[1] JHEP 07 (2019) 050,
[2] Phys.Rev.D 110 (2024) 6, 063535, [3] JHEP 05 (2024) 281,
[4] JCAP 08 (2025) 059, and [5] JCAP 11 (2025) 013.

Bridging the MeV-Gap for Light Higgs Portal Dark Matter

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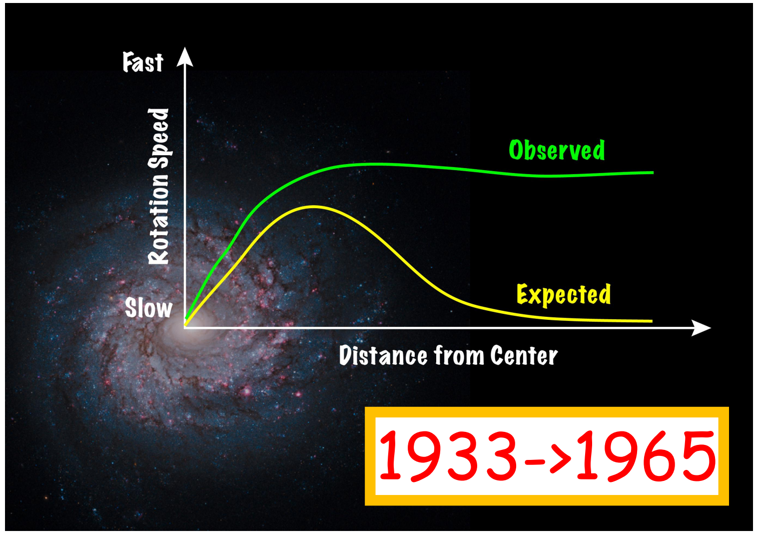
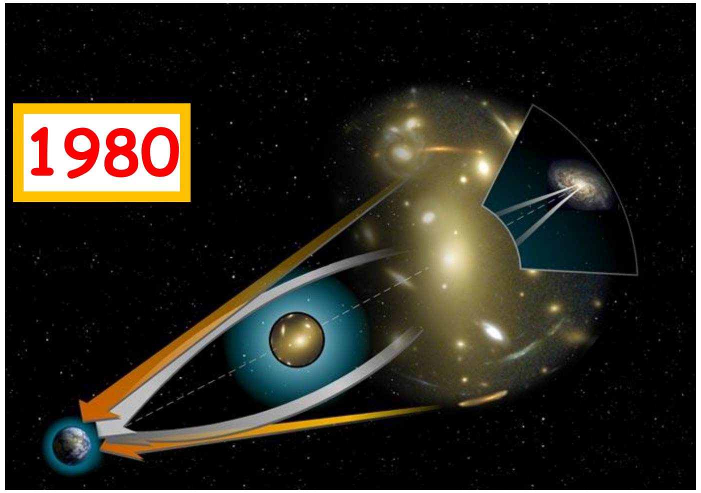
2025.12.21@HiggsPotential 2025

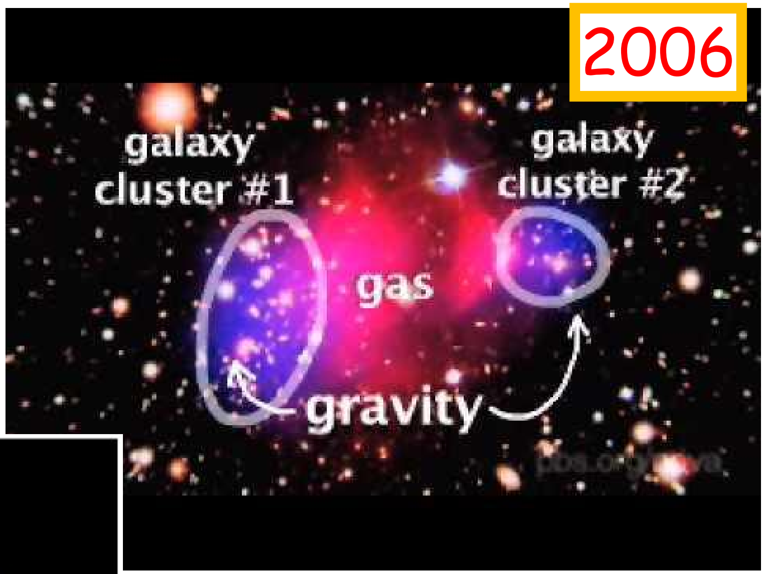
Outline

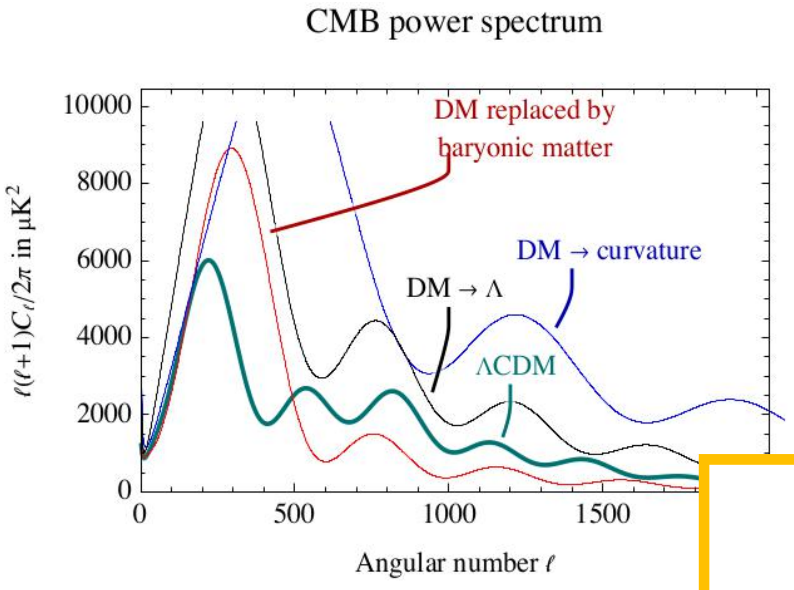
- ☐ Motivations.
- ☐ Minimal dark matter Models.
- ☐ Parameter space to be detected in gamma-ray telescope (VLAST).
- ☐ Results and summary.

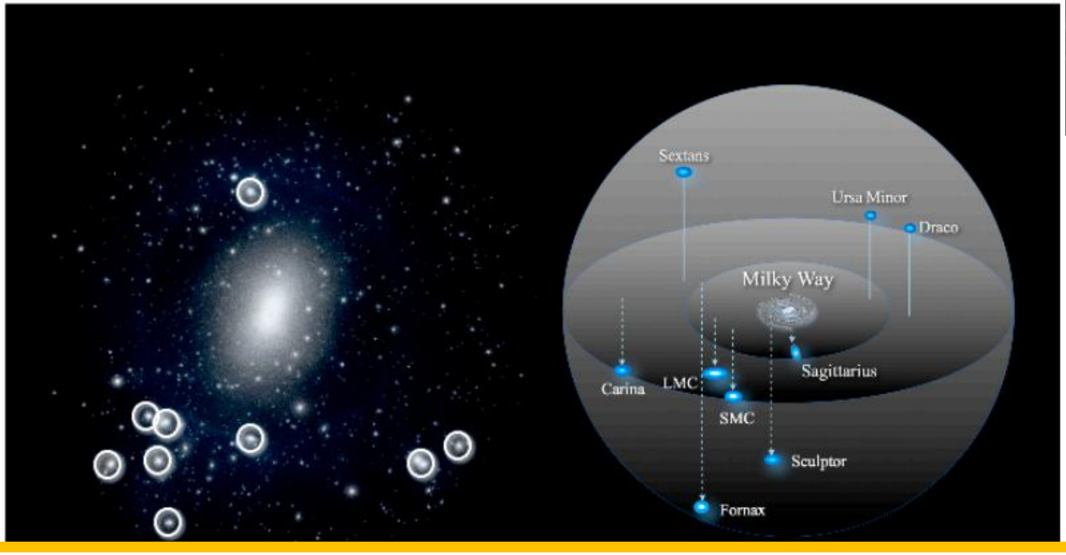
Dark Matter Problems





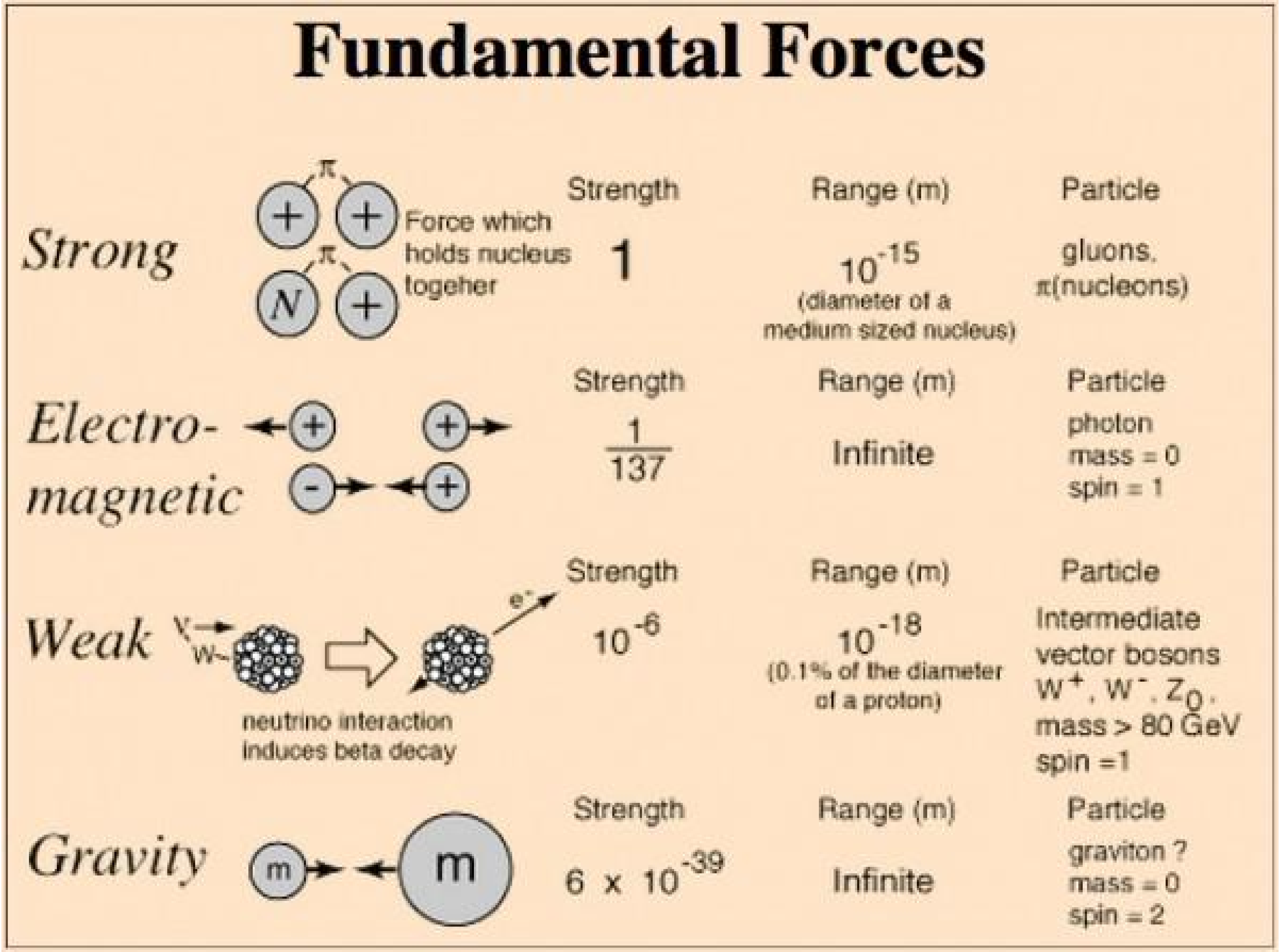






IF GR is correct, it will be difficult to explain the universe without DM assumption.

Diversity problem:
More and more dSphs were found!
Some of them are DM-rich but some are DM-poor.

