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# Light Thermal Self-Interacting Dark Matter in the Shadow of Non-Standard Cosmology

Based on: 2310.05676

In collaboration with P. Ko and S. Ho

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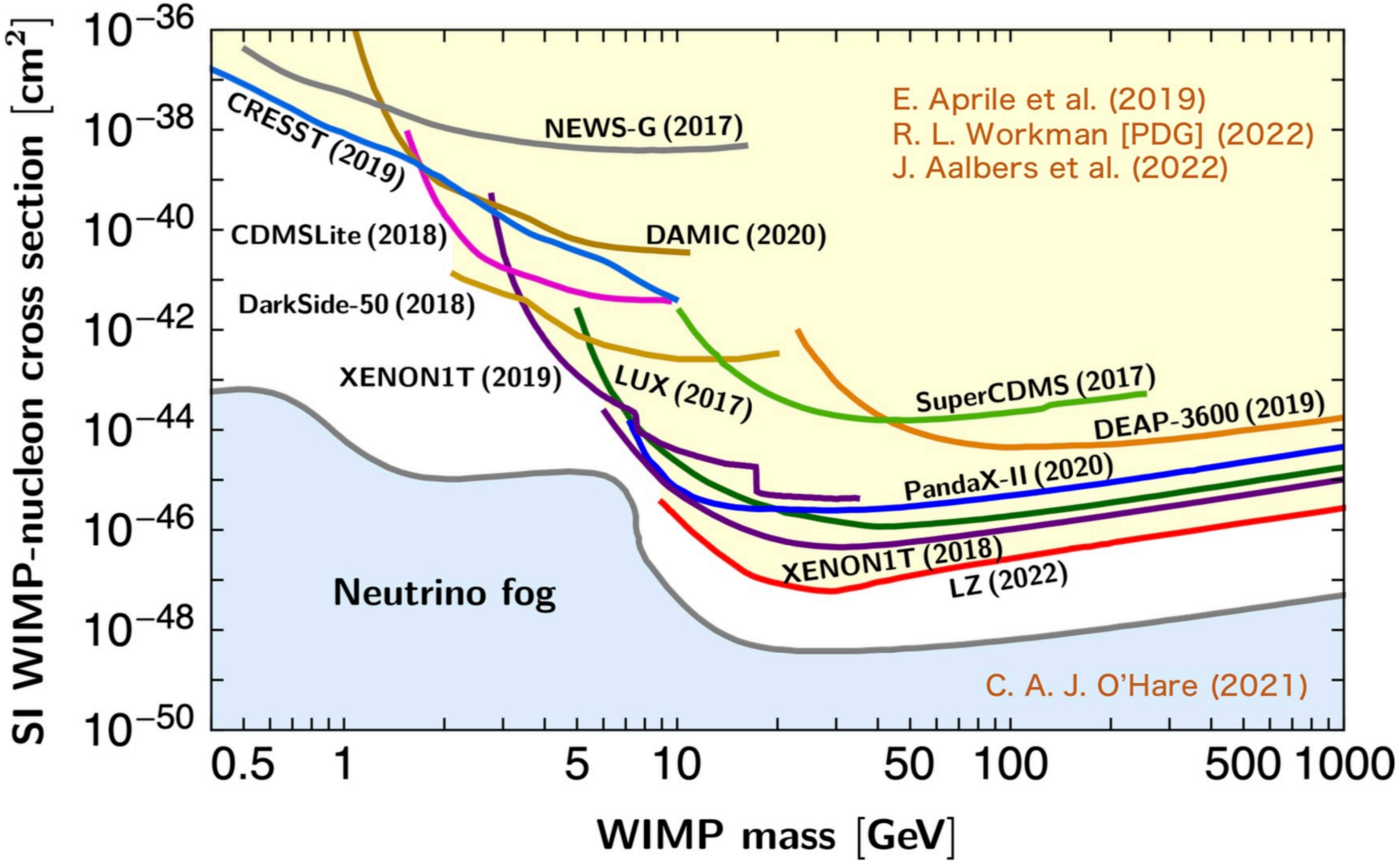
November 15th, 2023

The 3rd International Joint Workshop on the Standard Model and Beyond and The 11th KIAS Workshop on Particle Physics and Cosmology

# Motivations change with time!

- Null results in direct detection experiments pushed the thermal WIMP scenarios in tension.
- Many different possibilities have been proposed to evade such strong DD bounds.
- There are many alternative proposals, such as…
- Freeze-in Dark Matter
- Strongly interacting Dark Matter
- Forbidden Dark Matter
- Secluded Dark matter
- ….

