Nucleon - Light Dark Matter Annihilation through Baryon Number Violation

Mingjie Jin (金明杰)

IHEP

collaborated with Yu Gao (高宇)

base on arXiv:1808.10644

November 11, 2018

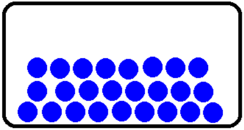
Outline

Background

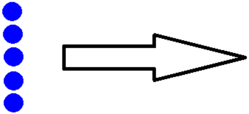
Neutron decay (β decay):

$$n \to p + e^- + \bar{\nu}_e$$

Two experiments: Bottle and beam



(Gravitational trap)



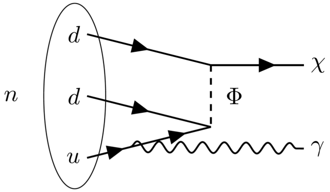
Counting: remaining neutrons | protons

$$\tau_{bottle} = 879.6 \pm 0.6 \text{ s} \qquad \tau_{beam} = 888.0 \pm 2.0 \text{ s}$$

$$\Delta\tau \approx 8s \ \ (\sim 1\%)$$

Background

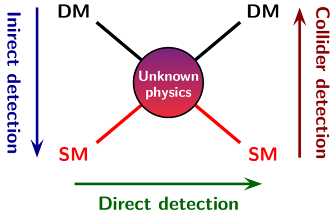
B. Fornal and B. Grinstein (arXiv:1801.01124) proposed:

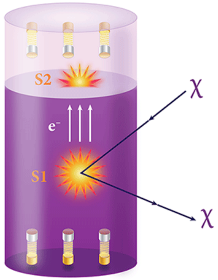


$$n \to \chi + \gamma \quad (\sim 1\%)$$

$$0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV}$$

Background


DM
DM
Unknown physics
SM
SM
Inirect detection
Collider detection
Direct detection


S2
e^-
S1
χ
χ

Dark matter model

A color triplet, iso-singlet scalar Φ with $Y = -\frac{1}{3}$ or $+\frac{2}{3}$ and a fermionic dark matter (DM) χ

$$\begin{aligned} \mathcal{L}_1 &= \lambda_1 \Phi^* \chi d_R + \lambda_1' \Phi u_R d_R + m_\Phi^2 |\Phi|^2 + \frac{1}{2} m_\chi \bar{\chi}^c \chi + \text{c.c.} \qquad \textbf{(I)} \\ \mathcal{L}_2 &= \lambda_2 \Phi^* \chi u_R + \lambda_{2ij}' \Phi d_{Ri} d_{Rj} + m_\Phi^2 |\Phi|^2 + \frac{1}{2} m_\chi \bar{\chi}^c \chi + \text{c.c.} \qquad \textbf{(II)} \end{aligned}$$

In model II, two down-type quarks in the second term must be different flavor due to antisymmetric color indices. Here DM is Majorana or Dirac fermion.

$\chi - n$ mixing

If the scalar $m_\Phi \gg \mathcal{O}(\text{TeV})$ and $m_\chi \sim \mathcal{O}(GeV)$,

$$\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d_R),$$

where $\beta_{udd} \approx 0.0144$ GeV^3 ($\sim \Lambda_{QCD}^3$) from LQCD (only 1st gen.).(Aoki et al. 1705.01338).

Obviously, the (anti-) dark matter (χ) mixes with neutron (udd).

DM Mass region

- If $m_\chi > m_p + m_e$, DM decay

$$\begin{aligned} \chi &\rightarrow p + e^- + \bar{\nu}_e \\ &\rightarrow \bar{p} + e^+ + \nu_e \end{aligned}$$

