Neutrons and Fundamental Symmetries Experimental I: Neutron Beta-decays

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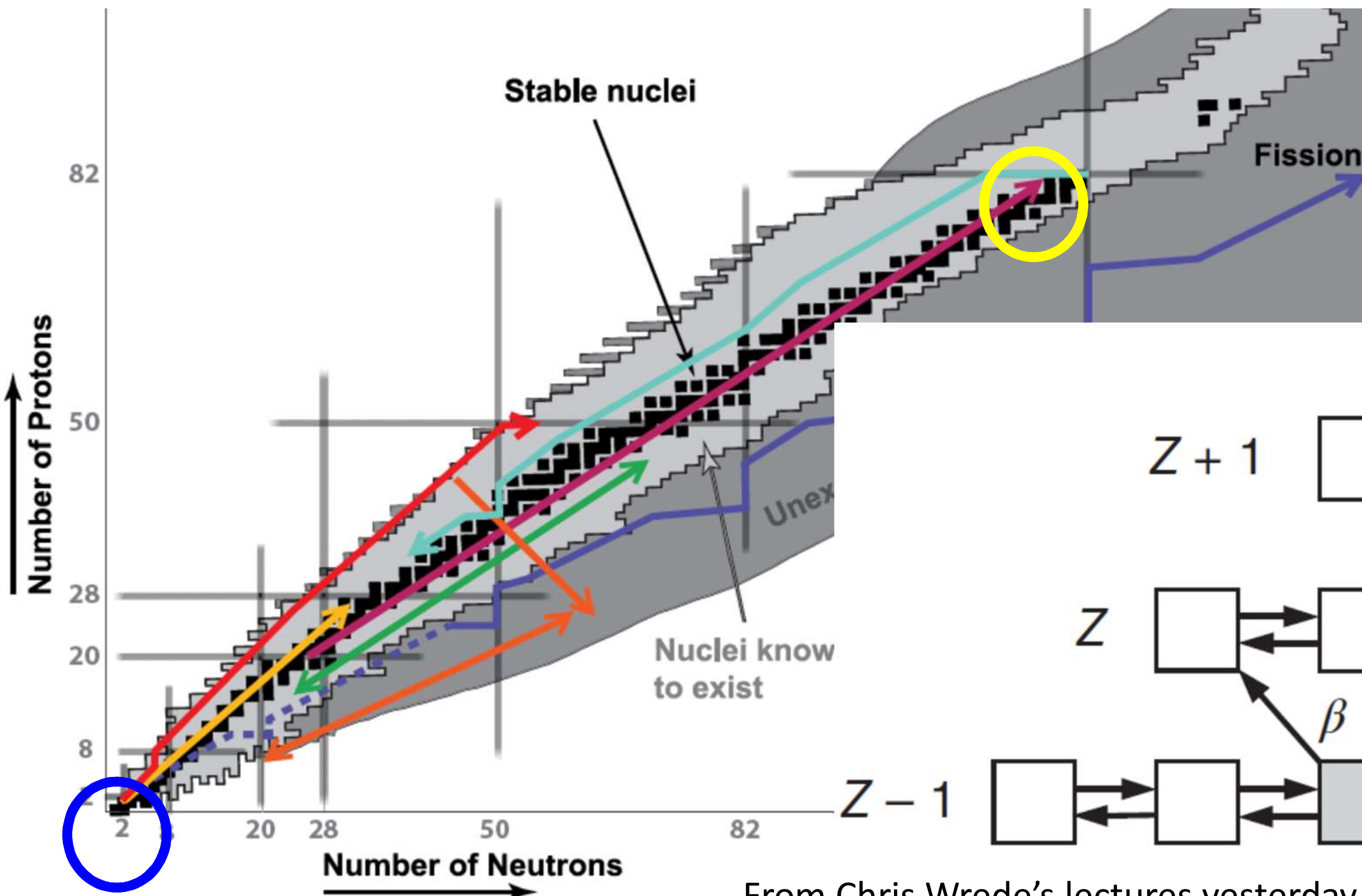
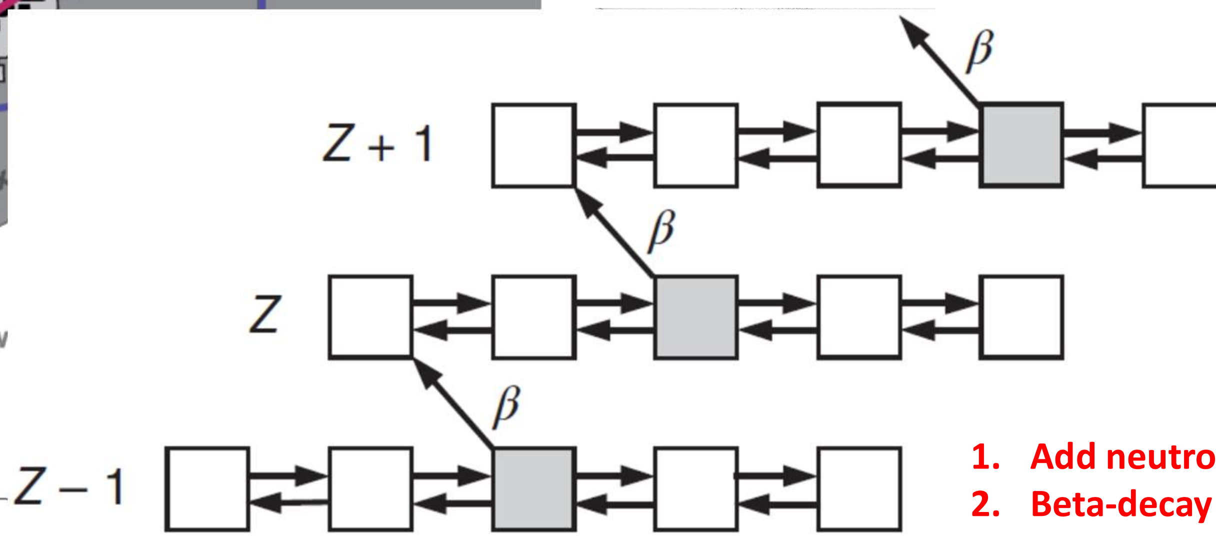
How to turn things into Gold?

$^{197}Au_{79}$:79 protons; 118 neutrons



King Midas & the Golden Touch



1. **Add neutrons**
2. **Beta-decay**

From Chris Wrede's lectures yesterday

Topics I will cover:

Q: Why is beta-decay much slower than other nuclear processes?

Lecture 1: beta-decay

- A brief history of the electroweak theory---the precursor to the Standard Model.
- Neutron decay to test the V-A theory & beyond the SM interactions
- Current status with neutron experiments on gA & lifetime
- Physics is Symmetries

Lecture 2: EDM

- CP violation
- Electric Dipole Moments: Highly sensitive low-energy probes of new Physics
- muon- g-2

Lecture 3: other symmetry violation measurements/tests

- Baryogenesis & symmetry violations
- Nnbar oscillation: B violation
- Hadronic weak interactions: P violation
- NOPTREX: T violation
- Neutron interferometry: Lorentz symmetry violation

Emil Konopinski
(1911 - 1990)
IU: 1938-1990

Larry Langer
(1914--2000)
IU: 1938-1979
Department chair: ‘65-’73

Continuous* Beta spectrum

***Crisis in the 1930s**: Energy in beta-decays is not conserved! Pauli proposed the (non-detectable) neutrino, which carries away the missing energy.

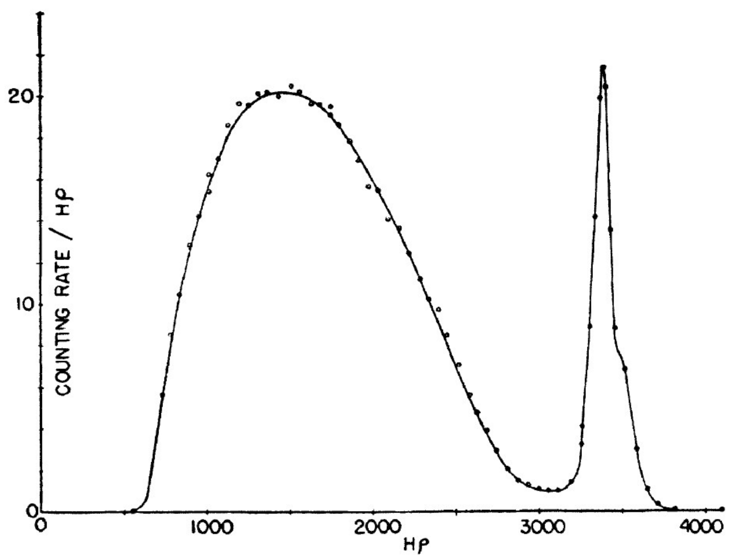


FIG. 1. Cs^{137} β-ray spectrum.

Fermi (1934)

$$P(W)\,dW = G^2\,|M|^2\,f(Z,W)\,(W_o - W)^2\,(W^2 - 1)^{1/2}\,W\,dW,$$

Konopinski & Ulenbeck (1935)

$$P(W)dW = G^2|M|^2\,f(Z,W)\,(W_o - W)^4(W^2 - 1)^{1/2}\,WdW$$

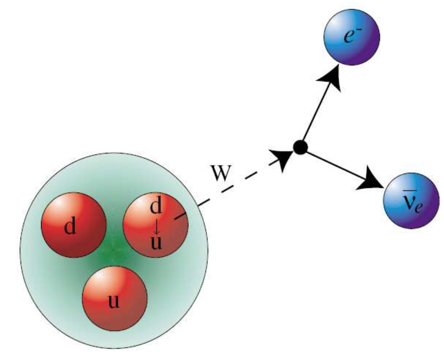
J. Townsend, et al., PRB 79, 99 (1948)

"The Beta-Spectrum of Tritium and the Mass of the Neutrino," L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952)

Theory of Nuclear Beta-decay

- Pauli showed 5 possible forms of Lorentz-invariant couplings:

$$(\bar{\phi}_p \hat{O}_i \phi_n)(\bar{\phi}_e \hat{O}_i \phi_\nu)$$



$$n \rightarrow p^+ + e^- + \overline{\nu}_e + 782 \text{ keV}$$

Table 1.2. Elementary fermion transition operators

$\hat{O}_i$	Transformation property of $\overline{\Psi}\hat{O}_i\Psi$	Number of matrices
1	Scalar (S)	1
γ^μ	Vector (V)	4
$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$	Tensor (T)	6
$\gamma^\mu\gamma_5$	Axial vector (A)	4
$\gamma_5 = -i\gamma_0\gamma_1\gamma_2\gamma_3 = i\gamma^0\gamma^1\gamma^2\gamma^3$	Pseudoscalar (P)	1

For non-relativistic fermions in nuclear beta decay

$\phi_p^\dagger \phi_n$ Fermi (spin-preserving)

$\phi_p^\dagger \sigma \phi_n$ Gamow-Teller (spin-changing, ΔI = ±1,0)

0

Spectral measurements (pre-1950)

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

5x2x2 = 20 coupling constants

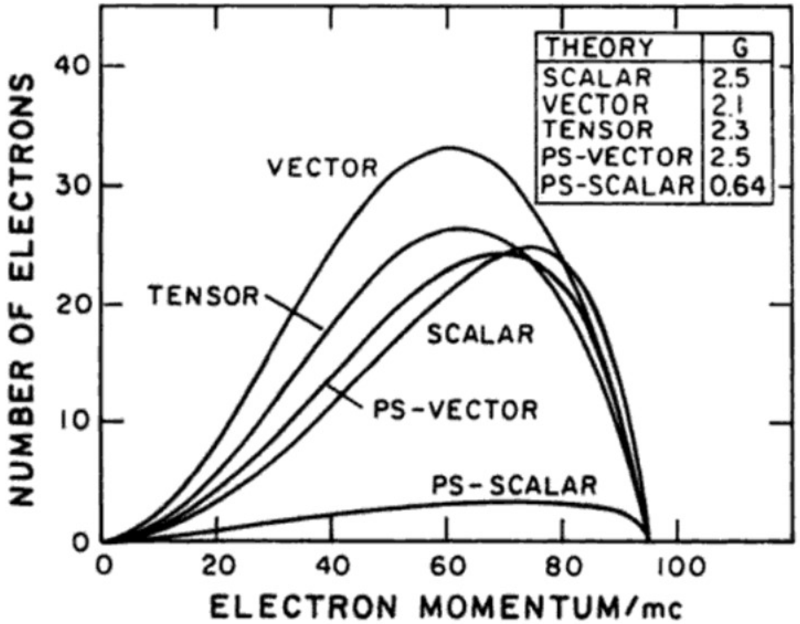


Figure 2.4. "Influence of form of coupling on shape of spectrum for fixed values of the mass of the μ-and μ_0 meson. Contrast this result with the case of ordinary beta-decay, where the atomic nucleus has negligible velocity and the decay curves have the same shape in all five cases" (Tiomno and Wheeler 1949a, p. 148).

"Experiment, Right or Wrong" by Allen Franklin (Cambridge University Press, 1990)

THE EXPERIMENTAL CLARIFICATION OF THE THEORY OF β-DECAY[1]

1953

By E. J. Konopinski and L. M. Langer
Physics Department, Indiana University, Bloomington, Indiana

INTRODUCTION

Fermi advanced his successful theory of β-decay in 1934. It has since then undergone development in which two general directions may be discerned. One has been a broadening of the scope of the theory, the other a narrowing of its initial ambiguities.

The Fermi type of interaction was invented expressly for nucleonic β-processes but now promises to apply to all known processes involving the direct interaction of four fermions (spin 1/2 particles). The known fermions are: the electron ($e^{\pm}$), the neutrino (ν), and antineutrino ($\bar{\nu}$), the nucleon (N or P) and the μ-meson or muon ($\mu^{\pm}$). The direct interactions among these for which evidence exists are listed in Table I. This review is primarily concerned with the β-processes only. The relation of the others to β-decay is briefly summarized in the section on the *Universal Fermi interaction*.

"Their 1953 Annual Review article on what was then known about beta decay was a world standard."

--- Andrew Bacher, Robert Bent, Timothy Londergan, and Dan Miller (memorial resolution to the Bloomington Faculty Council)

The other direction of development has been toward a progressive experimental clarification. Fermi provided criteria for a β-coupling which are not quite sufficient to give it a unique form. An arbitrary linear combination of five interaction forms (symbolized by S, V, T, A, and P) is consistent with the a priori provisions of the Fermi theory. The experimental effort has been to reduce this arbitrariness. As we shall interpret the evidence here, the correct law must be what is known as an STP combination. This remains for the present a phenomenological result. No principle has been suggested so far (cf. THE A PRIORI THEORETICAL BASIS) which escapes contradiction by the experiments as interpreted here.

TABLE II*

SELECTION RULES

Order	Nuclear Matrix Element $\int\Omega$	Occurring for Interaction Type	Selection Rules on Nuclear Spin, I
Allowed (no parity change)	$\int 1$ (or $\int\beta$)	S, V	$\Delta I=0$
	$\int\boldsymbol{\sigma}$ (or $\int\beta\boldsymbol{\sigma}$)	T, A	$\Delta I=0, \pm 1$ (not $0\to 0$)
Once Forbidden (parity change)	$\int\gamma_5$ (or $\int\beta\gamma_5$)	P, A	$\Delta I=0$
	$\int\boldsymbol{r}$	S, V	$\Delta I=0, \pm 1$ (not $0\to 0$)
	$\int\boldsymbol{\alpha}$	V, T	
	$\int\boldsymbol{\sigma}\times\boldsymbol{r}$	T, A	
	$\int\boldsymbol{\sigma}\cdot\boldsymbol{r}$	T, A	$\Delta I=0$
	$S_{ij}=\int\sigma_i x_j+\sigma_j x_i-\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{r}\delta_{ij}$	T, A	$\Delta I=0, \pm 1, \pm 2$ (not $0\to 0$, $\frac{1}{2}\to\frac{1}{2}$, $0\leftrightarrow 1$)
Twice Forbidden (no parity change)	$\int\gamma_5\boldsymbol{r}$	P, A	$\Delta I=0, \pm 1$ (not $0\to 0$)
	$R_{ij}=\int x_i x_j-\frac{1}{3}r^2\delta_{ij}$	S, V	$\Delta I=0, \pm 1, \pm 2$ (not $0\to 0$, $\frac{1}{2}\to\frac{1}{2}$, $0\leftrightarrow 1$)
	$A_{ij}=\int\alpha_i x_j+\alpha_j x_i-\frac{2}{3}\boldsymbol{\alpha}\cdot\boldsymbol{r}\delta_{ij}$	V, T	
	$T_{ij}=\int[\boldsymbol{\sigma}\times\boldsymbol{r}]_i x_j+[\boldsymbol{\sigma}\times\boldsymbol{r}]_j x_i$	T, A	
	$\int\boldsymbol{\alpha}\cdot\boldsymbol{r}$	V, T	$\Delta I=0$
	$\int\boldsymbol{\alpha}\times\boldsymbol{r}$	V, T	$\Delta I=0, \pm 1$ (not $0\to 0$)
	$S_{ijk}=\int\sigma_i x_j x_k-\cdots$	T, A	$\Delta I=0, \pm 1, \pm 2, \pm 3$ (not $0\to 0$, $\frac{1}{2}\to\frac{1}{2}$, $\frac{1}{2}\leftrightarrow\frac{3}{2}$, $1\to 1$, $0\leftrightarrow 1$, $0\leftrightarrow 2$)

* Actually, the operator enters all the matrix elements arising from the S, T, and P interactions. It is ignored to permit contraction of the Table. It has no effect on selection rules, but may affect sizes which are treated as unknown here anyway.

^{210}Bi

The chief information gained from spectra other than RaE and the "unique" spectra, is that the Fierz-type of interference is absent. Its absence in allowed spectra forbids combining S and V or T and A. That, alone, narrows the alternatives to STP, SAP, VTP, and VAP. Next, the like absence of Fierz-type interference in once- and twice-forbidden spectra eliminates SA, AP, and VT combinations. Hence, from such arguments alone, one is left with only STP, or VP, or VA. Then VP must be discarded because it does not yield Gamow-Teller selection rules. However, STP is favored over VA only by the evidence of RaE.

Questions of Parity Conservation* in Weak Interactions
(T.D. Lee & C.N. Yang 1956)

*Crisis in the 1950s: Parity is not conserved (the θ-τ puzzle)!

