Annihilation Signatures of neutron dark decay

Po-Yan Tseng (Yonsei U.)

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

Reference: 1905.03401, JHEP09(2019)053

NCTS annual theory Meeting 2019, 13rd Dec.

Motivation

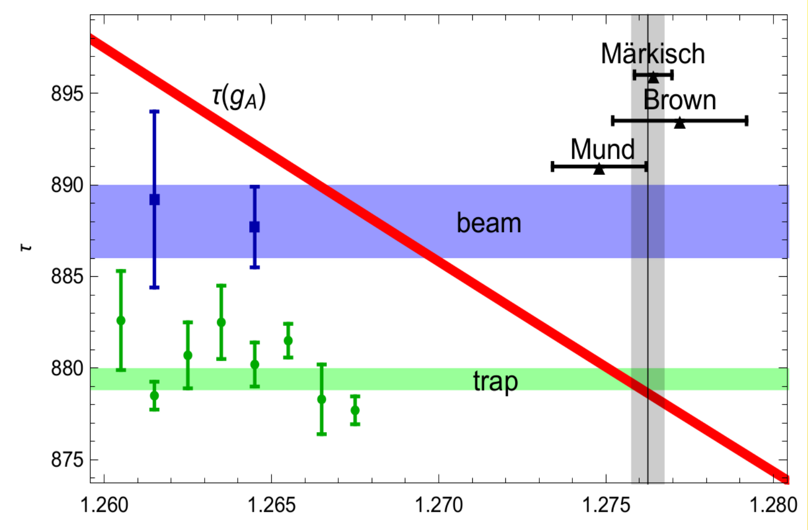
- The **neutron lifetime** is measured in ***bottle*** experiments and ***beam*** experiments.
- ***Bottle***: total lifetime is measured by counting the number of neutrons in a container.
- ***Beam***: count the number of protons from neutron decay.

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

Motivation

- 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.

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

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

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

Motivation

- 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.

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

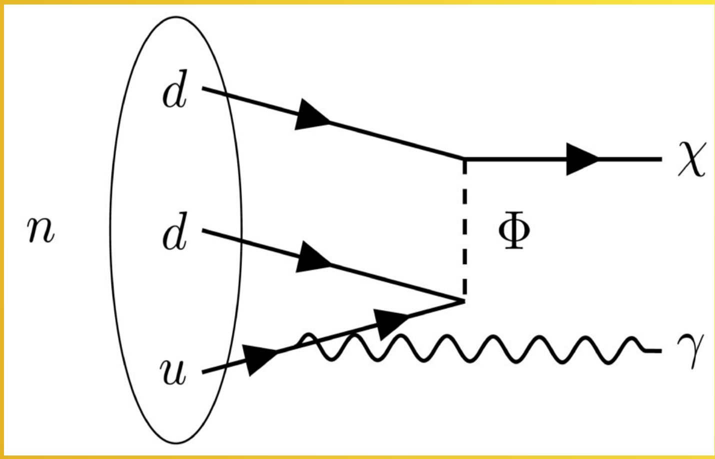
Models

- Two models, invoking dark decays on the neutron:

