Searching for hot new physics using ultracold neutrons: fundamental symmetries above the TeV scale.

by Kevin Hickerson (UCLA)

EP Seminar - Tuesday, 19 May 2015 from 11:00 to 12:00 at CERN (Main Auditorium)

Ultracold neutrons (UCN) are an exotic variant of the familiar unbound nucleon, but down-scattered to 1 mK. At this temperature, UCN propagate extremely slowly, a few meters per second, with only a few 10-7 electron volts of kinetic energy. By definition, UCN can be trapped inside of material bottles via strong interaction with the nuclei in the walls. They can also be magnetically polarized and guided by magnetic fields of a few Tesla. They even fall along parabolic paths due to earth's gravity, unable to ascend more than a few meters. Along with β decay, these interactions make UCN an ideal laboratory for testing all four forces and fundamental symmetries of the Standard Model in novel ways.

As it stands now, the Standard Model surely requires an extension to explain dark matter, baryon number asymmetry and unification with gravity. While assured near the Planck scale, the lower energy limit of these extensions have not yet been discovered at the LHC or anywhere. I'll show how precision UCN experiments can explore these symmetries at the 10 TeV scale, potentially competitive with accelerators. Several experiments such as UCNA, UCNb, UCNB and UCN τ at Los Alamos National Laboratory measure β decay correlation parameters such as the axial-vector coupling constant, g_A, the Fierz interference term, b, and the neutron lifetime, τn. The neutron electric dipole moment (nEDM) may contribute to a non-zero θ-term, typically removed from the QCD Lagrangian. A non vanishing θ may help find the CP violation necessary to explain the matter-antimatter imbalance of the universe. An experiment under development in the US, aims to measure the nEDM with an expected sensitivity of one hundred times previous attempts, sufficient to rule out (or rule in) predictions from SUSY and other popular theories. Other UCN experiments aim to discover neutron-antineutron oscillations, fifth-force Yukawa couplings and even extra dimensions.

These UCN experiments together can be used to constrain beyond the Standard Model physics and give new insight where to look for it next.

CERN EP Seminar
May 19, 2015

Searching for **Hot new** physics using **ultracold Neutrons**.

Fundamental symmetries above the TeV scale

Dr. Kevin Peter Hickerson

University of California Los Angeles

- What's so cool about Ultracold Neutrons?
  - And why do we use them?
- The Standard Model of a Neutron
  - The electroweak theory of the decay of neutrons in to protons
- Fundamental Symmetries with Neutrons
  - A fun place to look for physics beyond the Standard Model
- Ultracold Neutron Experimental Landscape
  - Leading experiments at LANSCE and ILL
- Ultracold Neutron Experimental Horizon
  - Up and coming experiment at LANSCE and SNS

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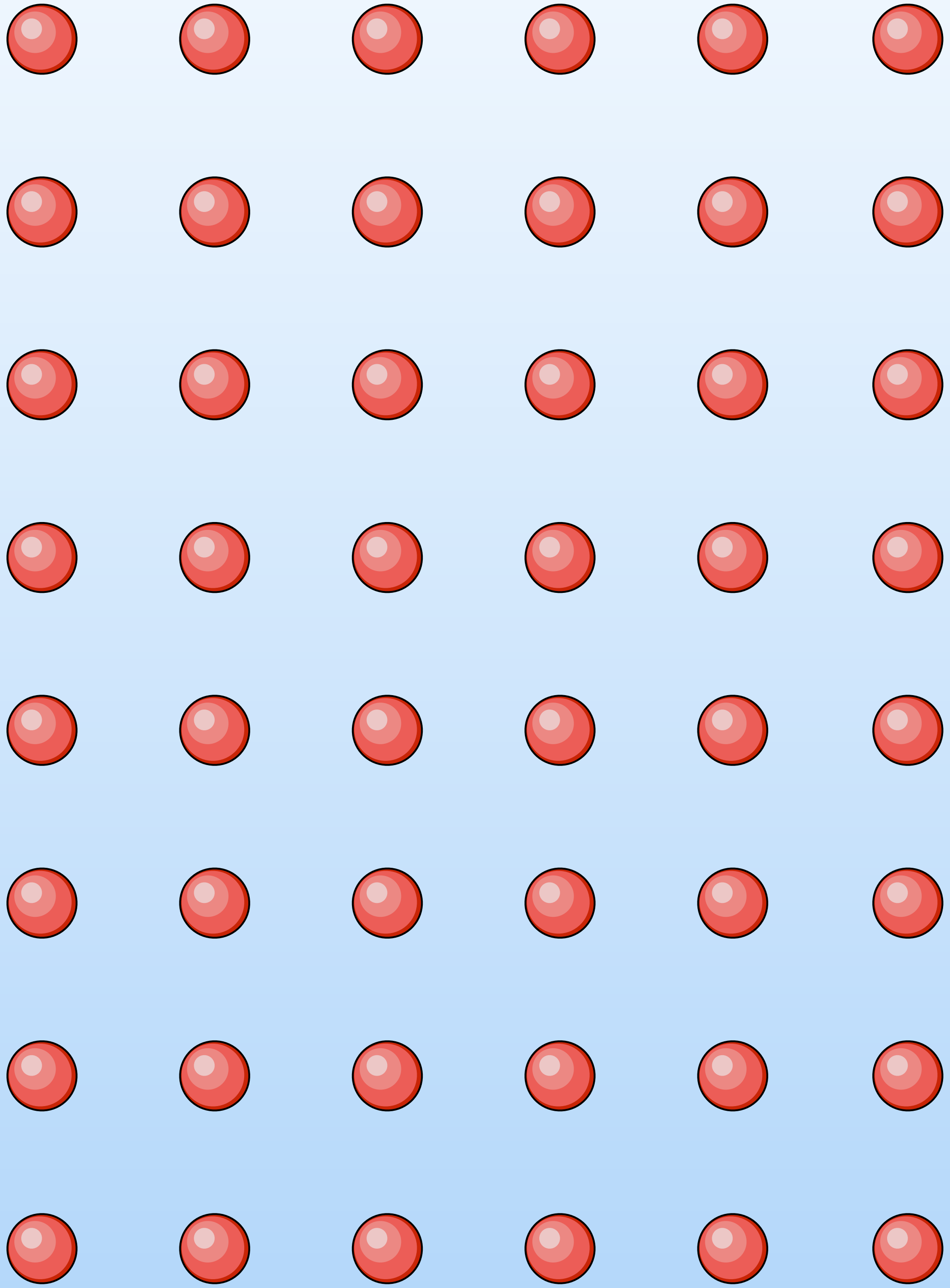
What are ultracold neutrons?

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

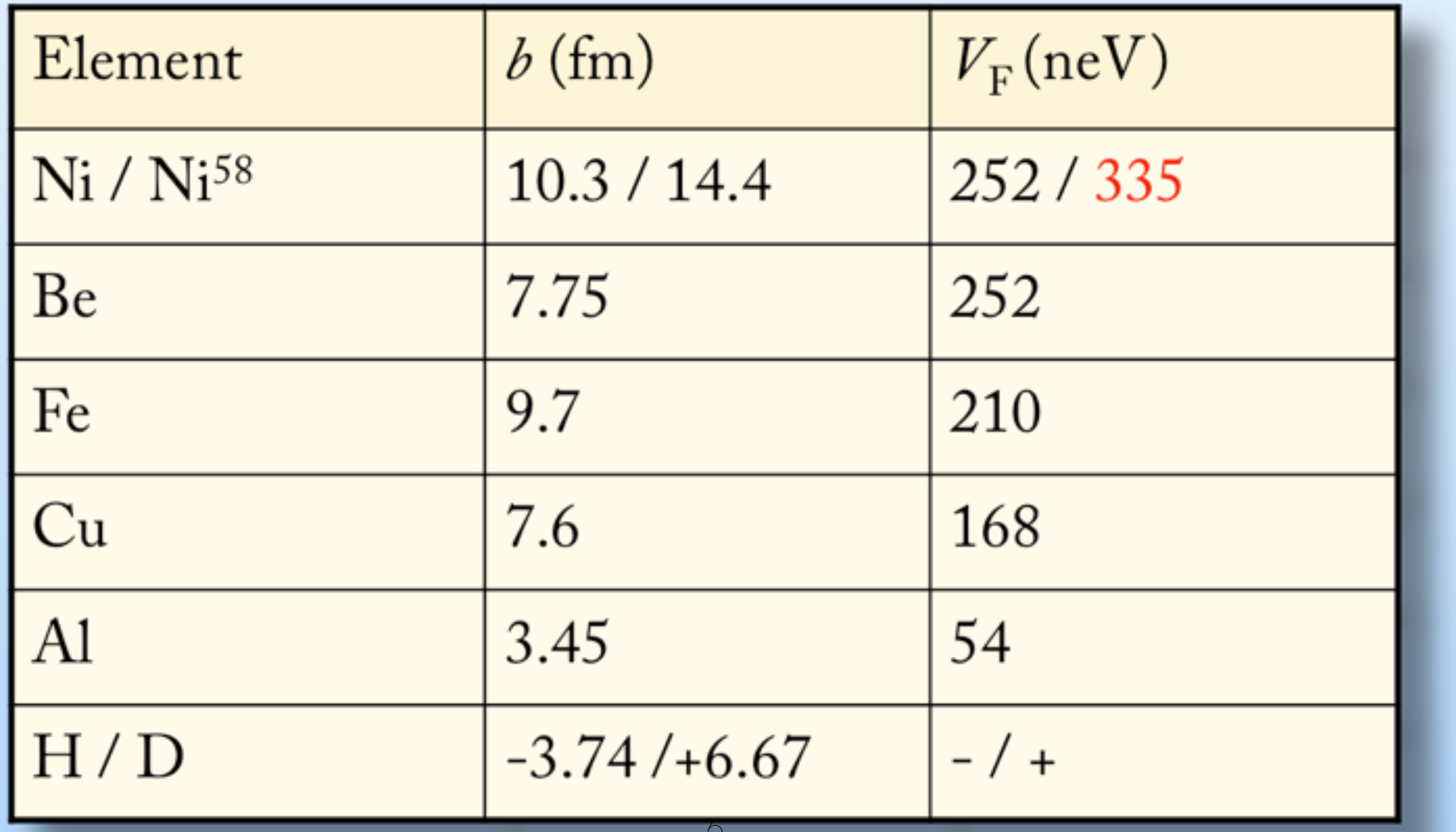
$$V_{\mathrm{F}} = \frac{2\pi\hbar^2}{m_n}\sum_i b_i\delta(\mathbf{r}-\mathbf{r}_i)$$



What are ultracold neutrons?

The Fermi Potential

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



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	- / +

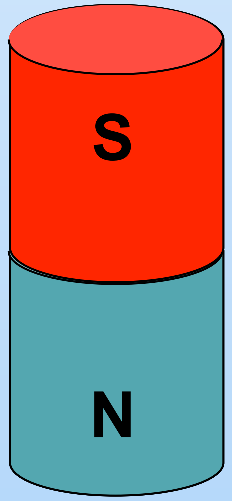
Why use ultracold neutrons?

The magnetic potential of polarized neutrons is

$$V_B = \pm \mu_n B$$

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

Ultracold neutrons can be polarized by $B = 6$ Tesla.



Why use Ultracold Neutrons?

The magnetic potential of polarized neutrons is

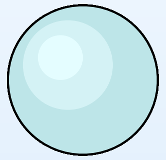
$$V_B = \pm \mu_n B$$

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

Low-field seeking UCN can be trapped by a magnetic bottle.

Why use Ultracold Neutrons?

