Indirect Detection of the Lightest WIMP

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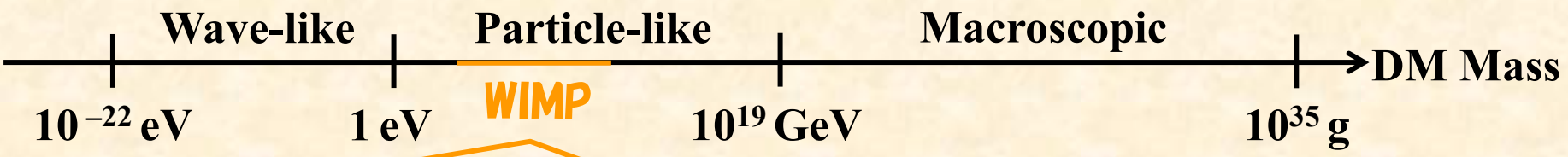
Yuki Watanabe and members of the COSI DM group.

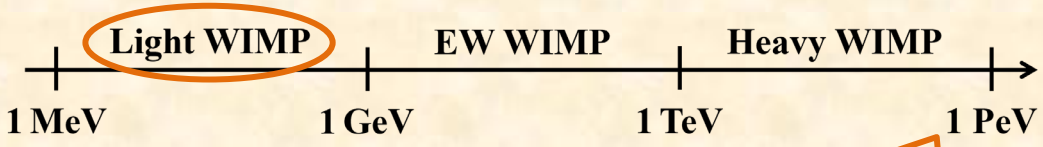
- ✓ The Lightest WIMP Among Dark Matter Candidates
- ✓ Experimental Searches: Direct, Indirect, and Collider Probes
- ✓ Theoretical and Cosmological Perspectives
- ✓ Future Prospects for Indirect Detection
- ✓ Conclusion and Outlook

Lightest WIMP among DM candidates



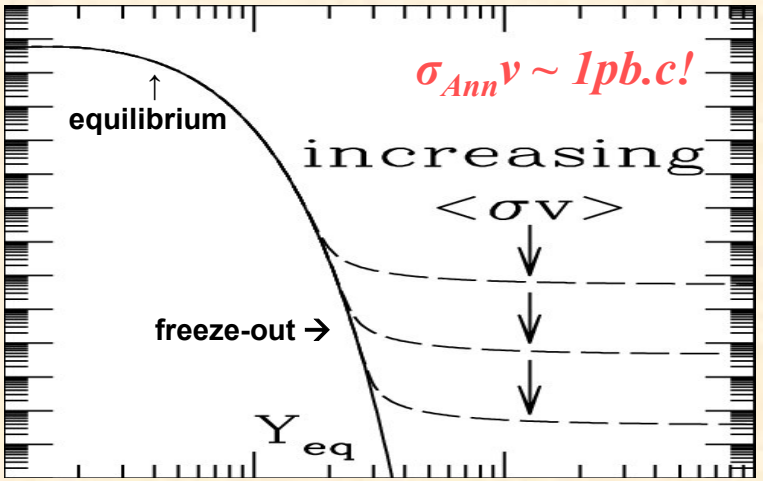
The WIMP was in thermal equilibrium with SM particles in the early U.
→ Free from the initial condition problem of the DM abundance.
The abundance is determined by the well-established freeze-out.
It can be detected via the interaction used for the equilibrium.
WIMP is predicted by various BMSs (SUSY, GUT, Hidden sector, etc.).

We focus on light WIMP!



Unitality limit on (σv)

