重要な暗黒物質候補と地下稀事象探査

地下施設における暗黒物質の直接探査
〃　　　ニュートリノ実験

松本 重貴 (カブリ数物連携宇宙研究機構)

共同研究者: 久野さん(名古屋大)、野尻さん(KEK),
青梨さん(IPMU), 渡部さん(IPMU), 渡邊さん (IPMU).

- ✓ Cosmic dark matter (DM) problem and influential DM candidates.
- ✓ Thermal (Weakly Interacting Massive Particle) DM candidates.
- ✓ Heavy thermal DM candidates and direct dark matter detection.
- ✓ Light thermal DM candidates and neutrino experiments.

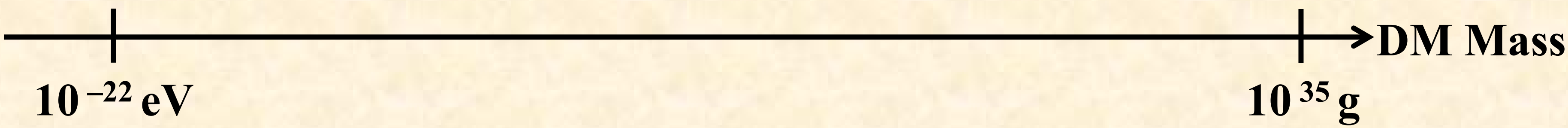
DM problem & What we Know about the DM

O The dark matter problem:

We know that dark matter (DM) 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.

Influential DM candidates

Wave-like | Particle-like | Macroscopic → DM Mass

10^{-22} eV | 0.1 eV | 10^{19} GeV | 10^{35} g

Axion・ALP | WIMP | pBH

○ 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.

○ An influential DM candidate at each mass region:

✓ Axion・ALP is introduced in the PQ mechanism for the strong CP problem or in the scenario of the string axiverse, etc.

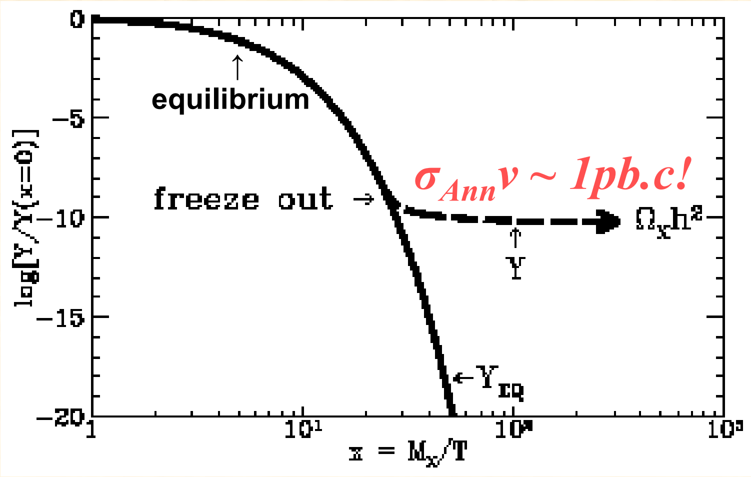
✓ pBH is only the DM candidate that is described in the minimal SM + GR framework. Some inflation models create the pBH.

✓ WIMP is a very attractive candidate from the viewpoint of cosmology. It is also often predicted by various BSM models.

Thermal (WIMP) DM

O Motivation

- ✓ Free from the initial condition problem of the DM abundance.
- ✓ Detectable via interactions for maintaining the equilibrium.
- ✓ The freeze-out mechanism determines the DM abundance.



O The WIMP mass must be between O(1)MeV and O(100)TeV!

