Dark Matter Catalyzed Baryon Destruction

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Minnesota U. → CERN

Baryon and Lepton Number Violation @ KIT Oct 08, 2024

Based on 2405.18472

with Robert McGehee, Maxim Pospelov, and Anupam Ray

Motivation & idea

- Interesting to speculate possible connection btw DM and baryon.

  e.g. coincidence problem, hylo-/co-genesis, asymmetric DM, etc.

- In this talk: what pheno implications if DM induces BNV process?

  (I will not discuss connection to baryogenesis)

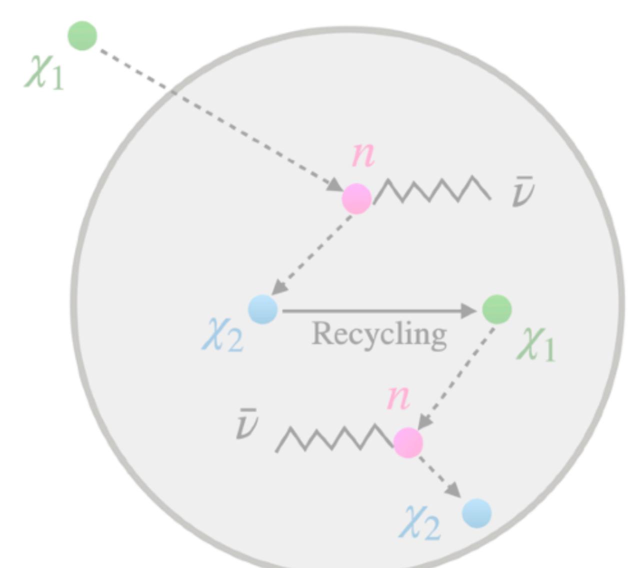
  1. Catalyzed baryon decay inside detectors (e.g. SuperK)

     See e.g. [Davoudiasl+ 10, 11; Demidov and Gorbunov 15]

  2. Neutron decay inside neutron star (NS) by captured DM

     ➡ NS heating by visible matter energy

     (can be way more efficient than e.g. DM annihilation)



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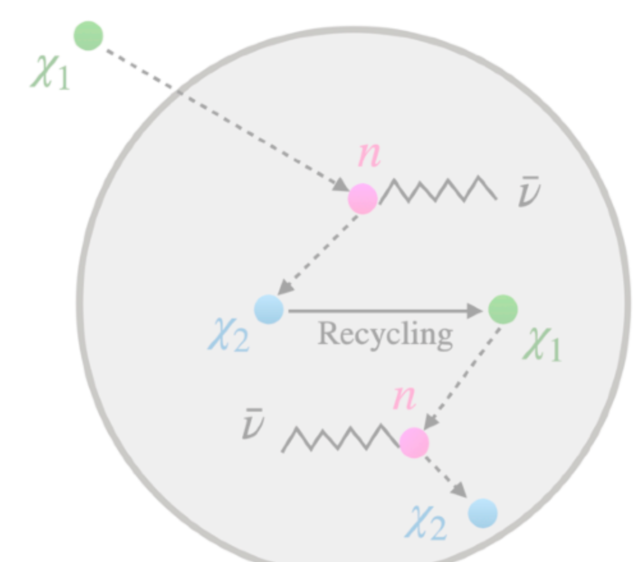

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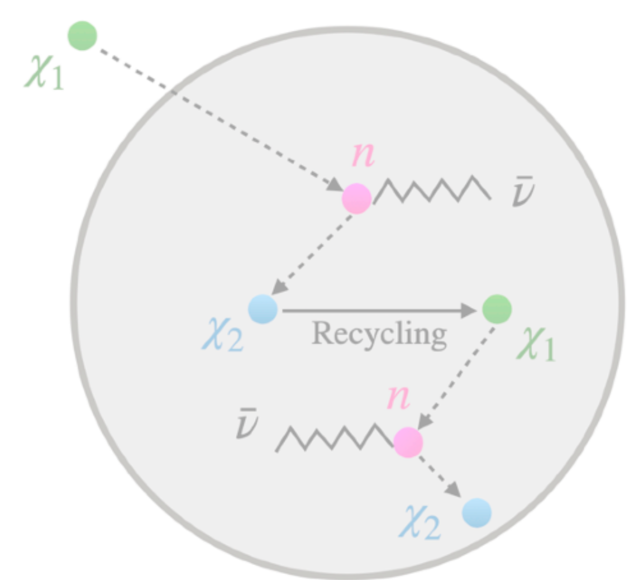

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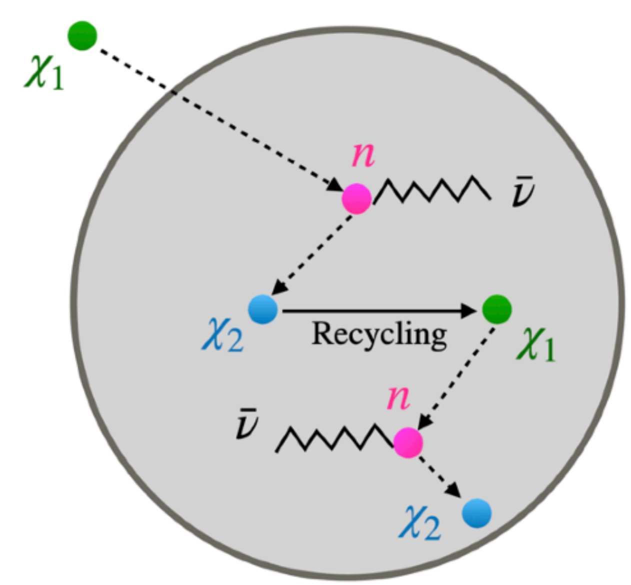


