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U.S. DEPARTMENT OF ENERGY

Search for New Physics with Neutron, Nuclei, Neutrinos (and the lack thereof)

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Test of Standard Model at Low Energy

- How to identify physics beyond the Standard Model at low energy:
  - Find deviations from precise SM predictions through precision measurements:
    - *deviations provide hints, but they don't specify the "new" physics*
  - Direct search of new physics phenomena
    - *predictions may exist already ⇒ evidence*
- Reaching energy regime unattainable by accelerators in certain low energy searches. (next slide)
- Focus of this talk:
  - *Neutrons, Nuclei and Neutrinos* as probes

BSM Physics - Energy Scale

V. Cirigliano, M.J. Ramsey-Musolf / Progress in Particle and Nuclear Physics 71 (2013) 2–20

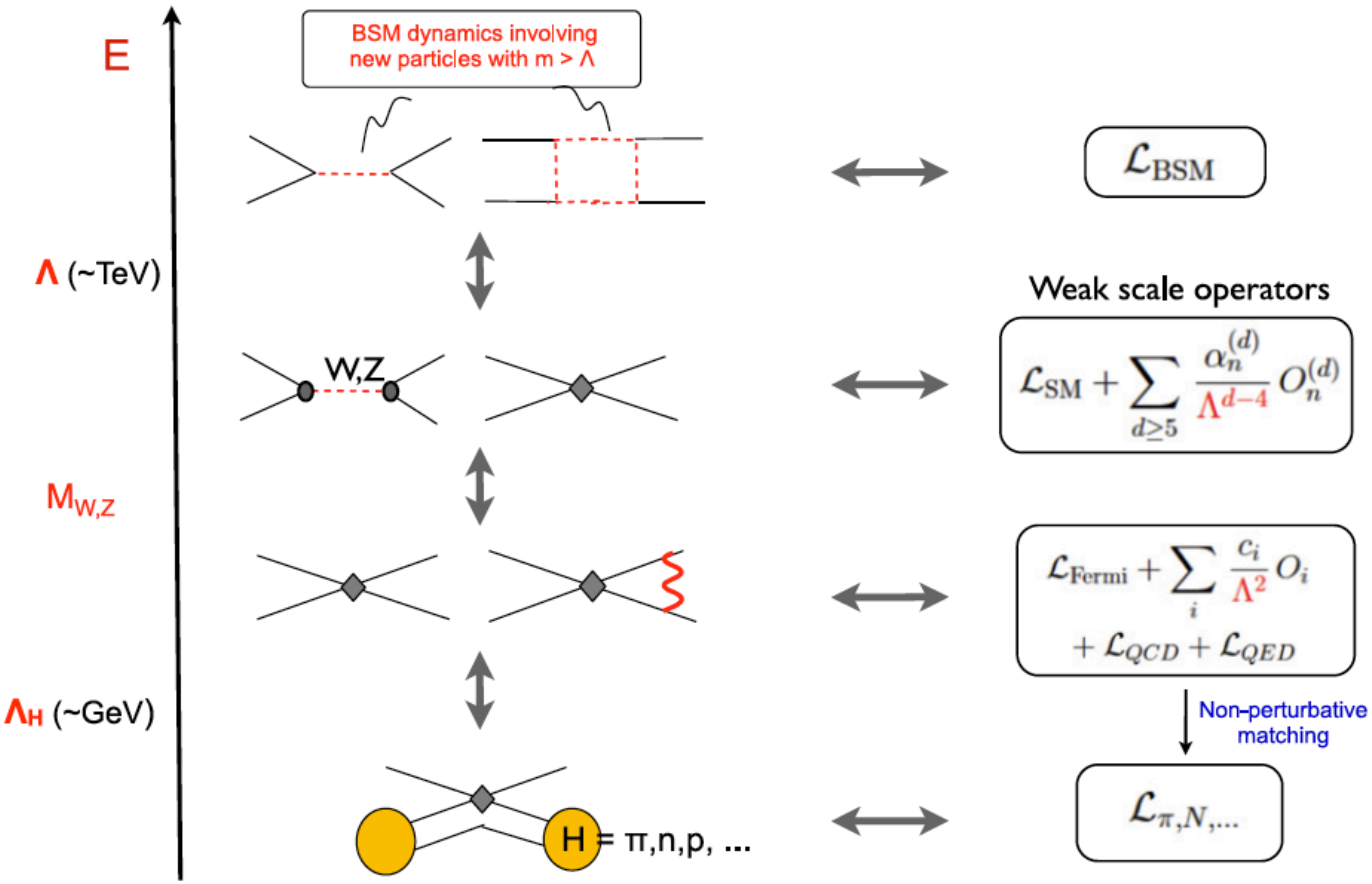
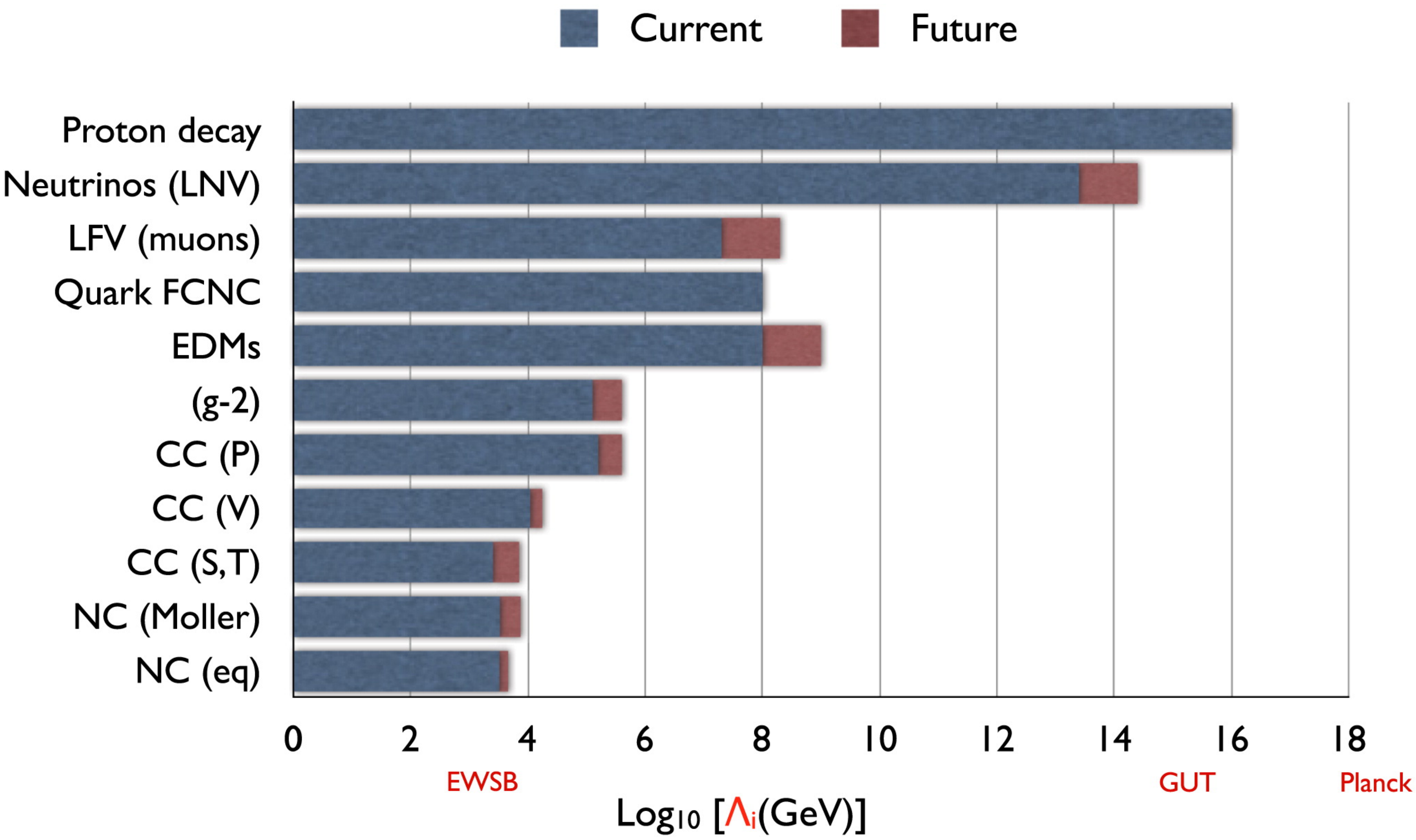


Fig. 1. Schematic representation of the series of effective field theories (EFTs) needed to describe the influence of new physics beyond the Standard Model on low-energy observables (see text for details).

Low energy probes of BSM physics



Λ: effective new physics scale

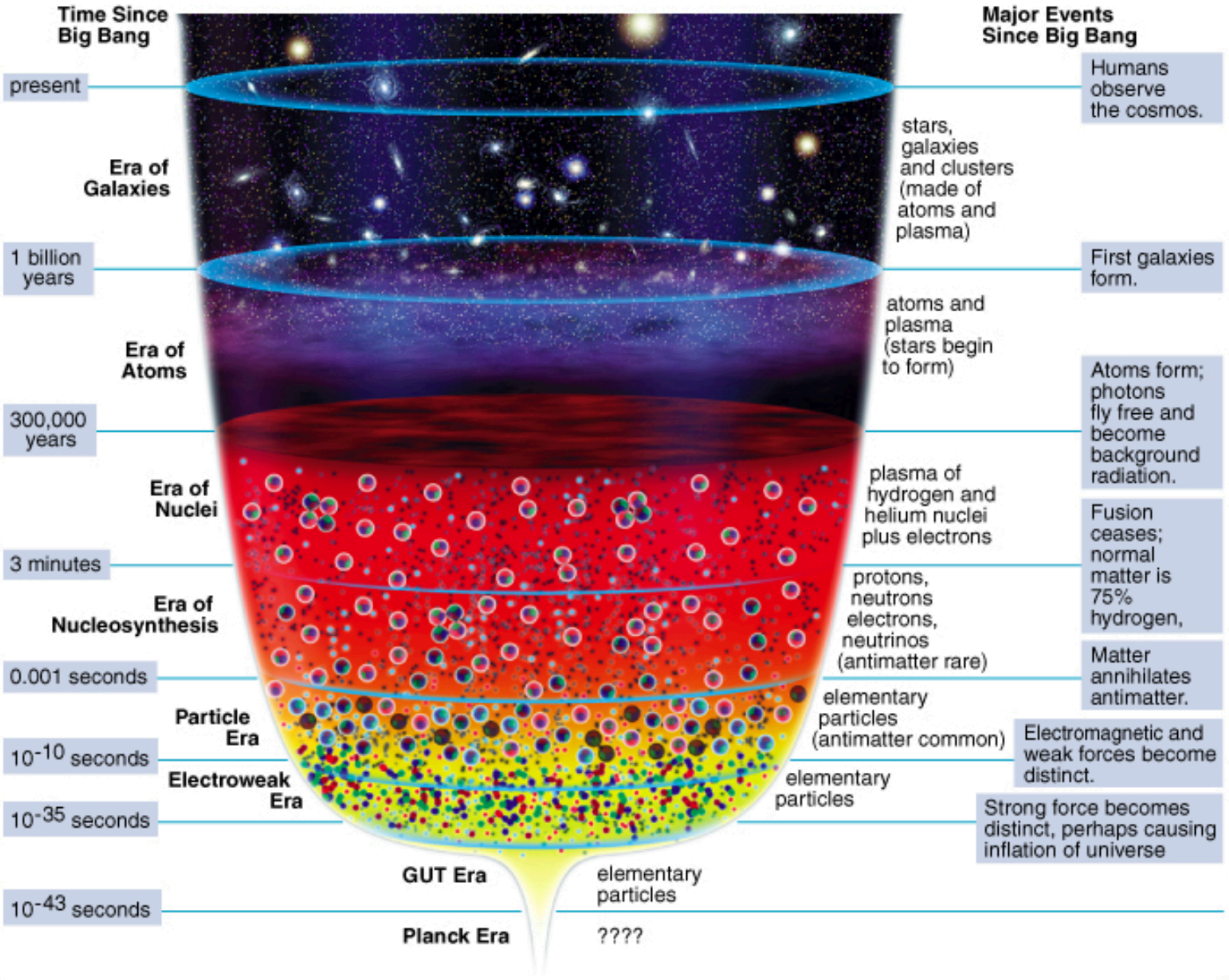
V. Cirigliano and M. Ramsey-Musolf, Prog. Part. Nucl. Phys, 71 (2013) 2-20

Neutron and super-allowed β decay

Neutron β Decay

- Pure V-A interaction
- Why study neutrons?
  - Big Bang Nucleosynthesis
    - τ_n determines light elements (particularly ^{4}He) formation
  - Standard Model tests:
    - CKM unitarity (high precision V_{ud} measurements)
    - Time reversal violation
    - Non-standard interactions (≠V-A)
- Precision measurements of:
  - neutron lifetime τ_n
  - β energy spectrum
  - angular correlations of the decay products (next slide)

$$n \rightarrow p + e^- + \overline{\nu_e}$$



Neutron β Decay

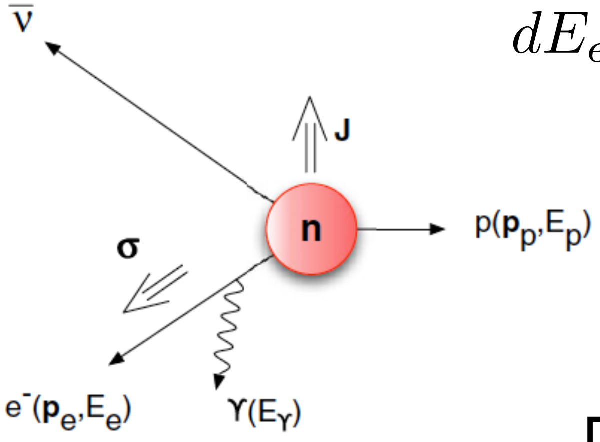
Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received January 28, 1957)

[Phys. Rev. 106, 517 (1957)]

$$
\begin{aligned}
H_{\text{int}} = {} & (\bar{\psi}_p\psi_n)(C_S\bar{\psi}_e\psi_\nu + C_S'\bar{\psi}_e\gamma_5\psi_\nu) \\
& + (\bar{\psi}_p\gamma_\mu\psi_n)(C_V\bar{\psi}_e\gamma_\mu\psi_\nu + C_V'\bar{\psi}_e\gamma_\mu\gamma_5\psi_\nu) \\
& + \tfrac{1}{2}(\bar{\psi}_p\sigma_{\lambda\mu}\psi_n)(C_T\bar{\psi}_e\sigma_{\lambda\mu}\psi_\nu + C_T'\bar{\psi}_e\sigma_{\lambda\mu}\gamma_5\psi_\nu) \\
& - (\bar{\psi}_p\gamma_\mu\gamma_5\psi_n)(C_A\bar{\psi}_e\gamma_\mu\gamma_5\psi_\nu + C_A'\bar{\psi}_e\gamma_\mu\psi_\nu) \\
& + (\bar{\psi}_p\gamma_5\psi_n)(C_P\bar{\psi}_e\gamma_5\psi_\nu + C_P'\bar{\psi}_e\psi_\nu) \qquad (1) \\
& + \text{Hermitian conjugate,}
\end{aligned}
$$

For neutron decay:



(Nico 2009)

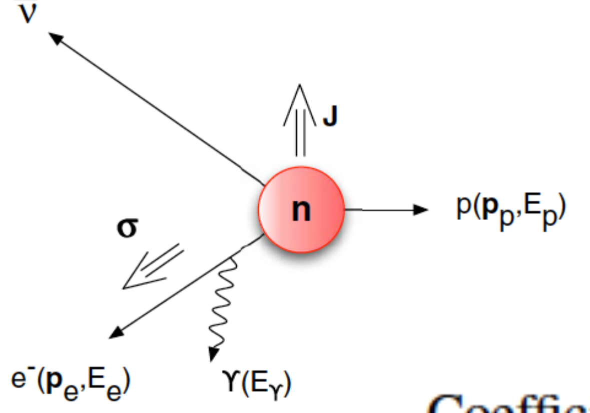
$$
\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2\left|V_{ud}\right|^2}{(2\pi)^5} p_e E_e \left(E_\circ - E_e\right)^2 \xi \left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} \right.
$$
$$
\left. \frac{\left\langle\vec{J}\right\rangle}{J}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right)\right]
$$

Measurements: a, b, A, B, D, τ_n

Correlation Coefficients

Neutron β Decay - Symmetry Tests

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2\left|V_{ud}\right|^2}{(2\pi)^5} p_e E_e \left(E_\circ - E_e\right)^2 \xi \left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} \right.$$
$$\left. \frac{\left\langle \vec{J} \right\rangle}{J} \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right]$$