The gravitational potential of neutron mass

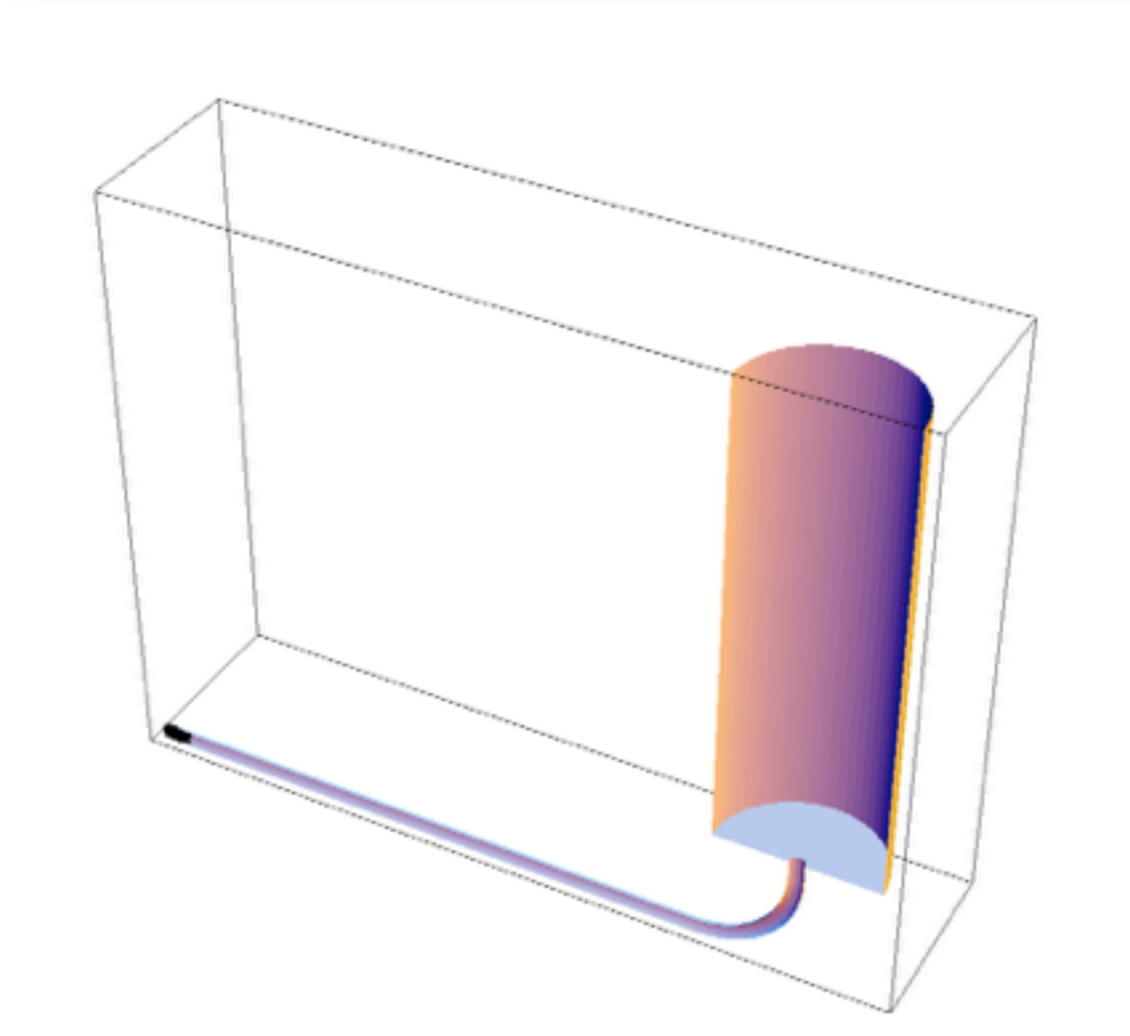


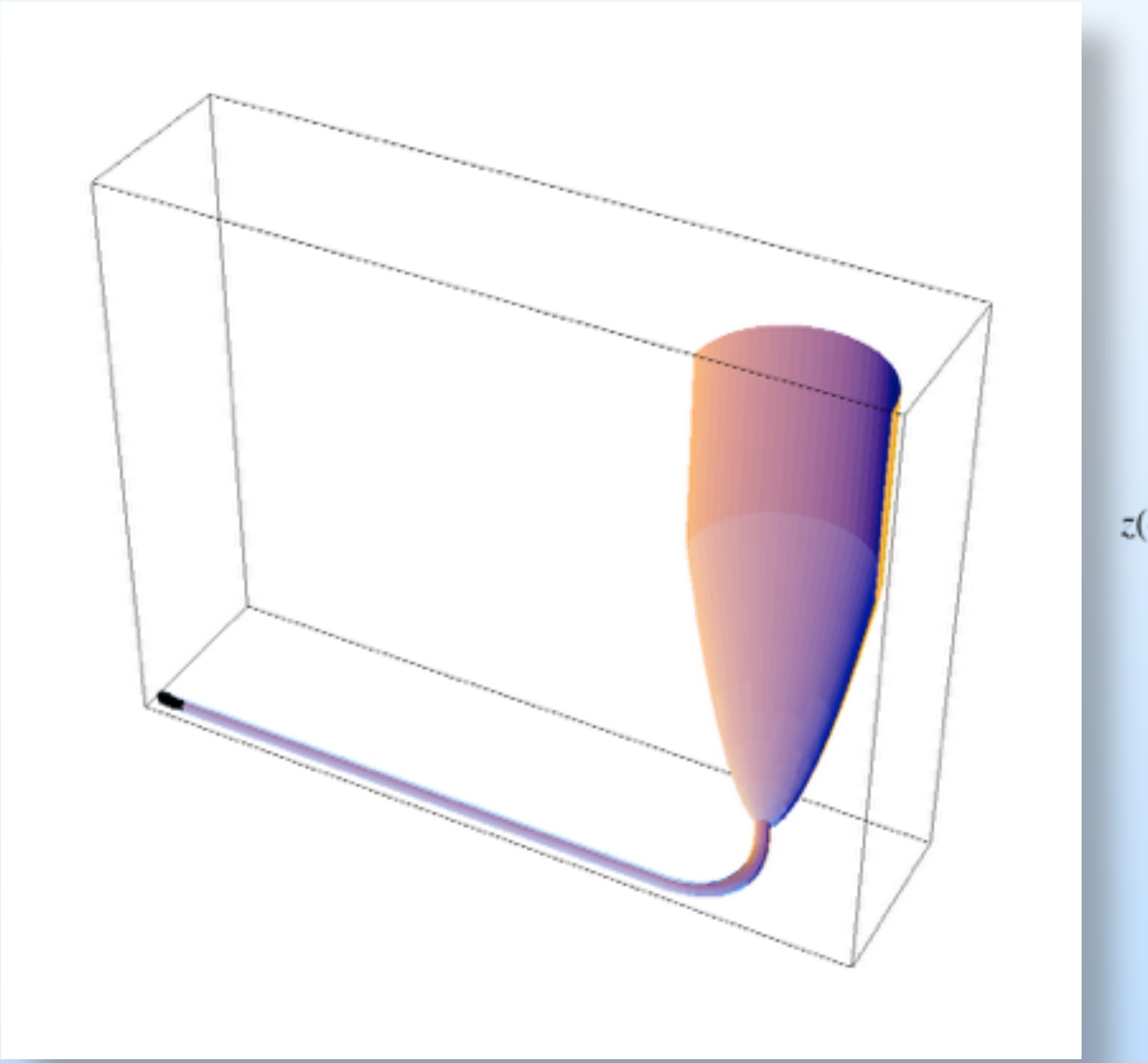
$$V_g = m_n g h$$

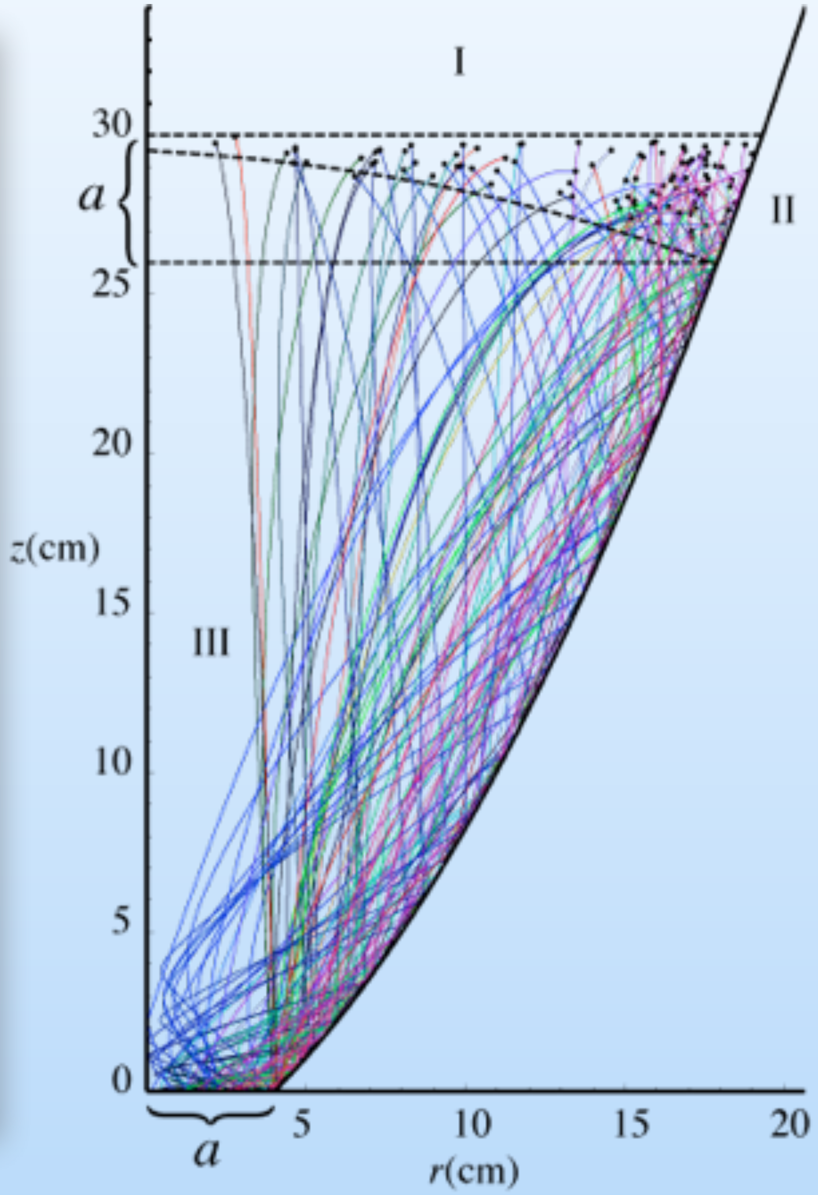
$$m_n g = 102.52 \text{ neV/m}$$

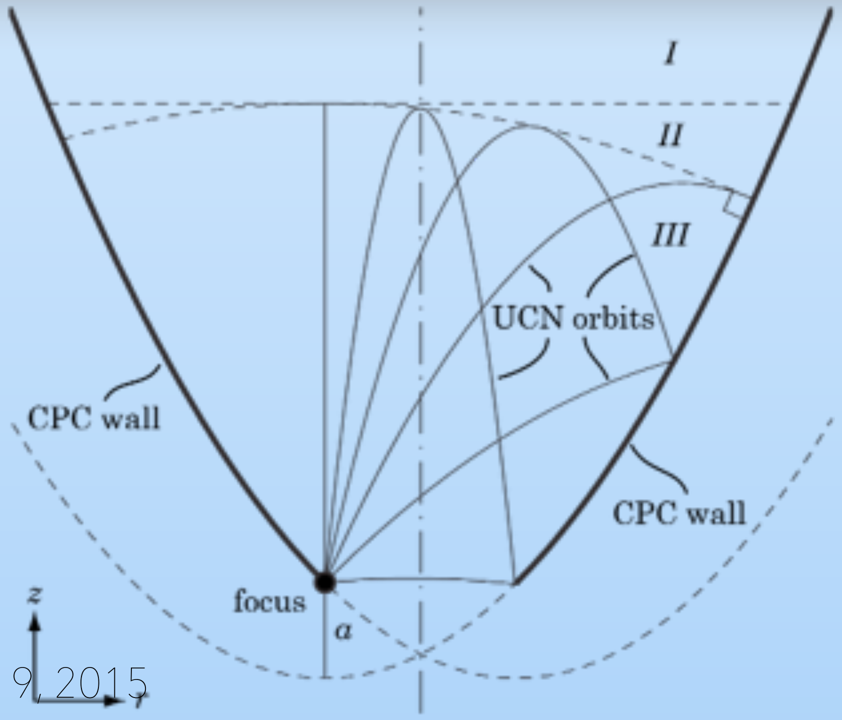
UCN can be trapped in a “bucket” 3.5 m deep!

UCN optics and transport

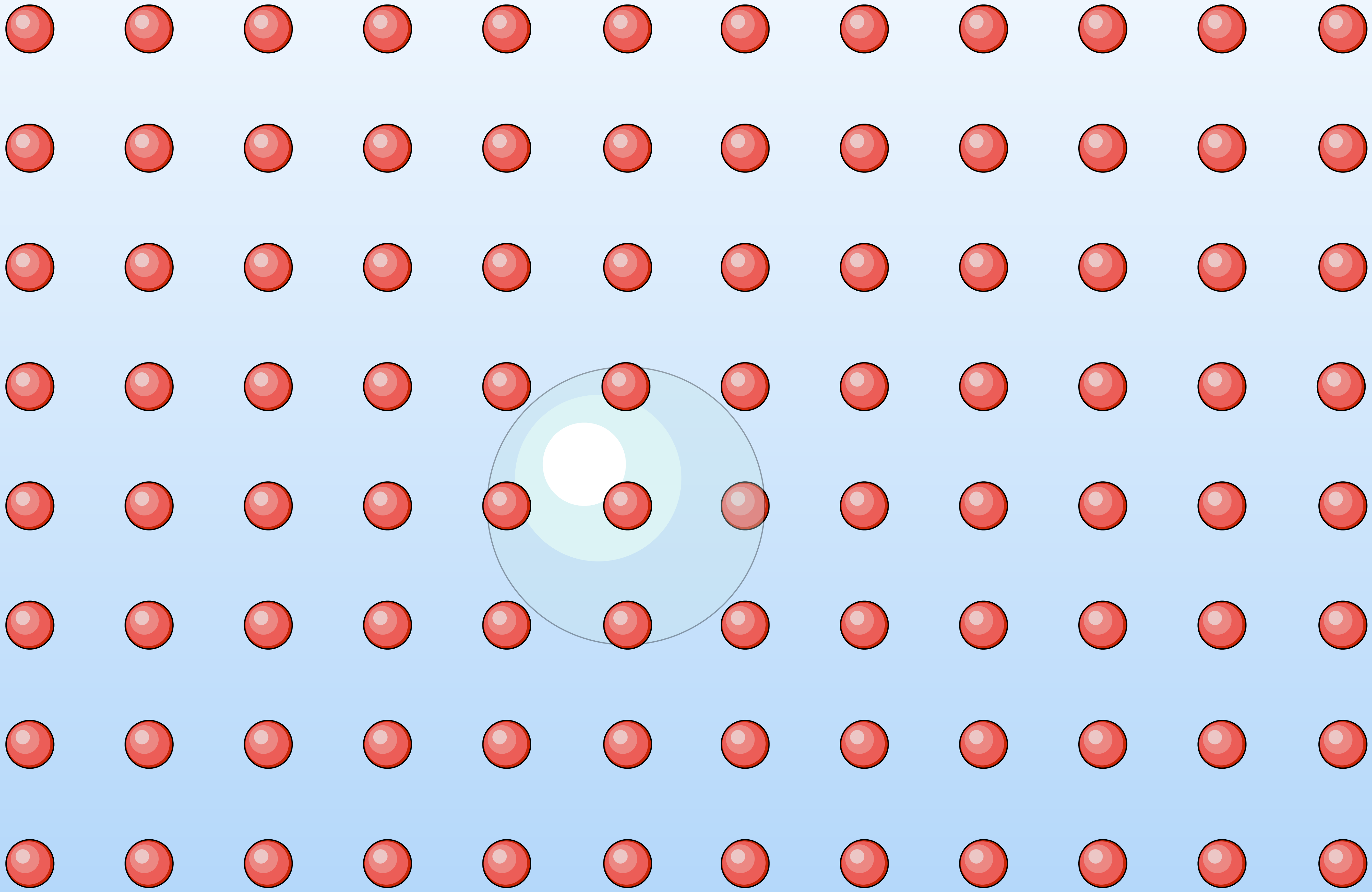




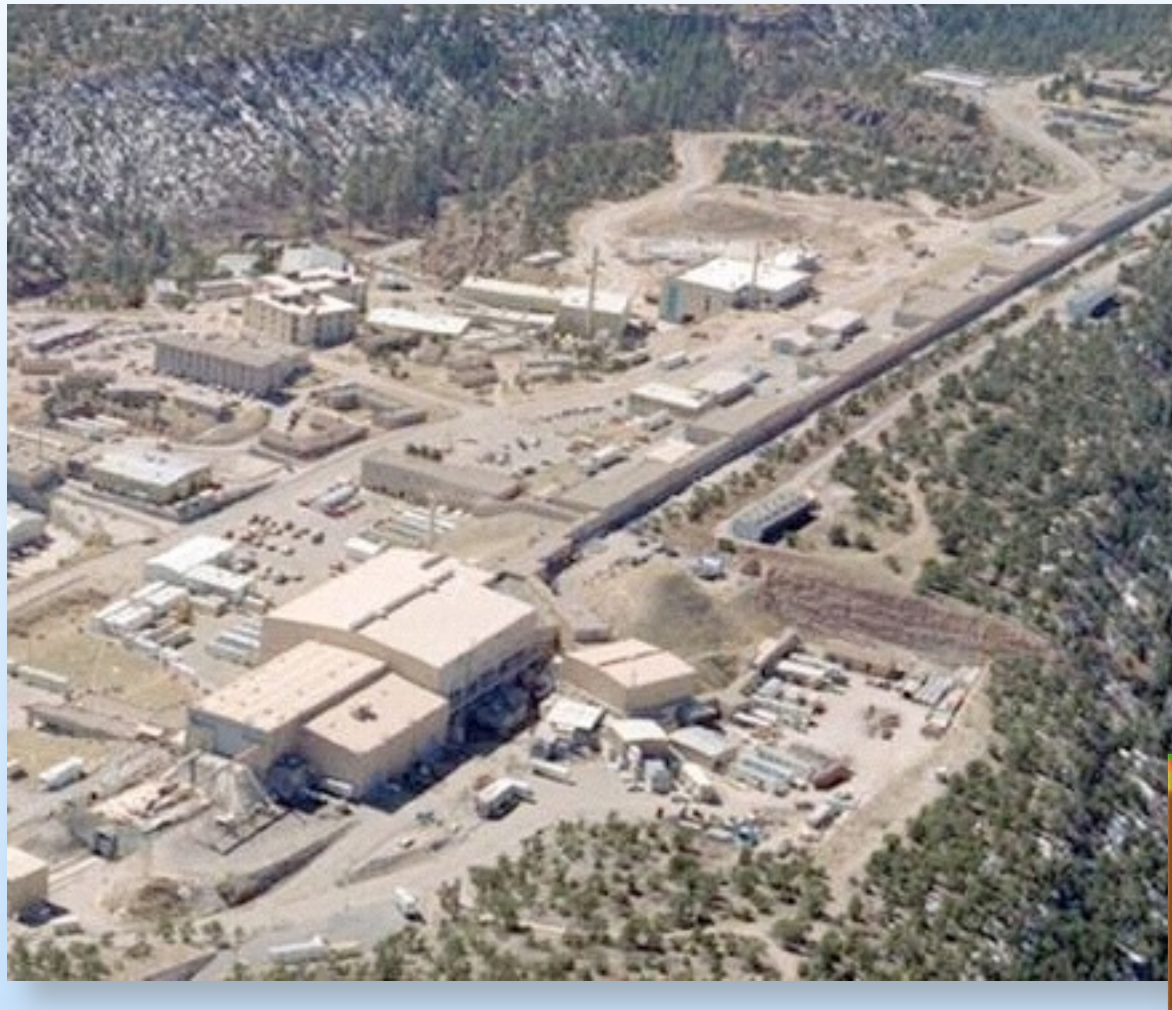




How do we make ultracold neutrons?

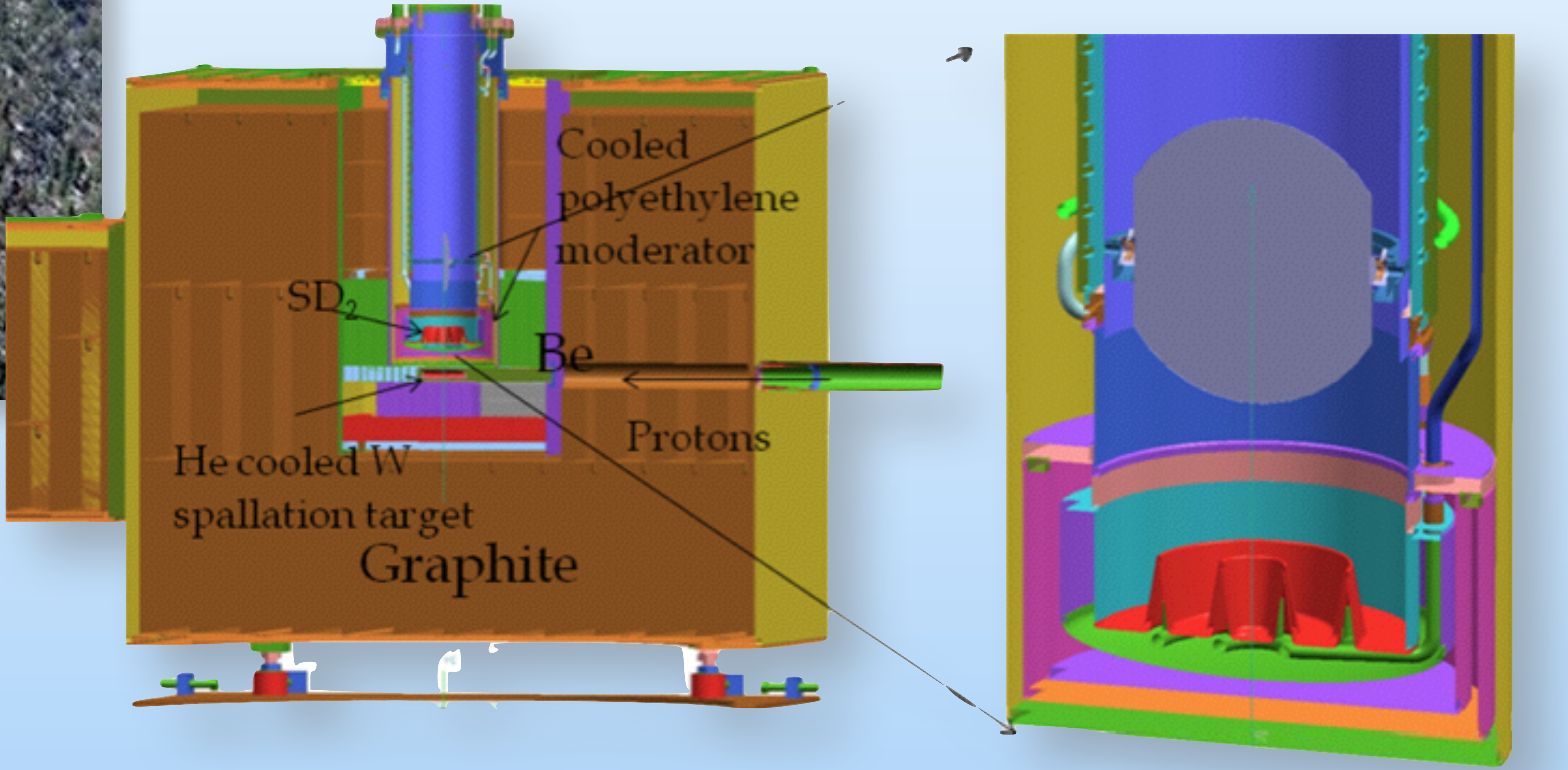


SD_2 UCN source at LANSCE



0.8 GeV proton beam at Los Alamos National Laboratory in New Mexico

Solid deuterium super thermal moderator from tungsten target spallation neutrons.



