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

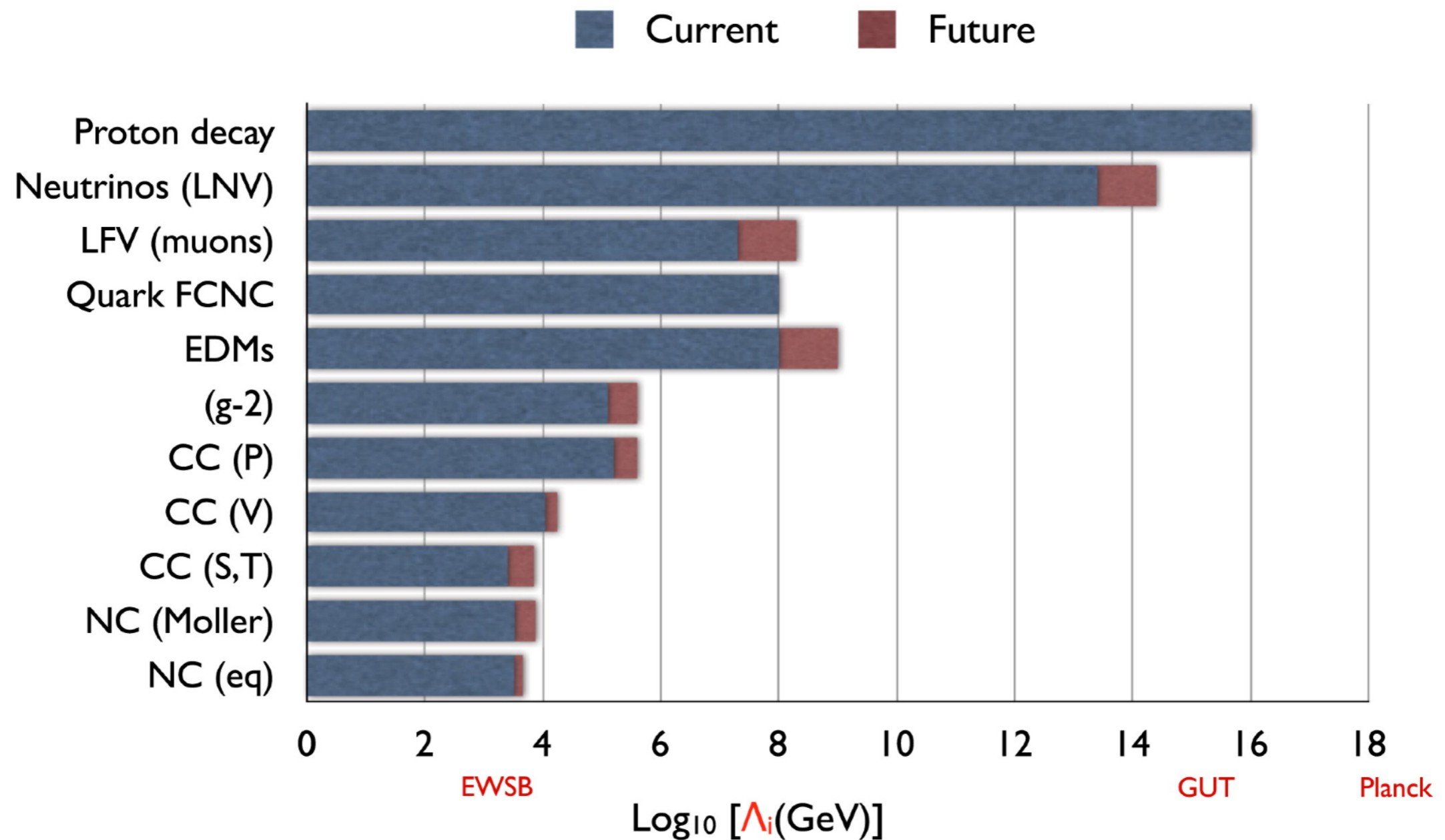
Alan Poon (awphoon@lbl.gov)

Nuclear Science Division

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 \Rightarrow evidence*
- Reaching energy regime unattainable by accelerators in certain low energy searches. (next slide)
- Focus of this talk:
 - *Neutrons, Nuclei and Neutrinos* as probes

Low energy probes of BSM physics

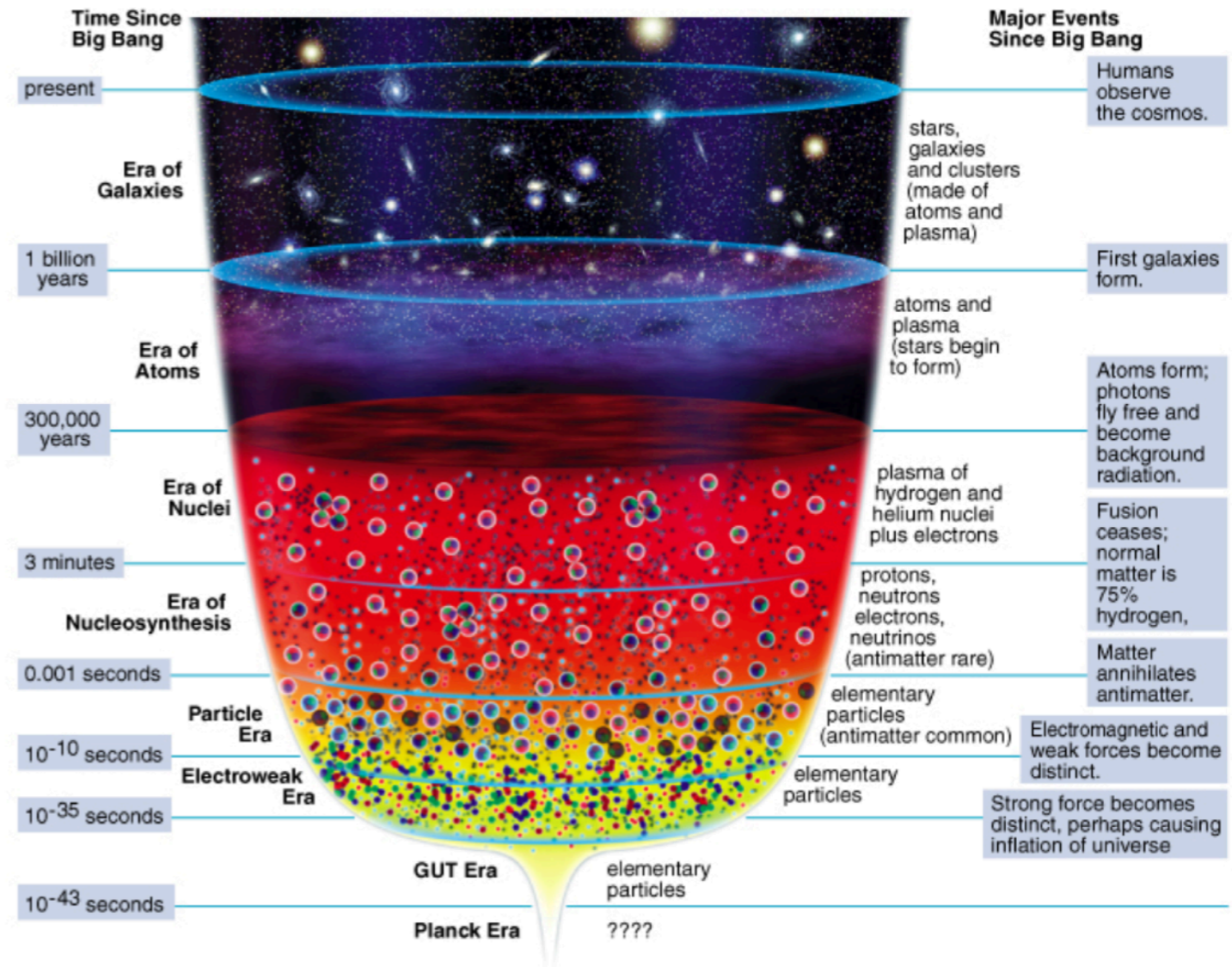
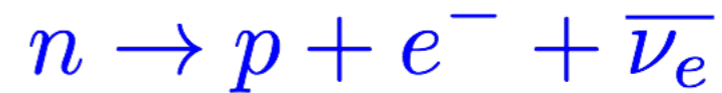


Λ: effective new physics scale

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 ^4He) formation
 - Standard Model tests:
 - CKM unitarity (high precision V_{ud} measurements)
 - Time reversal violation
 - Non-standard interactions ($\neq V-A$)
- Precision measurements of:
 - neutron lifetime τ_n
 - β energy spectrum
 - angular correlations of the decay products (next slide)



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)]

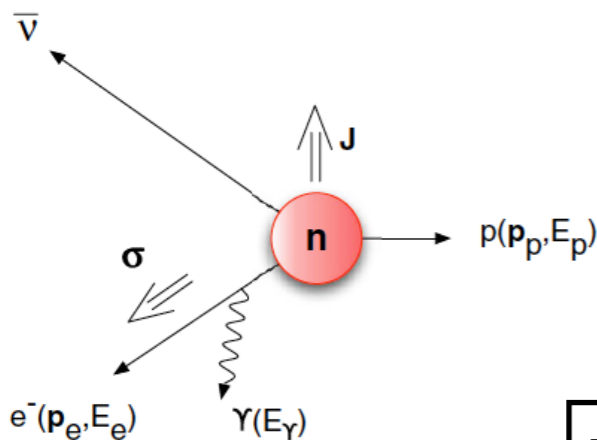
$$\begin{aligned}
 H_{\text{int}} = & (\bar{\psi}_p \psi_n) (C_S \bar{\psi}_e \psi_\nu + C_{S'} \bar{\psi}_e \gamma_5 \psi_\nu) \\
 & + (\bar{\psi}_p \gamma_\mu \psi_n) (C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C_{V'} \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) \\
 & + \frac{1}{2} (\bar{\psi}_p \sigma_{\lambda\mu} \psi_n) (C_T \bar{\psi}_e \sigma_{\lambda\mu} \psi_\nu + C_{T'} \bar{\psi}_e \sigma_{\lambda\mu} \gamma_5 \psi_\nu) \\
 & - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n) (C_A \bar{\psi}_e \gamma_\mu \psi_\nu + C_{A'} \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) \\
 & + (\bar{\psi}_p \gamma_5 \psi_n) (C_P \bar{\psi}_e \psi_\nu + C_{P'} \bar{\psi}_e \gamma_5 \psi_\nu) \quad (1) \\
 & + \text{Hermitian conjugate,}
 \end{aligned}$$



For neutron decay:

$$\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right.$$

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



Measurements: a, b, A, B, D, τ_n

(Nico 2009)

Neutron β Decay - Symmetry Tests

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

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

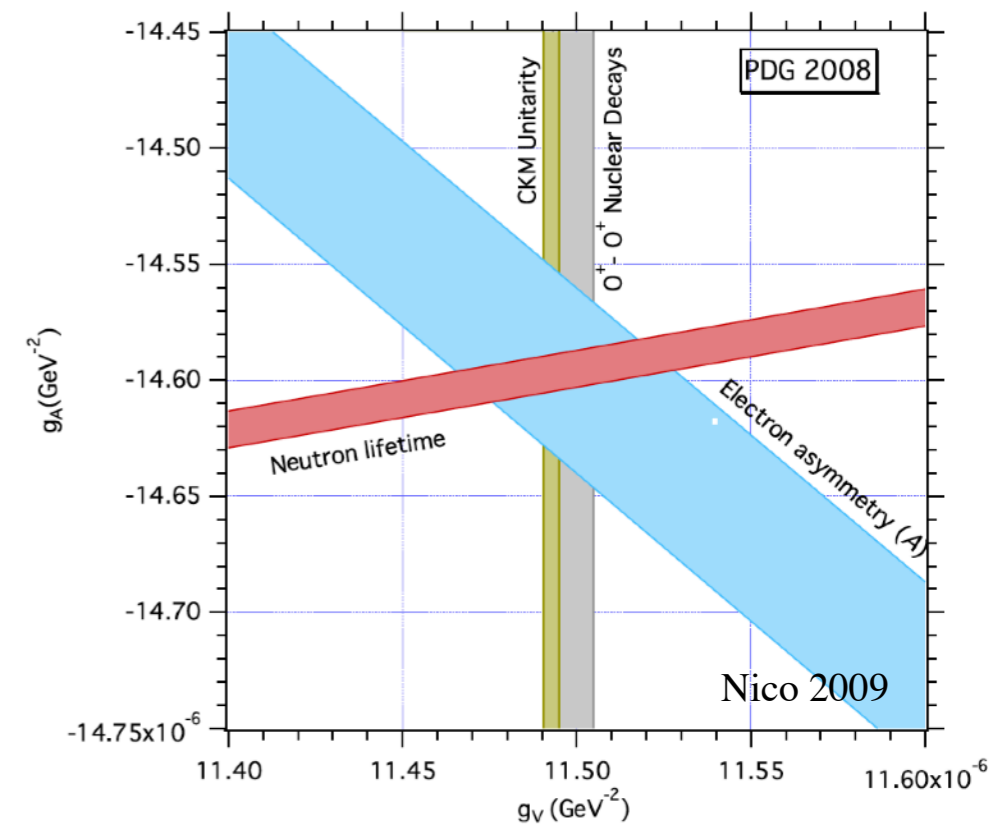
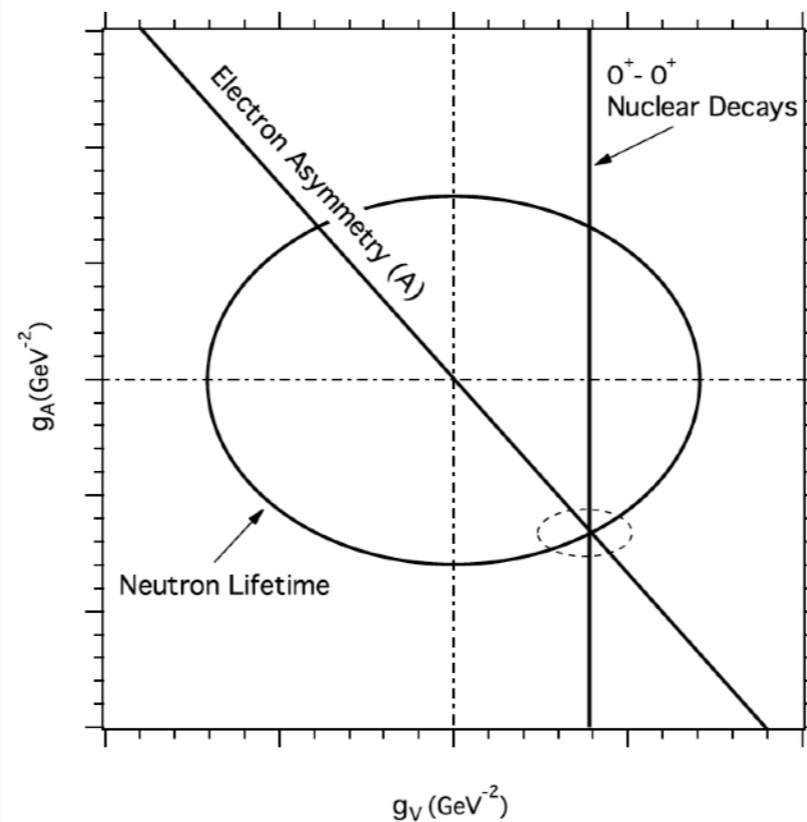
Neutron β Decay

