Neutron Lifetime – the bottle method

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PDG 2013

n $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.0086649160 \pm 0.0000000004$ u

Mass $m = 939.565379 \pm 0.000021$ MeV [a]

$(m_n - m_{\overline{n}})/\, m_n = (9 \pm 6) \times 10^{-5}$

$m_n - m_p = 1.2933322 \pm 0.0000004$ MeV

$= 0.00138844919(45)$ u

This talk: Mean life $\tau = 880.0 \pm 0.9$ s (S = 1.4)

$c\tau = 2.6381 \times 10^8$ km

Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$

T violation Electric dipole moment $d < 0.29 \times 10^{-25}$ e cm, CL = 90%

Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm^2 (S = 1.3)

Magnetic radius $\sqrt{\langle r_M^2 \rangle} = 0.862^{+0.009}_{-0.008}$ fm

Electric polarizability $\alpha = (11.6 \pm 1.5) \times 10^{-4}$ fm^3

Magnetic polarizability $\beta = (3.7 \pm 2.0) \times 10^{-4}$ fm^3

Low Energy QCD

Charge $q = (-0.2 \pm 0.8) \times 10^{-21}$ e

B violation Mean $n\overline{n}$-oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free n)

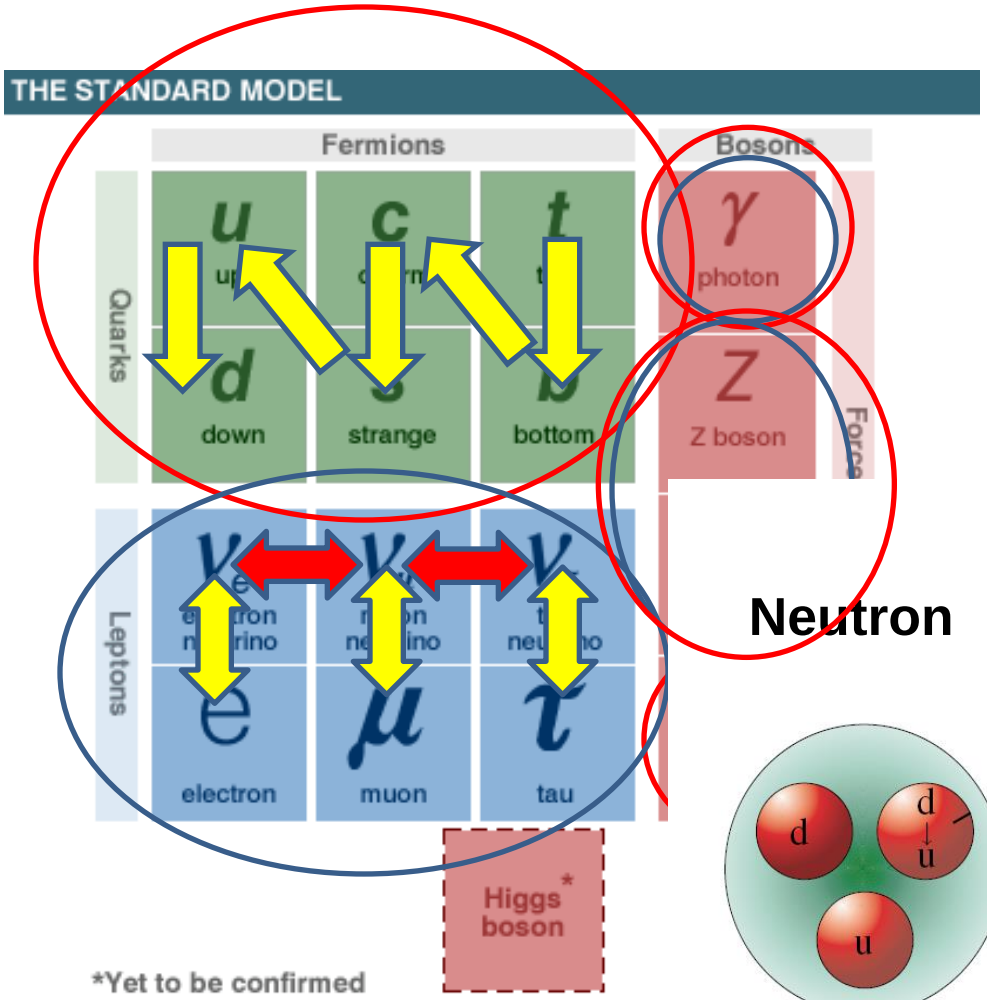
Mean $n\overline{n}$-oscillation time $> 1.3 \times 10^8$ s, CL = 90% [f] (bound n)

Mean nn'-oscillation time > 414 s, CL = 90% [g]

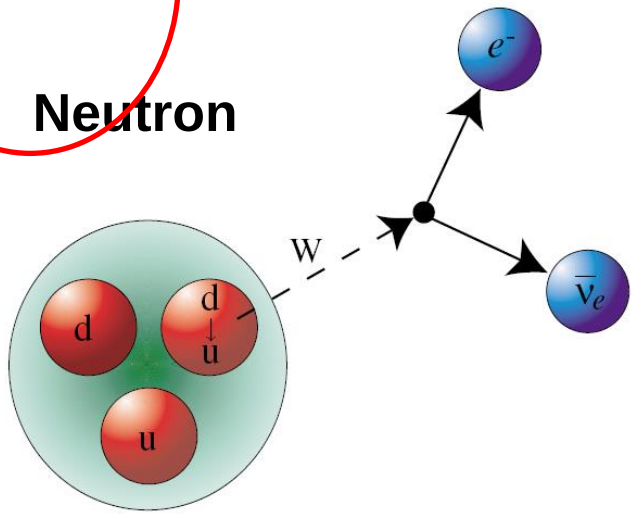
The Standard Model of Particle Physics

Hadrons

Leptons



Neutron



If the electrons were to feel the strong force, there would be no chemistry or crystallography or biology -- only nuclear physics. **S. Weinberg**

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

Heracles & the Hydra

Beyond the Standard Model (BSM) theories

Experimentalist

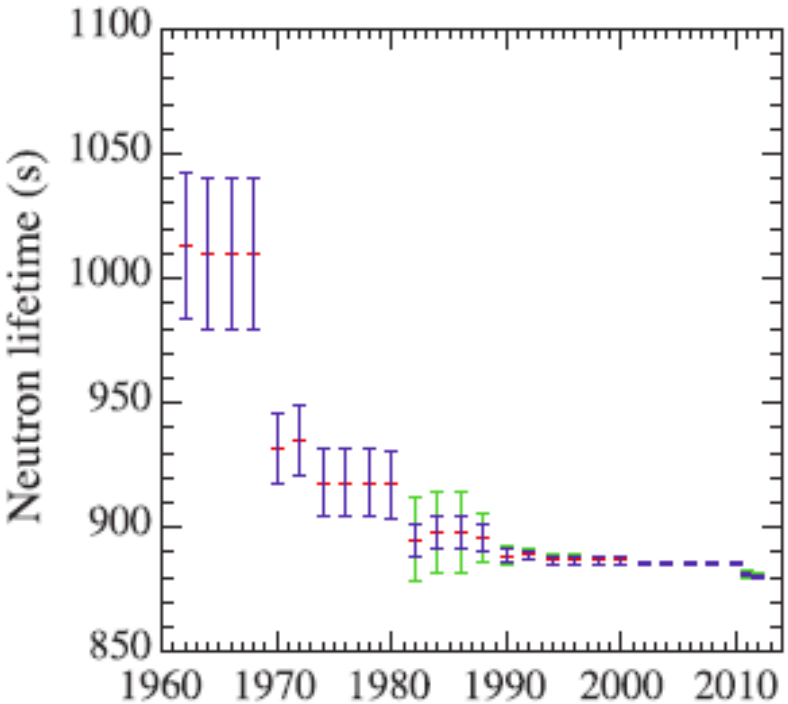
Outline

- Why?
  - Neutron beta-decay theory
  - Impacts to cosmology
- How?
  - Beam method
  - Bottle method (material, magnetic)

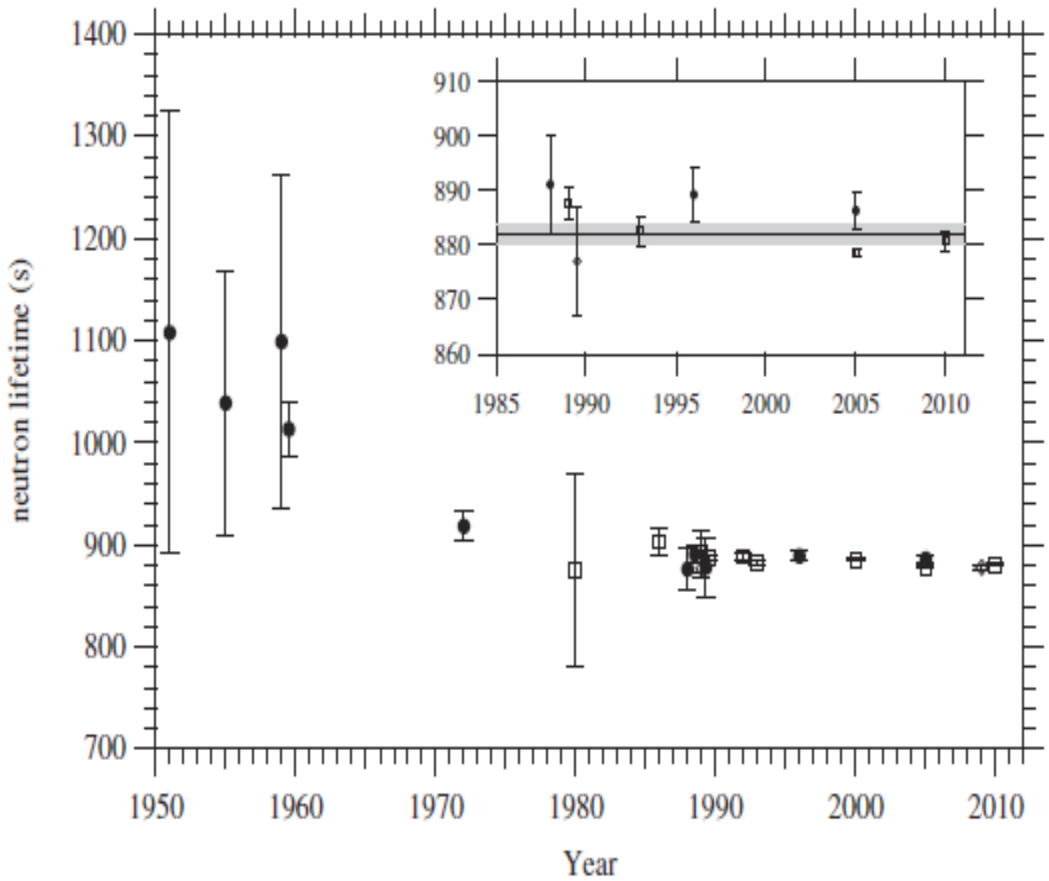
Houston, we got a problem! The two methods don't agree.

- What's the solution?
  - Current experiments (with the bottle technique)

Neutron Lifetime Measurement

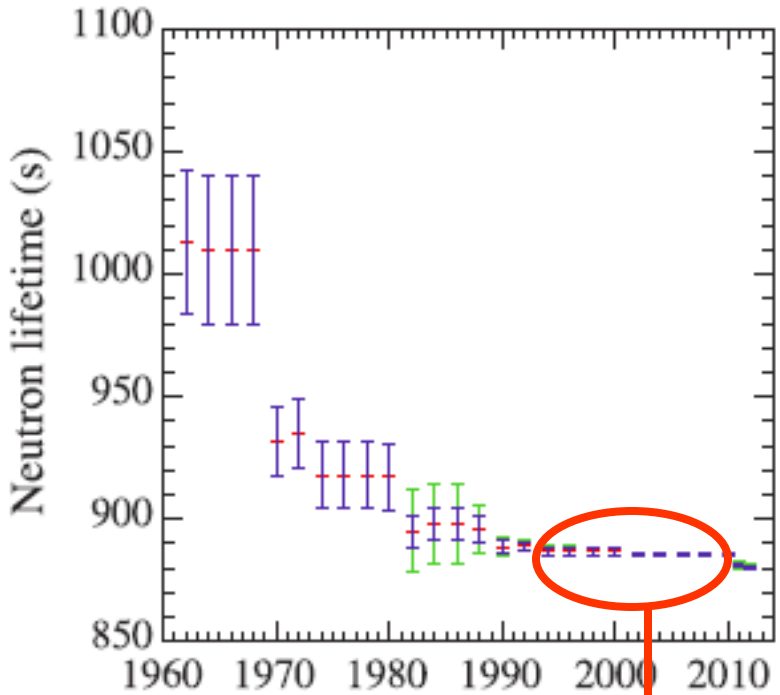


PDG average



Experiments

Measurements of Free Neutron Lifetime

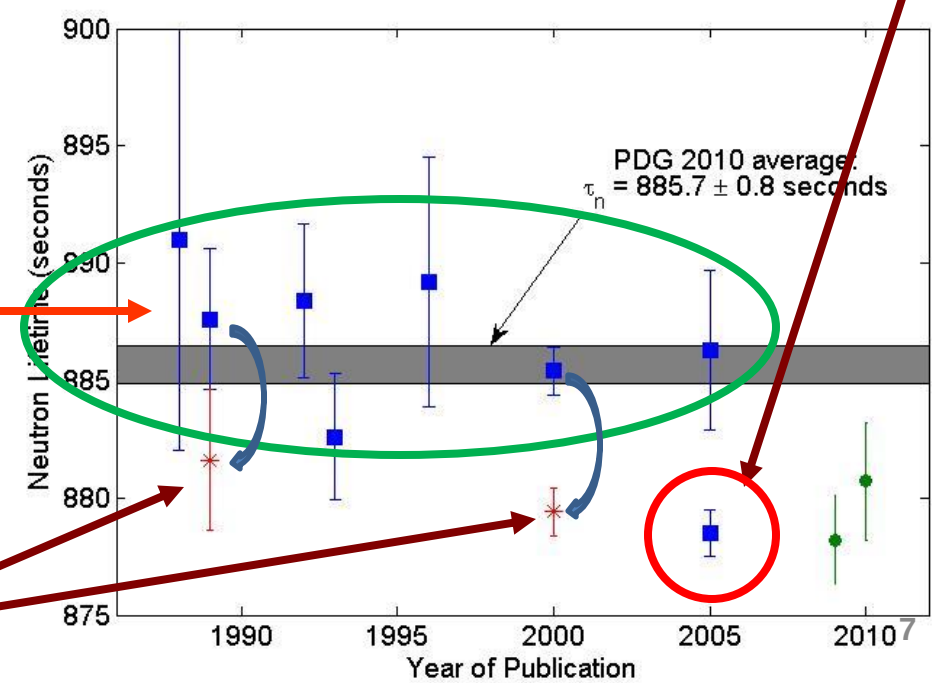


Precision improves over time, but accuracy?

PDG 2004-2010:	885.7 ± 0.8 s
PDG 2011:	881.0 ± 1.5 s
PDG 2013:	880.0 ± 0.9 s
PDG 2014:	880.3 ± 1.1 s

Serebrov et al.,

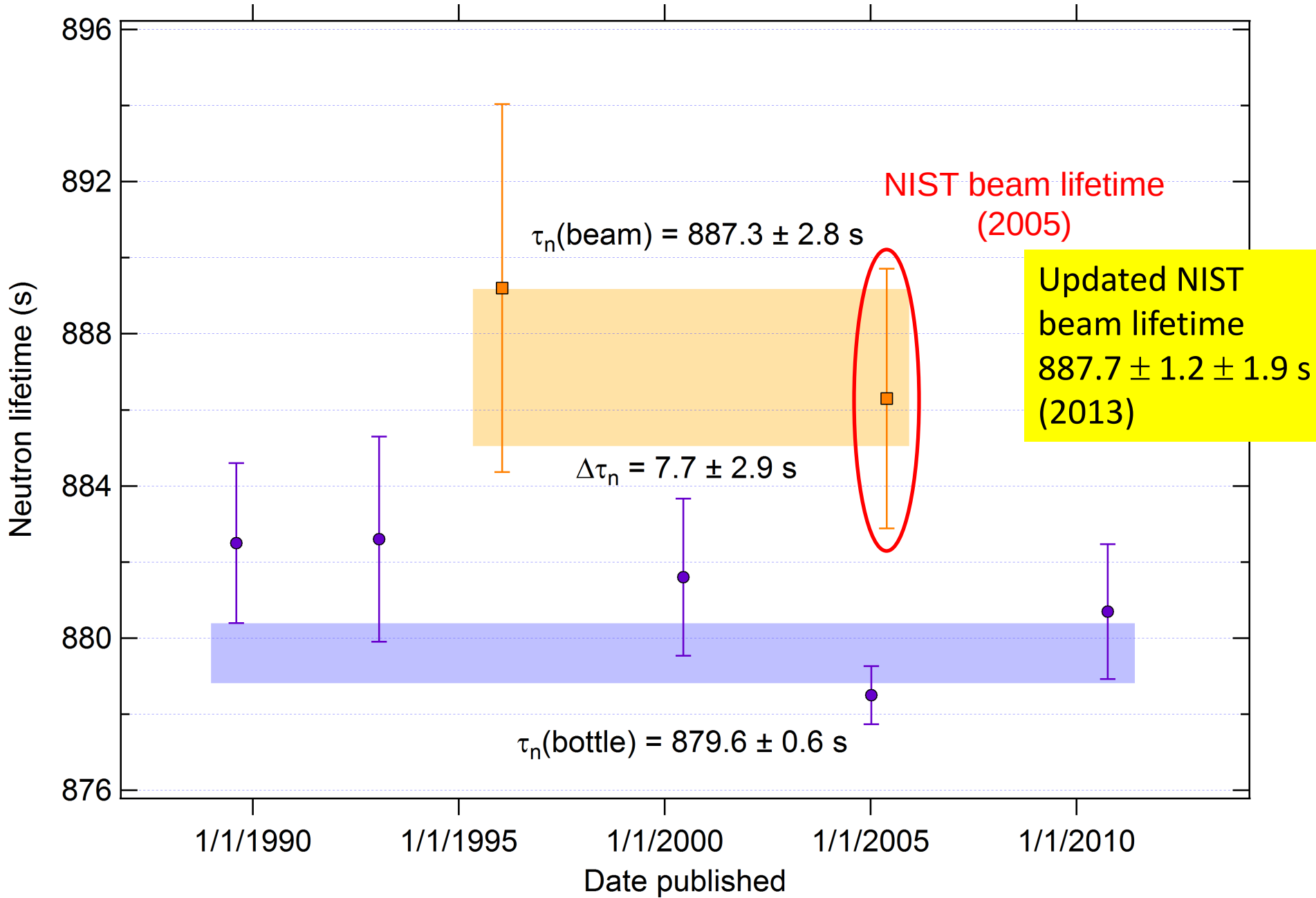
(878.5 ± 0.7 ± 0.3) seconds



Source	τ_n
PDG 2004–10	885.7 ± 0.8 sec
Serebrov 2005	878.5 ± 1.0
Pichlmaier 2010	880.7 ± 2.5
PDG 2012	880.1 ± 1.1
PDG 2014	880.3 ± 1.1

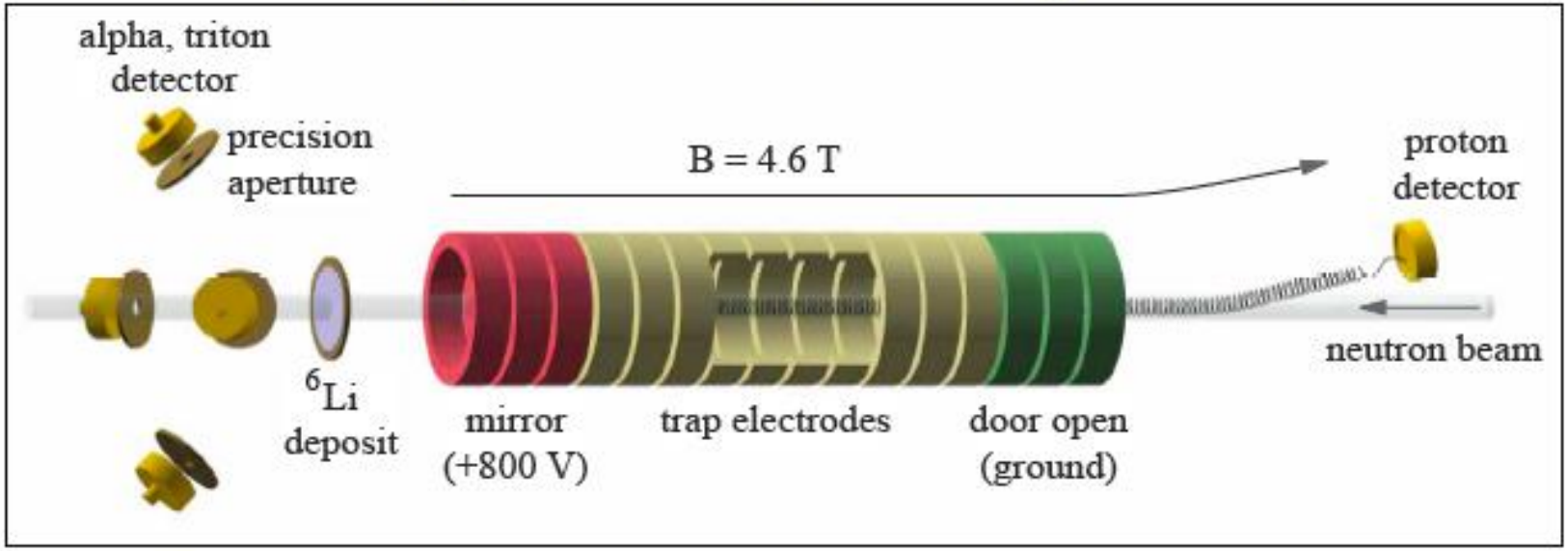
Reana
Serebr

Two Different Techniques, Two Lifetimes ?

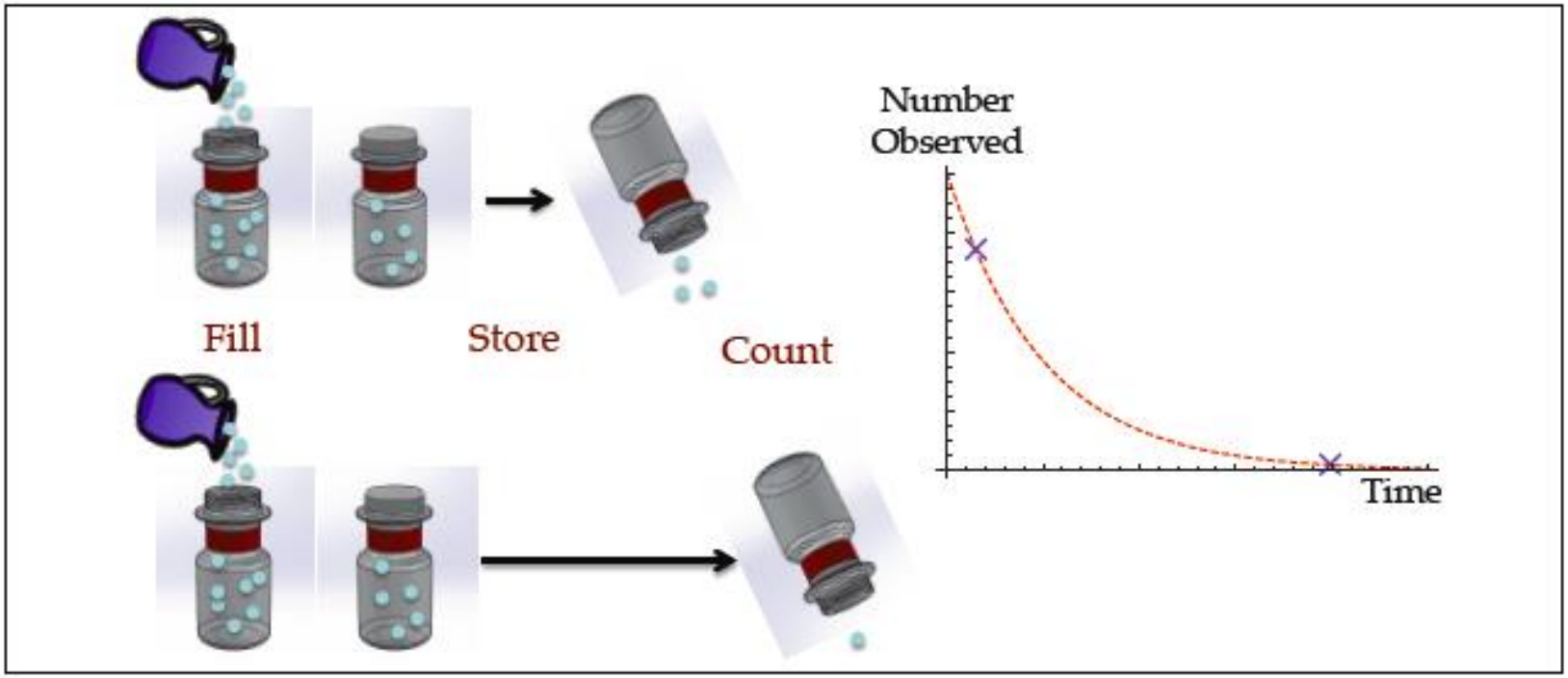


Two Complementary Techniques

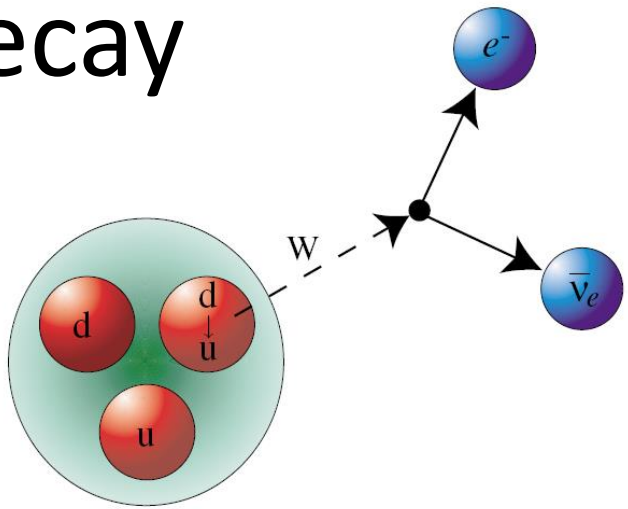
Cold Neutron Beam



Ultracold Neutron (UCN) Bottle



Neutron beta-decay



Parity violation:
V-A weak interaction

$$H_\beta = H_{V,A}$$

$$= \bar{e}\gamma_\lambda(1-\gamma^5)\nu_e\bar{p}(g_V + g_A\gamma^5)\gamma^\lambda n$$

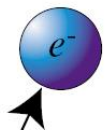
Vector (Fermi, ΔJ=0)

Axial Vector (Gamow-Teller, ΔJ=1)

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

***n* DECAY MODES**		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p e^- \bar{\nu}_e$		100	%	1
$p e^- \bar{\nu}_e \gamma$	[k]	$(3.09 \pm 0.32) \times 10^{-3}$		1

Neutron beta-decay



Parity violation:
V-A weak interaction

$pe^-\nu_e$ decay parameters [h]

$\lambda \equiv g_A / g_V = -1.2701 \pm 0.0025$
$A = -0.1176 \pm 0.0011 \quad (S = 2.1)$
$B = 0.9807 \pm 0.0030$
$C = -0.2377 \pm 0.0026$
$a = -0.103 \pm 0.004$
$\phi_{AV} = (180.017 \pm 0.026)^\circ$ [i]
$D = (-1.2 \pm 2.0) \times 10^{-4}$ [j]
$R = 0.004 \pm 0.013$ [j]

Vector (Fermi, ΔJ=0)

$$H_\beta = H_{V,A}$$
$$= \bar{e}\gamma_\lambda(1-\gamma^5)\nu_e \bar{p}(g_V + g_A\gamma^5)\gamma^\lambda n$$

Axial Vector (Gamow-Teller, ΔJ=1)

J. D. Jackson, S.B. Treiman, H.W. Wyld, Jr, Phys. Rev. 106, 517 (1957)

Polarized neutron

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

Electron-neutrino asymmetry **Beta asymmetry** **neutrino asymmetry** **Triple correlation**