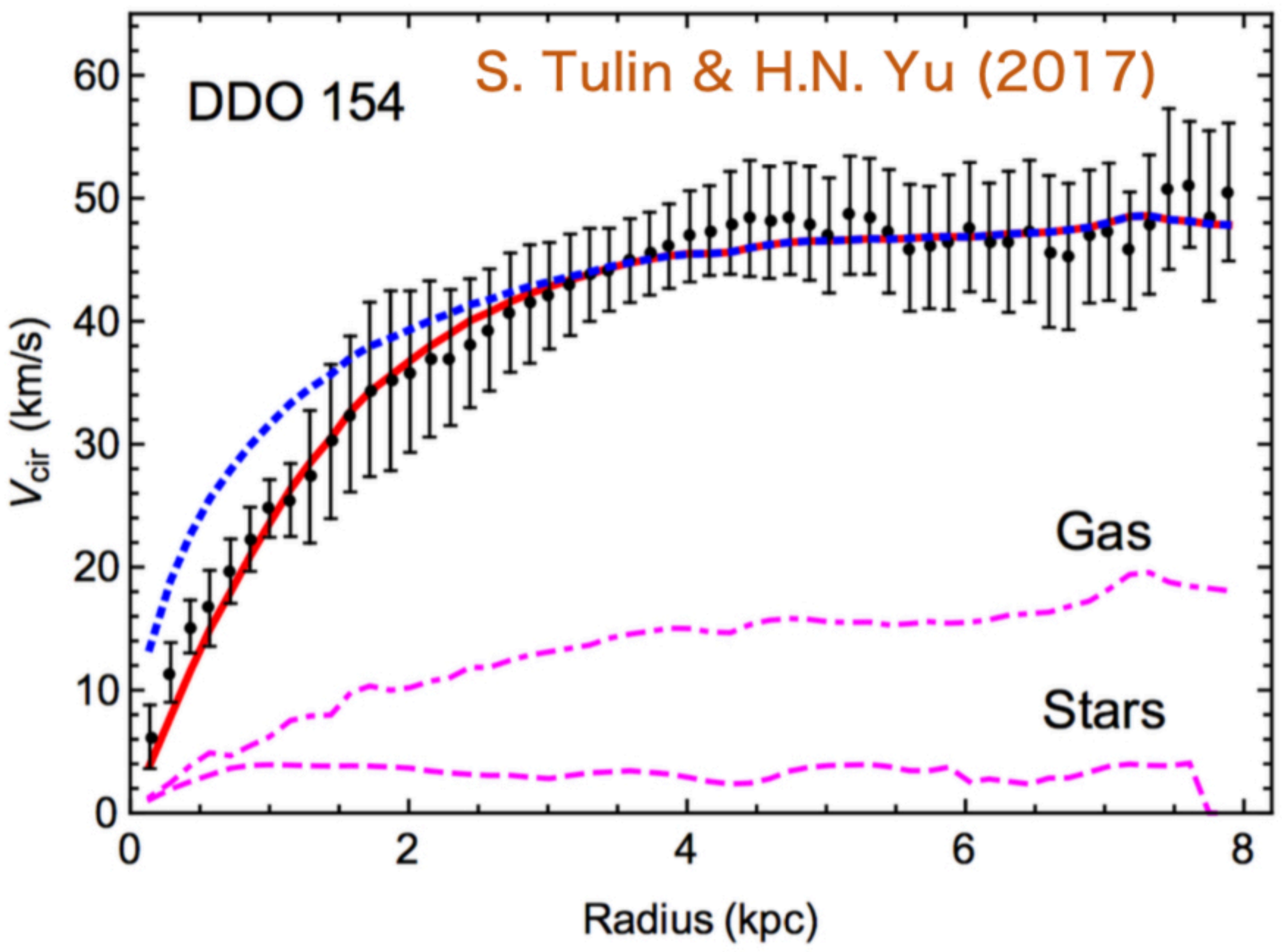


# Small-scale structures and DM self-interaction!

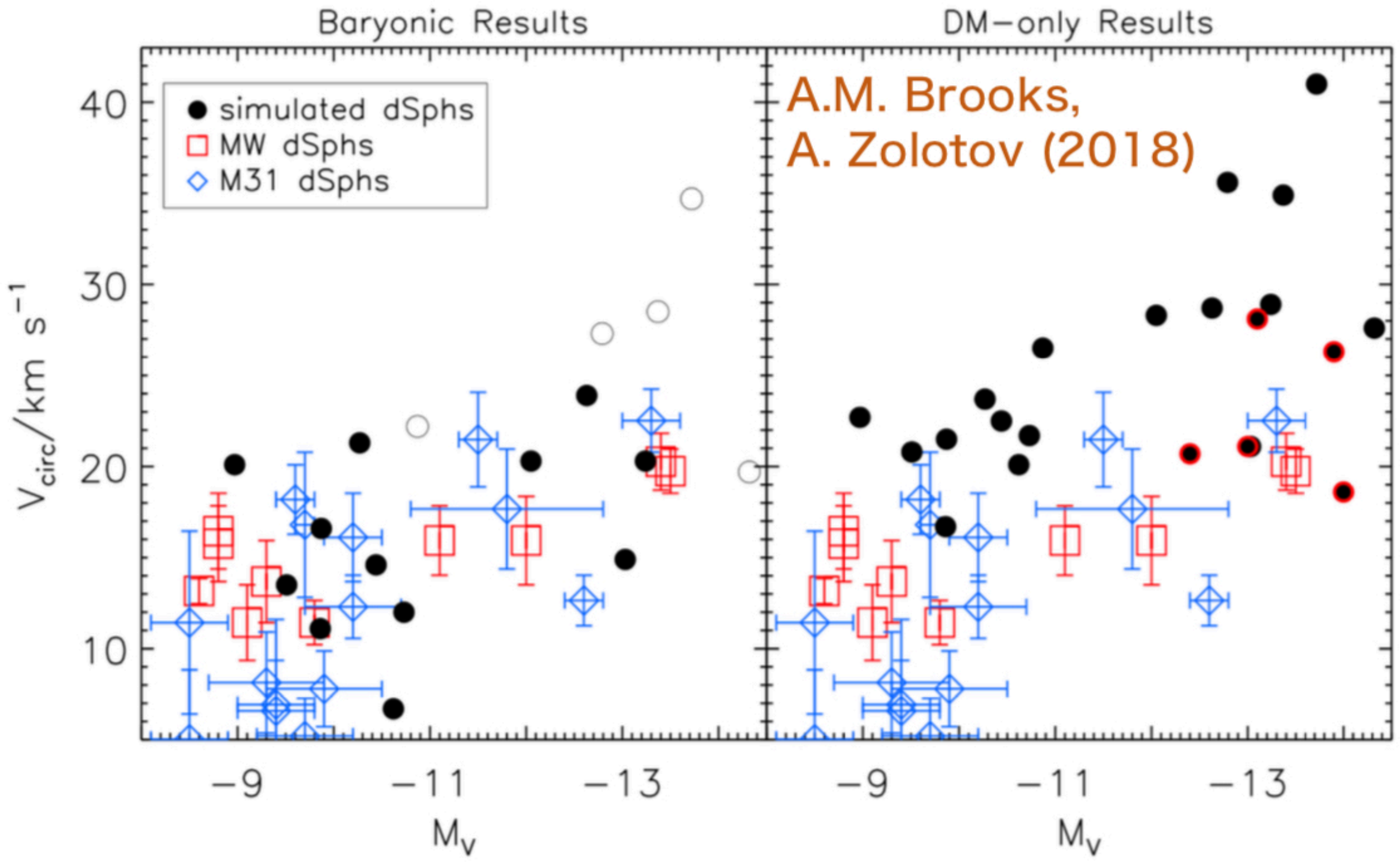
- Studies of astrophysical structure, combining both observations and N-body simulations, can confront the paradigm of cold, collisionless DM.

- While this paradigm works exceedingly well to explain data on large scales, the situation is less clear on smaller scales.

- Self-interacting DM are mainly motivated due to the potential to explain small scale structures.




core-vs-cusp problem




too-big-to-fail problem

# How much self-interaction do we need?

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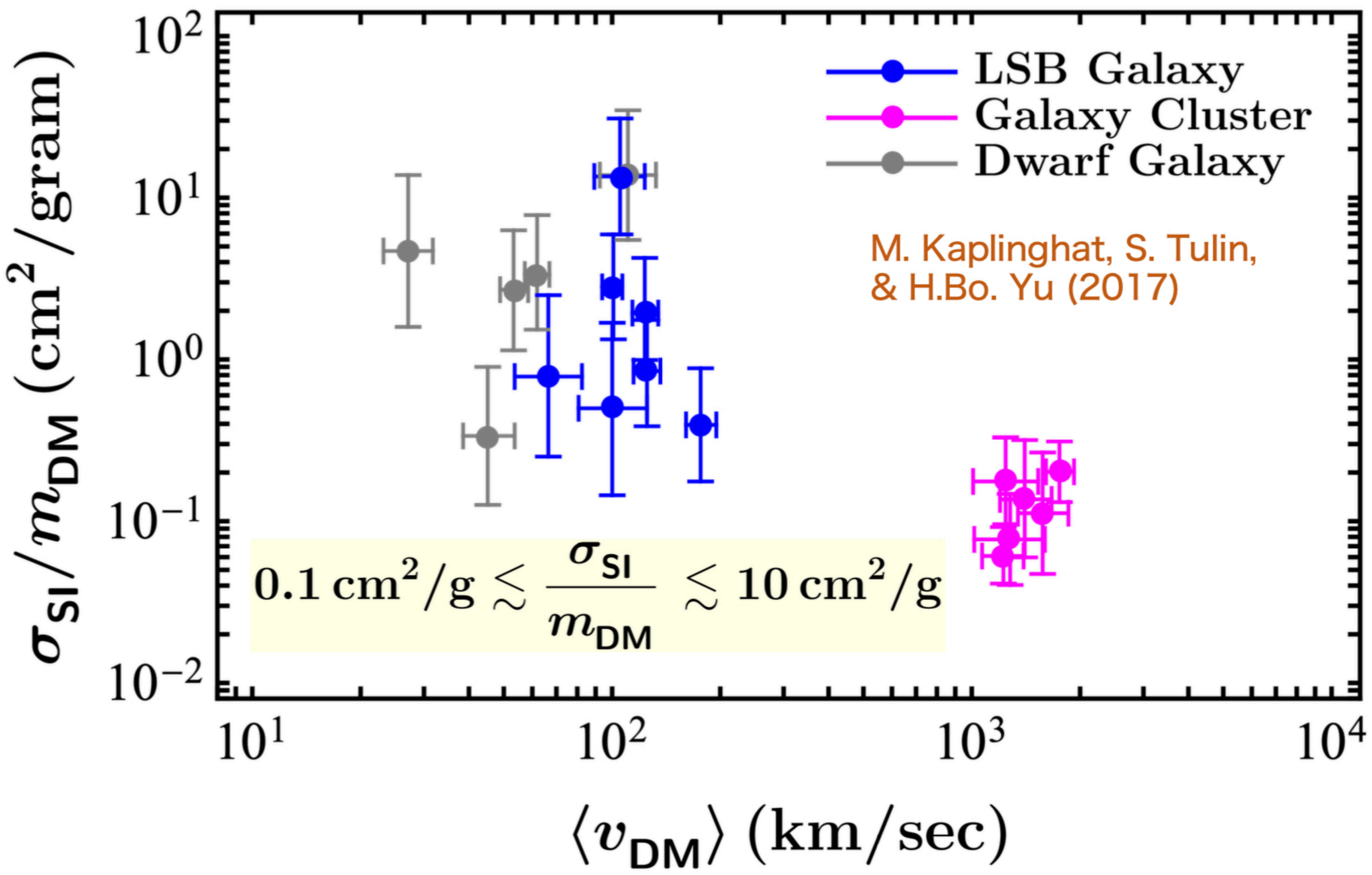
○ We need significantly strong interactions between DM particles to solve these issues.

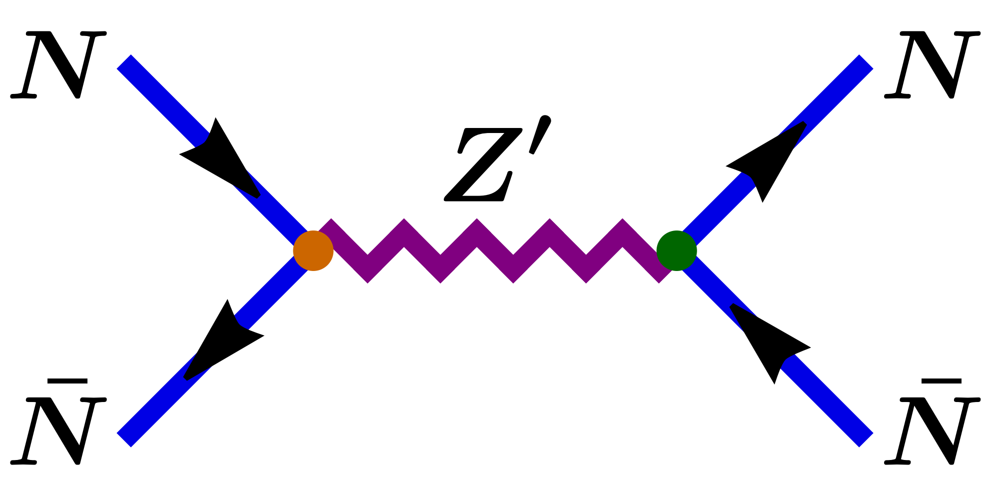
$$\mathscr{R}_{\rm scat} = \sigma v \rho_{DM}/m \approx 0.1\text{Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1 M_\odot/pc^3}\right)\left(\frac{v_{\rm rel}}{50\text{Km/sec}}\right)\left(\frac{\sigma/m}{1\text{cm}^2/\text{g}}\right)$$

