Indirect detection of sub-GeV dark matter

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Collaborators: T. Aonashi, T. Hayashi, Yu Watanabe,
Yuki Watanabe and members of the COSI DM group.

- ✓ Sub-GeV dark matter (light WIMP) among candidates.
- ✓ Experimental Searches: Direct, indirect, collider probes.
- ✓ Perspectives from theoretical and cosmological viewpoints.
- ✓ Future prospects for indirect Detection of light WIMPs.
- ✓ Summary

DM problem & What we Know about the DM

O The dark matter (DM) problem:

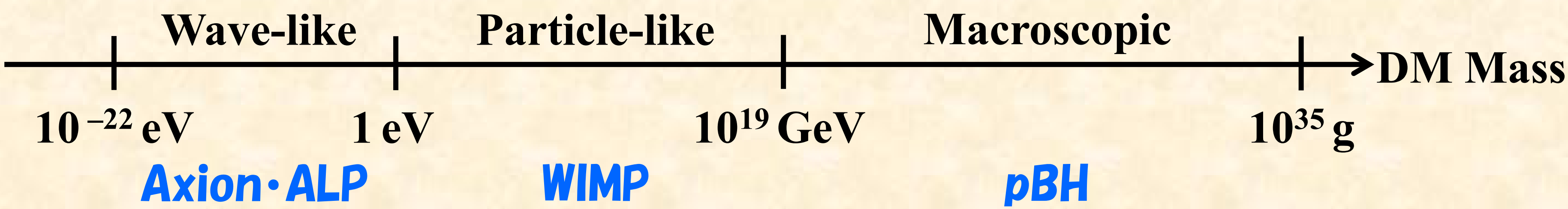
We Know that dark matter exists in our universe.
We Know how the DM is distributed in our universe.
We Know little about the microscopic nature of the DM.

O What we Know about the DM:

The DM must be (almost) electrically neutral.
The DM must be (enough) stable. (Its lifetime >> Age of U.)
The DM must be (enough) cold (non-relativistic) at present.
The DM must be (enough) weak-interacting.
The average mass density of the DM is 10^{-6} GeV/cm^3.
The mass of the DM must be between 10^{-22} eV and 10^{35} g.

$m_{DM} > 10^{-22}$ eV: λ_D(De Broglie W. L.) = $2\pi/(mv)$ < Galaxy size.
$m_{DM} < 10^{+35}$ g : DM must be lighter enough than a host galaxy.

Lightest WIMP among DM candidates



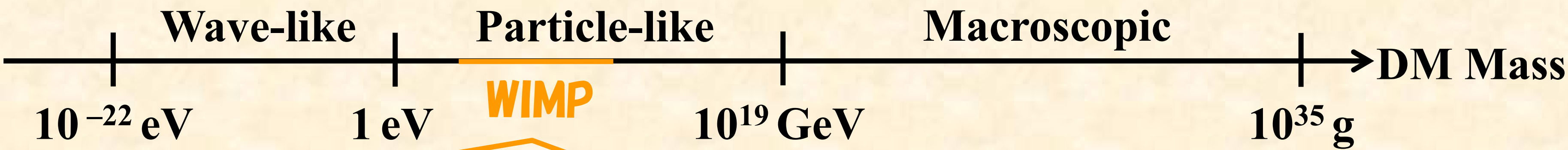
○ Three DM mass regions:

$m_{DM} < 10^{-1}$ eV: The occupation number of DM in a galaxy > O(1).

$m_{DM} > 10^{19}$GeV: DM cannot be a particle, $\lambda_C = 2\pi/m > r_S = 2m/m_{pl}^2$.

10^{-1} eV < m_{DM} < 10^{19}GeV: DM can be a particle in this region.

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.

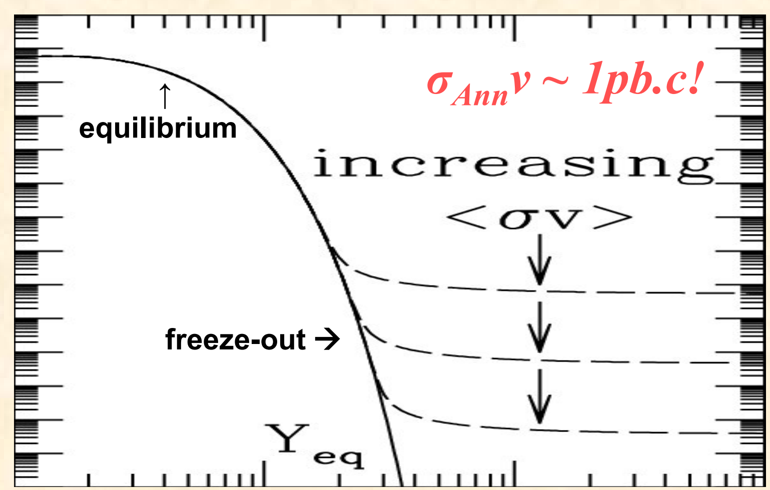
It can be detected via the interaction used for the equilibrium.