Proposed to measure P-violating observables, such as

$$p1 \cdot (p2 \times p3), \text{or}$$
$$\sigma \cdot p$$

(1) Beta asymmetry in oriented nucleus (Wu 1957)
(2) Circular polarization of gamma (Goldhaber 1958)
(3) Hyperon decays to form $p1 \cdot (p2 \times p3)$

Energy and angle distribution of the electron in an allowed transition:

$$N(W,\theta)dW\,\sin\theta d\theta = \frac{\xi}{4\pi^3}F(Z,W)pW(W_0-W)^2 \times\left(1+\frac{ap}{W}\cos\theta+\frac{b}{W}\right)dW\,\sin\theta d\theta, \quad \text{(A.2)}$$

where

Total decay rate

$$\xi = (|C_S|^2+|C_V|^2+|C_S'|^2+|C_V'|^2)|M_{\text{F.}}|^2 + (|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2)|M_{\text{G.T.}}|^2, \quad \text{(A.3)}$$

Electron-neutrino correlation

$$a\xi = \tfrac{1}{3}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2)|M_{\text{G.T.}}|^2 - (|C_S|^2-|C_V|^2+|C_S'|^2-|C_V'|^2)|M_{\text{F.}}|^2, \quad \text{(A.4)}$$

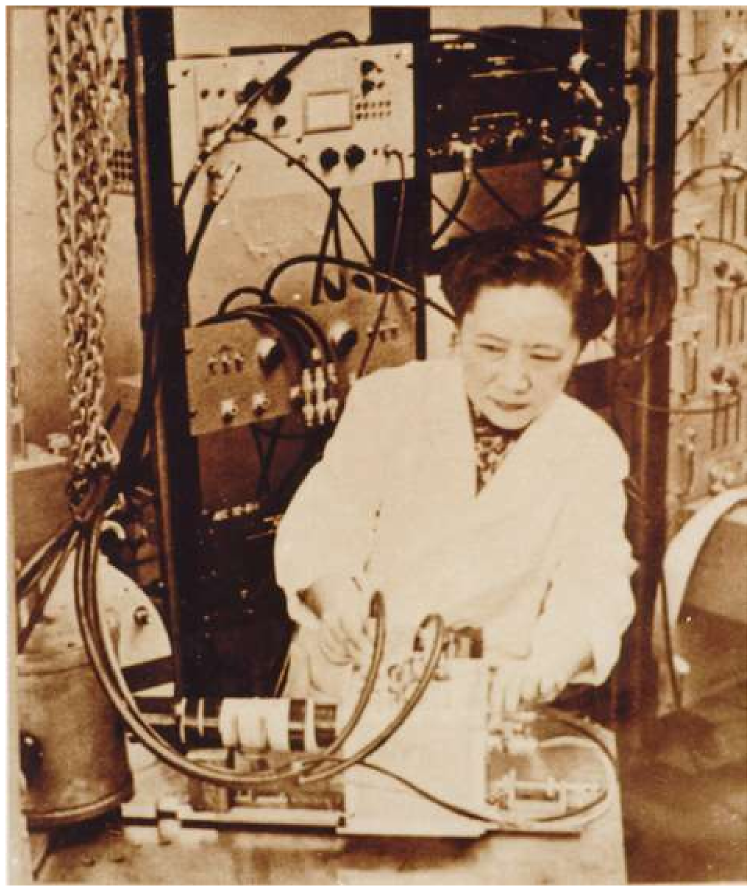
Fierz interference

$$b\xi = \gamma[(C_S^*C_V+C_SC_V^*)+(C_S'^*C_V'+C_S'C_V'^*)]|M_{\text{F.}}|^2 + \gamma[(C_T^*C_A+C_A^*C_T)+(C_T'^*C_A'+C_A'^*C_T')] \times |M_{\text{G.T.}}|^2. \quad \text{(A.5)}$$

Lee, Yang, Phys. Rev. 104, 254 (1956)

Parity is violated in ^{60}Co decay! (1957)

Chien-Shiung Wu (1912-1997)



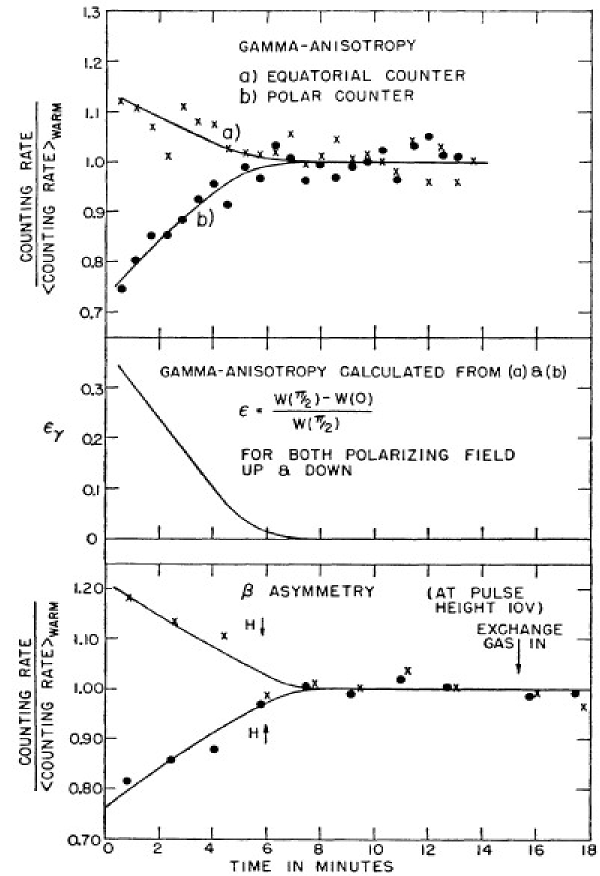
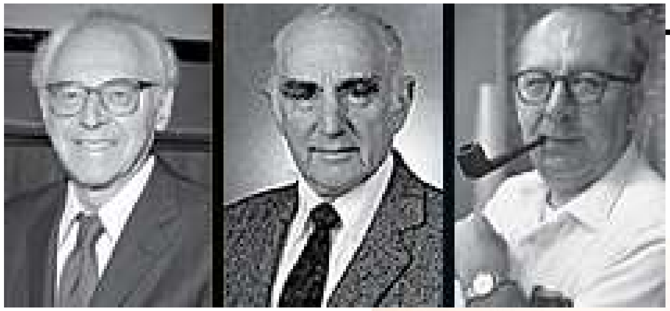
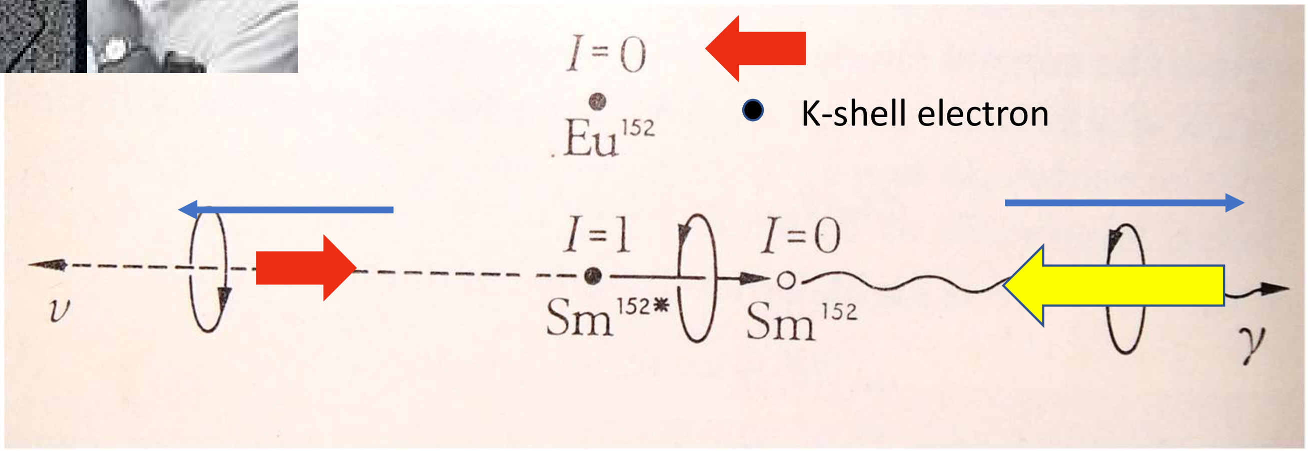


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Helicity of Neutrinos*



*How to measure the helicity state of neutrinos, while they cannot be detected?

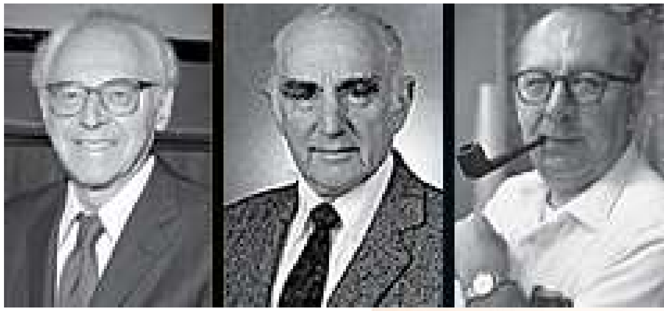


Negative helicity ($\sigma \cdot p$)

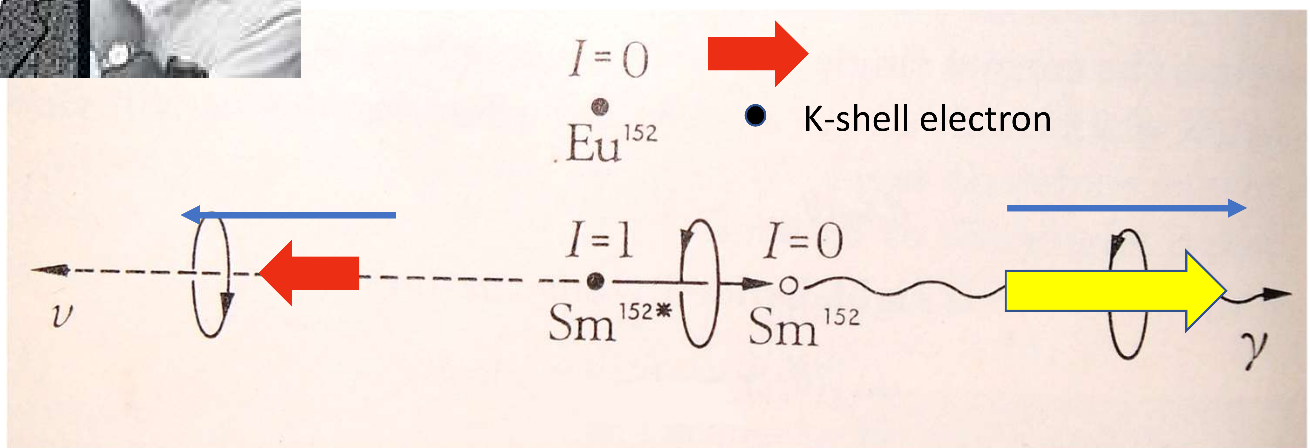
Negative helicity ($\sigma \cdot p$)

M. Goldhaber, L. Grodzins, A.W. Sunyar, Phys. Rev., 109, 1015 (1958)

Helicity of Neutrinos*



*How to measure the helicity state of neutrinos, while they cannot be detected?



Left circularly polarized

Positive helicity $(\sigma \cdot p)$

Positive helicity $(\sigma \cdot p)$

M. Goldhaber, L. Grodzins, A.W. Sunyar, Phys. Rev., 109, 1015 (1958)

Finally, it emerges the V—A theory!

The helicity projection operator P_- selects the LH particle

$$P'_{\pm} = \frac{1}{2}(1 \pm \gamma_5)$$

$$(\bar{\phi}_p \hat{O}_i \phi_n)(\bar{\phi}_e \hat{O}_i \phi_\nu)$$

↓

$$\begin{aligned}(\bar{\phi}_e^{RH})\hat{O}_i(\phi_\nu^{LH}) &= \overline{(\hat{P}'_+\phi_e)}\hat{O}_i(\hat{P}'_-\phi_\nu) \\ &= (\bar{\phi}_e)\hat{O}'_i(\phi_\nu)\end{aligned}$$

↓

$$\hat{O}'_i = \hat{P}'_+ \hat{O}'_i \hat{P}'_-$$

Table 1.3. Properties of helicity projected fermion transition operators

	$\hat{O}_i$	$\hat{O}'_i$
S	1	0
V	γ^μ	$\gamma^\mu \hat{P}'_- = \frac{1}{2}\gamma^\mu(1-\gamma_5)$
T	$\sigma^{\mu\nu}$	0
A	$\gamma^\mu\gamma_5$	$-\gamma^\mu \hat{P}'_- = -\frac{1}{2}\gamma^\mu(1-\gamma_5)$
P	γ_5	0

R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958);
E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. 109, 1860 (1958)

Measurements of Asymmetries in the Decay of Polarized Neutrons*

M. T. Burgy, V. E. Krohn, T. B. Novey, and G. R. Ringo,
Argonne National Laboratory, Lemont, Illinois

AND

V. L. Telegdi, *University of Chicago, Chicago, Illinois*

(Received April 17, 1958)

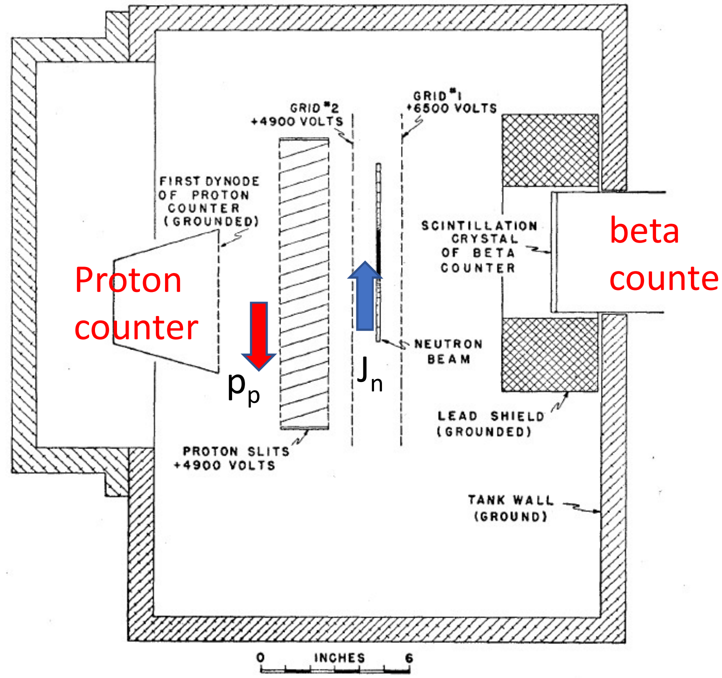


Fig. 1. Vertical cross section (normal to the neutron beam) through the detector system of the experiment measuring the correlation of the neutrino momentum and the neutron spin.

a (beta-neutrino correlation)
B (neutrino asymmetry)

Table II. Predicted values for $\mathcal{A}$ and $\mathcal{B}$.

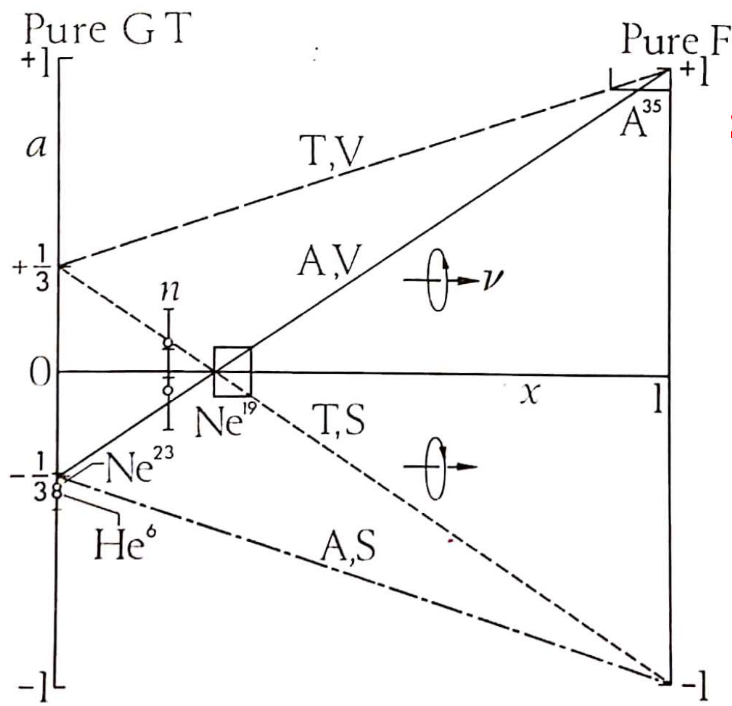
	$S+T$[a]		$S-T$		$V+A$		$V-A$[a]		
	$\bar{\nu}_L$[b]	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	Exp.
$\mathcal{A}$	−1	+1	−0.07[c]	0.07	+1	−1	0.07	−0.07	−0.09
$\mathcal{B}$	−0.07	0.07	−1	+1	−0.07	0.07	−1	+1	+0.88

[a] The relative signs in this row are those of the couplings present; i.e., $V-A$ means $C_A/C_V=-1.14$.
[b] $\bar{\nu}_{L(R)}$ means left (right) handed antineutrino; i.e., $\bar{\nu}_{L(R)}$ corresponds to $C_i/C_i'=-1(+1)$.
[c] The uncertainty of ±0.05 in x introduces an uncertainty of ±0.02 in this number, 0.07, wherever it appears.

Experimental supports for V—A (nuclear data)

beta-neutrino correlation, a

^{6}He, ^{8}Li, ...



