LA-UR- 10-06762

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Title: The Ultracold Neutorn Science Program at Los Alamos

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Intended for: PSI2010: Physics of Fundamental Symmetries and Interactions

Los Alamos
NATIONAL LABORATORY
EST. 1943

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Form 836 (7/06)

The Ultracold neutron science program at Los Alamos

Abstract

An ultra-cold neutron source has been constructed and is now operating at Los Alamos National Lab. This source, which is based on a solid deuterium converter driven by pulsed spallation-produced neutrons, provides UCN densities of 30 UCN/cc with negligible source-related backgrounds. The source is able to simultaneously provide UCNs to two experiment locations; the first is now occupied the by the UCNA experiment, but the second is available to user experiments. Our plans for continuing the operation of the source as a user facility, and the first planned experiments for both the UCNA apparatus and the second experiment station, will be described.

The Ultracold Neutron Science Program at Los Alamos

Alexander Saunders
Los Alamos National Laboratory

PSI Workshop 2010

Outline

- Introduction
- Motivation of neutron β decay measurements
- UCNA current status and plans
- A new UCN lifetime measurement
- UCNB plans and goals
- UCNb
- Summary

- Special Thanks to Mark Makela, Alejandro Garcia, Brad Plaster, and Kevin Hickerson

Neutron β decay and V_{ud}

Angular correlations in polarized neutron decay (Jackson *et al* '57)

$$d\Gamma = d\Gamma_0 \times \left[1 + a\frac{\overrightarrow{p_e}\cdot\overrightarrow{p_\nu}}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \overrightarrow{\sigma_n} \right\rangle \cdot \left(A\frac{\overrightarrow{p_e}}{E_e} + B\frac{\overrightarrow{p_\nu}}{E_\nu} + D\frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right) \right]$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}, \quad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}, \quad B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2}, \quad b_n = \frac{|b_F| - 3\lambda|b_{GT}|}{1+3\lambda^2}$$

$$\tau^{-1} = Kf^R(G_V{}^2 + 3G_A{}^2) \qquad B = B_0 + B_1\frac{m_e}{E_e}$$

$$\lambda \equiv \frac{G_A}{G_V}$$

In Standard Model:

$$B_1 = 0 \qquad b = 0$$

Neutron Decay and Unitarity

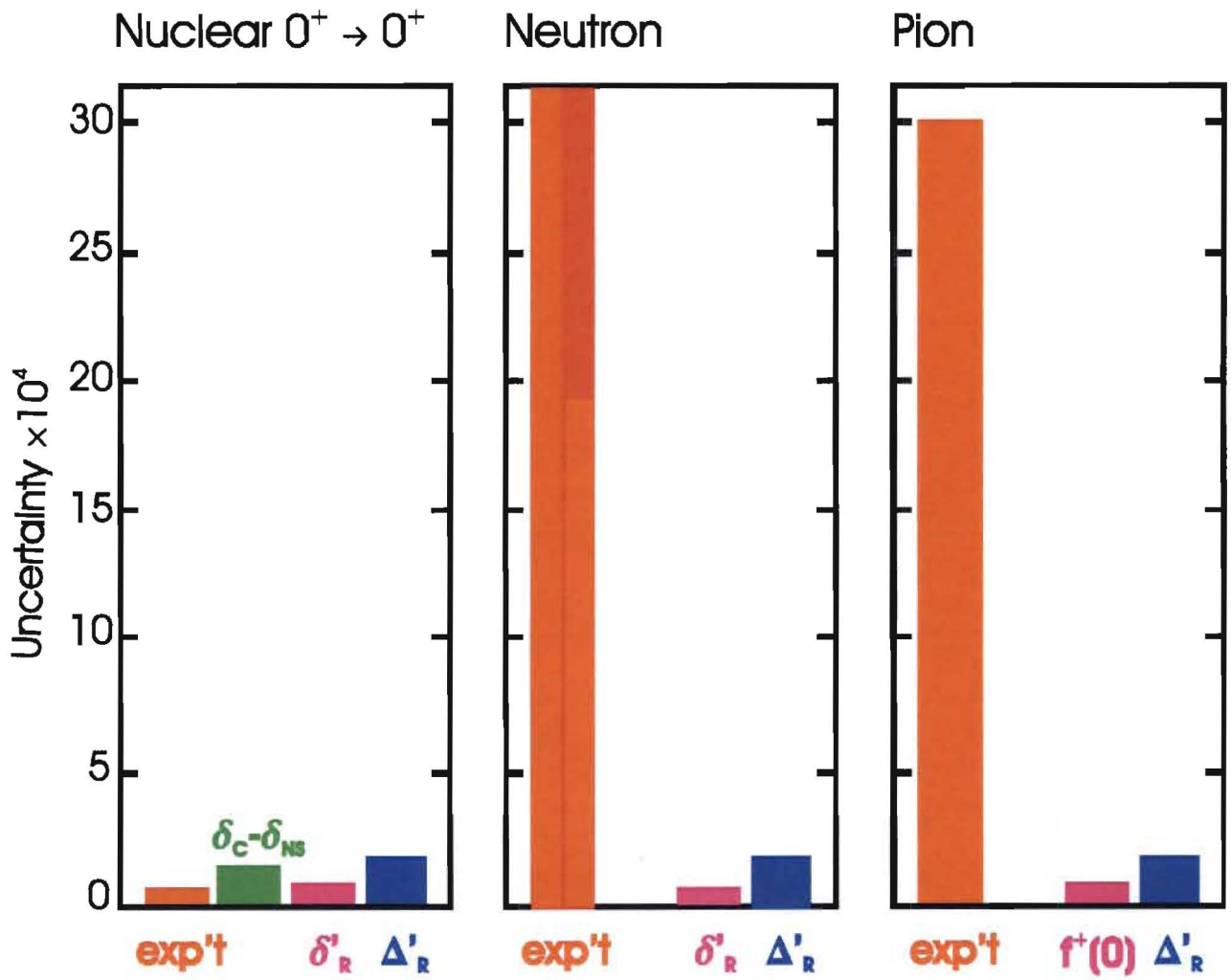
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cd} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} 0.975 & 0.22 & 0.005 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

Unitarity, eg. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, (or lack thereof) of CKM matrix tests existence of further quark generations and possible new physics (eg. Supersymmetry)

B. W. Filippone

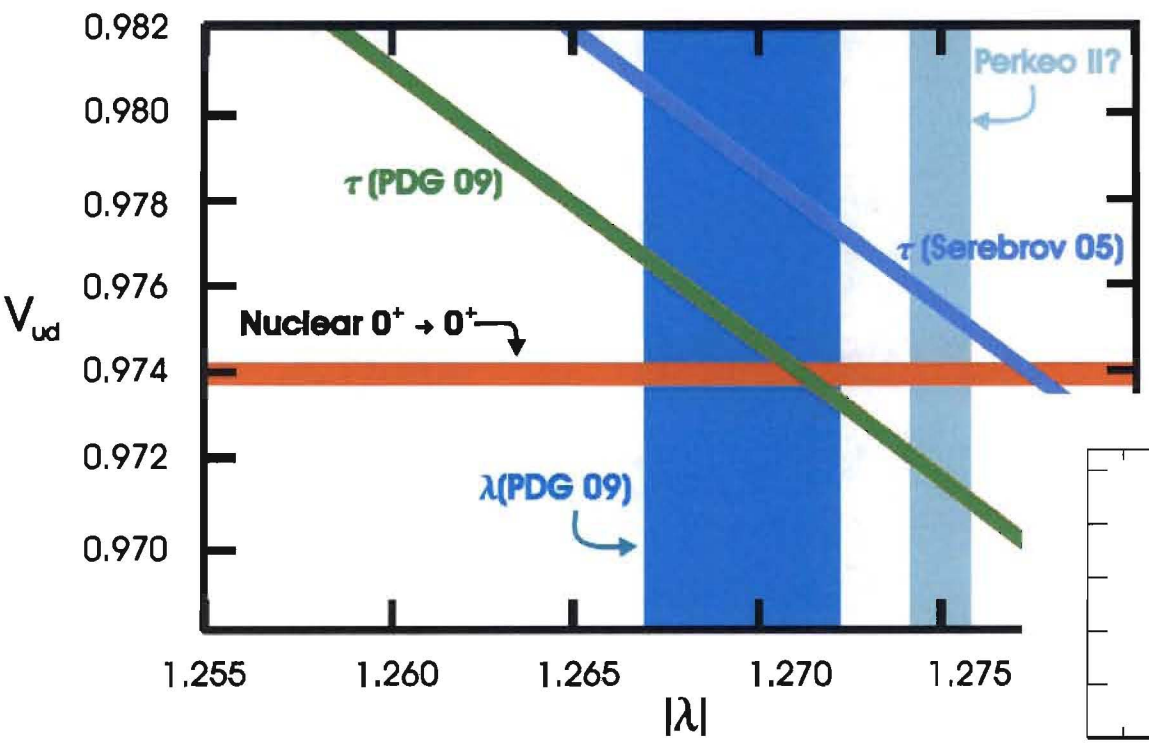
Motivation for A measurement: independent determination of V_{ud}

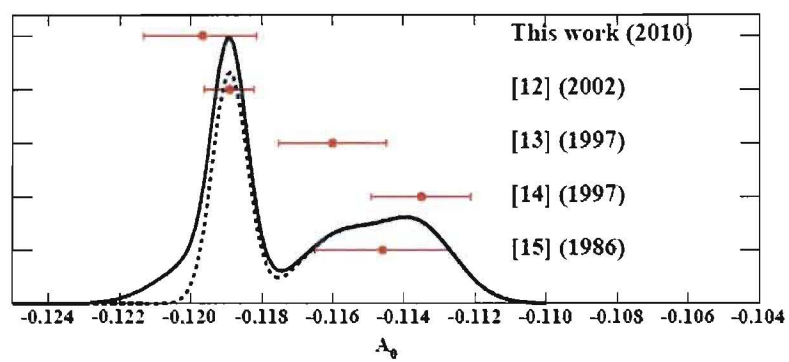


Motivation for A and τ measurement

Vud from neutron decay

$$\frac{1}{\tau} \approx \frac{C_V^{\,2}\, m_e^{\,5}}{2\pi^3\hbar}\left(3|\lambda|^2+1\right) f\left(1+RC\right) \qquad A \approx -2\,\frac{|\lambda|^2+|\lambda|\cos\varphi}{3|\lambda|^2+1}$$





Effects of $\lambda = G_A/G_v$

Where does the proton get its spin?

Some comes from the quarks, but how much and which quarks?

$G_A^3 = \Delta u - \Delta d$ Axial-vector weak charge Neutrons *et al.*

$G_A^8 = \Delta u + \Delta d - 2\Delta s$ SU(3) octet weak charge

$G_A^0 = \Delta u + \Delta d + \Delta s$ Flavor singlet weak charge DIS

Solar fusion rates and the Standard Solar Model

$$r_{pp} \propto \langle \sigma v \rangle_{pp} \propto \int_0^\infty E\sigma(E) e^{\left(\frac{-E}{kT}\right)} dE$$

$$\sigma(E) = \frac{S(E)}{E} e^{\frac{-2\pi\alpha}{v(E)}} \qquad S_{pp} \propto \left(\frac{G_A}{G_V}\right)^2$$

Motivation for b and B measurement: BSM Physics

- ε_s and ε_t are non-(V-A) contributions to the effective Hamiltonian

$$b = f_b\,(\varepsilon_{S,T} * g_{S,T})$$
$$B_1 = f_B\,(\varepsilon_{S,T} * g_{S,T})$$

$g_S \sim \langle p|\bar{u}d|n\rangle$

$g_T \sim \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$

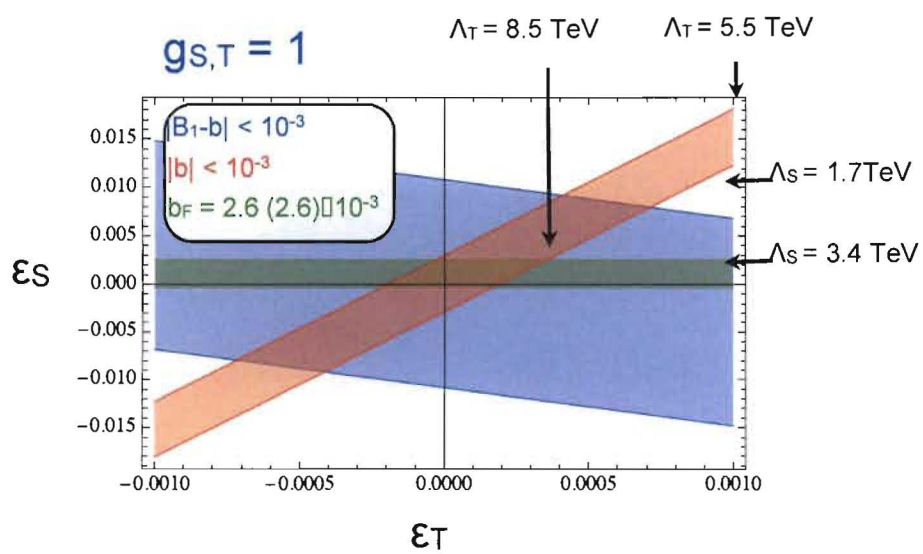
Measure these quantities with UCNs

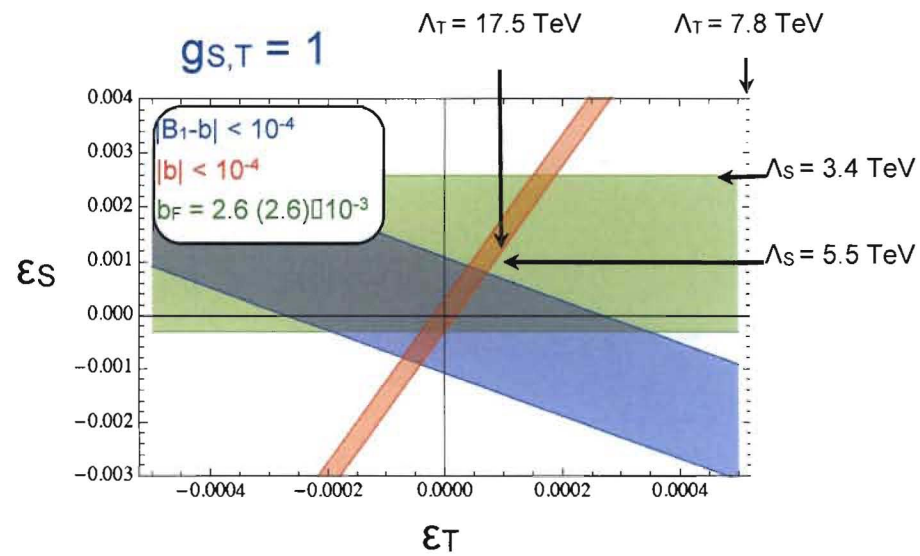
Calculate these hadronic matrix elements in QCD

Analyze relation of ε_S and ε_T to other measurements (including LHC signals) within BSM extensions

Phenomenology: preliminary study

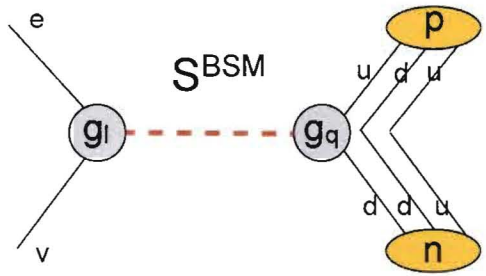
- Constraints on ε_S and ε_T from proposed experiments vs other measurements ($0^+ \rightarrow 0^+$; $\pi \rightarrow e\nu\gamma$ and collider not competitive)