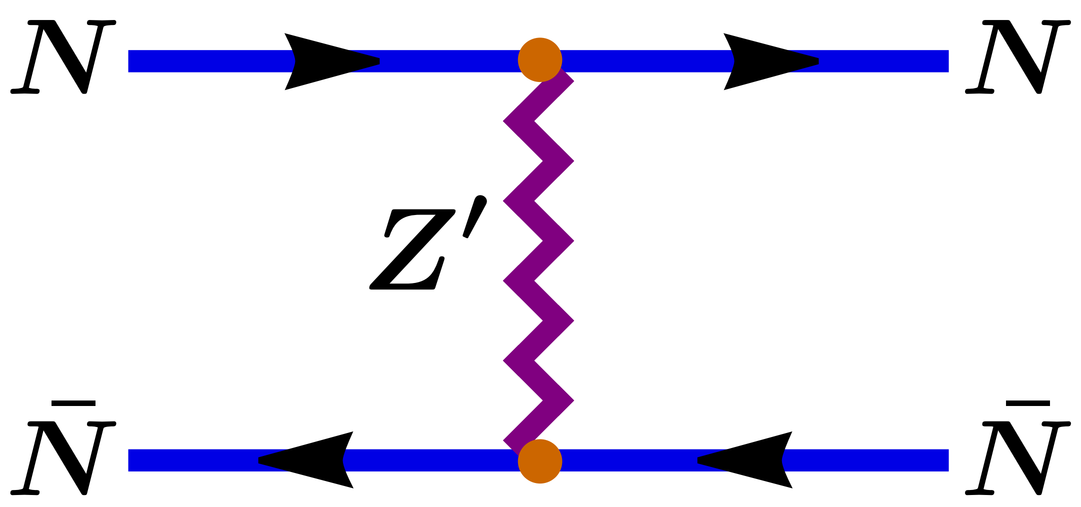


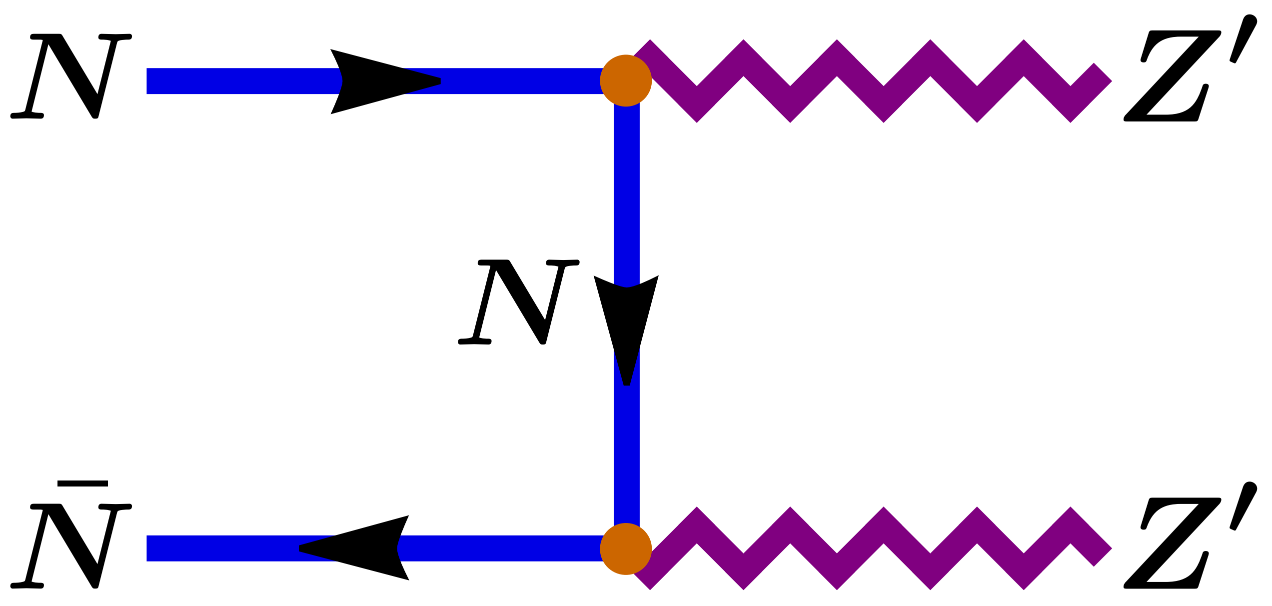
# A Minimal setup!

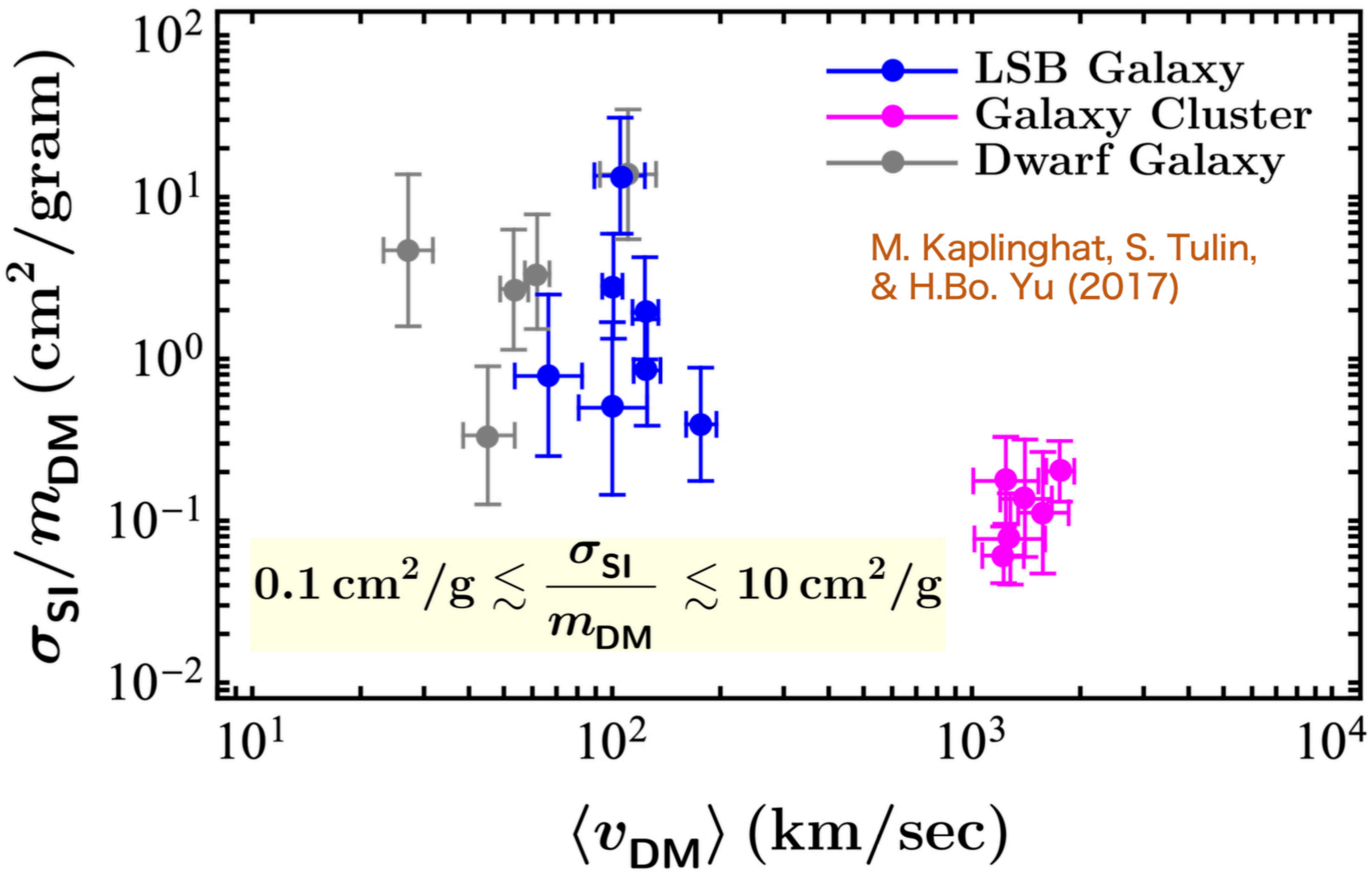
$$\mathscr{L} = g_X \overline{N} i \gamma_\mu N Z_X^\mu - M_N \overline{N} N$$

- The self interactions of dark matter can be mediated by a light gauge boson.
- Dark matter will dominantly annihilate to the pair of $Z_X$.



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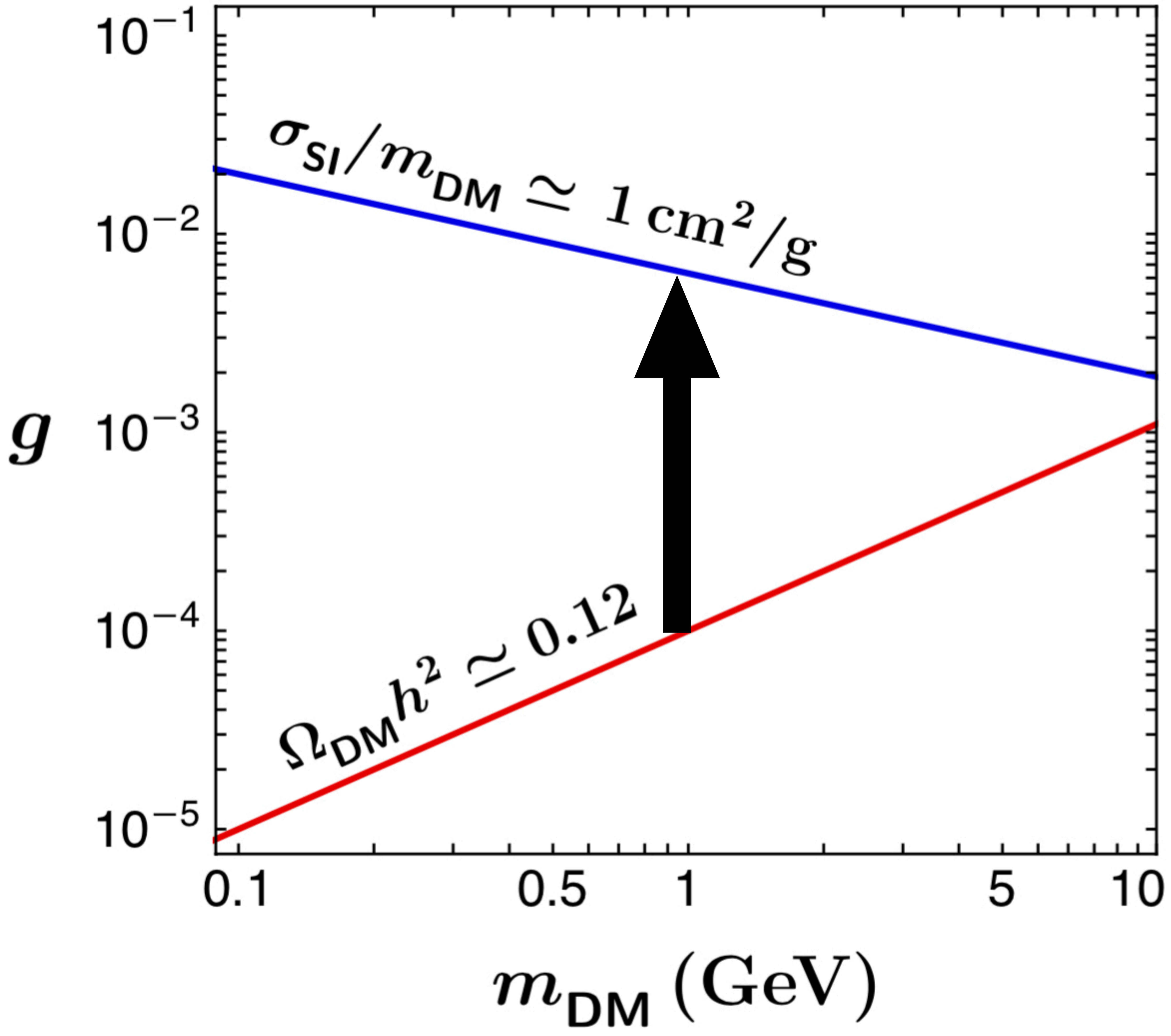
## Relic Abundance

