Nuclear Searches

for Physics Beyond the Standard Model

- Experimental Searches
  - What are the experiments
  - Where to do experiments
- Nuclear and neutron beta decay
- Neutrons for Searches Beyond the Standard Model
  - Ultra-Cold Neutrons (UCN)

Neutral Weak Phenomena - $\sin^2\theta_W$

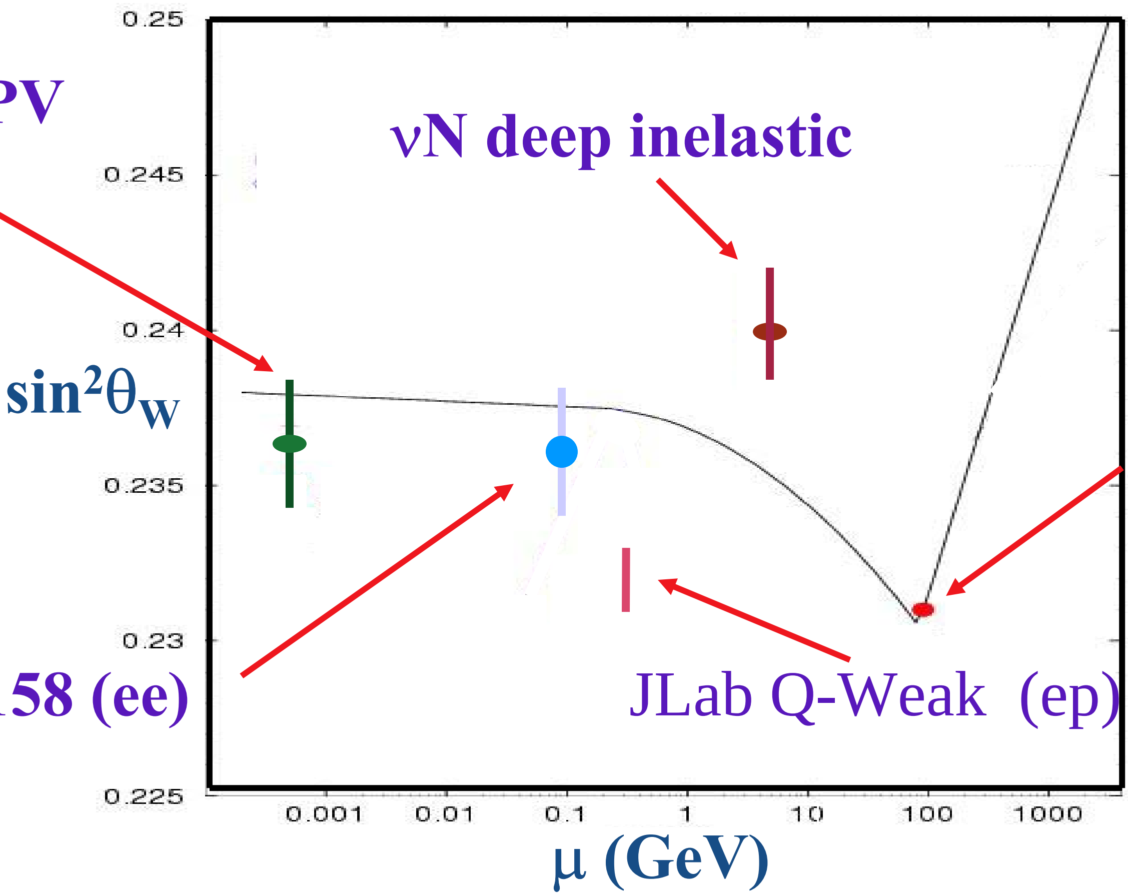
- Coupling constants in Standard Model are a function of the energy that it is being probed
  - Running of the couplings
- Standard Model predicts this energy dependence
- Can study by measuring neutral weak cross sections vs energy
  - e^+ - e^- ,neutrino-nucleus, electron-nucleus

$$\mathbf{d\sigma = (EM + Weak)^2 = EM^2 + Weak^2 + \boxed{2EM \cdot Weak}}$$

Parity Violating

Neutral Weak Phenomena - $\sin^2\theta_W$

Czarnecki, Marciano Erler.
Kurylov, Ramsey-Musolf



Atomic PV

νN deep inelastic

e^+e^- LEP, SLD

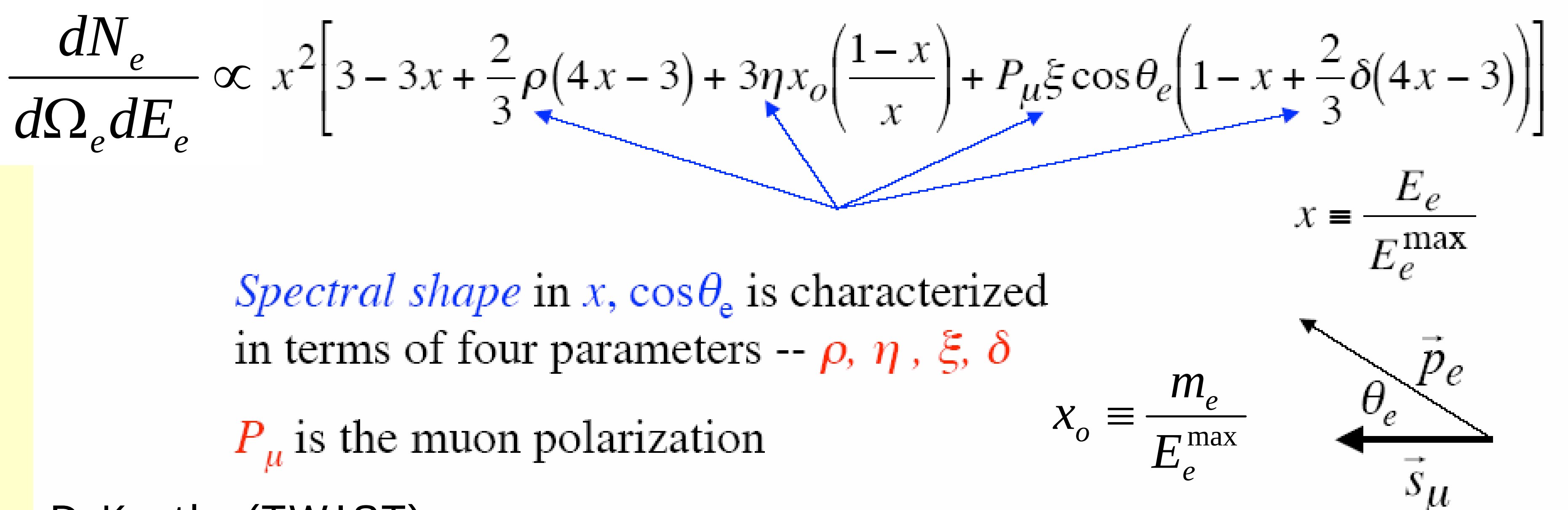
SLAC E158 (ee)

JLab Q-Weak (ep) (2010)

Muon Decay Distributions

$$\mu \rightarrow e\,\nu_\mu \nu_e$$

- Energy dependence
- Angular dependence
- Called Michel parameters



$$\frac{dN_e}{d\Omega_e\,dE_e} \propto x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+3\eta x_o\left(\frac{1-x}{x}\right)+P_\mu\xi\cos\theta_e\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

$$x \equiv \frac{E_e}{E_e^{\max}}$$

Spectral shape in x, $\cos\theta_e$ is characterized in terms of four parameters -- ρ, η , ξ, δ

P_μ is the muon polarization

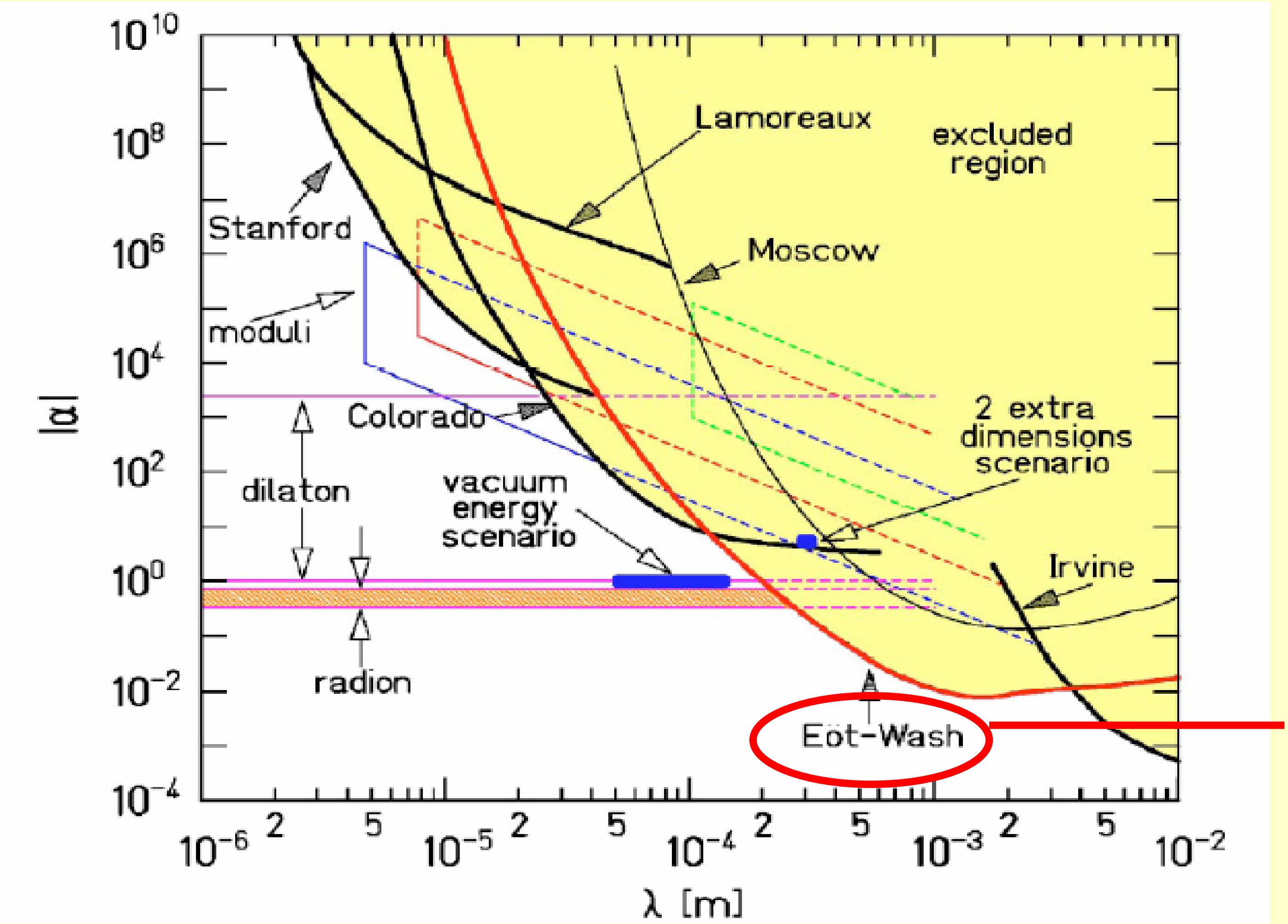
$$x_o \equiv \frac{m_e}{E_e^{\max}}$$

D. Koetke (TWIST)

Summary of Michel Parameters

Parameter	Standard Model	Data
ρ	¾	0.7509 ± 0.0010
η	0	0.001 ± 0.024
δ	¾	0.7495 ± 0.0012
ξP_μ	1	1.0027±0.0079±0.0030

Short-distance Gravity



UW Seattle

US Facilities for Fundamenal Physics (not Neutrons)

- Low Energy Facilities
  - ATLAS, HRIBF, NSCL, ISAC, LBNL, Stoneybrook & TAMU for 0^+-0^+ & other β-decay & EDM
- Medium Energy Facilities
  - JLAB for Q_{weak}, DIS-Parity
- Heavy-Ion Facilities
  - BNL for $(g-2)_\mu$ and EDM
  - High Energy Facilities e.g. SLAC for Moeller asymmetry

Cold and Ultra-Cold Neutrons

- Cold neutrons ~ 4 Å
  - High flux from Cold Moderator (20K)

- Ultra-Cold Neutrons (UCN) ~ 500 Å
  - Boltzmann tail from Reactor cold moderator
  - Superthermal Converters
    - LHe, SD_2

What good are UCN?

