KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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

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arXiv : 2310.05676

In collaboration with Prof. P. Ko & Dr. N. Dibyendu (KIAS)

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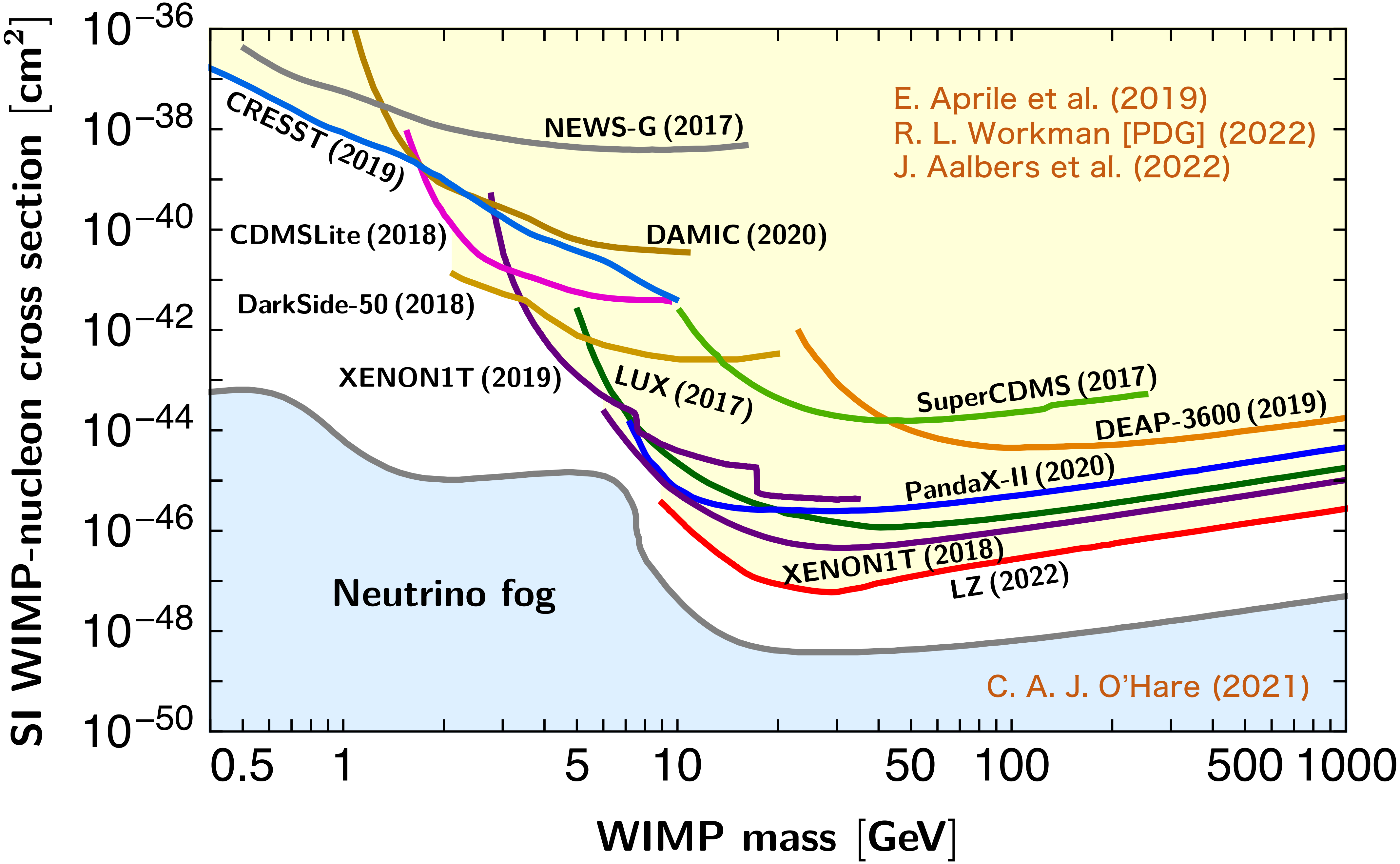
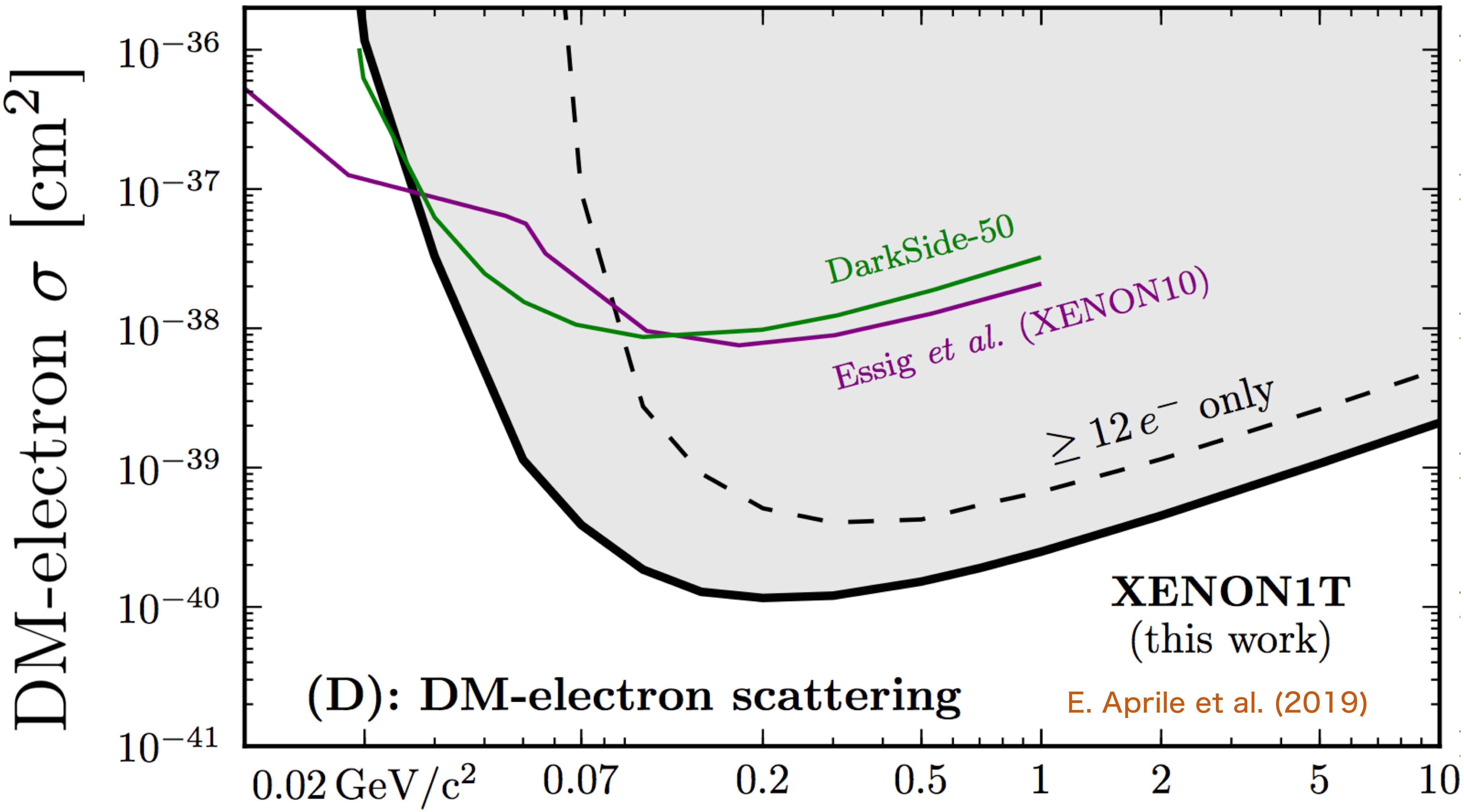
WIMP Dark Matter (DM) direct searches

