September 30, 2013

Tests for tensor currents and other new physics using

Ultracold Neutrons

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What's so cool about Ultracold Neutrons?

And why do we use them?

Standard Model Neutron Beta Decay

The electroweak theory of the neutron

Symmetries and Interference in Beta Decay

A place to look for physics beyond the Standard Model

Beta Spectroscopy with Polarized Ultracold Neutrons

The UCNA experiment at LANSCE

A Novel Experimental Prototype

The UCNb experiment at LANSCE

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What are Ultracold Neutrons?

The Fermi Potential

$$V_F = \frac{2\pi\hbar^2}{m_n}\sum_i b_i\delta(\mathbf{r}-\mathbf{r}_i) = \frac{2\pi\hbar^2}{m_n}bN$$

Element	b (fm)	V_F (neV)
Ni / Ni^{58}	10.3 / 14.4	252 / 335
Be	7.75	252
Fe	9.7	210
Cu	7.6	168
Al	3.45	54
H / D	-3.74 /+6.67	- / +

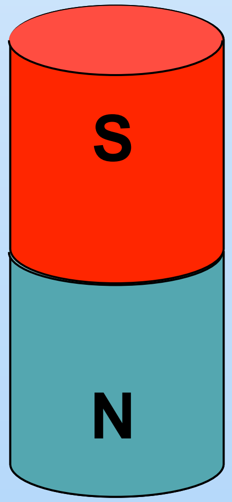
Why use Ultracold Neutrons?

The magnetic potential of polarized neutrons

$$V_B = \pm \mu_n B$$

$$\mu_n = -60.307739(14)\ \mathrm{neV/T}$$

All UCN can be polarized by B = 6 T.



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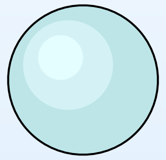
$$V_B = \pm \mu_n B$$

$$\mu_n = -60.307739(14)\ \mathrm{neV/T}$$

Low-field seeking UCN can be trapped by *B* bottle.

Why use Ultracold Neutrons?

The gravitational potential of neutron mass

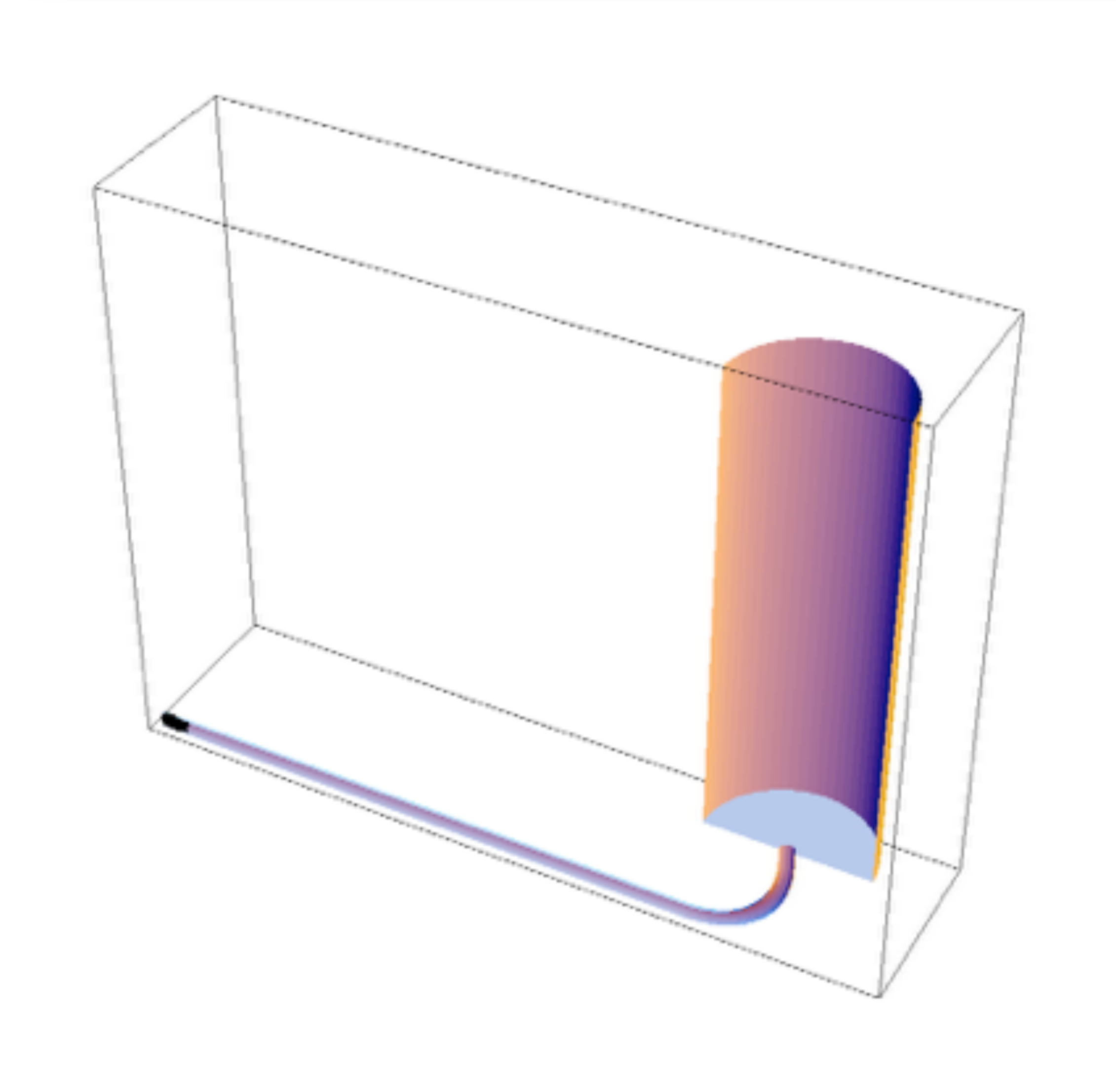


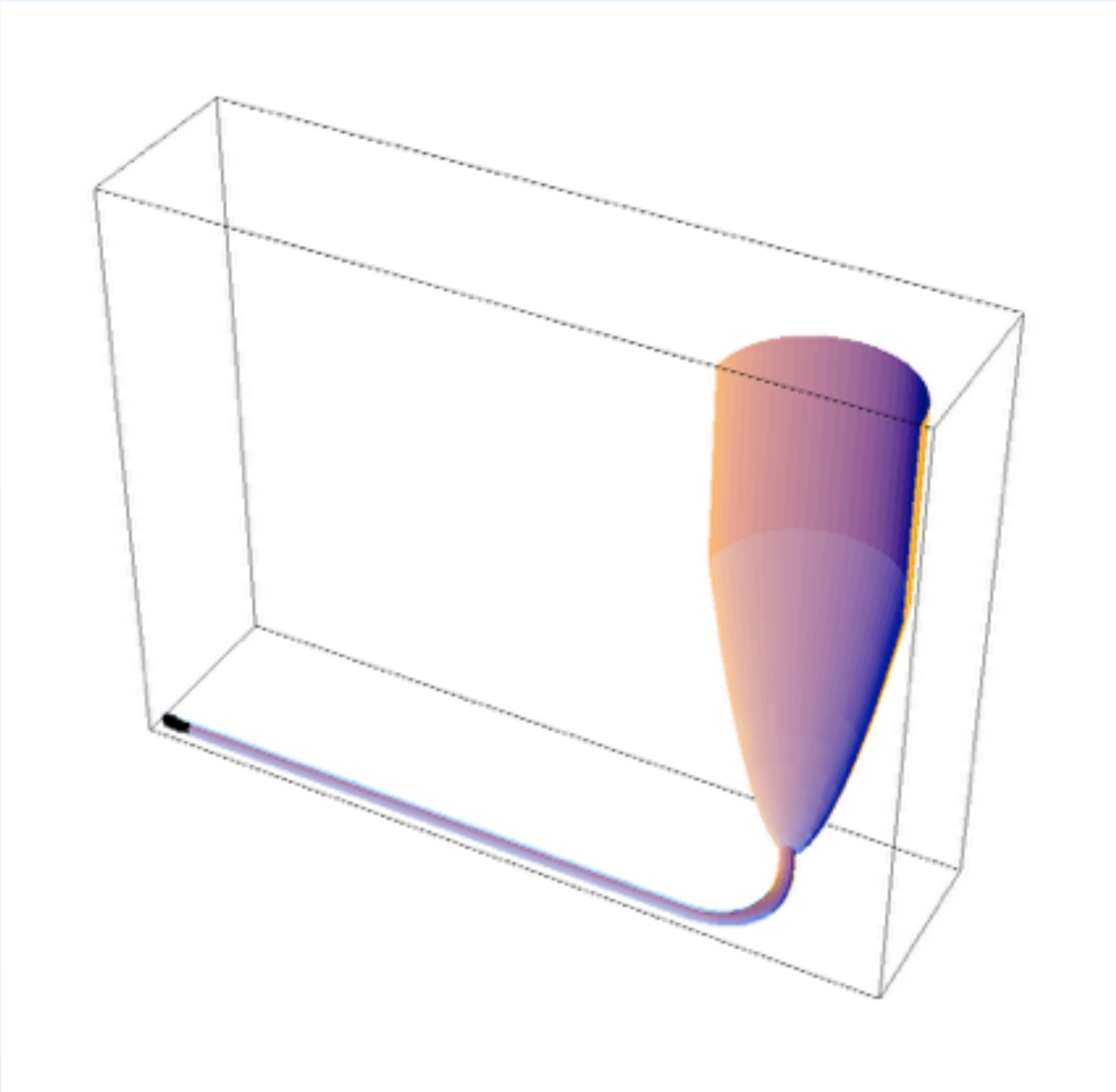
$$V_g = m_n g h$$

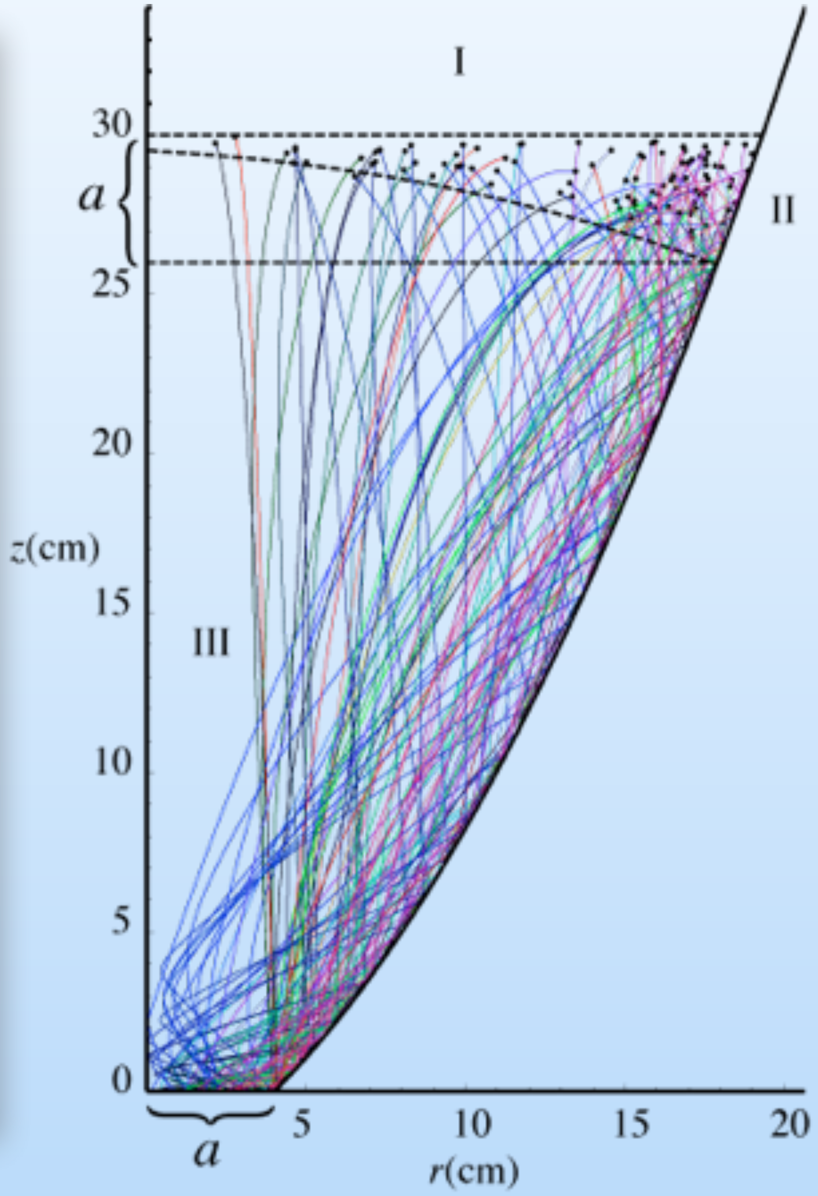
$$m_n g = 102.52 \text{ neV/m}$$

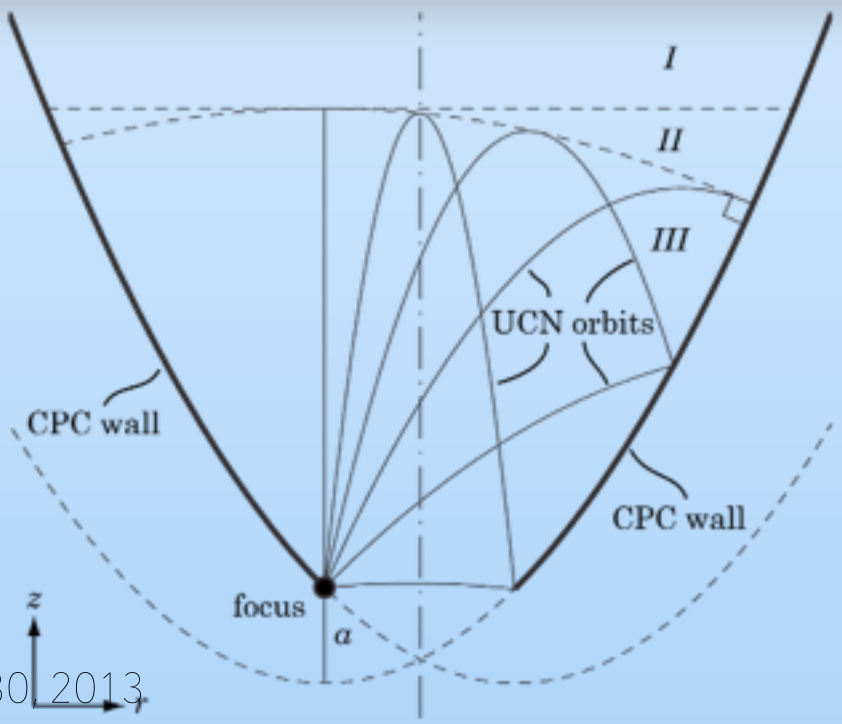
UCN can be trapped in a “bucket” 3.5 m deep!

UCN optics and transport









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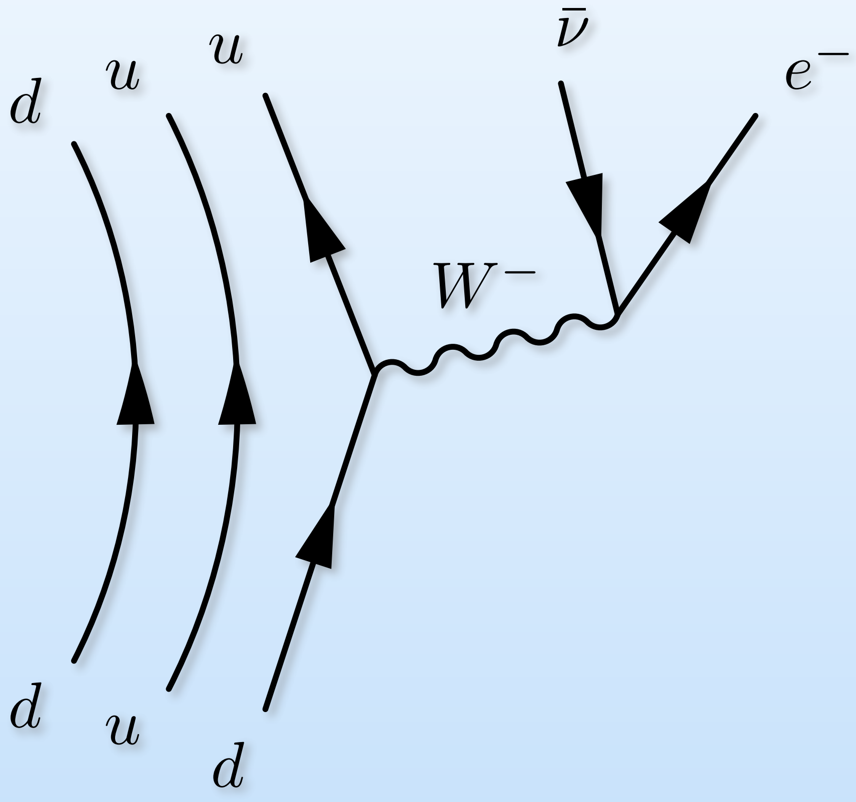
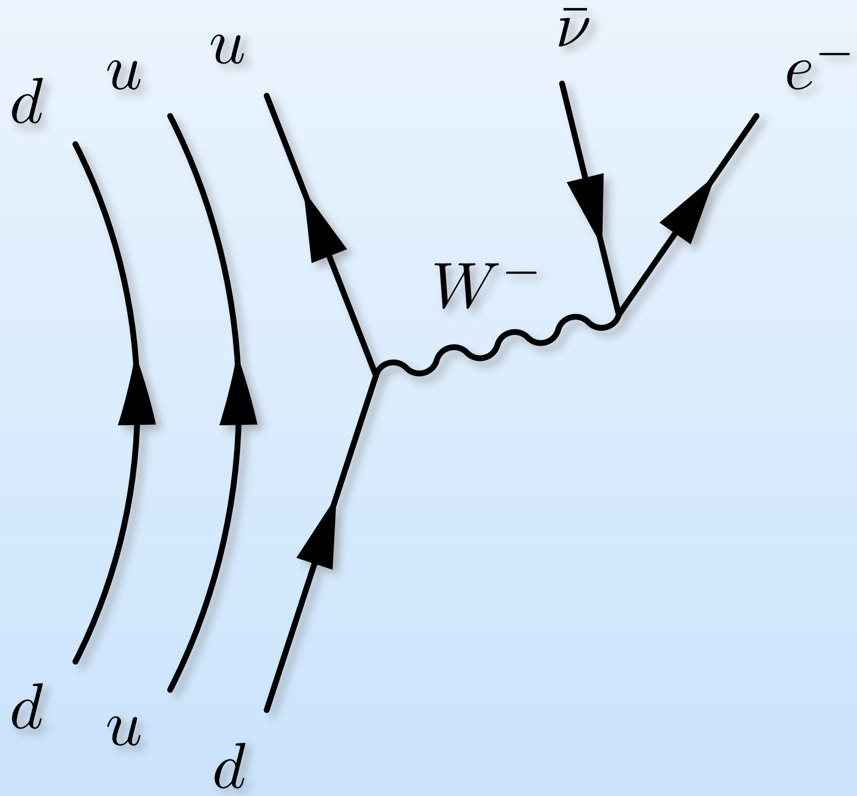
Neutron beta decay

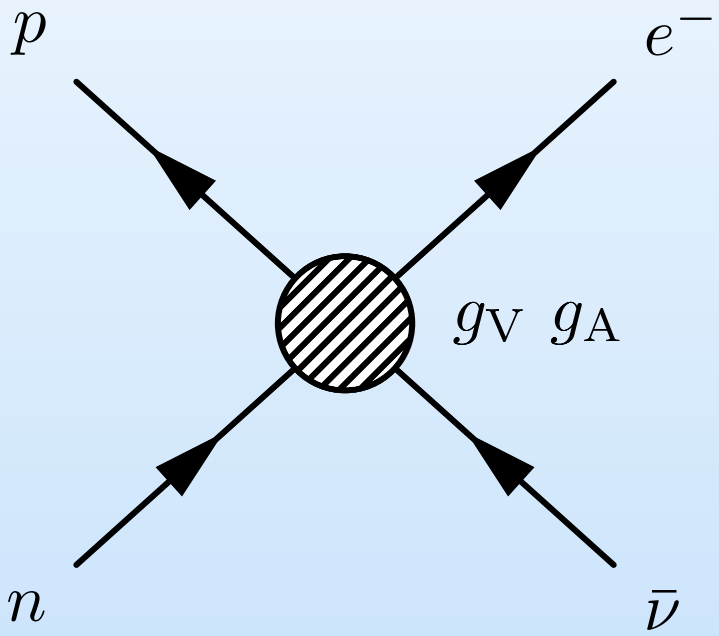


$$n \to p + e + \bar{\nu}_e$$

Neutron beta decay

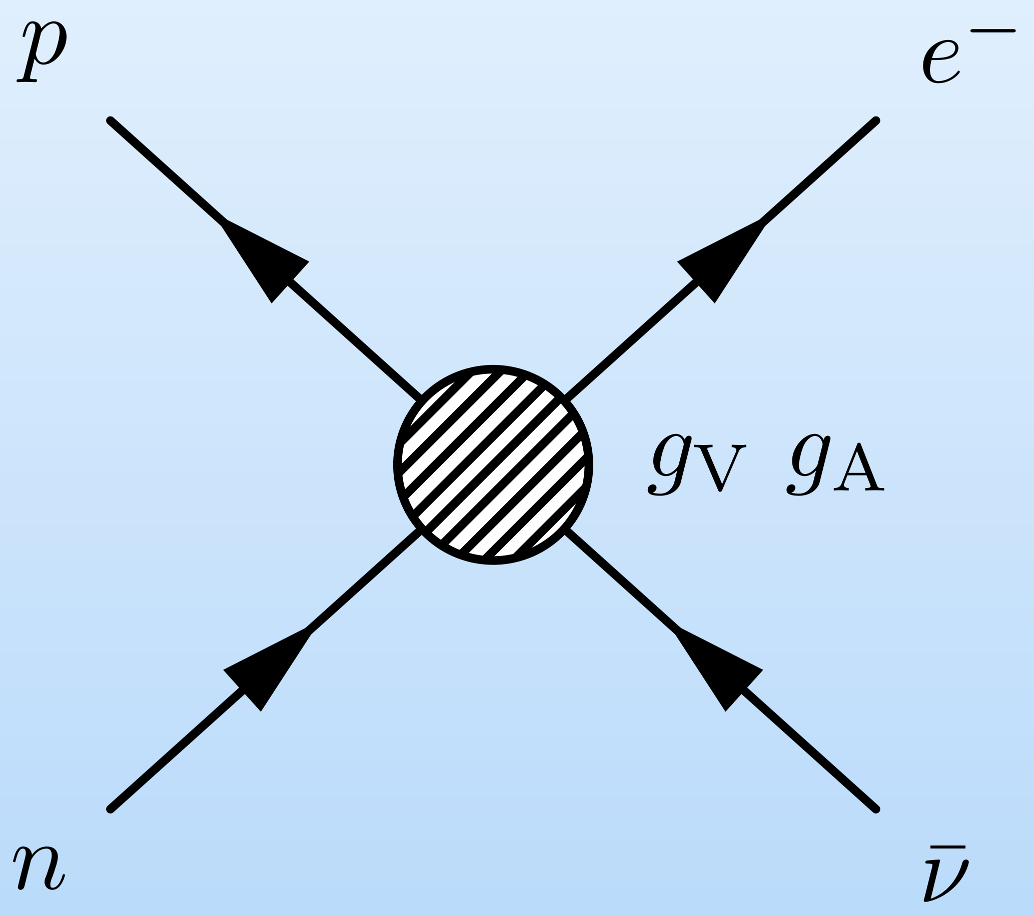


$$n \to p + e + \bar{\nu}_e$$



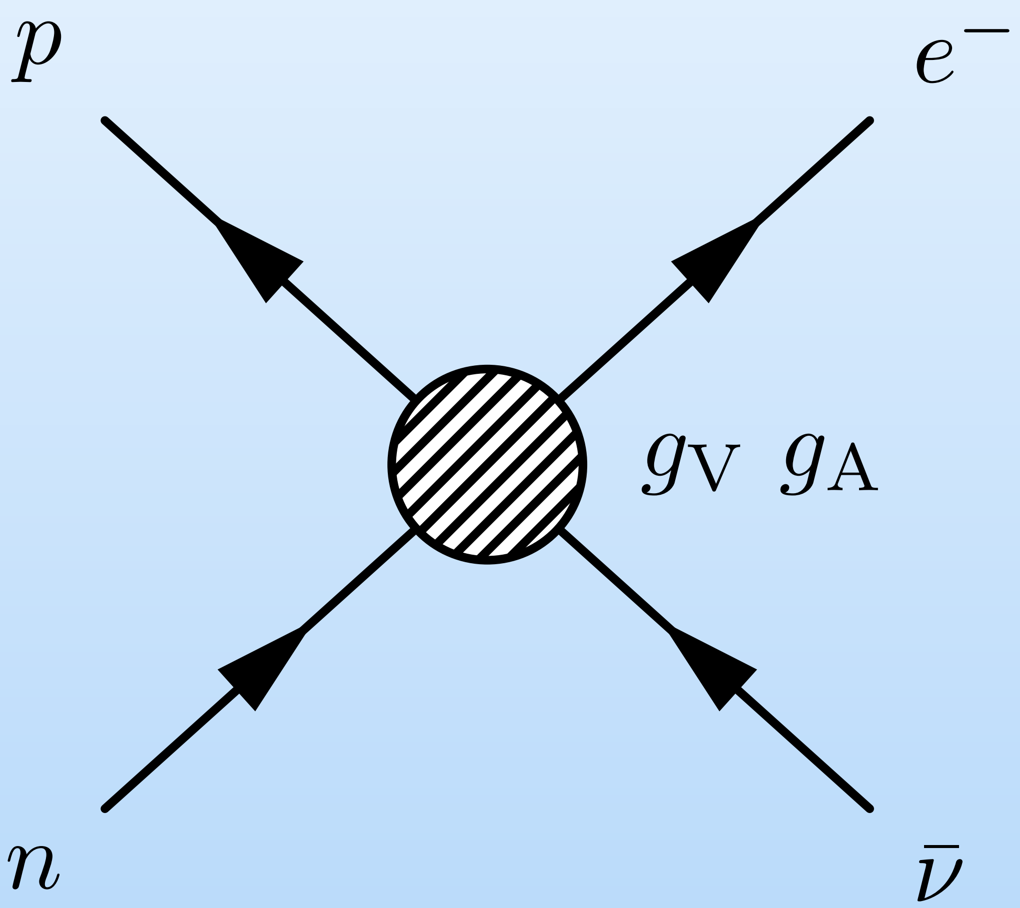
Effective beta decay

$$\mathcal{L}_\beta = \sqrt{8} G_{\mathrm{F}} V_{ud}\, \bar{p}\gamma^\mu \left(g_V - g_A\gamma^5\right) n\, \bar{e}\gamma_\mu \left(1-\gamma^5\right)\nu_e .$$



Effective beta decay

$$\mathcal{L}_\beta = \sqrt{8} G_{\rm F} V_{ud}\, \bar{p}\gamma^\mu \left(g_V - g_A\gamma^5\right) n\; \bar{e}\gamma_\mu \left(1-\gamma^5\right)\nu_e.$$



$$g_{\rm V} = 1.0000(3)$$

$$\lambda \equiv g_{\rm A}/g_{\rm V} = -1.2701(25)$$

PDG (2012)

Neutron lifetime

$$\tau_n^{-1} = \frac{G_\mathrm{F}^2}{2\pi^3}(1+3\lambda^2)\,|V_{ud}|^2\,m_e^5 I_0(1+\Delta)$$

where

$$I_k = \int_1^{x_0} x^{1-k}(x-x_0)^2\sqrt{x^2-1}\,dx; \qquad x \equiv \frac{E}{m_e}$$

and Δ encapsulates electroweak, recoil and Fermi function corrections

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Generalized weak decay structure

The most general Lagrangian for beta decay over all Dirac matrices and chiralities

$$\mathcal{L} = -\frac{4G_{F\mu}}{\sqrt{2}} a^{\gamma}_{\alpha\delta} \bar{e}_{\alpha} \Gamma^{\gamma} \nu_e \bar{u} \Gamma_{\gamma} d_{\delta}$$

$$\Gamma^{\mathrm{S}} = 1, \quad \Gamma^{\mathrm{V}} = \gamma^{\alpha}, \quad \Gamma^{\mathrm{T}} = \sigma^{\alpha\beta}/\sqrt{2}$$

In the Standard Model including radiative corrections

$$a^{V}_{LL} = V_{ud}(1 + \Delta_{\beta} + \Delta_{\mu}), \quad a^{\gamma}_{\epsilon\delta} = 0$$

All other couplings serve as test for new physics!

