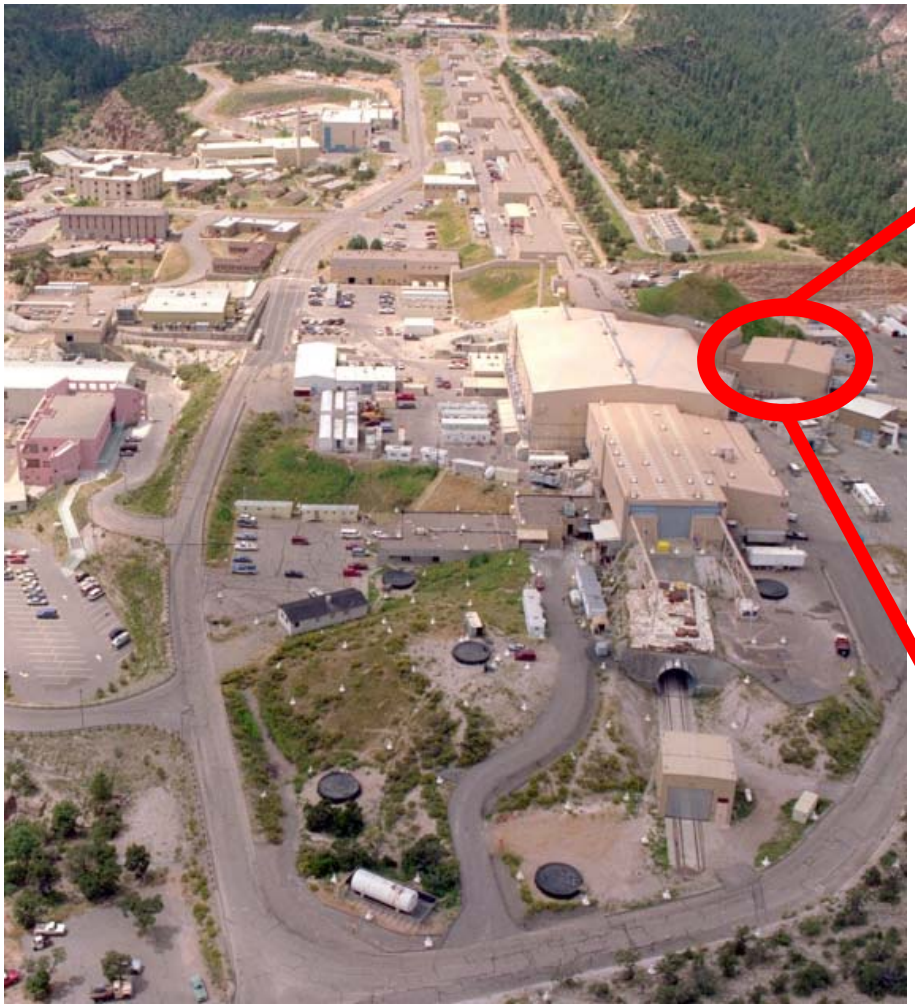
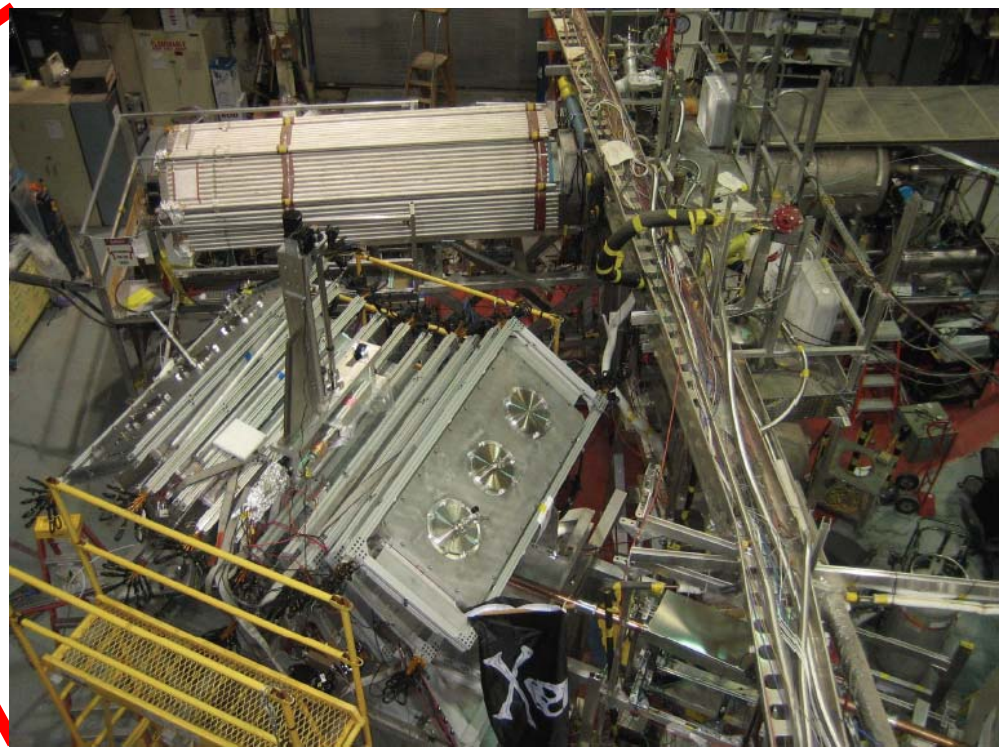
Ultracold Neutron Research at LANSCE

Brad Plaster, University of Kentucky



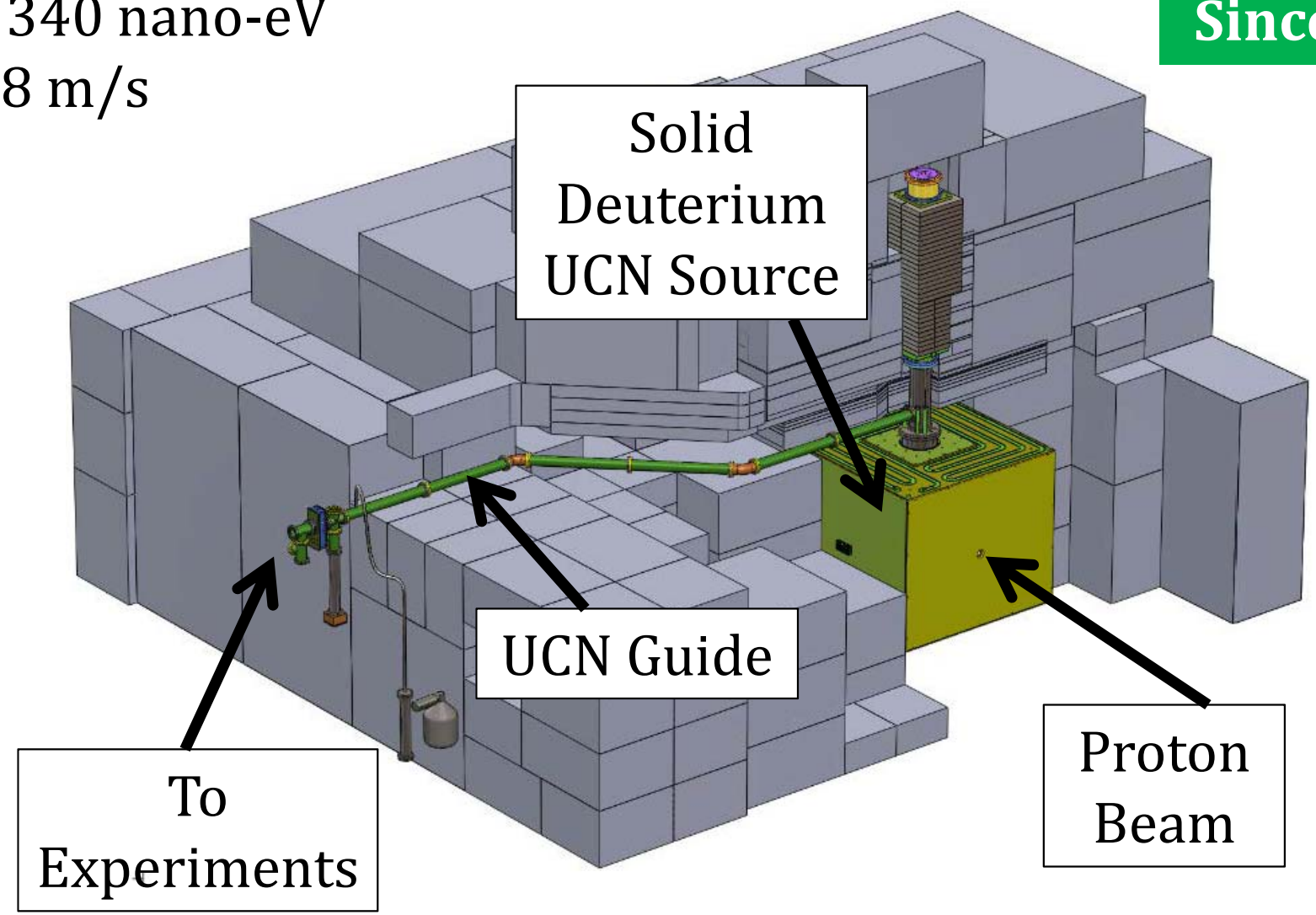


LANSCE User Group Meeting
November 3, 2015

LANSCE UCN Source

Ultracold Neutrons (UCN)
T < 340 nano-eV
v < 8 m/s

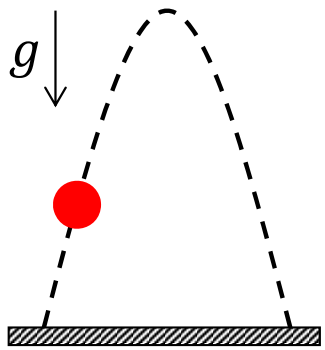
Operating Since 2004



A.R. Young et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 114007
A. Saunders et al, Rev. Sci. Instrum. 84 (2013) 013304
A. Saunders et al., Phys. Lett. B 593 (2004) 55

UCN as a Probe of Fundamental Interactions

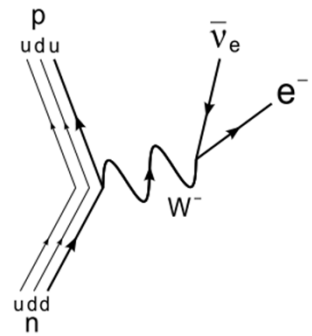
Gravity

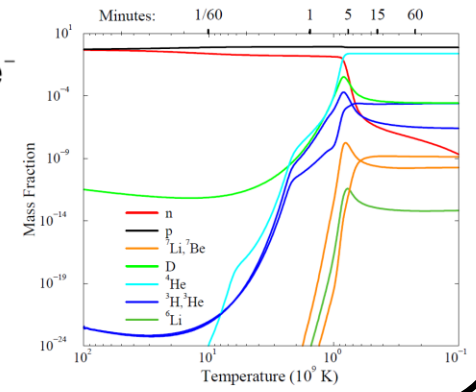


$$V_g = mgz$$

$$\hat{H}\psi_n = E_n \psi_n$$

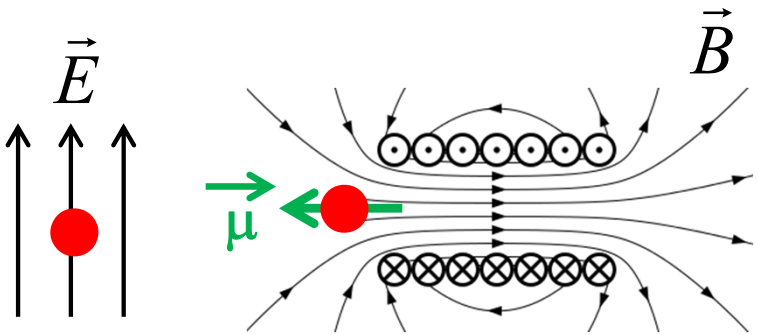
Weak



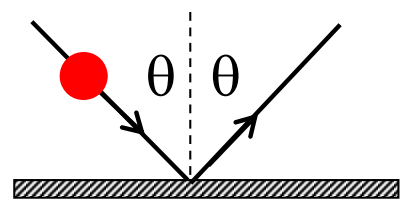


S. Burles, K.M. Nollett, and M.S. Turner, astro-ph/9903300

Electromagnetic



Strong



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

$$\vec{n} + {}^3\vec{\mathrm{He}} \rightarrow p + \mathrm{T}$$

J.S. Nico and W.M. Snow, Annu. Rev. Nucl. Part. Sci. 55 (2005) 27
H. Abele, Prog. Part. Nucl. Phys. 60 (2008) 1
D. Dubbers and M. Schmidt, Rev. Mod. Phys. 83 (2011) 1111

LANSCE UCN Source Performance

Source	Converter	Density in storage vol UCN cm^{-3}	Useful current 10^4 UCN s^{-1}	Source storage time (s)
Available now:				
LANL area B [78]	SD_2	52	10	40
ILL turbine [75]	liq. D_2	>40	100	< 1 sec
ILL LHe [79]	LHe	>55	0.14	67
RCNP [81]	LHe	26	1	81
PSI [82]	SD_2	23	4.2	90
Mainz [83]	SD_2	18	0.12	Few sec
Planned (date)		Target parameters:		
PULSTAR [84] (2014+)	SD_2	>30	>10	Few sec
FRM II [85] (2015+)	SD_2	5000	3000	N/A
TRIUMF [86] (2016)	LHe	1500*	100*	150
WWR-M [87] (2016)	LHe	12000	7000	10

* polarized UCN

A.R. Young et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 114007

Many Users !

The UCN Science Program

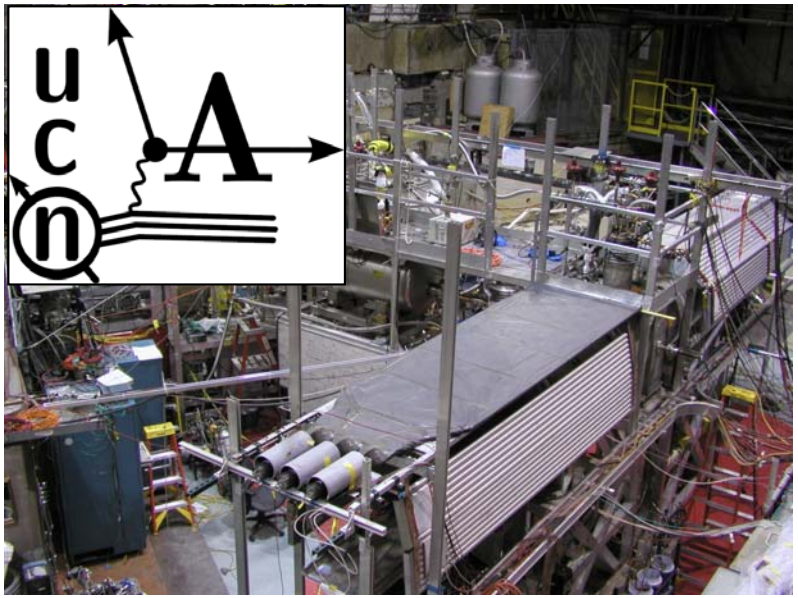
5. Fundamental Symmetries and Neutrinos

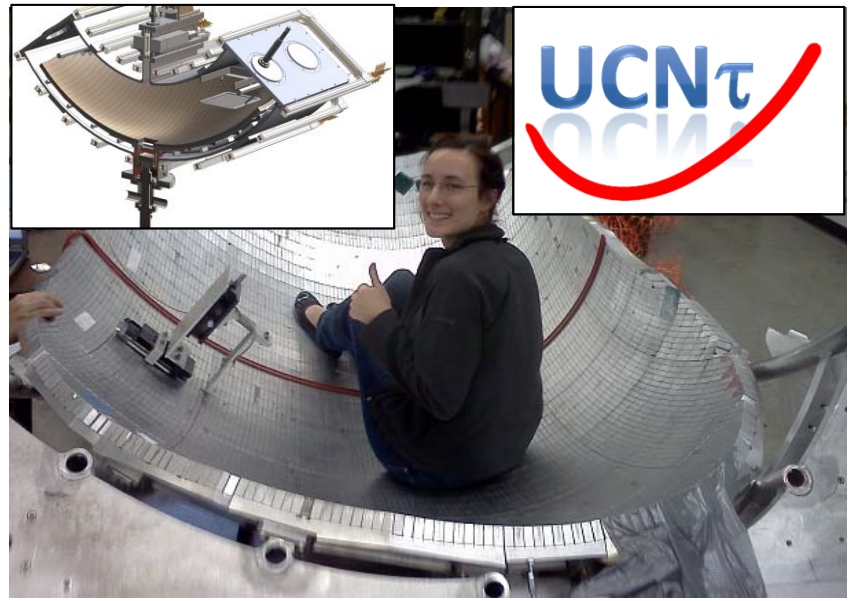
Discovering and characterizing the basic forces of nature have been at the forefront of physics research for centuries. From the apple falling in Lincolnshire, England, to the appearance of the Higgs boson at CERN, these endeavors continue to the present day.

- **What are the absolute masses of neutrinos, and how have they shaped the evolution of the universe?**
- **Are neutrinos their own antiparticles?**
- **Why is there more matter than antimatter in the present universe?**
- **What are the unseen forces that disappeared from view as the universe expanded and cooled?**

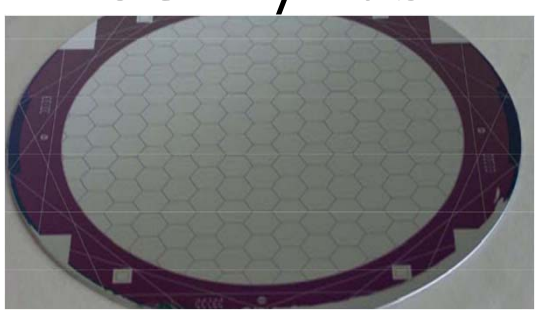
"Reaching for the Horizon", The 2015 Long Range Plan for Nuclear Science
http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

