The TUCAN EDM experiment

TRIUMF Ultracold Advanced Neutron Electric Dipole Moment

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TUCAN

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Why?

- The universe is dominated by matter
- Some early universe process must have produced this excess
- Sakharov conditions for this process:
  - Baryon number violation
  - C and CP symmetry violation
  - Departure from thermal equilibrium

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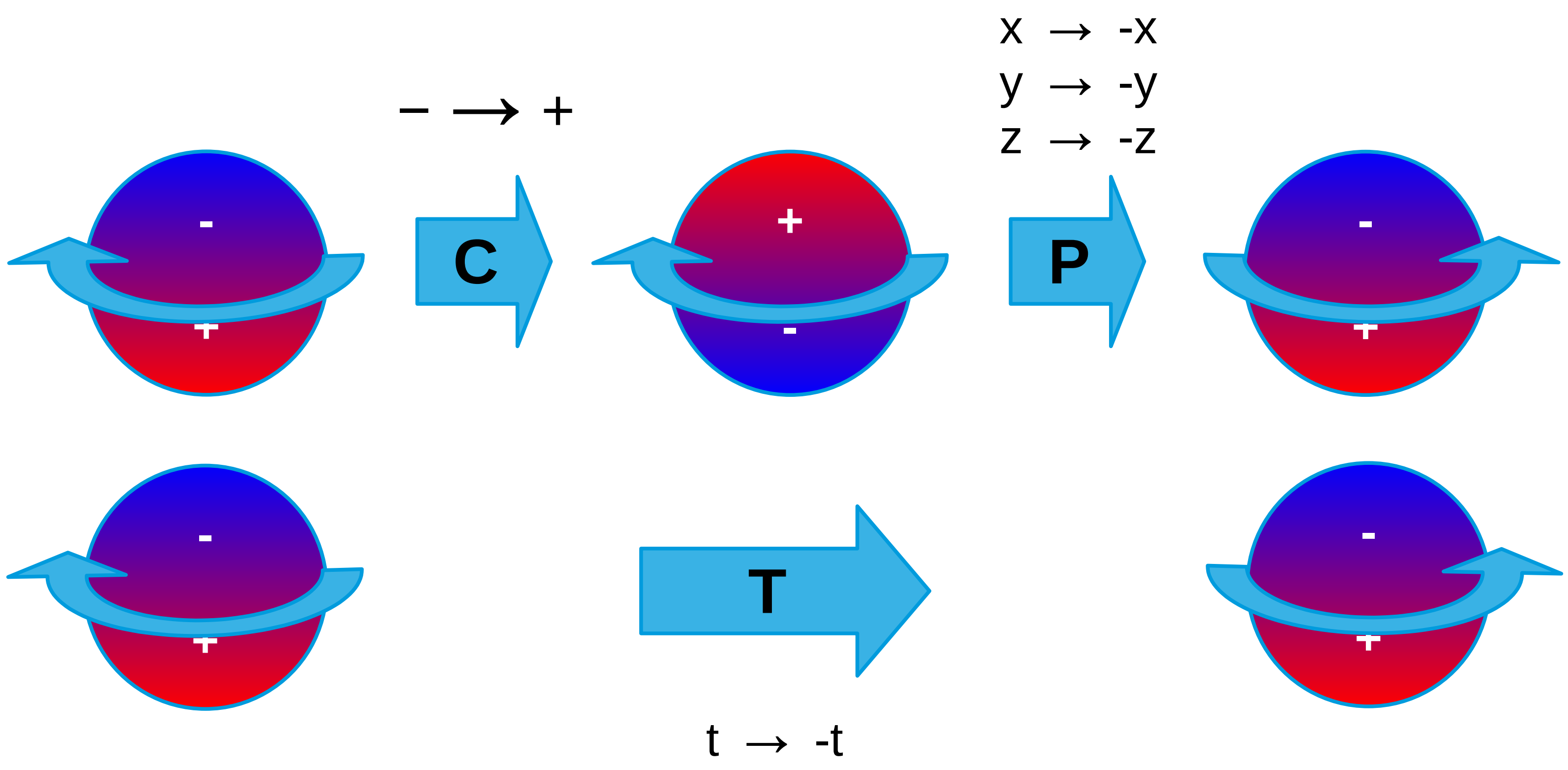
The Standard Model does not currently have enough of this!

CP vs T symmetry



Why EDMs?

- The Hamiltonian for a particle with spin in an electromagnetic field is:

$$H = \hbar\omega = -\mu\mathbf{B}\cdot\mathbf{S} - d\mathbf{E}\cdot\mathbf{S}$$

- If we reverse time (i.e. apply a T transformation)

$$\mathbf{T}(H) = \hbar\omega = -\mu\mathbf{B}\cdot\mathbf{S} + d\mathbf{E}\cdot\mathbf{S}$$

- The Hamiltonian is not the same!
  - T symmetry (and therefore CP symmetry) is violated in this system, but only if *d* is nonzero – a permanent EDM.

Electric Dipole Moments

- Describes the distribution of charge in an object

$$d = \Delta x \cdot q$$

Dipole moment

Displacement of charge in object

Charge being displaced

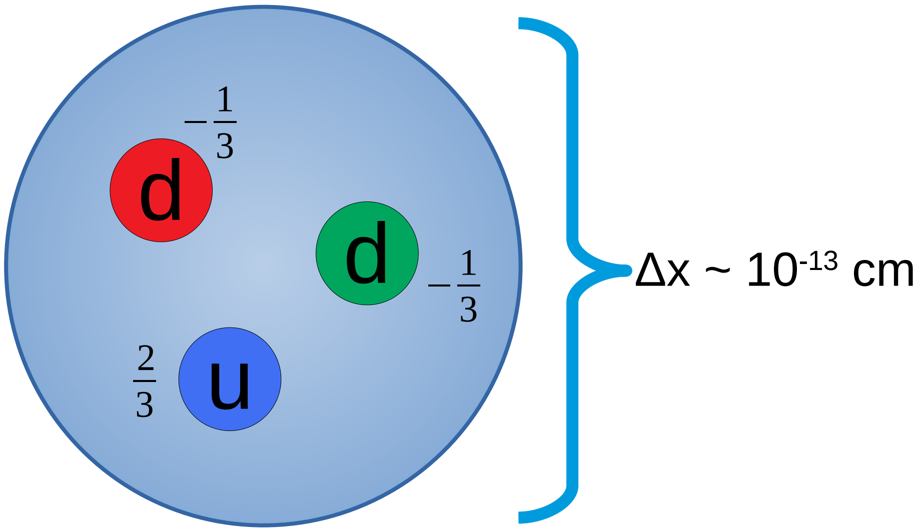
The Neutron Electric Dipole Moment

- Neutrons are *overall* electrically neutral
- Quarks have charge
- The nEDM describes the distribution of these charges
- The current best measurement performed by the PSI nEDM collaboration:

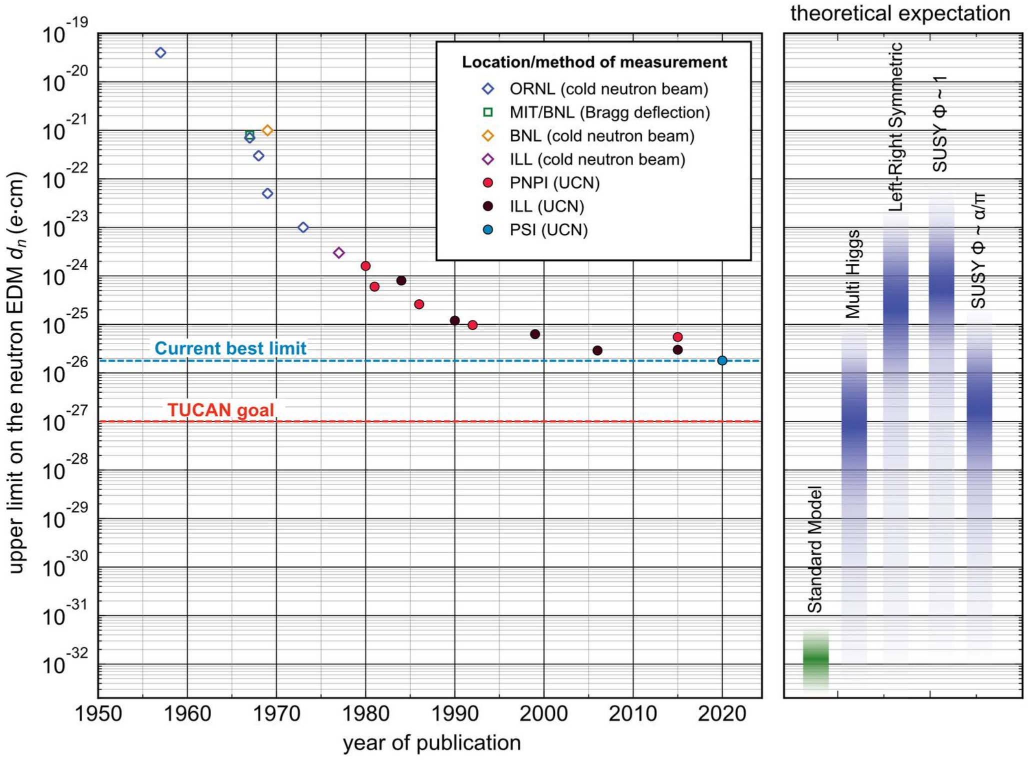
$$|d_n| < 1.8 \times 10^{-26} e \cdot \mathrm{cm} \ (90\% \ \mathrm{C.L.})$$