- If $m_\chi < m_p - m_e$, Proton decay

$$p \rightarrow \chi + e^+ + \nu_e$$

Thus,

$$m_p - m_e < m_\chi < m_p + m_e$$

Mixing angle θ

The Lagrangian

$$\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d_R)$$

Define the mixing parameter

$$\varepsilon = \frac{\beta\lambda'\lambda}{m_\Phi^2}$$

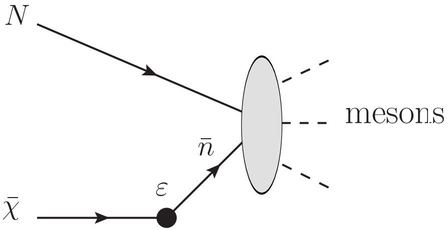
The mixing angle θ in mass eigenstate basis when $\varepsilon \ll m_n - m_\chi$

$$\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$$

where $\beta_{udd} \approx 0.0144$ GeV^3, $m_n \approx 0.94$ GeV and assume $\lambda, \lambda' \sim \mathcal{O}(1)$.
Note the Min$(\lambda, \lambda') \sim \mathcal{O}(0.07)$ at $m_\Phi \sim \mathcal{O}$(TeV) from collider constraint.

Nucleon - Dark matter Annihilation

The nucleon - DM annihilation cross section $\sigma_{N\chi}$,



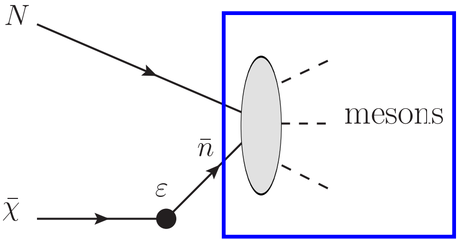
$$\sigma_{N\chi} = \theta^2 \sigma_{N\bar{n}}$$

$$\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$$

The $\sigma_{N\bar{n}}$ is the annihilation cross section of nucleon - antineutron, fixed by experimental data.

Nucleon - Dark matter Annihilation

The nucleon - DM annihilation cross section $\sigma_{N\chi}$,



$$\sigma_{N\chi} = \theta^2 \sigma_{N\bar{n}}$$

$$\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$$

The $\sigma_{N\bar{n}}$ is the annihilation cross section of nucleon - antineutron, fixed by experimental data.

$\bar{n} - p$ Annihilation

The $\bar{n} - p$ annihilation cross section at low energy,

$$\sigma_{p\bar{n}}^{ann}(\mathrm{mb}) = a + b/P_{\bar{n}}(\mathrm{GeV})$$

where a, b are fixed by data.

At low energy,

- s-wave is the most dominant contribution for $\sigma_{p\bar{n}}^{ann}$
- $\sigma_{p\bar{n}}^{ann} \propto v^{-1}$ if only s-wave
- $\sigma v(P_{\bar{n}} = 0) = 44 \pm 3.5$ mb when $v \to 0$ (Mutchler et al.PRD38, 742)

$\bar{n} - A$ annihilation

Besides, $\sigma^{ann}_{\bar{n}A}$ with six different nuclei (C, Al, Cu, Ag, Sn and Pb targets)

$$\sigma(P_{\bar{n}}, A) = \sigma_0(P_{\bar{n}})A^{2/3}, \quad (r = r_0 A^{1/3})$$

where A is atomic number and $\sigma_0(P_{\bar{n}})$ is antineutron $-$ nucleon cross section.

$$\sigma_0 = \alpha\sigma_{p\bar{n}}(P_{\bar{n}}) + (1-\alpha)\sigma_{n\bar{n}}(P_{\bar{n}})$$

where $\alpha = Z/A$, Z is proton number.

For α= 0.5 (carbon) and 0.4 (lead), the cross section σ_0 is insensitive to α. (Astrua et al. Nucl. Phys. A697, 209)

$\bar{n} - A$ annihilation

Therefore,

$$\sigma_0(P_{\bar{n}}) \simeq \sigma_{p\bar{n}}(P_{\bar{n}}) \approx \sigma_{n\bar{n}}(P_{\bar{n}})$$

Then the annihilation cross section for dark matter and nucleon (nucleus)

$$\begin{aligned}
\sigma_{\chi N} v_\chi &\approx 44 \times \frac{(\beta\lambda'\lambda)^2}{m_\Phi^4 (m_n - m_\chi)^2} \\
\sigma_{\chi A} v_\chi &\approx 44 \times \frac{(\beta\lambda'\lambda)^2 A^{2/3}}{m_\Phi^4 (m_n - m_\chi)^2}
\end{aligned}$$

Constraint

Due to same final state, the constraint from n-$\bar{n}$ oscillation search at Super Kamiokande (SK) or SNO.

