Laboratory Cosmology with Slow Neutrons

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(0) Neutron Sources and Optics

Three scientific examples:
(1) Neutron lifetime
(2) Neutron Searches for Time Reversal and Baryon Number Violation
(3) Neutron Interferometry and Gravity

A couple of articles:

W. M. Snow, **Exotic Physics with Slow Neutrons**, Physics Today **66**, 50 (2013).
G. L. Greene and P. Geltenbort, **A Puzzle Lies at the Heart of the Atom**, Scientific American, April 2016.

Slides from: D. Bowman, V. Gudkov, H. Shimizu, C-Y Liu, G. Greene, P. Schmidt-Wellenberg, V. Santoro,…

Nuclear/Particle/Astrophysics with Slow Neutrons...

is Nuclear physics, but with an "isotope of nothing"

is Particle Physics: but at an energy of 10^{-20} TeV, using a low energy decelerator

employs a particle which, according to Big Bang Cosmology, is lucky to be alive

relies on experimental techniques and ideas from nuclear, particle, atomic, and condensed matter physics

is pursued at facilities built mainly for chemistry, materials science, and biology

Advantages of Slow Neutrons for Nuclear/Particle/Astrophysics

zero electric charge, zero electric dipole moment, small electric polarizability, small magnetic dipole moment

-> negligible quantum decoherence from environment

-> precision tests of symmetry principles are possible

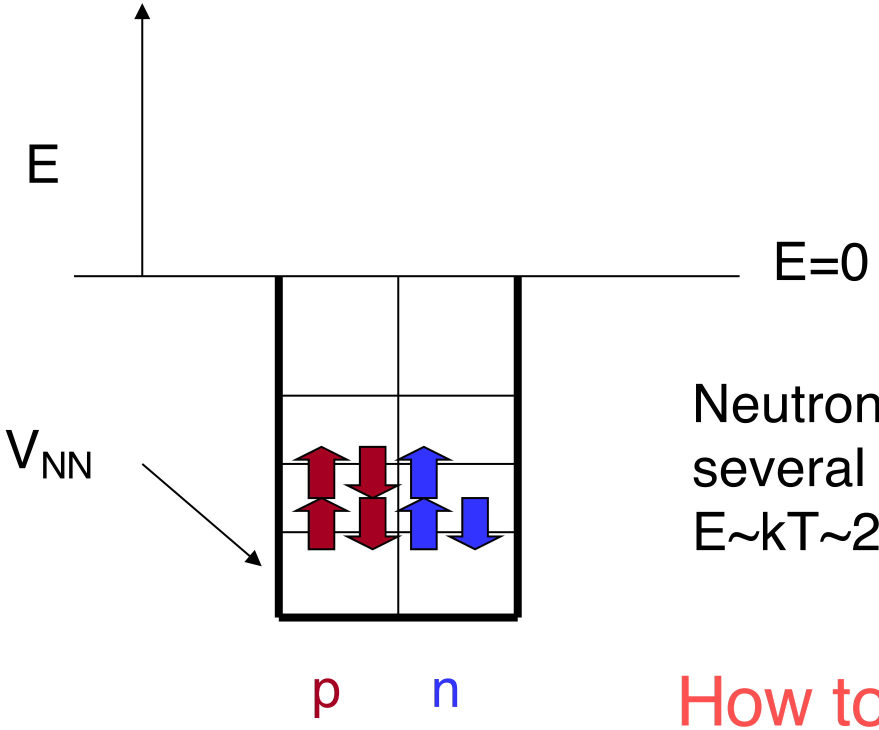
Slow decay rate, strong interaction with nucleus

-> timescales relevant for Big Bang Cosmology

-> can use the nucleus as an "amplifier" of symmetry violation

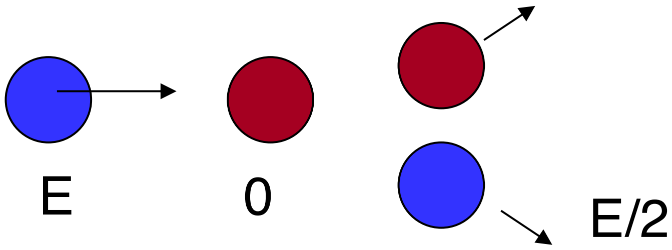
To use free neutrons: need to liberate and cool them

Why is it such hard work to get slow neutrons?



Neutrons are bound in nuclei, need several MeV for liberation. We want E~kT~25 meV (room temperature) or less

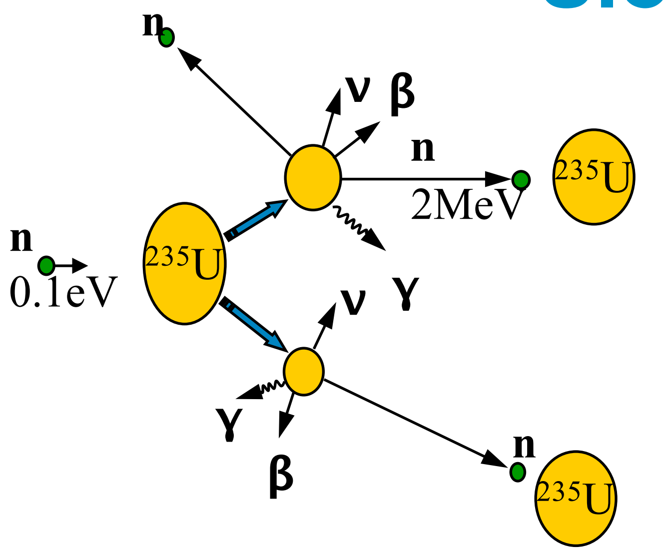
How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions…

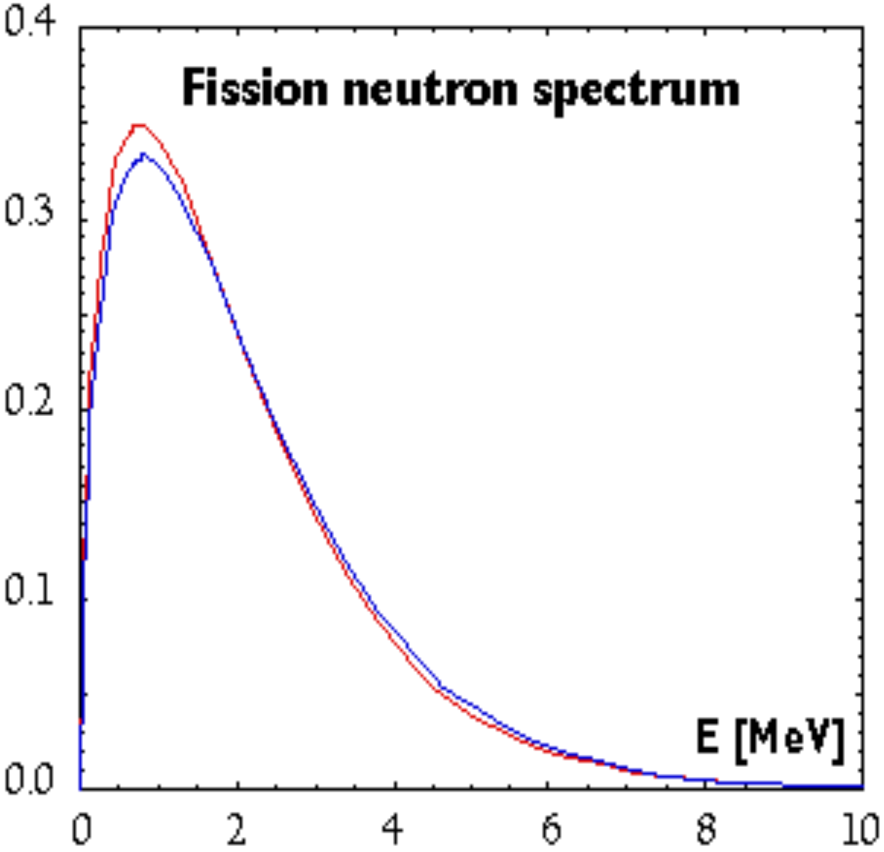


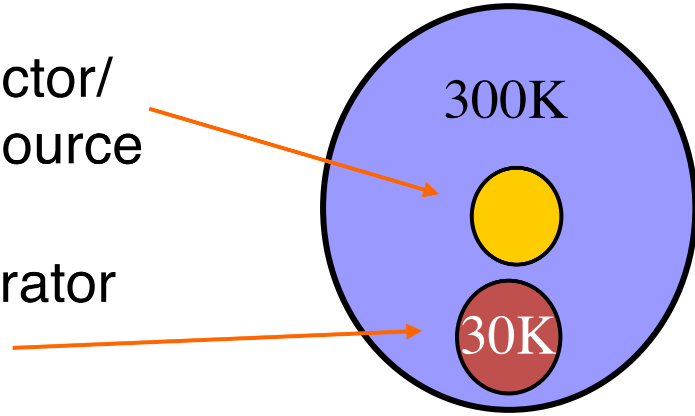
$[1/2]^N$=(1 MeV)/(25 meV) for N collisions

Neutrons are unstable when free->not easy to accumulate

"Slow" Neutrons: MeV to neV

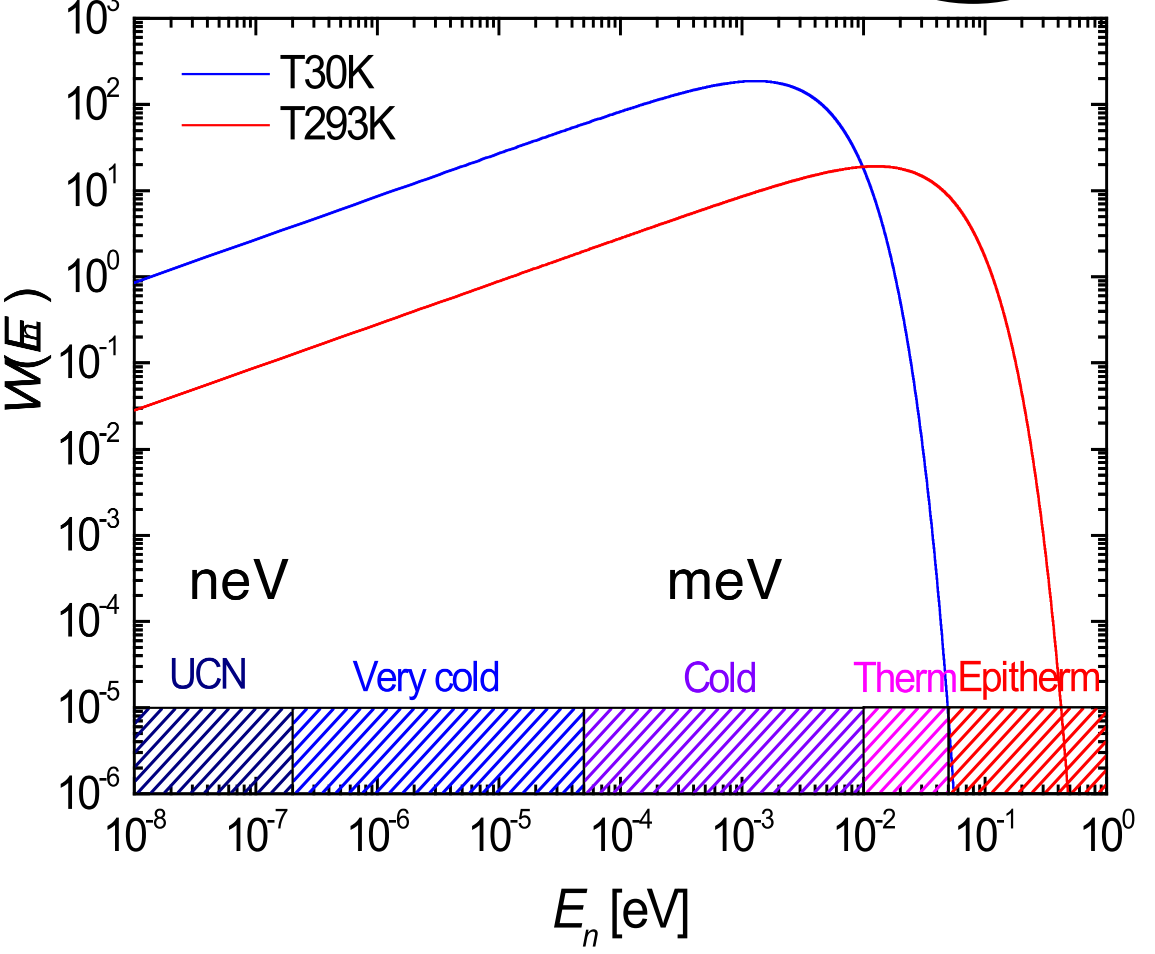




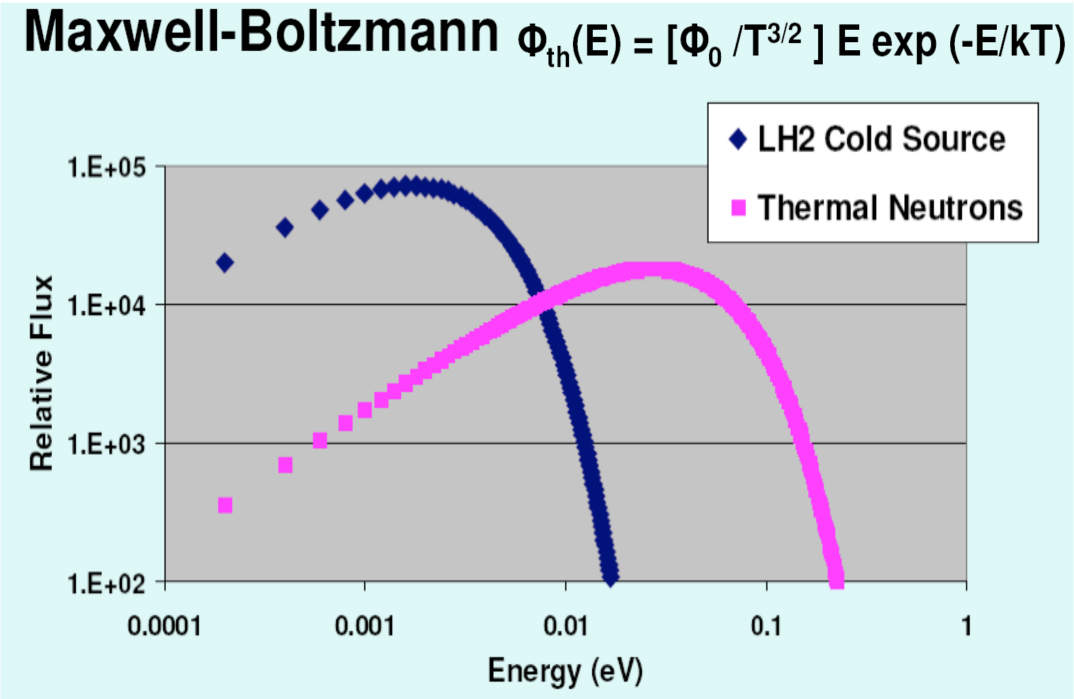


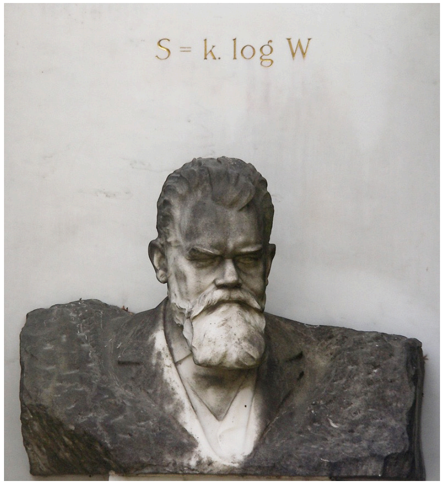
Nuclear reactor/
Spallation source

Neutron Moderator
(LH2, LD2)



