KOREA INSTITUTE FOR ADVANCED STUDY

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

Shu-Yu HO (KIAS)

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In collaboration with P. Ko (KIAS) & N. Dibyendu (Bhubaneswar, Inst. Phys.)

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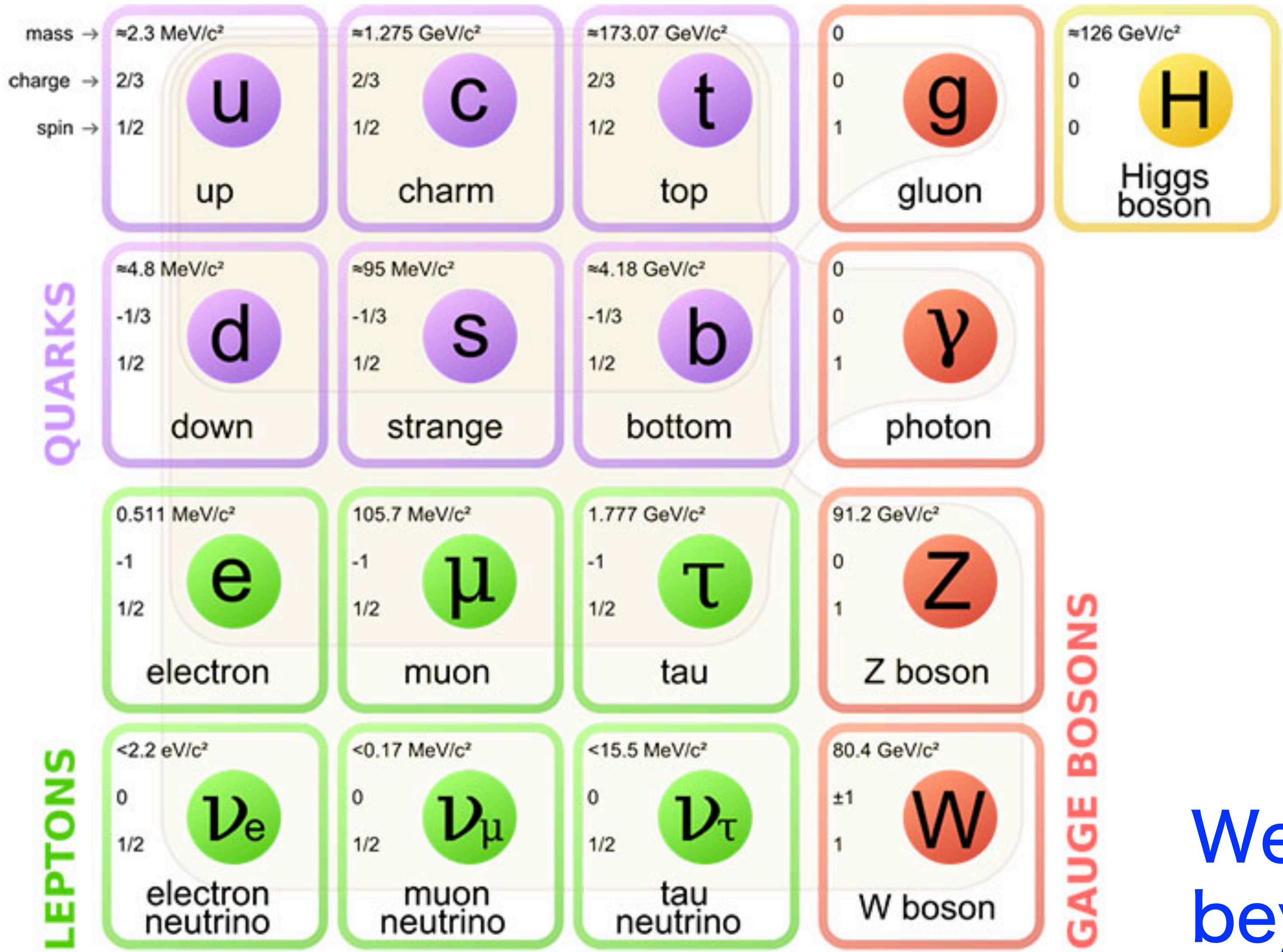
The Dark Side of the Universe, DSU2024, Corfu Workshop, Greece

Contents

- Dark Matter
- Light Dark Matter in a Fast Expanding Universe
- Model
- Results & Conclusion

The Standard Model (SM) of particle physics

- The SM well describes the microscopic interactions, but …



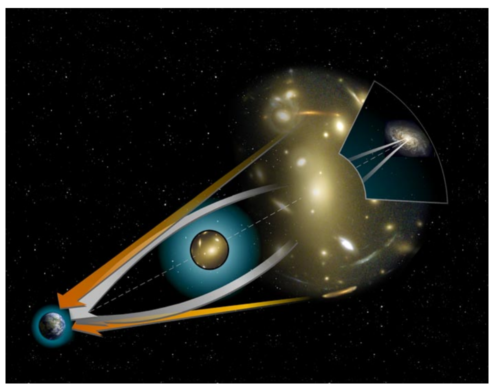
Unsolved problems

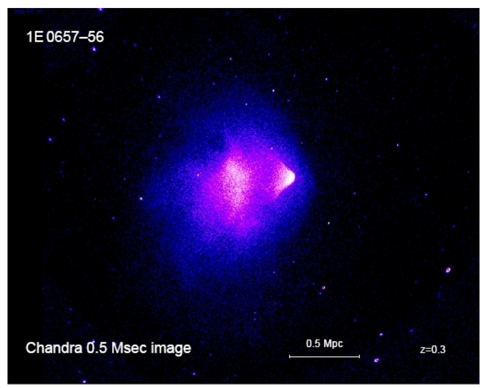
- Dark Matter (DM)
- Dark energy
- Neutrino mass
- Baryon asymmetry
- Gravity
- ………

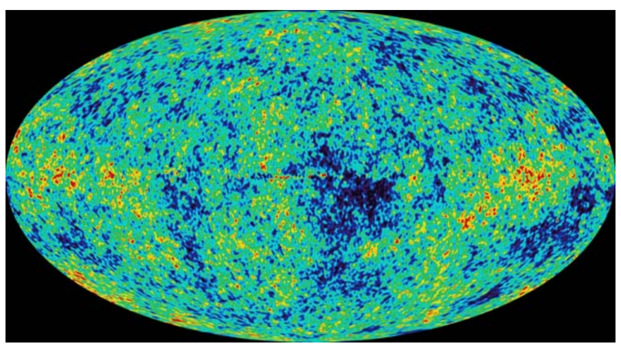
We need new physics beyond the SM (BSM)!!!

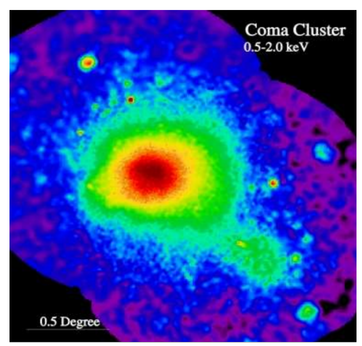
Evidence of dark matter

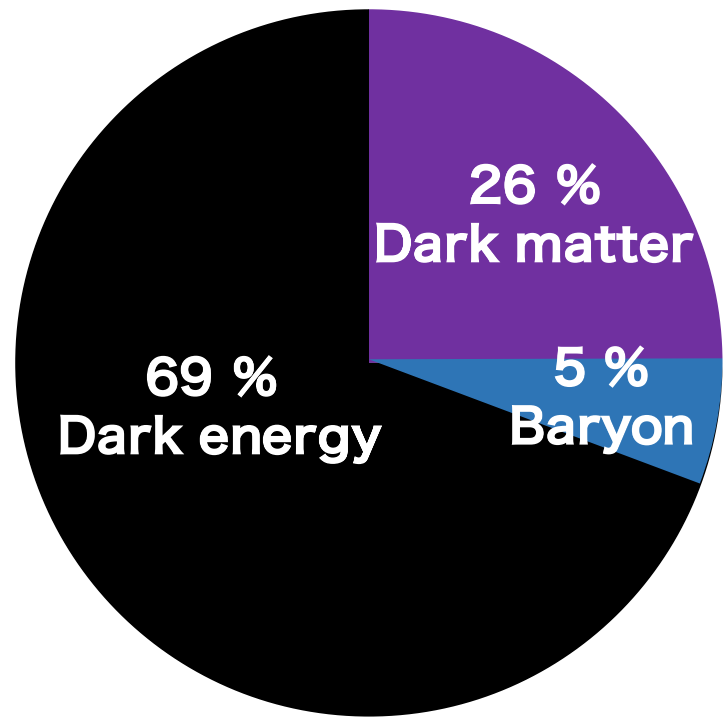
- There are overwhelming evidences for dark matter in a wide range of distance scales.

