MeV-PeV質量領域に跨る熱的DMとその探査

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上記研究班では、様々な興味深い研究が行われ、その成果が発表されてきた。本公演では、学術研究“地下から解き明かす宇宙の歴史と物質の進化”の重要なトピックの一つである、熱的暗黒物質の直接検出に関わる理論的な背景(動機等)について、幾つかの研究を紹介させて頂く。

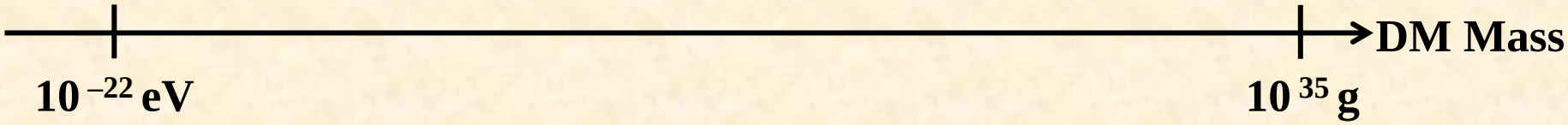
The dark matter problem

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 DM.

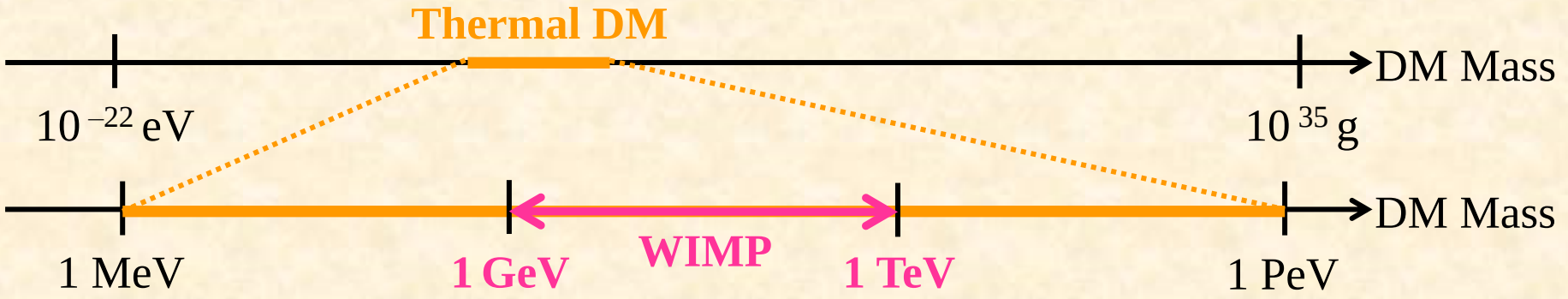
What we know about the DM:

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 DM abundance (averaged mass density) is 10^{-6} GeV cm^3.
The DM mass 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.

The thermal dark matter



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}.

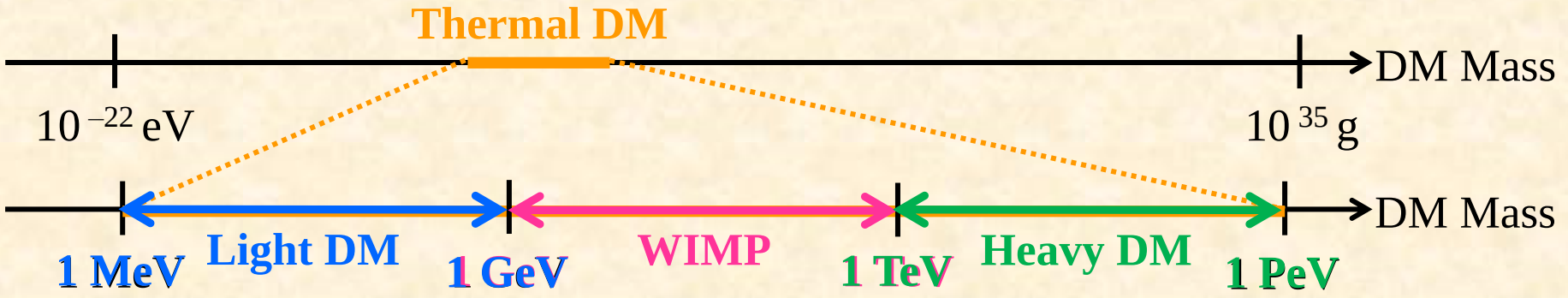
  $m_{DM} < 1$ PeV: Unitarity limit not to be DM density overabundant.

