Di-quark Assisted Dark Decay of the Neutron

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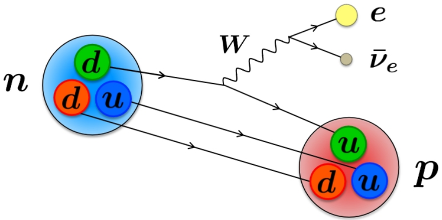
Preliminary results
(in collaboration with Svjetlana Fajfer)

Outline

- Neutron decay anomaly
- Proposal
- Astrophysical Implications
- Complementary tests at colliders

Free Neutron Decay (β^- decay)

Mean lifetime decay: $\sim$ 15 mins



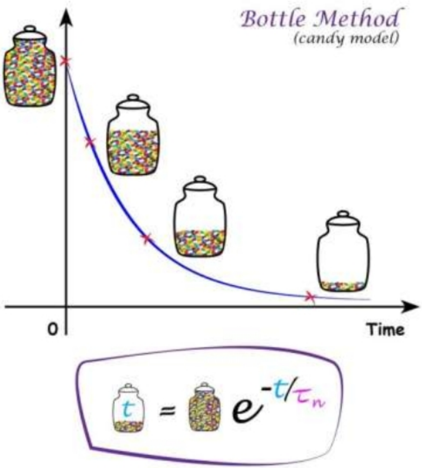
$$\mathrm{Br}(n \to p^+ + e^- + \overline{\nu}_e) \sim 99\%$$

$$\mathrm{Br}(n \to p^+ + e^- + \overline{\nu}_e + \gamma) \sim 1\%$$

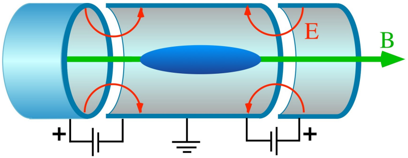
$$\mathrm{Br}(n \to H + \nu_e) \sim 4 \cdot 10^{-6}\%$$

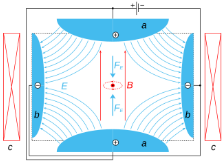
Lifetime: Bottle Experimental

- Ultracold neutrons are stored and the "neutrons" inside it are counted (N_n)

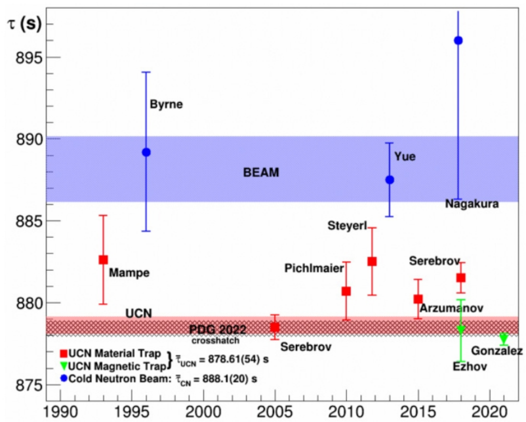


- A collimated beam of cold neutrons passes through a quasi-Penning trap. The "protons" from neutron decays are trapped and counted (N_p)





Long-standing puzzle



$$\tau_n^{\text{bottle}} = 878.4 \pm 0.5s \qquad \tau_n^{\text{beam}} = 888.0 \pm 2.0s$$

$$\sim 14.64\text{min} \qquad \sim 14.8\text{min}$$

$$\Delta\tau_n = 9.6s \quad \Rightarrow \text{discrepancy of } 4\sigma$$

Interpretation of the anomaly

- SM: $Br(n \to p + \text{anything}) = 1$

- Experiments:

$$\frac{\tau_n^{\text{bottle}}}{\tau_n^{\text{beam}}} = \text{BR}(n \to p + \text{anything}) < 1$$

$\Rightarrow$ Missing protons! $\Rightarrow$ BSM!

- Consistency of two types of experiments:

$$\text{BR}(n \to \text{anything} \neq p) \approx 1\%$$

BSM explanation

- $\mathrm{BR}(n \to \text{anything} \neq p) \approx 1\%$
  $\Rightarrow$ neutron dark decays!

