Light Fermionic Thermal Dark Matter with Light Scalar Mediator

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collaborating with
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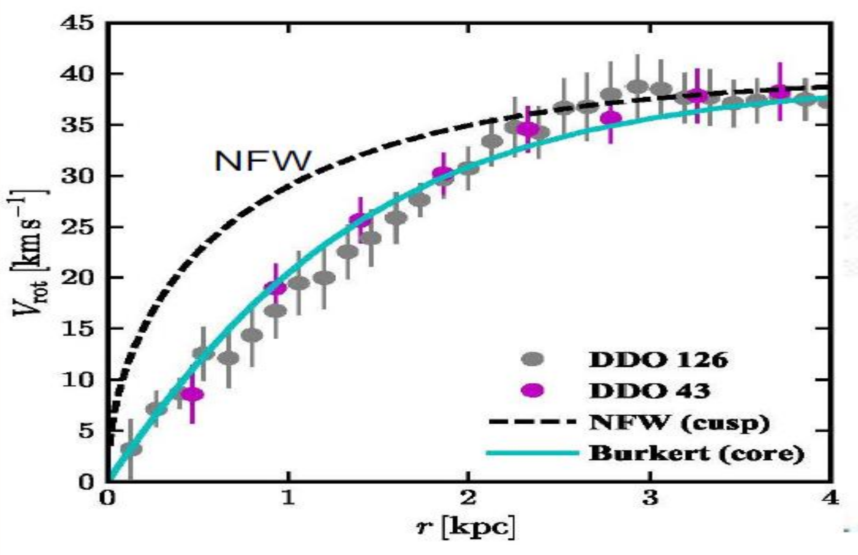
Talk based on arXiv:1811.03292.

- Motivation for a light (< EW scale) dark matter (DM).
- The minimal model of Light Fermionic Thermal DM.
- Physics of Light Fermionic Thermal DM.
- Current status and Future prospects of the model.

Why we are thinking 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.

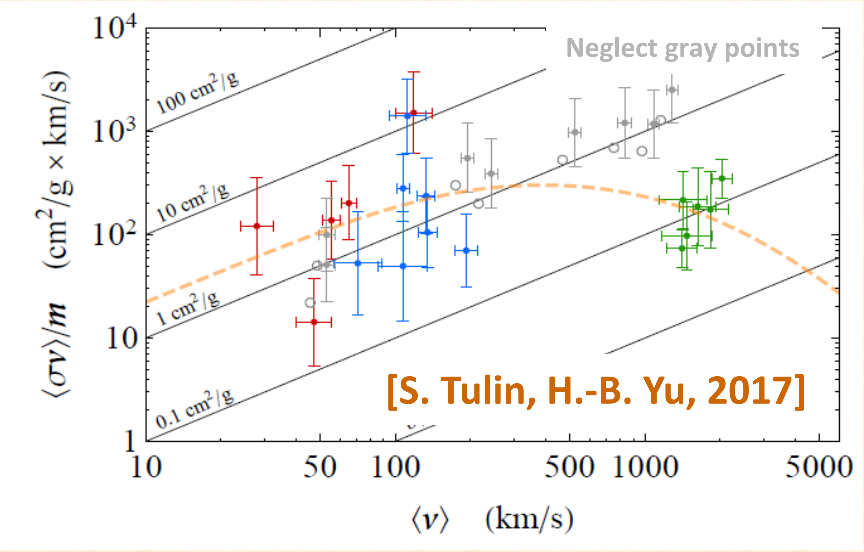
DM density becomes so high that it reaches to a global isothermal equi-librium making the core profile!

● Knowledge from observations.

$\sigma/m >> 0.1[cm^2/g] \sim 1[b/GeV]$

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

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



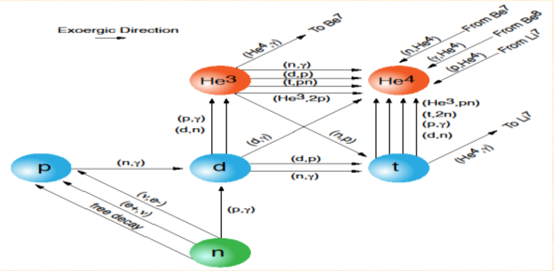
How the DM is created in the Universe?

