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Author(s): Salvat, Daniel

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Measuring the Neutron Lifetime with a Magnetic Neutron Trap at LANL

Daniel J. Salvat

8 May 2014

DePauw	A. Komives
Hamilton	G. Jones
IU	E.R. Adamek, N.B. Callahan, W. Fox, A.T. Holley, C.-Y. Liu, D.J. Salvat, B.A. Slaughter, W.M. Snow, K. Solberg, J. Vanderwerp
JINR	E.I. Sharapov
LANL	D. Barlow, L.J. Broussard, S.M. Clayton, T. Ito, M. Makela, J. Medina, D.J. Morley, C.L. Morris, J. Ramsey, A. Saunders, S.J. Seestrom, S.K.L. Sjue, P. Walstrom, Z. Wang T.L. Womack
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ORNL	J.D. Bowman, S.I. Penttilä
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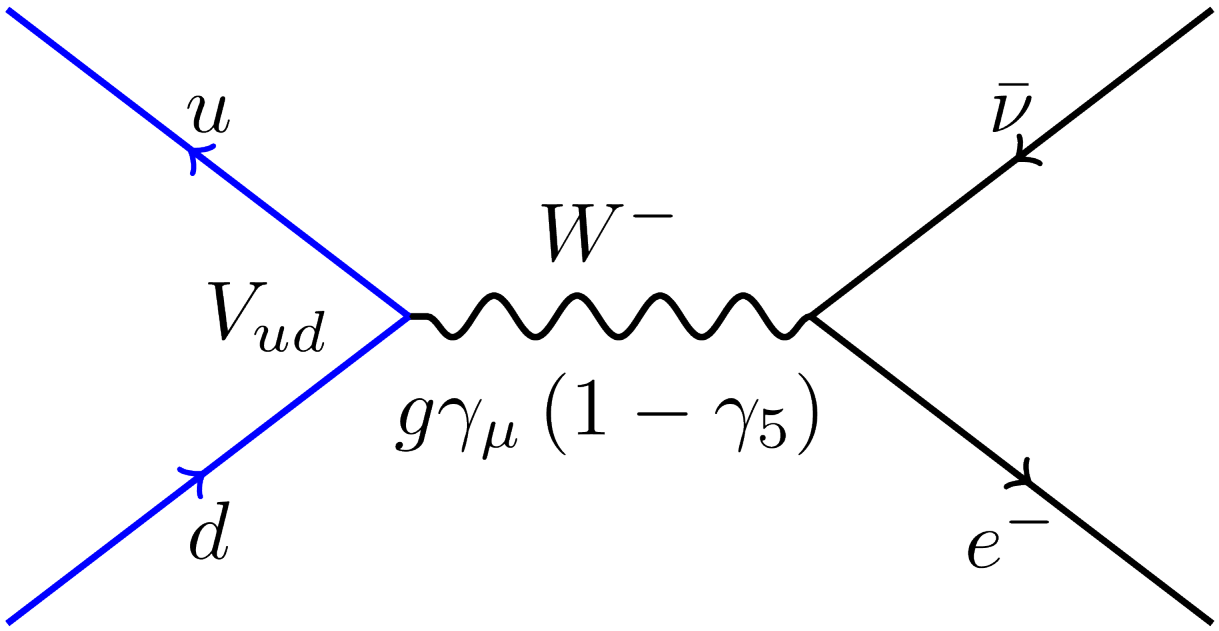
Section 1

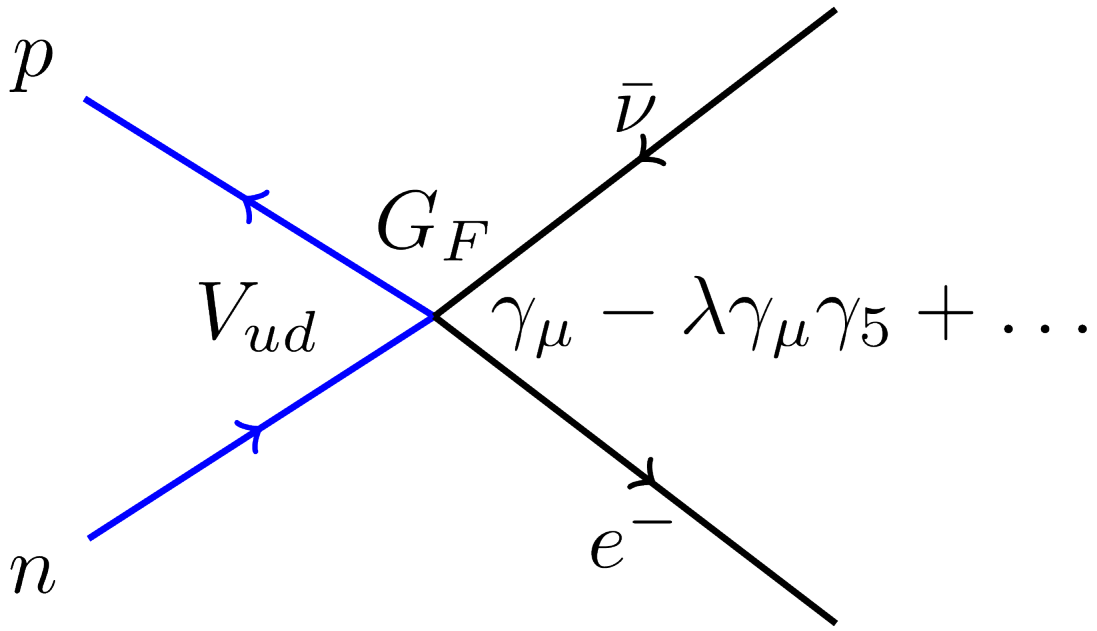
Neutron Decay, Ultracold Neutrons, and τ_n



$$\mathcal{H} = \bar{p}\gamma^\mu\left[g_V - g_A\gamma_5\right] n \times \bar{e}\gamma_\mu\left[1-\gamma_5\right]\nu$$

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

$$\Gamma \propto 1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \sigma\cdot\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_e E_\nu}\right)$$



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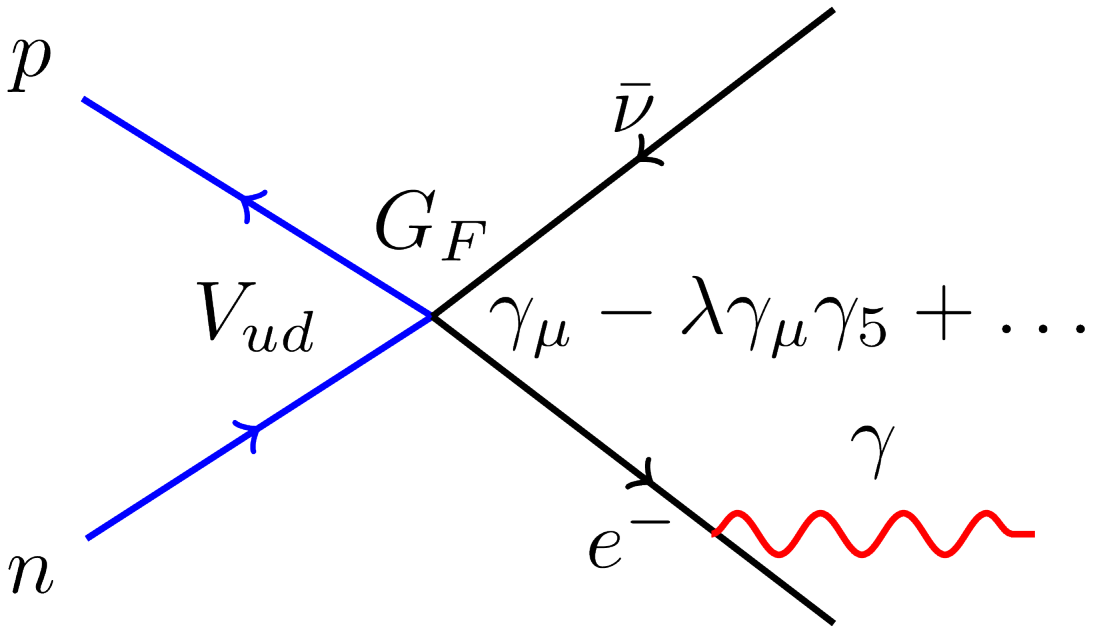

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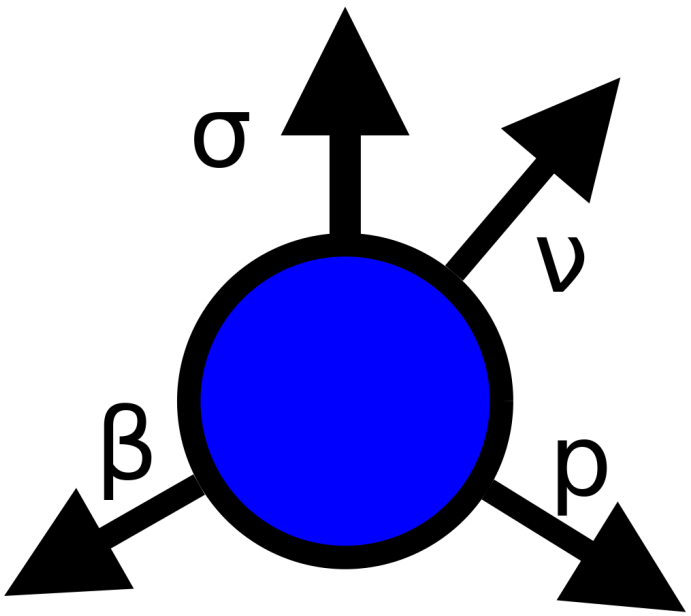

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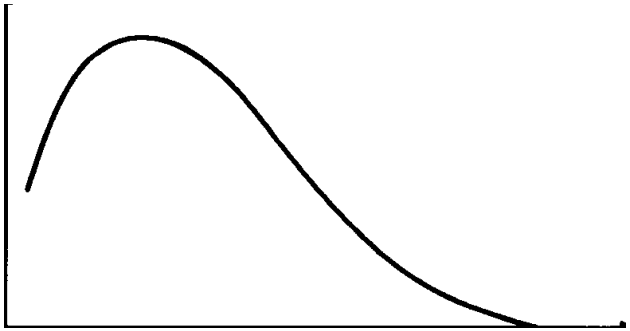
1930



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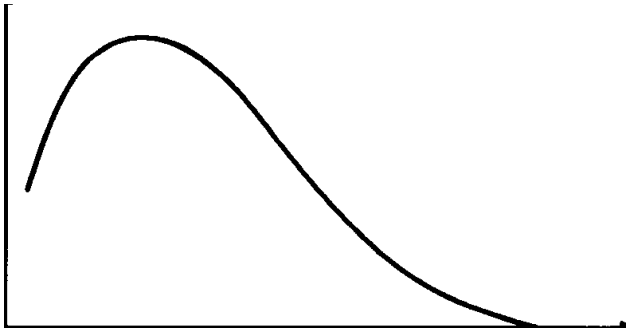

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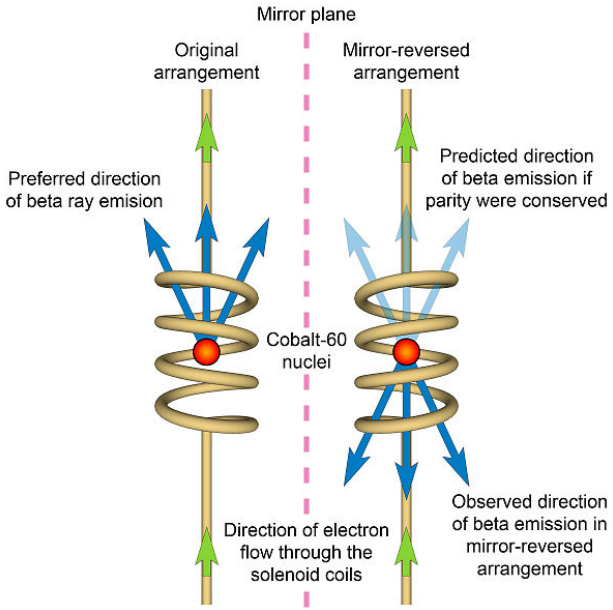
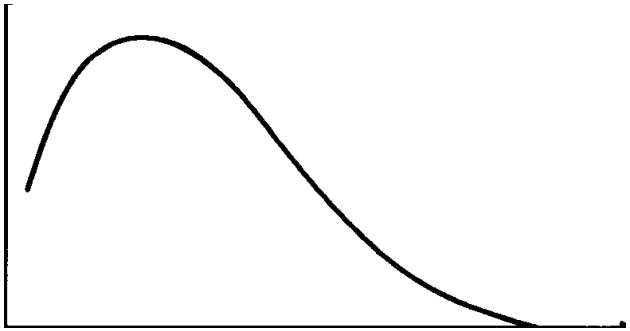

Mirror plane
Original arrangement
Mirror-reversed arrangement
Preferred direction of beta ray emision
Predicted direction of beta emission if parity were conserved
Cobalt-60 nuclei
Direction of electron flow through the solenoid coils
Observed direction of beta emission in mirror-reversed arrangement

1930



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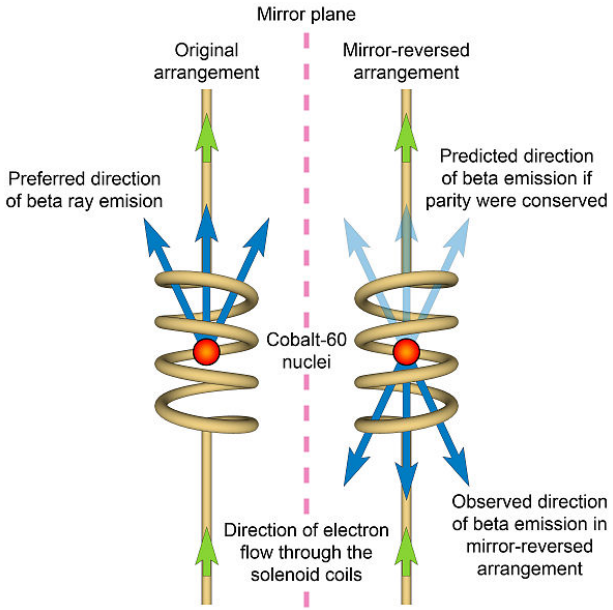
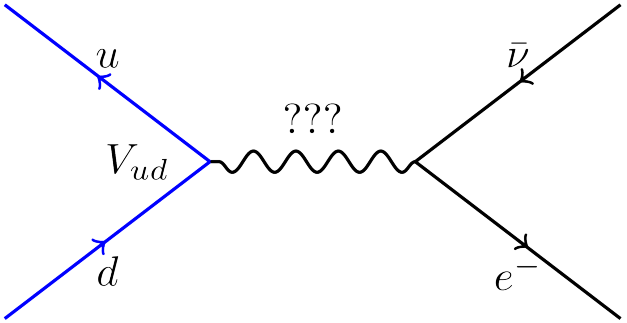