WIMP is predicted by various BMSs (SUSY, GUT, Hidden sector, etc.).

We focus on light WIMP!

Unitality limit on (σv)

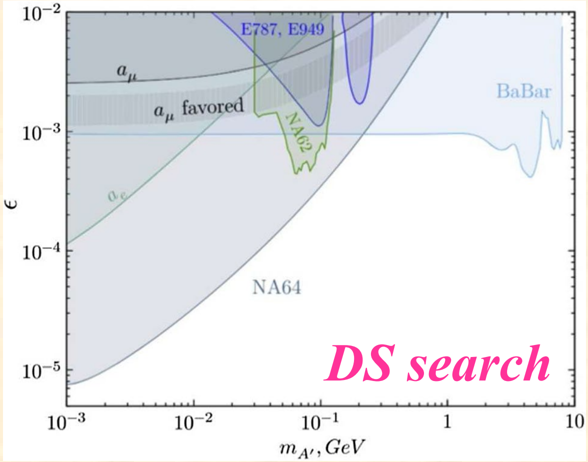
Consistency with cosmology



Experimental searches for light WIMP

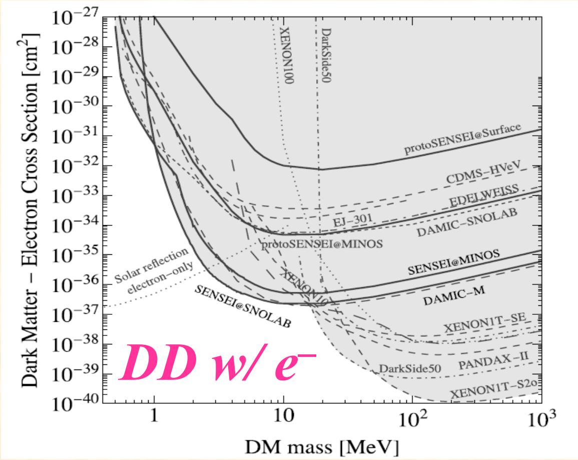
✓ Strategy of the light WIMP search

@ Accelerator exps.



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

@ Underground labs.



[Rouven Essig, 2024]

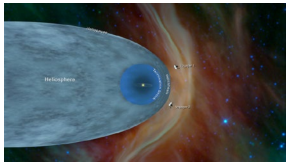
@ Astrophysical obs.

DM + DM → γ, e, ν

ν: Various ν detectors.

e: Heliosphere prevents.

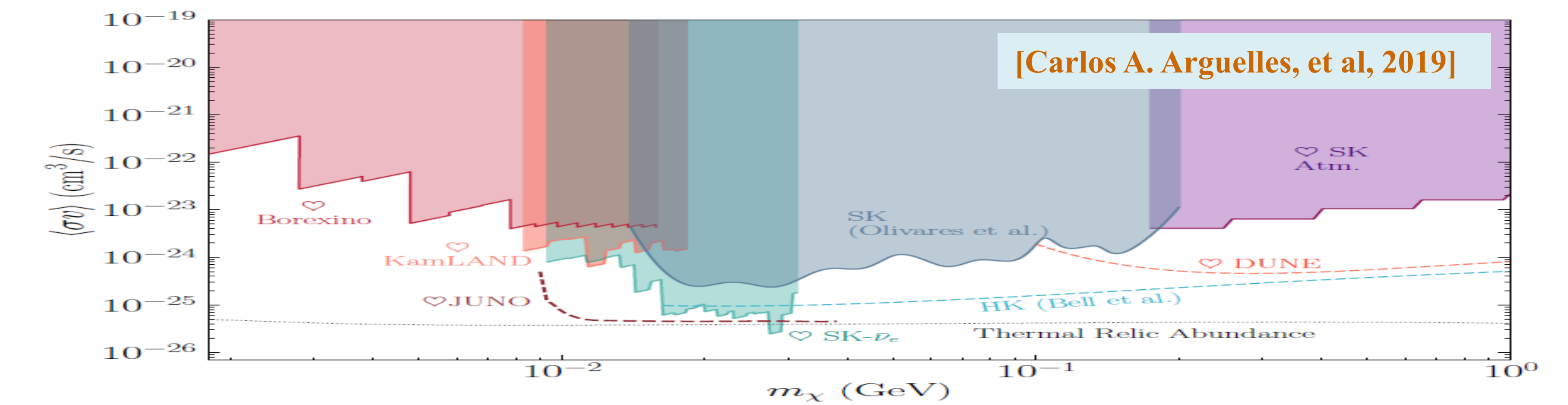
[Voyager can, when m_{DM} > 10 MeV.]