- Can be trapped in certain materials
- Can be easily polarized (B = 6T)
- Allow precision measurements with free neutrons

US Facilities for Fundamenal Physics (with Neutrons)

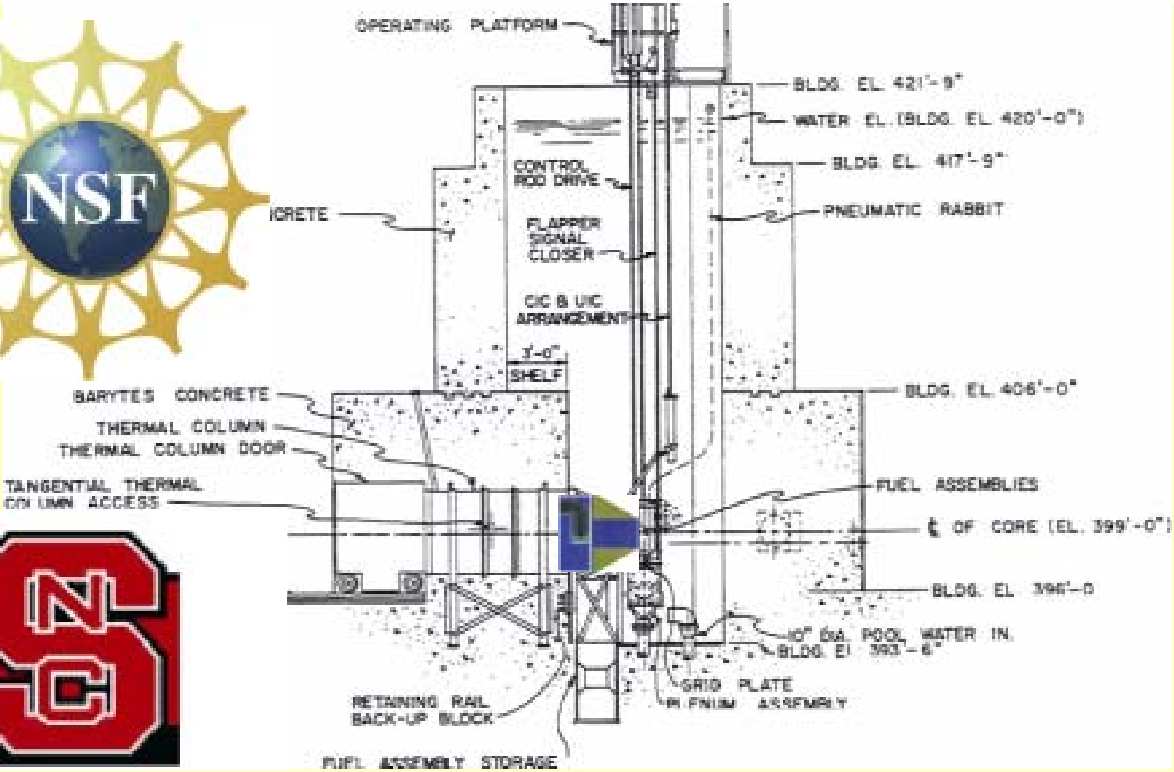
- LANSCE
  - Flight Path 12 (FP12) - Pulsed Cold Neutrons
  - Area B - UCN
- NIST
  - NG6 - Cold Neutron Lines
- SNS
  - Fundamental Neutron Physics Beamline (FNPB)
- Other Initiatives
  - PULSTAR Reactor @ NCSU
  - LENS Cold neutrons @ IUCF

Non-US Neutron Facilities

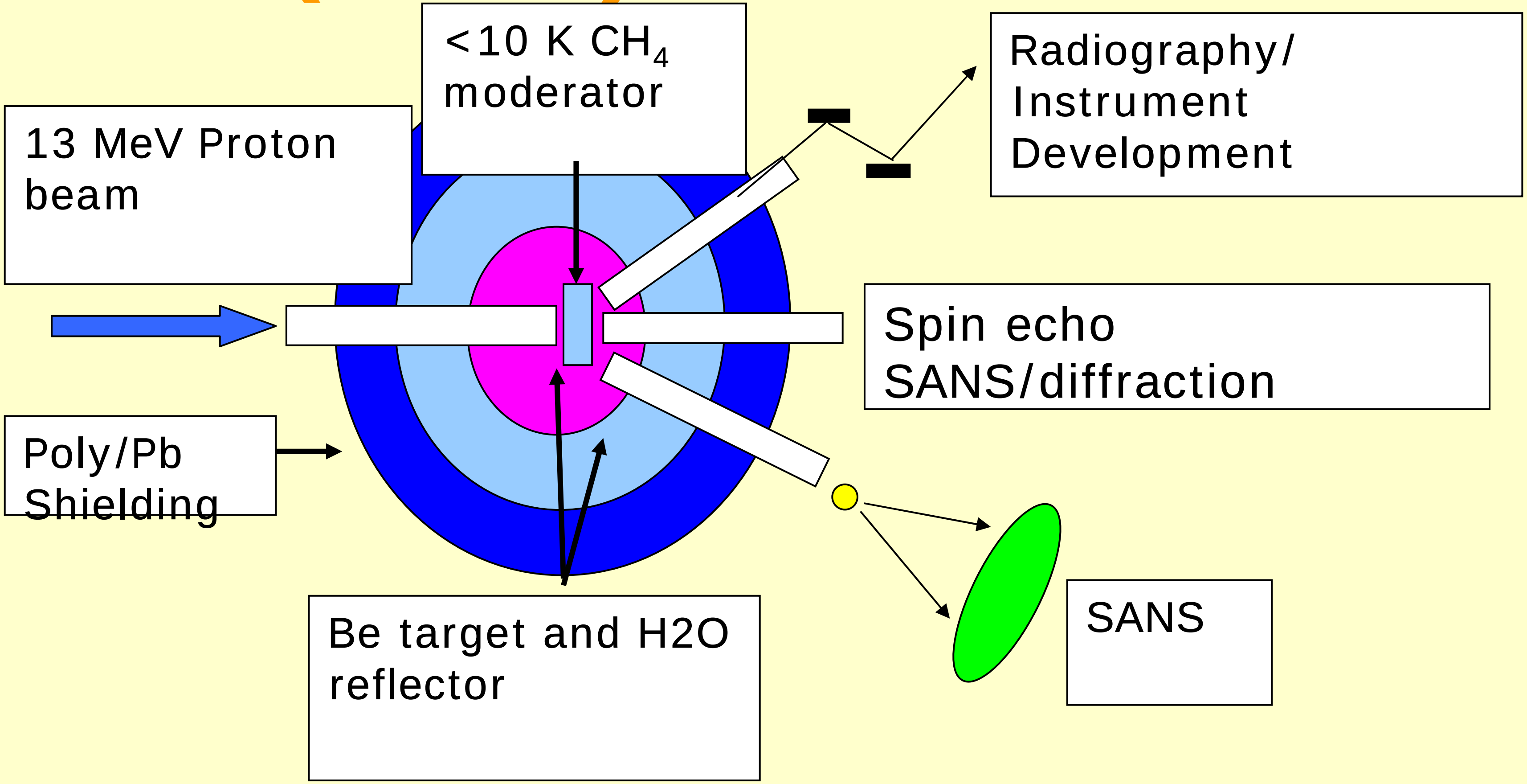
- ILL(Institut Laue-Langevain) – Cold & Ultra-Cold neutrons
  - Improved EDM experiment (Cryo-EDM)
  - Improved correlation experiments (<.5%)
- PSI – Spallation SD_2 UCN source
  - Proposal for EDM exists
- Germany - FRM-II 20MW research reactor
  - Working on SD_2 source insert for UCN
- Japan
  - Osaka UCN, JPARC?

NCSU PULSTAR UCN Source

- PULSTAR is a 1MW research reactor on NCSU campus
- UCN source expected to provide densities > 1,000/cm^3
- Dedicated to nuclear physics research
- Source construction funded by NSF (1.2M$), operational by Jan. 2007
- Reactor operations funded by State of North Carolina, upgrades may be funded through DOE, INIE program



Low Energy Neutron Source (LENS) at Indiana



<10 K CH_4 moderator

13 MeV Proton beam

Radiography/ Instrument Development

Spin echo SANS/diffraction

Poly/Pb Shielding

SANS

Be target and H2O reflector

University-based pulsed cold neutron source

Vertical UCN beam possible, replace CH_4 → CH_4+solid O_2

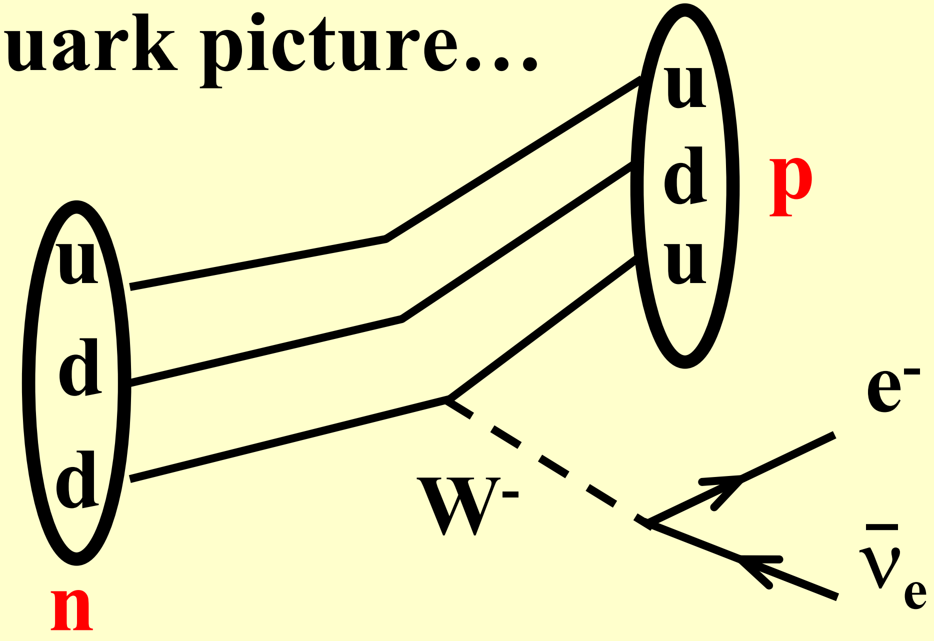
Neutron & Nuclear Beta Decay

$$\mathrm{n} \Rightarrow \mathrm{p} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

$$\tau_{\mathrm{n}} \approx 15\ \mathrm{min.},\quad t_{\frac{1}{2}} \approx 10\ \mathrm{min.}$$