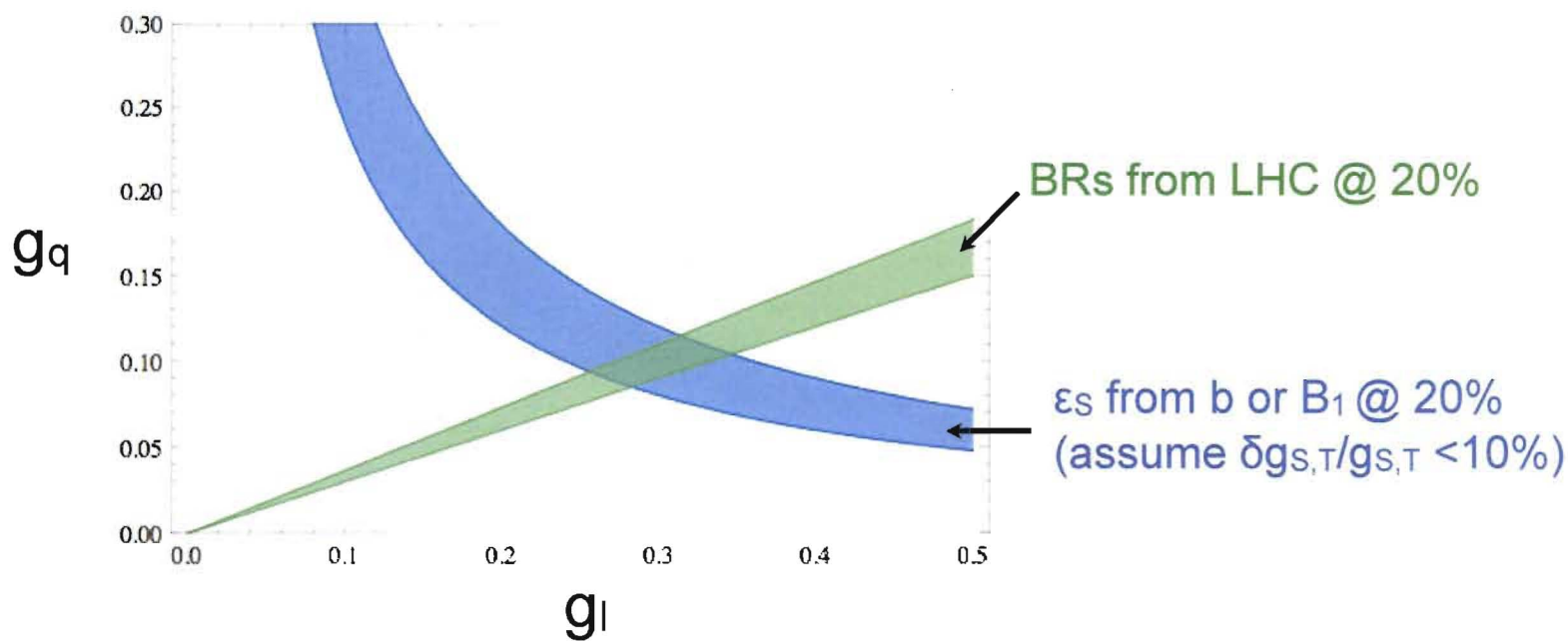
- Already 10^{-3} measurements probe multi-TeV scale; stringent constraint on existence of scalar and tensor BSM interactions

- Example: charged scalar resonance with M_S=1 TeV, g_l=0.3, g_q=0.1

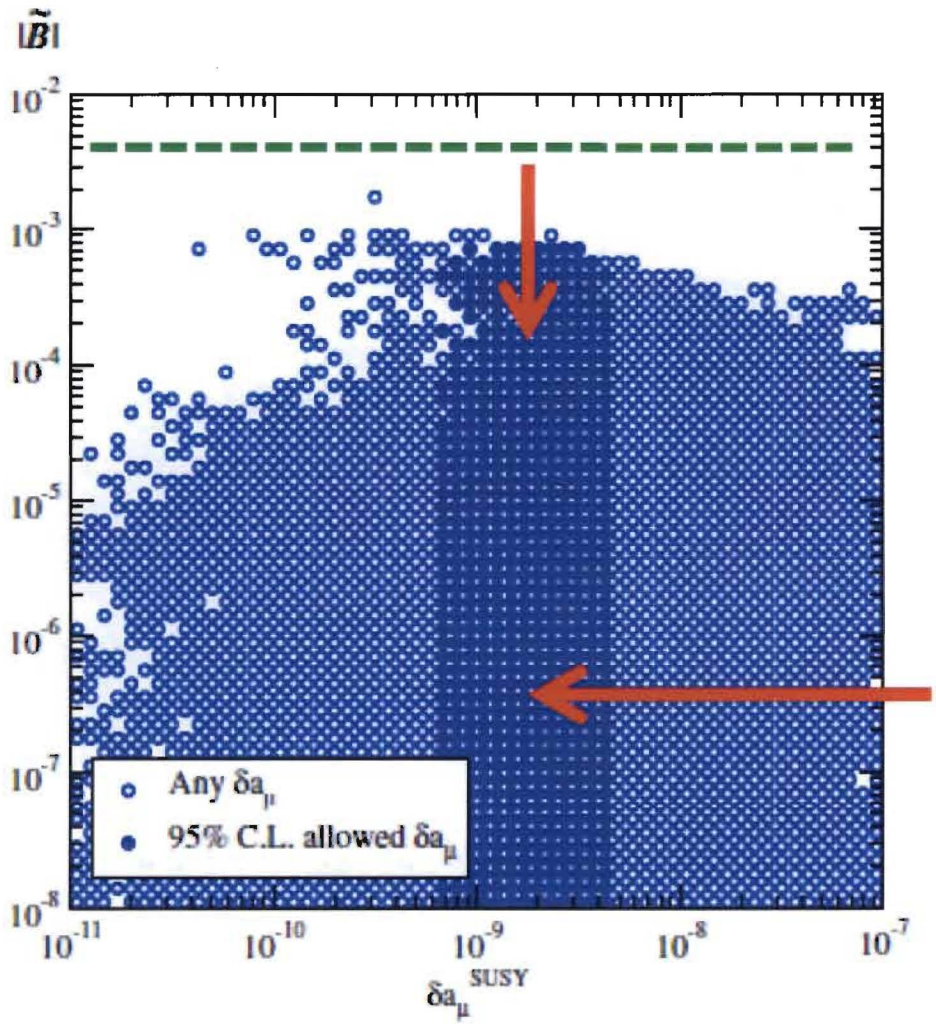


(e.g. 2nd Higgs doublet with non-standard couplings)

- LHC would measure M_S and $g_q/g_l = [BR(ud)/BR(e\nu)]^{1/2}$
- n decay sensitive to $G_F{*}\varepsilon_S = g_l\, g_q/M_S^2$ (ε_S=1.8 10^{-3})



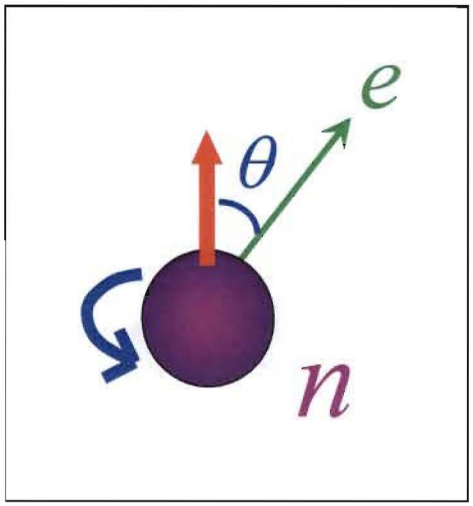
MSSM parameter space



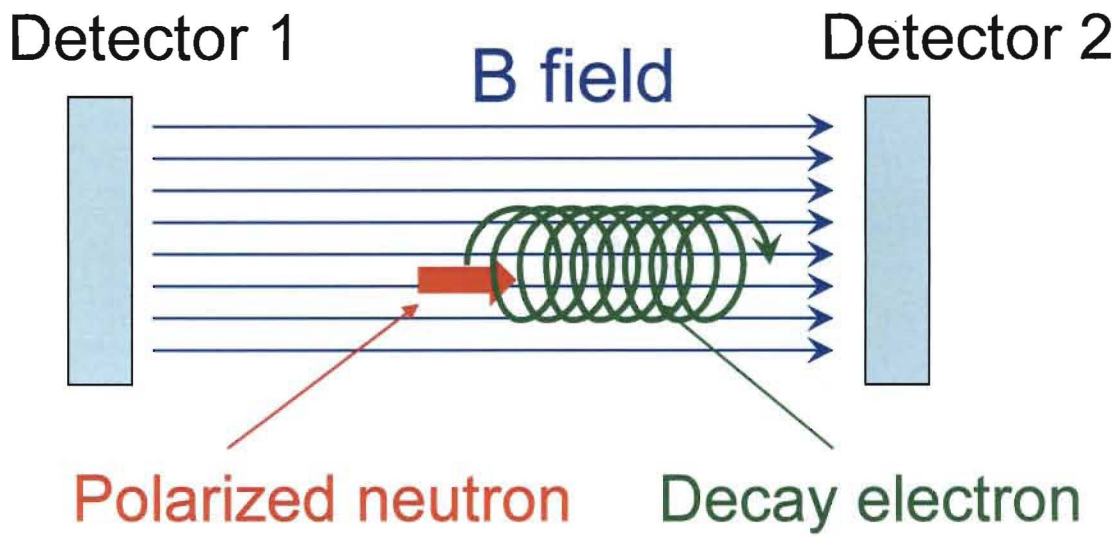
Current 0.3%
Precision on B

Muon g-2 allows these

Principle of the *A*-coefficient Measurement



$$dW = [1 + \beta P A \cos\theta] d\Gamma(E)$$



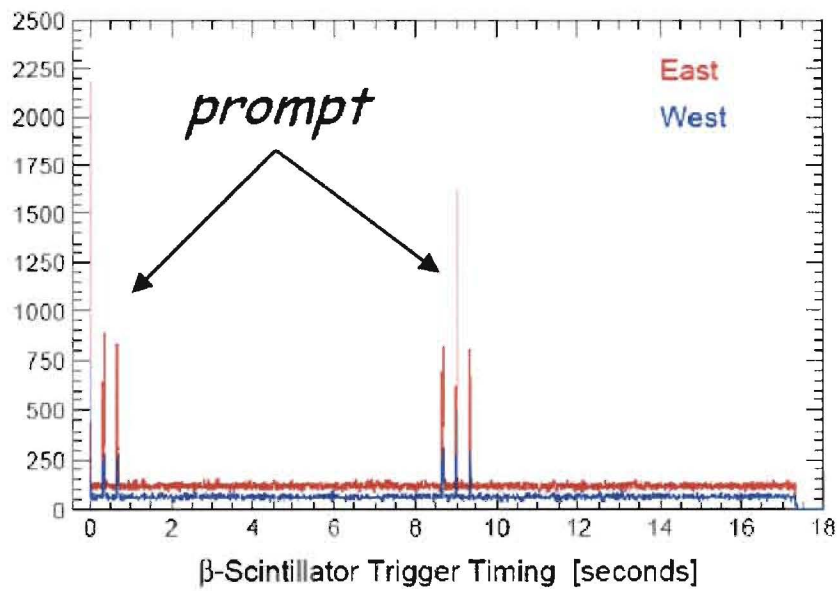
$$A_{\exp}(E) = \frac{N_1(E) - N_2(E)}{N_1(E) + N_2(E)} \approx \langle P \rangle A \beta \langle \cos\theta \rangle$$

(End point energy = 782 keV)

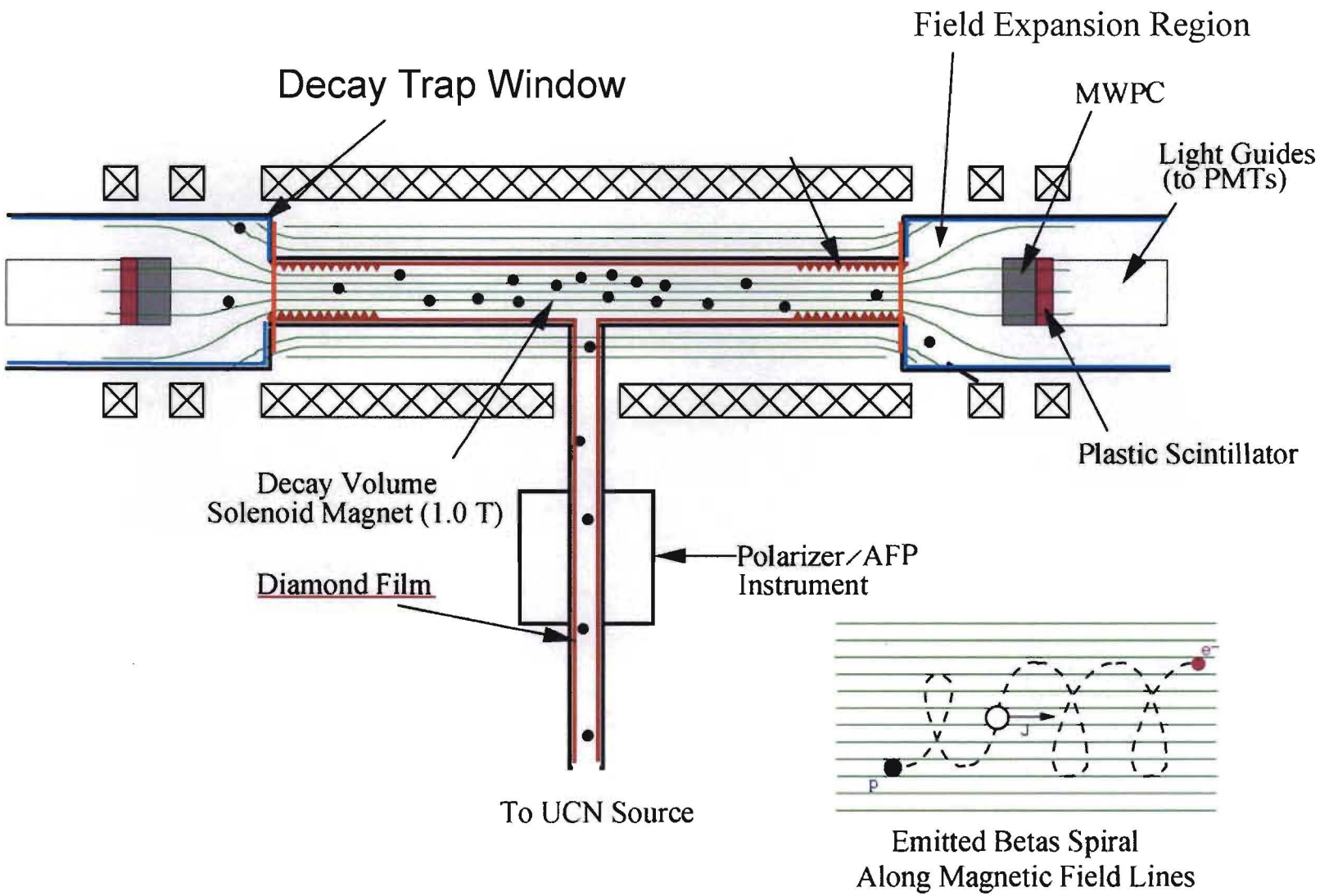
UCNA Experiment — General Approach

Novel features: UCN from pulsed spallation source
MWPC + plastic scintillator as β detector
Ultimate Goal: 0.2% measurement of A ($\delta A/A$ = 0.2%)

- Neutron Polarization
  - UCN (can produce >99% polarization with 7T magnetic field)
  - Copper and diamond-like carbon coated neutron guide (low depolarization)
- Background
  - Pulsed UCN source
  - MWPC+Plastic scintillator
- Electron backscattering
  - MWPC+Plastic scintillator
- Fiducial volume selection
  - MWPC