Neutron Energy, Momentum, and Wavelength


Maxwell-Boltzmann $\Phi_{th}(E) = [\Phi_0 / T^{3/2}]\, E \exp(-E/kT)$



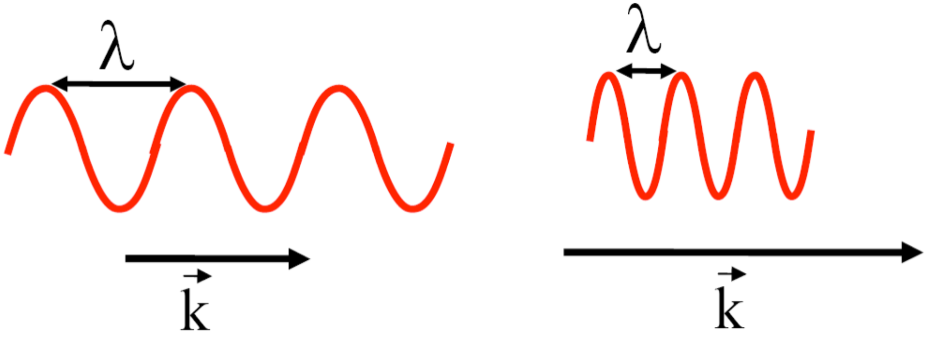
Moderator Temperature (K)	Most Probable Energy (meV)	Wavelength (Angstroms)
315	30	1.6
20	2	6.4

Energy:

$$E = \frac{1}{2} m v^2 = \frac{\hbar^2}{2m} k^2 = \hbar\omega$$

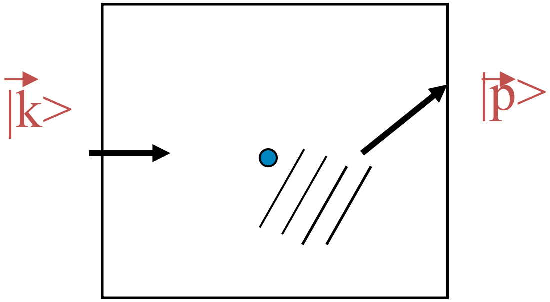
Momentum:

$$m\vec{v} = \vec{p} = \hbar\vec{k} = \hbar\,\frac{2\pi}{\lambda}$$

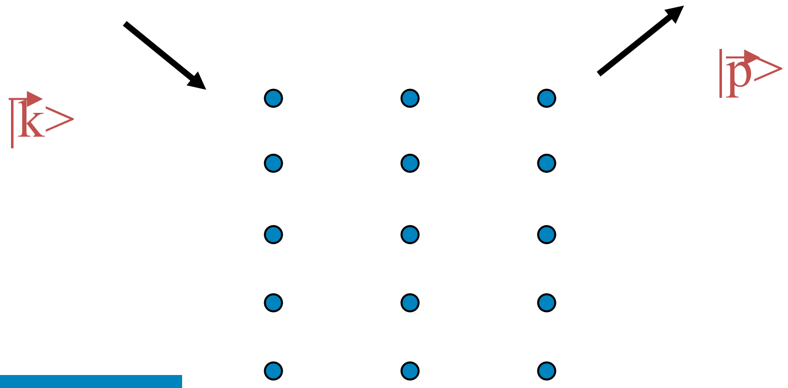


Neutrons in Condensed Matter

for a “thermal” neutron ($E_K = mv^2/2 = 3/2\, k_B T$, T=300K-> E_K=25 meV) the de Broglie wavelength of the neutron is $\lambda \approx 2$ Angstroms



phonon



diffraction

Thermal neutrons have the right energies and momenta to match excitations (phonons, spin waves, molecular rotations…) and static structures (crystals, molecular shapes,…) in condensed media

Potential step -> neutron index of refraction

with

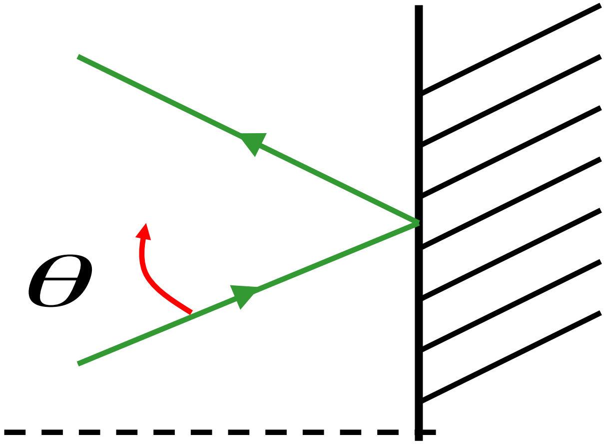
$$n = \sqrt{1 - \frac{V_0}{E_n}}$$

$$\boxed{V_0 = \frac{2\pi a\hbar^2 n_0}{m_n}}$$

Neutron kinetic energy

If a > 0, total external reflection

$$\mathbf{n_{out} = 1}$$



$$\mathbf{n_{in} = \sqrt{1 - \frac{V_0}{E}}}$$

All forces contribute to the neutron optical potential:

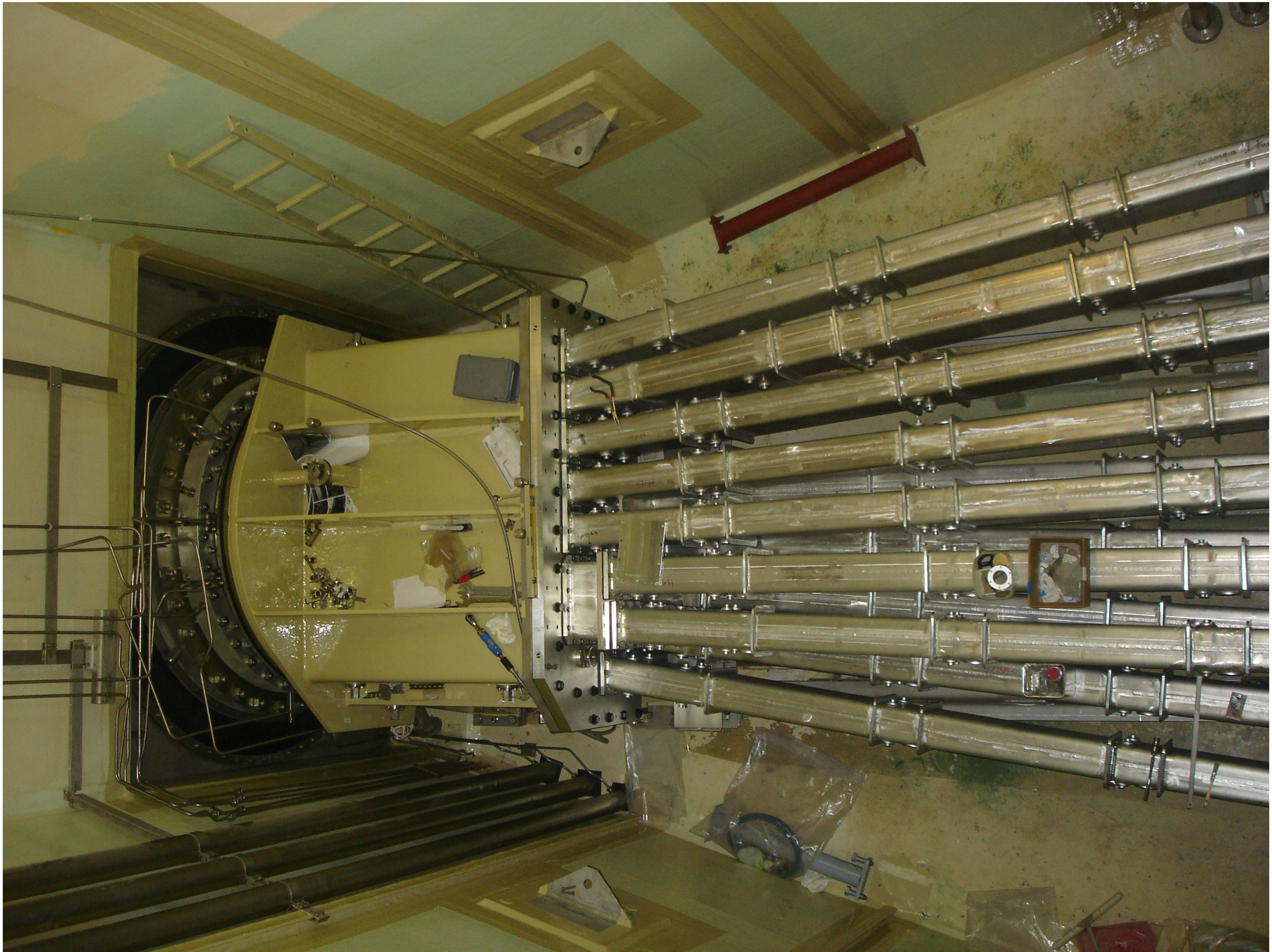
$<V_{strong}>=2\pi h^2\rho b_s/m$, ~+/- 100 neV

$<V_{mag}>=\mu B$, ~+/- 60 neV/Tesla

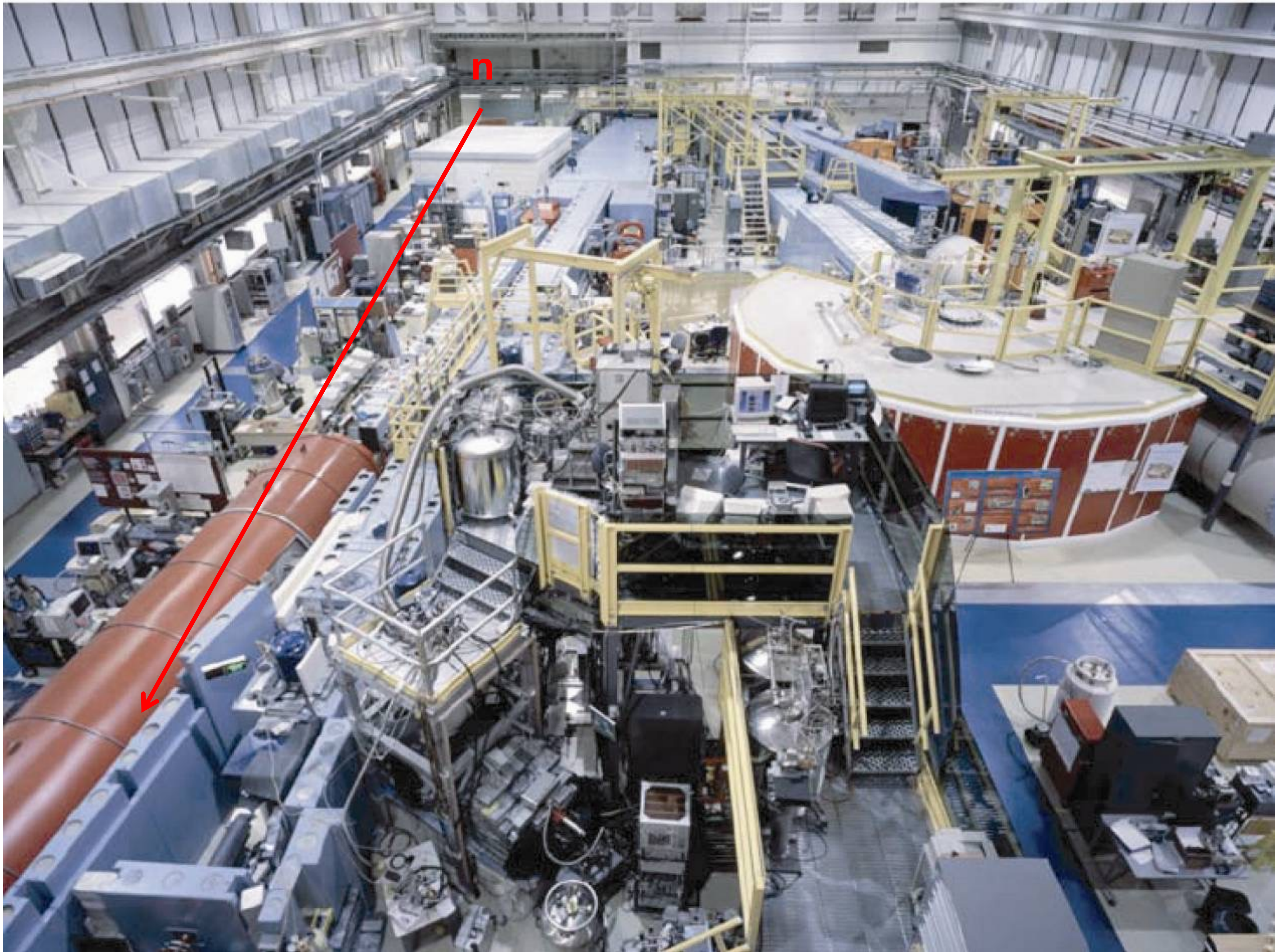
$<V_{grav}>=mgz$~100 neV/m

$<V_{weak}>=[2\pi h^2\rho b_w/m]s\cdot k/|k| \sim 10\text{-}^7 <V_{strong}>$

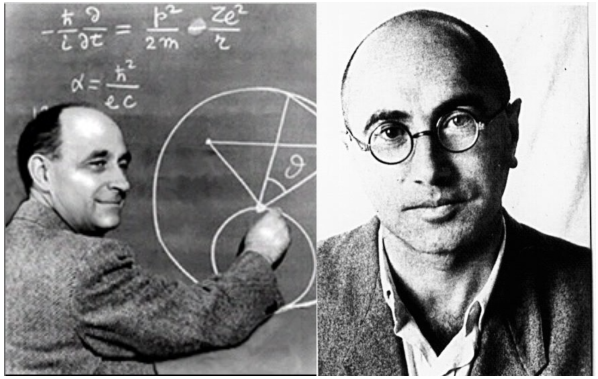
Neutron optical guides at ILL/Grenoble (top view)



Cold Neutron Guide Hall at NIST



Ultra-Cold Neutrons (UCN) (Fermi/Zeldovich)



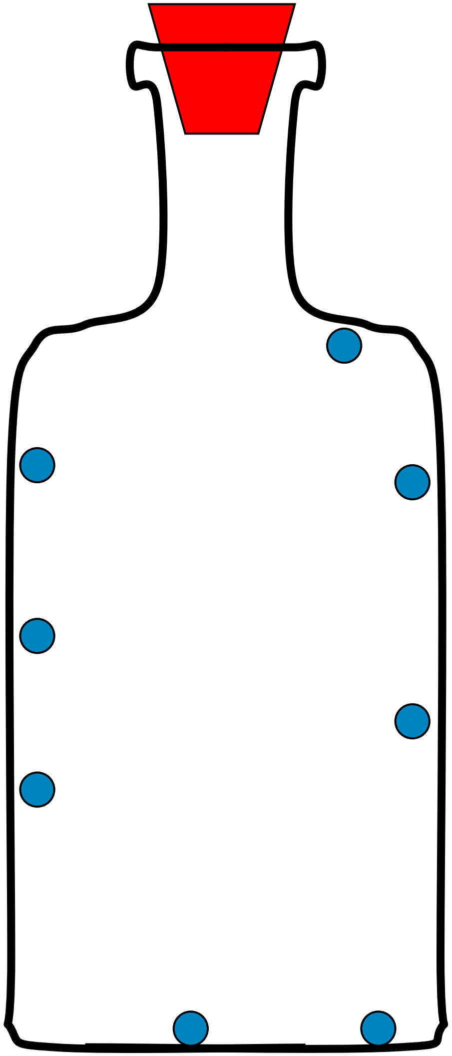
- What are UCN ?
  - Very slow neutrons

($v < 8$ m/s, $\lambda > 500$ Å, $E<V_{optical}$)

