Measuring the neutron lifetime using a magneto-gravitational trap for ultracold neutrons

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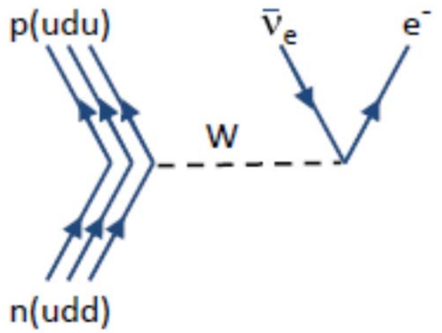
Outline

- Why study weak interactions via the neutron beta decay lifetime?
  - Because of the scientific reach
  - Because of the impact across nuclear and particle physics
- How to measure the neutron lifetime
- The UCNτ experiment
  - The design of the experiment
  - Recent results
  - Planned improvements

Neutron Decay Parameters



- Semi-leptonic decay
  - Lifetime 880 s
  - Endpoint energy 782 keV

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

- Just two free parameters in SM
  - CKM mixing matrix element
  - Ratio of weak coupling constants
  - Uncertainty comes from radiative corrections

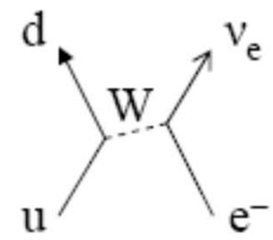
$$\tau_n = \frac{4908.7 \pm 1.9\ s}{|V_{ud}|^2 \left(1 + 3\lambda^2\right)}$$

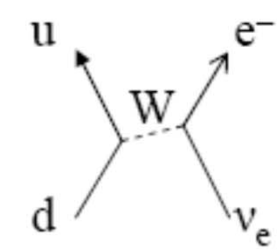
$$\lambda = g_A / g_V$$

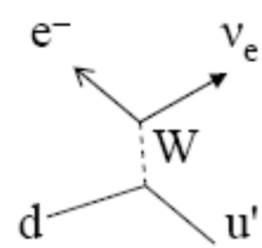
Neutron beta decay can inform many areas of physics

- Many reactions share the same Feynman diagram as neutron beta decay

Primordial element formation	$n + e+ \to p + \nu'_e$	$\sigma_\nu \sim 1/\tau$
(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \to n + \nu_e$	$\sigma_\nu \sim 1/\tau$
	$n \to p + e^- + \nu'_e$	τ
Solar cycle	$p + p \to {}^2H + e^+ + \nu_e$	
	$p + p + e^- \to {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$
Neutron star formation	$p + e^- \to n + \nu_e$	
Pion decay	$\pi^- \to \pi^0 + e^- + \nu'_e$	
Neutrino detectors	$\nu'_e + p \to e^+ + n$	
Neutrino forward scattering	$\nu_e + n \to e^- + p$ etc.	
W and Z production	$u' + d \to W^- \to e^- + \nu'_e$ etc.	







Dubbers 2011

Neutron Lifetime affects BBN

Light elements from ^{2}H up to ^{7}Li created in "first three minutes"

Weak reactions between particles:

$$n + e^+ \leftrightarrow p + \bar{\nu}_e, \qquad \sigma_\nu \sim 1/\tau_n$$

$$n + \nu_e \leftrightarrow p + e^-, \qquad \text{(all have same Feynman diagram)}$$

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

At time $\approx$ 1 s, at "freeze-out" temperature $T_f \approx 1$ MeV:

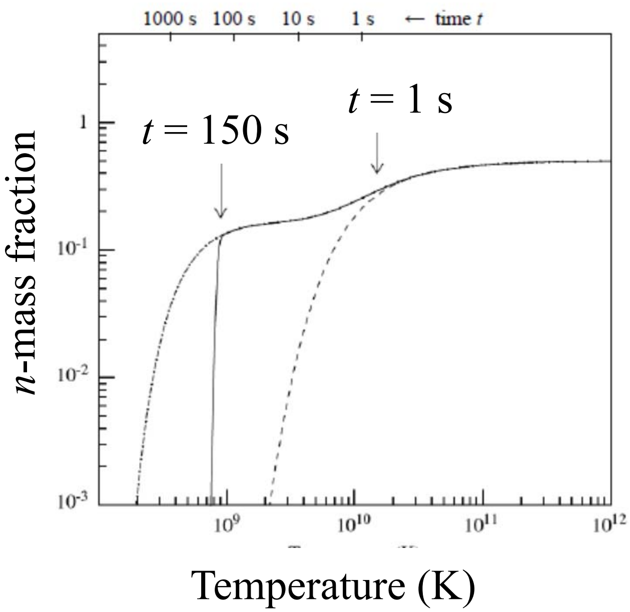
neutron to proton ratio frozen to:

$$n/p = \exp(-\Delta m/kT_f) \approx 1/6. \qquad \Delta m = m_n - m_p = 1.3 \text{ MeV}$$

After another ≈ 150 s, practically all neutron wind up in ^{4}He,

i.e., He mass fraction $Y_p = 2 \times$ neutron mass fraction $\approx 25\%$.

Primordial nucleosynthesis:



Dubbers 2013

And ratio of He/n depends directly on n lifetime: 1% lifetime uncertainty shifts calculated He fraction of Y=0.2480+/- .0003 by 0.0015, or 5 sigma!

Lifetime uncertainty has grown recently

And central value has shifted by almost 1%!

PDG 2001
Serebrov e
Pichlmaier
PDG 2012

005)
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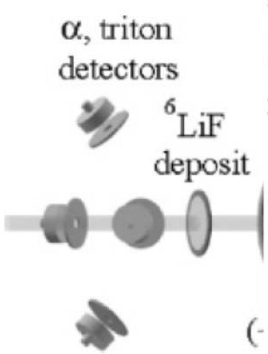
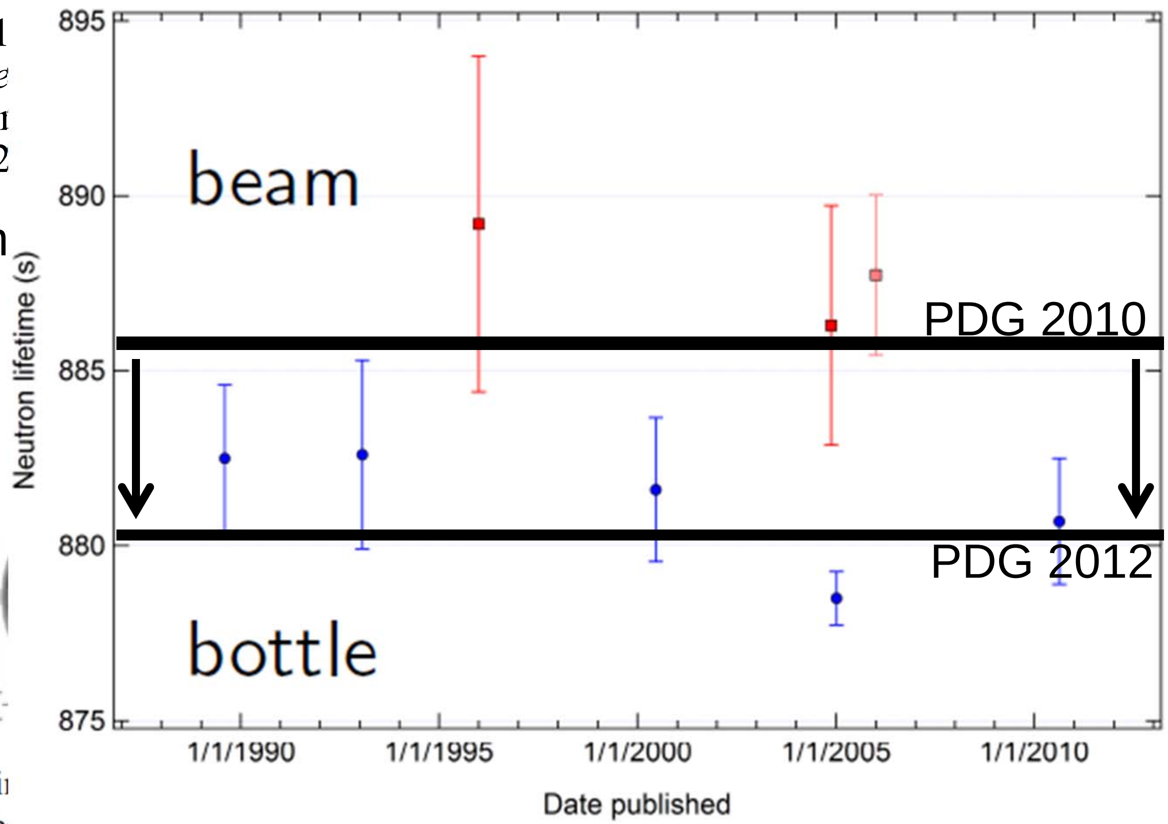
2010)

Beam

unt the survivors





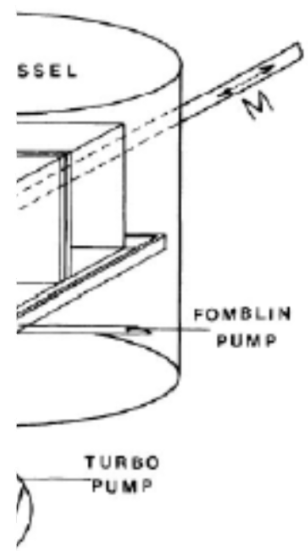


FIG. 2. Experi
neutrons and trapp

Danger: absolute monitor efficiency needed!