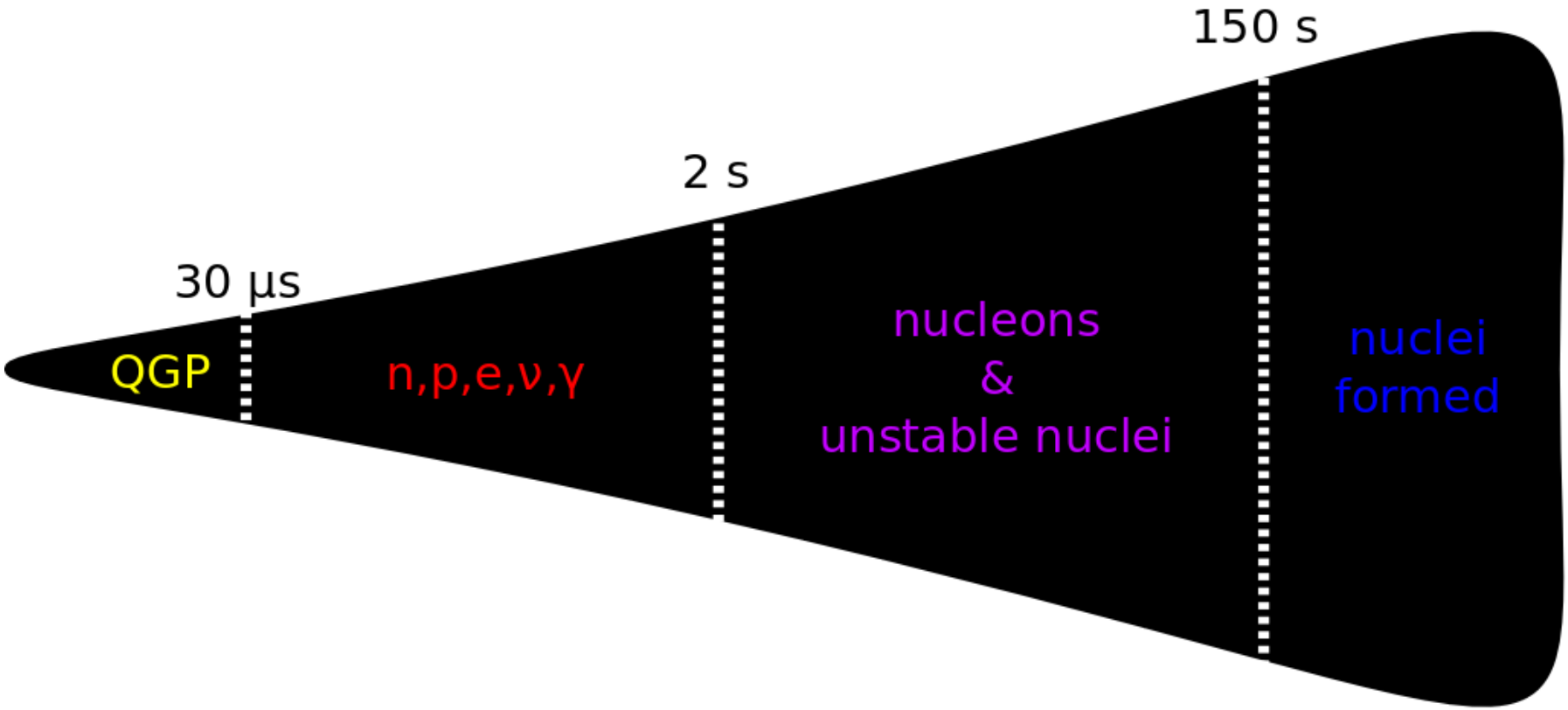
today



$$\text{precision} \sim \left(\frac{v}{\Lambda_{\text{BSM}}}\right)^2$$

$$\Lambda_{\text{BSM}} \sim \frac{v}{\sqrt{5 \times 10^{-4}}}$$

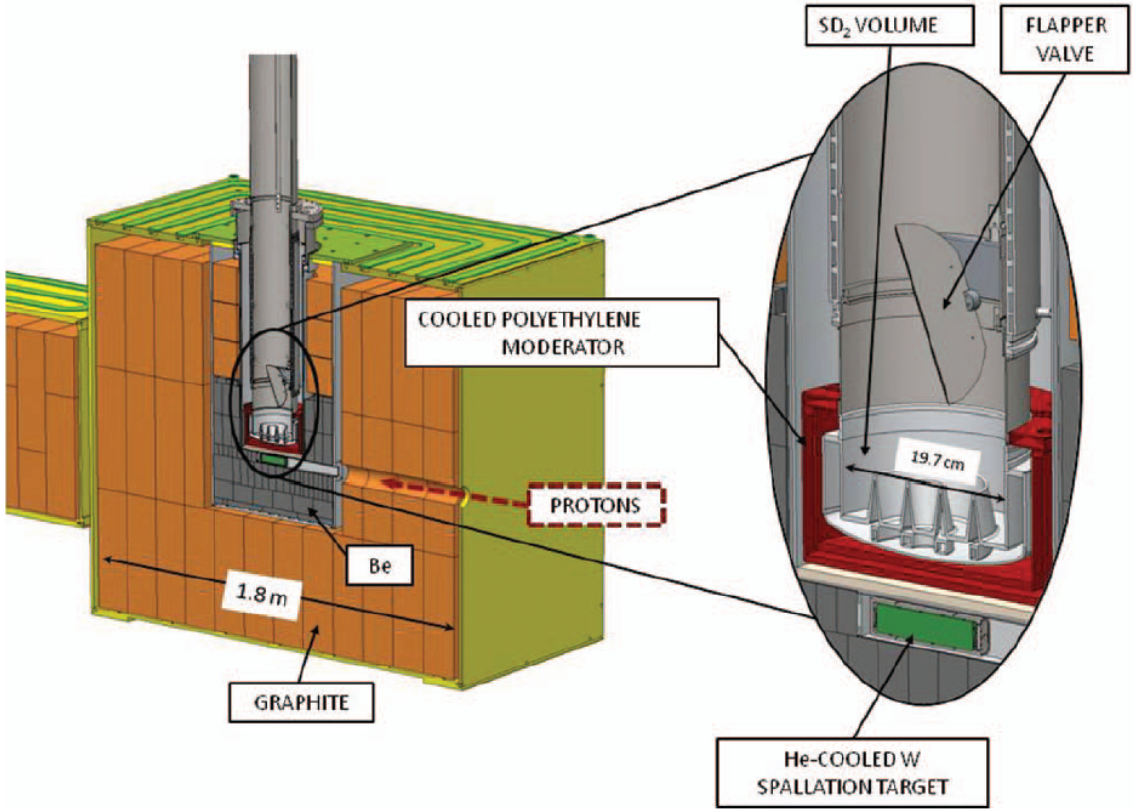
$$\Lambda_{\text{BSM}} \sim 10 \text{ TeV}$$

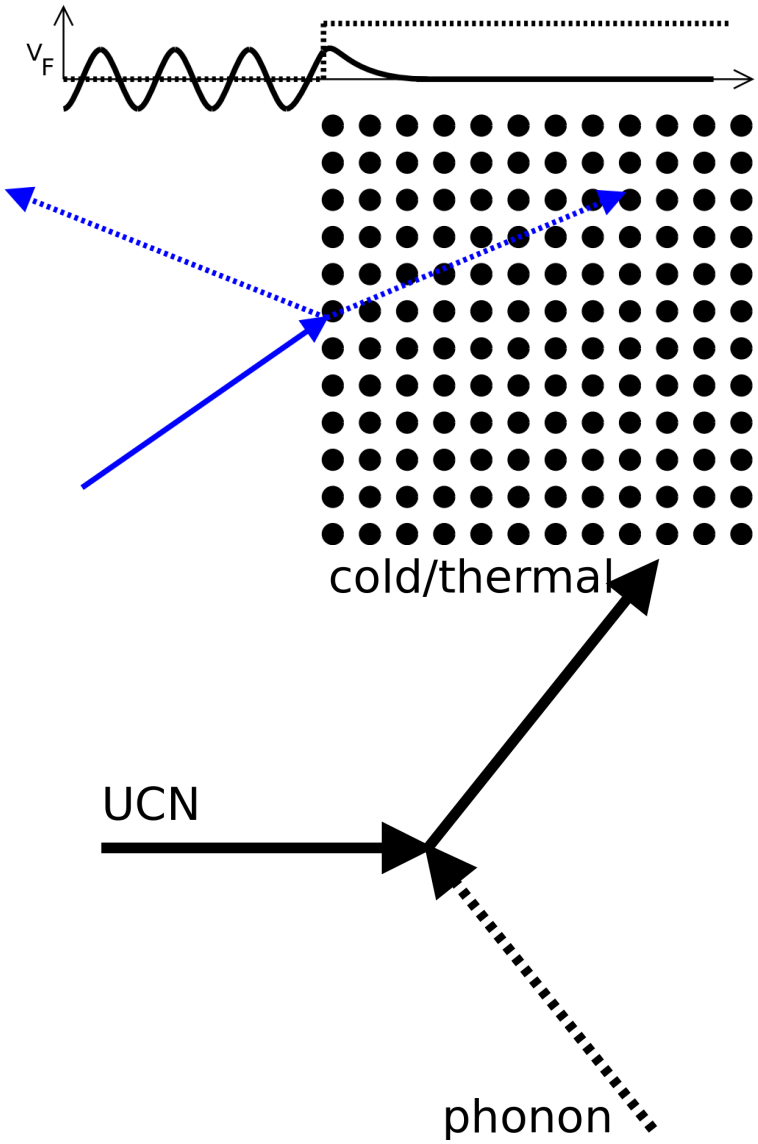


$$Y_p \approx \frac{2\exp\left(-t_d/\tau_n\right)}{1+\exp\left(\Delta m/kT_f\right)}$$

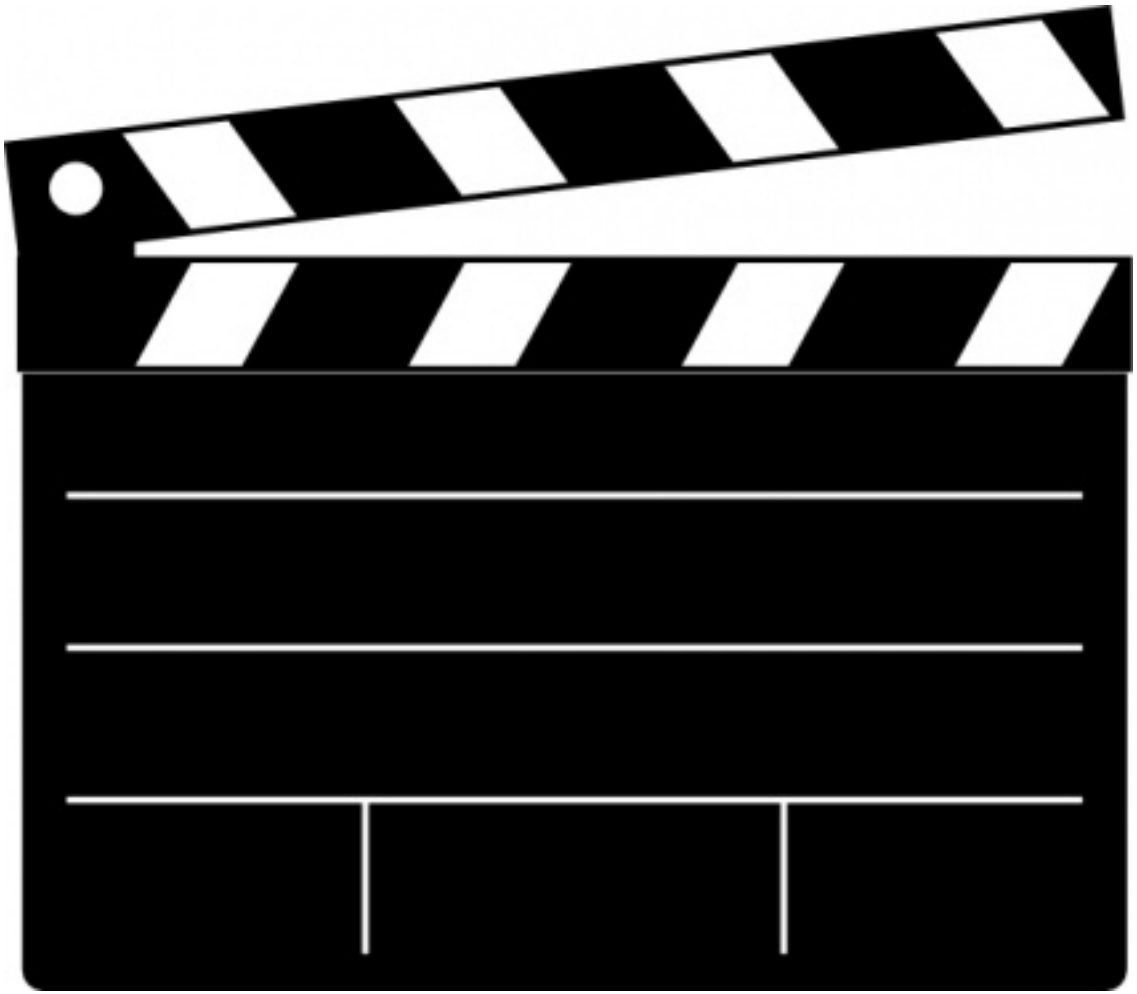
lifetime along with N_f, η, Y_p constrains BBN predictions $\Rightarrow$ constraints on new physics!

name	E	v [m/s]	λ [Å]	T [K]
thermal	25 to 100 meV	2200 to 4000	1.2 to 2.5	290 to 1200
cold	1 to 25 meV	440 to 2200	2.5 to 13	12 to 290
very cold	300 neV to 1 meV	8 to 440	13 to 740	0.003 to 12
ultra cold	0 to 300 neV	0 to 8	>740	0 to 0.003

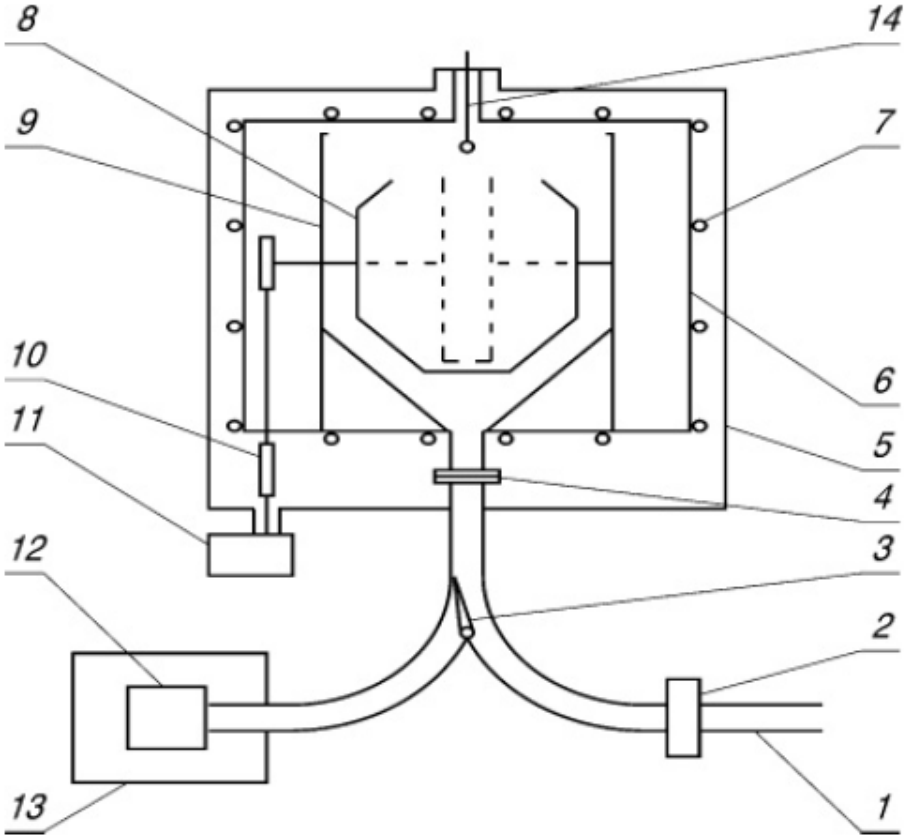




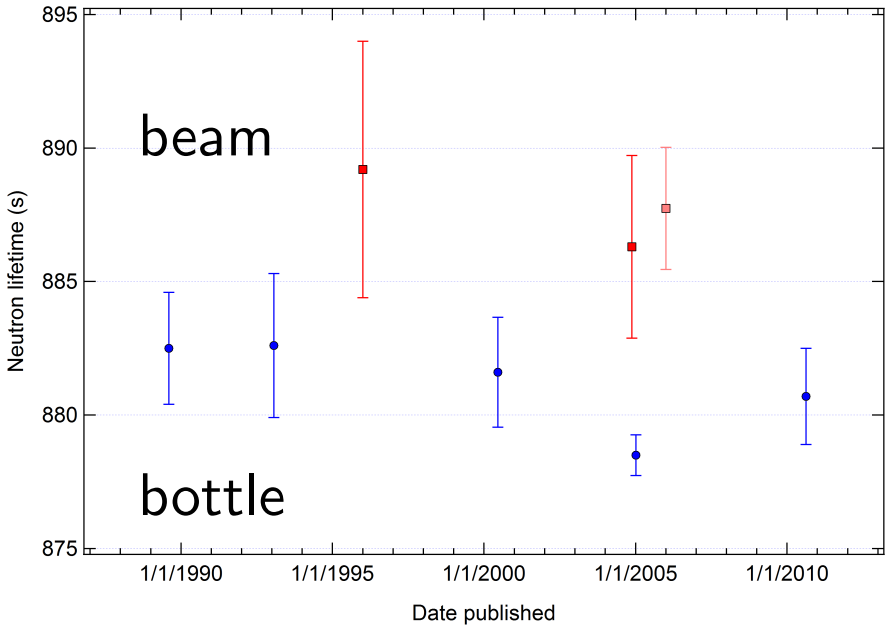
- $V_{eff} = \frac{2\pi\hbar^2}{m_n} nb \approx 100$ neV
- $V_M = \pm\mu_N B \approx \pm(60 \text{ neV/T})B$
- $V_G = m_n g z \approx (102 \text{ neV/m})z$
- $\mu(E,\theta) = 2\eta\sqrt{\frac{E\cos^2\theta}{V - E\cos^2\theta}}$
- $\sigma_{up} \sim \int_0^\infty \frac{e^{-2W}\sqrt{\omega}g(\omega)}{e^{\hbar\omega/kT}-1} d\omega$



disagreement between neutron beam and "bottle" techniques



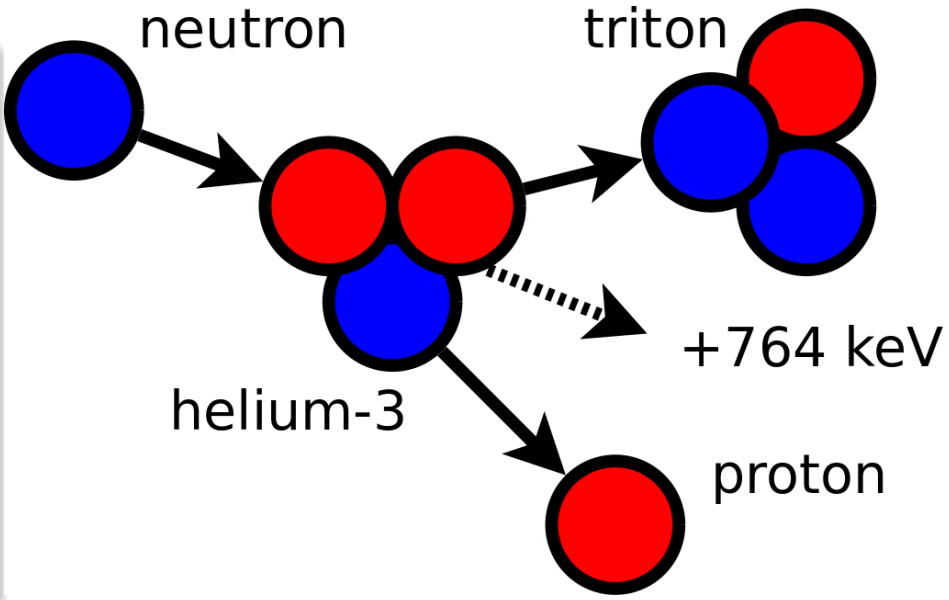
from A. Yue, et al.

