Light Neutrinophilic Thermal Dark Matter

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arXiv:2601.09310

The Nature of Dark Matter

- Electrically (almost) neutral
- Stable on cosmological timescales
- Non-relativistic at structure formation
- Present density : 10^{-6} GeV/cm^3
- (Self-interaction)

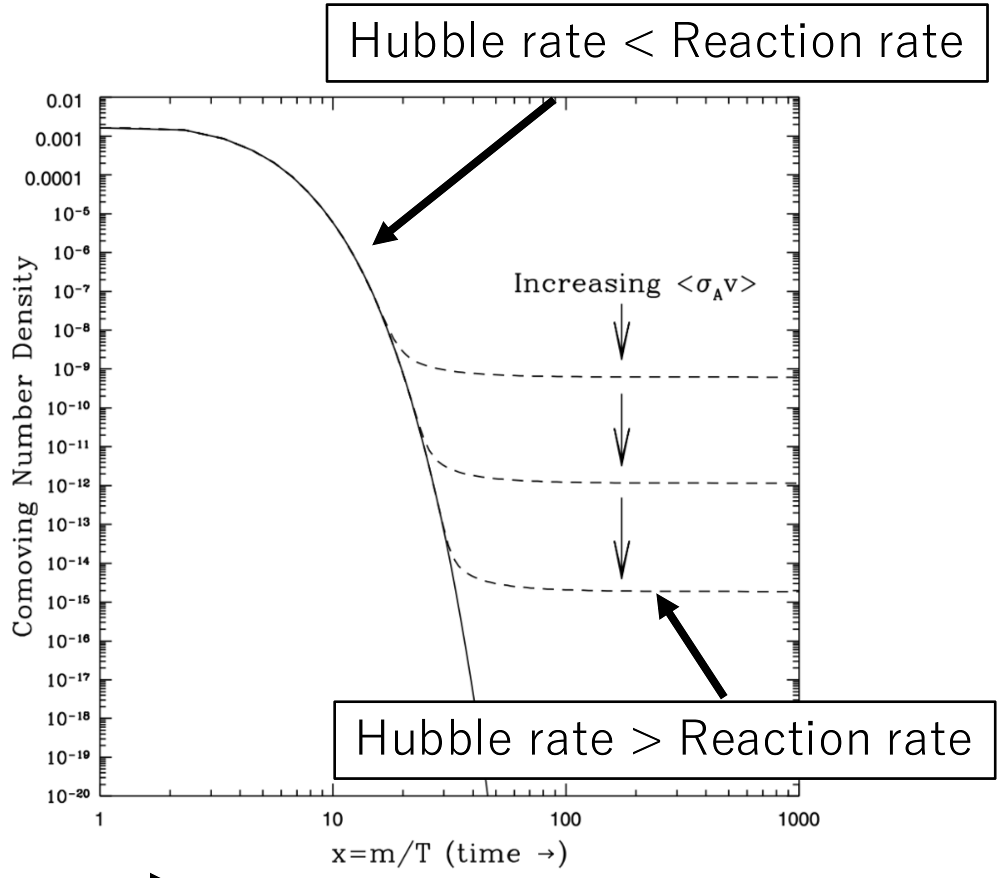
→ MeV Dark Matter as an Attractive Candidate

