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Dark Matter in White Dwarfs

In collaboration with:
G. Busoni, N. Bell, S. Robles & M. Virgato

Based on:
JCAP 10 (2021), 083
e-Print: 2104.14367 [hep-ph]

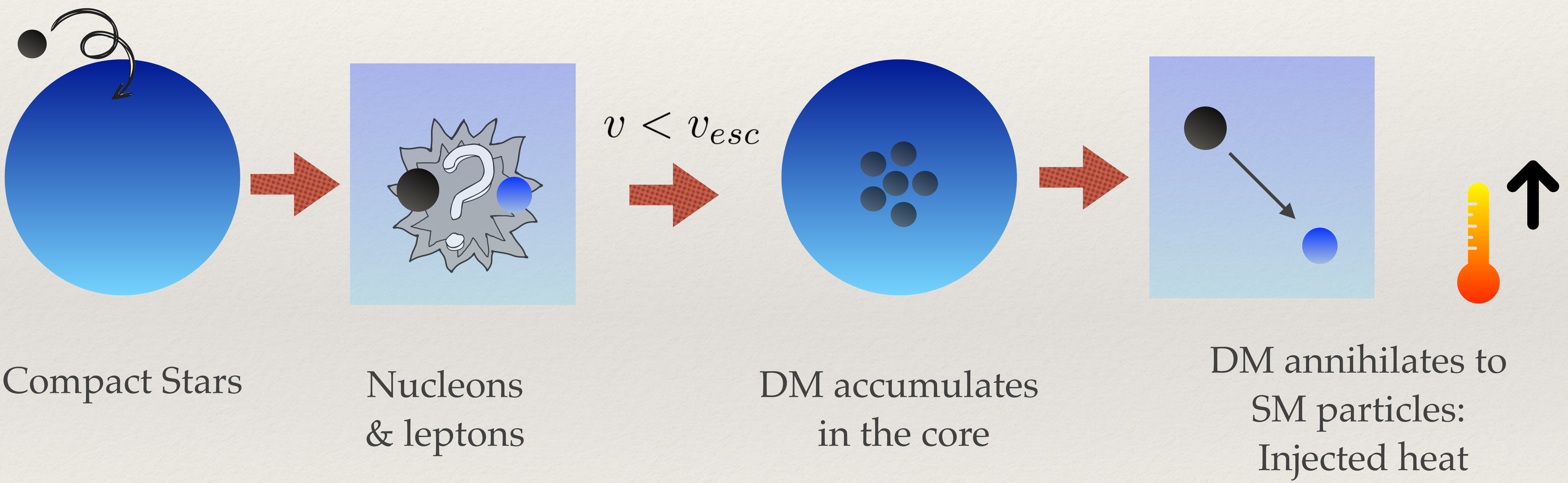
Neutron star heating and the $(g-2)_\mu$ discrepancy

In collaboration with:
K. Hamaguchi & N. Nagata

Based on:
JHEP 10 (2022) 088
e-Print: 2204.02413 [hep-ph]

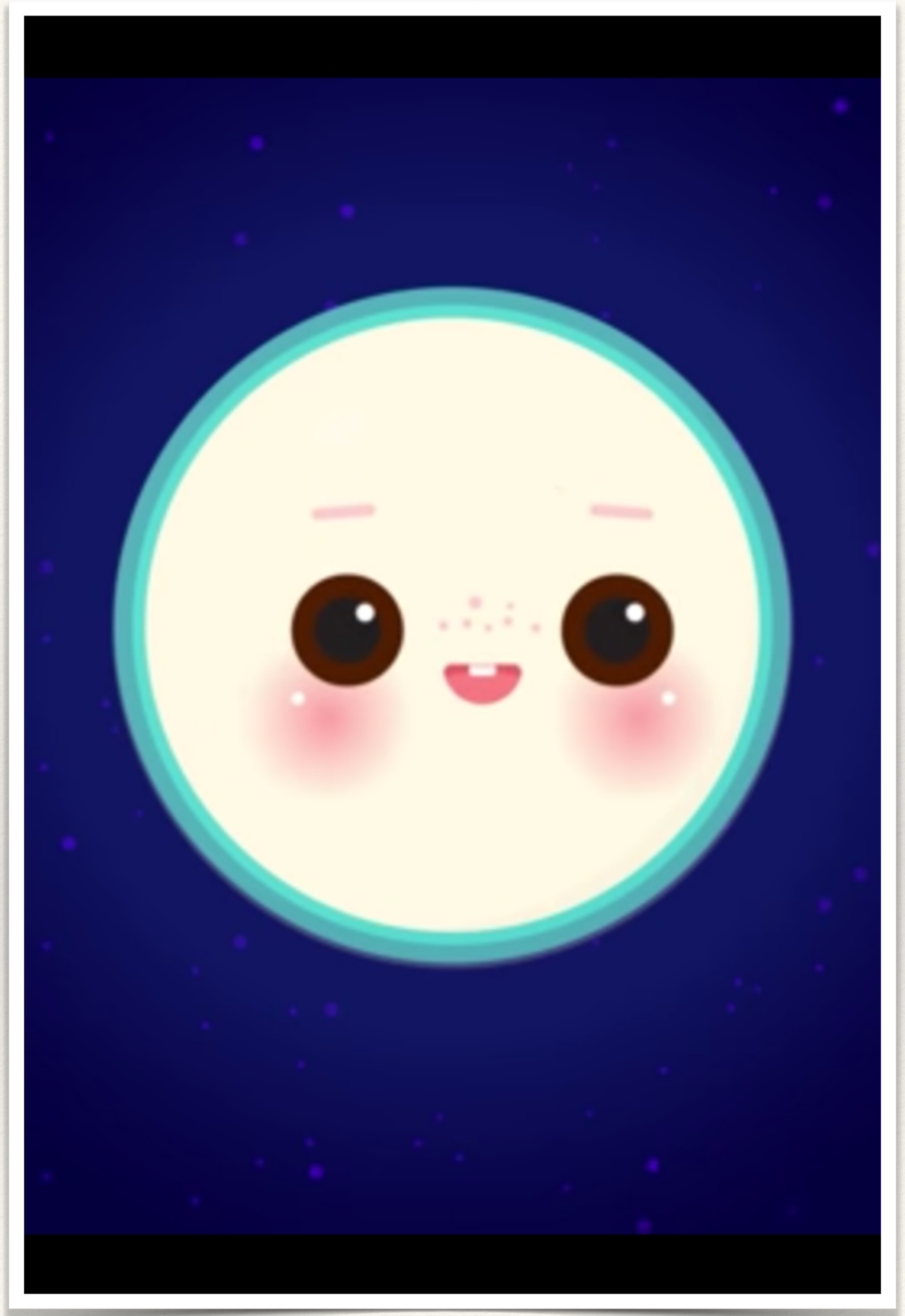
General picture

- Dark matter can heat compact stars and generate an observable signal.



Part I:
About White Dwarfs…

Dark Matter in White Dwarfs



Capture rate: ions

$$C = \frac{\rho_\chi}{m_\chi} \int_0^{R_\star} 4\pi r^2 \, \eta(r) \, dr \int_0^\infty du_\chi \frac{\omega(r)}{u_\chi} f_{MB}(u_\chi) \, \Omega^-(\omega)$$

$\eta(r) \rightarrow$ Star Opacity

$f_{MB}(u_\chi) \rightarrow$ Maxwell Boltzmann distribution

$\Omega^-(\omega) \rightarrow$ DM interaction rate

Capture rate: ions

- We calculate bounds on the cut off scale of the dimension 6 EFT operators that describe DM interactions with WD targets: ions and electrons.

$$\frac{d\sigma_{T\chi}}{d\cos\theta} = \frac{1}{32\pi}\frac{|\overline{M}_T|^2}{(m_\chi + m_T)^2}$$

We have introduced the nuclear response function for carbon–12

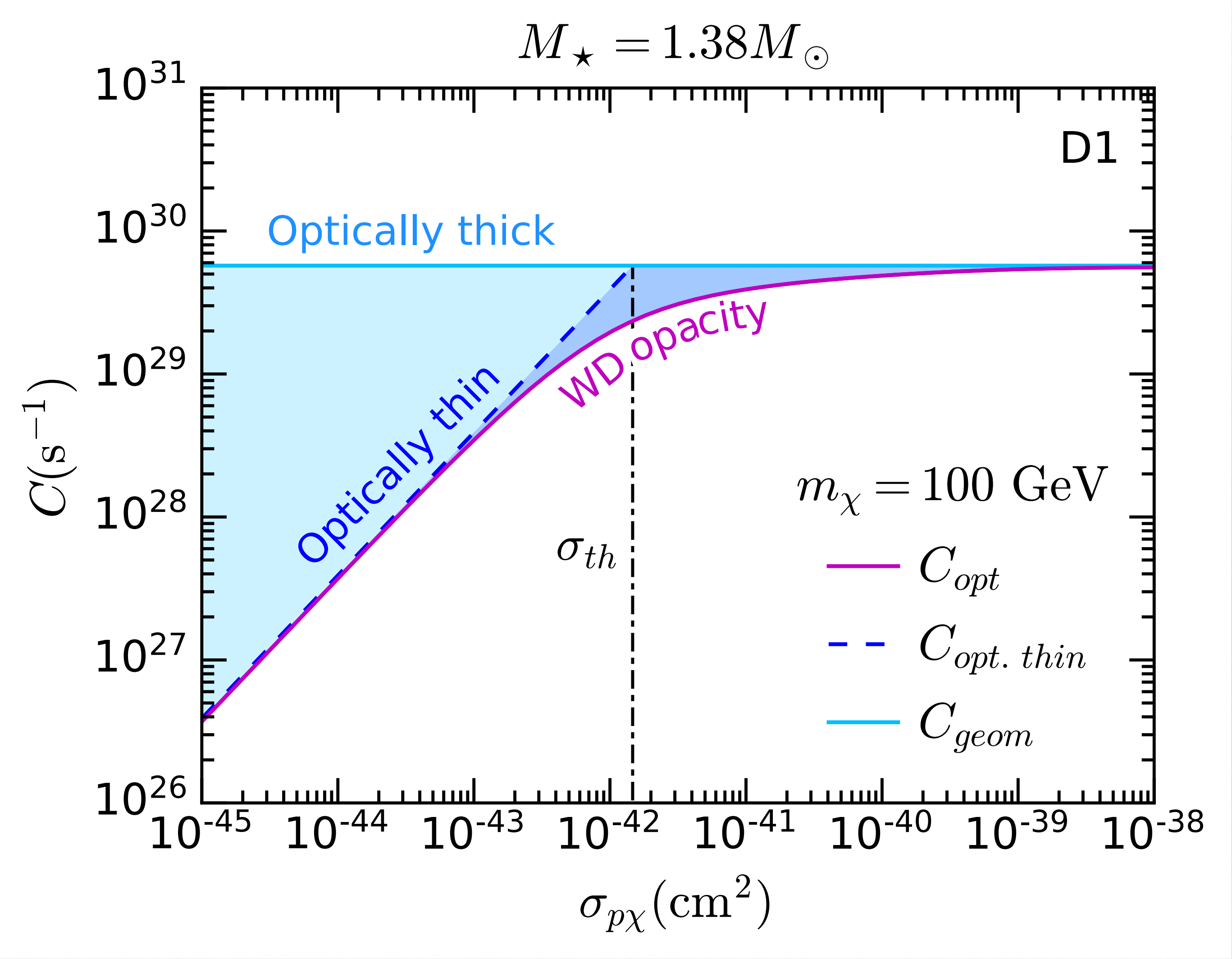
arxiv: 1501.03729

	Name	Operator	Coupling
✓	D1	$\bar{\chi}\chi\ \bar{f}f$	y_f/Λ_f^2
✓	D2	$\bar{\chi}\gamma^5\chi\ \bar{f}f$	iy_f/Λ_f^2
	D3	$\bar{\chi}\chi\ \bar{f}\gamma^5 f$	iy_f/Λ_f^2
	D4	$\bar{\chi}\gamma^5\chi\ \bar{f}\gamma^5 f$	y_f/Λ_f^2
✓	D5	$\bar{\chi}\gamma_\mu\chi\ \bar{f}\gamma^\mu f$	$1/\Lambda_f^2$
✓	D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{f}\gamma^\mu f$	$1/\Lambda_f^2$
	D7	$\bar{\chi}\gamma_\mu\chi\ \bar{f}\gamma^\mu\gamma^5 f$	$1/\Lambda_f^2$
	D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{f}\gamma^\mu\gamma^5 f$	$1/\Lambda_f^2$
	D9	$\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{f}\sigma^{\mu\nu} f$	$1/\Lambda_f^2$
✓	D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{f}\sigma^{\mu\nu} f$	i/Λ_f^2