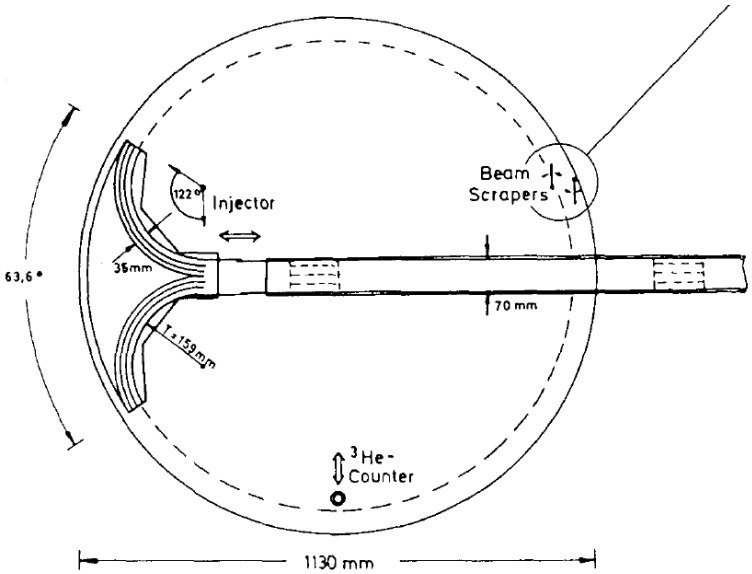


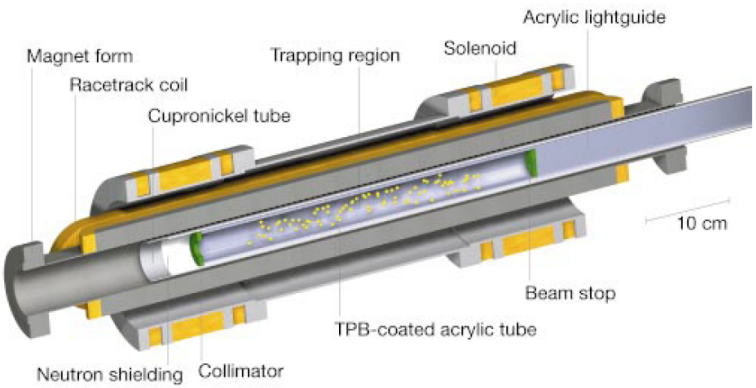
$$\tau_{store}^{-1} = (t_2 - t_1)(\log(N_1/N_2))$$

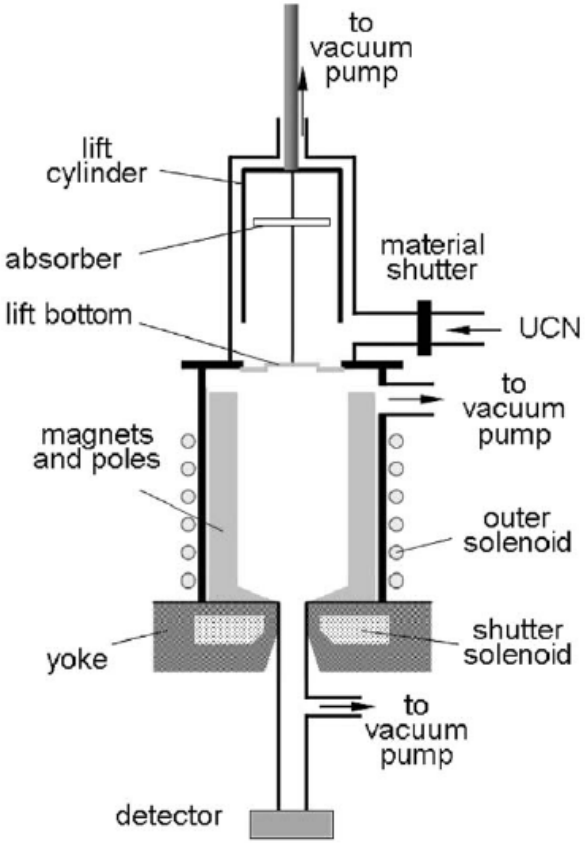
$$\begin{aligned} \tau_{store}^{-1} &= \tau_n^{-1} + \tau_{loss}^{-1} \\ &= \tau_n^{-1} + \eta\gamma(E) \end{aligned}$$

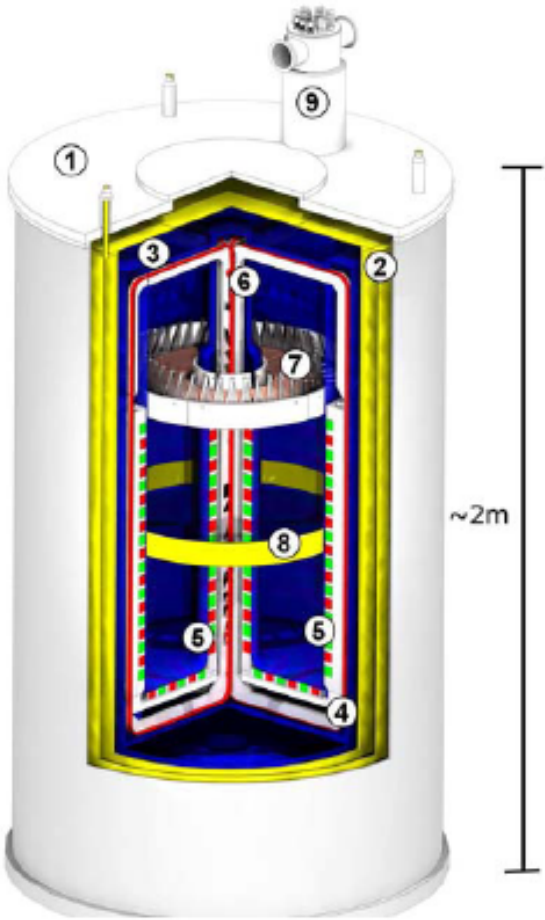
- Not a lot of neutrons (cf. 10^{12} muon decays)
- Long lifetime (cf. 2200 ns muon lifetime)
- You must destroy a slow neutron to detect it (cf. $+1$ muon charge)

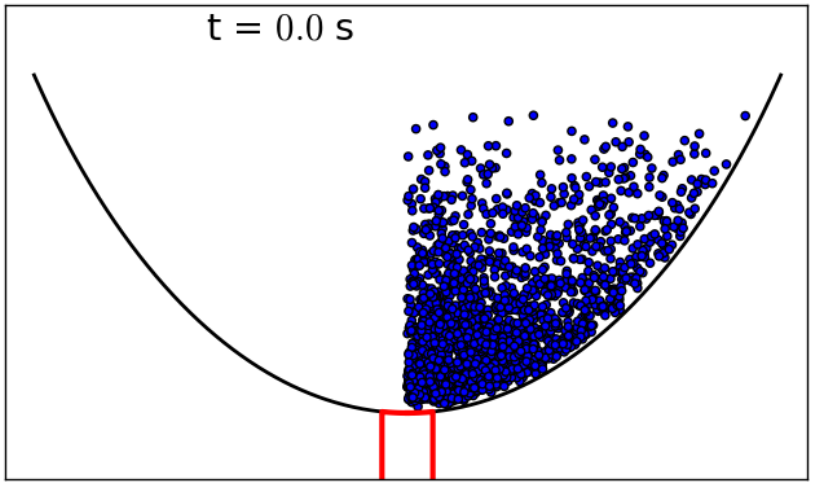



Beam Scrapers
Injector
122°
63,6°
35mm
70 mm
^{3}He-Counter
1130 mm

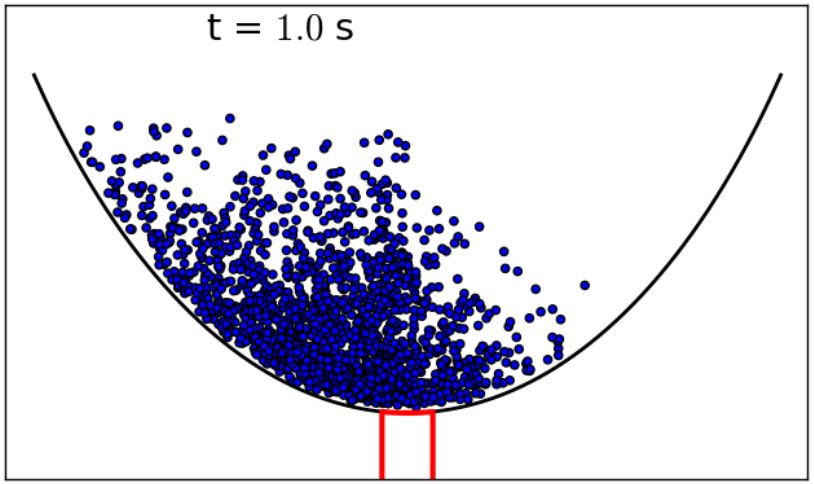

Acrylic lightguide
Magnet form
Trapping region
Solenoid
Racetrack coil
Cupronickel tube
10 cm
Beam stop
TPB-coated acrylic tube
Neutron shielding
Collimator


to vacuum pump
lift cylinder
absorber
material shutter
lift bottom
UCN
to vacuum pump
magnets and poles
outer solenoid
yoke
shutter solenoid
to vacuum pump
detector


~2m



- previous analyses rely on kinetic equilibrium
- how badly is it violated?
- leads to a few effects
  - phase space sensitivity
  - marginally trapped UCN
  - spectral evolution
- magnetic traps avoid some issues



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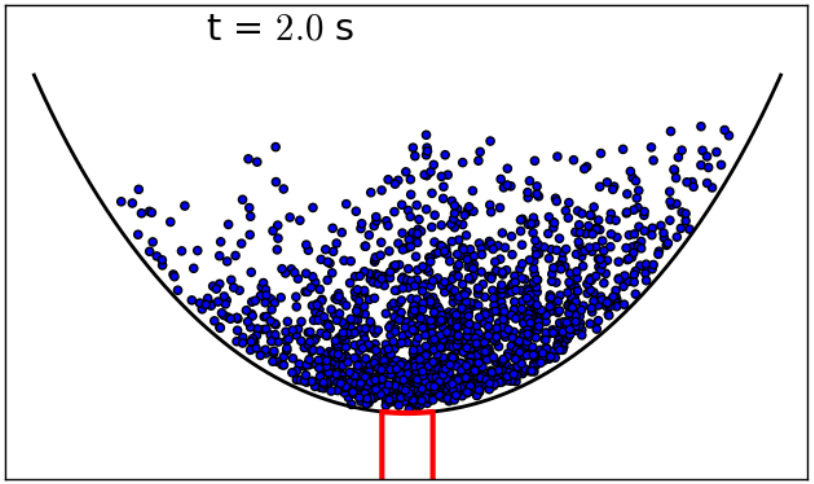

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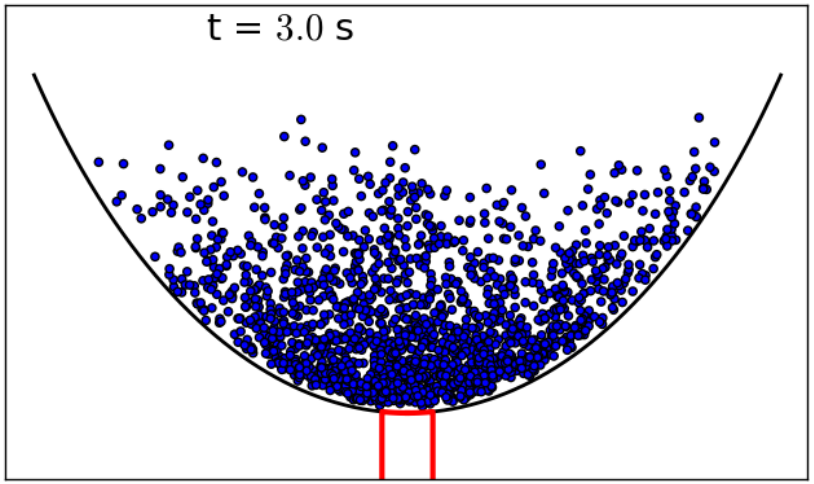

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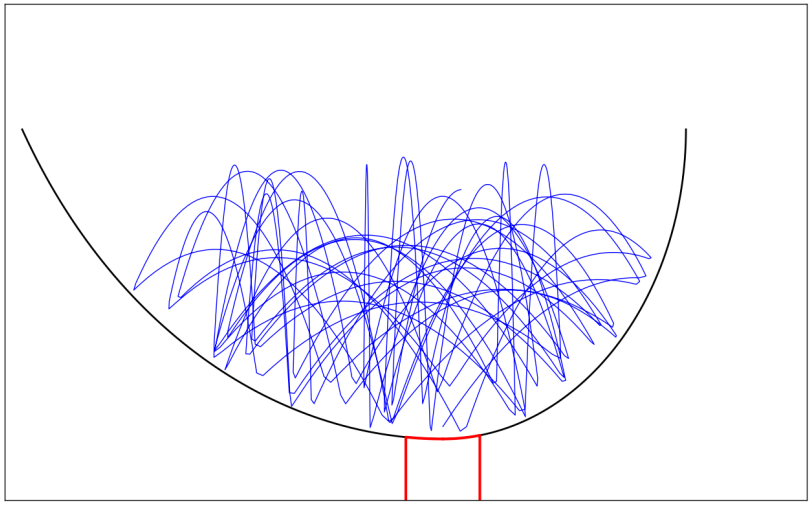

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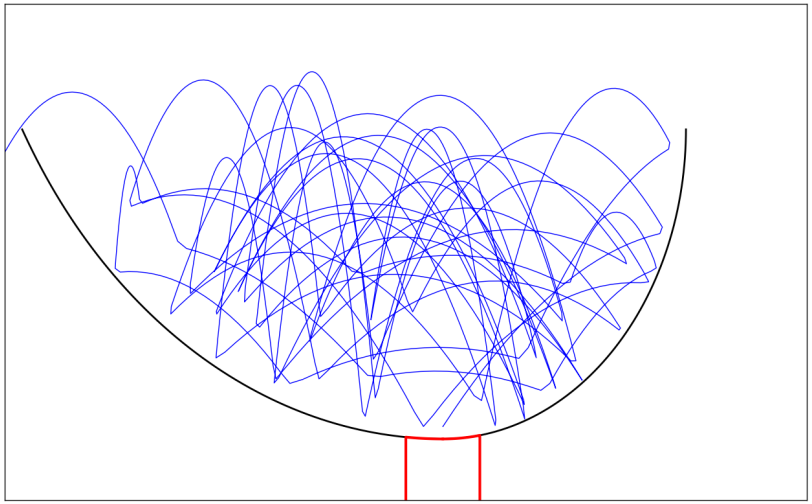

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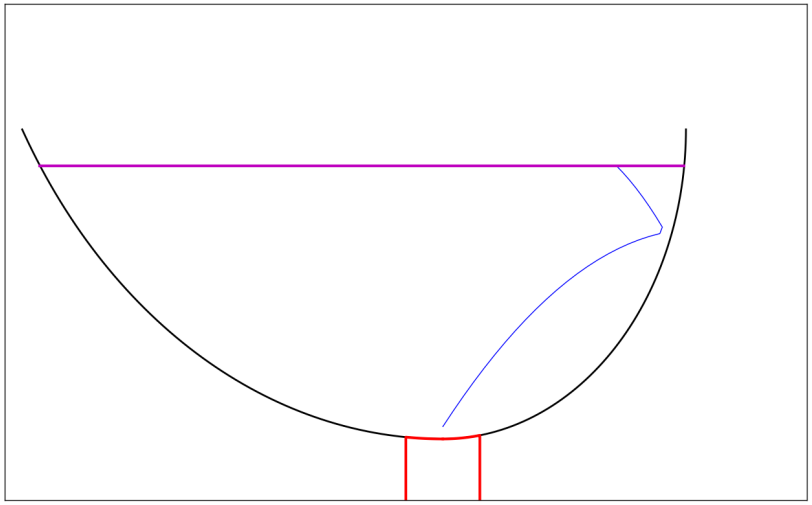

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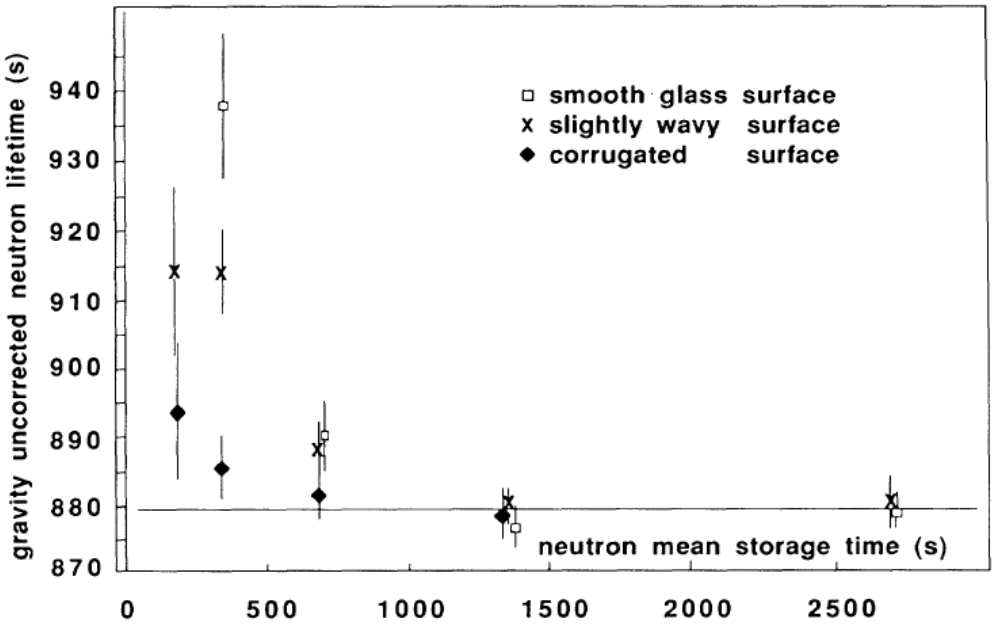

FIG. 3. Dependence of the experimental gravity-uncorrected neutron lifetime on the storage-time interval for different bottle surface structures. The remaining shift in the case of the corrugated surface and short storage times disappears after correction for gravitational effects.