The WIMP mass regions:

The thermal relic abundance that is predicted by the freeze-out mechanism coincides naturally with DM density today. It means the origin of the DM mass may be the same as EWSB's.

→ The WIMP is intensively searched for at many large-scale experiments. No robust signals have been detected so far.

The thermal dark matter



Heavy DM region:

When the DM has a weak-charge, its mass is predicted to be more than O(1)TeV, as the physics of DM is basically governed by the weak interaction with the coupling ~ (weak isospin) g.

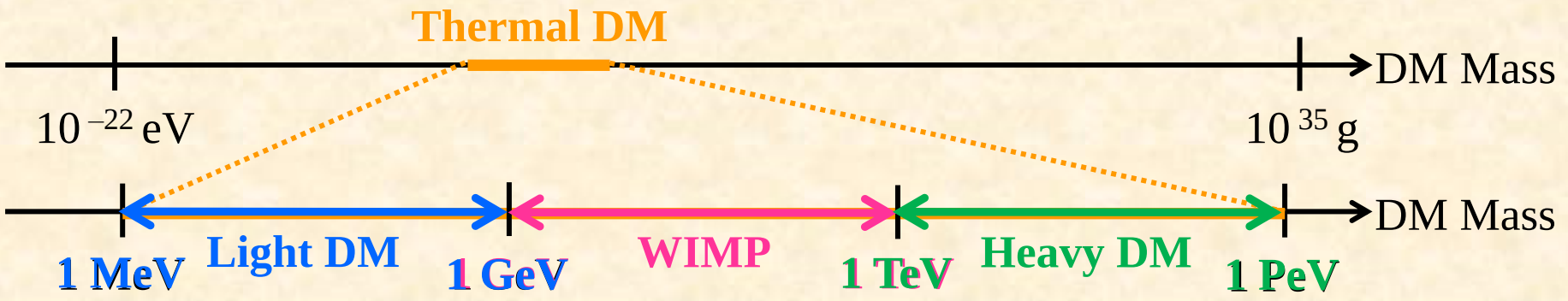
→ The DM is attractive from the viewpoint of minimality!

Light DM region:

When the DM is singlet under the SM gauge group, its mass can be much lower than the EW scale. Such DM candidates can have a large self-scattering cross-section, say $\sigma/m = 0.1\text{-}1\,\mathrm{cm}^2/\mathrm{g}$.

→ The DM is attractive as it may solve the so-called core and cusp problem at the small-scale structure of the universe!

The thermal dark matter



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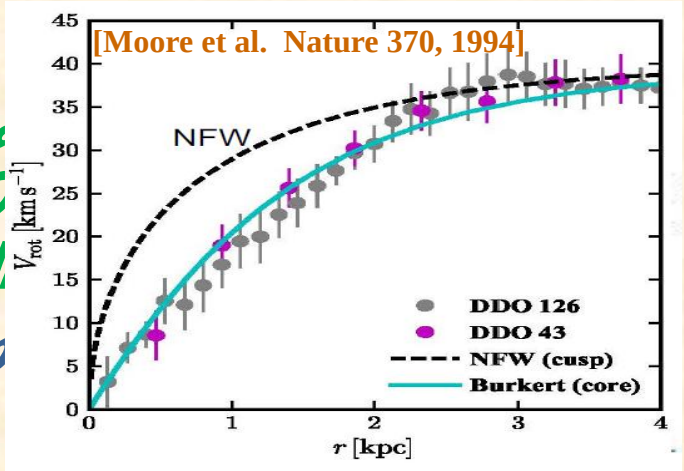