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

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

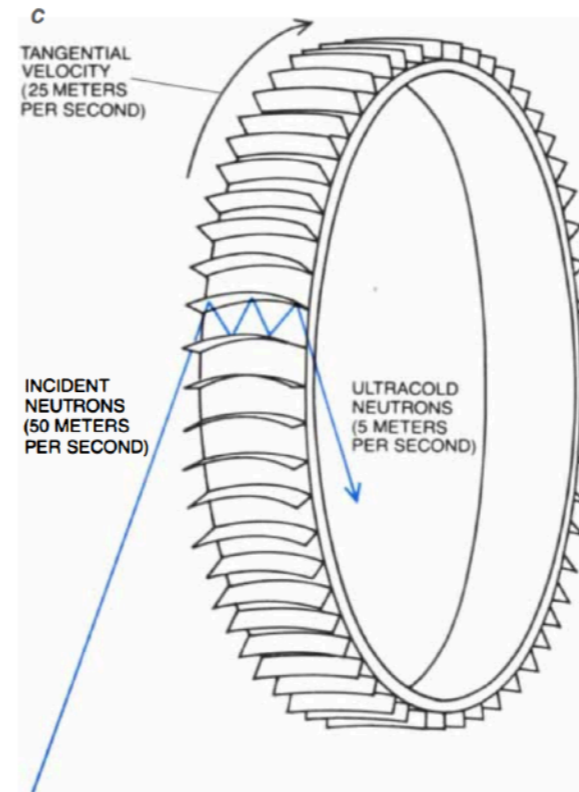
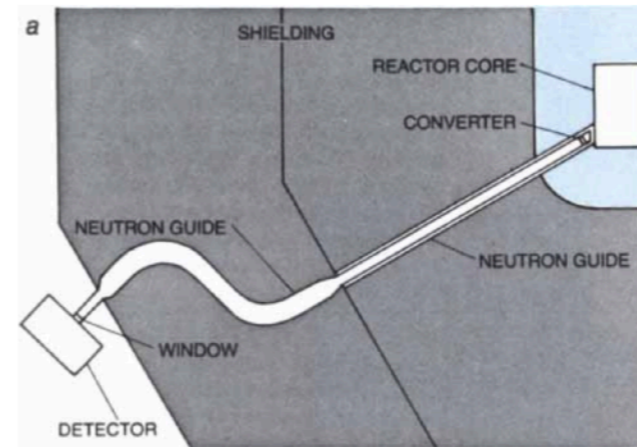
$$\begin{aligned} a &= \frac{1 - \lambda^2}{1 + 3\lambda^2} \\ b &= 0 \\ A &= -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \\ B &= 2 \frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \\ D &= 0 \\ \tau_n &\propto \frac{1}{g_V^2 + 3g_A^2} \end{aligned}$$

g_A and g_V from various n decay measurements

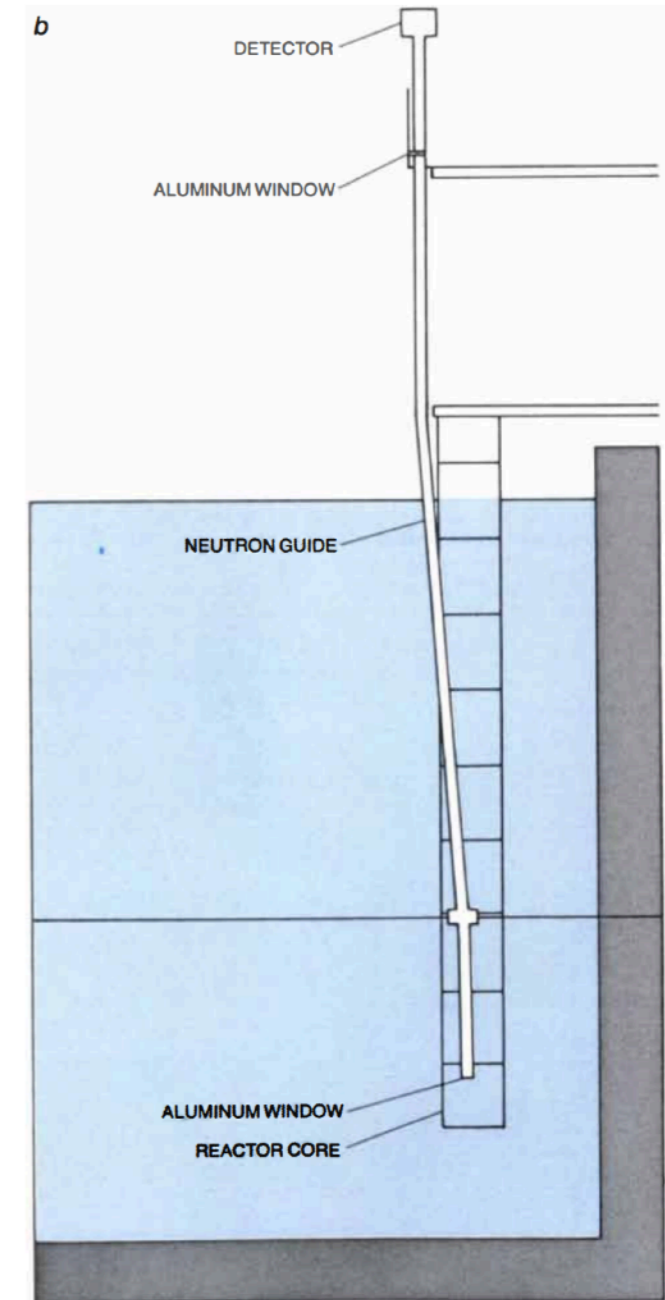


Neutron sources

- 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)
 - $T \sim 20 \text{ K} \sim 2 \text{ meV}$
- Ultra-cold neutron (UCN)
 - $T < 4 \text{ mK} \sim 300 \text{ neV}$
 - 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 some-



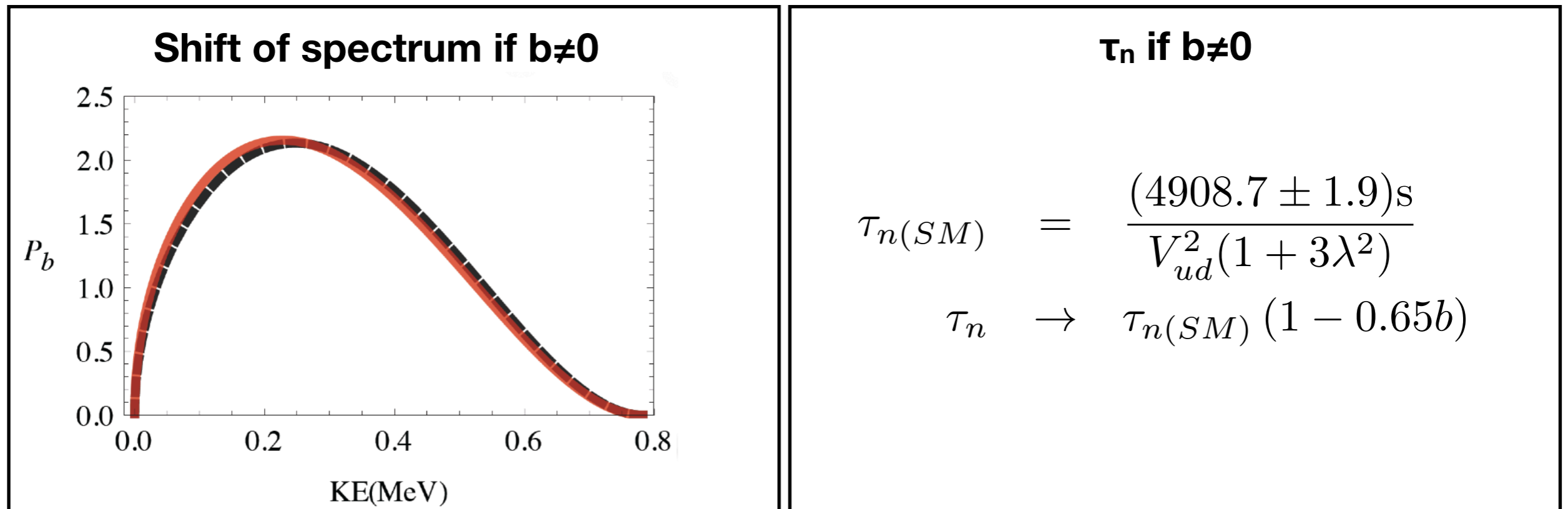
what higher than ultracold energy at the bottom, but in climbing to the apparatus at the top they are slowed to the ultracold-energy range by the earth's gravitational field. In a neutron turbine (c) neutrons moving at about 50 meters per second bounce several times from the receding blades of a rapidly 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



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

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

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

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

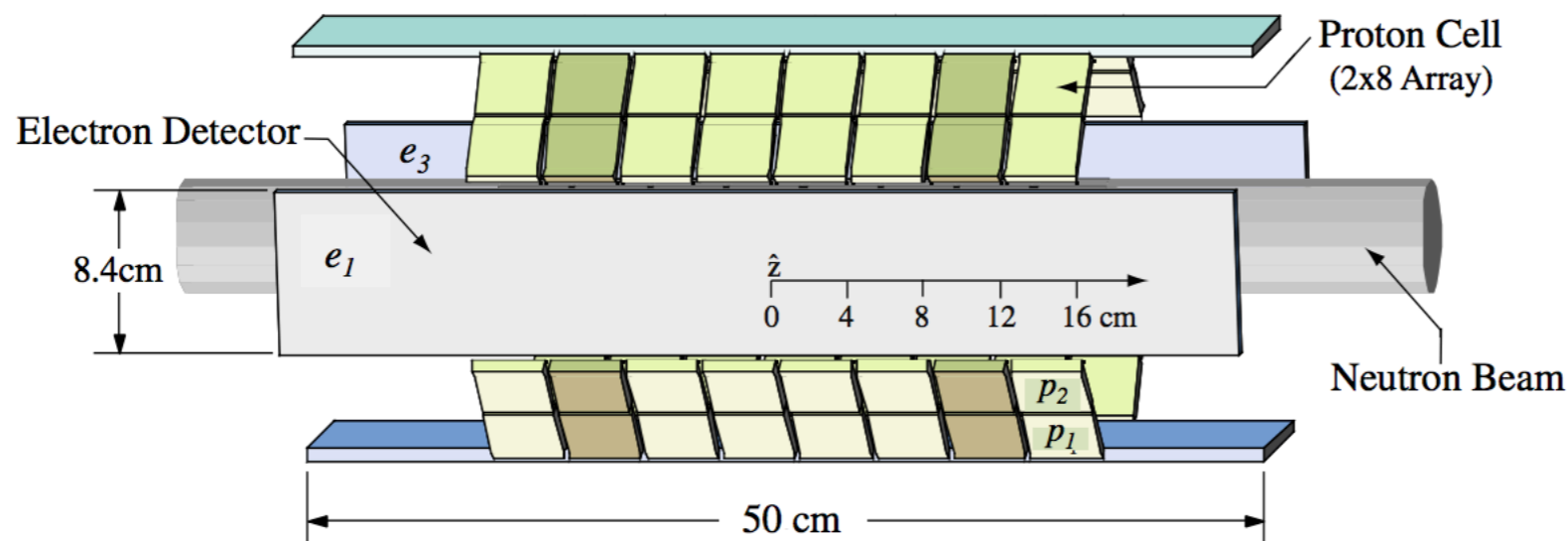
Neutron β Decay - Search for BSM Physics

Examples:

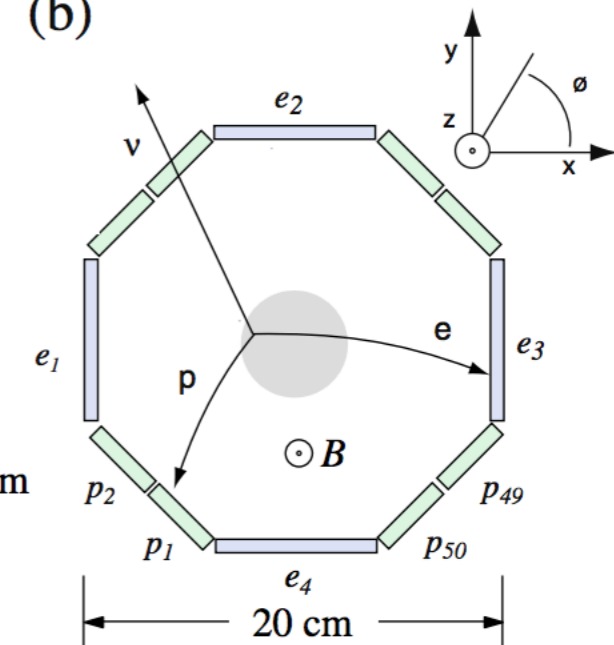
- D : Time Reversal Invariance

emiT Experiment:

(a)



(b)



$$D = (-1.2 \pm 2.0) \times 10^{-4} \quad (\text{published emiT limit, PDG 2018})$$

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 \neq Mass eigenstates

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

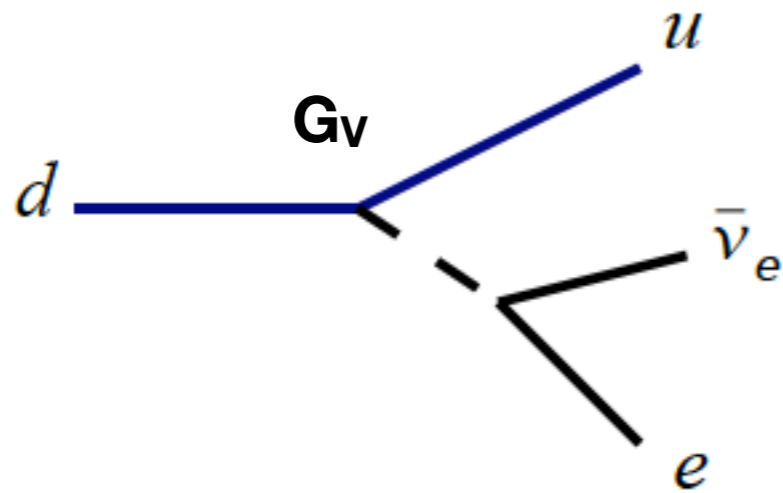
$|V_{ud}|^2$: neutron/nuclear decay, π decay