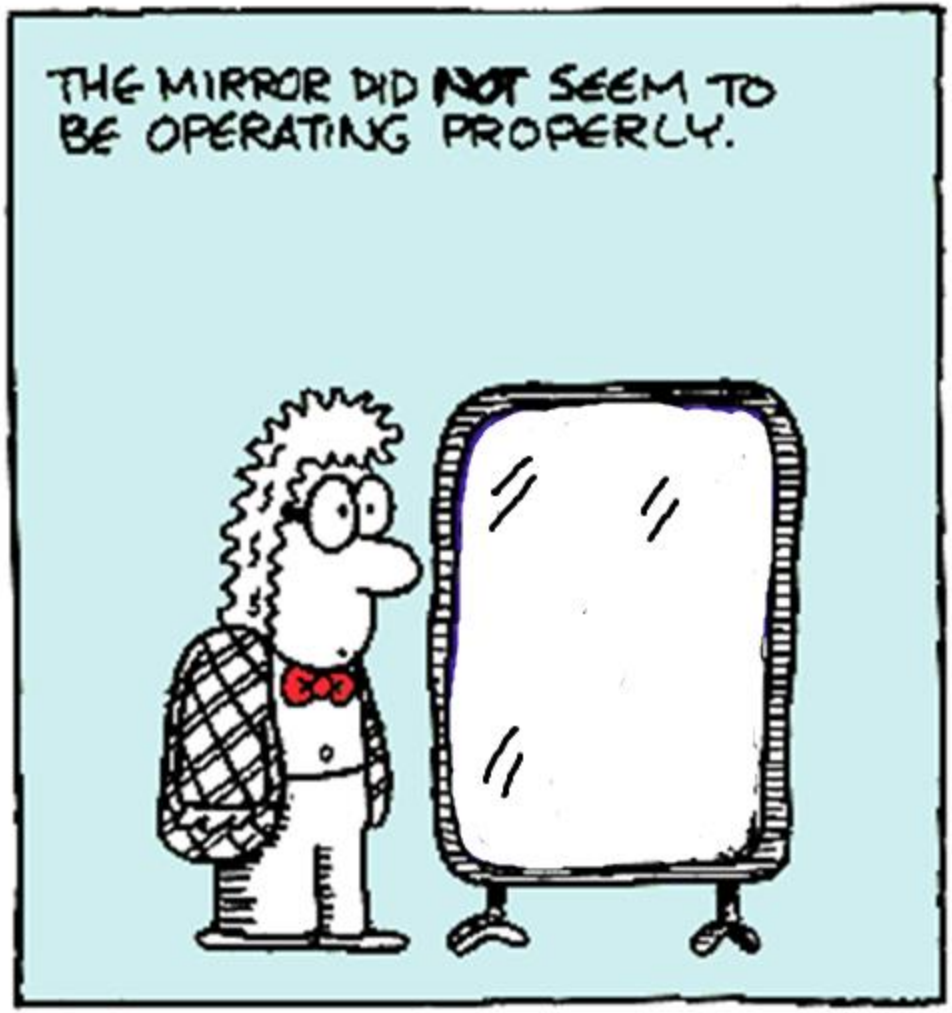
The Weak-Interaction Dance Party

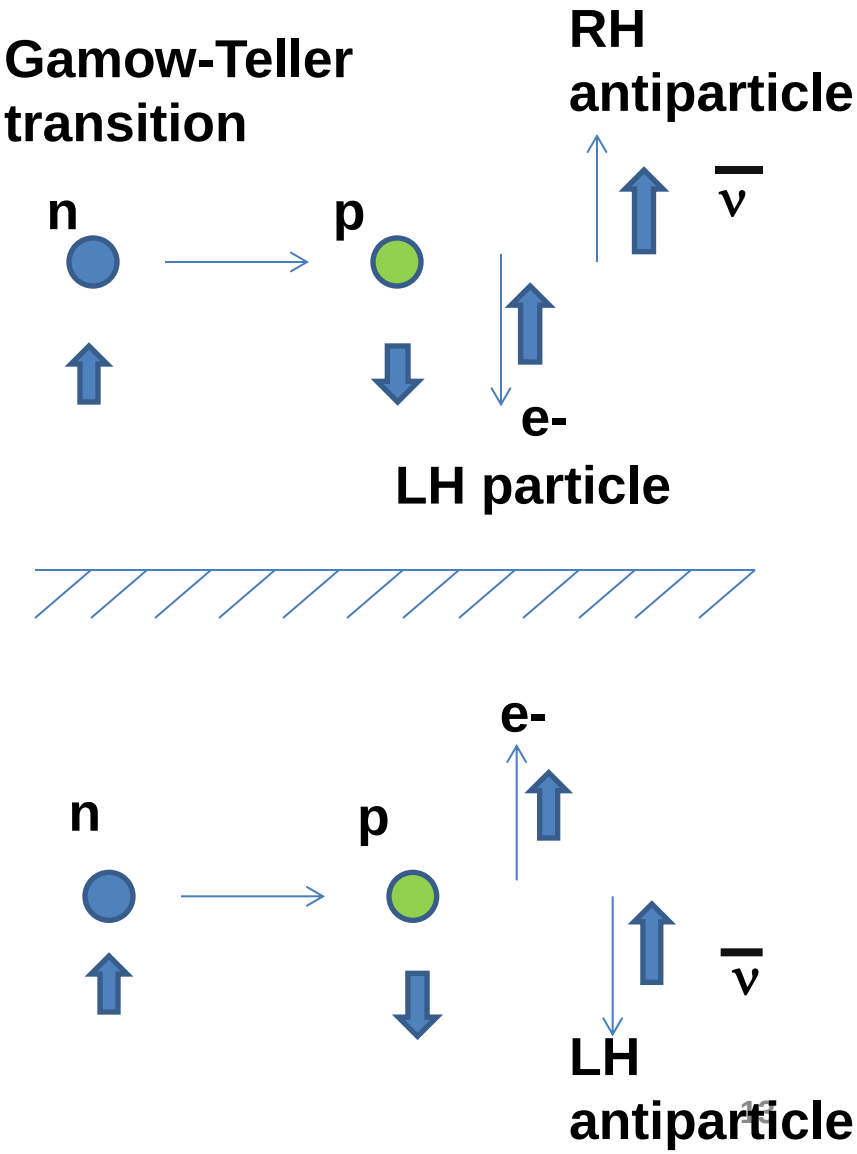
This Saturday!
Wine and beer
Dress casual
Please observe the "Wienberg-Glashaw-Salem" rules → Left-Handed Particles Only

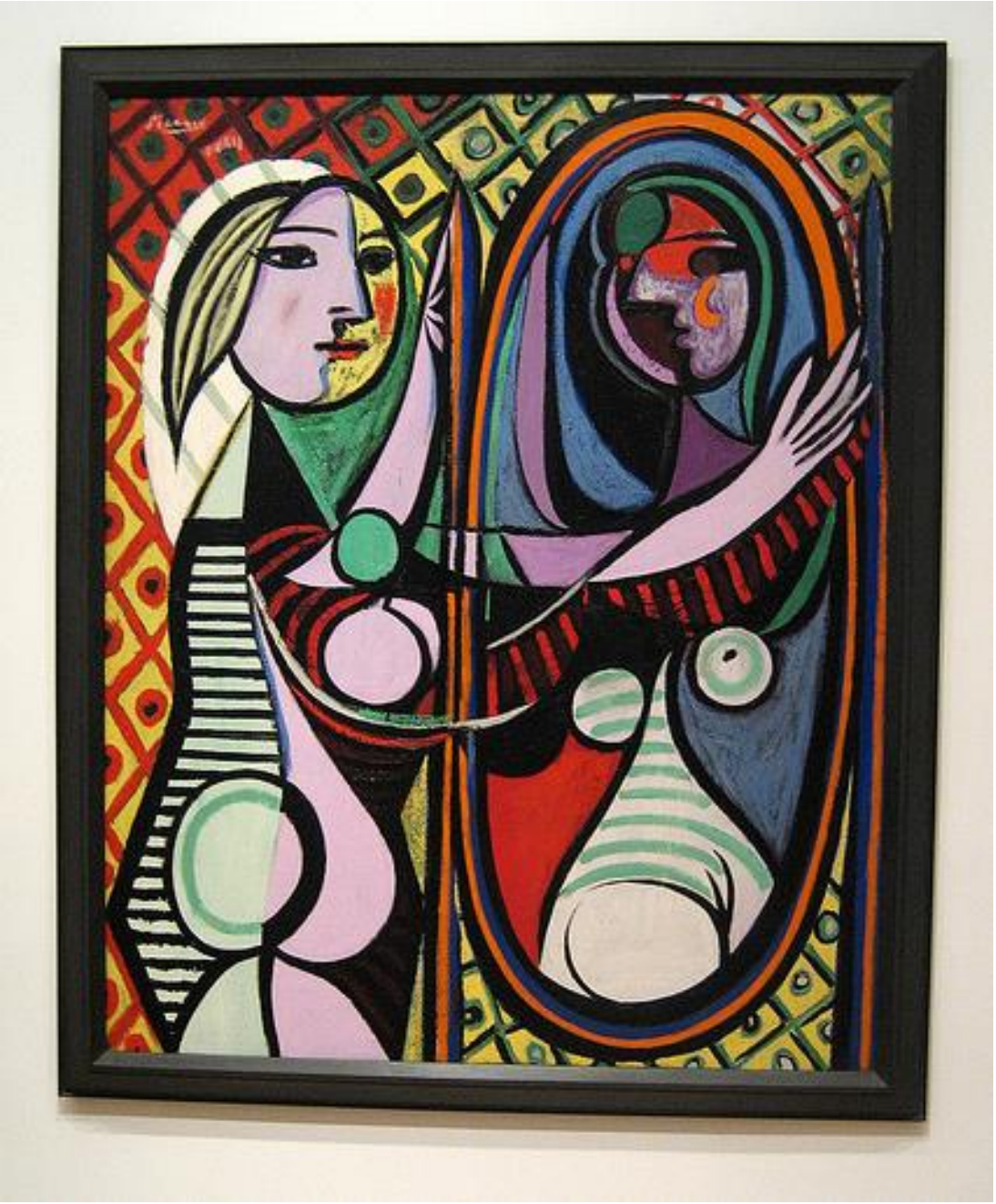
Left-Handed
(admitted)

Right-Handed
(Not allowed)

Mirror Symmetry is Broken!







Girl before a mirror, Picasso
1932

Cabbibo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} \mathbf{0.97419(22)} & \mathbf{0.2257(10)} & 0.003959(16) \\ 0.9750(8) & 0.223(4) & 0.0035(25) \\ 0.2256(10) & 0.97334(23) & 0.0415(11) \\ 0.222(3) & 0.9742(8) & 0.040(3) \\ 0.00874(37) & 0.0407(10) & 0.999133(43) \\ 0.009(5) & 0.039(4) & 0.9992(2) \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

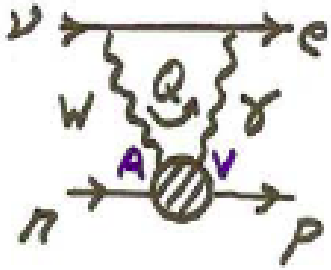
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014 < 1$$ PGD2002

$$= \mathbf{1.0000 \pm 0.0004}$$ **PGD2009**

Good agreement with unitarity!

V_{ud} for CKM Unitarity Test

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



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

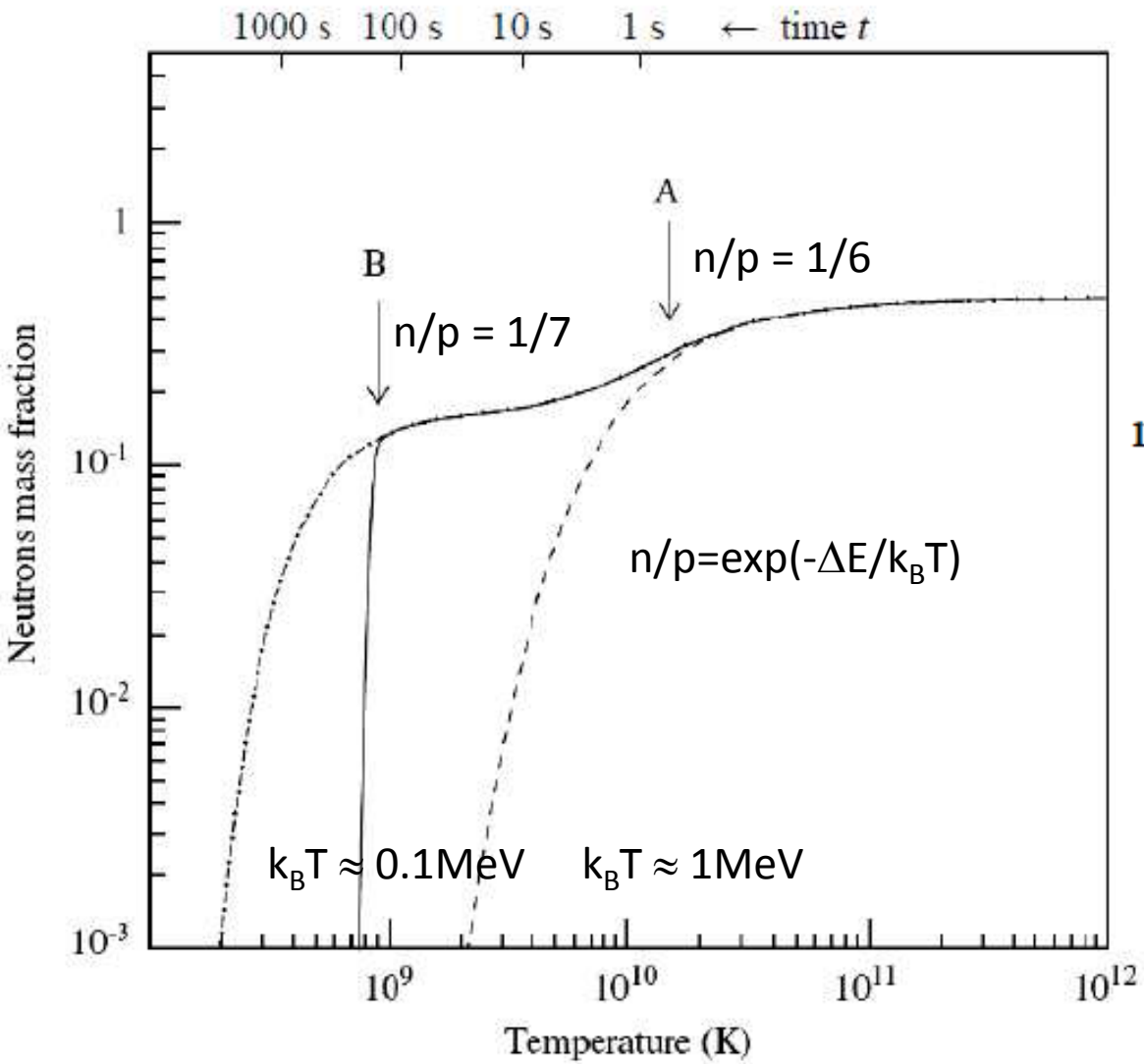
$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ \frac{m_W^2}{Q^2+m_W^2} F(Q^2)$$

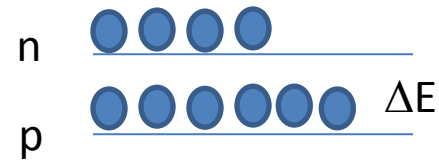
From μ-decay: 0.6 ppm (MuLan 2011)

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

- To be comparable to the theoretical uncertainty: 4×10^{-4}, requires experimental uncertainty: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 4 \times 10^{-4}$.
- Significance in Astrophysics (more coming).

Cosmology: Primordial Nucleosynthesis





$\Delta E = 1.293$ MeV

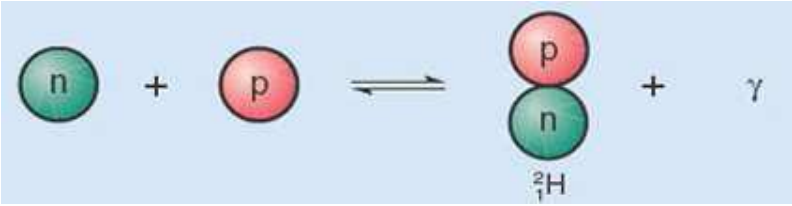
$$n + e^+ \leftrightarrow p + \bar{\nu}_e ,$$

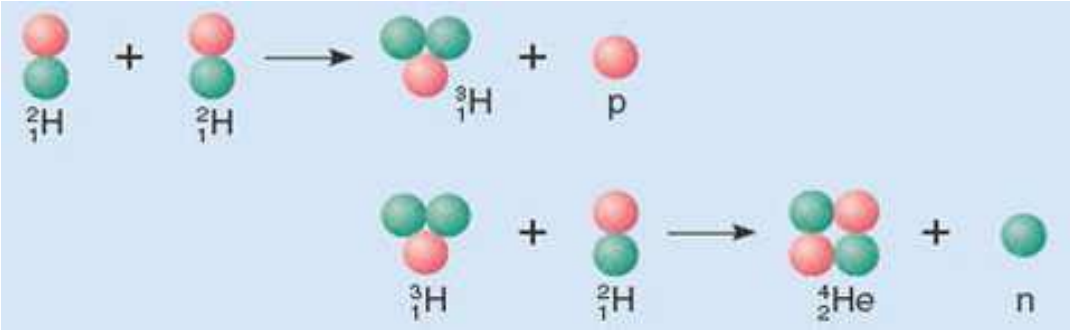
$$n + \nu_e \leftrightarrow p + e^-$$

neutron decay

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

Big-Bang Nucleosynthesis





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

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

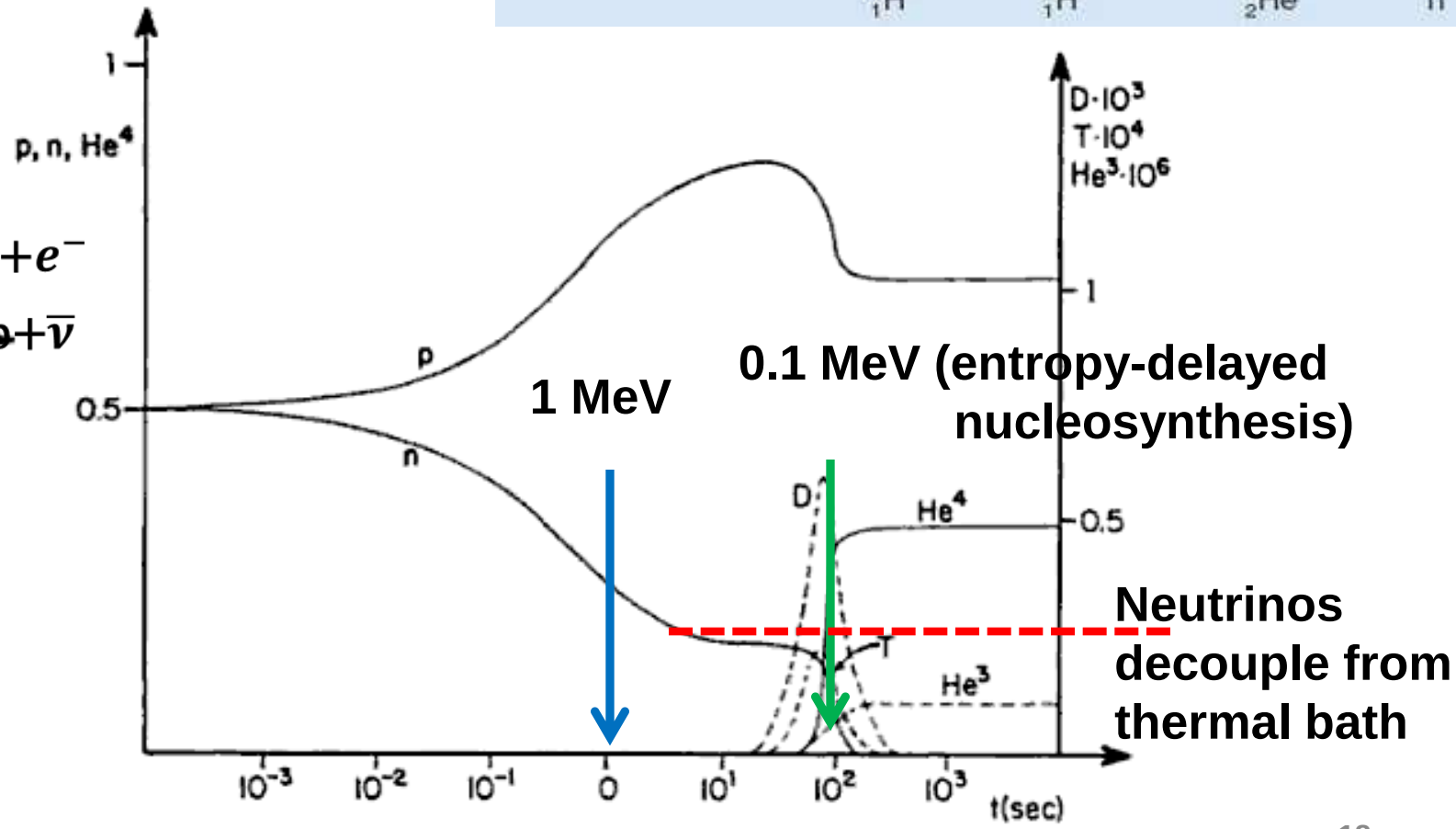
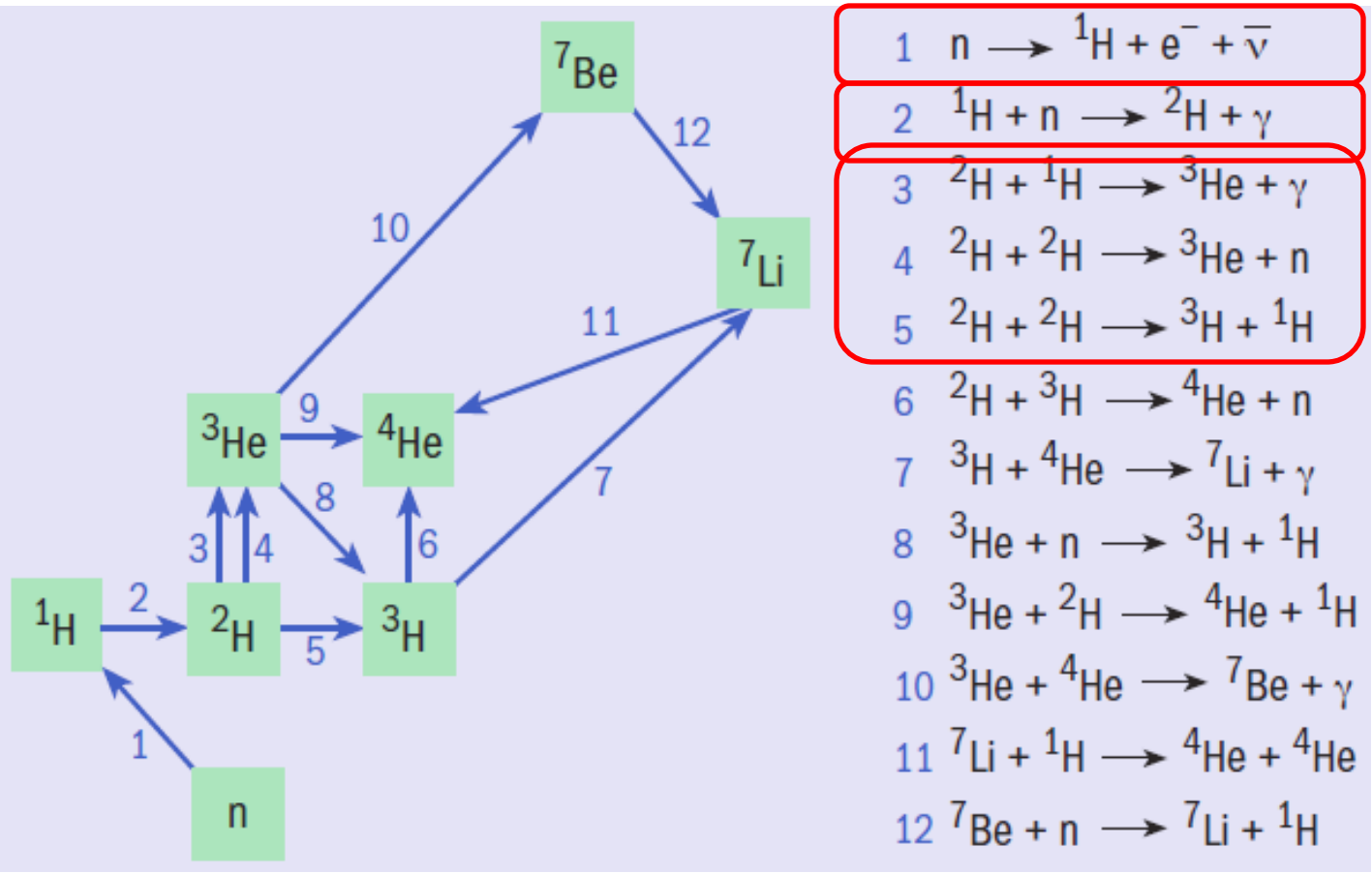
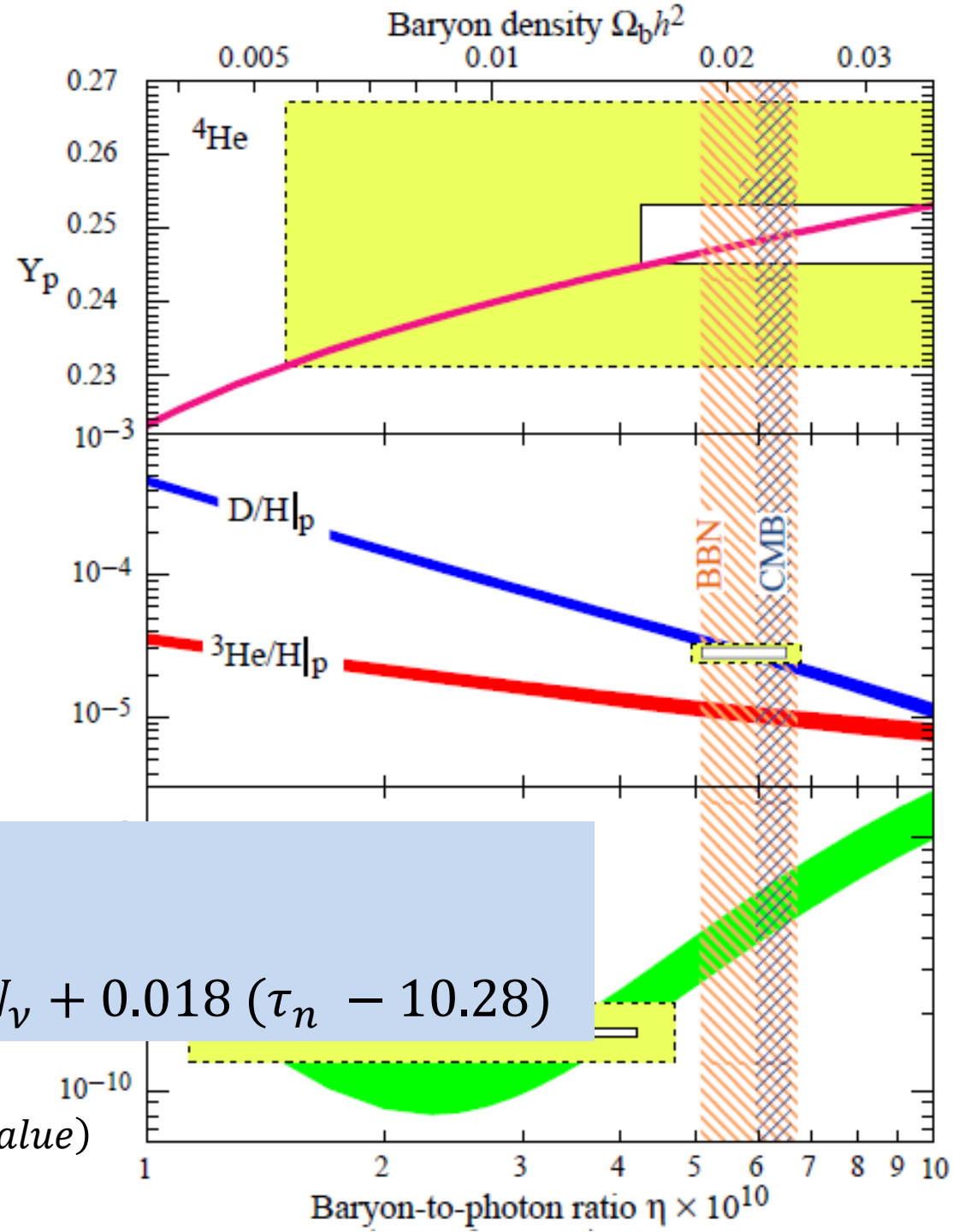


Fig. 7.3. Composition of matter in the early universe.

