
# Probing for BSM Physics with Precision Measurements of the Neutron Lifetime and the Neutron Electric Dipole Moment

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Developing New Directions in Fundamental Physics (DND) 2020 Workshop

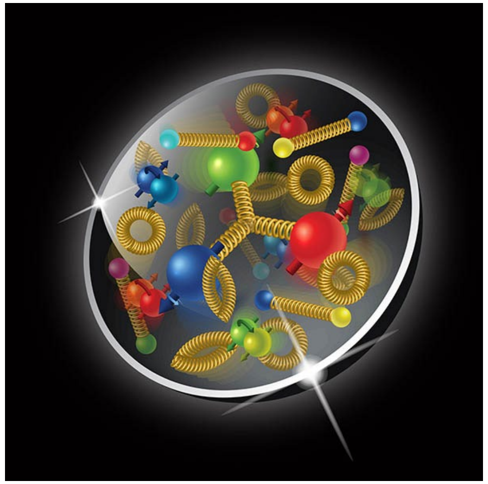
LANSCE Los Alamos Neutron Science Center

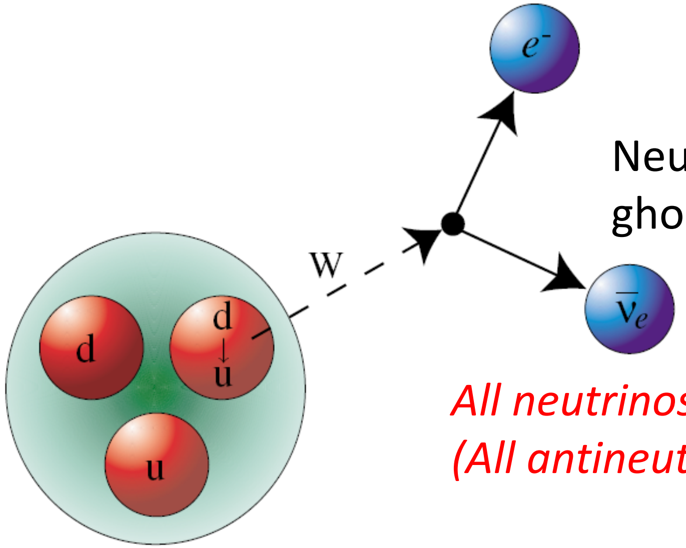
U.S. DEPARTMENT OF ENERGY Office of Science

NSF

# Neutrons are a unique laboratory to study the four fundamental forces of nature.

## Strong force

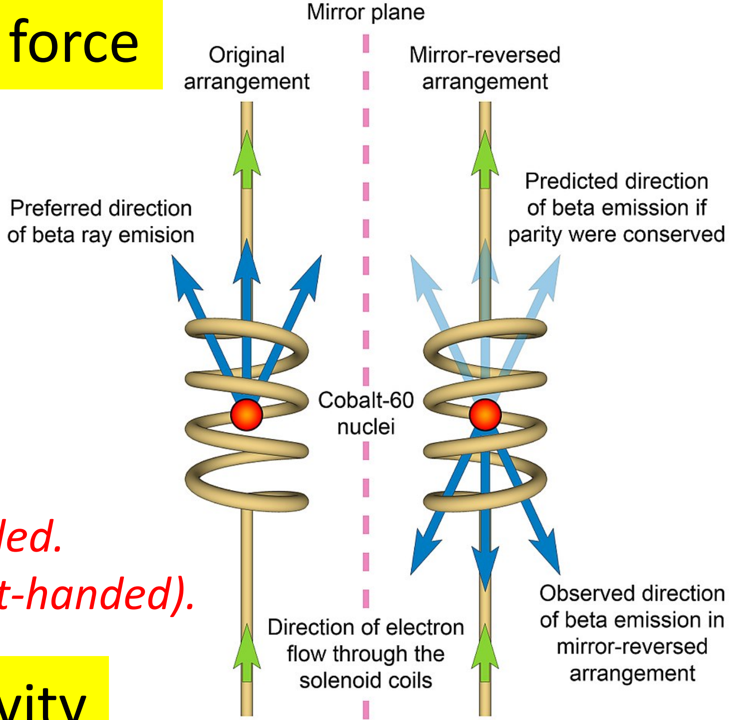




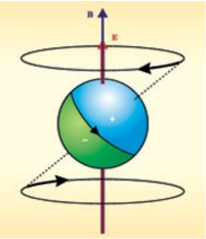

Neutrino, the ghost particle

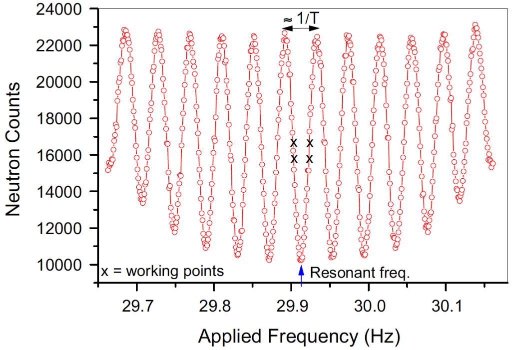
*All neutrinos are left-handed.*
*(All antineutrinos are right-handed).*

## Weak force




## Electromagnetic force

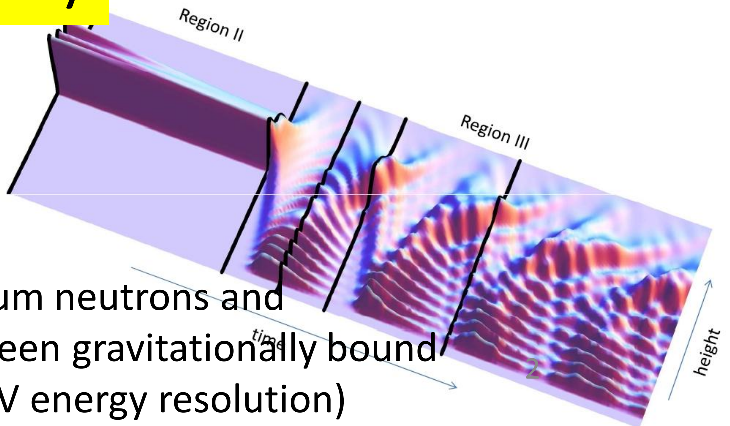





$$n \longrightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$

Neutron beta decay is the archetype of nuclear transmutation.

## Gravity



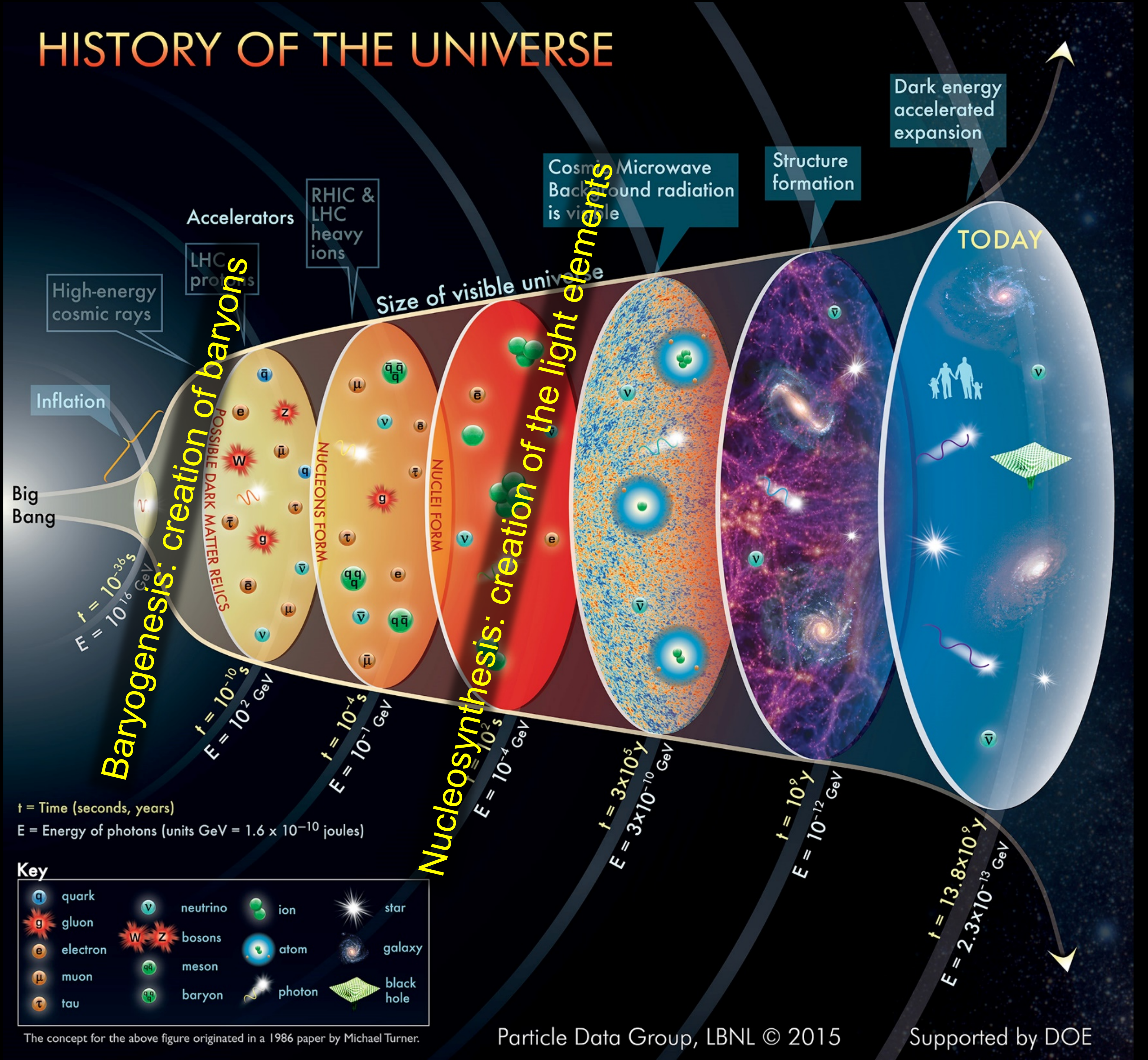

Bouncing quantum neutrons and transitions between gravitationally bound neutrons (w/ peV energy resolution)

# Big Questions:

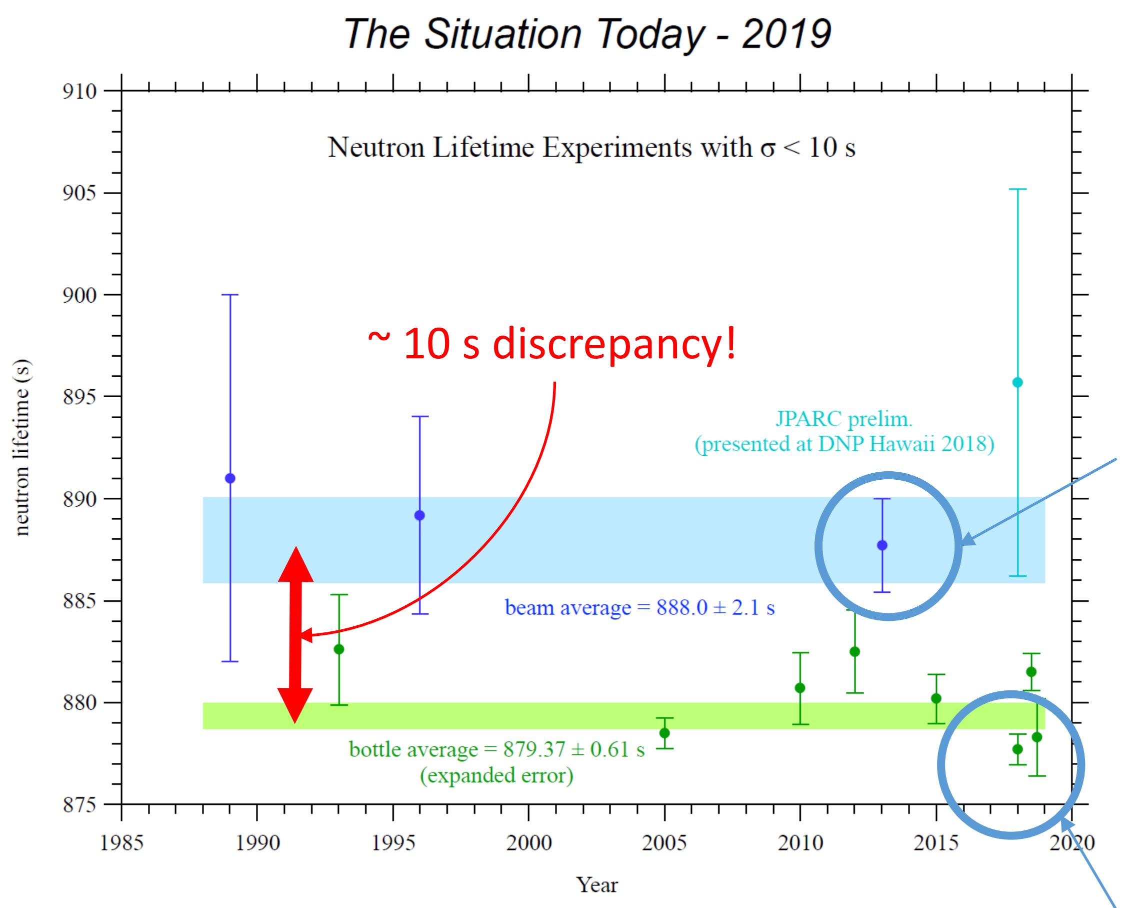
1. Why does the universe have matter?
2. How were the elements made in the Big Bang?
3. What is the nature of the physics beyond the standard model?

Neutron experiments can help to answer these questions.

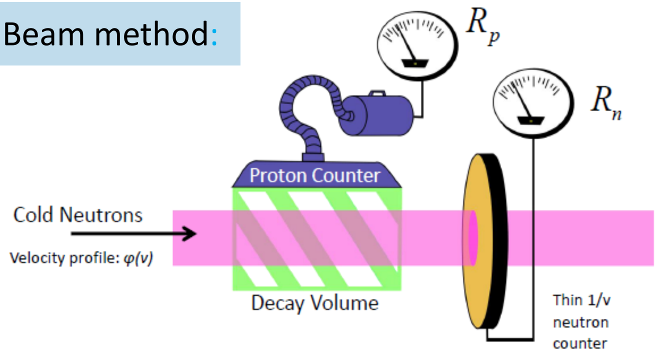
For example:
EDM→ baryogenesis
N lifetime→BBN



# Currently, the neutron lifetime values **between two leading methods to measure the neutron lifetime** disagree by ~10 s.



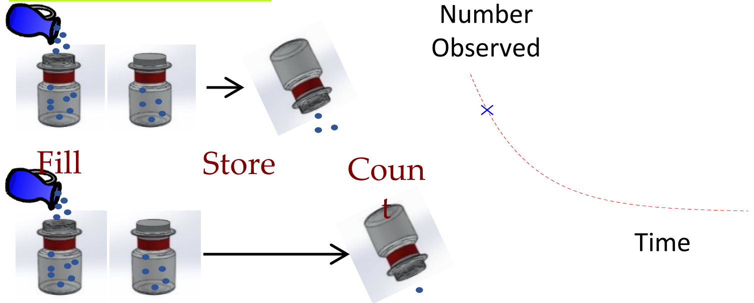

Beam method:




Most precise Beam: $\tau_n$ = 887.1 ± 2.2 s

Yue et al., Phys. Rev. Lett. 111, 222501 (2013)

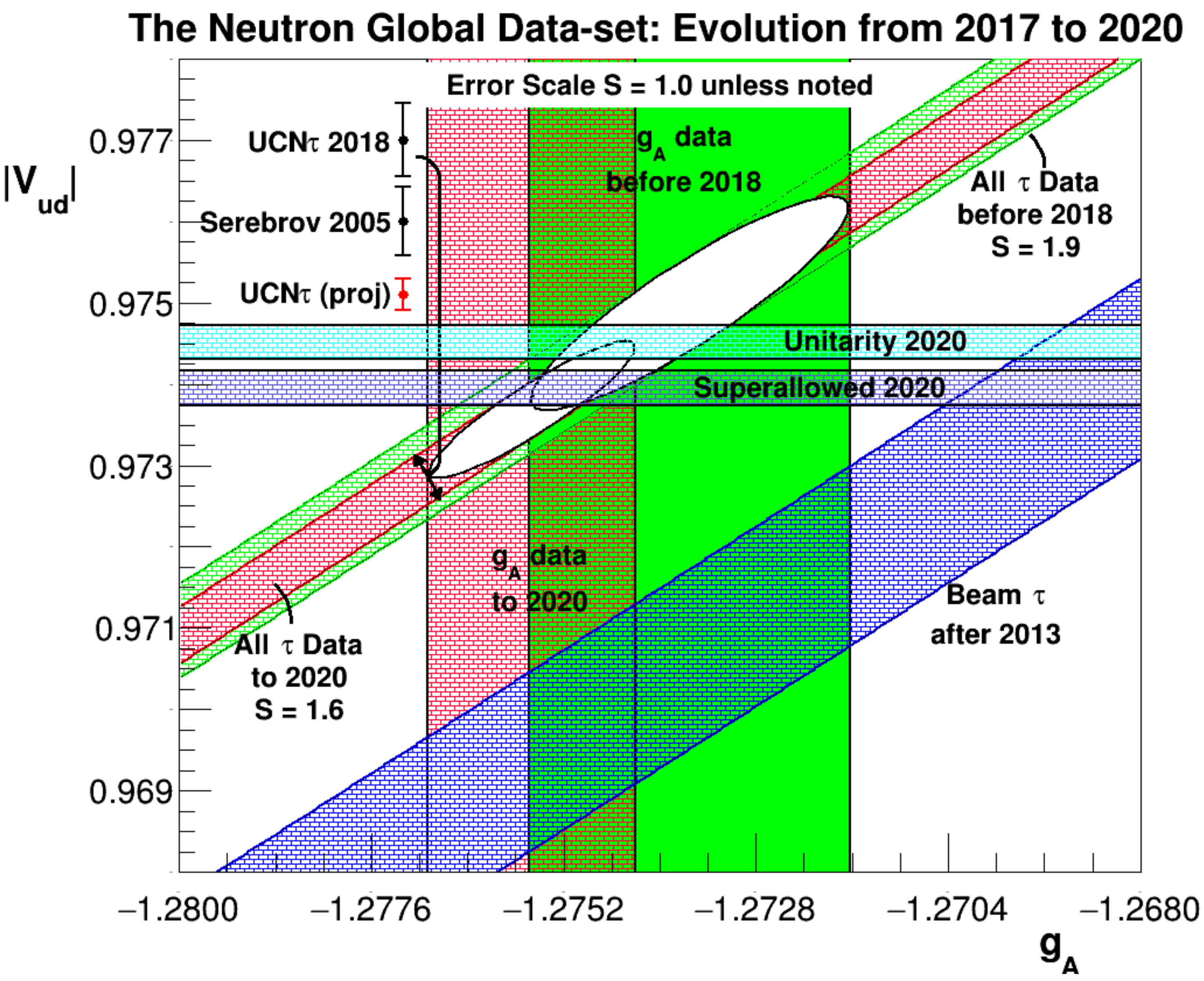
Bottle method:




Most precise Bottle: $\tau_n$ = 877.7 ± 0.75 s

Pattie, *et al.*, *Science*, 360, 627 (2018)

# Goal: reach 2e-4 to match the level of theoretical uncertainties




CKM Unitarity ?

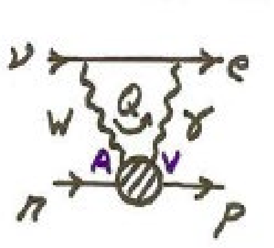
Plot credit: Leendert Hayen←Albert Young

# Precision of 2e-4 needed for CKM Unitarity test

*f*: Phase space factor=1.6886
(Fermi function, nuclear mass, size, recoil)

$$1/\tau_n = f G_F^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(\underline{1+RC})/2\pi^3$$

From $\mu$-decay: 0.6 ppm (MuLan 2011)



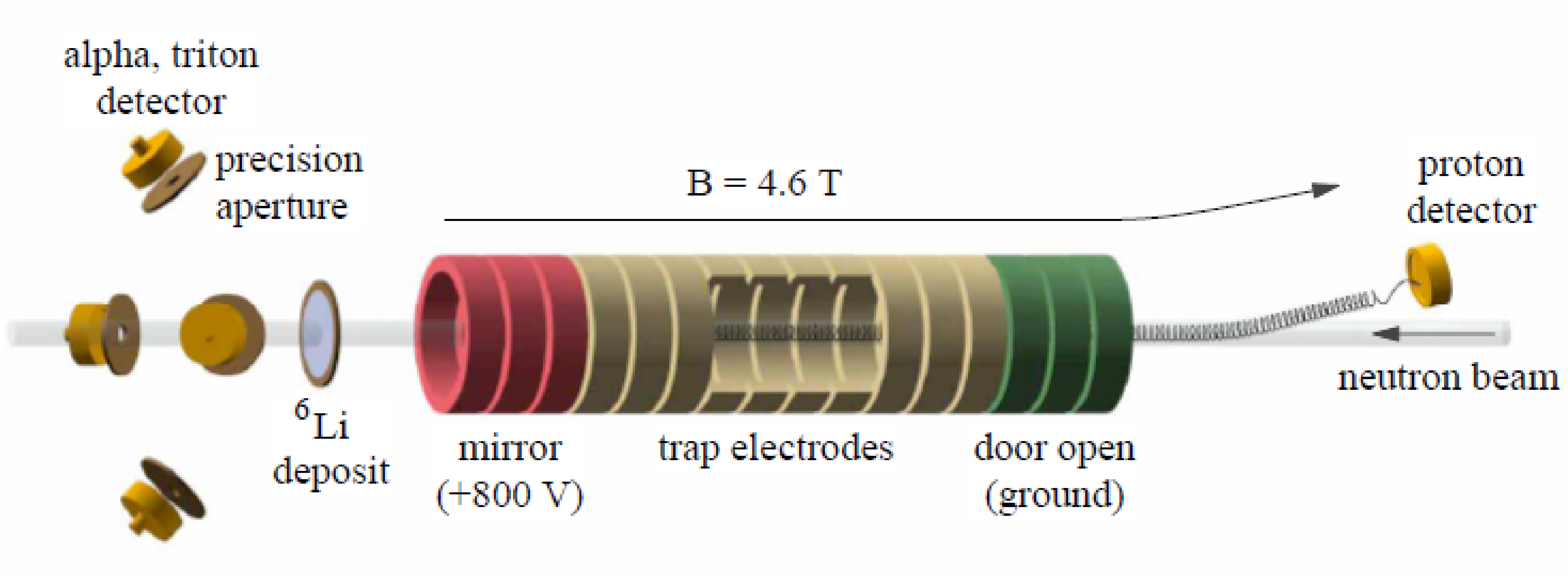

$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ \frac{m_W{}^2}{Q^2 + m_W{}^2} F(Q^2)$$

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9 s}{\tau_n (g_V + 3g_A^2)}$$

To math the theoretical uncertainty: 2 $\times 10^{-4,}$ it requires experimental uncertainties of: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 2 \times 10^{-4}$.