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 others in the universe.

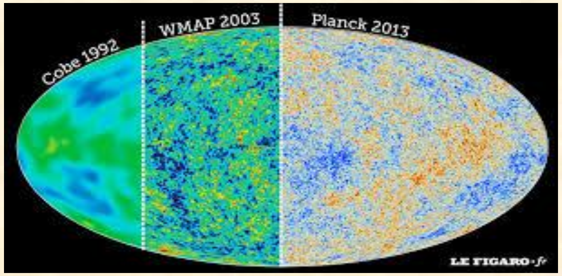
BBN (Success 1)

Abundances of various light elements are from equilibrium and decoupling among the elements.
(Neutron, Proton, Deuteron Helium, Lithium, …)



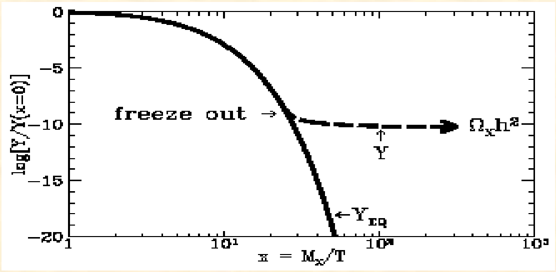
Recombination (Success 2)

Abundance of photons is from equilibrium and decoupling with electrons, ions (protons, etc.).
(Double Compton scattering & Bremsstrahlung)



Dark matter

Abundance of dark matter is from equilibrium and decoupling with standard model particles.
(Predictions: Coldness & $\Omega h^2 \sim 1\,\mathrm{pb}\cdot c/\langle\sigma_a v\rangle$)



Which quantum number the DM should have?

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

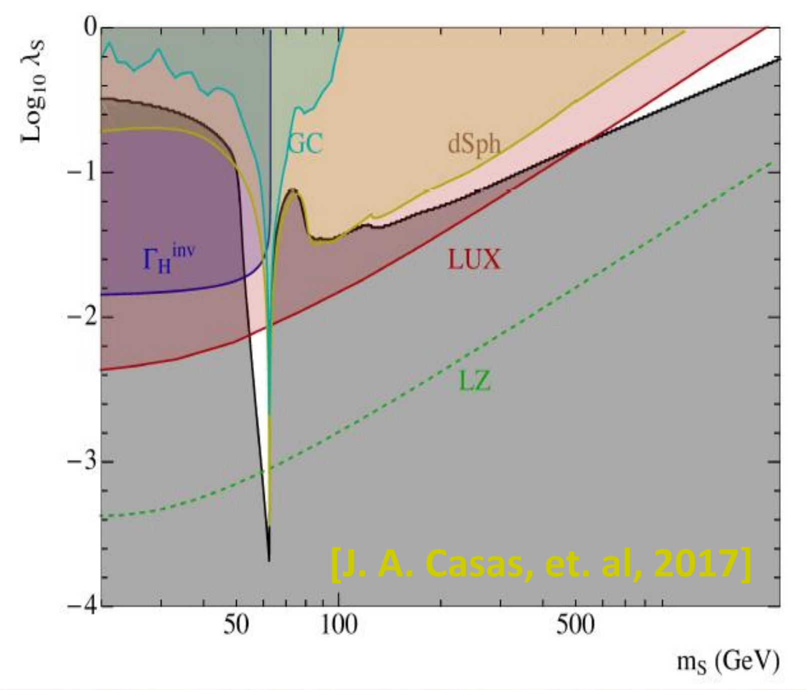
The quantum number of SO(3, 1), the spin of the DM, could be either 0, ½, or 1 if it has a renormalizable interaction to SM below M_{pl} scale.

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.

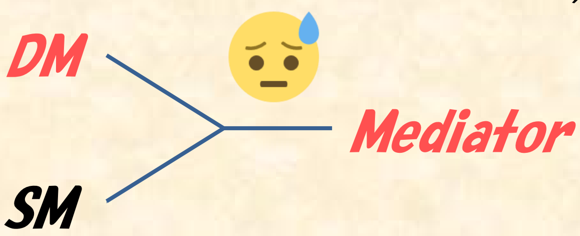
It may be possible to find a favorable model if we go beyond the minimality.