Big-Bang Nucleosynthesis

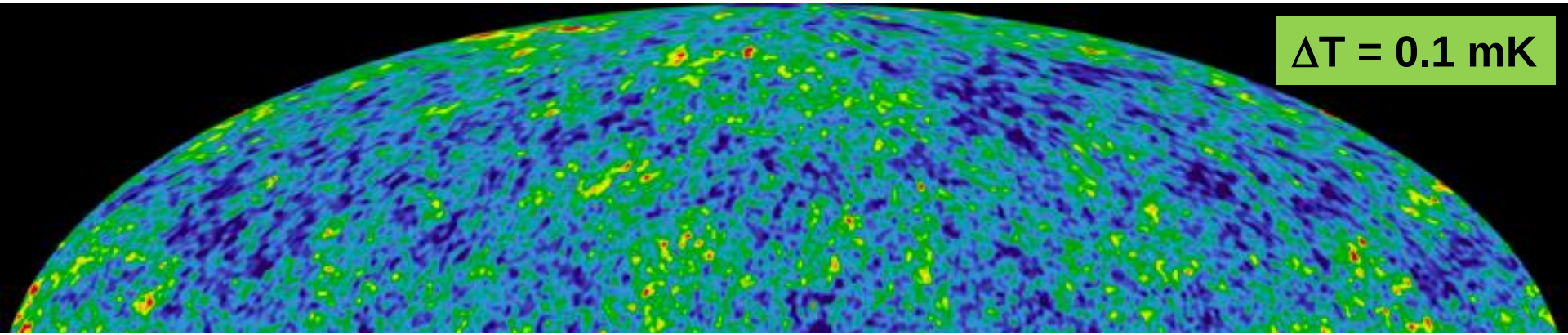


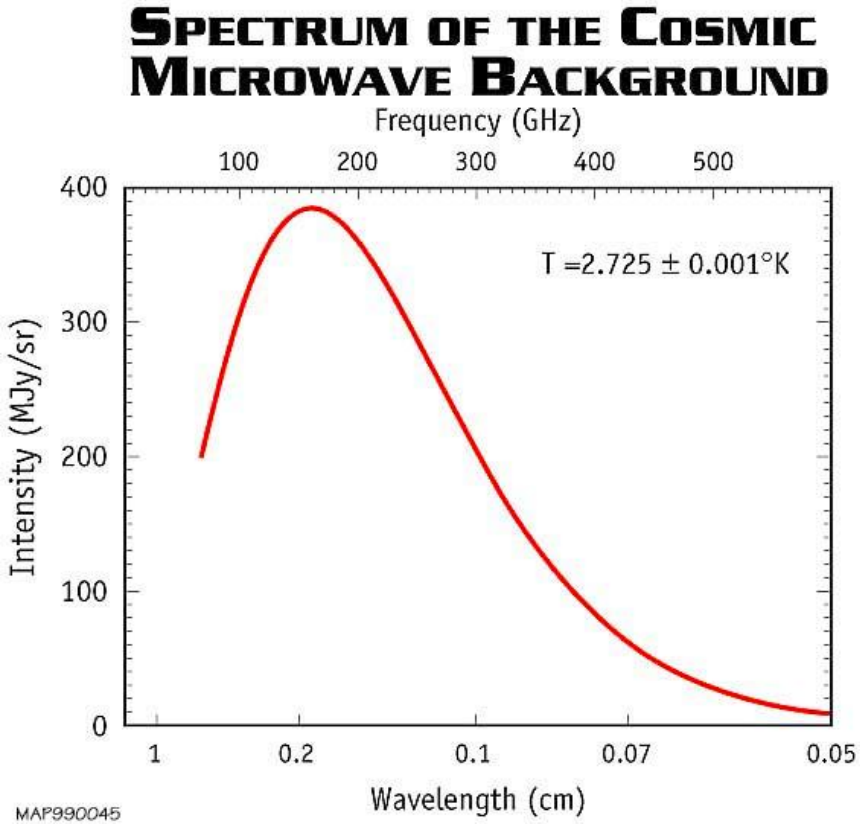


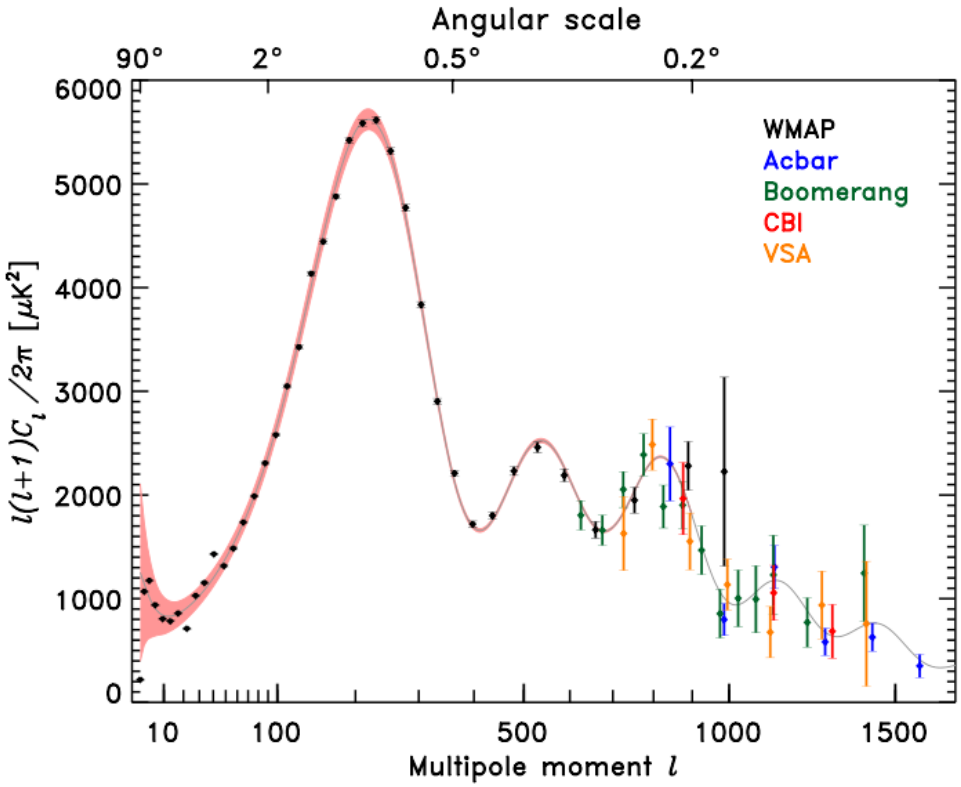
$$Y_p = 0.228 + 0.023 \log \eta_{10} + 0.012\, N_\nu + 0.018\, (\tau_n - 10.28)$$

$$Y_P = 0.2471 \pm 0.0002\,(theory) \pm 0.0002\,(\tau_n, 2014\ PDG\ value) \pm 0.0001(CMB)$$

Cosmic Microwave Background







Y_p & Non-Standard Model Cosmology

- Sensitive to the number of relativistic particle (neutrino) species.

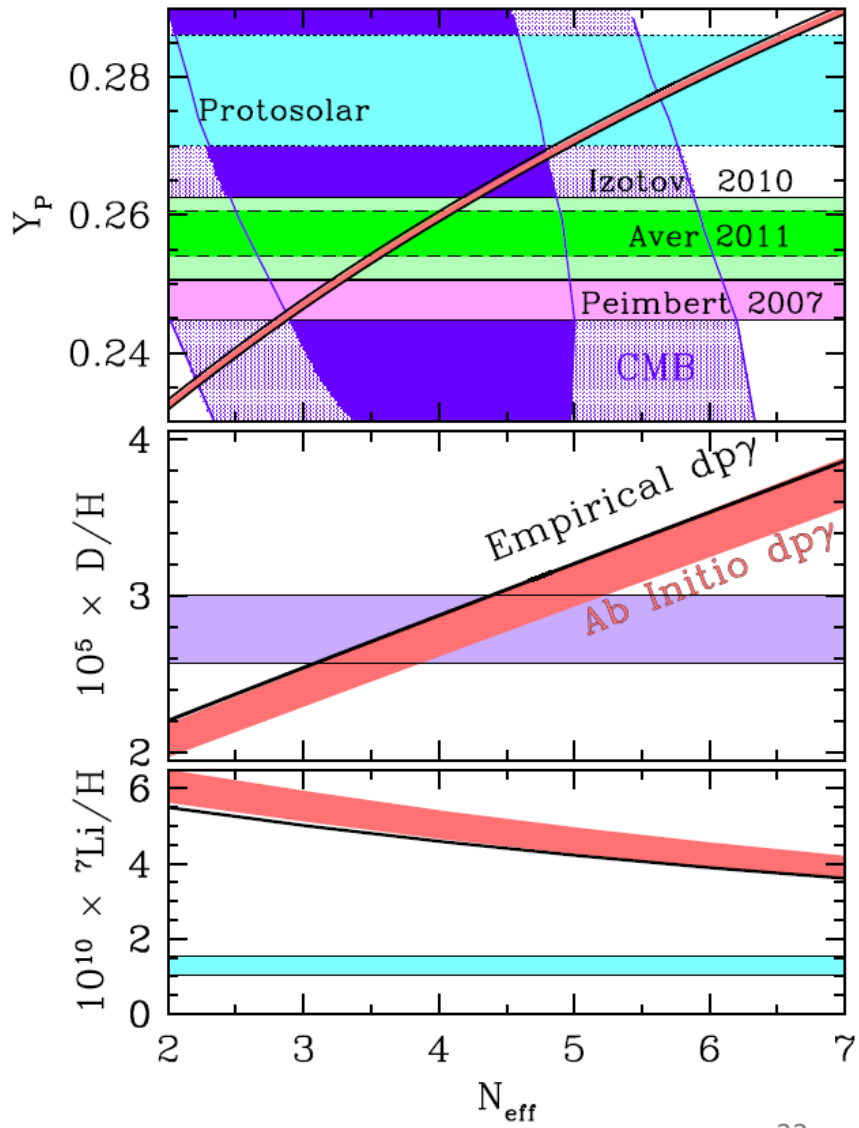
$$\tau = 885.7(8)\text{s} \Rightarrow 878.5(8)\text{s}$$
$$\Rightarrow \Delta Y_p / Y_p = -0.0015$$
$$\Rightarrow \Delta N_\nu = +-0.12$$

where N_ν is the # of light neutrino species (N_ν=3 in Standard Model)

present value of *N_ν=3.68 +0.4/-0.3 (Izotov/Thuan 2010)*

ΔN_ν improves to ±0.2 from Planck data (2013)

Will we get N_ν=4 at 5σ?



K. Nollett, G.P. Holder (2011)

What kind of universe we would have today,

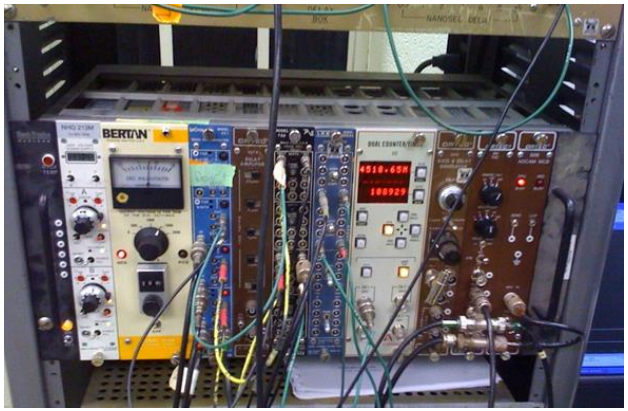
- if the neutron is lighter than the proton?
- if the G_F is stronger by an order of magnitude?
- if the neutron does not decay?

Ref: “The eighteen arbitrary parameters of the standard model in your everyday life” Robert N. Cahn, Rev. Mod. Phys. 68, 951 (1996)

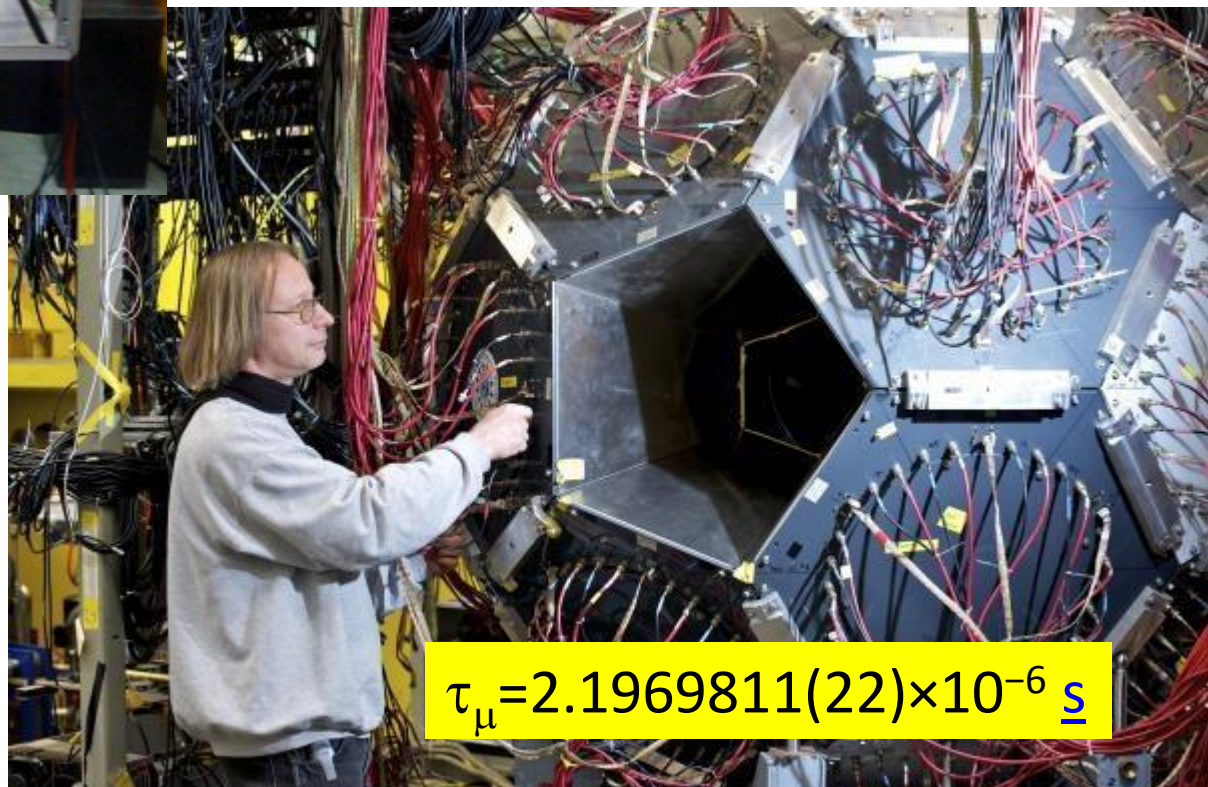
Other Relevant Processes

$n + e^+ \leftrightarrow p + \bar{\nu}$ (big-bang nucleosynthesis)
$p + e^- \leftrightarrow n + \nu$ (big-bang nucleosynthesis, neutron star formation)
$p + p \rightarrow {}^2H + e^+ + \nu$ (solar fusion)
$p + p + e^- \rightarrow {}^2H + \nu$ (solar fusion)
$\nu + n \rightarrow e^- + p$ (neutrino detection)
$\bar{\nu} + p \rightarrow e^+ + n$ (antineutrino detection).

Measure the Muon Lifetime



IU P451 Modern Physics Laboratory:
Cosmic Ray



τ_μ=2.1969811(22)×10^{-6} s

MuLAN experiment, PSI

“Why is it so hard to measure the neutron lifetime”?
Give me three reasons:

“Why is it so hard to measure the neutron lifetime”? Give me three reasons:

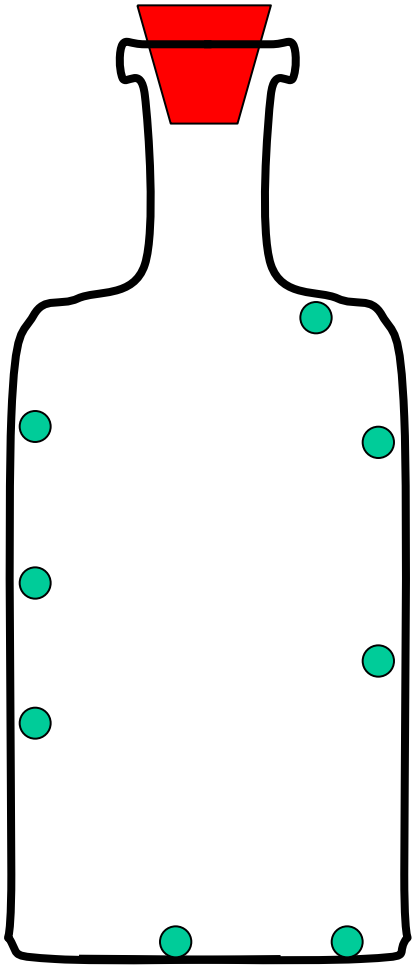
- Neutron is charge-neutral
  - Hard to guide and focus.
  - Hard to detect. Low energy neutrons are non-ionizing.
- Low S/N: Low density of free neutrons & large BG
  - Cold neutron beam: 10^{10}/cm^2-s (cold neutrons)$\rightarrow$ 10^5 /c.c.
  - UCN: 40 /c.c.
- Long lifetime, susceptible to other loss mechanisms (capture, upscattering, etc..)

Ultra-Cold Neutrons (UCN)

- What are UCN ?
  - Very slow neutrons

    ($v < 8$ m/s → $\lambda > 500$ Å)

    that cannot penetrate into certain material.



- **Long storage time**
- **Low radiation background**
- **100% polarization**

→ **Precision measurements**

Material Potential

$$V_F = \frac{2\pi\hbar^2 N b_C}{m_n}$$

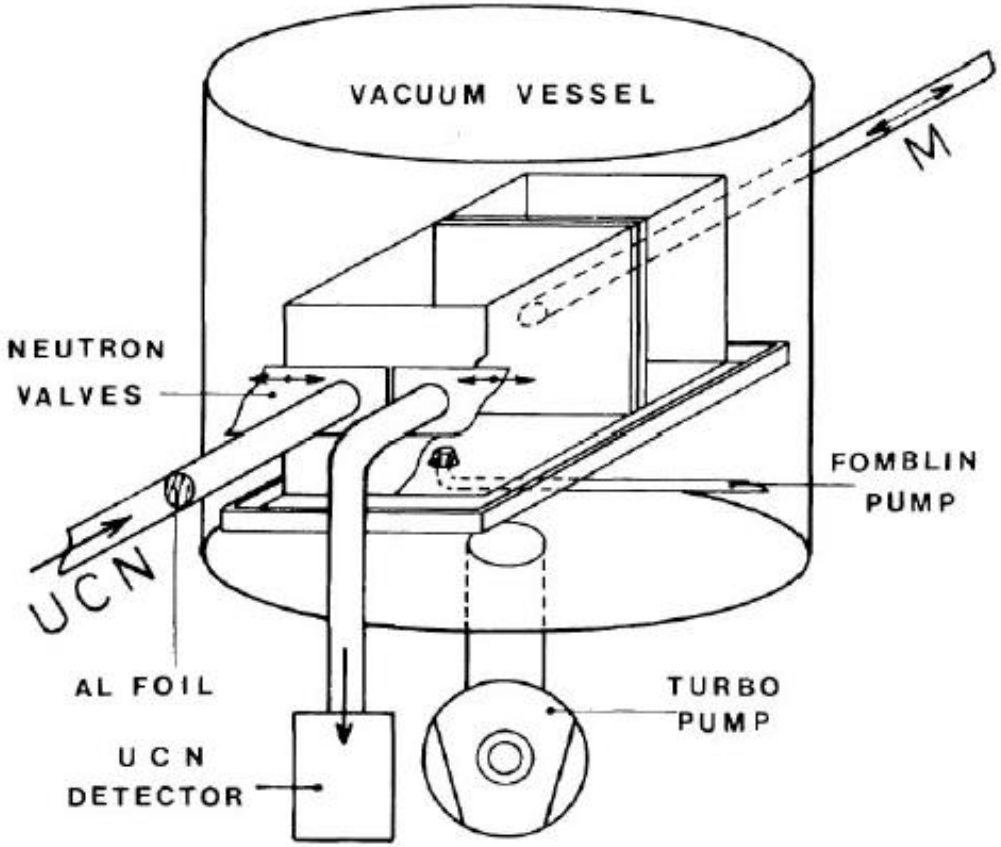
Fermi potential

Material	V_F(neV)	v_c (m/s)	η ($\times 10^{-4}$)
D_2O	170	5.6	
Be (BeO)	250	6.9	2.0-8.5
C	180	5.8	
Mg	60	3.4	
Al	50	3.2	2.9-10
SiO_2 (quartz)	110	4.6	
Cu	170	5.6	2.1-16
Fe	220	6.5	1.7-28
Co	70	3.7	
Ni	230	6.8	5.1

Critical velocity

$$v_c = \sqrt{\frac{2V_F}{m_n}}$$

Neutron Trap Experiments



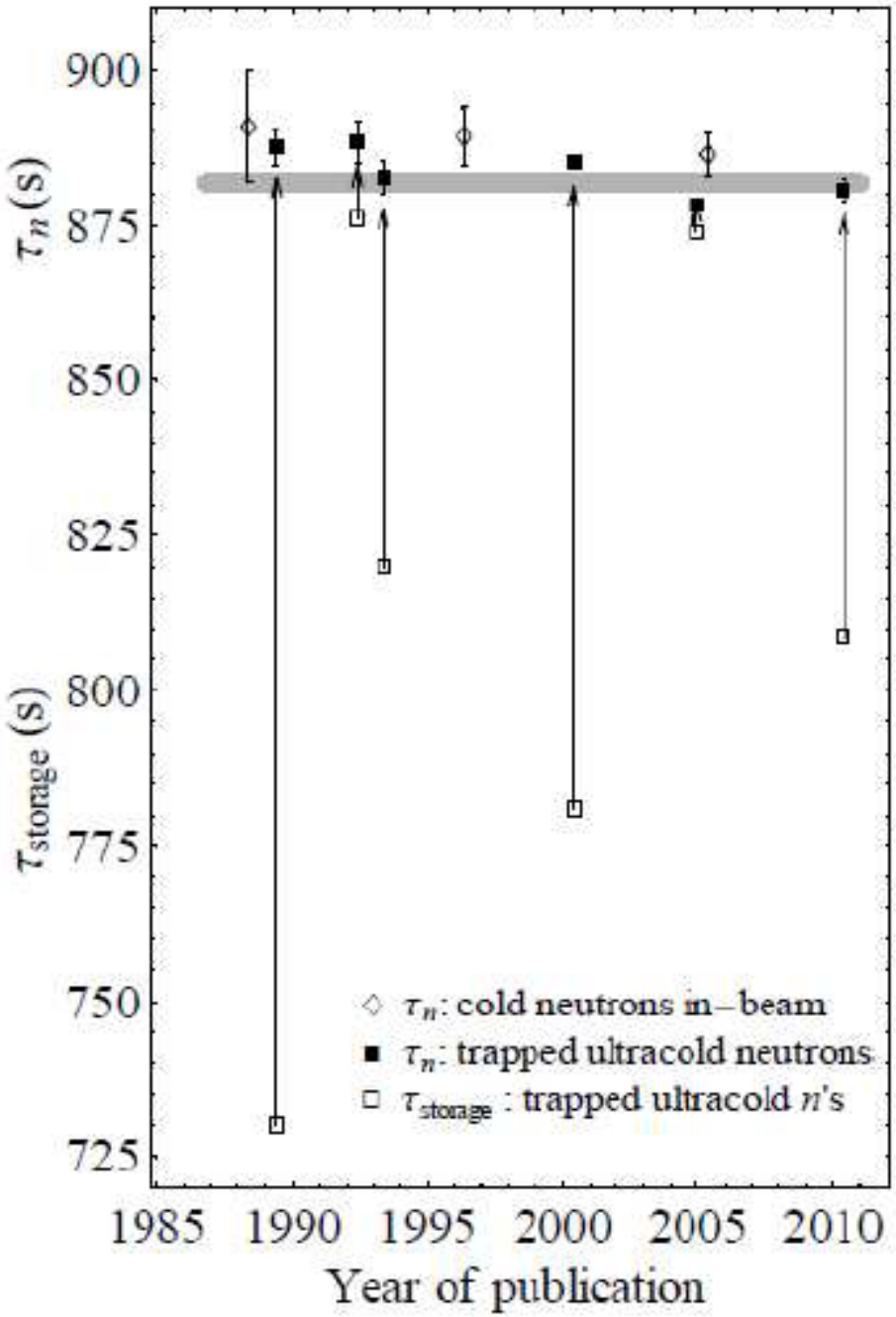
Mambo (Mampe's bottle)

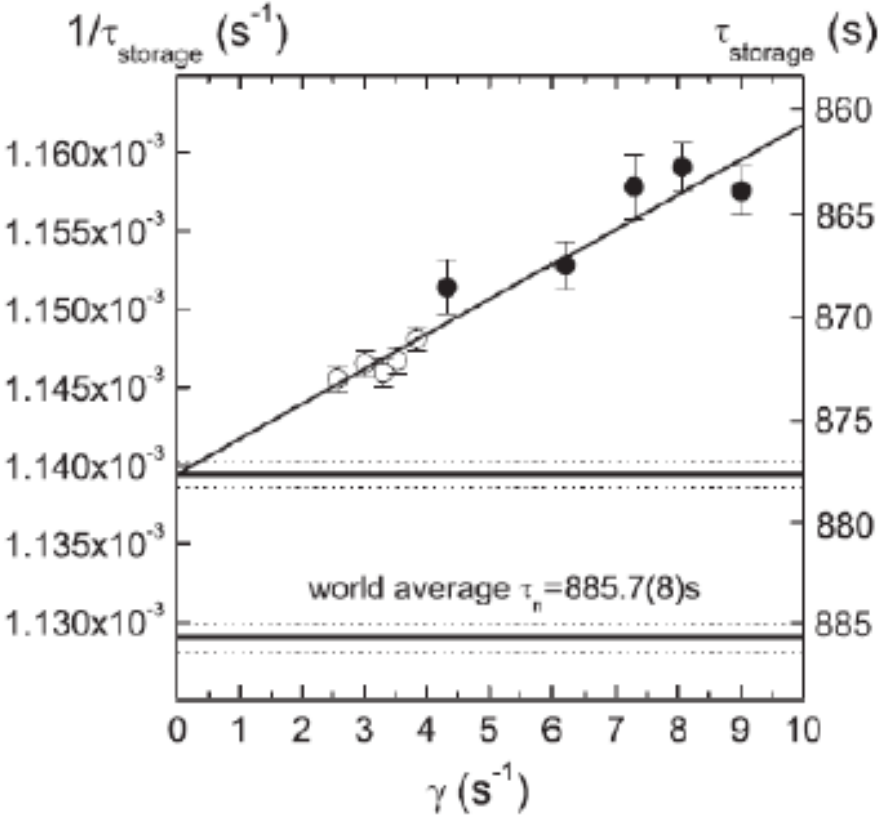
- Fomblin Oil
- Vary V/A ratio
- Mambo II: pre-spectrum

Measures the Storage Time

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

Material Bottle





A. Serebrov (2008)

Dubbers & Schmidt (2011)

The size of correction:

$$\tau_\beta - \tau_{mea} = \Delta\tau = 1\ s$$

$$\tau_{ab} = \frac{\tau_{mea}\tau_\beta}{\tau_\beta - \tau_{mea}} = \frac{\tau_{mea}}{\Delta\tau}\tau_\beta \approx\ 10^6 s$$ = 12 days

Q: How well do we have to measure each (non-beta-decay) loss time?

A. the same precision as the lifetime.
B. 10 times more precise than the lifetime.
C. 10 time less precise than the lifetime.
D. 100 times less precise than the lifetime.

How well to measure each non-beta-decay loss?