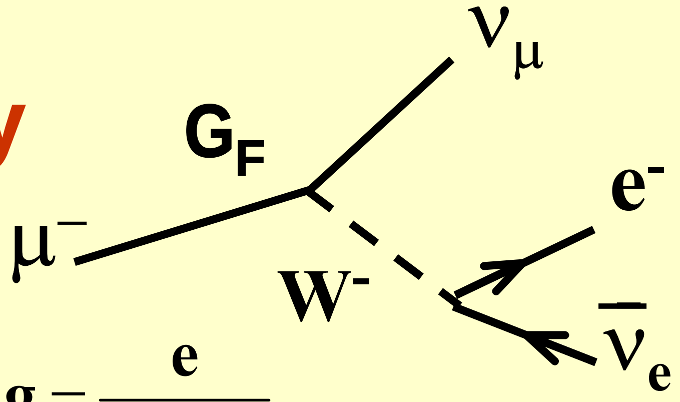
$$\sum_{\mathrm{p,e,\nu}} \mathrm{K.E.} = 0.78\ \mathrm{MeV}$$

or in quark picture…



Weak Decays

- Consider muon decay



$$G_F = \frac{\sqrt{2}g^2}{8M_W^2}; \text{ since } m_\mu << M_W \text{ and } g = \frac{e}{\sin\theta_W}$$

$$= 1.16637(1) \cdot 10^{-5} (\hbar c)^3 \text{ GeV}^{-2}$$

- Can calculate muon lifetime

$$\frac{1}{\tau_\mu} = \int d\Gamma_\mu \propto \int |M|^2 d\text{LIPS}$$

LIPS = Lorentz Invariant Phase Space

$$M = \frac{G_F}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\mu (1 - \gamma^5) u_\mu \bar{u}_e \gamma_\mu (1 - \gamma^5) v_{\nu_e}$$

Weak Decays

- Ignoring small kinematic corrections

$$\tau_\mu \approx \frac{192\pi^3\hbar^7}{G_F^2 m_\mu^5 c^4} = 2.187 \text{ x } 10^{-6} \text{ sec}$$

$$\tau_\mu^{exp} = 2.19703(4) \text{ x } 10^{-6} \text{ sec}$$

- Key feature of Electroweak Standard Model is UNIVERSALITY - lepton and quark weak interactions are identical ... modulo the CKM matrix. Thus

$$M_{n-p} = \frac{1}{\sqrt{2}} \bar{u}_p \gamma^\mu (G_V - G_A\gamma^5) u_n \bar{u}_e \gamma_\mu (1-\gamma^5) v_{\nu_e}$$

$$\tau_n \approx \frac{2\pi^3\hbar^7}{G_F^2 m_e^5 c^4} = 8{,}611 \text{ sec} \qquad \tau_n^{exp} = 885(1) \text{ sec}$$

Neutron Decay in the Standard Model

$$\tau_n = \left(\frac{2\pi^3\hbar^7}{m_e^5 c^4}\right)\left(\frac{1}{G_F^2\left|V_{ud}\right|^2}\right)\left[\frac{1}{1+3\left(G_A/G_V\right)^2}\right]\frac{1}{f(1+\Delta_R)}$$

G_F = Fermi Constant (known from μ decay)
V_{ud} = up-down quark weak coupling (more later)
G_A = Axial vector weak coupling constant
G_V = Vector weak coupling constant
f = phase space integral
Δ_R = Electroweak radiative correction
Note: Z^0 Boson (M=91 GeV) gives 2% correction!

G_A/G_V from parity violating decay asymmetry in n decay

$$A = \frac{-2\lambda(1+\lambda)}{1+3\lambda^2} \quad , \quad \lambda = \frac{G_A}{G_V}$$

Polarized Neutron decay

$$d\Gamma = \Gamma_n\left(1 + \mathbf{b}\frac{m_e}{E_e} + \mathbf{a}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \mathbf{A}\frac{\vec{\sigma}_n\cdot\vec{p}_e}{E_e} + \mathbf{B}\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \mathbf{D}\,\vec{\sigma}_n\cdot\frac{\vec{p}_e \times \vec{p}_\nu}{E_e}\right)$$

- **Γ_n =1/τ_n total decay rate (depends on G_A and G_V)**
- **Correlations a, A and B depend on G_A and G_V**
- **Coefficient b requires S or T interaction**
- **Correlation D violates Time Reversal Invariance**

Must measure two observables to extract G_A and G_V (eg. G_n and A)

Precision neutron decay measurements

- **Neutron lifetime essential in Big-Bang Nucleosynthesis Calculations**
- **Can provide most precise measurement of V_{ud}**

Weak eigenstates

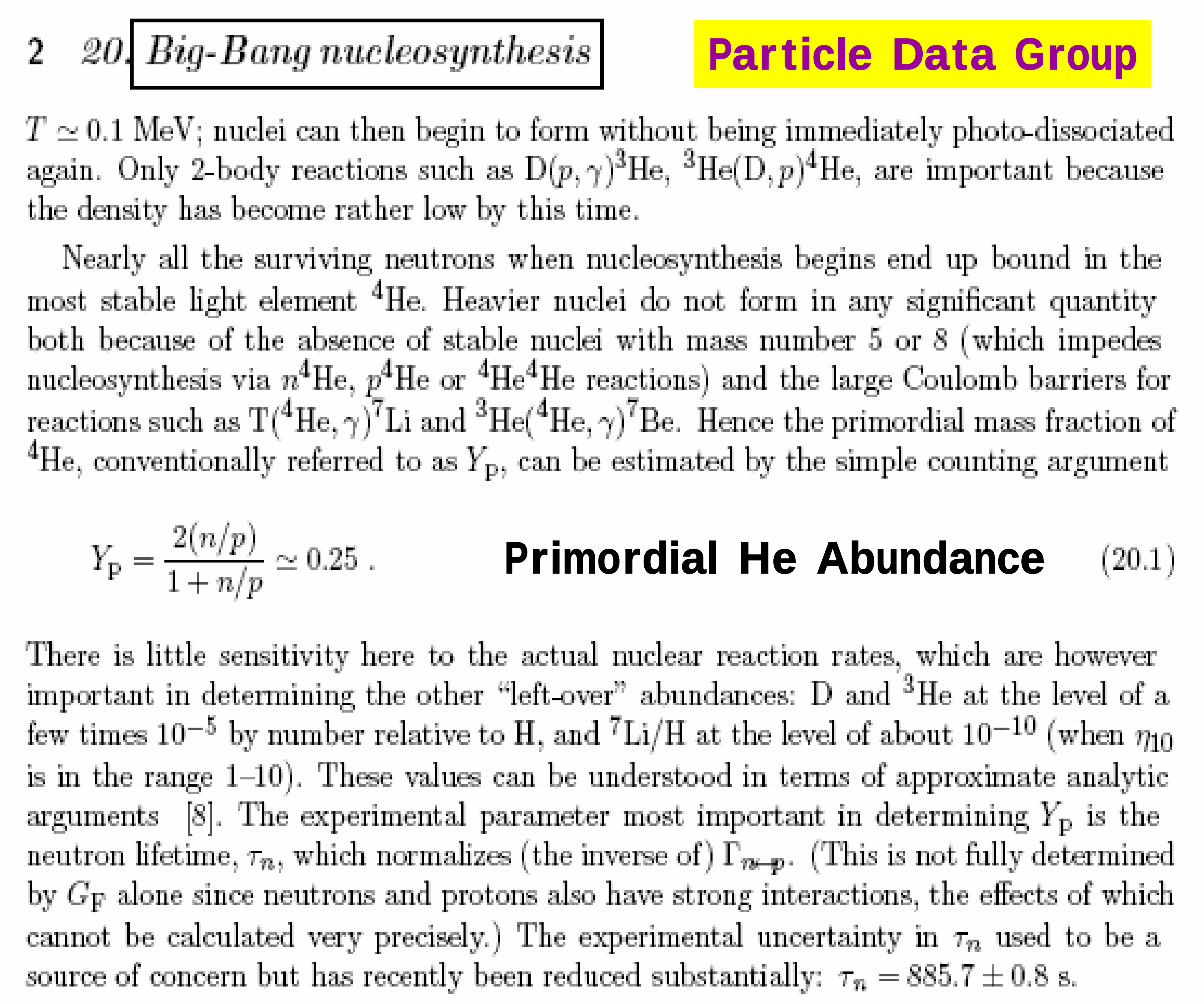
Mass eigenstates

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

Single complex phase is possible (gives “CP” Violation -more later)

- **$< 0.3\%$ measurements can be sensitive to new physics** (from loops in electroweak field theory)

a.k.a. Radiative Corrections



Particle Data Group

$T \simeq 0.1$ MeV; nuclei can then begin to form without being immediately photo-dissociated again. Only 2-body reactions such as $\mathrm{D}(p,\gamma)^3\mathrm{He}$, $^3\mathrm{He}(\mathrm{D},p)^4\mathrm{He}$, are important because the density has become rather low by this time.

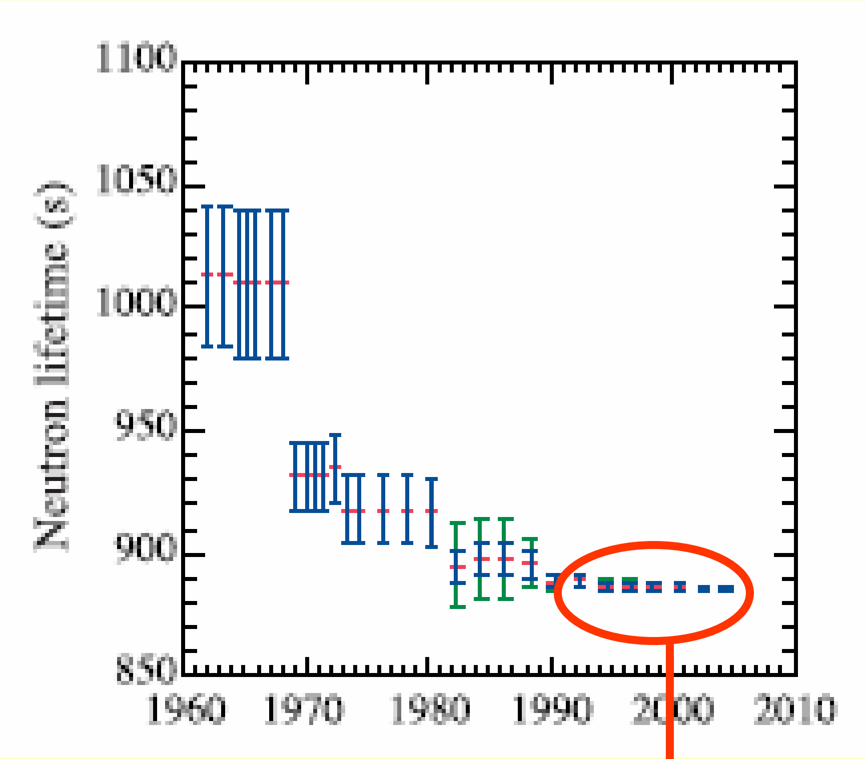
Nearly all the surviving neutrons when nucleosynthesis begins end up bound in the most stable light element ^{4}He. Heavier nuclei do not form in any significant quantity both because of the absence of stable nuclei with mass number 5 or 8 (which impedes nucleosynthesis via n^4He, p^4He or ^{4}He^{4}He reactions) and the large Coulomb barriers for reactions such as $\mathrm{T}(^4\mathrm{He},\gamma)^7\mathrm{Li}$ and $^3\mathrm{He}(^4\mathrm{He},\gamma)^7\mathrm{Be}$. Hence the primordial mass fraction of ^{4}He, conventionally referred to as Y_p, can be estimated by the simple counting argument

