Present status of WIMP dark matter: light, normal, and heavy candidates

Shigeki Matsumoto (Kavli IPMU, U. Tokyo)

We briefly review the present status of the WIMP dark matter in various mass regions and address their relevance to direct dark matter detection. The contents of my talk involve

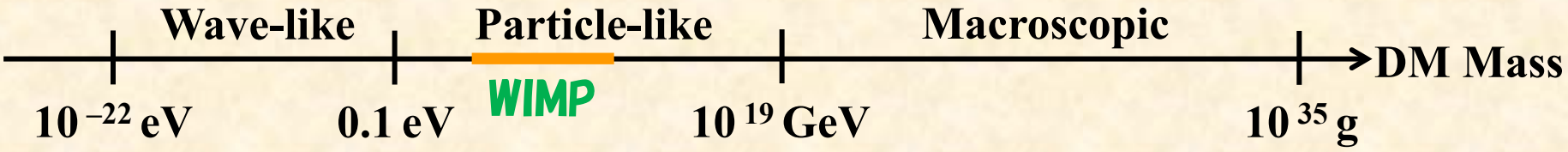
1. Heavy WIMP (TeV-scale WIMP) region.
2. Traditional WIMP (GeV-scale WIMP) region.
3. Light WIMP (MeV-scale WIMP) region.

Let me start with an introduction to WIMP candidates.

Thermal Dark Matter (WIMP)

Thermal DM: The one that was in thermal equilibrium with SMs.

- Free from the initial condition problem of DM abundance.
- Detectable based on interactions maintaining the equilibrium.



$m_{DM} > 1$ MeV: Not to alter the thermal history of CMB via ΔN_{eff}.

$m_{DM} < 1$ PeV: Unitarity limit not to be DM density overabundant.

Three WIMP mass regions (MeV, GeV, and TeV scales):

- ✓ Traditional (GeV-scale) WIMP is well-motivated by various BSM models (SUSY, etc.) concerning the origin of the EWSB.
- ✓ Heavy (TeV-scale) WIMP is motivated by the minimality (weak-charged WIMP) and various BSM models (AMSB, etc.).
- ✓ Light (MeV-scale) WIMP is motivated by other BSM models (hidden sector models) and the small-scale crisis of the U.

Classification of WIMP candidates

WIMP candidates can be classified by quantum numbers (spin & weak-isospin), meaning the physics of WIMP can be discussed without relying on any specific new physics models (SUSY, etc.).

	Singlet	Weak-charged	Well-tempered
Boson			★
Fermion			★

Direct DM detection is robust!

Well-tempered WIMP

↕

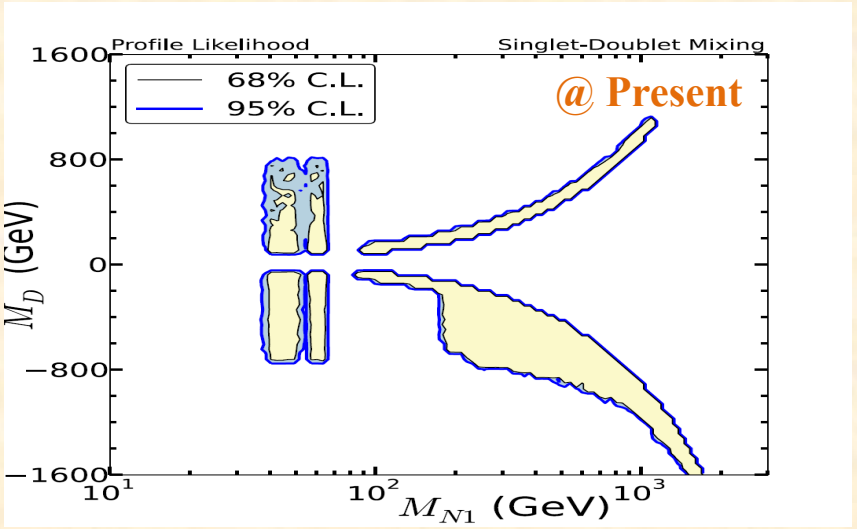
DM Yukawa interactions

↕

DM-DM-h(Z) couplings

This is a common feature shared by all the well-tempered WIMPs, regardless of the spin of WIMP.