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

$$dF = -\left(\frac{d\tau_{mea}}{\tau_{mea}}\right)\frac{1}{\tau_{mea}} = -\left(\frac{d\tau_\beta}{\tau_\beta}\right)\frac{1}{\tau_\beta} - \left(\frac{d\tau_{ab}}{\tau_{ab}}\right)\frac{1}{\tau_{ab}} + \ \ldots$$

$$\left(\frac{d\tau_\beta}{\tau_\beta}\right) = \left(\frac{d\tau_{mea}}{\tau_{mea}}\right)\frac{\tau_\beta}{\tau_{mea}} - \left(\frac{d\tau_{ab}}{\tau_{ab}}\right)\frac{\tau_\beta}{\tau_{ab}} + \ \ldots$$

Each loss is a new degree of freedom, so this is a vector sum.

$$\left(\frac{d\tau_\beta}{\tau_\beta}\right) = \sqrt{\left[\left(\frac{d\tau_{mea}}{\tau_{mea}}\right)\frac{\tau_\beta}{\tau_{mea}}\right]^2 + \left[\left(\frac{d\tau_{ab}}{\tau_{ab}}\right)\frac{\tau_\beta}{\tau_{ab}}\right]^2 + \ \ldots}$$

If the trap storage time is long, so that the correction to the beta-decay lifetime is short:

$$\tau_{ab} = \frac{\tau_{mea}\tau_\beta}{\tau_\beta - \tau_{mea}} = \frac{\tau_{mea}}{\Delta\tau}\tau_\beta \approx 10^6 s$$

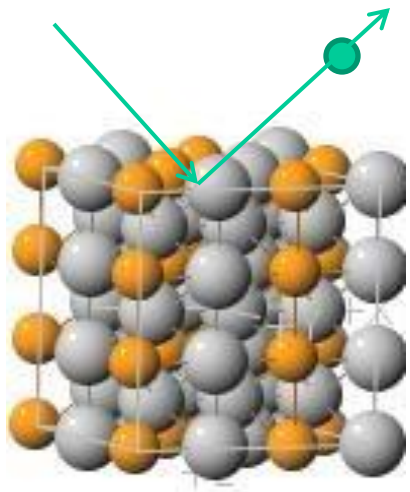
$$\left(\frac{d\tau_{ab}}{\tau_{ab}}\right)\frac{\tau_\beta}{\tau_{ab}} = \left(\frac{d\tau_{ab}}{\tau_{ab}}\right)\frac{\Delta\tau}{\tau_{mea}} = p \times \frac{1}{10}$$

$$\left(\frac{d\tau_\beta}{\tau_\beta}\right) = p$$

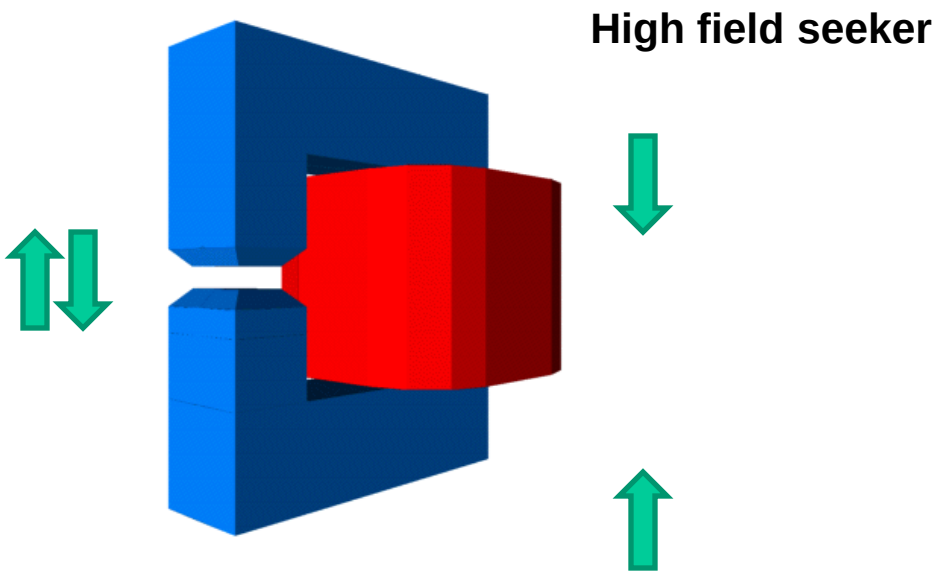
$$\left(\frac{d\tau_{ab}}{\tau_{ab}}\right) = p \times \frac{1}{10} \times \frac{\tau_{mea}}{\Delta\tau} = 100\,p$$

Ways to manipulate UCN:

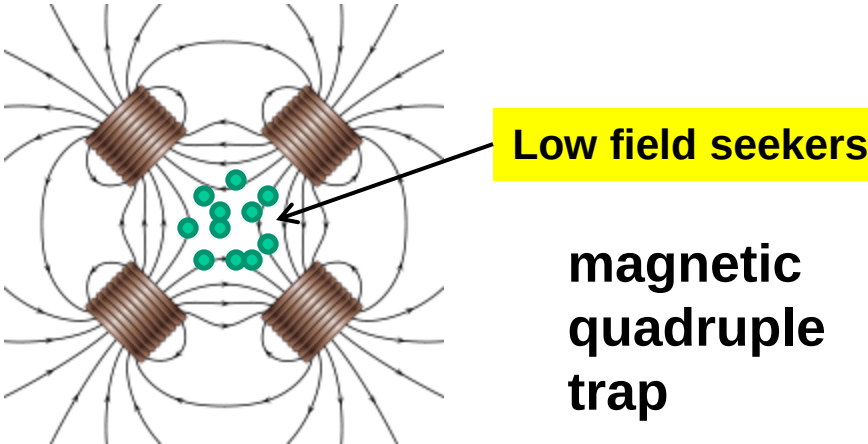
- Nuclear force (max: 350neV)



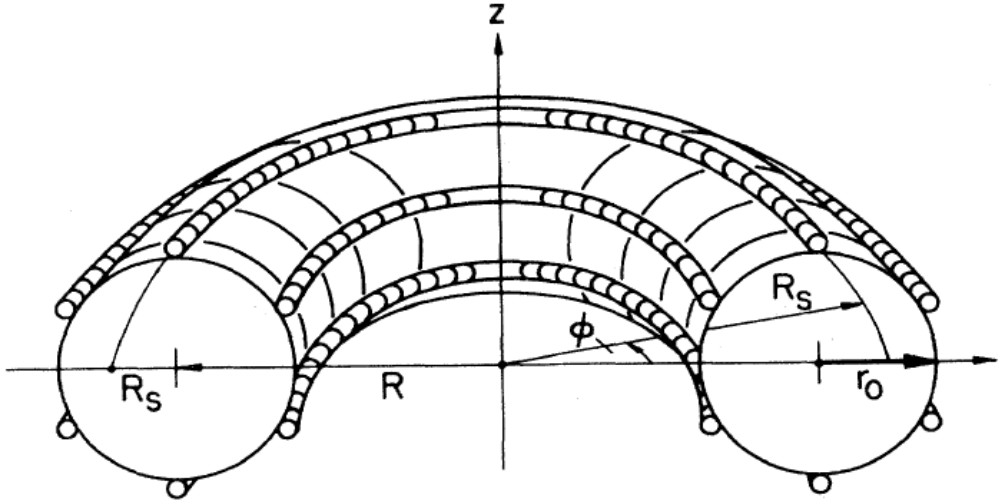
- Magnetic force (60neV/T)

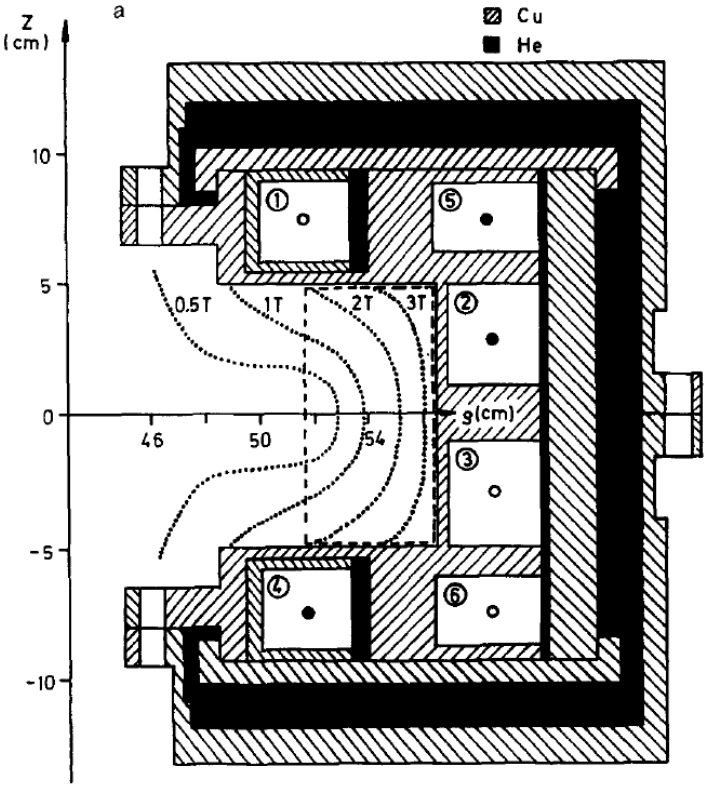


- Gravitational force (100neV/m)



NEtron STOrage Ring (NESTOR)





R ~ 0.5 m, Bmax = 3.5 T, current density: 250 A/mm

W. Paul et al (1970)

1989: $\tau_n = (877.0 \pm 10)$ s

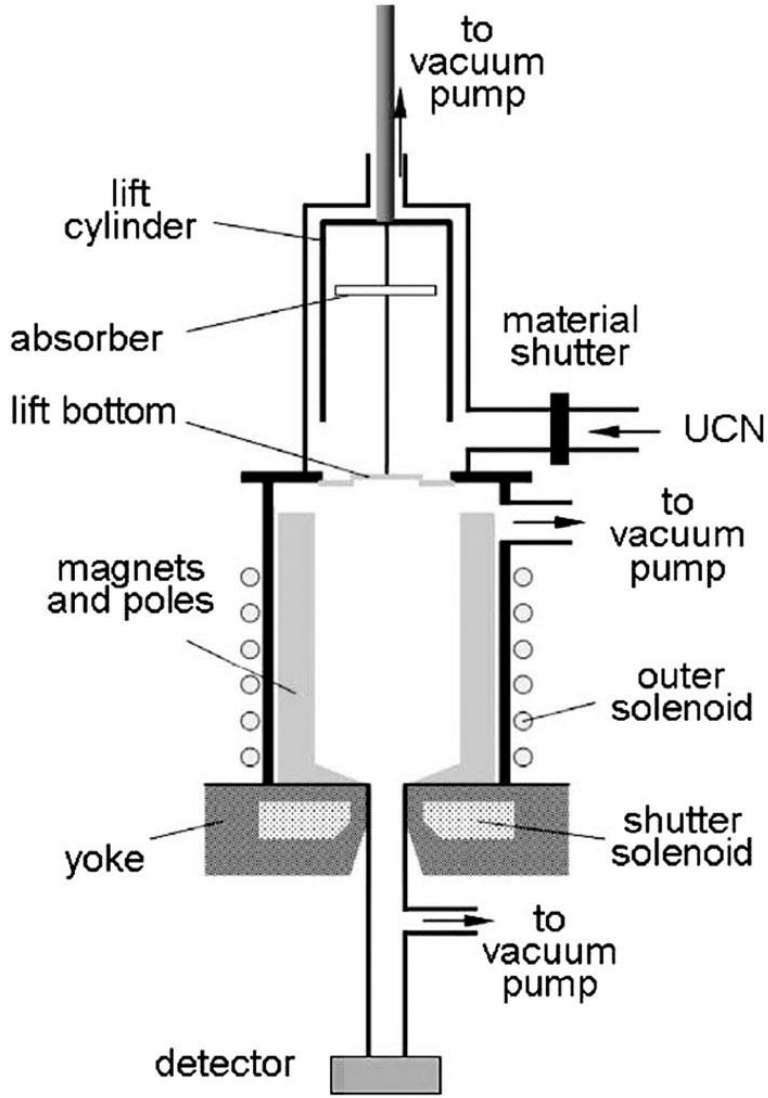
Problem: betatron motions mix with the cyclotron motion

UCN Lifetime Experiment at Institut Laue-Langevin

2004

increase storage volume from 3.6 l to **15 l**

P. Geltenbort (V. Ezhov) Universida

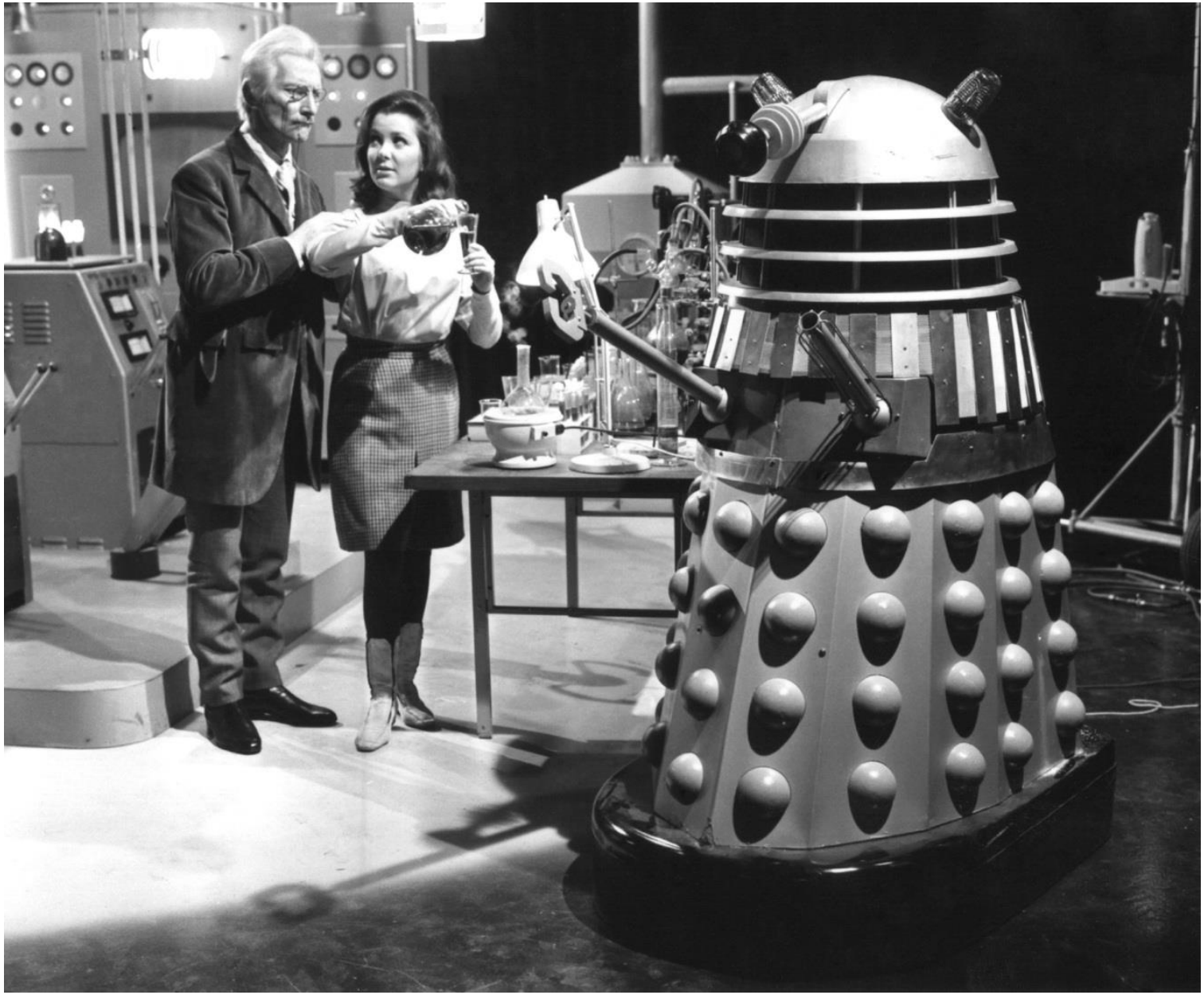


Neutrons from the ILL turbine.

Trapped with permanent magnets and gravity.

Surviving neutrons counted.

V. Ezhov *et al.*, J. Res. NIST 110 (2005) 345

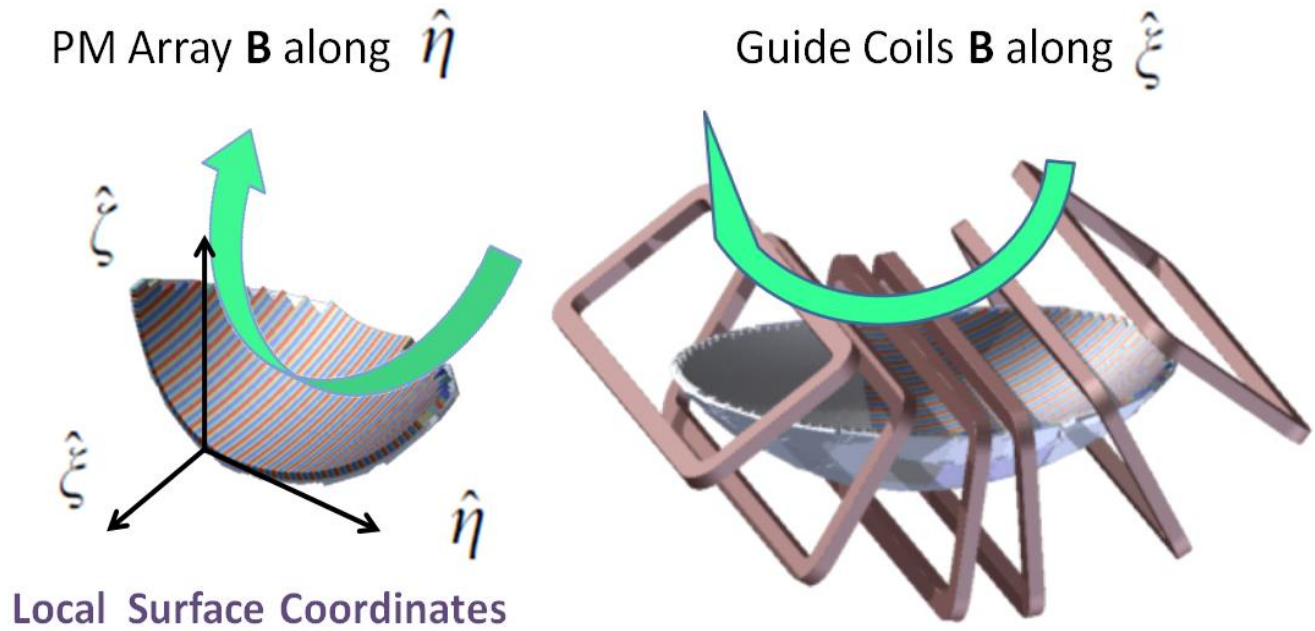


Dr. Who & a captured Dalek

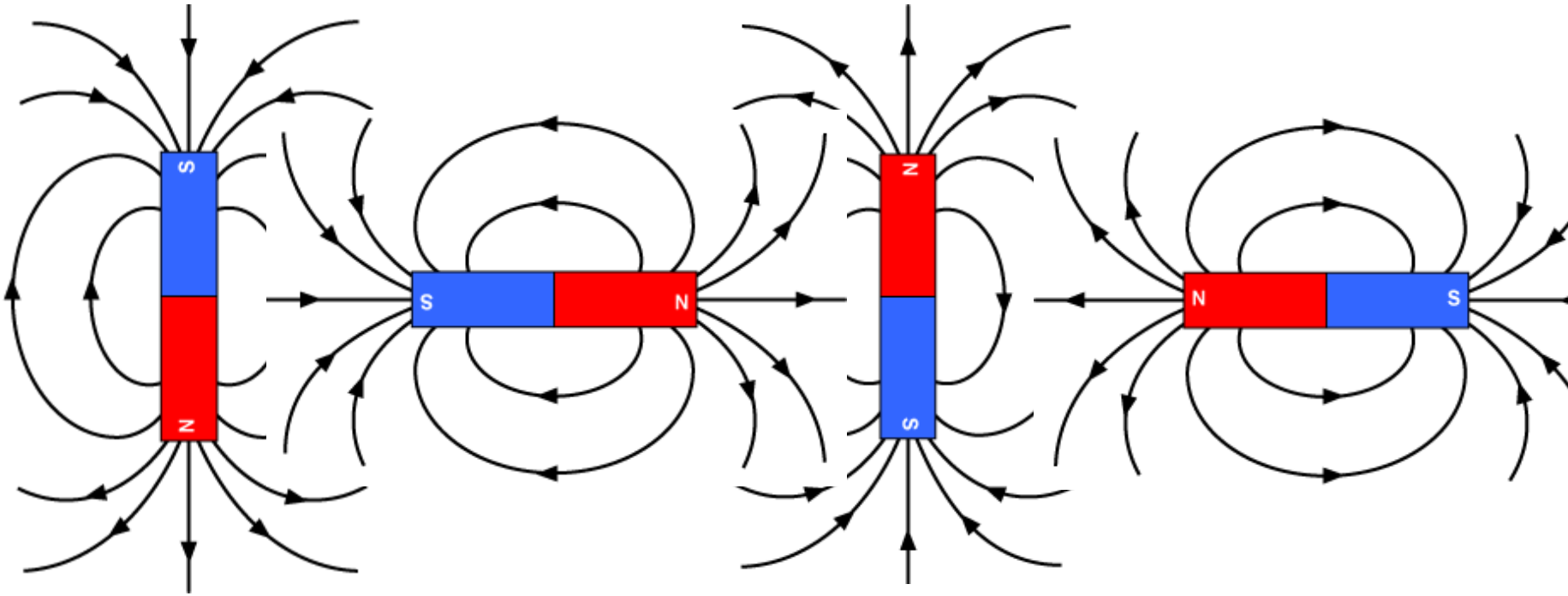
UCNτ: Magneto-Gravitational Trap

- **Avoid material loss (magnetic trap)**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).



Halbach magnetic array

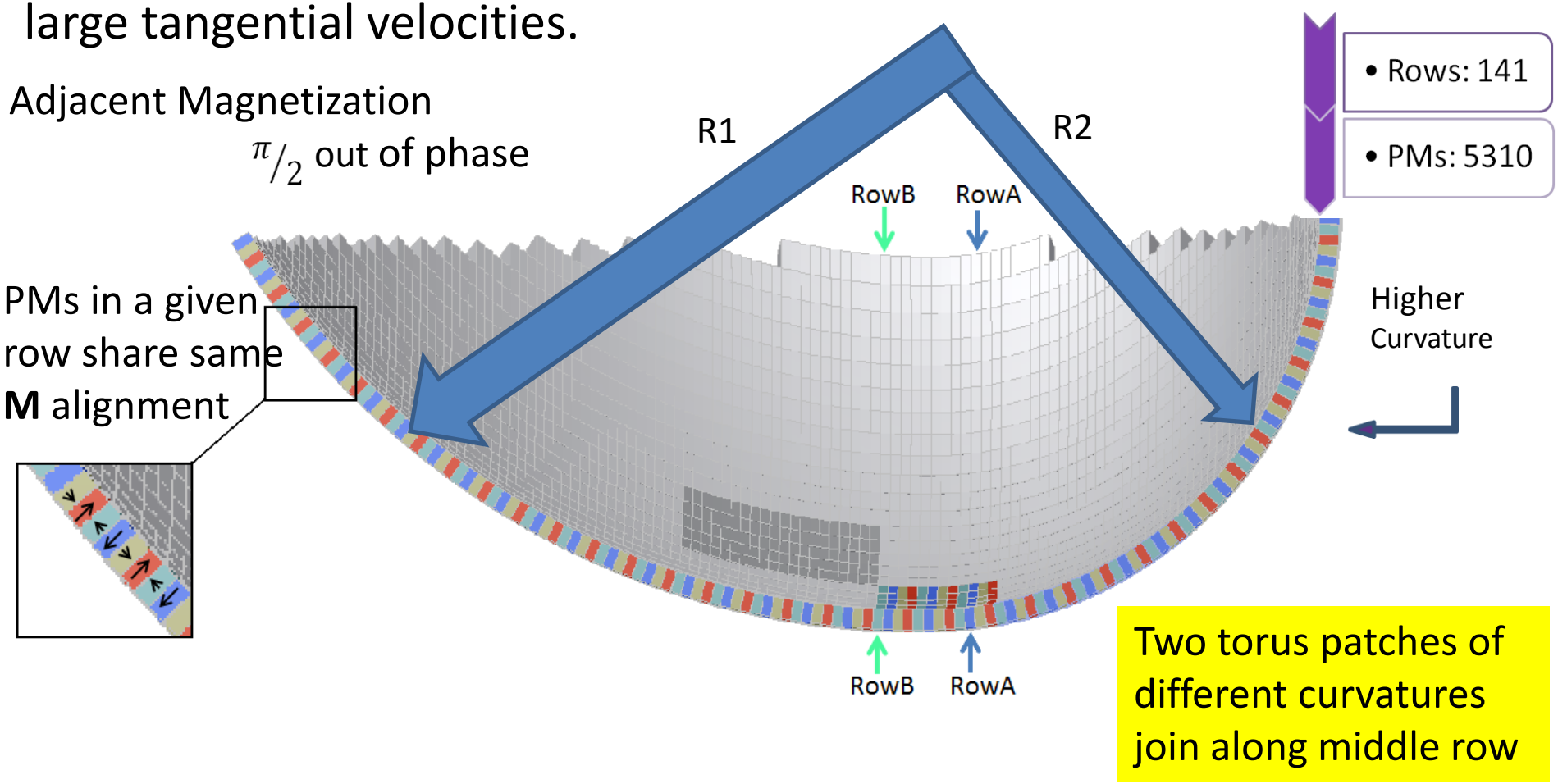


Fields on the top are enhanced.
Fields on the bottom are cancelled.

Asymmetric Trap induces ``Phase Space Mixing”

Low symmetry, together with **field ripples**, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

→ **quick cleaning** (~ 10s of seconds) of the ‘quasi-bound’ UCN with large tangential velocities.