How about a light fermionic DM?

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".

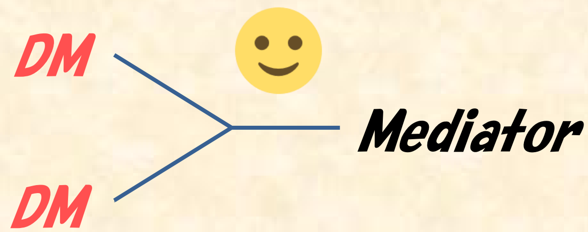
↓

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.



(Z₂-odd mediator)

OR.



(Z₂-even mediator)

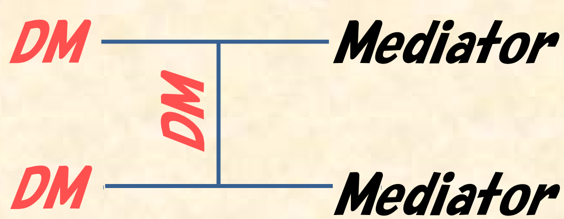
← It must be SM singlet, & Bosonic!

↓

Light mediator is welcome from the "core-cusp problem" viewpoint!

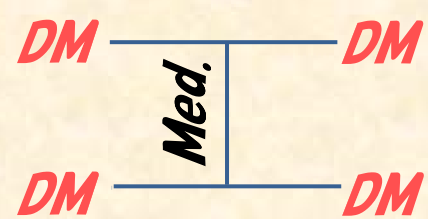
The mediator provides

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



(Annihilation)

VS.

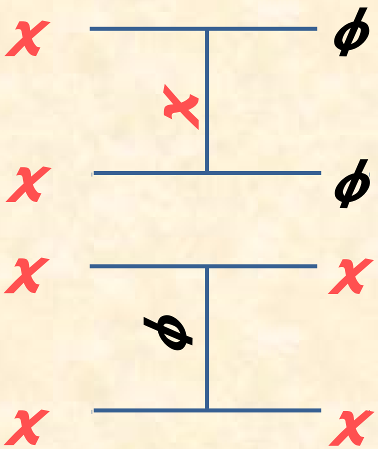


(Scattering)

The minimal model for a light fermionic DM

Scalar mediator case

$$\mathcal{L} \supset -\frac{c_s}{2}\phi\bar{\chi}\chi - \frac{c_p}{2}i\phi\bar{\chi}\gamma^5\chi + A_\phi\,\phi H^\dagger H + \frac{\lambda_\phi}{2}\phi^2 H^\dagger H + \mu_1^3\phi + \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3}{3!}\phi^3 + \frac{\lambda_4}{4!}\phi^4$$



The basic structure of the minimal model is as follows:

Dark Matter — **Mediator** — **Standard model**

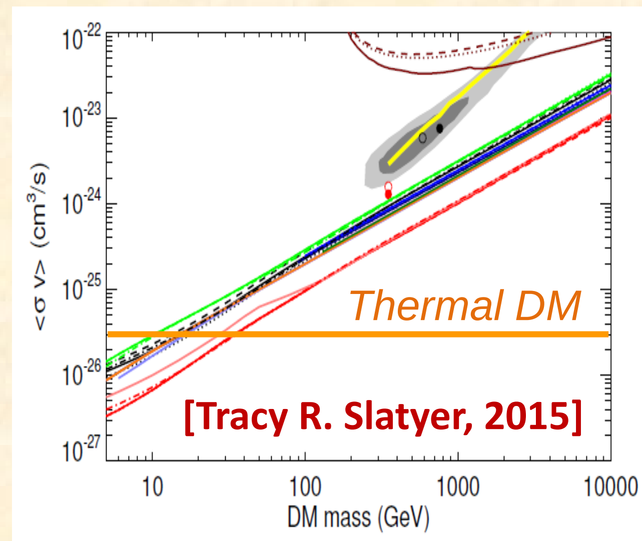
ΦHH (ϕ—h mixing)

Φ ΦHH (ϕ→hh decay)

Interactions between ϕ & SM particles must be weak.