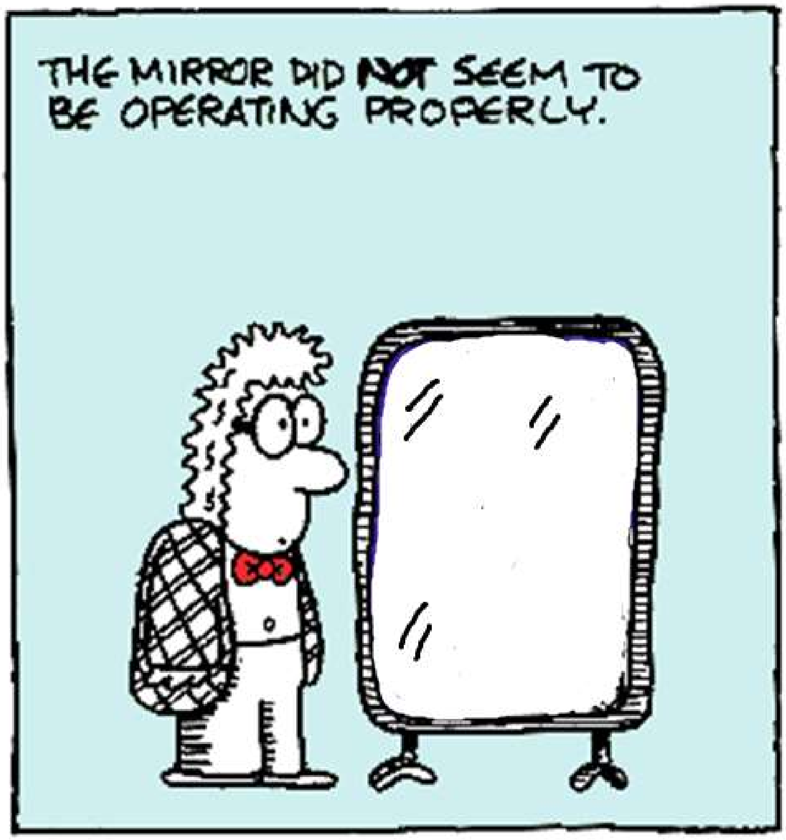
Superallowed $0^{+} \rightarrow 0^{+}$
^{10}C, ^{14}O, etc.

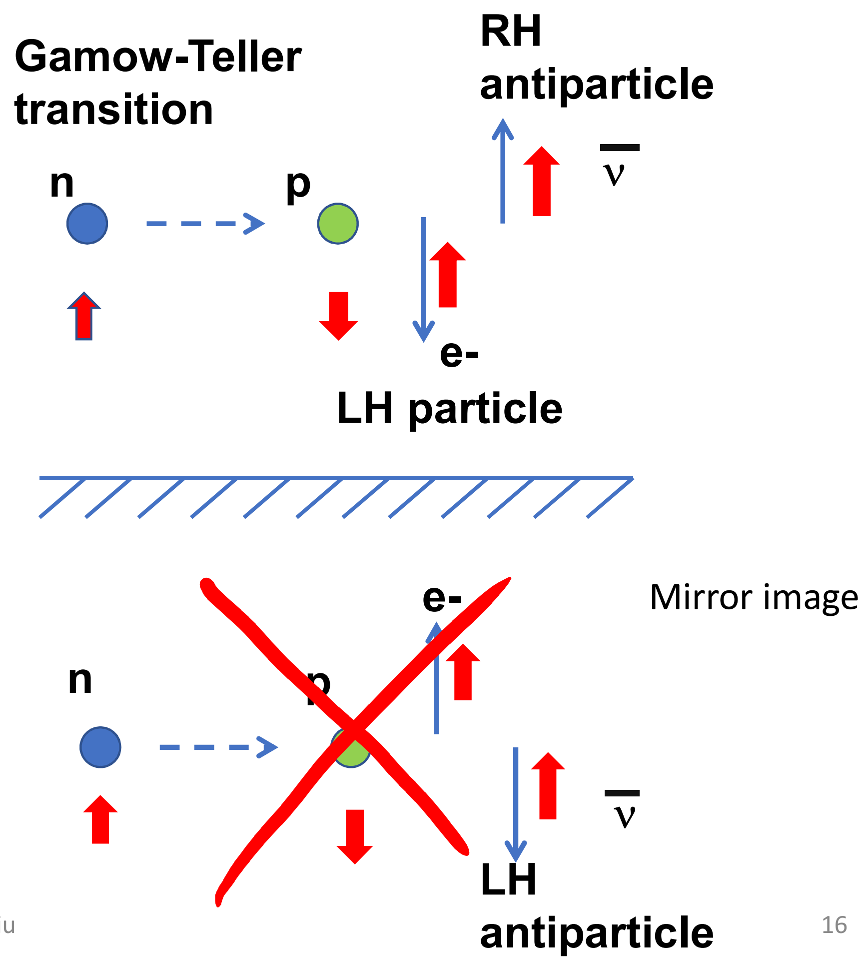
$$x = \frac{g_A M_{GT}}{g_V M_F}$$

Neutron,
Mirror Nuclei:
^{37}K, ^{19}Ne, ^{21}Na, ^{35}Ar

“The Theory of Beta Radioactivity” by E. J. Konopinski, Oxford Clarendon Press (1966)

The Spatial Inversion Symmetry (or Parity) is Broken!

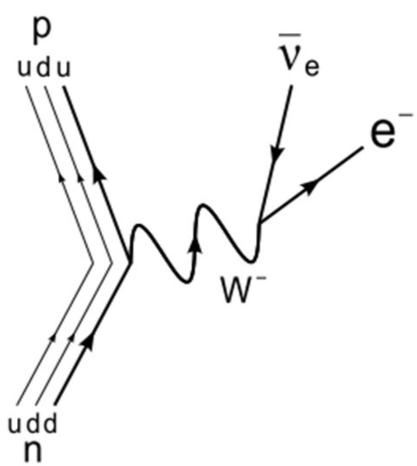




Girl before a mirror,
Pablo Picasso (1932)

The Museum of Modern Art
(*MoMA)*, New York

Neutron beta-decay (minimal V—A)



$$H_\beta = H_{V,A} = \frac{G_F V_{ud}}{\sqrt{2}} \bar{\phi}_e \gamma_i (1-\gamma^5)\phi_{\nu_e} \bar{\phi}_p (g_V + g_A \gamma^5)\gamma^i \phi_n$$

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

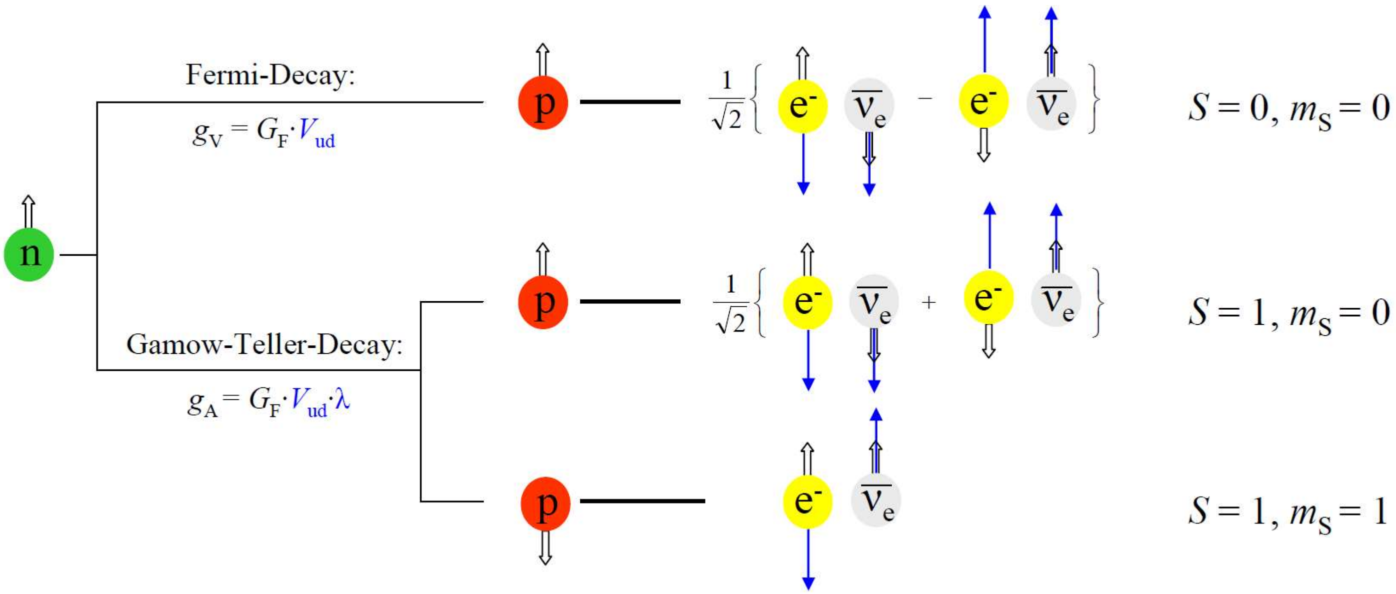
= 1 (CVC)

$$g_V(\bar{p}\gamma_\mu n) = \langle p | \bar{u}\gamma_\mu d | n \rangle$$

$$g_A(\bar{p}\gamma_\mu \gamma_5 n) = \langle p | \bar{u}\gamma_\mu \gamma_5 d | n \rangle$$

Gerstein S. S. and Zeldovich Ya. B.: Zh. Eksp. Teor. Fiz. *29* (1955) 698.
Feynman R. P. and Gell-Mann M.: Phys. Rev. *109* (1958) 193.

Neutron beta-decay

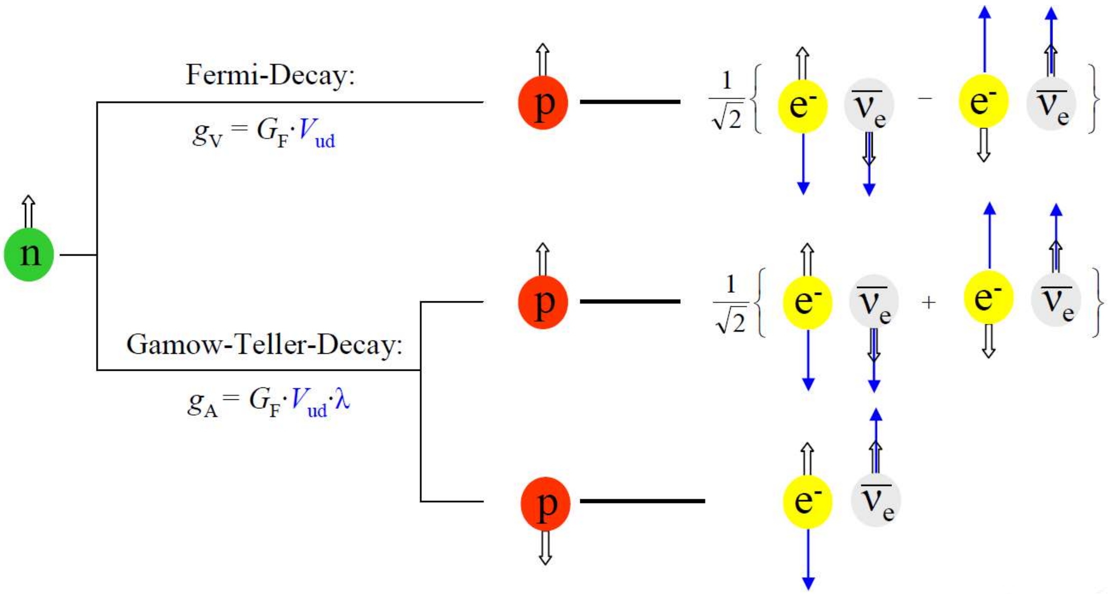


Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\tau_n \approx 885$ s

Graph credit: S. Baessler

Neutron beta-decay & angular correlations



Beta asymmetry	Neutrino asymmetry	beta-neutrino correlation
A = 0	B = 0	a = 1
A = 0	B = 0	a = 1
A =-1	B = 1	a = -1

$$A = -2\frac{\lambda^2 + \lambda}{1+3\lambda^2} \approx -0.1$$

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \sim -0.1$$

Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

$$B = 2\frac{\lambda^2 - \lambda}{1+3\lambda^2} \approx 0.98$$

1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\quad \tau_n \approx 885\ \text{s}$

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

More angular correlations

Oriented nucleus:

$$\omega(\langle J\rangle | E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \frac{1}{(2\pi)^5} p_e E_e (E^0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \xi \Bigg\{ 1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} - \frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J-1)}\right] + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\Bigg\}. \quad (2)$$

Electron polarization in non-oriented nucleus:

$$\omega(\boldsymbol{\sigma} | E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \frac{1}{(2\pi)^5} p_e E_e (E^0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \tfrac{1}{2}\xi \Bigg\{ 1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma}\cdot\left[G\frac{\mathbf{p}_e}{E_e} + H\frac{\mathbf{p}_\nu}{E_\nu} + K\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}\right) + L\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\Bigg\}.$$

In oriented nucleus:

$$\omega(\langle\mathbf{J}\rangle,\boldsymbol{\sigma} | E_e,\Omega_e)dE_e d\Omega_e = \frac{1}{(2\pi)^4} p_e E_e (E^0-E_e)^2 dE_e d\Omega_e \times \xi \Bigg\{ 1 + b\frac{m}{E_e} + \left(A\frac{\langle\mathbf{J}\rangle}{J} + G\boldsymbol{\sigma}\right)\cdot\frac{\mathbf{p}_e}{E_e} + \boldsymbol{\sigma}\cdot\left[N\frac{\langle\mathbf{J}\rangle}{J} + Q\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e}\right) + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\right]\Bigg\}.$$

Jackson, Treiman, Wyld, Phys. Rev. 106, 517 (1957)

Measurement of the Transverse Polarization of Electrons Emitted in Free-Neutron Decay

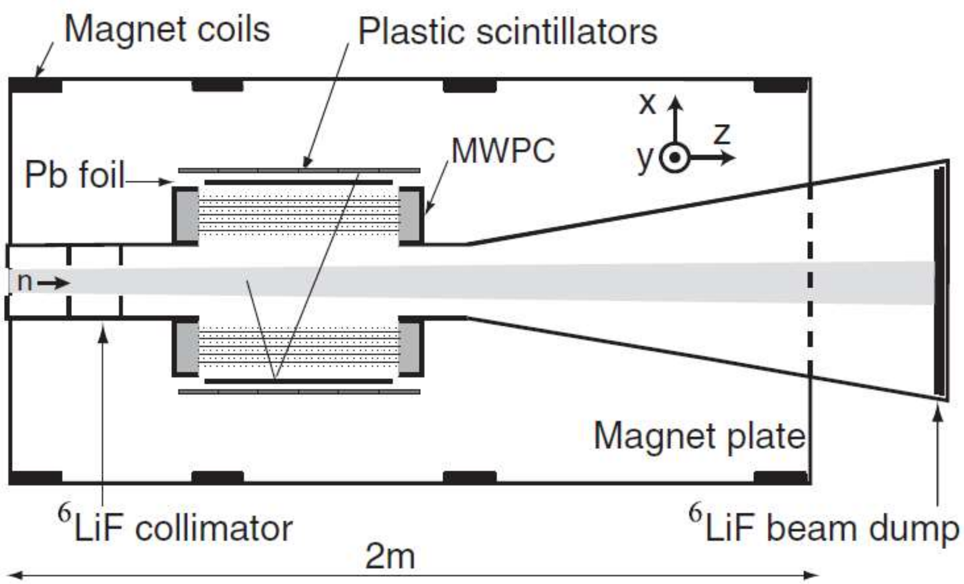


FIG. 1. Schematic top view of the experimental setup. A sample projection of an electron V-track event is indicated.

Linear sensitivity to S & T

Spin-electron polarization asymmetry

$$N = -0.218\text{Re}(S) + 0.335\text{Re}(T) - \frac{m}{E}A,$$

Spin-electron polarization-beta momentum (triple) corr.

$$R = -0.218\text{Im}(S) + 0.335\text{Im}(T) - \frac{m}{137p}A,$$

$N = 0.056 \pm 0.011 \pm 0.005$,

$R = 0.008 \pm 0.015 \pm 0.005$.

A. Kozela, et al. PRL 102, 172301 (2009)

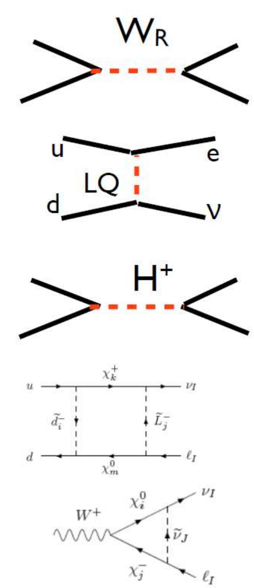
Beta decays and new physics models

- Model → <u>set overall size and pattern</u> of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture:

Can be made quantitative

	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓

YOUR FAVORITE MODEL ... ...