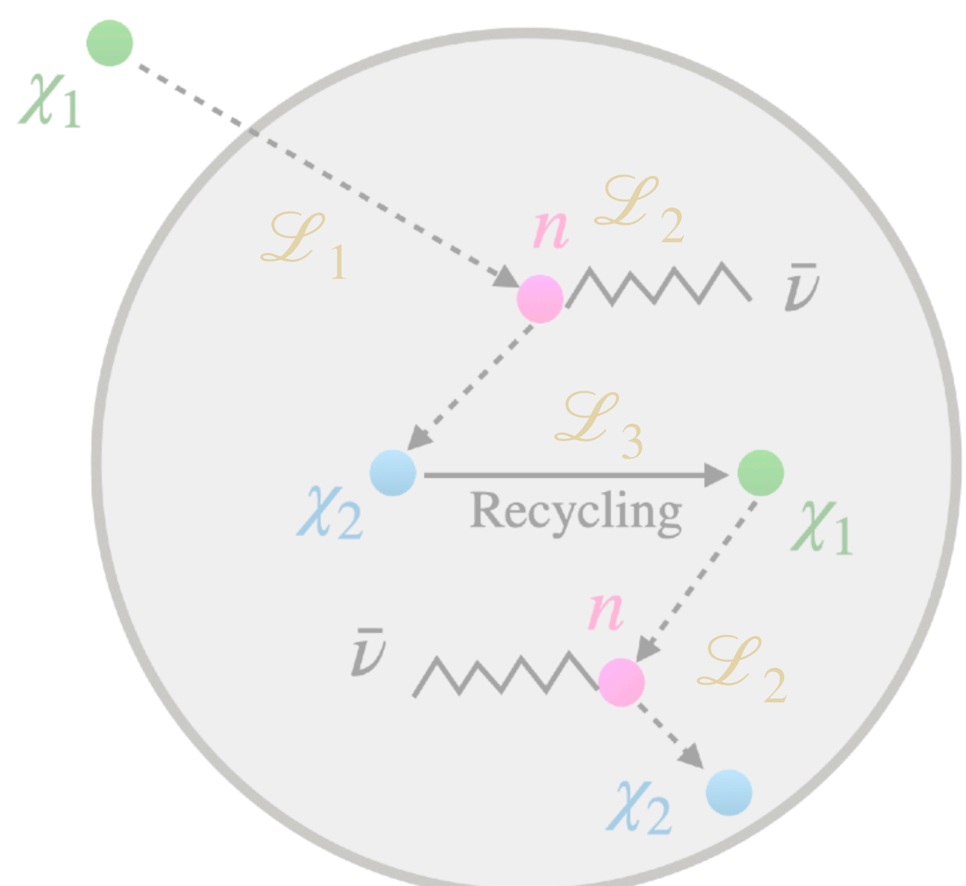
Toy model

A toy model to realize the idea: three ingredients

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3$$

1. $\mathscr{L}_1 = G_\chi(\bar{\chi}_1\gamma^\mu\chi_1 + \bar{\chi}_2\gamma^\mu\chi_2) \times (\bar{p}\gamma_\mu p + \bar{n}\gamma_\mu n)$: χ_i captured by neutron stars.
2. $\mathscr{L}_2 = G_{\rm BNV}\bar{\chi}_2\gamma^\mu\chi_1 \times \left(\bar{e}^c\gamma^\mu p + \bar{\nu}^c\gamma^\mu n\right) + ({\rm h.c.})$: Baryon destruction by χ_1.
3. $\mathscr{L}_3 = -\frac{\Delta m_\chi}{2}\bar{\chi}_2\chi_1 + ({\rm h.c.})$: "Recycle" $\chi_2 \to \chi_1$ through oscillation.

(BNV without external χ_i only when $\Delta m_\chi \neq 0$)



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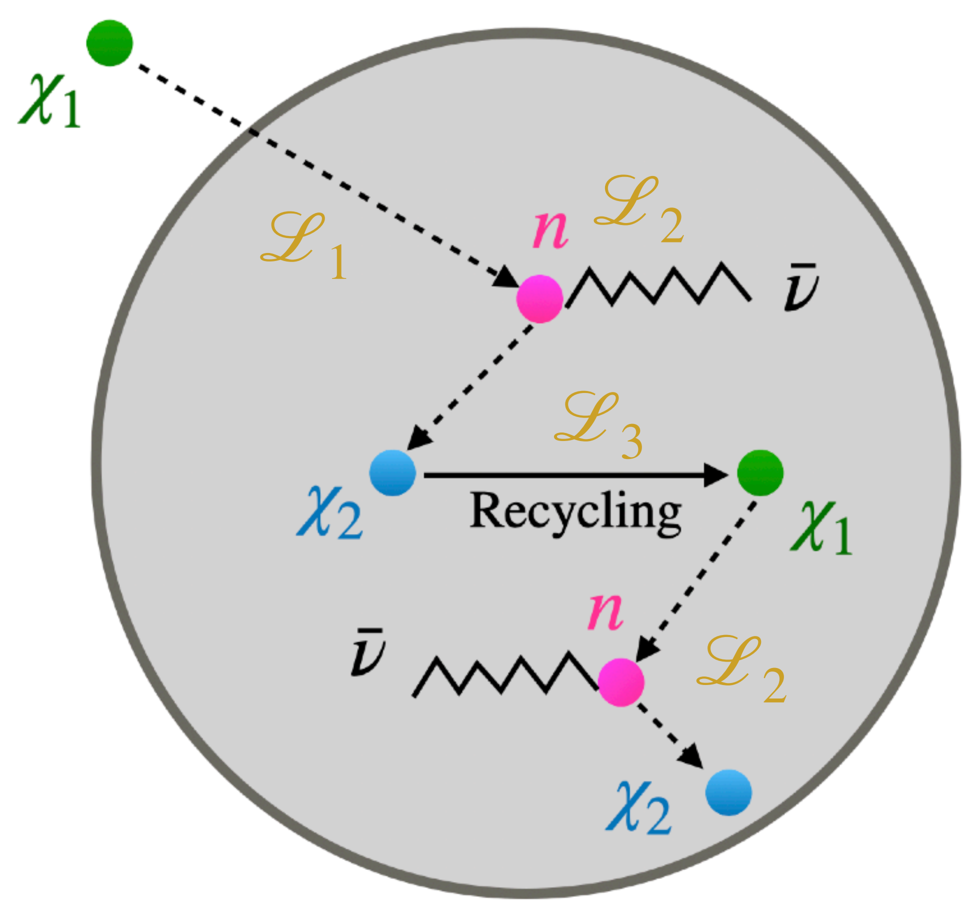