Dark Matter Present Density

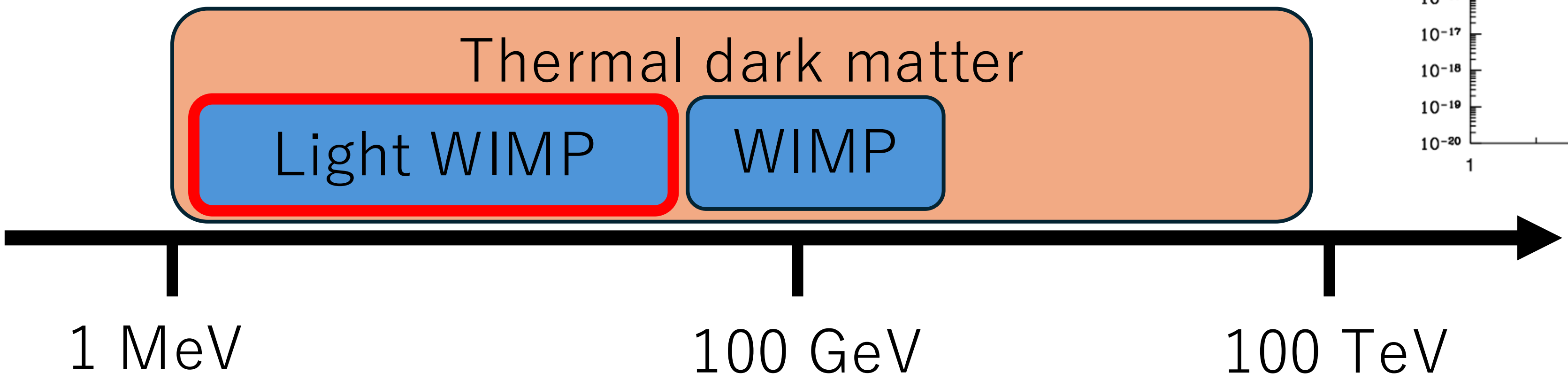
DM density can be explained by Freeze-out mechanism

Advantages

1. Independent from initial condition
2. Same mechanism as BBN
3. Requires a sizable interaction strength



S. Matarrese. et al. Springer (2011)

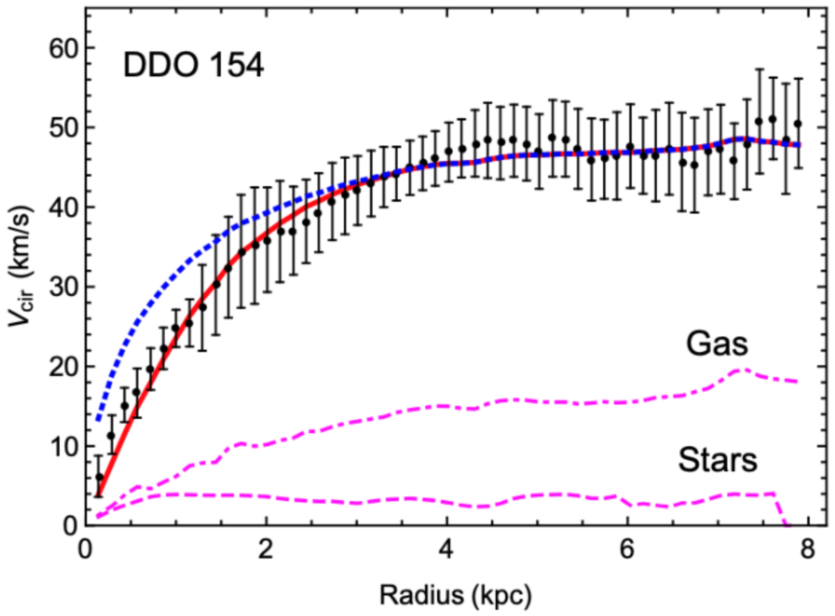


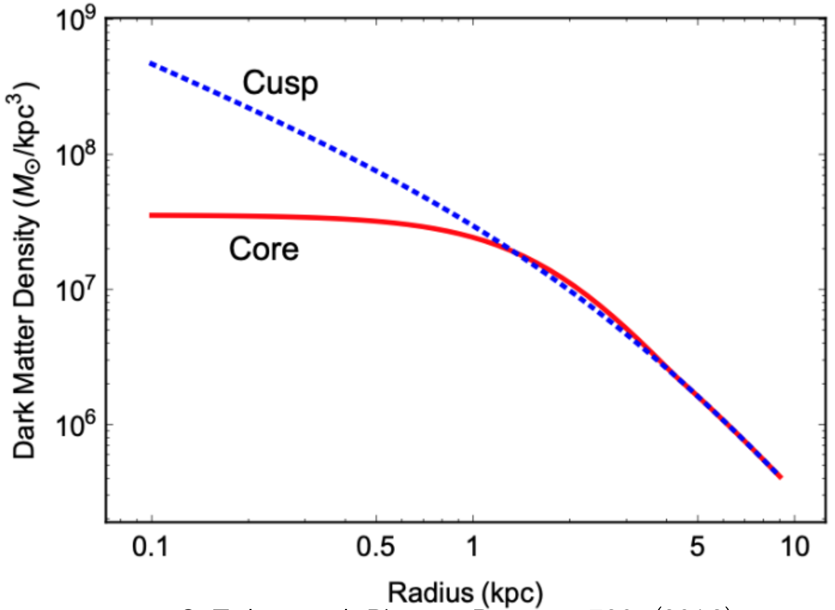
Dark Matter Self-scattering

Some observations indicate that the central DM density is lower than the cuspy NFW profile.
(Core-cusp problem)

