Heating Neutron Star with light Dark Matter

Po-Yan Tseng (Yonsei U.)

Collaborators:
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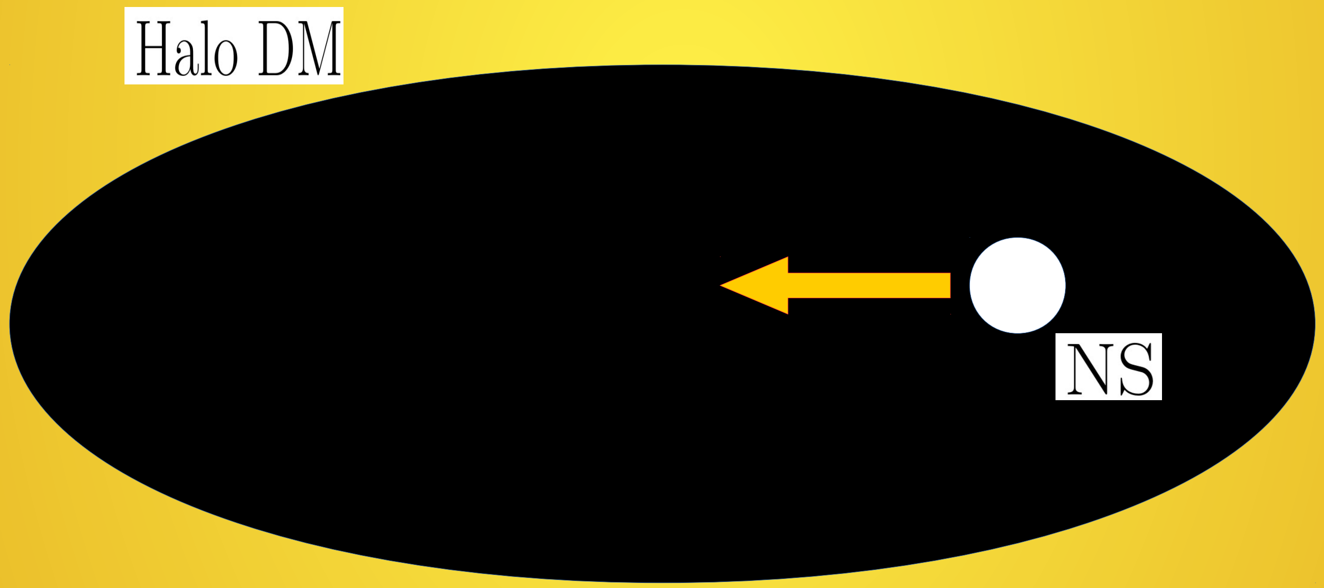
Danny Marfatia (U. of Hawaii, Manoa)

Reference: 1905.03401, JHEP09(2019)053,
work in progress: arXiv:2001......

Kavli IPMU, APEC seminar, 24 Jan. 2020

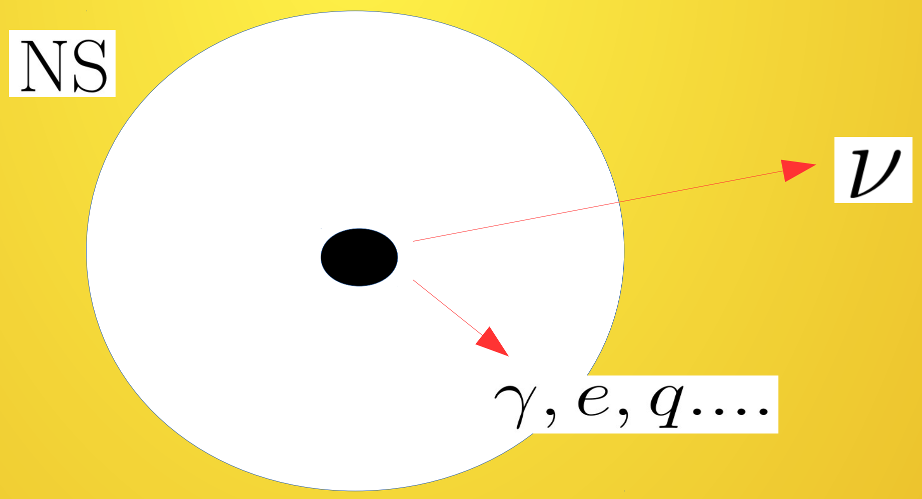
Introduction

- The **dark matter** be captured by **neutron star.**



Introduction

- What **DM** can do to **NS**, after be captured?
- After thermalization, **DM** accumulate at center of **NS**.
- DM-DM annihilate and emit neutrinos.

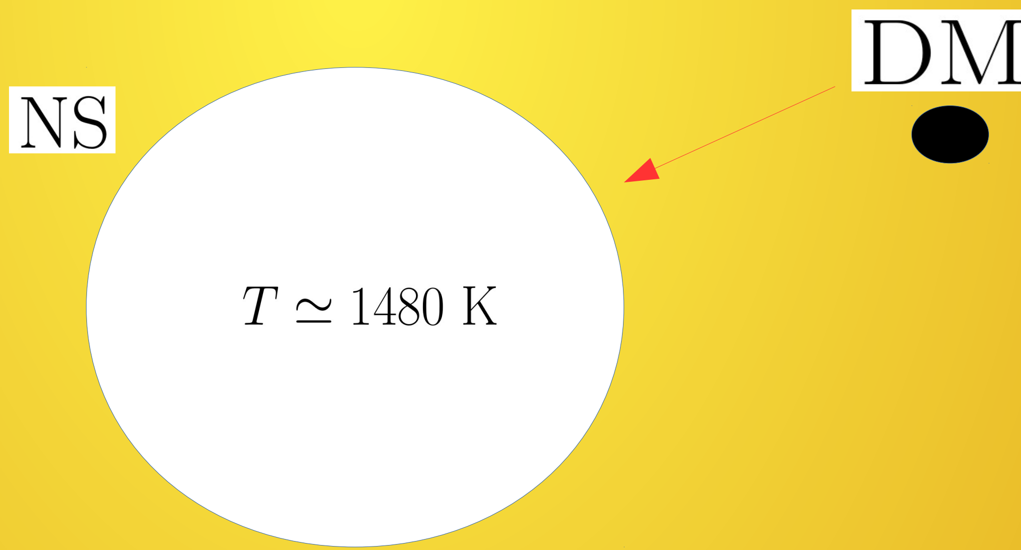


Introduction

- What **DM** can do to **NS**, after be captured?

- **DM** can kinematic heats **NS**, due to strong gravitational potential of **NS**, **DM** is accelerated to v~0.6 c.

$$\frac{1}{2} m_\chi v_{\rm esc}^2 = \frac{G M m_\chi}{R}$$



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- What **DM** can do to **NS**, after be captured?
- **DM** can kinematic heats **NS**, which increase **NS** temperature by **1480 K**.

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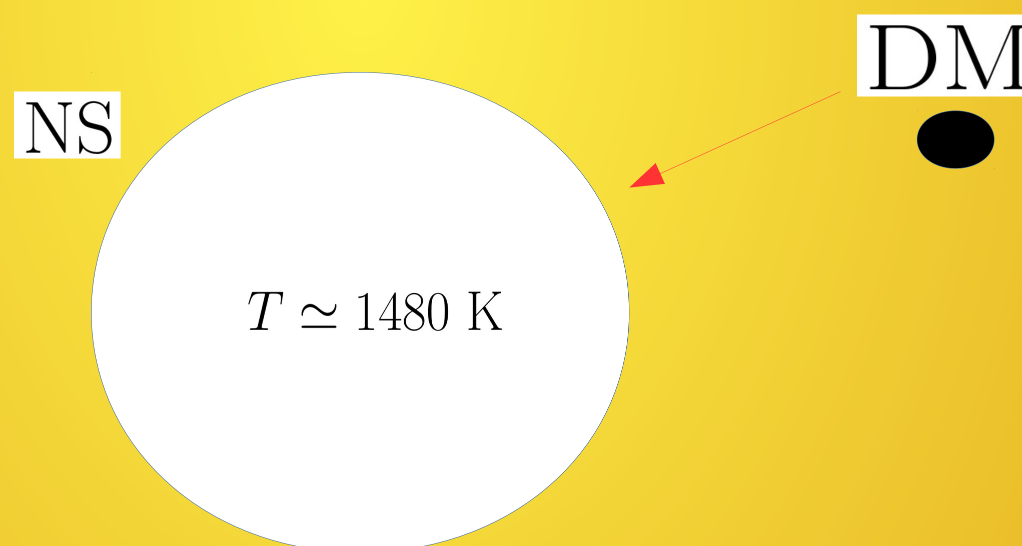

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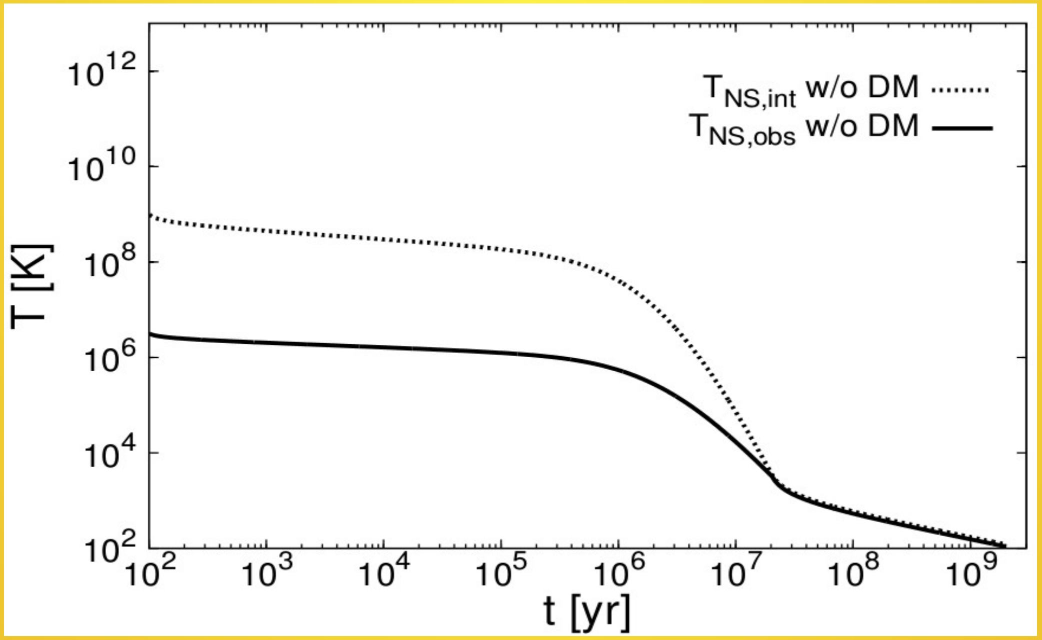

W.Y.Keung, D.Marfatia, P.Y.Tseng: 2001.......

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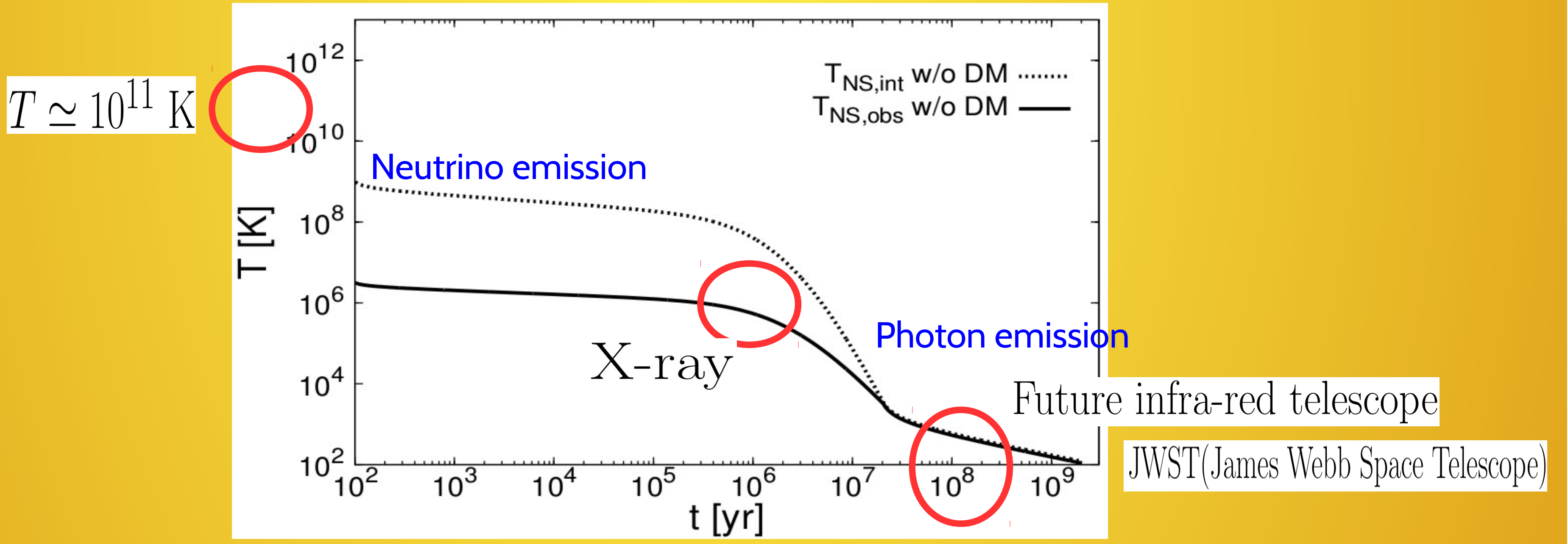

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[1] T. Gver, A. E. Erkoca, M. Hall Reno and I. Sarcevic, JCAP **1405**, 013 (2014), [arXiv:1201.2400 [hep-ph]].

[2] C. S. Chen and Y. H. Lin, JHEP **1808**, 069 (2018), [arXiv:1804.03409 [hep-ph]].

[3] S. D. McDermott, H. B. Yu and K. M. Zurek, Phys. Rev. D **85**, 023519 (2012), [arXiv:1103.5472 [hep-ph]].

[4] R. Garani, Y. Genolini and T. Hambye, JCAP **1905**, 035 (2019), [arXiv:1812.08773 [hep-ph]].

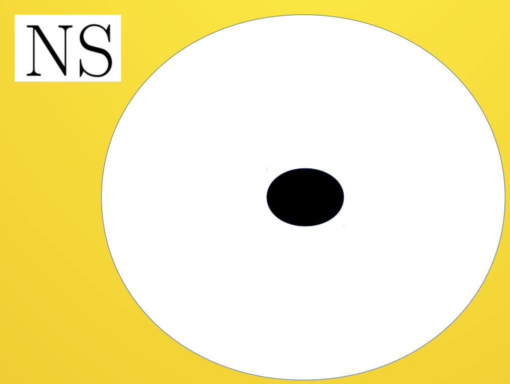
[5] N. F. Bell, G. Busoni and S. Robles, JCAP **1906**, 054 (2019), [arXiv:1904.09803 [hep-ph]].

[6] R. Garani and J. Heeck, Phys. Rev. D **100**, no. 3, 035039 (2019), [arXiv:1906.10145 [hep-ph]].

[7] M. Baryakhtar, J. Bramante, S. W. Li, T. Linden and N. Raj, Phys. Rev. Lett. **119**, no. 13, 131801 (2017), [arXiv:1704.01577 [hep-ph]].