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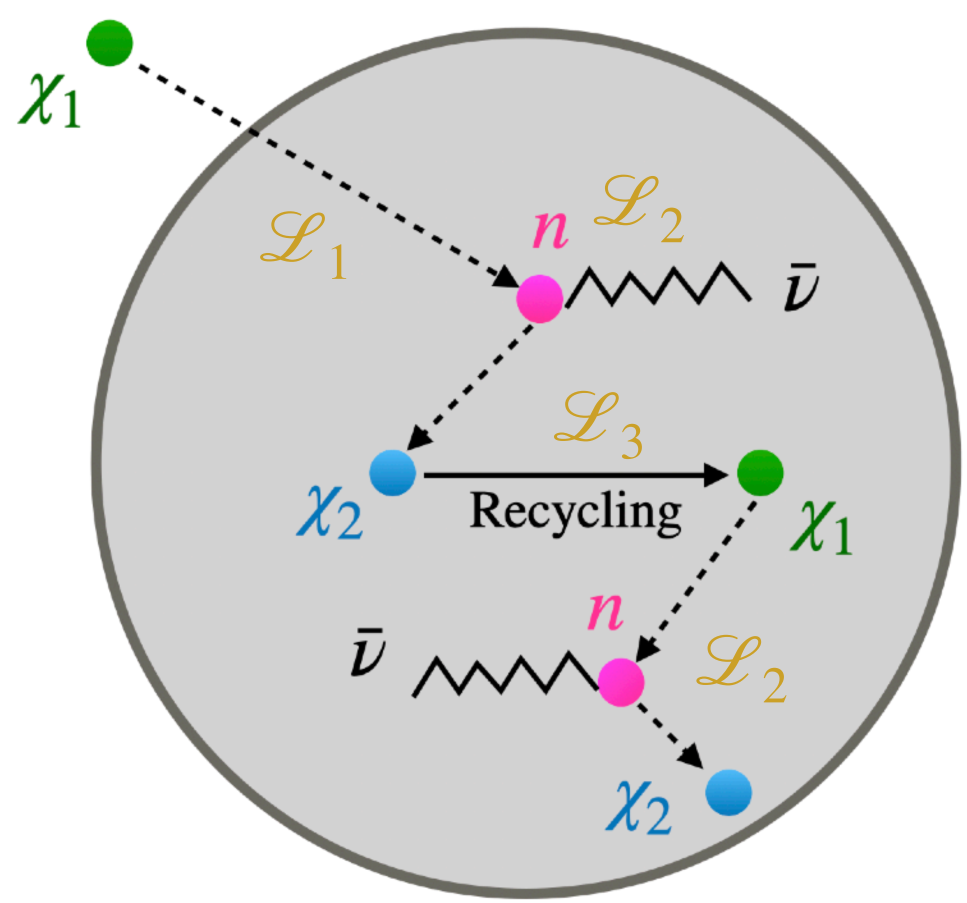

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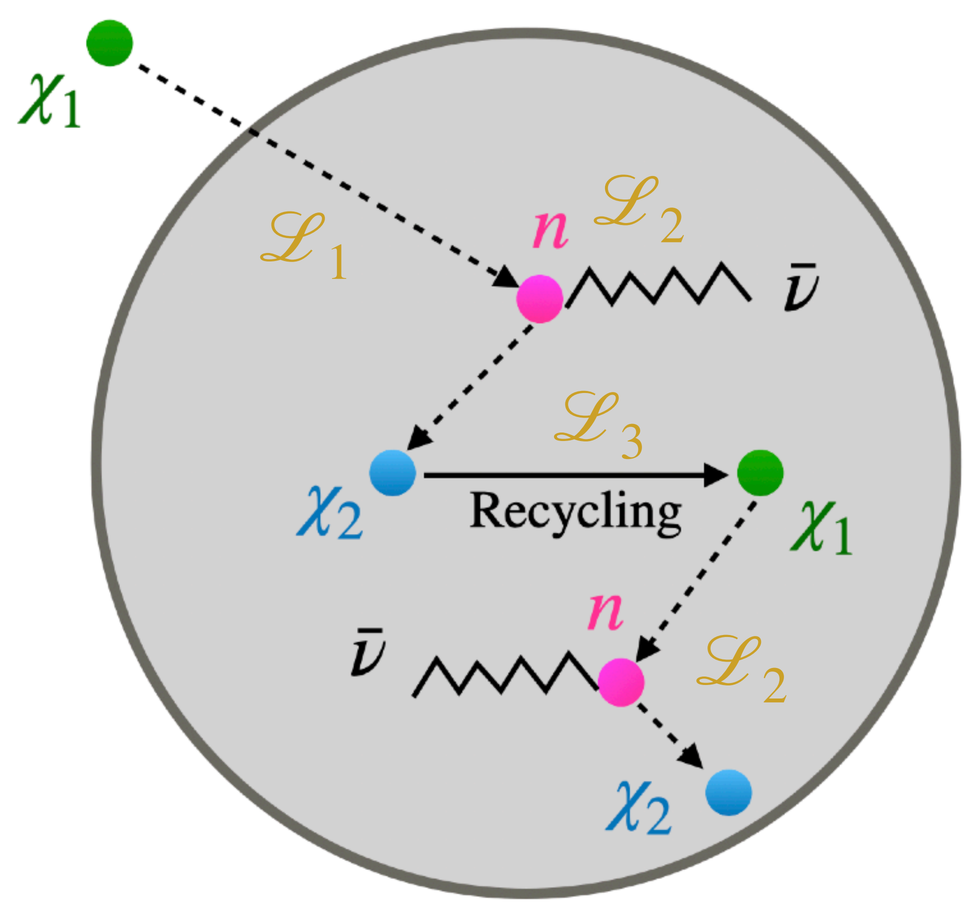

Catalyzed decay inside Super-K

- Assuming χ is DM, it catalyzes baryons inside Super-K

See e.g. [Davoudiasl+ 10, 11; Demidov and Gorbunov 15]

$$\begin{cases} \chi_1 + p \to \chi_2 + e^+, \\ \chi_1 + p \to \chi_2 + e^+ + (1,\cdots,6)\pi^0 . \end{cases}$$

Rate: $R_{\rm SK} = \dfrac{\rho_\chi}{m_\chi} \times \sigma_{\rm BNV} v \times N_p^{\rm SK} \sim 8 \times 10^{-4}\,{\rm day}^{-1} \times \left(\dfrac{100\,{\rm GeV}}{m_\chi}\right)\left(\dfrac{\sigma_{\rm BNV} v}{10^{-50}\,{\rm cm}^2}\right)$

- First process mimics atmospheric $\nu_e + \bar{\nu}_e$ with the rate $\sim 2\,{\rm events/day}$.

