Light fermionic dark matter

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With Ran Huo and Wanqiang Liu,
Based on 1812.05699 and 19XX.XXXXX

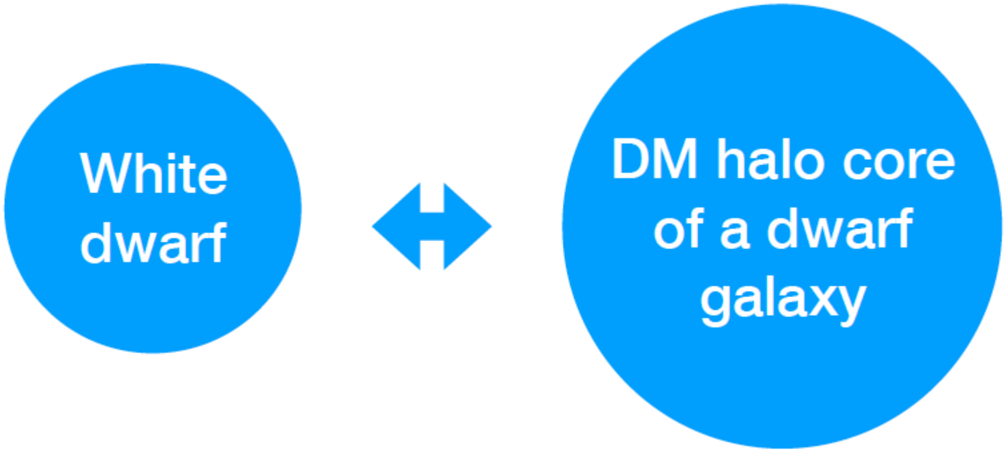
Strong DM and LDM, ESI, Vienna, 2019

Motivations

- Small scale anomalies:
  - Core-cusp
  - Too big to fail
  - Missing satellites
  - …
- Solutions:
  - Baryonic feedback
  - Self-interaction
  - Fuzzy dark matter
  - …

Motivations

- From White dwarves to dwarf galaxies



Tremaine and Gunn PRL 42, 407 (1979).

…

Core-cusp problem fixes m_D

- Dwarf galaxy:
  - 10^8 solar mass
  - Core size 500 pc
  - V ~ 10^{-4}

$$n_D \sim \frac{1}{(2\pi)^3}\frac{4\pi m_D^3 v_F^3}{3}$$

$$\frac{\mathcal{M}_{\rm DG}}{m_D} \sim \frac{4\pi R_{\rm DG}^3}{3} \times n_D$$

$$m_D \sim \left[\frac{(2\pi)^3 \mathcal{M}_{\rm DG}}{(R_{\rm DG} v_F)^3}\left(\frac{3}{4\pi}\right)^2\right]^{1/4}$$

$$= 240\ \text{eV} \times \left(\frac{\mathcal{M}_{\rm DG}}{10^8 M_\odot}\right)^{1/4}\left(\frac{R_{\rm DG}}{500\ \text{pc}}\right)^{-3/4}\left(\frac{v_F}{10^{-4}}\right)^{-3/4}$$

Core-cusp problem fixes m_D

- Dwarf galaxy:
  - 10^8 solar mass
  - Core size 500 pc
  - V ~ 10^{-4}
- $70\ \text{eV} < m_D < 400\ \text{eV}$

L. Randall, J. Scholtz, J. Unwin, Mon. Not. Roy. Astron. Soc. 467, no. 2, 1515 (2017)

- $245\ \text{eV} < m_D < 305\ \text{eV}$

B.G.Glimore, R. Peschanski, arXiv:1806.07283

The constraints

- For light DM if its temperature is comparable to SM, its free streaming length may erase the small scale structure of the universe.
- Lyman-alpha forests observations can detect the structure of the universe down to about a few hundred kpc.
- For warm DM model with two fermionic degrees of freedom,

$$T_{\rm WDM} > 5.3\ {\rm keV}\ (3.5\ {\rm keV})$$

V. Iršič *et al.*, Phys. Rev. D **96**, no. 2, 023522 (2017) doi:10.1103/PhysRevD.96.023522 [arXiv:1702.01764 [astro-ph.CO]].