S. Profumo, M.J. Ramsey-Musolf and S. Tulin, PRD 77, 075017 (2007)

Alphabet soup

In the Standard Model, to leading order, we have,

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

Neutron decay parameters

In the Standard Model...

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

...have constraints coming from g_A/g_V but others are forbidden.

$$a_0 = \frac{1-\lambda^2}{1+3\lambda^2}, \qquad A_0 = -\frac{2\lambda(1+\lambda)}{1+3\lambda^2}, \qquad B_0 = -\frac{2\lambda(1-\lambda)}{1+3\lambda^2}, \qquad b = 0.$$

Neutron decay parameters

Beta asymmetry can be observed...

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

...if neutron polarization and electron momentum is measured.

$$\Gamma(\theta) = \left(1 + A\langle P \rangle \frac{v}{c} \cos\theta \right) \Gamma_{\mathrm{SM}}$$

Neutron decay parameters

Only the Fierz interference term...

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

...is polarization and momentum independent.

$$d\Gamma_b = d\Gamma_{\mathrm{SM}} \left(1 + b\frac{m_e}{E_e} \right)$$

Fierz interference

The most general Fierz term for nuclear beta decay

$$b = \pm \frac{2\ \mathrm{Re}\left[M_F^2 g_V g_S a_{LL}^V (a_{RL}^S + a_{RR}^S)^* - 2M_{GT}^2 g_A g_T a_{LL}^V a_{RL}^{T*}\right]}{M_F^2\left(g_V^2 |a_{LL}^V|^2 + g_S^2 |a_{RL}^S + a_{RR}^S|^2\right) + M_{GT}^2\left(g_A^2 |a_{LL}^V|^2 + 4g_T^2 |a_{RL}^T|^2\right)}$$

Fermi and Gamow-Teller terms are special cases

$$b_F = 2\frac{g_S}{g_V}\frac{a_{RL}^S + a_{RR}^S}{a_{LL}^V} \qquad b_{GT} = -4\frac{g_T}{g_A}\frac{a_{RL}^T}{a_{LL}^V}$$

Neutron beta-decay provides a combination

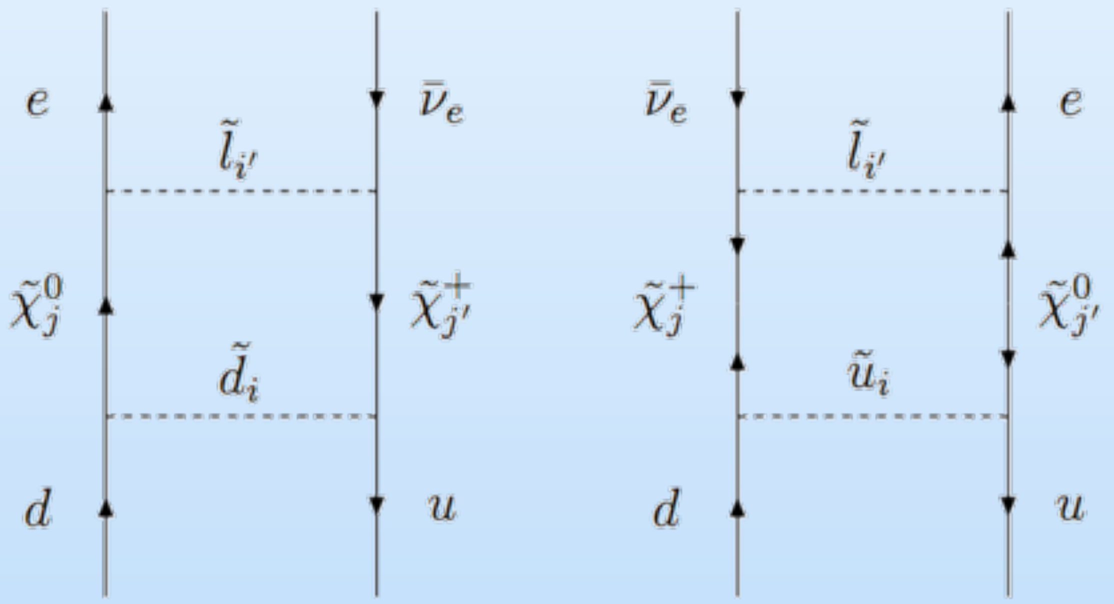
$$b_n = \frac{b_F + 3\lambda^2 b_{GT}}{1 + 3\lambda^2}$$

S. Profumo, M.J. Ramsey-Musolf and S. Tulin, PRD 77, 075017 (2007)

Testing Supersymmetry with b

One loop corrections to SM from MSSM and NMSSM

10^{-3} possible (but not likely)



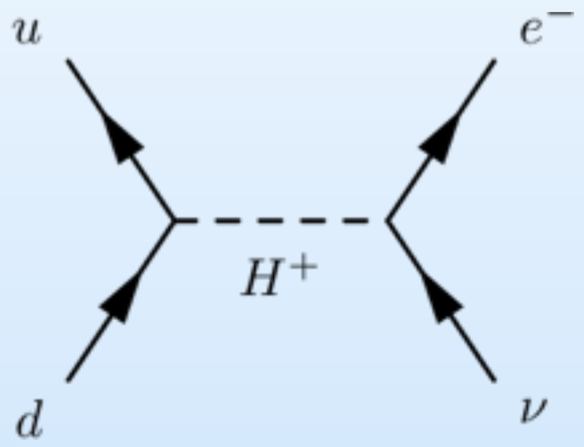
(a) (b)

- NMSSM adds the “singilino”
- Same loop diagrams
- likely little change to neutrilino mass scale

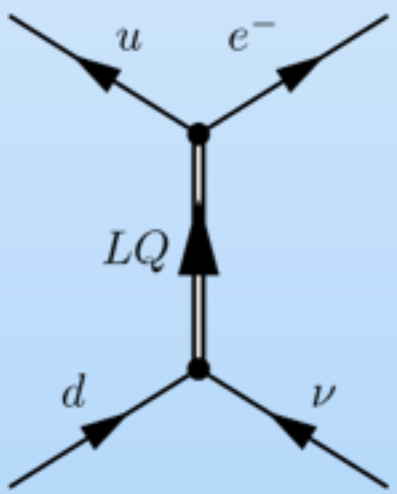
S. Profumo, M.J. Ramsey-Musolf and S. Tulin, PRD 77, 075017 (2007)

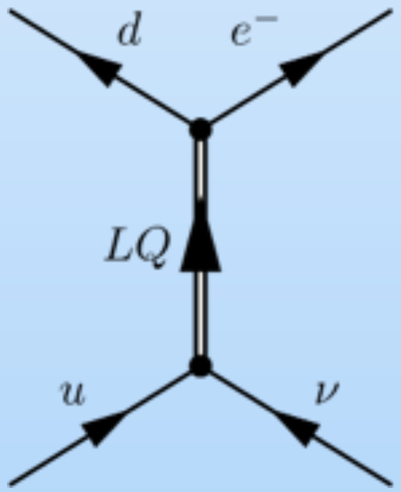
Testing BSM with b

- Tree level contributions from BSM charged Higgs



- Leptoquarks also may enter at tree level





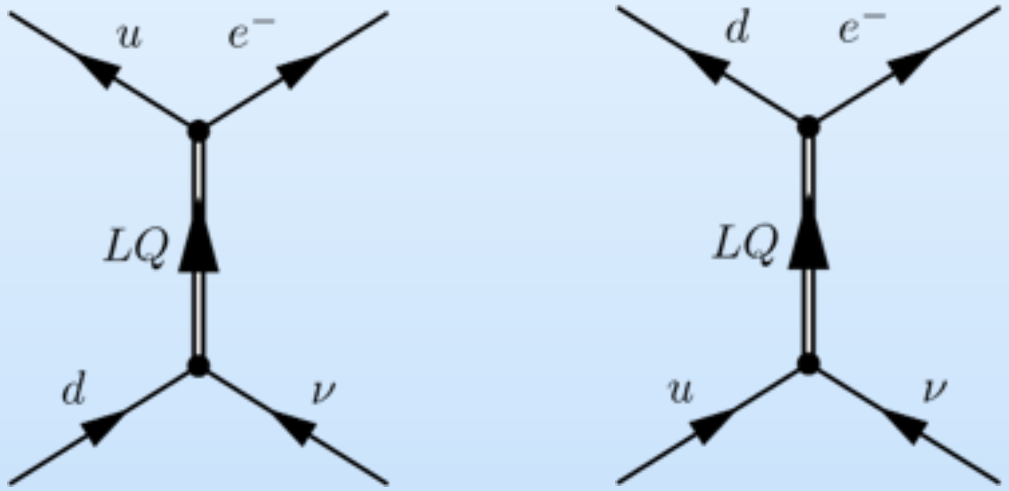
Leptoquarks

$$\mathcal{L}^{\mathrm{S}}_{\mathrm{LQ}} = \lambda^{(R)}_{S_0} \cdot \overline{u^c} P_R e \cdot S_0^{R\dagger} + \lambda^{(R)}_{\tilde{S}_0} \cdot \overline{d^c} P_R e \cdot \tilde{S}_0^{\dagger}$$
$$+ \lambda^{(R)}_{S_{1/2}} \cdot \overline{u} P_L l \cdot S_{1/2}^{R\dagger} + \lambda^{(R)}_{\tilde{S}_{1/2}} \cdot \overline{d} P_L l \cdot \tilde{S}_{1/2}^{\dagger}$$
$$+ \lambda^{(L)}_{S_0} \cdot \overline{q^c} P_L i\tau_2 l \cdot S_0^{L\dagger} + \lambda^{(L)}_{S_{1/2}} \cdot \overline{q} P_R i\tau_2 e \cdot S_{1/2}^{L\dagger}$$
$$+ \lambda^{(L)}_{S_1} \cdot \overline{q^c} P_L i\tau_2 \vec{\tau} \vec{S}_1^{\dagger} l + \mathrm{h.c.}$$

$$b_{\mathrm{GT}} = \frac{g_T}{2\lambda} \left(\frac{\lambda^L_{S_0} \lambda^{R*}_{S_0}}{M^2_{S_0}} + 4 \frac{\lambda^L_{S_{1/2}} \lambda^{R*}_{S_{1/2}}}{M^2_{\tilde{S}_{1/2}}} \right)$$

$$\mathcal{L}^{\mathrm{V}}_{\mathrm{LQ}} = \lambda^{(R)}_{V_0} \cdot \overline{d} \gamma^\mu P_R e \cdot V_{0\mu}^{R\dagger} + \lambda^{(R)}_{\tilde{V}_0} \cdot \overline{u} \gamma^\mu P_R e \cdot \tilde{V}_{0\mu}^{\dagger}$$
$$+ \lambda^{(R)}_{V_{1/2}} \cdot \overline{d^c} \gamma^\mu P_L l \cdot V_{1/2\mu}^{R\dagger} + \lambda^{(R)}_{\tilde{V}_{1/2}} \cdot \overline{u^c} \gamma^\mu P_L l \cdot \tilde{V}_{1/2\mu}^{\dagger}$$
$$+ \lambda^{(L)}_{V_0} \cdot \overline{q} \gamma^\mu P_L l \cdot V_{0\mu}^{L\dagger} + \lambda^{(L)}_{V_{1/2}} \cdot \overline{q^c} \gamma^\mu P_R e \cdot V_{1/2\mu}^{L\dagger}$$
$$+ \lambda^{(L)}_{V_1} \cdot \overline{q} \gamma^\mu P_L \hat{V}_{1\mu}^{\dagger} l + \mathrm{h.c.}$$

- Leptoquarks also may enter at tree level
- 10^{-3} possible



V. Cirigliano and E. Passemar 77(5) (2008)

Current experimental limits

Best limits for b_n come from superallowed $J^\pi = 0^+ \to 0^+$ β-decay ft values

$$b_F = -0.0022 \pm 0.0026$$

Hardy and Towner, Phys. Rev. C 79(5) (2009)

isotope	$g_T \epsilon_T$ (90% C.L.)	γ	b_{GT} (90% C.L.)	ref.
^{60}Co	$^{+1.5\times10^{-2}}_{-2.9\times10^{-3}}$	0.980	$^{+0.018}_{-0.092}$	Wauters (2010)
^{114}In	$^{+1.3\times10^{-2}}_{-2.2\times10^{-2}}$	0.934	$^{+0.139}_{-0.082}$	Wauters (2008)
^{107}In	$< 3.1 \times 10^{-3}$	0.94	$< 1.9 \times 10^{-2}$	Severijns (2000)
^{19}Ne	-	0.99	$^{+0.040}_{-0.020}$	Holstein (1977)

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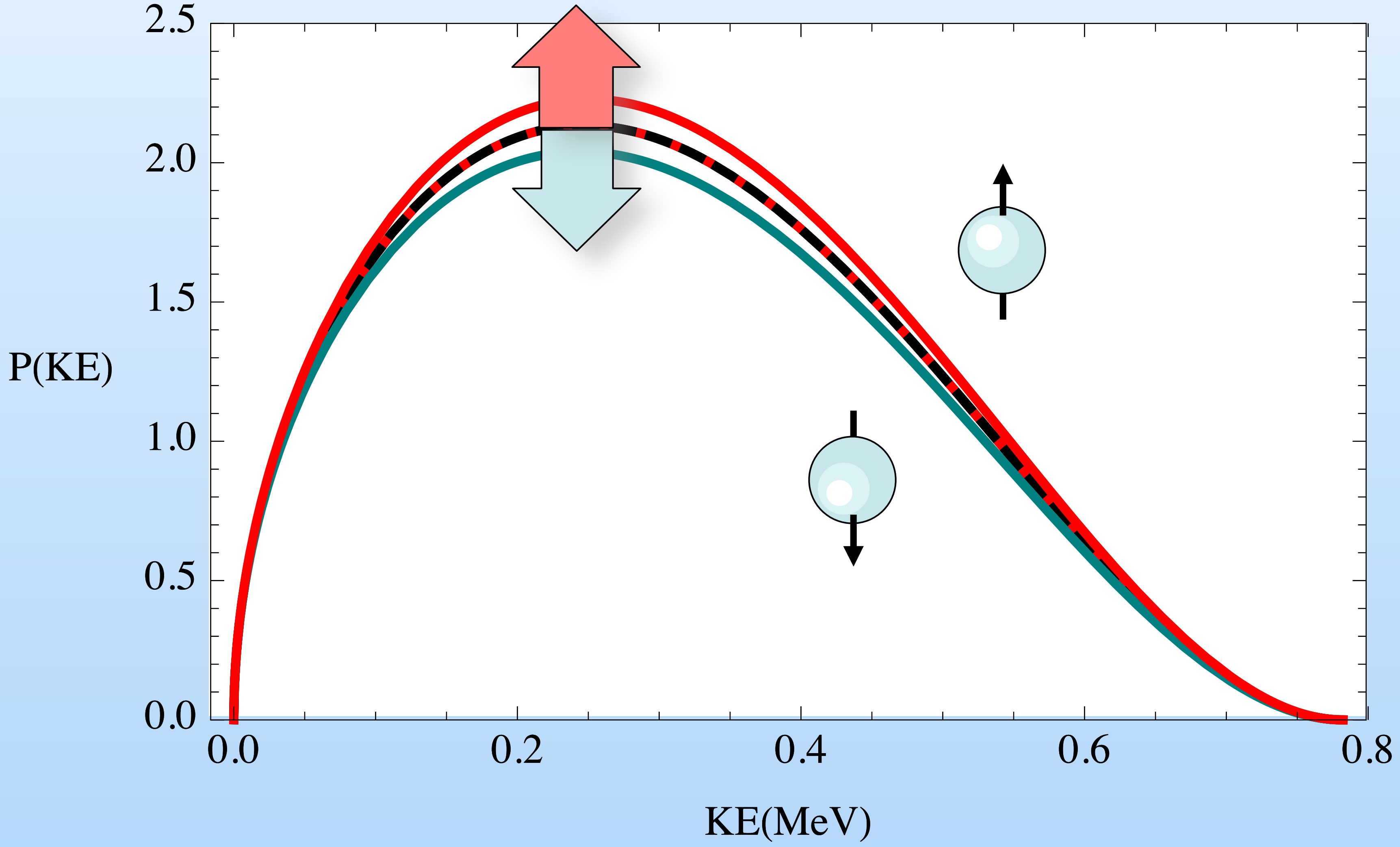
Beta asymmetry term from two spectra

Beta asymmetry term splits the neutron beta spectrum by n spin

$$\Gamma_{\pm} = \left(1 + A(E)\frac{v}{c}\langle P\rangle\langle\cos\theta\rangle\right)\Gamma_{\mathrm{SM}}$$

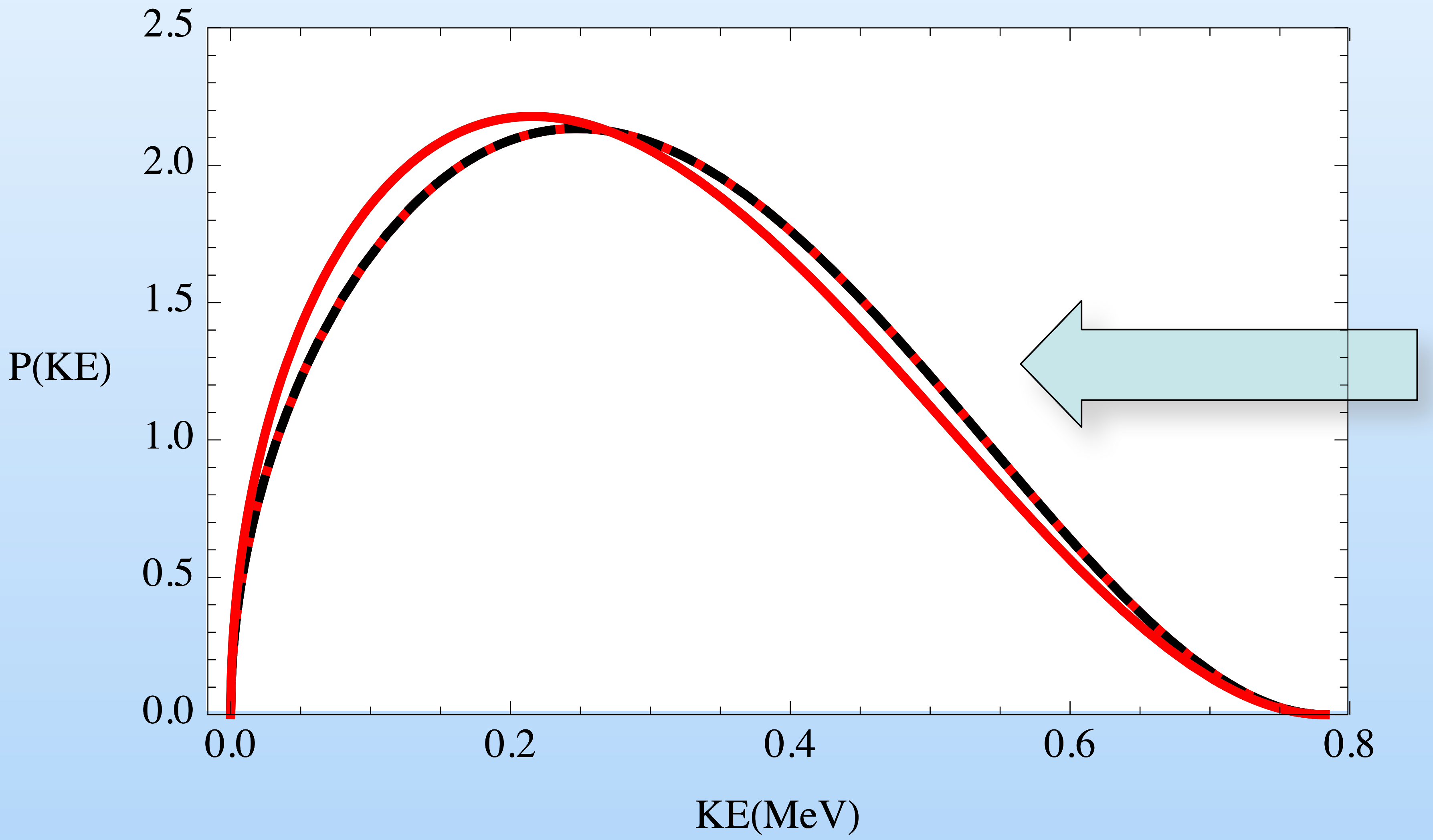


Pattie et al., Phys. Rev. Lett. 102(012301) (2009)

$$\sigma_A = \frac{2.7}{\sqrt{N}}$$

Fierz term from beta-spectrum

Fierz term shifts the neutron beta spectrum



$$P_b = P_{\mathrm{SM}} \left(\frac{1 + b\frac{m_e}{E_e}}{1 + b\left\langle \frac{m_e}{E_e} \right\rangle} \right)$$

$$\frac{1}{\sigma_b^2} = N \left\langle \left(\frac{m_e}{E_e} - \left\langle \frac{m_e}{E_e} \right\rangle \right)^2 \right\rangle$$