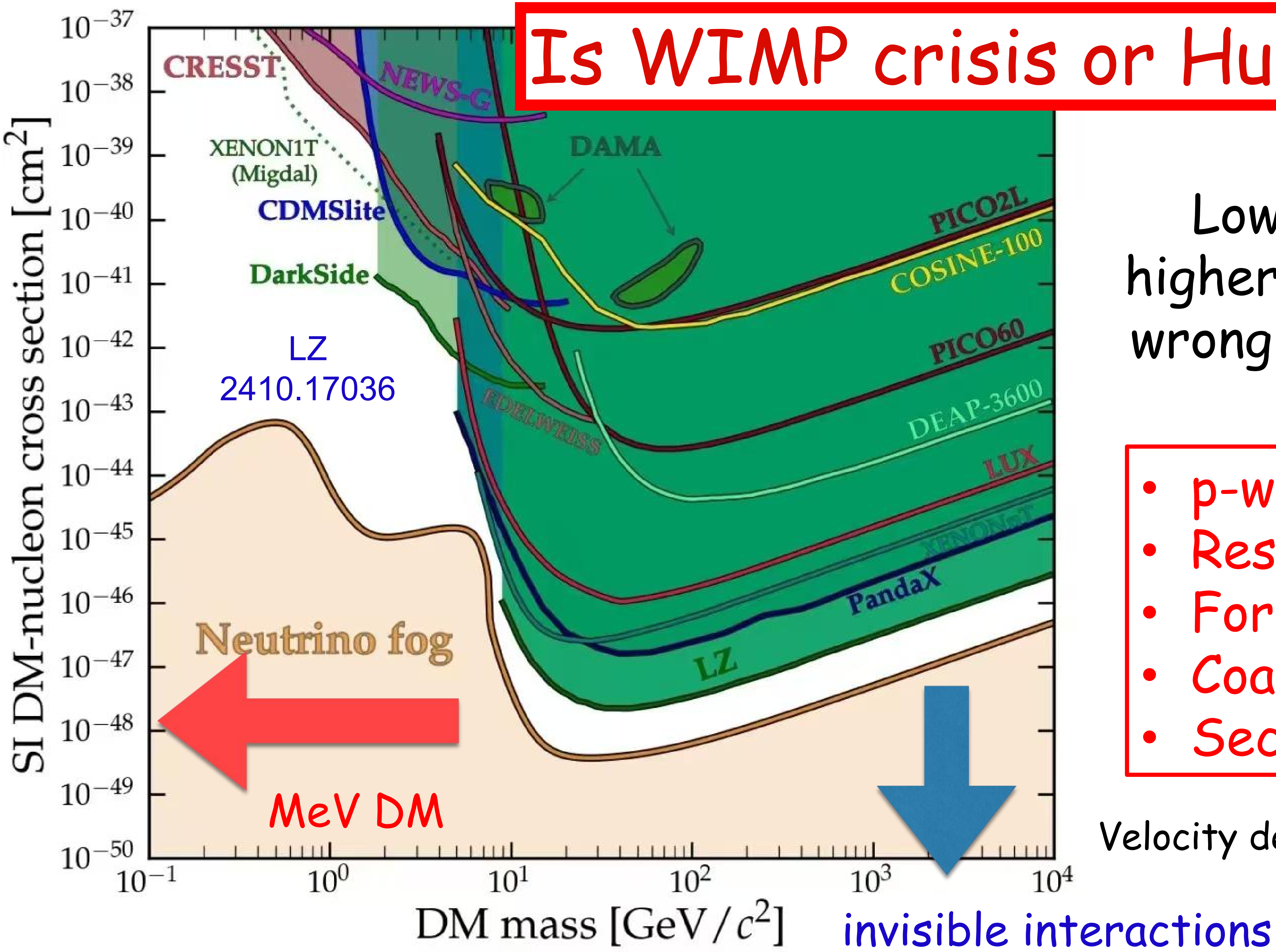


How is possible that no interaction between 1e-6 and 1e-39?

If new interaction greater than Gravity...

What is the portal?

Is WIMP crisis or Human panic?

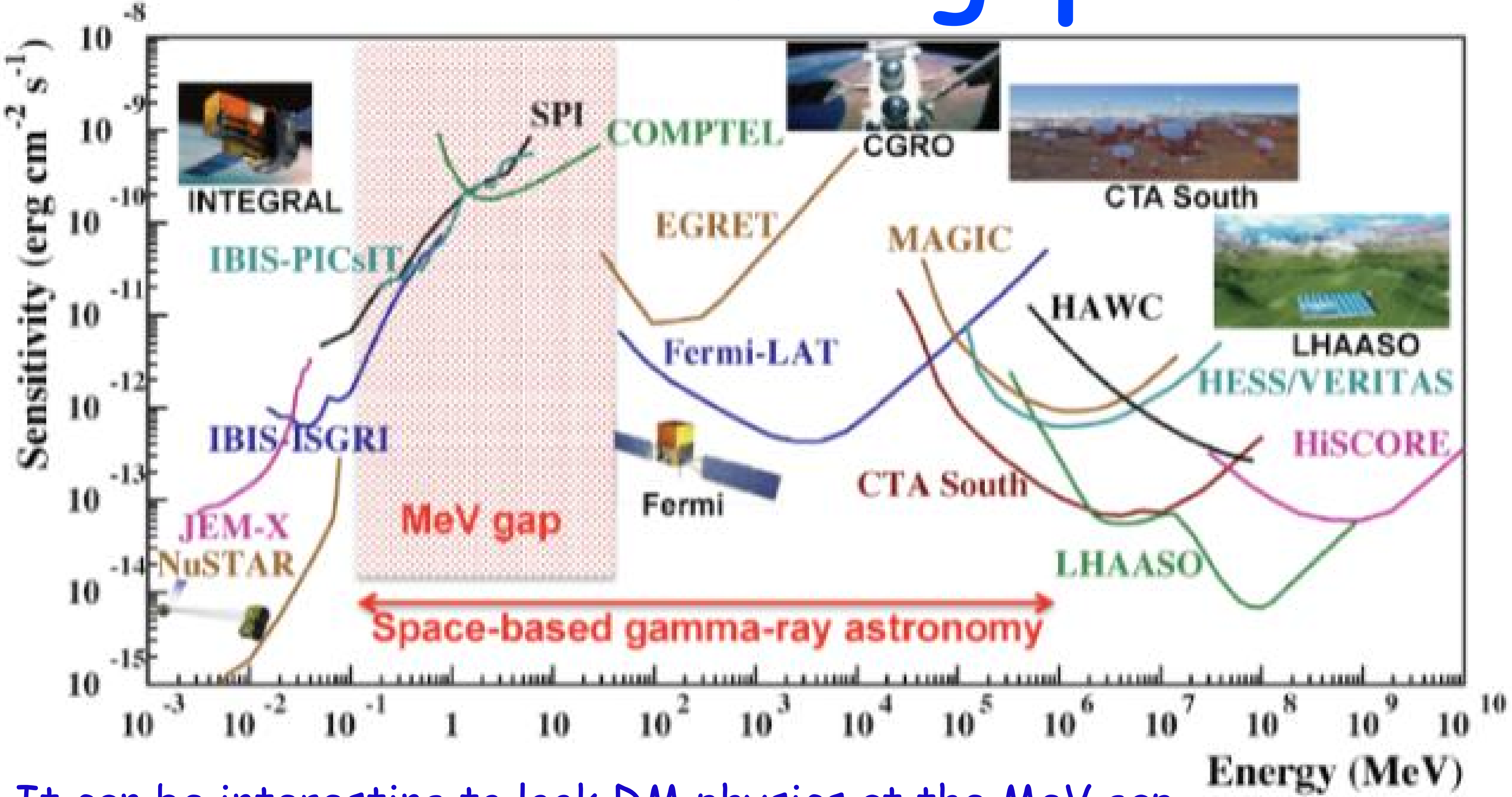


Lower energy,
higher exposure, or
wrong DM density?

- p-wave
- Resonance
- Forbidden DM
- Coannihilation
- Secluded DM

Velocity dependent annihilations!

The MeV gap



It can be interesting to look DM physics at the MeV gap.

Challenges of MeV dark matter

The light DM mass region

Can we go to the region below GeV?

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Cosmological Lower Bound on Heavy-Neutrino Masses

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and

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(Received 13 May 1977)

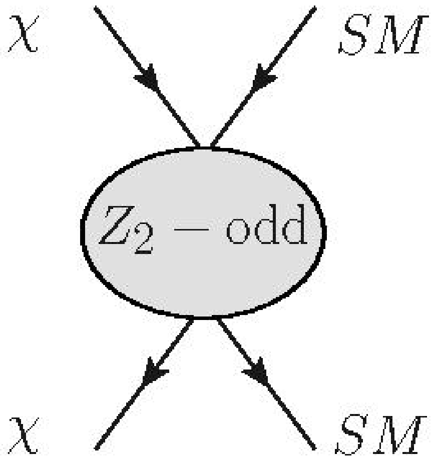
If only a DM introduced...

g=Weak coupling

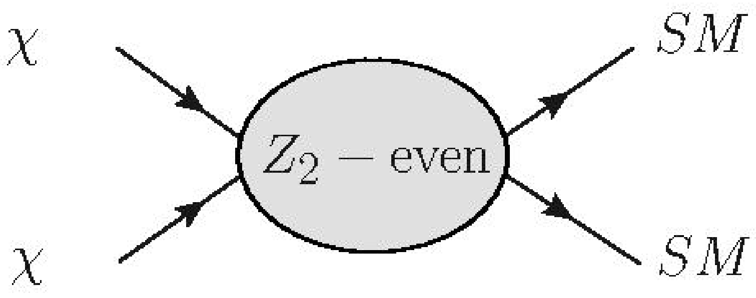
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Unless, a new light mediator is introduced!

Simplicity and Light mediator



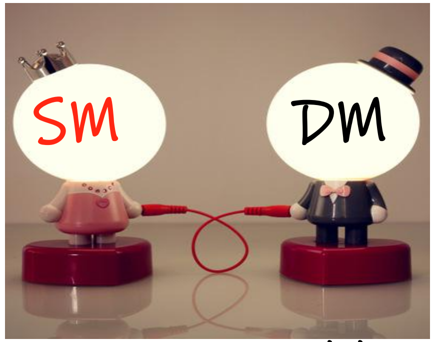
t-channel annihilation



s-channel annihilation

① Z_2 odd scalar mediator (like squark) + SM fermion. LEP mass limit for charged mediator is heavier than 100 GeV.

② Z_2 odd fermion mediator (like Chargino) + SM gauge boson. Invisible decay gives a severe limit.

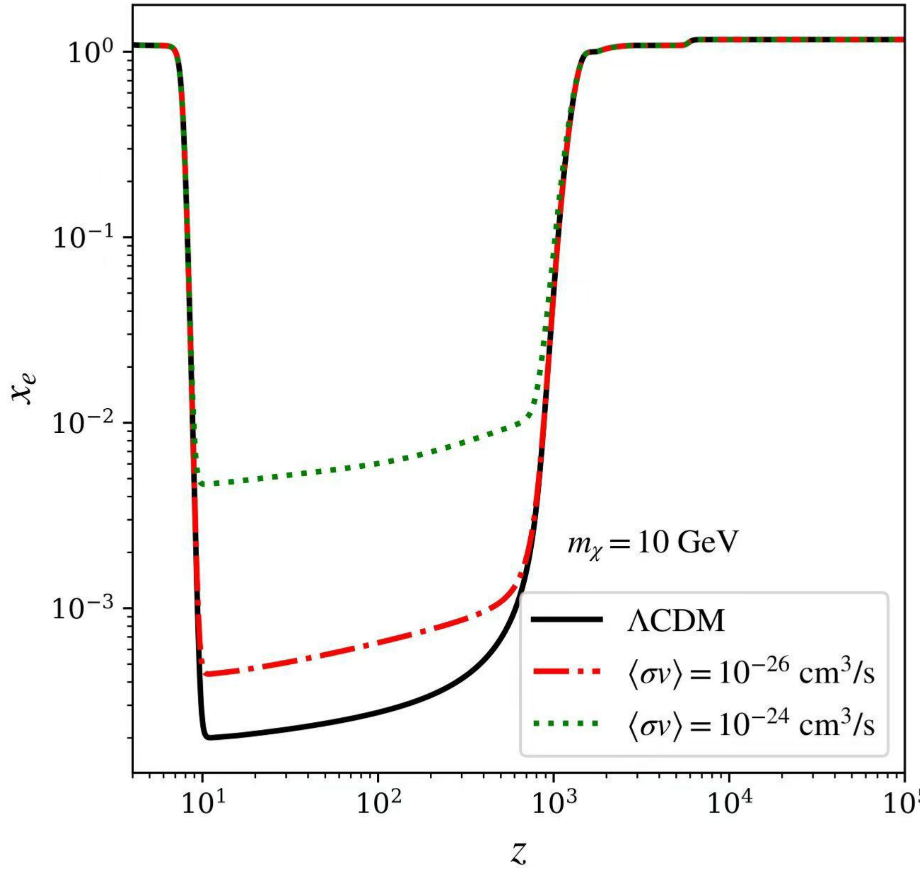


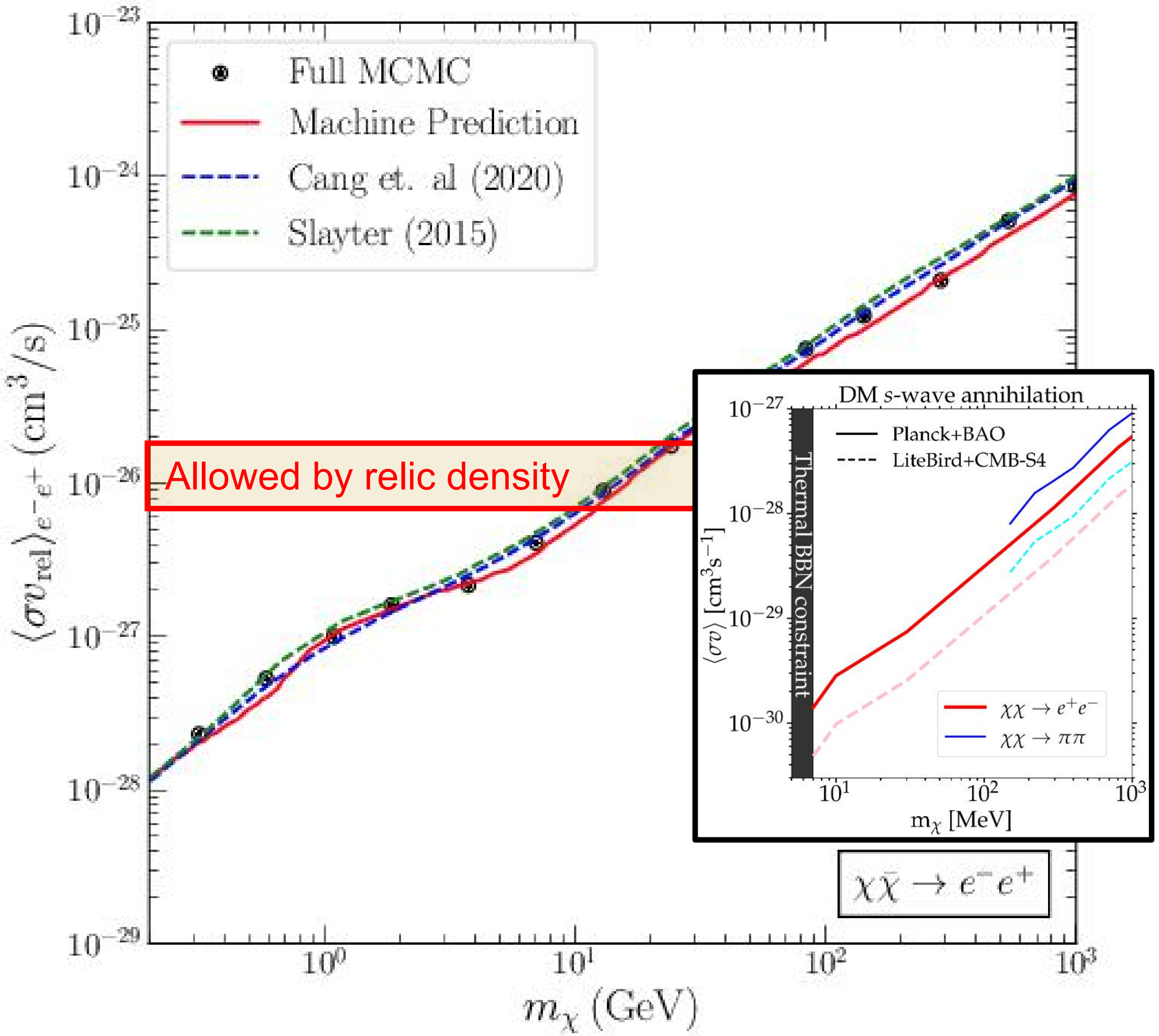
even odd

Therefore, an MeV mediator of the the DM annihilation to SM pair via t-channel CANNOT be Z_2-odd.