$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

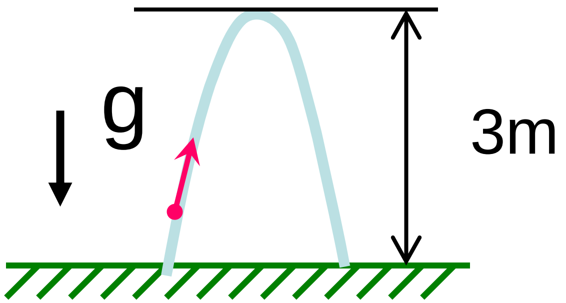
Wietfeldt and Greene,
Rev. Mod. Phys. **83**, 1173 (2011)

Interlude — What are ultracold neutrons?

- Very slow neutrons (v < 8m/s)
- Totally reflected by some materials

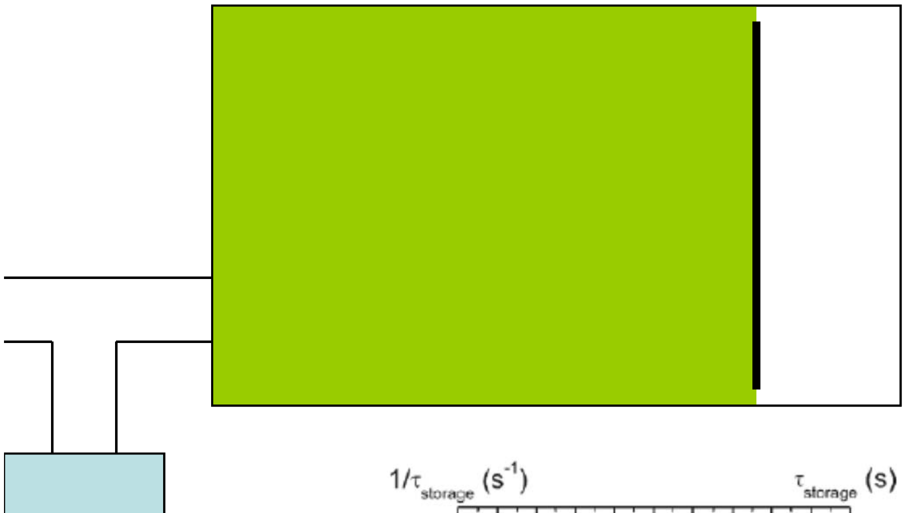
- Hence, they can be totally confined within a bottle for periods in excess of 100 seconds.

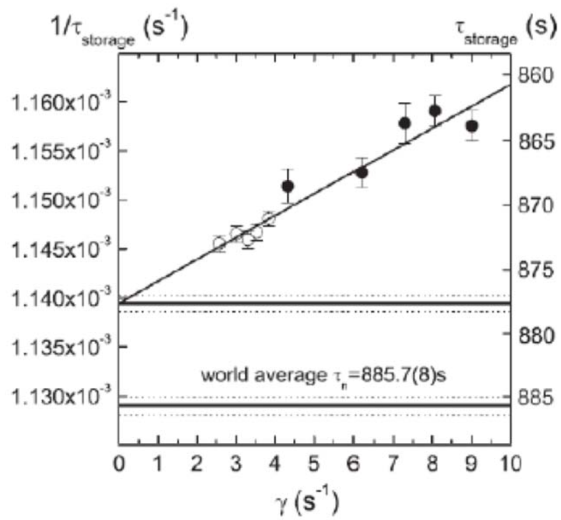
- Typically: velocity < 8m/s
  kinetic energy < 3×10^{-7} eV
  wavelength > 500Å
  or temperature < 4 mK

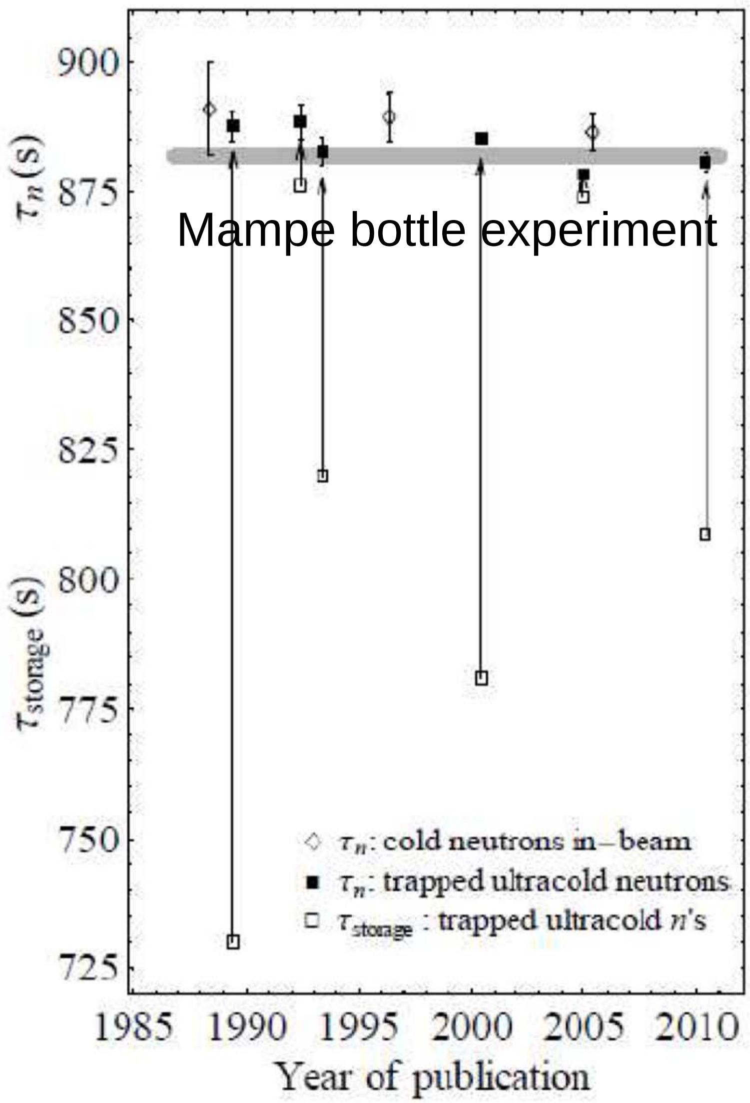


- *cf:* Gravity: 10^{-7} eV/ meter.
  Magnetic field (μB): 10^{-7} eV/ 1.7 T.

