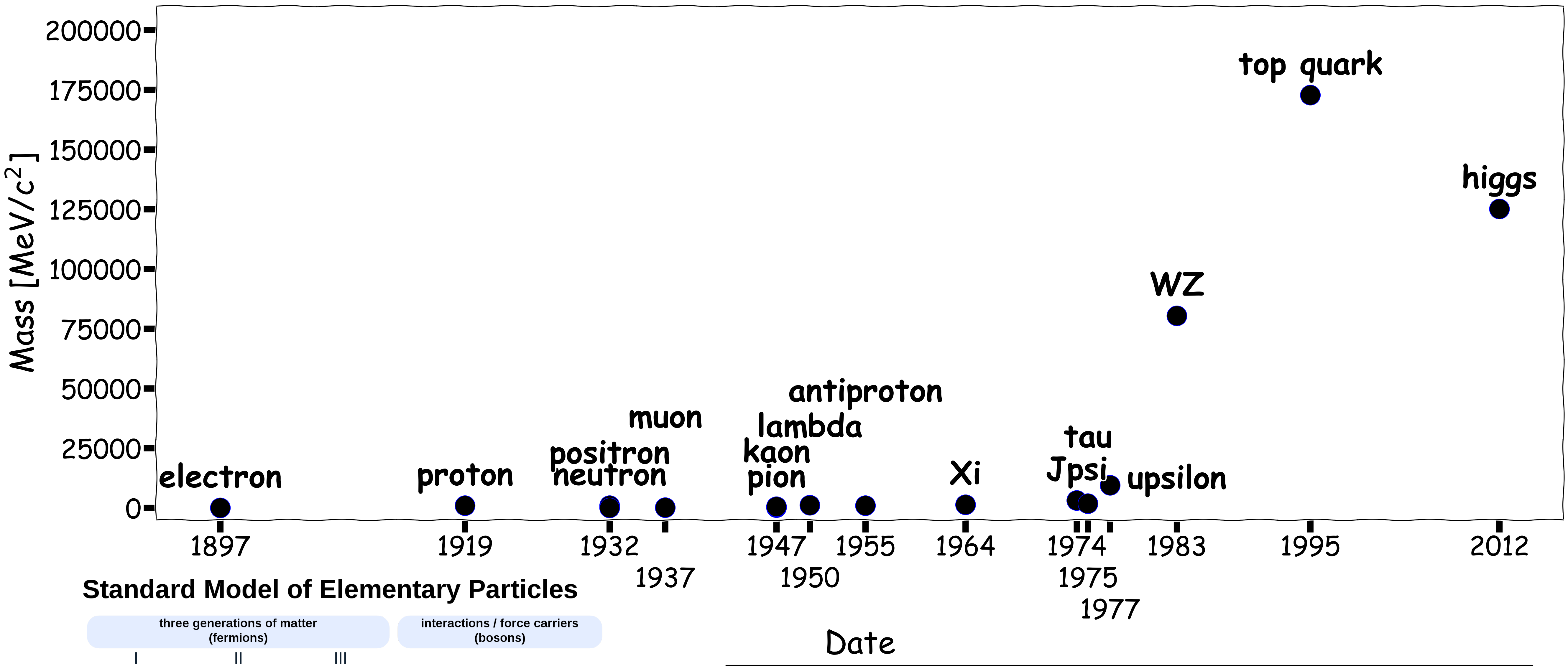
Neutrons II

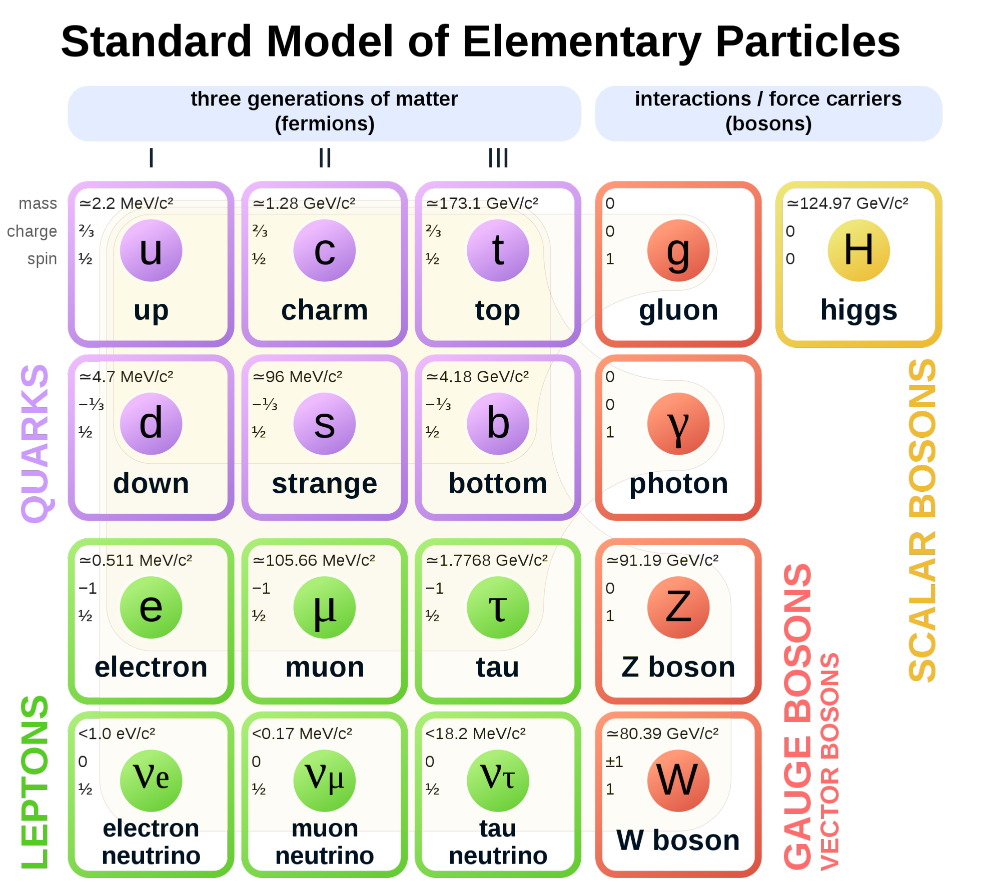
II.1 β-decay in Particle Physics
II.2 CKM Unitarity
II.3 Ultracold Neutrons

Adam Holley
Tennessee Technological University

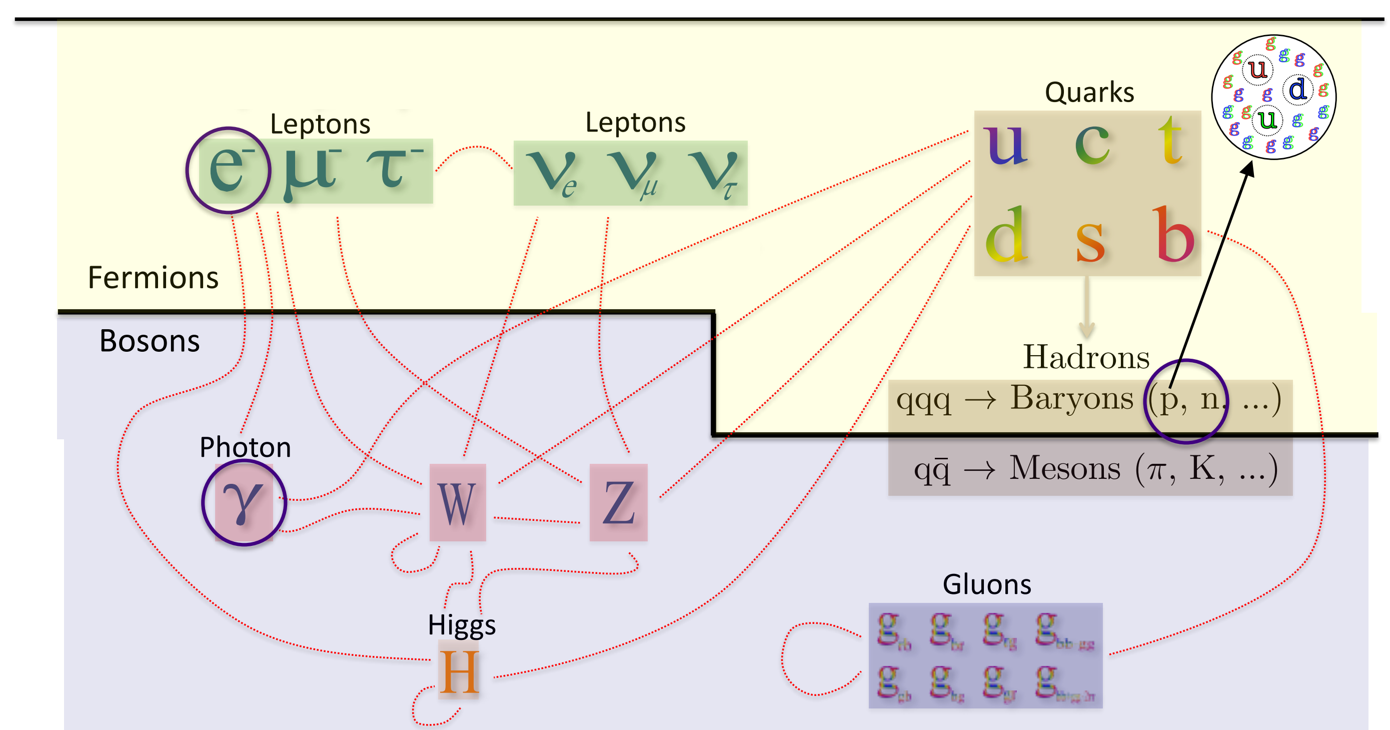
36th National Nuclear Summer School, July 2024
Indiana University, Bloomington

The Standard Model





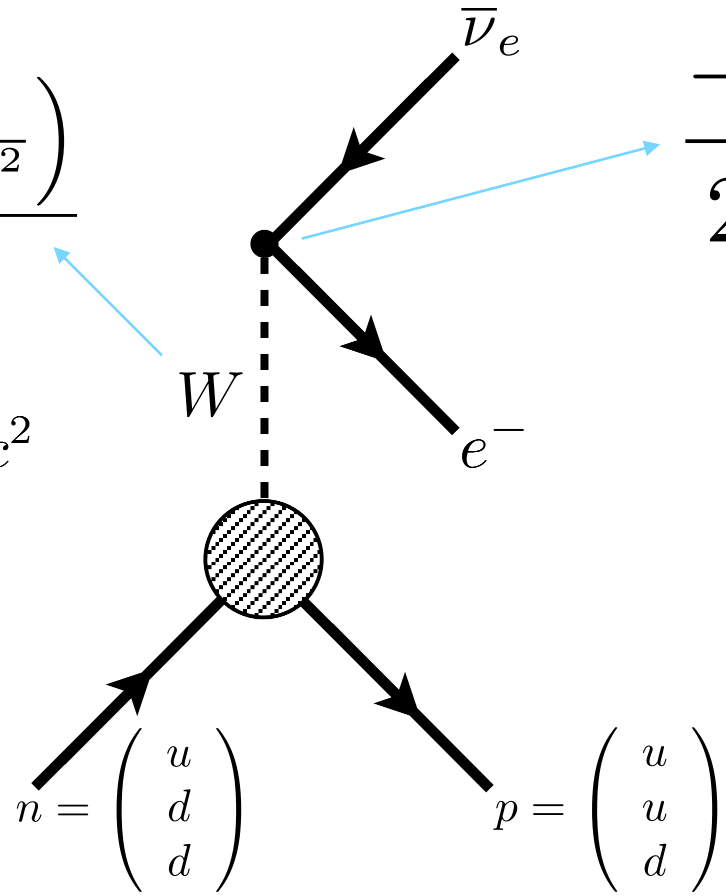
https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg



β-Decay "Particle Physics"

$$\frac{-i\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2 c^2}\right)}{q^2 - M_W^2 c^2}$$

$$M_W \simeq 80 \text{ GeV}/c^2$$



$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$ Weak "V-A" Coupling

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

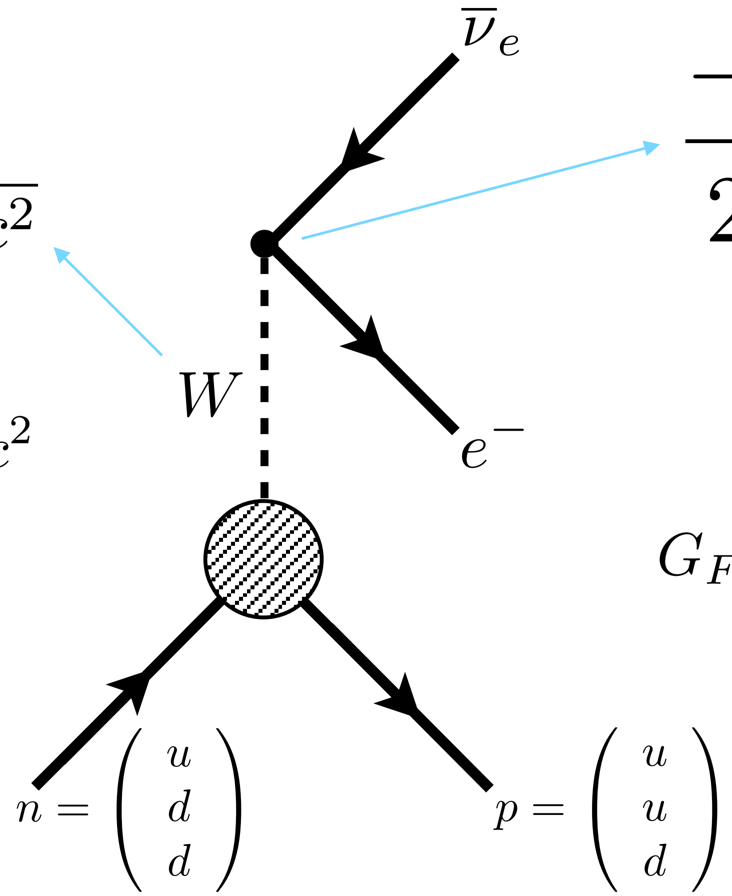
$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$P : \psi \longrightarrow \gamma^0\psi$$

$$\overline{\psi} \equiv \psi^\dagger\gamma^0$$

$\overline{\psi}\psi$	scalar
$\overline{\psi}\gamma^5\psi$	pseudoscalar
$\overline{\psi}\gamma^\mu\psi$	vector
$\overline{\psi}\gamma^\mu\gamma^5\psi$	pseudovector
$\overline{\psi}\frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\psi$	antisymmetric tensor

β-Decay "Particle Physics"



$$\frac{i g_{\mu\nu}}{M_W^2 c^2}$$

$$\frac{-i g_w}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5)$$ Weak "V-A" Coupling

$$M_W \simeq 80 \text{ GeV}/c^2$$

$$G_F/(\hbar c)^3 \equiv \frac{\sqrt{2}}{8} \left(\frac{g_w}{M_W c^2} \right)^2 \approx 1.2 \times 10^{-5} \ 1/\text{GeV}^2$$

Fermi Coupling Constant

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

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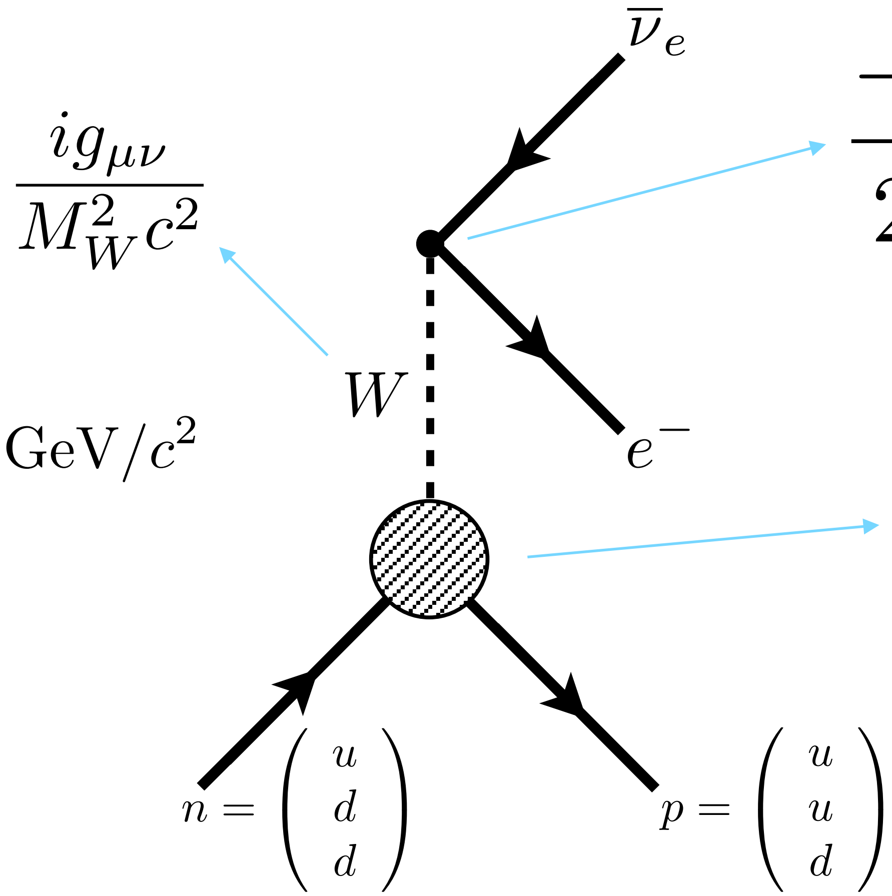