Higgs portal or dark photon portal?

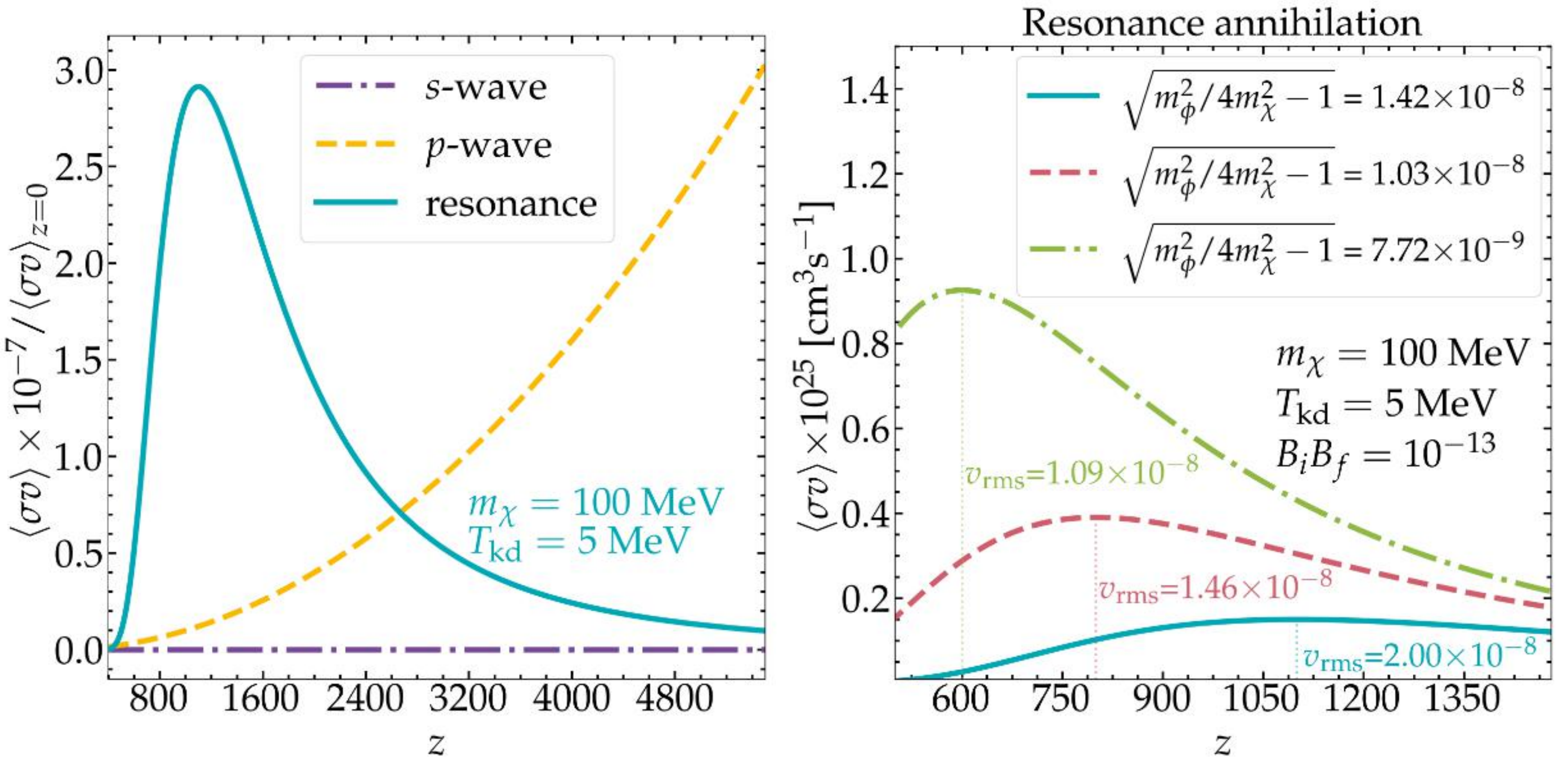
CMB constraints





- DM annihihlation injects energy into gas to ionize and heat Hydrogen.
- For sub-GeV DM with correct relic density, s-wave may be exculded?

CMB constraints



	s-wave	p-wave	resonance
Cross-section	$\langle\sigma v_{rel}\rangle \propto a_s$	$\langle\sigma v_{rel}\rangle \equiv b\langle v_\chi^2\rangle$	$\langle\sigma v_{rel}\rangle = \frac{576}{\sqrt{3}} \frac{\pi^{3/2}}{m_\phi^2} \frac{\gamma}{v_{rms}^3} e^{-3\xi/v_{rms}^2} B_i B_f$
Free parameters	$\langle\sigma v_{rel}\rangle$, m_χ	b, T_{kd}, m_χ	B_iB_f, T_{kd}, m_χ

- The velocity is ~10^{-8} c during recombination epoch.
- *p*-wave annihilation cross-section is suppressed by the velocity .
- It requires an extreme fine-tunning for resonance annihilation in order to be testable in CMB data.

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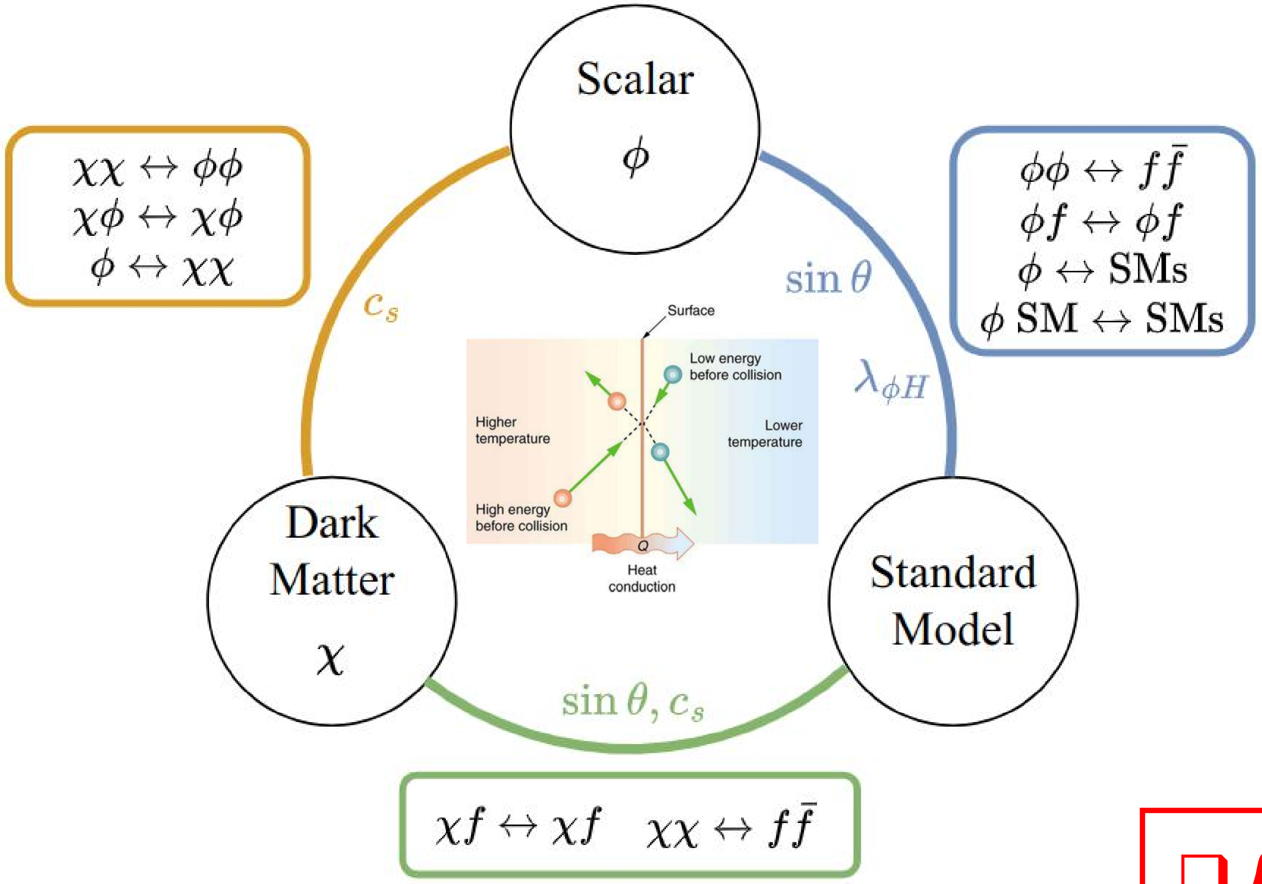
Thermal dark matter