Marciano & Sirlin, PRL 96, 032002 (2006)
Seng, Gorchtein, Patel, Ramsey-Musolf, Phys. Rev. Lett. 121, 241804 (2018)

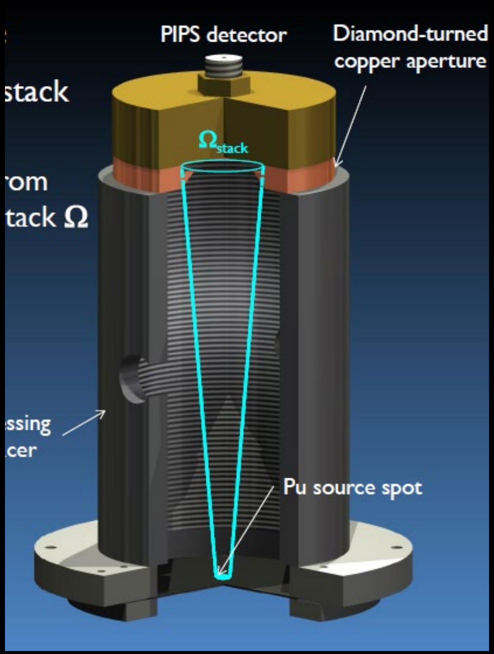
# The best beam lifetime experiment is at NIST



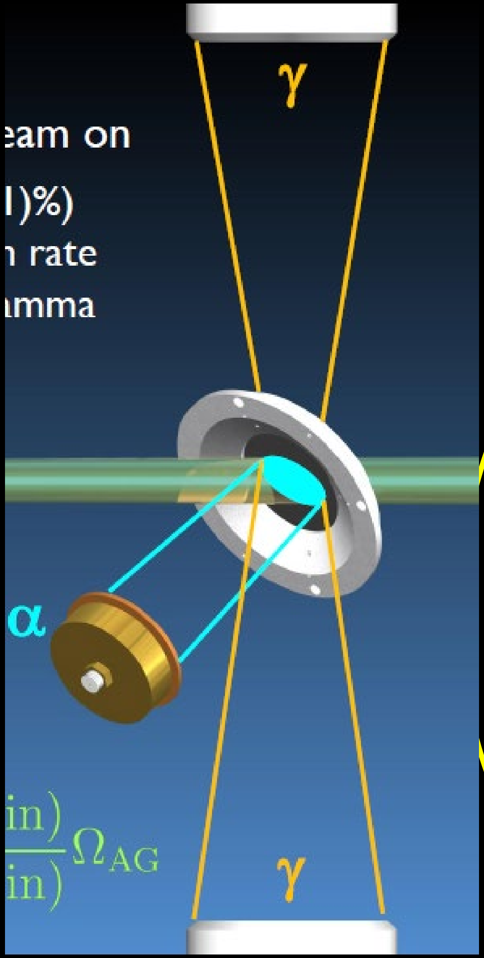

- A cold neutron beam, collimated to 2 mm (BL2) → 30mm (BL3).
- A quasi-penning trap electrostatically traps beta-decay protons. When the door electrodes are set to ground, the protons are guided by a B field to an external detector (surface barrier Si detector).
- A neutron monitor measures the incident neutron flux by counting $n + {}^6Li \rightarrow \alpha + t$.

1. Measure the absolute flux of an α source (Pu)

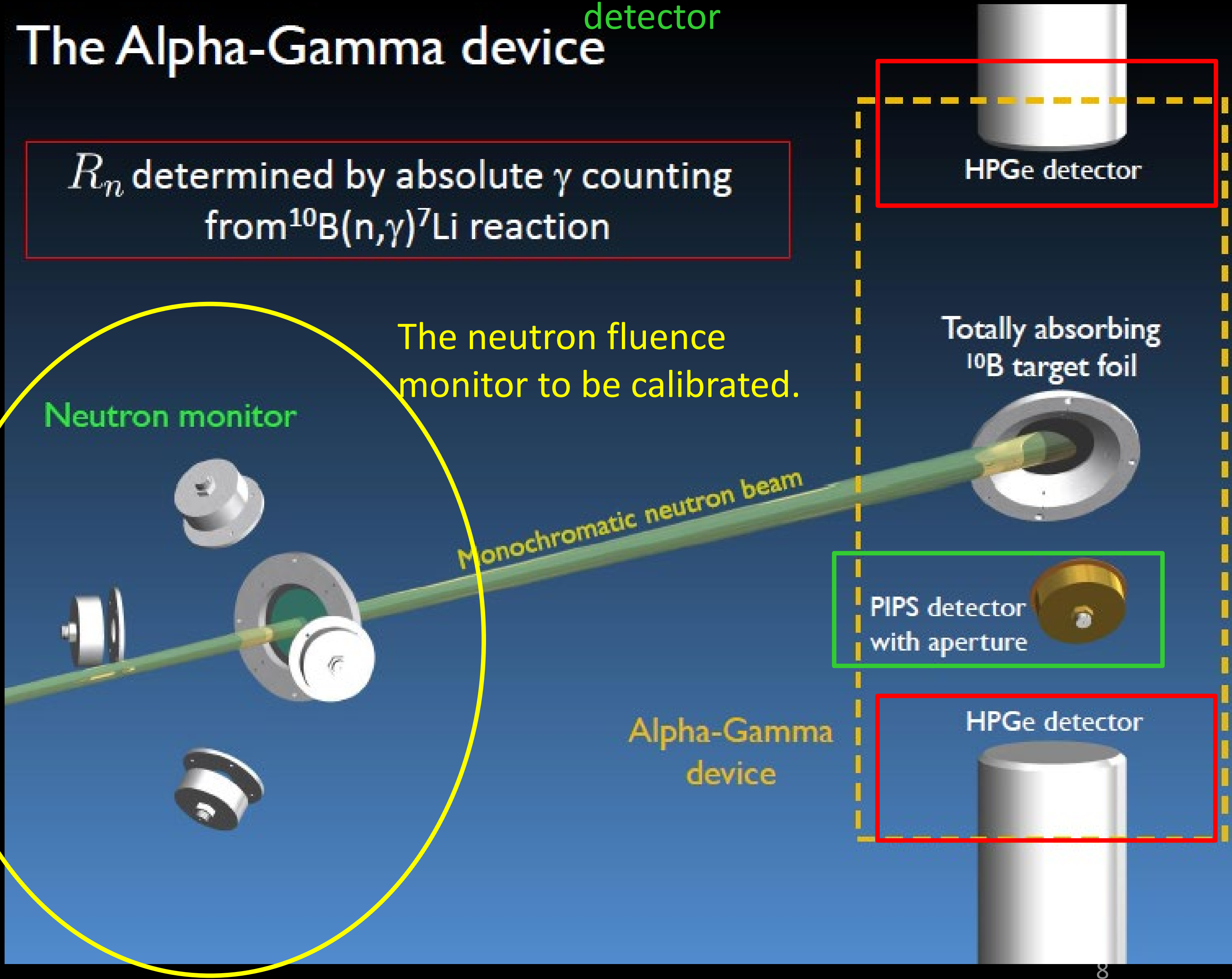
**Andrew Yue, UT Ph.D. thesis (2013), Advisor: Geoff Greene**

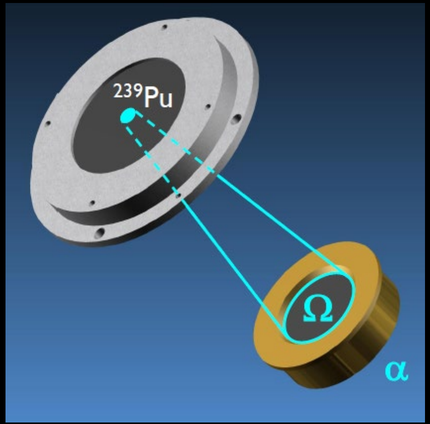



3. Use the (α, γ) reaction on a thin B foil to transfer the calibration to the Gamma detector




4. A thick B foil in to measure the neutron flux using the Gamma detector






2. Use the source to determine the solid angle of the Alpha detector

# Alpha-Gamma version 1 (AG-1) uses this 4-step calibration transfer process to calibrate the BL2 neutron fluence monitor.

1. $n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha(1.472\text{MeV}) + \gamma(478\text{ keV})$, BR=93.7%
   1. Alpha source ($^{239}Pu$, 5.2MeV): 5 μg/cm$^2$. 3mm diameter $PuO_2$, evaporated on a single-crystal silicon wafer.
   2. thick B foil target: elemental $^{10}B$ deposit on single-crystal silicon substrate, 25 μ g/cm$^2$
   3. thin B foil target (98%-enriched $^{10}B_4C$)
   4. Detector set: 1x alpha detector + 2x gamma detectors

2. Monochromatic beam line:

Mean neutron wavelength (using Bragg diffraction from a perfect silicon crystal) determined to a precision of 0.024%→ 0.01%

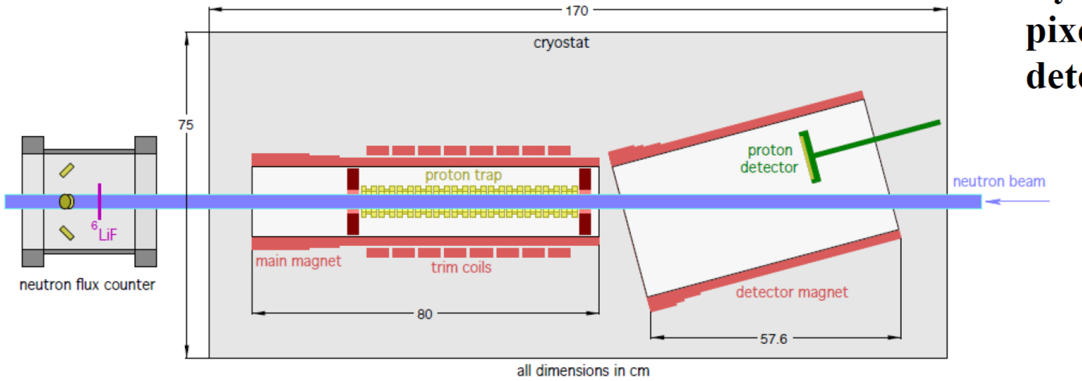
→ Uncertainty of the neutron detection efficiency (on the $^6Li$ deposit): 0.058%

| | | |
|---|---|---|
| 886.3 ± 1.2 [stat] ± 3.4 [sys] seconds | Nico et al 2005 | ← limited by the knowledge of the neutron absorption cross-section on $^6Li$. |
| 887.7 ± 1.2 [stat] ± 1.9 [sys] seconds | Yue et al 2013 | ← the neutron monitor is calibrated using the AG device. |

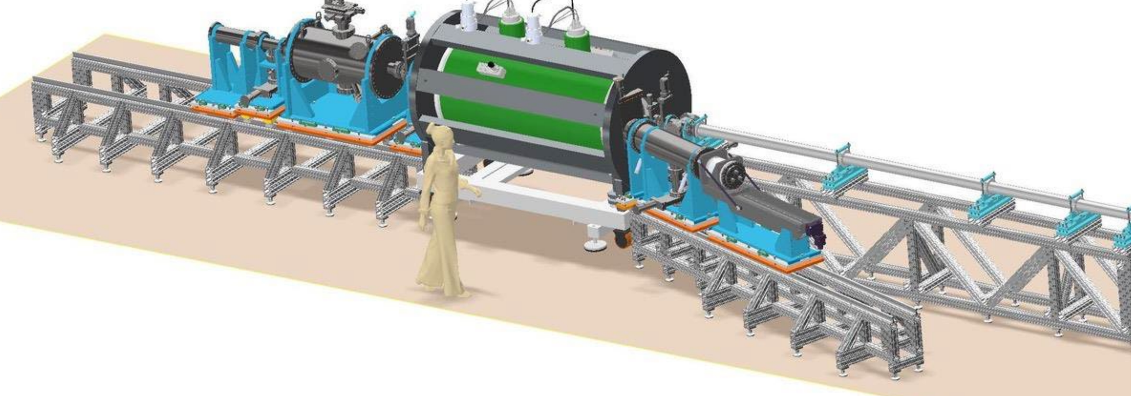
# The new BL3 experiment aims for 0.3 s lifetime precision

**Bigger!**

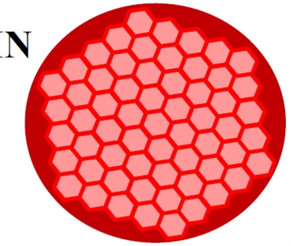
- Increased neutron beam diameter
  *7 mm → 35 mm*
- Uniformity requirements:
  *$\Delta B/B < 10^{-3}$ (in proton trap)*
- 50x increase in trapping volume



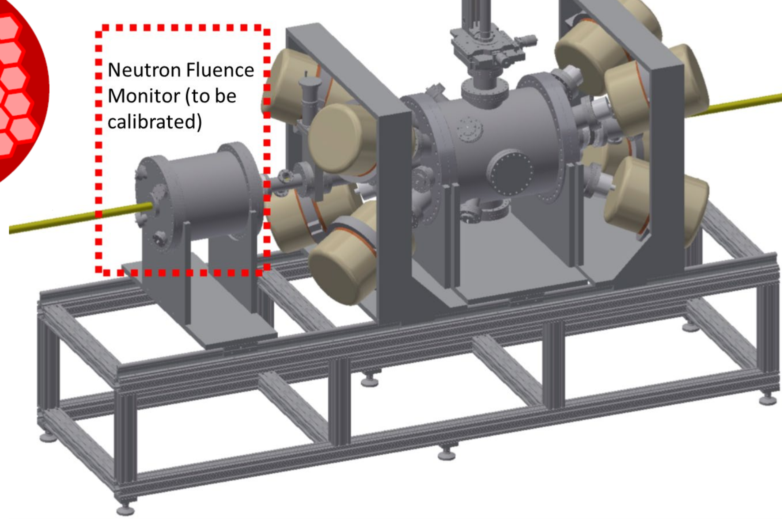

BL3 apparatus



**Nab/UNCB/KATRIN style pixelated proton detector**



AG-2



# Ongoing neutron lifetime experiments

**INT Workshop INT-19-75W (11/2019), Fundamental Symmetries Research with Beta Decay**

| Experiment | Type | Status | Sensitivity (s) | | Best measured lifetime (s) | Extrapolation (s) | Projected (s) |
|---|---|---|---|---|---|---|---|
| | | | Stat. | Sys. | | | |
| BL2 | Beam | DAQ | 1.2 | 1.9 | | 5.3 (Li thick) | 1 |
| BL3 | | R&D | - | - | | | 0.3 |
| J-PARC | beam (TPC); LiNA | DAQ | 10 | 14 | | | 1 |
| Probe | UCN | R&D | - | - | | | 2 |
| Gravitrap 2 | Material bottle | DAQ | 0.7 | 0.6 | 865 | 16 (wall loss) | |
| HOPE | Magnetic bottle (PM) | Ready for DAQ | 39 | - | 835 | 45 (wall loss) | 0.7 |
| Ezhov | Magnetic bottle (PM) | Upgrade | 1.6 | 1.0 | 874.6 | 3.7 (spin flip) | 0.2 |
| UCNtau | Magnetic bottle (PM) | DAQ | 0.7 | 0.3 | 877.4 | 0.16 (residual gas upscattering) | 0.3 |
| tauSpect | Magnetic bottle (SC) | DAQ | - | - | - | - | |
| PENeLOPE | Magnetic bottle (SC) | Construction | - | - | - | - | 0.1 |

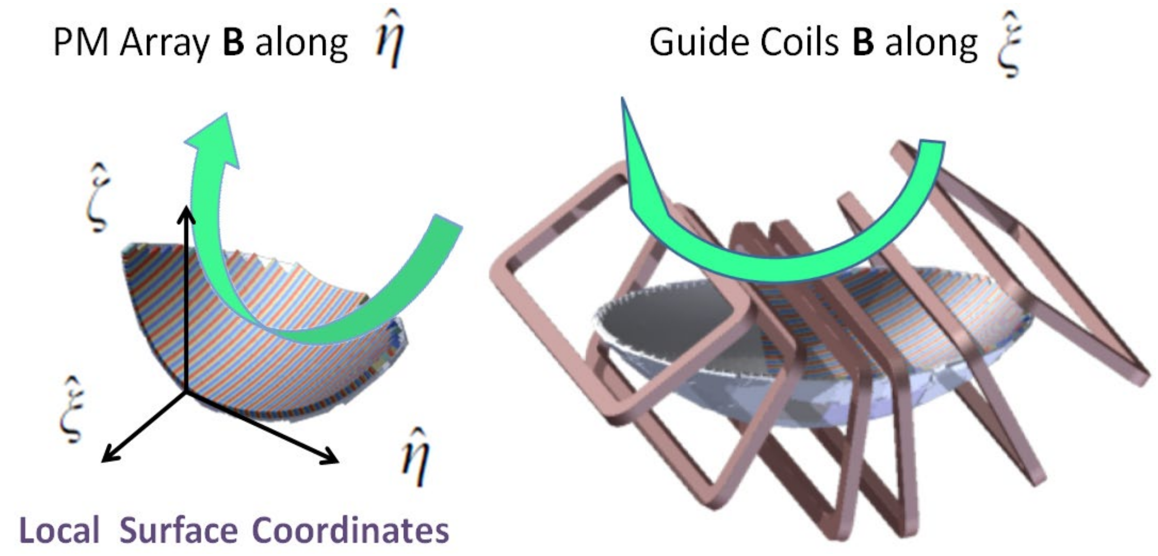
Magnetic bottle

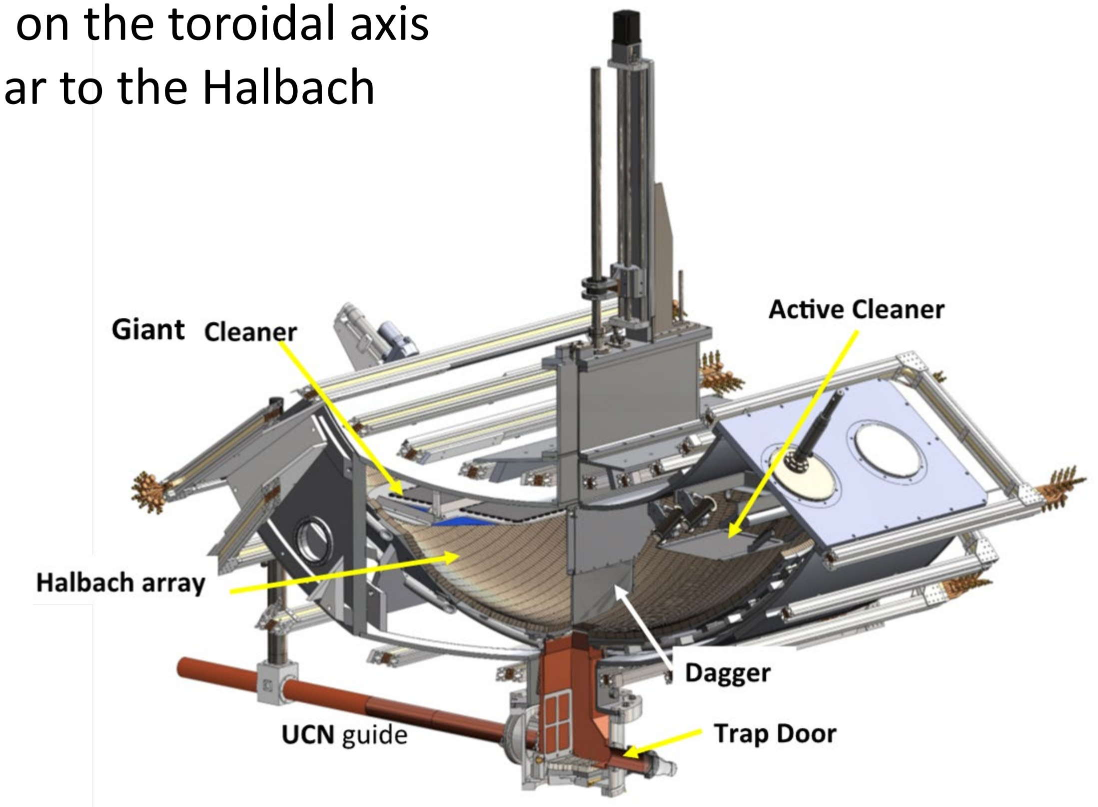
# The UCNτ experiment uses a Magneto-Gravitational trap to mitigate the leading systematic effect of neutron loss on material surfaces.

- **Magnetic trapping**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

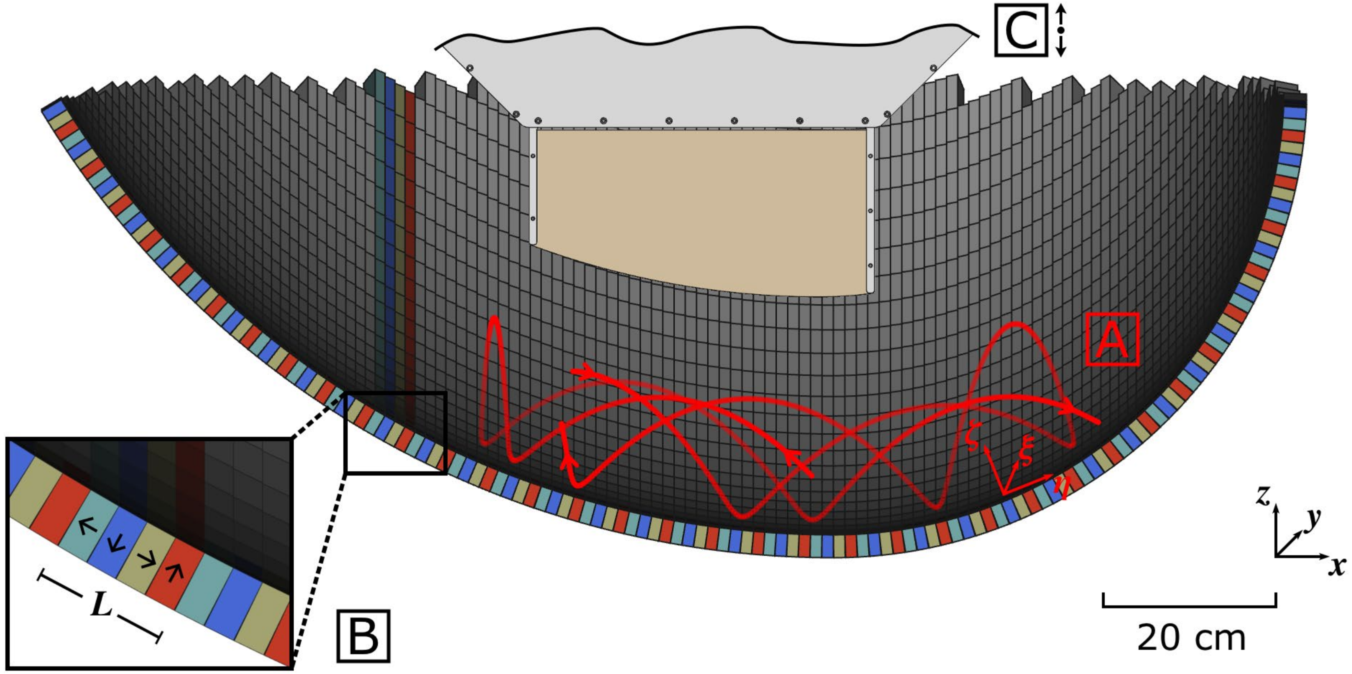
Walstrom et al, NIMA, 599, 82 (2009)
Pattie, *et al.*, *Science*, 360, 627 (2018)

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).



