Dark Side of the Neutron?

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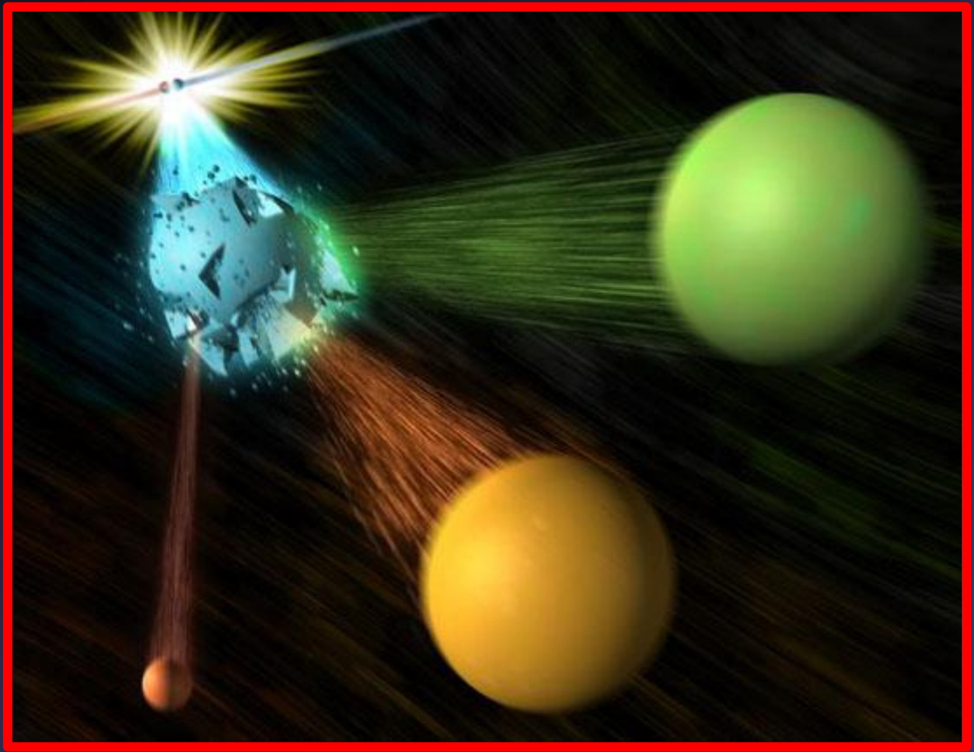
In collaboration with: ***Bartosz (Bart) Fornal***