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

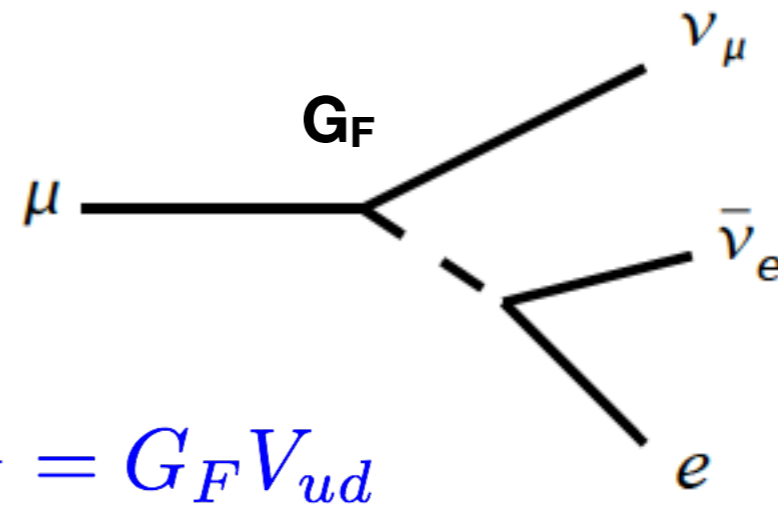
$|V_{ub}|^2$: B decay

CKM Matrix and V_{ud}

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



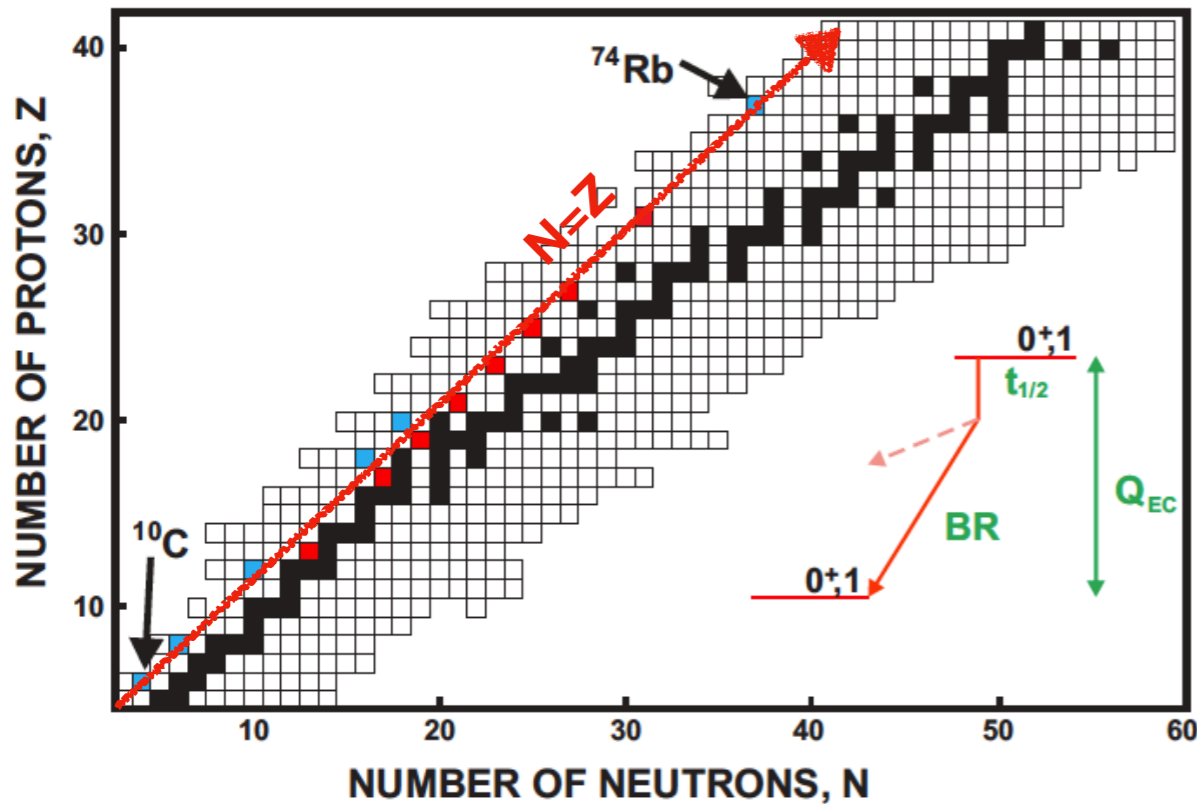
neutron/nuclear β decays



Precisely measure in muon decays

$$G_V = G_F V_{ud}$$

Super-allowed $0^+ \rightarrow 0^+$ beta decays



Beta-decay “ft” value:

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

*phase
space*

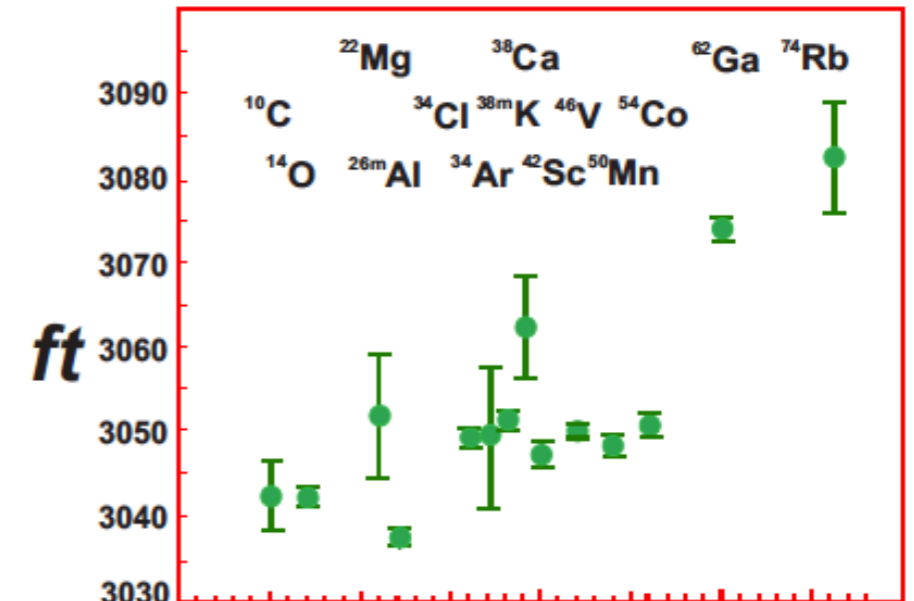
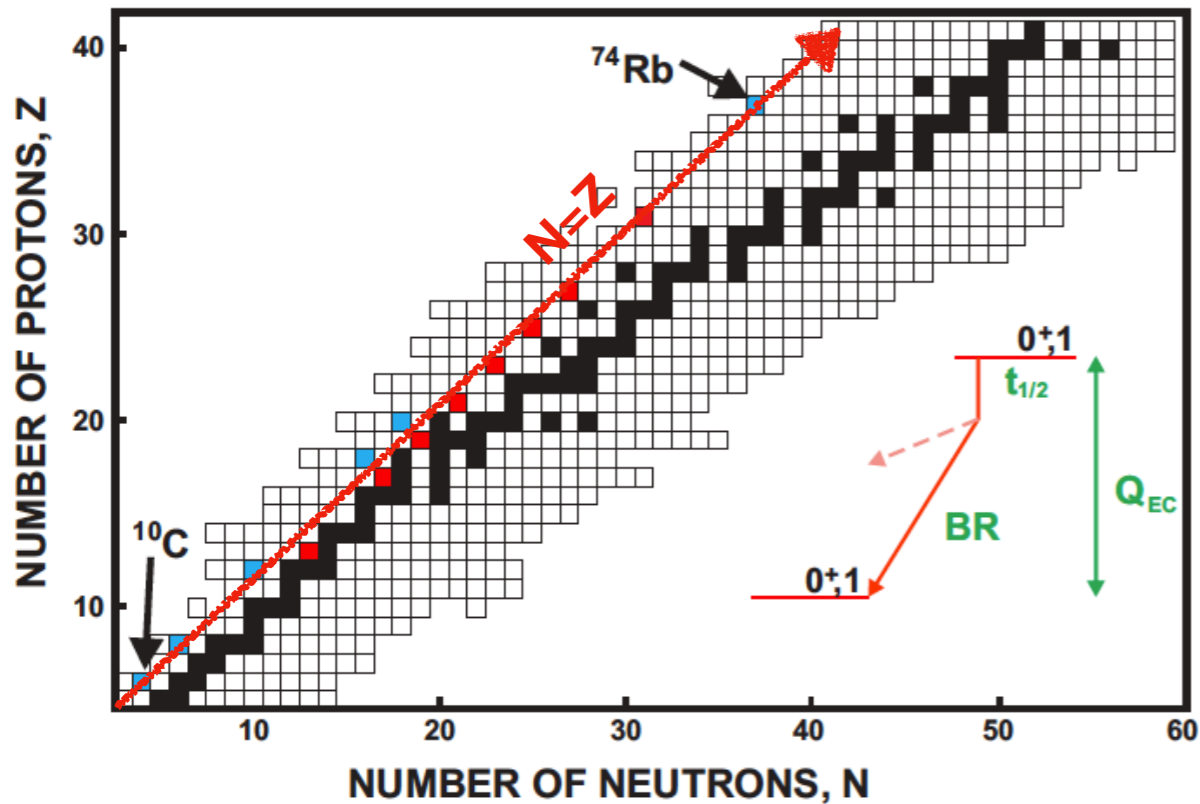
Super-allowed $0^+ \rightarrow 0^+$ beta-decay:

$$g^2 = g_V^2 (1 + \Delta_R)$$

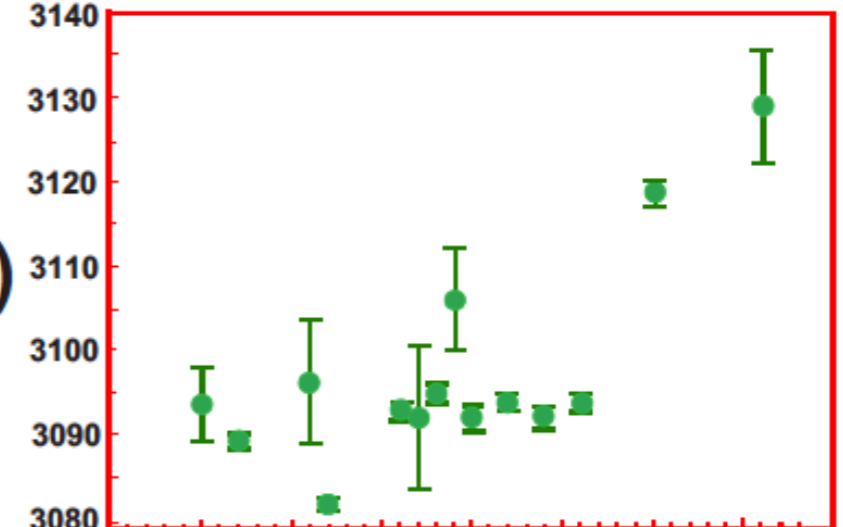
$$|\overline{M}'_{fi}|^2 = 2(1 - \delta_C)$$

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

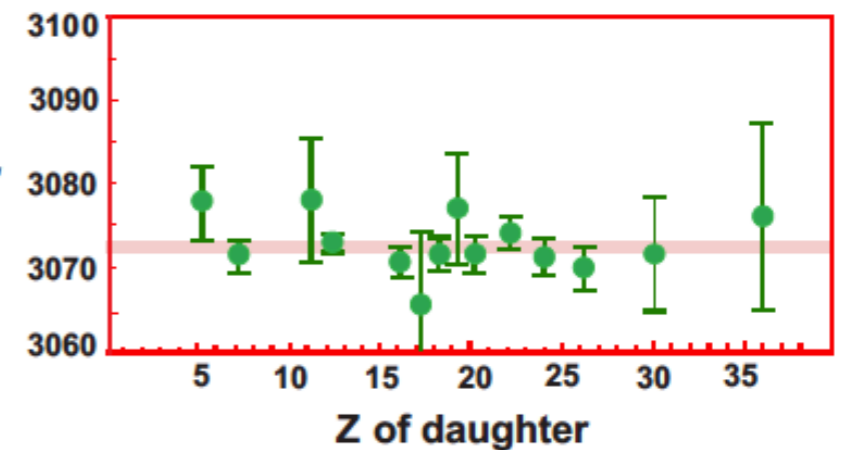
Super-allowed $0^+ \rightarrow 0^+$ beta decays



