Freeze-in Dark Matter in Neutron Stars

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Introduction

- Neutron stars (NS) are born aftermath of the Supernova (SN) explosion. They are very dense (density comparable to atomic nucleus) object.

- Due to high density and strong gravitational field, neutron stars provide excellent environment to study Dark matter (DM) properties.

- Talk's focus will be on Freeze-in (FI) type of Dark Matter.

Idea and Motivation

Right after explosion, proto-neutron star with temperature $T \sim \mathcal{O}(10^{11})K \sim \mathcal{O}(10\ MeV)$ is born.

↓

Exotic particles can be produced from Standard Model (SM) particles in that environment.

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Produced particles will get captured by the gravity of NS

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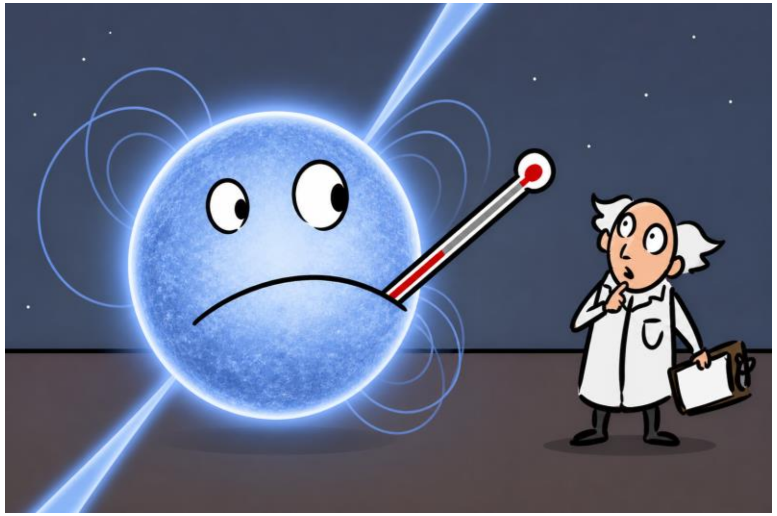
The population of DM will undergo annihilation back to SM during cooling of NS

↓

Late heating of NS

Idea and Motivation



Reheating signature

Late Heating of NS

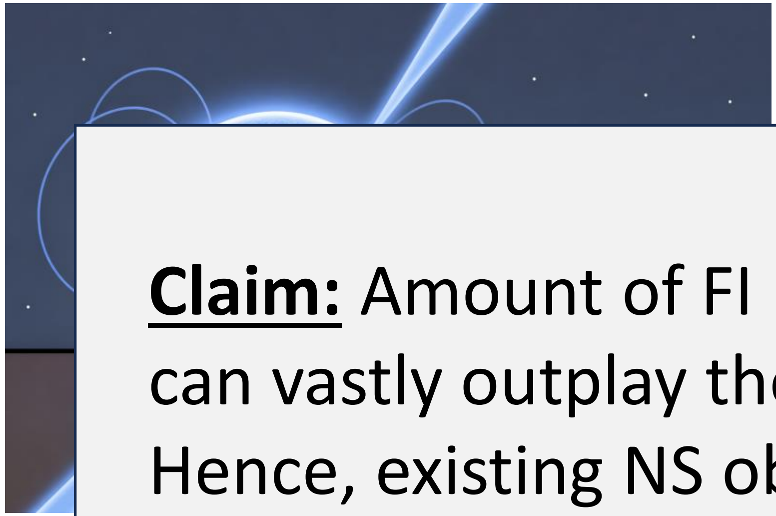
Heavily constrained

Coldest known NS/pulsar

PSR J2144-3933

$T \lesssim 3\ eV$ Ref: S. Guillot et.al 2019

Idea and Motivation



Claim: Amount of FI DM produced in explosion and retained inside NS can vastly outplay the amount that can be captured from outside. Hence, existing NS observation is enough to put constraint.