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

Table: The branching ratios for the $\bar{n}$+nucleon annihilations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data.(SK,1109.4227)

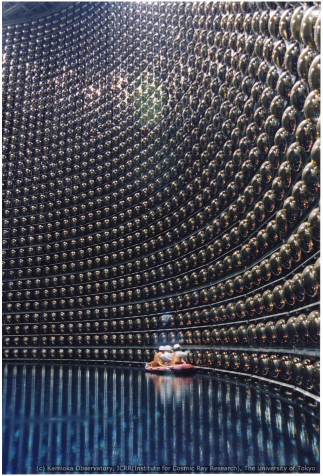


Figure: SK (from SK homepage)

Constraint

In SK, the dark matter can annihilate with proton and oxygen nucleus.

The corresponding event rate,

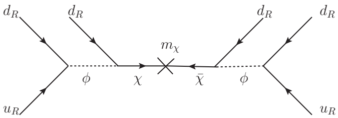
$$R = \frac{\mathrm{d}N_\mathrm{t}}{\mathrm{d}t} = A_{eff}\phi_\chi = \eta N_\mathrm{t} n_\chi \sigma_{\chi\mathrm{t}} v_\chi$$

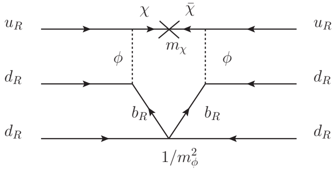
where the effective area of target $A_{eff} = \eta\sigma_{\chi\mathrm{t}} N_\mathrm{t}$ and the flux density $\phi_\chi = n_\chi v_\chi$. $\eta = 12.1\%$, $n_\chi \simeq 0.43\,\mathrm{cm}^{-3}$, $N_p \simeq 6.13\times 10^{33}$, $N_\mathrm{o} \simeq 3.06\times 10^{33}$ (SK, 1109.4227). Here 22.5 kton water during 1489 live-day.

Comparison: n-$\bar{n}$ oscillation

If the dark matter is the Majorana fermion, $\mathcal{L} \supset \frac{\beta\lambda'\lambda}{m_\Phi^2}(\chi u_R d_R d'_R)$ is $\Delta B = 1$ operater, it generates n-$\bar{n}$ oscillation.

Only know about $\beta_{udd} = 0.0144\mathrm{GeV}^3$(1st gen.).





1st gen. (McKeen et al. 1512.05359) 3rd gen. (Dutta et al. 1712.0271)

n-$\bar{n}$ oscillation

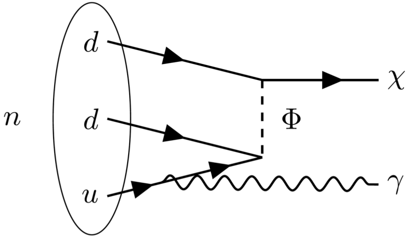
The n-$\bar{n}$ oscillation time

$$\tau_{n\bar{n}} \simeq \begin{cases} \left(\frac{\beta^2 \lambda_2'^2 \lambda_2^2 m_\chi}{m_\Phi^4 (m_n^2 - m_\chi^2)}\right)^{-1} & \text{(1st gen.)} \\ \\ \left(\frac{\lambda_1'^4 \lambda_1^2 m_\chi \ln\left(m_\Phi^2 / m_\chi^2\right) \Lambda_{QCD}^6}{(16\pi^2 m_\Phi^6)}\right)^{-1} & \text{(3rd gen.)} \end{cases}$$

where $\tau_{n\bar{n}} > 2.7 \times 10^8$ s (SK) and $\Lambda_{QCD}^6 = \beta^2 \sim \mathcal{O}(10^{-4})$ GeV^6 (S. Rao, R. E. Shrock, Nucl. Phys. B232).