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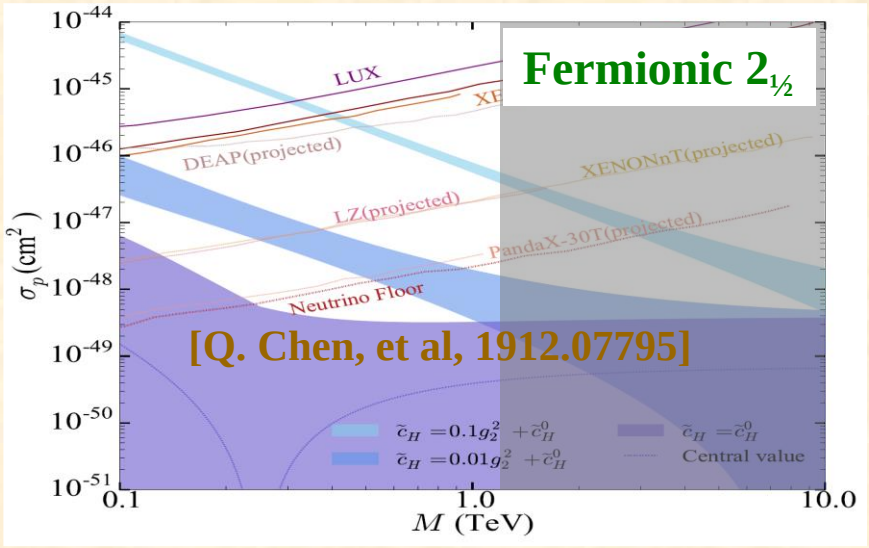
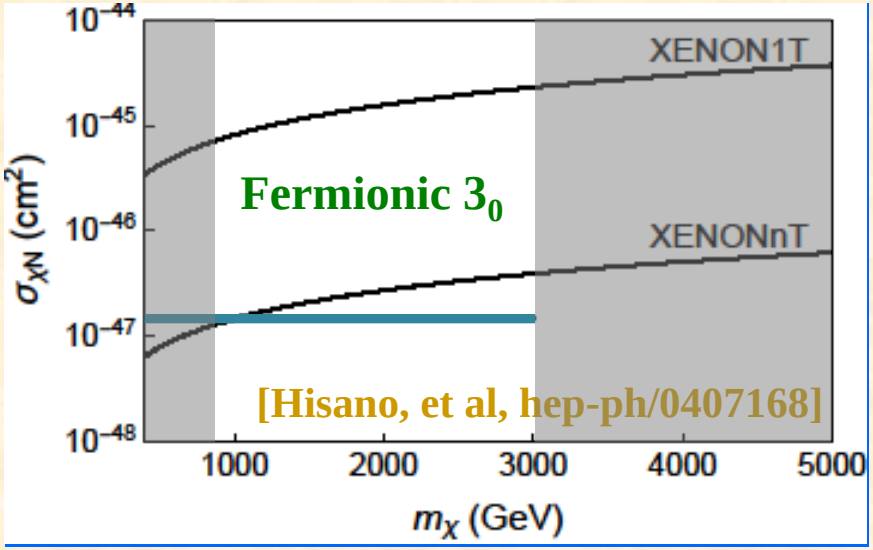
Heavy thermal DM (Weak-charged DM)

General properties:

- ✓ Various cases considered $2_{1/2}$, 3_0, 3_1, $4_{1/2}$, $4_{3/2}$, 5_0, 5_1, 5_2, ….
  (Mixed DM cases are not favored due to direct DM detection constraints.)
- ✓ $\exists$ $SU(2)_L$ partners that are highly degenerated in mass.
  (The partners become long-lived: e.g., $c\tau$ = 7cm for the case of 3_0)
  [H. Cheng, et. al. (1999); Y. Yamada (2010); M. Ibe, S. M., R. Sato (2013)]
- ✓ The DM annihilation is boosted by the Sommerfeld effect.
  [J. Hisano, S. M., M. Nojiri (2004); J. Hisano, S. M., M. Nojiri, O. Saito (2005)]
- ✓ The signal strength at DD depends on the spin of the DM!