Light WIMP | EW WIMP | Heavy WIMP — WIMP Mass

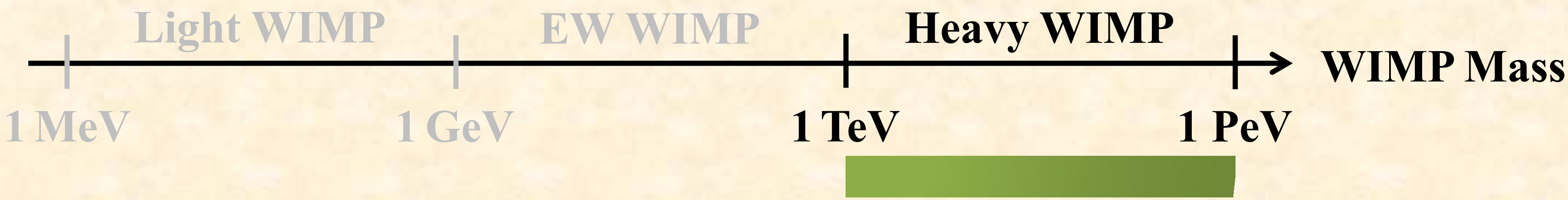
1 MeV | 1 GeV | 1 TeV | 1 PeV

Underground and collider experiments already set stringent limits!
Only a few scenarios (leptophilic, pNGB, H-blind, etc.) remain viable.

m_{WIMP} > O(1)MeV: Consistency with cosmology (∵ CMB, BBN obs.).

m_{WIMP} < O(100)TeV: Unitality (upper) limit on WIMP annihilation.

Heavy WIMP DM



WIMPs that feel the SM weak interaction.

Composite WIMPs

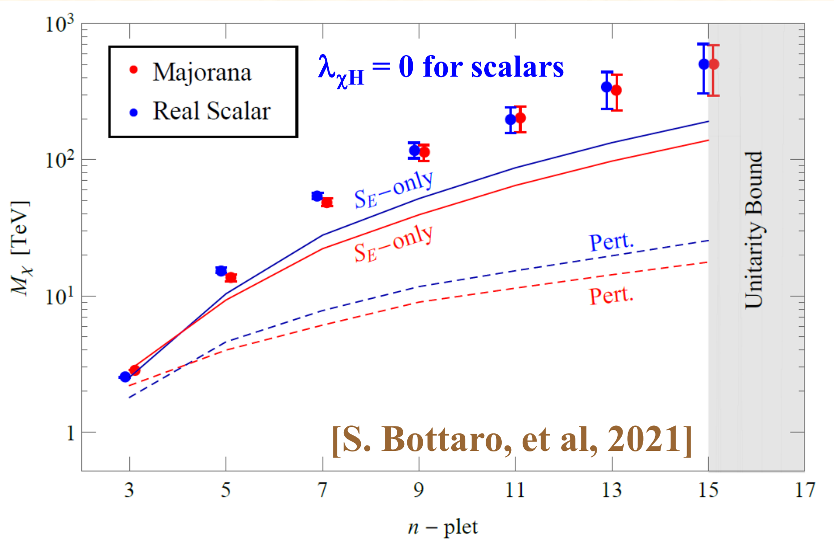
○ There are many candidates, depending on their weak charges.

Hypercharge

Weak charge	0	1/2	1	3/2	2	5/2	⋯
1/2		●					
1	●		●				
3/2		●		●			
2	●		●		●		
5/2		●		●		●	
⋮							

[Mixed WIMPs are not welcome.]

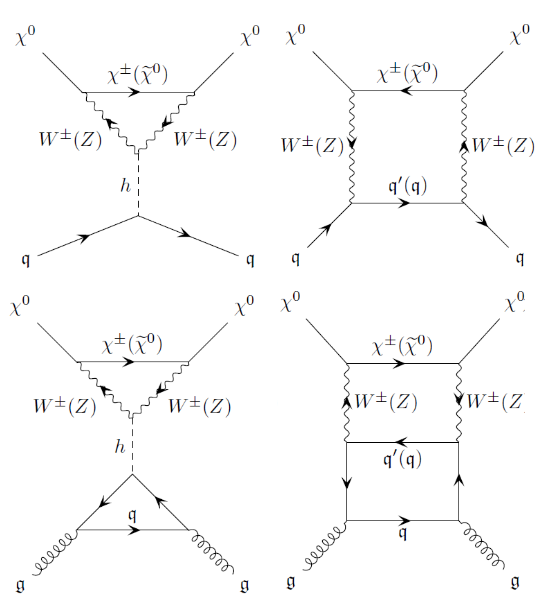
From the relic abundance cond.