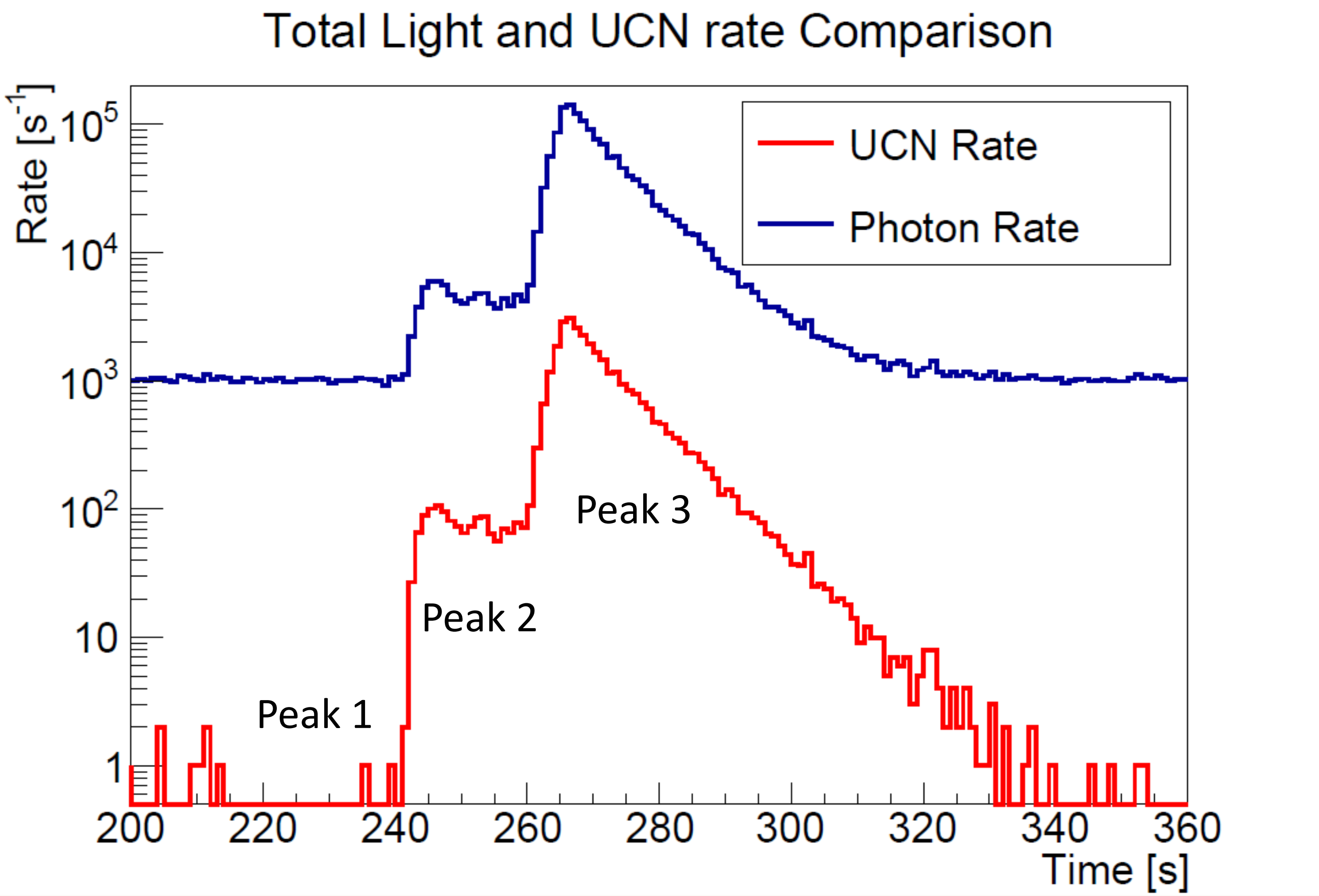



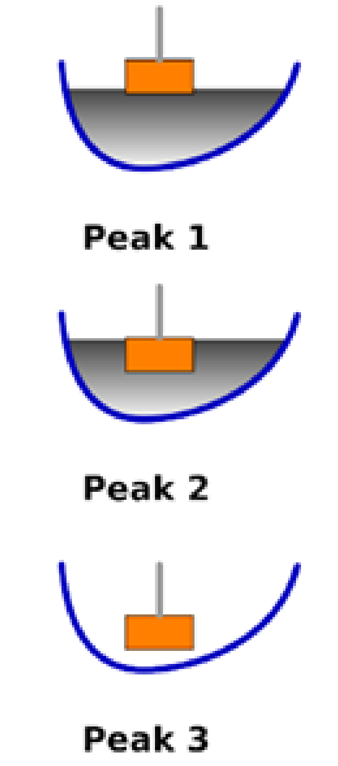
UCN are trapped by fields.
UCN are detected using an *in-situ* detector.



# Singles vs Coincidence

- Singles - High Background (100-400 s correction)
- Coincidence - Pileup/Deadtime (as high as 3 s)



The UCNτ experiment uses a Magneto-Gravitational trap to mitigate the leading systematic effect of neutron loss on material surfaces.



# PRELIMINARY uncertainties

Magnitude of rate-dependent effects significantly increased

- Previously published value calculated using raw p.e. counts, dead time per UCN ~0.2 $\mu$s
- New value calculated using reconstructed UCN events, dead time per UCN ~2 $\mu$s

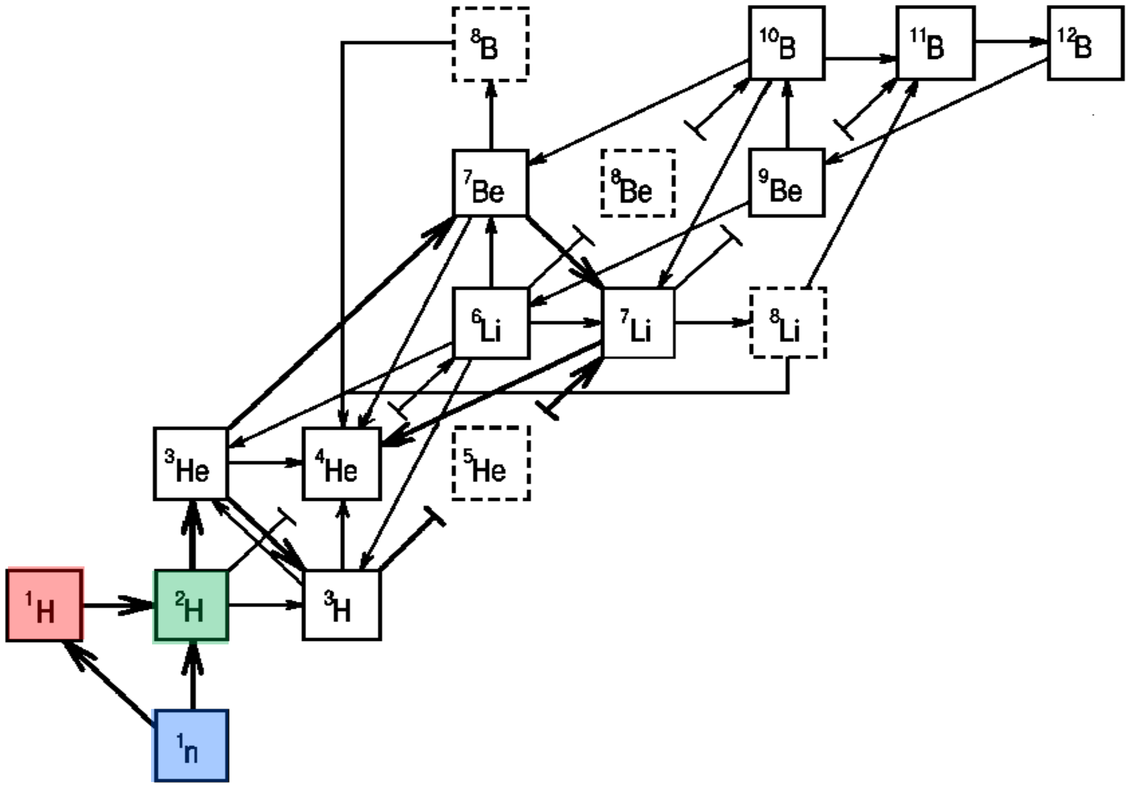
Monte Carlo approach to estimating systematic effects: RG00003 tomorrow at 8:54 CT

Correction and uncertainty budget

| Effect | Previously published value [s] | New value [s] |
|---|---|---|
| Dead time | $-0.20 \pm 0.04$ | $-0.7$ to $-1.5$ (typ.) $\pm 0.05$ |
| Other RDEs | N/A | 0.1 to 0.3 (typ.) $\pm 0.10$ |
| Residual gas interactions | $0.16 \pm 0.03$ | $0.05 \pm 0.01$ |
| Phase space evolution | $0 \pm 0.10$ | $0.029 \pm 0.003$ |
| Microphonic heating | $0 + 0.24$ | $0 + 0.07$ |
| Insufficient cleaning | $0 + 0.07$ | $0 + 0.06$ |
| Depolarlization | $0 + 0.07$ | no change |
| Total systematics | $-0.04^{+0.28}_{-0.11}$ | -0.5 to -1.2 (typ.) $^{+0.16}_{-0.11}$ |

| | Previously published value [s] | New value [s] |
|---|---|---|
| Statistical uncertainty | $\pm 0.7$ | $\leq \pm 0.3$ |
| Combined uncertainty | $^{+0.75}_{-0.71}$ | $\leq ^{+0.34}_{-0.32}$ |

# Neutron Lifetime is an important input into the Big-Bang Nucleosynthesis, which creates light elements




- Weak interactions control the neutron-proton ratio, via freeze out, etc..
- BBN describes the production of the "light elements", $^4$He, D, $^3$He and $^7$Li
- The number of free parameters that enters in standard BBN has now been reduced to zero: tests of new physics.

# Big-bang nucleosynthesis of $^4$He and other light elements: the $^4$He abundance ($Y_p$) depends on the value of the neutron lifetime and the number of light neutrino species

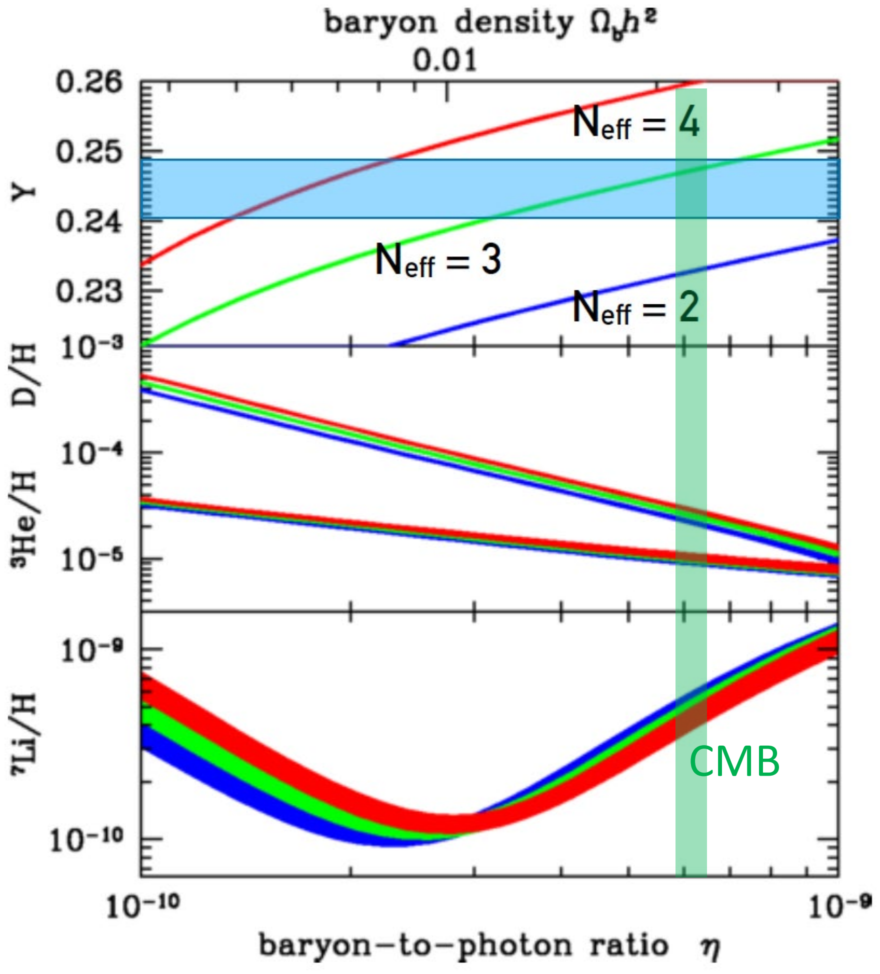
$$Y_p = 0.24703 \left(\frac{10^{10}\eta}{6.10}\right)^{0.039} \left(\frac{N_\nu}{3.0}\right)^{0.163} \left(\frac{G_N}{G_{N,0}}\right)^{0.35} \left(\frac{\tau_n}{880.3s}\right)^{0.73} p(n,\gamma)d]^{0.005}[d(d,n)^3\mathrm{He}]^{0.006}[d(d,p)t]^{0.005}$$

BBN CMB

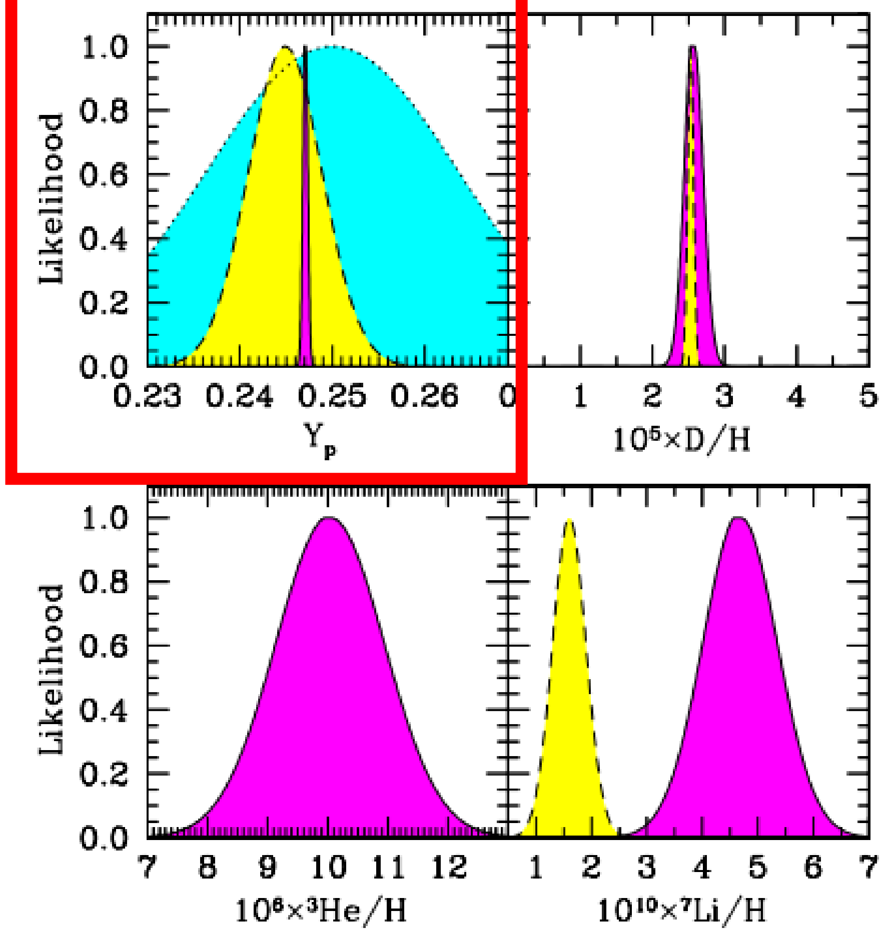
Astrophysical Observations

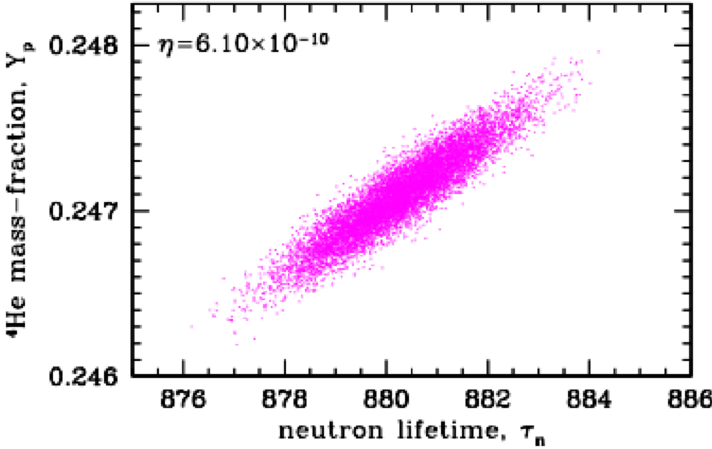
$$Y_p \sim \frac{2e^{-t_d/\tau_n}}{1+e^{\Delta m/kT_f}}$$

Sensitive to $\tau_n$




Rev. Mod. Phys. 88, 015004 (2016)

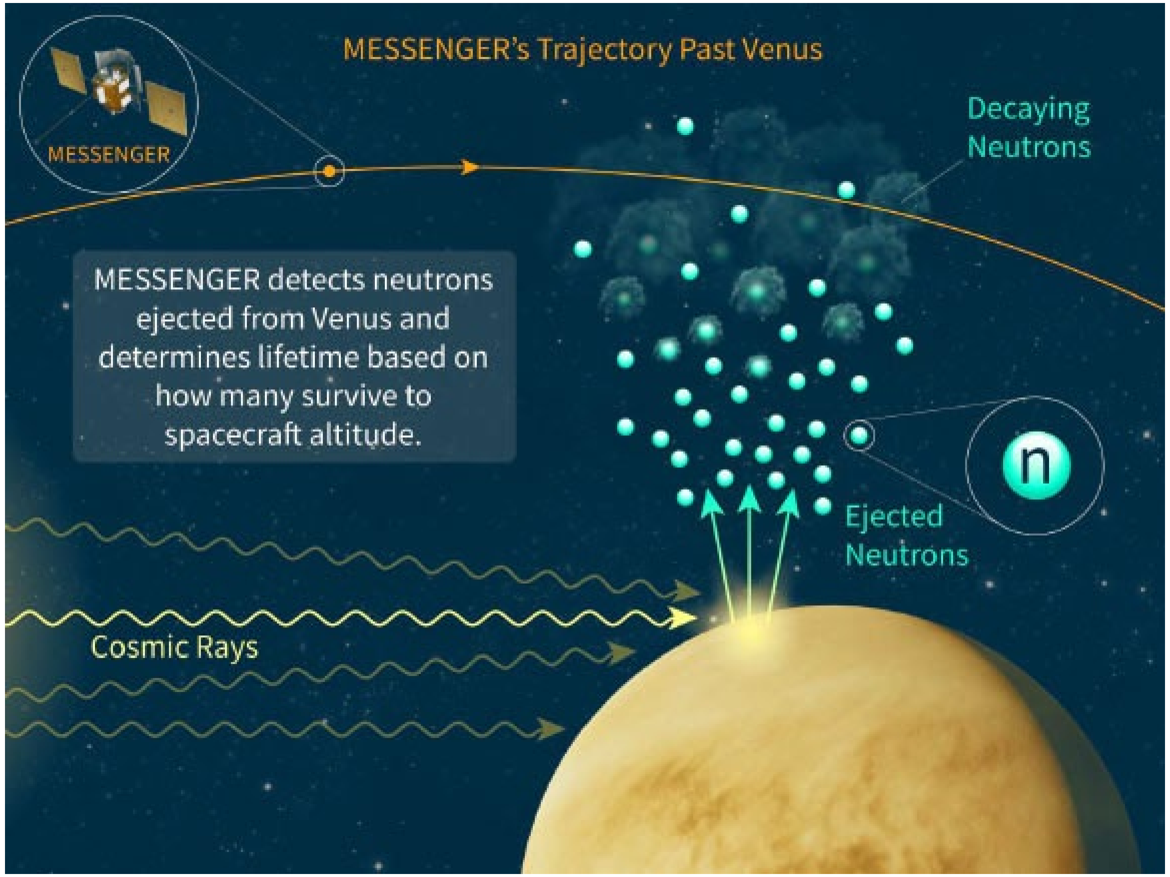



-R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, Rev. Mod. Phys. 88, 015004 (2016)

-L. Salvati *et al.* JCAP 1603 (2016) no.03, 055

# Using data acquired in 2007 and 2008 during flybys of Venus and Mercury by NASA's MESSENGER spacecraft, researchers found the neutron lifetime to be 780 seconds.

