Neutron Dark Decay:

Portal to a Baryonic Dark Sector

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University of Utah

Workshop on Baryon and Lepton Number Violation
Case Western Reserve University, July 7, 2020

In collaboration with: ***Benjamin Grinstein***

Neutron dark decay

Nuclear physics
(theory and experiment)

Model
building

Astrophysics

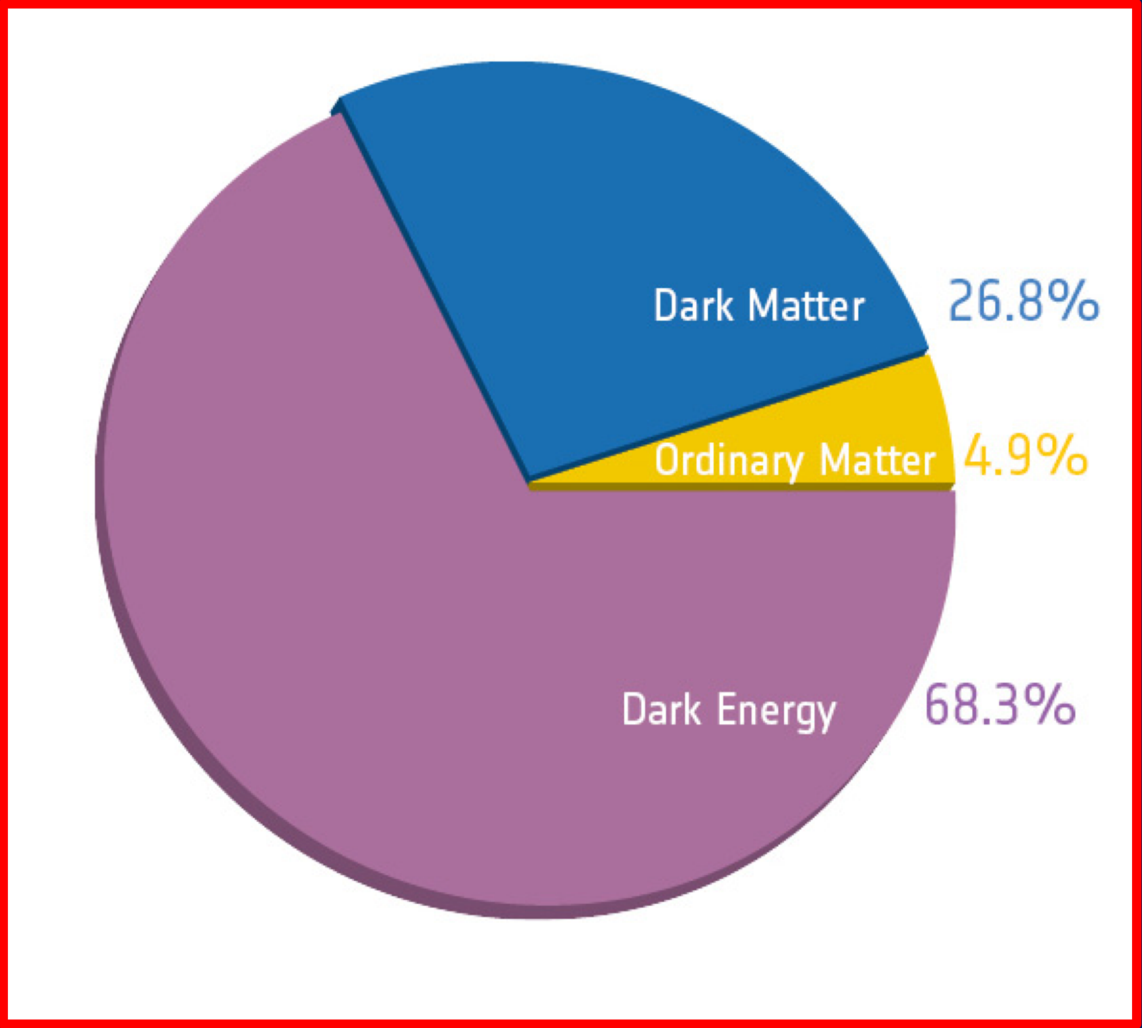
Collider
physics
(LHC, FCC)

Neutrino
experiments
(Super-K, DUNE)

Dark matter
direct detection
(PandaX, XENON1T)

Connection to
other anomalies

We have a problem !

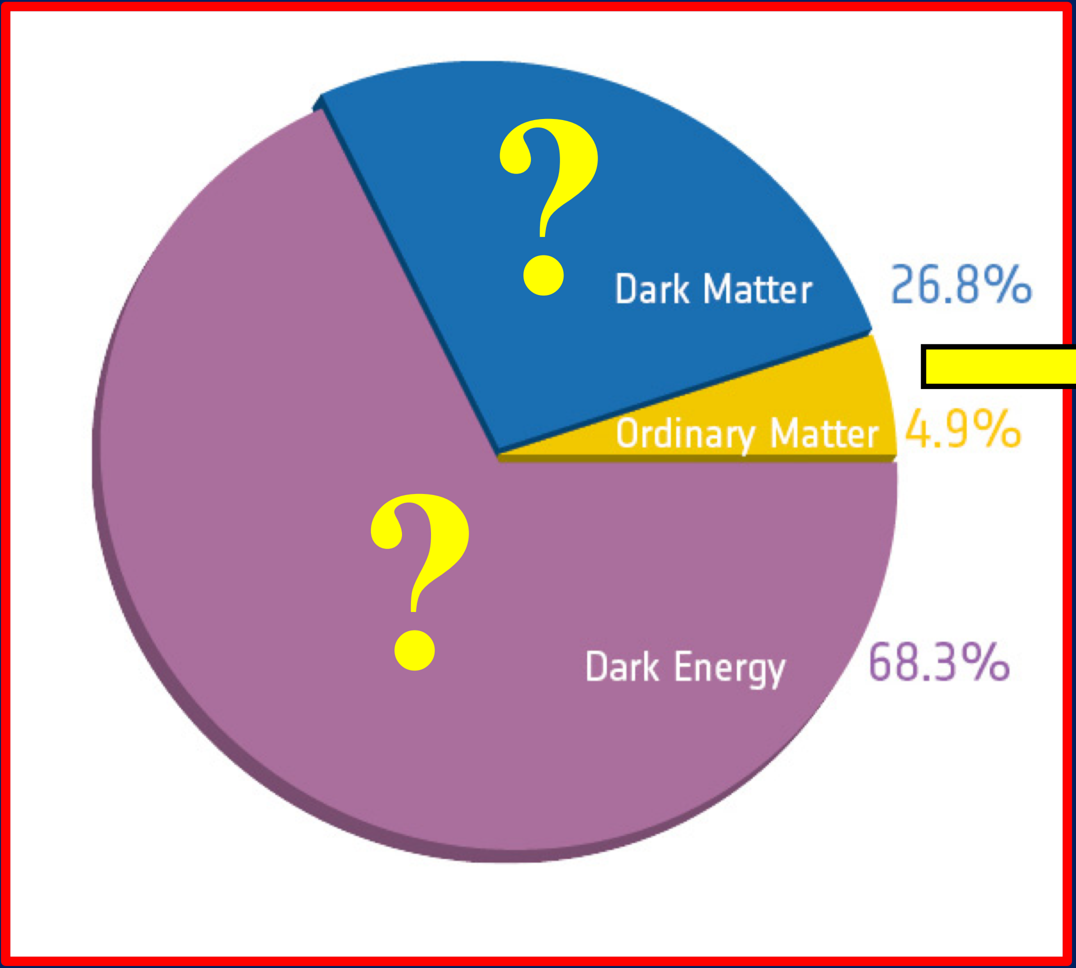


DARK MATTER


Source: https://en.wikipedia.org

Vera Rubin

Current knowledge about the Universe



What exactly is dark matter?

https://www.motorauthority.com

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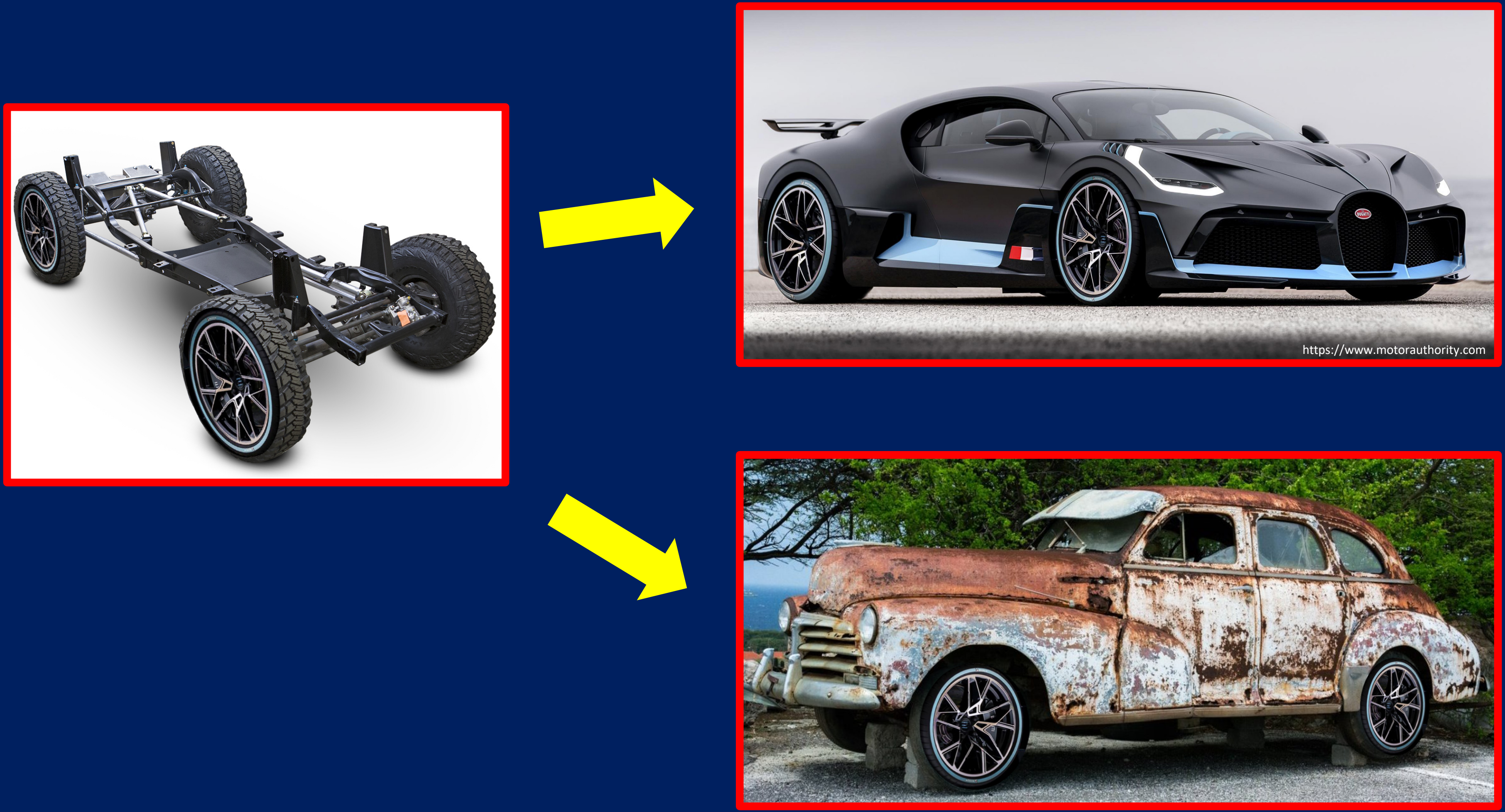


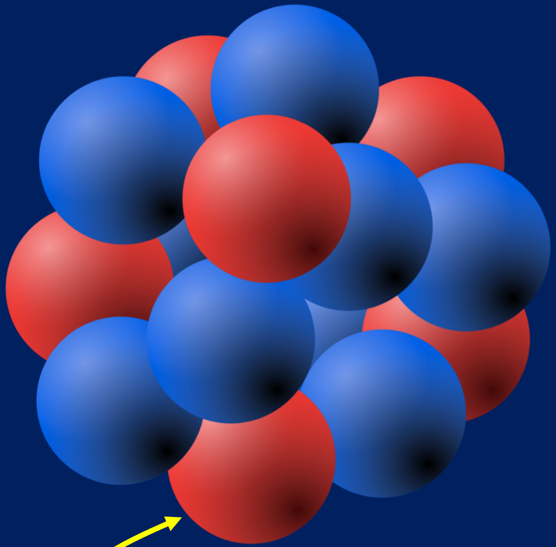
https://www.motorauthority.com

What exactly is dark matter?

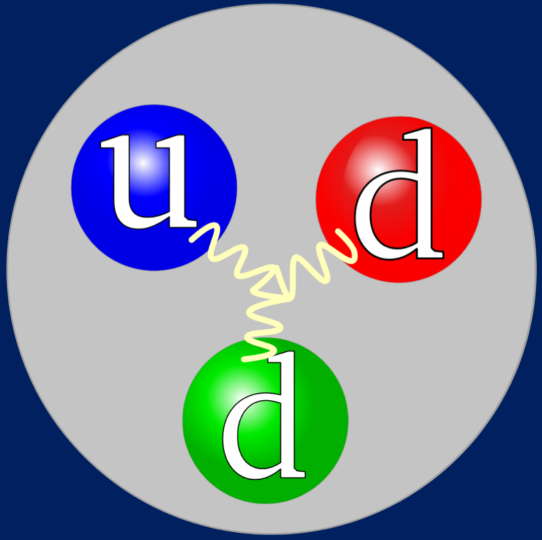
https://www.motorauthority.com

Can neutron be the key?

atomic nucleus



neutron



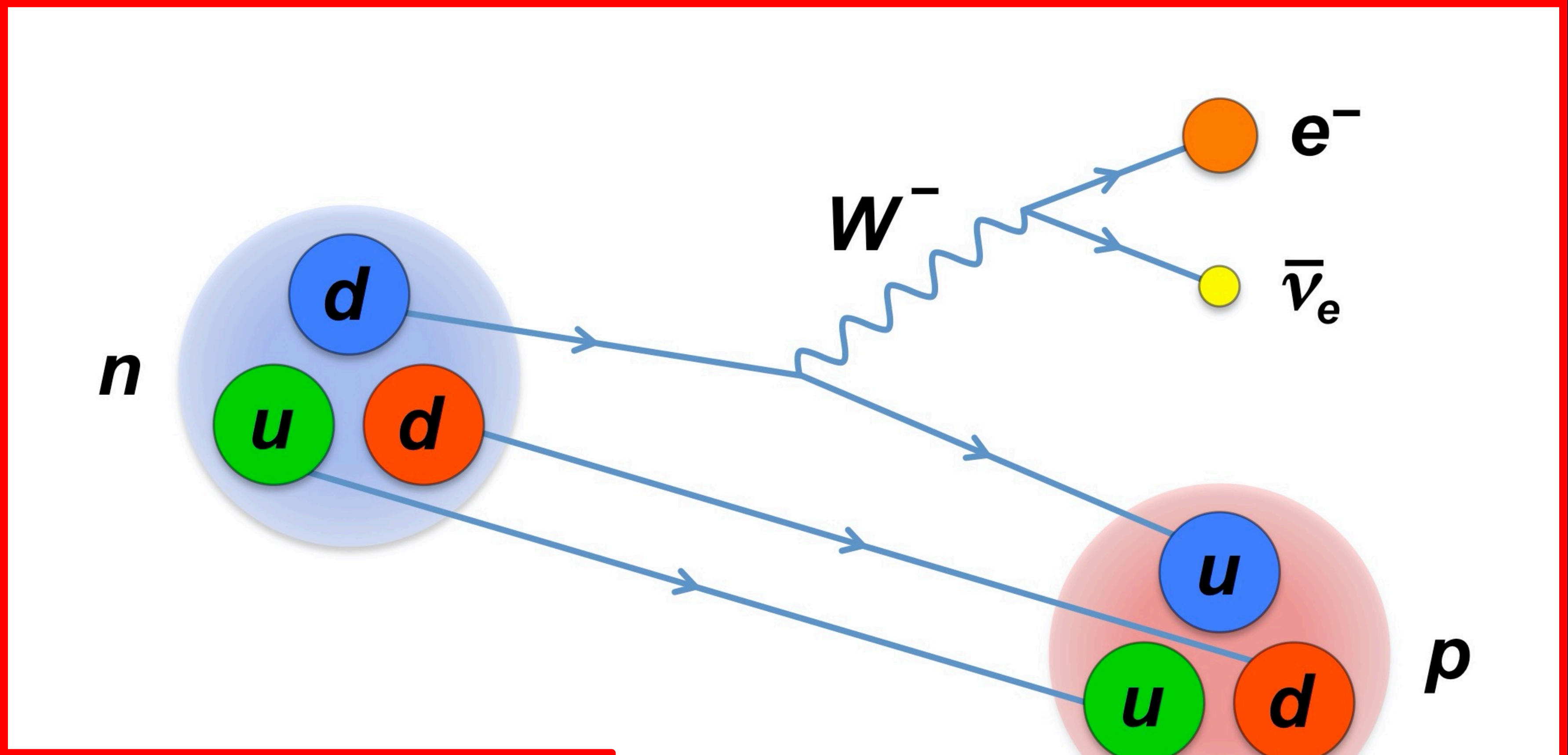
proton

$$\boxed{\tau_n \approx 15\ \text{min}}$$

Irène Joliot-Curie

James Chadwick

Neutron decay in the Standard Model



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

Neutron lifetime in the Standard Model

Theoretical prediction

$$\tau_n = \frac{4908.6(1.9)\,\mathrm{s}}{|V_{ud}|^2(1+3g_A^2)}$$

Czarnecki, Marciano & Sirlin, PRL 120, 202002 (2018)

$$\mathcal{M} = \frac{1}{\sqrt{2}} G_F V_{ud}\, g_V \left[\bar{p}\,\gamma_\mu n - g_A \bar{p}\,\gamma_5 \gamma_\mu n\right] \left[\bar{e}\,\gamma^\mu (1-\gamma_5)\nu\right]$$