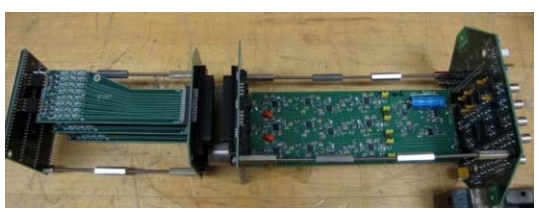
The Experiments

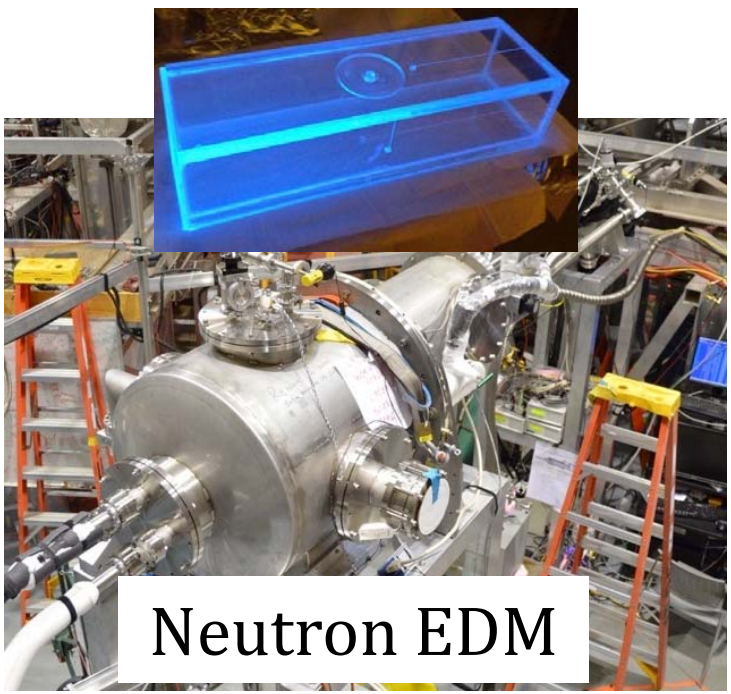


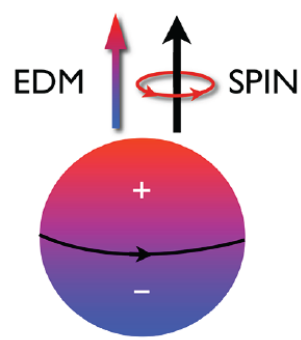


UCNB/Nab

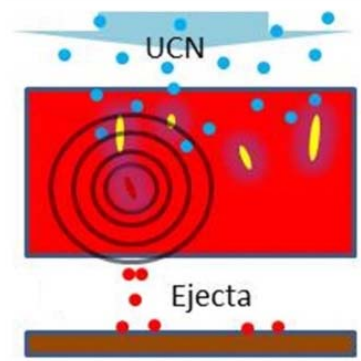




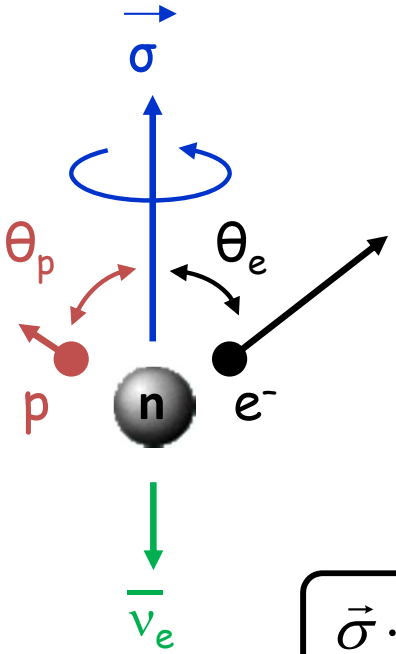


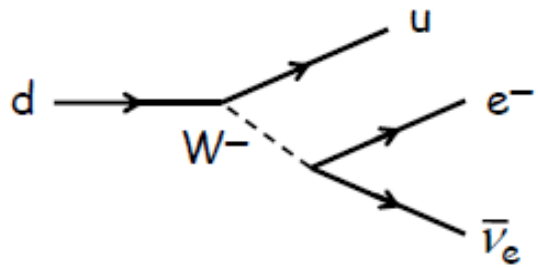


UCNS



Precision Neutron β-Decay: UCNA

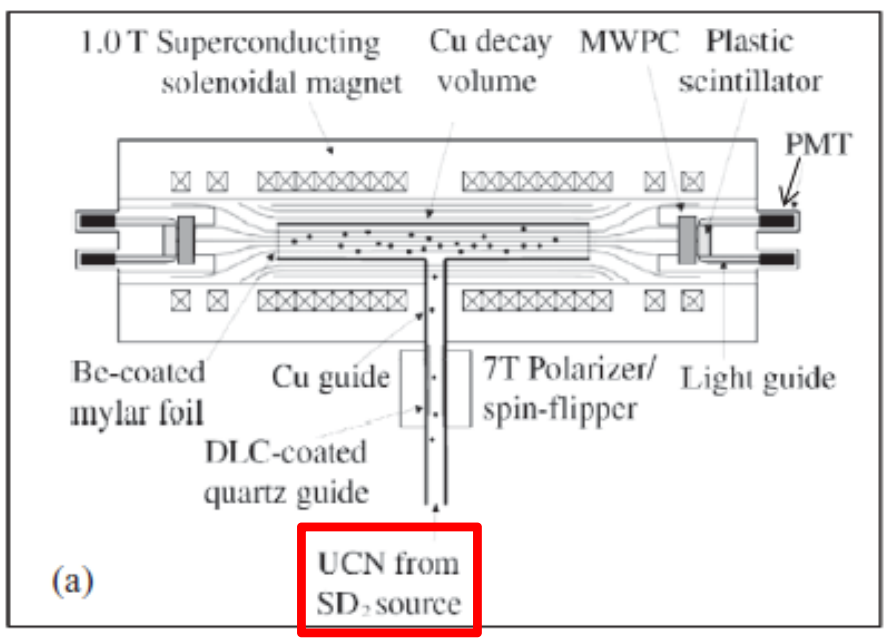


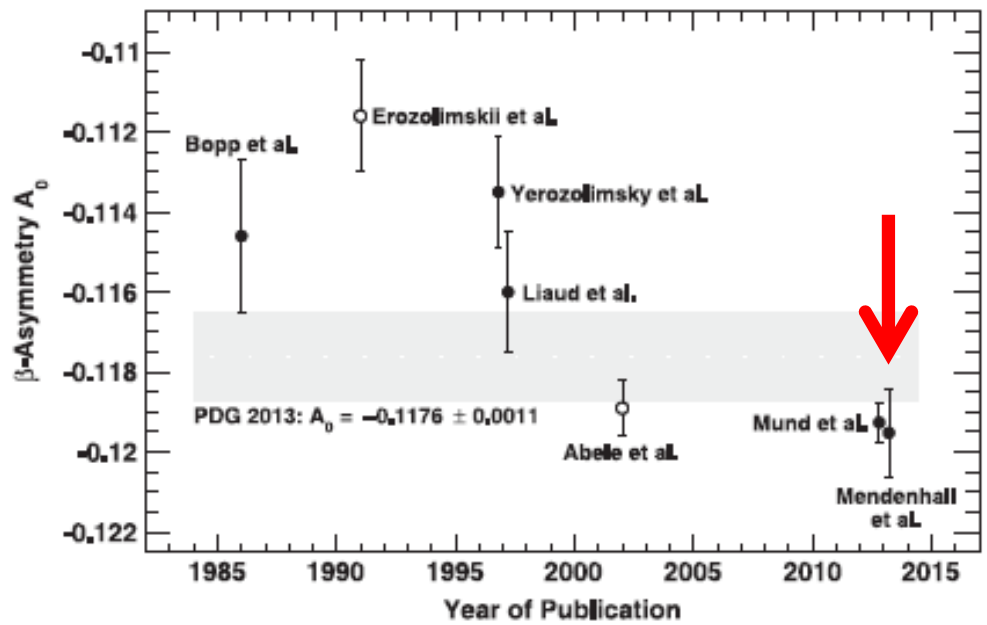


"V – A" Law

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \langle p | J^\mu | n \rangle L_\mu$$

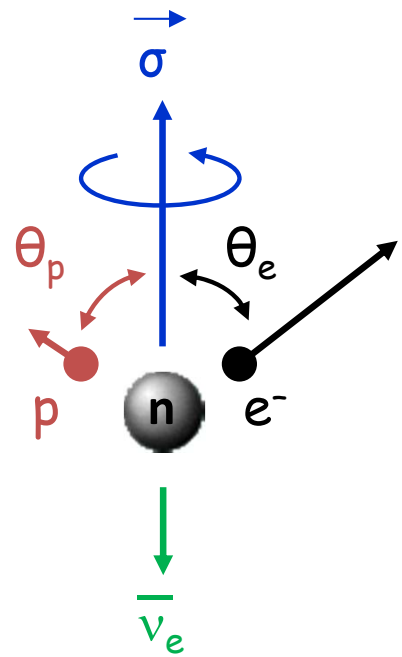
$\vec{\sigma} \cdot \vec{p}_e \longrightarrow$ "A"





M.P. Mendenhall et al., PRC 87 (2013) 032501
B. Plaster et al., PRC 86 (2012) 055501

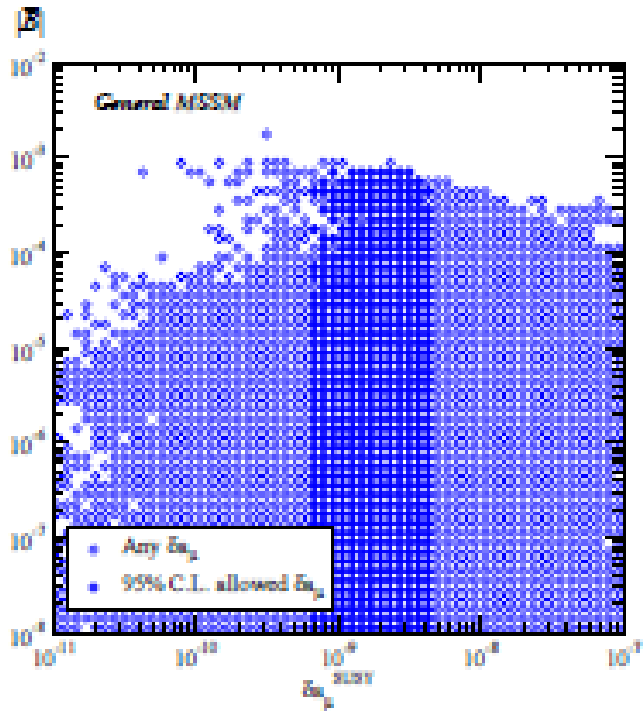
Precision Neutron β-Decay: UCNB, Nab (SNS)



$$\vec{\sigma}\cdot\vec{p}_\nu$$

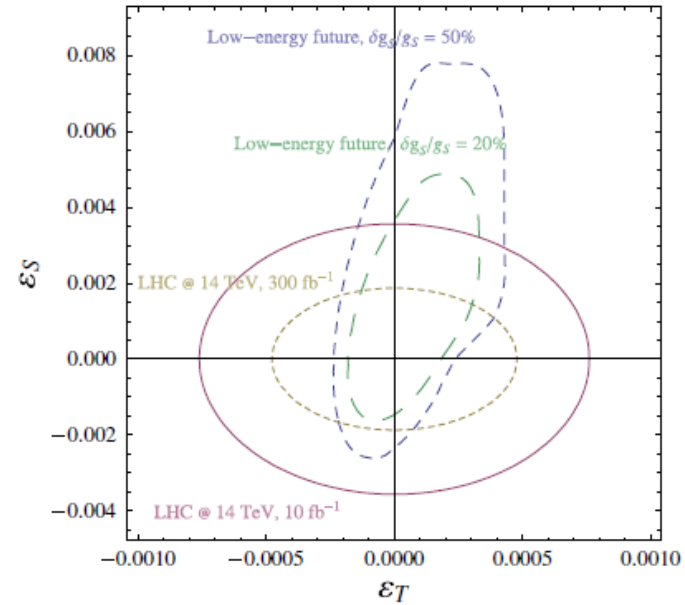
$$B = B_0 + b_\nu \frac{m_e}{E_e}$$

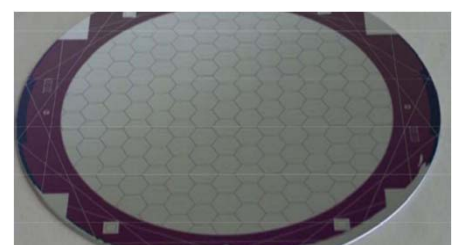
$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu}\right.$$

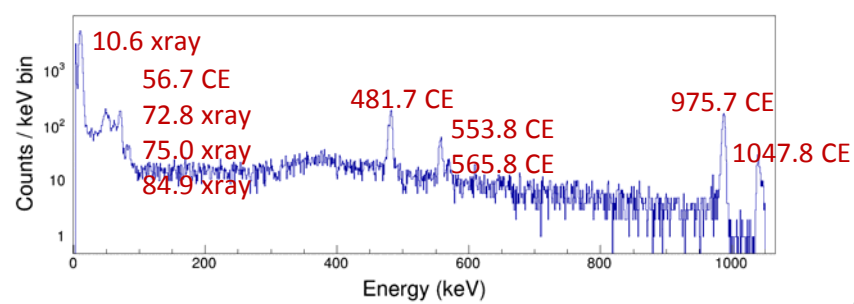


S. Profumo, M.J. Ramsey-Musolf, and S. Tulin, PRD 75 (2007) 075107

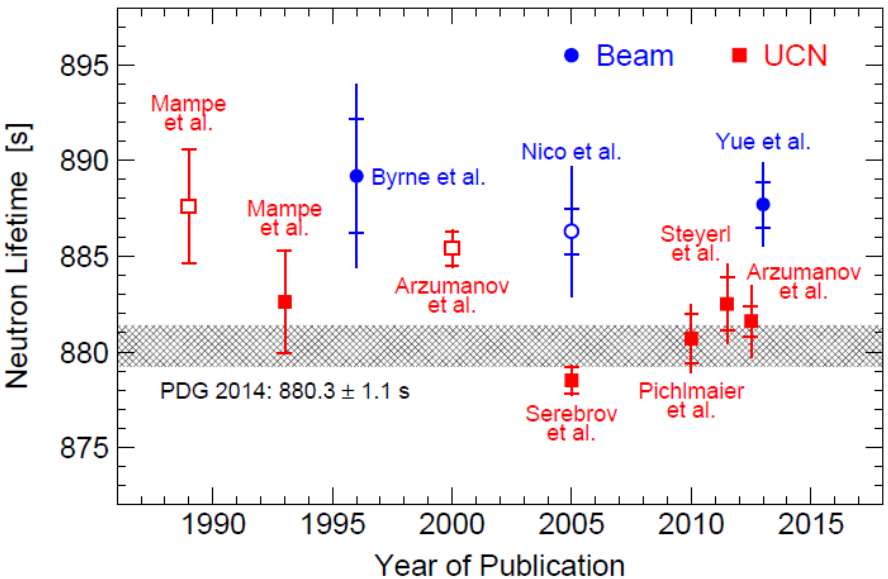
T. Bhattacharya et al., PRD 85 (2012) 054512



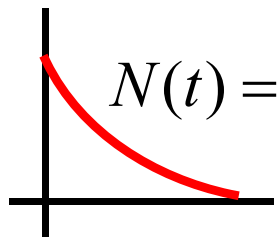




Precision Neutron β-Decay: UCNτ



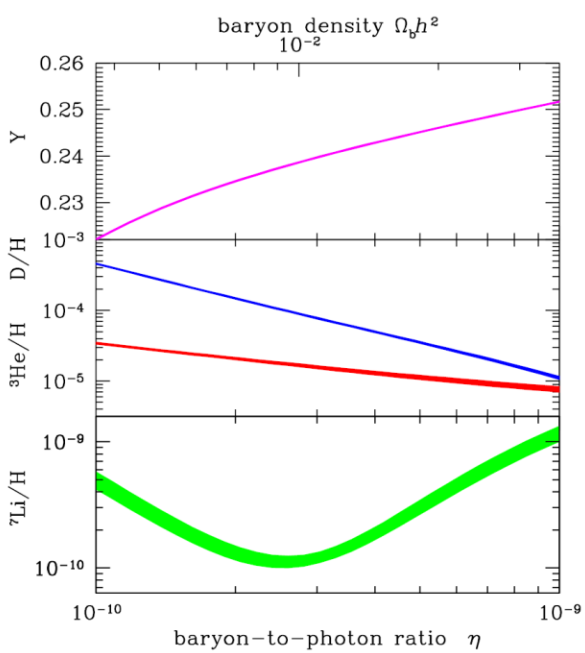
"Count the Living"

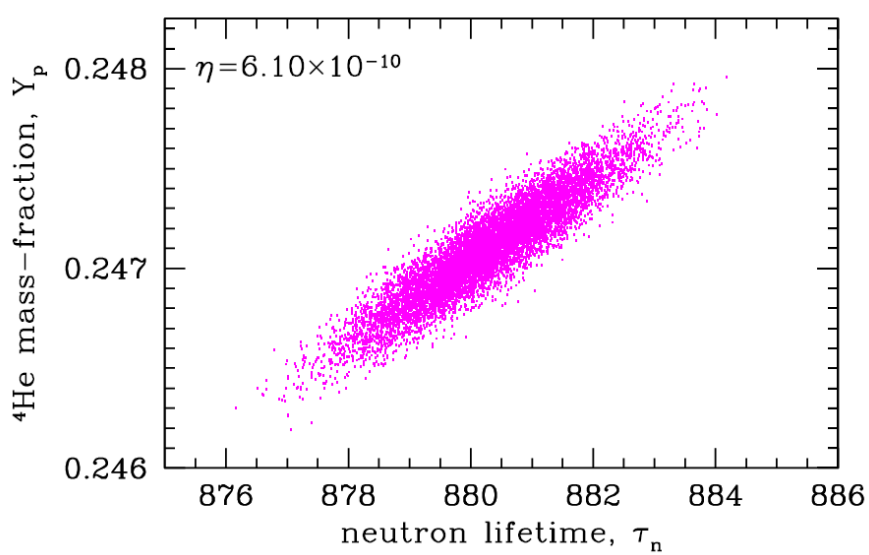


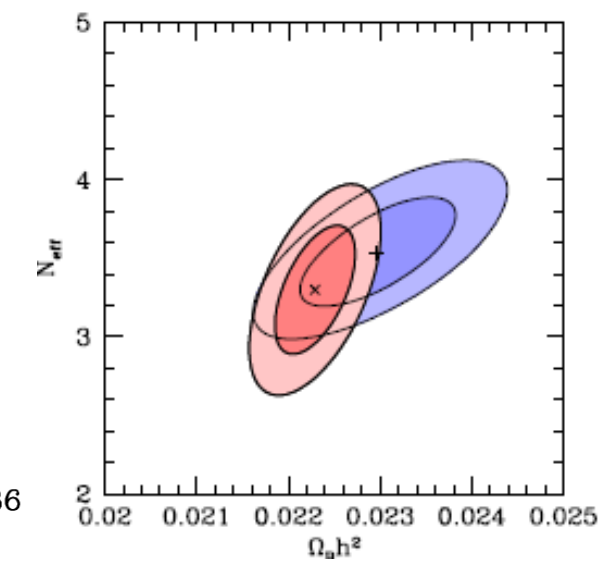
$$N(t) = N_0 e^{-t/\tau_\beta}$$

"Count the Dead"

$$\left|\frac{dN}{dt}\right| = \frac{N_0}{\tau_\beta}$$







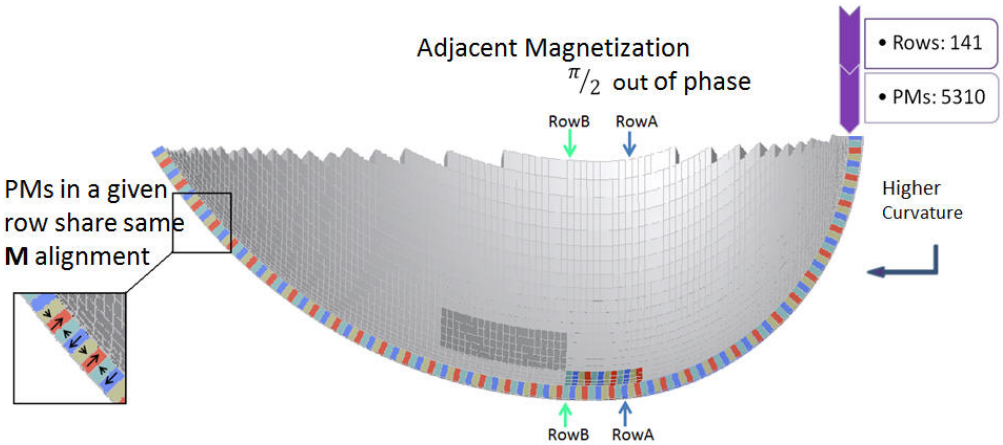
R.H. Cyburt et al., arXiv:1505.01076

K. Nollett. update of arXiv:1312.5725

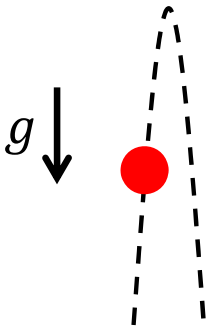
Precision Neutron β-Decay: UCNτ

Magneto-

Halbach array



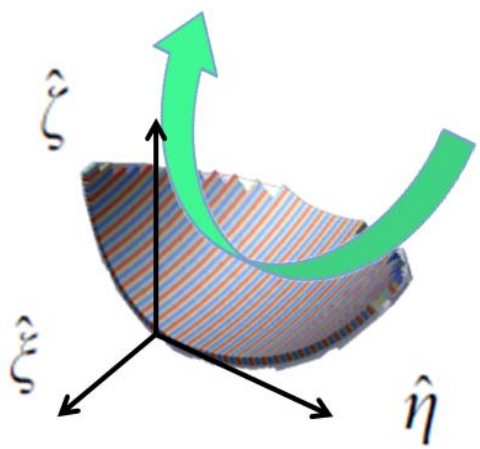
Gravitational Trap



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

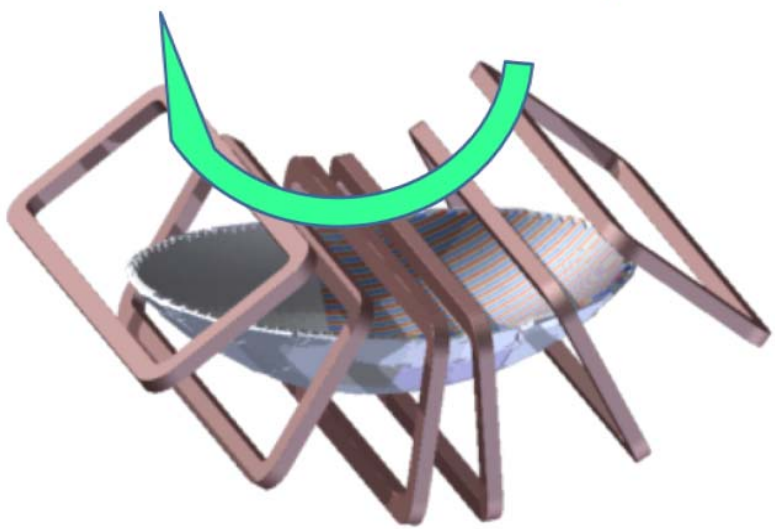
$$\tau_s^{-1} = \tau_\beta^{-1} + \cancel{\tau_w^{-1}} + \tau_0^{-1}$$