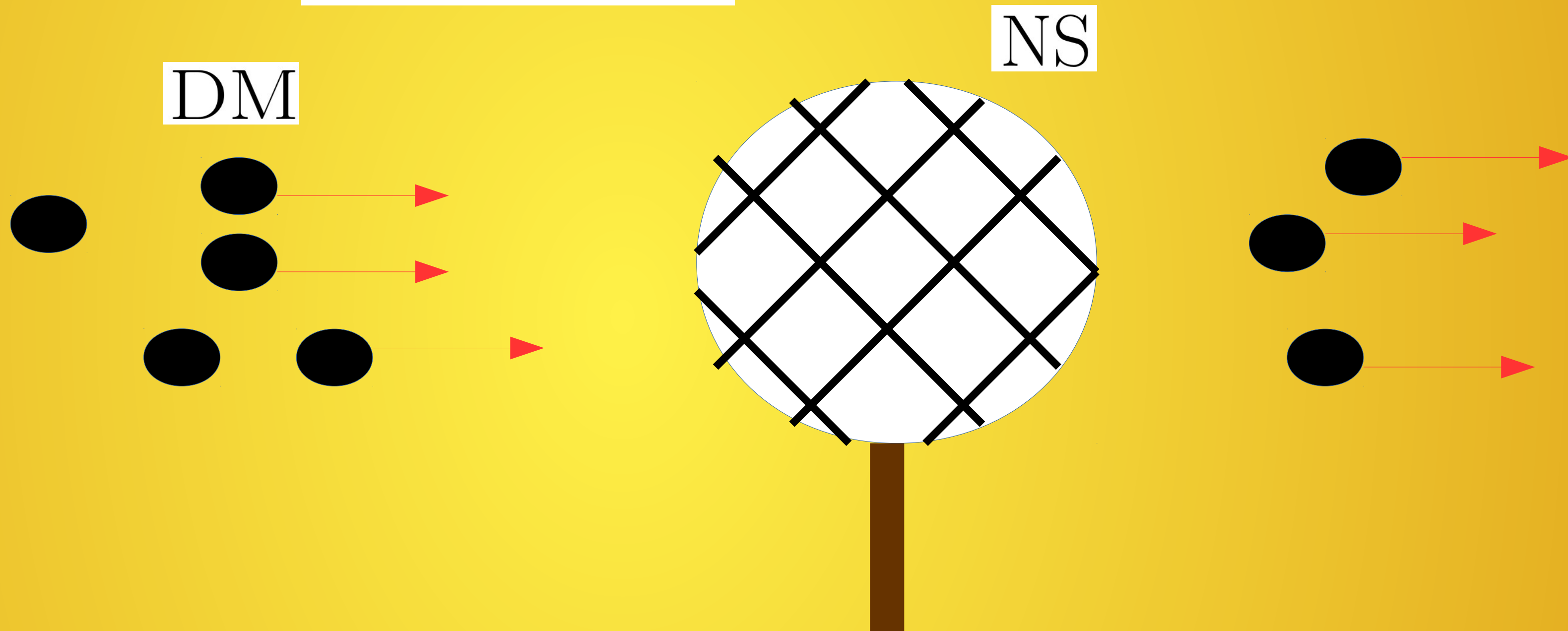
Introduction

- DM self-interaction help to increase the **DM capture rate**.
- There is **maximal** capture rate (*geometric limit*), due to the DM density~0.3 [GeV/cm^3]. It is about $\sigma_{\chi n} \simeq \mathcal{O}(10^{-45})\ \mathrm{cm}^2$
- For 10^8 year old **NS**, captured **DM** is 10^{-18} of total mass.



Introduction

- *geometric limit* $N_n \sigma_{\chi n} \leq \pi R^2$



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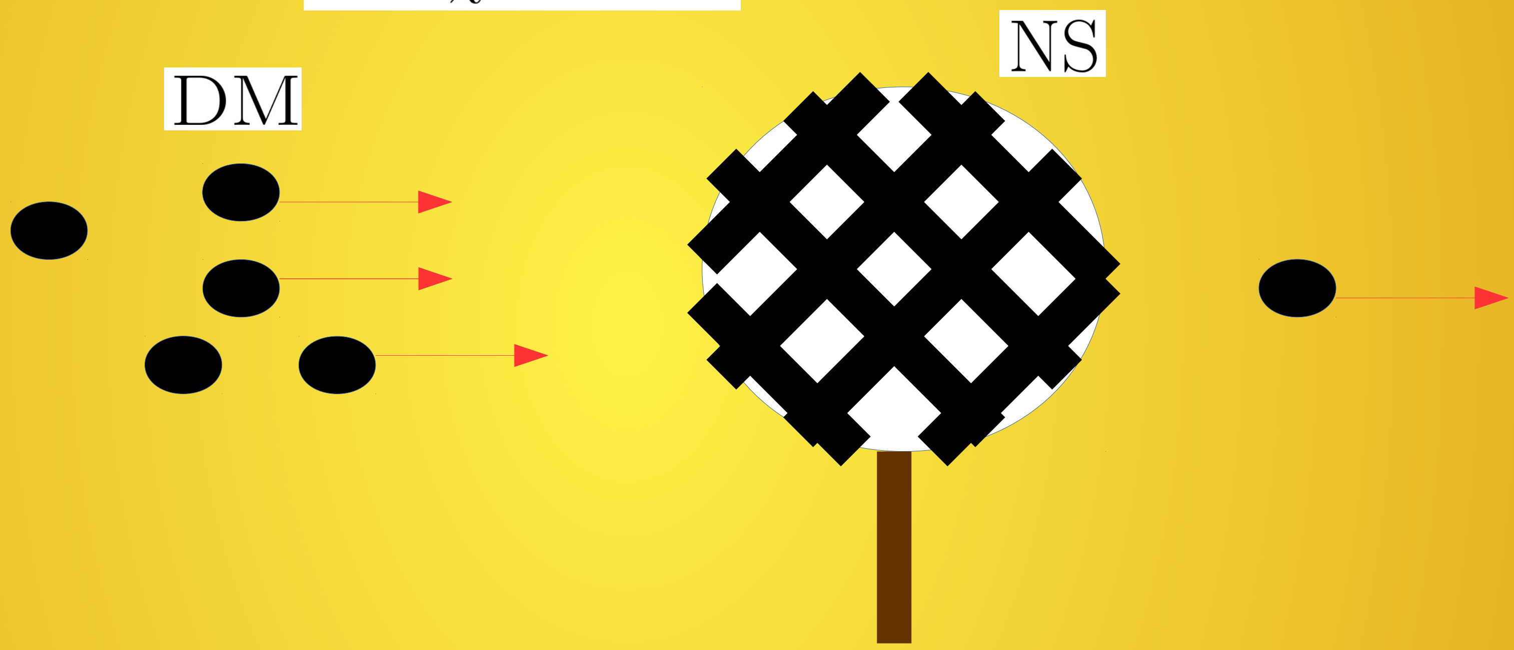

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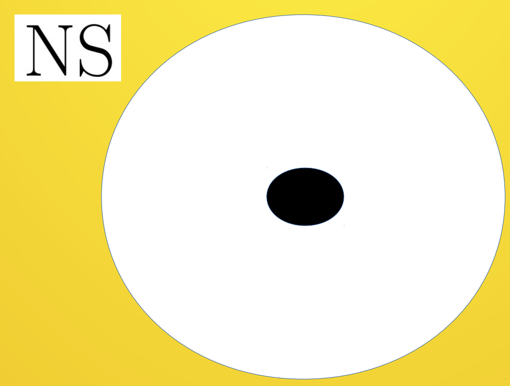
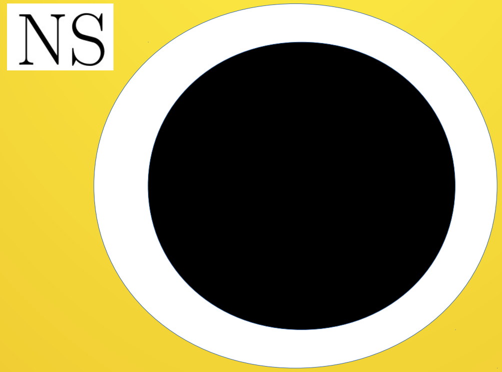


Introduction

- DM self-interaction help to increase the **DM capture rate**.
- However, in neutron dark decay model, **neutron** will convert into **DM** inside NS.
- More than 10% of **NS** could be **DM**. It helps to heat **NS**.



DM captured rate

- The **halo DM** captured rate by **NS** is

$$\frac{dN_{\rm DM}}{dt} = \begin{cases} C_c + C_s^{\chi\chi}(N_{\rm DM} + N_\chi)\,, & \text{If DM is } \chi \\ C_c + (C_s^{\bar\chi\bar\chi} N_{\rm DM} + C_s^{\bar\chi\chi} N_\chi) - C_a N_{\rm DM} N_\chi\,, & \text{If DM is } \bar\chi \end{cases}$$

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Captured by neutron → $\bar{\sigma}_{\chi n}^{\rm elatic}$

DM-self captured → $\sigma_{\chi\chi\to\chi\chi}$

DM annihilation → $\langle \sigma_{\chi\bar\chi}^{\rm ann} v_\chi \rangle$

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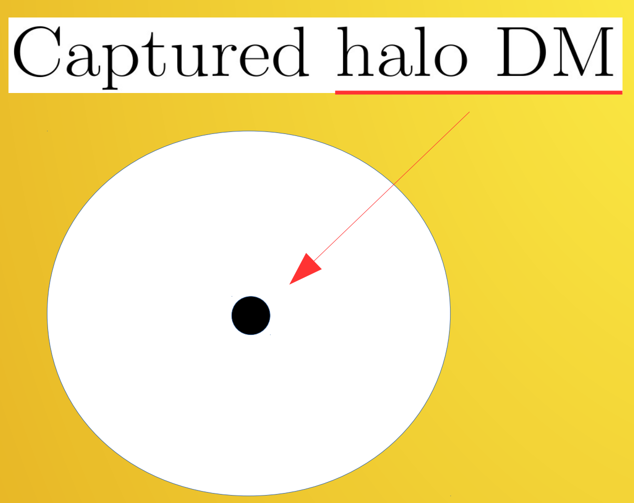

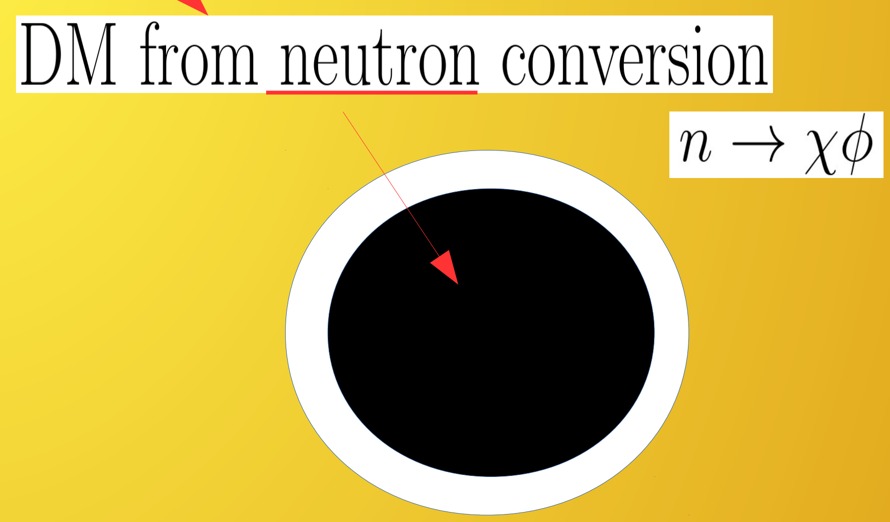

NS temperature evolution

- The evolution of NS temperature

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

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$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

$$\epsilon_\nu \simeq 1.81 \times 10^{-27}\ {\rm GeV}^4 {\rm yr}^{-1} \left(\frac{n_F}{n_0}\right)^{2/3} \left(\frac{T_{\rm int}}{10^7\ {\rm K}}\right)^8$$

NS temperature evolution

- The evolution of NS temperature

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

$$L_\gamma = 4\pi R^2 \sigma_{\rm SB} T_{\rm sur}^4 \simeq 5.00 \times 10^{11}\ {\rm GeV\,s^{-1}} \left(\frac{T_{\rm sur}}{\rm K}\right)^4$$

Stefan-Boltzmann's law

NS temperature evolution

- The evolution of NS temperature

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

$$\epsilon_\chi = \begin{cases} \text{DM annihilations} \\ \text{DM kinematic heating} \\ \text{DM-NS thermal transition} \end{cases}$$

NS temperature evolution

- The evolution of NS temperature

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

Heat capacity of ideal Fermi gas

$$c_V = \frac{k_B^2 T_{\rm int}}{3} \sum_{i=\chi,n} p_{F,i}\sqrt{m_i^2 + p_{F,i}^2}$$

$$p_{F,\chi} = 0.34\ {\rm GeV}\left(\frac{n_F \tilde{r}_\chi}{n_0}\right)^{1/3},$$

$$p_{F,n} = 0.34\ {\rm GeV}\left(\frac{n_F(1-\tilde{r}_\chi)}{n_0}\right)^{1/3}$$

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- The evolution of NS temperature

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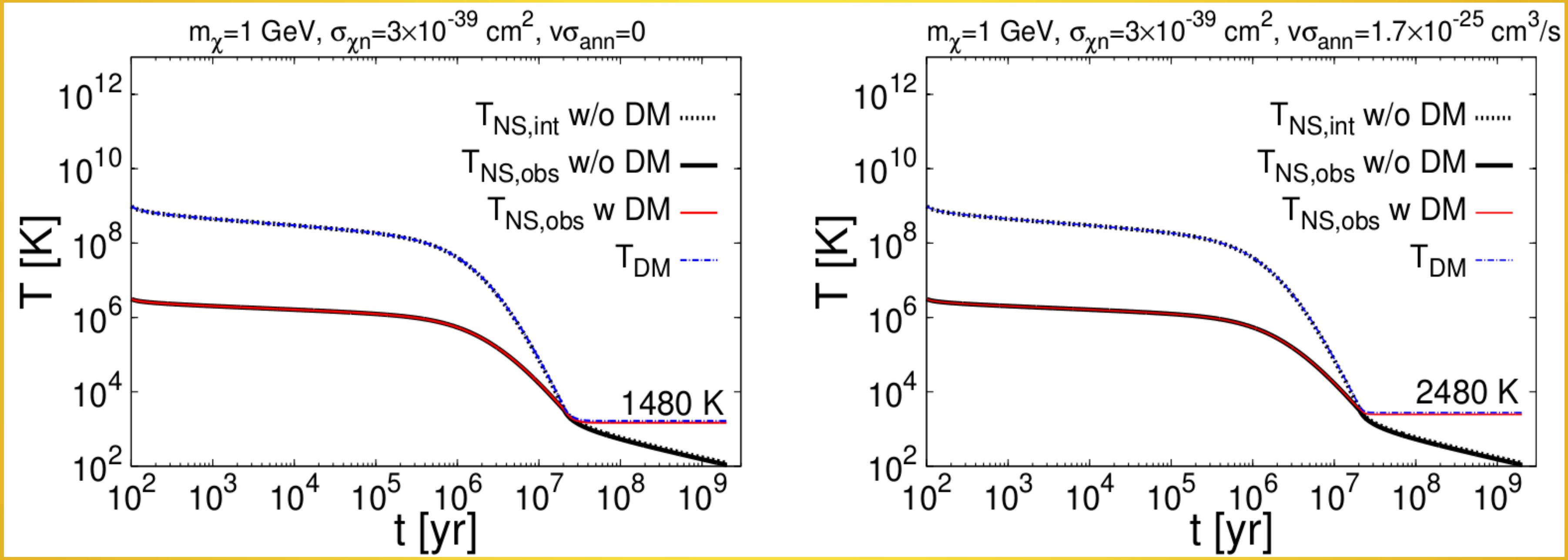


- **DM capture rate** had reached *geometric limit*, increase cross section do not increase NS temperature.