γ: MeV gap (→ See below)

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

✓ Various ν-telescopes are available now & in the near future.



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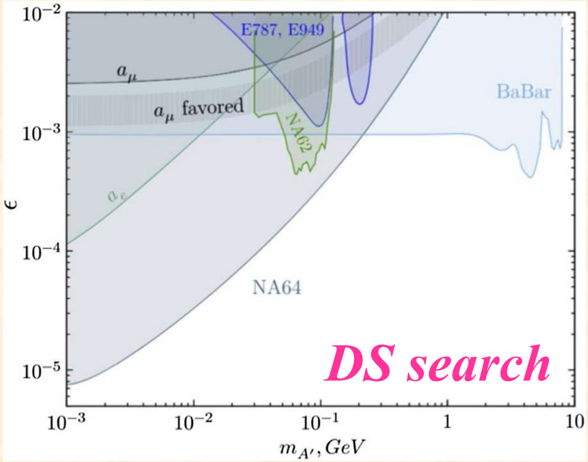

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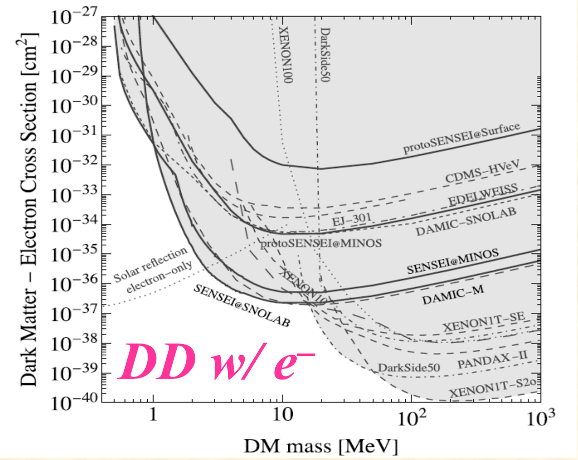

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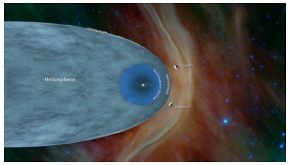

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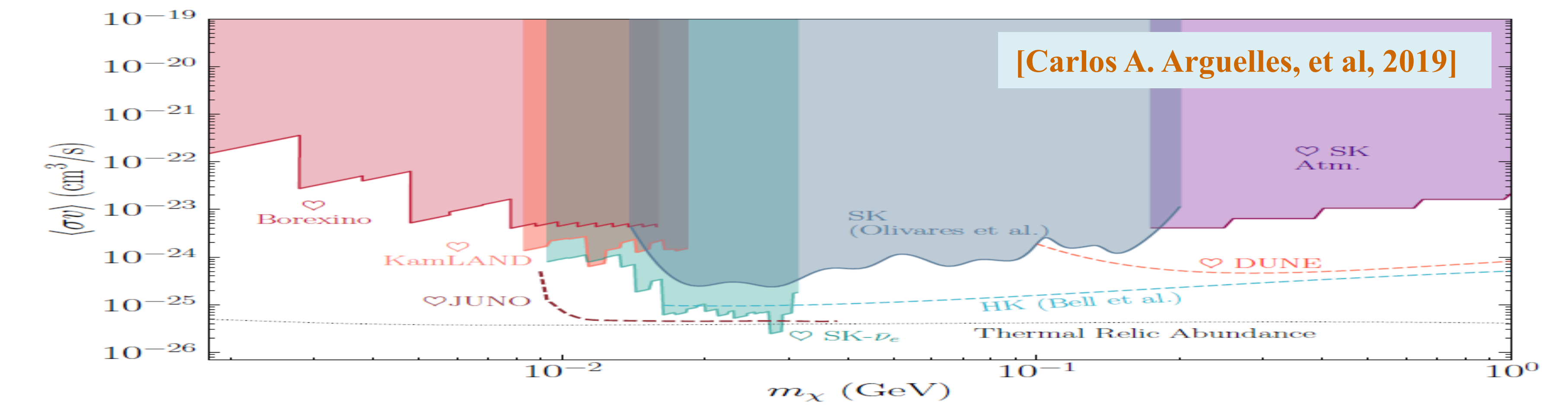