$$Y_\mathrm{p} = \frac{2(n/p)}{1+n/p} \simeq 0.25\ . \qquad (20.1)$$

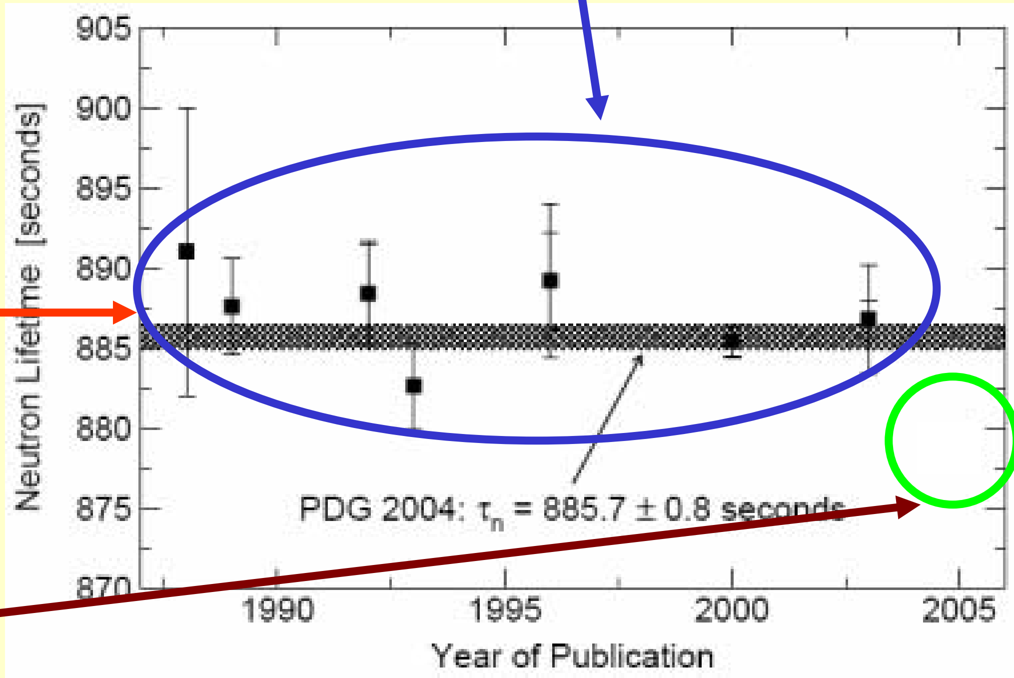
Primordial He Abundance

There is little sensitivity here to the actual nuclear reaction rates, which are however important in determining the other “left-over” abundances: D and ^{3}He at the level of a few times 10^{-5} by number relative to H, and ^{7}Li/H at the level of about 10^{-10} (when η_{10} is in the range 1–10). These values can be understood in terms of approximate analytic arguments [8]. The experimental parameter most important in determining Y_p is the neutron lifetime, τ_n, which normalizes (the inverse of) $\Gamma_{n\leftrightarrow p}$. (This is not fully determined by G_F alone since neutrons and protons also have strong interactions, the effects of which cannot be calculated very precisely.) The experimental uncertainty in τ_n used to be a source of concern but has recently been reduced substantially: $\tau_n = 885.7 \pm 0.8$ s.

Neutron Lifetime versus Year



**Data points used by
Particle Data Group (PDG)
2004 for averaging**

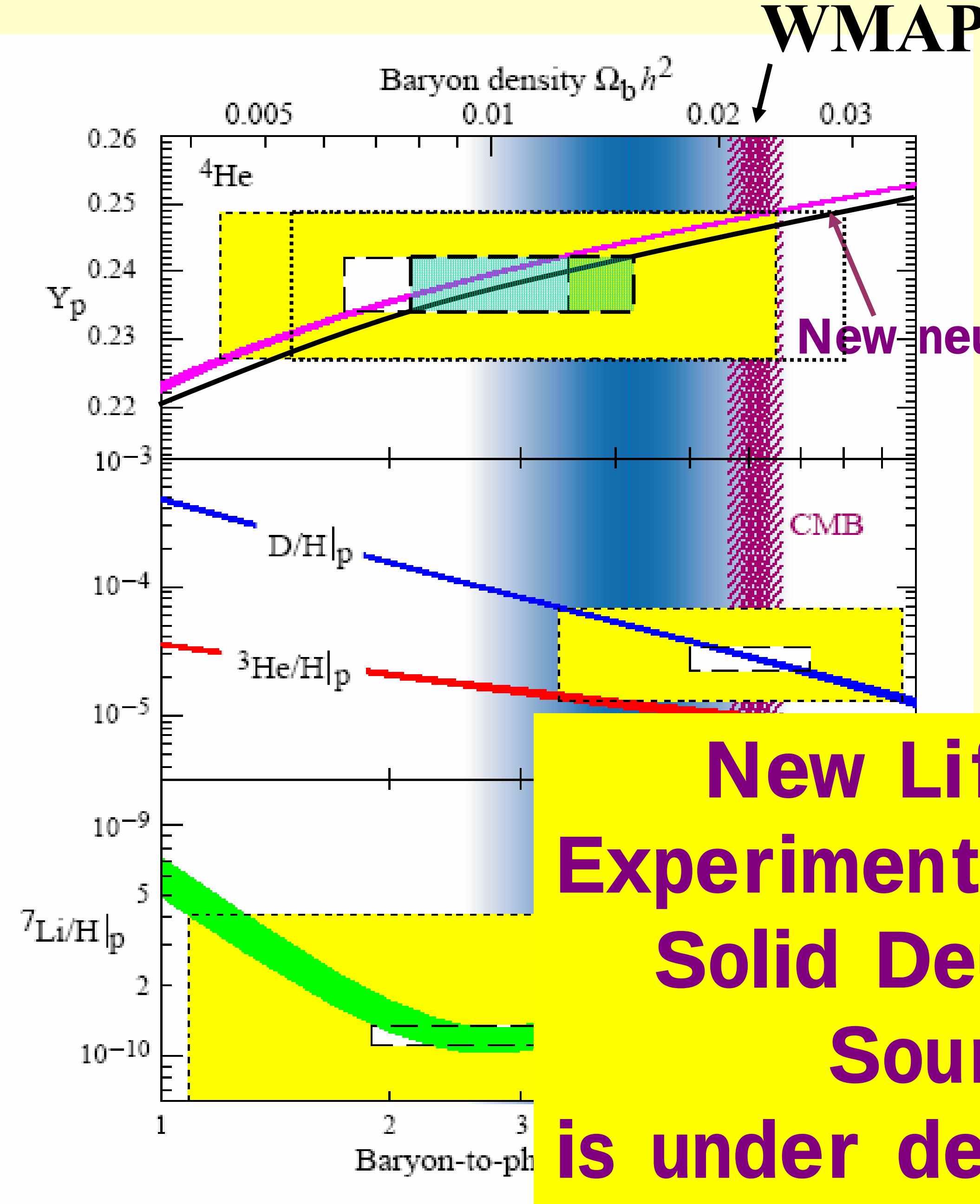


Serebrov *et al.*,

Phys. Lett. B 605, 72 (2005)