Neutron dark decay model

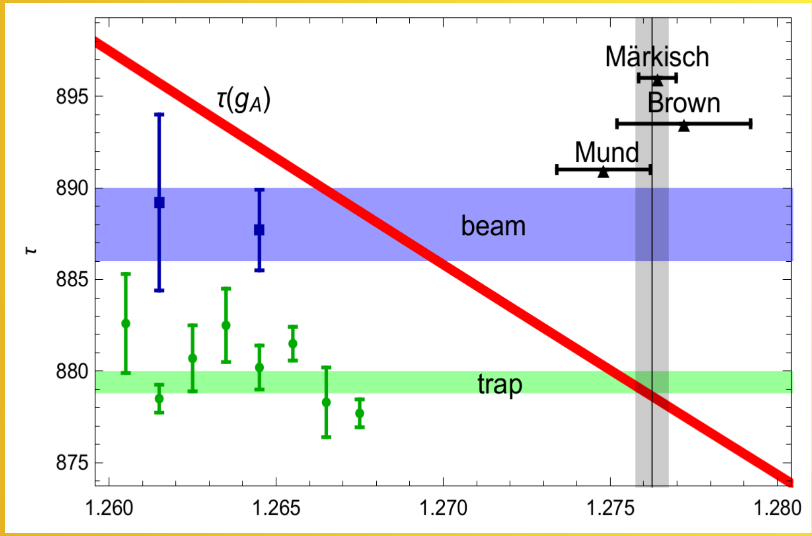
- The **neutron lifetime** is measured in ***bottle*** experiments and ***beam*** experiments.
- ***Bottle***: total lifetime is measured by counting the number of neutrons in a container.
- ***Beam***: count the number of protons from neutron decay.

$$\tau_n^{\mathrm{beam}} = \frac{\tau_n^{\mathrm{bottle}}}{\mathrm{Br}(n \to p + \mathrm{anything})}$$

Neutron dark decay model

- From **SM** prediction, ***bottle*** and ***beam*** experiments are almost equal.

- However, there is **4-sigma** tension between bottle and beam:



$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}$$

$$\tau_n^{\text{beam}} = 888.0 \pm 2.0 \text{ s}$$

B.Belfatto, R.Beradze, Z.Berezhiani, 1906.02714.

Particle Data Group, Chin.Phys.C40, 10, 100001 (2016),
G.L.Greene, P.Geltenbort, Sci.Am.314,36 (2016).

Neutron dark decay model

- From **SM** prediction, ***bottle*** and ***beam*** experiments are almost equal.

- However, there is **4-sigma** tension between bottle and beam:

- To explain the discrepancy, **1%** of neutron decay into channel without proton.

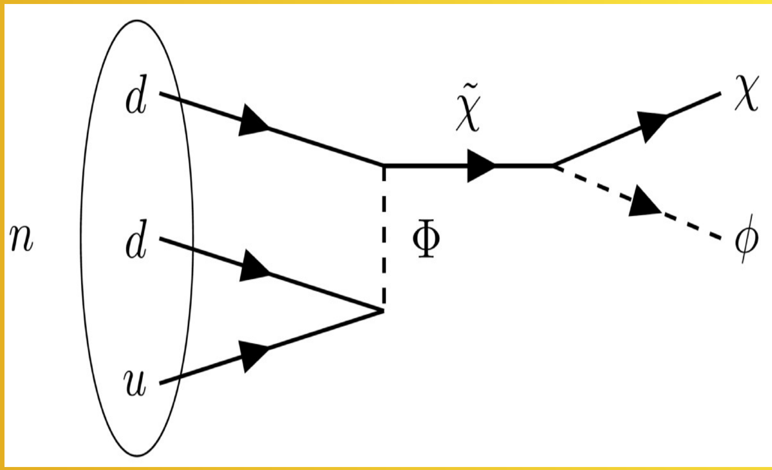
$$\Delta\Gamma(n \to \text{no proton}) \simeq 7.1 \times 10^{-30}\ \text{GeV}$$

Neutron dark decay model

- The model, invoking dark decays on neutron:

B.Fornal, B.Grinstein, PRL 120, 19, 191801 (2018), 1801.01124, 1810.00862.

$$n \to \chi + \phi$$



$$937.992 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV}$$
$$937.992 \text{ MeV} < m_{\tilde{\chi}} ,$$
$$|m_\chi - m_\phi| < m_p + m_e = 938.783081 \text{ MeV}$$

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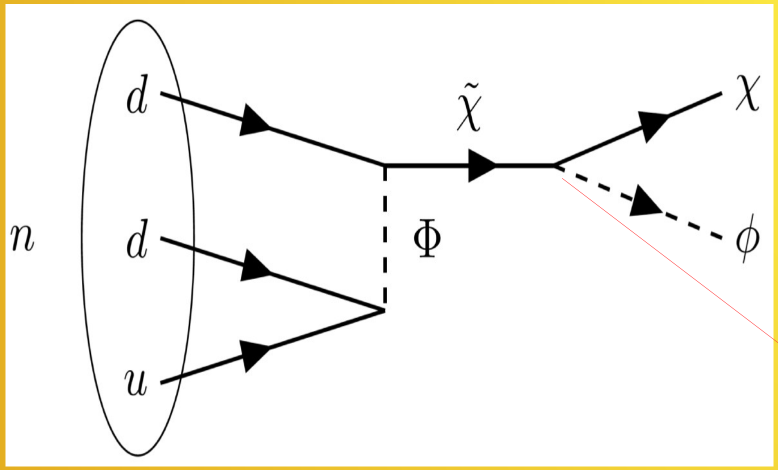

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$$\lambda_\phi \simeq 0.04$$

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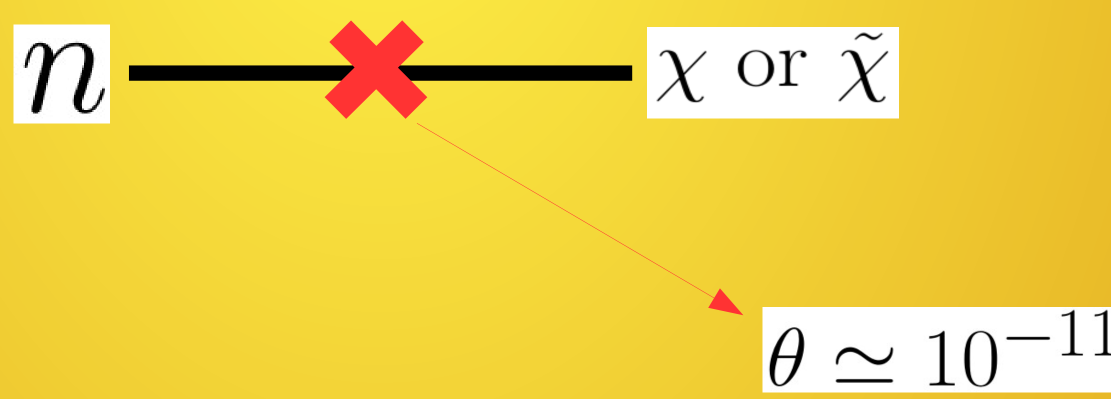
- The model, invoking dark decays on neutron
- **DM** mass is ~GeV, mixing with neutron, carries baryon number.

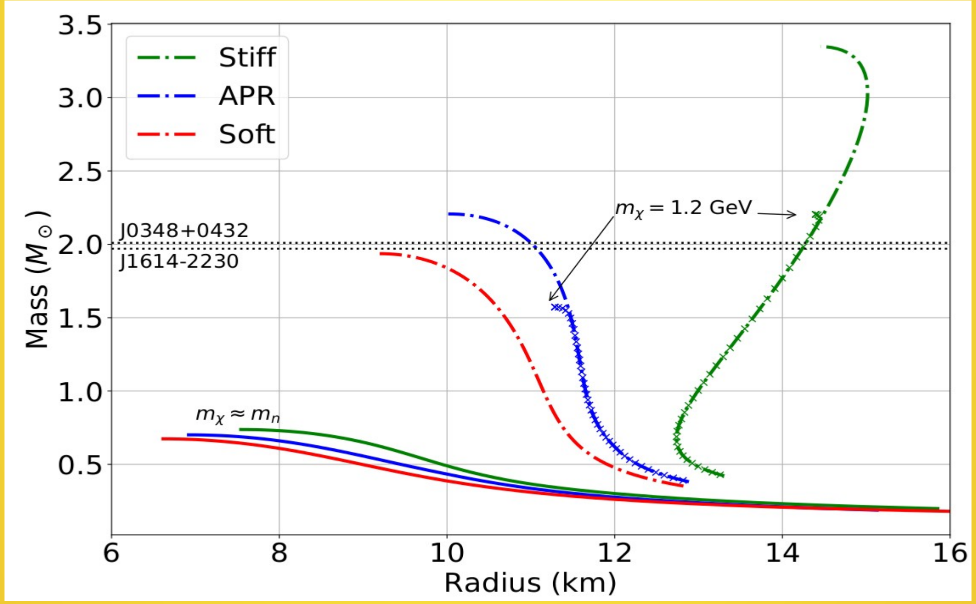
B.Fornal, B.Grinstein, PRL 120, 19, 191801 (2018), 1801.01124, 1810.00862.



Stability of neutron star

- **NS** becomes **unstable**: Equation of State (EoS) is too soft to maintain NS heavier than two solar mass.

$$n \to \chi + \phi$$



D.McKeen, A.E.Nelson, S.Reddy, and D.Zhou, 1802.08244.

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- Cure by adding DM-neutron interaction, and repulsive DM-self interaction. B.Grinstein, C. Kouvaris, N.G. Nielsen, 1811.06546.
- The EoS and energy density are

$$\varepsilon(n_n, n_\chi) = \varepsilon_{\rm nuc}(n_n) + \varepsilon_\chi(n_\chi) + \frac{n_\chi n_n}{2z^2}$$

$$\varepsilon_\chi = \frac{m_\chi^4}{8\pi^2}\left[x\sqrt{1+x^2}(1+2x^2) - \ln(x+\sqrt{1+x^2})\right] \pm \frac{n_\chi^2}{2z'^2}$$

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- The amount of **DM** inside **NS** can be determined by

$$0 = \frac{\partial \varepsilon(n_F - n_\chi, n_\chi)}{\partial n_\chi} = \mu_\chi(n_\chi) - \mu_{\rm nuc}(n_n) + \frac{n_F - 2n_\chi}{2z^2}$$

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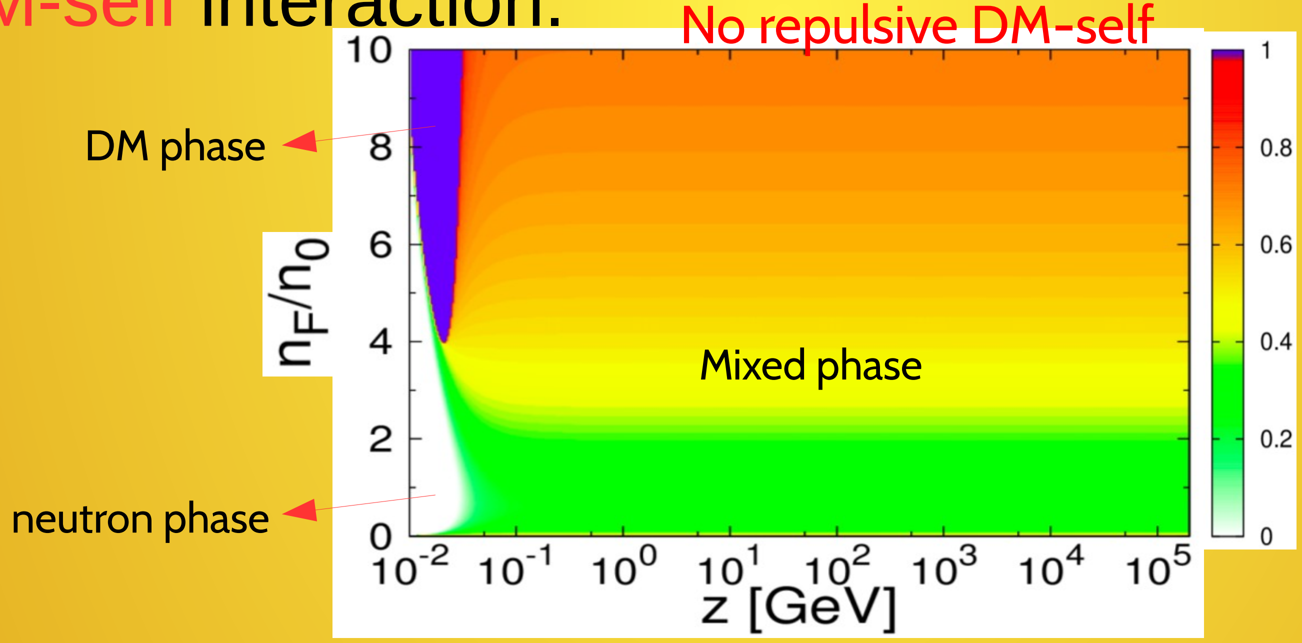

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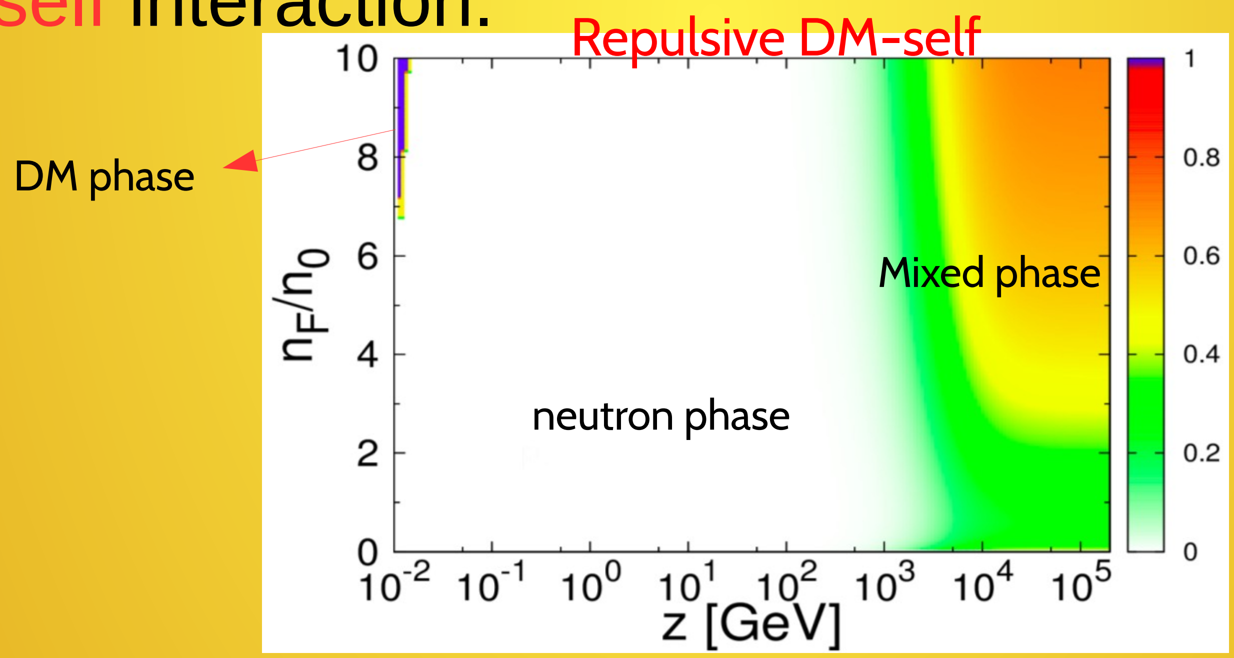