$$g_X \approx 10^{-3} \left( \frac{M_{DM}}{10\text{GeV}} \right)$$

## Self-interaction

$$g_X \approx 2 \times 10^{-3} \left( \frac{M_{DM}}{10\text{GeV}} \right)^{-1/2}$$

for $m_{Z_X} \approx 10$ MeV



# ID bounds on light thermal DM!

$$\mathscr{L} = g_X \bar{N} i\gamma_\mu N Z_X^\mu - M_N \bar{N} N$$

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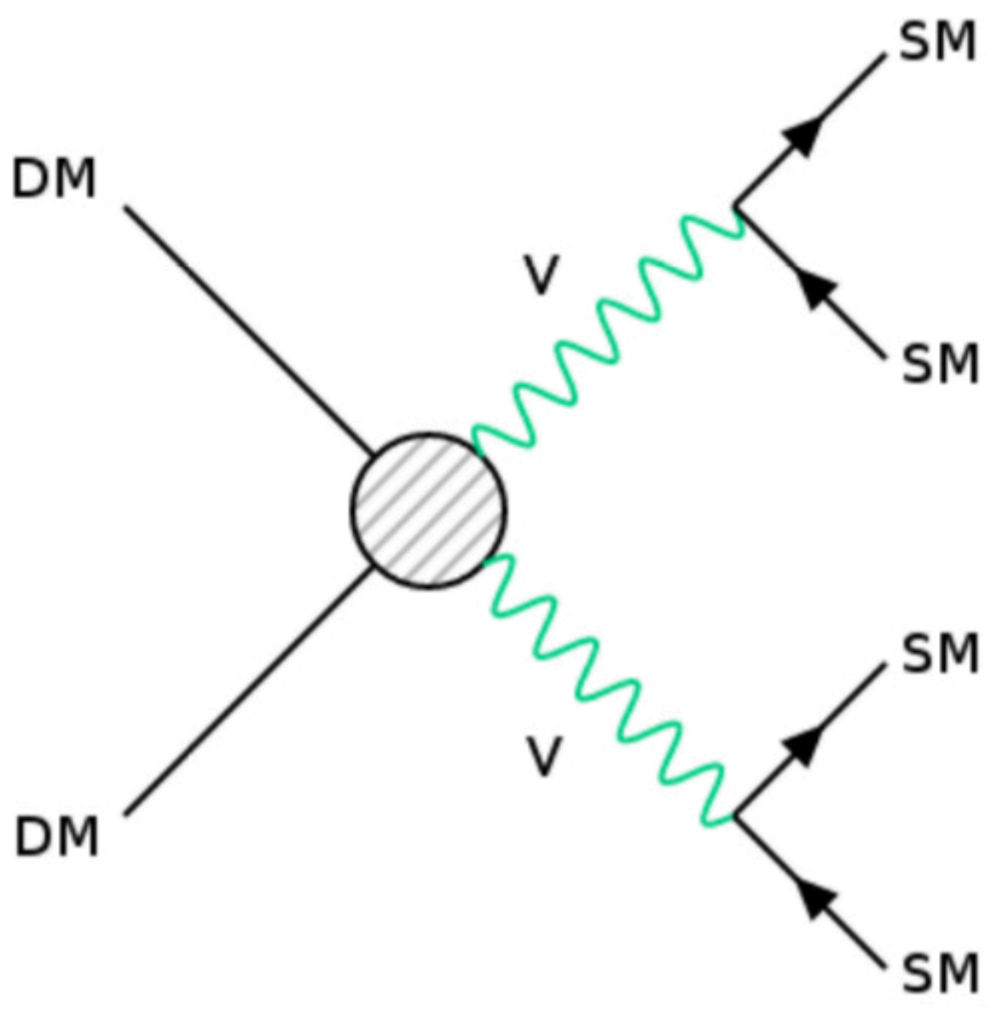
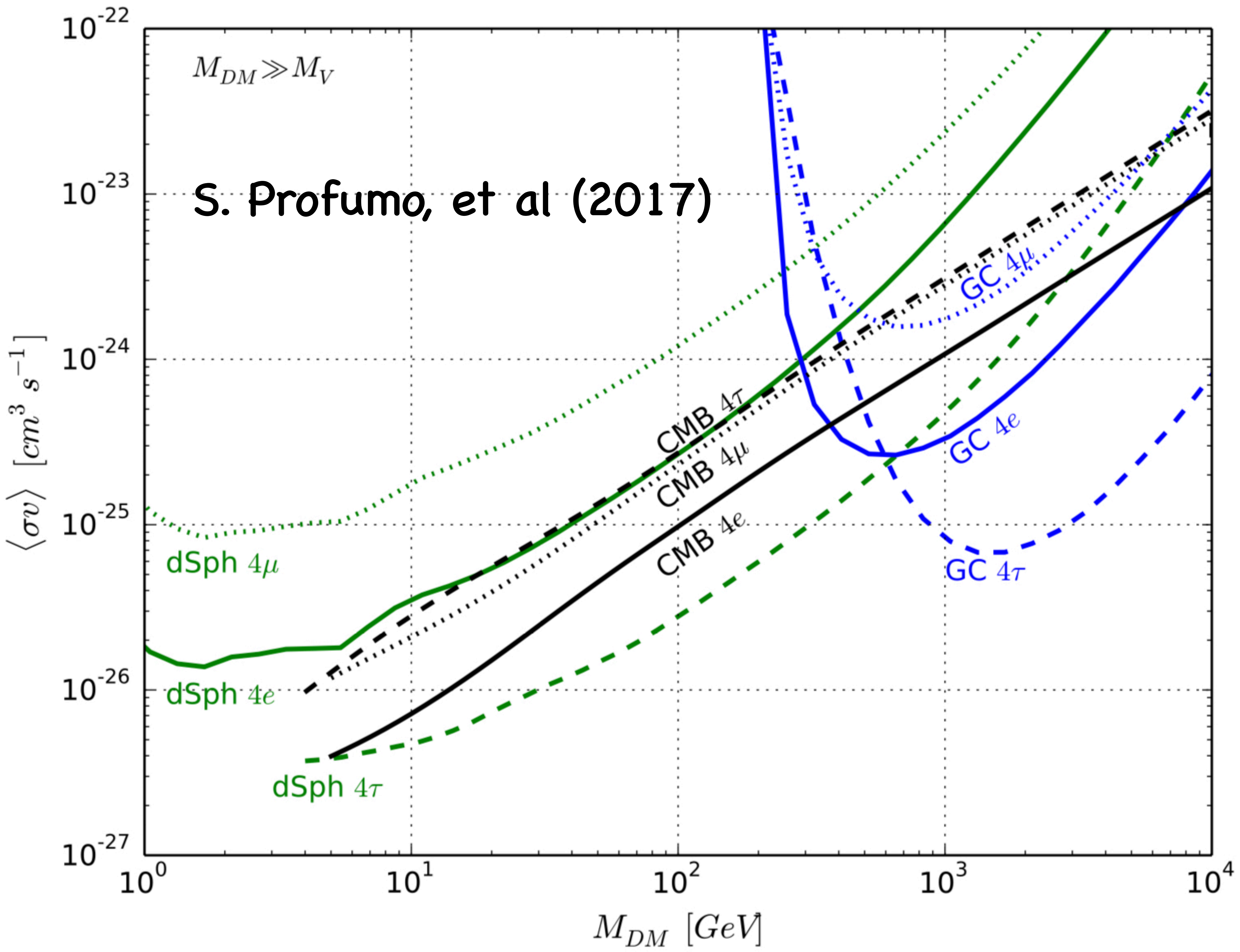
- Light DM particles that annihilate directly into SM particles are severely constrained from ID.

- In case of secluded DM, the mediator ($Z_X$) can decay to the SM particles due to the kinetic mixing.

- Otherwise, they will be stable over the cosmological scale and will contribute to DM.

$$\frac{dE}{dtdV}_{\rm inj}(z) = \rho_c \Omega_{DM_0}^2 (1+z)^6 \left( \frac{\langle \sigma v \rangle}{M_{DM}} \right)$$