Using the PDG average for g_A

$$880.5\,\mathrm{s} < \tau_n < 886.0\,\mathrm{s}$$

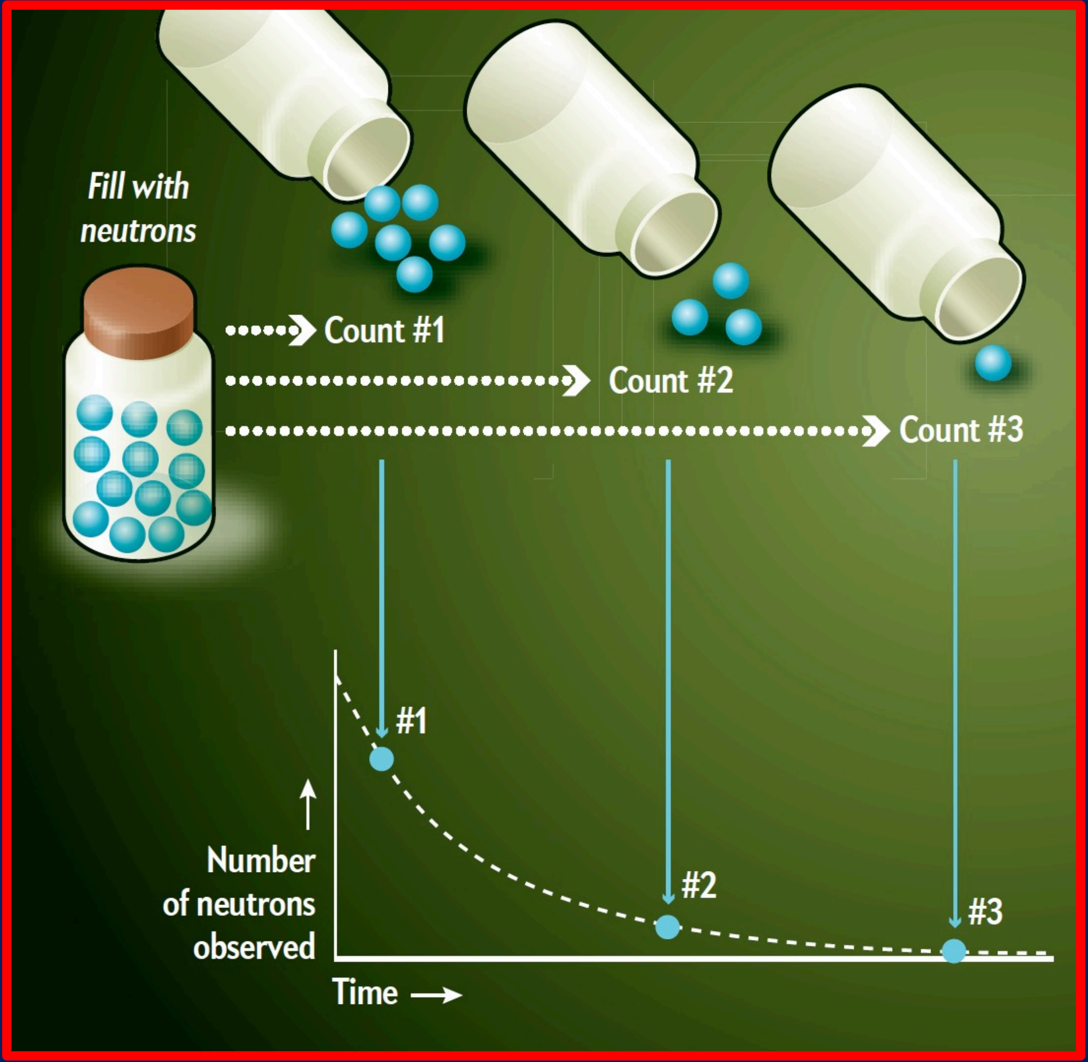
Lattice result

$$870\,\mathrm{s} < \tau_n < 900\,\mathrm{s}$$

Chang et al., Nature 558, 91 (2018)

$$g_A = 1.271 \pm 0.013$$

Bottle experiments



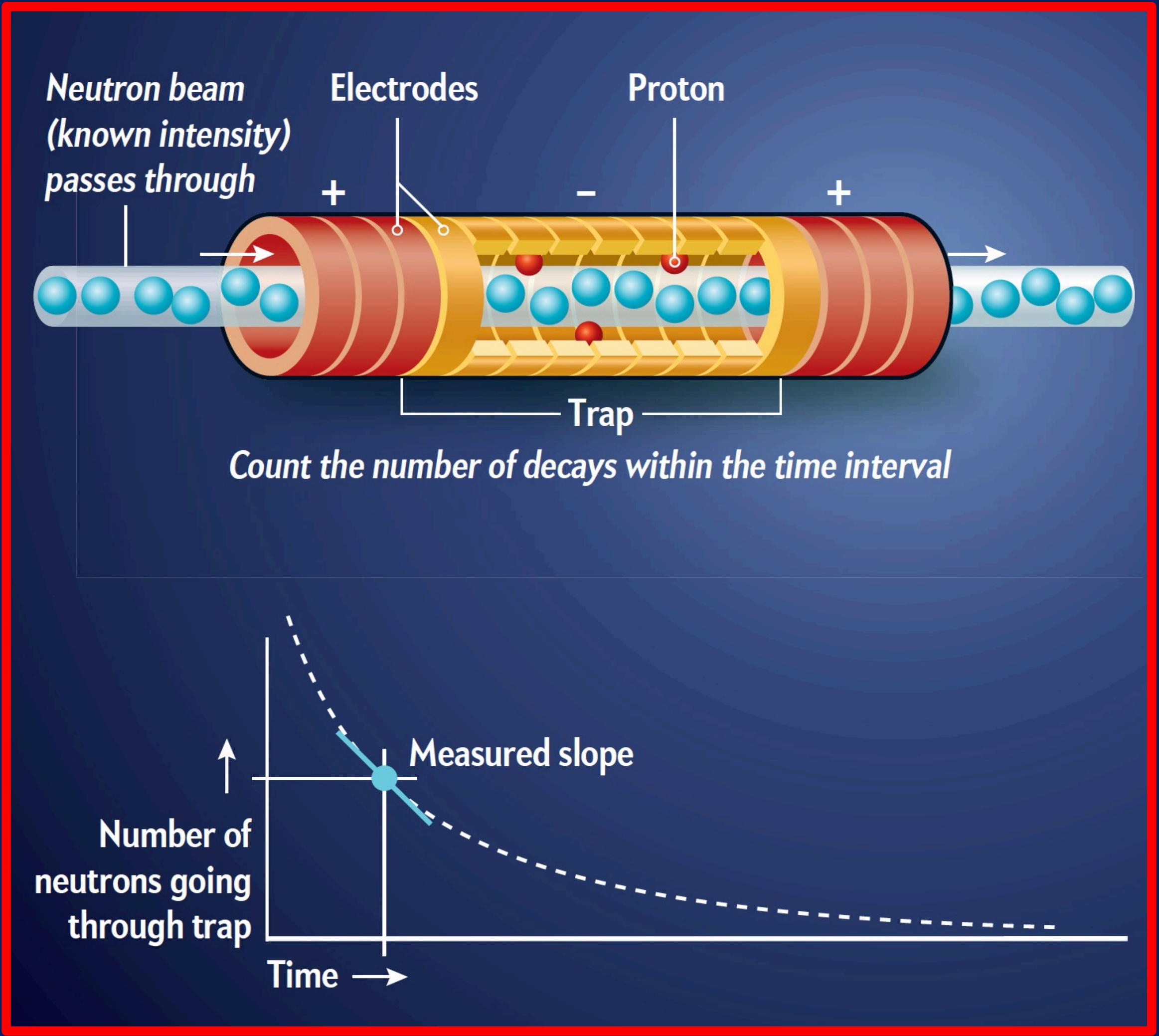
Source: https://www.scientificamerican.com

$$\boxed{N_n(t) = N_n(0)\, e^{-t/\tau_n}}$$

Fit of an exponent to decay data points

$$\boxed{\tau_n^{\text{bottle}} = \tau_n}$$

Beam experiments



Source: https://www.scientificamerican.com

The decay rate to protons is measured

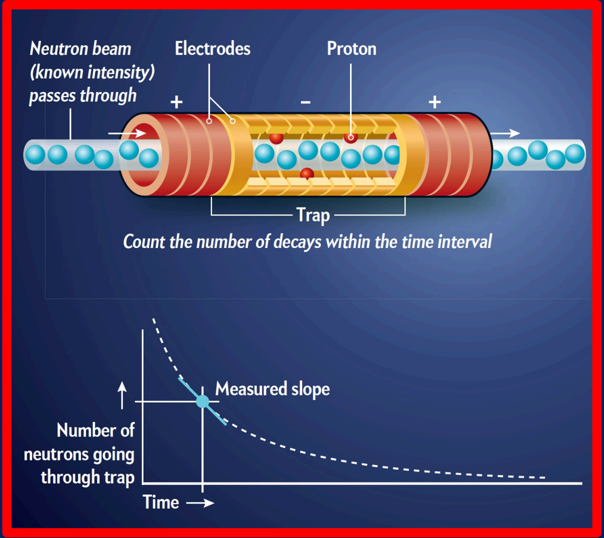
$$\frac{dN_p(t)}{dt} = -\frac{N_n(t)}{\tau_n^{\text{beam}}}$$

$$\tau_n^{\text{beam}} = -\frac{N_n}{dN_p/dt}$$

If neutron decays only via beta decay

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

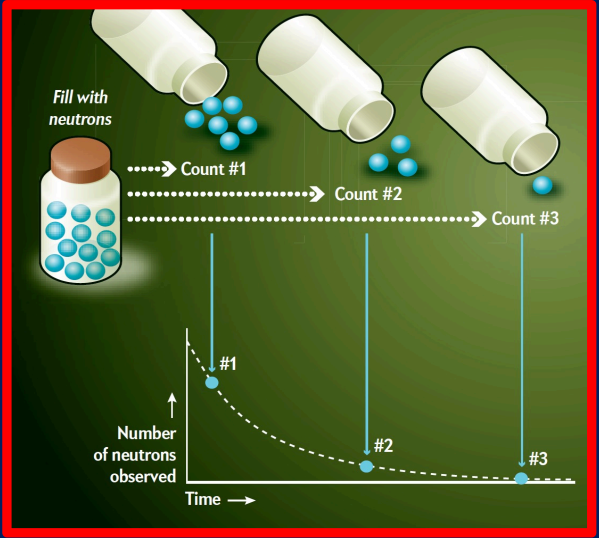
Beam experiments



there should be the equality:

$$\tau_n^{\text{beam}} = \tau_n^{\text{bottle}}$$

Bottle experiments



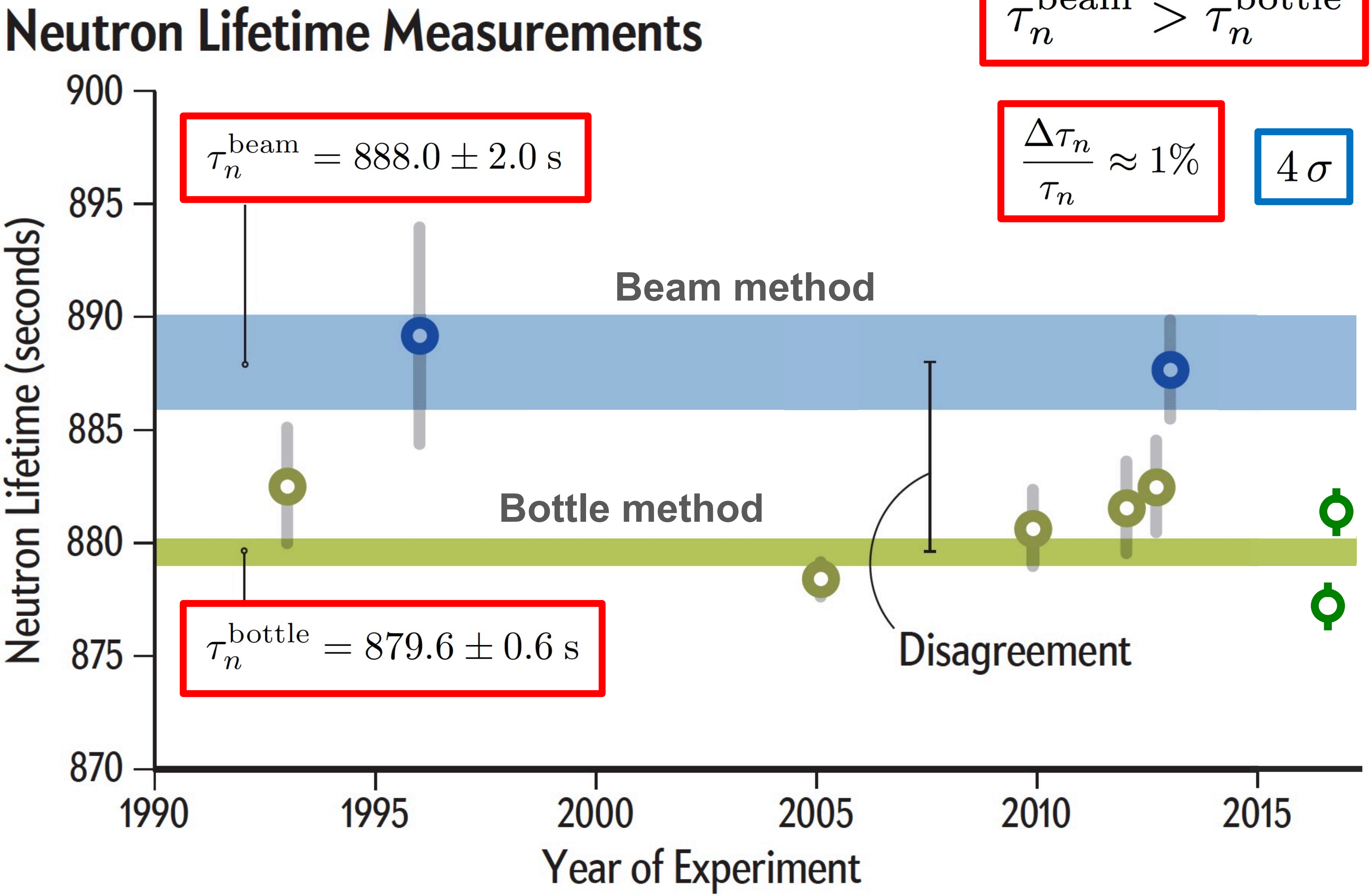
but

$$\tau_n^{\text{beam}} = 888.0(2.1)\,\mathrm{s} \ > \ \tau_n^{\text{bottle}} = 879.3(0.8)\,\mathrm{s}$$

$$\tau_n^{\text{beam}} > \tau_n^{\text{bottle}}$$

$$\frac{\Delta \tau_n}{\tau_n} \approx 1\%$$

$$4\,\sigma$$



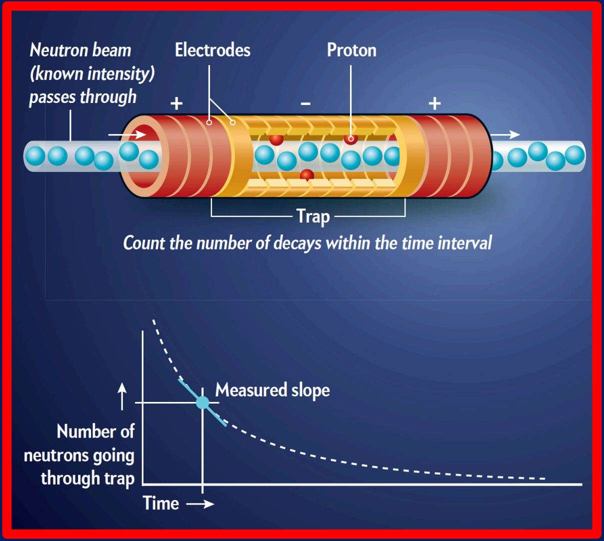
Neutron Lifetime Measurements

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

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

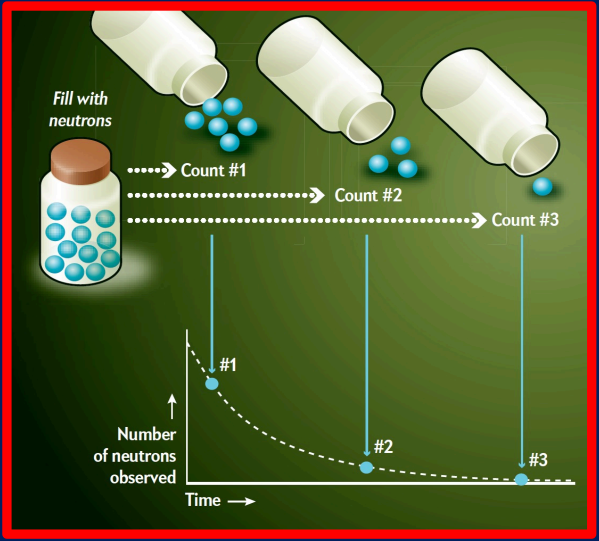
https://www.scientificamerican.com, modified

Beam experiments



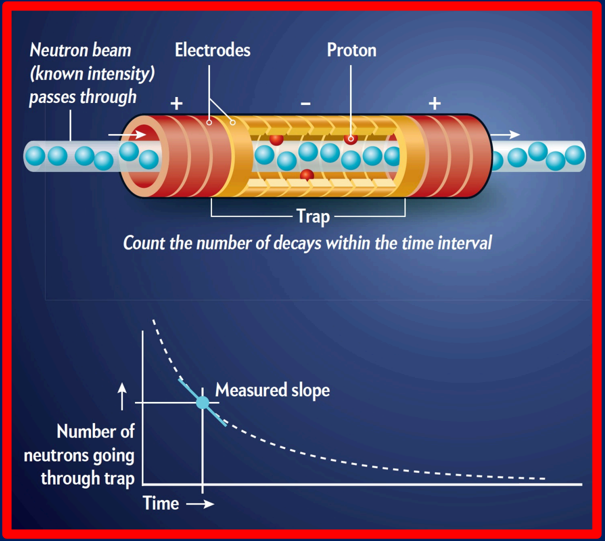
$$\tau_n^{\text{beam}} > \tau_n^{\text{bottle}}$$

Bottle experiments

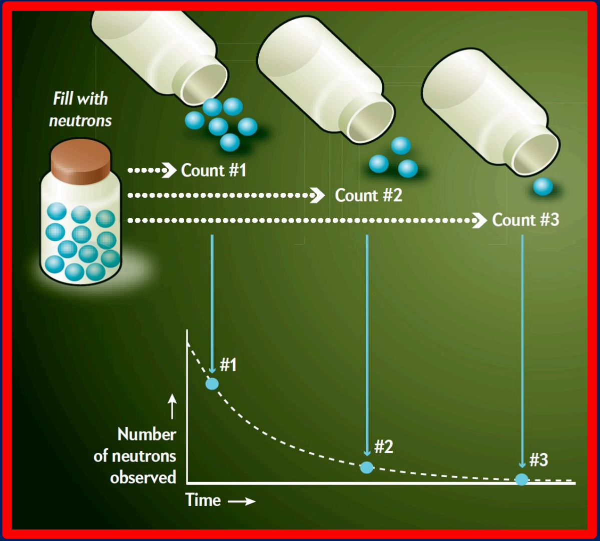


$$\tau_n^{\text{beam}} = -\frac{N_n}{dN_p/dt}$$

Beam experiments



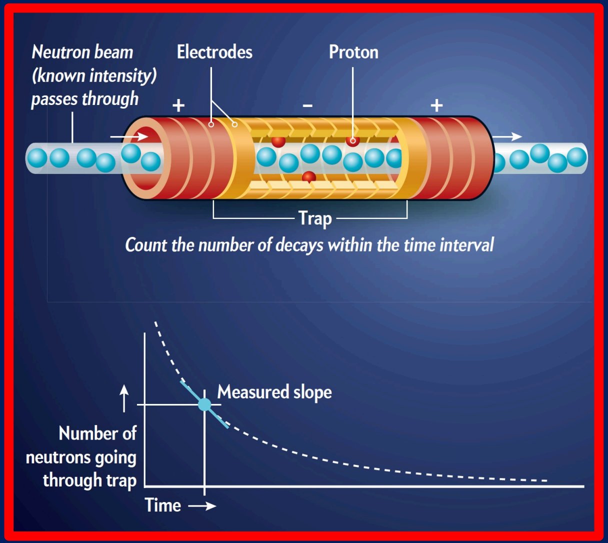
Bottle experiments



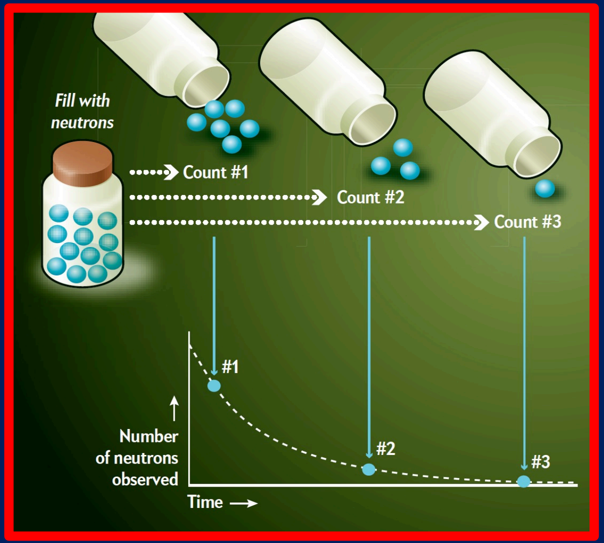
$$\tau_n^{\text{beam}} > \tau_n^{\text{bottle}}$$

$$\tau_n^{\text{beam}} = -\frac{N_n}{dN_p/dt} = -\frac{N_n}{\text{Br}(n \to p + \text{anything})\, dN_n/dt}$$