Material bottle experiments involved 100 s extrapolations due to wall losses



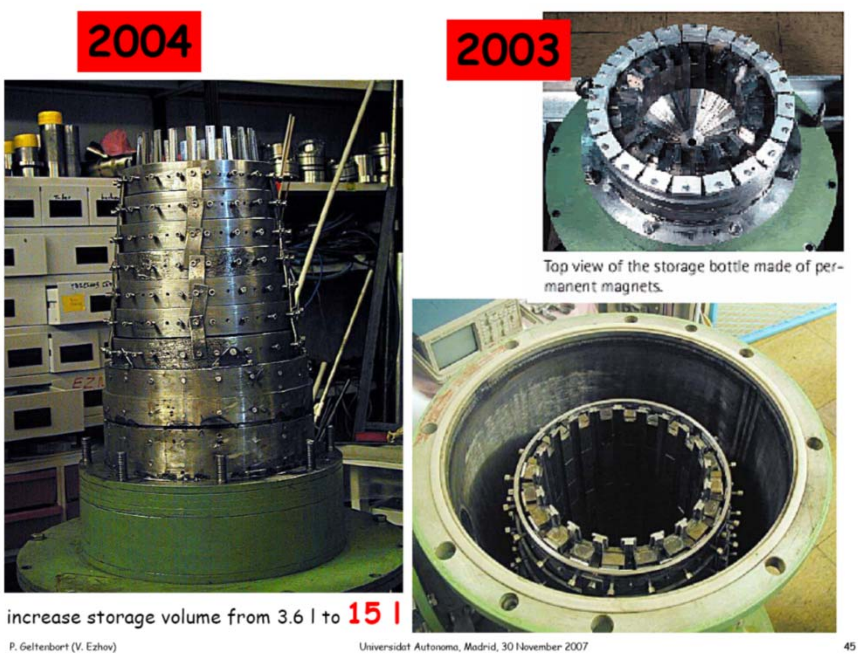




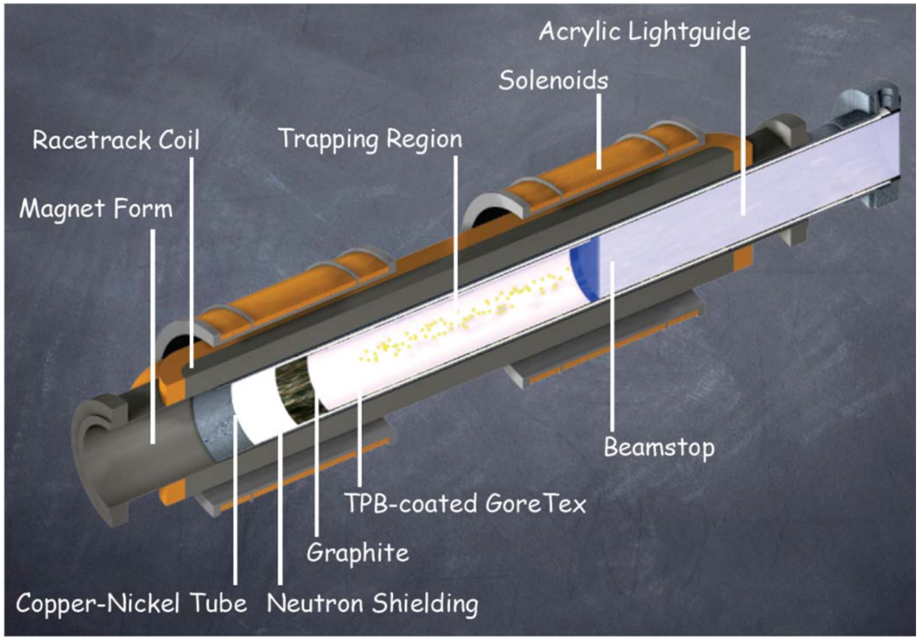
Solution: eliminate wall losses using magnetic bottle

- A new crop of experiments using magnetic traps is now under development
- Stern-Gerlach effect repels polarized neutrons from walls

ILL Ezhov Bottle filled with vacuum



NIST UCN trap filled with superfluid 4He

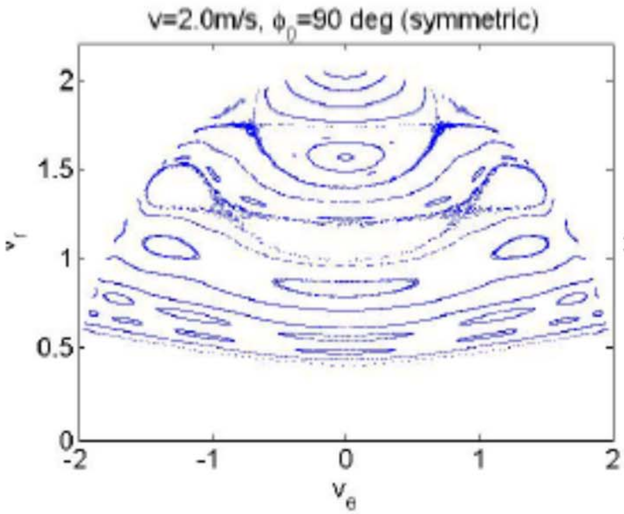


Both have acquired commissioning data;
HOPE at Munich also in design stage

An outstanding problem: phase space evolution

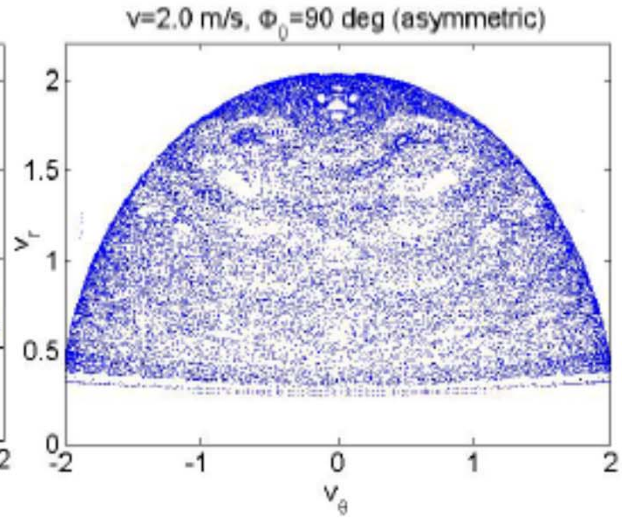
- Neutron losses on scale of neutron lifetime (quasibound orbits)
- Detector efficiency changes with time
- Must fill phase space evenly, quickly: chaos!

Symmetric Trap has stable orbits



Thin stochastic regions bounded by KAM curves.

Asymmetric Trap has chaotic orbits



Strong perturbation, KAM curves are destroyed.

