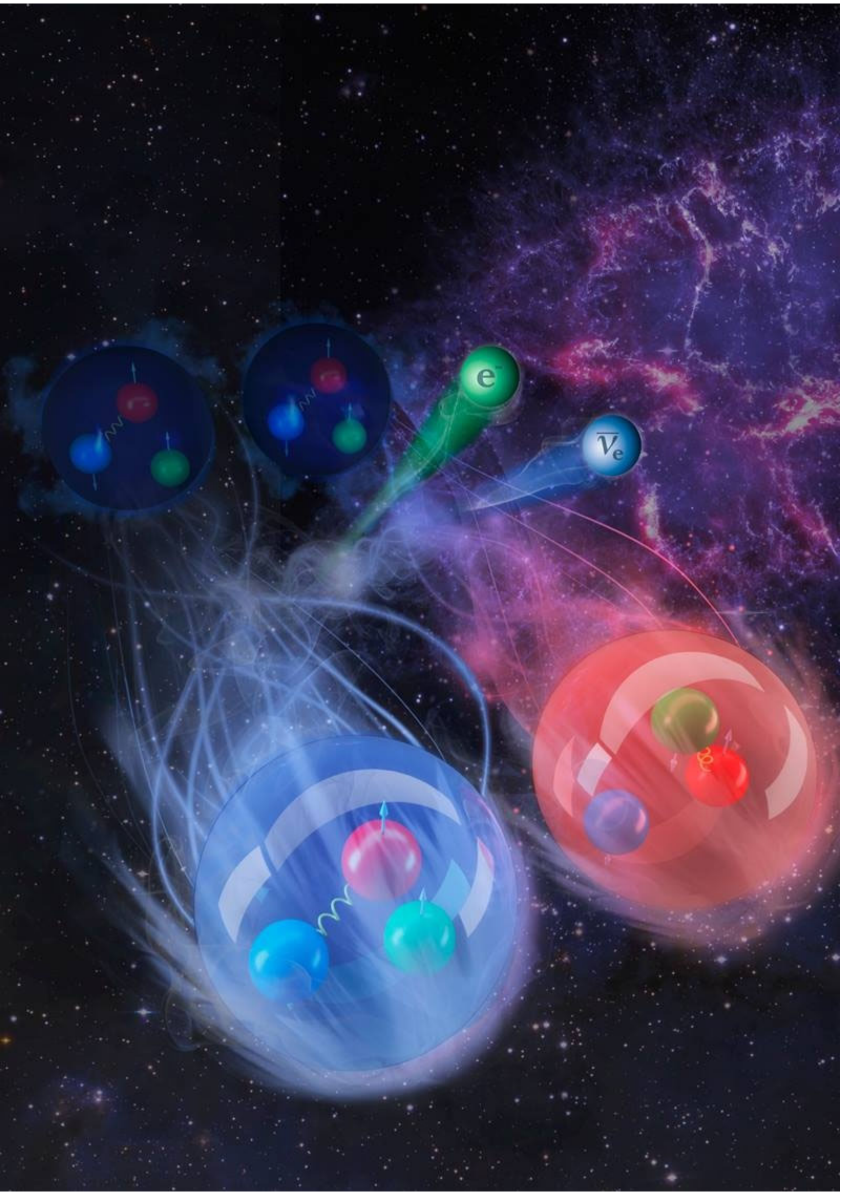


Fundamental Neutron Physics: Probing TeV physics with neV neutrons

Chen-Yu Liu

Indiana University/University of Illinois at Urbana-Champaign

6/7/2022

S@INT

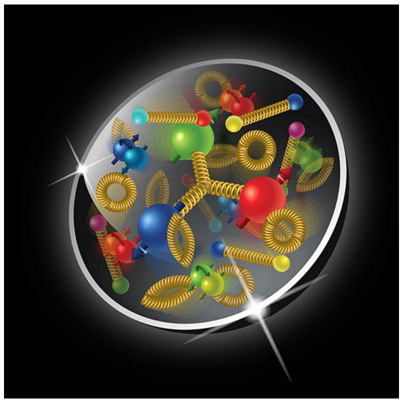
LANSCE Los Alamos Neutron Science Center

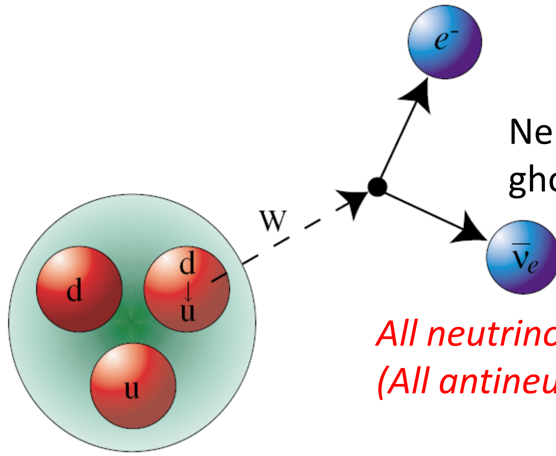
U.S. DEPARTMENT OF ENERGY Office of Science

NSF

Neutrons are a unique laboratory to study the four fundamental forces of nature.

Strong force

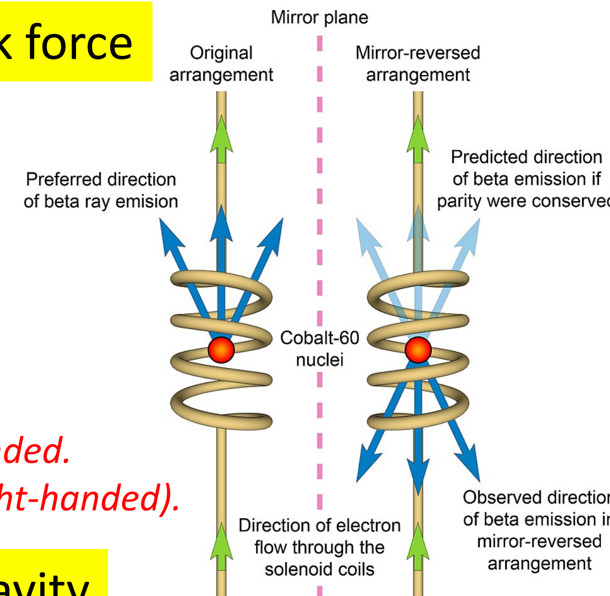




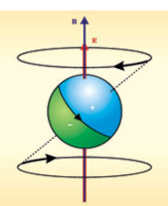
Neutrino, the ghost particle

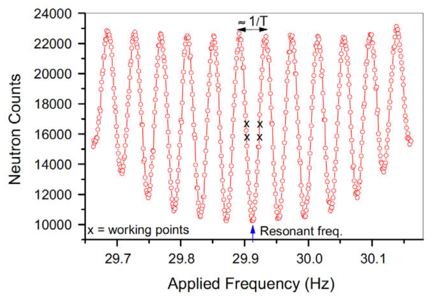
All neutrinos are left-handed.
(All antineutrinos are right-handed).

Weak force



Electromagnetic force

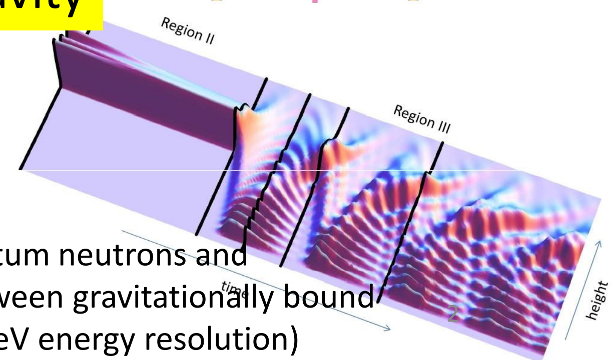




$$n \rightarrow p^+ + e^- + \bar{\nu}_e + 782\ \text{keV}$$

Neutron beta decay is the archetype of nuclear transmutation.

Gravity

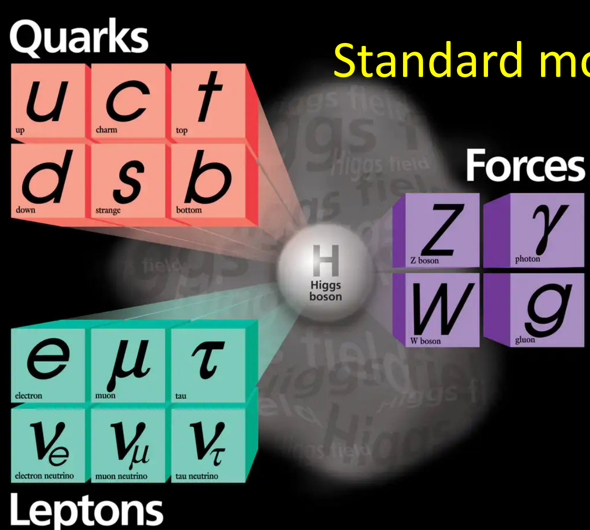


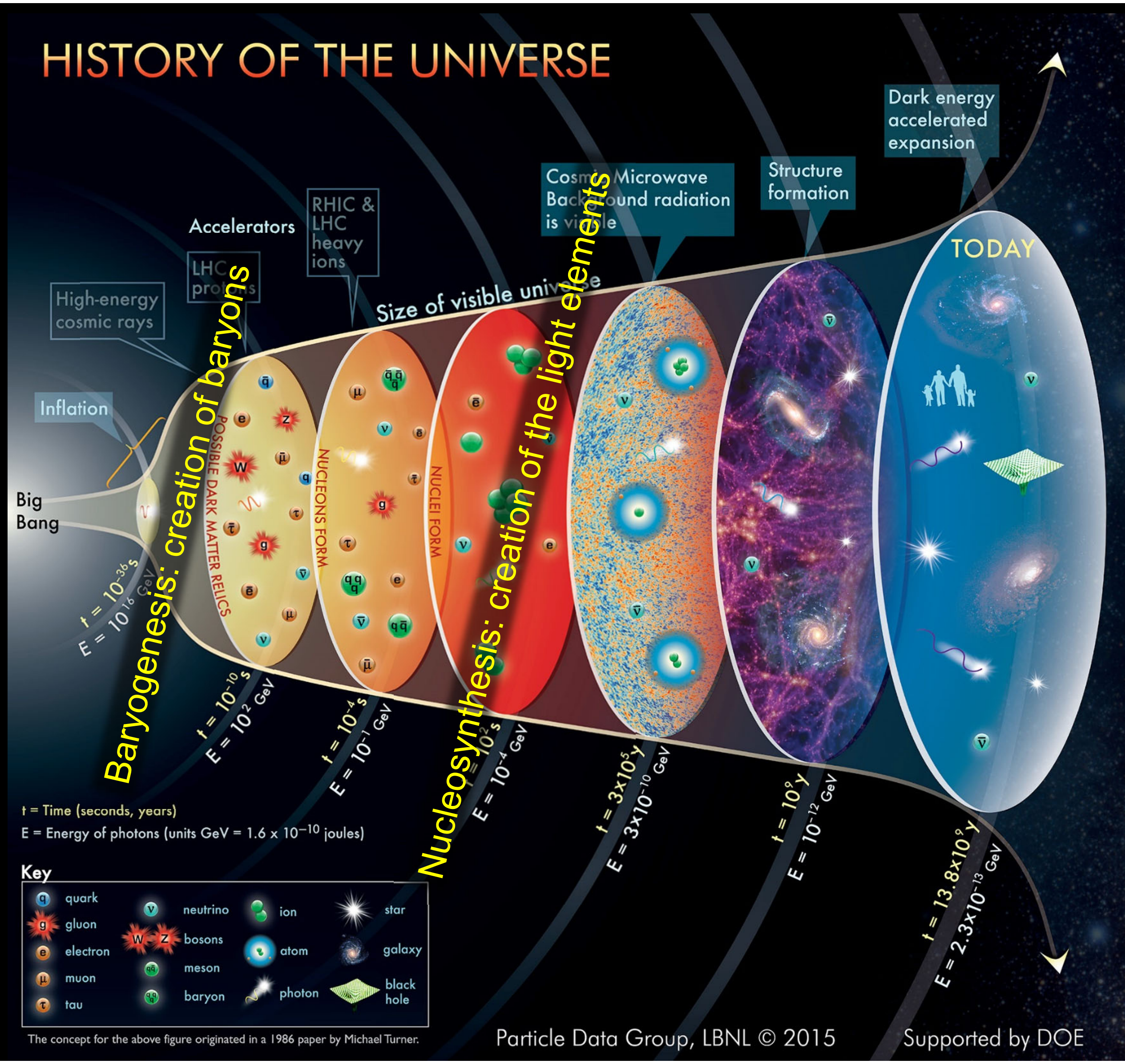
Bouncing quantum neutrons and transitions between gravitationally bound neutrons (w/ peV energy resolution)

Big Questions:

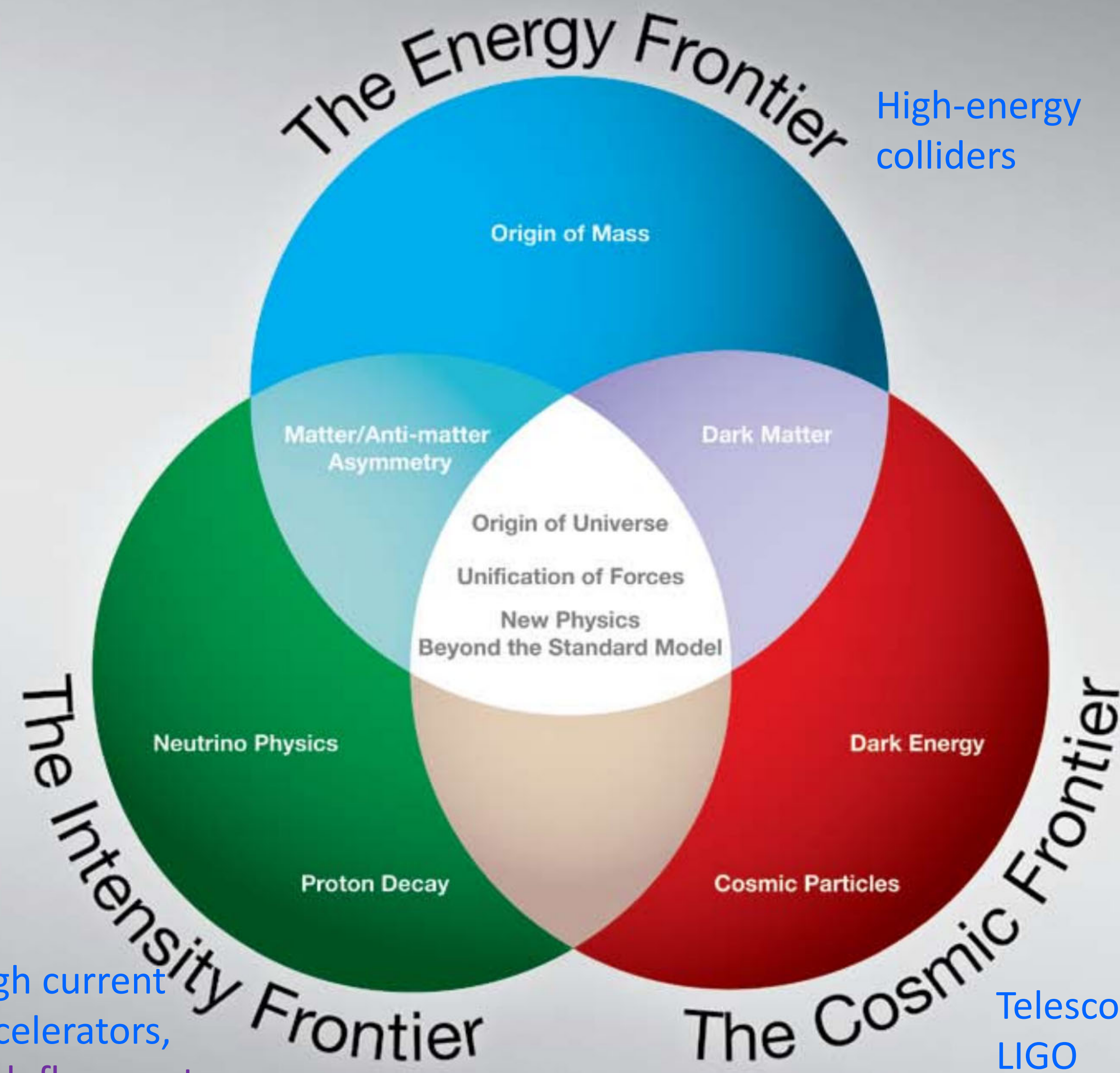
1. How was matter created?
2. How were the elements made in the Big Bang?
3. What are the fundamental particles and their interactions?

Standard model





P5 Report (Particle Physics Project Priorization Panel)



High-energy colliders

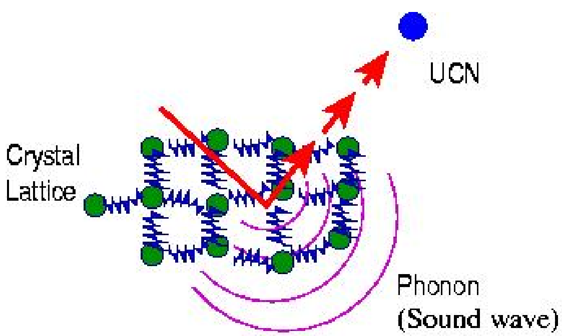
High current accelerators, high flux reactors

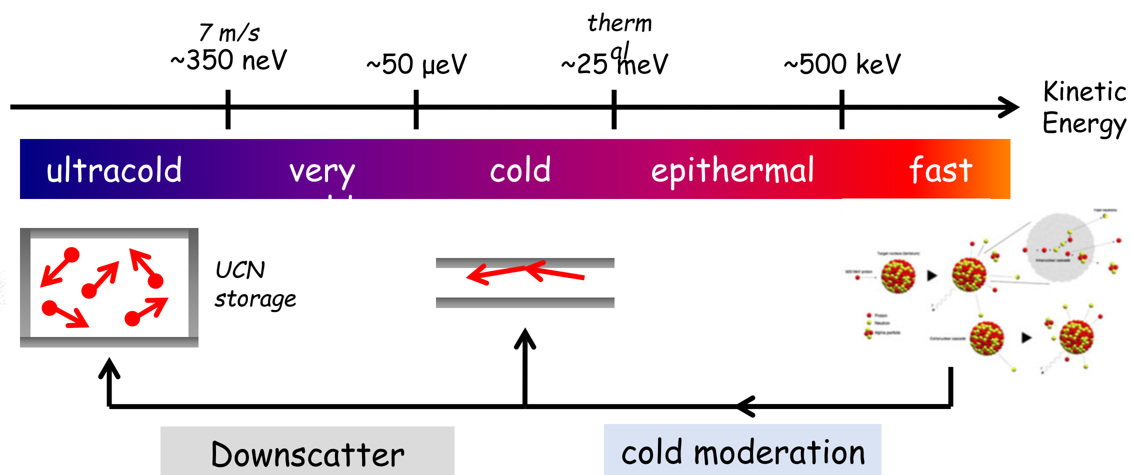
Telescopes, LIGO

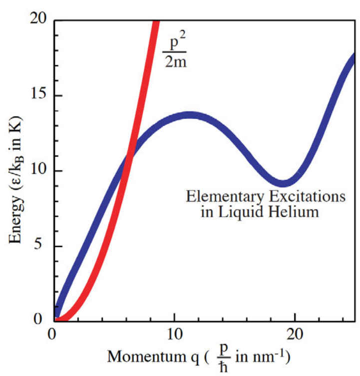
Fundamental Neutron Physics

How to make neV Ultracold Neutrons (UCN)?

v [m/s]	E [eV]	λ [m]	Description
14000	2 MeV	0.3 Å	Fast
2000	25 meV	2 Å	Thermal
200	<25 meV	20 Å	Cold
5	**<300 neV**	**800 Å**	**Ultracold**