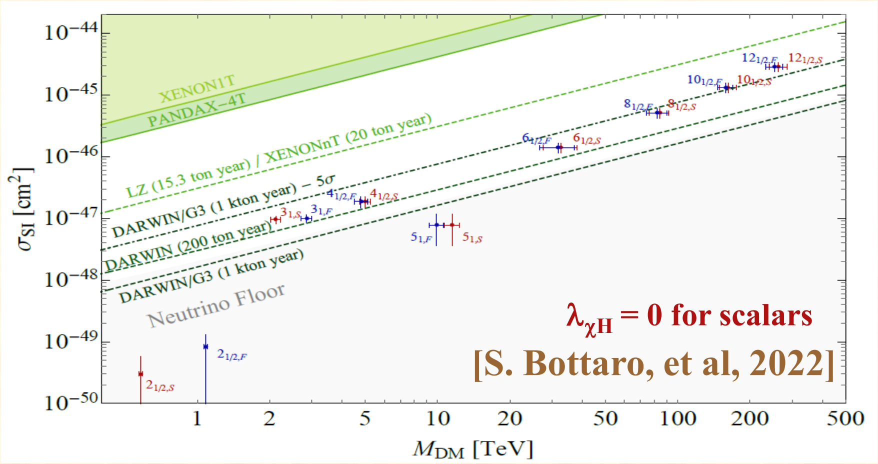
The mass is O(1—100) TeV!

Heavy WIMP DM

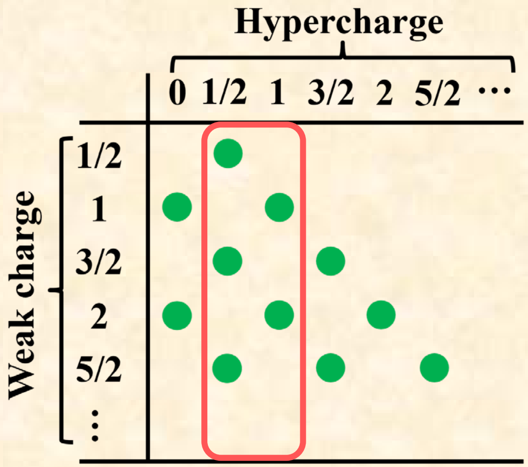
O Direct detection of the WIMPs at underground laboratories!



✓ Scattering via the weak interaction



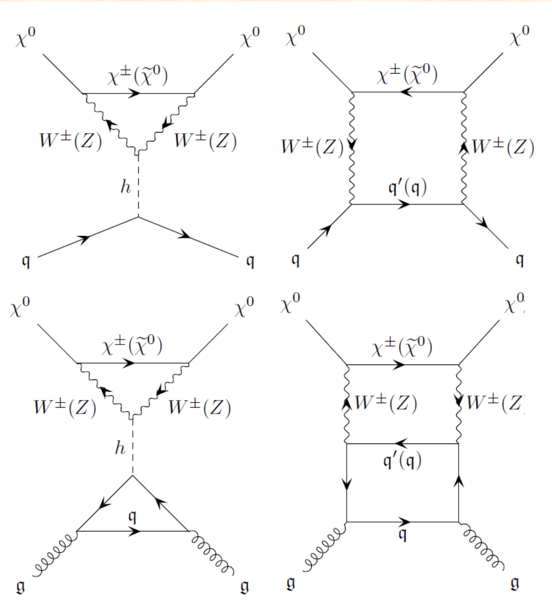
σ_{SI} is suppressed but above the floor!



[Mixed WIMPs are not welcome.]

Heavy WIMP DM

O Direct detection of the WIMPs at underground laboratories!