Warm DM model

- $\rho_{\rm DM} = m_{\rm WDM} \times n_{\rm WDM}$

- In the early universe when DM is relativistic

$$n_{\rm WDM} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} 2T_D^3 \Rightarrow T_D/T_{\rm SM} \approx 0.1$$

$$T_{\rm WDM} > 5.3\ {\rm keV}\ (3.5\ {\rm keV})$$

- In tension with the request for solving the core-cusp problem! (even with much colder DM)

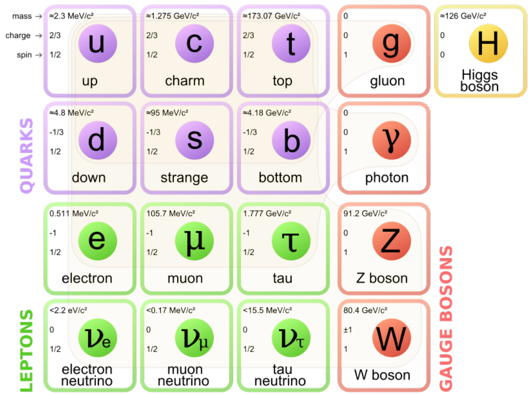
Our goal

- To build a model with O(100) eV fermionic DM which can avoid the Lyman-alpha constraint.

- Two models:

    - Freeze-in self interacting DM
    - Light fermionic DM from scalar decay

Freeze-in model



QED

Dirac fermion, the DM candidate

$$\bar{\chi}(i\gamma^\mu D_\mu - m_D)\chi$$

Connecting the DM to the SM sector

$$-\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V^2$$

$$-\frac{\kappa'}{2}B^{\mu\nu}V_{\mu\nu}$$

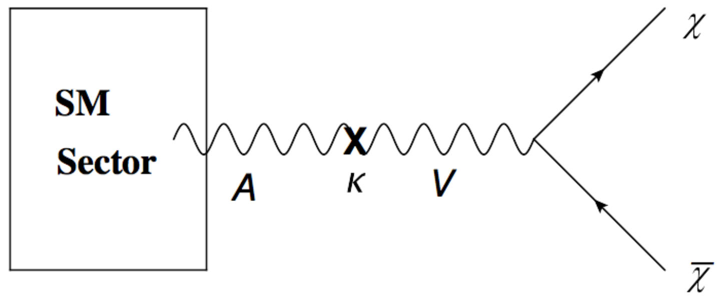
Spontaneous symmetry breaking

$$-\frac{\kappa}{2}F^{\mu\nu}V_{\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{QED}} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \bar{\chi}(\gamma^\mu D_\mu - m_D)\chi$$

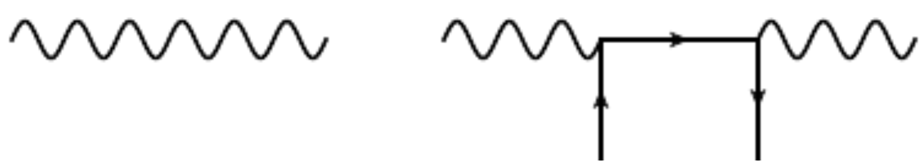
$$m_V \sim 1\ \mathrm{MeV}\ , \quad \alpha_{\mathrm{D}} \sim \alpha_{\mathrm{EM}}\ , \quad \kappa \sim 10^{-11}\ , \quad \mathrm{m_D} \ll \mathrm{m_V}$$

Freeze-in model



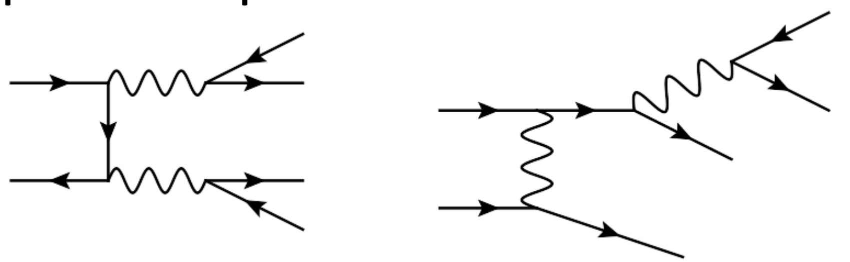
1. $e^+e^- \to \chi\bar{\chi}$

2. Plamson decay   Photon gets a "mass"



Dark sector cools down through self-replication

- 2 to 4 self-replication processes



- If self-replication is fast enough, the DM can be seen as a thermal relic. (warm dark matter)

