Light Fermionic Thermal Dark Matter with Light Scalar Mediator

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collaborating with
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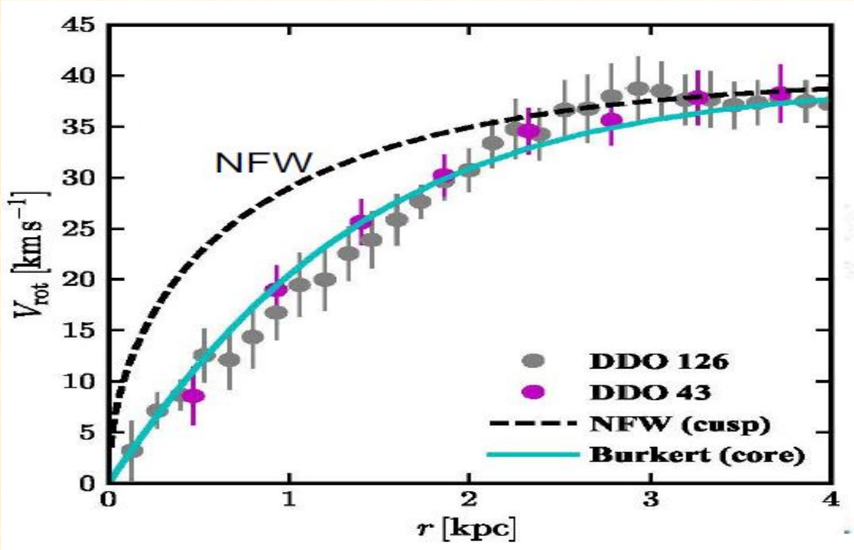
Talk based on JHEP1907 (2019) 050,
& A. Kojima, SM, Y. Tsai, K. Yanagi, 2019?

- **Why** we want to think about a light (<< EW scale) DM?
- **What** is the minimal model of the Light Thermal DM?
- **How** we can test the minimal Light Thermal DM?

Why we want to think about a light DM?

● *Core-cusp problem ⊂ Small Scale Crisis* [Moore, Ben, et al. Nature 370, 1994]



DM profiles of various galaxies are not matched with ΛCDM prediction!

↓

One of solutions to this problem is to use the self-interaction of DMs.

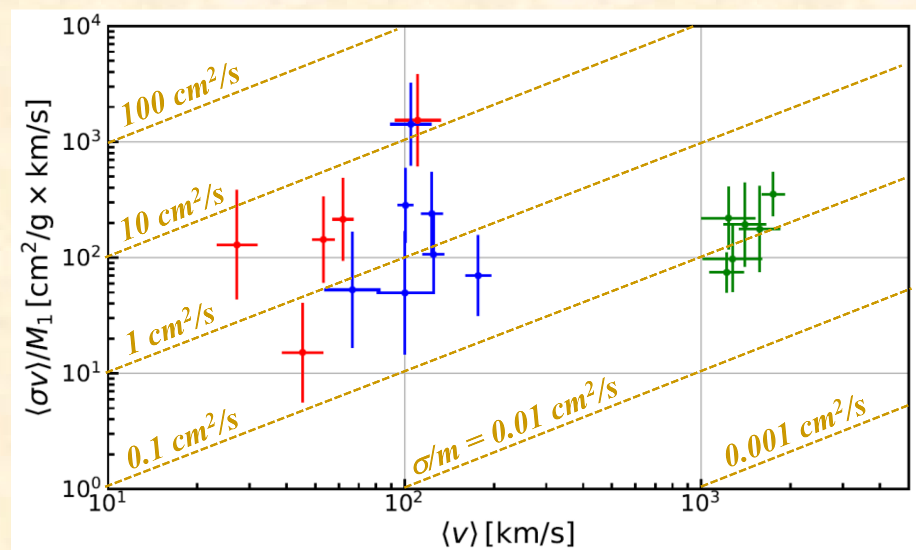
DM density becomes so high that it reaches to a global isothermal equi-librium making the profile cored!

● *Knowledge from observations.*

σ/m >> 0.1[cm^2/g] ~ 1[b/GeV]

It indicates that the mass of DM should be less enough than 1 GeV.