signature

Preliminary Estimates

Define

$$R_{in} = \langle \sigma_{\mathrm{SM} \to \chi\bar{\chi}} v \rangle$$

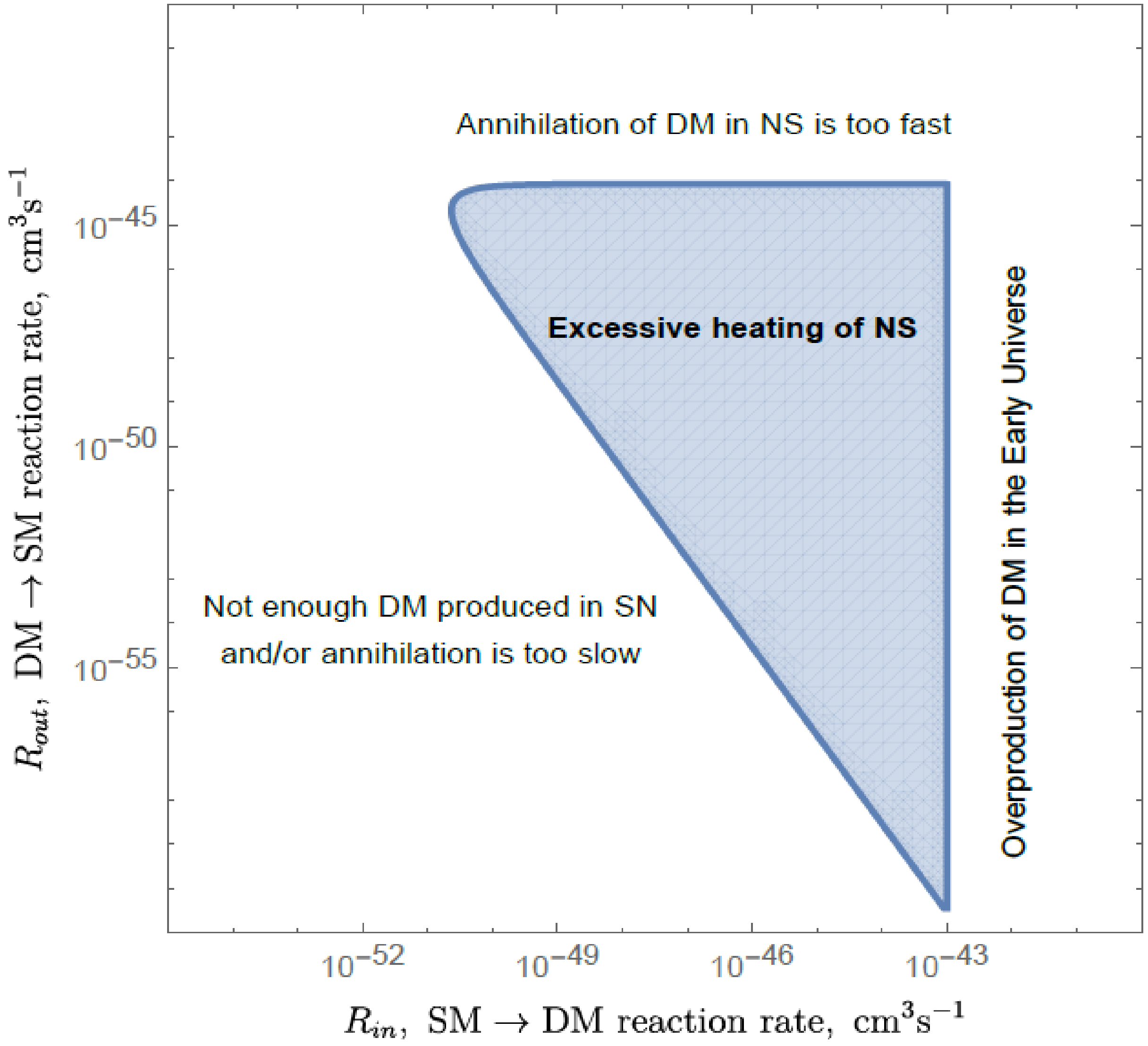
$$R_{out} = \langle \sigma_{\chi\bar{\chi} \to \mathrm{SM}} v \rangle$$

Preliminary Estimates

Define

$$R_{in} = \langle \sigma_{\mathrm{SM}\to\chi\bar{\chi}} v \rangle$$

$$R_{out} = \langle \sigma_{\chi\bar{\chi}\to\mathrm{SM}} v \rangle$$



Specific Example of an FI DM Model

To simplify the understanding, we choose a model of FI DM

$$\mathcal{L} = \mathcal{L}_{L_\mu - L_\tau} + \mathcal{L}_{dark} + \mathcal{L}_{portal},$$
$$\mathcal{L}_{L_\mu - L_\tau} = \sum_{j=\mu,\tau} \bar{L}_{(j)} \gamma_\alpha (i\partial_\alpha \pm g_L X_\alpha) L_{(j)}$$
$$\mathcal{L}_{dark} = \bar{\chi}(\gamma_\alpha(i\partial_\alpha + g_d V_\alpha) - m_\chi)\chi$$
$$\mathcal{L}_{portal} = \varepsilon \frac{1}{2} X_{\mu\nu} V_{\mu\nu}$$

Possible Scenario

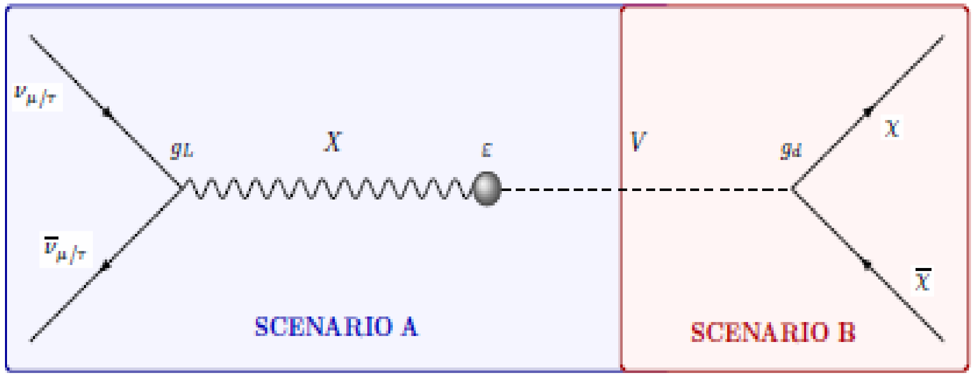
Scenario A

- The main FI process is $\nu\bar{\nu} \rightarrow V$

Scenario B

- The main FI process is $V \rightarrow \chi\bar{\chi}$

FREEZE-IN →



← ANNIHILATION

Specific Example of an FI DM Model

Define FI coupling as:

$$A: \ \alpha_{\rm FI} \equiv \frac{g_L^2 \varepsilon^2}{4\pi} \times \frac{m_V^4}{(m_V^2 - m_X^2)^2}; \quad B: \alpha_{\rm FI} \equiv \frac{g_d^2}{4\pi}.$$

FI coupling value which reproduces the observed DM abundance $m_V = 3m_\chi$

$$\alpha_{\rm FI} \simeq 6 \times 10^{-27}$$

Almost same for both scenario with $\frac{m_V}{m_\chi} = 3$!!