Experimental searches for light WIMP

✓ Strategy of the light WIMP search

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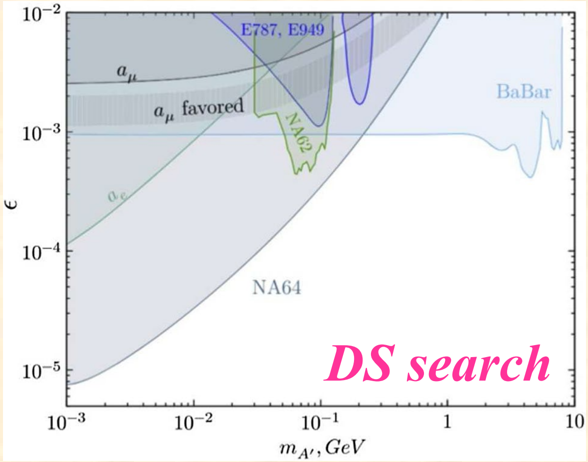

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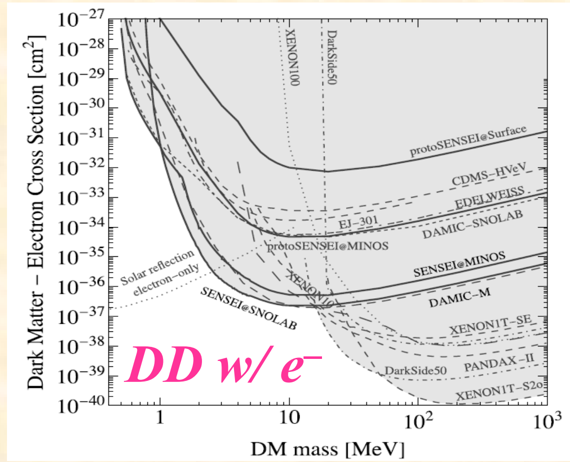

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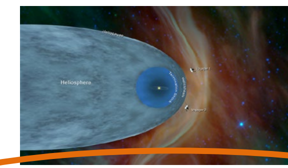
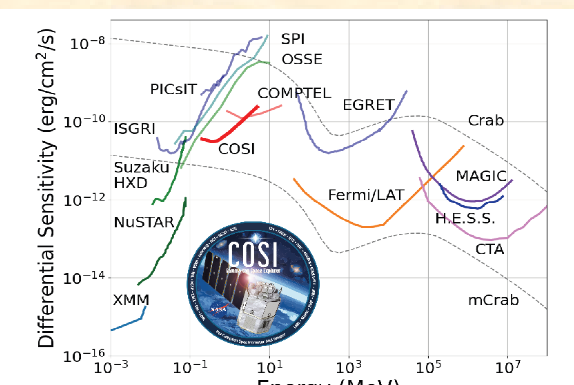


γ: MeV gap (→ See below)

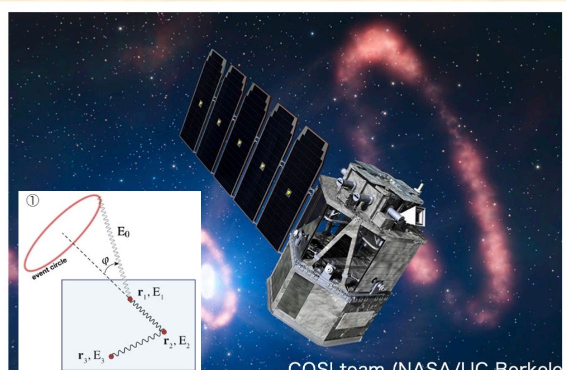
[M. Boudaud, J. Lavalle, P. Salati, 2016]

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

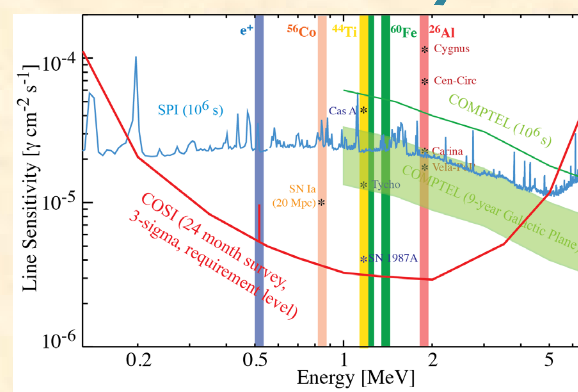
Continuum sensitivity



COSI satellite



Line sensitivity



Theoretical & cosmological perspectives

✓ Theory

Light & Singlet

Dark Matter — Mediator — Standard Model

Singlet

No direct coupling

An exception (non-singlet one) exists.