Scalar and Tensor Couplings – beyond the Standard Model

$$H_S = \frac{G_F V_{ud}}{\sqrt{2}} \varepsilon_S \left[\left(\bar{e}(1+\gamma_5)\nu \right) g_S \left(pn \right) \right] + \text{h.c.}$$

$$H_T = \frac{G_F V_{ud}}{\sqrt{2}} 4\varepsilon_T \left[\left(\bar{e}\sigma_{\lambda\mu}(1+\gamma_5)\nu \right) g_T \left(p\sigma_{\lambda\mu} n \right) \right] + \text{h.c.}$$

$$\varepsilon_{S,T} \sim \left(\frac{v}{\Lambda_{S,T}} \right)^2 \sim 10^{-3}$$

$$v = (2\sqrt{2}G_F)^{-1/2} \approx 174\ \text{GeV}$$

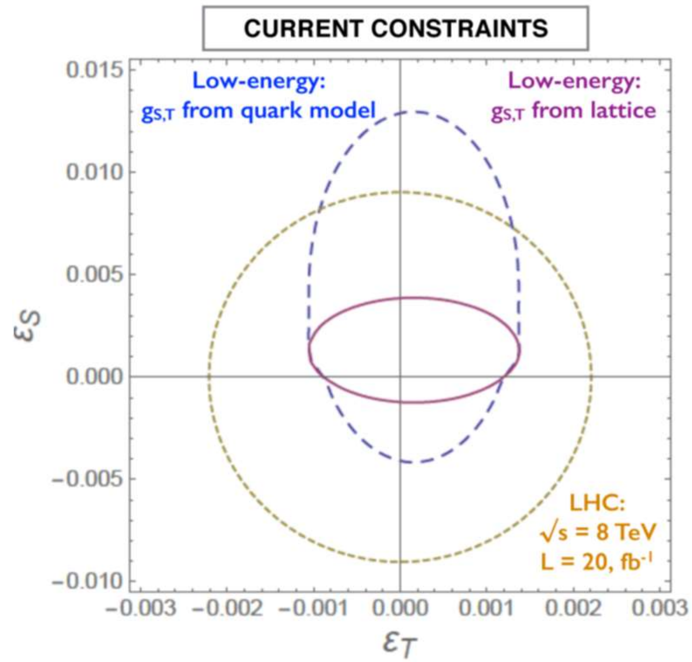
$$g_S^{u,d} = 0.97(12)(6)$$

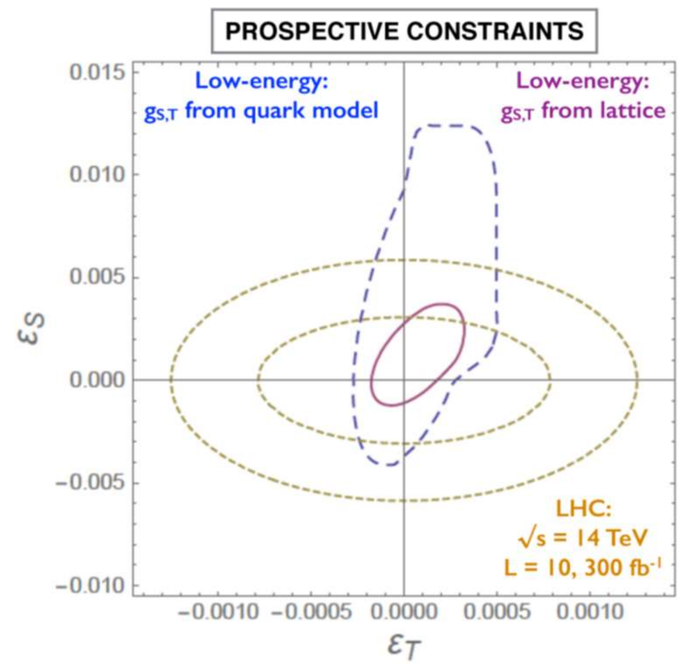
$$g_T^{u,d} = 0.987(51)(20)$$

PNDME: PRD 94, 054508 (2016)
PRD 92, 094511 (2015)

T. Bhattacharya et al., PRD 85, 054512 (2012)
V. Cirigliano, S. Gardner, and B. Holstein, Prog. Part. Nucl. Phys. 71, 93 (2013)

Scalar and Tensor Couplings – beyond the Standard Model



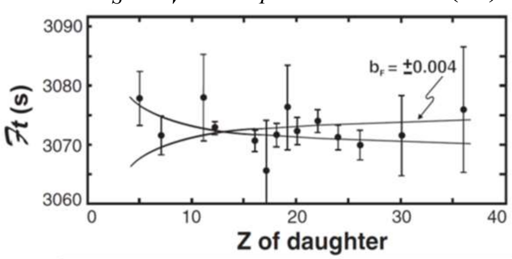


Fierz interference

Scalar Currents: b_F

$f \propto 1 + \langle b_F \gamma_1 m_e / E_e \rangle \qquad \gamma_1 = \sqrt{1-\alpha^2 Z^2}$

$C_S / C_V = -b_F / 2 = 0.0014(13)$



LHC: $pp \rightarrow e\nu + X$

ε_S: $0^+ \rightarrow 0^+$ Fierz b_F

ε_T: $\pi \rightarrow e\,\nu\,\gamma$

$\Lambda_S > 7$ TeV

$\Lambda_T > 13$ TeV

Future ε_S, ε_T: Neutron b, b_ν

Future ε_T: ^{6}He b

T. Bhattacharya, V. Cirigliano, S.D. Cohen, R. Gupta, H.-W. Lin, and B. Yoon (PNDME Collaboration), PRD 94, 054508 (2016)

CKM unitarity test

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

	V	V,A	A
V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$	$\pi \to \mu\nu$
V_{us}	$K \to \pi l \nu$	$\Lambda \to p e \bar{\nu}, \ldots$	$K \to \mu\nu$

- Currently, the most precise input comes from pure V or A channels
  - V: nuclear decays and semi-leptonic K decays (need $f_+(0)$)
  - A: leptonic decays → V_{us} / V_{ud} (need f_K/f_π)

Hardy-Towner1411.5987

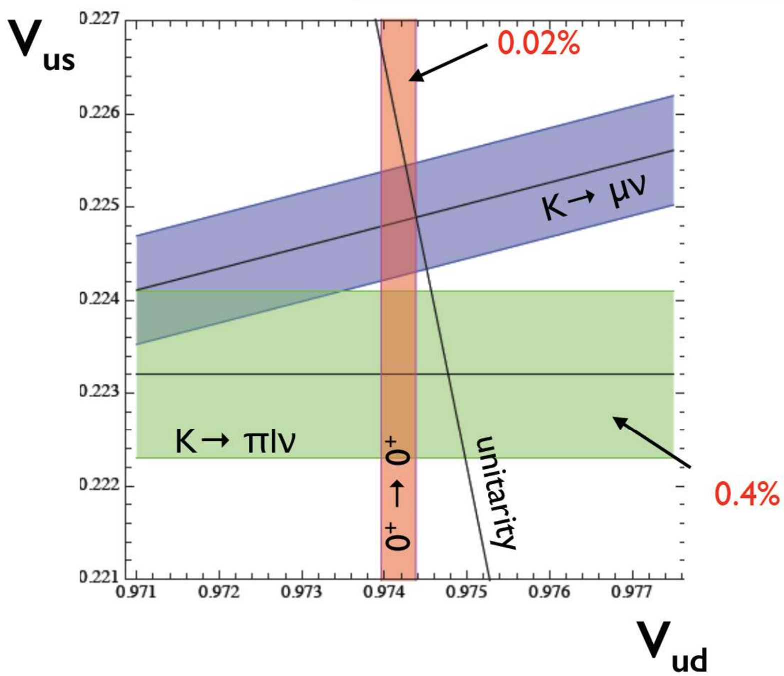
FLAVIANET report 1005.2323

Lattice QCD input from FLAG 1607.00299

Slide: V. Cirigliano

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



Hardy-Towner1411.5987
FLAVIANET report 1005.2323
Lattice QCD input from FLAG 1607.00299

V_{us} from K→ μν (pi→ μν)

Δ_{CKM} = - (4 ± 5)∗10^{-4} 0.9σ

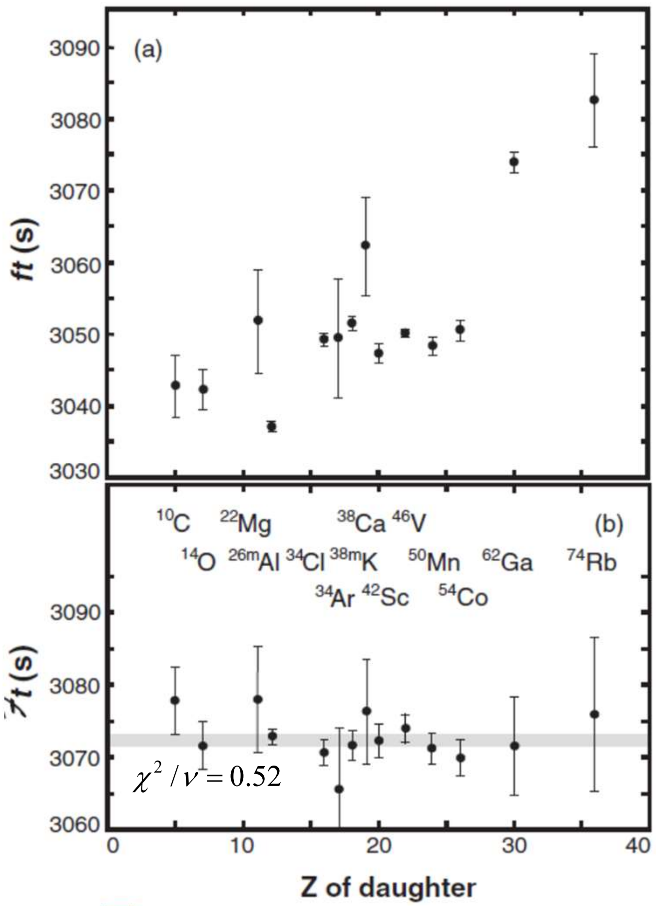
Δ_{CKM} = - (12 ± 6)∗10^{-4} 2.1σ

V_{us} from K→ πlν

Worth a closer look: at the level of the best LEP EW precision tests

Slide: V. Cirigliano

V_{ud} from Superallowed $0^+ \rightarrow 0^+$ Decays



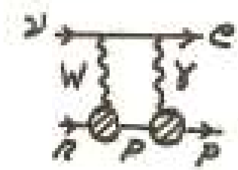
$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2\left(1+\Delta_R^V\right)}$$

$\sim$1.5%

0.5% – 1.2%

2.361(38)%

$$G_V = G_F \cdot V_{ud}$$



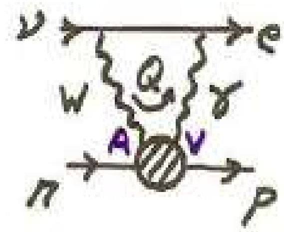
J.C. Hardy and I.S. Towner, PRC 91, 025501 (2015)

V_{ud} from neutron decays

Marciano & Sirlin, PRL 96, 032002 (2006)

f: Phase space factor=1.6886
(Fermi function, nuclear mass, size, recoil)

$$1/\tau_n = f G_F^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(\underline{1+RC})/2\pi^3$$



$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ \frac{m_W{}^2}{Q^2 + m_W{}^2} F(Q^2)$$

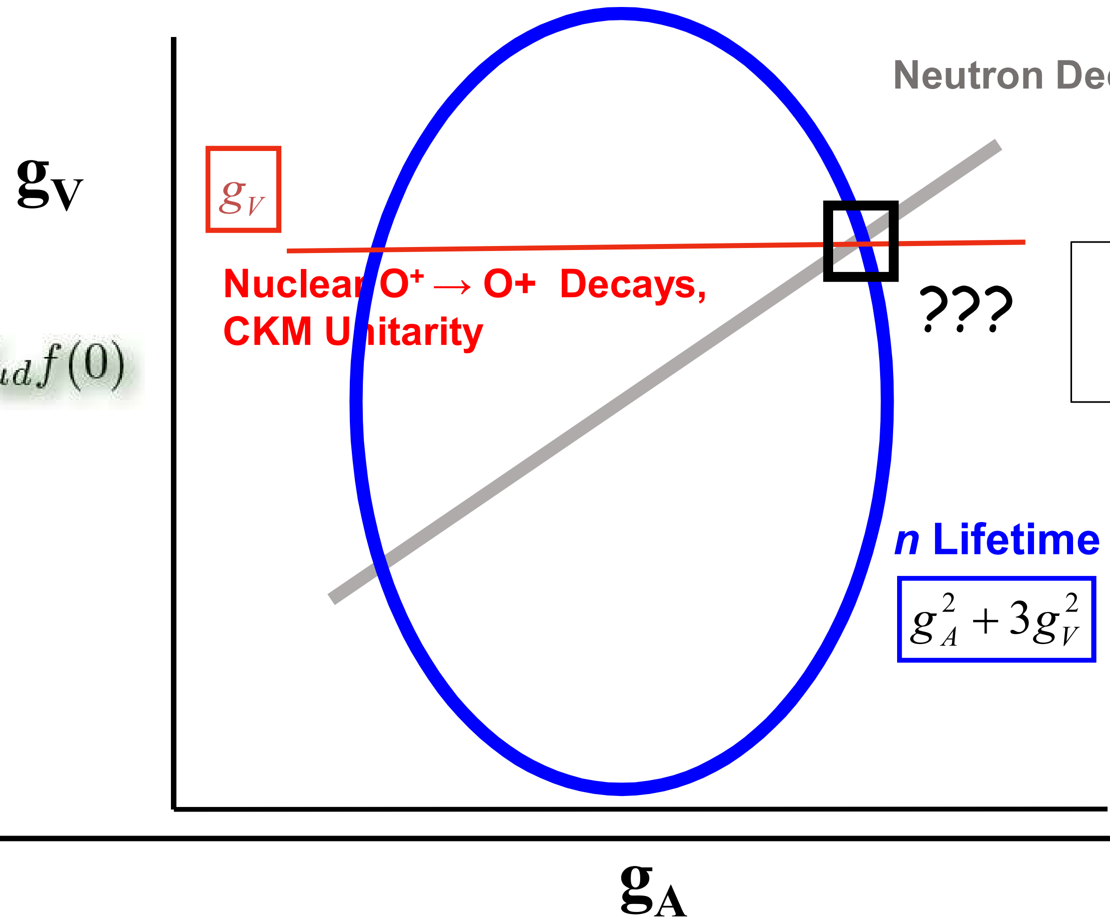
From μ-decay: 0.6 ppm (MuLan 2011)

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9s}{\tau_n(g_V + 3g_A^2)}$$

To math the theoretical uncertainty: $4 \times 10^{-4,}$ it requires experimental uncertainties of: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 4 \times 10^{-4}$.

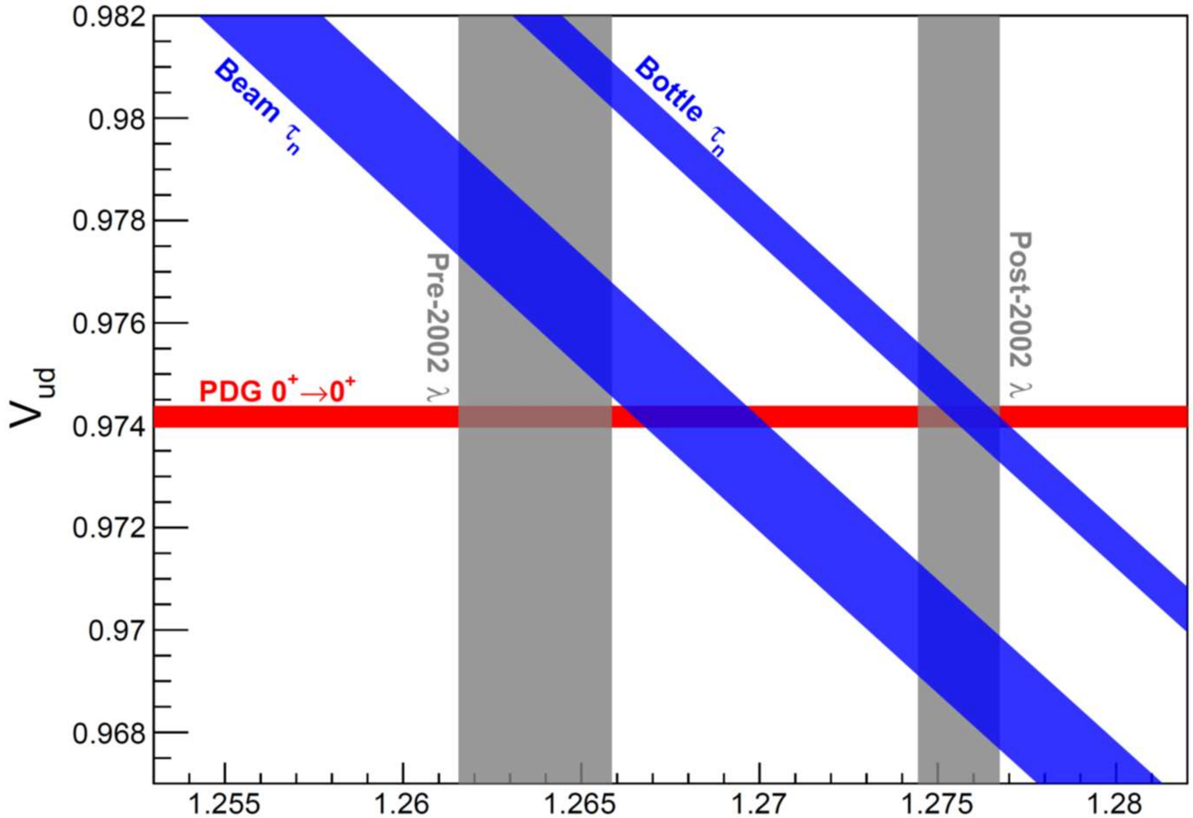
V_{ud} from neutron decays

$g_V \equiv G_F V_{ud} f(0)$



How thick are the bands and do they overlap ?

The confusing situation of g_A, g_V & V_{ud}

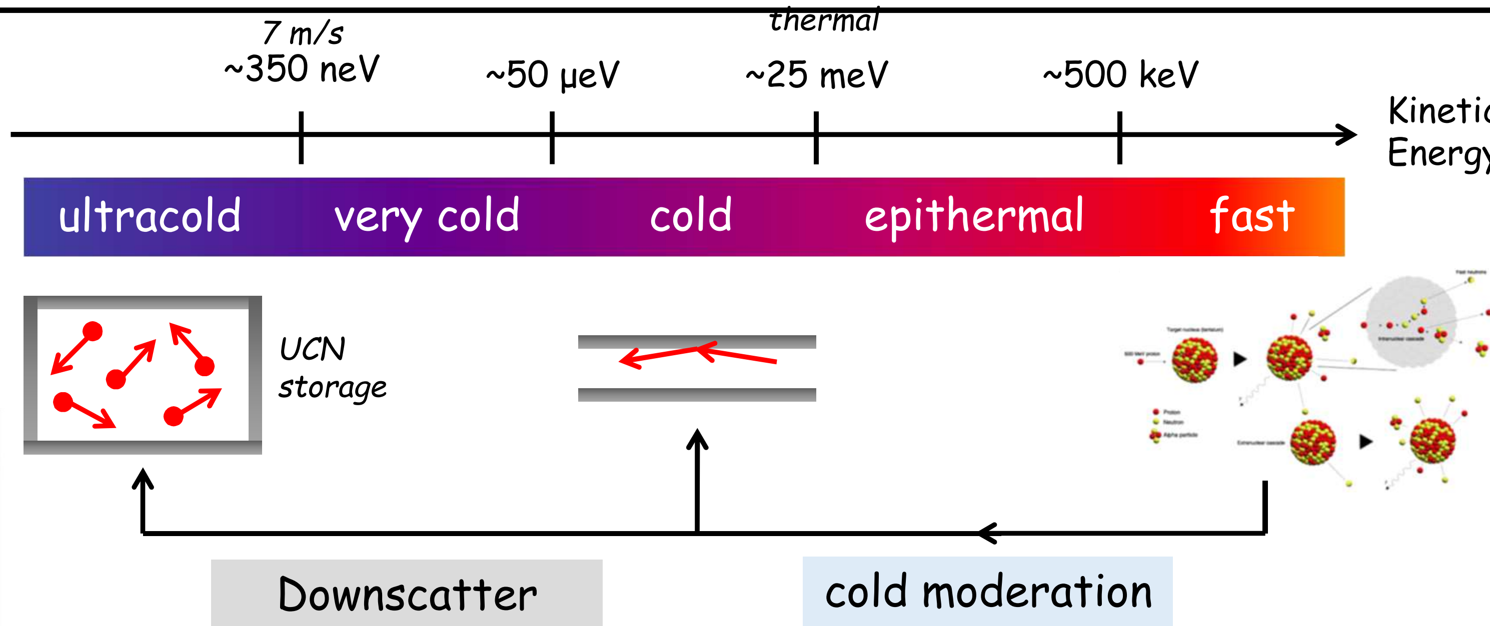


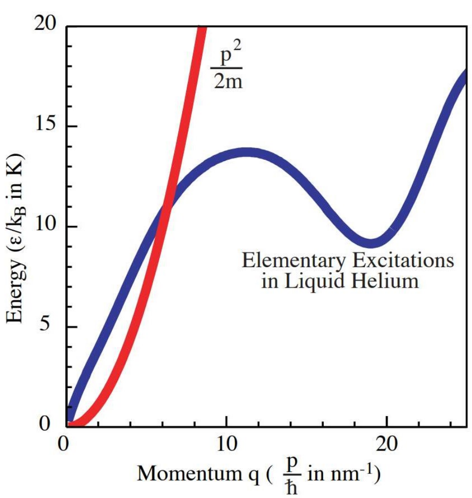
$|\lambda| = |g_A / g_V|$

$$\tau_n = \frac{4908.7 \pm 1.9s}{|V_{ud}|^2 \, (g_V + 3g_A^2)}$$

Figure Credit: M. A.-P. Brown

Ultracold Neutrons (UCN)