DM Production & Retention

- Total number of DM particles produced per baryon using numerical simulation of temperature and number density profile of early stage of NS

  Ref: L. F. Roberts 2012
  Sumuyoshi, Kojo, Furusawa 2022

$$\frac{N_\chi + N_{\bar{\chi}}}{N_{B,\rm NS}} \simeq 2.5 \times 10^{-6} \times \frac{\alpha_{\rm FI}}{6\times 10^{-27}} \times \left(\frac{m_V}{30\,\rm MeV}\right)^3 \times \int \frac{dt}{10\,\rm s} \int_0^1 dx \, \frac{(100\,\rm MeV)^3}{n_B(x,t)} \times \frac{T(x,t)}{10\,\rm MeV} \times K_1\left(\frac{m_V}{T(x,t)}\right)$$

- Most of produced DM are too energetic, hence will escape NS

- Need to calculate produced DM confined to NS. Sensitively depends on ratio of m_V to m_χ

- The kinetic energy required to escape varies from $0.34 m_\chi$ at centre to $0.18 m_\chi$ at surface

- When $m_V : m_\chi = 3:1$, if V decays at rest, both $\chi\bar{\chi}$ will escape. So, V has to be boosted such that χ (or $\bar{\chi}$) emitted against velocity will be retained

DM Production & Retention

- The probability of retention for the representative ratio

$$P^{ret}(\Delta\Phi, \gamma_V) = \frac{1}{2}\frac{\Delta\Phi + 1 - \frac{3}{2}\gamma_V + \frac{\sqrt{5}}{2}\sqrt{\gamma_V^2 - 1}}{\sqrt{5}\sqrt{\gamma_V^2 - 1}}.$$

DM Production & Retention

- The probability of retention for the representative ratio of $m_V : m_\chi = 3:1$

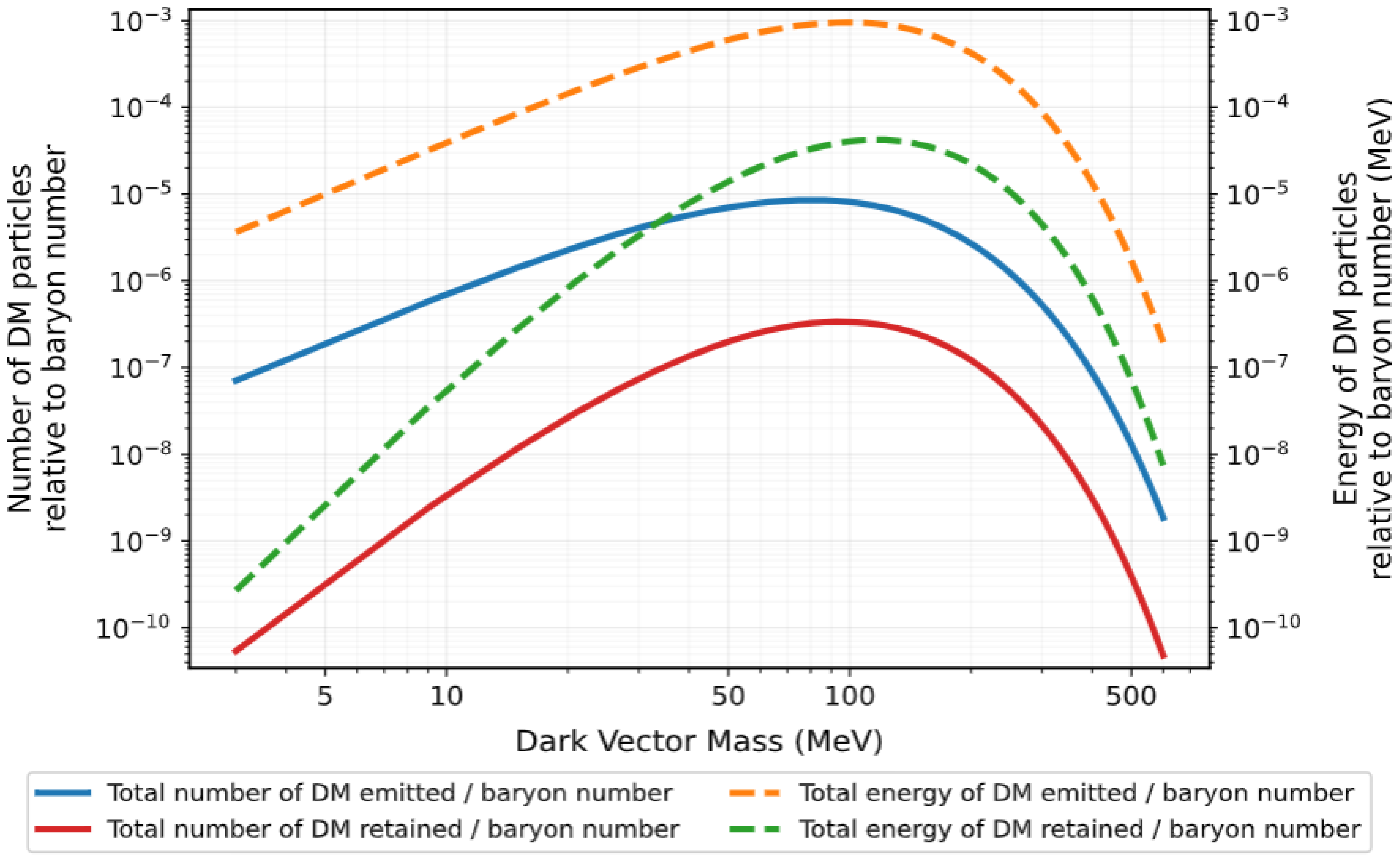
$$P^{ret}(\Delta\Phi, \gamma_V) = \frac{1}{2}\frac{\Delta\Phi + 1 - \frac{3}{2}\gamma_V + \frac{\sqrt{5}}{2}\sqrt{\gamma_V^2 - 1}}{\sqrt{5}\sqrt{\gamma_V^2 - 1}}$$