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

F. Glück, Joó, J. Last,
Nucl. Phys. A, 593 (1995)

UCNA at LANSCE

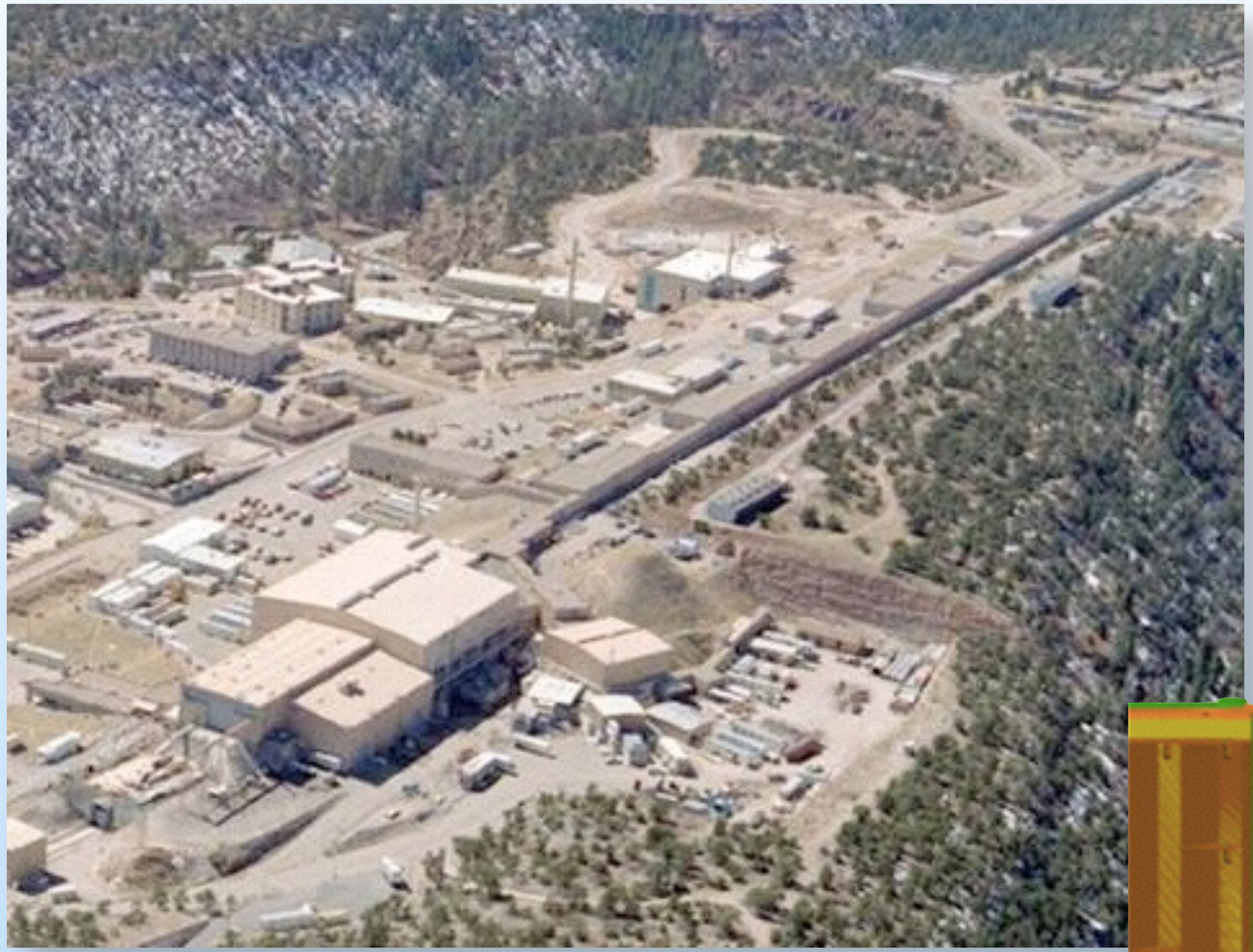
California Institute of Technology, Kellogg Radiation Laboratory
R. Carr, B. W. Filippone, K. P. Hickerson, M. P. Mendenhall, A. Perez-Galvan

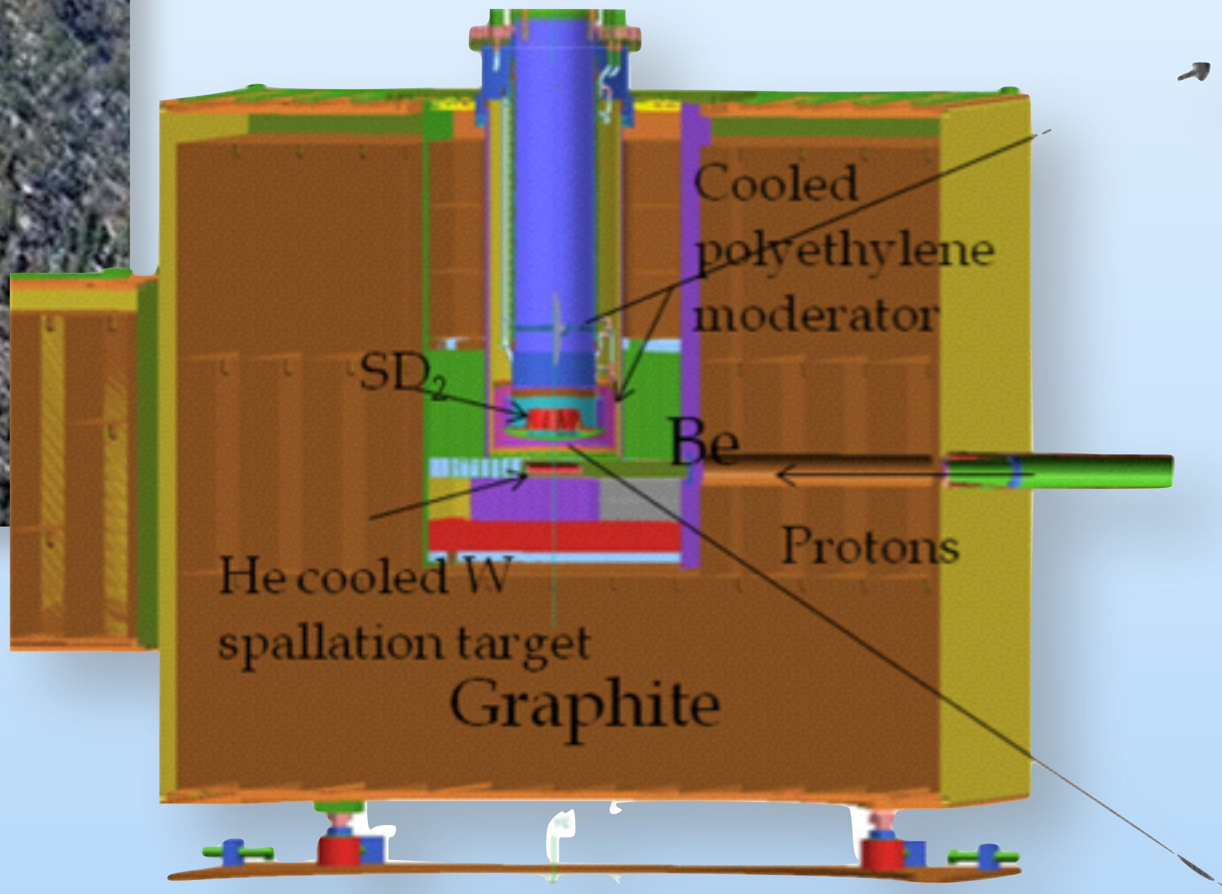
Los Alamos National Laboratory
S. Clayton, S. Currie, G. E. Hogan, T. M. Ito, M. Makela, C. L. Morris, J. Ramsey, R. Rios, S. J. Seestrom, W. E. Sondheim, A. Saunders, J. Bagdasarova

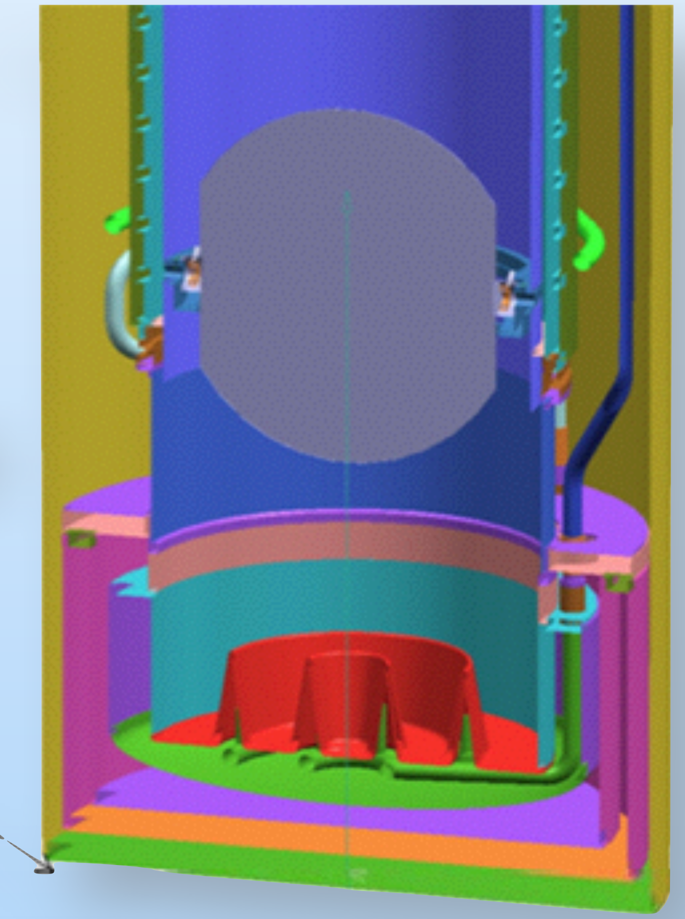
North Carolina State University
L. J. Broussard, A. T. Holley, J. Hoagland, R. W. Pattie, Jr., A. R. Young, B. Vorndick, S. D. Moore, B. A. Zeck

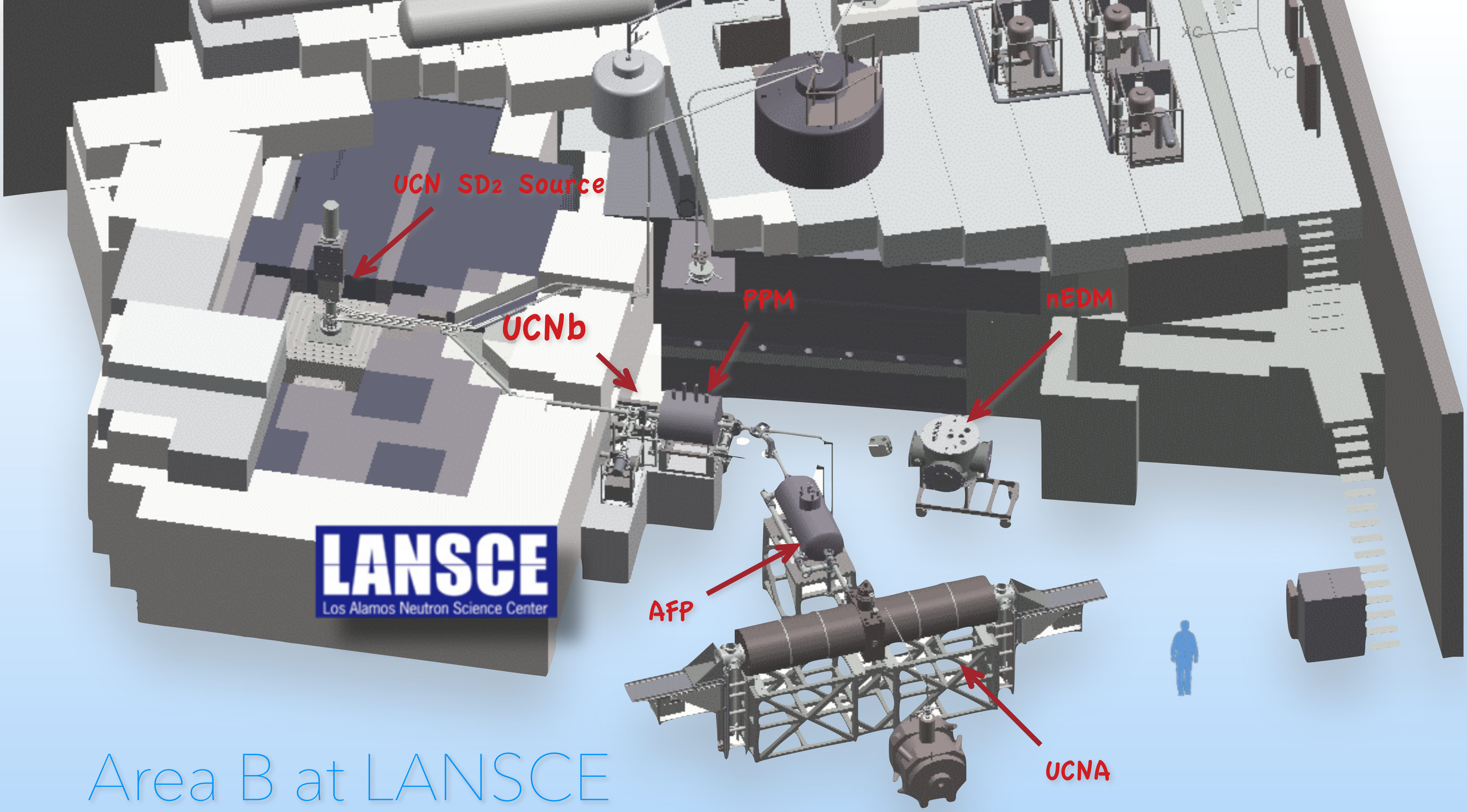
University of Kentucky, University of Winnipeg, Texas A&M, Institut Laue-Langevin, Idaho State University, Indiana University, University of Washington
A. Garcia, R. Hong, C. Wrede, B. Plaster, D. Melconian, P. Geltenbort, J. W. Martin R. R. Mammei, M. L. Pitt, R. B. Vogelaar, D. B. Berguno, E. Tatar, D. Xu