[SK collaboration 15]

- Second processes have a better handle due to γ (but with possible suppression)

$\Rightarrow$ $\sigma_{\rm BNV} v \lesssim 10^{-48}\,{\rm cm}^2 \left(\dfrac{m_\chi}{100\,{\rm GeV}}\right)$ expected from SuperK.

But NS heating by captured DM can be much more stringent.

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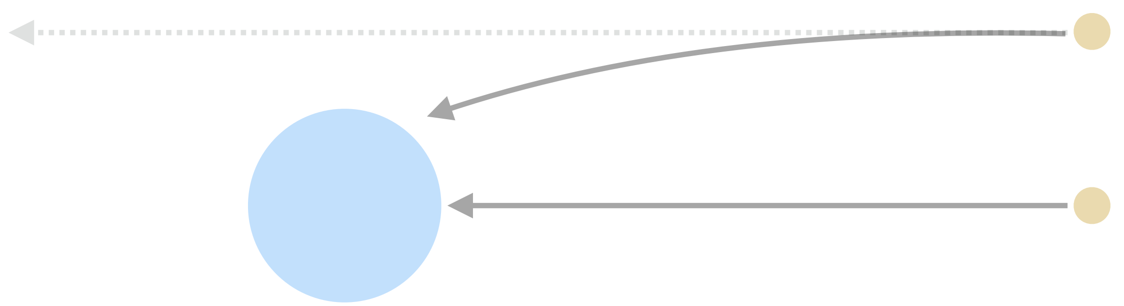
DM capture by neutron star

NS is an efficient DM captor due to gravity: $v_{\rm esc} \sim 0.6\, c$.

- Gravitational focusing: $\Phi_\chi \propto v_{\rm esc}^2 \propto 1/R_\star \rightarrow 10^5$ more DM passing through than the sun.



- Accelerated and one scattering sufficient to lose enough energy (for $m_\chi \lesssim 10^6\,{\rm GeV}$)

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c.f. $N_n \sim 10^{57}$ inside NS.

(A more elaborated formula in [Bramante+ 17] used)

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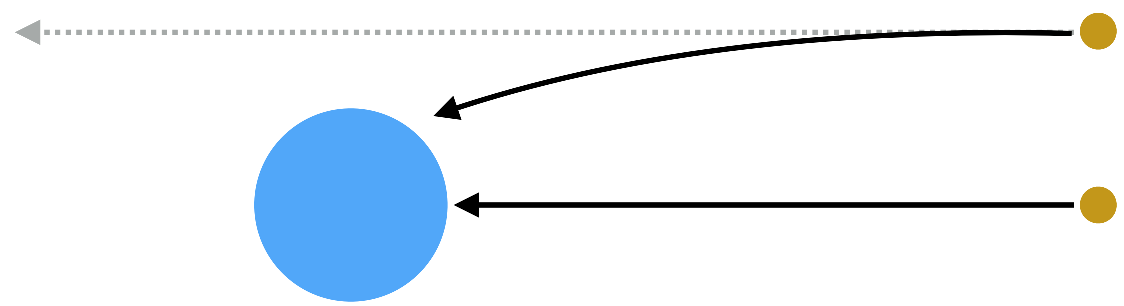

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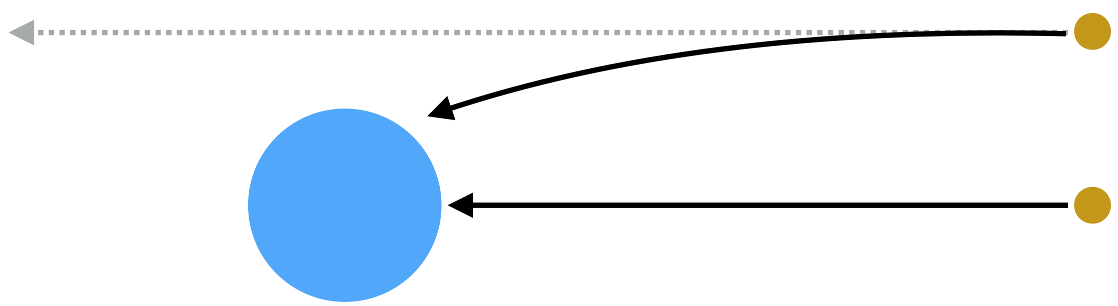

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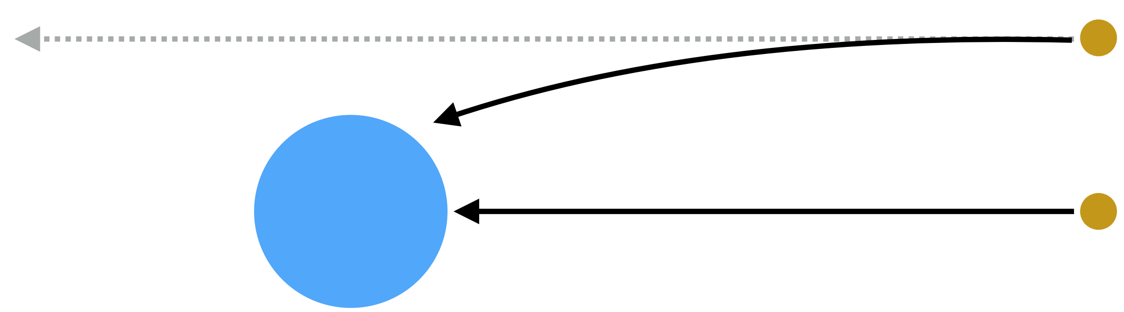

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Catalyzed heating of neutron star