- To compute the retained DM particles relative to baryon

$$\frac{N_\chi + N_{\bar{\chi}}}{N_{B,\mathrm{NS}}} \simeq 2.5 \times 10^{-6} \times \frac{\alpha_{\mathrm{FI}}}{6 \times 10^{-27}} \times \left(\frac{m_V}{30\,\mathrm{MeV}}\right)^3 \times \int \frac{dt}{10\,\mathrm{s}} \int_0^1 dx \frac{(100\,\mathrm{MeV})^3}{n_B(x,t)} \times \frac{T(x,t)}{10\,\mathrm{MeV}} \times K_1\left(\frac{m_V}{T(x,t)}\right)$$

$$m_V \int_1^\infty P^{ret}(\Delta\Phi(x), \gamma_V)\sqrt{\gamma_V^2 - 1}\,\exp\left(-\frac{m_V \gamma_V}{T(x,t)}\right) d\gamma_V$$

DM Production & Retention



Annihilation Process

- Should occur on very large time scale because of two factors : presence of n_χ^2 and off-shell V mediator
- The annihilation of DM injects energy via

$$\chi\bar{\chi} \to \nu_{\mu(\tau)}\bar{\nu}_{\mu(\tau)};\ \nu_i + N(e) \to \nu_i + N(e)$$

- The rate of energy injection is determined by the first process.
- Ignoring the small kinetic energy of DM particles, one can write the rate of energy injection as

$$\frac{dQ}{dt} = -2m_\chi \frac{dN_\chi}{dt} = -\frac{2m_\chi \langle \sigma_{ann} v \rangle N_\chi N_{\bar{\chi}}}{V_{\rm NS}} \times J,$$

$$J \equiv V_{\rm NS} \int \frac{n_\chi(r) n_{\bar{\chi}}(r)}{N_\chi N_{\bar{\chi}}} dV = V_{\rm NS} \int f_\chi(r) f_{\bar{\chi}}(r) dV.$$

Parametrizes deviation from uniform distribution (→ J)

Annihilation Process

- For scenario A, one can write

$$\sigma_{ann} v = \frac{\pi \alpha_{\rm FI} \alpha_d}{m_\chi^2} \frac{(4m_\chi^2)^4 (m_V^2 - m_X^2)^2}{m_V^4 (4m_\chi^2 - m_V^2)^2 (4m_\chi^2 - m_X^2)^2}$$

- Now utilize the observational limit on abnormal sources of energy for PSR J2144-3933

Ref: S. Guillot et.al 2019

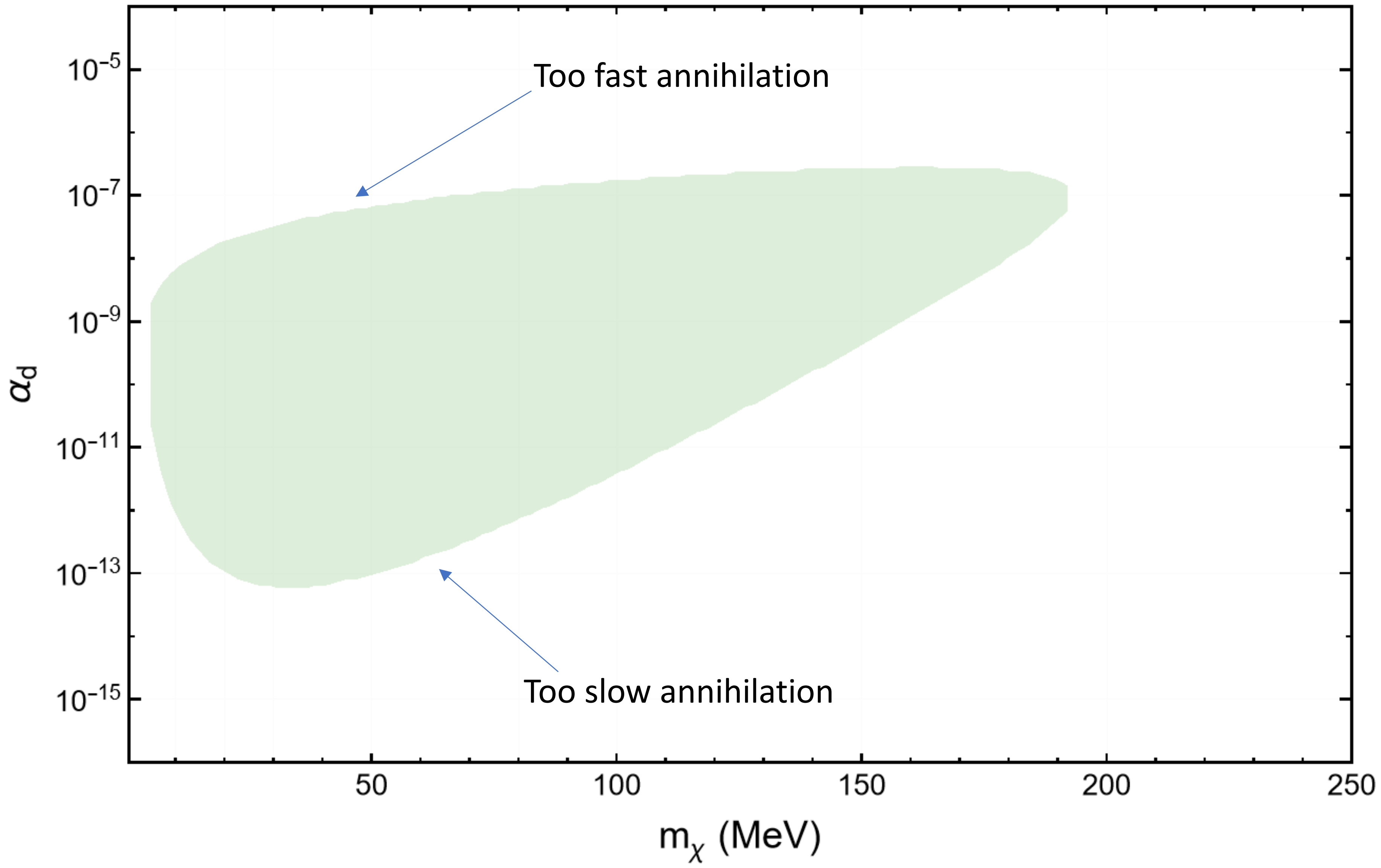
$$\frac{dQ}{dt}(t \sim 10^{16}\,{\rm s}) \lesssim 2.3 \times 10^{39}\,\frac{\rm eV}{\rm s}$$