# Important points:

$$\mathcal{L} = g_X \bar{N} i\gamma_\mu N Z_X^\mu - M_N \bar{N} N$$

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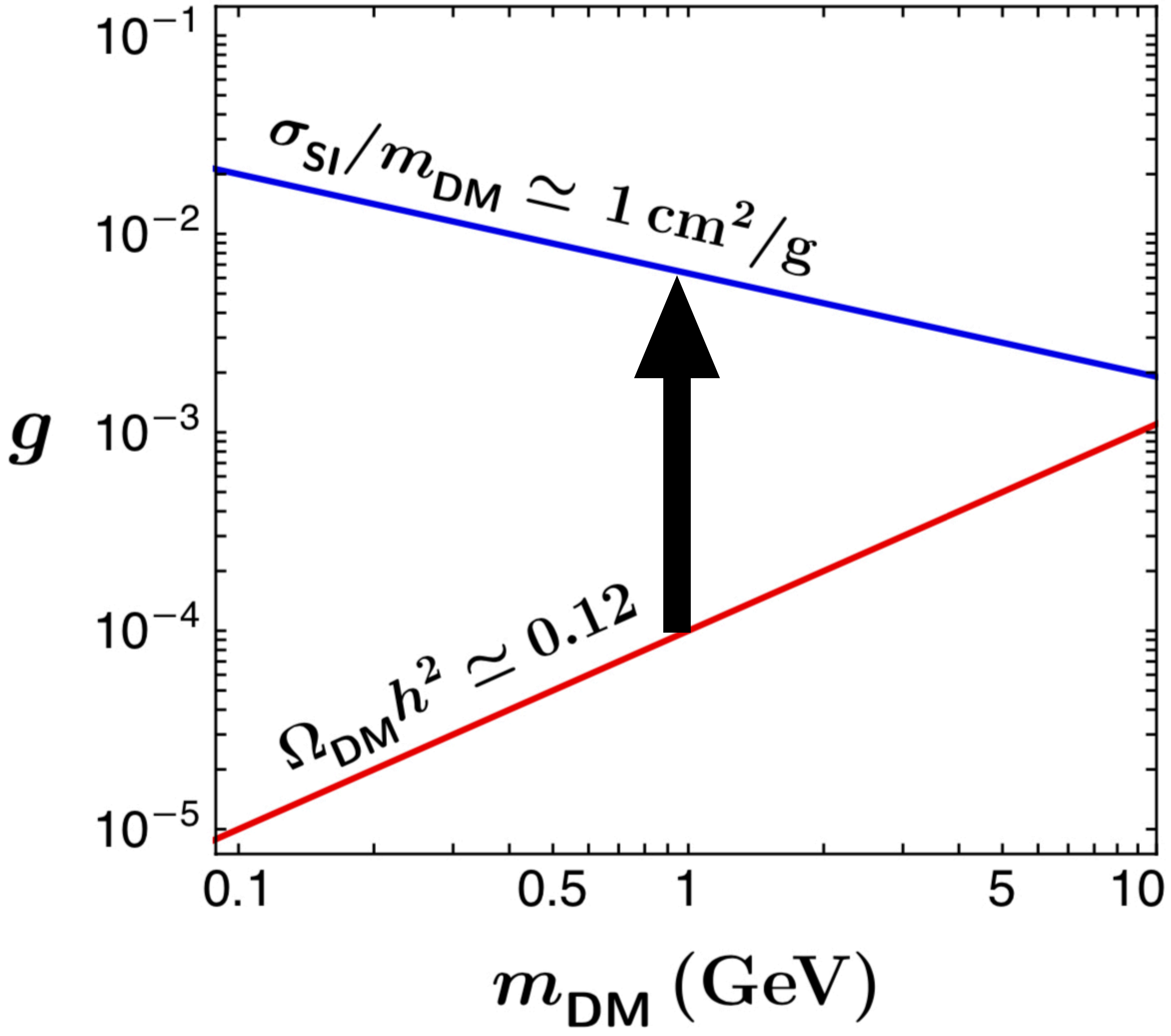
- The self interactions of dark matter can be mediated by a light gauge boson.
- Dark matter will dominantly annihilate to the pair of $Z_X$.
- The required $g_X$ for explaining $\sigma_{SI}$ is much larger than we need to explain relic abundance.
- The same parameter space is also in tension with the search in ID.




**Phenomenologists don't like to give up their model!**

Talk by Satyabrata.

# What was there before BBN?

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Kawasaki et. al 2000,

Ichikawa et. al. 2005

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$$\rho_\Phi \propto a^{-(4+n)}$$

- n=-1 corresponds to the EMD universe.
- $n > 0$ corresponds to a different scenario.

Talk by J.Kim on EMD.

D'Eramo, et al. 2017


Kawasaki et. al 2000,
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# What was there before BBN?

$$\rho_\Phi \propto a^{-(4+n)}$$

- n=-1 corresponds to the EMD universe. Talk by J.Kim on EMD.
- $n > 0$ corresponds to a different scenario.

D'Eramo, et al. 2017

**Something else ($\Phi$)!**


$$\rho_{\text{Total}} = \rho_\Phi + \rho_{\text{rad}}$$

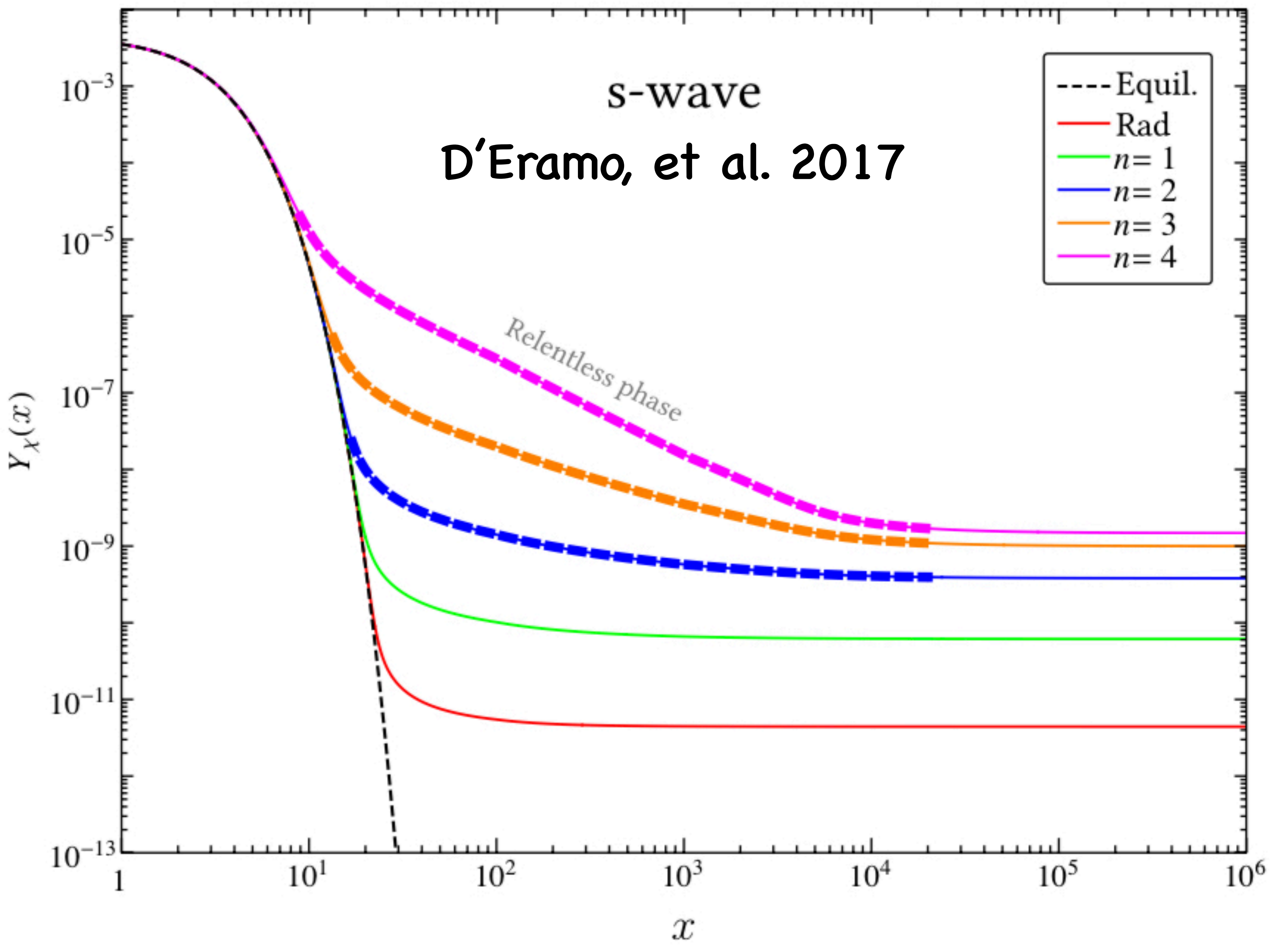
$$H(T) \approx \sqrt{\frac{\pi^2 g_\rho(T)}{90}} \frac{T^2}{M_{Pl}} \left(\frac{T}{T_r}\right)^{\frac{n}{2}}$$

- There are two parameters $(n, T_r)$.
- $T_r$ can not be arbitrarily small. $T_r \geq (15.4)^{1/n}$ MeV

# Consequences of faster expansion

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle \left( n_{DM}^2 - n_{DM}^{eq\ 2} \right)$$

$$H(T) \approx \sqrt{\frac{\pi^2 g_\rho(T)}{90}} \frac{T^2}{M_{Pl}} \left( \frac{T}{T_r} \right)^{\frac{n}{2}}$$




- Faster expansion can affect early universe any early universe relics.
- The ultralight relics ($\Delta_{N_{\rm eff}}$) can be concealed in CMB.

A. Biswas, D.K.Ghosh, DN, JCAP2022

# Possible Solution:

- Can such non-standard cosmology revive some part of the parameter space?

- Can we evade the CMB bound?