that cannot penetrate into

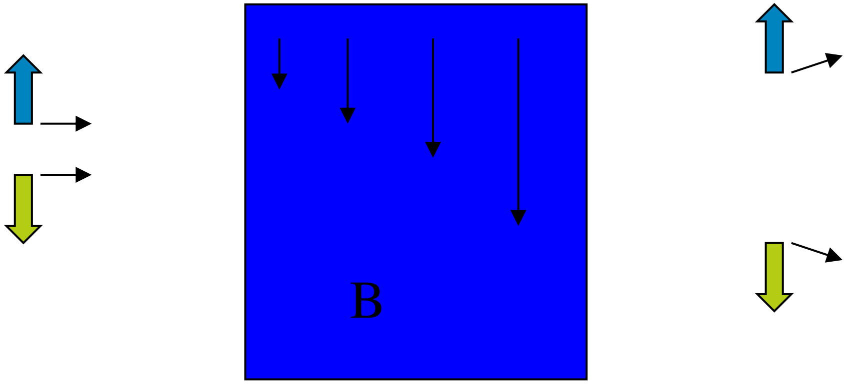
certain materials

Neutrons can be trapped in material bottles or by magnetic fields

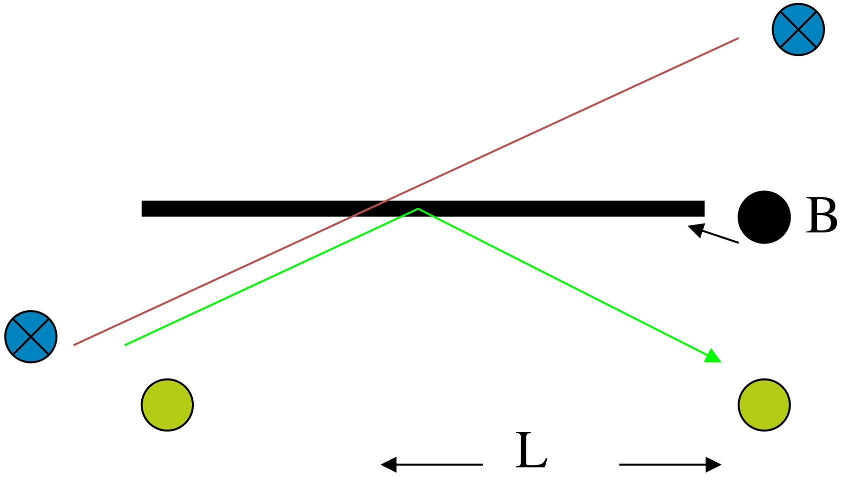


Many interesting nuclear/particle/ astrophysics neutron expts. use UCN

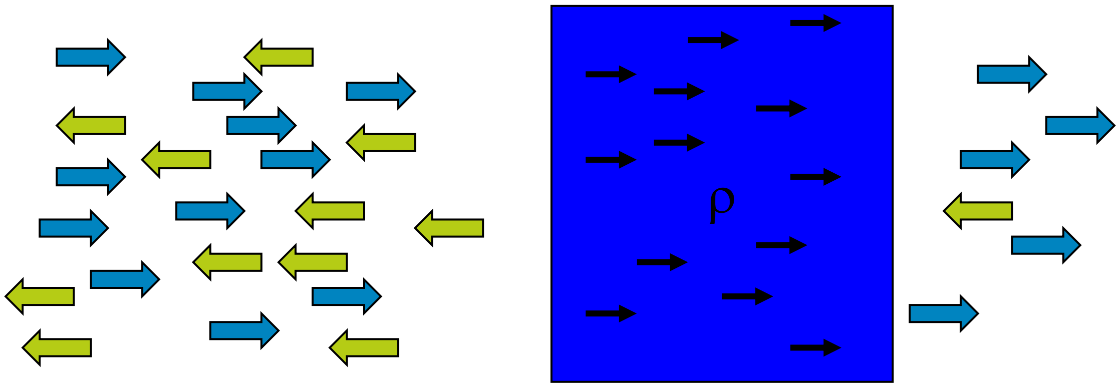
What methods are used to polarize neutrons?



B gradients (Stern-Gerlach, sextupole magnets)
electromagnetic
$F=(\mu\bullet\nabla)B$

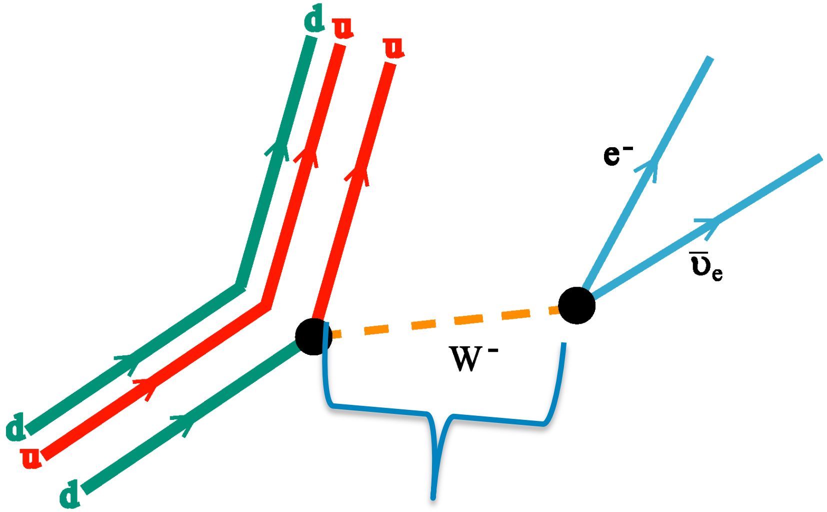


Reflection from magnetic mirror: electromagnetic+ strong
f±=a(strong) +/- a(EM)
with | a(strong)|=| a(EM)|
⇒f+=2a, f-=0

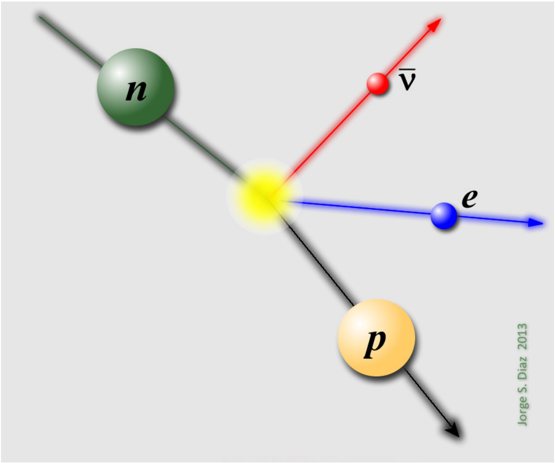


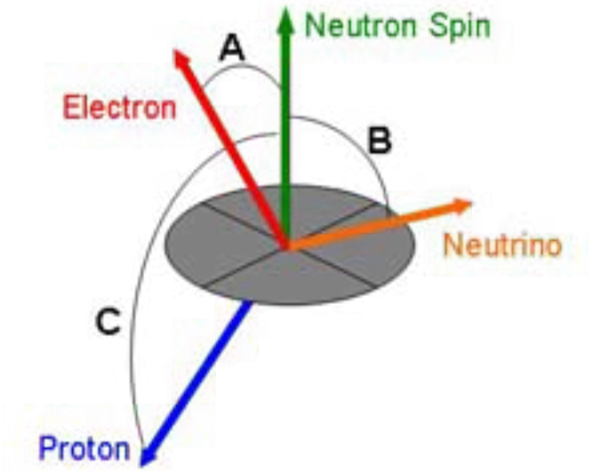
Transmission through polarized nuclei: strong
σ+≠ σ- ⇒ T+ ≠ T–
Spin Filter:$T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

Neutron β-decay: an “80 GeV event”



distance exaggerated here
by factor 100





amplitude for
beta decay
process

$$= \frac{1}{M_W^2} \bar{\psi}_\nu \bar{\psi}_e \psi_u \psi_d$$

M_W~80 GeV

Measurement of neutron decay correlations to 10^{-4} precision is sensitive to new physics at a scale ~10 TeV

~ one order of magnitude in energy scale beyond reach of LHC

uses the simplest three-quark bound state (->theory is clean)

Big Bang nucleosynthesis

1 μs

Thermal equilibrium
(T > 1 MeV)

$$\frac{n}{p} \propto e^{-Q/T}$$

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

$$n + \nu_e \leftrightarrow p + e^-$$

1 s

After freezeout
n/p decreases due to
neutron decay

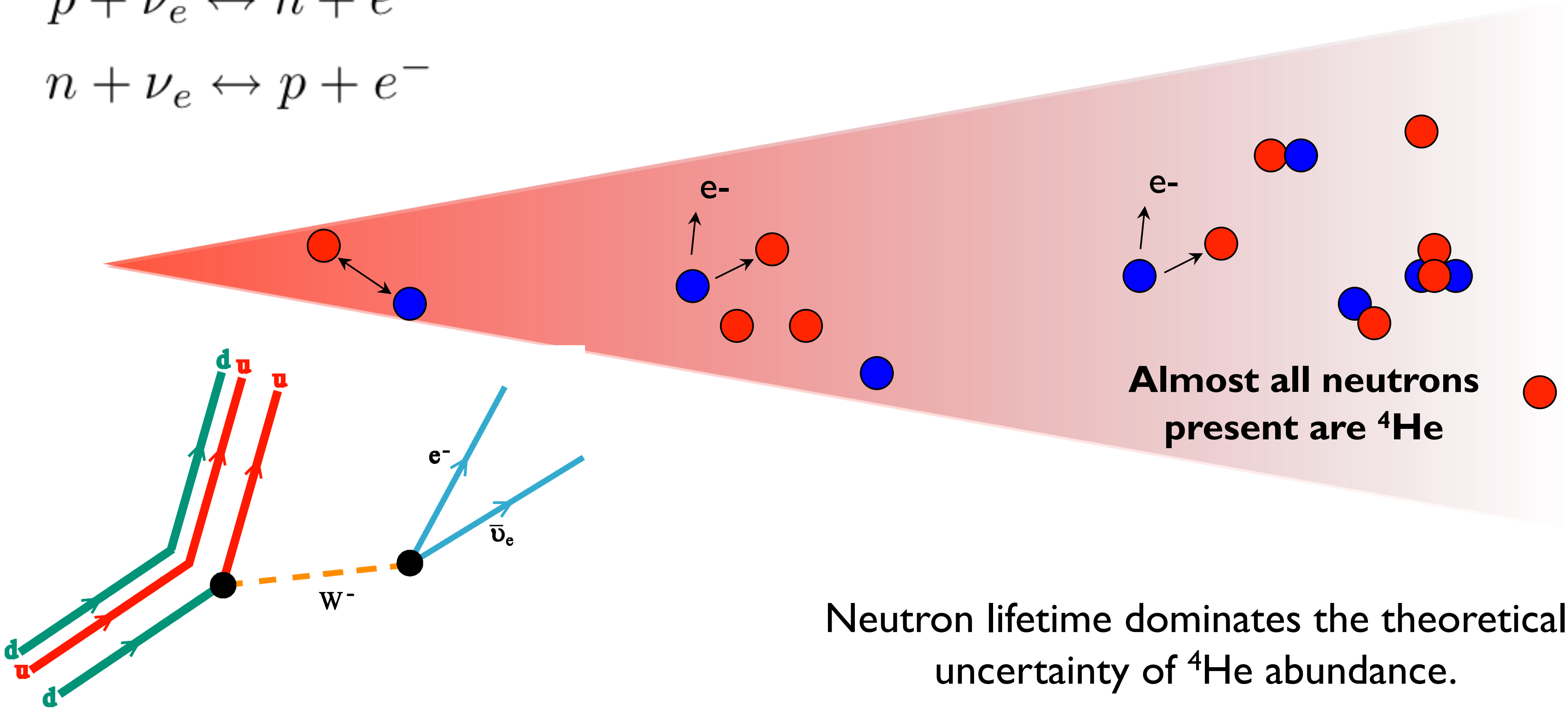
$$n \rightarrow p + e^- + \bar{\nu}_e$$

100s

Nucleosynthesis (T~0.1 MeV)
Light elements are formed

$$p + n \rightarrow d + \gamma$$

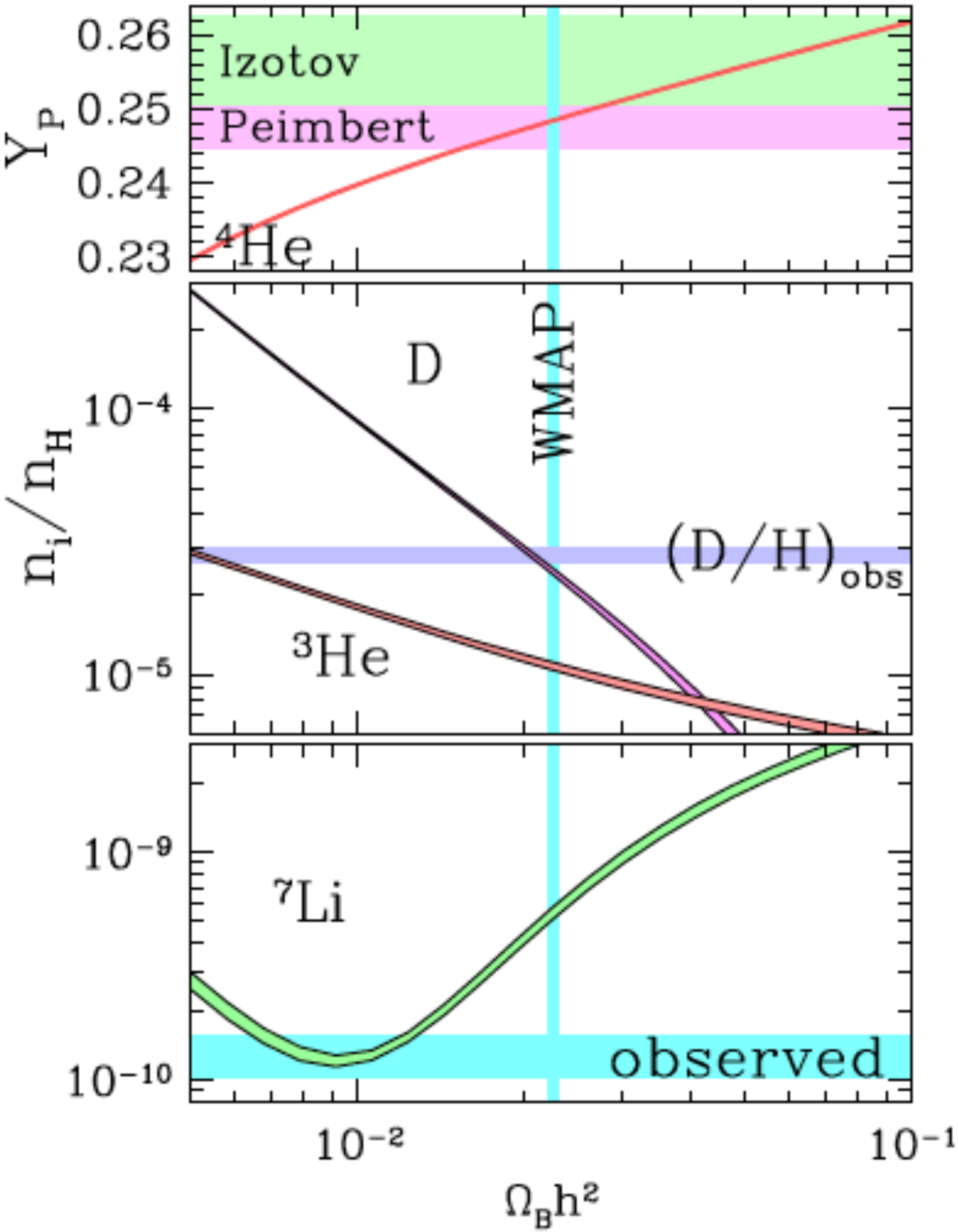
$$d + d \rightarrow {}^4\mathrm{He} + \gamma$$



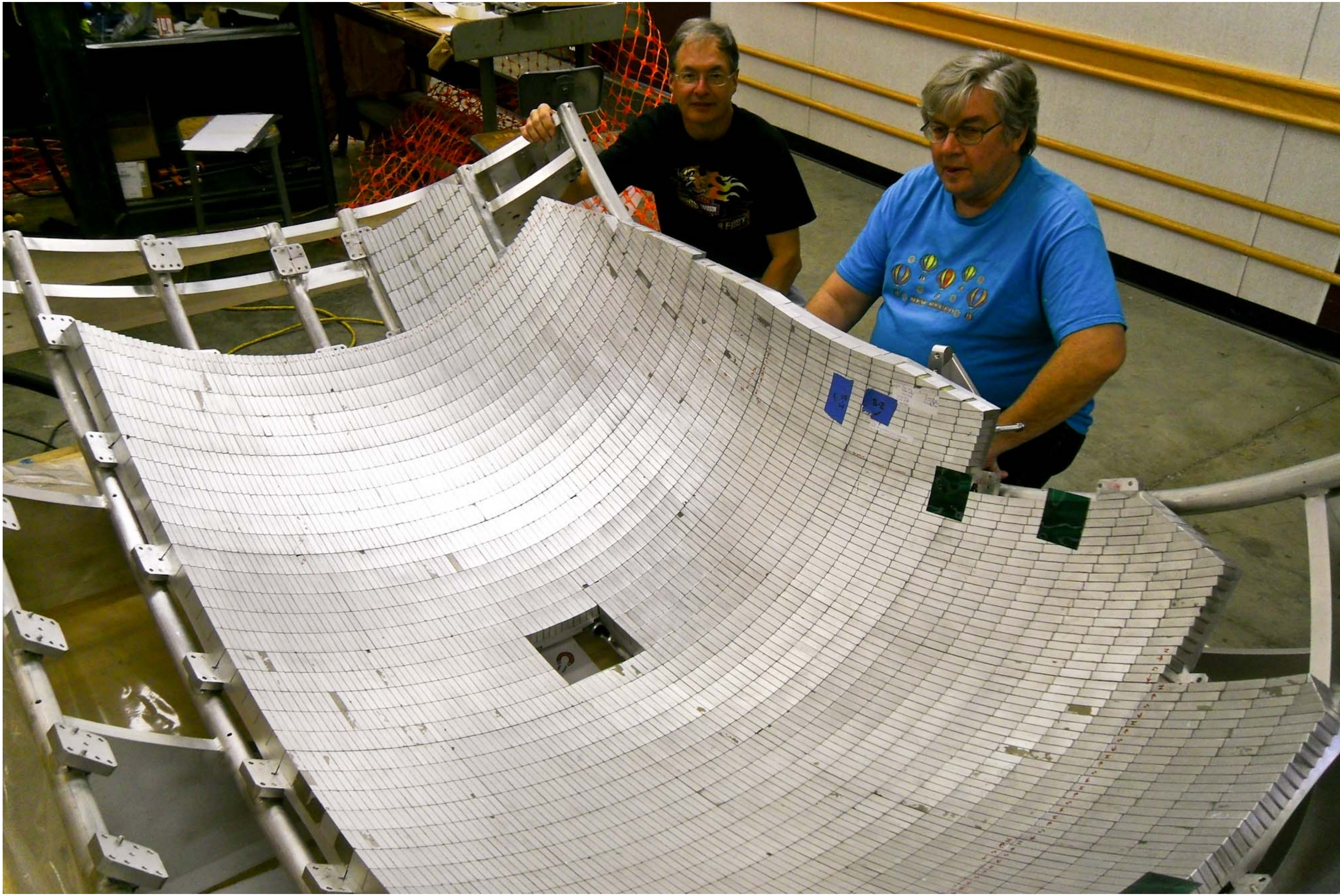
Almost all neutrons present are ^{4}He

Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.

