Ultra Cold Neutrons and (some of) their Applications in Fundamental Physics

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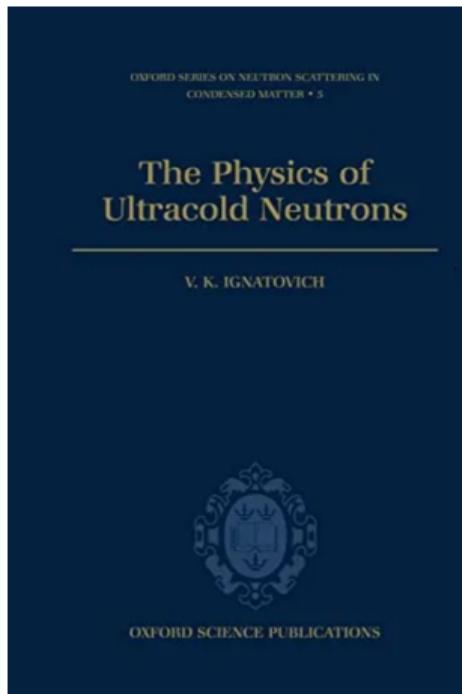UCANS11, February 2025

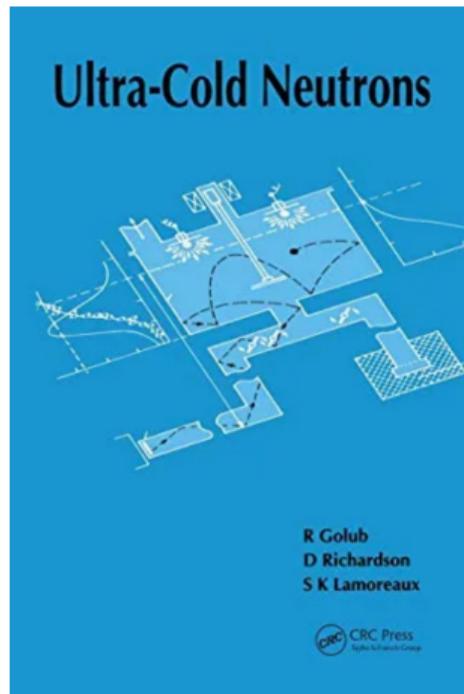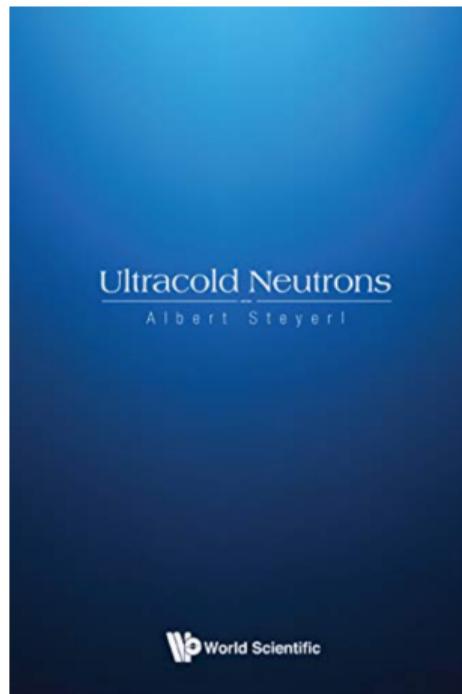# Outline

Introduction

Vladimir Kazimirovich
Ignatovich, 1990

Robert Golub,
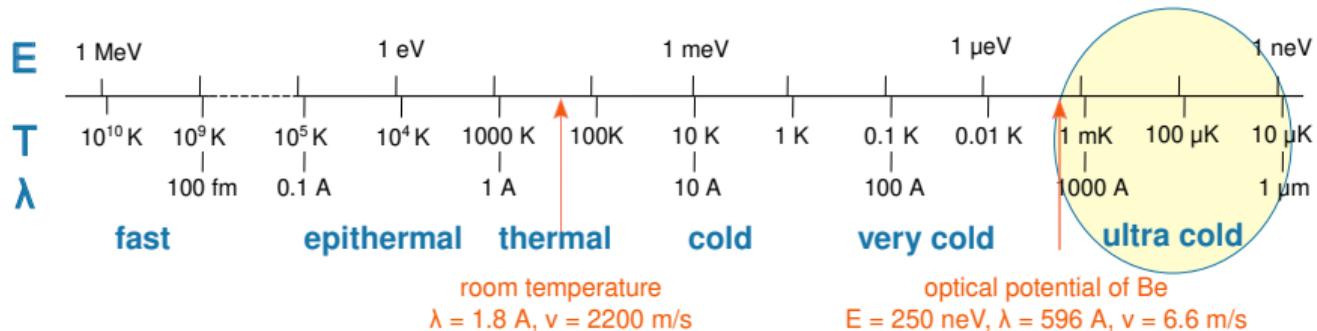David Richardson,
Steve Lamoreaux, 1991

Albert Steyerl, 2020

Ultracold Neutrons
Introduction

- UCNs are neutrons whose energy is so low that they are reflected under any angle of incidence