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

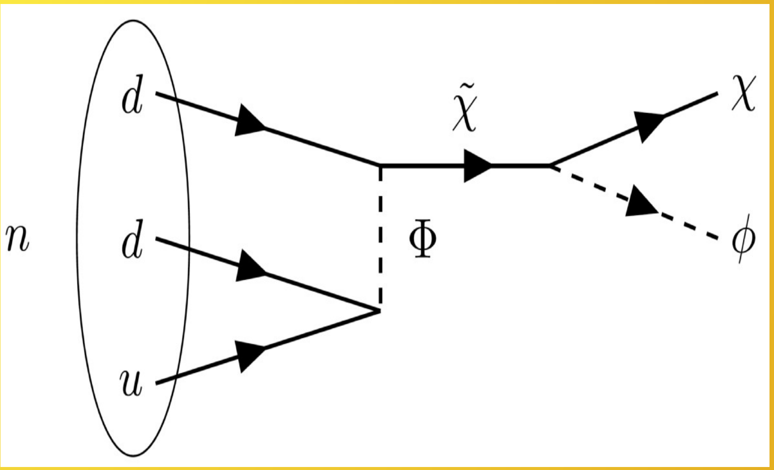
Model I

$$\boxed{n \to \chi + \gamma}$$



Model II

$$\boxed{n \to \chi + \phi}$$



Models

- The colored scalar should be heavier than TeV:

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n ——— χ or $\tilde{\chi}$

$$\boxed{\theta \simeq \frac{\varepsilon}{m_n - m_\chi}}$$

Models

- It can couple to photon and pion:

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Model I	Model II
$\boxed{n \to \chi + \gamma}$	$\boxed{n \to \chi + \phi}$

$$n \;\text{———}\!\times\!\text{———}\; \chi \text{ or } \tilde{\chi}$$

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

Models

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

Model I

$$\boxed{n \to \chi + \gamma}$$

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

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

Model II

$$\boxed{n \to \chi + \phi}$$

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

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

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

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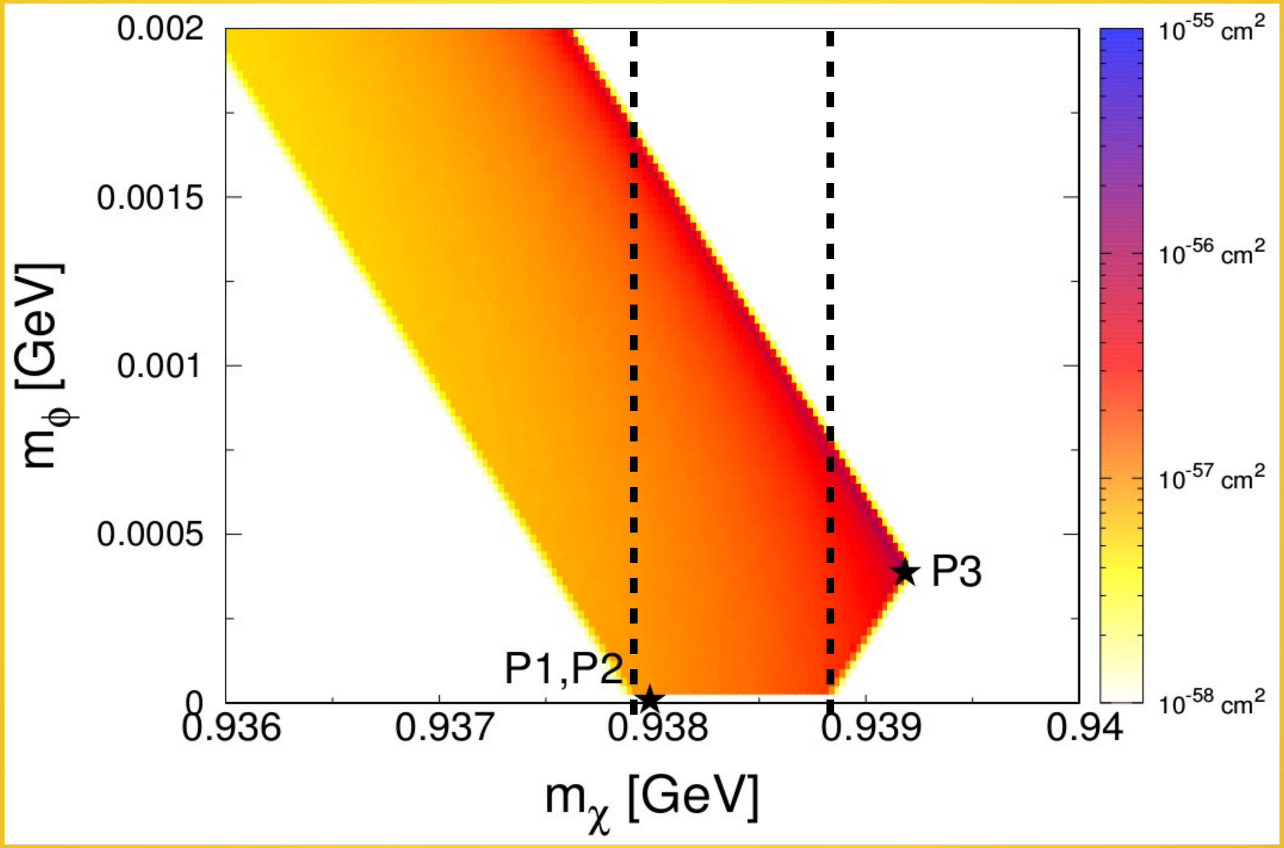
Parameter Space