$$f(E) = \frac{g_D}{1 + \exp(E/T_D)}$$

Relic abundance

- Boltzmann equation

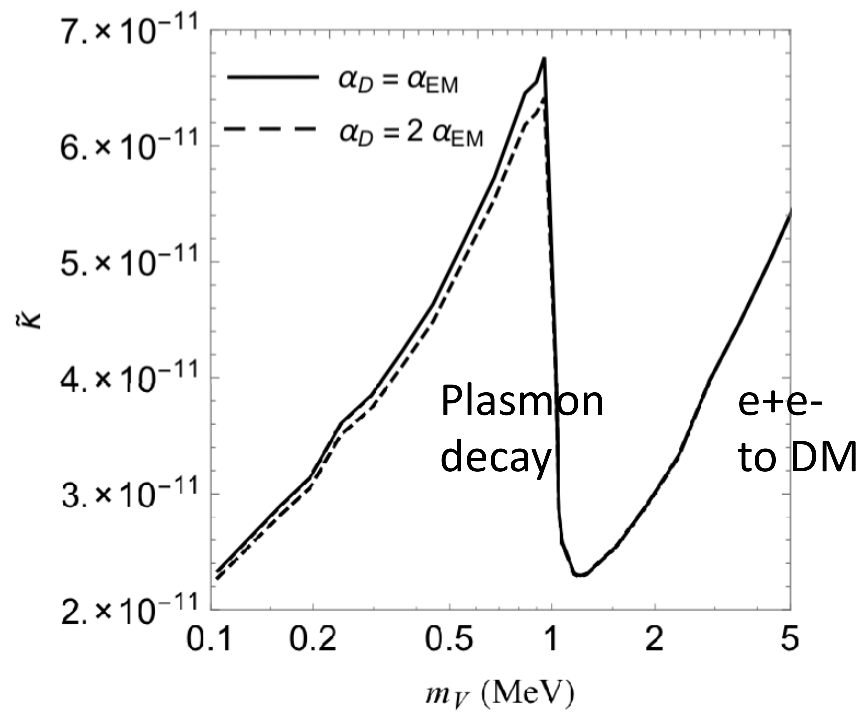
$$\frac{d\rho_\chi}{dt} + 4H\rho_\chi = \Gamma_{e^\pm}^{\rho\chi} + \Gamma_R^{\rho\chi}$$

$$\kappa = \tilde{\kappa}(\alpha_D, m_V) \times \left(\frac{m_D}{200\ \mathrm{eV}}\right)^{-2/3}$$

1. $e^+e^- \to \chi\bar{\chi}$

2. Plamson decay

To generate the observed DM relic abundance



Constraints on model

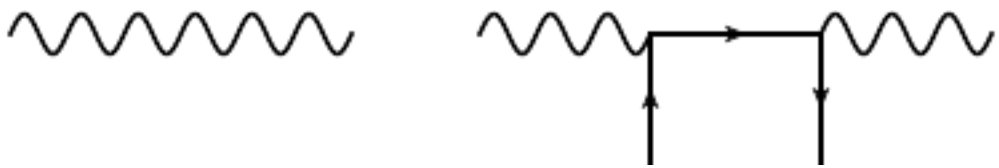
- Stellar constraints (DM is light)

- Lyman-alpha constraints (DM is light)

- From the bullet cluster and the shape of clusters (Self interaction)

Stellar constraints

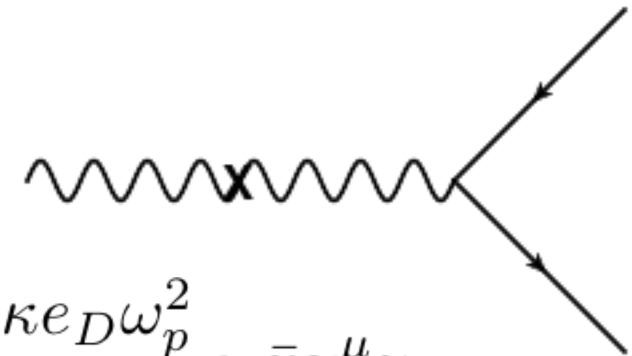
- Energy loss to the dark side can change the evolution of stars.
- Inside the stars is thermal plasma. (NR)



- Change the dispersion relations
  - Transverse $\omega^2 - k^2 = \omega_p^2$
  - Longitudinal $\omega = \omega_p \quad (k < \omega_p)$

Stellar constraints

- "Photon decay"



$$\mathcal{M} = \frac{\kappa e_D q^2}{q^2 - m_V^2} \epsilon_\mu \bar{v} \gamma^\mu u \approx \frac{\kappa e_D \omega_p^2}{m_V^2} \epsilon_\mu \bar{v} \gamma^\mu u$$

$$\Gamma_\chi \propto \left(\frac{\omega_p}{m_V} \right)^4 \qquad \omega_p^2 \approx \frac{4\pi \alpha_{\rm EM} n_e}{m_e}$$

- We need stars with large density and high temperature.
- In supernova, *V* can be produced on shell, so the resonant conversion process is also important.