- Our goal is an order of magnitude improvement!

$$d = \Delta x \cdot q$$



Why neutrons?



- Sensitive to some BSM physics models
- Standard Model prediction is far far below experimental limits
  - Essentially SM background-free
- Bare nucleon directly feels impact of applied fields
  - No screening effects

How do we measure an EDM?

- Observable property is precession frequency:

E & **B** parallel → $$\nu_{\upuparrows} = \frac{2\mu_n}{h}B + \frac{2d_n}{h}E$$

E & **B** *anti*parallel → $$\nu_{\uparrow\downarrow} = \frac{2\mu_n}{h}B - \frac{2d_n}{h}E$$

How do we measure an EDM?

Subtracting the previous two equations:

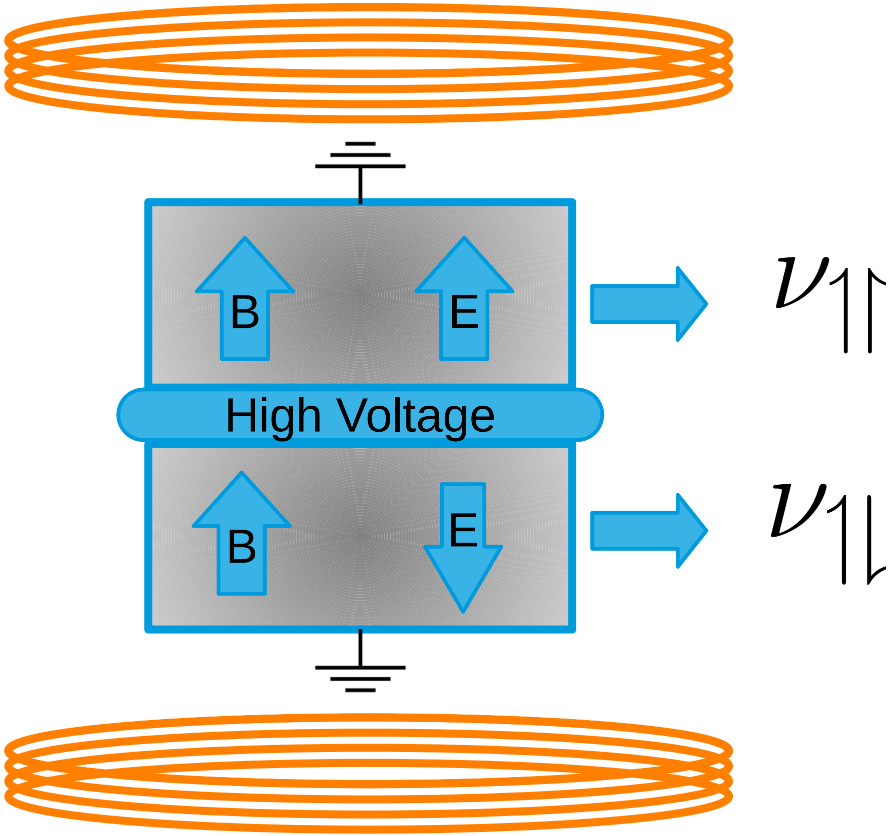
Get this...