$ft (1 + \delta'_R)$

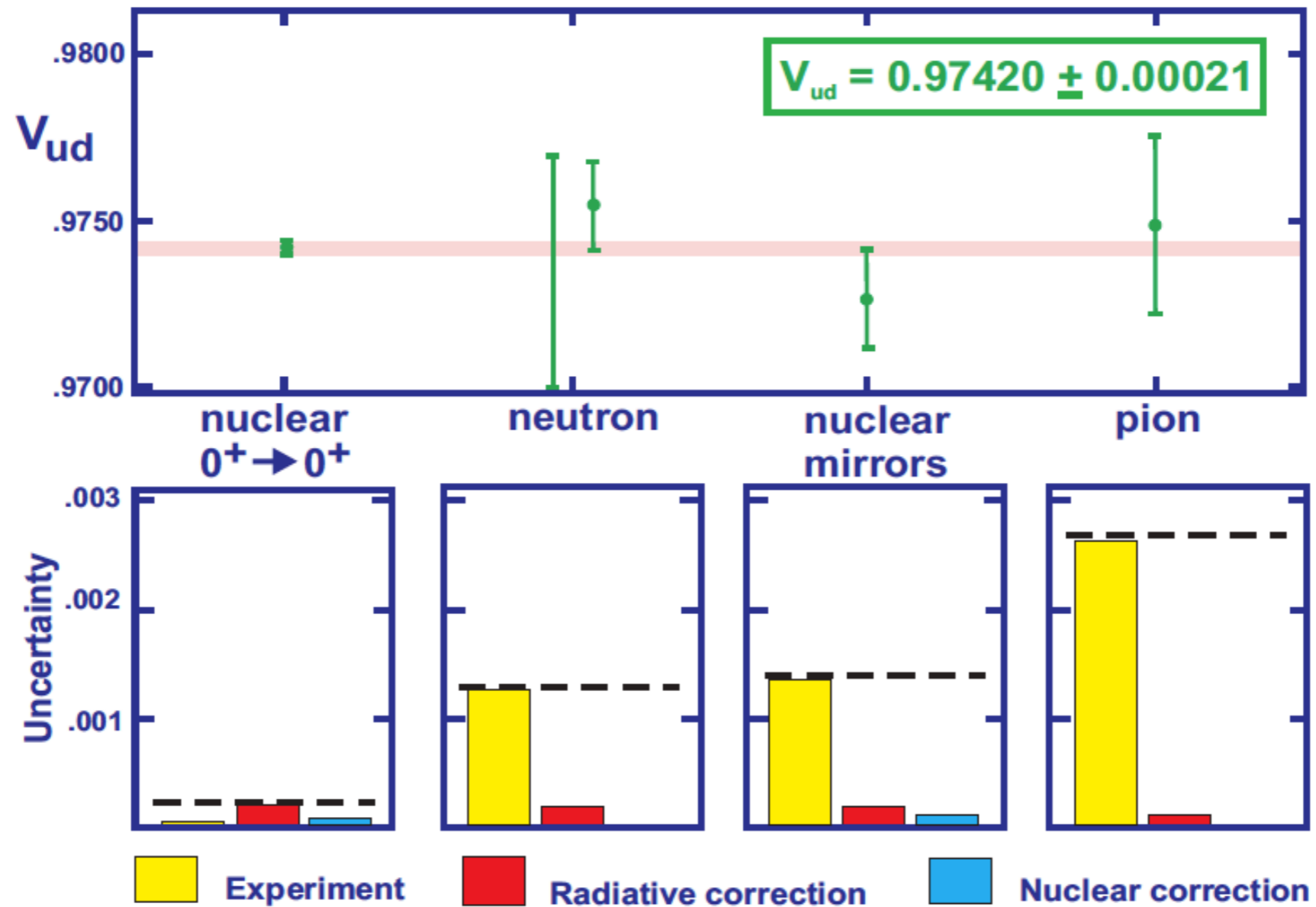


$\mathcal{F}t$



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

CKM Matrix and V_{ud}



$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99962 \pm 0.00049$$

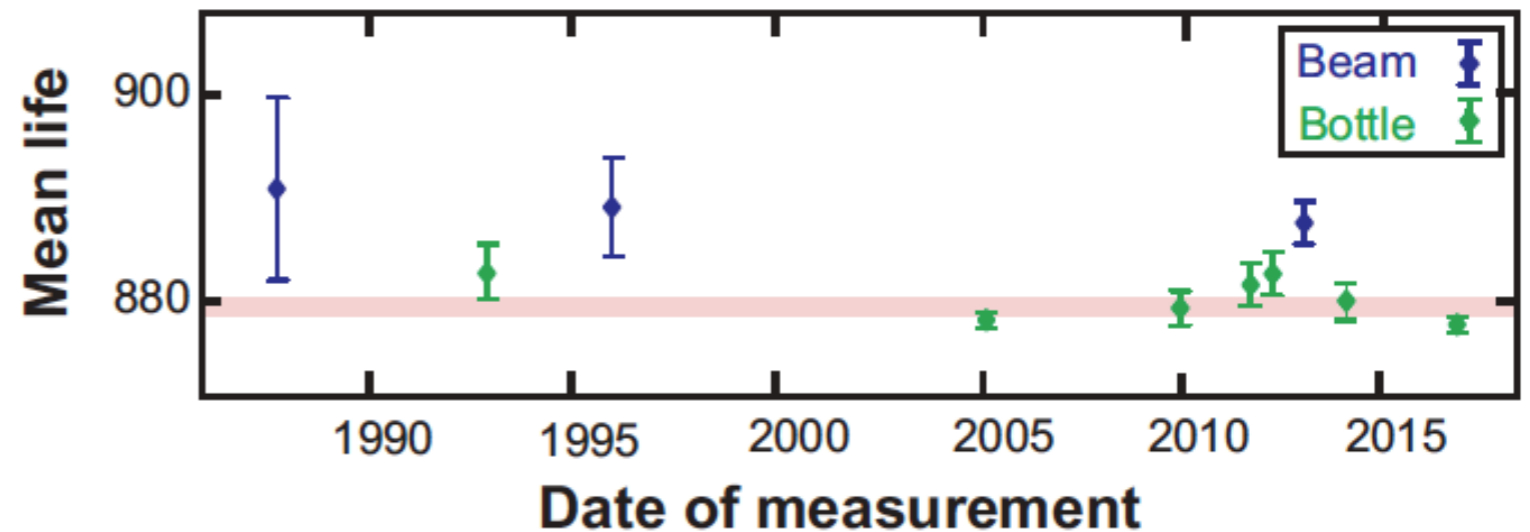
Neutron β Decay Data (2018)

Mean life:

$$\tau = 879.4 \pm 0.9 \text{ s}$$

$$\chi^2/N = 4.2$$

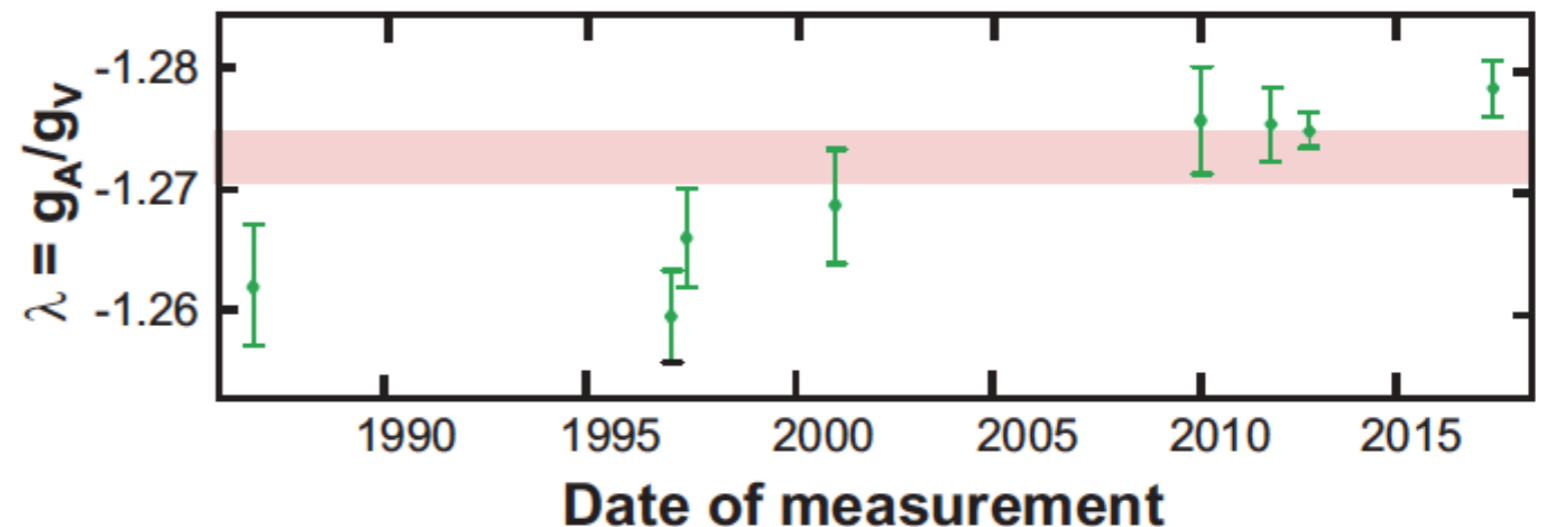
Beam: $888.1 \pm 2.0 \text{ s}$
 Bottle: $878.9 \pm 0.6 \text{ s}$



β asymmetry:

$$\lambda = -1.2735 \pm 0.0019$$

$$\chi^2/N = 4.3$$



$V_{ud} = 0.9755 \pm 0.0013$

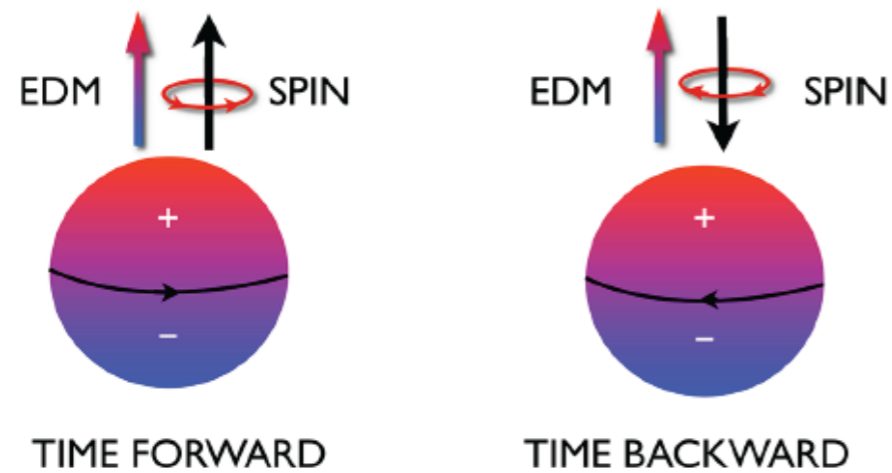
Beam-bottle span
 $0.9700 \leq V_{ud} \leq 0.9770$

vs.

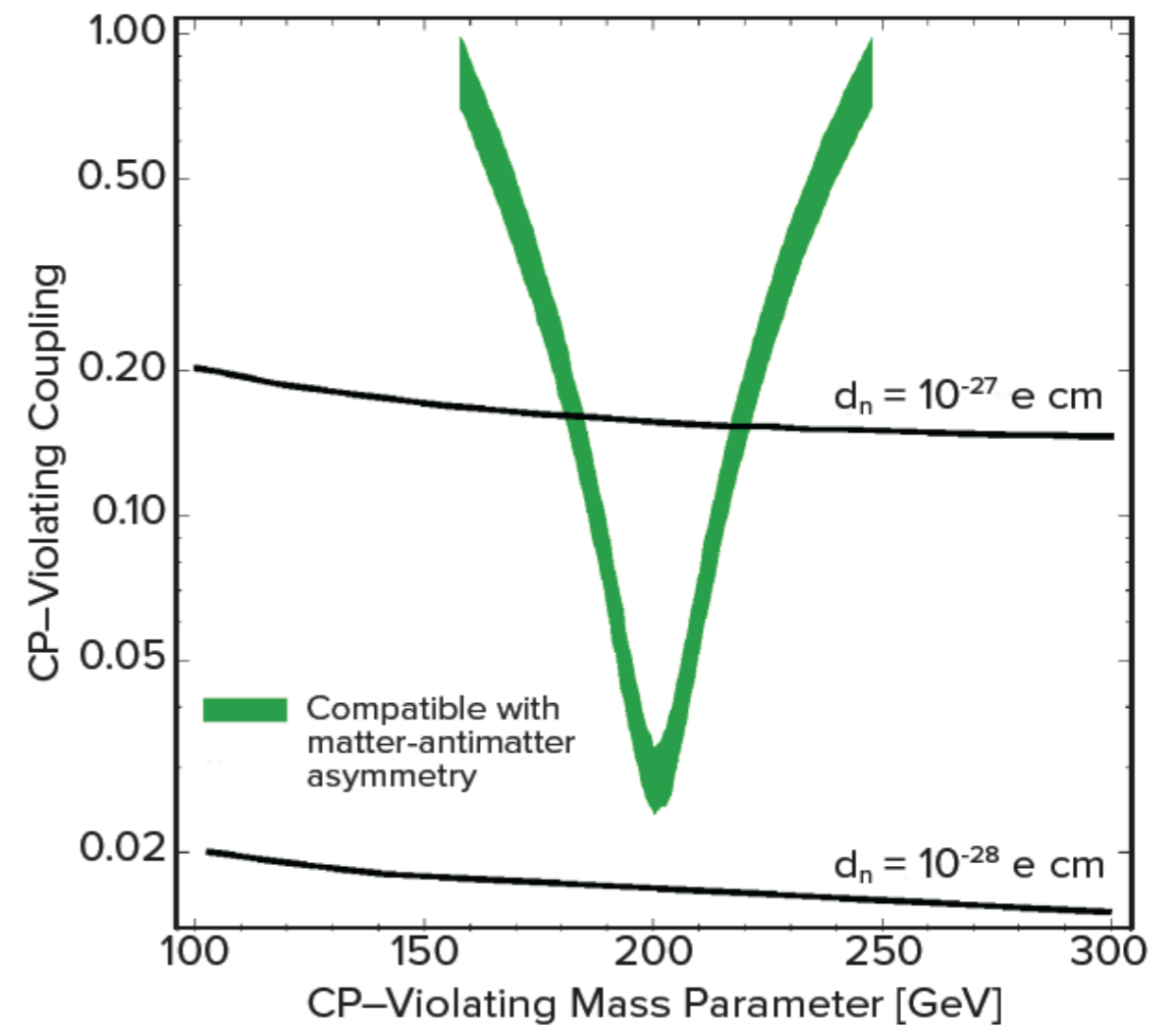
nuclear $0^+ \rightarrow 0^+$
 $V_{ud} = 0.9742 \pm 0.0002$

Neutron electric dipole moment (nEDM)

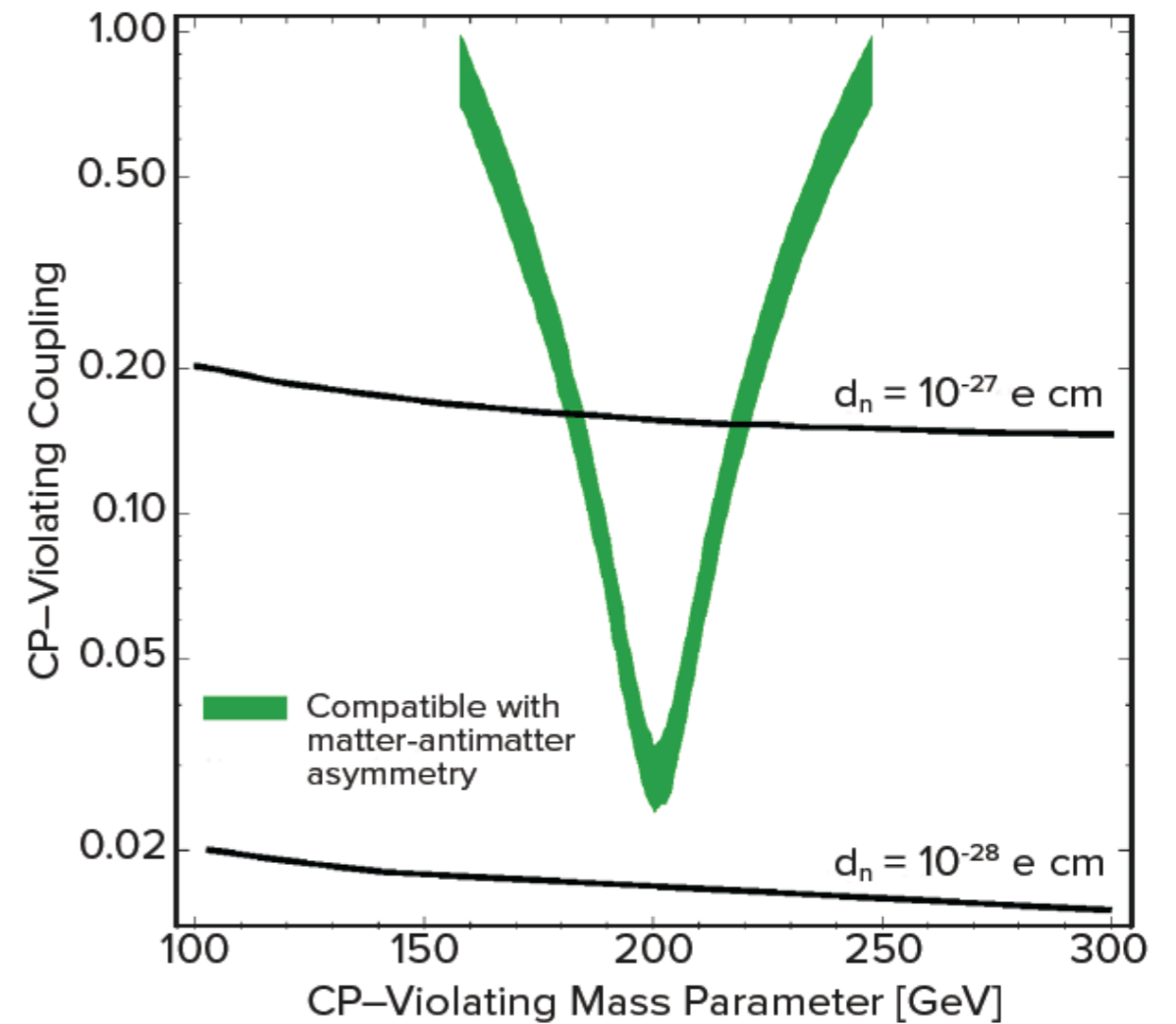
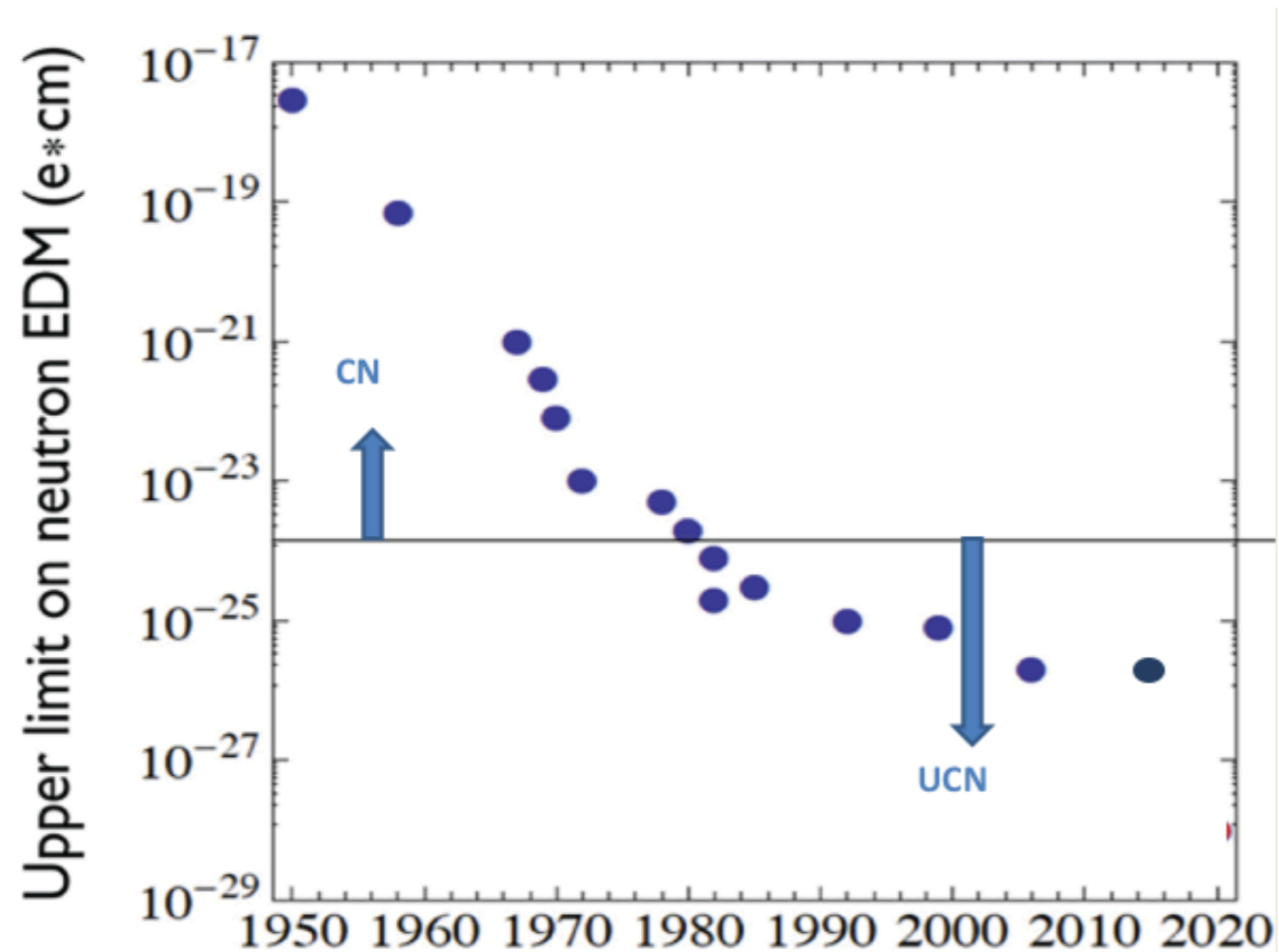
Neutron Electric Dipole Moment (nEDM)