Heavy thermal DM (Weak-charged DM)

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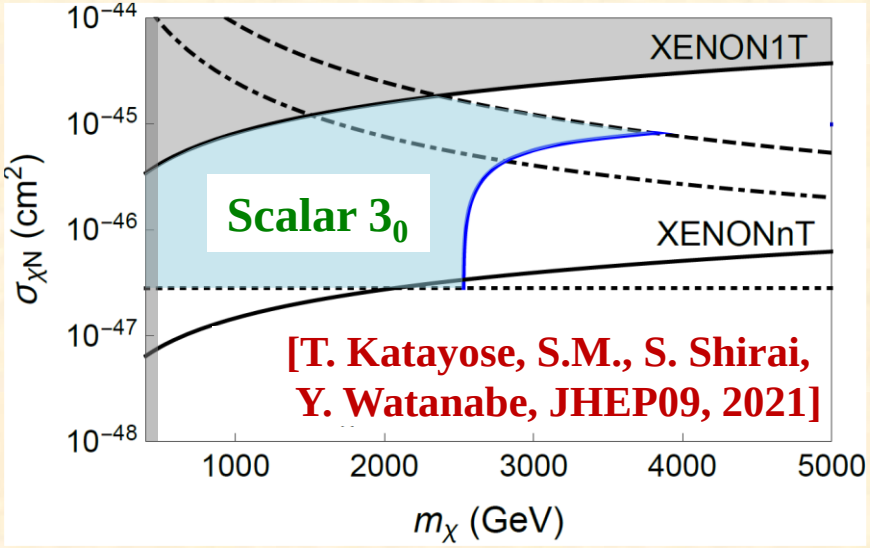


The scattering cross-section is loop-suppressed when fermionic. (Or from higher dimensional Ops.)

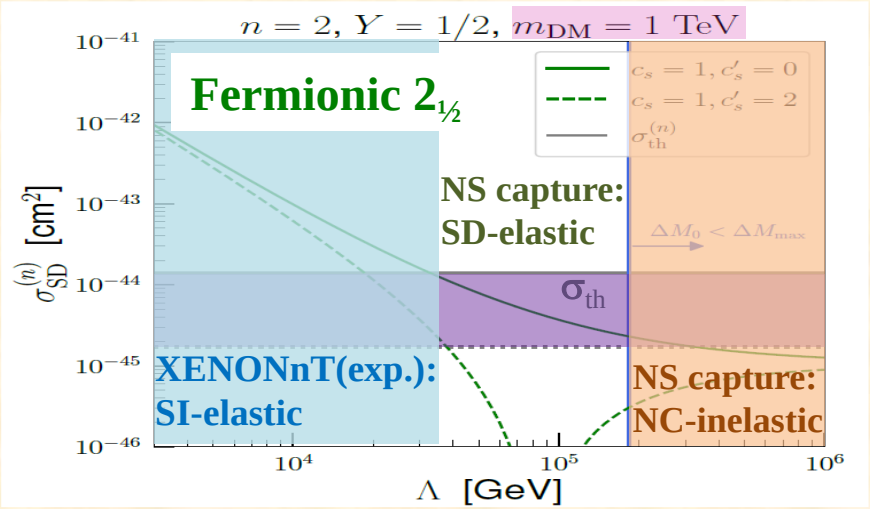
The scattering cross-section is from tree-level thanks to direct coupling with Higgs when bosonic. (But it is suppressed by m_h/m_{DM}.)

How should we explore the region below the neutrino floor?

The DM is captured by NSs, and heating those. The effect may be detected by observing old NSs.