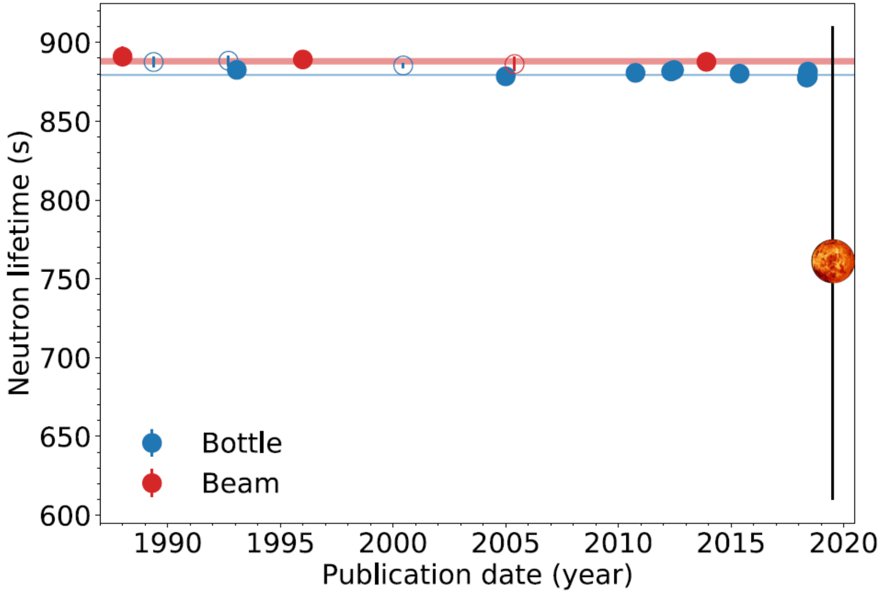




Jack T. Wilson, David J. Lawrence, Patrick N. Peplowski, Vincent R. Eke, and Jacob A. Kegerreis
Phys. Rev. Research **2**, 023316 – Published 11 June 2020


- *Cosmic-ray-generated thermal neutrons* are strongly gravitationally influenced by the host planetary body.
- *Gravitationally bound neutrons:* characteristic time-of-flight ~ 900 s
- Surface-to-sensor neutron transport based on Newtonian mechanics

MESSENGER's flyby of Venus provided a low-statistics and low-systematic measurement of $\tau_n$ of 760±50 s.



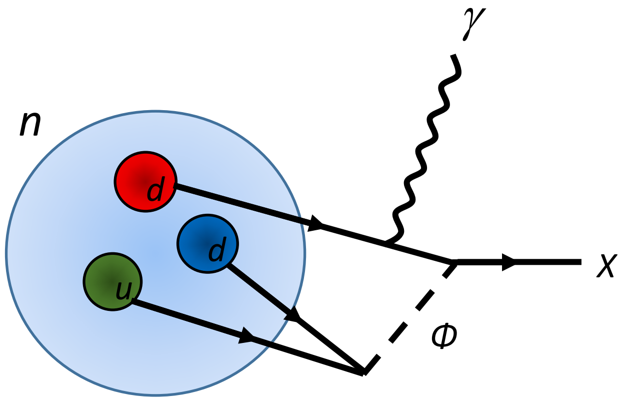
Discrepancy explained if 1% of neutrons decay to the dark sector

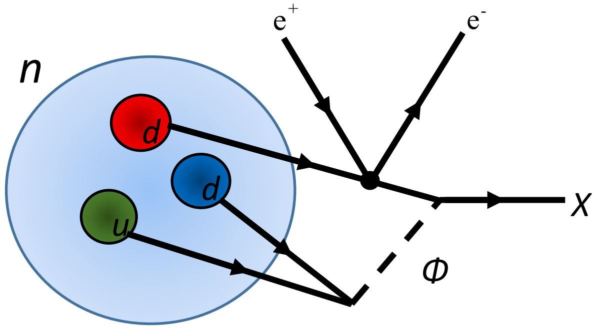
# n dark matter decay

3 decays proposed

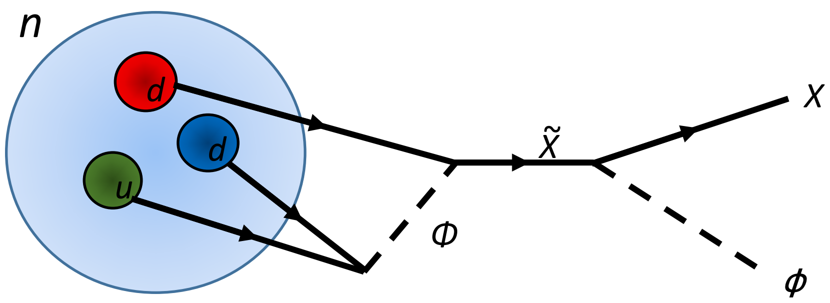
2 are detectable (with modern technology)

**Dark Matter Interpretation of the Neutron Decay Anomaly**
Bartosz Fornal and Benjamín Grinstein
Phys. Rev. Lett. **120**, 191801 (2018)




1 is a purely dark decay



# n dark matter decay

3 decays proposed by Fornal and Grinstein

[Dark Matter Interpretation of the Neutron Decay Anomaly](#)
Bartosz Fornal and Benjamín Grinstein

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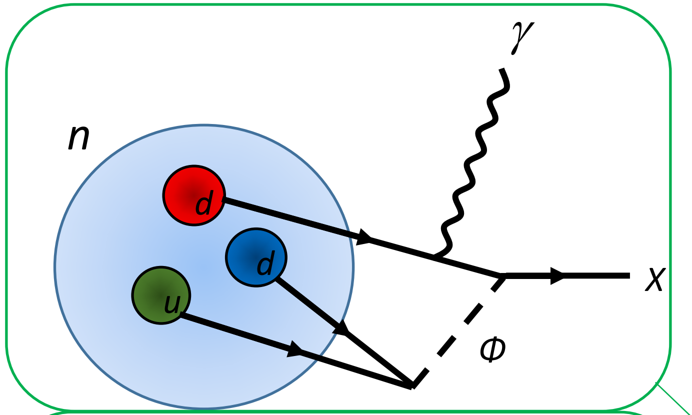


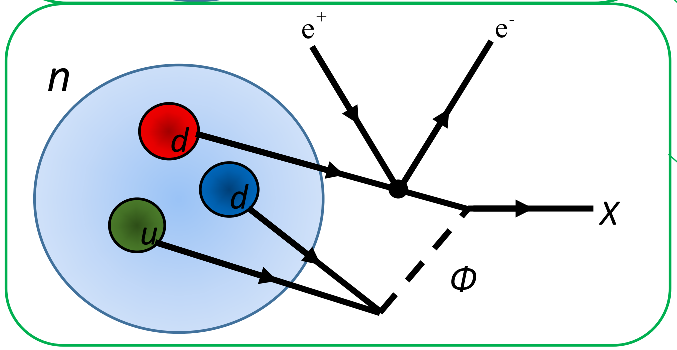


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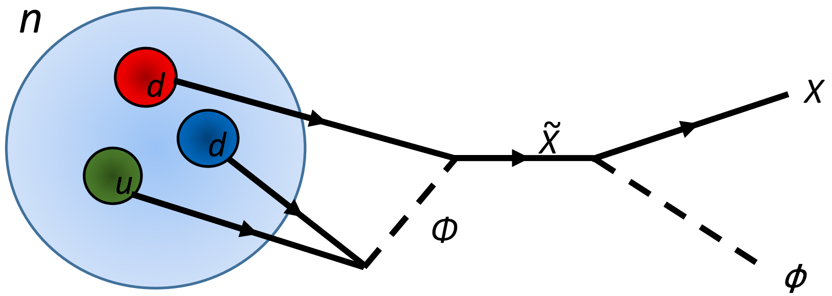


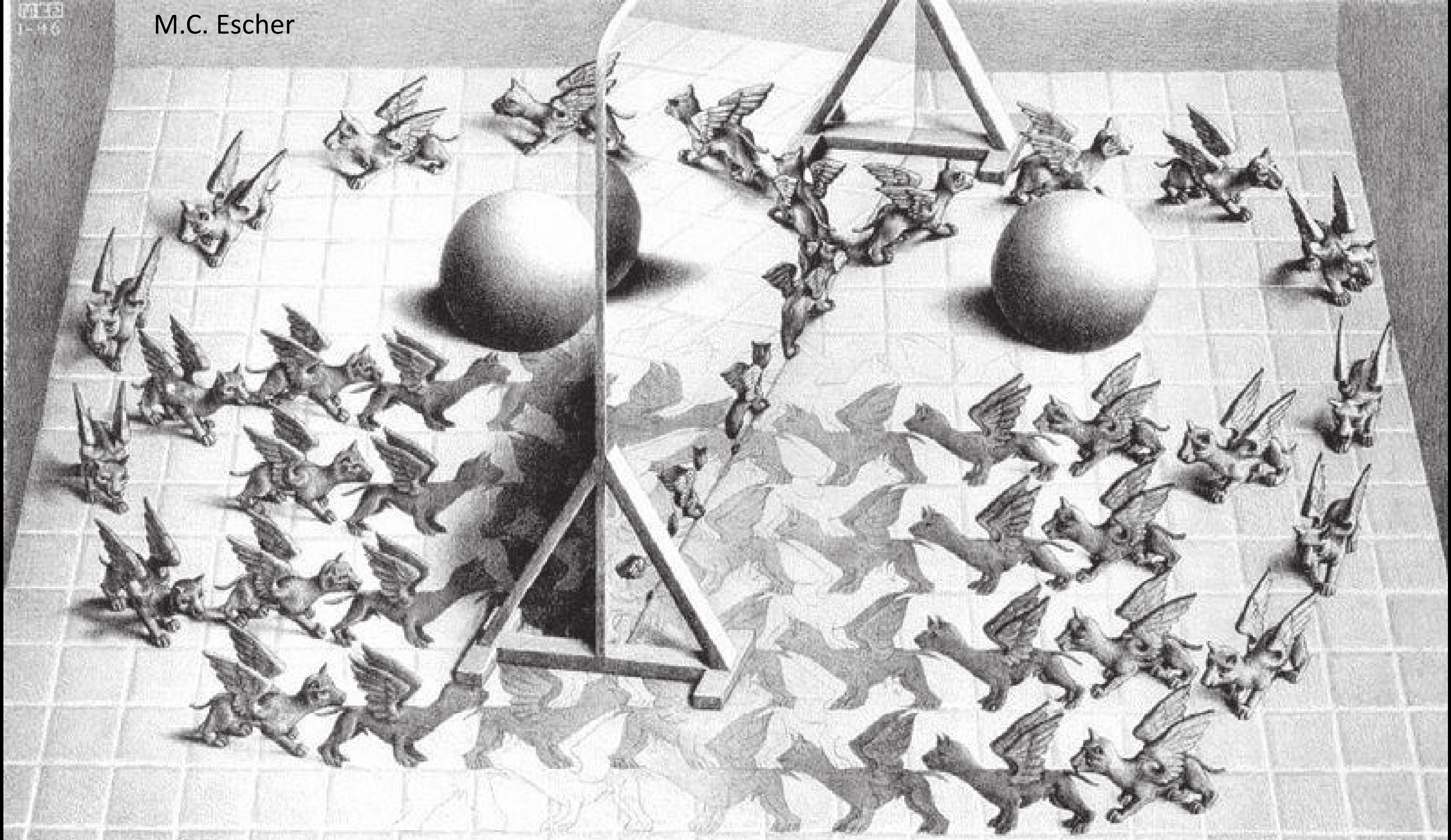

UCN Dark Matter apparatus (Round House) has sensitivity to this proposed decay.

UCNtau collaboration, Phys. Rev. Lett. 121, 022505 (2018)

UCNA apparatus has sensitivity to this proposed decay.

UCNA collaboration, Phys. Rev. C 97, 052501 (2018)

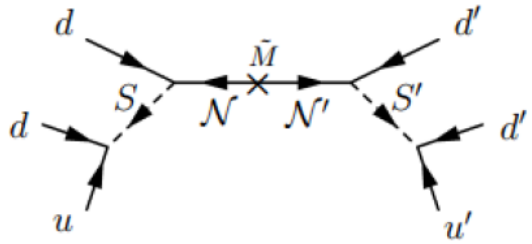
M.C. Escher



## A theoretical conjecture: Neutrons oscillate into the mirror world

# Sterile "mirror" neutron oscillations

Slide from Leah Broussard
DNP workshop on Frontiers
in Neutron Physics




- Similar concept to $n - \bar{n}$: mixing of neutron with sterile twin
  - Less demanding magnetic field requirements
- Small mirror magnetic field $\boldsymbol{B}'$ possible from MM captured by earth

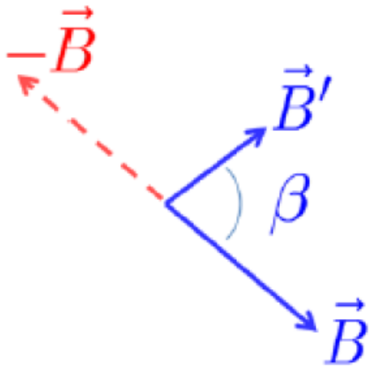
$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \epsilon \\ \epsilon & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix} \qquad \text{oscillation time } \tau_{nn'} = \frac{1}{\epsilon}$$

- $n - n'$ mass splitting ($10^{-24}$ GeV) or magnetic field (mG) can strongly suppress oscillation:
- Not sensitive to large $\Delta m_{nn'}$ in laboratory, control $\vec{B}$ for resonance in probability:

$$\mathrm{P}(n \to n') = \frac{\sin^2[(\omega-\omega')t]}{[(\omega-\omega')]^2 2\tau^2} + \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2} + \cos\beta\left[\frac{\sin^2[(\omega-\omega')t]}{(\omega-\omega')^2 2\tau^2} - \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2}\right]$$

$$\omega = \frac{1}{2}|\mu B|,\ \omega' = \frac{1}{2}|\mu' B'|,\ \ \mu = \mu' \text{ and } \tau = \frac{1}{\varepsilon}$$

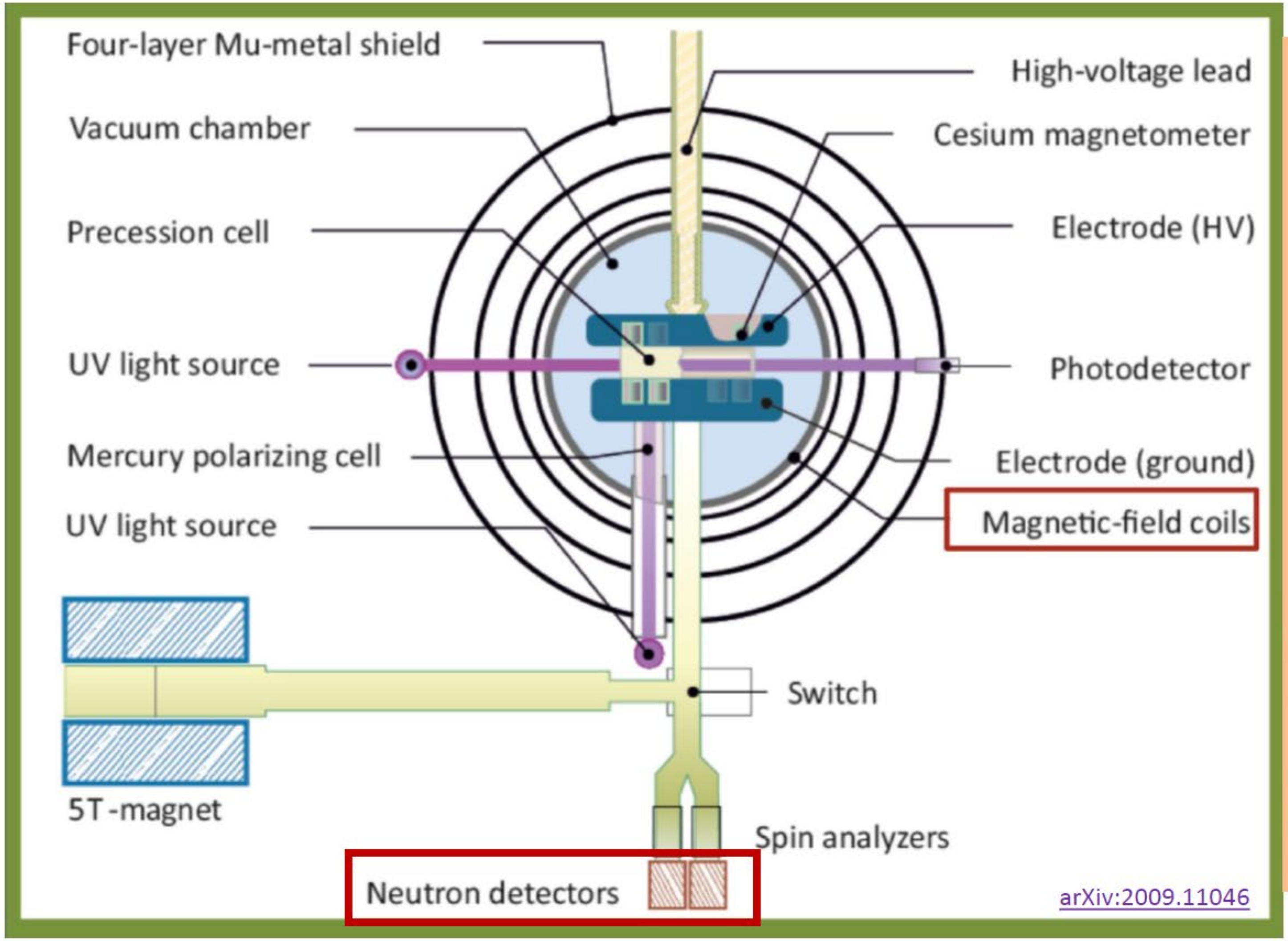
- Near $B \approx B'$ resonance: $\mathrm{P}(n \to n') \propto \left(\frac{t}{\tau}\right)^2$. Signal maximum when $\cos\beta = 1$




Berezhiani and Bento *PRL* **96** 081801 (2006), Berezhiani *EPJC* **64** 421 (2009), Berezhiani *EPJC* **72** 1974 (2012)

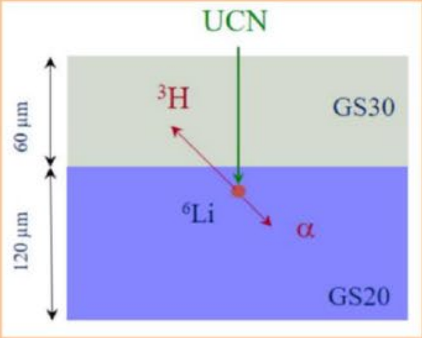
Slide from Leah Broussard

# n → n’ with PSI nEDM




1. Hg199: Co-magnetometer
   Average B-field
2. Cs-Magnetometers
   Spatial B-gradients
3. SFC
   Removes static fields
4. Mu-Metal
   Damps External mag. fields
5. New $B_0$ power supply
   Precise to 12μA (0.7nT)

7. NANOSc Detectors
   $Li^6$ neutron capture

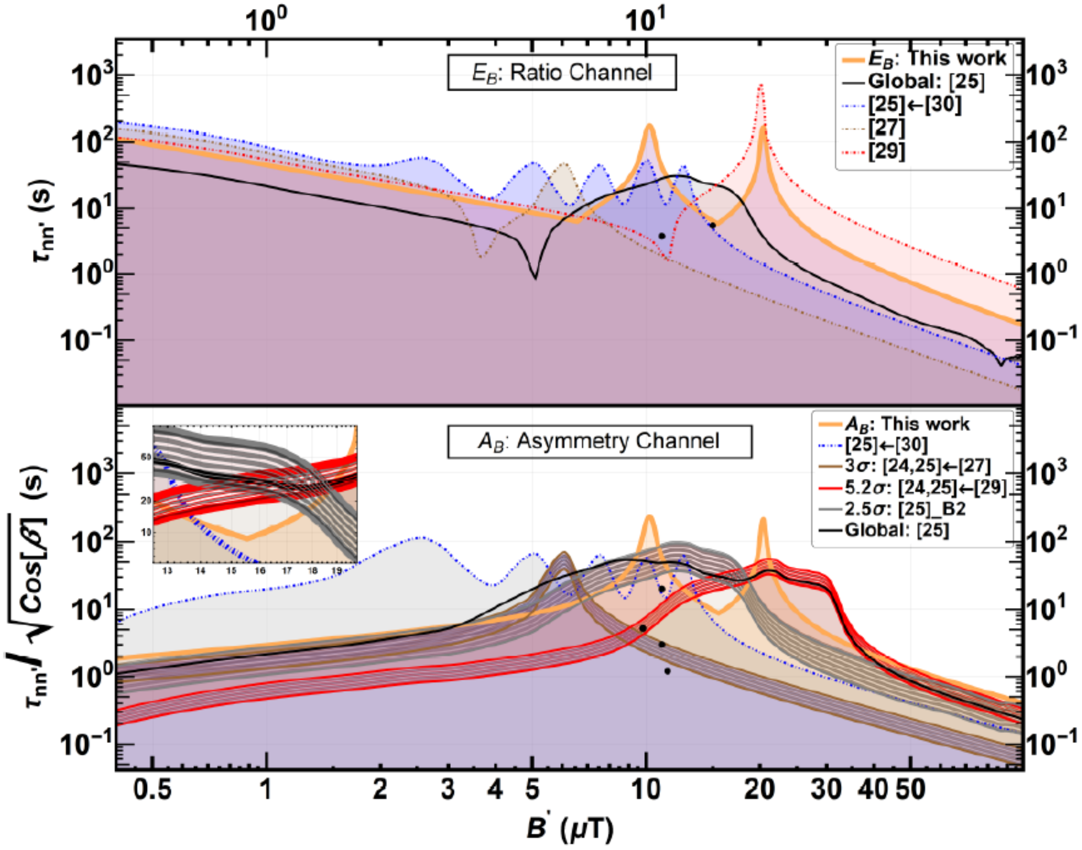



Thanks Prajwal Mohanmurthy

Slide from Leah Broussard

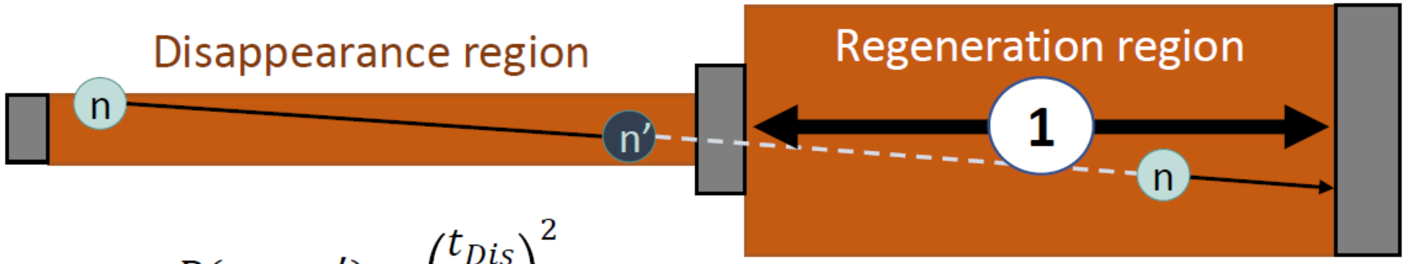
# Limits from prior searches

- First searches for $n \rightarrow n'$ used UCN to place strong limits assuming $B' = 0$: (Ratio channel)
  - $\tau_{nn'} > 448$ s (90% CL) NIMA **611** (2008) 137-140
  - Reanalysis with $B' \neq 0$ found anomalies in Asymmetry channel EPJC **72** (2012) 1974 (with update EPJC 78 (2018) 717)
- Dedicated search with $B' \neq 0$
  - $\tau_{nn'} > 12$ s for $0.4\mu T < B' < 12.5\ \mu T$ (95% CL) PRD 80 (2009) 032003
- PSI nEDM (arXiv:2009.11046) refutes anomalous signals reported in EPJC **72** (2012) 1974, excludes some (not all) regions where anomalous "bands" overlap EPJC 78 (2018) 717