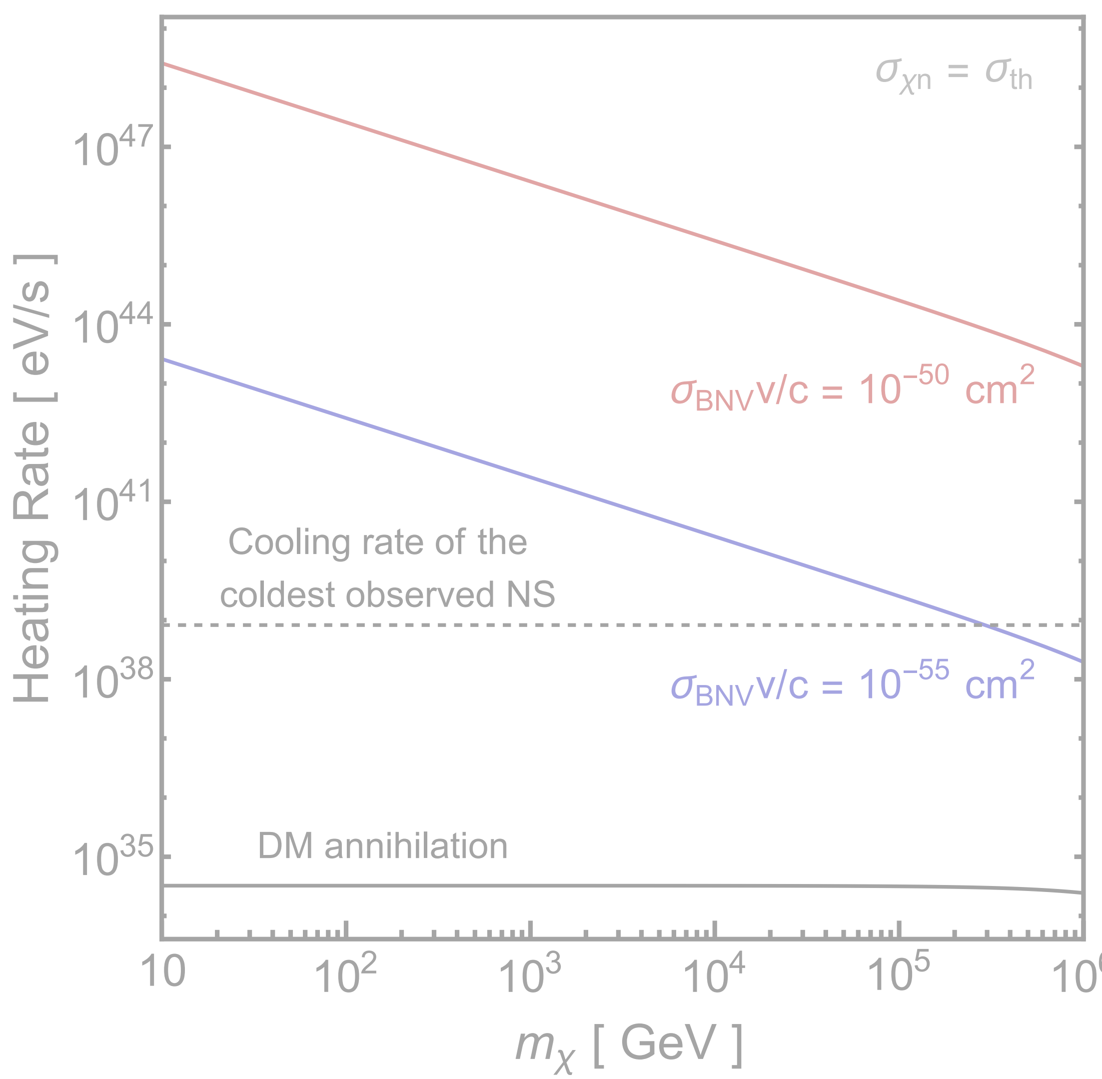
- Once captured, DM can catalyze baryon decay via BNV interaction.

$$\frac{dE_{\rm BNV}}{dt} = N_\chi \times \sigma_{\rm BNV} v \times n_n m_n \sim 10^{42} \frac{\rm eV}{\rm s} \left(\frac{100\,{\rm GeV}}{m_\chi} \right) \left(\frac{\sigma_{\rm BNV} v}{10^{-50}\,{\rm cm}^2} \right) \left(\frac{\sigma_{\chi n}}{10^{-50}\,{\rm cm}^2} \right)$$

- Emitted $\bar{\nu}$ has $\sim 1\,{\rm GeV} \to$ NS is opaque and energy consumed to heating up.

- Energy sourced by visible matter, more efficient than DM annihilation.

$$\frac{dE_{\rm ann}}{dt} \leq m_\chi \Phi_\chi \sim 3 \times 10^{34} \frac{\rm eV}{\rm s}\,.$$