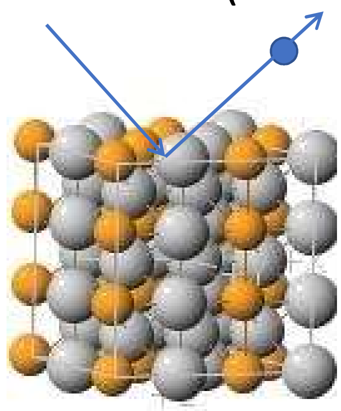


superthermal production:
UCN can be accumulated to a density higher than the Boltzmann factor, $e^{-\Delta E/kT}$

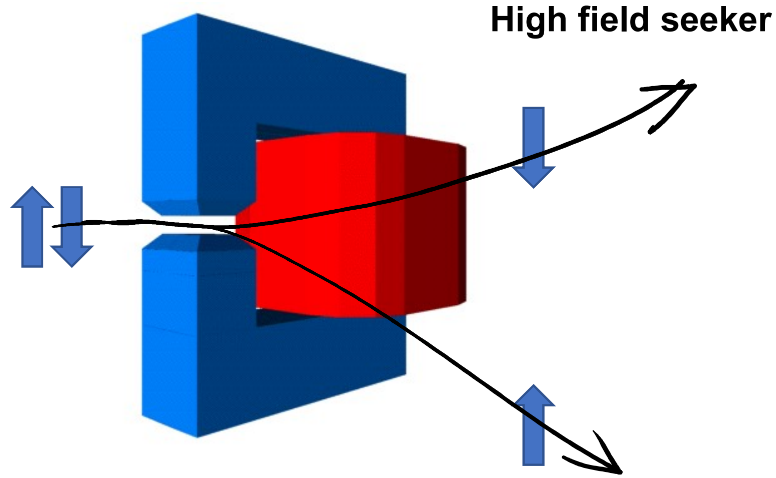
R. Golub and J.M. Pendlebury, PLA 53, 133 (1975)
R. Golub and J.M. Pendlebury, PLA 62, 337 (1977)
C.L. Morris et al., PRL 89, 272501 (2002)
F. Atchinson et al., PRL 95, 182502 (2005)
C.M. Lavelle et al., PRC 82, 015502 (2010)

Different ways to manipulate UCN

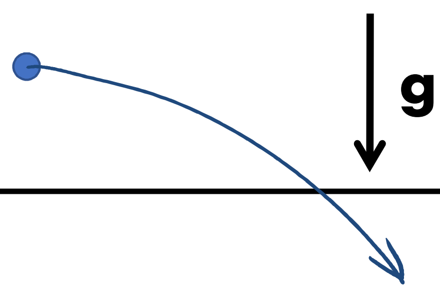
- Nuclear force (max: 350neV)

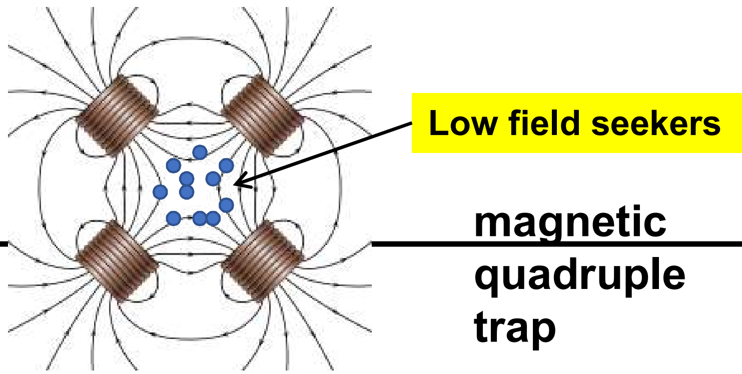


- Magnetic force (60neV/T)



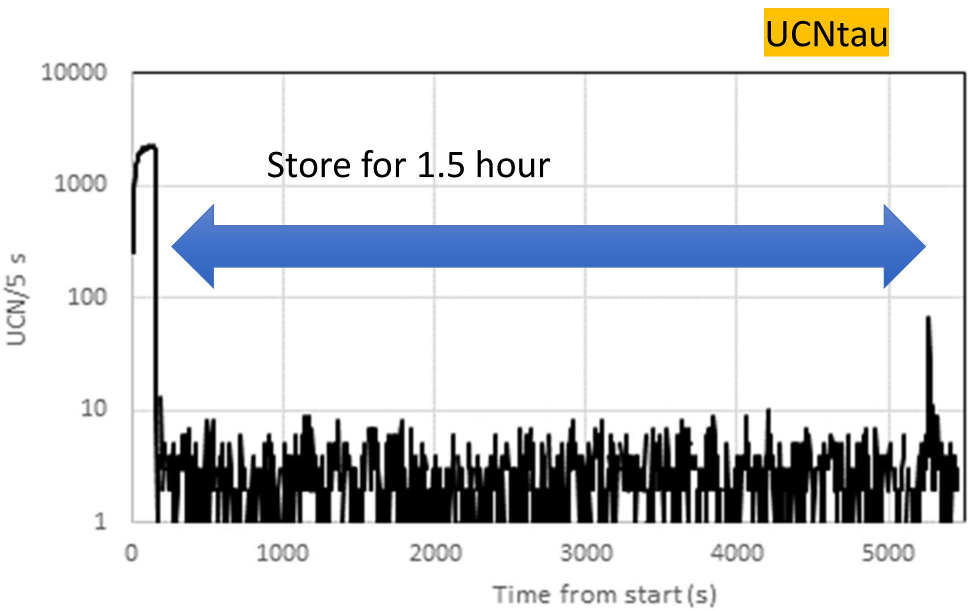
- Gravitational force (100neV/m)

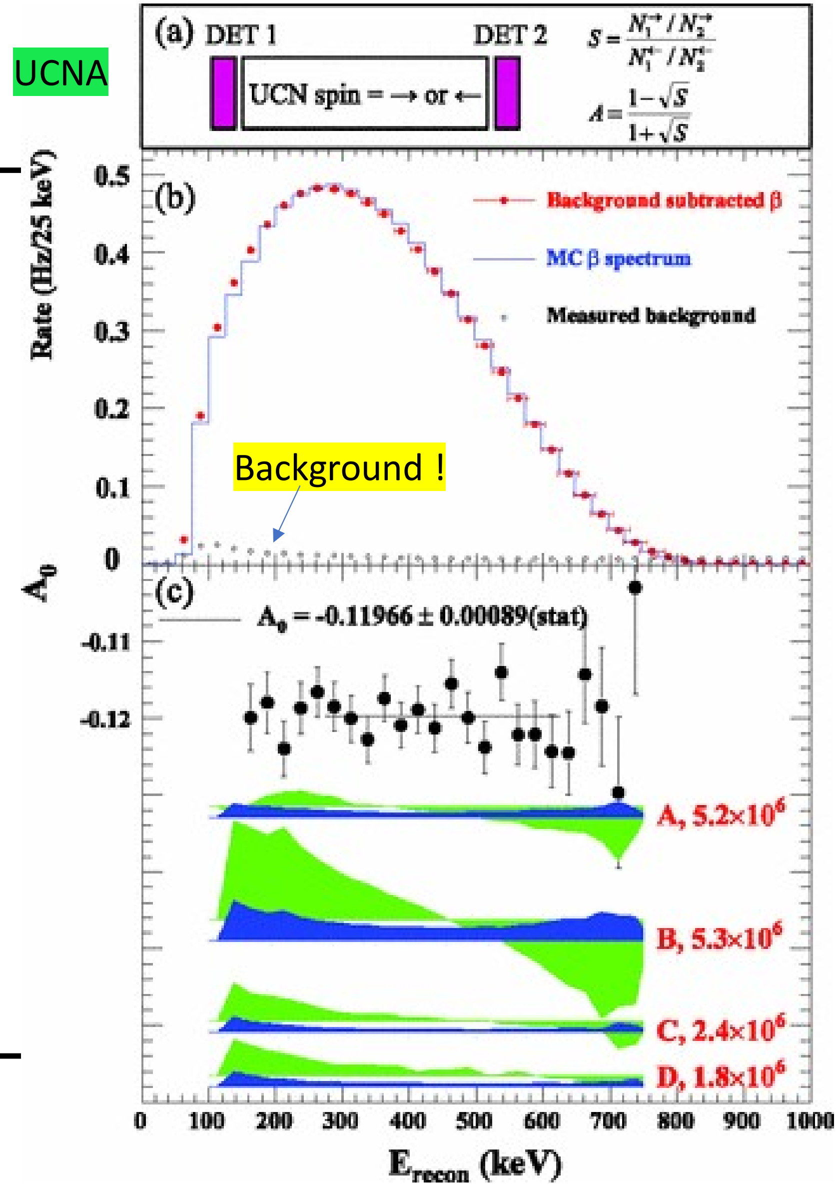




UCN improve data quality

Low background
Long storage time

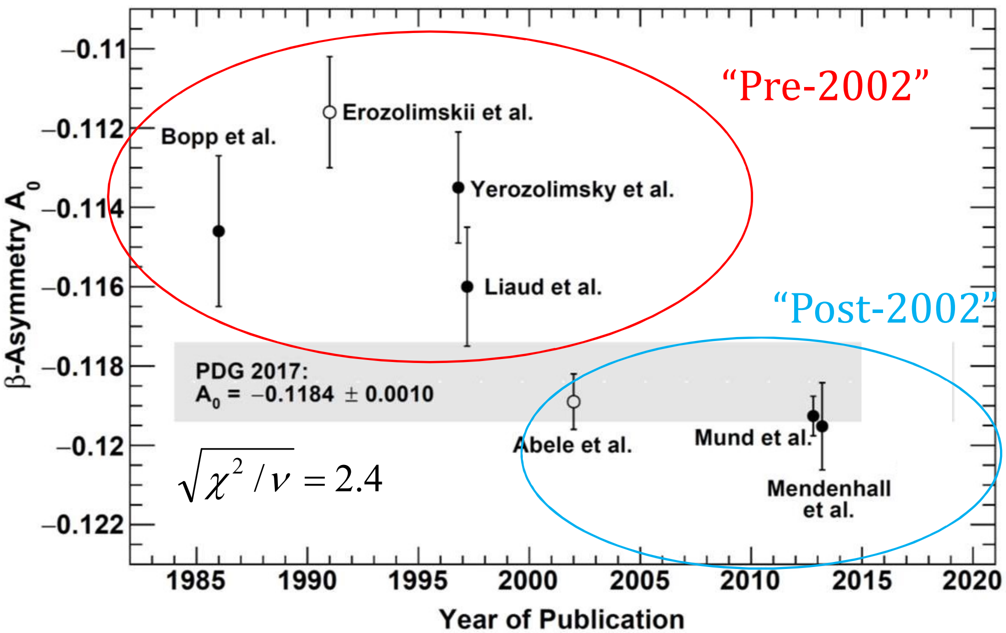


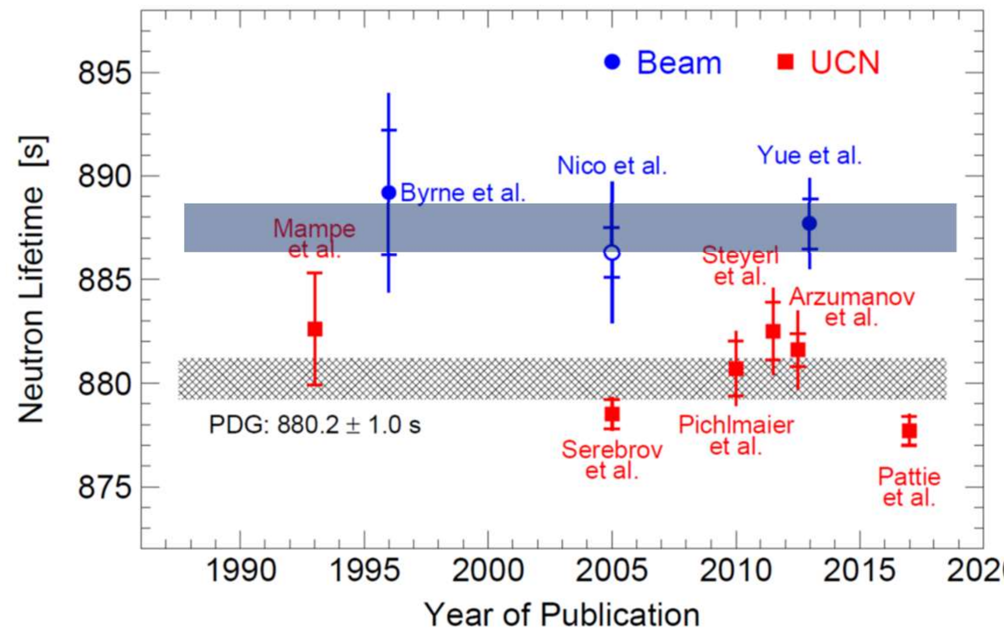


Chen-Yu Liu

J. Liu *et al.* (UCNA Collaboration)
Phys. Rev. Lett. **105**, 181803

However, the values of the Beta asymmetry and Neutron lifetime are changing…

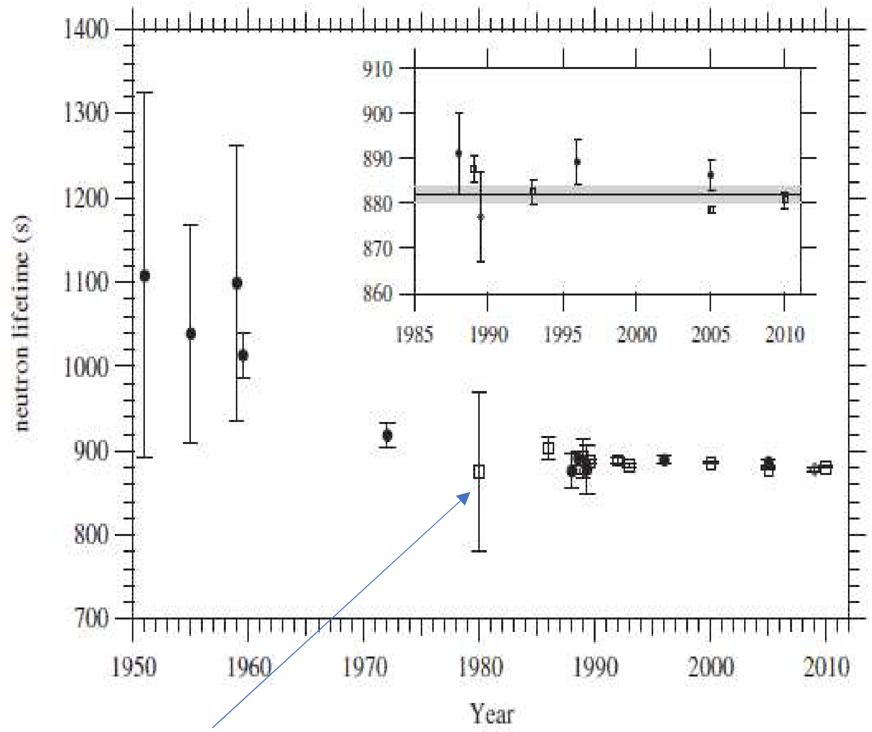


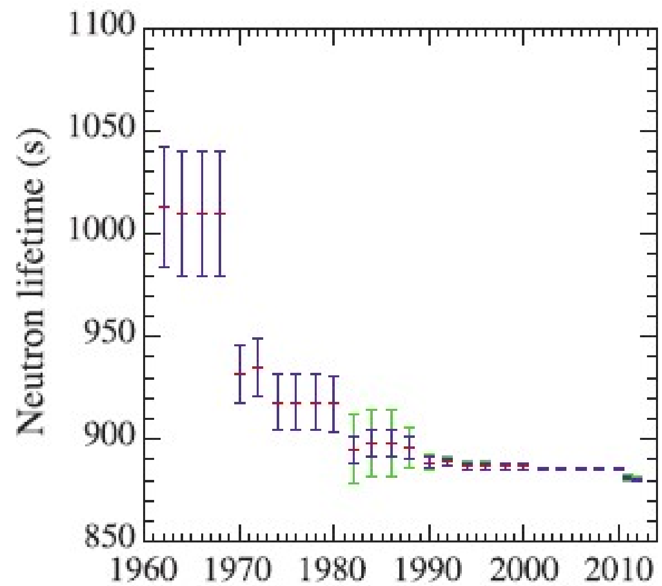


~0.1% Result for A_0 would remove older results from χ^2

Beam and UCN measurements disagree by 10 s!