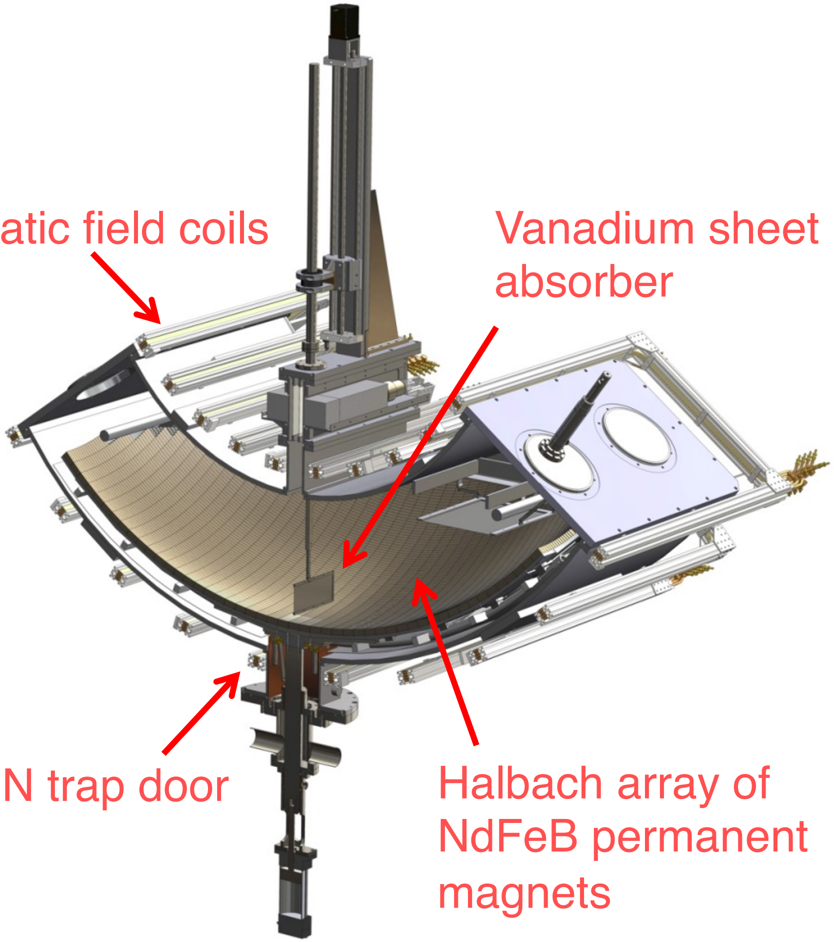
Big Bang nucleosynthesis: theory and observation



Proportions in agreement with astro observations! (except for ^{7}Li…)


B-2

Gravity↓ Magnetism↑
A nearly perfect neutron trap!

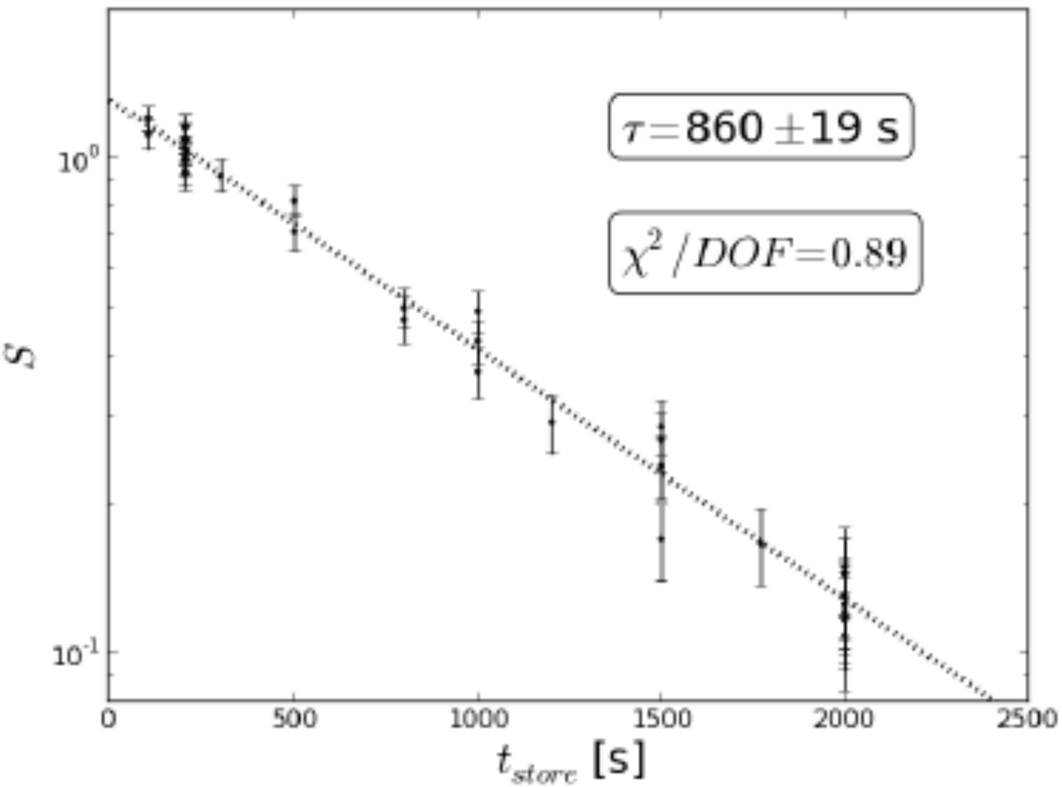


Static field coils

Vanadium sheet absorber

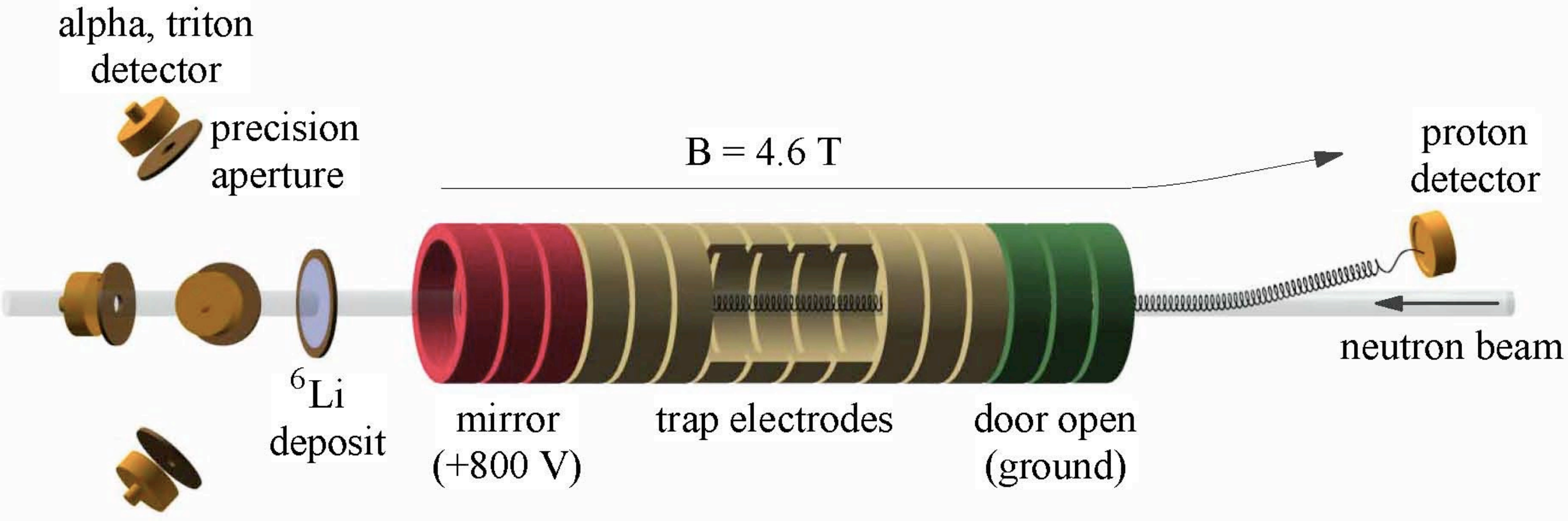
UCN trap door

Halbach array of NdFeB permanent magnets



D.J. Salvat et al. 1310.5759v3

Neutron Lifetime Measurement with a Proton Trap and Flux Monitor (Dewey et al)

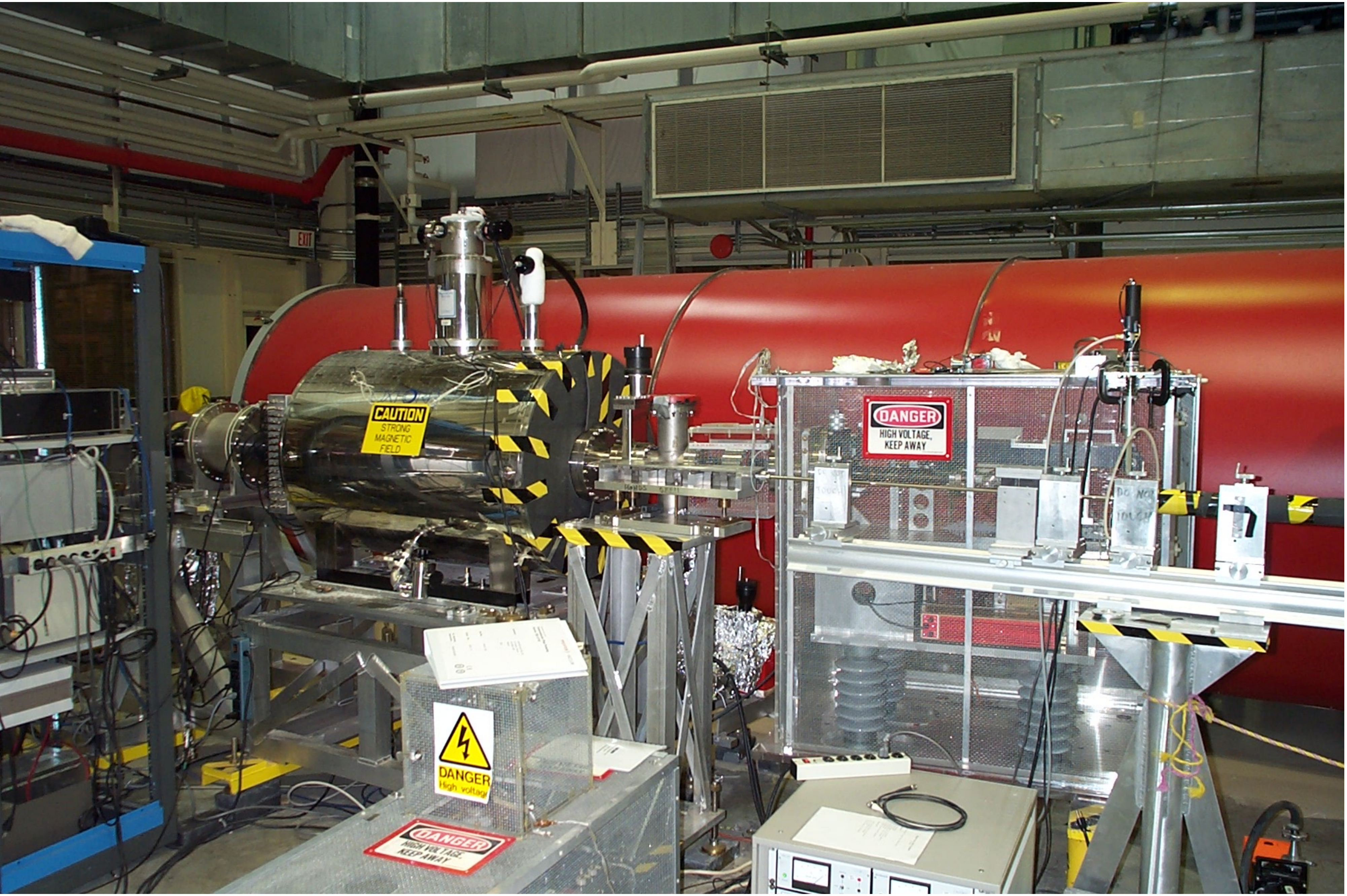


$dN(t)/dt=-N(t)/\tau$, measure decay rate and total # of neutrons in a known beam volume

Protons from neutron decay trapped in a Penning trap and counted

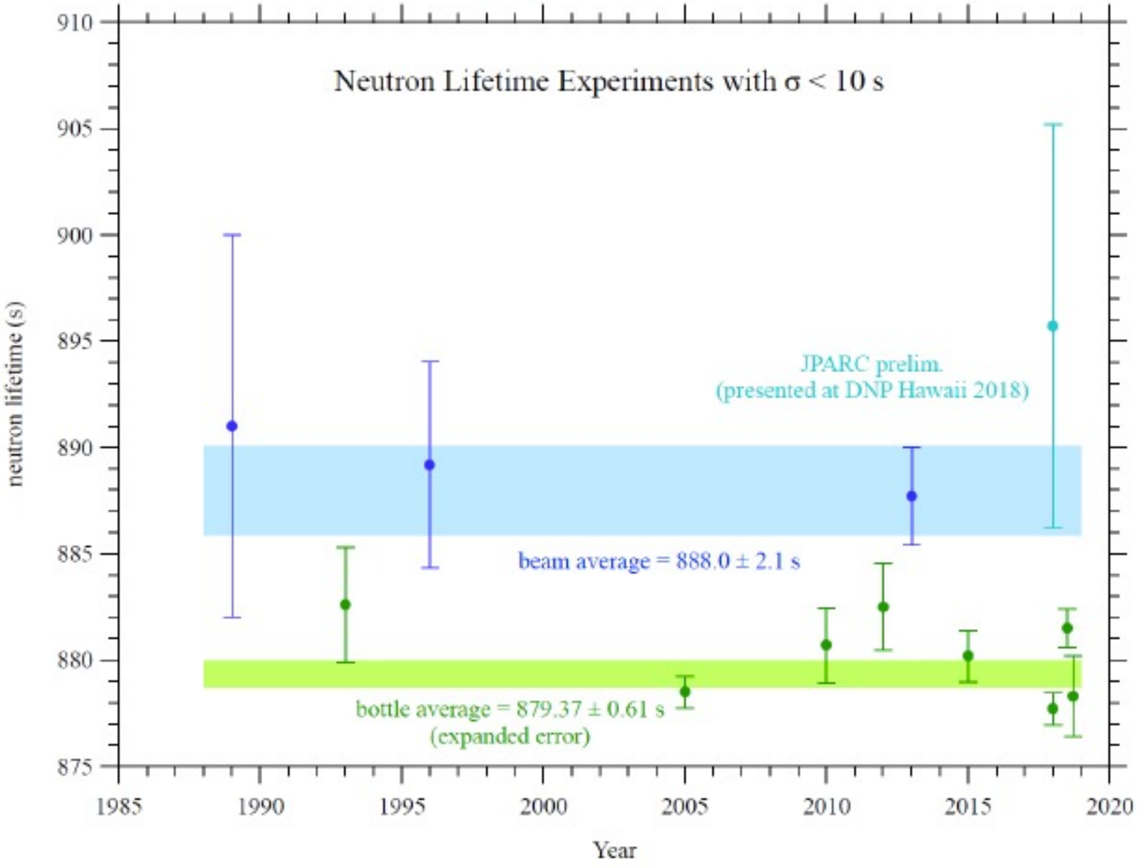
Neutron # in trap inferred from flux monitor

In-Beam Lifetime Apparatus @ NIST

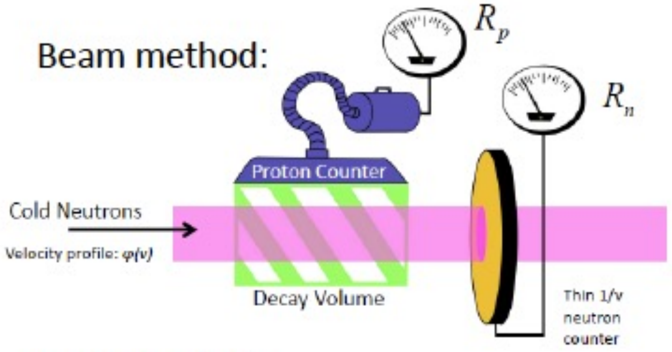


However, there is a unresolved discrepancy between two leading methods to measure the neutron lifetime.