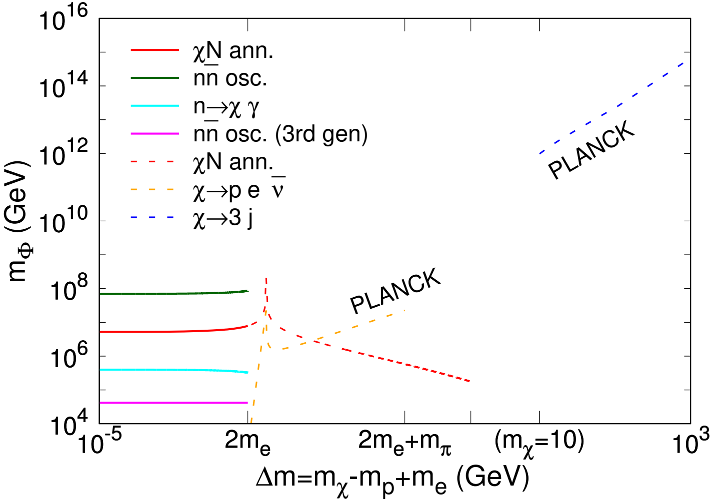
Comparison: Neutron decay

Since $m_\chi < m_n$, adding neutron magnetic moment $\bar{n}\sigma^{\mu\nu} n F_{\mu\nu}$



$$\frac{\varepsilon}{m_n - m_\chi} \bar{\chi}\sigma^{\mu\nu} F_{\mu\nu} n$$

$m_\Phi - \Delta m$ limits



$\chi - N$ annihilation: $m_\Phi \sim \mathcal{O}(10^7)$GeV, Majorana & Dirac fermion.

Dark matter decay

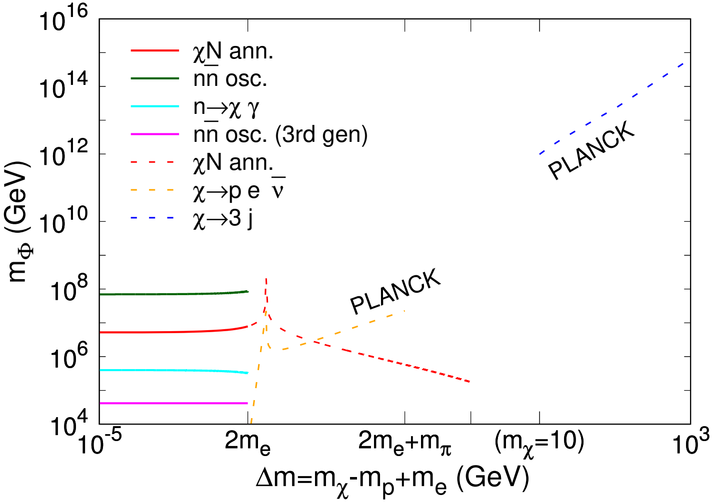
If $m_\chi > m_p + m_e$,

$$\begin{array}{lll} \chi & \rightarrow & p + e^{-} + \bar{\nu} \quad (m_p + m_e < m_\chi < m_p + m_e + m_\pi) \\ \chi & \rightarrow & 3 \text{ jets} \quad (m_\chi > 10\,\text{GeV}) \quad (b - \text{quark}) \end{array}$$

where $\tau_\chi = 10^{24}$ s from PLANCK with $\mathrm{e}^+\mathrm{e}^-$ and $\mathrm{b}\bar{\mathrm{b}}$ channels. (Slatyer et al. 1610.06933)

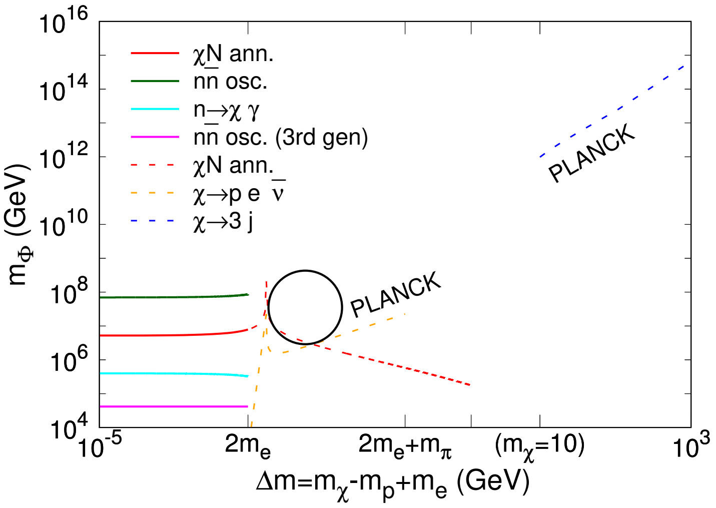
In addition, the mixing angle $\theta = \frac{\beta\lambda'\lambda}{m_\Phi^2(m_n - m_\chi)}$ and there exits a pole in mixing angle when $m_\chi = m_n$.