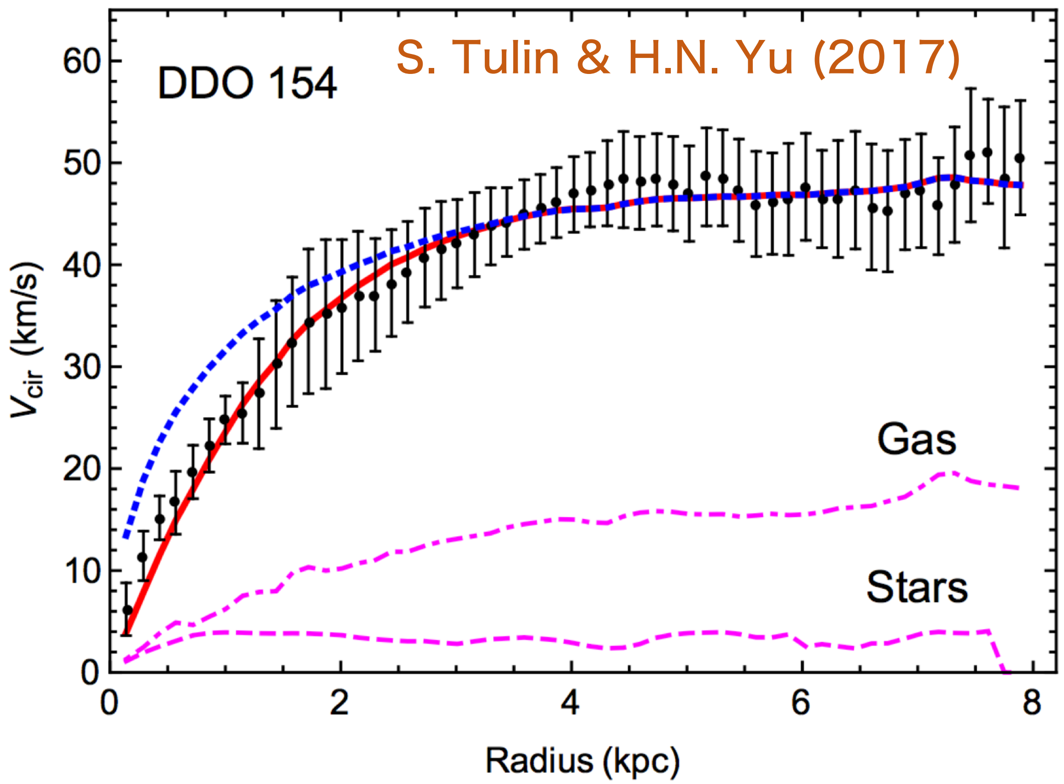


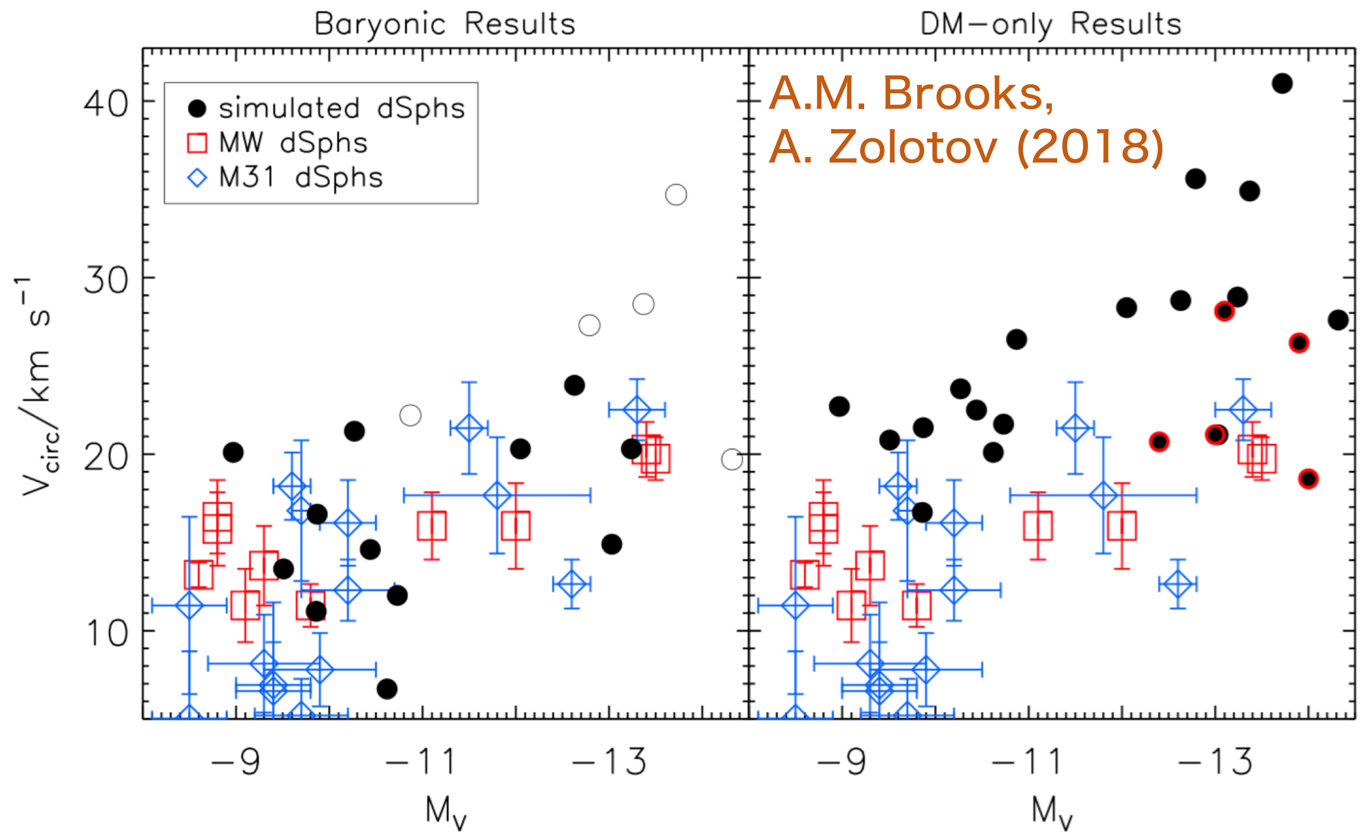
Current experiments of light DM detections



Issues of small scale structures (< 1Mpc)

- Discrepancy between N-body simulations and observations :