$$d_n = \frac{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow})}{4E}$$

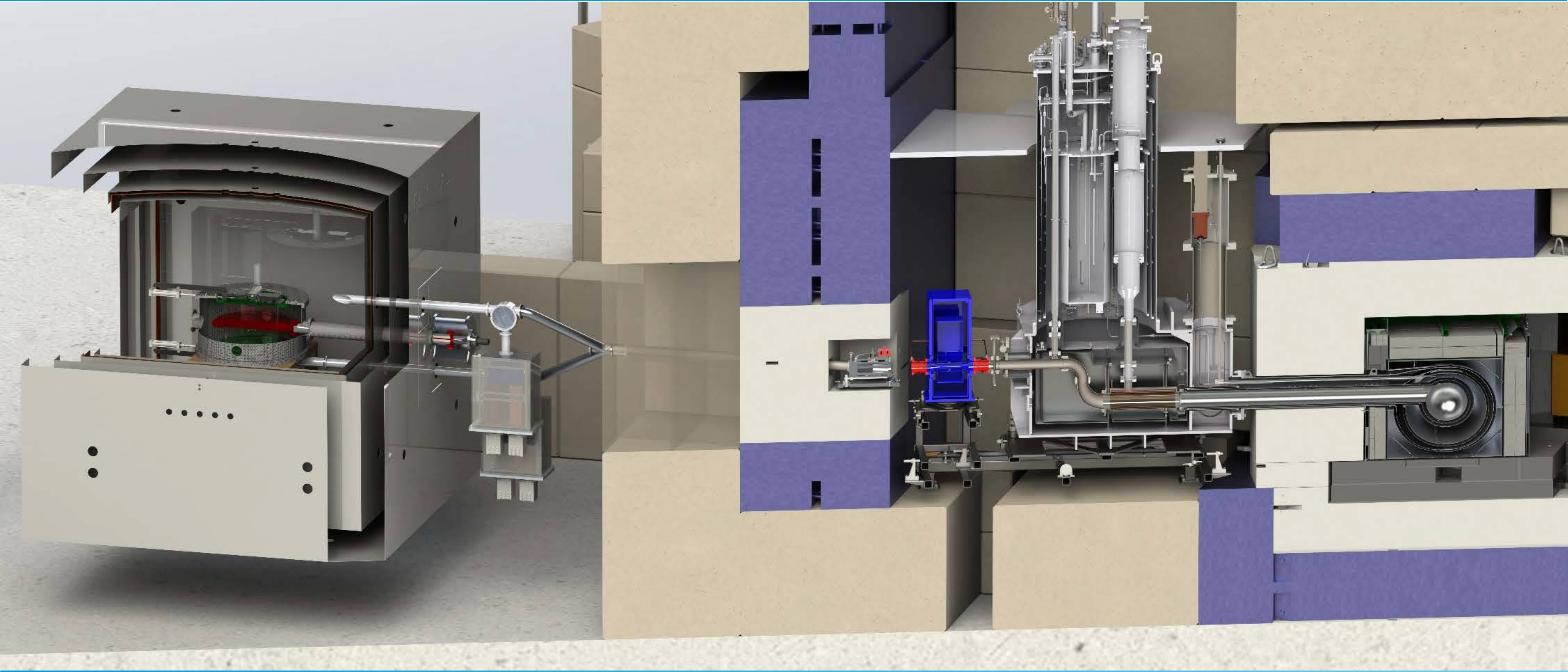
...by measuring this

while controlling this

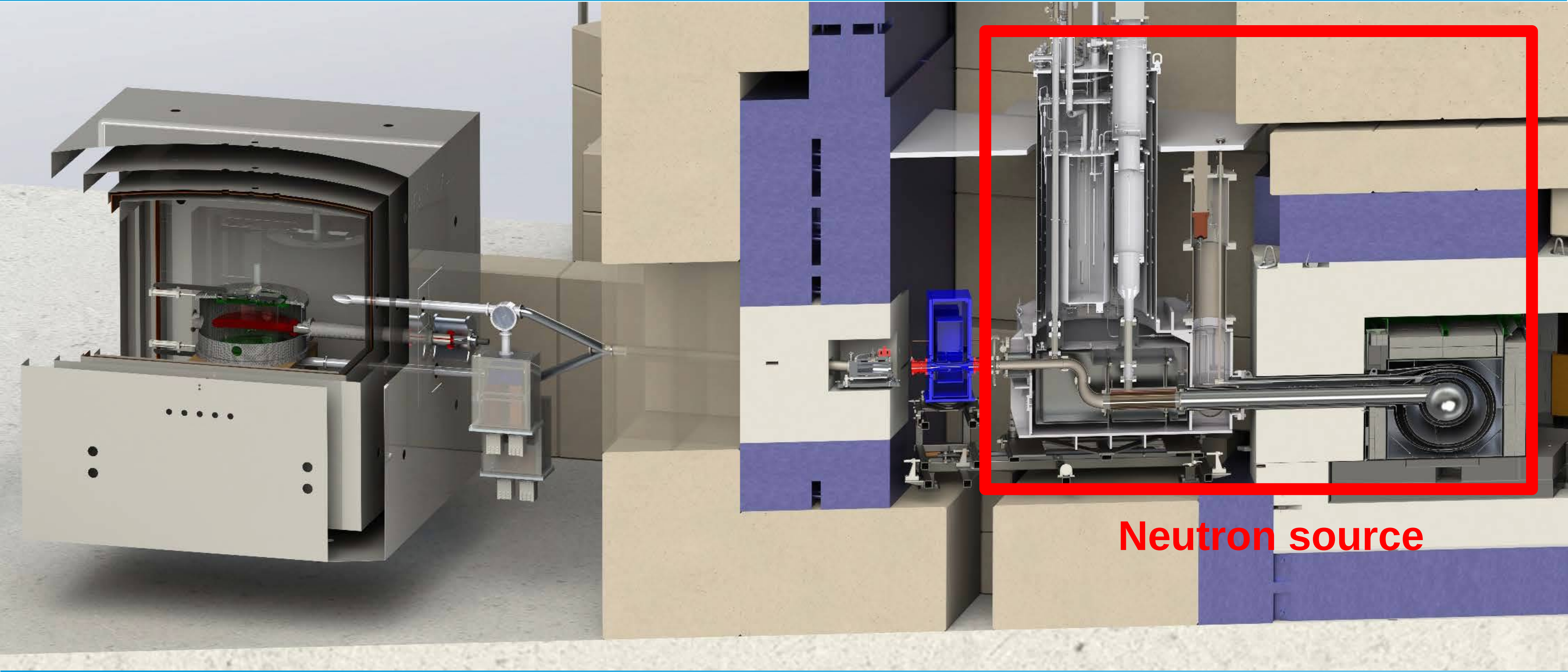
Basic idea



The TUCAN EDM experiment



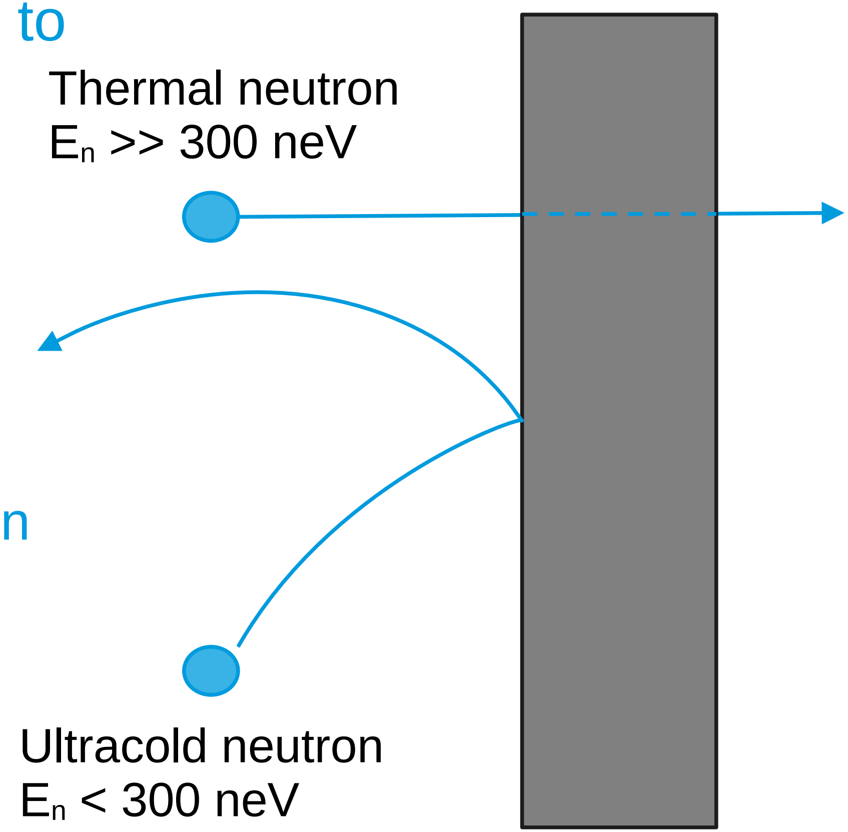
The TUCAN EDM experiment



Ultracold Neutrons

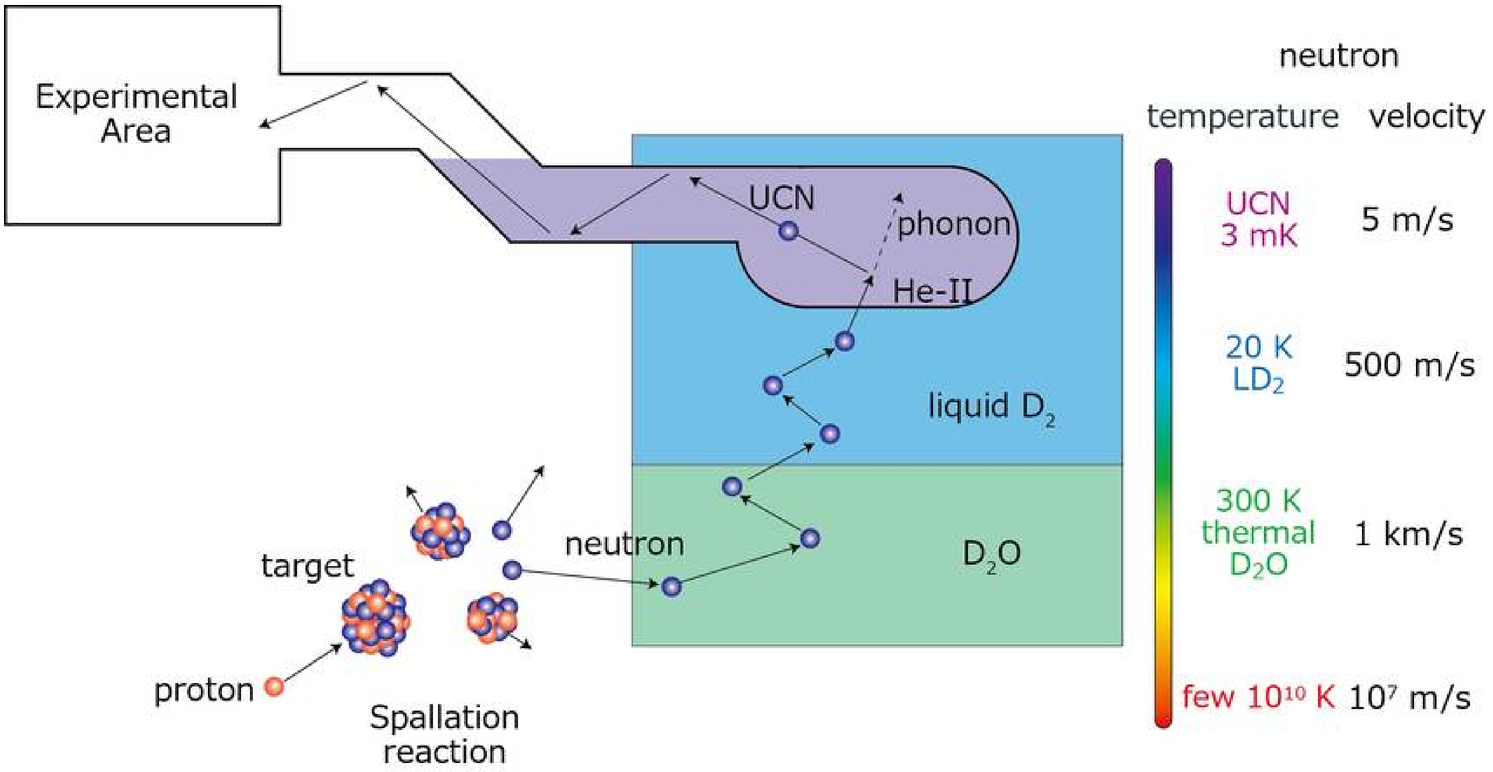
- Neutrons are notoriously difficult to hold on to
  - Electrically neutral → can't feel Coulomb force