PM Array **B** along $\hat{\eta}$



Local Surface Coordinates

Guide Coils **B** along $\hat{\xi}$

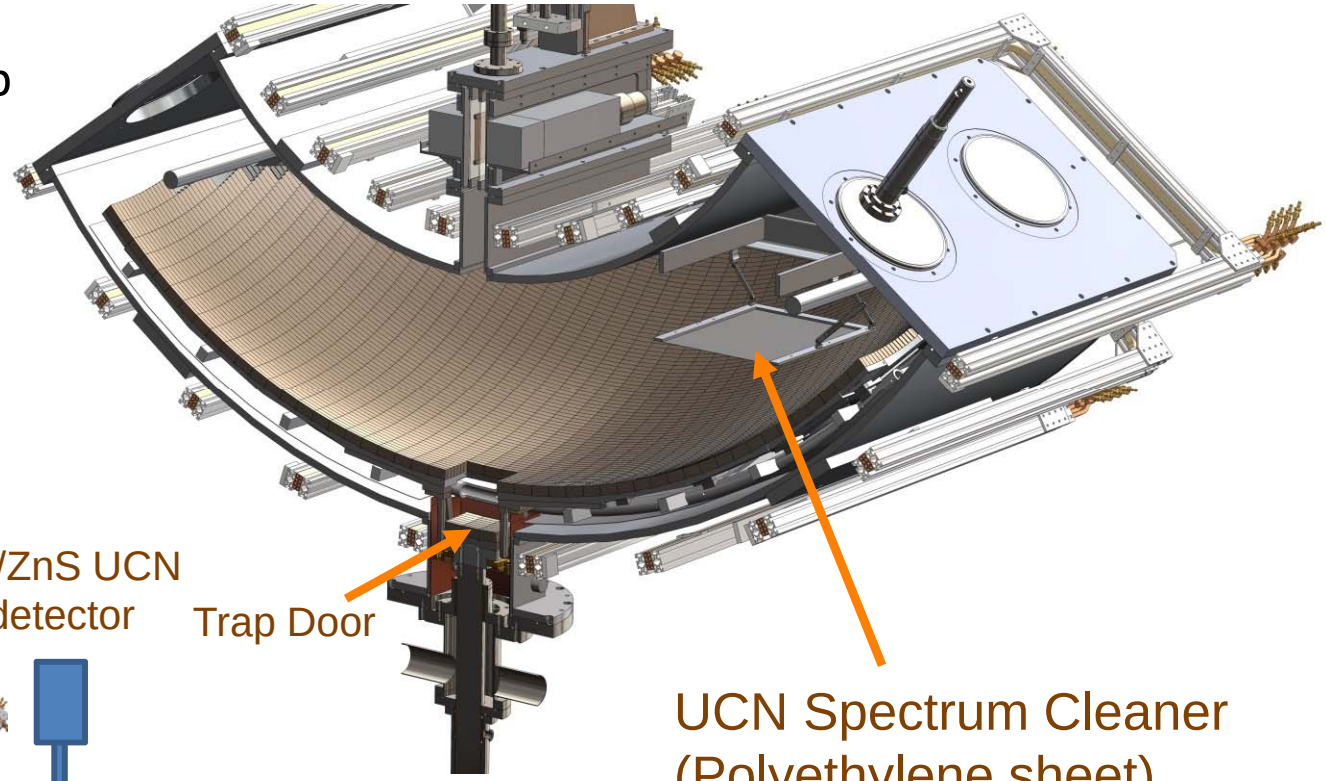


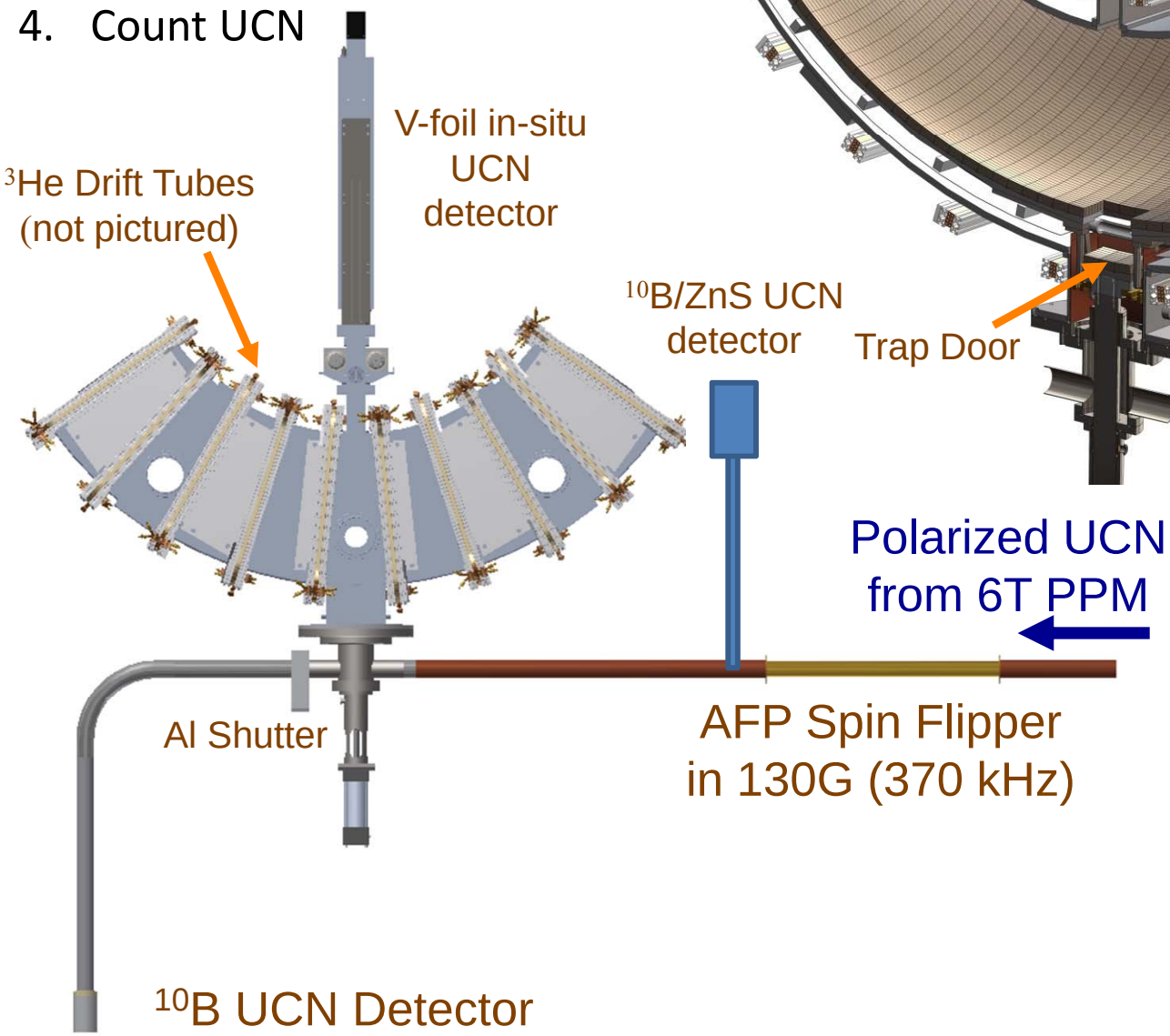
P. Walstrom et al, NIM A 599 (2009) 82
D.J. Salvat et al., PRC 89 (2014) 052501

The UCNτ Experiment is operational since 2013

"*Fill-Store-Count*" cycle

1. Fill polarized UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Count UCN





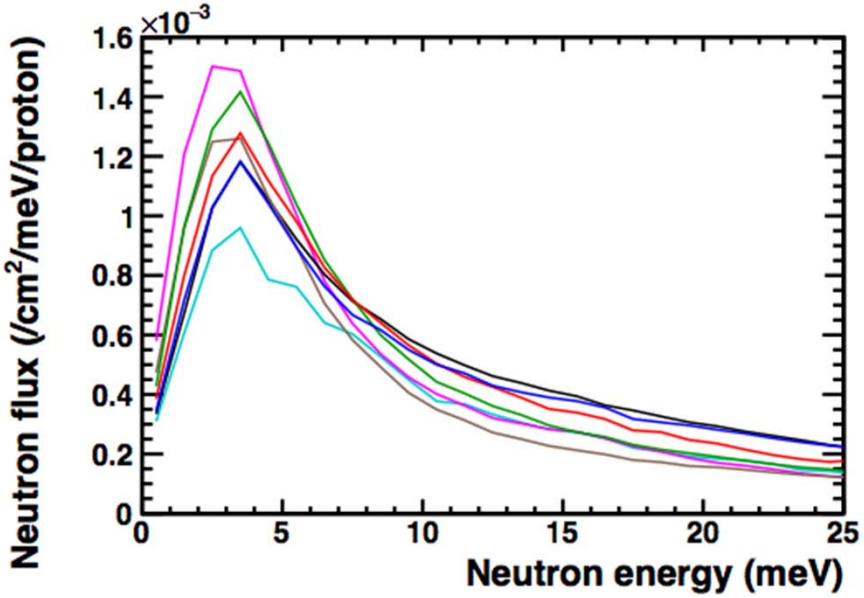
Detector R&D:

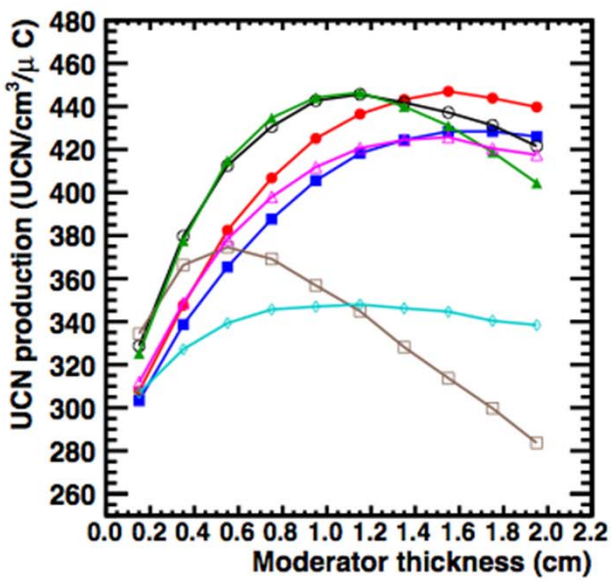
2013: External UCN detector

2014-2015: V-foil *in-situ* UCN detector

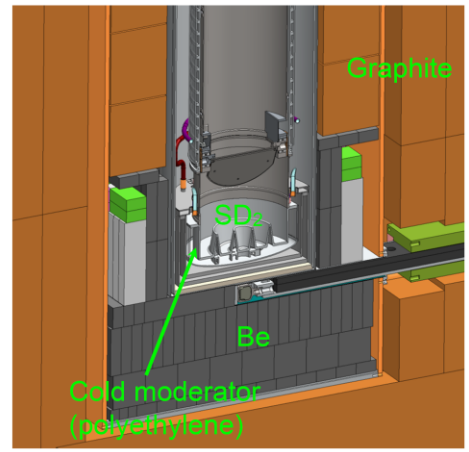
2015-2016: 10B/ZnS *in-situ* UCN detector

Source Upgrade in Progress

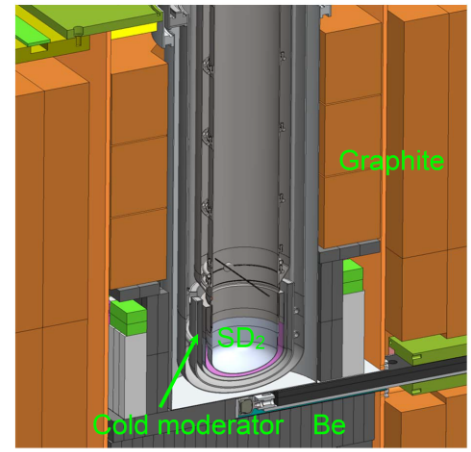




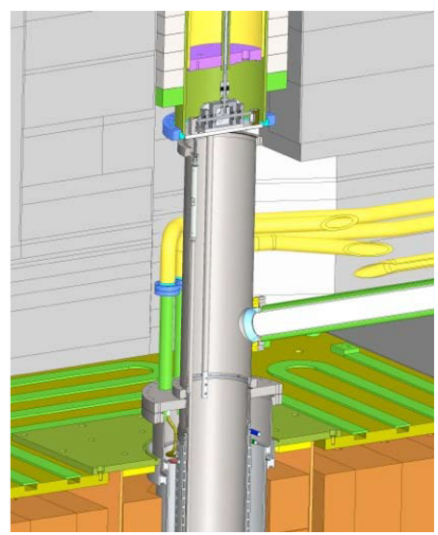
Current



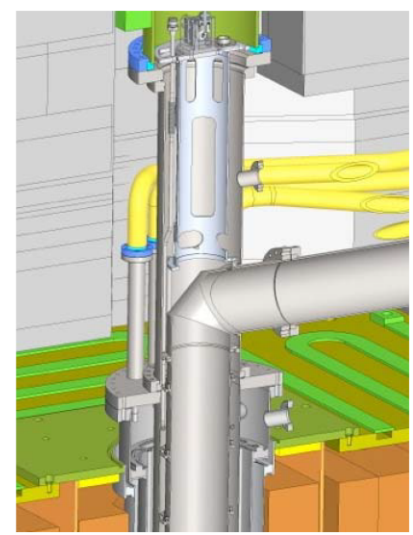
New



Current

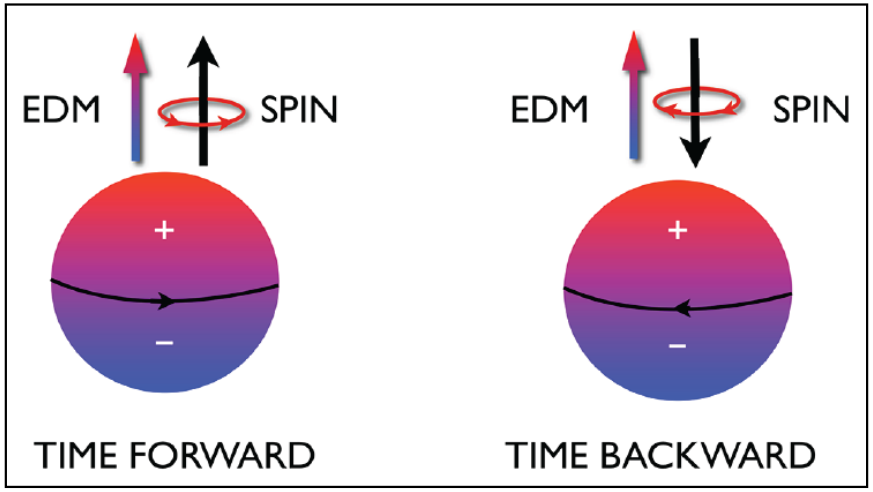


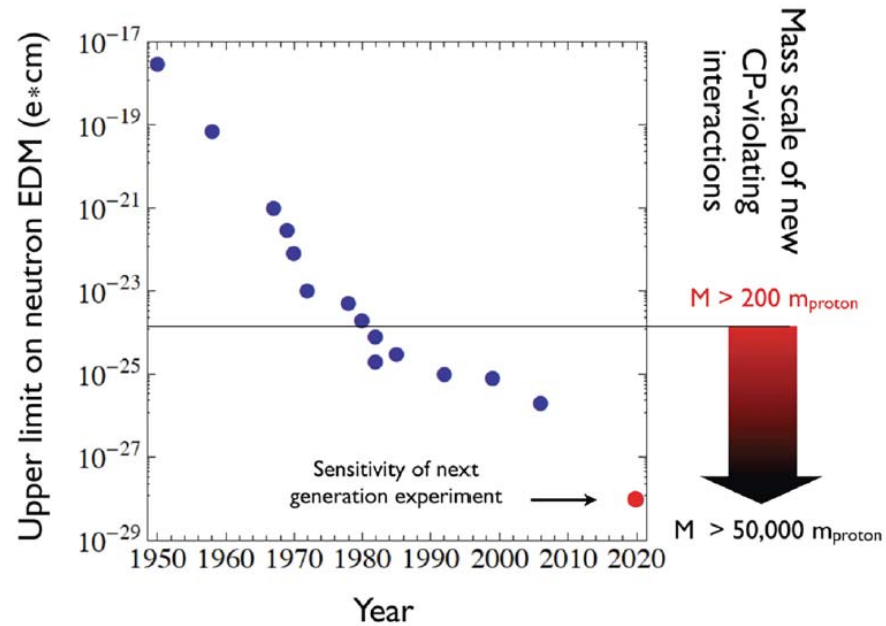
New



LDRD Project #20140015DR: "Probing New Sources of Time-Reversal Violation with Neutron EDM", T. Ito (PI)

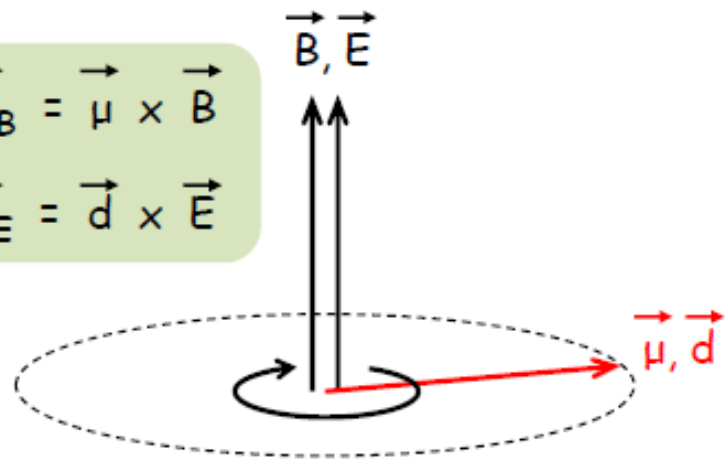
Source Upgrade in Progress → Neutron EDM





$$\vec{\tau}_B = \vec{\mu} \times \vec{B}$$

$$\vec{\tau}_E = \vec{d} \times \vec{E}$$



$$h\nu_{\uparrow\uparrow} = -2\mu B - 2dE$$

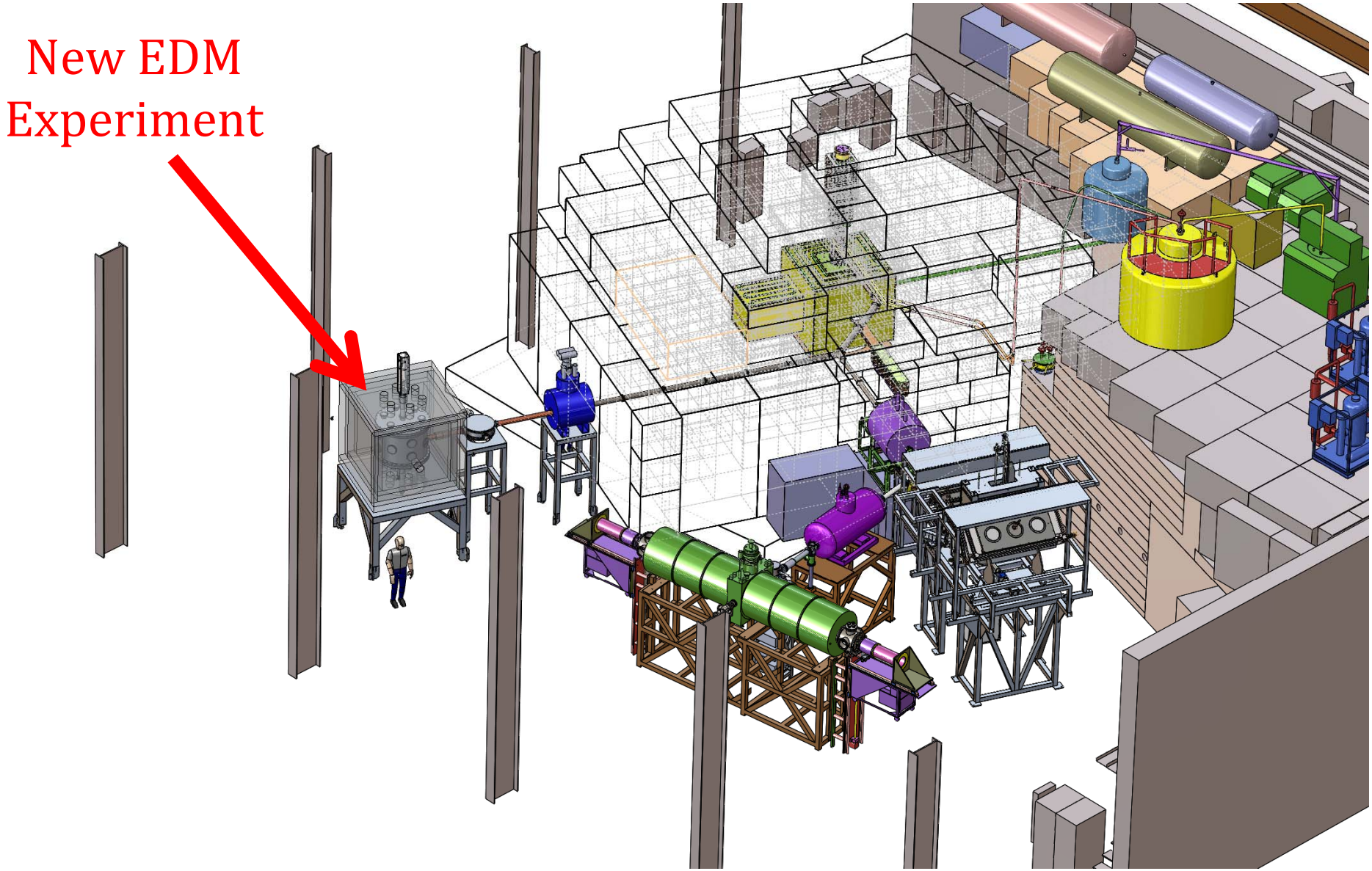
$$h\nu_{\uparrow\downarrow} = -2\mu B + 2dE$$

$$d = -\frac{h\Delta\nu}{4E}$$

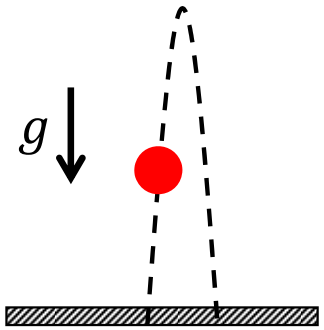
$$\delta d \sim \frac{1}{\left|\vec{E}\right| T\sqrt{N}}$$