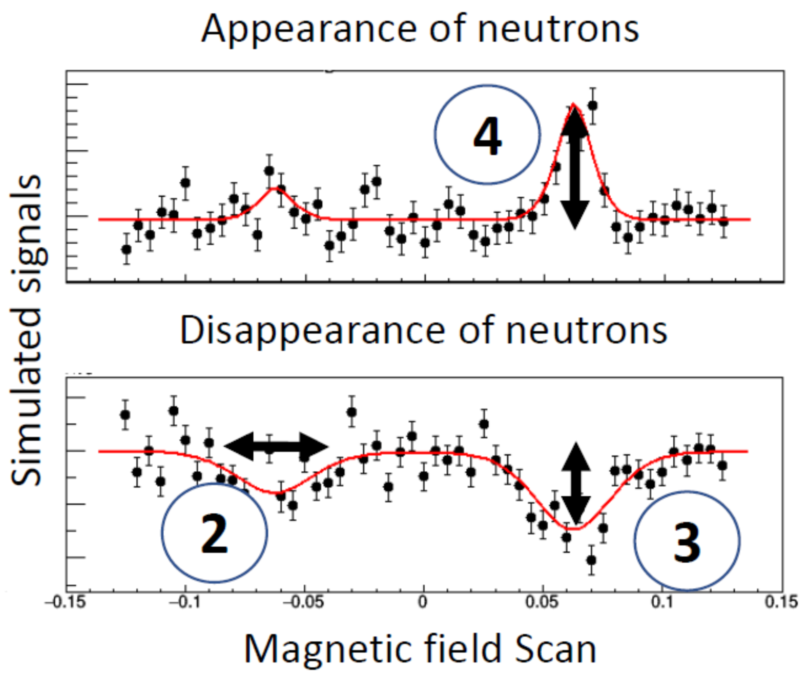
# Ingredients for a resonance search

$$P(n \to n' \to n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



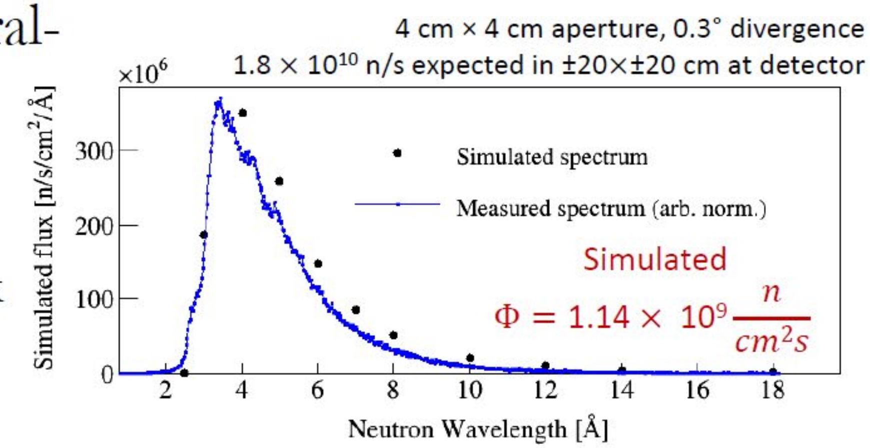

$$P(n \to n') \propto \left(\frac{t_{Dis}}{\tau}\right)^2$$

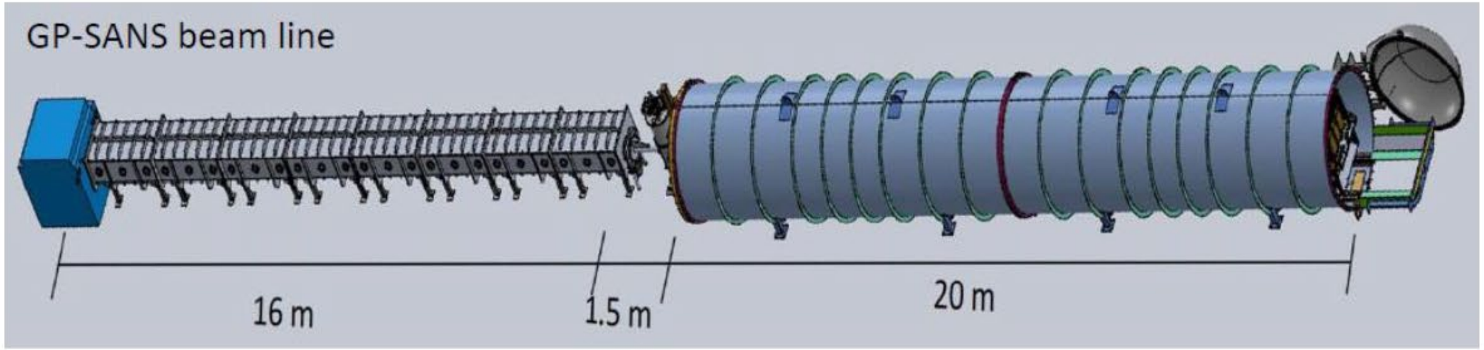
1. High neutron flux + long, large area guides
2. Magnetic field uniformity and control (~mG)
3. Precise monitoring of changes in transmission
4. Regeneration: large area, low bkgd detector

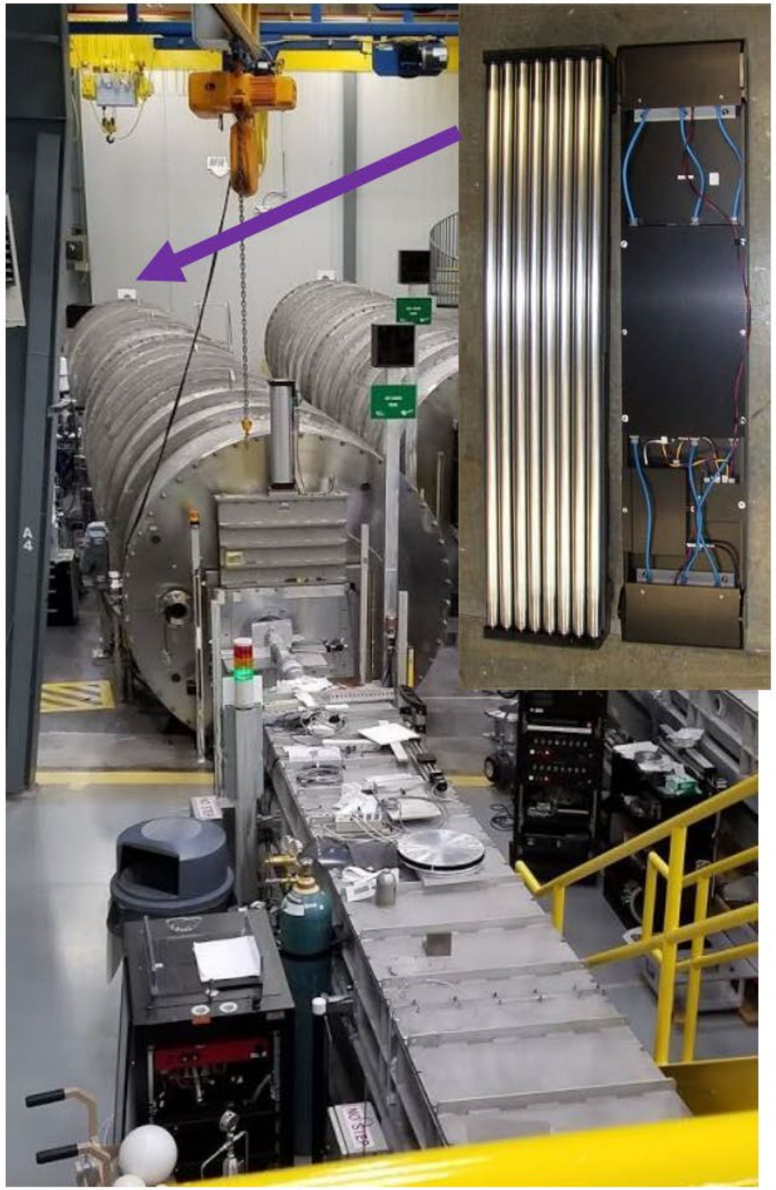


# Search at ORNL

- High Flux Isotope Reactor - 85 MW: highest reactor-based source of neutrons for research in US
- Existing instrument: General-Purpose Small Angle Neutron Scattering
  - 1 m x 1 m $^3$He neutron detector in Cd shielded tank
  - Sensitivity: $\tau > 24$ s (dis), $\tau > 20$ s (regen), 95% CL

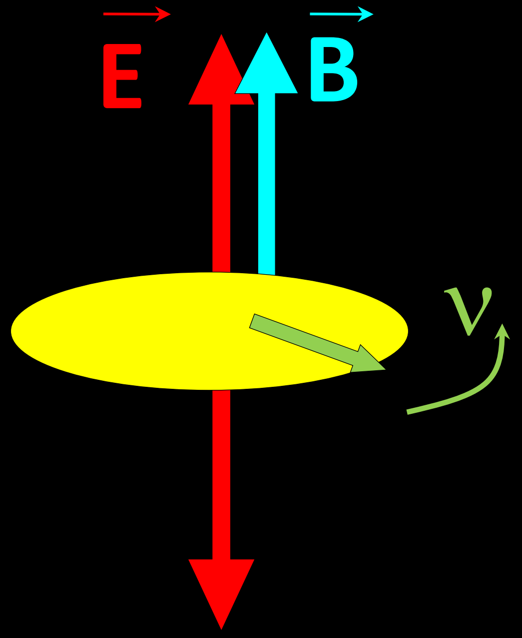


- Long, large area beamguides for both disappearance and regeneration

# Magnetic Resonance to measure the EDM




$$\nu = \left(2\mu_n B \pm 2d_n E\right)/h$$

$$\Delta\nu = 4d_n E/h$$

$$\delta d_n = h\frac{\delta\Delta\nu}{4E}$$

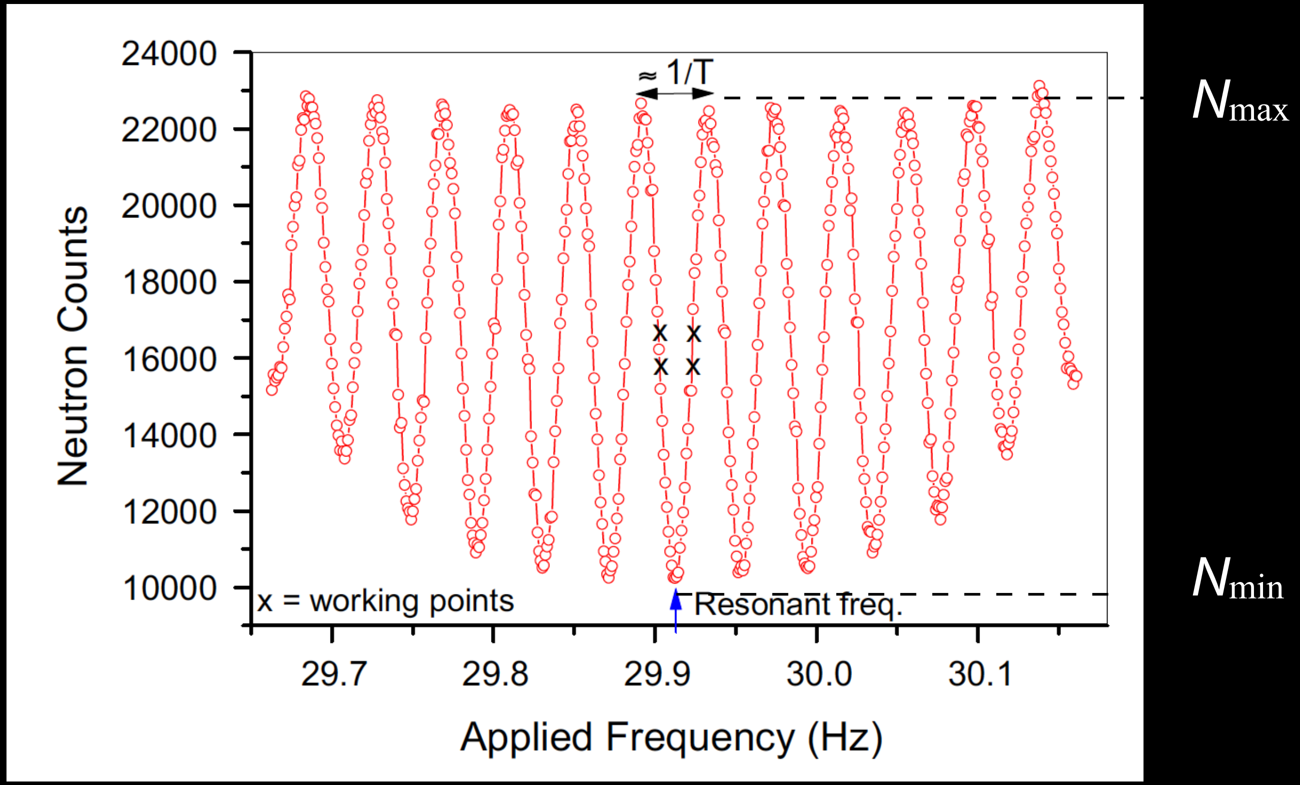
$$\delta d_n^{(i)} = \frac{\hbar}{2\sqrt{2}\alpha E T_{\text{free}}\sqrt{N}}$$

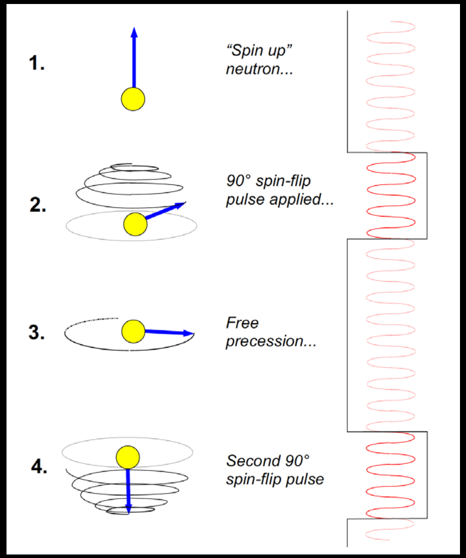
- For B ~ 10mG, $\nu$ = 30 Hz
- For E = 10kV/cm and $d_n$= 3x10$^{-27}$ e·cm,
  $\delta\nu$ = 30 nHz

*One part per billion precision!*

# Ramsey's method of separated oscillatory fields with UCN achieves the exquisite EDM measurements

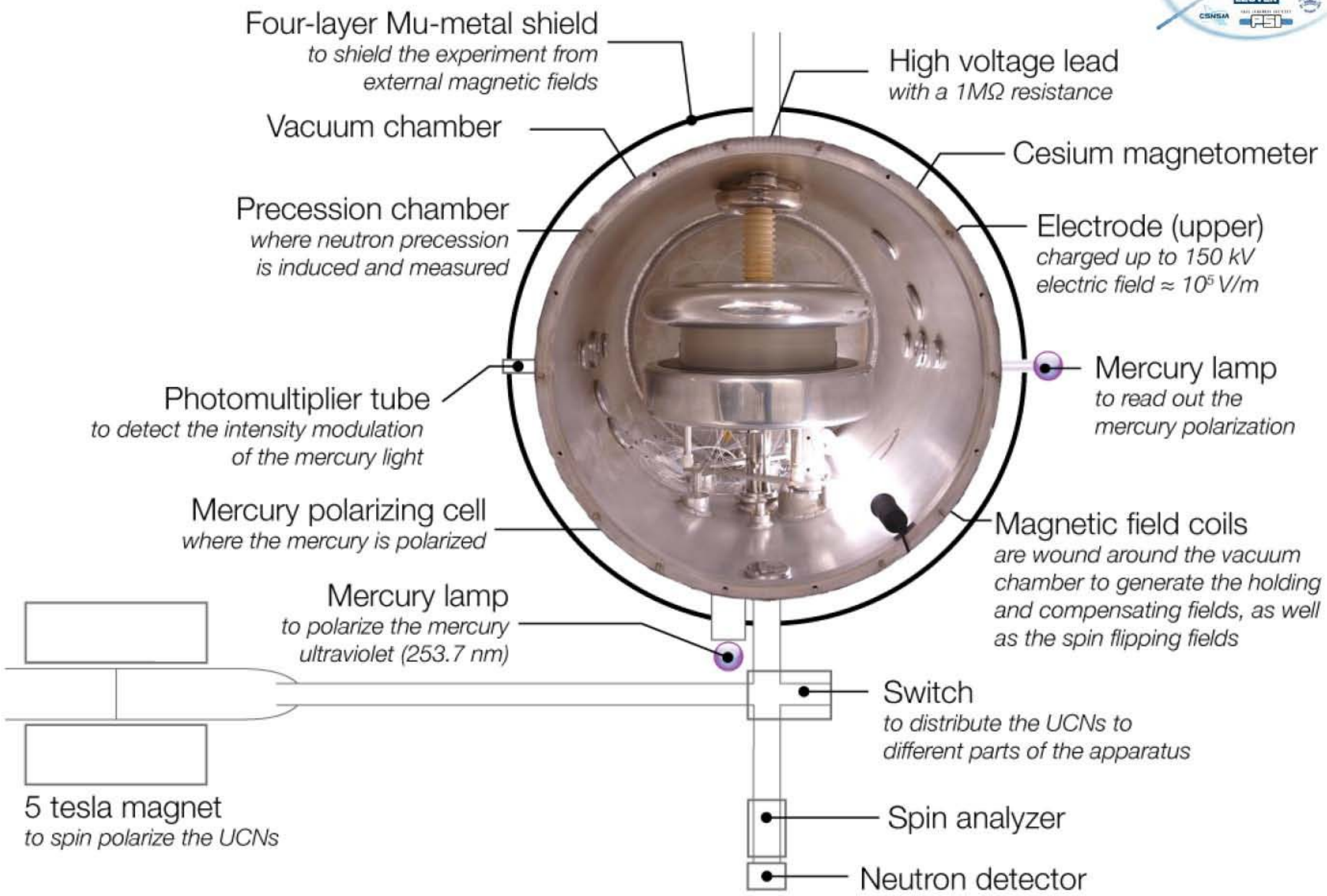
Nobel Prize in Physics in 1989 for the "for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"