Coefficient	Correlation	Parity ($\mathcal{P}$)	Time ($\mathcal{T}$)
a (Electron–antineutrino correlation)	$\mathbf{p}_e \cdot \mathbf{p}_\nu / E_e E_\nu$	Even	Even
b (Fierz interference)	m_e / E_e	Even	Even
A (Spin-electron asymmetry)	$\langle\mathbf{J}\rangle \cdot \mathbf{p}_e / E_e$	Odd	Even
B (Spin-antineutrino asymmetry)	$\langle\mathbf{J}\rangle \cdot \mathbf{p}_\nu / E_\nu$	Odd	Even
C (Spin-proton asymmetry)	$\langle\mathbf{J}\rangle \cdot \mathbf{p}_p / E_p$	Odd	Even
D (Triple correlation)	$\langle\mathbf{J}\rangle \cdot (\mathbf{p}_e \times \mathbf{p}_\nu) / E_e E_\nu$	Even	Odd
N (Spin-electron spin)	$\boldsymbol{\sigma} \cdot \langle\mathbf{J}\rangle$	Even	Even
R (Electron spin triple correlation)	$\boldsymbol{\sigma} \cdot (\langle\mathbf{J}\rangle \times \mathbf{p}_e) / E_e$	Odd	Odd

from J S Nico, J. Phys. G: Nucl. Part. Phys. 36 (2009) 104001

Each coefficient has a different physics significance

Neutron β Decay

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2\left|V_{ud}\right|^2}{(2\pi)^5} p_e E_e \left(E_\circ - E_e\right)^2 \xi \left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right.$$

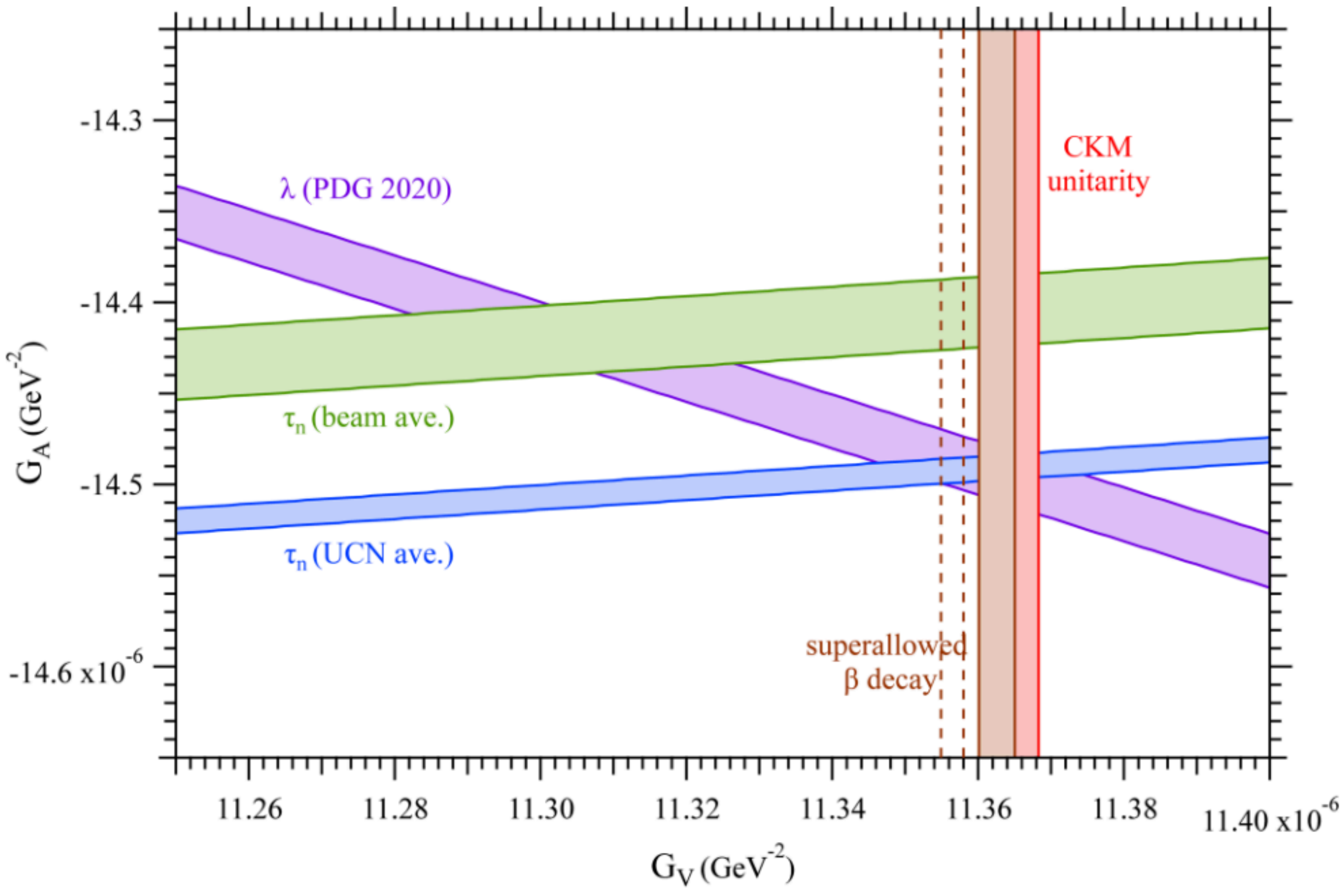
$$\left.\frac{\langle\vec{J}\rangle}{J}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right]$$

$$\lambda = \frac{g_A}{g_V}$$

$$\begin{aligned} a &= \frac{1-\lambda^2}{1+3\lambda^2} \\ b &= 0 \\ A &= -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \\ B &= 2\frac{\lambda^2-\lambda}{1+3\lambda^2} \\ D &= 0 \\ \tau_n &\propto \frac{1}{g_V^2+3g_A^2} \end{aligned}$$

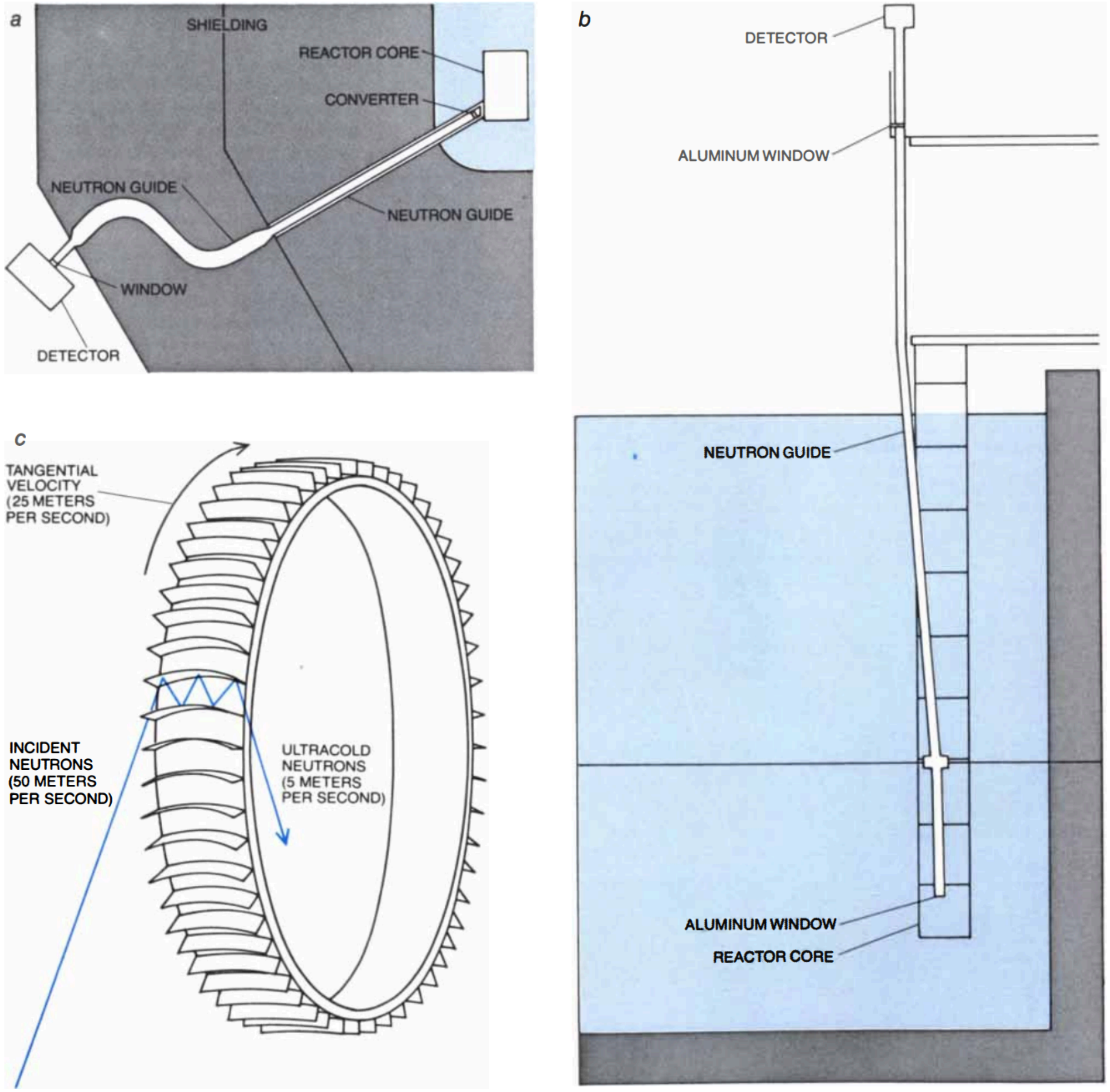
g_A and g_V from various n decay measurements

PHYSICAL REVIEW C **103**, 045502 (2021)



Neutron sources

- Free neutron production:
    - Fission at reactor
    - Nuclear reactions at accelerator (spallation, (d,n) reaction…etc)
- Cold neutron (CM)
    - Take thermal neutron (25 meV) to lower temperature
    - Use cold moderator (e.g. liquid hydrogen)
    - T ~ 20 K ~2 meV
- Ultra-cold neutron (UCN)
    - T < 4 mK ~300 neV
    - Magnetically trapped or bottled



EXTRACTION OF ULTRACOLD NEUTRONS from the vicinity of a reactor core can be accomplished by several means. A horizontal guide tube (*a*) conducts the neutrons through the shielding that must surround the core; if the tube curves, neutrons of higher energy pass through the walls and are lost, whereas ultracold neutrons follow the curves. A vertical guide tube (*b*) accepts neutrons of energies somewhat higher than ultracold energy at the bottom, but in climbing to the apparatus at the top they are slowed to the ultracold-energy range by the earth's gravitational field. In a neutron turbine (*c*) neutrons moving at about 50 meters per second bounce several times from the receding blades of a rapidly spinning wheel, losing energy with each bounce. They emerge with a speed of about five meters per second.

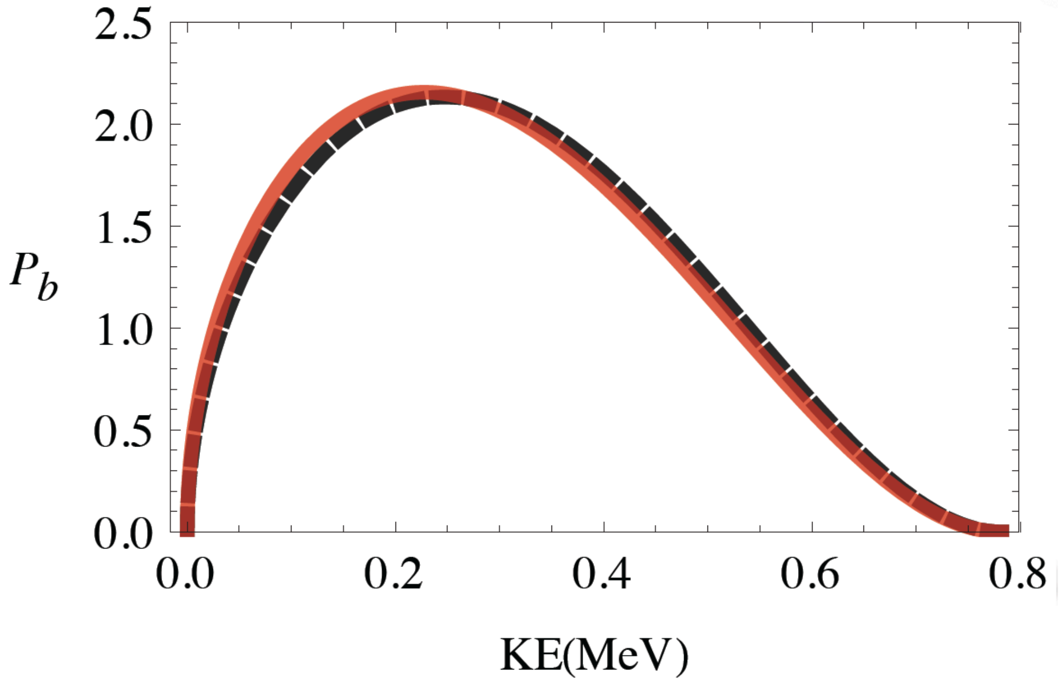
R. Golub, W. Mampe, J. M. Pendelbury & P. Ageron *Scientific American*, June 1979

Neutron β Decay - Search for BSM Physics

Examples:

- b: Search for interference (“Fierz interference”) with V-A

Shift of spectrum if b≠0



τ_n if b≠0

$$\tau_{n(SM)} = \frac{(4908.7 \pm 1.9)\mathrm{s}}{V_{ud}^2(1+3\lambda^2)}$$

$$\tau_n \rightarrow \tau_{n(SM)}\,(1-0.65b)$$

- Mostovoy parameters: model-independent test of V-A:

Yu. Mostovoy and A. Frank, JETP Lett., 24, (1976), 38

$$F_1 = 1 + A - B - a = 0$$

$$F_2 = aB - A - A^2 = 0$$

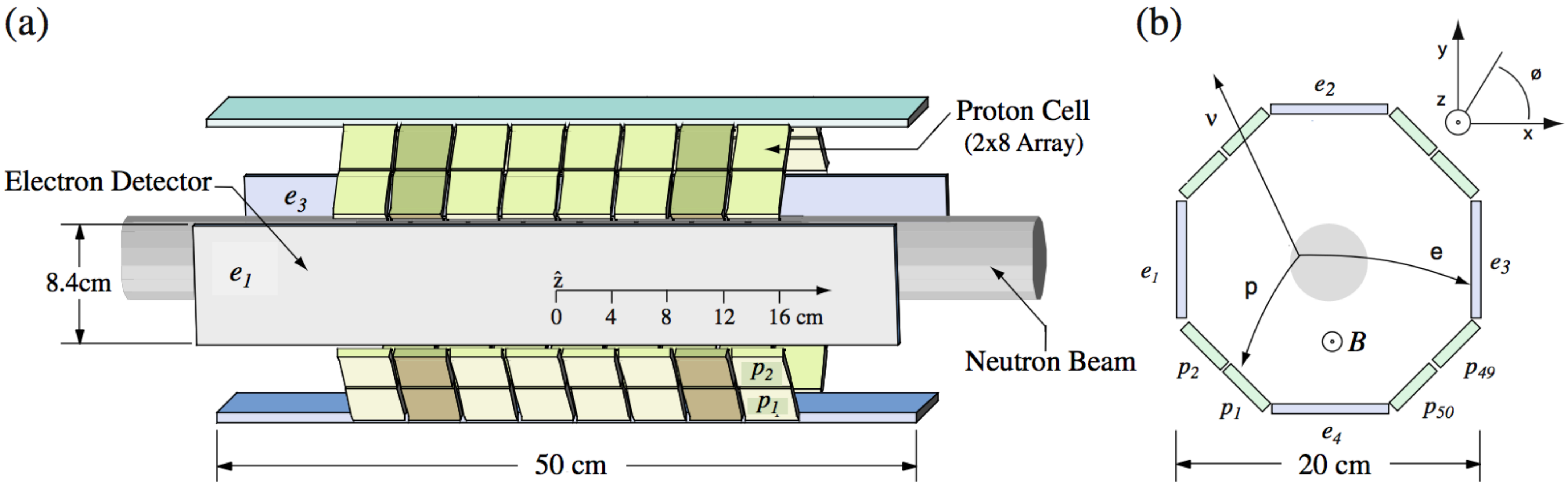
Neutron β Decay - Search for BSM Physics

Examples:

- D: Time Reversal Invariance

$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_{\nu_e}} = \frac{G_F^2\,|V_{ud}|^2}{(2\pi)^5}\,p_e E_e\,(E_\circ - E_e)^2\,\xi\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{J}\rangle}{J}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right)\right]$$

emiT Experiment:



D = (-1.2 ± 2.0) x 10^{-4} (published emiT limit, PDG 2018)

CKM Matrix and V$_{ud}$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Weak eigenstates ≠ Mass eigenstates
- V_{CKM} is unitary: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1(?)$