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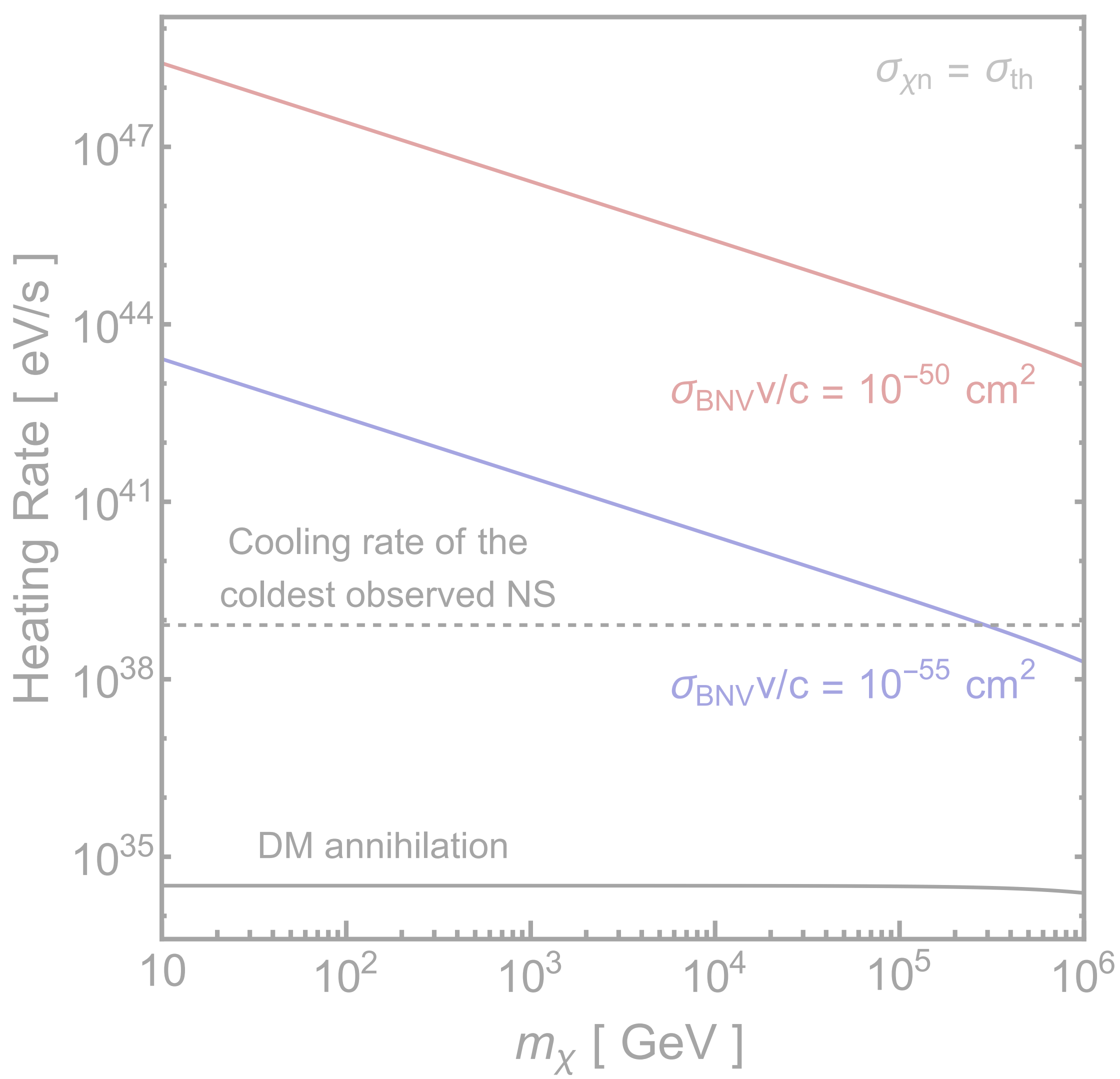

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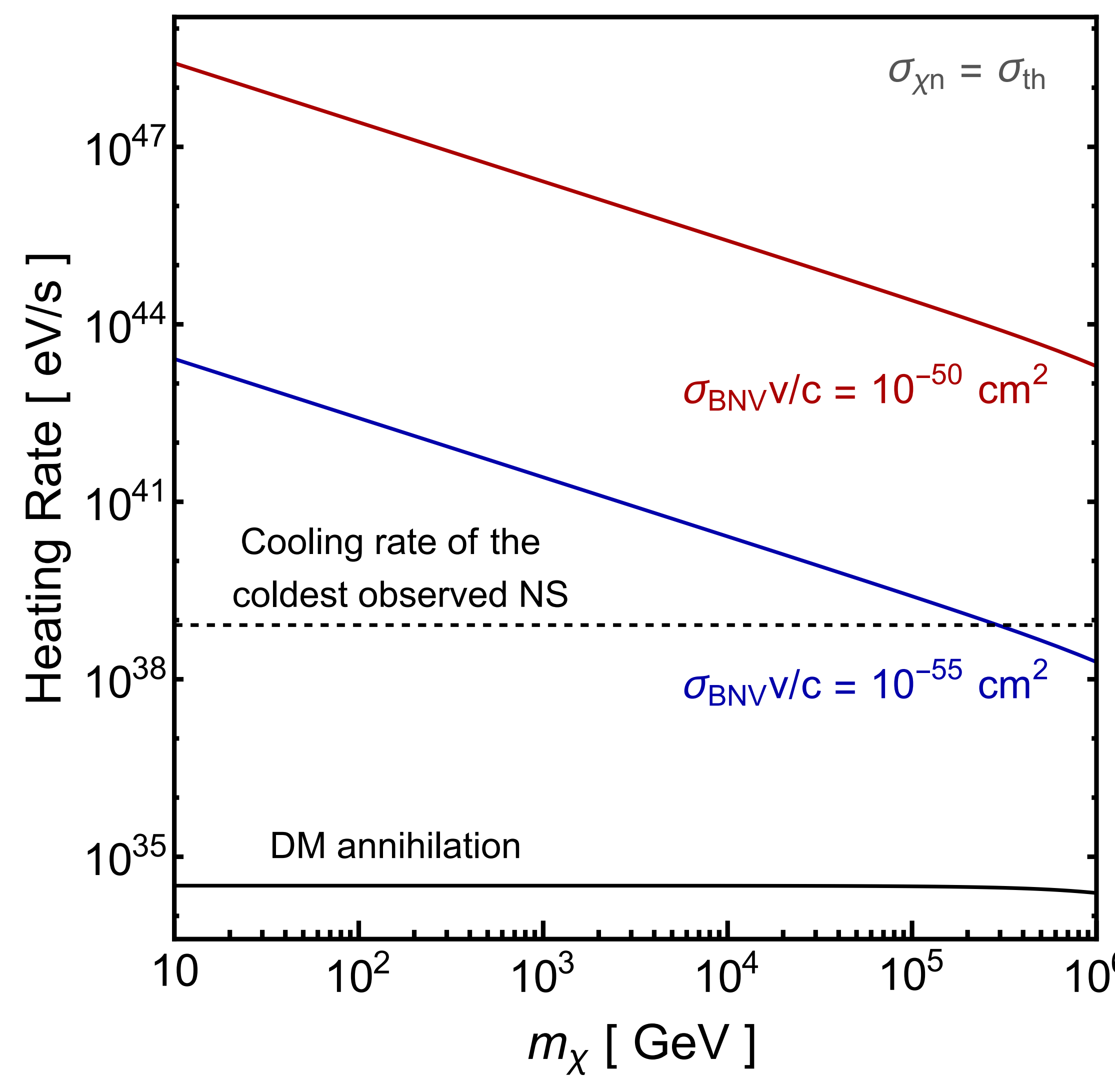
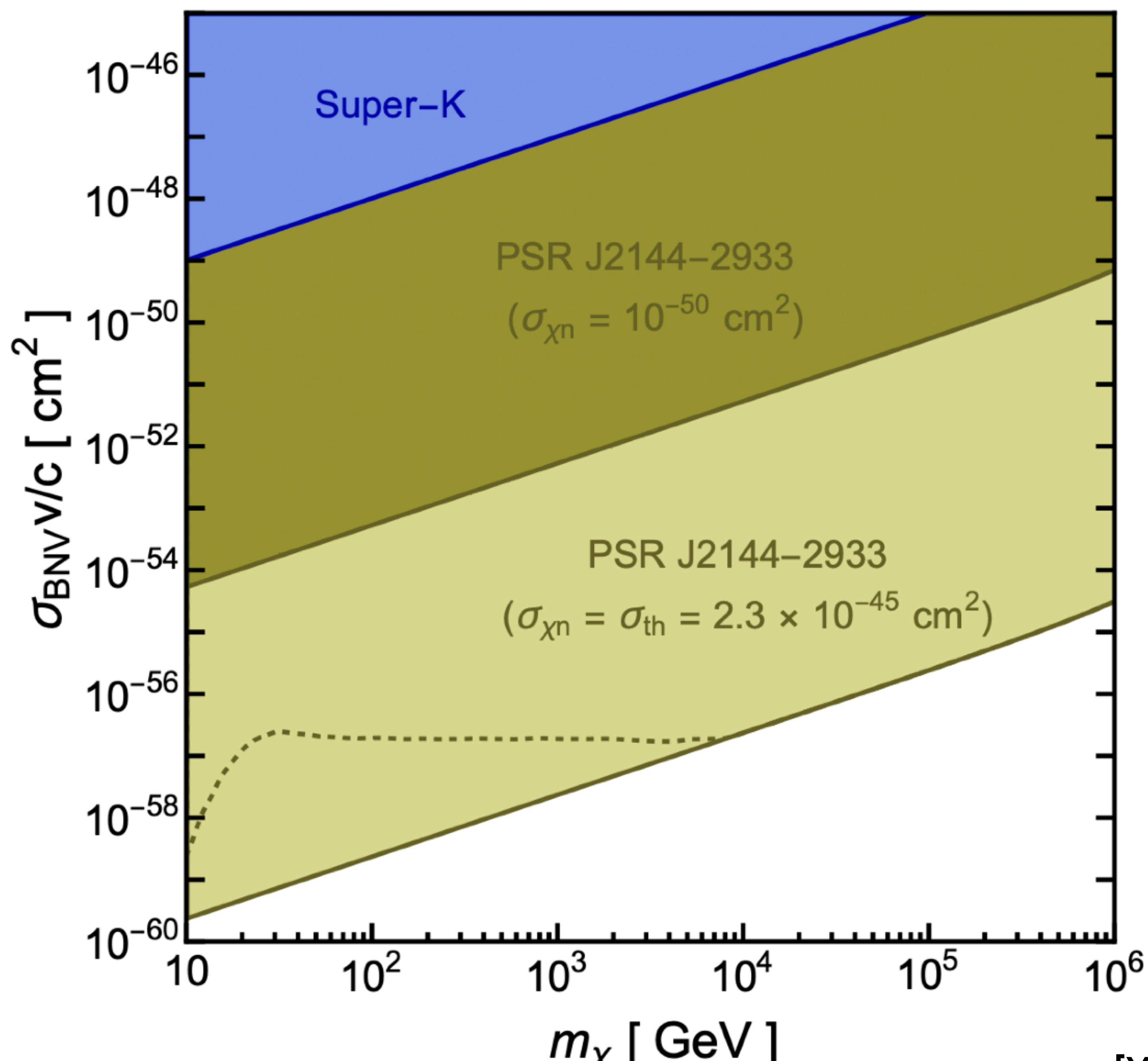