- Model II:



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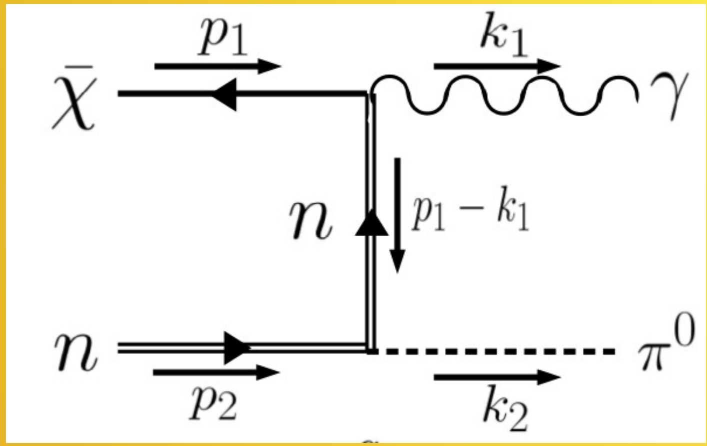
Signatures

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

Model I

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



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Model II

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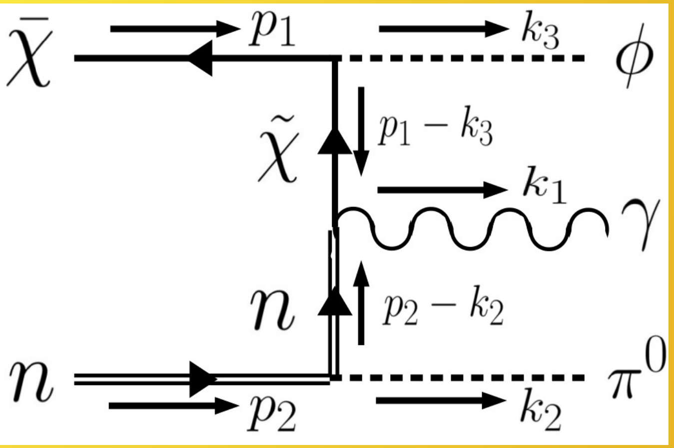

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Halo DM

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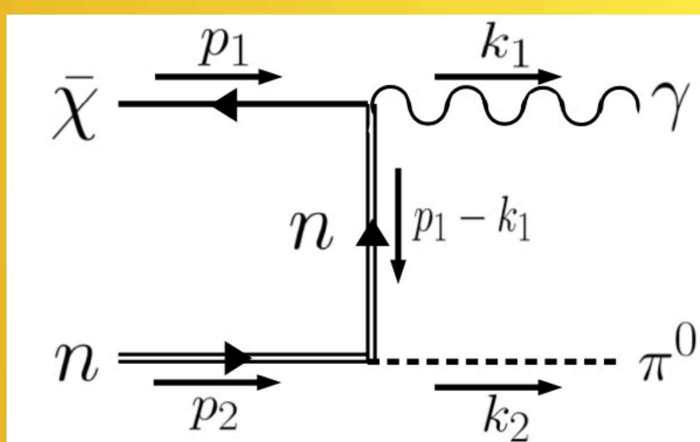