E	1 MeV		1 eV			1 meV			1 µeV			1 neV
T	10^{10} K	10^{9} K	10^{5} K	10^{4} K	1000 K	100K	10 K	1 K	0.1 K	0.01 K	1 mK	100 µK	10 µK
λ			100 fm	0.1 A		1 A		10 A		100 A		1000 A	1 µm
	fast		**epithermal**		**thermal**		**cold**		**very cold**			**ultra cold**

room temperature
λ = 1.8 A, v = 2200 m/s

optical potential of Be
E = 250 neV, λ = 596 A, v = 6.6 m/s
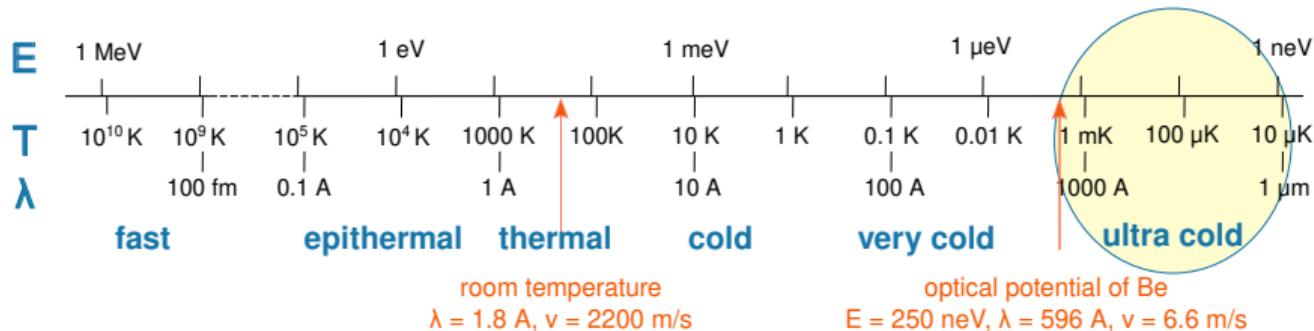
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- Velocities of several m/s.
  "They are the pedestrians under the neutrons"

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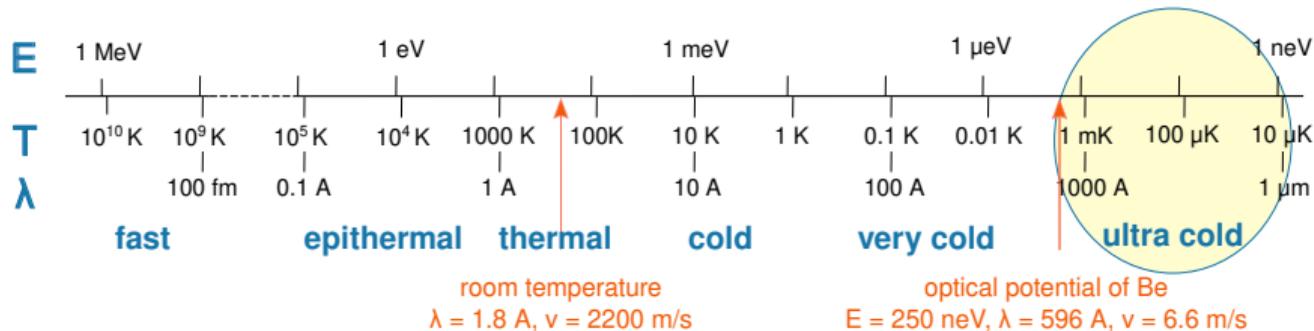E = 250 neV, λ = 596 A, v = 6.6 m/s

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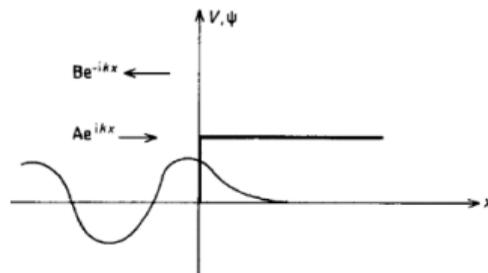**UCNs are important objects for fundamental physics experiments**

E	1 MeV				1 eV			1 meV			1 µeV			1 neV
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How to store them?
Introduction

Trapping potential #1:

- Neutron optical potential of material: **V + iW**
- Physical origin:
  Interference of incident plane wave with spherically scattered waves in forward direction
- refractive index

$$n = \frac{k'}{k} = \sqrt{1 - \frac{V}{E}} \qquad V = \frac{2\pi\hbar^2}{m} Na$$

⇨ UCN are contained in "neutron bottles" of dedicated material

Typical values for V:

  Be: 252 neV

  Al: 54 neV

  Ti: -48 neV

Trapping potential #2:

- Gravity acting on the neutron: **mgh**
- for $\Delta z = 1$ m: $\Delta E = 100$ neV

- as good for trapping as a material closure
  (if bottle is tall enough)

Trapping potential #3:

- magnetic interaction: $\pm\boldsymbol{\mu}\boldsymbol{B}$
- for $\Delta B = 1$ T: $\Delta E = \pm 60$ neV
- Adiabatic spin transport if

$$\frac{1}{|\boldsymbol{B}|} \cdot \left| \frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t} \right| \ll \frac{\boldsymbol{\mu} \cdot \boldsymbol{B}}{\hbar} = \omega_{\mathrm{L}}$$

- $\rightarrow$ mT fields sufficient in typical situations

Halbach octupole permanent magnet array

$\Rightarrow$ Magnetic gradient fields suppress losses due to wall collisions

Three selected applications of UCNs

Gravity Bound States

Theory - Airy function

Schrödinger Equation for particles in gravity potential:

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + mgz \right) \psi(z) = E\psi(z)$$

Boundary condition on flat surfaces
(QM → bound states):

$$\psi(z \leq 0) = \psi(z \to \infty) = 0$$

Solutions using the Airy function (Ai [a]) are:

$$\psi_n(z) = c_n \, \text{Ai}\left(\frac{z}{z_0} - \frac{E_n}{E_0} \right)$$

c_n being a normalization constant.
For neutrons: $z_0 \sim 5.87\,\mu\text{m}$, $E_0 \sim 0.602\,\text{peV}$