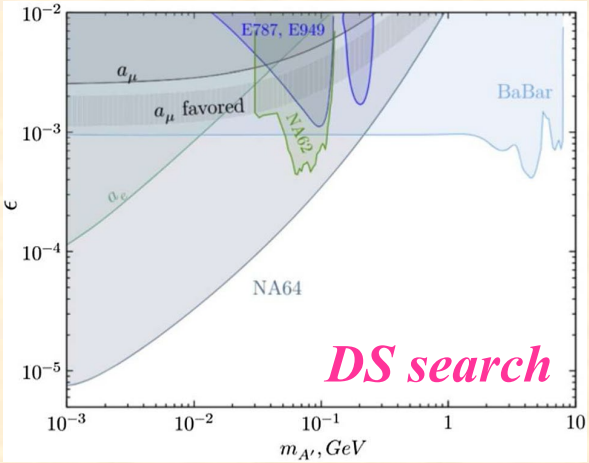
Consistency with cosmology



Experimental searches for light WIMP

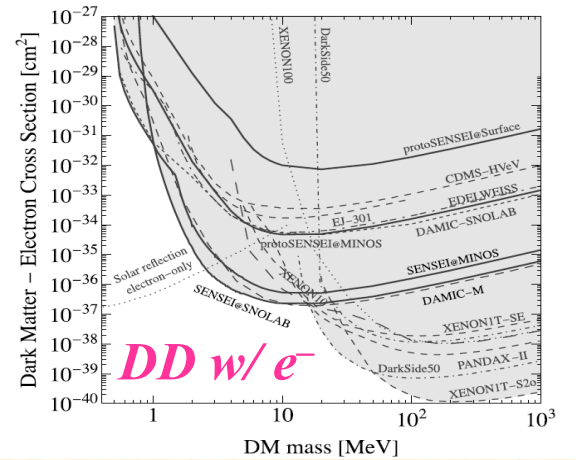
✓ Strategy of the light WIMP search

@ Accelerator exps.



[D. Banerjee, V. E. Burtsev, et al, 2019]

@ Underground labs.



[Rouven Essig, 2024]

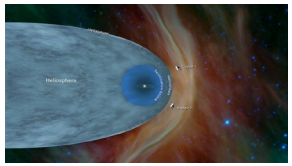
@ Astrophysical obs.

DM + DM → γ, e, ν

ν: Various ν detectors.

e: Heliosphere prevents.

[Voyager can, when m_{DM} > 10 MeV.]

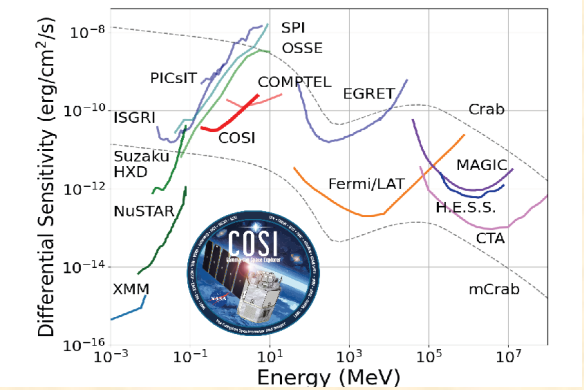


γ: MeV gap (→ See below)

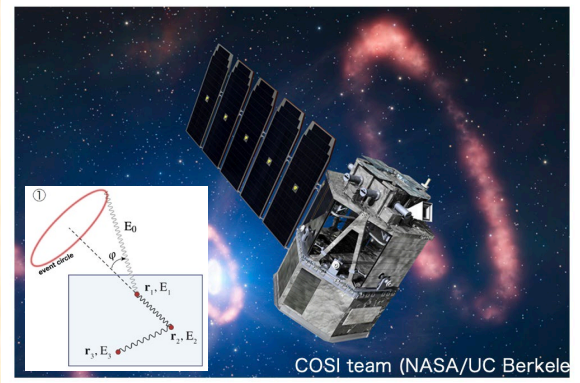
[M. Boudaud, J. Lavalle, P. Salati, 2016]

✓ MeV gamma-ray observatory, COSI, will be launched in 2027

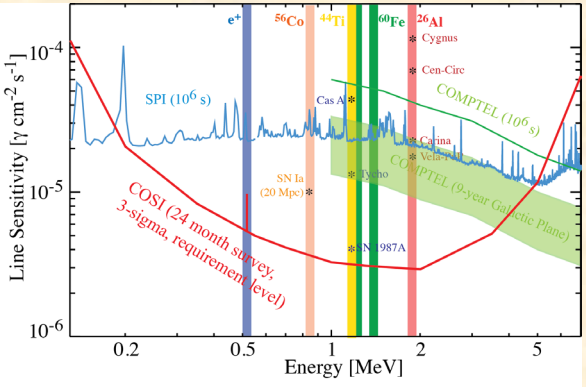
Continuum sensitivity



COSI satellite



Line sensitivity



Theoretical & cosmological perspectives

✓ Theory

Light & Singlet

Dark Matter — Mediator — Standard Model

Singlet

No direct coupling

Exception: Yuji's & Johannes's talks.