Figures:
"Reaching for the Horizon", The 2015 Long Range Plan for Nuclear Science
http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

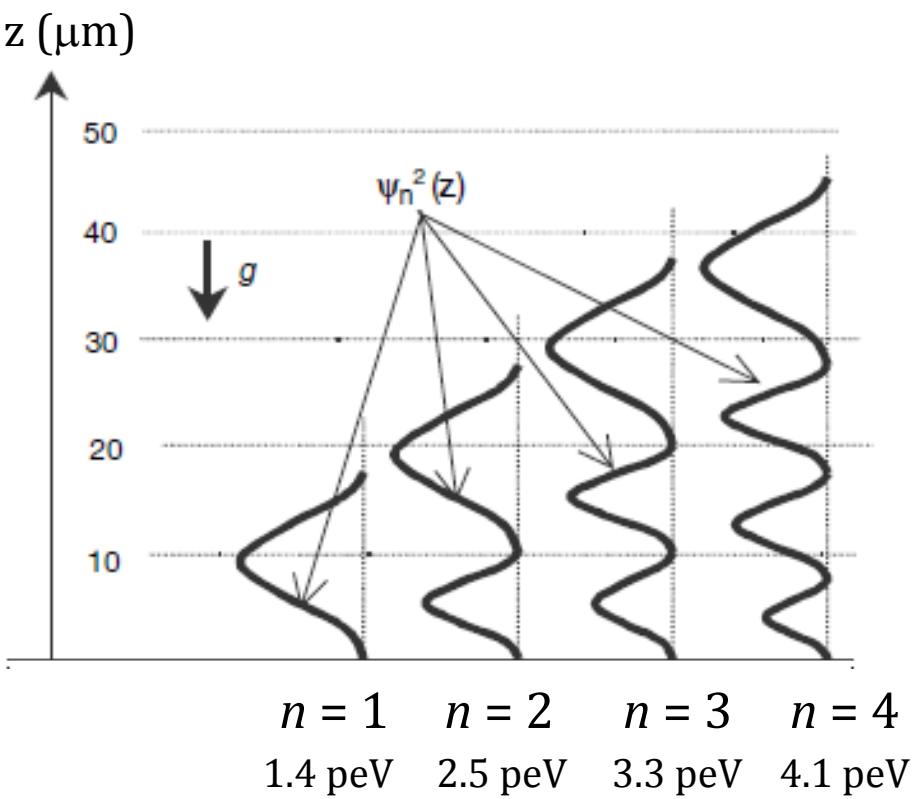
Source Upgrade in Progress → Neutron EDM

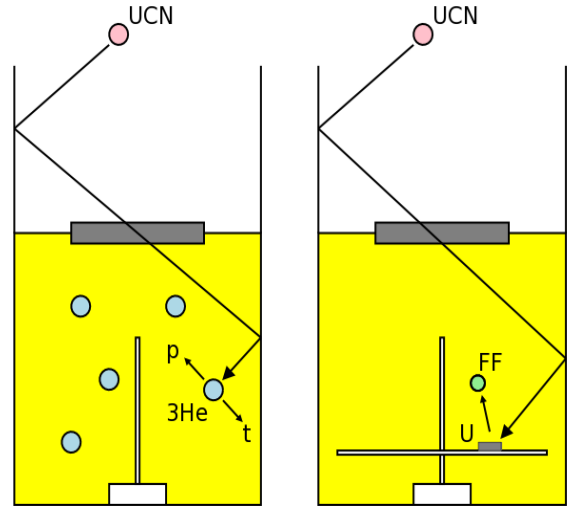


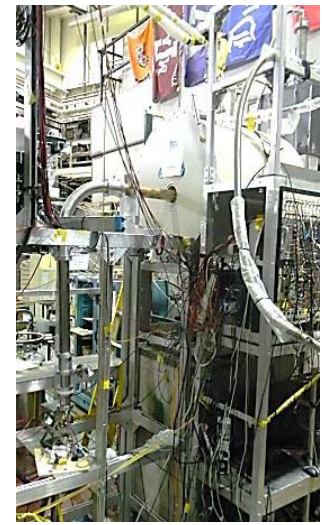
Other Exciting Opportunities

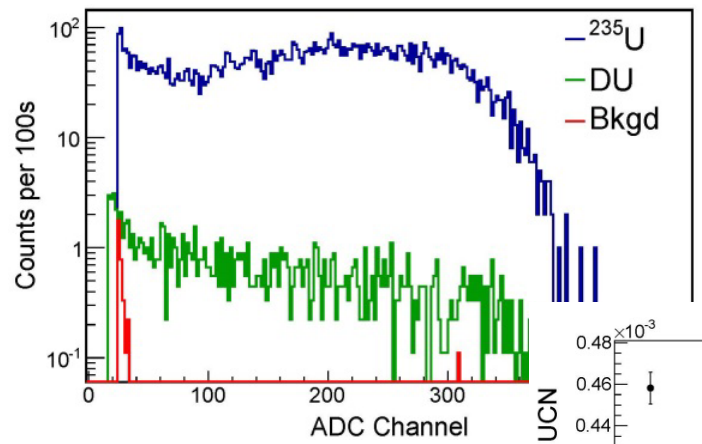


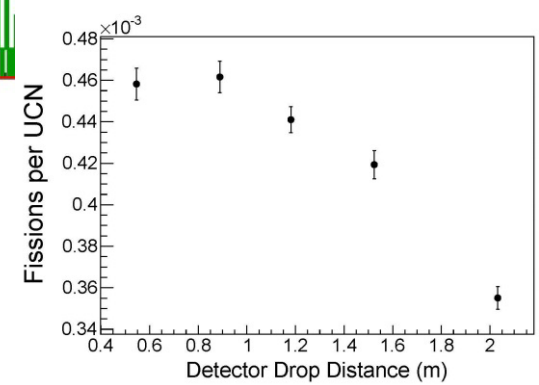
$$V_g = mgz$$
$$\hat{H}\psi_n = E_n \psi_n$$











V. Nesvizhevsky et al., Nature 415 (2002) 297
T. Jenke et al., Nature Phys. 7 (2011) 468
A. R. Young et al.

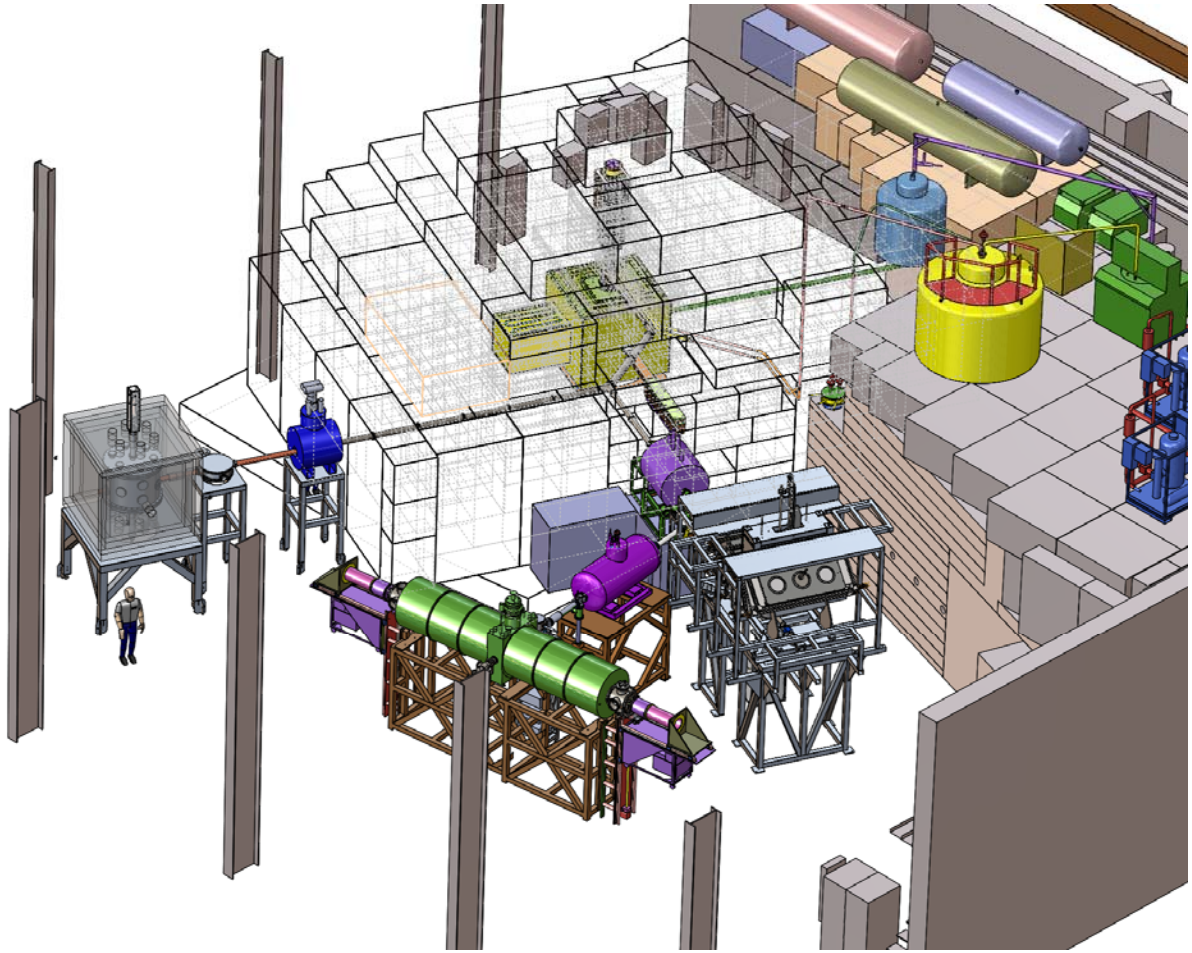
L.J. Broussard et al.

UCN Facility "Wish List"

Ability to run 24/7
(beam currently switched from pRAD)

Ability to run with higher beam currents

Cryogenic plant (2 LHe liquefiers + 3 compressors) = very loud environment



Summary

Broad scope of research using UCN addressing fundamental problems at the forefront of nuclear physics research

Large and active community of users

I acknowledge support under DOE Award Number DE-SC0014622

Extra Slides

The Neutron Lifetime Experiment at LANL

S. Clayton, M. Makela, C. Morris, J. Ramsey, A. Saunders, S. Seestrom, P. Walstrom, Z. Wang (LANL)

D. Bowman, S. Penttila (ORNL)

E. Adamek, W. Fox, A. Holley, M. Hozo, C.-Y. Liu, N. Callahan, D. Salvat, J. Vanderwerp, B. Slaughter, K. Solberg, M. Snow (Indiana U.)

B. Vogelaar (V. Tech)

K. Hickerson (UCLA)

A. R. Young, B. VornDick, E. B. Dees, C. Cude (NCSU)

The UCNA Collaboration

California Institute of Technology

M. Blatnik,, R. Carr, B. W. Filippone, A. Perez-Galvan, S. Slutsky, X. Sun, C. Swank

Indiana University

C.-Y. Liu, D. Salvat

Institut Laue-Langevin

P. Geltenbort

Los Alamos National Laboratory

T. J. Bowles, L. J. Broussard, S. Clayton, S. Currie, G. Hogan, T. M. Ito, M. Makela, C. L. Morris, R. W. Pattie, J. Ramsey, A. Saunders (co-spokesperson), S. Seestrom, S. Sjue, W. Sondheim, T. Womack

NIST

M. P. Mendenhall

North Carolina State University/TUNL

C. Cude-Woods, E. B. Dees, D. G. Phillips II, B. M. VornDick, A. R. Young (co-spokesperson), , J. Wexler, B. A. Zeck

Shanghai Jiao Tong University

J. L. Liu

Tennessee Technological Univeristy

A. T. Holley

Texas A&M University

D. Melconian

University of California, Los Angeles

K. P. Hickerson

University of Kentucky

B. Allgeier, M. A. Brown, S. Hasan, B. Plaster

University of Winnipeg

J. W. Martin

Virginia Polytechnic Institute and State University

X. Ding, M. L. Pitt, R. B. Vogelaar

UCNB / Nab Collaborations

Los Alamos National Laboratory
L. J. Broussard, T. Ito, M. Makela, P. McGaughey, J. Mirabal, C. Morris, R. W. Pattie, J. Ramsey, A. Saunders, S. Sjue, Z. Wang, S. Wilburn, T. Womack, B. Zeck

Oak Ridge National Laboratory
D. Bowman, V. Cianciolo, R. Grzywacz, M. Middlebrook, S. Penttila, K. Rykaczewsk, J. Thomison

Arizona State University
R. Alarcon,A. Barkan, S. Balascuta

University of California, Los Angeles
K. P. Hickerson

Indiana University
A. T. Holley, D. J. Salvat, C.-Y. Liu

University of Kentucky
M. Brown, C. Crawford, B. Plaster, A. Sprow

Karlruhe Institute of Technology
F. Glueck

Universidad Nacional Autónoma de México
L. B. Palos

University of Manitoba
M. Gericke, S. Page

University of Michigan
T. Chupp

University of New Hampshire
J. Calarco, B. Hersman

North Carolina State University
E.B. Dees, J. Hoagland, B. VornDick, A. R. Young

University of Southern Carolina
V. Gudkov

University of Sussex
J. Byrne

University of Tennessee, Knoxville
N. Birge, N. Fomin, G. Greene, E. M. Scott

University of Virginia
P. Alonzi,S. Baessler, M. Bychov, E. Frlez, H. Li, D. Pocanic, A. Salas-Bacci, Z. Tompkins

Virginia Tech
X. Ding, R. B. Vogelaar

University of Winnipeg
D. Harrison, J. Martin

LANL nEDM Collaboration

S. Clayton, S. Currie, T. Ito, M. Makela, C. Morris, R. Pattie Jr.,
J. Ramsey, A. Saunders, S. Sjue, Z.Tang, W. Wei
Los Alamos National Laboratory

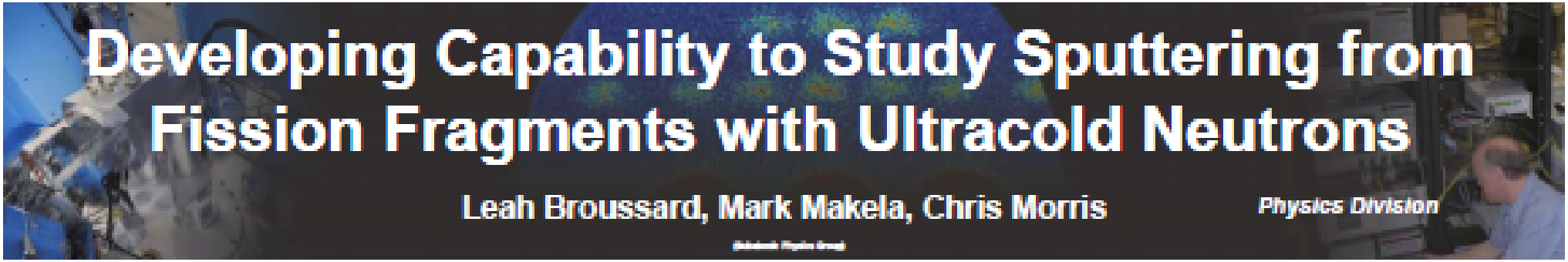
C.-Y. Liu, J. Long, W. Snow
Indiana University

B. Plaster
University of Kentucky

S. K. Lamoreaux
Yale University

E. Sharapov
Joint Institute of Nuclear Research

UCNS


Developing Capability to Study Sputtering from Fission Fragments with Ultracold Neutrons
Leah Broussard, Mark Makela, Chris Morris
Physics Division

