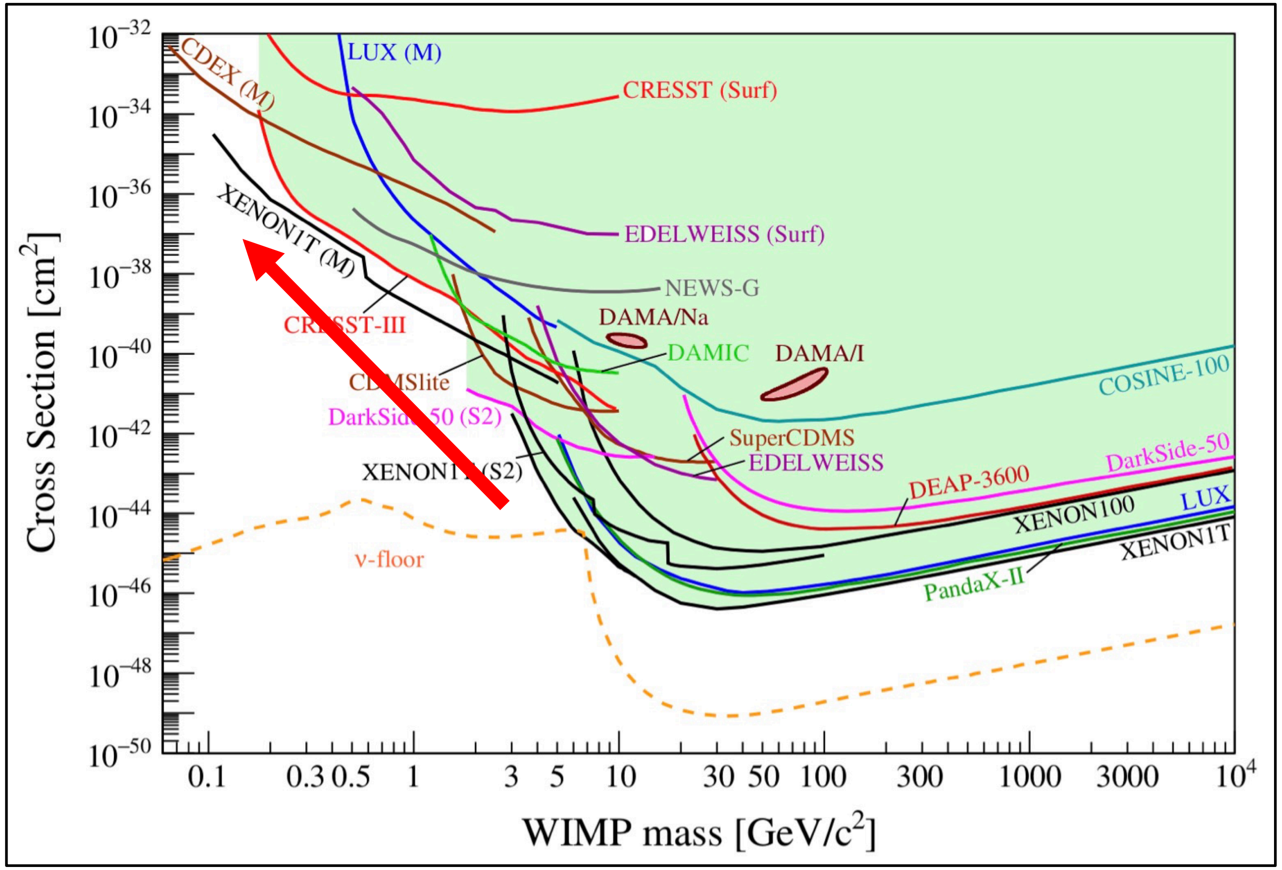
$$\frac{\Omega_\chi h^2}{0.12} \sim \left(\frac{2\times 10^{-9}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)\left(\frac{80}{g_\star}\right)^{1/2}\left(\frac{x_f}{23}\right)$$



► 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?

Neutrino floor is coming and No evidence for WIMPs!