Example: Fermionic S-D case:



[S. Banerjee, S. M., K. Mukaida, Y. Tsai, 2016]

Classification of WIMP candidates

WIMP candidates can be classified by quantum numbers (spin & weak-isospin), meaning the physics of WIMP can be discussed without relying on any specific new physics models (SUSY, etc.).

	Singlet	Weak-charged	Well-tempered
Boson			★
Fermion			★

Direct DM detection is robust!

Well-tempered WIMP

↕

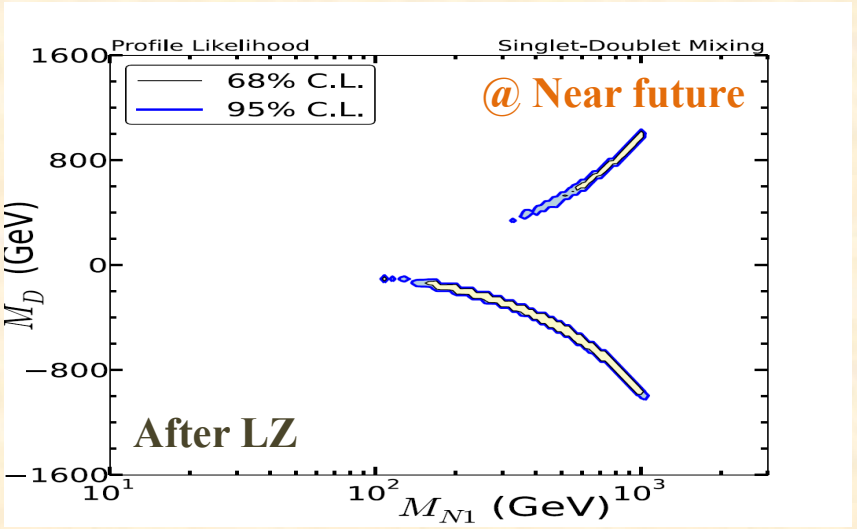
DM Yukawa interactions

↕

DM-DM-h(Z) couplings

This is a common feature shared by all the well-tempered WIMPs, regardless of the spin of WIMP.

Example: Fermionic S-D case:



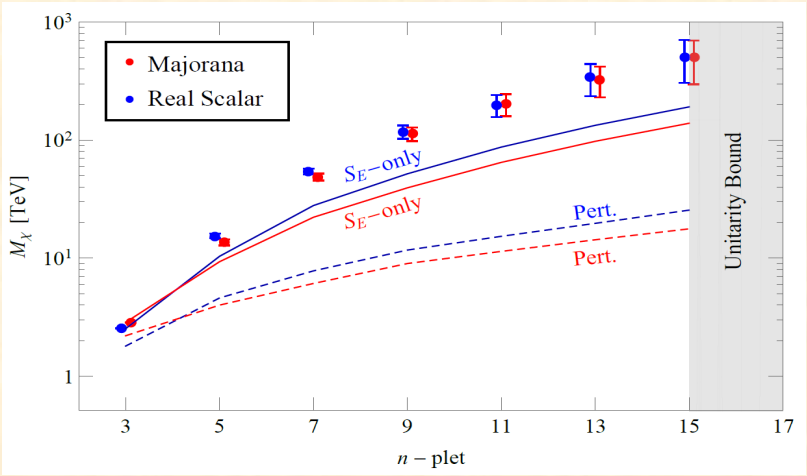
[S. Banerjee, S. M., K. Mukaida, Y. Tsai, 2016]

Heavy (TeV-scale) WIMP

When WIMP is weak-charged, its mass is predicted to be >1 TeV.