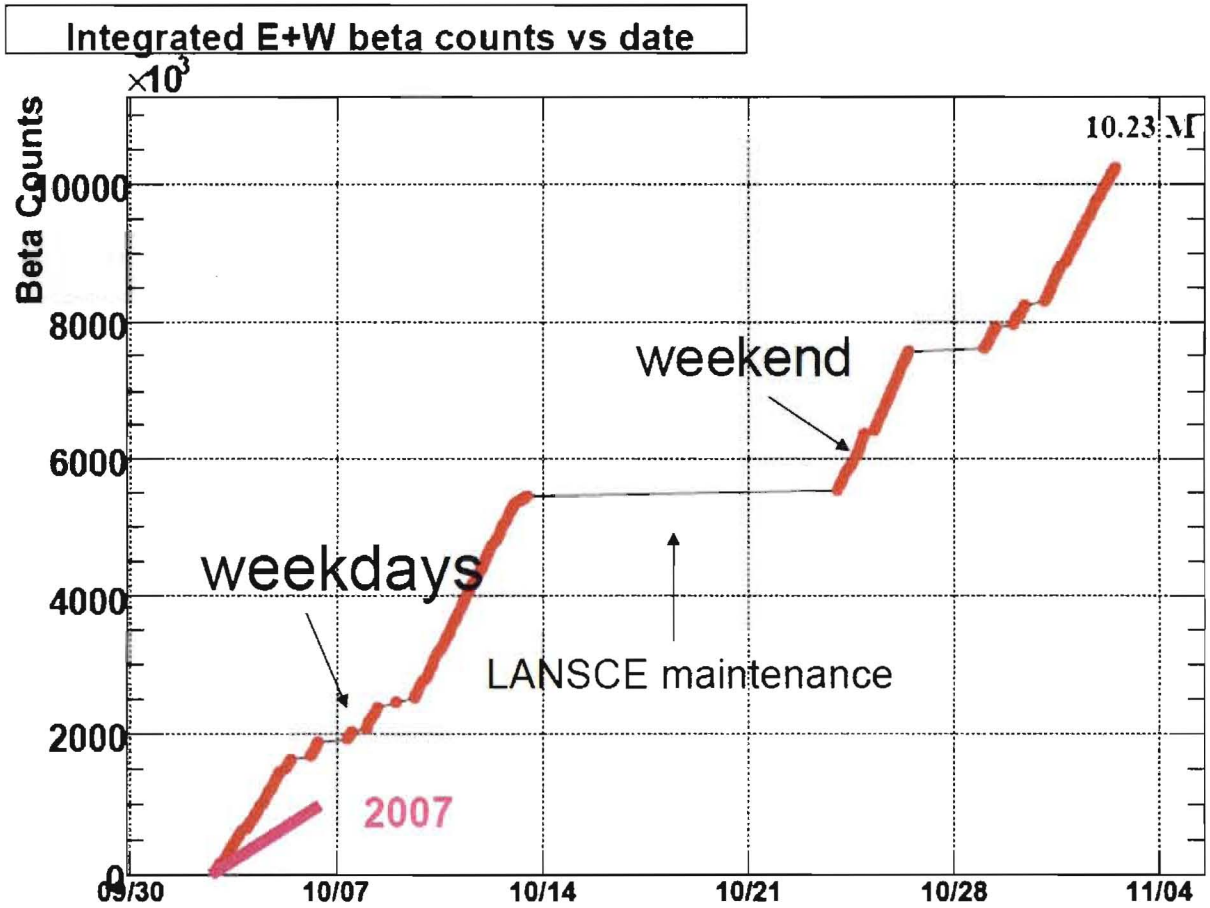


UCNA Experiment — Apparatus



UCNA Apparatus in LANSCE Area B

2008 Data run: 32 M decays



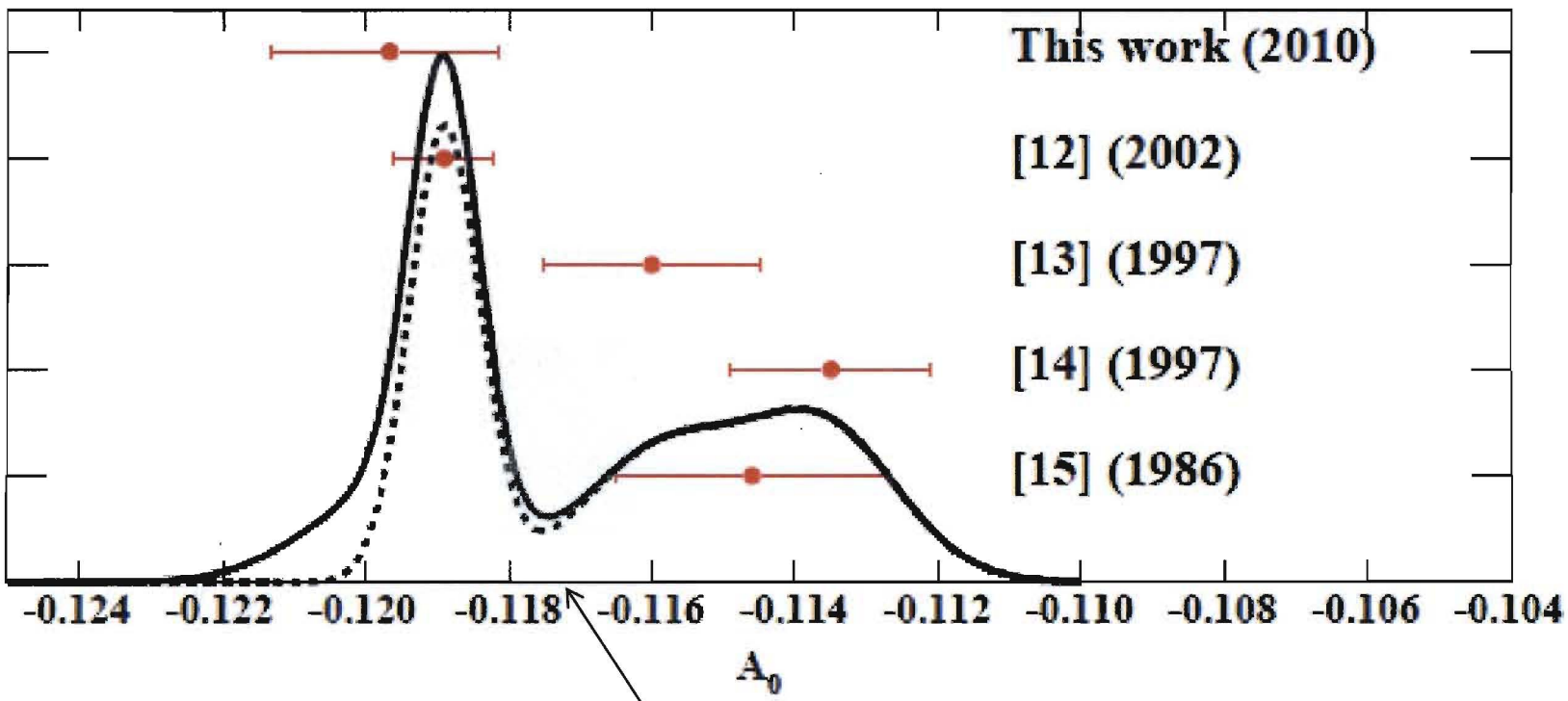
One of three data periods

UCNA Uncertainty Budget

	2007		2008/2009	
	Correction(%)	Uncertainty(%)	Correction(%)	Uncertainty(%)
Statistical	n/a	4	n/a	0.7
Polarization	0	1.3	0	+0.52-0
Energy Calib	0	1.5	0	0.47
Angle effect	-1.6	0.5	-1.8,-3.2,-0.5,-0.36	0.5,0.8,0.2,0.1
Backscattering	1.1	0.4	1.3,4.3,1.1,1.1	0.4,1.3,0.3,0.3
Cosmic rays			0	0.3
Field dip			0	0.2
UCN Background			0	0.02
Live time			0	0.24
Fiducial cut			0	0.24
Recoil-order corr.			-1.79	0.03
Radiative corr.			0.1	0.05

Ultimate goal is 0.2% measurement of A

A Correlation history

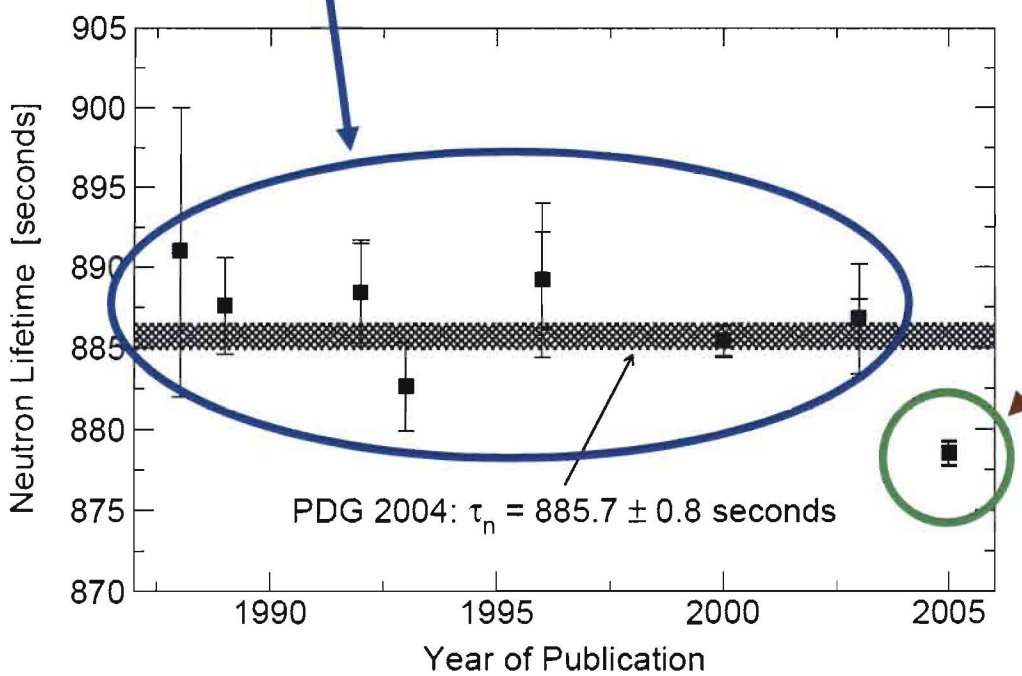


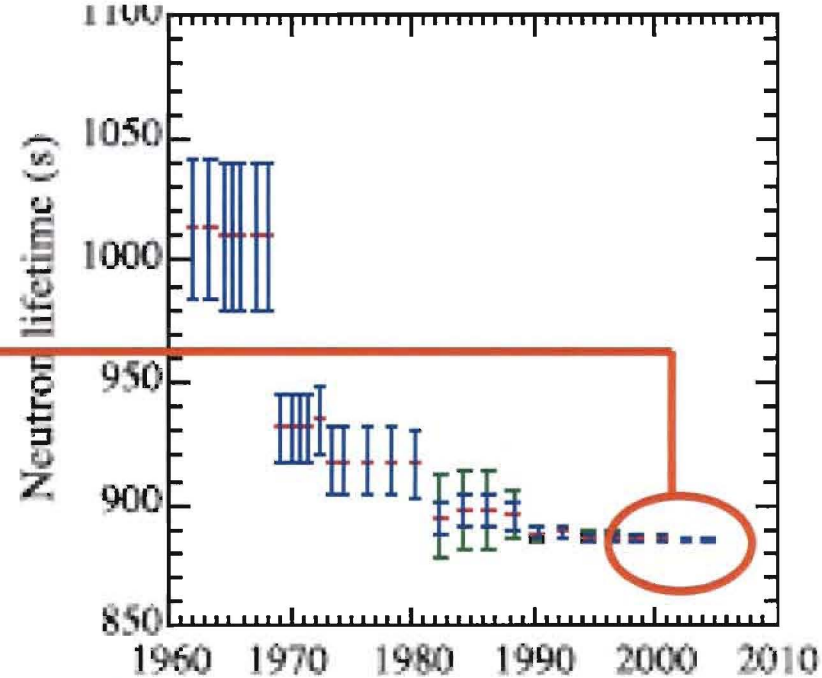
PDG Value (w/ 2.3x inflation)

Neutron lifetime measurement using UCNs in magnetic trap

Neutron Lifetime versus Year

Data points used by PDG 2004 for averaging





Serebrov *et al.*,

Phys. Lett. B 605, 72 (2005)

(878.5 ± 0.7 ± 0.3) seconds

1 s uncertainty, 7 s discrepancy

B. W. Filippone

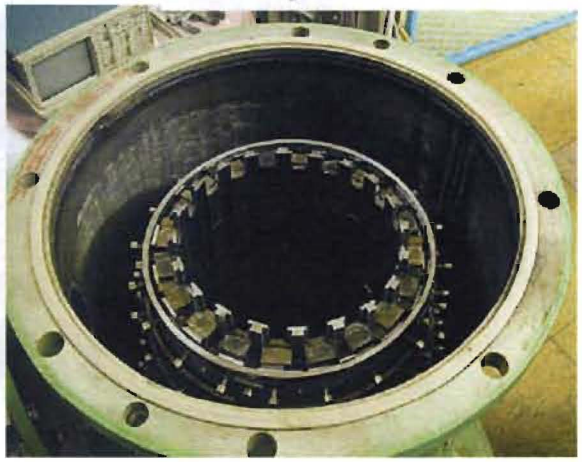
UCN Lifetime Experiment at the ILL

2004

increase storage volume from 3.6 l to 15 l

2003

Top view of the storage bottle made of permanent magnets.

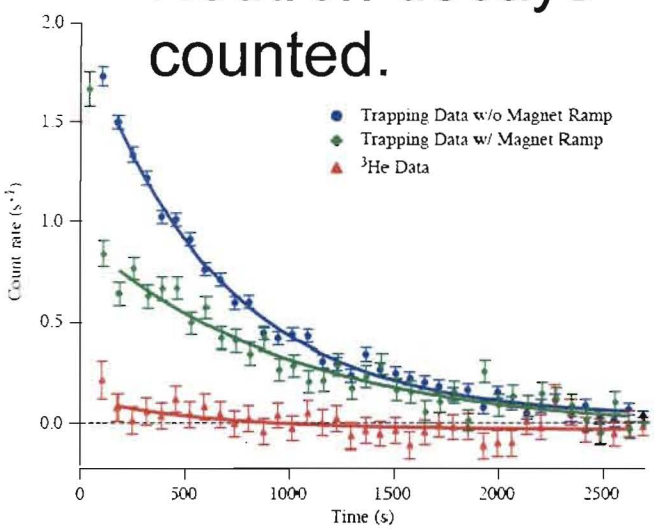


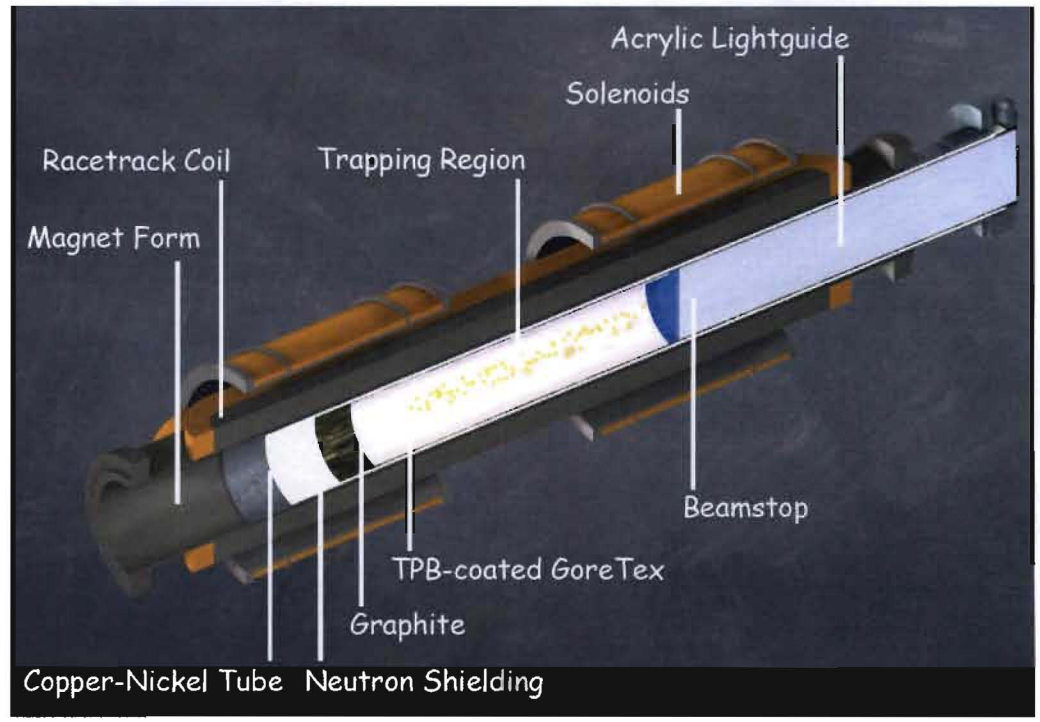
- Neutrons from the ILL turbine.
- Trapped with permanent magnets and gravity.
- Surviving neutrons counted.