✓ Cosmology

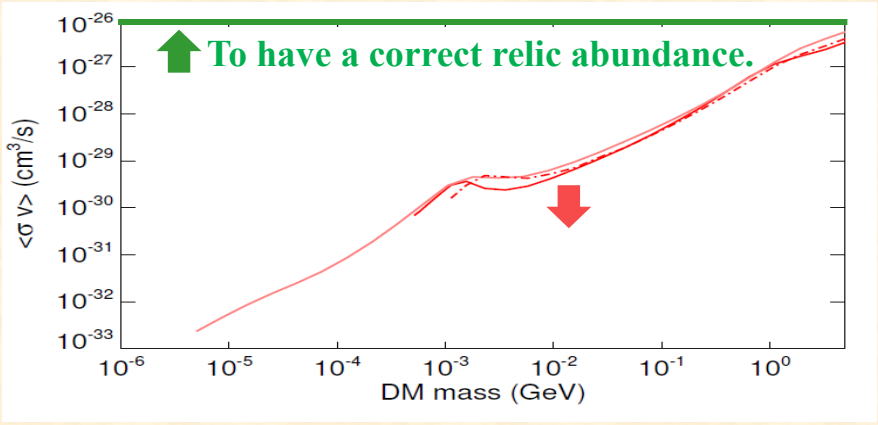
$\therefore m_{WIMP} > O(1)$ MeV.

Photo-dissociation

Light WIMP

CMB | BBN | ν-decoupling | T

2.7K | 3000K | 0.1MeV | 2MeV | (1eV=10^4K)

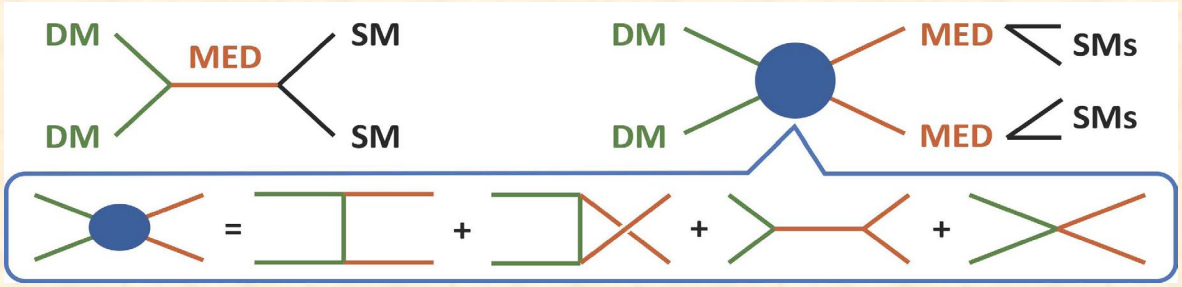


[M. Kawasaki, K. Nakayama, et al, 2010, 2015, 2021]
[Tracy R. Slatyer, PRD93, 2016]

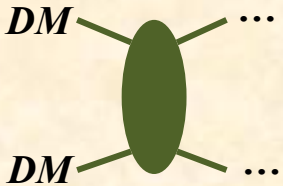
- ✓ WIMP has a velocity-dependent annihilation cross-section @ NR.
- ✓ WIMP annihilates into harmless particles, namely neutrinos.
- ✓ Relic abundance is determined by another process rather than ann.
- ✓ Taking non-standard cosmology.

Velocity-dependent scenario

Thanks to ∃Mediator, the velocity dependence @ NR is realized!