UCN SD_2 source at LANSCE





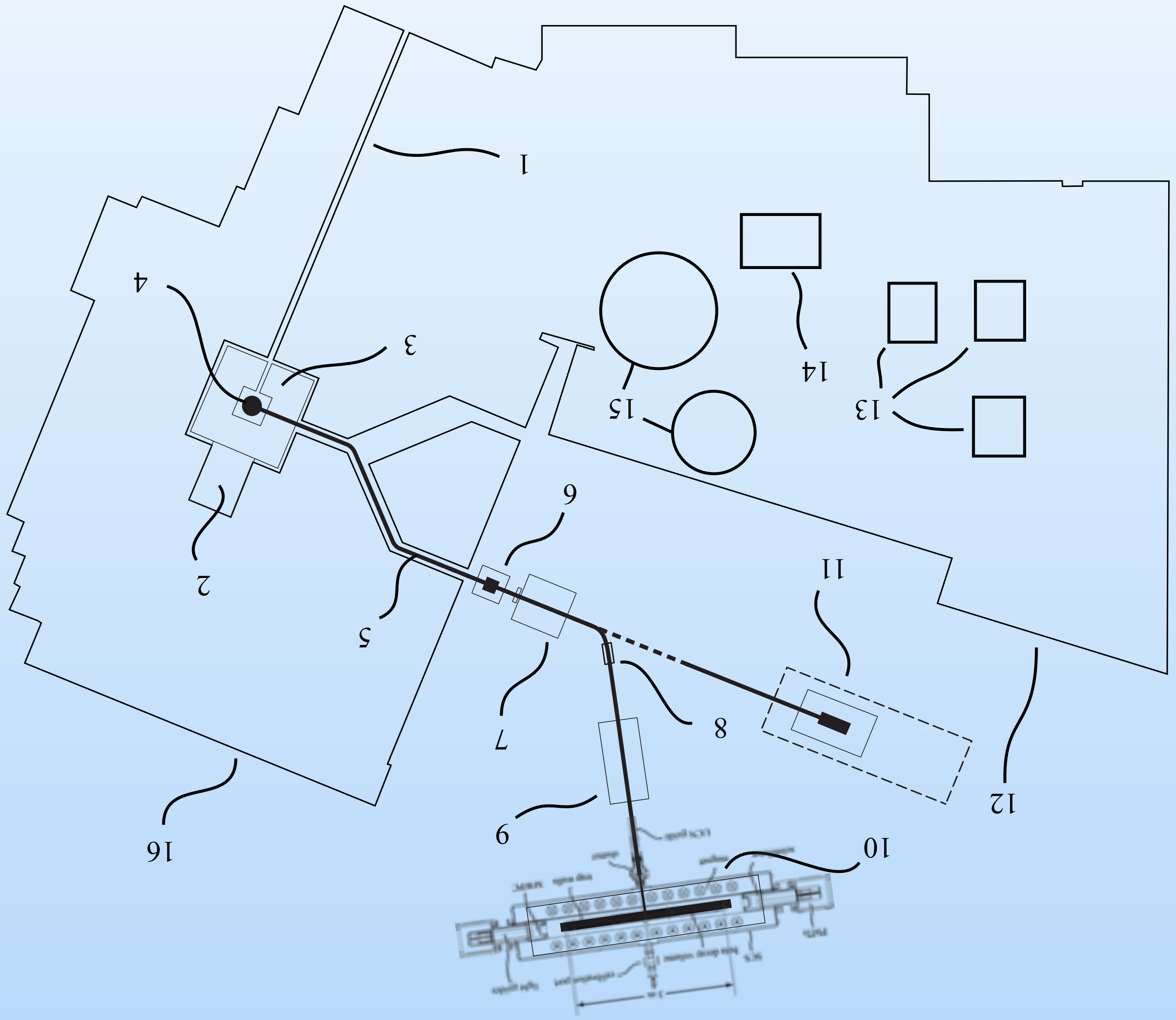




Area B at LANSCE

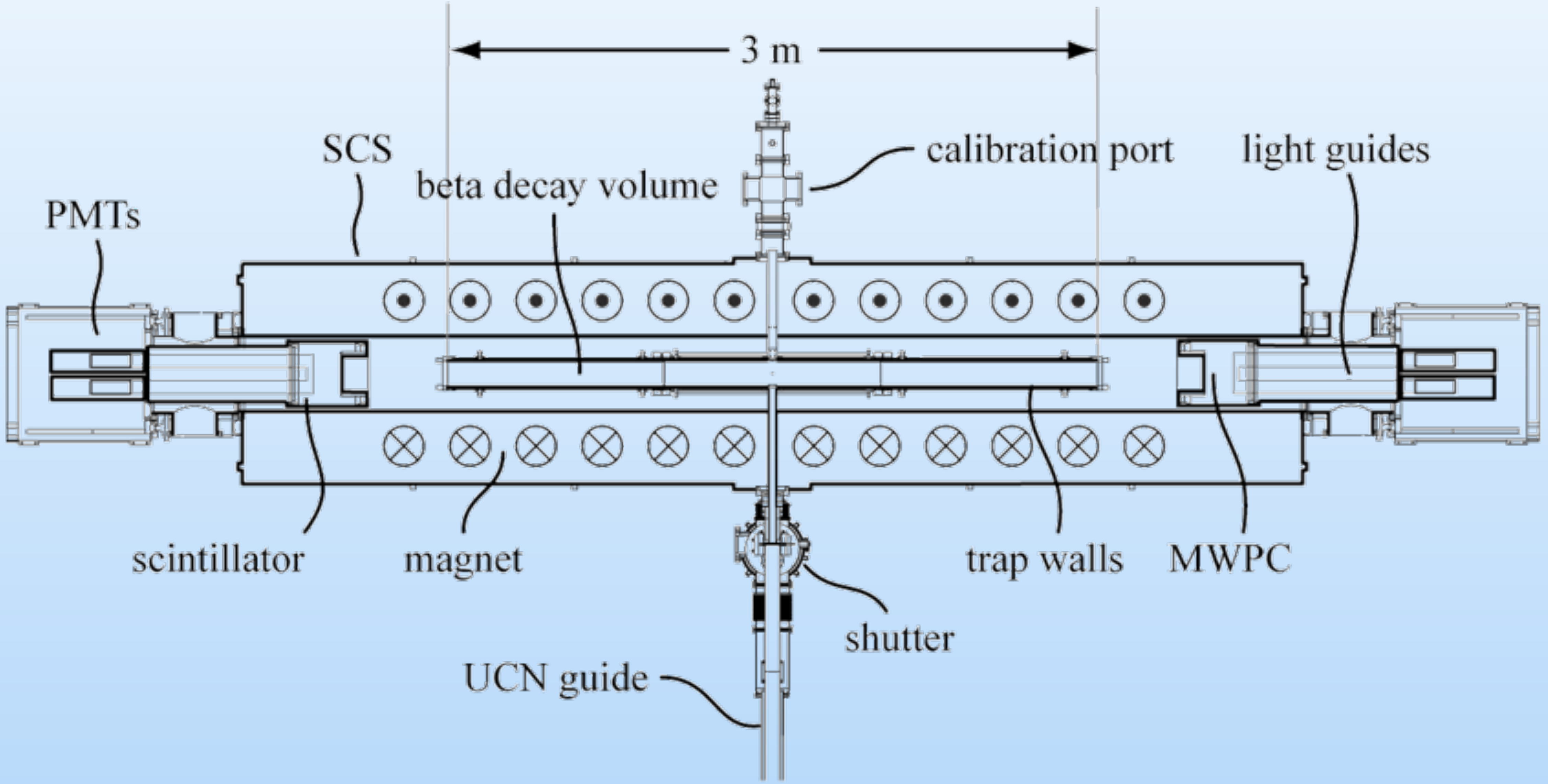
UCNA

Superconducting Spectrometer

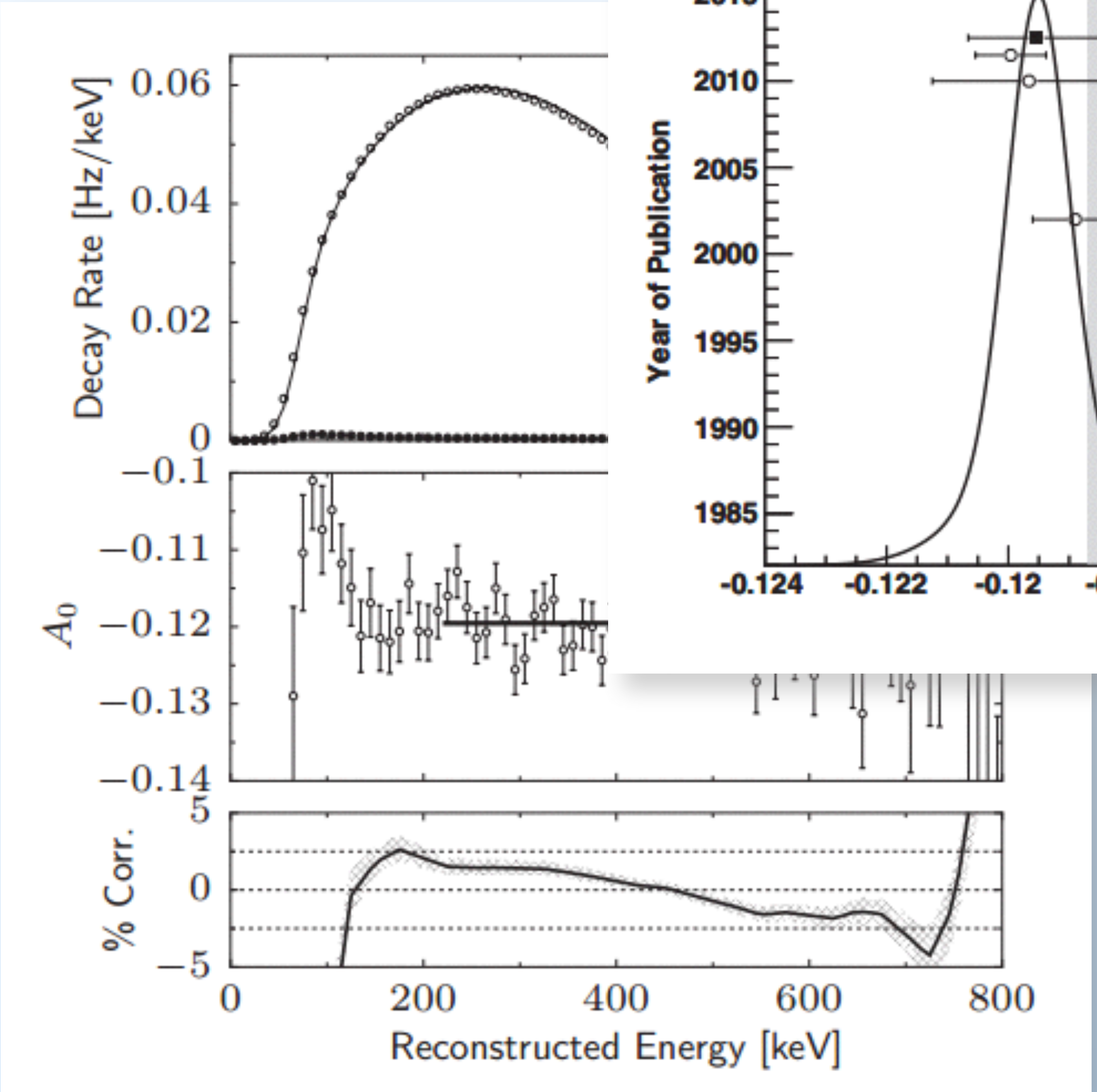


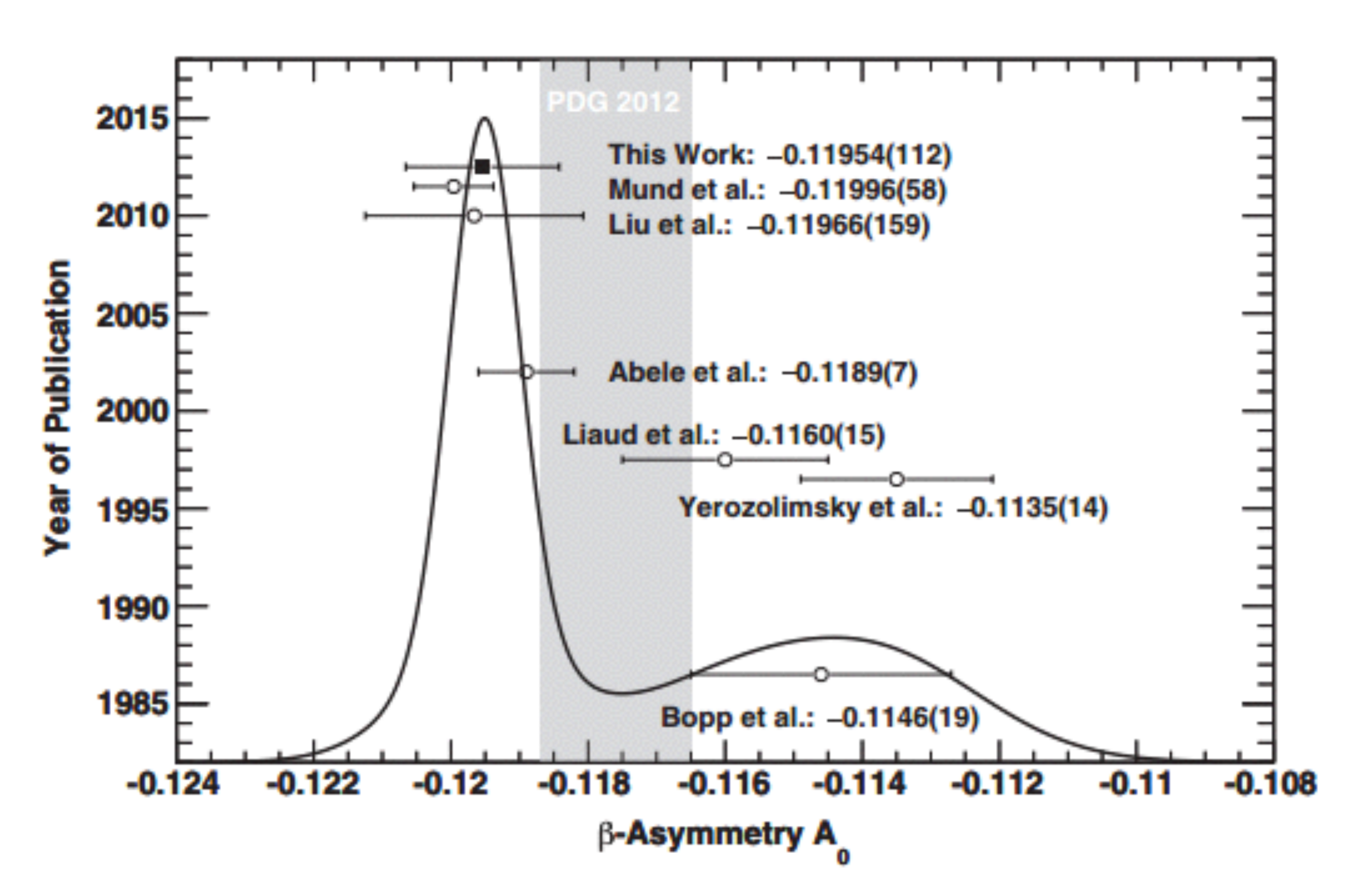
UCNA

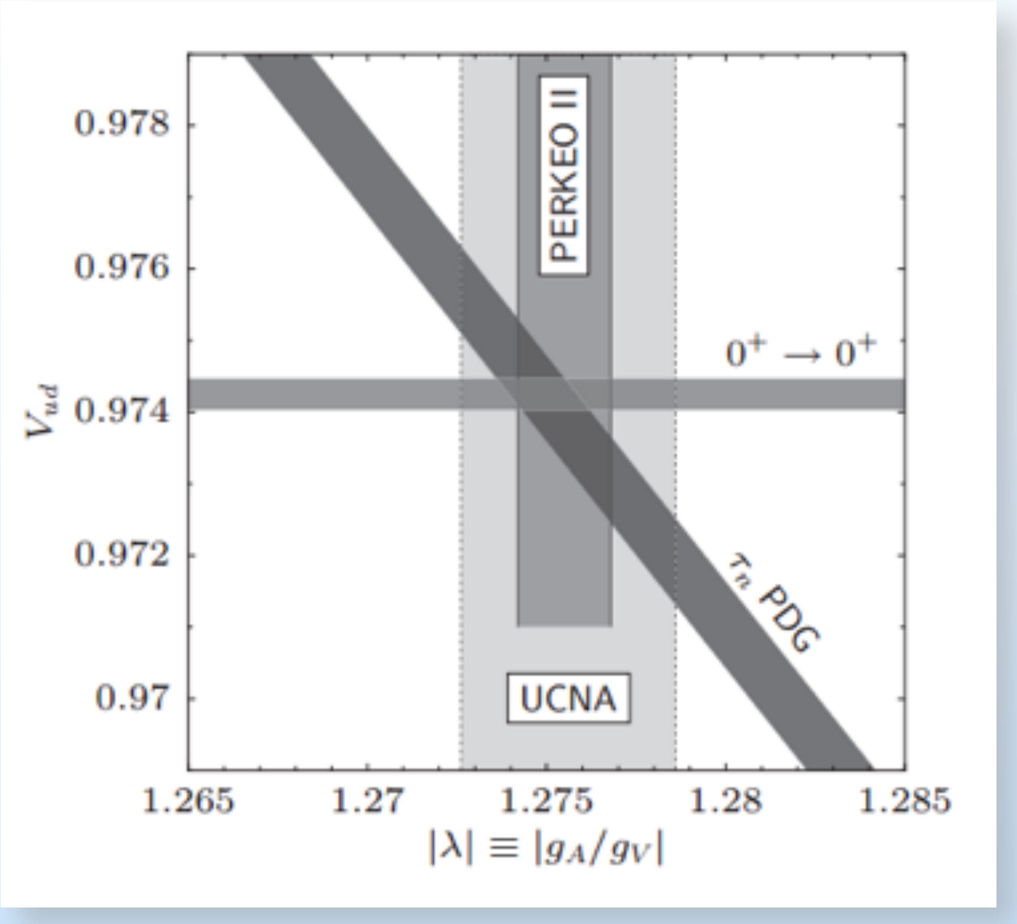
Superconducting Spectrometer



Standard Model asymmetry results from 2010







$A_0 = -0.11954 \pm 0.00055_{stat} \pm 0.00098_{sys}$

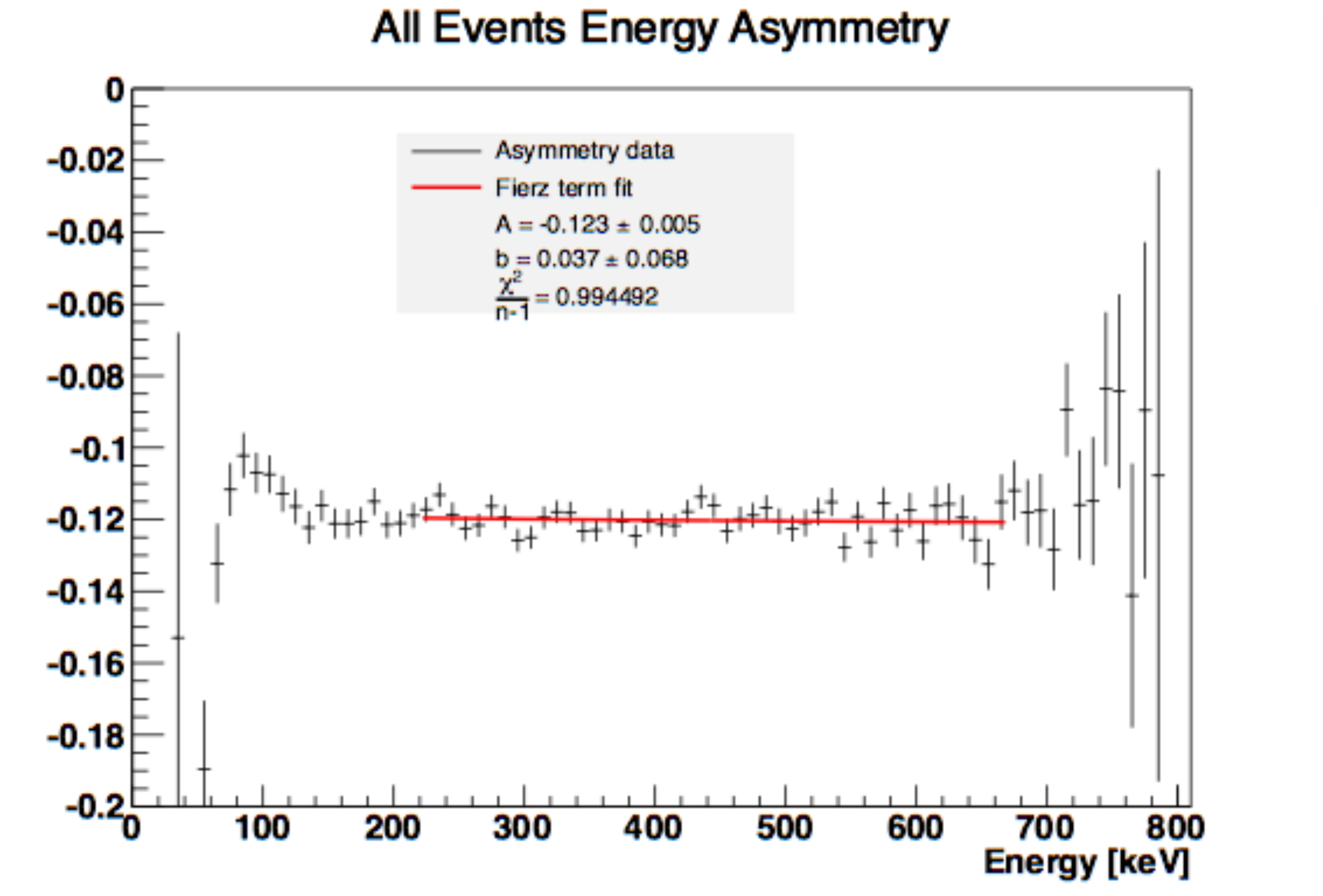
$\lambda = g_A/g_V = -1.2756 \pm 0.0030$

Mendenhall et al., Phys. Rev. C 87, 032501(R) (2012)

General asymmetry fit from UCNA 2010 data

$$\sigma_A = \frac{20}{\sqrt{N}} \qquad \sigma_b = \frac{305}{\sqrt{N}}$$

$$\rho = -0.993$$



$$S = \frac{r_1^{\uparrow} r_2^{\downarrow}}{r_1^{\downarrow} r_2^{\uparrow}}$$

$$A(E,\theta) = \frac{1-\sqrt{S}}{1+\sqrt{S}}$$

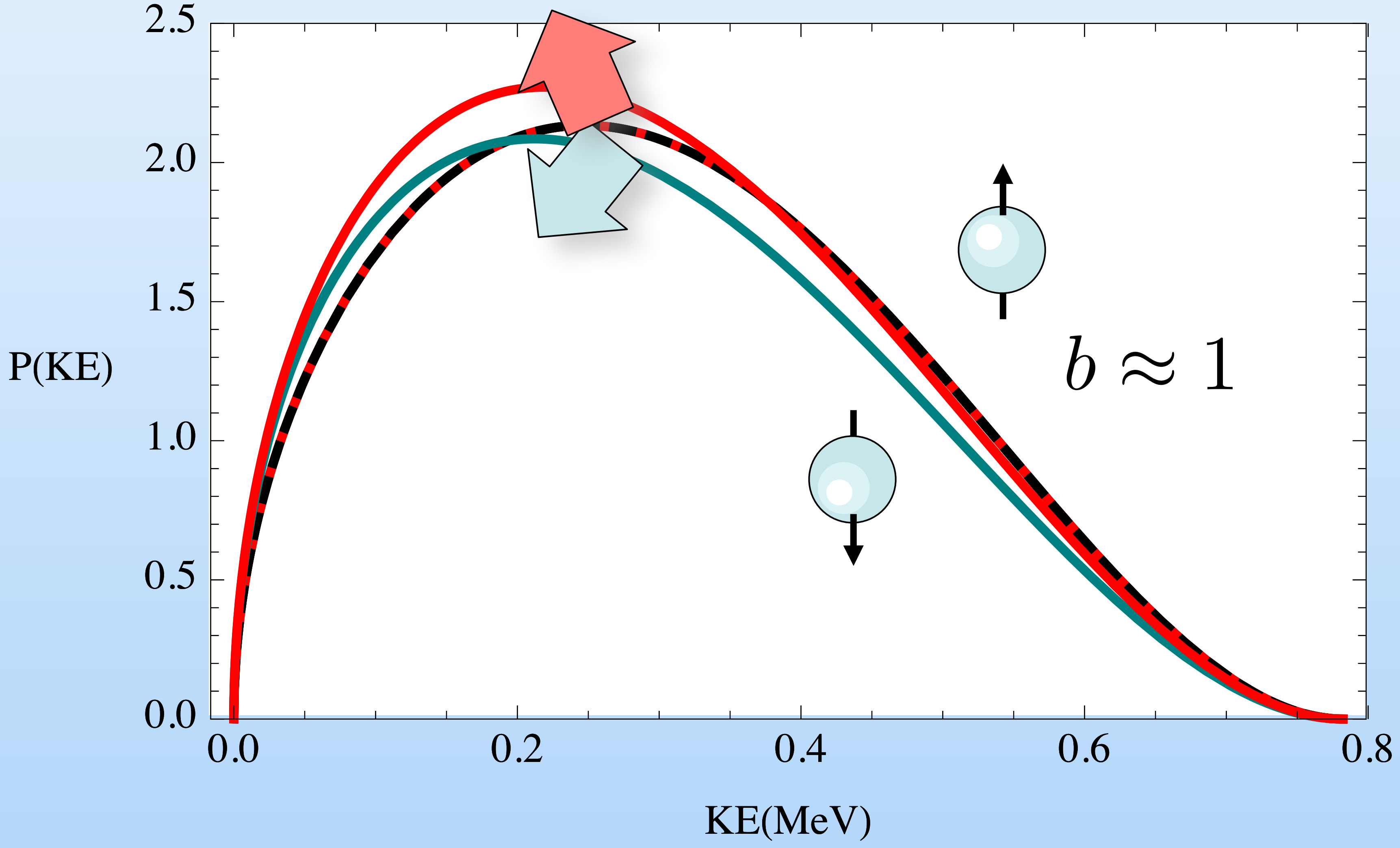
$$= \frac{A_0 \langle P \rangle \beta \cos\theta}{1 + b(m_e/E)}$$

$A_0 = -0.123 \pm 0.005_{stat}$

$b_n = 0.037 \pm 0.068_{stat} \pm 0.03_{sys}$

Combined fit of spectrum and asymmetry

- Beta asymmetry term splits the neutron beta spectrum and Fierz term shifts it



Combined fit of spectrum and asymmetry

Since we have 4 rate measurements, we can extract spectral and asymmetry data simultaneously

Combined systematics studies still needed (coming soon)

$$[\mathrm{cov}(A,b)]^{-1} = N \begin{pmatrix} \frac{1}{4}\langle\beta^2\rangle & -\frac{1}{4}A\left\langle\frac{\beta^2}{x}\right\rangle \\ -\frac{1}{4}A\left\langle\frac{\beta^2}{x}\right\rangle & \langle x^{-2}\rangle - \langle x^{-1}\rangle^2 \end{pmatrix}$$

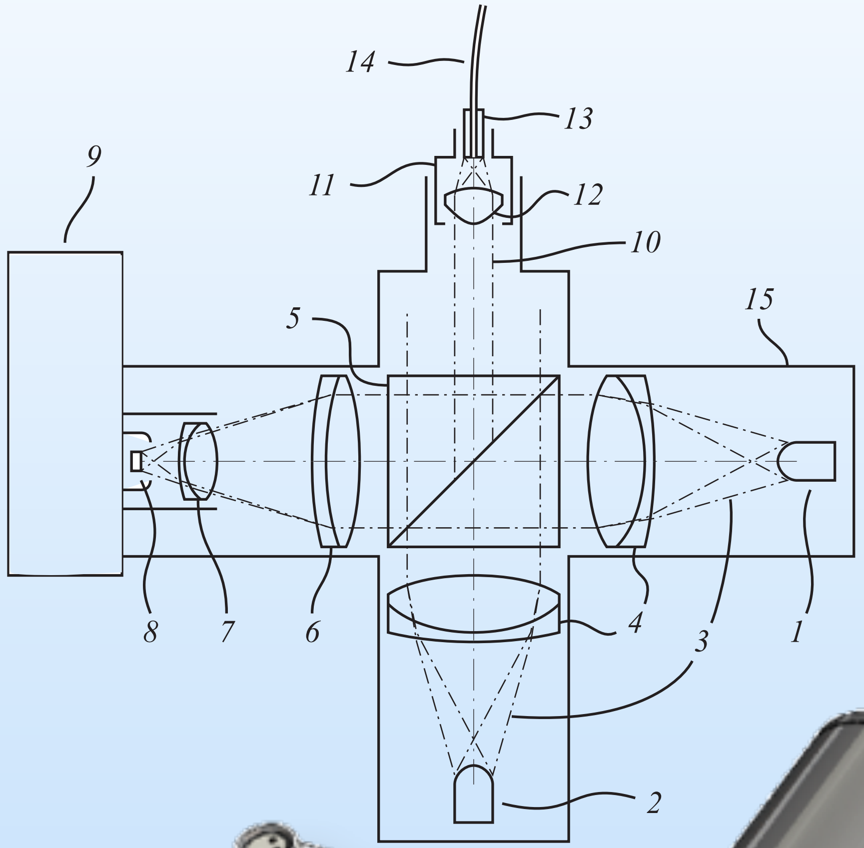
$$\sigma_A = \frac{2.7}{\sqrt{N}} \qquad \sigma_b = \frac{14.8}{\sqrt{N}}$$

$$\rho = 0.201$$

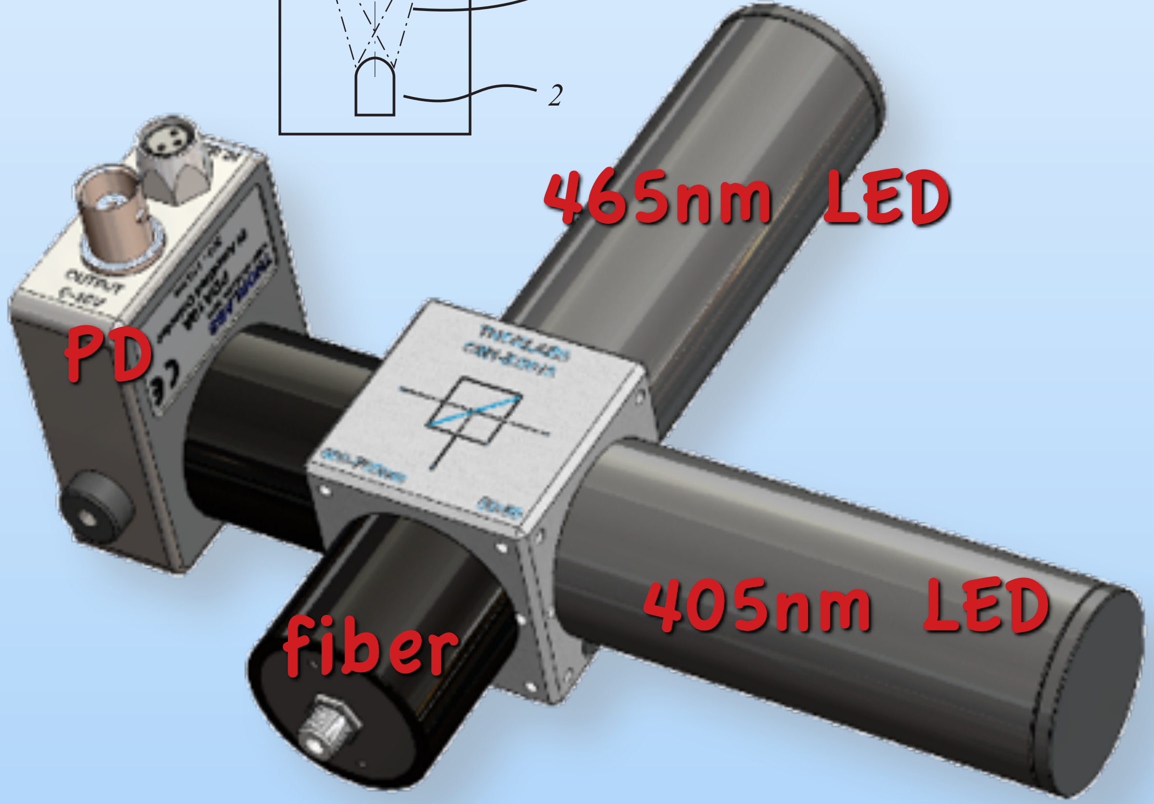
$A_0 = \pm\ 0.0006_{stat}$

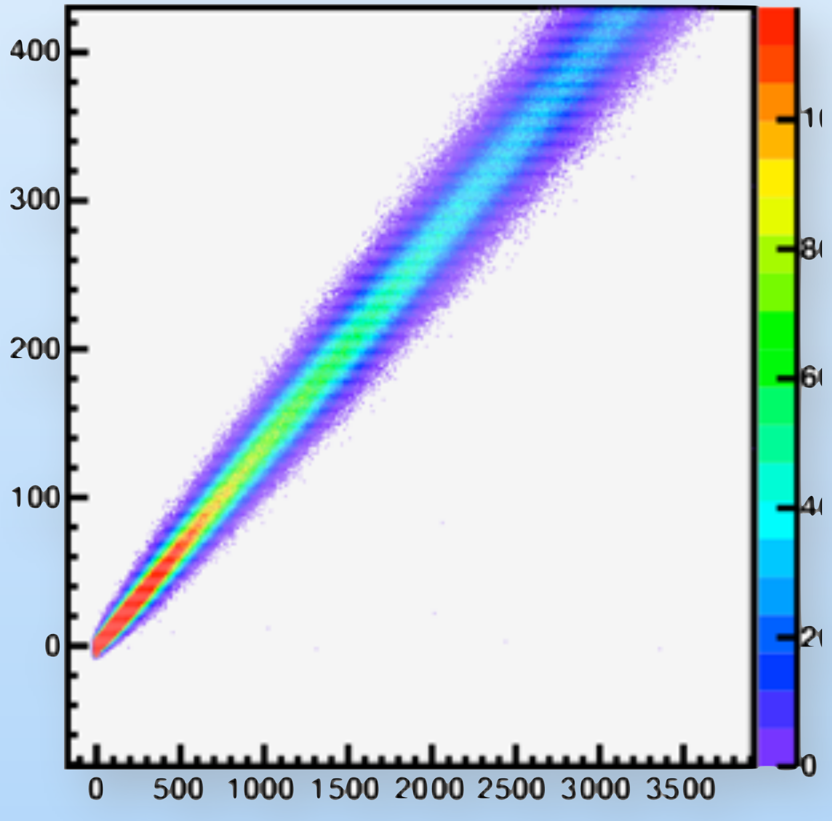
$b_n = \pm\ 0.003_{stat}$

Gain and linearity calibration

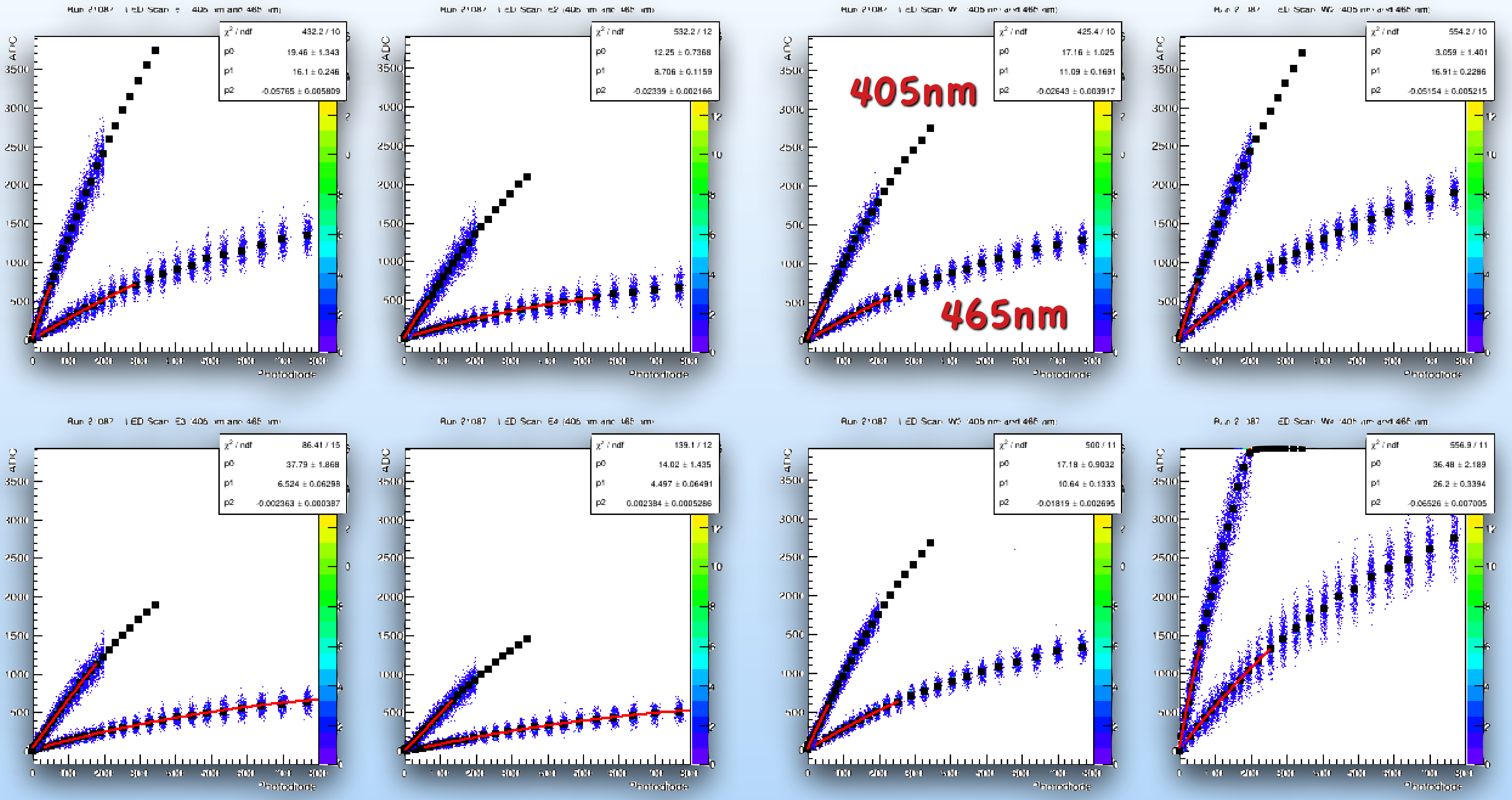


- LED/Photodiode pair
- Dual wavelength
- UCNA 2012 analysis pending





Linearity for UCNA 2012 data



What's so cool about Ultracold Neutrons?