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[a] $\text{Ai}(\sigma) = \frac{1}{\pi} \int\limits_{0}^{\infty} \cos\left(\frac{t^3}{3} + \sigma t \right) \mathrm{d}t$

Solutions of $\psi_n(z)$

First observations (2002)
Gravity Bound States

Proposal: *Luschikov and Frank, JETP Lett 28 (1978) 559*

Nesvizhevsky, Abele et al., Nature 415 (2002) 299

Quantum bouncing ball
Gravity Bound States

$$\Psi(z, t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar} \psi_n(z)$$

$$\psi_n(z) \sim Ai\left[\frac{z}{z_0} - \frac{E_n}{E_0}\right]$$

$$c_n = \int_0^{\infty} \Psi(z, 0)\psi(z)dz$$

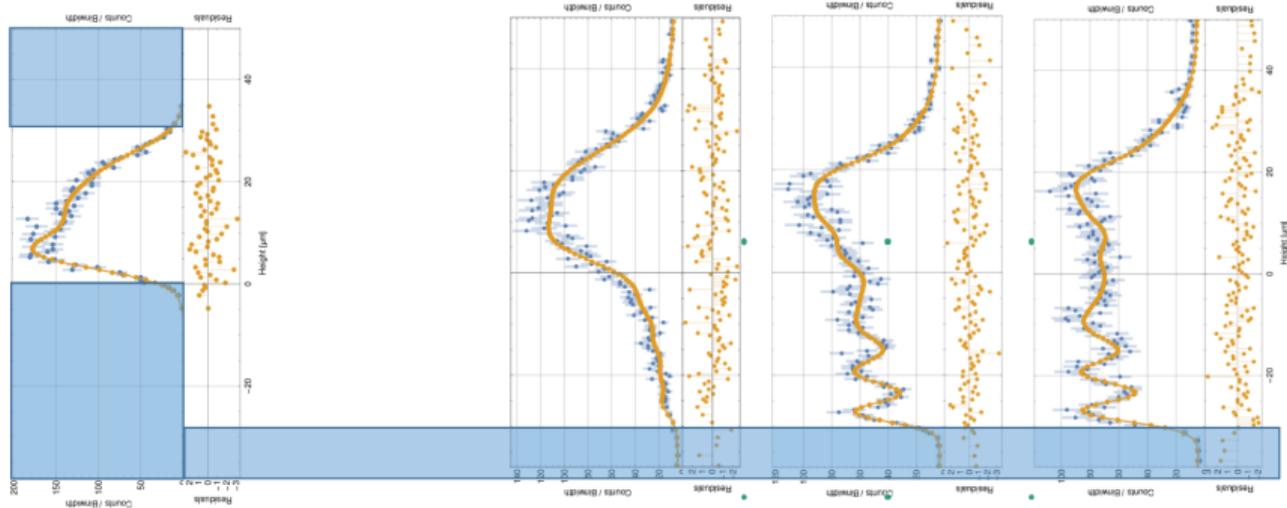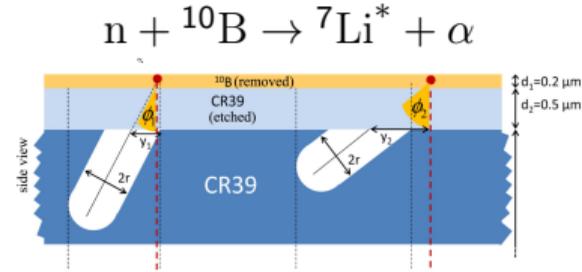$\Rightarrow |\Psi(z, t)|^2$ contains interference terms between the eigenstates.

Time evolution of the neutron's wave function after falling down a step [1]

[1] Jenke et al. (2015), arXiv.1510.03078
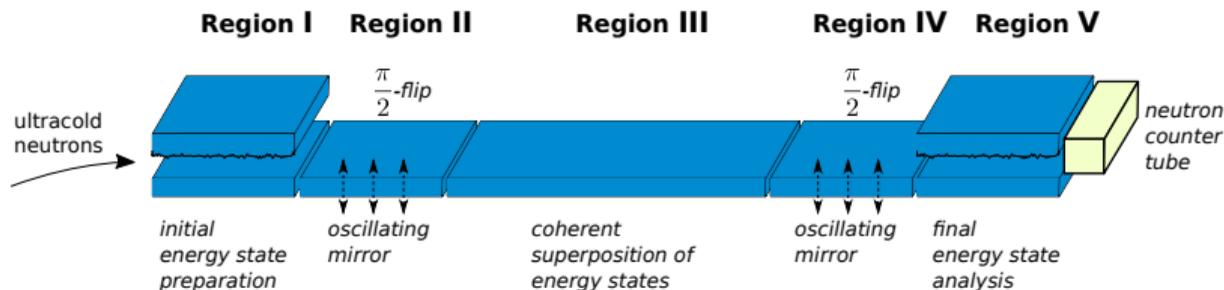
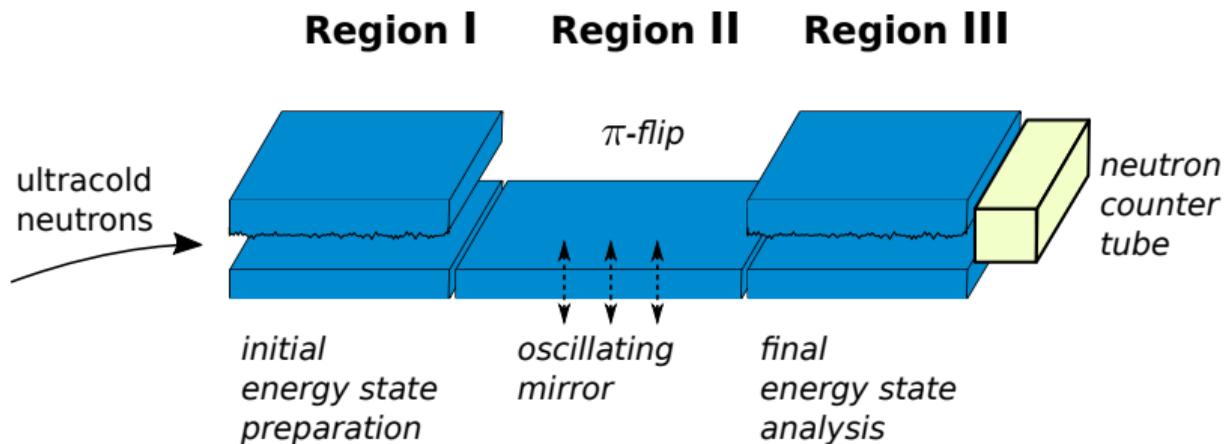# Experimental realization of the Quantum Bouncing Ball
Gravity Bound States