EDM violates T → violates CP
New sources of CP → BAU



Neutron Electric Dipole Moment (nEDM)



EDM searches

Experiments are largely the same:

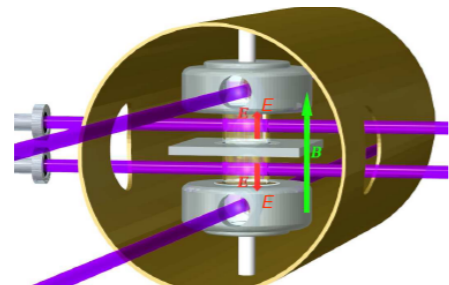
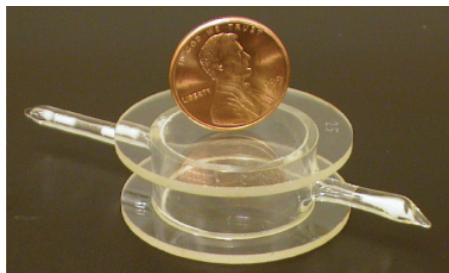
- Precess spin in **B** field with parallel and anti-parallel **E**
- Measure the frequency difference



Arthur Schawlow:

“Never measure anything but frequency”

^{199}Hg @ Seattle

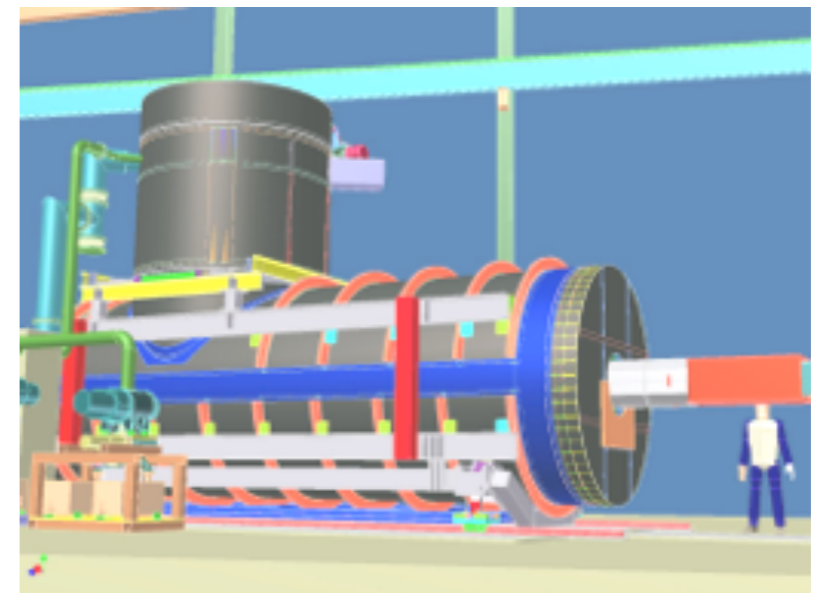


- $|d_{\text{Hg}}| < 7.4 \times 10^{-30} \text{ e cm (95\% CL)}$

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

- 2020 and beyond: $6 \times 10^{-31} \text{ e cm}$

nEDM @ SNS



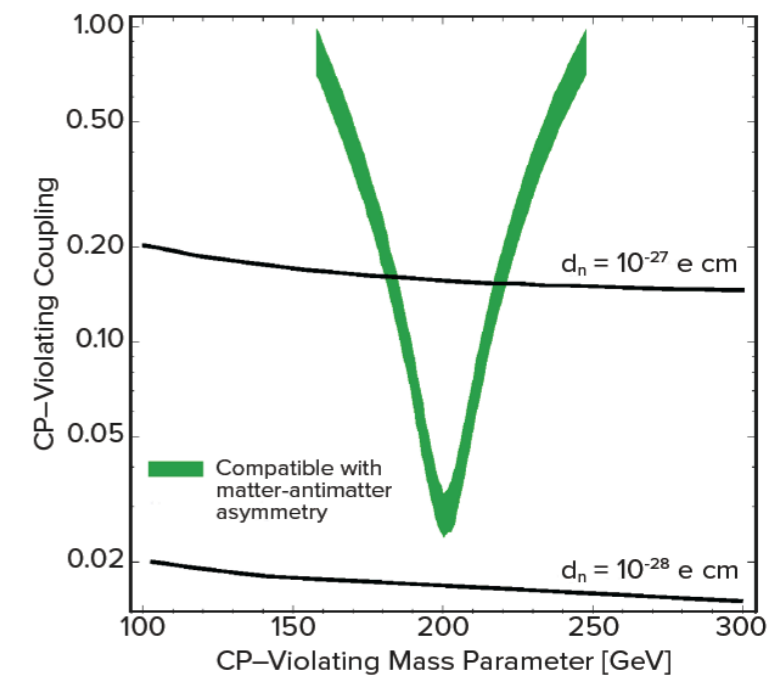
- $|d_n| \text{ (ILL)} < 3.6 \times 10^{-26} \text{ e cm (95\% CL)}$

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

- nEDM@SNS a high priority in the US; R&D in progress

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 ³ He & 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



Lepton number violation (neutrinos)

Lepton number in SM

The screenshot shows a website titled "THE PARTICLE ADVENTURE: THE FUNDAMENTALS OF MATTER AND FORCE". The left sidebar has a menu under "THE STANDARD MODEL" with "Lepton type conservation" highlighted. The main content area shows a breadcrumb trail: "The Standard Model > What is the world made of? > Lepton type conservation".

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.

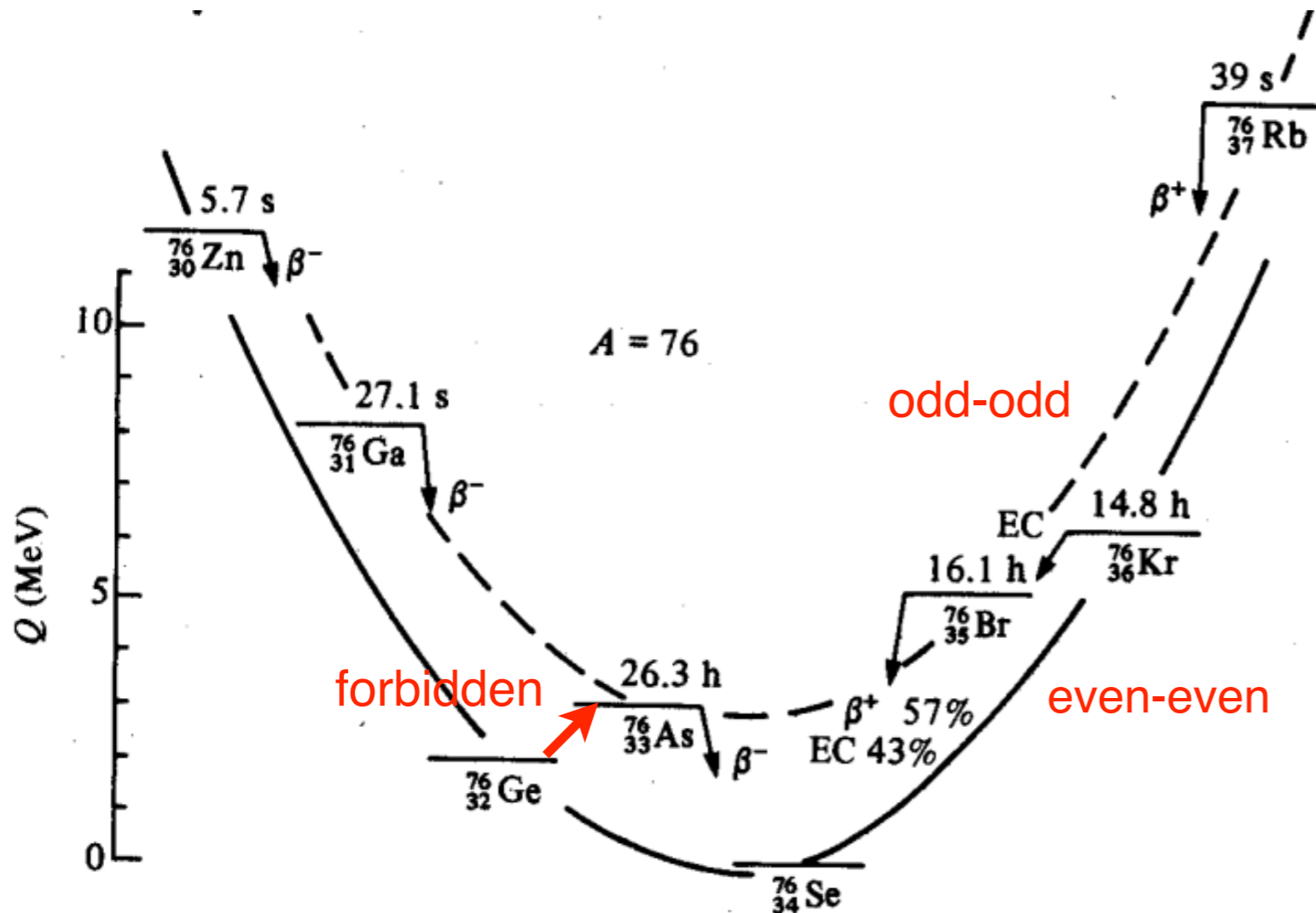
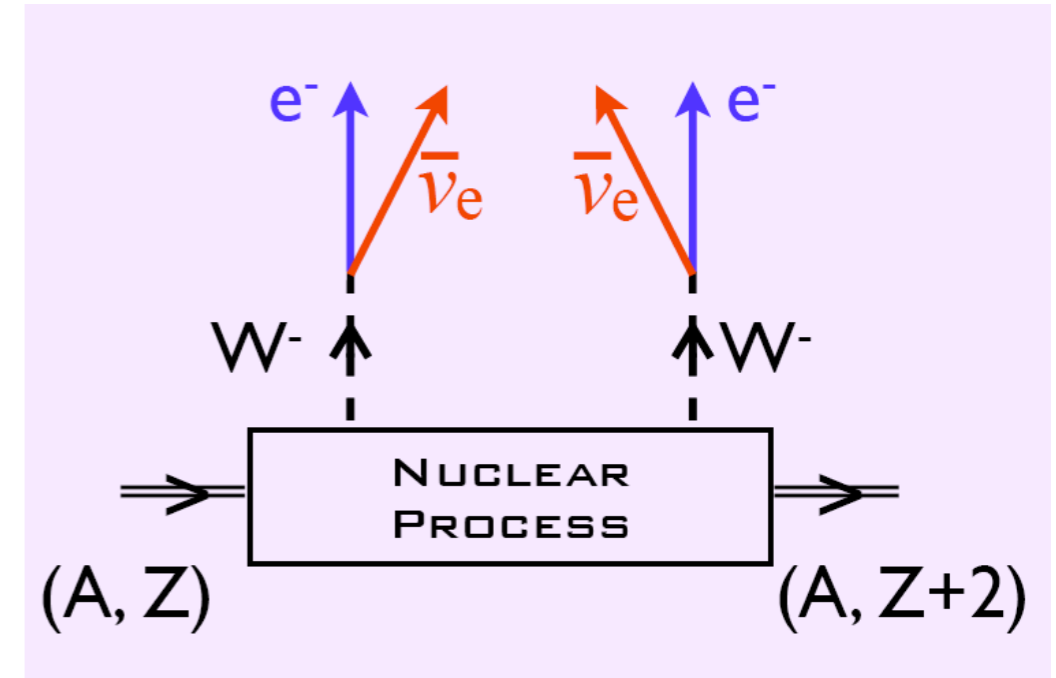
A muon decays into a muon neutrino, an electron, and an electron antineutrino:

	muon		muon neutrino		electron		electron 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.