(878.5 ± 0.7 ± 0.3) seconds

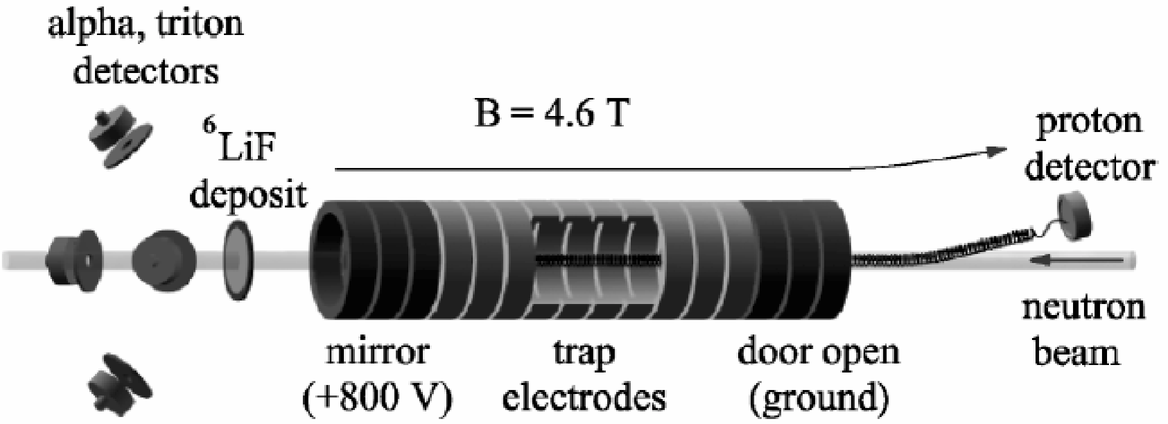
Big-Bang Nucleosynthesis Constraints

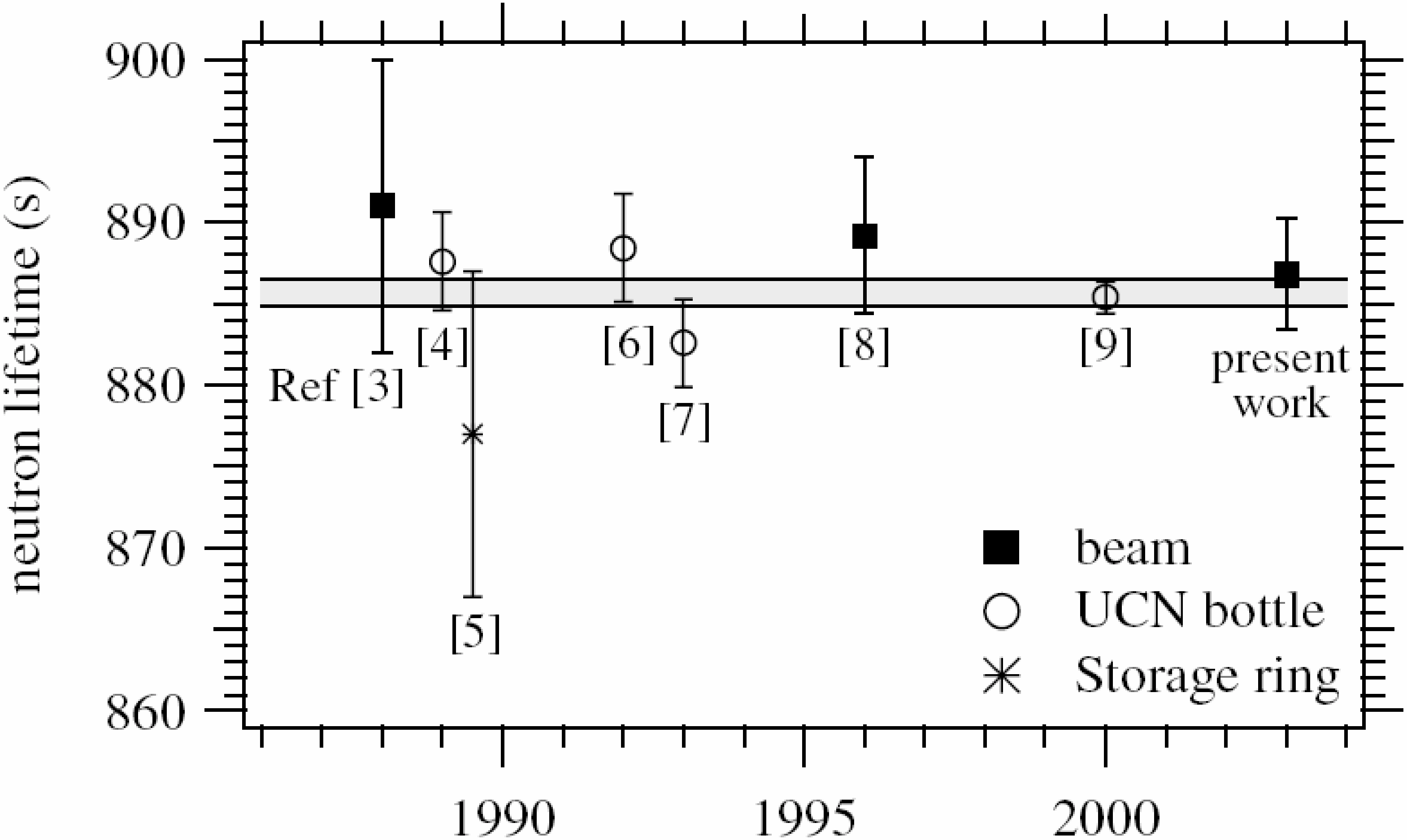


New neutron lifetime

New Lifetime Experiment using our Solid Deuterium Source is under development

Neutron τ_n @ NIST





New Neutron Lifetime Measurement UCN @ ILL

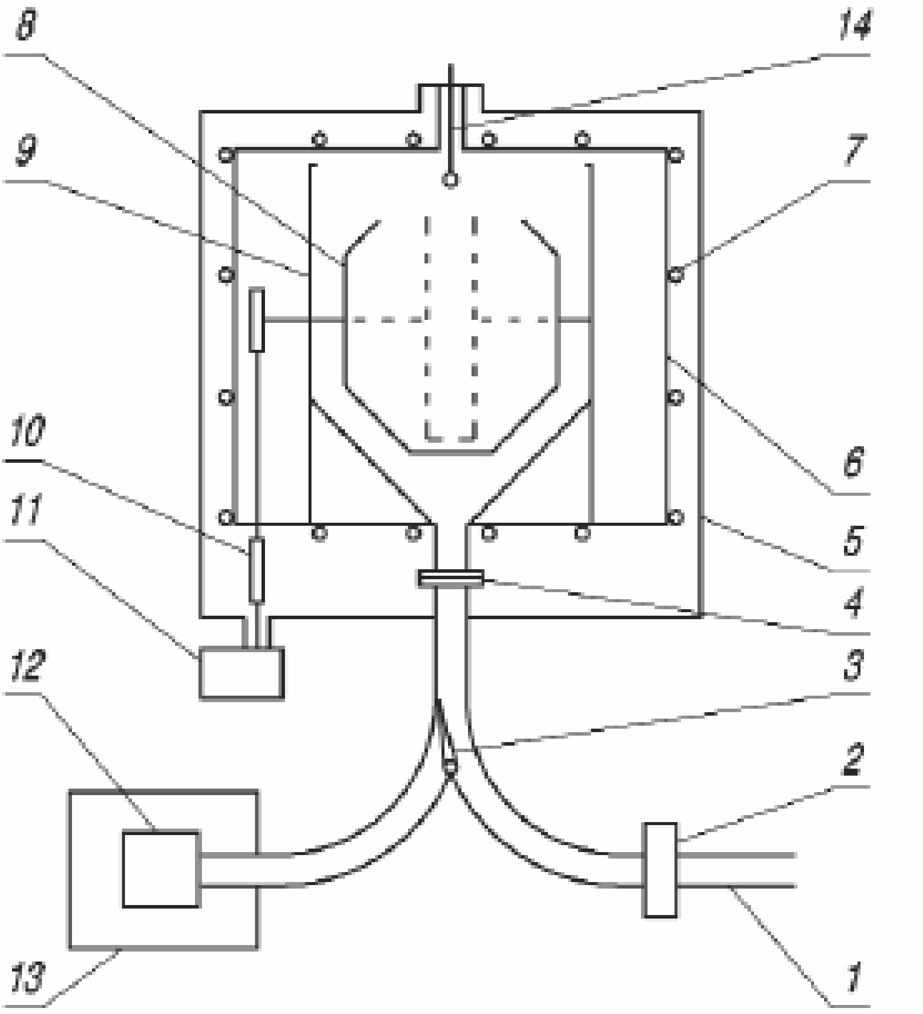
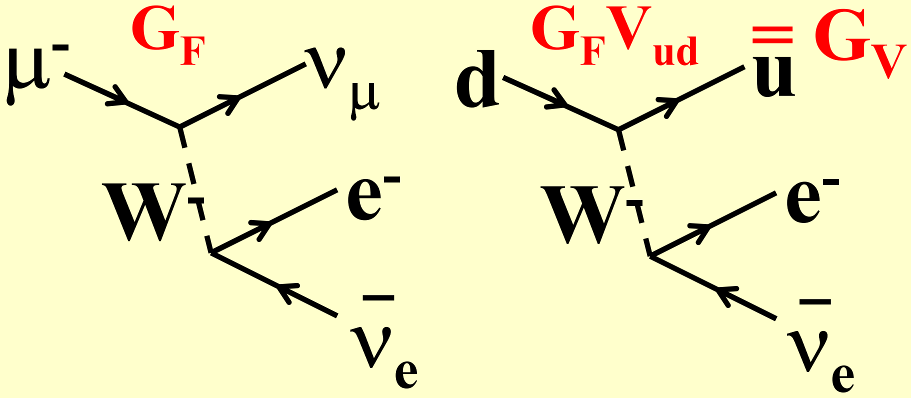


Fig. 1. The Scheme of "Gravitrap", the gravitational UCN storage system. 1: neutron guide from UCN Turbine; 2: UCN inlet valve; 3: beam distribution flap valve (shown in the filling position); 4: connection unit; 5: "high" vacuum volume; 6: "rough" vacuum volume; 7: cooling coils; 8: UCN storage trap (the narrow cylindrical trap is shown by a dashed line); 9: cryostat; 10: mechanics for trap rotation; 11: stepping motor; 12: UCN detector; 13: detector shielding; 14: evaporator.

Need More Lifetime experiments

V_{ud} from β-decay

- G_V is related to Fermi coupling G_F via V_{ud}

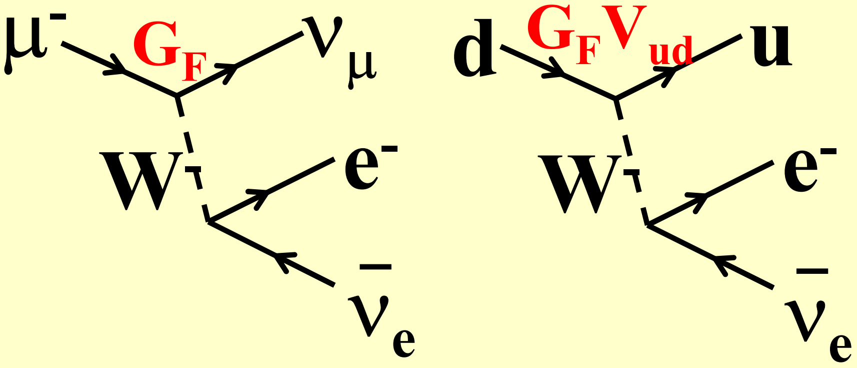


- G_V measured in β-decay (u→d)
  - 0^+-0^+ nuclear decay (must include nuclear corrections)
  - neutron decay (must extract G_V and G_A)

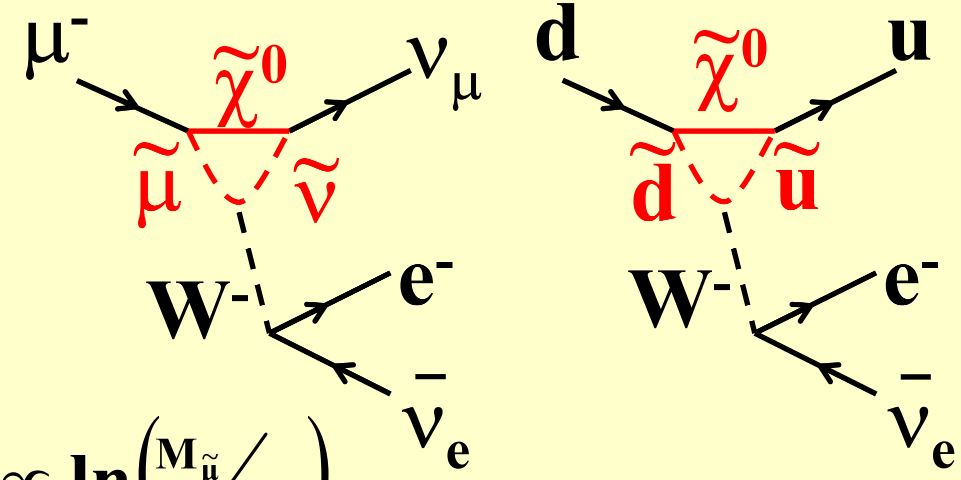
Sensitivity to New Physics?

Kurylov&Ramsey-Musolf
Phys. Rev. Lett. 88, 071804 (2002)

- V_{ud} in Standard Model (from μ vs. β-decay)



- Supersymmetric particles produce loop corrections



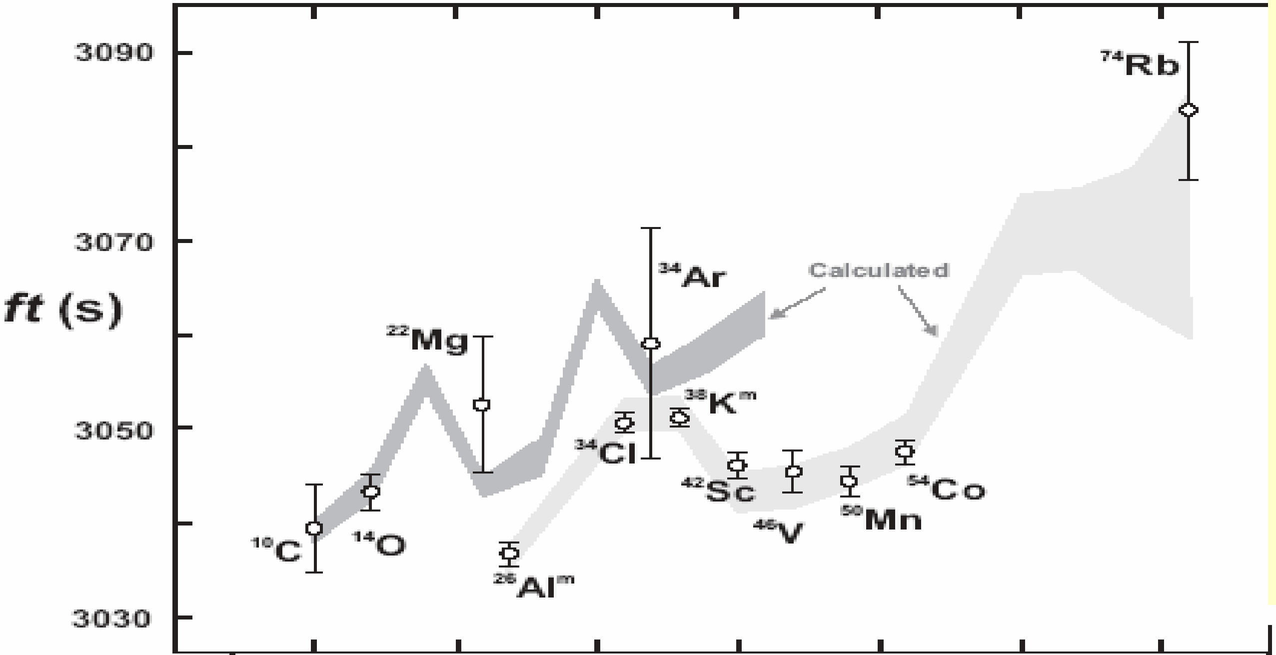
$$V_{ud}^{super} = V_{ud}^{SM}\left(1-\Delta_{loop}\right) : \Delta_{loop} \propto \ln\left(M_{\tilde{\mu}} \big/ M_{\tilde{q}}\right)$$