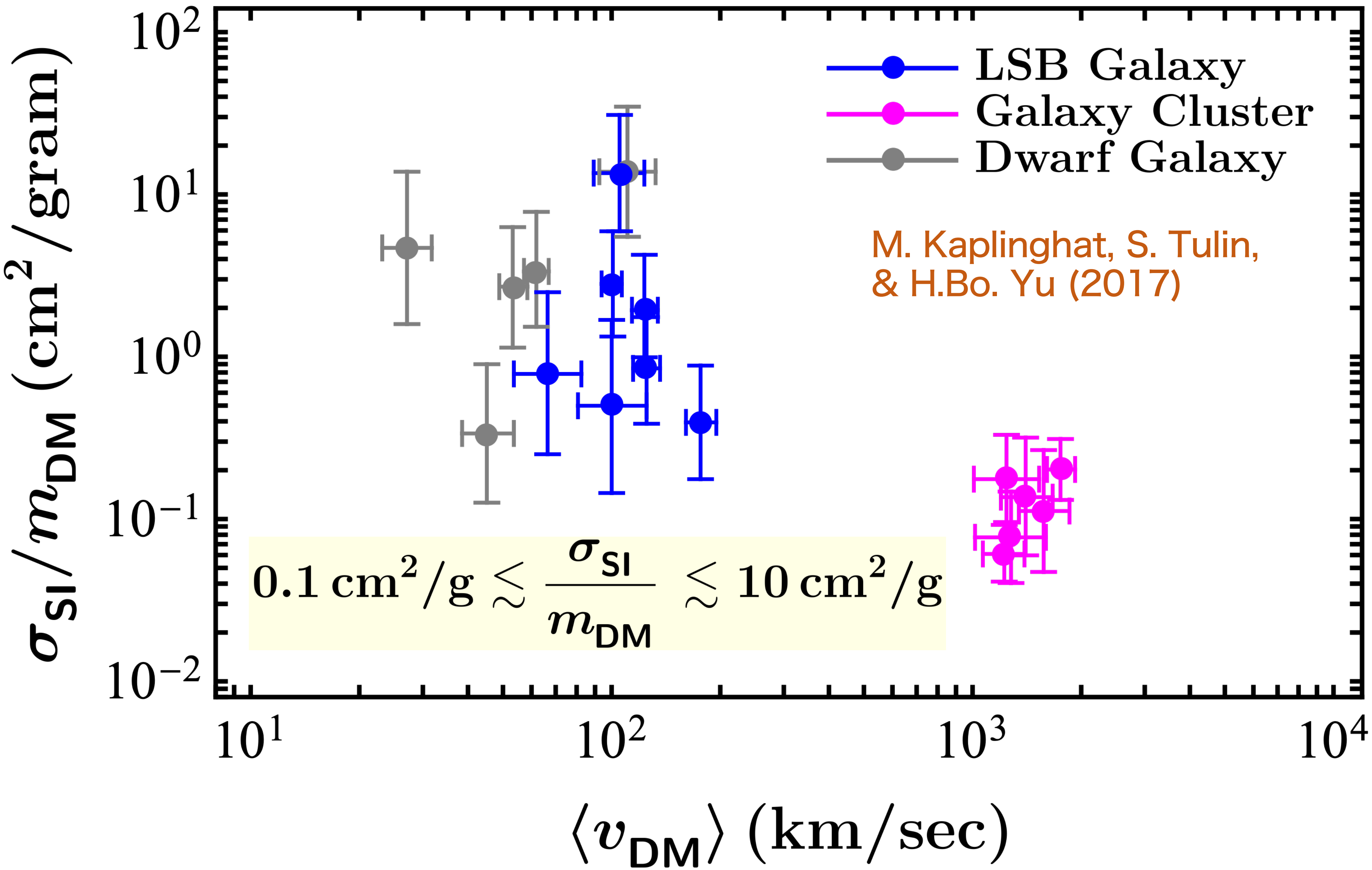


core-vs-cusp problem

too-big-to-fail problem

- DM with a sizable self-interacting (SI) cross-section can resolve these astrophysical problems/issues.

Bounds on DM self-interacting cross-section



Can we have light thermal (WIMP) DM with a sizable self-interacting cross-section?

WIMP DM

- Relic abundance of WIMP DM

annihilation cross-section

$$\Omega_{\rm WIMP} h^2 \simeq 0.12 \left(\frac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right) \Rightarrow \langle \sigma v \rangle \simeq 10^{-8}\,\mathrm{GeV}^{-2}$$

- Mass scale and coupling strength of WIMP DM

$$\langle \sigma v \rangle = \frac{g^2}{m_{\rm DM}^2} \Rightarrow g \simeq 10^{-2} \left(\frac{m_{\rm DM}}{100\,\mathrm{GeV}} \right)$$ (WIMP miracle)

g : dimensionless coupling

$$\simeq 10^{-3} \left(\frac{m_{\rm DM}}{10\,\mathrm{GeV}} \right)$$ (Our work)

WIMP DM

SI cross-section via a contact-interaction

$$\left.\frac{\sigma_{\rm SI}}{m_{\rm DM}}\right|_{\rm obs} \simeq 1\,{\rm cm}^2/{\rm g} \simeq 4.6\times 10^3\,{\rm GeV}^{-3}$$

SIMP, Forbidden DM,⋯

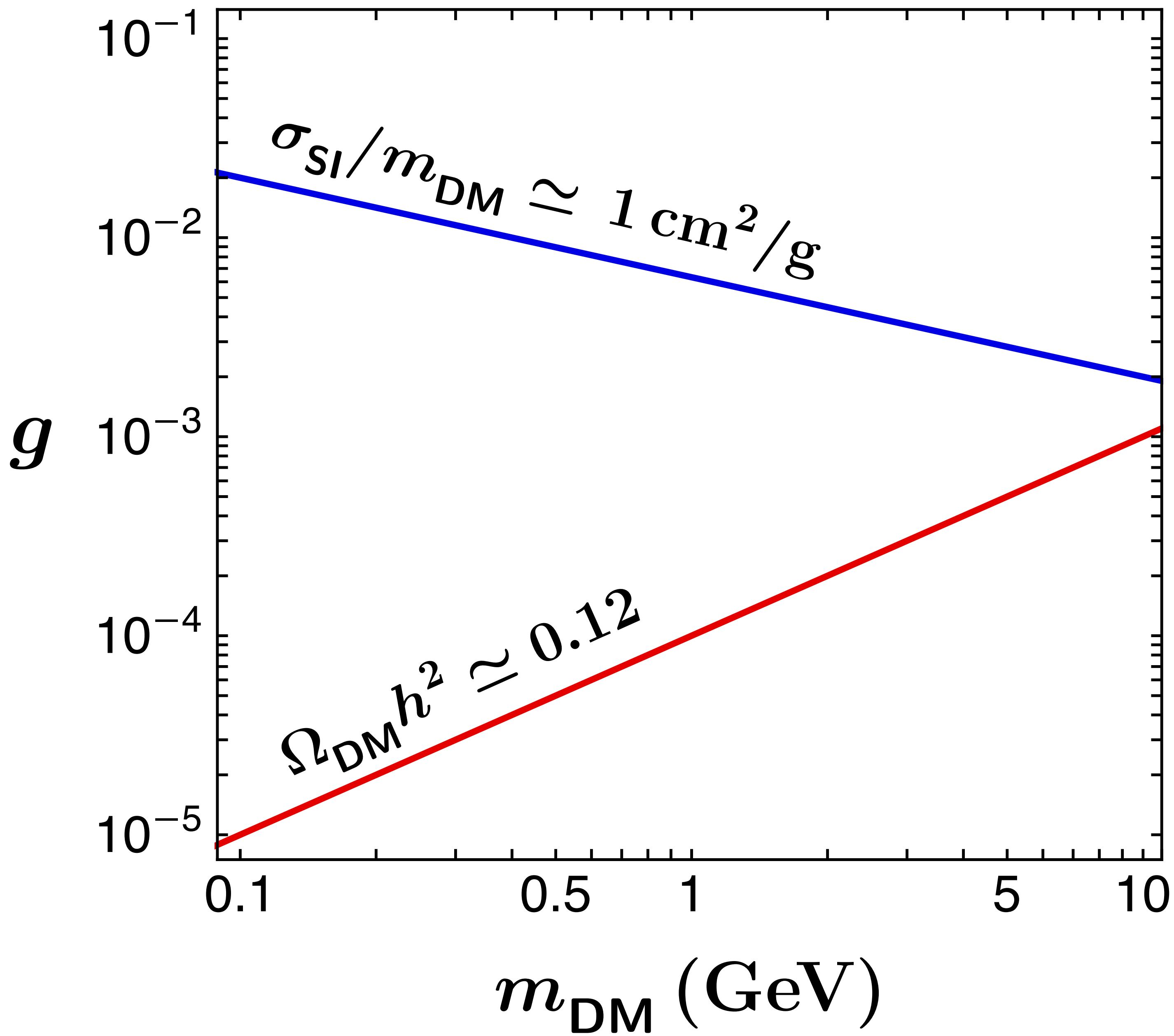
$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} = \frac{g^2}{m_{\rm DM}^3} \Rightarrow g \simeq 2\times 10^3\left(\frac{m_{\rm DM}}{10\,{\rm GeV}}\right)^{3/2} \simeq \mathcal{O}(1)\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)^{3/2}$$