Unpublished; in development

UCN Lifetime Experiment at NIST

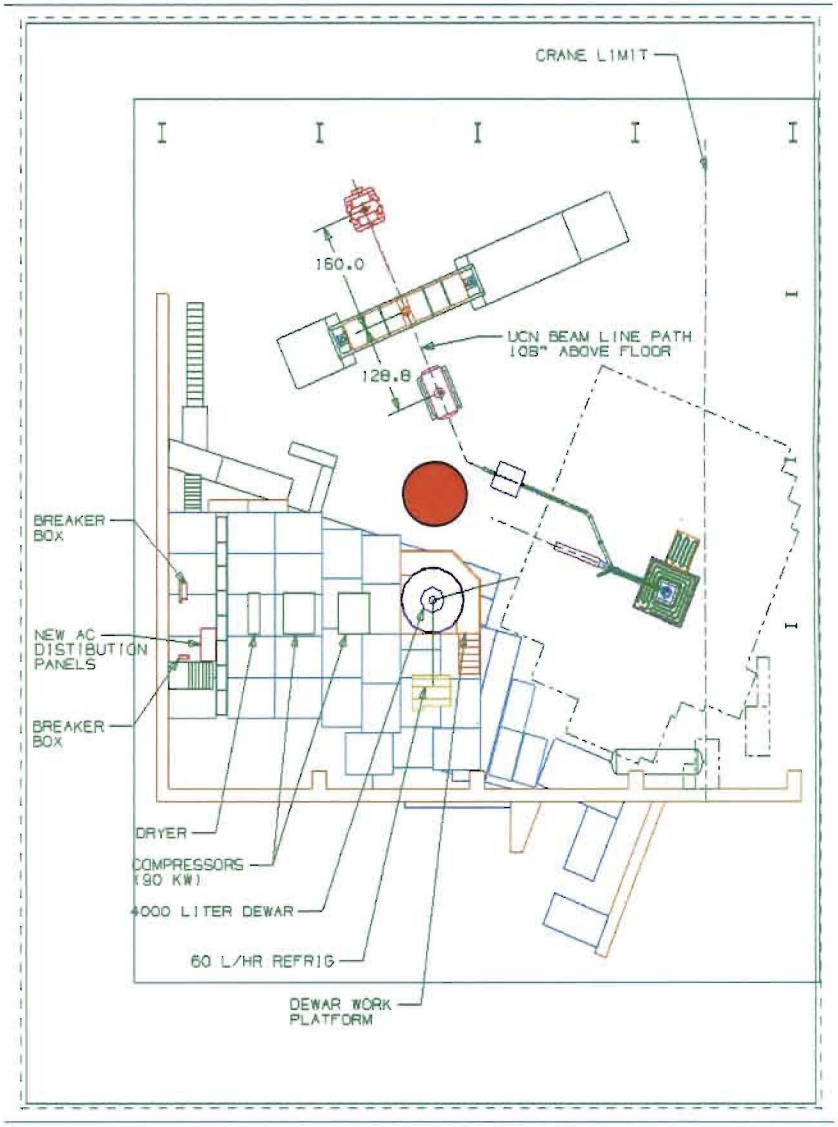
- Liquid He Source
- Magnetically trapped in liquid Helium.
- Neutron decays counted.





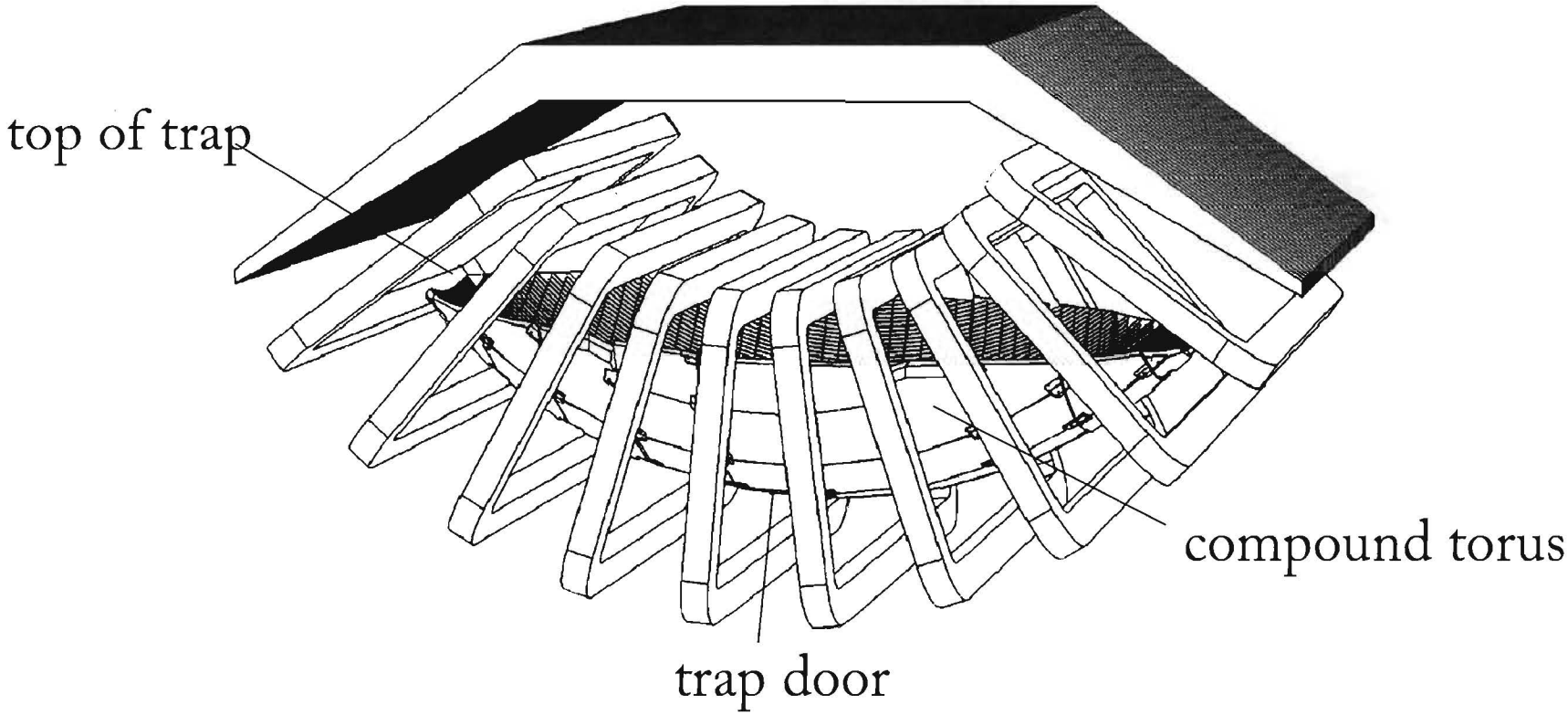
New neutron lifetime experiment at LANSCE

- Will use operating UCN D_2 spallation source at LANSCE
- Next to UCNA experiment
- PPM and spin flipper can select spin state
- >10 UCN/cm^3 at shield wall
- An experiment with no material interactions during UCN storage time
- Eliminates leading systematic of all previous experiments



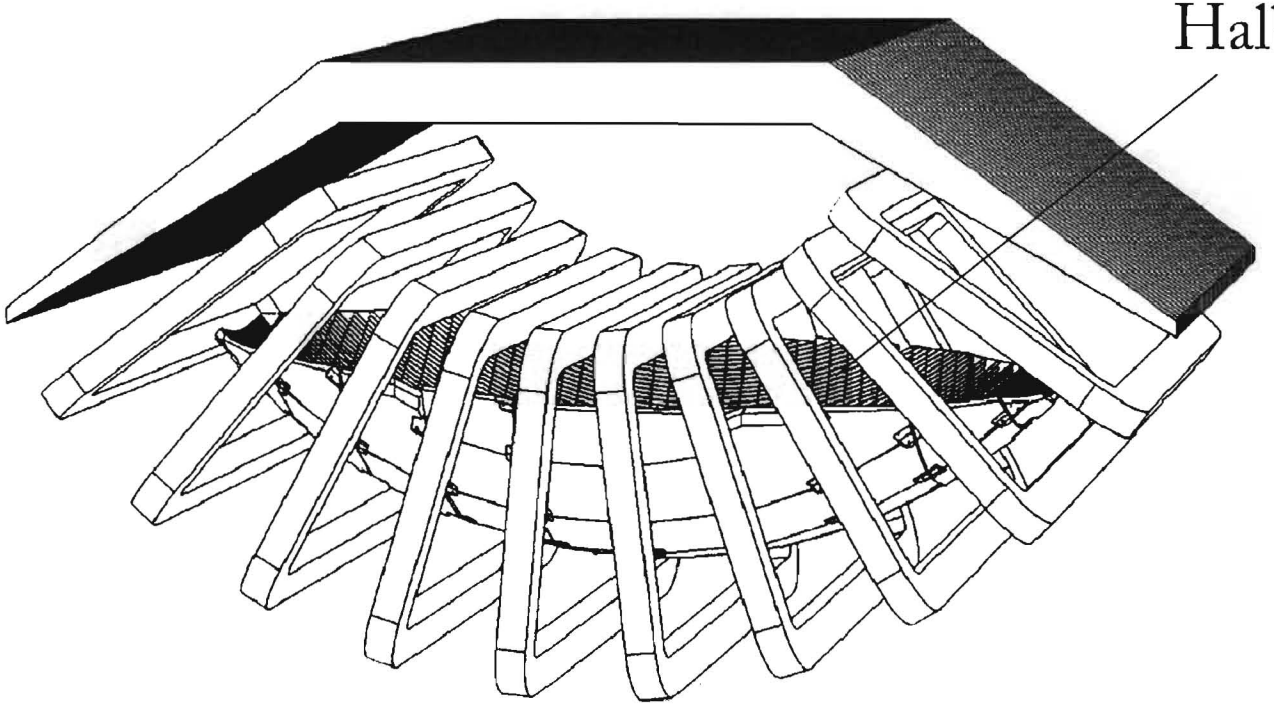
Overview of Experiment

- Asymmetric compound toroidal trap
- UCN trapped by gravity in open-top bowl ("the bathtub")
- Permanent magnets repels UCN on bottom
- Minimize material interactions



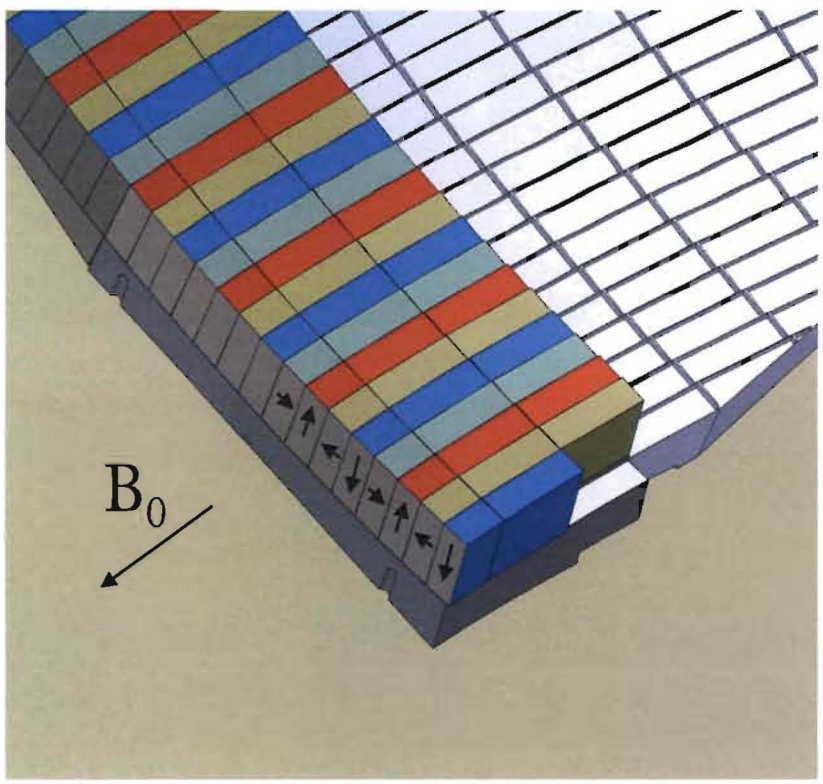
Overview of Experiment

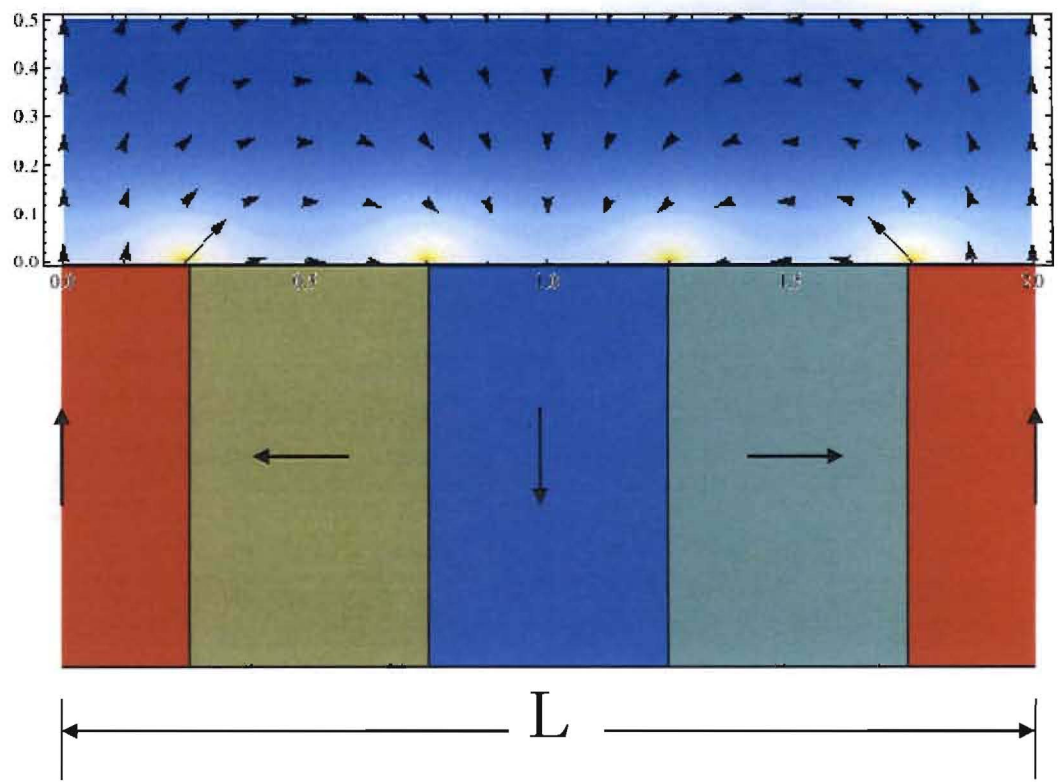
- **Polarized** UCN ("low-field seekers"or "positive energy eigenstates)
- High strength neoymium-iron-boron (NdFeB) magnet **Halbach array** walls.
- Halbach array surface strength near 0.8 T