✓ Cosmology

∴ m_{WIMP} > O(1) MeV.

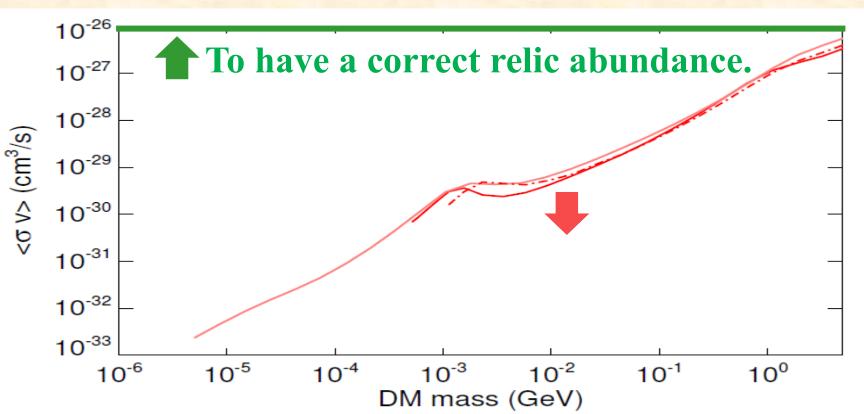
Photo-dissociation

Light WIMP

CMB   BBN   ν-decoupling

T

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



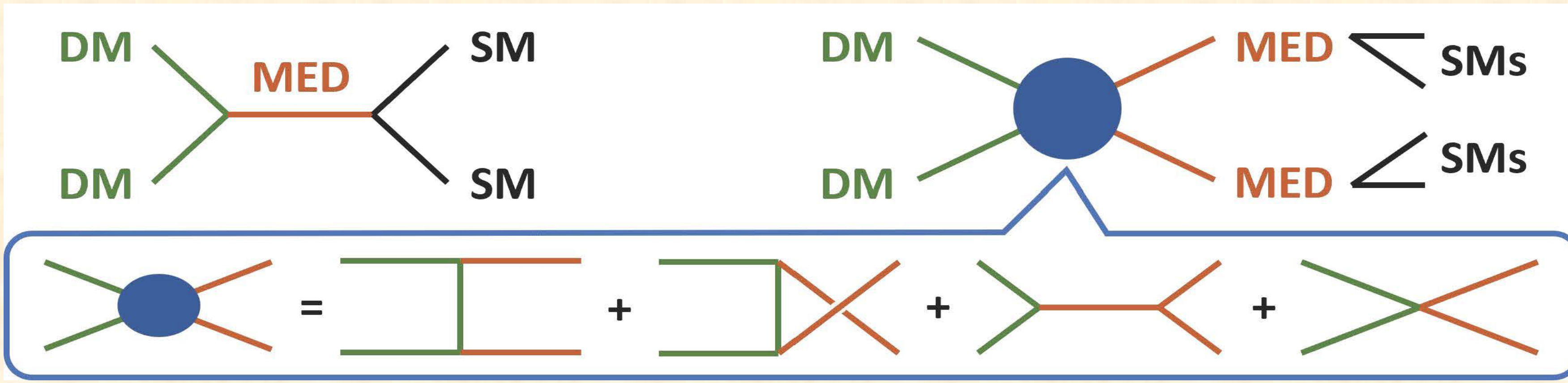
[M. Kawasaki, K. Nakayama, et al, 2010, 2015, 2021]
[Tracy R. Slatyer, PRD93, 2016]

- ✓ 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.

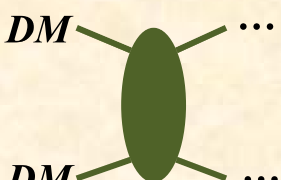
Velocity-dependent scenario

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

All possible diagrams in the framework of the SM + dark matter (DM) + mediator (MED), assuming renormalizable interactions.