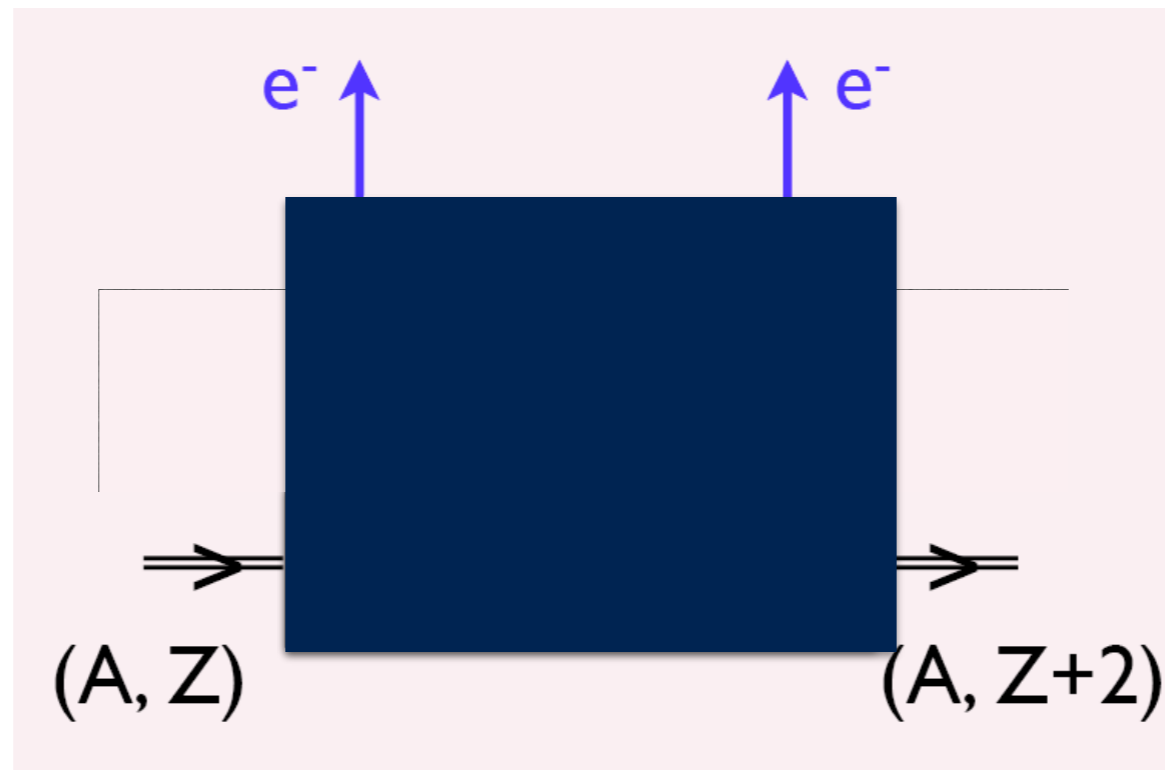
Two-neutrino double beta decay ($2\nu\beta\beta$)

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



Isotope	$T_{1/2}^{2\nu}$ (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]

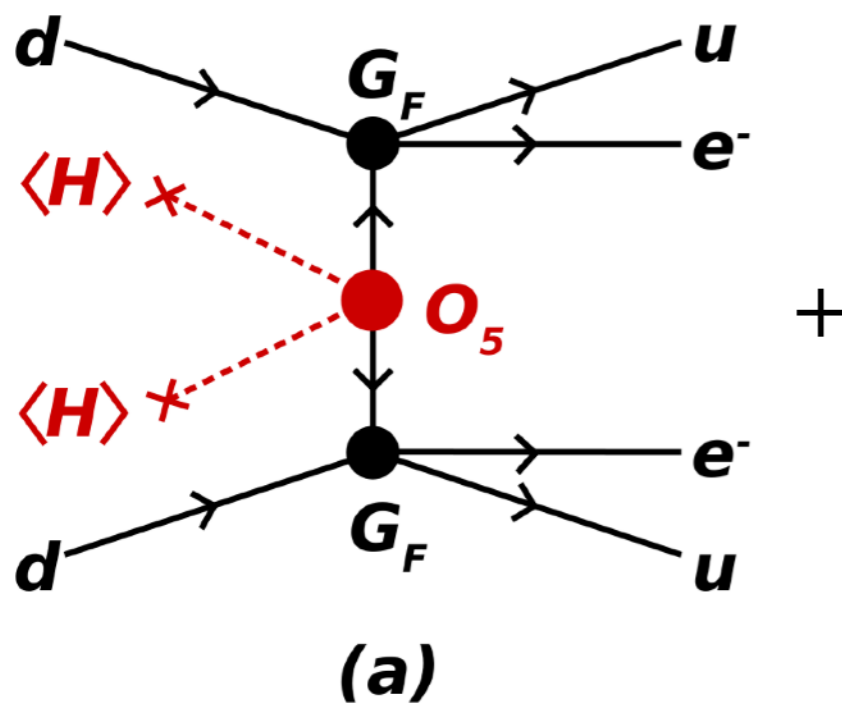
If $0\nu\beta\beta$ is seen:

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

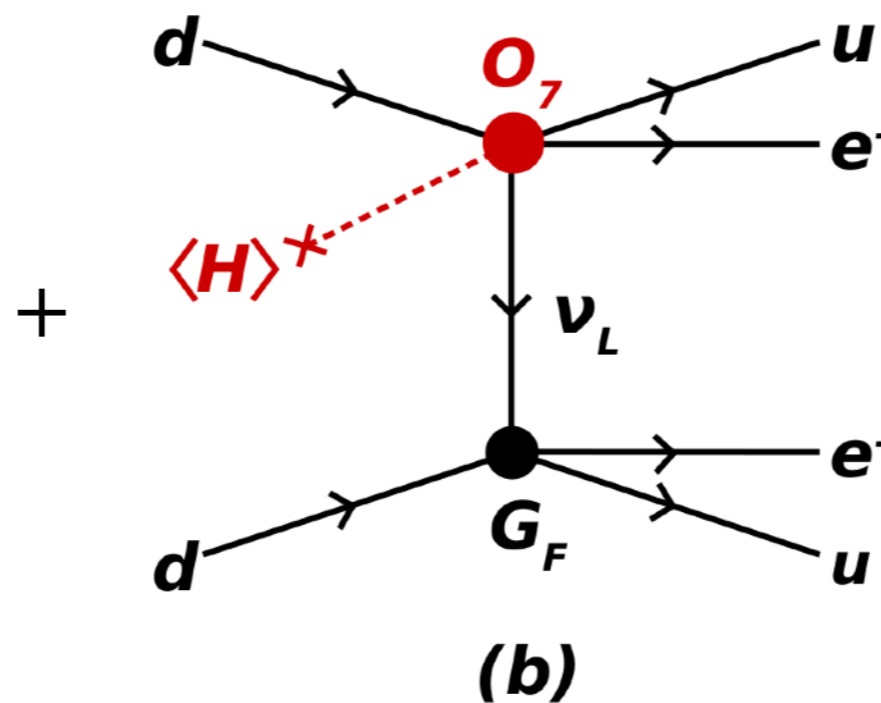
regardless of the dominant $0\nu\beta\beta$ mechanism.

What are the possibilities inside the black box?

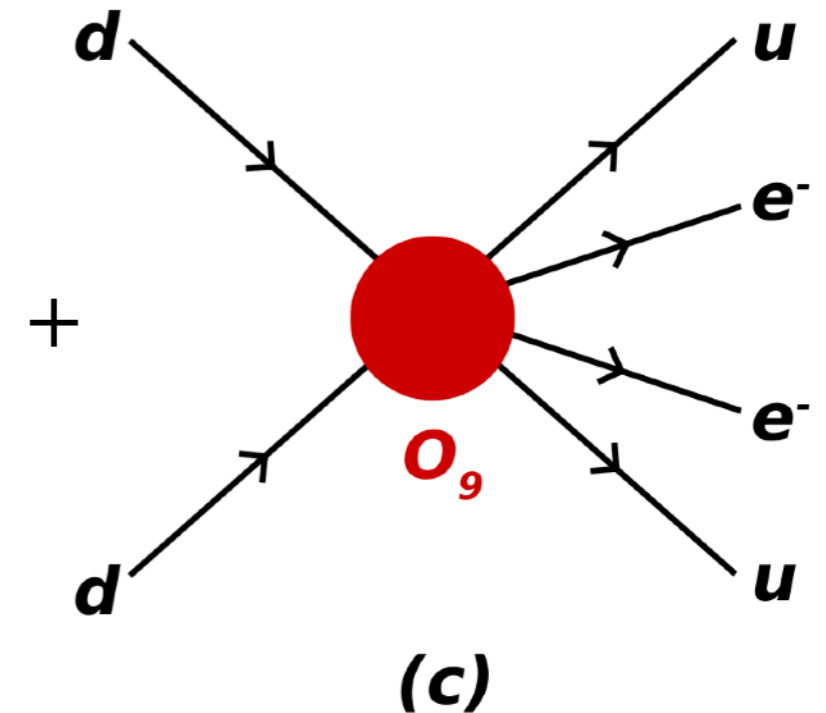
$$\Delta L = 2$$



Mass mechanism



“Long-range”



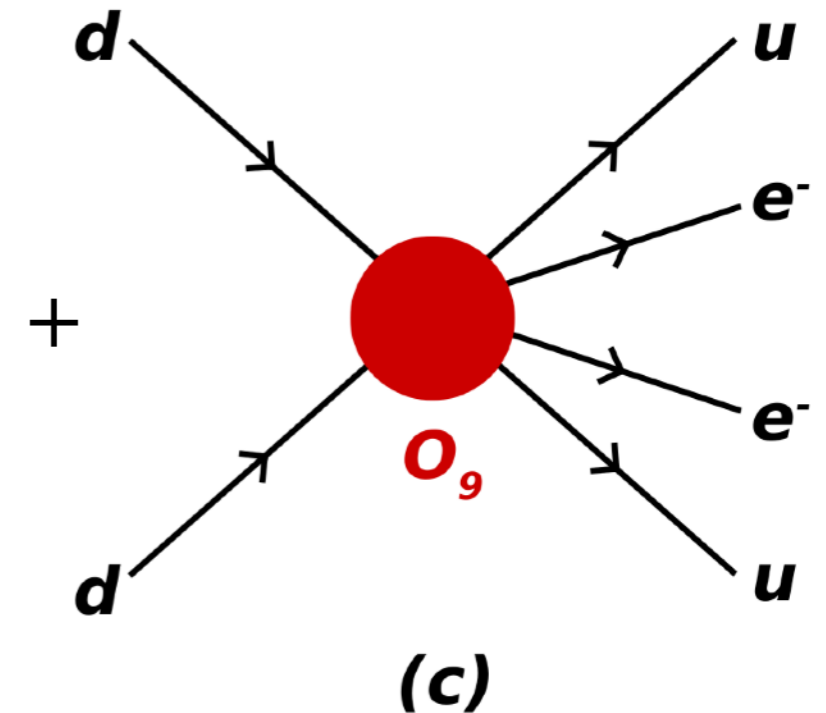
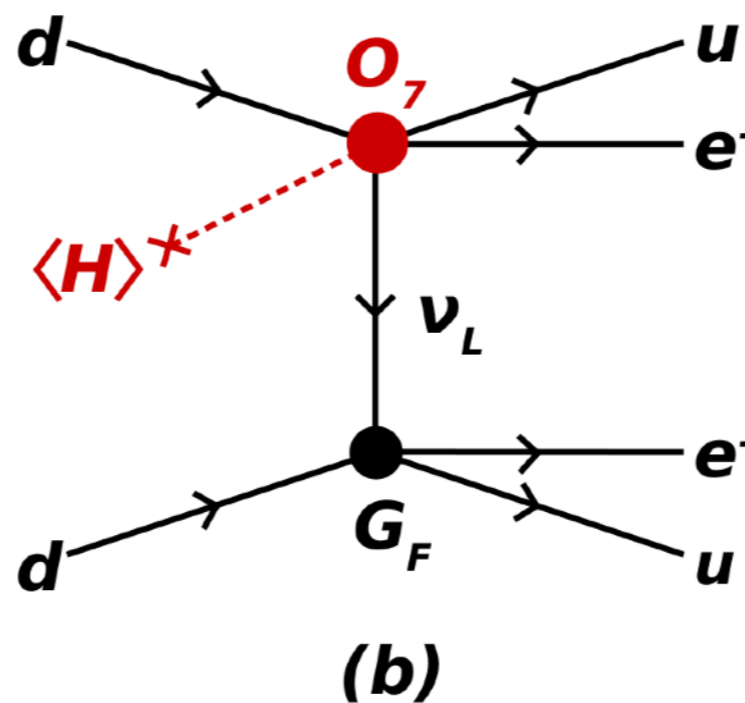
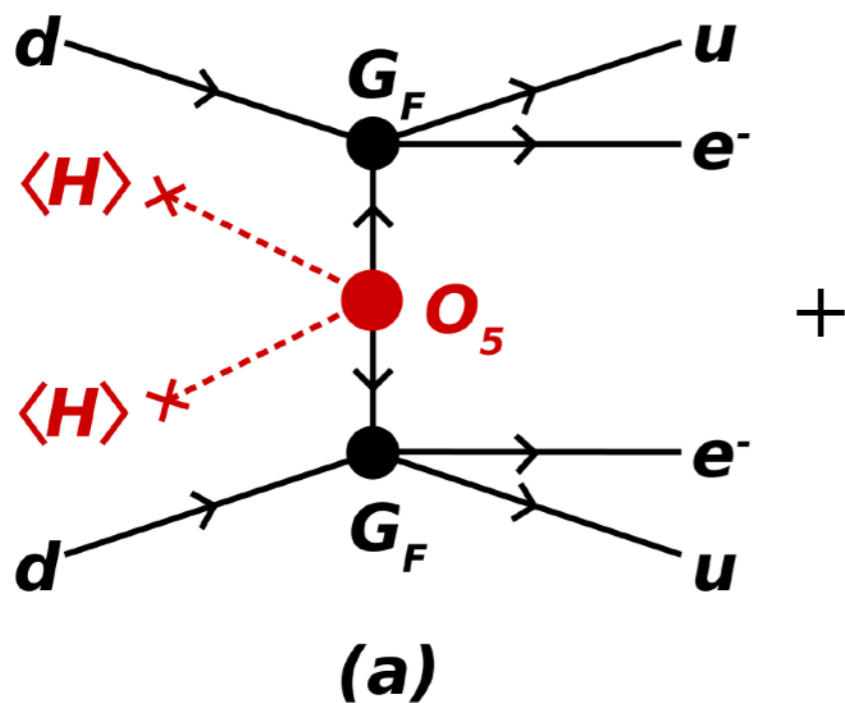
“Short-range”

What are the possibilities inside the black box?

$$\Delta L = 2$$

GUT scale / seesaw

LHC energy



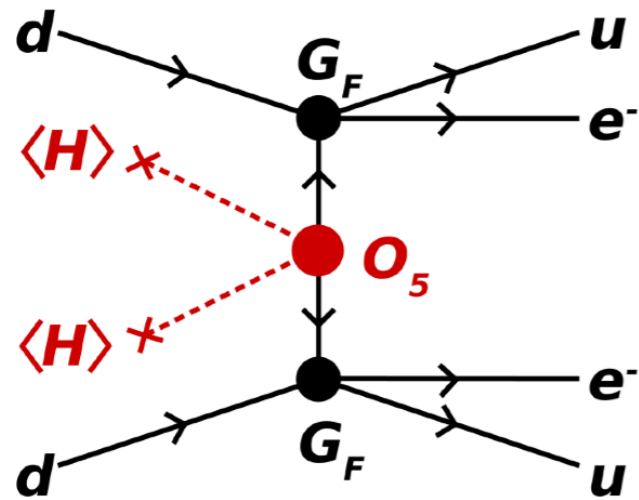
Mass mechanism

“Long-range”