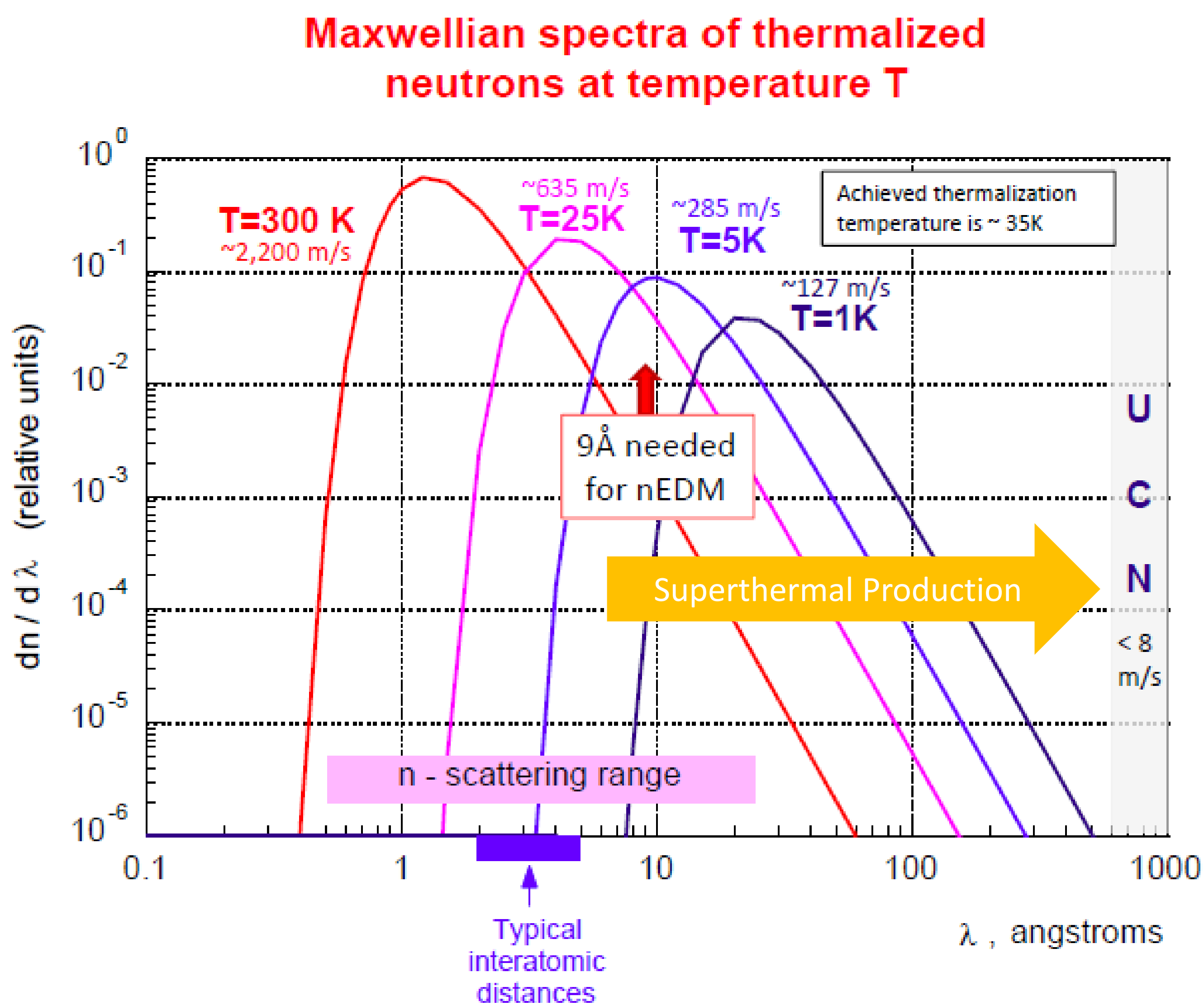






superthermal production:
UCN can be accumulated to a density higher than the Boltzmann factor, $e^{-\Delta E/kT}$

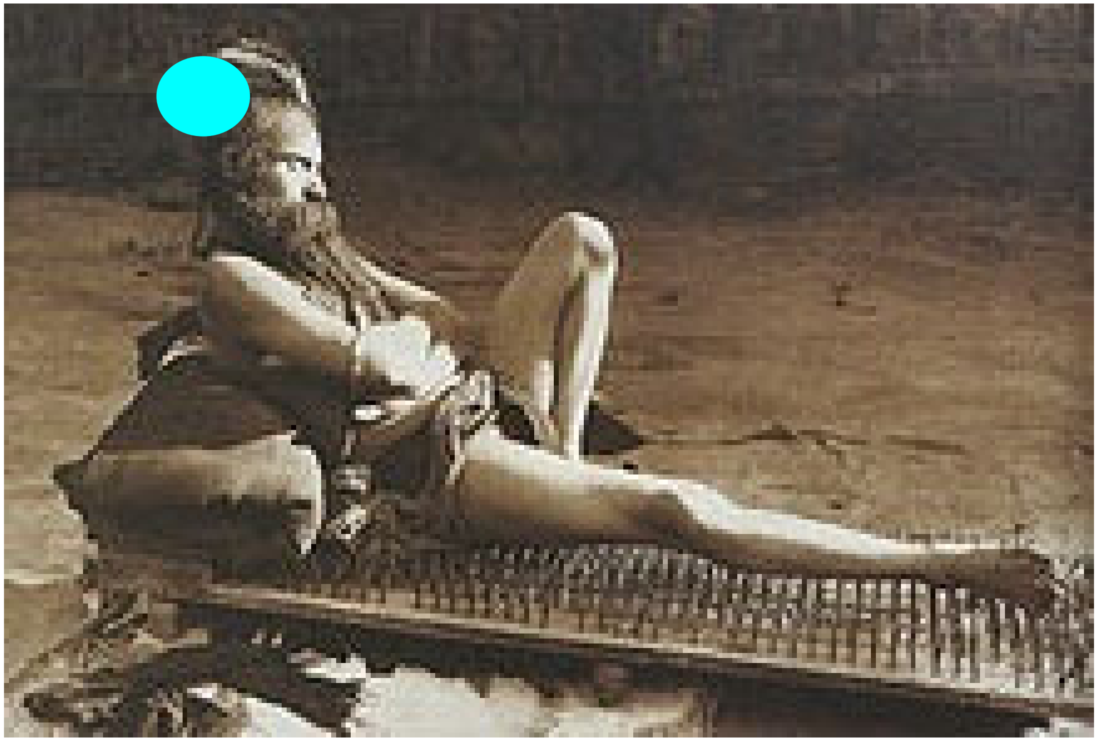
R. Golub and J.M. Pendlebury, PLA 53, 133 (1975)
R. Golub and J.M. Pendlebury, PLA 62, 337 (1977)
C.L. Morris et al., PRL 89, 272501 (2002)
F. Atchinson et al., PRL 95, 182502 (2005)
C.M. Lavelle et al., PRC 82, 015502 (2010)



UCN are milli-Kelvin baryons!

Ultracold neutrons (with long de Broglie wavelengths) are reflected by material potentials.

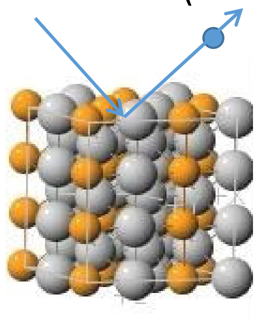
Fermi potential: $$V_F = \frac{2\pi h^2 N b_c}{m_n}$$



Material	V_F(neV)
D_2O	170
Be (BeO)	250
C	180
Mg	60
Al	50
SiO_2 (quartz)	110
Cu	170
Fe	220
Co	70
Ni	230

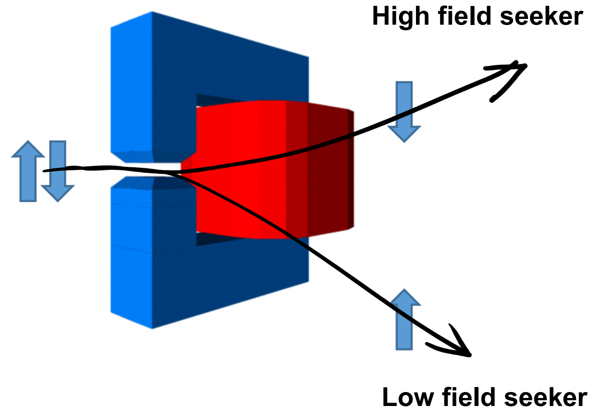
UCN experiences the four fundamental forces at a comparable energy scales of ~100 neV

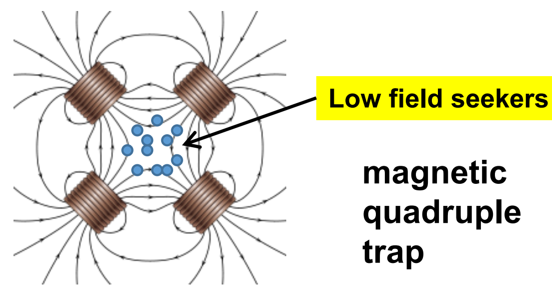
- Nuclear force (max: 350neV)

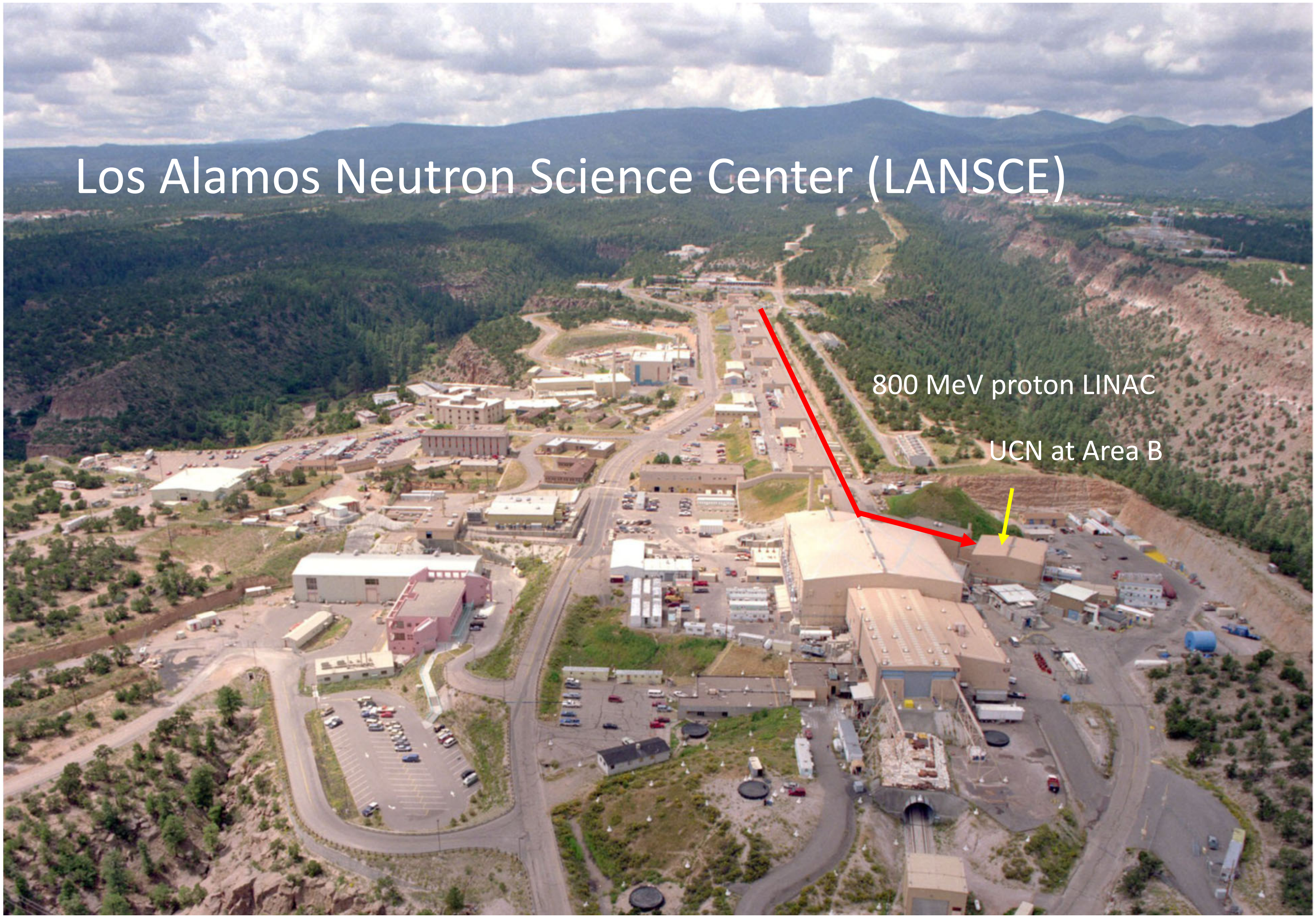


- Gravitational force (100neV/m)

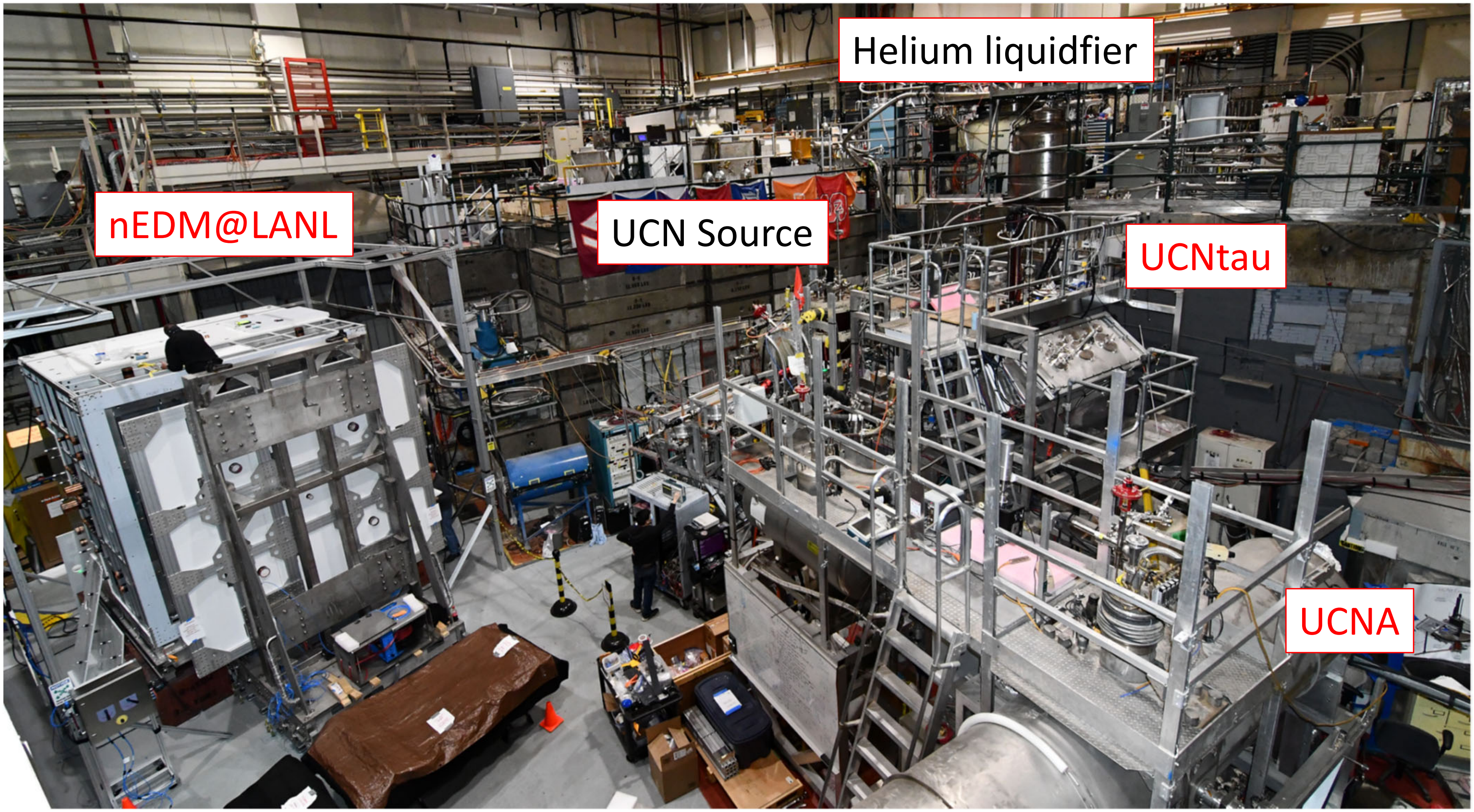
- Magnetic force (60neV/T)



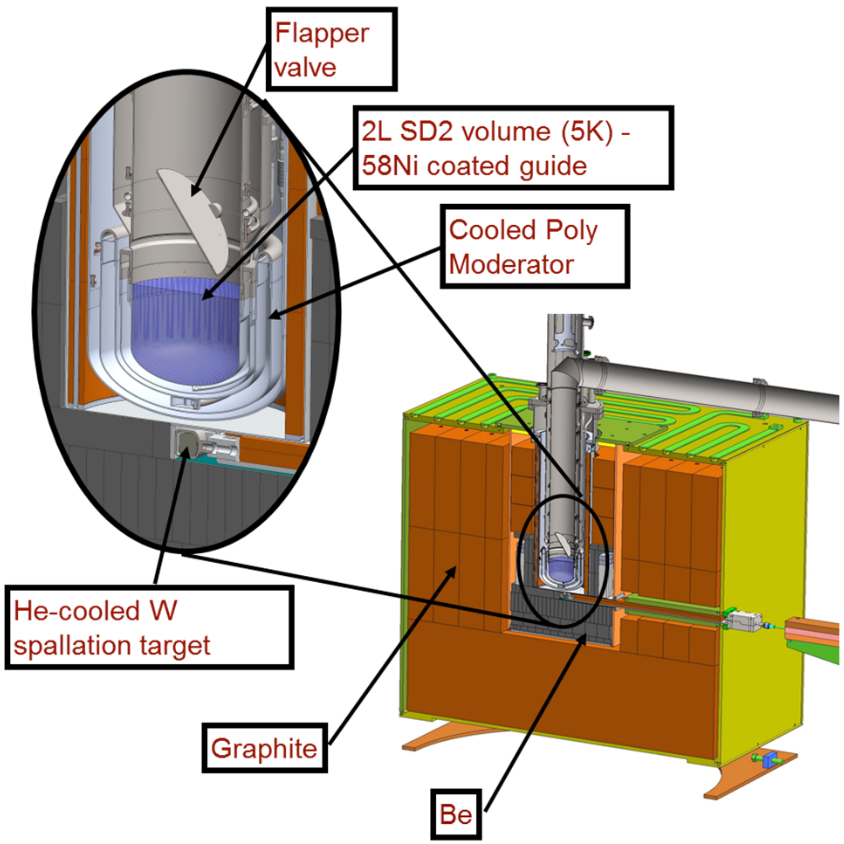



Los Alamos Neutron Science Center (LANSCE)
800 MeV proton LINAC
UCN at Area B

LANSCE UCN Experimental Area (2021)



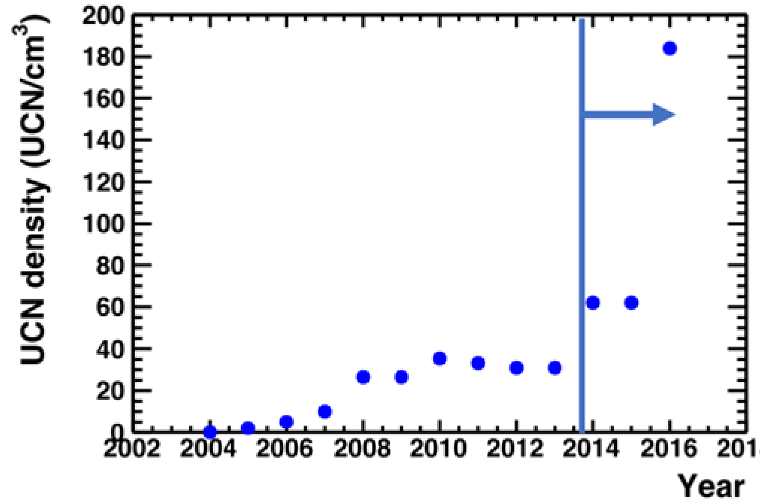
UCN "*Pokotilovsky*" source operating at the Los Alamos Neutron Science Center (LANSCE)



Source upgrade (2016):

- Better moderator cooling
- NiP guides
- Optimized geometry

UCN density measured by Vanadium activation: 184 UCN/cc.