p-wave

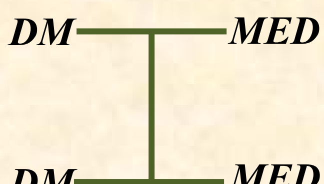


$\sigma v \propto v^2$

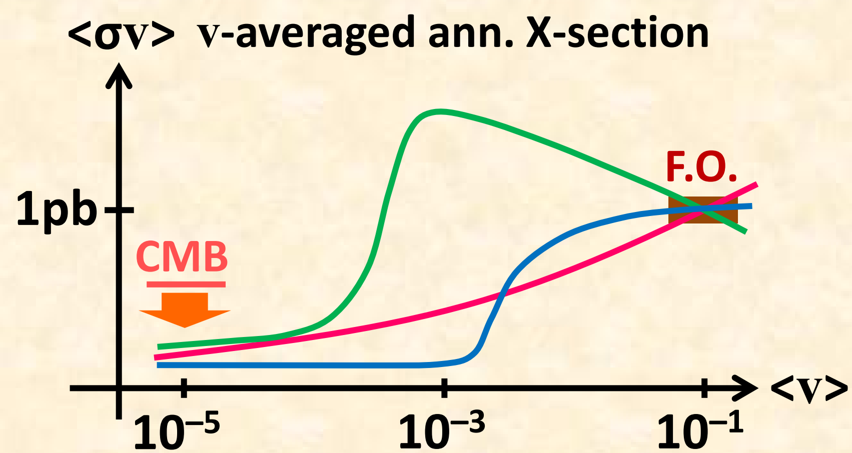
Resonance

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

Forbidden



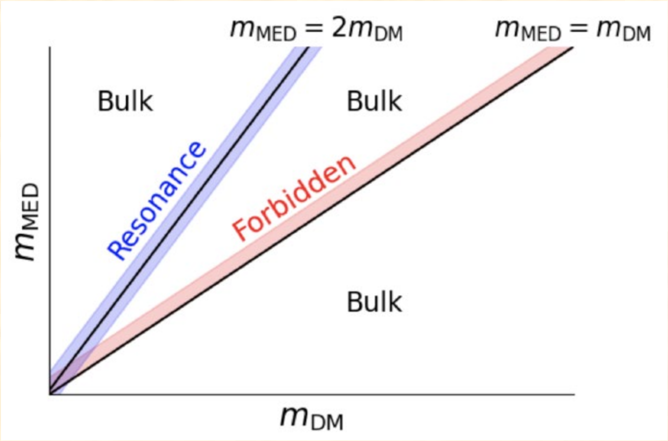
$m_{DM} \lesssim m_{MED}$



Velocity-dependent scenario

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 entries for the bulk regions are provided in these tables.

Velocity-dependent scenario

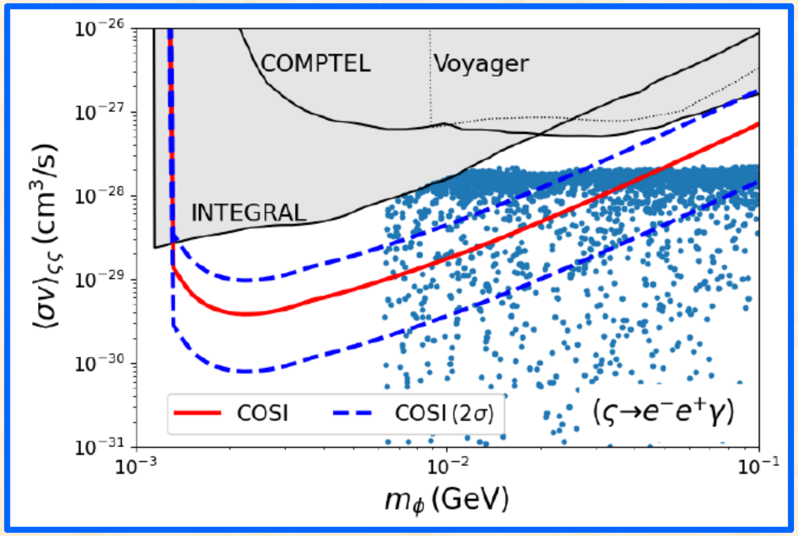
✓ ∃ Viable parameter space?

	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	–

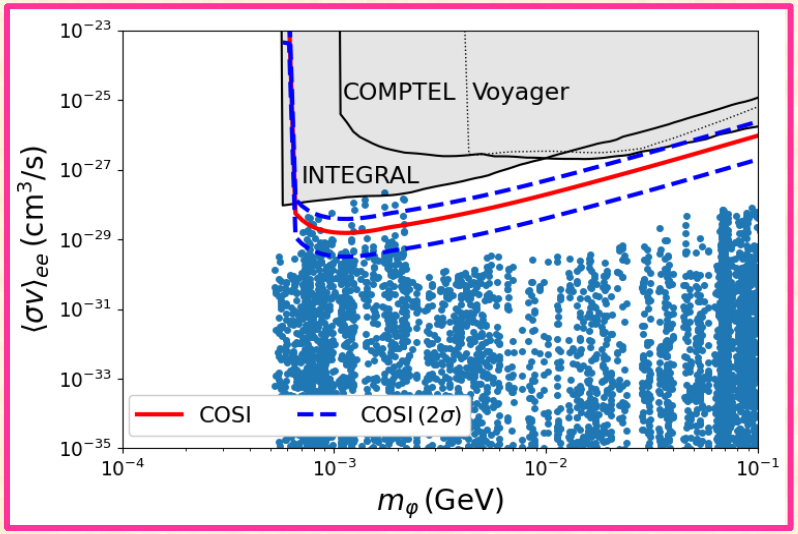
✓ ∃ Signal @ COSI?