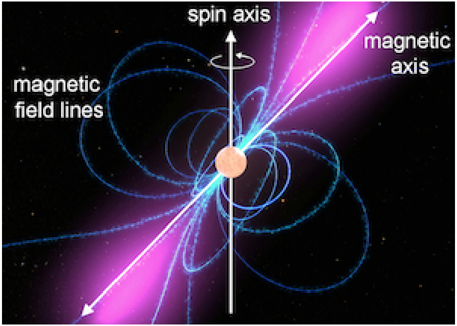
- Minimal possibility: $n \to \chi\gamma$ with χ a fermion with $B_\chi = 1$
  Fornal and Grinstein 2018

- By operator: $\mathcal{O} = n\,\chi$.

- Experimental consequences: Astrophysical and terrestrial.

Neutron stars

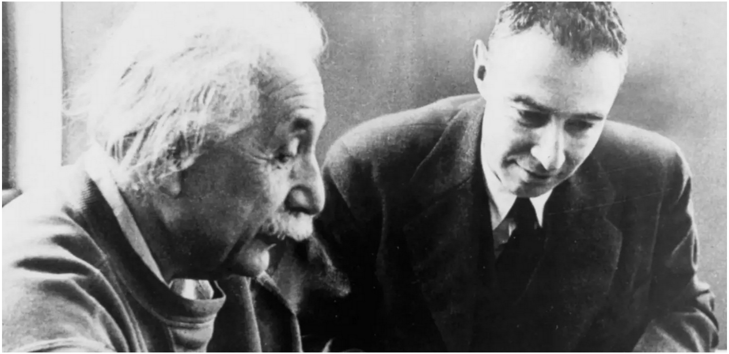
- The most compact stars known in the Universe $\sim 10^{57}$ neutrons!
- $R \sim \mathcal{O}(10)$ Km; $\quad R/R_\odot \sim 10^{-5}$
- Typically $M \sim 1.4 M_\odot$
- Central density $\rho \sim (10-20)\rho_0$



Tolman-Oppenheimer-Volkoff equations

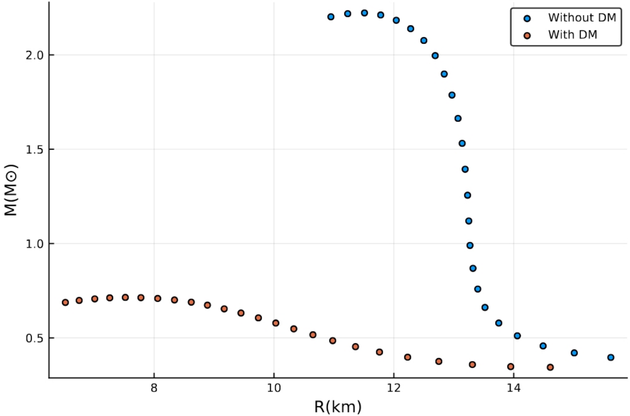
$$\frac{dp}{dr} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2 r^2}\left[1 + \frac{p(r)}{\epsilon(r)}\right]\left[1 + \frac{4\pi r^3 p(r)}{\mathcal{M}(r)c^2}\right]\left[1 - \frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2 \rho(r)$$



Tolman 1939, Oppenheimer, Volkoff 1939

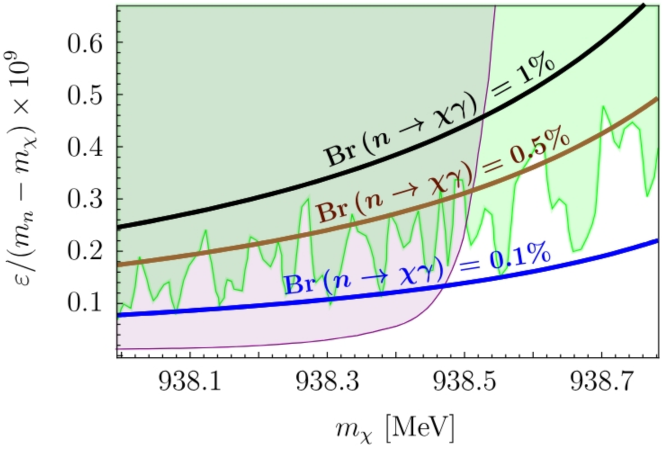
Mass-Radius relation



Rules out $(m_\chi \approx m_n)$: $n \to \chi\gamma \quad (n \to \chi e^+e^-,\ n \to \chi\phi)$