Beam experiments



Bottle experiments

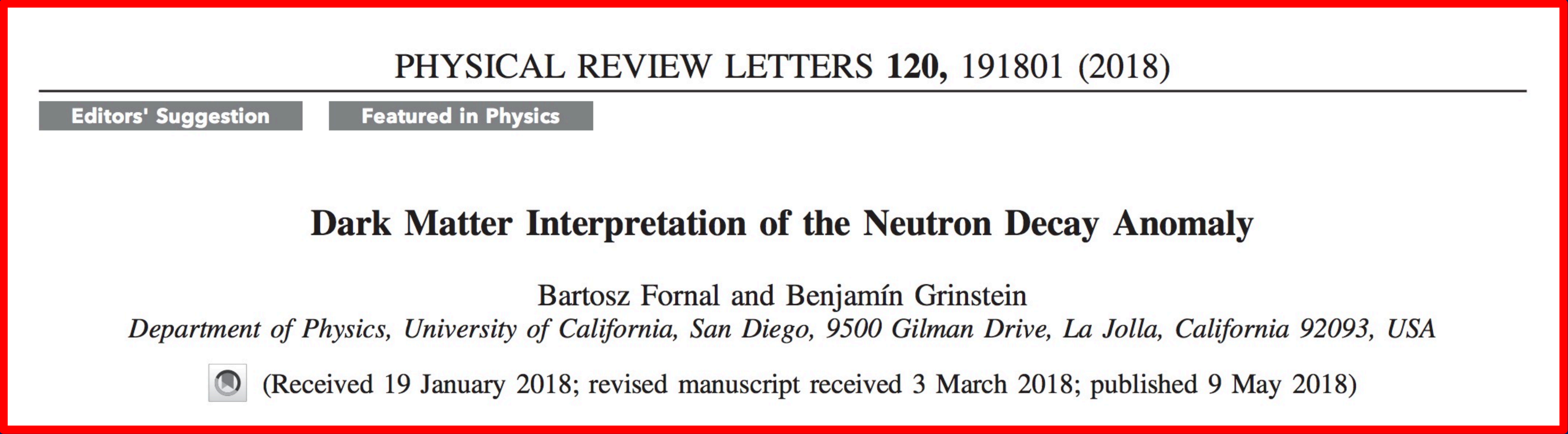


$$\tau_n^{\text{beam}} > \tau_n^{\text{bottle}}$$

$$\tau_n^{\text{beam}} = -\frac{N_n}{dN_p/dt} = -\frac{N_n}{\mathrm{Br}(n \to p + \text{anything})\, dN_n/dt}$$

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

Neutron dark decay


PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion **Featured in Physics**

Dark Matter Interpretation of the Neutron Decay Anomaly

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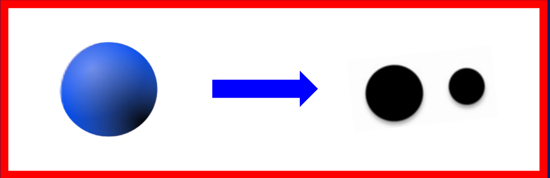
(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)



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

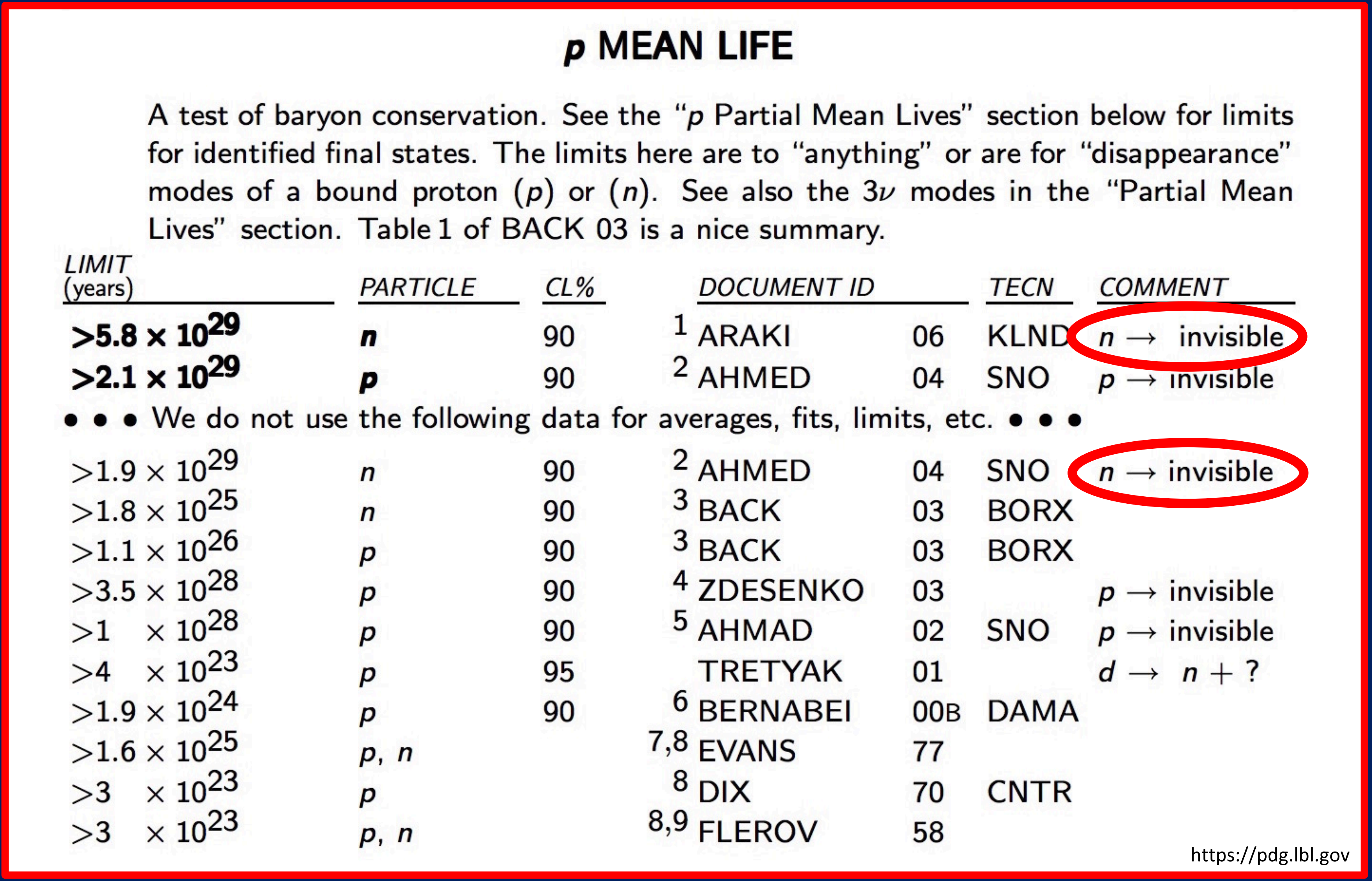
$$\mathrm{Br}(n \to \mathrm{anything} \neq p) \approx 1\%$$

$$\tau_{n \to \mathrm{dark}} \approx 1 \ \mathrm{day}$$

$$n \to \ \mathrm{dark\ particles}$$

$$n \to \ \mathrm{dark\ particle(s)} + \mathrm{SM\ particle(s)}$$

Nuclear physics bounds



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.

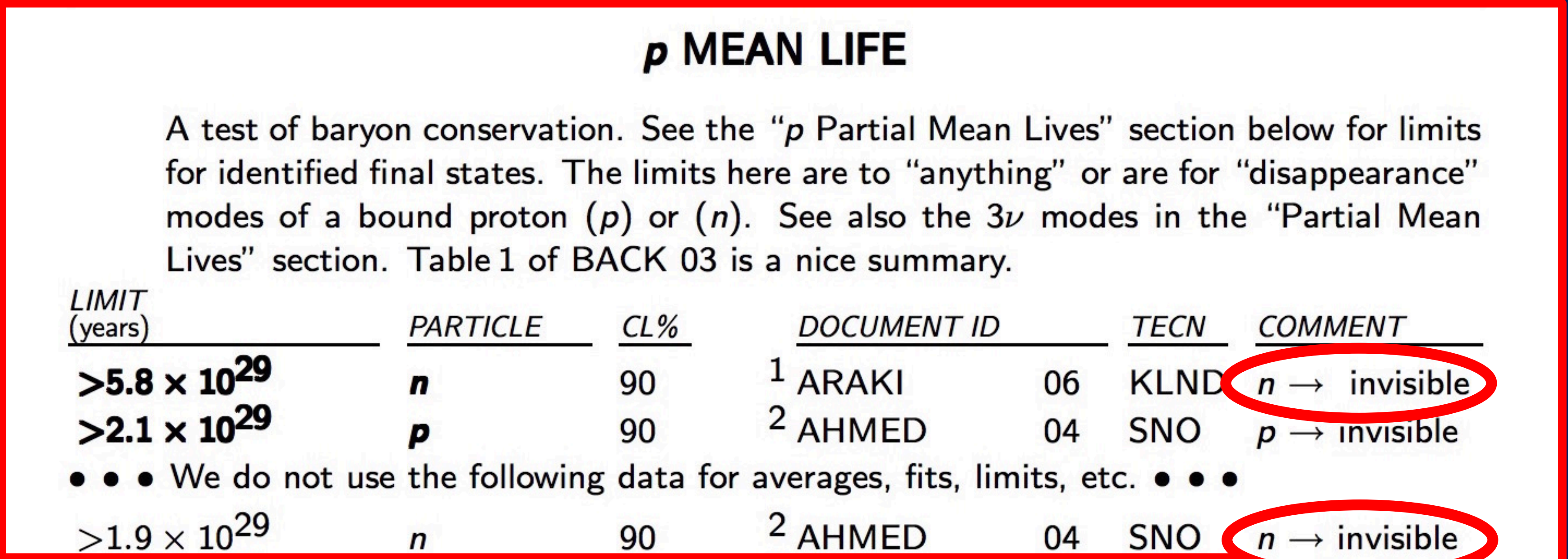
LIMIT (years)	*PARTICLE*	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{>5.8 \times 10^{29}}$	***n***	90	[1] ARAKI	06	KLND	$n \rightarrow$ invisible
$\mathbf{>2.1 \times 10^{29}}$	***p***	90	[2] AHMED	04	SNO	$p \rightarrow$ invisible

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (years)	*PARTICLE*	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>1.9 \times 10^{29}$	*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		

https://pdg.lbl.gov

Nuclear physics bounds



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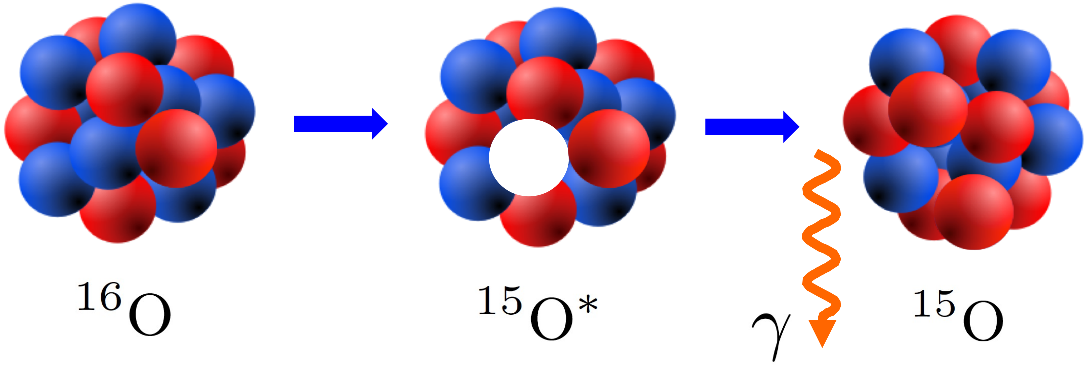


$p \rightarrow$ invisible

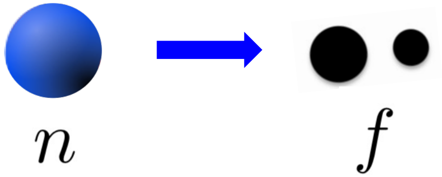
$p \rightarrow$ invisible

$d \rightarrow n + ?$

https://pdg.lbl.gov

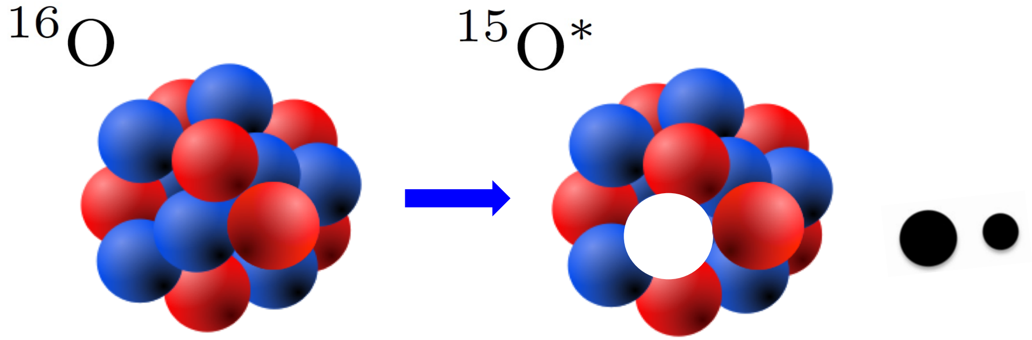
Nuclear physics bounds

Neutron dark decay



$$M_f < m_n$$

For dark decay of a neutron in ^{16}O to happen



$$M_{(^{16}\mathrm{O})} =$$
$$M_{(^{15}\mathrm{O})} + m_n - S(n)_{(^{16}\mathrm{O})} \;>\; M_{(^{15}\mathrm{O})} + E_{\mathrm{ex}} + M_f$$

The region

$$m_n - S(n)_{(^{16}\mathrm{O})} - E_{\mathrm{ex}} < M_f$$

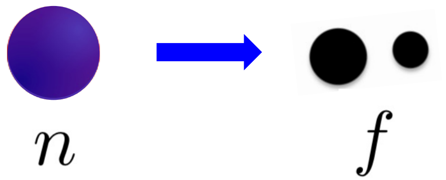
i.e.,

$$m_n - 20.9\ \mathrm{MeV} < M_f < m_n$$

is not ruled out!

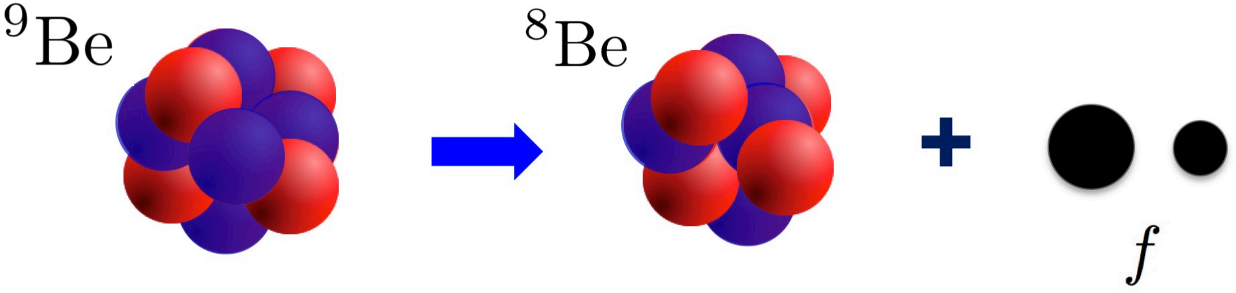
Nuclear physics bounds – ^{9}Be

Neutron dark decay



$$M_f < m_n$$

^{9}Be would dark decay if



$$M_{(^{9}\mathrm{Be})} = M_{(^{8}\mathrm{Be})} + m_n - 1.664\ \mathrm{MeV} \quad > \quad M_{(^{8}\mathrm{Be})} + M_f$$

^{9}Be remains stable if

$$m_n - 1.664\ \mathrm{MeV} < M_f < m_n$$

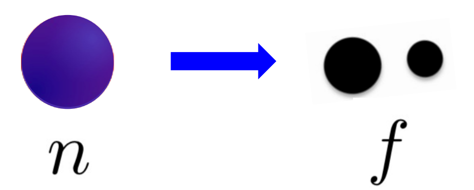
i.e.,

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

Nuclear physics bounds – ^{9}Be

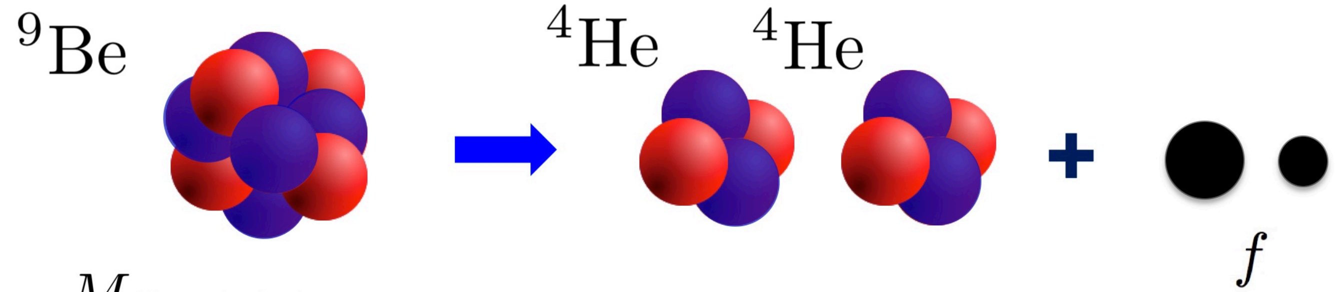
(and considering the instability of ^{8}Be)