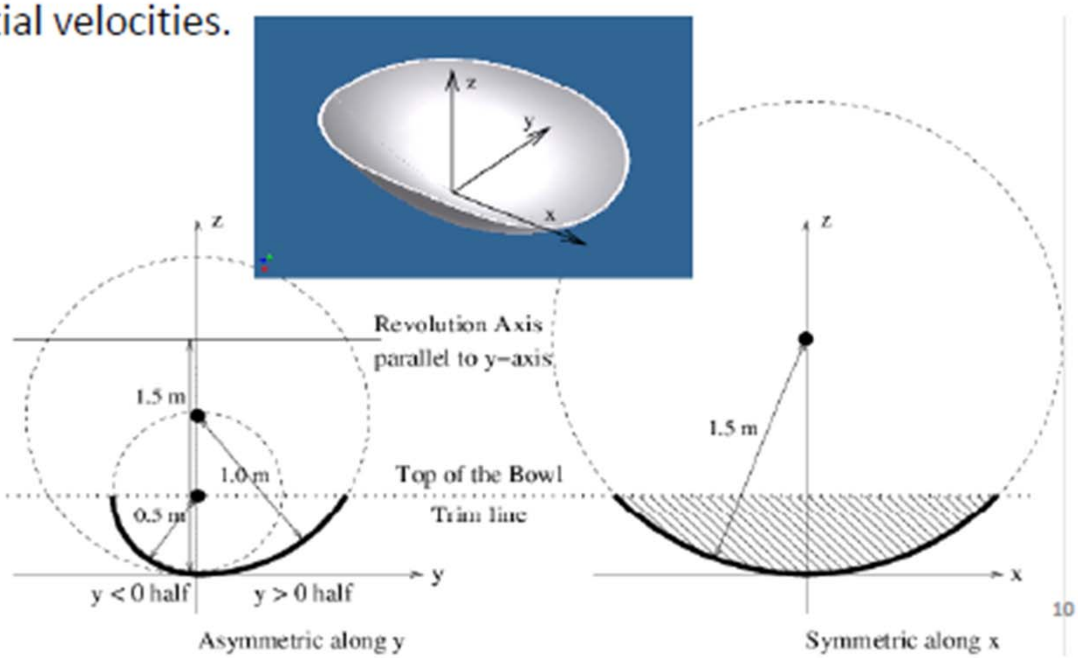
C.-Y. Liu, 2012

UCNτ experiment is designed to overcome phase space issues

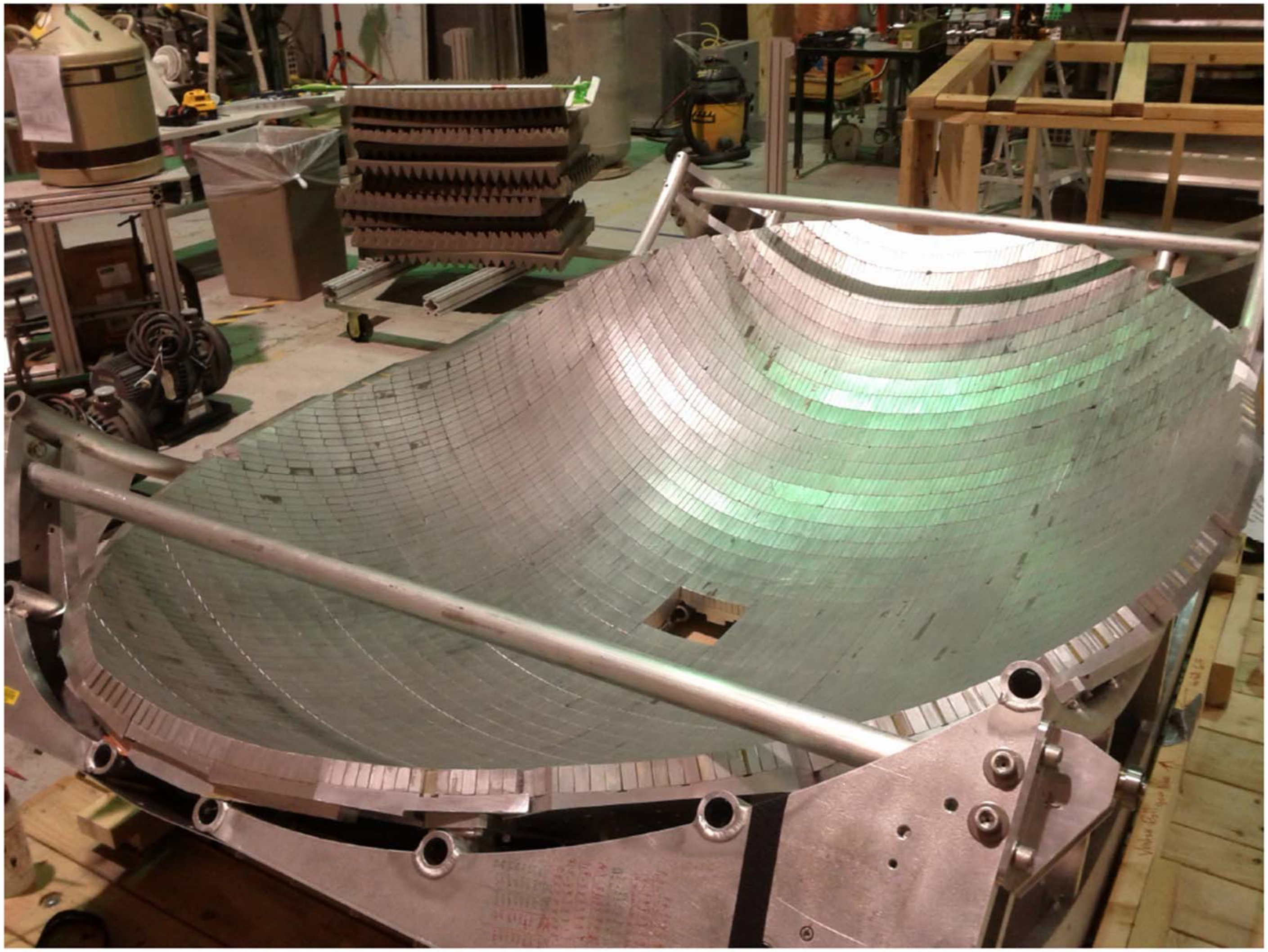
Asymmetric Trap → Phase Space Mixing

- **Low symmetry** (together with **field ripples**) induces states mixing between circular orbits, through chaotic motion (or not).

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

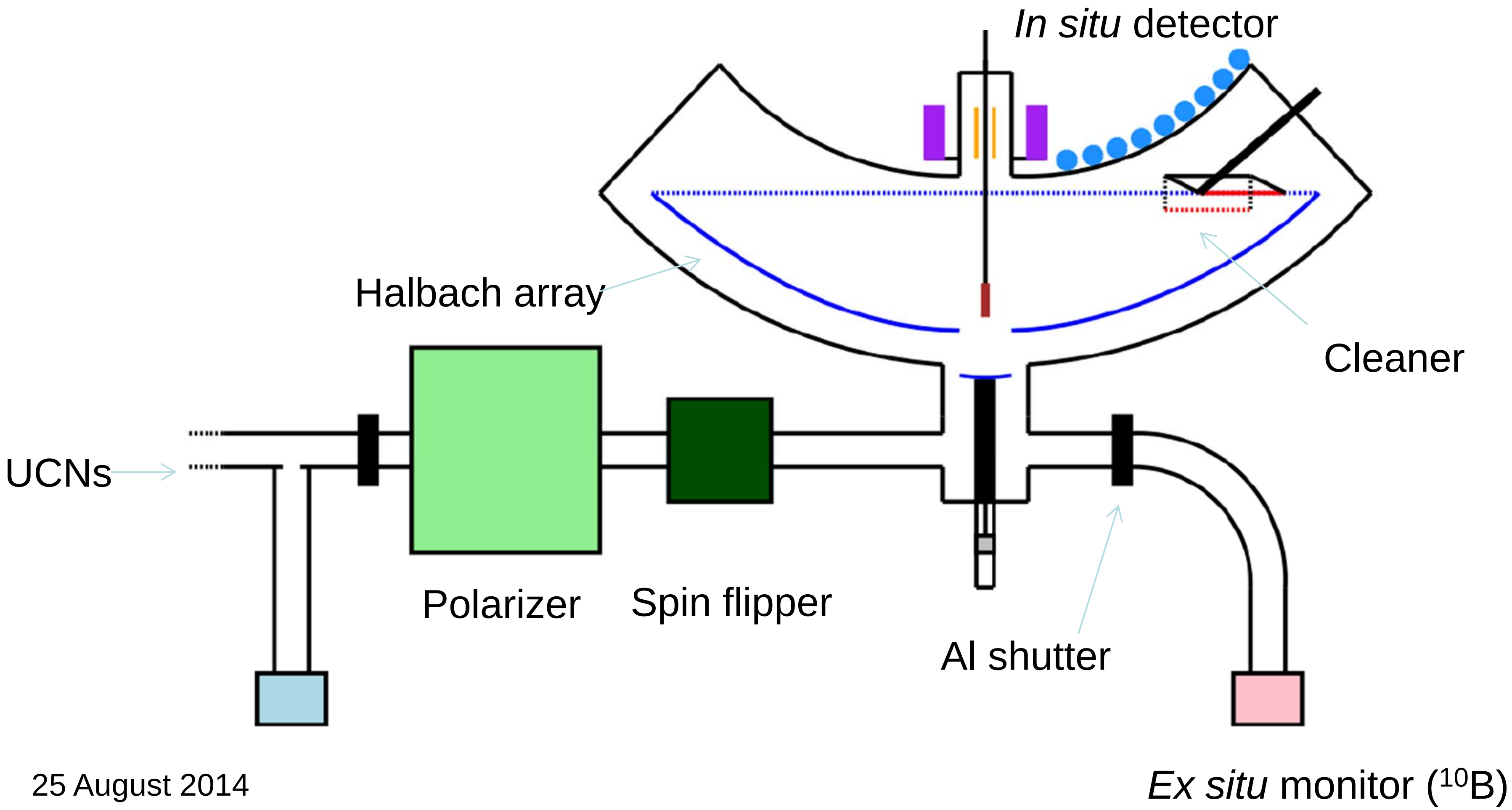


The UCNτ experiment trap is formed by an array of ~5000 permanent magnets forming a "bathtub"