Baym et. al. 2018, McKeen et. al. 2018, Motta et. al. 2018

Neutron decay: Lab bounds



Rules out (0.782 MeV $< E_\gamma <$ 1.664 MeV): $n \to \chi\gamma$

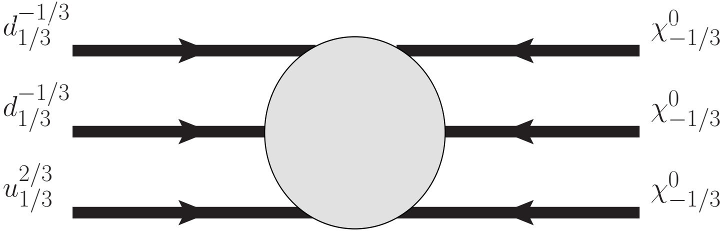
Los Alamos 2018, Borexino, McKeen et. al. 2020

Towards a Viable Model

- $n \to \chi\gamma$, $\chi e^+ e^-, \chi\phi$: $\quad B_\chi = B_n$
- In equilibrium, $\mu_\chi = \mu_n$
  $\Rightarrow$ EoS becomes softer
- Strumia's observation: $n \to 3\chi \quad B_\chi = \frac{B_n}{3}$
  Strumia 2021
- In equilibrium, $\mu_\chi = \frac{1}{3}\mu_n$
  $\Rightarrow$ Stiffening the EoS

Our Proposal

$n \to 3\chi$:



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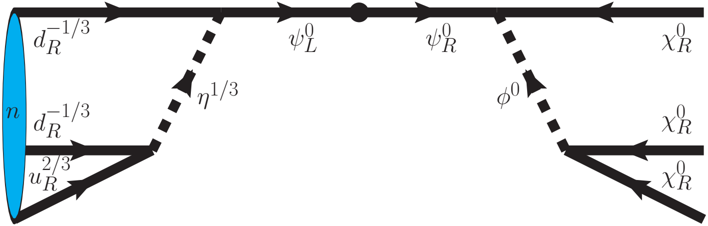
Our Proposed Model



Field	Type	$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_B$
χ	F	$(1, 1, 0, -\frac{1}{3})$
ψ	F	$(1, 1, 0, +1)$
ϕ	S	$(1, 1, 0, -\frac{2}{3})$
η	S	$(\overline{3}, 1, \frac{1}{3}, +\frac{2}{3})$

$m_\phi > 2m_\chi$ and $m_\psi > m_n$

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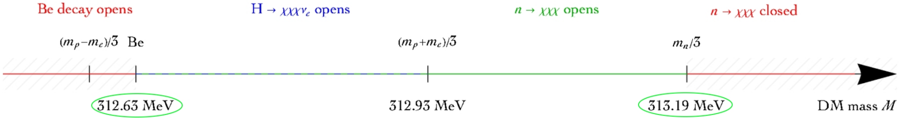
Predicting the Mass



Strumia 2021

Expected Scale

Nucleon level

$$\mathcal{L}^{\mathrm{d}=6} \supset \frac{1}{3!\Lambda_n^2} \left(X^T C y P_R X\right) \left(\overline{n} y' P_R X\right) + h.c.$$

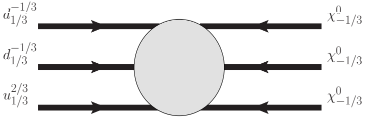
leading to

$$\Gamma_{n\to\chi\chi\chi} \approx \frac{m_n^5 \epsilon^2}{128\pi^3 \Lambda_n^4} \sim \epsilon \Delta\Gamma \left(\frac{100\mathrm{TeV}}{\Lambda_n}\right) \left(\frac{m_n - 3m_\chi}{E_{Be}}\right)$$

$\epsilon \equiv 1 - 3m_\chi / m_n$.