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$$M_W \simeq 80 \text{ GeV}/c^2$$

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(g_V^0 - g_A^0\gamma^5)$$

$$g_V^0 \equiv g_V(q^2=0)$$
$$g_A^0 \equiv g_A(q^2=0)$$

$$\text{CVC} \implies g_V^0 = 1$$ Required by Electroweak Unification

$$\lambda \equiv \frac{g_A^0}{g_V^0} \approx -1.275$$

"Partially" Conserved Axial Vector Current

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

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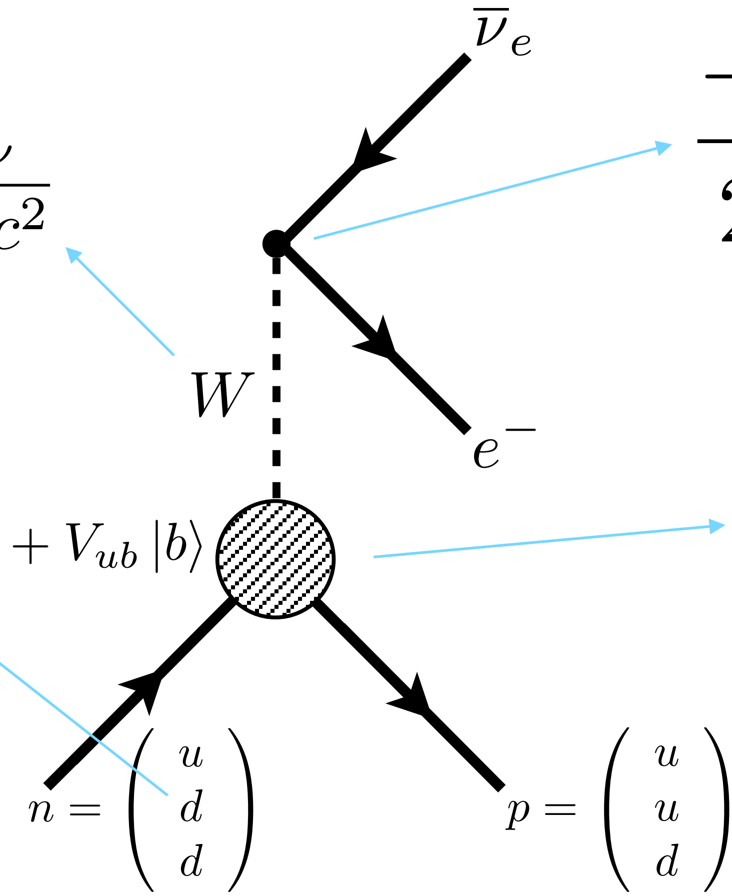

$$\frac{ig_{\mu\nu}}{M_W^2 c^2}$$

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$ Weak "V-A" Coupling

$$V_{ud}\,|d\rangle + V_{us}\,|s\rangle + V_{ub}\,|b\rangle$$

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(g_V^0 - g_A^0\gamma^5)$$

weak eigenstates — mass eigenstates

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

CKM Matrix

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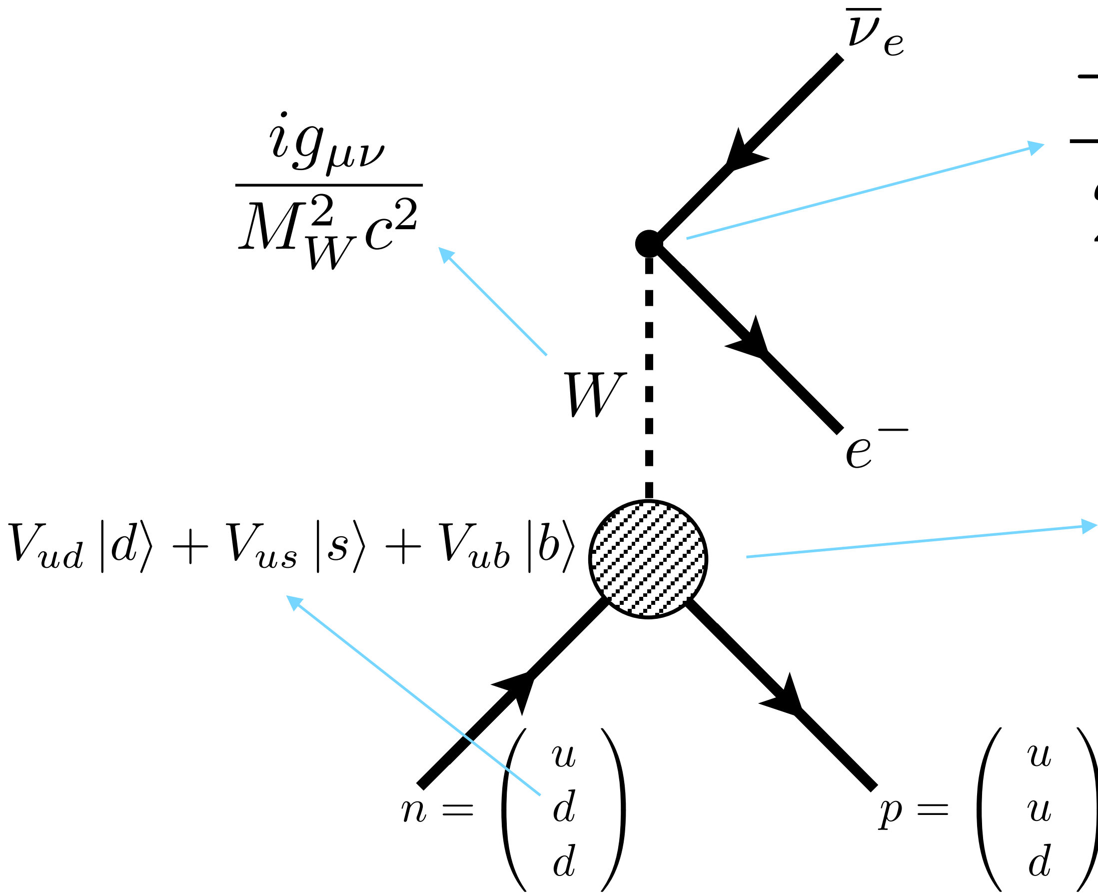

$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$ Weak "V-A" Coupling

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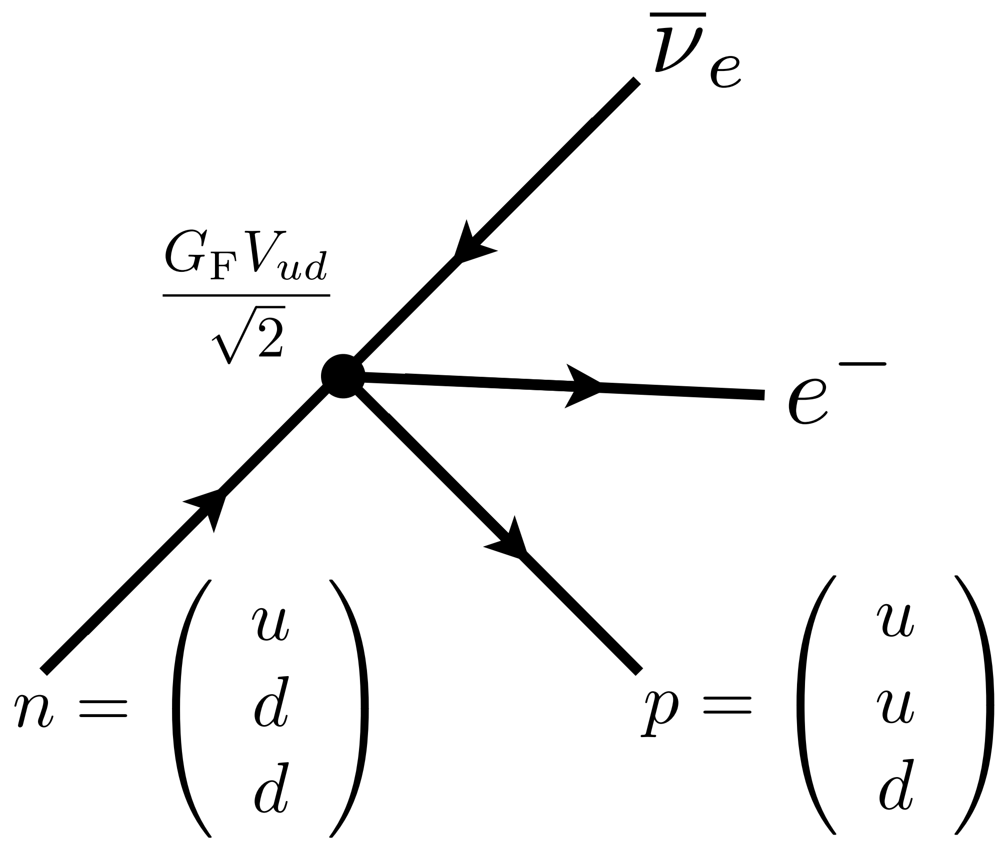


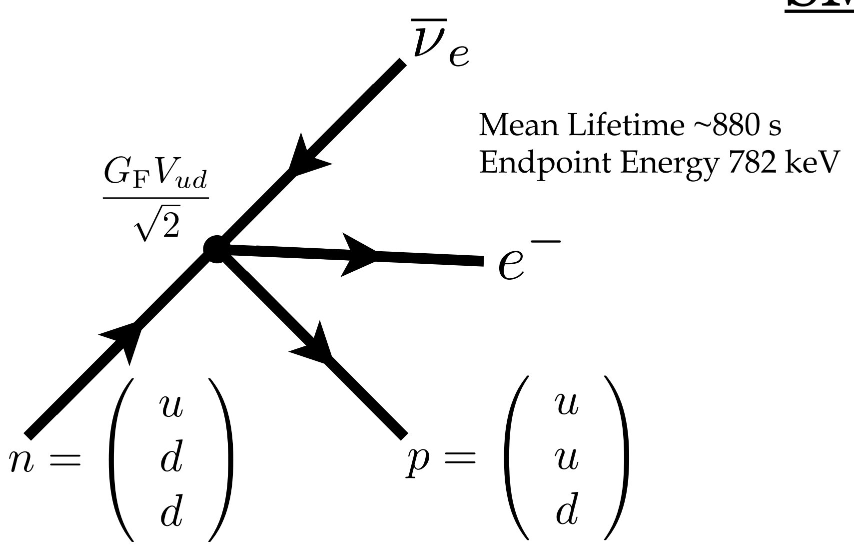
$$G_F \equiv \frac{\sqrt{2}}{8} \left(\frac{g_w}{M_W c^2} \right)^2$$

$$\overline{u}_p \left[\frac{-i g_w V_{ud}}{2\sqrt{2}} \gamma^\mu \left(g_V^0 - g_A^0 \gamma^5 \right) \right] u_n \left[\frac{i g_{\mu\nu}}{M_W^2 c^2} \right] \overline{u}_e \left[\frac{-i g_w}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5) \right] u_{\bar{\nu}}$$

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \, \overline{u}_p \left[\gamma^\mu \left(g_V^0 - g_A^0 \gamma^5 \right) \right] u_n \overline{u}_e \left[\gamma_\mu (1 - \gamma^5) \right] u_{\bar{\nu}}$$

1% Weak Magnetism q-dependent term (tensor coupling) not included

β-Decay "Particle Physics"



SM β-decay parameters

CKM Matrix Element V_{ud}

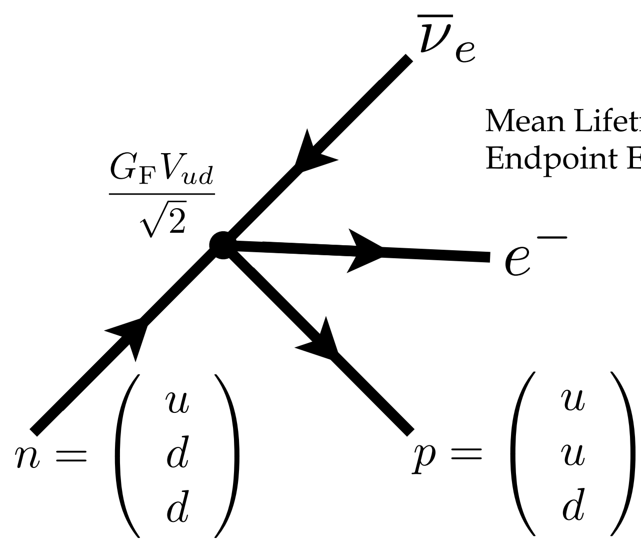
Ratio of axial-vector to vector form factors $\lambda \equiv \left| \frac{g_A}{g_V} \right| e^{i\phi}$

$$\tau_n = \left[\frac{2\pi^3 \hbar^7 c^6}{G_F^2 (m_e c^2)^5} \right] \left[\frac{1}{V_{ud}^2 (1 + 3|\lambda|^2)} \right]$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \propto G_\mathrm{F}^2 \left|V_{ud}\right|^2 \left(g_V^2 + 3g_A^2\right) F(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_e} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

β-Decay "Particle Physics"

SM β-decay parameters



Mean Lifetime ~880 s
Endpoint Energy 782 keV

CKM Matrix Element V_{ud}

Ratio of axial-vector to vector form factors $\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{i\phi}$

$\frac{\Delta\tau_n}{\tau_n} \simeq 0.5\%^*$

$$\tau_n = \frac{(4908.7 \pm 1.9)s}{|V_{ud}|^2(1+3|\lambda|^2)}$$

$\frac{\Delta\lambda}{\lambda} = 0.2\%$

$D = (-1 \pm 2) \times 10^{-4}$

$\phi = (180.02 \pm 0.03)^\circ$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \propto G_F^2 |V_{ud}|^2 (g_V^2 + 3g_A^2) F(E_e) \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_e} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

Electron-Antineutrino Asymmetry (a), $\frac{\Delta a}{a} = 3.8\%$

Fierz Interference (b)

T-odd Triple Product (D)

Spin-Antineutrino Asymmetry (B), $\frac{\Delta B}{B} = 0.8\%$

β-Asymmetry (A), $\frac{\Delta A}{A} = 0.8\%^*$

$$b = \frac{2}{1+3|\lambda|^2}[g_S \varepsilon_S - 12\lambda g_T \varepsilon_T]$$

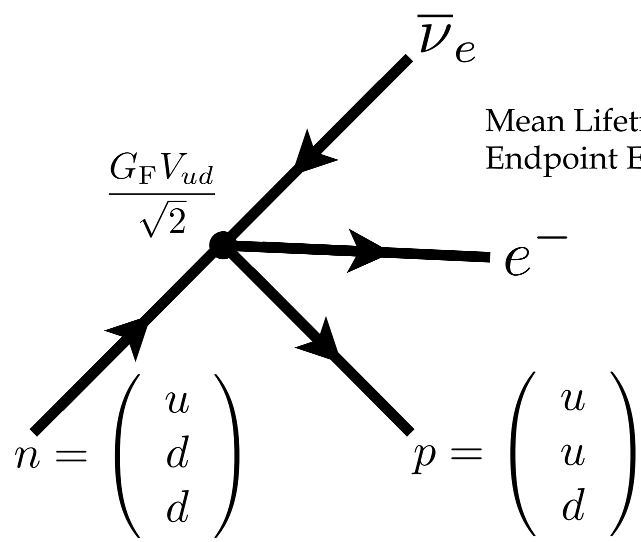
$$A_{\mathrm{meas}}(E_e) = \frac{A(E_e)}{1 + b\frac{m_e}{E_e}}$$

$$A_0 = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$

$$B = B_0 + \frac{m_e}{E_e} b_\nu$$

$$b_\nu = \frac{2}{1+3|\lambda|^2}[g_S \varepsilon_S \lambda - 4 g_T \varepsilon_T (1 + 2\lambda)]$$

Testing the Standard Model: CKM Unitarity



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o vector form factors $\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{i\phi}$

$= \frac{(4908.7 \pm 1.}{|V_{ud}|^2(1+3}$

In the SM, the x is unitary,
e.g. $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$
This affords a classic SM test!