The History of Neutron Lifetime Measurement





1st UCN bottle lifetime experiment

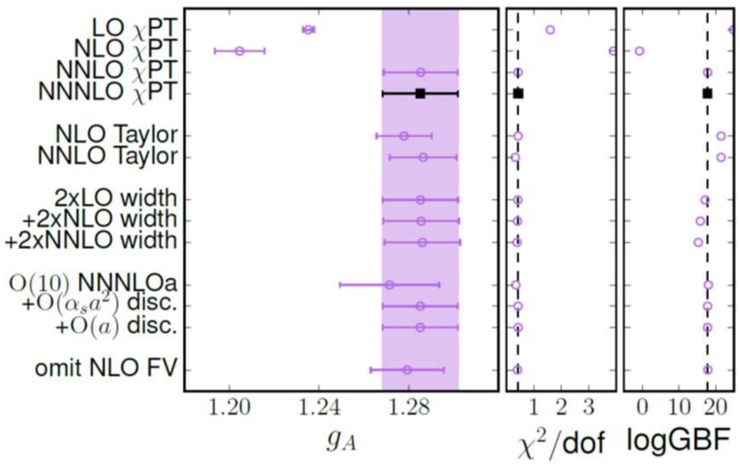
Experiments

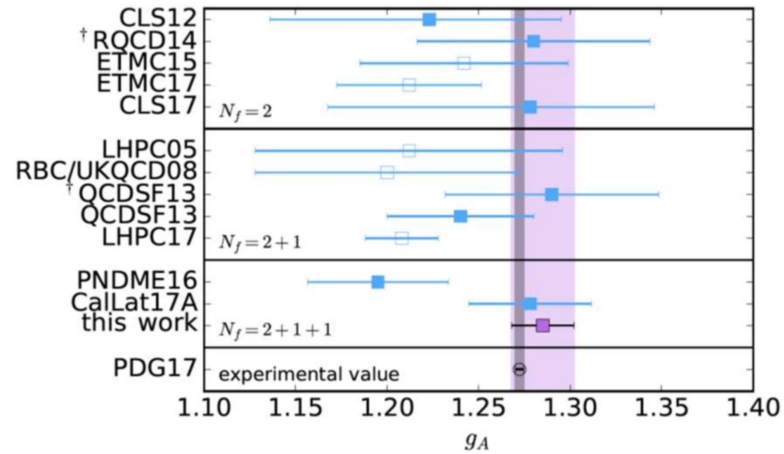
PDG average

g_A From Lattice QCD

C.C. Chang et al., arXiv:1710.06523

→ **1.33% Result for g_A !**

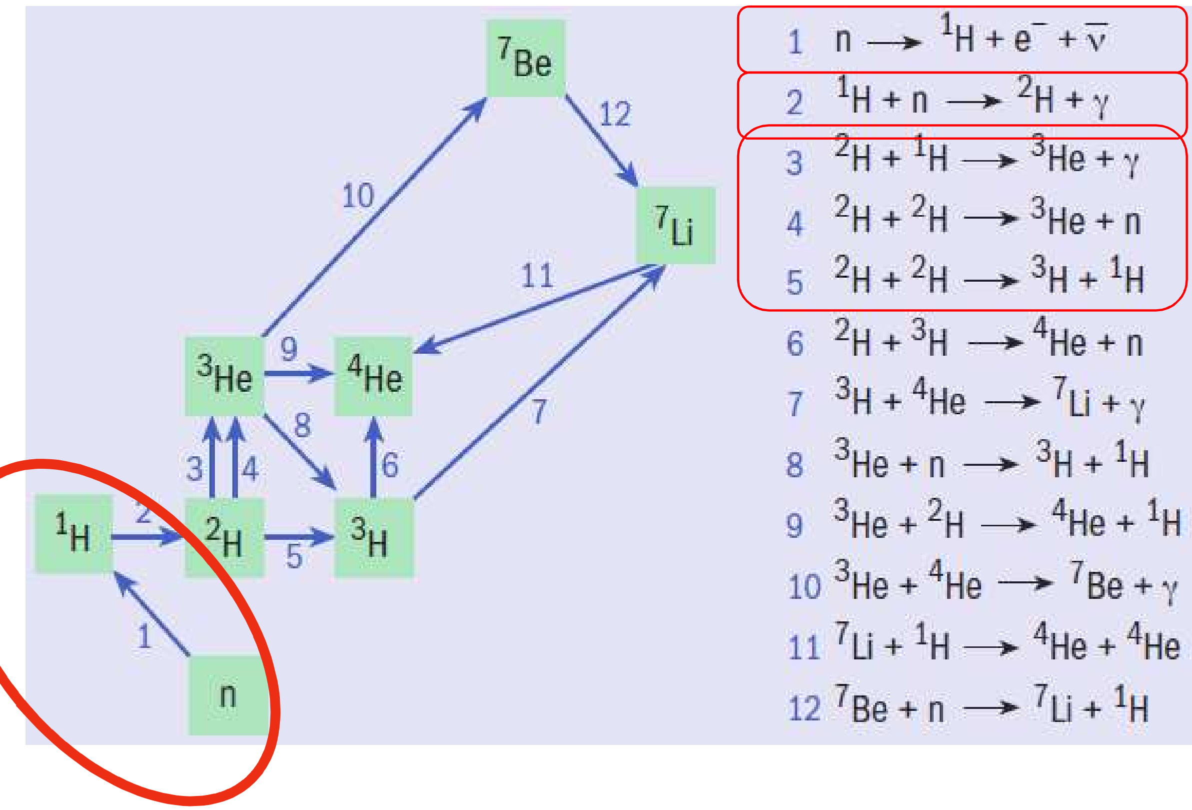




Cirigliano, Gardner, Holstein,
Prog. Part. Nucl. Phys. 71, 93 (2013):

Experiments: $(1-2\varepsilon_R)g_A/g_V$ ⟷ Lattice: g_A

Big-Bang Nucleosynthesis:
a sensitive probe to early universe (1000 s after the BB)



The ingredients:
protons & neutrons

Big Bang nucleosynthesis

1 μs

Thermal equilibrium
(T > 1 MeV)

$$\frac{n}{p} \propto e^{-Q/T}$$

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

$$n + \nu_e \leftrightarrow p + e^-$$

1 s

After freezeout
n/p decreases due to neutron decay

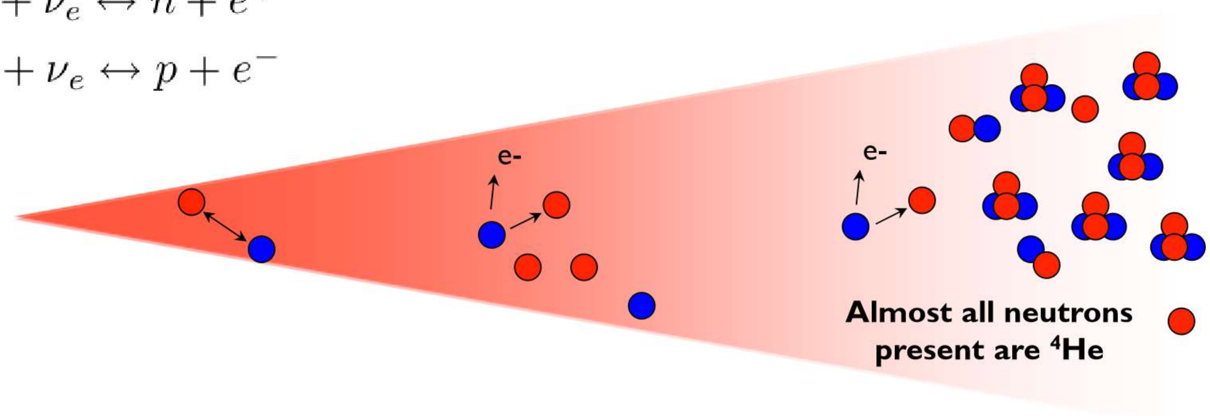
$$n \rightarrow p + e^- + \bar{\nu}_e$$

100s

Nucleosynthesis (T~0.1 MeV)
Light elements are formed

$$p + n \rightarrow d + \gamma$$

$$d + d \rightarrow {}^4\mathrm{He} + \gamma$$



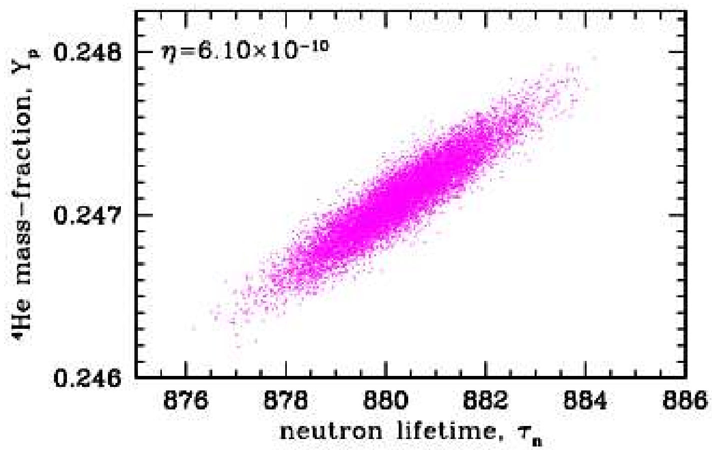
Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.

Slide courtesy of H. P. Mumm

Big Bang Nucleosynthesis (BBN): Neutron lifetime & the primordial ^{4}He abundance (Y_p)

$$Y_p \sim \frac{2e^{-t_d/\tau_n}}{1 + e^{\Delta m/kT_f}}$$

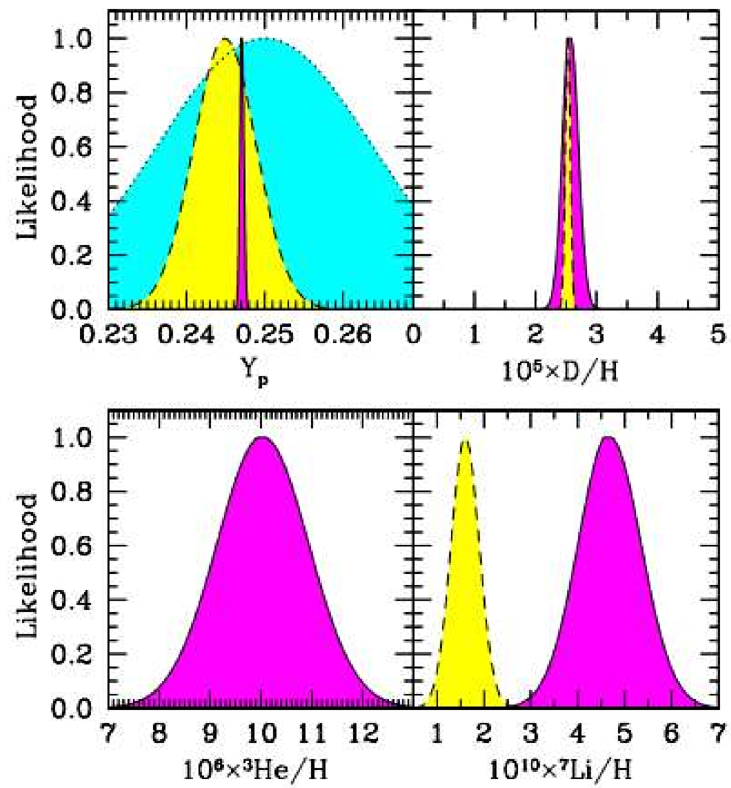
Sensitive to τ_n



BBN (with τ_n=880 s)

CMB

Astrophysical Observations

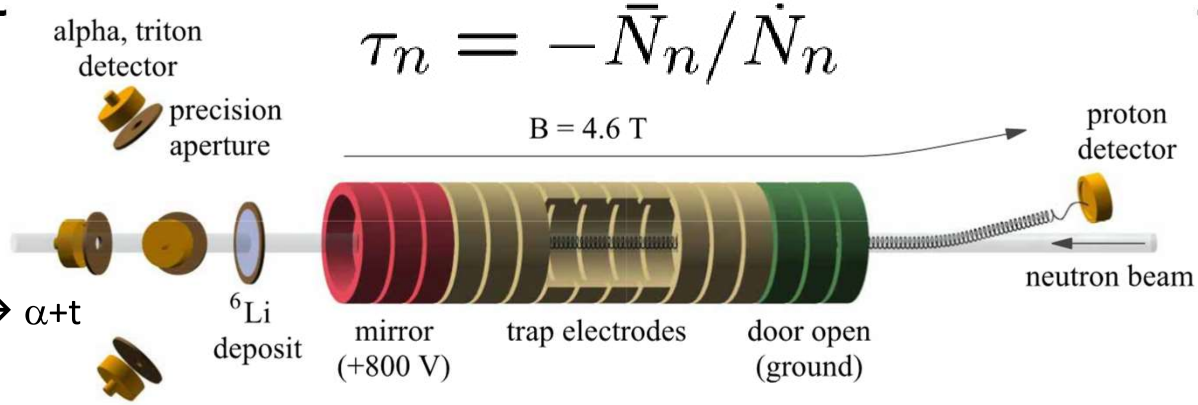


R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, Rev. Mod. Phys. 88, 015004 (2016)
L. Salvati et al. JCAP 1603 (2016) no.03, 055

Two ways to measure the neutron lifetime τ_n

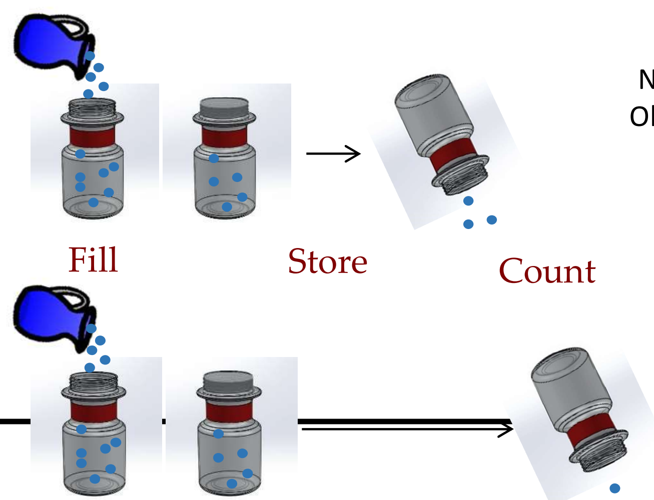
$$\tau_n = -\bar{N}_n / \dot{N}_n$$

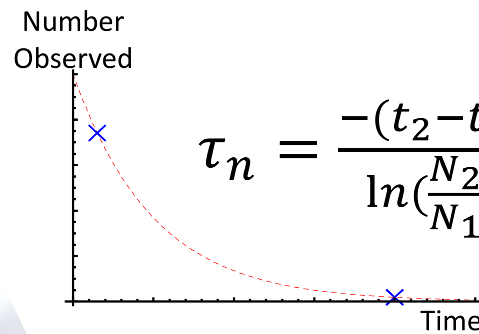
Cold Neutron Beam



n+^{6}Li→ α+t

Ultracold Neutron (UCN) Bottle





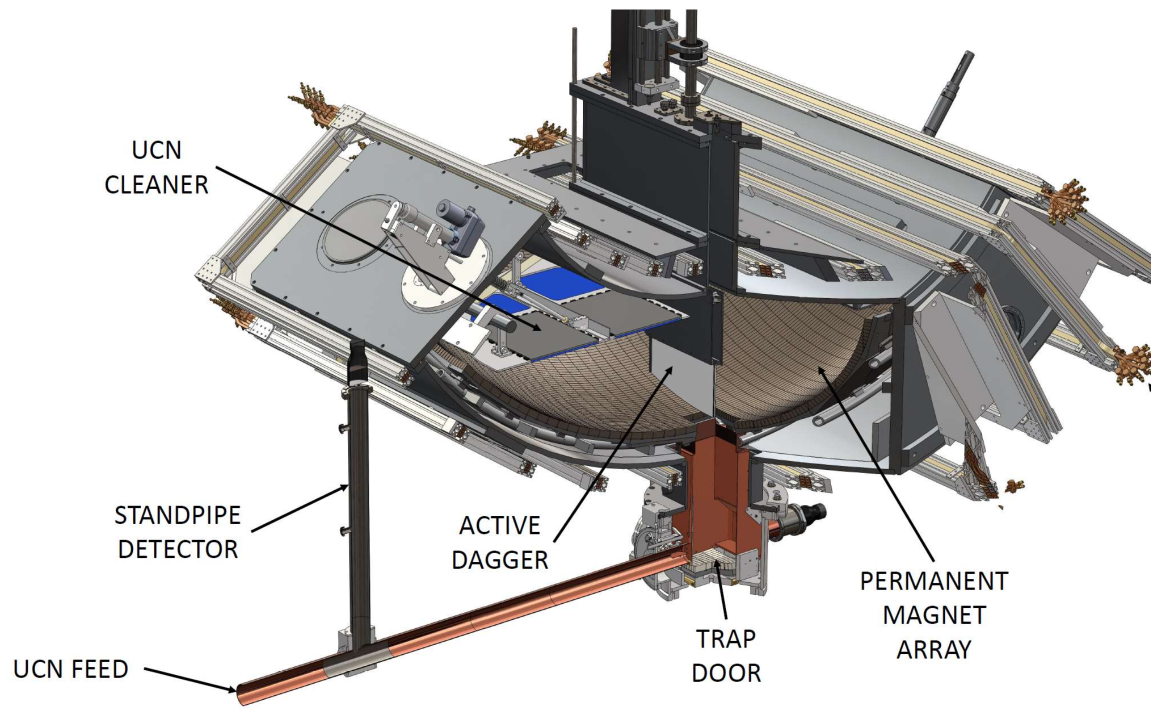
$$\tau_n = \frac{-(t_2 - t_1)}{\ln(\frac{N_2}{N_1})}$$

Halbach Array Completion: Dec 2012

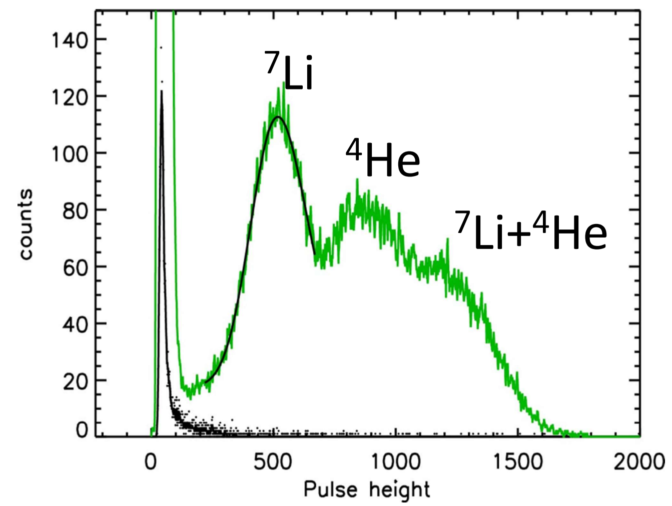
First UCN storage, D. Salvat, Phys. Rev. C 89, 052501 (2014)