And why do we use them?

Standard Model Neutron Beta Decay

The electroweak theory of the neutron

Symmetries and Interference in Beta Decay

A place to look for physics beyond the Standard Model

Beta Spectroscopy with Polarized Ultracold Neutrons

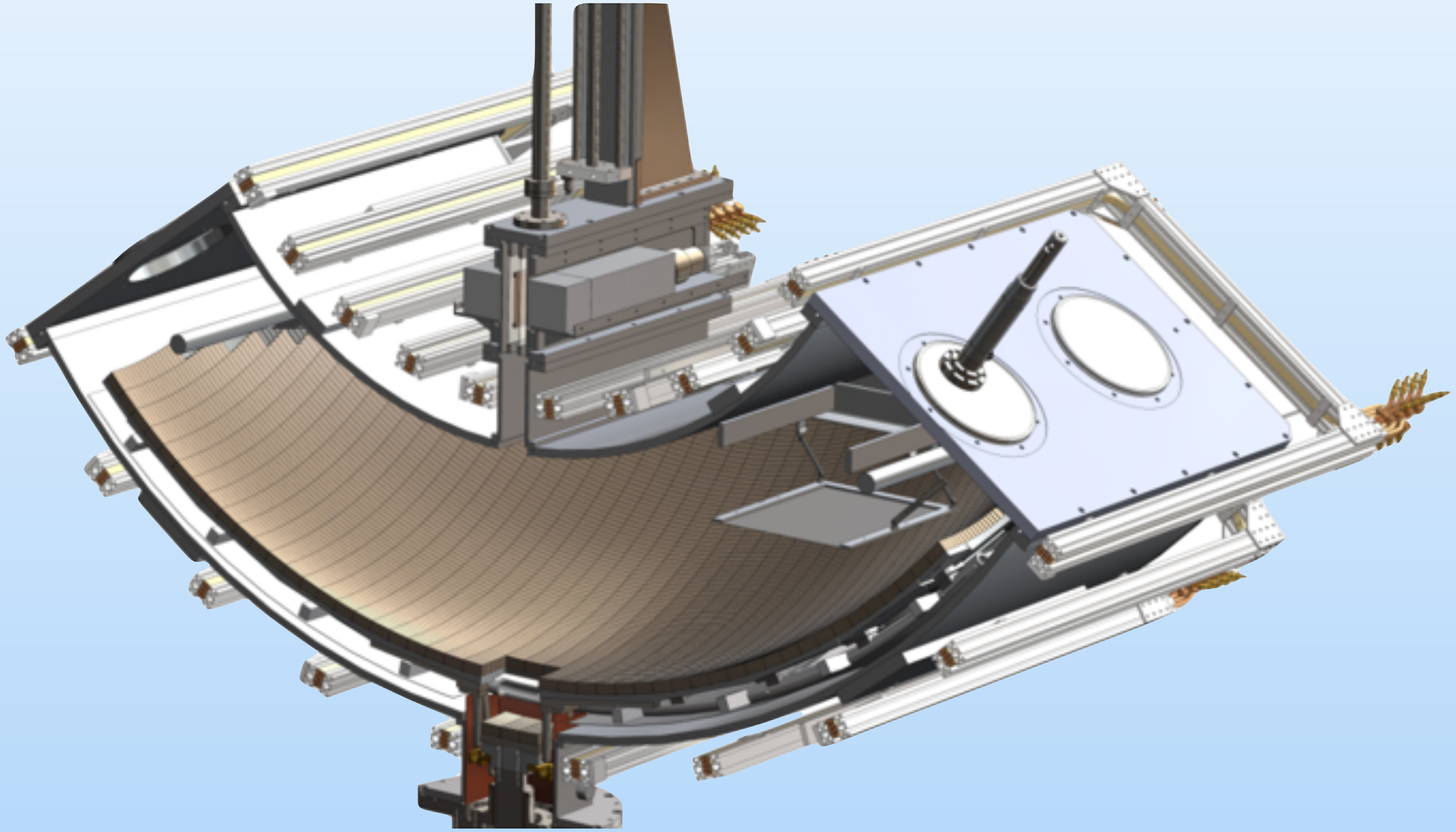
The UCNA experiment at LANSCE

A new way to measure the neutron lifetime

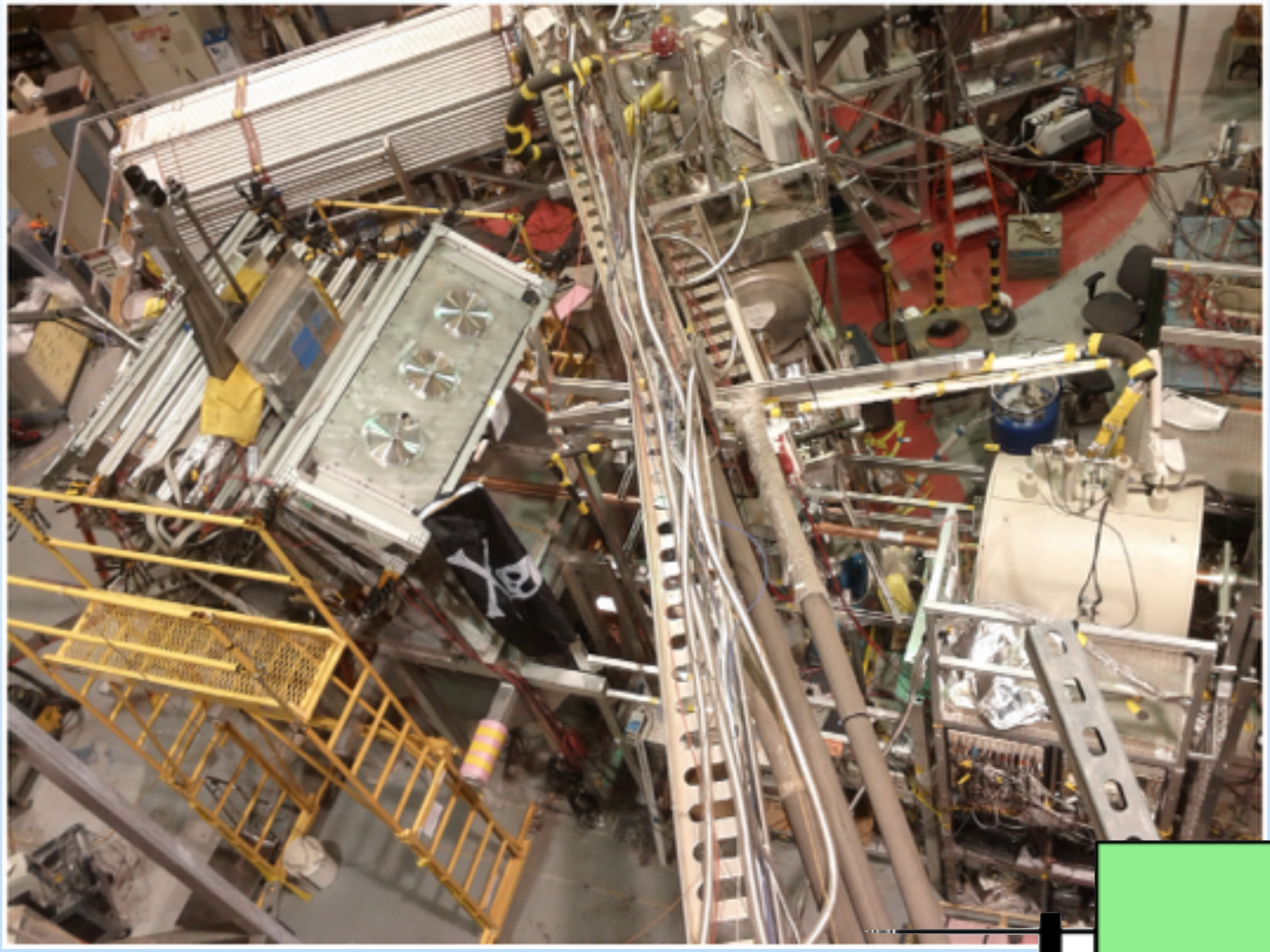
A UCN experiment at LANSCE

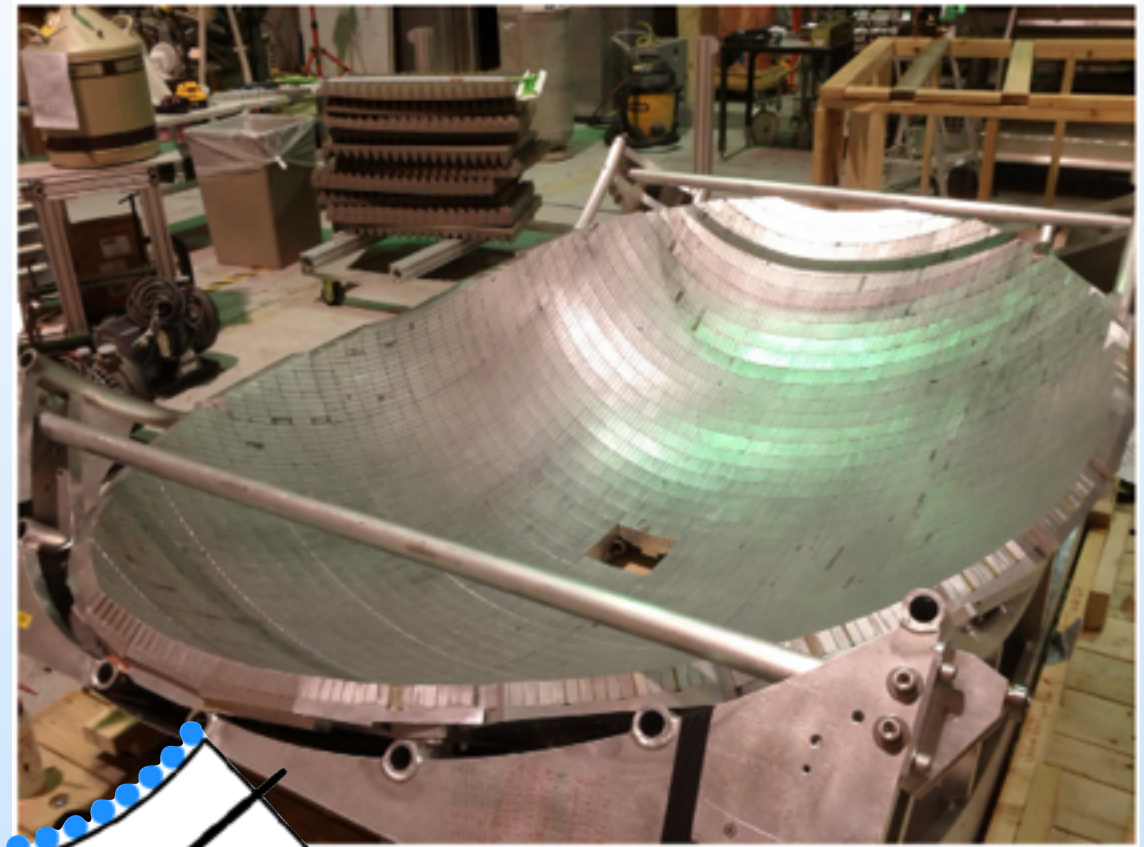
Neutron lifetime using UCN

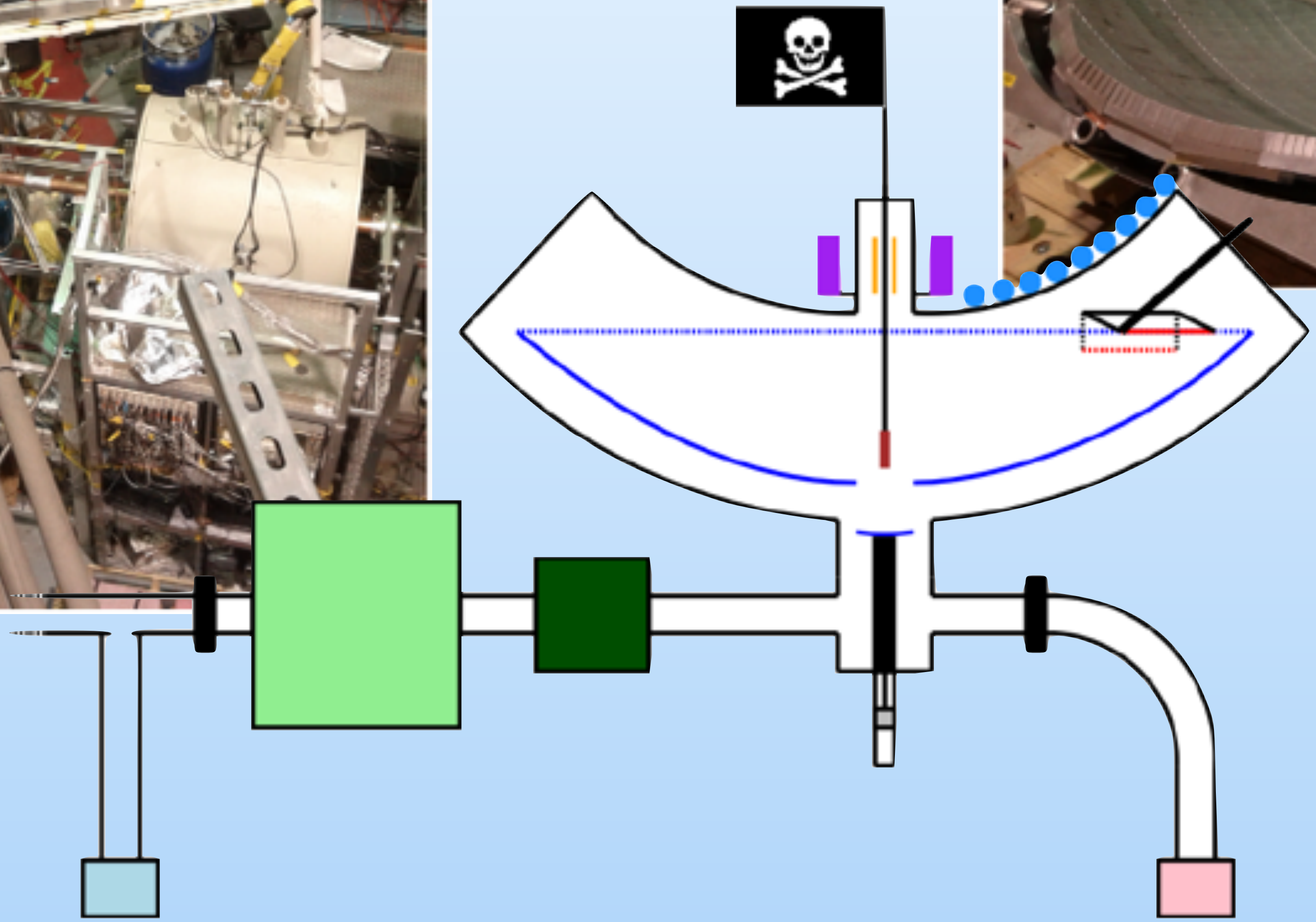
Loading



Nutron lifetime at LANL

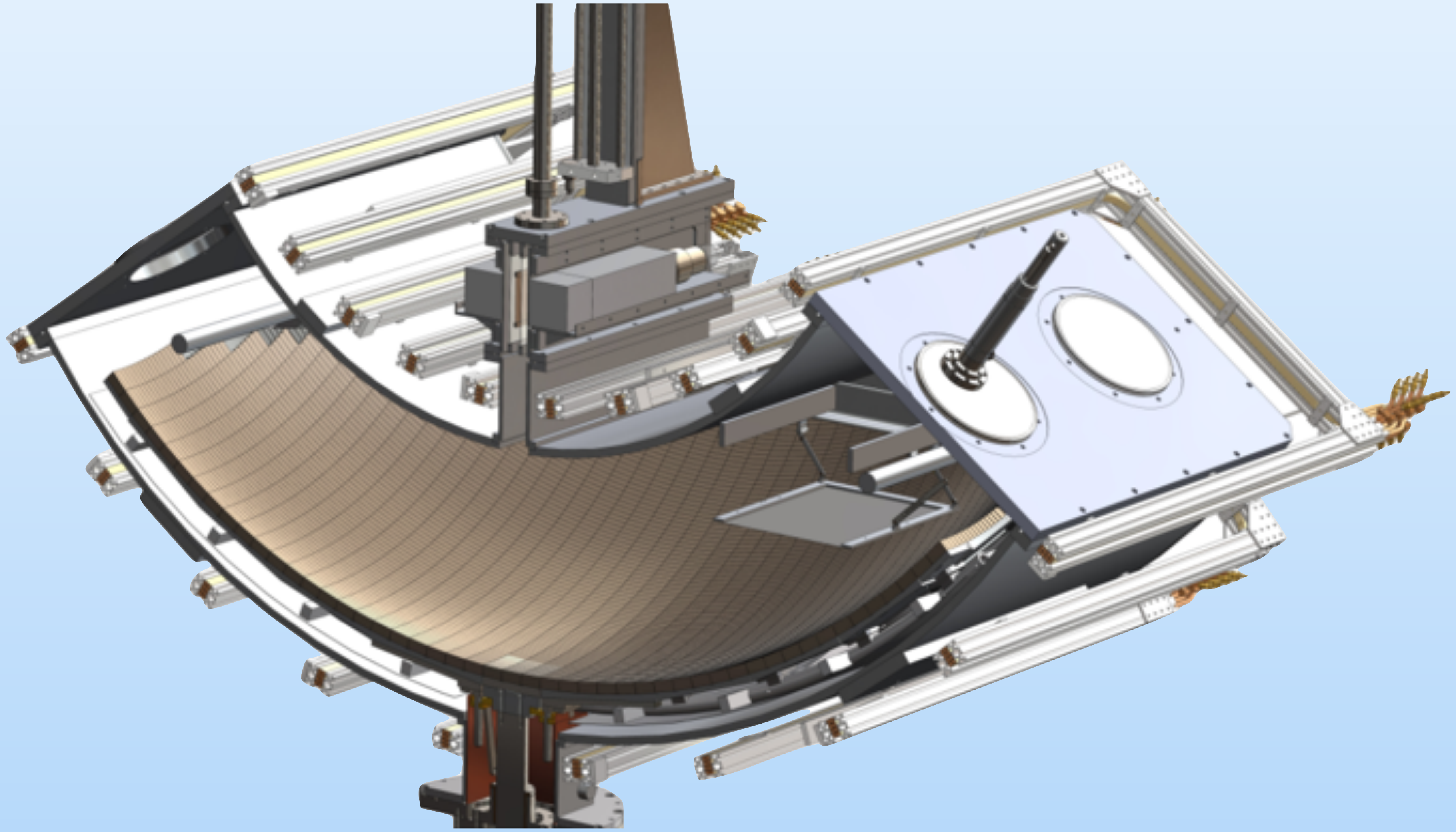






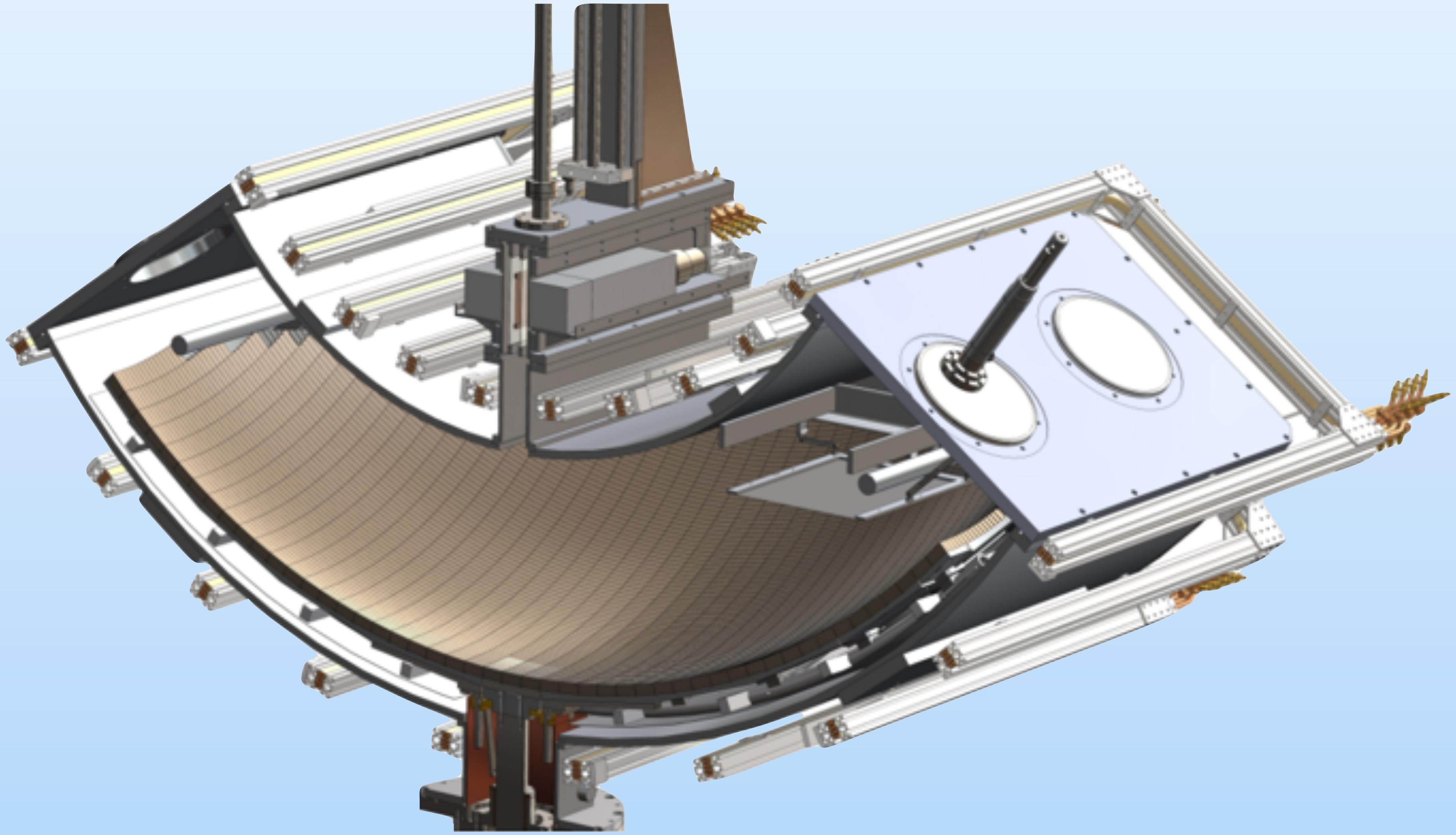
Neutron lifetime using UCN

Cleaning



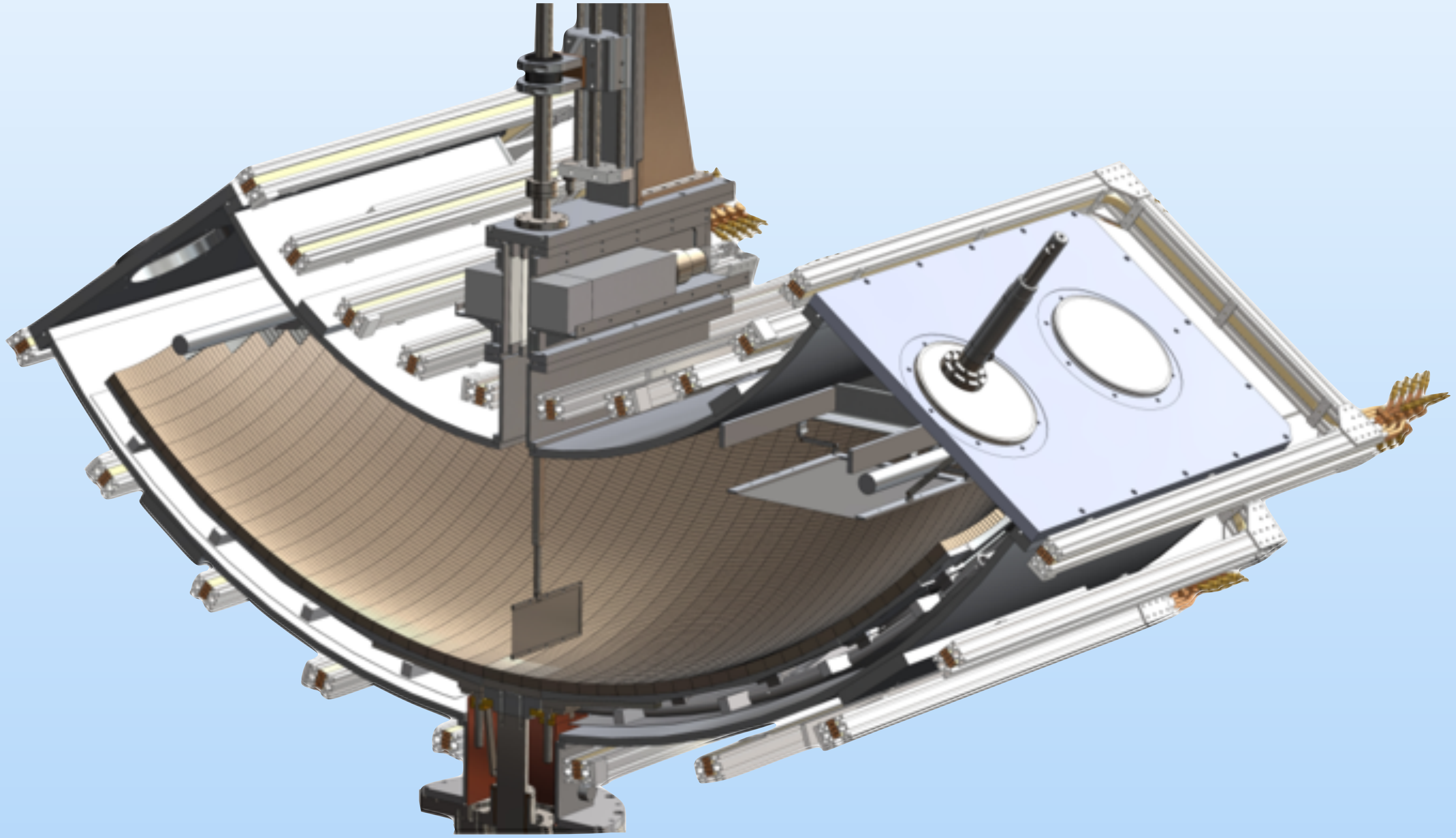
Neutron lifetime using UCN

Beta decay



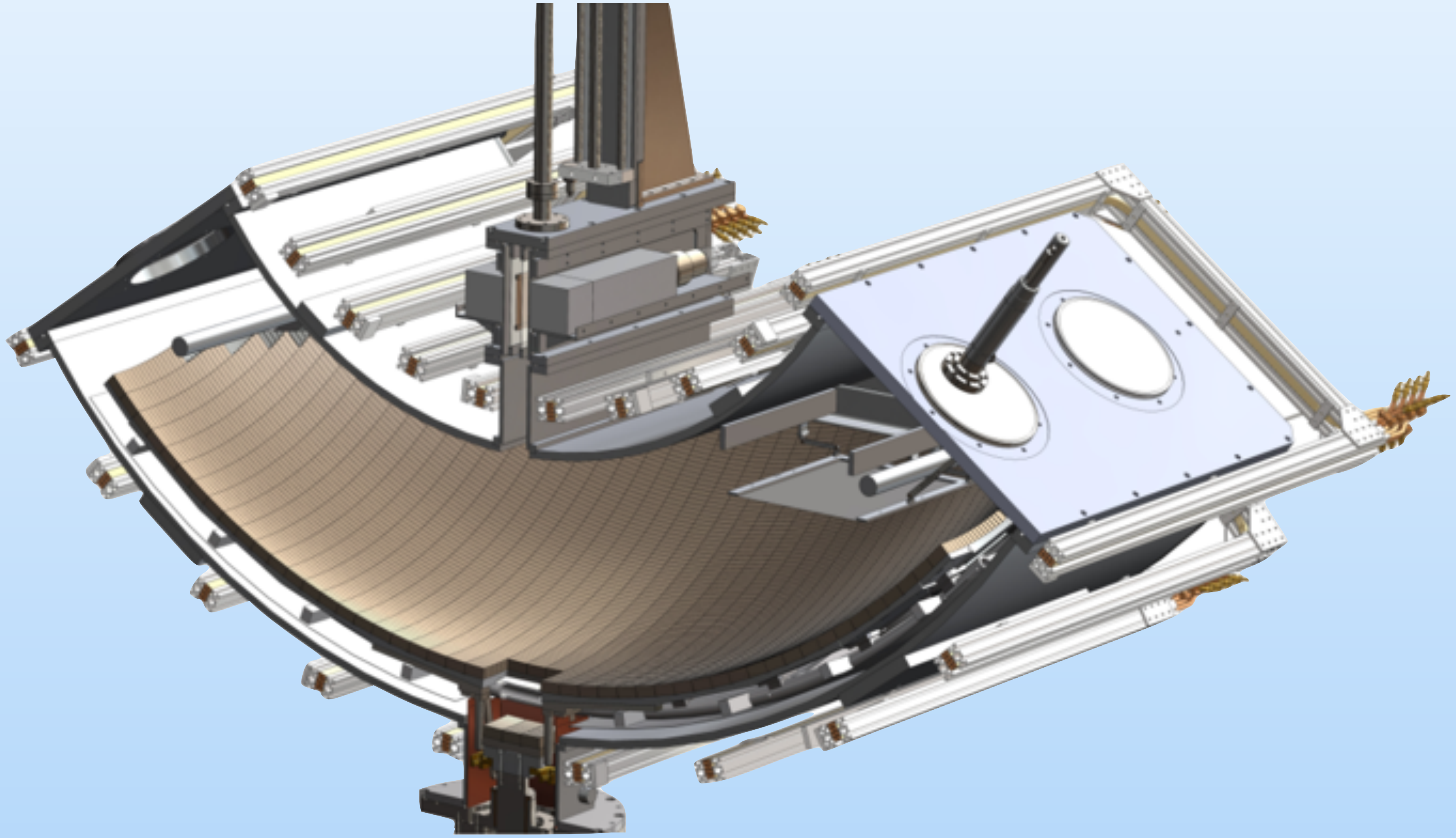
Neutron lifetime using UCN

Using a vanadium dagger to absorb neutrons



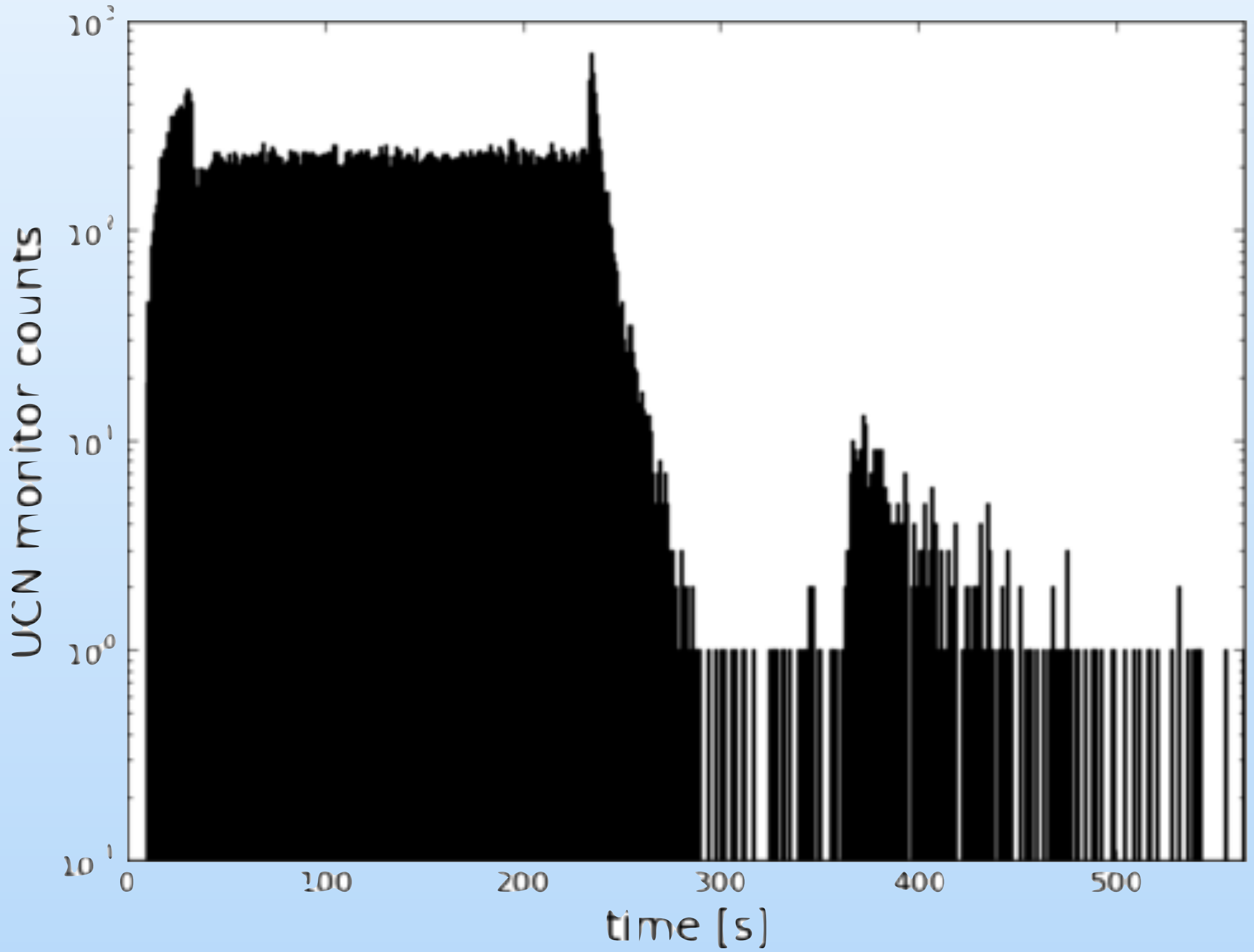
Neutron lifetime using UCN

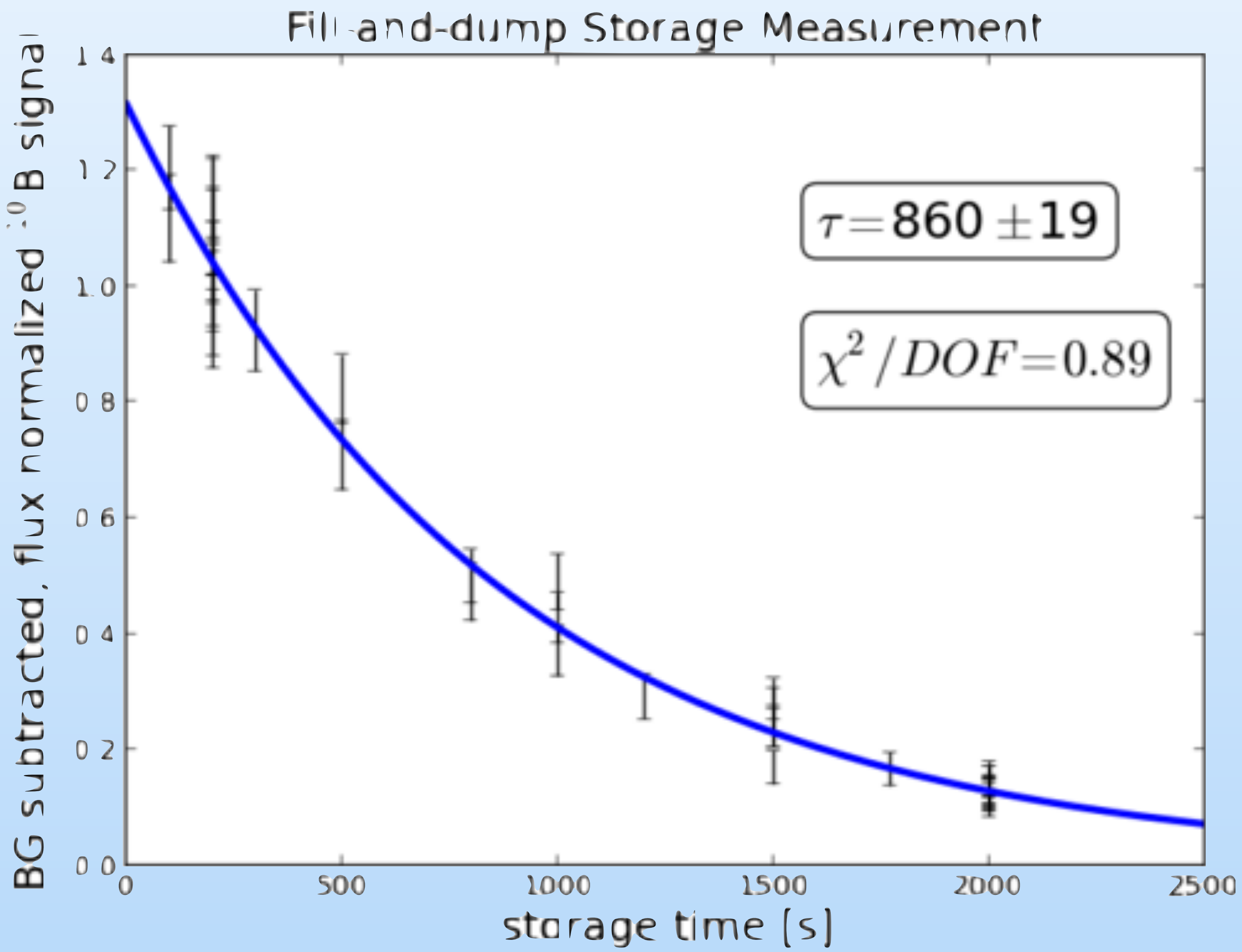
dumping