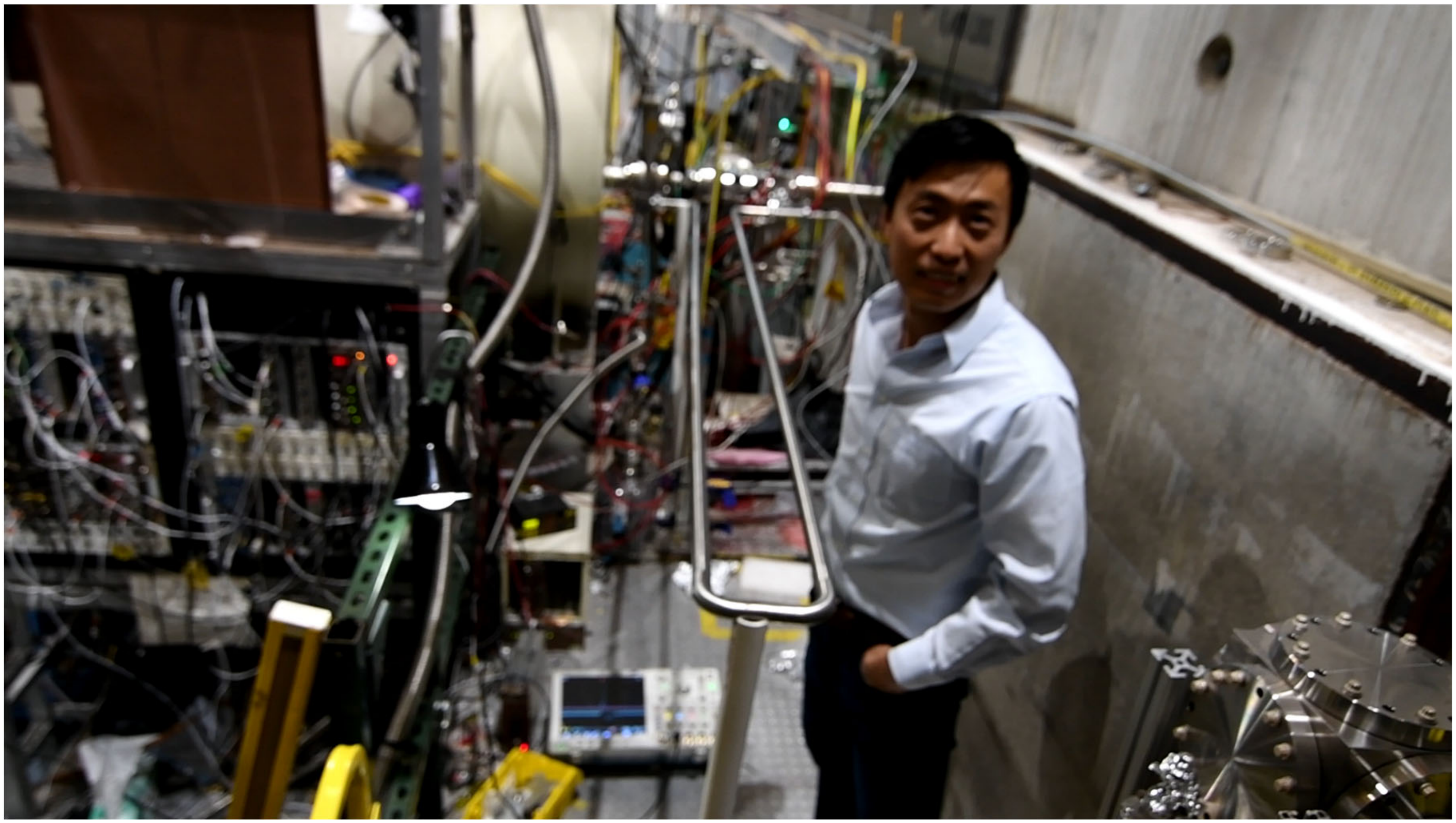


A. Saunders, et al. RSI 84, 013304 (2013); T. M. Ito *et al.* Phys. Rev. C **97**, 012501(R) (2018)

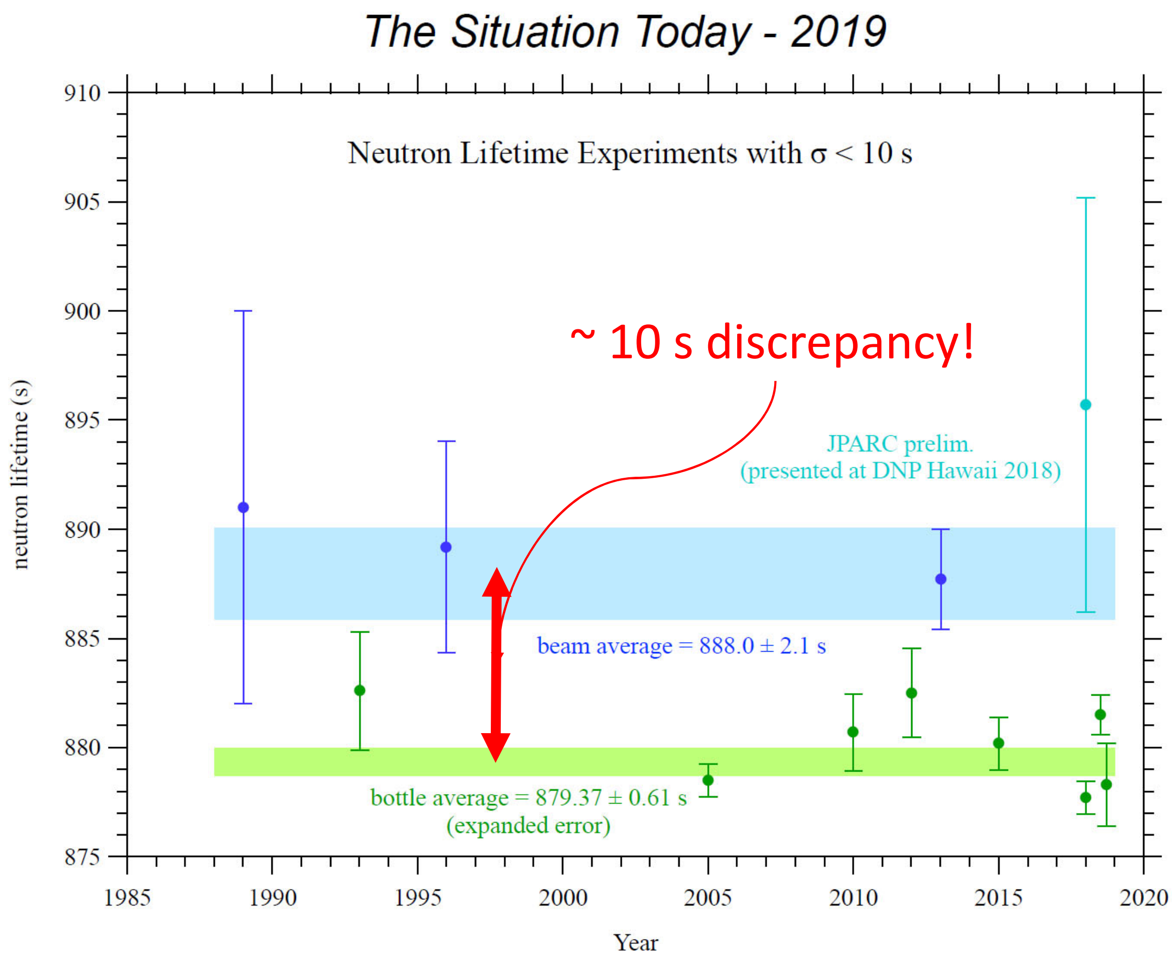
At the Los Alamos Neutron Science Center (LANSCE), we fill an empty bottle with UCN and dump them into a detector:

Demonstration of a UCN Gravity Spectrometer

narrator: Chris Morris
operator: Zhaowen Tang



There is an unresolved discrepancy between two leading methods to measure the neutron lifetime: neutrons in a bottle seem to disappear faster.

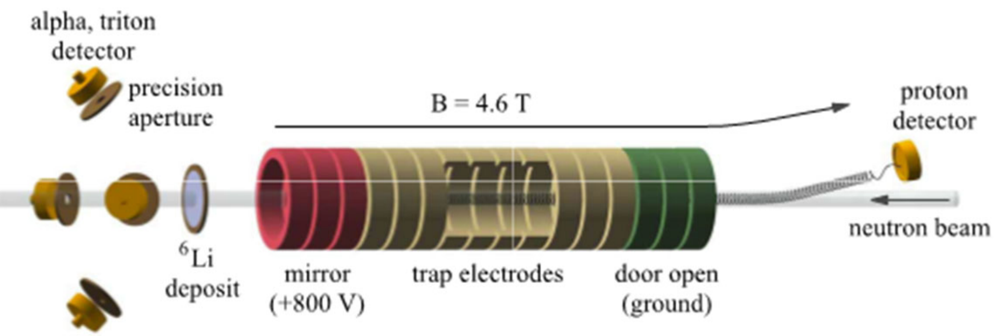


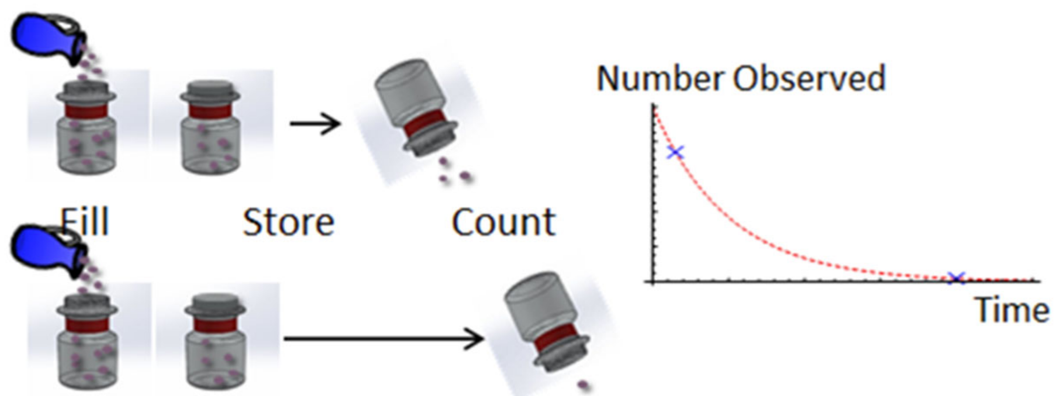
The “beam” and “bottle” techniques

$$\tau_n = \frac{L}{v_n} \frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

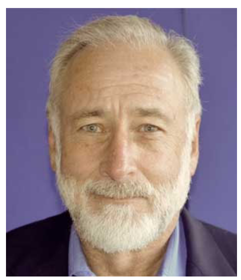
$$Y(t) = Y_0 e^{-t\,/\,\tau_{meas}}$$

$$\tau_{meas}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$$





“It sounds hard, and it is hard”
said Geoff Greene.
(2021 Bonner Prize Recipient)

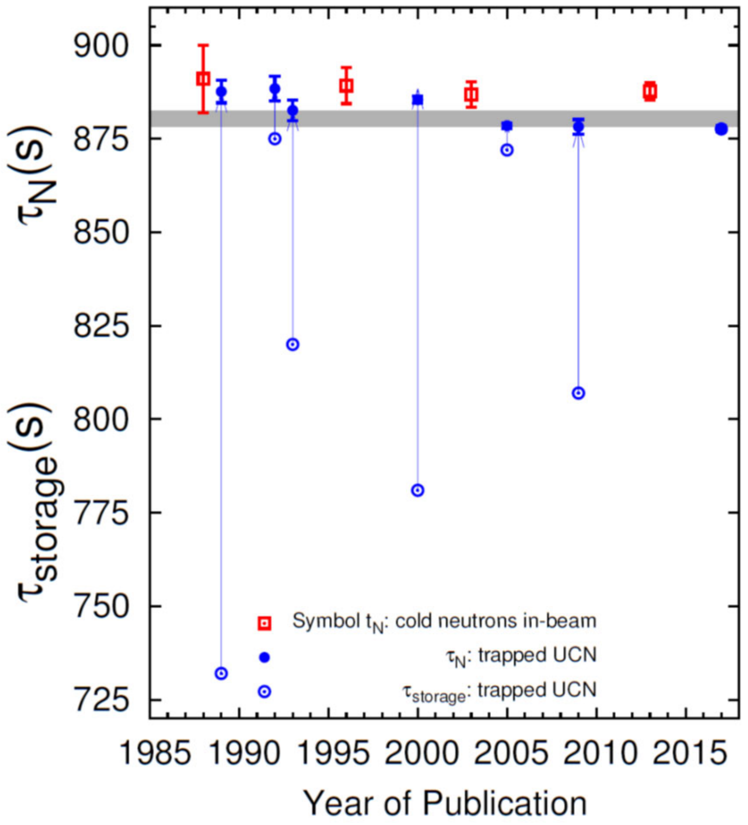


“It sounds easy, and it is hard”
said Geoff Greene.

Many experiments need to correct for the systematic effects and extrapolate from the measured lifetime to report the Neutron Lifetime

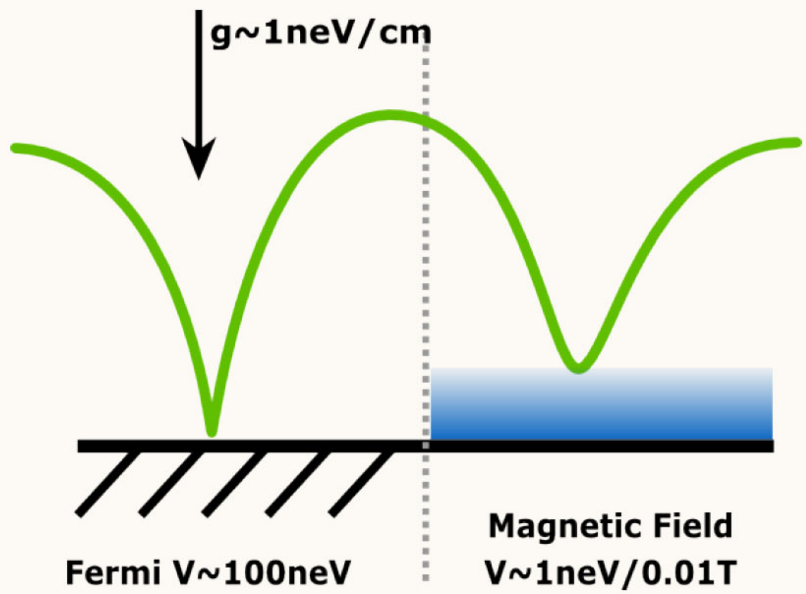
$$1/\tau_{\text{bottle}} = 1/\tau_n + 1/\tau_{\text{wall}} + 1/\tau_{\text{gas}} + \ldots$$

Author	$\sigma_{\text{stat.}}$ [s]	$\Delta\tau_{\text{sys.}}$ [s]	Extrap. [s]	Method
Arzumanov 2015	0.64	3.6	40-280	Bottle
Steyerl 2012	1.4	$\sim$7	$>$200 s	Bottle
Pichlmaier 2010	1.3	1	110-300	Bottle
Serebrov 2005	0.7	0.4	10-20	Bottle
Yue 2013	1.2	1	2-15	Beam
Byrne 1996	3	5.9	-	Beam



Neutron-wall interactions

Material bottle Magnetic bottle



- Material - $V_f \sim \mathcal{O}(100\text{s neV})$
- Magnetic Field - $V_B \sim 1\text{neV}/1000$ Gauss
- Gravity - $V_g \sim 1$ neV/cm

The UCNτ Magneto-Gravitational Trap using a "Halbach" array

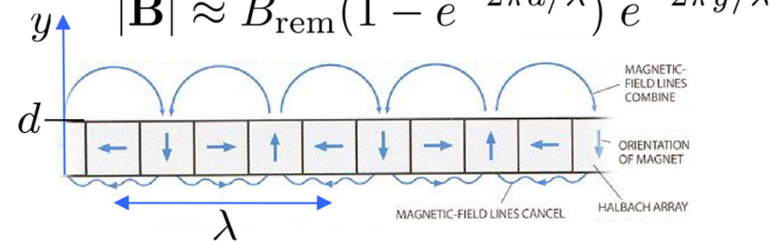
DESIGN OF PERMANENT MULTIPOLE MAGNETS
WITH ORIENTED RARE EARTH COBALT MATERIAL*

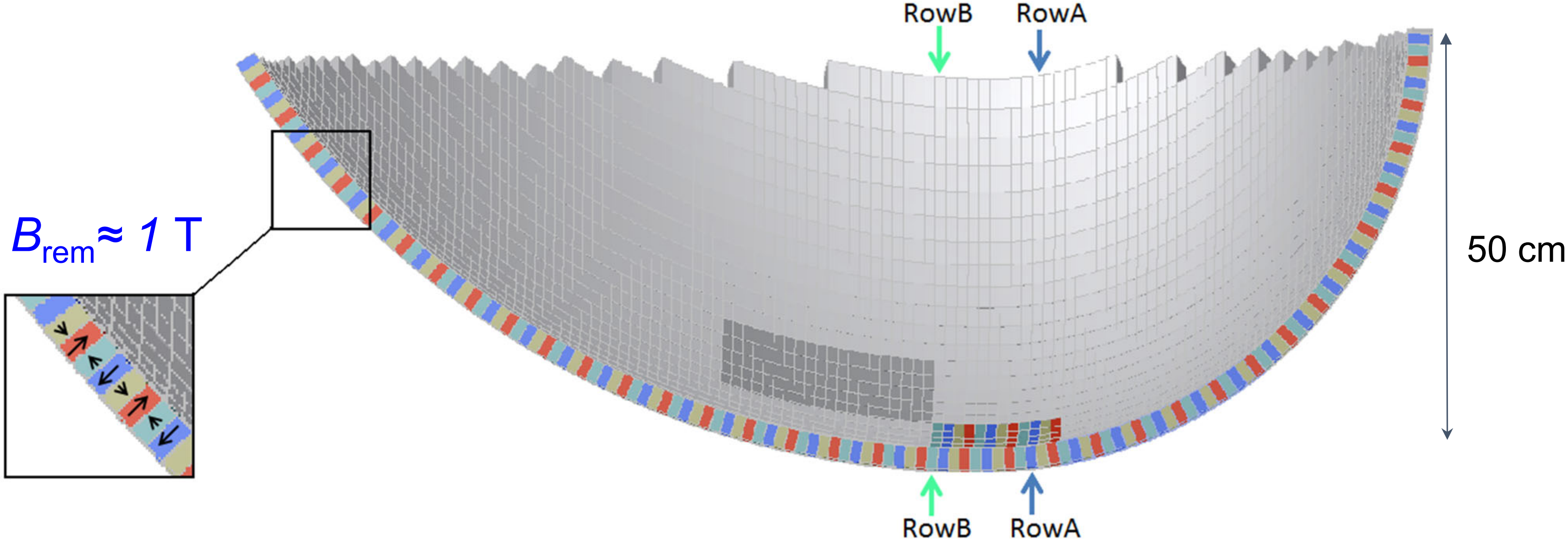
K. HALBACH

University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

Received 20 August 1979

$$|\mathbf{B}| \approx B_{\mathrm{rem}}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$





Bailey inside the Halbach array performing field mapping (before Christmas 2012)