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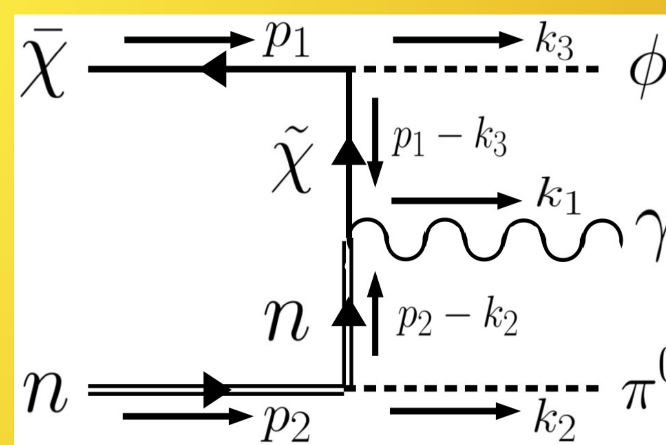
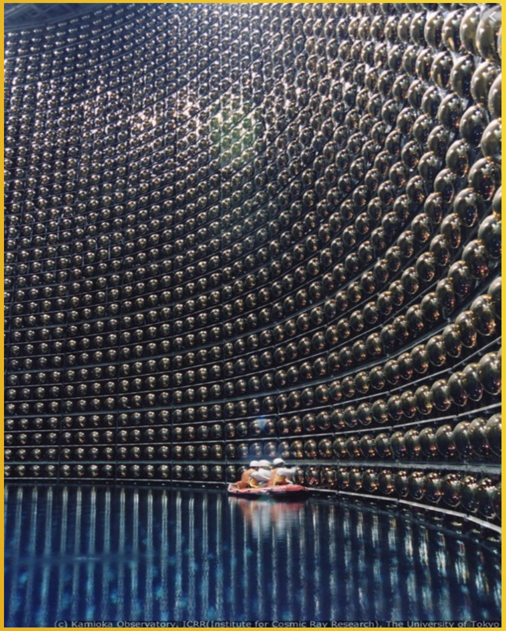
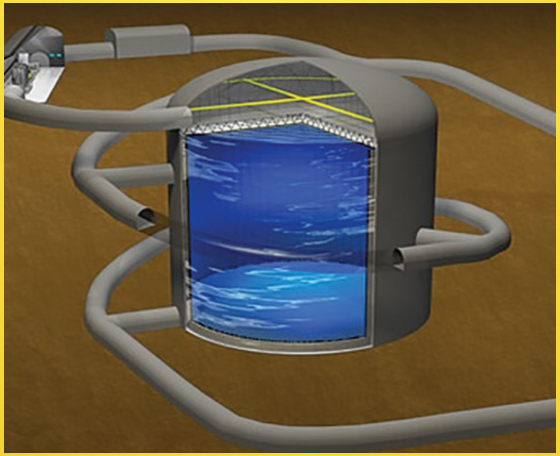


Signatures

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

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





Signatures

- Signal events:

	Model I		Model II P1	P2	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}

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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.