$m_\Phi - \Delta m$ limits



$\chi - N$ annihilation: $m_\Phi \sim \mathcal{O}(10^7)$GeV, Majorana & Dirac fermion.

$m_\Phi - \Delta m$ limits



$\chi - N$ annihilation: $m_\Phi \sim \mathcal{O}(10^7)$GeV, Majorana & Dirac fermion.

Alternative searches-Indirect detection

- The DM annihilates with hydrogen and helium of ISM (Interstellar medium).

- The differential γ-flux,

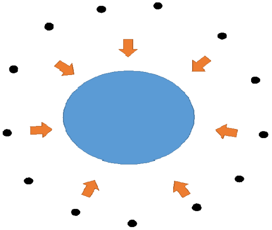
$$\frac{\mathrm{d}\phi_\gamma(\chi N)}{\mathrm{d}E\mathrm{d}\Omega} = \theta^2 \frac{\langle v\sigma_{\chi N}\rangle}{8\pi m_\chi m_N} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \int_{\mathrm{los}} \rho_\chi \rho_B \mathrm{d}s$$

$$\frac{\mathrm{d}\phi_\gamma(\chi\chi)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\langle v\sigma_{\chi\chi}\rangle}{8\pi m_\chi^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \int_{\mathrm{los}} \rho_\chi^2 \mathrm{d}s$$

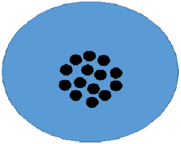
- ρ_B smaller than ρ_χ two orders of magnitude.

- The $\theta^2\langle\sigma v\rangle(\pi^0)_{\gamma\gamma} \sim \mathcal{O}(10^{-41})\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_\Phi \sim \mathcal{O}(10^7)$ GeV , while $\langle\sigma v\rangle(\chi\bar{\chi})_{\gamma\gamma} \geq 10^{-30}\,\mathrm{cm}^3\mathrm{s}^{-1}$ from Fermi-LAT, thus it is impossible to detect the signal from $\chi - N$ annihilation at present.

Alternative searches-Neutron star (NS) heating



(a) DM elastically scatter off neutron in NS.



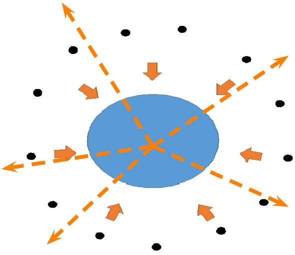
(b) DM annihilation in NS.

Total Energy: $E_t \approx 1.35 m_\chi$, at saturation(100%), when heating $\leftrightarrow$ radiation

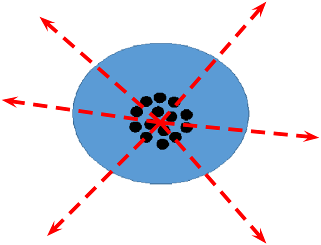
T=1750 K

T=2480 K

Alternative searches-Neutron star (NS) heating



(c) DM elastically scatter off neutron in NS.



(d) DM annihilation in NS.

Total Energy: $E_t \approx 1.35 m_\chi$, at saturation(100%), when heating $\leftrightarrow$ radiation