$$n + {}^{10}B \rightarrow {}^{7}Li^* + \alpha$$

- Detection with boron coated CR39 imaging plates

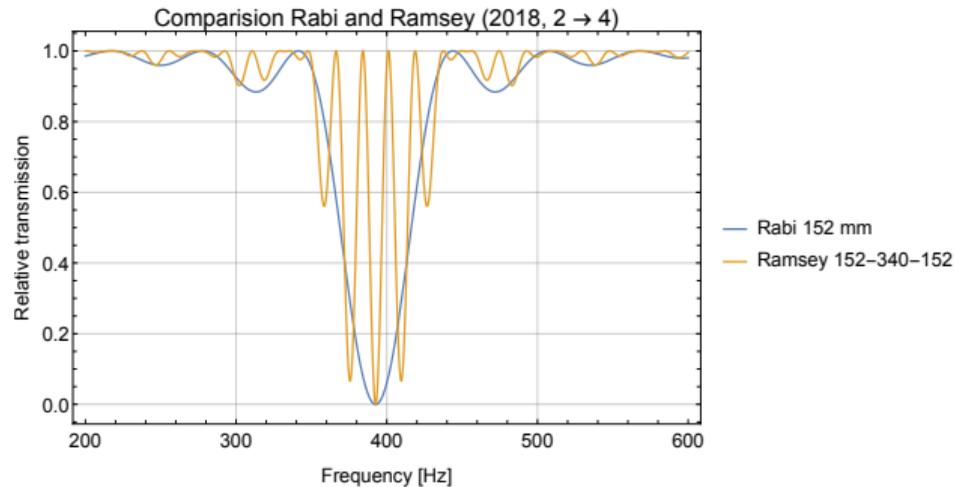# Gravity Resonance Spectroscopy (GRS)
Gravity Bound States

Comparison Rabi and Ramsey transition: $|2\rangle \rightarrow |4\rangle$
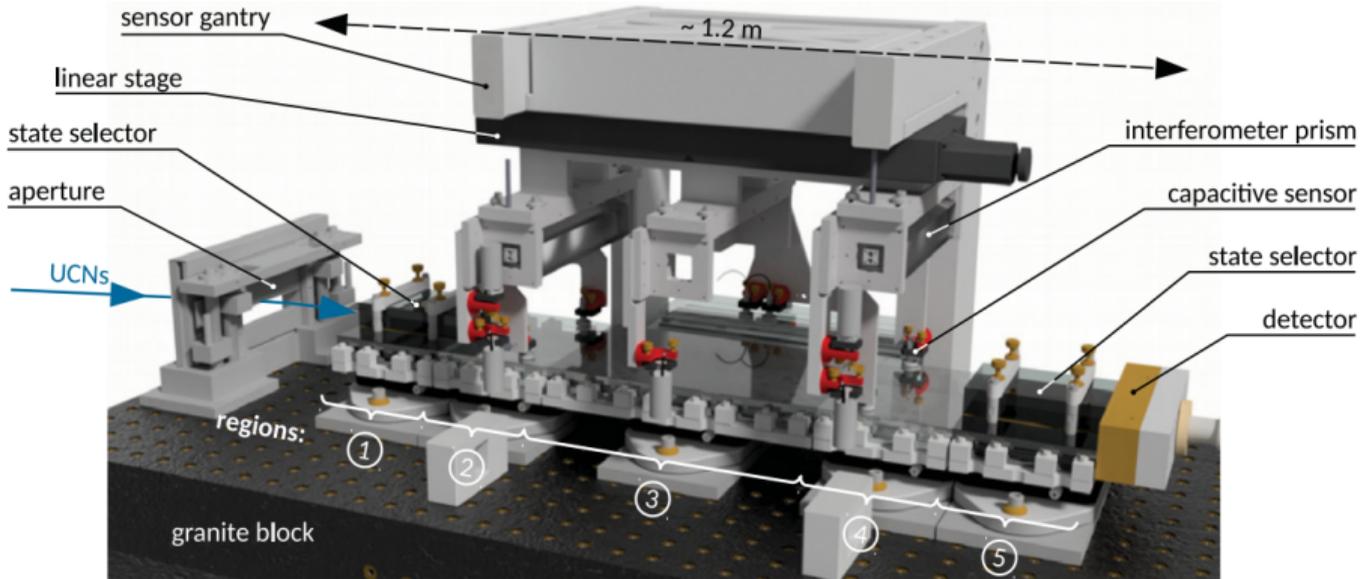Gravity Bound States