Particle decay



Source: https://www6.slac.stanford.edu

① Decays to at least two particles

① Sum of final state particle masses smaller than the initial particle mass

② Conservation of energy and momentum

① Quantum numbers conserved

Particle decay

Decay rate

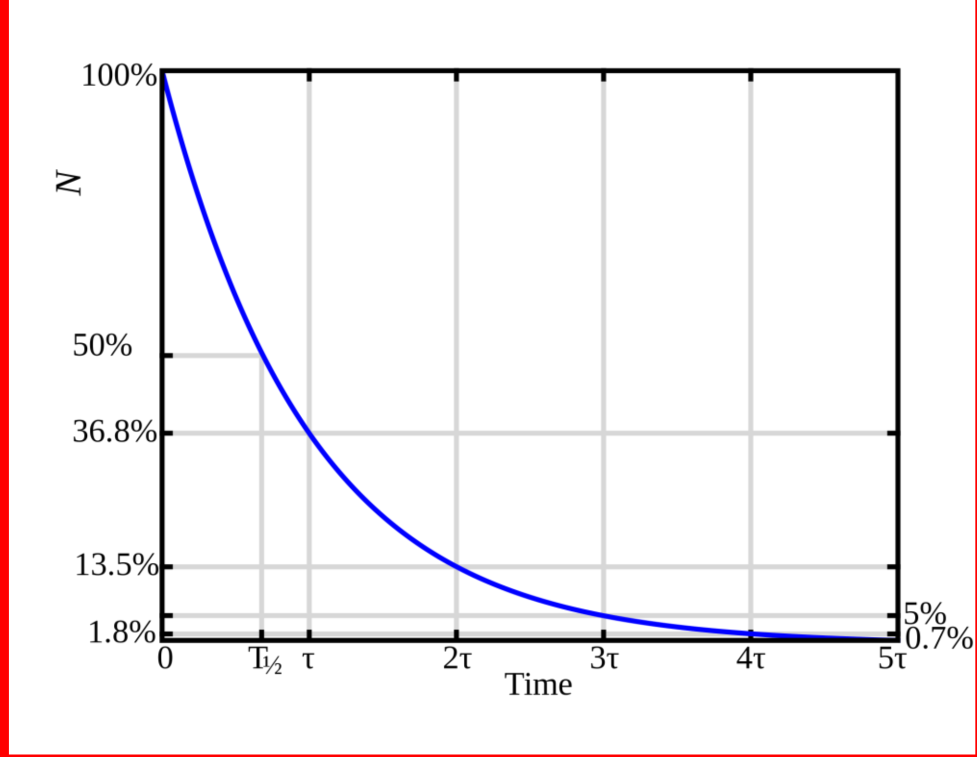
$$\frac{dN}{dt} = -\lambda N$$

Number of particles

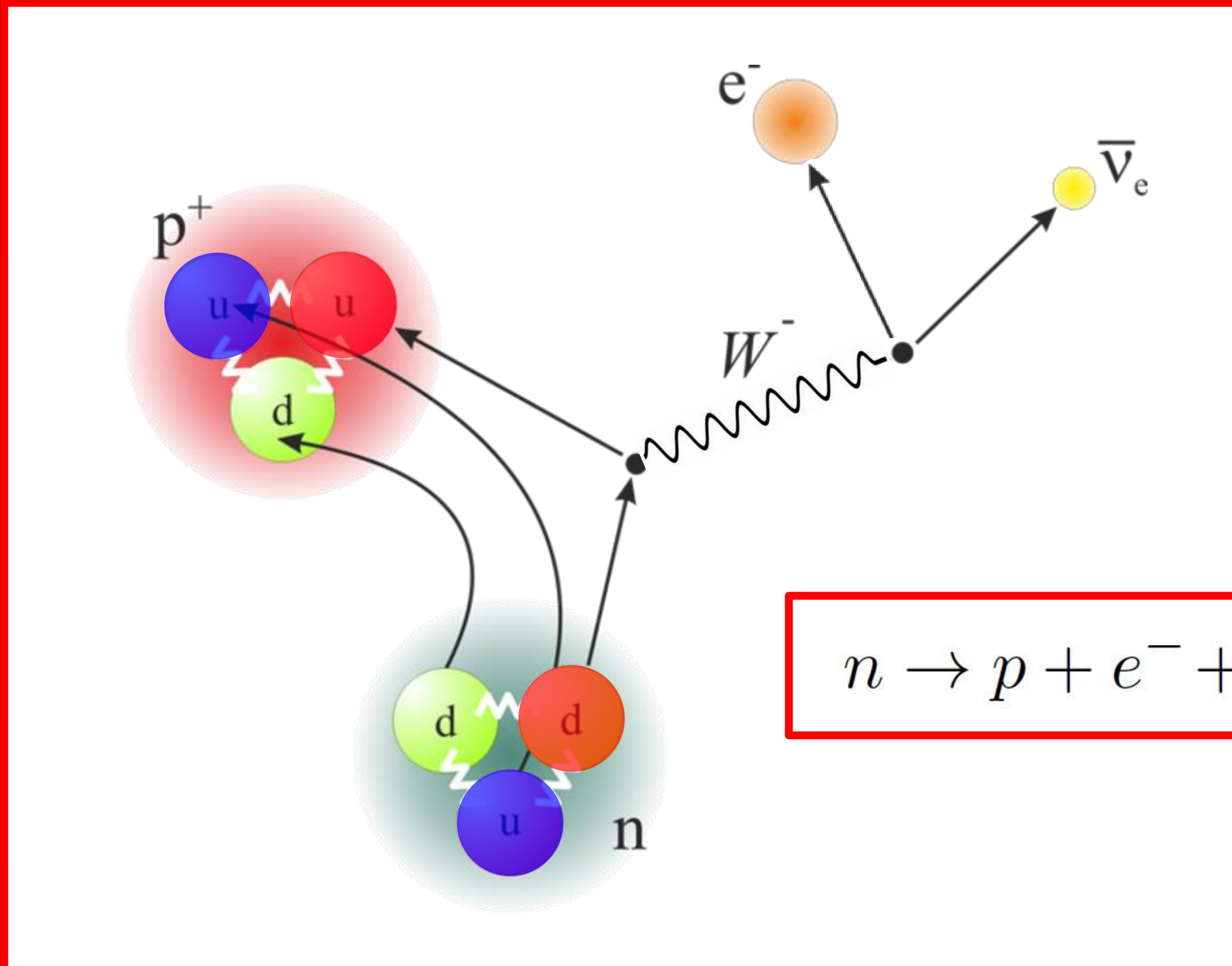
$$N = N_0\, e^{-\lambda t}$$

Lifetime

$$\tau = \frac{1}{\lambda}$$



Neutron beta decay



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

Neutron lifetime

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

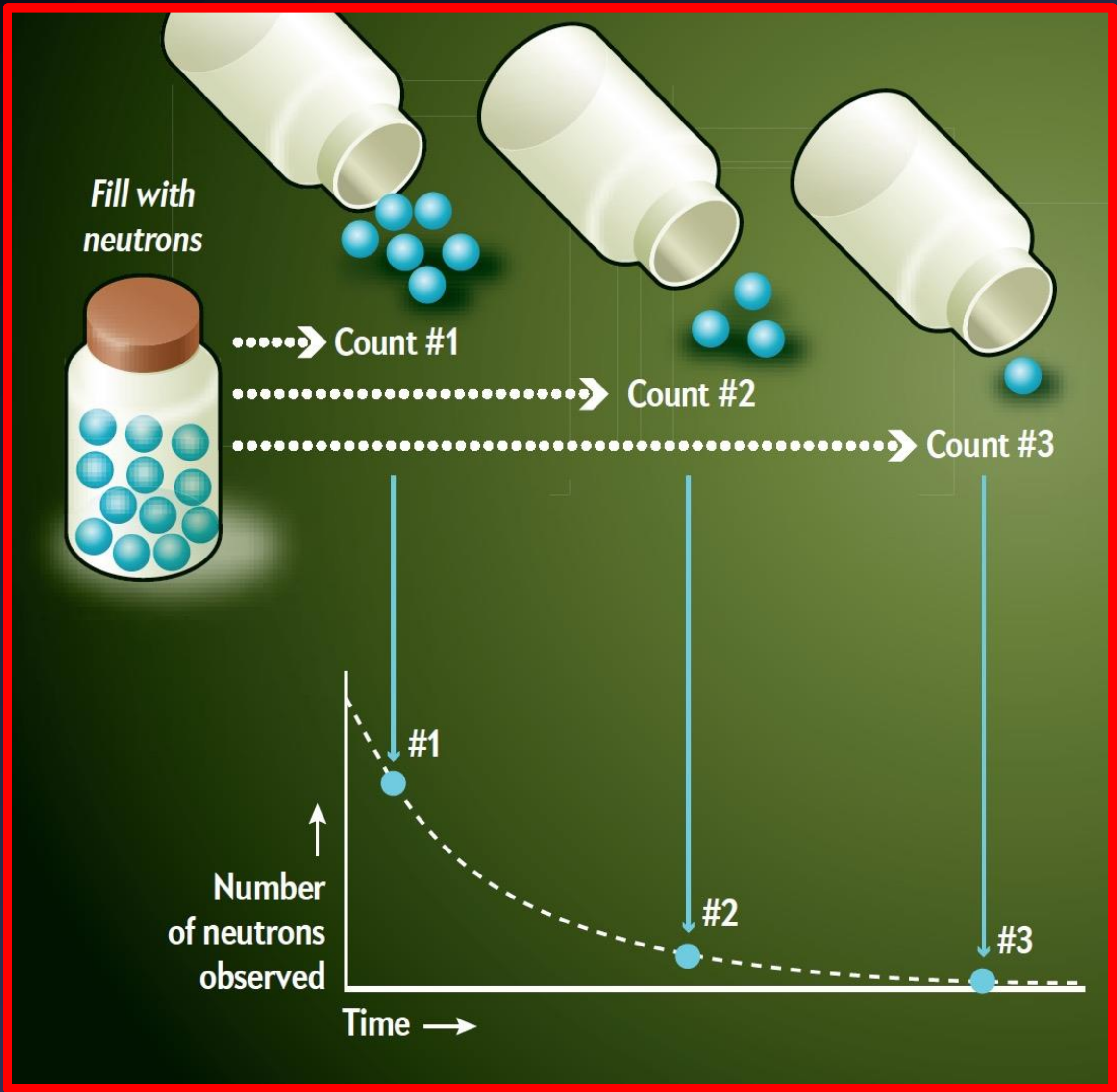
Beam experiments $$\tau_n^{\text{beam}} = 888.0 \pm 2.0 \text{ s}$$

Discrepancy $$\frac{\Delta\tau_n}{\tau_n} = \frac{\Delta\Gamma_n}{\Gamma_n} \approx 1\%$$

Theoretical predictions rely on

$$\mathcal{M} = \left[G_V \, \bar{p}\, \gamma_\mu n - G_A \, \bar{p}\, \gamma_5 \gamma_\mu n \right] \left[\bar{e}\, \gamma_\mu (1 - \gamma_5) \nu \right]$$