SI cross-section via a light mediator in the small velocity limit

$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} = \frac{g^2}{m_{\rm DM}^3}\left(\frac{m_{\rm DM}}{m_{Z'}}\right)^4 \Rightarrow g \simeq 2\times 10^{-3}\left(\frac{m_{Z'}}{10\,{\rm MeV}}\right)^2\left(\frac{m_{\rm DM}}{10\,{\rm GeV}}\right)^{-1/2}$$

>>1

DM mass v.s. coupling



Relic abundance

$$g \simeq 10^{-3}\left(\frac{m_{\text{DM}}}{10\,\text{GeV}}\right)$$

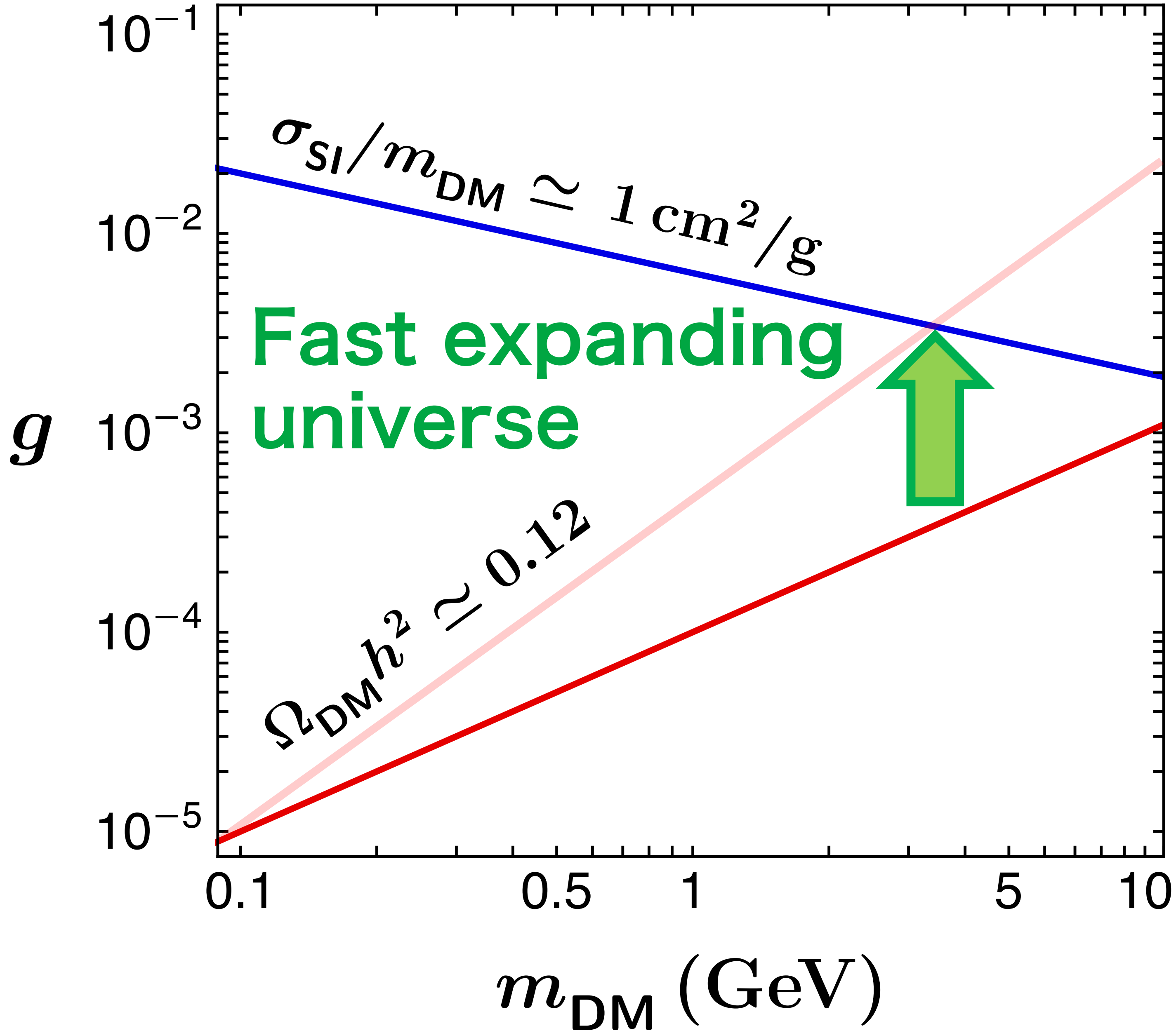
Self-interaction

$$g \simeq 2\times 10^{-3}\left(\frac{m_{\text{DM}}}{10\,\text{GeV}}\right)^{-1/2}$$

$m_{Z'} \sim \mathcal{O}(10)\,\text{MeV}$

DM is under-abundant in low mass regime due to too large annihilation cross section

DM mass v.s. coupling



Relic abundance

$$g \simeq 10^{-3}\left(\frac{m_{\rm DM}}{10\,\mathrm{GeV}}\right)$$

Self-interaction

$$g \simeq 2\times 10^{-3}\left(\frac{m_{\rm DM}}{10\,\mathrm{GeV}}\right)^{-1/2}$$

$$m_{Z'} \sim \mathcal{O}(10)\,\mathrm{MeV}$$

DM is under-abundant in low mass regime due to too large annihilation cross section

Fast expanding universe

D'Eramo, et al (2017)

- Assuming the early universe is dominated by a species ϕ that redshifts faster than radiation :

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

a : scale factor

$n > 0$

- The total energy density :

$$\rho_{\text{tot}}(T) = \rho_\phi(T) + \rho_\gamma(T) = \rho_\gamma(T)\left\{1 + \frac{g_\rho(T_r)}{g_\rho(T)}\left[\frac{g_s(T)}{g_s(T_r)}\right]^{\frac{4+n}{3}}\left(\frac{T}{T_r}\right)^n\right\}$$

$$\mathcal{H}(T) \simeq \sqrt{\frac{\pi^2 g_\rho(T)}{90}}\frac{T^2}{m_{\text{Pl}}}\left(\frac{T}{T_r}\right)^{n/2}$$

$$\rho_\phi(T_r) = \rho_\gamma(T_r)$$

Parameters : (n, T_r)

- $\Delta N_\nu(T_{\text{BBN}} \simeq 1\,\text{MeV})$ constraint : $T_r \gtrsim (15.4)^{1/n}\,\text{MeV}$

A simple light thermal self-interacting DM model

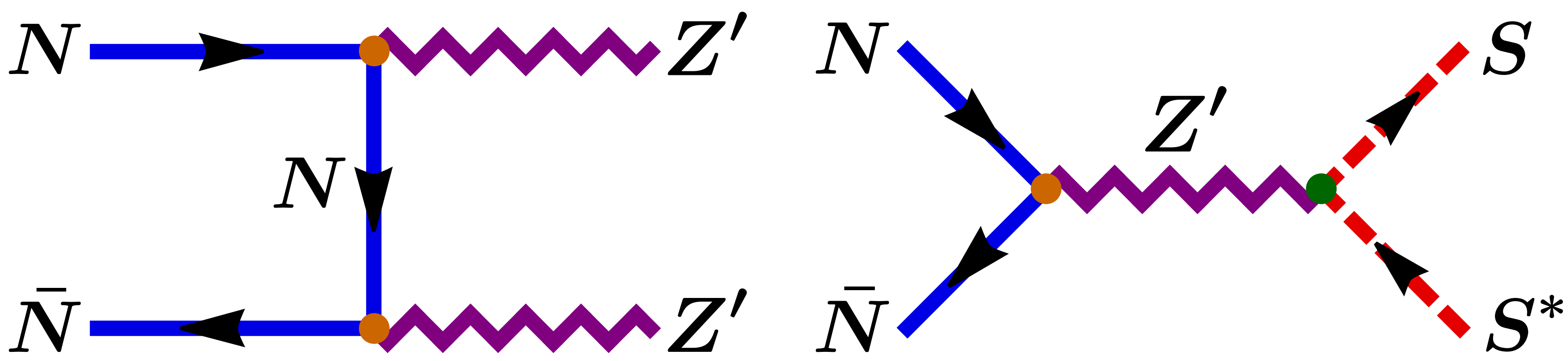
- Particle content & charge assignment under $\mathrm{G_{SM}} \otimes \mathrm{U(1)_D}$