Sensitivity

- The coldest NS, PSR J2144-2933, has temperature $T_\star \leq 2.85\,\text{eV}$ [Guillot+ 19]

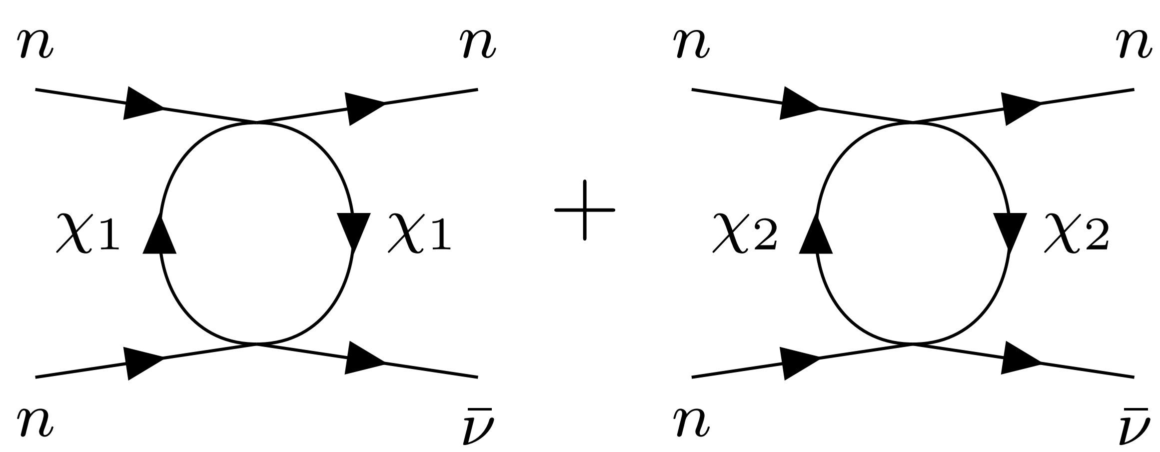
$$\text{Require } \frac{dE_\text{BNV}}{dt} < \frac{dE_\text{loss}}{dt} = 6.4 \times 10^{38}\frac{\text{eV}}{\text{s}}\left(\frac{R_\star}{11\,\text{km}}\right)^2\left(\frac{T_\star}{2.85\,\text{eV}}\right)^4$$



[YE, McGehee, Pospelov, Ray 24]

Di-nucleon decay $NN \to Ne/N\nu$

- Off-shell χ induces di-nucleon decay $NN \to Ne/N\nu$ through loop:



(in the mass basis)

$$\tau(nn \to n\bar{\nu}) \sim 10^{30}\,\mathrm{yrs} \times \left(\frac{m_\chi}{10^7\,\Delta m_\chi}\right)^2 \left(\frac{10^{-50}\,\mathrm{cm}^2}{\sigma_{\mathrm{BNV}} v}\right)\left(\frac{10^{-45}\,\mathrm{cm}^2}{\sigma_{\chi n}}\right)$$