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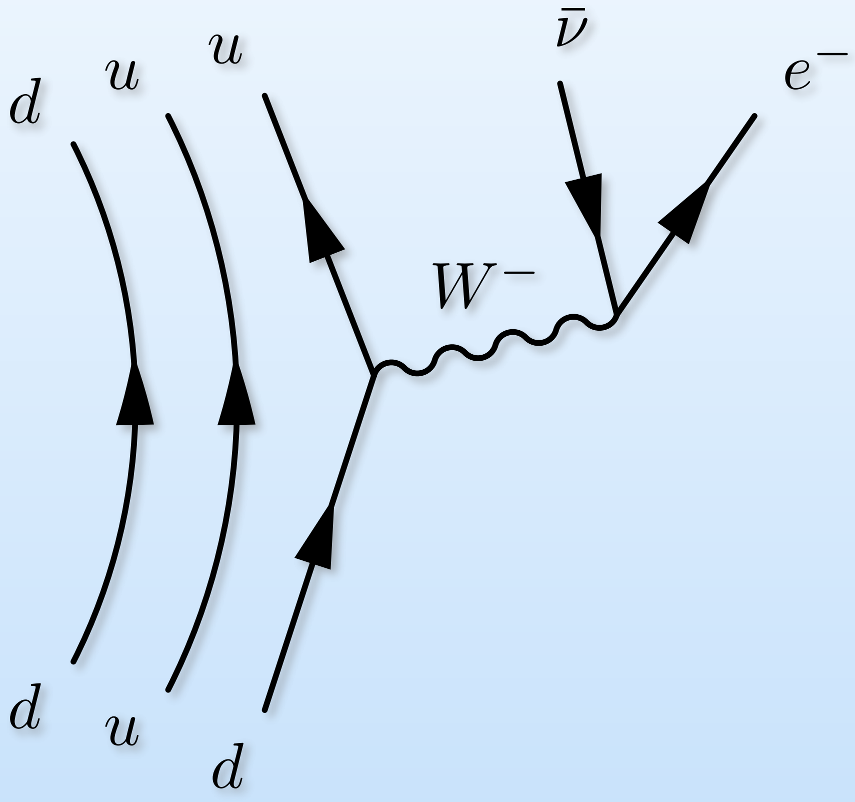
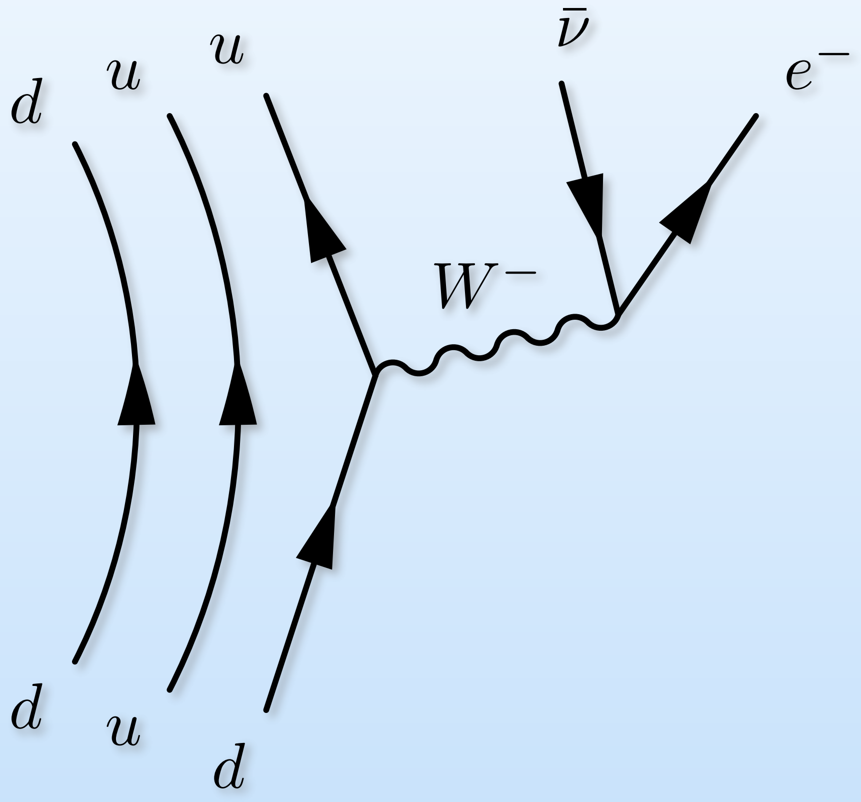
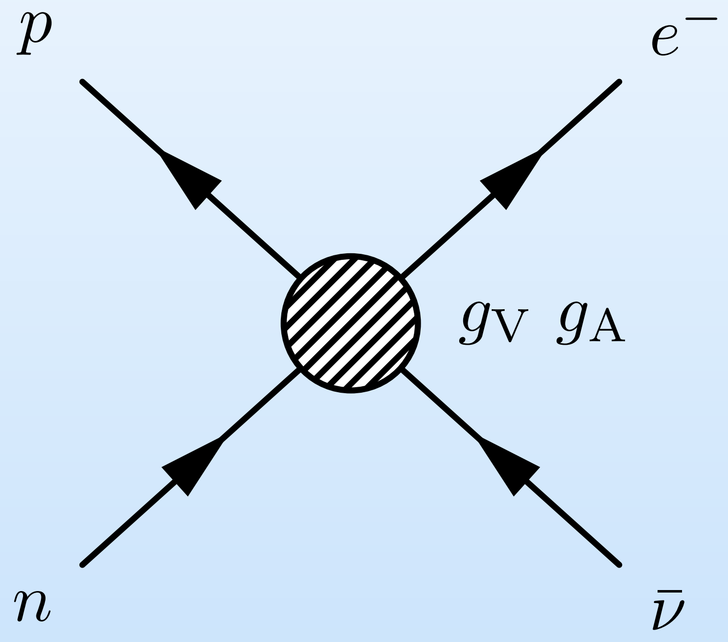
Neutron beta decay



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

Neutron beta decay

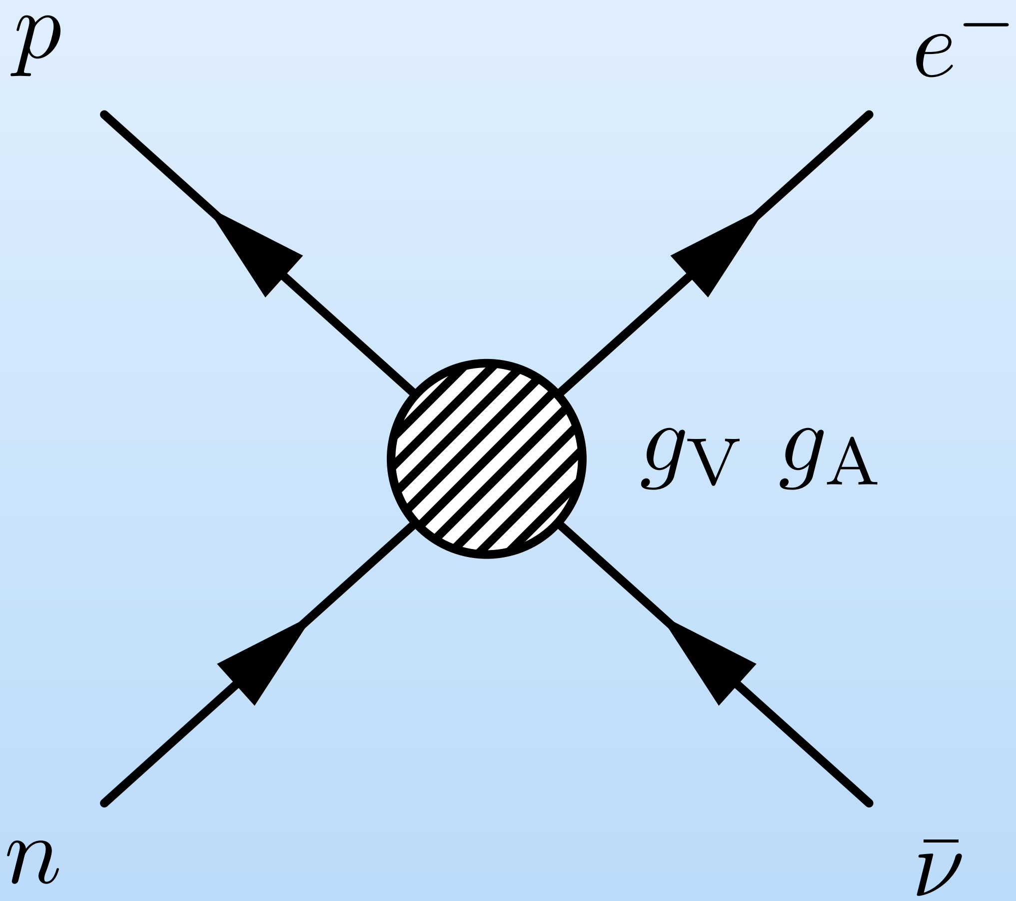




$$n \rightarrow p + e + \bar{\nu}_e$$

Effective beta decay

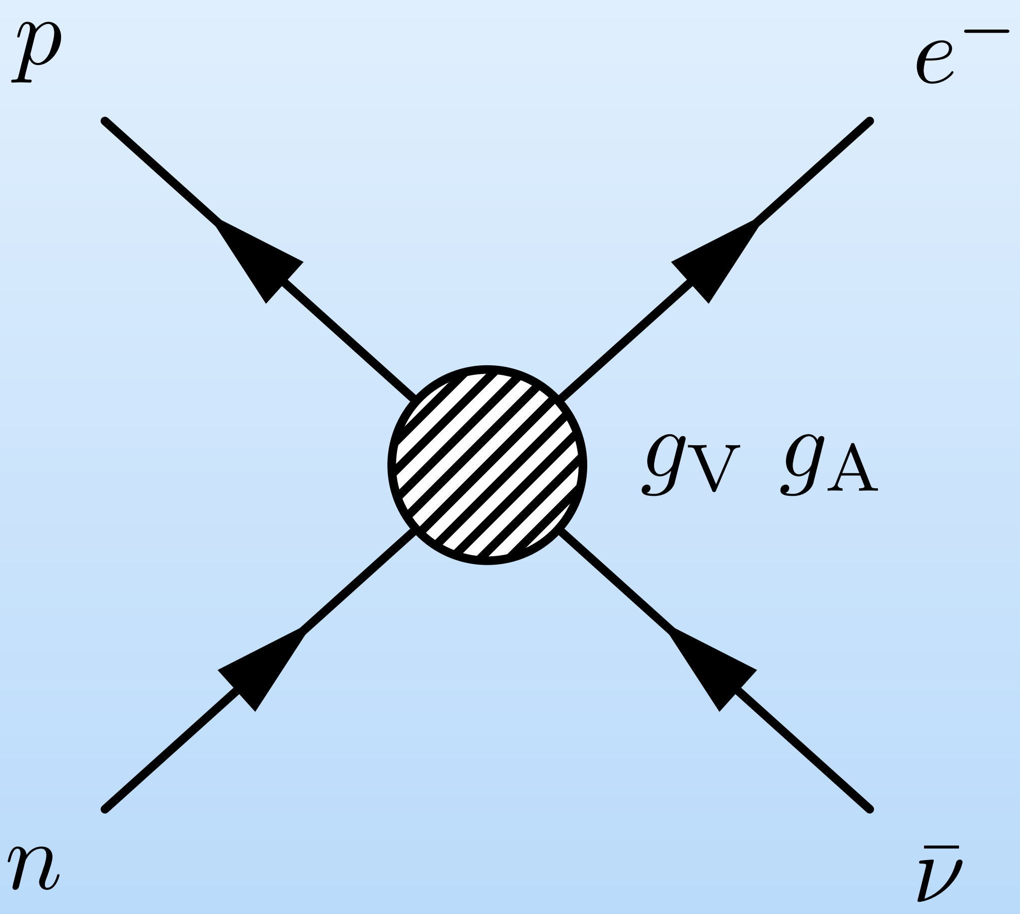
$$\mathcal{L}_\beta = \sqrt{8} G_\mathrm{F} V_{ud}\, \bar{p}\gamma^\mu \left(g_V - g_A\gamma^5\right) n\, \bar{e}\gamma_\mu \left(1-\gamma^5\right)\nu_e .$$



May 19, 2015

Effective beta decay

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



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

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

PDG (2012)

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Generalized electroweak symmetries

Full 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)

Neutron decay parameters

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

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

Alphabet soup

In the Standard Model...

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

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

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

Beta asymmetry

Beta asymmetry can be observed...

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

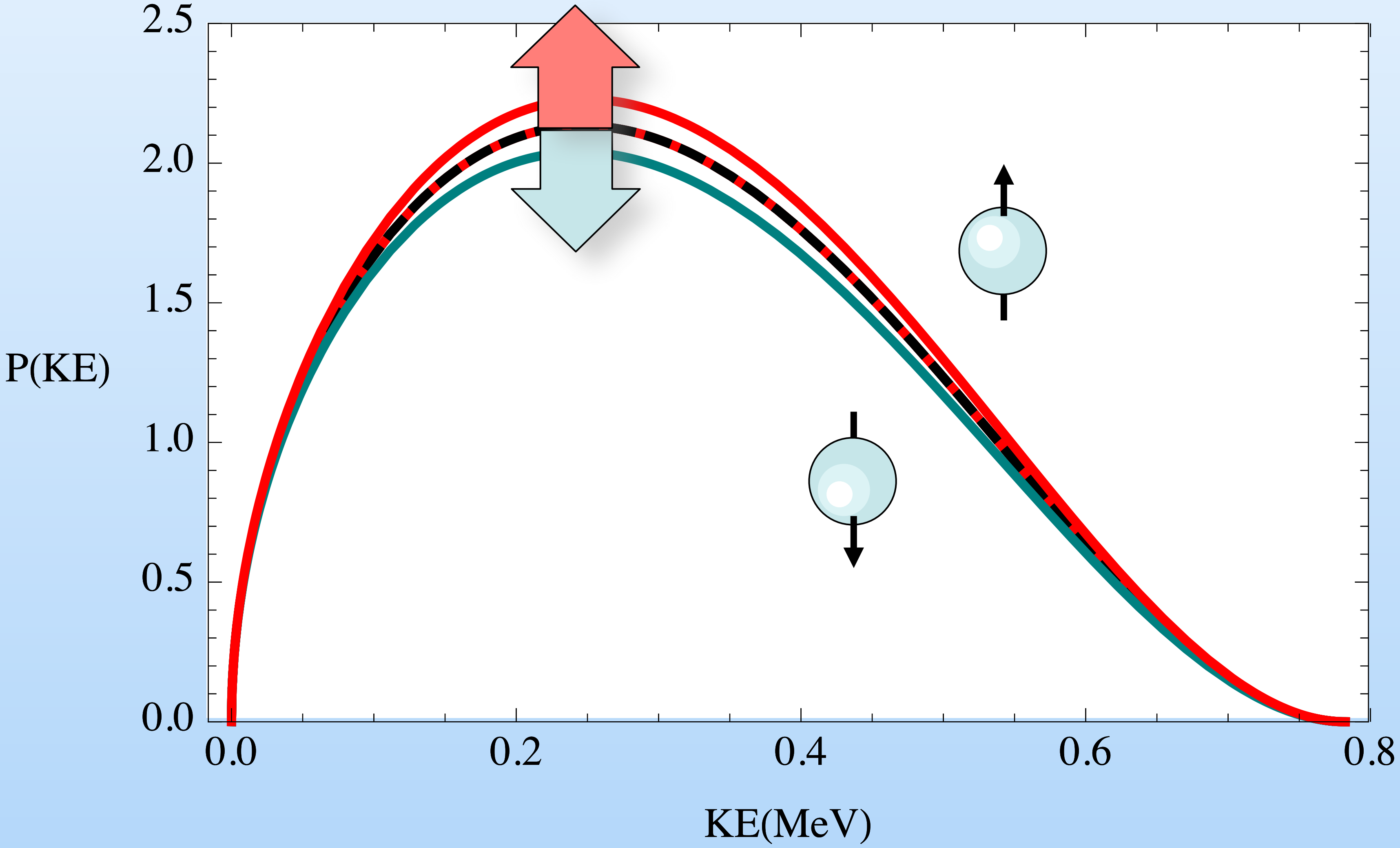
...if neutron only polarization and electron momentum is measured.

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

Beta asymmetry term from two spectra

Beta asymmetry term splits the
neutron beta spectrum by 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 interference term

Only the Fierz interference term...

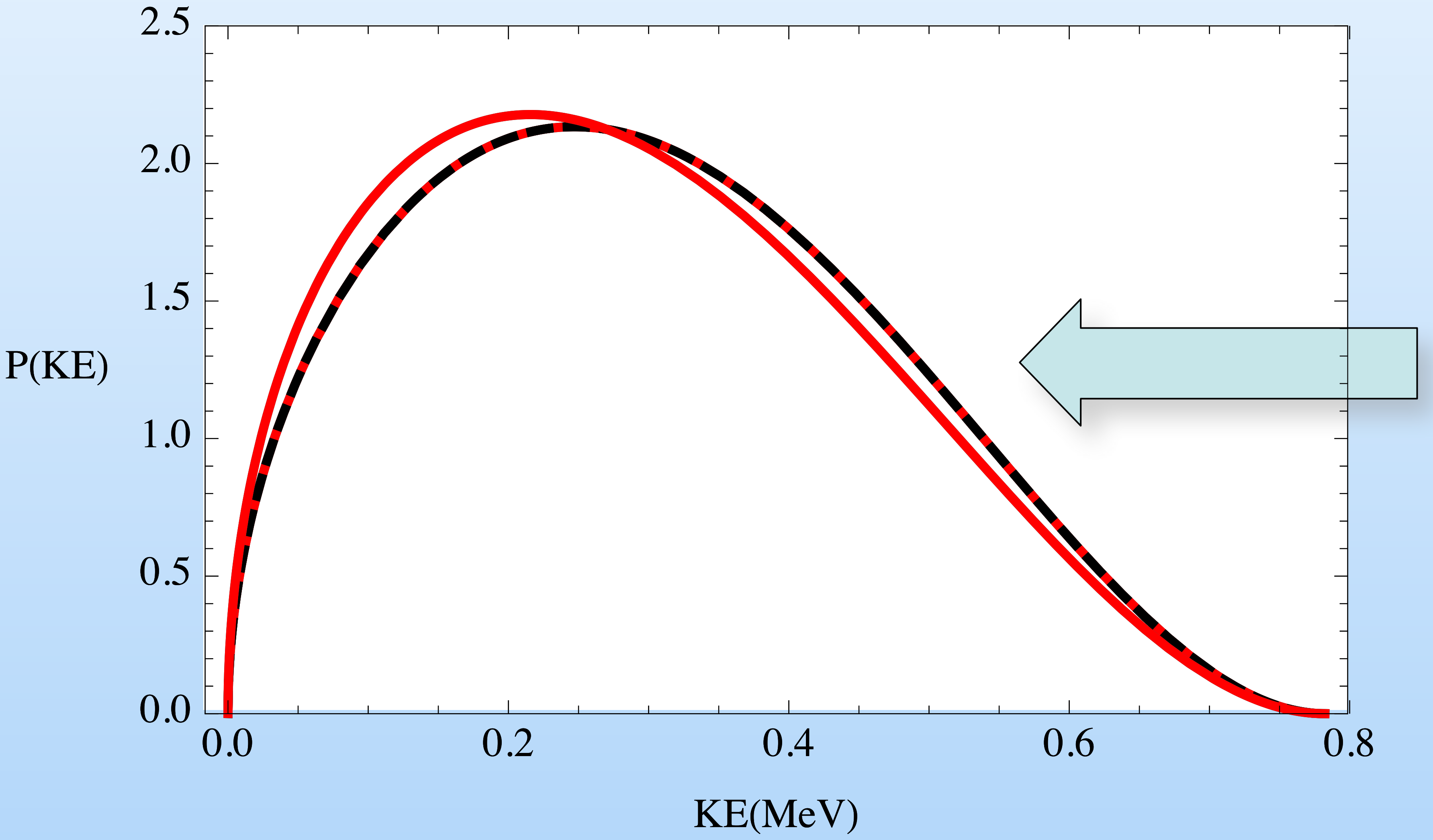
$$\frac{d\Gamma}{dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a \xcancel{\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}} + b \frac{m_e}{E_e} \right.$$
$$\left. + A \xcancel{\frac{\vec{p}_e \cdot \vec{J}}{E_e}} + B \xcancel{\frac{\vec{p}_\nu \cdot \vec{J}}{E_\nu}} + D \xcancel{\frac{\vec{p}_e \times \vec{p}_\nu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

...is polarization and momentum independent. But affects neutron lifetime!