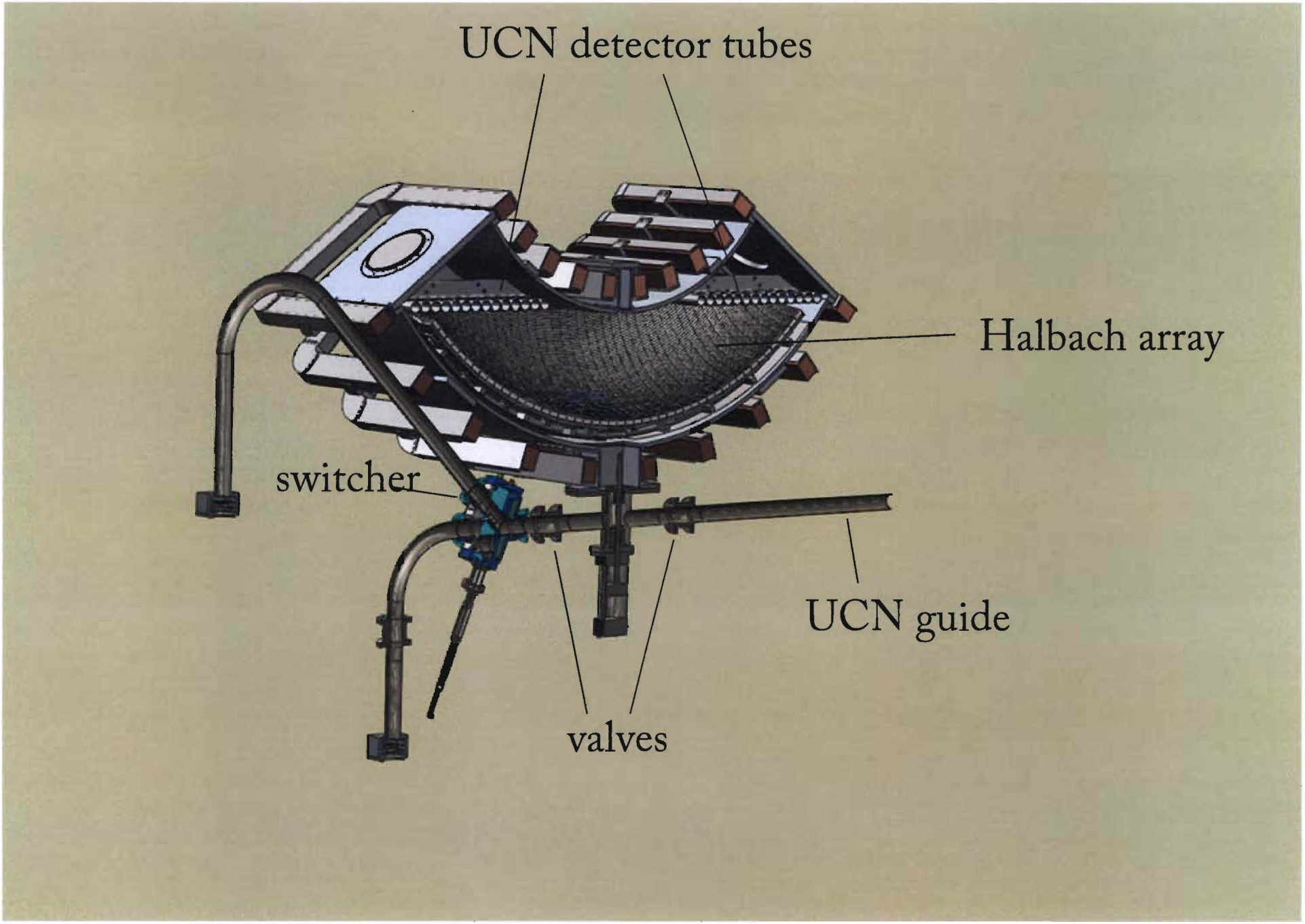


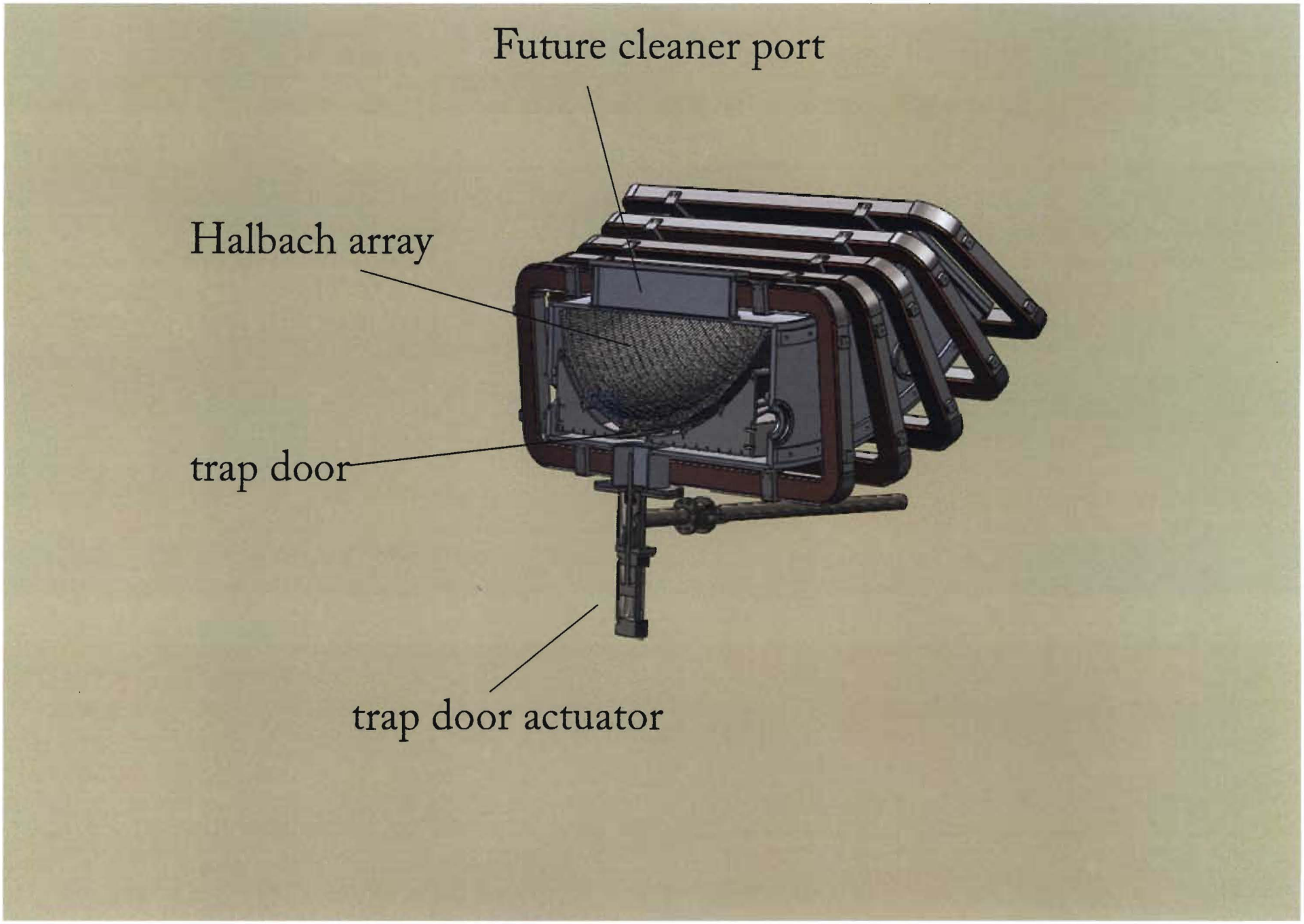
Halbach array

- Each magnet 90° out of phase with its neighbor.
- The array has B field "ripples" of scale L/4 = 0.5 in
- Rotating field is orthogonal to holding field B_0



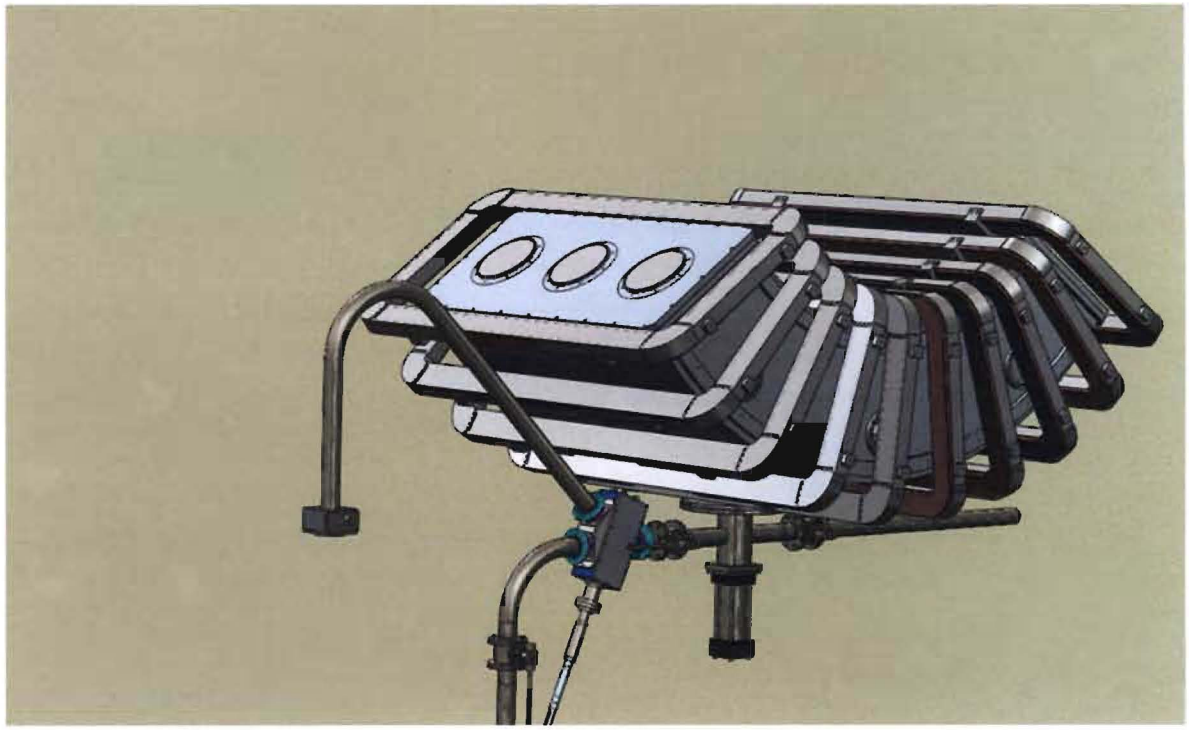



UCN detector tubes
Halbach array
switcher
UCN guide
valves


Future cleaner port
Halbach array
trap door
trap door actuator

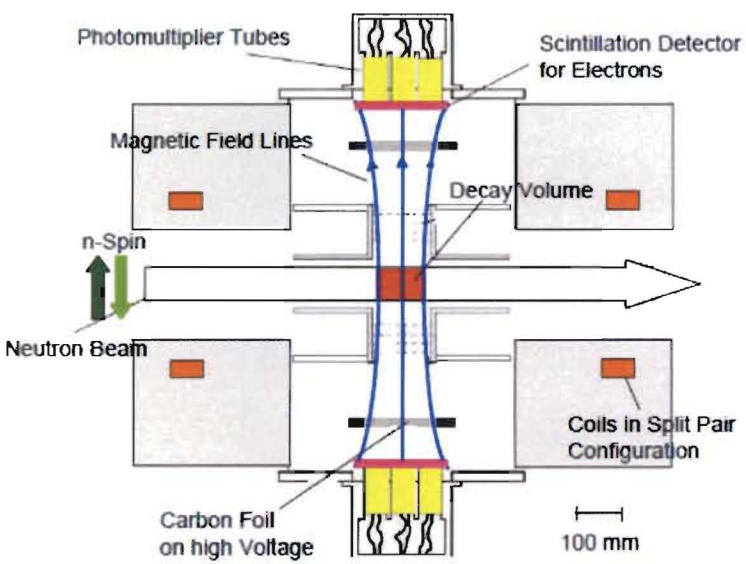
Sensitivity

- Effective trap volume is 0.6 m^3
- UCN may trap up to E = 48 neV
- LANSCE source can produce >10 UCN cm^{-3} at gate valve
- Trap density >1 UCN/cc: 600,000 UCN per fill
- We hope for a sensitivity of 0.1 s



B History

VALUE	DOCUMENT ID		TECN	COMMENT	P =
0.9807±0.0030 OUR AVERAGE					
0.9802±0.0034±0.0036	SCHUMANN	07	CNTR	Cold *n*, polarized	0.997(1)
0.967 ±0.006 ±0.010	KREUZ	05	CNTR	Cold *n*, polarized	0.987(5)
0.9801±0.0046	SEREBROV	98	CNTR	Cold *n*, polarized	0.975(3)
0.9894±0.0083	KUZNETSOV	95	CNTR	Cold *n*, polarized	0.669(2)
1.00 ±0.05	CHRISTENSEN	70	CNTR	Cold *n*, polarized	0.87(3)
0.995 ±0.034	EROZOLIM...	70C	CNTR	Cold *n*, polarized	0.74(1)



PERKEO IIB

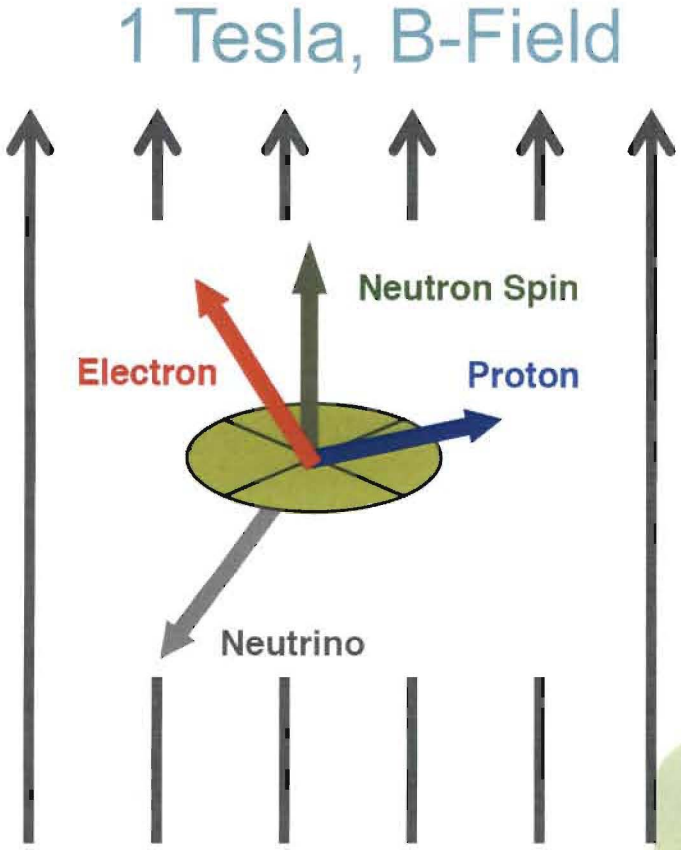
M. Schumann et al., PRL 99, 191803 (2007); and Ph.D. Thesis

$$B_{\exp}(E_e) = \frac{N^{--}(E_e) - N^{++}(E_e)}{N^{--}(E_e) + N^{++}(E_e)}$$

$B_{exp}(E_e)$ related to B via integration of W over the hemispheres

The "UCNB" concept

[W.S. Wilburn et al., submitted to Rev. Mex. Fis.]



Basic Idea: Detect e-p coincidences

e: "start" (prompt)

p: "slow" (~ μs - ms)

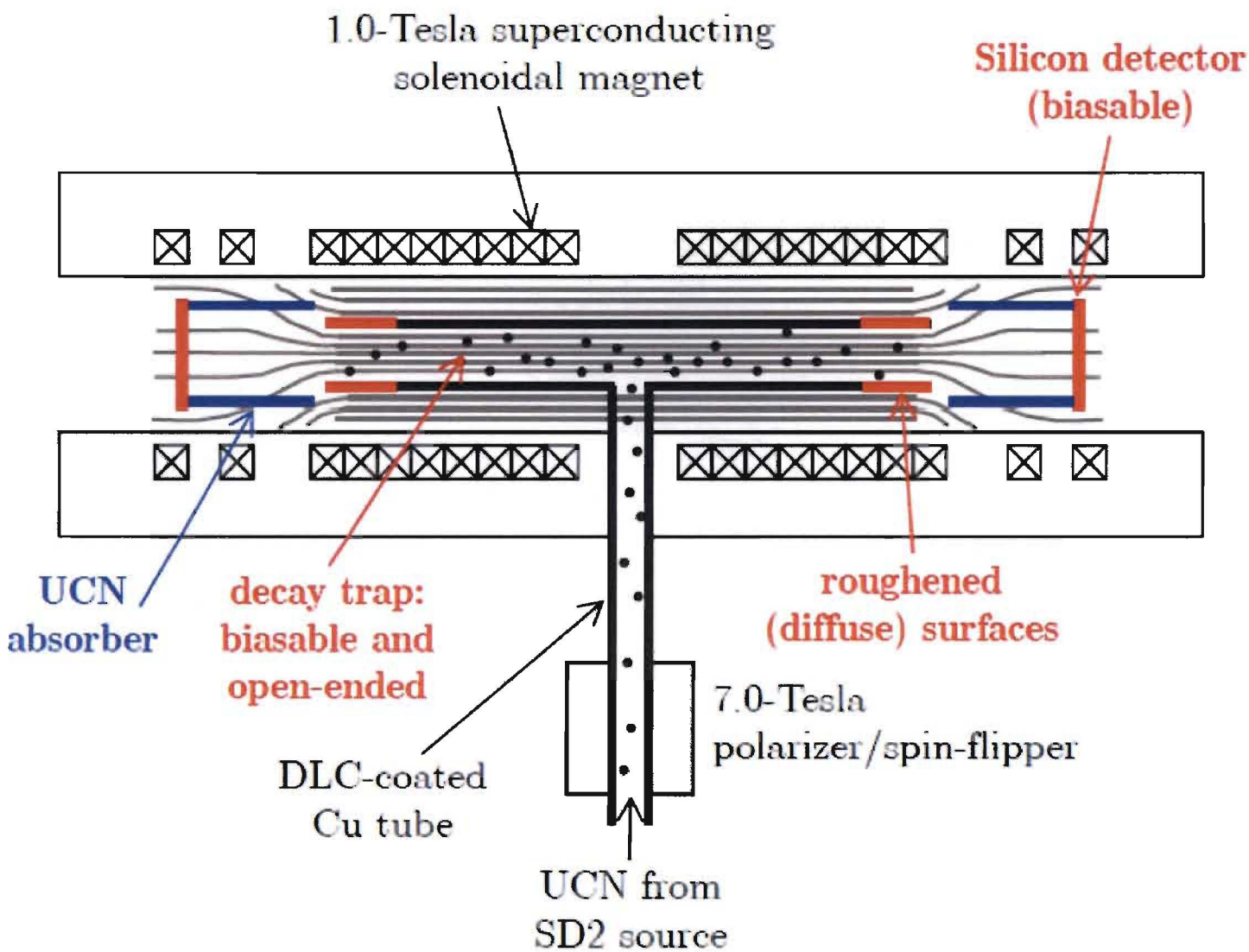
First-Pass Goal: 0.1% on B

UCNB Observables

Neutron Polarization

Electron and Proton Directions

Electron Energy


1.0-Tesla superconducting
solenoidal magnet
Silicon detector
(biasable)
UCN
absorber
decay trap:
biasable and
open-ended
roughened
(diffuse) surfaces
7.0-Tesla
polarizer/spin-flipper
DLC-coated
Cu tube
UCN from
SD2 source