Results from last year

Fill and dump results





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The UCNA experiment at LANSCE

A Novel Experimental Prototype

The UCNb experiment at LANSCE

UCNb at LANSCE

California Institute of Technology, Kellogg Radiation Laboratory
C. Feng, B. W. Filippone, K. P. Hickerson, M. P. Mendenhall, R. Russell

Los Alamos National Laboratory, Physics Division
J. Hoagland, T. Ito, A. Lopez, M. Makela,
P. McGaughey, C. Morris, J. C. Ramsey, R. Rios,
A. Saunders, W. Sondheim, Z. Wang, S. Wilburn

Los Alamos National Laboratory, Theory Division
T. Bhattacharya, V. Cirigliano, M. Graesser, R. Gupta

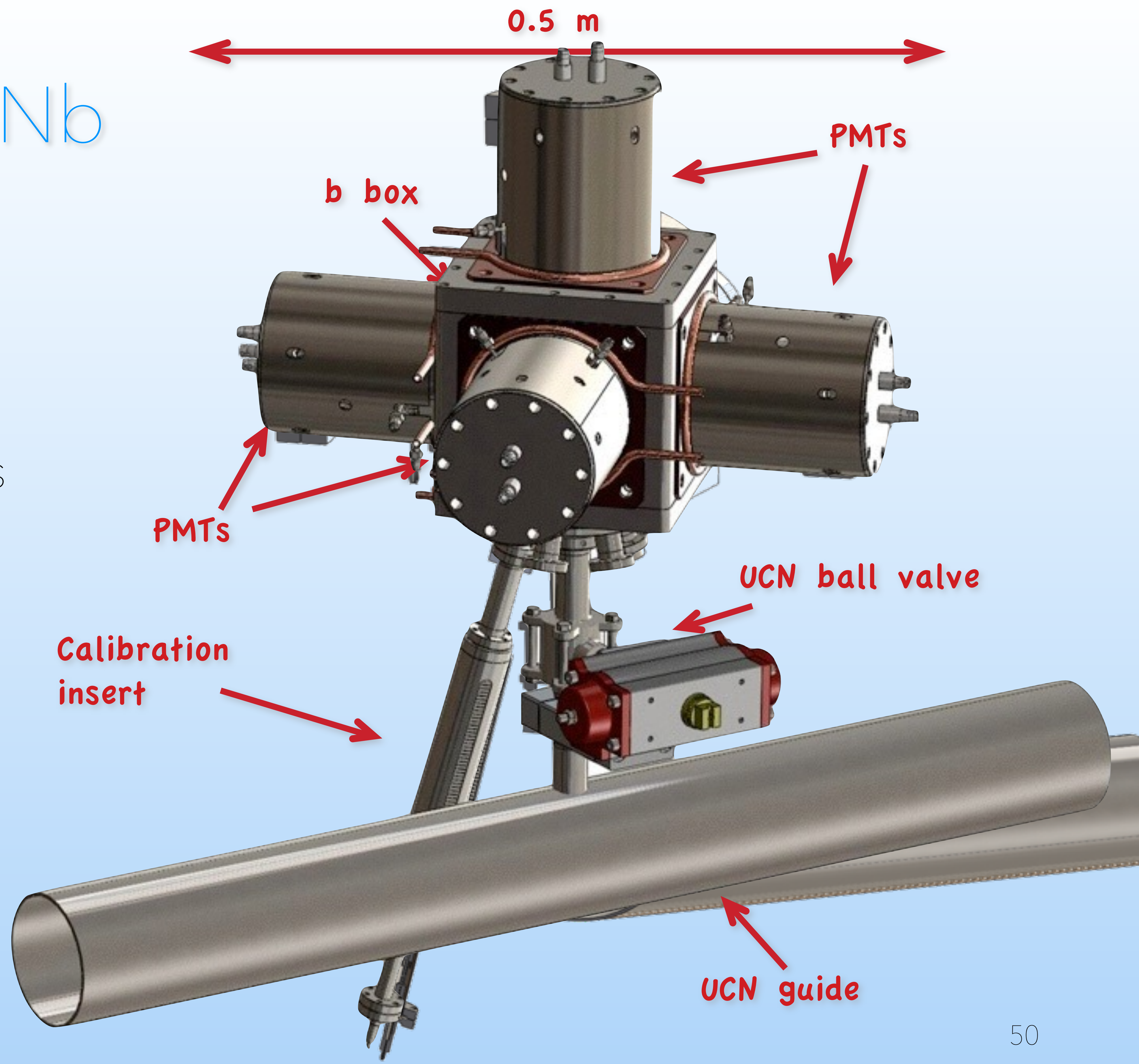
North Carolina State University
R. Pattie, L. Broussard, A. T. Holley, A. Young

Los Alamos
NATIONAL LABORATORY
EST. 1943

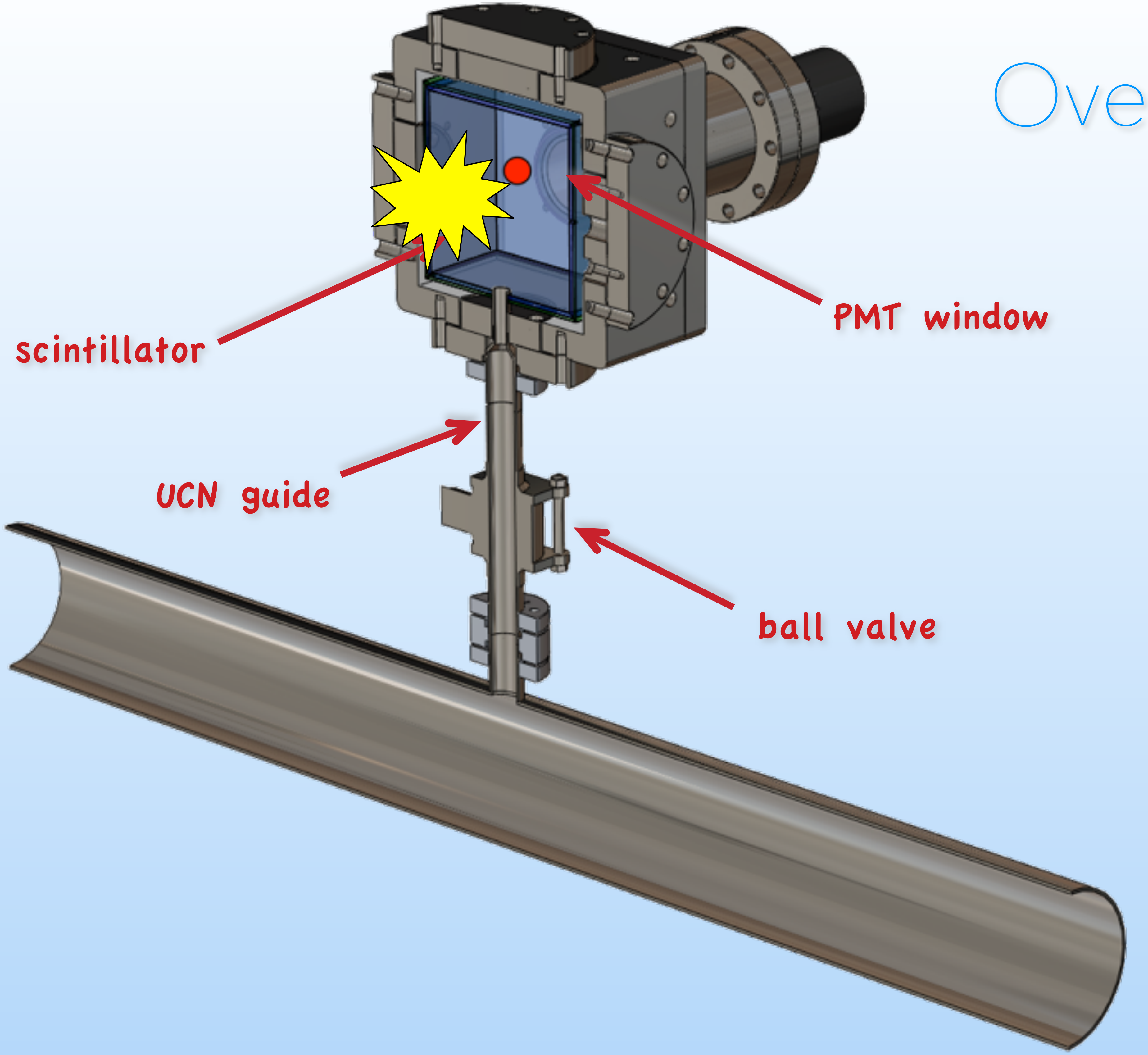
LANSCE
Los Alamos Neutron Science Center

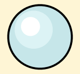
Overview of UCNb

- Compact chamber
- Integrating cube
- Near UCN source
- Up to five 2" Super Bialkali PMTs