	L	E	H	N	S	Z'
$\mathrm{SU(2)}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$-1/2$	-1	$+1/2$	0	0	0
$\mathrm{U(1)_D}$	0	0	0	$\mathcal{Q}_N$	$\mathcal{Q}_S$	0
spin	$1/2$	$1/2$	0	$1/2$	0	1

- N plays the role of fermionic dark matter
- S develops VEV that breaks the Dark gauge symmetry
- Z' is a mediator responding the DM self-interaction

Feynman diagrams

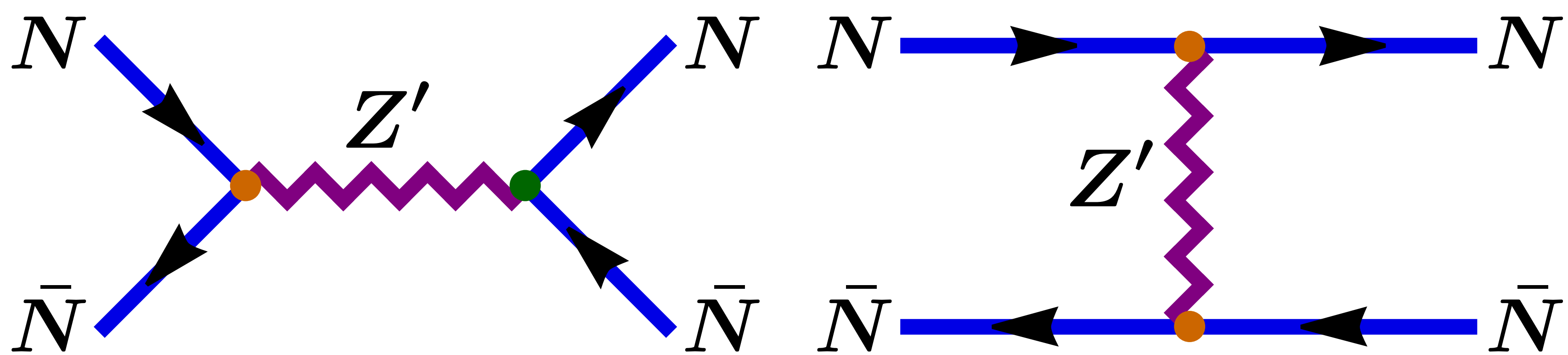
DM annihilation cross-section



$$\langle \sigma v \rangle = \frac{g_{\mathsf{D}}^4}{128\pi m_N^2}$$

(s-wave)