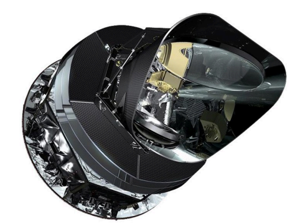












Planck 2018

Dark matter candidates

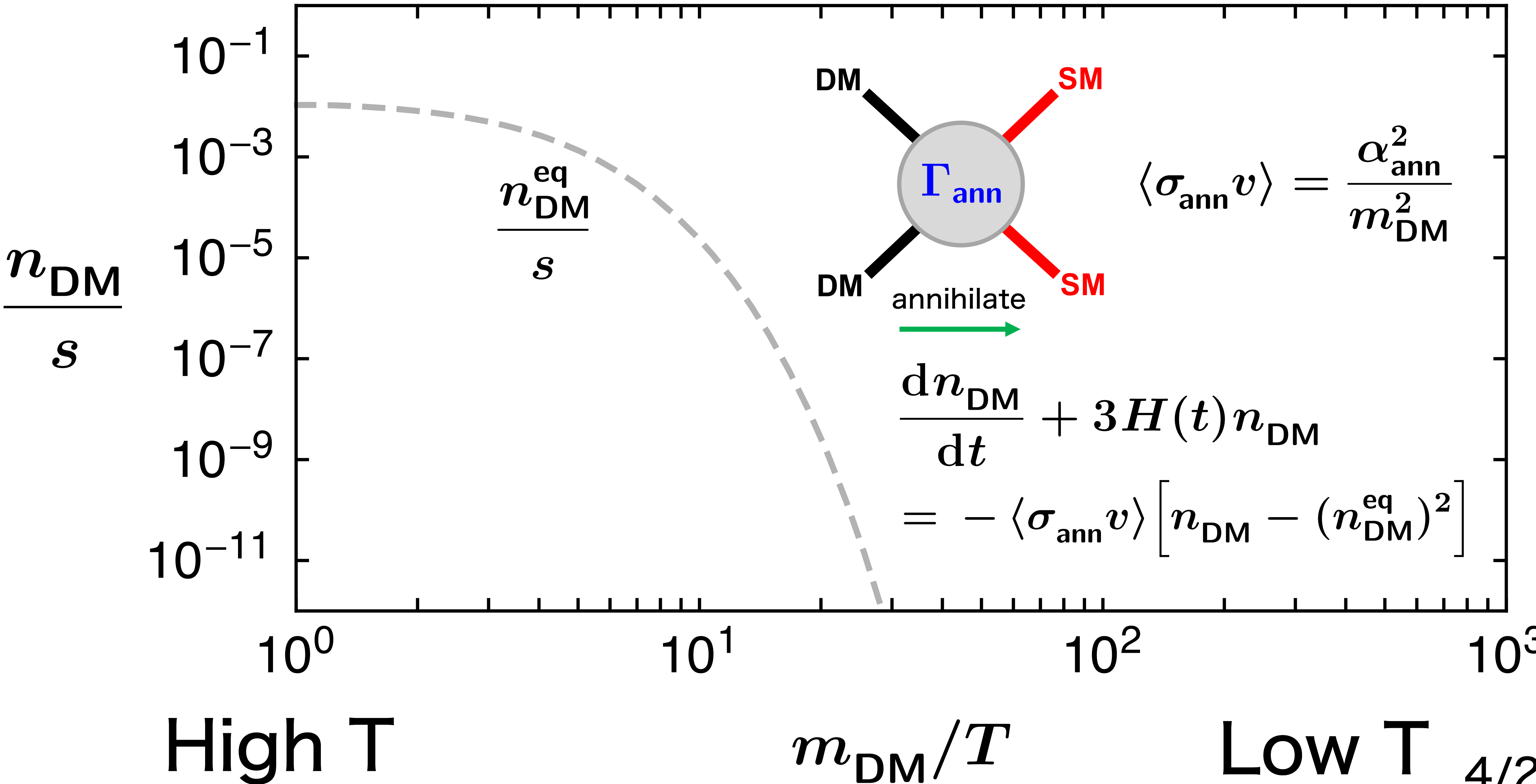
Thermal production

- Weakly interacting massive particles (WIMP) — B.W. Lee & S. Weinberg (1977)
- Strongly interacting massive particles (SIMP) — Y. Hochberg, etal (2014)
- Elastically decoupling relic (ELDER) — E. Kuflik, etal (2016)
- Forbidden dark matter — R. T. D'Agnolo, & J. T. Ruderman (2015)
- ....

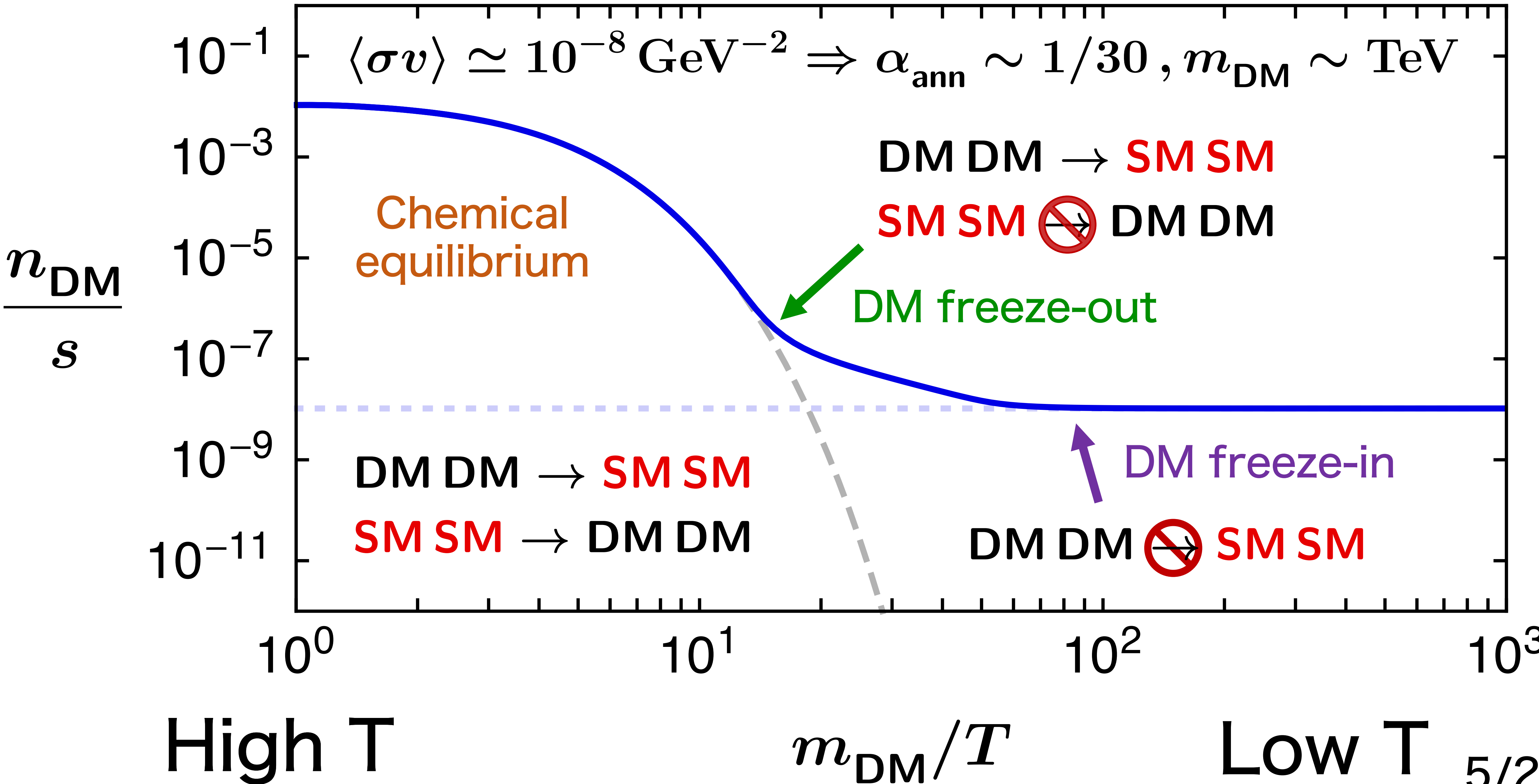
Non-thermal production

- The QCD axion/axion-like particles (ALP) — P. Arias, et al. (2012)
- Feebly interacting massive particles (FIMP) — L. J. Hall (2009)
- Hidden monopole dark matter — H. Murayama, J. Shu (2009)
- Primordial black hole (PBH) — Ya.B. Zel'dovich and I.D. Novikov (1967)
- ....

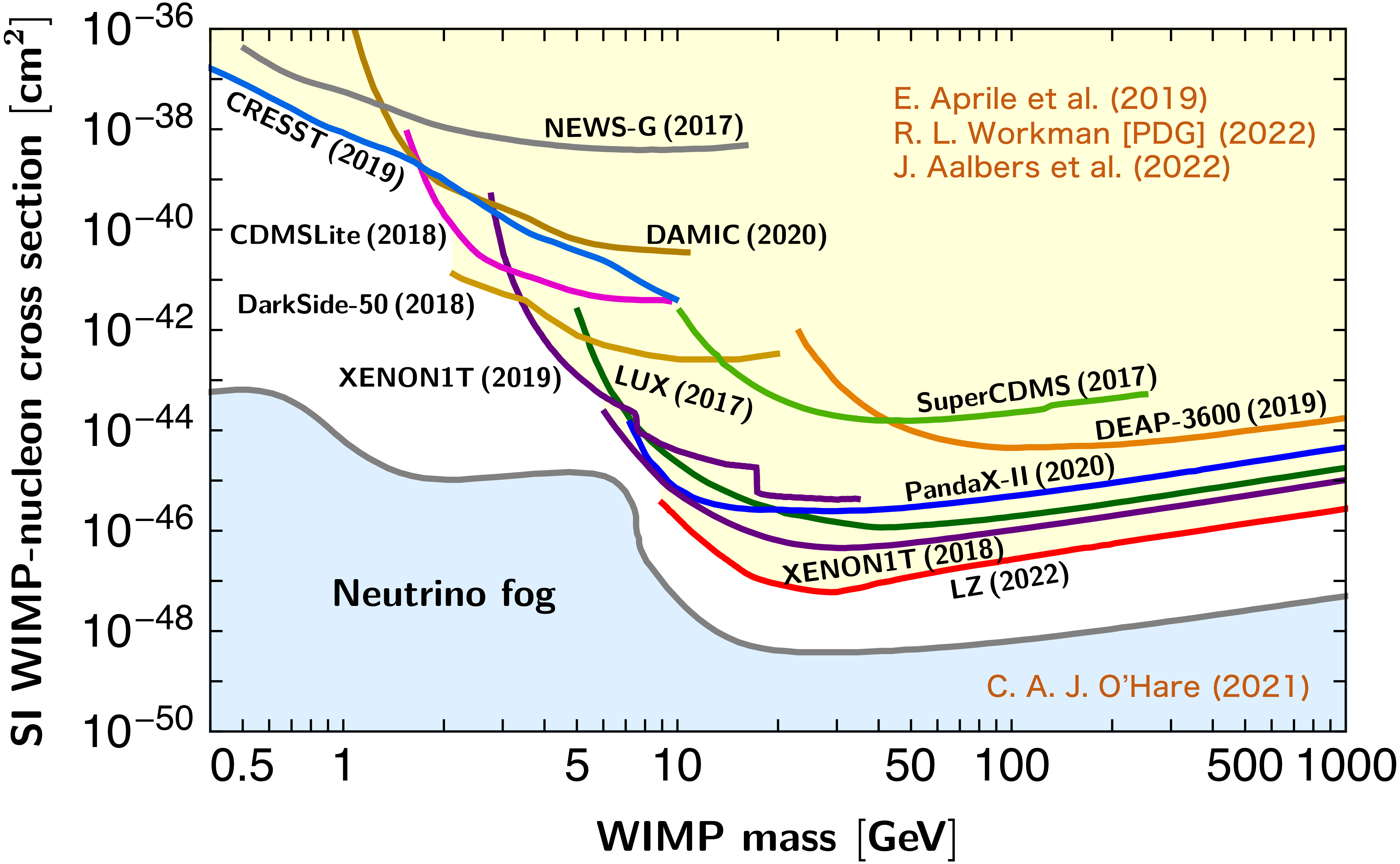
Weakly Interacting Massive Particle (WIMP) DM