Neutron dark decay



$$M_f < m_n$$

^{9}Be would dark decay if



$$M_{(^{9}\mathrm{Be})} =$$
$$M_{(^{8}\mathrm{Be})} + m_n - 1.664\ \mathrm{MeV} \ > \ 2\,M_{(^{4}\mathrm{He})} + M_f$$

^{9}Be remains stable if

$$m_n - 1.664\ \mathrm{MeV} + 0.093\ \mathrm{MeV} < M_f < m_n$$

i.e.,

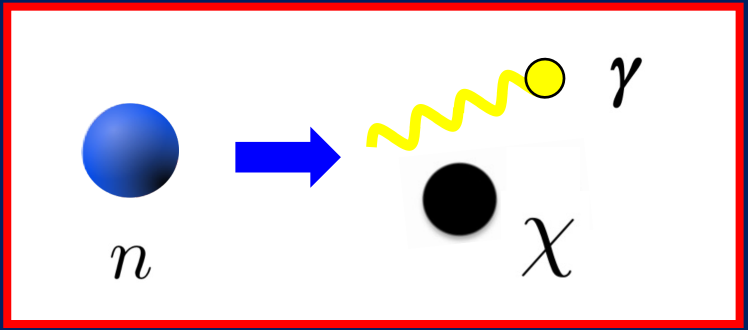
$$937.993\ \mathrm{MeV} < M_f < 939.565\ \mathrm{MeV}$$

Pfutzner & Riisager, PRC 97, 042501(R) (2018)

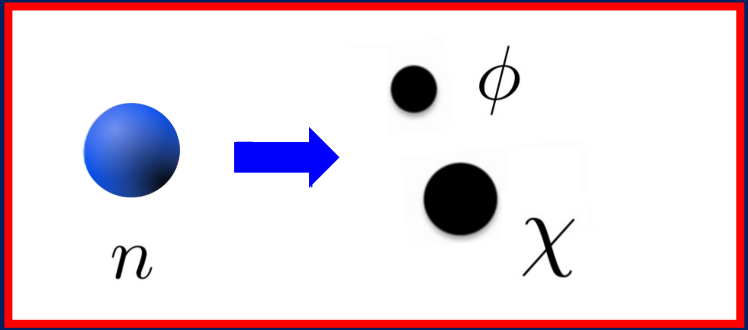
New neutron decay channels

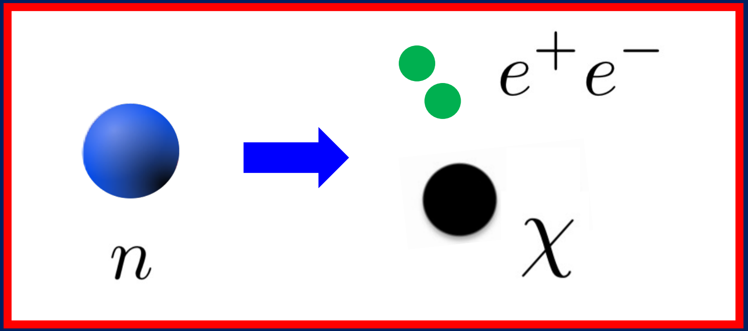
$$937.993\ \text{MeV} < M_f < 939.565\ \text{MeV}$$

Scenario I



Scenario II



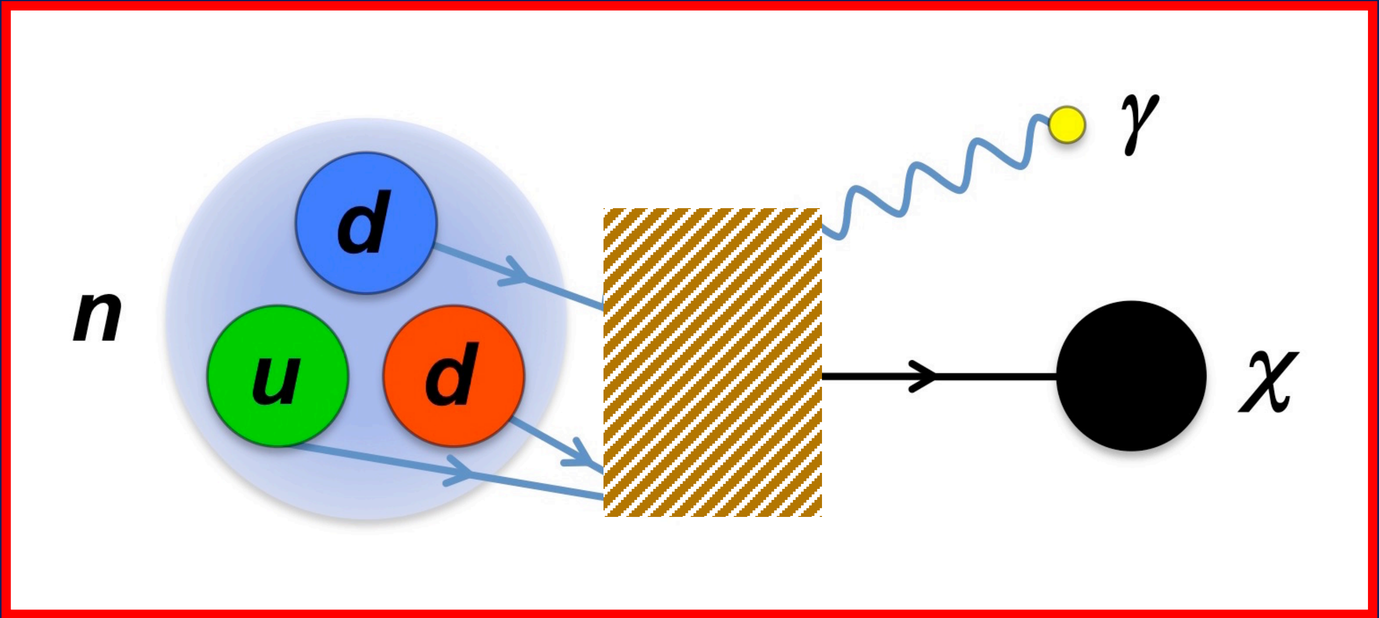


Scenario III

. . .

Scenario I

Neutron ⟶ dark particle + photon



Dirac fermion

$$B_\chi = 1$$

Dark particle mass

$$937.993\ \mathrm{MeV} < m_\chi < 939.565\ \mathrm{MeV}$$

Photon energy

$$0 < E_\gamma < 1.572\ \mathrm{MeV}$$

Baryonic dark matter

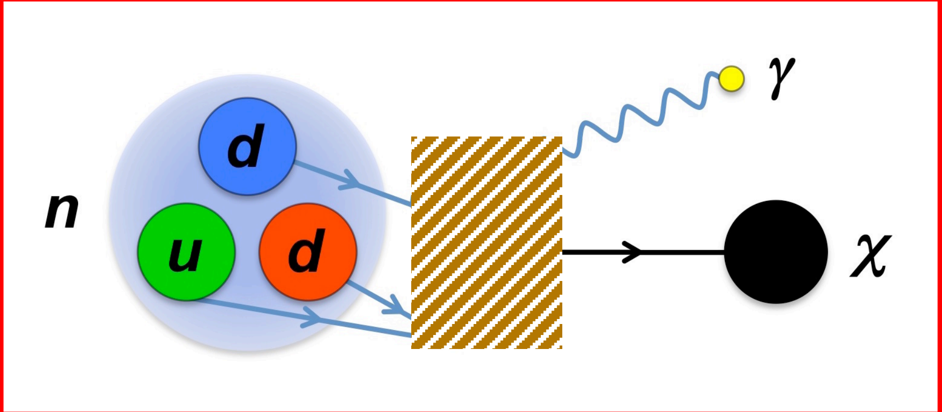
$$937.993\ \mathrm{MeV} < m_\chi < 938.783\ \mathrm{MeV}$$

$$0.782\ \mathrm{MeV} < E_\gamma < 1.572\ \mathrm{MeV}$$

DM with baryon number also in: Duerr, Fileviez Perez & Wise, PRL 110, 231801 (2013)

Scenario I

Neutron ⟶ dark particle + photon



Effective Lagrangian

$$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\not{\partial} - m_n + \frac{g_n e}{8m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}\left(i\not{\partial} - m_\chi\right)\chi + \varepsilon\left(\bar{n}\chi + \bar{\chi}n\right)$$

$$\mathcal{L}_{n\to\chi\gamma}^{\text{eff}} = \frac{g_n e}{8m_n}\frac{\varepsilon}{(m_n - m_\chi)}\,\bar{\chi}\,\sigma^{\mu\nu}F_{\mu\nu}\,n$$

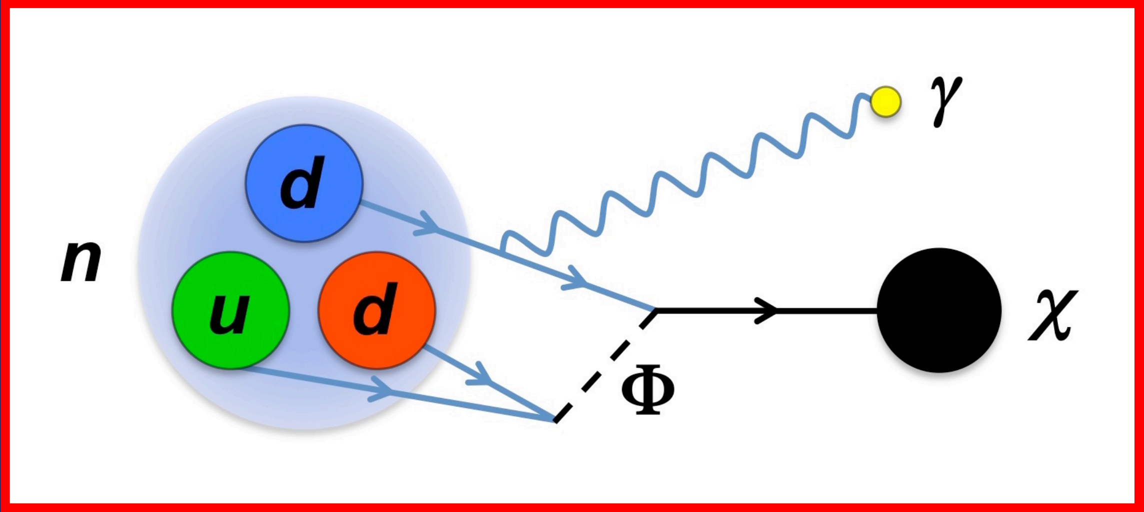
Neutron dark decay rate

$$\Delta\Gamma_{n\to\chi\gamma} = \frac{g_n^2 e^2}{128\pi}\left(1 - \frac{m_\chi^2}{m_n^2}\right)^3 \frac{m_n\,\varepsilon^2}{(m_n - m_\chi)^2}$$

Scenario I

Model 1

(minimal)



Lagrangian

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

Mixing parameter $\boxed{\varepsilon = \frac{\beta\, \lambda_q \lambda_\chi}{M_\Phi^2}}$ $\boxed{\langle 0|\epsilon^{ijk} \left(\overline{u^c_{Li}} d_{Rj}\right) d^\rho_{Rk}|n\rangle = \beta\, \left(\frac{1+\gamma_5}{2}\right)^\rho_{\ \sigma} u^\sigma}$

Lattice calculation gives

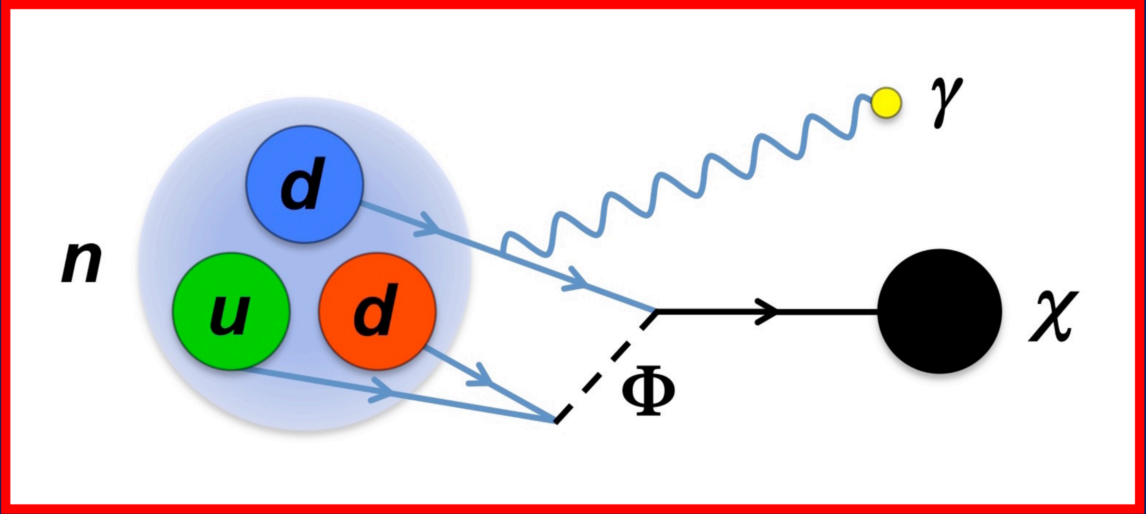
$$\boxed{\beta \approx 0.014\ \text{GeV}^3}$$

Aoki et al., PRD 96, 014506 (2017)

Scenario I

Model 1

(minimal)



Lagrangian

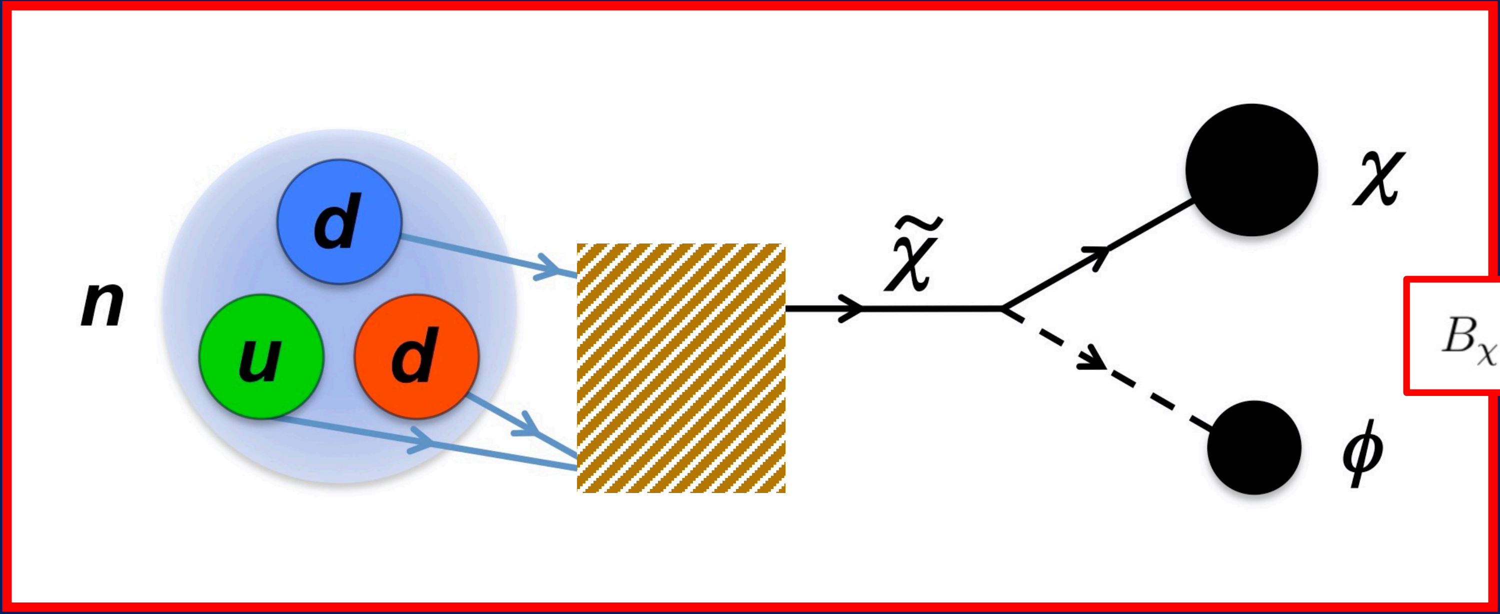
$$\mathcal{L}_1 = \left(\lambda_q \, \epsilon^{ijk} \, \overline{u_{Li}^c} \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\chi} \, d_{Ri} + \text{h.c.}\right) - M_\Phi^2 |\Phi|^2 - m_\chi \, \bar{\chi} \, \chi$$

To explain the neutron lifetime discrepancy

$$\Delta\Gamma_{n\to\chi\gamma} \approx \Gamma_n/100 \quad \Longrightarrow \quad \frac{M_\Phi}{\sqrt{|\lambda_q \lambda_\chi|}} \approx 200 \text{ TeV}$$

Scenario II

Neutron ⟶ two dark particles



Dirac fermion

$$B_\chi + B_\phi = 1$$

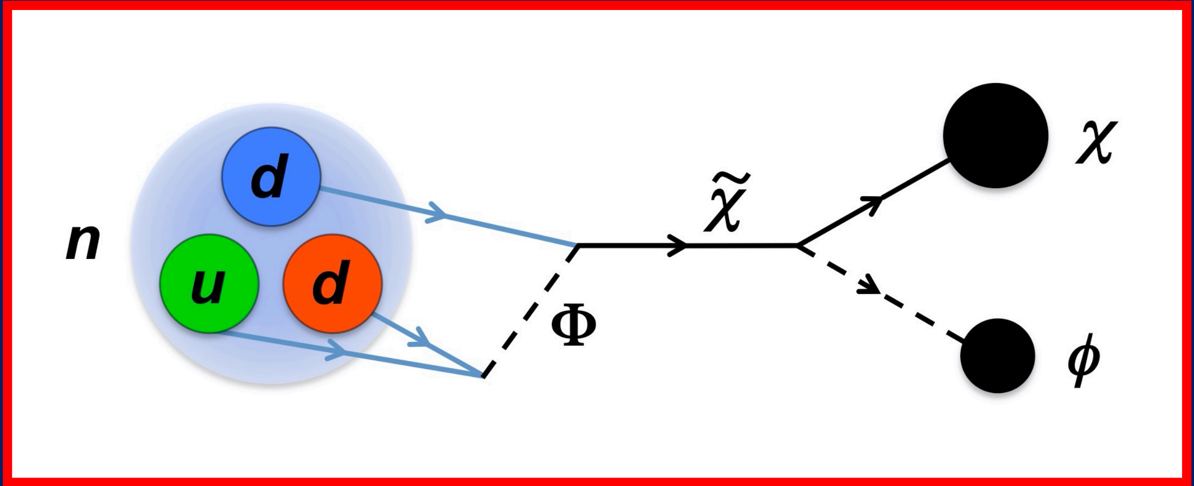
Constraints on masses

$$937.993\ \mathrm{MeV} < m_\chi + m_\phi < 939.565\ \mathrm{MeV}$$

$$937.993\ \mathrm{MeV} < m_{\tilde{\chi}}$$

Scenario II

Model 2



Neutron dark decay rate

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

$$\boxed{f(x,y) = [(1-x)^2 - y^2]\,[(1+x)^2 - y^2]^3}$$

$$\boxed{x = m_\chi/m_n}$$

$$\boxed{y = m_\phi/m_n}$$

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

$$\boxed{\Delta\Gamma_{n\to\chi\phi} \approx \Gamma_n/100} \Rightarrow \boxed{\frac{M_\Phi}{\sqrt{|\lambda_q\lambda_{\tilde{\chi}}\lambda_\phi|}} \approx 300\ \text{TeV}}$$