#Modal parameters = 8 (m_χ, c_s, c_p, $\sin\theta$, 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. →



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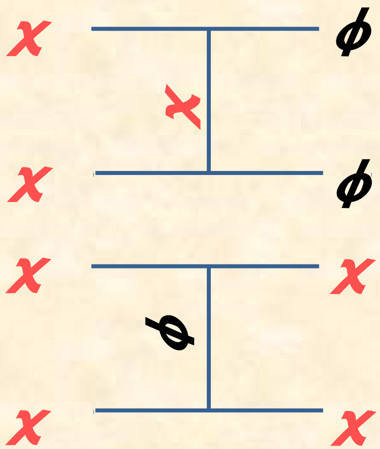

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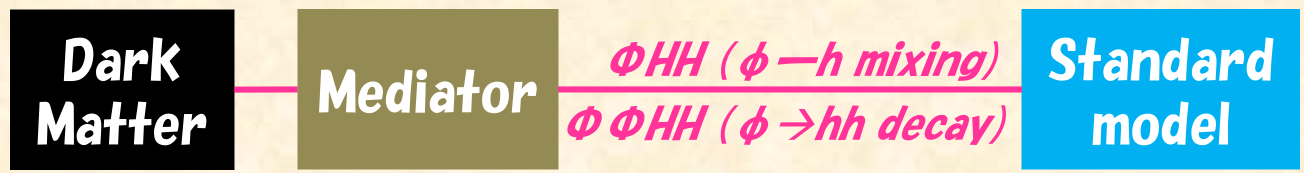

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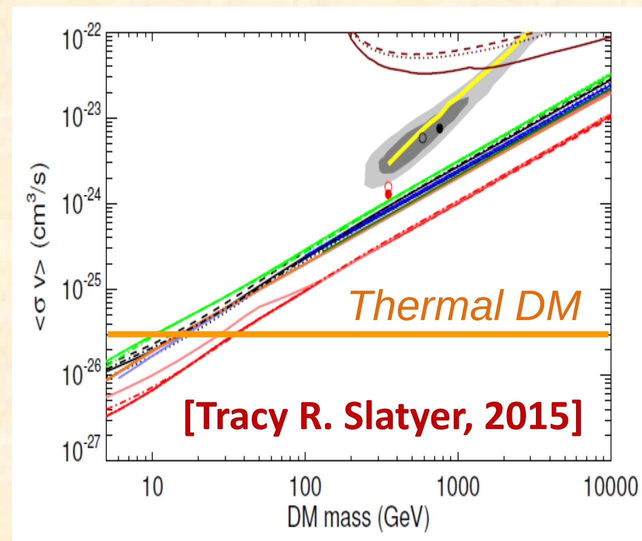
For the case of a scalar mediator, $\chi\chi \to \phi\phi$ with $\phi \to$ SMs, the annihilation cross section is velocity-suppressed if CP is conserved.



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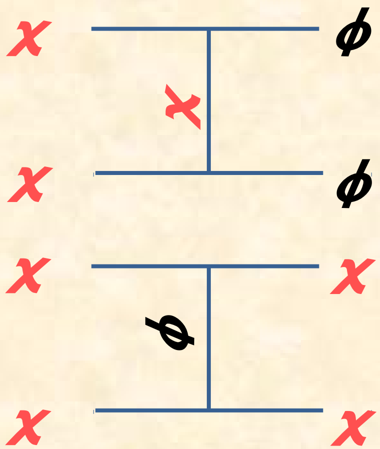

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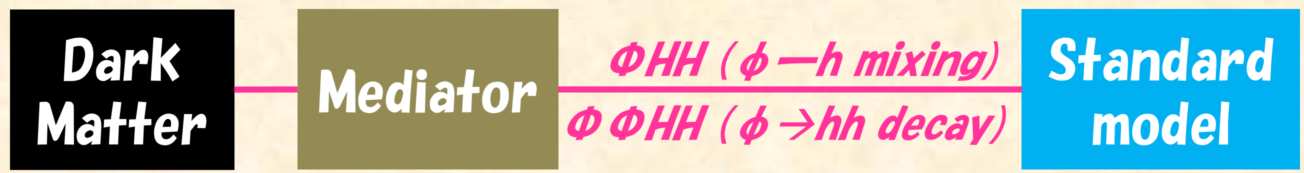