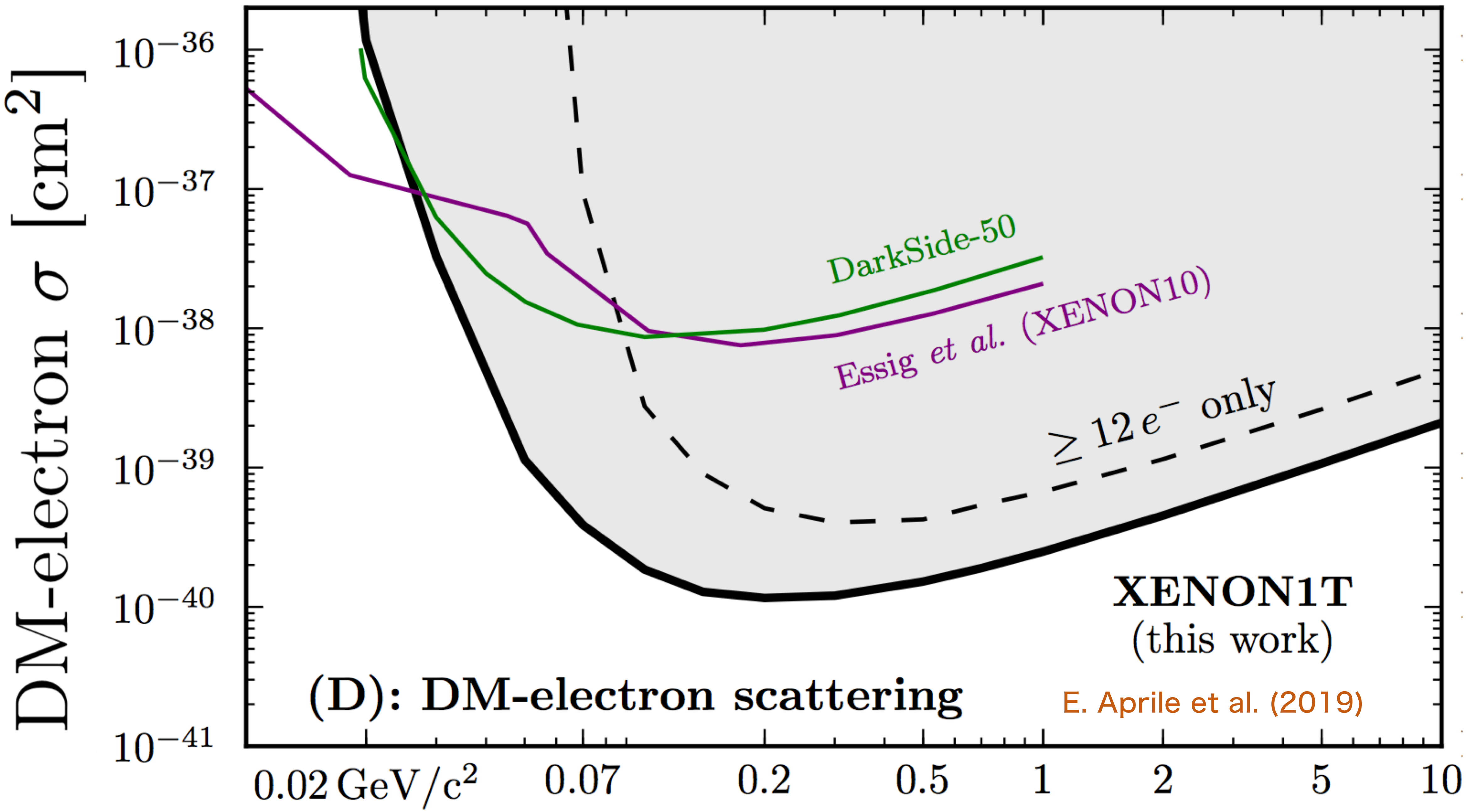
Weakly Interacting Massive Particle (WIMP) DM



WIMP Dark Matter (DM) direct searches

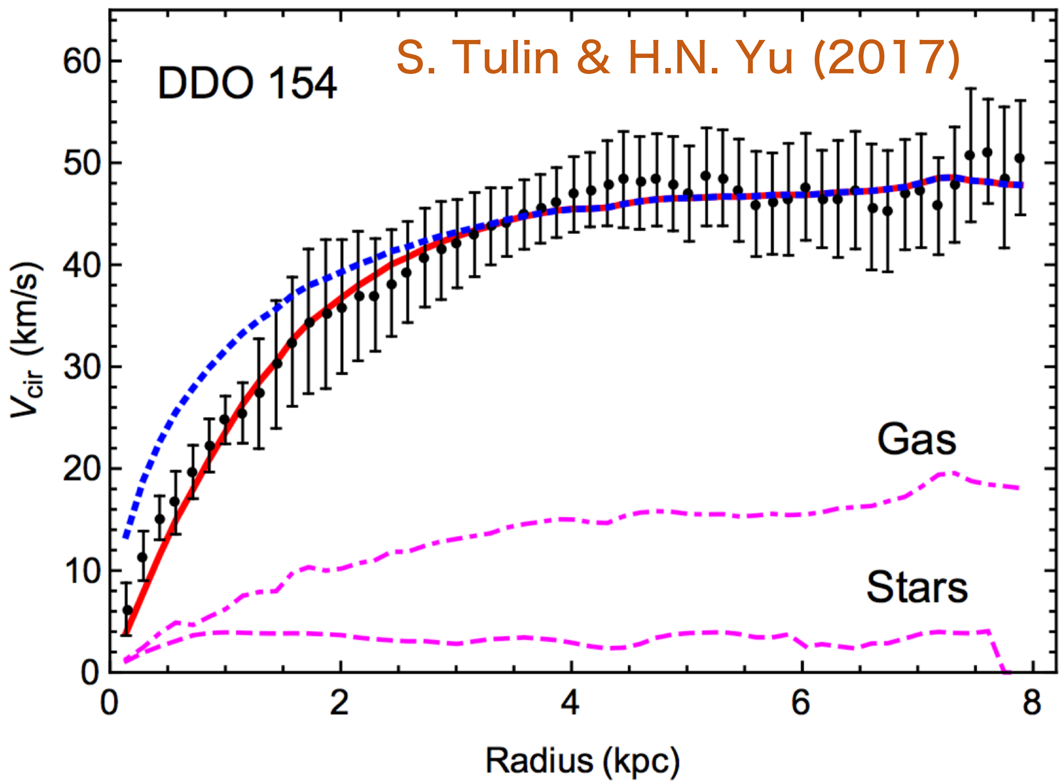


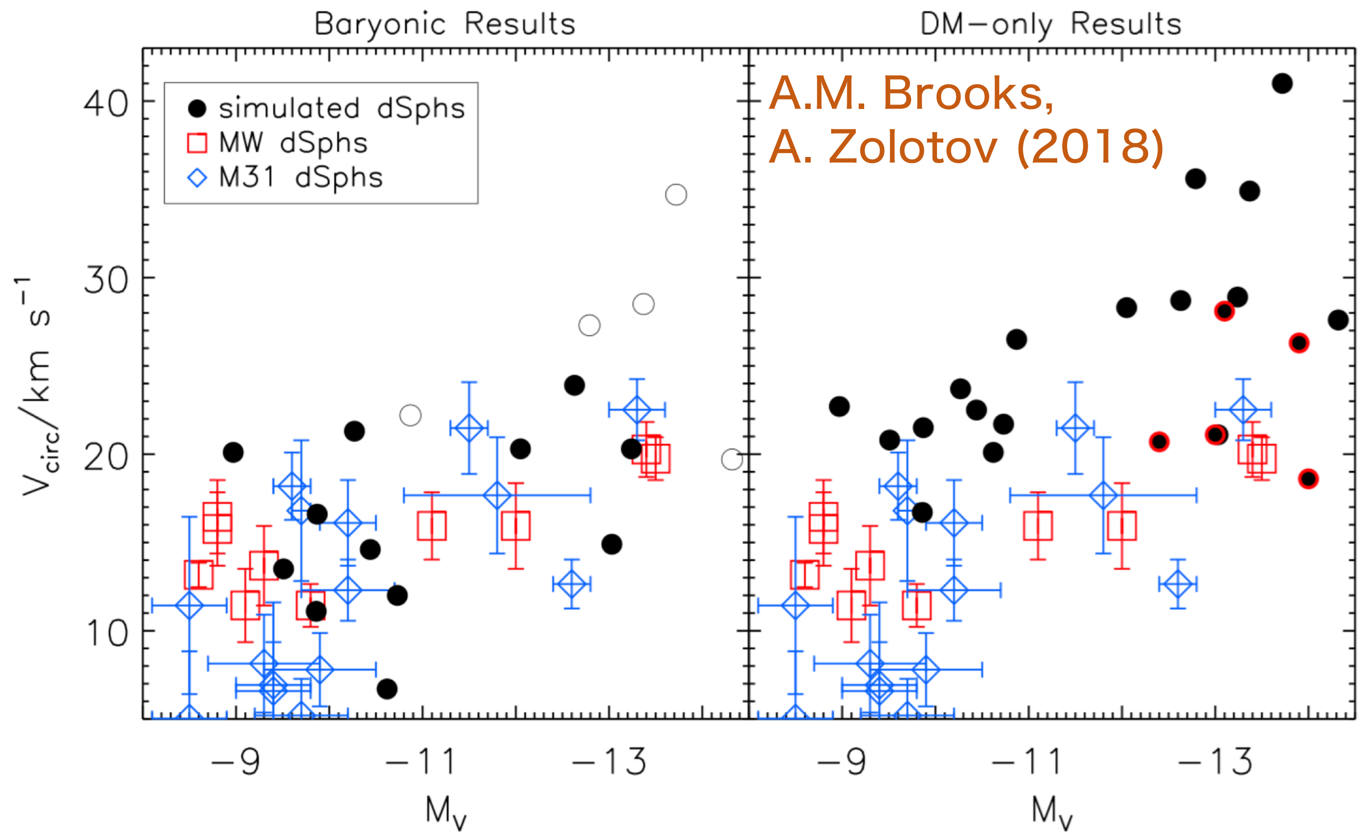
Current experiments of light DM detections