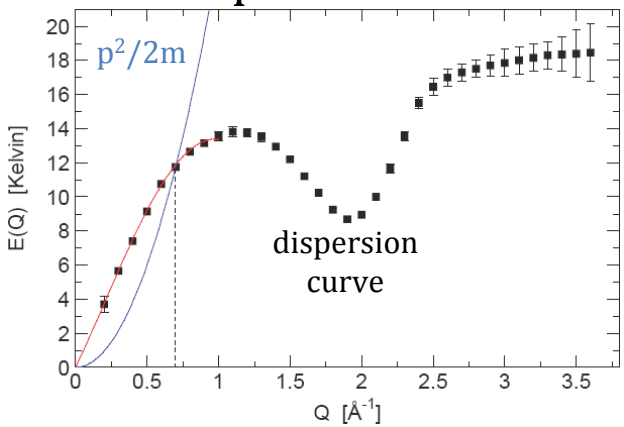
Cold vs. Ultracold

mK 1 – 300 K

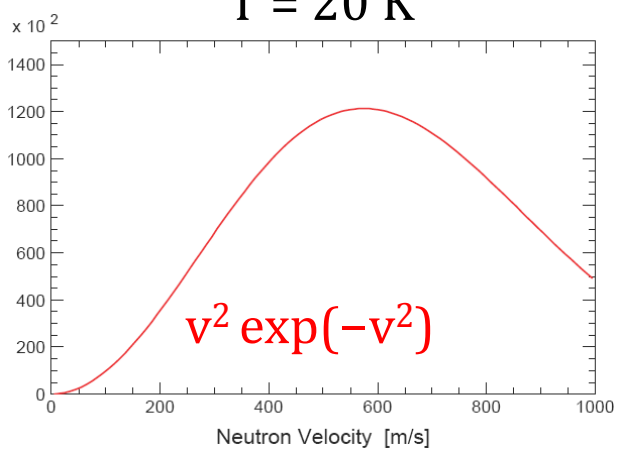
ultracold cold fast

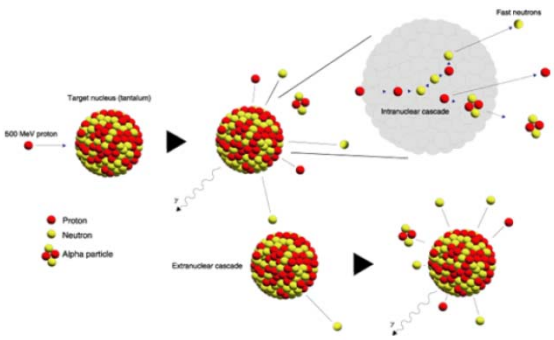
< 350 neV 0.05–25 meV MeV

Superfluid ^{4}He

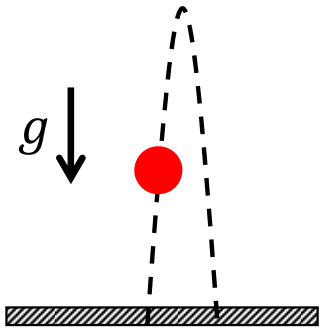


T = 20 K

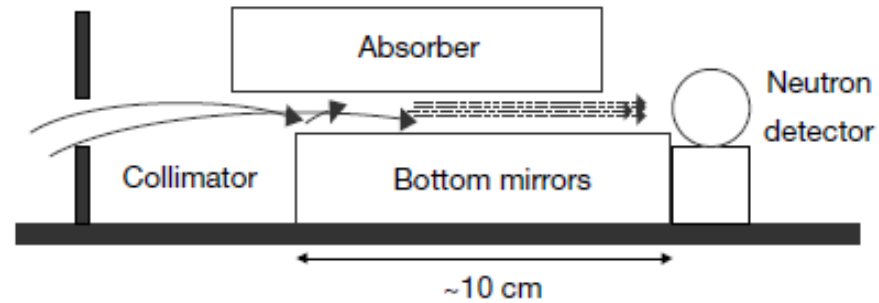


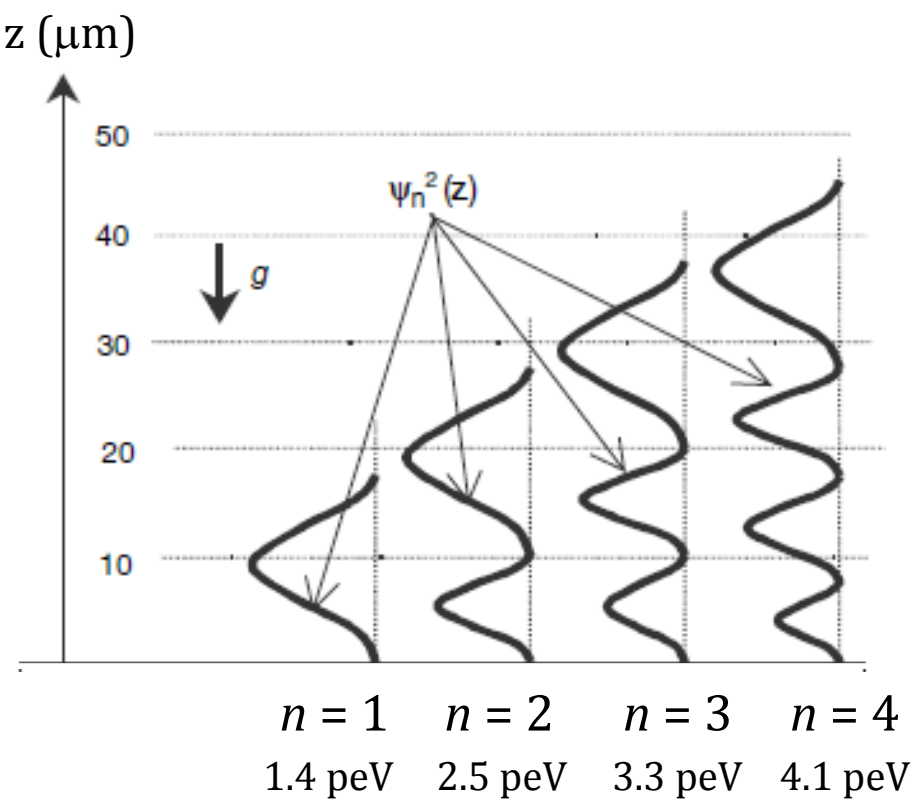


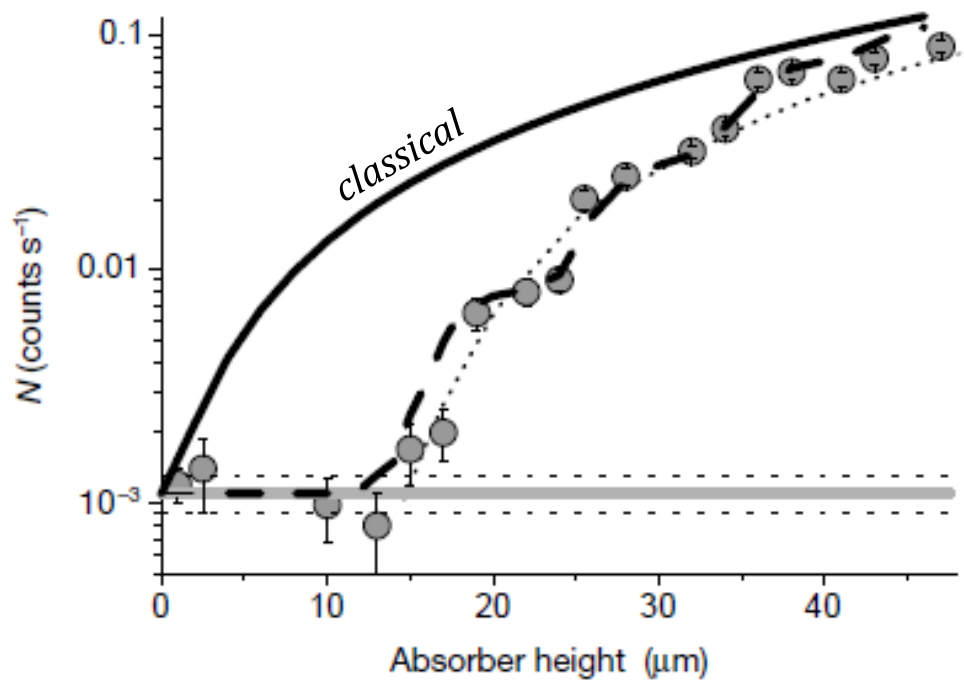
Gravity and Short-Range Interactions



$$V_g = mgz$$
$$\hat{H}\psi_n = E_n \psi_n$$







V. Nesvizhevsky et al., Nature 415, 297 (2002)

Gravity and Short-Range Interactions

Spectroscopy

$\Delta E_{pq} = E_p - E_q$

New Short-Range Interactions:
Chameleons, Axions, …

Weak Equivalence Principle:

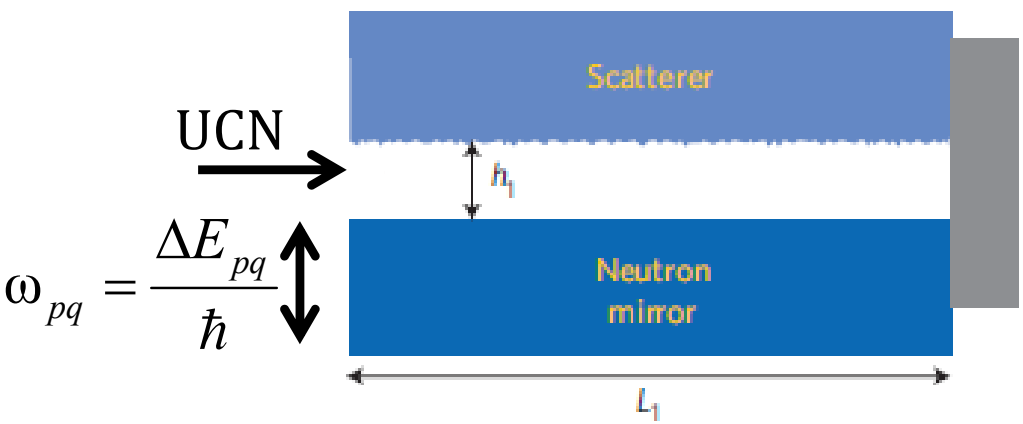
$$\left(-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + mgz\right)\psi_n = E_n\psi_n$$

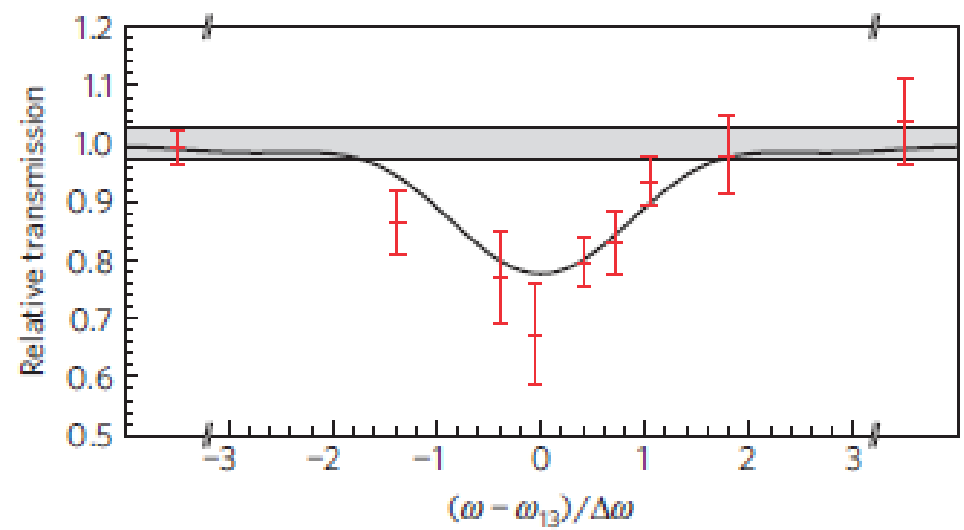
Neutrons $q = 0$

No EM backgrounds !

Casimir, van der Waals

"Gravitational Resonance Spectroscopy"



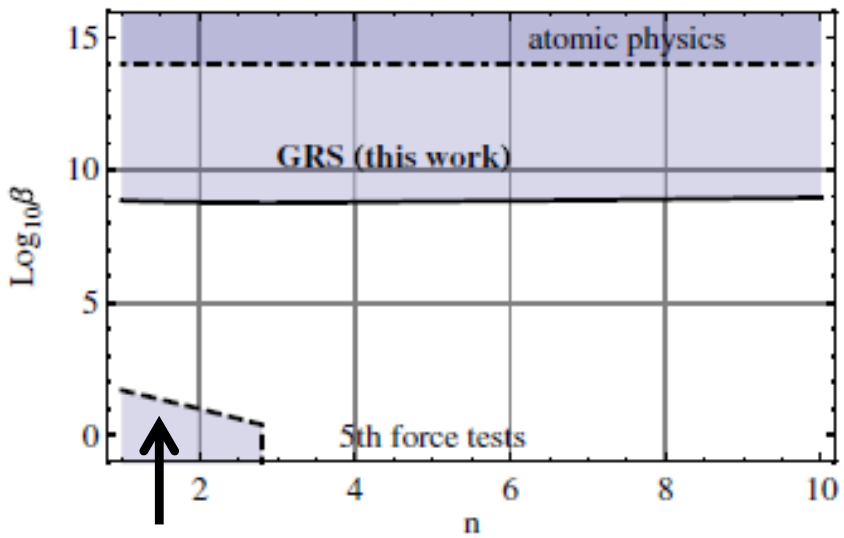


T. Jenke et al., Nature Phys. 7, 468 (2011)

Gravity and Short-Range Interactions

Dark Energy Chameleon Fields

$$V_{\text{eff}} = V(\Phi, n) + e^{\beta\Phi/M_{\text{Pl}}}\rho$$

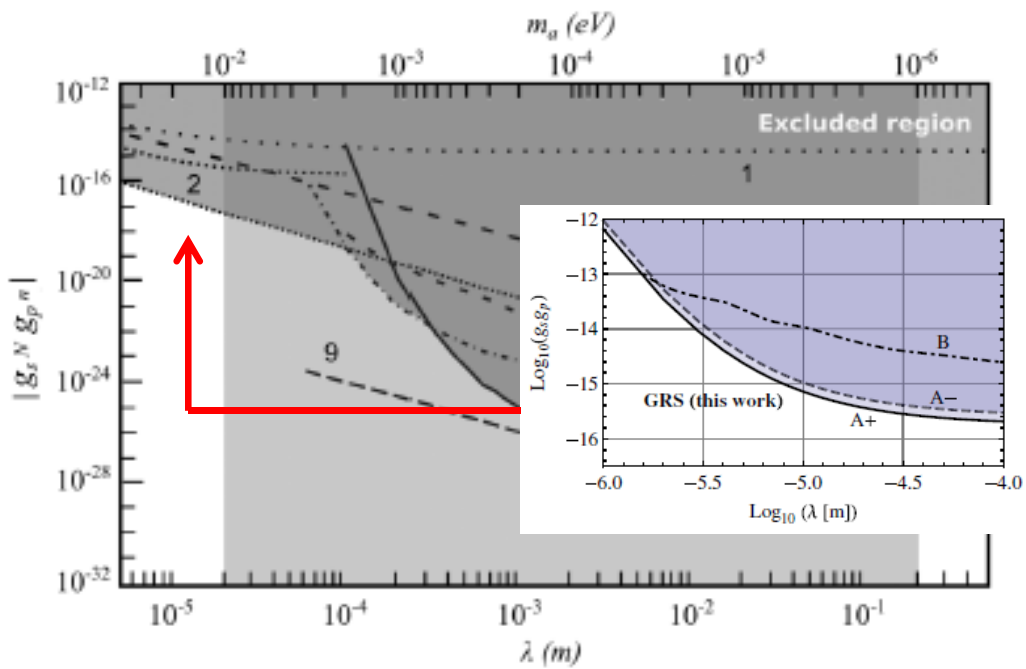


torsion pendulum

KE.00006: T. Sakuta
KE.00007: S. Saiba
KE.00008: E. Dees
KE.00009: M. Kitaguchi

Axion Dark Matter

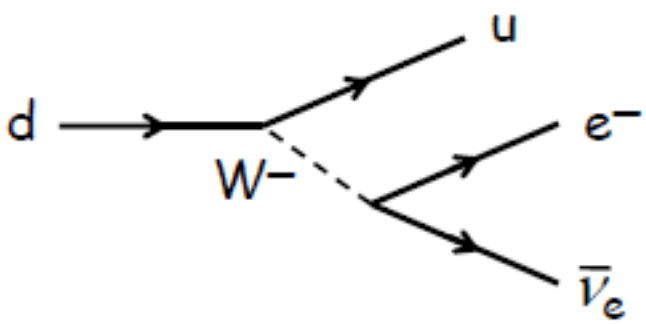
$$V(\vec{r}) = \hbar^2 g_s g_p \frac{\vec{\sigma}\cdot\vec{r}}{8\pi m_M r}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$



Gravity as a practical tool ... →

T. Jenke et al., PRL 112, 151105 (2014); K. Tullney et al., PRL 111, 100801 (2013); A.N. Ivanov et al., PRD 87, 105013 (2013); T. Jenke et al., arXiv:1208.3875

Neutron β-Decay: Lifetime



"V – A" Law

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \langle p | J^\mu | n \rangle L_\mu$$

$$= \bar{u}_e \gamma_\mu (1 - \gamma_5) u_{\bar{\nu}}$$

$$\langle p(p') | \bar{u} \gamma^\mu d | n(p) \rangle \equiv \bar{u}_p(p') \left[f_1(q^2) \gamma^\mu - i \frac{f_2(q^2)}{M} \sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M} q^\mu \right] u_n(p),$$

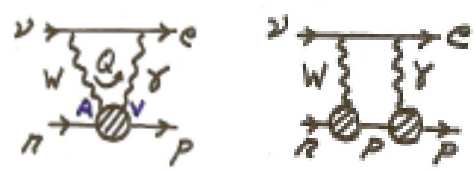
$$\langle p(p') | \bar{u} \gamma^\mu \gamma_5 d | n(p) \rangle \equiv \bar{u}_p(p') \left[g_1(q^2) \gamma^\mu \gamma_5 - i \frac{g_2(q^2)}{M} \sigma^{\mu\nu} \gamma_5 q_\nu + \frac{g_3(q^2)}{M} \gamma_5 q^\mu \right] u_n(p)$$

Parameters:

$\lambda = g_A / g_V$

V_{ud}

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

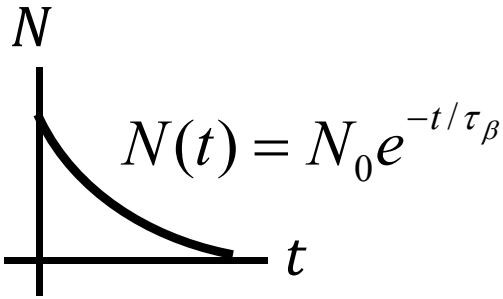


What if there are Scalar, Tensor ?

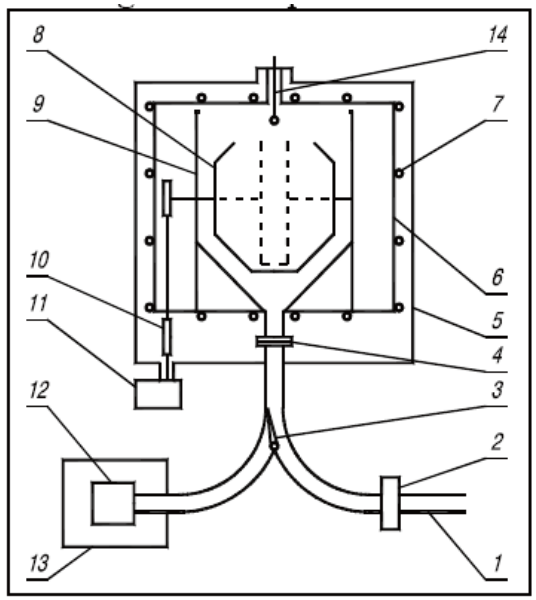
W. Marciano and A. Sirlin, PRL 96, 032002 (2006);
W. Marciano, talk at Santa Fe Lifetime Workshop (2012)

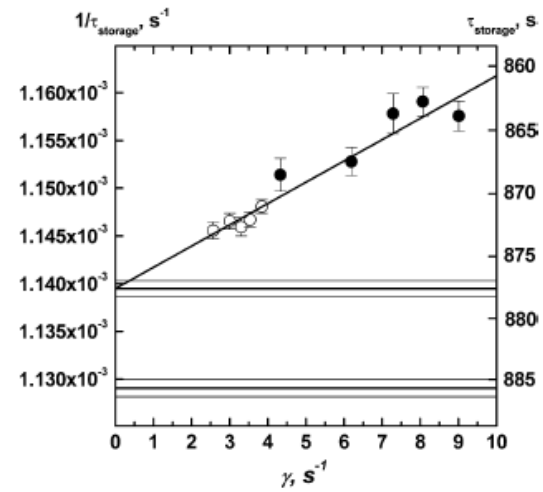
Lifetime: Techniques

"Count the Living"



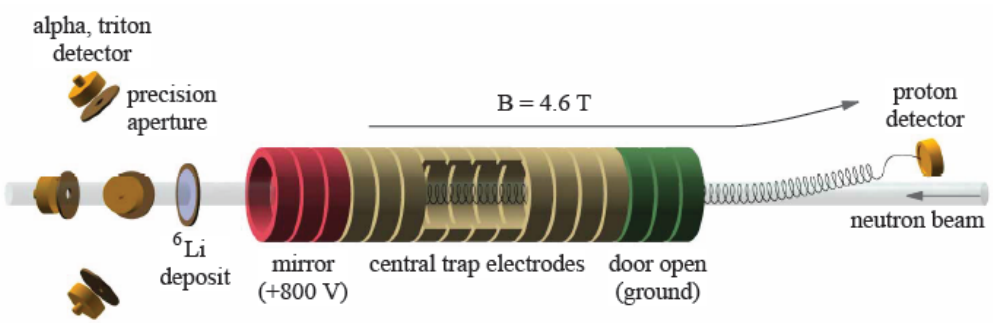
$$N(t) = N_0 e^{-t/\tau_\beta}$$

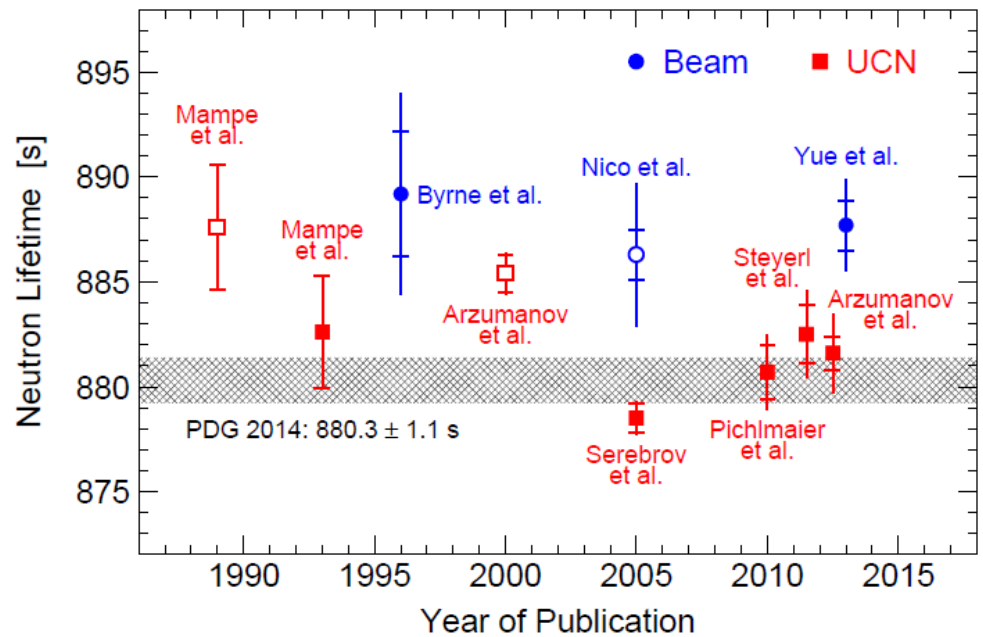




"Count the Dead"