[M. Fujiwara, K. Hamaguchi, N. Nagata, J. Zheng, arXiv: 2204.02238]

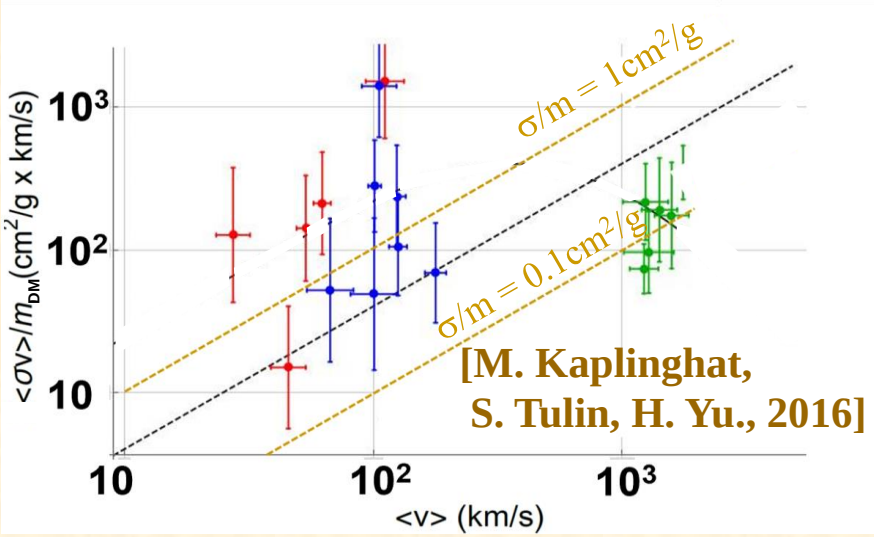
The DM velocity is boosted, so various scatterings contribute!



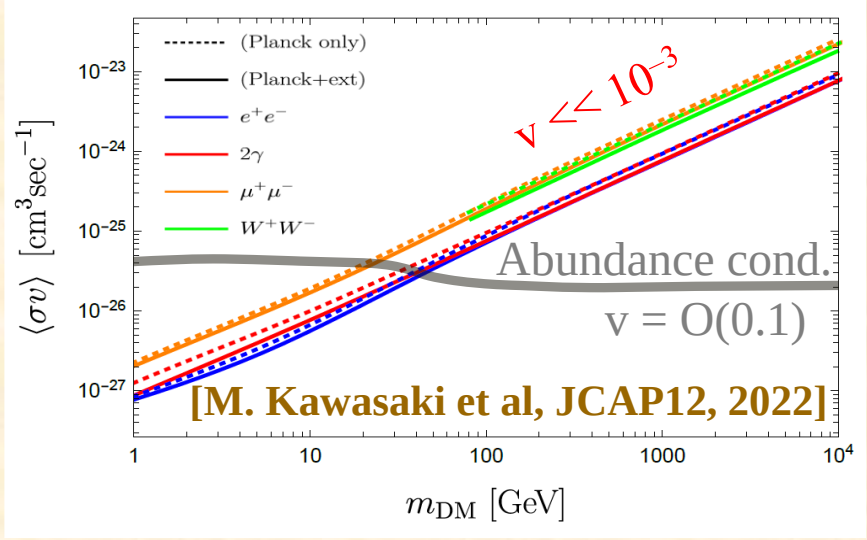
Light thermal DM

General properties:

- ✓ ∃ Many mechanisms for its abundance (SIMP, Semi-Ann, ADM).
- ✓ ∃ New particles connecting DM & SM particles, i.e., mediators.
  (Those could be long-lived particles, giving distinctive signatures at col.)
- ✓ ∃ Large scattering X-section, solving the core & cusp prob.
- ✓ DM annihilation X-section is severely constrained by CMB.



Velocity-dependent scattering X-section is favored by data.

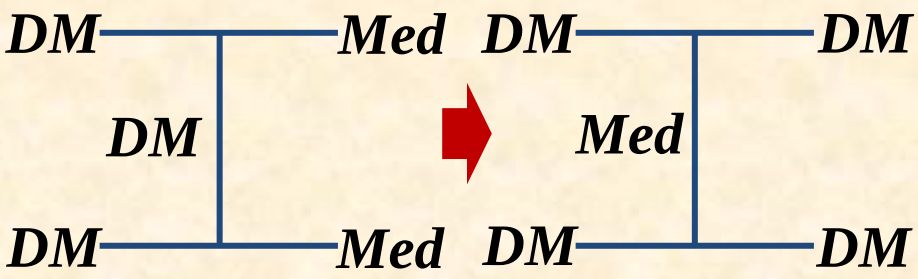


When the DM annihilates simply in the s-wave, $m_{DM} > 10$GeV!