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto G_F^2 |V_{ud}|^2 (g_V^2 + 3g_A^2) F(E_e) \left[1 \quad \frac{\vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_e} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)\right]$$

Electron-Antineutrino Asymmetry

Spin-Antineutrino Asymmetry

β-Asymmetry

$$A_0 = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$

weak eigenstates mass eigenstates

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

CKM Matrix

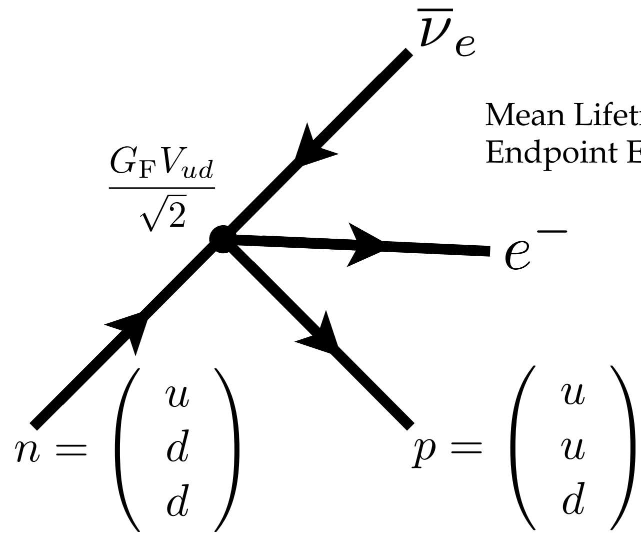
$|V_{ud}| = 0.97373 \pm 0.00031$

$|V_{us}| = 0.2243 \pm 0.0008 \longrightarrow$ $K_L^0 \longrightarrow \pi e \nu,\ K_L^0 \longrightarrow \pi \mu \nu$; $K^\pm \longrightarrow \pi^0 e^\pm \nu,\ K^\pm \longrightarrow \pi^0 \mu^\pm \nu$; $K_S^0 \longrightarrow \pi e \nu$

$|V_{ub}| = (3.81 \pm 0.20) \times 10^{-3}$ (inclusive $B \longrightarrow X_u l \overline{\nu}$)

Testing the Standard Model: CKM Unitarity

SM β-decay parameters



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Electron-Antineutrino Asymmetry (a)

Spin-Antineutrino Asymmetry (B)

β-Asymmetry (A)

For $0^+ \longrightarrow 0^+$, $|M_{GT}| = 0$

outer radiative corrections (1.5%)

isospin breaking

$$ft_{1/2}(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{2\pi^3\hbar^7 \ln(2)}{m_e^5 c^4} \frac{1}{2V_{ud}^2 G_F^2 (1+\Delta_R^V)}$$

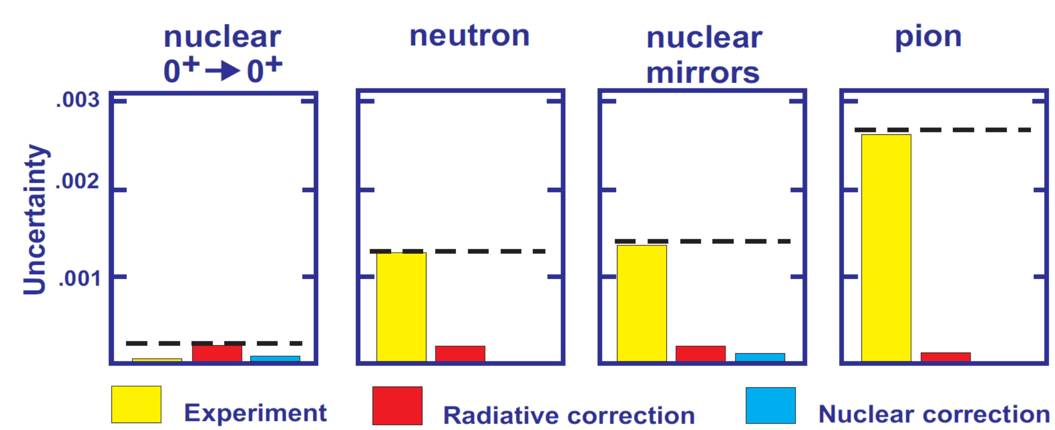
experimental observable

nuclear structure

0.3% – 1.5%

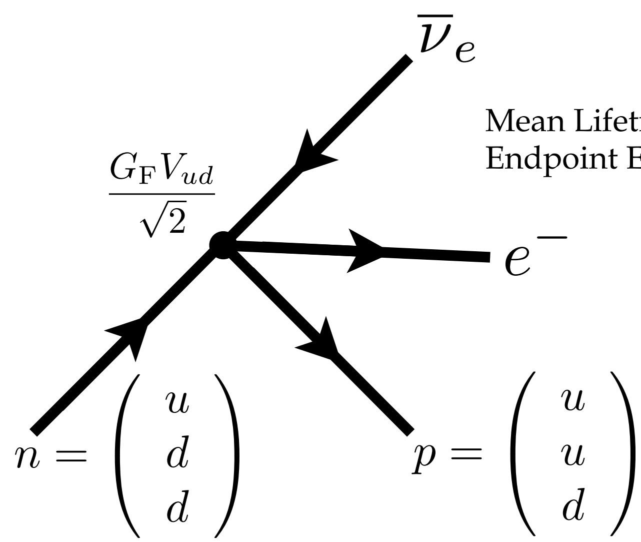
universal transition independent or "inner"
2.4%

$$A_0 = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$



Hardy and Towner CIPANP 2015

Testing the Standard Model: CKM Unitarity



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For $0^+ \longrightarrow 0^+,\ |M_{GT}| = 0$

All infrared-seneitive RC not included in Fermi function

outer radiative corrections (1.5%)

Deviation of M_{fi} from $\sqrt{2}$

isospin breaking

$$ft_{1/2}(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{2\pi^3\hbar^7\ln(2)}{m_e^5c^4}\frac{1}{2V_{ud}^2G_F^2(1+\Delta_R^V)}$$

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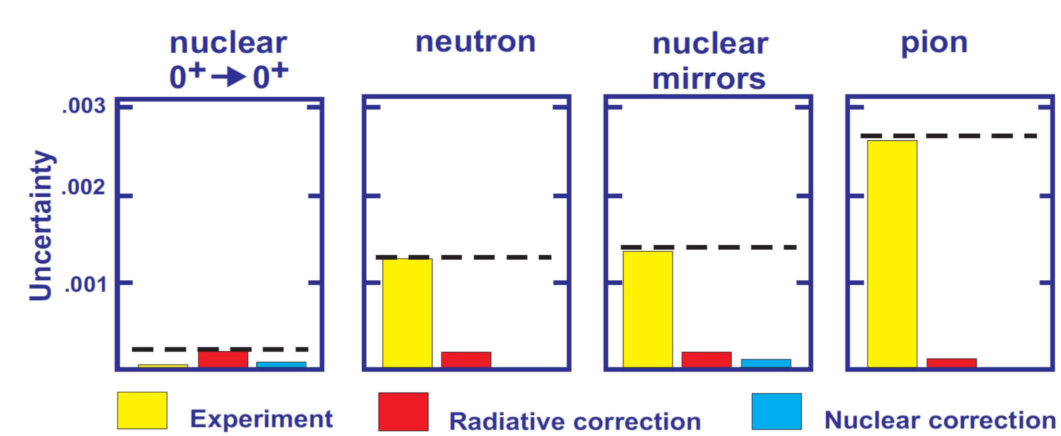

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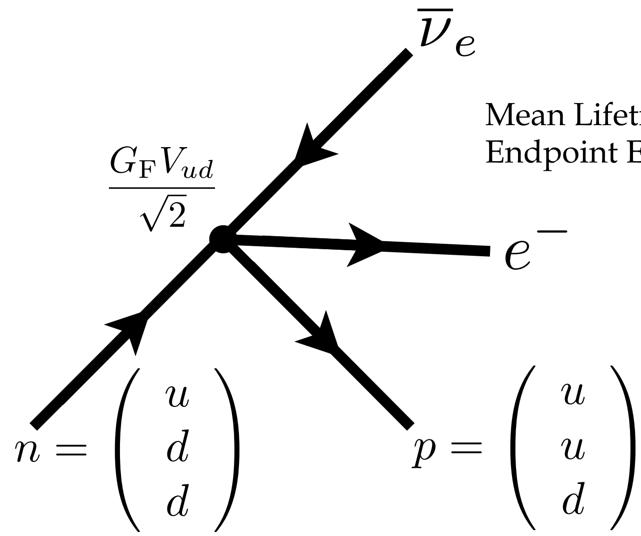

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Recently "in the news"

For $0^+ \longrightarrow 0^+$, $|M_{GT}| = 0$

outer radiative corrections (1.5%)

$$ft_{1/2}(1 + \delta_R')(1 + \delta_{NS} - \delta_C) = \frac{2\pi^3 \hbar^7 \ln(2)}{m_e^5 c^4} \frac{1}{2V_{ud}^2 G_F^2 (1 + \Delta_R^V)}$$

experimental observable

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0.3% – 1.5%

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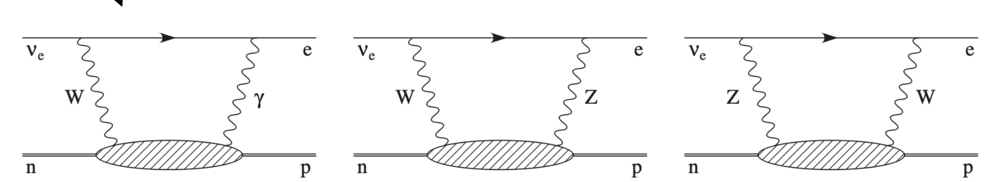
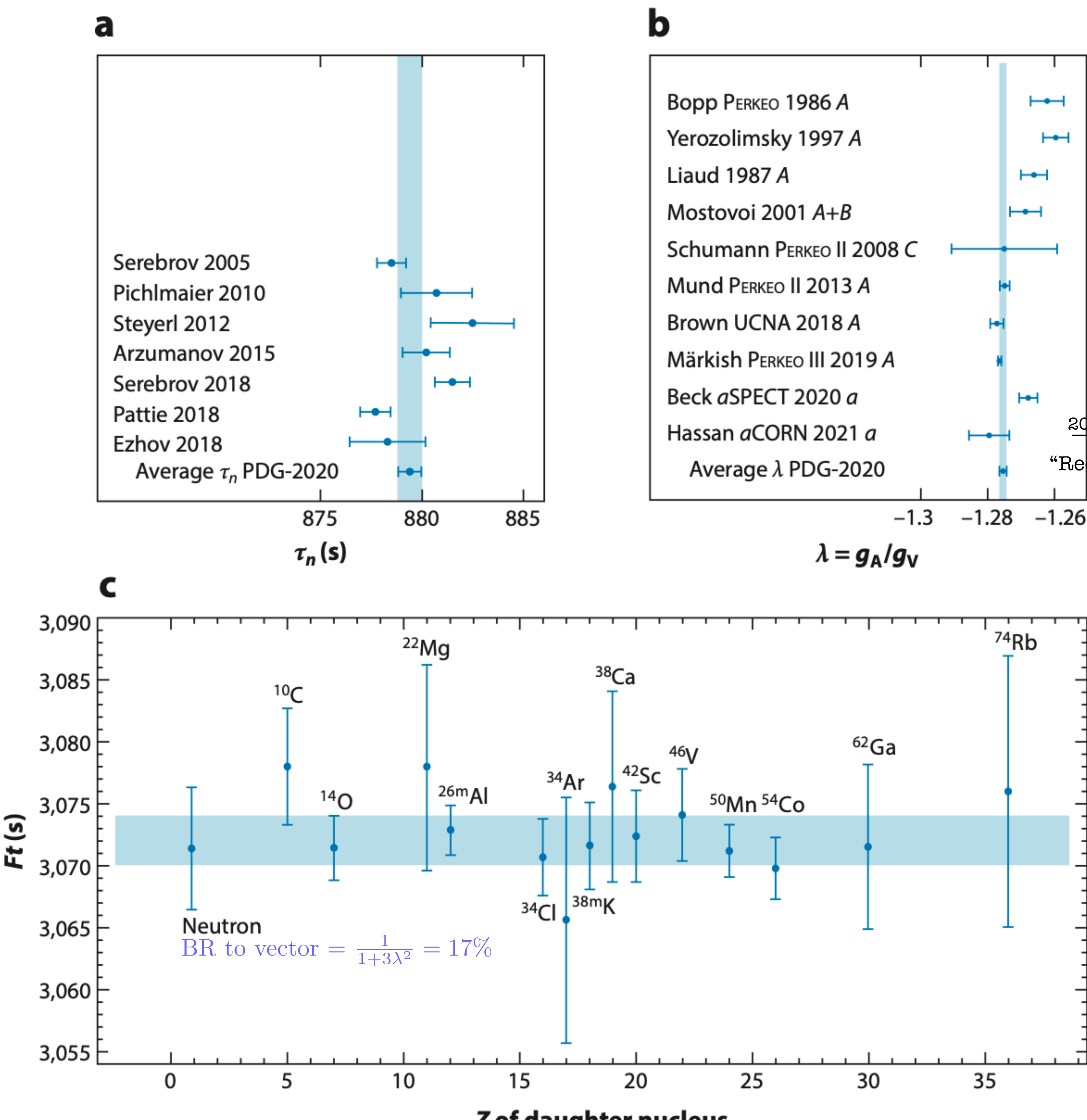
$\square_{\gamma W}$