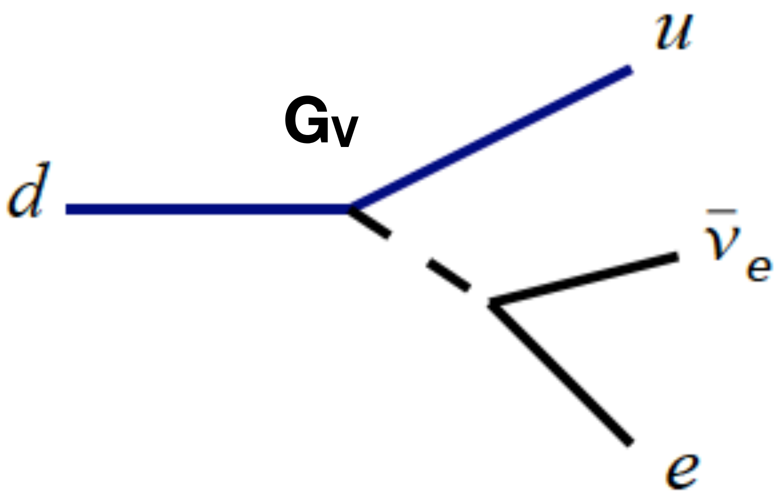
$|V_{ud}|^2$: neutron/nuclear decay, π decay

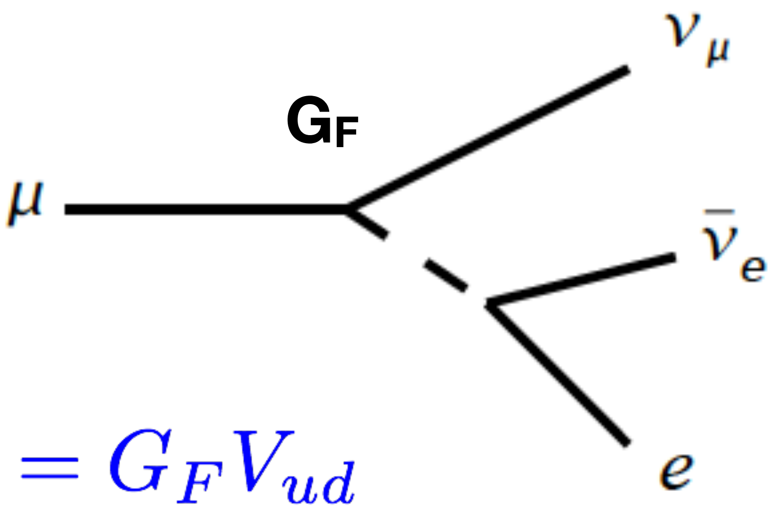
$|V_{us}|^2$: K decay

$|V_{ub}|^2$: B decay

CKM Matrix and V_{ud}

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



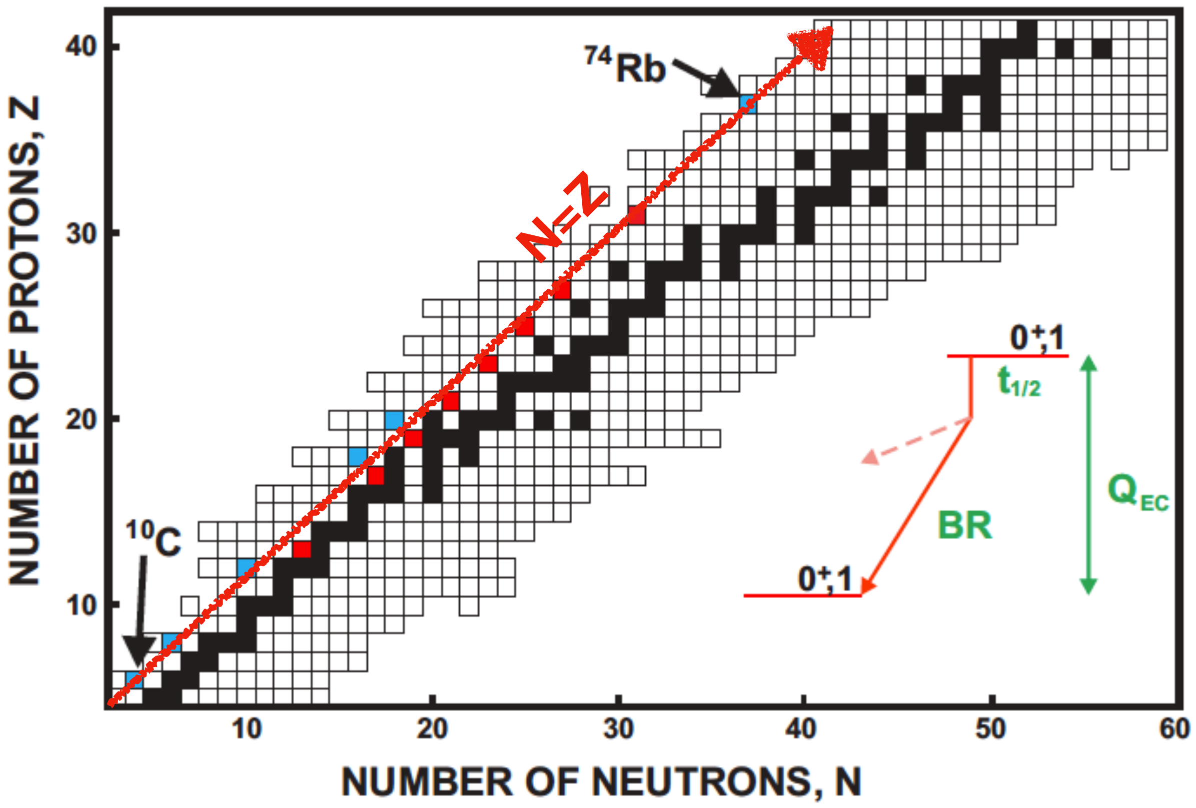


$$G_V = G_F V_{ud}$$

neutron/nuclear β decays

Precisely measured in muon decays

Super-allowed 0+→0+ beta decays



Beta-decay “ft” value:

$$ft = f(Q)\frac{t_{1/2}}{BR} = \frac{K}{g^2|\overline{M}'_{fi}|^2}$$

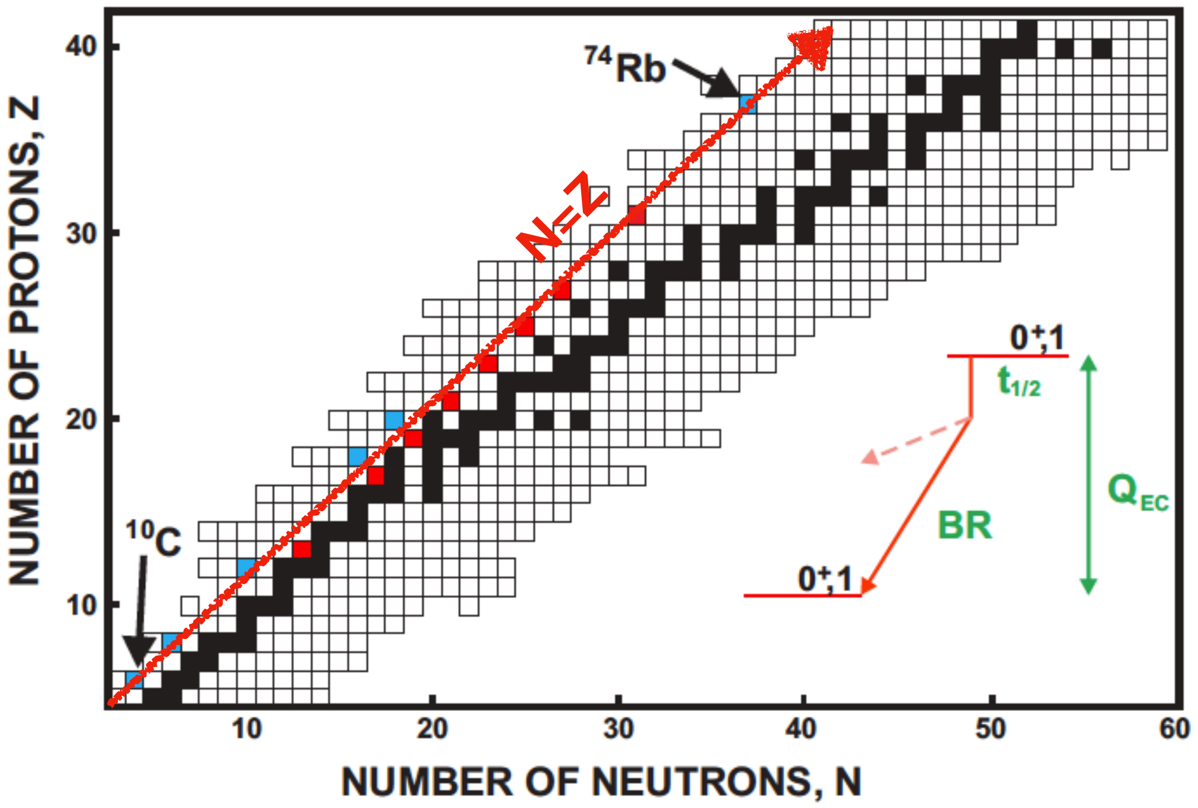
phase space

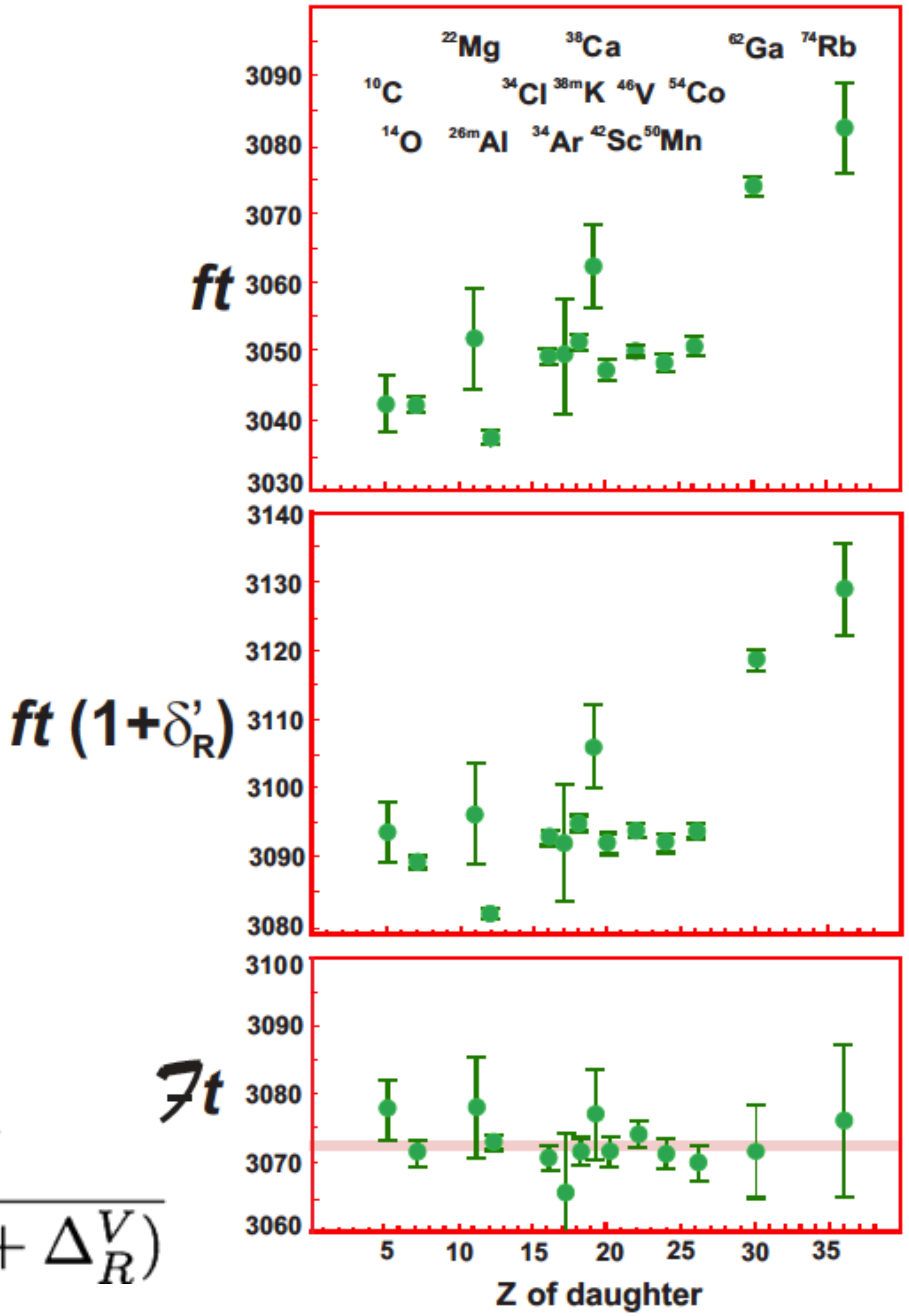
Super-allowed 0+→0+ beta-decay:

$$\begin{aligned} g^2 &= g_V^2(1+\Delta_R) \\ |\overline{M}'_{fi}|^2 &= 2(1-\delta_C) \end{aligned}$$

$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

Super-allowed 0+→0+ beta decays





$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

J. Hardy @CIPANP, June 2018

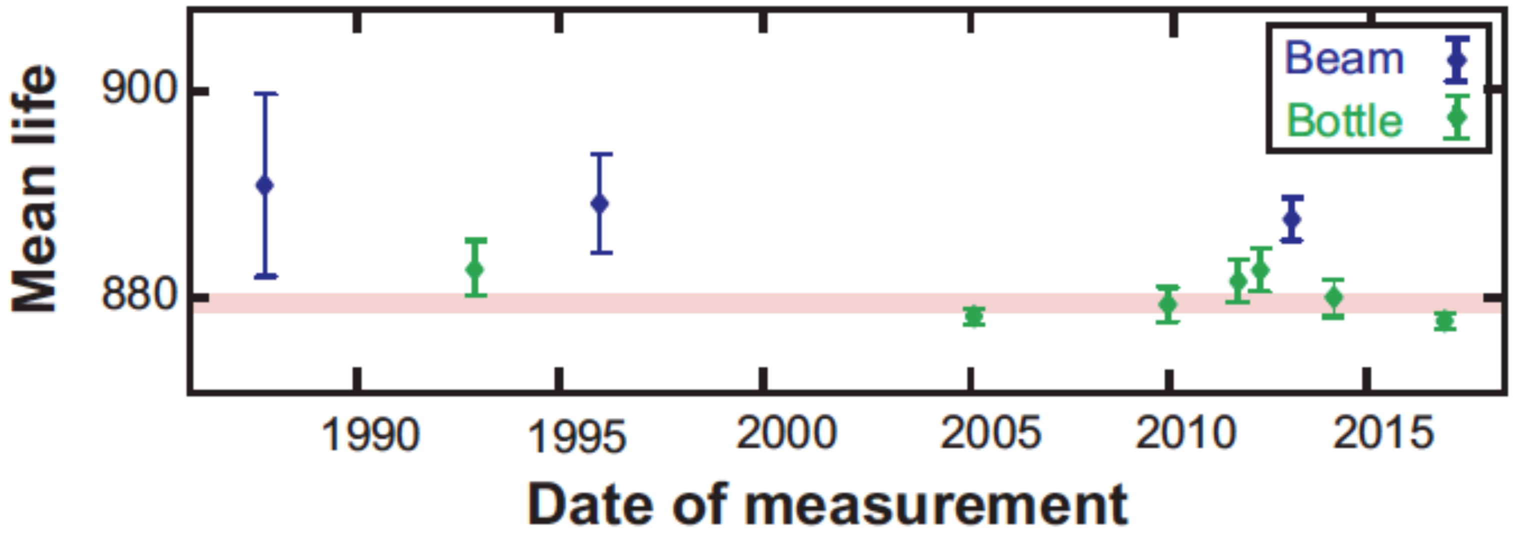
Neutron β Decay Data (2018)

Mean life:

$\tau = 879.4 \pm 0.9$ s

$\chi^2/N = 4.2$

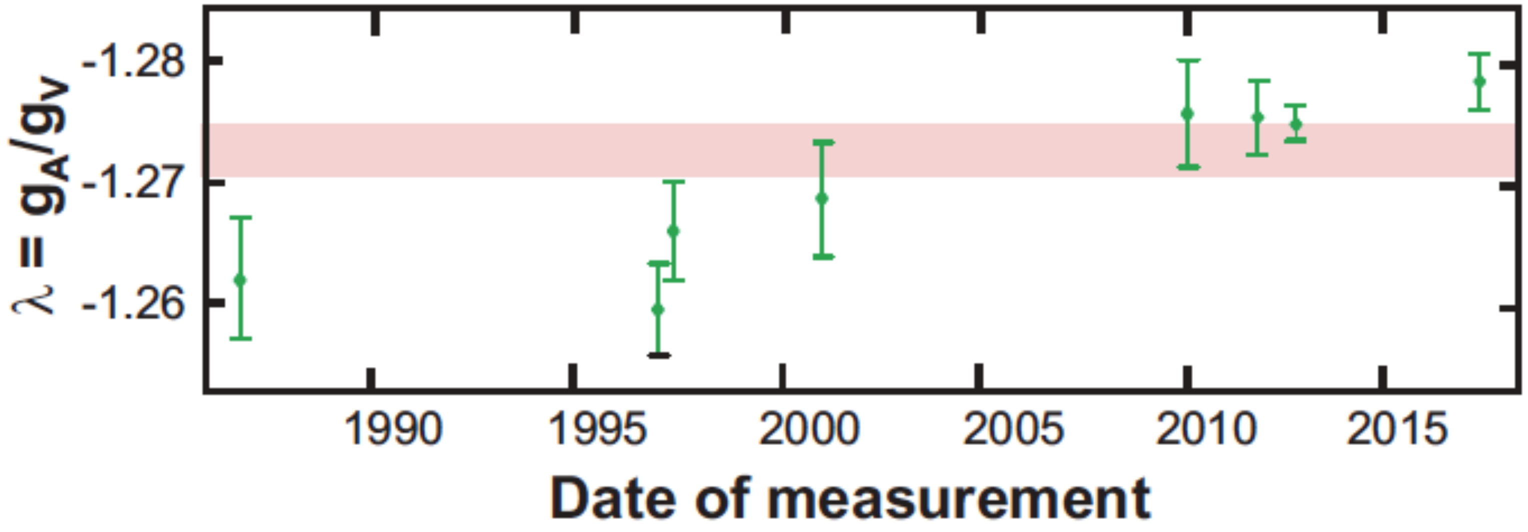
Beam: 888.1 ± 2.0 s
Bottle: 878.9 ± 0.6 s