Light thermal DM

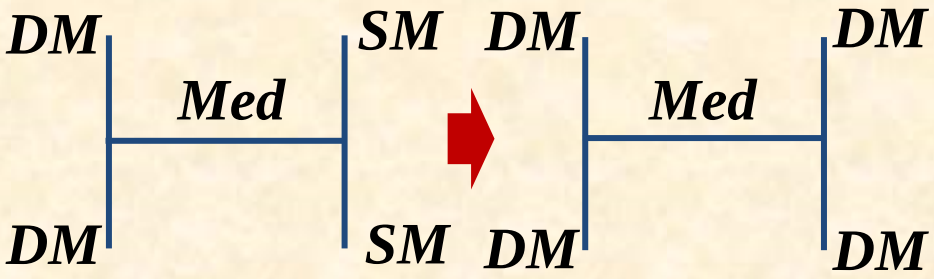
Possible models:

O Majorana DM + Scalar mediator

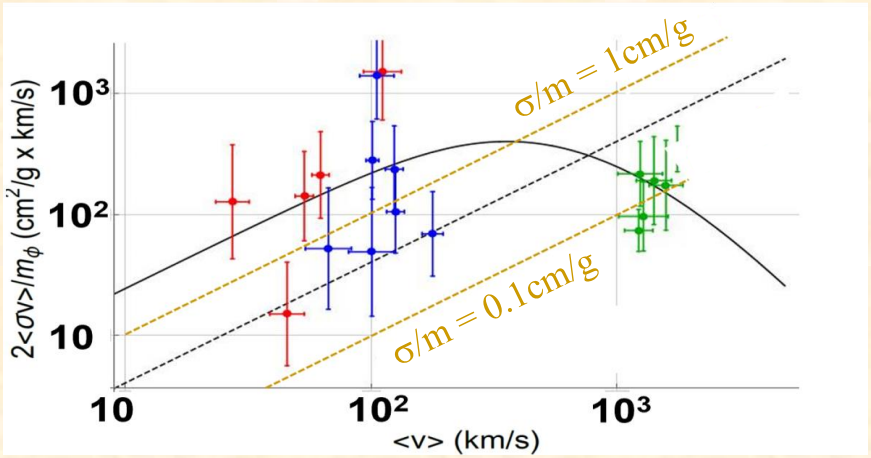


P-wave ann.

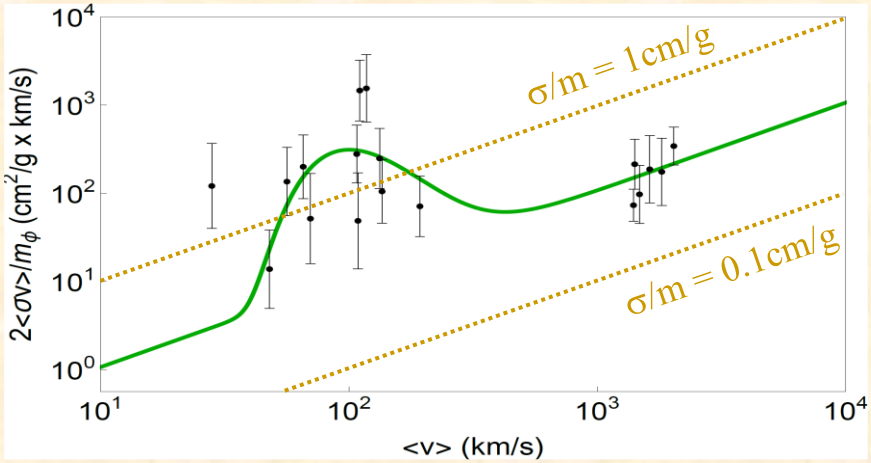
O Scalar DM + Scalar mediator



Resonance ann.