Rabi and Ramsey Resonance Curves

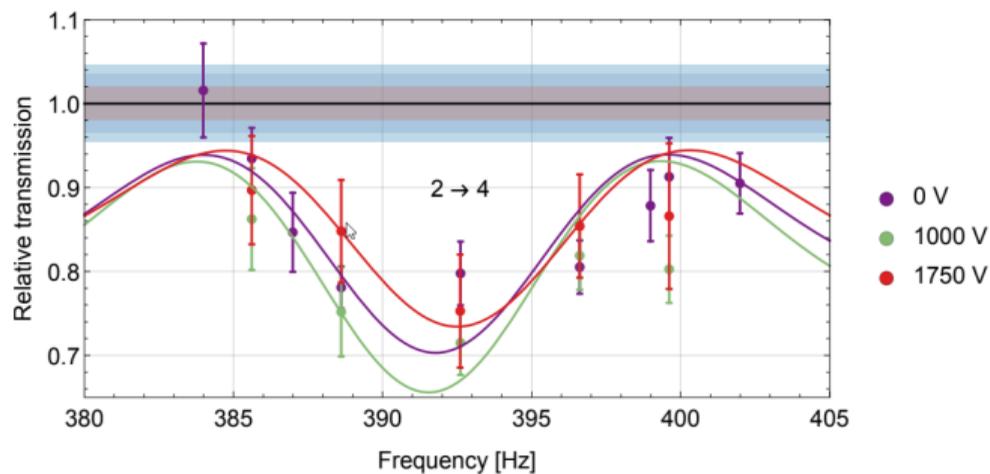$\Rightarrow$ Ramsey-Setup has a significant higher sensitivity.

Plot courtesy of J. Bosina

Simplified view of the Ramsey GRS setup on the granite block

Rams$\vec{E}$y - Electric Charge Measurement
Gravity Bound States

- Proof-of-concept Neutron charge measurements with a Ramsey GRS setup
- High electric fields applied in *Region III*
- Limit in the order of 10^{-17} elementary charges

Bosina et al. Proceedings of the 56th RENCONTRES DE MORIOND - Gravitation 2022 and
J. Bosina, PhD Thesis TU Wien (2024)
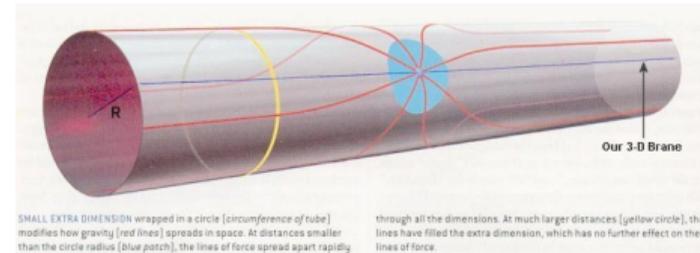
Further GRS Application
Gravity Bound States

- Studying Gravitation at the μm scale

- Search for New Physics
  - Dark Matter
  - Dark Energy

- Setting limits
  - Hypothetical gravity-like interactions, Axions/ALPs, Chameleons, Symmetrons, neutron electric charge . . .

Modification of gravity with n additional dimensions at distances $r < R$:

$$F = -G\frac{m_1 m_2}{r^2} \rightarrow -G^*\frac{m_1 m_2}{r^{2+n}}$$

Small extra-dimensions: Explanation why gravity is such a weak force?

SMALL EXTRA DIMENSION wrapped in a circle [circumference of tube] modifies how gravity [red lines] spreads in space. At distances smaller than the circle radius [blue patch], the lines of force spread apart rapidly through all the dimensions. At much larger distances [yellow circle], the lines have filled the extra dimension, which has no further effect on the lines of force.