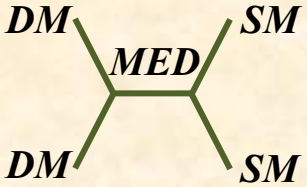


p-wave



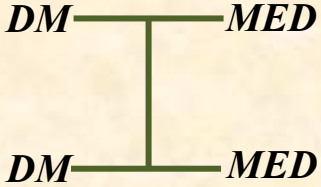
$\sigma v \propto v^2$

Resonance

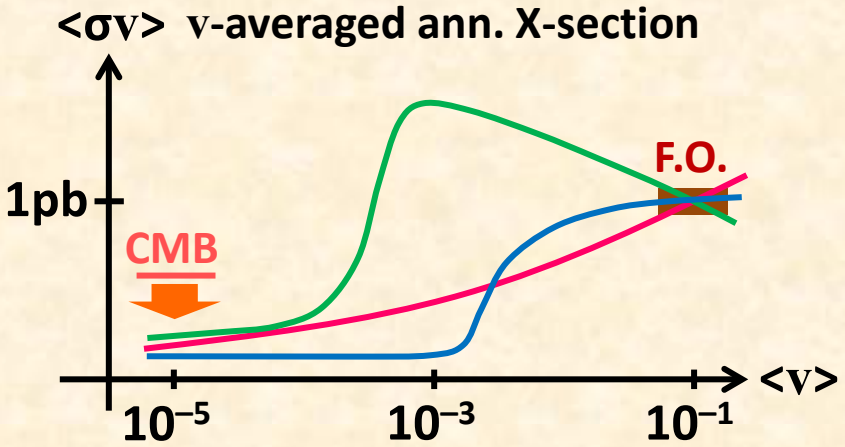


$2m_{DM} \sim m_{MED}$

Forbidden

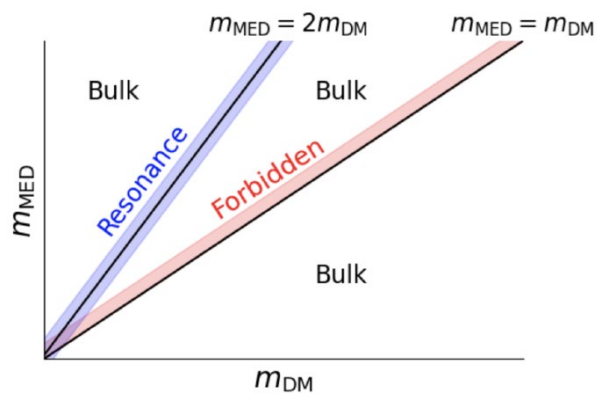


$m_{DM} \lesssim m_{MED}$



	Scalar mediator	"Dark photon" mediator	$U(1)_B$ mediator
Scalar WIMP	SS	SV	SV(B)
Fermionic WIMP	FS	FV	FV(B)

∋



Constructing $\mathcal{L}$ & Putting constraints.

∃Viable parameter space? ∃Signal @ COSI?

Velocity-dependent scenario

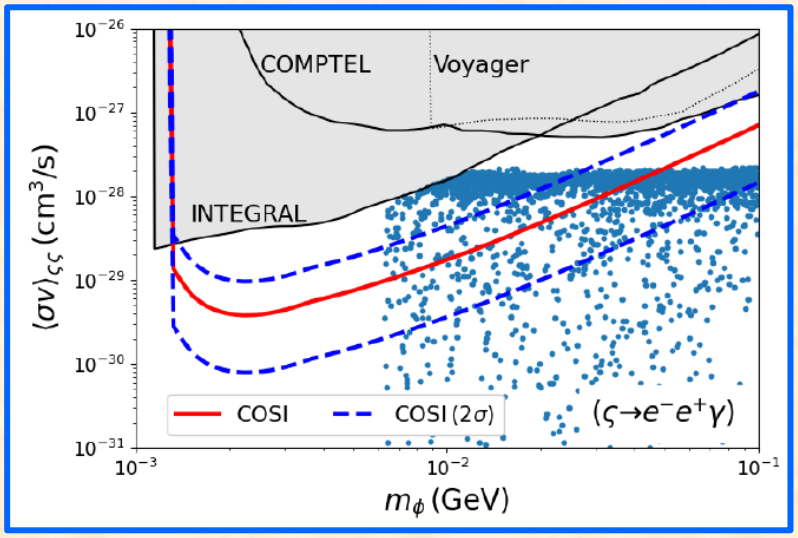
✓ ∃ Viable parameter space?