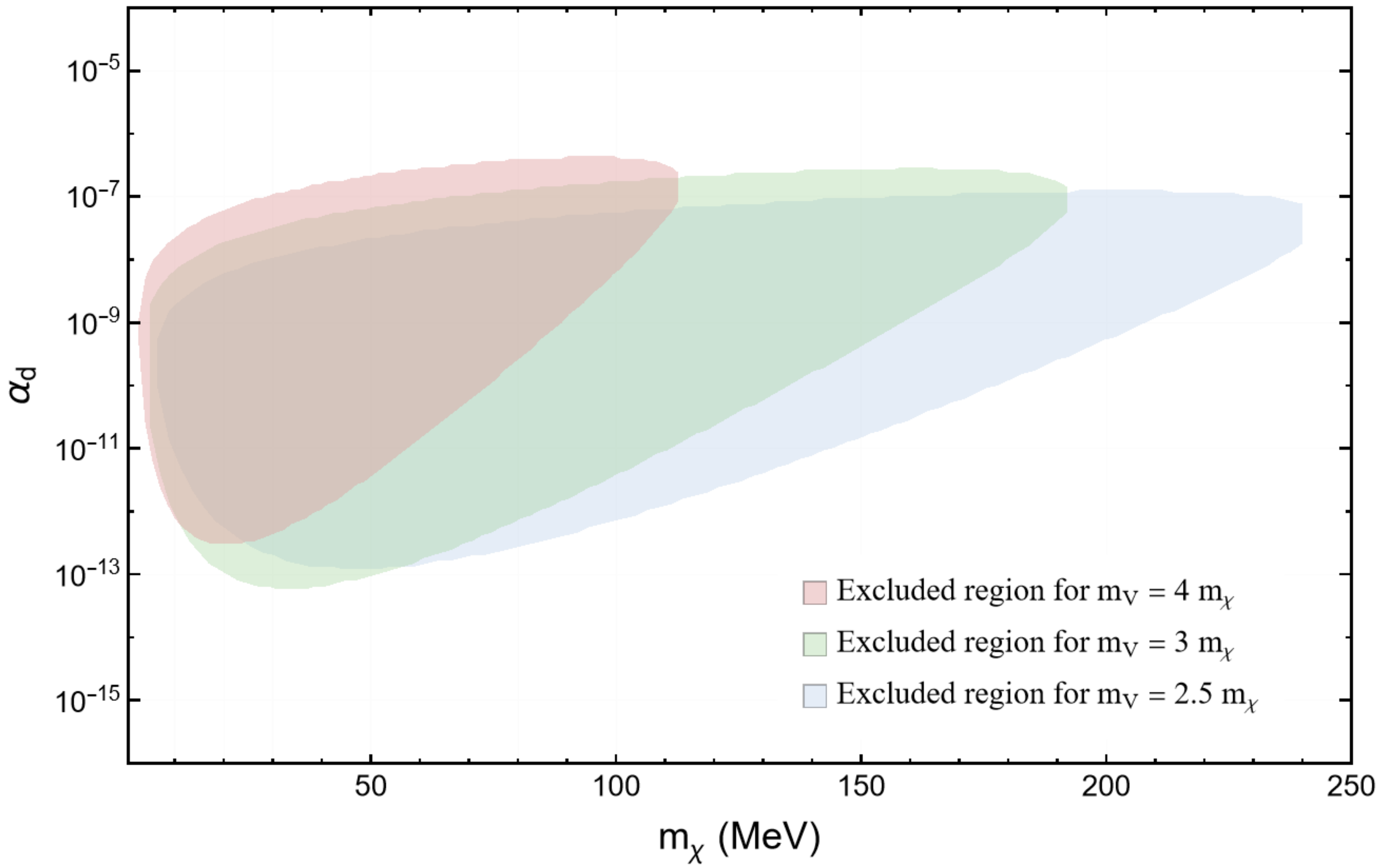
Constraint From Late Time Heating of NS

- Constraint on $\{\alpha_d, m_\chi\}$ parameter space for fixed FI coupling

- Constraint on $\{\alpha_{\mathrm{FI}}, m_\chi\}$ parameter space for fixed dark coupling