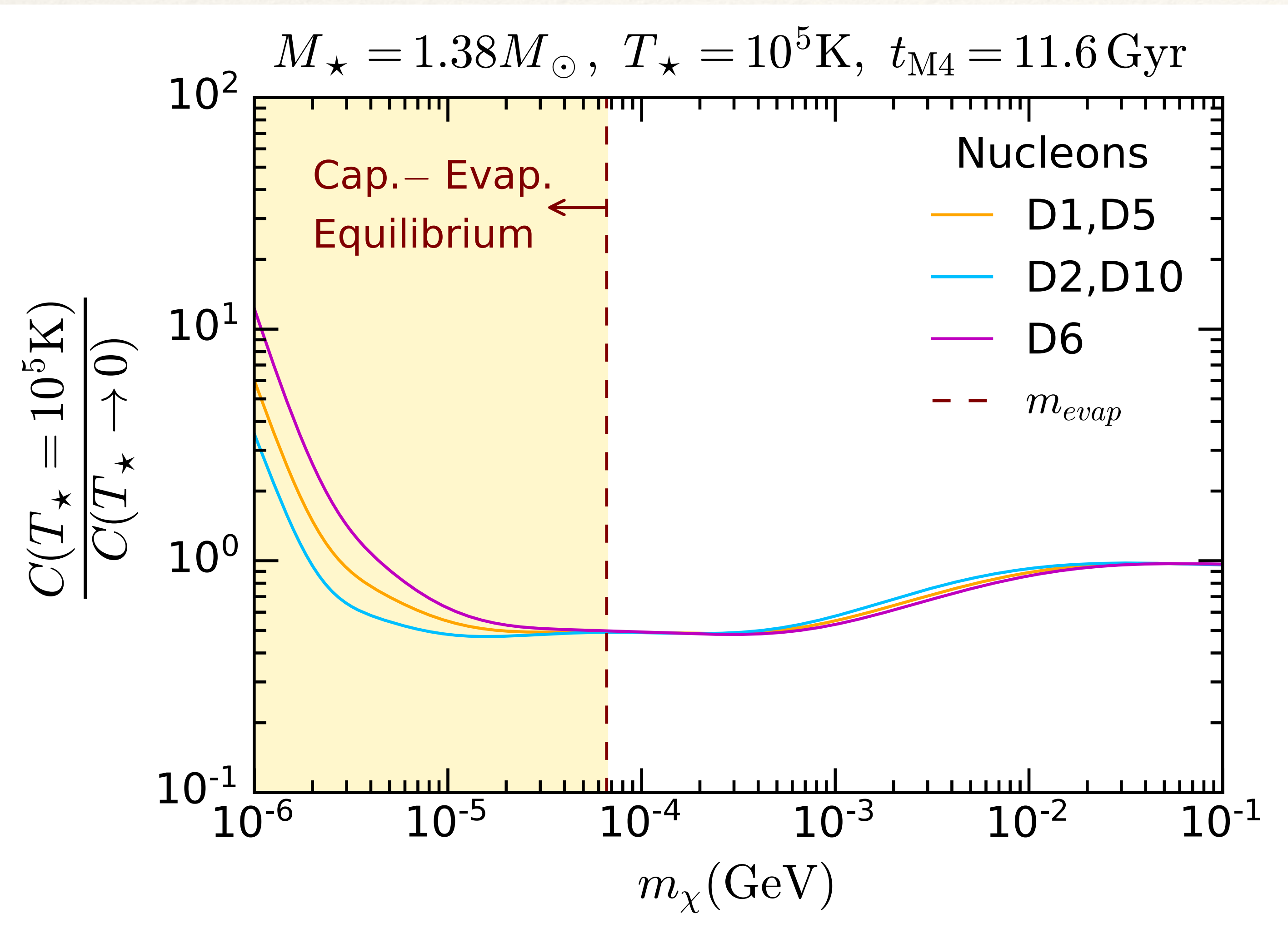
Capture rate: ions

In the $T_\star \to 0$ limit,

- Maximum capture: Geometric limit $\Omega^-(\omega) \to 1$
- Optically thin limit: $\eta(r) \to 1$
- The complete treatment includes the inner structure of the WD as well as



Capture rate: ions



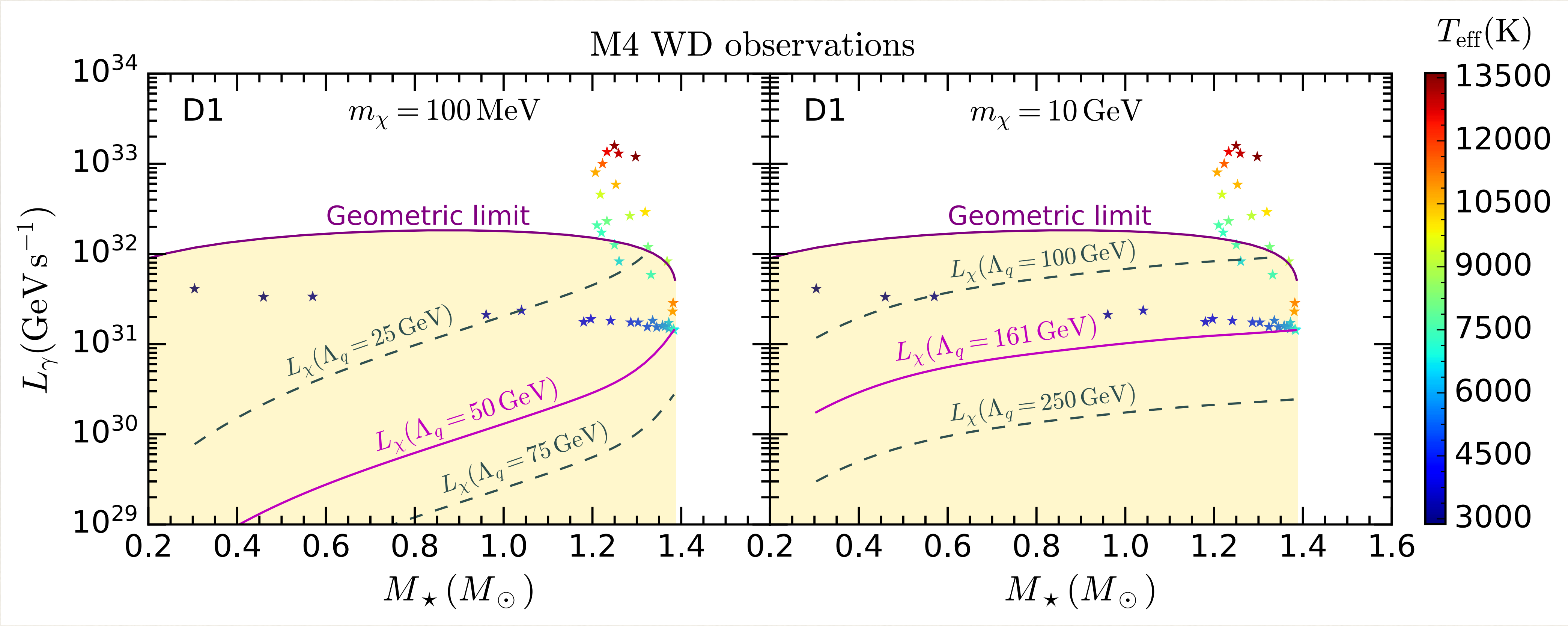
Finite temperature ($T_\star = const$)

- For the oldest and heaviest WDs in M4, $T_\star = 10^5$ K
- Ratio starts to deviate from 1 at $m_\chi \sim 10\,\text{MeV}$
- Evaporation mass $m_{evap} \sim 70\,\text{keV}$

- Observed luminosity of the faintest WD in M4: Assumed to be composed of Carbon-12
- Since DM capture and annihilation processes are in equilibrium, the star luminosity due to DM is

$$L_\chi = m_\chi C(m_\chi, \Lambda_f)$$

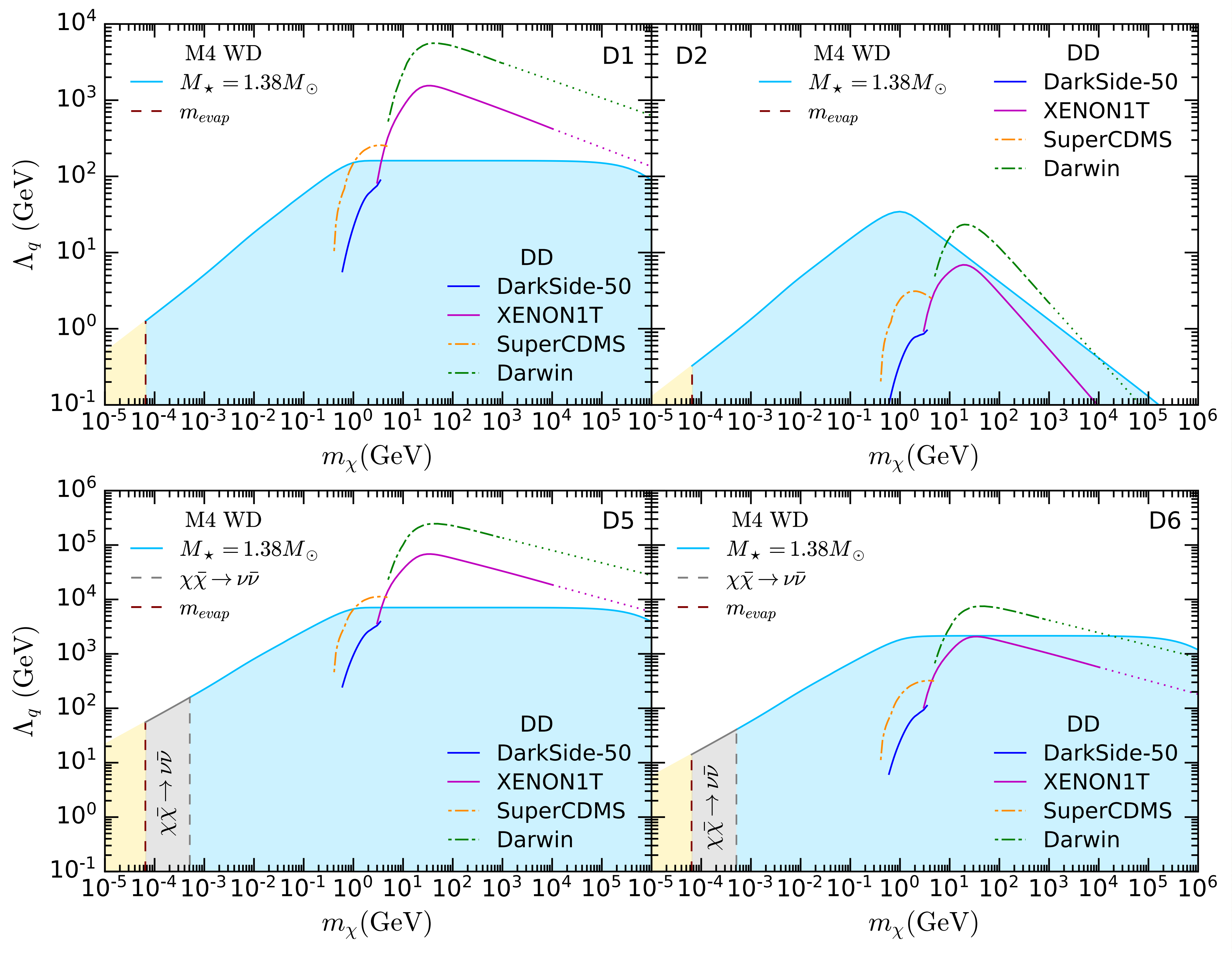
- We compare the WD observed luminosity L_γ to L_χ
- L_γ should be at least equal to the luminosity from DM contribution.