	Singlet	Weak-charged	Well-tempered
Boson		★	
Fermion		★	

Because of the Sommerfeld effect and the bound state effect, the mass is predicted to be O(1-100) TeV, depending on its weak charge.



[S. Bottaro, D. Buttazzo, M. Costa, et al, 2021]

Sommerfeld effect: The WIMP feels the long-range force caused by EW boson exchanges before it is annihilated, modifying the incident WIMP wave function and boosts the annihilation cross-section.

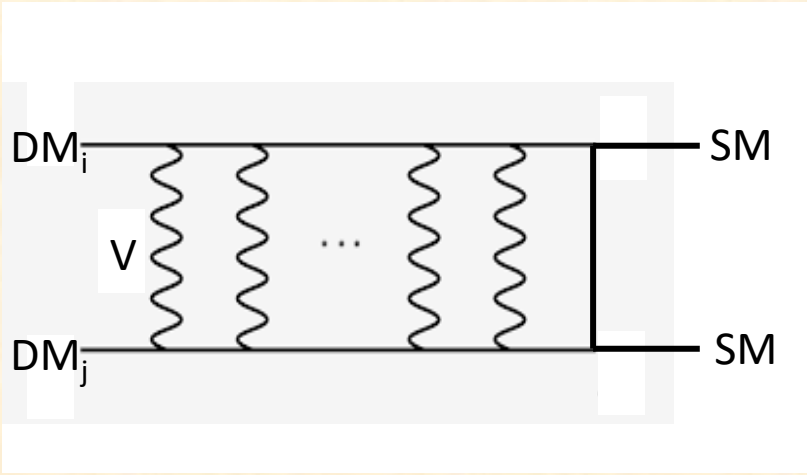
Bound state effect: The WIMP annihilates to a WIMP bound state, which decays into SM particles, by emitting an EW gauge boson.

Heavy (TeV-scale) WIMP

When WIMP is weak-charged, its mass is predicted to be >1 TeV.

	Singlet	Weak-charged	Well-tempered
Boson		★	
Fermion		★	

Because of the Sommerfeld effect and the bound state effect, the mass is predicted to be O(1-100) TeV, depending on its weak charge.



[J. Hisano, S.M., M. Nagai, O. Saito, et al, 2007]

Sommerfeld effect: The WIMP feels the long-range force caused by EW boson exchanges before it is annihilated, modifying the incident WIMP wave function and boosts the annihilation cross-section.

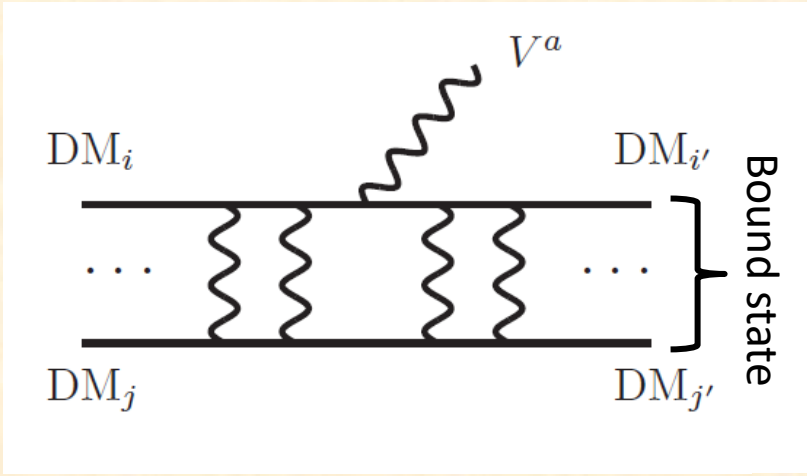
Bound state effect: The WIMP annihilates to a WIMP bound state, which decays into SM particles, by emitting an EW gauge boson.

Heavy (TeV-scale) WIMP

When WIMP is weak-charged, its mass is predicted to be >1 TeV.