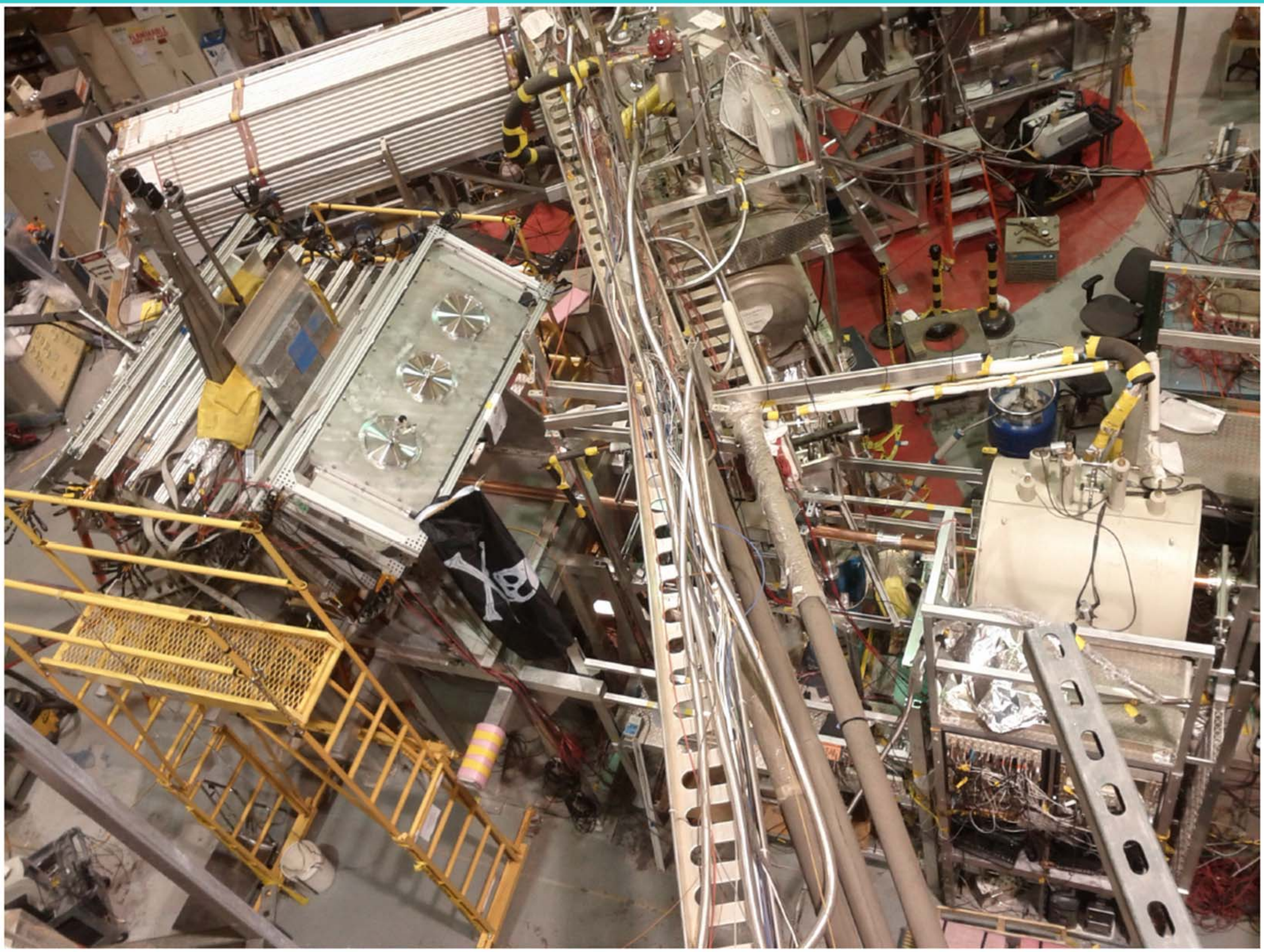


UCNτ Testbed: Magneto-gravitational storage vessel

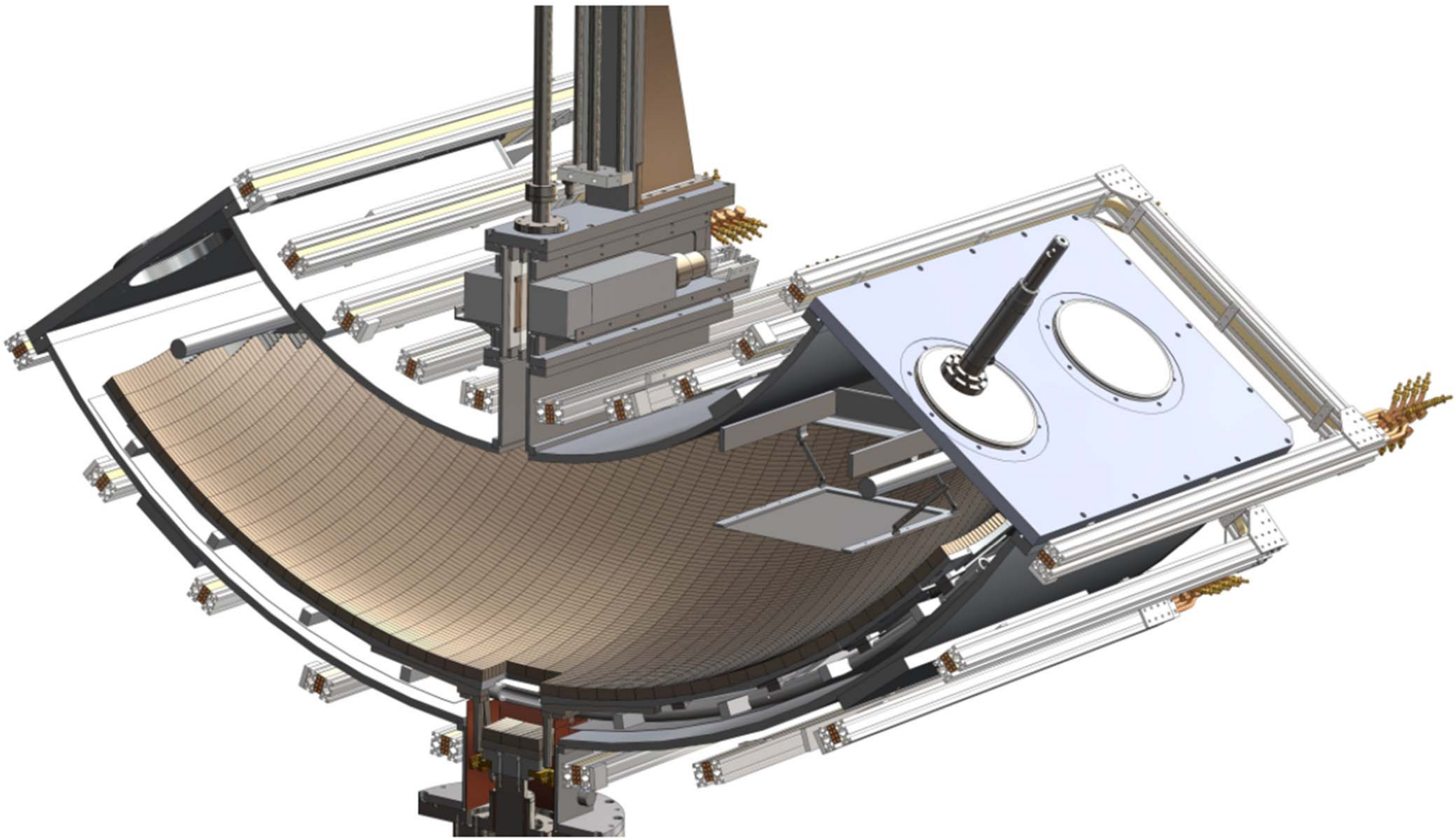
Halbach array of permanent magnets
No material interactions during storage period
In situ (V-foil activation) or *ex situ* (fill and dump) neutron detection possible



The UCNτ experiment is installed in the UCN facility at Los Alamos's LANSCE accelerator

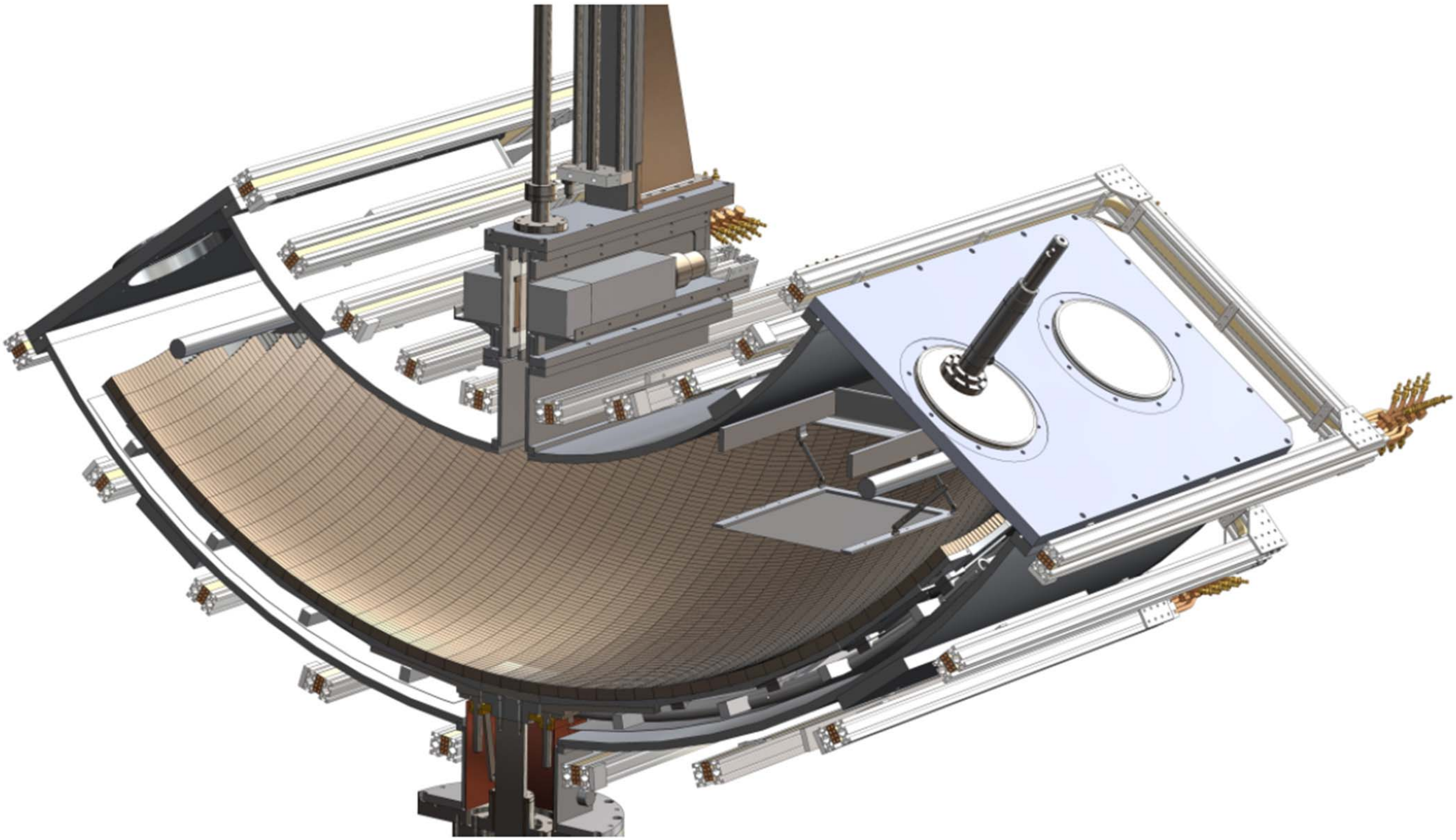


“Fill and dump cycle”: Fill and monitor (~200 s)