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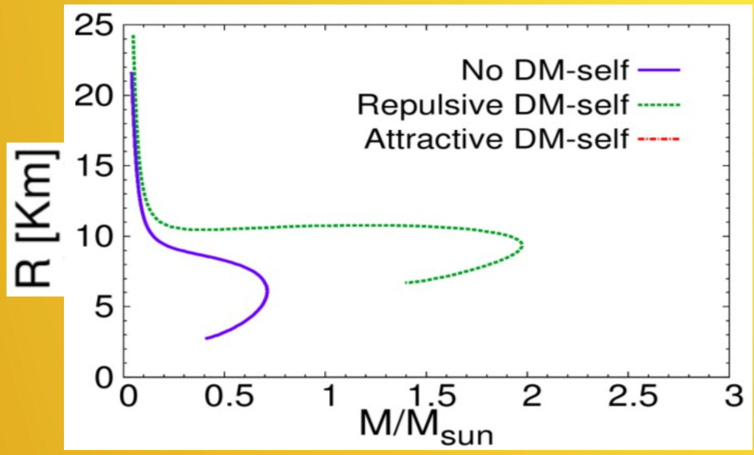
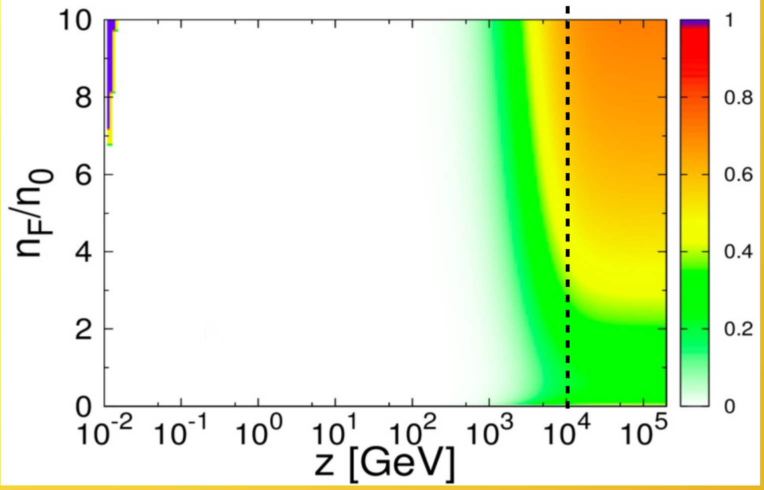


$z = 10^4$ GeV



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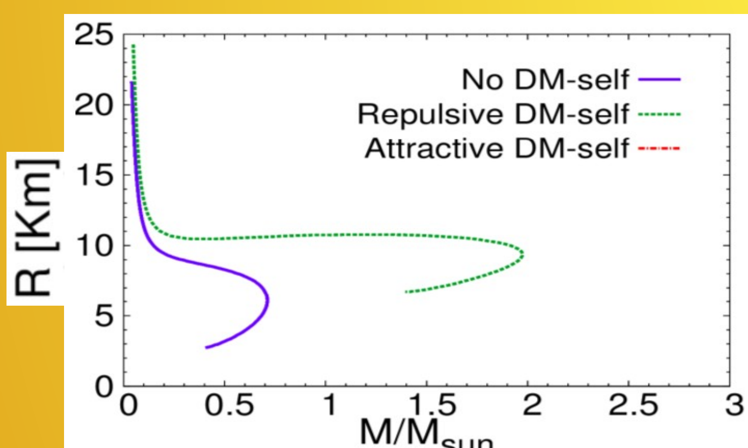

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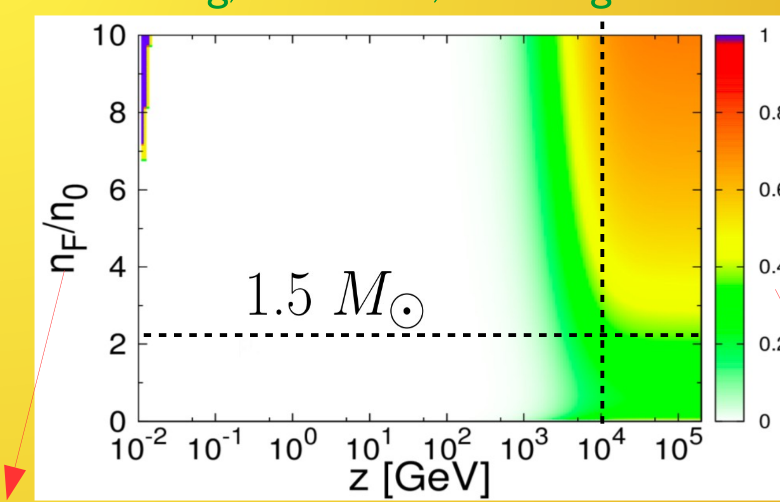

central ♯ density

DM ratio

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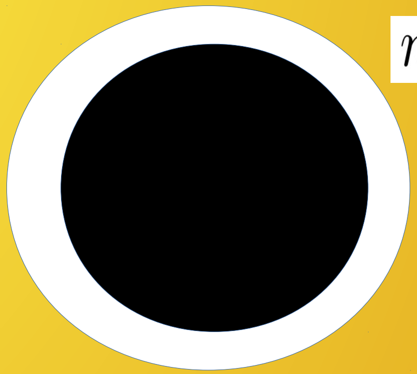
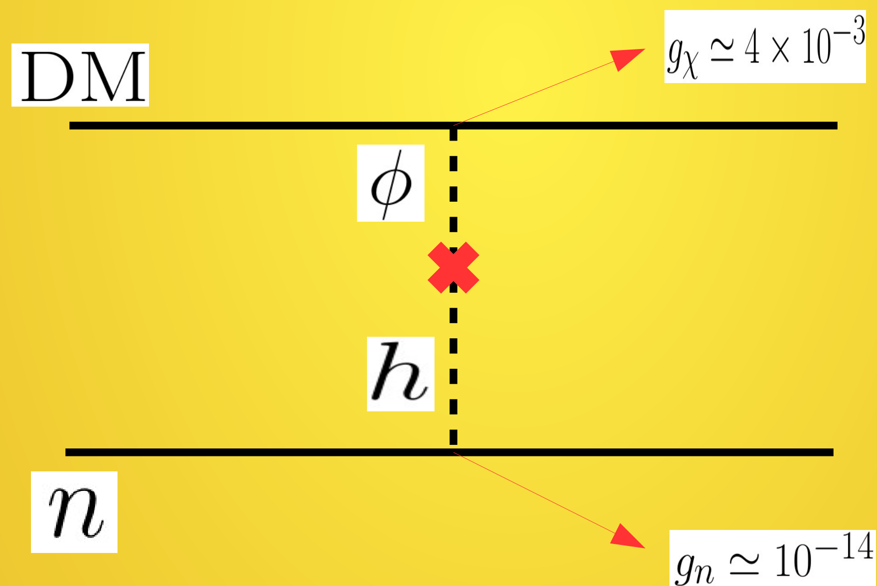
- **NS** can be composed by **30% of DM** and stable from neutron dark decay model.

$n \to \chi\phi$



Heating NS by neutron dark decay

- Neutron dark decay model: the DM-neutron cross section is $\mathcal{O}(10^{-60})\ \mathrm{cm}^2 \ll \mathcal{O}(10^{-45})\ \mathrm{cm}^2$, therefore the DM captured rate is much smaller than *geometric limit*.



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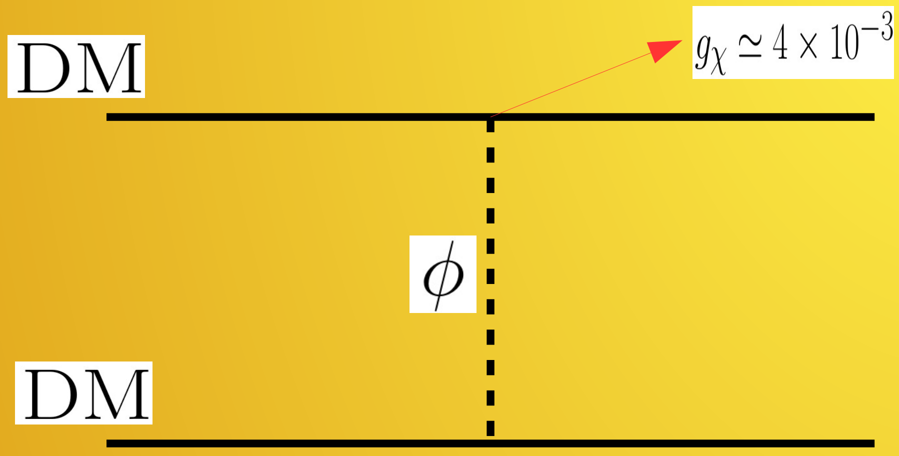
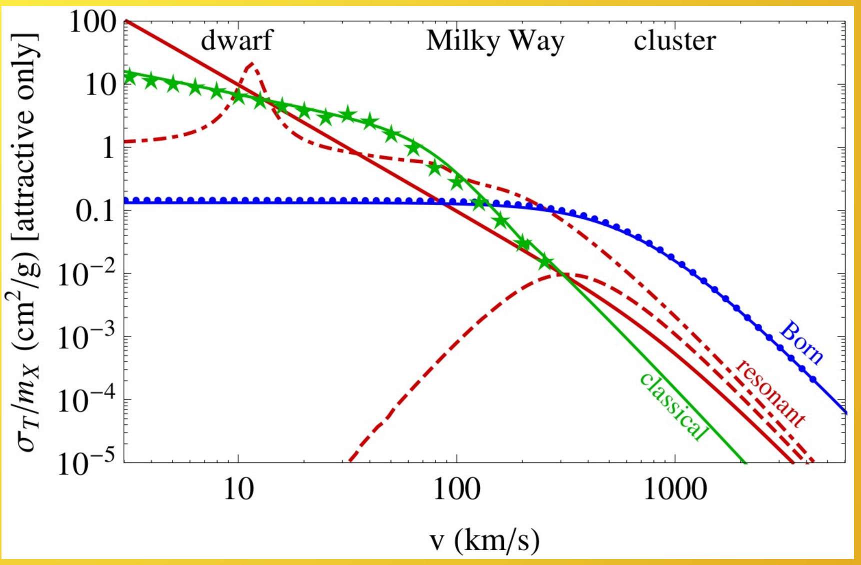


➢ S.Tulin, H.B.Yu, K.M.Zurek: PRL,110(2013),111301



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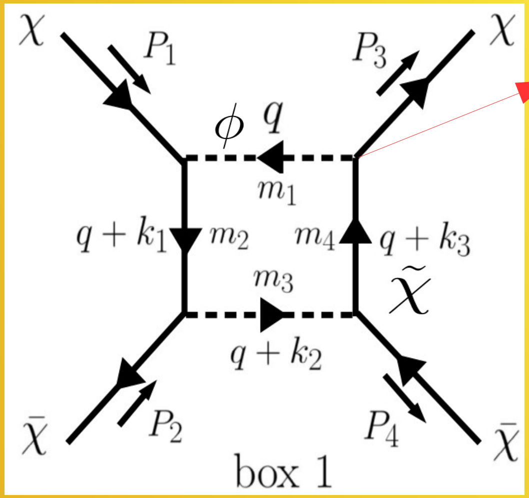

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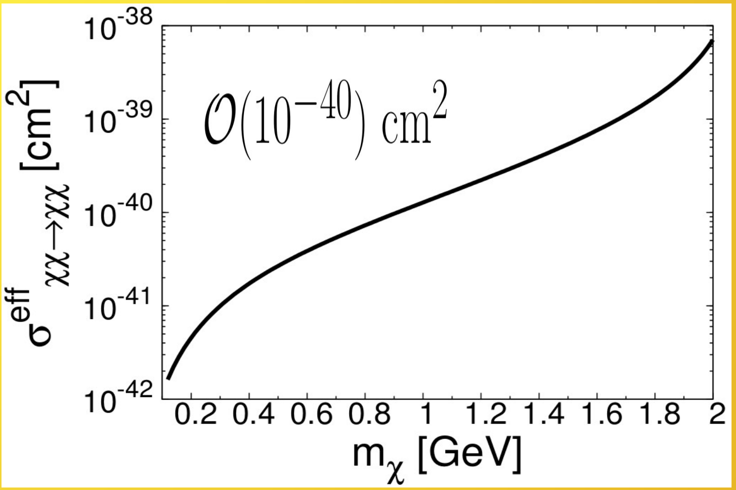
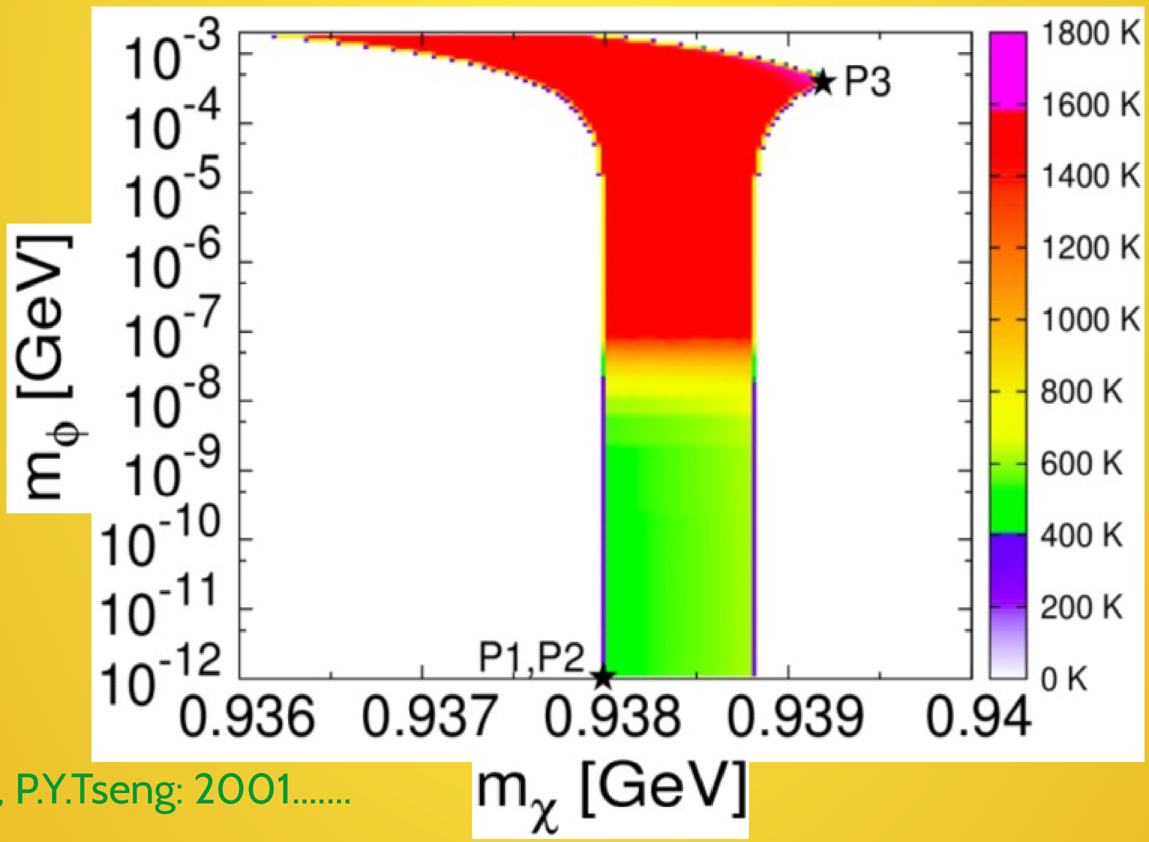


Heating NS by neutron dark decay

- Neutron dark decay model: can heat up NS more than 1500 K by i) **NS** is composed by *substantial* amount of **DM**. ii) DM-self cross section is *large enough*.