“Short-range”

$0\nu\beta\beta$ allows us to probe the GUT scale

“Vanilla” mass mechanism



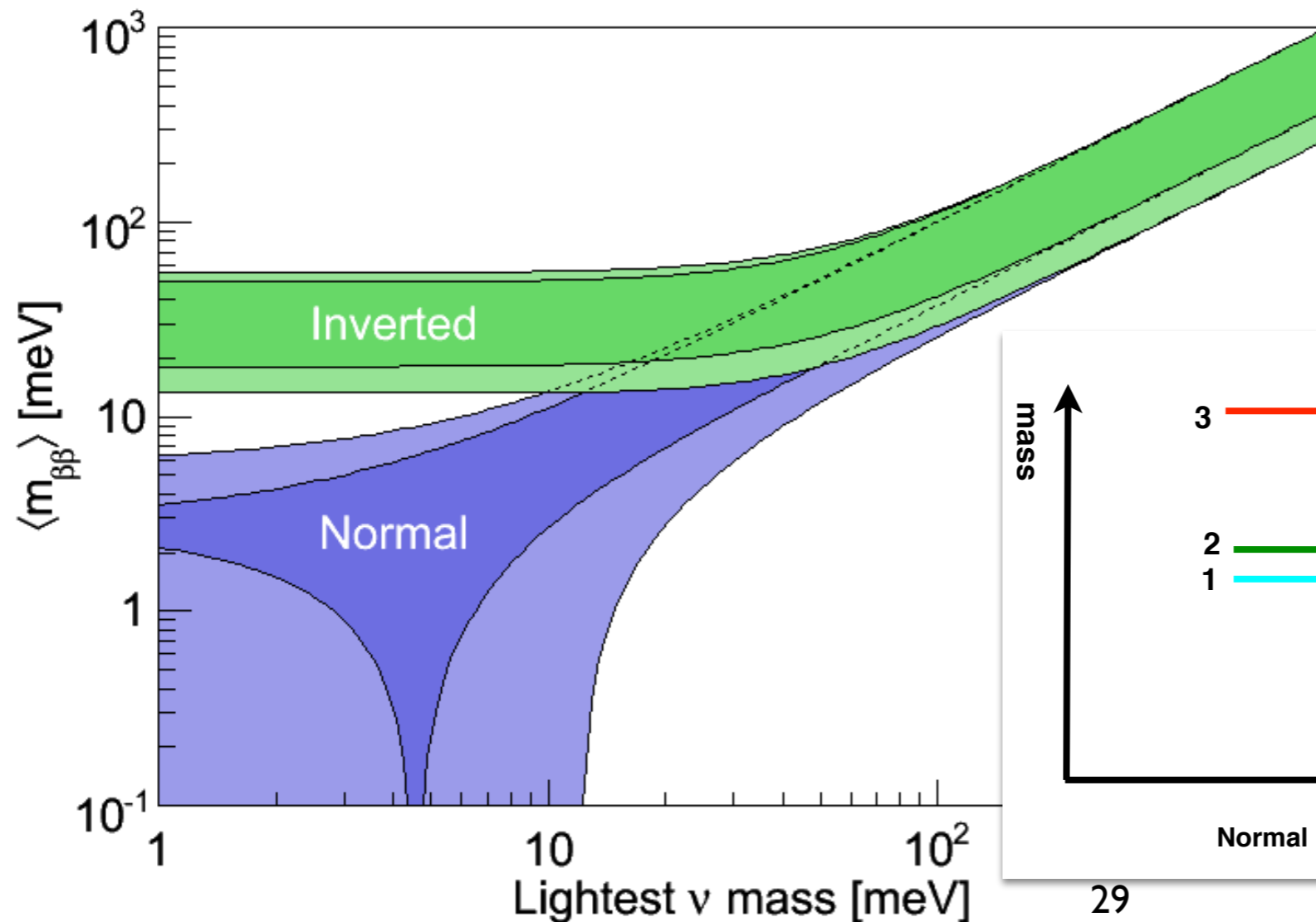
From half-life to mass scale:

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

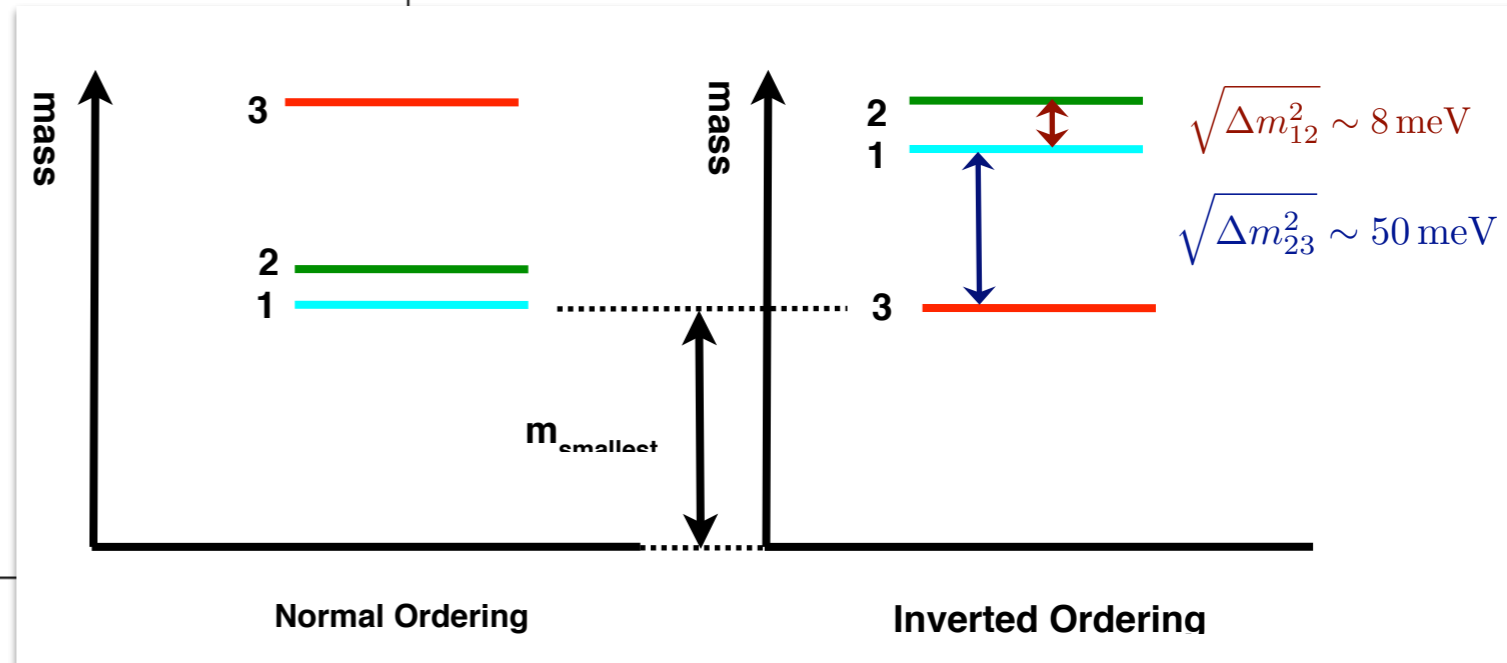
form factor

nuclear matrix element

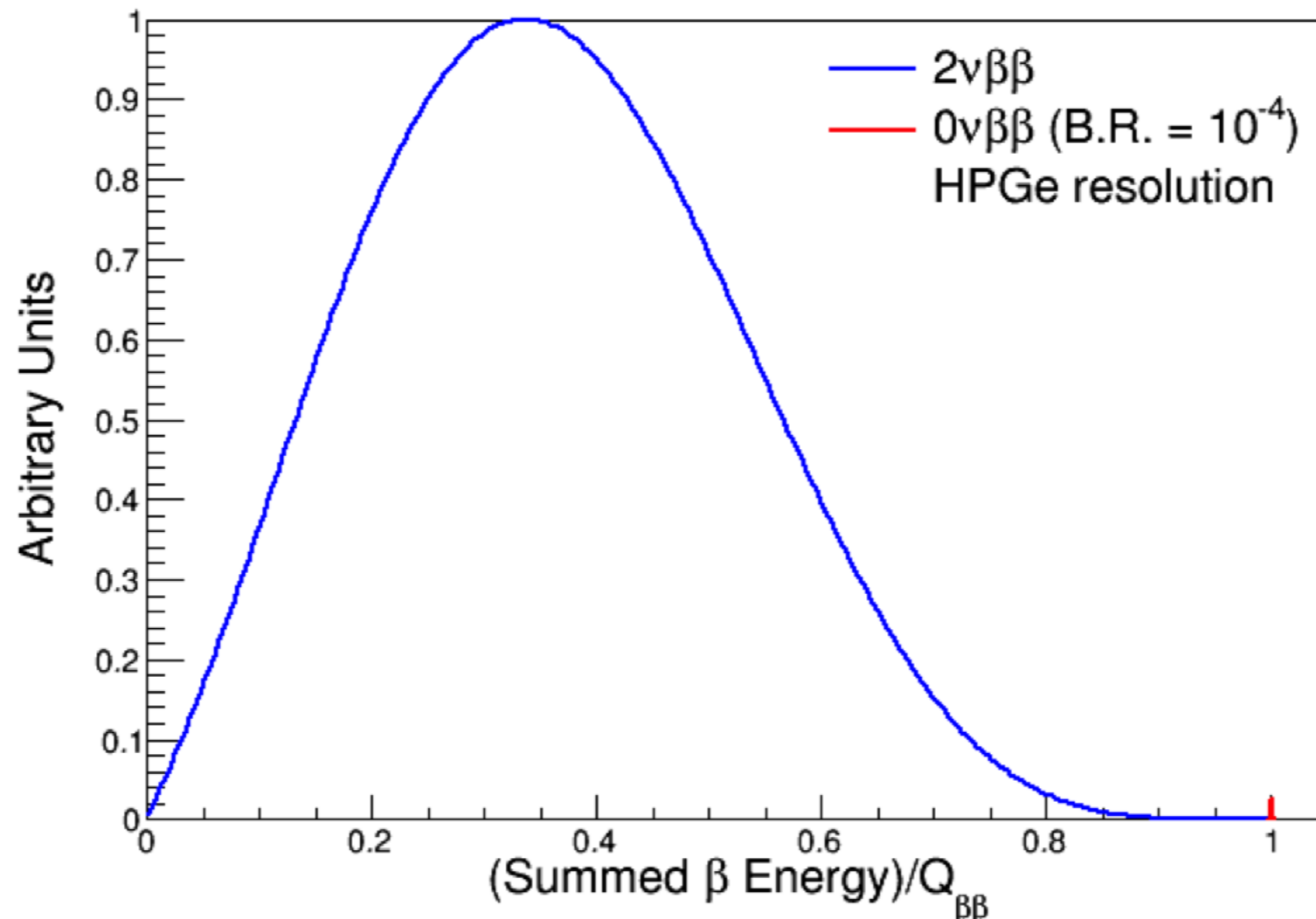
effective Majorana mass



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



Experimental signature

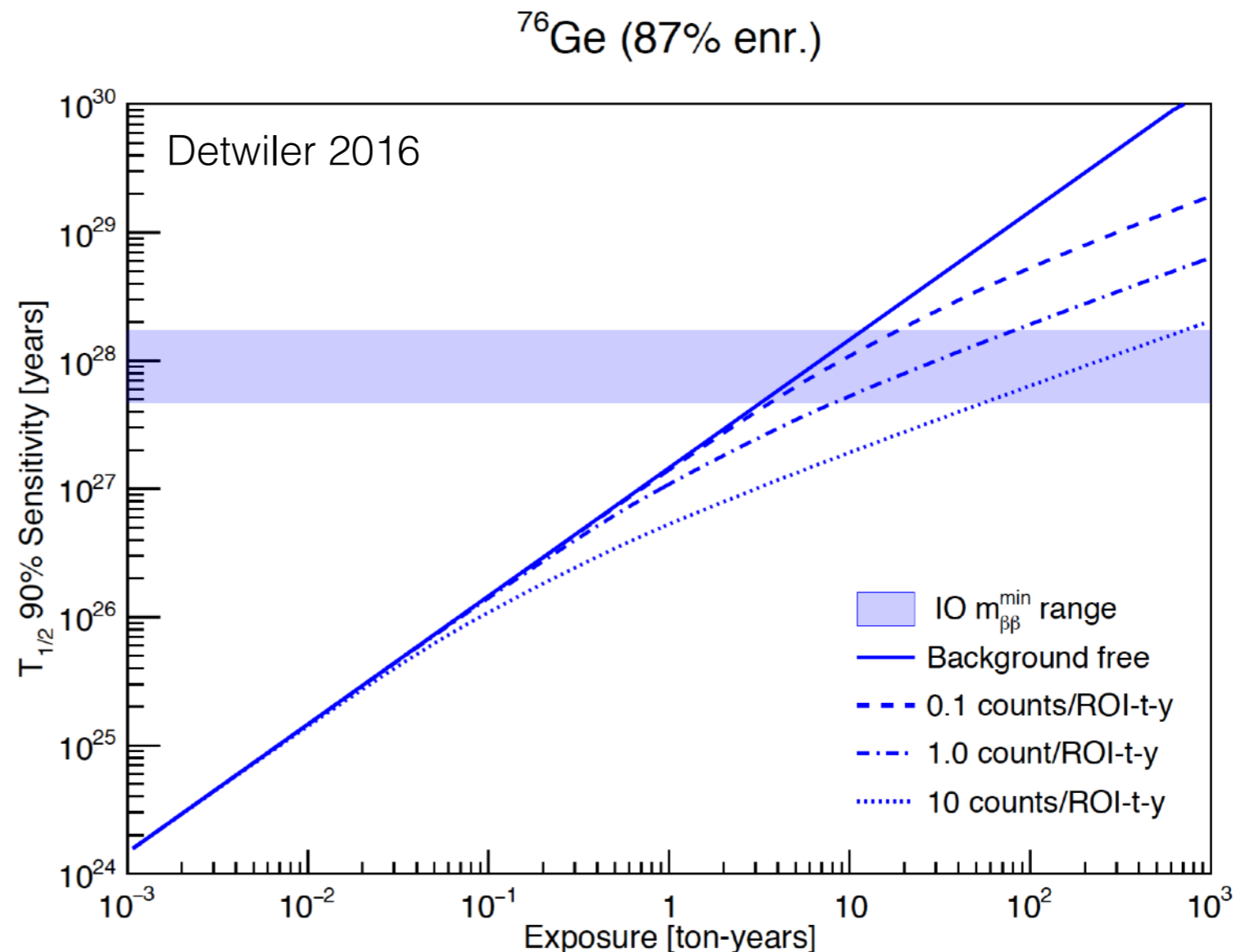


For ^{76}Ge ($Q = 2039$ keV):

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

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

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



Need a “large-scale” experiment

&

Background index $< \sim O(0.1)$ count/(ton-Ge yr) in ROI

How crazy is 0.1 count/(ton yr)?