Bottle experiments



Source: https://www.scientificamerican.com

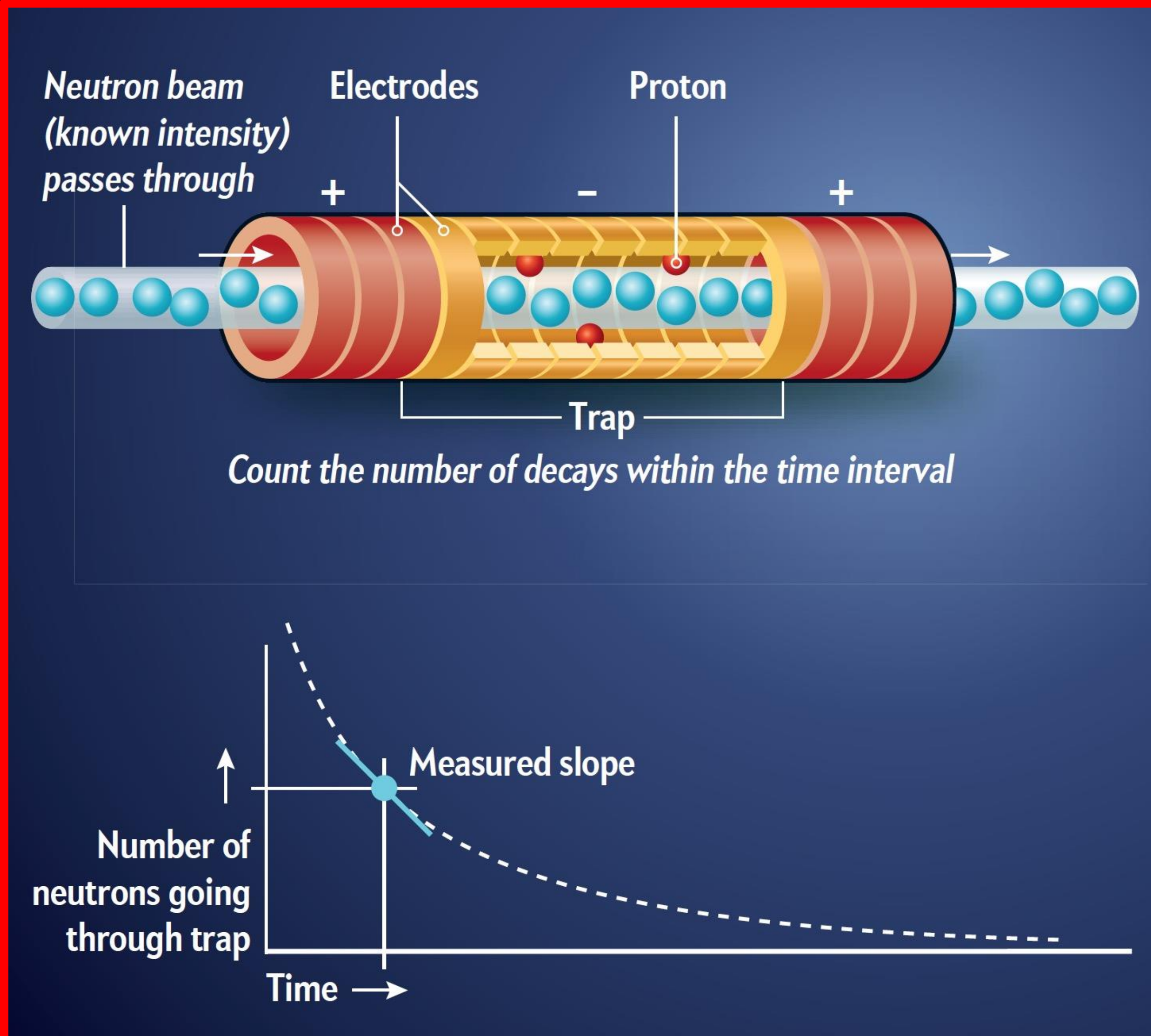
Fitting to an exponential decay

$$N = N_0 \, e^{-\lambda t}$$

Lifetime

$$\tau = \frac{1}{\lambda}$$

Beam experiments

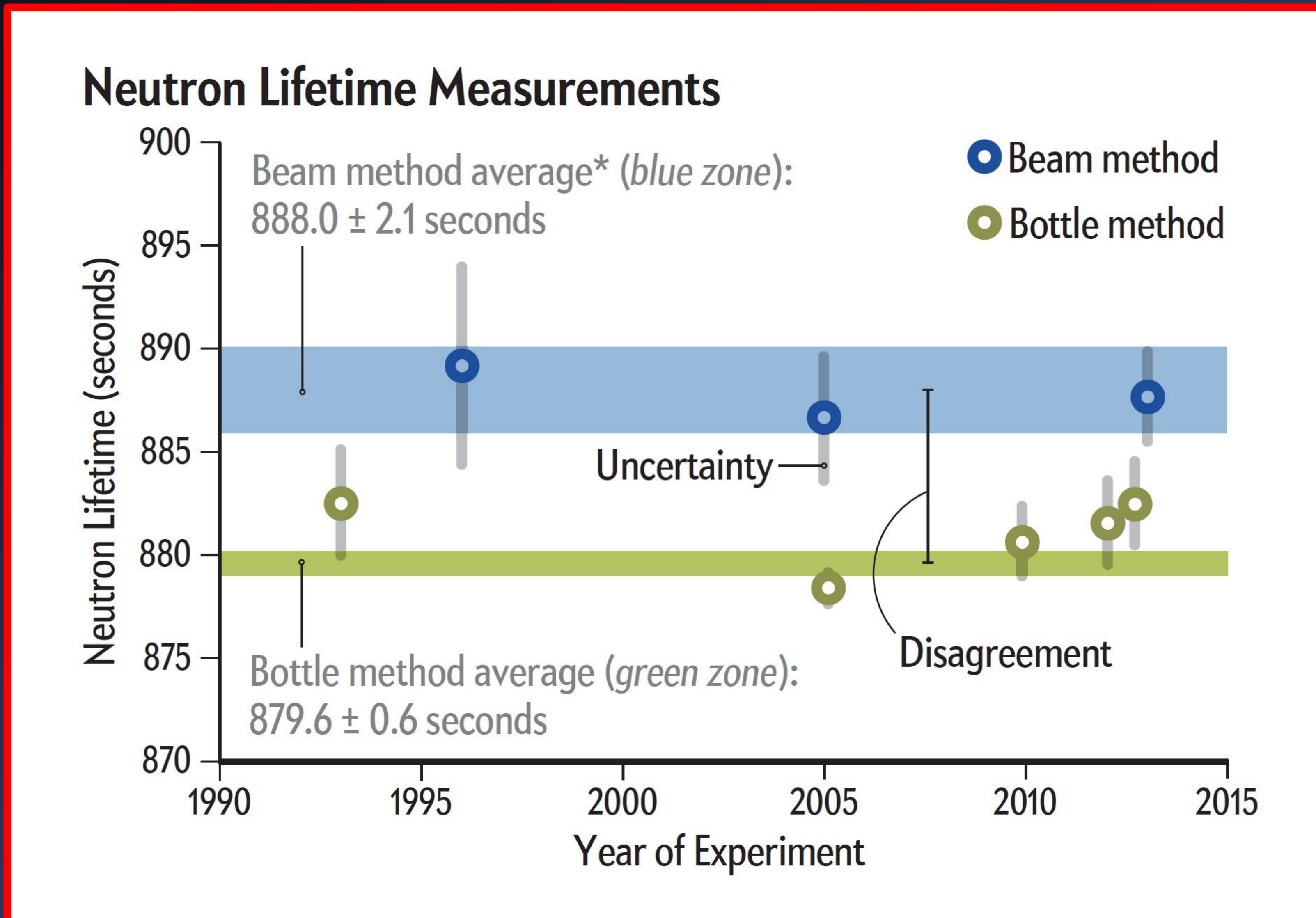


Source: https://www.scientificamerican.com

Measuring the rate

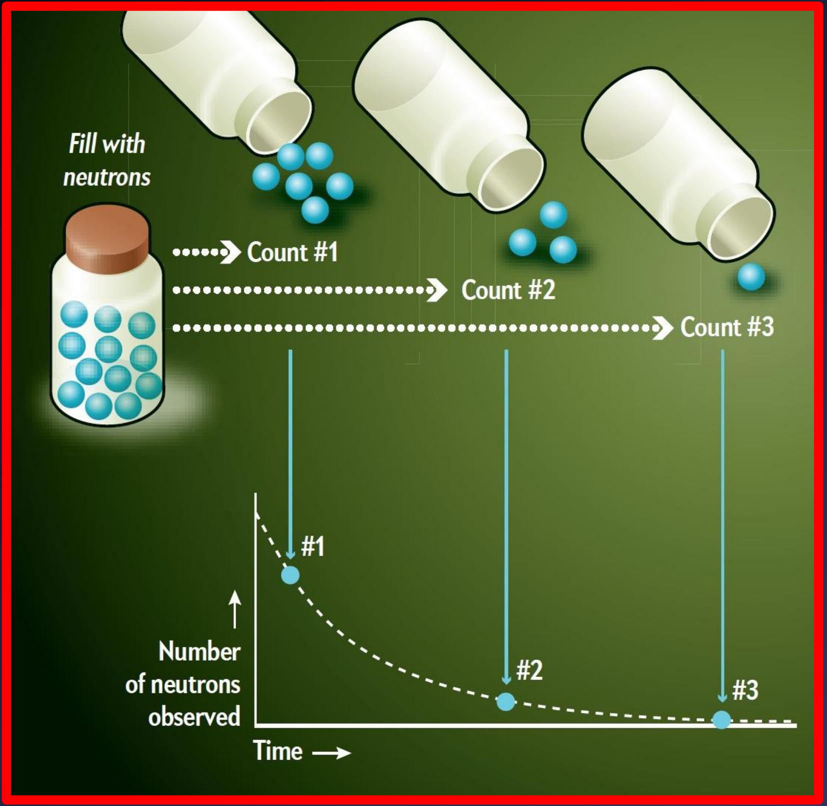
$$\frac{dN}{dt} = -\lambda N$$

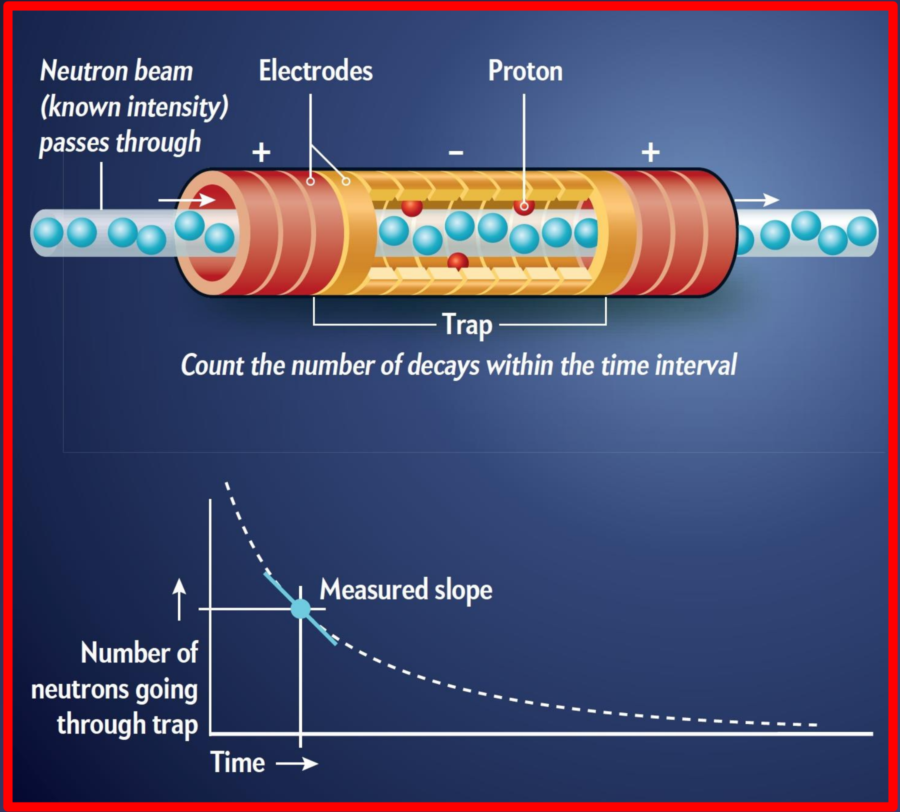
Neutron lifetime measurements



Source: https://www.scientificamerican.com

Neutron lifetime discrepancy





Source: https://www.scientificamerican.com

BF & BG: Beam measures protons only!

$$\frac{1}{N(n)}\frac{dN(p)}{dt} = -(\lambda \mathrm{Br}(n \to p))t$$

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

Neutron dark decay

B Fornal & BG, *Dark Matter Interpretation of the Neutron Decay Anomaly*, arXiv:1801.01124 [hep-ph]

$$\boxed{\mathrm{Br}(n \to p + \text{anything}) \approx 99\%}$$

Remaining 1% :

➡ $\boxed{n \to \text{SM particles (other than } p)}$

➡ $\boxed{n \to \text{dark particle(s)} + \text{SM particle(s)}}$

➡ $\boxed{n \to \text{dark particles}}$

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$$\boxed{n \to \text{ dark particles}}$$