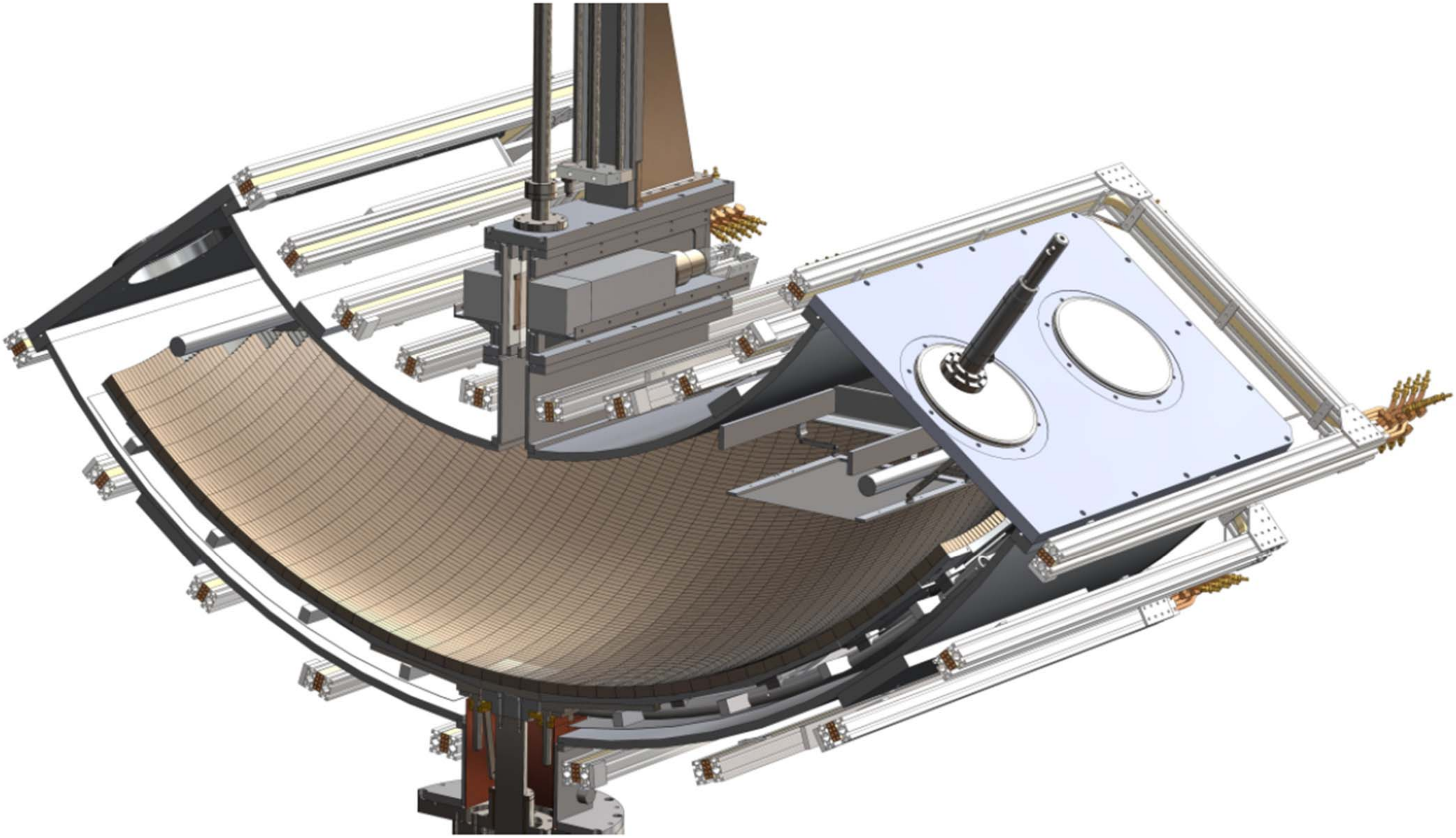


PANIC, Hamburg

“Fill and dump” cycle: clean (~30 s)

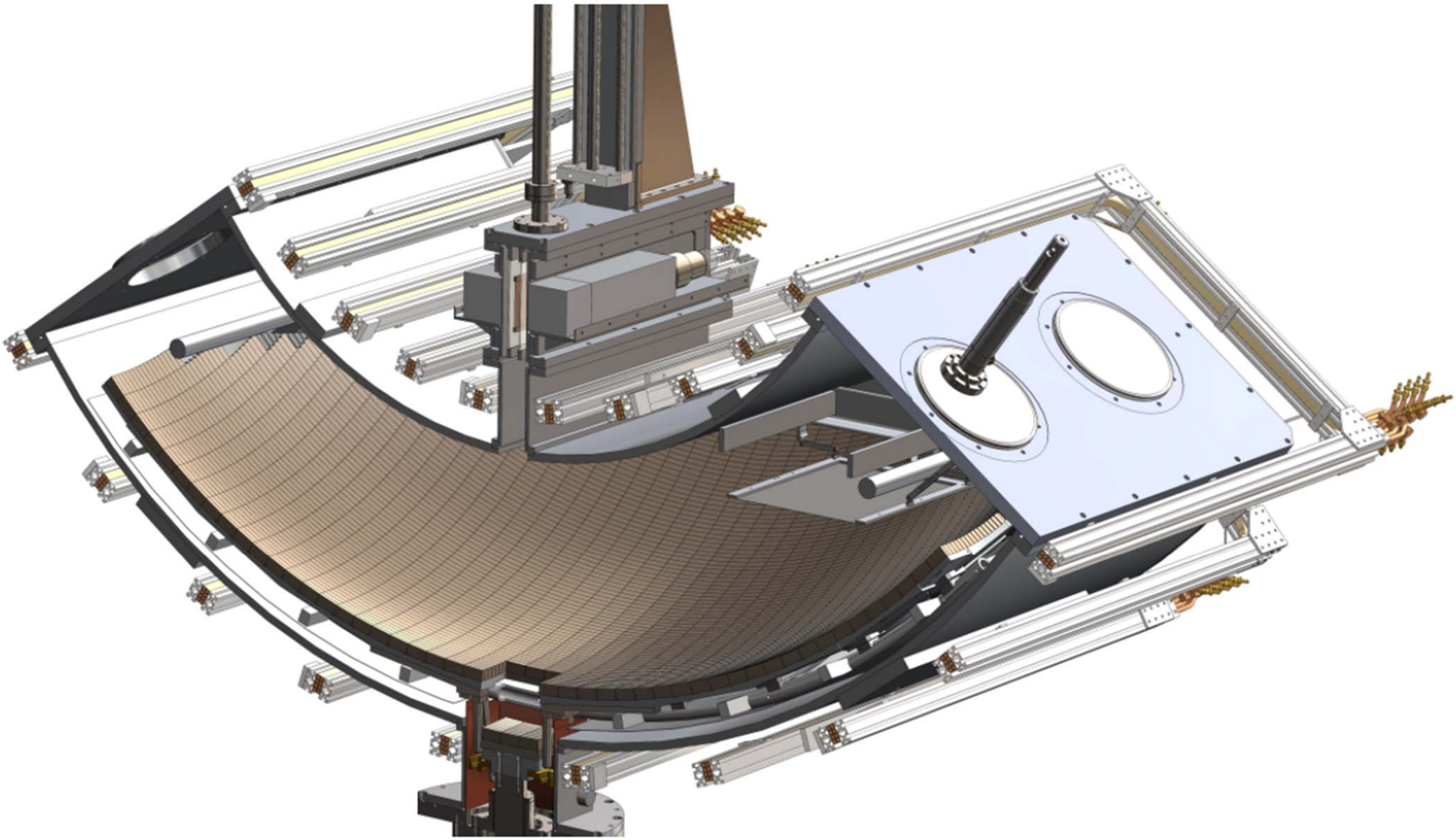


“Fill and dump” cycle: store (100-2000 s)