ADD model from N.Arkani-Hamed, S.Dimopoulos and G. Dvali (Phys. Lett. B 429 263)
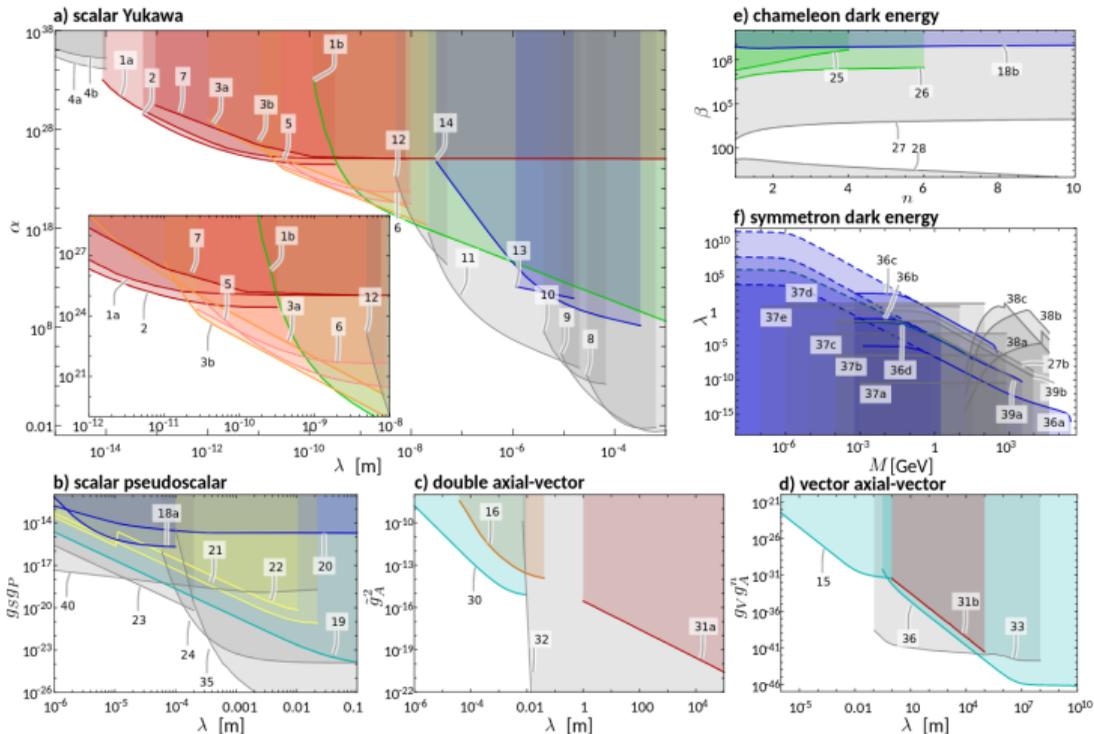
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Further GRS Application
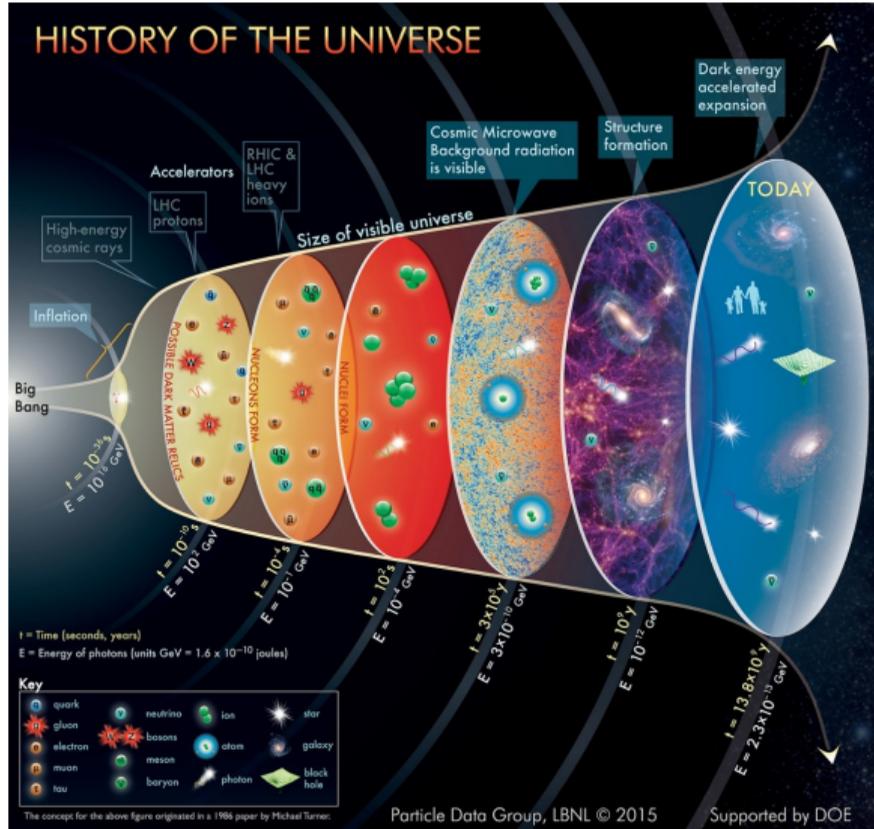## Gravity Bound States

Compiled limits on
non-Newtonian interactions

*Sponar, S., Sedmik, R.I.P.,
Pitschmann, M. et al.,
Nat Rev Phys 3, 309–327 (2021)*

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Neutron EDM

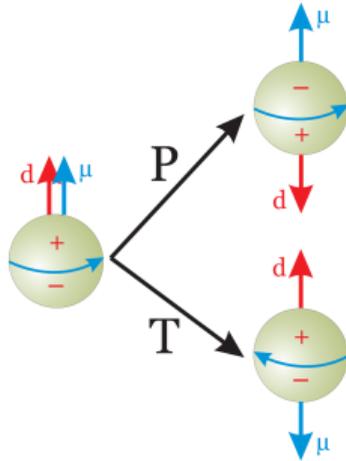# The Matter-Antimatter asymmetry after Baryogenesis
Neutron EDM

- Standard Model (SM) of Particle Physics fails to account for the observed baryon asymmetry in the Universe (BAU).
- CP violation (and C-Violation) is one of the Sakharov conditions[a] that have to be fulfilled for theories that explain BAU.
- Known contributions from the SM are too weak.
- ⇨ Need to find further processes that contribute to it.