A. Czarnecki, et al. Phys. Rev. D **100**, 073008 (2019)

Testing the Standard Model: CKM Unitarity



$\xrightarrow{2024} -1.2712 \pm 0.0061$

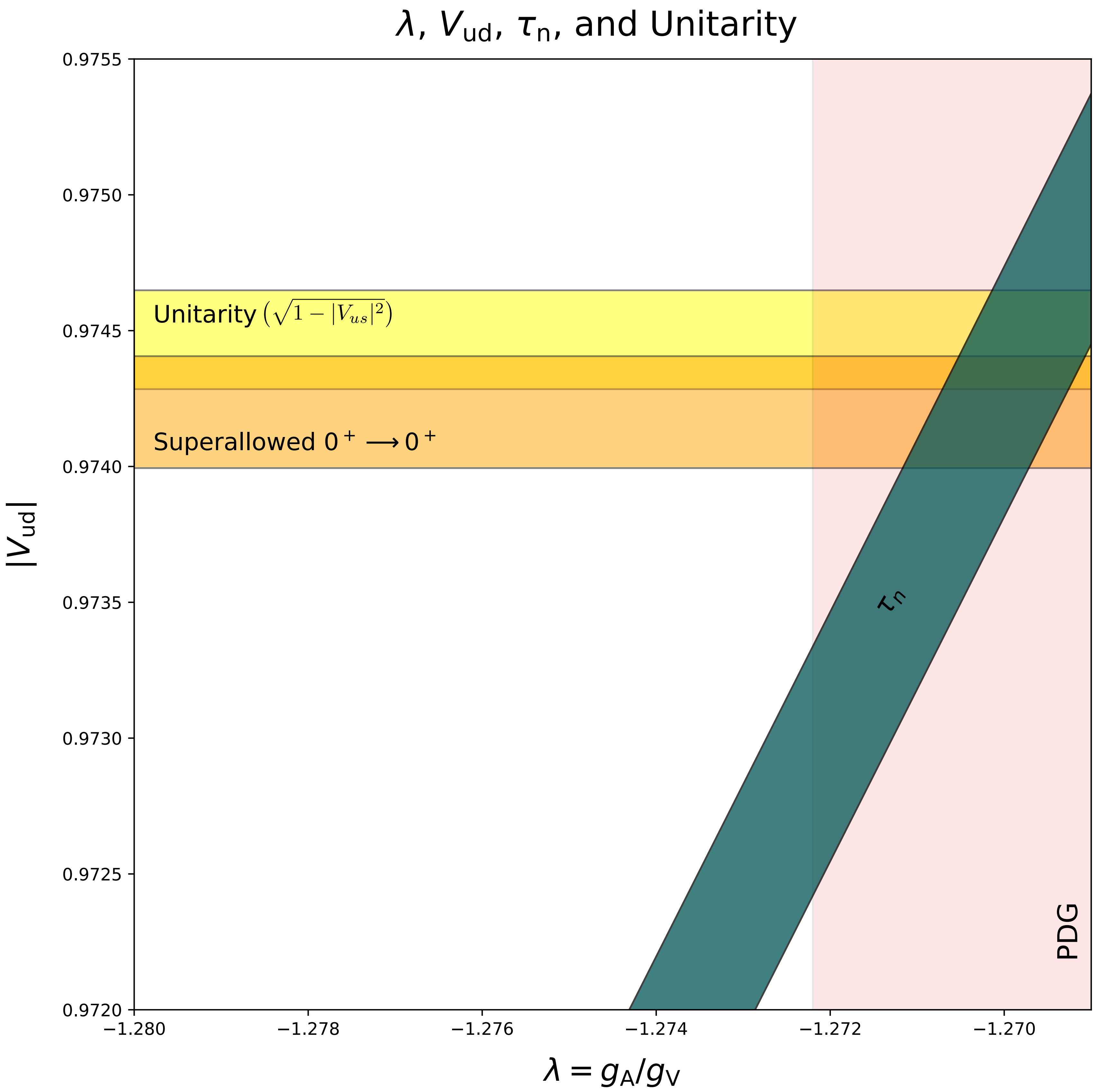
"Recoil" Outer Radiative Corrections

includes non-universal corrections →

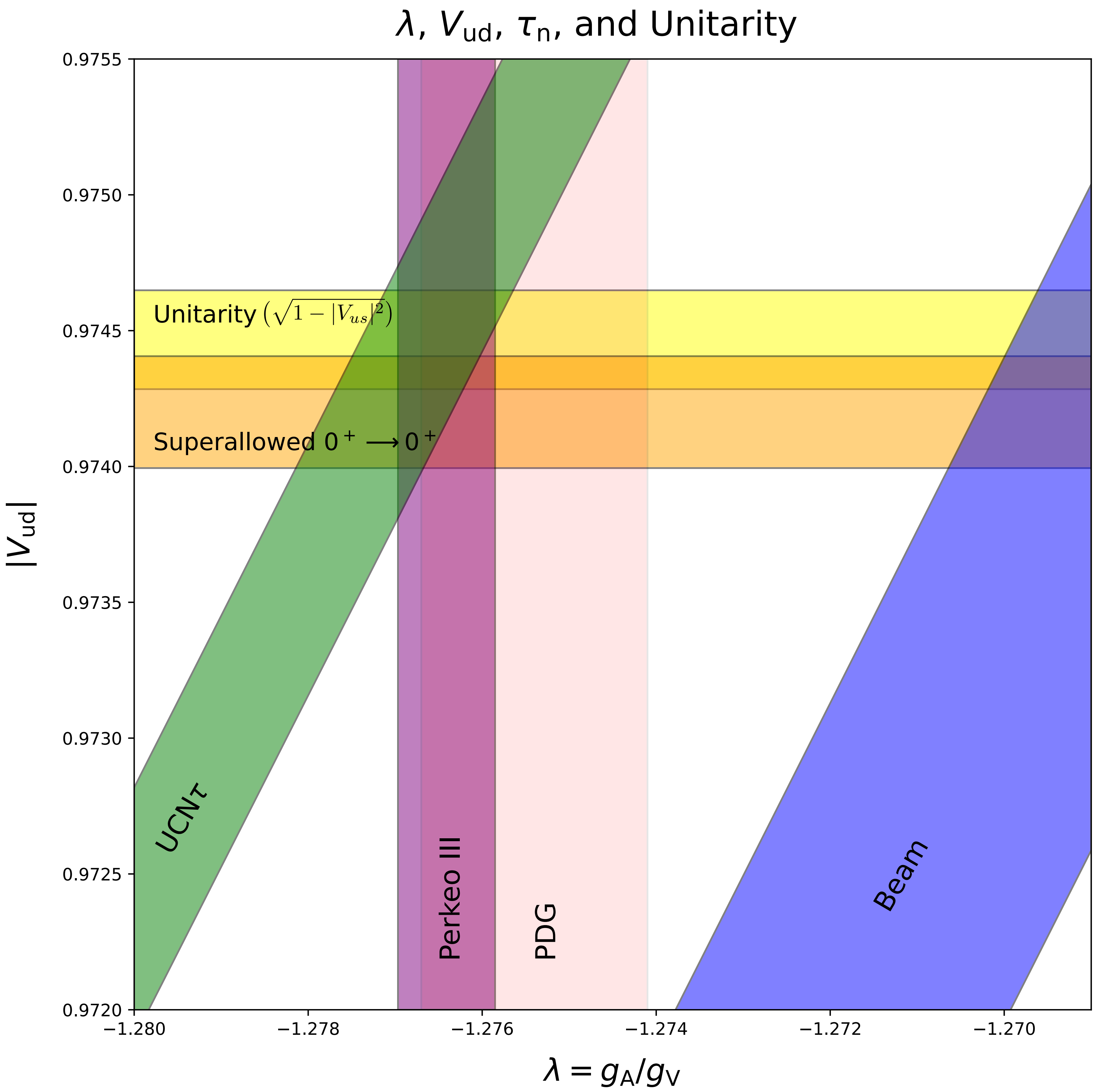
BR to vector $= \frac{1}{1+3\lambda^2} = 17\%$

D. Dubbers and B. Märkisch, Annu. Rev. Nucl. Part. Sci. 2021.71:139-163

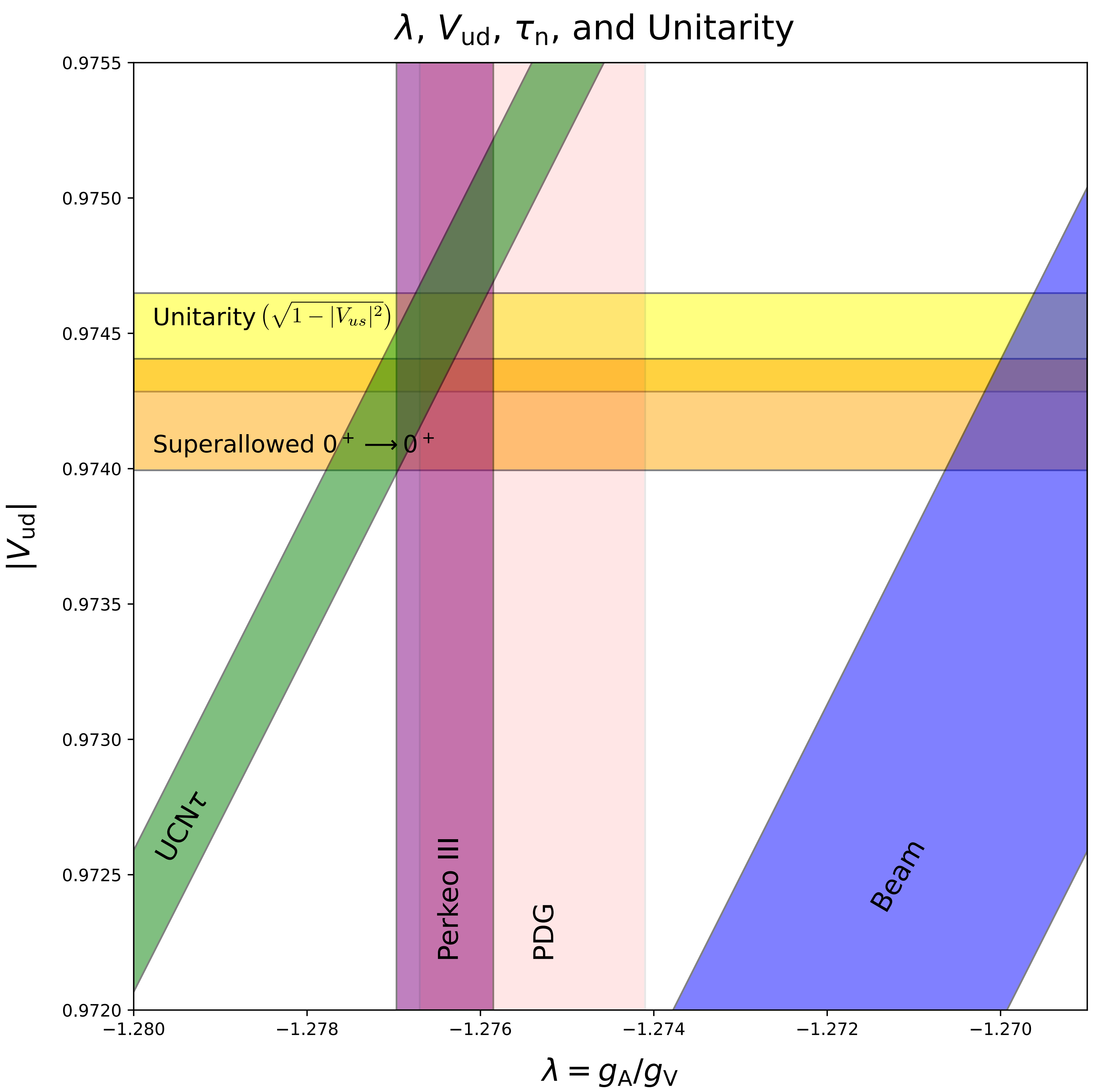
Testing the Standard Model (before 2010)



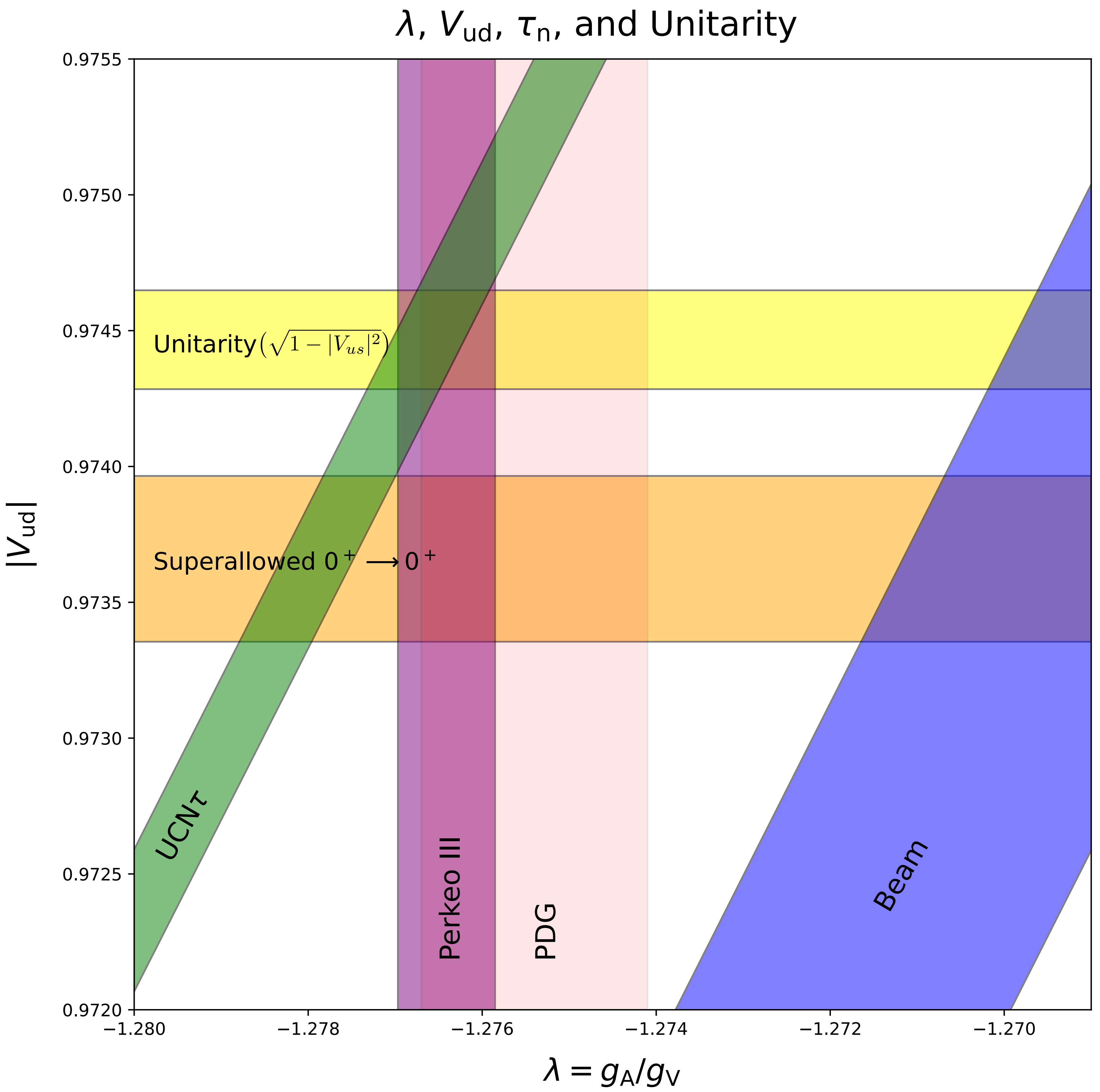
Testing the Standard Model (circa early 2017)



Testing the Standard Model (circa early 2018)



Testing the Standard Model (circa late 2018)



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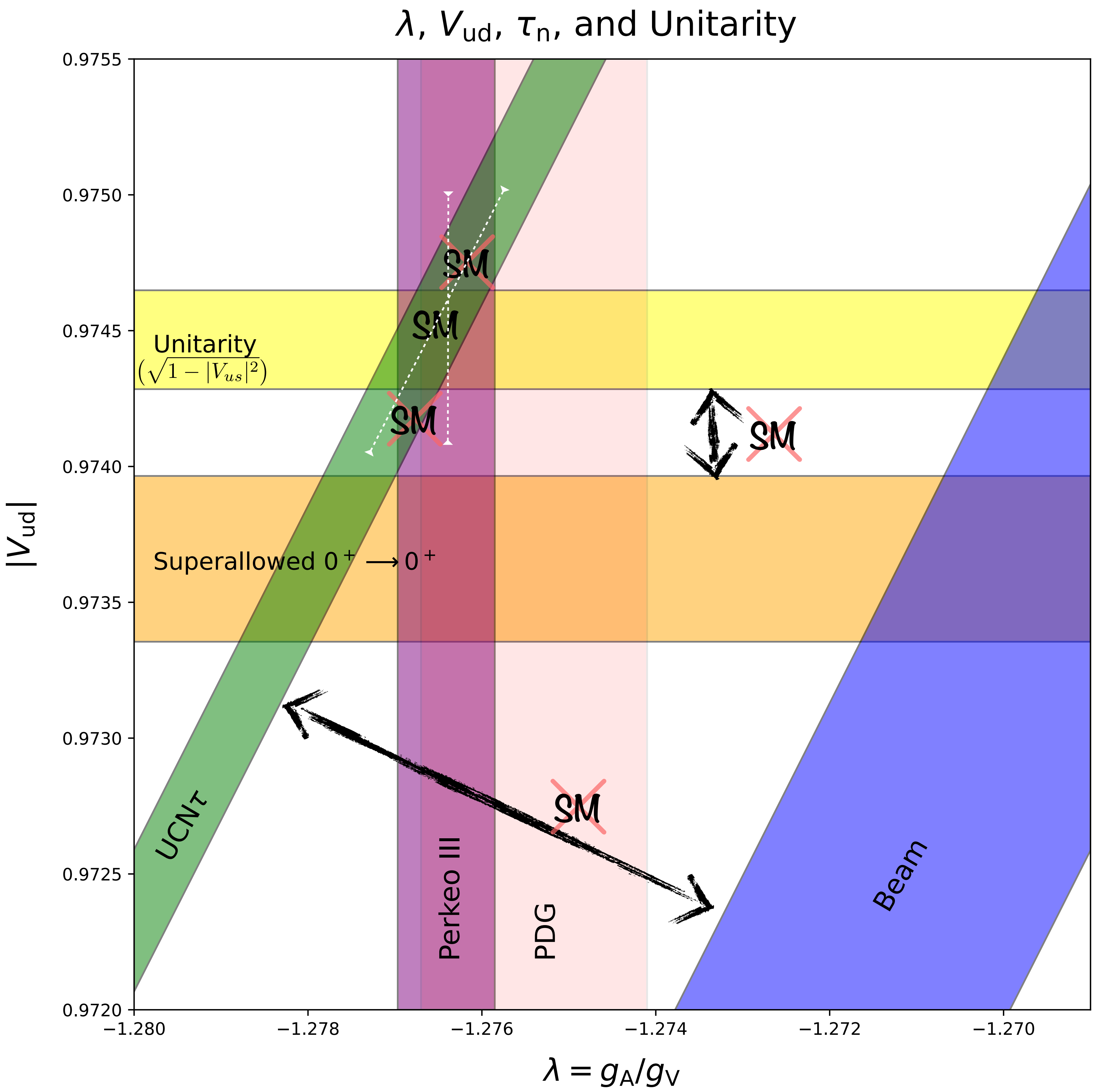