T=1750 K

T=2480 K

Alternative searches-Neutron star (NS) heating

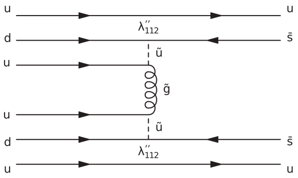
- The DM annihilates with neutron in NS, $E_t \sim 2.2$ GeV.
- For an typical old NS, $M = 1.5 M_\odot$, $R = 10\,\mathrm{km}$.
- The heating rate: $\dot{E} = E_t \dot{N} f$, where $\dot{N} = \pi b^2 v_\chi n_\chi$ is the number rate of dark matter flux, f is the capture efficiency, $f = \min\left[\sigma_{\chi N}/\sigma_{th}, 1\right]$.
- The NS luminosity is $L = \dot{E} = 4\pi\sigma_B R^2 (T/\sqrt{1 - 2GM/R})^4$.
- For relativistic DM, $\sigma^{ann}_{\chi n} \approx \theta^2 (38.0 + 35.0/P_{\bar{n}}(\mathrm{GeV}))$, $P_{\bar{n}} \approx 0.85\mathrm{GeV}$.
- When DM heating $\leftrightarrow$ black-body radiation, at $m_\Phi \sim \mathcal{O}(10^7)$ GeV, surface temperature $T_s \simeq 134$ K.
- For a distant observer, $T_o \simeq 100$ K due to gravitational redshift, and is below the current experimental sensitivities.

$\Lambda - \bar{\Lambda}$ oscillation search @ BES-III

- The $\Lambda - \bar{\Lambda}$ oscillation time at BES-III($10 \times 10^9 J/\Psi$ and $3 \times 10^9 \Psi(2S)$) (X. W. Kang et al. 0906.0230)

$$\tau_{\Lambda-\bar{\Lambda}} > 10^{-6}\ \mathrm{s} \qquad (\Lambda = uds)$$

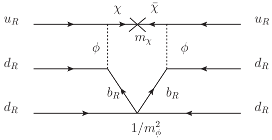
- The $\Lambda - \bar{\Lambda}$ oscillation is $\Delta s = 2$ process. $pp \to K^+K^+$ search in $^{16}\mathrm{O} \to ^{14}\mathrm{C}K^+K^+$ at SK, $\Lambda - \bar{\Lambda}$ oscillation times (at tree level)(K. Aitken et al. 1708.01259)



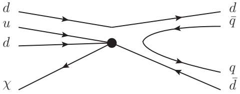
$$\tau_{\Lambda-\bar{\Lambda}} > \mathcal{O}(10^6)\ \mathrm{s}$$

where $\beta_{uds} \sim 10^{-2}$.

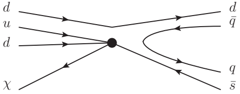
s/b quark contribution



$\Delta b = 2$ at loop-level



(e) $n + \chi \to \pi + \pi$



(f) $n+\chi \to \pi+K \, (\Delta s = 1)$

$$\sigma_{\pi K} \sim \sigma_{\pi\pi}$$

Except K, π mass difference in the final state. $m_\Phi \sim \mathcal{O}(10^{6-7})$ GeV for $\Delta s = 1$ operator.

Summary

- DM can directly annihilate with baryons through BNV. Assuming color-triplet, iso-singlet scalar(s) and a fermionic dark matter (Majorama or Dirac).
- From the $n - \bar{n}$ oscillation at the SuperK experiment, we constrain the stringent limit m_Φ up to 10^7 GeV.
- For Majorana-DM, the constraint is one order in magnitude lower than $n - \bar{n}$ oscillation.
- In the Dirac case, DM - nucleon annihilation gives much stronger bounds than neutron decay ($n \to \chi + \gamma$).
- In DM decay($m_\chi > m_p + m_e$), the SuperK bounds exceed that from DM stability (from PLANCK) at a small mass range.
- We also consider indirect detection, neutron star heating, which are significantly below the reach of current experiments at $m_\Phi \sim 10^7$ GeV.

Summary

- DM can directly annihilate with baryons through BNV. Assuming color-triplet, iso-singlet scalar(s) and a fermionic dark matter (Majorama or Dirac).
- From the $n - \bar{n}$ oscillation at the SuperK experiment, we constrain the stringent limit m_Φ up to 10^7 GeV.
- For Majorana-DM, the constraint is one order in magnitude lower than $n - \bar{n}$ oscillation.
- In the Dirac case, DM - nucleon annihilation gives much stronger bounds than neutron decay $(n \to \chi + \gamma)$.
- In DM decay($m_\chi > m_p + m_e$), the SuperK bounds exceed that from DM stability (from PLANCK) at a small mass range.
- We also consider indirect detection, neutron star heating, which are significantly below the reach of current experiments at $m_\Phi \sim 10^7$ GeV.

Thank you!