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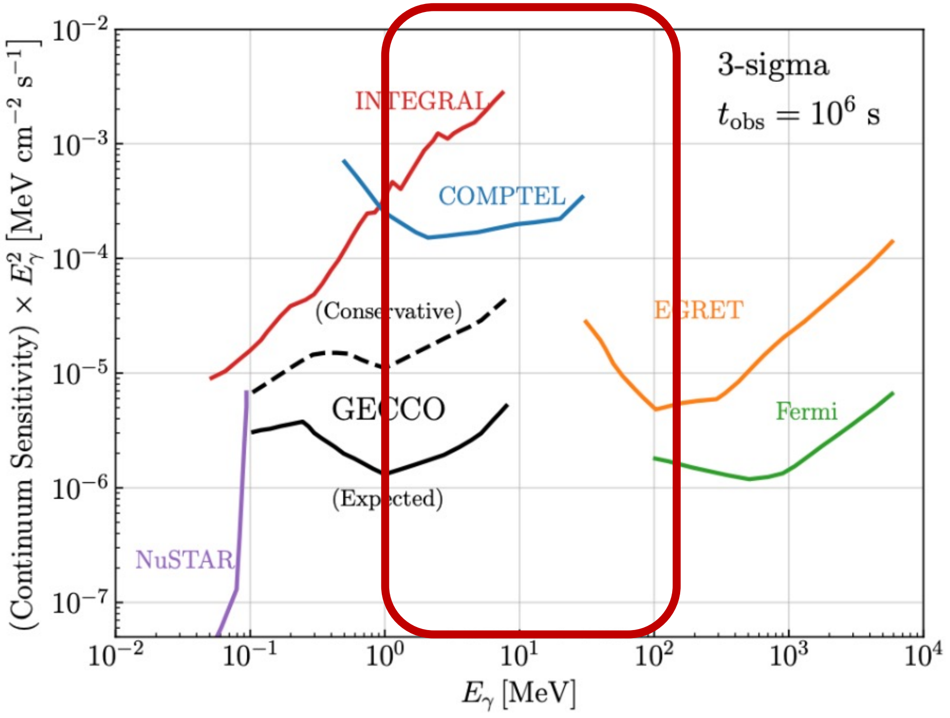
- DM mass region above GeV is highly constrained by direct detection ;
- Sub-GeV DM still has a large parameter space;
- The search for sub-GeV DM is turning to indirect detection.

Future Indirect Detection : Great opportunity to explore MeV dark matter

GECCO (2112.07190)