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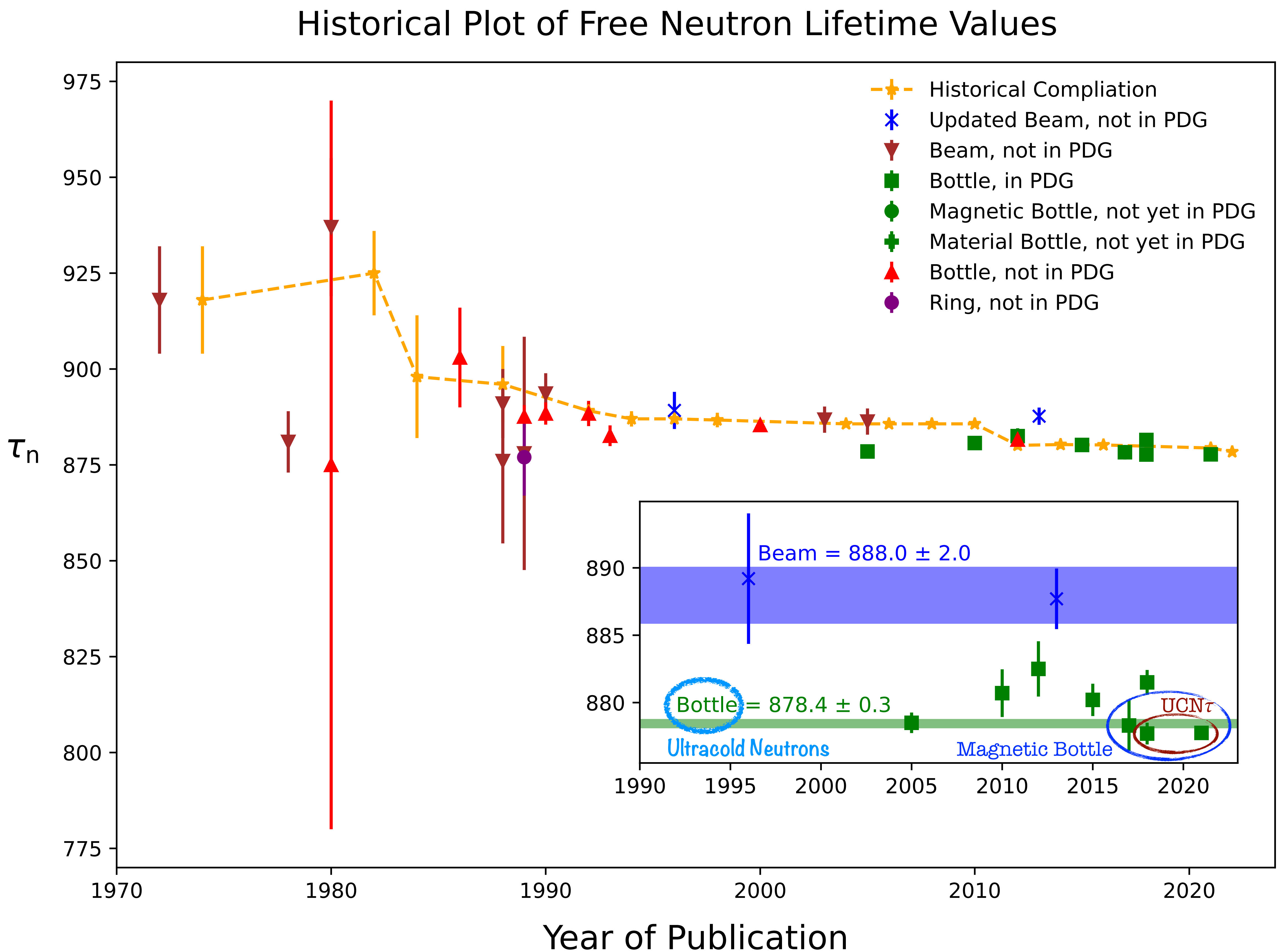


Also Part of the Neutron Lifetime Story

CMB η

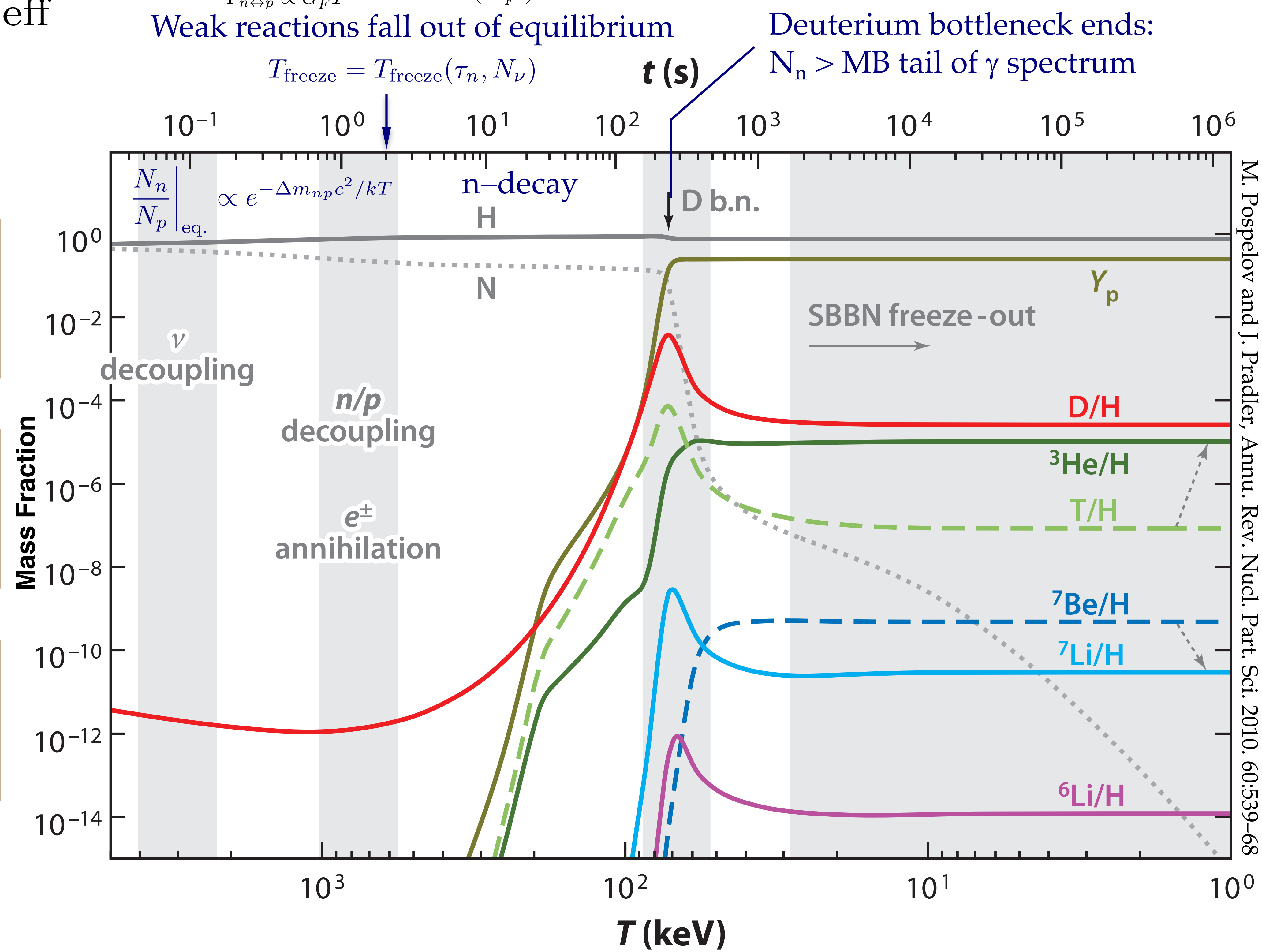
β–decay τ_n ——— SBBN ———→ Y_p Astrophysical Obs. / CMB

SM/CMB $N_{\rm eff}$

$H \propto \sqrt{g_* G_N} T^2$

$\Gamma_{n \leftrightarrow p} \propto G_F^2 T^5$

$T_{\rm freeze} \propto \left(\frac{g_* G_N}{G_F^4}\right)^{1/6} \simeq 1 \text{ MeV}$



⁴He mass fraction

$$Y_p = \frac{4(N_n/2N_p)}{1 + N_n/N_p}$$

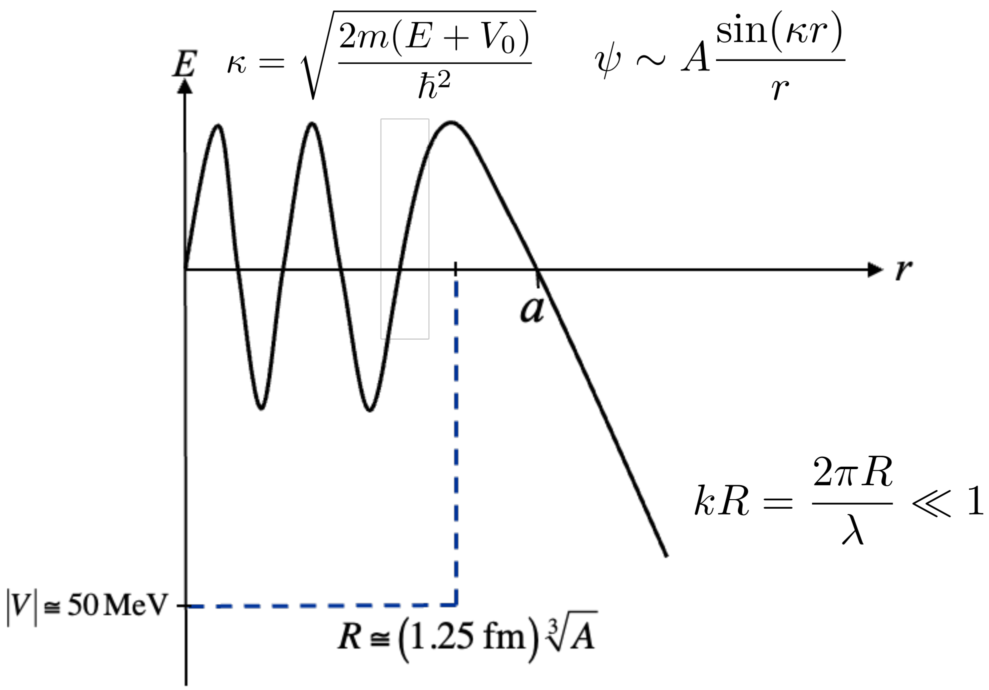
Baryon to Photon Ratio

$$\eta = n_b/n_\gamma$$

Effective neutrino flavors $N_{\rm eff}$

"Ultracold" Neutrons

Neutron Interactions with Matter: Scattering from a Nucleus



Scattering Amplitude

$$\psi = e^{i\vec{k}\cdot\vec{r}} + f(\theta)\frac{e^{ikr}}{r}$$

For low energy, s-wave (l=0) scattering dominates

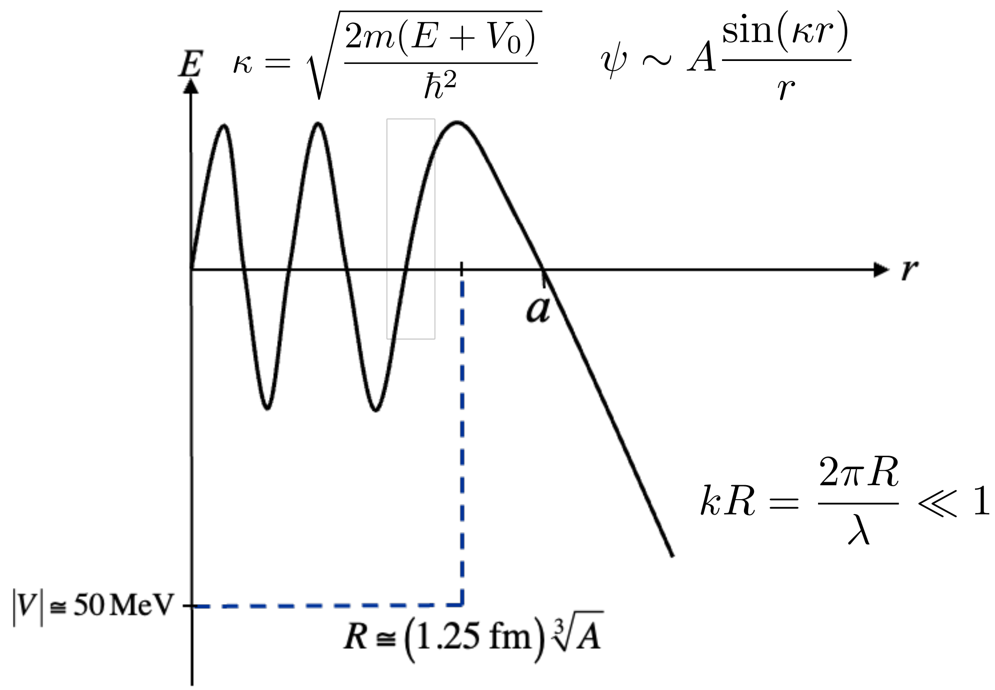
$$L = mvb = \hbar \implies b \sim \frac{\hbar}{mv} = \lambda_n \sim 50\ \mathrm{nm} \gg R$$

So... $f(\theta) = \text{const.} \equiv -a$ Scattering Length

$E_n < 1$ keV

neutron/nucleus interaction is well approximated by scattering off a <u>hard sphere</u> of radius **Re(a)** with absorption characterized by **Im(a)**.

Neutron Interactions with Matter: Fermi Pseudo Potential



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$E_n < 1$ keV
neutron/nucleus interaction is well approximated by scattering off a hard sphere of radius **Re(a)** with absorption characterized by **Im(a)**.

Overall the wave function changes... so perturbation theory with V won't work well.
But the wave function outside the potential only changes a little...

$$f(\theta) = -\frac{\mu}{2\pi\hbar^2}\langle\vec{k}_f|U|\vec{k}_i\rangle = -\frac{\mu}{2\pi\hbar^2}\int d^3r'\ U(\vec{r}')e^{i(\vec{k}_i-\vec{k}_f)\cdot\vec{r}'}$$ First-Order Born Approximation

The nucleus looks very small to a low energy neutron: $U(r) = \frac{2\pi\hbar^2}{\mu}a\delta(r) \implies f^{(1)} = -a$

$$U_{\text{material}} = \frac{2\pi\hbar^2}{m_n}\sum_i n_i(\vec{r})a_i^{(\text{B})}$$

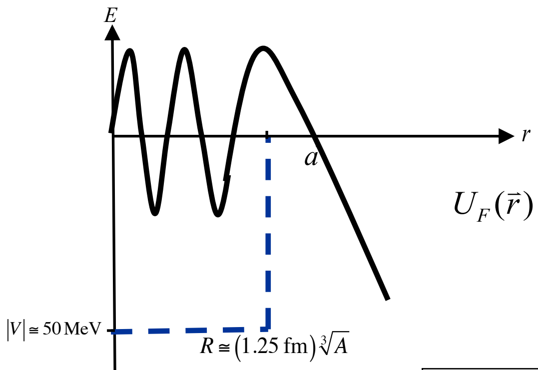
$a^{(\text{B})} \equiv \frac{m}{\mu}a$

Fermi Potential: 1st order far-field behavior w/o near field complications

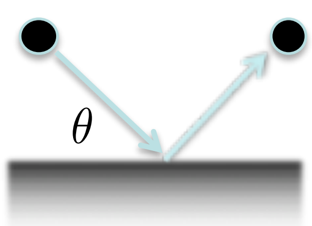
Note the attractive interaction generates a repulsive potential for a > 0.

Neutron Interaction Scale

Nuclear Interaction

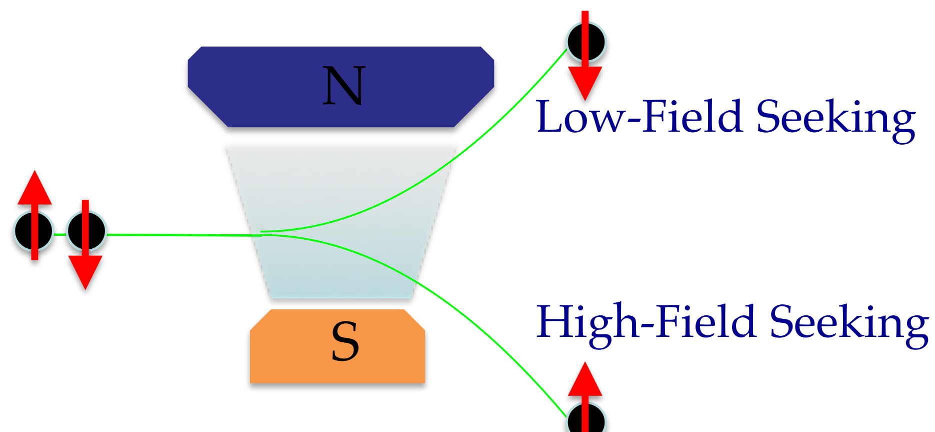


$$U_F(\vec{r}) = \frac{2\pi\hbar^2 a}{\mu}\delta^{(3)}(\vec{r})$$



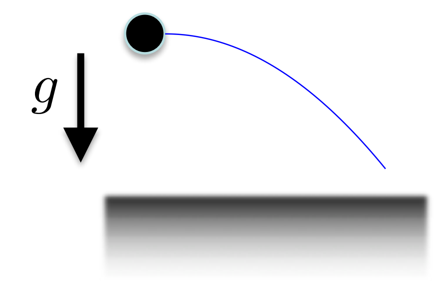
Material	V_F [neV]
Be	252
SS	180
Cu	168
Al	54

Magnetic Interaction



$$U = -\left[\,-|\gamma_n|\vec{S}\,\right]\cdot\vec{B} \sim \pm 60\ \mathrm{neV/T}$$