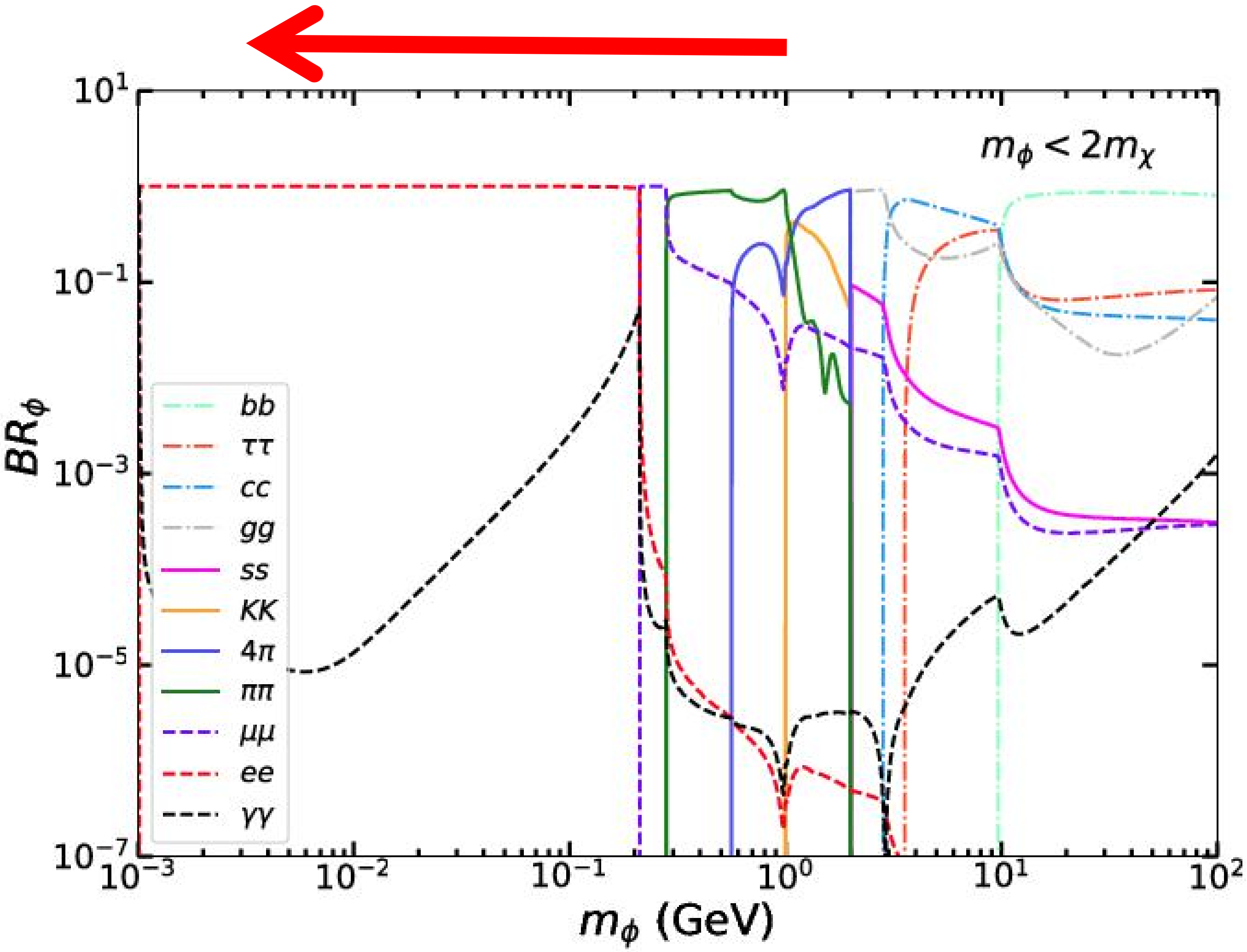


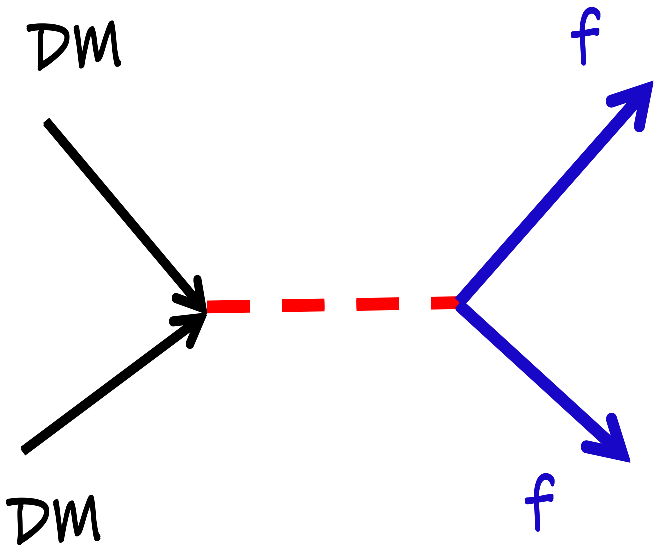
	Likelihood	Constraints
Relic abundance	Gaussian	$\Omega_\chi^{\rm exp}h^2 = 0.1193 \pm 0.0014$ [90]; $\sigma_{\rm sys} = 10\% \times \Omega_\chi^{\rm th}h^2$.
Equilibrium	Conditions	either $(\Gamma_{\chi\rm SM}^{\rm FO} \geq H_{\rm FO})$, or $(\Gamma_{\phi\rm SM}^{\rm FO} \geq H_{\rm FO}$ and $\Gamma_{\chi\phi}^{\rm FO} \geq H_{\rm FO})$
DM direct detection	Half Gaussian	$9\,\mathrm{GeV} < m_\phi < 10\,\mathrm{TeV}$ (LZ [91]), $3.5\,\mathrm{GeV} < m_\phi < 9\,\mathrm{GeV}$ (PANDAX-4T [16]), $60\,\mathrm{MeV} < m_\phi < 5\,\mathrm{GeV}$ (DarkSide [92]).
$\triangle N_{\rm eff}$	Half Gaussian	$\triangle N_{\rm eff} < 0.17$ for 95% C.L. [90]
BBN	Conditions	if $(m_\phi \geq 2m_\pi)$ then $\tau_\phi \leq 1$ s [93], if $(m_\phi \leq 2m_\pi)$ then $\tau_\phi \leq 10^5$ s [94].

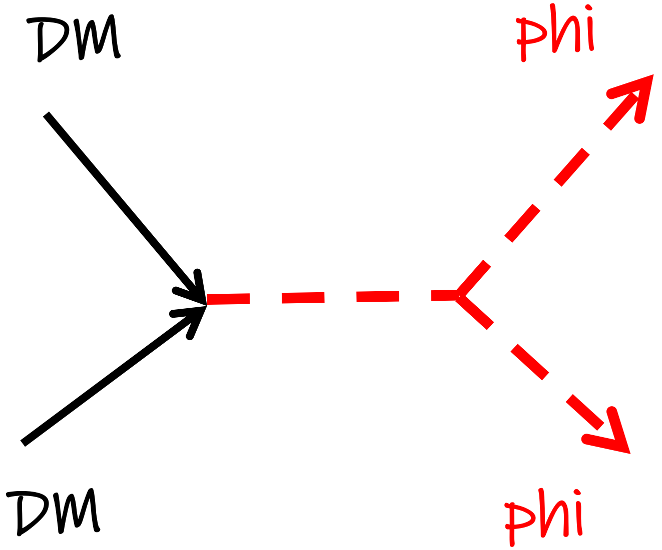
Heat transfer can be via the green or orange+blue.

- ❑ **Must be frequent momentum exchange! (Common Problems of MeV DM)**
- ❑ **Number density can be discribed by n~exp(-m/T)!**

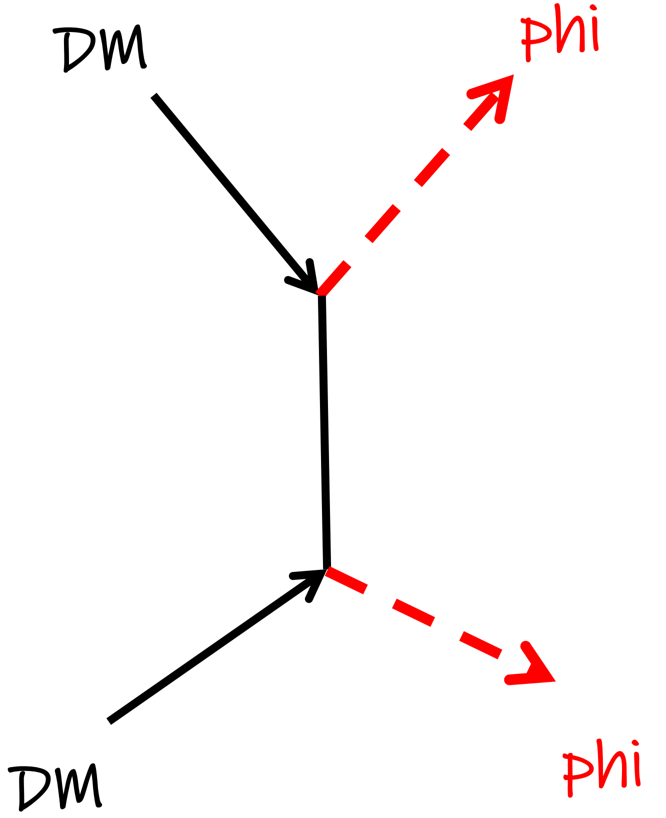
Sub-GeV Leptophilic Dark Matter interactions







types	Lagrangian	$\langle\sigma v\rangle_{2\mu} \simeq a + bv^2$	$\langle\sigma v\rangle_{4\mu} \simeq a + bv^2$	DD
	Z_2 even mediator			
χ and ϕ	$\mathcal{L}_1 = (g_D\bar{\chi}\chi + g_f\bar{f}f)\phi$	$a=0$	$a=0$	Eq. (B1)
	$\mathcal{L}_2 = (g_D\bar{\chi}\chi + g_f\bar{f}i\gamma^5 f)\phi$	$a=0$	$a=0$	—
	$\mathcal{L}_3 = (g_D\bar{\chi}i\gamma^5\chi + g_f\bar{f}f)\phi$	Case (i)	$a=0$	Eq. (B2)
	$\mathcal{L}_4 = (g_D\bar{\chi}i\gamma^5\chi + g_f\bar{f}i\gamma^5 f)\phi$	Case (i)	$a=0$	—
χ and V_μ	$\mathcal{L}_5 = (g_D\bar{\chi}\gamma^\mu\gamma^5\chi + g_f\bar{f}\gamma^\mu f)V_\mu$	$a=0$	Case (A)	Eq. (B3)
	$\mathcal{L}_6 = (g_D\bar{\chi}\gamma^\mu\gamma^5\chi + g_f\bar{f}\gamma^\mu\gamma^5 f)V_\mu$	Case (ii)	Case (A)	—
	$\mathcal{L}_7 = (g_D\bar{\chi}\gamma^\mu\chi + g_f\bar{f}\gamma^\mu f)V_\mu$	Case (i)	Case (C)	Eq. (B4)
	$\mathcal{L}_8 = (g_D\bar{\chi}\gamma^\mu\chi + g_f\bar{f}\gamma^\mu\gamma^5 f)V_\mu$	Case (i)	Case (C)	—
S and ϕ	$\mathcal{L}_9 = (M_{D\phi}S^\dagger S + g_f\bar{f}f)\phi$	Case (i)	Case (B)	Eq. (B5)
	$\mathcal{L}_{10} = (M_{D\phi}S^\dagger S + g_f\bar{f}i\gamma^5 f)\phi$	Case (i)	Case (B)	—
	$\mathcal{L}_{9'} = (g_D S^\dagger S\phi + g_f\bar{f}f)\phi$	—	$b=0$	—
	$\mathcal{L}_{10'} = (g_D S^\dagger S\phi + g_f\bar{f}i\gamma^5 f)\phi$	—	$b=0$	—
S and V_μ	$\mathcal{L}_{11} = (ig_D S^\dagger\overleftrightarrow{\partial_\mu}S + g_D^2 S^\dagger SV_\mu + g_f\bar{f}\gamma_\mu f)V^\mu$	$a=0$	Case (C)	Eq. (B6)
	$\mathcal{L}_{12} = (ig_D S^\dagger\overleftrightarrow{\partial_\mu}S + g_D^2 S^\dagger SV_\mu + g_f\bar{f}\gamma_\mu\gamma^5 f)V^\mu$	$a=0$	Case (C)	—
X_μ and ϕ	$\mathcal{L}_{13} = (M_{D\phi}X^\mu X_\mu^\dagger + g_f\bar{f}f)\phi$	Case (i)	Case (D)	Eq. (B7)
	$\mathcal{L}_{14} = (M_{D\phi}X^\mu X_\mu^\dagger + g_f\bar{f}i\gamma^5 f)\phi$	Case (i)	Case (D)	—
	$\mathcal{L}_{13'} = (g_D X^\mu X_\mu^\dagger\phi + g_f\bar{f}f)\phi$	—	$b=0$	—
	$\mathcal{L}_{14'} = (g_D X^\mu X_\mu^\dagger\phi + g_f\bar{f}i\gamma^5 f)\phi$	—	$b=0$	—
X_μ and V_μ	$\mathcal{L}_{15} = ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu - X^{\mu\nu\dagger}X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f\bar{f}\gamma^\mu fV_\mu$	$a=0$	Case (C)	Eq. (B8)
	$\mathcal{L}_{16} = ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu - X^{\mu\nu\dagger}X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f\bar{f}\gamma^\mu\gamma^5 fV_\mu$	$a=0$	Case (C)	—



$$\mathscr{L}_{\rm int} \supset -\frac{\cos\theta}{2}(c_s\phi\bar{\chi}\chi + c_p\phi\bar{\chi}i\gamma_5\chi) + \frac{\sin\theta}{2}(c_s h\bar{\chi}\chi + c_p h\bar{\chi}i\gamma_5\chi).$$

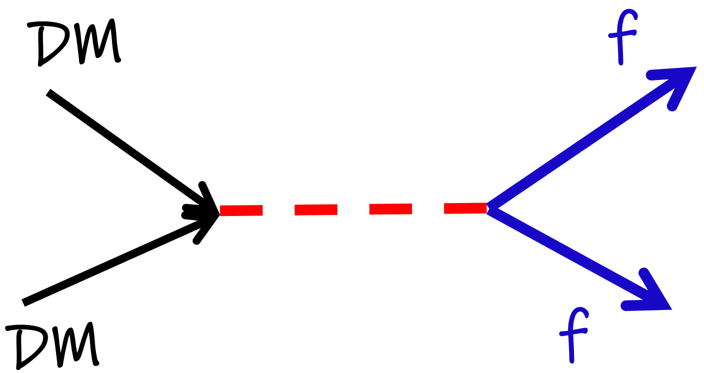
Abdughani, Fan, Lu, Tang and Tsai, JHEP 07 (2022), 127

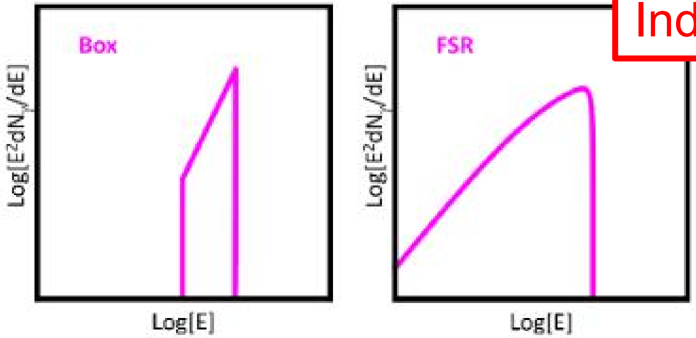
The joint contribution of $|c_s| \approx |c_p|$ leads to s-wave annihilation of $\chi\chi \to \phi\phi$

Minimum leptonphilic Lagrangian

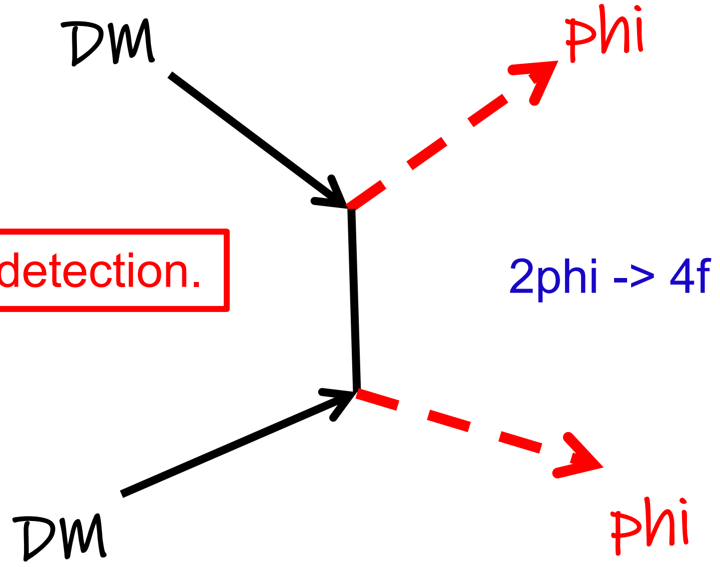
(i) Scalar DM and scalar mediator (s-wave): $\mathcal{L}_{SS} = M_D S^\dagger S \phi + g_f \bar{f} f \phi,$

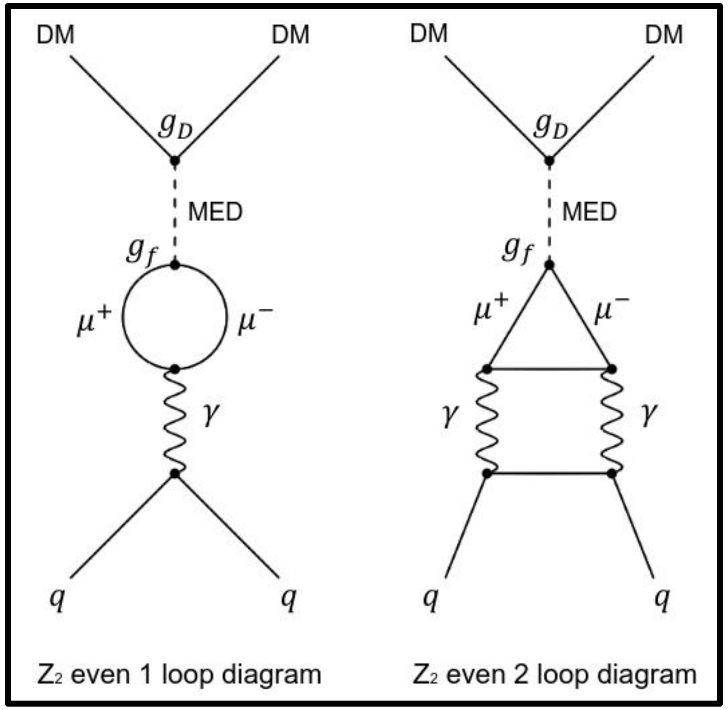
(ii) Dirac DM and scalar mediator (*p*-wave): $\mathcal{L}_{FS} = g_D \bar{\chi} \chi \phi + g_f \bar{f} f \phi.$





Indirect detection.