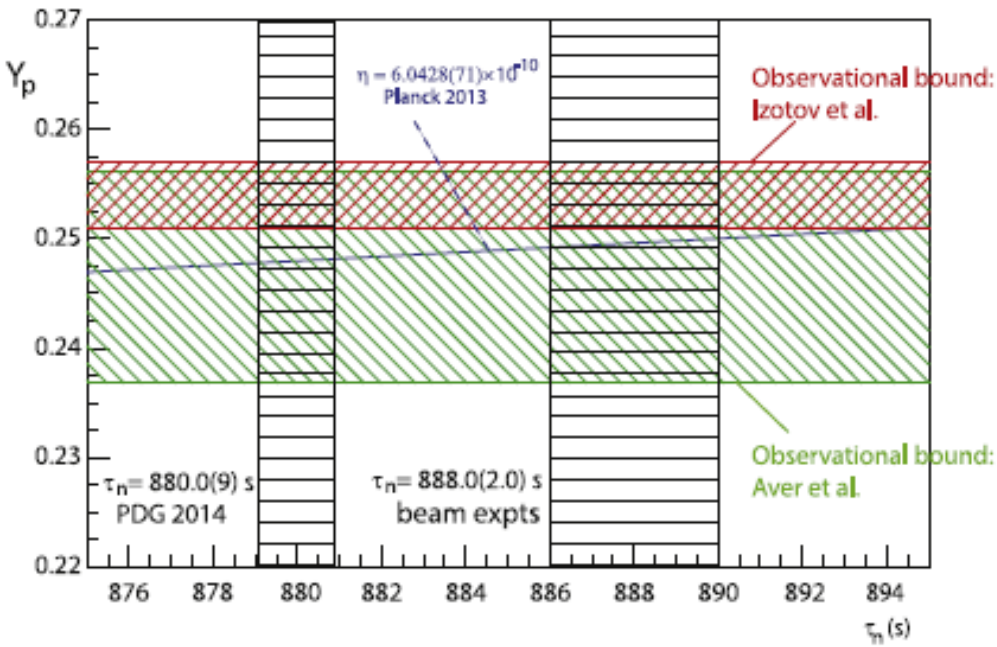
$$|\dot{N}| = N_0 / \tau_\beta$$





A. Serebrov et al., Phys. Lett. B 605, 72 (2005); J.S. Nico et al., PRC 71, 055502 (2005); A. Yue et al., PRL 111, 222501 (2013)

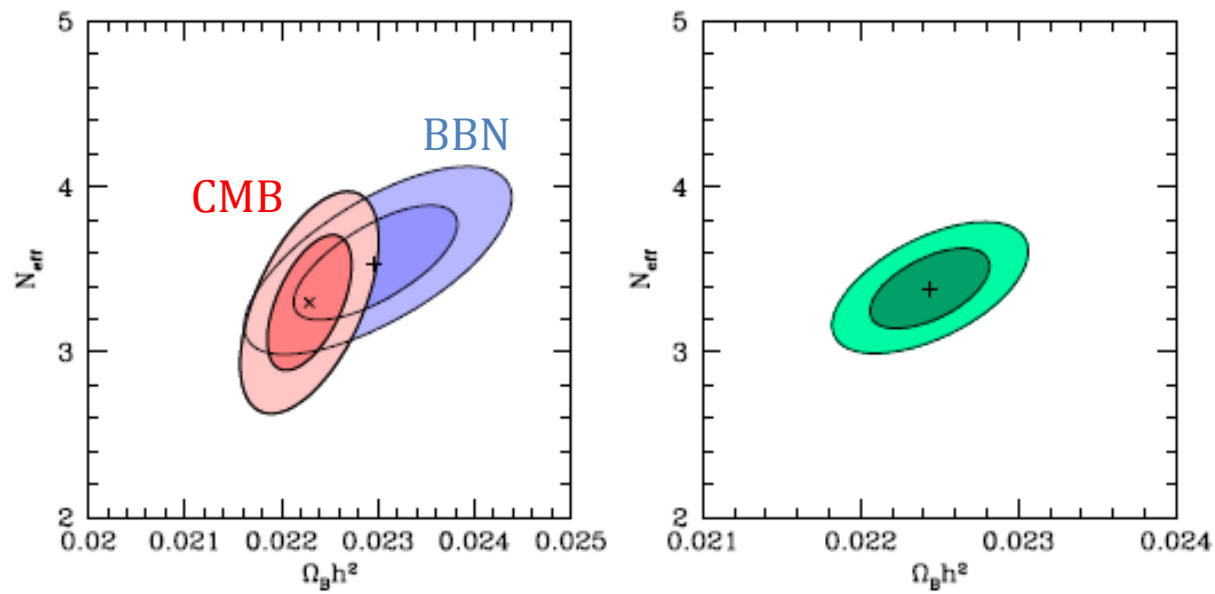
Lifetime: BBN and N_{eff}



$$\left(\frac{\Delta Y_p}{Y_p}\right)_{\text{BBN}} = 0.39\frac{\Delta\eta}{\eta} + 0.73\frac{\Delta\tau_n}{\tau_n} + 0.19\frac{\Delta N_{\text{eff}}}{N_{\text{eff}}} - 0.04\left(\frac{\Delta N_{\text{eff}}}{N_{\text{eff}}}\right)^2$$

Standard Model: $N_{\text{eff}} = 3.046$

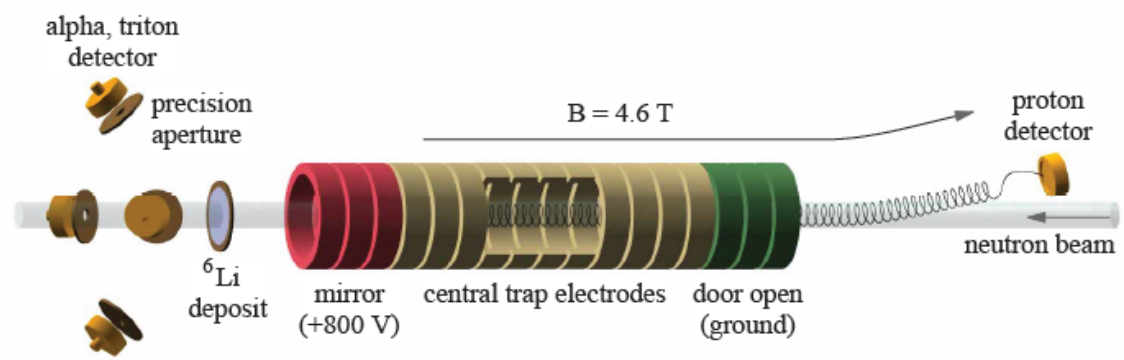
$\Delta\tau \sim 8$ s $\rightarrow$ $\Delta N_{\text{eff}} \sim 0.12$

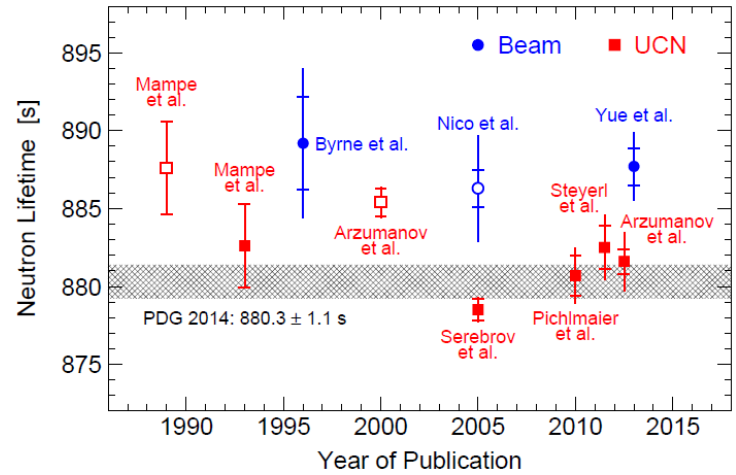


A. Coc et al., arXiv:1403.6694;
A.R. Young et al., J. Phys. G (in press)

K. Nollett, talk at ACFI Workshop on "Measuring the Neutron Lifetime"; update of arXiv:1312.5725

Lifetime: Beam

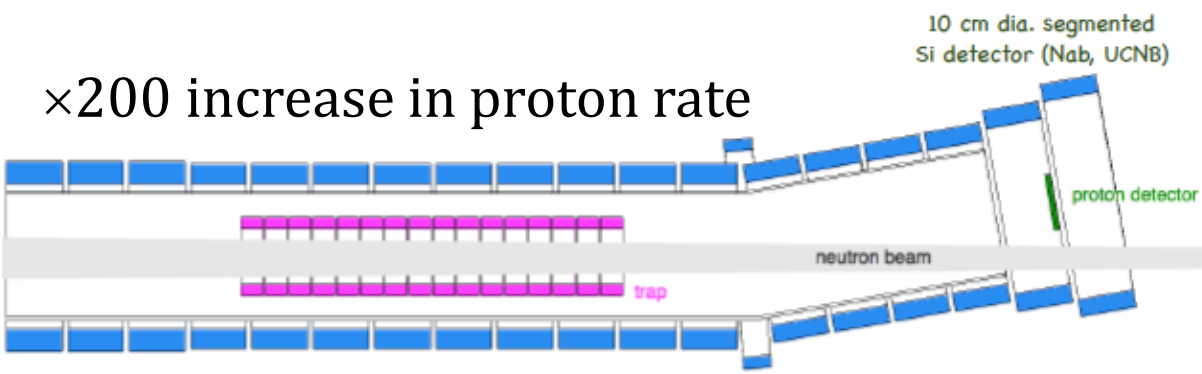




BL2 Experiment NIST: $\delta\tau_n \sim 1$ s

BL3 Experiment NIST: $\delta\tau_n < 0.3$ s

×200 increase in proton rate



FE.00006: K. Mishima
FE.00007: G. Tanaka
FE.00008: J. Mulholland
FE.00011: T. Yamada
KE.00010: R. Sakakibara

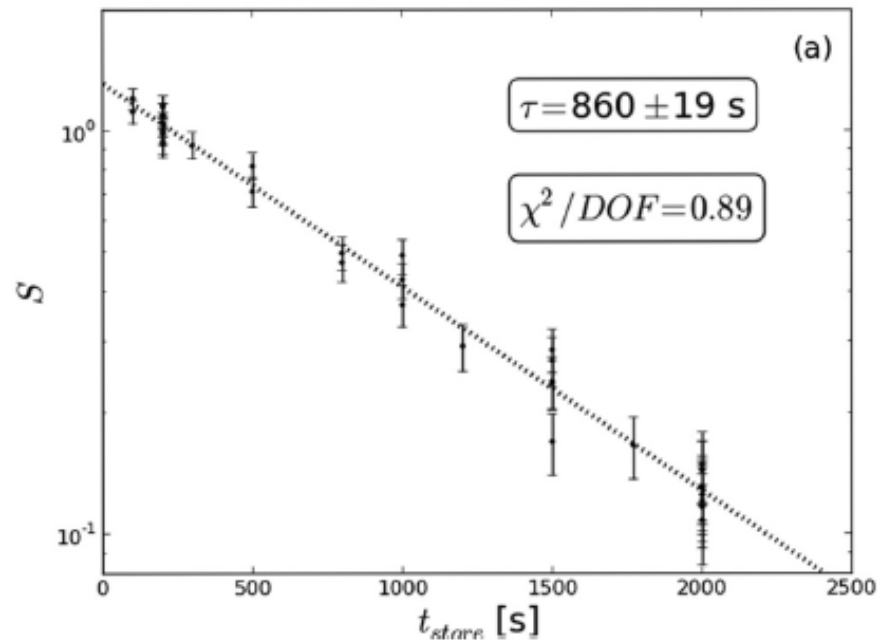
A. Yue et al., PRL 111, 22 (2013); J.S. Nico et al., PRC 71, 055502 (2005);
F. Wietfeldt talk at ACFI Workshop on "Measuring the Neutron Lifetime"

Lifetime: UCN Storage

Material-wall UCN storage experiments

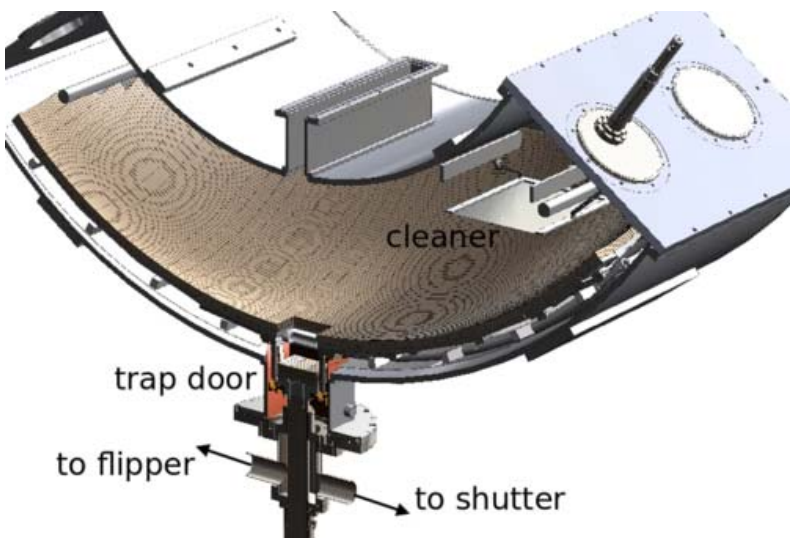
$$\tau_s^{-1} = \tau_\beta^{-1} + \tau_w^{-1} + \tau_0^{-1}$$

$$\tau_w^{-1} = \tau_u^{-1} + \tau_c^{-1} + \tau_{sb}^{-1} + \tau_g^{-1}$$



Next-generation: (nearly) eliminate wall losses !

UCNτ



ED.00008: S. Seestrom
FE.00004: D. Salvat
FE.00005: A. Holley
KE.00011: R. Pattie
KE.00012: Z. Wang
ME.00013: N. Callahan

D. Salvat et al., PRC 89, 052501(R) (2014)

Neutron β-Decay: Angular Correlations

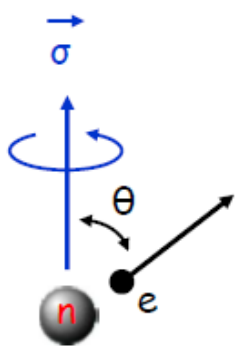
Differential distribution:

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

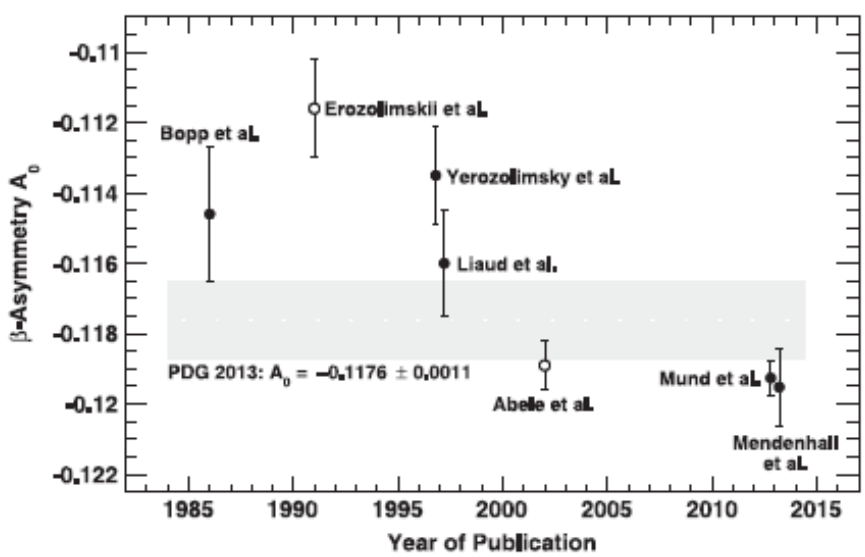
BSM

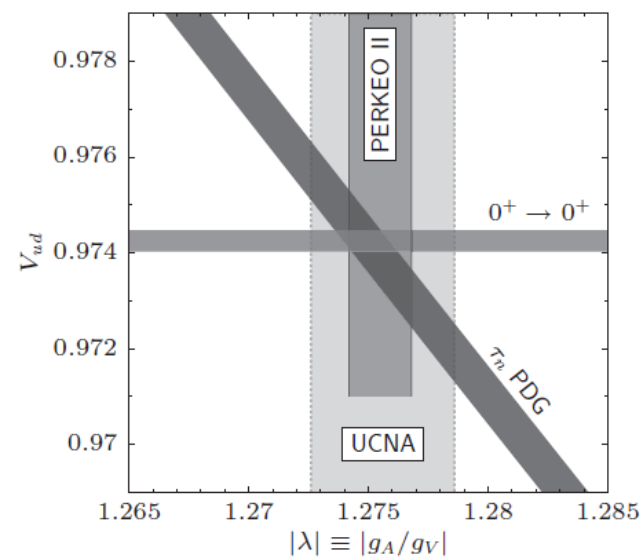
λ BSM λ BSM

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

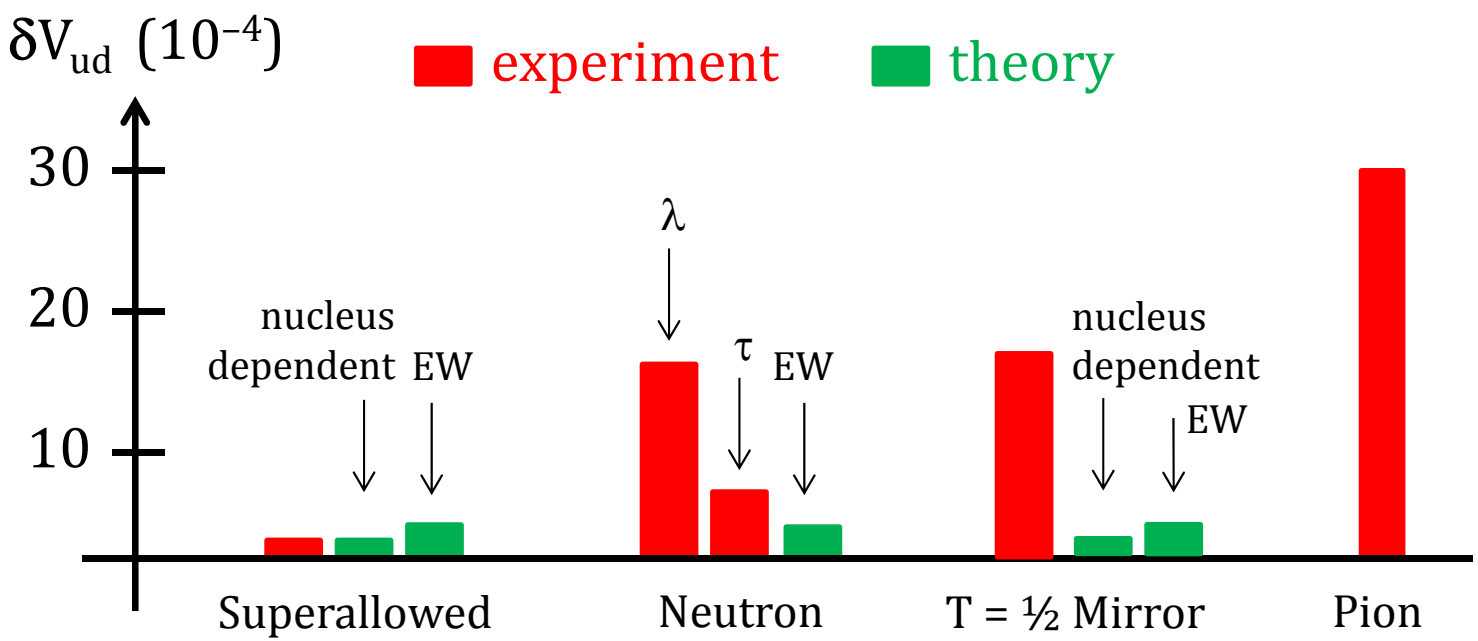


$$A_0 = -2\frac{|\lambda|(|\lambda|-1)}{1+3\lambda^2}$$





V_{ud}



PDG τ : $\sqrt{\chi^2/\nu} = 1.4$

PDG λ : $\sqrt{\chi^2/\nu} = 1.9$

$$\frac{|V_{ud}^{0^+\to 0^+}|^2}{|V_{ud}^{n\to pe\bar{\nu}}|^2} = 1 + b_{0^+}^{\mathrm{BSM}}\frac{I_1(\tilde{x}_0)}{I_0(\tilde{x}_0)} - b_n^{\mathrm{BSM}}\left(\frac{I_1(x_0)}{I_0(x_0)} - \frac{6\lambda^2}{1+3\lambda^2}c\right)$$

What is needed?