Chen-Yu Liu

An *in-situ* UCN (dagger) detector

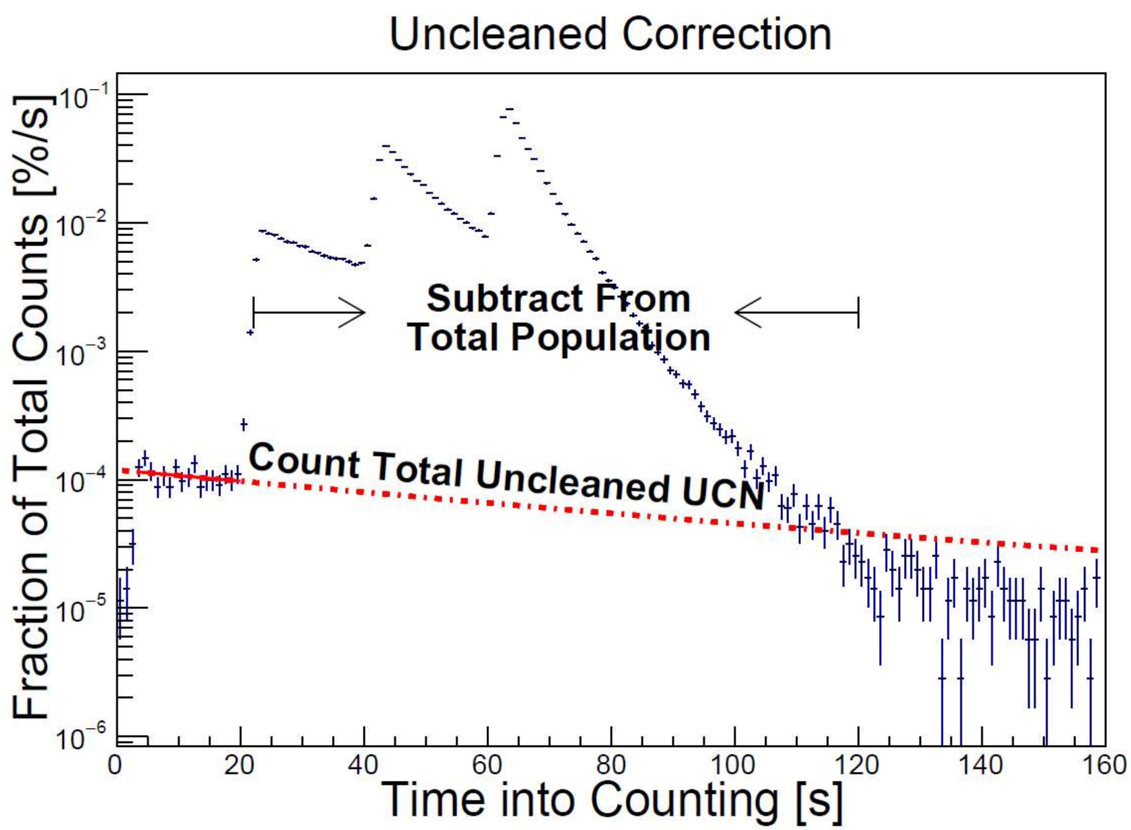


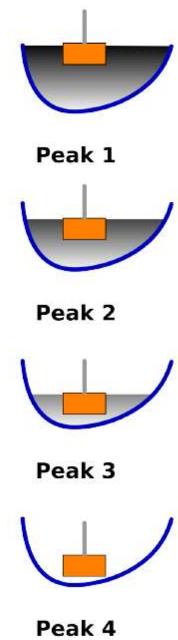
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$



Z. Wang et al., NIMA 798, 30 (2015).
C. Morris et al., RSI 88, 053508 (2017)

Multi-step UCN detection →control over-threshold UCN





Lifetime measurements better than 10^{-3} are challenging

- In UCNtau, we store N_1=25,000 neutrons, and count N_2=6000 neutrons after storing them for t_2-t_1=1000 s.
  100 neutrons unaccounted for (due to upscatter, spin flip, or heating) will *decrease* the measured neutron lifetime by 10 s.

$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ldots$$

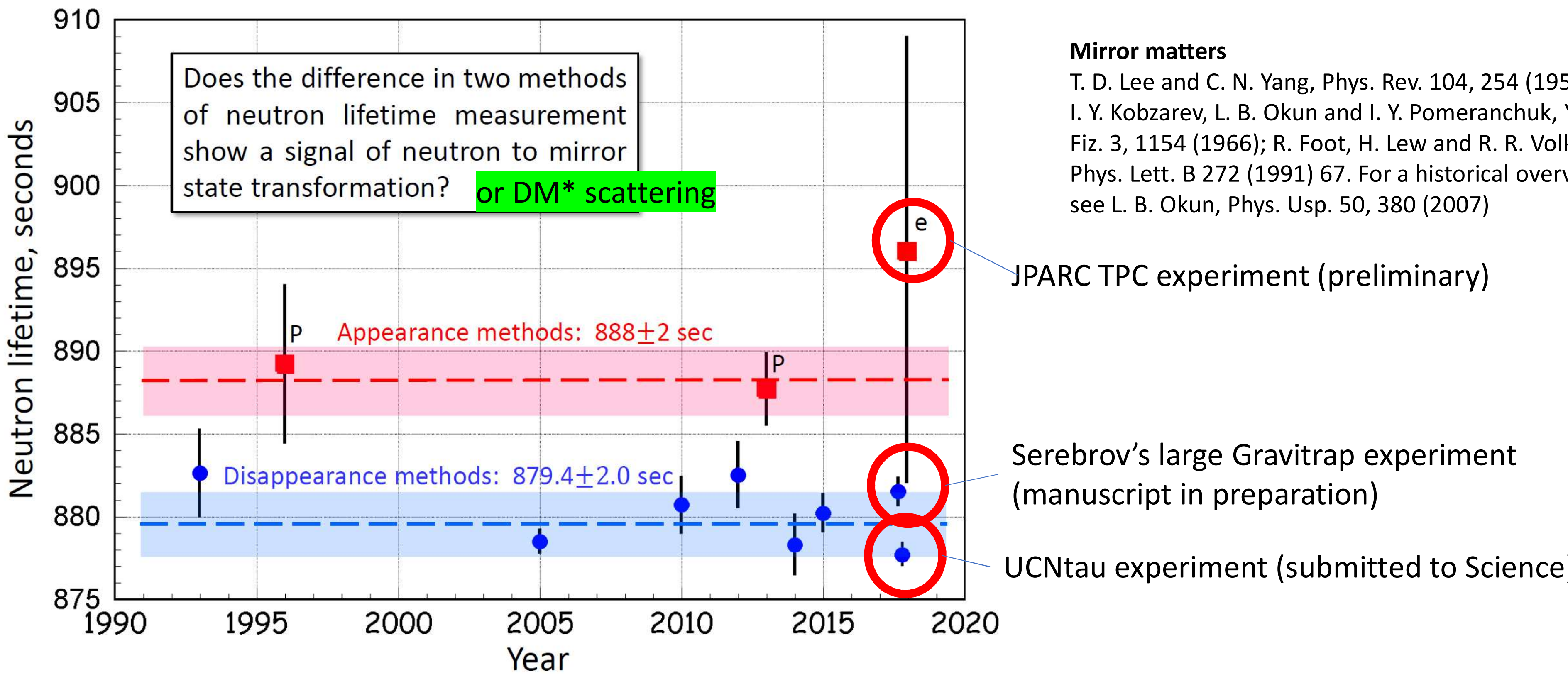
-

To reach 1 s, we can miss no more than 10 neutrons (per run).
To reach 0.1 s, no more than 1 neutron.

- In the beam experiment, underestimating the proton efficiency (storage, transport, detection) by 1 % will *increase* the measured neutron lifetime by 8 s.

Are neutrons disappearing at a rate faster than the rate of beta-decay?

*Crisis in 2000: mass density is dominated by unidentified dark matter & dark energy

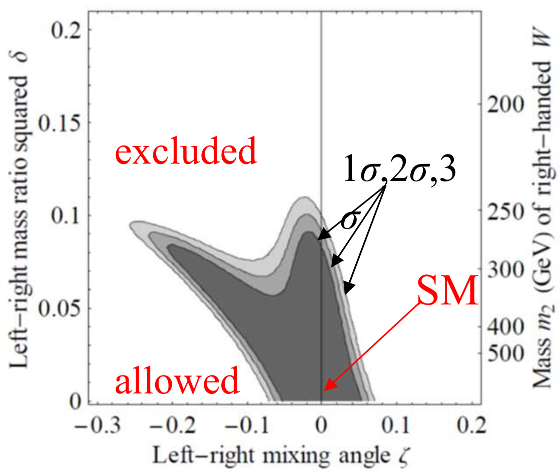


Mirror matters

T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956); I. Y. Kobzarev, L. B. Okun and I. Y. Pomeranchuk, Yad. Fiz. 3, 1154 (1966); R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B 272 (1991) 67. For a historical overview, see L. B. Okun, Phys. Usp. 50, 380 (2007)

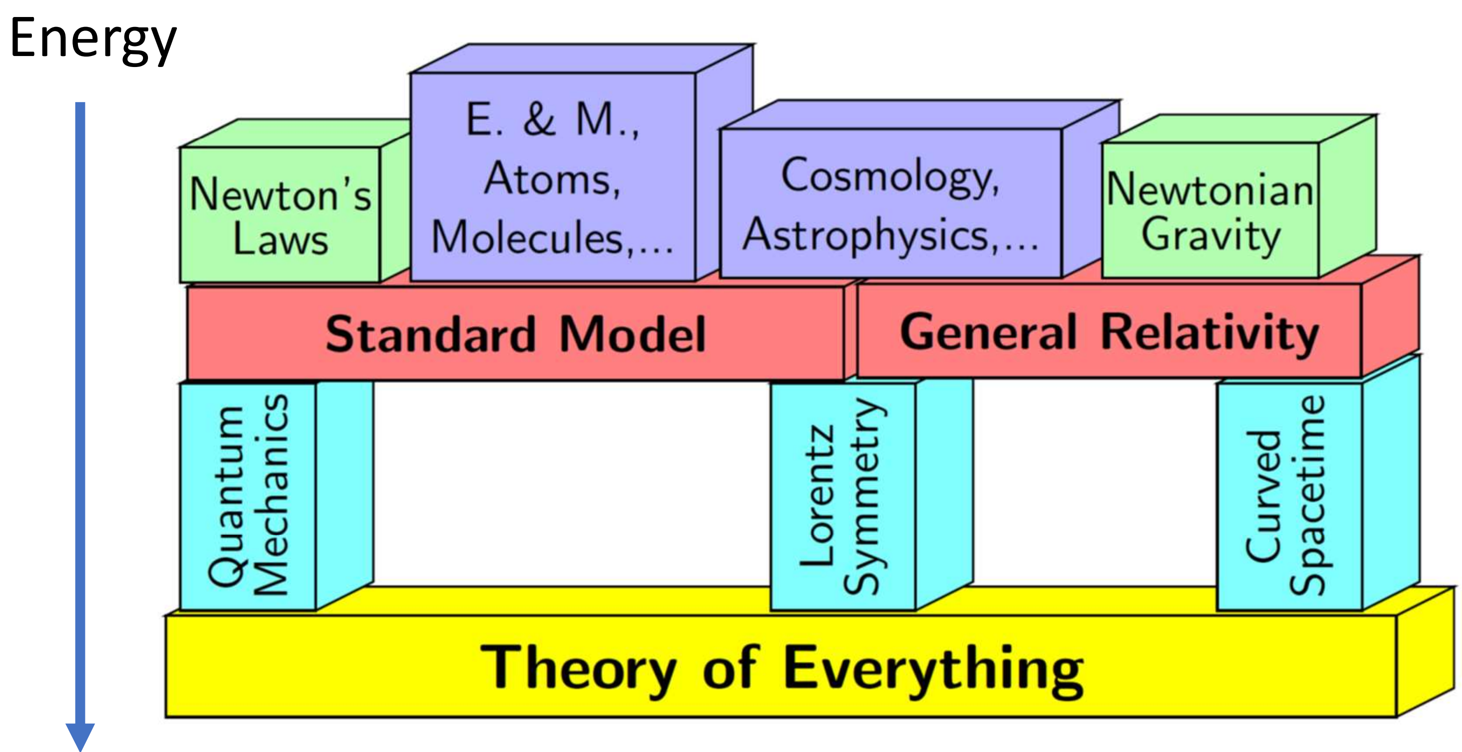
Summary on neutron beta-decay experiments

- SM tests:
  - A single parameter yields $\lambda = g_A/g_V$, multiple angular correlations yield V_{ud} (and S, T couplings)
  - New measurements on both *A* and τ_n have been shifting values.
  - CKM unitarity: Do neutrons and super-allowed beta decays agree?
- Searches for BSM new physics
  - right-handed currents (250 GeV limit from n decay)
  - Scalar and tensor couplings from *B* and *b*
- Neutron lifetime discrepancy
  - Neutron decays (bottle experiments) *faster* than the rate of beta-decay (beam experiments)



Holeczek et al., Acta Phys.Polon. B42 (2011) 2493-2499; arxiv 1303.5295 (2013)

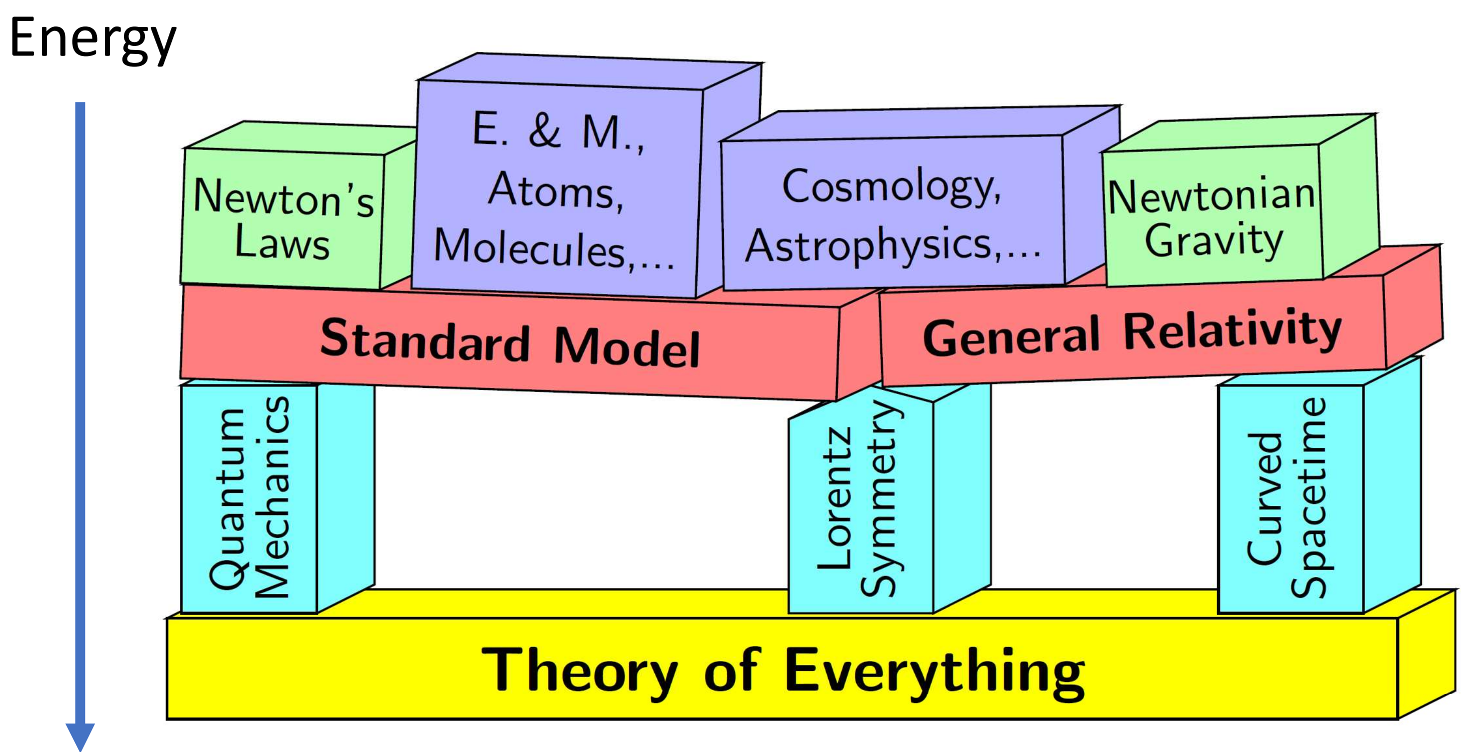
Physics is Symmetries



String theory, quantum gravity, non-commutative geometry,...

Slide courtesy: Matt Mewes

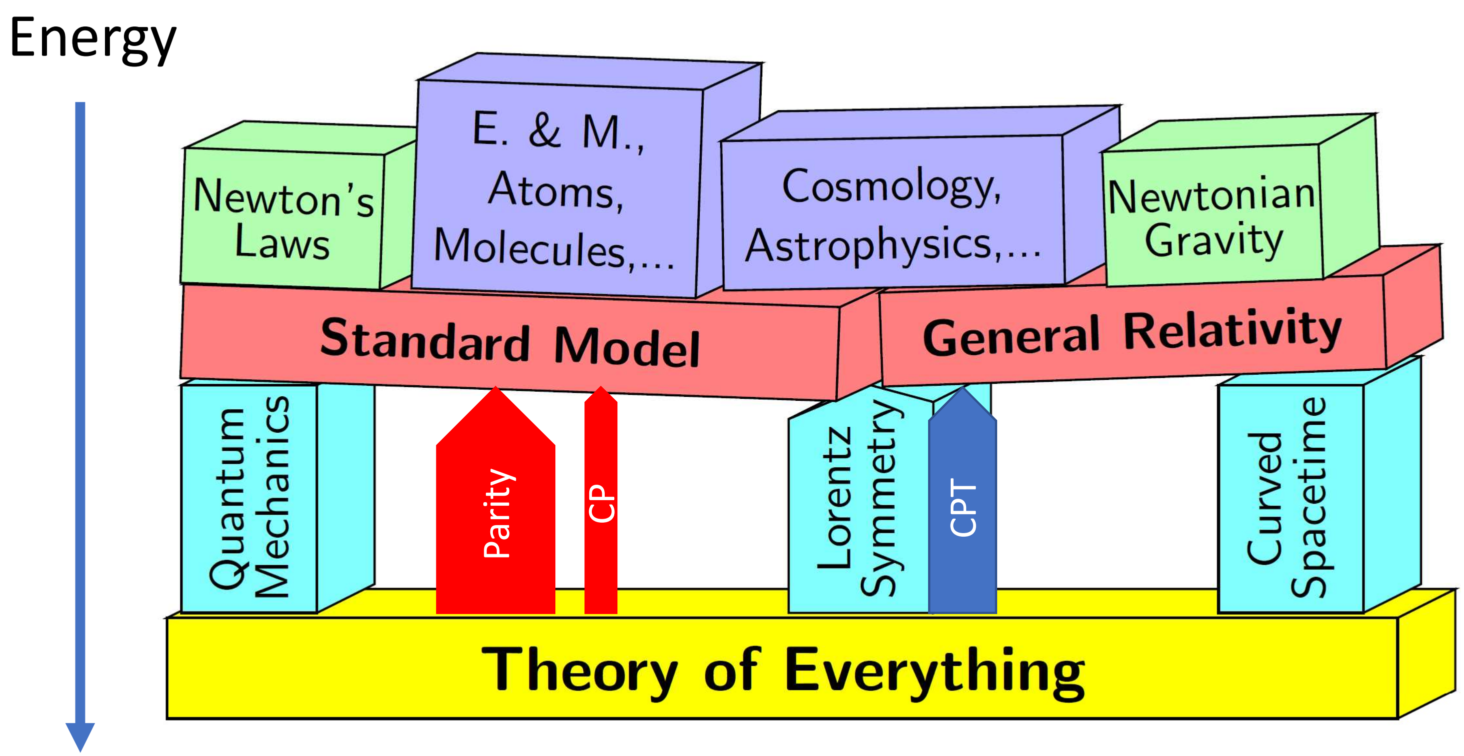
Question: Why Lorentz Violation?