[S. M., Y. Tsai, P. Tseng, JHEP, 2019]



[T. Binder, S. Chakraborti, S. M., Y. Watanabe, 2022]

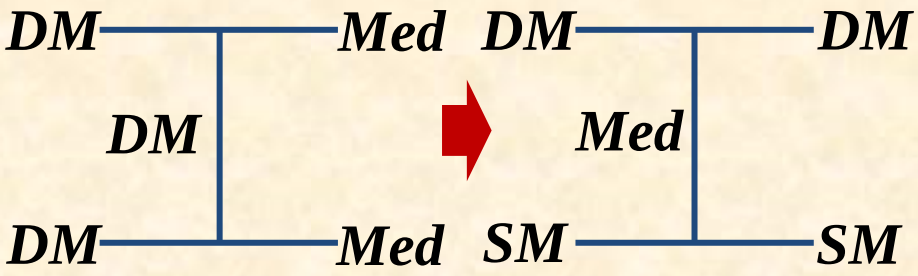
Velocity-dependent ann. leads to velocity-dependent self-scat.

What is the prospect of the DMs at direct DM detection exp.?

Light thermal DM

Possible models:

O Majorana DM + Scalar mediator



P-wave ann.

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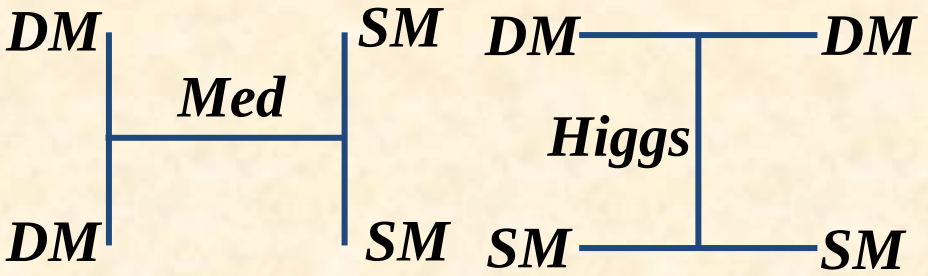

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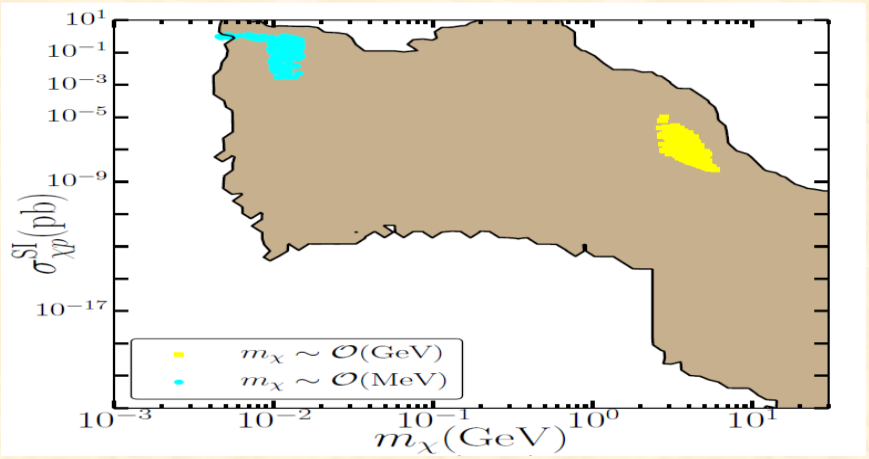