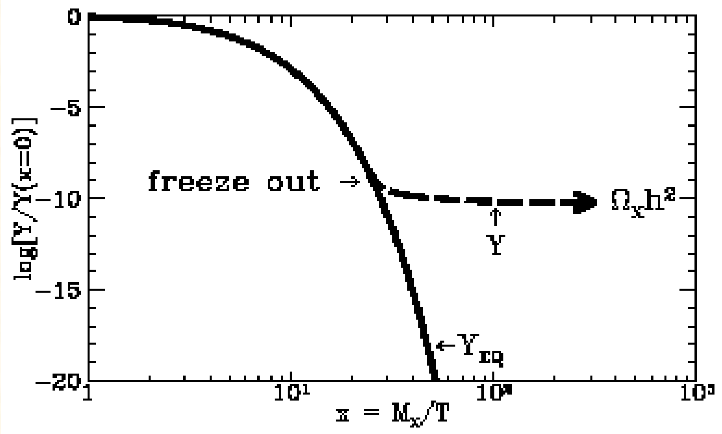
The cross section should be small enough when v ~ 10^{-2}, favoring a velocity-depending scattering.



Let us focus on the thermal DM scenario!

DM abundance was fixed by the so-called thermal freeze-out process!

Freeze-out: Abundance of a species is determined by the competition between the expansion rate of the universe and the reaction rate to maintain equilibrium between the species and SM particles in the universe. This scenario succeeded to explain various cosmological phenomena!



What is nature (spin and various charges) of such a light thermal DM?

Charges: Light DM should not have electric, weak, and color charges, otherwise it should already have been discovered at past experiments. Therefore, the light thermal DM should be singlet under SM gauge int!

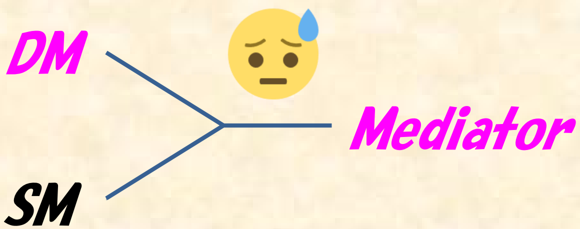
Spin: When light DM is bosonic, it have an interaction with Higgs boson, $DM^2|H|^2$. Its coupling must be large enough to explain the DM abundance observed today, while it induces an invisible Higgs decay with a large branching ratio. Therefore, the light thermal DM should be fermionic!

Light fermionic thermal DM turns out to be favorable for the crisis!

How nice Light fermionic thermal DM is!

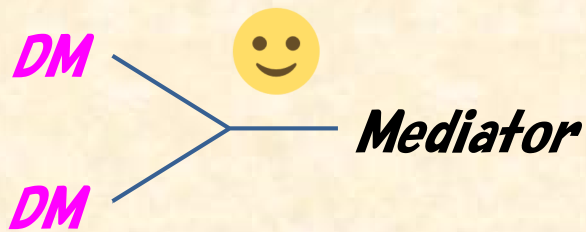
No renormalizable interactions can be written between the DM and SM particles due to the $SU(3)_c \times SU(2)_L \times U(1)_Y$ and Z_2 symmetries, so that we have to introduce an additional new particle called "the mediator".

The mediator must be as light as or lighter than the DM to satisfy the thermal relic condition, leading to the fact that it is singlet & bosonic.



(Z_2-odd mediator)

Or

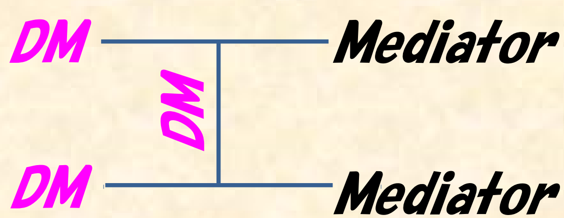


(Z_2-even mediator)

It must be SM singlet, & Bosonic!