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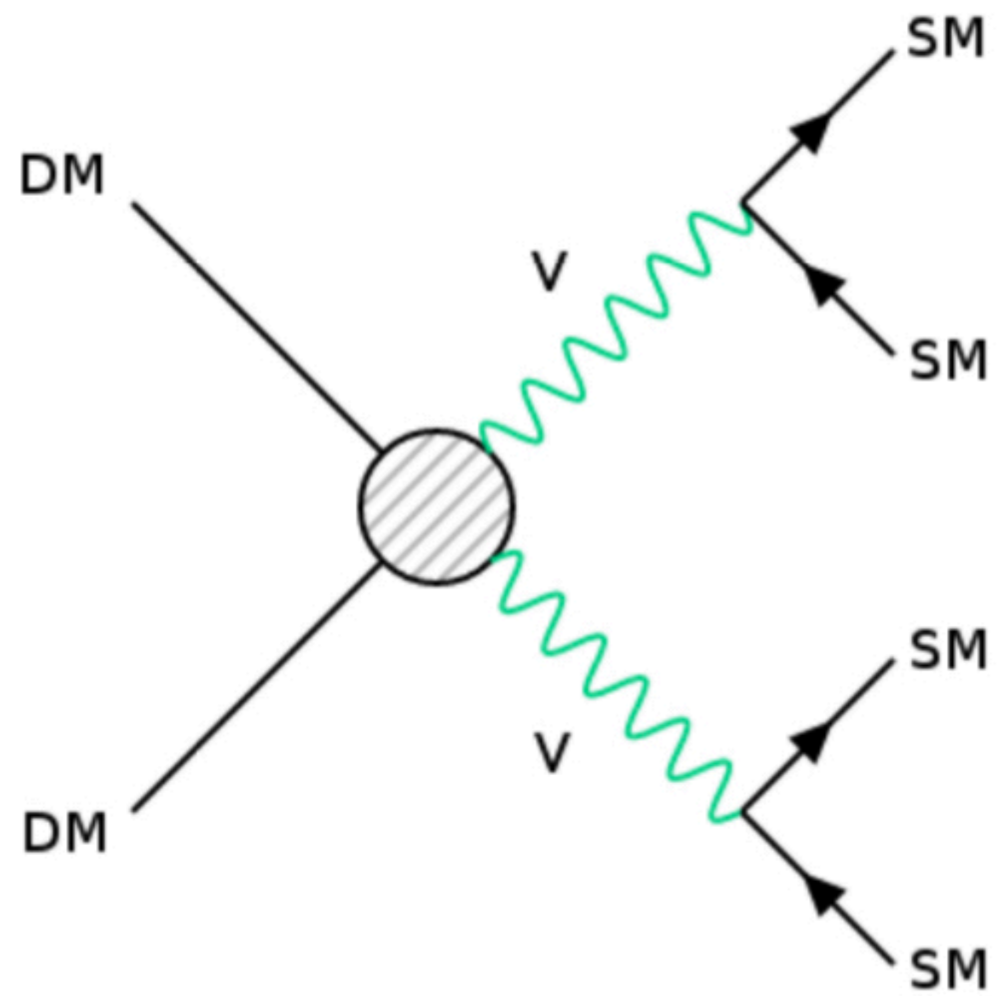
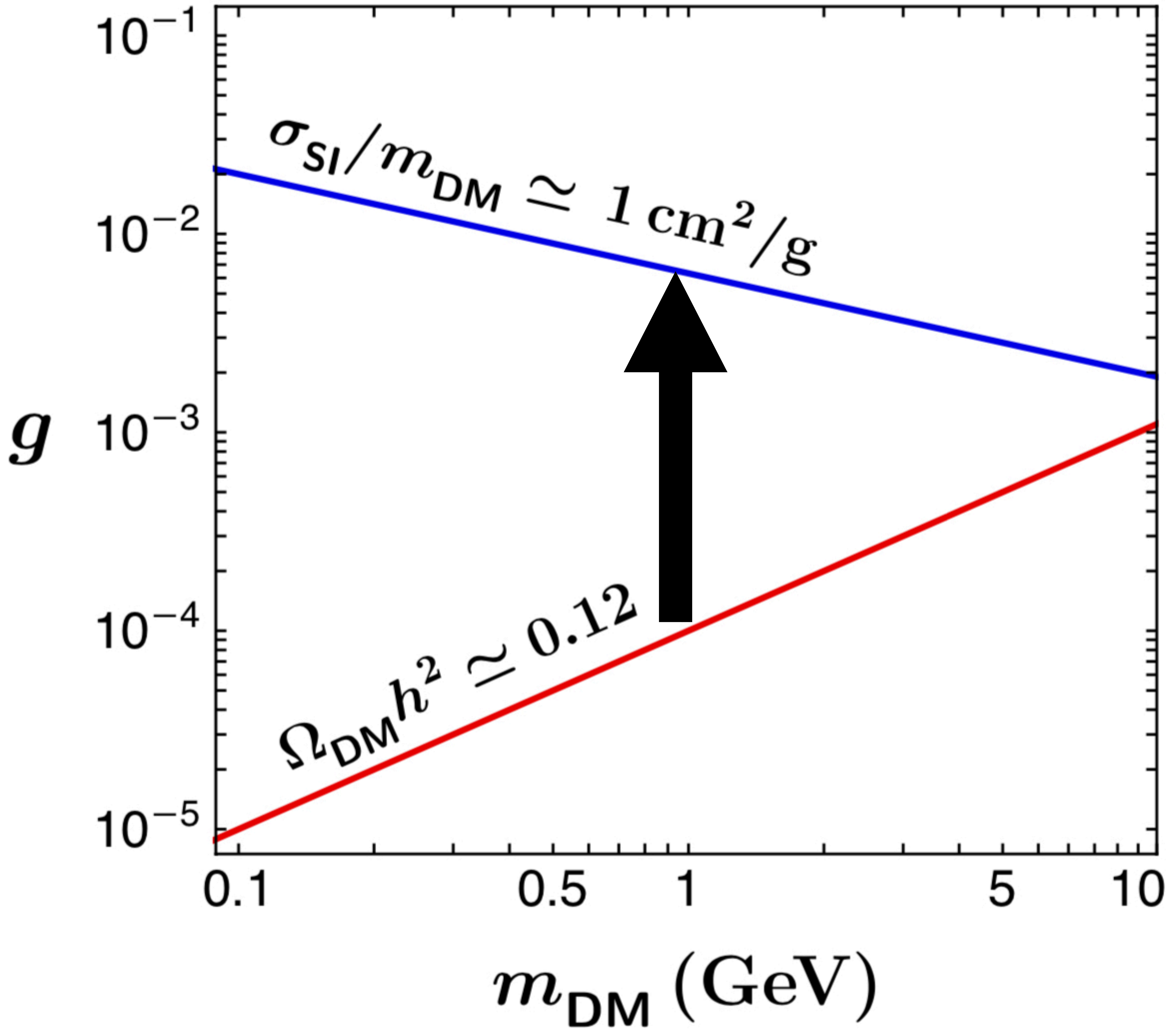


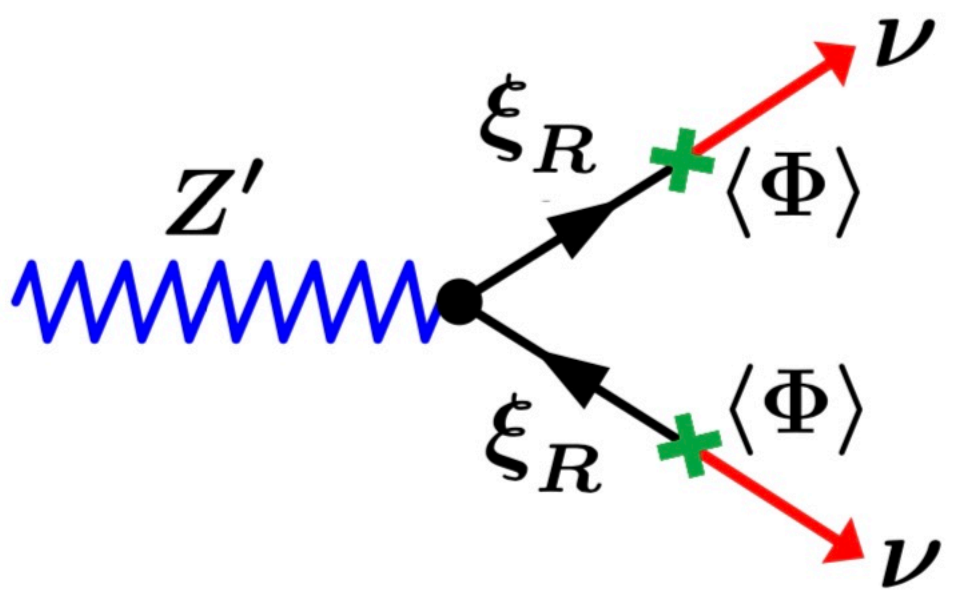

- Increasing H also means increasing $\langle\sigma v\rangle$.

# Possible Solution :

- Can such non-standard cosmology revive some part of the parameter space?

- Can we evade the CMB bound?

$$\mathscr{L} = g_X \overline{N} i\gamma_\mu N Z_X^\mu + \overline{\xi_R} i\gamma_\mu \xi_R Z_X^\mu + \overline{\chi_L} i\gamma_\mu \chi_L Z_X^\mu - \left[ y_\psi \overline{L_L} \tilde{\Phi} \xi_R + H.c. \right]$$




| | $N$ | $\xi_R$ | $\chi_L$ | $\Delta$ | $\Phi$ | $Z'$ |
|---|---|---|---|---|---|---|
| $SU(2)_L$ | **1** | **1** | **1** | **1** | **2** | **1** |
| $U(1)_Y$ | 0 | 0 | 0 | 0 | +1/2 | 0 |
| $U(1)_D$ | +1/2 | +1 | +1 | +1 | +1 | 0 |
| spin | 1/2 | 1/2 | 1/2 | 0 | 0 | 1 |

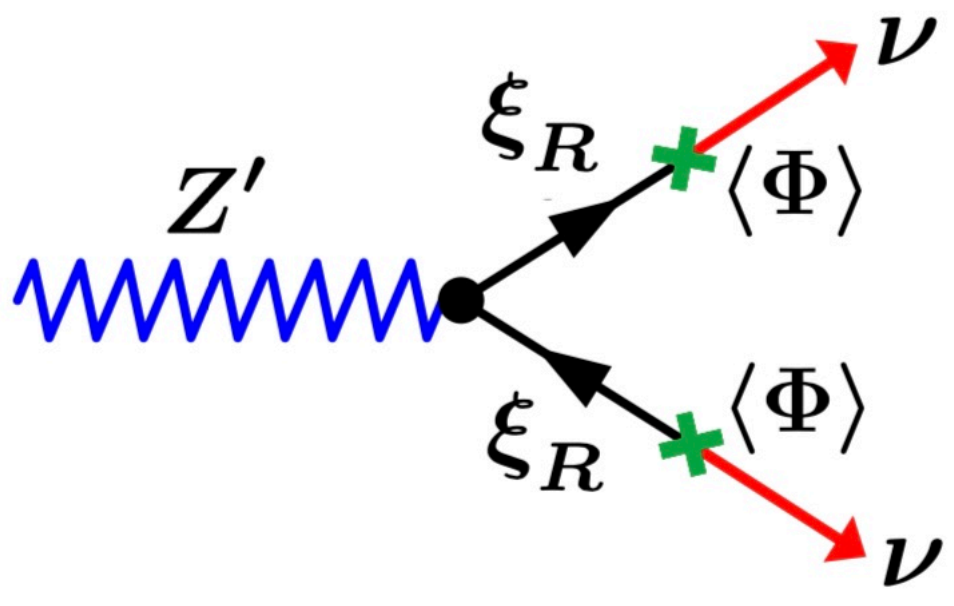
- In case, the Kinetic mixing is much smaller than the mixing!