	Singlet	Weak-charged	Well-tempered
Boson		★	
Fermion		★	

Because of the Sommerfeld effect and the bound state effect, the mass is predicted to be O(1-100) TeV, depending on its weak charge.

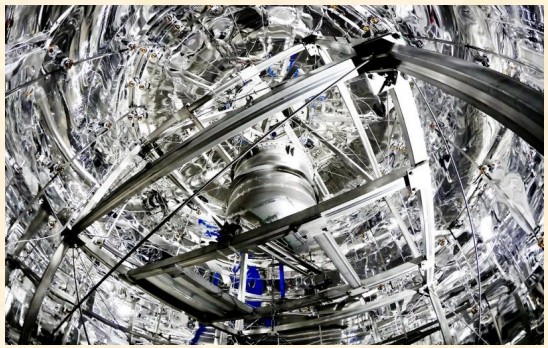


[A. Mitridate, M. Redi, J. Smirnov, A. Strumia, 2017]

Sommerfeld effect: The WIMP feels the long-range force caused by EW boson exchanges before it is annihilated, modifying the incident WIMP wave function and boosts the annihilation cross-section.

Bound state effect: The WIMP annihilates to a WIMP bound state, which decays into SM particles, by emitting an EW gauge boson.

Heavy (TeV-scale) WIMP



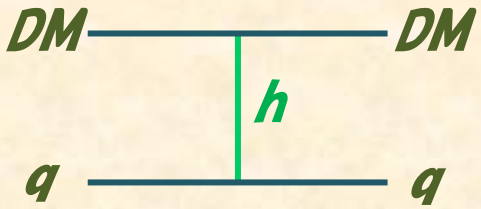
For the case of weak-charged WIMPs:

When it is fermionic,

Loop suppressed!

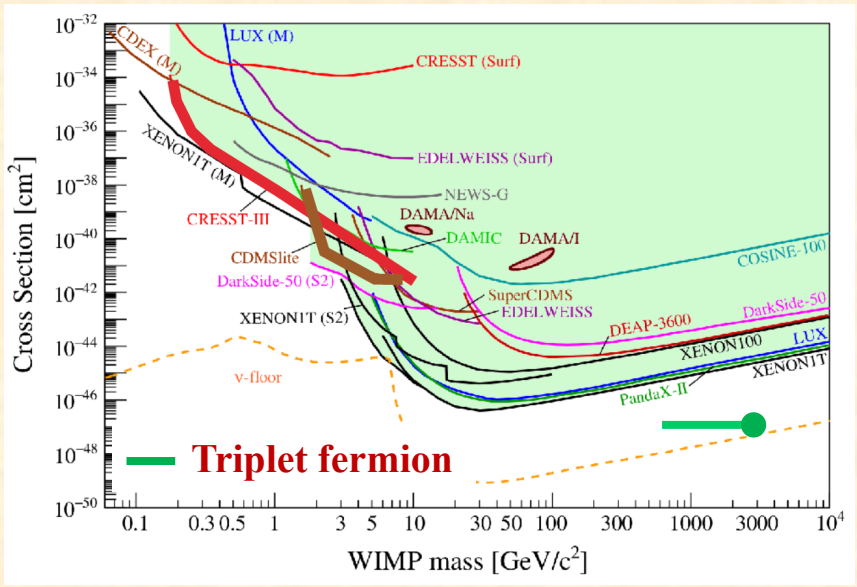
[Hisano, S.M., Nojiri, Saito, 2005]