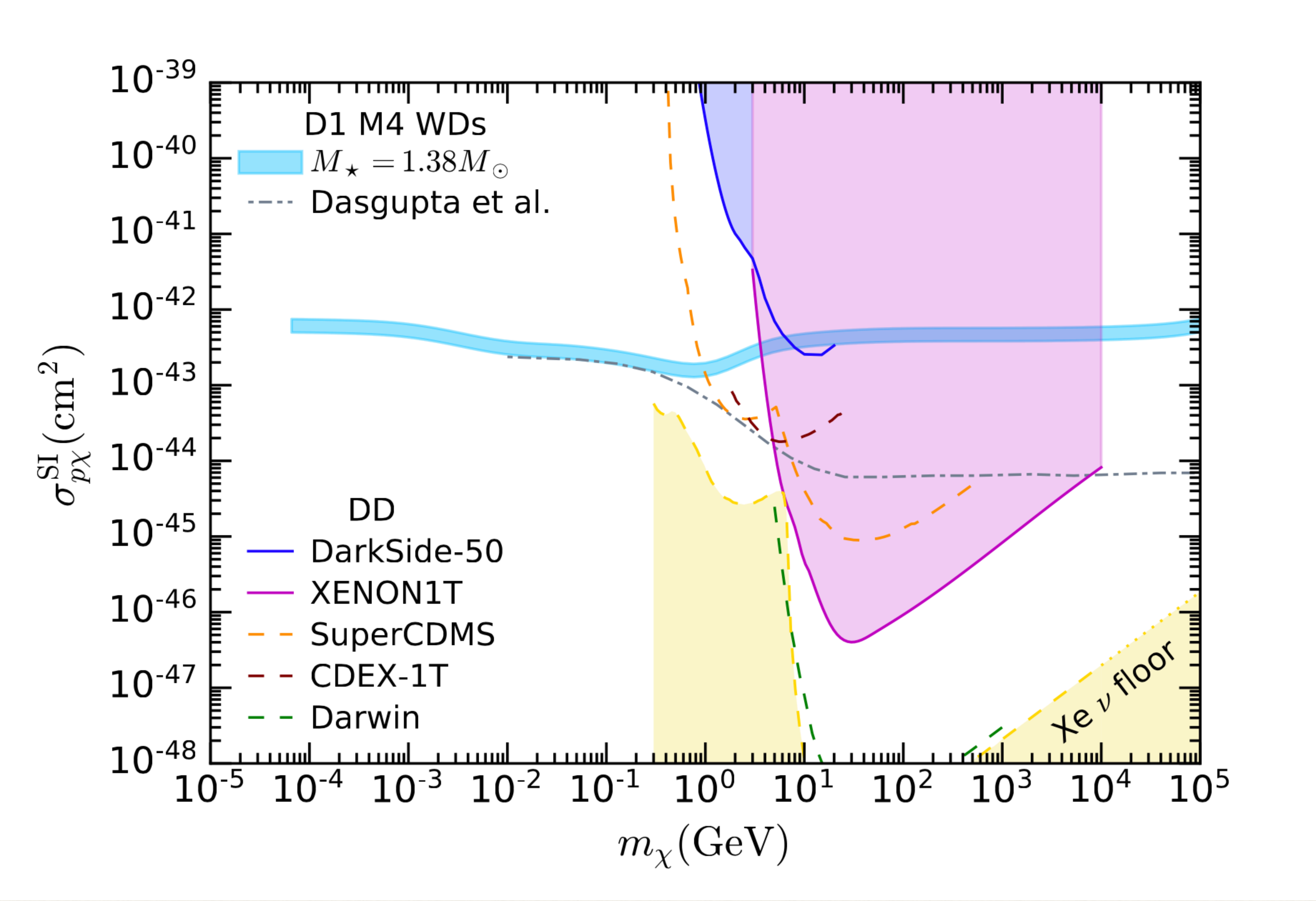


$M_\star \sim 1.38\,{\rm M}_\odot$

If DM is presented in M4

$\rho_\chi = 798\,\mathrm{GeV cm^{-3}}$ for a contracted NFW profile





D1 M4 WDs
$M_\star = 1.38 M_\odot$
Dasgupta et al.
DD
DarkSide-50
XENON1T
SuperCDMS
CDEX-1T
Darwin
Xe ν floor
$\sigma^{SI}_{p\chi}(\mathrm{cm}^2)$
$m_\chi(\mathrm{GeV})$
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}

- Improvement of previous calculations of DM capture rate in WDs
  - Realistic nuclear response functions
  - WD internal structure (FMT-EOS)
  - Star opacity
  - Temperature effects

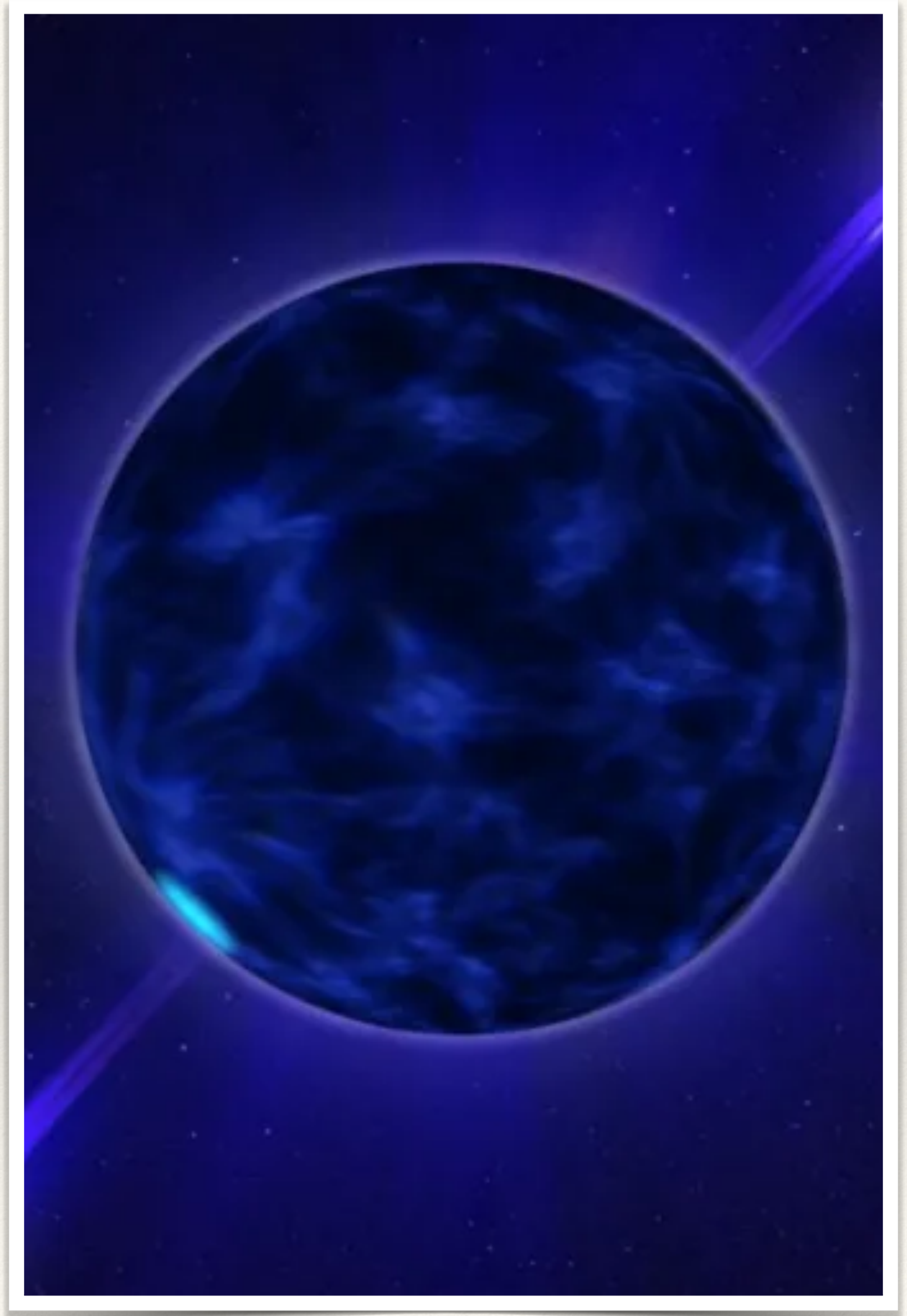
- Estimate the evaporation mass:
  for the heaviest WD in M4 with a core temperature of $T_\star = 10^5$ K,

$$m_{evap} \sim \mathcal{O}(\mathrm{keV})$$

- If there is DM in M4,
  - For DM-nucleon SI cross section: constraints from old WDs in M4 are stronger than DD experiments:
    - Sub-GeV DM mass regime
    - velocity and momentum dependent

Part II:
About Neutron Stars…

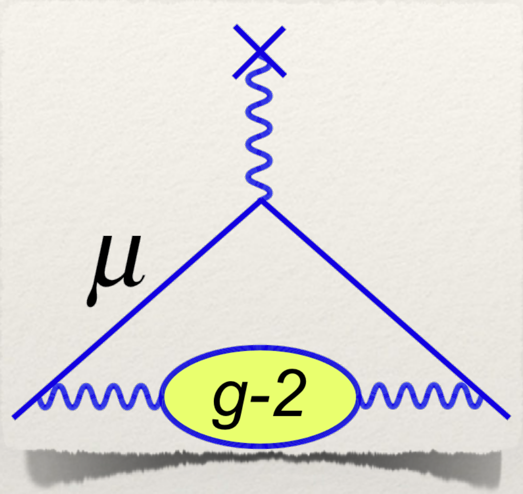
Neutron star heating and the $(g-2)_\mu$ discrepancy

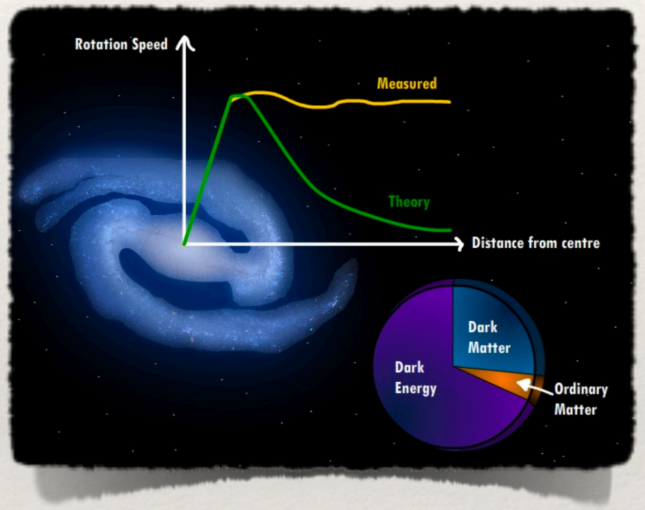


Several BSM scenarios have been proposed in order to explain this discrepancy

→ Weakly-interacting massive particles (WIMPs) coupling to muons

These scenarios could explain





→ Large number of possibilities for this class of extension models:

1. Model I: Majorana fermion DM couples to the Higgs field at tree level.
2. Model II: Majorana fermion DM doesn't couples to the Higgs field at tree level.

DM + $(g-2)_\mu$

Model I

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\left(\chi_S, \xi_{D^0}, \eta_{D^0}\right)\mathcal{M}_\chi \begin{pmatrix}\chi_S \\ \xi_{D^0} \\ \eta_{D^0}\end{pmatrix} - M_{F_D}\xi_{D^-}\eta_{D^+} + \text{h.c.}$$
$$-M_{\tilde{e}}^2|\tilde{e}|^2 - M_{\tilde{\nu}}^2|\tilde{\nu}|^2 \ ,$$

$$0 < M_{\chi_1} \le M_{\chi_2} \le M_{\chi_3}$$

DM candidate

$$\begin{pmatrix}\chi_S \\ \xi_{D^0} \\ \eta_{D^0}\end{pmatrix} = V_\chi \begin{pmatrix}\chi_1 \\ \chi_2 \\ \chi_3\end{pmatrix} .$$

Unitary matrix

$$\mathcal{L}_{\rm Yukawa} = -\frac{h}{\sqrt{2}}\overline{\psi_i^0}\left[\left(C_{\chi hL}\right)_{ij}P_L + \left(C_{\chi hR}\right)_{ij}P_R\right]\psi_j^0$$
$$-\left\{\overline{\psi_i^0}\left[y_1\left(V_\chi\right)_{1i}P_L + y_2^*\left(V_\chi\right)^*_{2i}P_R\right]\mu\,\tilde{e}^* + \text{h.c.}\right\}$$
$$-\left[y_1\left(V_\chi\right)_{1i}\overline{\psi_i^0}P_L\nu\tilde{\nu}^* - y_2\bar{\mu}P_L\psi^-\tilde{\nu} + \text{h.c.}\right]$$