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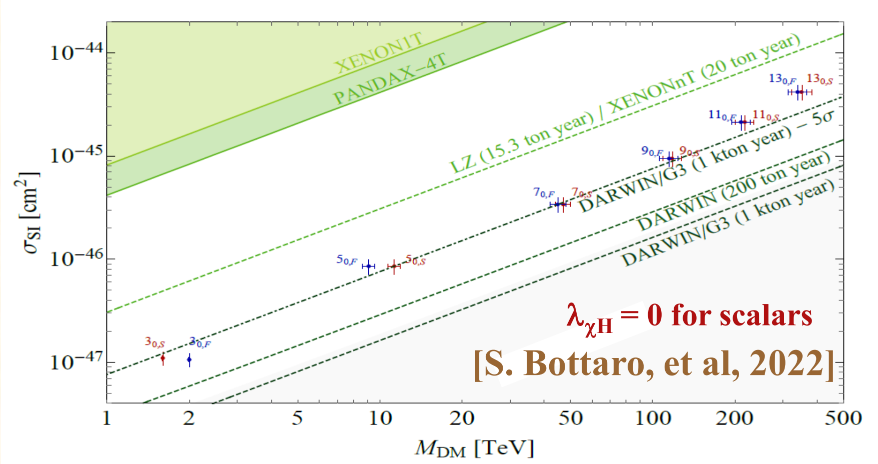

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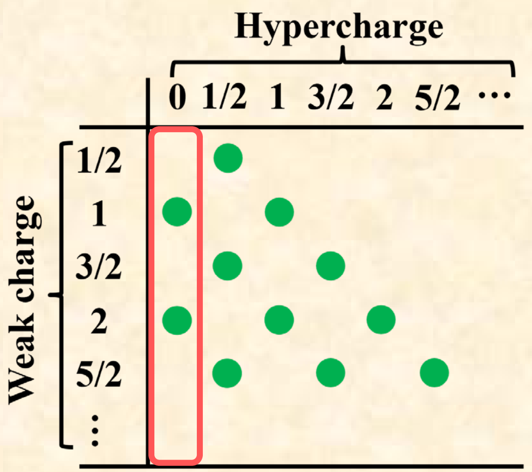
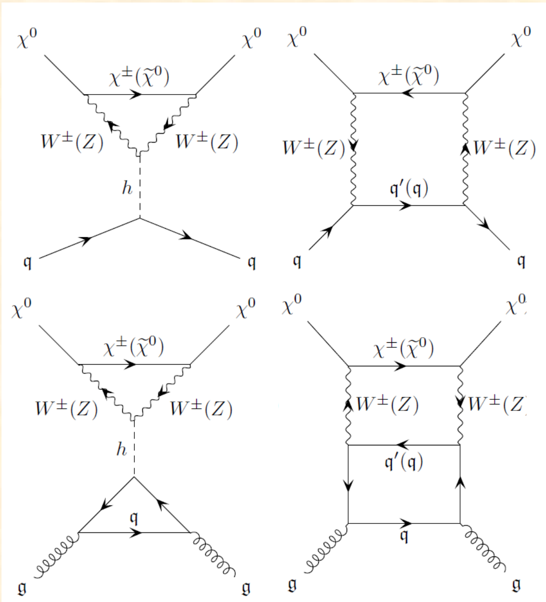


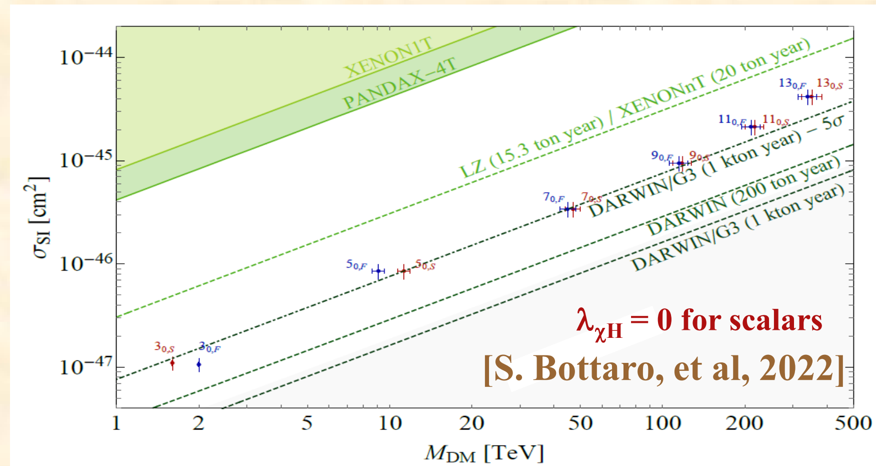
[Mixed WIMPs are not welcome.]