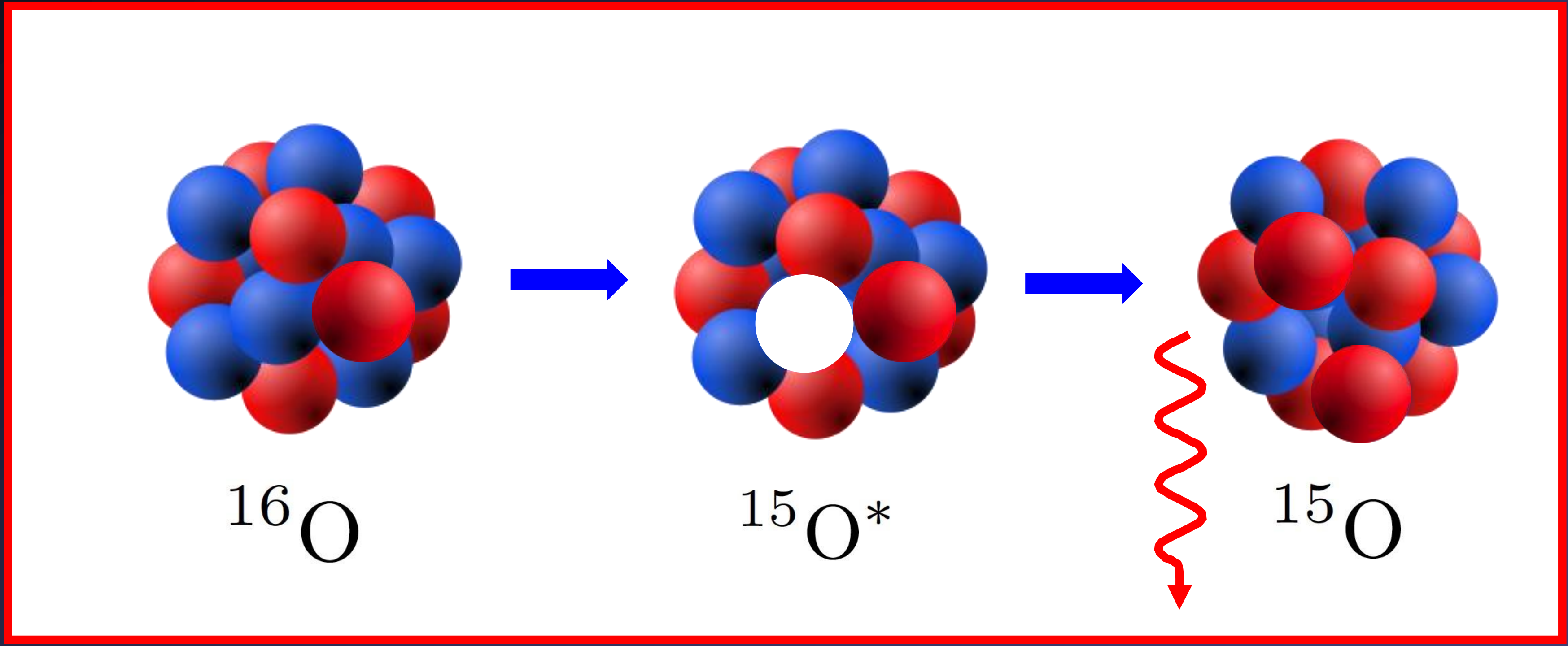
Particle Data Group

p MEAN LIFE

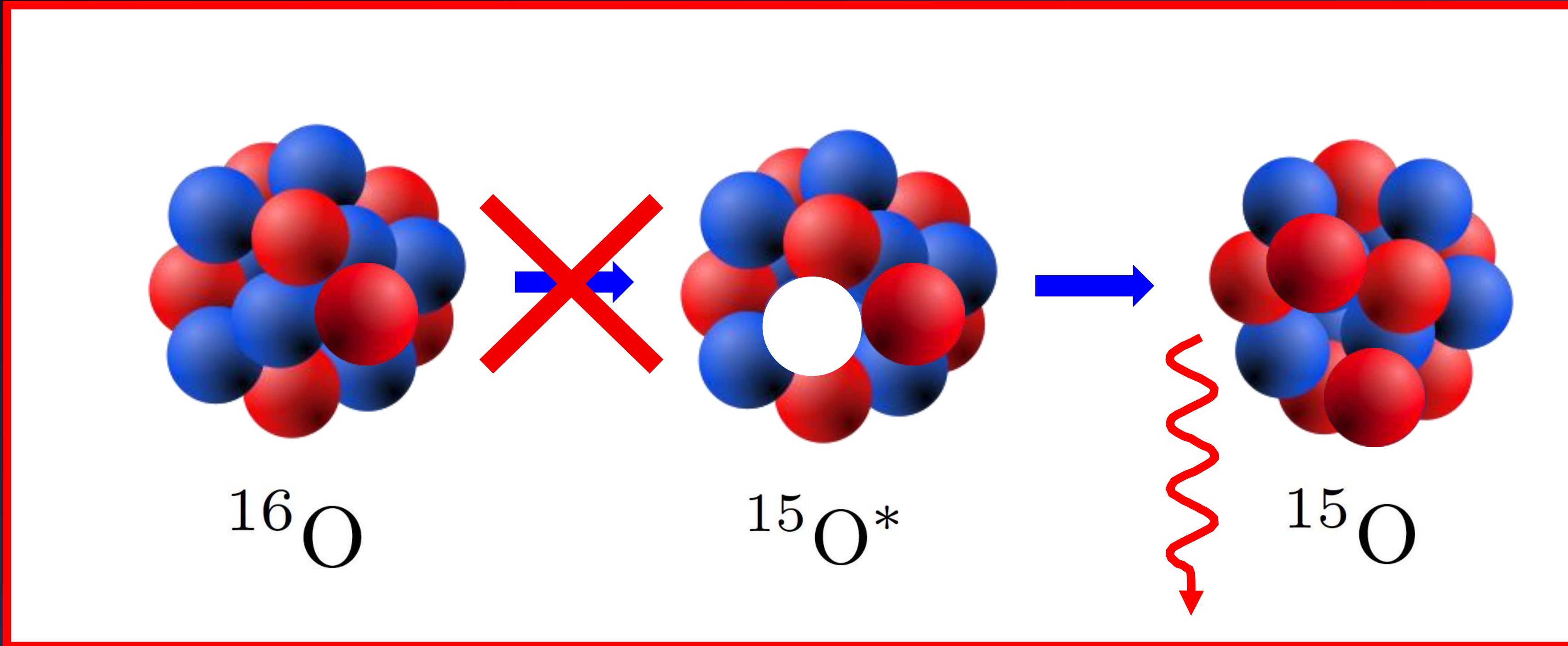
A test of baryon conservation. See the "p Partial Mean Lives" section below for limits for identified final states. The limits here are to "anything" or are for "disappearance" modes of a bound proton (p) or (n). See also the 3ν modes in the "Partial Mean Lives" section. Table 1 of BACK 03 is a nice summary.

LIMIT (years)	PARTICLE	CL%	DOCUMENT ID		TECN	COMMENT
$>5.8 \times 10^{29}$	**n**	90	[1] ARAKI	06	KLND	$n \rightarrow$ invisible
$>2.1 \times 10^{29}$	**p**	90	[2] AHMED	04	SNO	$p \rightarrow$ invisible
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$>1.9 \times 10^{29}$	n	90	[2] AHMED	04	SNO	$n \rightarrow$ invisible
$>1.8 \times 10^{25}$	n	90	[3] BACK	03	BORX	
$>1.1 \times 10^{26}$	p	90	[3] BACK	03	BORX	
$>3.5 \times 10^{28}$	p	90	[4] ZDESENKO	03		$p \rightarrow$ invisible
$>1 \times 10^{28}$	p	90	[5] AHMAD	02	SNO	$p \rightarrow$ invisible
$>4 \times 10^{23}$	p	95	TRETYAK	01		$d \rightarrow n + ?$
$>1.9 \times 10^{24}$	p	90	[6] BERNABEI	00B	DAMA	
$>1.6 \times 10^{25}$	p, n		[7,8] EVANS	77		
$>3 \times 10^{23}$	p		[8] DIX	70	CNTR	
$>3 \times 10^{23}$	p, n		[8,9] FLEROV	58		