When it is bosonic,

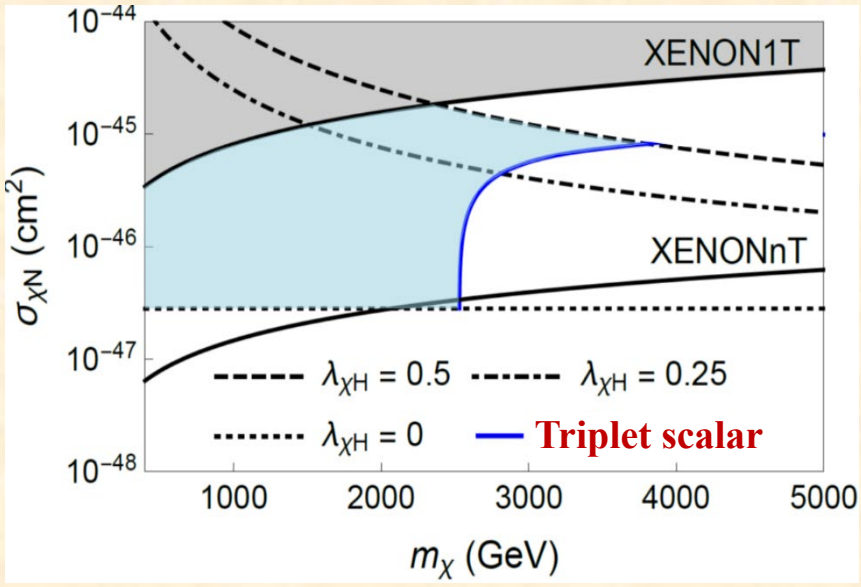


v_{EM}/m_{DM} suppressed!

[The vertex is from $L_{int} \sim DM^2|H|^2$]



[J. Hisano, K. Ishiwata, N. Nagata, 2012]



[T. Katayose, S. M., S. Shirai, Y. Watanabe, 2021]

Traditional (GeV-scale) WIMP

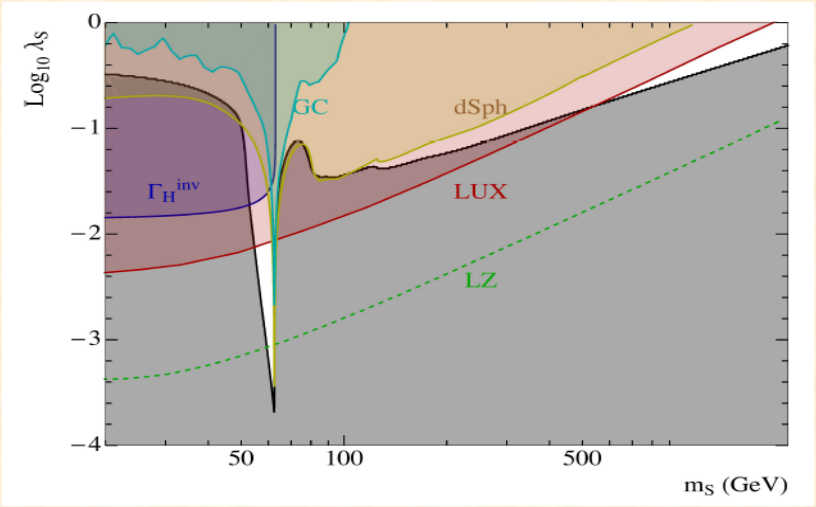
In addition to the well-tempered WIMP mentioned before, that singlet under the SM symmetry is a candidate for the GeV WIMP.

	Singlet	Weak-charged	Well-tempered
Boson	★		
Fermion			

The minimal model for the singlet bosonic (scalar) WIMP is the so-called "Higgs-portal DM," which has an interaction of $S^2|H|^2$.

The low-mass region is excluded by LHC (Invisible Higgs search).

The GeV-mass region is excluded by direct detection experiments!



[J. A. Casas, D. G. Cerdeño, J. M. Moreno, J. Quilis, 2017]

The GeV-scale bosonic WIMP is still viable in the next minimal models, e.g., the pNB dark matter. [V. Barger, et al, 2010; C. Gross, at al, 2017]

Traditional (GeV-scale) WIMP

Another new particle (mediator) is introduced for fermionic DM.