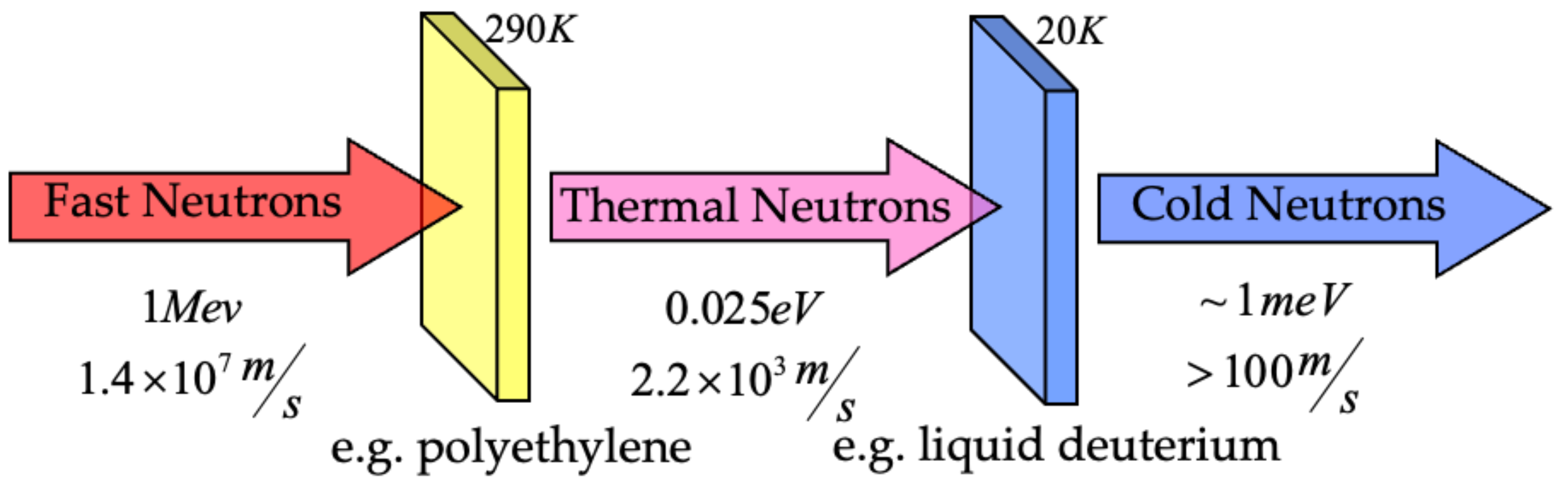
Gravitational Interaction

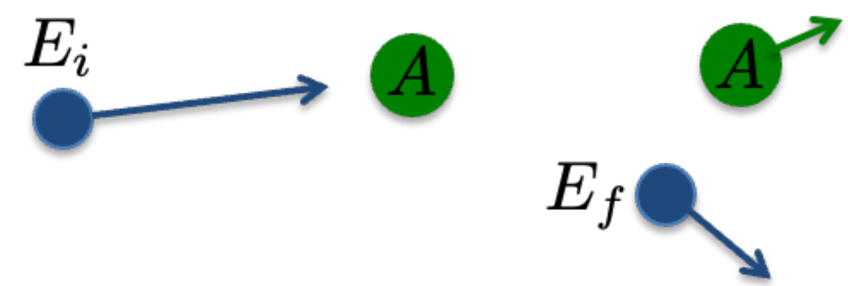


$$U/h = mg \sim 100\ \mathrm{neV/m}$$

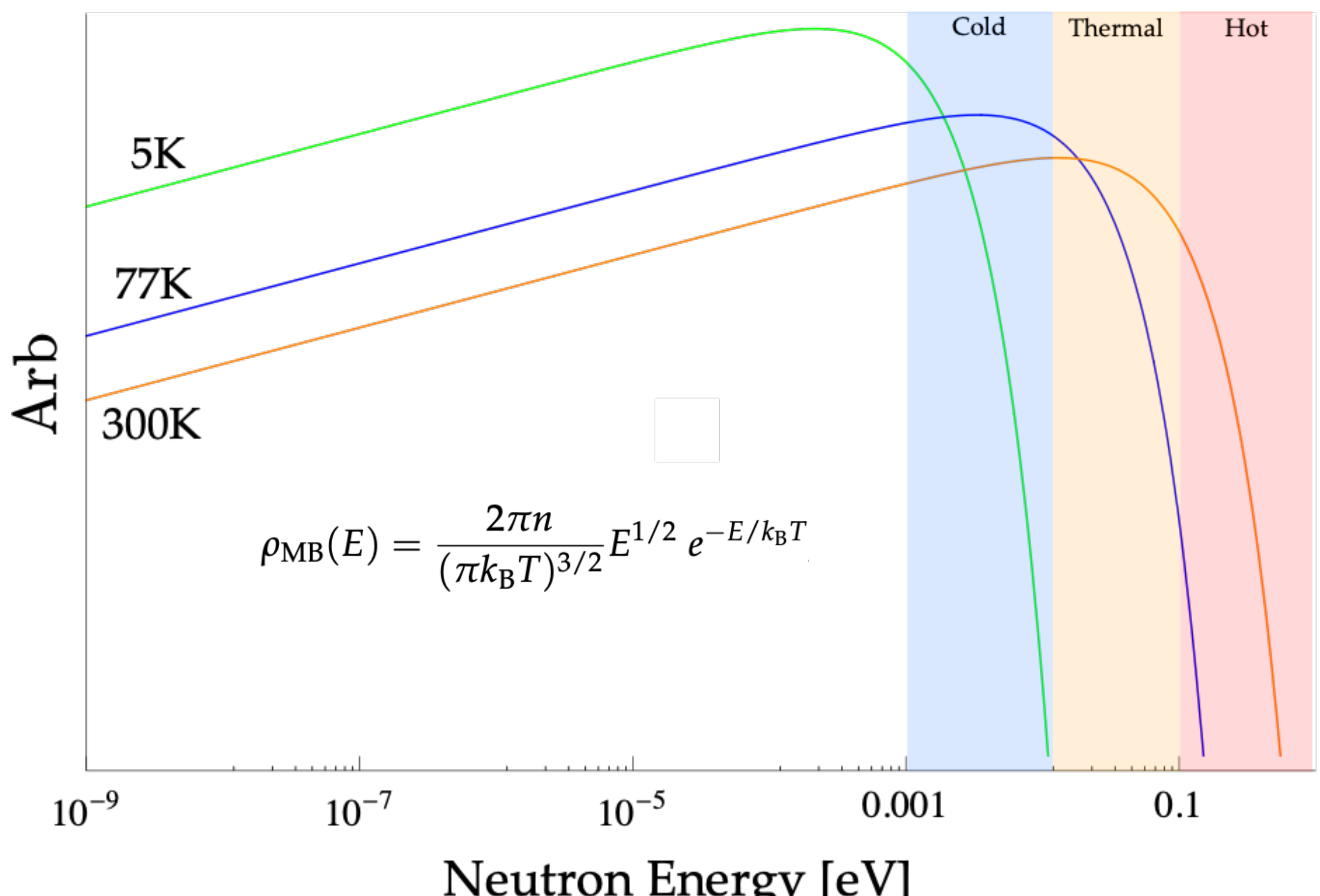
Material	a_{coh} [fm]	a_{inc} [fm]	U_F [neV]	σ_{abs} [b]	n $\times 10^{22}$ [cm^{-3}]
Al	3.45	0.256	$54 - i\,0.0012$	0.231	6.02
Be	7.79	0.12	$250 - i\,0.00125$[a]	0.0076	4.88
^{12}C	6.65	0	$195 - i\,0.0012$	0.0035	5.34
^{63}Cu	6.43	0.22	$142 - i\,0.022$	4.50	7.11
^{58}Ni	14.1	0	$342 - i\,0.029$	4.6	6.59
^{1}H	-3.74	25.27	-	0.333	-
^{2}H	6.67	4.04	102[b]	0.00052	10.2[b]
^{4}He	3.26	0	19[c]	0	2.18[c]
H_2O	-1.68	50.54	-14.6	-	18.0

Neutron Moderation





$$\left(\frac{E_f}{E_i}\right)_{\min} = \left(\frac{A-1}{A+1}\right)^2$$

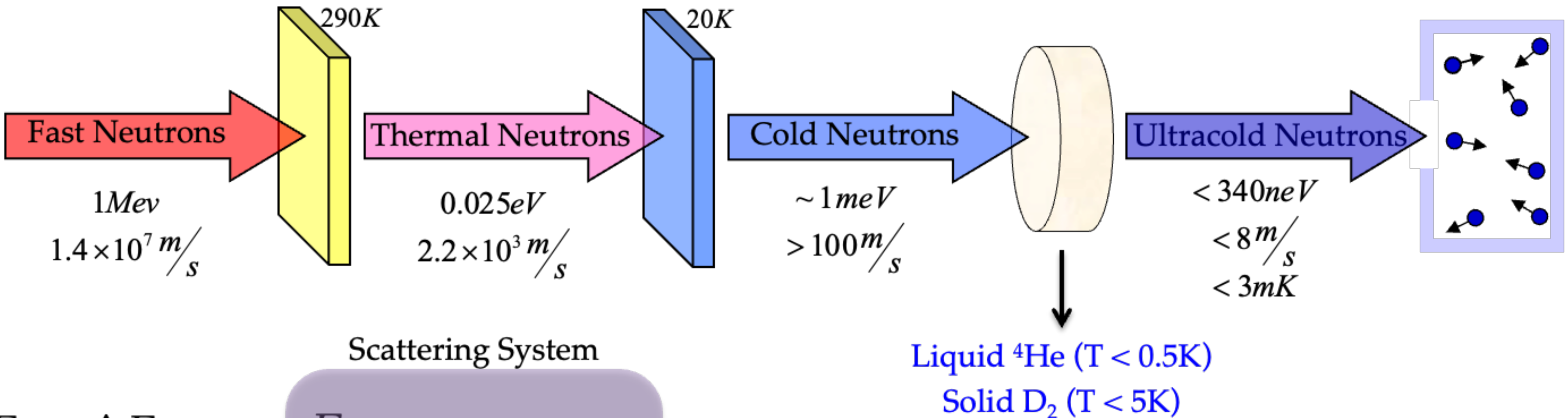


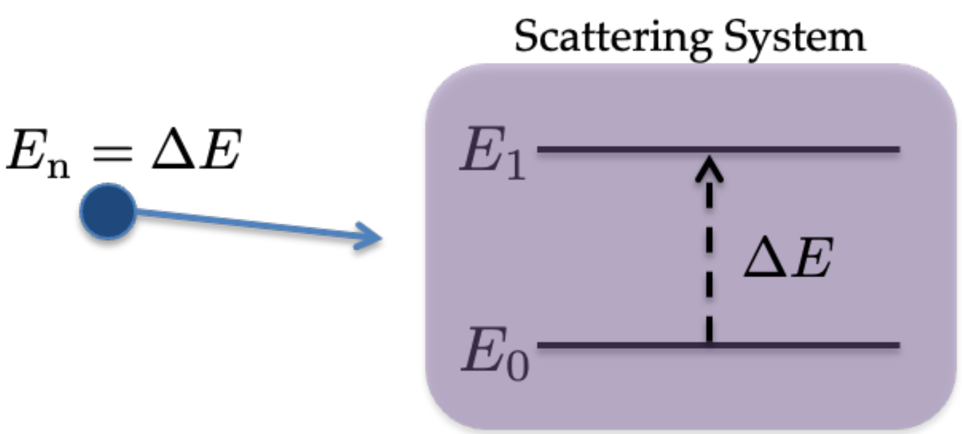
Elastic scattering dominates for energetic neutrons.

Light nuclei maximize transfer of energy.

Nucleus	#Scatters Fast to Thermal
^{1}H	18
^{4}He	25
^{12}C	110

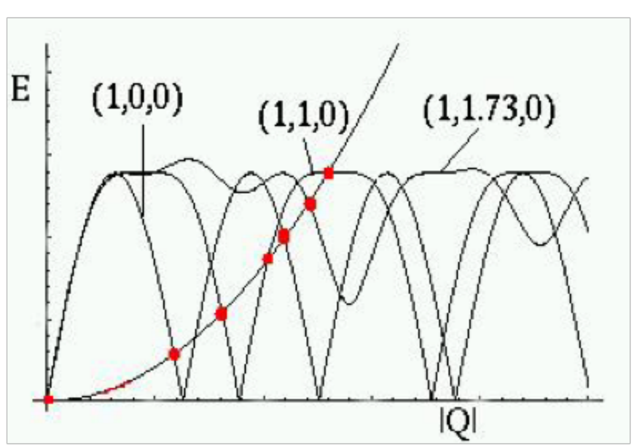
"Ultracold" Neutron Production



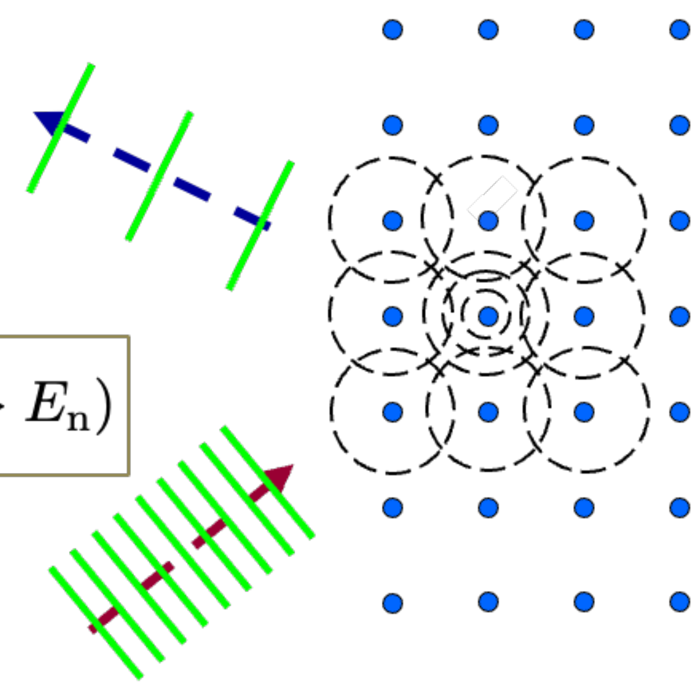


"Detailed Balance"

$$\sigma(E_n \longrightarrow E_n + \Delta E) = \frac{E_n + \Delta E}{E_n} e^{-\Delta E/k_B T} \sigma(E_n + \Delta E \longrightarrow E_n)$$

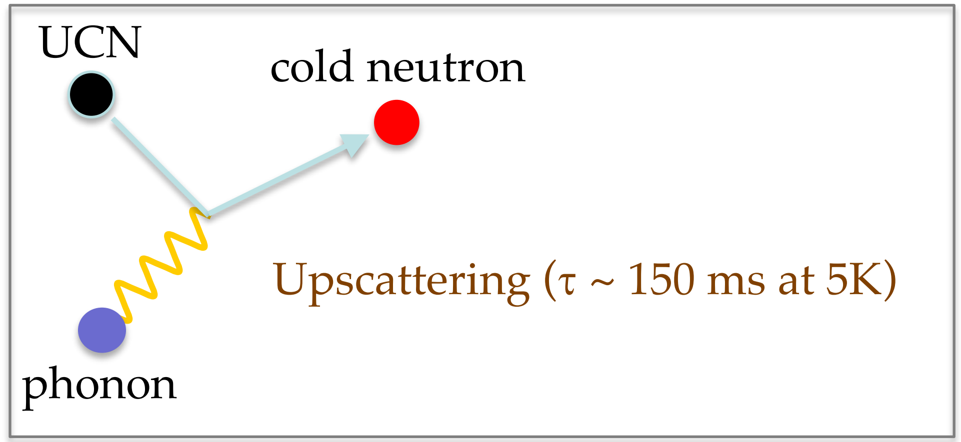


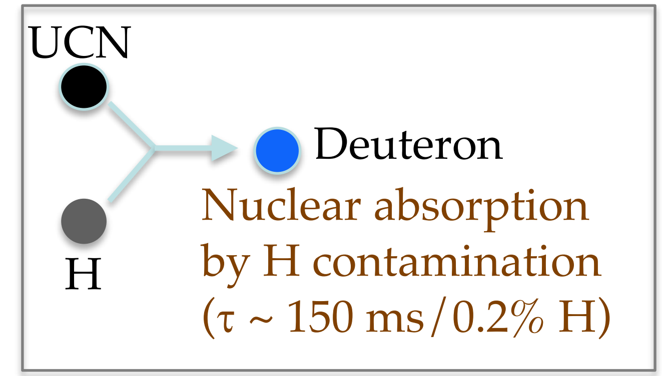
SD_2 provides a number of possible downscattering energies