- For B ~ 10mG, $\nu$ = 30 Hz

# The nEDM spectrometer

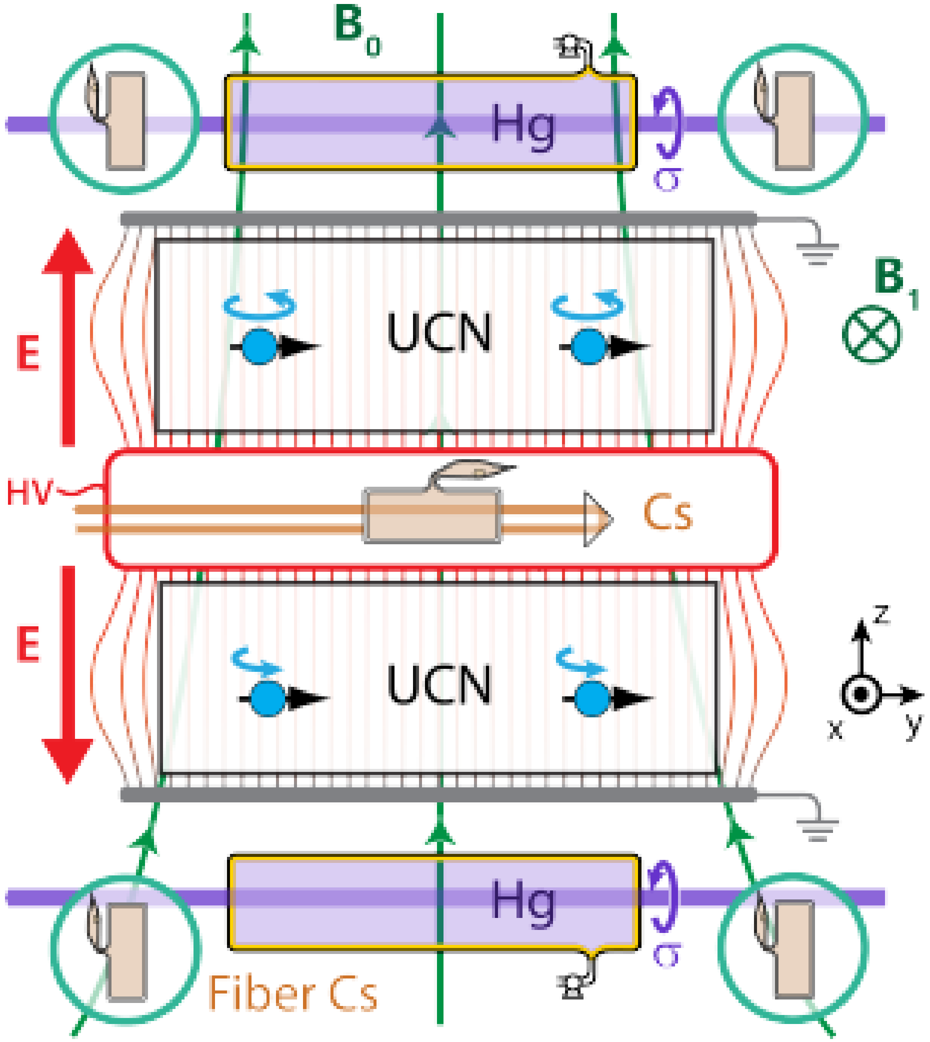


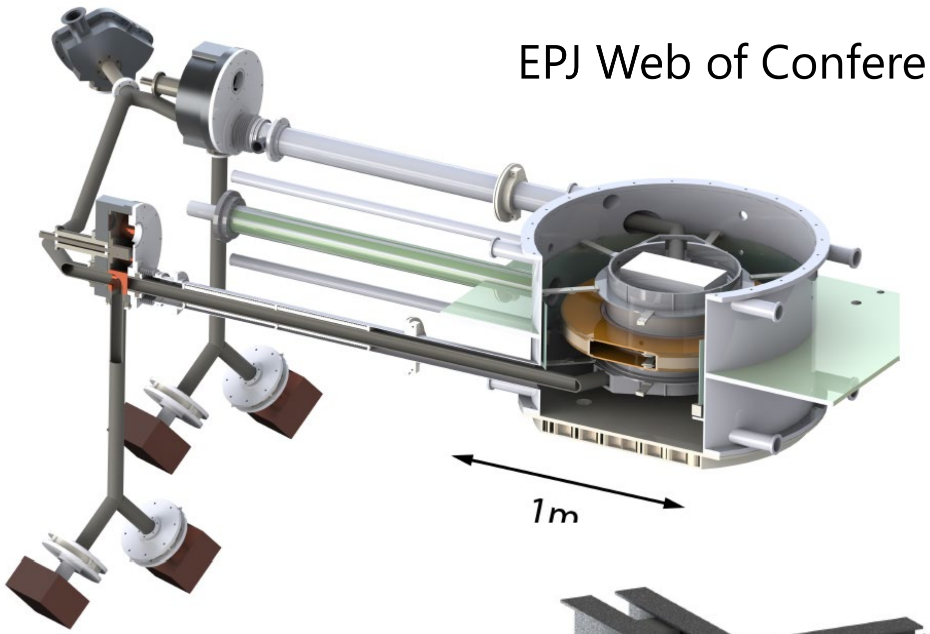


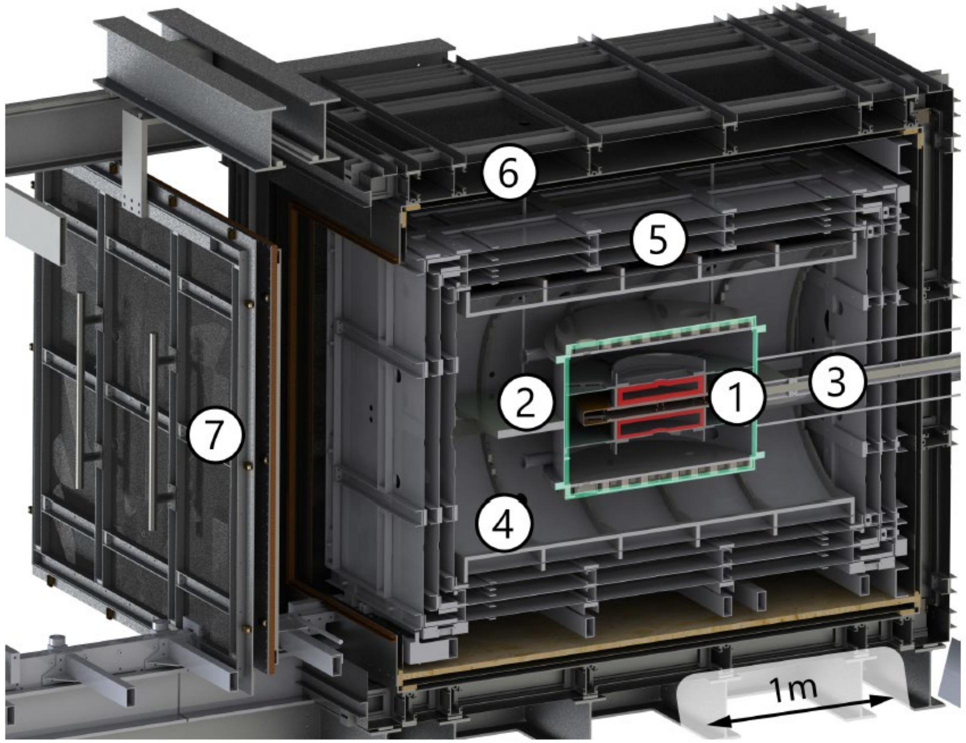

Slide from Klaus Kirch

# PanEDM@ILL

EPJ Web of Conferences **219**, 02006 (2019)

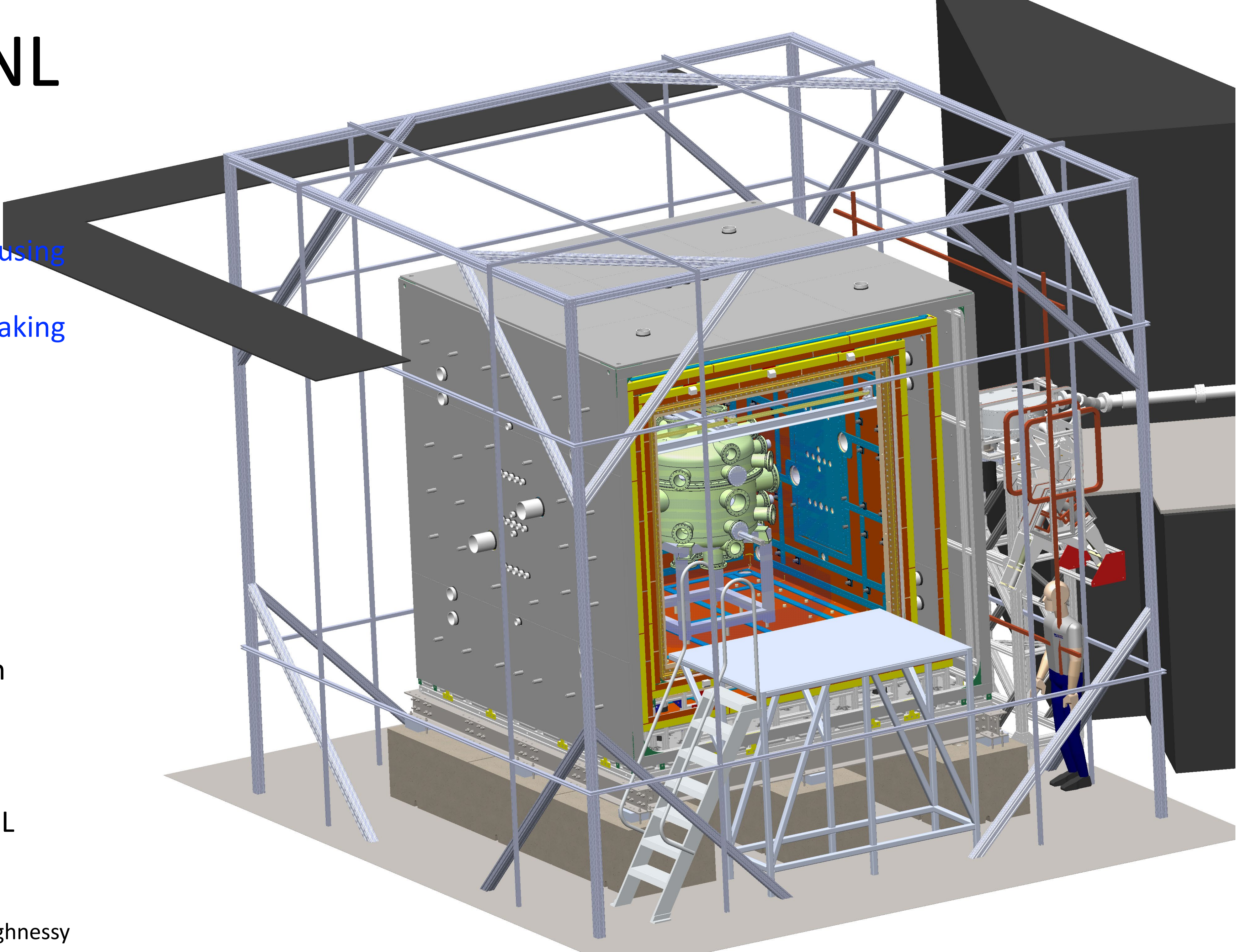


# nEDM@LANL

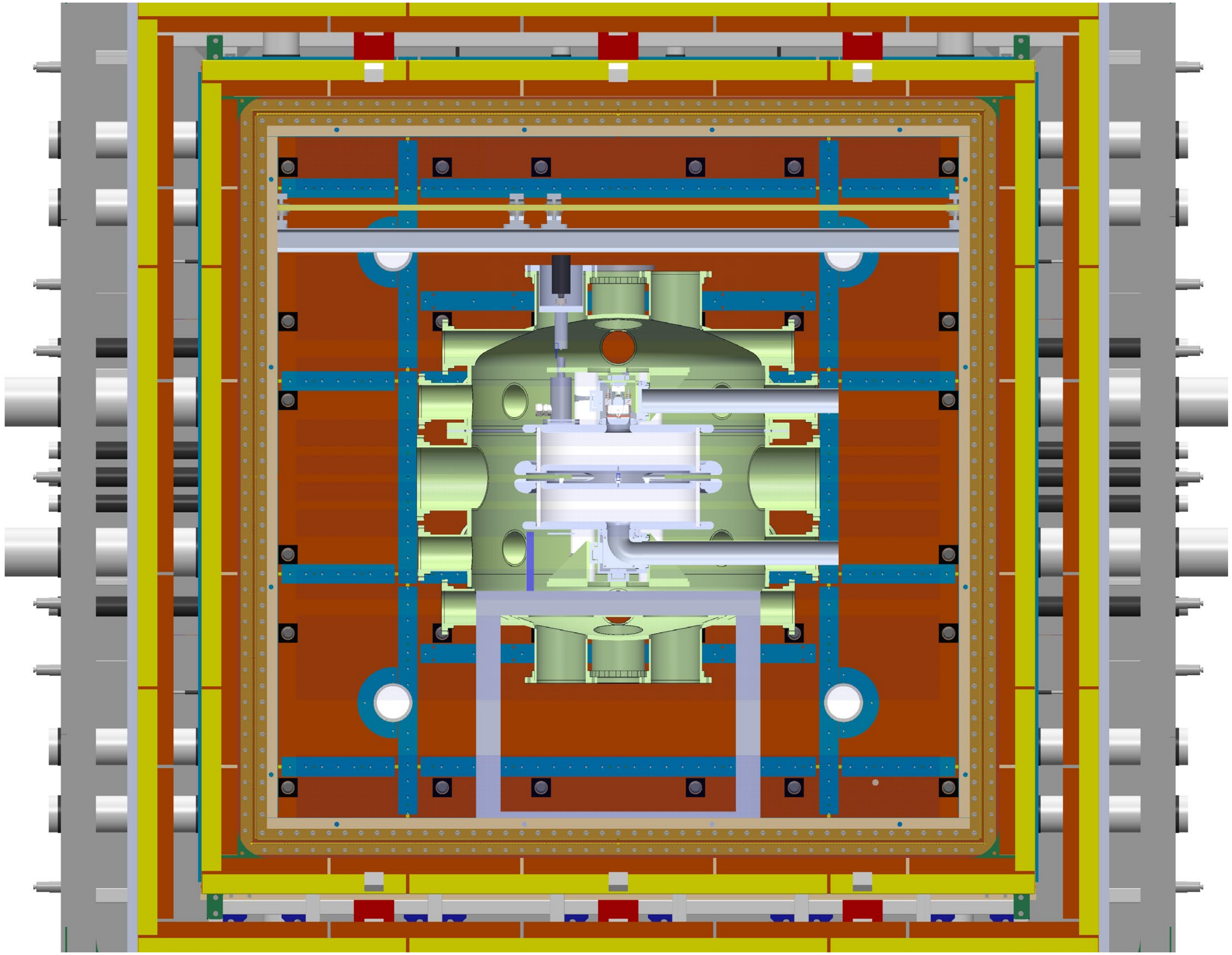
- Guiding Principles:
  -take advantage of the upgraded UCN source;
  -minimized R&D efforts by using proven technology;
  -move towards EDM data-taking in a 3-year time frame.



Design features:
- Double cell
- Hg co-magnetometer
- Cs external magnetometers
- Magnetically shielded room
- Room temperature operation

- Construction (NSF MRI + LANL LDRD): 2018-2021

Image by Chris O'Shaughnessy

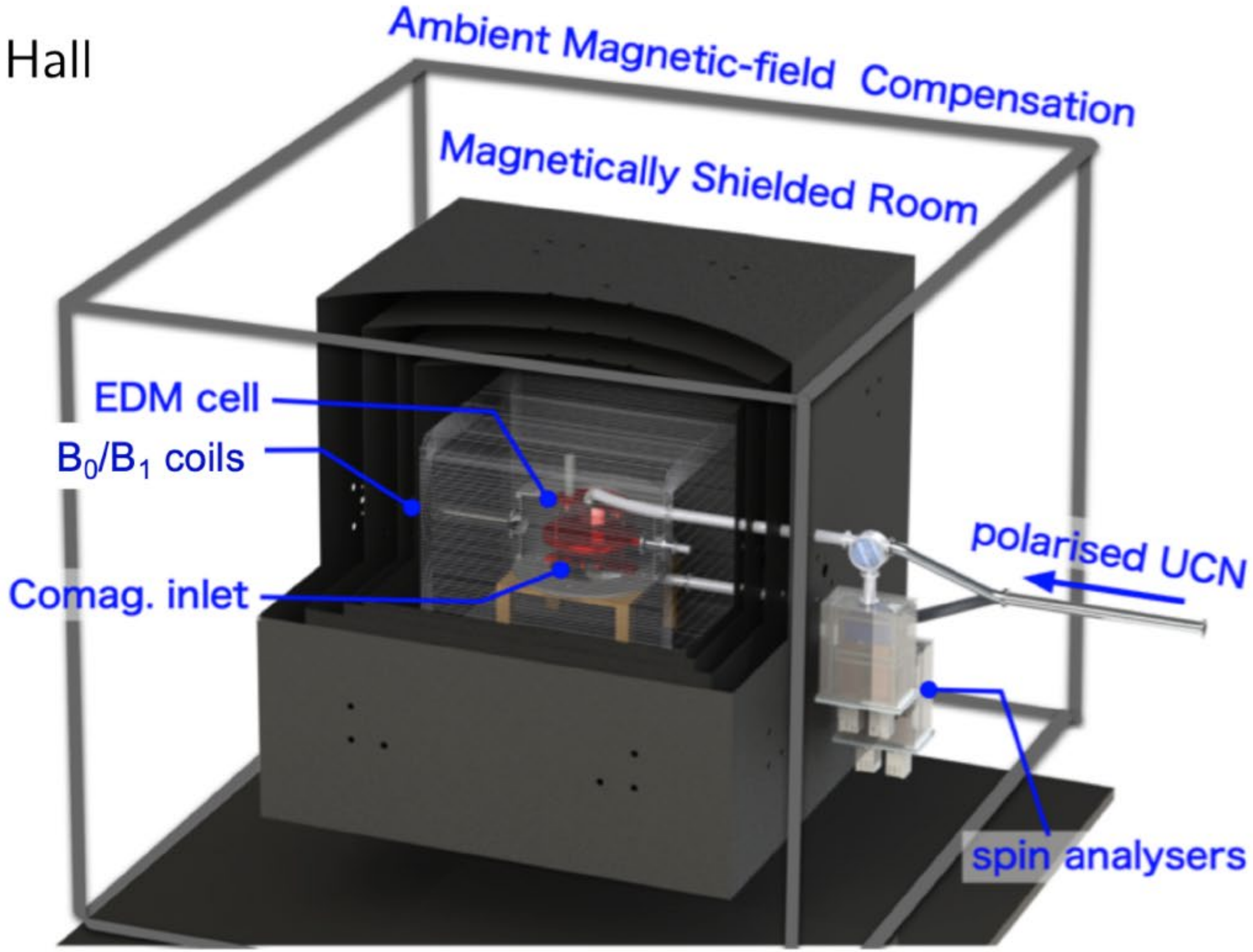


Slide from Beatrice Franke

# nEDM spectrometer



- Will be installed in TRIUMF Meson Hall
- Design and construction ongoing
- Magnetic field-related subsystems:
  - $B_0$ coil
  - $B_1$ coil
  - Shim coils
  - **Comagnetometer**
  - Cs magnetometers
  - **Magnetically Shielded Room (MSR)**
  - **Ambient magnetic-field compensation (AMC)**

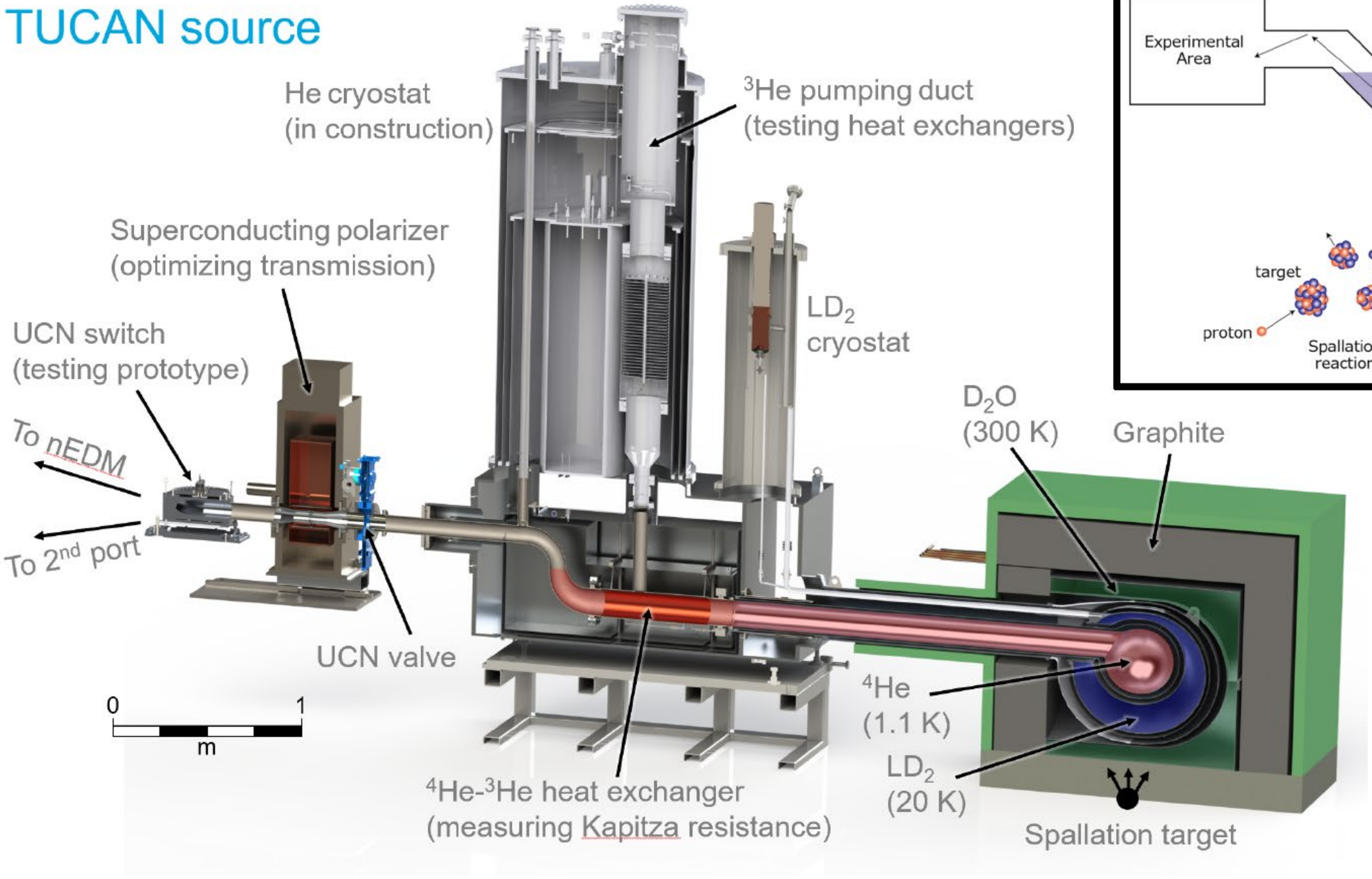


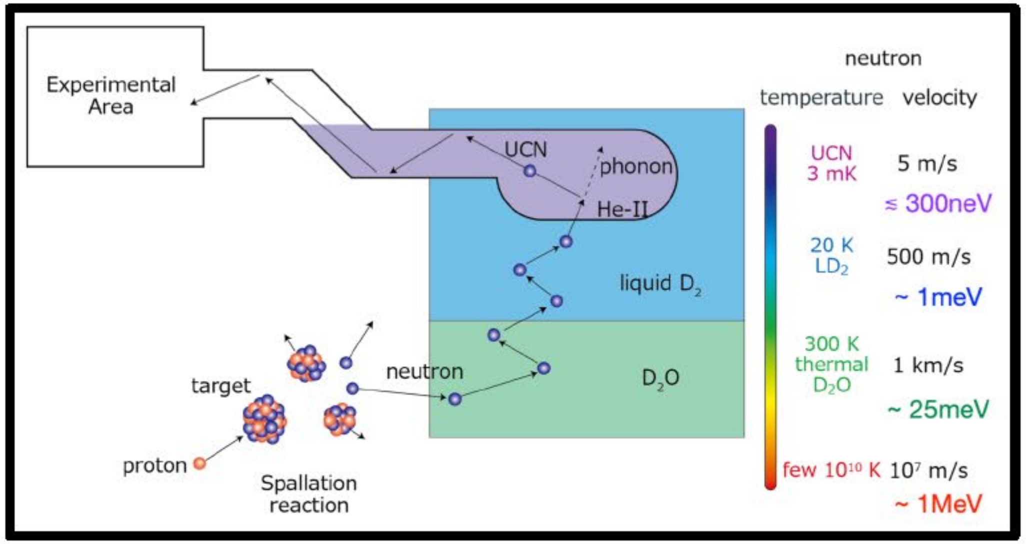
Slide from Beatrice Franke

# The new UCN source at TRIUMF: (commissioning 2021)



## TUCAN source



# nEDM@SNS

Neutron electric-dipole moment, ultracold neutrons and polarized $^3$He**

R. Golub[a] and Steve K. Lamoreaux[b]

[a]Hahn–Meitner Institut, Postfach 39 01 28, Glienicker Strasse 100, 14109 Berlin, Germany
[b]University of Washington, Department of Physics FM-15, Seattle, WA 98 195, USA

Physics Reports **237**, 1 (1994)