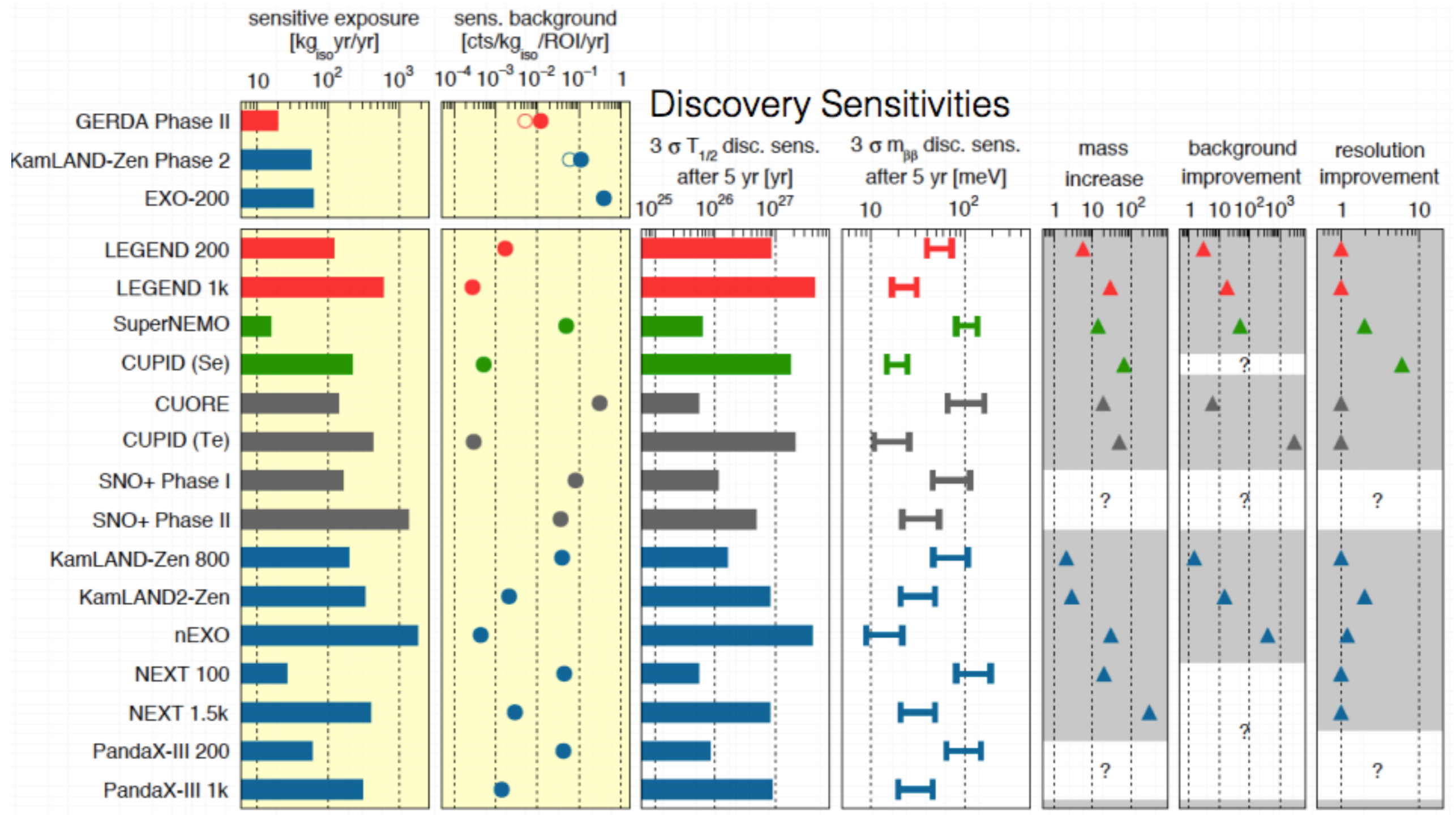
500 M Ω SMD resistor used by GERDA

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 \pm 2	1.9 \pm 0.3	0.6 \pm 0.2	10 \pm 4	46 \pm 5
0402 0.153 mm ³ /pc 0.6 mg/pc	2 \pm 1	0.7 \pm 0.1	0.2 \pm 0.1	< 2.6	32 \pm 3

Cattadori, LRT 2015

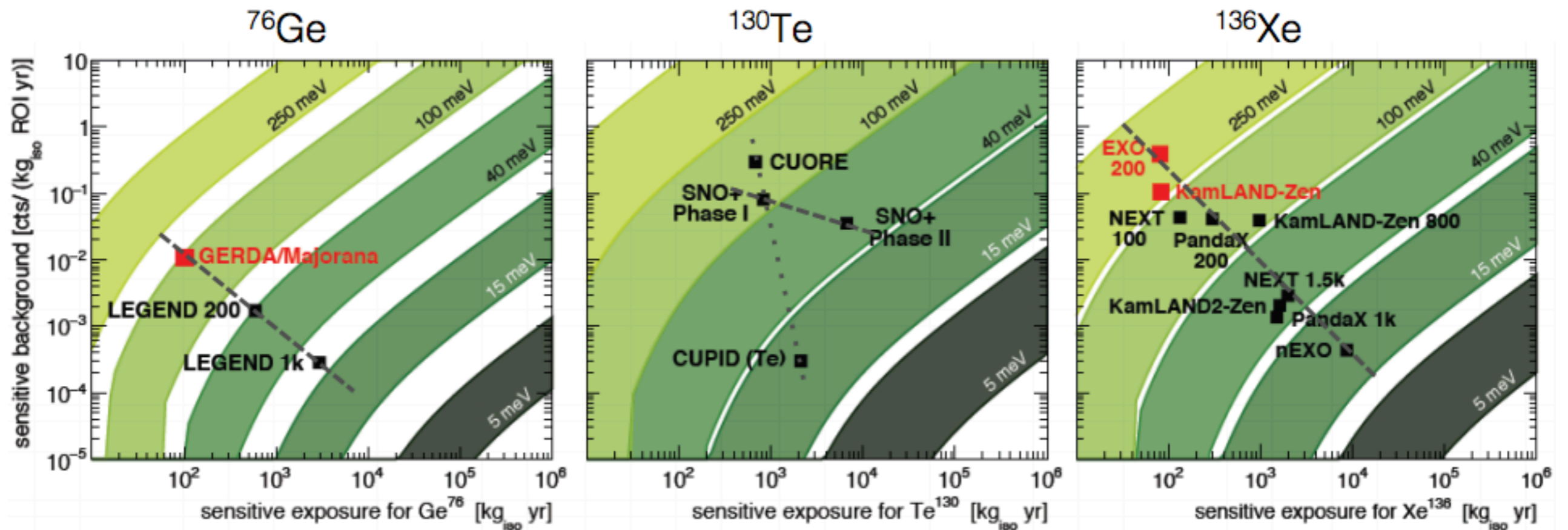
1 μ Bq \approx 0.1 / day

Comparison of $0\nu\beta\beta$ experiments



No clear winner! Experiments are complementary to each other.

Discovery potential (“vanilla”)



LEGEND

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

Mission: The collaboration aims to develop a phased, ^{76}Ge -based double-beta decay experimental program with discovery potential at a **half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.**

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

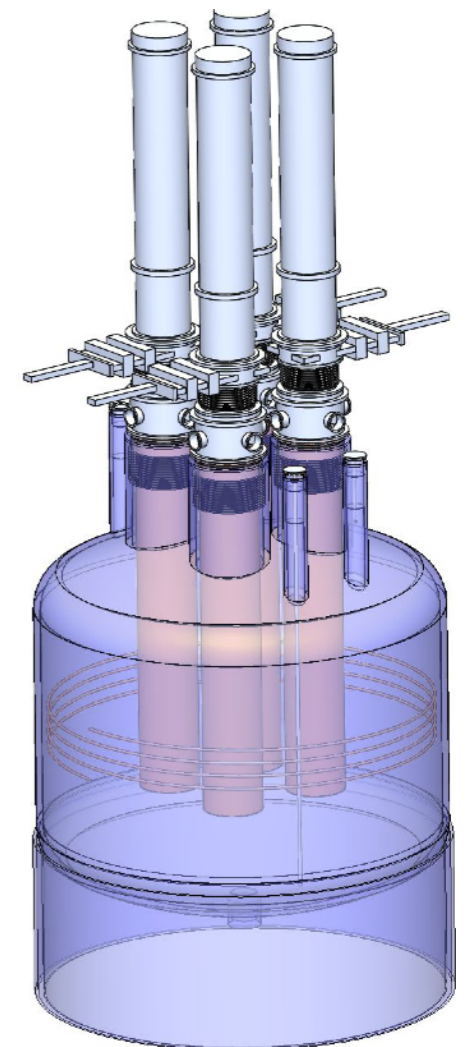
First phase:

- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BI goal (x5 lower) 0.6 c / (FWHM t y)
- start by 2021



Subsequent stages:

- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BI goal (x30 lower) 0.1 c / (FWHM t y)
- 2-3 kg per detector
- Location: TBD. Required depth under investigation



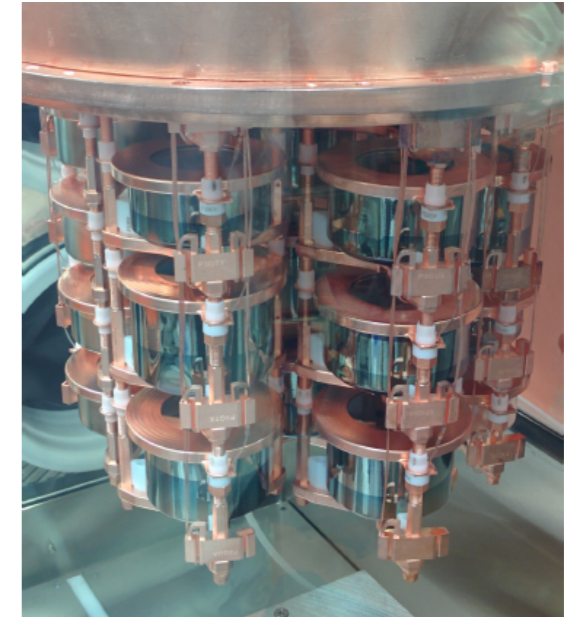
LEGEND - Best of both worlds

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

MAJORANA

- Radiopurity of nearby parts (front-end electronics, cables, Cu mounts, etc.)
- Low noise electronics
- Low energy threshold (cosmogenic and low-E background)

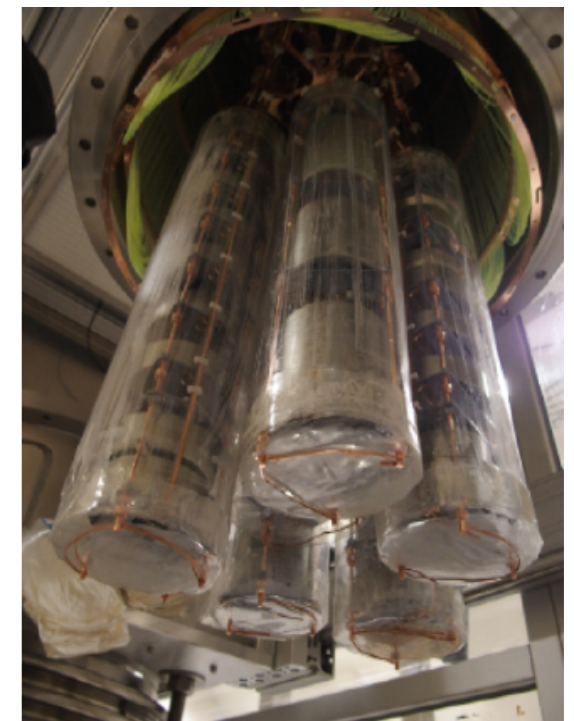


GERDA

- LAr active veto
- Low-A shield, no Pb

Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors



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.

<p><i>EDM searches:</i></p> <p><i>BSM CPV, Origin of Matter</i></p>	<p><i>$0\nu\beta\beta$ decay searches:</i></p> <p><i>Nature of neutrino, Lepton number violation, Origin of Matter</i></p>
<p><i>Charged leptons:</i></p> <p><i>SM Precision Tests, BSM “diagnostic” probes</i></p>	<p><i>Other studies:</i></p> <p><i>Weak decays, m_ν, “dark photons”, non-Newtonian gravity, theory...</i></p>

- 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.

Backup

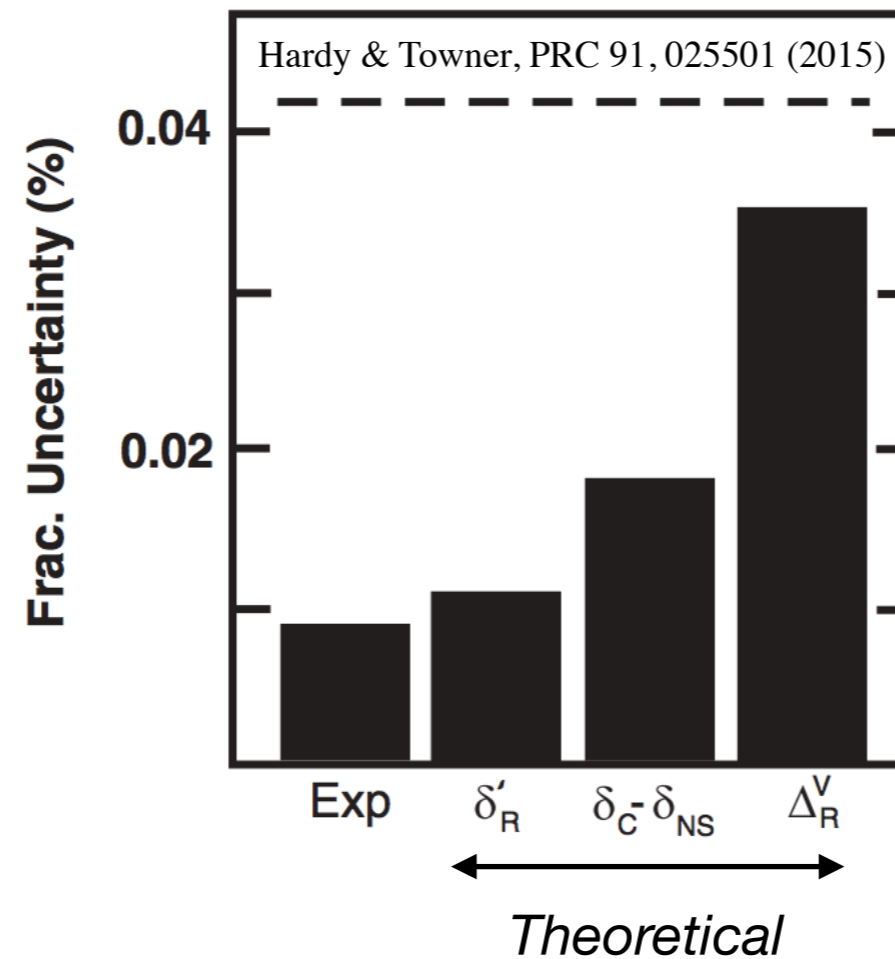
β decays

Transition	L	ΔI	$\Delta \pi$
Fermi	0	0	0
Gamow–Teller	0	0, 1	0
first-forbidden (parity change)	1	0, 1, 2	1
second-forbidden (no parity change)	2	2, 3	0
third-forbidden (parity change)	3	3, 4	1
fourth-forbidden (no parity change)	4	4, 5	0

from Wikipedia

Neutron β Decay - V_{ud}

$$V_{ud}^2 = \frac{K}{G_F^2 (1 + \delta_R)(1 + \Delta_R^V)(1 + 3\lambda^2) f \tau_n}$$



LEGEND: 3σ discovery