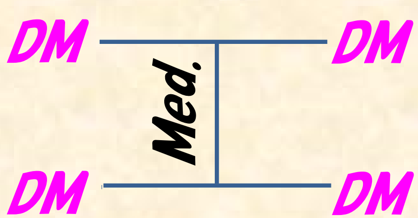
The mediator provides

1. A hierarchy between elastic & inelastic ones.
2. Velocity-dependent scattering among DMs.



(Annihilation)

Vs

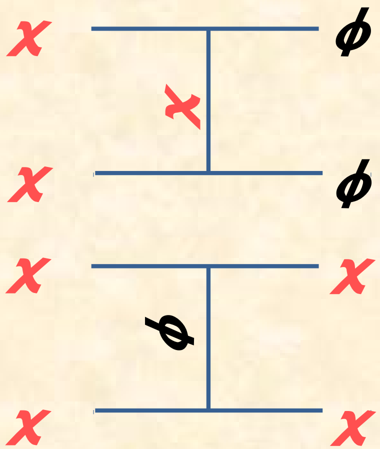


(Scattering)

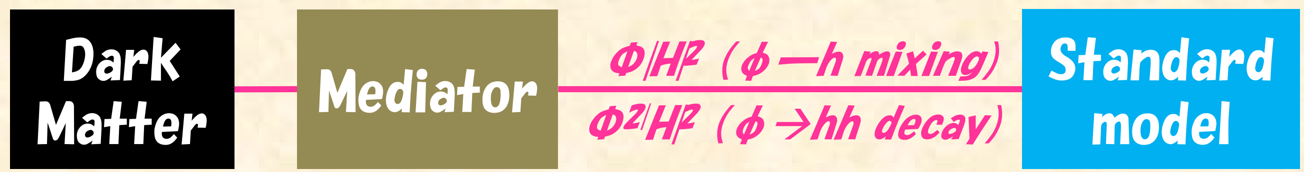
The minimal model of Light fermionic DM?

$$\mathcal{L} \supset -\frac{c_s}{2}\phi\bar{\chi}\chi + A_\phi \phi H^\dagger H + \frac{\lambda_\phi}{2}\phi^2 H^\dagger H + \mu_1^3\phi + \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3}{3!}\phi^3 + \frac{\lambda_4}{4!}\phi^4$$

CP invariance assumed.



The basic structure of the minimal model is as follows:



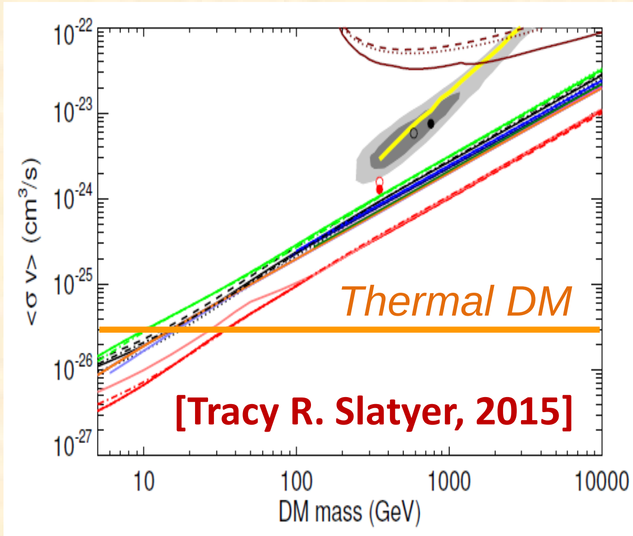
Interactions between ϕ & SM particles must be weak.

#Modal parameters = 7 (m_χ, c_s, $\sin\theta$, m_ϕ, μ_ϕ, μ_3, λ_4)

If a light DM annihilates into SM particles w/o velocity suppression in NR limit, it is difficult to be a thermal DM due to CMB observation. →

For the case of a scalar mediator, χ χ → ϕ ϕ with ϕ → SMs, the annihilation cross section is velocity-suppressed if CP is conserved.

For the vector mediator case, the annihilation is not velocity-suppressed. Careful MB needed.