Nuclear physics bounds

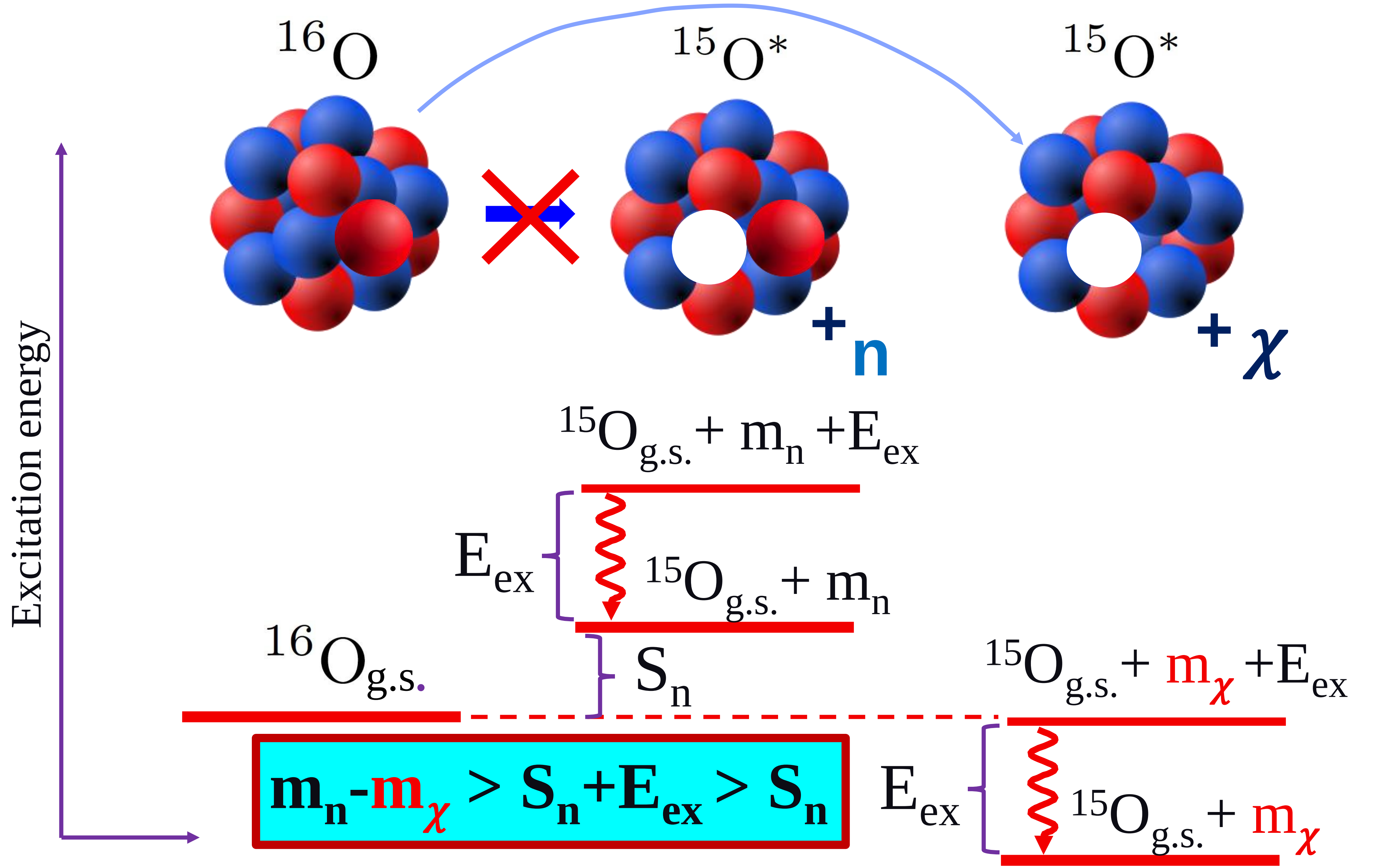


Nuclear physics bounds

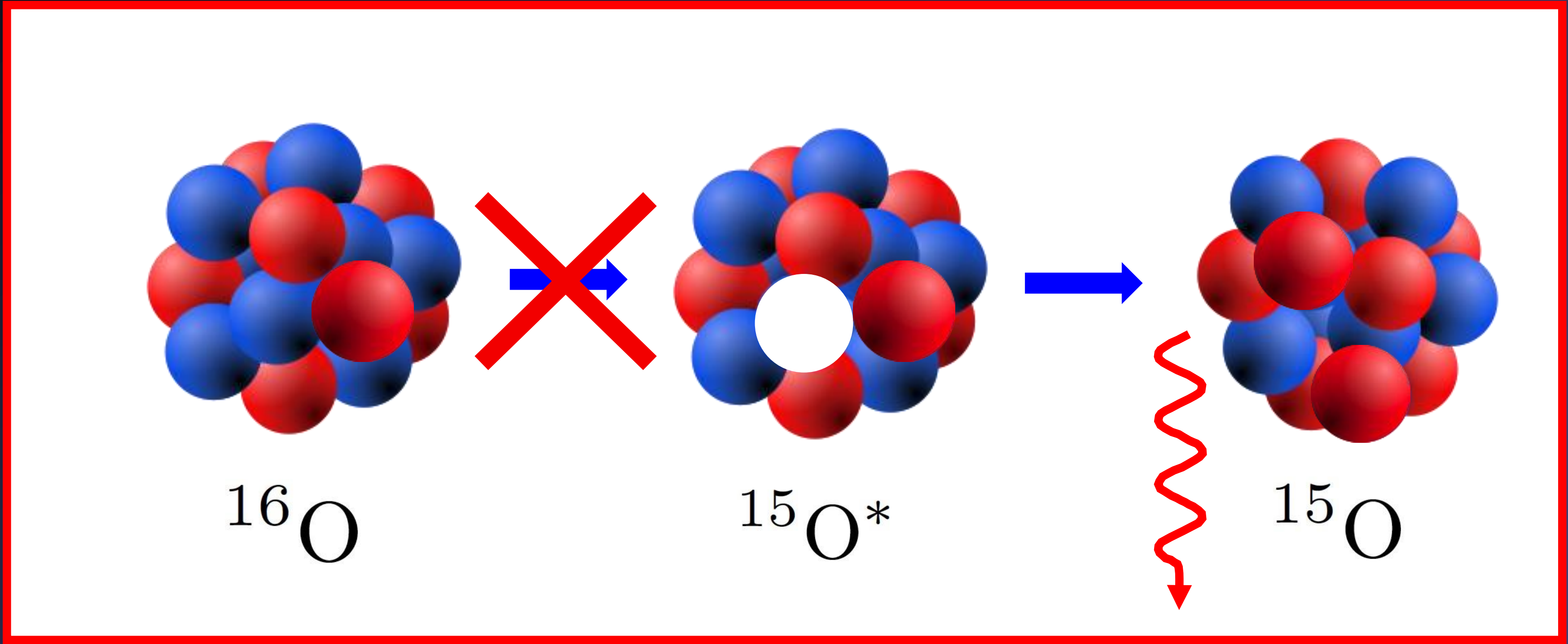


$$\boxed{M_f > m_n - S(n) - E_{\rm ex}}$$

Nuclear physics bounds



Nuclear physics bounds



$$\boxed{M_f > m_n - S(n) - E_{\mathrm{ex}}}$$

Bound from beryllium-9

^{9}Be stability

$$\boxed{{}^{9}\mathrm{Be} \not\to {}^{8}\mathrm{Be}^{*} \to 2\,\alpha}$$

imposes the constraint

$$\boxed{\Delta M < M_f < m_n}$$

$$\boxed{937.900\ \mathrm{MeV} < M_f < 939.565\ \mathrm{MeV}}$$

guaranteeing also proton stability since $\Delta M > m_p - m_e$

Dark matter scenario

Assuming the final state dark particle *χ* is the dark matter, its stability

$$\boxed{\chi \cancel{\rightarrow} p + e^- + \bar{\nu}_e}$$

requires

$$\boxed{m_\chi < m_p + m_e = 938.783\ \mathrm{MeV}}$$

The dark matter mass is therefore

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

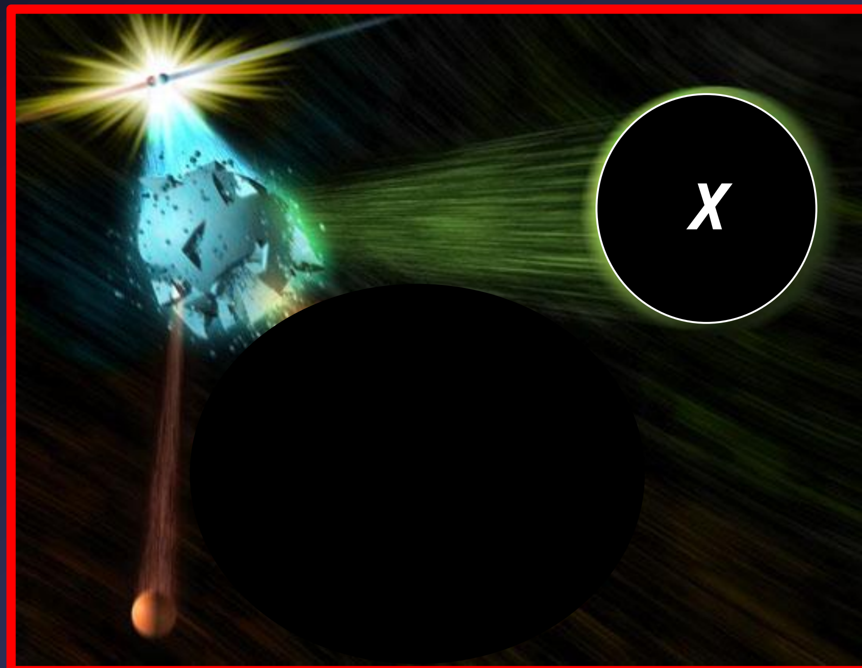
Possible decay channels

(A) Neutron $\longrightarrow$ dark particle + photon

(B) Neutron $\longrightarrow$ dark particle + e^+e^-

(B) Neutron $\longrightarrow$ two dark particles

(A) Neutron ⟶ dark matter + photon

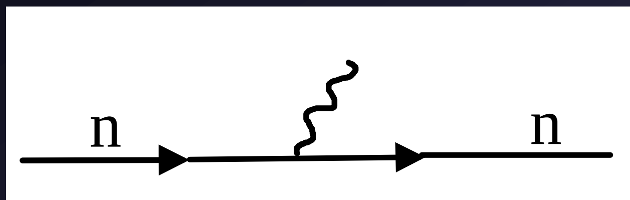


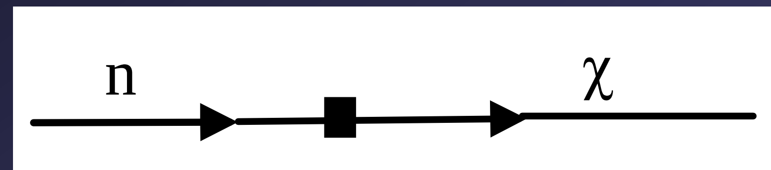
$$937.900 \text{ MeV} < m_\chi < 938.783 \text{ MeV}$$

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

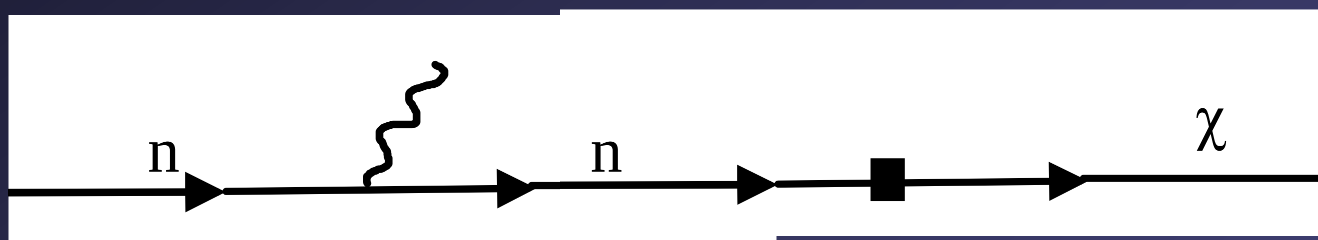
Case (A) – quantitative description

Example of a theory with "B-violating" *χn* interaction

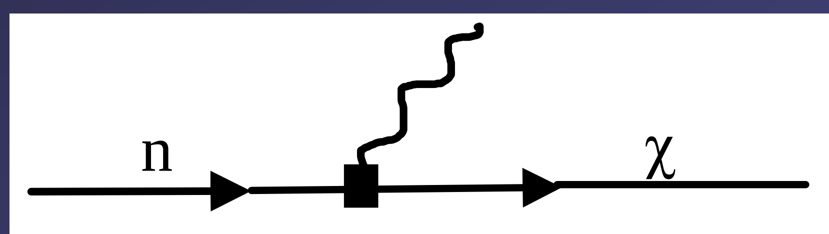




gives

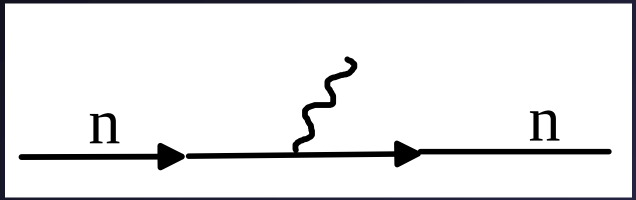


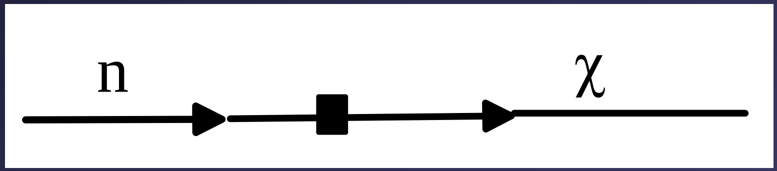
In terms of mass eigenstates, neutron dark decay



Case (A) – quantitative description

Example of a theory with "B-violating" *χn* interaction





$$\mathcal{L}^{\rm eff} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \varepsilon\left(\bar{n}\chi + \bar{\chi}n\right)$$

In terms of mass eigenstates, neutron dark decay

$$\mathcal{L}^{\rm eff}_{n\to\chi\gamma} = \frac{g_n e}{2m_n}\frac{\varepsilon}{(m_n - m_\chi)}\,\bar{\chi}\,\sigma^{\mu\nu}F_{\mu\nu}\,n$$