Heavy WIMP DM

O Direct detection of the WIMPs at underground laboratories!

✓ Scattering via the weak interaction

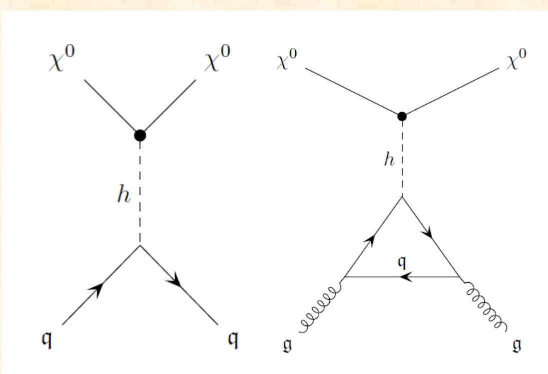


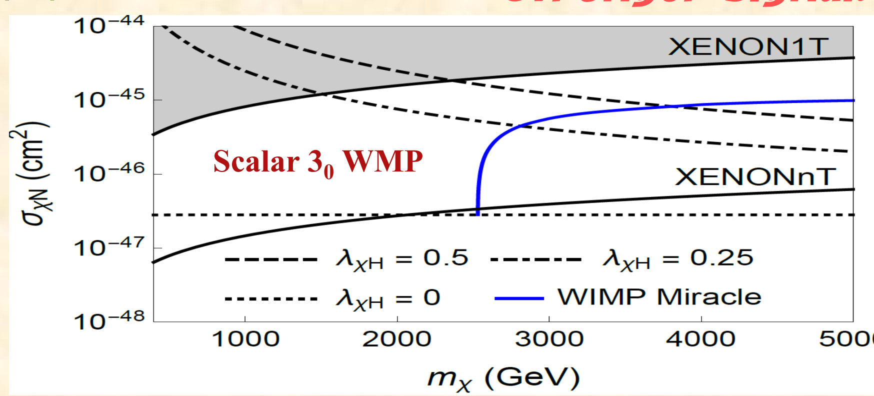


σ_{SI} is suppressed but above the floor!

✓ Scattering via the $\lambda_{\phi H} \Phi^2 |H|^2$ interaction

Stronger signal!