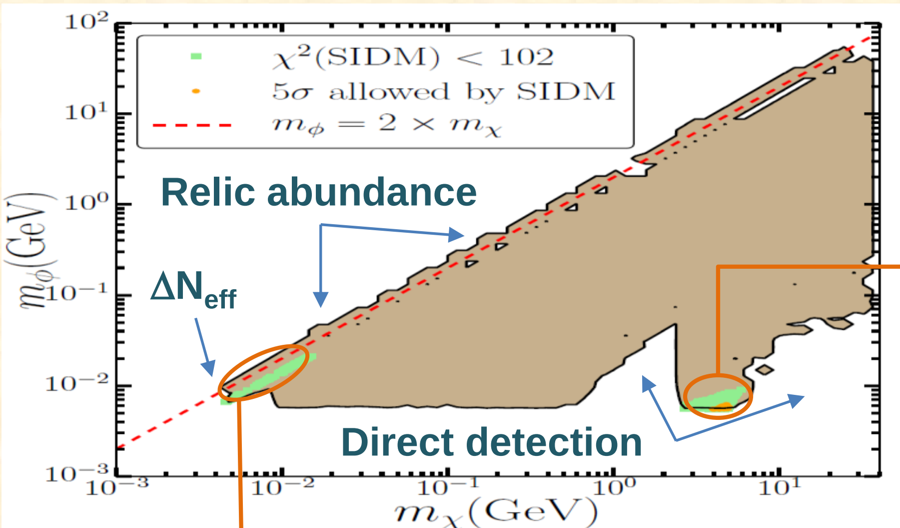


Constraints on the model

Relic Abundance & Thermal cond.	PLANCK
Direct dark matter detection	XENON1T, etc.
ΔN eff at Recombination epoch.	PLANCK
Big Bang Nucleosynthesis (BBN)	1605.07195, etc.
Υ decay with prompt ϕ decay	CLEO, BaBar
B decay with prompt ϕ decay	Belle, LHCb, etc.
〃 with displaced ϕ decay	BaBar, LHCb
〃 with long-lived ϕ decay	Belle, BaBar
K decay with prompt ϕ decay	NA48/2, KTeV
〃 with displaced ϕ decay	CHARM
〃 with long-lived ϕ decay	E949, KEK E931
H decay with prompt ϕ decay	LHC
〃 with displaced ϕ decay	LHC
〃 with long-lived ϕ decay	LHC
Direct ϕ production @ Colliders	LEP

Favored parameter regions

Scan 7D parameter scape & cast the result on an appropriate 2D plane.



Light mediator region (m_ϕ << m_χ)

- ✓ Annihilation mode: $\chi\chi \to \phi\phi$
- ✓ Scattering mode: ϕ exchange

DM mass is required to be O(1)GeV to have a v-dependent X-section.

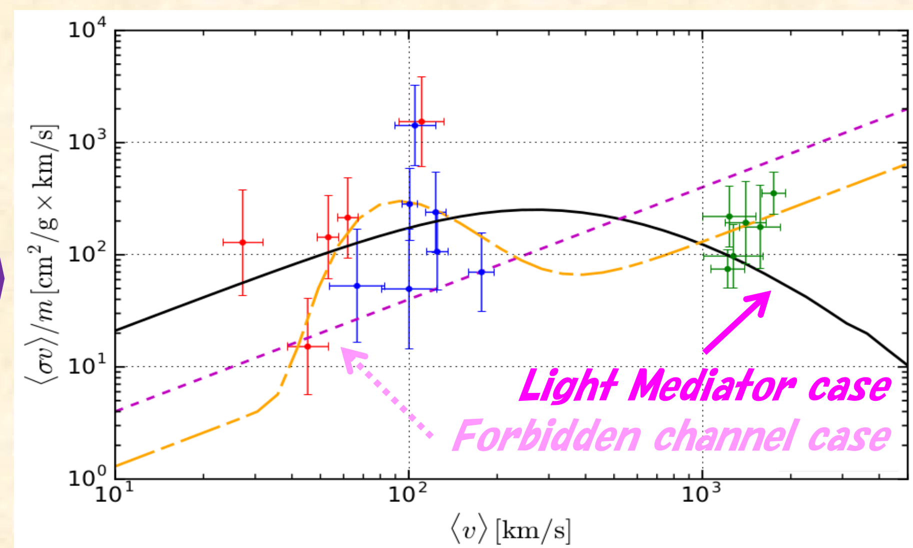
ϕ couples to SM sector via $\Phi^2|H|^2$. (ϕ-h mixing is very suppressed.)