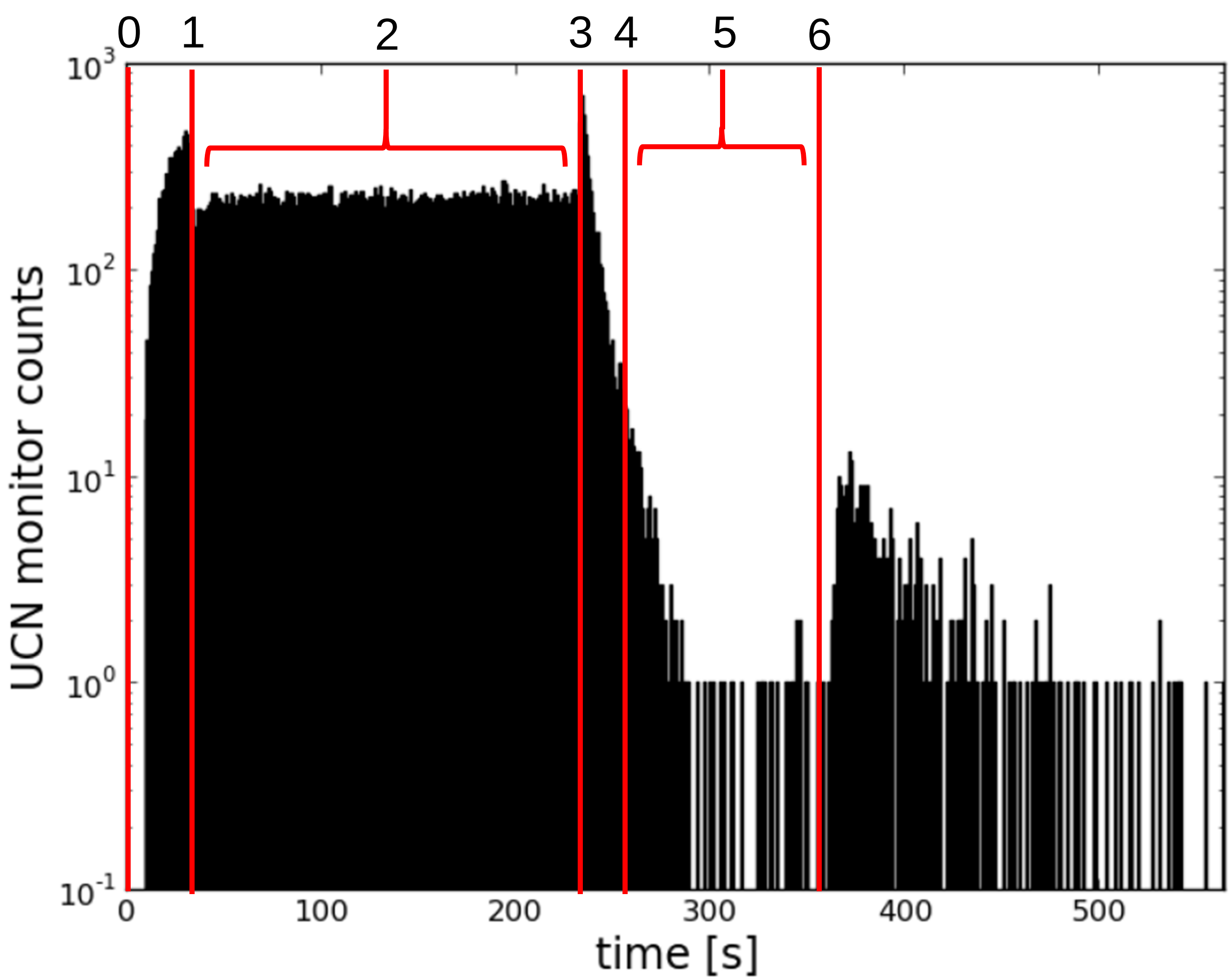
PANIC, Hamburg

“Fill and dump” cycle: count (~100 s)



PANIC, Hamburg

"Fill and dump" measurement cycle: UCNs detected in *ex situ* monitor



0: Start UCN flow: beam on, shutter open, trap door open; cleaner inserted

1: Shutter closes

2: Filling and cleaning; superbarrier UCNs to monitor

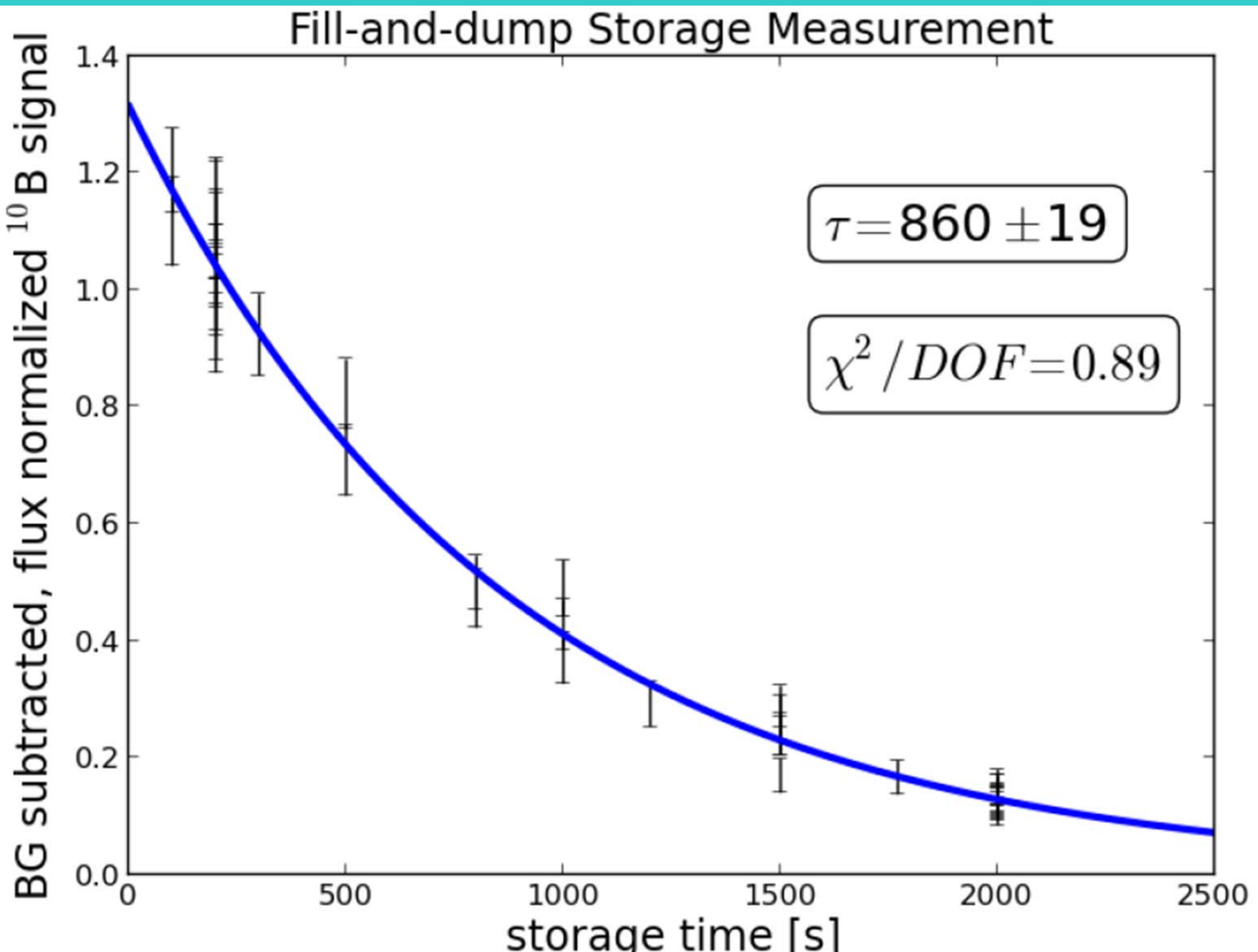
3: Trap door closes, shutter opens; beam off; UCNs in guide to monitor; cleaning