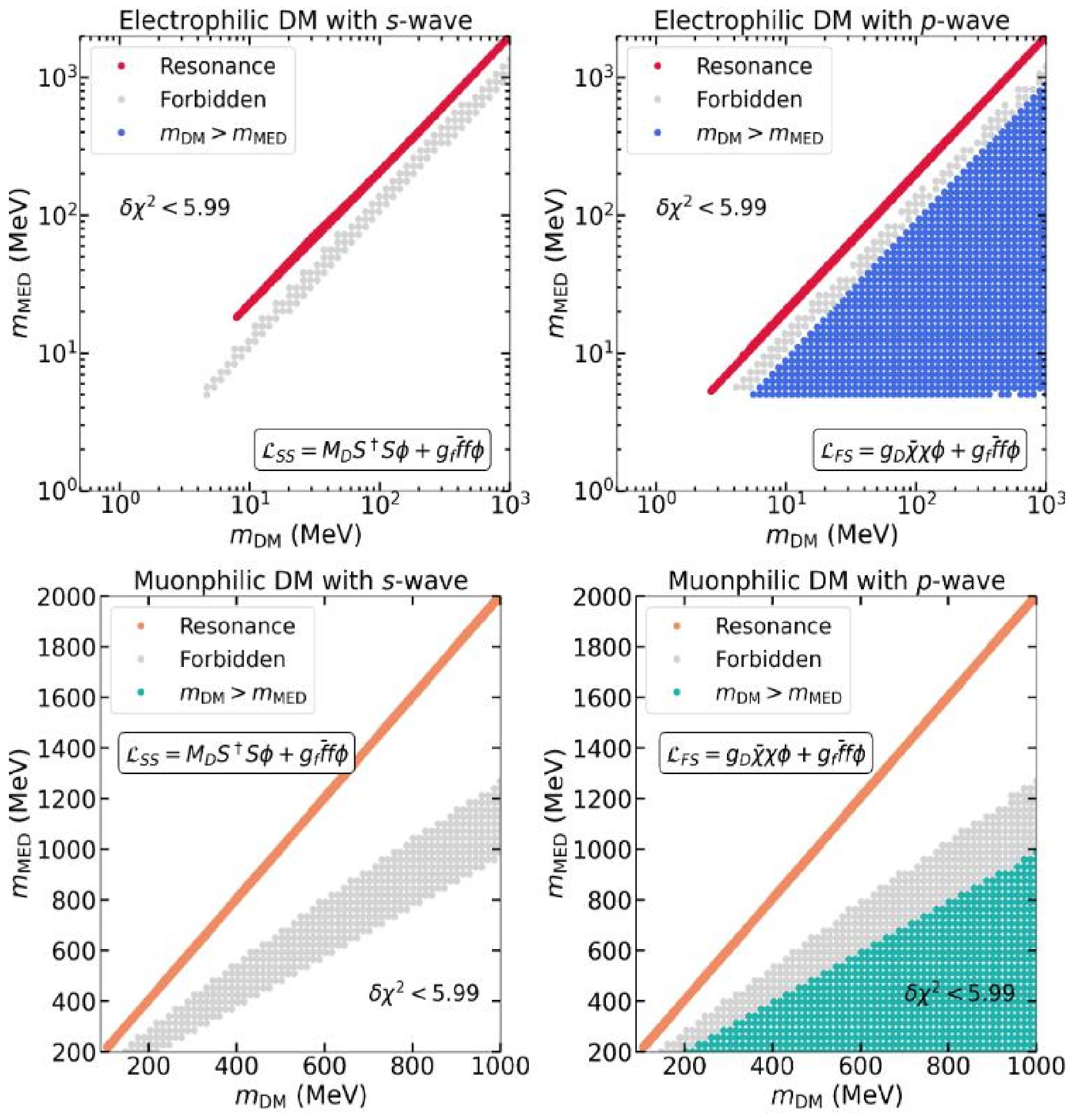




Direct detection.

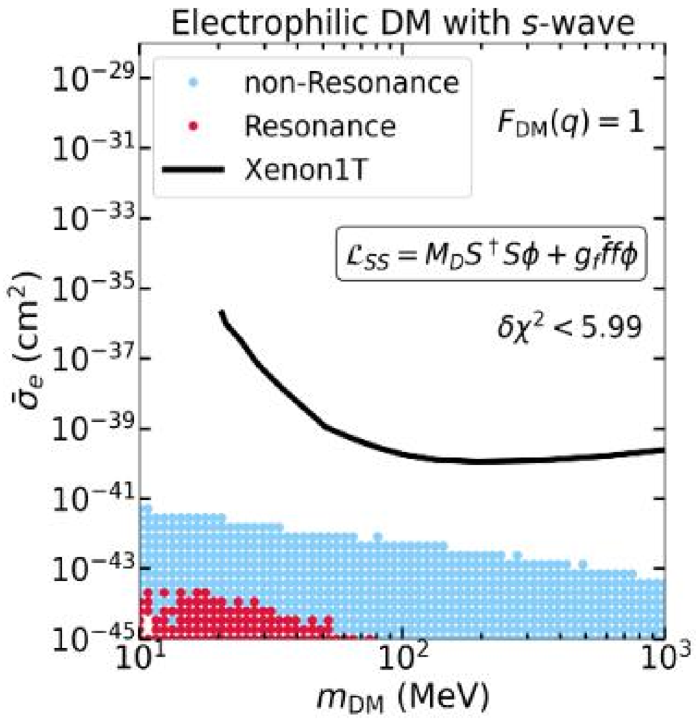
SM+ Z_2-odd DM+ Z_2-even mediator.

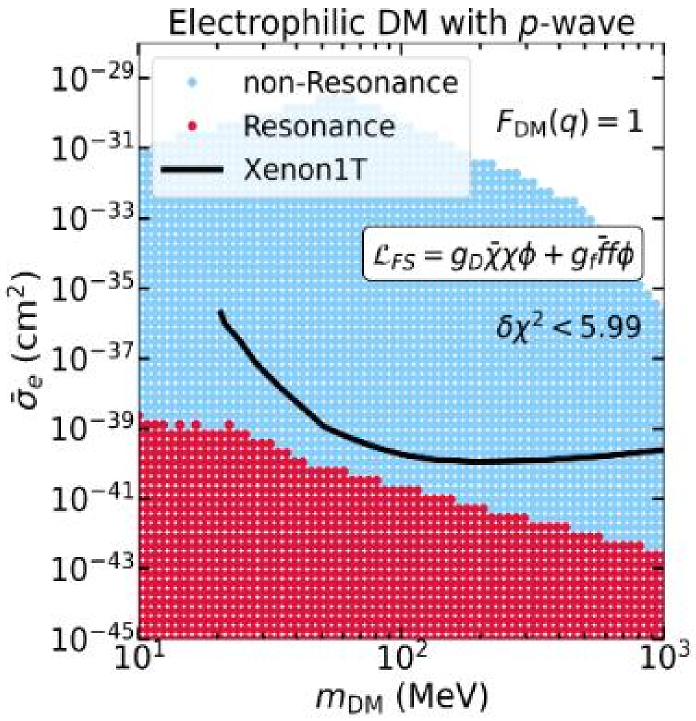
Allowed parameter space

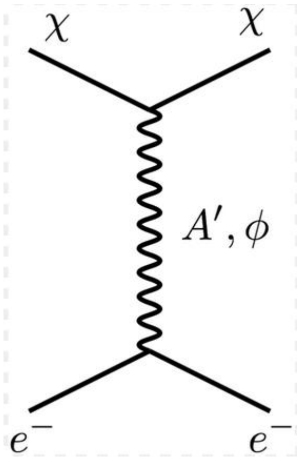


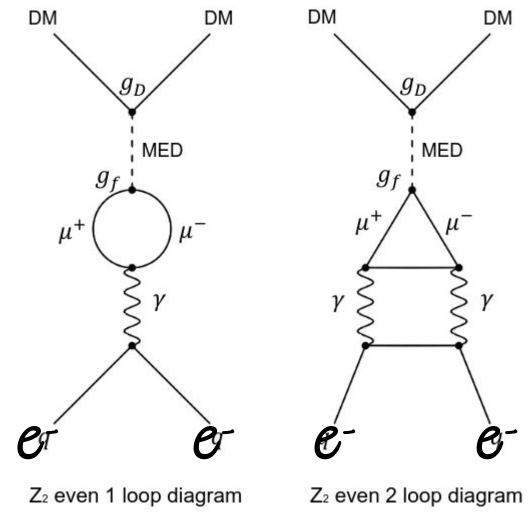
- Only resonance, forbidden, and secluded annihilation mechanisms remain.
- Secluded DM with s-wave annihilation is completely excluded.
- The lower mass limits for DM vary between the three mechanisms.

DM-electron scattering









- In the electrophilic case, direct detection experiments impose strong constraints on **the non-resonance parameter space** due to tree-level DM-electron scattering.
- However, VLAST can effectively probe the resonance region that escapes these bounds.

Light thermal dark matter in minimal Higgs portal model

Basic and minimum Lagrangian

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

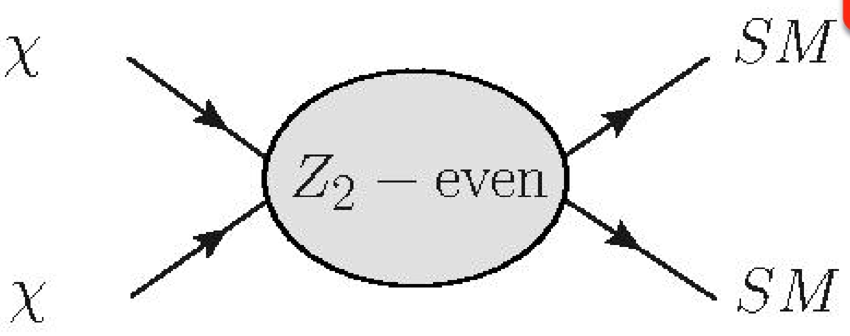
Majorana DM

SM singlet scalar

Scalar interaction

pseudo-scalar interaction

Mixing between New mediator and SM Higgs.



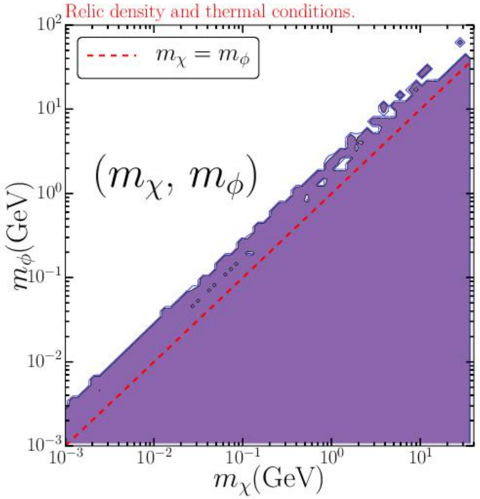
$$\mathscr{L}_{\rm int} \supset -\frac{\cos\theta}{2}(c_s\phi\bar{\chi}\chi + c_p\phi\bar{\chi}i\gamma_5\chi) + \frac{\sin\theta}{2}(c_s h\bar{\chi}\chi + c_p h\bar{\chi}i\gamma_5\chi).$$

A minimum setup:
one SM singlet Majorana DM + one SM singlet scalar mediator.