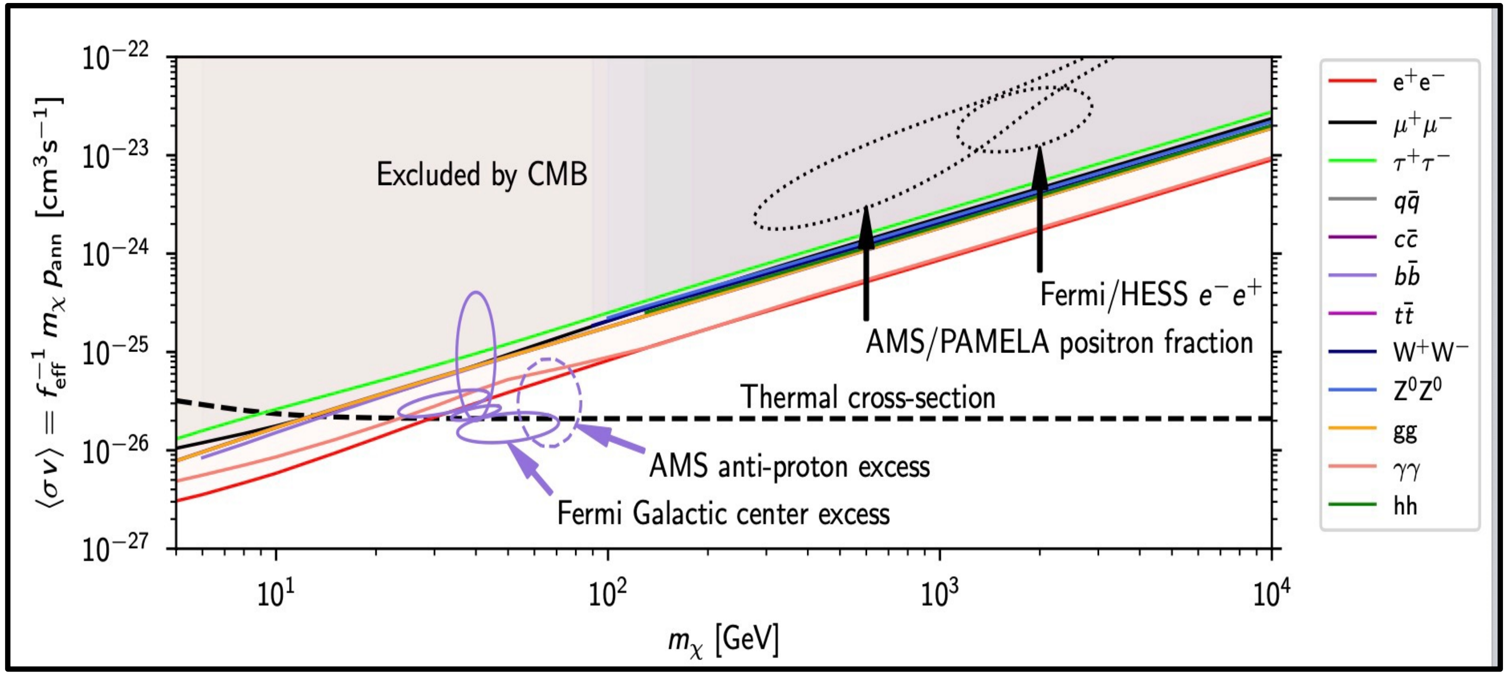
Telescope	Status	Energy Range	Reference
INTEGRAL	On 2002 October 17	15 keV to 10 MeV	0801.2086 1107.0200
e−ASTROGAM	2029	0.3 MeV to 3 GeV	1711.01265
COSI	2025	0.2 MeV to 5 MeV	2109.10403
GECCO	?	0.1 MeV to 8 MeV	2112.07190
AMEGO	?	0.2 MeV to 10 GeV	1907.07558
VLAST	?	100 MeV to 20 TeV	chinaXiv:202203.00033V2