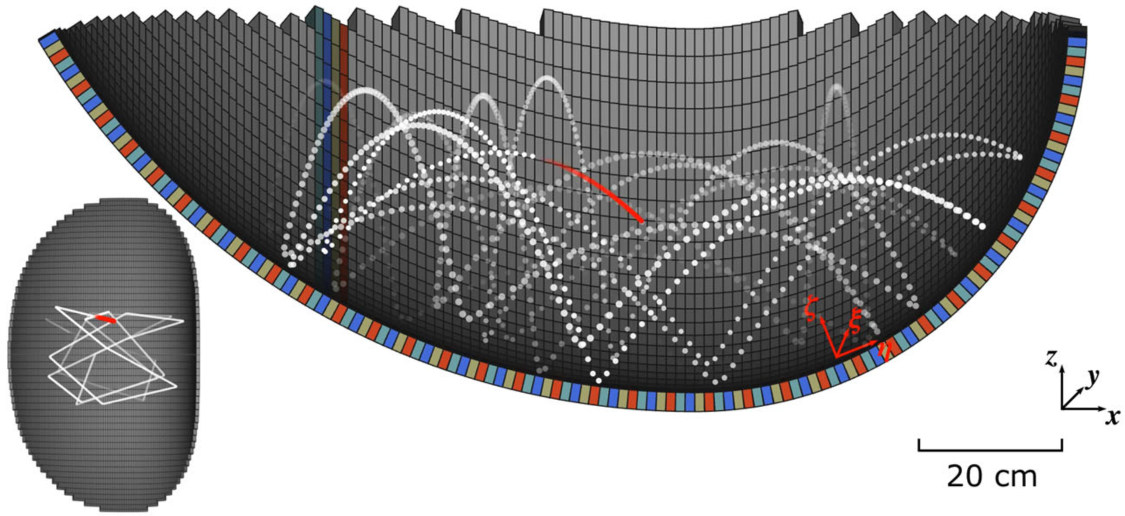
Tweeted by Canadian astronaut, Chris Hadfield:

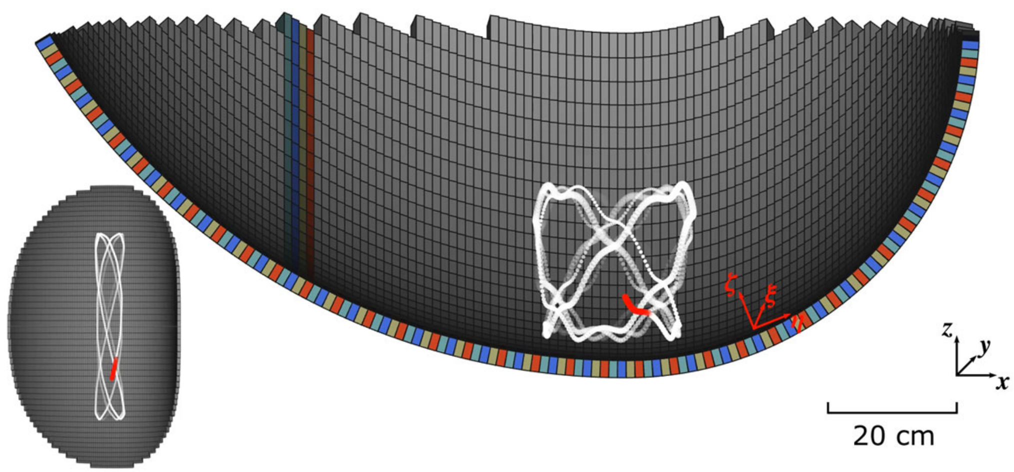
Tweet

Chris Hadfield
@Cmdr_Hadfield

That's Bailey in a neutron bottle. She helped discover that neutrons in the wild last 14.629 minutes (in an atom they can last billions of years).
@LosAlamosNatLab
The details: bit.ly/3mBp5Tm

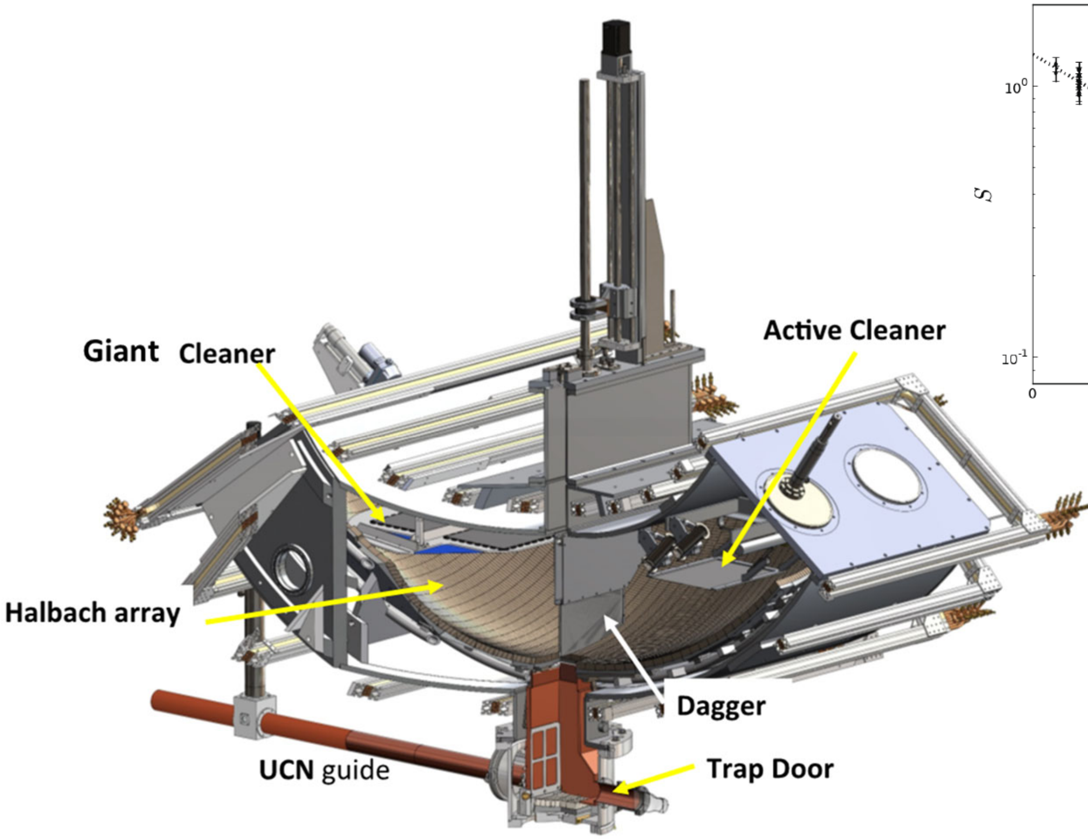
9:20 AM · Nov 2, 2021 · Twitter Web App



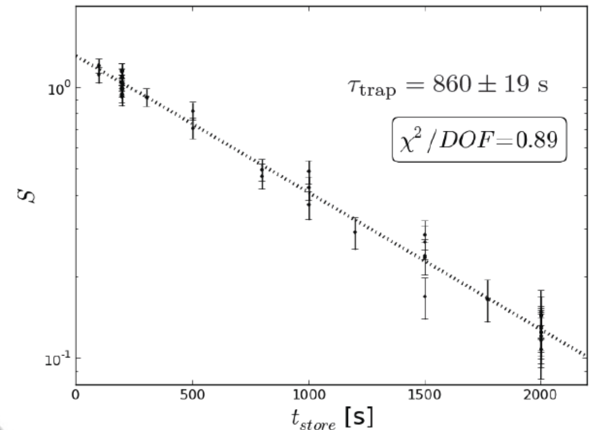


Simulation by Nathan Callahan

The UCNτ Apparatus

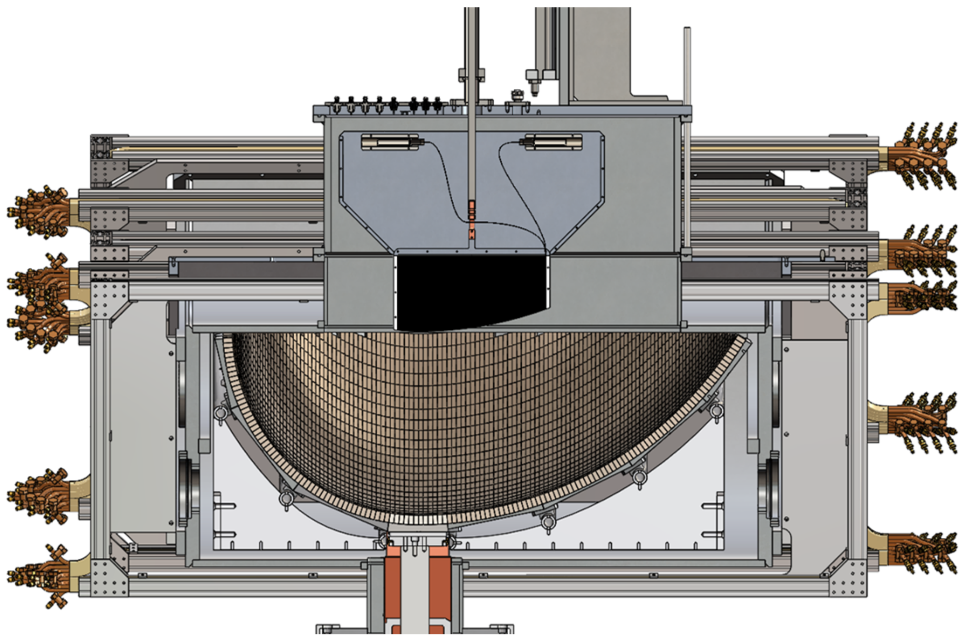


First Physics Data: 2013

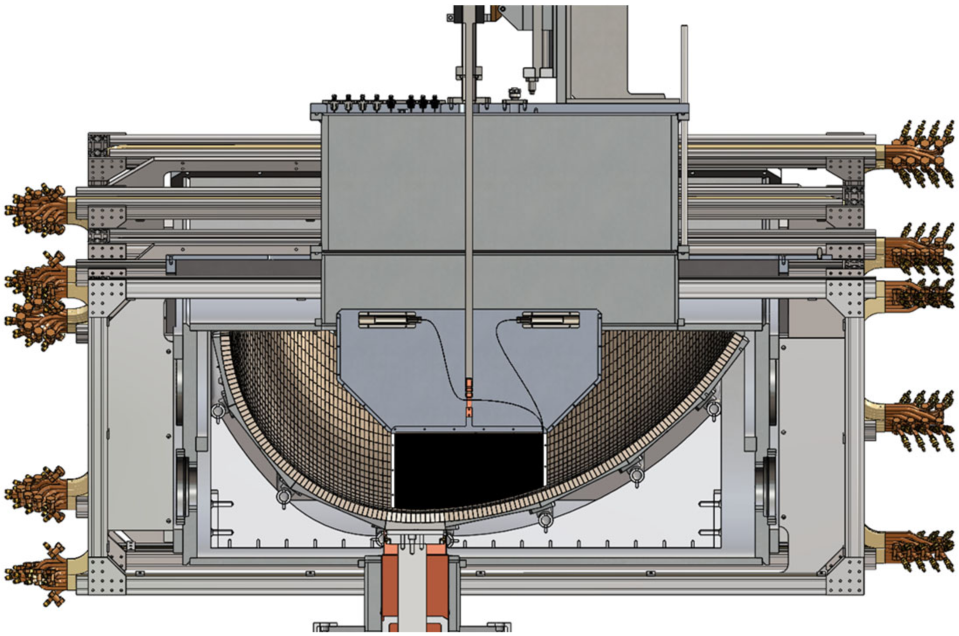


D. Salvat, PRC 89, 052501 (2014)

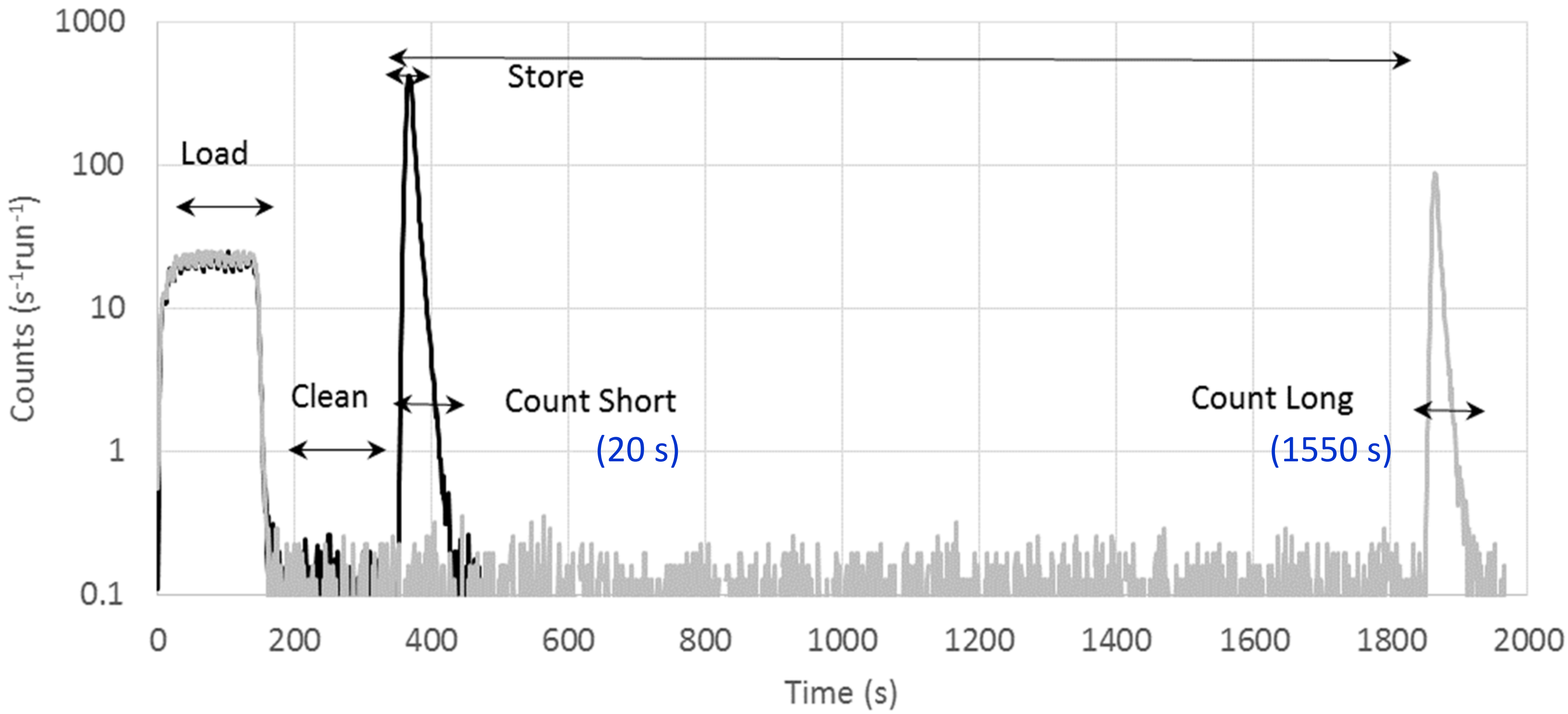
We also implemented a new way to count the trapped neutrons:



In-situ UCN detection using a "dagger" detector: detection time ~ 8 s



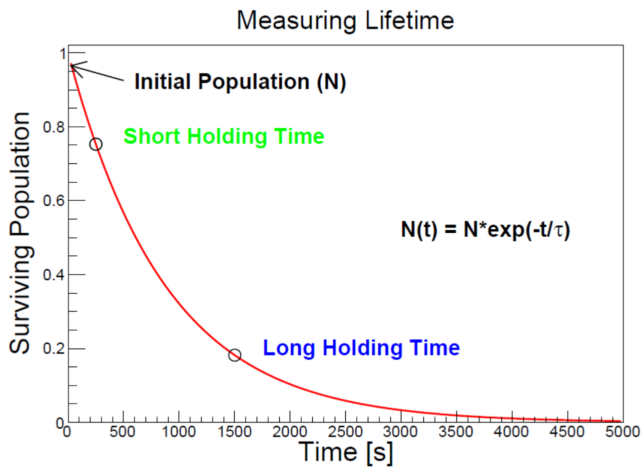
Paired runs:
a short-storage followed by a long-storage:



The principle of Bottle Method is simple:

The lifetime is derived from the Exponential Decay Law:

$$N(t) = N_0 e^{-t/\tau}$$



1. We compare the number of neutrons after a short hold,

$$N_1 = N(t_1) = N_0 e^{-t_1/\tau}$$

to the number of neutrons after a long hold,

$$N_2 = N(t_2) = N_0 e^{-t_2/\tau}$$

2. We take the ratio of the neutron counts: $\frac{N_1}{N_2} = e^{-(t_1 - t_2)/\tau}$

3. The neutron lifetime is then:

$$\tau = \frac{\Delta t}{\ln \frac{N_1}{N_2}}$$ for each measurement cycle.

4. Then we repeat many measurement cycles of the same short hold-long hold pattern.

Quiz: How should we average the data from repeated runs?

The lifetime formula: $\tau = \dfrac{\Delta t}{\ln \dfrac{N_1}{N_2}}$

Given a set of normalized data $\{N_{1i}, N_{2i}\}$, $i = 1,2, \dots, M$,

which of the following is the un-biased evaluation of the lifetime?

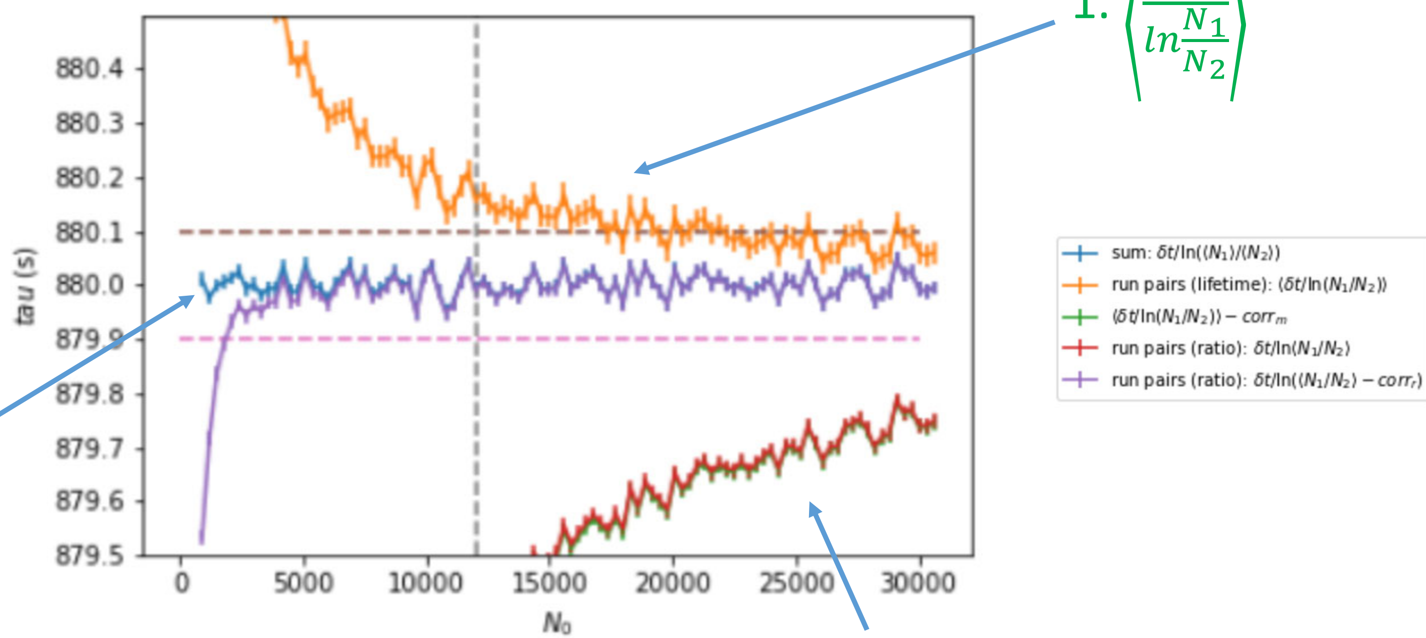
1. $\left\langle \dfrac{\Delta t}{ln \dfrac{N_1}{N_2}} \right\rangle$: take the mean of pair-wise τ_i

$\langle \ \rangle$ defines the (unweighted) mean: $\langle x \rangle = \dfrac{1}{M} \sum_i^M x_i$

2. $\dfrac{\Delta t}{\ln \left\langle \dfrac{N_1}{N_2} \right\rangle}$: take the mean of the ratio of the counts, then plug into the lifetime formula.