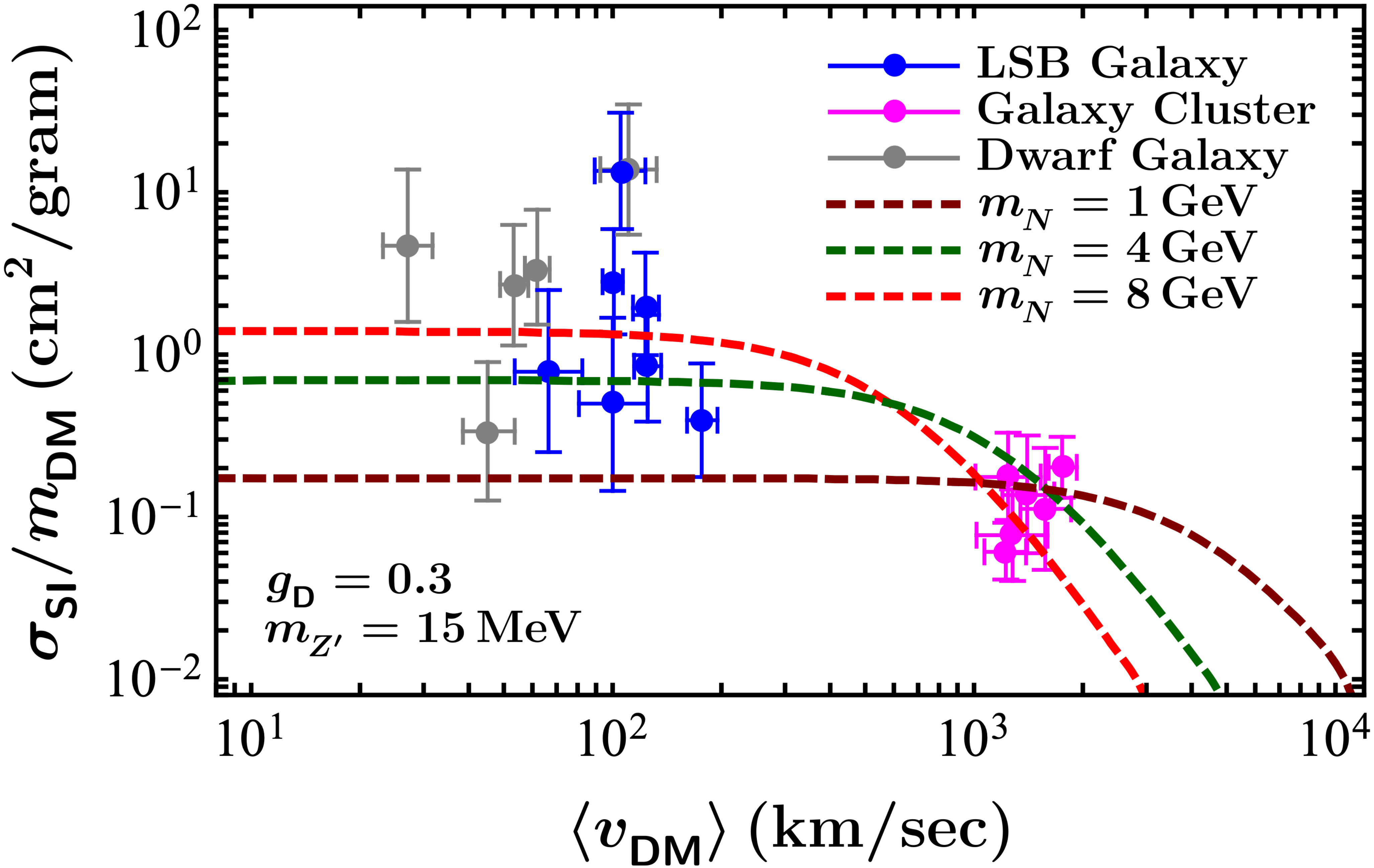
SI cross-section/DM mass



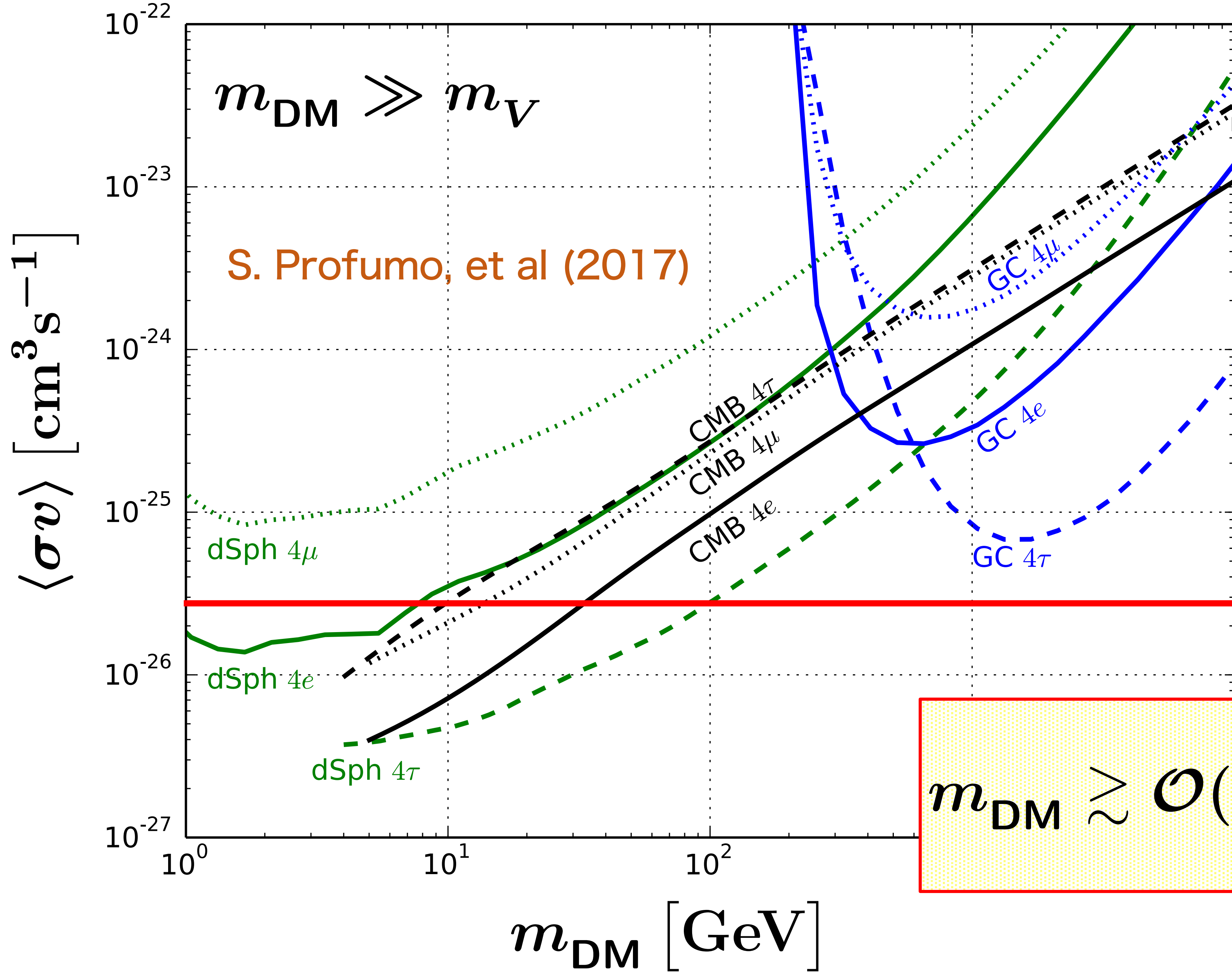
$$\sigma_{\mathsf{SI}} = \frac{\pi}{m_{Z'}^2} f(\beta)$$

$$\beta = \frac{2\alpha_{\mathsf{D}} m_{Z'}}{m_N v_{\mathsf{DM}}^2}$$

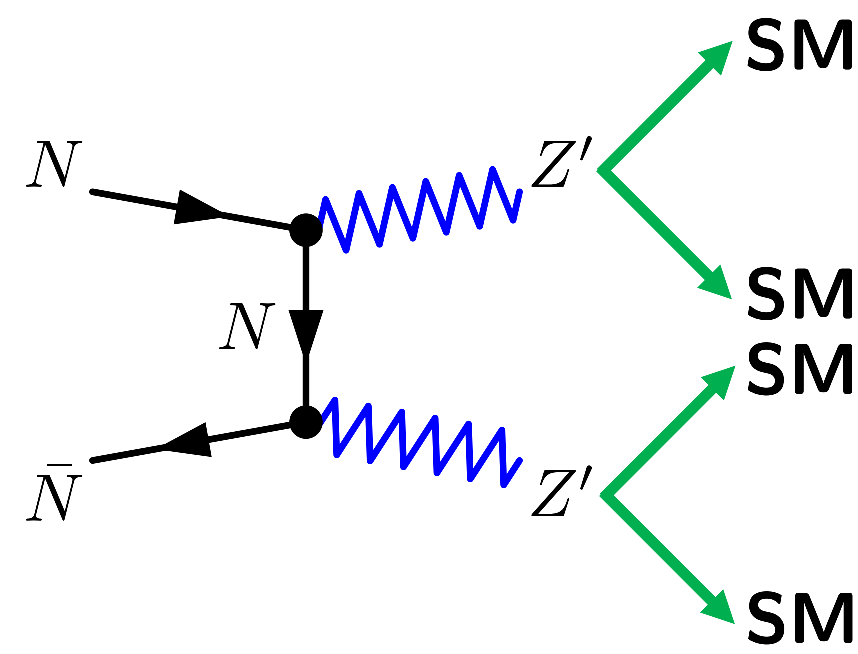
Prediction of DM SI cross-section



CMB constraint on light DM mass



Secluded DM



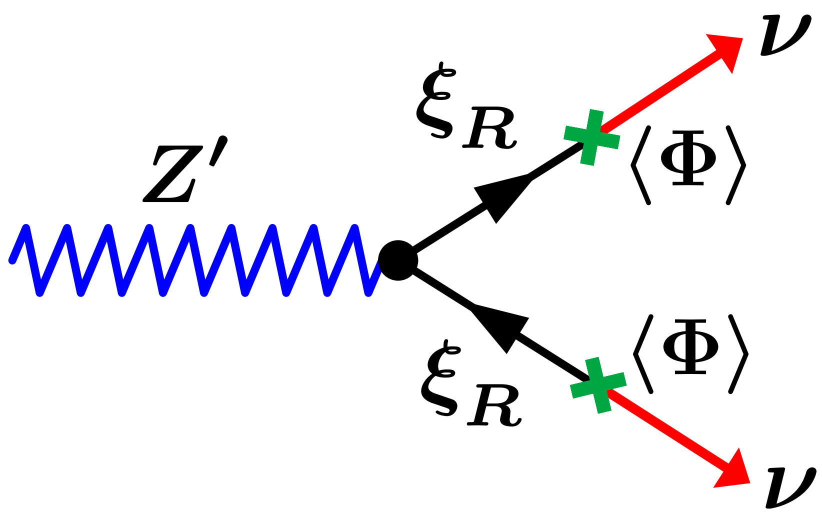
$$m_{\mathrm{DM}} \gtrsim \mathcal{O}(10\,\mathrm{GeV}) \left[\frac{\langle \sigma v \rangle}{10^{-8}\,\mathrm{GeV}^{-2}} \right]$$

A viable light thermal self-interacting DM model

- Particle content & charge assignment under $\mathrm{G_{SM}} \otimes \mathrm{U}(1)_{\mathrm{D}}$