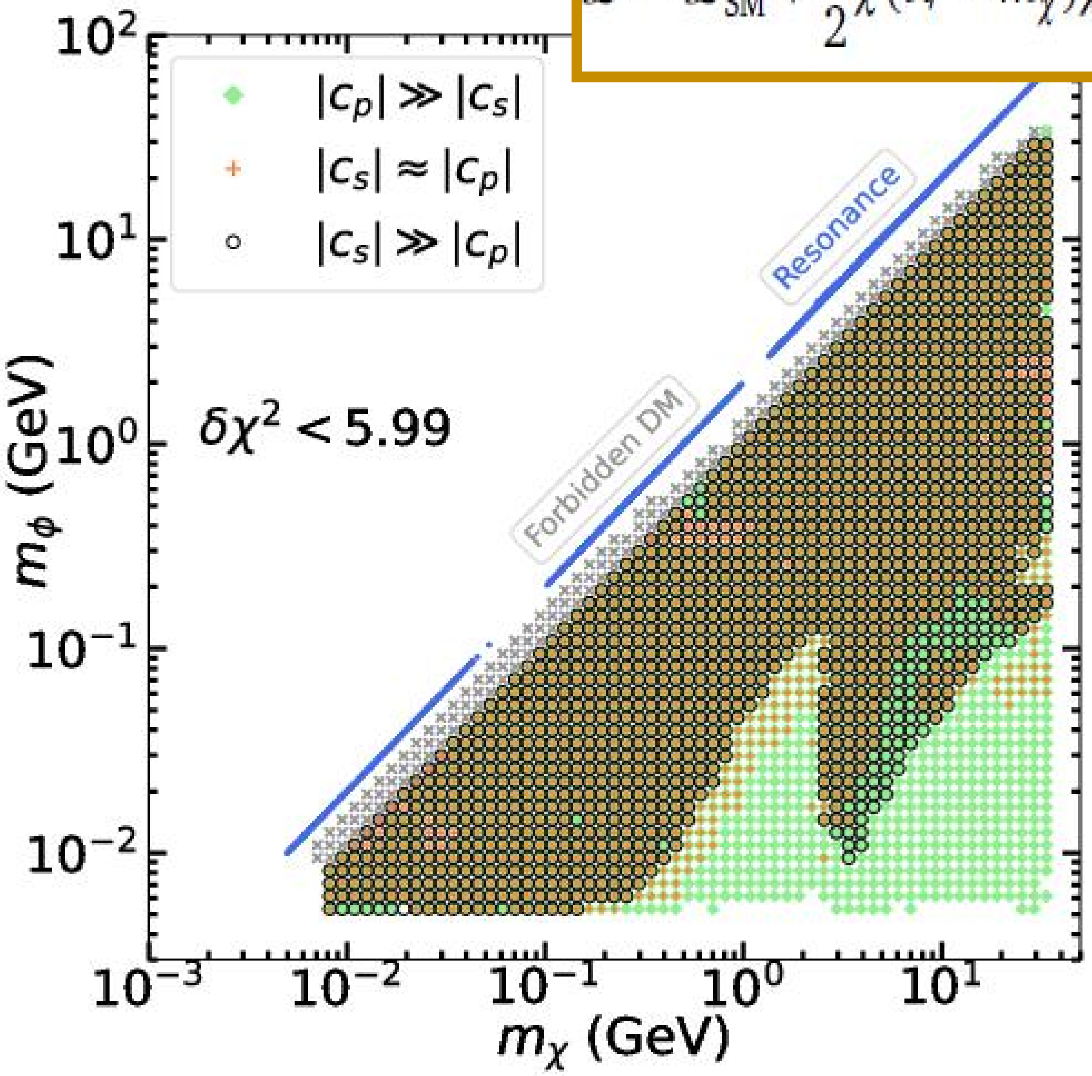
Possible parameter space

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

The unitarity, stability, and perturbative constraints.

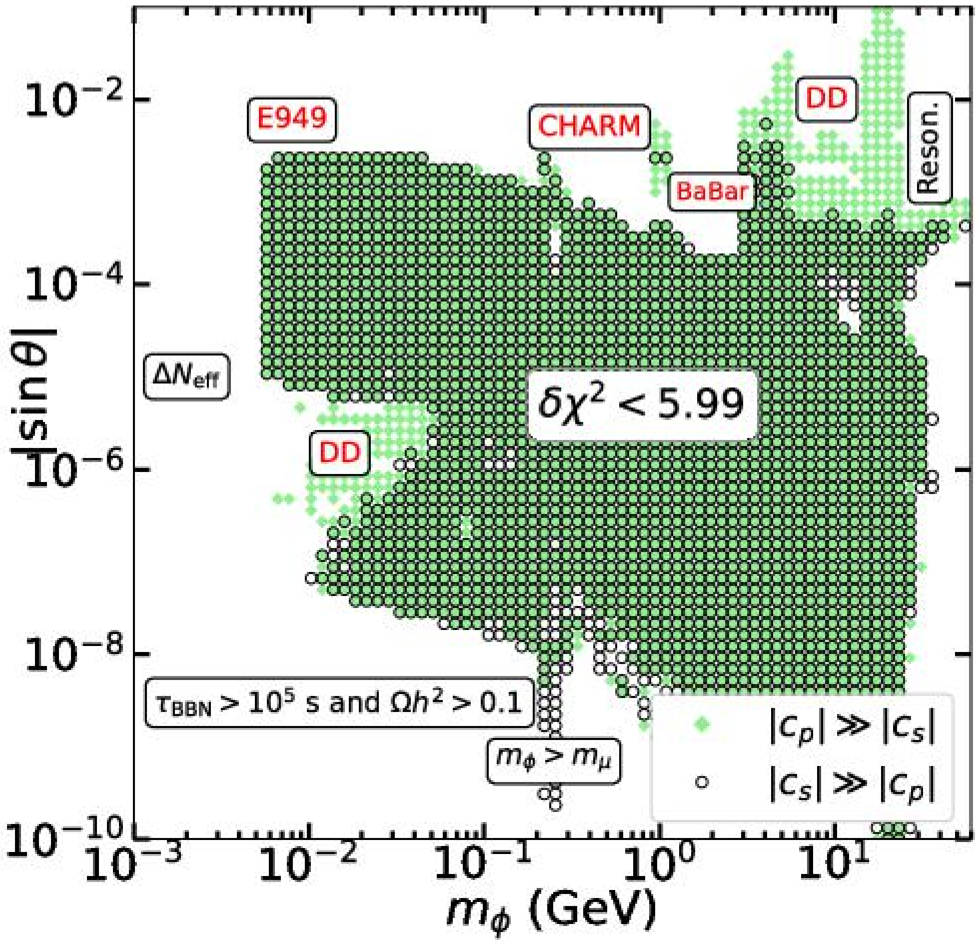


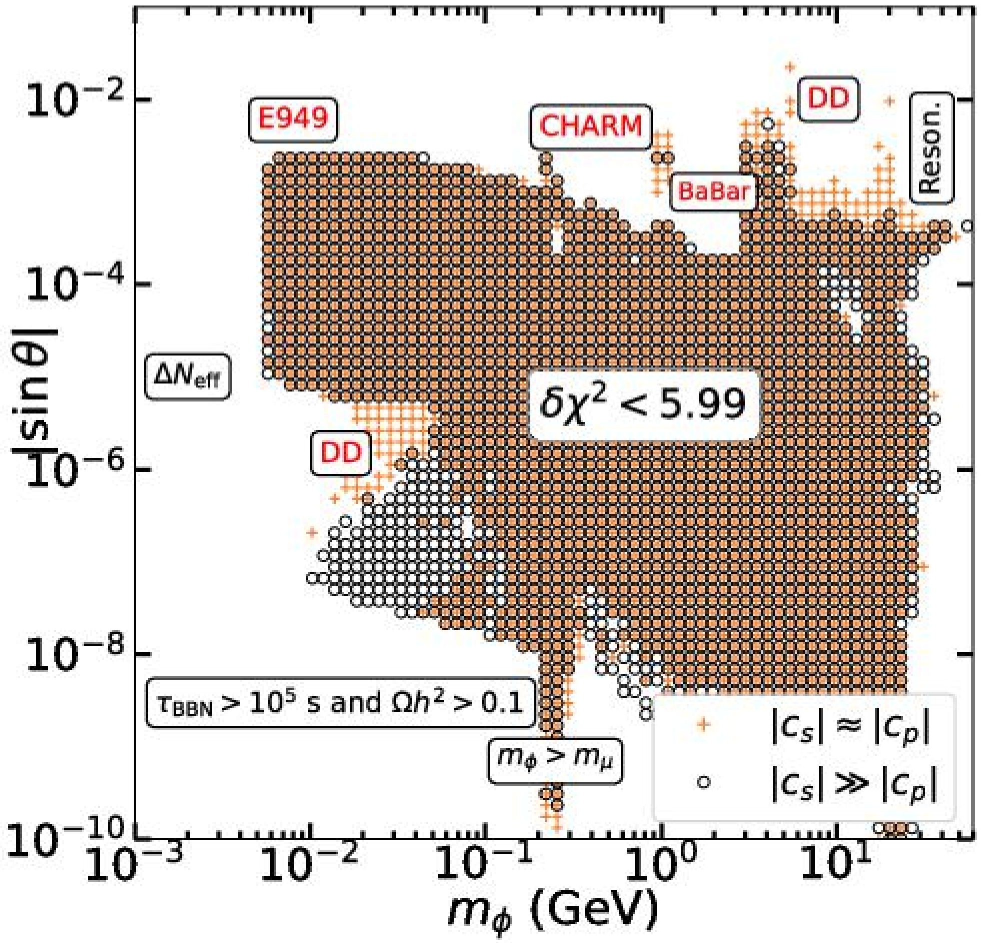
$$
\begin{aligned}
1\ \text{MeV} \le\ & m_\chi \le 30\,\text{GeV},\\
-1 \le\ & c_p \le 1,\\
-1 \le\ & c_s \le 1,\\
1\ \text{MeV} \le\ & m_\phi \le 60\,\text{GeV},\\
-\pi/6 \le\ & \theta \le \pi/6,\\
-1\,\text{TeV}^2 \le\ & \mu_\Phi^2 \le 1\,\text{TeV}^2,\\
-1\,\text{TeV} \le\ & \mu_3 \le 1\,\text{TeV},\\
-1 \le\ & \lambda_\Phi \le 1.
\end{aligned}
$$



	ϕ signature	Constraints
Higgs decay	Prompt*	See the upper limits of BR($h \to \phi\phi$)BR($\phi \to ll$)^2 from Fig. 12 of Ref. [99] and Fig. 7 of Ref. [100].
	Displaced*	See Ref. [101, 102]
	Long-lived*	BR($h \to$ inv.)$_{\rm BSM} \le 0.145$ [103]
B decay	Prompt	BR($B^\pm \to K^\pm\mu^-\mu^+$) $\lesssim 3\times10^{-7}$ [104]
	Displaced	(1) $\sin^2\theta \gtrsim 2\times10^{-8}$ for the region $0.5 < m_\phi/$ GeV < 1.5 and $1 < c\tau_\phi/$cm < 20 [105] (2) See Fig. 5 of Ref. [106] for details.
	Long-lived*	P_p BR($B^\pm \to K^\pm\nu\bar{\nu}$) $= (2.3\pm0.7)\times10^{-5}$ [107]
Kaon decay	Prompt	(1) BR($K^+ \to \pi^+\mu^-\mu^+$) $\le 4\times10^{-8}$ [108] (2) BR($K_L \to \pi^0 e^- e^+$) $\lesssim 2.8\times10^{-10}$ [109] (3) BR($K_L \to \pi^0\mu^-\mu^+$) $\lesssim 3\times10^{-10}$ [110]
	Displaced	CHARM detected events $\gtrsim 2.3$ [111]
	Long-lived*	(1) BR($K_L \to \pi^0\nu\bar{\nu}$) $\le 3.0\times10^{-9}$[112] (2) See BR($K^+ \to \pi^+\nu\bar{\nu}$) limits from Fig. 18 of Ref. [113] and Fig. 4 of Ref. [114] for details.

Possible parameter space





Parameter space is finite and we may be able to probe them ALL!

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- [ ] Parameter space to be detected in gamma-ray telescope (VLAST).
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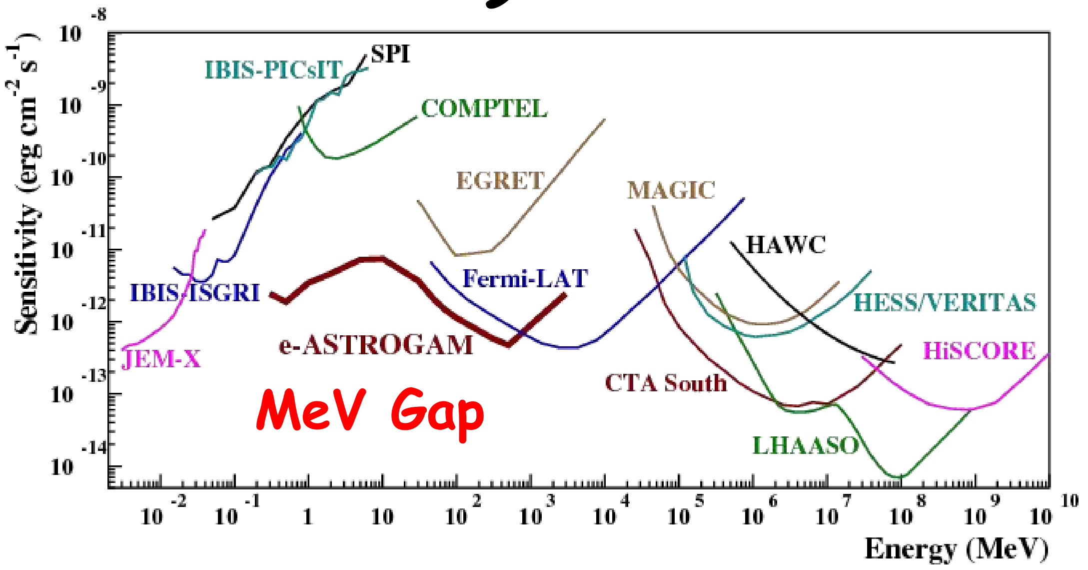
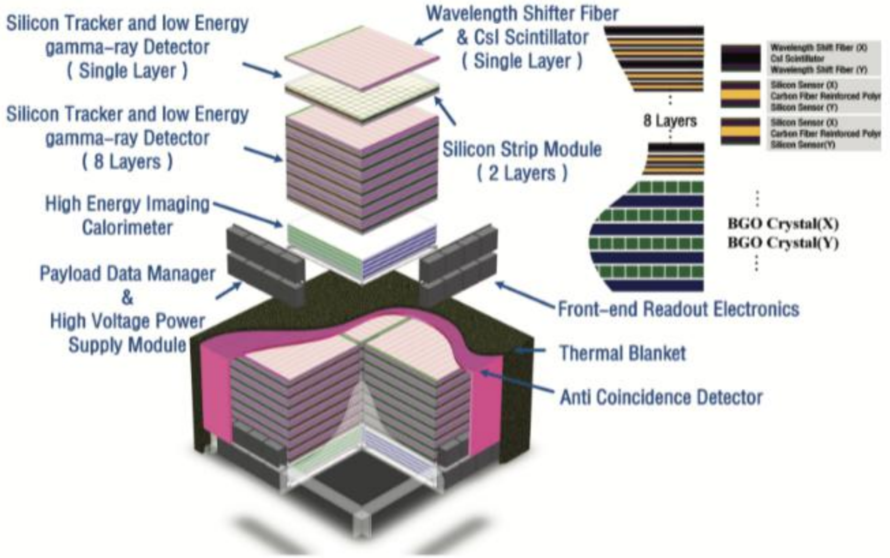