Theoretical and experimental developments

Theory

- Neutron star constraints
- Self-interacting dark sector
- Repulsive DM-baryon interactions
- Baryogenesis, meson dark decays
- Dark matter capture
- Neutron-dark matter annihilation
- Connection to other anomalies

Experiment

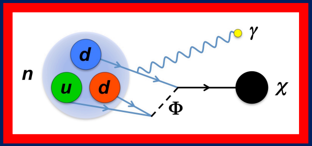
- Neutron dark decays
- Nuclear dark decays
- Beam and bottle measurements

Neutron star constraints

- *McKeen, Nelson, Reddy & Zhou,*
PRL 121, 061802 (2018), arXiv:1802.08244

- *Baym, Beck, Geltenbort & Shelton,*
PRL 121, 061801 (2018), arXiv:1802.08282

- *Motta, Guichon & Thomas,*
J. Phys. G 45, 05LT01 (2018), arXiv:1802.08427



↓

Neutron star masses < 0.8 $M_\odot$

From observation: neutron stars with masses up to 2 $M_\odot$

Neutron star constraints

- *McKeen, Nelson, Reddy & Zhou,*
PRL 121, 061802 (2018), arXiv:1802.08244

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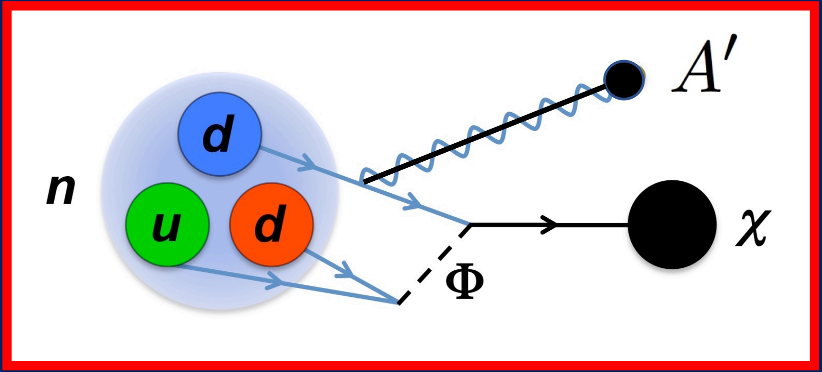
Observed neutron star masses allowed if there are:

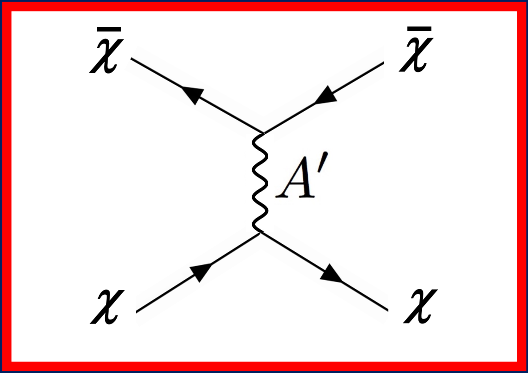
→ **strong repulsive self-interactions in the dark sector**

~ ***SIDM (Spergel & Steinhardt, PRL 84, 3760 (2000))***

Model with dark sector self-interactions (1)

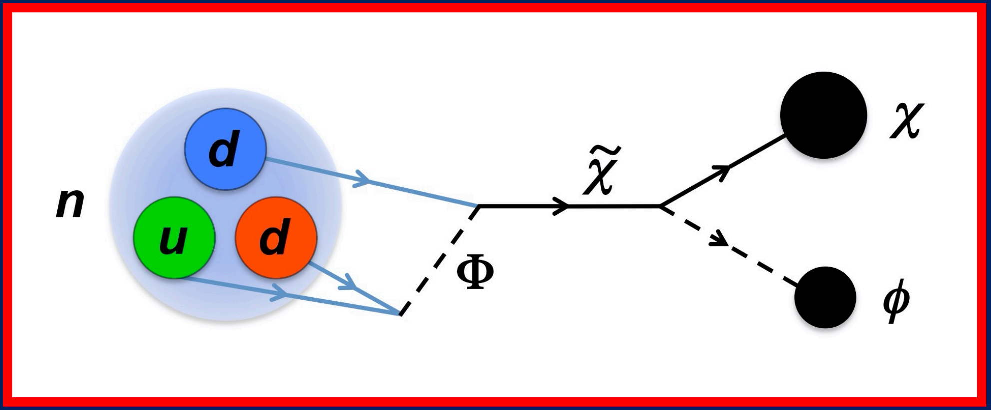
Neutron decay to a dark particle and a dark photon

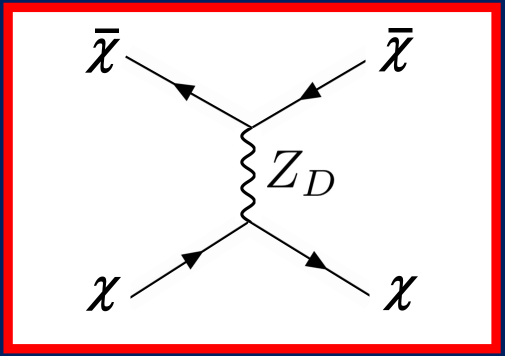




Cline & Cornell, JHEP 07, 081 (2018)

Model with dark sector self-interactions (2)



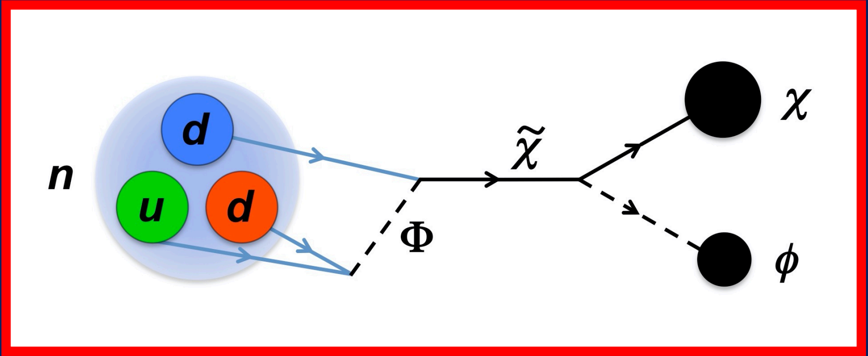


Karananas & Kassiteridis, JCAP 09, 036 (2018)

Highlights of the model:

- χ can constitute all of the dark matter in the universe; model consistent with astrophysical constraints
- solves small-scale structure problems of ΛCDM

Model with DM-neutron repulsive interactions



Lagrangian

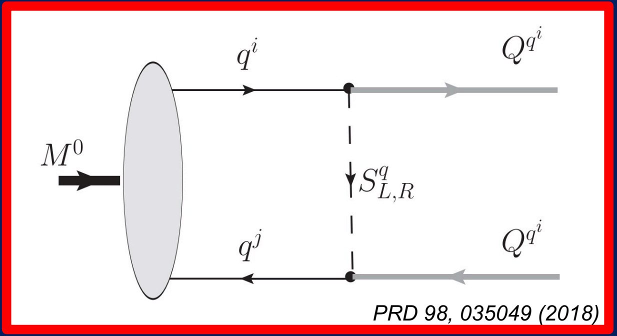
$$\mathcal{L} = \lambda_q \, \epsilon^{ijk} \, \overline{u^c_{L\,i}} \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}} \, d_{Ri} + \lambda_\phi \, \bar{\tilde{\chi}} \, \chi \, \phi$$
$$+ \mu H^\dagger H \phi + g_\chi \bar{\chi} \chi \, \phi + \text{h.c.}$$

Grinstein, Kouvaris & Nielsen,
PRL 123 (2019) 091601

Other theoretical follow-ups

Neutral hadron dark decays

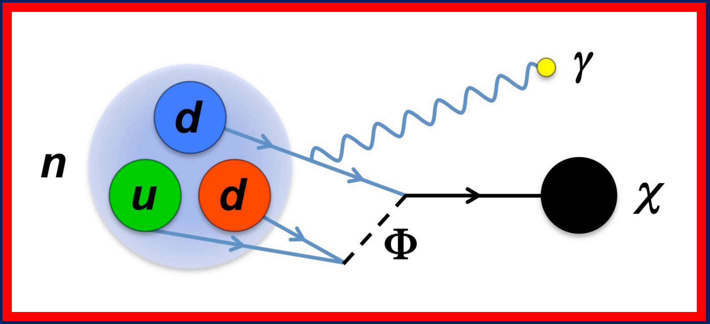
Barducci, Fabbrichesi & Gabrielli, PRD 98, 035049 (2018)

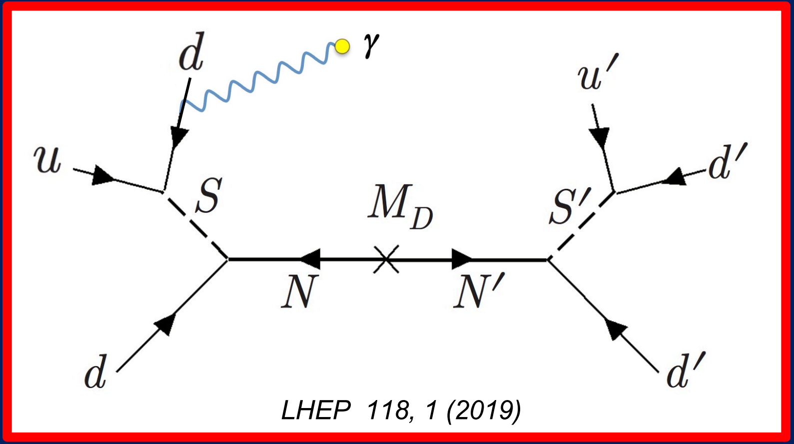


PRD 98, 035049 (2018)

Neutron-mirror neutron oscillations

Berezhiani, EPJ C 79, 484 (2019); LHEP 118, 1 (2019); Tan, PLB 797, 134921 (2019); BF & Grinstein, arXiv:1902.08975





LHEP 118, 1 (2019)

Special case of neutron dark decay with $\boxed{\chi = n'}$

Other theoretical follow-ups

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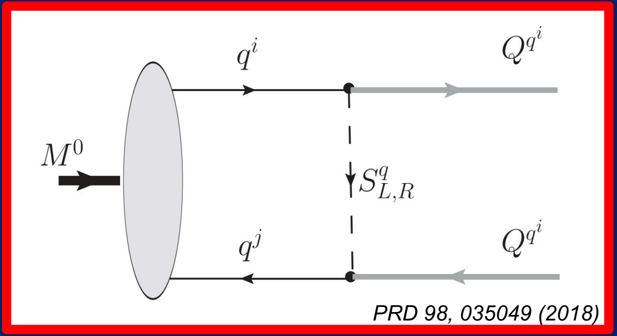

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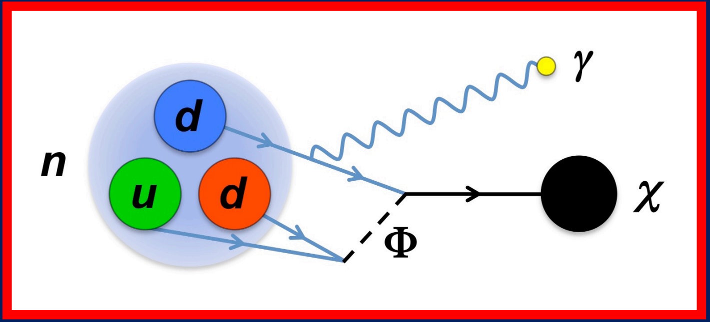
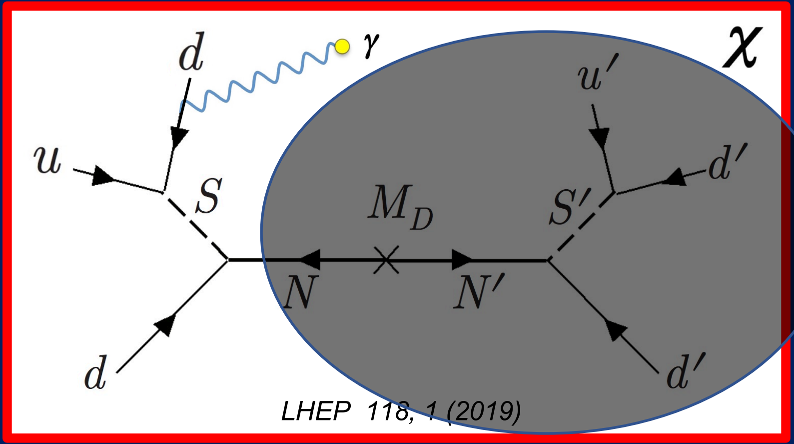


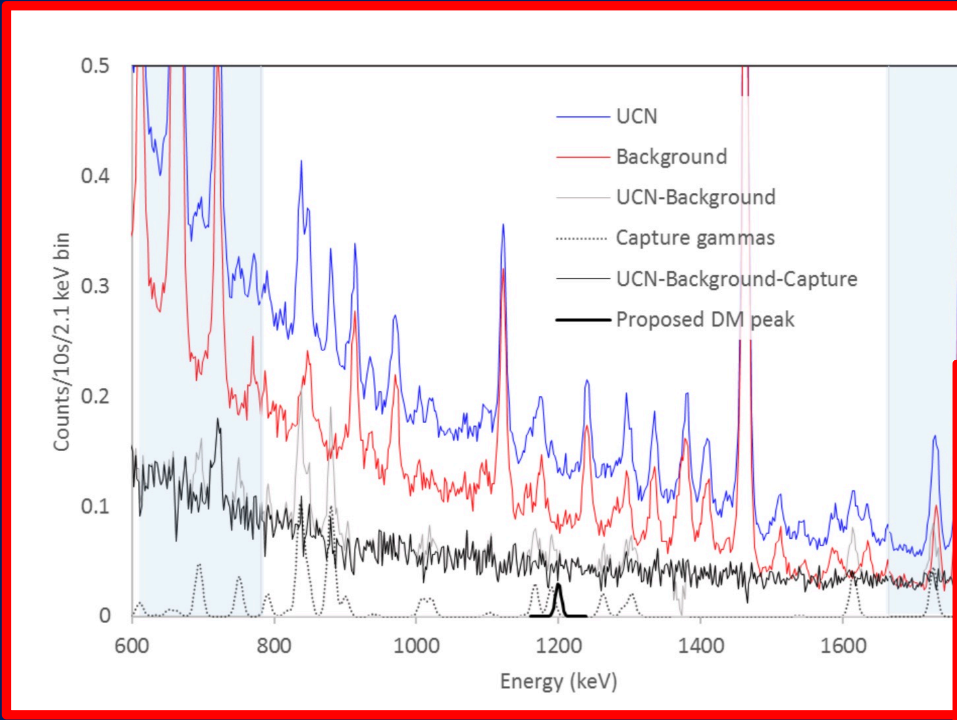


LHEP 118, 1 (2019)

Special case of neutron dark decay with $\boxed{\chi = n'}$

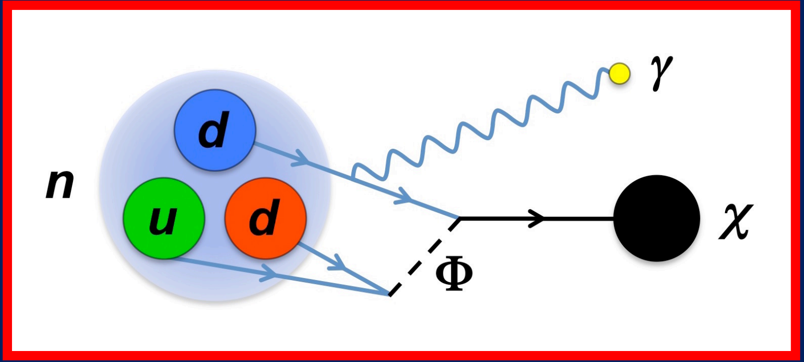
Experiment: Neutron ➡ dark matter + photon

Los Alamos UCN



Tang et al., PRL 121, 022505 (2018)

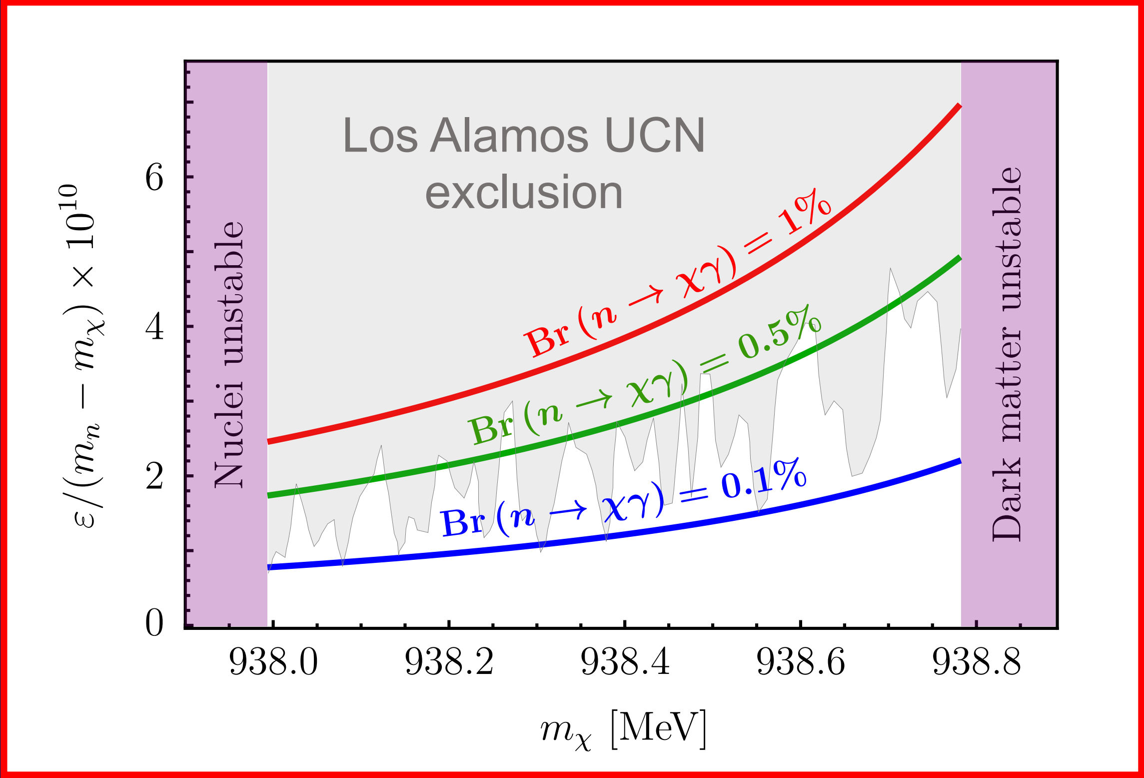
$\boxed{2.2\,\sigma}$ **exclusion**



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

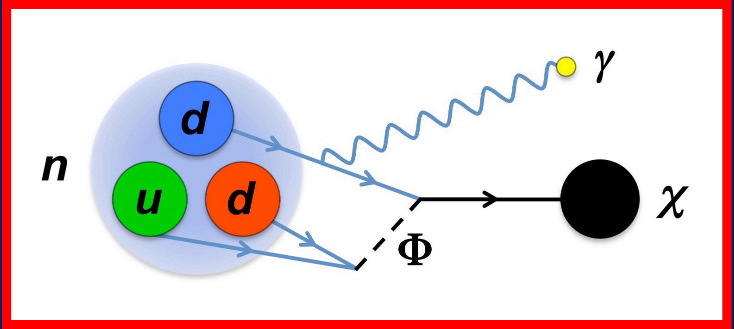
https://phys.org

Experiment: Neutron ➡ dark matter + photon



McKeen & Pospelov,

arXiv:2003.02270 [hep-ph]