One solution : DM self-scattering

For sufficiently strong self-scattering, MeV scale DM is preferred.





S. Tulin. et al. Physics Reports. 730 (2018)

Stringent CMB Bounds on MeV Dark Matter

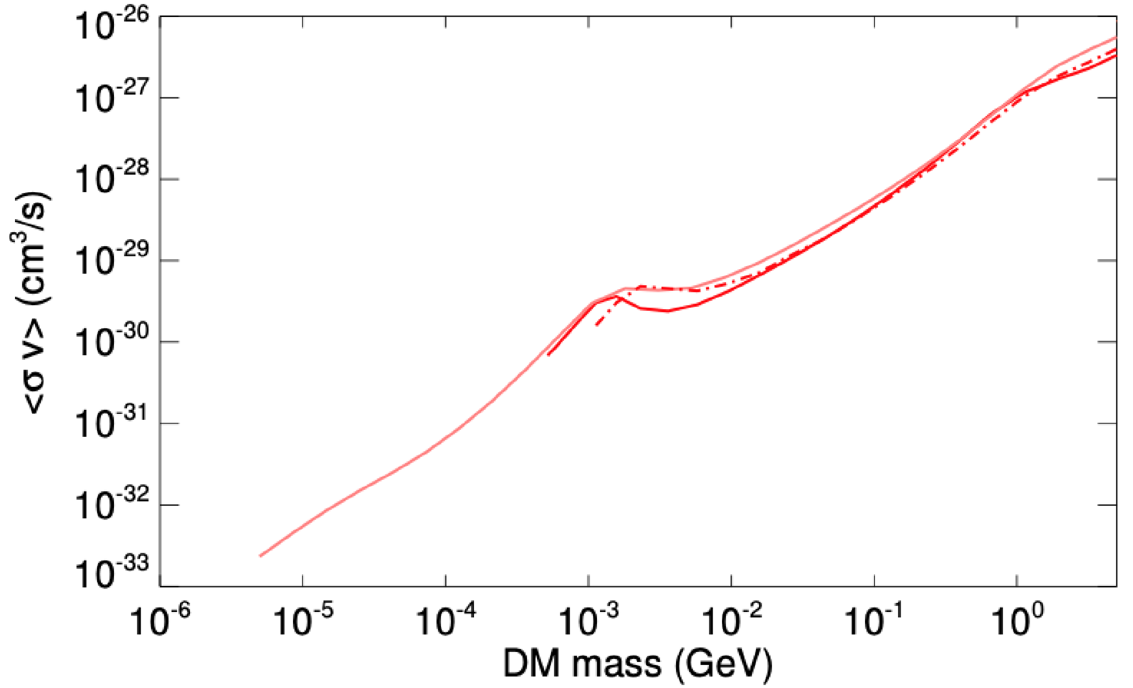
DM annihilation into photons or electrons can reionize neutral hydrogen

Limit on the annihilation cross section for 10 MeV DM

$$\langle \sigma_A v \rangle < 10^{-29} \mathrm{cm}^3/\mathrm{s}$$

Typical annihilation cross section (s-wave) for freeze-out

$$\langle \sigma_A v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$$



T. R. Slatyer. Phys. Rev. D. 93 (2016)

→ We focus on a scnario in which DM annihilates mainly into neutrinos

Model

Introduce a $U(1)_{B-L+xY}$ gauge symmetry(V) and a charged scalar DM(φ).