- 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

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



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

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

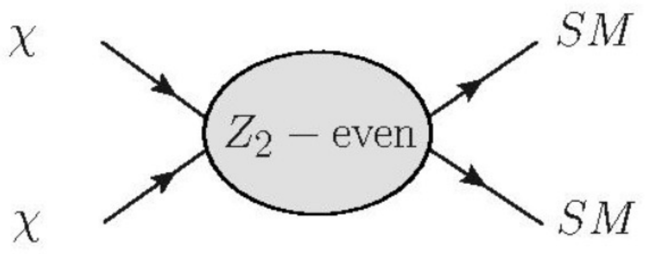
Majorana DM

SM singlet scalar

Scalar interaction (p-wave)

Pseudo-scalar interaction (s/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 & astrophysical constraints

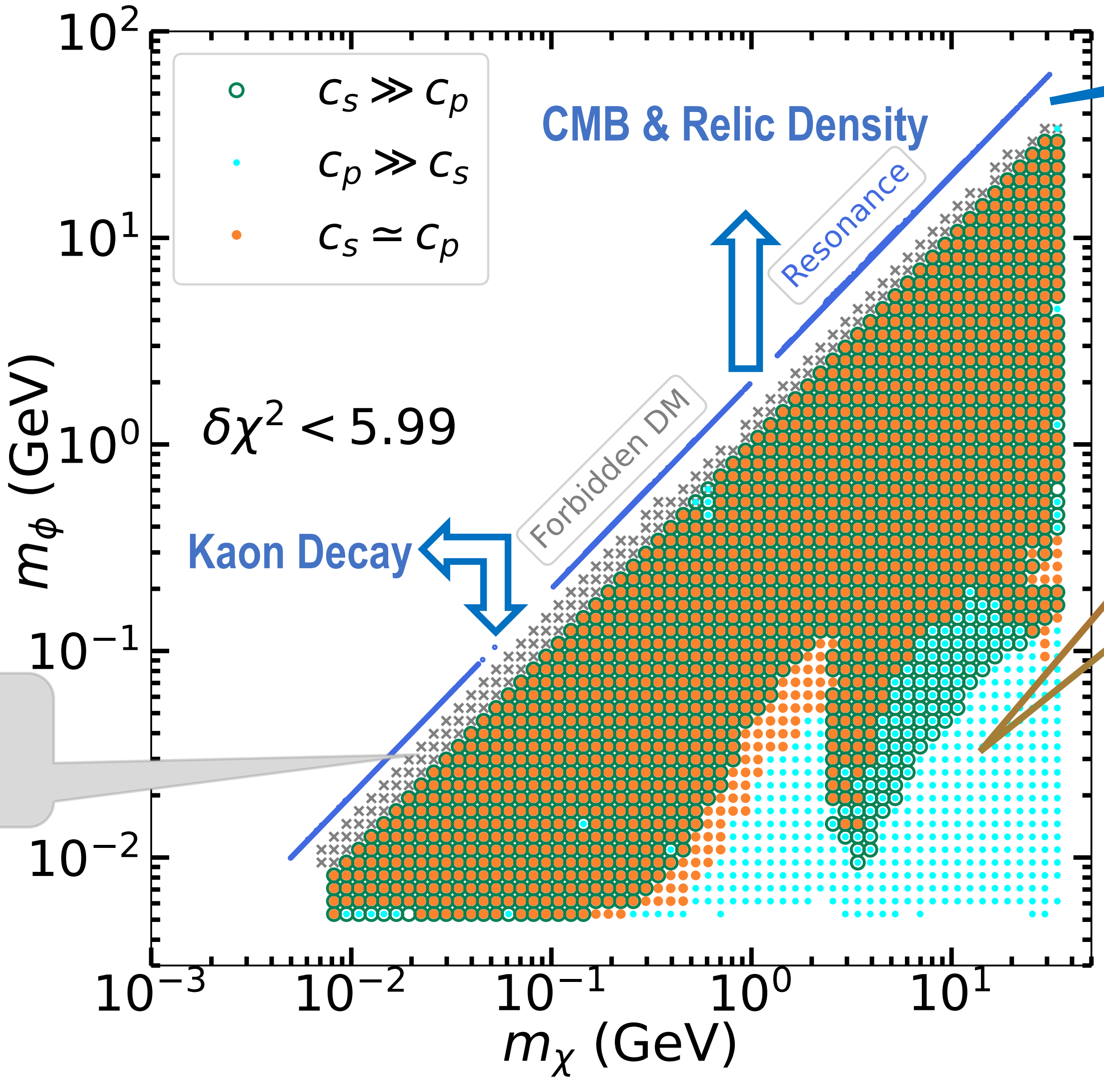
	Likelihood	Constraints
Relic abundance	Gaussian	$\Omega_\chi^{\rm exp} h^2 = 0.1193 \pm 0.0014$ [10]; $\sigma_{\rm sys} = 10\% \times \Omega_\chi^{\rm th} h^2$.
Equilibrium	Conditions	either $(\Gamma_{\chi\rm SM}^{\rm FO} \geq H_{\rm FO})$, or $(\Gamma_{\chi\rm SM}^{\rm FO} \geq H_{\rm FO}$ and $\Gamma_{\chi\phi}^{\rm FO} \geq H_{\rm FO})$
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]).
$\Delta N_{\rm eff}$	Half Gaussian	$\Delta N_{\rm eff} < 0.17$ 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

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

Preliminary Result : (m_χ, m_ϕ)