Forbidden channel region (m_ϕ~m_χ)

- ✓ Annihilation mode: $\chi\chi \to \phi\phi$
- ✓ Scattering mode: ϕ exchange

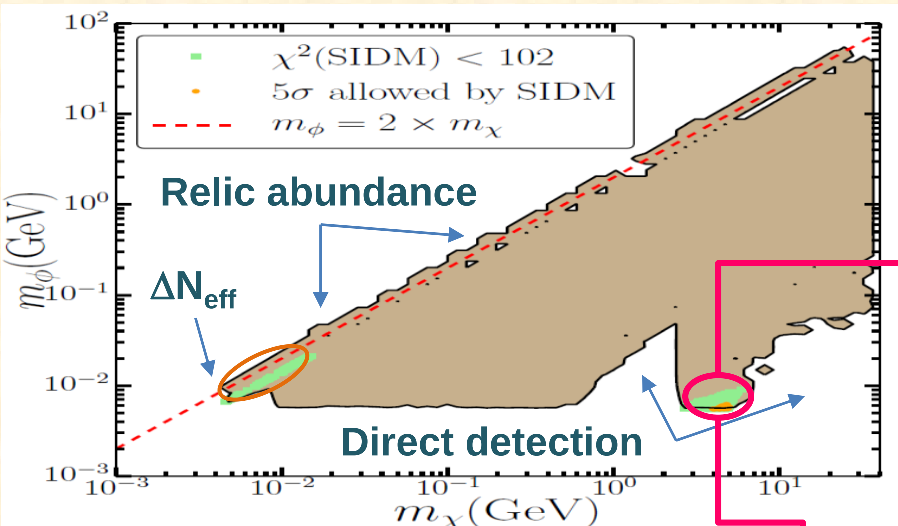
DM mass is required to be smaller than O(10)MeV due to the channel.

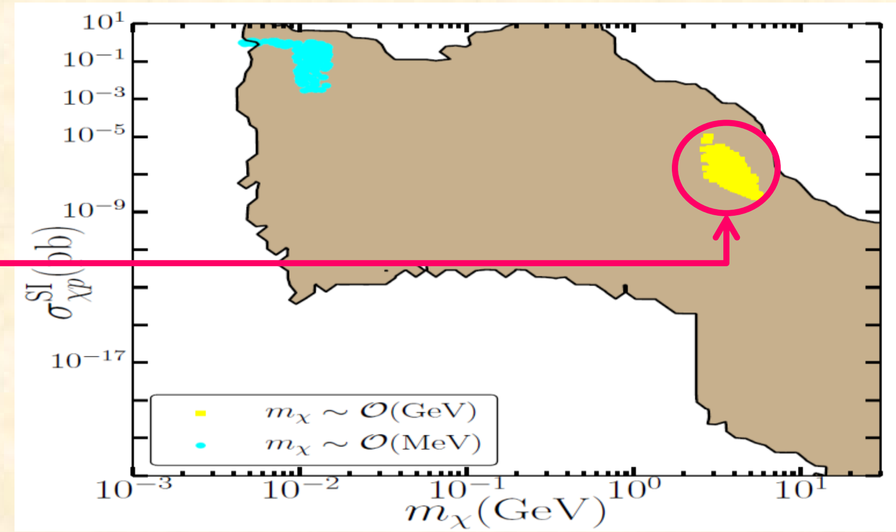
ϕ couples to SM sector by $\Phi|H|^2$ int. (The level of ϕ-h mixing is ~10^{-3}).