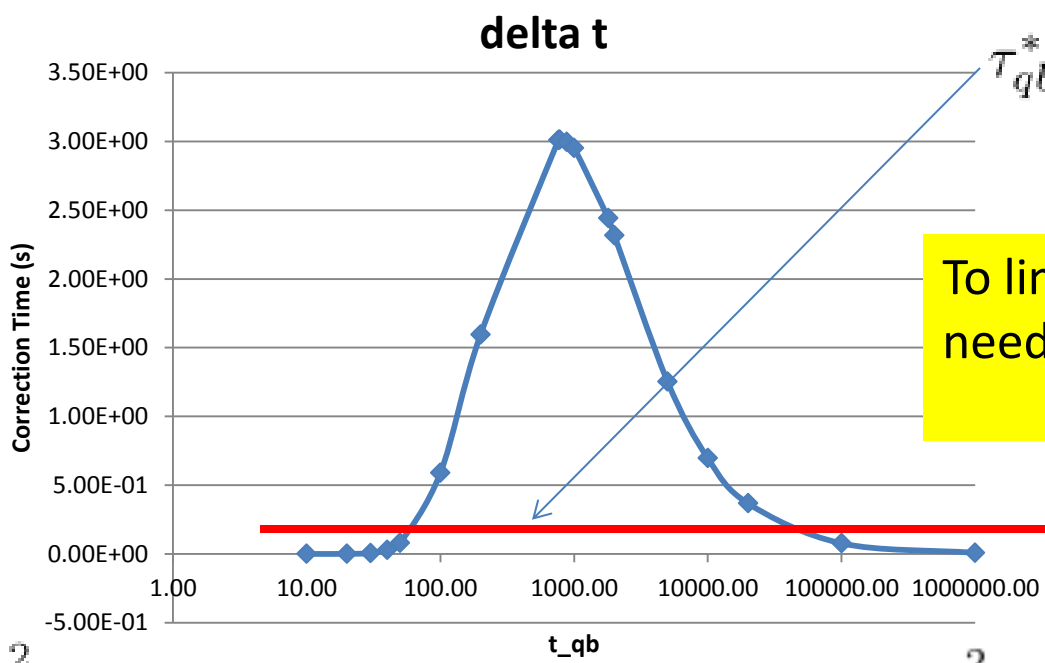


Quasi-bound Neutrons

If the QB neutrons are not sufficiently cleaned, they will leak out of the trap with its own characteristic time constant τ_{qb}. The resulting correction time is:

$$\Delta\tau = \frac{\tau_\beta^2}{(t_2 - t_1)}\epsilon\left[\exp(-t_1/\tau_{qb}) - \exp(-t_2/\tau_{qb})\right]$$

t_2 = 2000 s
t_1 = 200 s
ε = 0.01



$$\tau_{qb}^* = \frac{t_2 - t_1}{\ln(\frac{t_2}{t_1})}$$

To limit $\Delta t < 0.1$ s for all τ_{qb}, need $\varepsilon < 3e\text{-}4$

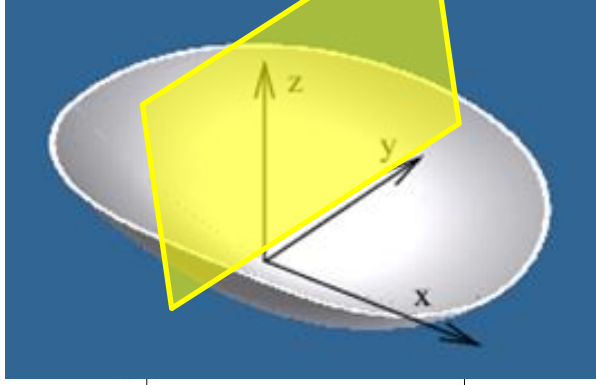
$\Delta t = 0.1$ s

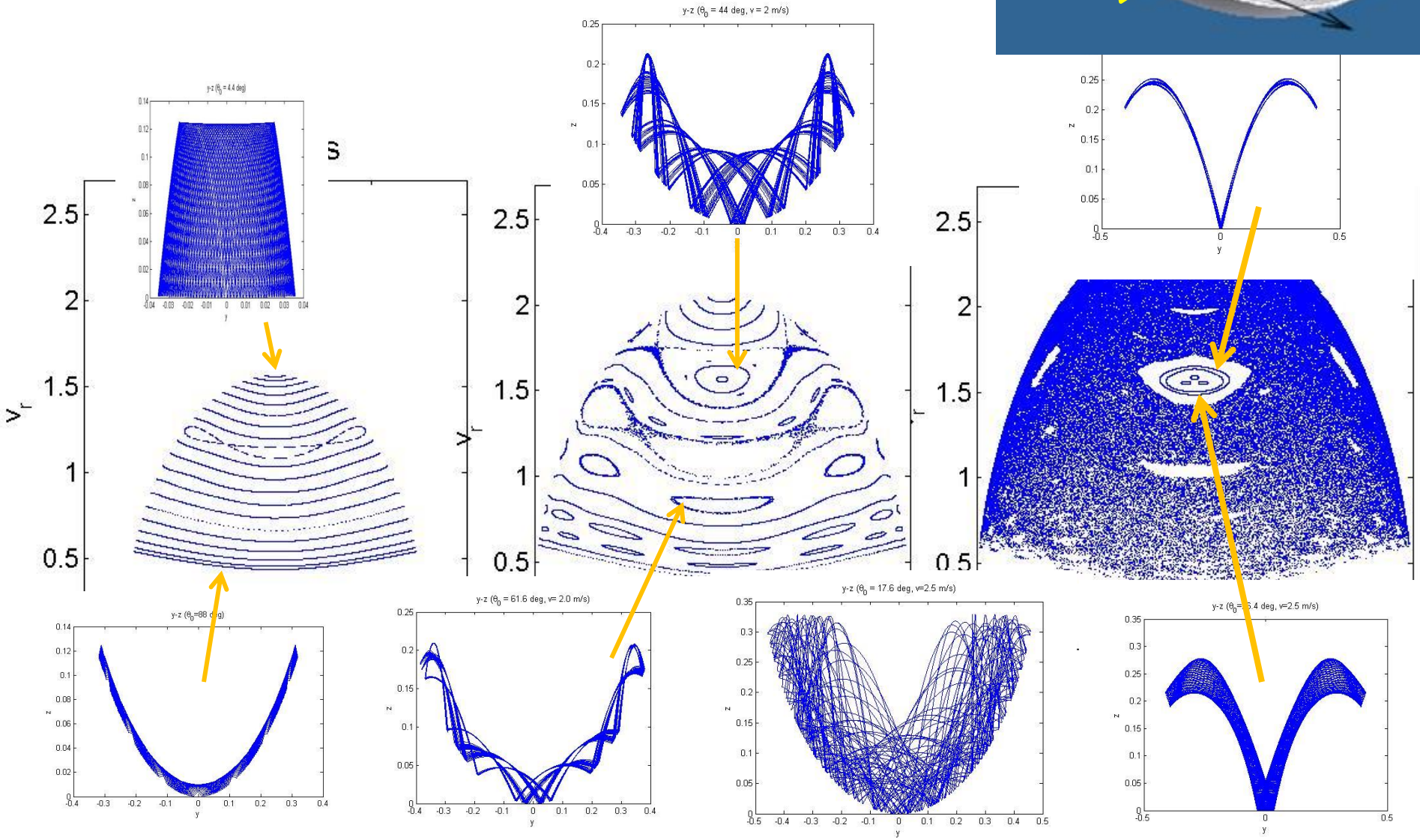
$$\Delta\tau \cong \frac{\tau_\beta^2 \epsilon \tau_{qb}}{t_1 t_2} \text{ for } \tau_{qb} \to 0$$

$$\Delta\tau \cong \frac{\tau_\beta^2 \epsilon}{\tau_{qb}} \text{ for } \tau_{qb} \to \infty$$

Poincare's Section of Surface

Two degrees of freedom

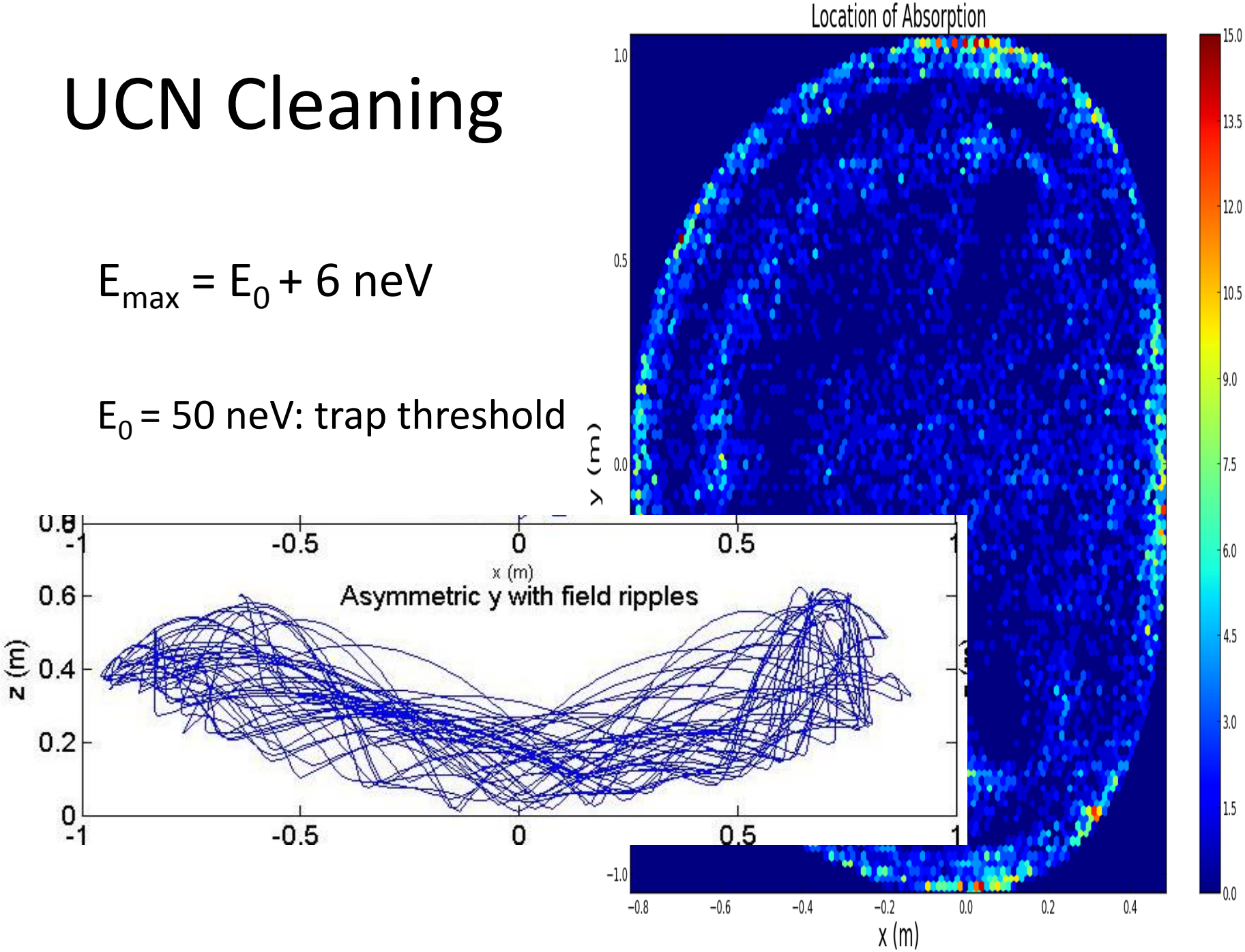




UCN Cleaning

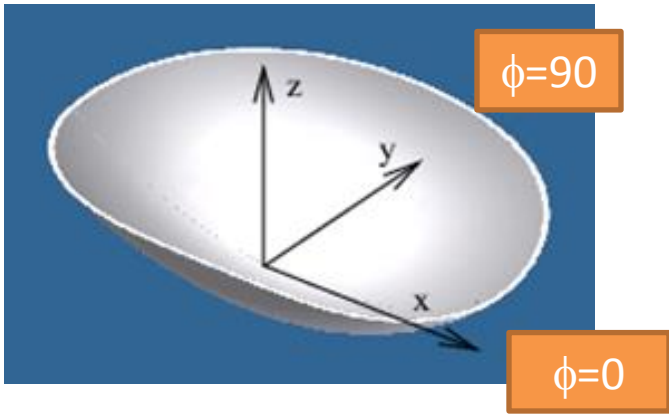
$E_{max} = E_0 + 6$ neV

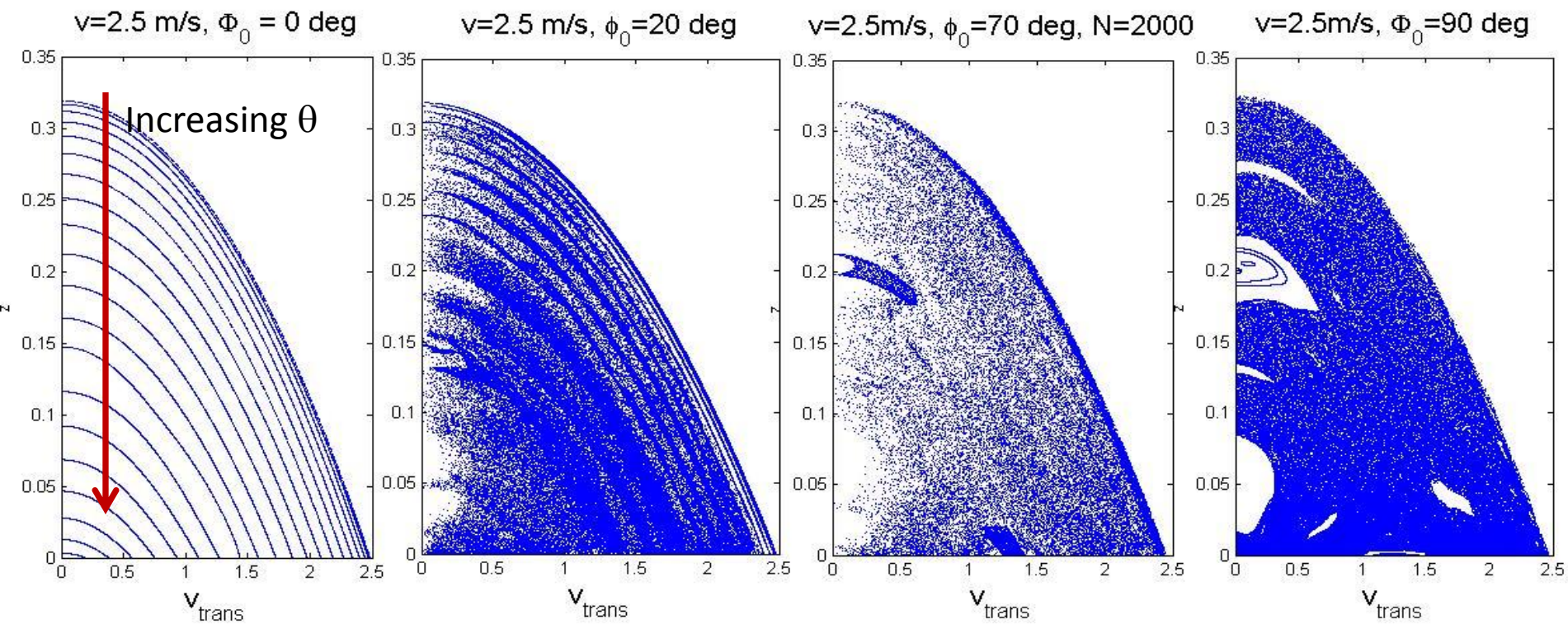
$E_0 = 50$ neV: trap threshold



Incident Angle

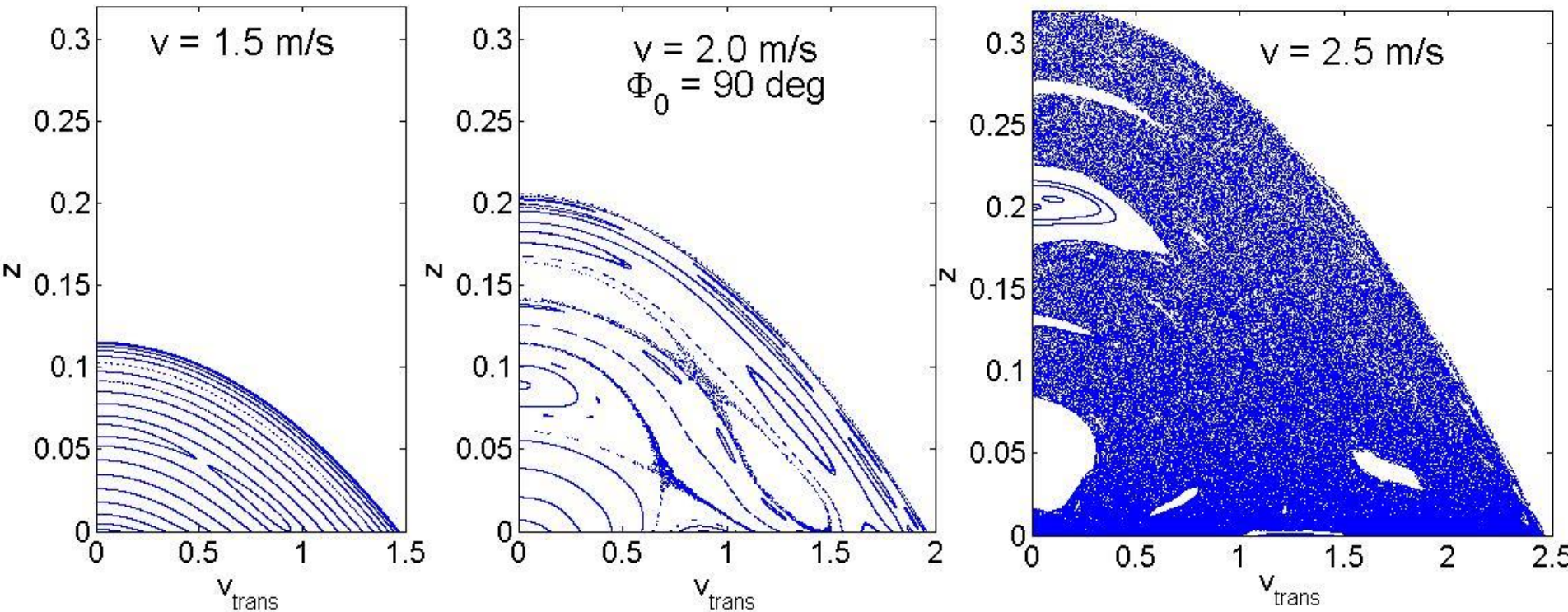
Different azimuthal angels ϕ





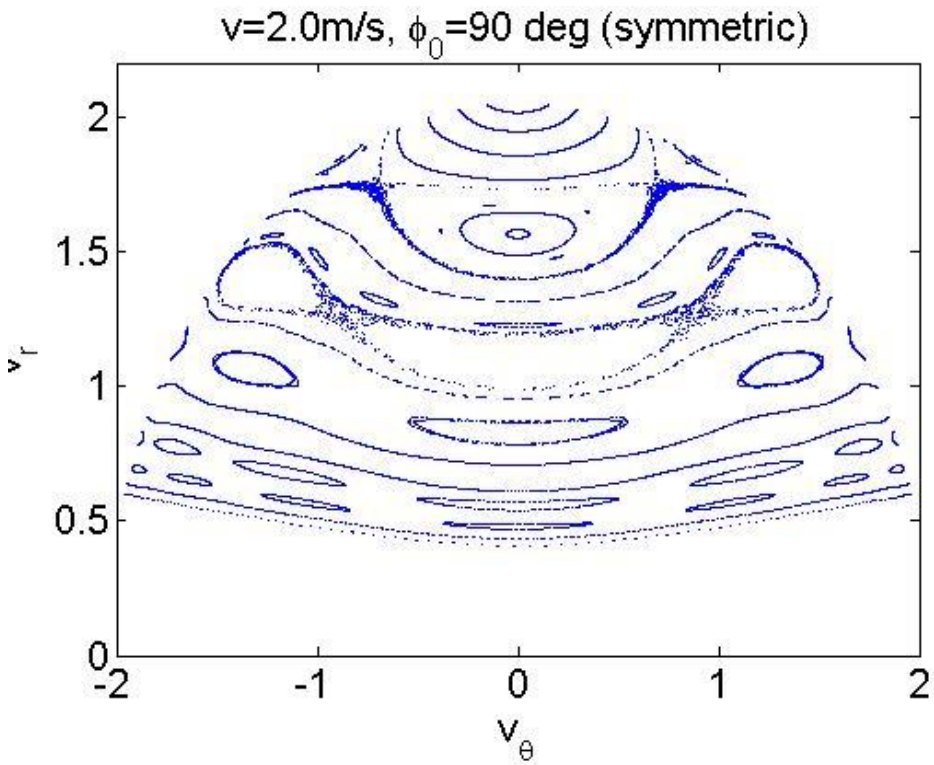
Increasing stochasticity with ϕ

Height vs. Transverse Velocity

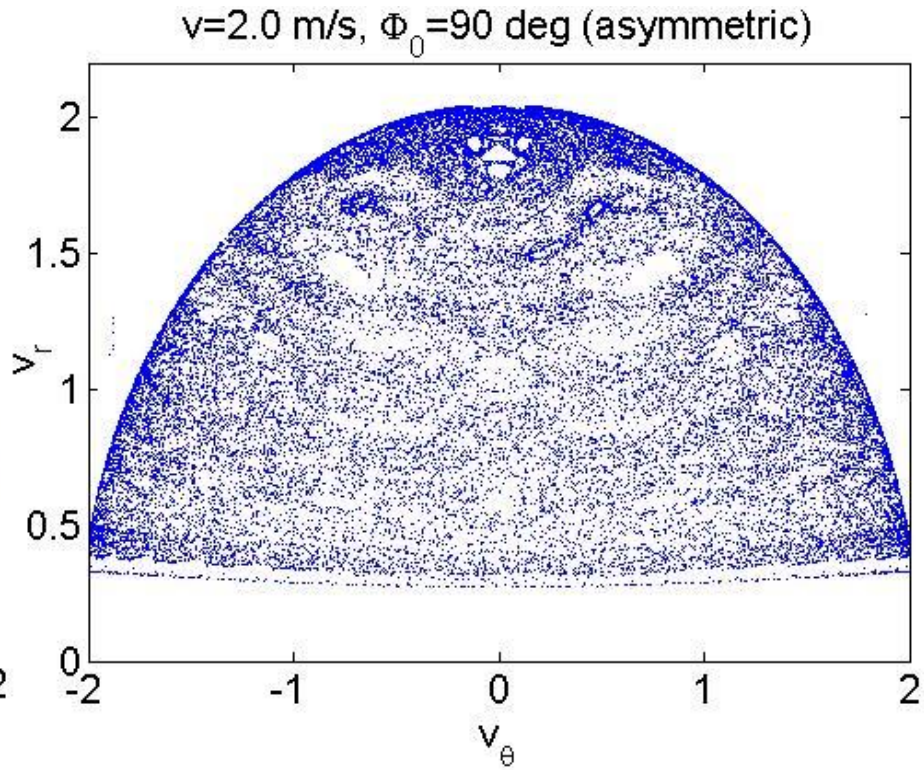


UCN motion becomes chaotic when the height reaches R/2.

Make the bowl asymmetric (R1≠R2)

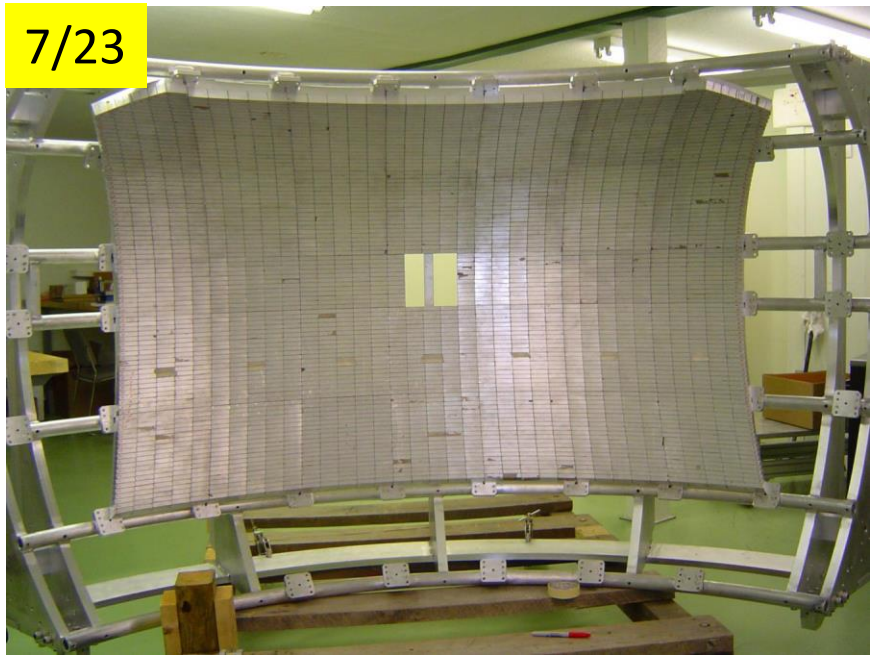


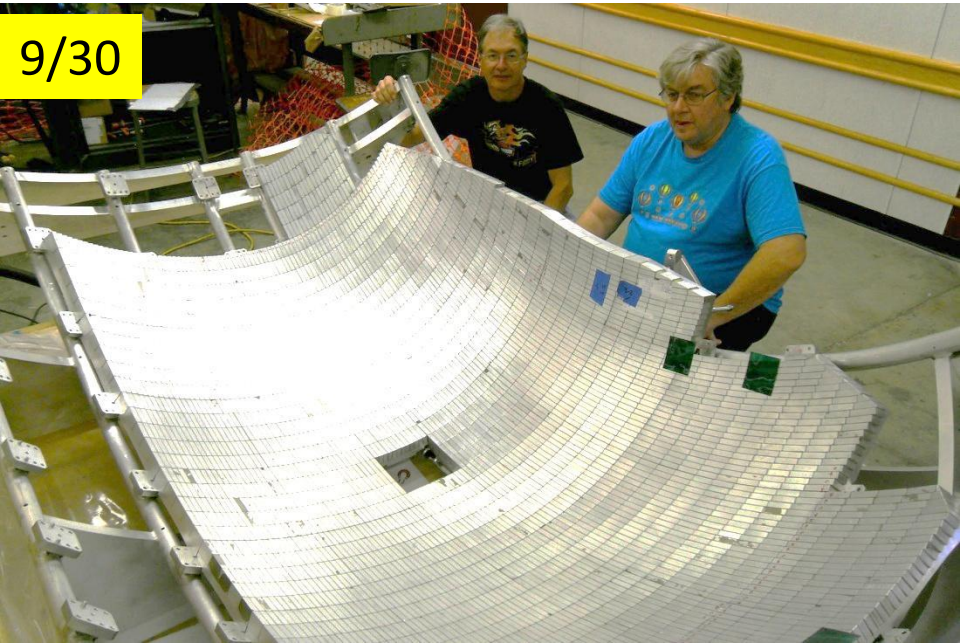
Thin stochastic regions bounded by KAM curves.

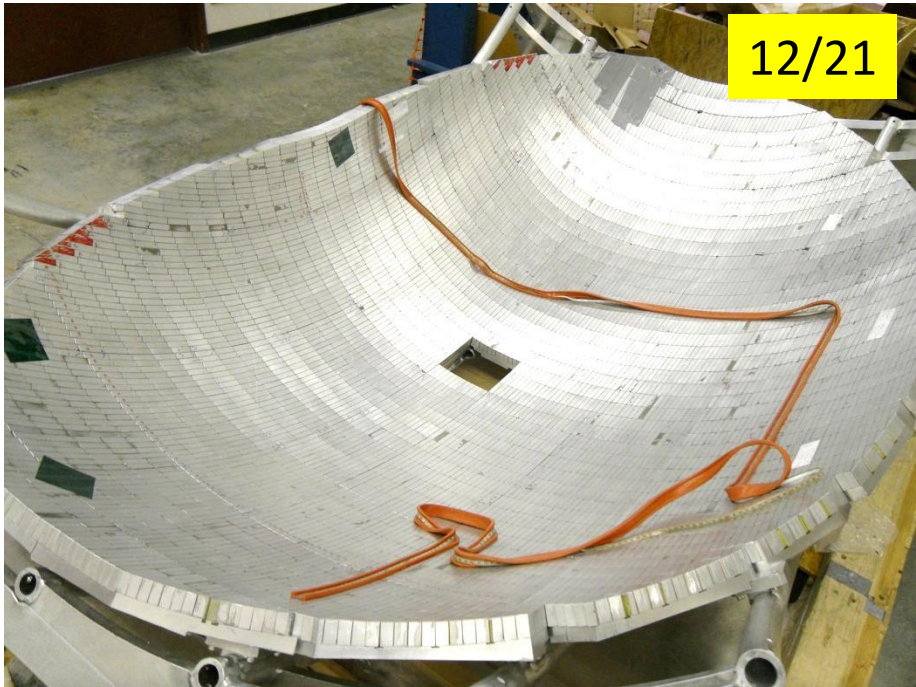


Strong perturbation, KAM curves are destroyed.