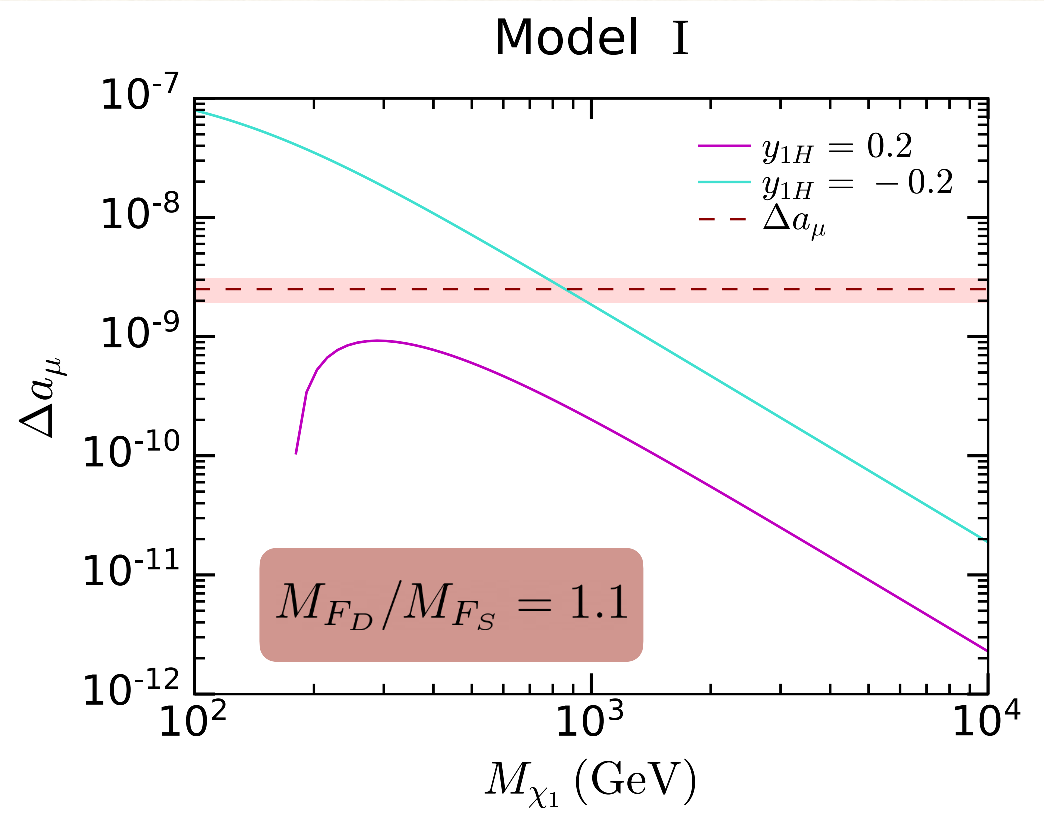
DM -muon interaction

Two cases

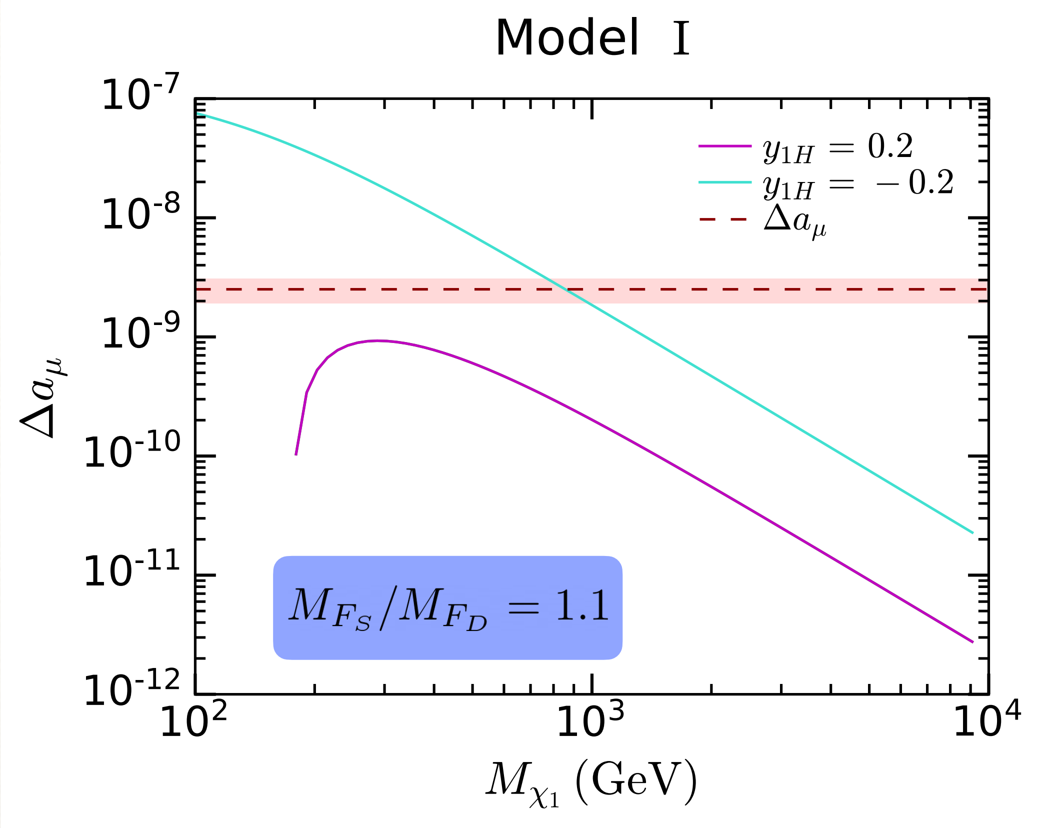
- Singlet-like

  $M_{F_S} < M_{F_D}$
- Doublet-like

  $M_{F_S} > M_{F_D}$



Singlet-like



Doublet-like

This model could explain the observed discrepancy in the $(g-2)_\mu$ if the DM mass is

$$M_{\chi_1} \simeq 1\,\text{TeV}$$

$$M_{\chi 1} \simeq 800\ \text{GeV}$$

The relic abundance of χ_1 can coincide with the observed DM density

arXiv: 1804.00009

DM + $(g-2)_\mu$

Model II

$$\mathcal{L}_{\text{mass}} = -\left(\tfrac{1}{2}M_{F_S}\chi_S\chi_S + \text{h.c.}\right) - \left(\widetilde{e}^*,\ \widetilde{\bar{e}}\right)\mathcal{M}_e^2\begin{pmatrix}\widetilde{e}\\ \widetilde{\bar{e}}^*\end{pmatrix} - M_{\tilde{\nu}}^2\,|\widetilde{\nu}|^2$$

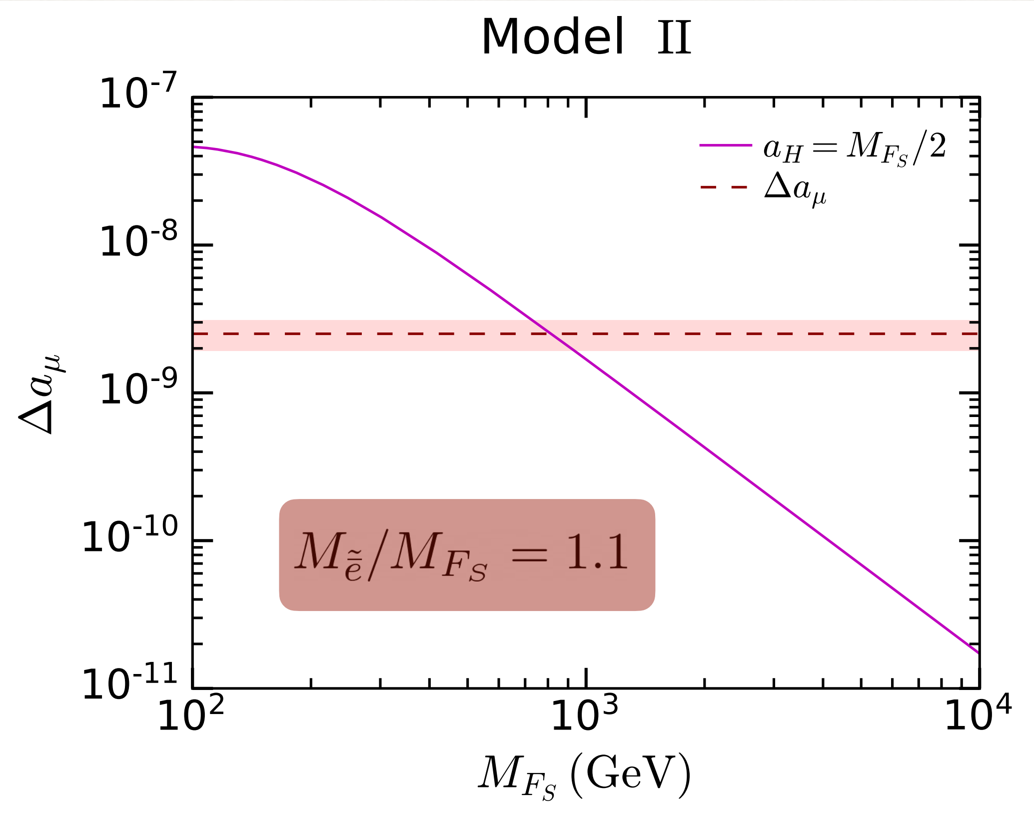
DM candidate

Unitary matrix

$$\begin{pmatrix}\widetilde{e}\\ \widetilde{\bar{e}}^*\end{pmatrix} = U_e\begin{pmatrix}\widetilde{e}_1\\ \widetilde{e}_2\end{pmatrix}$$

$$\mathcal{L}_{\text{Yukawa}} = -\left\{\overline{\psi^0}\left[y_1\,(U_e)^*_{1i}\,P_L + y_2^*\,(U_e)^*_{2i}\,P_R\right]\mu\,\widetilde{e}_i^* + \text{h.c.}\right\} - \left[y_1\overline{\psi^0}P_L\nu\widetilde{\nu}^* + \text{h.c.}\right]$$

DM -muon interaction



The observed deviation the $(g-2)_\mu$ can be explained if the DM mass is

$$M_{F_S} \simeq 800\,\text{GeV}$$

The observed DM density can be explained with the size of the DM mass

arXiv:2002.12534

Limitations..?

Masses of ~ 1 TeV to explain dark matter and $(g-2)_\mu$

- The new particles in our model do not have color charge: hard to probe them in the LHC
  - The DM particles would be invisible to any detector near the collision point.
- Direct detection experiments: considerable regions of parameter space are beyond the reach of the next-generation DM direct detection experiments.

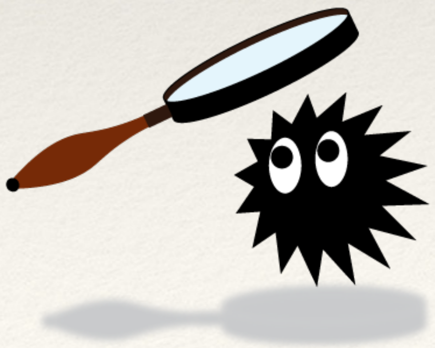
Alternatives…?

- DM can heat NS up to $\sim$ a few $\times\, 10^3$ K

- NS efficiently capture DM particles $m_\chi \sim 10^2$ TeV after a single scattering

arXiv: 2004.14888

The temperature observation of neutron stars offers a promising way to probe these scenarios through DM accretion and annihilation in their core.