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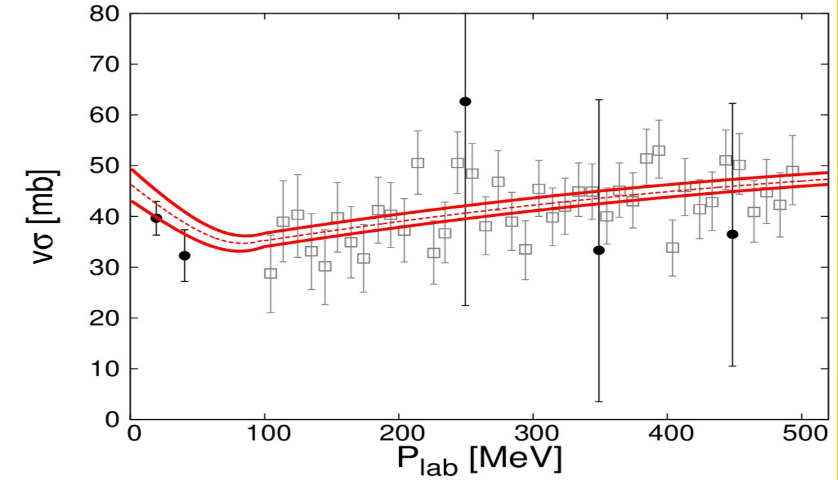

$$\boxed{\frac{v}{c}\sigma(\bar{n}p \to \text{multi-pions})_{\text{exp}} = 44 \pm 3.5 \text{ mb}}$$

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

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

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

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

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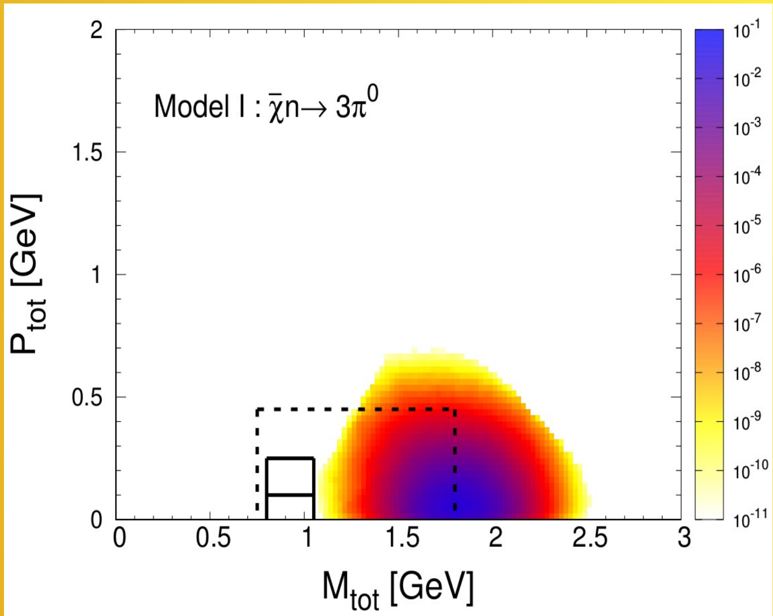