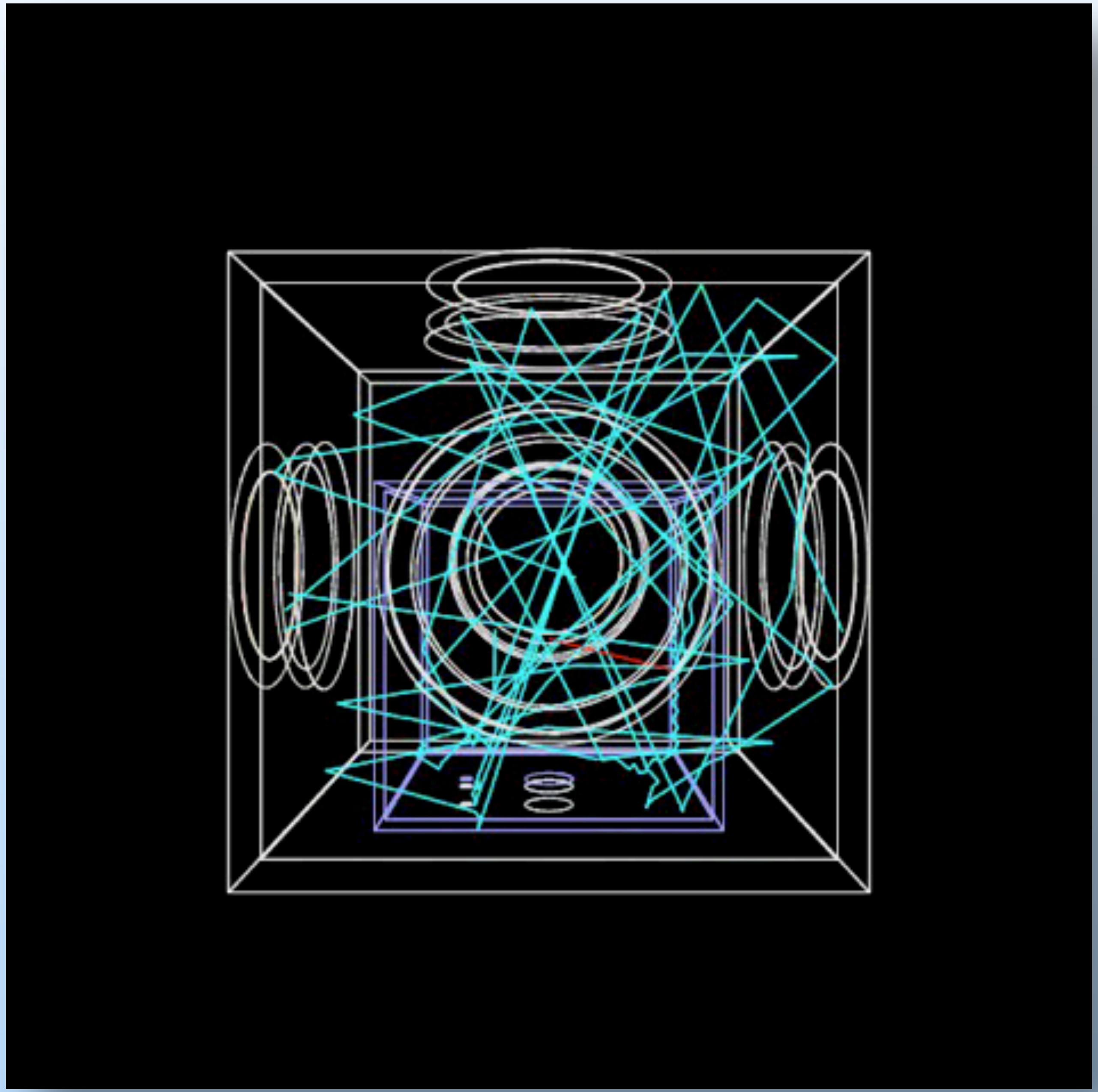


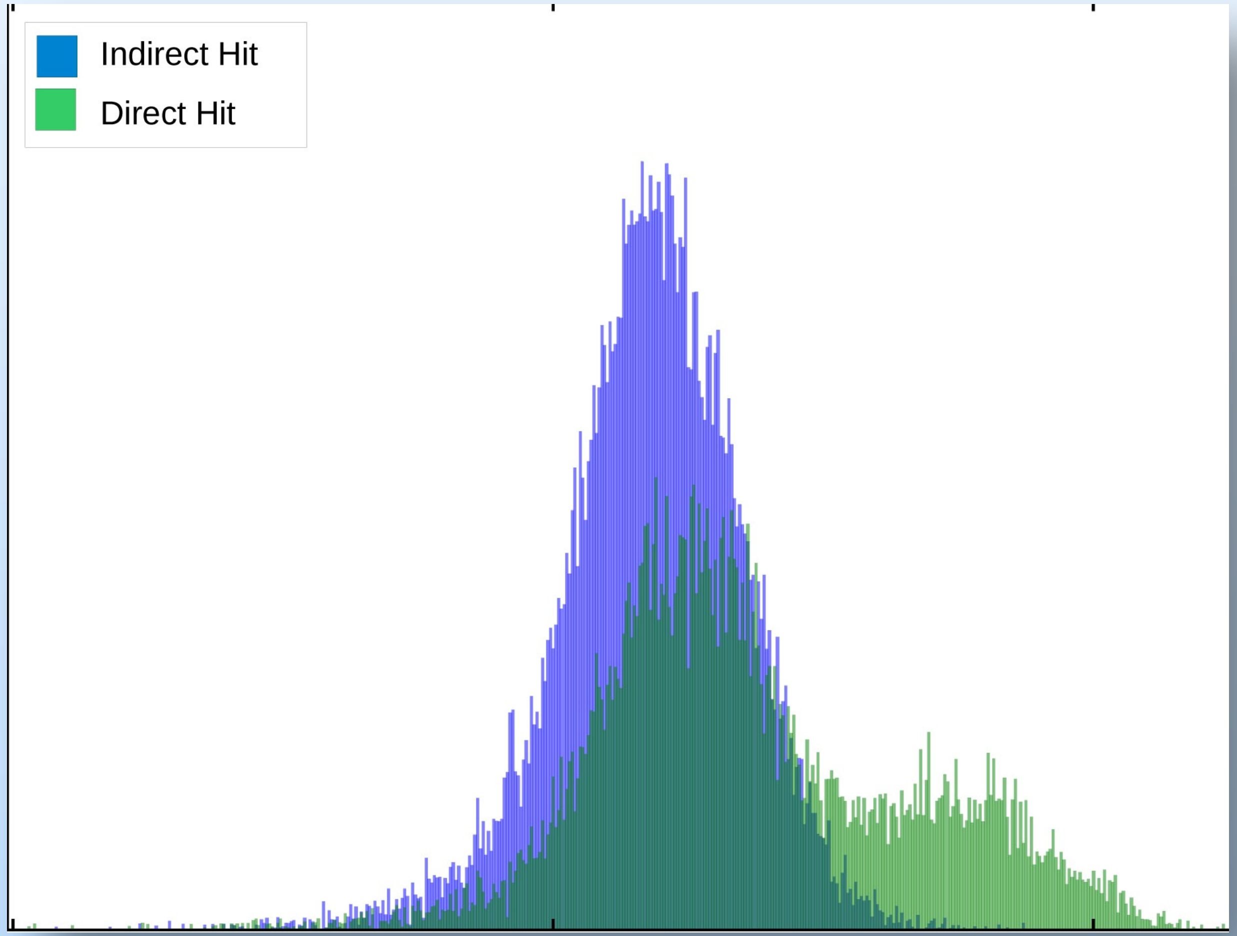
Overview of UCNb



	neutron
	electron
	photon

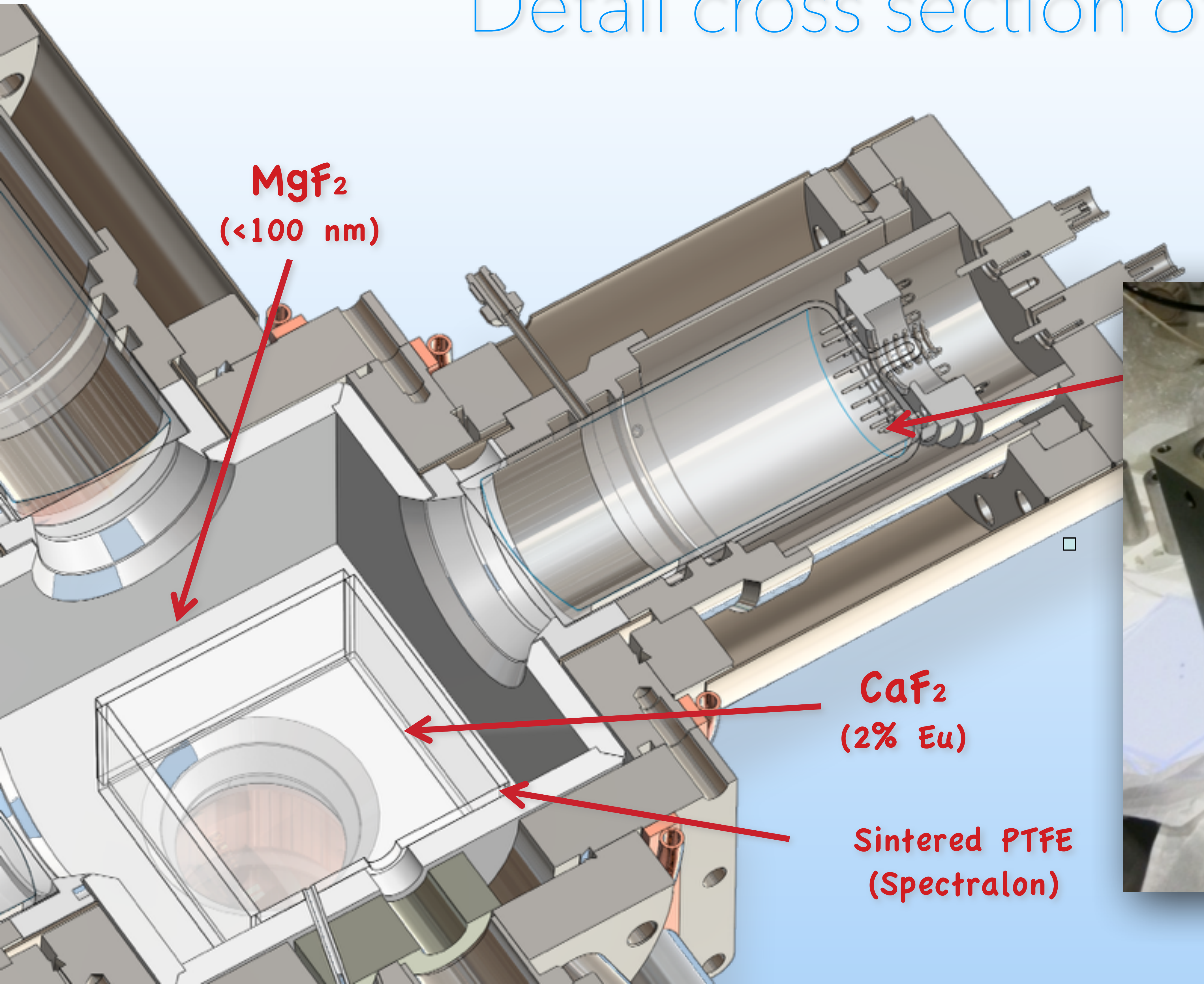
GEANT4 electron and photon simulation

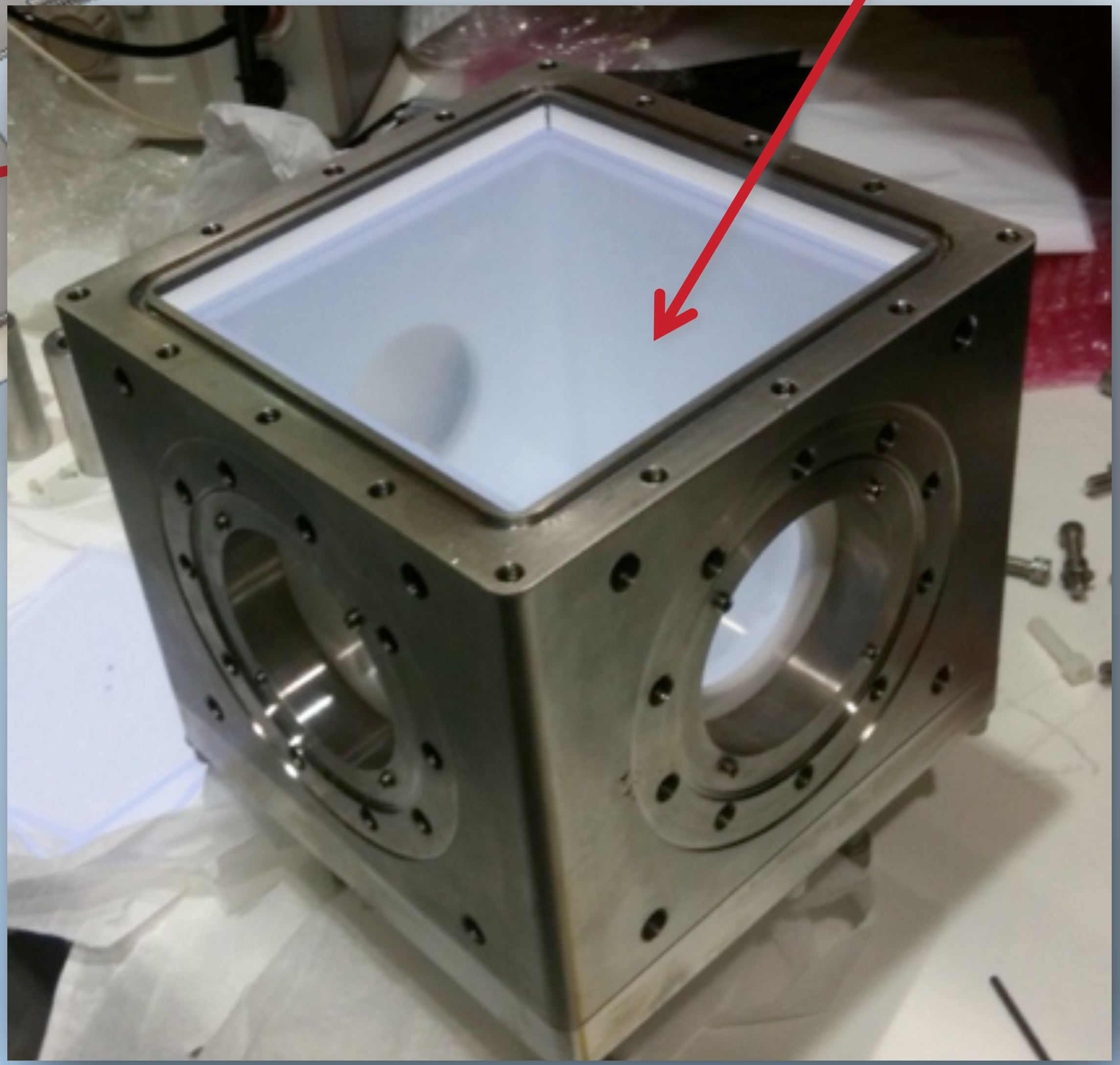




C. Feng, K.P. Hickerson, B.W. Filippone (2011)

Detail cross section of UCNb



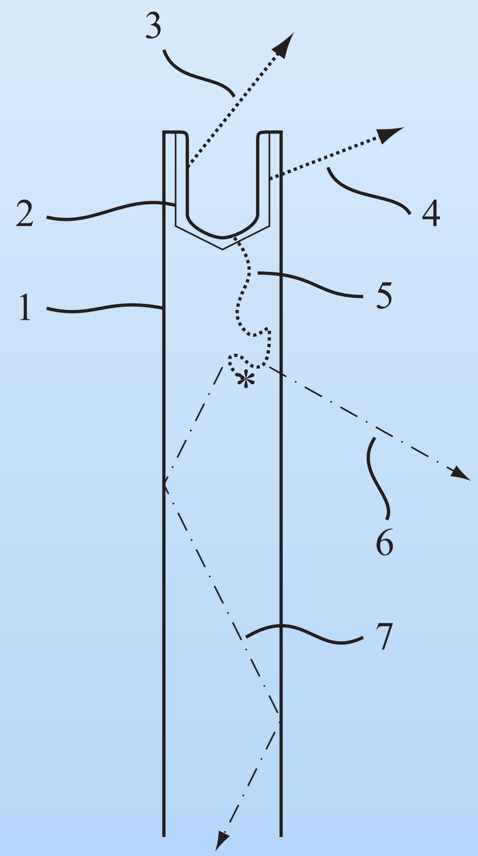


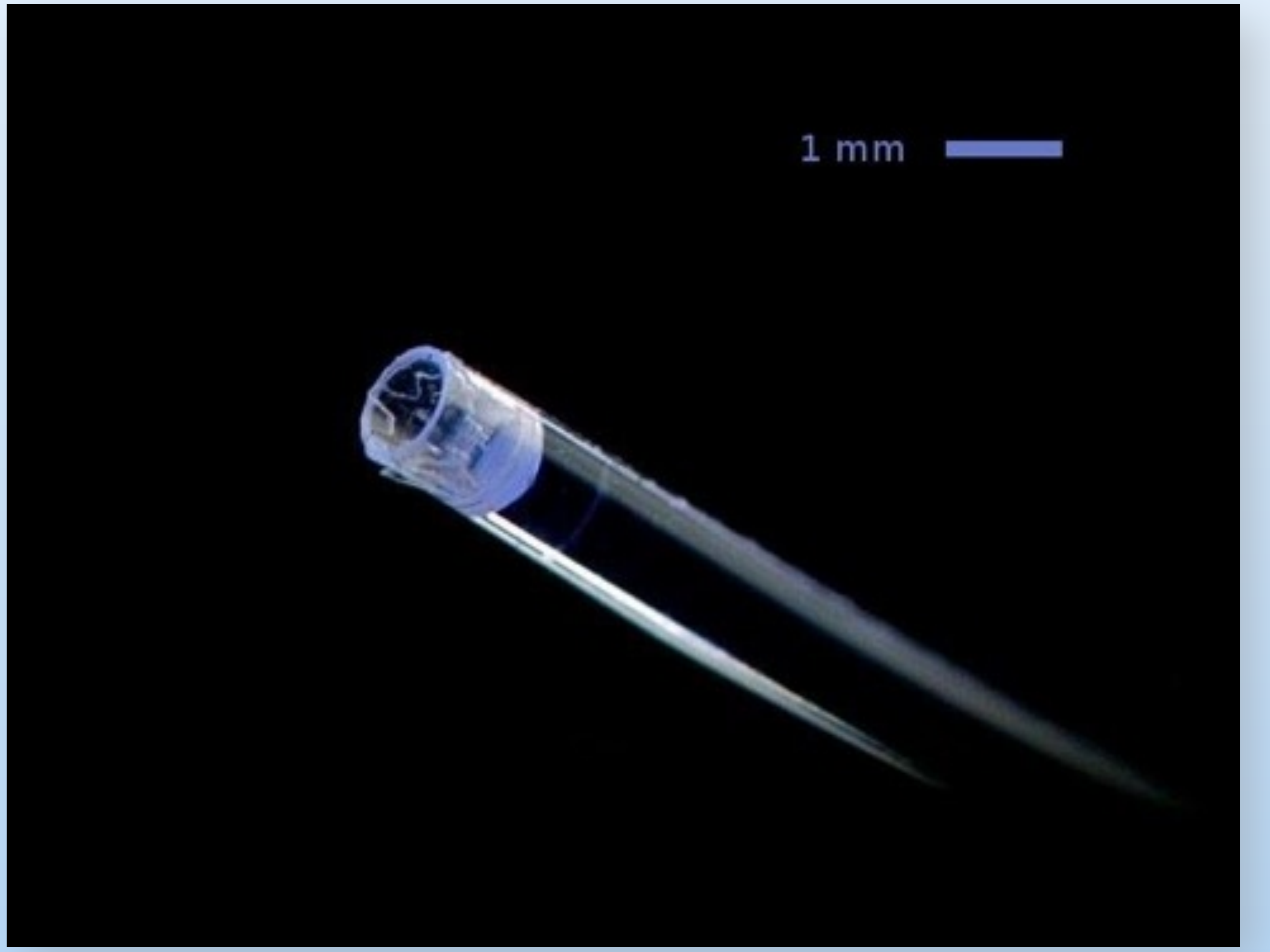
Calibration insertable sources (2012)

Insertable 1000 μm scintillating fiber sources

^{113}Sn and ^{207}Bi

Lost energy and event tagging



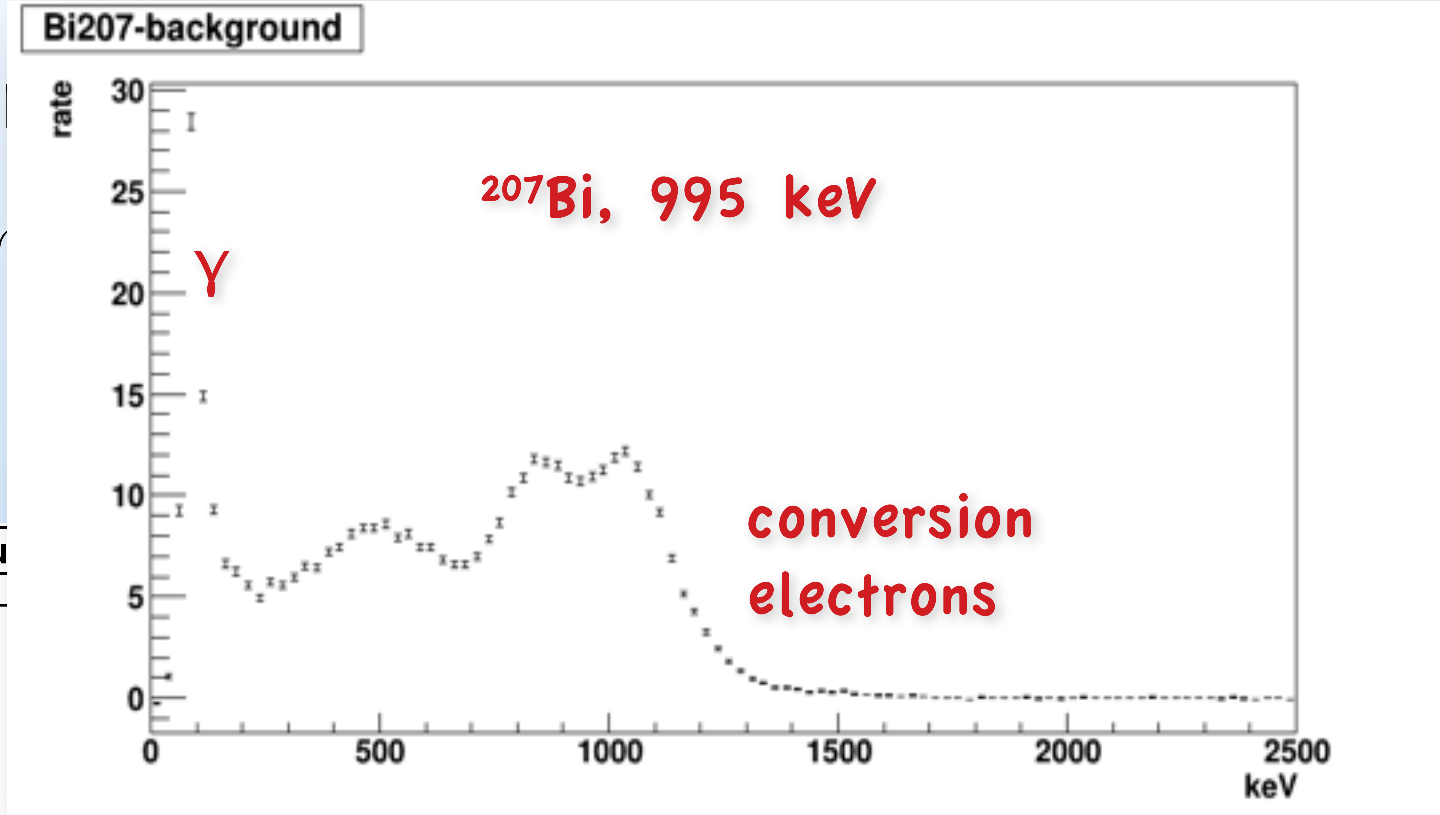


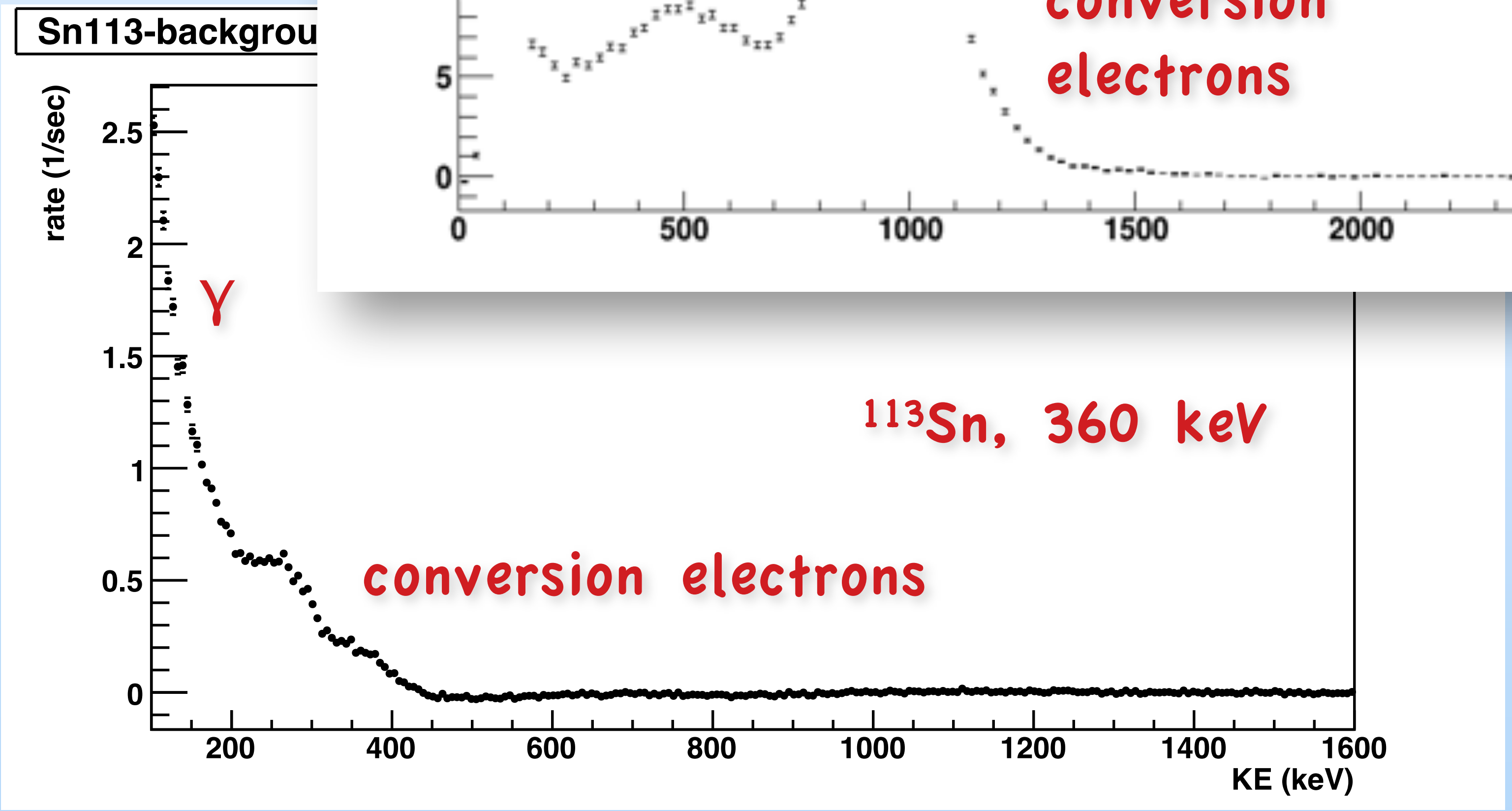
Calibration insertable sources (2012)