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

Fierz term from beta-spectrum

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



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

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

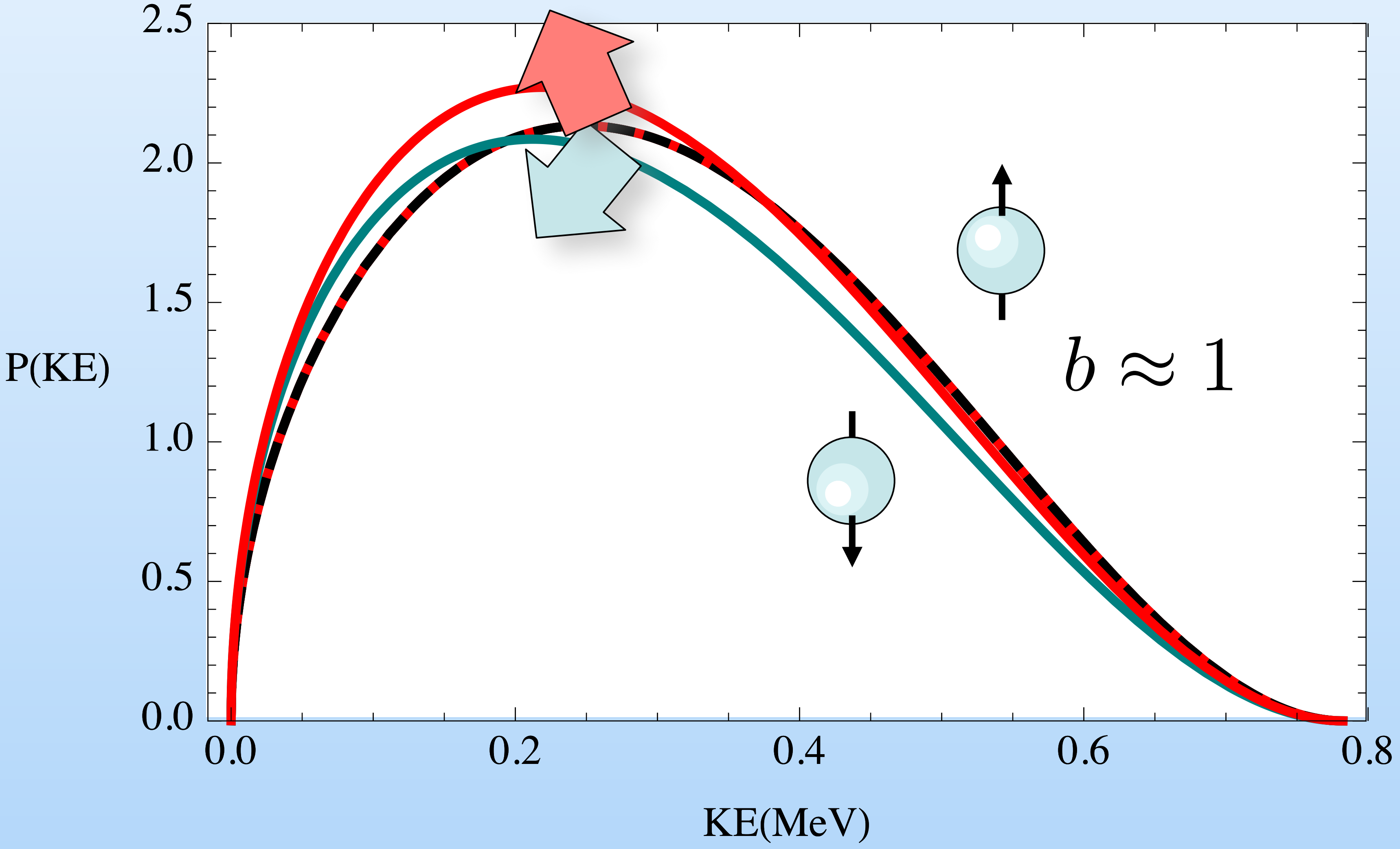
$$\sigma_b = \frac{7.5}{\sqrt{N}}$$

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

Combined fit of spectrum and asymmetry

Fierz term shifts the neutron beta spectrum

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



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

$$\rho = 0.201$$

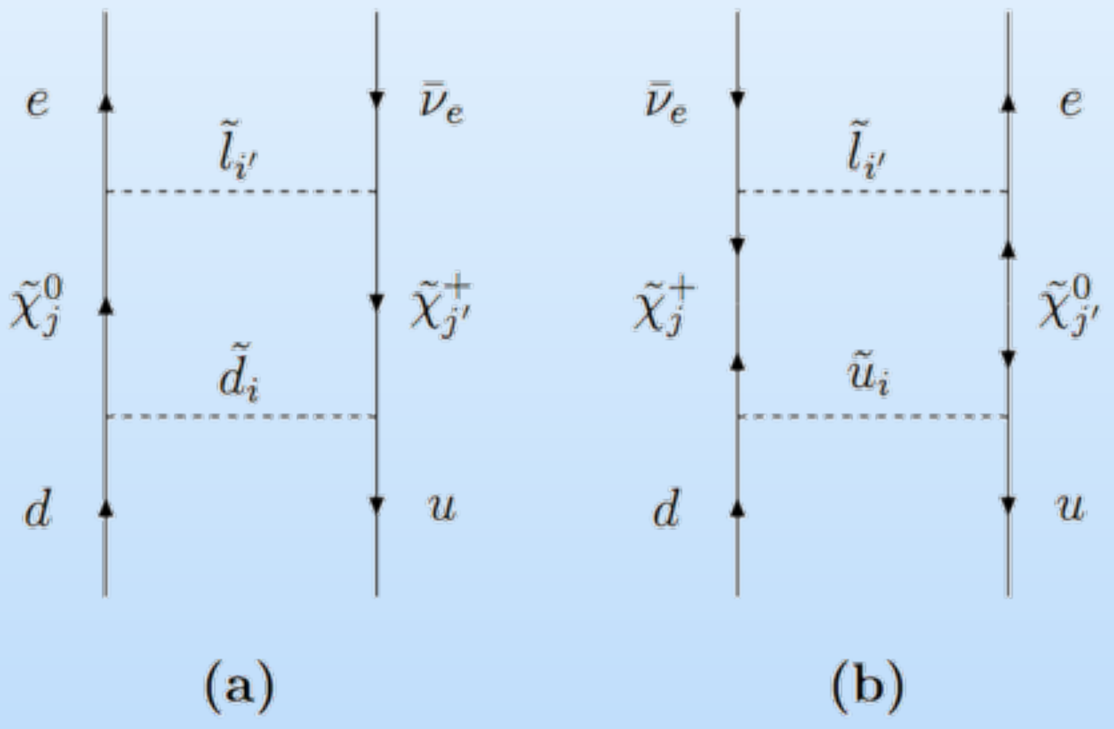
A_0 = ± 0.0006_{stat}

b_n = ± 0.003_{stat}

> 10 TeV scale!

Testing Supersymmetry with b

One loop corrections to SM from MSSM and NMSSM
10^{-3} possible (but not likely…)

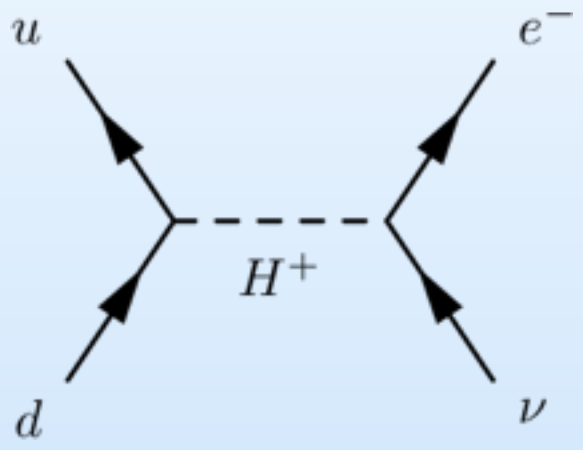


- NMSSM adds the singilino
- Same loop diagrams
- likely little change to neutrilino mass scale
- Improbable landscape parameters
- LHC may have already ruled out?

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

$$\mathcal{L}^{\rm S}_{\rm LQ} = \lambda^{(R)}_{S_0}\cdot\overline{u^c}P_R e\cdot S_0^{R\dagger} + \lambda^{(R)}_{\tilde S_0}\cdot\overline{d^c}P_R e\cdot\tilde S_0^\dagger$$

$$+\lambda^{(R)}_{S_{1/2}}\cdot\bar u P_L l\cdot S^{R\dagger}_{1/2} + \lambda^{(R)}_{\tilde S_{1/2}}\cdot\bar d P_L l\cdot\tilde S^\dagger_{1/2}$$

$$+\lambda^{(L)}_{S_0}\cdot\overline{q^c}P_L i\tau_2 l\cdot S_0^{L\dagger}+\lambda^{(L)}_{S_{1/2}}\cdot\bar q P_R i\tau_2 e\cdot S^{L\dagger}_{1/2}$$

$$+\lambda^{(L)}_{S_1}\cdot\overline{q^c}P_L i\tau_2\vec\tau\cdot\vec S_1^\dagger l + \text{h.c.}$$

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

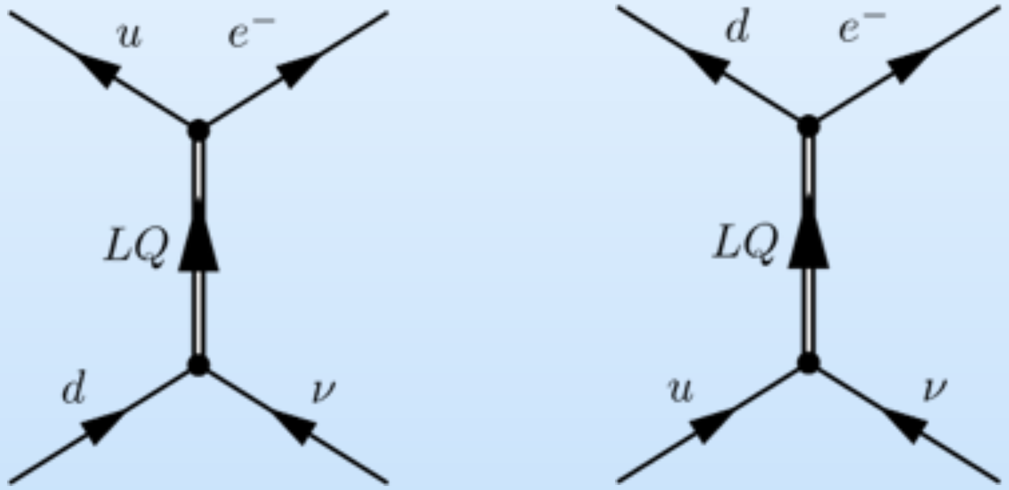
$$\mathcal{L}^{\rm V}_{\rm LQ} = \lambda^{(R)}_{V_0}\cdot\bar d\gamma^\mu P_R e\cdot V^{R\dagger}_{0\mu} + \lambda^{(R)}_{\tilde V_0}\cdot\bar u\gamma^\mu P_R e\cdot\tilde V^\dagger_{0\mu}$$

$$+\lambda^{(R)}_{V_{1/2}}\cdot\overline{d^c}\gamma^\mu P_L l\cdot V^{R\dagger}_{1/2\mu} + \lambda^{(R)}_{\tilde V_{1/2}}\cdot\overline{u^c}\gamma^\mu P_L l\cdot\tilde V^\dagger_{1/2\mu}$$

$$+\lambda^{(L)}_{V_0}\cdot\bar q\gamma^\mu P_L l\cdot V^{L\dagger}_{0\mu} + \lambda^{(L)}_{V_{1/2}}\cdot\overline{q^c}\gamma^\mu P_R e\cdot V^{L\dagger}_{1/2\mu}$$

$$+\lambda^{(L)}_{V_1}\cdot\bar q\gamma^\mu P_L\hat V^\dagger_{1\mu} l + \text{h.c.}$$

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



M. Hirsch et al., Phys. Lett. D 77(5) (2008)

V. Cirigliano and E. Passemar

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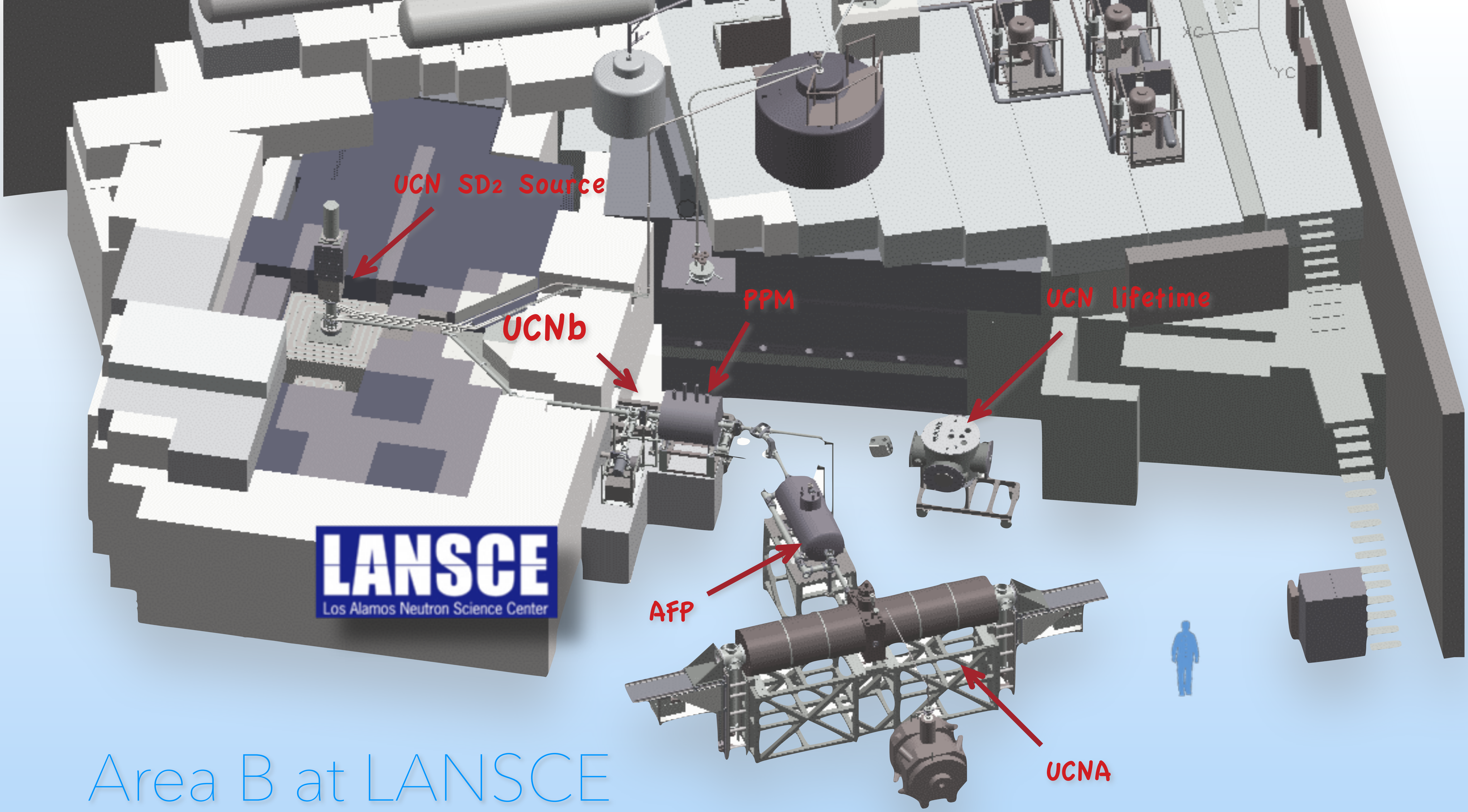
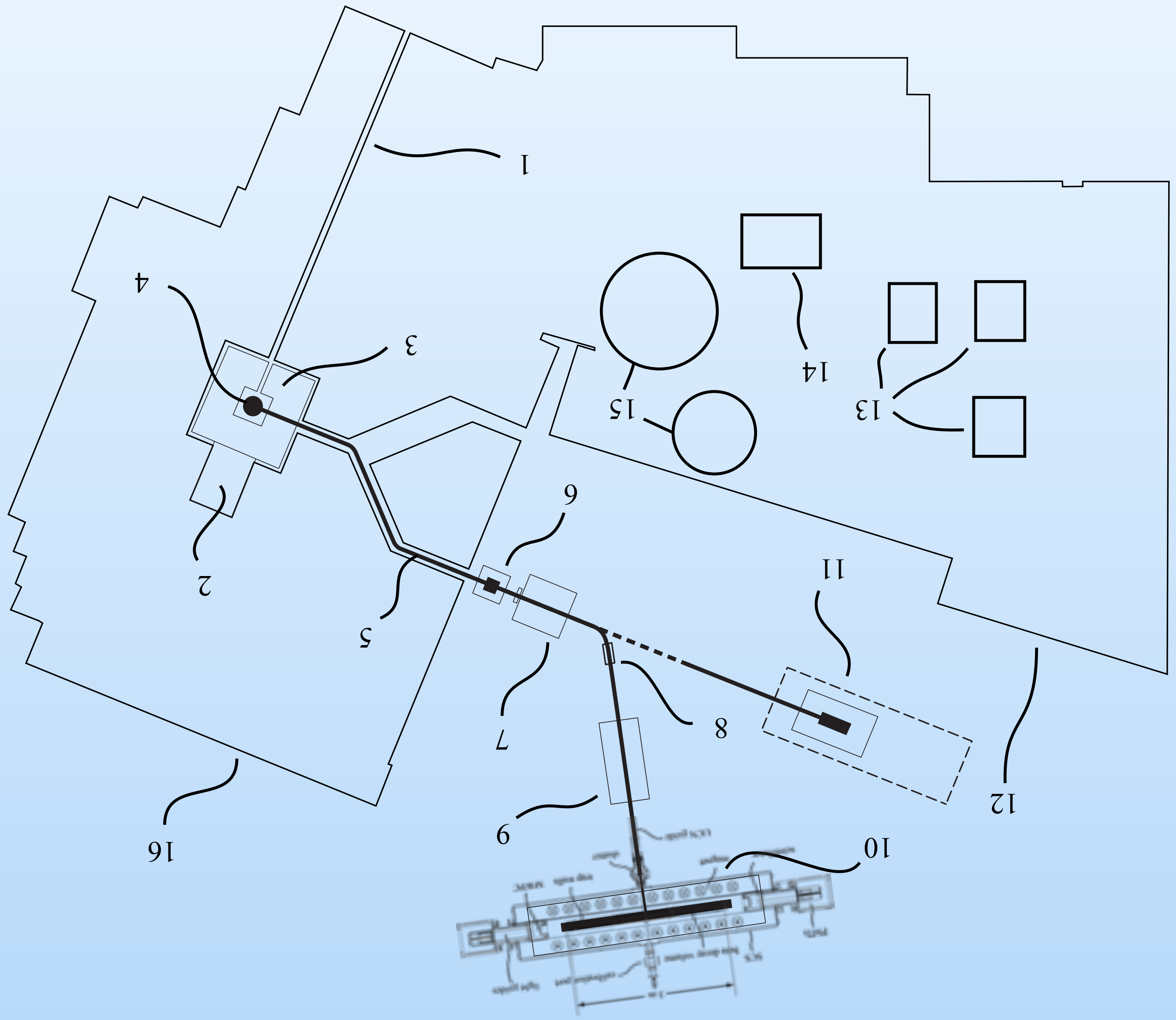