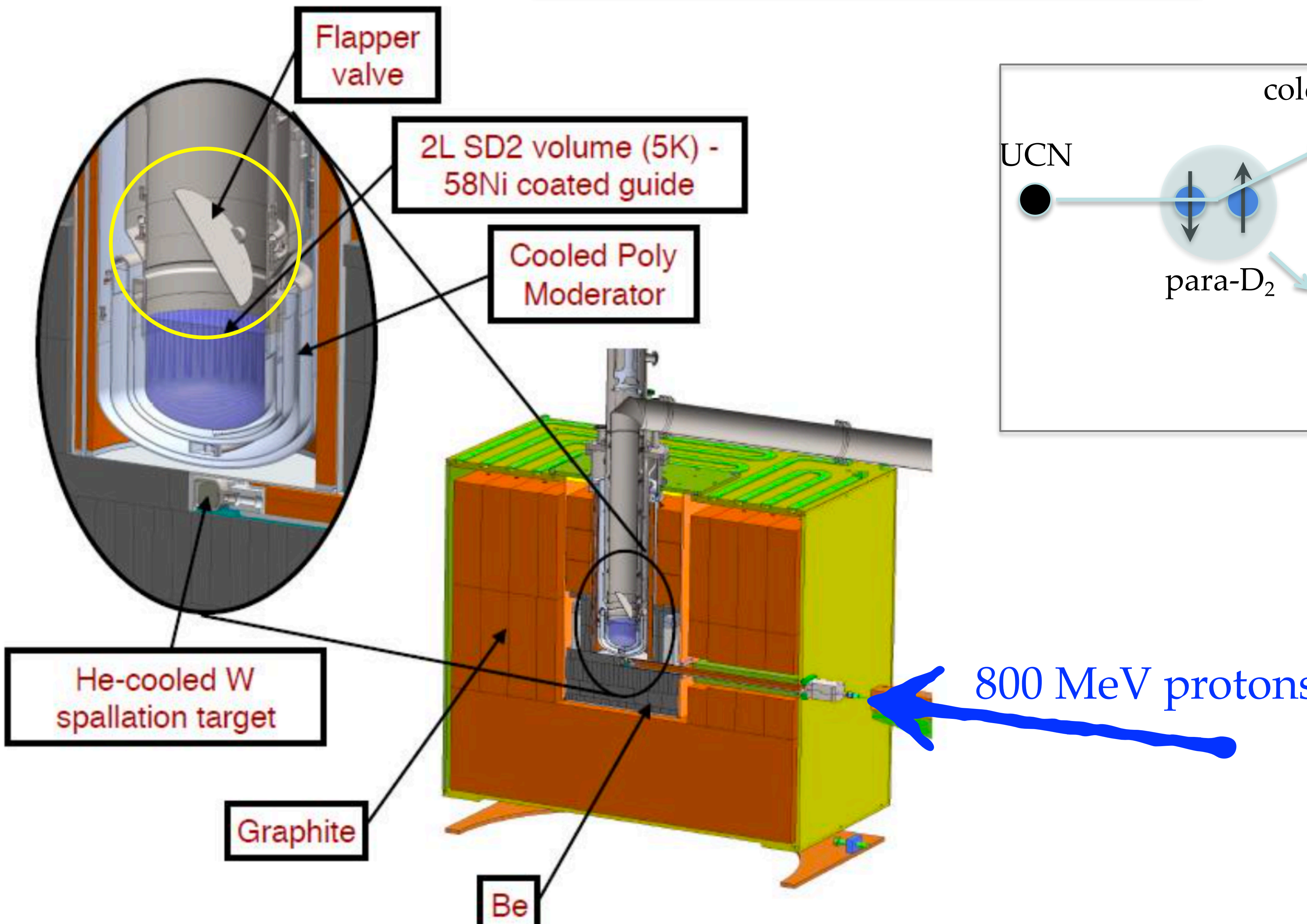


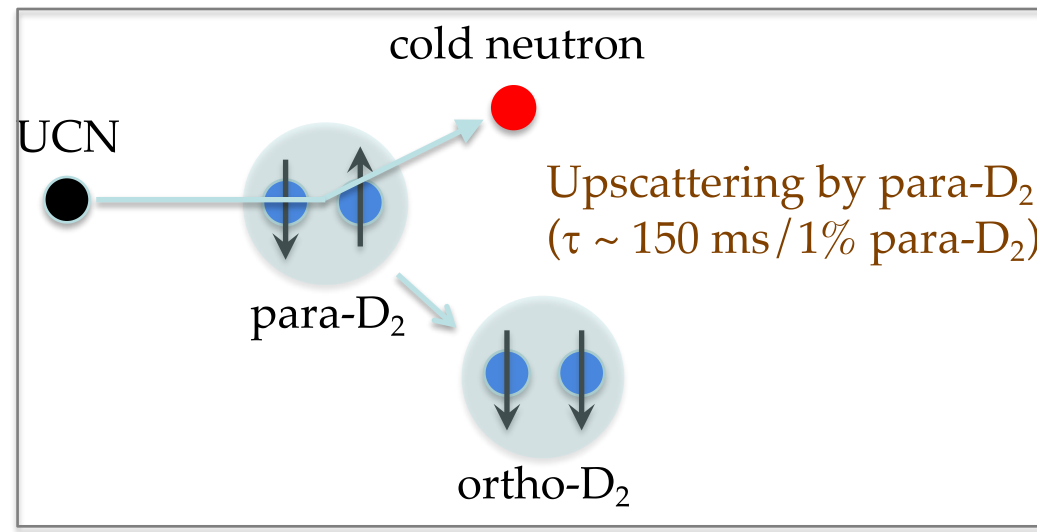
"Superthermal" far-from-equilibrium production

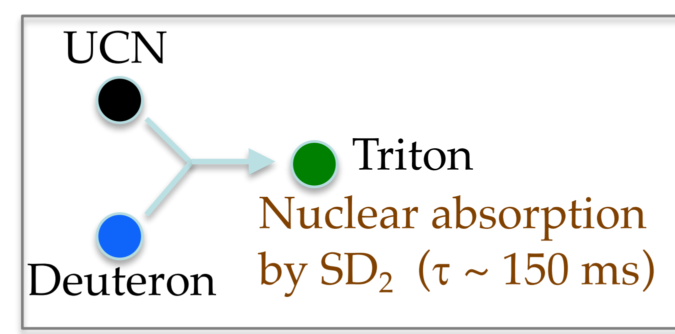
"Ultracold" Neutron Production in Solid Deuterium





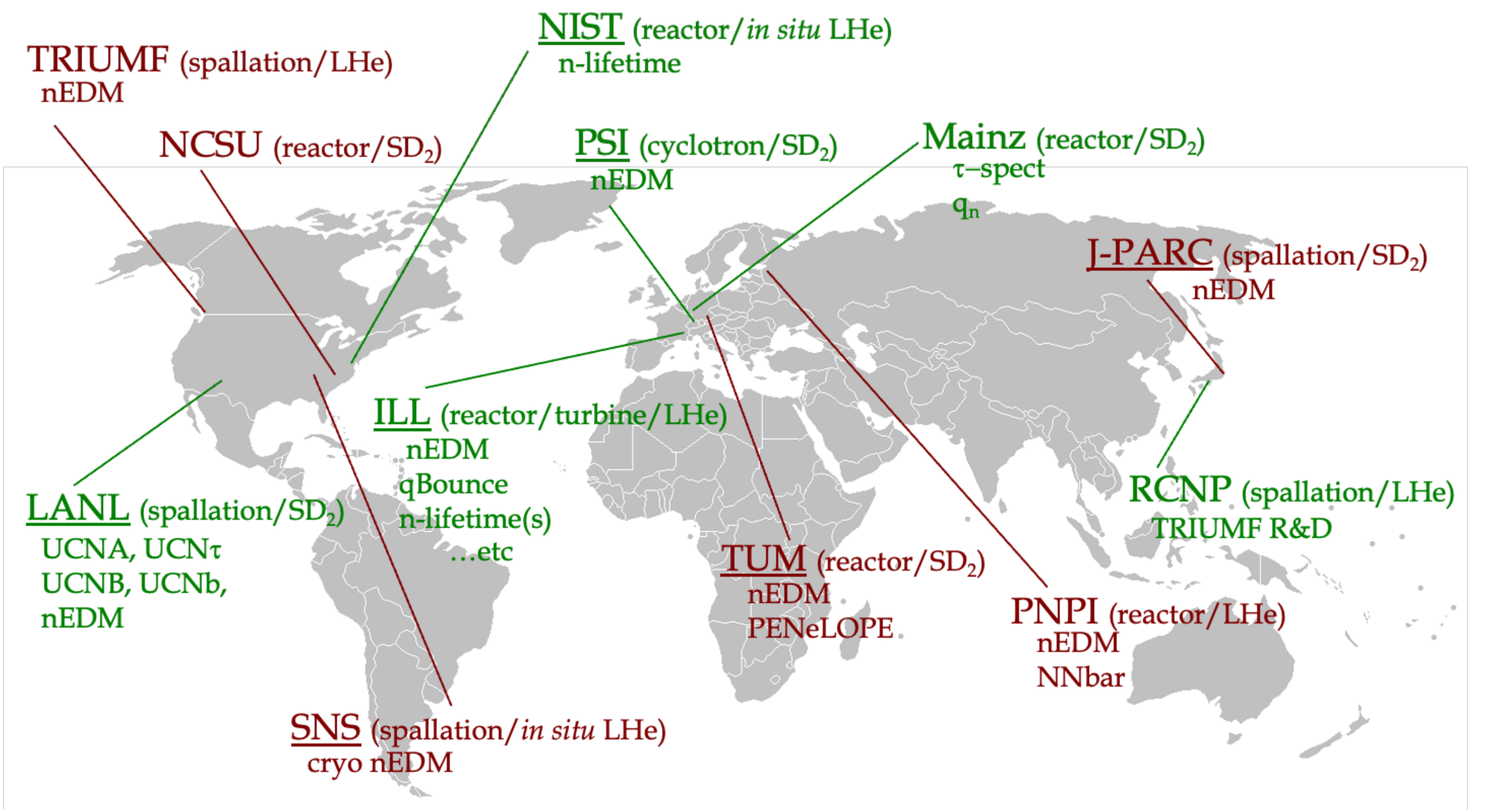






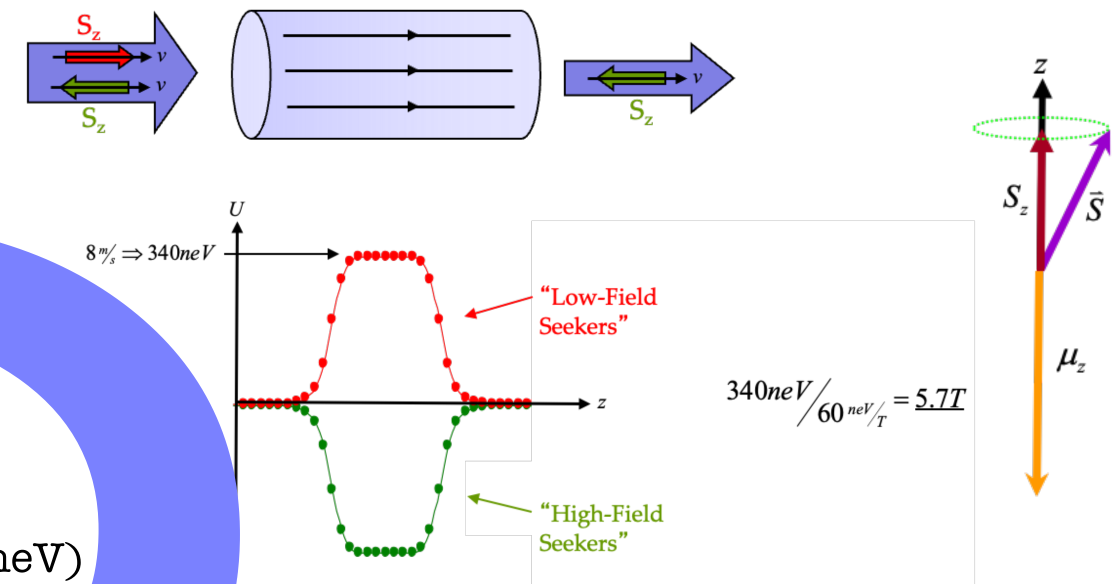
$$\frac{1}{40\text{ ms}} \approx 4 \times \frac{1}{150\text{ ms}}$$

Ultracold Neutron Sources

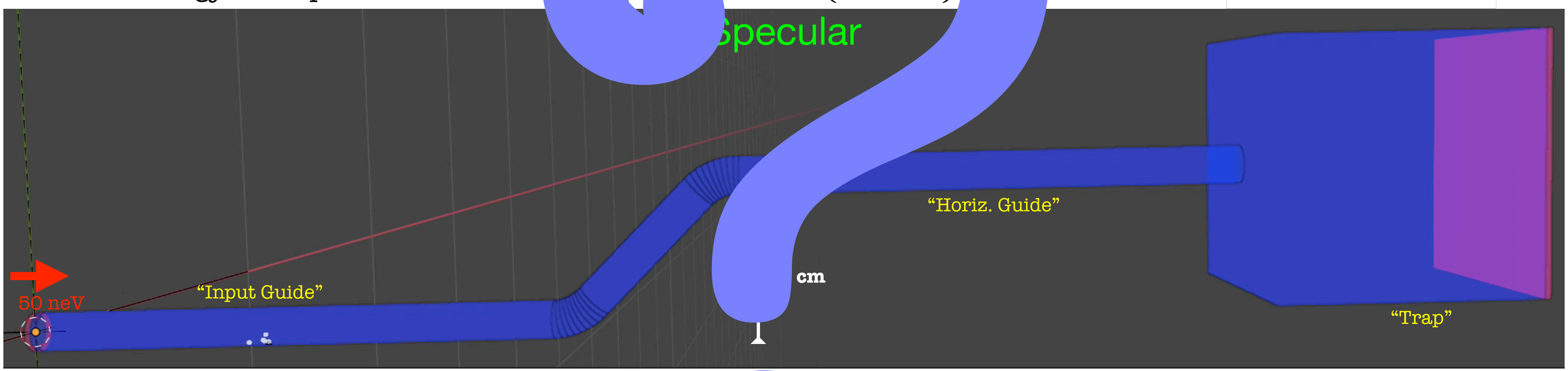


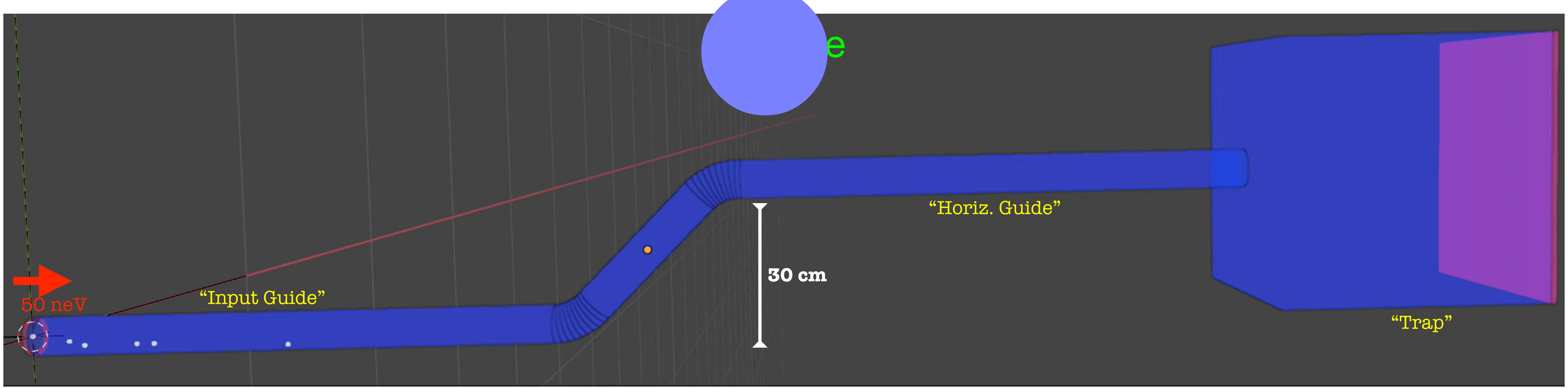
Ultracold Neutrons (UCN) are neutrons with energies on the order of 100 neV*:

- "Optical" reflection for any angle of incidence for many substances
- Classical motion is that of a spinning magnetic bouncy ball
- Can be pushed around by a refrigerator magnet
- Can be 100% polarized via Stern Gerlach by a 6 T field
- They behave much like a non-interactin