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

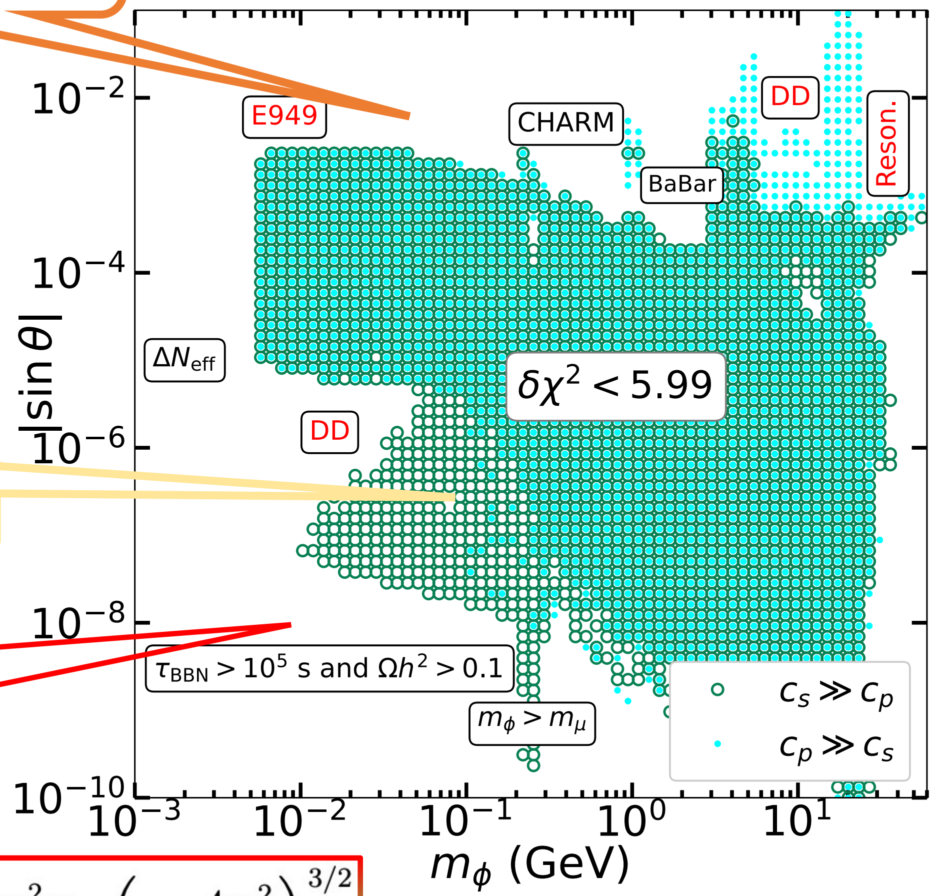
arXiv:1609.09079

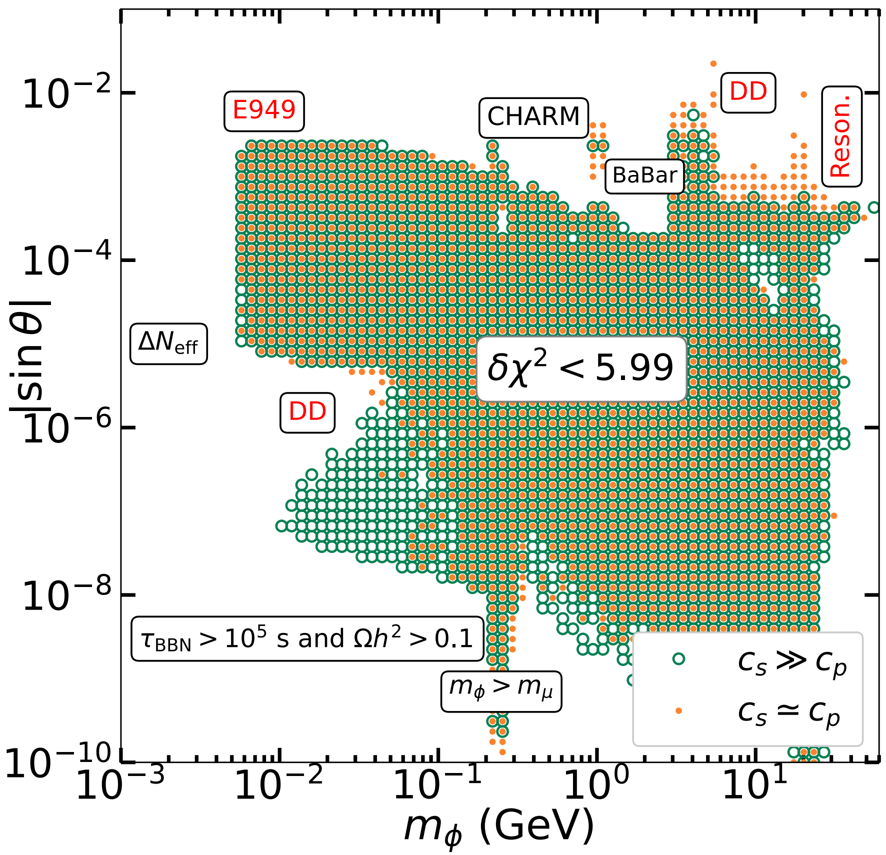
Preliminary Result : $(m_\phi, |\sin\theta|)$