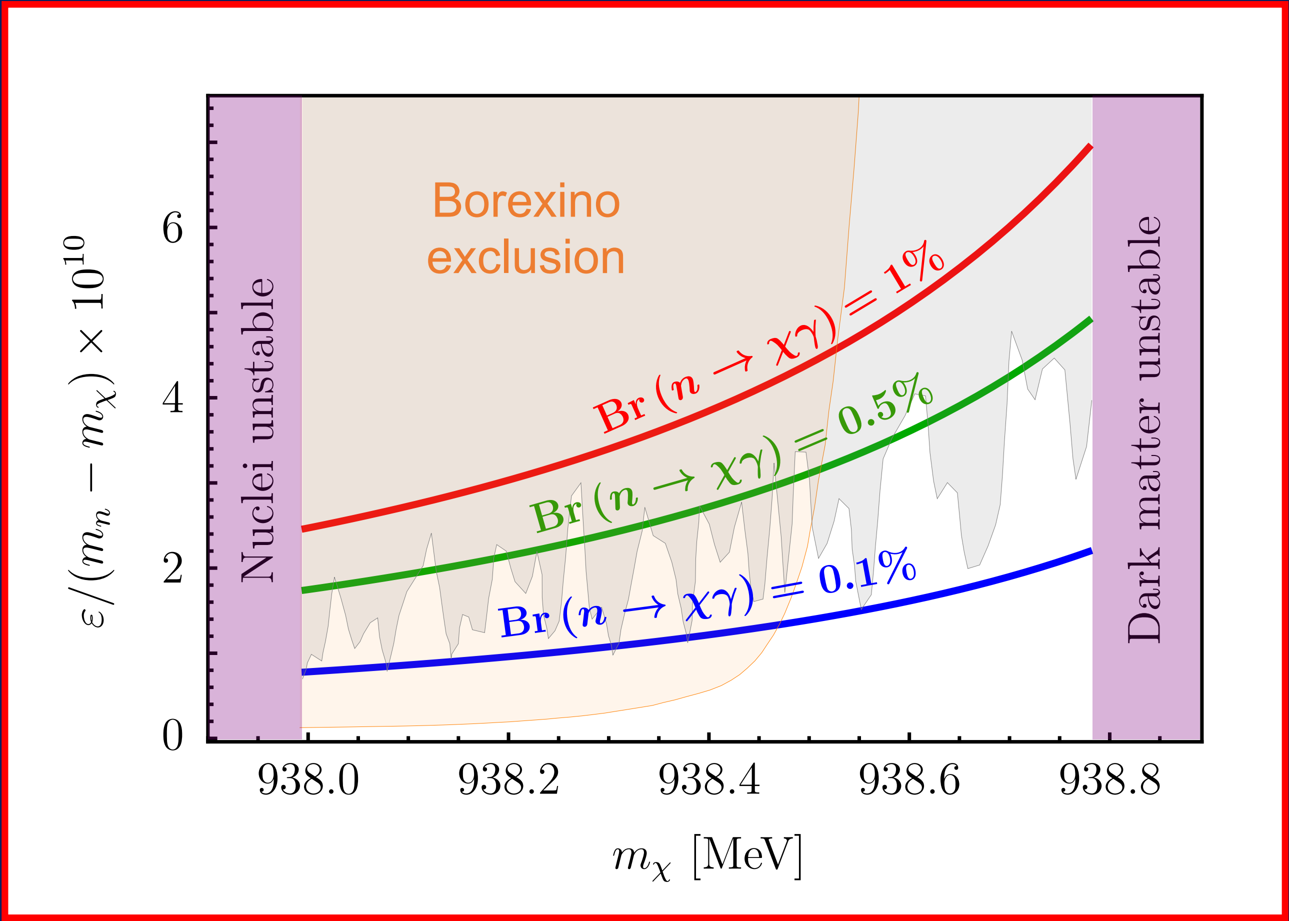


$$0.782\ \mathrm{MeV} < E_\gamma < 1.664\ \mathrm{MeV}$$

Limits from hydrogen dark decay

$\mathrm{H} \rightarrow \chi\,\nu_e$

Berezhiani, LHEP 2 (2019) 1, 118
McKeen & Pospelov, arXiv:2003.02270



McKeen & Pospelov, arXiv:2003.02270 [hep-ph]

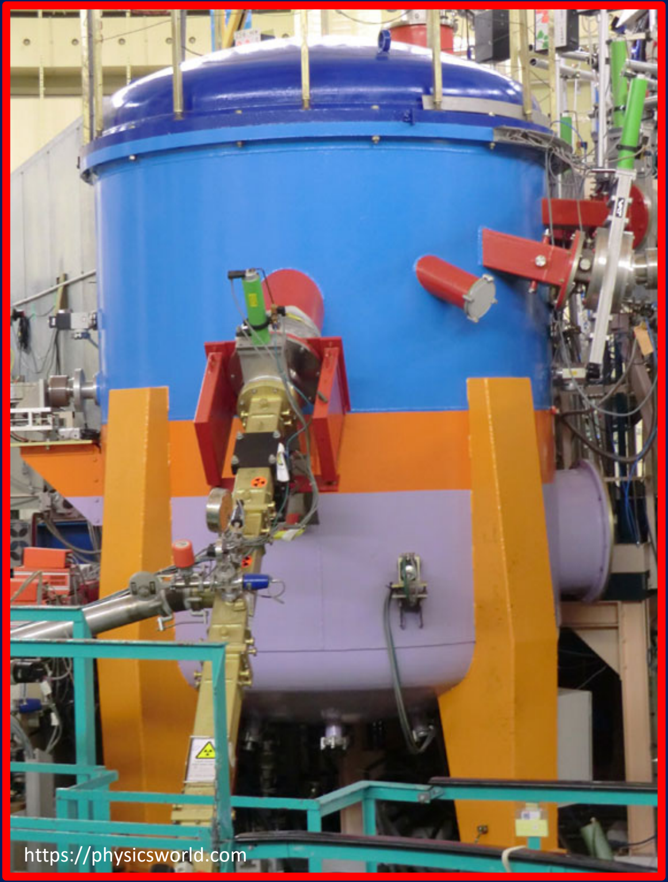
Experiment: Neutron → dark particle + e^+e^-

Los Alamos UCN

https://phys.org

Sun et al., PRC 97, 052501 (2018)

ILL, Grenoble

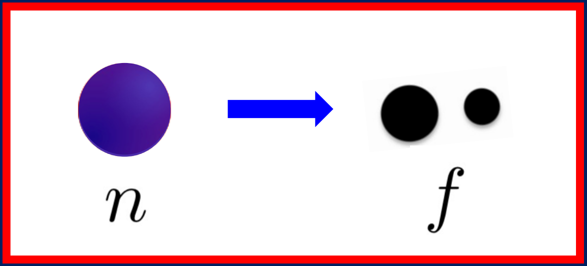


https://physicsworld.com

Klopf et al., PRL 122, 222503 (2019)

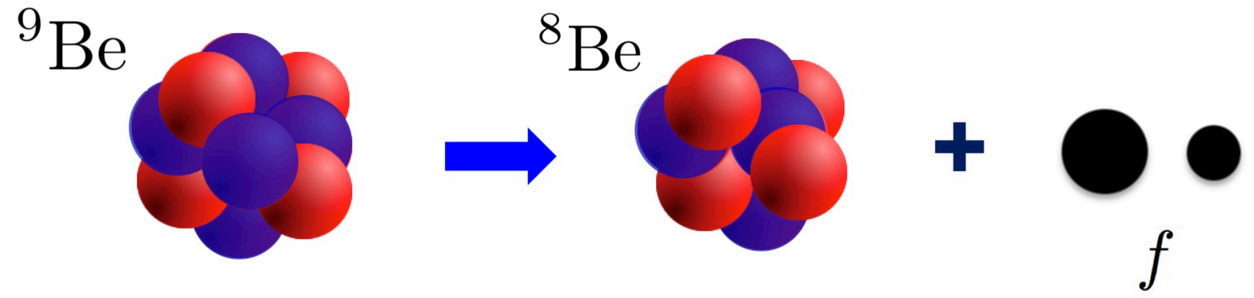
Nuclear physics bounds – *reminder*

Neutron dark decay



$$M_f < m_n$$

^{9}Be would dark decay if



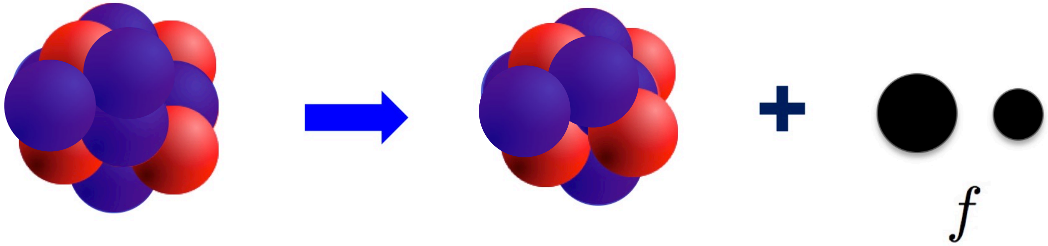
$$M_{(^9\mathrm{Be})} =$$
$$M_{(^8\mathrm{Be})} + m_n - 1.664\ \mathrm{MeV} \quad > \quad M_{(^8\mathrm{Be})} + M_f$$

^{9}Be remains stable if

$$m_n - 1.664\ \mathrm{MeV} < M_f < m_n$$

Nuclear dark decays

Dark decays possible in unstable nuclei with S(n) < 1.664 MeV



$$M + m_n - S(n) \quad > \quad M + M_f$$

$$\boxed{937.993\,\mathrm{MeV} < M_f < m_n - S(n)}$$

Nuclear dark decays

An example of an unstable nucleus with S(n) < 1.572 MeV is ^{11}Li with S(n)$_{11\mathrm{Li}}$ = 0.4 MeV that could decay via

$$^{11}\mathrm{Li} \to {}^{10}\mathrm{Li} + \chi$$

as long as

$$937.993\ \mathrm{MeV} < M_f < m_n - S_n$$

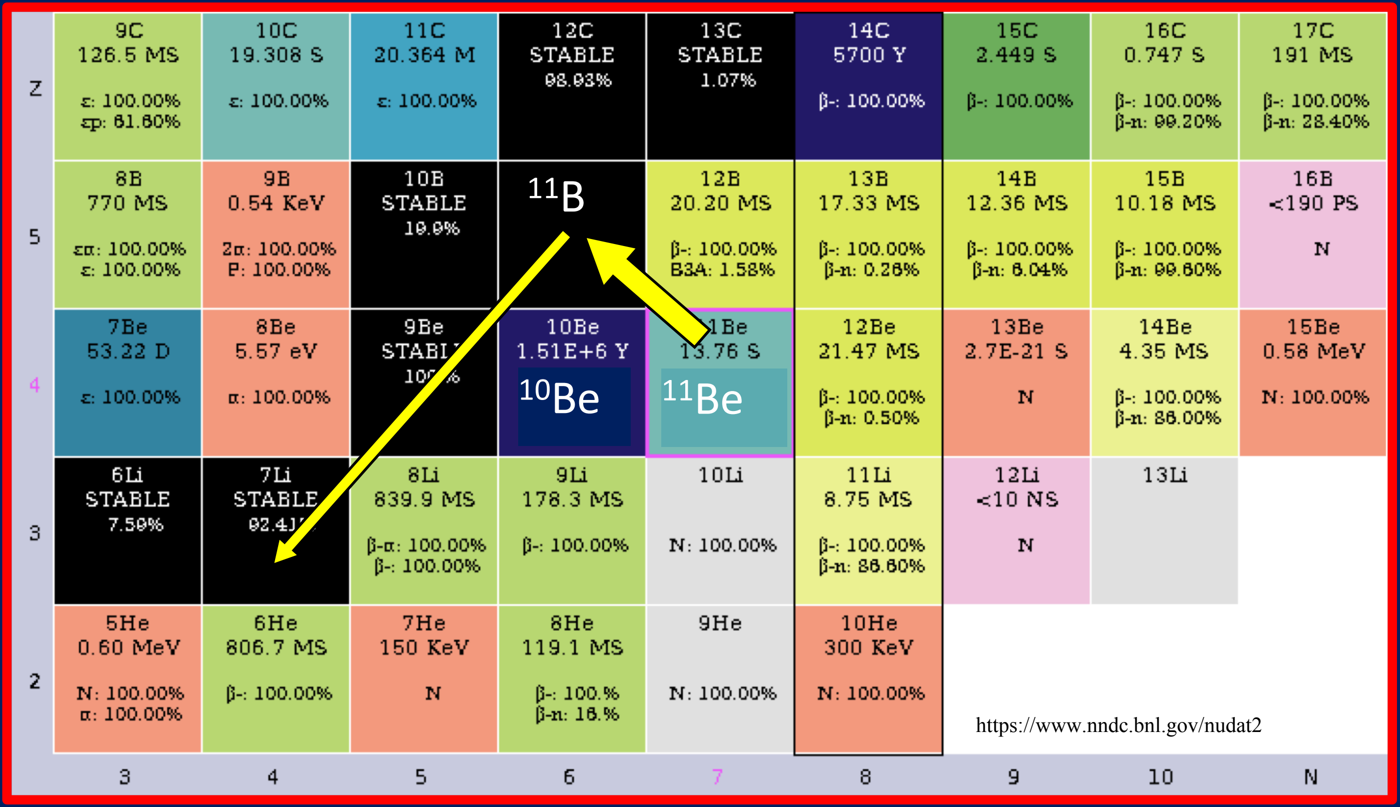
Better candidate (with a halo neutron):

➡ $$^{11}\mathrm{Be}$$

Pfutzner & Riisager, Examining the possibility to observe neutron dark decay in nuclei, PRC 97, 042501(R) (2018)

$$S(n)_{(^{11}\mathrm{Be})} = 0.502\ \mathrm{MeV}$$

^{11}Be decay channels



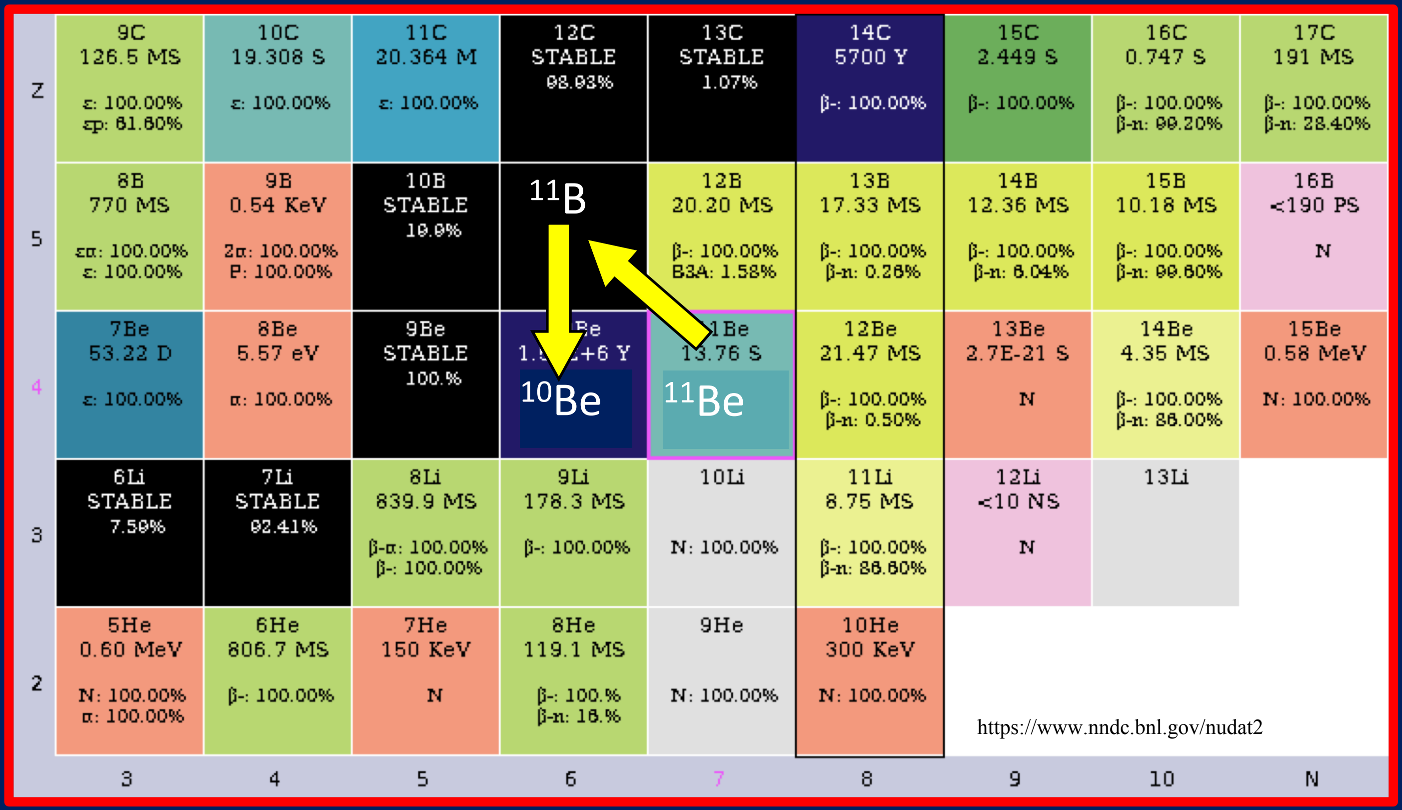
Z	9C 126.5 MS ε: 100.00% εp: 61.60%	10C 19.308 S ε: 100.00%	11C 20.364 M ε: 100.00%	12C STABLE 98.93%	13C STABLE 1.07%	14C 5700 Y β-: 100.00%	15C 2.449 S β-: 100.00%	16C 0.747 S β-: 100.00% β-n: 99.20%	17C 191 MS β-: 100.00% β-n: 28.40%
5	8B 770 MS εα: 100.00% ε: 100.00%	9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	^{11}B	12B 20.20 MS β-: 100.00% B3A: 1.58%	13B 17.33 MS β-: 100.00% β-n: 0.28%	14B 12.36 MS β-: 100.00% β-n: 6.04%	15B 10.18 MS β-: 100.00% β-n: 99.60%	16B <190 PS N
4	7Be 53.22 D ε: 100.00%	8Be 5.57 eV α: 100.00%	9Be STABL 10 %	10Be 1.51E+6 Y ^{10}Be	1Be 13.76 S ^{11}Be	12Be 21.47 MS β-: 100.00% β-n: 0.50%	13Be 2.7E-21 S N	14Be 4.35 MS β-: 100.00% β-n: 86.00%	15Be 0.58 MeV N: 100.00%
3	6Li STABLE 7.59%	7Li STABLE 92.4	8Li 839.9 MS β-α: 100.00% β-: 100.00%	9Li 178.3 MS β-: 100.00%	10Li N: 100.00%	11Li 8.75 MS β-: 100.00% β-n: 86.60%	12Li <10 NS N	13Li	
2	5He 0.60 MeV N: 100.00% α: 100.00%	6He 806.7 MS β-: 100.00%	7He 150 KeV N	8He 119.1 MS β-: 100.% β-n: 16.%	9He N: 100.00%	10He 300 KeV N: 100.00%			
	3	4	5	6	7	8	9	10	N

https://www.nndc.bnl.gov/nudat2

$$\boxed{\mathrm{Br}\left({}^{11}\mathrm{Be} \xrightarrow{\beta^-} {}^{11}\mathrm{B}\right) = 97.1\%}$$

$$\boxed{\mathrm{Br}\left({}^{11}\mathrm{Be} \xrightarrow{\beta^-,\,\alpha} {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}\right) = 2.9\%}$$