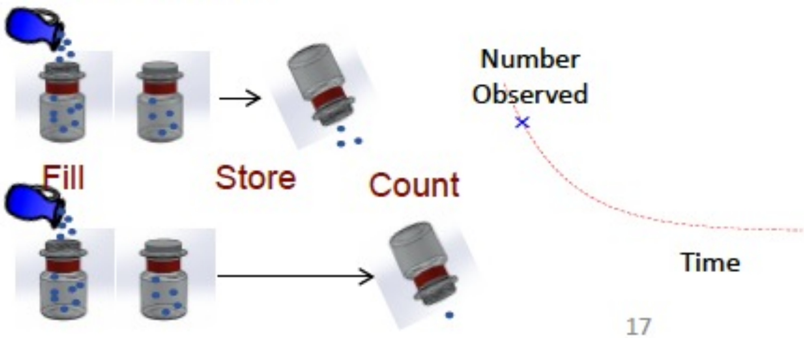
The Situation Today - 2019



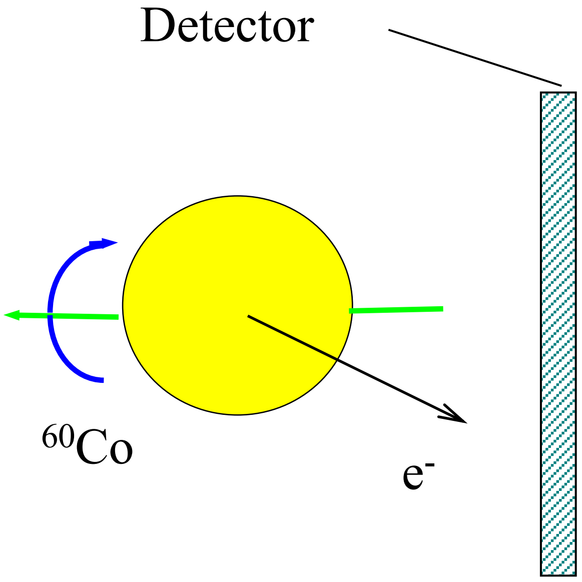
Beam method:



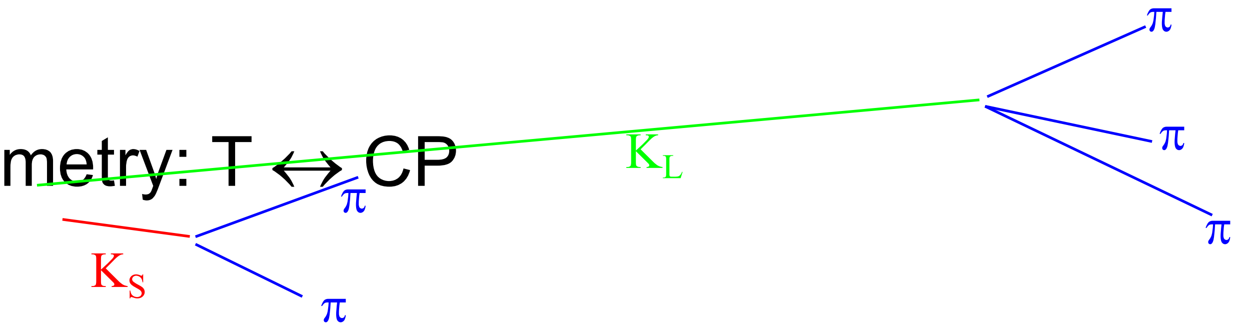
Bottle method:



P, CP, T, and CPT

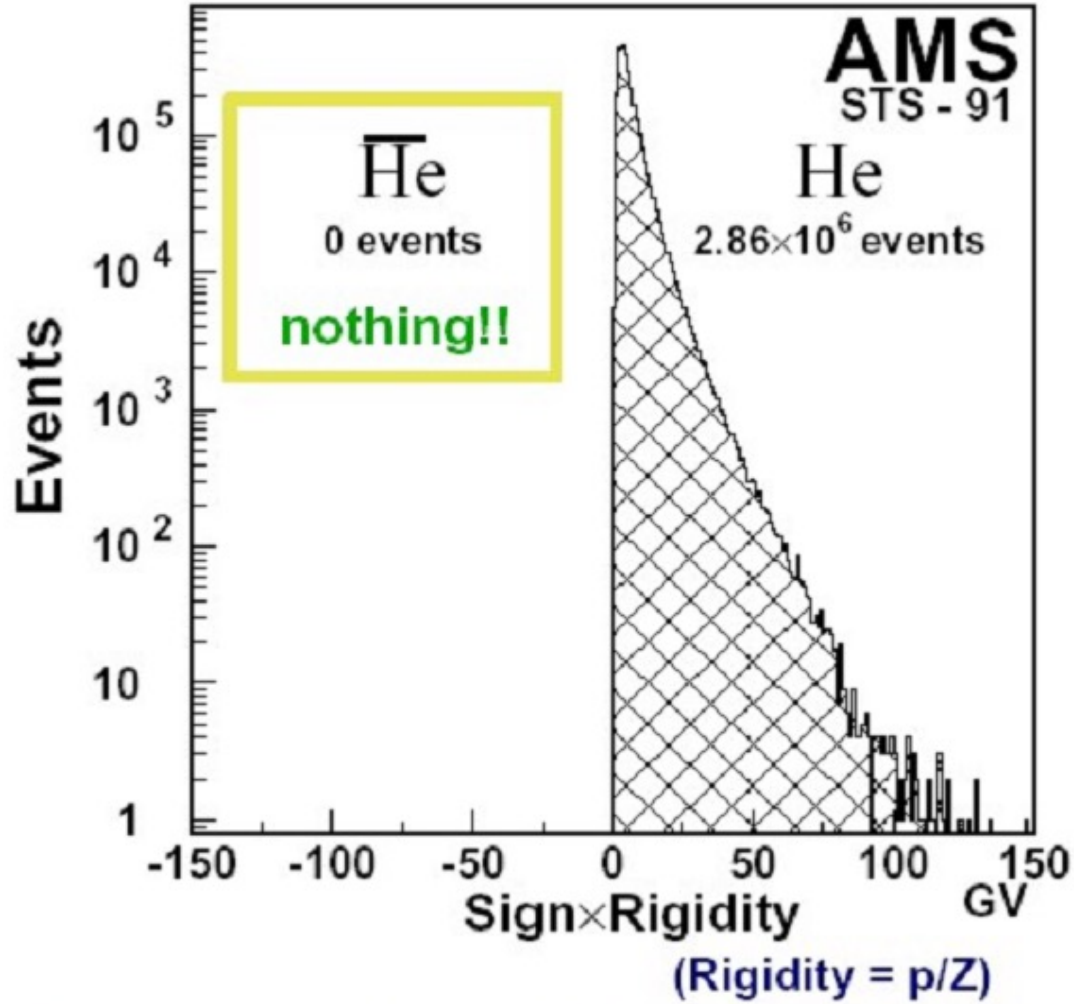


- Parity violation (1956)
  - only in weak interaction
- CP violation (1964)
  - parametrised but not understood
  - only seen so far in oscillating neutral meson systems
  - Doesn’t seem to be responsible for baryon asymmetry of universe
- T violation (1999)
  - CPT is good symmetry: T ↔ CP



Matter Asymmetry of the Universe

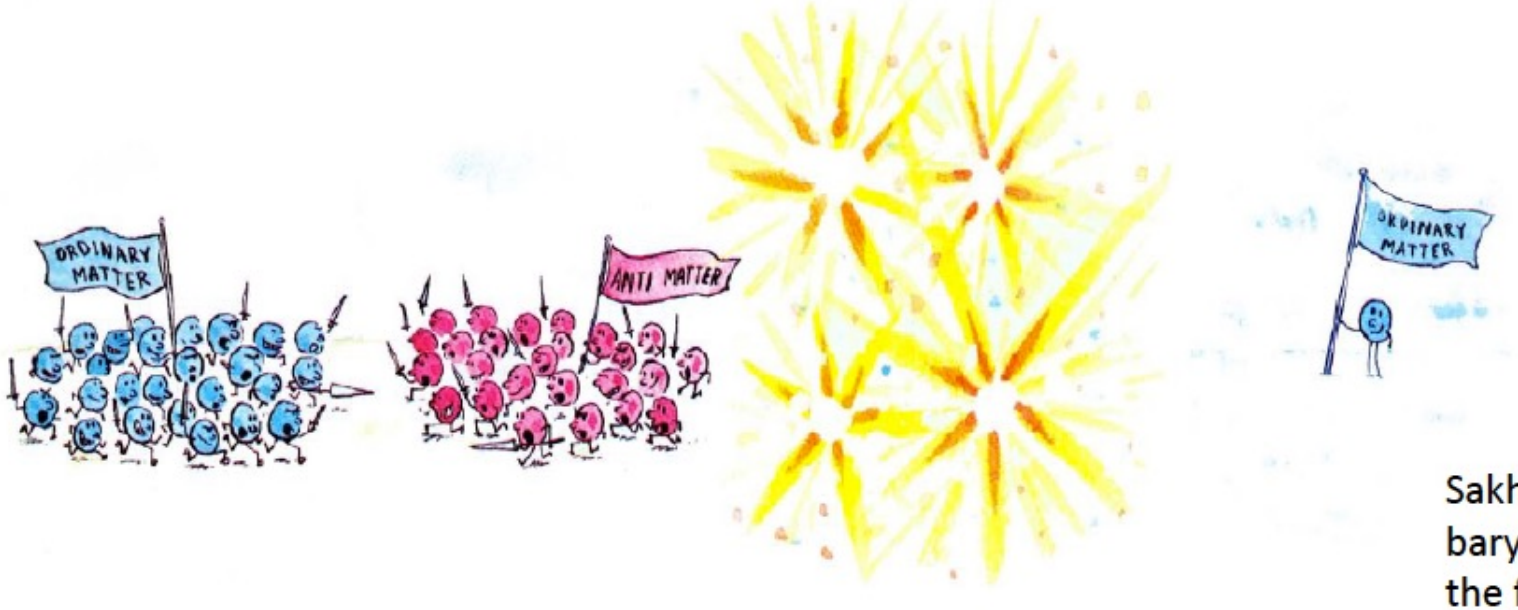
Q: Why is there more matter than antimatter in the Universe?



In the lab we make equal amounts of matter and antimatter
So why is the universe lopsided? Is it just an accident?

"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.

Anti-matter annihilates with matter; Big-bang nucleosynthesis somehow created a slight excess of matter to seed the universe



$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$ η: baryon asymmetry of the universe (BAU)

Planck telescope: $\eta = (6.10 \pm 0.04) \times 10^{-10}$

Sakharov: The mechanism of baryogenesis needs to have the following criteria:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Matter/Antimatter Asymmetry in Big Bang

n_B-$n_{\underline{B}}$ starts from zero (otherwise inflation is destroyed, Dolgov)

Today: $(n_B - n_{\underline{B}})/n_\gamma \sim 6 \times 10^{-10}$ (E. Komatsu et al, ApLS, 192 (2011))

Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics (A.D. Sakharov, JETP Lett. 5, 24-27 (1967))

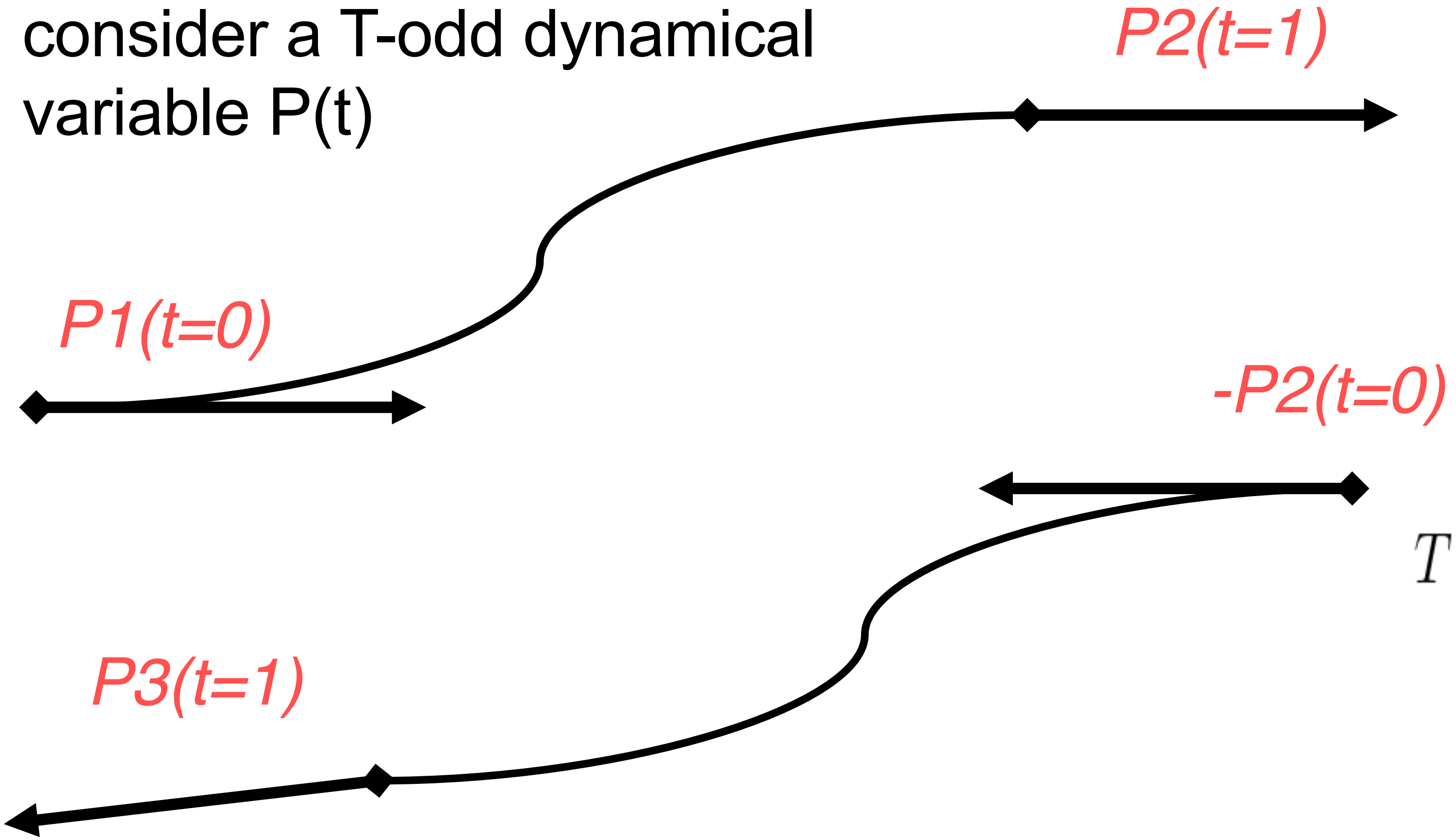
(1) Baryon Number Violation (not yet seen)
(2) Departure from Thermal Equilibrium
(3) C and CP Violation (seen)
(1+2+3) far too small given the known Higgs mass

Searches for T and B violation with neutrons:

Electric Dipole Moment Searches (E~0)
T-odd Polarized Neutron Optics (E~6 MeV)
Neutron/antineutron Oscillations

Time Reversal: “running the film backwards”

consider a T-odd dynamical variable P(t)



$$T\mathbf{r}T^{-1} = \mathbf{r}$$

$$T\mathbf{p}T^{-1} = -\mathbf{p}$$

$$T\boldsymbol{\sigma}T^{-1} = -\boldsymbol{\sigma}$$

$$T[\mathbf{r},\mathbf{p}]T^{-1} = -[\mathbf{r},\mathbf{p}]$$

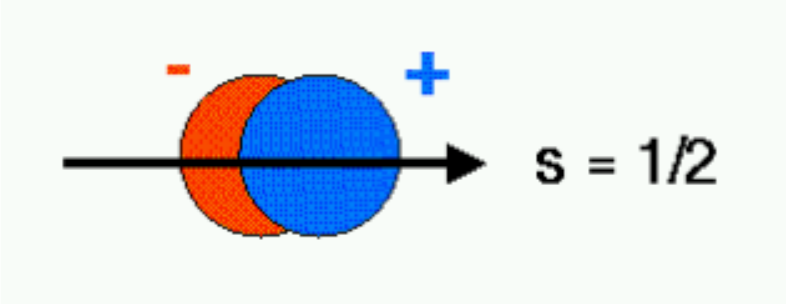
Etc.