VLAST-closing the MeV gap



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甚大面积伽马射线空间望远镜计划*

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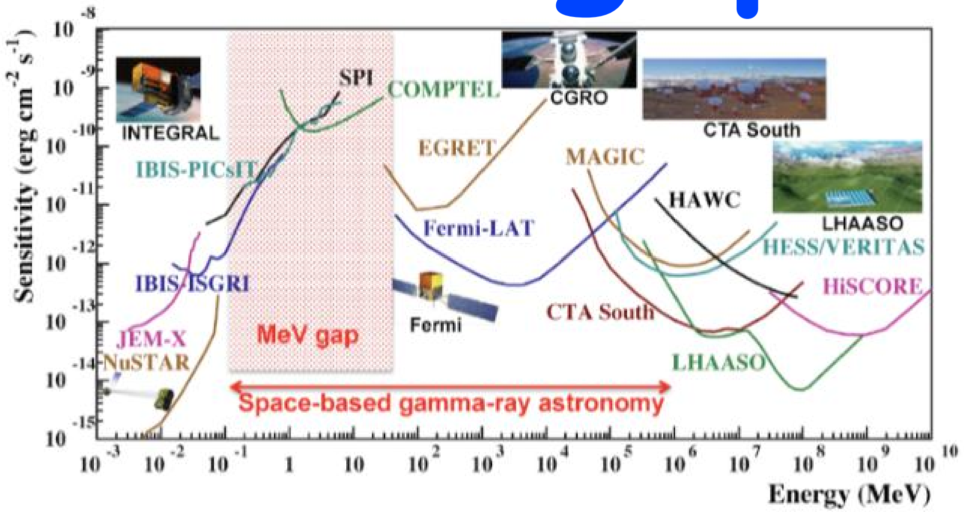
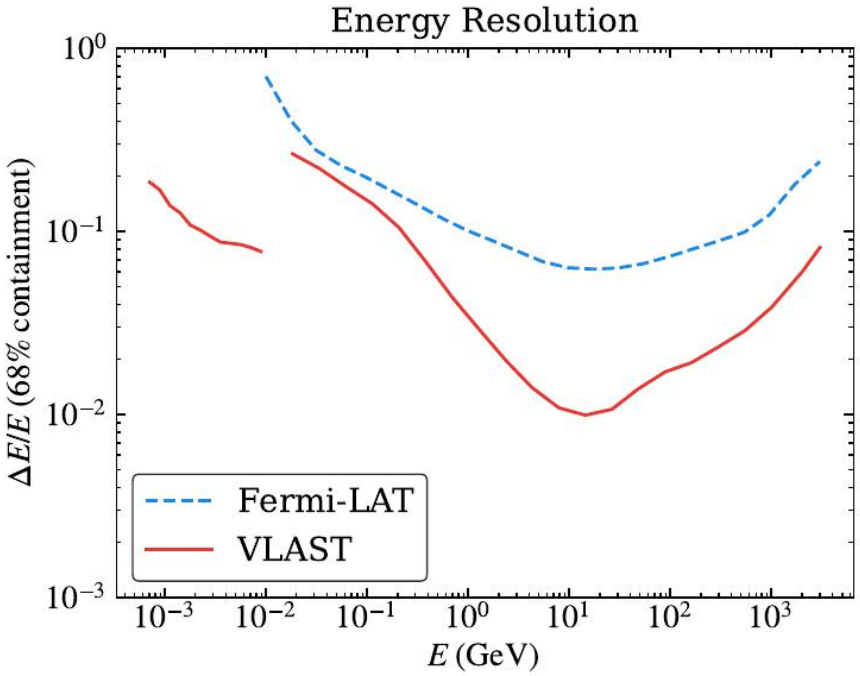
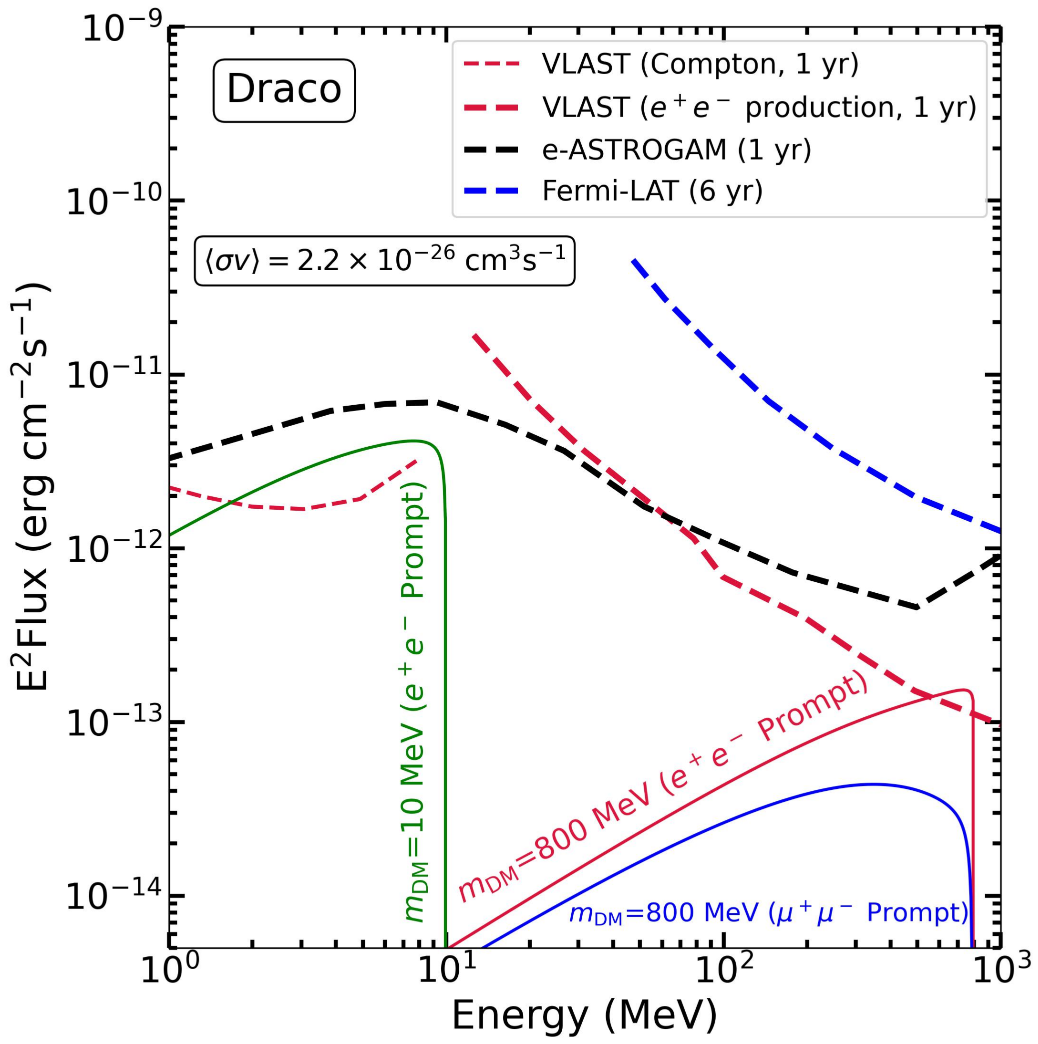
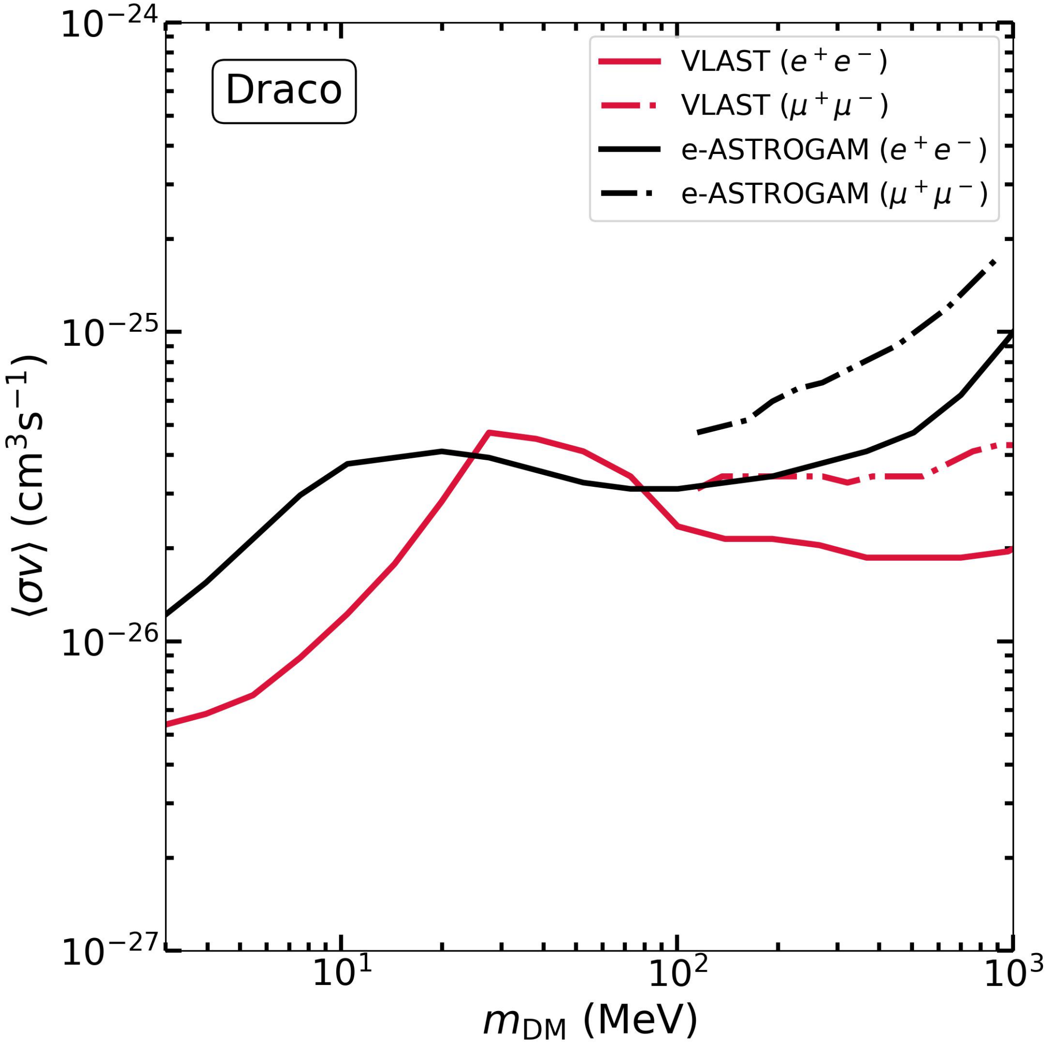




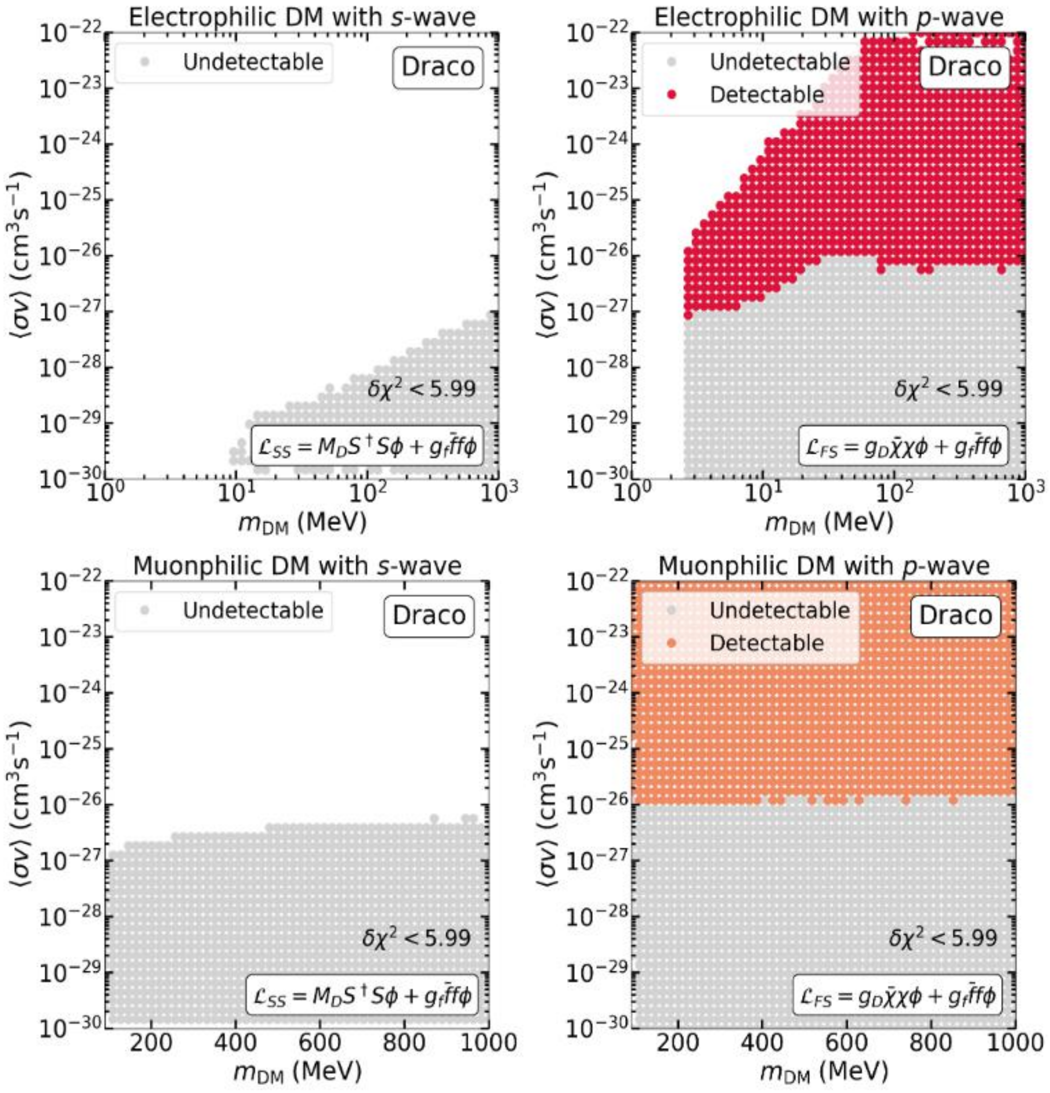
- Very Large Area gamma-ray Space Telescope (VLAST), the successor of DAMPE
- The first 10 m^2 sr level gamma-ray satellite (~20 tons)
- Leading the research on dark matter detection and time-domain astronomy based on MeV - TeV gamma-rays