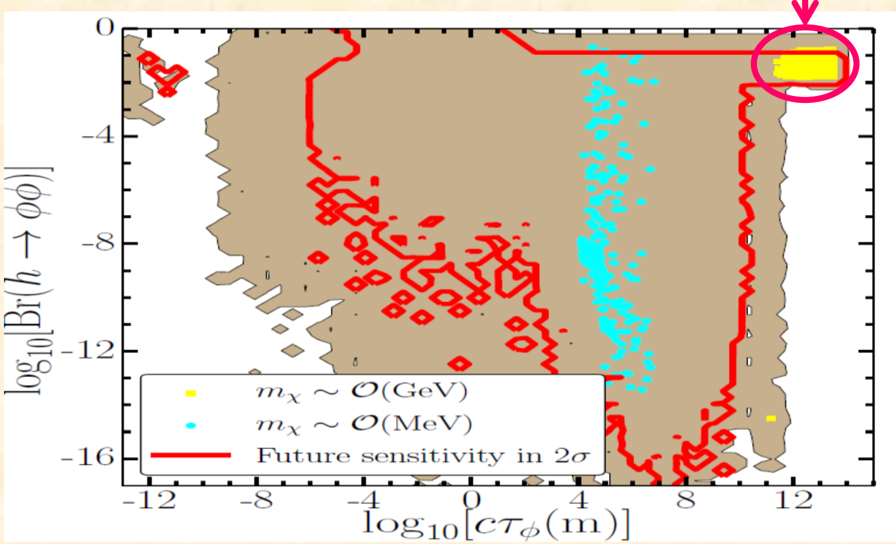
How we can test the regions?

The scanning result is cast on a plane relevant to physical observables.





(Near) future direct detection exp for light DM particle can test the light mediator region of the model.



Higgs invisible width searches at future lepton colliders (ILC, CEPC, FCC-ee, etc.) allows us to test the light mediator region of the model.

Summary

Light fermionic thermal dark matter is attractive from the viewpoint of cosmology (thermal relic abundance & core-cusp problem), because it naturally gives correct mass density of the present universe and a nice velocity-dependent self-scattering cross section among DMs.

We comprehensively analyzed the minimal model of the light thermal fermionic thermal dark matter by taking all robust constraints into account. It is found that a parameter region that can solve the core-cusp problem remains survived, which will be tested in (near) future by direct DM detection, and Higgs invisible width search at colliders.

Backup 1

The light DM must be neutral under $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry!

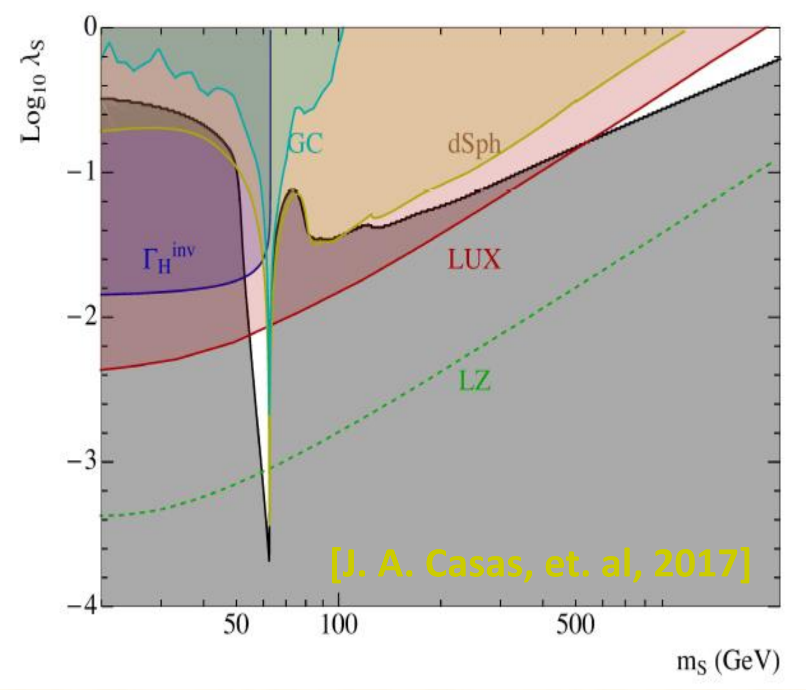
The quantum number of SO(3, 1), the spin of the DM, could be either 0, ½, or 1 if it has a renormalizable interaction to SM below M_{pl} scale.

The mass of the DM is determined by solving the Boltzmann equation.

● The minimal model of a light scalar DM

Z_2 symmetry imposed.

$$\mathcal{L}_{\rm SHP} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_0^2 S^2 - \frac{1}{2}\lambda_S |H|^2 S^2 - \frac{1}{4!}\lambda_4 S^4$$



Light DM region below the EW scale is excluded by the invisible decay width measurement of Higgs boson at LHC.