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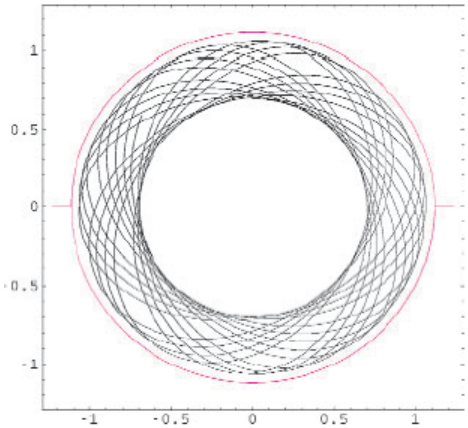
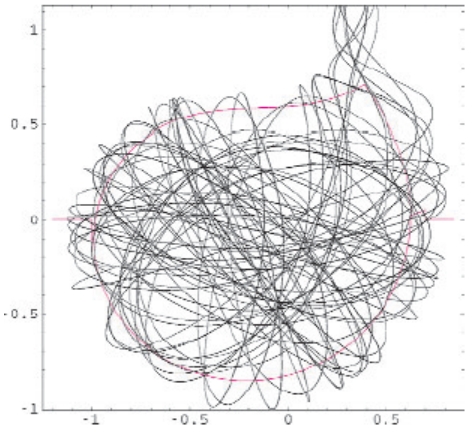
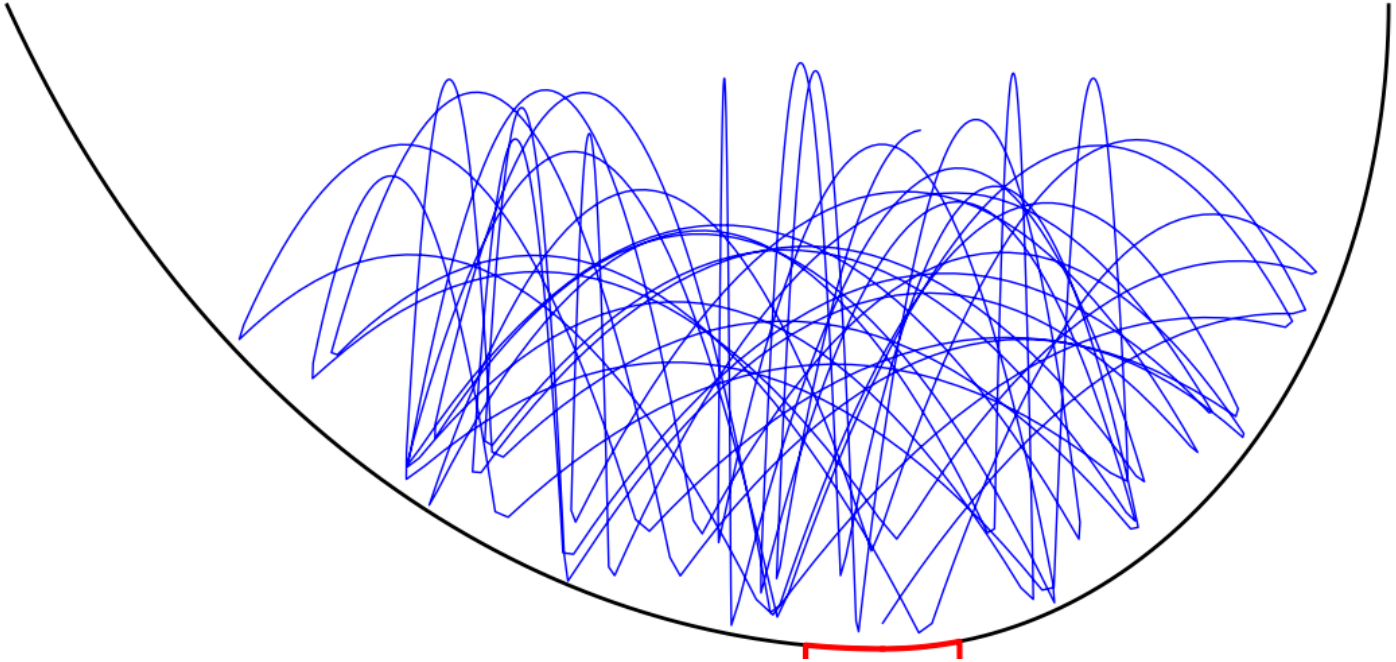






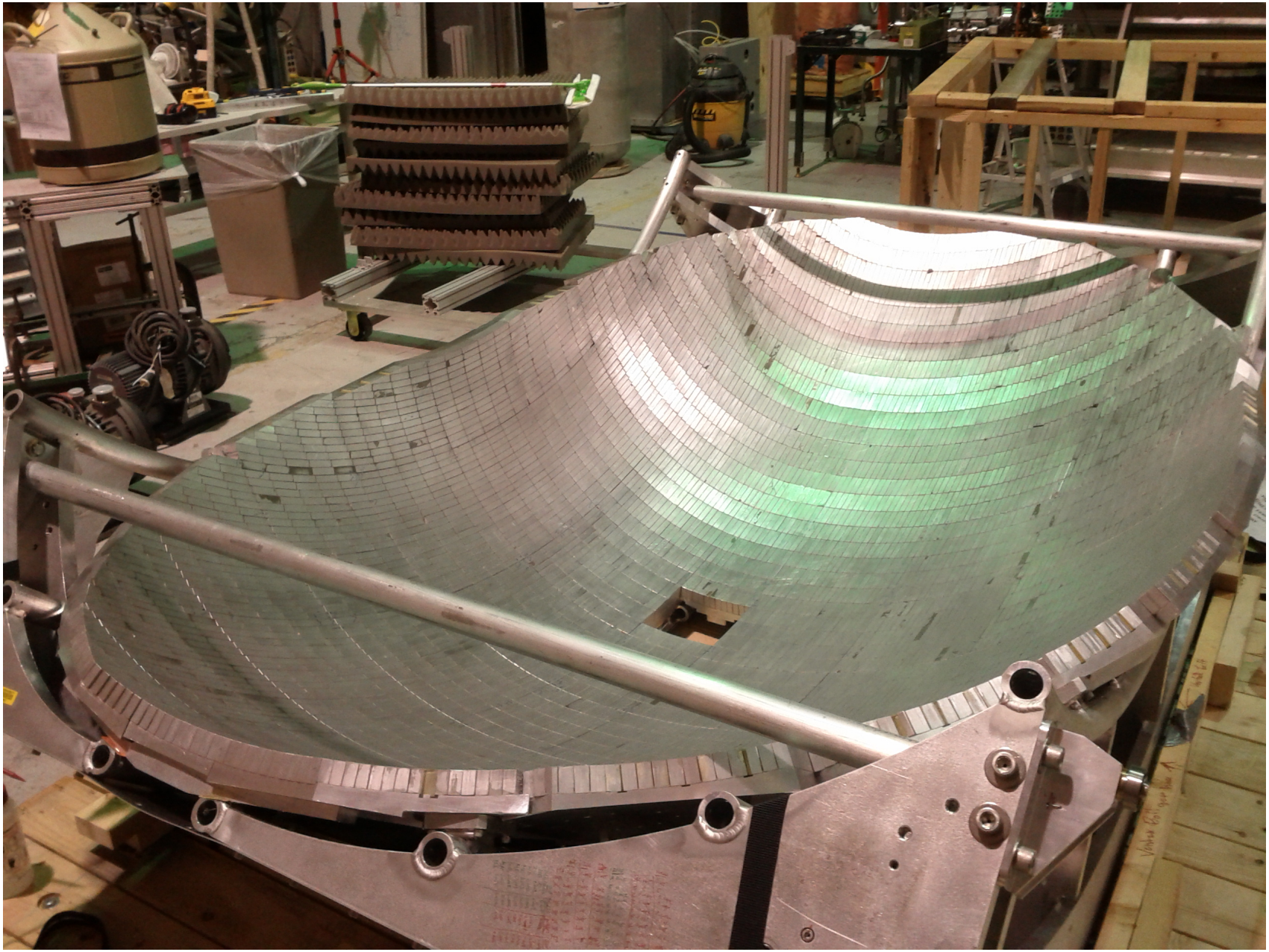
J.D. Bowman & S.I. Penttila. *J Res NIST* **110** (2005) 361-366.

P.L. Walstrom, et al. *NIM A* **599** (2009) 82-92.

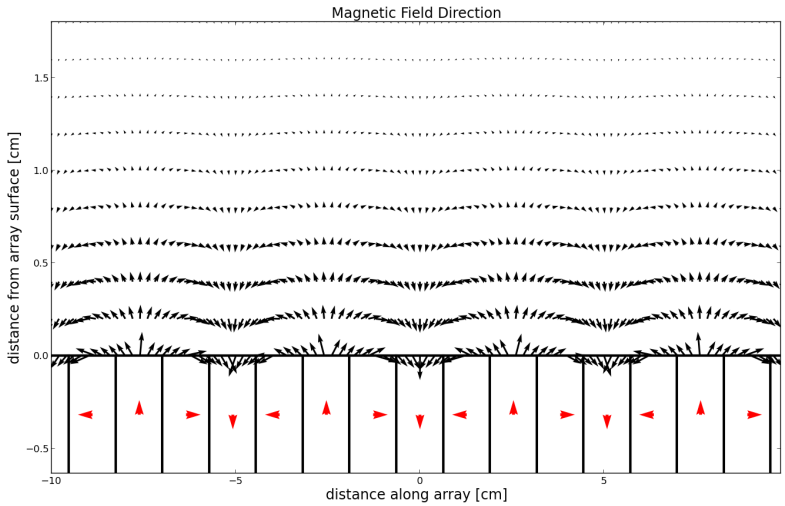
- new τ_n measurements timely – resolve discrepancy, probe BSM, cosmology
- hints of issues with material traps – magnetic traps well motivated
- need a test-bed for new techniques
- theoretical studies of UCN dynamics useful for motivating new experiments

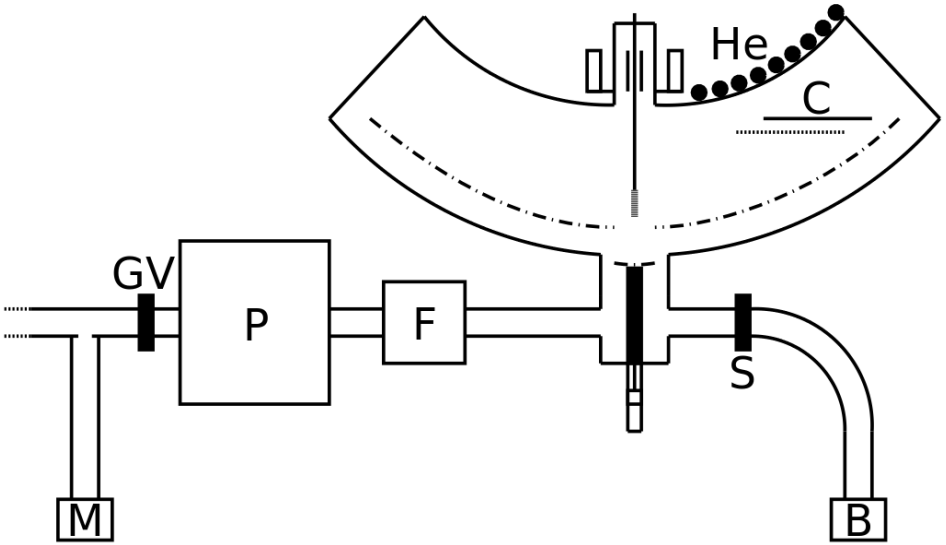
Section 2

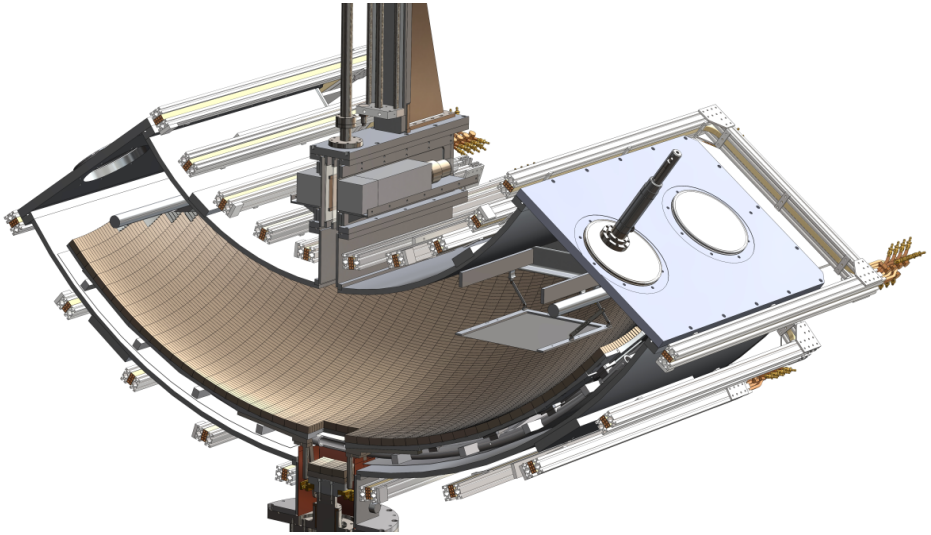
A Neutron Bathtub

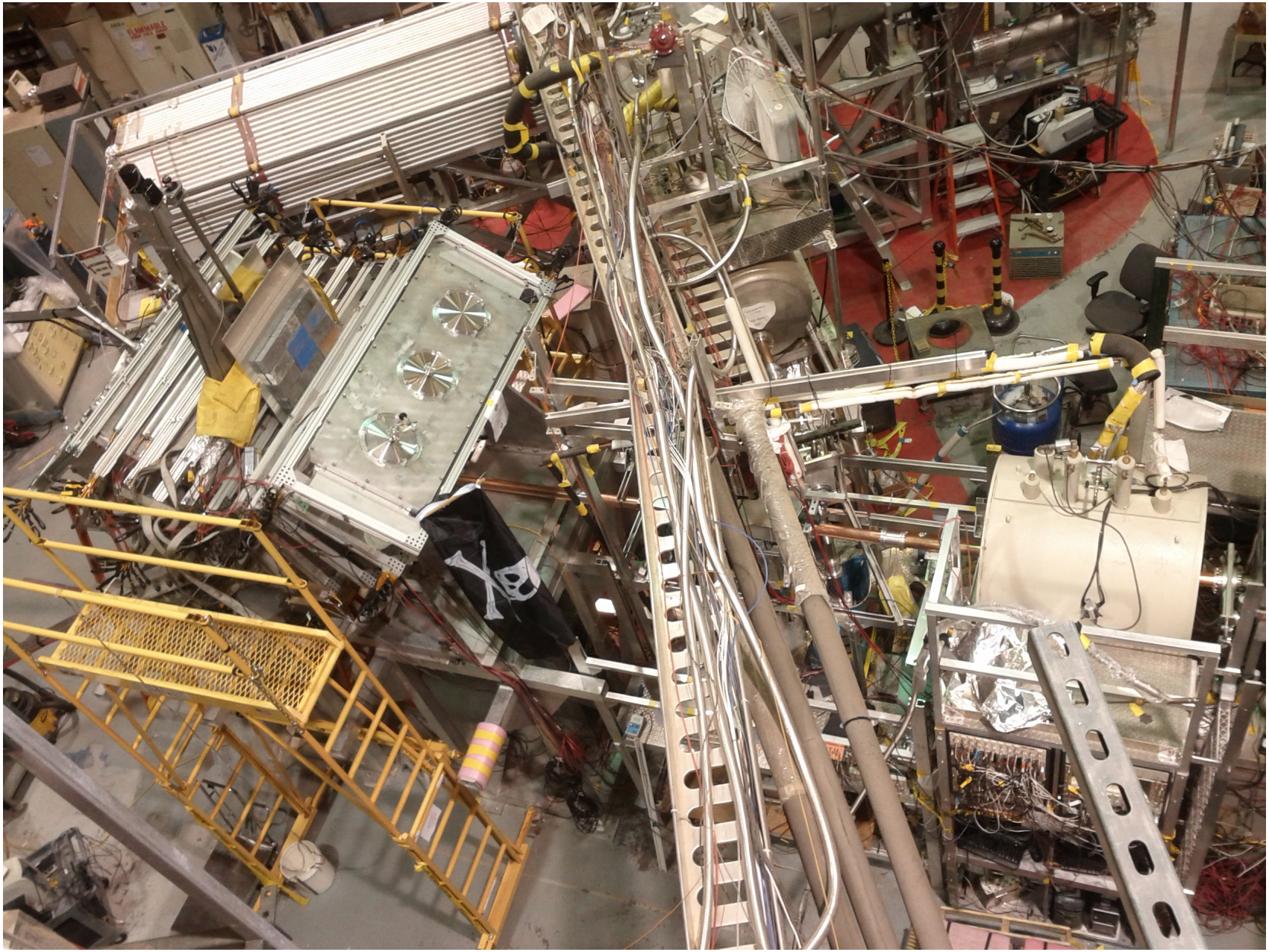


- $\tau_{store}^{-1} = \tau_n^{-1} + \cancel{\eta\gamma(E)}$
- trapping force $\mathbf{F} = -\mu\nabla|\mathbf{B}|$
- 670 liter, 50 cm deep
- background "holding" field to assure $\mathbf{B} \neq 0$