- Solution:
  - Make them cold
  - UCN feel an effective "Fermi" potential when they encounter a physical material due to strong interactions with the nuclei in the material



Ultracold Neutrons

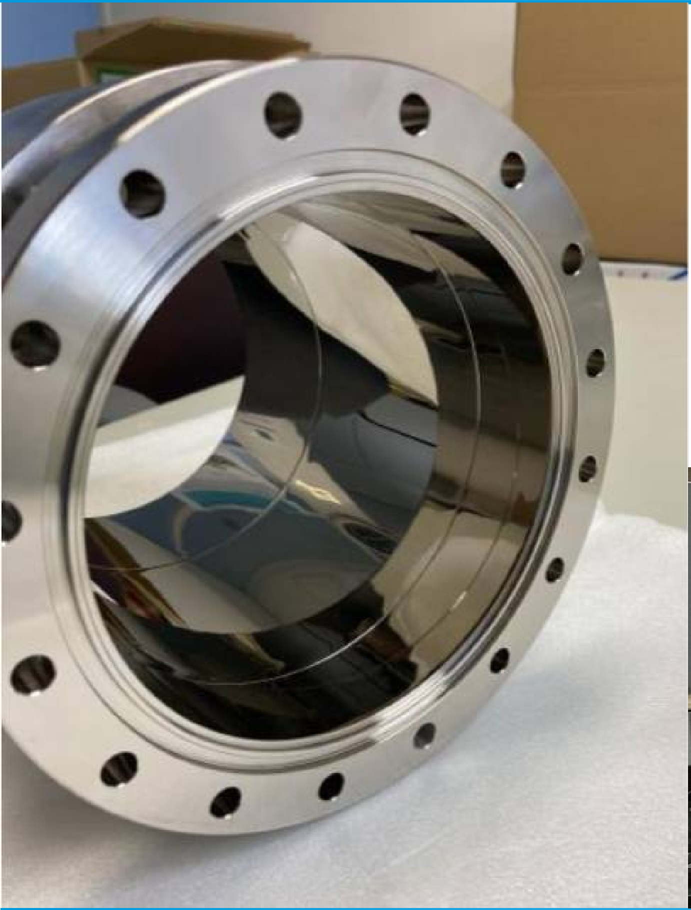
- Spallation neutrons lose almost all their energy in liquid Helium



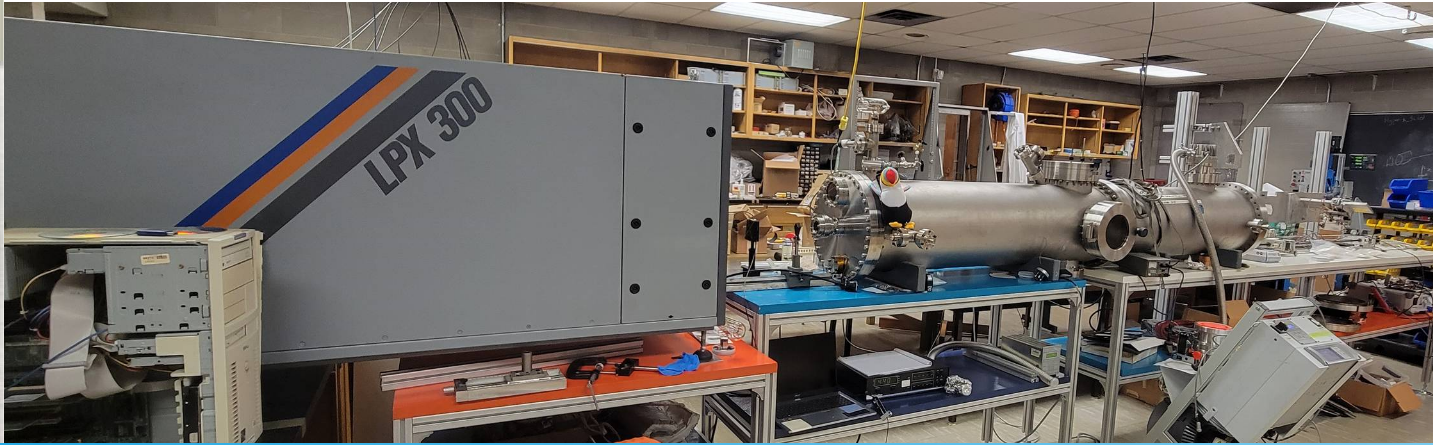
- PSI measured on average 11400 UCN per cycle
- TUCAN source is expected to produce enough to measure 1400000 UCN per cycle

Figure: Kawasaki, Shinsuke & Okamura, Takahiro. (2020). *Development of a Helium-3 Cryostat for a Ultra-Cold Neutron Source*. IOP Conference Series: Materials Science and Engineering. 755. 012140. 10.1088/1757-899X/755/1/012140.

Ultracold Neutrons



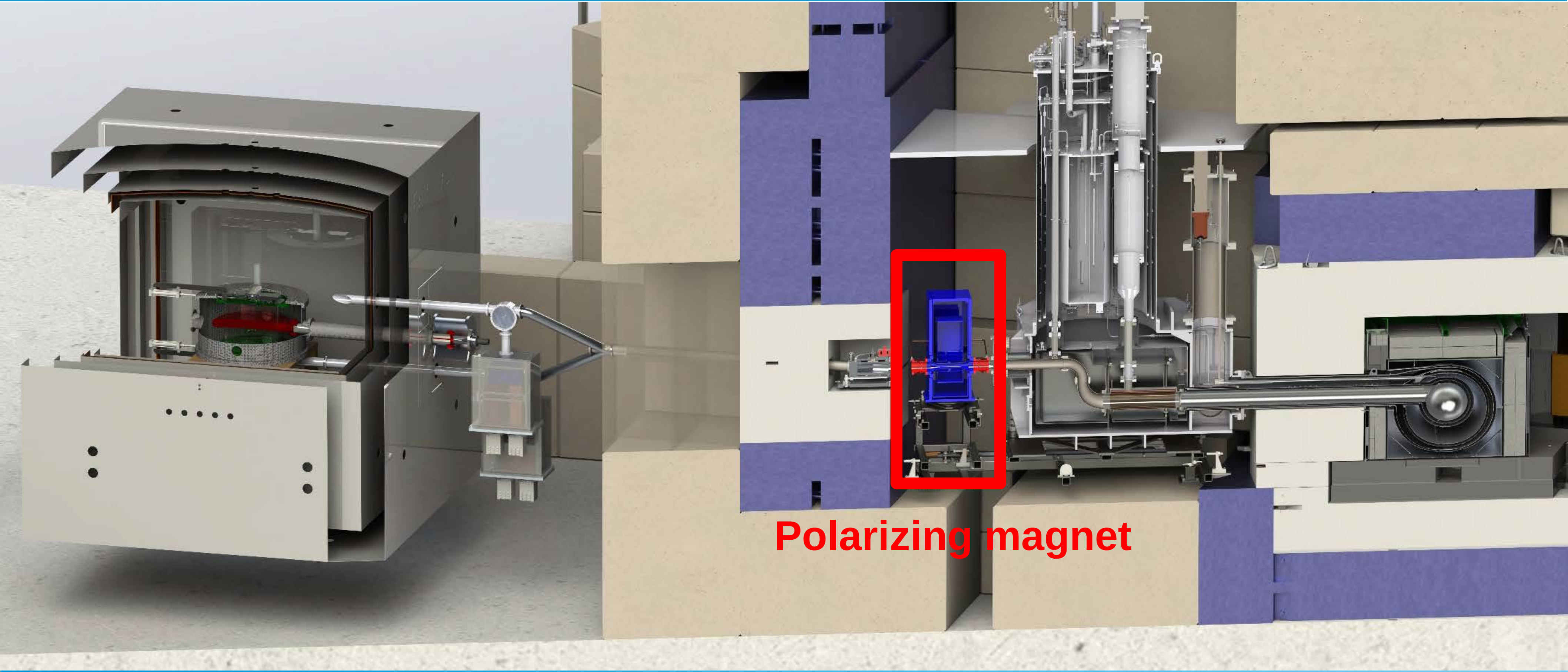
- UCN can be trapped and directed using physical guides
  - Special coating on the guides raises the effective Fermi potential
- **Left**: a section of guide polished and coated with NiP
- **Below**: a facility at UWinnipeg for coating guides with diamond-like carbon