Three right-handed neutrinos are required to cancel gauge anomaly.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L+xY}$
New Higgs (S)	**1**	**1**	0	2
Right-handed neutrino (N)	**1**	**1**	0	-1
DM (φ)	**1**	**1**	0	q_φ

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm BLxY} + \mathscr{L}_{\rm DM},$$

$$\mathscr{L}_{\rm BLxY} = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + |D_\mu S|^2 + \sum_{i=1}^{3}\bar{N}_i\, i\gamma^\mu D_\mu N_i + V(S,H)$$

$$\mathscr{L}_{\rm DM} = |D_\mu\varphi|^2 - M_\varphi^2|\varphi|^2 - \frac{\lambda_{\varphi H}}{4}|\varphi|^2|H|^2 - \frac{\lambda_{\varphi S}}{4}|\varphi|^2|S|^2 - \frac{\lambda_\varphi}{4}|\varphi|^4$$

Lagrangian below the Electroweak Scale

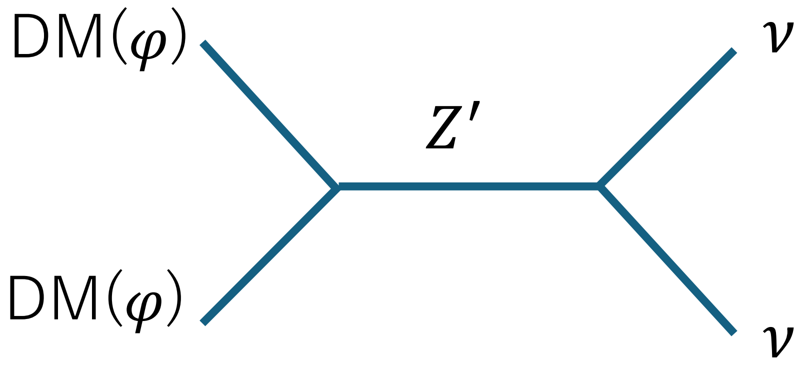
We focus on $x \simeq -1/\cos^2\theta_W$

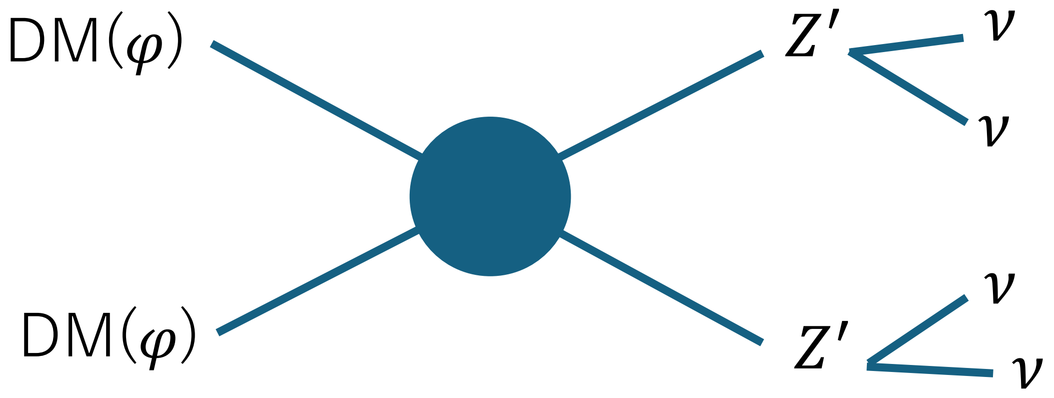
➡ After mass diagonalization of the gauge bosons ($m_Z \gg m_{Z'}$), gauge boson(Z') couples to SM fermions via

$$\mathcal{L}_{\mathrm{EW}} \supset -g_f \bar{f}\gamma^\mu f\, Z'_\mu, \qquad g_f \simeq (B_f - L_f - Q_f)\tilde{g} \quad (Q_f : \text{electric charge})$$

For charged lepton and proton, $B - L - Q = 0$.