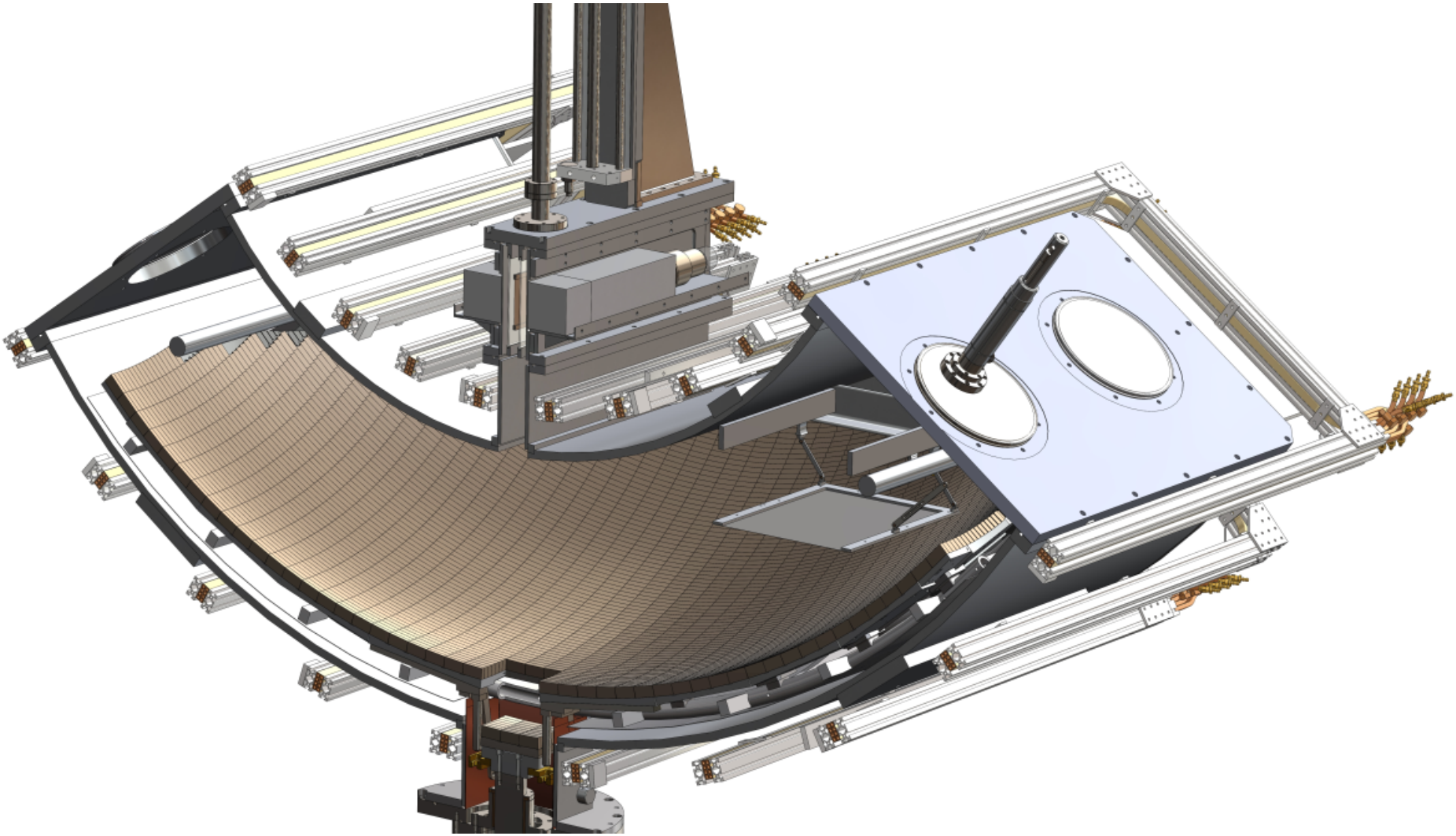




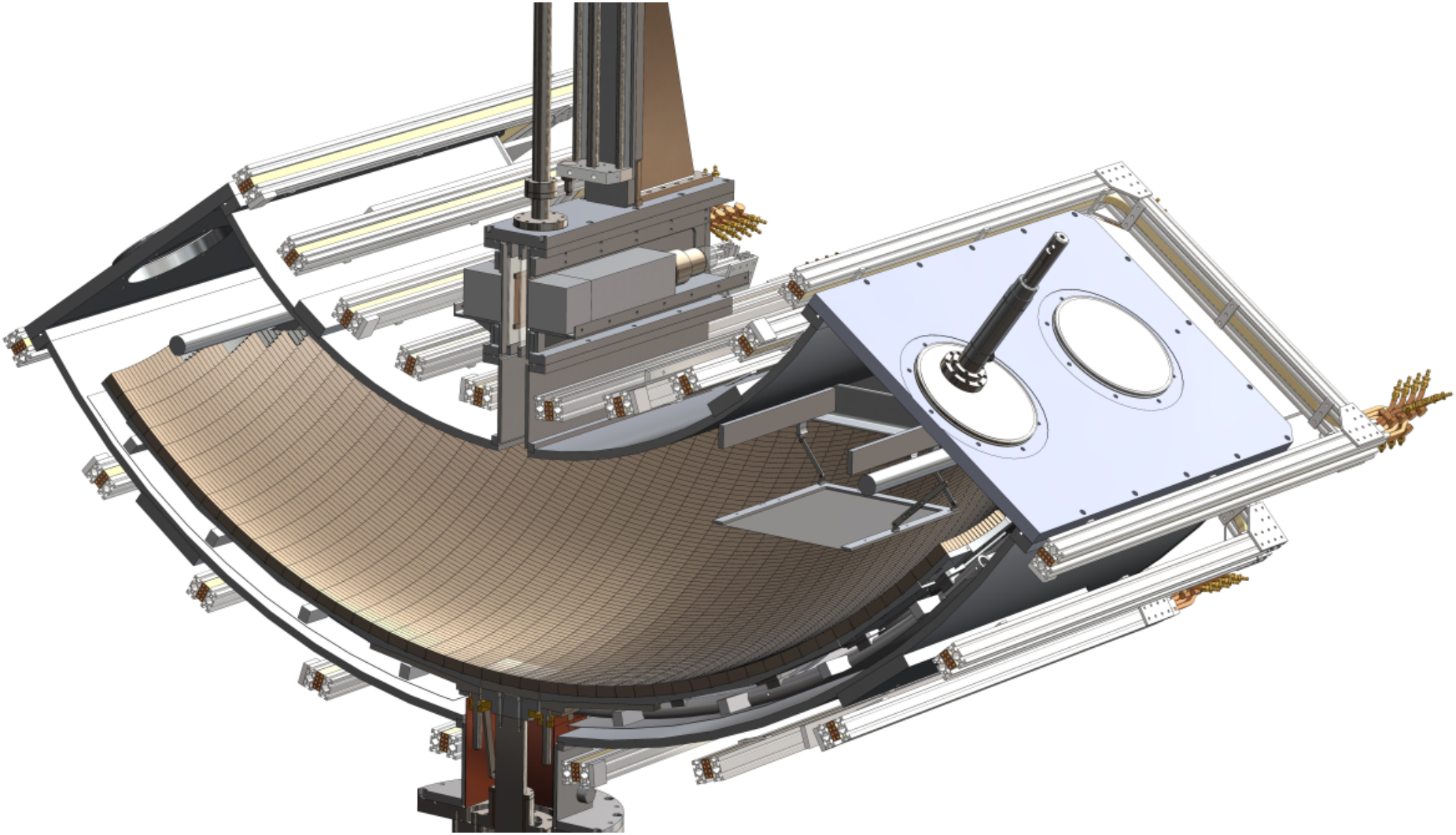




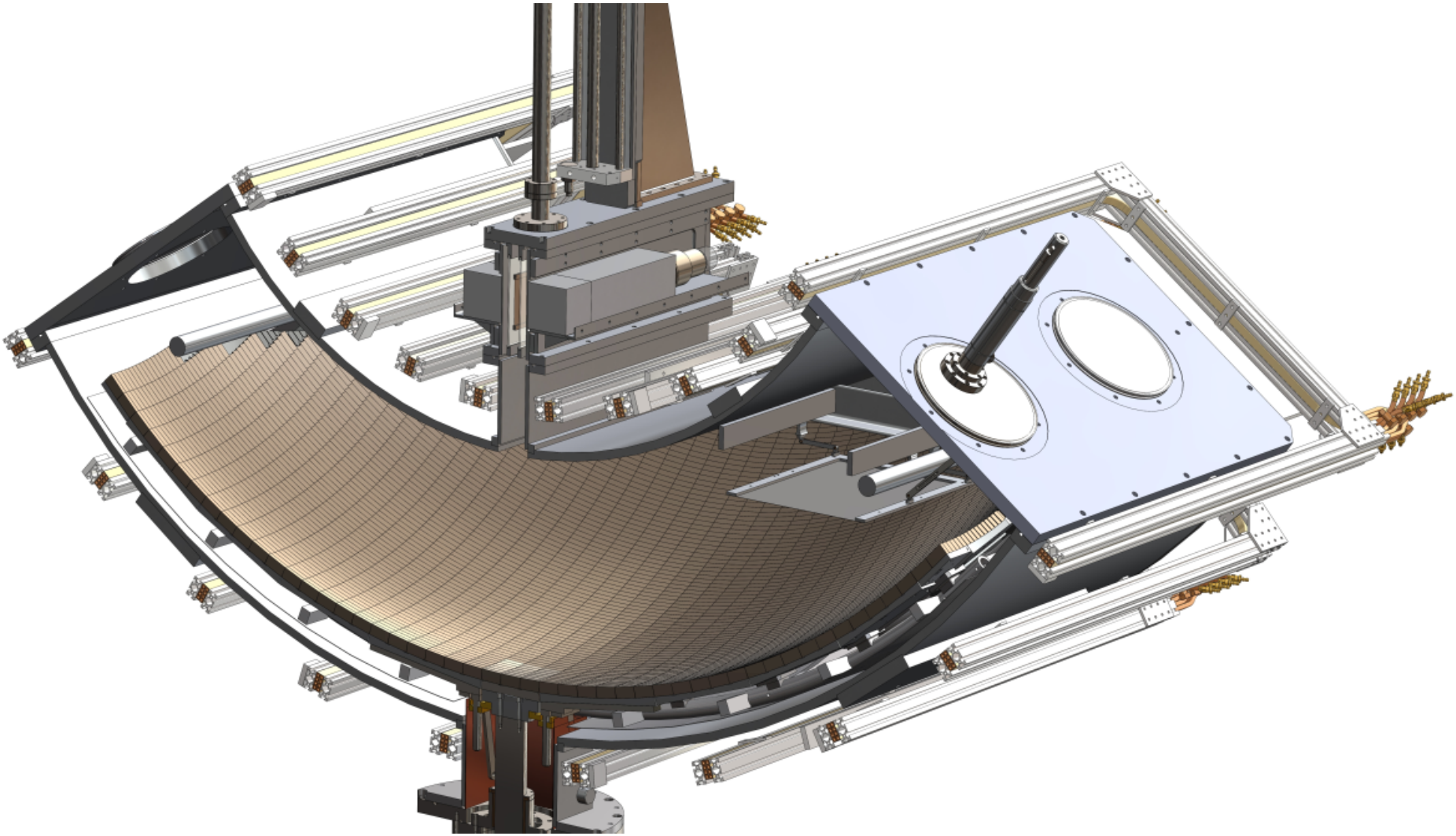
Fill & Monitor ($t \sim 200$ s)



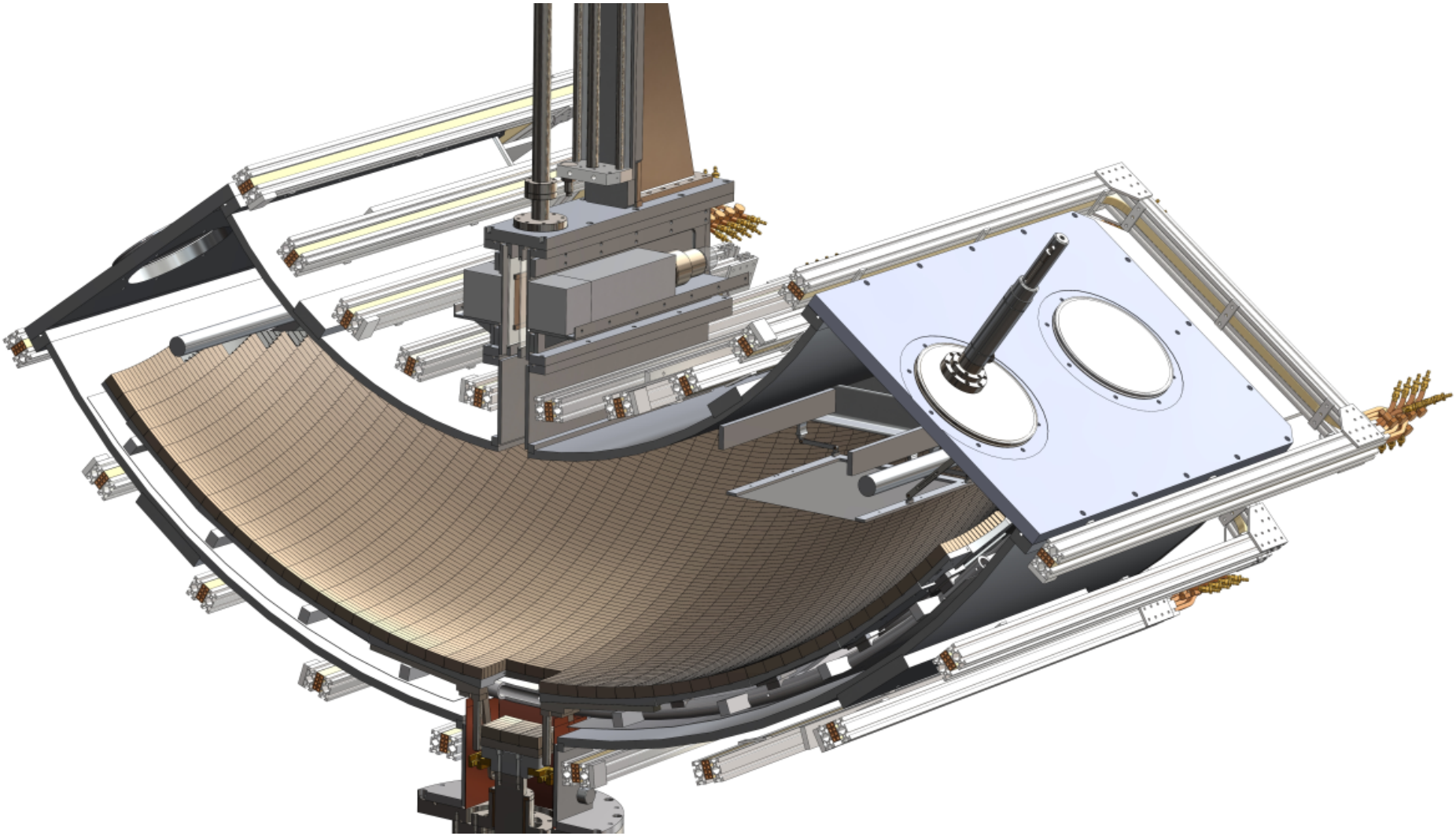
Clean ($t \sim 30$ s)



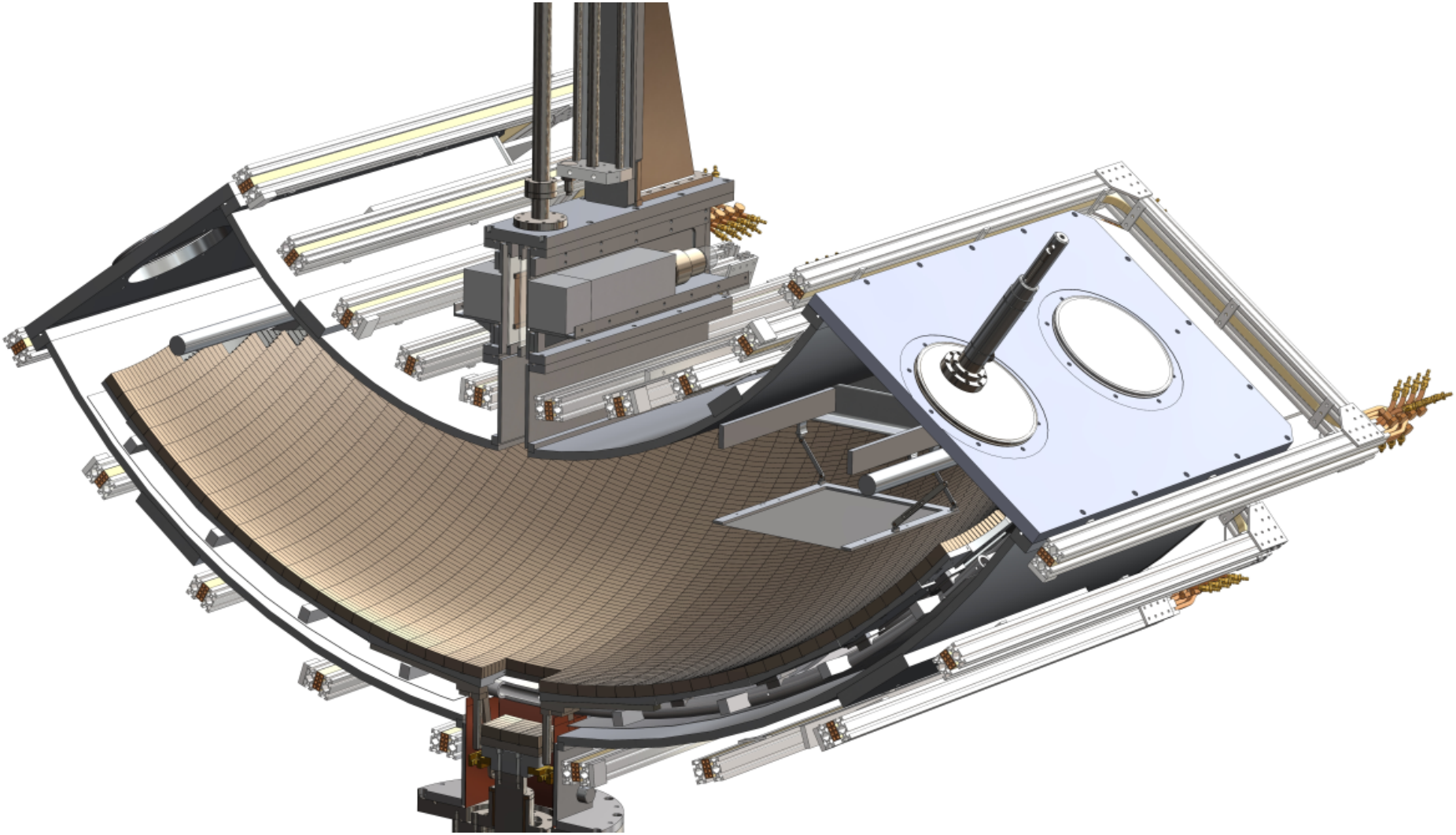
Store ($t \sim 100$ to 2000 s)



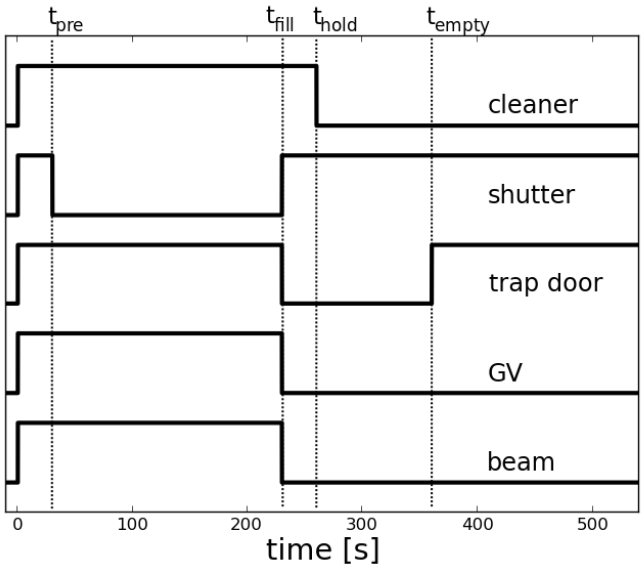
Empty ($t \sim 100$ s)