$\Rightarrow \Lambda_n \approx 20$ TeV.

Scale: Naive Expectation



Fundamental level:

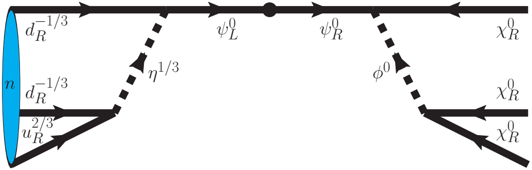
$$\mathcal{L}^{d=9} \supset \frac{udd\chi\chi\chi}{3!\Lambda_{\chi q}^5}$$

Lattice: $\langle 0|(ud)_R d_R|n\rangle = \beta_R n, \quad |\beta_R| \sim \Lambda_{\rm QCD}^3.$

$$\frac{1}{\Lambda_n^2} \sim \frac{\Lambda_{\rm QCD}^3}{\Lambda_{\chi q}^5}$$

For a single NP scale: $\Lambda_{\chi q} \sim 23$ GeV

Scale of New Physics



$$\mathcal{L}^{d=9} \to m_\psi \overline{\psi}\psi + \mathcal{L}^{d=6} \supset \frac{\overline{\psi}udd}{\Lambda_{\psi q}^2} + \frac{\psi\chi\chi\chi}{3!\Lambda_{\psi\chi}^2}$$

$$\frac{\beta_R}{3!\Lambda_{\chi q}^5} \sim \frac{\Lambda_{\rm QCD}^3}{\Lambda_{\psi q}^2} \frac{1}{m_\psi} \frac{1}{3!\Lambda_{\psi\chi}^2}$$

$$\Lambda_{\chi q} \sim \left(m_\psi m_\phi^2 m_\eta^2\right)^{1/5} \sim 23 \text{ GeV}$$

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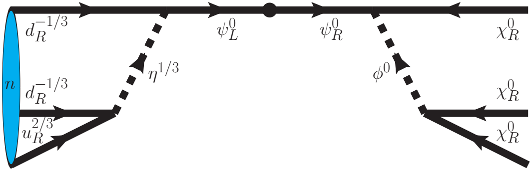
Predicting NP Scales



- $m_\phi < 2m_\chi$ then $\mathcal{O} \sim n\psi$, therefore $n \to \chi\phi$
- $m_\phi > 2m_\chi$ we can have $n \to 3\chi$
- $m_\psi > m_n$: neutron star bound

$$m_\eta \lesssim 4\ \mathrm{TeV} \quad !$$

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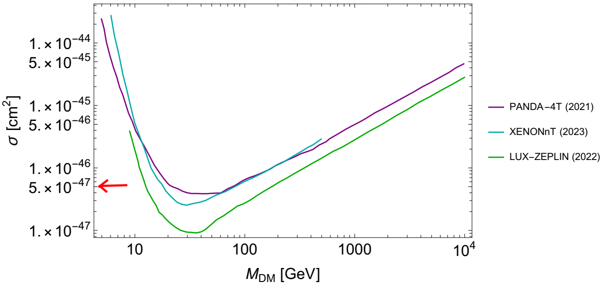
DM direct detection

- $\overline{\chi} n \to \chi\chi$, $\chi \overline{n} \to \overline{\chi\chi}$: kinematically open today.

$$\sigma_{\overline{\chi} n \to \chi\chi} \approx \frac{m_n^2}{4\pi \Lambda_n^4} \sim 10^{-46}\mathrm{cm}^2 \left(\frac{20\mathrm{TeV}}{\Lambda_n}\right)^4$$