LANSCE
Los Alamos Neutron Science Center

Area B at LANSCE

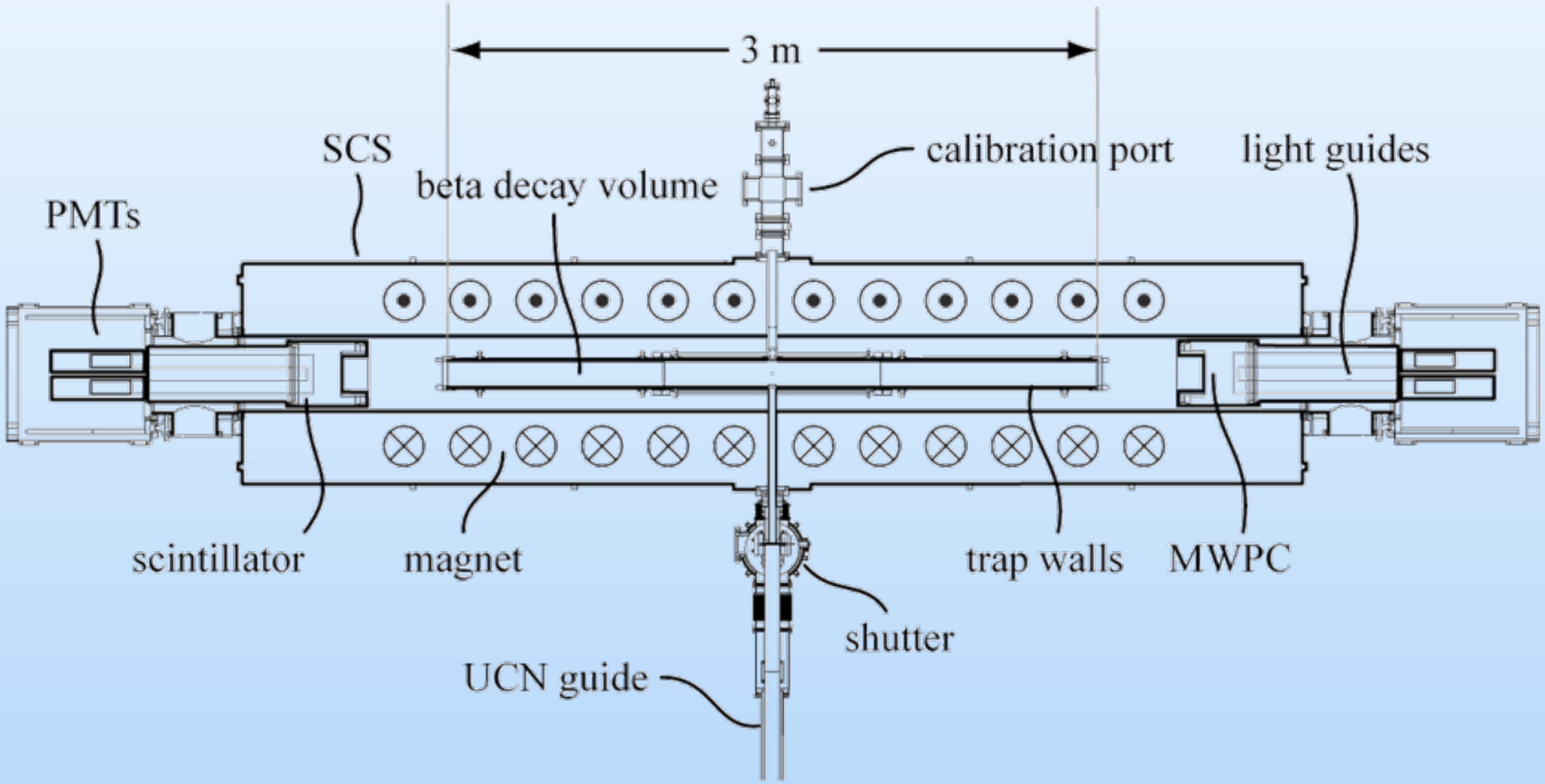
UCNA

Superconducting Spectrometer

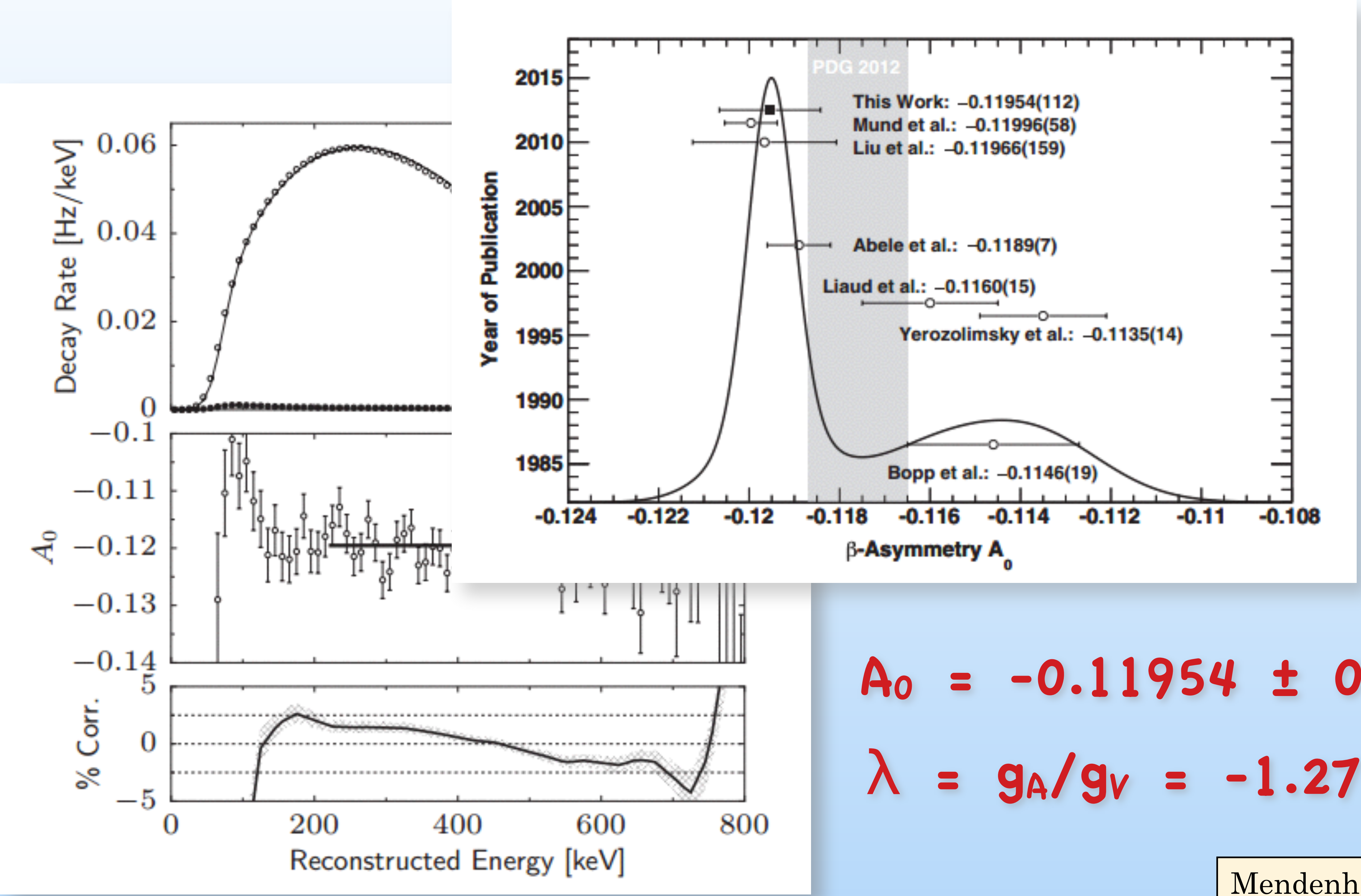


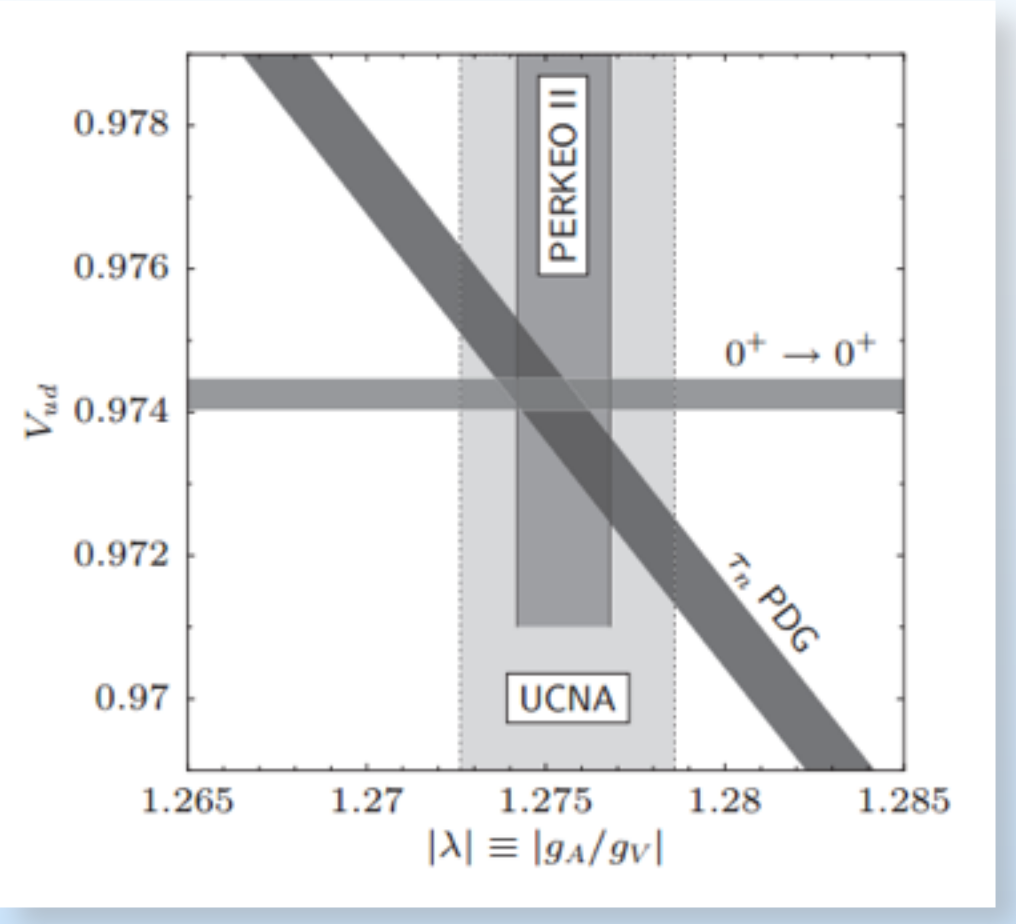
UCNA

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)

Combined fit of spectrum and asymmetry

Coming soon! Spectral and asymmetry data simultaneously

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

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

$$\rho = 0.201$$

$A = \pm\ 0.0003_{\mathrm{stat}}$

$b = \pm\ 0.002_{\mathrm{stat}}$

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Neutron lifetime

Lifetime from W mass, quark mixing, QCD axial-vector coupling,

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

and phase space terms where

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

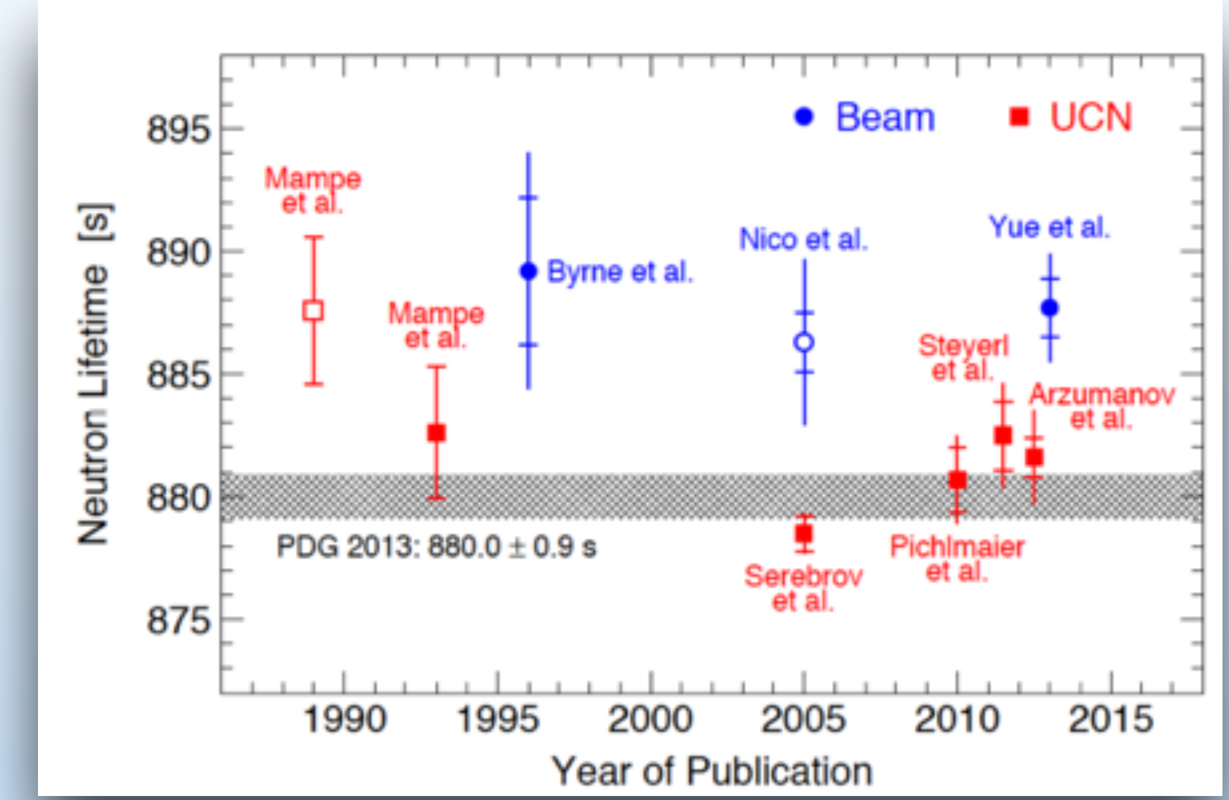
and Δ encapsulates electroweak, recoil and Fermi function corrections

Neutron lifetime

PDG 2001-2010 $\tau_n = (885.7 \pm 0.8)$ s $(S = 1)$
Serebrov *et al.* 2005 $\tau_n = (878.5 \pm 0.8)$ s
Pichlmaier *et al.* 2010 $\tau_n = (880.7 \pm 1.8)$ s
PDG 2012 $\tau_n = (880.1 \pm 1.1)$ s $(S = 1.8)$

The neutron lifetime is in a state of panic…

- Big Bang Nucleosynthesis (BBN)
- Consistency of CKM or tensor currents
- Reactor anomaly?
- What is the systematic? UCN bottles? partially trap orbits? Mirror neutrons!?