	Singlet	Weak-charged	Well-tempered
Boson			
Fermion	★		

A comprehensive study via EFT, including WIMP and SM particles,

$$\mathcal{L}_{\rm EFT} \quad \frac{c_S}{2\Lambda}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H)$$

① ② ③ ④

or simplified models obtained by integrated-in the interactions.

According to the comprehensive analysis imposing the thermal relic condition and various constraints from DM detection exps, surviving parameter regions are [S. M., S. Mukhopadhyay, Y. Tsai, 2014]

① **Higgs-funnel:** $\bar{\chi}\chi|H|^2$ **governs the annihilation with** $m_\chi \sim m_h/2$.

② **CPV H-portal:** $\bar{\chi}i\gamma_5\chi|H|^2$ **governs 〃 without 〃 .**

③ **Leptophilic:** $(\bar{\chi}\gamma^\mu\gamma_5\chi)(f\gamma_\mu f)$ **governs 〃 with f = L, E (leptons).**

④ **Z boson-funnel:** $(\bar{\chi}\gamma^\mu\gamma_5\chi)(Hi\overleftrightarrow{D}_\mu H)$ **governs 〃 with** $m_\chi \sim m_Z/2$.

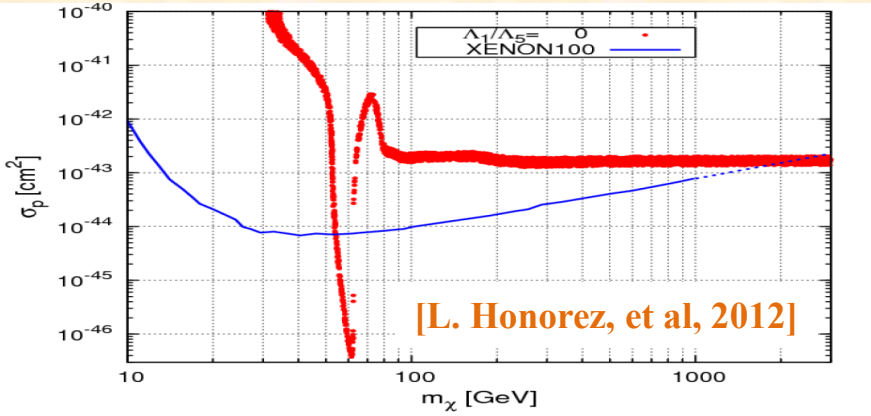
Traditional (GeV-scale) WIMP

Another new particle (mediator) is introduced for fermionic DM.

	Singlet	Weak-charged	Well-tempered
Boson			
Fermion	★		

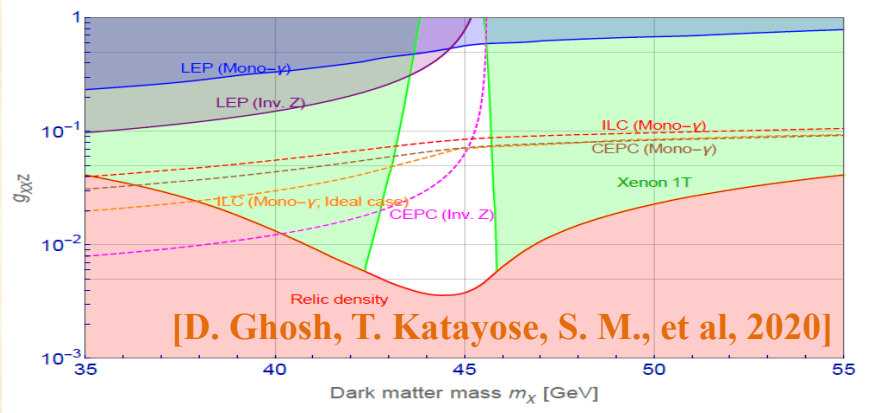
Direct detection plays a central role in probing some of them!

① Higgs funnel region:



The same as the scalar DM!

④ Z boson-funnel region:



Spin-dependent scattering!