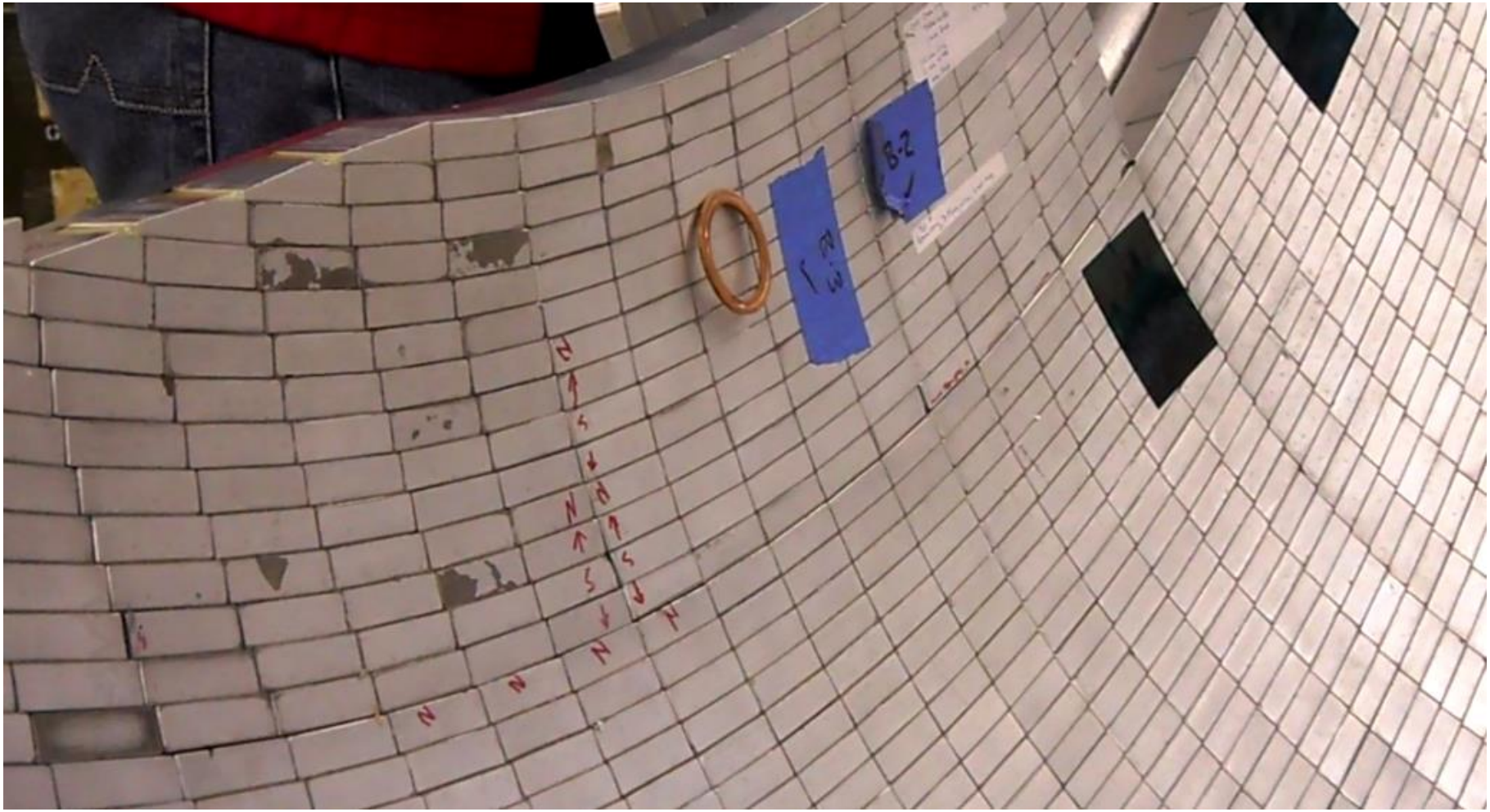
Assembly of the Halbach Array @ IU CEEM (July-Dec. 2012)



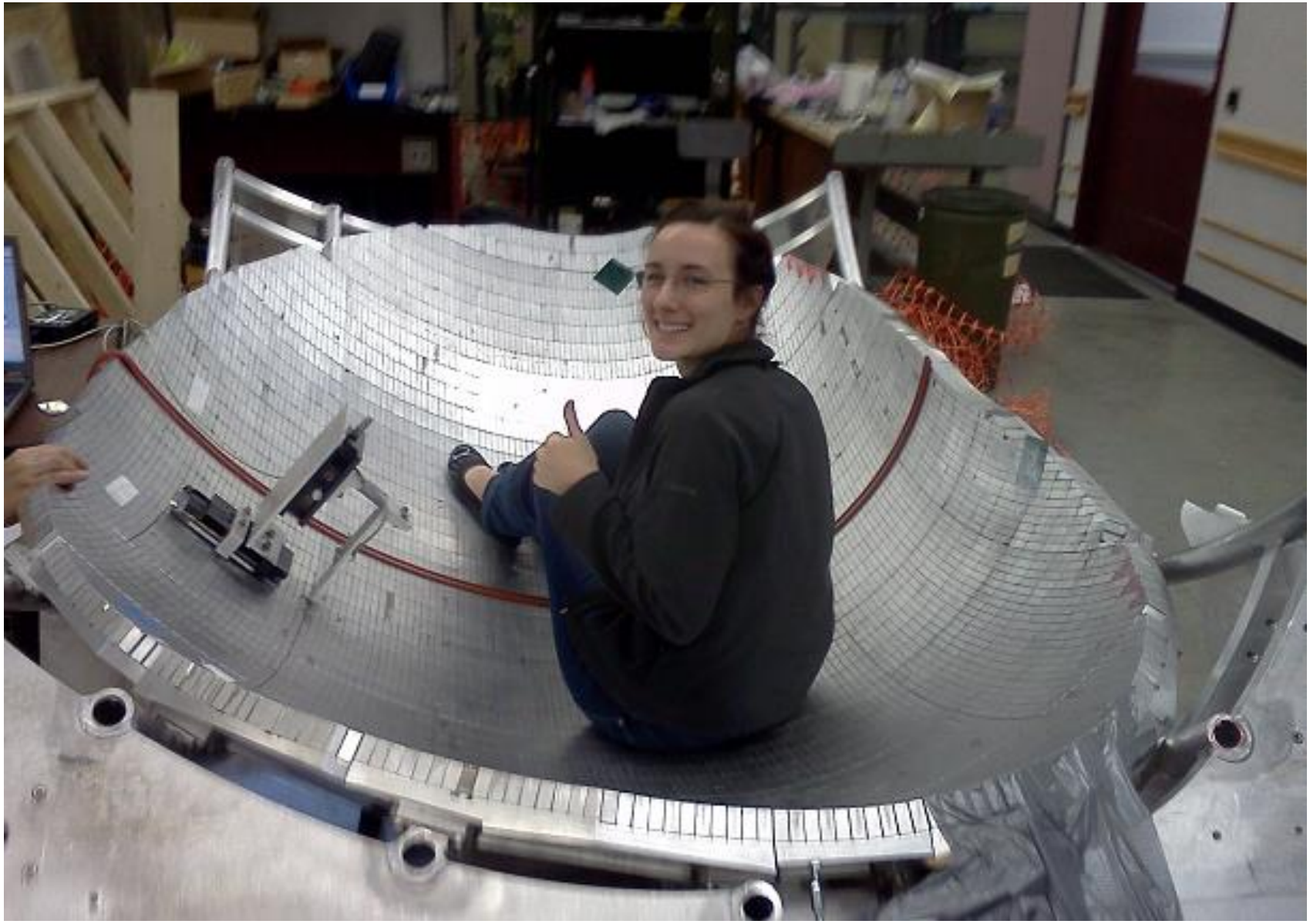




Field Ripples on the Halbach Array

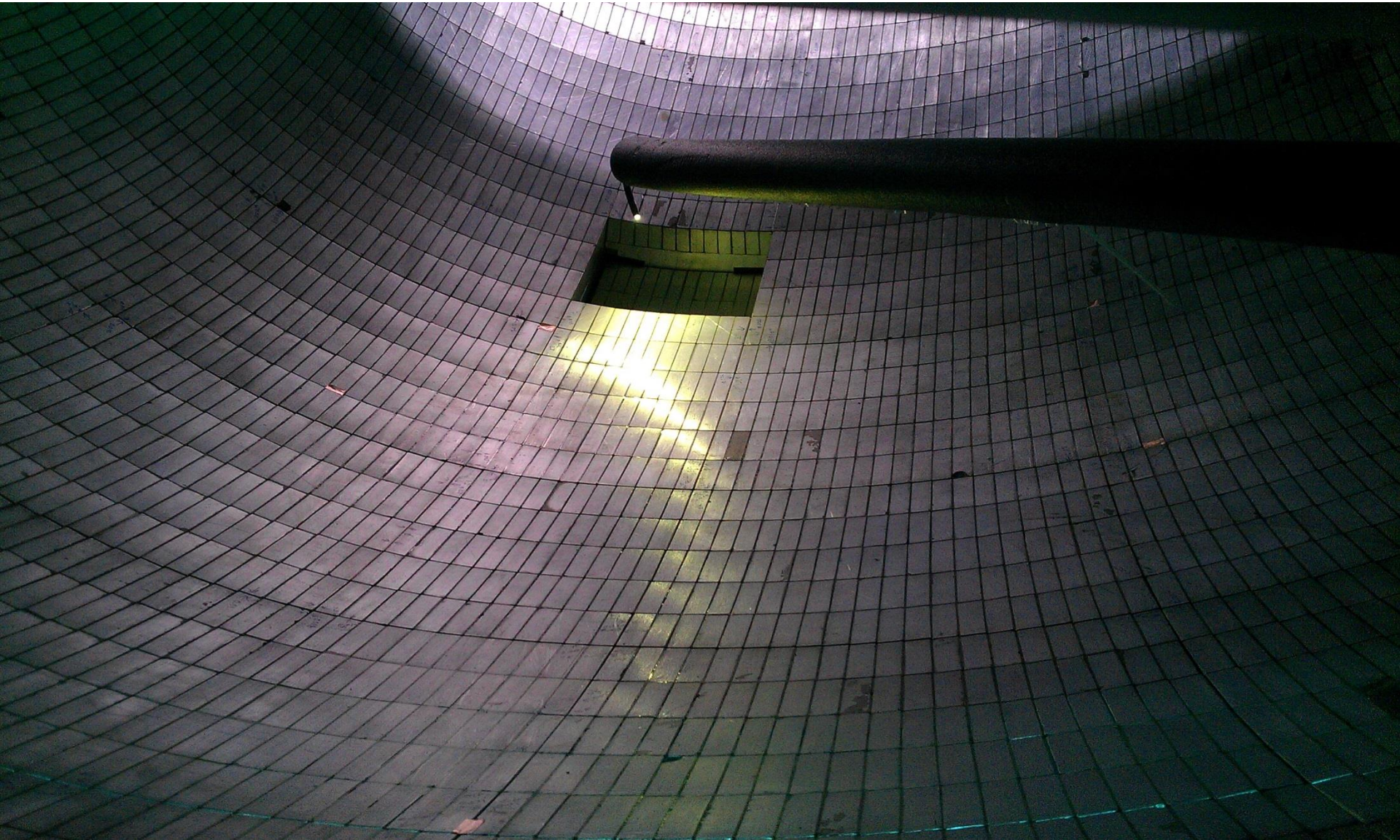


Video Video2



Array Insertion at LANL (Jan. 2013)

Halbach Array Trap + ε (copper tape)

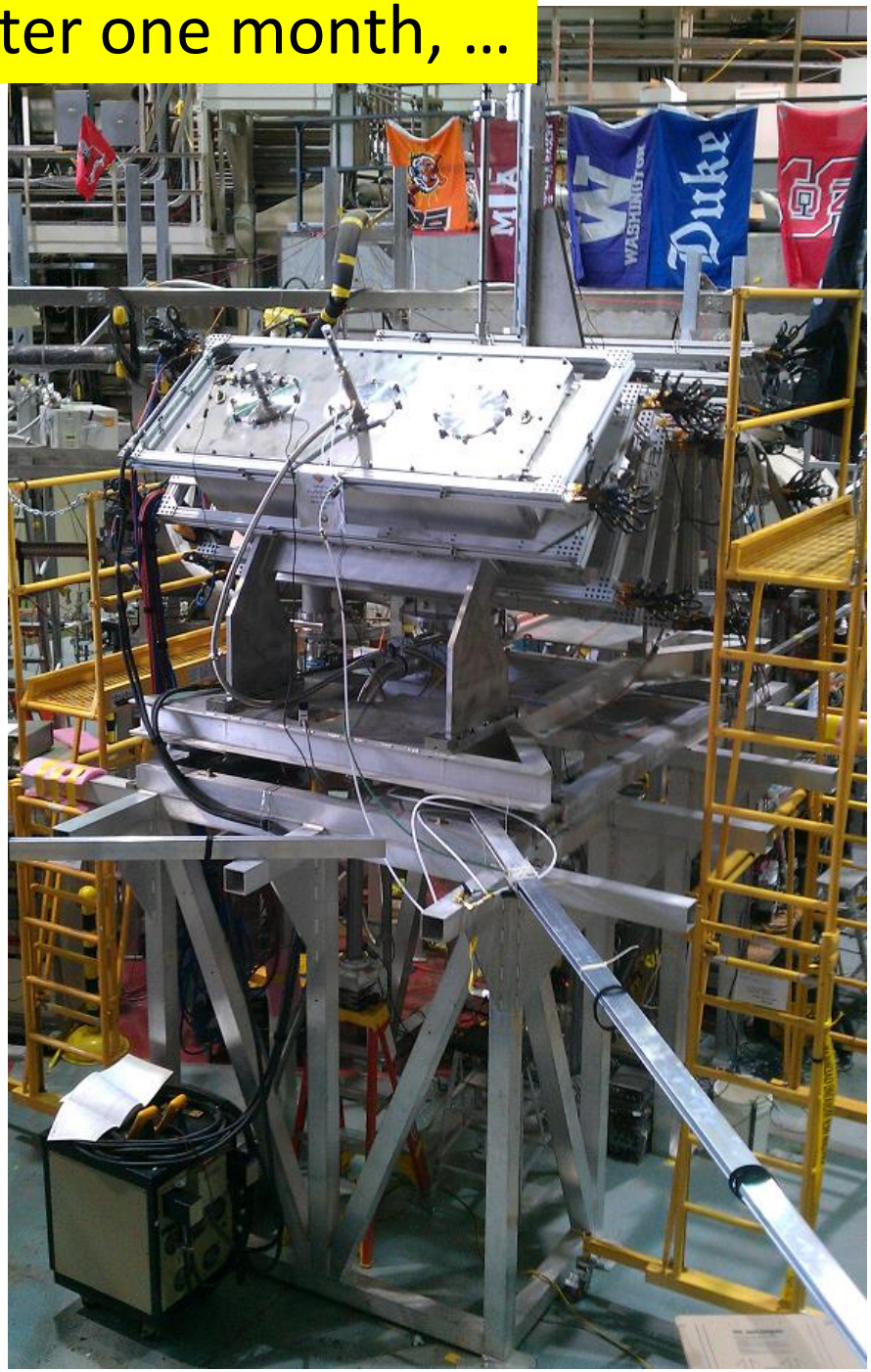


A critical component: The trap door

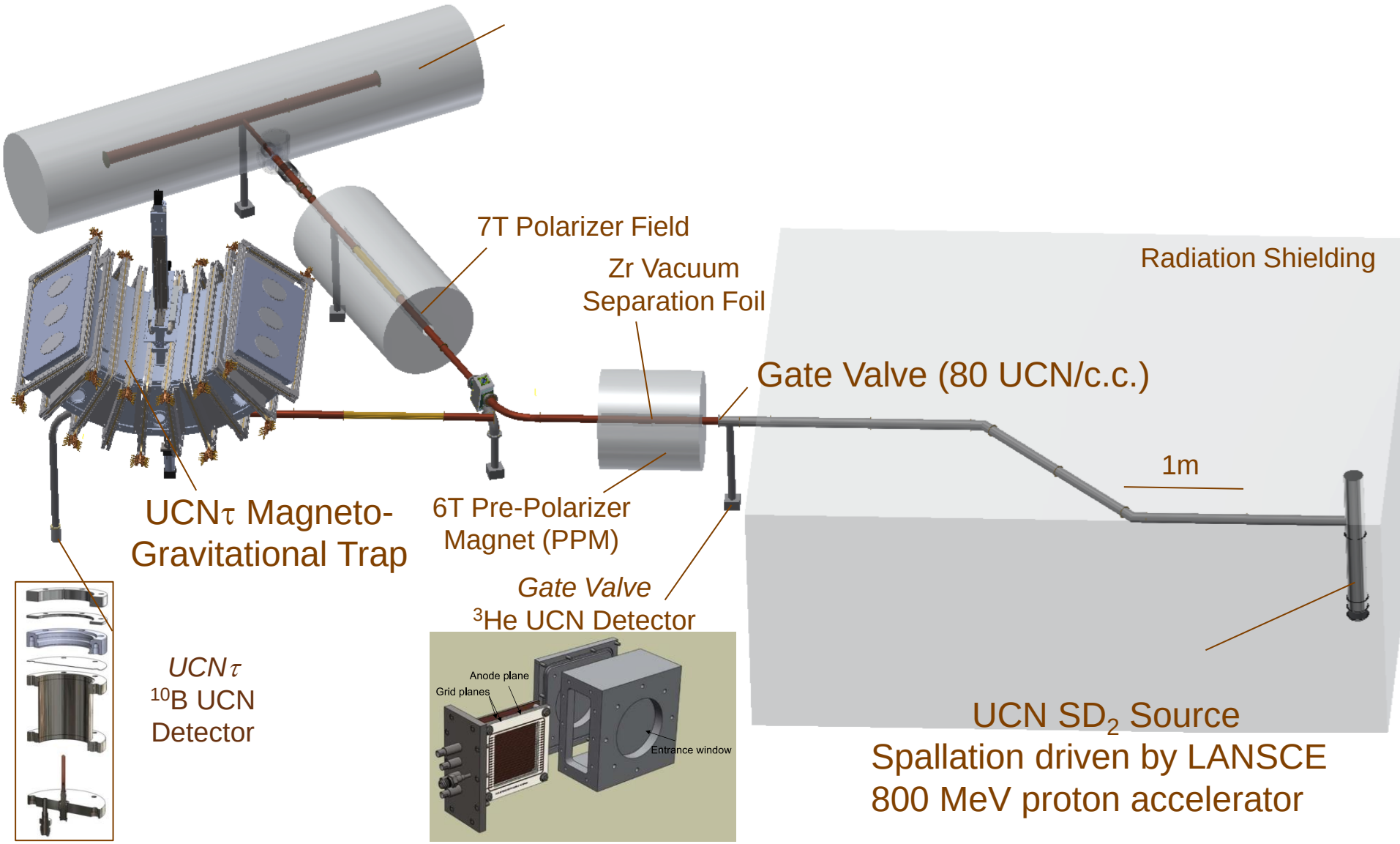
Gap size ~ 0.003 in. Don’t expect UCN to leak around the trap door.

Holding Field Coils

After one month, …



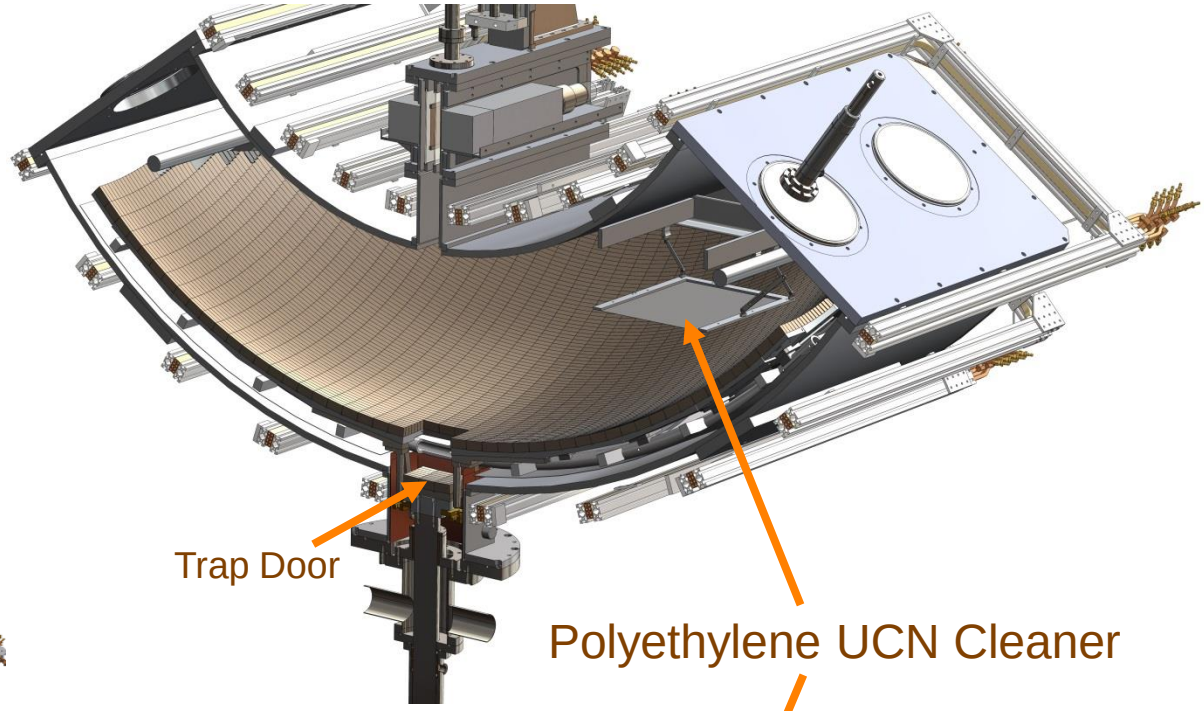
The UCNτ Experiment at LANSCE

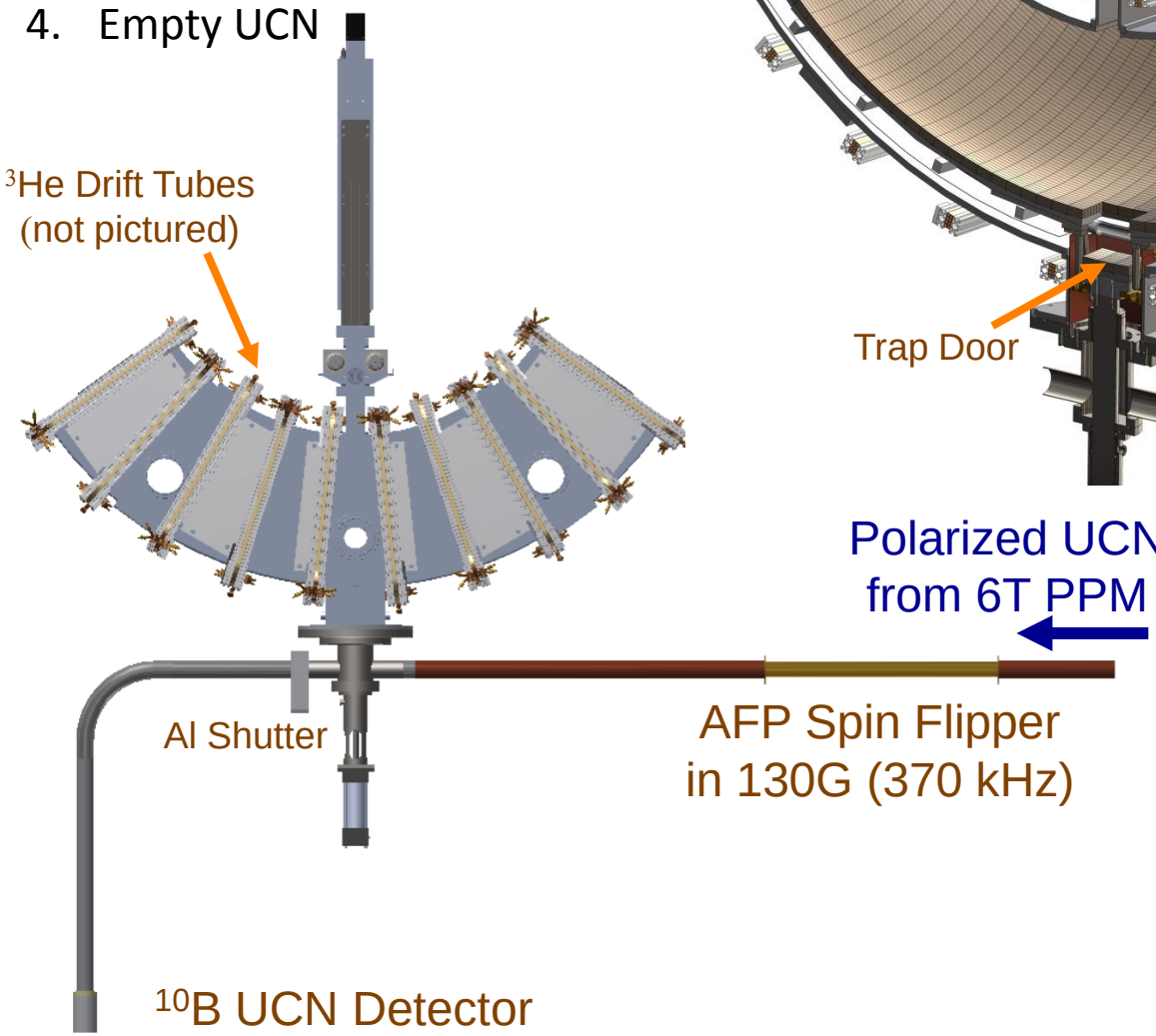


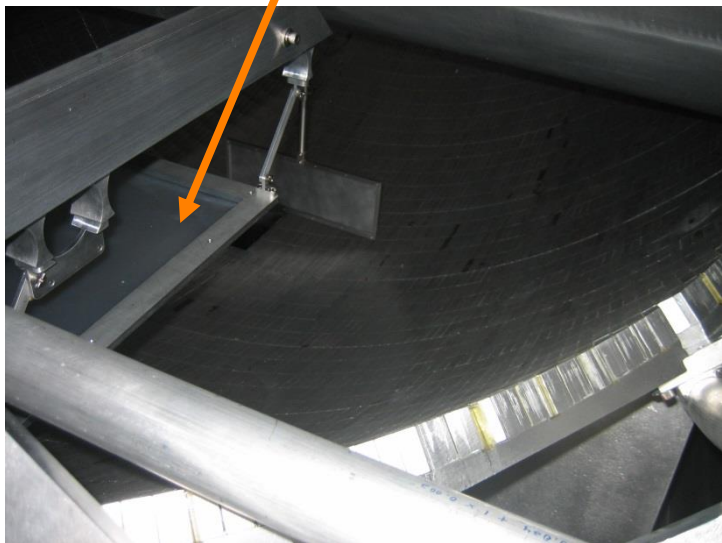
Operation of the UCNτ Experiment

"Fill & Empty" cycle

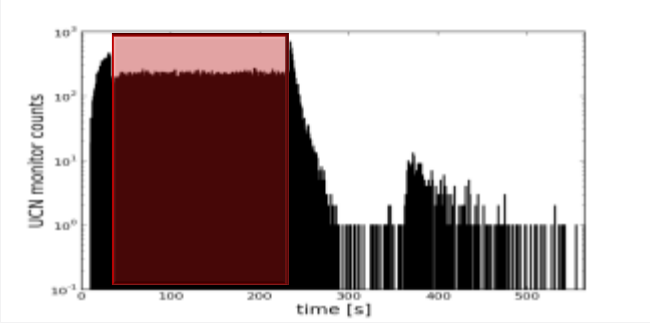
1. fill UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Empty UCN