Issues of small scale structures (< 1Mpc)

- Discrepancy between N-body simulations and observations :



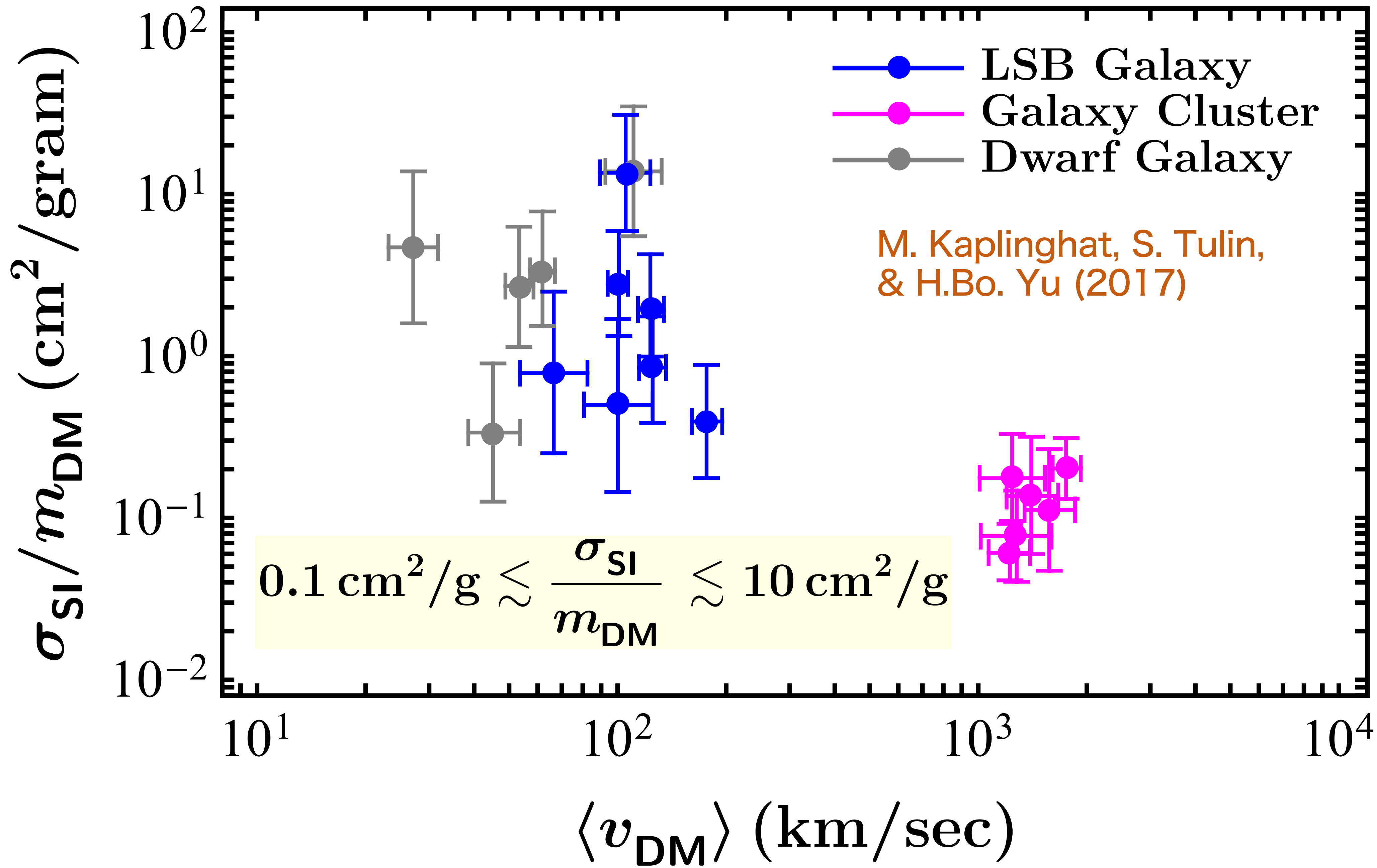


core-vs-cusp problem

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-interaction?

WIMP DM

- Relic abundance of WIMP DM

annihilation cross-section

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

- Mass scale and coupling strength of WIMP DM

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

g : dimensionless coupling

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

WIMP DM

- SI cross-section via a contact-interaction with small velocity

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

SIMP, Forbidden DM,⋯

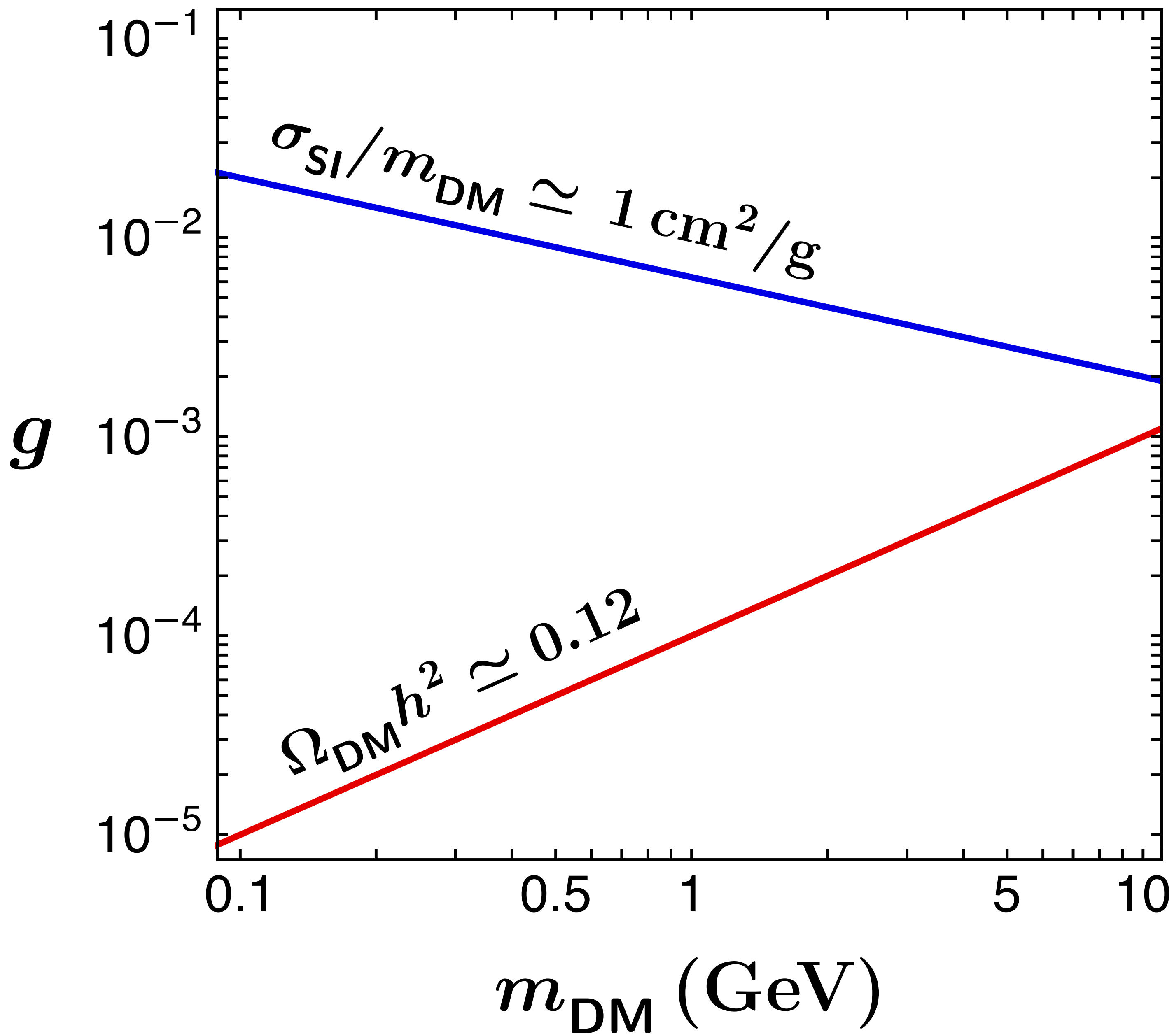
$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} = \frac{g^2}{m_{\rm DM}^3} \Rightarrow g \simeq 2 \times 10^3 \left(\frac{m_{\rm DM}}{10\,{\rm GeV}}\right)^{3/2} \simeq \mathcal{O}(1) \left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)^{3/2}$$