$\delta a/a, \delta A/A < 0.1\%$

$\delta\tau < 0.3$ s

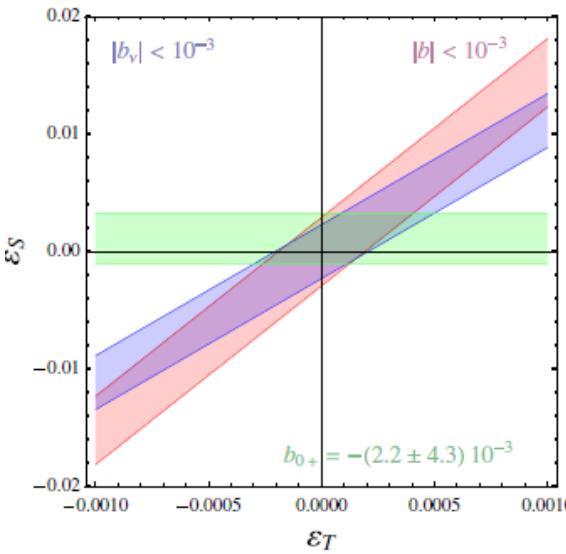
T. Bhattacharya et al., PRD 85, 054512 (2012)

Angular Correlations: BSM Physics

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

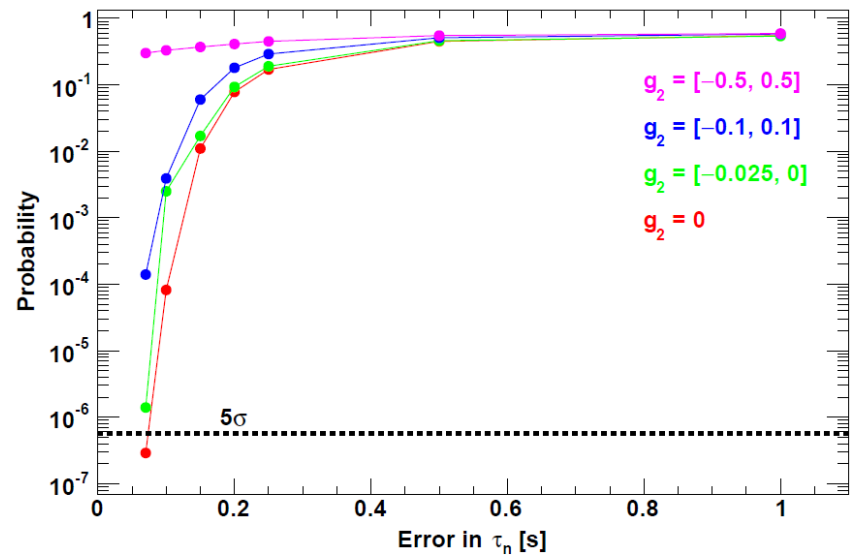
Nab: $\delta b \sim 3 \times 10^{-3}$

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



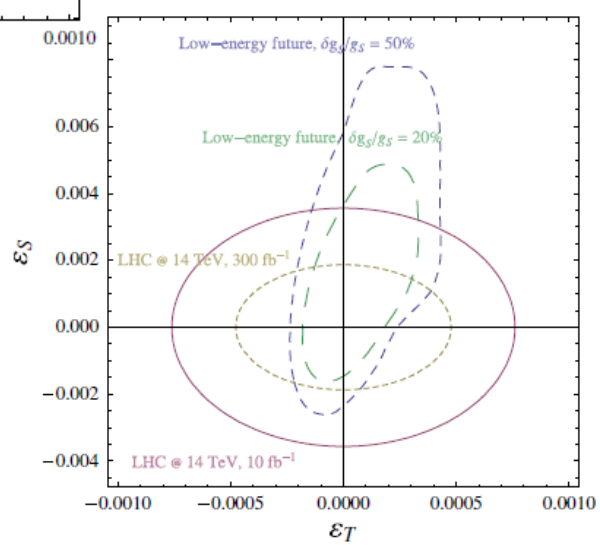
b, b_ν
(disentangled)

"*a*", "*A*" to 0.03% + τ_n to …



Neutrons
vs. LHC

$pp \to e\nu$ + X



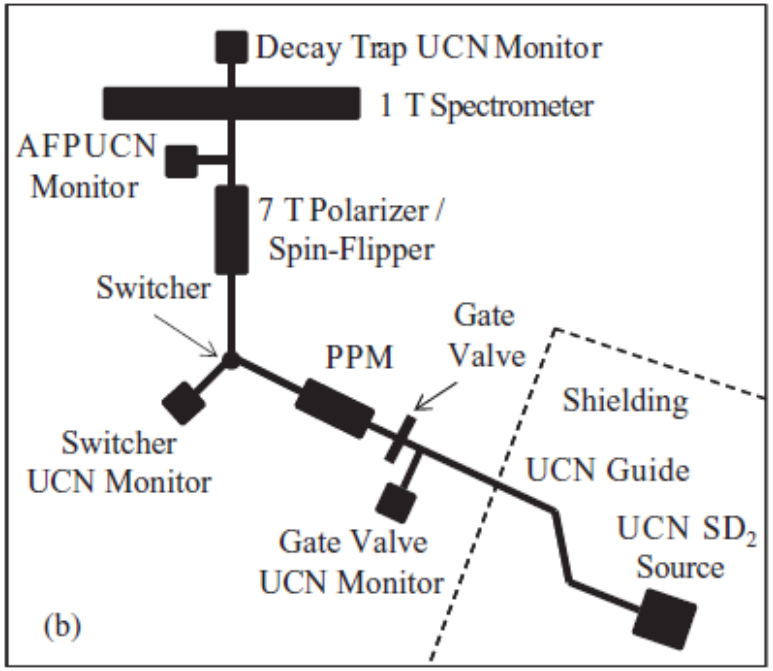
FE.00010: K. Hickerson

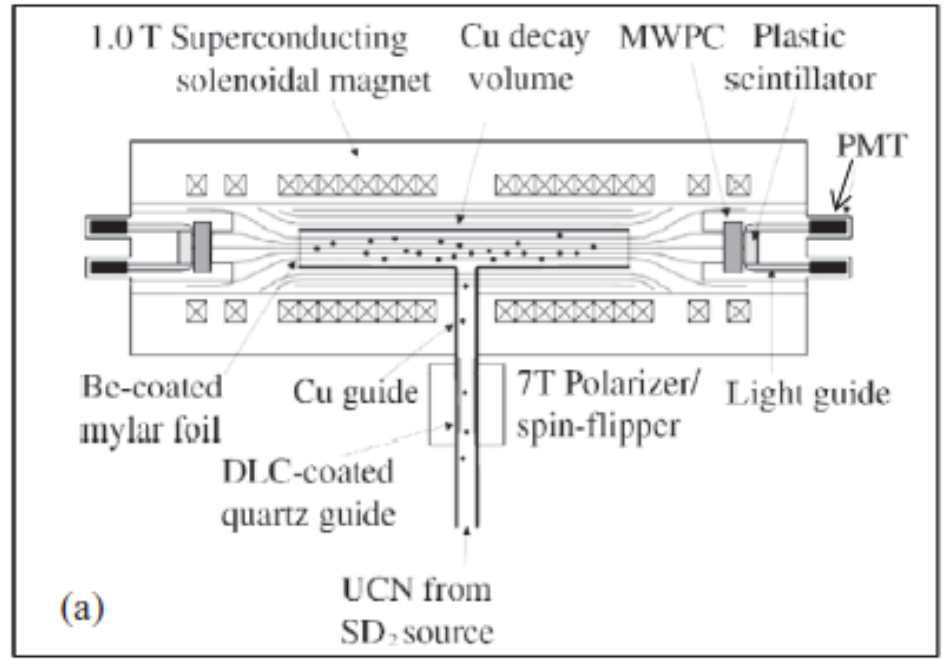
T. Bhattacharya et al., PRD 85, 054512 (2012);
S. Gardner and B. Plaster, PRC 87, 065504 (2013)

BP, S.K.L. Sjue, and A.R. Young, in preparation

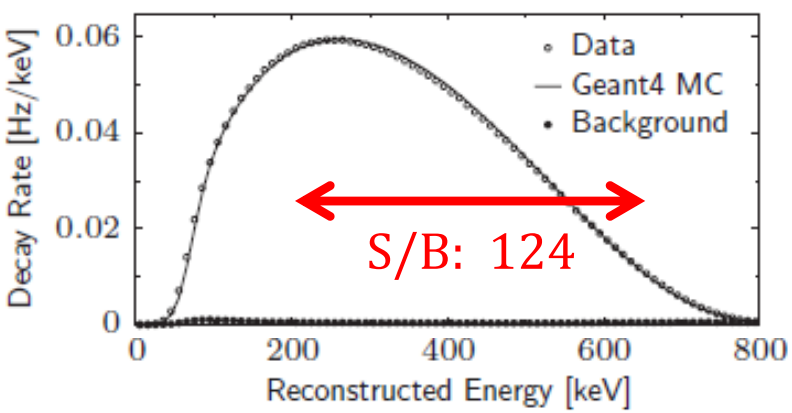
A_0

UCNA at LANL





2010: 0.94%



2011 – 2013

Statistics ~ 0.45%
Systematics < 0.5%

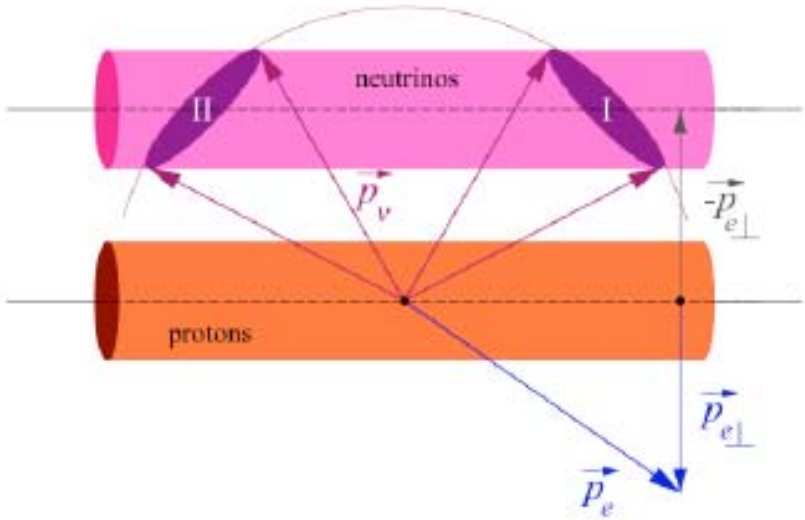
DNP Thesis Prize: M.P. Mendenhall

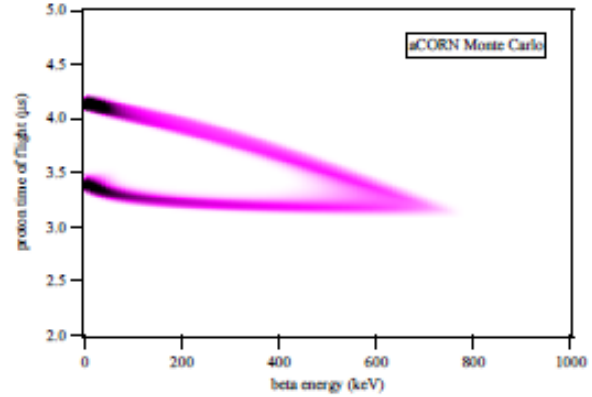
FE.00002: M. Brown
FE.00003: A. Saunders
ME.00006: X. Ding

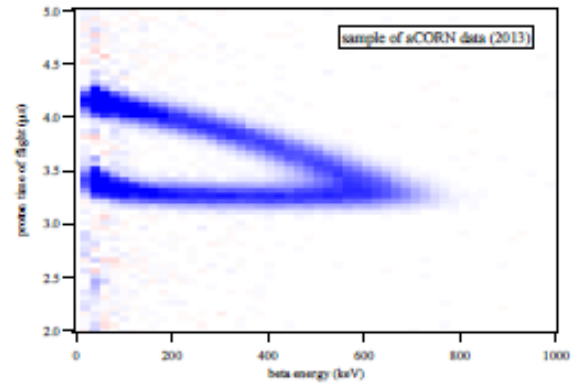
M.P. Mendenhall et al. PRC 87, 032501(R) (2013);
BP et al., PRC 86, 055501 (2012)

a_0

aCORN at NIST



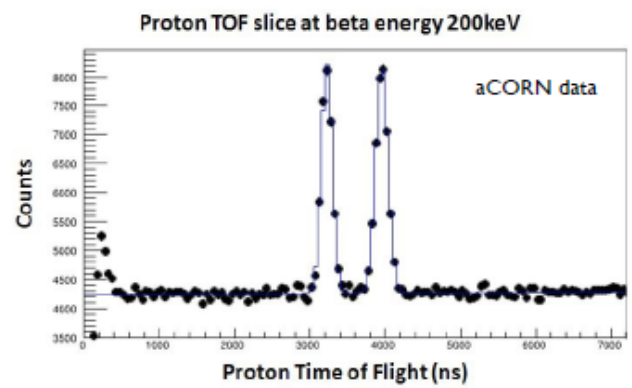




2013: ~3%

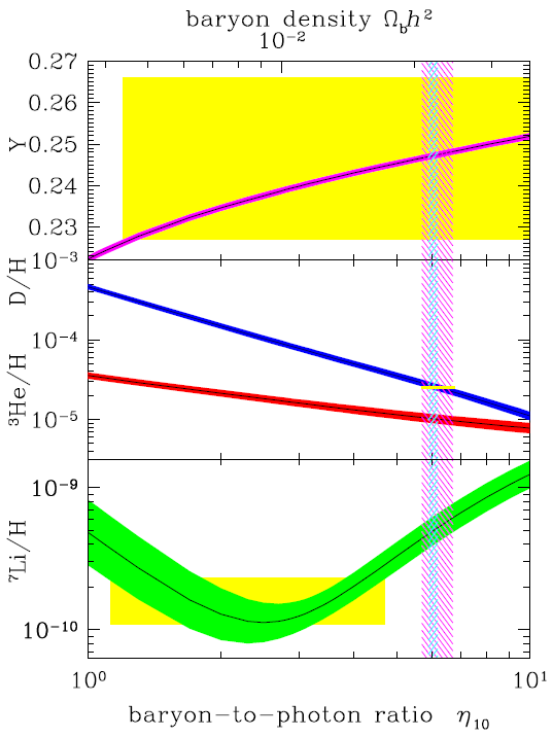
moving to new guide hall

2015: ~1%



Courtesy: F. Wietfeldt

The Problem of the Baryon Asymmetry



$\eta \neq 0$

How can this be ?

Fun tidbit:
1975 Nobel Peace Prize!

Baryon Number Violation

C and CP Violation

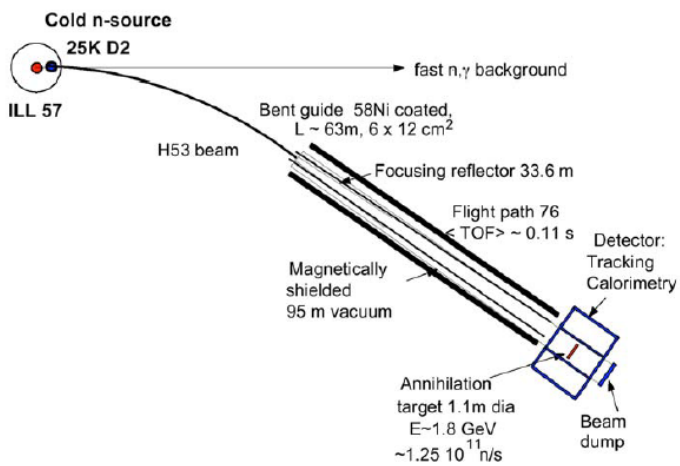
Interactions out of Thermal Equilibrium

B Violation: n-$\bar{n}$ Oscillations

Canonical idea: 2×2 matrix

$$i\hbar\partial_t \begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta \\ \delta & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \xrightarrow{\delta << \Delta E = E_n - E_{\bar{n}}} \boxed{P_{\bar{n}}(t) \sim \frac{\delta^2}{(\Delta E)^2} \sin^2(\Delta E\, t) \sim \delta^2 t^2}$$

ILL (1994): $\tau > 8.6 \times 10^7$ s



10^{11}/s; $t \sim 0.1$ s

European Spallation Source:

^{58}Ni guide $\rightarrow$ m~6 super mirrors

Increase in flight path

Gain Factors of 100–1000

But … also new idea !

n and $\bar{n}$ of opposite spins in an external magnetic field have same energy !

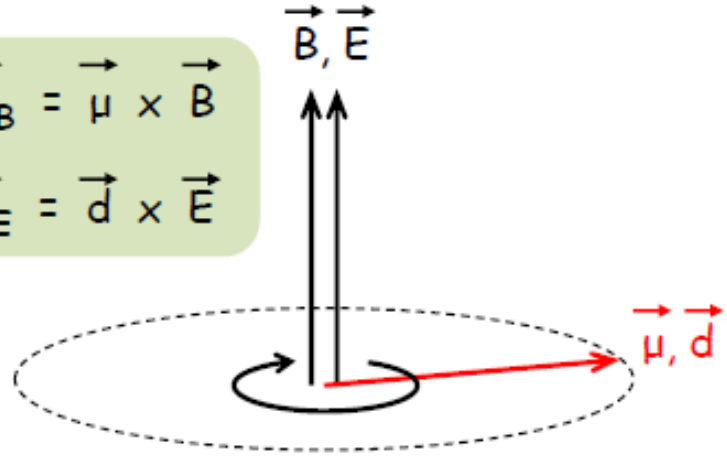
KE.00001: S. Gardner

D.G. Phillips et al., arXiv:1410.1100 [hep-ex] ;
S. Gardner and E. Jafari, arXiv:1408.2264

CP Violation: Neutron EDM

$$\vec{\tau}_B = \vec{\mu} \times \vec{B}$$

$$\vec{\tau}_E = \vec{d} \times \vec{E}$$



$$h\nu_{\uparrow\uparrow} = -2\mu B - 2dE$$

$$h\nu_{\uparrow\downarrow} = -2\mu B + 2dE$$

$$d = -\frac{h\Delta\nu}{4E}$$

Sensitivity per measurement cycle:

$$\delta d_n \sim \frac{1}{\left|\vec{E}\right| T\sqrt{N}}$$

ILL:

E ~ 10 kV/cm

T ~ 130 s

N ~ 14000

density ~ 0.7/cm^3

Stat: 1.6 × 10^{-26} e-cm

Therefore, for ~10^{-28} e-cm:

E ~ 5×

T ~ 4×

N ~ 25×

Minimum: Higher UCN densities !

ME.00001: M. Makela
ME.00002: T. Ito
ME.00003: E. Pierre
ME.00004: J. Martin

Worldwide Effort: ~10 Experiments

Experiment	UCN Source	Cell	Measurement Technique	σ_d (10^{-28} e·cm)
CryoEDM (ILL)	Superfluid ^{4}He	^{4}He	Ramsey technique for ω External SQUID magnetometers	Phase 1 ≈ 50 Phase 2 < 5
PNPI (ILL)	ILL turbine PNPI/Solid D_2	Vacuum	Ramsey technique for ω $\vec{E} = 0$ cell for magnetometer	Phase 1 < 100 Phase 2 < 10
Crystal (ILL)	Cold neutrons	Solid	Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vacuum	Ramsey technique for ω External Cs and $^3\vec{\text{He}}$ magnetometers Possible Hg or Xe comagnetometer	Phase 1 ≈ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vacuum	Under construction Similar to PSI EDM	< 5
nEDM (SNS)	Superfluid ^{4}He	^{4}He	^{3}He capture for ω ^{3}He comagnetometer SQUIDS & Dressed spins	< 5
RCNP Osaka	Superfluid ^{4}He	Vacuum	Phase I	< 50
TRIUMF	Superfluid ^{4}He	Vacuum	Phase II	< 5
JPARC	Solid D_2	Vacuum	Under development	< 5
LANL	Solid D_2	Vacuum	R&D	~30

Differences in experimental techniques :

- Measure ω or accumulated phase $\phi = \omega t$?
- Magnetic field monitoring ? "Co-magnetometer" ?
- UCN production / transport ?