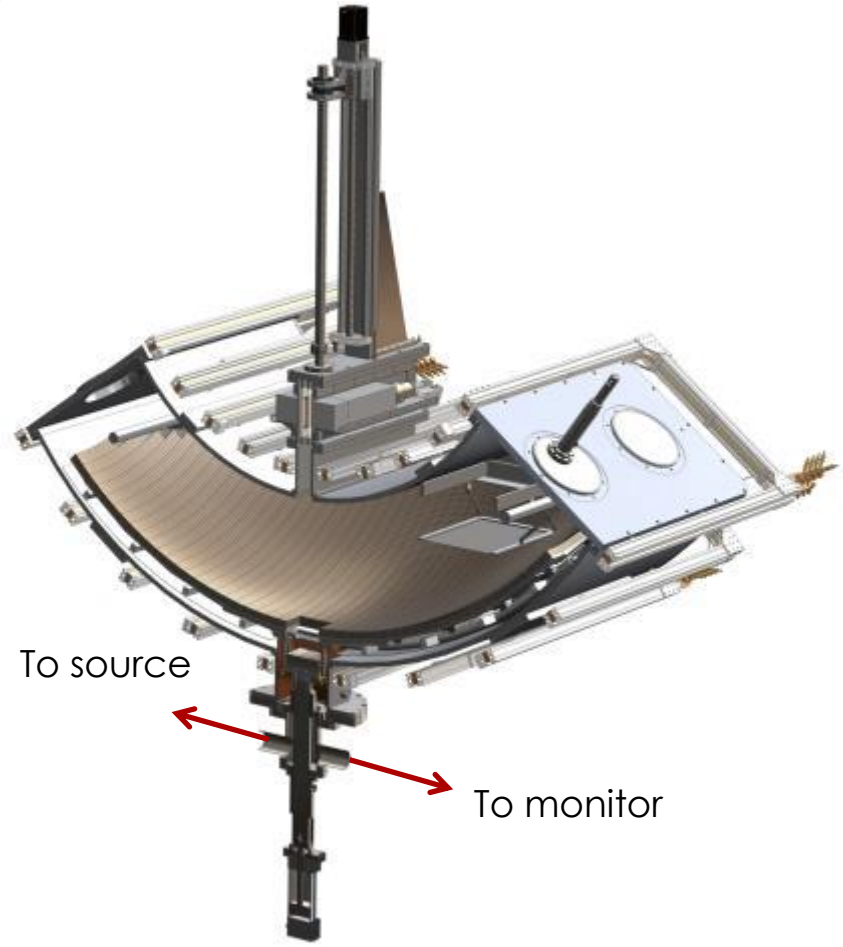




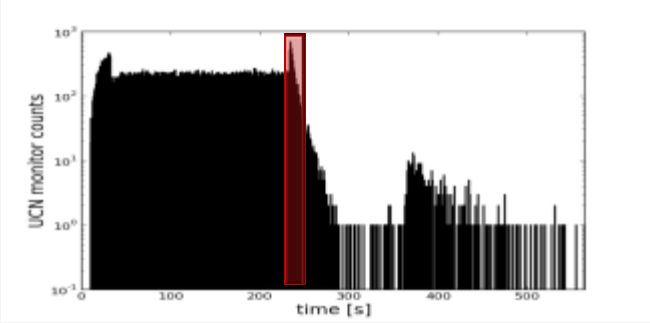


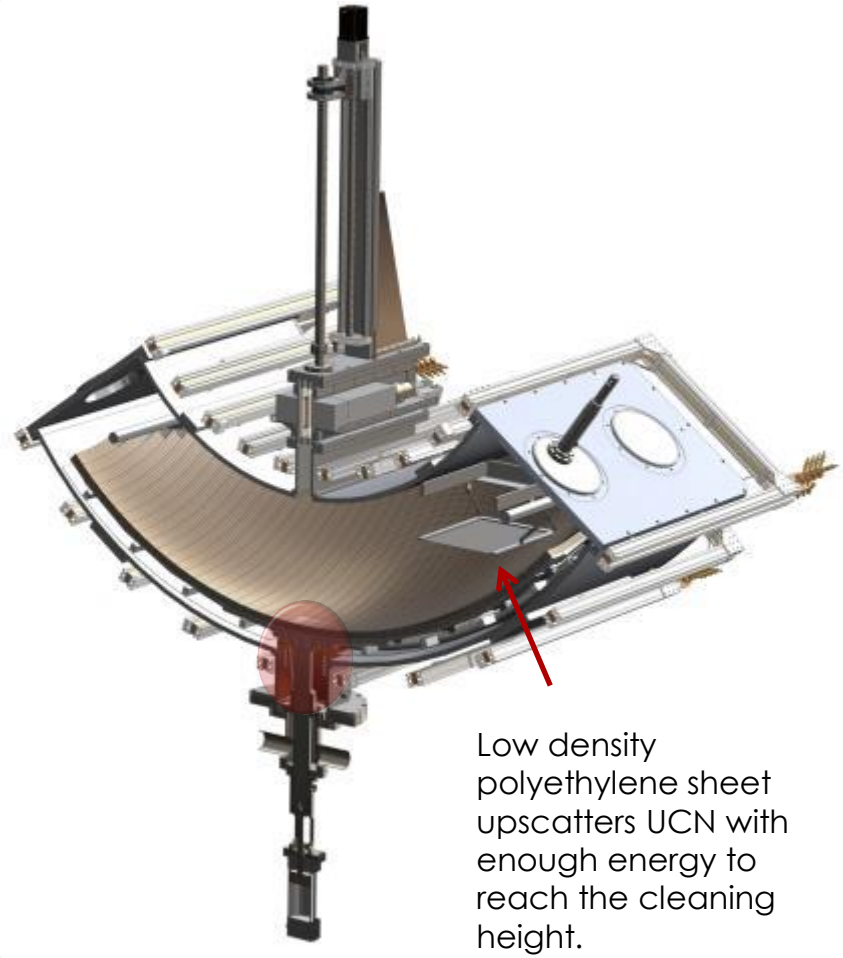
1. Fill ~200s


UCN monitor counts
time [s]
0
100
200
300
400
500

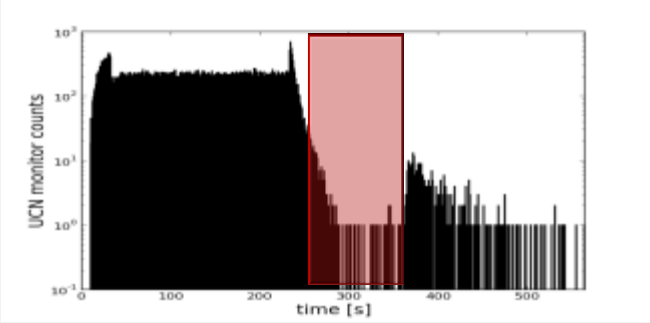

To source
To monitor

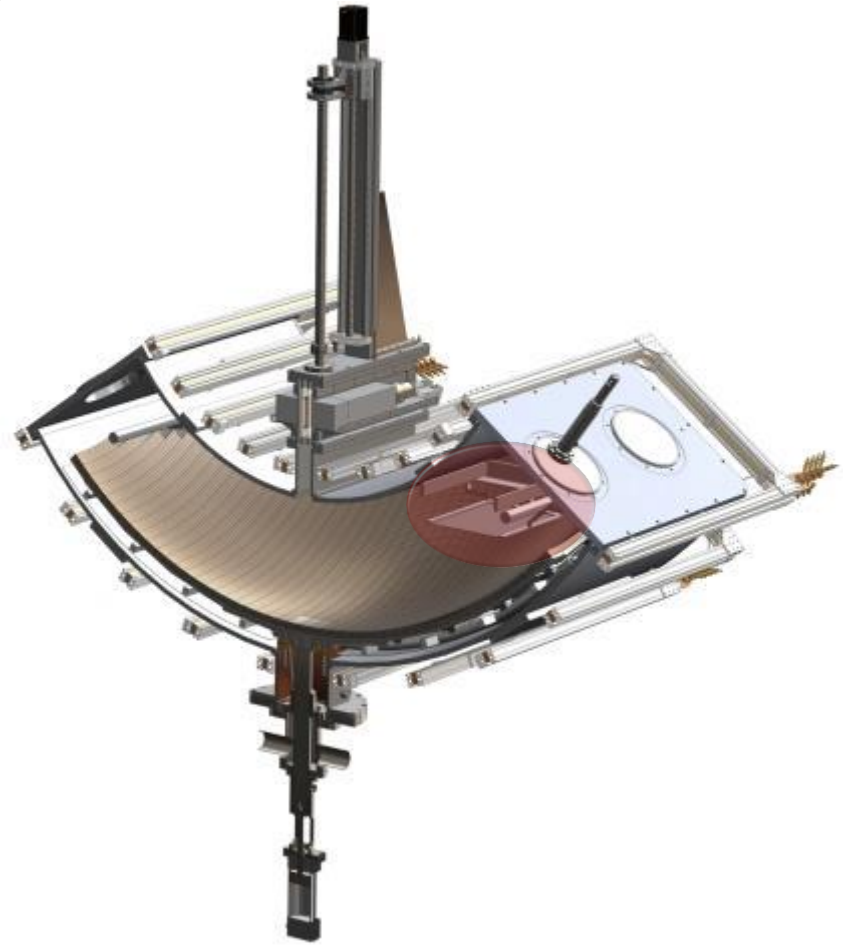
2. Clean (the E spectrum) ~30s



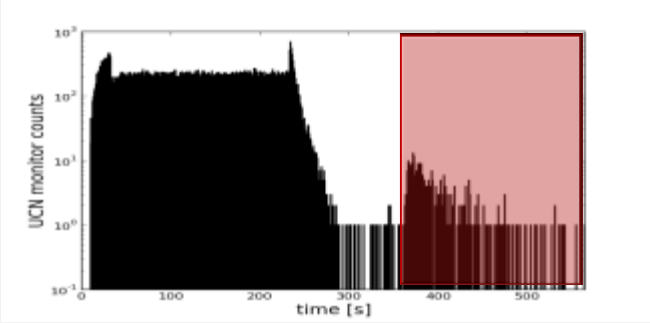


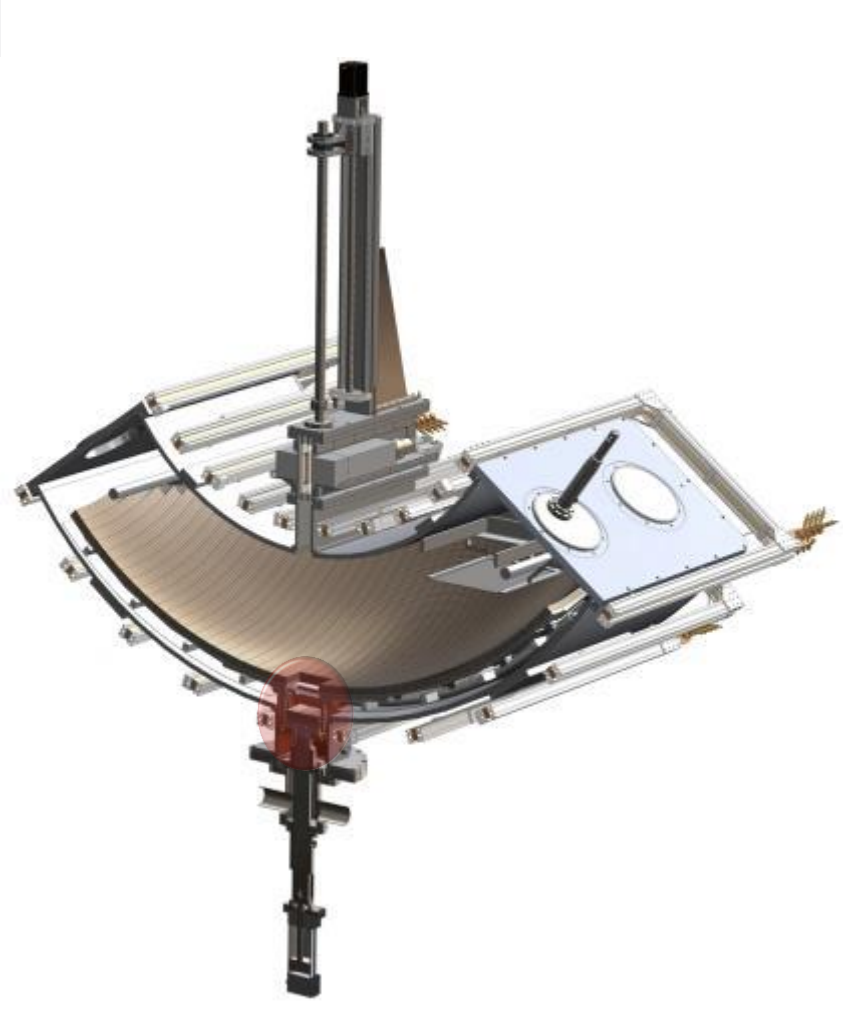
3. Store ~50-2000s





4. Dump >200s

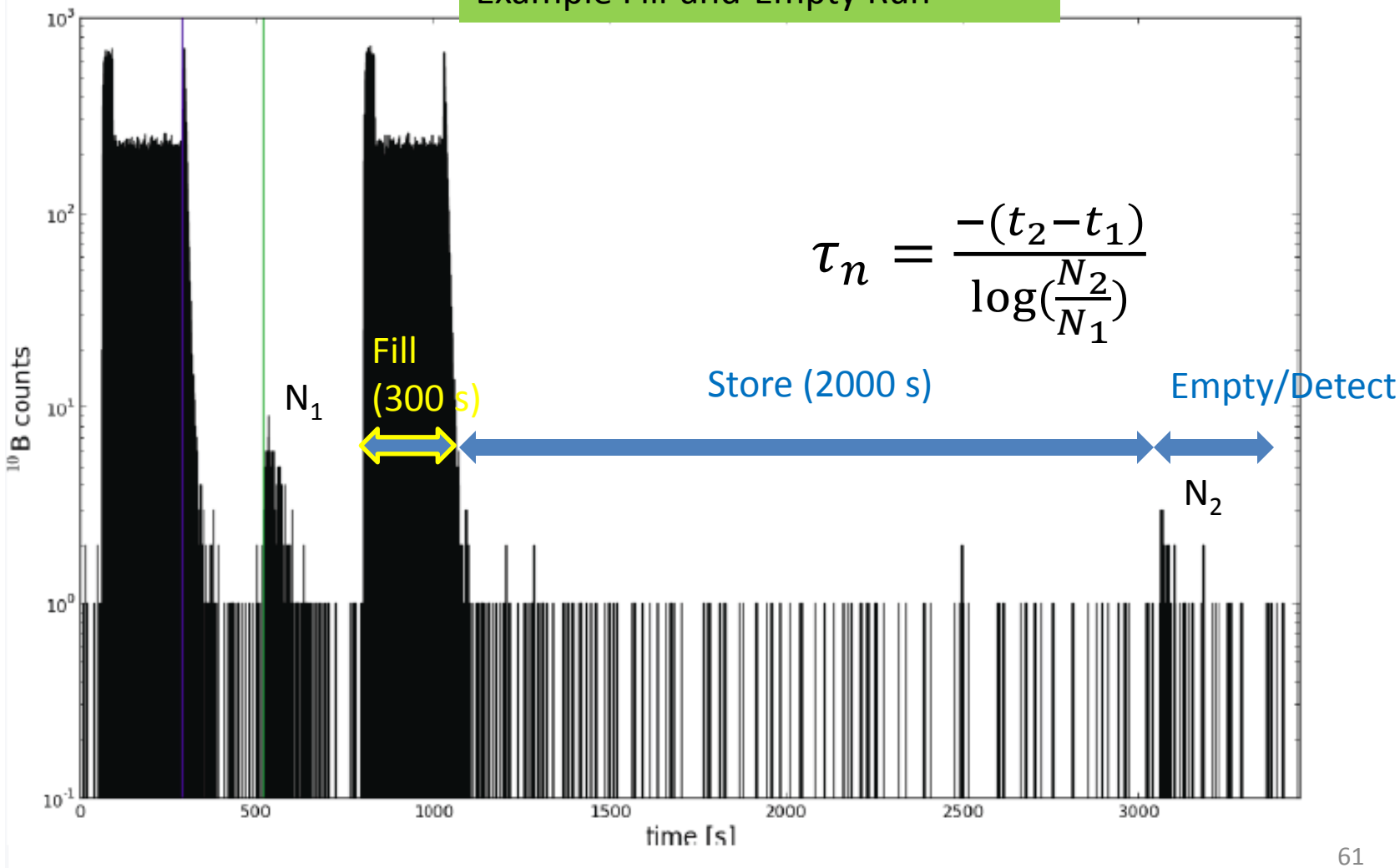




Counts in the dump detector

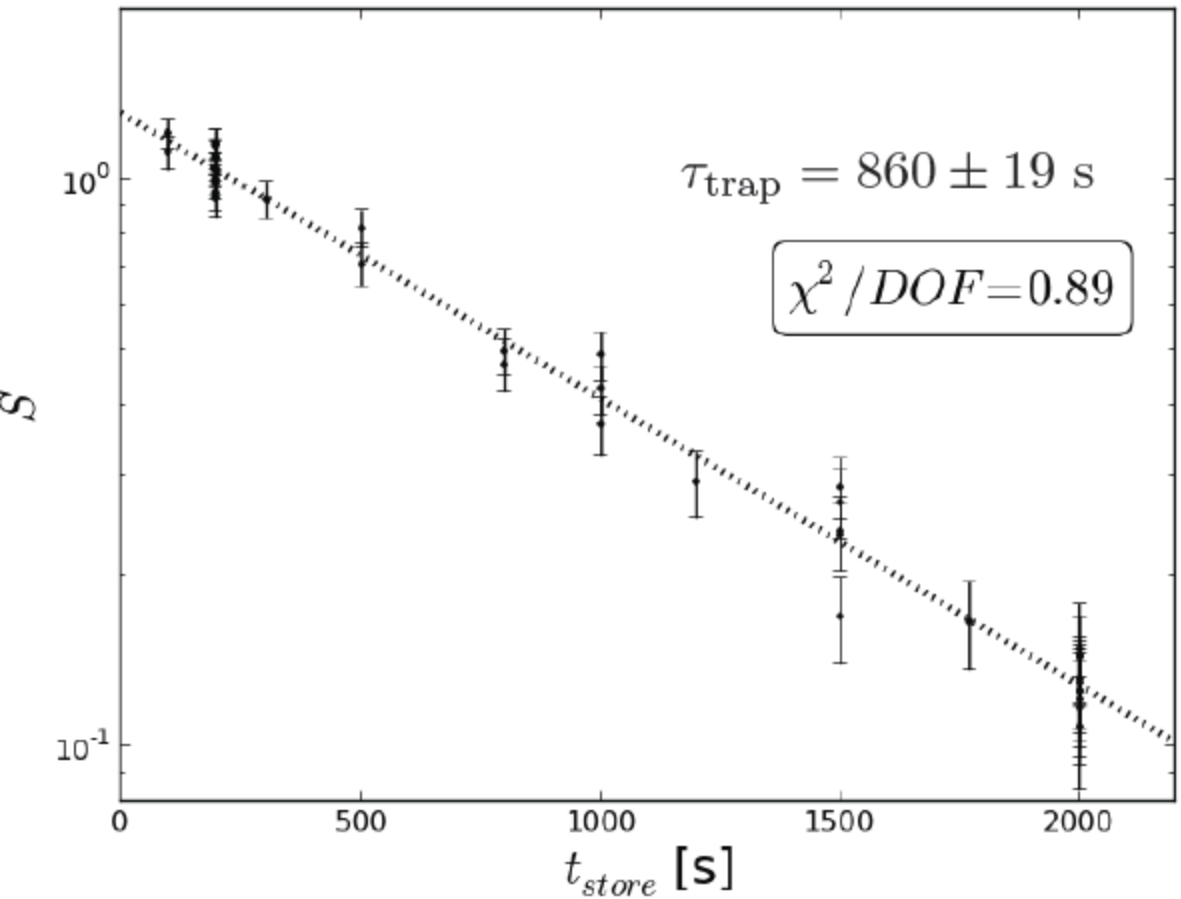
200 s storage run, followed by a 2000 second storage run

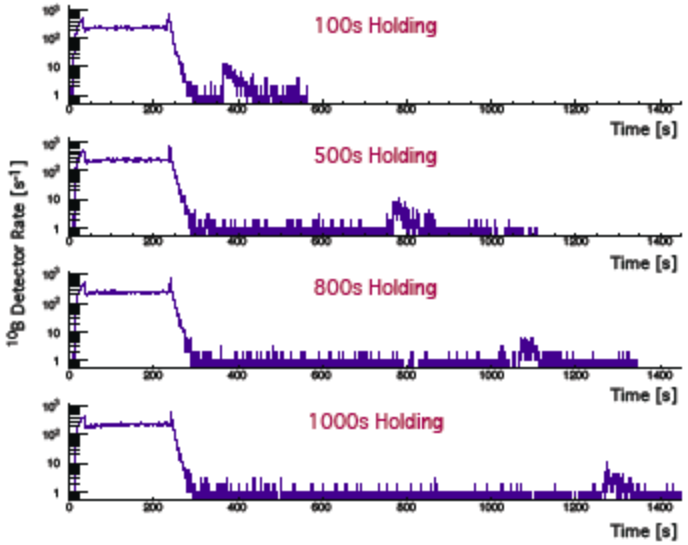
Example Fill-and-Empty Run



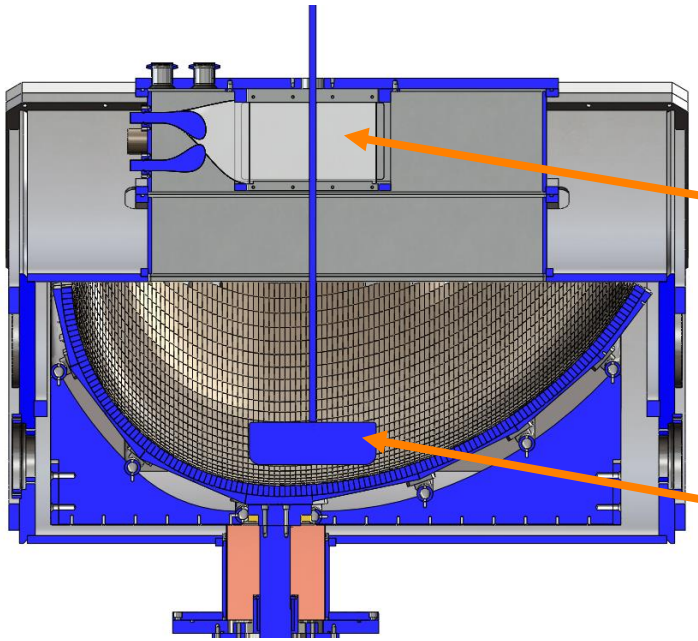
$$\tau_n = \frac{-(t_2 - t_1)}{\log(\frac{N_2}{N_1})}$$

2013 "Fill and Empty" Measurements





An *in-situ* Vanadium Detector → control phase-space evolution



Plastic Scintillator for β's

NaI for γ's

coincidence: suppress background

① V foil lowered into trap from above (~1s)
② Remaining UCN are absorbed (~20s for current small foil)
③ V foil raised and activity is measured

Neutron scattering lengths and cross sections							
Isotope	conc	Coh b	Inc b	Coh xs	Inc xs	Scatt xs	Abs xs
V	---	-0.3824	---	0.0184	5.08	5.1	5.08
50V	0.25	7.6	---	7.3(1.1)	0.5	7.8(1.0)	60.(40.)
51V	99.75	-0.402	6.35	0.0203	5.07	5.09	4.9

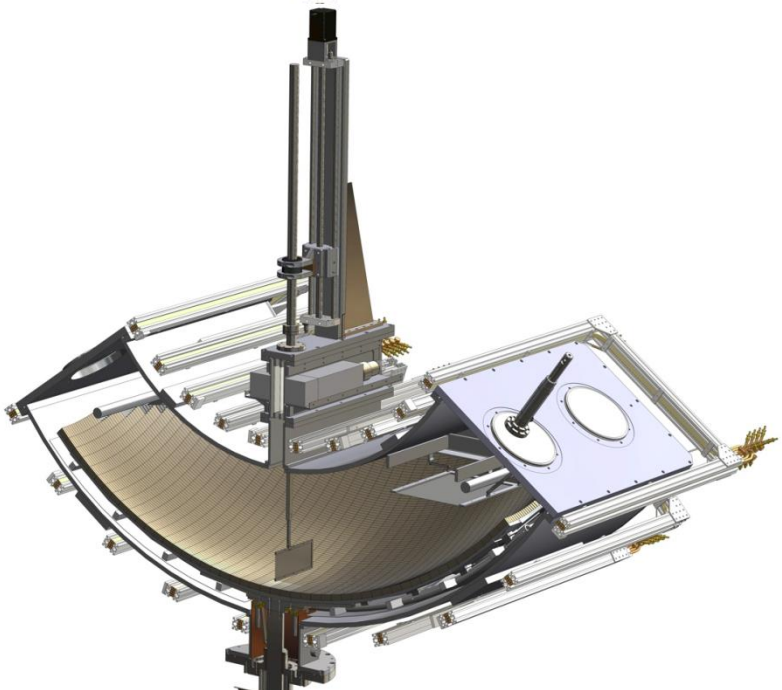
Negative Material Potential

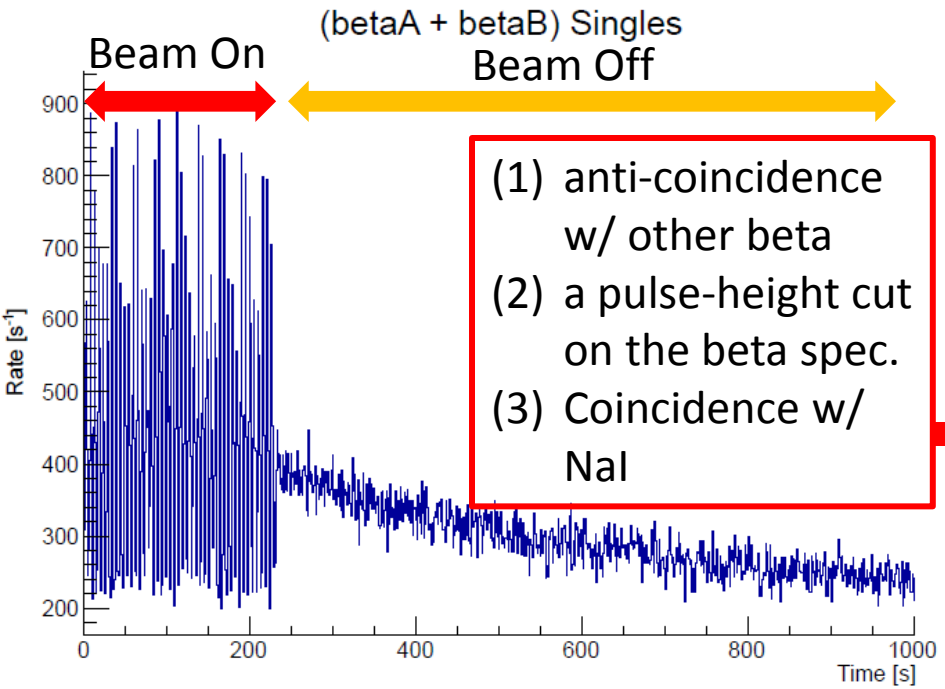
Good n Absorber

$$^{51}\mathrm{V} + \mathrm{n} \rightarrow {}^{52}\mathrm{V}$$

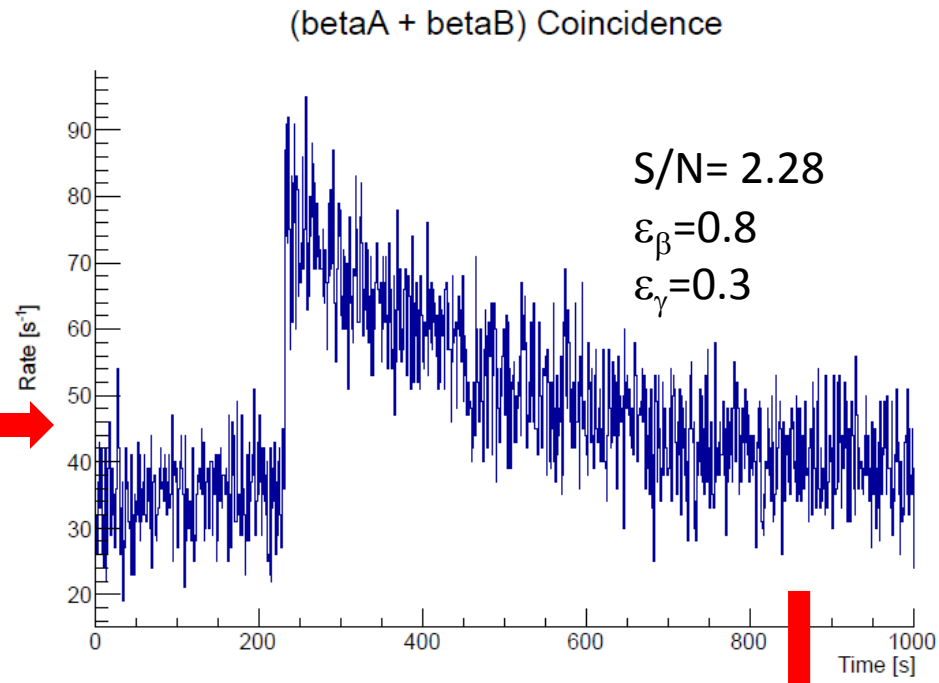
$$T_{1/2} = 3.7 \text{ min.}$$

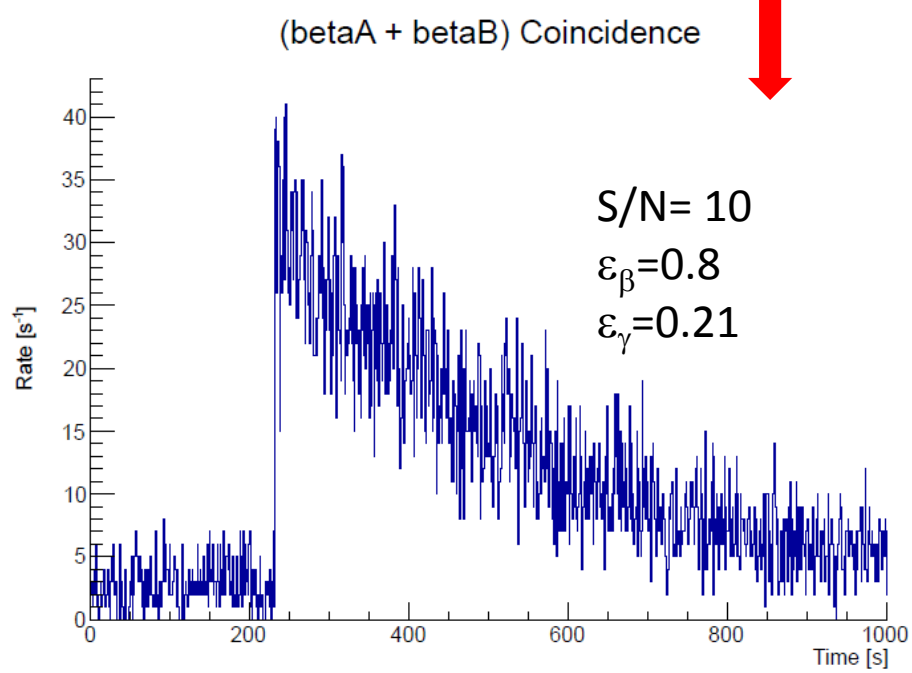
$$^{52}\mathrm{V} \rightarrow {}^{52}\mathrm{Cr} + \beta^{-}(0 \text{ -- } 2.54 \text{ MeV}) + \gamma\ (1.43 \text{ MeV})$$





(1) anti-coincidence w/ other beta
(2) a pulse-height cut on the beta spec.
(3) Coincidence w/ NaI