	Bulk	Resonance ($\delta > 0$)	Resonance ($\delta < 0$)	Forbidden
SS	N/A	No viable region	No viable region	◎
FS	Weak	No viable region	No viable region	Weak
SV	Weak	○	◎	◎
FV	N/A	○	No viable region	Weak
SV(B)	–	✓	No viable region	–
FV(B)	–	✓	No viable region	–

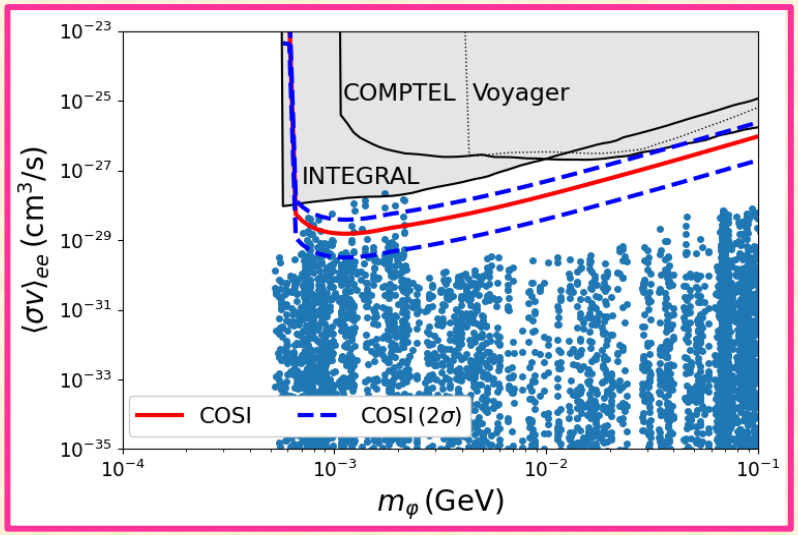
✓ ∃ Signal @ COSI?

The accelerator and direct detection searches are not good at exploring resonance and forbidden scenarios.