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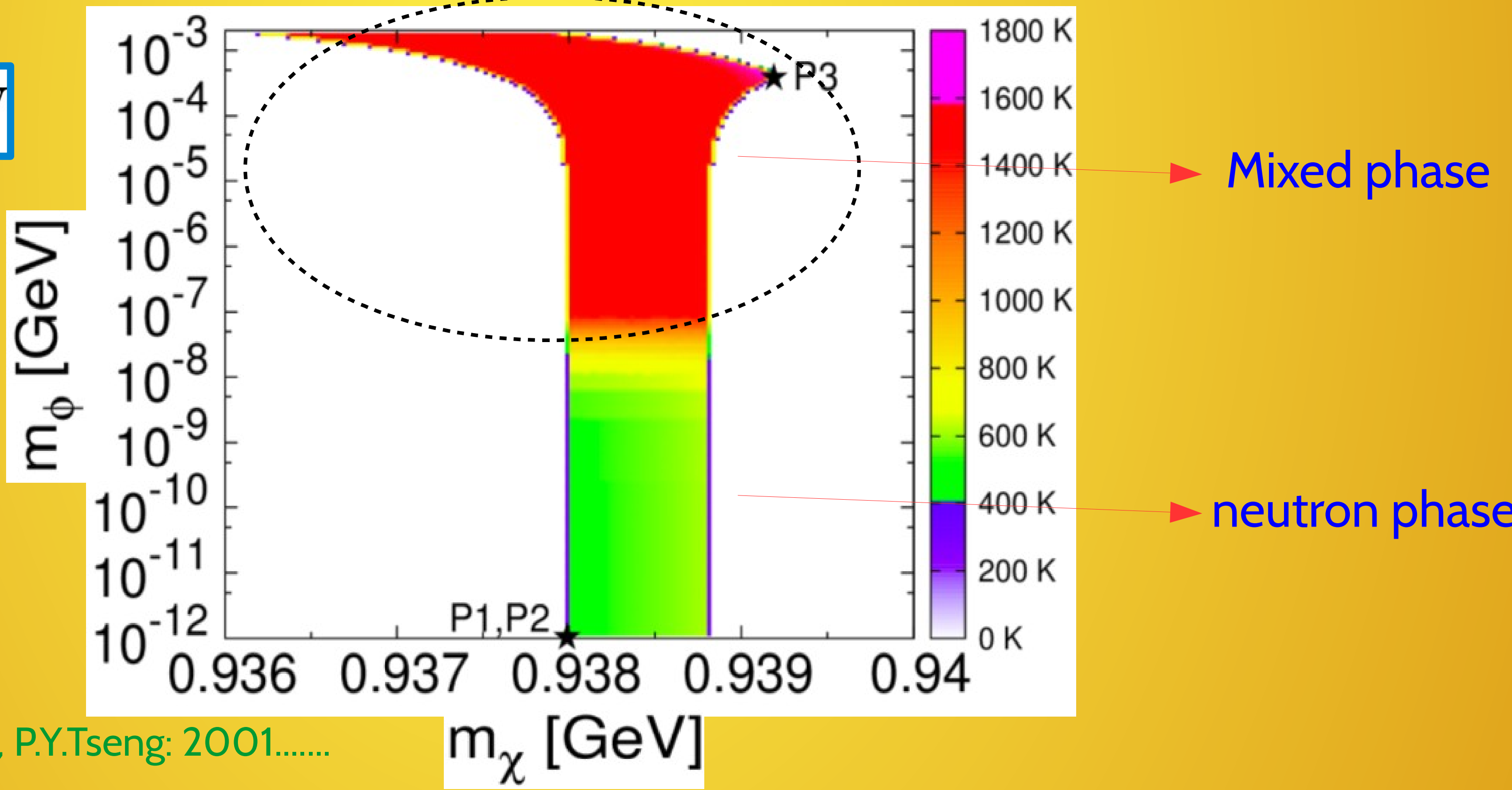
$m_\phi \gtrsim 100 \text{ eV}$



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Quark vector portal DM

- Quark vector portal DM model:

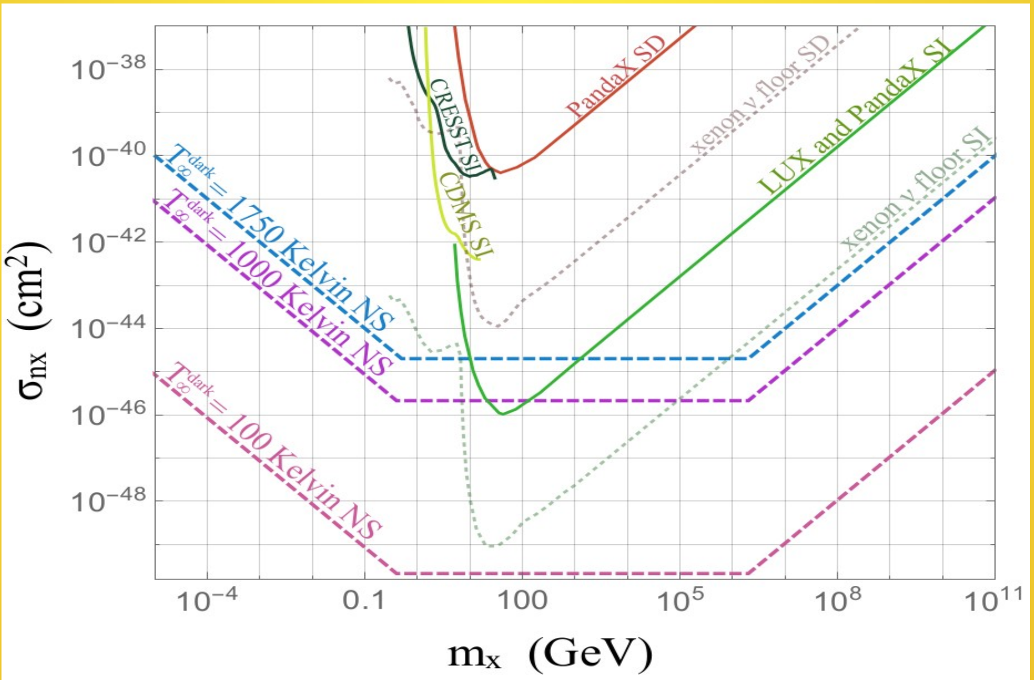
$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- **DM** less than **GeV mass** is difficult to probe by **DM direct detection** experiments.
- It is within the range of constraint from **heating NS**.
- For **DM** lighter than GeV, NS heating gradually loose the sensitivity due to the **Pauli-blocking** effect.

Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$



M.Baryakhtar, J.Bramante, S.W. Li, T. Linden, and N. Raj: 1704.01577

Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- Instead, DM-nucleon cross section need to be calculated in relativistic limit.

$$\frac{d\sigma_{\chi n,p}(s,t)}{d\cos\theta_{\rm cm}} = \left(\frac{c_{\chi n,p}}{\Lambda^4}\right) \frac{2(\bar{\mu}^2+1)^2 m_\chi^4 - 4(\bar{\mu}^2+1)\bar{\mu}^2 s m_\chi^2 + \bar{\mu}^4(2s^2+2st+t^2)}{16\pi\bar{\mu}^4 s} |F_n(E_R)|^2$$

N.F.Bell, G.Busoni, and S.Robles: 1807.02840

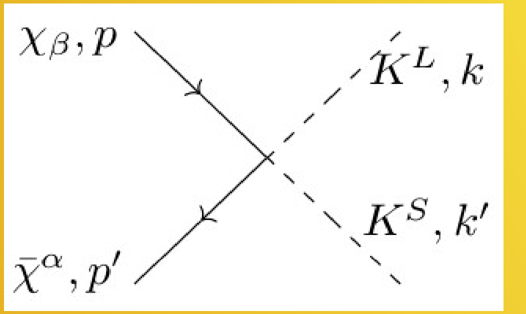
Quark vector portal DM

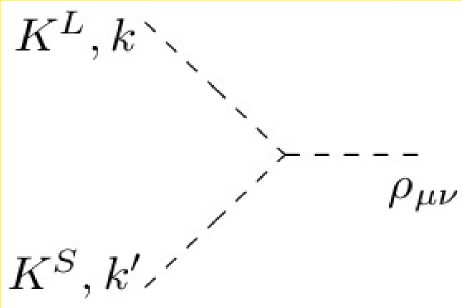
- Quark vector portal DM model:

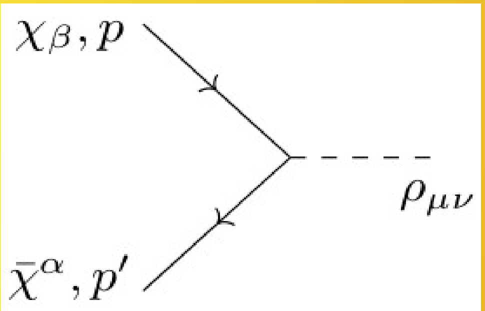
$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- At GeV scale, **chiral Lagrangian** is better description to calculate the DM-annihilation cross section.

D.Berger, A.Rajaraman, and J.Kumar: 1903.10632.
J.Kumar:1808.02579





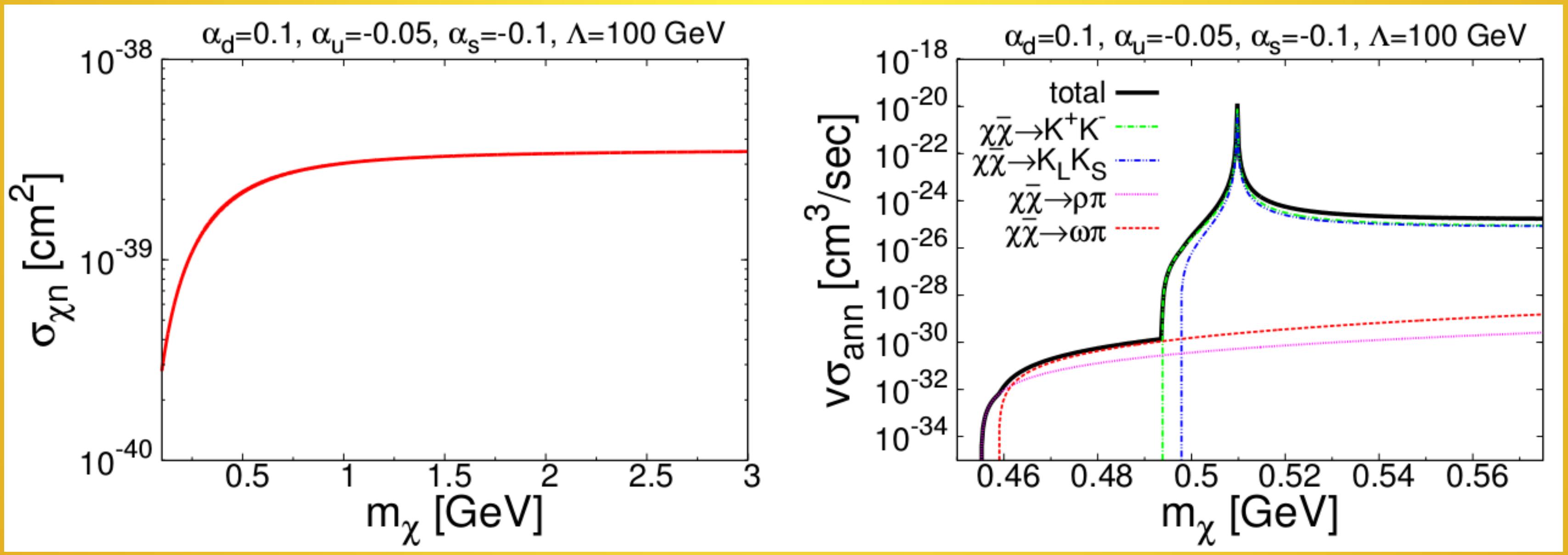


Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- The DM-neutron and DM-annihilation cross sections.



Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- The DM-neutron and DM-annihilation cross sections.

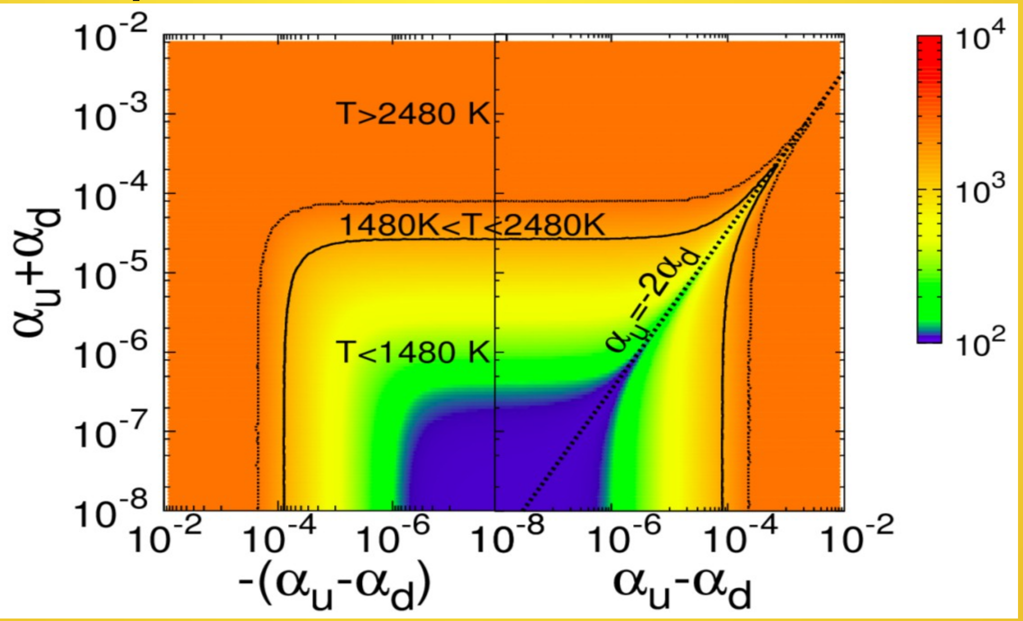
- The couplings of $\alpha_q \simeq 10^{-4}$, the **capture rate** reaches *geometric limit*. This is about the sensitivity from heating NS up to 1500 K.

Heating NS by Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

- Heating NS temperature:



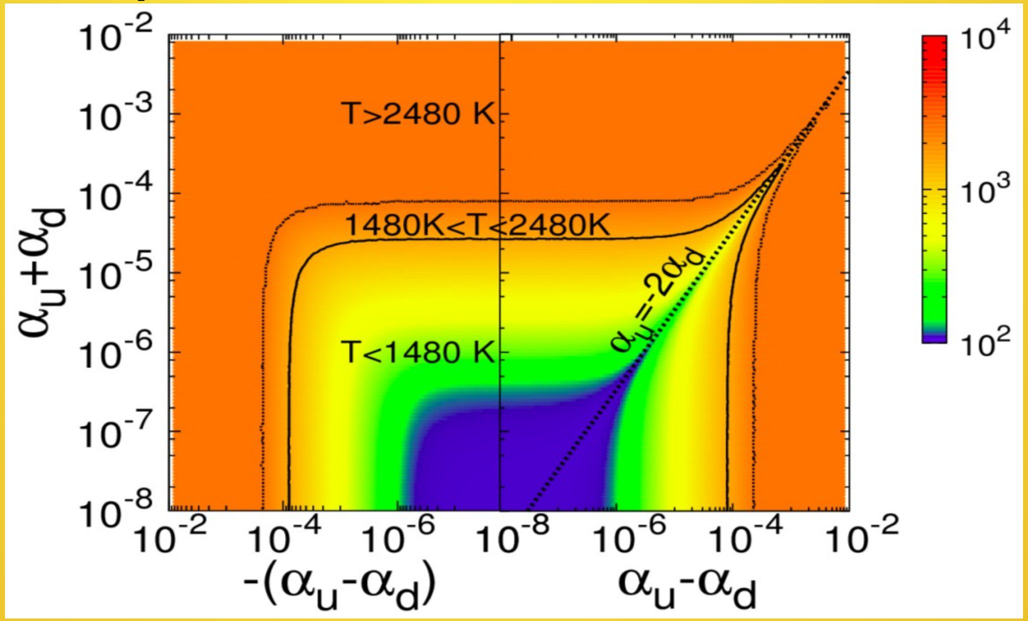
Heating NS by Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$$

- Heating NS temperature:

$$\alpha_{u,d} \gtrsim \mathcal{O}(10^{-4})$$



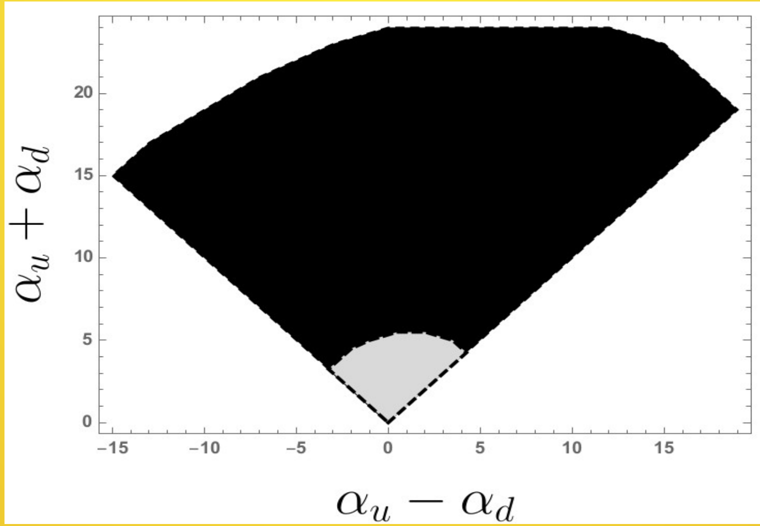
Heating NS by Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