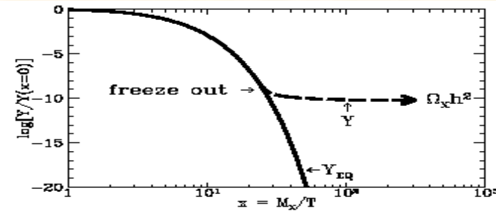
H-resonance region gives a velocity-dependent scattering, but DM mass is too heavy. [X. Chu, et. al, arXiv: 1810.04709]

The self-scattering via S^4 interaction doesn't provide velocity-dependence.

It may be possible to find a favorable model if we go beyond the minimality.

Backup 2

It is implicitly assumed that kinematical equilibrium is maintained between DM and SM particles during the freeze-out process. (Both has the same temp.)

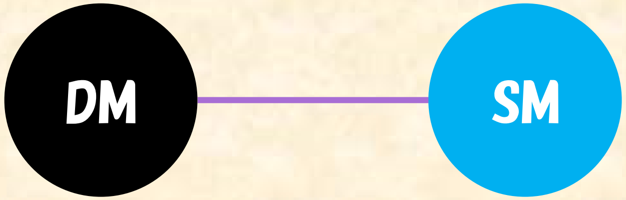


Usual thermal DM:

Annihilation rate: $\Gamma_a \sim \langle\sigma_a v\rangle\, n_{DM}(T_f)$

Scattering rate: $\Gamma_s \sim \langle\sigma_s v\rangle\, n_{SM}(T_f)$

$\therefore\ \Gamma_s >> \Gamma_a$, as $\langle\sigma_a v\rangle \sim \langle\sigma_s v\rangle$ & $n_{SM} >> n_{DM}$



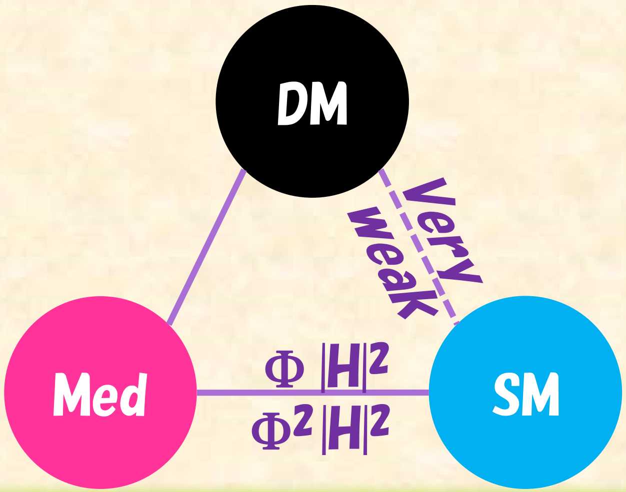
Hence, the kinematical equilibrium condition is automatically satisfied.

Light fermionic thermal DM:

Interaction between DM and SM is very weak.

Mediator was still in the universe during the freeze-out, so that DM can be in equilibrium with SM via the mediator, $T_{DM} \sim T_{med} \sim T_{SM}$.

Magnitude of the interaction, $\Phi|H|^2$ or $\Phi^2|H|^2$, must be large enough for the condition, and it guarantees the strength of some signals.



Backup 3

	Present	Future
Direct dark matter detection	XENON1T, etc.	LZ, NEWS, etc.
ΔN_{eff} at Recombination epoch.	PLANCK	CMB-S4
Big Bang Nucleosynthesis (BBN)	1605.07195, etc.	--------
Υ decay with prompt ϕ decay	CLEO, BaBar	Belle II
B decay with prompt ϕ decay	Belle, LHCb, etc.	Belle II
" with displaced ϕ decay	BaBar, LHCb	Belle II, LHCb
" with long-lived ϕ decay	Belle, BaBar	Belle II
K decay with prompt ϕ decay	NA48/2, KTeV	---------
" with displaced ϕ decay	CHARM	SHiP
" with long-lived ϕ decay	E949, KEK E931	NA62, KOTO
H decay with prompt ϕ decay	LHC	HL-LHC
" with displaced ϕ decay	LHC	(No study)
" with long-lived ϕ decay	LHC	HL-LHC
Direct ϕ production @ Colliders	LEP	(No study)