String theory, quantum gravity, non-commutative geometry,...

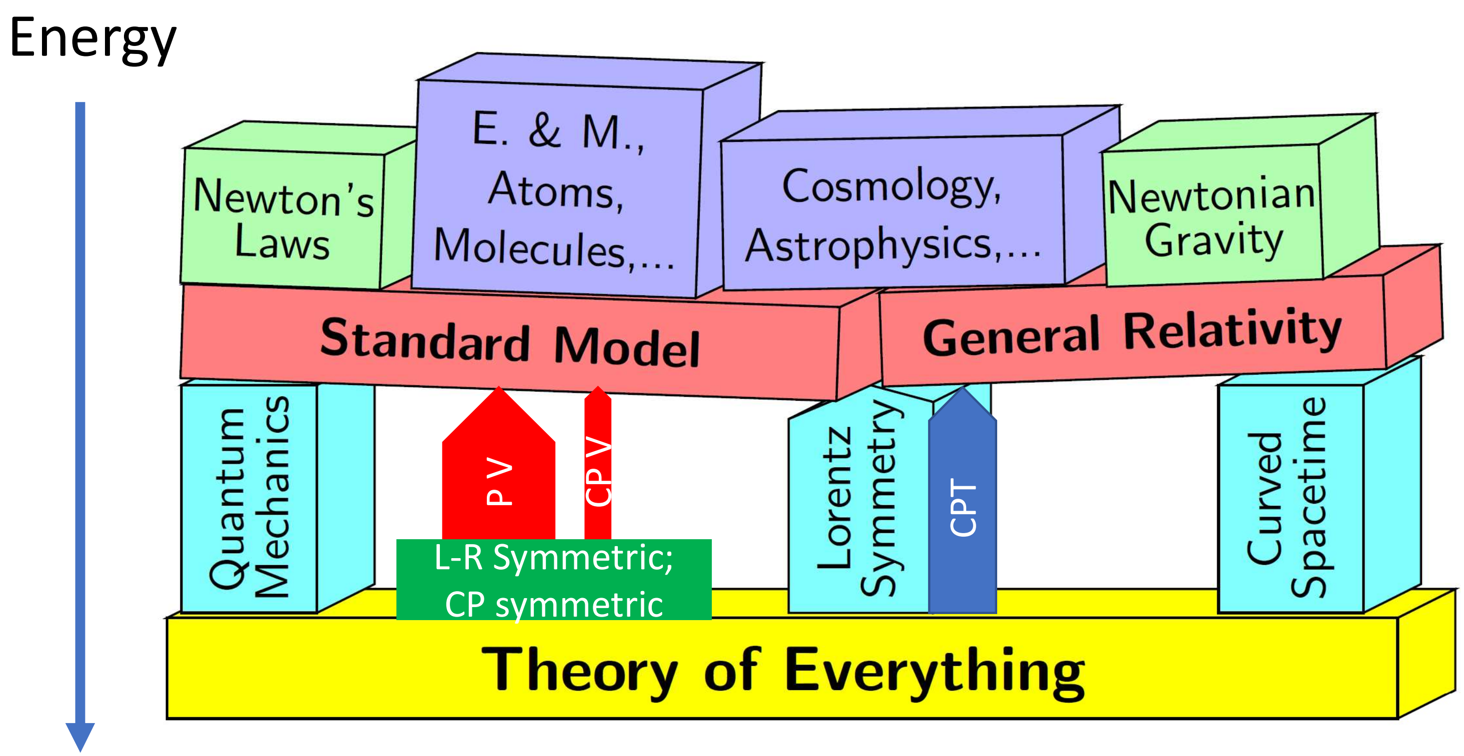
Slide courtesy: Matt Mewes

Question: Why Lorentz Violation? & Discrete Symmetries

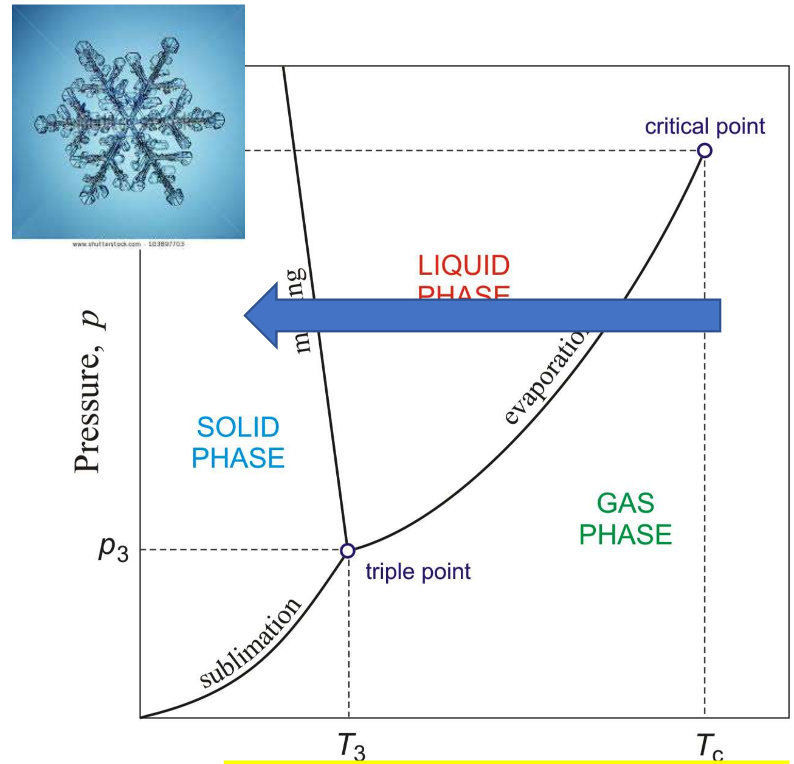


Question: Why Lorentz Violation?

& Discrete Symmetries

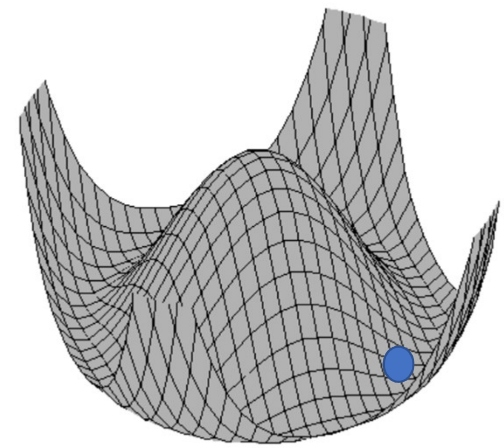


Phase Transitions



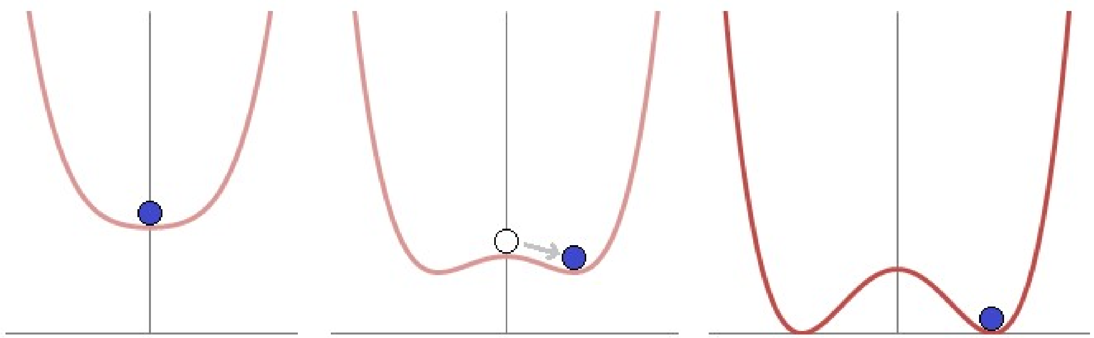
Symmetry is broken (at low T), after phase transition(s).

Spontaneous Symmetry Breaking

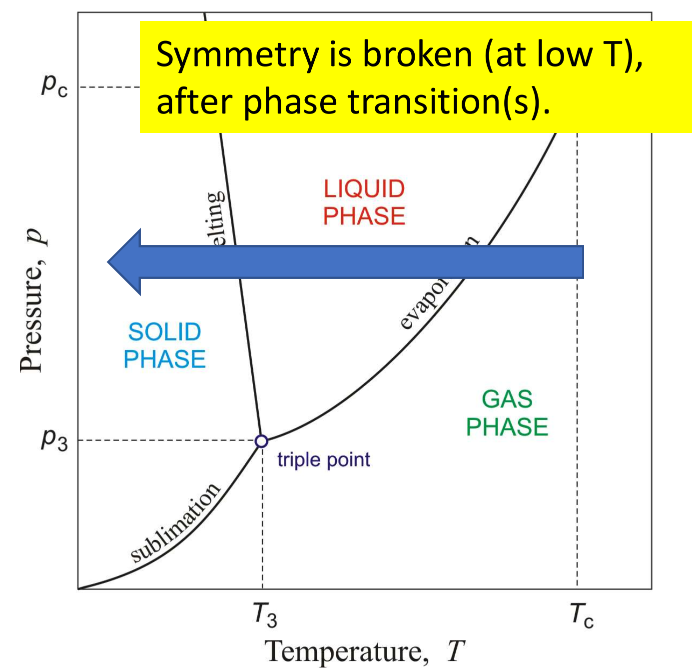


The simplest interacting QFT involves a Lorentz scalar field:

$$\mathcal{L} = \frac{1}{2}(\partial^{\mu}\phi)(\partial_{\nu}\phi) - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda\phi^4$$



L-R symmetry is broken

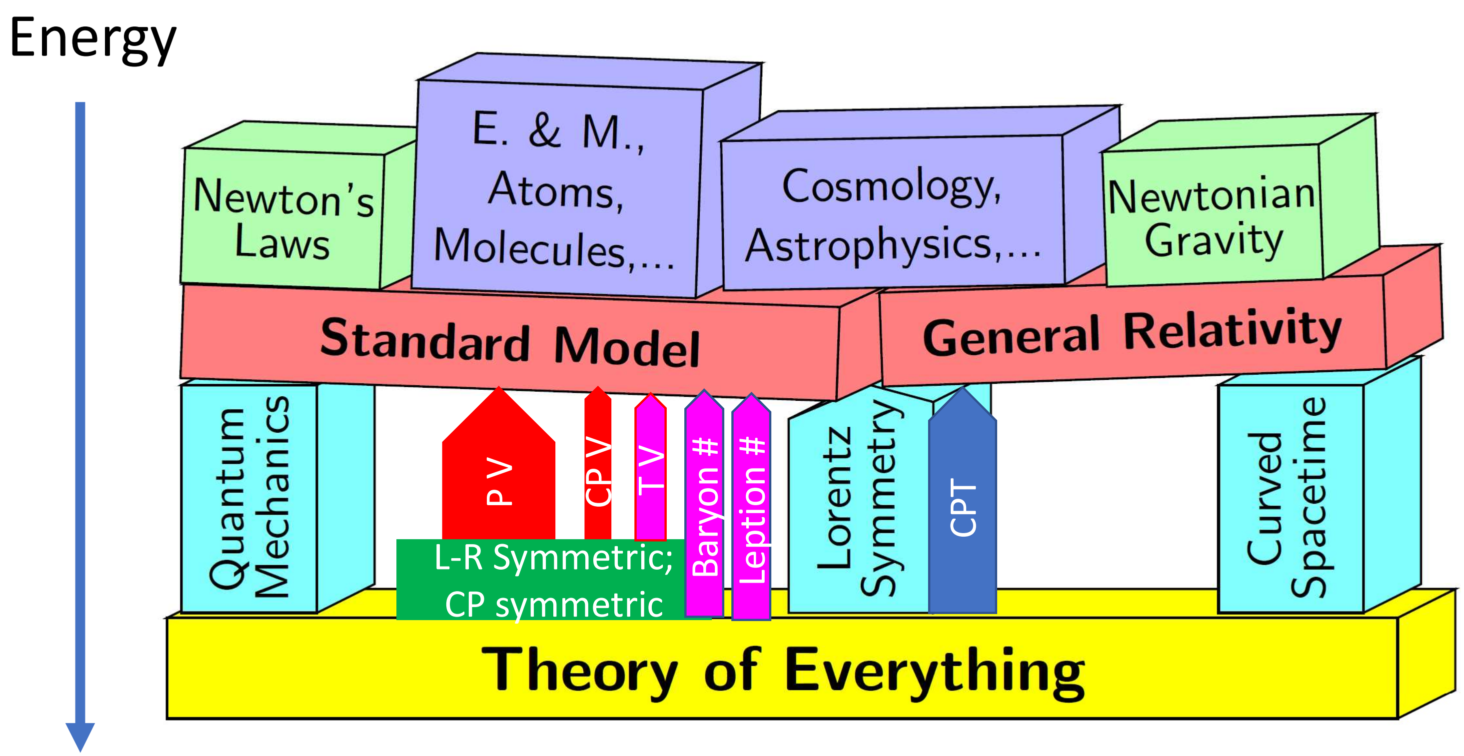


The (L-R) symmetry is respected in the Lagrangian,
but the (L-R) symmetry is broken in the particular solution.

Chen-Yu Liu

Question: Why Lorentz Violation?

& Discrete Symmetries



Answer: Symmetry violations (at low E-scales) are evidences, pointing to new physics that unifies all forces at high E-scales.

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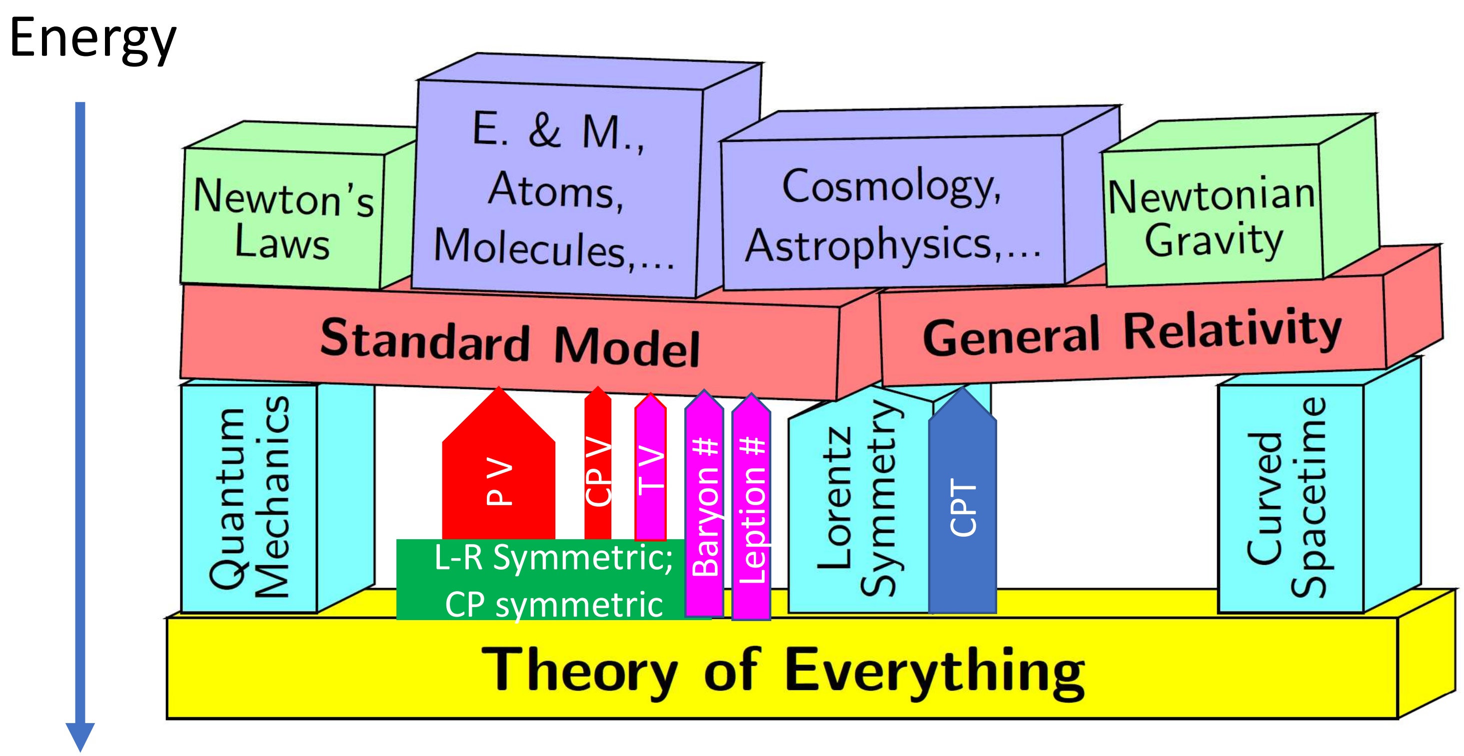

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Questions?