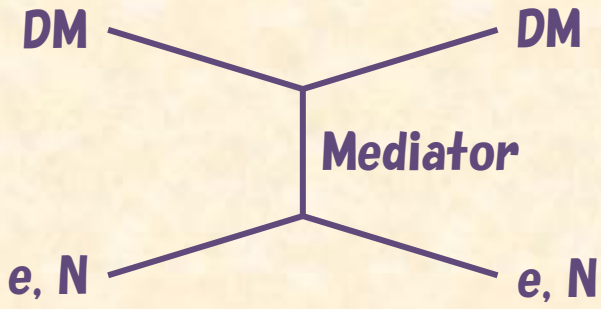
② CPV H-portal region: SI scattering induced radiatively, but …,

③ Leptophilic region: SD scattering induced radiatively, but …,

Light (GeV-scale) WIMP

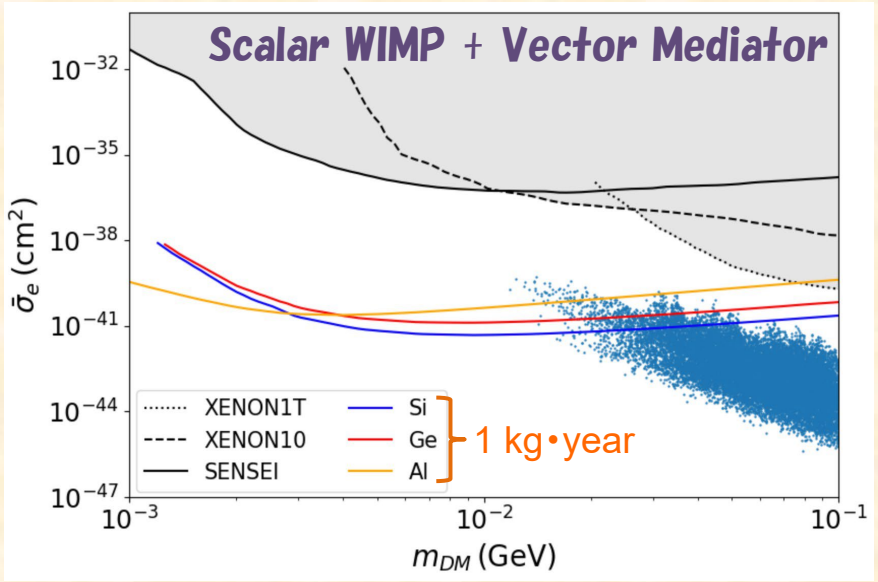
	Singlet	Weak-charged	Well-tempered
Boson	★		
Fermion	★		

- $m_{WIMP} > O(1)$ MeV not to contradict CMB & BBN observations.
- A light mediator is introduced. ∵ Relic abundance & collider.
- The WIMP scatters with e or N by exchanging the mediator.



Scattering w/ an electron is sensitive for the light WIMP.

Future detections will start to search for the light WIMP.



[Signal: S. M., Y. Watanabe, T. Takahashi, et al, 2021]
[Background: S. Knapen, J. Kozaczuk, T. Lin, 2021]

Summary

We discussed the present status of the WIMP in various mass regions and addressed their relevance to direct DM detection.

- ✓ Well-tempered WIMPs are currently being explored by DD.
- ✓ Heavy bosonic WIMPs will be explored by the near future DD.
- ✓ Heavy fermionic WIMPs will be explored by the future DD.
- ✓ Traditional bosonic WIMPs are being explored by DD.
- ✓ Many scenarios for traditional fermionic WIMPs:
  - H-funnel scenario is being explored by DD.
  - Z-funnel scenario will be explored by the near future DD.
  - Leptopilic and CPV H-portal scenarios are difficult.
- ✓ Light WIMPs will be explored via the electron scattering DD.

The above conclusion was obtained from the analysis based on the minimal model for each WIMP's quantum numbers. So, there will be many other possibilities in non-minimal models.