➡ When DM is lighter than charged pion ($m_\varphi < 140\ \mathrm{MeV}$), DM annihilates mainly into neutrinos (Neutrinophilic DM)





Constraints on Neutrinophilic Dark Matter

- DM self-scattering（core-cusp problem)
- DM density
- Collider experiment
- Cosmological constraint
- Indirect detection

Condition

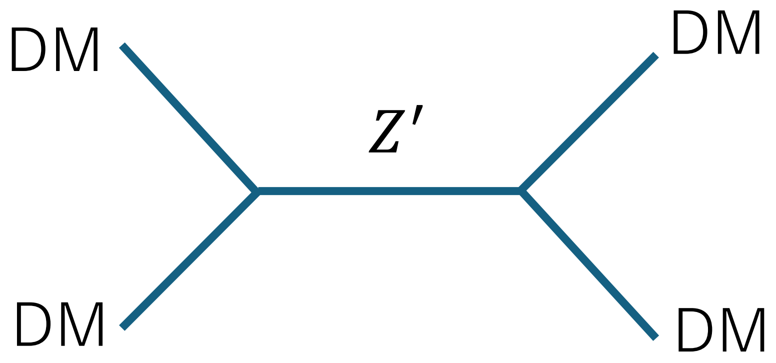
Constraint

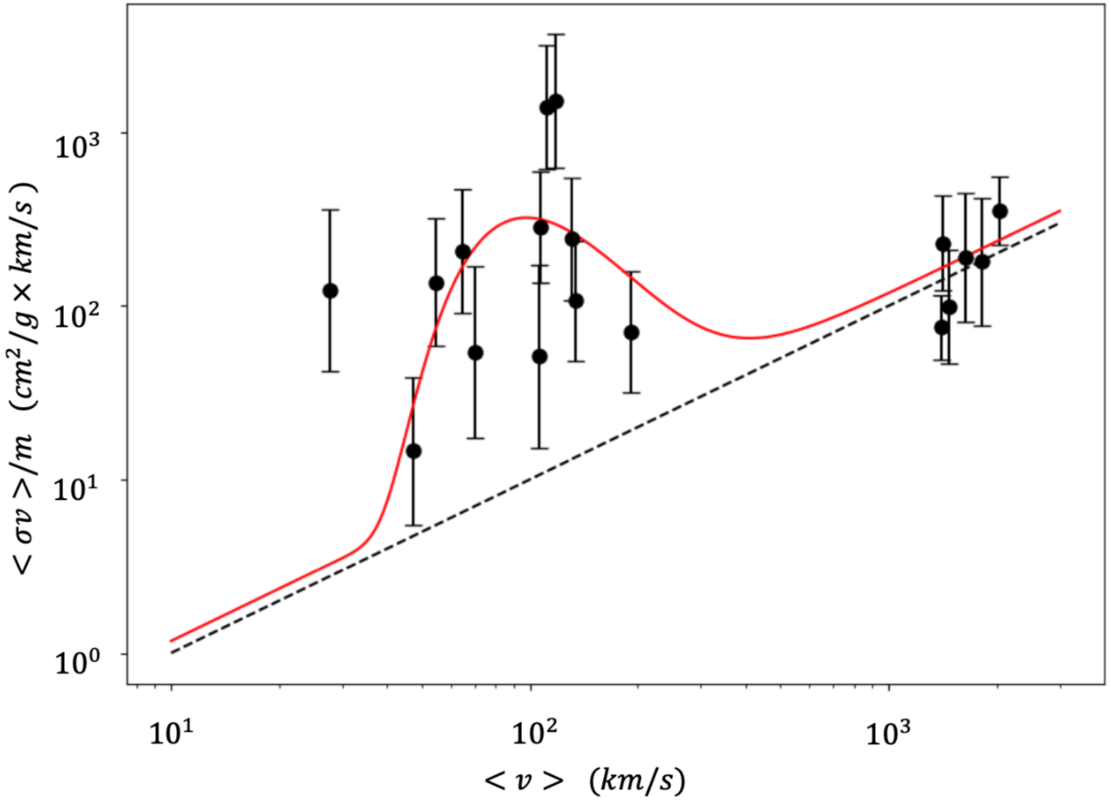
DM Self-scattering Condition

For each galaxy and galaxy cluster, the relative velocity and the dark matter self-scattering cross section are estimated from the central cored region.

Self-scattering is enhanced at $< v > \sim 100\ km/s$.

It can be realized by the s-channel resonance through Z' pole.