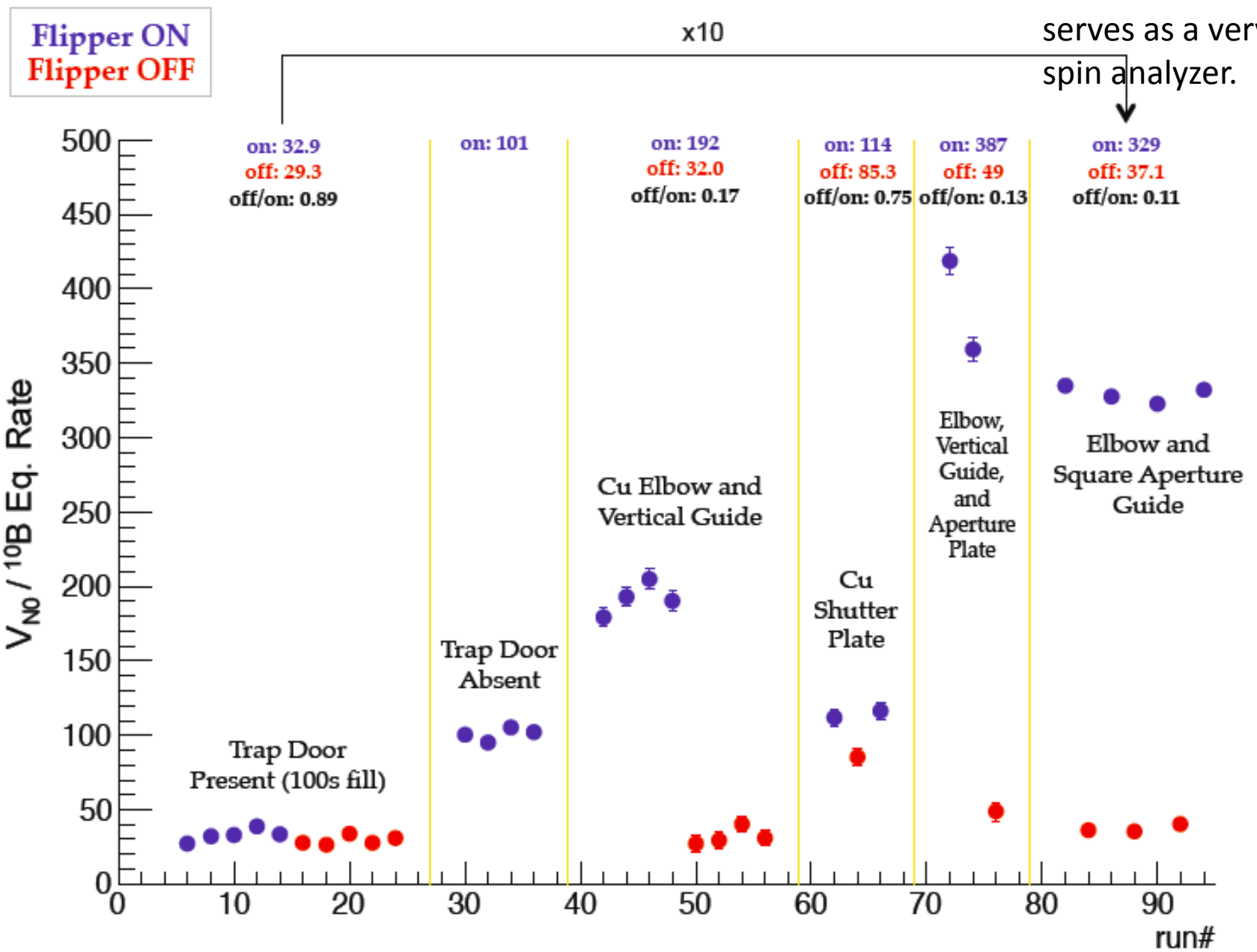




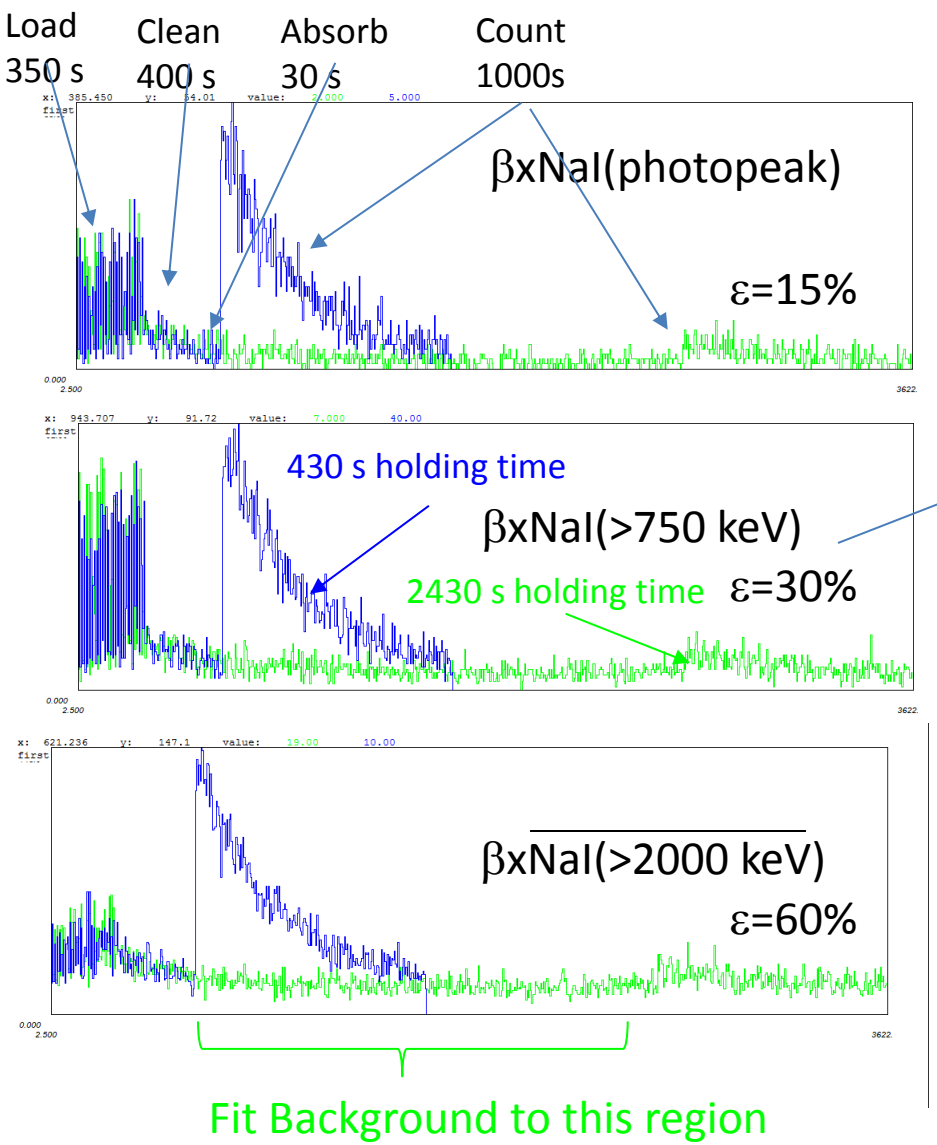
Cut Criteria:
(1) beta event is not coincident with a beta event in the other detector
(2) beta event pulse-height (460~8000).
(3) beta event is coincident with an NaI event
(4) NaI event a pulse-height (2500~3500)

UCNτ Loading Study (January 2014)

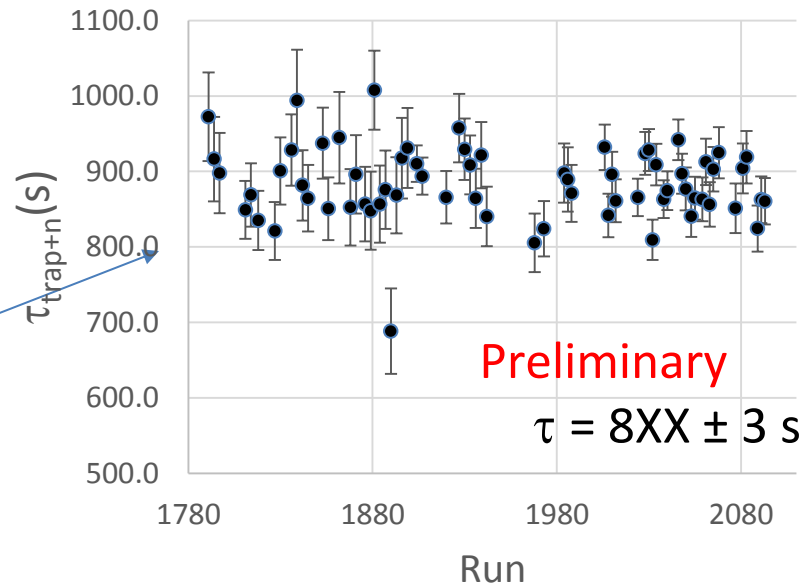
The Halbach array serves as a very good spin analyzer.



Mod 2 Results (2014-2015 run)

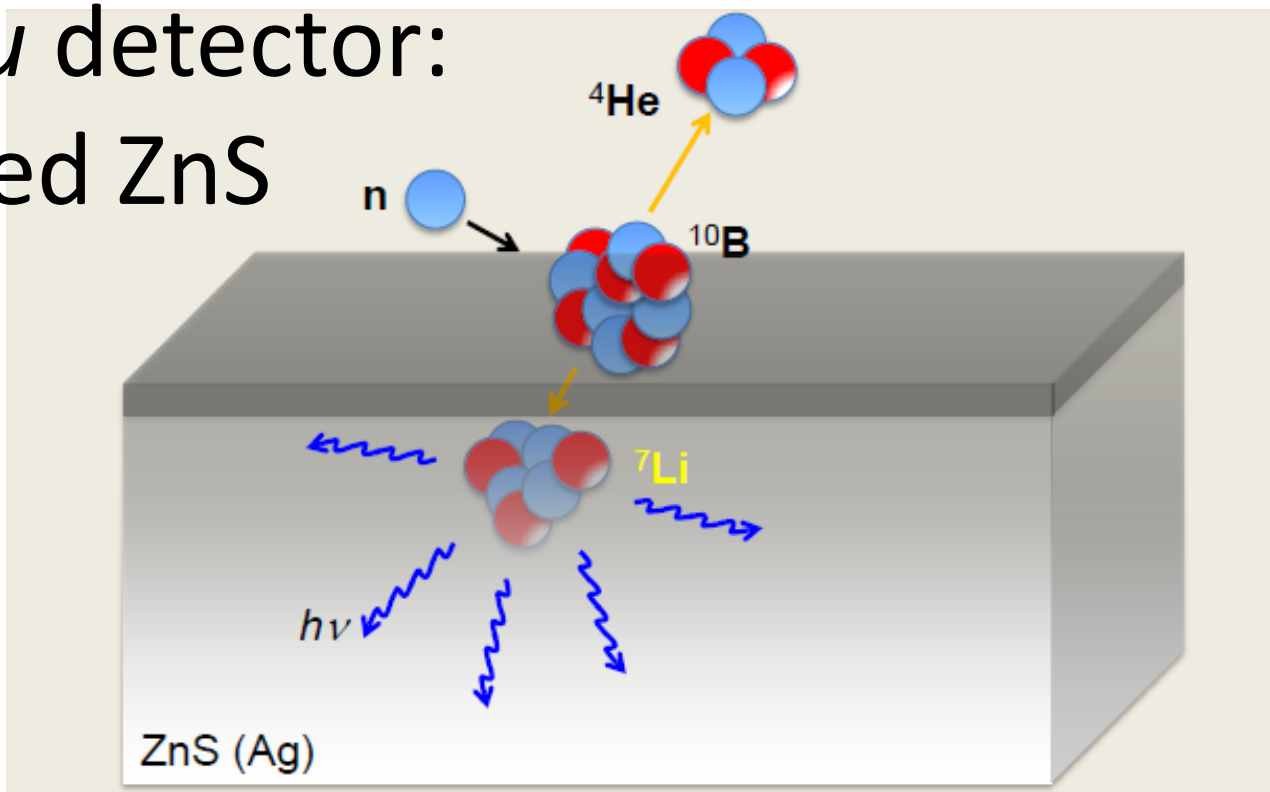


2014 run data: neutron lifetime measured w/ an *in-situ* V detector.

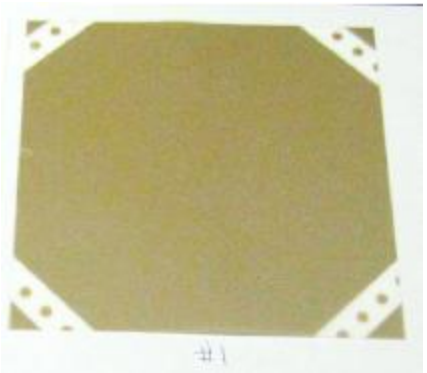


- Statistics are sufficient for < 3s.
- Systematics need much more study.
- Trap lifetime appears to be very long.

A new *in-situ* detector: ^{10}B coated ZnS



Thermal evaporation

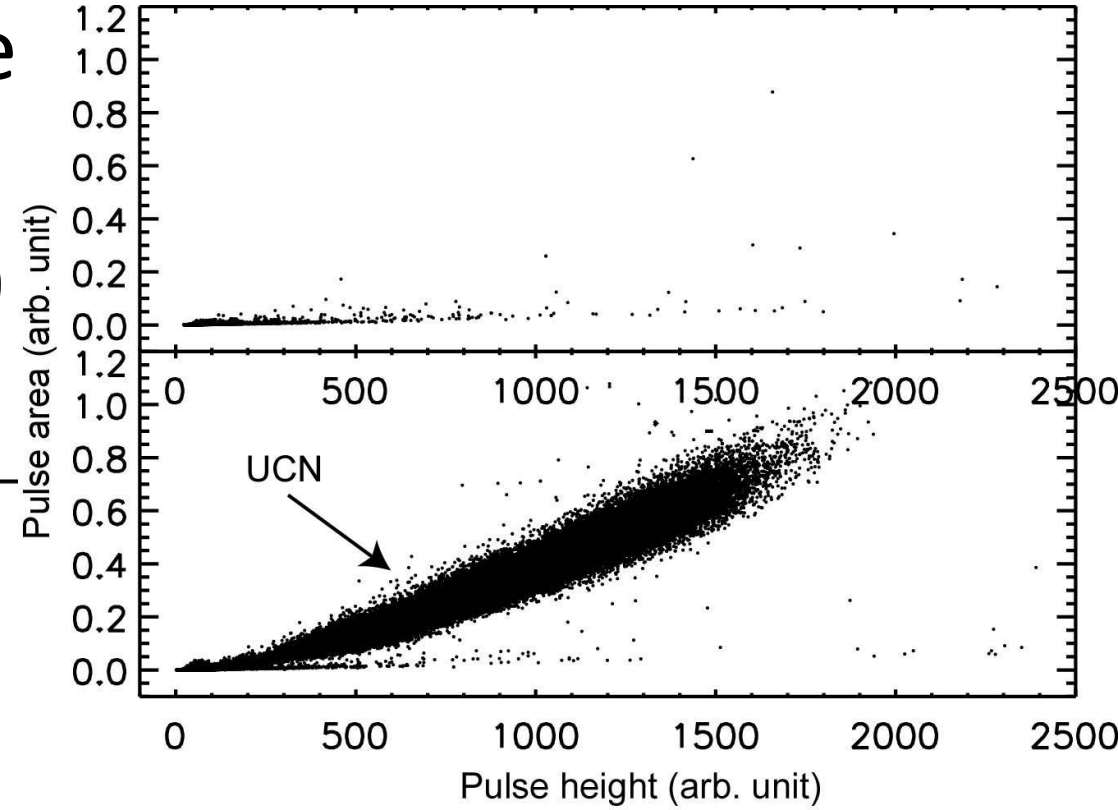


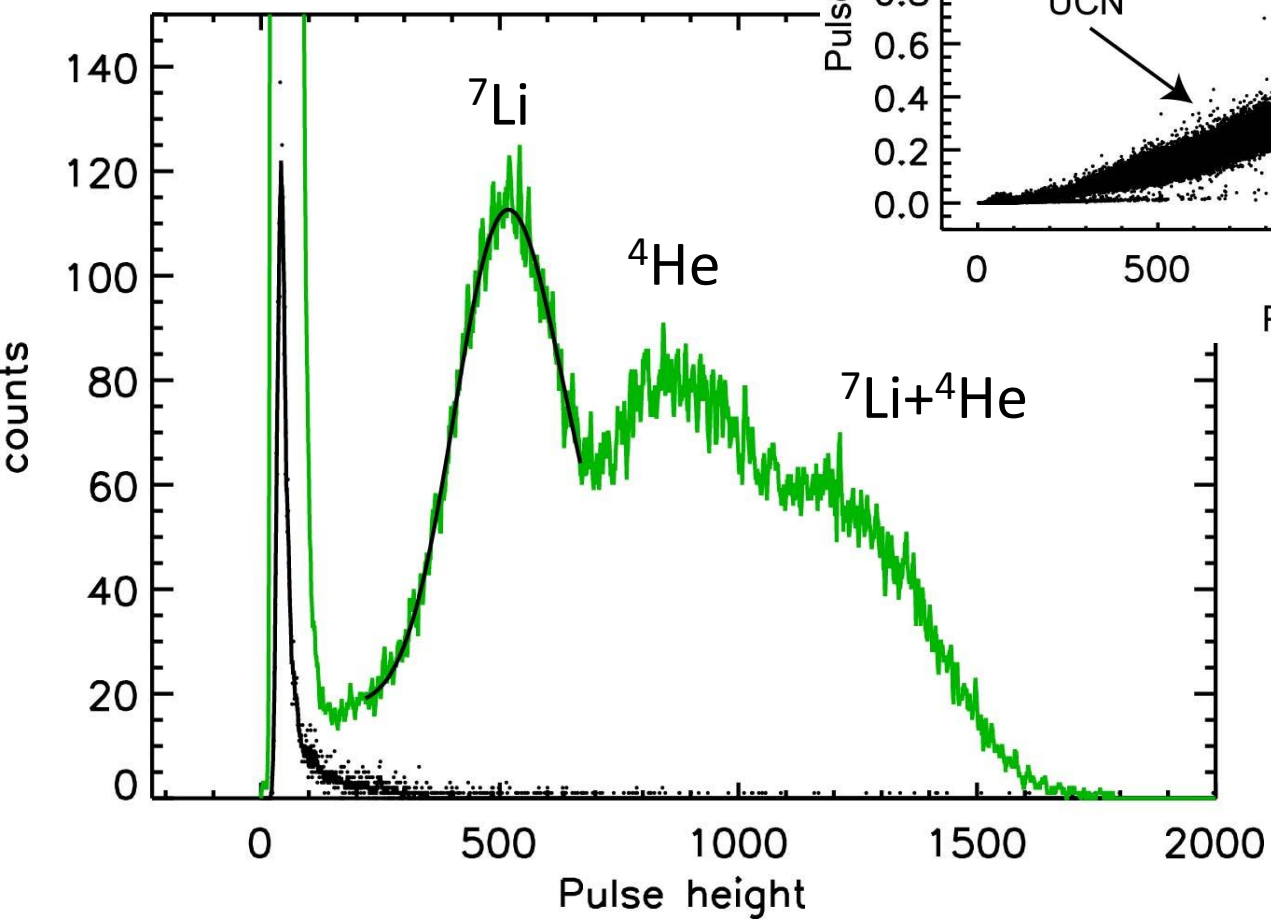
$$^{10}B + n \rightarrow \begin{cases} ^7Li\ (0.84\ \text{MeV}) + \alpha\ (1.47\ \text{MeV}) + \gamma\ (0.48\ \text{MeV}), & 94\% \\ ^7Li\ (1.02\ \text{MeV}) + \alpha\ (1.78\ \text{MeV}), & 6\% \end{cases}$$

Ion (Label i)	Energy (E_0^i, MeV)	Probability (w^i)	Range (R^i, μm)	R^i/λ_a	(thermal)	(UCN)
α (1)	1.47	94%	3.35	0.17		
α (2)	1.78	6%	4.15	0.21		
^{7}Li (3)	0.84	94%	1.78	0.09		
^{7}Li (4)	1.02	6%	2.04	0.10		

93.05556
115.2778
49.44444
56.66667

UCN signal from the ZnS detector (J. Wang, C. Morris)





Current Systematics Estimates Guiding 2015/2016 Plan

Effect	Upper Bound	Direction	Current Eval.	Method of Characterization
residual gas	$< 1 \times 10^{-4}$	+	meas	RGA/cross-section measurements
depolarization	$< 1 \times 10^{-4}$	+	calc	field map, *in situ* detection
material loss	$< 4 \times 10^{-4}$	+	calc	measure Cu tape loss-per-bounce
cleaning	$< 6 \times 10^{-4}$	+	sim	vary cleaning time/depth, active cleaner
cleaner reliability	$< 5 \times 10^{-4}$	±	sim	verify position reproducibility
microphonic heating	$< 1 \times 10^{-4}$	+	sim	accelerometer measurements
dead time/pileup	$< 1 \times 10^{-4}$	±	calc	pileup ID/artificial dead time
gain drifts	$< 2 \times 10^{-4}$	±	meas	spectral monitoring/gain monitoring
time-dep. background	$< 5 \times 10^{-4}$	±	meas	background data analysis
phase space evolution	$< 5 \times 10^{-4}$	±	sim	vanadium time studies, active detector
UCN monitoring	$< 3 \times 10^{-4}$	±	meas	measure monitor response/source stability
total	$< 1.2 \times 10^{-3}$	±		(uncorrelated sum)

Some other efforts

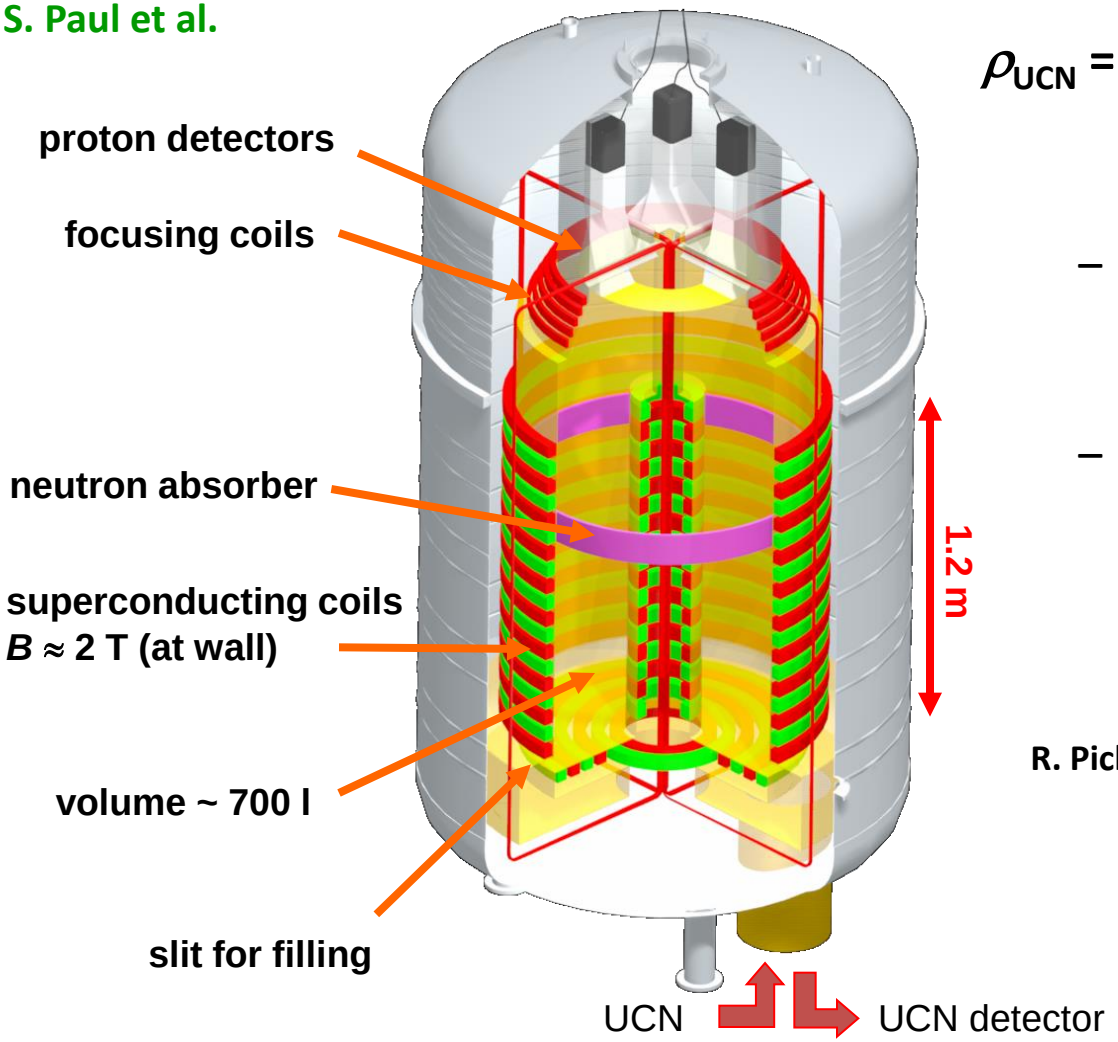
Proposed large volume magnetic storage experiment

$$N(t) = N(t_0)\exp\left(-\frac{t}{\tau_n}\right)$$

PENeLOPE

Magnetic storage of UCN & proton extraction

S. Paul et al.



ρ_{UCN} = $10^3 - 10^4$ cm^{-3} (PSI /FRM II):

$N_{stored} = 10^7 - 10^8$

– Statistical accuracy:

$\delta\tau_n$ ~ 0.1 s in 2-4 days

– Systematics:

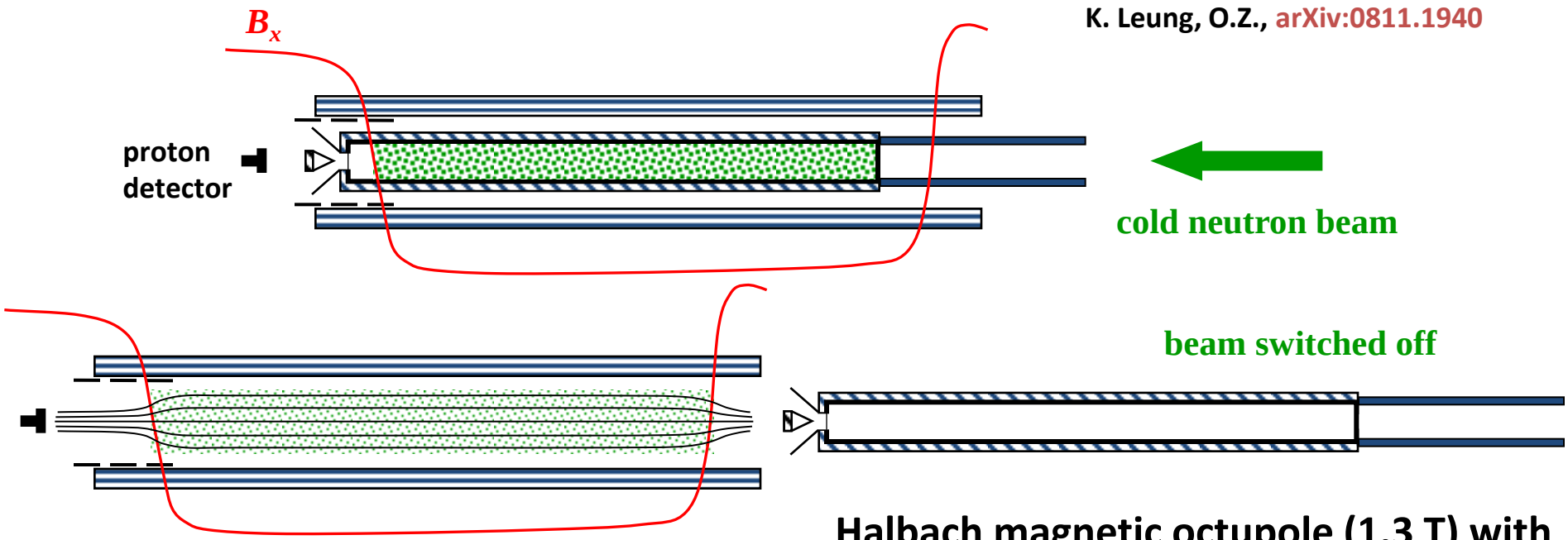
- Spin flips negligible (simulation)
- use different values B_{max} to check expected E_{UCN} independence of τ

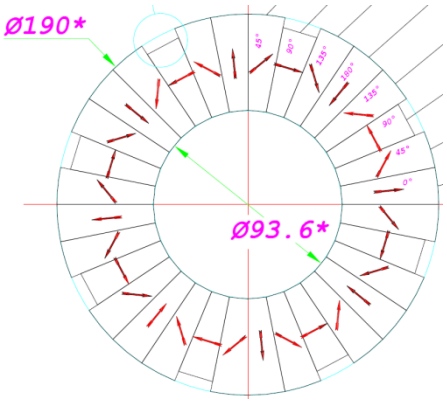
R. Picker et al., J. Res. NIST 110 (2005) 357

- Source not yet ready.
- Cryogenic experiment adds challenges.
- Symmetric trap.

ILL Neutron lifetime experiment with magneto-peristaltic UCN extraction from superfluid ^{4}He into a magnetic trap

O. Zimmer, NIM A 554 (2005) 363
K. Leung, O.Z., arXiv:0811.1940





Halbach magnetic octupole (1.3 T) with

V **= 5 liters and 10^6 neutrons per filling**

⇒ statistical accuracy: 0.1 s in 50 days

- Small Volume.
- Source not yet ready.
- Cryogenic experiment adds challenge.
- Symmetric trap.

Beam vs Bottle