- 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

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 :

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

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

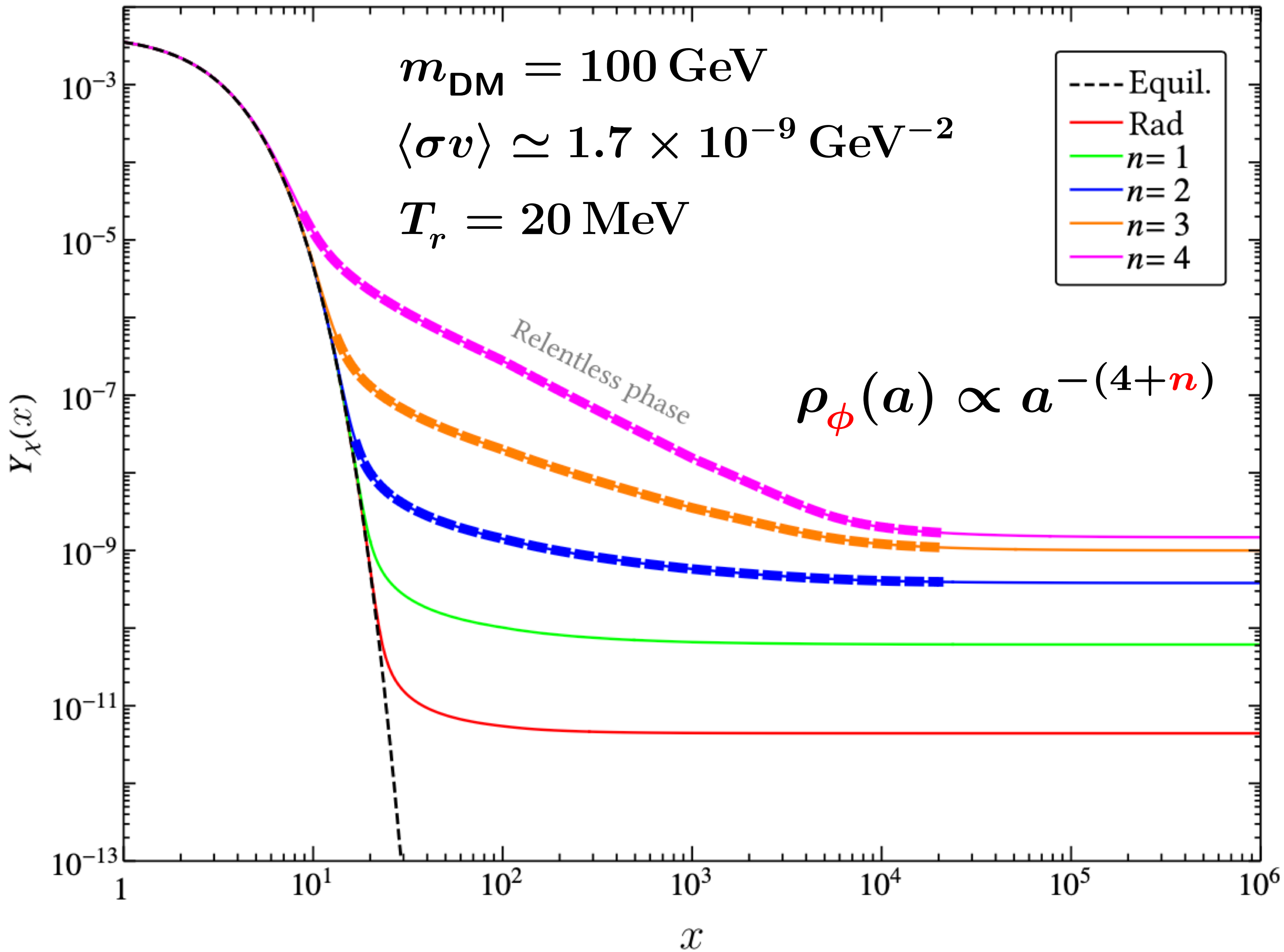
$$\rho_\phi(T_r) = \rho_\gamma(T_r)$$

Parameters : (n, T_r)

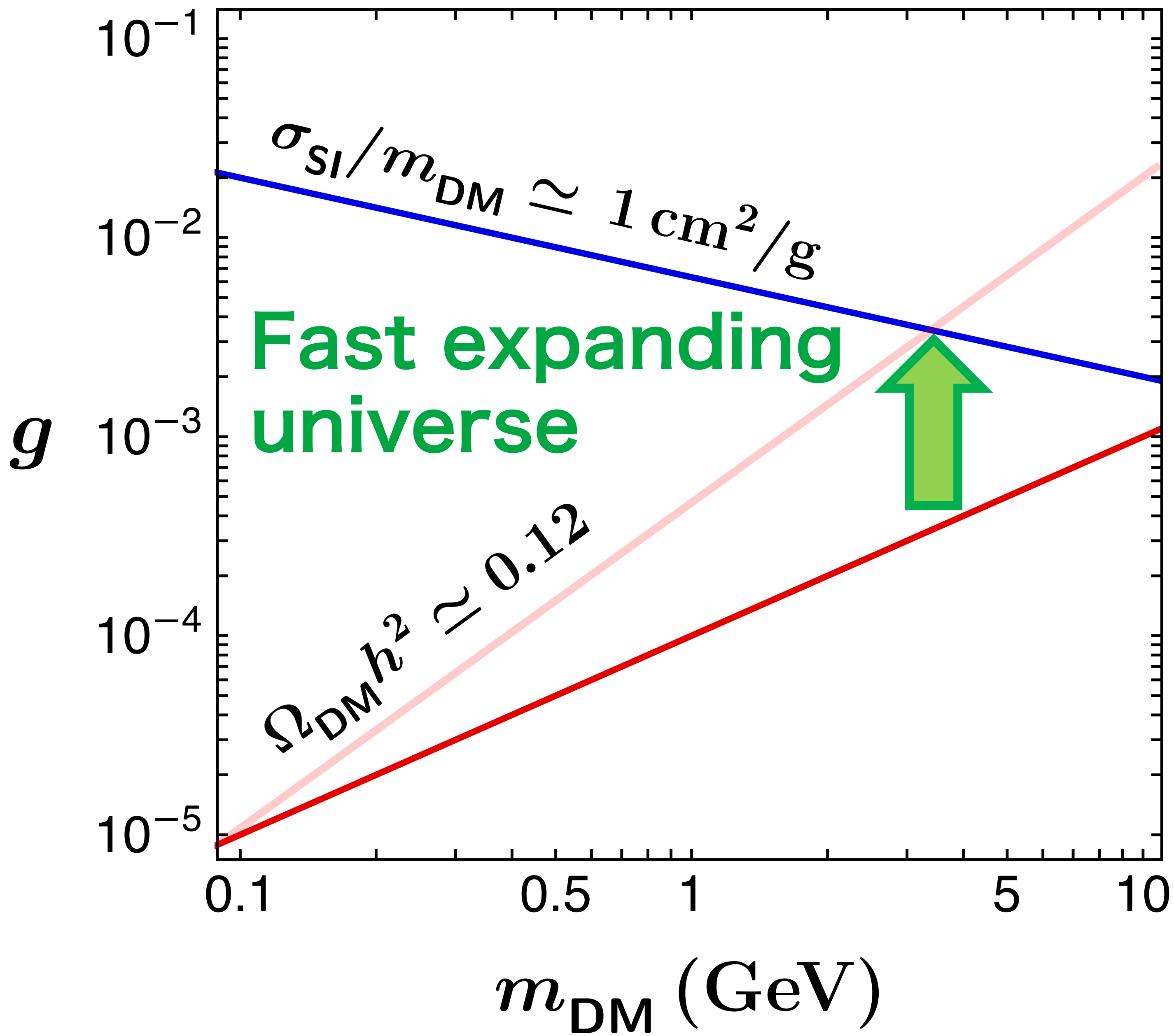
- $\Delta N_\nu(T_{\text{BBN}} \simeq 1\,\text{MeV})$ constraint : $T_r \gtrsim (15.4)^{1/n}\,\text{MeV}$

Relentless dark matter

D'Eramo, et al (2017)



DM mass v.s. coupling



Relic abundance

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

Self-interaction

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

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

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

A simple light thermal self-interacting DM model

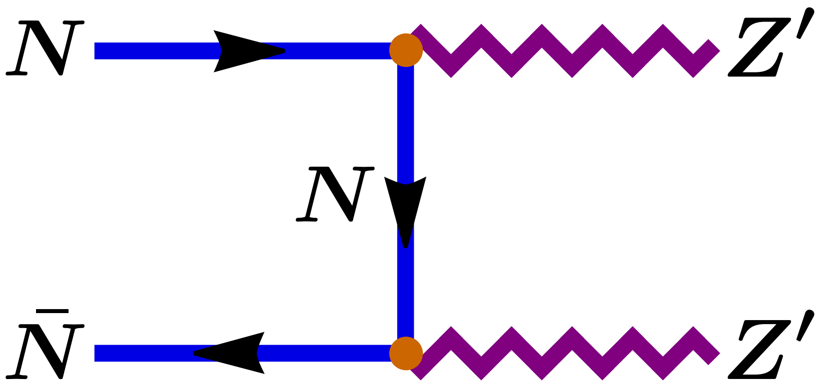
■ Particle content & charge assignment under $\mathrm{G_{SM}} \otimes \mathrm{U(1)_D}$