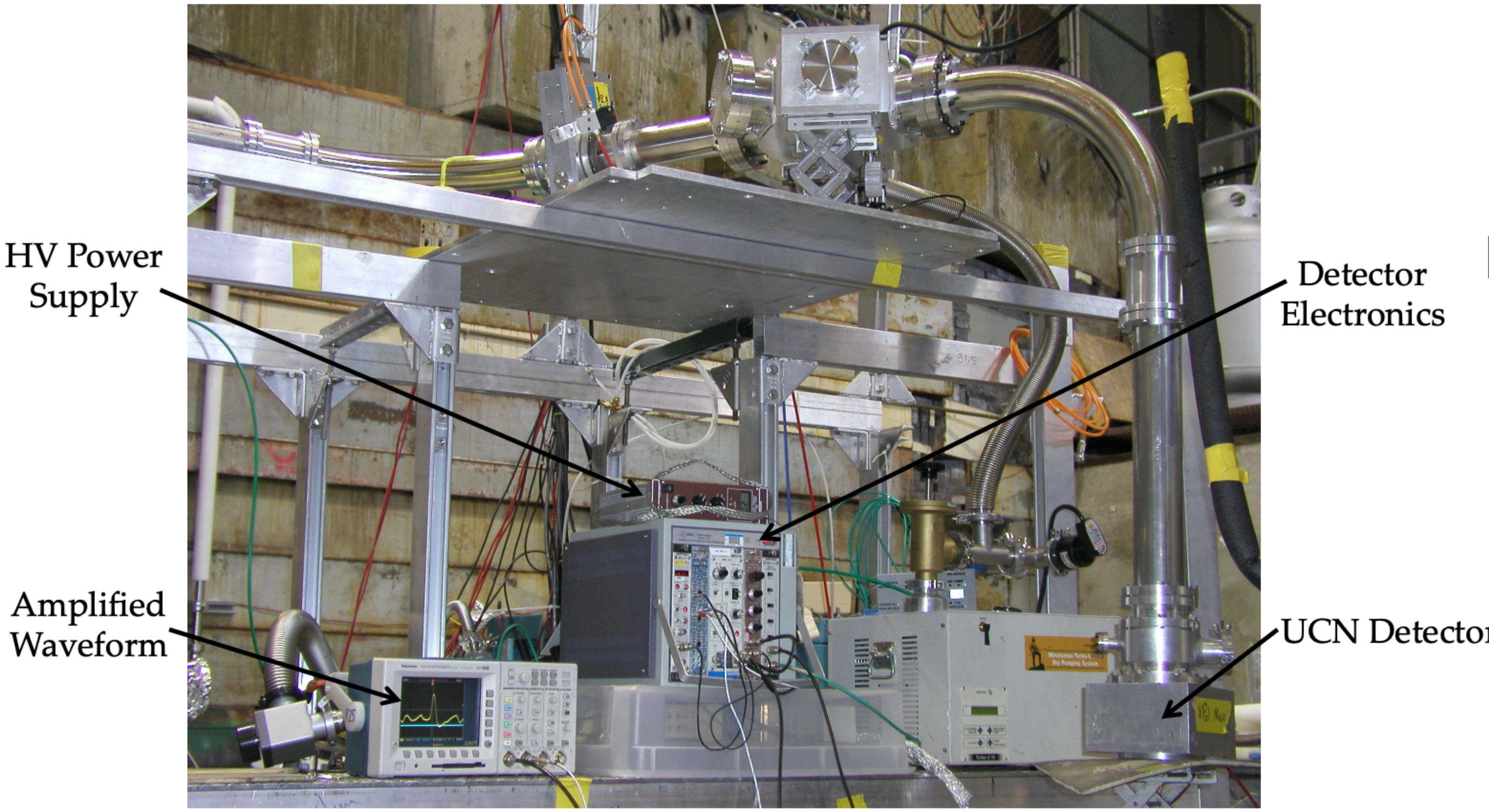


*Max UCN energy often quoted based on ma po l of ^{58}Ni (342 neV)

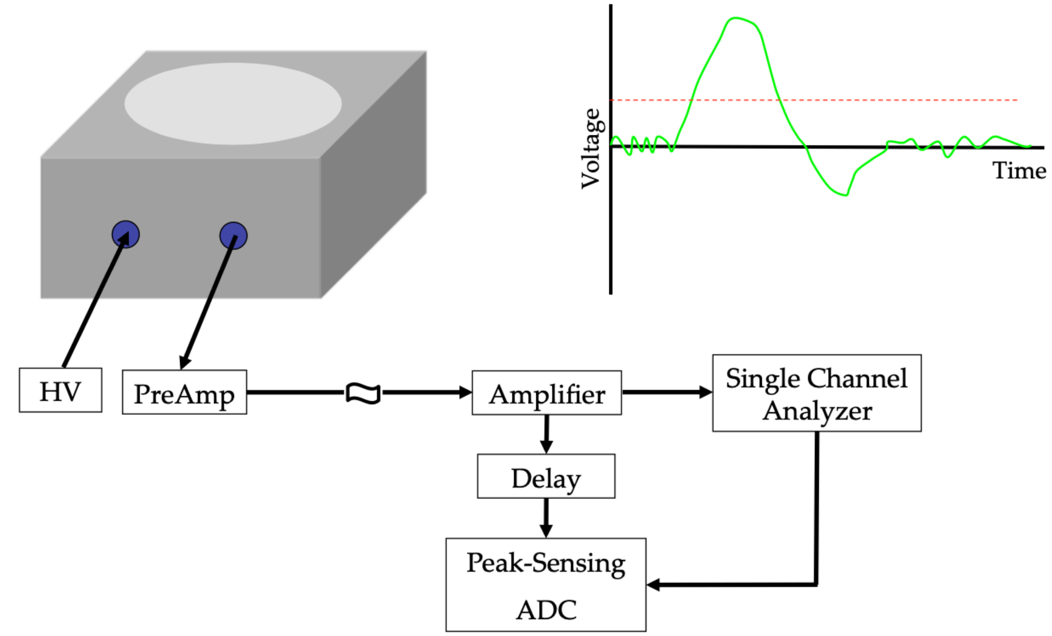


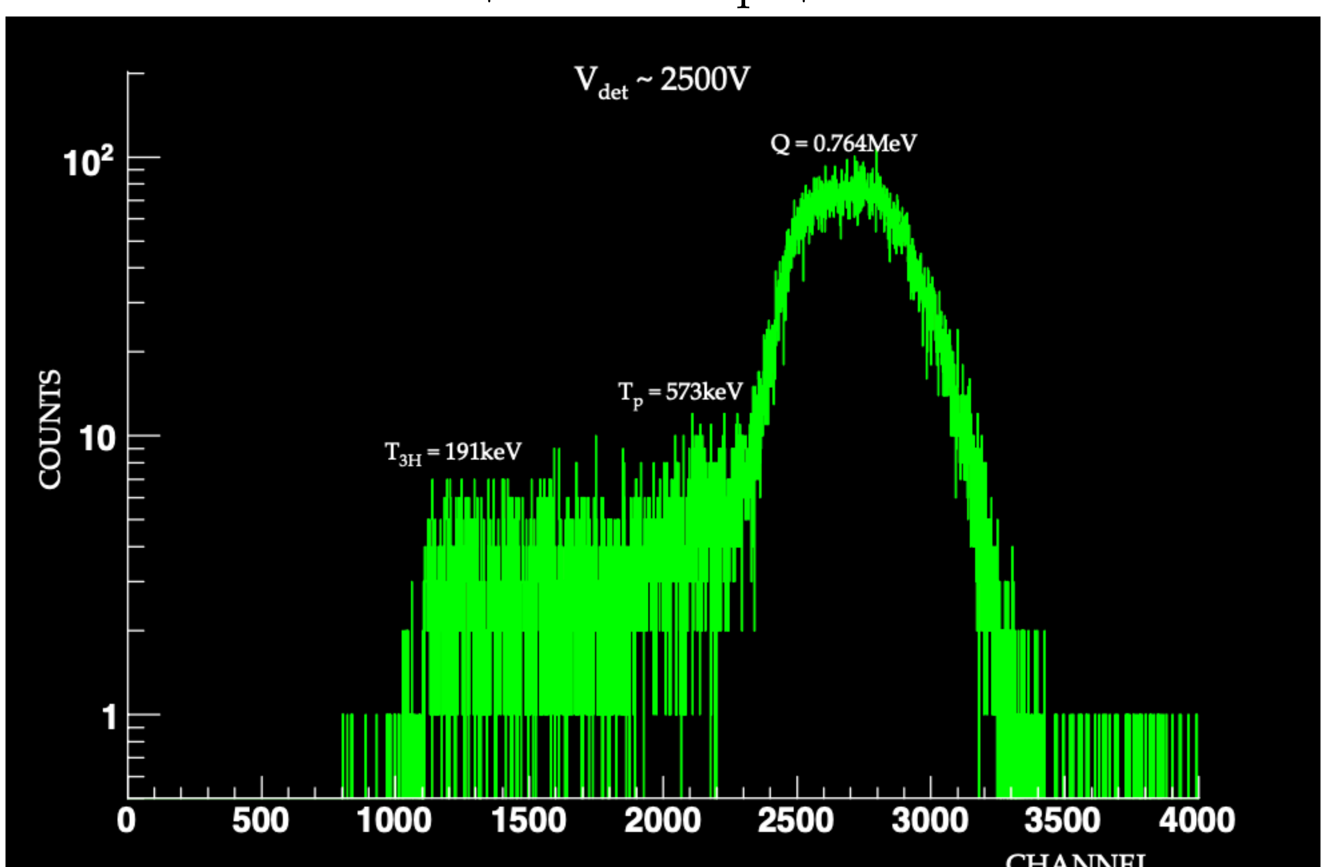


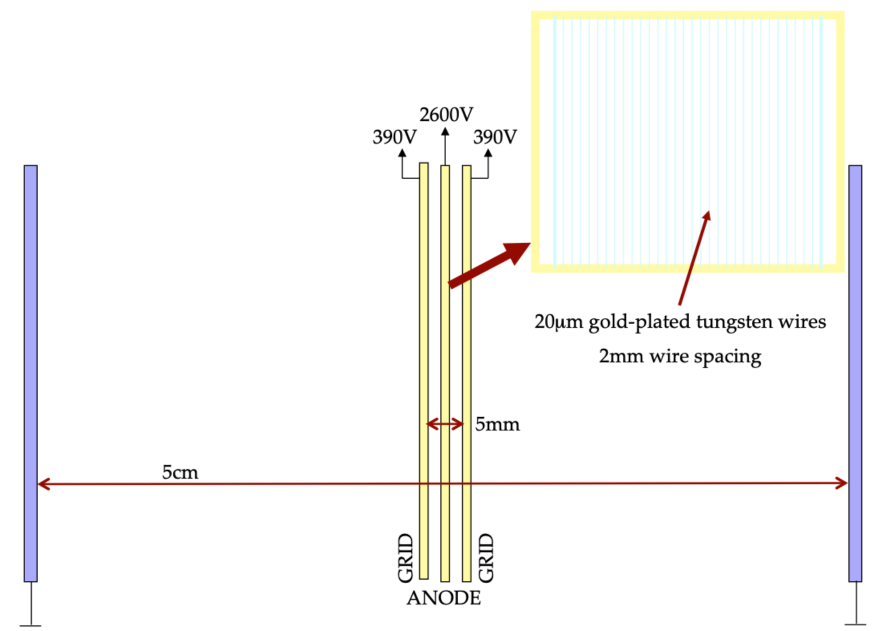
UCN Detection in the old days

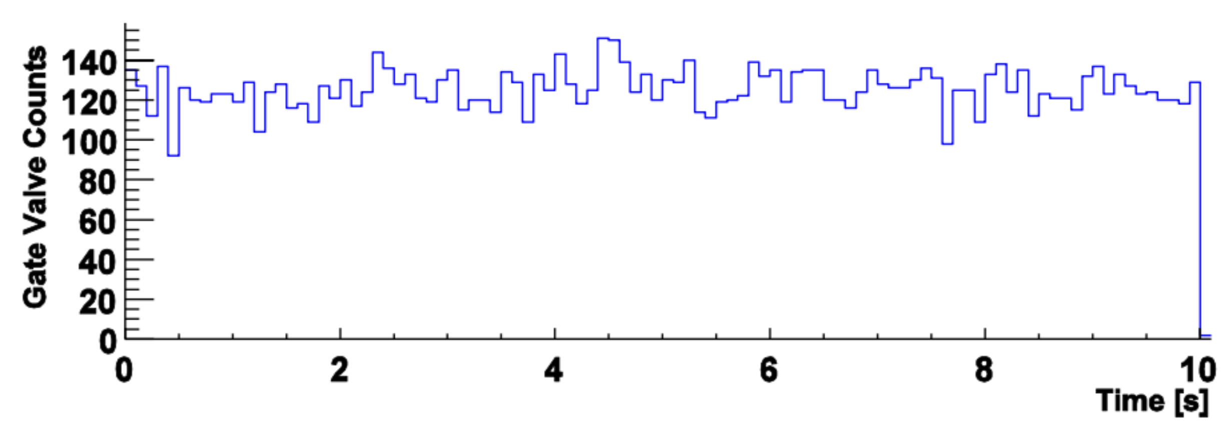


$$n + {}^3He \longrightarrow p + {}^3H$$



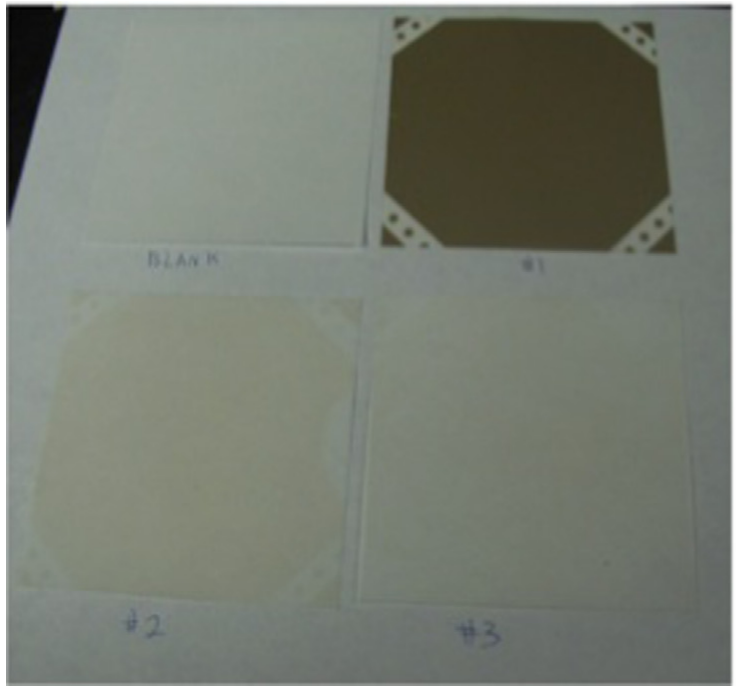


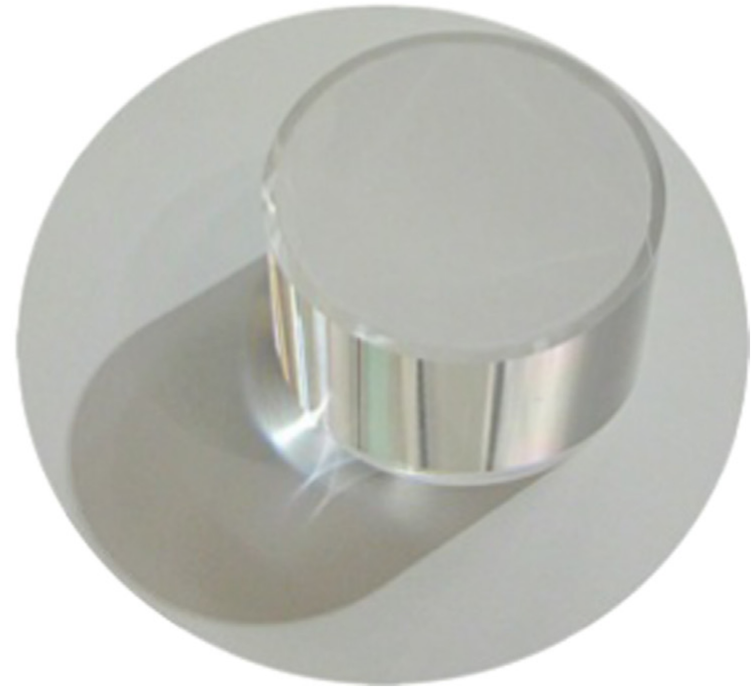




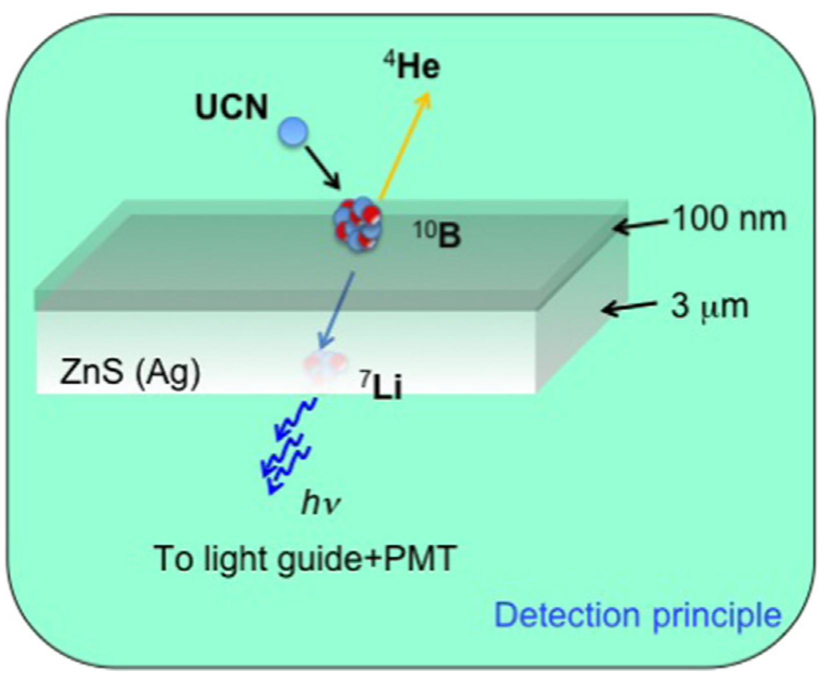
UCN Detection Now

^{10}B-coated ZnS Screens





^{10}B-coated ZnS Screen attached to light guide



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