β asymmetry:

$\lambda = -1.2735 \pm 0.0019$

$\chi^2/N = 4.3$



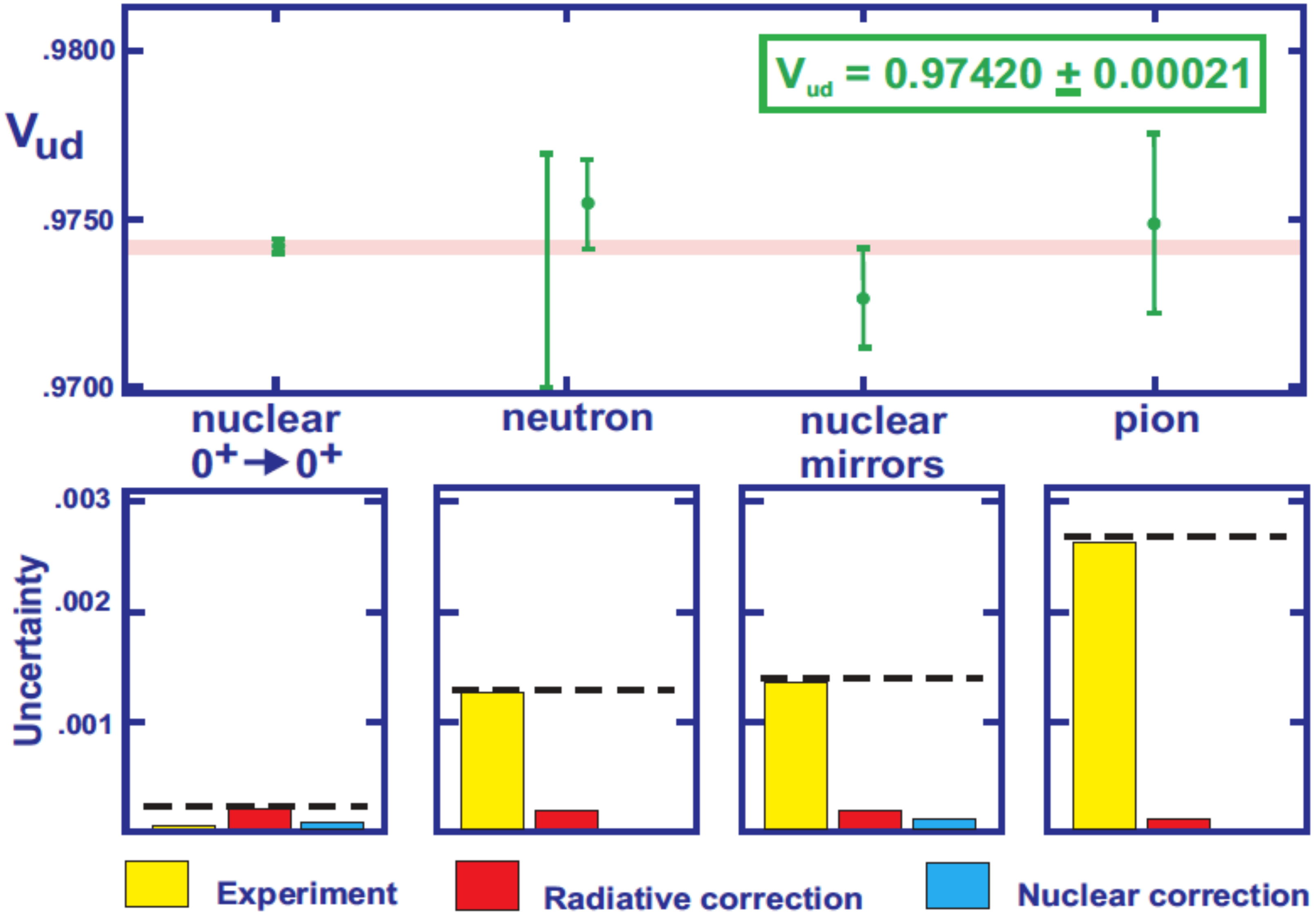
$V_{ud} = 0.9755 \pm 0.0013$

Beam-bottle span
$0.9700 \leq V_{ud} \leq 0.9770$

vs.

nuclear $0^+ \rightarrow 0^+$
$V_{ud} = 0.9742 \pm 0.0002$

CKM Matrix and V_{ud}



J. Hardy @CIPANP, June 2018

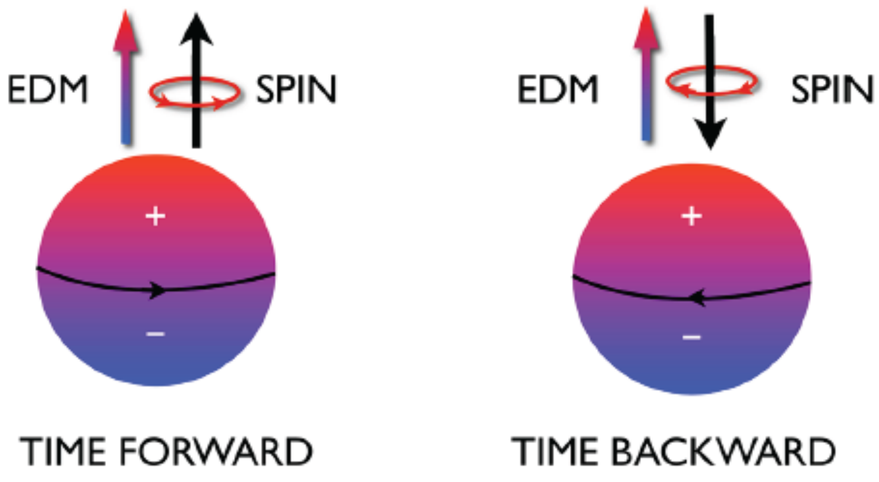
$$V_{ud} = 0.97373(11)_{\text{exp.,nucl.}}(9)_{\text{RC}}(27)_{\text{NS}} \ \text{(superallowed)}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)(4) \ \text{(fit - first row)}$$

2022 Particle Data Book

Neutron electric dipole moment (nEDM)

Neutron Electric Dipole Moment (nEDM)



A non-zero particle EDM violates P, T

Purcell and Ramsey, PR78(1950)807

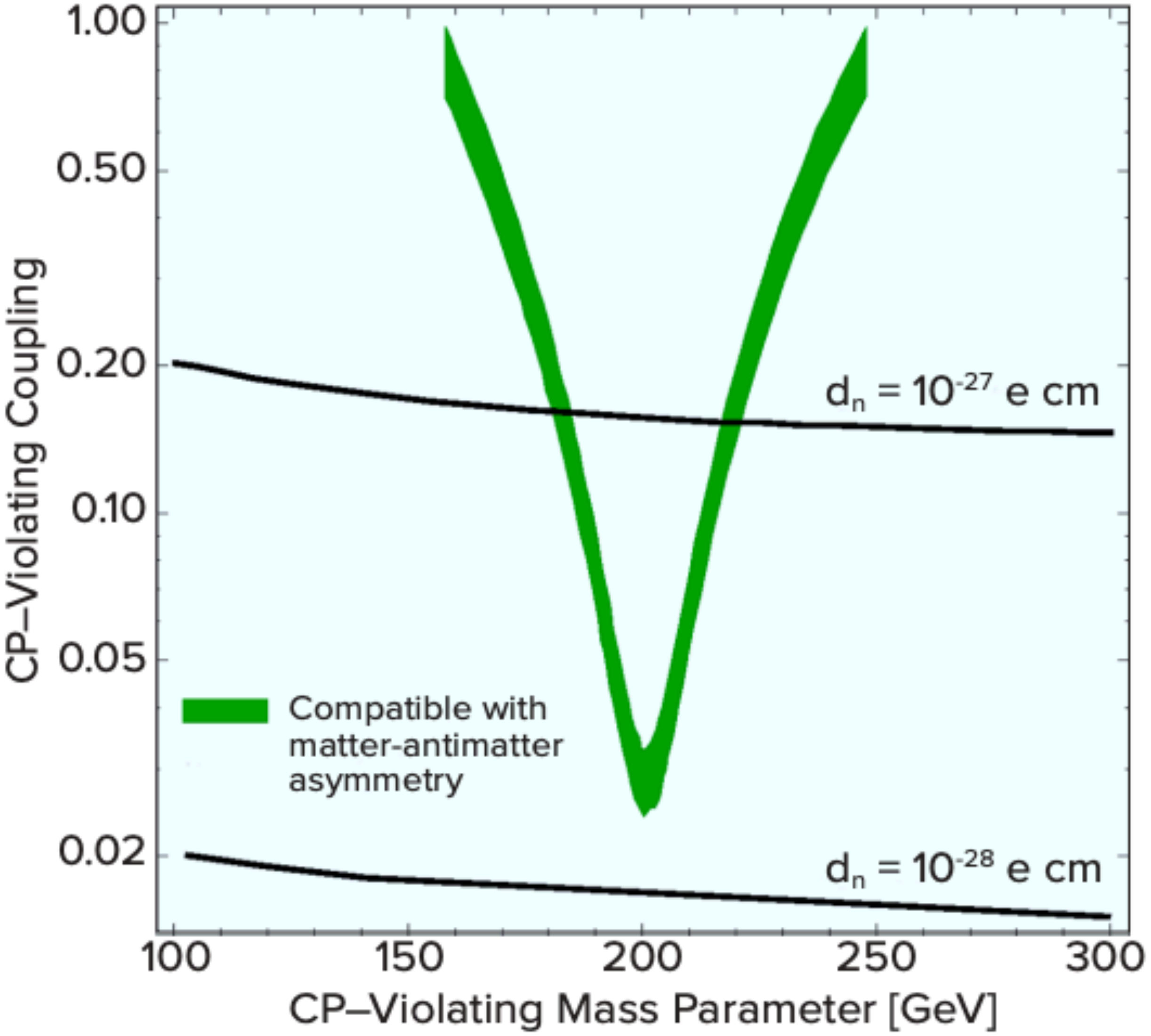


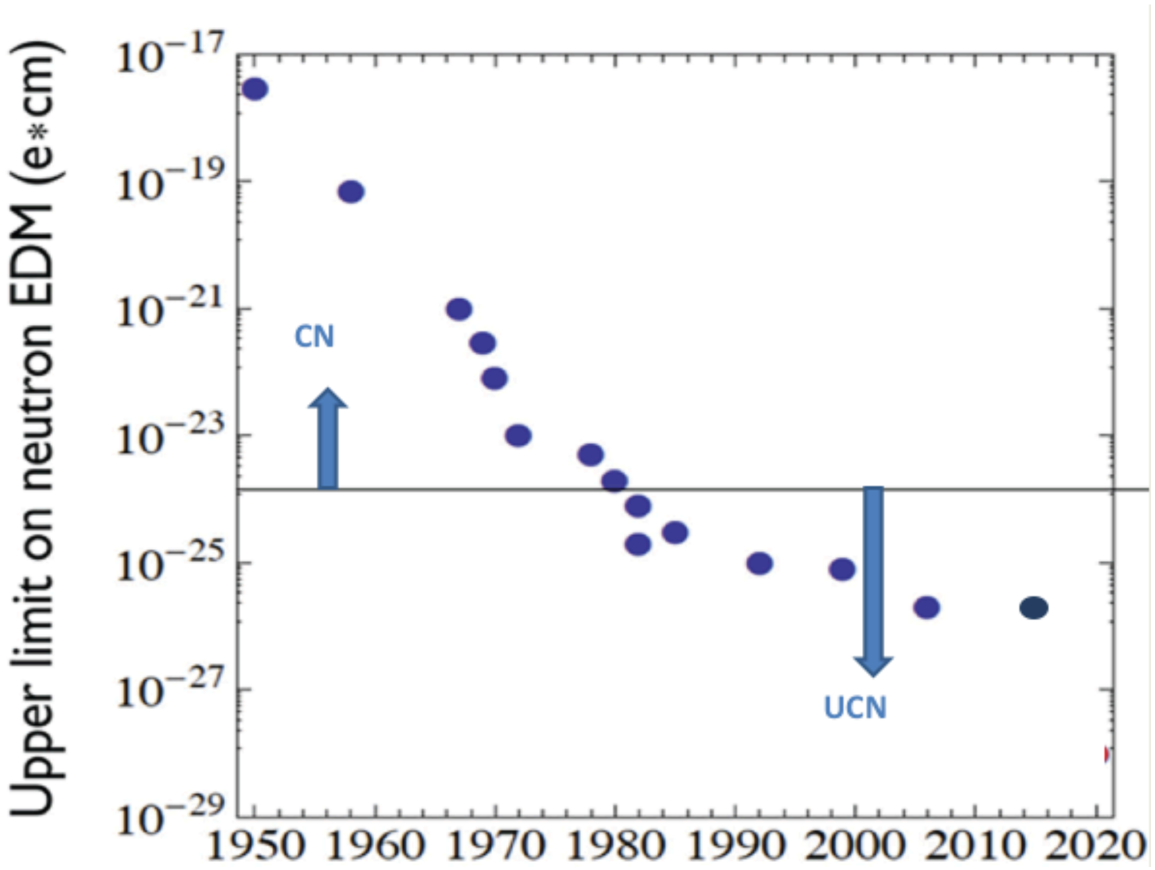
Figure 5.5: *The relationship between the relevant parameters in the minimal Supersymmetric Standard Model that are needed to account for the observed excess of matter over antimatter is shown as the green band. The nearly horizontal lines indicate the size of a neutron EDM as a function of these parameters. The neutron EDM search being developed at the FNPB would probe nearly all of this parameter space.*

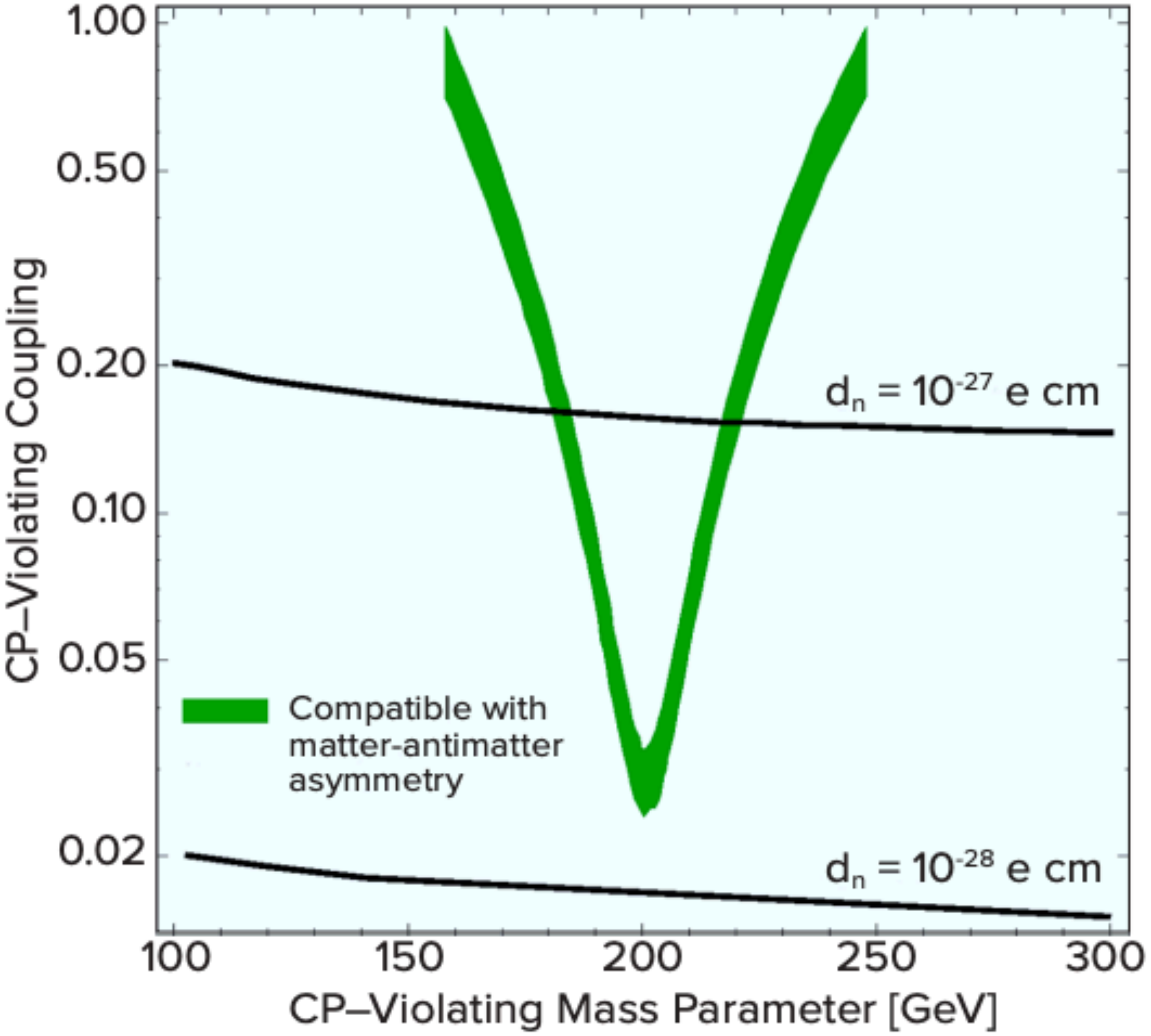
EDM violates T → violates CP

New sources of CP → Baryon Asymmetry in the Universe (BAU)