Let's look at the representative case i.e. when $m_V = 3m_\chi$





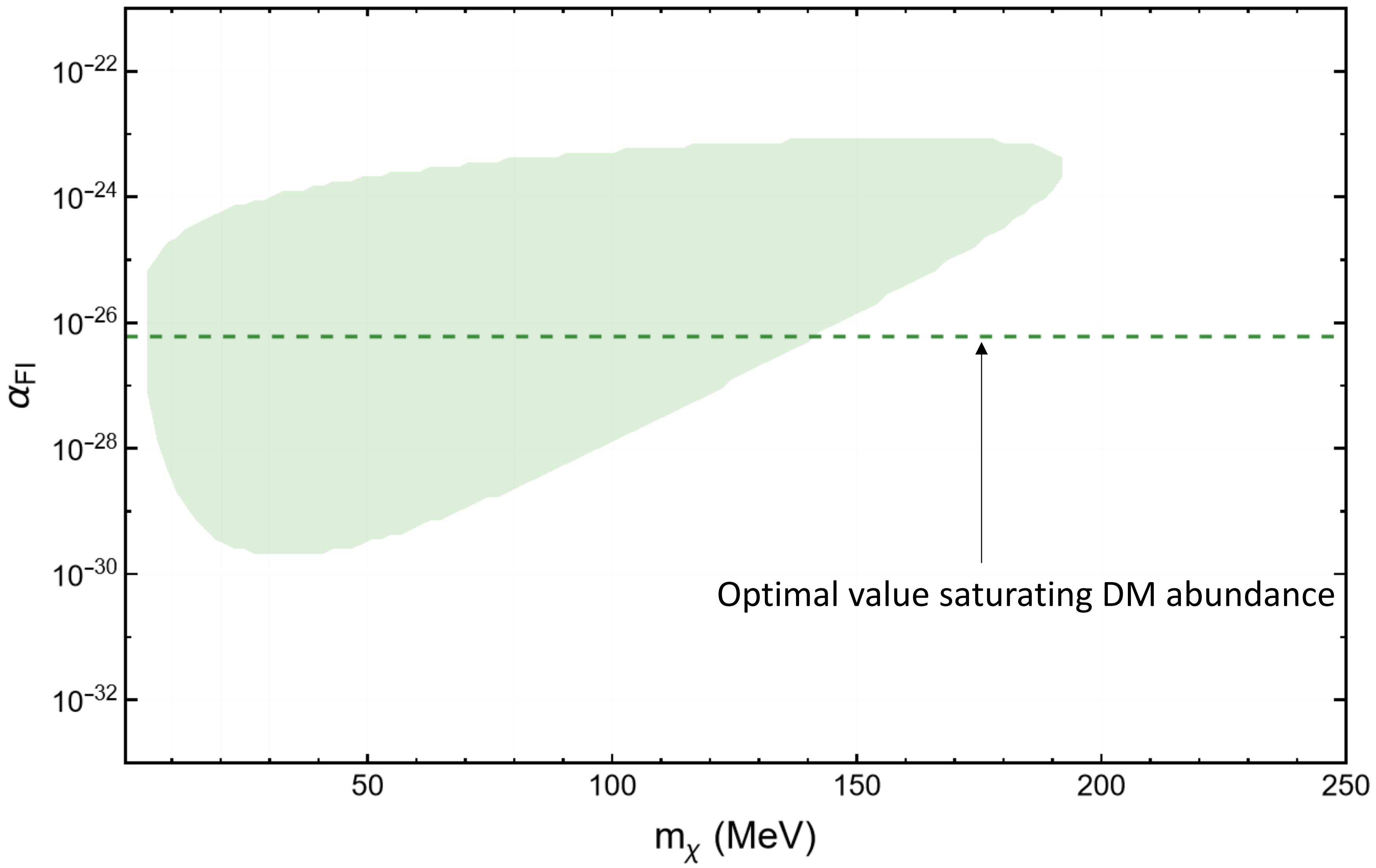
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
α_d
50
100
150
200
250
m_χ (MeV)
Excluded region for $m_V = 4\ m_\chi$
Excluded region for $m_V = 3\ m_\chi$
Excluded region for $m_V = 2.5\ m_\chi$