(A) Neutron $\longrightarrow$ dark matter + photon

Neutron dark decay rate

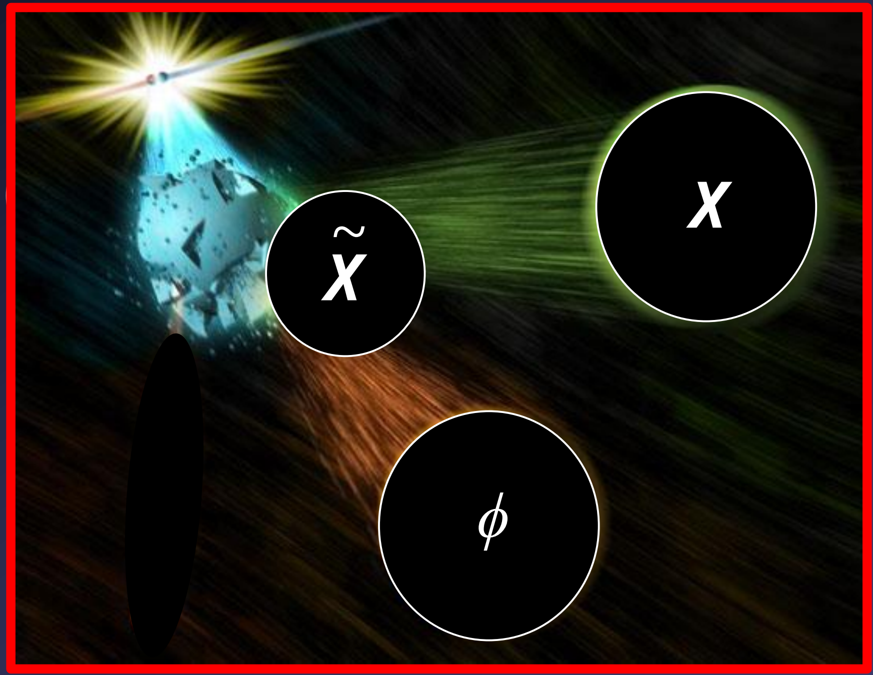
$$\boxed{\Delta\Gamma_{n\to\chi\gamma} = \frac{g_n^2 e^2}{8\pi}\left(1 - \frac{m_\chi^2}{m_n^2}\right)^3 \frac{m_n\,\varepsilon^2}{(m_n - m_\chi)^2}}$$

$$\boxed{\frac{\Delta\Gamma_{n\to\chi\gamma}}{\Gamma_n} \approx 1\%}$$

Possible photon energies

$$\boxed{0 < E_\gamma < 1.664\ \mathrm{MeV}}$$

(C) Neutron ⟶ two dark particles



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

$$m_{\tilde{\chi}} > 937.900 \text{ MeV}$$

Case (C) – quantitative description

Example of a theory with B-violating "*$\tilde{\chi}n$*" *interaction*

$$\mathcal{L}^{\mathrm{eff}} = \bar{n}\Big(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\Big)n + \bar{\tilde{\chi}}\left(i\partial\!\!\!/ - m_{\tilde{\chi}}\right)\tilde{\chi} + \bar{\chi}\left(i\partial\!\!\!/ - m_{\chi}\right)\chi + \partial_\mu\phi^*\partial^\mu\phi - m_\phi^2|\phi|^2 + \varepsilon\left(\bar{n}\tilde{\chi} + \bar{\tilde{\chi}}n\right) + \left(\lambda_\phi\,\bar{\tilde{\chi}}\,\chi\,\phi + \mathrm{h.c.}\right)$$

Term corresponding to neutron dark decay

$$\mathcal{L}^{\mathrm{eff}}_{n\to\chi\phi} = \frac{\lambda_\phi\,\varepsilon}{m_n - m_{\tilde{\chi}}}\,\bar{\chi}\,n\,\phi^*$$

(C) Neutron $\longrightarrow$ two dark particles

Neutron dark decay rate

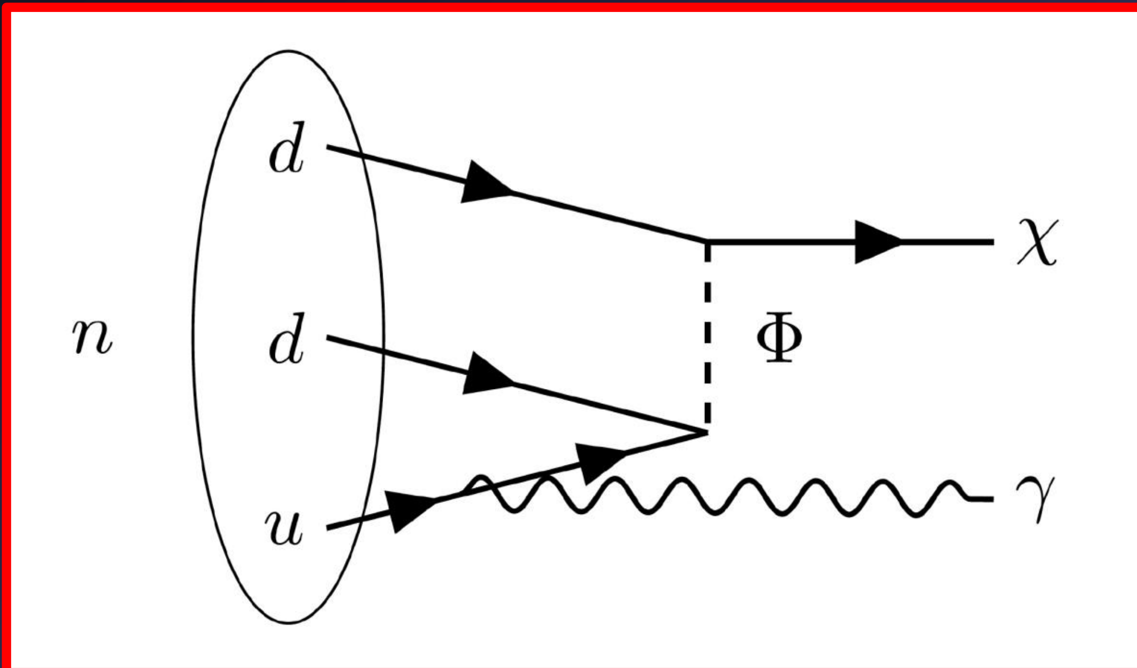
$$\boxed{\Delta\Gamma_{n\to\chi\phi} = \frac{|\lambda_\phi|^2}{16\pi}\sqrt{f(x,y)}\,\frac{m_n\,\varepsilon^2}{(m_n - m_{\tilde{\chi}})^2}}$$

Competition between channels (A) and (C)

$$\boxed{\frac{\Delta\Gamma_{n\to\chi\gamma} + \Delta\Gamma_{n\to\chi\phi}}{\Gamma_n} \approx 1\%}$$

Model 1

Neutron dark decay



New particles:

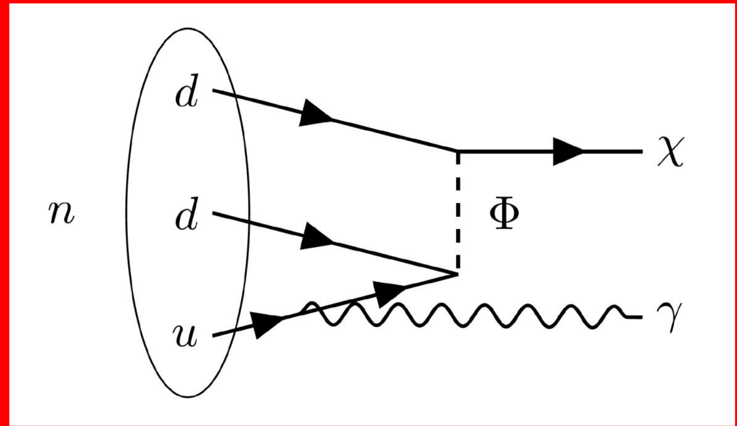
- dark matter χ
- heavy scalar Φ

Lagrangian

$$\mathcal{L}_1 = \left(\lambda_q\,\epsilon^{ijk}\,\overline{u^c_{L}}_i\,d_{Rj}\,\Phi_k + \lambda_\chi \Phi^{*i}\bar{\chi}\,d_{Ri} + \mathrm{h.c.}\right) - M_\Phi^2|\Phi|^2 - m_\chi\,\bar{\chi}\,\chi$$

Model 1

$$\mathcal{L}^{\text{eff}} = \bar{n}\left(i\not{\partial} - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}\left(i\not{\partial} - m_\chi\right)\chi + \varepsilon\left(\bar{n}\chi + \bar{\chi}n\right)$$



$$\Delta\Gamma_{n\to\chi\gamma} = \frac{g_n^2 e^2}{8\pi}\left(1 - \frac{m_\chi^2}{m_n^2}\right)^3 \frac{m_n\,\varepsilon^2}{(m_n - m_\chi)^2}$$

with $$\varepsilon = \frac{\beta\,\lambda_q\lambda_\chi}{M_\Phi^2}$$

$$\langle 0|\epsilon^{ijk}\,\overline{u_{L\,i}^{c}}\,d_{Rj}d_{Rk}|n\rangle = \beta\,P_R\,u_n$$

To explain the neutron lifetime discrepancy

$$\frac{|\lambda_q\lambda_\chi|}{M_\Phi^2} \approx 6.7\times 10^{-6}\ \text{TeV}^{-2}$$

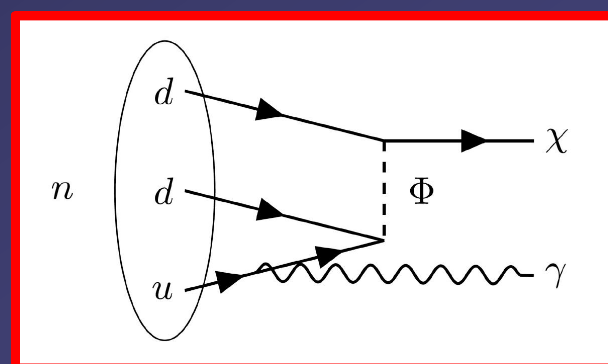
LHC signatures

Φ can be singly produced through ***u d*** **→ Φ**
or pair produced via gluon fusion ***g g*** **→ Φ Φ**

Collider signatures involve:

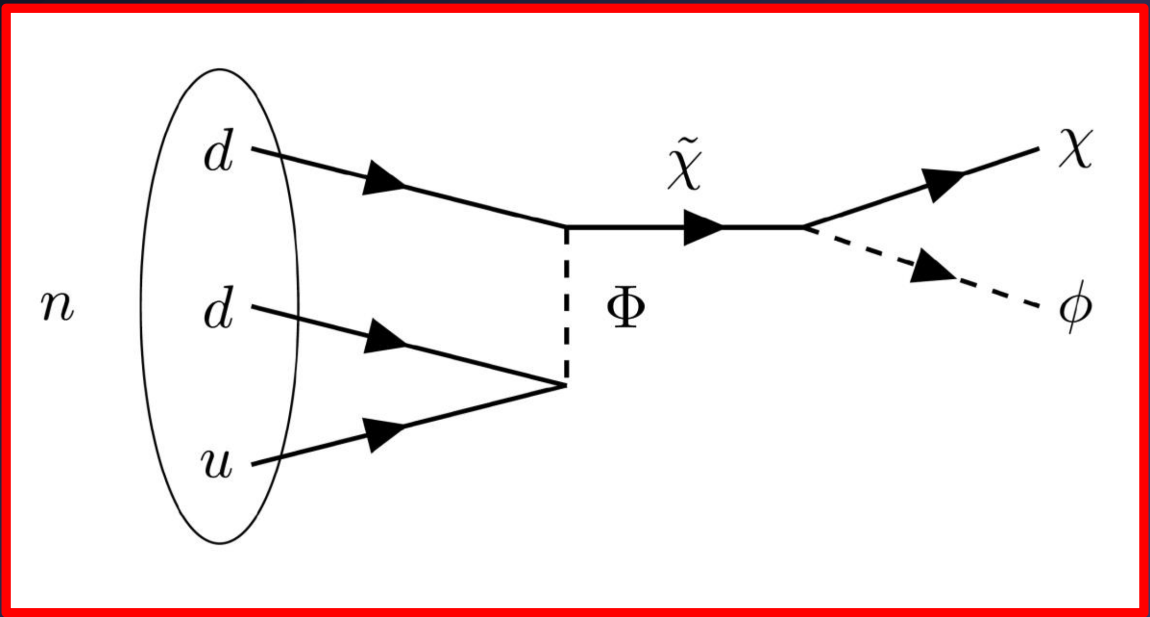
- **2 jets, monojet + MET**
- **2 jets + MET, 3 jets + MET, 4 jets**

$$\frac{M_\Phi}{\sqrt{|\lambda_q \lambda_\chi|}} \approx 400\ \mathrm{TeV}$$



Model 2

Neutron dark decay



New particles:

→ dark χ, $\tilde{\chi}$, ϕ

→ heavy scalar Φ

Lagrangian

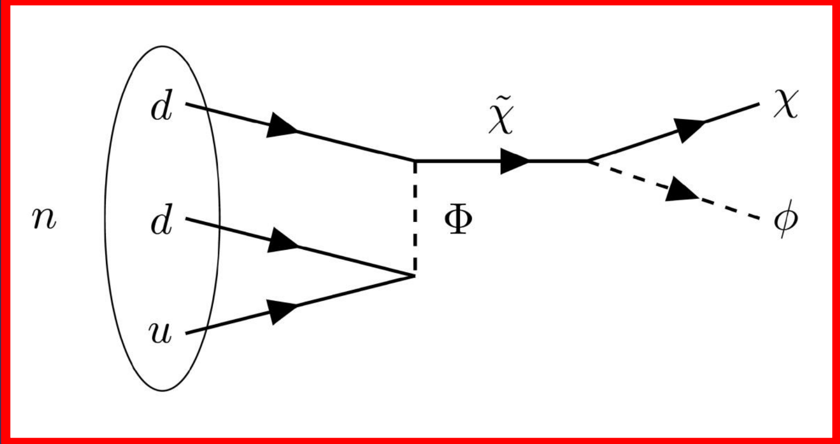
$$\mathcal{L}_2 = \left(\lambda_q\, \epsilon^{ijk}\, \overline{u^c_{L}}_i\, d_{Rj}\, \Phi_k + \lambda_\chi \Phi^{*i}\, \bar{\tilde{\chi}}\, d_{Ri} + \lambda_\phi\, \bar{\tilde{\chi}}\, \chi\, \phi + \text{h.c.}\right)$$
$$- M_\Phi^2\, |\Phi|^2 - m_\phi^2 |\phi|^2 - m_\chi\, \bar{\chi}\, \chi - m_{\tilde{\chi}}\,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

Model 2

$$\mathcal{L}^{\rm eff} = \bar{n}\big(i\not{\partial} - m_n + \tfrac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\big)n + \bar{\tilde{\chi}}\left(i\not{\partial} - m_{\tilde{\chi}}\right)\tilde{\chi}$$
$$+ \bar{\chi}\left(i\not{\partial} - m_{\chi}\right)\chi + \partial_\mu\phi^*\partial^\mu\phi - m_\phi^2|\phi|^2$$
$$+ \varepsilon\left(\bar{n}\tilde{\chi} + \bar{\tilde{\chi}}n\right) + \left(\lambda_\phi\,\bar{\tilde{\chi}}\,\chi\,\phi + \text{h.c.}\right)$$

$$\Delta\Gamma_{n\to\chi\phi} = \frac{|\lambda_\phi|^2}{16\pi}\sqrt{f(x,y)}\,\frac{m_n\,\varepsilon^2}{(m_n - m_{\tilde{\chi}})^2}$$

$$\varepsilon = \frac{\beta\,\lambda_q\lambda_\chi}{M_\Phi^2}$$



To explain the neutron lifetime discrepancy

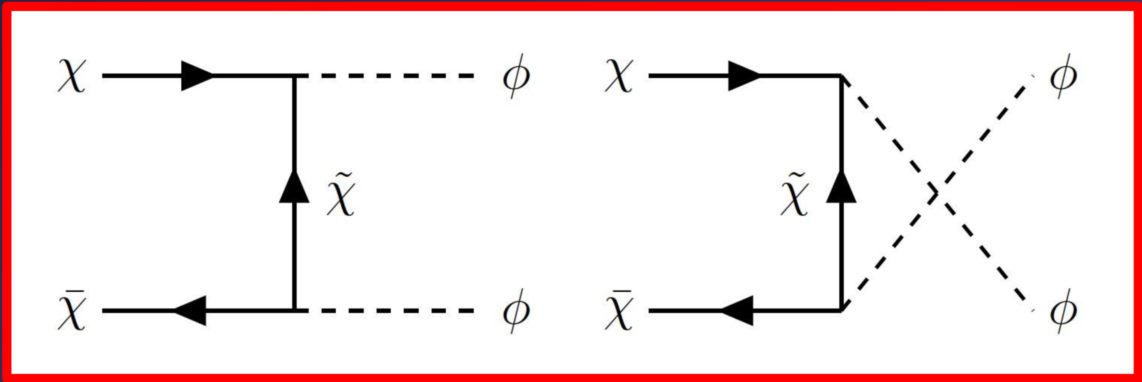
$$\boxed{\frac{|\lambda_q\lambda_\chi|}{M_\Phi^2}\,\frac{|\lambda_\phi|}{0.04} \approx 4.9\times 10^{-7}\ \text{TeV}^{-2}}$$

Dark matter

Model 1: non-thermal DM production

Model 2: (a) DM non-thermally produced

(b) DM thermally produced



DM annihilation

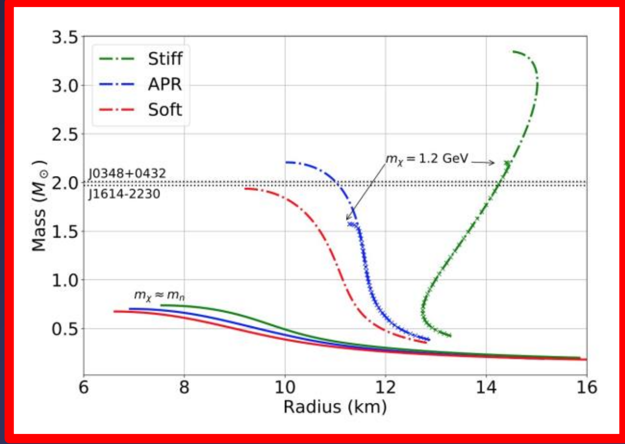
$$\boxed{\lambda_\phi \, \bar{\tilde{\chi}} \, \chi \, \phi}$$

Observed DM relic abundance for:

$$\boxed{\lambda_\phi \approx 0.04}$$

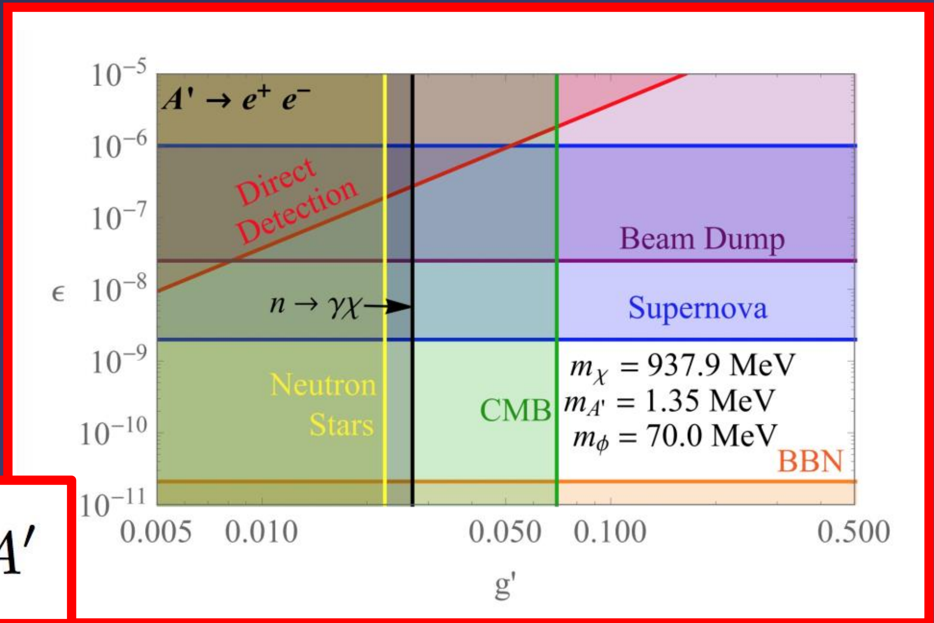
Neutron star constraints

- Neutron dark decay channel and no DM self-interactions imply neutron star masses < 0.8 $M_{\odot}$ (arXiv:1802.08244, 1802.08282, 1802.08427)



- DM self-interactions can block the neutron dark decay, allowing observed neutron star masses

- Complete model:
  dark matter + dark photon
  (Cline & Cornell, arXiv:1803.04961)