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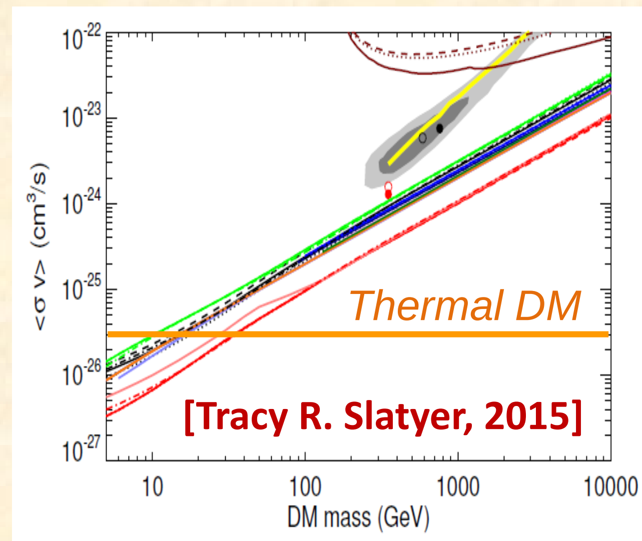
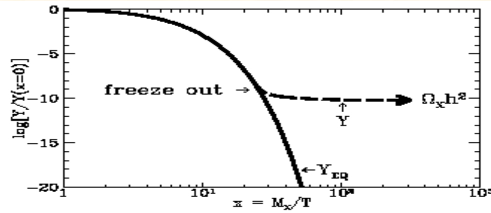
For the vector mediator case, the annihilation is not velocity-suppressed. Careful MB needed.



Kinematical equilibrium condition

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

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

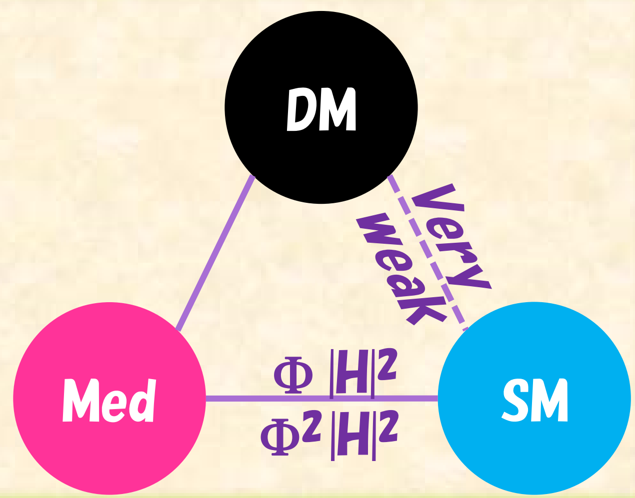
Hence, the kinematical equilibrium condition is automatically satisfied.

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.