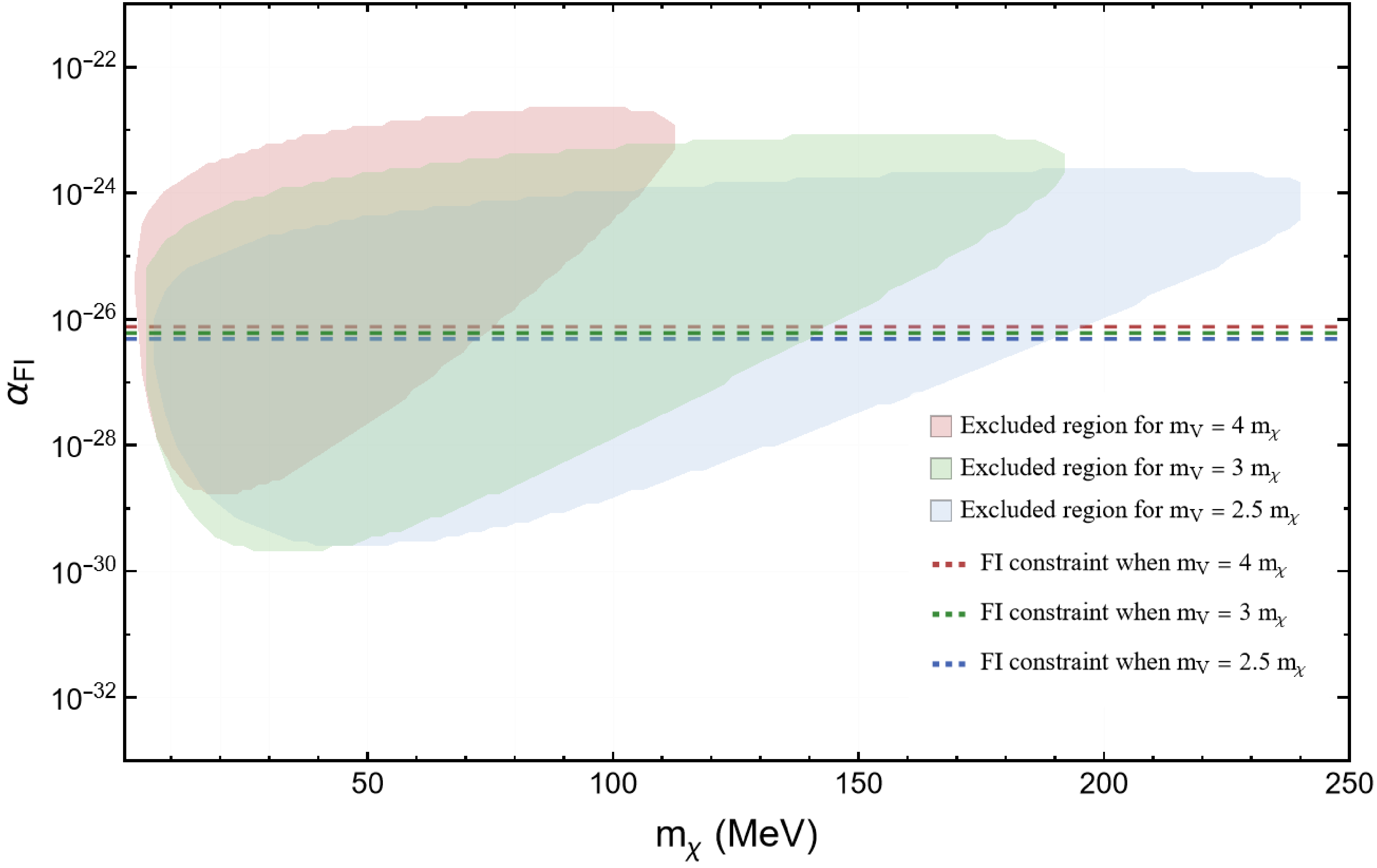
Constraint From NS Late Time Heating

- Constraint on $\{\alpha_d, m_\chi\}$ parameter space for fixed value of FI coupling

- Constraint on $\{\alpha_{\text{FI}}, m_\chi\}$ parameter space for fixed value of dark coupling

Let’s look at the representative case, $m_V = 3m_\chi$ at first when $\alpha_d = 10^{-10}$





10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
α_{FI}
50
100
150
200
250
m_χ (MeV)
Excluded region for $m_V = 4\, m_\chi$
Excluded region for $m_V = 3\, m_\chi$
Excluded region for $m_V = 2.5\, m_\chi$
FI constraint when $m_V = 4\, m_\chi$
FI constraint when $m_V = 3\, m_\chi$
FI constraint when $m_V = 2.5\, m_\chi$

Conclusion & Summary

- The late time heating of NS because of FI dark matter is a new strong tool to constraint stable DM of mass range MeV-100 MeV.

- One can estimate the scattering cross-section of DM with electrons for our case, With $\alpha_d = 10^{-10}$ and $m_V = 100\ MeV$, we estimate $\sigma_{\chi e} \sim 10^{-70}\ cm^2$ (almost 25 order smaller than direct detection limit)

- Motivates investigation of FI DM induced collapse of NS to black hole for scalar DM (e.g. Bramante &Raj 2023, Kouvaris &Tinyakov 2011) and electromagnetic emission signature from FI DM annihilating outside of NS.