^{11}Be decay channels



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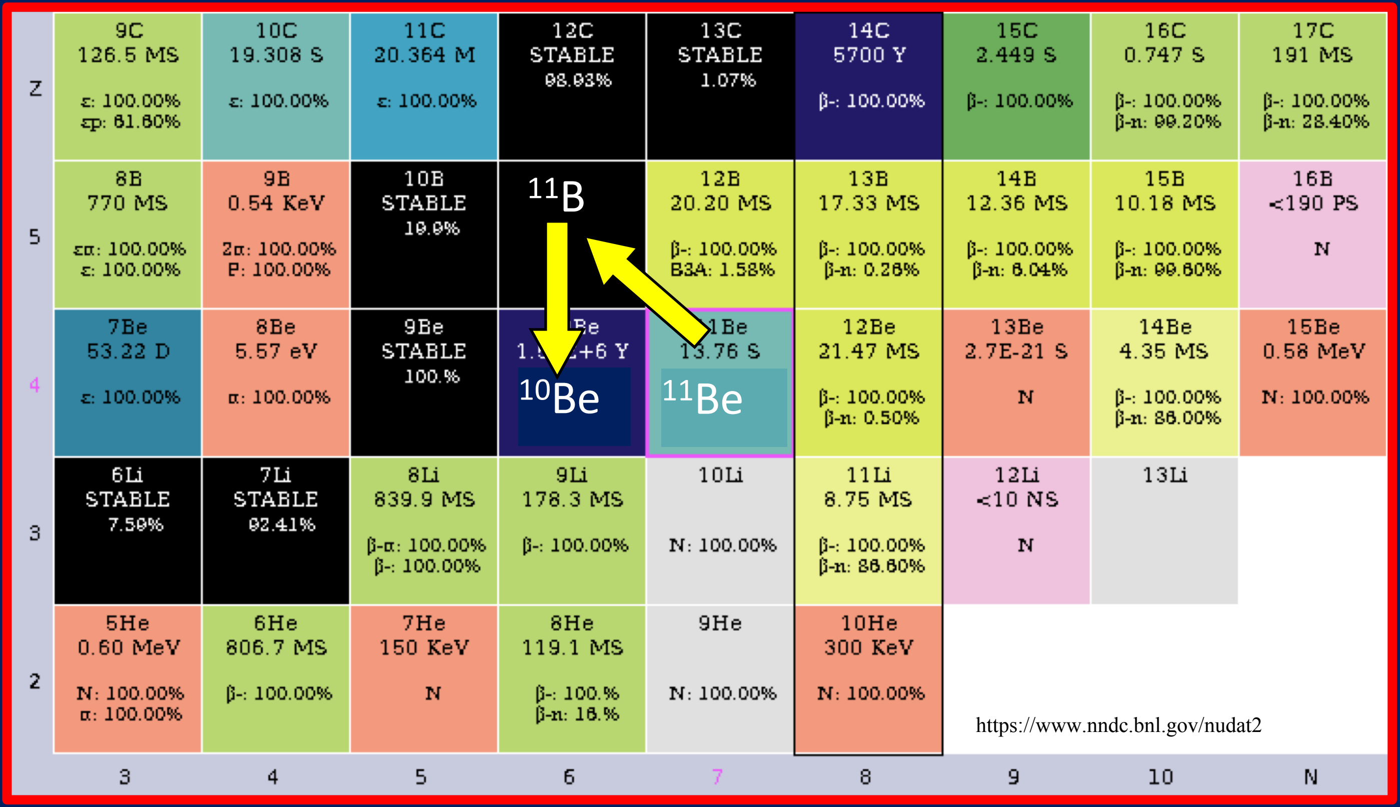
https://www.nndc.bnl.gov/nudat2

Theoretical estimate for β-delayed proton emission:

$$\boxed{\mathrm{Br}(^{11}\mathrm{Be} \xrightarrow{\beta} {}^{11}\mathrm{B} \to {}^{10}\mathrm{Be} + p) \approx 2 \times 10^{-8}}$$

Unexplained result in ^{11}Be decays



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	3	4	5	6	7	8	9	10	N

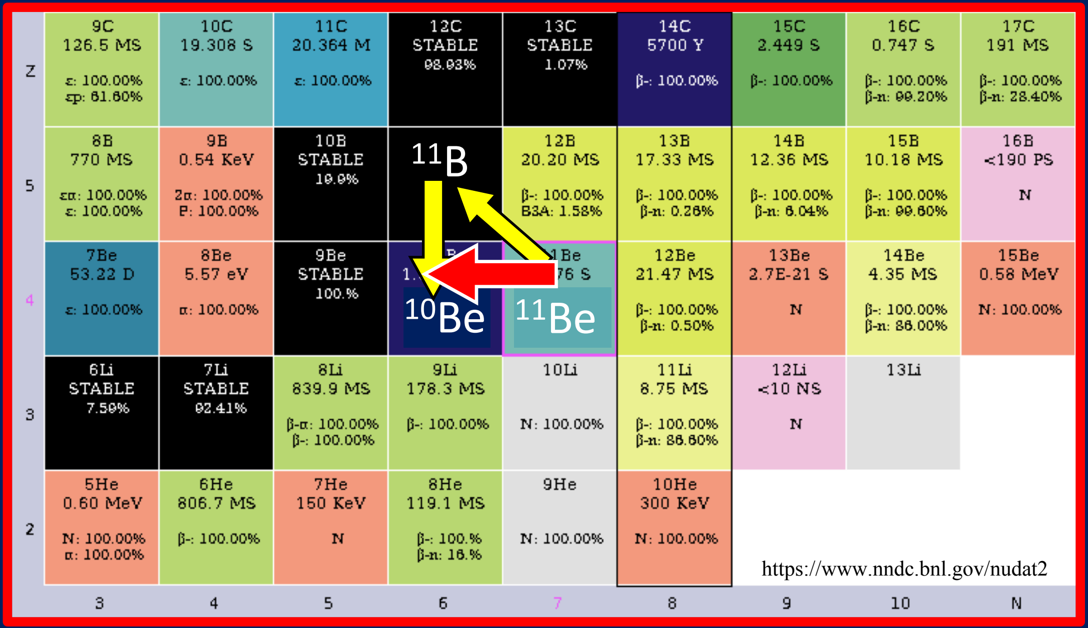
https://www.nndc.bnl.gov/nudat2

Unexpectedly high number of ^{10}Be nuclei produced in ^{11}Be decays was observed

$$\mathrm{Br}\left({}^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + ?\right) \approx 8 \times 10^{-6}$$

Riisager et al., ^{11}Be(βp), a quasi-free neutron decay?, PLB 732, 305 (2014)

Question



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https://www.nndc.bnl.gov/nudat2

Is it an undiscovered narrow resonance in ^{11}B yielding large

$$\mathrm{Br}(^{11}\mathrm{Be} \xrightarrow{\beta} {}^{11}\mathrm{B} \rightarrow {}^{10}\mathrm{Be} + p)$$

or dark decay

$$^{11}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + \chi + \phi$$

?

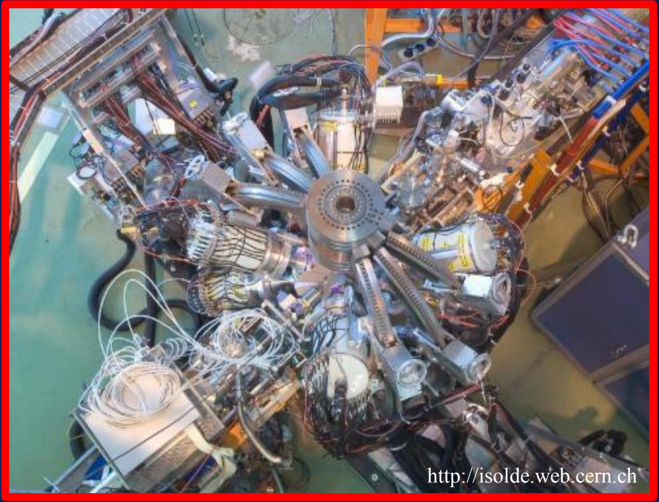
^{11}Be decay experiments

Are there protons in the final state of ^{11}Be decays?

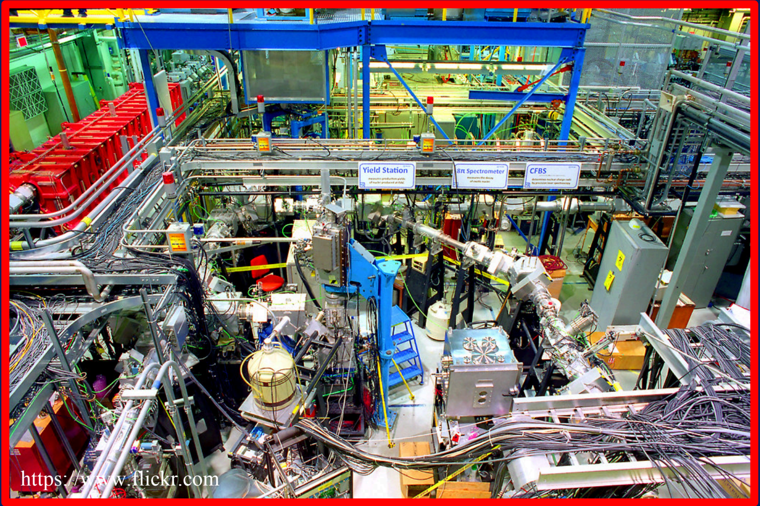
This would test ALL neutron dark decay channels with:

$$\boxed{937.993 \text{ MeV} < M_f < 939.064 \text{ MeV}}$$

CERN – ISOLDE


http://isolde.web.cern.ch

TRIUMF & MSU


https://www.flickr.com

Ayyad et al., PRL 123, 082501 (2019)

^{11}Be decay experiments

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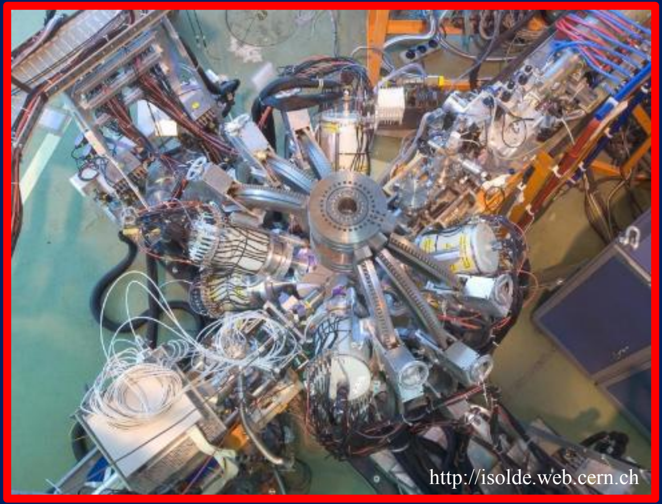
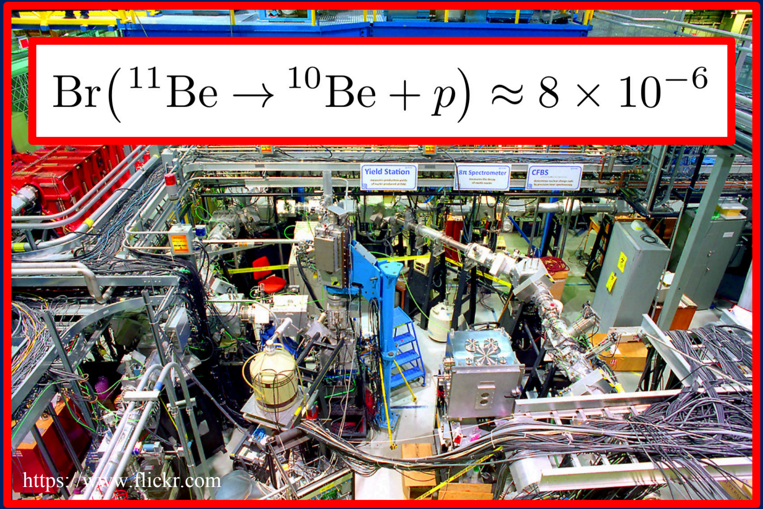
CERN – ISOLDE

TRIUMF & MSU



http://isolde.web.cern.ch



$$\mathrm{Br}\left(^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + p\right) \approx 8 \times 10^{-6}$$

https://www.flickr.com

Ayyad et al., PRL 123, 082501 (2019)

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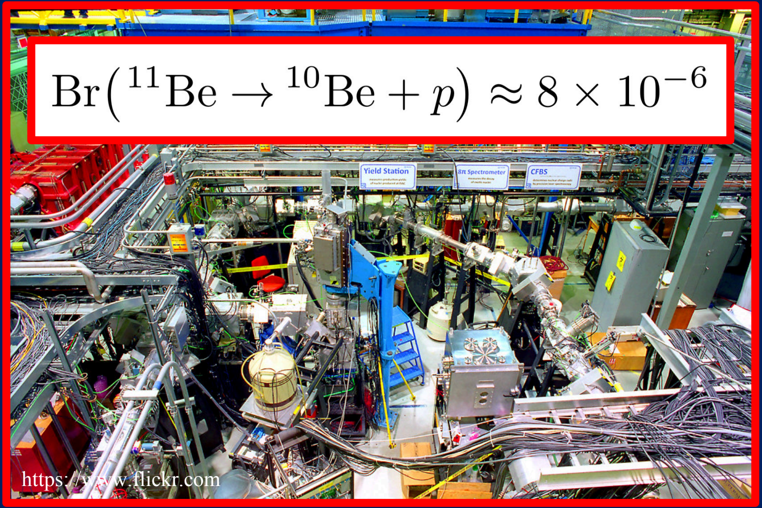


$$\mathrm{Br}\left({}^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + p\right) \approx 8 \times 10^{-6}$$

https://www.flickr.com

Ayyad et al., PRL 123, 082501 (2019)

New narrow, near-threshold resonance in ^{11}B suggested also by a numerical calculation

Okołowicz, Ploszajczak & Nazarewicz, PRL 124, 042502 (2020)

^{11}Be decay experiments

Are there protons in the final state of ^{11}Be decays?

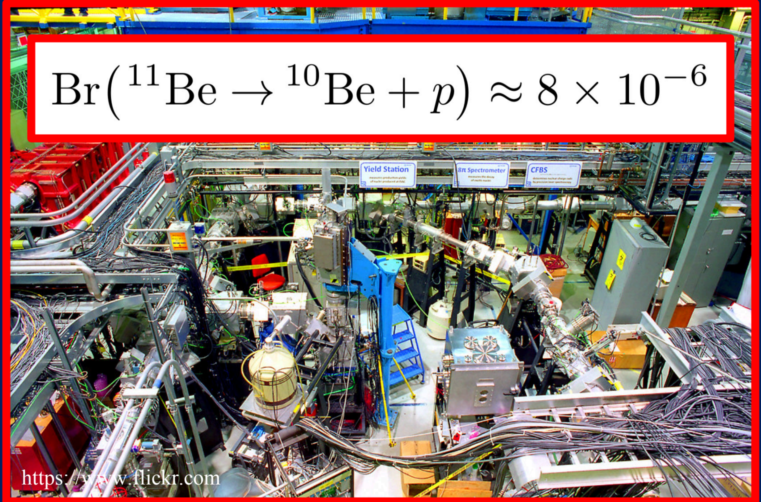
This would test ALL neutron dark decay channels with:

$$937.993\ \text{MeV} < M_f < 939.064\ \text{MeV}$$

TRIUMF & MSU

$$\text{Br}(^{11}\text{Be} \to {}^{10}\text{Be} + ?) \lesssim 2.2 \times 10^{-6}$$

Riisager et al., EPJ A 56 (2020) 3, 100



$$\text{Br}\left(^{11}\text{Be} \to {}^{10}\text{Be} + p\right) \approx 8 \times 10^{-6}$$

https://www.flickr.com

Ayyad et al., PRL 123, 082501 (2019)