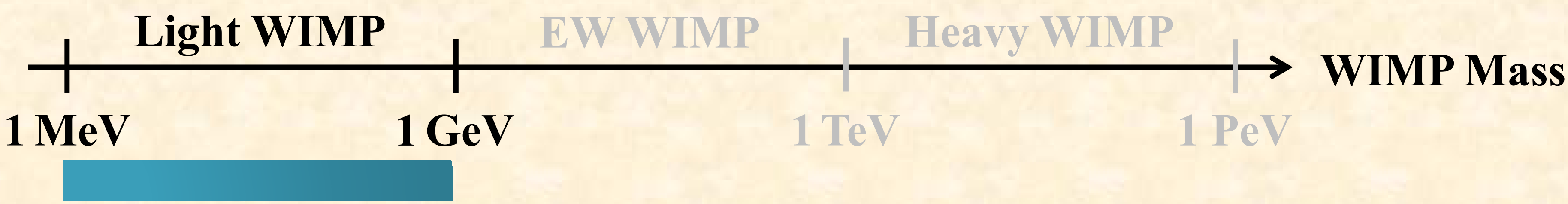




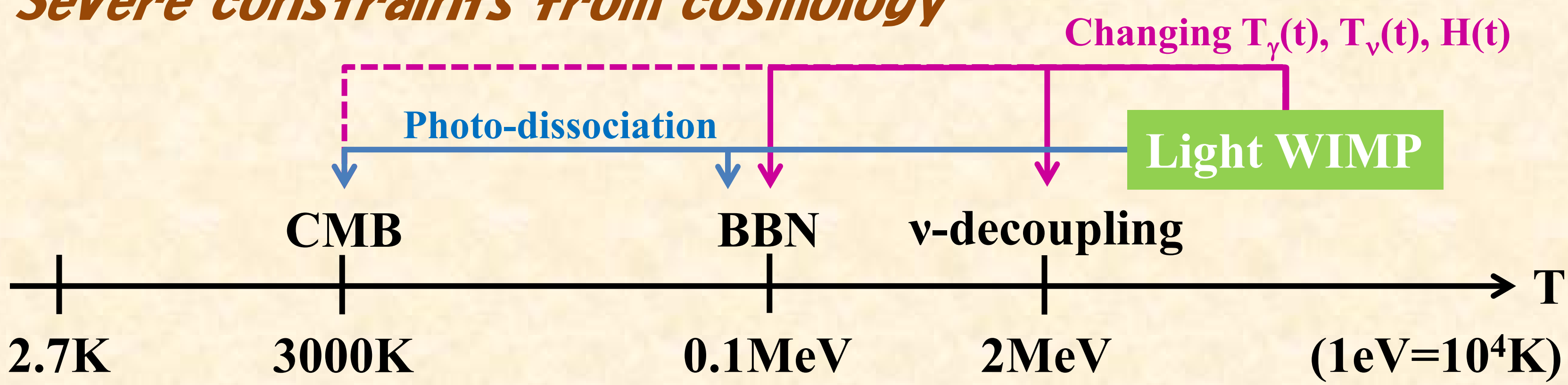
Scalar WIMP has a direct int.

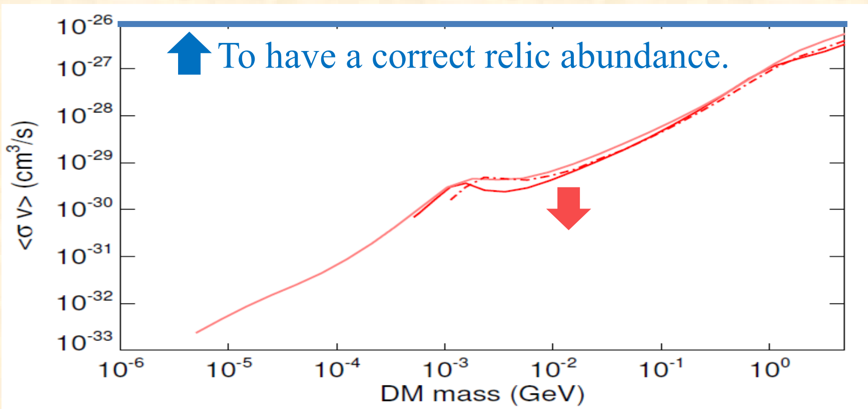
[T. Katayose, S. M, Y. Watanabe, S. Shiri, 2021]
[Vector WIMP: M. Fujiwara, 2020, 2021, 2025]