Is the final state of the motion with time-reversed final conditions P3(t=1) the same as the time-reversed initial condition -P1(t=0)?

In QM: reversal of initial and final states:

<a|O|b> -> <b|O_T|a> $\to TiT^{-1} = -i \quad T = UK,$ K=complex conjugation

Electric Dipole Moments: P-odd/ T-odd Observable



$$\vec{d}_n = \int \vec{x}\rho(x)d^3x = d_n\hat{s}$$

Non-zero d_n violates both P and T

Under a parity operation:

$$\hat{s} \rightarrow \hat{s}\,, \quad \vec{E} \rightarrow -\vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

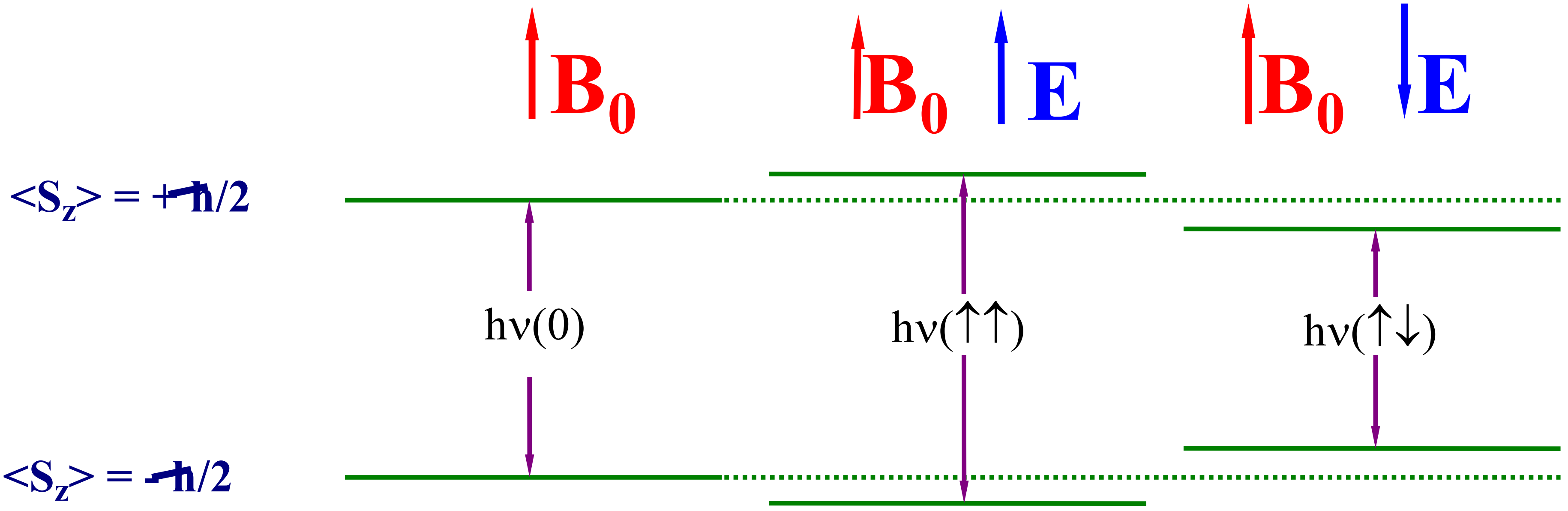
Under a time-reversal operation:

$$\hat{s} \rightarrow -\hat{s}\,, \quad \vec{E} \rightarrow \vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

EDMs are “null tests” of time reversal invariance (no “final state effects” can fake an EDM) |i>=|f>

EDM Measurement Principle/Sensitivity



$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/\,h$$

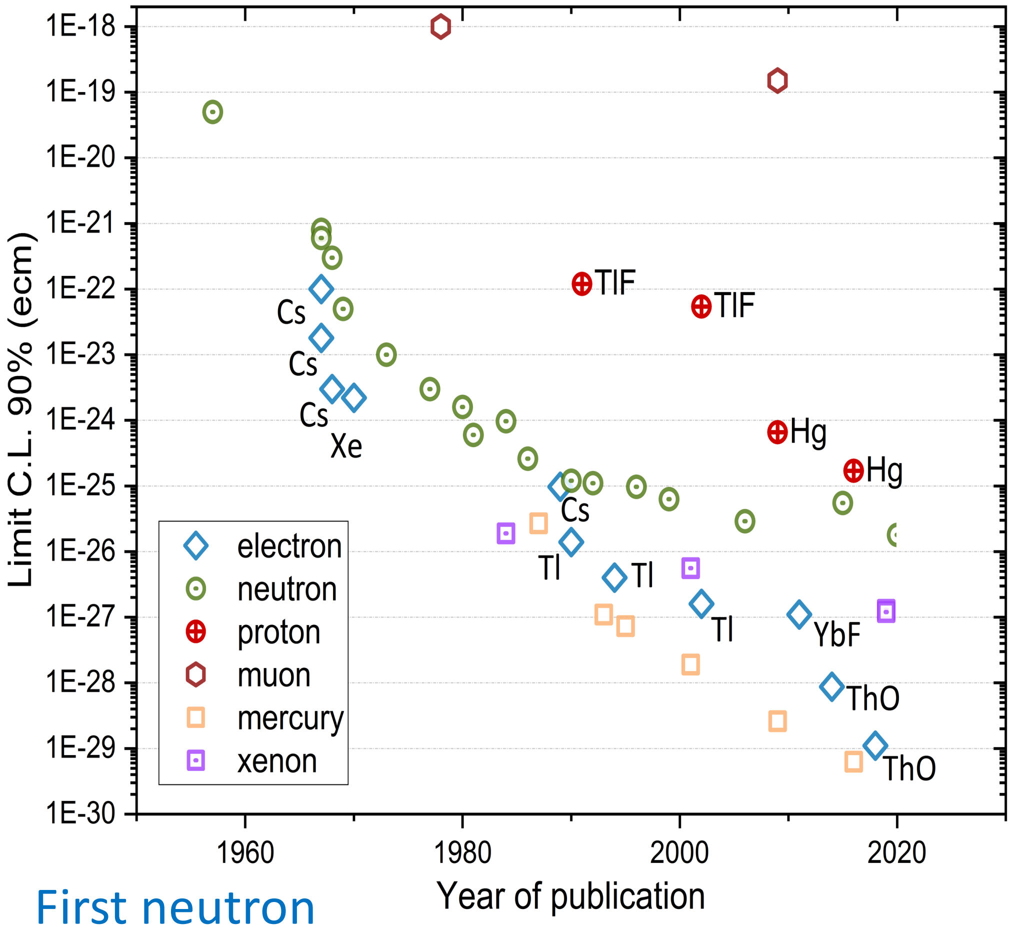
assuming **B** unchanged when **E** is reversed.

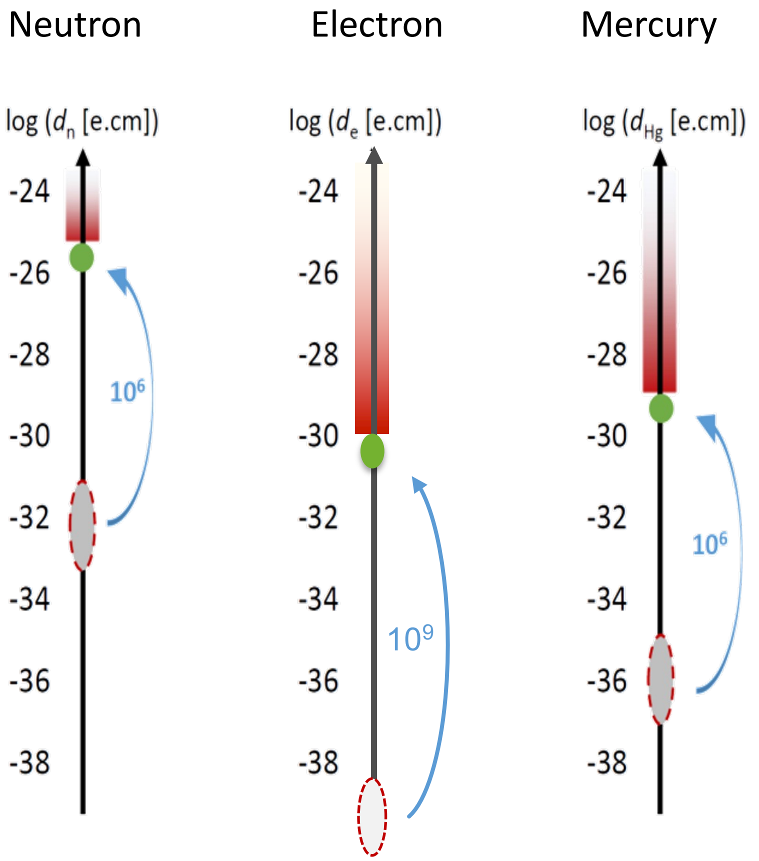
EDM limits -> ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-11}

T violation from CKM phases smaller by ~5 orders of magnitude here

EDMs are ground state properties of the system: excitation energy ~0

A brief history of EDM searches





Previous

RAL-Sussex-ILL

$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

J.M. Pendlebury et al., PRD 92 (2015) 092003

First neutron

Smith, Purcell, Ramsey

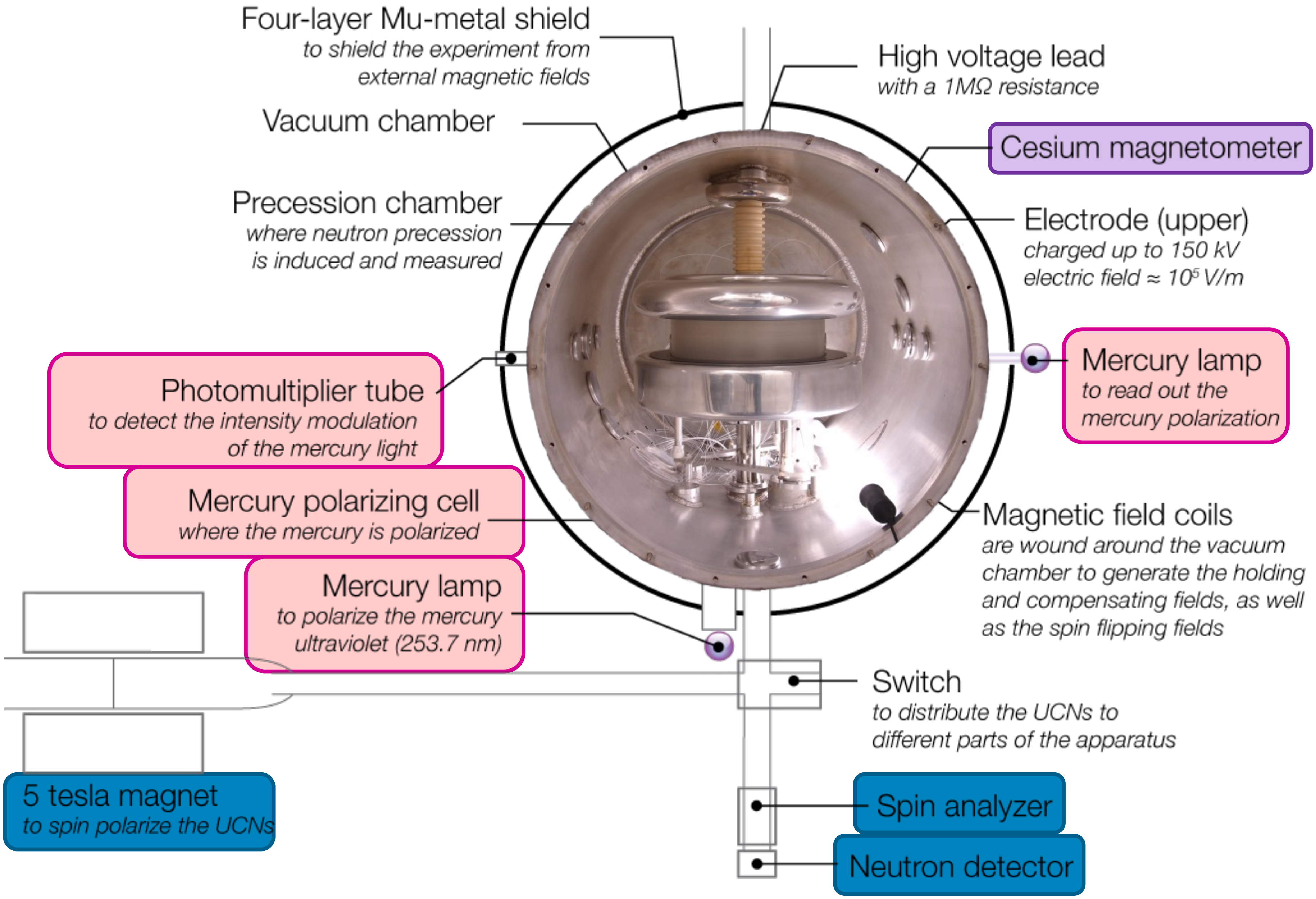
$d_n < 5 \times 10^{-20}$ e cm

PR 108 (1957) 120

~ 60 years

P. Schmidt-Wellenburg

The nEDM spectrometer at PSI



Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

High voltage lead
with a 1MΩ resistance

Vacuum chamber

Cesium magnetometer

Precession chamber
where neutron precession is induced and measured

Electrode (upper)
charged up to 150 kV
electric field ≈ 10^5 V/m

Photomultiplier tube
to detect the intensity modulation of the mercury light

Mercury lamp
to read out the mercury polarization

Mercury polarizing cell
where the mercury is polarized

Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)