3. $\dfrac{\Delta t}{\ln \dfrac{\langle N_1 \rangle}{\langle N_2 \rangle}}$: average the counts before taking the ratio, then plug into the lifetime formula.

Different ways to average the data set could lead to non-zero "statistical bias"; it becomes important when dt → 0.2 s



1. $\left\langle \frac{\Delta t}{ln\frac{N_1}{N_2}} \right\rangle$

2. $\frac{\Delta t}{\ln\left\langle\frac{N_1}{N_2}\right\rangle}$

3. $\frac{\Delta t}{\ln\frac{\langle N_1\rangle}{\langle N_2\rangle}}$

The principle of Bottle Method is simple:

The lifetime is derived from the Exponential Decay Law:

The 'expectation value' of the neutron counts

$$N(t) = N_0 e^{-t/\tau} \rightarrow \langle N(t) \rangle = N_0 e^{-t/\tau}$$

1. We compare the number of neutrons after a short hold,

$$\langle N_1 \rangle = \langle N(t_1) \rangle = N_0 e^{-t_1/\tau}$$

to the number of neutrons after a long hold,

$$\langle N_2 \rangle = \langle N(t_2) \rangle = N_0 e^{-t_1/\tau}$$

2. We take the ratio of the neutron counts: $\frac{\langle N_1 \rangle}{\langle N_2 \rangle} = e^{-(t_1 - t_2)/\tau}$

3. The neutron lifetime is then:

$\tau = \frac{\Delta t}{ln\frac{\langle N_1 \rangle}{\langle N_2 \rangle}}$ for each measurement cycle.

4. Then we repeat many measurement cycles of the same short hold-long hold pattern.

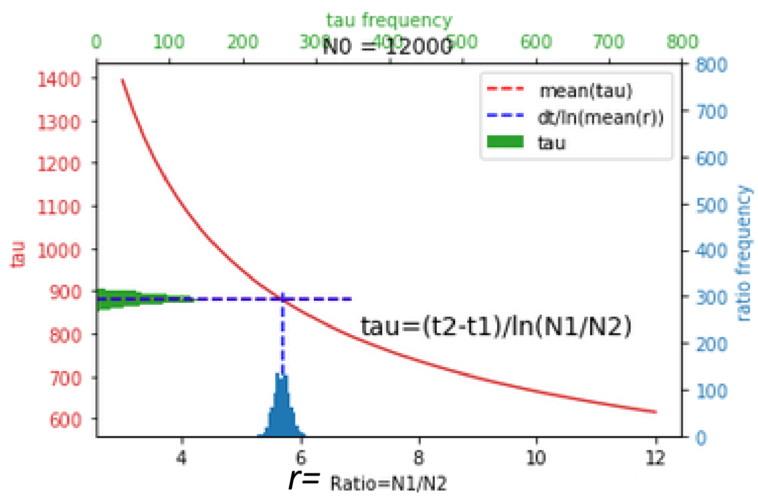
Therefore, option 3 is the only correct way to average data.

Correcting the statistical bias on the '*neutron lifetime*'

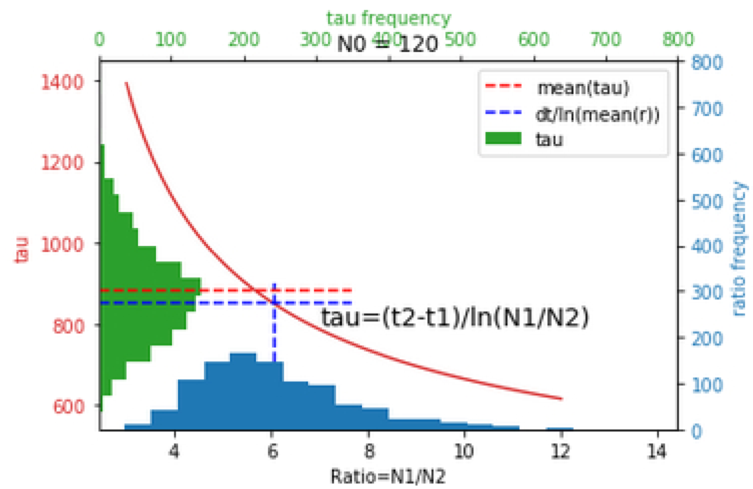
The lifetime formula: $\tau = \frac{\Delta t}{\ln\frac{N_1}{N_2}}$

The 'nonlinear' mapping from the measured variable to the derived variable introduces a distortion in the probability distributions.

Moderate counting statistics: *N_0*=12,000 per load



Small counting statistics: *N_0*=120 per load



$$\tau = \frac{\Delta t}{\ln(\mu_r)} + \frac{1}{2}\frac{d^2 f}{d\mu^2}\sigma_r^2 + O(\sigma_r^3)$$

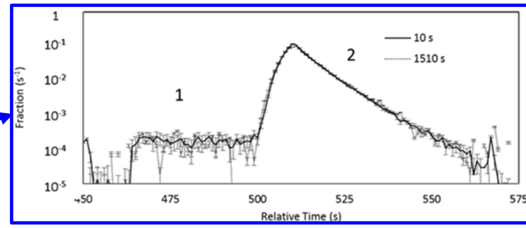
$$\langle\tau\rangle = \frac{\Delta t}{\ln(\mu_r)} + \boxed{\frac{1}{2}\Delta t\{\frac{2+\ln(\mu_r)}{\ln^3(\mu_r)\mu_r^2}\}\sigma_r^2 + O(\sigma_r^3)}$$

Statistical bias

Analyzing data...

Single p.e. dagger counts

UCN events passing cuts

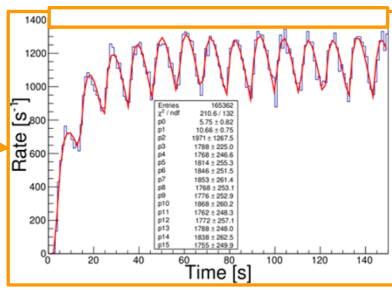


Dagger unload counts

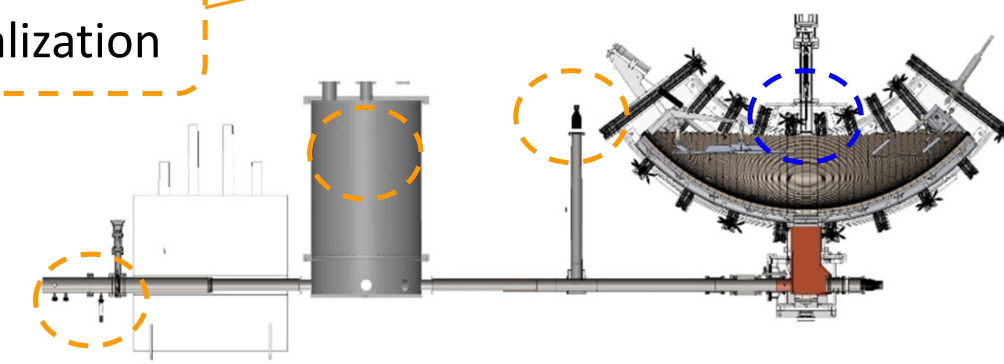
Background measurements

$$Y_t = \frac{D_t - B}{M}$$

"Monitor" detector counts

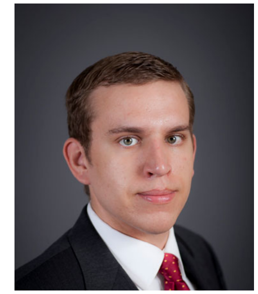


"**M**onitor" normalization



3 bears; 3 independent analyses

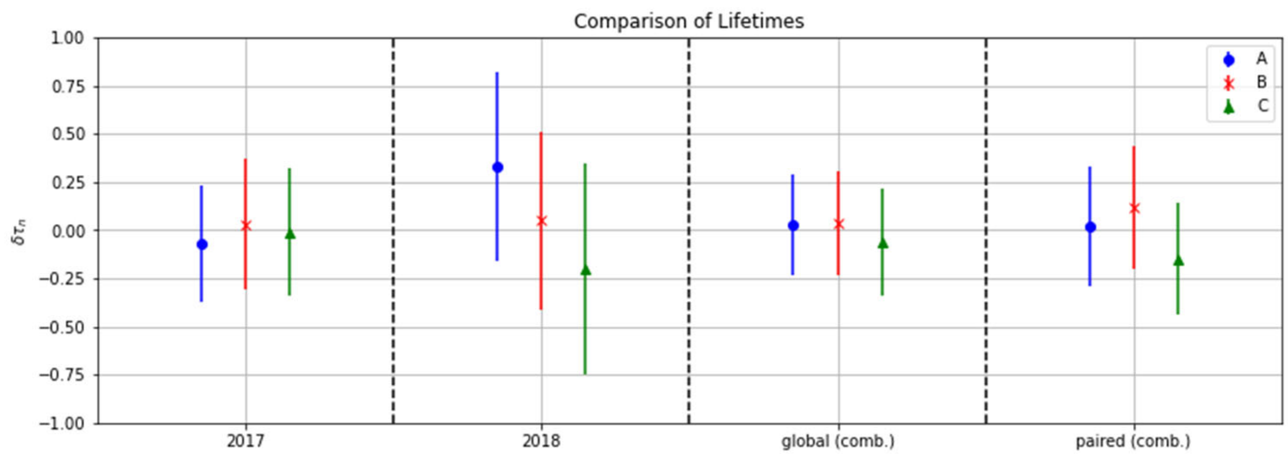
Frank Gonzalez (Indiana)



Eric Fries (Caltech)

Chris Morris (LANL)

- Blinded data:
  - Holding time is modified
  - Measured lifetime blinded by up to ± 15 s
- Unblinding Criteria:
  - Three complete (statistical and systematic) analyses
  - After cross-checking analyses, lifetimes combined via unweighted average, using largest uncertainties



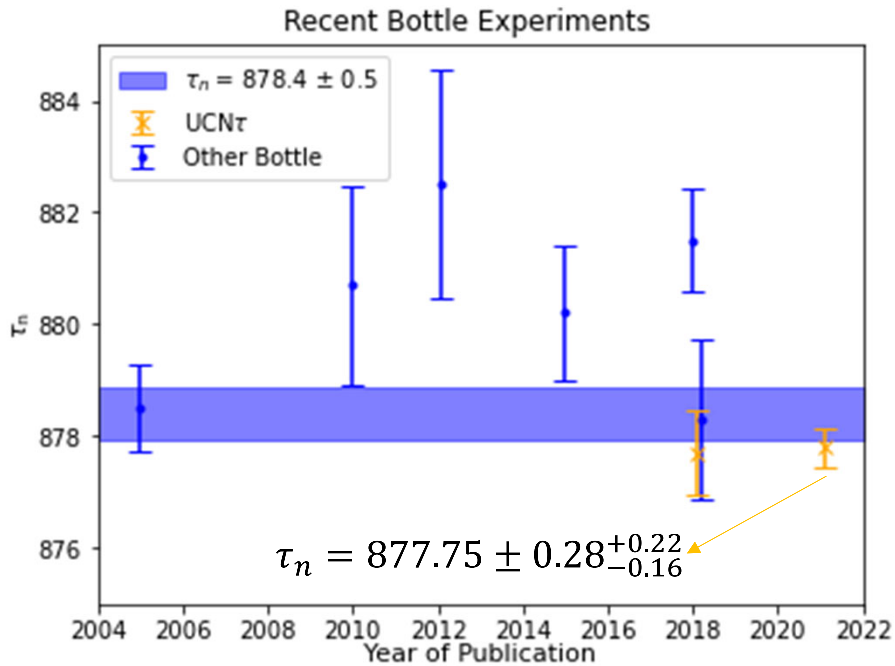
New Result: $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap…
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$	

UCNτ

F. M. Gonzalez et al. Phys. Rev. Lett. 127 162501 (October 13, 2021)

Neutron Lifetime Measurements



We report a measurement of τ_n with 0.34 s (0.039%) uncertainty, improving upon our past results by a factor of 2.25 using two blinded datasets from 2017 and 2018. The new result incorporates improved experimental and analysis techniques over our previous result [Science **360**, 627 (2018)].

Limits on lifetimes for *bound* neutrons are given in the section"p PARTIAL MEAN LIVES."

We average seven of the best eight measurements, those made with ultracold neutrons (UCN's). If we include the one in-beam measurement with a comparable error (YUE 2013), we get 879.6 ± 0.8 s, where the scale factor is now 2.0.

For a recent discussion of the long-standing disagreement between in-beam and UCN results, see CZARNECKI 2018 (Physical Review Letters 120 202002 (2018)). For a full review of all matters concerning the neutron lifetime until about 2010, see WIETFELDT 2011 , F.E. Wietfeldt and G.L. Greene, "The neutron lifetime," Reviews of Modern Physics 83 1173 (2011).

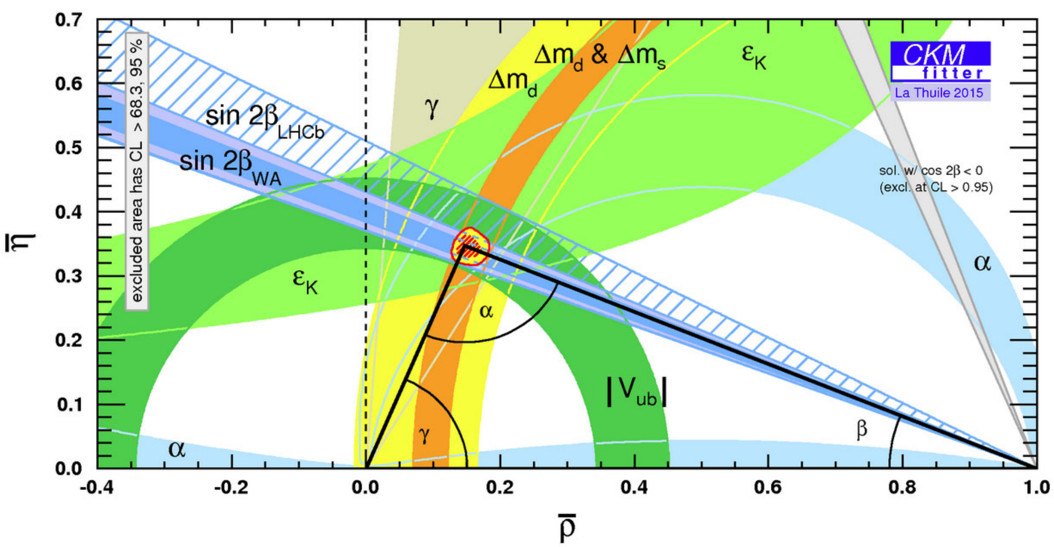
VALUE (s)	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{878.4 \pm 0.5}$	**OUR AVERAGE** Error includes scale factor of 1.8. See the ideogram below.			
$877.75 \pm 0.28\ ^{+0.22}_{-0.16}$	GONZALEZ	2021	CNTR	UCN asym. magnetic trap
$878.3 \pm 1.6 \pm 1.0$	EZHOV	2018	CNTR	UCN magneto-gravit. trap
$877.7 \pm 0.7\ ^{+0.4}_{-0.2}$	[1] PATTIE	2018	CNTR	UCN asym. magnetic trap
$881.5 \pm 0.7 \pm 0.6$	SEREBROV	2018	CNTR	UCN gravitational trap
880.2 ± 1.2	[2] ARZUMANOV	2015	CNTR	UCN double bottle
$882.5 \pm 1.4 \pm 1.5$	[3] STEYERL	2012	CNTR	UCN material bottle
$880.7 \pm 1.3 \pm 1.2$	PICHLMAIER	2010	CNTR	UCN material bottle
$878.5 \pm 0.7 \pm 0.3$	SEREBROV	2005	CNTR	UCN gravitational trap
• • We do not use the following data for averages, fits, limits, etc. • •				
$887 \pm 14\ ^{+7}_{-3}$	[4] WILSON	2021	CNTR	space-based n rate
$887.7 \pm 1.2 \pm 1.9$	[5] YUE	2013	CNTR	In-beam n, trapped p
$881.6 \pm 0.8 \pm 1.9$	[6] ARZUMANOV	2012	CNTR	See ARZUMANOV 2015
$886.3 \pm 1.2 \pm 3.2$	NICO	2005	CNTR	See YUE 2013
$886.8 \pm 1.2 \pm 3.2$	DEWEY	2003	CNTR	See NICO 2005

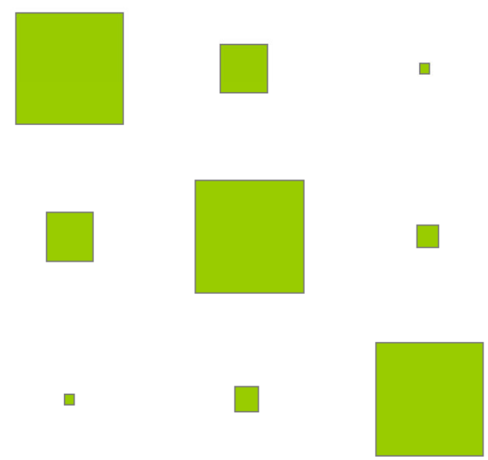
The CKM matrix quantifies the quark flavor mixing.

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

Wolfenstein parameterization – expansion in λ = sin Θ_c ~0.22

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$





V_{us}=λ=sin Θ_c

Θ_c: Cabbibo Angle

Area of the triangle → CP-violating phase

Precision Test on the CKM Unitarity

First Row: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{BSM}$

$V_{ub} \ll V_{ud}$ and V_{us}, so negligible contribution

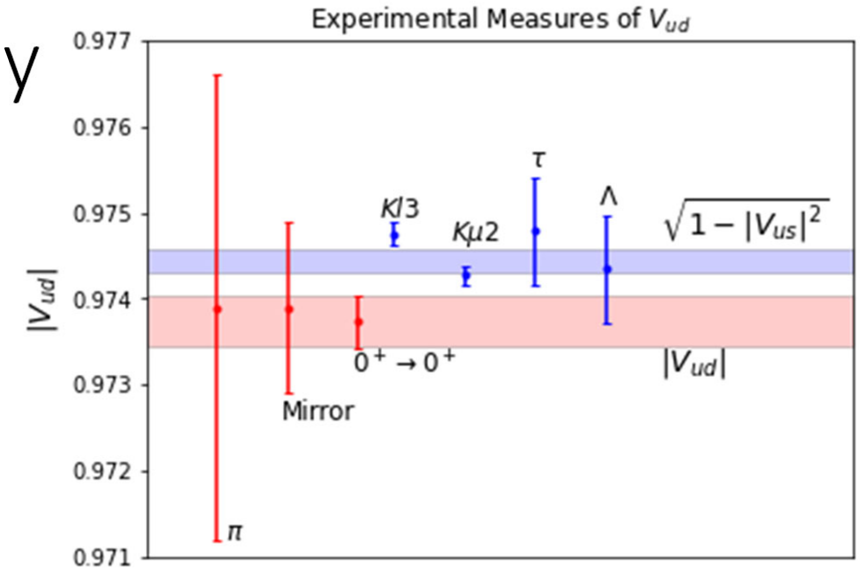
Measurements of V_{ud}:

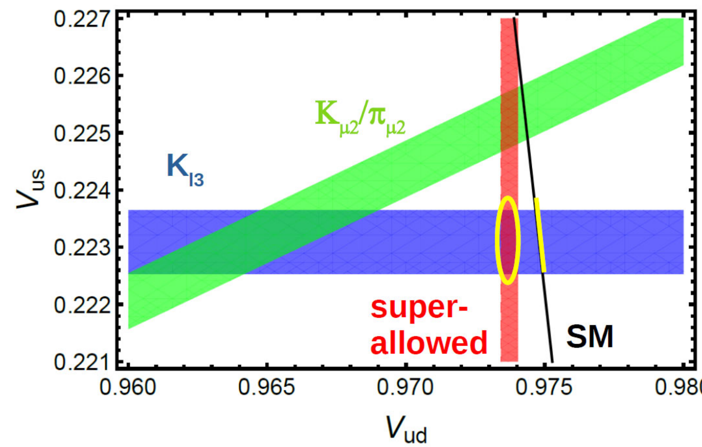
- Most precise "Superallowed" $0^+ \to 0^+$ decays
- Mirror nuclei and Pions less precise
- Large theoretical uncertainties from radiative corrections and nuclear structure

Measurements of V_{us}:

- Most precise from Kaon decays
- Cabibbo angle anomaly (V_{us}=λ=sin Θ_c) between different decay channels
- Also limits from τ and Λ hyperons

Most precise measurements disagree (up to 3σ)!