Measuring ν_n

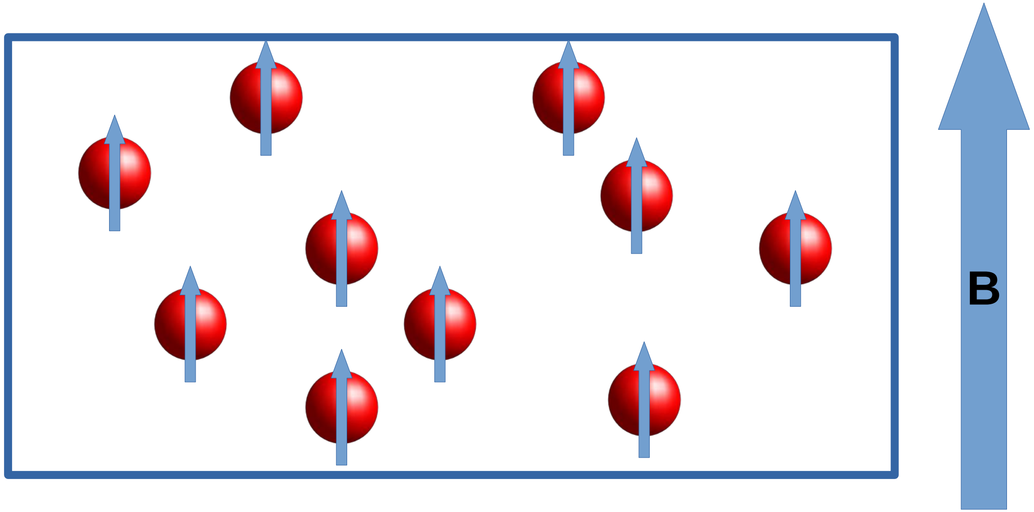
- Can’t look at neutrons
  - No optical interrogation of precession
- What **can** we do to neutrons?
  - Polarize them
  - NMR-style spin manipulation
  - Sort spin up from spin down
  - Count them

The TUCAN EDM experiment



Measuring ν_n

- Each cycle the UCNs start out polarized with spins pointing along $\mathbf{B_0}$ thanks to the polarizing magnet
  - No precession since spins are aligned with field



Getting them to precess

- Applying RF at the correct frequency causes the spin of the neutron to tip
- Applying it for the correct duration stops the tilt at exactly π/2

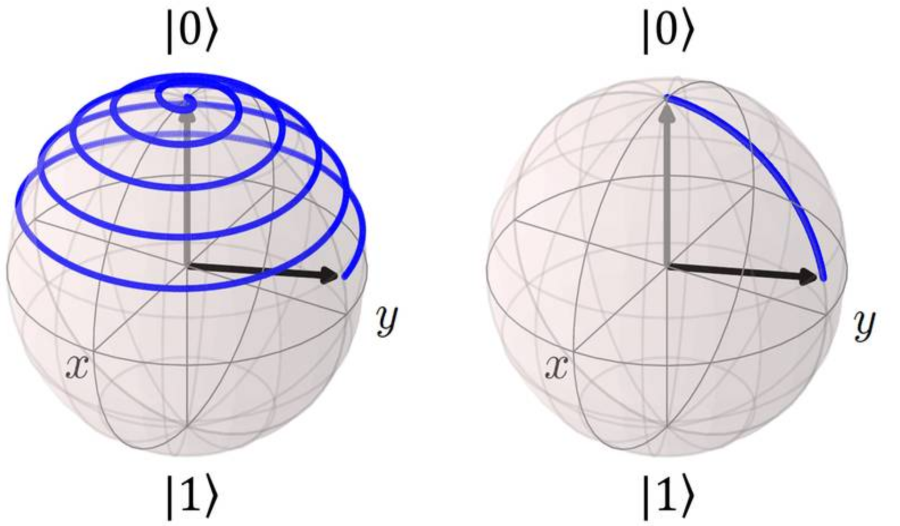
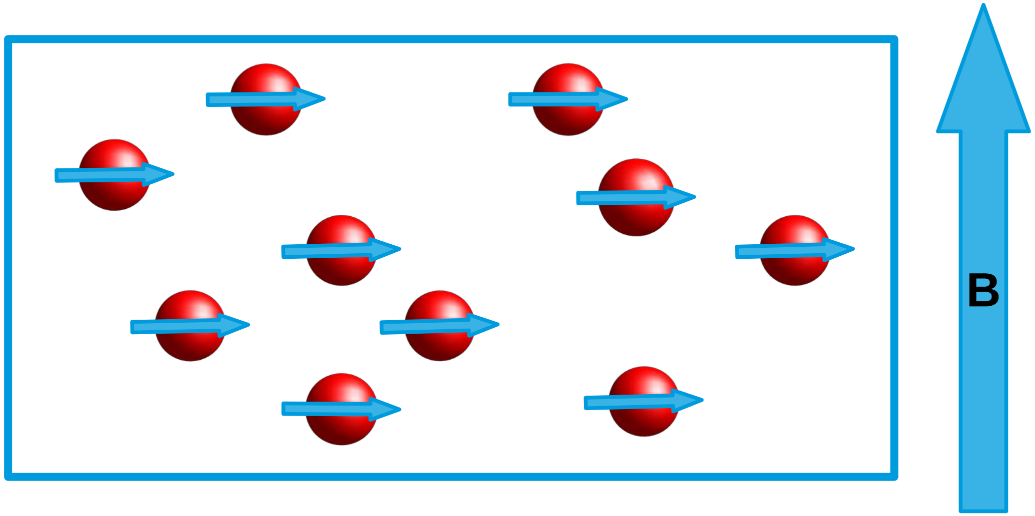