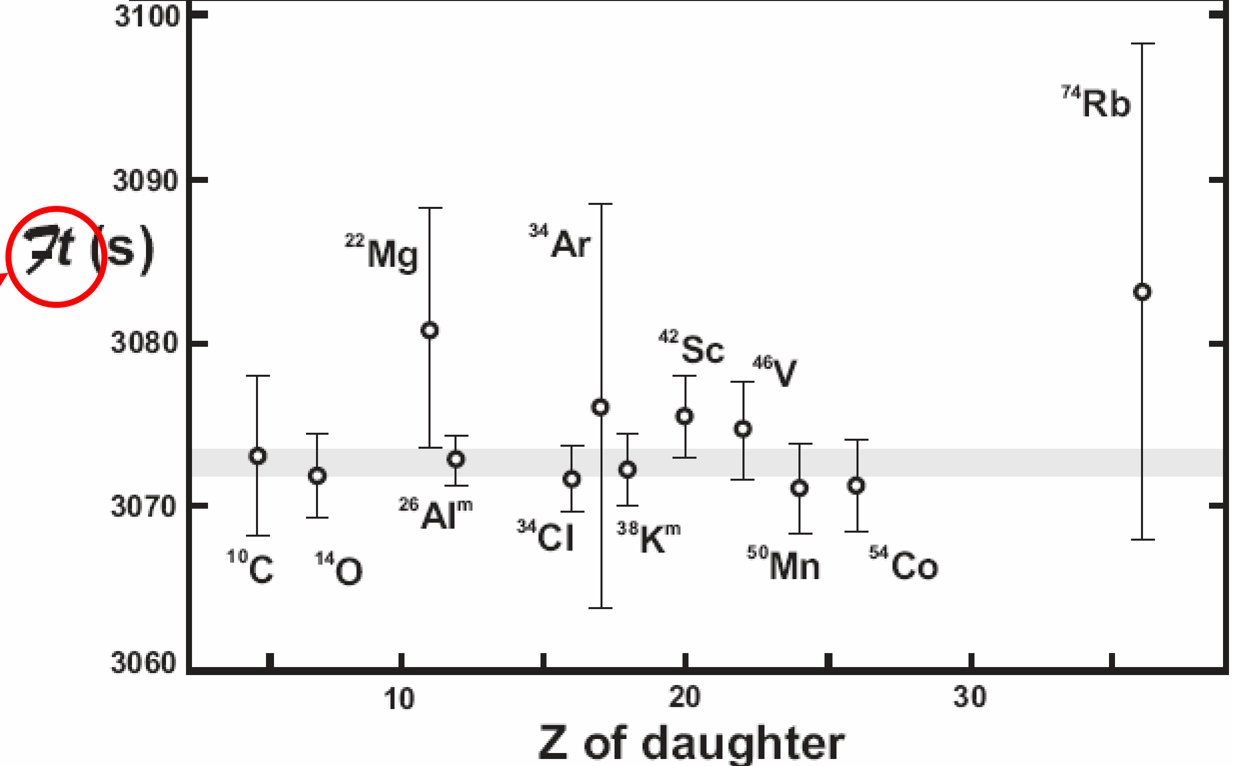
Nuclear β-Decay

0^+ - 0^+

f = phase space
t = half-life

$$ft \propto \frac{1}{G_V^2}$$



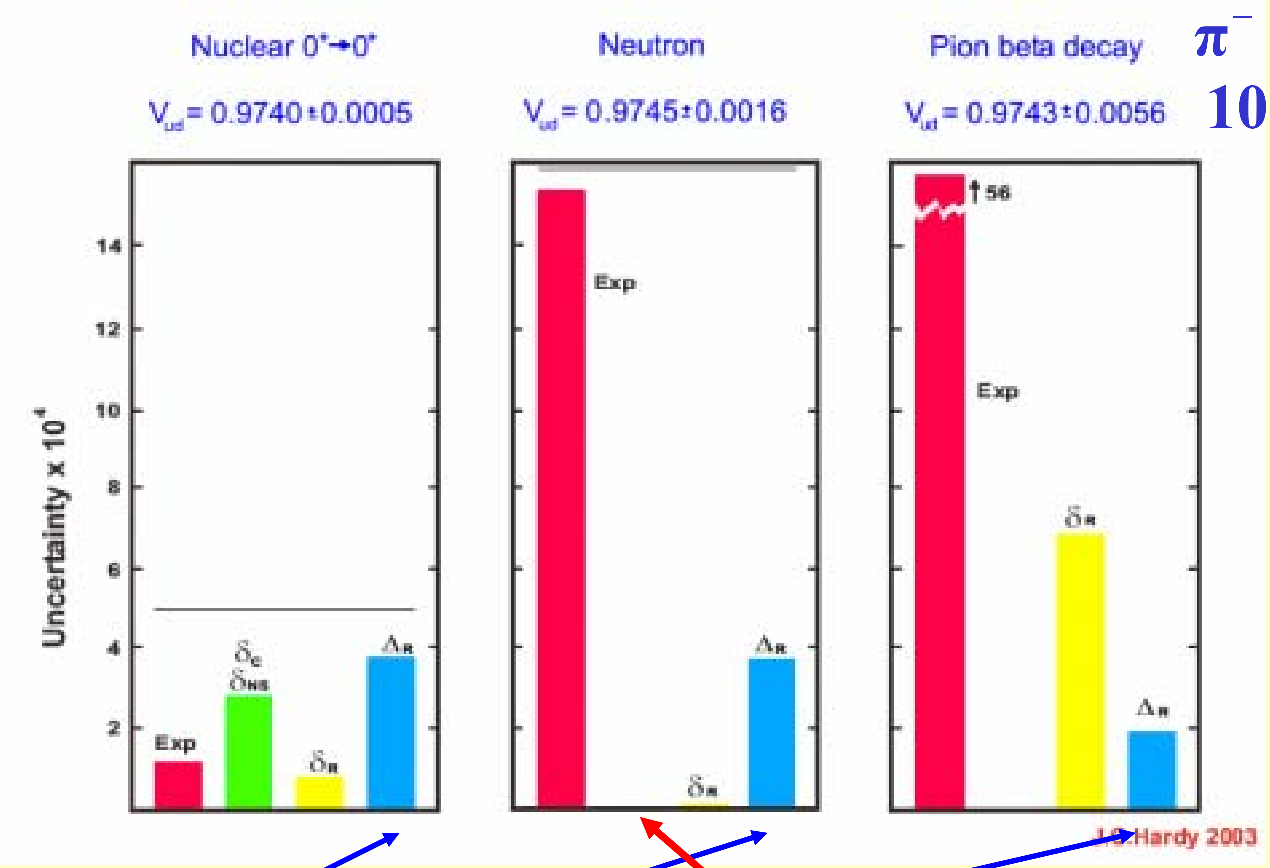


Including Nuclear Corrections

Uncertainties in V_{ud}

$\pi^- \rightarrow \pi^0 e^- \overline{\nu}_e$

10^{-8} branch

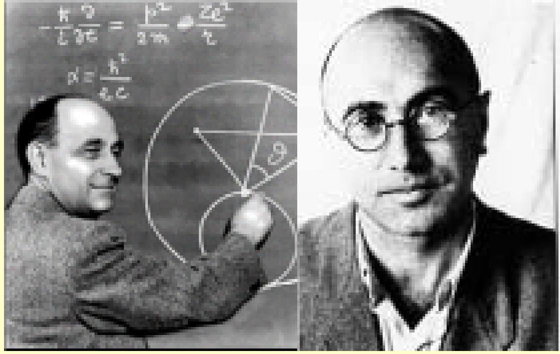


J.C.Hardy 2003

Electroweak corrections (Z^0 and hadron loops)

Improved neutron Experiments needed

Ultra-Cold Neutrons (UCN) (Fermi/Zeldovich)

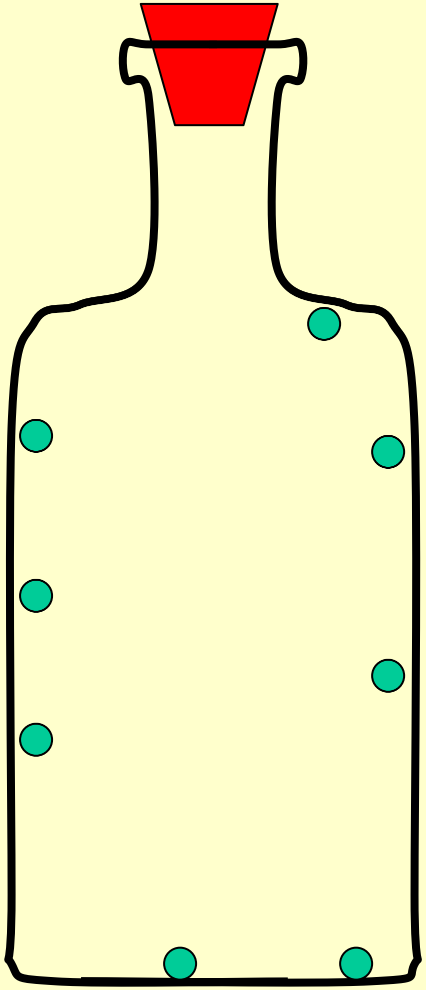


- What are UCN ?
  - Very slow neutrons

    ($v < 8$ m/s → $\lambda > 500$ Å)

    that cannot penetrate into certain materials

Neutrons can be trapped in bottles or by magnetic field



But… nuclear force is attractive at low energies. Where does repulsion come from?

Recall (for short-range potential):

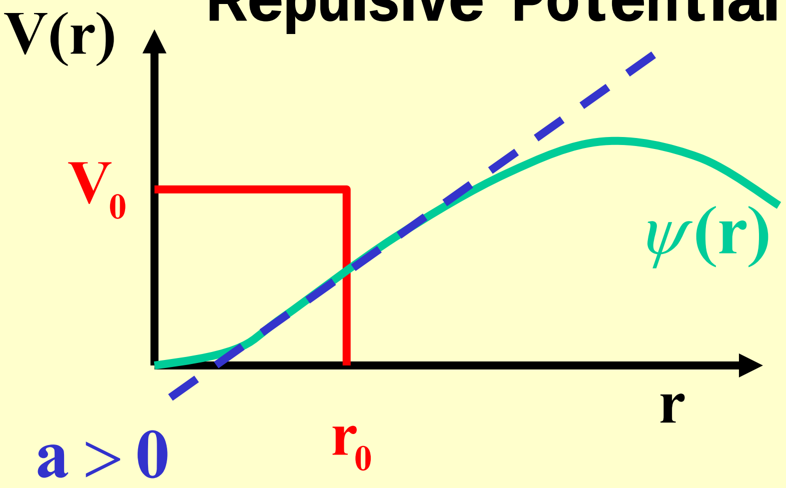
At low energies ($kr_0 << 1$; eg s-wave) elastic scattering determined solely by scattering length **a**

$$\text{For } k \to 0$$

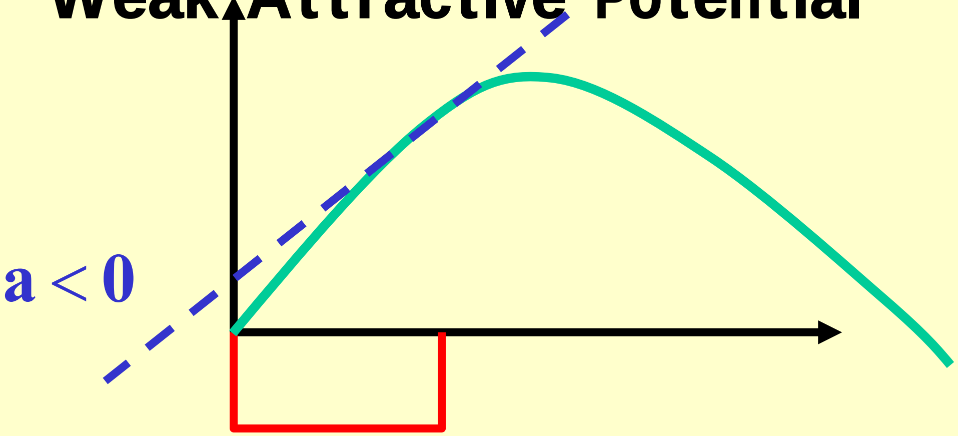
$$\sigma_{\text{elas}} = 4\pi \mathbf{a}^2$$