"Cabibbo Angle Anomaly (CAA)" ~ 3σ

Discovery potential of the beta decay anomalies

A concrete example: First-row CKM unitarity with $|V_{ud}|$ from 0^+ beta decay and $|V_{us}|$ from K_{l3} decay

$$|V_{ud}|^2_{0+} + |V_{us}|^2_{K\ell 3} + \cancel{|V_{ub}|^2} - 1 = -0.0021(7)$$

SOURCES OF UNCERTAINTY:

$\delta|V_{ud}|^2_{0+}$, **RC:**

Theory uncertainties in the single-nucleon radiative corrections (RC)

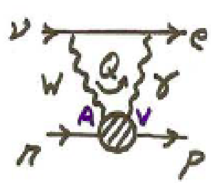
$\|V_{ud}\|^2_{0+} + \|V_{us}\|^2_{K_{\ell 3}} - 1$	-2.1×10^{-3}
$\delta\|V_{ud}\|^2_{0+}$, **exp**	2.1×10^{-4}
$\delta\|V_{ud}\|^2_{0+}$, **RC**	1.8×10^{-4}
$\delta\|V_{ud}\|^2_{0+}$, **NS**	5.3×10^{-4}
$\delta\|V_{us}\|^2_{K_{\ell 3}}$, **exp+th**	1.8×10^{-4}
$\delta\|V_{us}\|^2_{K_{\ell 3}}$, **lat**	1.7×10^{-4}
Total uncertainty	6.5×10^{-4}
Significance level	3.2σ

CYS, Galviz, Marciano and Meißner, 2107.14708

Chien-Yeah Seng's talk DNP 2021

Extracting V_{ud} with neutron decays

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



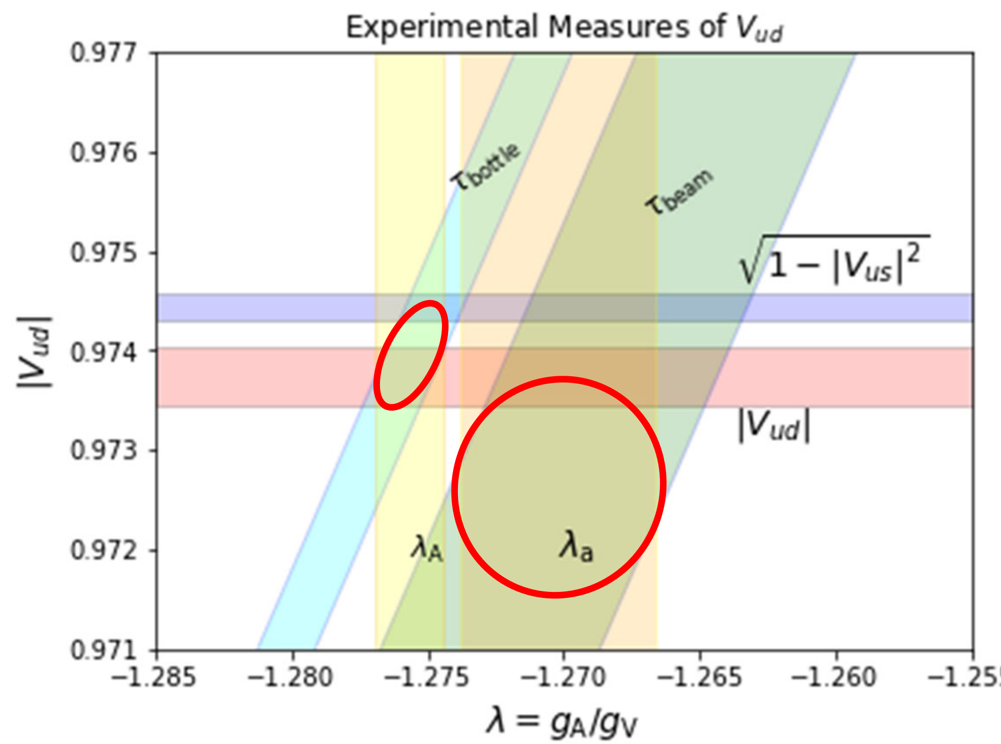
$1/\tau_n = fG_F^2|V_{ud}|^2 m_e^5(1+3g_A^2)(\underline{1+RC})/2\pi^3$

From μ-decay: 0.6 ppm (MuLan 2011)

$$|V_{ud}|^2 = \frac{4905.7 \pm 1.7\ s}{\tau_n(g_V + 3g_A^2)}$$

Marciano & Sirlin, PRL 96, 032002 (2006)
Seng et al, PRL 121 (2018); Seng et al, PRD 100 (2019);
Czarnecki, Marciano & Sirlin, PRD 100 (2019)

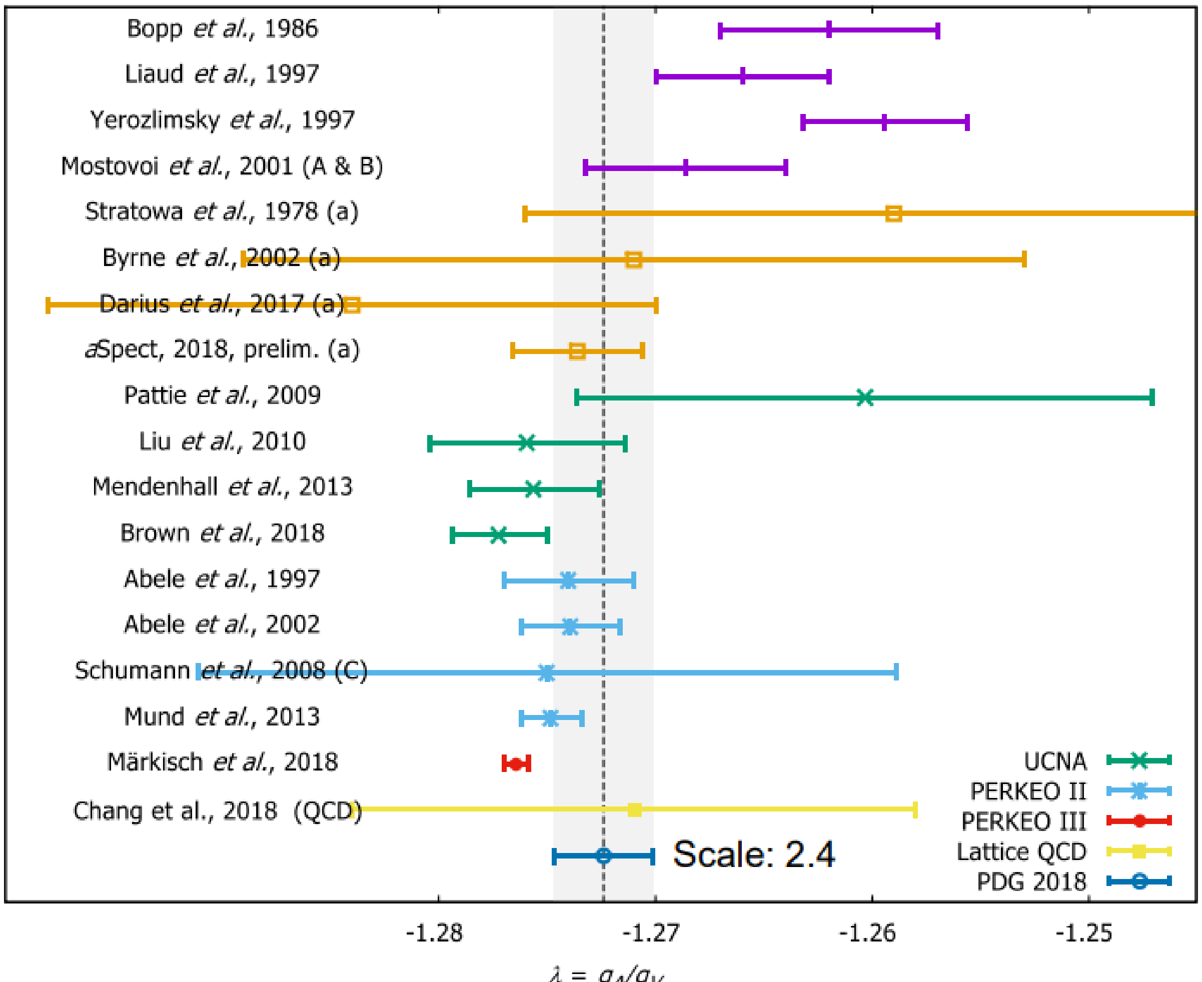
To match the theoretical uncertainty: 3.5 ×10^{-4}, it requires experimental uncertainties of: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 3.5 \times 10^{-4}$.



To be consistent with CKM unitarity, it requires a smaller $|g_A|$, or a shorter τ_n.

Axial Coupling: Status

Results from beta asymmetry A, unless where noted otherwise



PERKEO I

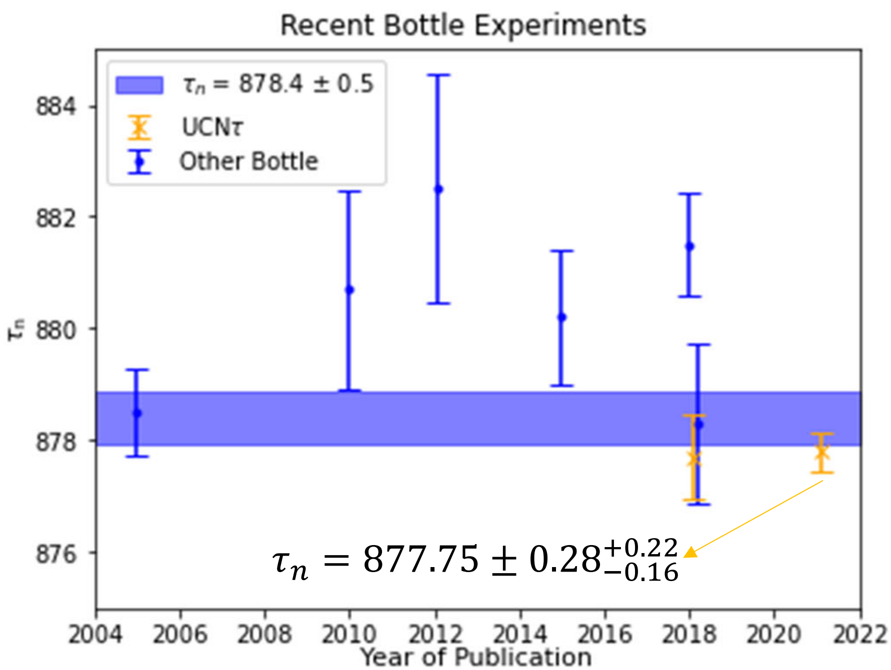
electron-neutrino correlation *a*

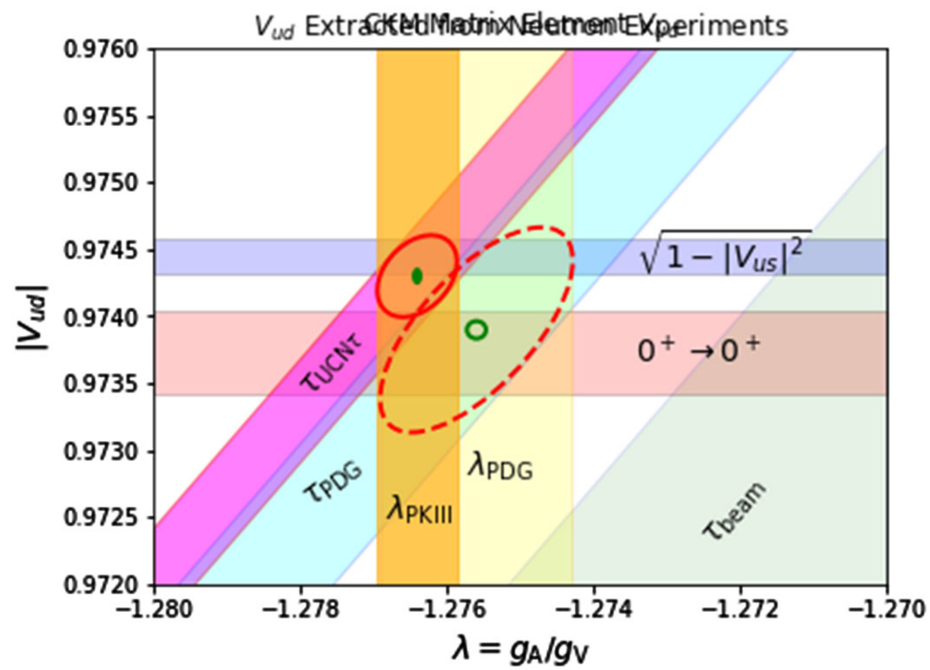
UCNA
(newer results mostly include older data)

PERKEO II
(newer A results include older data)

PERKEO III

With new UCNτ lifetime result (+ Perkeo III), the extracted V_{ud} agrees with the CKM unitarity.





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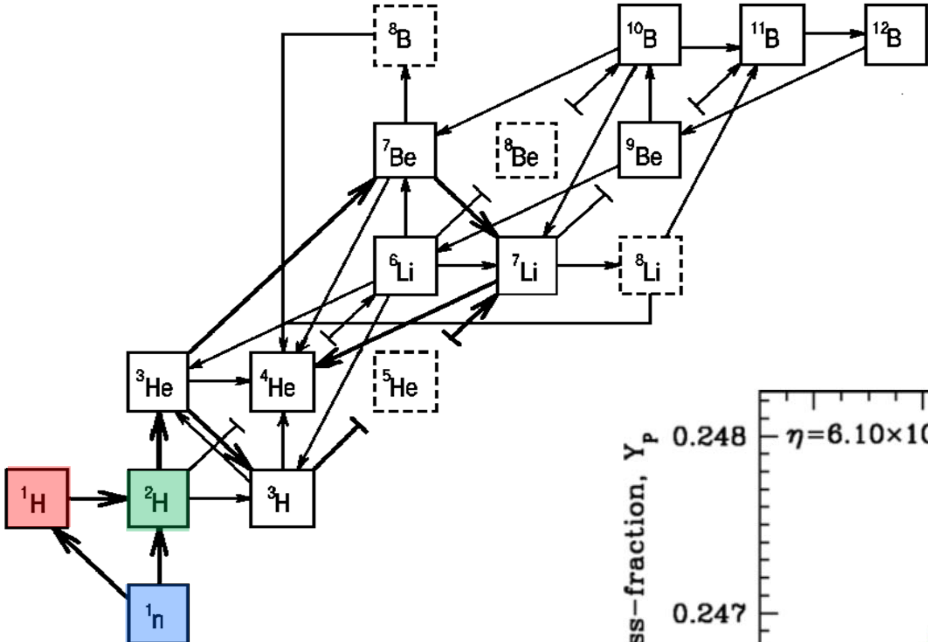
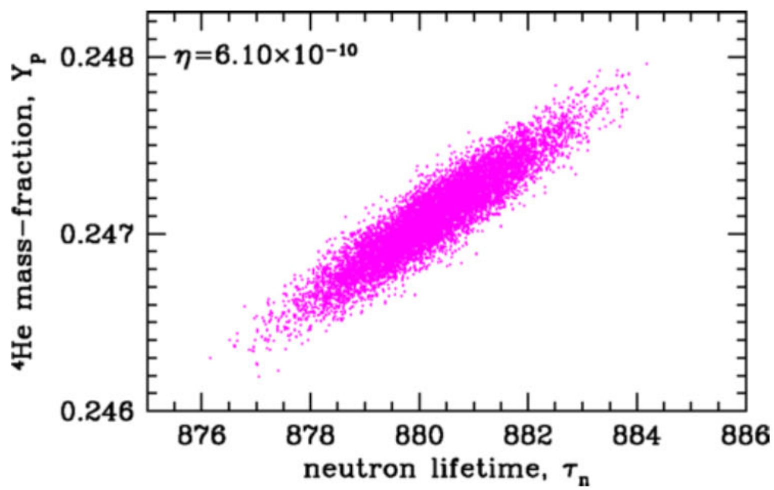
This is the first neutron lifetime measurement precise enough to confront SM theoretical uncertainties.

Neutron Lifetime is an important input into the Big-Bang Nucleosynthesis, which creates light elements



- Weak interactions control the neutron-proton ratio, via freeze out, etc..
- BBN describes the production of the "light elements", ^{4}He, D, ^{3}He and ^{7}Li
- The number of free parameters that enters in standard BBN has now been reduced to zero: tests of new physics.



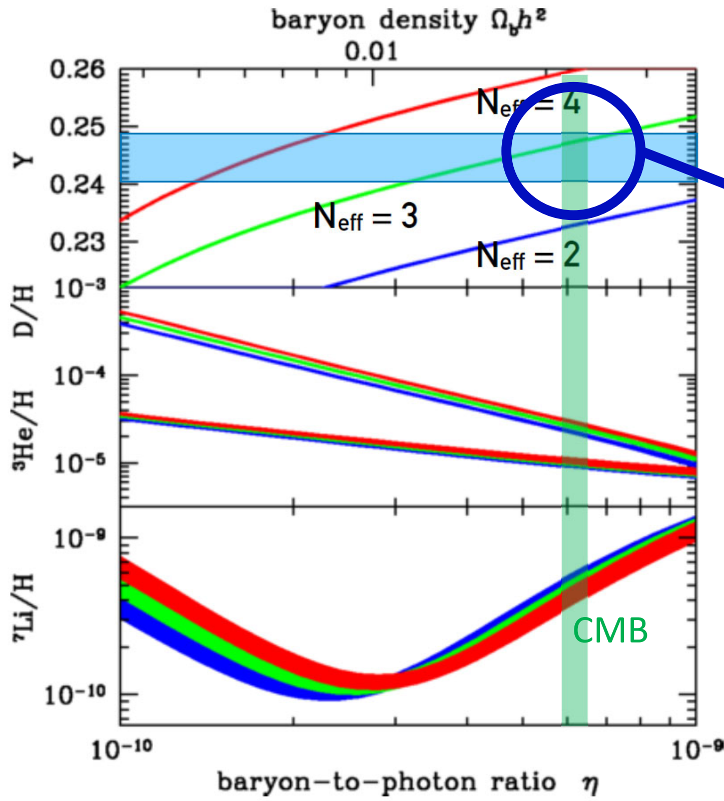
Rev. Mod. Phys. 88, 015004 (2016)

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

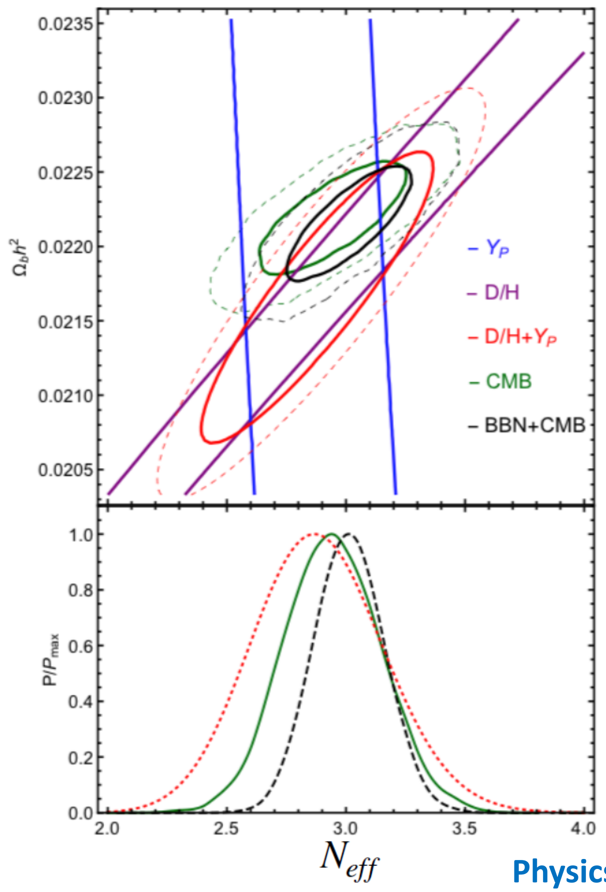
lifetime remains largest uncertainty in calculating helium abundance