Signal: nuclear de-excitation + $8\,\mathrm{MeV}\,\gamma$ by Gd capture of n ($?$)

- By requiring $\tau(nn \to n\bar{\nu}) > 1.4 \times 10^{30}\,\mathrm{yrs}$: bound on invisible n-decay,

[KamLAND collaboration 06]

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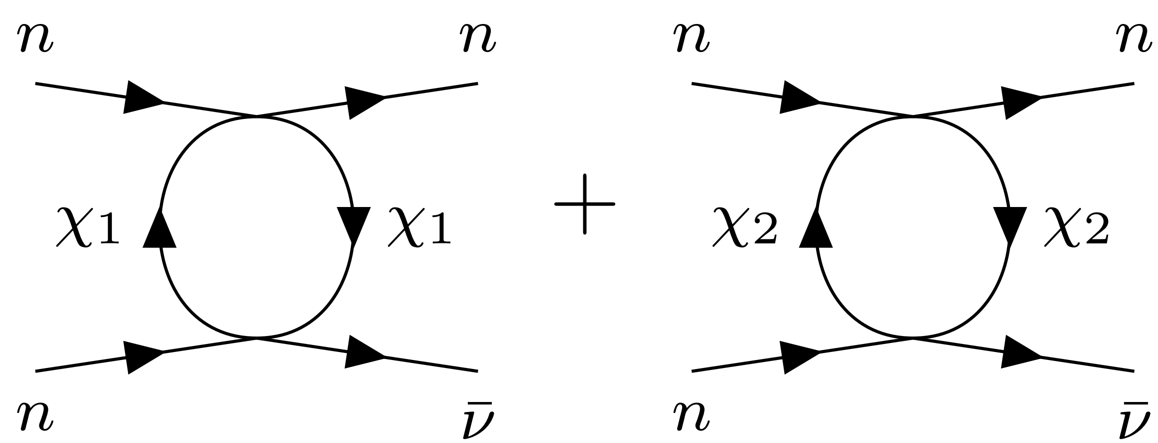

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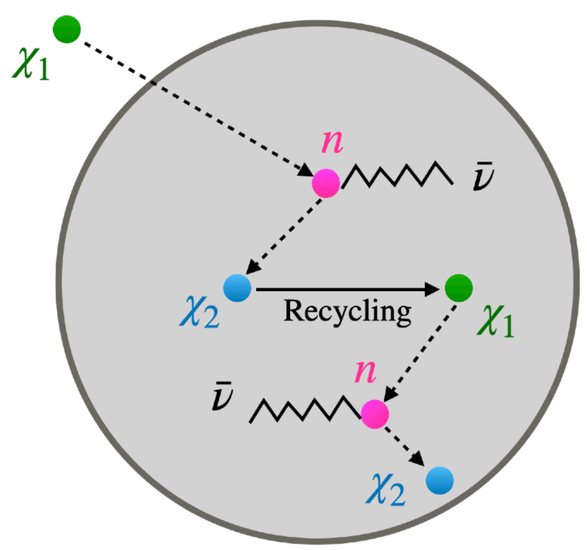
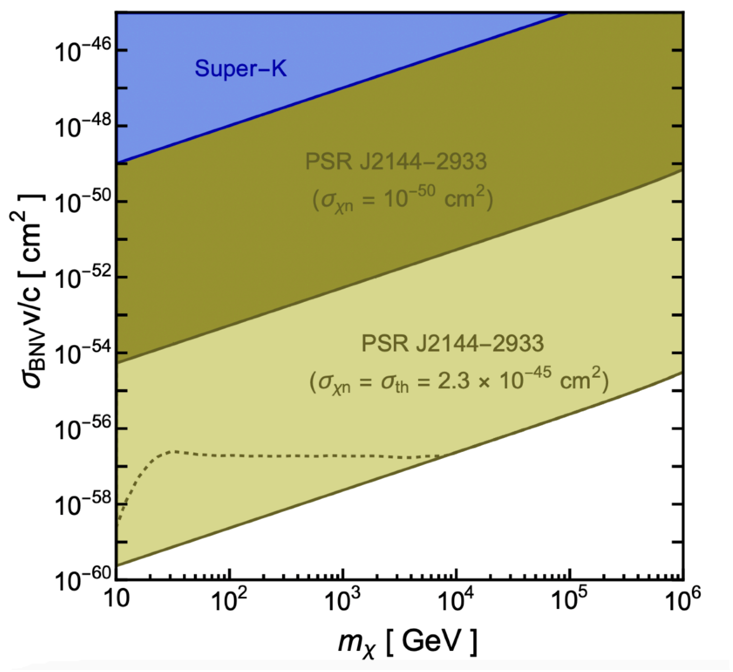
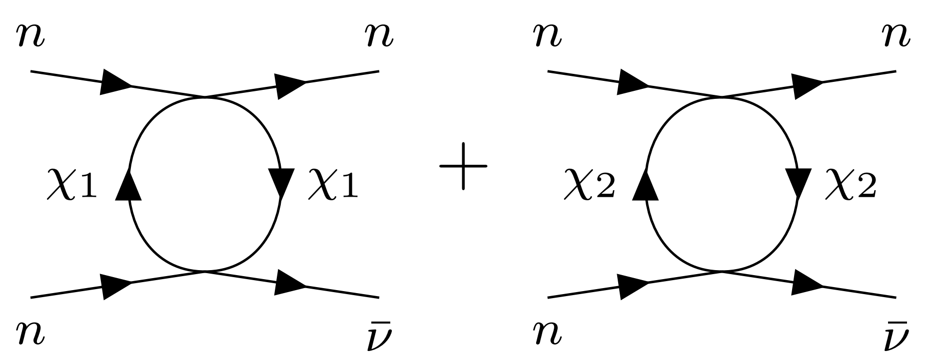
Summary

- Main question: pheno implication if DM induces BNV processes?
- DM catalyzes baryons inside SuperK.
- More interestingly, captured DM can catalyze neutrons and heat up NSs.
- Experimentally, di-nucleon decay $NN \to Ne/N\nu$ may be interesting to look at.







Backup

DM direct detection constraint

[LZ 2022]