[a] *A. Sakharov, JETP Lett. 5 (1967) 24*

Fundamental Symmetries Violation
Neutron EDM

- A non-zero particle EDM violates T (time reversal symmetry) and parity P (reflection in space)
- Assuming CPT conservation, there is also CP violation.
  C being the operation of charge conjugation (Matter ↔ Antimatter)
- ⇒ Neutron EDM possible source for CP-Violation necessary for BAU
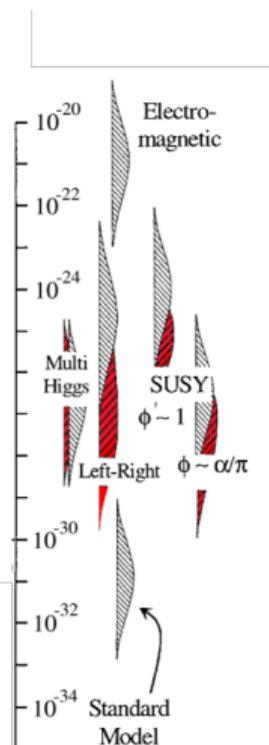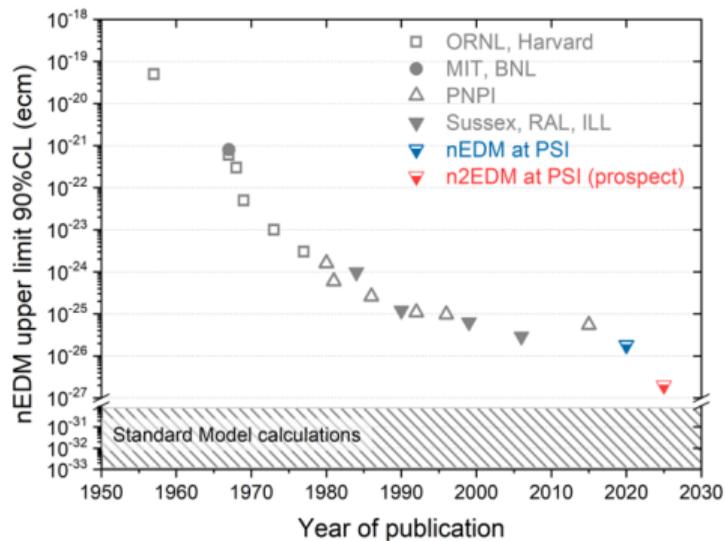
CPT Theorem

CPT symmetry holds for all physical phenomena
"Any Lorentz invariant local quantum field theory with a Hermitian Hamiltonian must have CPT symmetry"

- first appeared in the work of Julian Schwinger (1951) later proven by Lüders, Pauli and Bell (1954).
- Implications: individual violations of permutations of C, P and T must cancel. Violation of CP would require violation of T → time has a preferred direction on the fundamental scale.

Limits and Predictions
Neutron EDM

- nEDM prediction in the SM is tiny (10^{31} ecm), but large in many beyond-SM theories
- nEDM sensitive probe to search new fundamental forces

Best current limit:

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} e.\text{cm}$$

from the nEDM collaboration at the PSI.
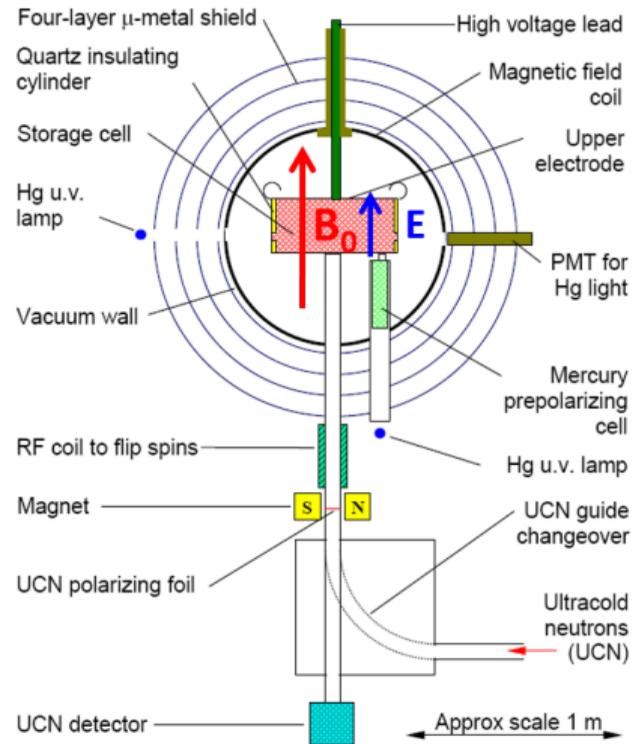
Abel et al. Phys. Rev. Lett. 124, 081803 (2020)

Measurment Setup

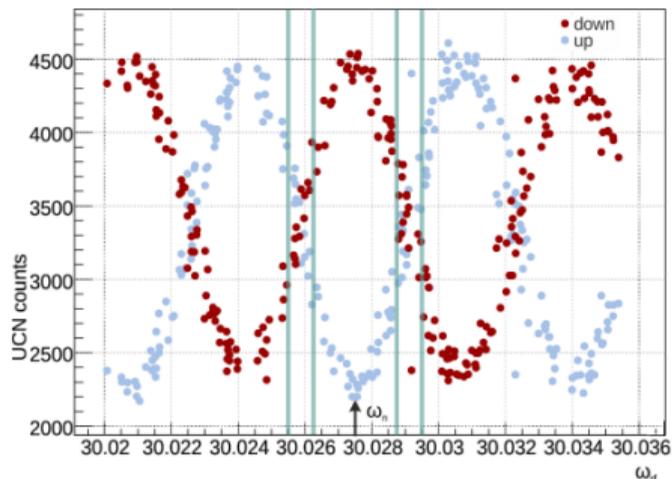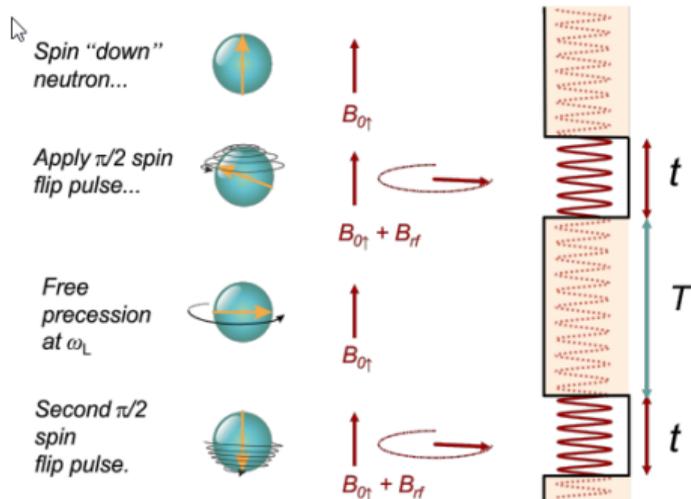**RAL-Sussex-ILL experiment**
(more than 20 years of effort)

- UCNs trapped in single Ramsey cell ($\sim$50cm) at room temperature
- ^{99}Hg co-magnetometer corrects for magnetic field drifts

Baker et al., PRL 63 (2006) 131801

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Measurement Principle
Neutron EDM

EDM changes frequency:

$$\hbar\omega_L \sim \mu_{\mathrm{n}}B \pm d_{\mathrm{n}}E$$

Experimental sensitivity:

$$\sigma_{d_{\mathrm{n}}} = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

Image from P. Schmidt-Wellenberg (2016), arXiv:1607.06609

Biggest challenge is to control the systematics

PSI n2EDM apparatus

Core of the n2EDM apparatus.