** "The Miracle of Helium"

$$\boxed{\sigma \propto \frac{1}{E\sqrt{N\tau}}}$$

**Improve statistical precision by x100.**

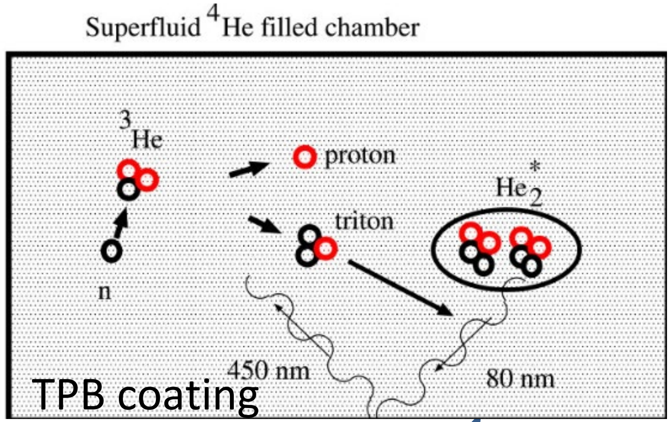
- *Increase E*: LHe permits very large electric fields; ~70 kV/cm in our measurement cell
- *Increase N*: LHe allows production of a high density of "ultracold" neutrons (UCN); ~few $10^2$ UCN/cc
- *Increase t*: With T < 0.5K UCN can be stored for ~ a thousand seconds

**Additionally allows use of Helium-3 as a:**

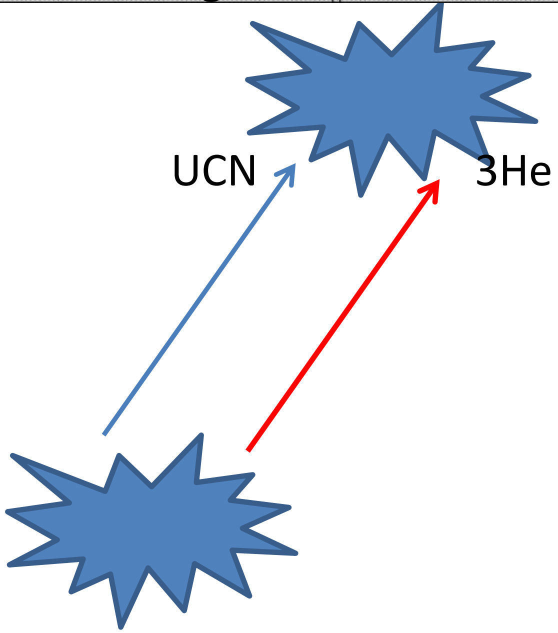
- *Spin analyzer*, providing continual measurement of the precession frequency
- *Co-magnetometer*, providing exquisite monitoring of the magnetic field

# Experiment uses $^3$He as detector

*R. Golub and S. K. Lamoreaux, Phys. Rep. 237 (1994) 1*




- UCN too dilute to detect with magnetometer (SQUID)
- Inject small concentration (~ $10^{-11}$) of polarized $^3$He
- Look for reaction: n + $^3$He → t + p + 764 keV
    - t, p scintillate in $^4$He
    - Pipe through light guides and detect with PMT




- n + $^3$He → t + p:

  $\sigma$ ($^3$He, n: ↑↓singlet) ~ $10^7$ b

  $\sigma$ ($^3$He, n: ↑↑ triplet) < $10^4$ b

- $\mu_{He}/\mu_n = 1.11$

  $^3$He spins will rotate ahead of n spins in same *B*

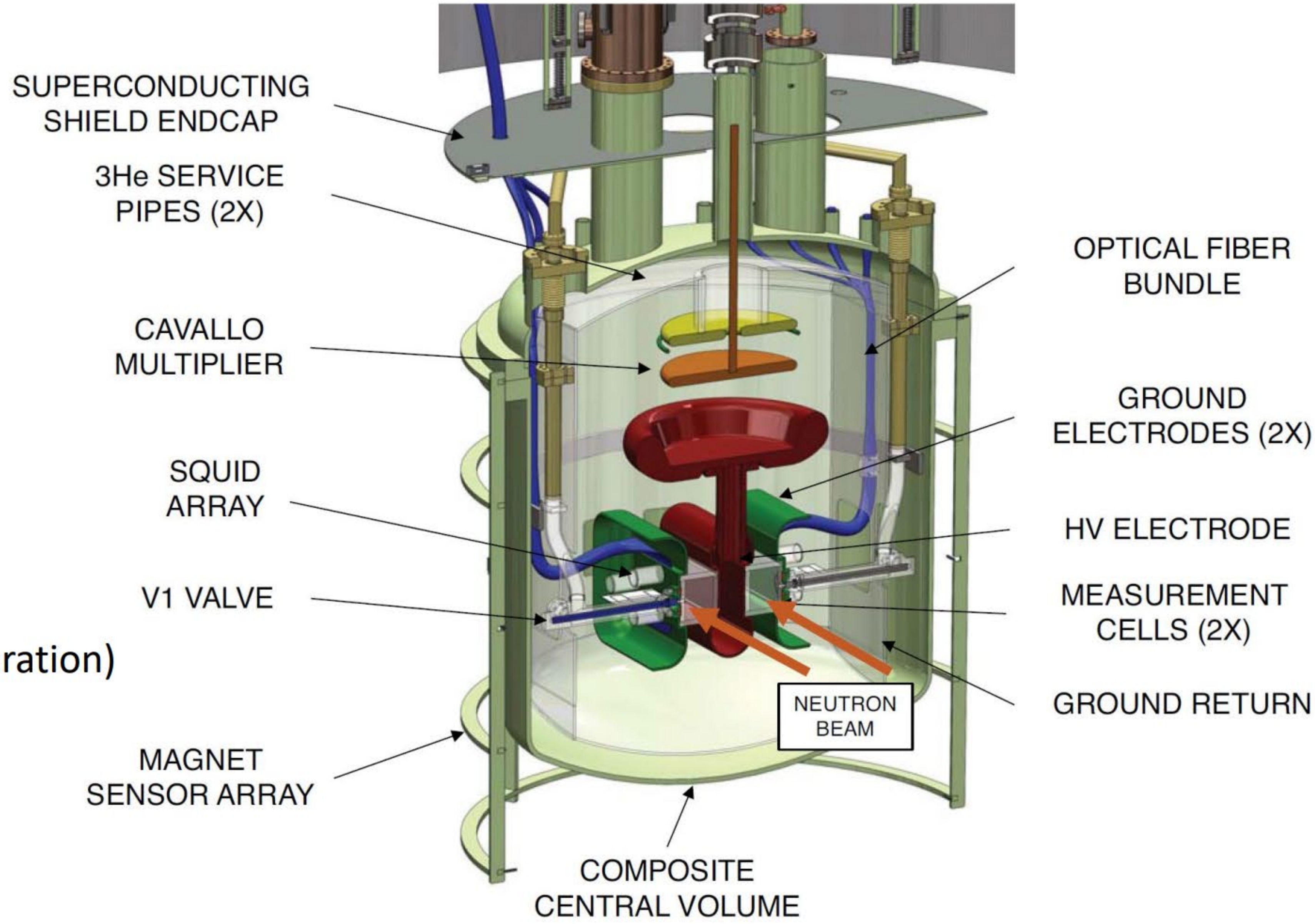
Scintillation light according to $\Phi = \Phi_0 \sin(\omega_{He} - \omega_n)\,t \sim 1 - P_n P_3 \cos(\omega_{He} - \omega_n)t$

- Independent monitor of $^3$He spins with SQUIDs

# Central Detection System

Highlights

- 75 kV/cm Electric field
- Cavallo's Multiplier
- Squid Magnetometer
- 1600 L of super fluid helium
- Light collection
- $^3$He Comagnetometer
  - (SQUIDs and Signal Generation)



# Study the Systematic Effects below 1e-26 e-cm

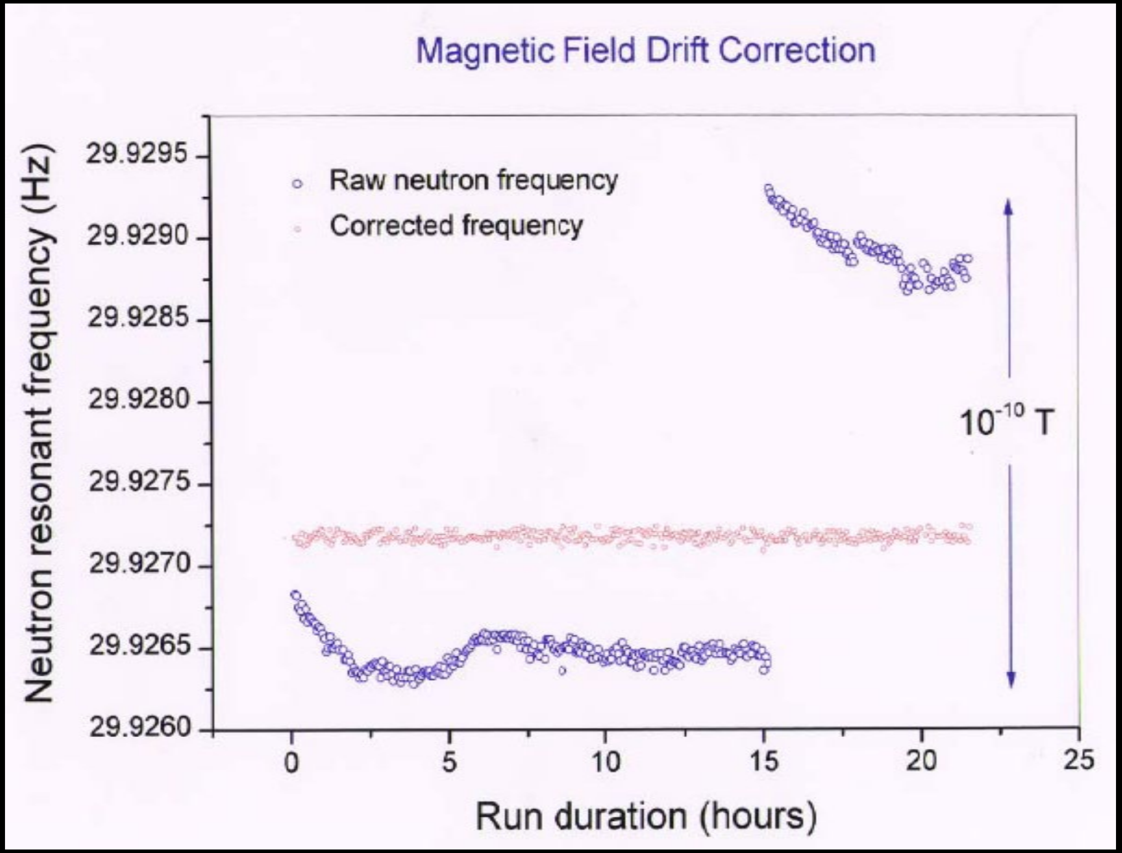

- Low-frequency field drift
  - Cancelled by Hg signal
- Leakage current

# Magnetic Field Fluctuations Corrected by “Co-magnetometer”

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

A B field of 2 fT would cause a 0.1 μHz shift in frequency, equivalent to a EDM signal of $10^{-26}$ e·cm in a 10kV/cm field.

A “co-magnetometer” Uniformly samples the B Field, faster than its relaxation time.




Data: ILL nEDM experiment with $^{199}$Hg co-magnetometer

Polarized $^{199}$Hg atoms; EDM of $^{199}$Hg < $10^{-29}$ e-cm (measured)

# Study the Systematic Effects below 1e-26 e-cm


- Low-frequency field drift
  - Cancelled by Hg signal
- Leakage current
- Geometric Phase Effects
  - The field gradient coupled to the motion of UCN
- Gravitational induced frequency shift
  - Different velocity of UCN and Hg
- Earth rotation
  - Frequency shift in an accelerating frame.
- Pseudo magnetic field
  - Spin-dependent scattering between UCN & Hg
- …….

# Outlook for Fundamental Neutron Physics

❖ *Given the opportunity, our community will (continue to) make creative use of high-flux neutrons to do great science.*

❖ High priority science a decade or more out: difficult to predict

- Precise knowledge of Neutron decay and EDM → confirm symmetry-violating physics needed for baryogenesis (& nucleosynthesis) to account for the matter-antimatter asymmetry of the universe: high priority for 50 years, likely to remain so.
- High probability of new targets of opportunity:
    - Neutron-antineutron experiment → search for Baryon number violation
    - Neutron beta-decay, angular correlations, parity violation → high precision tests of Standard Model
    - Quantum physics w/ neutrons: bouncing quantum neutrons, transitions between gravitational bound states, limits on short range interaction, studies of neutron orbital angular momentum states, entangled neutrons, …

❖ Intensity is everything!

- All experiments above are statistically limited: even a factor of 3 to 5 can be a game changer.

# IU Cyclotron Facility (1976-2010)

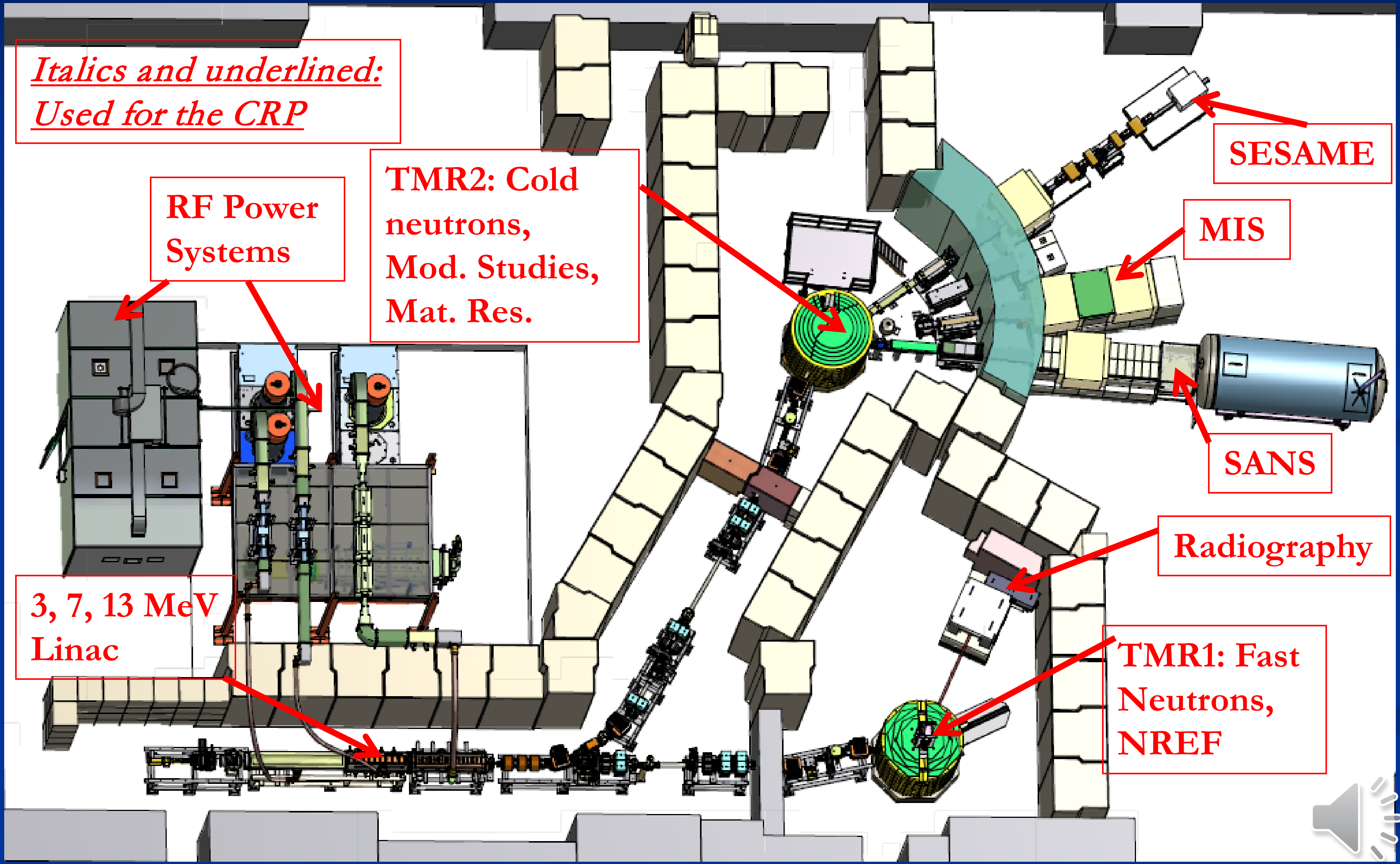
- Accelerate protons to 200 MeV. Other light ions d, 3,4He and 6,7Li were also accelerated.
- High-intensity polarized ion source + an electron cooler ring.
- Some activities converting the IU cyclotron facility
  - Proton Cancer Therapy (1998—2014)
  - Low Energy Neutron Source (2005—now)
  - Advanced eLectron PHoton Accelerator (ALPHA) for Radiation Effects Research and Testing (2003—2017)

# n-Source Energy budgets:

- D-D, D-T ( <*μl*): $>4\text{x}10^{11}$ n/J
- Fission (*Dl*): $3\text{x}10^{10}$ n/J
- High-E proton spallation (*l*): $2\text{x}10^{11}$ n/J
  - ESS, SNS, JSNS, SINQ, ISIS
- Low-E Proton (p,n)Be ~13MeV (*ml*): $3\text{x}10^{9}$ n/J
  - LENS, CPHS, RANS, ESS-B, HBS, SONATE,…
- Threshold (d,n)Be (p,n)Li (<*ml*): $0.5\text{-}1\text{x}10^{9}$ n/J
- Electron on W [high-Z target] (*cl*): $2\text{x}10^{9}$ n/J
  - HUNS, Bariloche, RPI, …

**O($10^{14}$ n/s) requires target power ~50-100kW for CANS**

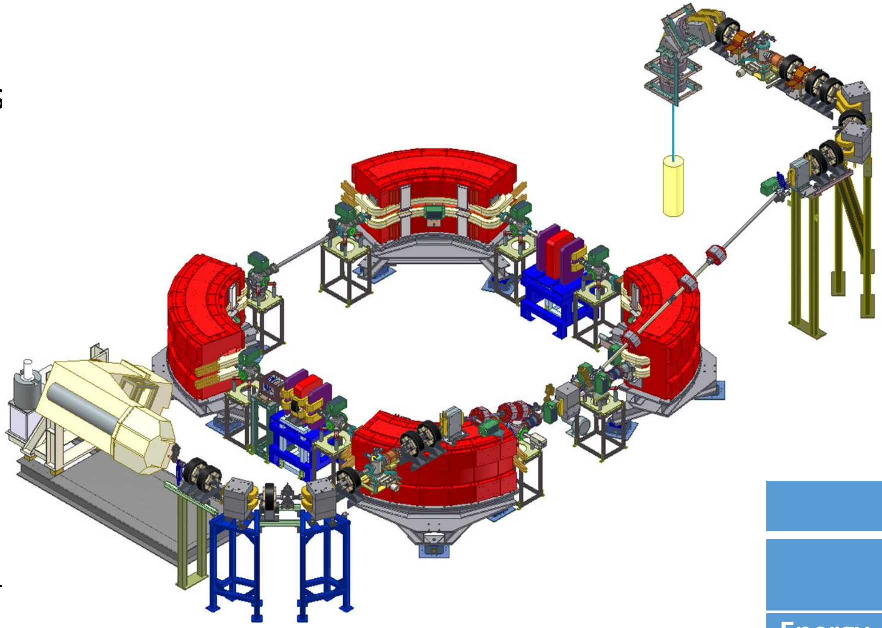
# IU LENS: 2018


*Italics and underlined:*
*Used for the CRP*
RF Power Systems
TMR2: Cold neutrons, Mod. Studies, Mat. Res.
SESAME
MIS
SANS
Radiography
3, 7, 13 MeV Linac
TMR1: Fast Neutrons, NREF

# The Indiana University – NAVSEA Crane ALPHA Project (2003-2017)

## Advanced eLectron PHoton Accelerator for Radiation Effects Research and Testing

- Goals
  - Reduce testing costs
  - Eliminate RF Modulation
  - Provide higher dose rates for survivability tes
  - Provide higher fidelity test environment
    - More uniform beam
    - Larger area exposure
    - More hospitable test environment
    - Low electronic noise
- Solution
  - Couple a LINAC with a electron storage ring
    - Long pulse mode (up to 4 μS) – Debunching
    - Short Pulse mode (0.1-50 nS) – High dose rate (> 10¹
  - Use non linear optics to shape beam
    - Eliminate masking and associated secondary scattering
    - More efficient use of beam



| | Requiremen |
|---|---|
| Instantaneous Dose Rate | $0.4\times10^{10}$ Rad/s |
| Beam Size | 6.45 $cm^2$ |
| Pulse Length | 4 μS |
| Repetition Rate | 10 Hz |
| LINAC Current | 0.068 A |

**The primary objectives of the ALF:**

| | | Requirement | Goal |
|---|---|---|---|
| **Energy** | MeV | 40 | **10-60** |
| **Pulse Length (narrow)** | nsec | 5-100 | **5-200** |
| **Pulse Length (wide)** | usec | 1-5 | **1-10** |
| **Dose Rate (MAX)** | Rad/sec | $5\times10^{12}$ | **$1\times10^{13}$** |
| **Rep Rate** | Hz | 1 | **10** |
| **Target Area (85% uniformity)** | mm (diam) | 40 | **65** |
| **Bremsstrahlung Mode** | $cal/cm^2$ | .5 | **1.0** |
| **Resonant Frequency (RF)** | **Hz** | **none** | **none** |

# Backup slides

# Preliminary Results on UCNtau 2017-2018 dataset

| Effect | Previously Published Value (s) | Data Driven New Value (s) | Monte Carlo New Value (s) | Method of evaluation |
|---|---|---|---|---|
| Rate Dependent Effects | $-0.20 \pm 0.04$ | -- | $-0.6 \text{ to } -1.3\ (\text{typ.}) \pm 0.11$ | MC Simulations + Known hardware dead time |
| Microphonic heating | $0 + 0.24$ | $0 + 0.07$ | $0.031 \pm 0.005$ | MC Simulations + Detector for heated neutrons |
| Insufficient cleaning | $0 + 0.07$ | $0 + 0.06$ | $0.034 \pm 0.016$ | MC Simulations + Detector for uncleaned neutrons |
| Phase space evolution | $0 \pm 0.10$ | $0.029 \pm 0.003$ | -- | Measured neutron arrival time |
| Aluminum Block* | -- | $0.15 \pm 0.13$ | $0.3 \pm 0.2$ | MC Simulations + Polyethylene coated block |
| Residual gas interactions | $0.16 \pm 0.03$ | $0.05 \pm 0.01$ | -- | Measured gas cross sections and pressure |
| Depolarization | $0 \pm 0.07$ | -- | -- | Varied external holding field |
| **Total Systematics** | $\mathbf{-0.04^{+0.28}_{-0.11}}$ | $\mathbf{-0.5 \text{ to } -1.2\ (\text{typ.})^{+0.16}_{-0.11}}$ | | (Sum, Excluding Aluminum Block) |