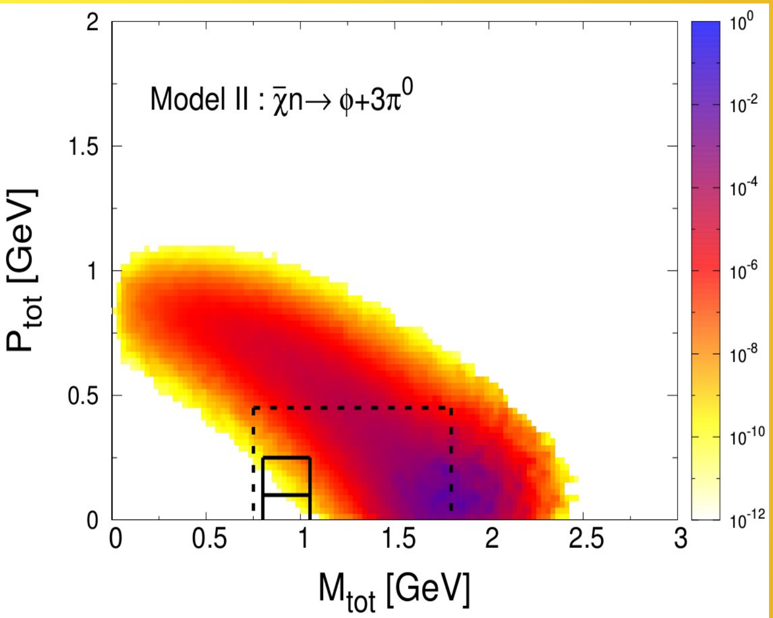

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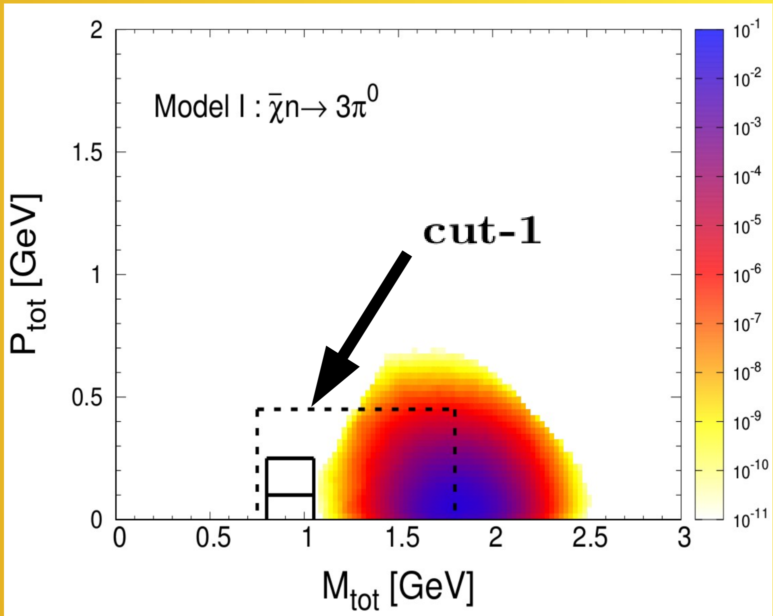

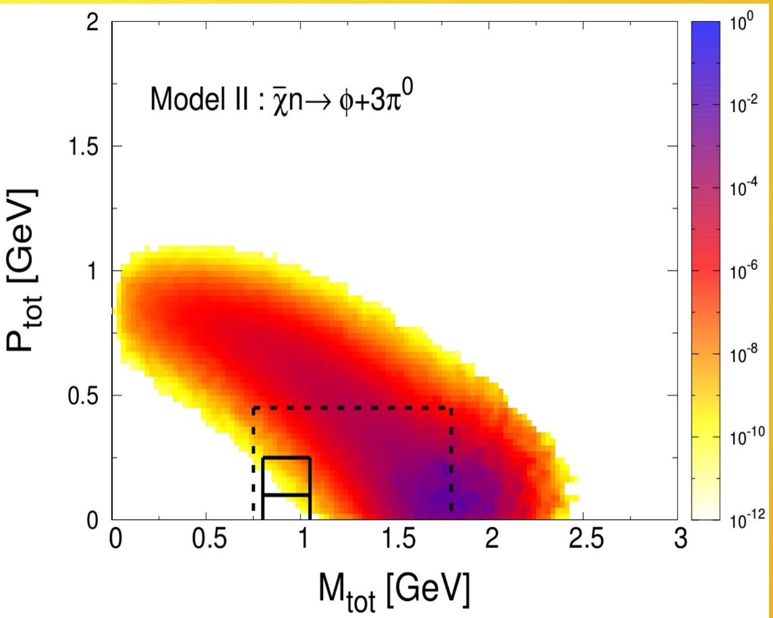

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Signatures

- 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} %

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	$\bar{\chi}n \to$ 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

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	$\bar{\chi}n \to$ 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.