Stellar constraints

- Red giant stars:
  - $T_C \approx 8.6 \text{ keV} \ , \ \ \omega_p \approx 20 \text{ keV}$
  - Dark radiation < 10% of the luminosity

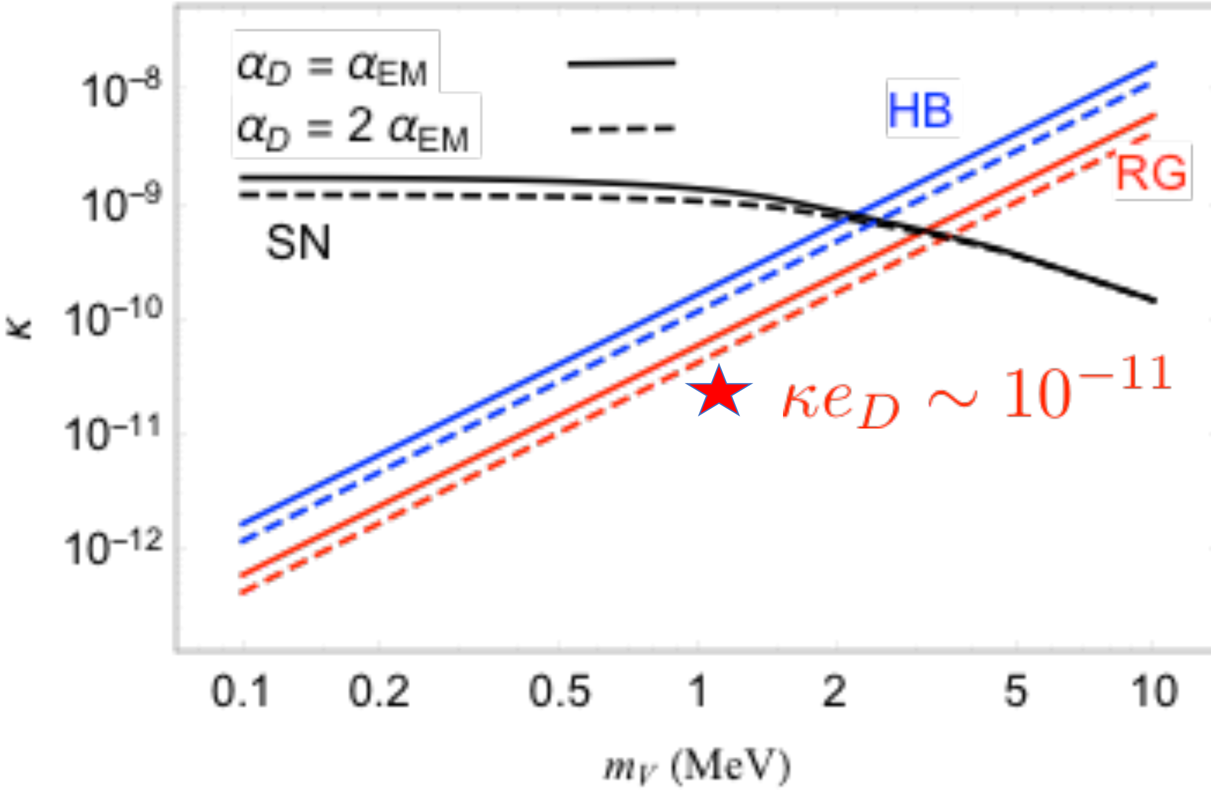
$$\Gamma_\chi \propto \left(\frac{\omega_p}{m_V}\right)^4$$

J. Redondo and G. Raffelt, JCAP 1308, 034 (2013)

- Supernovae
  - $T_C \approx 20 \text{ MeV} \ , \ \ \omega_p \approx 10 \text{ MeV}$
  - Stronger constraint in the large m_V region
  - We reinterpret the constraints on dark photon and milli-charged particles.

J. H. Chang, R. Essig, S. D. McDermott, arXiv:1803.00993

Stellar constraints



Constraints on self interaction

- Clusters (~ 100 kpc) has mass deficit in the inner 3 kpc compared to NFW. *Newman et al. APJ 765, 25 (2013)*
- Can be solved if DM has a self-interaction

$$\sigma_T/m_D \sim 0.1\ \mathrm{cm}^2/\mathrm{gram}$$

Kaplinghat et al.PRL 116, no.4 041302 (2016), 1508.03339

- Because of the effect of baryonic processes, observations of clusters alone cannot provide unambiguous support for DM theories. *Newman et al. APJ 765, 25 (2013)*
- $\sigma_T/m_D > 0.1\ \mathrm{cm}^2/\mathrm{gram}$ is disfavored. *Elbert et al. 1609.08626*
- This is stronger than the constraints from bullet cluster that