Big-bang nucleosynthesis of ^{4}He and other light elements: the ^{4}He abundance (Y_p) depends on the value of the neutron lifetime and the number of light neutrino species

$$Y_p = 0.24703\left(\frac{10^{10}\eta}{6.10}\right)^{0.039}\left(\frac{N_\nu}{3.0}\right)^{0.163}\left(\frac{G_N}{G_{N,0}}\right)^{0.35}\left(\frac{\tau_n}{880.3s}\right)^{0.73} p(n,\gamma)d]^{0.005}[d(d,n)^3\mathrm{He}]^{0.006}[d(d,p)t]^{0.005}$$



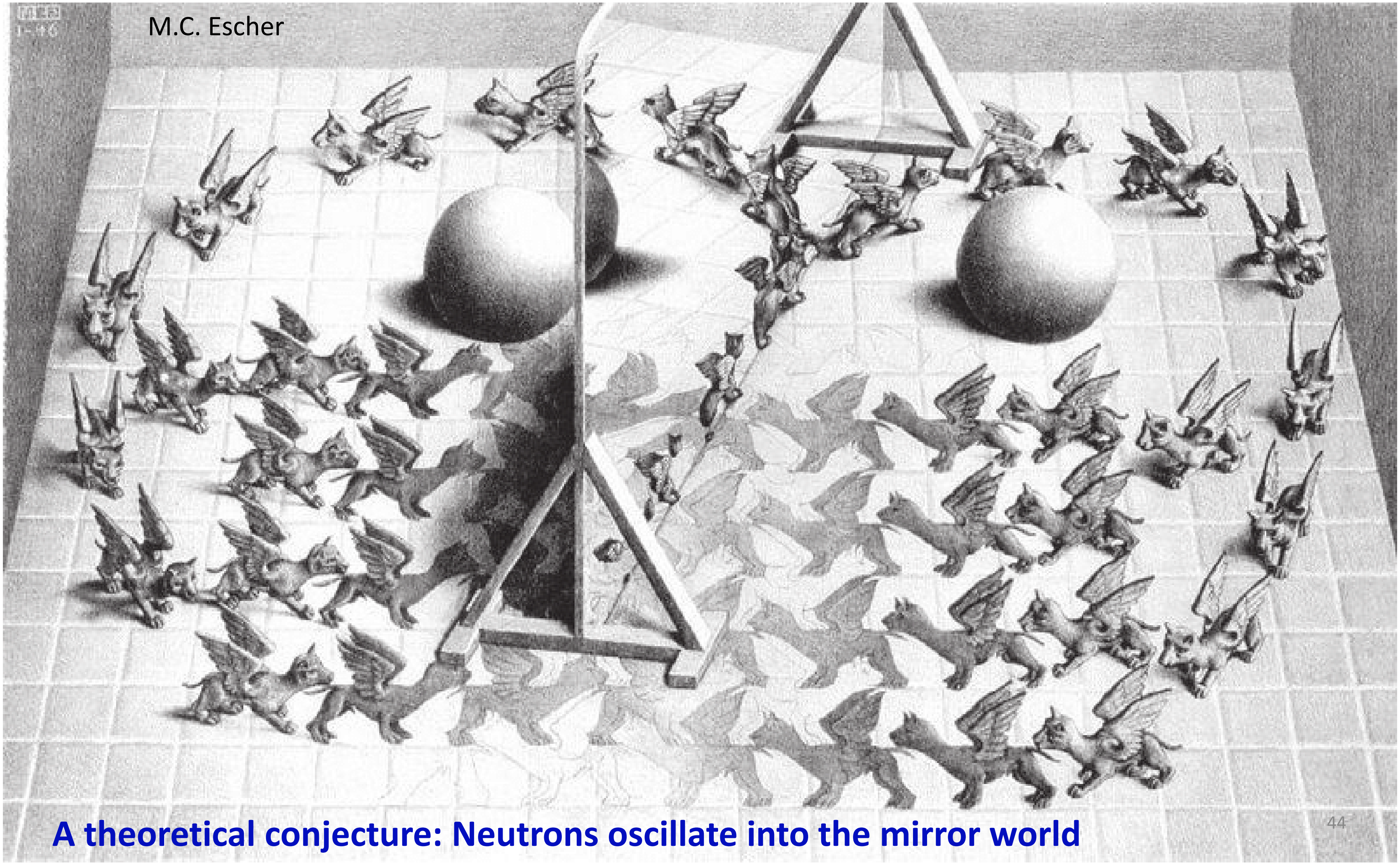
Rev. Mod. Phys. 88, 015004 (2016)



Physics Reports 754, 1-66 (2018)

After ~ 10 years of work,
we concluded that the neutron lifetime in a bottle is shorter than the pre-2010 PDG value.

The discrepancy of neutron lifetime persists.



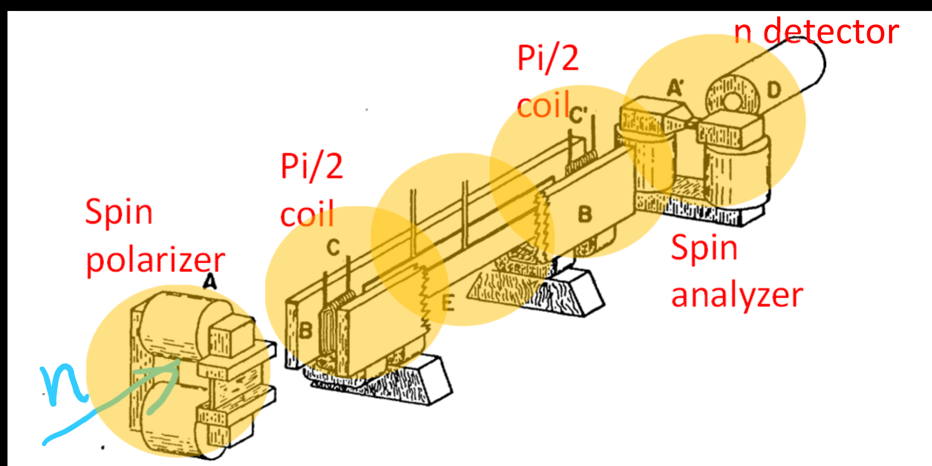
M.C. Escher

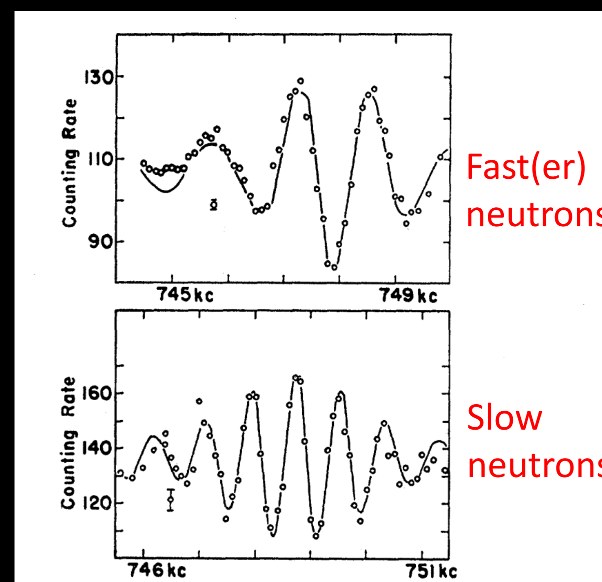
A theoretical conjecture: Neutrons oscillate into the mirror world

A particular arrangement that is more advantageous in many cases is one in which the oscillating field is confined to a small region at the beginning of the space in which the energy levels are being studies and to another small region at the end, there being no oscillating field in between.

-- N. Ramsey (1950)

Smith, Purcell, Ramsey, Phys. Rev. 108, 120 (1957)





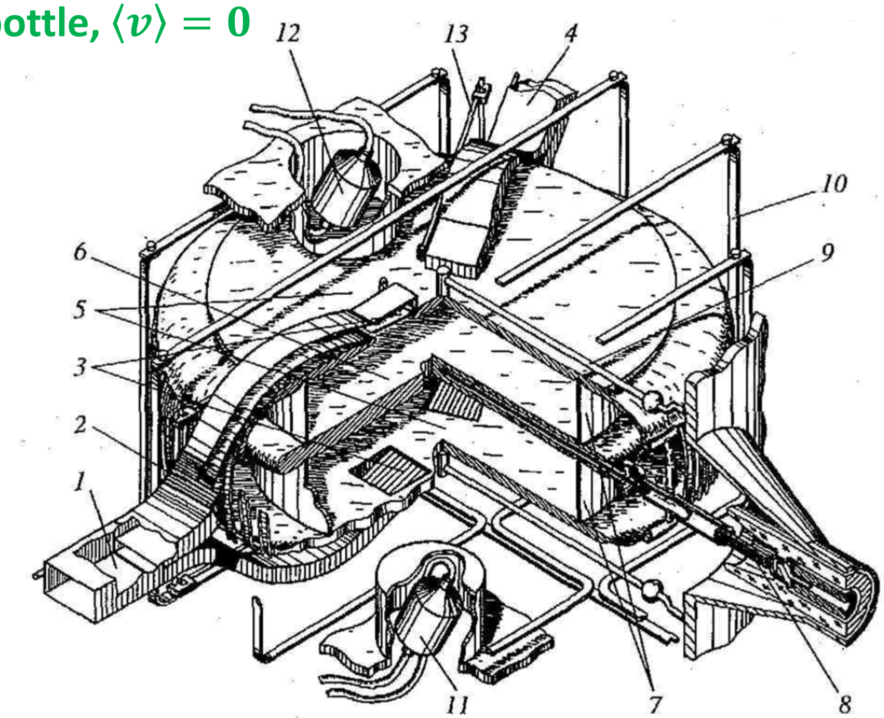
Features of the separated oscillatory fields:

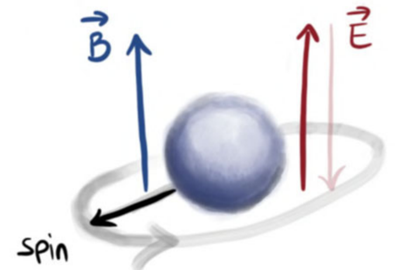
1. Narrow fringes
2. Not sensitive to the field uniformity.

UCN Bottle nEDM experiments

Problem: $v \times E$ motional field

Mitigation: UCN in a bottle, $\langle v \rangle = 0$





$$2\pi f = \frac{2\mu}{\hbar}B \pm \frac{2d}{\hbar}E$$

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{4}{2\pi\hbar}dE$$

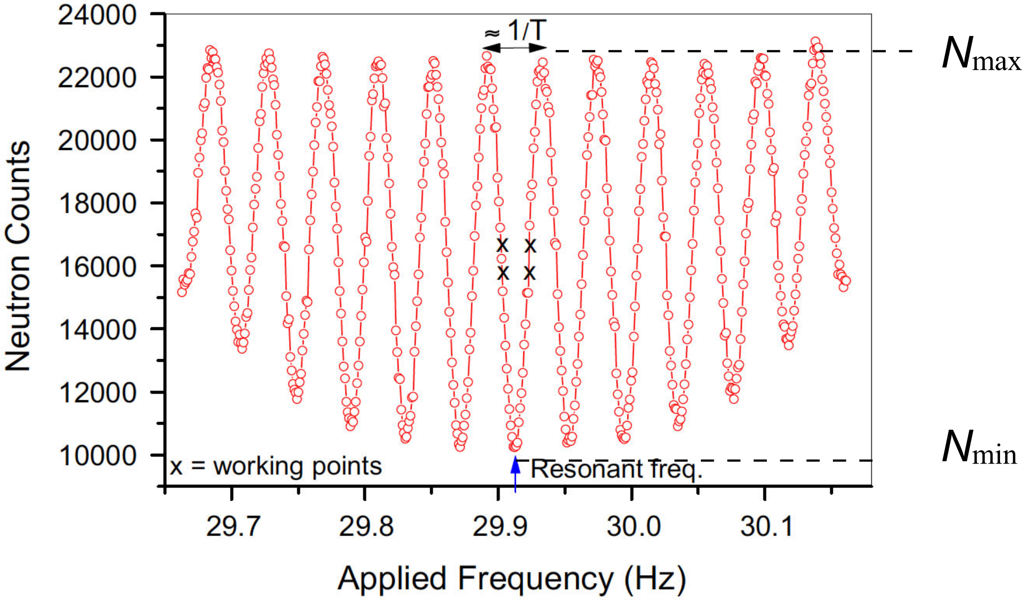
Double-cell configuration:

In one load, the EDM is extracted by the frequency difference between the two cells.

→ Less sensitive to *temporal drifts* of the background B fields.

nEDM sensitivity:

The principle is to measure frequency of spin precession, but in practice we are still <u>counting</u> neutrons.



$$\sigma(d_n) \geq \frac{\hbar}{2\alpha E T\sqrt{N}\sqrt{M}}$$

α: fringe visibility

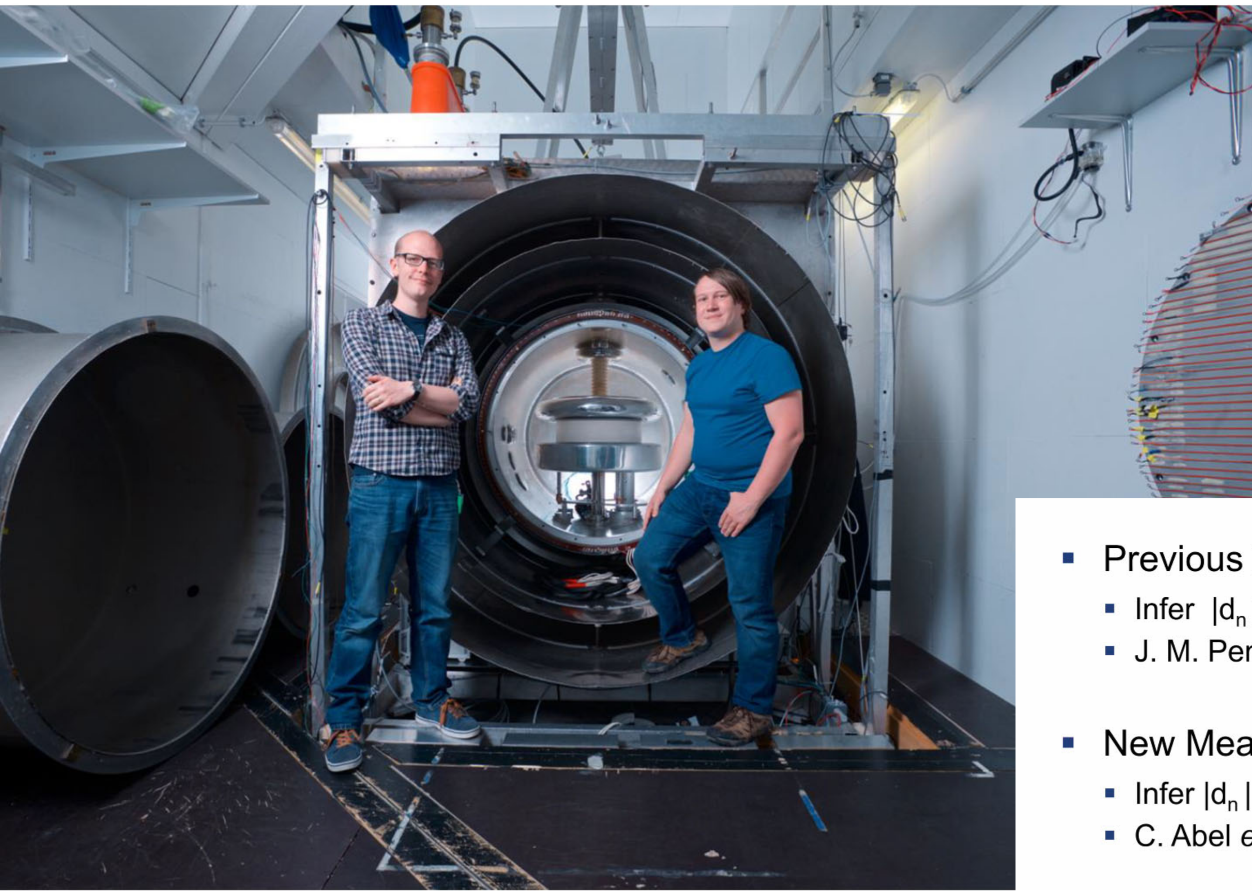
E: Electric field

T: Free precession time

N: number of neutrons counted

M: number of repeats

PSI published a new nEDM limit (2020)



$$\sigma(d_n) \geq \frac{\hbar}{2\alpha ET\sqrt{N}\sqrt{M}}$$

$$\alpha = 0.76$$
$$E = 11 \text{ kV/cm}$$
$$T = 180 \text{ s}$$
$$N = 11{,}400$$

M = 288 cycles/day

2005-2015: improving OILL apparatus @ PSI
2015-2016: physics data taking
2017: field mapping

- Previous Measurement: $(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{sys}}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 3 \times 10^{-26}$ e cm (90% CL)
  - J. M. Pendlebury *et al.* Phys. Rev. D **92**, 092003 (2015)
- New Measurement: $(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 1.8 \times 10^{-26}$ e cm (90% CL)
  - C. Abel *et al.* PRL **124**, 081803 (2020)

Additional Systematics

Effect	Shift (x10^{-28} e cm)	Error (x10^{-28} e cm)
Error on $\langle z \rangle$	⋯	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	−0.1	0.1
Local dipole fields	⋯	4
$v \times E$ UCN net motion	⋯	2
Quadratic $v \times E$	⋯	0.1
Uncompensated G drift	⋯	7.5
Mercury light shift	⋯	0.4
Inc. scattering ^{199}Hg	⋯	7
TOTAL	69	18

Included in Crossing Lines Fit (Error on $\langle z \rangle$, Higher-order gradients, Transverse field correction)

Dedicated mapping measurements (Higher-order gradients, Transverse field correction)

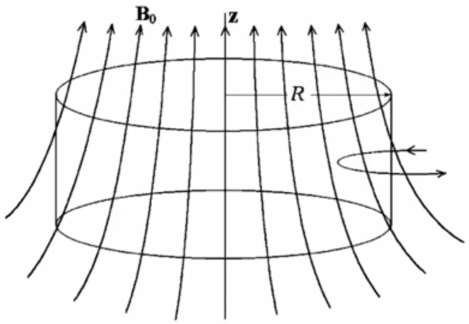
Constrained with measurement at PTB Berlin (Local dipole fields)

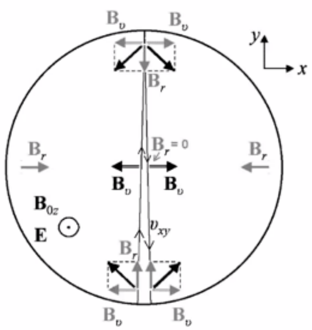
Cs Magnetometers (Uncompensated G drift)

Not anticipated at design, bear in mind for next time (Inc. scattering ^{199}Hg)

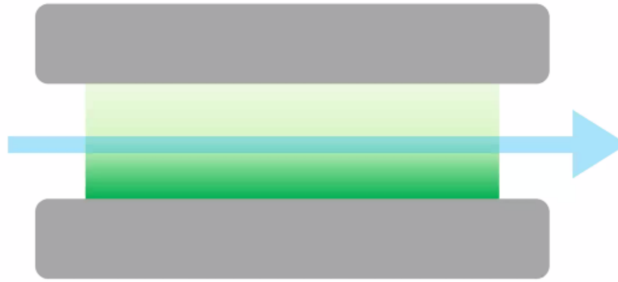
Total systematic error **0.18 x 10^{-26} e cm**
Factor 5 improvement on previous measurement
Only 20% of statistical error