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

CMB constrain

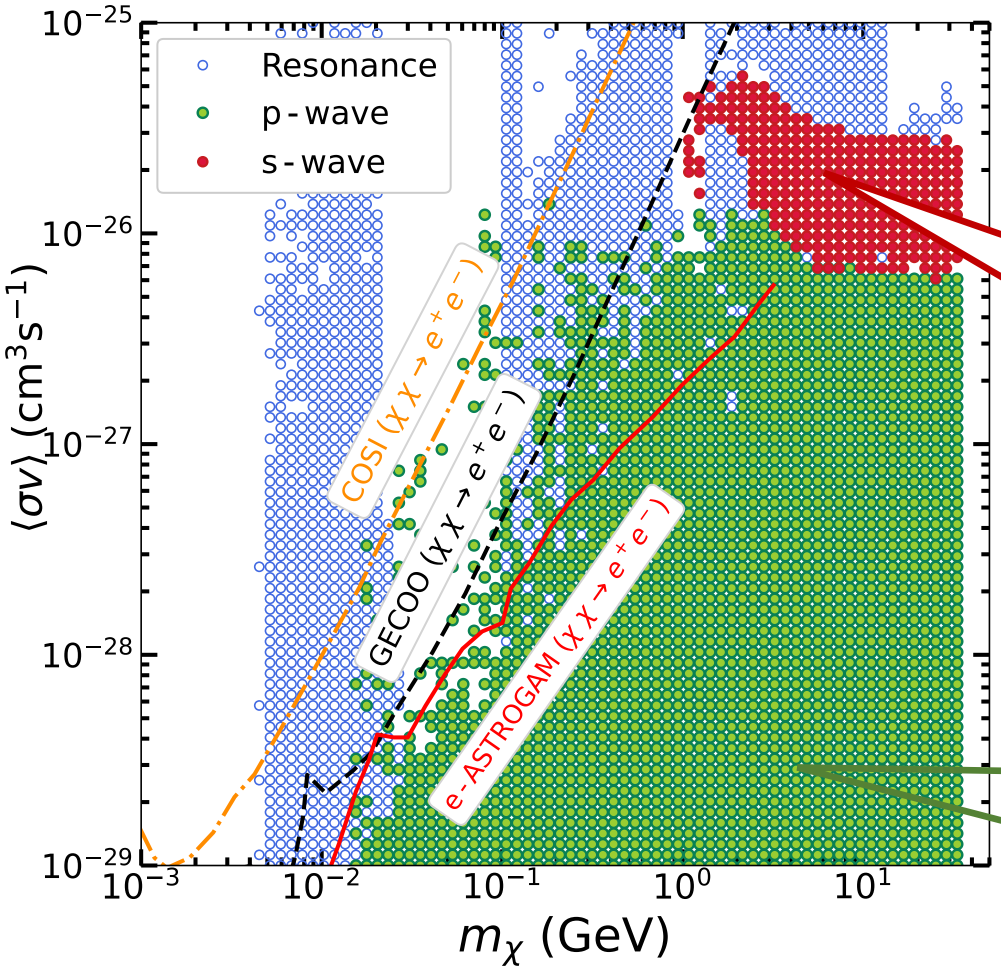
BBN constrain
$(\sin\theta > 10^{-8})$





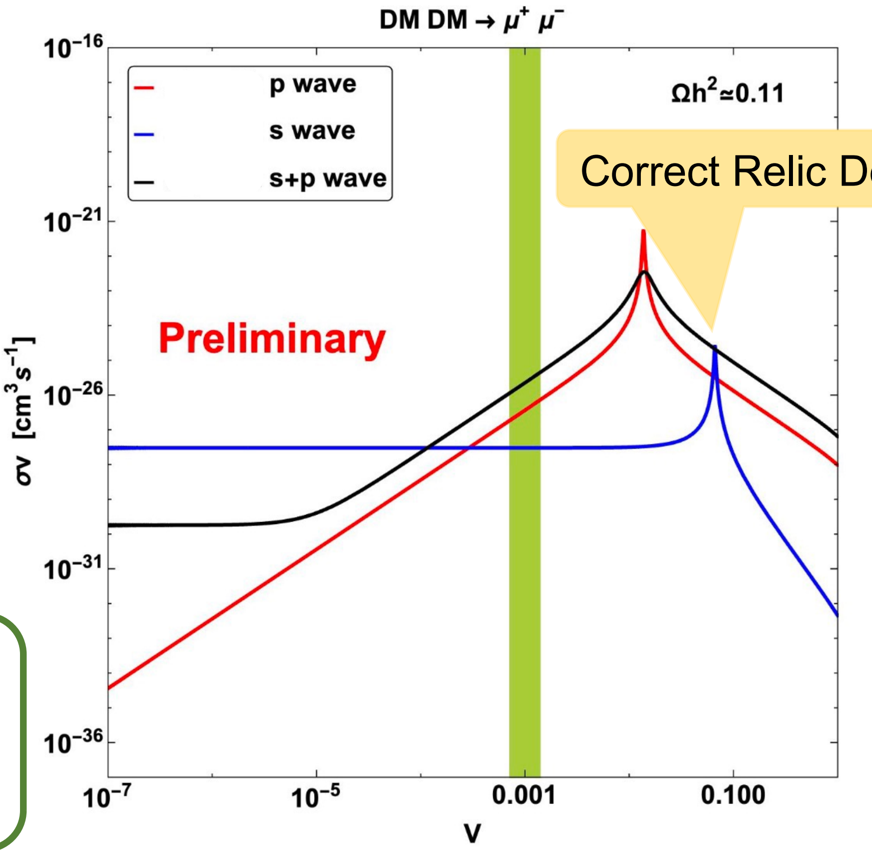
$$\Gamma(\phi \to e^+e^-) = \sin^2\theta \times \frac{m_e^2 m_\phi}{8\pi v_H^2}\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{3/2}$$