Scattering Length

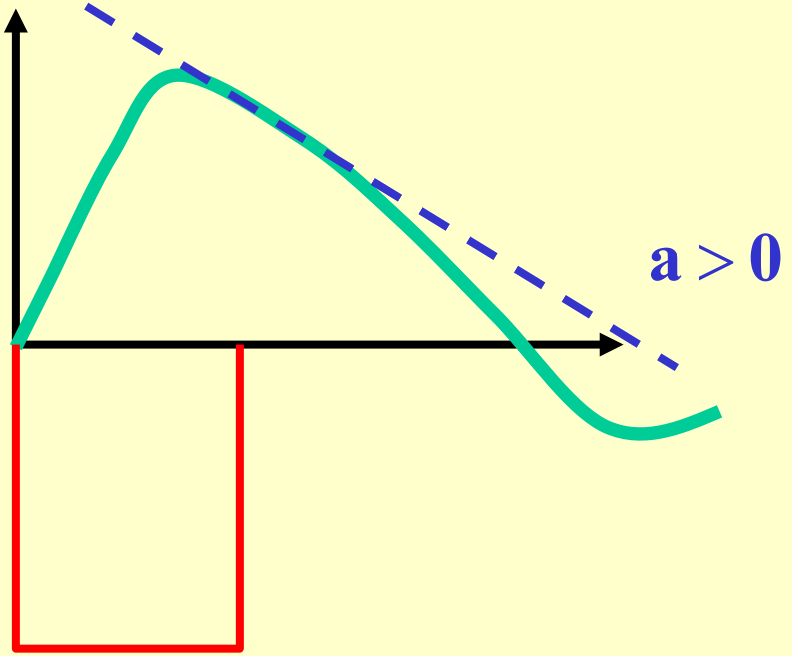
Repulsive Potential



Weak Attractive Potential



Strong Attractive Potential



Thus many different V_0 and r_0 can give same *a*

$$\text{eg.} \quad V(\vec{r}) = \frac{a\hbar^2}{2m_n}(4\pi)\,\delta(\vec{r})$$

Fermi Pseudopotential

Then for many nuclei in a solid: →

$$V(\vec{r}) = \frac{4\pi\hbar^2}{2m_n} \sum_i a_i \delta(\vec{r} - \vec{r}_i')$$

And if $a_i = a$ and $\lambda \gg$ atomic spacing: →

$$V(\vec{r}) = \frac{4\pi\, a\, \hbar^2}{2m_n} N_0 \int \frac{d^3r'}{V} \delta(\vec{r} - \vec{r}')$$

$$= \frac{2\pi\, a\, \hbar^2 n_0}{m_n} \theta(\vec{r} \notin V) \equiv V_0 \theta(\vec{r} \notin V)$$

Fermi Pseudopotential

Potential step analogous to index of refraction in optics

with

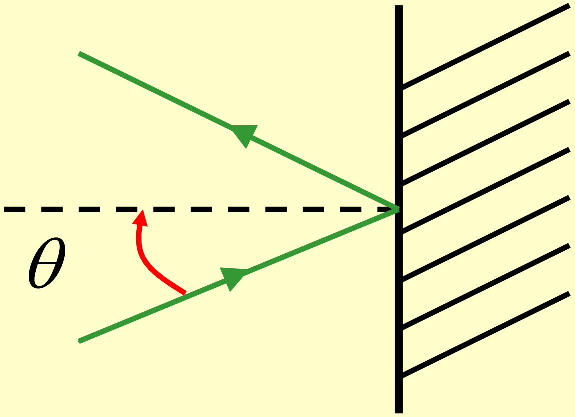
$$n = \sqrt{1 - \frac{V_0}{E_n}}$$

$$\boxed{V_0 = \frac{2\pi a \hbar^2 n_0}{m_n}}$$

Neutron kinetic energy

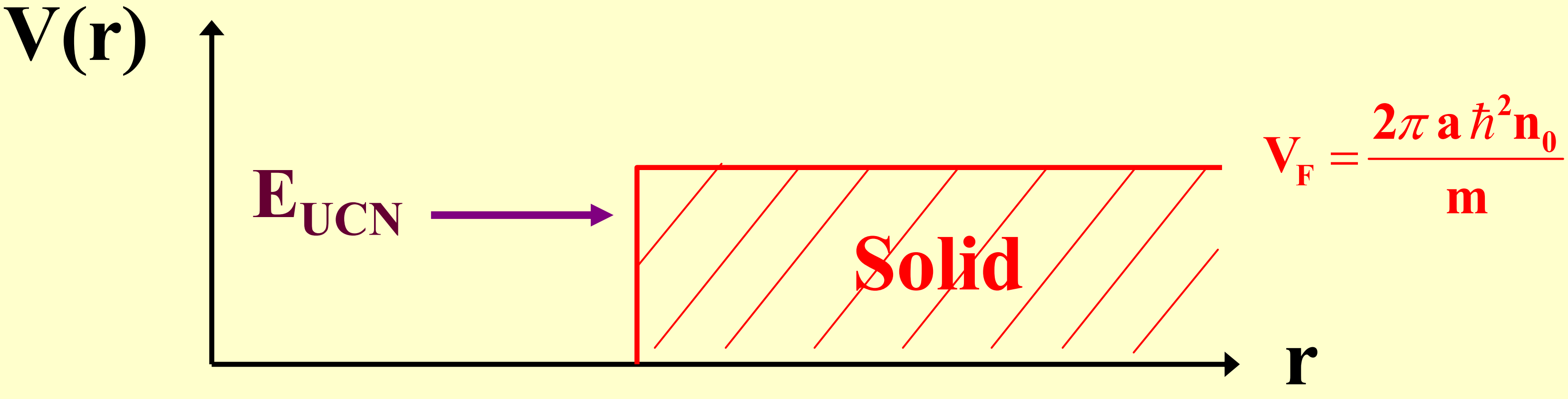
And if a > 0 can have total *external* reflection

$$n_{out} = 1$$



$$n_{in} = \sqrt{1 - \frac{V_0}{E}}$$

Fermi Pseudo-potential



$$V_F = \frac{2\pi a \hbar^2 n_0}{m}$$

The coherent nuclear potential can lead to repulsive pseudopotential (Fermi potential) for a > 0

For $E_{UCN} < V_F$, UCN are trapped

Attractive potential can also lead to neutron absorption but often $L_{mfp} >> \lambda_n$ (~10^{-5} probability per bounce)

Typical Fermi Potentials

Material	V_F (neV)
Al	54
^{58}Ni	350
Ti	- 48
Graphite	180
Stainless Steel	188
Diamond-like Carbon	282

350 → **neutron velocity**
$v_n \sim 8$ m/s

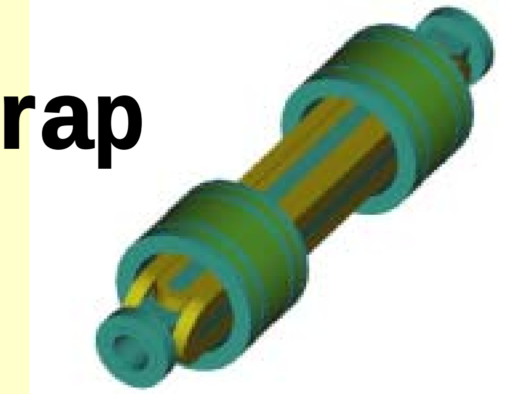
Magnetic Bottles also possible

- B-field and neutron magnet moment produces a potential

$$V = -\vec{\mu} \cdot \vec{B} \qquad (\text{Note}: \ \mu_n < 0)$$

- Thus can produce a 3D potential well at a B-field minimum

Ioffe Trap

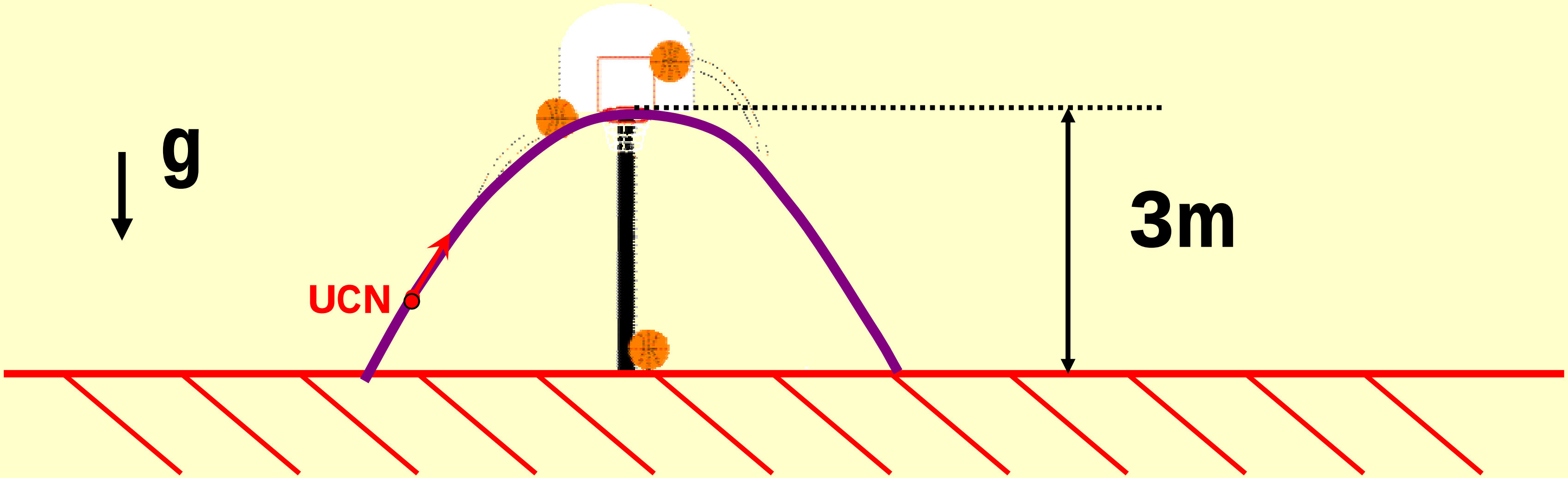


Traps one spin state: "Low field seekers"
Spin anti-aligned with magnetic field

For v_n<8 m/s need B<6T

UCN Properties

- $v_{UCN} \leq 8\ \text{m/s}\ \ (\approx 18\ \text{mi/hr})$
- $\lambda_{UCN} \geq 500\ \mathring{A}\ \ (50\ \text{nm})$
- $"T_{UCN}" \leq 4\ \text{mK}$
- Maximum height due to gravity : $\sim 3\ \text{m}$



How to make UCN?