$$\sigma_T/m_D < 1.25\ \mathrm{cm}^2/\mathrm{gram}$$

Constraints from Lyman-alpha forests observations

- Free streaming distance

$$l_{\rm fs} = \int_0^{t_0} \frac{a_{\rm today}}{a(t)} v_{\rm phys}(t) dt$$

Constraints from Lyman-alpha forests observations

- Free streaming distance

$$l_{\rm fs} = \int_0^{t_0} \frac{a_{\rm today}}{a(t)} v_{\rm phys}(t) dt$$

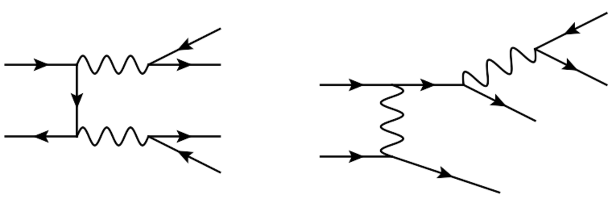
$0 \rightarrow t_{\rm fs}$

- With self scattering, the free streaming becomes Brownian motion.

Constraints from Lyman-alpha forests observations

- Free streaming distance

$$l_{\rm fs} = \int_0^{t_0} \frac{a_{\rm today}}{a(t)} v_{\rm phys}(t) dt$$



Smaller with lower temperature

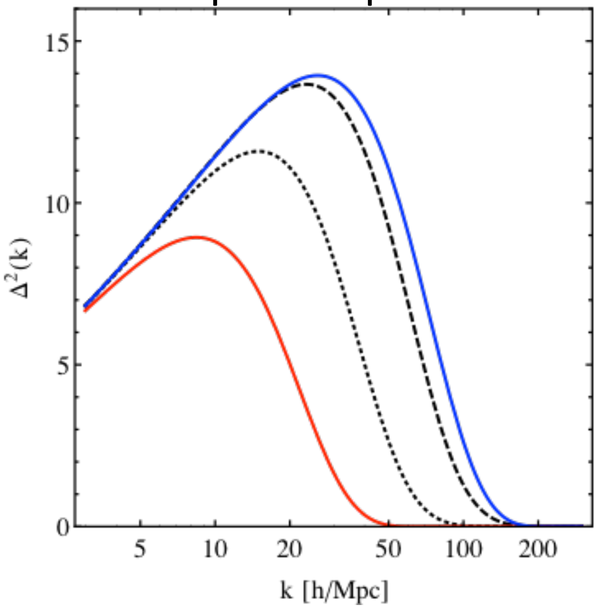
- The best one can do is to make it like WDM.

Self scattering and Lyman-alpha bound

- Scattering turns free-streaming into Brownian motion, migration distance much shorter.

$$T_{\rm fs} \approx 1\ {\rm eV} \times \left(\frac{\alpha_D}{\alpha_{\rm EM}}\right)^{-1} \left(\frac{T_D/T_{\rm SM}}{0.1}\right)^{-1/2} \left(\frac{m_V}{1\ {\rm MeV}}\right)^2$$