Inse… …ource

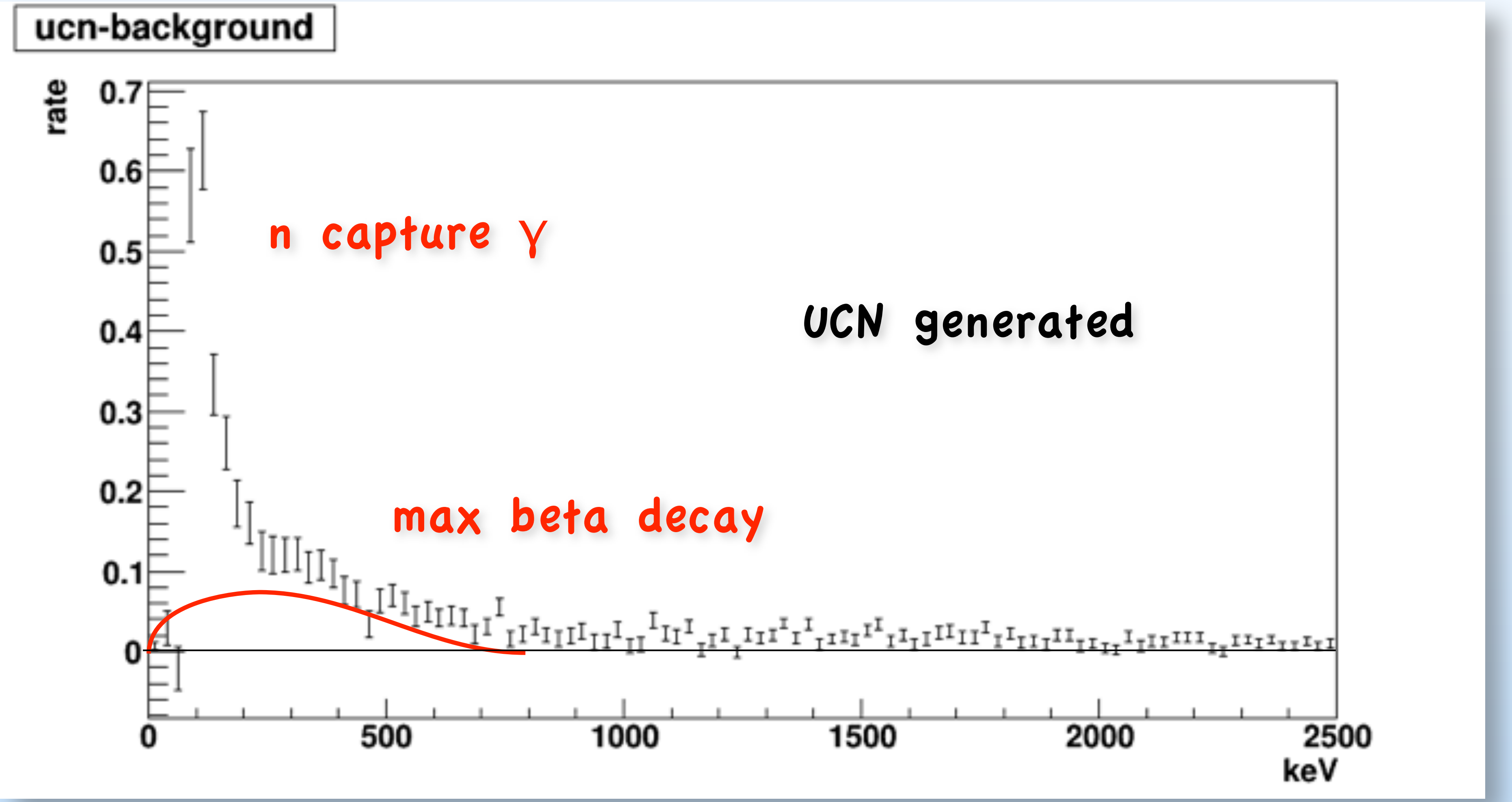
^{113}Sr…

Lost…





UCNb results from early 2012



5 Hz

UCN generated signal

at most 2 UCN/cc from beta decay

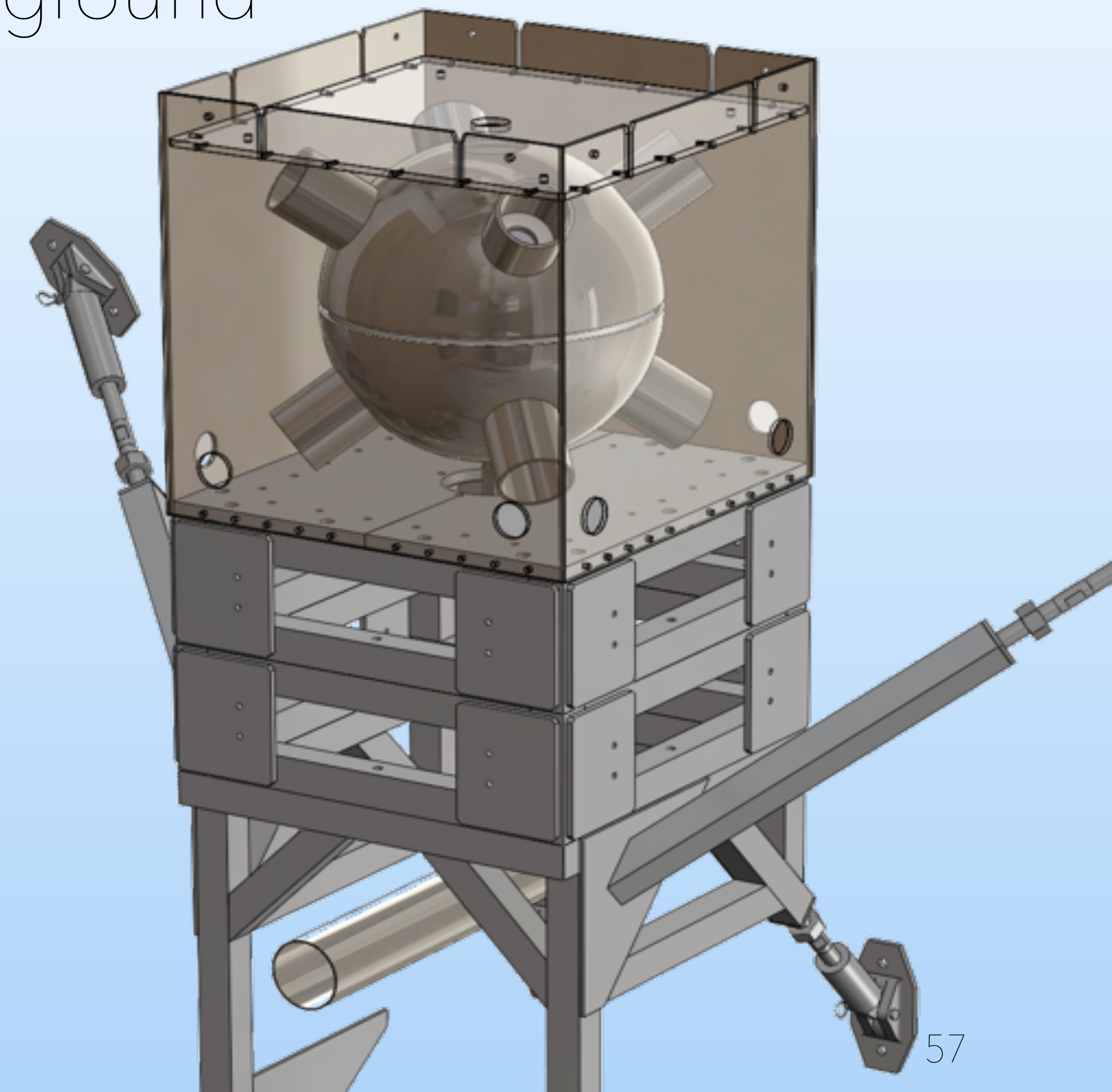
Future directions

Larger cell
- Increase beta / UCN generated background ratio
- Vary size of storage cell to measure background

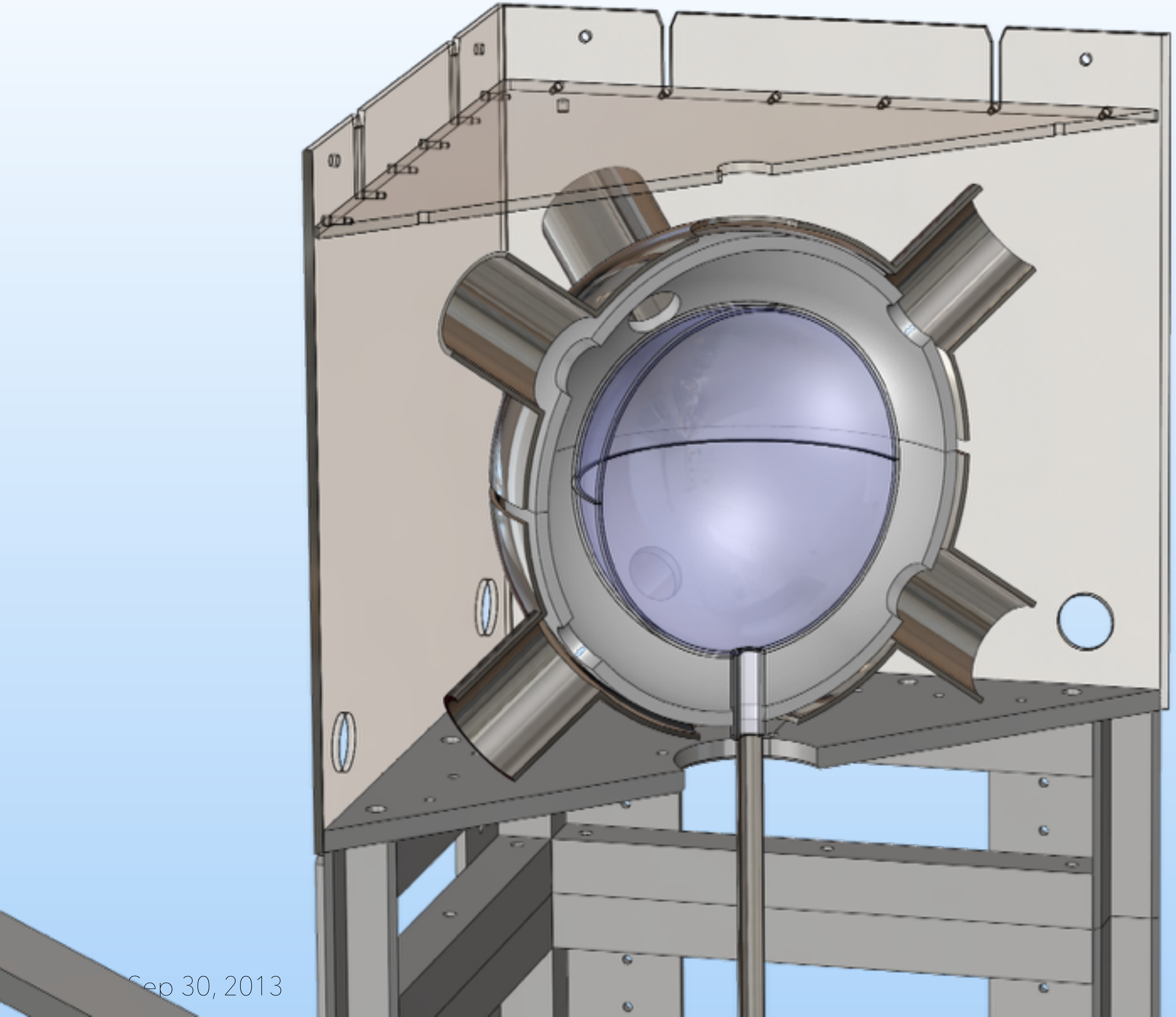
Super/ultra bialkali
- 35% - 45% quantum efficiency

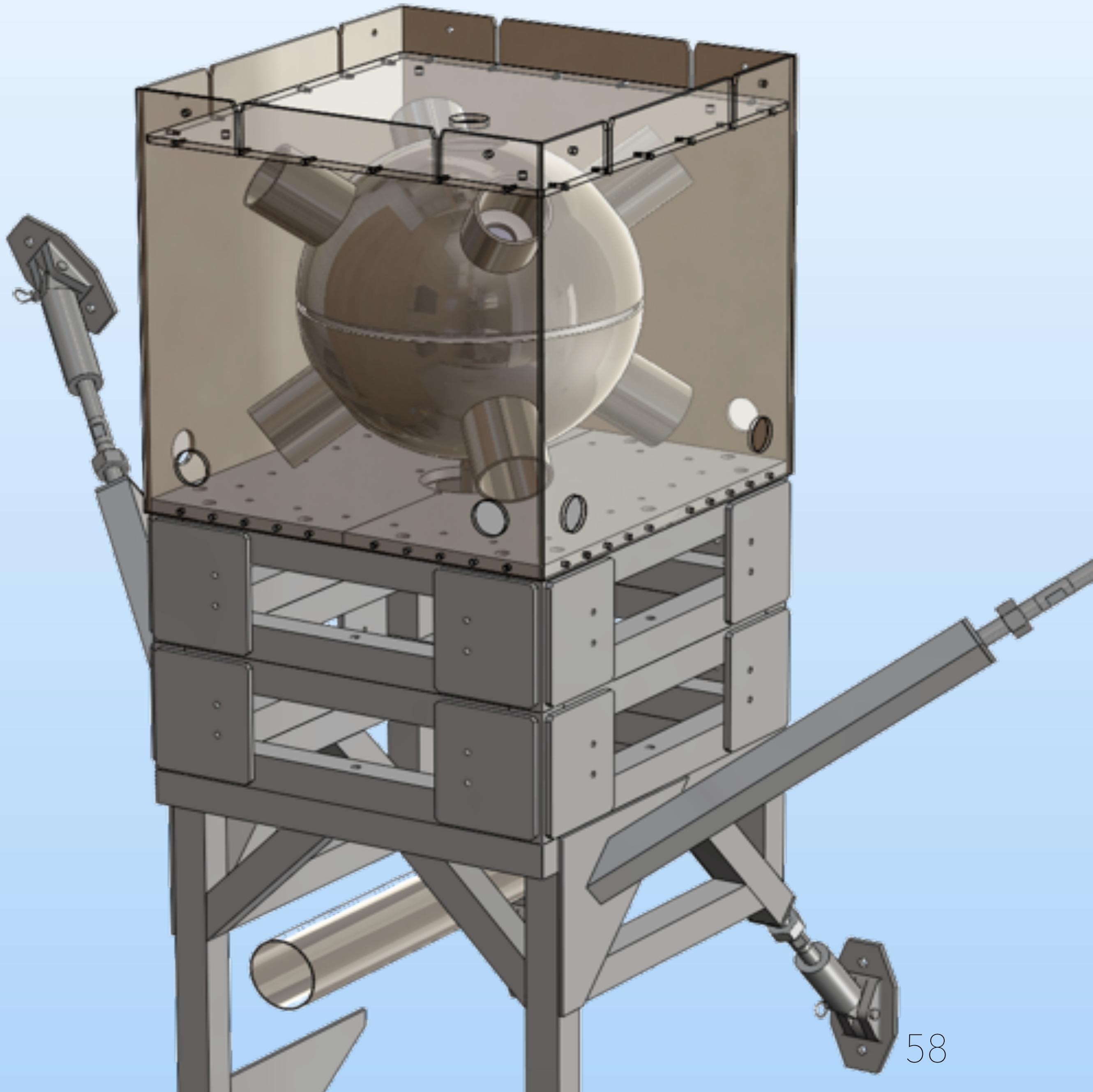
Improved calibration
- Identify calibration gases (Xe, Ar, etc.)

Background rejection
- Proton detection
- neutron capture multiplicity veto

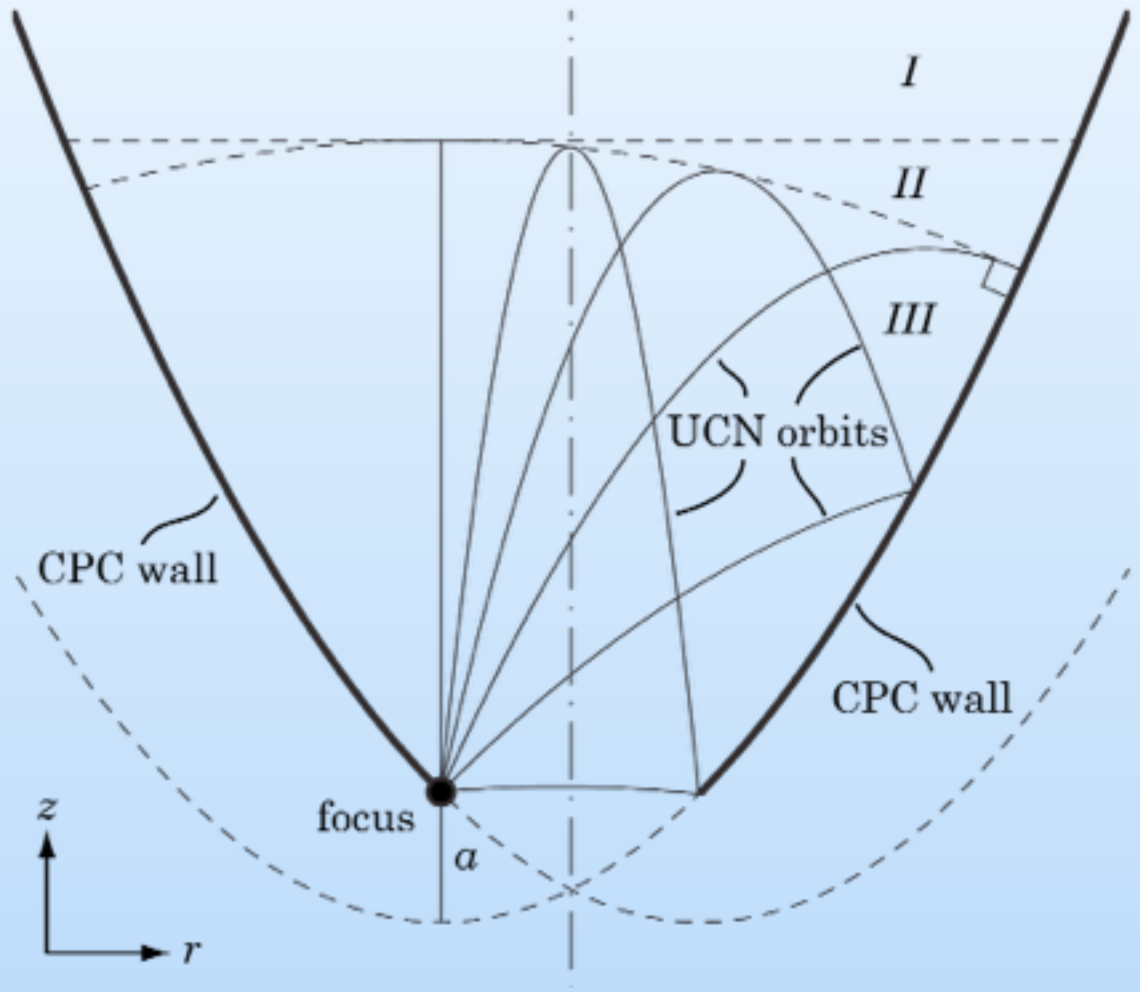


Future directions





The vertical CPC



The 'neutron fountain' property of a parabola images UCN

The area of the input aperture is

$$A = \pi a^2$$

The time for each orbit is

$$\oint dt = \frac{2v_a}{g}, \quad v_a^2 = v_0^2 + 2ag$$

All UCN reach Region II

Properties of a CPC

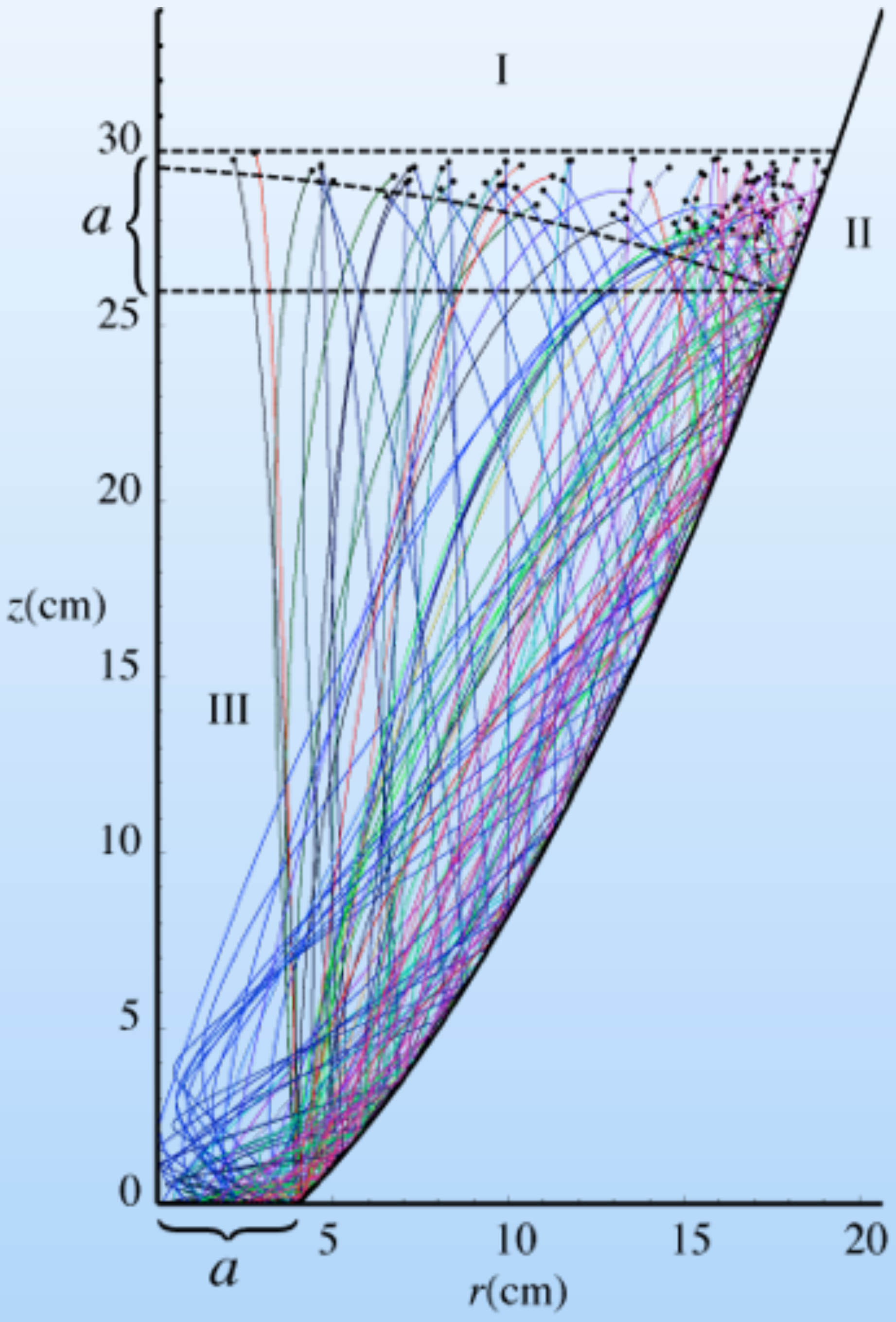
- UCN reach region II.
- Maximum height depends only on initial energy.

$$\max z = \frac{E_0}{mg}$$

- The width of this region is the input aperture radius, *a*.

$$\frac{E_0}{mg} - a < z < \frac{E_0}{mg}$$

- Because this region is narrow, mono-energetic UCN move together in a bunch.



Thank you!