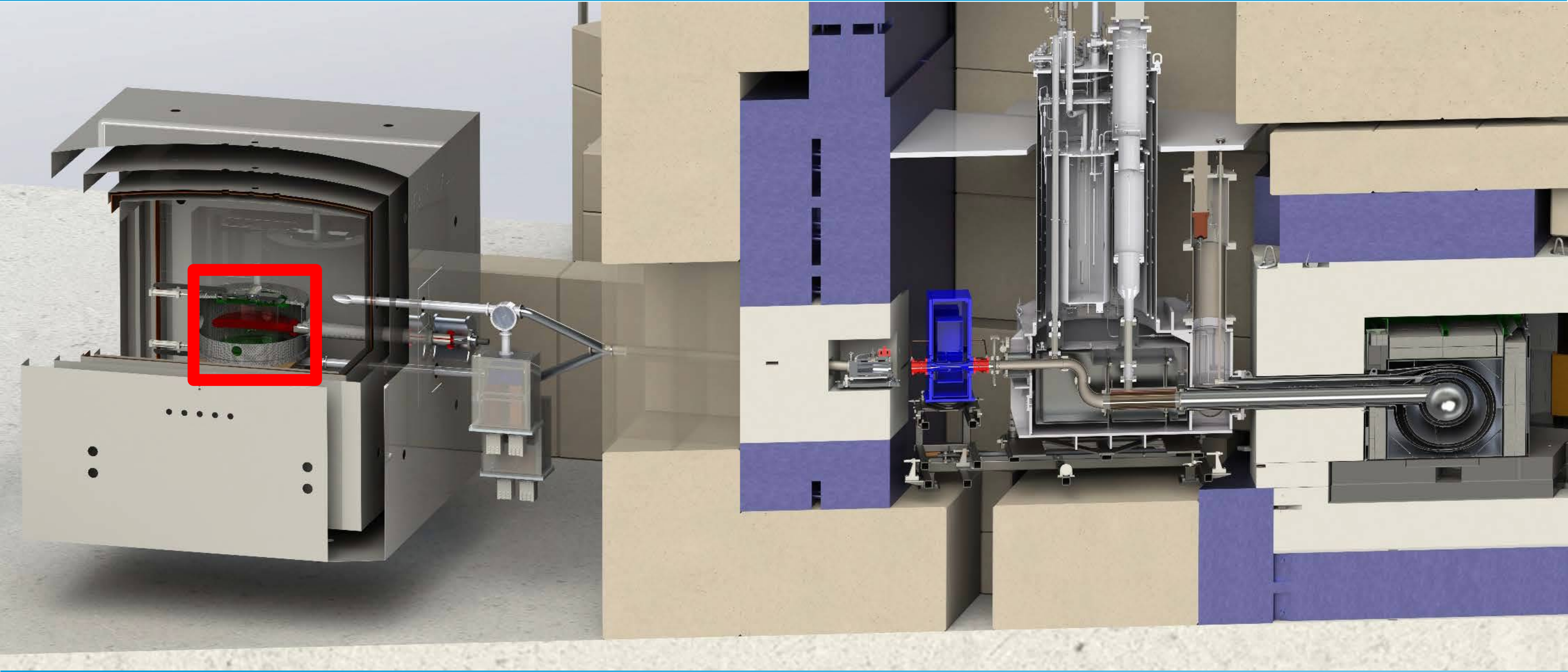
Figure: Godfrin, Clément. (2017). *Quantum information processing using a molecular magnet single nuclear spin qubit.*

Measuring ν_n

- NMR-style $\pi/2$ pulse tips spins into horizontal plane
  - Now UCNs precess at their Larmor frequency

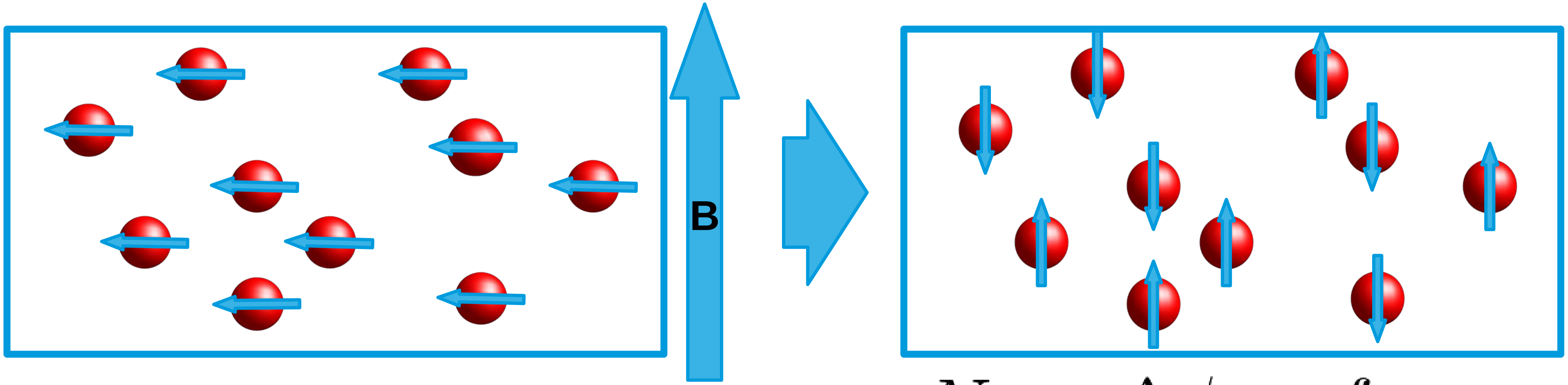


Precession chambers



Measuring ν_n

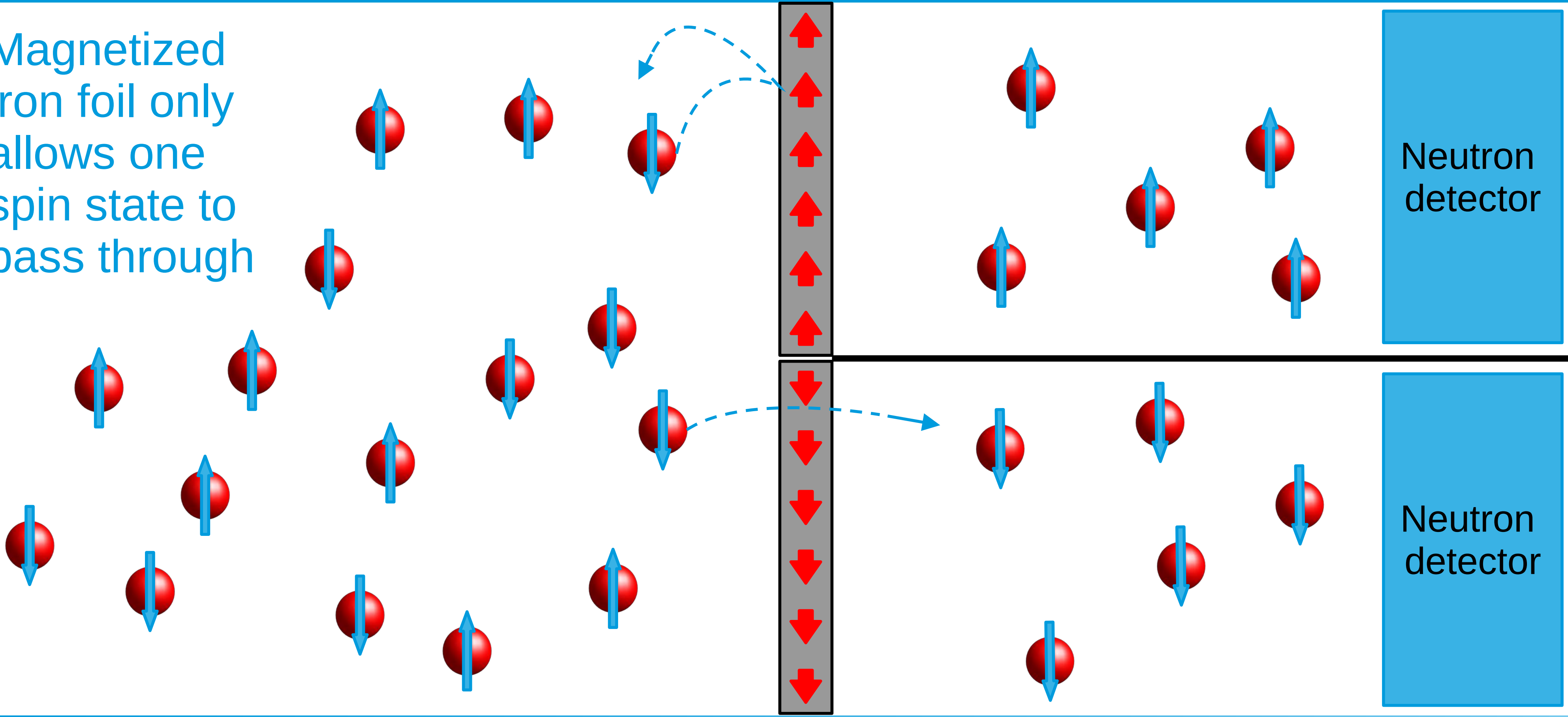
- After some relatively long time (100s of seconds) another spin-tipping pulse is applied
- **Key part:** the second pulse is carefully chosen so that the resulting ratio of spin up/spin down is extremely sensitive to the accumulated phase of the neutrons