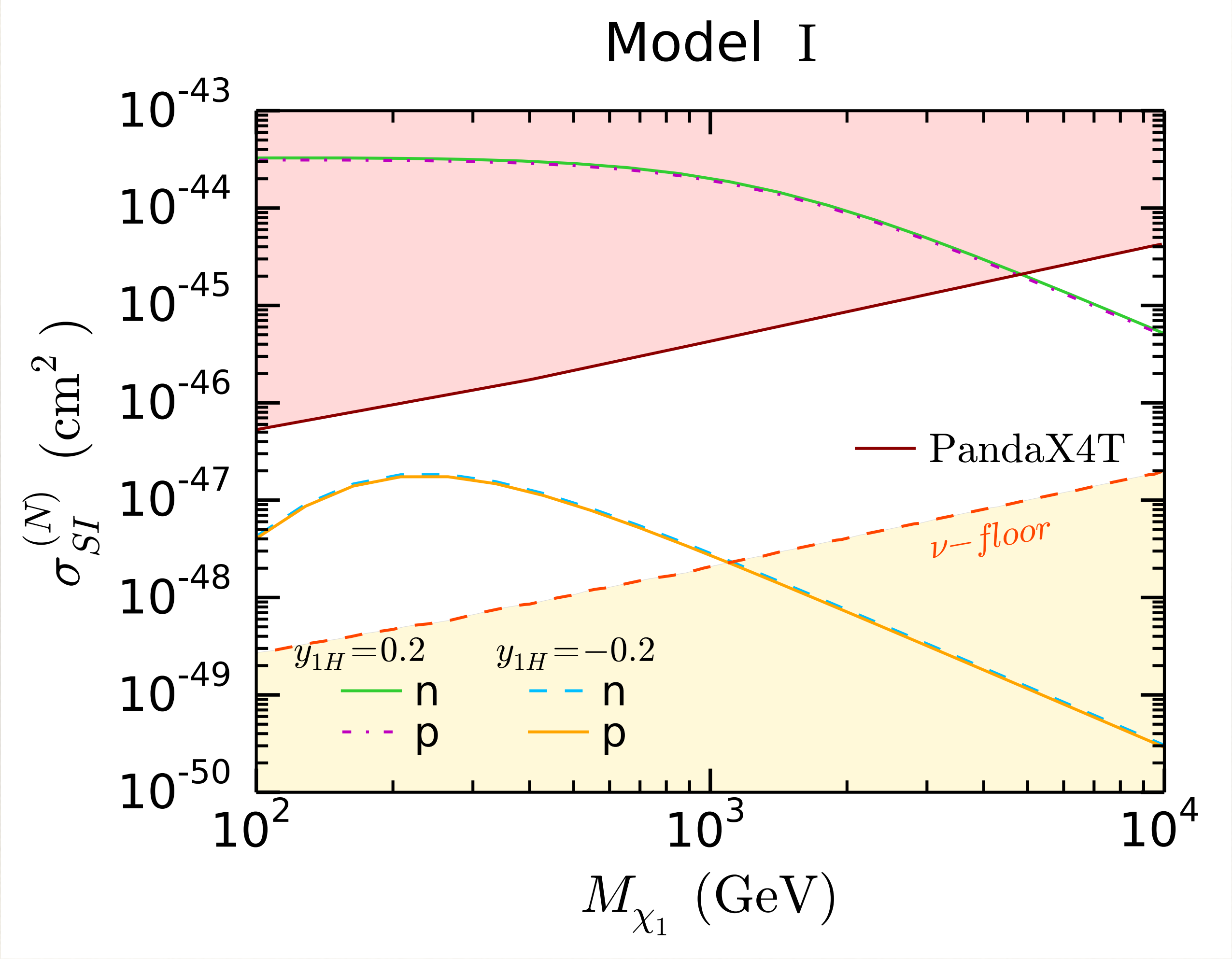


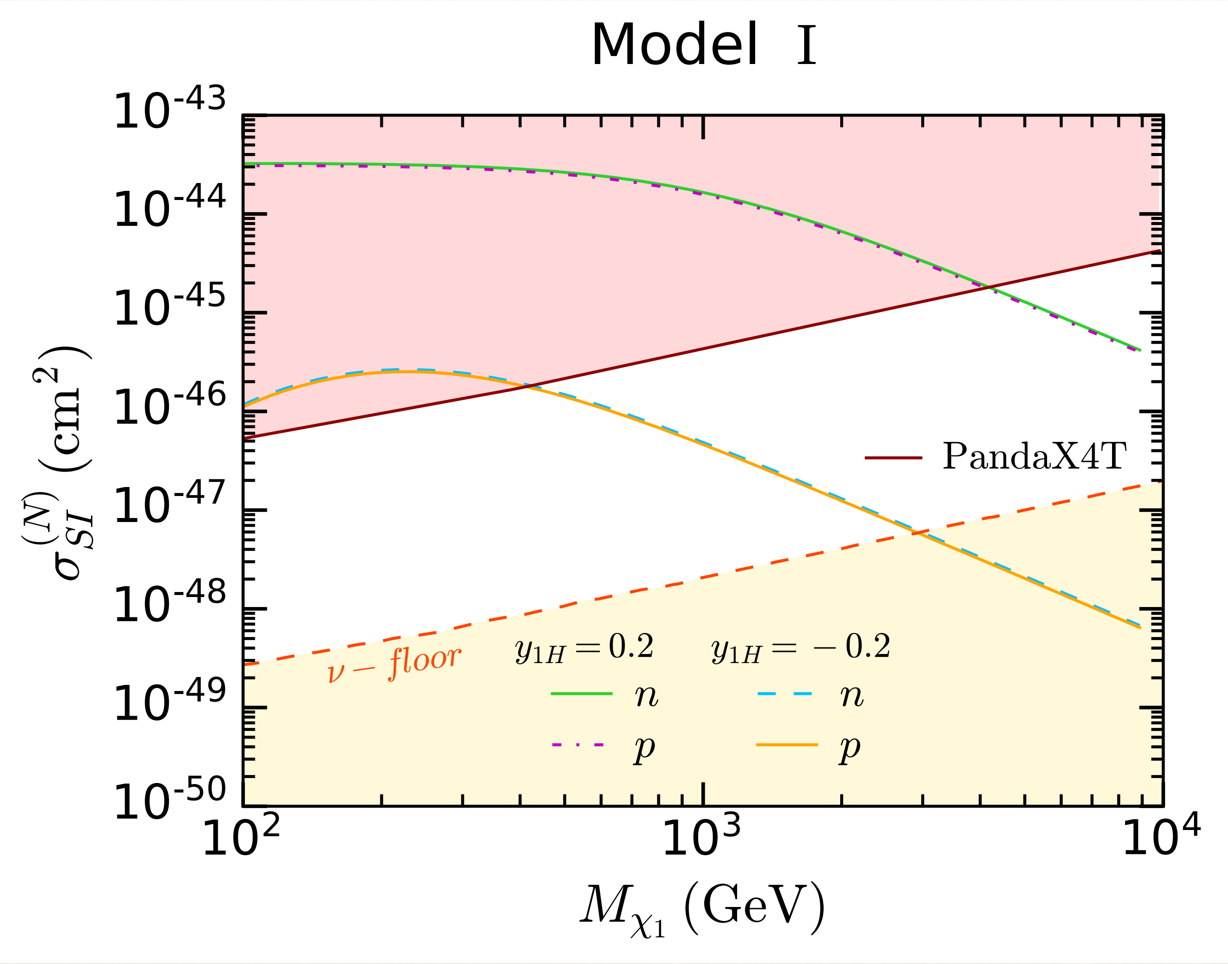
Model I: DM-nucleon cross section

Tree-level Higgs-boson exchange

$$\mathcal{L}_N = f_N \bar{\chi}_1 \chi_1 \bar{N} N$$

$$\sigma_{SI}^{(N)} = \frac{4}{\pi}\left(\frac{m_N M_{\chi_1}}{m_N + M_{\chi_1}}\right)^2 f_N^2$$



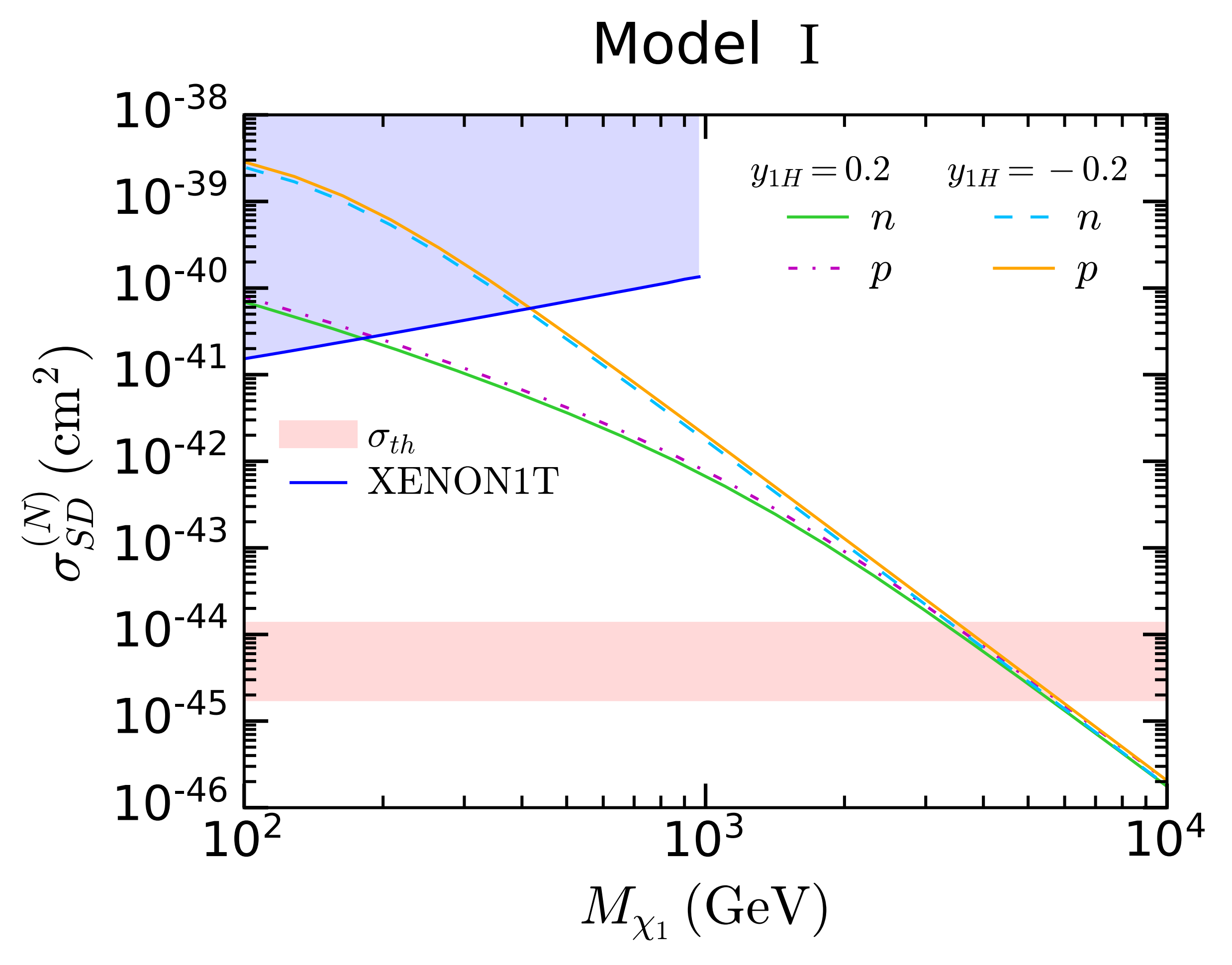


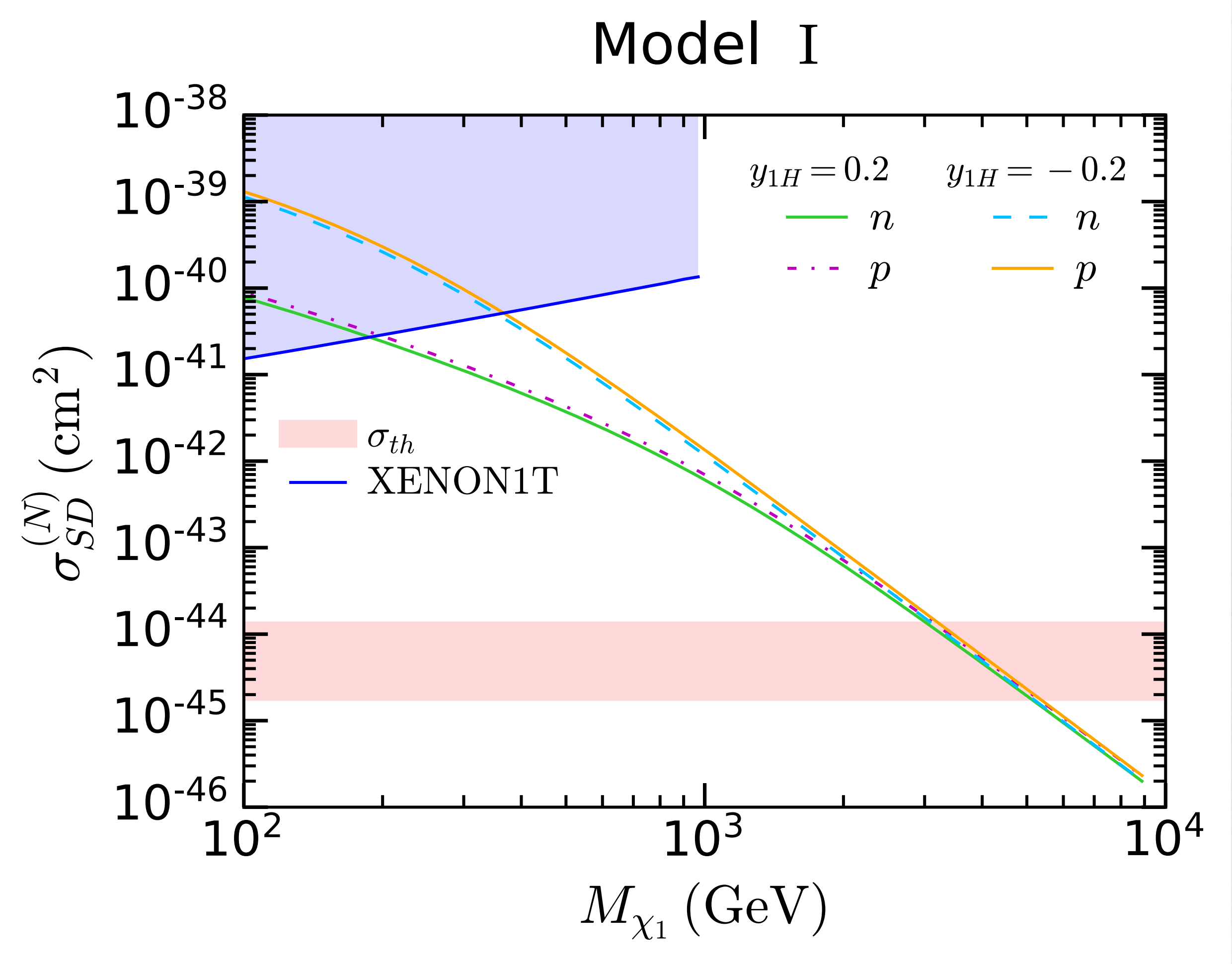
Model I: DM-nucleon cross section

Tree-level Z-boson exchange

$$\mathcal{L}_q = d_q \bar{\chi}_1 \gamma_\mu \gamma_5 \chi_1 \bar{q} \gamma^\mu \gamma^5 q$$