# Requirements:

$$\mathscr{L} = g_X \overline{N} i\gamma_\mu N Z_X^\mu + \overline{\xi_R} i\gamma_\mu \xi_R Z_X^\mu + \overline{\chi_L} i\gamma_\mu \chi_L Z_X^\mu - \left[ y_\psi \overline{L_L} \tilde{\Phi} \xi_R + H.c. \right]$$

- In case, the Kinetic mixing is smaller than the mixing between active neutrinos and the $\xi$.

$$\epsilon << 1.57 \times 10^{-6} \left(\frac{g_D}{0.3}\right)\left(\frac{y_\psi}{0.5}\right)\left(\frac{v_\Phi}{50\text{MeV}}\right)^2\left(\frac{m_\psi}{10\text{GeV}}\right)^{-2}$$




| | $N$ | $\xi_R$ | $\chi_L$ | $\Delta$ | $\Phi$ | $Z'$ |
|---|---|---|---|---|---|---|
| $SU(2)_L$ | **1** | **1** | **1** | **1** | **2** | **1** |
| $U(1)_Y$ | 0 | 0 | 0 | 0 | +1/2 | 0 |
| $U(1)_D$ | +1/2 | +1 | +1 | +1 | +1 | 0 |
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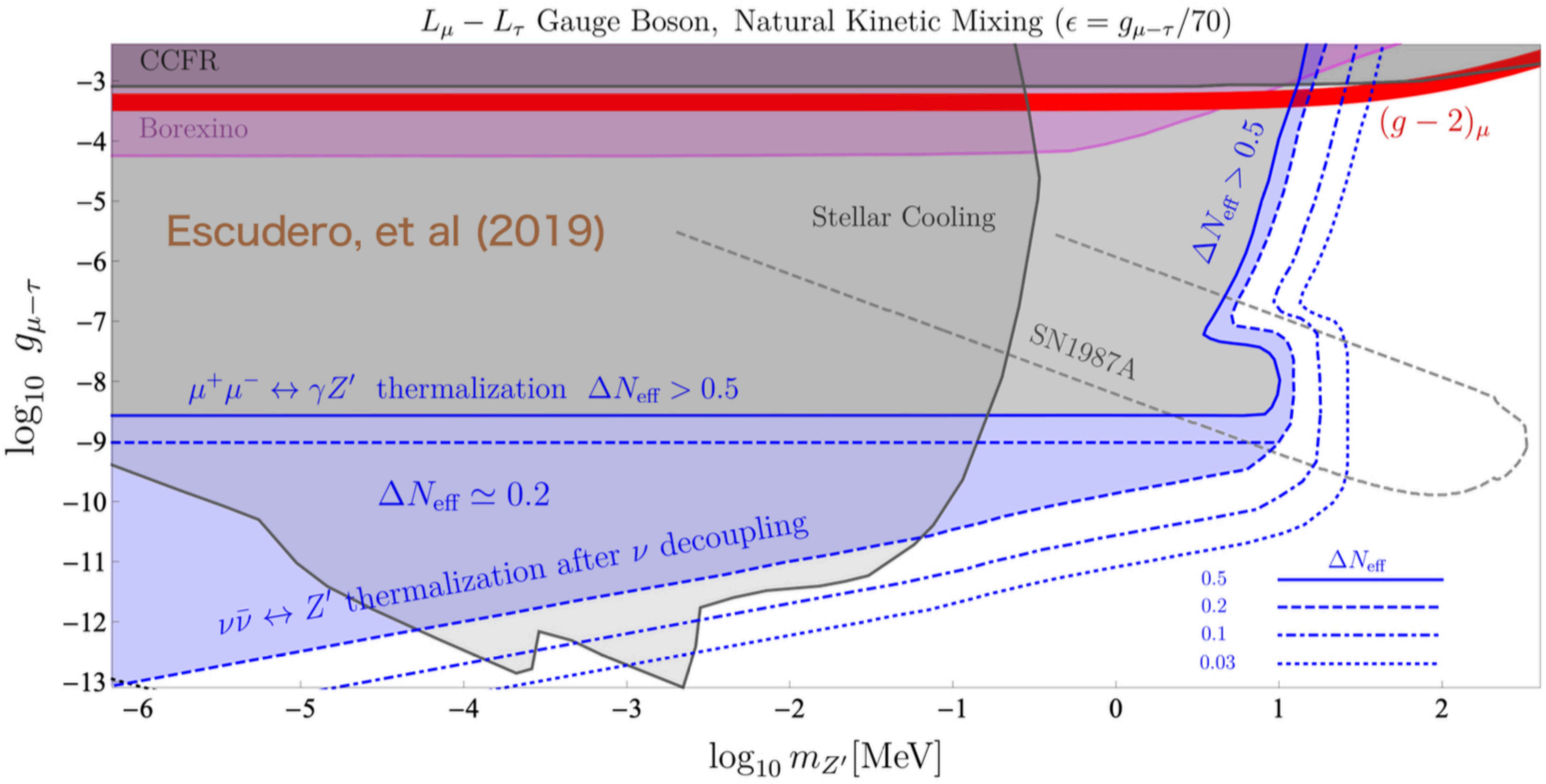
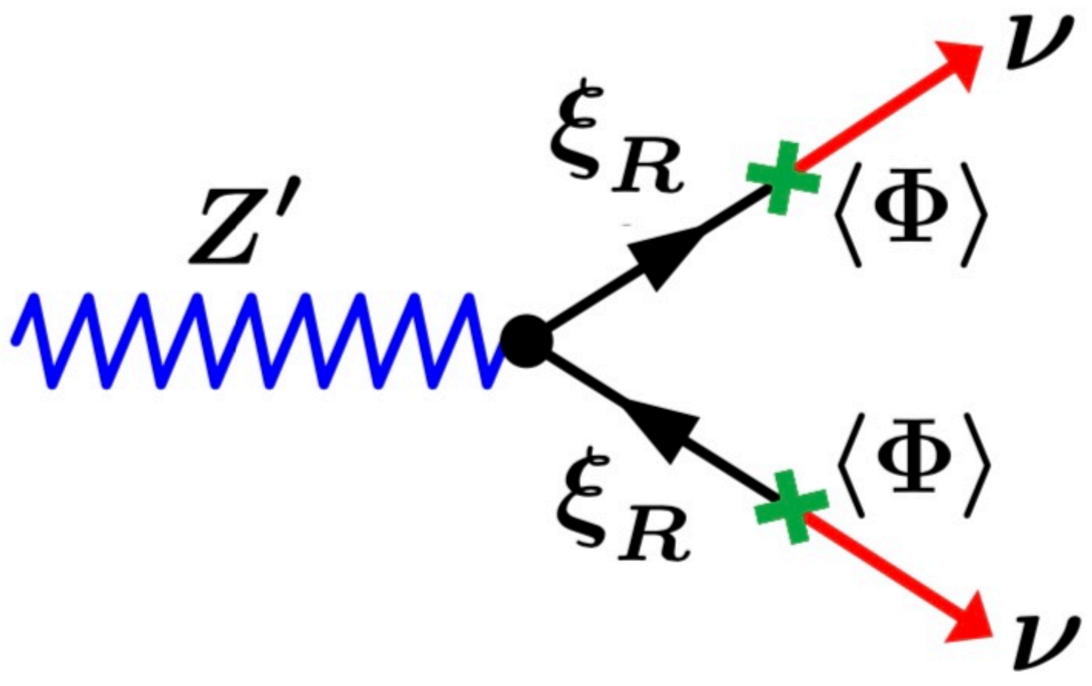
# Possible Solution :

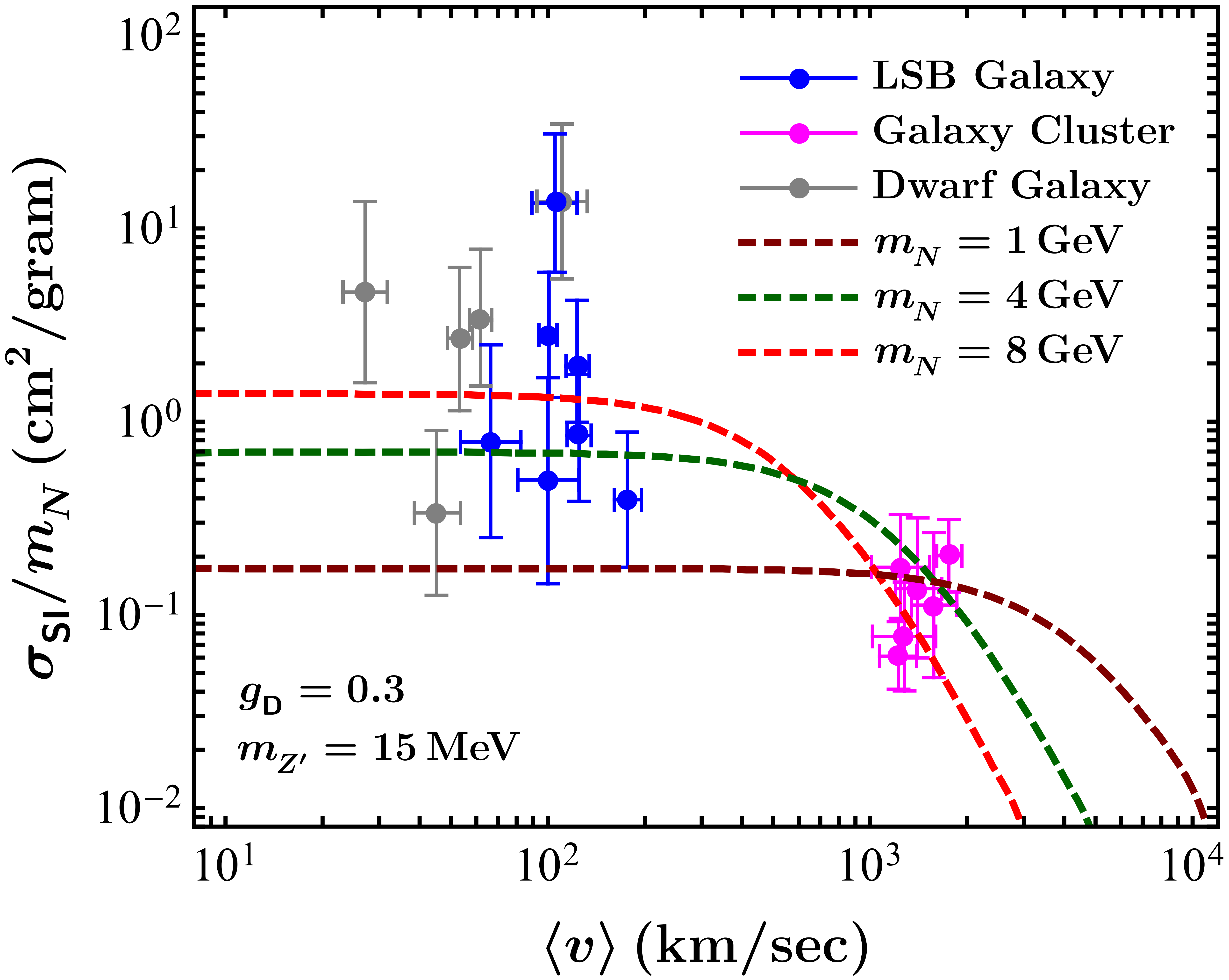
$$\mathscr{L} = g_X \overline{N} i\gamma_\mu N Z_X^\mu + \overline{\xi_R} i\gamma_\mu Z_X^\mu \xi_R + \overline{\chi_L} i\gamma_\mu Z_X^\mu \chi_L - \left[ y_\psi \overline{L_L} \tilde{\Phi} \xi_R + H.c. \right]$$

- $Z_X$ can not be very long lived, otherwise it will produce too much $\Delta N_{\rm eff}$.