Backup Slides

Preliminary Estimates

Define

$$R_{in} = \langle \sigma_{\mathrm{SM} \to \chi\bar{\chi}} v \rangle$$

$$R_{out} = \langle \sigma_{\chi\bar{\chi} \to \mathrm{SM}} v \rangle$$

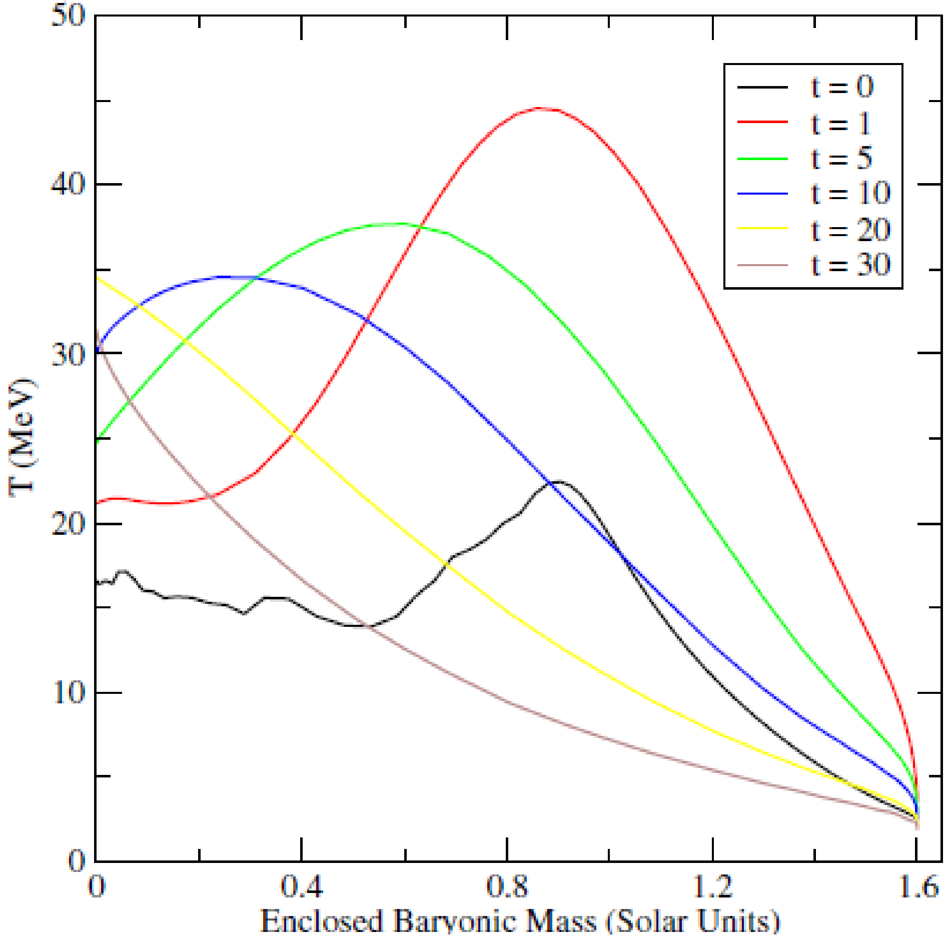
Fractional amount of DM generated

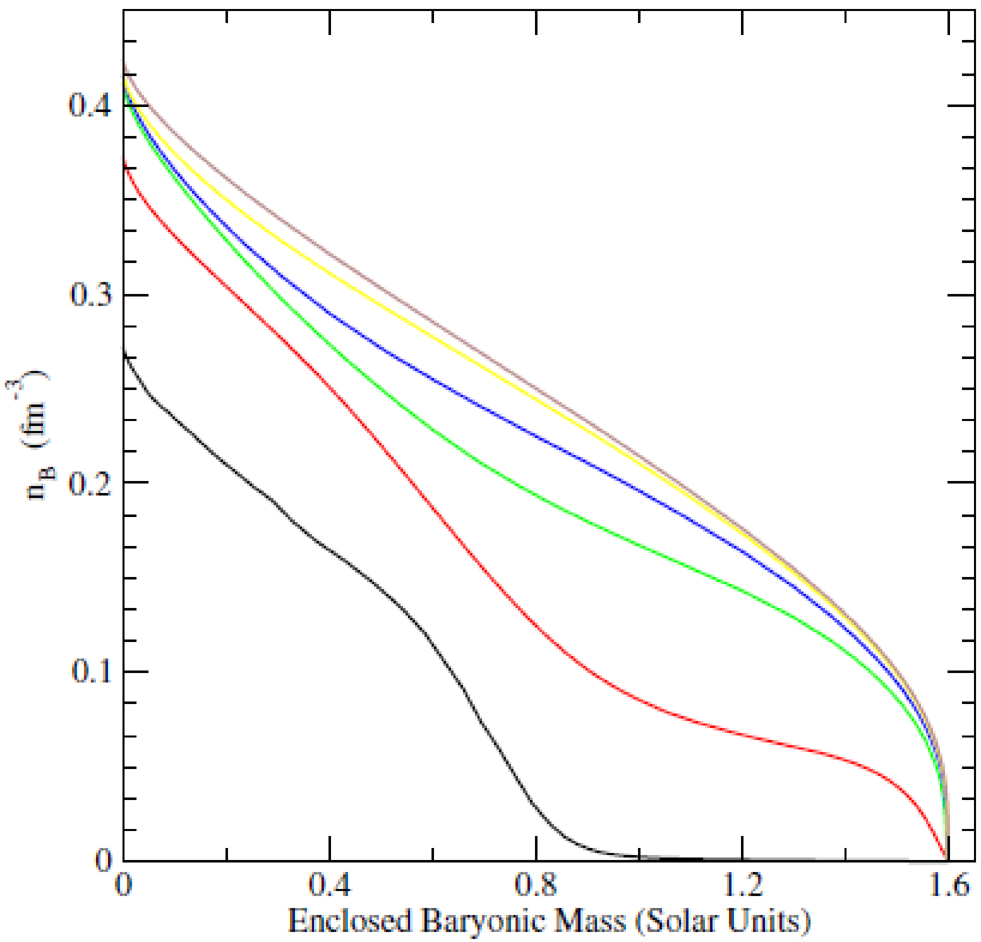
$$\frac{n_{\chi, t\simeq 0}}{n_{\mathrm{SM}}} \propto R_{in} n_{\mathrm{SM}} \times \Delta t$$

Amount of heat generated per volume because of annihilation

$$\frac{dQ}{dV dt} \propto m_\chi \times R_{out} n_\chi(t)^2$$

Temperature and Number Density Profile of NS





Ref: L. F. Roberts 2012

DM Retention

In general, for $m_V = nm_\chi$, where $n > 2$, probability of retention is given as

$$P^{\rm ret}(\Delta\Phi, \gamma_V; n) = \frac{1}{2}\,\frac{\Delta\Phi + 1 - \frac{n}{2}\gamma_V + \sqrt{\left(\frac{n^2}{4} - 1\right)\left(\gamma_V^2 - 1\right)}}{\sqrt{n^2 - 4}\sqrt{\gamma_V^2 - 1}}$$

This holds true when $e_{\min} < 1 + \Delta\Phi < e_{\max}$

$$e_{\min,\max} = \frac{n}{2}\gamma_V \mp \sqrt{\left(\frac{n^2}{4} - 1\right)\left(\gamma_V^2 - 1\right)}$$

Vanishes when $1 + \Delta\Phi \le e_{\min}$

Equals to unity when $1 + \Delta\Phi \ge e_{\max}$

DM Population

- After DM is bound to star, the entire star goes into a cooling regime

Scenario A

- DM-DM scattering leads to thermalization of DM population and develop "dark" temperature (T_d)
- A small portion of Boltzmann tail will evaporate leading to decrease in T_d and N_χ
- The cooling occurs faster than particle loss (since only high energy particles can escape)

$$\frac{d\log N_\chi(t)/dt}{d\log T_d(t)/dt} \ll 1.$$

DM Population

Scenario B:

- Since α_d is small, self-interaction is negligible
- DM population can still develop a temperature because of scattering with μ^-

Cooling is much more uncertain!!