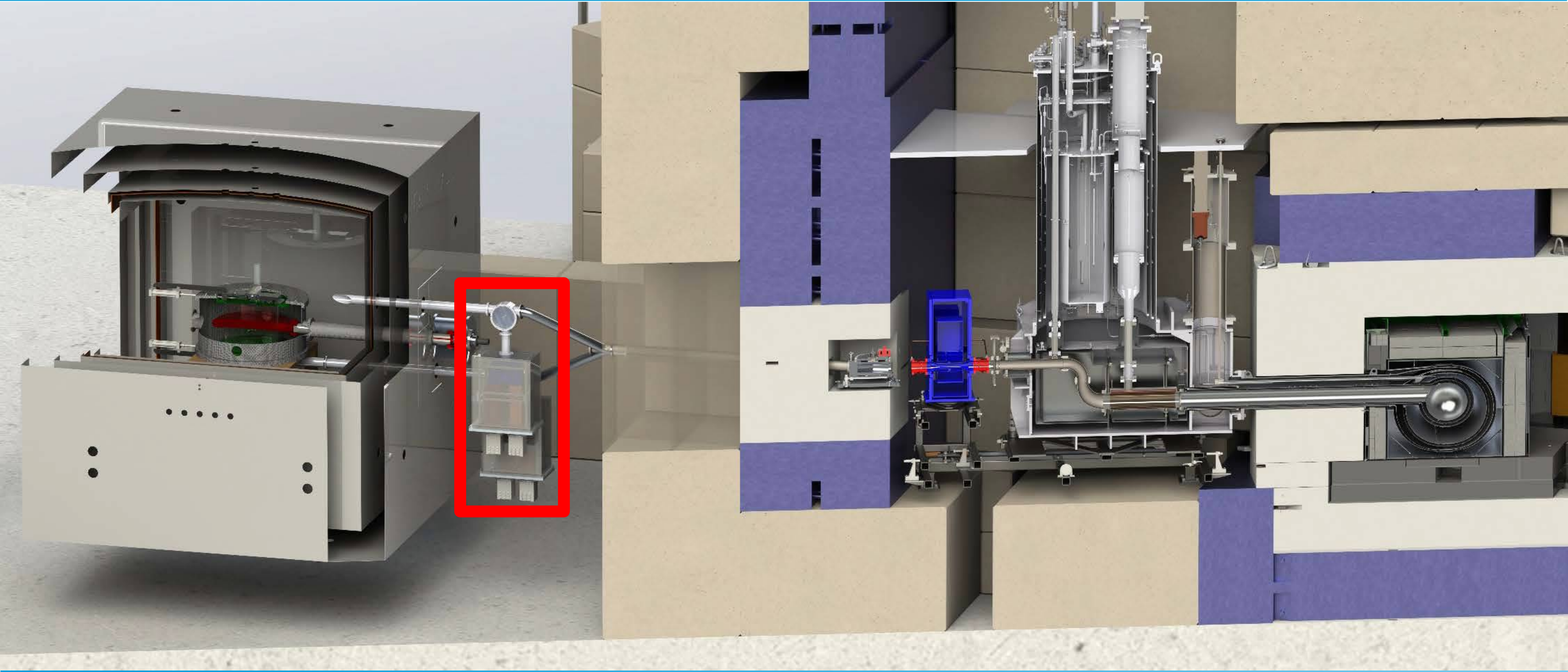
$$N_{\uparrow} \propto \Delta\phi \propto f_{precess}$$

Sorting spin up from spin down

- Magnetized iron foil only allows one spin state to pass through

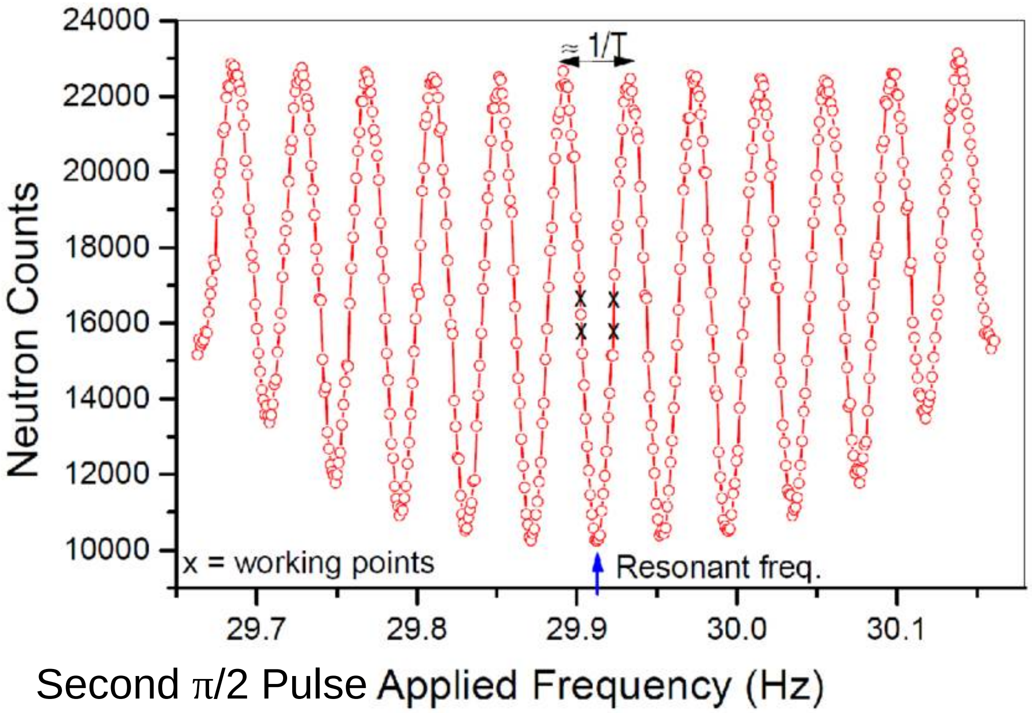


Spin analyzers



Ramsey resonance

- Frequency is now determined by fitting neutron counts to the following theoretical curve:



- This technique is called "Ramsey interferometry" or "separated oscillating fields method" if you want to look up further details

Figure: Chesnevskaya, S.. (2015). *Investigation of electric fields, losses and depolarization of ultra-cold neutrons for the new nEDM experiment at FRM II*. 10.13140/RG.2.2.21271.01444.

How precise?

- **B** = 1 μT
  - Neutron has a magnetic moment so precesses at ~30 Hz in this field
- **E** = 10 kV/cm
  - If the EDM was just barely smaller than the current upper limit (best case scenario) it would precess at ~5 nHz