Phys. Rev. C 71, 055502 (2005)

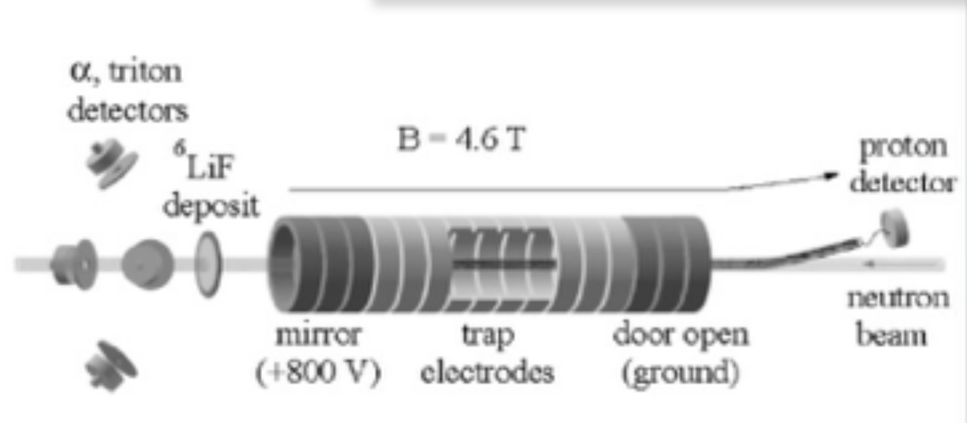
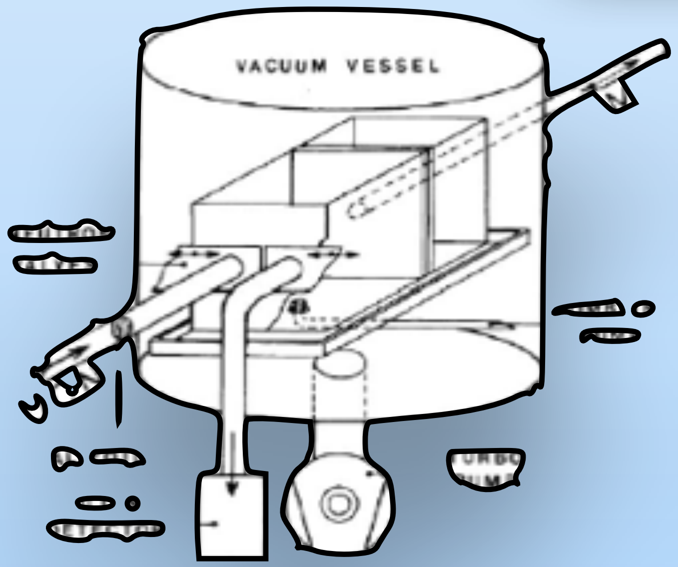


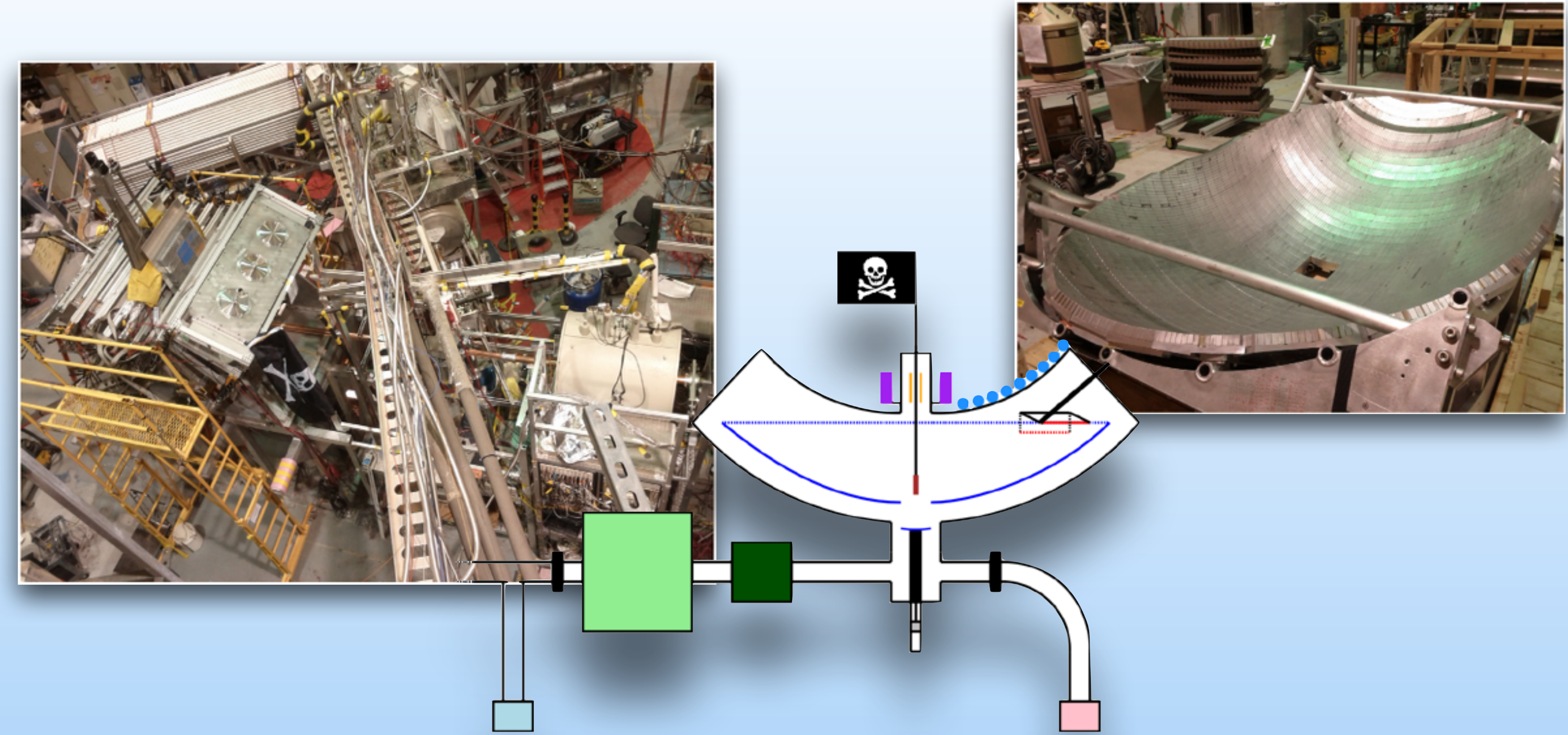
FIG. 2. Experimental method for measuring lifetime by counting neutrons and trapped protons.

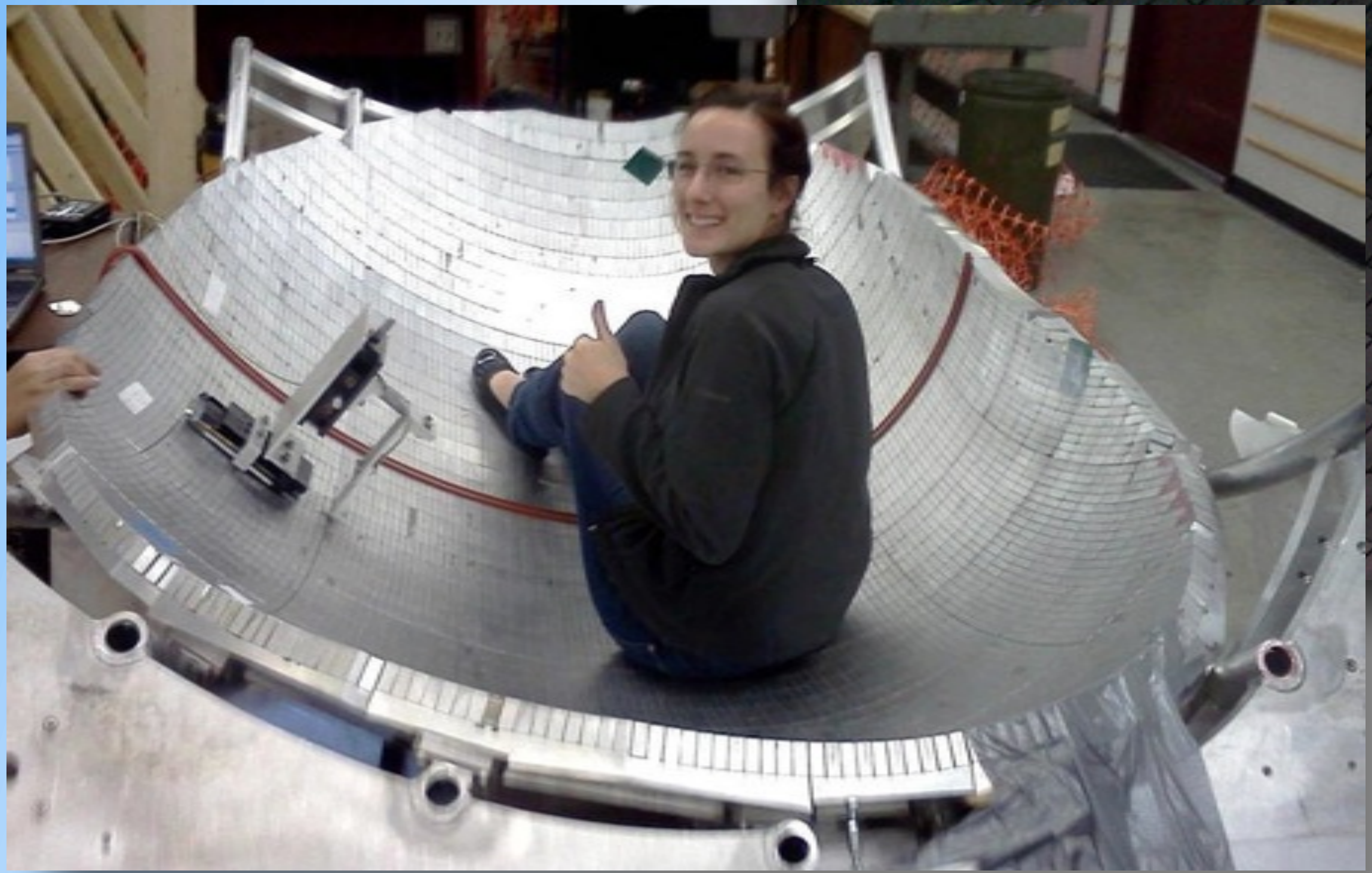


Serebrov et al., PL B 605, 72 (2005)

Pichlmaier et al., PL B 693, 221 (2010)

Neutron lifetime at LANL

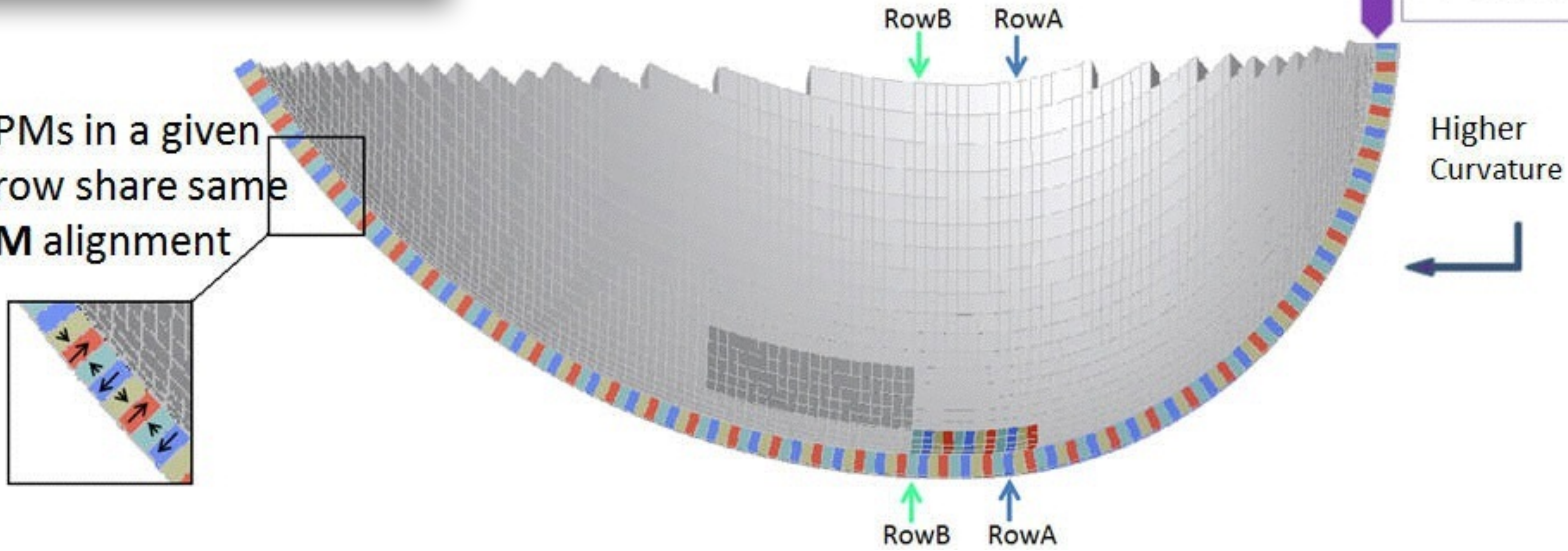




Adjacent Magnetization $^{\pi}/_{2}$ out of phase

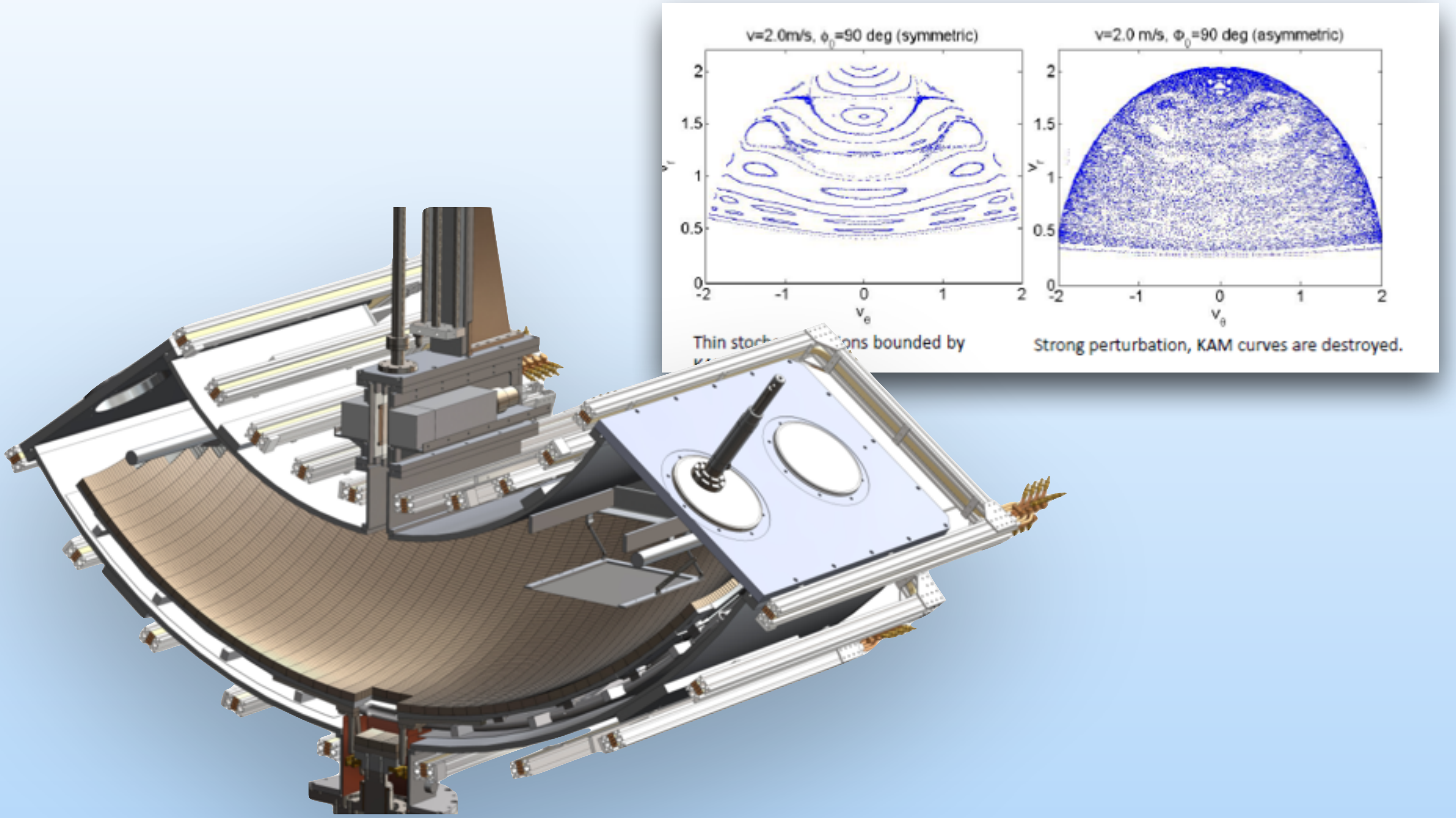
- Rows: 141
- PMs: 5310

PMs in a given row share same **M** alignment



Neutron lifetime using UCN

Loading

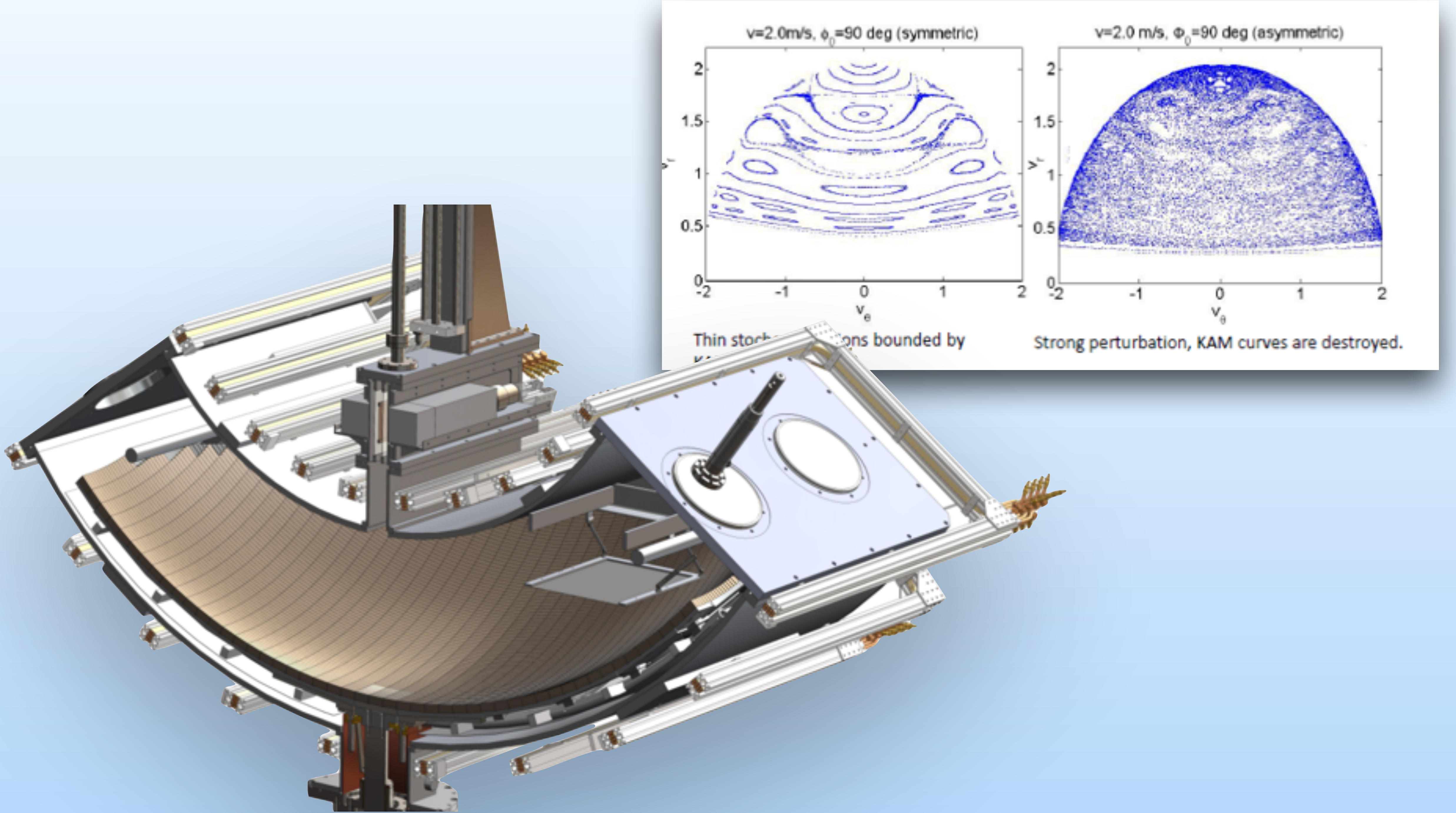


Thin stoc ons bounded by

Strong perturbation, KAM curves are destroyed.