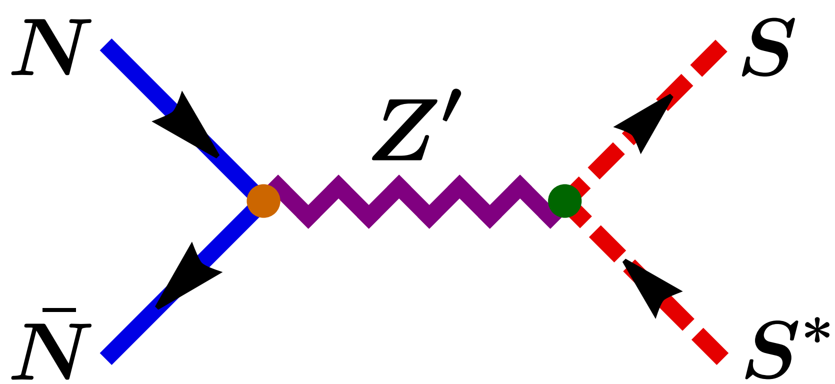
	L	E	H	N	S	Z'
SU(2)	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$-1/2$	-1	$+1/2$	0	0	0
$\mathrm{U(1)_D}$	0	0	0	$\mathcal{Q}_N$	$\mathcal{Q}_S$	0
spin	$1/2$	$1/2$	0	$1/2$	0	1

- 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

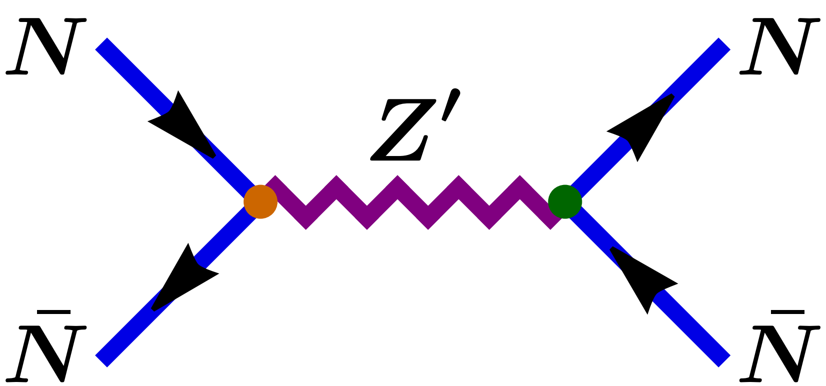


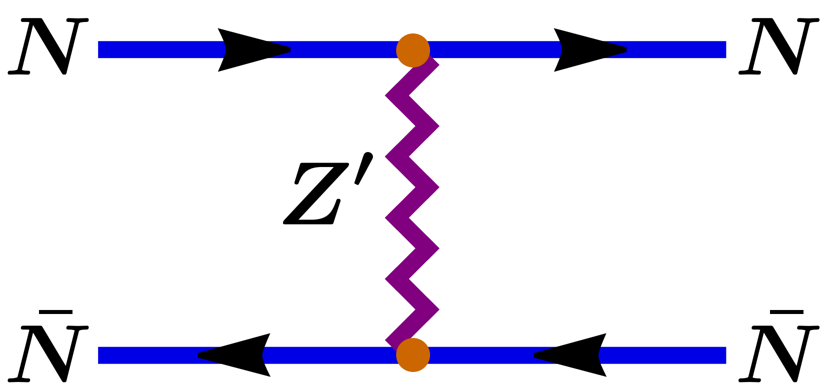


$$\langle \sigma v \rangle = \frac{g_{\mathsf{D}}^4}{128\pi m_N^2}$$

(s-wave)

SI cross-section/DM mass

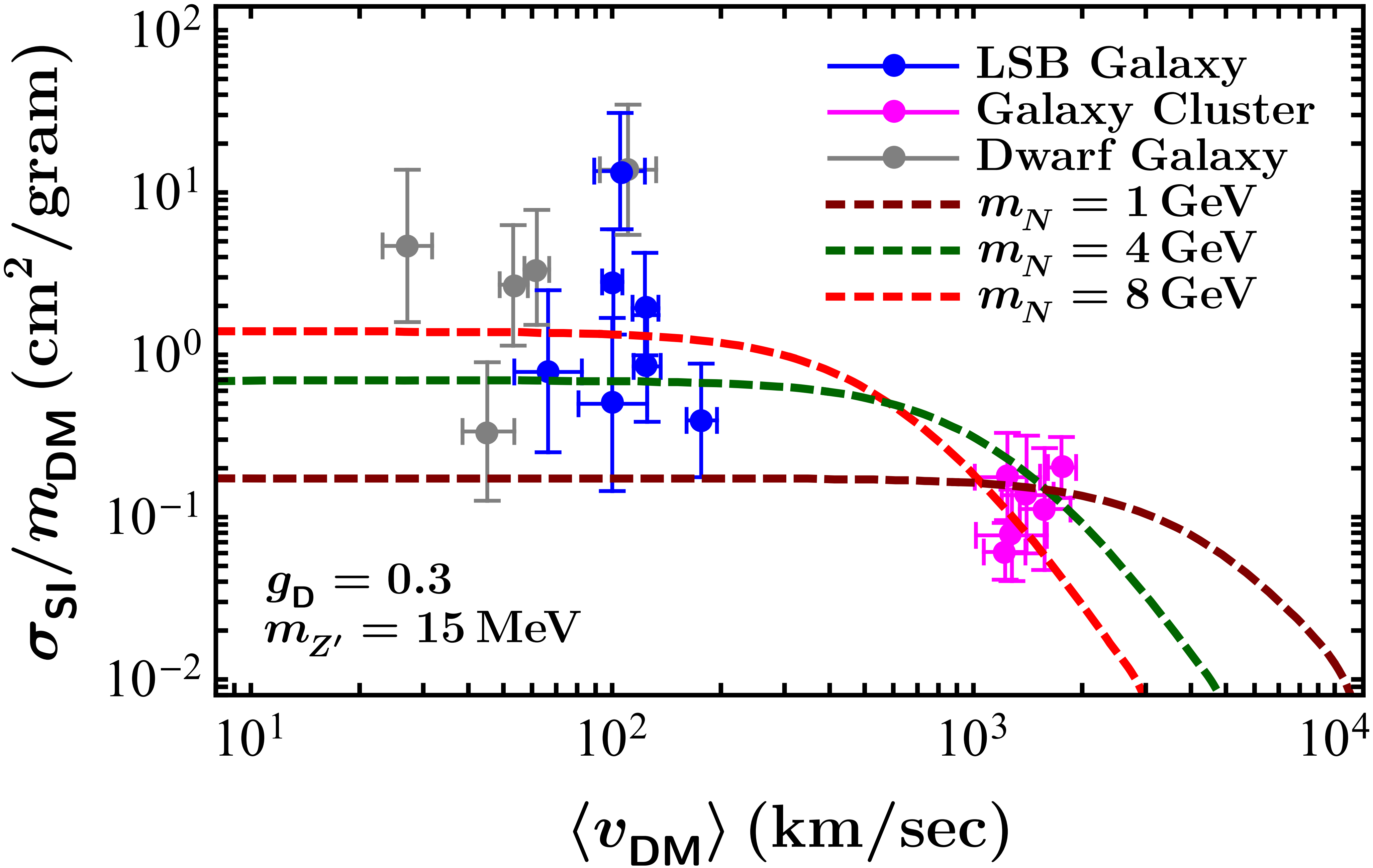




$$\sigma_{\mathsf{SI}} = \frac{\pi}{m_{Z'}^2} f(\beta)$$

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

Prediction of DM SI cross-section



CMB constraint on light DM mass

- DM annihilation continues to take place after decoupling & cause significant effects on cosmology and astrophysics.

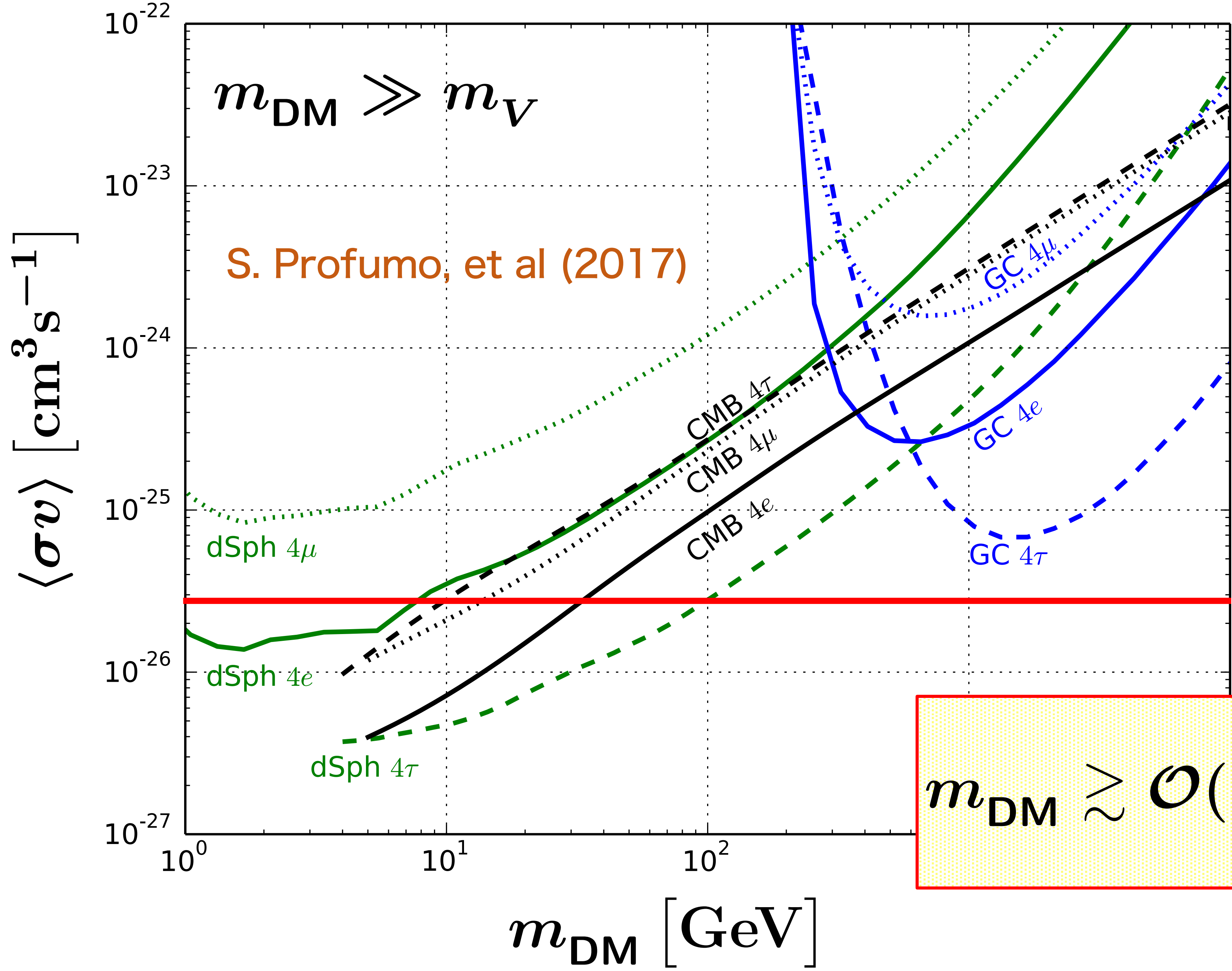
- Energy released per DM annihilation $E_{\rm DM} \approx 2m_{\rm DM}$