Graphics from NSAC 2015 Long Range Plan

Neutron Electric Dipole Moment (nEDM)





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Graphics from NSAC 2015 Long Range Plan

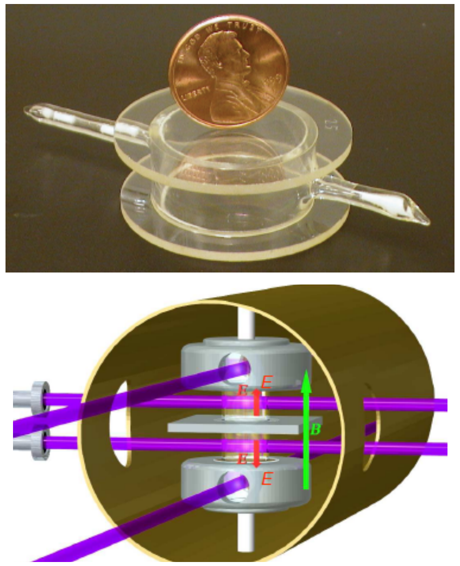
EDM searches

Arthur Schawlow:
“Never measure anything but frequency”

Experiments are largely the same:

- Precess spin in B field with parallel and anti-parallel E
- Measure the frequency difference

^{199}Hg @ Seattle

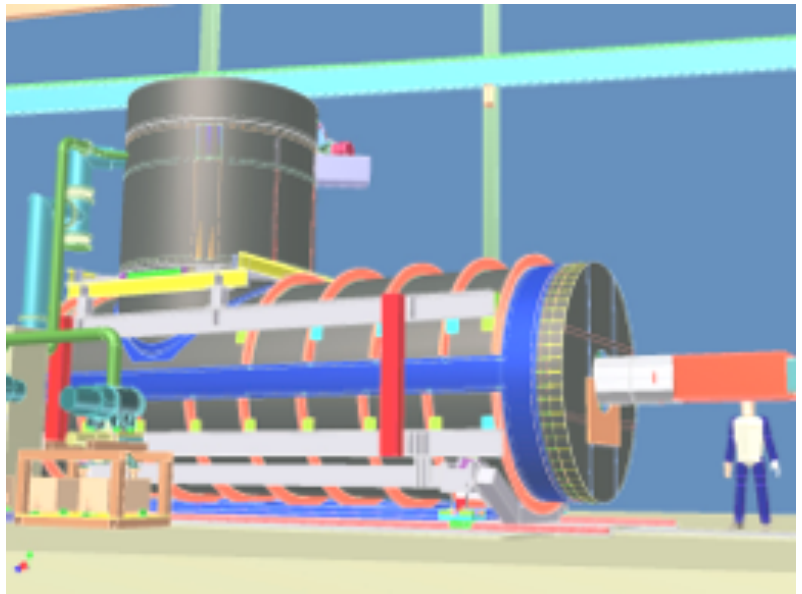


- **$|d_{Hg}| < 7.4 \times 10^{-30}$ e cm (95% CL)**

Phys. Rev. Lett. **119**, 119901 (2017)

- 2020 and beyond: 6×10^{-31} e cm

nEDM @ SNS



- **$|d_n|$ (ILL) $< 3.6 \times 10^{-26}$ e cm (95% CL)**

Phys. Rev D **92**, 092003 (2015)

- nEDM@SNS a high priority in the US;

EDM searches

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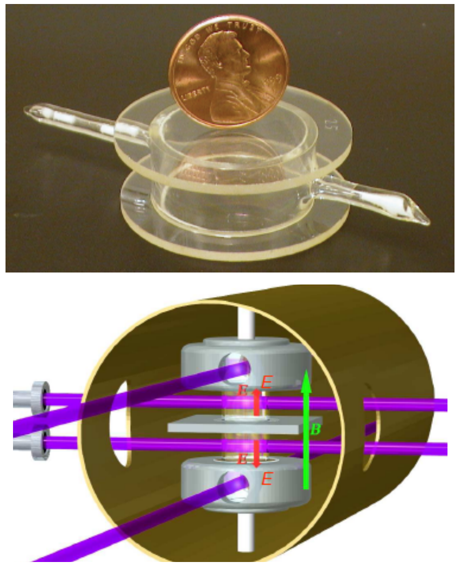

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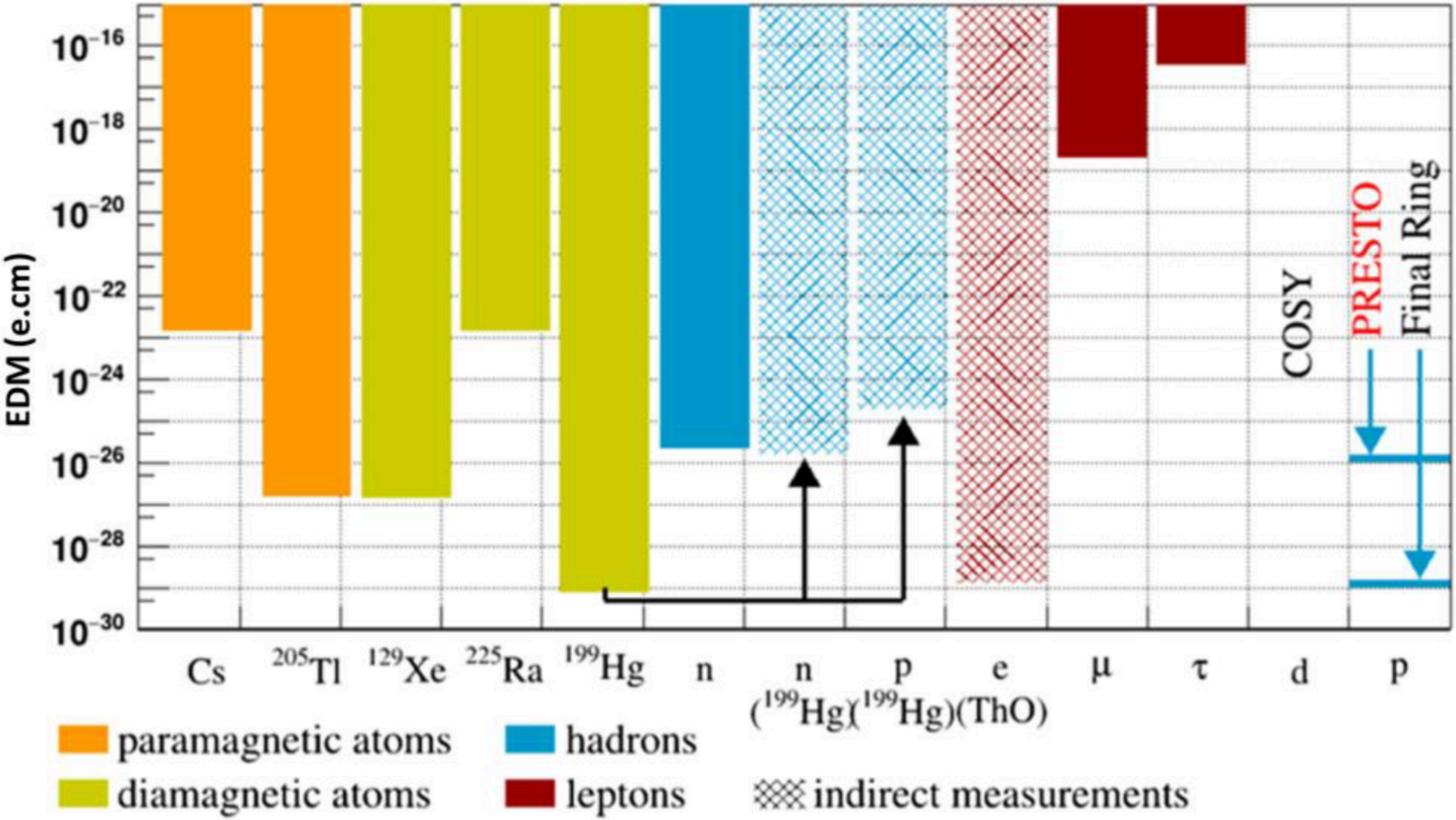
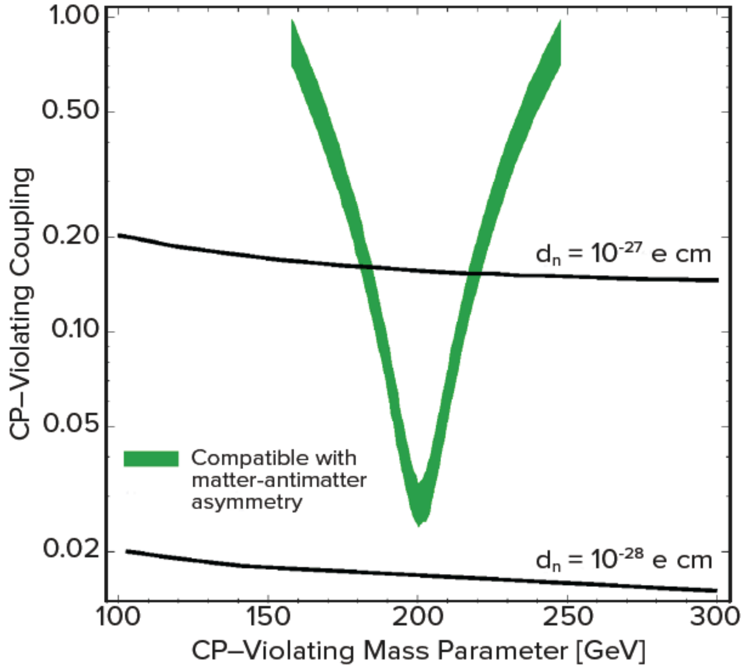


DOI: 10.3390/particles6010020

nEDM searches

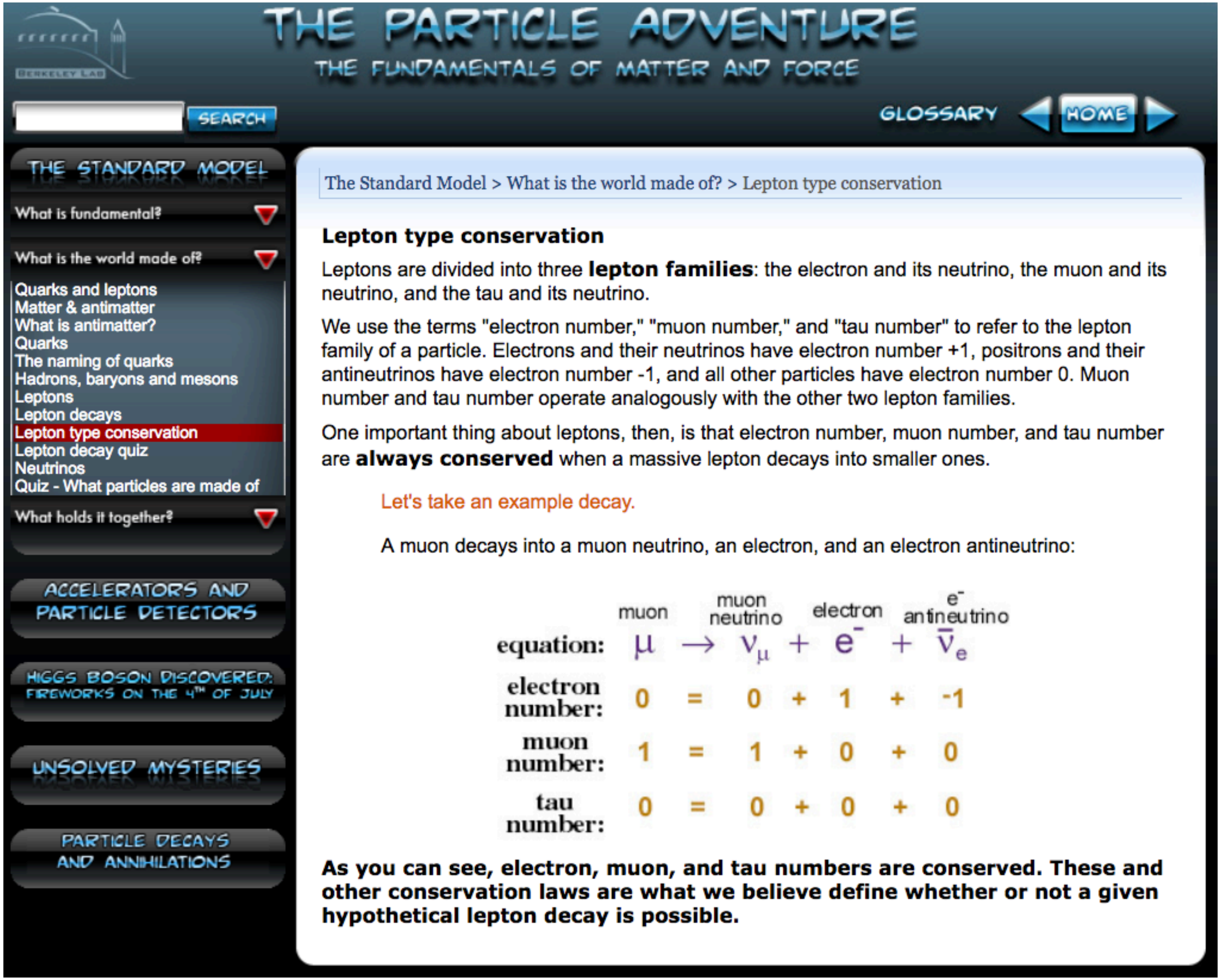
Experiment	**UCN source**	**cell**	**Measurement techniques**	**σ_d Goal (10^{-28} e-cm)**
				Present neutron EDM limit < 300
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey, external Cs & Hg co-mag Xe or Hg co-magnetometer	Phase1 ~ 100 Phase 2 < 20
Munich FRMII/ILL	Solid D_2	Vac.	Room Temp. , Hg co-mag., also external 3He & Cs mag.	< 5
(TUCAN) RCNP/ TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 100 < 20
SNS nEDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
LANL	Solid D_2	Vac.	R & D, Ramsey tech., Hg co-mag.	< 50



B. Filipone @CIPANP, June 2018

Lepton number violation (neutrinos)

Lepton number in SM



Lepton type conservation

Leptons are divided into three **lepton families**: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino.

We use the terms "electron number," "muon number," and "tau number" to refer to the lepton family of a particle. Electrons and their neutrinos have electron number +1, positrons and their antineutrinos have electron number -1, and all other particles have electron number 0. Muon number and tau number operate analogously with the other two lepton families.

One important thing about leptons, then, is that electron number, muon number, and tau number are **always conserved** when a massive lepton decays into smaller ones.

Let's take an example decay.