4: Cleaner retracted; storage begins

5: Storage

6: Trap door opens; UCNs in trap to monitor

Initial Storage Measurement with UCNτ Trap

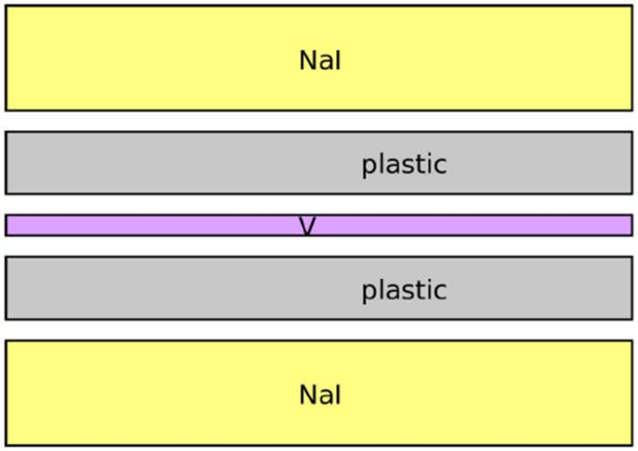


Note: statistical uncertainties only

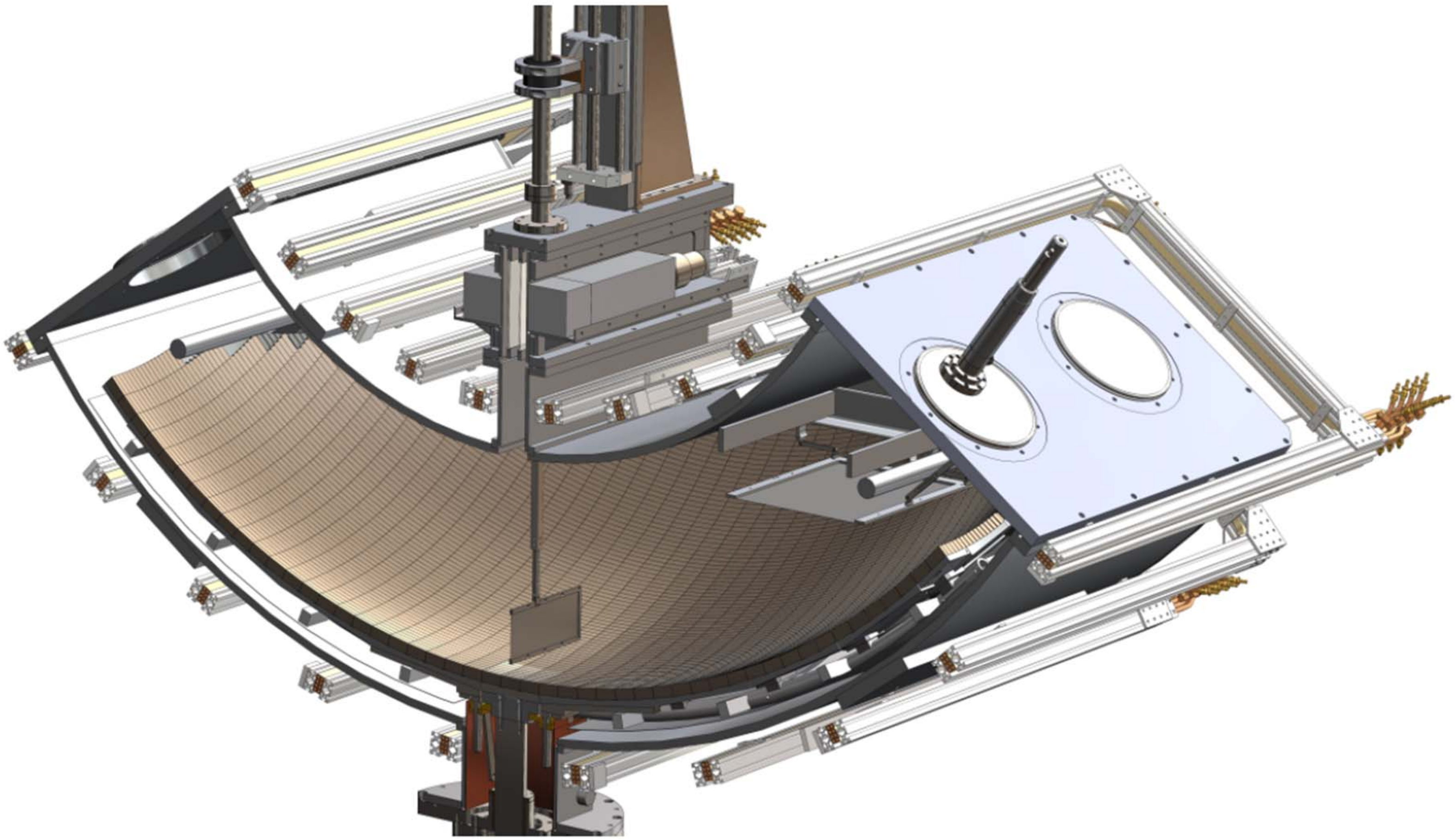
Cude, Chris. "Overview and status update on the UCNtau experiment." *Bulletin of the APS* **58** (2013)

The next step: in situ detection of surviving neutrons

- $^{51}V(n,\gamma)^{52}V$
- $^{52}V \rightarrow ^{52}Cr + \beta + \gamma$
- $V_F \approx -7$ neV
- $\ell_{abs} = 12.6\ \mu m$ at 1 m/s
- $(\ell_{up})_{meas} = 1.36 \pm 0.49$ mm at 1 m/s

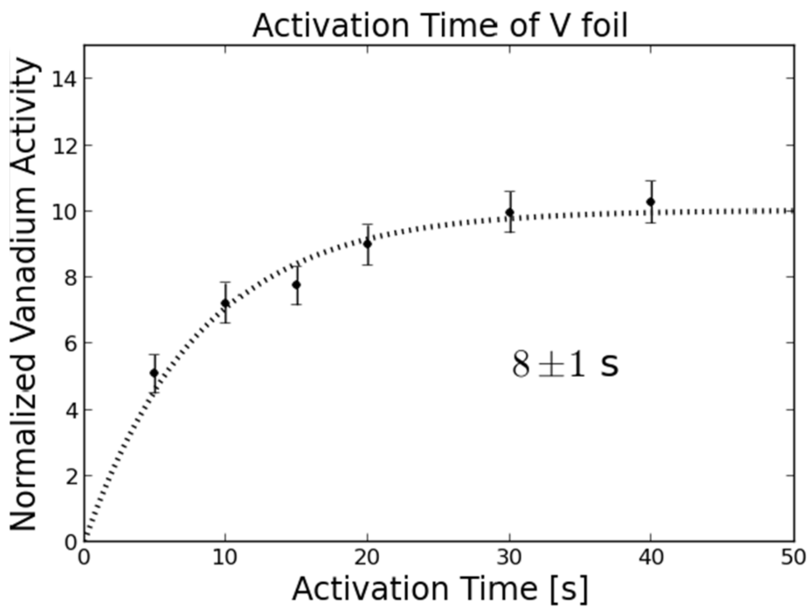


The neutron absorber/detector in the lowered position

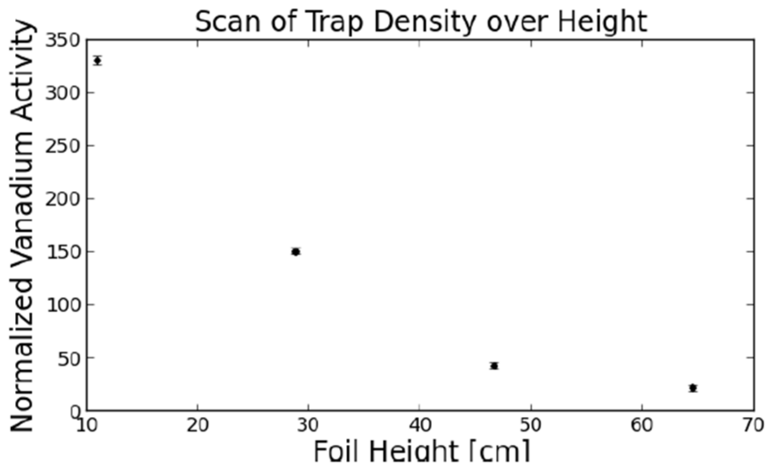


The V absorber can rapidly count all the neutrons in the trap

- Absorption time is at least an order of magnitude less than trap draining time
- Can be reduced further by installing larger V foil, also testing systematic variations



- Absorber can be positioned at different heights in the trap
- Distribution of neutrons can be compared to MC models
- Efficiency of cleaning can be tested by positioning foil above cleaning height



Plans for 2014 LANSCE accelerator cycle

- Demonstrate improved neutron transmission into trap
  - Redesigned trap door should provide ~10^5 neutrons per fill, yielding ~1% statistics per week
- Demonstrate improved S/B ratio in V absorber detector
  - Added shielding, improved detectors
- Investigate additional possible systematics, e.g.:
  - Vibrations
  - Magnetic field interactions with other experiments
  - Proton-beam related backgrounds
  - Neutron-beam related backgrounds
  - UCN beam flux and spectrum monitoring

Conclusions

- Precise knowledge of the neutron lifetime is important across nuclear and particle phsyics
- There is an imperative need for a new independent experiment with ~1 s precision
- The UCNτ experiment has unique capabilities to reduce systematics that affected previous experiments
- Initial results look promising, but there is much work still to do!

- Thank you to my collaborators and especially Dirk Dubbers, Bastian Maerkisch, Chen-Yu Liu, Albert Young

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