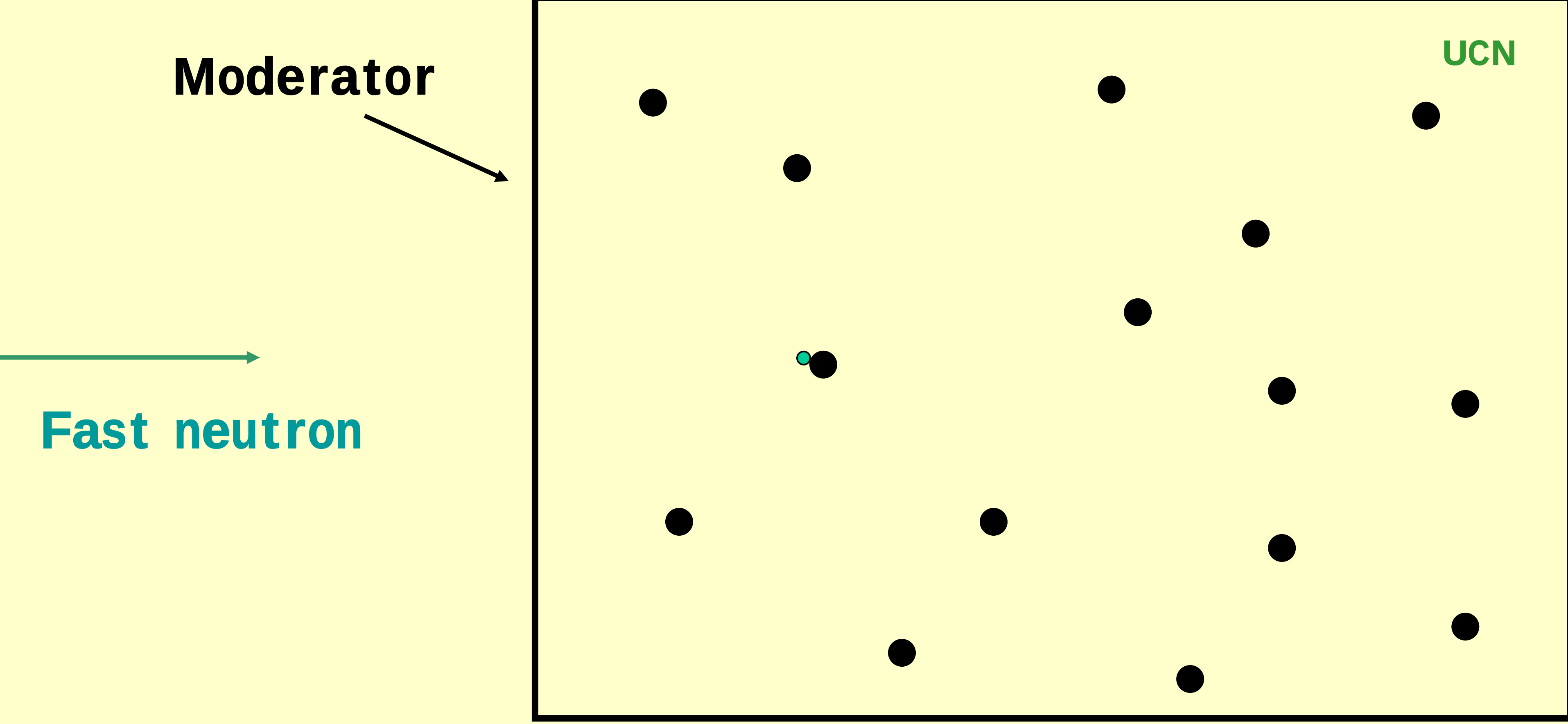
- **Conventional Approach:**
  - Start with neutrons from nuclear reactor core

$$E_n \approx 5 - 10\ \mathrm{MeV}$$
$$v_n \approx 4 \cdot 10^7\ \mathrm{m/s}$$

  - Use collisions with nuclei to slow down neutrons

Some of neutron's energy lost to nuclear recoil in each collision

Gives a Maxwell-Boltzmann Distribution



After 20-100 collisions E_n ~ 1/40 eV (Room Temp)
Slowing down takes ~ 100 μs

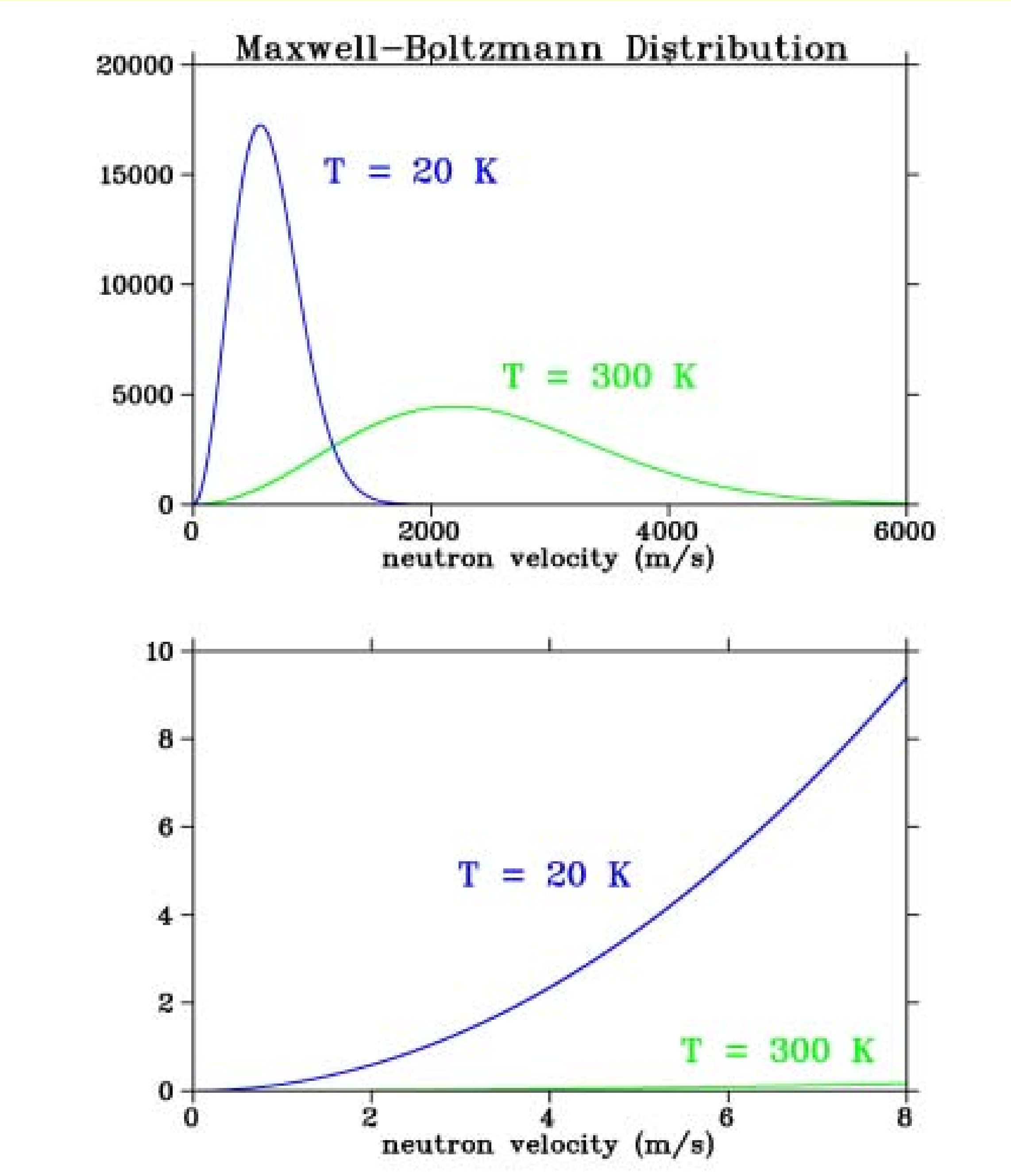
Maxwell-Boltzmann Distribution

$$P(E) \propto E^{\frac{1}{2}} e^{-\frac{E}{kT}}$$

But…

- Only small fraction of neutron distribution is UCN

$$\sim 10^{-8} \text{ for } T = 300\text{ K}$$
$$\sim 10^{-6} \text{ for } T = 20\text{ K (liquid } H_2)$$

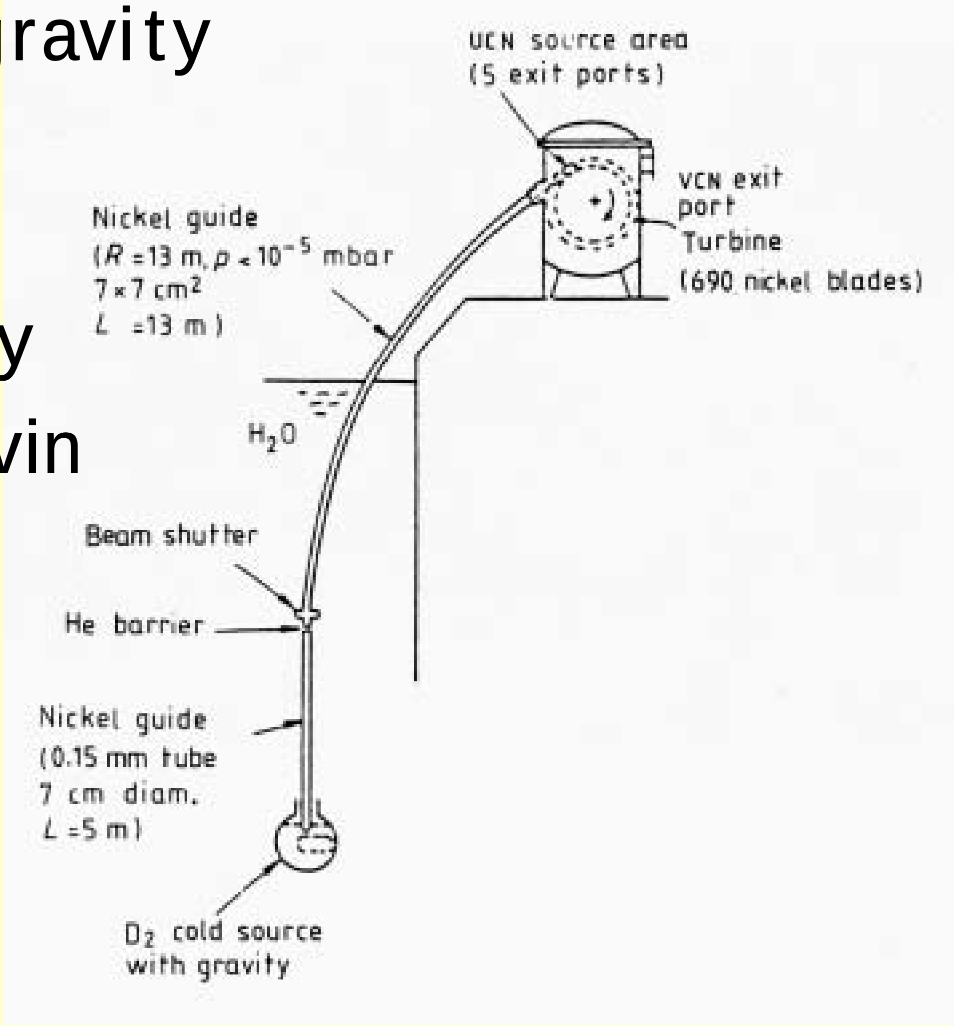


- Can improve some via gravity and moving turbines

- Previous record density at Institut Laue-Langevin (ILL) reactor in Grenoble

≈ 40 UCN/cm^3 stored in bottle

(1971)



Best vacuum on earth
~10^4 atoms/cm^3

Can we make more?