Preliminary Result: Indirect Detection



s-wave DM can survive in the mass range above 1 GeV

p-wave DM can meet all constraints in sub-GeV range



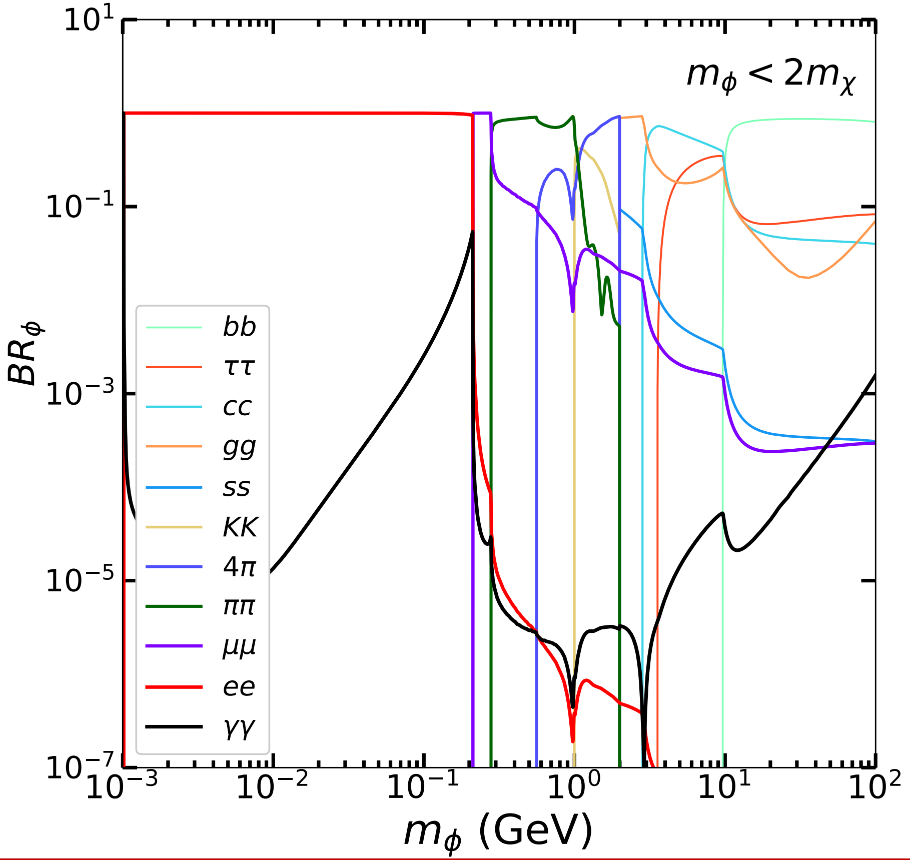
Correct Relic Density

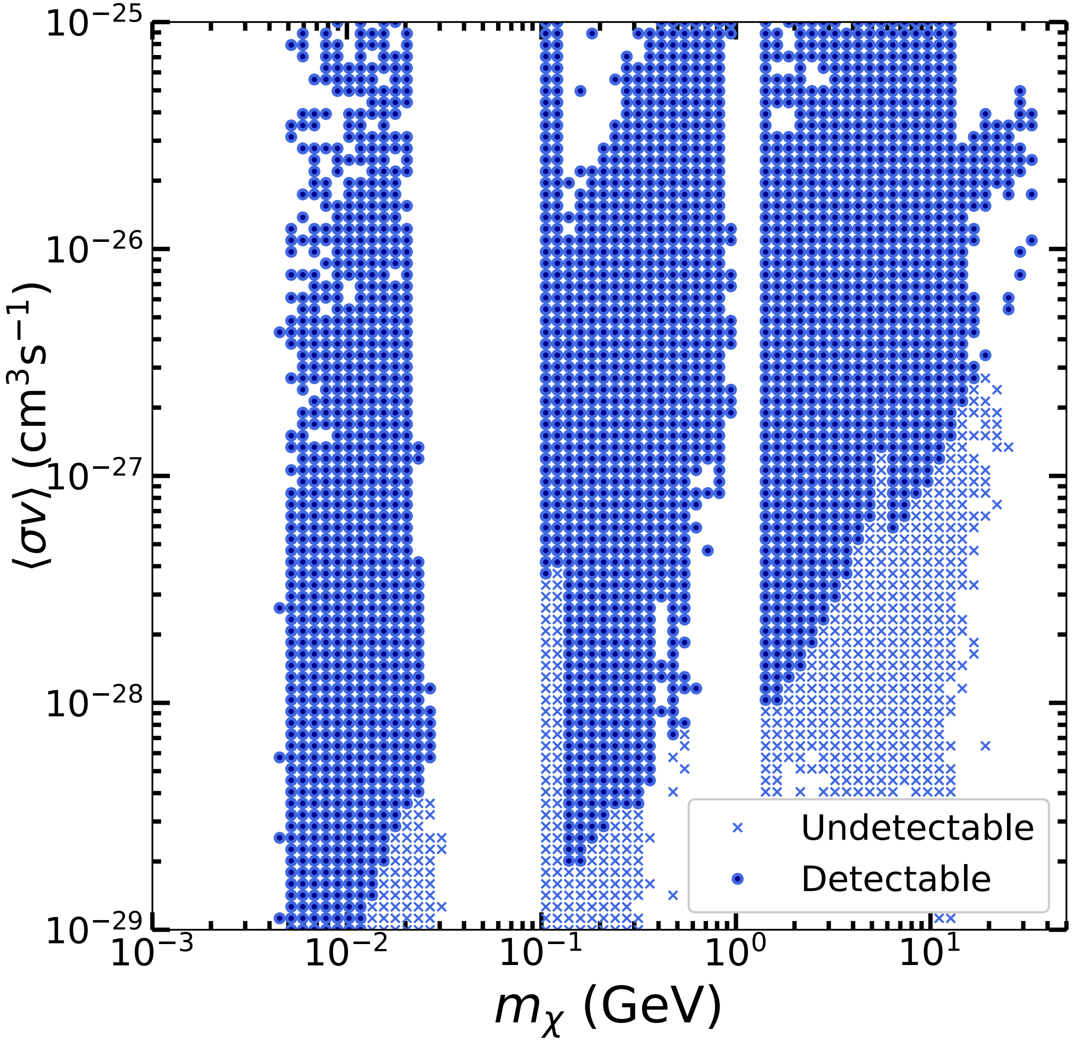
Only resonant state can be observed in future indirect detection experiments!

Preliminary Result: Indirect Detection with Breit-Wigner Resonance

$$\sigma = \frac{16\pi}{E_{\rm cm}^2 \bar{\beta}_i \beta_i} \frac{M^2\Gamma^2}{(E_{\rm cm}^2 - M^2)^2 + M^2\Gamma^2} B_i B_f$$

$$\langle \sigma v \rangle_{ann,95} = \frac{\langle \sigma v \rangle_{e^- e^+,95} \cdot N_{e^- e^+}}{\sum_i BR_i N_i}$$





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 !

谢谢！