Ongoing beam and bottle experiments

beam

https://www.ncnr.nist.gov

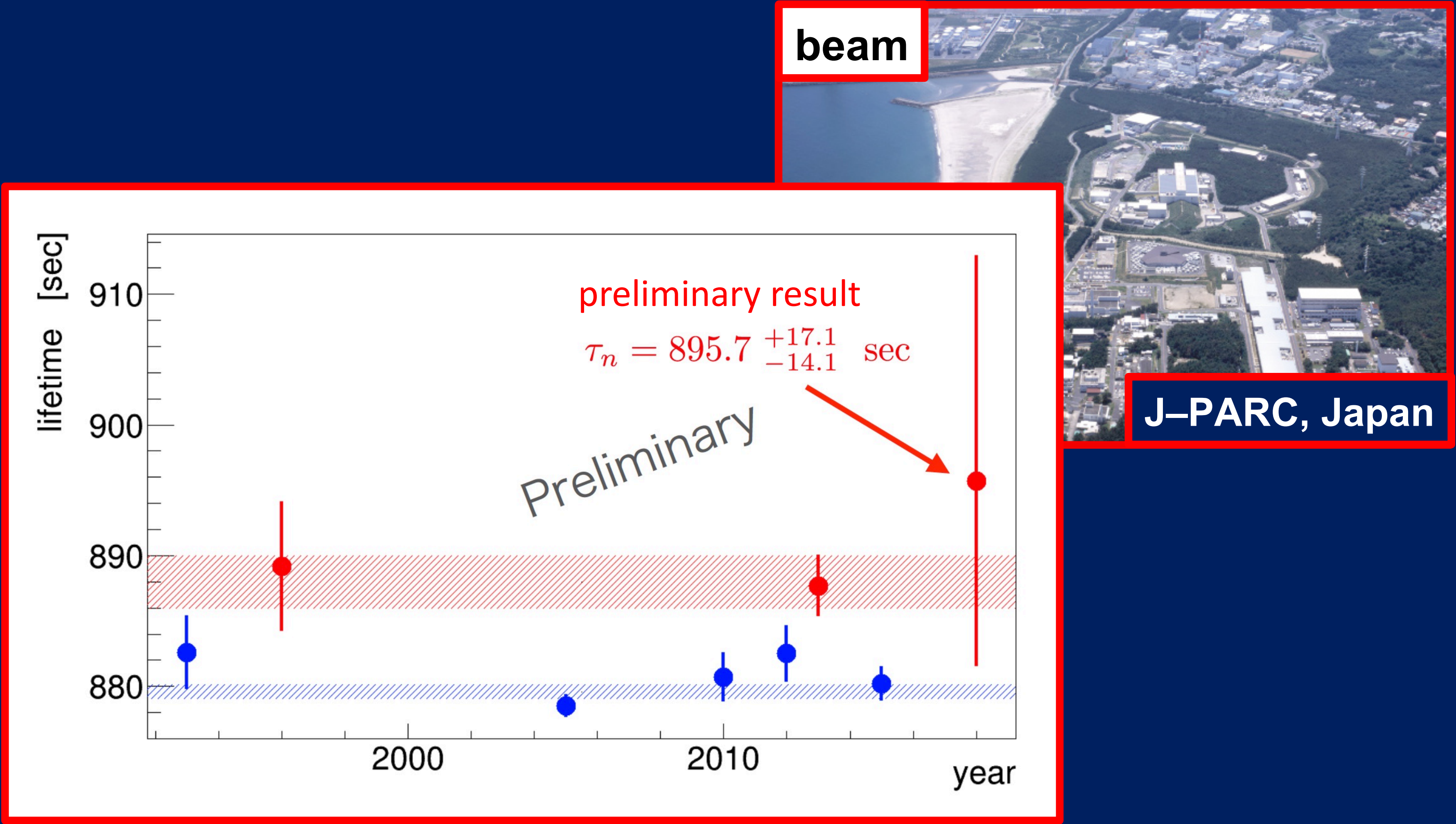
NIST Center for Neutron Research

beam

https://nat-web.com

J–PARC, Japan

Ongoing beam and bottle experiments



beam

J–PARC, Japan

preliminary result

$\tau_n = 895.7\,^{+17.1}_{-14.1}$ sec

Nagakura, N., Talk at the International Workshop on Particle Physics at Neutron Sources, ILL, Grenoble, May 2018

Ongoing beam and bottle experiments

beam

https://www.ncnr.nist.gov

NIST Center for Neutron Research

beam

https://nat-web.com

J–PARC, Japan

bottle

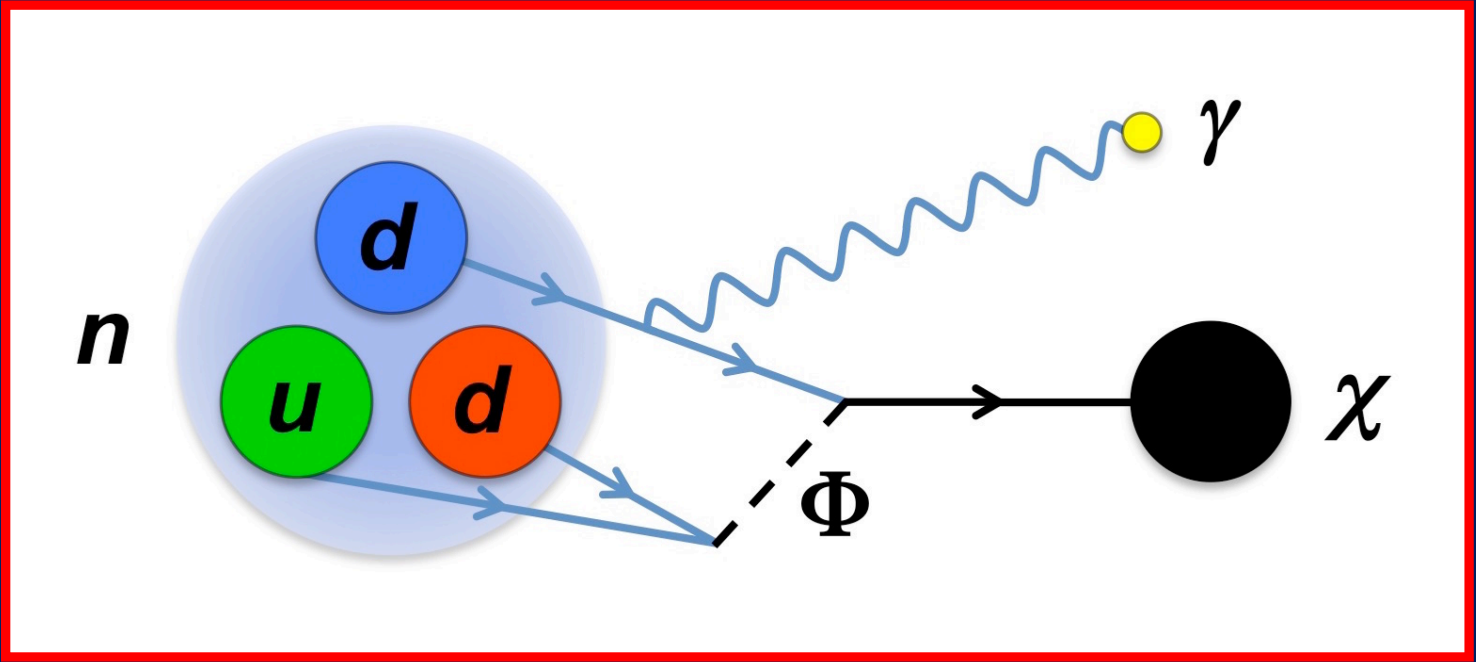
www.lanl.gov

Los Alamos Neutron
Science Center

➡ Add a proton
detection system in
bottle experiments !

UCNProBe experiment

Portal to a baryonic dark sector



(1) χ **is the dark matter particle** $B_\chi = 1$

(2) χ **is the anti-dark matter particle** $B_{\bar{\chi}} = -1$

Dark matter capture

$$\boxed{B_\chi = 1}$$

BF, Grinstein & Zhao, arXiv:2005.04240 [hep-ph]

Capture of χ from the DM halo by a nucleus *(A,Z) leads to*

$$\boxed{\chi + (A, Z) \rightarrow (A+1, Z)^* \rightarrow (A+1, Z) + \gamma_c}$$

Signature: cascade of photons with total energy

$$\boxed{E_c = S(n) - (m_n - m_\chi)}$$

Experiments:

➡ **DUNE, PandaX, XENON1T, …**

Neutron-dark matter annihilation

$\boxed{B_{\bar{\chi}} = -1}$

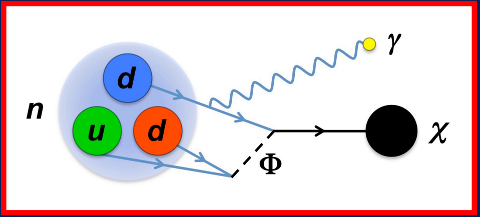
Keung, Marfatia & Tseng, JHEP 09 (2019) 053

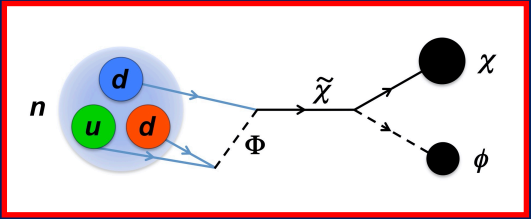
Annihilation channels

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

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

in models





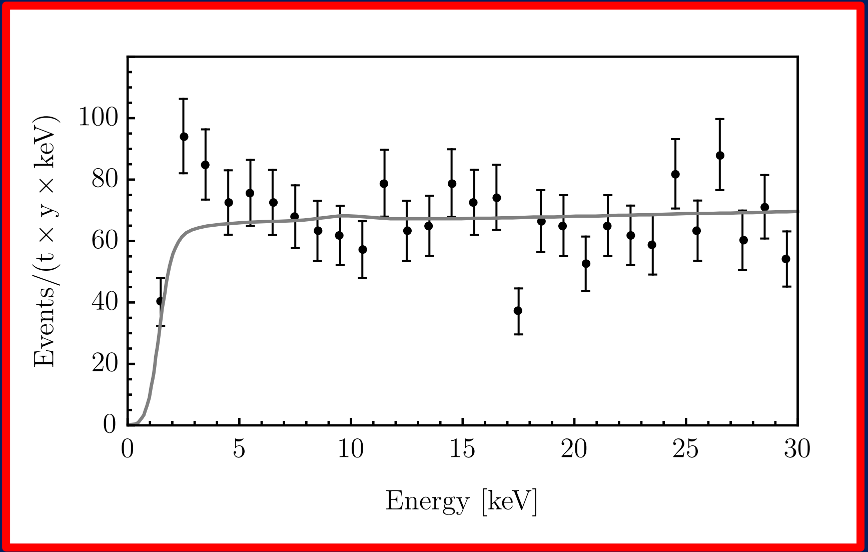
Experiments:

➡ **Super-K, DUNE, Hyper-K**

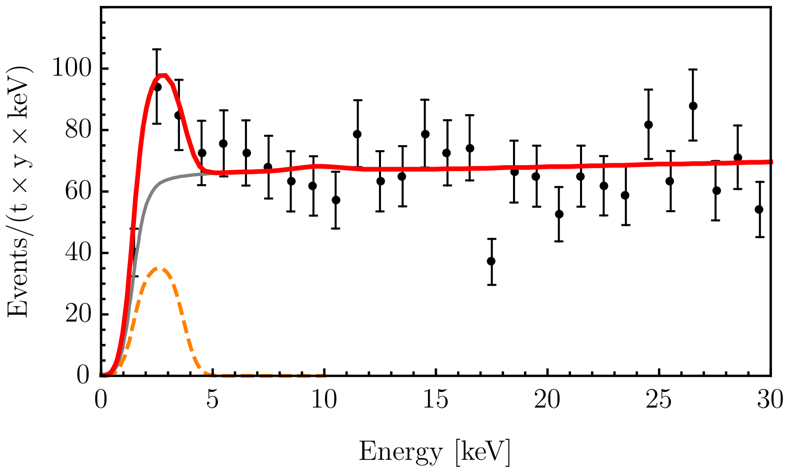
More general scenario:

➡ *Davoudiasl, Morrissey, Sigurdson & Tulin, PRL 105 (2010) 211304*

Connection to the XENON1T excess



Connection to the XENON1T excess



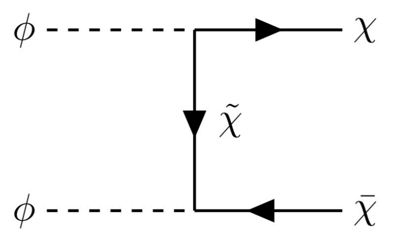
➡ Boosted dark matter

- *Kannike, Raidal, Veermae, Strumia & Teresi, arXiv:2006.10735 [hep-ph]*
- *BF, Sandick, Shu, Su & Zhao, arXiv:2006.11264 [hep-ph]*

➡ Model 2 realization

$$937.993 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV}$$

$$|m_\chi - m_\phi| < 938.783 \text{ MeV}$$



➡ Natural origin of boosted dark matter: hydrogen decay

- *McKeen, Pospelov & Raj, arXiv:2006.15140 [hep-ph]*

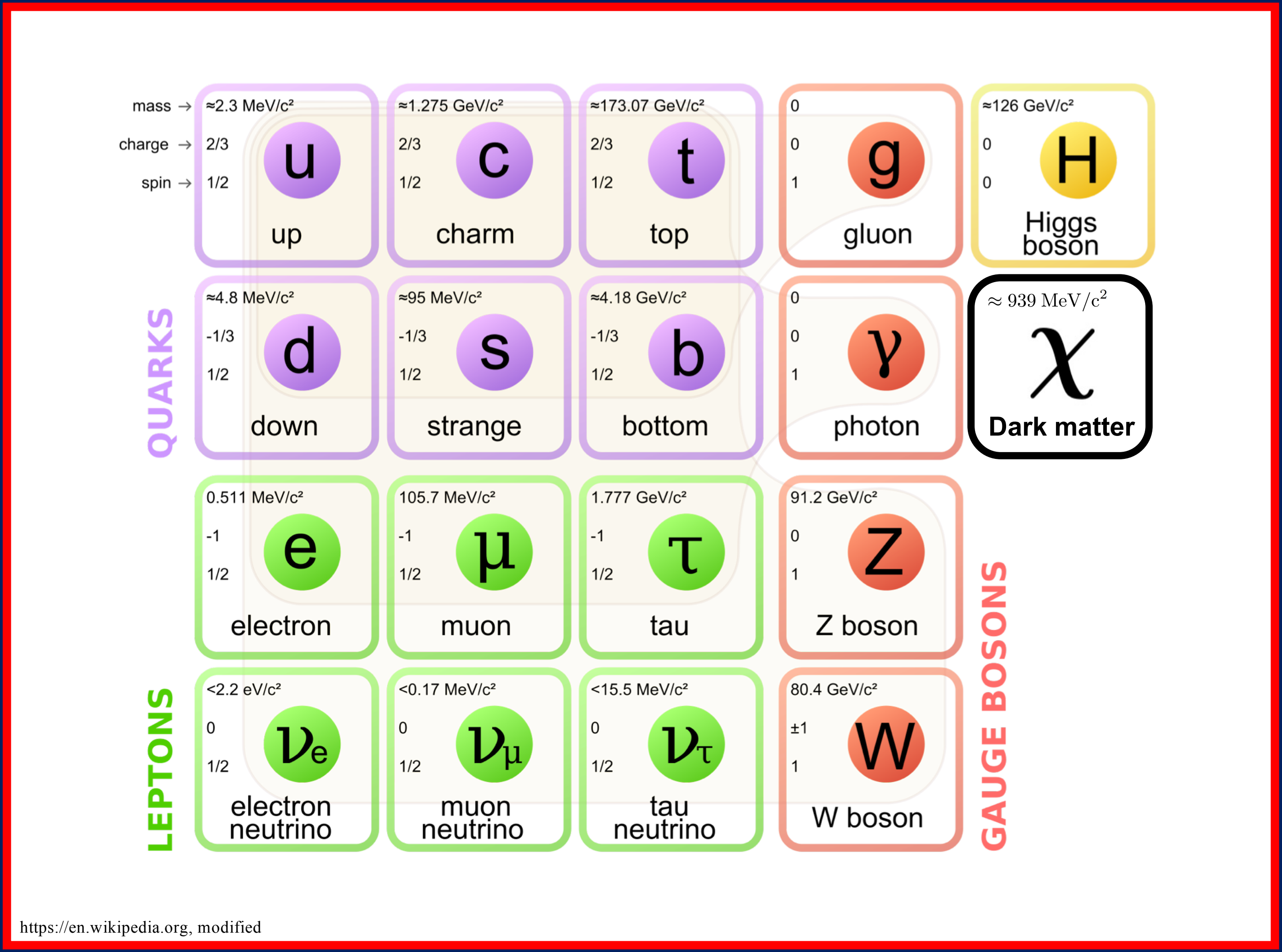
Final remarks

- There are working models explaining the neutron lifetime puzzle
- Neutron can undergo dark decays with a small branching fraction

$$\boxed{\frac{\Delta\Gamma_{n\to\chi+\ldots}}{\Gamma_n} \ll 1\%}$$

- Novel dark matter searches via nuclear capture and neutron annihilation
- Connection to other anomalies

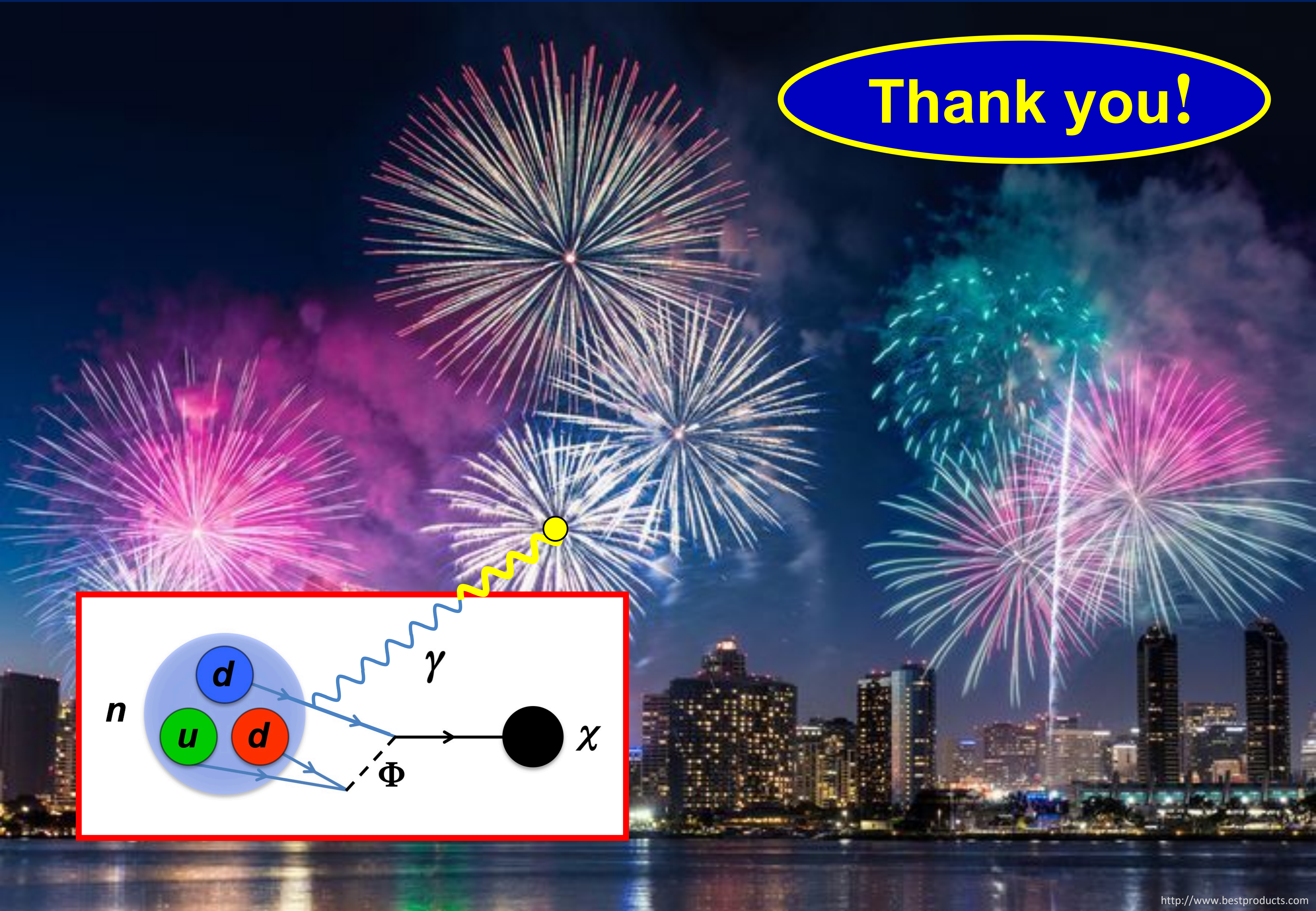
Very wishful thinking



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	$\approx 939\ \mathrm{MeV}/c^2$ χ **Dark matter**	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS	

https://en.wikipedia.org, modified

Thank you!



http://www.bestproducts.com