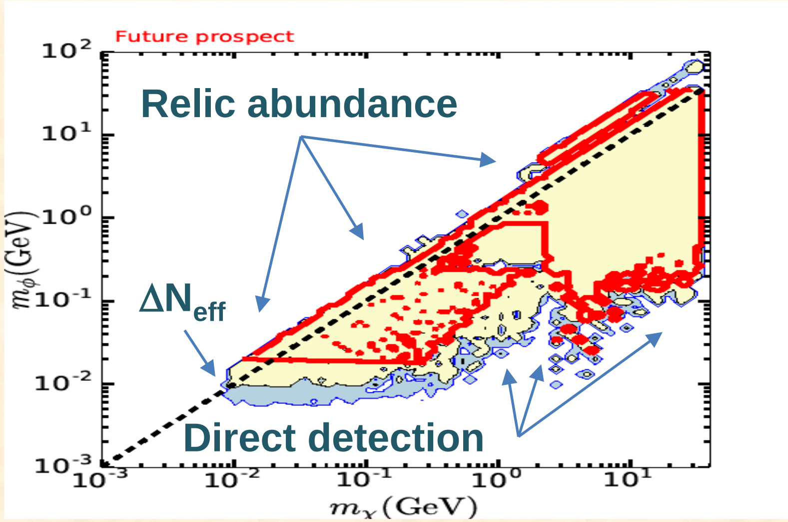
(Expected) Constraints

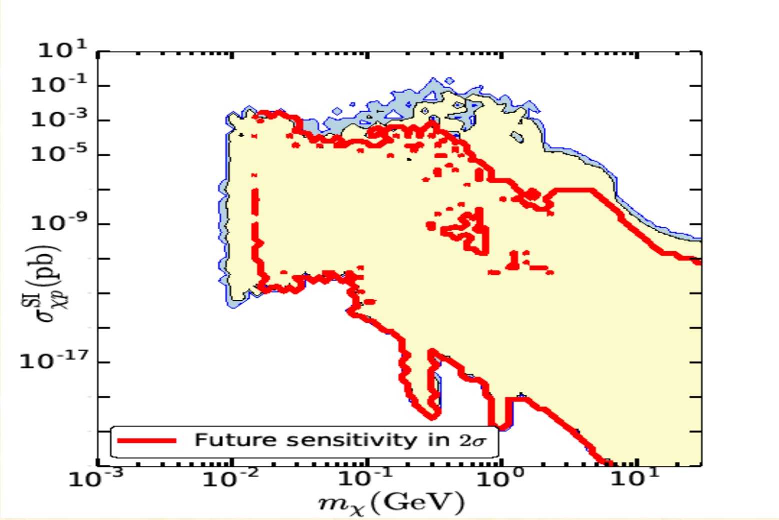
	Present	Future
Direct dark matter detection	XENON1T, etc.	LZ, NEWS, etc.
ΔN_{eff} at Recombination epoch.	PLANCK	CMB-S4
Big Bang Nucleosynthesis (BBN)	1605.07195, etc.	--------
Υ decay with prompt ϕ decay	CLEO, BaBar	Belle II
B decay with prompt ϕ decay	Belle, LHCb, etc.	Belle II
" with displaced ϕ decay	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)

Results of Global scanning

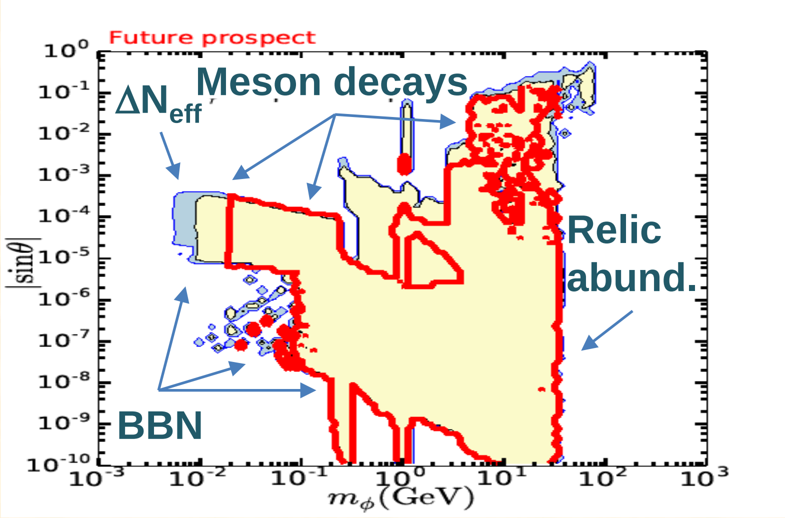
Scan 7D parameter scape & cast the result on an appropriate 2D plane.

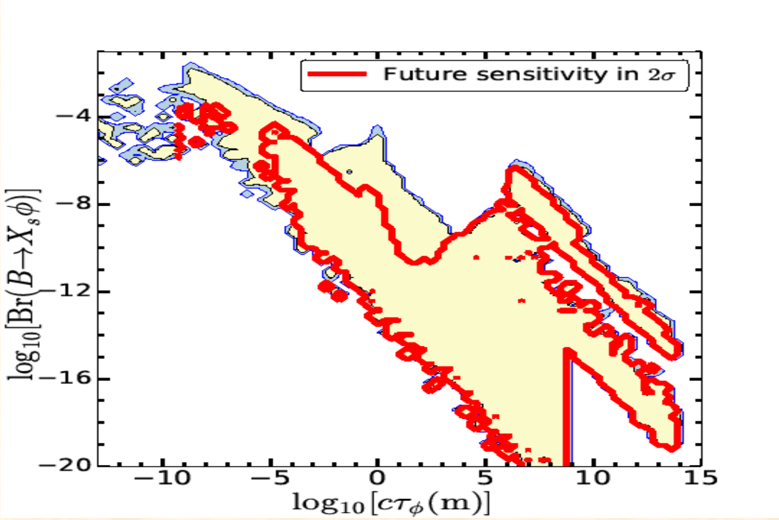
Results on 2D planes that are relevant to Light fermionic thermal DM.