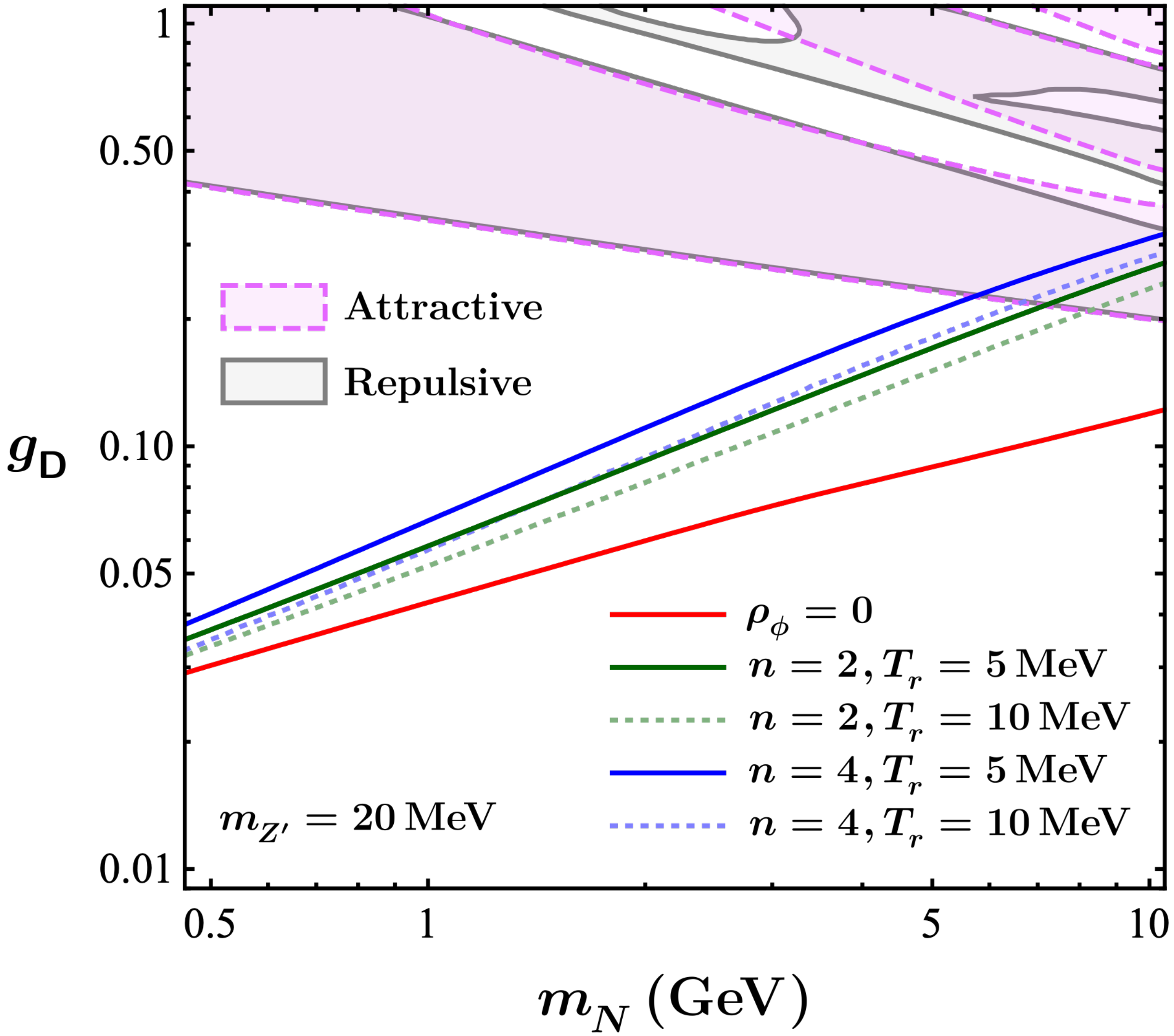
	L	E	H	N	ξ_R	χ_L	Φ	S	Z'
SU(2)	**2**	**1**	**2**	**1**	**1**	**1**	**2**	**1**	**1**
$\mathrm{U}(1)_\mathrm{Y}$	$-1/2$	-1	$+1/2$	0	0	0	$+1/2$	0	0
$\mathrm{U}(1)_\mathrm{D}$	0	0	0	$+1/2$	$+1$	$+1$	$+1$	$+1$	0
spin	$1/2$	$1/2$	0	$1/2$	$1/2$	$1/2$	0	0	1

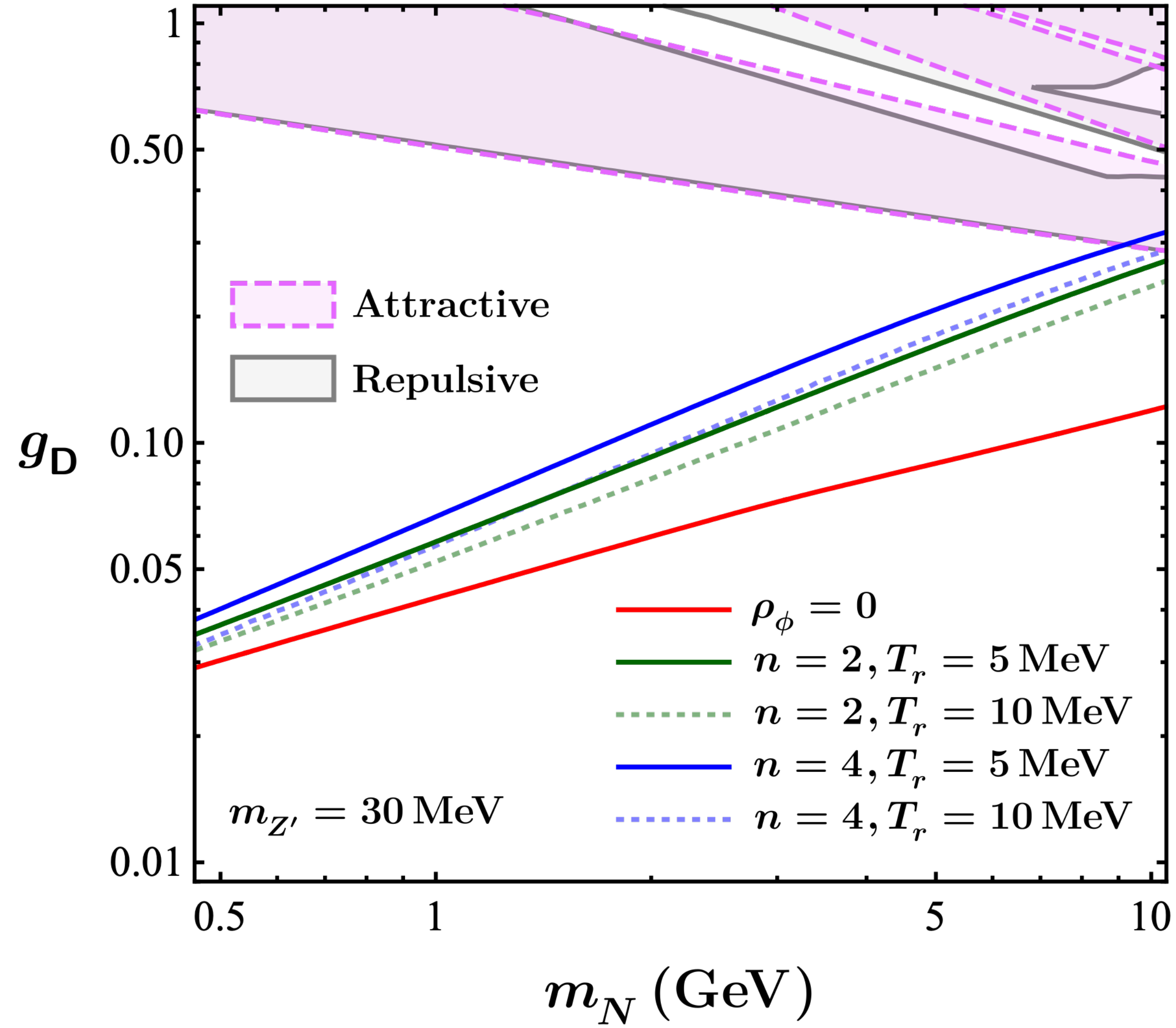
- $\mathcal{L} = \mathcal{Y}_\psi \overline{L_L}\, \widetilde{\Phi}\, \xi_R$:



Light mediator mainly decays into neutrinos at CMB epoch

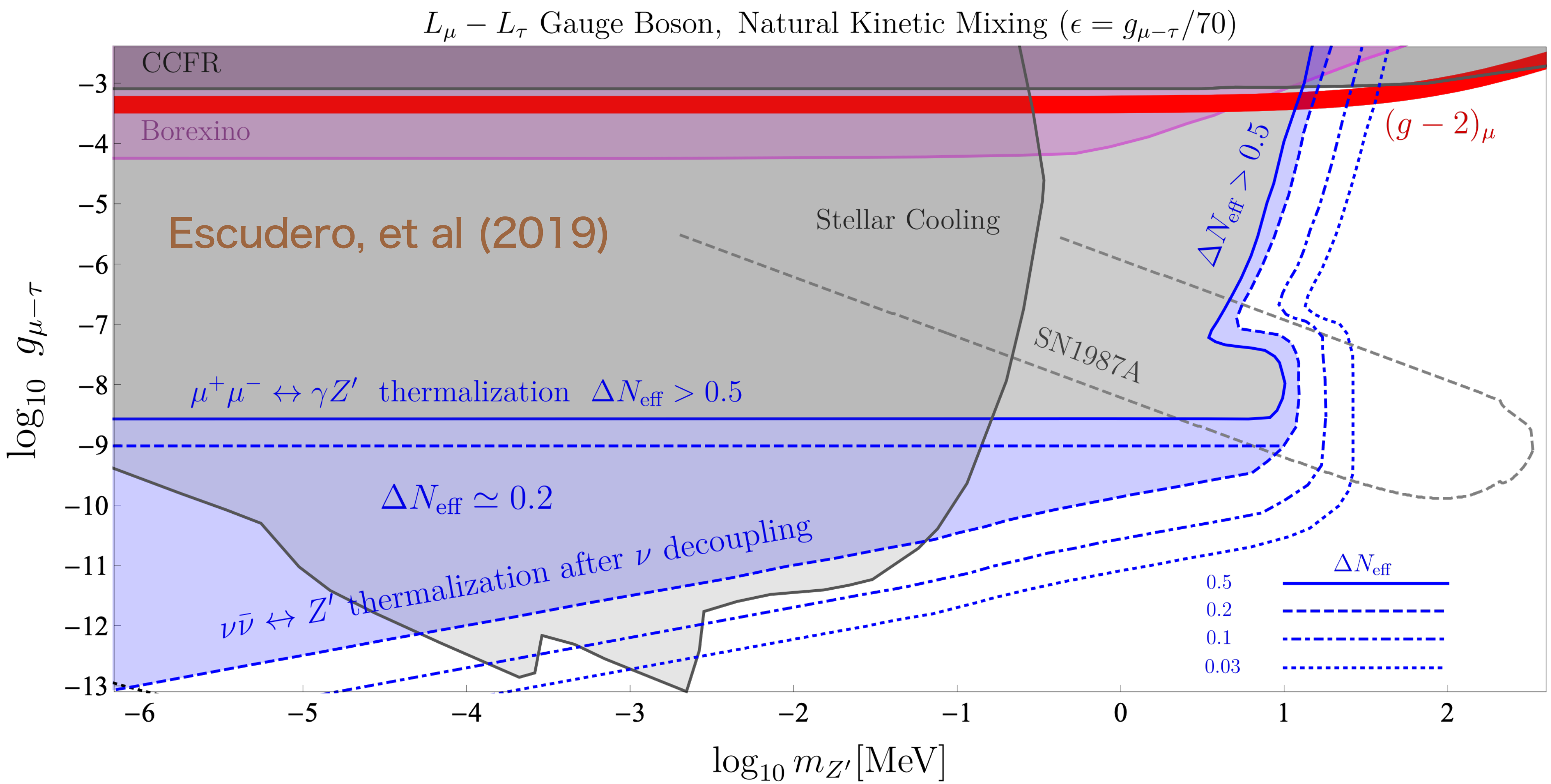
Numerical results



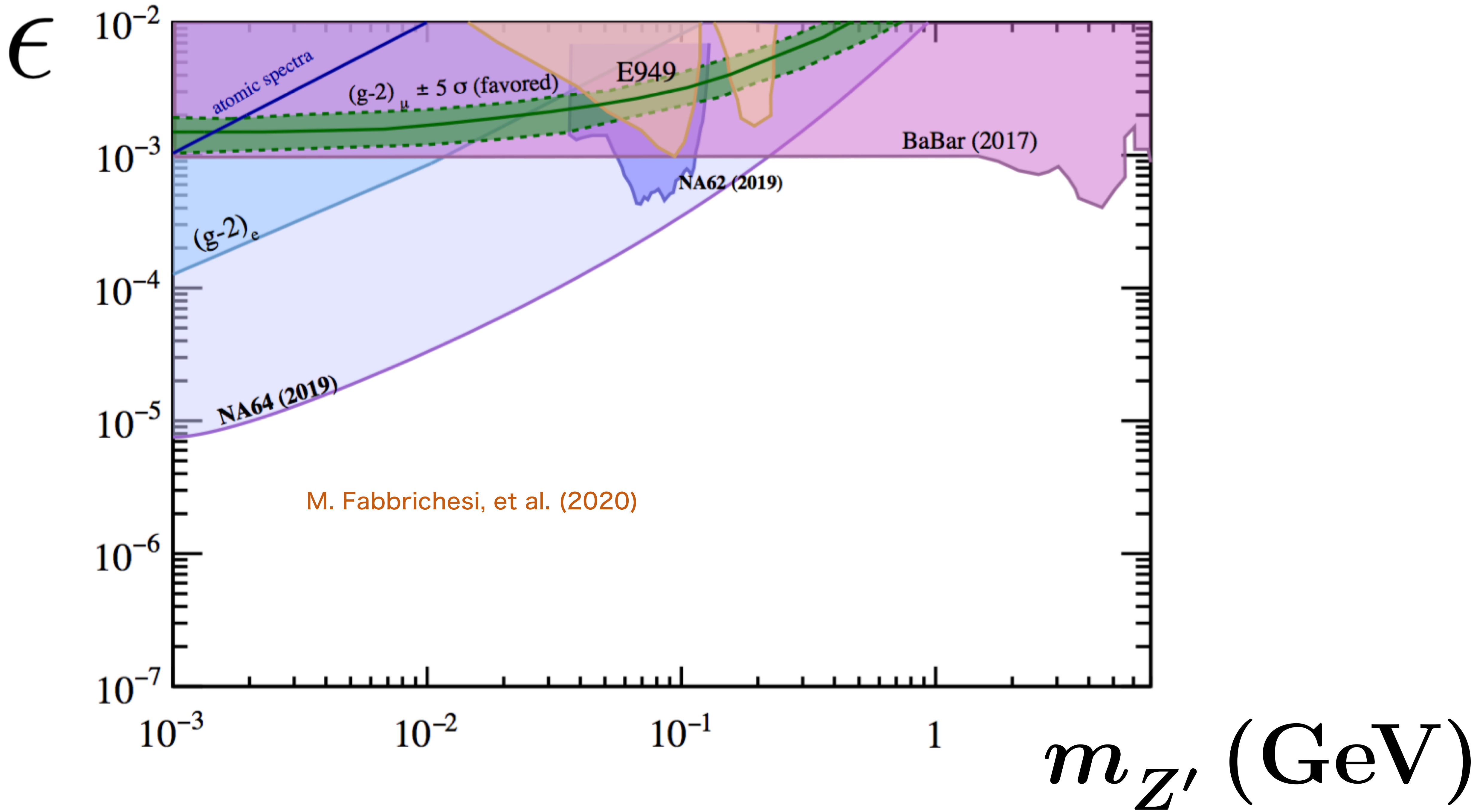


- Light thermal self-interacting DM can be used to test the non-standard cosmological evolution of the universe.

Backup



- **Early Universe Equilibrium:** If $g_{\mu-\tau} \gtrsim 4 \times 10^{-9}$, the Z' population thermalizes with the SM bath at early times and decays into neutrinos when $T \sim m_{Z'}/3$. If these decays occur predominantly after the neutrinos and photons decouple, they contribute to the neutrino energy density and thereby increase the value of $N_{\rm eff}$. Furthermore, in the presence of non-negligible kinetic mixing with the photon, Z' interactions with charged particles can delay the neutrino-photon decoupling, quantitatively affecting $N_{\rm eff}$.



ϵ
atomic spectra
(g-2)μ ± 5 σ (favored)
E949
BaBar (2017)
NA62 (2019)
(g-2)e
NA64 (2019)
M. Fabbrichesi, et al. (2020)
10−2
10−3
10−4
10−5
10−6
10−7
10−3
10−2
10−1
1
mZ′ (GeV)