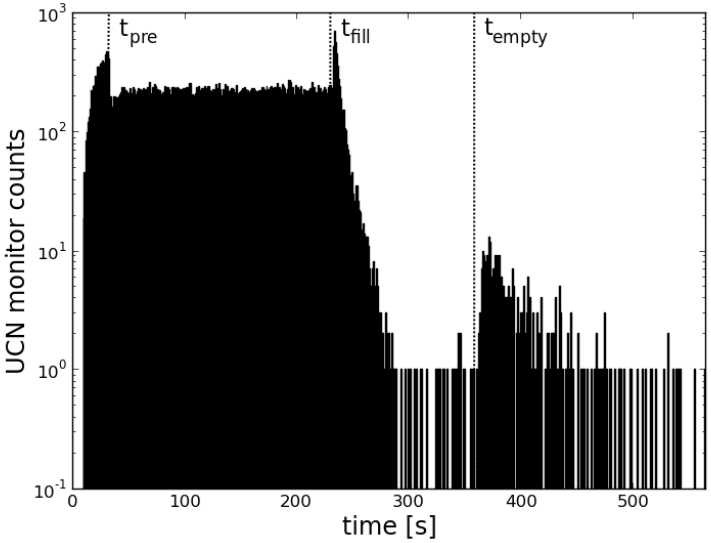


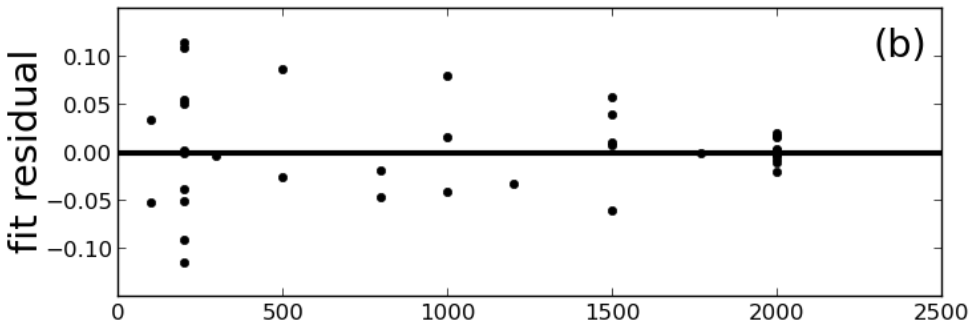
Repeat

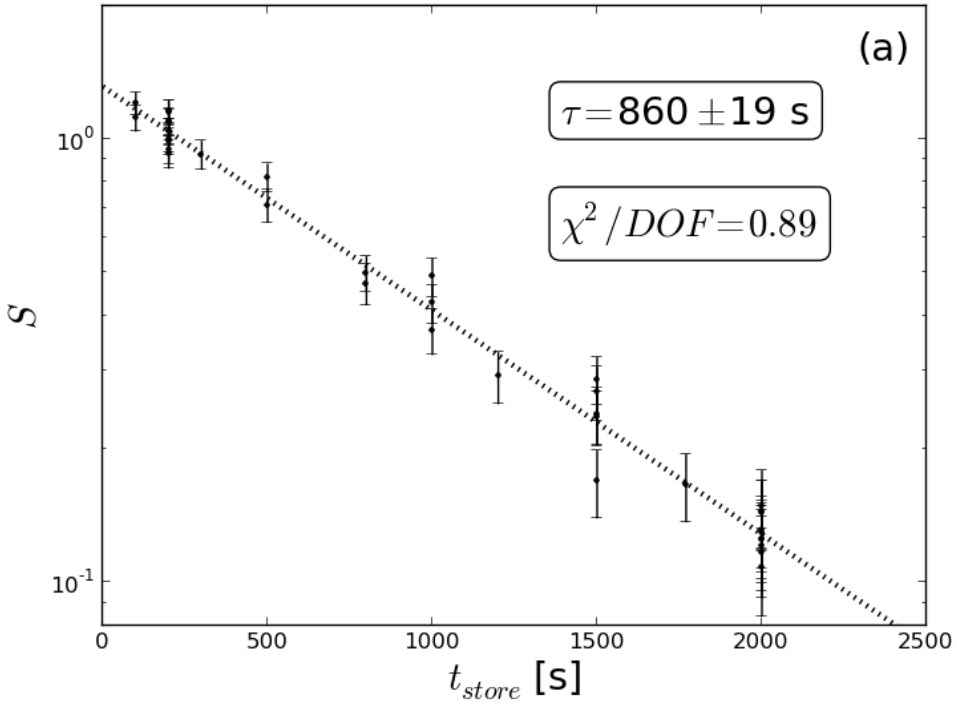


Fill and Empty Measurement

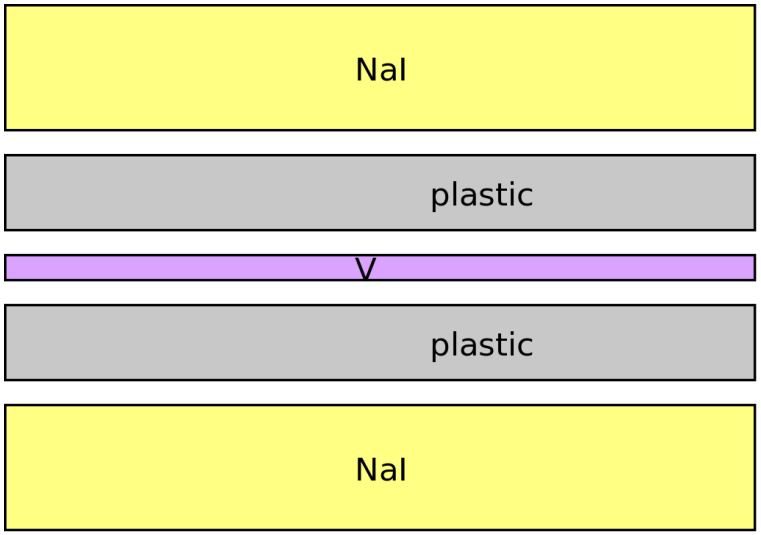


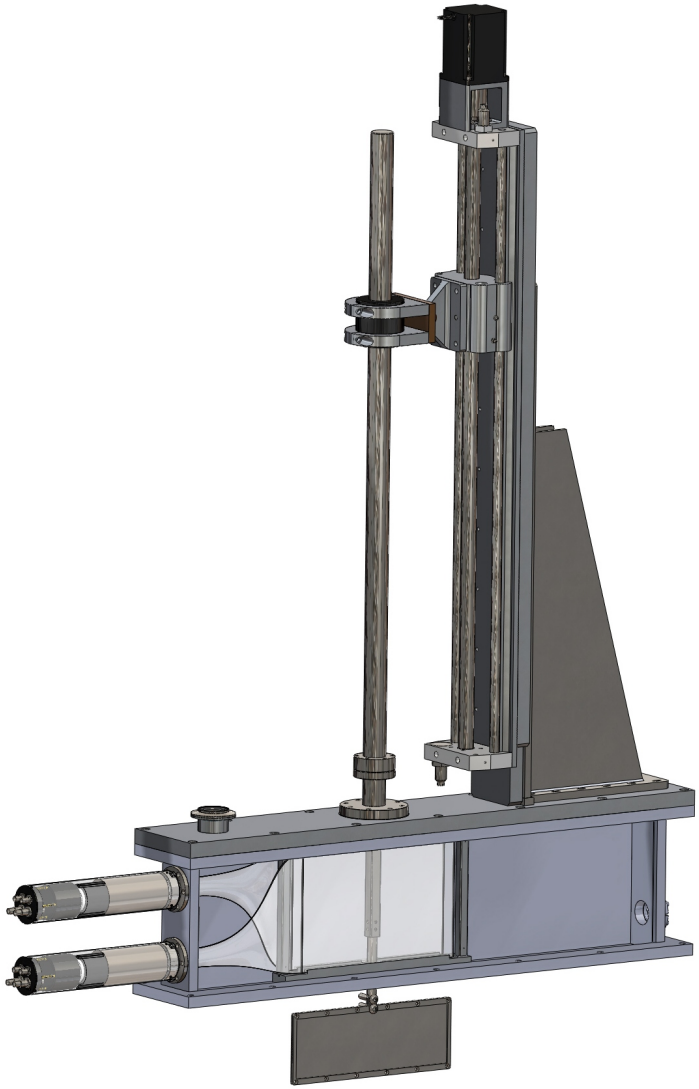




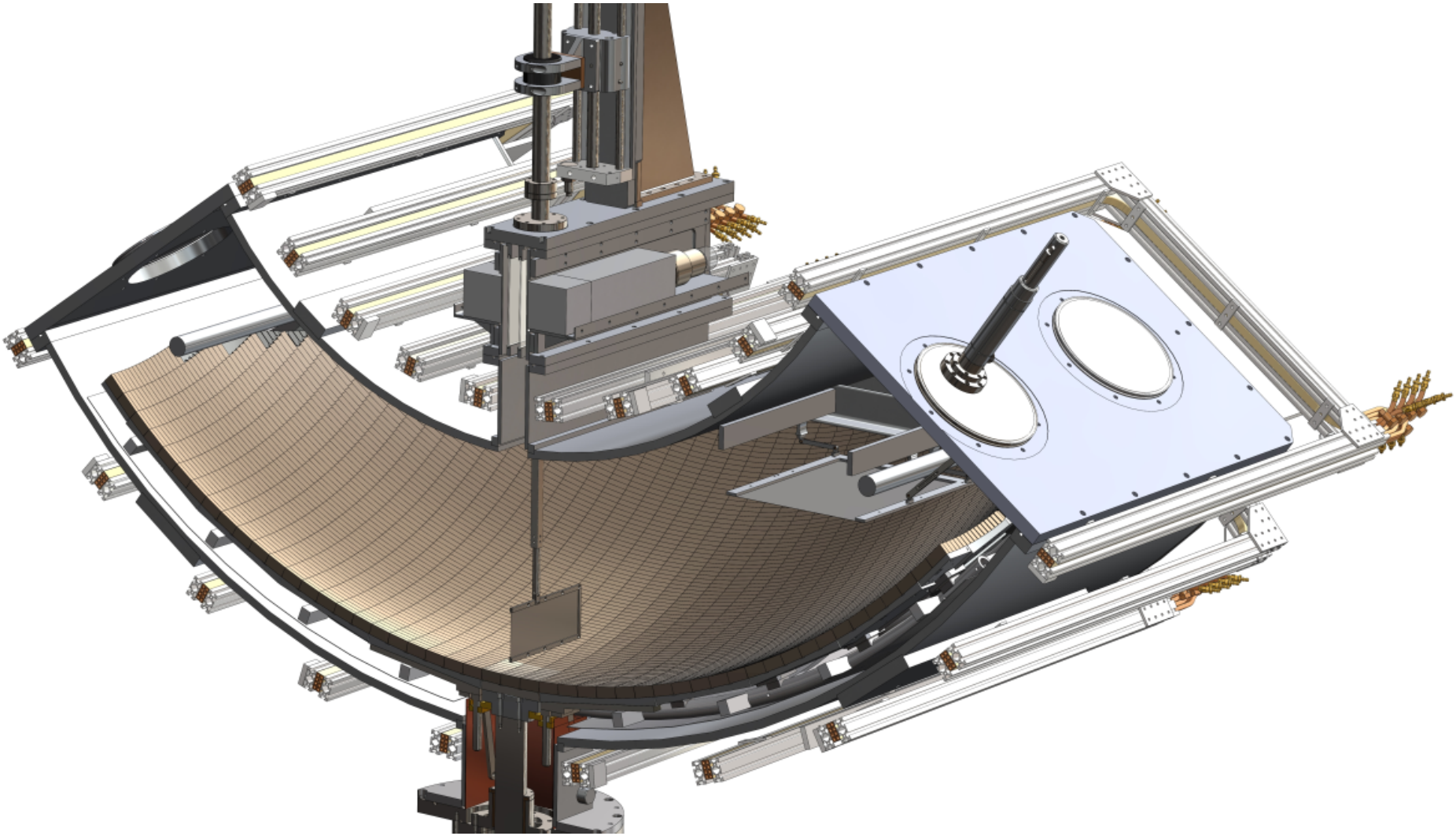


- $^{51}\mathrm{V}(n,\gamma)^{52}\mathrm{V}$
- $^{52}\mathrm{V} \rightarrow ^{52}\mathrm{Cr} + \beta + \gamma$
- $V_F \approx -7$ neV
- $\ell_{abs} = 12.6\ \mu$m at 1 m/s
- $(\ell_{up})_{meas} = 1.36 \pm 0.49$ mm at 1 m/s

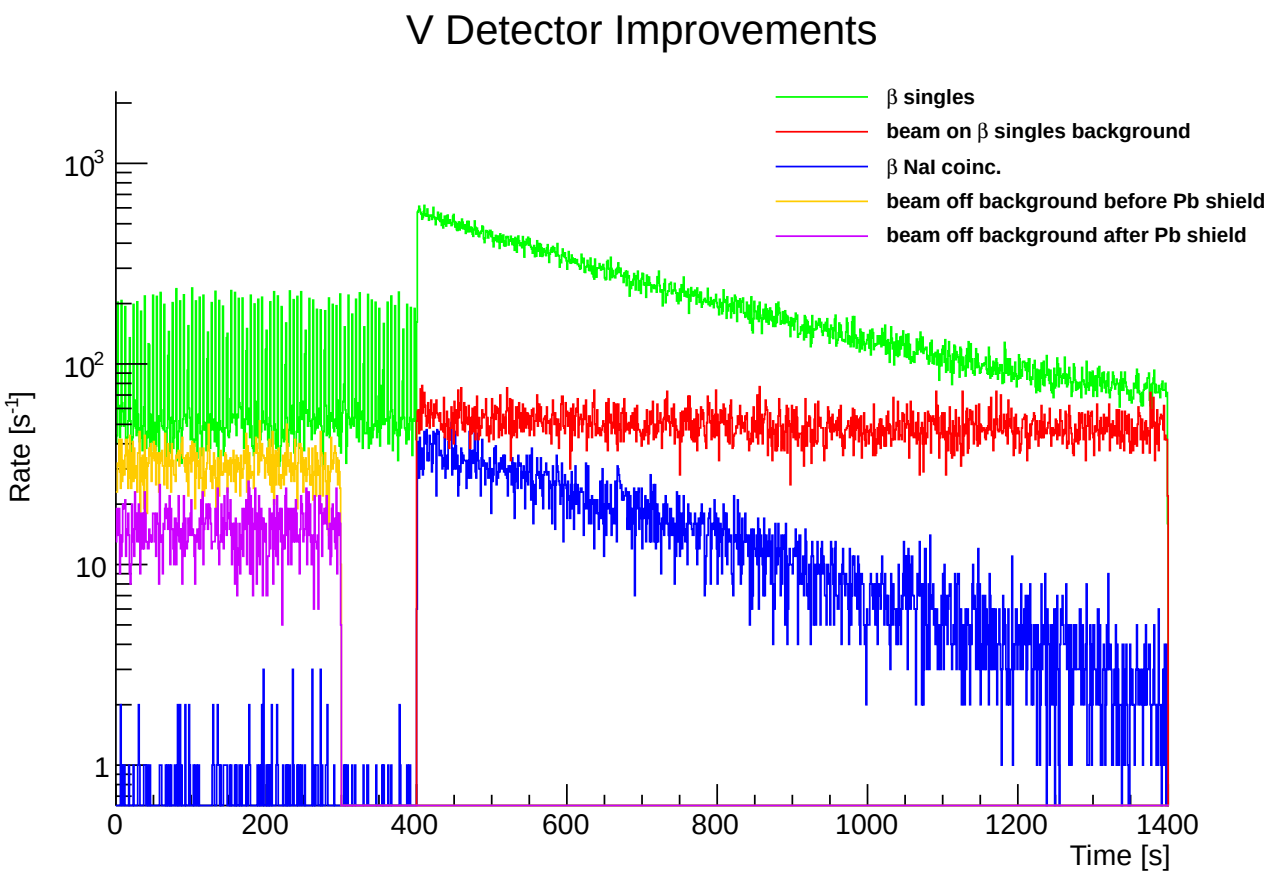




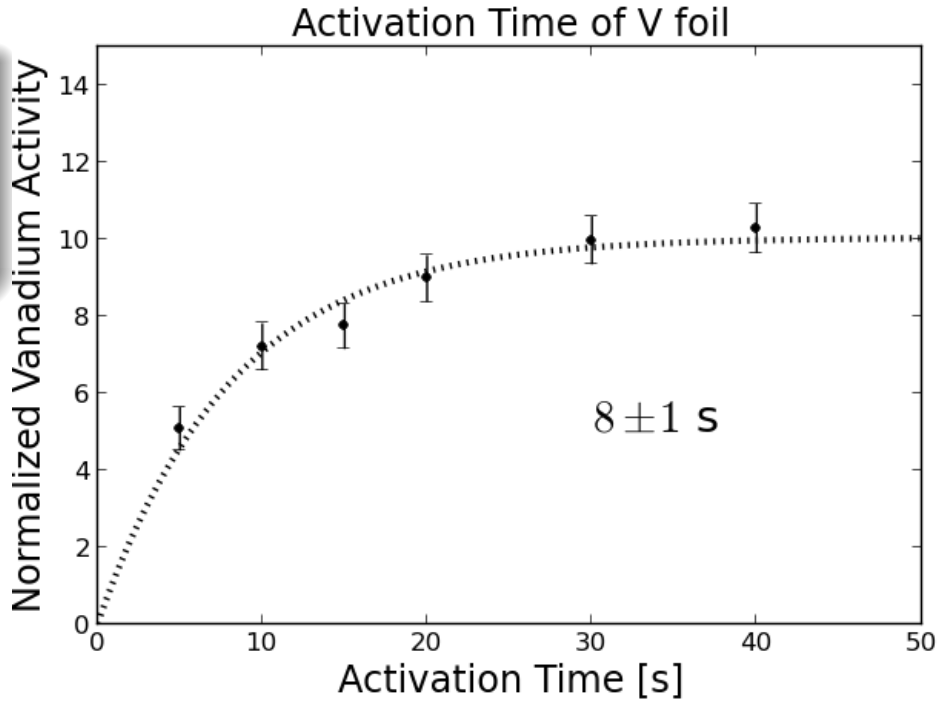
Absorb ($t \sim 30$ s)