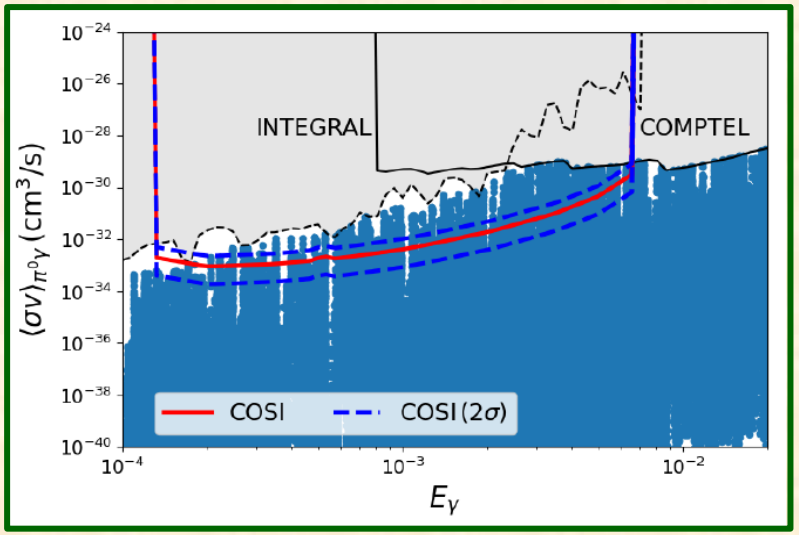
SS-F: ϕϕ → ςς & ς → $e^-e^+\gamma$



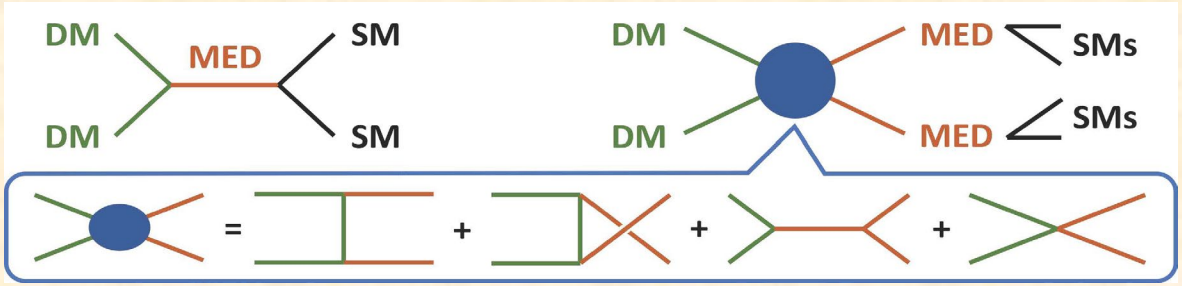
SV-R: ϕϕ → Z' → $e^-e^+\gamma$



FV(B)-R: χχ → $\pi^0\gamma$



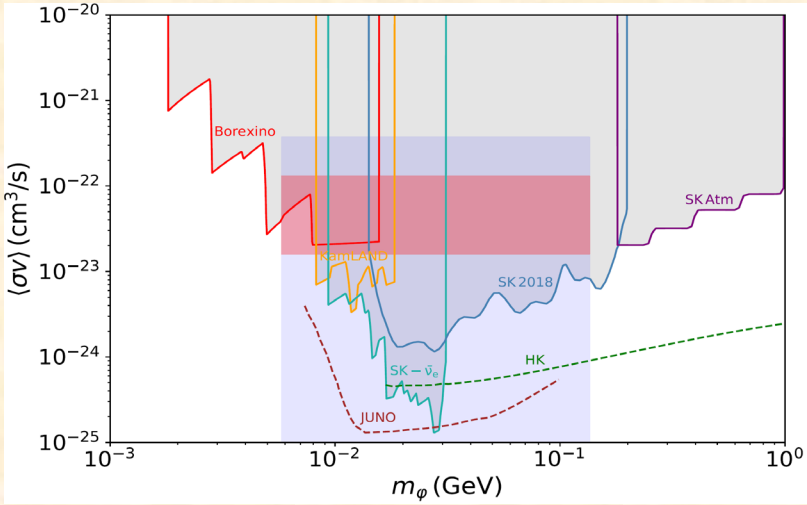
Neutrinophilic scenario



Existence of a mediator connecting DM only with νs at the low scale.
This is not trivial because ν is in a lepton doublet $L=(\nu, e)^T$ in the SM.

- ✓ **Majoron-type scalar mediator**
  $\phi LHLH$ with $\langle\phi\rangle=0$ type int.
  [N. Bell, M. Dolan, A. Ghosh, M. Virgato, 2025.]
- ✓ **$U(1)_{L_\mu - L_\tau}$ gauge boson 〃**
  Z' does not couple to $e^\pm$.
  [P. Foldenauer, PRD 2019, arXiv:1808.03647.]
- ✓ **$U(1)_{B-L+xY}$ gauge boson 〃**
  New U(1) mixed with G_{SM}.
  [T. Aonashi, S.M., Y. Watanabe, et al, 2025(exp).]

Z' does not couple both to e & p.
→ Difficult to detect at DD & COL.



Summary

We have discussed the lightest WIMP, whose mass is of O(1-10)MeV.

- ✓ The lightest WIMP requires a mediator that connects the WIMP to SM particles. Moreover, its mass and interactions are constrained by cosmological observations, leading to four viable possibilities, such as velocity-dependent or neutrinophilic WIMP.

- ✓ The lightest WIMP annihilates and produces MeV gamma rays in space, a signal that has not been extensively explored due to observational challenges. Recent technological developments make it possible to probe this energy range, and the velocity-dependent WIMP will be explored, notably by the upcoming COSI observation.