$$\frac{\mathrm{nHz}}{\mathrm{Hz}} = \mathrm{ppb}$$

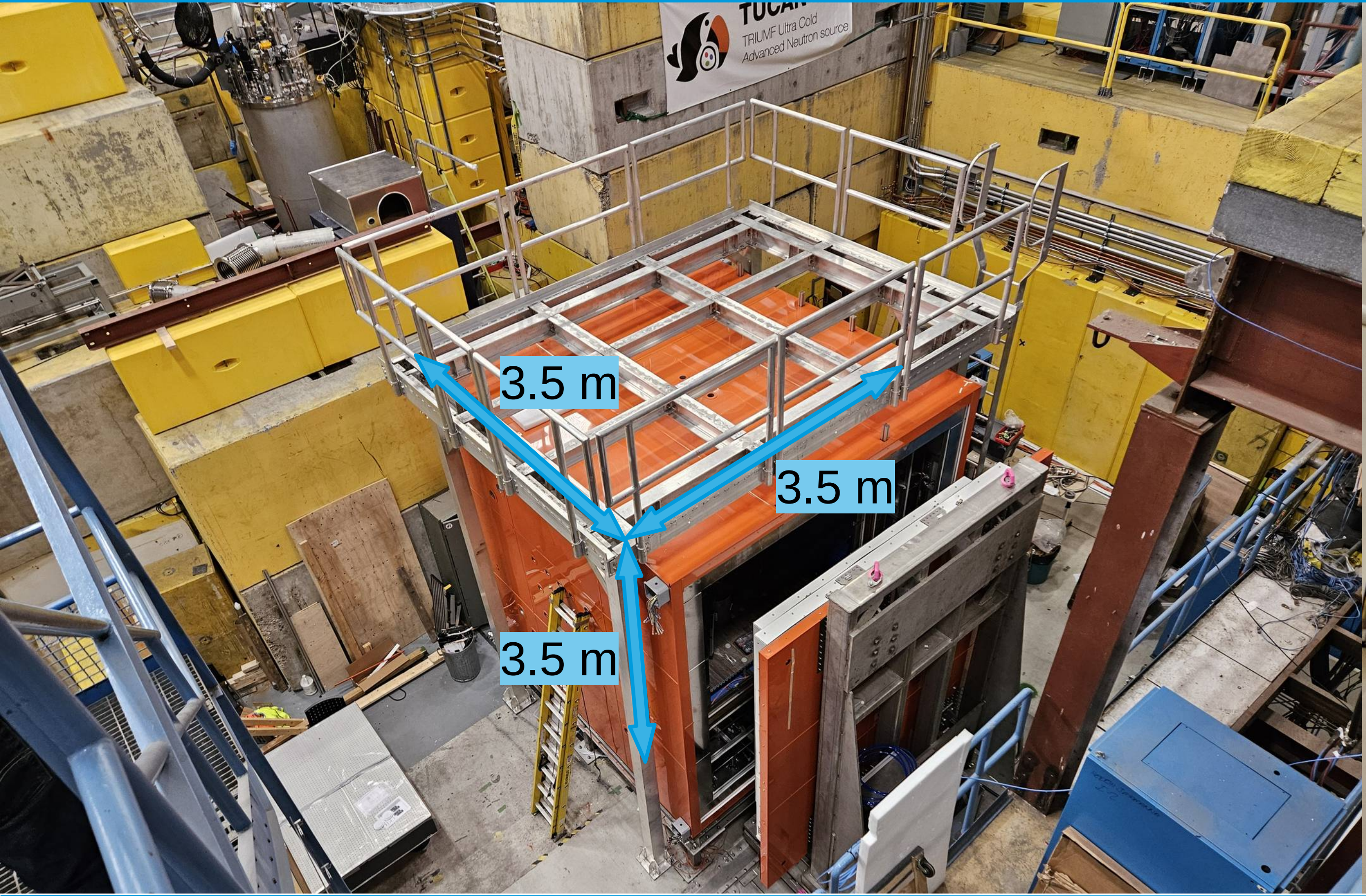
Magnetic fields

- We want to measure a parts-per-billion frequency shift ***due to the electric field polarity switch***
- ***Other*** frequency shifts are potential systematic errors
- Changes in the magnetic field at the ppb level can cause shifts of the same order
- Need to measure B within 1 μT*1ppb = 1 fT = 1×10^{-15} T

As magnetic as your thoughts (literally)

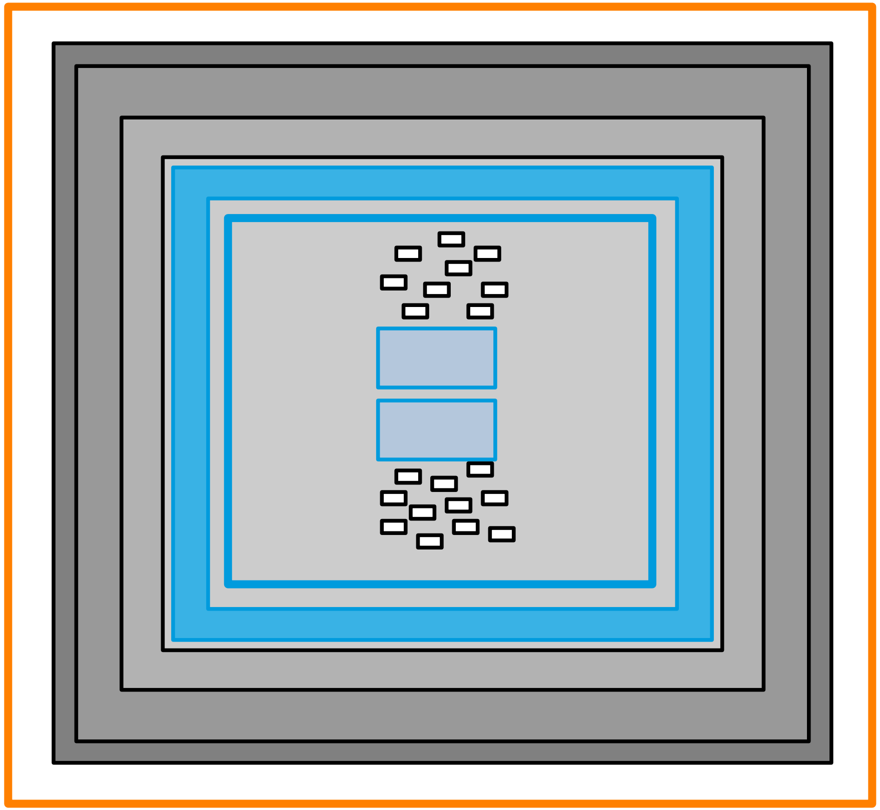
The TUCAN MSR

The TUCAN MSR



Magnetic control

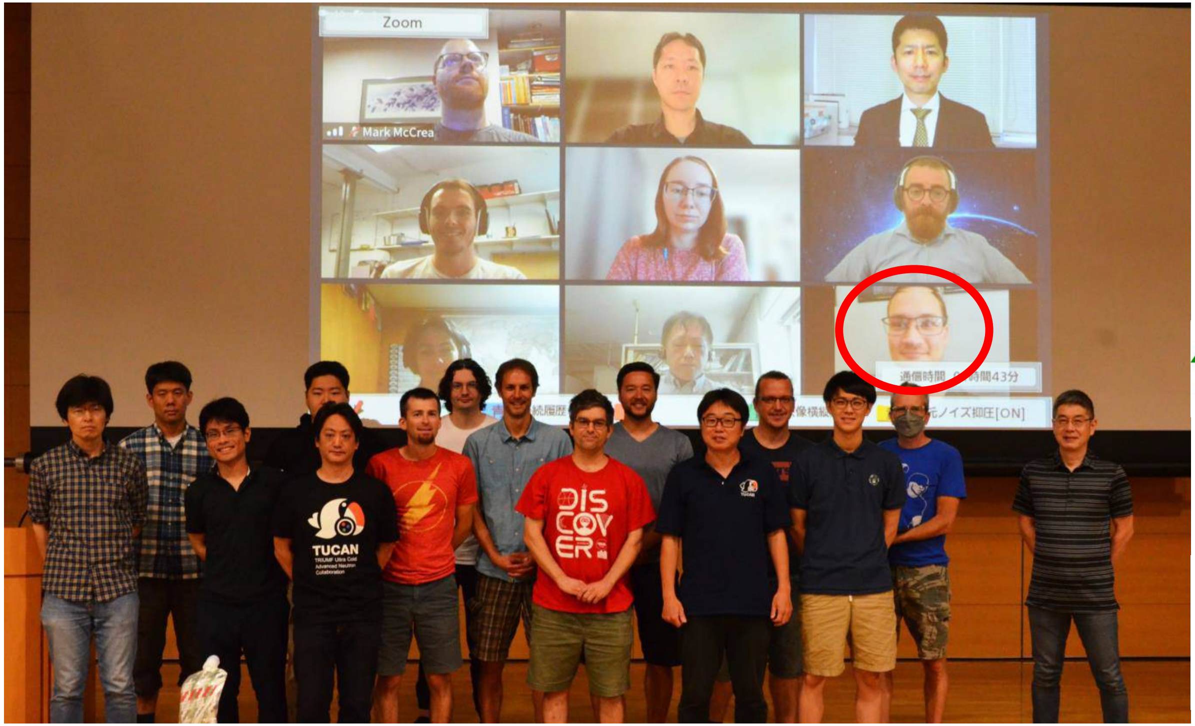
- Active magnetic compensation
  - Bucks majority of cyclotron field, keeps MSR well below saturation
- 5 later μ-metal MSR
  - Passively shields remaining meson hall field
- Self-shielded B_0 coil
  - Provides very uniform 1 μT field for experiment
- N-by-N square shim coils
  - Buck remaining gradients in B_0
- Hg comagnetometer
  - Hg based optical magnetometry in the same volume as the neutrons track the field they experience
- Set of 20 Cs magnetometers
  - Measures high order gradients in field



Conclusion

- nEDM measurements have the potential to shed light on baryogenesis in the early universe
- TUCANs world-leading source of UCN will make our EDM measurement competitive with the current leaders in the field
- The unique constraints of this experiment has lead/will lead to the development of novel cryogenics and magnetics technologies

Acknowledgements



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Questions?