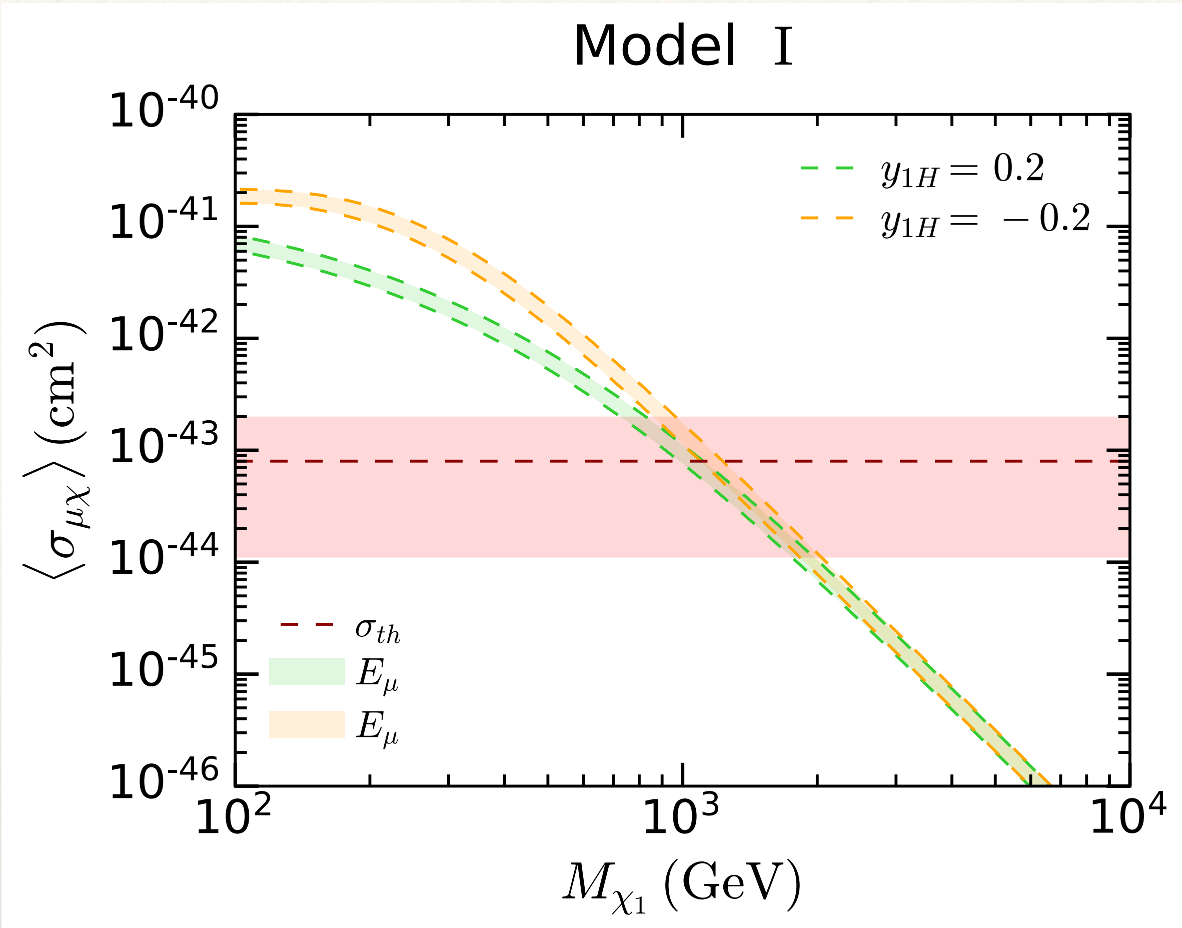
$$\sigma_{SD}^{(N)} = \frac{12}{\pi} \left(\frac{m_N M_{\chi_1}}{m_N + M_{\chi_1}} \right)^2 a_N^2$$





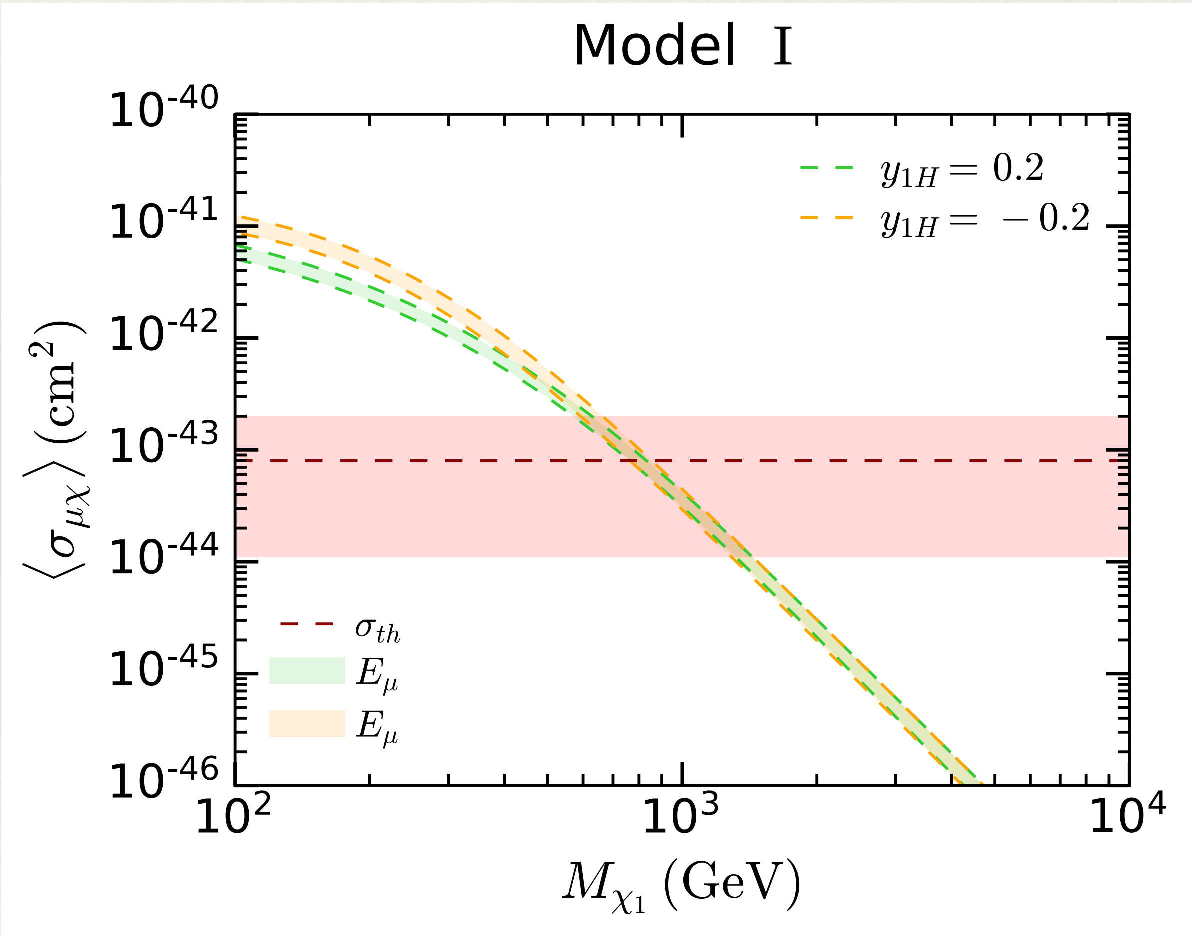
$$\sigma_{\rm th} \simeq [1.7 \times 10^{-45}, 1.4 \times 10^{-44}]\ \ {\rm cm}^2$$

arXiv:2108.02525
arXiv: 2004.14888

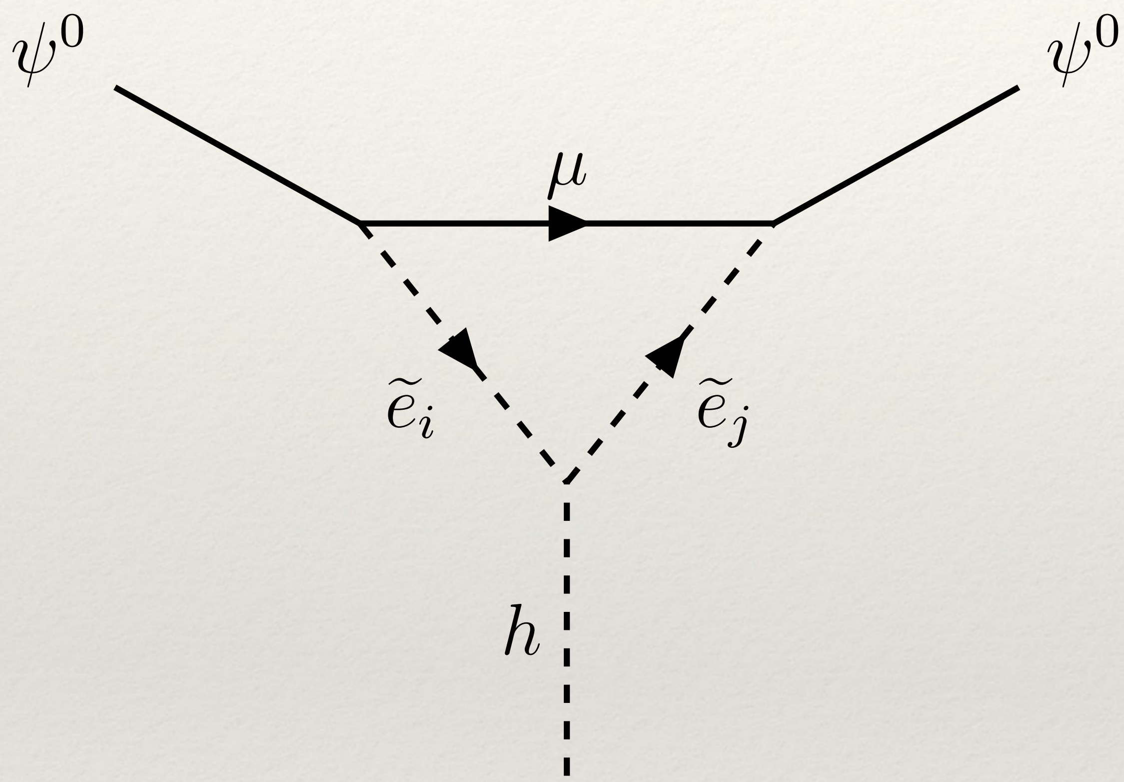


arXiv: 2010.13257

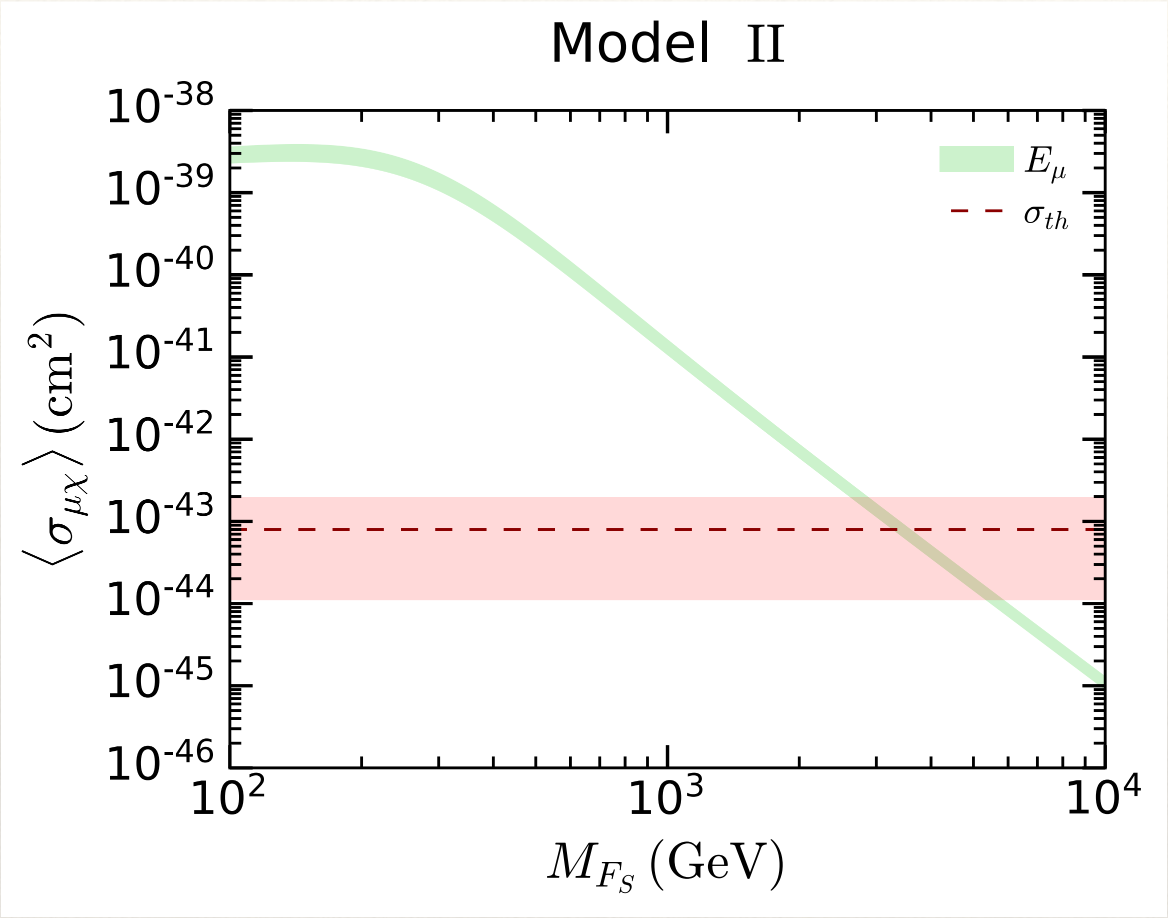
$$\sigma_{\rm th} \simeq 8 \times 10^{-44}\ \mathrm{cm}^2$$
$$M_{\rm NS} = 1.5\ M_\odot$$
$$R_{\rm NS} = 12.593\,\mathrm{km}$$