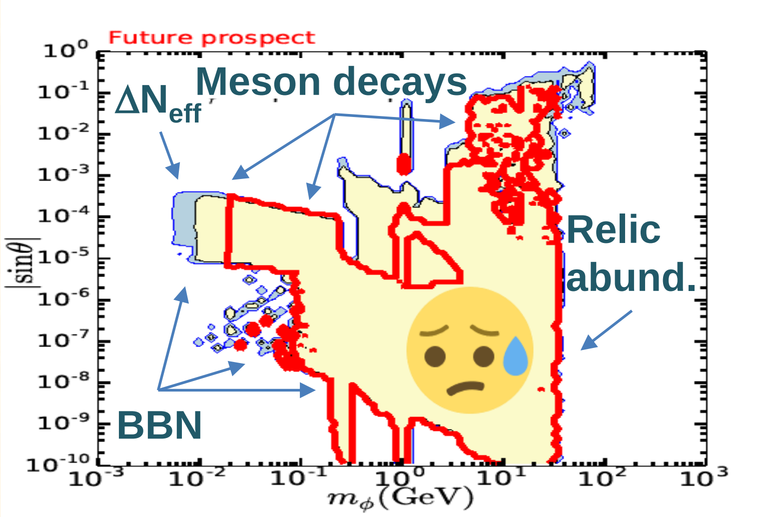


Results on 2D planes that are relevant to the light scalar mediator ϕ.

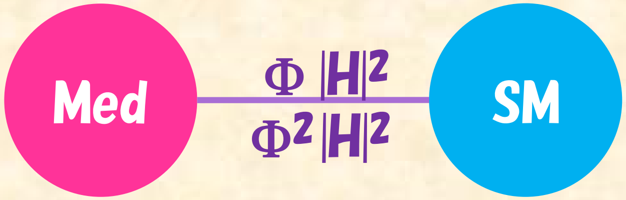




Higgs precision measurements



Interactions between Mediator and SM

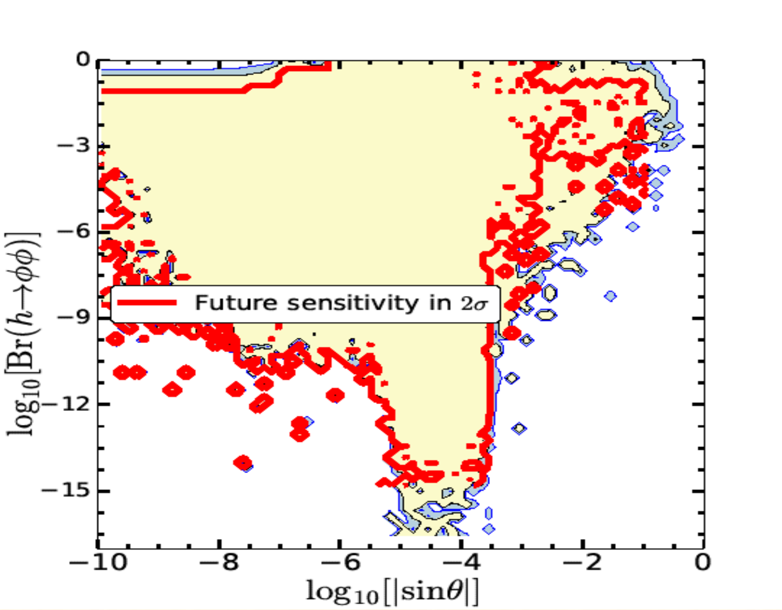


When the mixing angle ($\Phi |H|^2$) is small, the magnitude of another one ($\Phi^2 |H|^2$) must be large enough. → H to $\phi\phi$ decay.