Switch
to distribute the UCNs to different parts of the apparatus

5 tesla magnet
to spin polarize the UCNs

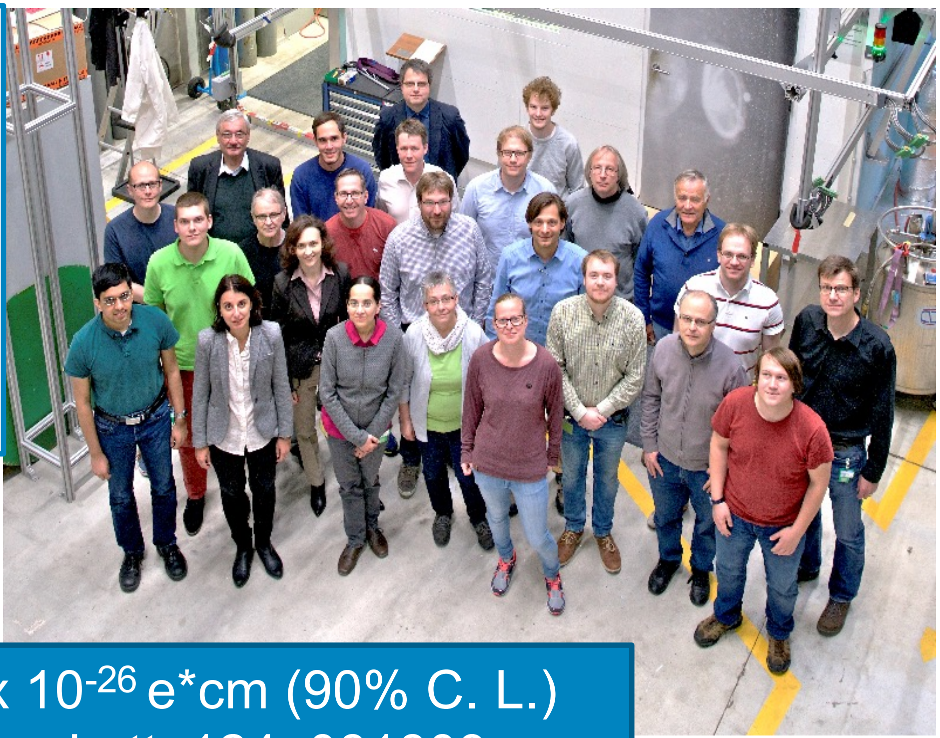
Spin analyzer

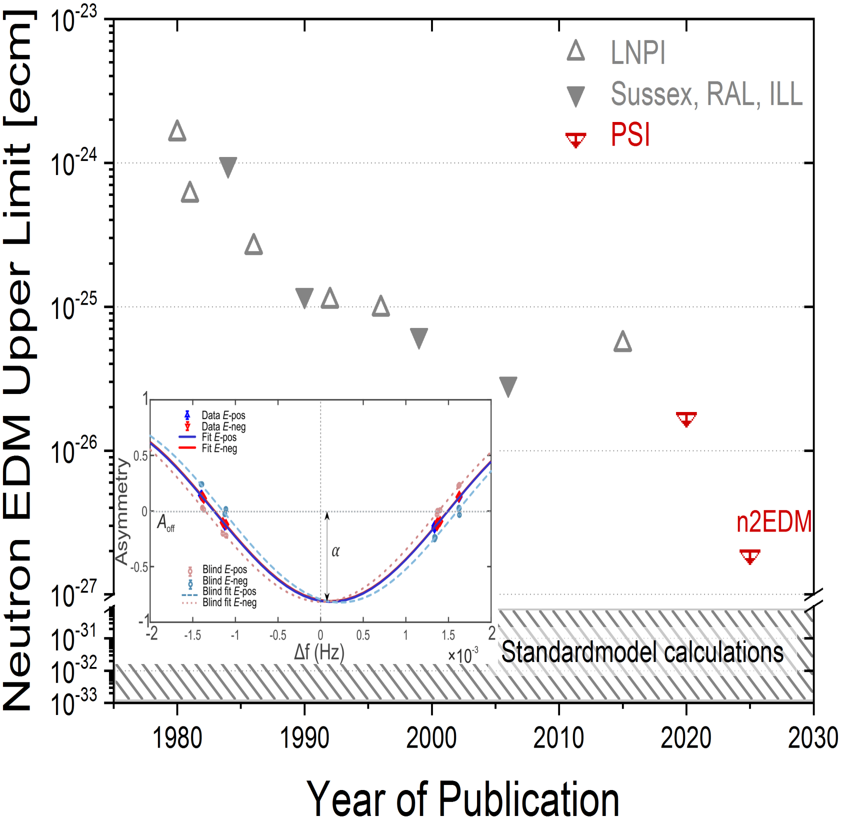
Neutron detector

Most sensitive result on neutron electric dipole moment (EDM) measured at the PSI UCN source

EDMs unambiguously indicate charge parity violation (CPV)

- CPV natural in beyond standard model theories
- CPV required for matter / antimatter asymmetry
- Neutron EDM uniquely sensitive to strong CPV





$d_n < 1.8 \times 10^{-26}$ e*cm (90% C. L.)
Phys. Rev. Lett. 124, 081803 (2020)

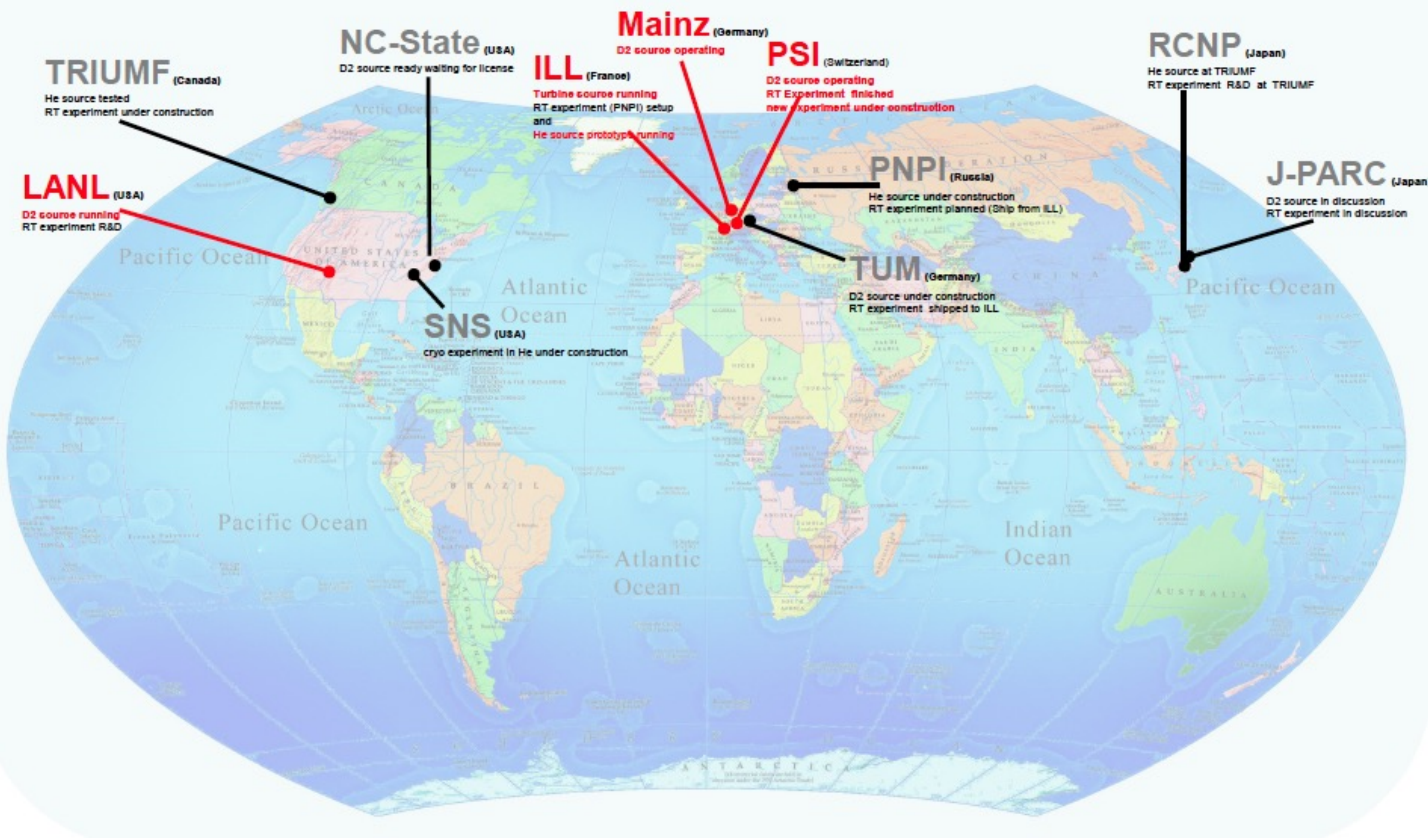
Unique features of result published in **PRL**

- Limit improved by factor 1.7
- Systematic errors reduced by factor five
- Full comprehension of systematic effects from higher order magnetic field non-uniformity
- First fully blinded analysis in two distinct teams

P. Schmidt-Wellenburg

PAUL SCHERRER INSTITUT PSI

ULTRACOLD NEUTRON SOURCES AND NEDM EXPERIMENTS: THE WORLDVIEW



TRIUMF (Canada)
He source tested
RT experiment under construction

LANL (USA)
D2 source running
RT experiment R&D

NC-State (USA)
D2 source ready waiting for license

SNS (USA)
cryo experiment in He under construction

ILL (France)
Turbine source running
RT experiment (PNPI) setup
and
He source prototype running

Mainz (Germany)
D2 source operating

PSI (Switzerland)
D2 source operating
RT Experiment finished
new experiment under construction

PNPI (Russia)
He source under construction
RT experiment planned (Ship from ILL)

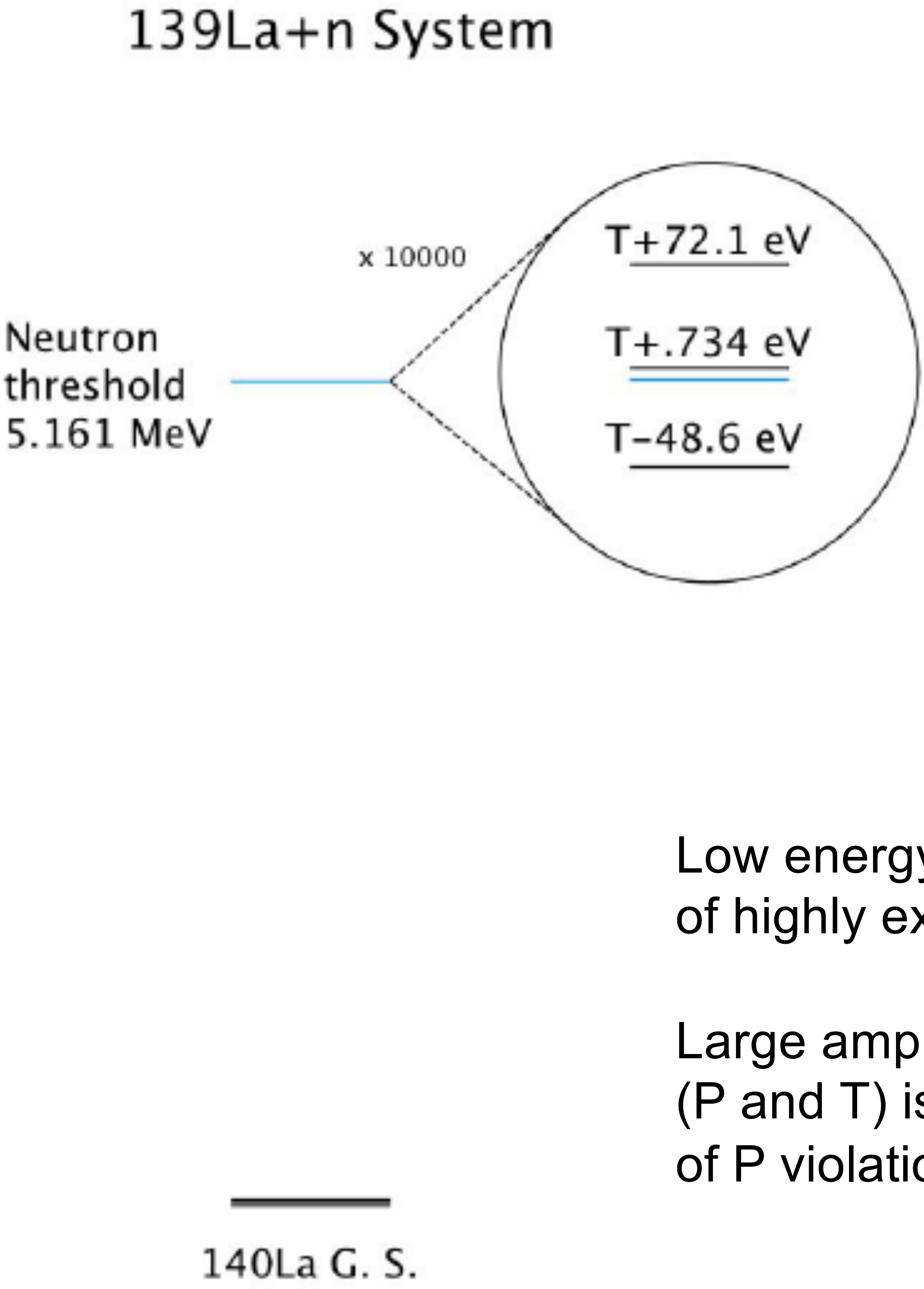
TUM (Germany)
D2 source under construction
RT experiment shipped to ILL

RCNP (Japan)
He source at TRIUMF
RT experiment R&D at TRIUMF

J-PARC (Japan)
D2 source in discussion
RT experiment in discussion

B. Lauss, AFCI workshop

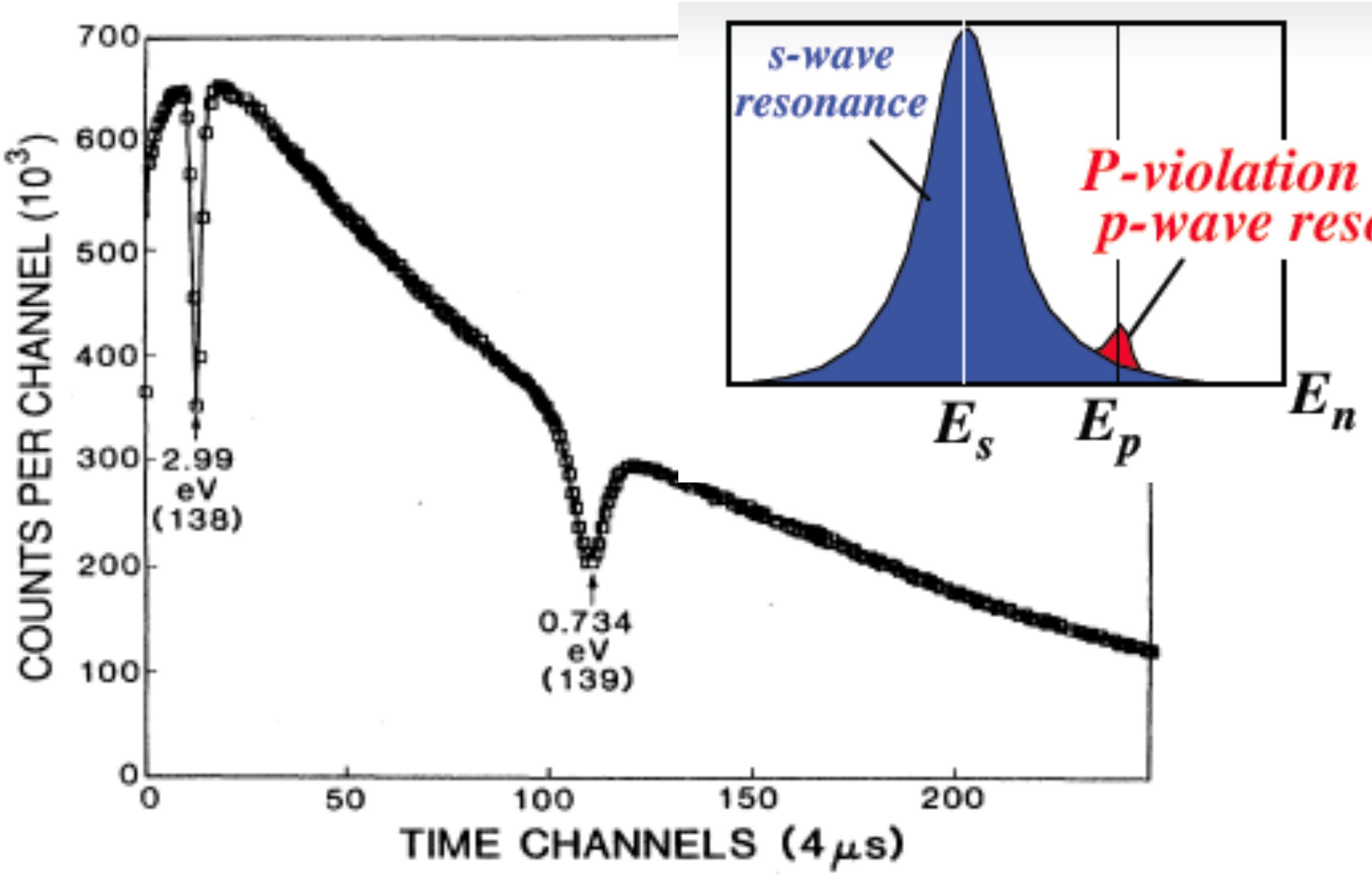
Compound-Nuclear States in ^{139}La+n system



Low energy neutrons can access a dense forest of highly excited states in the compound nucleus.