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

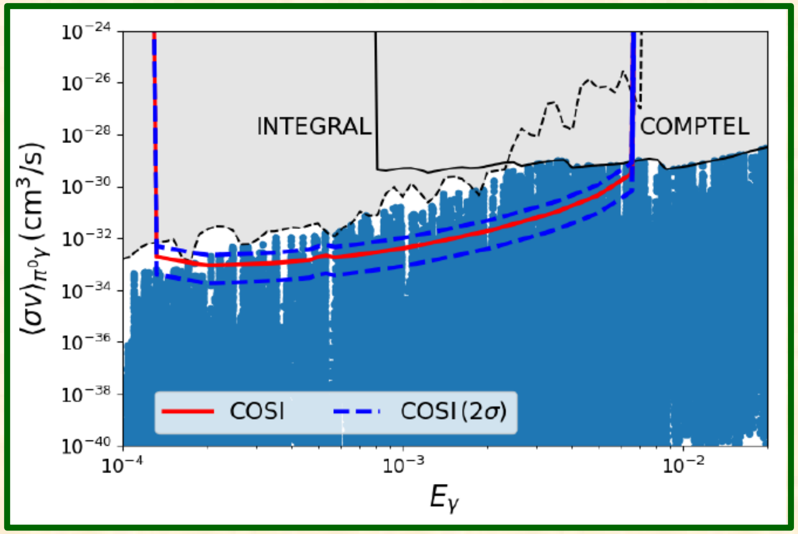
SS-F: $\phi\phi \rightarrow \varsigma\varsigma$ & $\varsigma \rightarrow e^- e^+ \gamma$



SV-R: $\phi\phi \rightarrow Z' \rightarrow e^- e^+ \gamma$



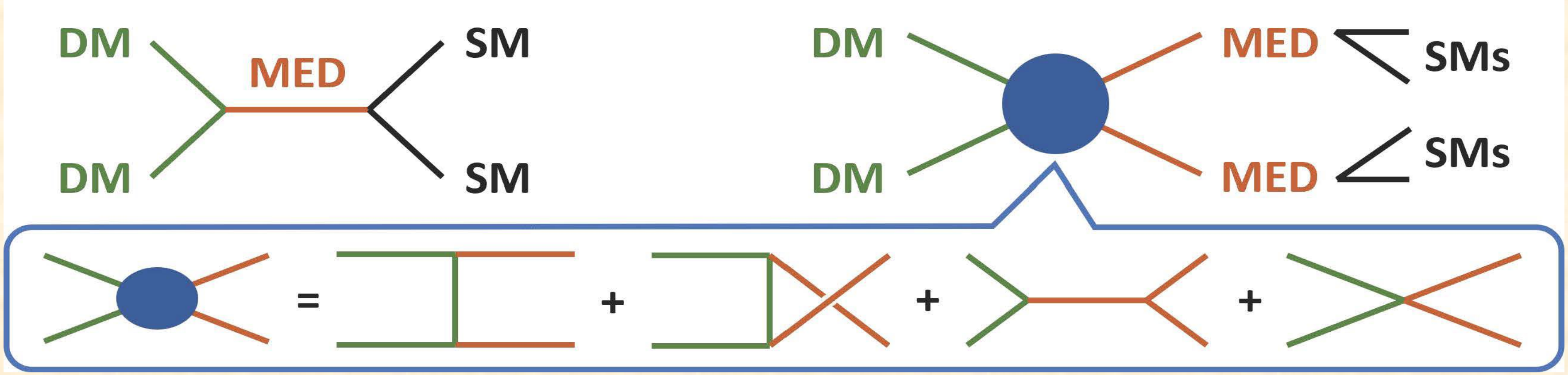
FV(B)-R: $\chi\chi \rightarrow \pi^0 \gamma$



Neutrinophilic scenario

∃Mediator that couples only to neutrinos at low energy scales!

I.e., it does not couple to electrons! ⤴



Having such a neutrinophilic mediator is nontrivial, since the neutrino is a part of the left-handed lepton doublet in the SM.