Highly Segmented Si Detector

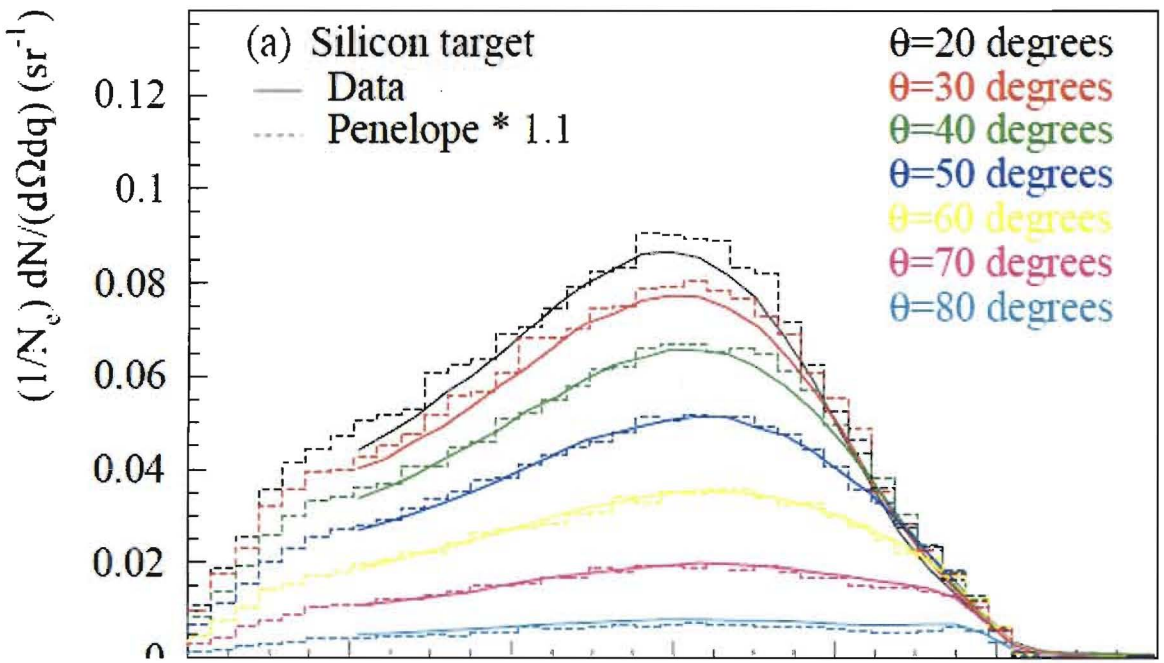
- Developed by LANL with LDRD funding
- .5, 1, 1.5 and 2mm thick
- New level of resolution
- Background reduction with e-p coincidence
- <100nm dead layer, p-gun

Preliminary Systematics + Statistical Error

Table 1: Major corrections and error table for "Bexp (E)"			
Major Systematic	Correction	Error	Source
Statistics	n/a	0.05%	Assuming a year long run
Neutron polarization	<0.1%	0.02%	UCNA experience
Det. calibration, linearity, response	0.10%	<0.01%	Projected silicon detector linearity
Proton backscatter	0.07%	<0.01%	[8]
Electron Backscatter	0.30%	0.06%	[10]
Missed coincidences	0.10%	<0.03%	1 ms window [9]
Accidental coincidences	-0.10%	<0.01%	Rate 10/s ~ 1 ms window [9]
Mirroring effects in B field expansion	-0.04%	0.02%	UCN absorbers
Total	0.30%	<0.07%	"Cexp (E)"

Electron Backscatter Modeled

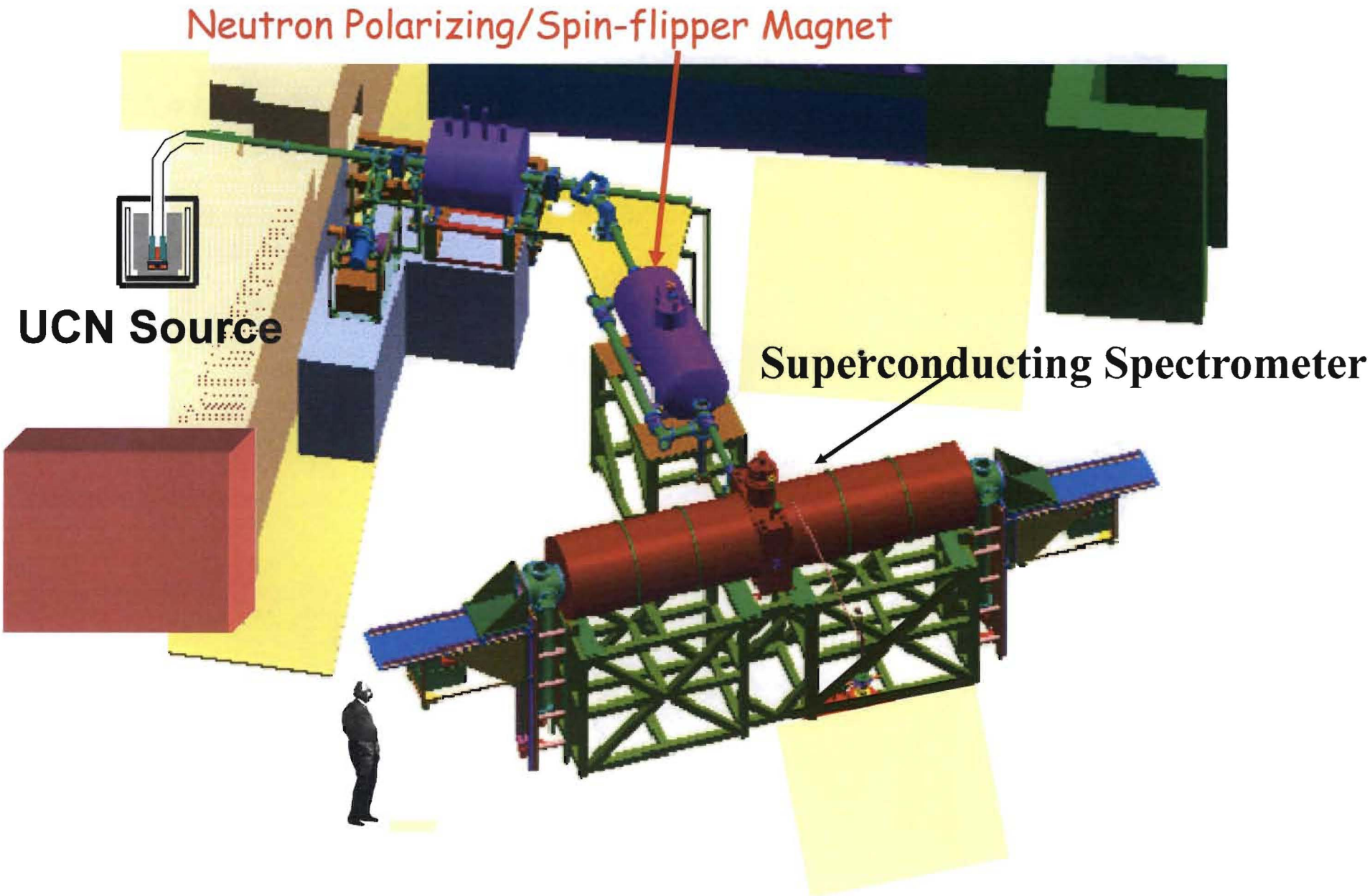
PHYSICAL REVIEW C **68**, 055503 (2003)



- Monte Carlos exist – UCNA
- Only effects energy in "C"
- Can use bias to under stand low energy response

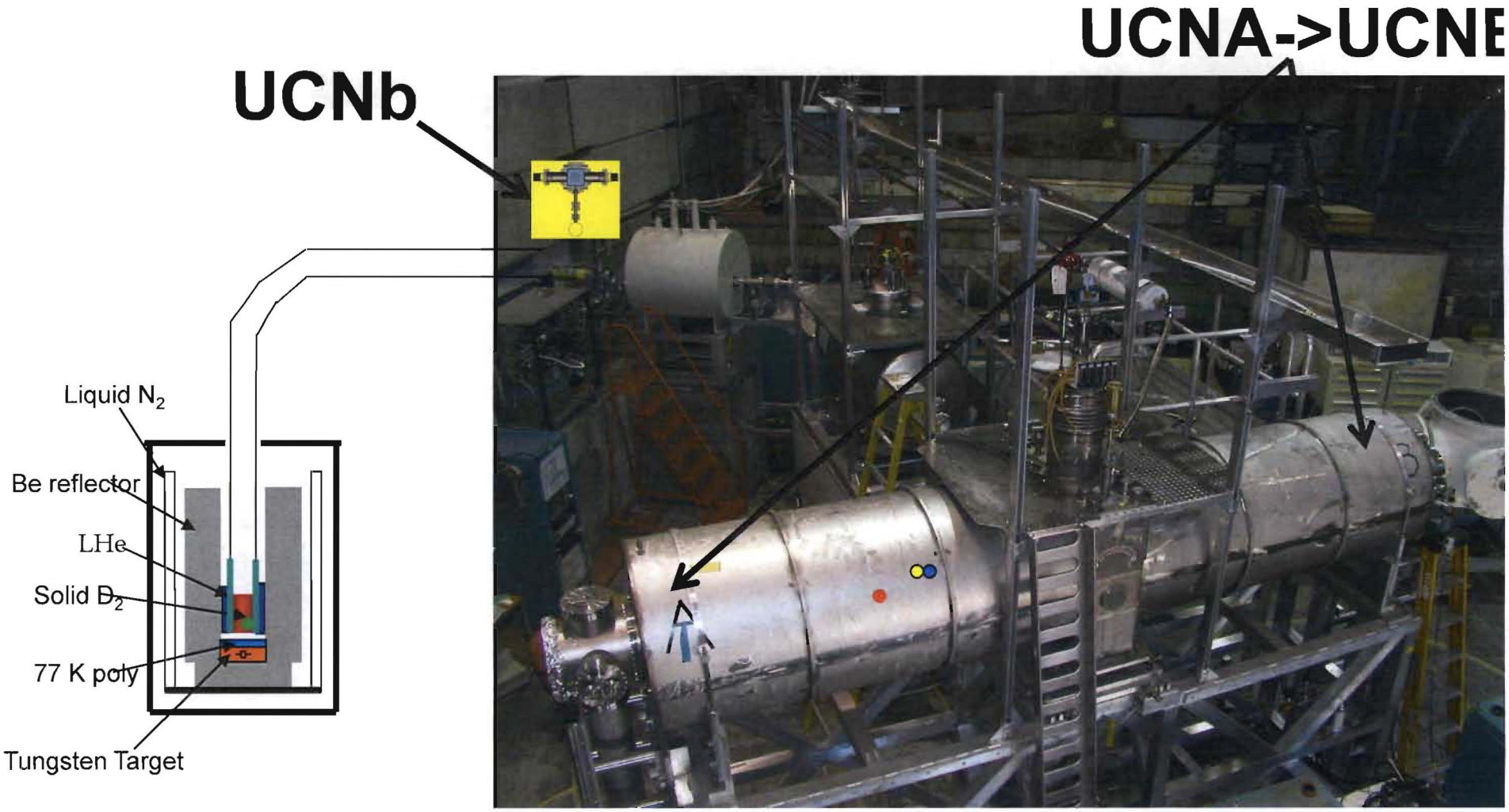
125 KeV data from Caltech e-gun

UCN Hall Layout



UCNA->UCNb, UCNB

Current facility DOE and NSF funded

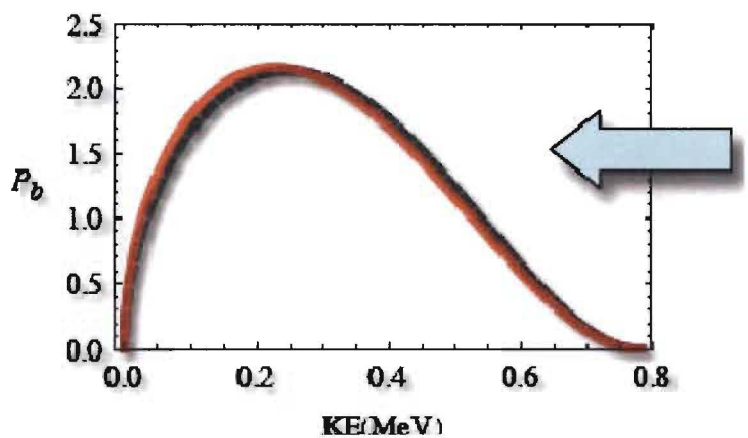


UCNb: the Fierz Interference Term

$$d\Gamma = d\Gamma_0 \times \left[1 + a\frac{\overrightarrow{p_e}\cdot\overrightarrow{p_\nu}}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \overrightarrow{\sigma_n} \right\rangle \cdot \left(A\frac{\overrightarrow{p_e}}{E_e} + B\frac{\overrightarrow{p_\nu}}{E_\nu} + D\frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right) \right]$$