- Comparing to future constraint from MeV-gap cosmic gamma-ray of **DM indirect detection**:

D.Berger, A.Rajaraman, and J.Kumar: 1903.10632.
J.Kumar:1808.02579

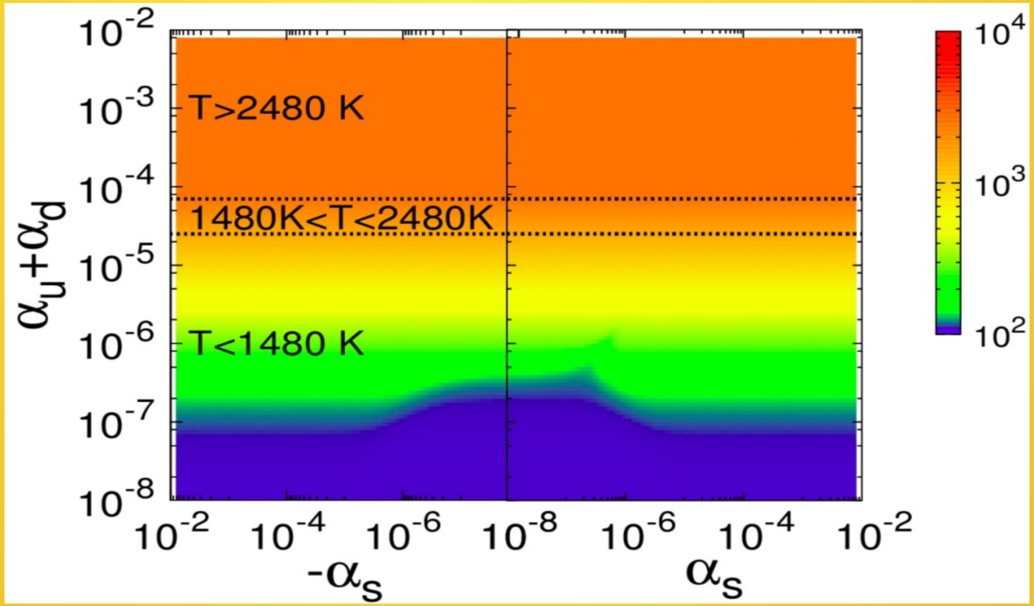


Heating NS by Quark vector portal DM

- Quark vector portal DM model:

$$\mathcal{L}_{int} = \sum_{q=u,d,s} \frac{\alpha_q}{\Lambda^2} \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

- Heating NS temperature varying α_s :



Heating NS by Quark vector portal DM

- Quark vector portal DM model:

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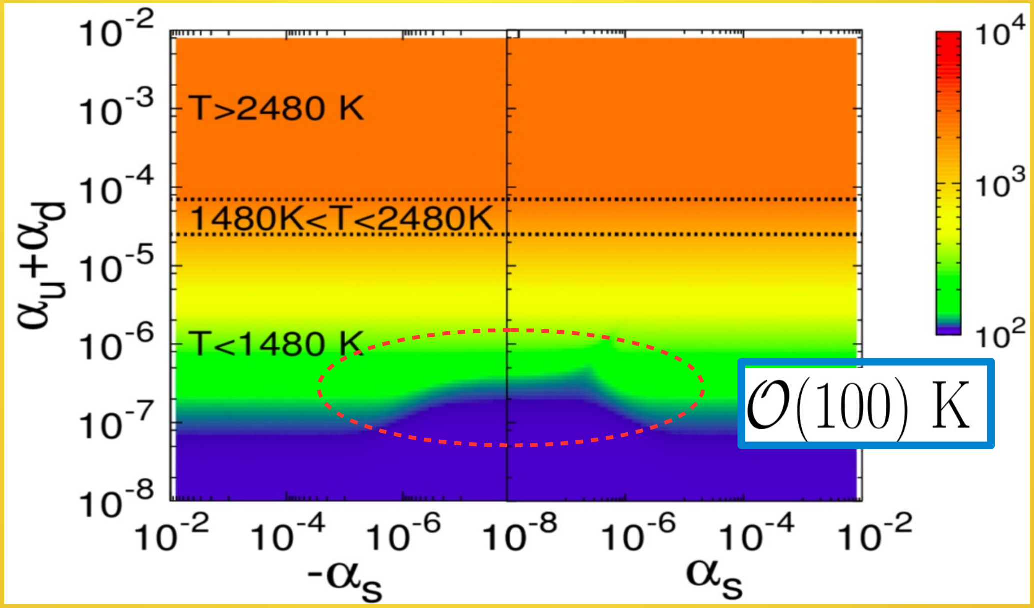
- Heating NS temperature varying α_s:



Summary

- We studied the GeV-mass **DM** captured by **NS**
- In general, neutron can convert into **DM**, which becomes substantial part of **NS**. DM-self interaction helps to enhance the DM captured rate,and **heating NS** up to 1000 K.
- **Old NS** observation from future infra-red telescopes will give constraints.

Summary

- GeV-mass DM from Neutron dark decay model and quark vector portal DM model to illustrate the constraints.
- Neutron dark decay model: entire region of $m_\phi \gtrsim 100 \text{ eV}$ can be probed.
- Quark vector portal DM model: $\alpha_{u,d} \gtrsim \mathcal{O}(10^{-4})$ can achieve It is more stringent than **DM direct detection** and **indirect detection** from MeV-gap gamma-ray.

Thank You!
Happy Chinese New Year

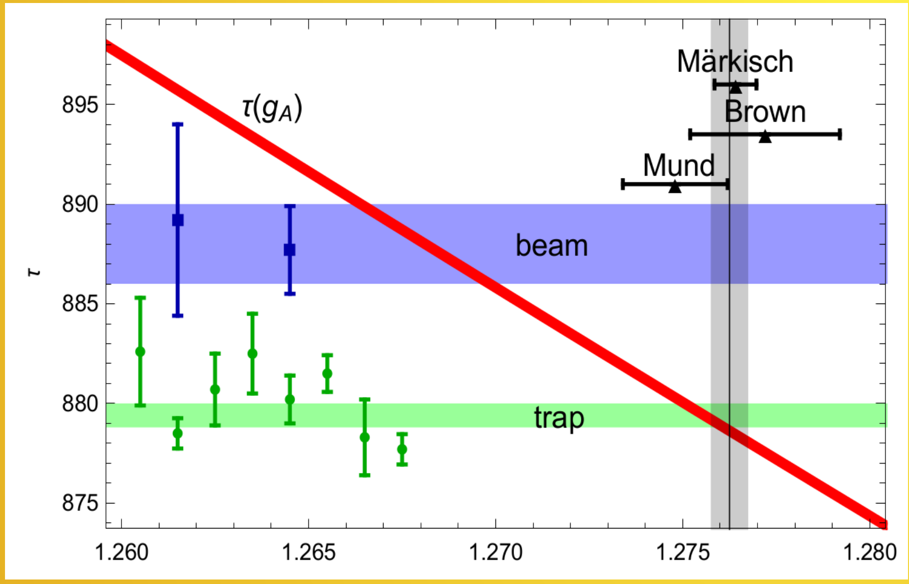
Back Up

Introduction

- From SM prediction, bottle and beam experiments are almost equal.

- However, there is 4-sigma tension between bottle and beam:

B.Belfatto, R.Beradze, Z.Berezhiani, 1906.02714.



$$\tau_n = \frac{2\mathcal{F}t}{\ln 2\, \mathcal{F}_n (1 + 3g_A^2)} = \frac{5172.0(1.1)\ \mathrm{s}}{1 + 3g_A^2}$$

Uncertainties

- From factor:

$$\mathcal{L}^{\text{eff}} \supset \frac{g_n e}{2m_n} F_{\bar{n}\gamma n}(Q^2)\, \bar{n}\sigma^{\mu\nu} F_{\mu\nu} n$$

$$\begin{aligned}\mathcal{L}^{\text{eff}} &\supset \frac{g_{n\pi}}{\sqrt{4\pi}} F_{\bar{n}\pi n}(Q^2)\, \bar{N}(\vec{\tau} \cdot \vec{\pi}) i\gamma_5 N \\ &= \frac{g_{n\pi}}{\sqrt{4\pi}} F_{\bar{n}\pi n}(Q^2) \left(-\bar{n}i\gamma_5 n\pi^0 + \bar{p}i\gamma_5 p\pi^0 + \sqrt{2}\bar{p}i\gamma_5 n\pi^+ + \sqrt{2}\bar{n}i\gamma_5 p\pi^-\right)\end{aligned}$$

$$F_{\bar{n}\pi n}(Q^2) = \left(\frac{1 - m_n^2/\Lambda_n^2}{1 + Q^2/\Lambda_n^2}\right)^y$$

Model II

- Lagrangian:

B.Fornal, B.Grinstein, PRL 120, 19, 191801 (2018), 1801.01124, 1810.00862.

$$\mathcal{L}_2 = \left(\lambda_q \, \epsilon^{ijk} \, \overline{u^c_{L}}_i \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}} \, d_{Ri} + \lambda_\phi \, \bar{\tilde{\chi}} \, \chi \, \phi + \text{h.c.}\right) + M_\Phi^2 \, |\Phi|^2 + m_\phi^2 |\phi|^2 + m_\chi \, \bar{\chi} \, \chi + m_{\tilde{\chi}} \, \bar{\tilde{\chi}} \, \tilde{\chi} \, . \tag{38}$$

$$\mathcal{L}_1 \supset \lambda_1 \Phi^* \chi d_R + \lambda_1' \Phi u_R d_R + \text{h.c.}$$

$$\mathcal{L} \subset \frac{\lambda_1 \lambda_1'}{m_\Phi^2} (\chi u_R d_R d_R) = \frac{\lambda_1 \lambda_1'}{m_\Phi^2} \beta (\chi n)$$

Models

- It can couple to photon and pion:

B.Fornal, B.Grinstein, PRL 120, 19, 191801 (2018), 1801.01124, 1810.00862.

Model I

$$n \rightarrow \chi + \gamma$$

Model II

$$n \rightarrow \chi + \phi$$

$$F_{\bar{n}\gamma n}(Q^2)\,\bar{n}\sigma^{\mu\nu}F_{\mu\nu}n \qquad F_{\bar{n}\pi n}(Q^2)\,\bar{N}(\vec{\tau}\cdot\vec{\pi})i\gamma_5 N$$

Models

- Requirement of $^9\mathrm{Be}$ stability, and prevent χ decay into proton. It becomes good DM candidate.

Model I

$$n \to \chi + \gamma$$

$$937.900\ \mathrm{MeV} < m_\chi < 938.783\ \mathrm{MeV}$$

$m_p + m_e$

W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Model II

$$n \to \chi + \phi$$

m_n

$$937.900\ \mathrm{MeV} < m_\chi + m_\phi < 939.565\ \mathrm{MeV}$$

$$937.900\ \mathrm{MeV} < m_{\tilde{\chi}}\,,$$

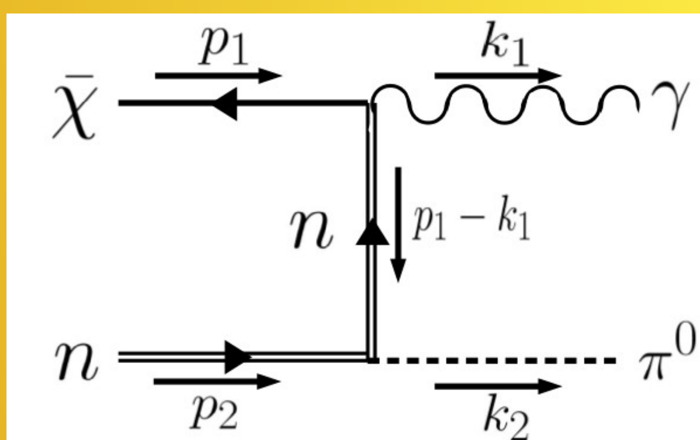
$$|m_\chi - m_\phi| < m_p + m_e = 938.783081\ \mathrm{MeV}$$

Signatures

- What signatures are expected from **Model I** and **II**:

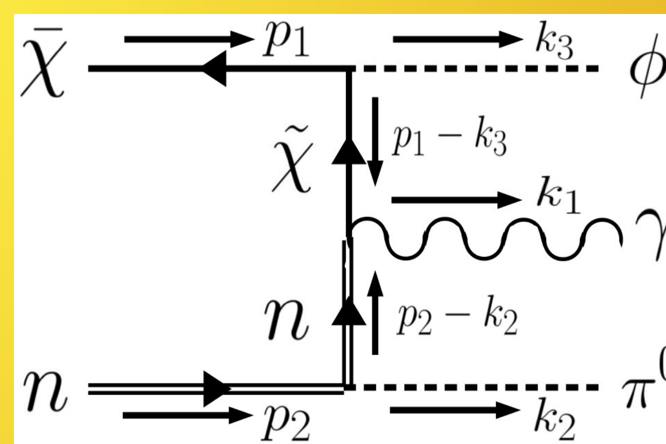
Model I

$$\bar{\chi} + n \to \gamma + \pi^0$$



Model II

$$\bar{\chi} + n \to \phi + \gamma + \pi^0$$

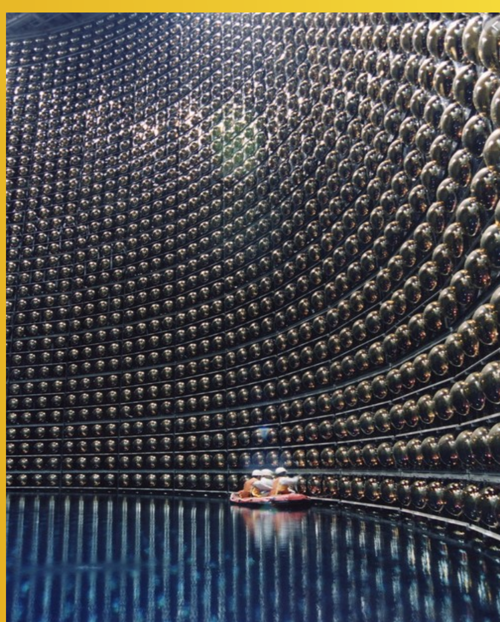


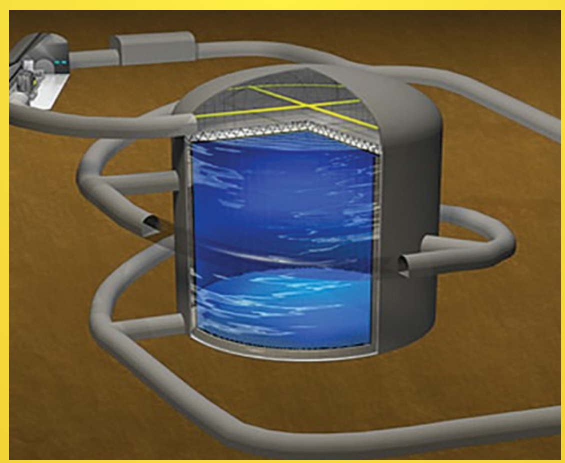
W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Signatures

- GeV **DM** annihilate with neutron, produce GeV **photon** and **pions**.

- **SuperK**, **HyperK**, and **DUNE** can detect these signals.