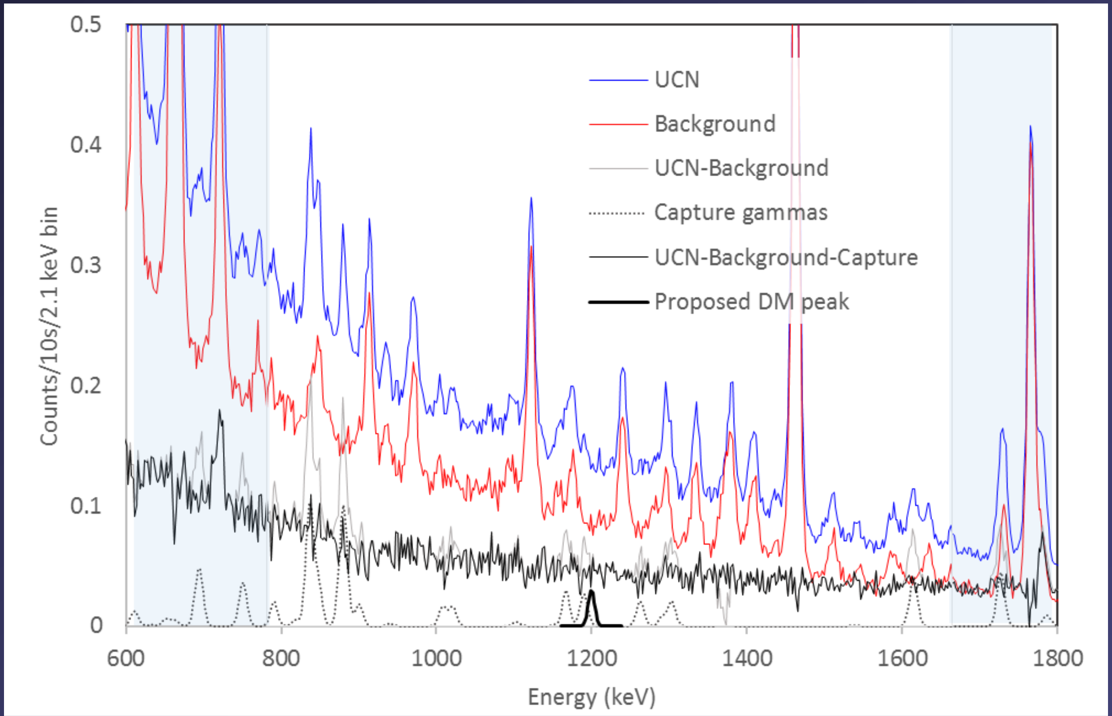
$$n \to \chi A'$$

Signature of neutron dark decay

➡ **(A) monochromatic photons with Br = 1%**

$$\boxed{0 < E_\gamma < 1.664\ \mathrm{MeV}}$$

(arXiv:1802.01595 [nucl-ex])



Signature of neutron dark decay

- (A) monochromatic photons with Br = 1%

$$\boxed{0 < E_\gamma < 1.664\ \mathrm{MeV}}$$

(arXiv:1802.01595 [nucl-ex])

- (B) e^+e^- pairs $\boxed{E_{e^+e^-} < 1.665\ \mathrm{MeV}}$

(arXiv:1803.10890 [nucl-ex])

- LHC searches

- nuclear physics search – sensitive to

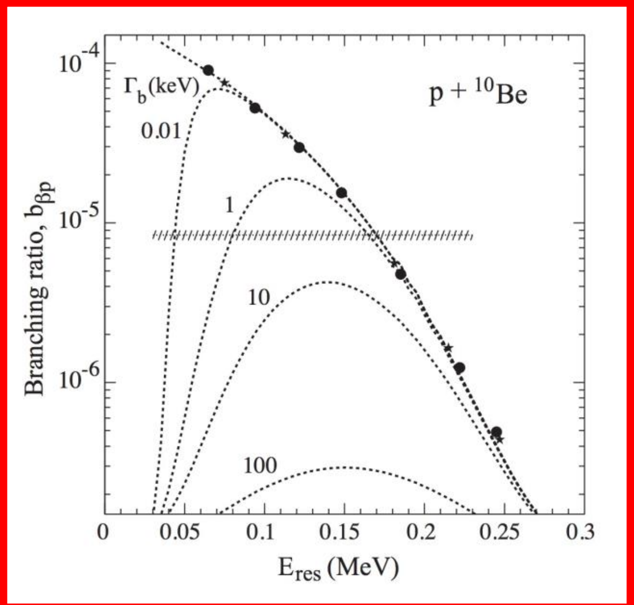
(C) pure dark decay

$$\boxed{{}^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + \chi}$$

Hint from ^{11}Be decays? (arXiv:1803.01334)

- ^{11}Be: one-neutron halo nucleus
- experiment suggests $\boxed{\mathrm{Br}\left({}^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + ?\right) \approx 8 \times 10^{-6}}$

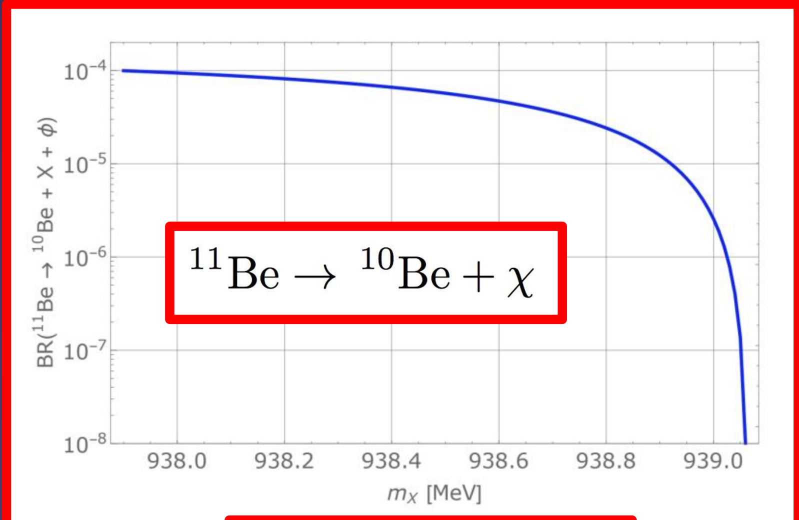
(*Riisager, K. et al., PLB (2014)*, arXiv:1402.1645)



?

Resonance or dark decay

?



$\boxed{m_\chi \approx 938.9\ \mathrm{MeV}}$

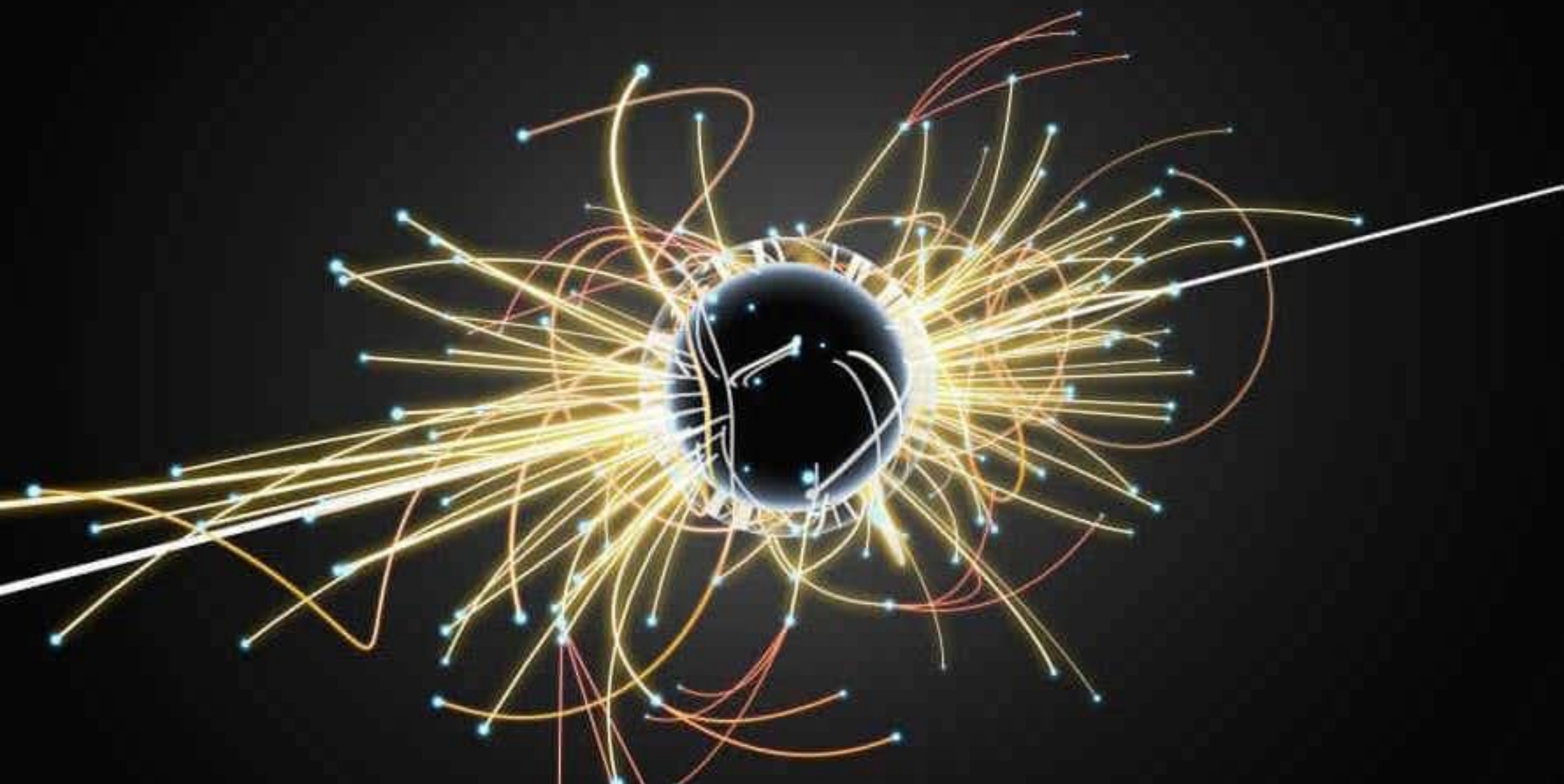
Neutron experiments

Conclusions

- "Missing Neutrons May Lead a Secret Life as Dark Matter", Clara Moskowitz, *Scientific American (January 29, 2018)*

- It would be truly amazing if the good old neutron turned out to be the particle enabling us to probe the dark matter sector of the universe.

- It is up to the experiment to be the final judge.



Thank you!