How to Improve Sensitivity?
Neutron EDM

Figure of Merit: $\sigma_{d_n} \sim \frac{1}{ET\sqrt{N}}$

Current Neutron EDM Experiments

- New sources of Ultra-Cold Neutrons providing more neutrons N
  - Solid Deuterium, Superfluid He (e.g. TUCAN source at TRIUMF)

- New technologies for higher $|\vec{E}|$
  - Put whole measurment cell in superfluid He
  - Vacuum (10kV/cm) $\Rightarrow$ lHe (75kV/cm)
  - would also increase T

Image courtesy Chen-Yu Liu

Neutron EDM has excluded more particle physics theories than any other experiment!

Neutron Lifetime τ_{n}
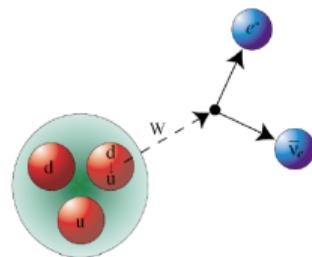
$$n \to p + e^- + \bar{\nu}_e + 782\text{keV}$$

Free neutron lifetime

$$\tau_n = 874.4 \pm 0.5\text{s}$$

[PDG 2024]

- **Particle physics**
  Determination of CKM matrix element V_{ud}

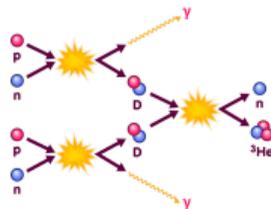- **Astrophysics and Neutrinos**
  cross sections of semileptonic weak interactions, e.g:
  Solar Fusion $\quad\quad p + p \to d + e^+ + \nu_e$
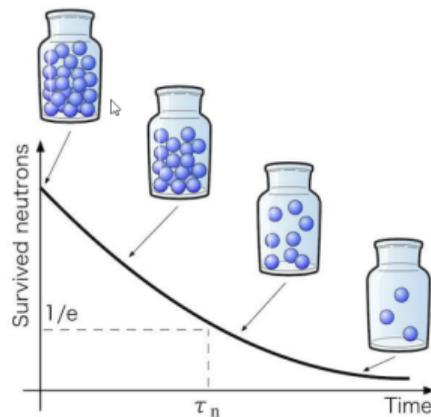 Neutrino detection $\quad \bar{\nu}_\mu + p \to \mu^+ + n$

- **Big Bang Nucleosynthesis**
  Predicting the yields of primordial abundances of light
  elements

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Measurement Principle
Neutron Lifetime τ_n

Bottle Method

UCNs are stored in a bottle, the number of neutrons that survived remaining in the bottle after a certain storage time t are counted.

$$N(t) = N(0)e^{-t/\tau_n}$$

Neutron lifetime experiment with low-T „fomblin" oil coated walls

$\tau_n = 881.5 \pm 0.7_{stat} \pm 0.6_{syst}$ s

Serebrov et al. PRC 97, 055503 (2018)

Trap length 2m

Experimental difficulty:
Loss per wall collision for trapped UCN neutrons big contribution to systematic error. Hard to reliably calculate.

UCNτ Experiment at Los Alamos
Neutron Lifetime τ_n

- filling volume
- trap volume
- cleaner
- primary detector
- monitor

polarizing magnet
M_1
M_2 spin-flipper
M_3
buffer volume
M_4
Halbach array

1 meter

- magneto-gravitational trapping
- asymmetric trap $\rightarrow$ chaotic trajectories

20 cm

Best current limit: $\tau_n = 877.75 \pm 0.28$s

Pattie et al. Science 360 (2018) 627
Gonzalez et al. Phys. Rev. Lett. 127 162501

Alternative Measurement Method
Neutron Lifetime τ_{n}

Illustration courtesy of F. Wietfeldt

Beam Method

A detector records the decay products in a well defined part of a neutron beam. A neutron beam is indeed radioactive due to beta decay.

$$-\frac{dN}{dt} = \frac{N}{\tau_n}$$

The Neutron Lifetime Puzzle

UNRESOLVED DIFFERENCES
Mysteriously, neutrons in a beam live several seconds longer on average than do those trapped in a vacuum bottle.

● Results using beam method   ● Bottle method

Beam method average

Bottle method average

Latest UCNτ result

Neutron lifetime (s)

- The discrepancy is still unsettled.
- As a solution for the neutron lifetime puzzle, several scenarios of exotic decay modes of a neutron are discussed
- Discovery of a branching ratio of about 1%, into e.g. a mirror neutron or dark particles would solve the puzzle.

(Short) Conclusion

(Further) Experiments with UCNs
(Short) Conclusion

- Gravity Bound States of the Neutron
- Neutron Electric Dipole Moment (nEDM) Experiments
- Neutron Lifetime Experiments

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- **Measurement of Cross Sections for the UCN Energy Range**

Acknowledgment

Thank you for your attention!