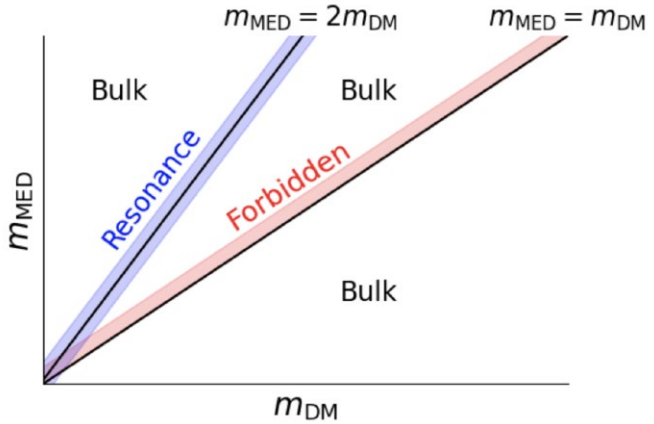
- ✓ A WIMP annihilating only into neutrinos, i.e., a neutrinophilic WIMP, evades the CMB bound on the annihilation cross-section. Realizing such a WIMP requires careful model-building, as the neutrino is part of an $SU(2)$ doublet with the electron. With couplings to protons often forbidden, neutrino-based detection is essential.

Buckup 1

O Comprehensive study of light WIMPs

	Scalar mediator	"Dark photon" mediator	$U(1)_B$ mediator
Scalar WIMP	**SS**	**SV**	**SV(B)**
Fermionic WIMP	**FS**	**FV**	**FV(B)**

	Bulk ("p-wave") region	Resonance region	Forbidden region
SS model	N/A	**SS-R**	**SS-F**
FS "	**FS-B**	**FS-R**	**FS-F**
SV "	**SV-B**	**SV-R**	**SV-F**
FV "	N/A	**FV-R**	**FV-F**
SV(B) "	–	**SV(B)-R**	–
FV(B) "	–	**FV(B)-R**	–



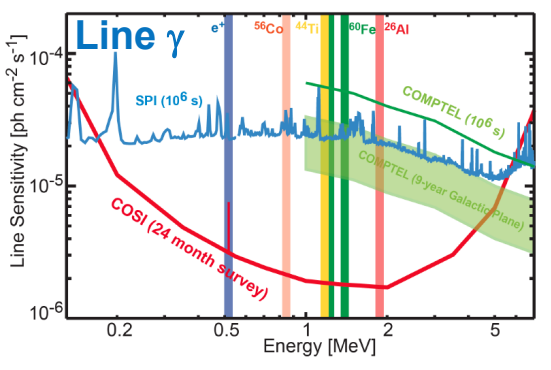
Lagrangian based on the minimality and renormalizability:

	Masses		DM-MED Int.		DM-SM Int.	MED-SM Int.		Self Int.		
SS-F	m_ϕ	v_{th}	$C_{\varsigma\phi\phi}$	$C_{\varsigma\varsigma\phi\phi}$	$C_{h\phi\phi}$	$\sin\theta$	$C_{\varsigma\varsigma h}$	λ_ϕ	$C_{\varsigma\varsigma\varsigma}$	λ_S
SV-F	m_φ	v_{th}	g_φ		$\lambda_{h\varphi\varphi}$	ξ		λ_φ		
SV-R	m_φ	δ	g_φ		$\lambda_{h\varphi\varphi}$	ξ		λ_φ		
FV-R	m_ψ	δ	g_ψ			ξ				
SV(B)-R	m_φ	δ	g_φ		$\lambda_{h\varphi\varphi}$	ξ	g_B	λ_φ		
FV(B)-R	m_ψ	δ	g_ψ			ξ	g_B			