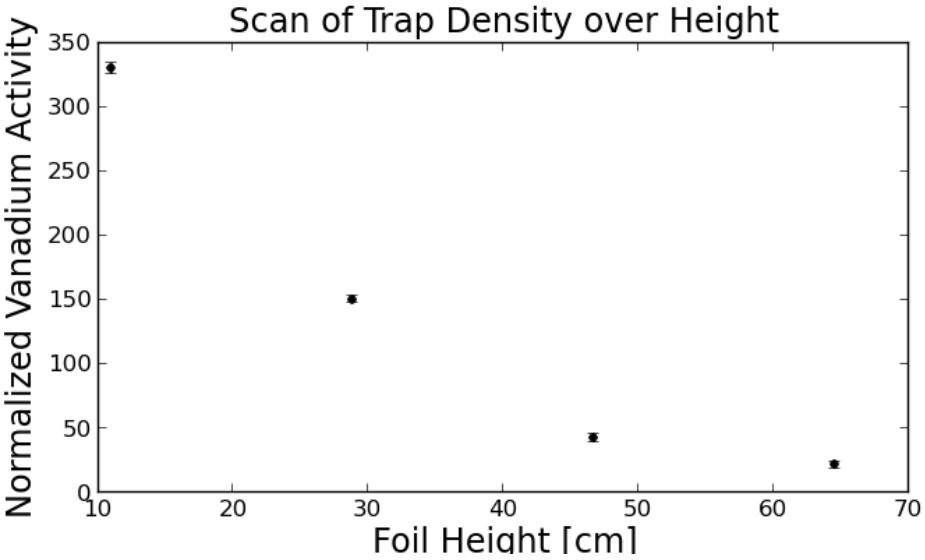


- greatly increased S/B with β/γ coincidences
- identified major source of background – *n*-activation of NaI



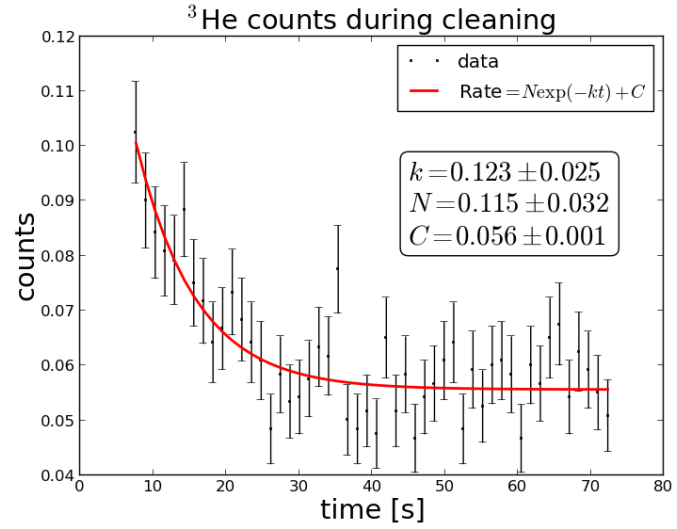
- measure UCN density vs. height
- compare to models, MC, test neutron cleaning efficiency

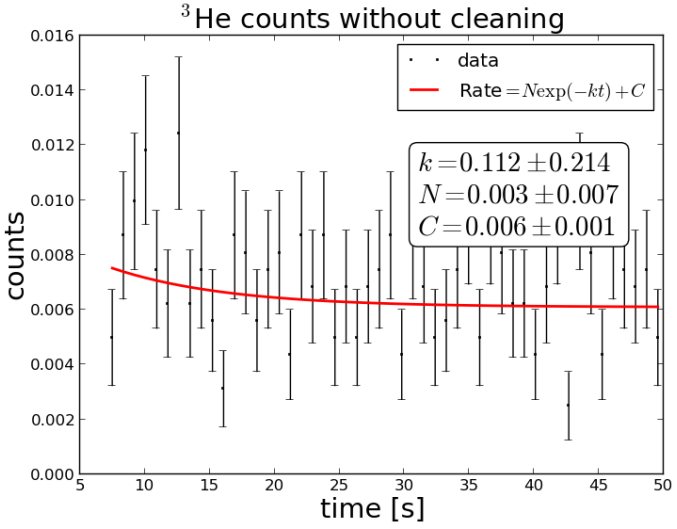




- suggests rapid absorption compared to previous methods
- can be varied to test systematic effects

- up-scattered neutrons can be detected
- improved efficiency/background reduction forthcoming
- need to separate sources of up-scattering
- can use V foil height scan as a check





- no major losses observed in trap
- expect 10^5 UCN per fill in future run campaigns
- V detector commissioning succesful – promising for τ_n measurement, probing dynamics of the trap
- we have a test-bed for new experimental techniques

Section 3

Going Non-Linear

$$\rho = \rho(z, t)$$

$$\epsilon = \epsilon(\rho(z, t))$$

$$\tau_n = \frac{t_2 - t_1}{\ln\left(S_1(\epsilon(t))/S_2(\epsilon(t))\right)}$$

$$\rho = \rho(z, t)$$

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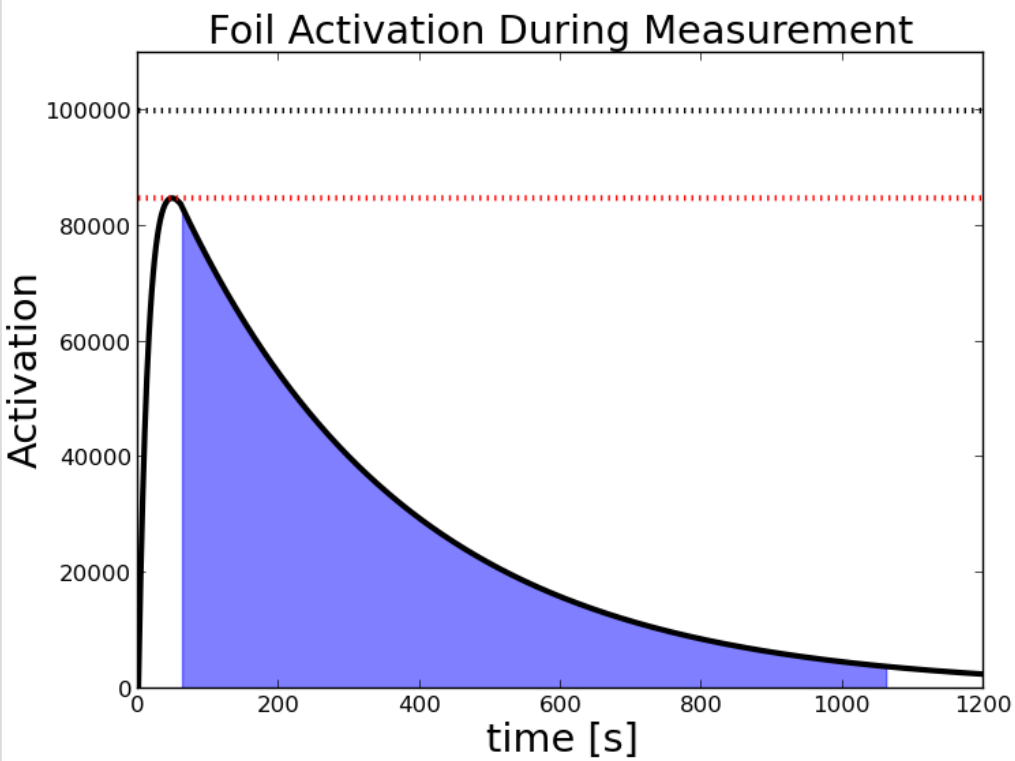
$$\tau_n = \frac{t_2 - t_1}{\ln\left(S_1(\epsilon(t))/S_2(\epsilon(t))\right)}$$

$$\epsilon(\cancel{\rho(z, t)})$$

$$A(t) = D(t)N_{UCN} \approx \tau_D^{-1} N_{UCN}$$

$$\tau_{D(long)}^{-1} = \tau_{D(short)}^{-1}(1 + \eta)$$



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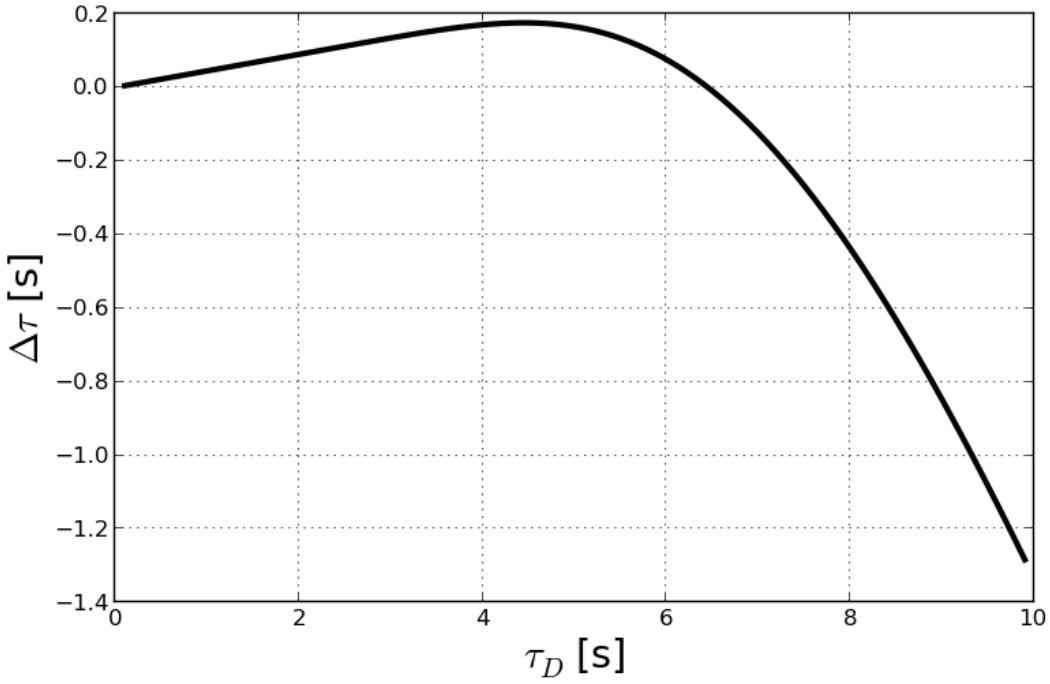


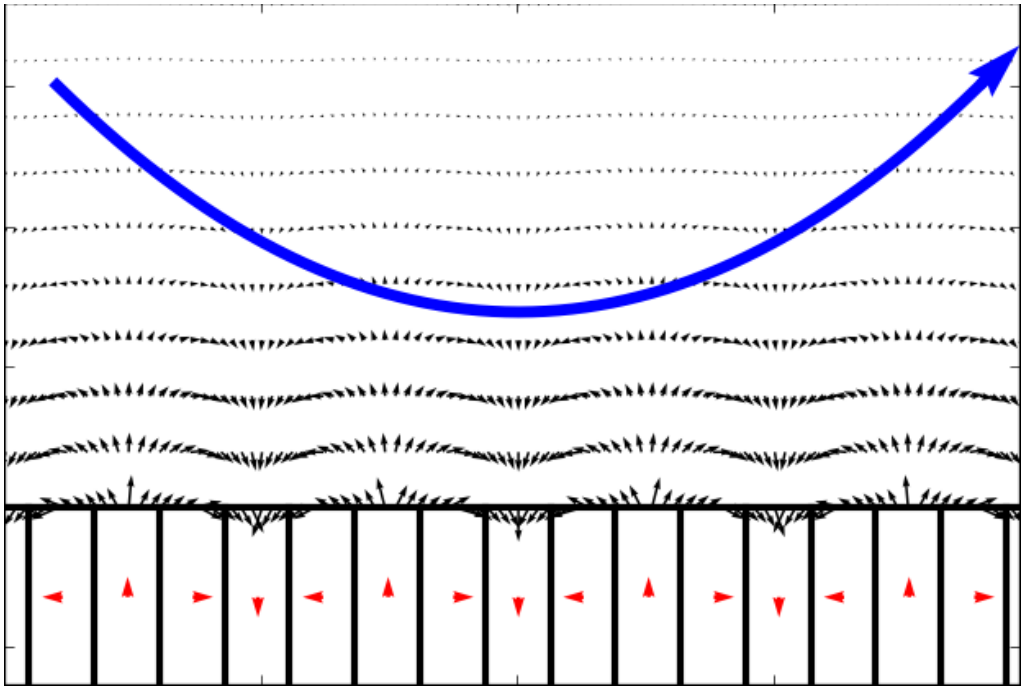
$$\frac{\lambda^3}{V} = \left(\frac{100\ \text{nm}}{1\ \text{m}}\right)^3 \ll 1$$

$$\ell_{\text{UCN-UCN}} \sim 10^{21}\ \text{m}$$

$$\partial_t \mathcal{H} = 0$$

$$\omega_L \gg |\dot{\mathbf{B}}|/|\mathbf{B}|$$

$$\rho(v)dv \propto v^n dv$$



$$\mathcal{H} = \frac{p^2}{2} + gz \pm \mu\,|\mathbf{B}|$$

$$|\mathbf{B}|^2 = B_h^2 \frac{(r+R)^2}{x^2+z^2} + \frac{8B_r^2}{\pi^2} \times \sum C_n C_m e^{-(k_n+k_m)\zeta} \cos\left(k_n - k_m\right)\eta$$

```
for (i=0;i<order;i++)
{
        force(x,a);

        for (n=0;n<3;n++)
        {
                p[n]+=coeff1[i]*a[n]*dt;
        }

        for (n=0;n<3;n++)
        {
                x[n]+=coeff2[i]*p[n]*dt;
        }
}
```

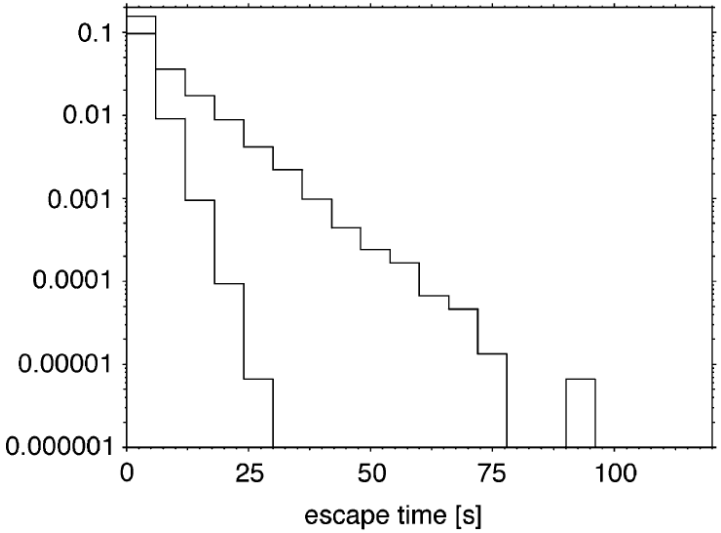
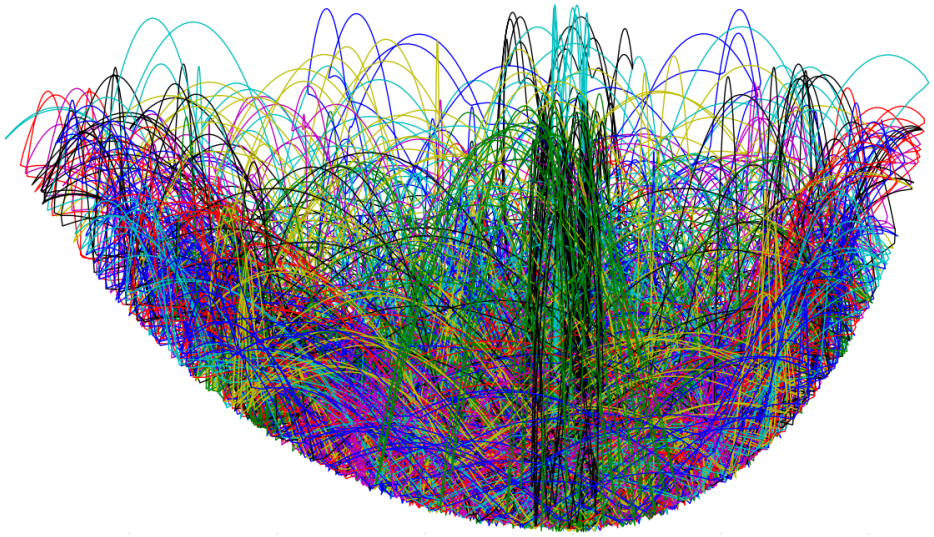
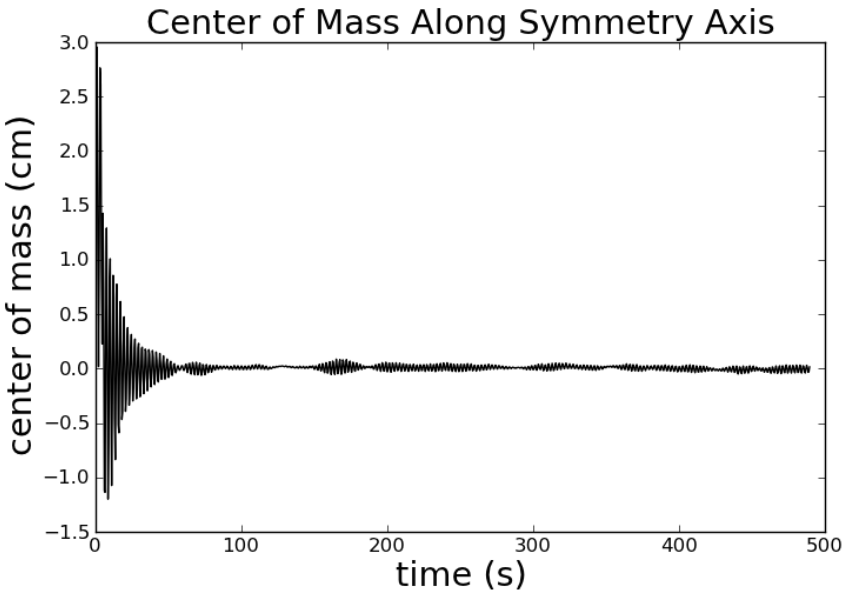
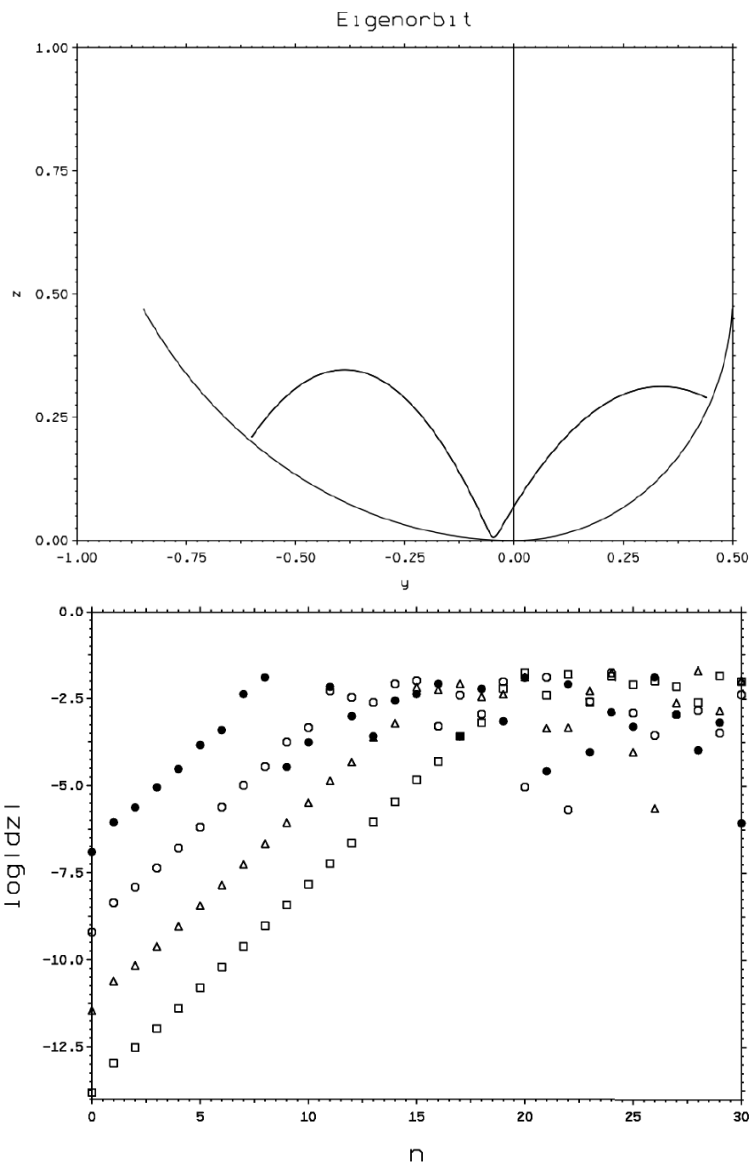
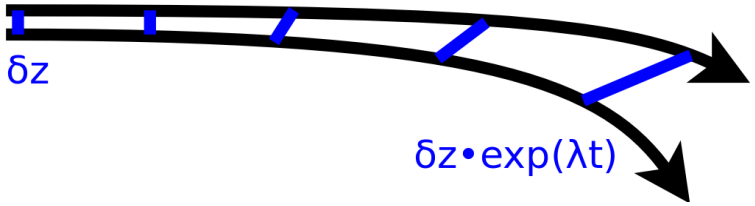


Fig. 7. Escape-time histograms for the two-way ripple model with a guide field of 0.1 T and two different cleaning heights: $h_{\text{clean}} = 44$ cm for the upper curve and 42 cm for the lower curve.