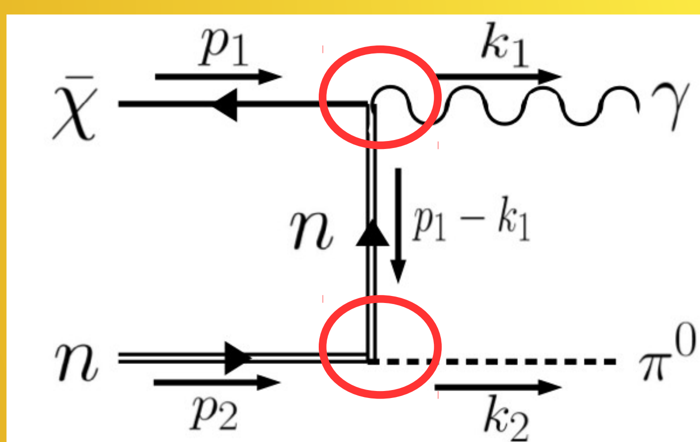
Signatures

- What signatures are expected from **Model I** and **II**:

Halo DM

Model I

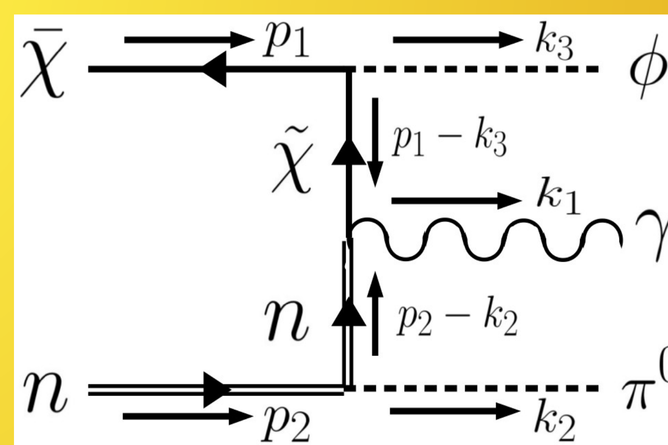
$$\bar{\chi} + n \to \gamma + \pi^0$$



W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Model II

$$\bar{\chi} + n \to \phi + \gamma + \pi^0$$



Signatures

- Signal events:

	Model I		Model II P1	Model II P2	Model II P3
m_χ [MeV]	937.900	938.783	937.900	937.900	939.174
m_ϕ [MeV]	-	-	0	0	0.391
$m_{\tilde{\chi}}$ [MeV]	-	-	937.900	$2m_n$	940.000
λ_ϕ	-	-	0.04	0.04	0.04
$\lvert\theta\rvert$	5.64×10^{-11}	1.75×10^{-10}	4.09×10^{-12}	4.10×10^{-12}	4.03×10^{-11}
$\Gamma_{n\to\chi\gamma\ (\text{or}\ \tilde{\chi}\gamma)}$ [GeV]	7.1×10^{-30}	7.1×10^{-30}	3.7×10^{-32}	0	0
$\Gamma_{n\to\chi\phi}$ [GeV]	-	-	7.06×10^{-30}	7.10×10^{-30}	7.10×10^{-30}
	$\bar{\chi}n \to \gamma\pi^0\ (y=2)$		$\bar{\chi}n \to \phi\gamma\pi^0\ (y=2)$		
$\frac{v}{c}\sigma$ [cm^2]	5.76×10^{-52}	5.53×10^{-51}	4.74×10^{-57}	1.27×10^{-57}	3.02×10^{-55}
Super-K events	5.67	54.4	4.7×10^{-5}	1.3×10^{-5}	3.0×10^{-3}
Hyper-K events	138	1322	1.1×10^{-3}	3.0×10^{-4}	7.2×10^{-2}
DUNE events	9.29	89.4	7.7×10^{-5}	2.0×10^{-5}	4.9×10^{-3}

Signatures

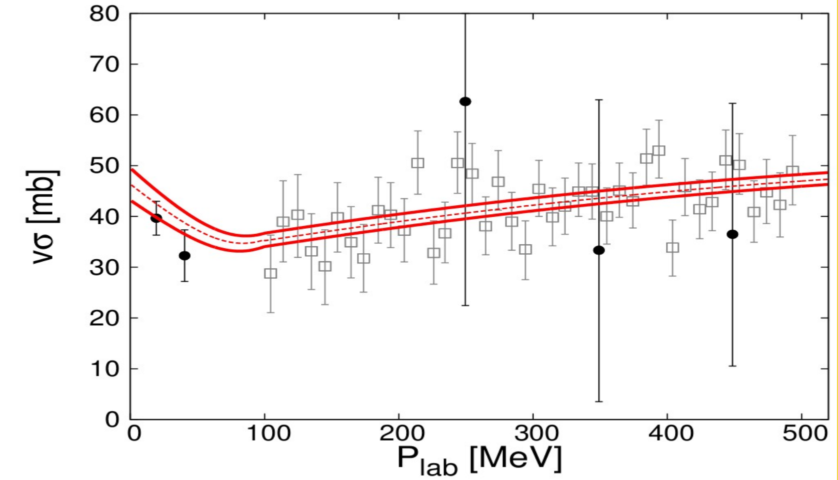
- The predominating channel is **multi-pions**:

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	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%

The Super-Kamiokande Collaboration: 1109.4227.

Signatures

- The predominating channel is **multi-pions**:



$$\frac{v}{c}\sigma(\bar{n}p \to \text{multi-pions})_{\text{exp}} = 44 \pm 3.5\ \text{mb}$$

$$\frac{v}{c}\sigma(\bar{\chi}n \to \text{multi-pions}) = \theta^2\,\frac{v}{c}\sigma(\bar{n}p \to \text{multi-pions})_{\text{exp}}$$

W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Signatures

- The predominating channel is **multi-pions**.
- The signal is similar to the **antineutron-neutron oscillation** searched at **SuperK**.

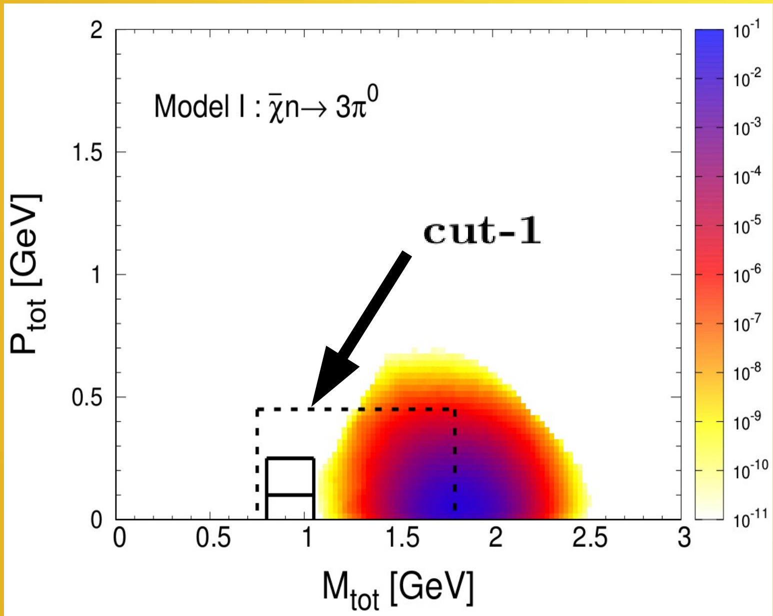
The Super-Kamiokande Collaboration: 1109.4227.

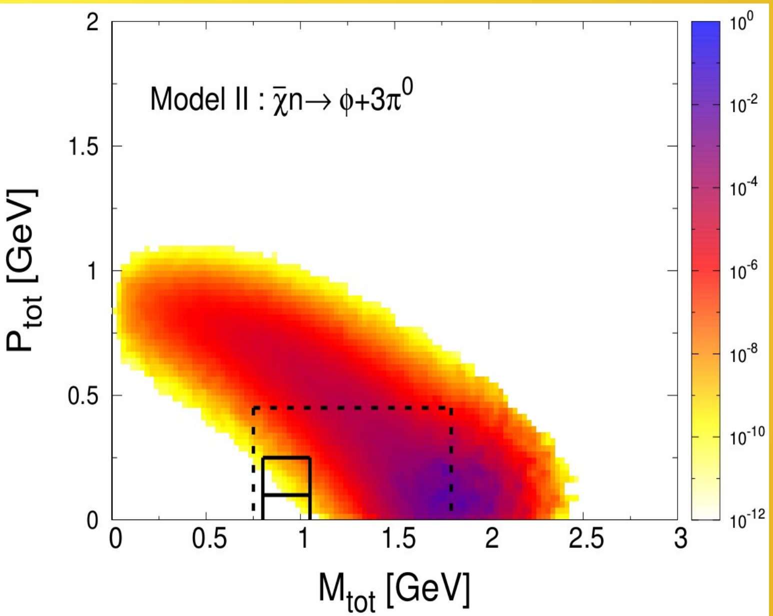
	Kinematic cuts (in MeV)	N_{obs}	N_{bkgd}	$N^{3\sigma}_{\text{Super-K}}$	$N^{3\sigma}_{\text{Hyper-K}}$	$N^{3\sigma}_{\text{DUNE}}$
cut-1	$P_{\text{tot}} \subset [0, 450]$ $M_{\text{tot}} \subset [750, 1800]$ [17]	24	24.1	$[0, 22.5]$	$[0, 75]$	$[0, 27]$
cut-2	$P_{\text{tot}} \subset [0, 100]$, $M_{\text{tot}} \subset [800, 1050]$ [16]	0	0.07	$[0, 7]$	$[0, 5.5]$	$[0, 4]$
cut-3	$P_{\text{tot}} \subset [100, 250]$, $M_{\text{tot}} \subset [800, 1050]$ [16]	0	0.54	$[0, 6.5]$	$[0, 7]$	$[0, 5.8]$

W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Signatures

- The predominating channel is **multi-pions**.
- The signal is similar to the **antineutron-neutron oscillation** searches at **SuperK**.





W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Signatures

- The percentage of events pass the kinematic cuts:

Table 3. Percentage of events that pass the kinematic cuts.

	Model I: $m_\chi = 937.992$ MeV			**Model II: P1**		
	$\bar{\chi}n \to \gamma\pi^0$	$\bar{\chi}n \to 3\pi^0$	$\bar{\chi}n \to 5\pi^0$	$\bar{\chi}n \to \phi\gamma\pi^0$	$\bar{\chi}n \to \phi 3\pi^0$	$\bar{\chi}n \to \phi 5\pi^0$
cut-1	31.2 %	41.0 %	79.7 %	15.4 %	78.3 %	71.8 %
cut-2	2.9×10^{-9} %	1.1×10^{-9} %	5.7×10^{-9} %	2.4×10^{-6} %	2.4×10^{-7} %	1.5×10^{-7} %
cut-3	2.7×10^{-10} %	5.7×10^{-10} %	1.0×10^{-10} %	3.8×10^{-4} %	2.3×10^{-5} %	1.5×10^{-5} %
	Model II: P2			**Model II: P3**		
	$\bar{\chi}n \to \phi\gamma\pi^0$	$\bar{\chi}n \to \phi 3\pi^0$	$\bar{\chi}n \to \phi 5\pi^0$	$\bar{\chi}n \to \phi\gamma\pi^0$	$\bar{\chi}n \to \phi 3\pi^0$	$\bar{\chi}n \to \phi 5\pi^0$
cut-1	1.76 %	57.6 %	93.5 %	14.6 %	57.5 %	87.3 %
cut-2	1.3×10^{-6} %	7.8×10^{-6} %	4.6×10^{-6} %	3.2×10^{-6} %	1.0×10^{-6} %	3.6×10^{-7} %
cut-3	2.8×10^{-4} %	1.1×10^{-3} %	1.1×10^{-3} %	5.0×10^{-4} %	1.0×10^{-4} %	5.8×10^{-5} %

W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

Signatures

- The predominating channel is **multi-pions**.

	Model I		Model II P1	Model II P2	Model II P3
m_χ [MeV]	937.900	938.783	937.900	937.900	939.174
m_ϕ [MeV]	-	-	0	0	0.391
$m_{\tilde{\chi}}$ [MeV]	-	-	937.900	$2m_n$	940.000
λ_ϕ	-	-	0.04	0.04	0.04
$\lvert\theta\rvert$	5.64×10^{-11}	1.75×10^{-10}	4.09×10^{-12}	4.10×10^{-12}	4.03×10^{-11}
$\Gamma_{n\to\chi\gamma\ (\text{or}\ \tilde{\chi}\gamma)}$ [GeV]	7.1×10^{-30}	7.1×10^{-30}	3.7×10^{-32}	0	0
$\Gamma_{n\to\chi\phi}$ [GeV]	-	-	7.06×10^{-30}	7.10×10^{-30}	7.10×10^{-30}
	$\bar{\chi}n \to$ multi-pions		$\bar{\chi}n \to \phi 3\pi^0\ (y = 0.542)$ & $\bar{\chi}n \to \phi 5\pi^0\ (y = 0.337)$		
$\frac{v}{c}\sigma$ [cm^2]	1.40×10^{-46}	1.35×10^{-45}	2.37×10^{-51}	5.14×10^{-54}	7.04×10^{-50}
Super-K events	1.38×10^{6}	1.33×10^{7}	23.3	5.1×10^{-2}	693
Hyper-K events	3.35×10^{7}	3.22×10^{8}	567	1.23	16824
DUNE events	2.26×10^{6}	2.18×10^{7}	38.4	8.3×10^{-2}	1137

W.Y.Keung, D.Marfatia, P.Y.Tseng: 1905.03401.

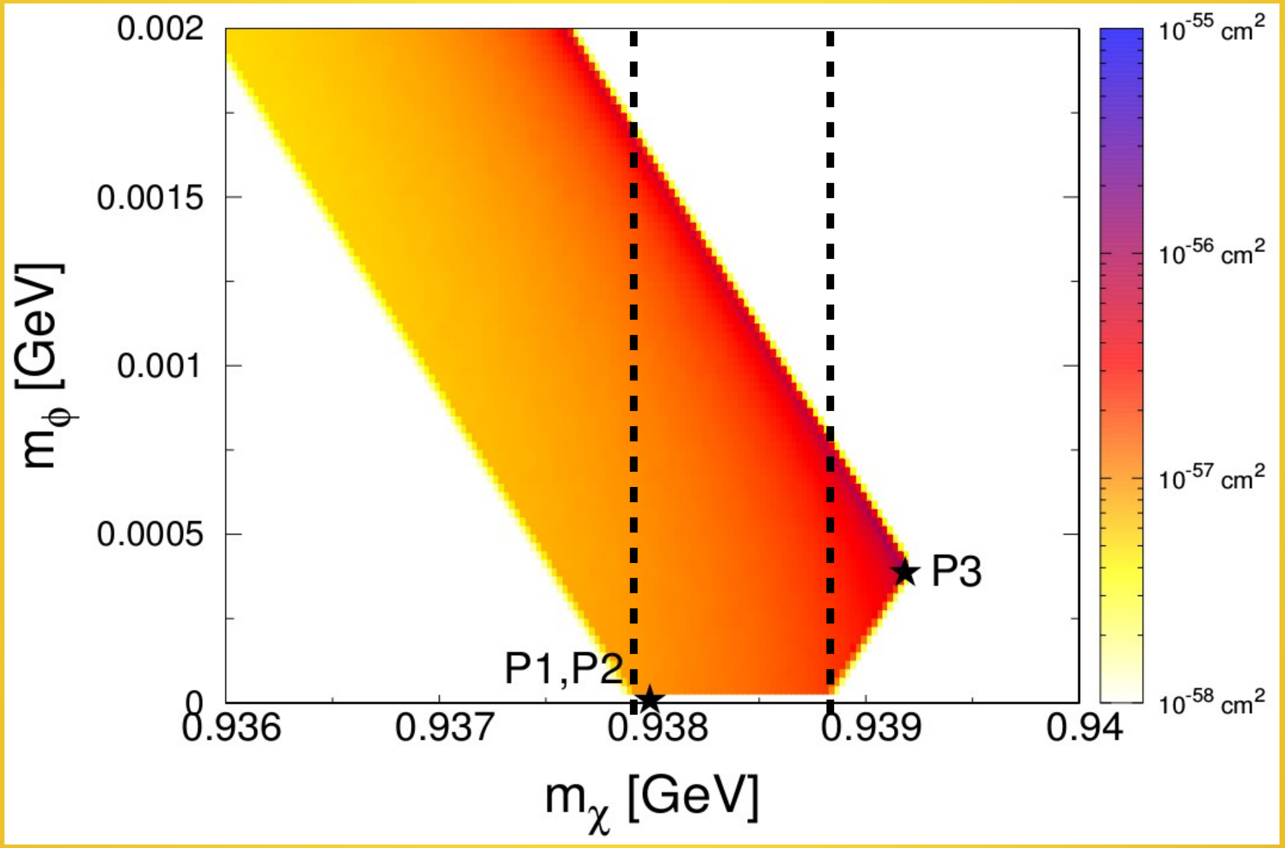
Uncertainties

- From factor:

	P1	P2	P3
Super-K			
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.807	-3.48	-0.236
$\bar{\chi}n \to \phi 3\pi^0$	0.229	-0.721	0.883
$\bar{\chi}n \to \phi 5\pi^0$	0.260	-0.502	0.735
Hyper-K			
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.434	-2.88	0.172
$\bar{\chi}n \to \phi 3\pi^0$	0.658	-0.371	1.297
$\bar{\chi}n \to \phi 5\pi^0$	0.535	-0.261	1.003
DUNE			
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.751	-3.38	-0.173
$\bar{\chi}n \to \phi 3\pi^0$	0.296	-0.665	0.948
$\bar{\chi}n \to \phi 5\pi^0$	0.304	-0.464	0.777

Parameter Space

- Model II:



Signatures

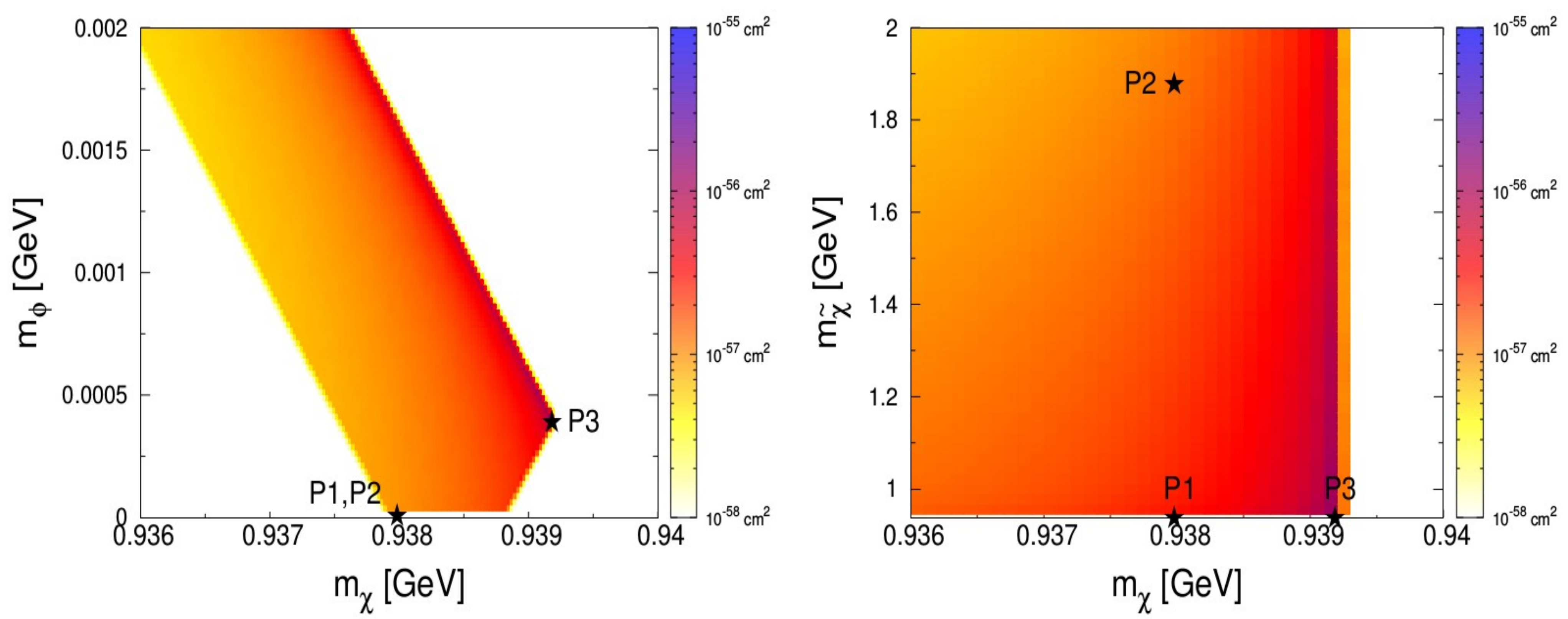
- Mixing angle between **Model I** and **II**:

$$\frac{\Delta\Gamma_{n\to\chi\gamma}}{\Delta\Gamma_{n\to\chi\phi}} = \frac{2g_n^2 e^2}{|\lambda_\phi^2|}\frac{(1-x_1^2)^3}{\sqrt{f(x_1,x_2)}}\left(\frac{m_n - m_{\tilde{\chi}}}{m_n - m_\chi}\right)^2 \simeq \mathcal{O}(10^{-2})$$

where $f(x_1,x_2) \equiv [(1-x_1)^2 - x_2^2][(1+x_1)^2 - x_2^2]^3$ with $x_1 \equiv m_\chi/m_n$ and $x_2 \equiv m_\phi/m_n$.

Uncertainties

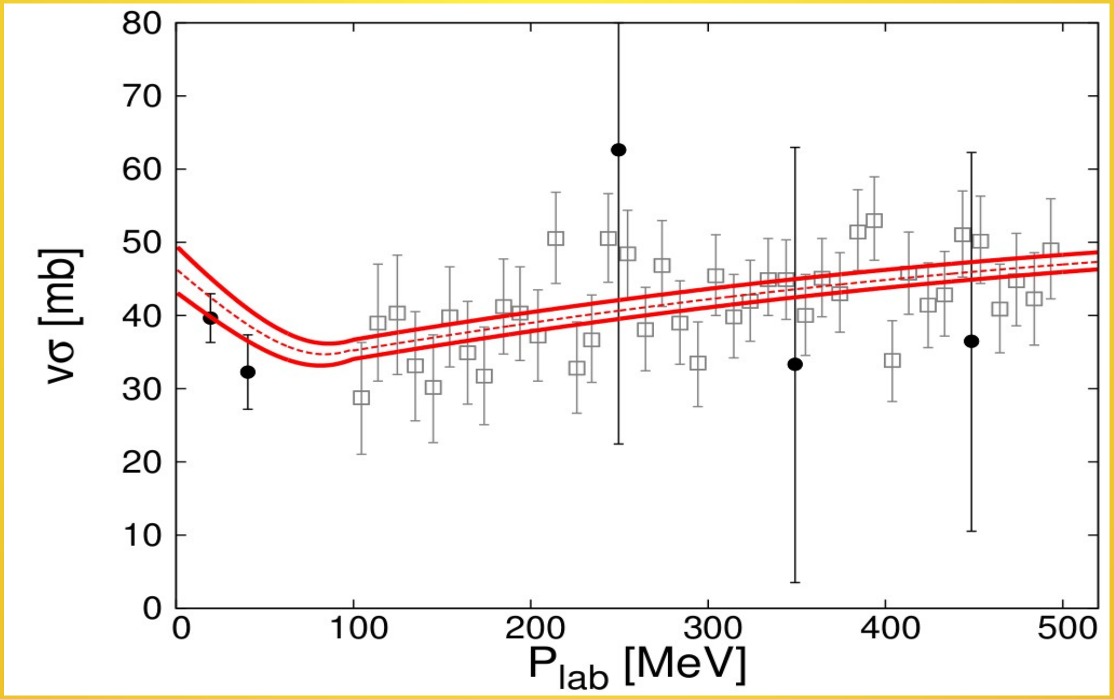
- Model II:



Uncertainties

- Antineutron-proton annihilation cross section:

$$\frac{v}{c}\sigma(\bar{n}p \to \text{multi-pions})_{\text{exp}} = 44 \pm 3.5 \text{ mb}$$



Uncertainties

- From factor:

Super-K			
	P1	**P2**	**P3**
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.807	-3.48	-0.236
$\bar{\chi}n \to \phi 3\pi^0$	0.229	-0.721	0.883
$\bar{\chi}n \to \phi 5\pi^0$	0.260	-0.502	0.735
Hyper-K			
	P1	**P2**	**P3**
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.434	-2.88	0.172
$\bar{\chi}n \to \phi 3\pi^0$	0.658	-0.371	1.297
$\bar{\chi}n \to \phi 5\pi^0$	0.535	-0.261	1.003
DUNE			
	P1	**P2**	**P3**
$\bar{\chi}n \to \phi\gamma\pi^0$	-0.751	-3.38	-0.173
$\bar{\chi}n \to \phi 3\pi^0$	0.296	-0.665	0.948
$\bar{\chi}n \to \phi 5\pi^0$	0.304	-0.464	0.777

Other constraints

- Stability of neutron star (NS).

B.Grinstein, C. Kouvaris, N.G. Nielsen, 1811.06546.

- Equation of State (EoS) describes pressure and energy density at NS.

$$\varepsilon(n_n, n_\chi) = \varepsilon_{\rm nuc}(n_n) + \varepsilon_\chi(n_\chi) + \frac{n_\chi n_n}{2z^2}$$

- DM makes the EoS **softer** such that NS mass < 2 solar mass.

$$\Delta E \equiv \frac{\partial \varepsilon(n_{\rm F} - n_\chi, n_\chi)}{\partial n_\chi} = \mu_\chi(n_\chi) - \mu_{\rm nuc}(n_n) + \frac{n_{\rm F} - 2n_\chi}{2z^2}$$

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B.Grinstein, C. Kouvaris, N.G. Nielsen, 1811.06546.

$$\mathcal{L}_2 = \left(\lambda_q\, \epsilon^{ijk}\, \overline{u^c_{L}}_i\, d_{Rj}\, \Phi_k + \lambda_\chi \Phi^{*i}\, \bar{\tilde{\chi}}\, d_{Ri} + \lambda_\phi\, \bar{\tilde{\chi}}\, \chi\, \phi + \text{h.c.}\right) + M_\Phi^2\, |\Phi|^2 + m_\phi^2 |\phi|^2 + m_\chi\, \bar{\chi}\, \chi + m_{\tilde{\chi}}\, \bar{\tilde{\chi}}\, \tilde{\chi}\,. \quad (38)$$

$$+ \mu H^\dagger H \phi + g_\chi \bar{\chi} \chi\, \phi$$

- Higgs portal and DM-self interactions:

$$g_n \bar{n} n \phi \qquad g_n = \frac{\mu \sigma_{\pi n}}{m_h^2}$$

Other constraints

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$$\mathcal{L}_2 = \left(\lambda_q\, \epsilon^{ijk}\, \overline{u^c_{L}}_i\, d_{Rj}\, \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}}\, d_{Ri} + \lambda_\phi\, \bar{\tilde{\chi}}\, \chi\, \phi + \text{h.c.}\right) + M^2_\Phi\, |\Phi|^2 + m^2_\phi |\phi|^2 + m_\chi\, \bar{\chi}\, \chi + m_{\tilde{\chi}}\, \bar{\tilde{\chi}}\, \tilde{\chi}\,. \qquad (38)$$

$$+\, \mu H^\dagger H \phi + g_\chi \bar{\chi} \chi\, \phi$$

- Higgs portal and DM-self interactions:

$$g_n \bar{n} n \phi \qquad z \equiv m_\phi / \sqrt{|g_\chi g_n|}$$

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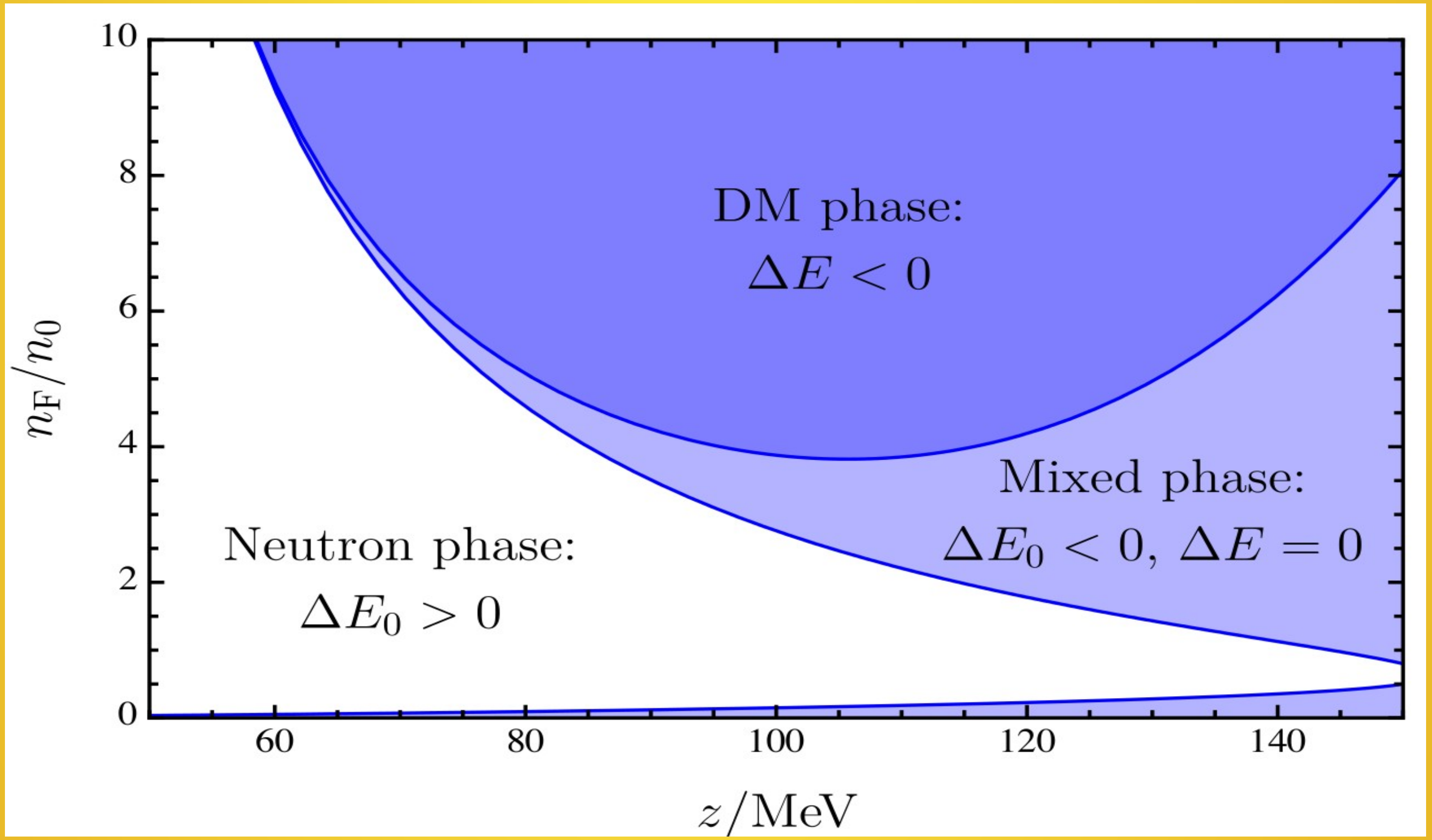
B.Grinstein, C. Kouvaris, N.G. Nielsen, 1811.06546.



TOV Eq.

- **NS** becomes **unstable**: Equation of State (EoS) is too soft to maintain NS heavier than two solar mass.

B.Grinstein, C. Kouvaris, N.G. Nielsen, 1811.06546.

- Tolman-Oppenheimer-Volkoff (TOV) equation:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1},$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2\rho\ , \qquad (11)$$

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