$$b_n = \frac{|b_F| - 3\lambda |b_{GT}|}{1 + 3\lambda^2}$$

b_F is measured via super-allowed nuclear beta decay



b_n shifts the electron energy spectrum
And has never been measured…

$$\sigma_b = \frac{7.5}{\sqrt{N}}$$

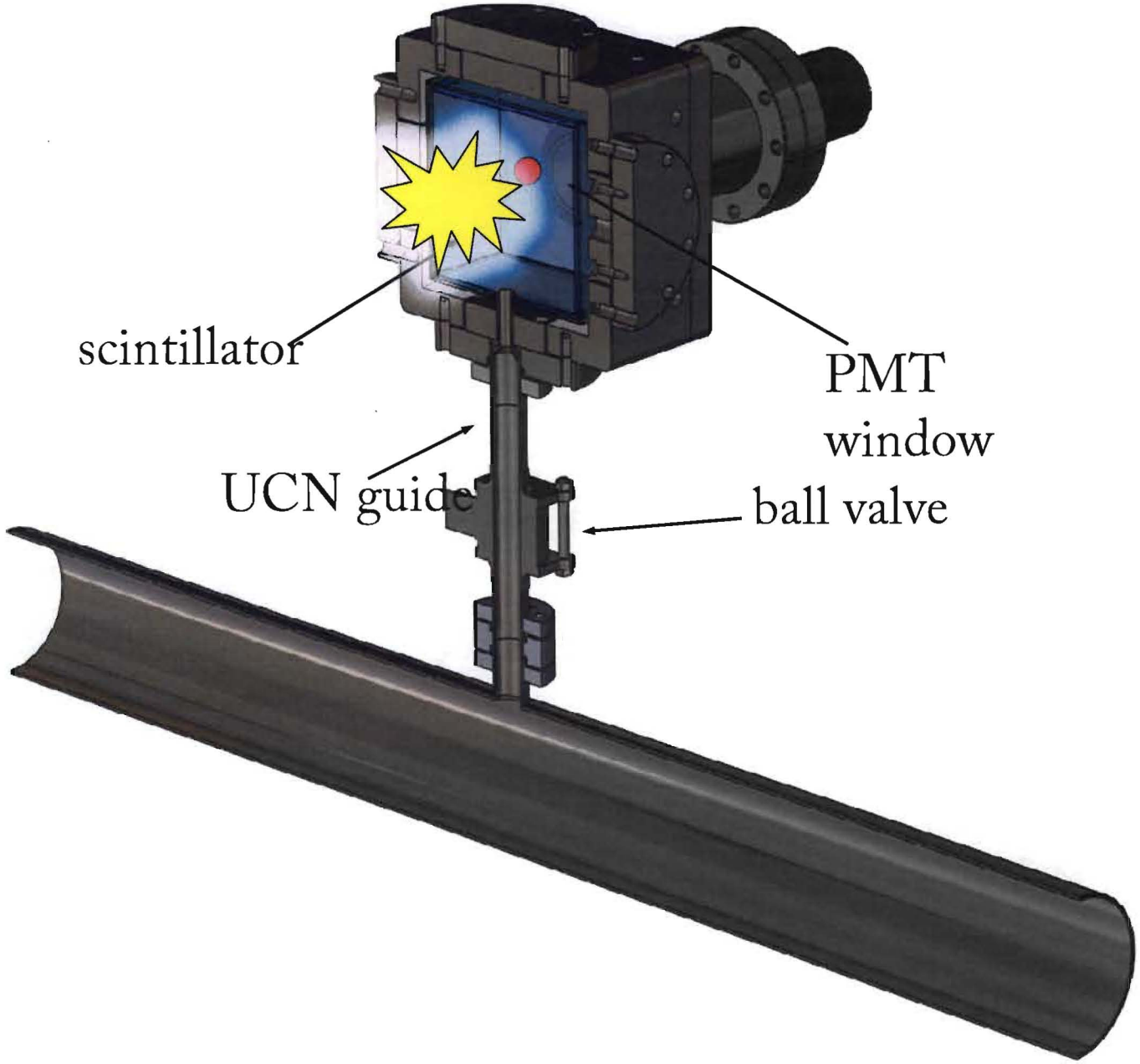
The UCNb experiment

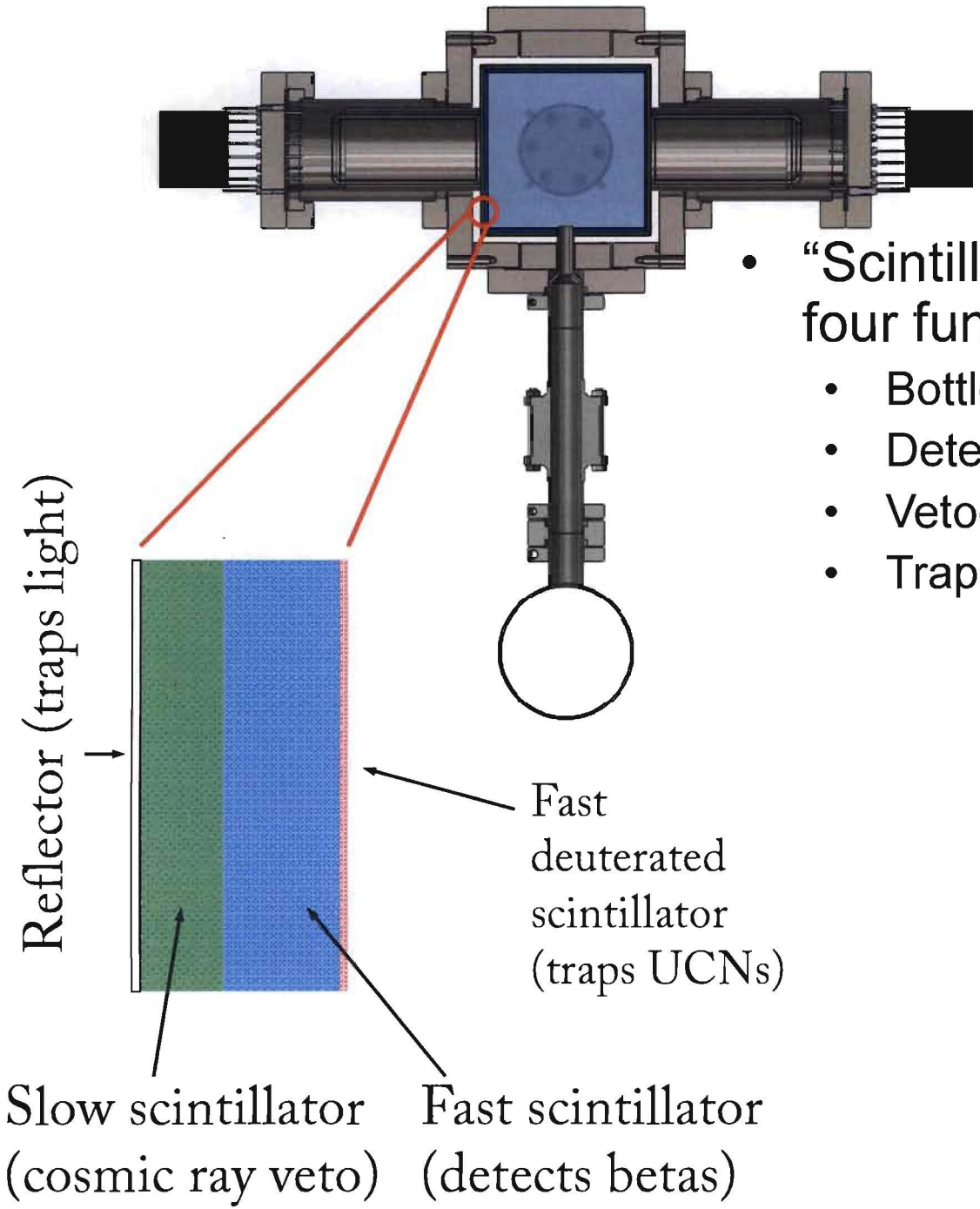
Overview of UCNb

- Compact calorimeter
- Integrating "sphere"
- 2×2" PMT (up to 4)
- Near UCN source
- Sifts off main guide

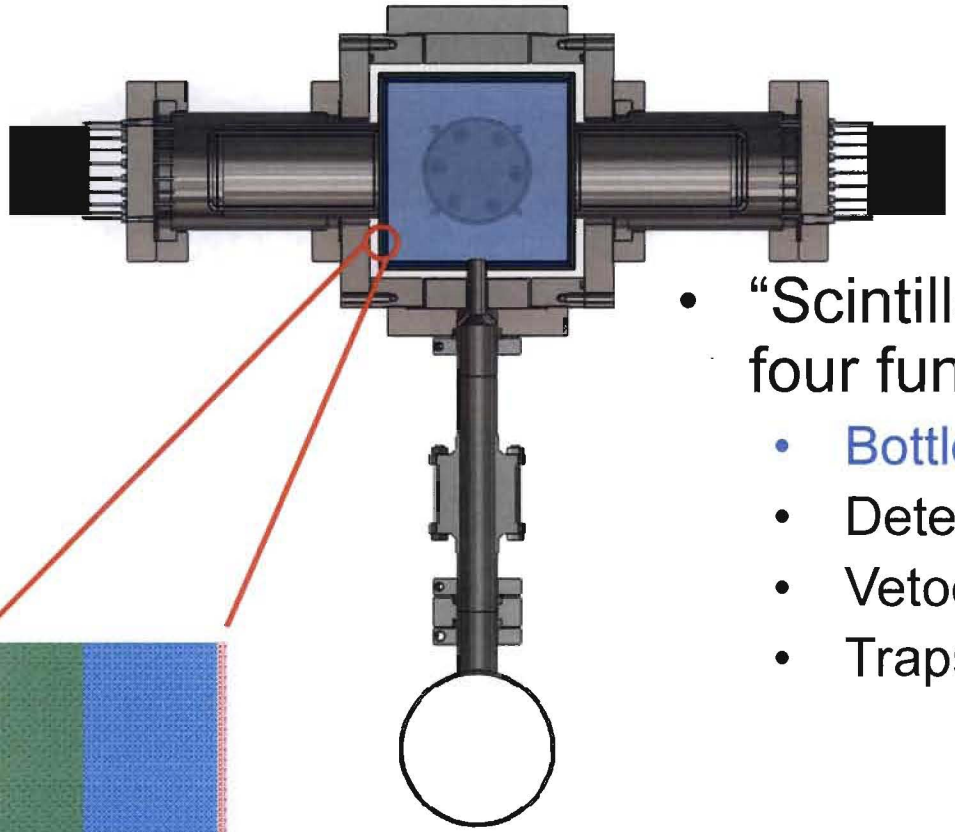
size	12×12×12 cm
volume	1.73 L
area	864 cm^2
density	10 – 30 cm^{-3}
β rate	20 – 60 Hz

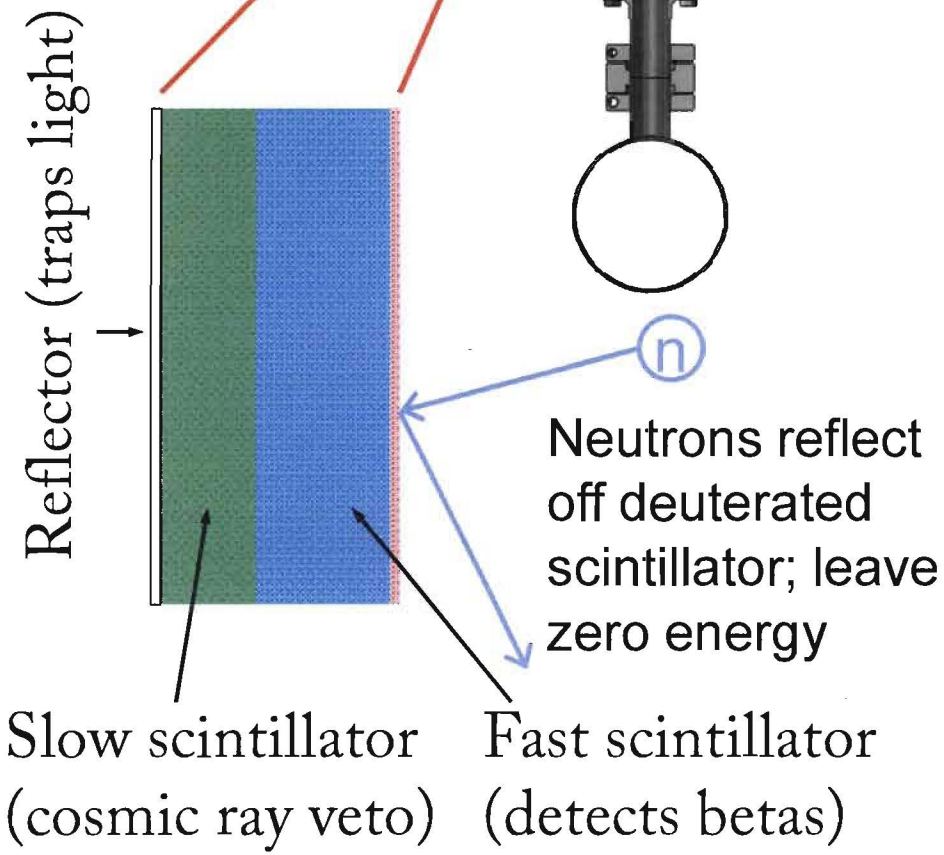
Hickerson


scintillator
PMT
window
UCN guide
ball valve



- "Scintillator sandwich" performs four functions:
  - Bottles neutrons
  - Detects decay beta particles
  - Vetoes cosmic ray background
  - Traps scintillation light





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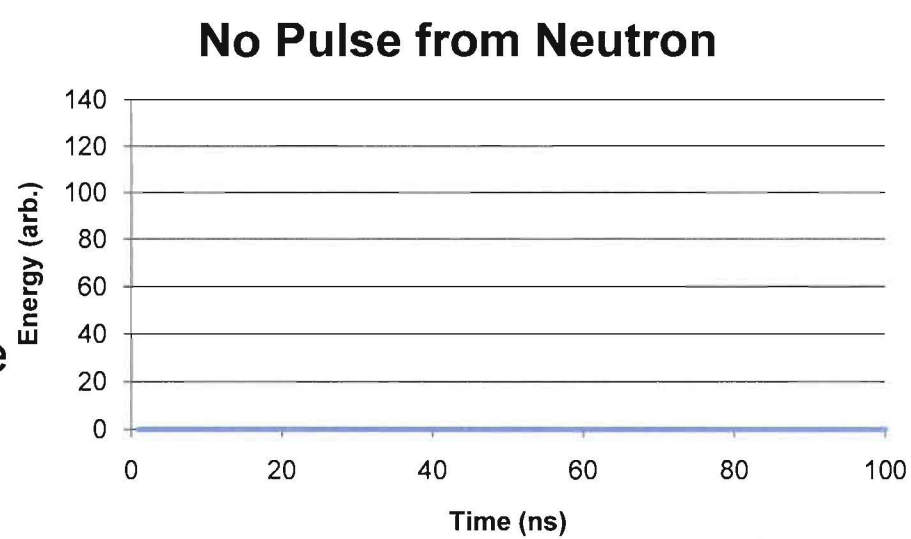

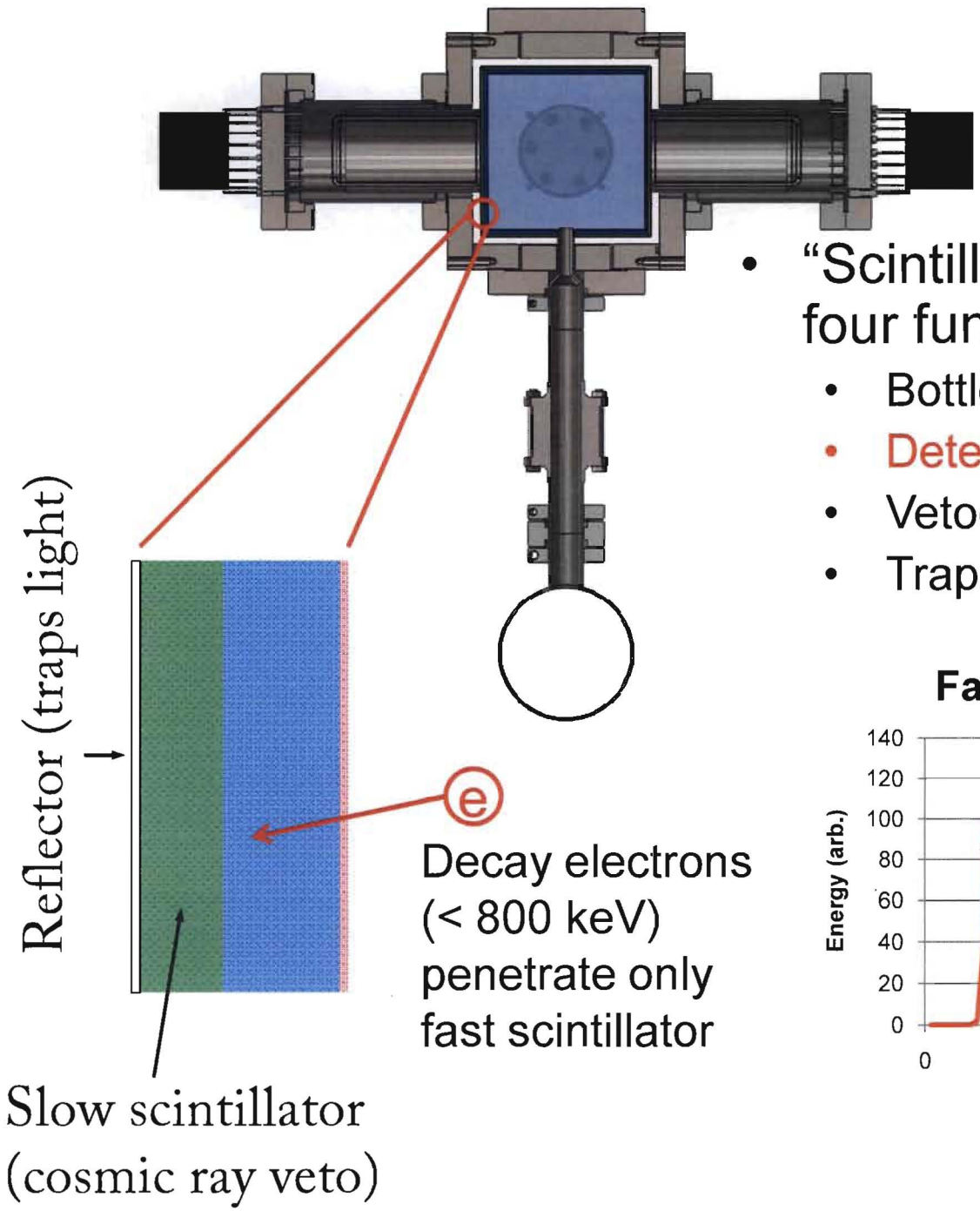

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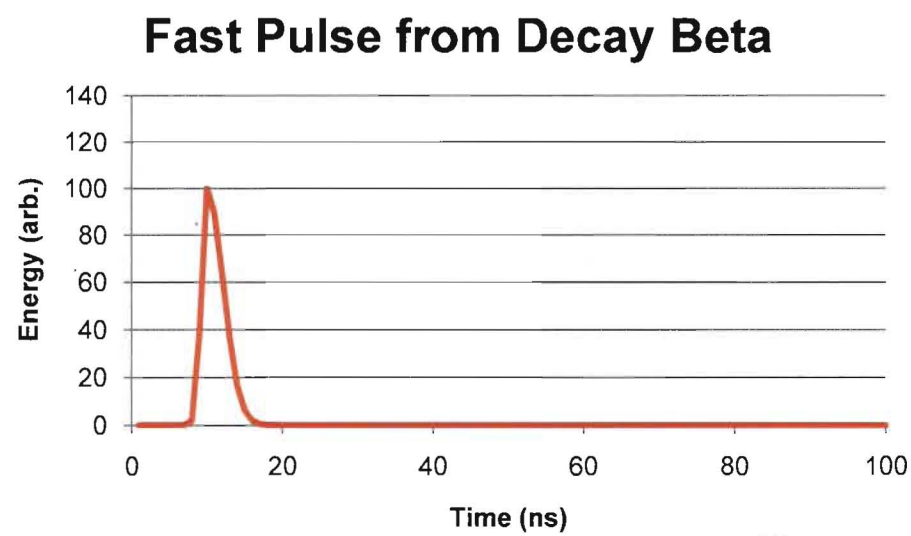