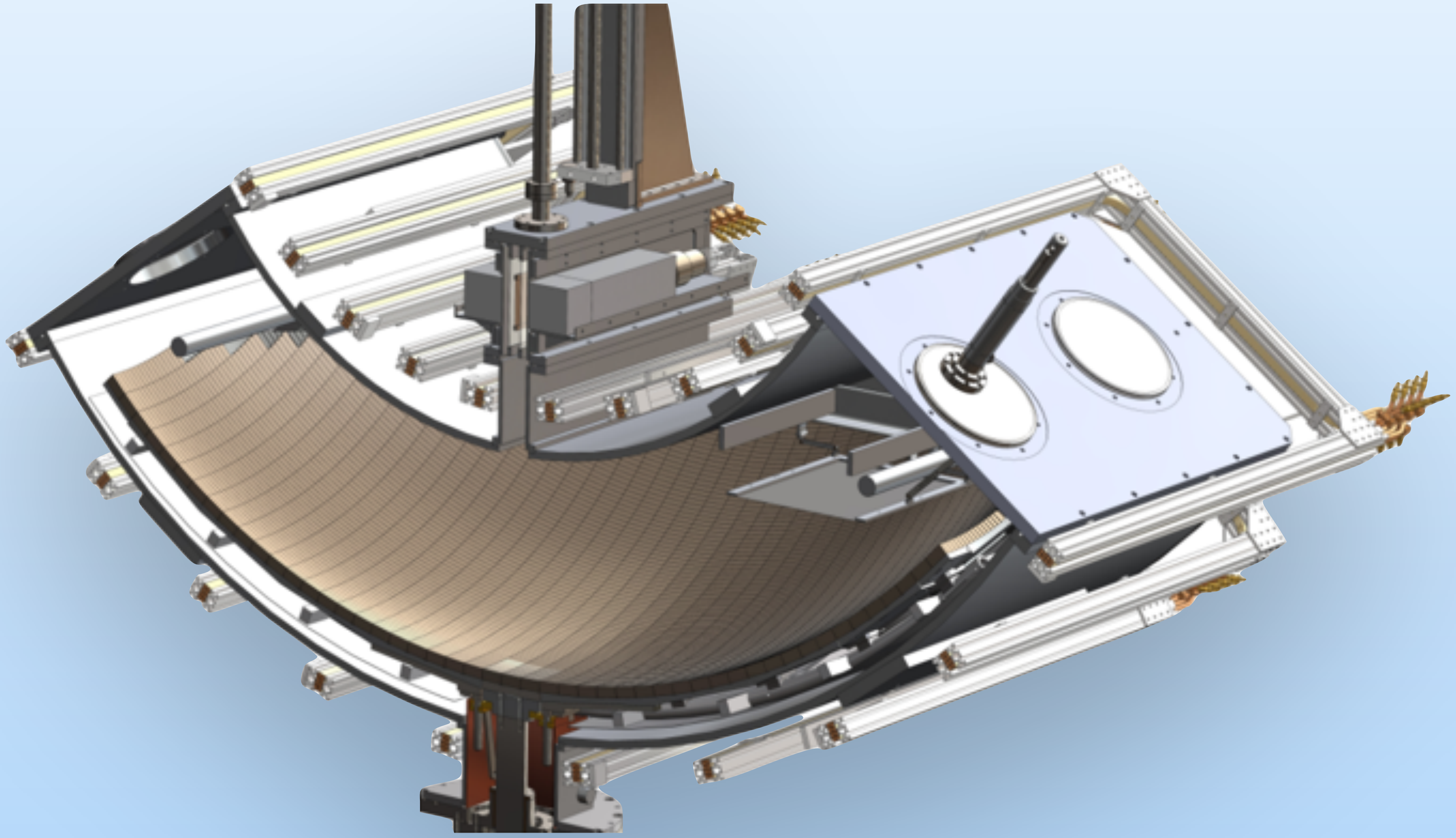
Neutron lifetime using UCN

Cleaning



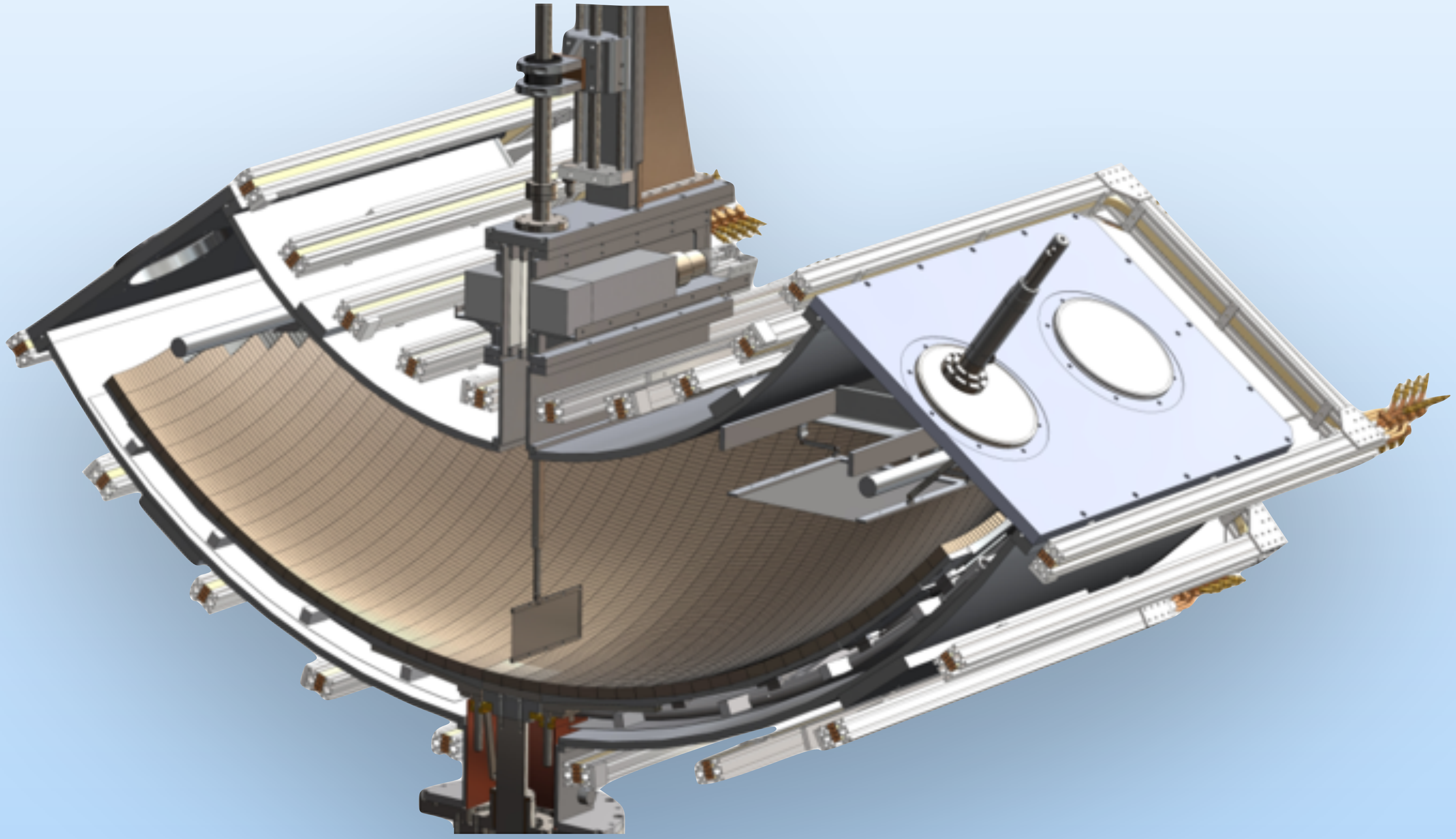
Neutron lifetime using UCN

Beta decay



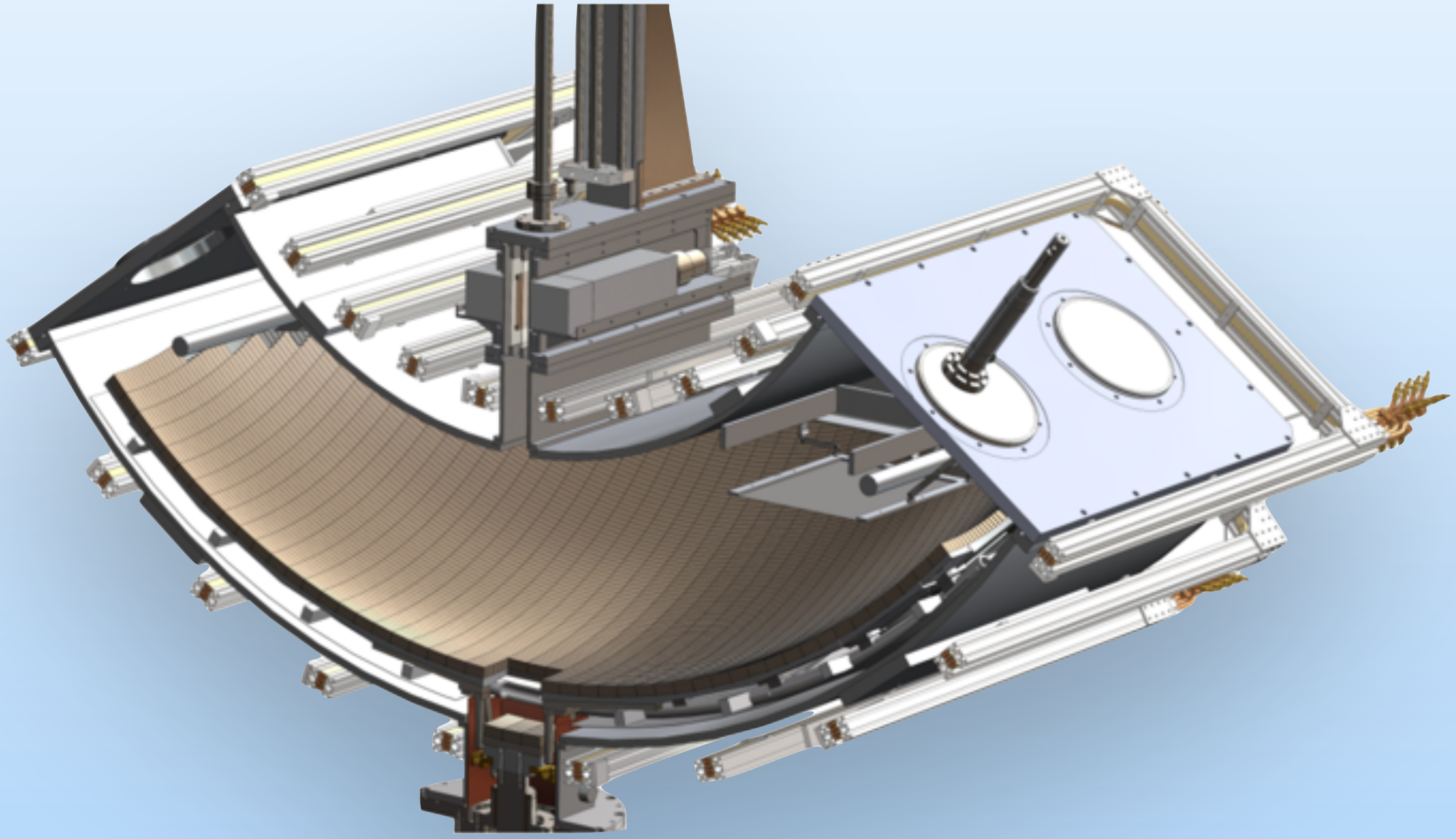
Neutron lifetime using UCN

Using a vanadium dagger to absorb neutrons



Neutron lifetime using UCN

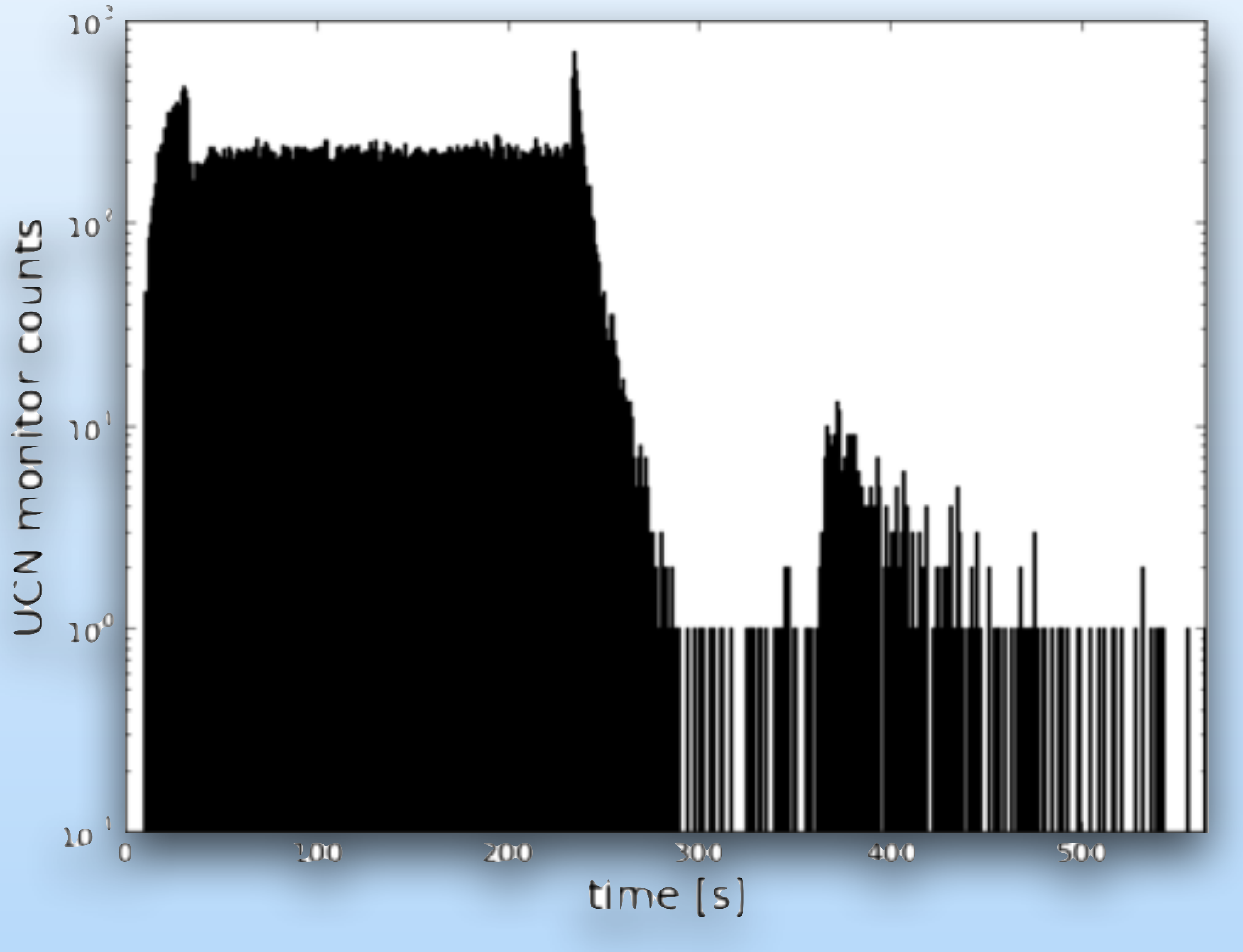
dumping

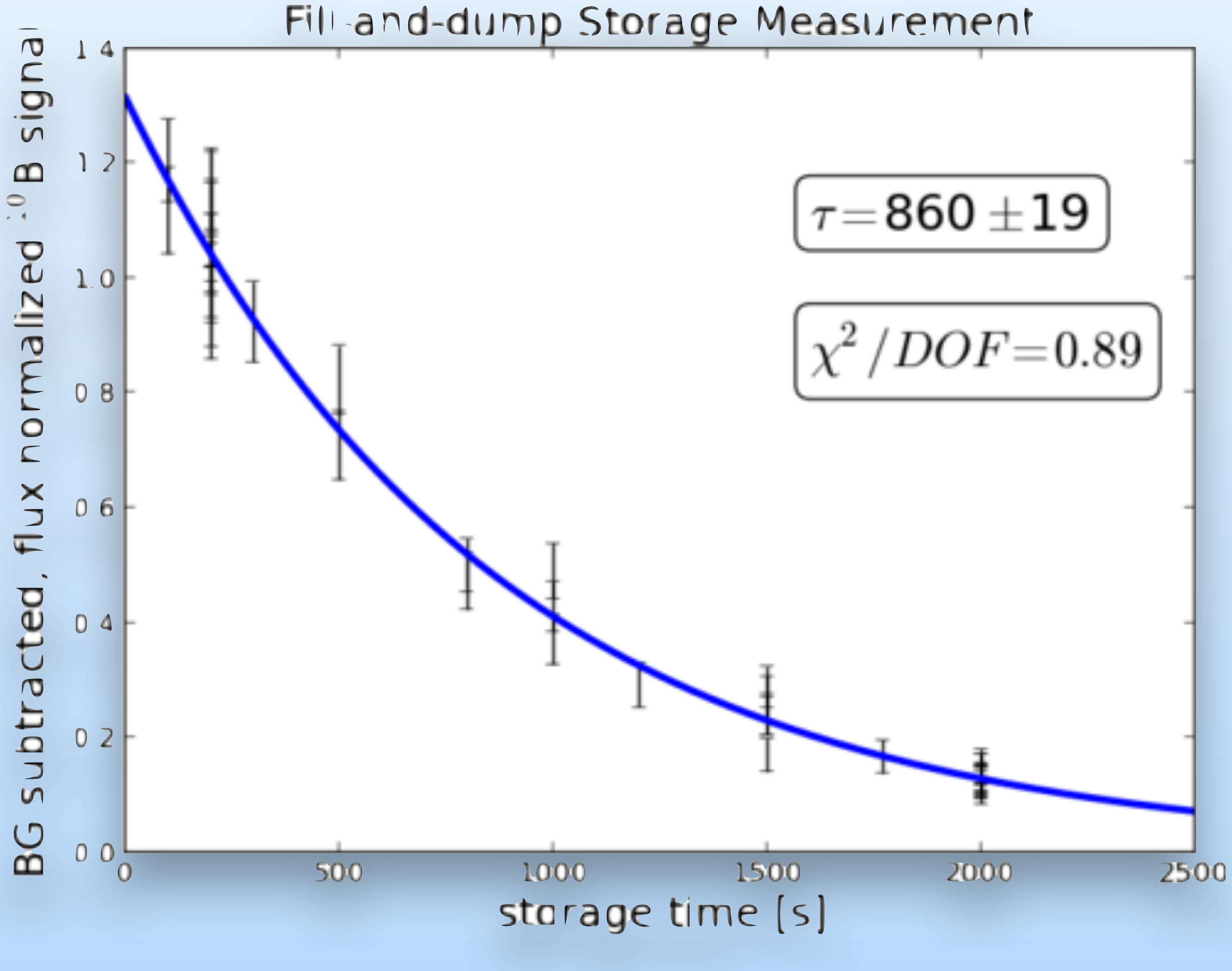


Commissioning results

Fill and dump results - this year we will run with high statistics

New results from 2014–2015 are in and coming very soon!