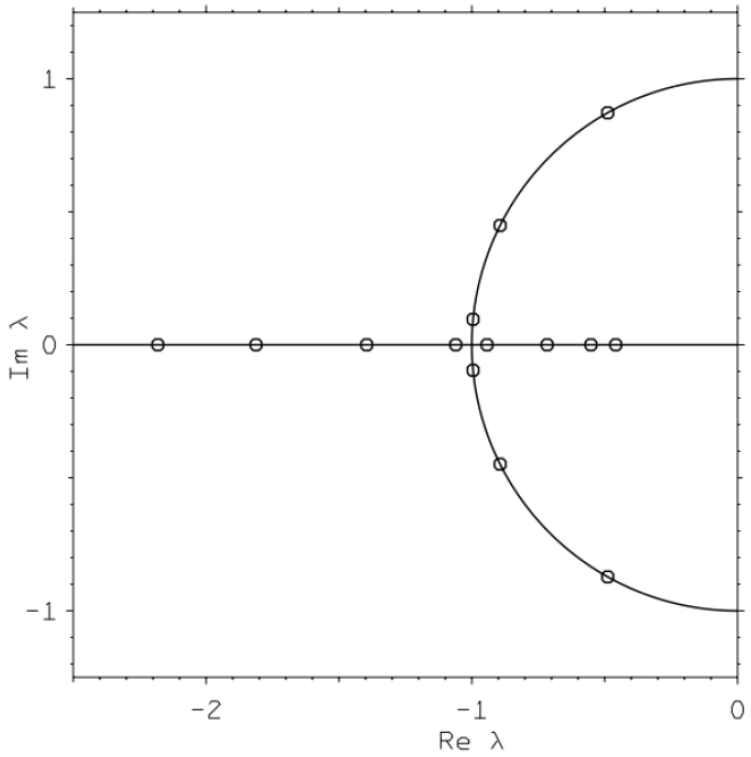




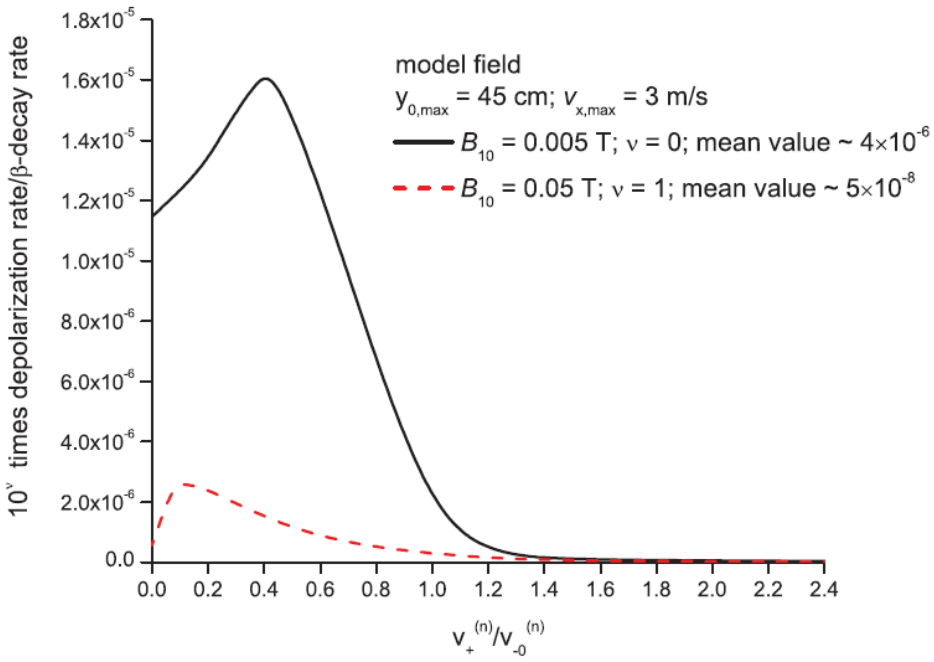




$$\dot{\vec{\delta z}} = \mathbf{J} \cdot \mathbf{D}^2 H\Big|_{z=z_0(t)} \cdot \vec{\delta z}$$



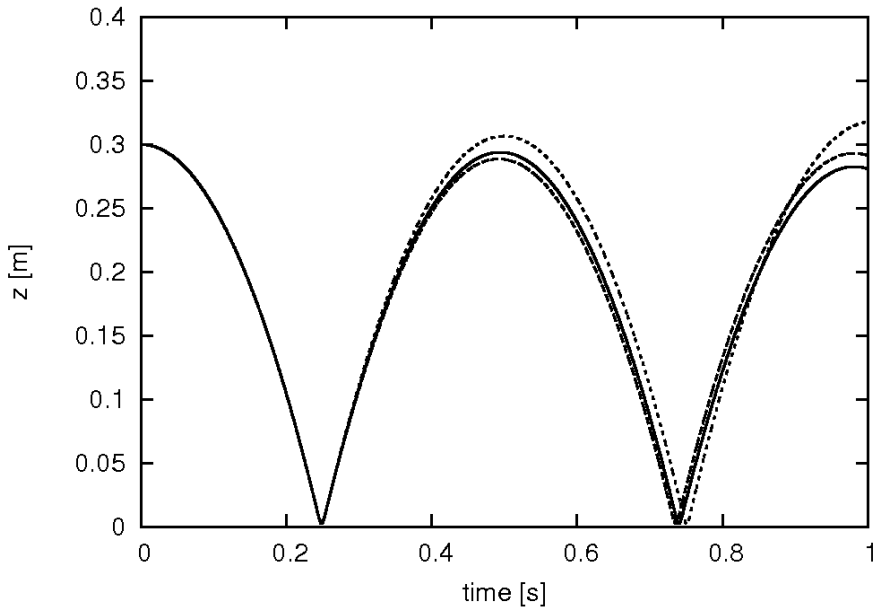
$$
\begin{aligned}
E\phi_+ &= -\frac{\hbar}{2m}\left[\phi_+'' - \left(k_x^2 + k_z^2\right)\phi_+\right] + mgy\phi_+ + |\mu_n|B\phi_+ \\
E\phi_- &= -\frac{\hbar}{2m}\left[\phi_-'' - \left(k_x^2 + k_z^2\right)\phi_- + \left(\theta'\phi_+' - Kk_x\phi_+\sin\theta\right)\right] \\
&\quad + mgy\phi_- - |\mu_n|B\phi_-
\end{aligned}
$$



- Majorana Spin Flips
  - caused by field nodes
  - field mapping
  - negligible loss achievable
- Non-adiabaticity
  - ongoing work (Steyerl 2012)
  - expected to be $\mathcal{O}\left(10^{-5}\right)$
  - hard to measure

$$V(z,t) = Ae^{-k(z+A\sin(\omega t+\phi))} + gz$$

- 1-D tracking studies indicate $\lesssim 10^{-4}$
- mitigated by lower cleaning height
- studied using accelerometers
- affect on orbit stability?



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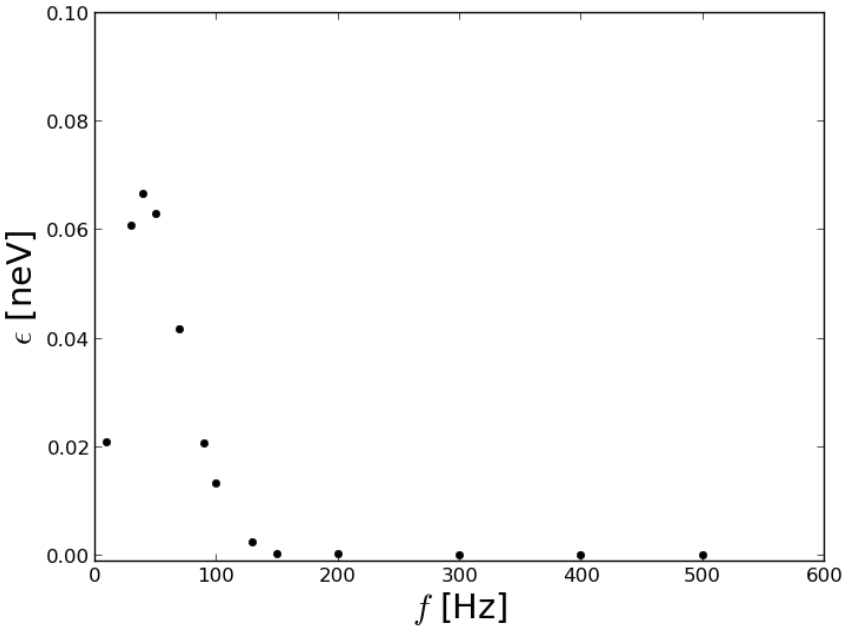

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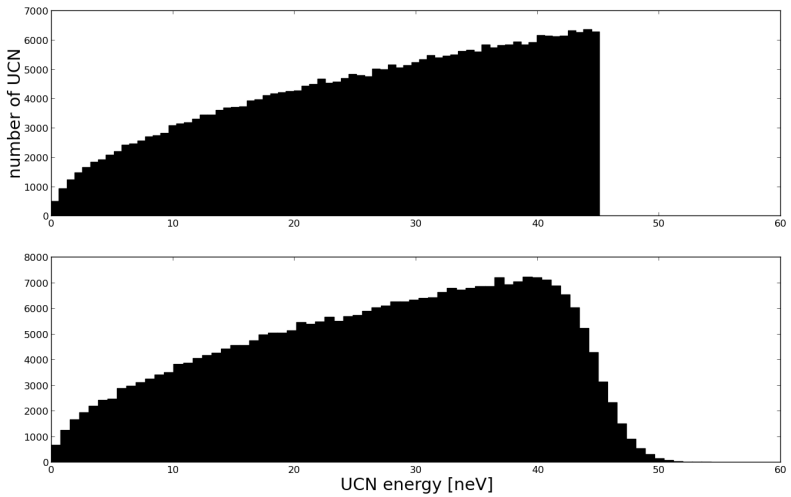

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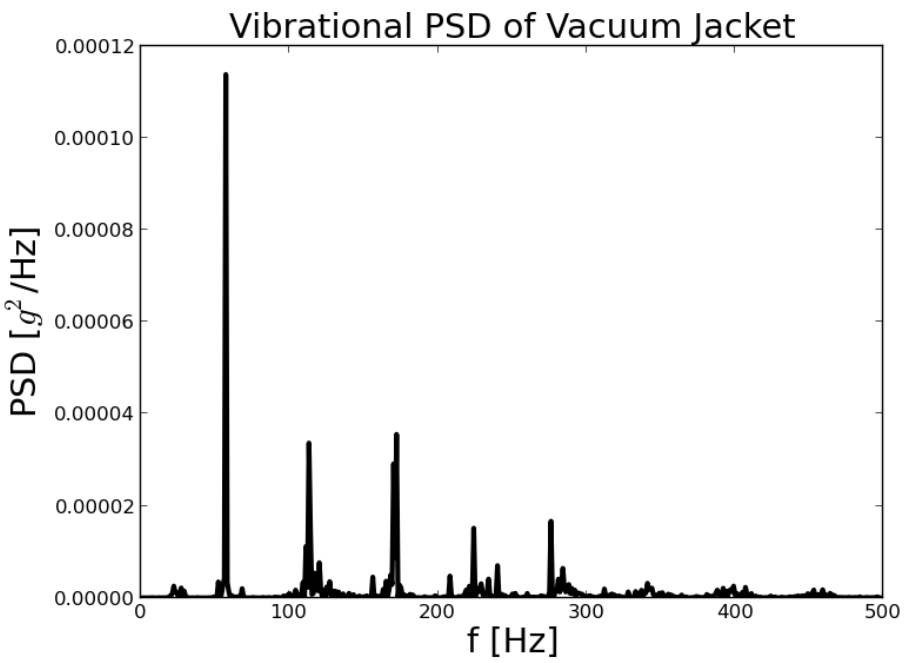
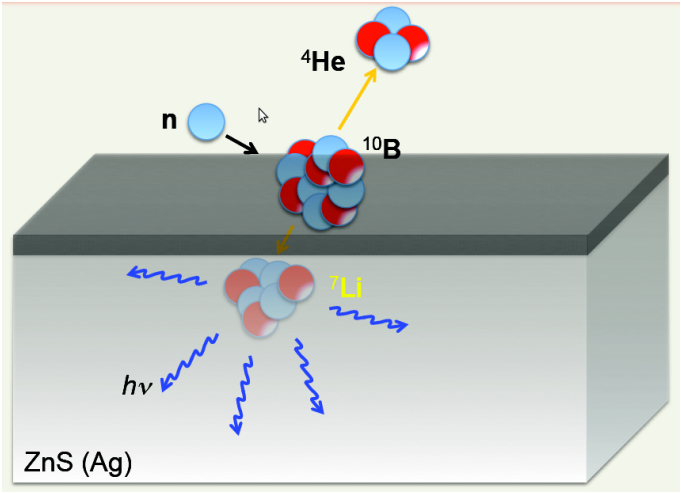


- complications: spin dynamics, vibrations, trap imperfections
- can we use statements about chaos/instability to constrain systematics?
- what is the ultimate path to cleaning, phase-space-insensitivity?
- what is the ultimate trap?



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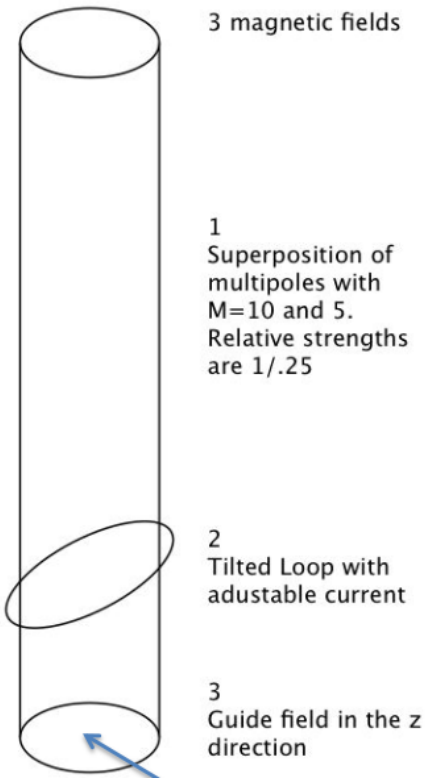

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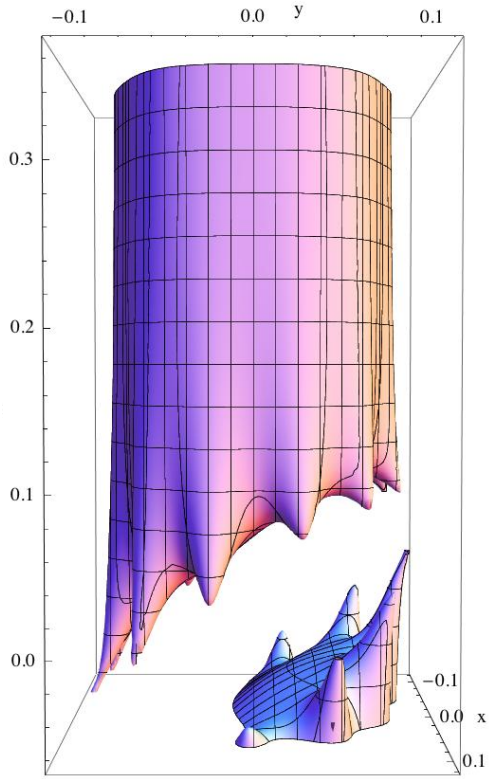

- our trap is a trap
- new detection schemes are promising to improve upon "fill-and-empty" technique
- now have the motive, means, and opportunity to perform first τ_n measurement in a magnetic bottle – ~ 1 s in reach