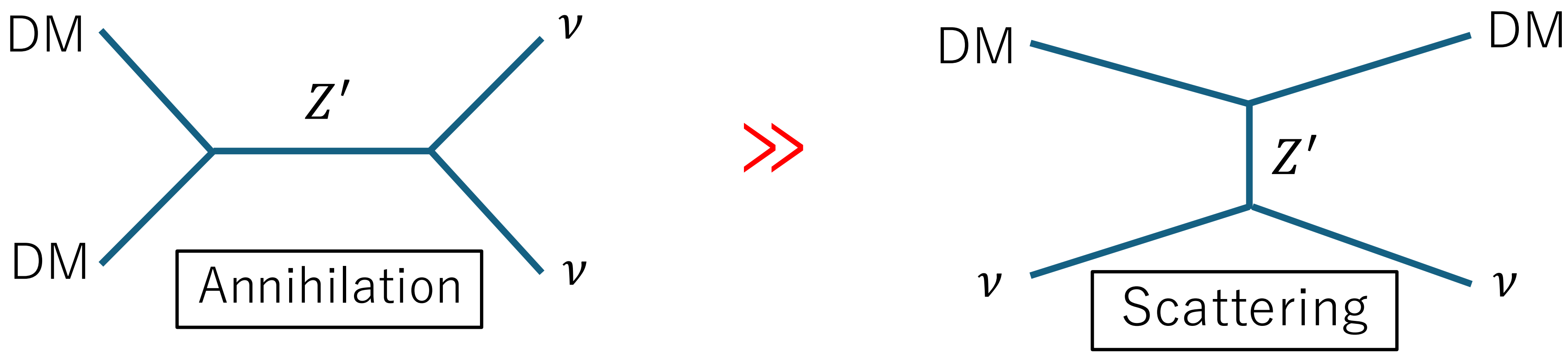
M. Kaplinghat. et. al. Phys. Rev. Lett. 116 (2016)

Dark Matter Density Condition

DM annihilation into neutrinos can also be enhanced by s-channel resonance.

➡ Kinetic decoupling occurs before DM density is fixed, and $T_{DM} \neq T_{\nu}$.

➡ Calculate two Boltzmann equations for density and temperature.



Collider Experiment

The Z' couplings to charged leptons and proton are highly suppressed.

➡ Z' can't be efficiently explored in many collider and beam-dump experiment.

- CEνNS → $\tilde{g} < 1 \times 10^{-4}\,(m_{Z'}/100\,MeV)$ $(m_{Z'} > 100\,MeV)$
- $K^{\pm} \to \pi^{\pm} + Z'$ → $\tilde{g} < 2 \times 10^{-4}\,(m_{Z'}/100\,MeV)$ $(0 < m_{Z'} < 100\,MeV)$