Very Large Area Space Telescope (VLAST)





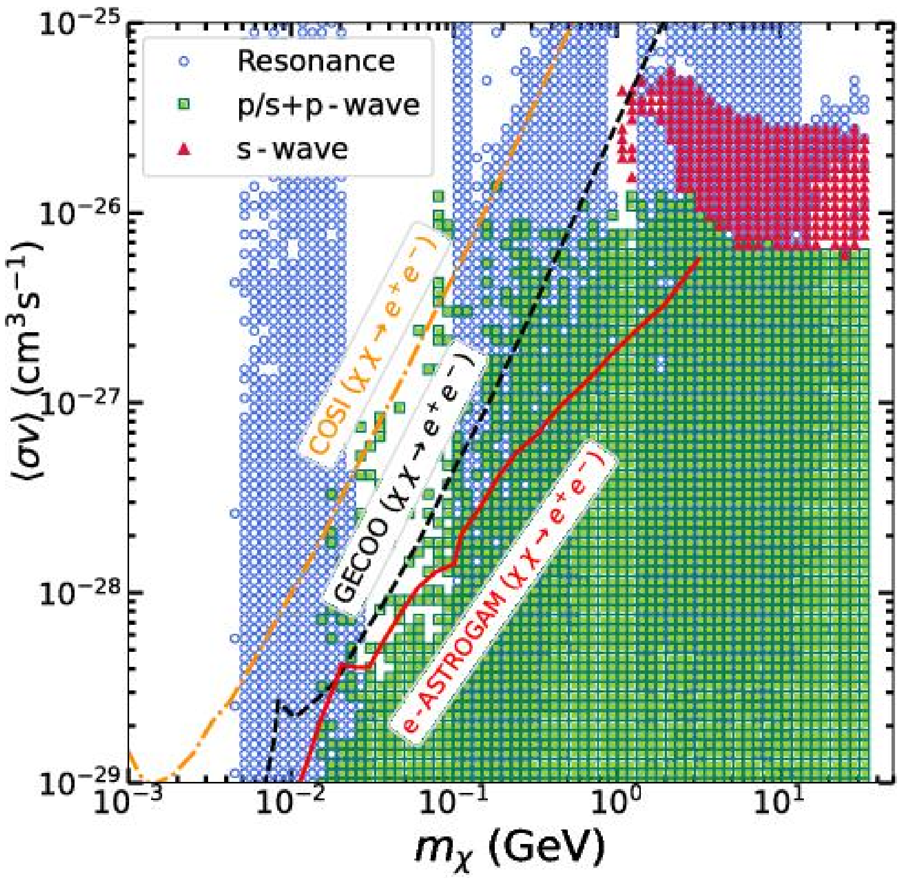
PROBING RESONANCE REGION BY VLAST (Leptonphilic)

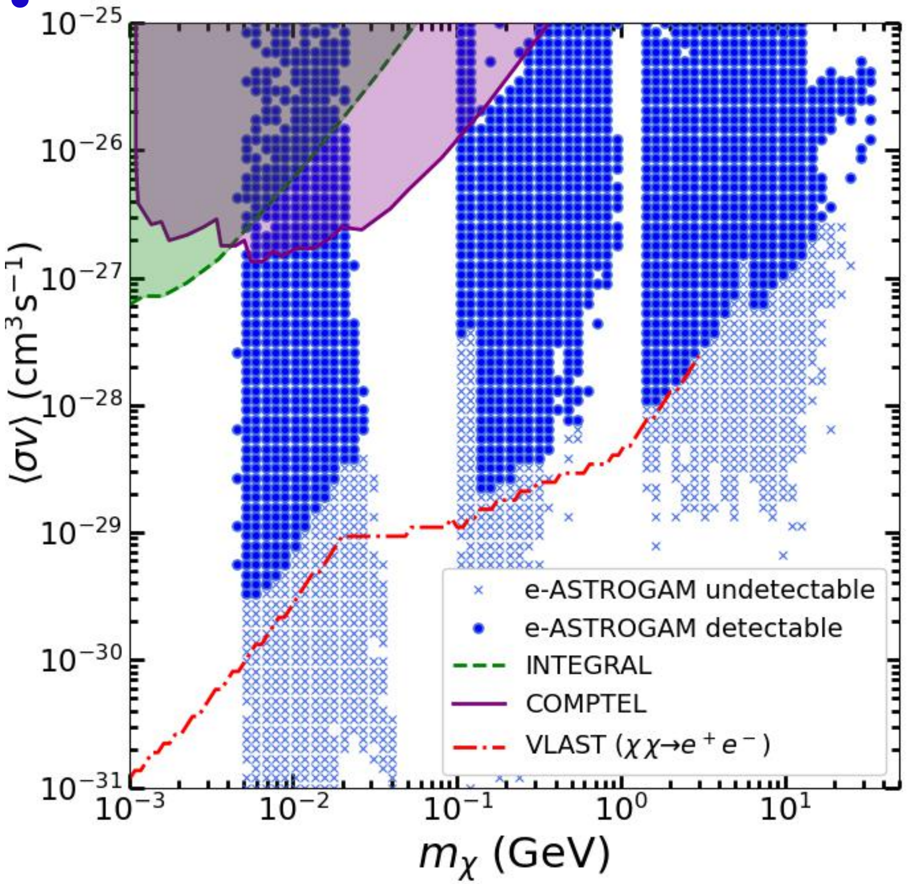


Property	Value	Notes
Distance	$\sim 76kpc$	From the Sun.
Stellar Mass (M_*)	$\sim 3 \times 10^5\ M_\odot$	Baryonic mass in stars.
Dynamical Mass (M_{dyn})	$\sim 5 \times 10^8\ M_\odot$	Total mass (stars + dark matter).
J-factor ($0.5°$)	$\sim 10^{18.9} GeV^2 cm^{-5}$	Dark matter annihilation luminosity.
Mass-to-Light Ratio (Υ)	$\sim 1000\ M_\odot / L_\odot$	Indicator of extreme dark matter dominance.

- Draco is an ideal source for DM gamma-ray detection.
- *s*-wave annihilation remains difficult to detect with future VLAST.

PROBING RESONANCE REGION BY VLAST (Higgs portal model)



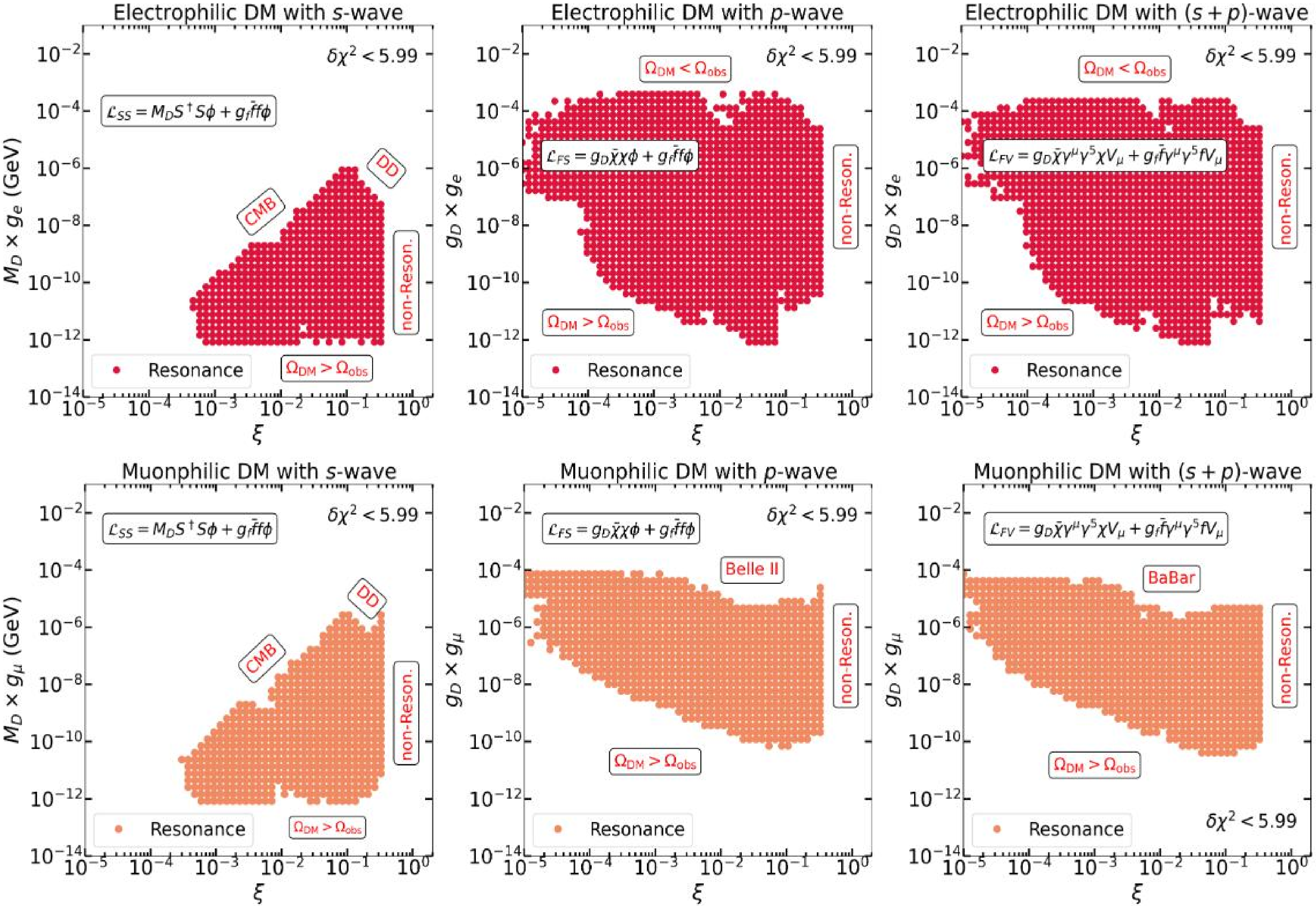


Future DM indirect detection (like VLAST) can probe resonance DM.

Summary

- The light thermal DM has a lower mass limit around MeV.
- Direct detection can also constrain the low mass mediator mass region, but pseudoscalar can relax this tension.
- Pseudoscalar can generate *s*-wave annihilation which is testable in indirect detection.
- Considering CMB constraints, most of *s*-wave annihilation with mass below GeV is excluded, while the resonance for *p*-wave annihilations are still testable in future MeV gamma ray telescopes, e.g. VLAST.

Thank you for listening and please stay on VLAST!


Electrophilic DM with s-wave
$\delta\chi^2 < 5.99$
$\mathcal{L}_{SS} = M_D S^\dagger S\phi + g_f \bar{f} f \phi$
CMB
DD
non-Reson.
Resonance
$\Omega_{DM} > \Omega_{obs}$
$M_D \times g_e$ (GeV)
ξ
Electrophilic DM with p-wave
$\delta\chi^2 < 5.99$
$\Omega_{DM} < \Omega_{obs}$
$\mathcal{L}_{FS} = g_D \bar{\chi}\chi\phi + g_f \bar{f} f \phi$
non-Reson.
$\Omega_{DM} > \Omega_{obs}$
Resonance
$g_D \times g_e$
ξ
Electrophilic DM with $(s+p)$-wave
$\delta\chi^2 < 5.99$
$\Omega_{DM} < \Omega_{obs}$
$\mathcal{L}_{FV} = g_D \bar{\chi}\gamma^\mu\gamma^5\chi V_\mu + g_f \bar{f}\gamma^\mu\gamma^5 f V_\mu$
non-Reson.
$\Omega_{DM} > \Omega_{obs}$
Resonance
$g_D \times g_e$
ξ
Muonphilic DM with s-wave
$\delta\chi^2 < 5.99$
$\mathcal{L}_{SS} = M_D S^\dagger S\phi + g_f \bar{f} f \phi$
DD
CMB
non-Reson.
Resonance
$\Omega_{DM} > \Omega_{obs}$
$M_D \times g_\mu$ (GeV)
ξ
Muonphilic DM with p-wave
$\delta\chi^2 < 5.99$
$\mathcal{L}_{FS} = g_D \bar{\chi}\chi\phi + g_f \bar{f} f \phi$
Belle II
non-Reson.
$\Omega_{DM} > \Omega_{obs}$
Resonance
$g_D \times g_\mu$
ξ
Muonphilic DM with $(s+p)$-wave
$\mathcal{L}_{FV} = g_D \bar{\chi}\gamma^\mu\gamma^5\chi V_\mu + g_f \bar{f}\gamma^\mu\gamma^5 f V_\mu$
BaBar
non-Reson.
$\Omega_{DM} > \Omega_{obs}$
Resonance
$\delta\chi^2 < 5.99$
$g_D \times g_\mu$
ξ