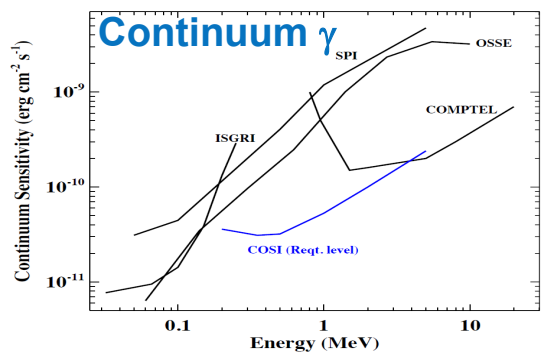
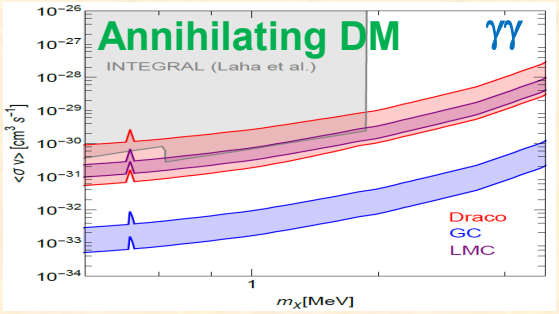
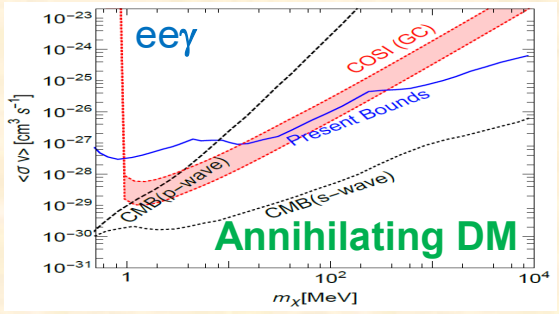
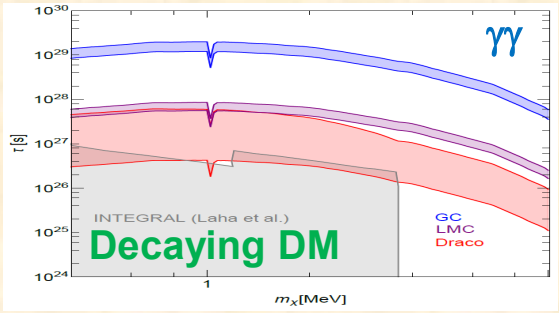
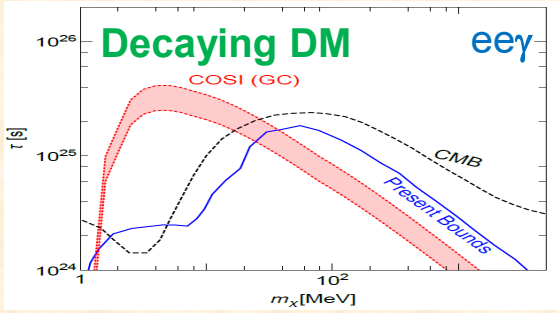
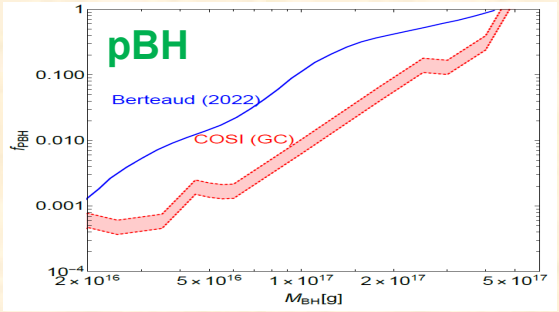
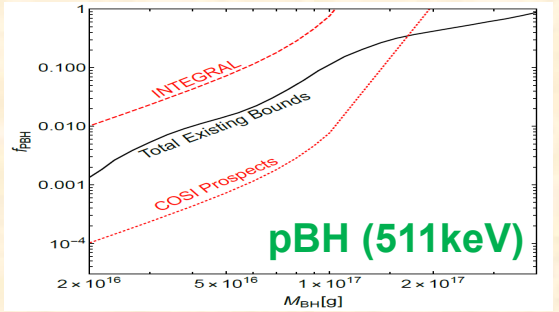
Likelihood analysis

	SS-R	FS-R	SV-R	FV-R	SV(B)-R	FV(B)-R	SS-F	FS-F	SV-F	FV-F
Relic abundance cond.	○	○	○	○	○	○	○	○	○	○
CMB & BBN on m_{DM}	○	○	○	○	○	○	○	○	○	○
CMB on $\langle\sigma v\rangle$	○	○	○	○	○	○	○	○	○	○
BBN on $\langle\sigma v\rangle$	○	○	○	○	○	○				
Accelerator detection	○	○	○	○	○	○	○	○	○	○
Indirect detection	○	○	○	○	○	○	○	○	○	○
Unitarity limit	○	○	○	○	○	○	○	○	○	○
Vacuum stability	○	○					○	○		

No regions for strong signals.



[J. A. Tomsick, et al., 2019]



[J. A. Tomsick, et al., 2023]