✓ Majoron-type scalar mediator ϕ (having a lepton number 2)

ϕ (LH)(LH) with $\langle\phi\rangle$=0 type interaction. (or ϕNN + LHN)

[N. Bell, M. Dolan, A. Ghosh, M. Virgato, 2025. (Inverse seesaw scenario)]

✓ $U(1)_{L\mu-L\tau}$ gauge boson Z' (not couples to the 1st generation)

Z' couples to $\mu^-\mu^+$, $\tau^-\tau^+$. $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$ (No 1st generation)

[P. Foldenauer, PRD 2019, arXiv:1808.03647. (Extended model required for n masses/mixings)]

Neutrinophilic scenario

✓ $U(1)_{B-L+xY}$ gauge boson Z' (Higgs doublet is also charged!)

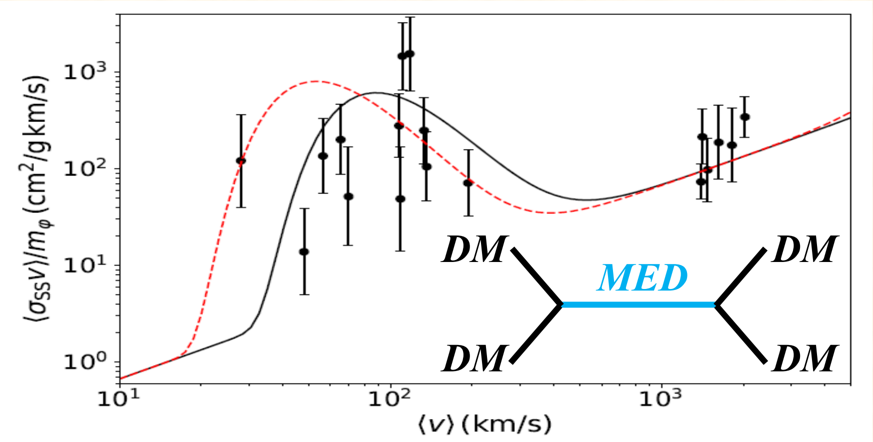
$x \sim -1/\cos^2\theta_W$ → Z' couples only to neutrinos at low energies.

[T. Aonashi, S.M., Yu. Watanabe, Yuki Watanabe, 2025.]

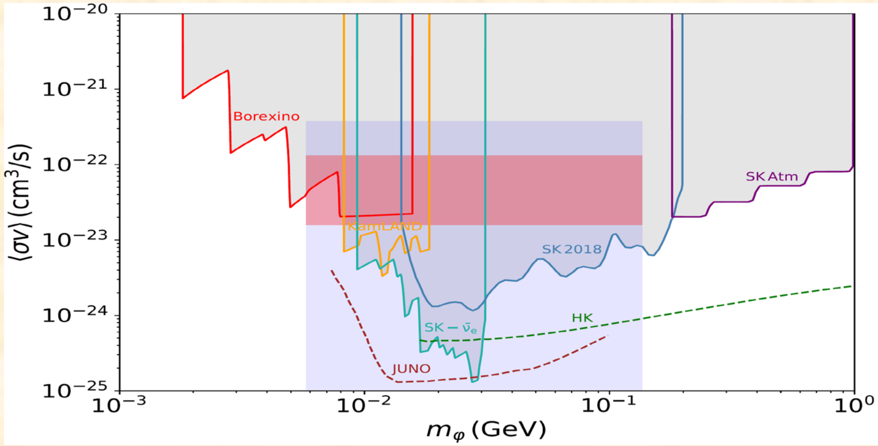
It accommodates both the seesaw & leptogenesis mechanisms!

In all the models, large parameter regions remain uncharted, being consistent with the relic abundance condition and with the constraints obtained so far from dark matter detections.

- It is even possible to have large self-scattering in the 3rd one.
- Indirect detection at neutrino telescopes plays a crucial role!



Solving the small-scale crisis?



It starts covering the region!

Summary

We have discussed the light WIMP, namely, the sub-GeV dark matter!

- ✓ The sub-GeV DM 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 WIMP, neutrinophilic WIMP, etc.

- ✓ Sub-GeV DM may annihilate and produce 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 DM will be explored, notably by the upcoming COSI observation.

- ✓ Sub-GeV DM annihilating only into neutrinos, i.e., neutrinophilic DM, evades the CMB bound on the annihilation cross-section. Realizing such a sub-GeV DM requires careful model-building, as the neutrino is part of an SU(2) doublet with the electron. Indirect dark matter detection at neutrino telescopes play a crucial role to test it.