Disappearance of Neutron

DM scattering makes ordinary matter radioactive

e.g., ${}^{16}O_8 \xrightarrow{\overline{\chi}} {}^{15}O_8 \rightarrow {}^{15}O_8 + \gamma[10 MeV] \rightarrow {}^{15}N_7 + e^+[MeV] + \nu_e$

with life-time

$$\tau = \left(\frac{1}{2m_\chi}\rho_{\rm DM} v \sigma_{\overline{\chi}n\rightarrow\chi\chi}\right)^{-1} \sim 2.5\times 10^{30}{\rm yr}$$

Experiments:

$$\tau(n\rightarrow \text{invisible}) > \begin{cases} 4.9\times 10^{26}{\rm yr} & \text{KAMIOKANDE} \\ 2.5\times 10^{29}{\rm yr} & \text{SNO} \\ 5.8\times 10^{29}{\rm yr} & \text{KAMLAND} \end{cases}$$

$\Gamma(n\rightarrow \chi\chi\chi\gamma) \sim 10^{-9}\Gamma(n\rightarrow\chi\chi\chi)$: also satisfied(Los Alamos).

Relic Abundance

- $m_\phi > 2m_\chi$, $\chi =$ DM.
- $\chi\chi \to f\overline{f}$ with $f = e, q$, via loop. Higgs decay to invisible bound. Not efficient enough. Simple extension?
- ω: $(B, L) = (-1/3, -1)$ and sterile neutrinos:

$$\mathcal{L} \supset \overline{\chi}_L \omega N_R + h.c.$$

- $\chi\overline{\chi} \to N_R \overline{N}_R$
- $m_N > m_\chi$: $\chi\overline{\chi} \to \nu\nu$
- Interesting experimental implications + Neutrino mass origin

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Neutron Star: EoS

$$\frac{dp}{dr} = \frac{-G}{r^2}\frac{(M+4\pi r^3 P)(\rho+p)}{1-2GM/r}, \quad \frac{dM}{dr} = 4\pi r^2\rho, \quad \epsilon(r) = \rho(r)c^2$$

EoS: $\epsilon(r) - p(r)$ relation

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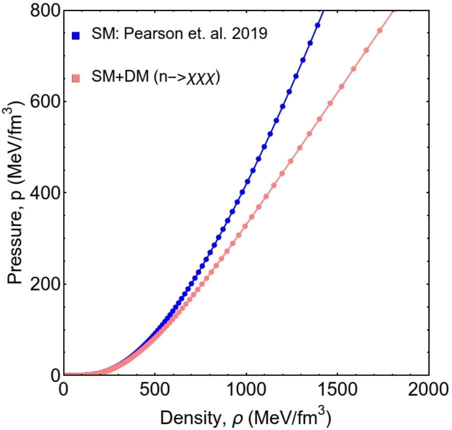
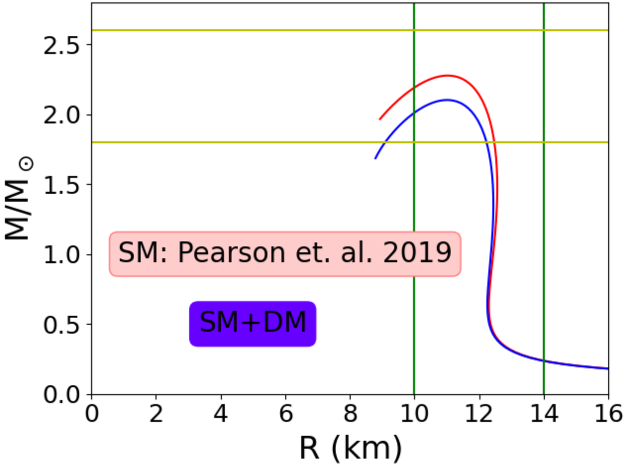


Effects on Neutron Stars



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Summary

- ❈ Neutron Decay : longstanding puzzle $\rightarrow$ New Physics?
- ❈ New Physics $\rightarrow$ Sub-GeV+TeV scale NP
- ❈ Strong Interplay with Astrophysics
- ❈ Dark Matter candidate + origin of Neutrino Mass
- ❈ Offers Colliders+Low-energy experimental probes

THANK YOU!