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t\,\mathrm{d}V}\right|_{\rm inj.}(z) = n_{\rm DM}^2(z)\langle\sigma v\rangle\left(2m_{\rm DM}\right) = \rho_{\rm c}^2\Omega_{\rm DM,0}^2(1+z)^6\left(\frac{\langle\sigma v\rangle}{m_{\rm DM}}\right)$$

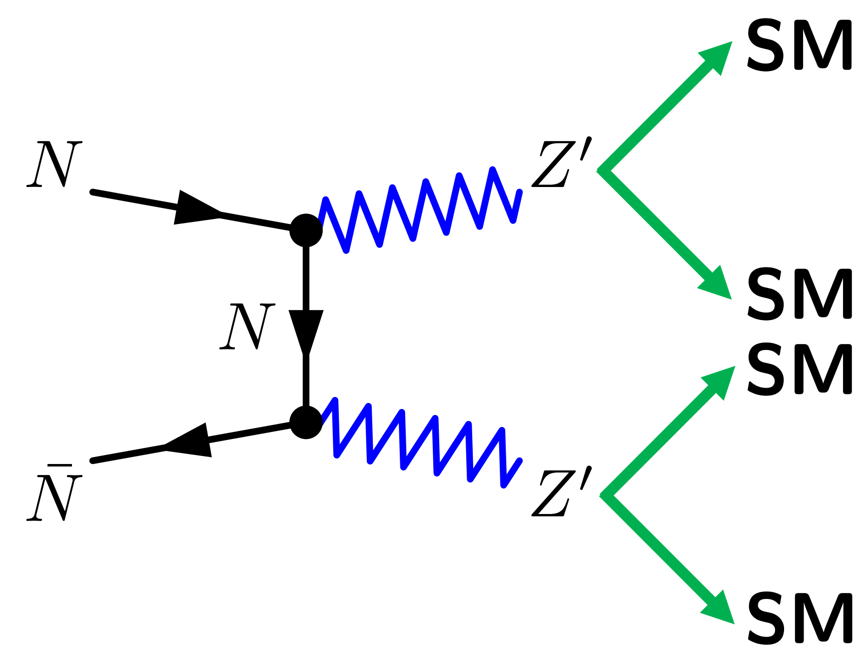
$$n_{\rm DM}(z) = \rho_{\rm c}\Omega_{\rm DM}(z)/m_{\rm DM} = \rho_{\rm c}\Omega_{\rm DM,0}(1+z)^3/m_{\rm DM}$$

Planck ➡ $$\langle\sigma v\rangle \leqslant \frac{4.1\times10^{-28}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{f_{\rm eff}}\left(\frac{m_{\rm DM}}{\mathrm{GeV}}\right)$$

CMB constraint on light DM mass



Secluded DM



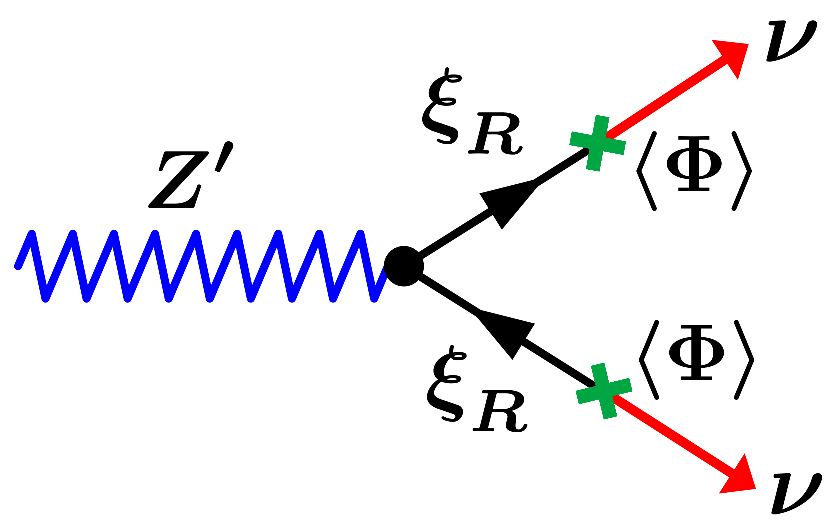
$$m_{\rm DM} \gtrsim \mathcal{O}(10\,{\rm GeV})\left[\frac{\langle \sigma v\rangle}{10^{-8}\,{\rm GeV}^{-2}}\right]$$

A viable light thermal self-interacting DM model

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

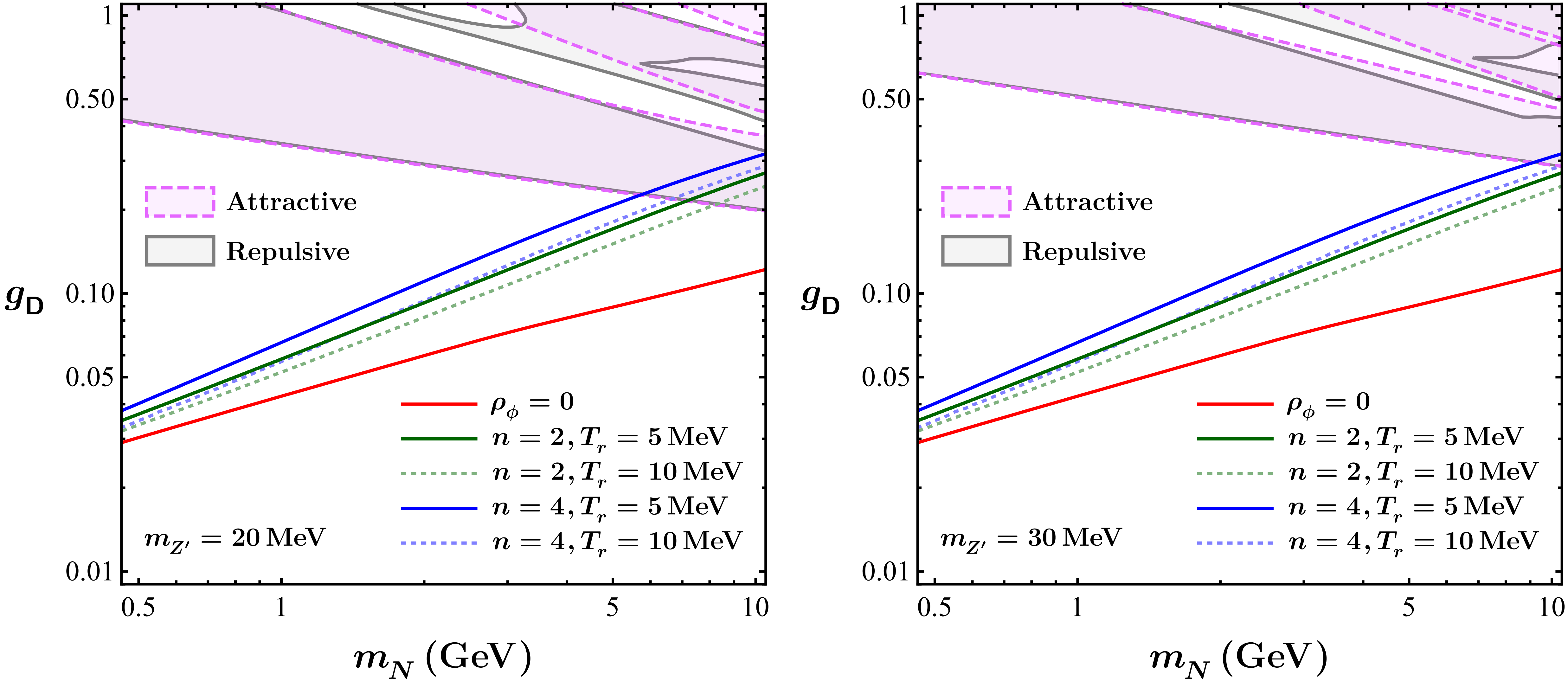
	L	E	H	N	ξ_R	χ_L	Φ	S	Z'
SU(2)	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$-1/2$	-1	$+1/2$	0	0	0	$+1/2$	0	0
$\mathrm{U(1)_D}$	0	0	0	$+1/2$	$+1$	$+1$	$+1$	$+1$	0
spin	$1/2$	$1/2$	0	$1/2$	$1/2$	$1/2$	0	0	1

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



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

What we know about dark matter

- Dark matter as a particle must be
  - Massive : gravitationally interact with ordinary matter
  - Cold : non-relativistic at the time of structures formation
  - Electric neutral : Almost no electromagnetic interaction
  - Stable or with lifetime longer than the age of Universe
  - Non-baryonic matter
  - Making up about a quarter of the energy density of the present universe