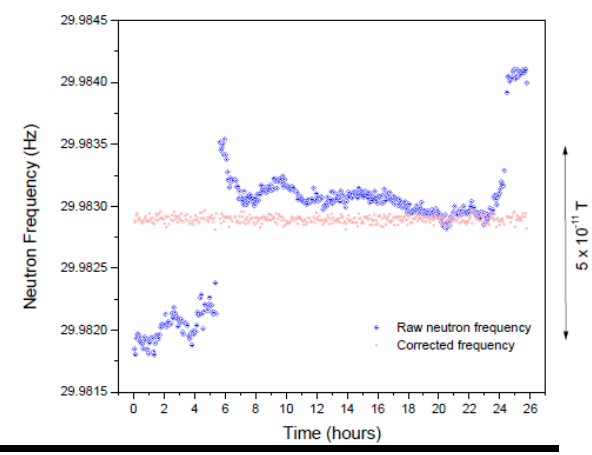
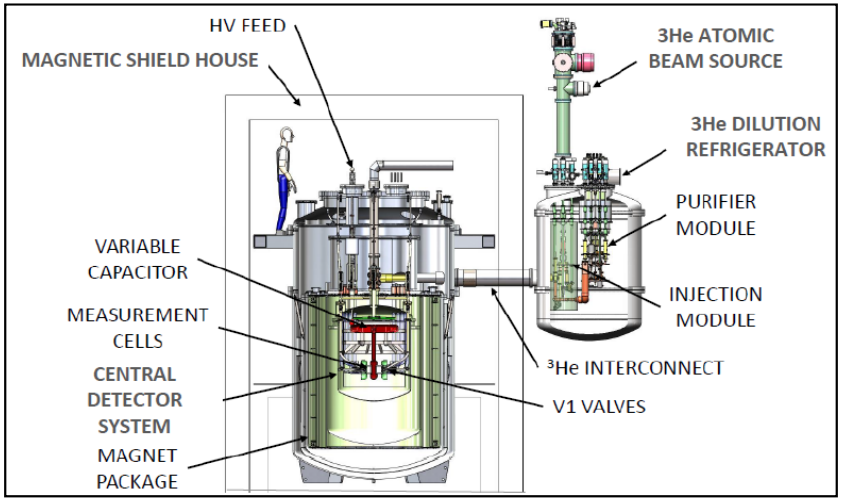
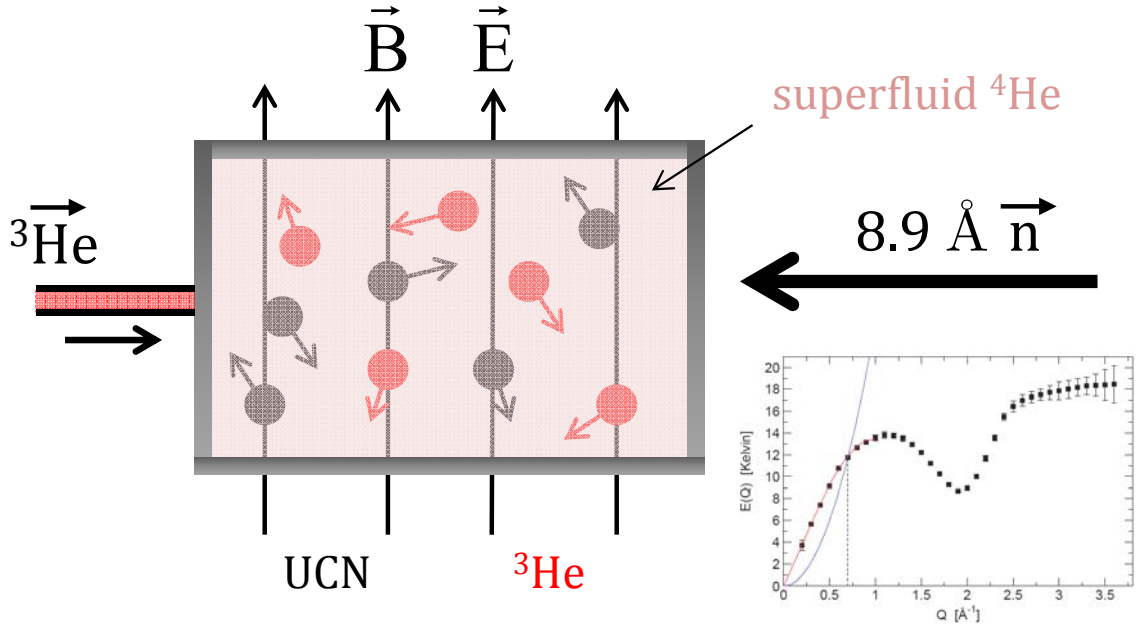
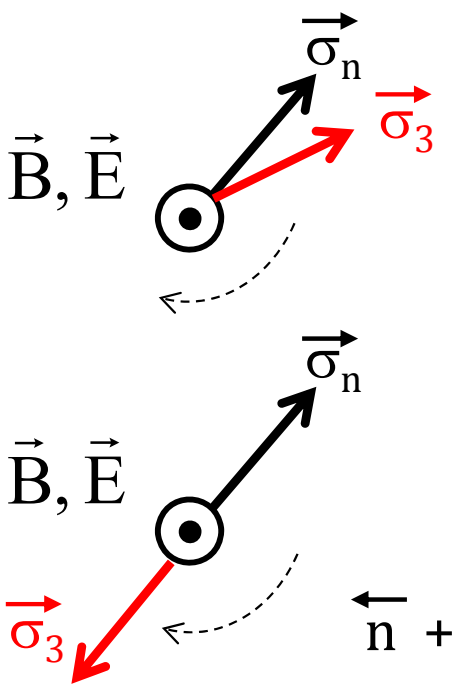


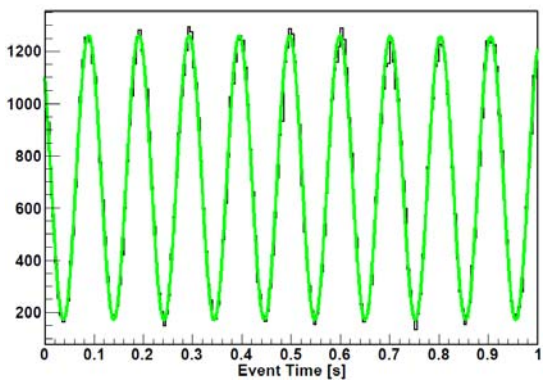
Table from: B. Filippone et al., SNS nEDM Experiment Position Paper

SNS nEDM Experiment









$\overleftarrow{n} + {}^3\overrightarrow{He} \rightarrow p + T$

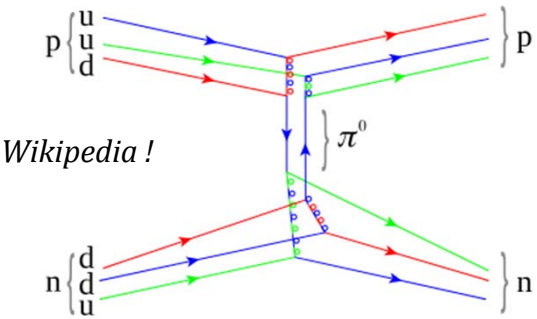
ED.00006: A. Reid
ED.00007: R. Dipert
ME.00010: C. Swank
ME.00011: N. Nouri
ME.00012: S. Slutsky

Strong interaction →

R. Golub and S.K. Lamoreaux, Phys. Rept. 237, 1 (1994)

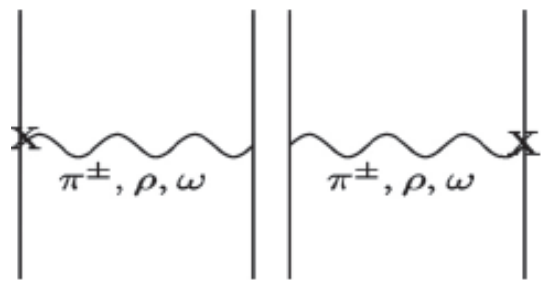
Hadronic Parity Violation

Parity Conserving



Wikipedia !

Parity Violating



Weak Couplings

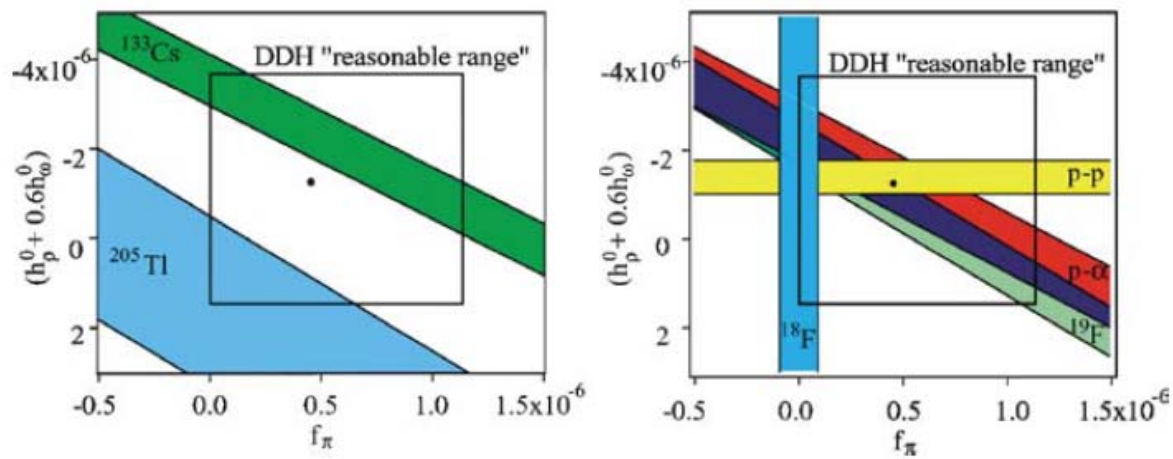
$$f_\pi^{(1)}, h_\rho^{(0)}, h_\rho^{(1)}, h_\rho^{(2)}, h_\omega^{(0)}, h_\omega^{(1)}$$

DDH: Quark Model + SU(6)

→ "DDH Reasonable Range"

PV coupling	DDH range	DDH best value
h_π^1	$0 \to 30$	$+12$
h_ρ^0	$30 \to -81$	-30
h_ρ^1	$-1 \to 0$	-0.5
h_ρ^2	$-20 \to -29$	-25
h_ω^0	$15 \to -27$	-5
h_ω^1	$-5 \to -2$	-3

All values are quoted in units of $g_\pi = 3.8 \times 10^{-8}$.



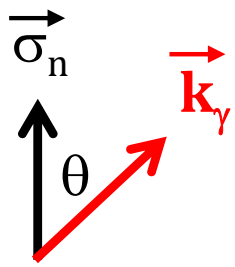
B.R. Holstein, J. Phys. G 36, 104003 (2009);
J.S. Nico and W.M. Snow, Annu. Rev. Nucl. Part. Sci. 55, 27 (2005)

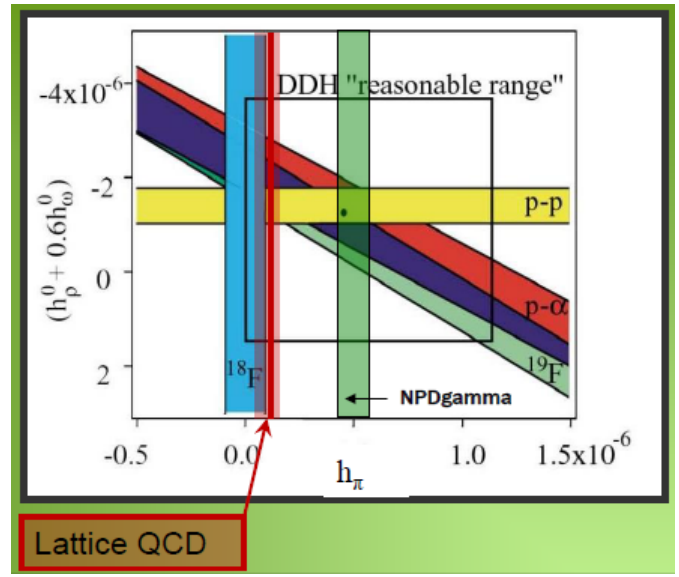
Hadronic Parity Violation: NPDGamma

$$\vec{n} + p \rightarrow d + \gamma$$

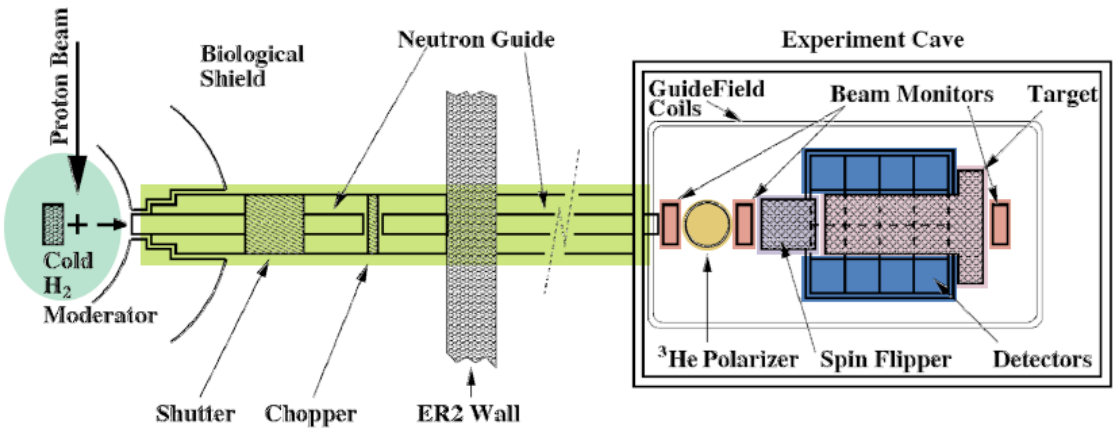
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

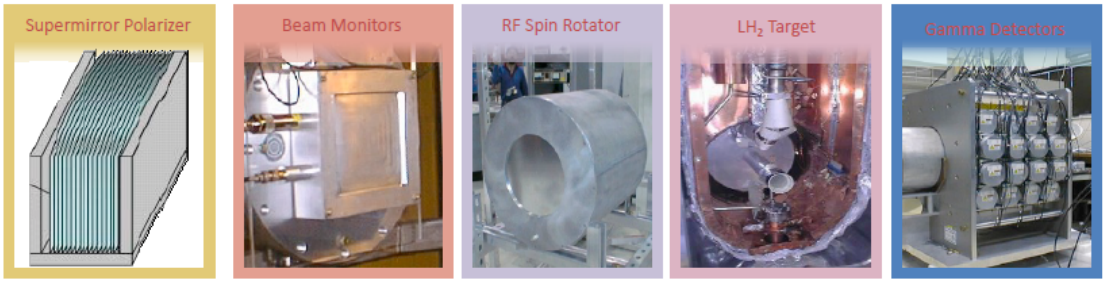
$$A_\gamma^{\mathrm{DDH}} \approx -0.11 f_\pi$$

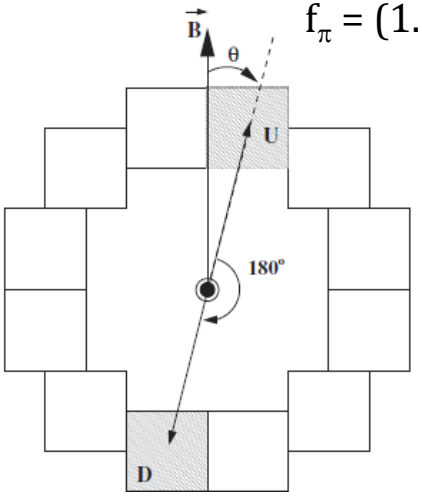




J. Wasem, PRC 85, 022501(R) (2012)
$f_\pi = (1.099 \pm 0.505 \pm 0.061) \times 10^{-7}$







NPDGamma Sensitivity:

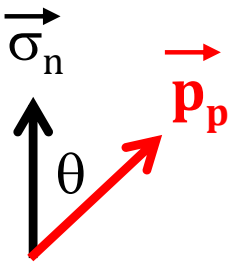
$\delta A_\gamma \sim 1 \times 10^{-8}$

KE.00003: D. Blyth

Hadronic Parity Violation: n-^{3}He

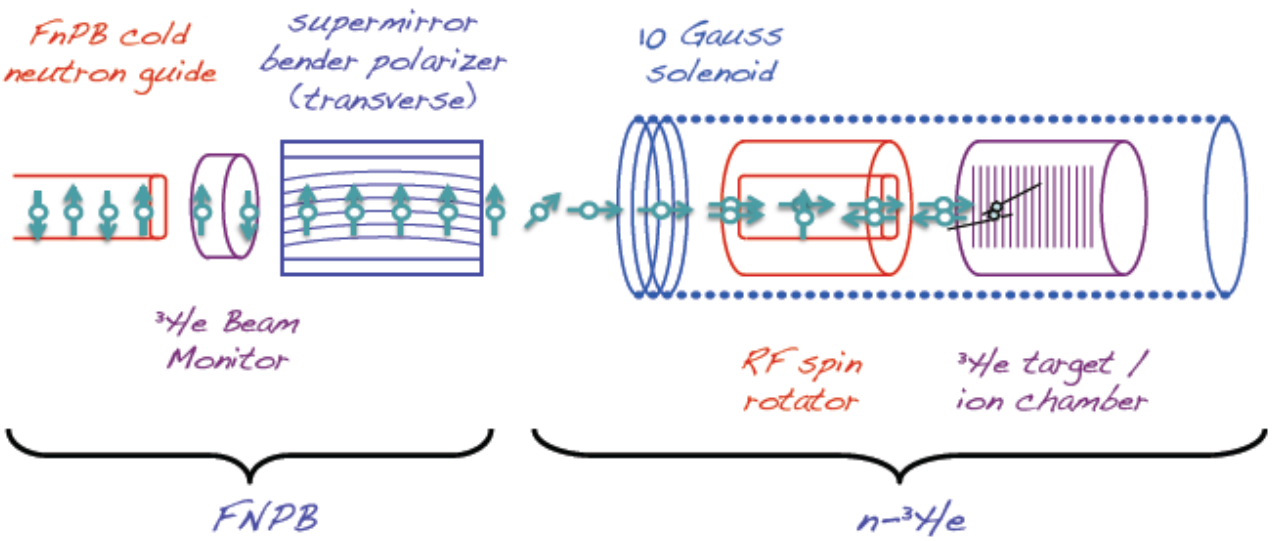
$\vec{n} + {}^3He \rightarrow p + T$

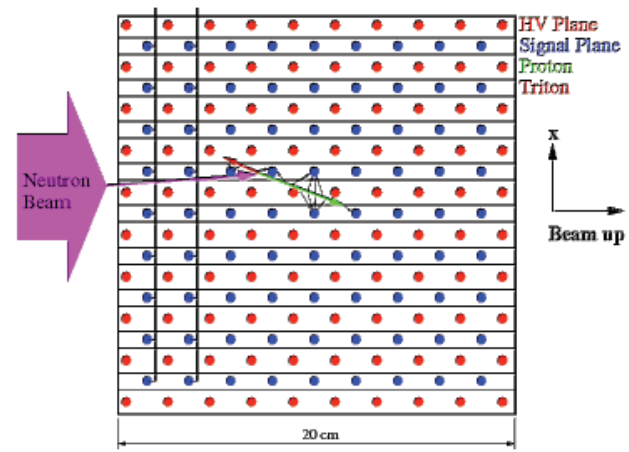
Proton Asymmetry !

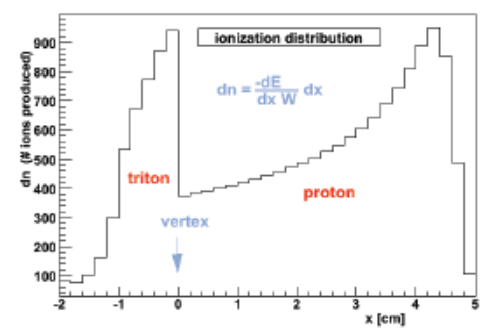


KE.00005: M. McCrea

$$A_p = -0.189\mathbf{h}^1_\pi - 0.036\mathbf{h}^0_\rho + 0.019h^1_\rho - 0.006\mathbf{h}^2_\rho - 0.0334\mathbf{h}^0_\omega + 0.0413h^1_\omega$$







Single-Wire Spin Asymmetries !