Leading Systematic: False EDMs and Gravitational Shift





Conspiracy between vertical gradient and motional magnetic field from Lorentz transform of *E* into Hg atom frame causes *E*-correlated frequency shift



Slow UCN hang at the bottom of the chamber
Shifts $\mathcal{R}$ shift proportional to vertical gradient

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{G_{1,0}}{1\ \mathrm{pT/cm}} * 4.4 * 10^{-27} \mathrm{e\ cm}$$

$$\mathcal{R} = \mathcal{R}_0\left(1 + G_{1,0}\frac{\Delta h}{B_0}\right) \qquad \Delta h \approx 0.35\ \mathrm{cm}$$

To first order these are proportional, but more complicated fields can cause a “phantom” effect

PRA **99**, 042112 (2019)

Beyond 1e-26 e-cm…

$$\sigma(d_n) \geq \frac{\hbar}{2\alpha ET\sqrt{N}\sqrt{M}}$$

Experiment	Facility	α	E (kV/cm)	T (s)	N	neutron density (1/c.c.)	Chamber D (cm) or volume	Coating	σ(d) per day (e-cm)	σ(d) (e-cm)
OILL	PSI-sD2	0.76	11	180	11,400	2	47	DLC + dPS	11e-26	1.5e-26
n2EDM	PSI-sD2	0.8	15	180	121,000	2	80	DLC + dPS	2.6e-26	
LANL	LANL-sD2	0.8	12	180	80,000	15	47	dPS	4 e-26	3.4e-27 (1y)
TUCAN	TRIUMF-lHe				600,000-2,000,000	200-400	30,000 c.c.	dPS		1e-27 (400d)
PanEDM	ILL—lHe					3.9 40		dPE	3.8e-26 (I) 7.9e-27 (II)	3.8e-27 (100d) 7.9e-28 (100d)
PNPI	PIK—lHe		12→ 27			200			1.5e-26	1e-27 (1y)
SNS	SNS—lHe		75	500	380,000	120	3,000 c.c.	dTPB-dPS		3e-28 (3y)
BeamEDM	ILL/ESS		40	4e-2			FP=50m		5e-26	

$$\sigma(d_n) \geq \frac{\hbar}{2\alpha E T \sqrt{N}\sqrt{M}}$$

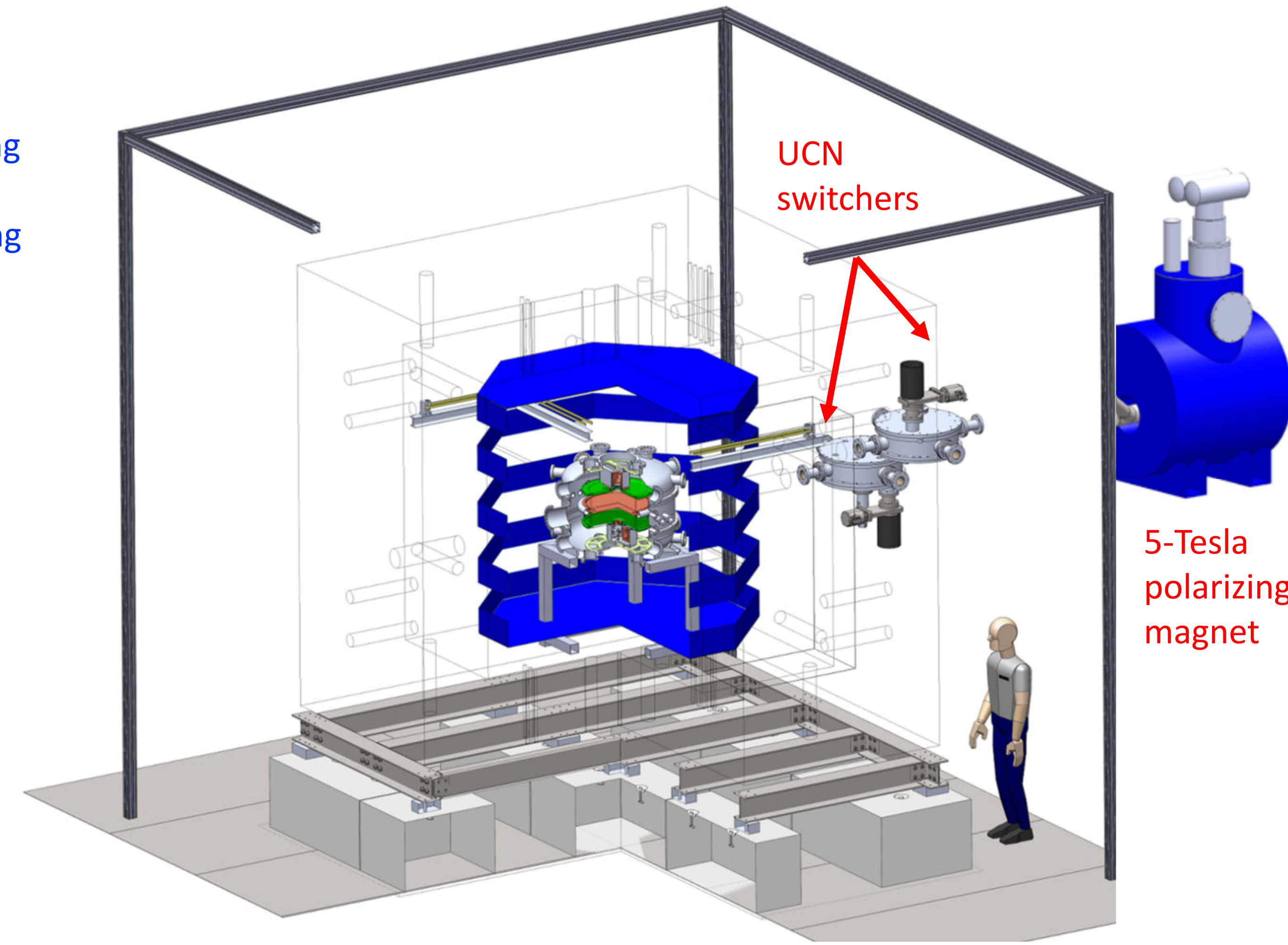
nEDM sensitivity is still limited by the UCN counting statistics → continuing efforts to make more intense UCN sources

Facility		Current	Power	UCN converter	Production volume (L)	UCN rate (1/s)	Storage (s)	Temperature (K)	Heat load in target (W)	Neutron density (1/c.c.)
PSI	590 MeV p	2.4 mA (1%)	1.4 MW	sD2	30			5		2
LANL	800 MeV p	9 µA	7.2 kW	sD2	2		40	5		15
TRIUMF	480 MeV p	40 µA	20 kW	lHe	27	1.4-1.6e+7	30	1.1	8.1+1.5	200-400
ILL	9A n flux			lHe	12			0.6		200
PNPI—PIK reactor	9A n flux	5e+8 (/cm^2-s-A)		lHe				1.15	3.85	350
SNS	9A n flux	5e+8 /s		lHe	3	0.31/c.c.		0.5		

nEDM@LANL

- Guiding Principles:
  -take advantage of the upgraded UCN source;
  -minimized R&D efforts by using proven technology;
  -move towards EDM data-taking in a 3-year time frame.

Design features:
- Double cell
- Hg co-magnetometer
- Cs external magnetometers
- Magnetically shielded room
- Room temperature operation



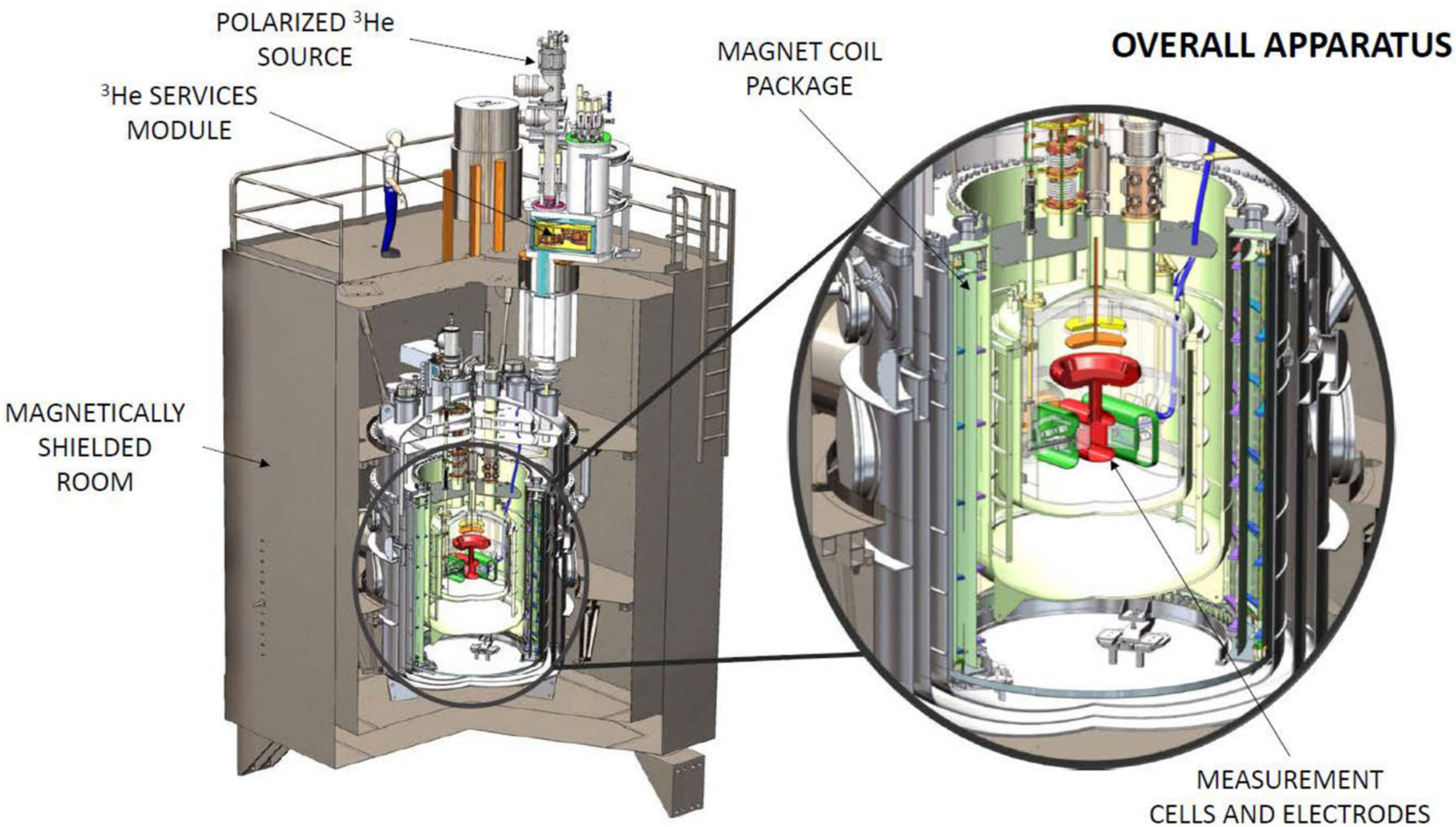
- Construction (NSF MRI + LANL LDRD): 2018-2021

nEDM@SNS

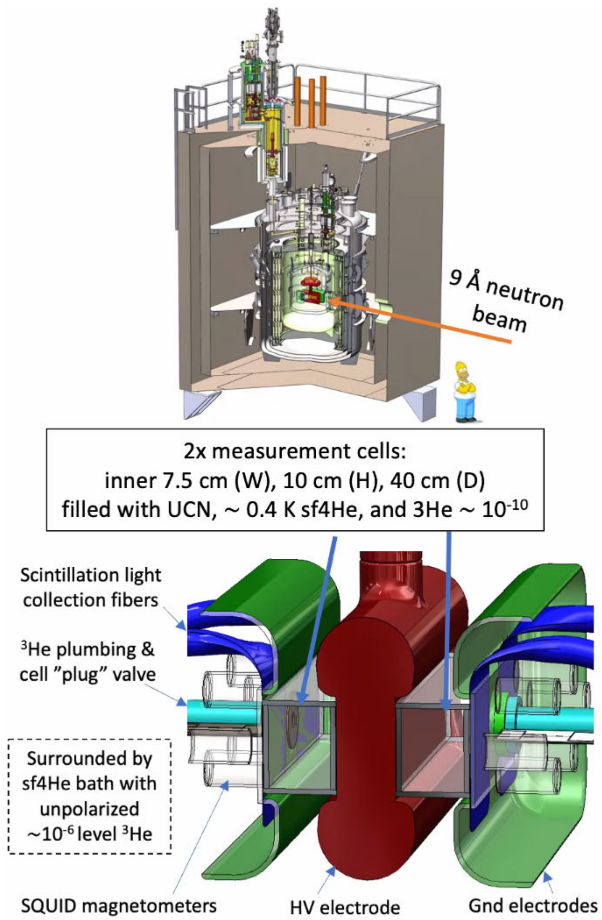
Neutron electric-dipole moment, ultracold neutrons and polarized ^{3}He ** "The Miracle of Helium"

R. Golub[a] and Steve K. Lamoreaux[b]

Physics Reports **237**, 1 (1994)



Steady progress in preparing for the big cryogenic nEDM experiment



The nEDM@SNS experiment

Talking: Kent Leung

Golub & Lamoreaux's technique: polarized **UCN** + polarized ^{3}**He** atoms + superfluid ^{4}**He**

Statistical "shot noise" limit: $$\sigma(d_n) \sim \frac{\hbar}{2\alpha E T \sqrt{N}}$$

$E =$ electric field (75 kV/cm thanks to sf-^{4}He. See Ito, Riley, Blatnik, Korsch talks.)

$\alpha =$ polarization contrast (UCN polarization ~ 98%)

$T =$ precession time (goal to use 1000 sec if wall loss times low enough)

$N =$ no. detected neutrons (high density from in-situ super-thermal production & accumulation. Density increases with $\tau_{storage}$. No need to transport. But "filling" time is ~ 1000 sec)

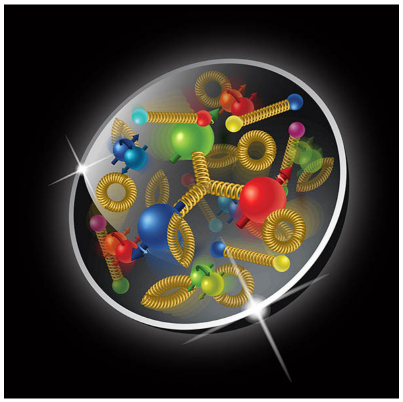
Polarized ^{3}He (~ 98%) serves as in-situ & live UCN spin analyzer (new type of signal!)

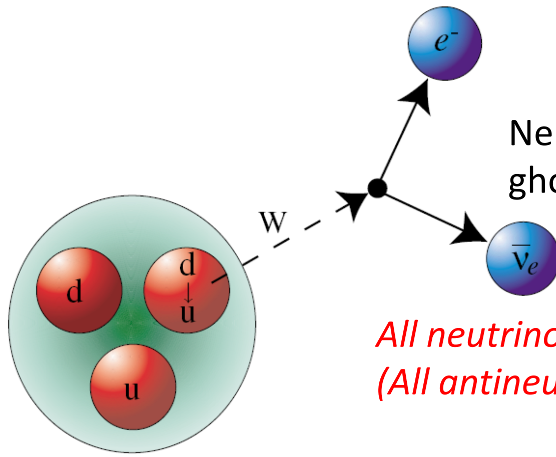
Low temperature (~ 0.4 K): SQUIDs and superconducting magnetic shielding

^{3}He + SQUIDs as co-magnetometer. Small changes of sf^{4}He temperature causes large changes (~ $T^{7.5}$) of ^{3}He mean-free-path as dominated by ^{3}He-phonon scattering. Great for co-magnetometer systematic checks .

Neutrons are a unique laboratory to study the four fundamental forces of nature.

Strong force

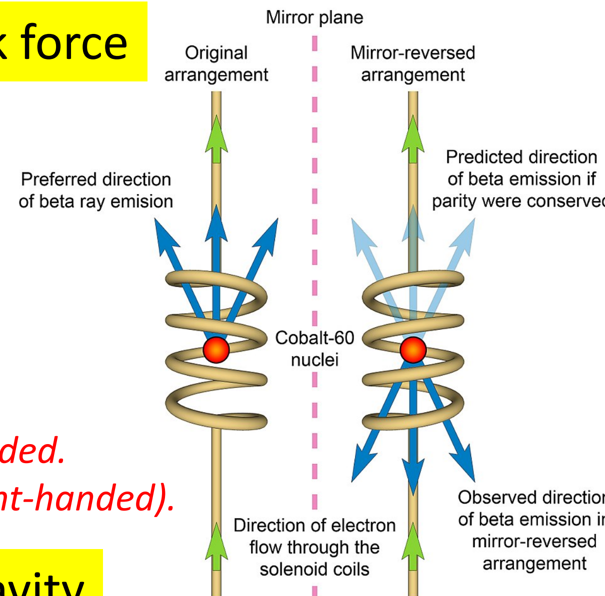




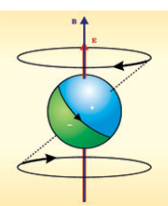
Neutrino, the ghost particle

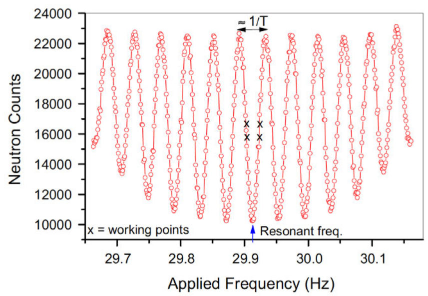
All neutrinos are left-handed.
(All antineutrinos are right-handed).

Weak force



Electromagnetic force

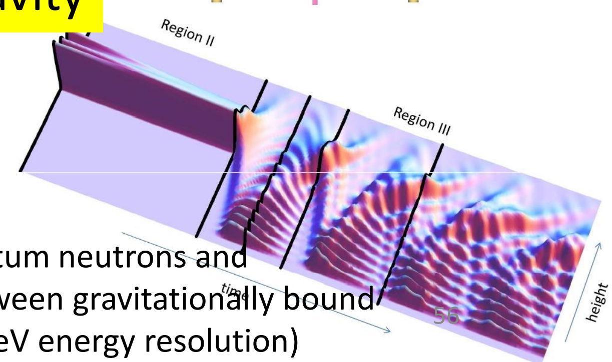




$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_e + 782\ \text{keV}$$

Neutron beta decay is the archetype of nuclear transmutation.

Gravity



Bouncing quantum neutrons and transitions between gravitationally bound neutrons (w/ peV energy resolution)

Summary

Low-energy neutrons are useful in testing the Standard Model of particle physics. Storage of UCN allows for the long observation times needed for precision measurement of many neutron observables. High-precision measurements, confronted with theoretical predictions, probe high-energy physics through loop effects.

1. Precision measurements on the neutron lifetime (δt< 0.1s), combined with the beta-decay asymmetry (δA/A< 0.1%), test the unitarity of the CKM matrix (to 1e-4 level of precision). Neutron decay offers improvements required, both theoretically and experimentally, to determine Vud better than 0+ → 0+ nuclear decays.

With UCNτ, all systematic uncertainties have been quantified by measurements.

- $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s (PRL 2021)

Moving forward:

- UCNτ +: elevator loading, reaching δt=0.1 s

2. Precise knowledge of Neutron decay and EDM → confirm symmetry-violating physics needed for baryogenesis (& nucleosynthesis) to account for the matter-antimatter asymmetry of the universe: high priority for 50 years, likely to remain so. In the US, two efforts are underway:

- nEDM@LANL plans to reach 3e-27 e-cm with the LANL UCN source, and
- nEDM@SNS aims for < 5e-28 e-cm using an innovative superfluid helium technique.

UCNτ

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UCN source operation + precession cells + HV

MSR requisition, spin analysis, slow control
Hg co-magnetometer,
He-3 magnetometer

Magnetic coils

External magnetometry

Hg co-magnetometer

DAQ, data storage

Spin transport simulation

NV diamond magnetometer

He-3 magnetometer; Surface coating R&D