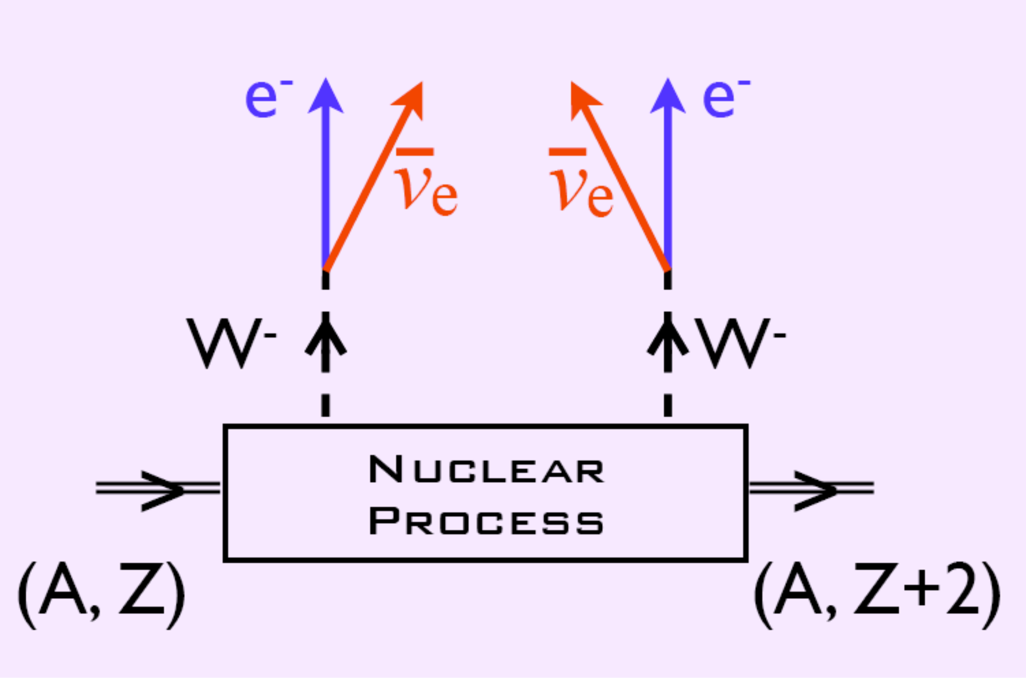
A muon decays into a muon neutrino, an electron, and an electron antineutrino:

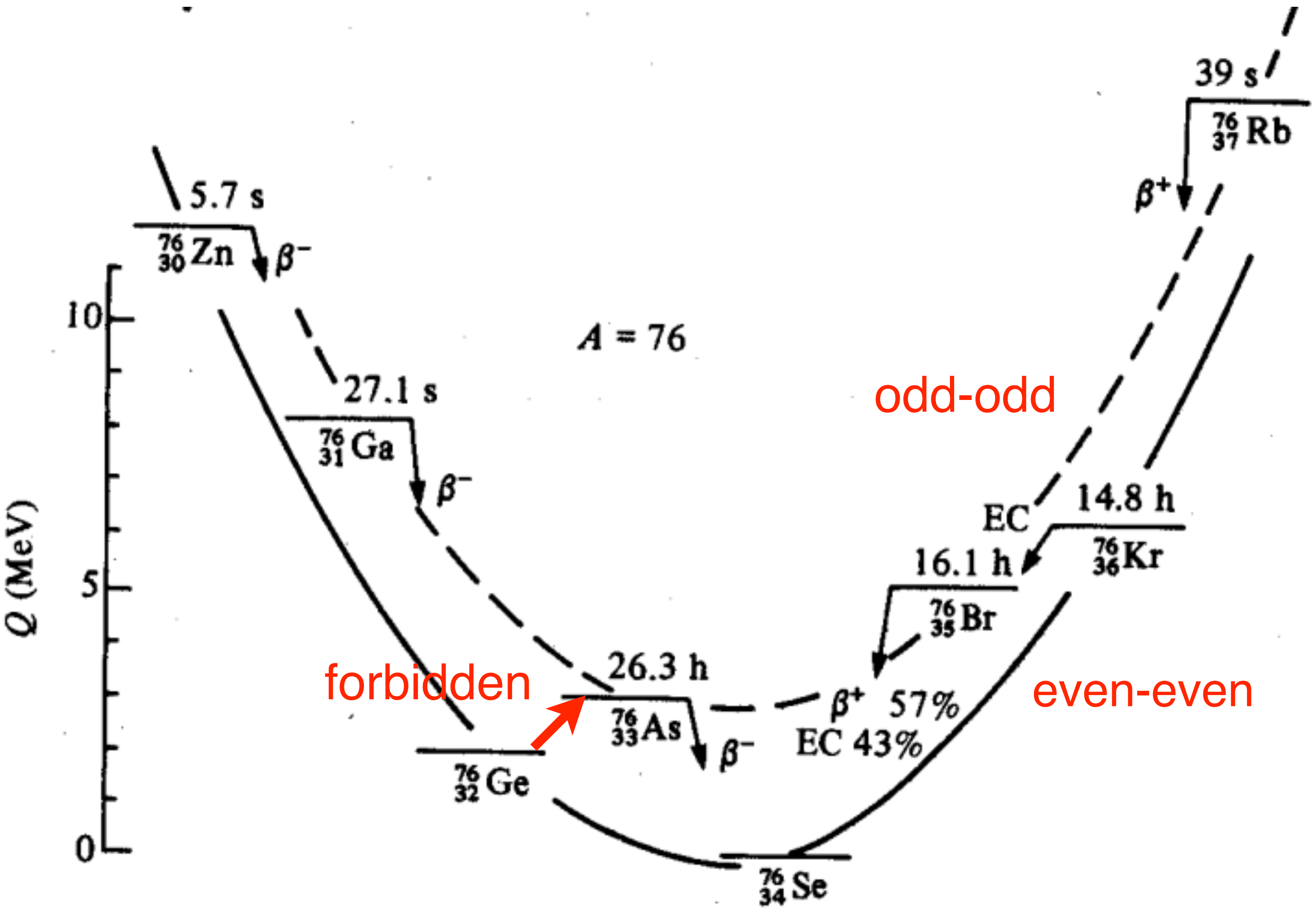
	muon		muon neutrino		electron		e⁻ antineutrino
equation:	μ	$\rightarrow$	ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0
tau number:	0	=	0	+	0	+	0

As you can see, electron, muon, and tau numbers are conserved. These and other conservation laws are what we believe define whether or not a given hypothetical lepton decay is possible.

Two-neutrino double beta decay (2νββ)

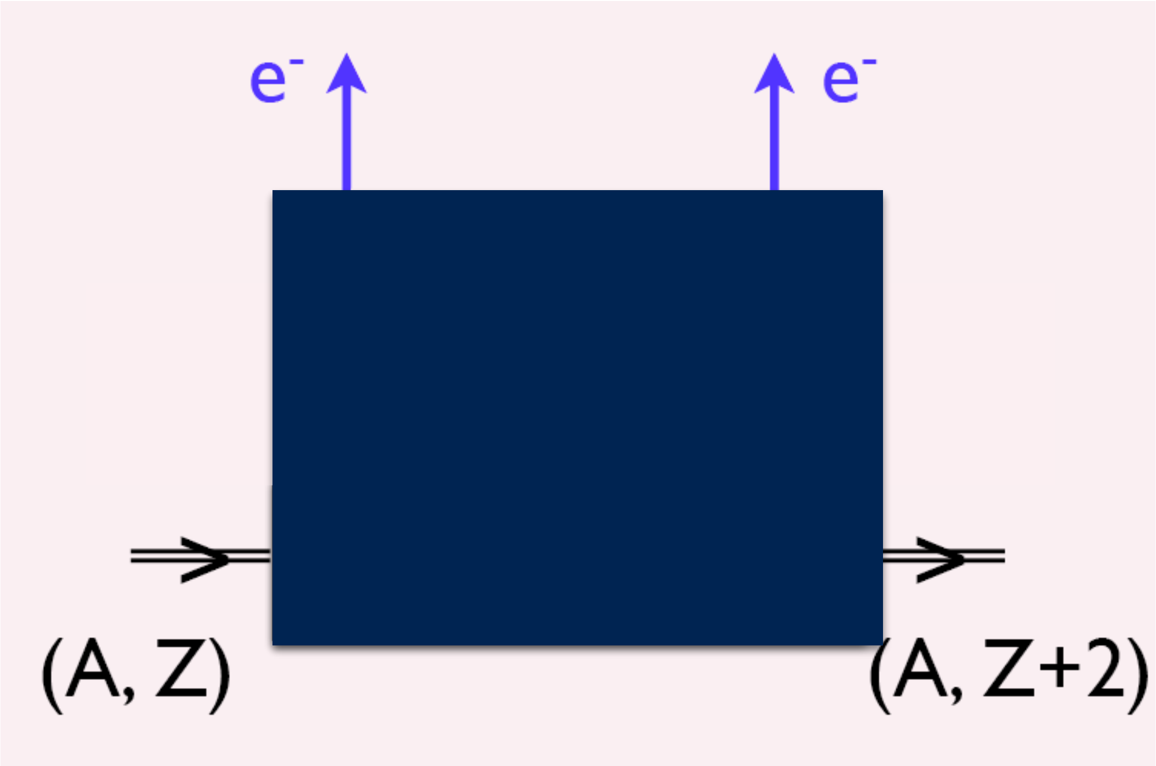
- Standard Model allowed process
- Second-order weak interactions
- $\Delta L = 0$





Isotope	$T^{2\nu}_{1/2}(years)$
^{48}Ca	$(4.4\ ^{+0.6}_{-0.5})\ \times 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$
^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$
^{128}Te	$(1.9 \pm 0.4) \times 10^{24}$
^{130}Te	$(1.5 \pm 0.1) \times 10^{20}$
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$
^{136}Xe	$(2.1 \pm 0.2) \times 10^{22}$

Zero-neutrino double beta decay ($0\nu\beta\beta$)



Schechter-Valle Black-box Theorem [Phys. Rev. D 25 (1982) 2951]

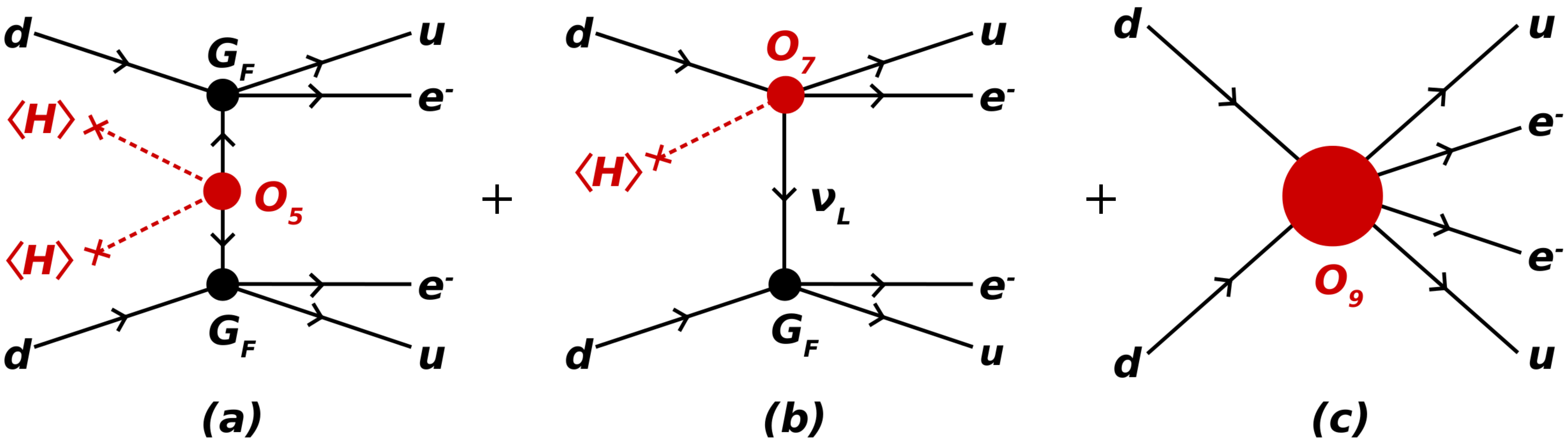
If $0\nu\beta\beta$ is seen:

- Neutrinos are Majorana fermion: $\nu = \bar{\nu}$
- Lepton number violation (LNV): $\Delta L = 2$

regardless of the dominant $0\nu\beta\beta$ mechanism.

What are the possibilities inside the black box?

$$\boxed{\Delta L = 2}$$



Mass mechanism

“Long-range”

“Short-range”

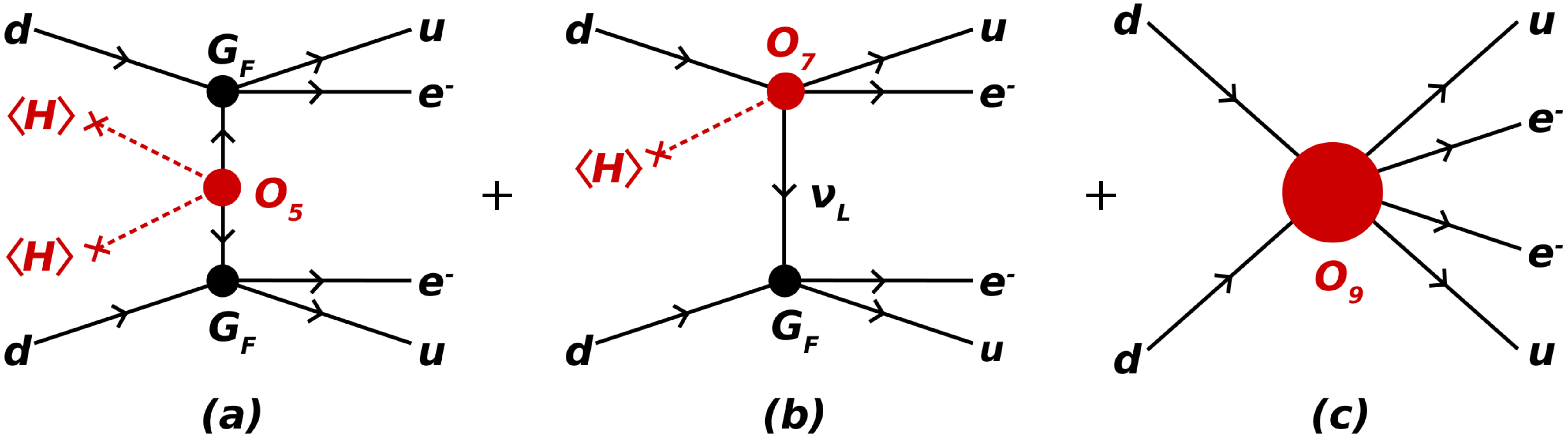
Graphics from Hirsch 2016

What are the possibilities inside the black box?

$$\boxed{\Delta L = 2}$$

GUT scale / seesaw

LHC energy



(a) (b) (c)

Mass mechanism

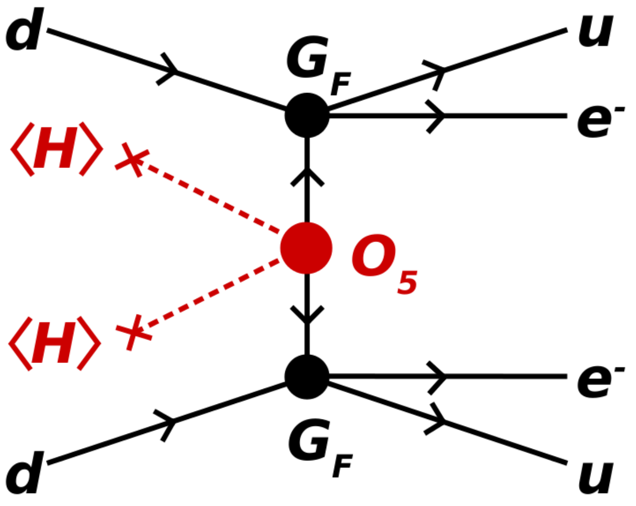
“Long-range”

“Short-range”