Model II: DM-nucleon cross section



- No tree-level coupling between the DM and the Higgs field: one-loop level.
- The scattering cross-section is suppressed by a factor of $y_i^2/(4\pi)^2 \sim 10^{-3}$.
- The resultant scattering cross-section is suppressed by a factor of $\sim 10^{-6}$.
- This leads to cross-section values of out of reach of future DM direct detection experiments.



arXiv: 2010.13257

$$\sigma_{\rm th} \simeq 8 \times 10^{-44}\ \mathrm{cm}^2$$
$$M_{\rm NS} = 1.5\ M_\odot$$
$$R_{\rm NS} = 12.593\,\mathrm{km}$$

The DM search using the NS temperature observation might play an important role in testing these scenarios in the future.

Summary

- We have studied two representative DM models, Model I and II, where WIMP DM particles have renormalisable couplings to muons.

  The experimental value of the $(g-2)_\mu$ discrepancy can be explained with a DM mass of ~ 1 TeV

- DM particles from these models efficiently accumulate in NSs:

  DM capture in NSs is effective, and the DM heating operates maximally

Temperature observation of old NSs provide a promising way of testing the WIMP DM models for the muon $(g-2)_\mu$ discrepancy.

However, despite using an excellent treatment on the capture rate in NS, here it is still very simplified and important effects might impact the capture probability.

Thank you!

Backup slides

Model I

$$\Delta a_\mu = -\frac{m_\mu}{8\pi^2 M_{\tilde{e}}^2}\sum_{i=1,2,3} M_{\chi_i}\mathrm{Re}\left[y_1 y_2 \left(V_\chi\right)_{1i}\left(V_\chi\right)_{2i}\right] f_{LR}^S\left(\frac{M_{\chi_i}^2}{M_{\tilde{e}}^2}\right)$$

$$-\frac{m_\mu^2}{8\pi^2 M_{\tilde{e}}^2}\sum_{i=1,2,3}\left[\left|y_1\left(V_\chi\right)_{1i}\right|^2+\left|y_2\left(V_\chi\right)_{2i}\right|^2\right] f_{LL}^S\left(\frac{M_{\chi_i}^2}{M_{\tilde{e}}^2}\right)$$

$$+\frac{m_\mu^2|y_2|^2}{8\pi^2 M_{\tilde{\nu}}^2} f_{LL}^F\left(\frac{M_{F_D}^2}{M_{\tilde{\nu}}^2}\right),$$

Model II

$$\Delta a_\mu = -\frac{m_\mu M_{F_S}}{8\pi^2}\sum_{i=1,2}\frac{1}{M_{e_i}^2}\mathrm{Re}\left[y_1 y_2 \left(U_e\right)_{1i}^*\left(U_e\right)_{2i}\right] f_{LR}^S\left(\frac{M_{F_S}^2}{M_{e_i}^2}\right)$$

$$-\frac{m_\mu^2}{8\pi^2}\sum_{i=1,2}\frac{1}{M_{e_i}^2}\left[\left|y_1\left(U_e\right)_{1i}^*\right|^2+\left|y_2\left(U_e\right)_{2i}\right|^2\right] f_{LL}^S\left(\frac{M_{F_S}^2}{M_{e_i}^2}\right)$$

DM-muon amplitude

$$\frac{d\sigma_{\chi\mu}}{dt} = \frac{1}{16\pi\lambda(s, M_{\mathrm{DM}}^2, m_\mu^2)}\cdot\frac{1}{4}\sum_{\mathrm{spins}}|\mathcal{A}|^2$$

$$\bar{s}\simeq M_{\mathrm{DM}}^2 \gg \bar{s}-M_{\mathrm{DM}}^2 \simeq 2E_\chi E_\mu \gg |t|, E_\mu^2$$

Model I

$$\mathcal{L}_{\text{mass}} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + M_{F_D}\xi_D\eta_D + \text{h.c.}\right) - M_{\tilde{L}}^2|\widetilde{L}|^2 \ ,$$

$$\mathcal{L}_{\text{Yukawa}} = -y_{1H}\chi_S(\xi_D \cdot H) - y_{2H}\chi_S\eta_D H^\dagger - y_1\chi_S L_\mu \widetilde{L}^\dagger - y_2\mu_R^c(\xi_D \cdot \widetilde{L}) + \text{h.c.} \ ,$$

$$\mathcal{L}_{\text{quart}} = -\lambda_L|\widetilde{L}|^2|H|^2 - \lambda'_L\widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \ldots \ ,$$

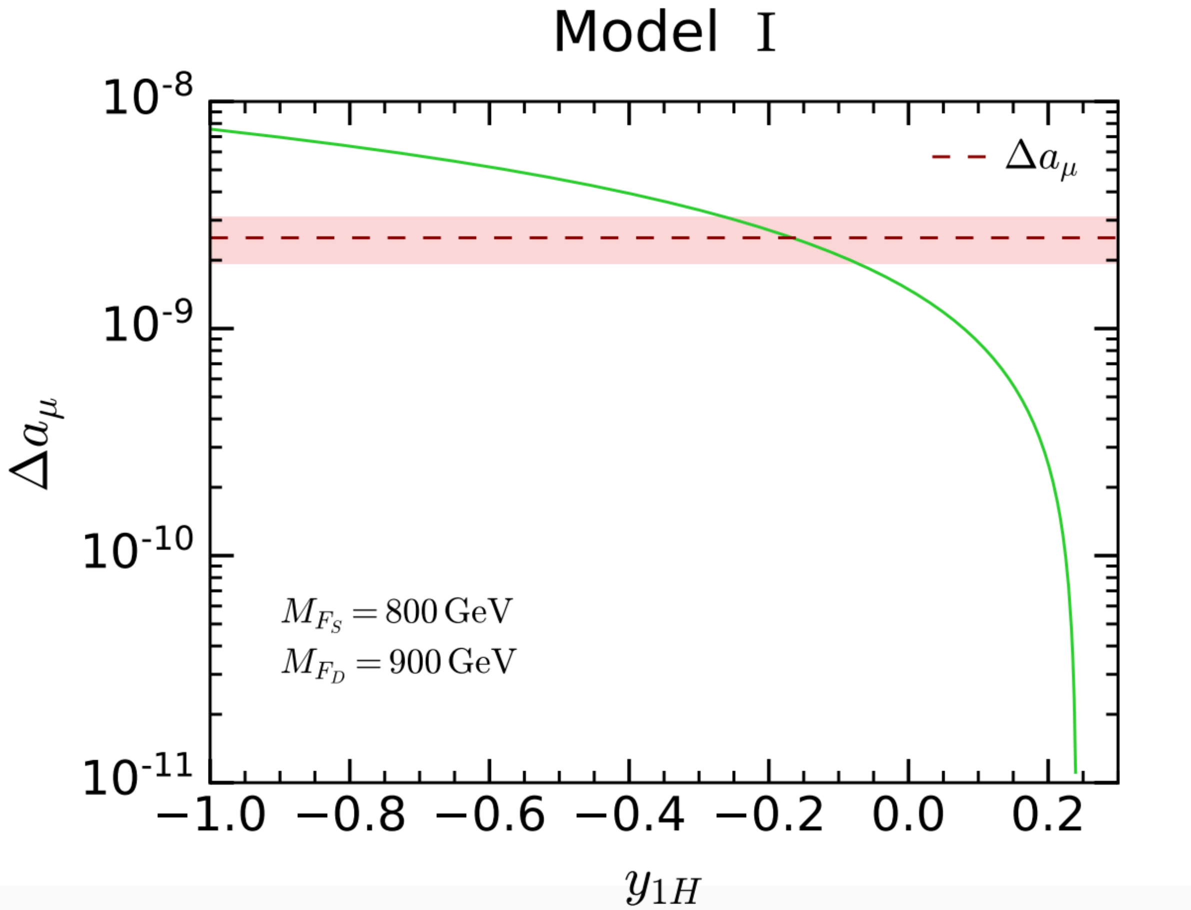
Model II

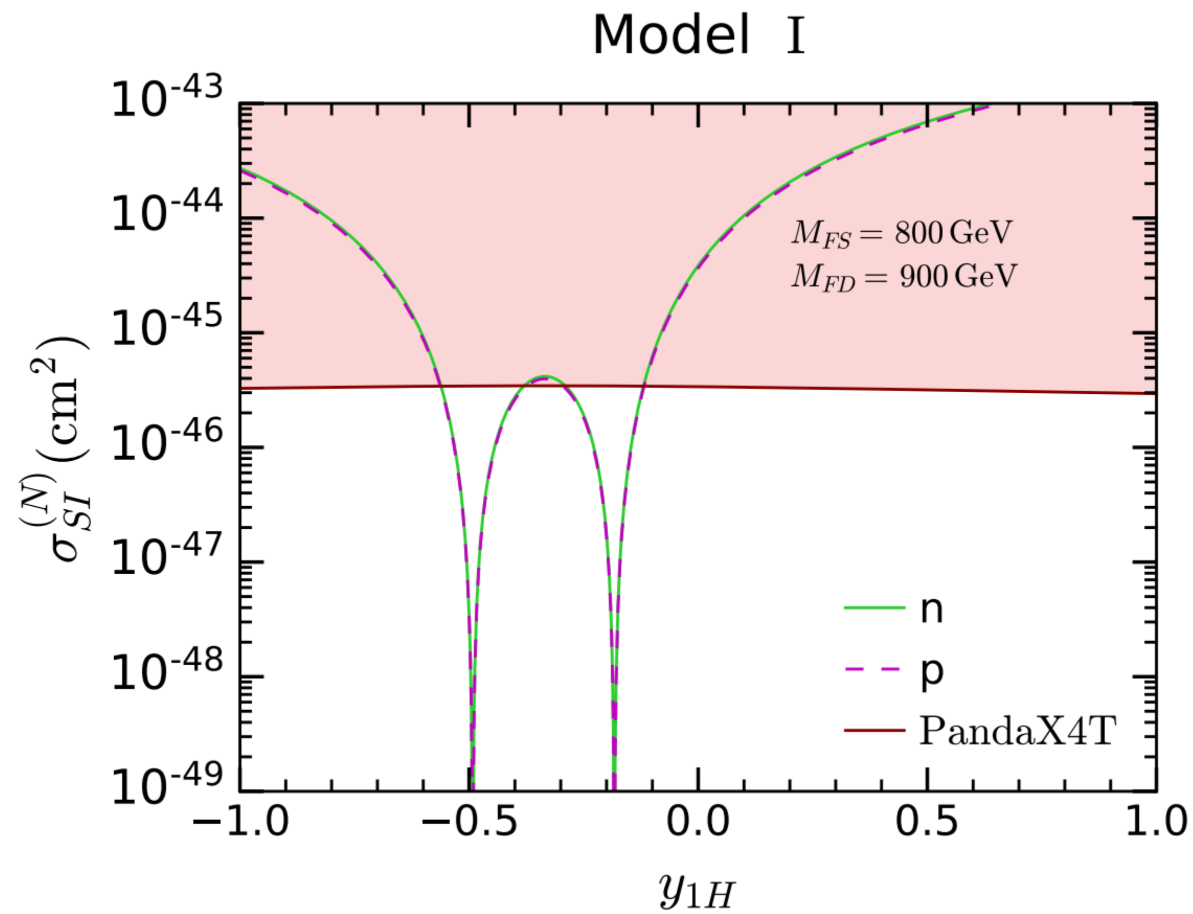
$$\mathcal{L}_{\text{mass}} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + \text{h.c.}\right) - M_{\tilde{L}}^2|\widetilde{L}|^2 - M_{\tilde{e}}^2|\widetilde{\bar{e}}|^2 \ ,$$

$$\mathcal{L}_{\text{Yukawa}} = -y_1\,\chi_S L_\mu \widetilde{L}^\dagger - y_2\,\chi_S\mu_R^c\widetilde{\bar{e}}^\dagger + \text{h.c.} \ ,$$