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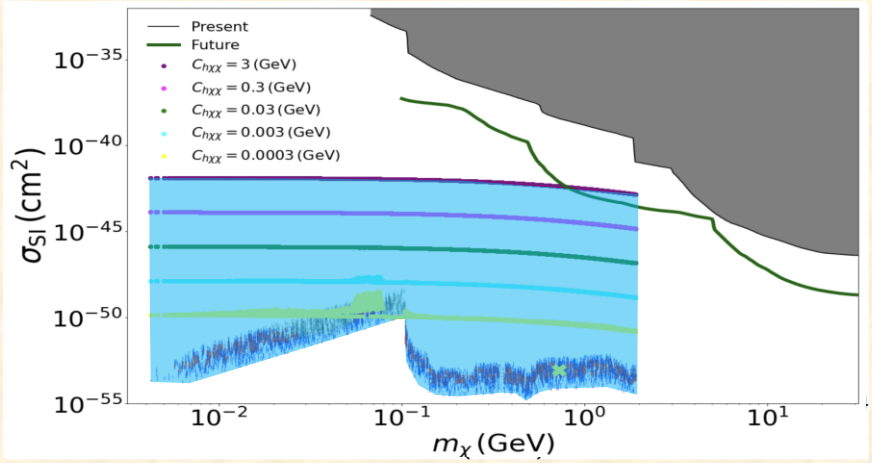


[T. Binder, S. Chakraborti, S. M., Y. Watanabe, 2022]

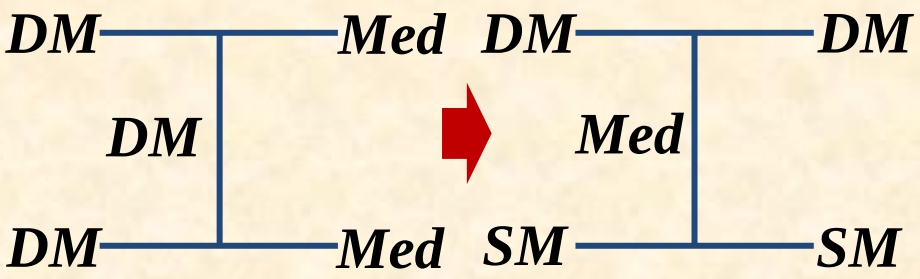
The signal could be as strong as those of future sensitivities!

What is the prospect of the DMs at direct DM detection exp.?

Light thermal DM

Possible models:

- Majorana DM + Scalar mediator
- Scalar DM + Scalar mediator



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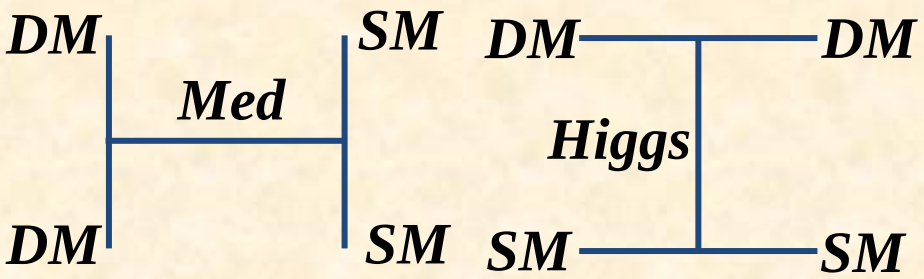

Resonance ann.

Majorana DM + Scalar mediator scenario:

Possible UV completion is NMSSM w/ light singlet/singlino multiplet.

Scalar DM + Scalar mediator scenario:

Interesting UV completion is a strongly-interacting gauge theory in the hidden sector. DM is a hidden meson, while the mediator is from a σ particle. [D. Kondo, R. McGehee, T. Melia, H. Murayama, arXiv: 2205.08088]

[S. M., Y. Tsai, P. Tseng, JHEP, 2019] [T. Binder, S. Chakraborti, S. M., Y. Watanabe, 2022]

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What is the prospect of the DMs at direct DM detection exp.?

Summary

We have discussed some activities of the E01 subgroup, focusing on the direct detection signal of various thermal dark matter candidates.

We have first emphasized that the thermal dark matter with the EW scale mass is being excluded by present direct detection experiments.

Next, we considered the heavy thermal dark matters and found those are yet experimentally uncarted. A large part of the parameter region will be covered by future direct detection experiments, while the rest may be covered by observing the temperature of old pulsars.

We have finally discussed the light thermal dark matters, which may resolve the so-called core & cusp problem. Those recently attracted much attention, and various efforts are being paid to construct their UV models. Using a few phenomenological models, we found that the scattering cross-section between the DM and a nucleon could be as large as 10^{-6}pb, which is within reach of future experiments.