# Typical CANS reactions

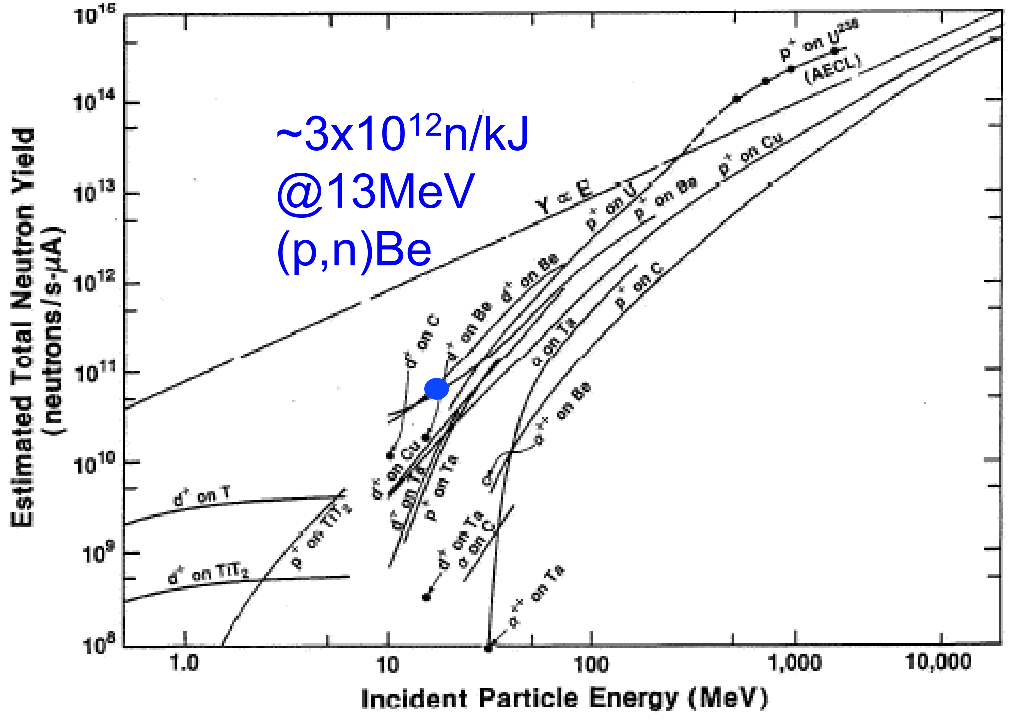



FIG. 2. Global thick-target neutron yields for various charged particle reactions versus particle energy. (Adapted from Stevens and Miller.[11])

From J. M. Carpenter and Yelon (1986)



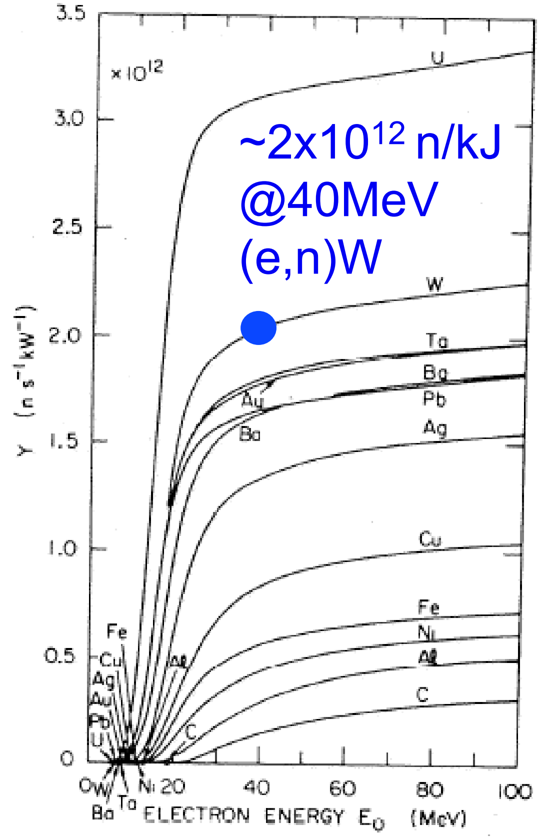



FIG. 11. Global neutron yield for electrons on various thick targets versus electron energy. (From Swanson.[30])

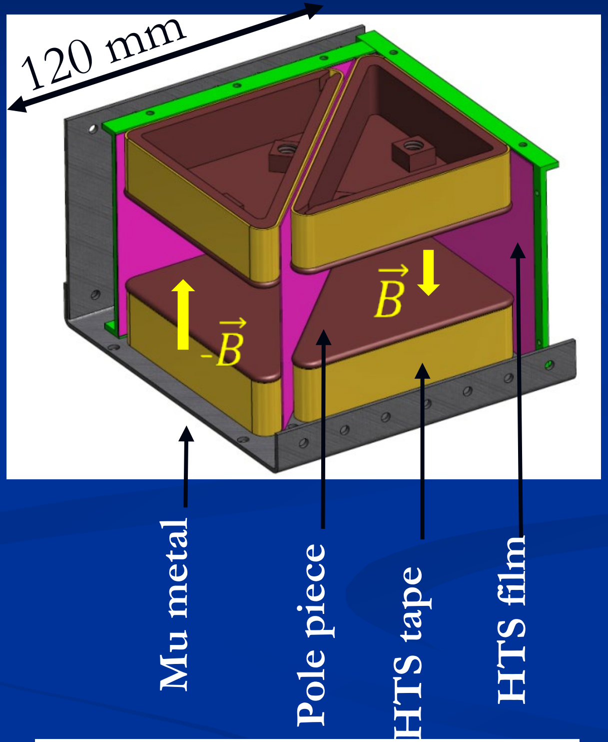
Proton, deuteron or electron accelerators can reach comparable neutron production rates for a given power, but differ in the accelerator energy needed and target design.

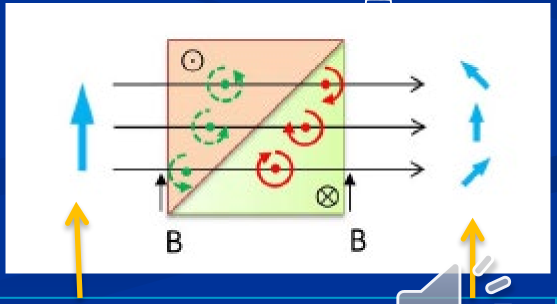
# Conclusions

- CANS make use of high-current relatively low energy accelerators (e, p).
- CANS with power levels up to 100kW are in development
- CW facilities are primarily being pursued for BNCT applications, for neutron scattering, pulse sources (10 to 500 Hz) are likely to be of more interest.

# HTS Magnetic Wollaston Prisms: (LENS)

- (Classical View) A neutron WP allows you to encode neutron trajectory information into the neutron phase (spin orientation). With this you can decouple momentum resolution from neutron intensity facilitating:
  - Increased energy resolution in neutron scattering
  - Spin-echo approaches to real-space correlations in materials
  - New contrast mechanisms to neutron radiography



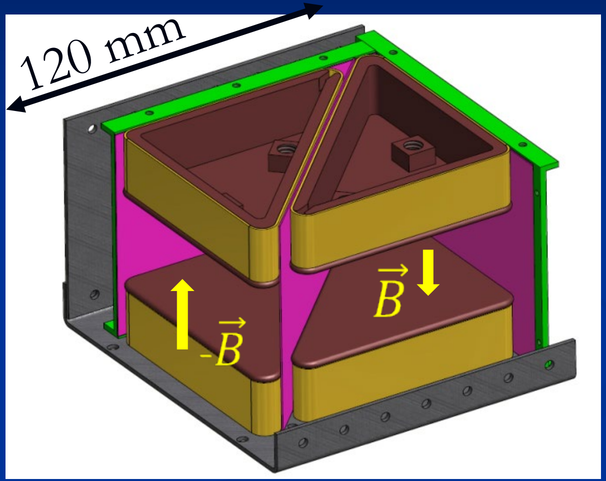



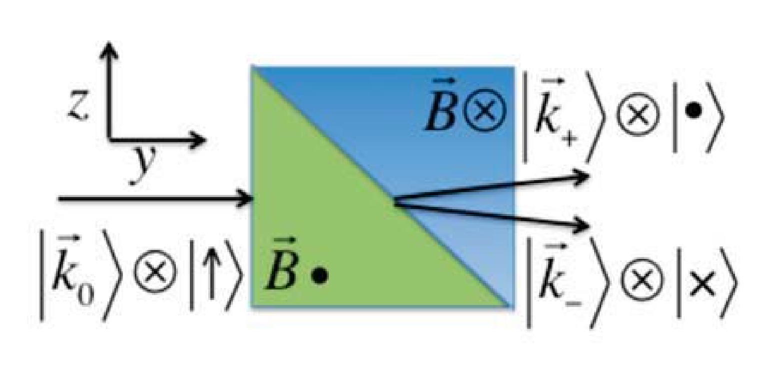

Neutron spin orientations

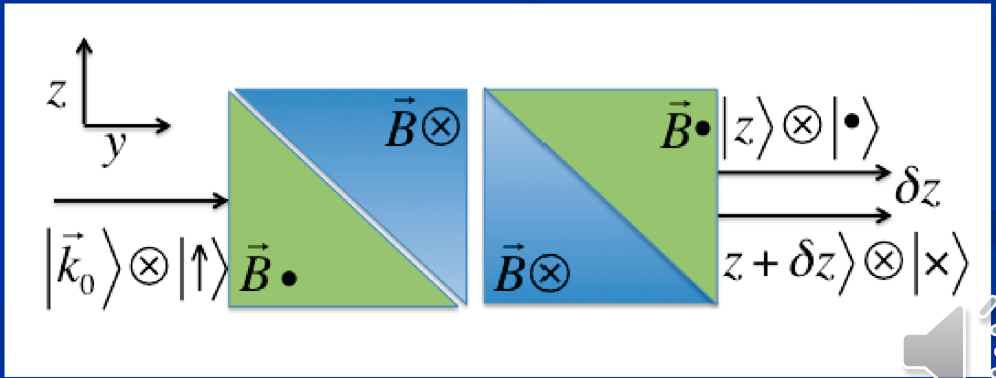
See Li et al. Rev. Sci. Inst. **86**, 023902 (2014), Li and Pynn, J. Appl. Cryst, **47**,1849 (2014) & perspective by F. Mezei, J. Appl. Cryst **47**,1807 (2014)

# HTS Magnetic Wollaston Prisms

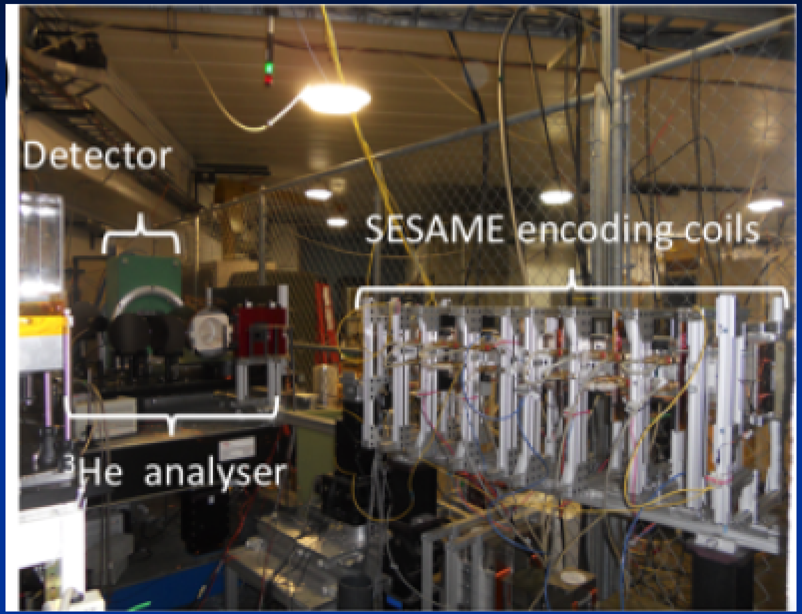
- (Quantum View) A neutron WP acts as a birefringent medium for neutrons. It allows one to entangle the neutron spin with either momentum or position:
  - Introduction of entangled spin states into neutron scattering

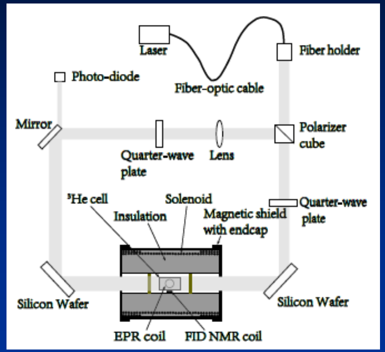


# SESAME Instrument



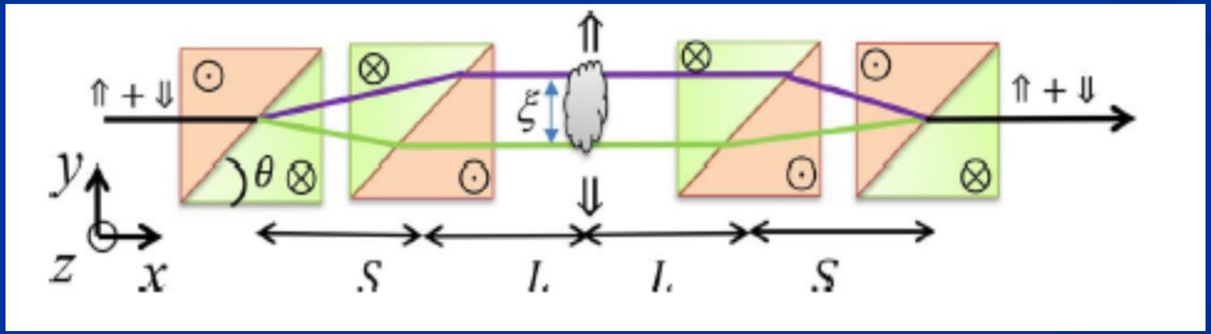




**On-line $^3$He polarization (SEOP) analysis**

S. R. Parnell et al., Rev. Sci. Inst. (2015)

$$P_s(\xi)/P_o(\xi)=\exp(\Sigma_t[G(\xi)-1])$$

**Real space correlations are determined directly from measuring the normalized polarization of the outgoing beam.**

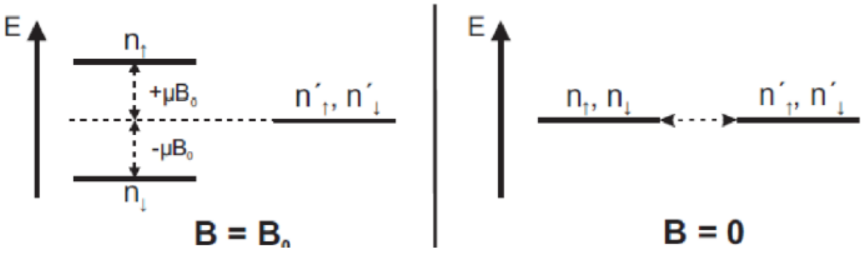


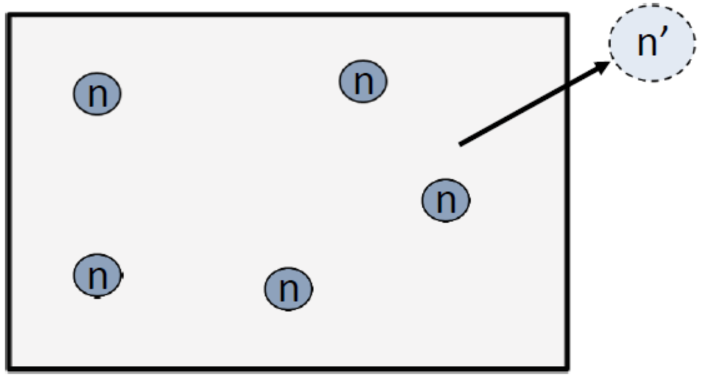

$\xi = cBS\lambda^2 B\cot(\theta)$ ; $c=2.476\times10^{14}\ T^{-1}\ m^{-2}$

$\xi = 30nm$ at $\lambda=0.5nm$, $B=1mT$, $S=0.5m$

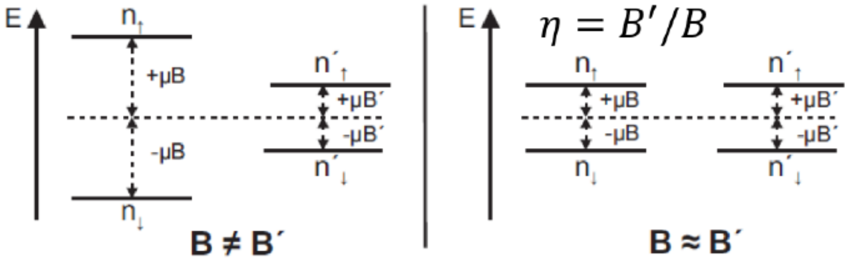
# Search for n → n' with UCN

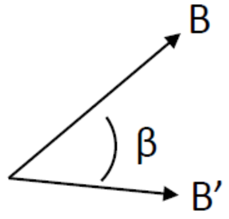
- Search for anomalous disappearance of UCN vs magnetic field with storage time measurements: two "channels" for searches
- Ratio $E_B(t_s) = \frac{N_b(t_s)+N_{-b}(t_s)}{N_B(t_s)+N_{-B}(t_s)} - 1 = \frac{t_s}{\langle t_f \rangle} \frac{\eta^2(3-\eta^2)}{2\omega'^2 \tau_{nn'}^2 (1-\eta^2)^2}$




- Asymmetry $A_B(t_s) = \frac{N_B(t_s)-N_{-B}(t_s)}{N_B(t_s)+N_{-B}(t_s)} - 1 = \frac{t_s}{\langle t_f \rangle} \frac{\eta^3 \cos\beta}{\omega^2 \tau_{nn'}^2 (1-\eta^2)^2}$




Kirch, INT 17-69W (2017)
Berezhiani, EPJC **64** 421 (2009)

# Atomic and Nuclear EDM

Electron EDM

TVPV pseudoscalar-scalar eN coupling

TVPV tensor eN coupling

Short-distance contribution to $d_n$

Short distance contribution to $d_p$

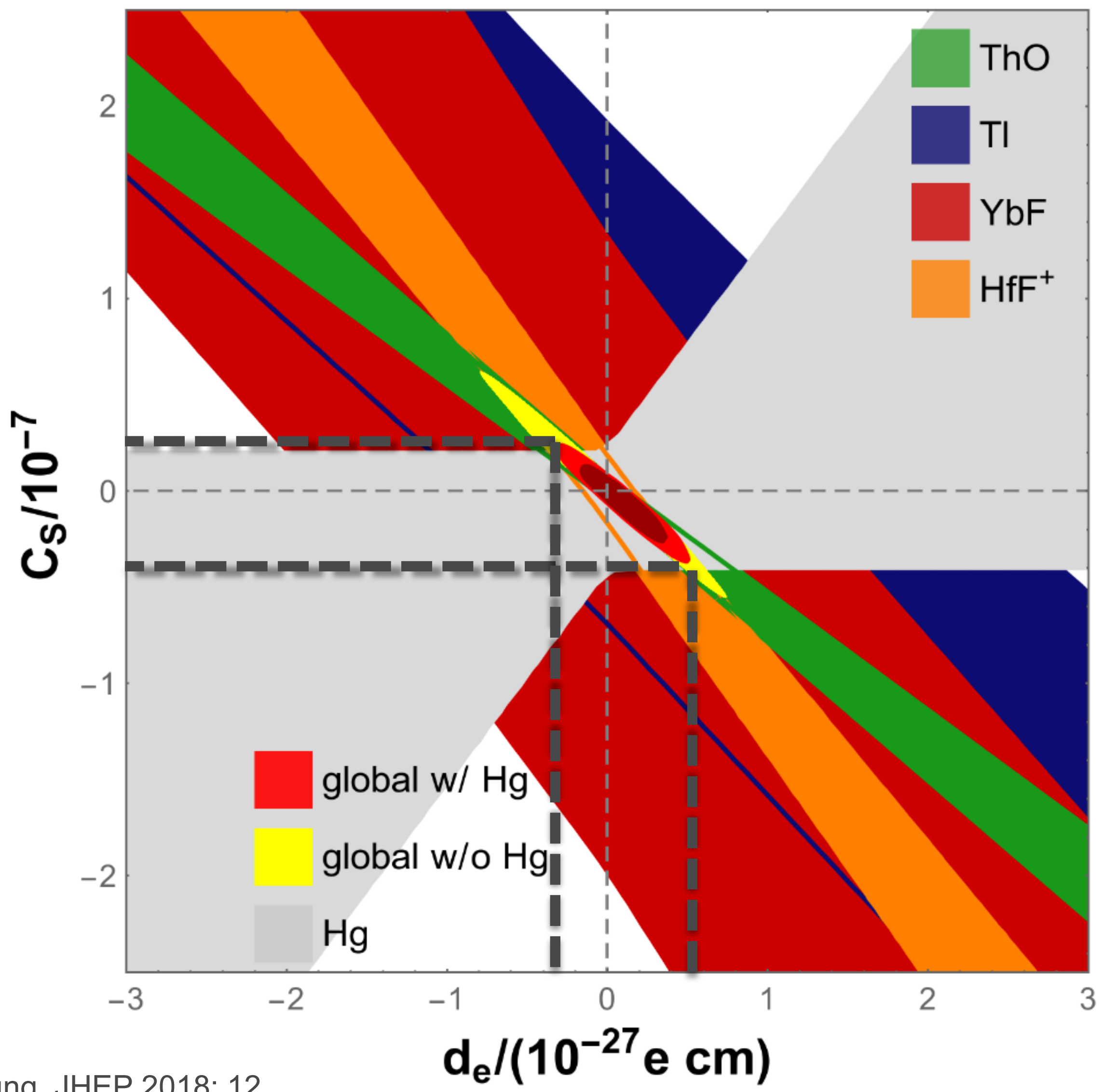
TVPV isoscalar $\pi$N coupling

TVPV isovector $\pi$N coupling

$$d = \underbrace{\alpha_{d_e} d_e + \alpha_{C_S} C_S}_{\text{Paramagnetic Systems}} + \underbrace{\alpha_{C_T} C_T + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1,}_{\text{Diamagnetic Systems}}$$

T. Chupp, M. Ramsey-Musolf, Phys. Rev. **C91** 035502 (2015)

# PHASE SPACE IN ELECTRON EDM




T. Fleig, M. Jung, JHEP 2018: 12