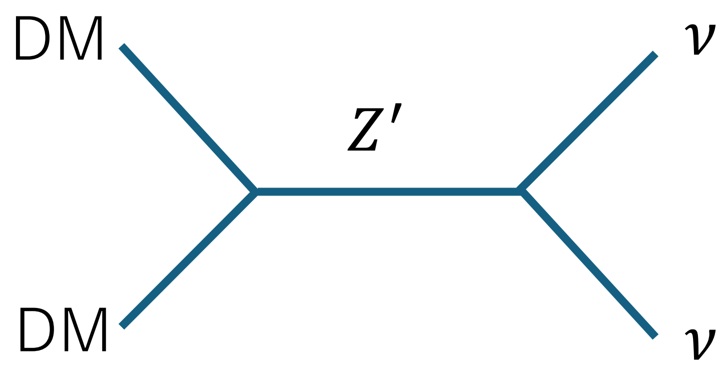
Cosmological Constraint

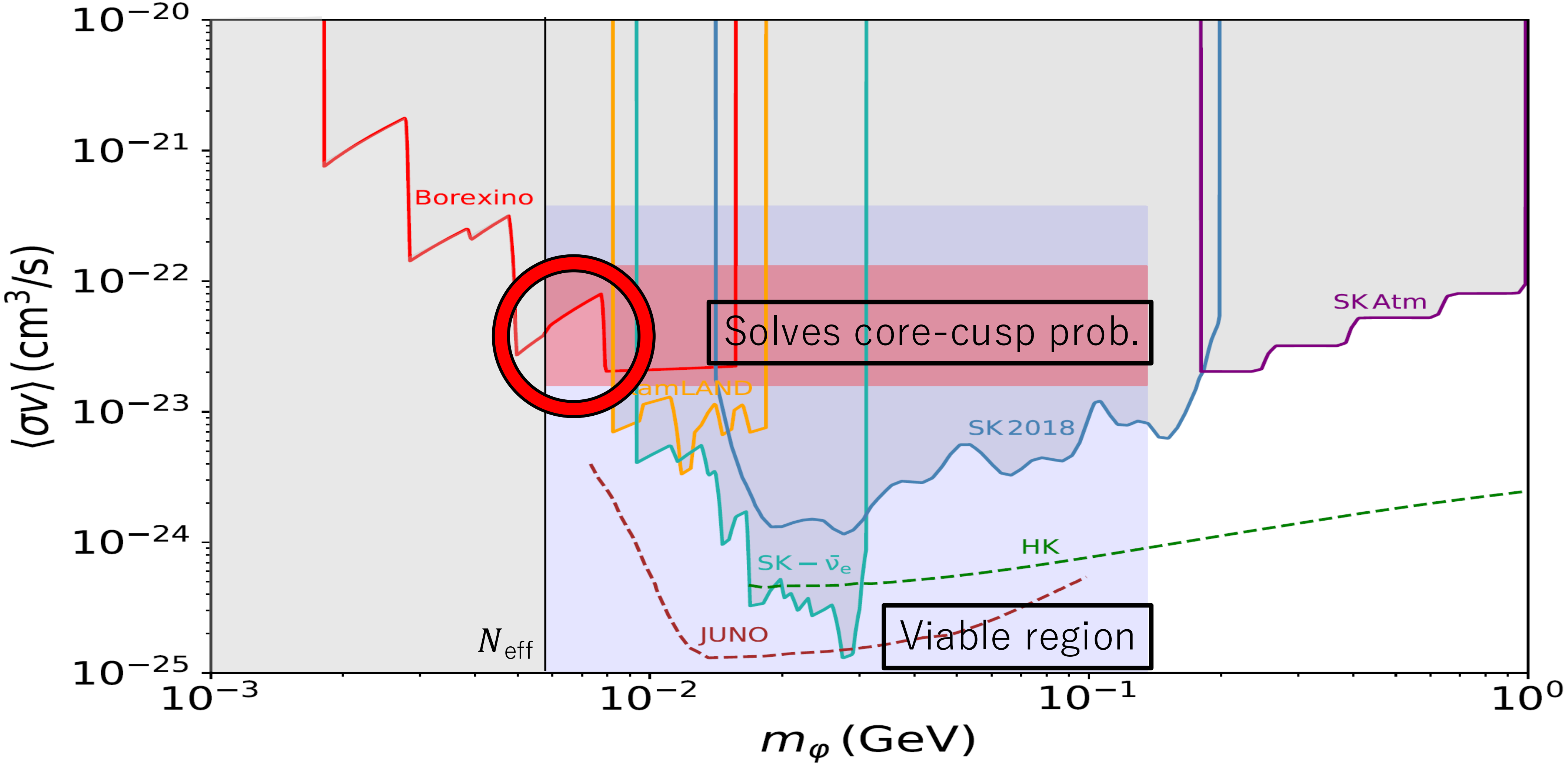
- e.g., $\nu - \nu$ interaction, $\nu - \mathrm{DM}$ interaction in the early universe
- Effective number of relativistic degrees of freedom ($N_{\rm eff}$)

  Given the Hubble tension, we conservatively adopt $N_{\rm eff} \leq 3.57$.

➡ $m_{DM} \geq 6\,MeV$

Indirect Detection (DM DM→ ν ν)





Summary

・We realize the neutrinophilic thermal dark matter model around MeV scale by introducing $U(1)_{B\text{-}L+xY}$ ($x \simeq -1/\cos^2\theta_W$).

・Since this model can evade severe bounds from electron-based experiments, we find that a wide viable region of parameter space still remains. And the part of this region can be probed by neutrino indirect detection searches.

・The parameter region where DM can solve the core-cusp problem also remains, and it can be probed by future CMB observation.