1D power spectrum



CAMB simulation result

5.3 keV WDM $\lambda_{\rm fs} \sim 0.02\ {\rm Mpc}$

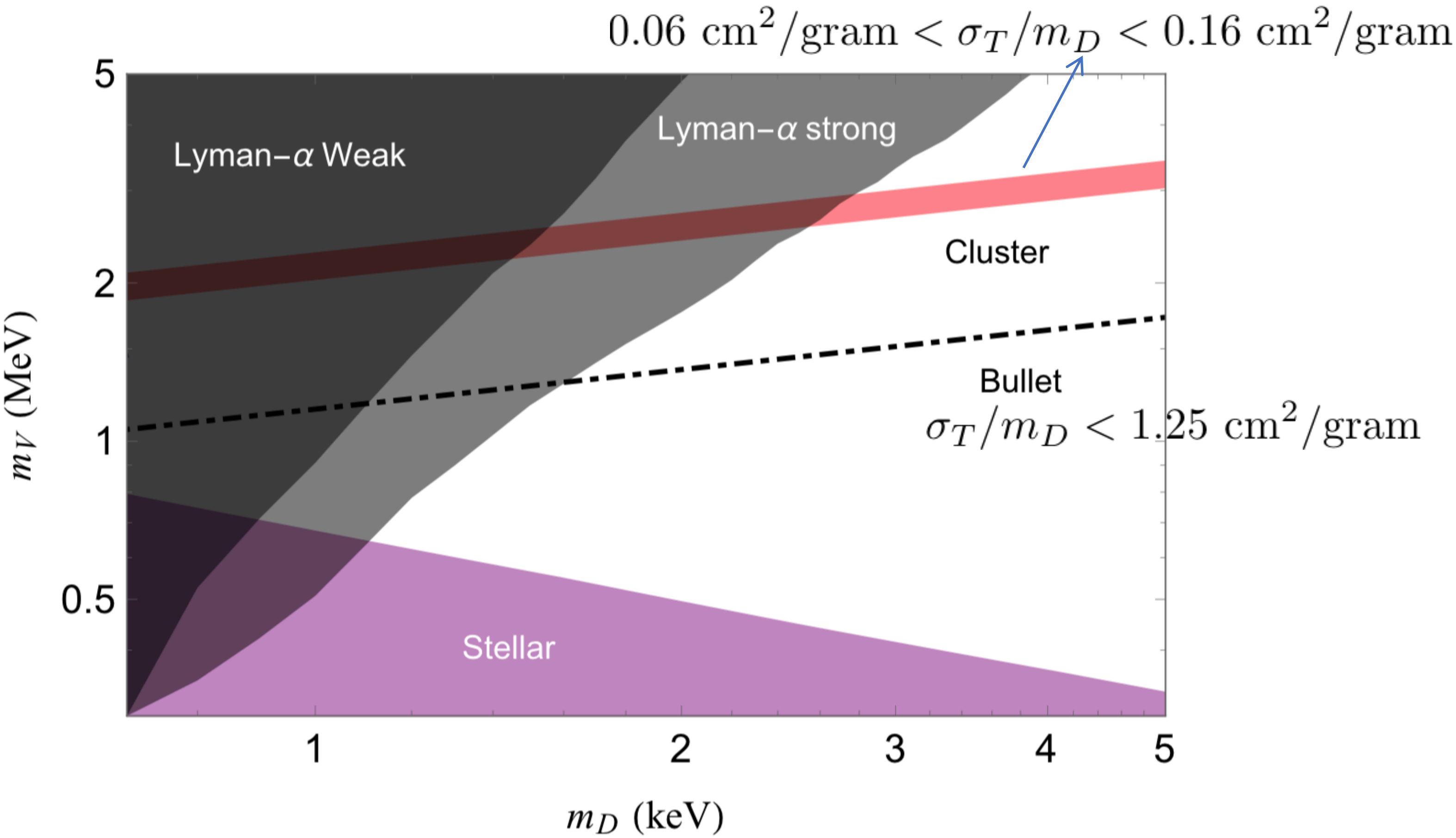
3.5 keV WDM

$m_D = 1\ {\rm keV},\ \sigma_T/m_D = 0.1\ {\rm cm}^2/{\rm gram}$

$m_D = 3\ {\rm keV},\ \sigma_T/m_D = 0.1\ {\rm cm}^2/{\rm gram}$

Cluster mass deficit problem

Numerical result



$$\kappa = \tilde{\kappa}(\alpha_D, m_V) \times \left(\frac{m_D}{200\ \mathrm{eV}}\right)^{-2/3}$$

Summary of the freeze-in model

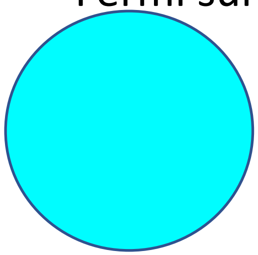
- We propose a freeze-in self-scattering warm dark matter model, which can generate the observed relic abundance.

- The self-scattering and self replication processes alleviate the Lyman-alpha constraints.

$$T_{\mathrm{WDM}} > 5.3\ \mathrm{keV}\ (3.5\ \mathrm{keV}) \Rightarrow m_D > 2.2\ \mathrm{keV}\ (1.4\ \mathrm{keV})$$

Light fermionic DM from scalar decay

- Fermions move at zero kelvin.



$$v_F > 0 \qquad \bar{v}_D \approx 4.6 \times m_D^{-4/3} \left(\frac{\rho_D}{g_D}\right)^{1/3}$$

- By comparing the free streaming length of zero temperature fermion to that of the WDM,

$$m_{\rm DM}^{(0{\rm K})} > 3.5 \ {\rm keV} \ (2.5 \ {\rm keV})$$

Light fermionic DM from moduli decay

- In the early universe the energy of the DM must be in the form of bosons.
- The model

$$\mathcal{L} = \phi + \mathcal{L}_\chi + \mathcal{L}_\psi + g(\phi\bar{\psi}\chi) + \text{h.c.}$$