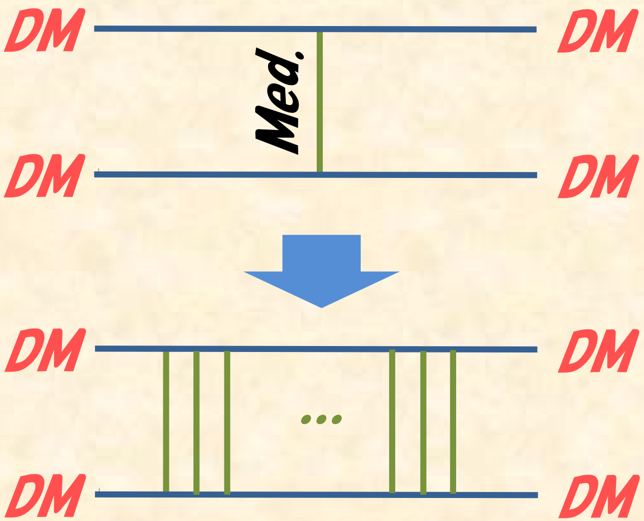
The branching ratio of the H-decay is predicted to be larger when the mixing is smaller, as shown in the right figure.

Future sensitivity line at the left-top corner is from the invisible H-decay search at HL-LHC. It can be tested at O(0.1)% level at future lepton colliders.

The displaced vertex search caused by H to $\phi\phi$ decay makes it more efficient.



Implication to the core-cusp problem

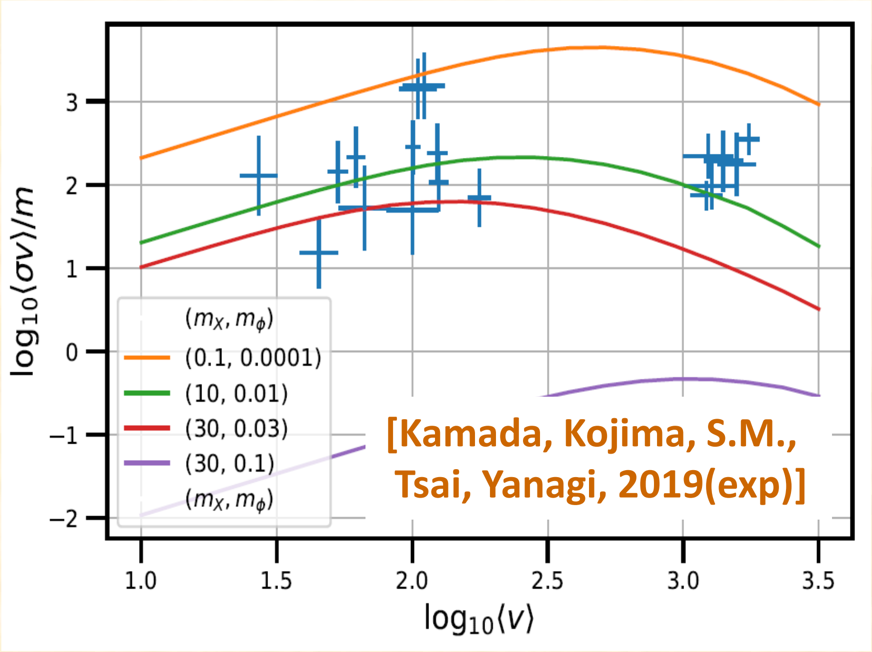


The velocity-dependent self-scattering of DM requires the condition as $m_\phi/m_\chi < 10^{-2}$.

In such a case, a perturbative computation does not work. Instead, we need to solve a Schrodinger equation in an efficient way.

Then, the cross section is suppressed at $v > 10^{-2}$, while it is constant at $v \ll 10^{-2}$.

Velocity-dependence of the cross section is shown for several sets of parameters & observation data.



Which a parameter region remains consistent with observation data requires a global scanning, which is now on-going & reported soon.

It becomes possible to figure out how it is tested at colliders, etc.

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 velocity-dependent self-scattering cross section of the dark matter.

We comprehensively analyzed the minimal model of the light fermionic thermal dark matter taking all robust constraints into account. It is found that a wide parameter region remains survived and yet remains uncharted in near future. Higgs precision measurements focusing on its exotic decays play an important role to test the uncarted region.