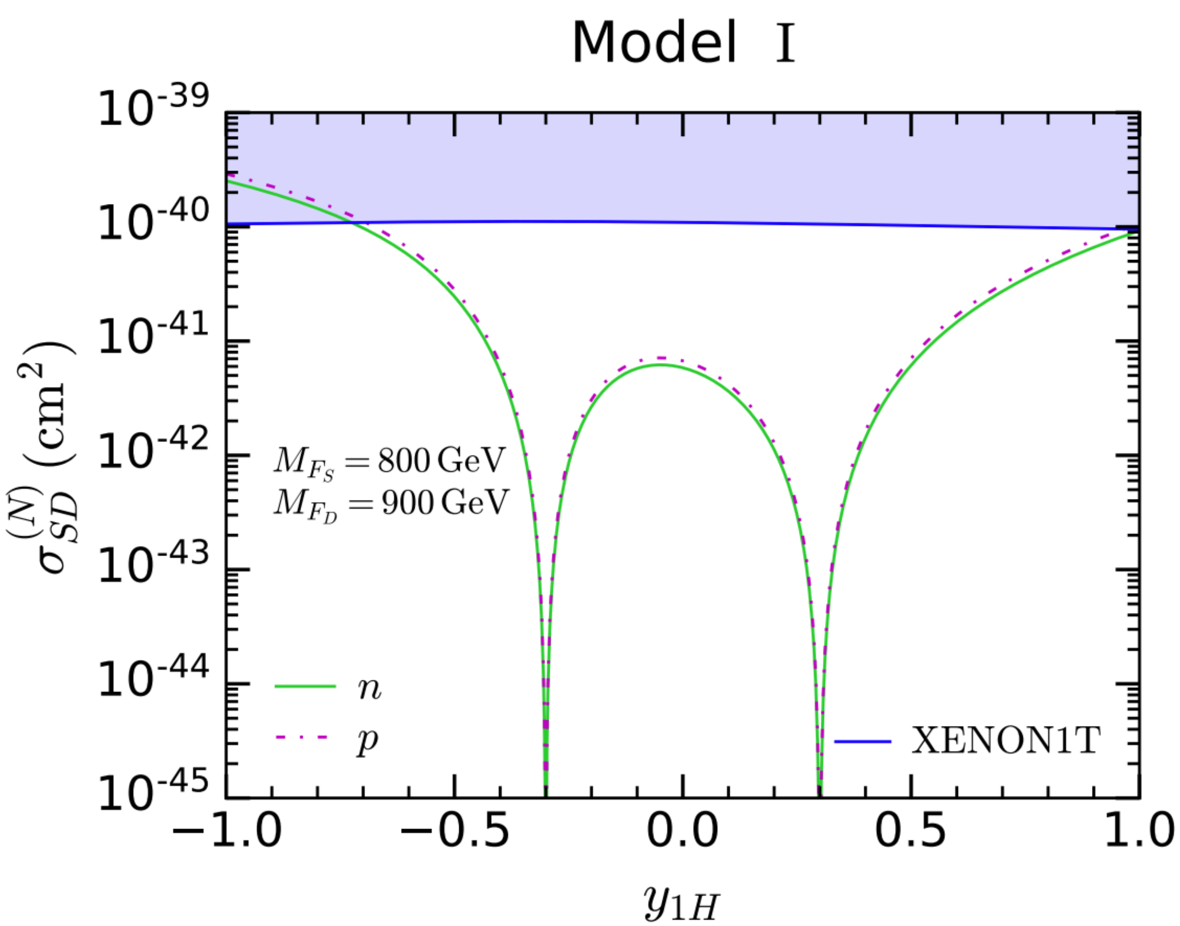
$$\mathcal{L}_{\text{tri}} = -a_H\,\widetilde{\bar{e}}\widetilde{L}H^\dagger + \text{h.c.} \ ,$$

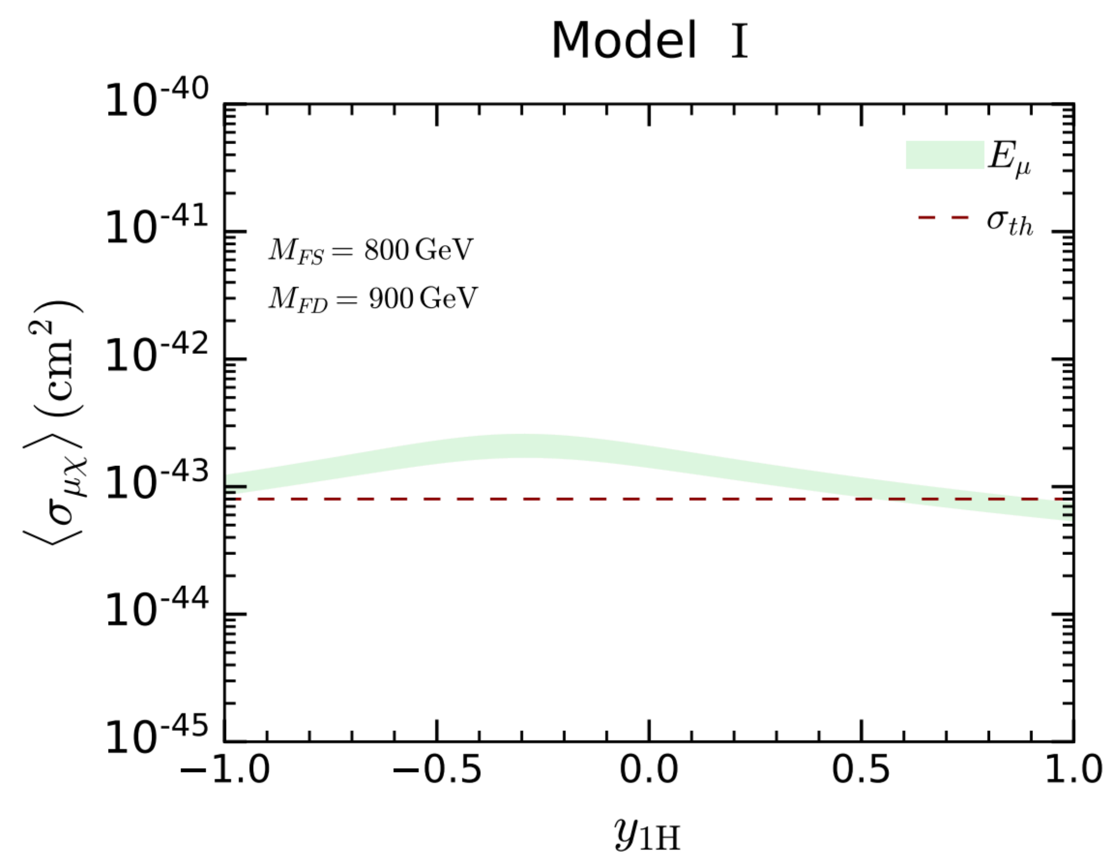
$$\mathcal{L}_{\text{quart}} = -\sum_{f=L,\bar{e}}\lambda_f|\widetilde{f}|^2|H|^2 - \lambda'_L\widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \ldots \ .$$

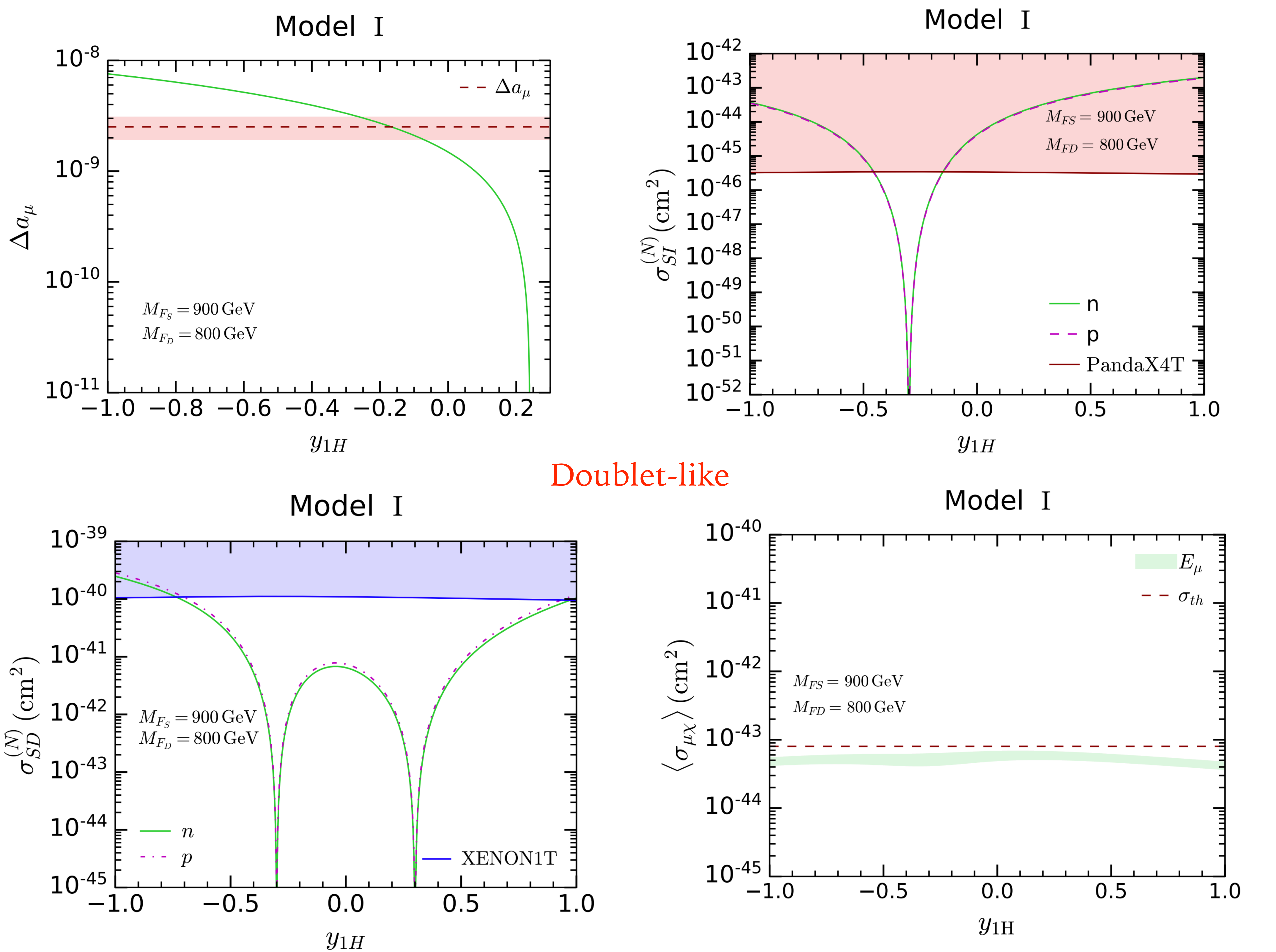




Singlet-like







Model I
Δa_μ
$M_{F_S} = 900\,\mathrm{GeV}$
$M_{F_D} = 800\,\mathrm{GeV}$
y_{1H}
Model I
$\sigma_{SI}^{(N)}\,(\mathrm{cm}^2)$
$M_{FS} = 900\,\mathrm{GeV}$
$M_{FD} = 800\,\mathrm{GeV}$
n
p
PandaX4T
y_{1H}
Doublet-like
Model I
$\sigma_{SD}^{(N)}\,(\mathrm{cm}^2)$
$M_{F_S} = 900\,\mathrm{GeV}$
$M_{F_D} = 800\,\mathrm{GeV}$
n
p
XENON1T
y_{1H}
Model I
$\langle \sigma_{\mu\chi} \rangle\,(\mathrm{cm}^2)$
E_μ
σ_{th}
$M_{FS} = 900\,\mathrm{GeV}$
$M_{FD} = 800\,\mathrm{GeV}$
$\mathrm{y_{1H}}$