0νββ allows us to probe the GUT scale

Graphics from Hirsch 2016

“Vanilla” mass mechanism



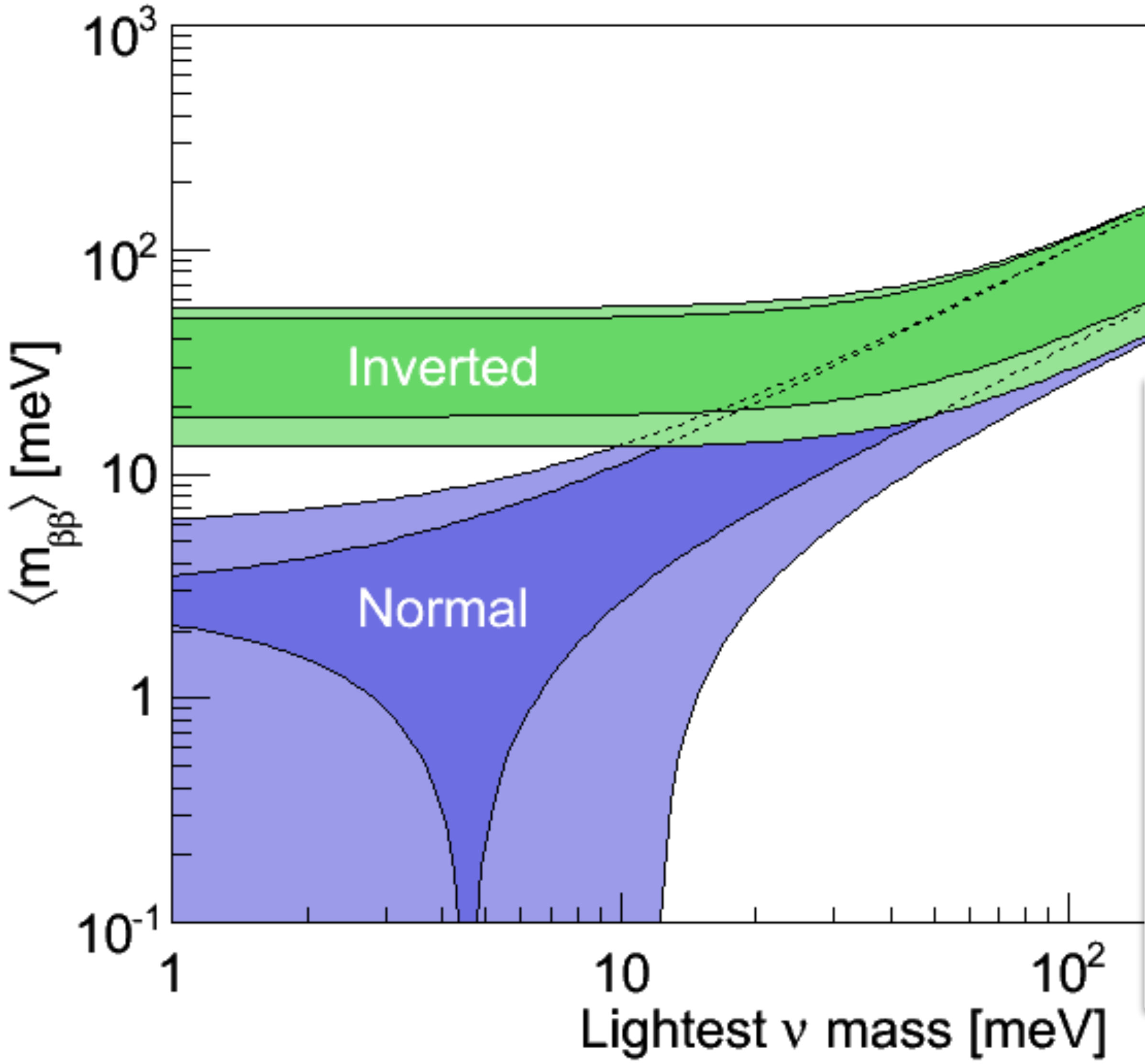
From half-life to mass scale:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$

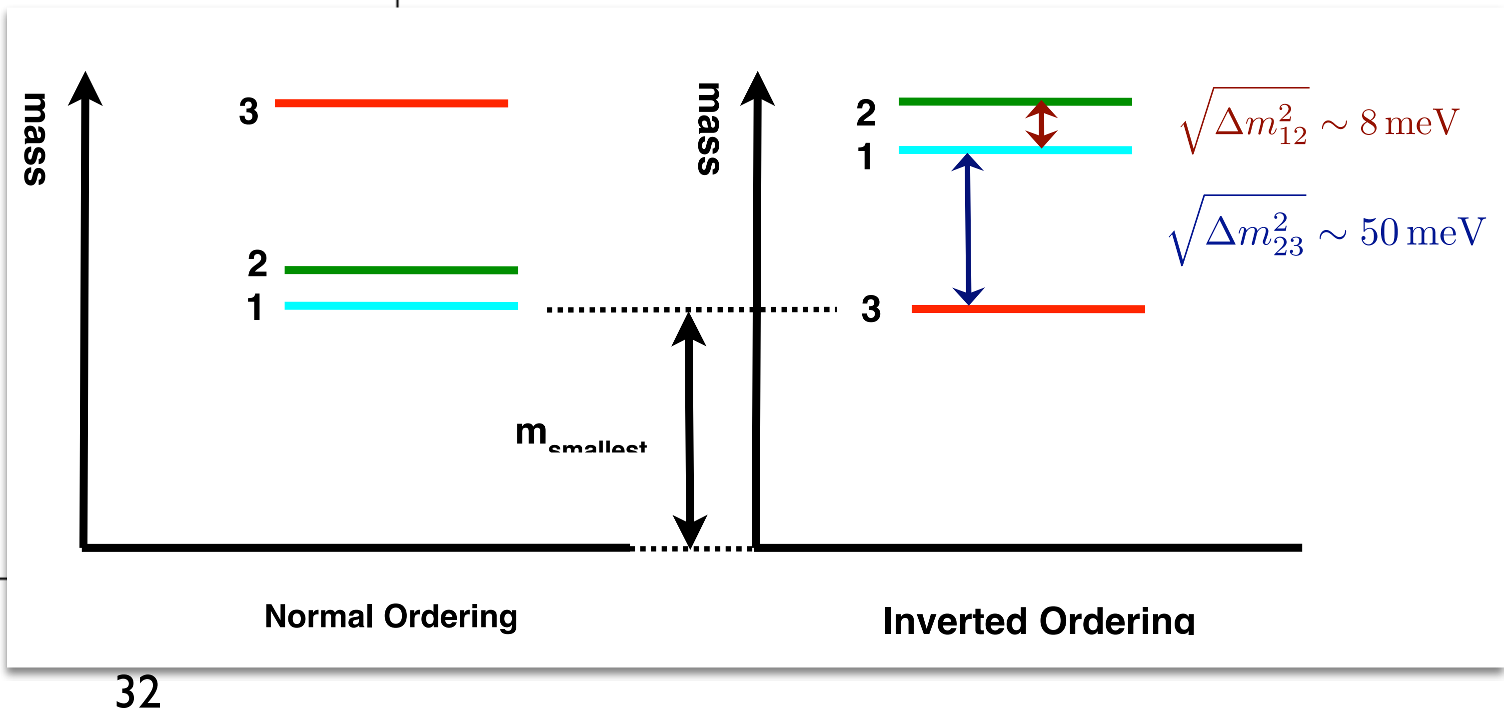
form factor

nuclear matrix element

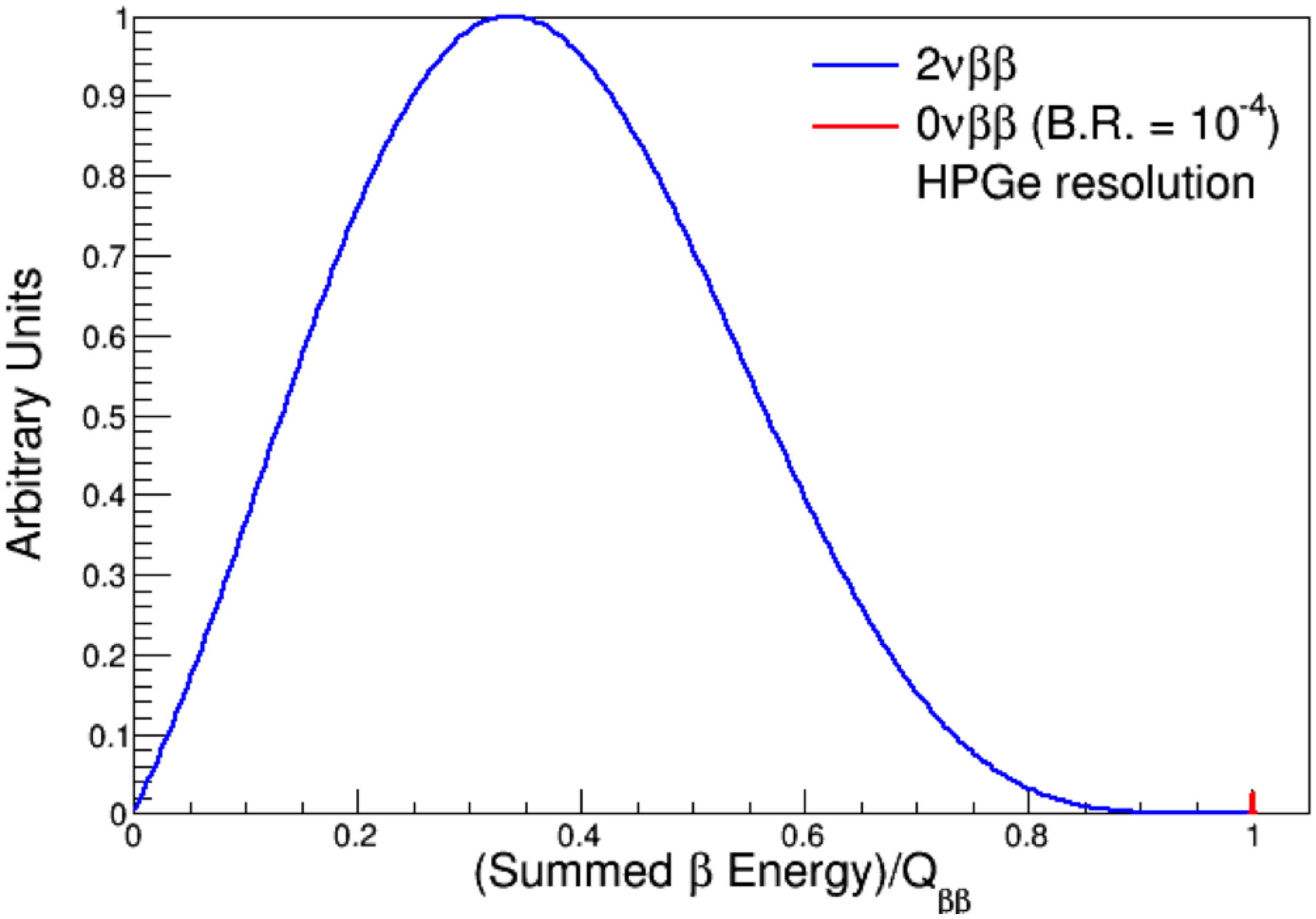
effective Majorana mass



$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



Experimental signature

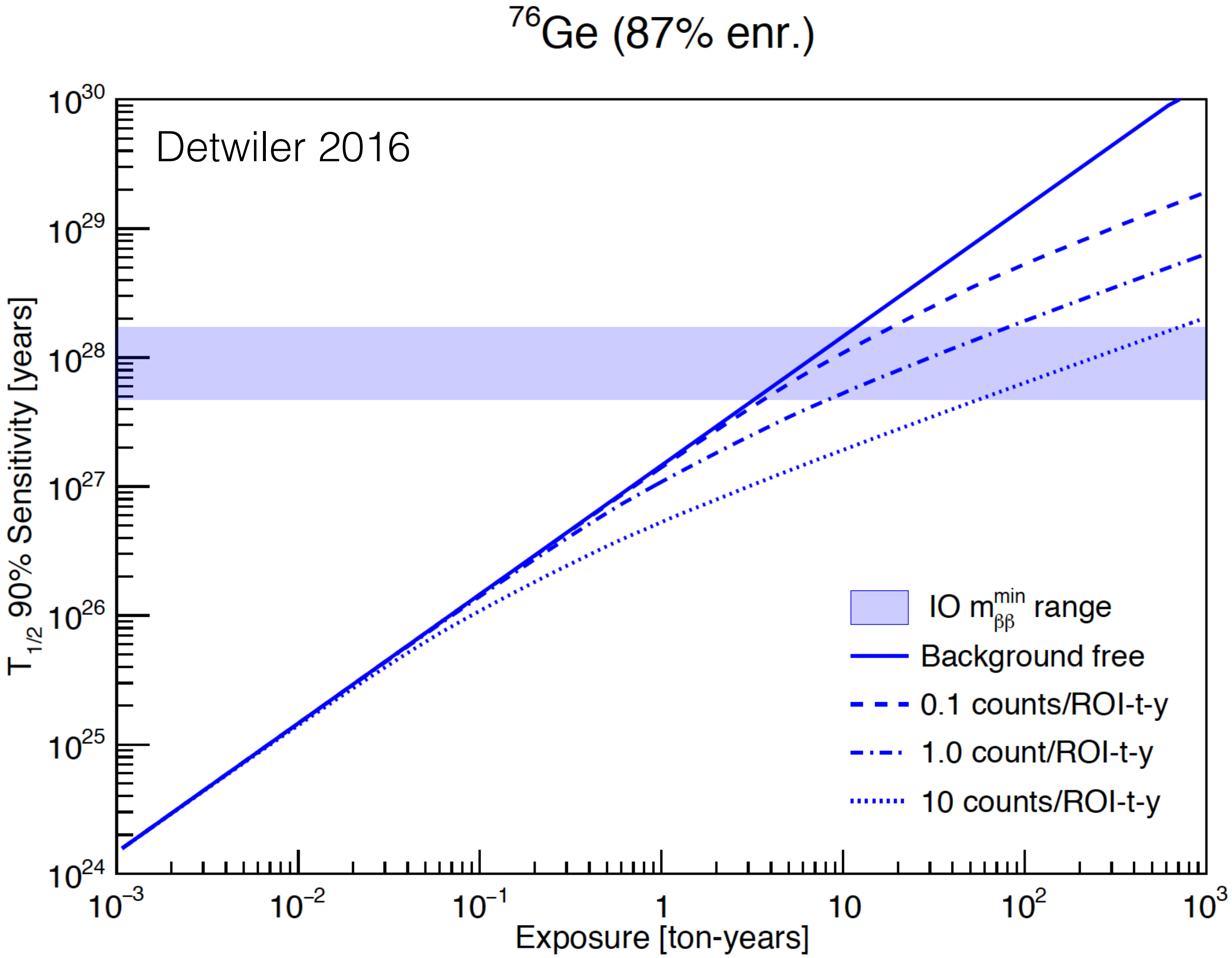


For ^{76}Ge (Q = 2039 keV):

- $T^{2\nu}_{1/2} \sim 10^{21}$ years → Rare process.
- $T^{0\nu}_{1/2} > 10^{26}$ years → Need low background and large mass, counting time.

Next-Generation $0\nu\beta\beta$ Experiments

$T_{1/2}$ (0ν)	Signal rate [cts/(ton-Ge y)]
10^{25} y	500
5 x 10^{26}	10
5 x 10^{27}	1
> 10^{29}	< 0.05



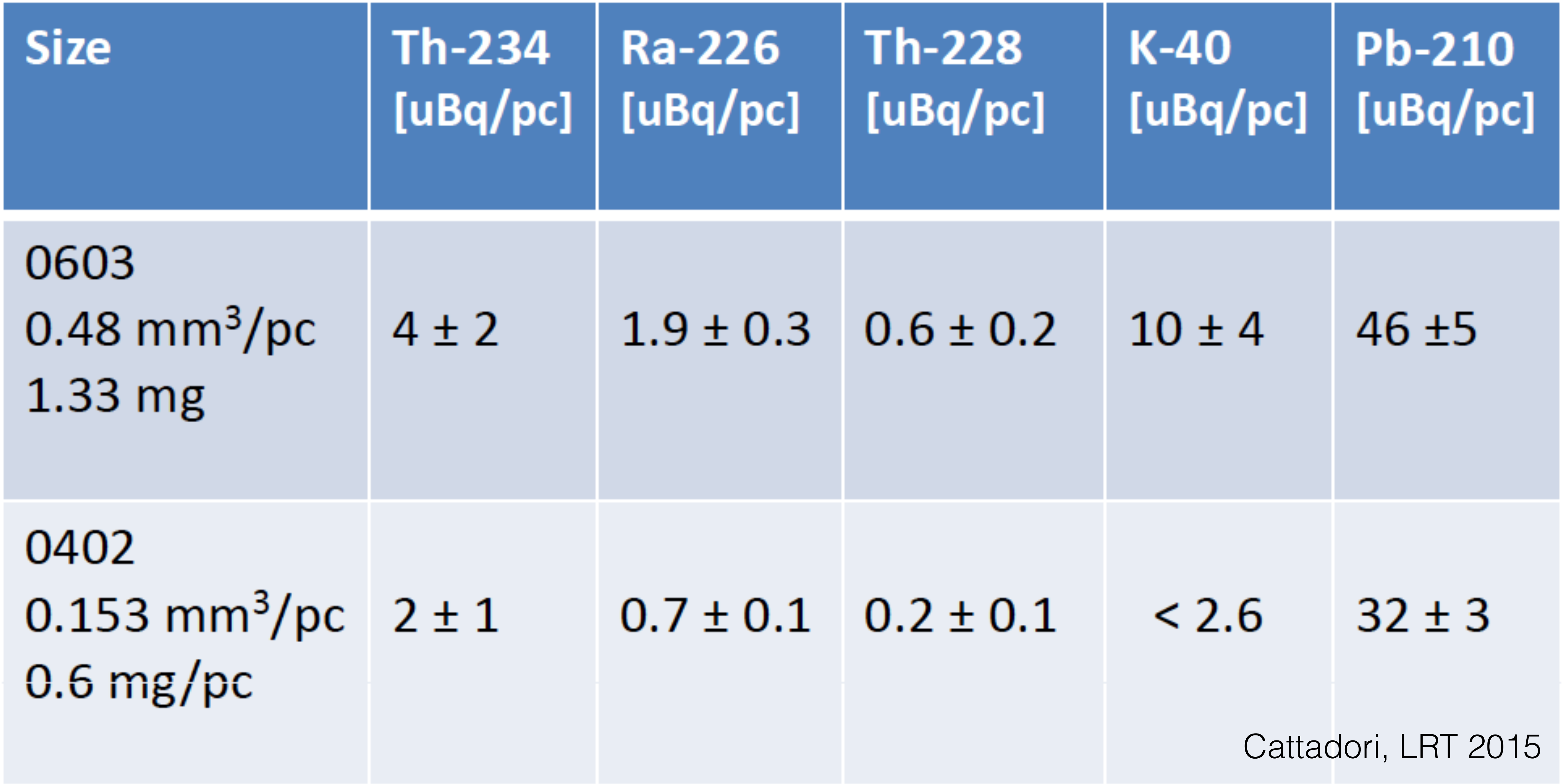
Need a "large-scale" experiment

&

Background index < ~ O(0.1) count/(ton-Ge yr) in ROI

How crazy is 0.1 count/(ton yr)?