DM

Dark radiation

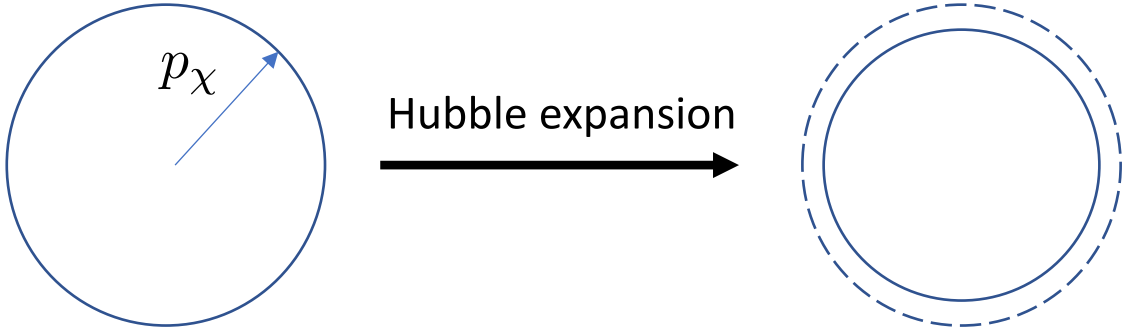
Scalar field, produced through mis-alignment

$$m_\phi \gtrsim m_\chi \gg m_\psi$$

The decay of the scalar field

- In 1 to 2 decay, in the rest frame of the mother particle the momenta of the final state particles are fixed.

- The Hubble expansion makes the momentum of DM smaller, which makes the decay possible.



- When the universe is large enough the effect of the Pauli exclusion principle can be neglected.

The decay of the scalar field

Physical momentum of χ in the rest frame of ϕ

$$\frac{dn_\phi}{dt} \approx -\frac{Ha^3p^3}{2\pi^2}\left[1-\exp\left(1-\frac{2\pi^2 n_\phi \Gamma_\phi}{a^3p^3H}\right)\right]$$