Summary

- We studied the possible signatures from neutron dark decay models at **SuperK**, **HyperK** and **DUNE**.
- **Photon+pion**, or **multi-pion** are the signals.
- **Model I** is ruled out by the current **antineutron-neutron oscillation** search at **SuperK**.
- **Model II** is difficult to completely explore the parameter space, and difficult to rule out. It will be explore by **HyperK** and **DUNE.**

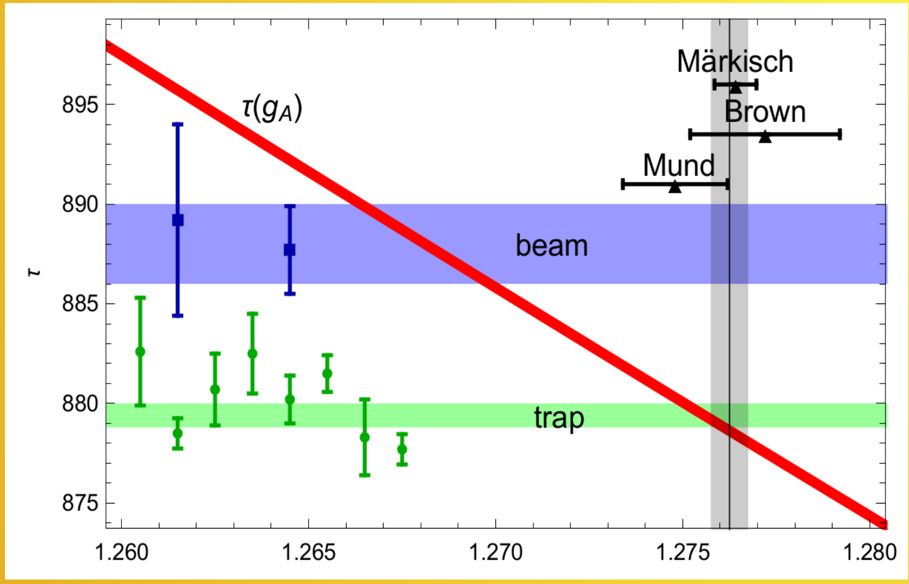
Thank You!

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:

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

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

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

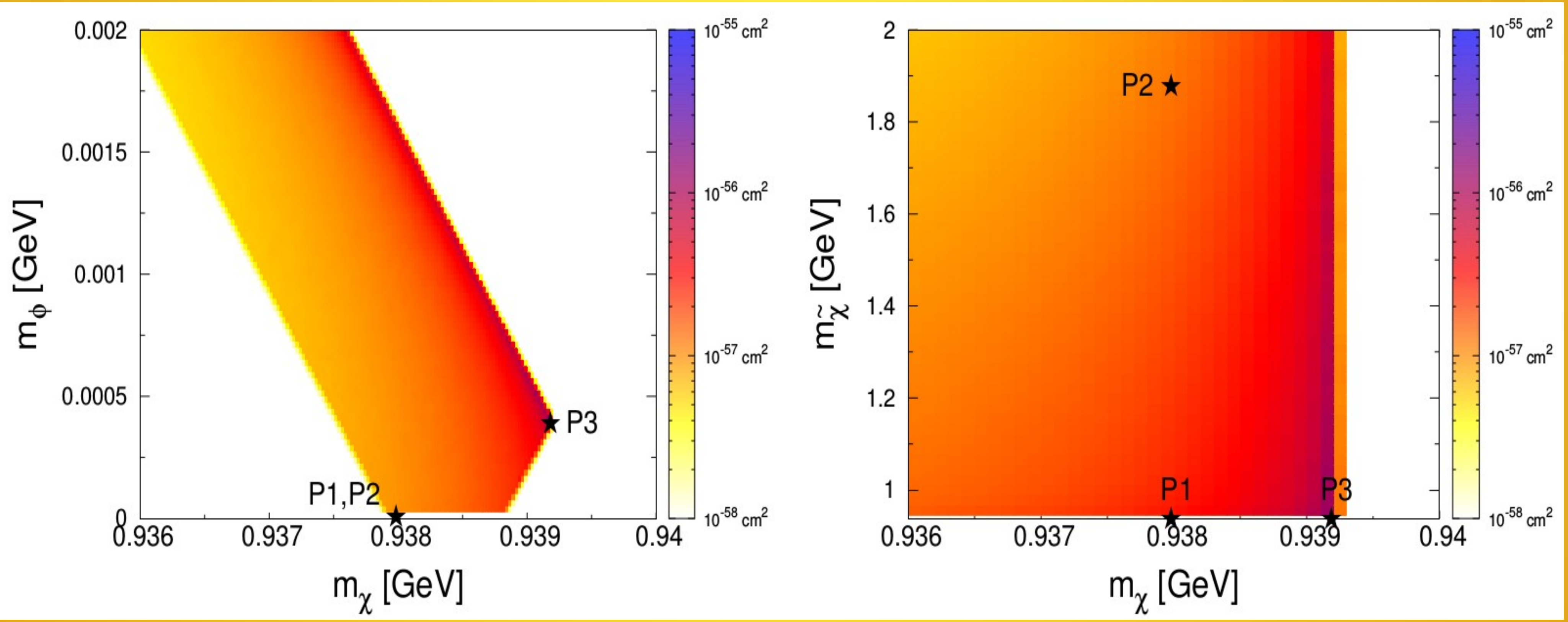
Uncertainties

- 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

Uncertainties

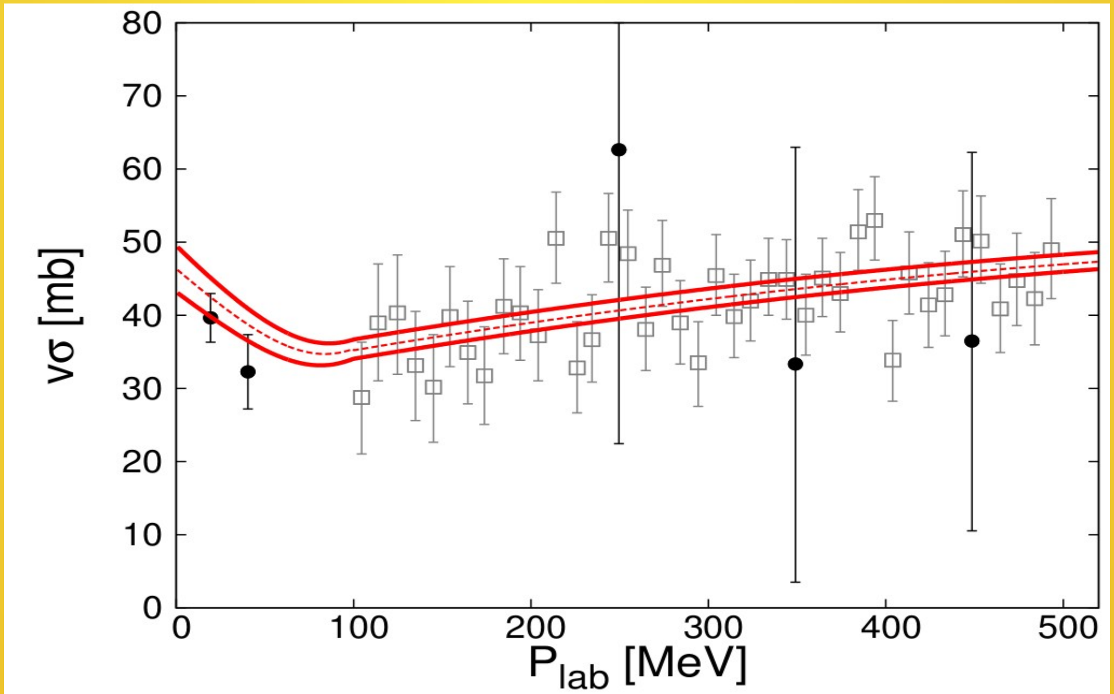
- Model II:



Uncertainties

- Antineutron-proton annihilation cross section:

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



Model II

- Lagrangian:

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

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