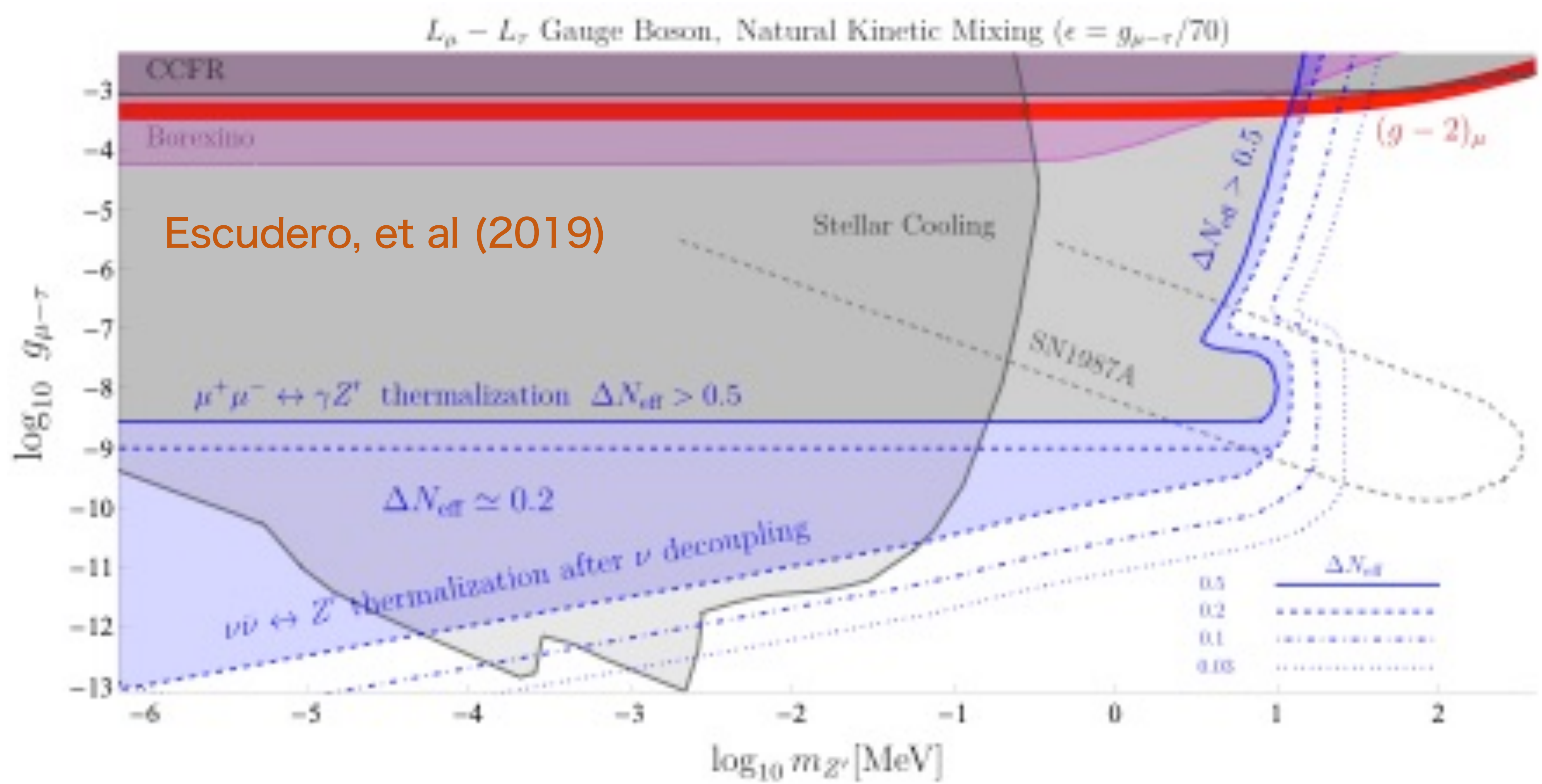
What we don't know about dark matter

- Unknown particle nature of dark matter
  - Mass : $10^{-31} M_{\text{proton}} < M_{\text{DM}} < 5 M_{\odot}$
  - Spin : Scalar or Vector Boson? Dirac or Majorana Fermion?
  - Number of species : There may exist more than one kind of dark matter in the universe. (Occam's razor?)
  - Interactions : Dark matter may have interactions with ordinary matter or itself (SIDM) other than the gravitational interaction.
- Unknown origin of dark matter
  - Thermal : Relic produced from the SM thermal plasma
  - Non-thermal : e.g. coherent oscillation, topological defect,……

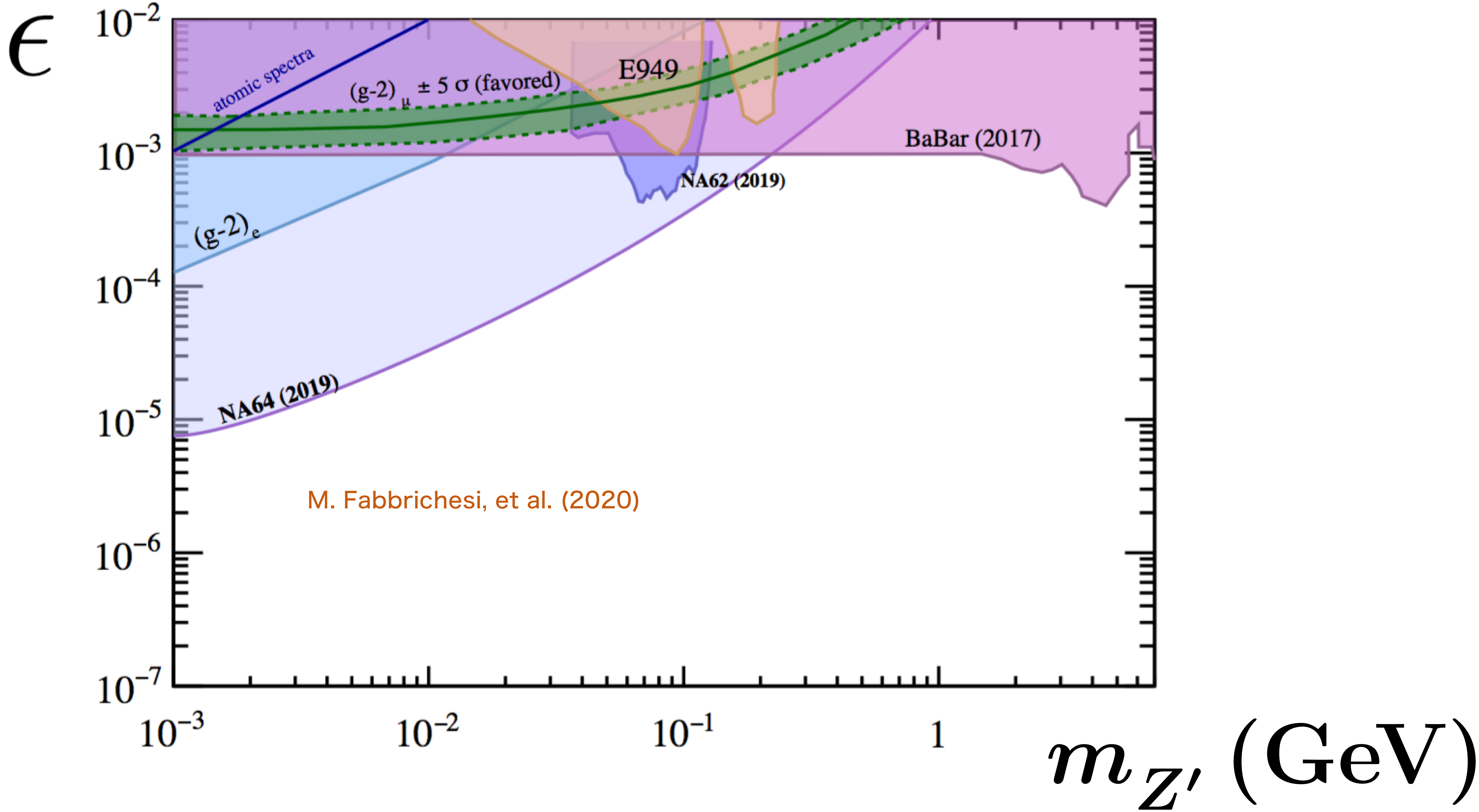
Weakly Interacting Massive Particle (WIMP) DM

Assumptions for WIMP DM (2 to n annihilations)

- $\mu_{\mathrm{DM}} = \mu_{\overline{\mathrm{DM}}}$ [$\mu_{\mathrm{DM}} \neq \mu_{\overline{\mathrm{DM}}} \Longrightarrow$ asymmetric DM]
  D. E. Kaplan, M. A. Luty, & K. M. Zurek (2009)
- $m_{\mathrm{DM}} > m_{\mathrm{SM}}$ [$m_{\mathrm{DM}} < m_{\mathrm{SM}} \Longrightarrow$ forbidden DM]
  R. T. D'Agnolo, & J. T. Ruderman (2015)
- $T_{\mathrm{FO}} < T_{\mathrm{RH}}$ [$T_{\mathrm{FO}} > T_{\mathrm{RH}} \Longrightarrow$ WIMPs during reheating]
  Nicolás Bernal & Yong Xu (2022)
- Standard cosmology [$\rho_\phi(a) \propto a^{-(4+n)} \Rightarrow$ relentless DM]
  F. D'Eramo, etal (2017)
- Collisionless [$\sigma_{\mathrm{SI}} \neq 0 \Longrightarrow$ Self-interacting dark matter]
- T invariance : $|\mathcal{M}_{\mathrm{DMDM}\to\mathrm{SMSM}}|^2 = |\mathcal{M}_{\mathrm{SMSM}\to\mathrm{DMDM}}|^2$ (?)



- **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
m_Z′ (GeV)