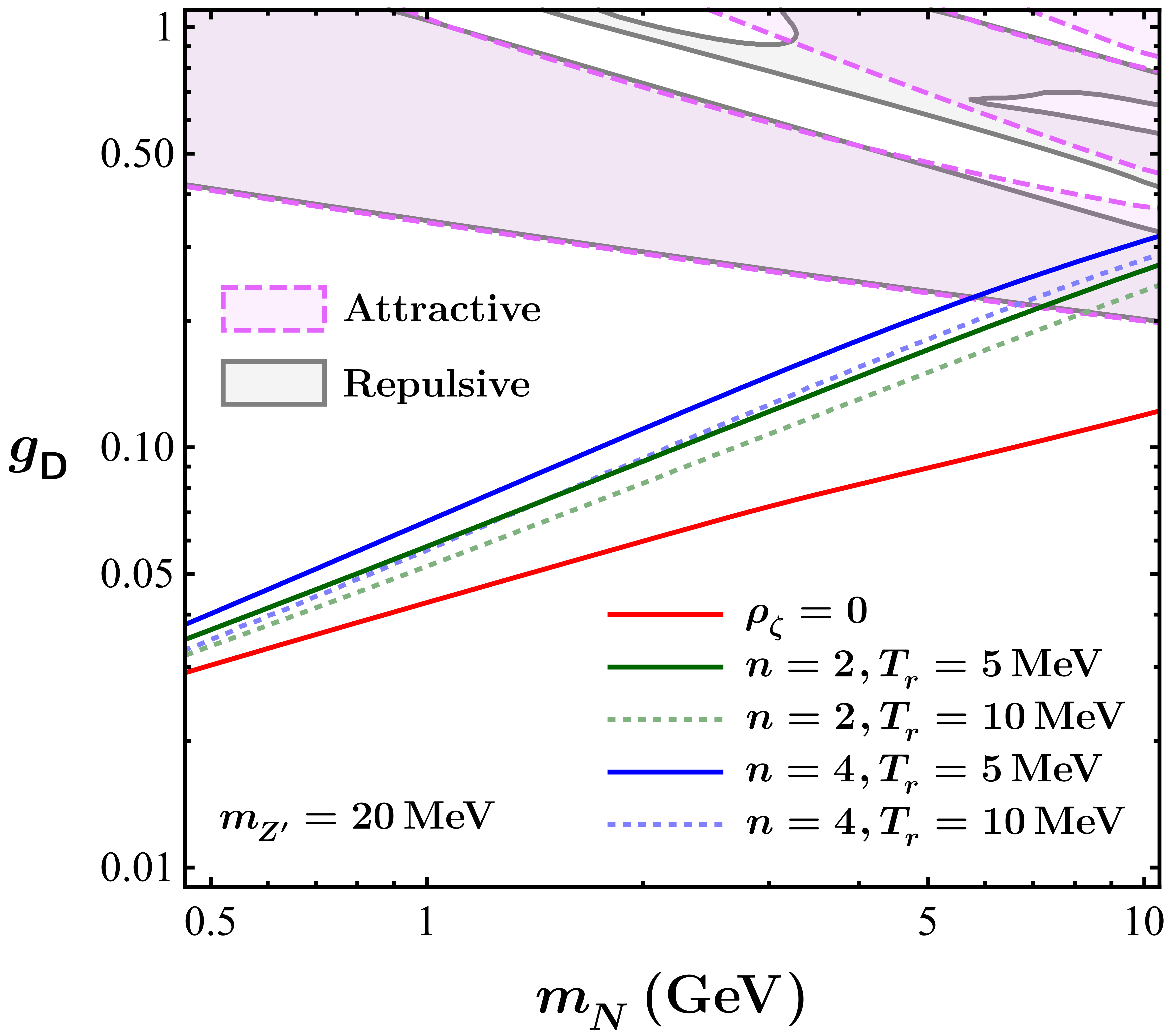


# Results



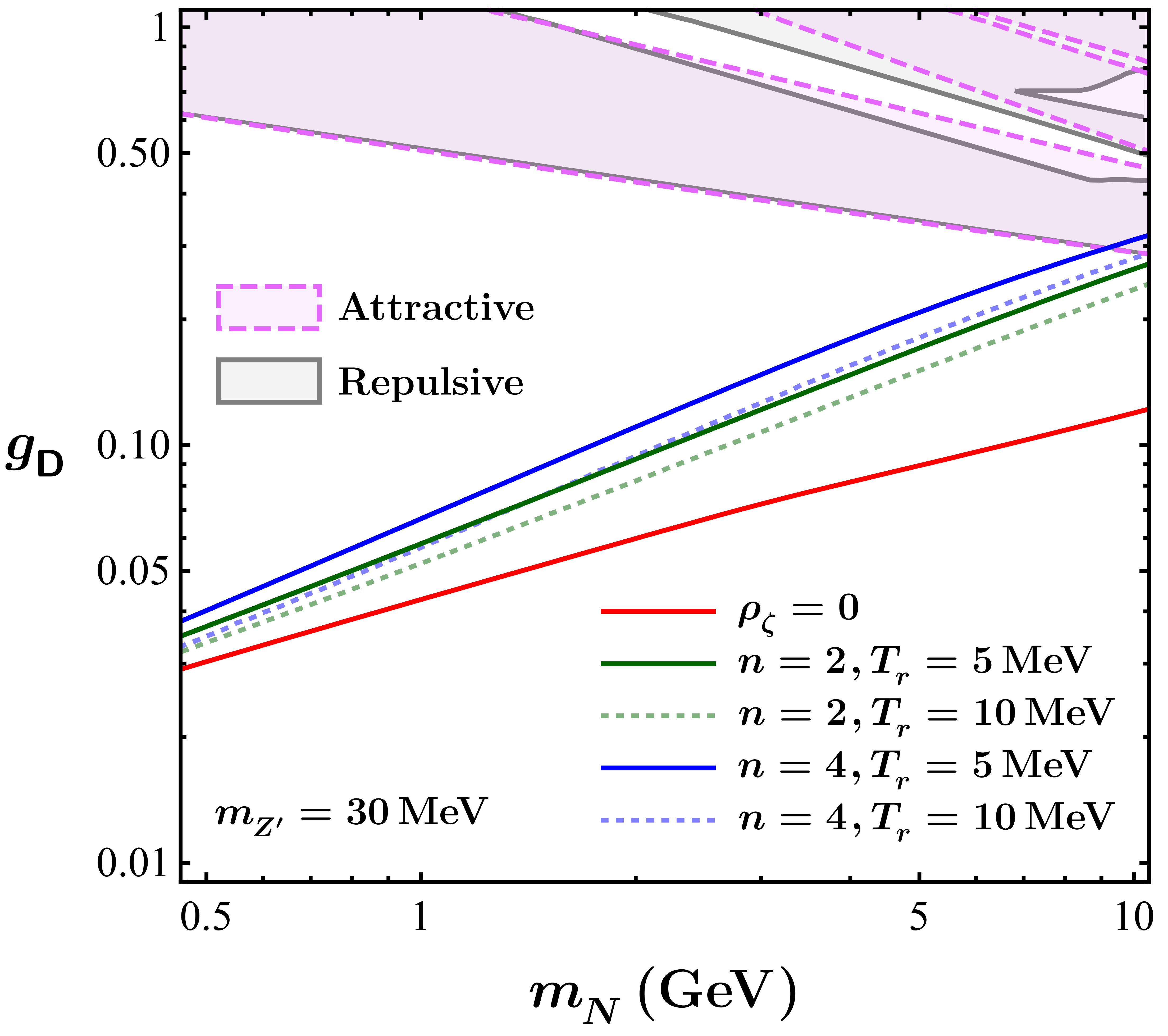
LSB Galaxy
Galaxy Cluster
Dwarf Galaxy
$m_N = 1\,\mathrm{GeV}$
$m_N = 4\,\mathrm{GeV}$
$m_N = 8\,\mathrm{GeV}$
$g_D = 0.3$
$m_{Z'} = 15\,\mathrm{MeV}$
$\sigma_{SI}/m_N$ (cm$^2$/gram)
$\langle v \rangle$ (km/sec)

Attractive
Repulsive
$\rho_\zeta = 0$
$n = 2, T_r = 5\,\mathrm{MeV}$
$n = 2, T_r = 10\,\mathrm{MeV}$
$n = 4, T_r = 5\,\mathrm{MeV}$
$n = 4, T_r = 10\,\mathrm{MeV}$
$m_{Z'} = 20\,\mathrm{MeV}$
$g_D$
$m_N$ (GeV)

# Results

- Heavier the $Z_X$ larger the $g_D$ we need to satisfy the $\sigma_{SI}$ that will take us further from relic density requirements.
- Lighter $Z_X$ is constrained from the measurement of $N_{\text{eff}}$.
- Even in presence of non-standard cosmology, it's still not possible to satisfy both SI and relic below 5 GeV together.
- The expansion rate becomes closer to the expansion rate in RD during the freeze-out of DM.



# Conclusions

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- The light thermal self-interacting DM is still a viable possibility.
- We showed that the CMB bounds can be eluded if the mediator particles decays into neutrino.
- Future CMB observations can probe $Z_X$ further from there contributions to $\Delta N_{\rm eff}$.
- However, we found that it's still not possible to satisfy both SI and relic below 5 GeV even in presence of non-standard cosmology.

# Thank you for listening!