Early universe

$$\frac{dn_\phi}{dt} \approx -\frac{Ha^3p^3}{2\pi^2}$$

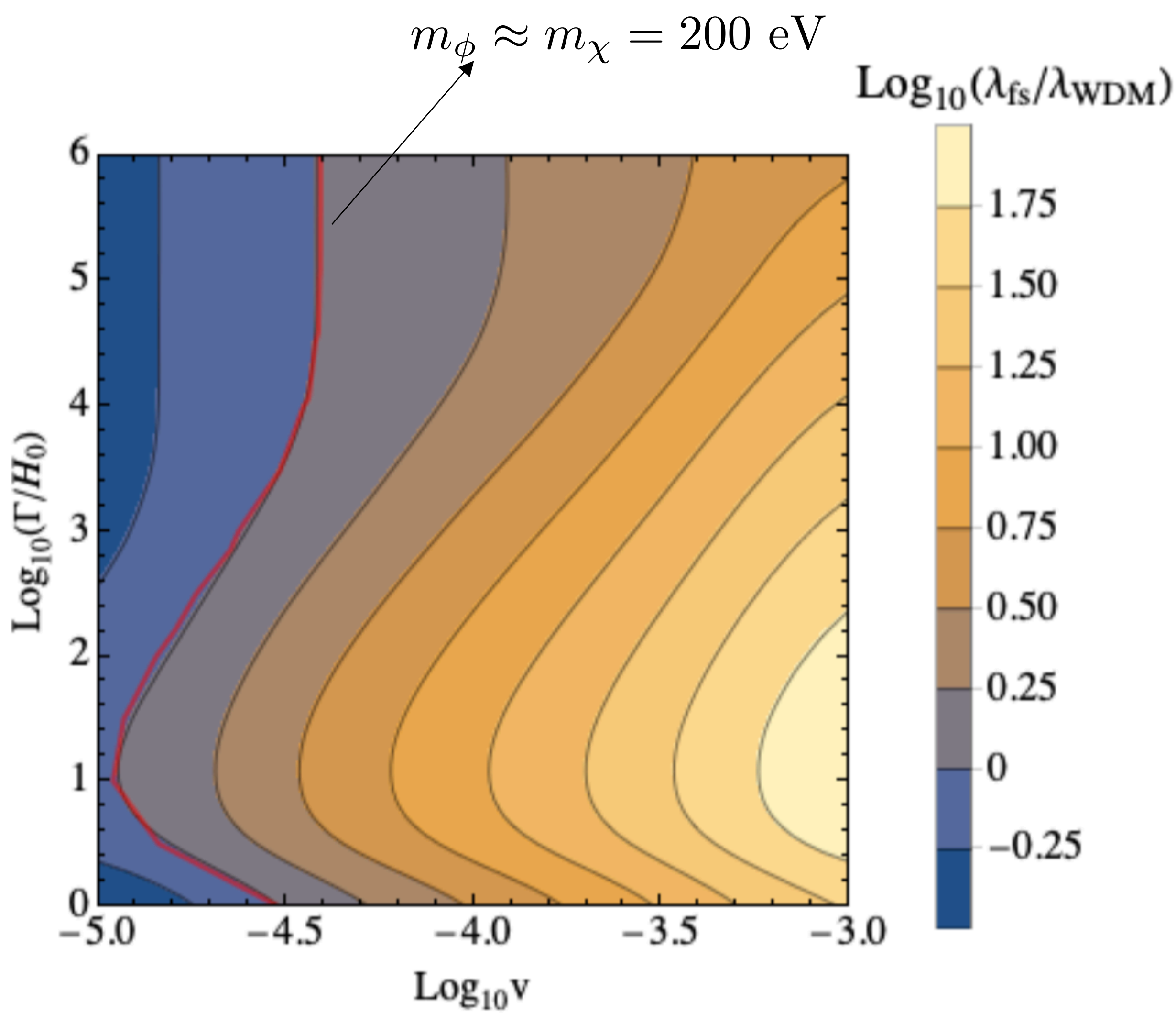
When the universe is large

$$\frac{dn_\phi}{dt} \approx -\Gamma_\phi n_\phi$$

The constraint from Lyman-alpha forests observations

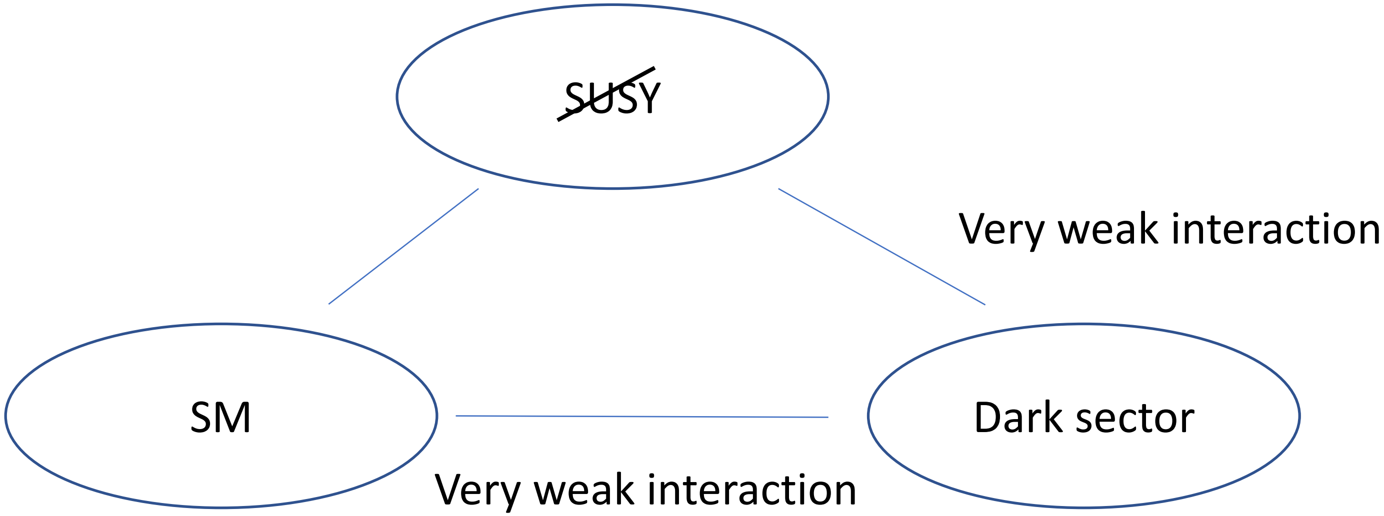
- We compare the free streaming length of χ to the free streaming length of WDM.
- In this model the free streaming length is proportional to the velocity of χ in the rest frame of ϕ.

Numerical result



Velocity of χ in the rest frame of ϕ

How to generate the small mass gap? (work in progress)



Summary

- We build a freeze-in DM model.
    - With the self scattering and the self replication processes, the Lyman-alpha constraint can be lowered to about 2 keV.
- If we want to have O(100) fermionic DM, the energy of the DM should be stored in the form of bosonic field.
    - The mass gap required is very small. Maybe we can realize a natural model with SUSY.