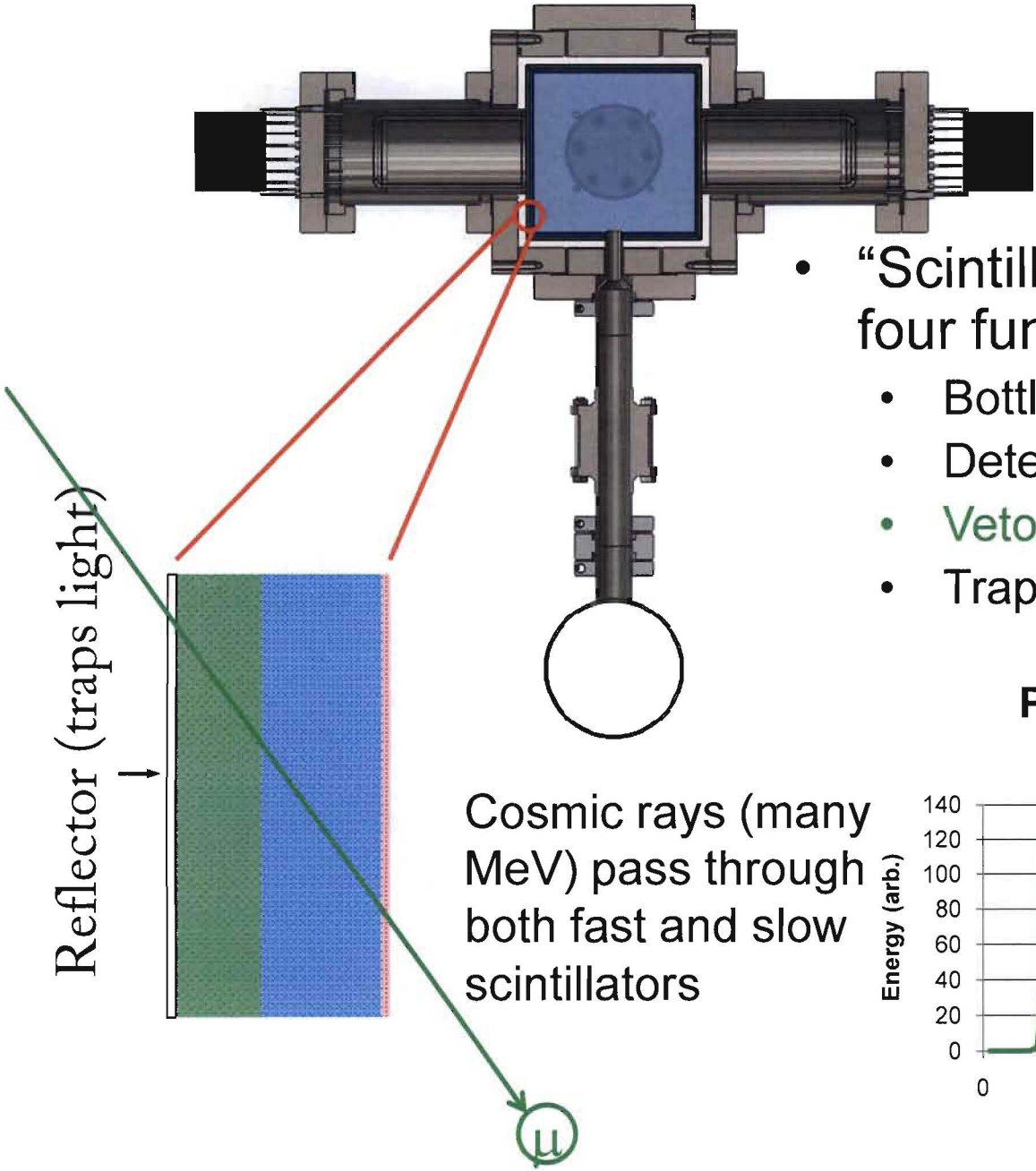

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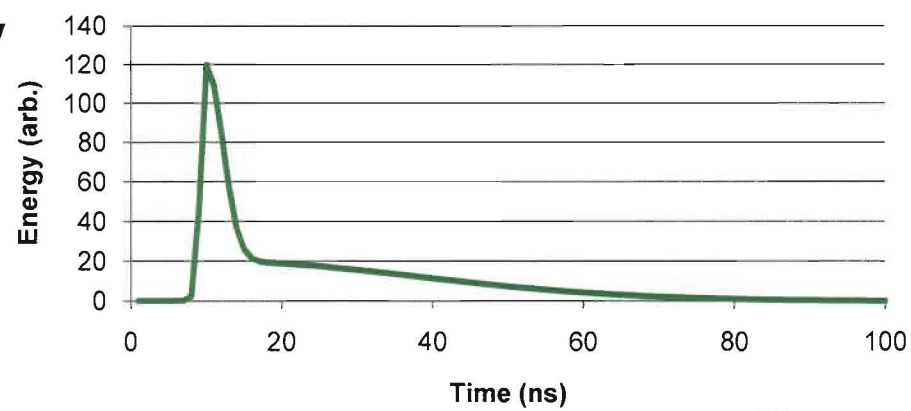
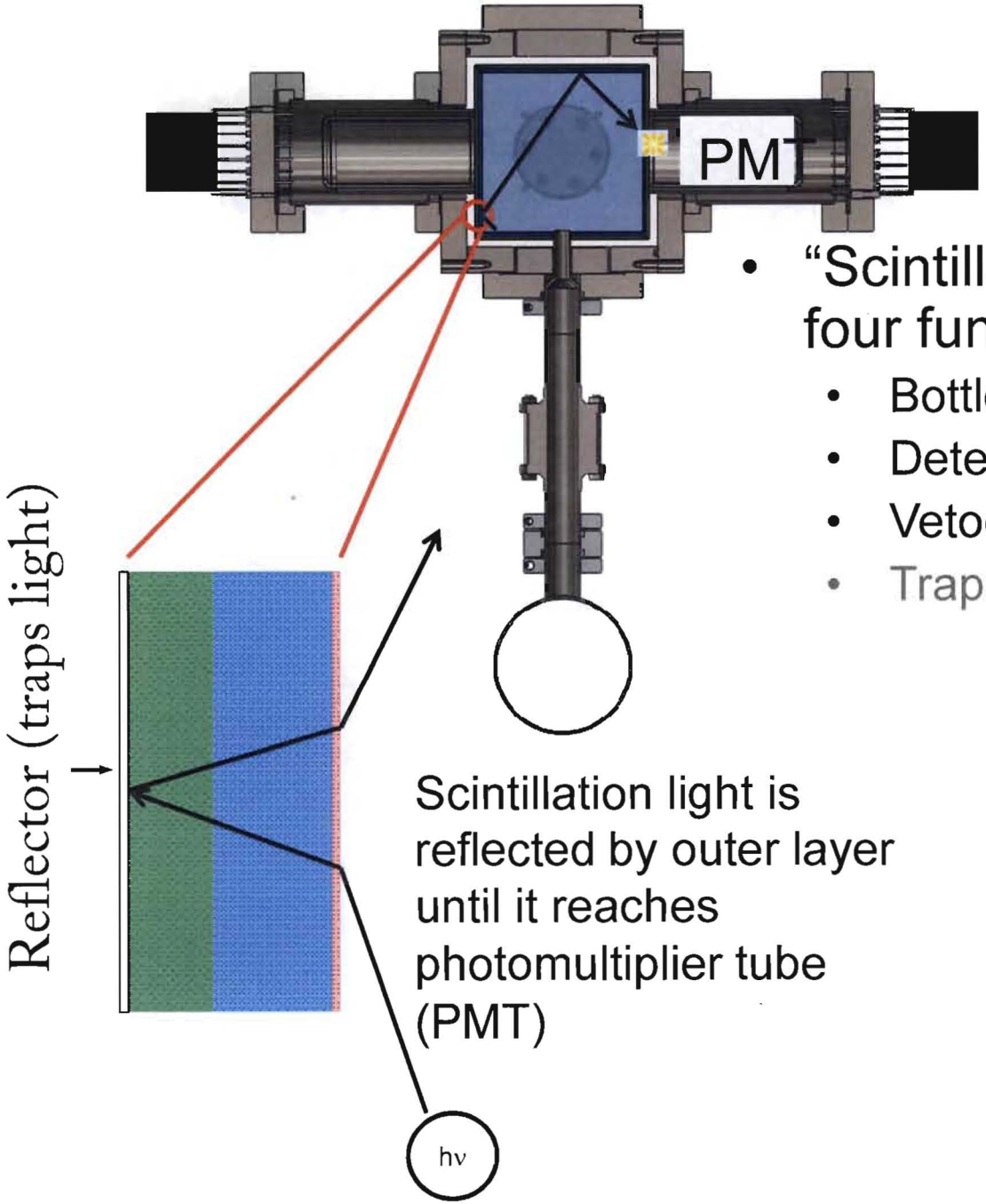
Cosmic rays (many MeV) pass through both fast and slow scintillators

Pulse with Slow Tail from Cosmic Ray





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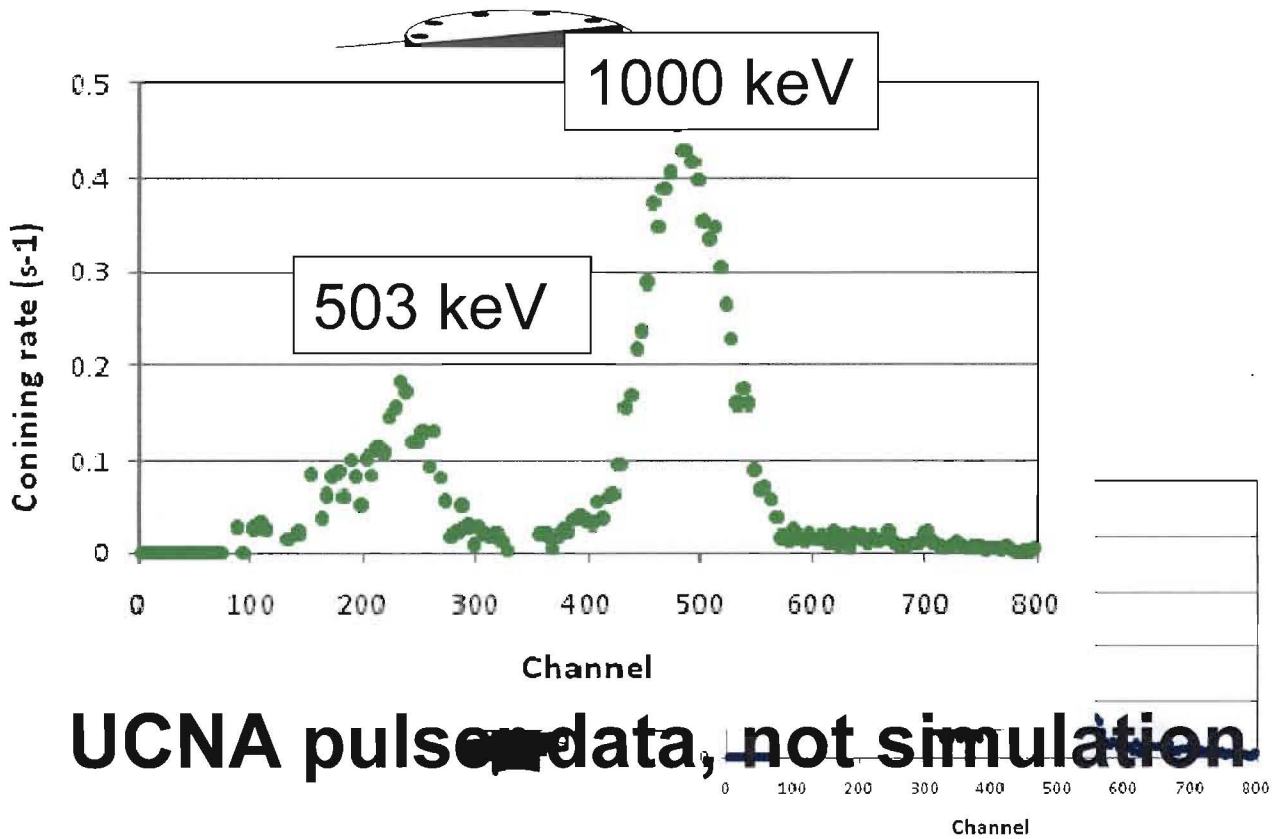
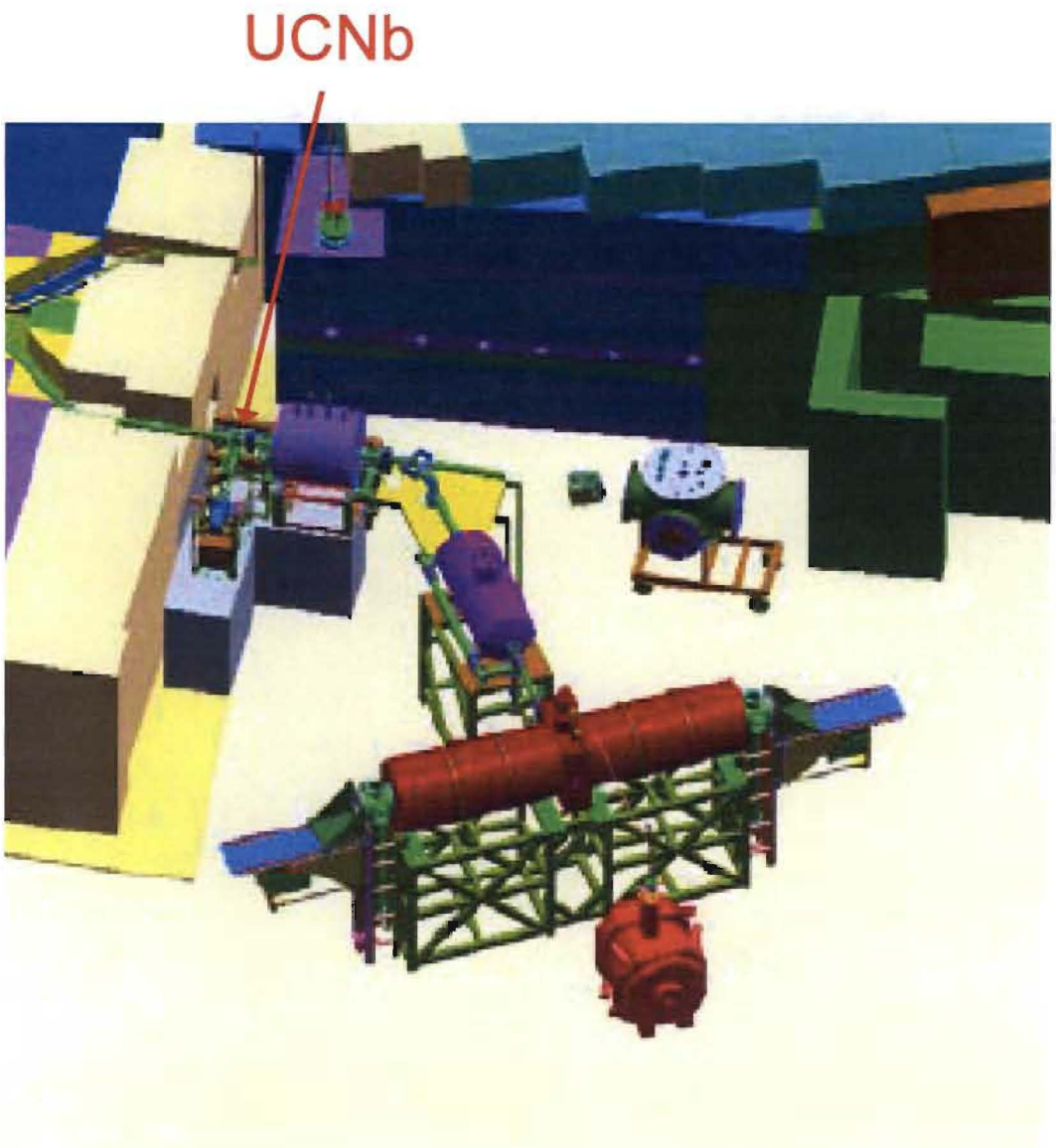
How to use β sources to calibrate UCNb



UCNA pulse data, not simulation

UCNb at LANSCE



$$\sigma_b = \frac{7.5}{\sqrt{N}}$$

Weak sensitivity implies 60 days needed for $<10^{-3}$ measurement (at 30 Hz)…
But can run in parallel with other experiments using UCN beam.

Hope to take data during 2010 run cycle

UCNA Collaboration

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UCNB and UCNb Collaborations

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[3]Los Alamos National Laboratory
[4]North Carolina State University

Conclusions

- Full suite of neutron beta correlation experiments at Los Alamos
- UCNs give unique advantages
- UCNA producing competitive results
  - Will eventually reach ~0.2%
- UCNτ will start acquiring data soon
- UCNB will probe new territory
- UCNb is a brand new measurement