What's so cool about Ultracold Neutrons?

And why do we use them?

The Standard Model of a Neutron

The electroweak theory of the decay of neutrons in to protons

Fundamental Symmetries with Neutrons

A fun place to look for physics beyond the Standard Model

Ultracold Neutron Experimental Landscape

Leading experiments at LANSCE and ILL

Ultracold Neutron Experimental Horizon

Up and coming experiment at LANSCE and SNS

Neutrons and the strong CP problem

There is a term “missing” from the QCD in the Standard Model

$$\mathcal{L}_\theta = \frac{\theta g^2}{8\pi^2}\ \mathrm{tr} F \wedge F = \frac{\theta g^2}{16\pi^2} \mathrm{tr}\ \varepsilon_{\mu\nu\alpha\beta} F_{\mu\nu} F^{\alpha\beta}$$

Best limits now are from UCN nEDM using $d_n = (2.4 \times 10^{-16})\ \bar{\theta}\ e\ \mathrm{cm}$

Pospelov (1999)

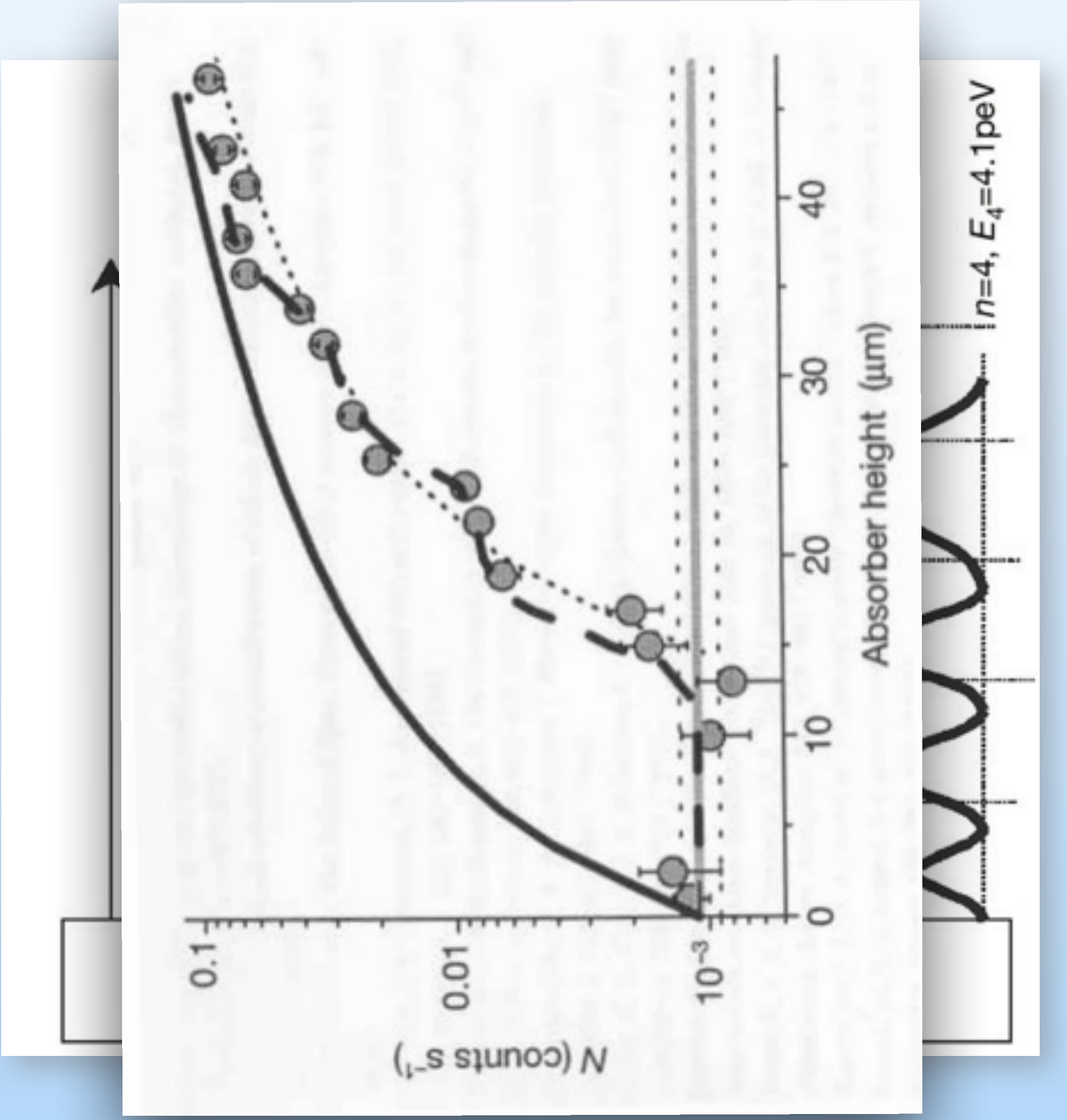
$$|d_n| < 2.9 \times 10^{-26}\ e\ \mathrm{cm} \quad (90\%\ \mathrm{C.L.})$$

$$|\bar{\theta}| < 1.2 \times 10^{-10} \quad (90\%\ \mathrm{C.L.}).$$

Baker (2006) and K. Lamoreaux (2006)

Probing for 5th force or extra dimensions

UCN have been used to measure gravity at the micron scale.

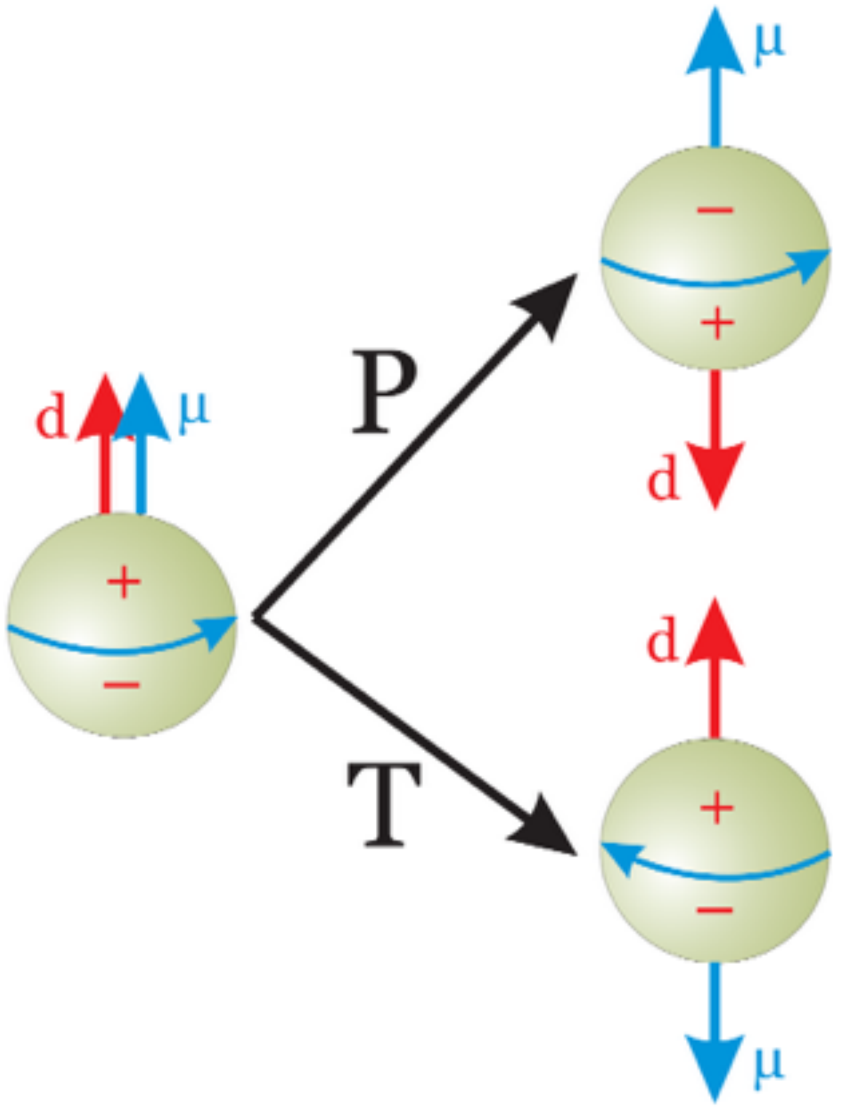


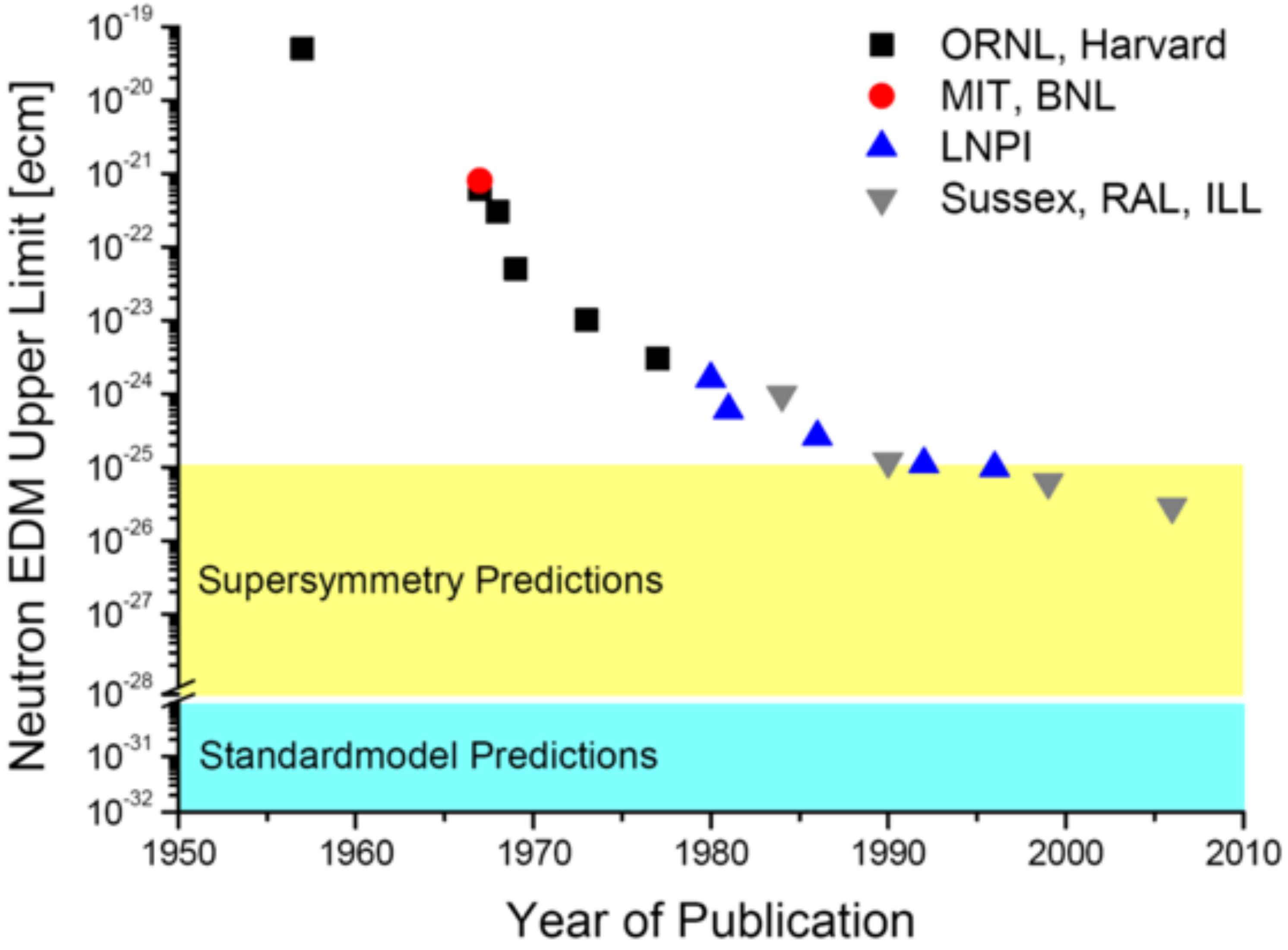
- UCN have been used to measure quantized levels due to a gravity well and a mirror.
- We can see a neutron no longer “bouncing” in its ground state.
- This also gives us sensitivity to short range Yukawa forces and extra dimensions.
- When polarized, other symmetries too.

Nature 415, 297-299 (17 January 2002) | doi:10.1038/415297a

Neutron electric dipole moment (nEDM)

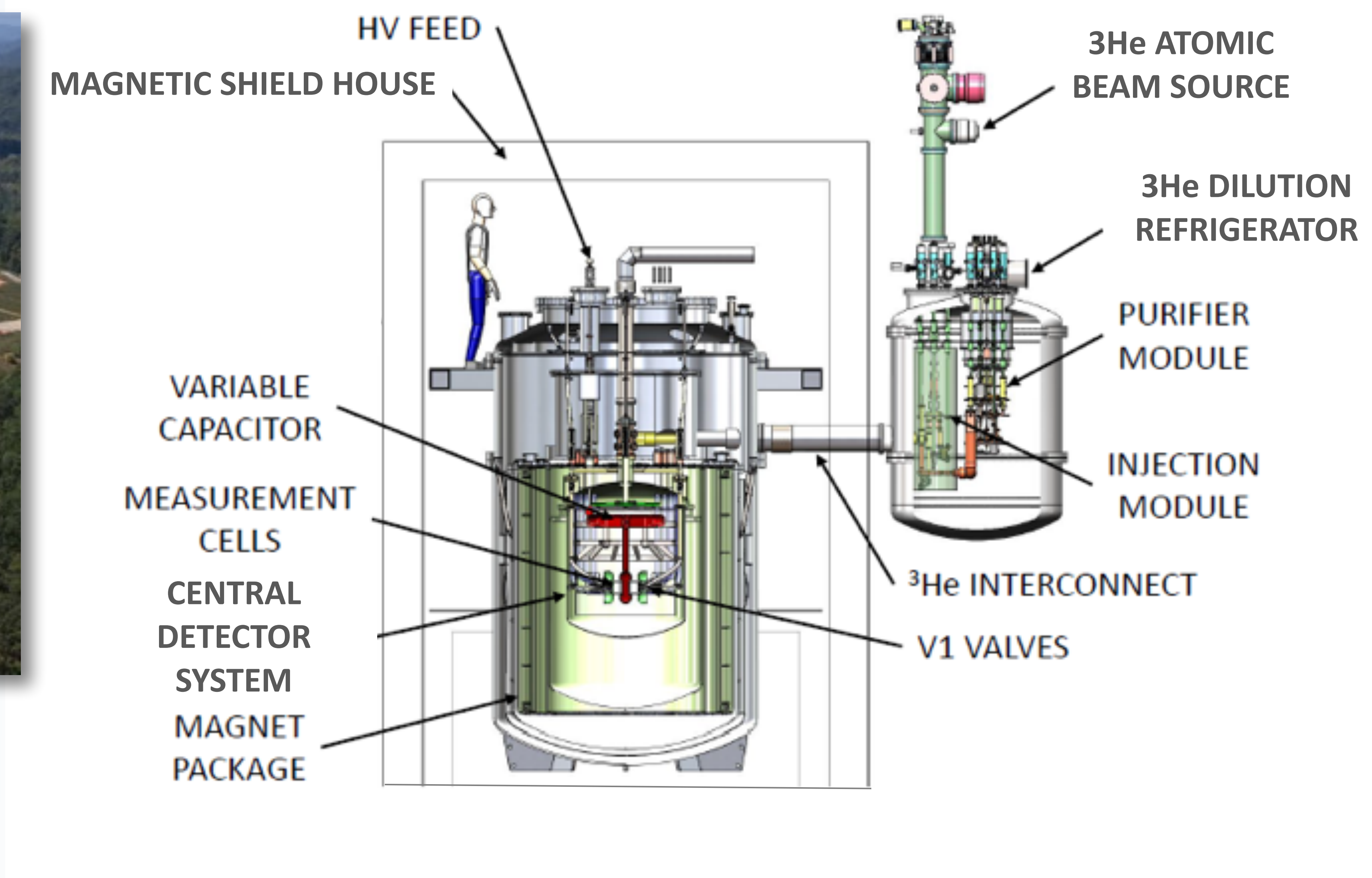
In the Standard Model, nEDM is VERY small! But SUSY is reachable!





Neutron electric dipole moment (nEDM)

A new experiment at Spallation Neutron Source (SNS) in Oak Ridge National Laboratory in Tennessee is aiming for a factor of 100x improvement.



Summary

The next big discovery may come from ultracold neutrons
So "watch out LHC!"

Ultracold neutrons have competitive strength for probing TeV scale fundamental symmetries.

Ultracold neutrons are useful for finding something "when you don't know what you are looking for"