Light WIMP DM



O Severe constraints from cosmology





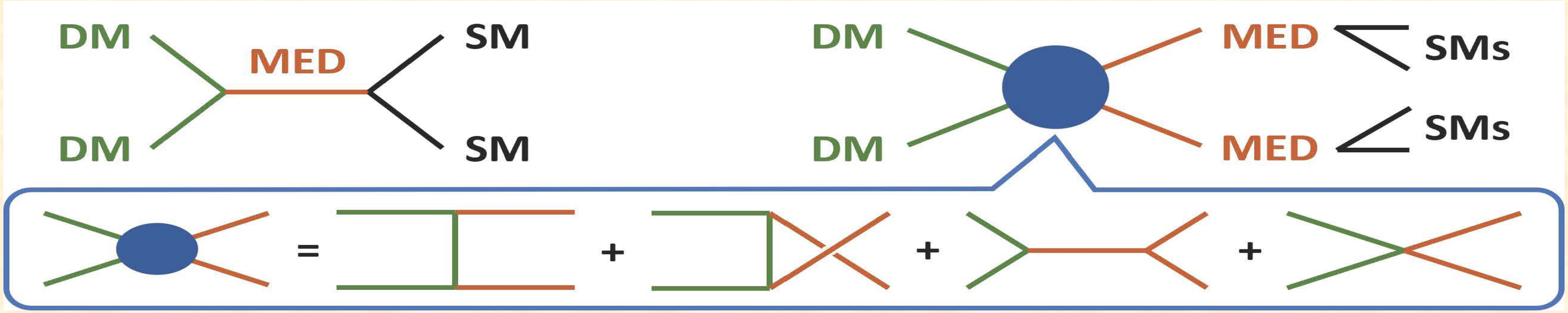
[M. Kawasaki, K. Nakayama, et al, 2010, 2015, 2021]
[Tracy R. Slatyer, PRD93, 2016]

- ✓ *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.*

Light WIMP DM

O Light WIMP interacts with the SM via Mediator: DM-MED-SM

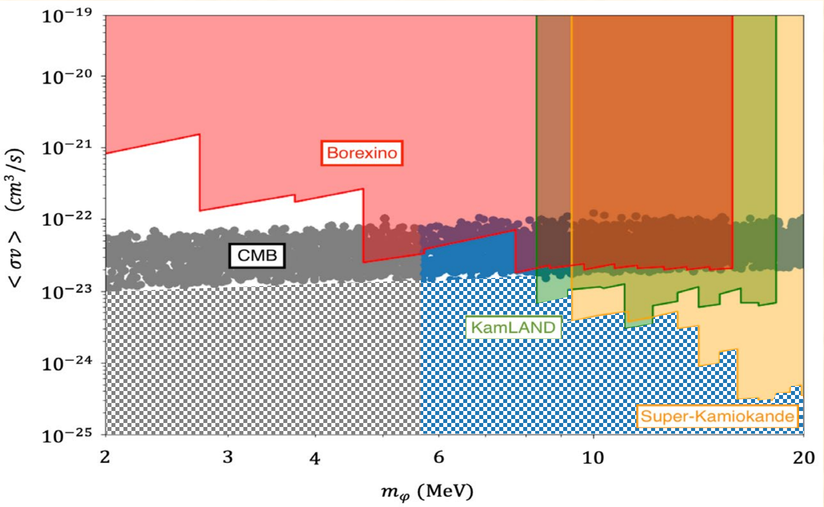
∵ Collider constraints



Neutrinophilic mediator required:
A mediator coupling to neutrinos but not to a pair of electrons!!

- ✓ **Majoron-type scalar mediator**
  [N. Bell, M. Dolan, A. Ghosh, M. Virgato, 2025.]
- ✓ **$U(1)_{L_\mu - L_\tau}$ gauge boson** 〃
  [P. Foldenauer, PRD 2019, arXiv:1808.03647.]
- ✓ **$U(1)_{B-L+xY}$ gauge boson** 〃
  [T. Aonashi, S.M., Y. Watanabe, et al, 2025(exp).]

O Detection @ Neutrino exps.



Summary

We have discussed well-motivated dark matter (DM) candidates that can be detected in rare event search experiments, such as direct DM detection and neutrino observatories in underground laboratories!

- ✓ First, we briefly reviewed the cosmic DM problem in our universe and introduced influential candidates across different mass ranges, i.e., wave-like, particle-like, and macroscopic. We then focused on WIMP (thermal) DM, discussing some of its details.

- ✓ The most influential WIMP candidates in the heavy mass region are those with a weak charge, meaning they are nearly eigenstates of the SM weak interaction. These WIMPs can be efficiently searched for in near-future and future direct DM detection experiments.

- ✓ In the low mass region, attractive candidates include neutrophilic WIMPs, which evade severe limits from cosmological observations. These WIMPs can be efficiently searched for in near-future and future indirect DM detection experiments at neutrino telescopes.