500 MΩ SMD resistor used by GERDA

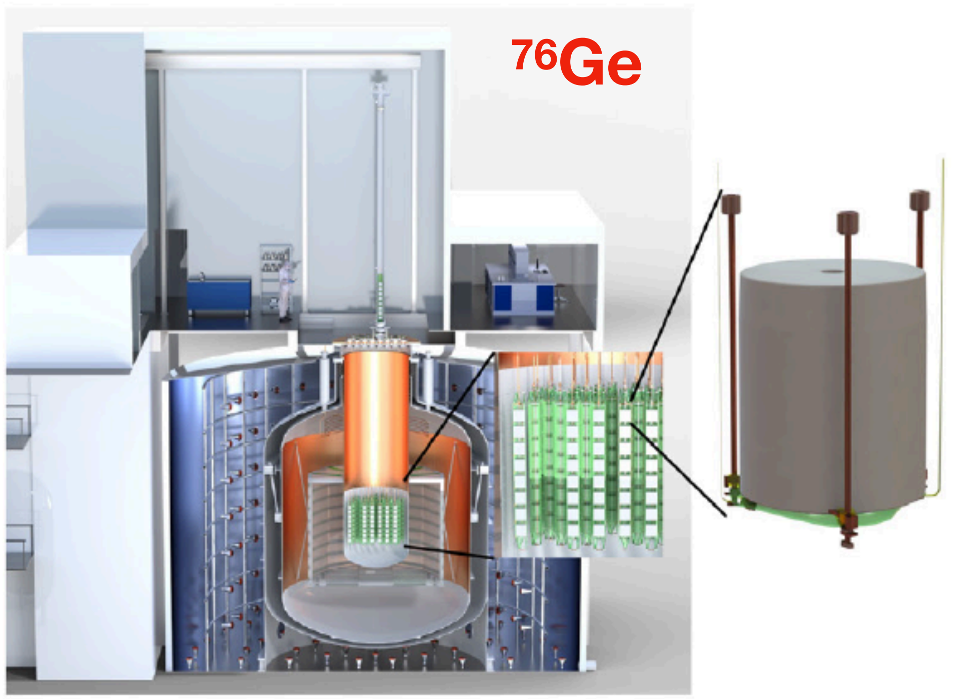


Size	Th-234 [uBq/pc]	Ra-226 [uBq/pc]	Th-228 [uBq/pc]	K-40 [uBq/pc]	Pb-210 [uBq/pc]
0603 0.48 mm^3/pc 1.33 mg	4 ± 2	1.9 ± 0.3	0.6 ± 0.2	10 ± 4	46 ±5
0402 0.153 mm^3/pc 0.6 mg/pc	2 ± 1	0.7 ± 0.1	0.2 ± 0.1	< 2.6	32 ± 3

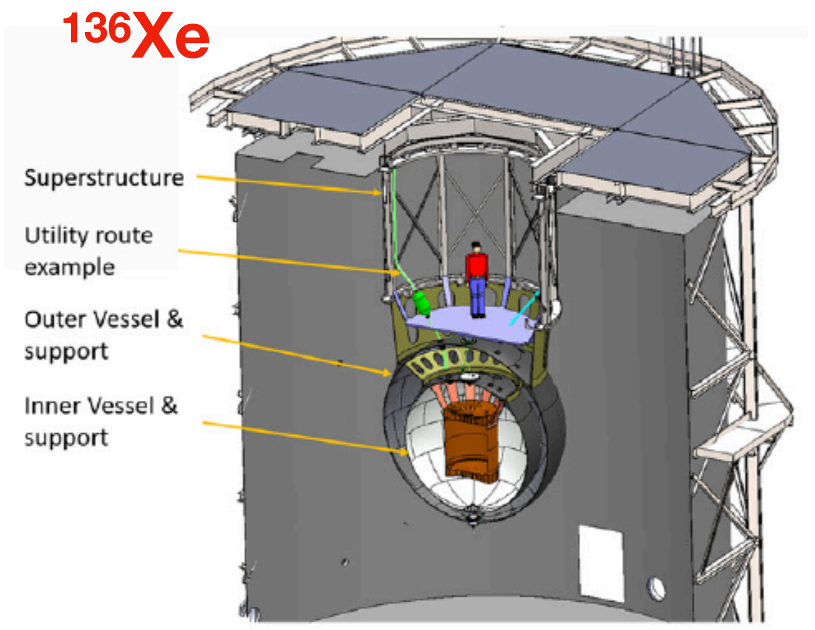
Cattadori, LRT 2015

1 μBq ≈ 0.1 / day

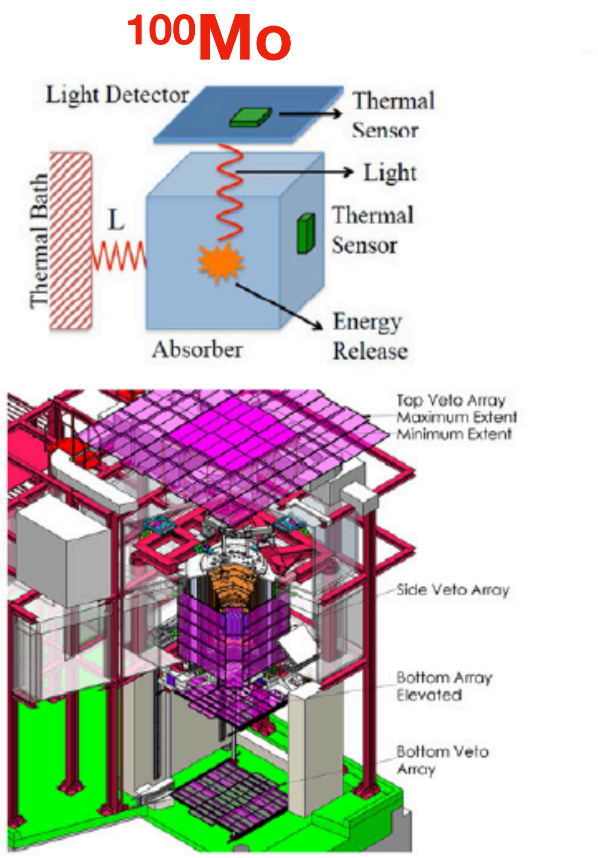
An International Program



LEGEND



nEXO



CUPID

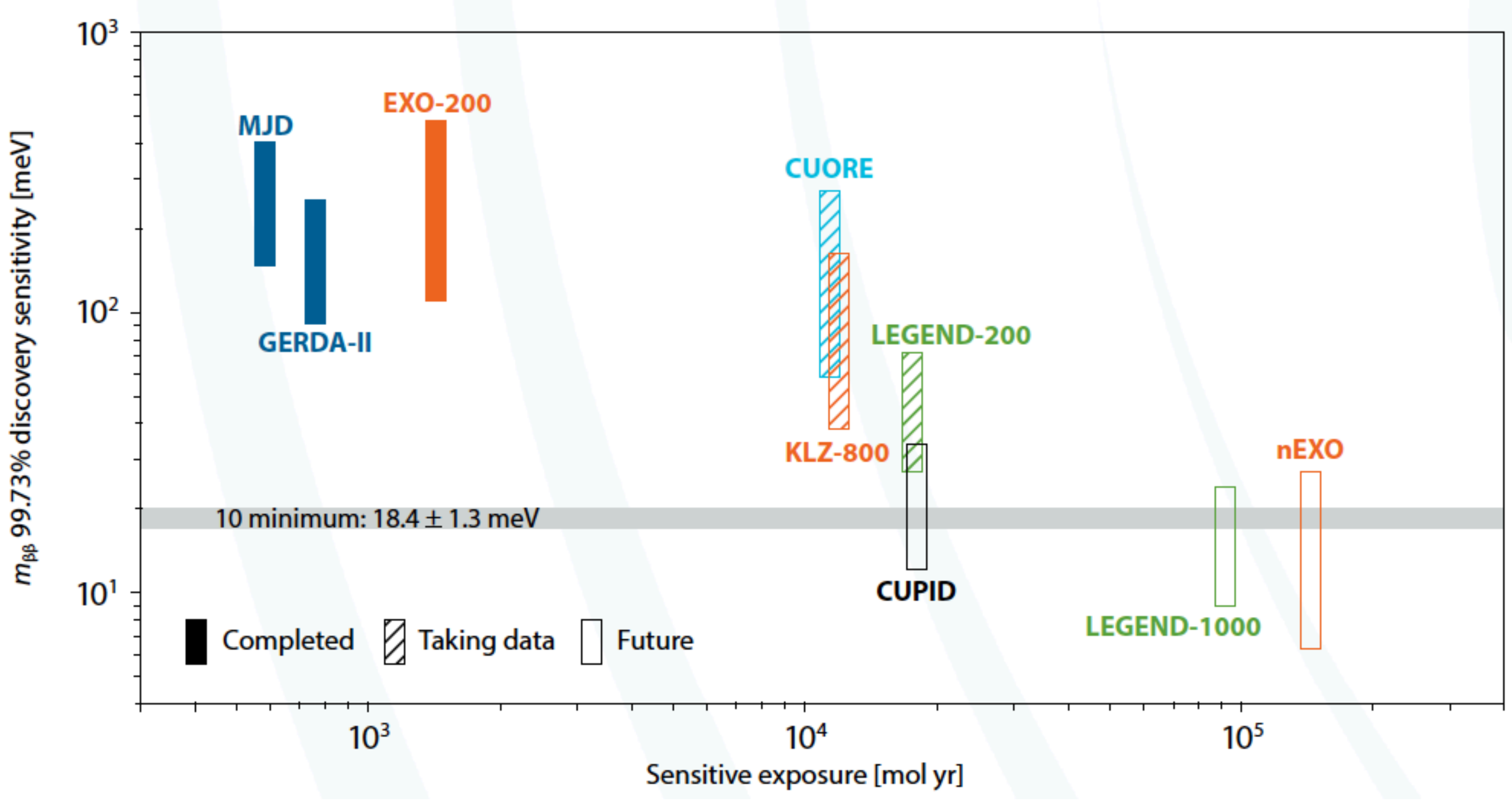
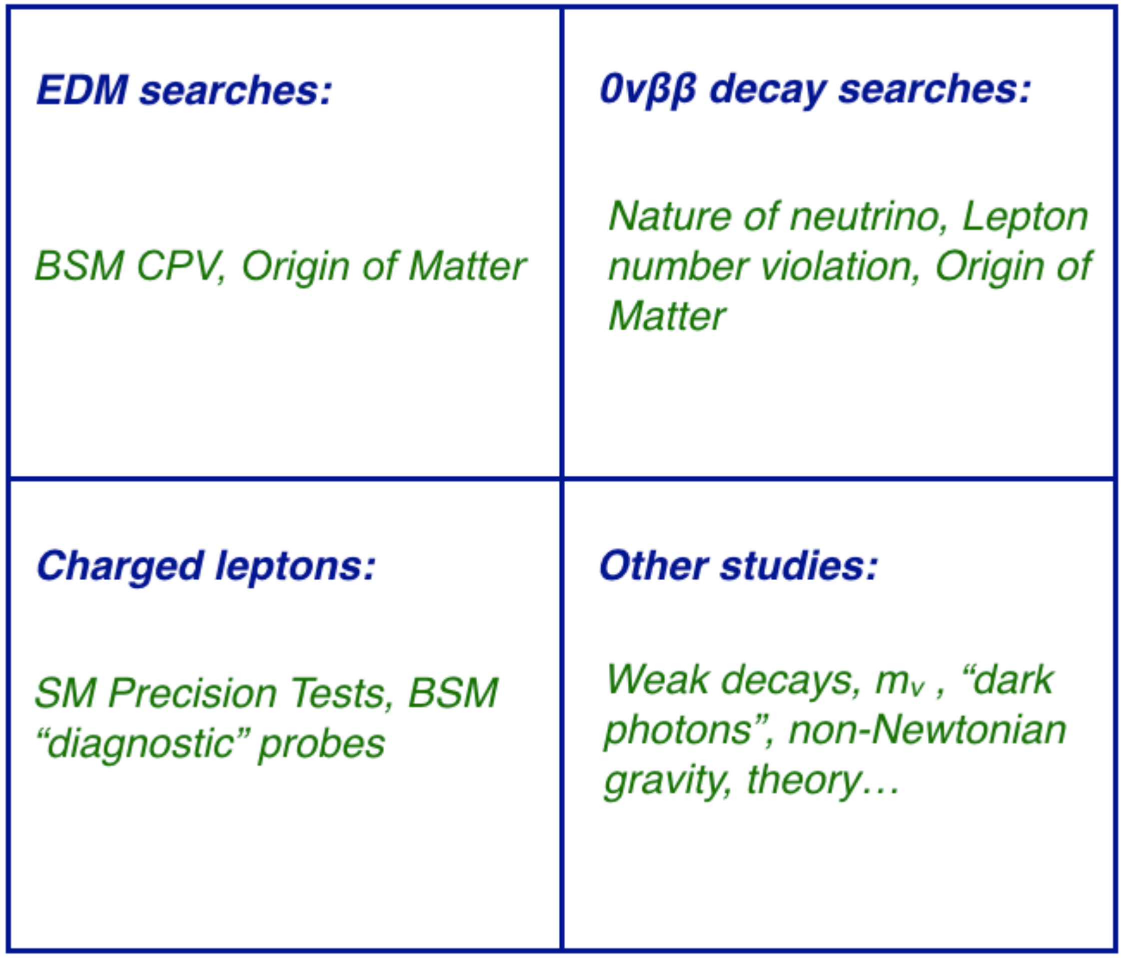


Figure 6.5. The ton-scale neutrinoless double beta decay experiments described in the text: LEGEND-1000, nEXO and CUPID. *The plot shows the results of past experiments (solid), the projected reach of currently running experiments (hatched), and future ton-scale experiments (open). The recommended ton-scale experiments probe the inverted ordering (gray band). Concepts for experiments beyond the ton scale to probe even further are discussed in the text.. (Note: This is a placeholder figure for a graphic currently in development. The final printed plan is intended to contain a different image.) [26].*

Summary

- Fundamental symmetry program at low energies is a rich, diverse and multidisciplinary research.
- Unique probes of beyond-Standard-Model physics, which may reach energy scale beyond what is accessible by accelerators in some cases.



EDM searches: *BSM CPV, Origin of Matter*	***$0\nu\beta\beta$ decay searches:*** *Nature of neutrino, Lepton number violation, Origin of Matter*
Charged leptons: *SM Precision Tests, BSM "diagnostic" probes*	***Other studies:*** *Weak decays, m_ν , "dark photons", non-Newtonian gravity, theory…*

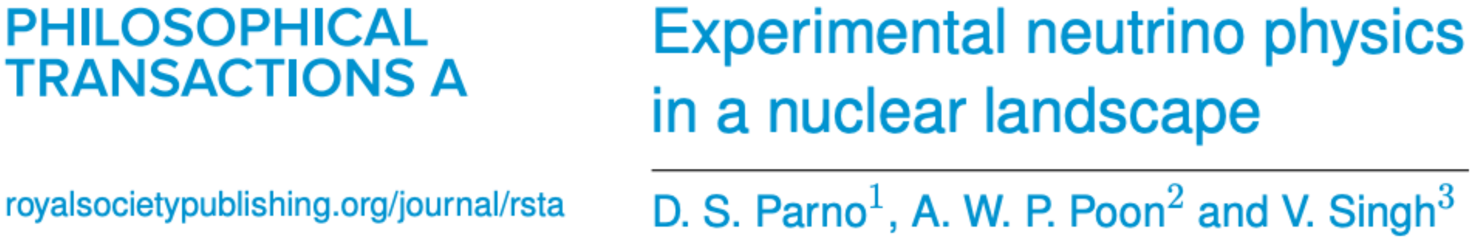
- Some of these studies try to answer the most fundamental questions in Nature, including the origin of matter, the mass nature of neutrinos, and violation of lepton number.

Matrix adapted from Ramsey-Musolf

A couple of references to read

- 2023 NSAC Long Range Plan
  - “Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 NSAC Long Range Plan”, arXiv:2304.03451

- Parno, AP, Singh, “Experimental neutrino physics in a nuclear landscape”, arXiv:2310.06207



PHILOSOPHICAL TRANSACTIONS A

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Experimental neutrino physics in a nuclear landscape

D. S. Parno[1], A. W. P. Poon[2] and V. Singh[3]