Large amplification of discrete symmetry violation (P and T) is possible. Very large amplifications of P violation were observed long ago

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma = 0.097 \pm .005$. Larger than nucleon-nucleon system by 10^6



P-violation is enhanced in p-wave resonance

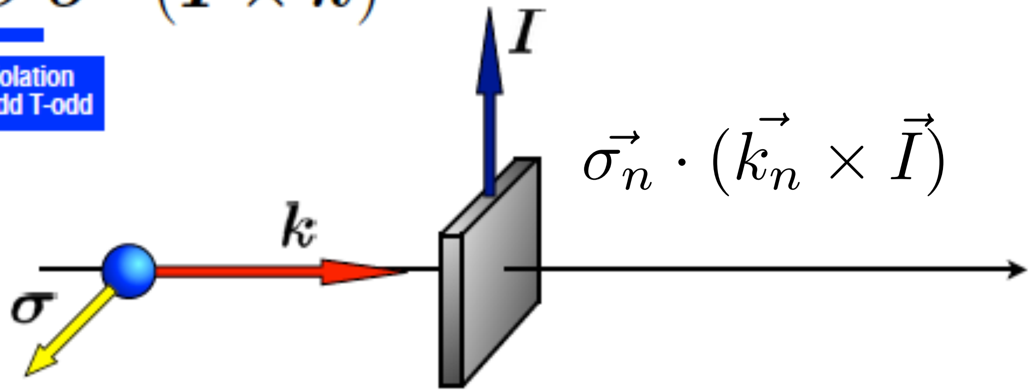
$$v = \langle s | W | p \rangle$$

How? Neutron spends ~10^6 more time in the nucleus on the resonance

Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

Forward Scattering Ampliltude

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$



$$\vec{\sigma_n}\cdot(\vec{k_n}\times\vec{I})$$

$$\begin{array}{ccccc} |s\rangle & |p\rangle & |p_{1/2}\rangle & |p_{3/2}\rangle & \\ J_s E_s \Gamma_s \Gamma^n_s & J_p E_p \Gamma_p \Gamma^n_p & \Gamma^n_{p,1/2} & \Gamma^n_{p,3/2} & \langle W\rangle \end{array}$$

The enhancement of P-odd/T-odd amplitude on p-wave resonance (σ.[*K* X *I*]) is (almost) the same as for P-odd amplitude (σ.*K*).

Experimental observable: ratio of P-odd/T-odd to P-odd amplitu $\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$

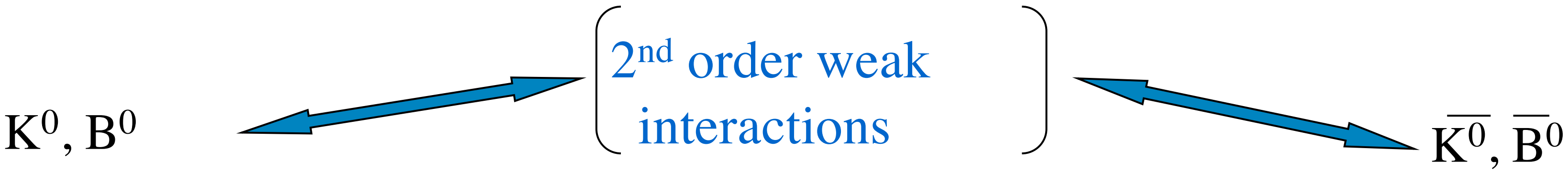
λ can be measured with a statistical uncertainty of ~10^{-5} in 10^7 sec at MW-class spallation neutron sources.

Ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-11}

Forward scattering neutron optics limit is null test for T (no final state effects)

$\bar{n} \leftrightarrow n$ oscillations

Neutral meson $|q\bar{q}\rangle$ states oscillate -

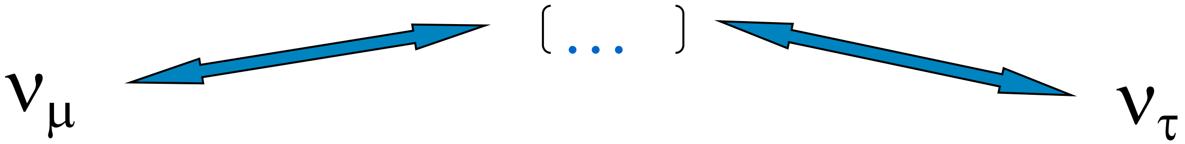


K^0, B^0

2nd order weak interactions

$\bar{K}^0, \bar{B}^0$

And neutral fermions can oscillate too -



ν_μ

. . .

ν_τ

So why not -

n

New physics

$\bar{n}$

?

Neutron is a long-lived neutral particle and can oscillate to an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model (SM) that violates Baryon number (B) by 2 units. This is expected in many new theories beyond SM at energy scale ~100 TeV

Neutron-Antineutron Oscillations: 2 x 2 Formalism

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

α≠0 allows oscillations

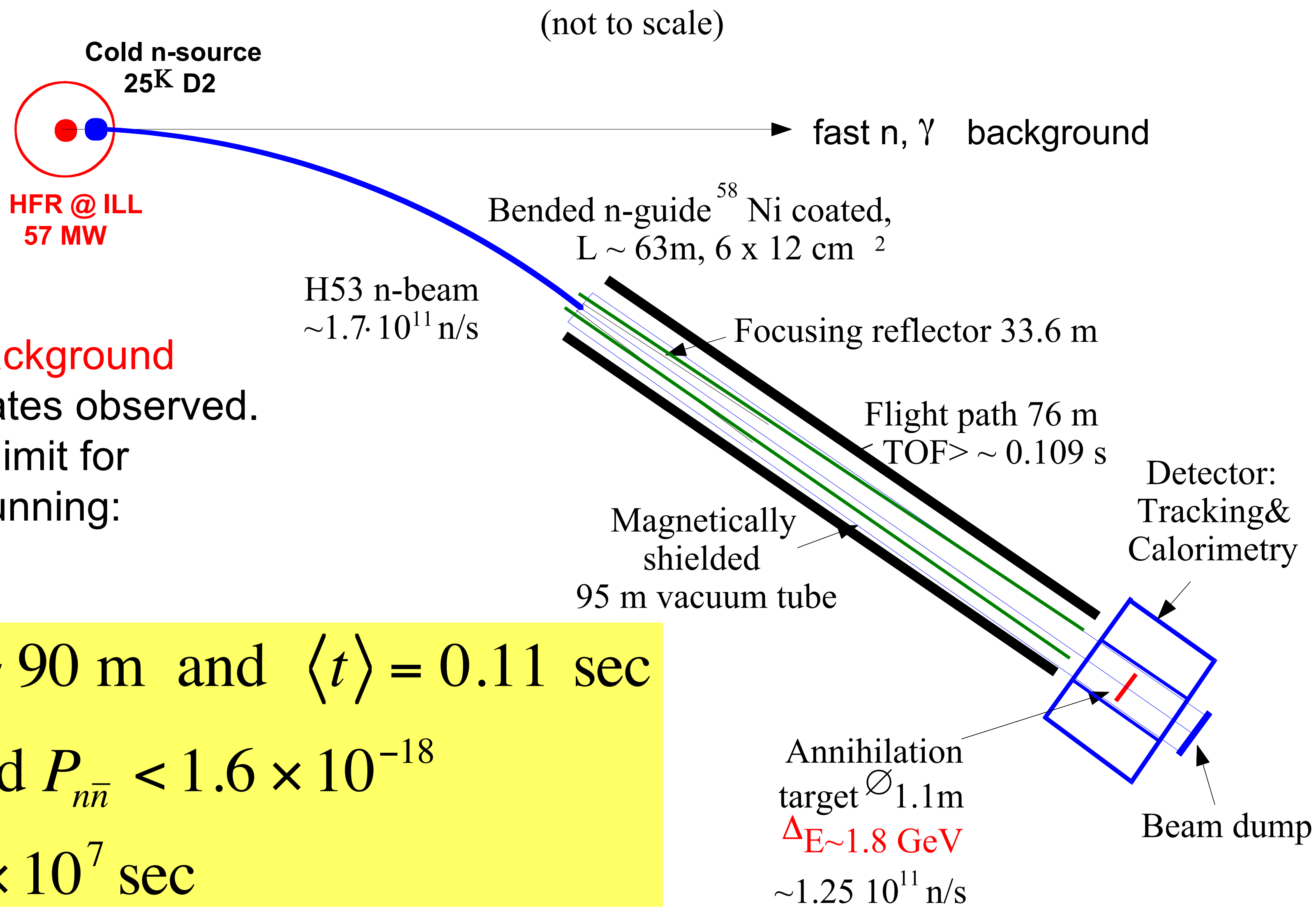
$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background

No candidates observed.

Measured limit for

a year of running:

$$\text{with L} \sim 90\ \text{m} \ \ \text{and} \ \ \langle t \rangle = 0.11\ \text{sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

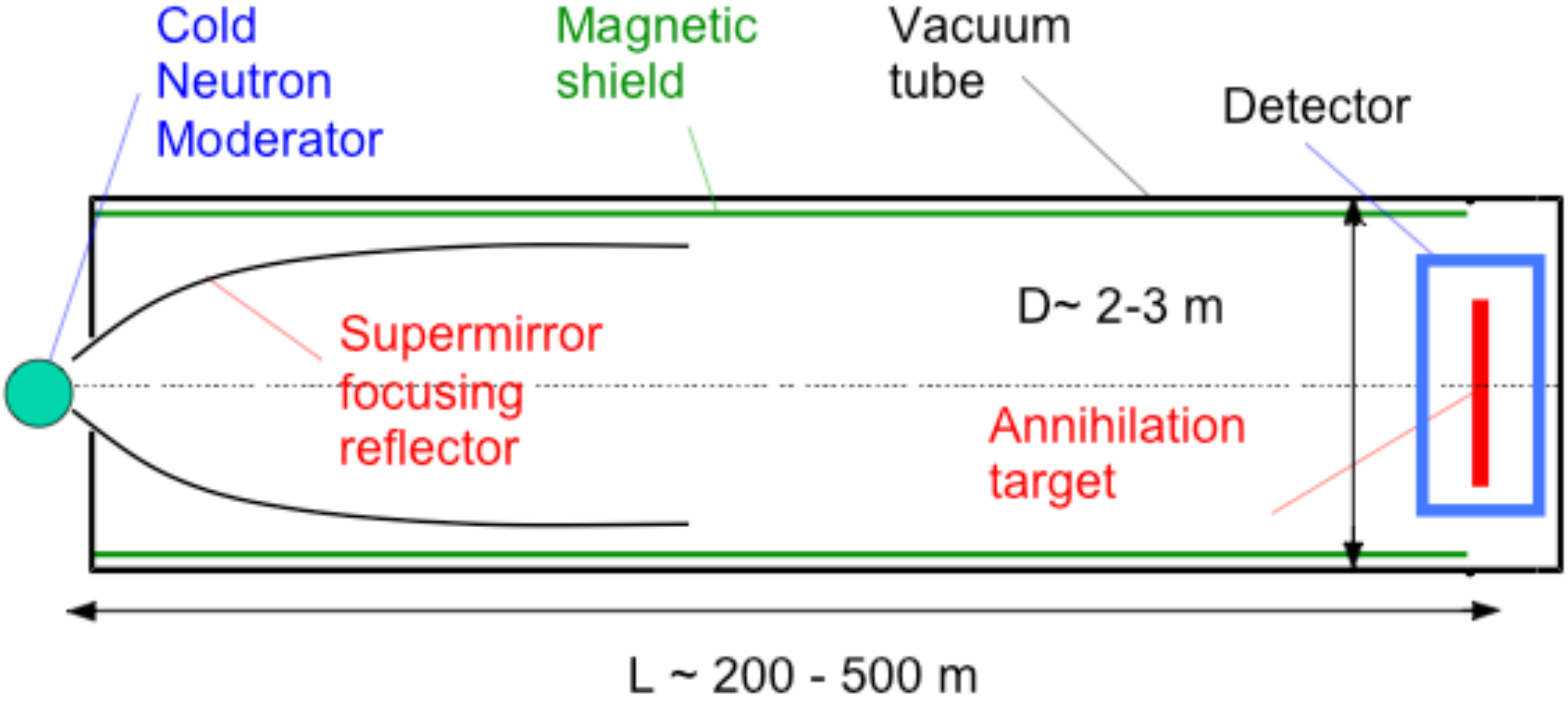
$$\tau > 8.6 \times 10^{7}\ \text{sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

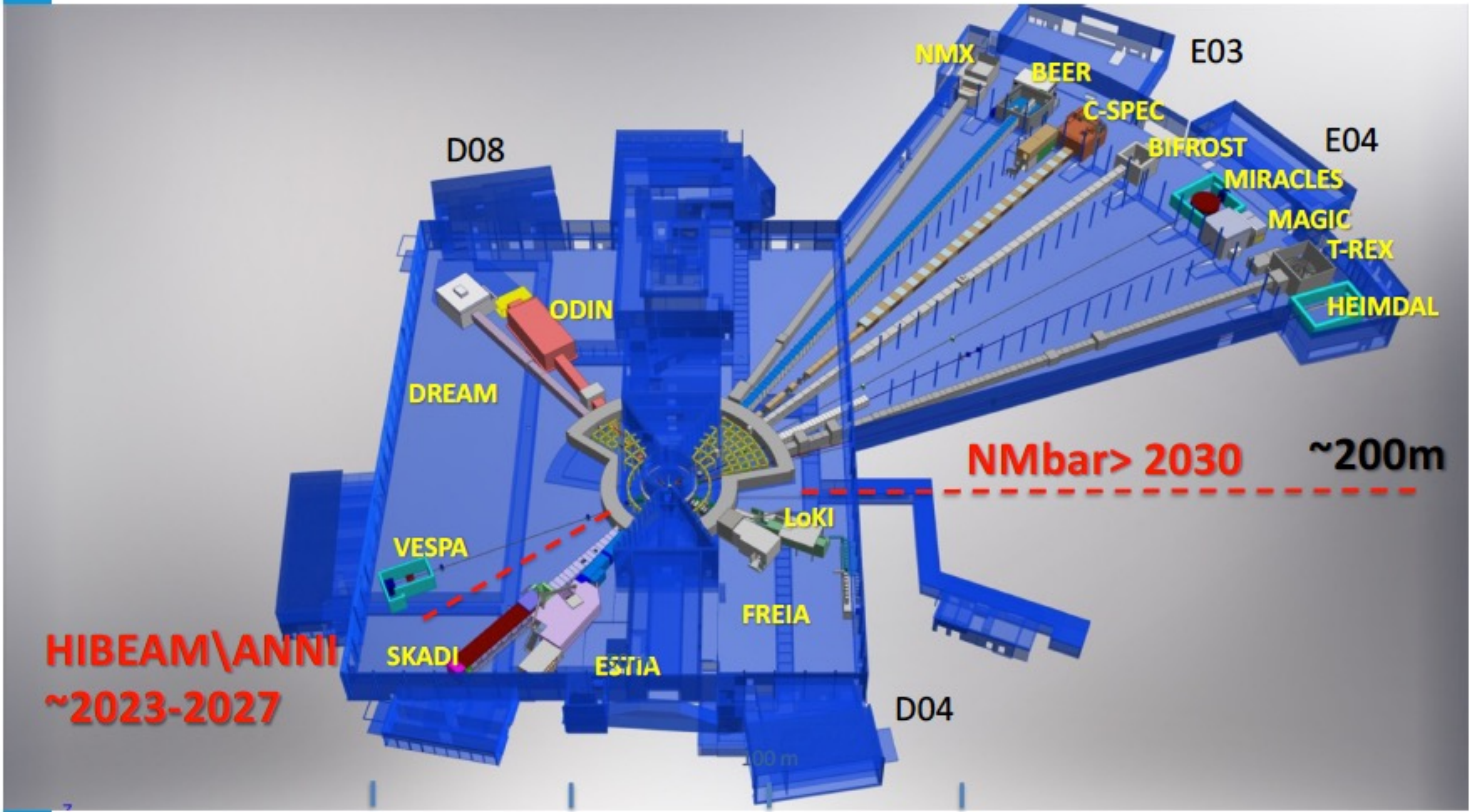
Better Cold Neutron Experiment (Horizontal beam

- need cold neutron source at high flux n source, close access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible! An uncommon opportunity…



ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations



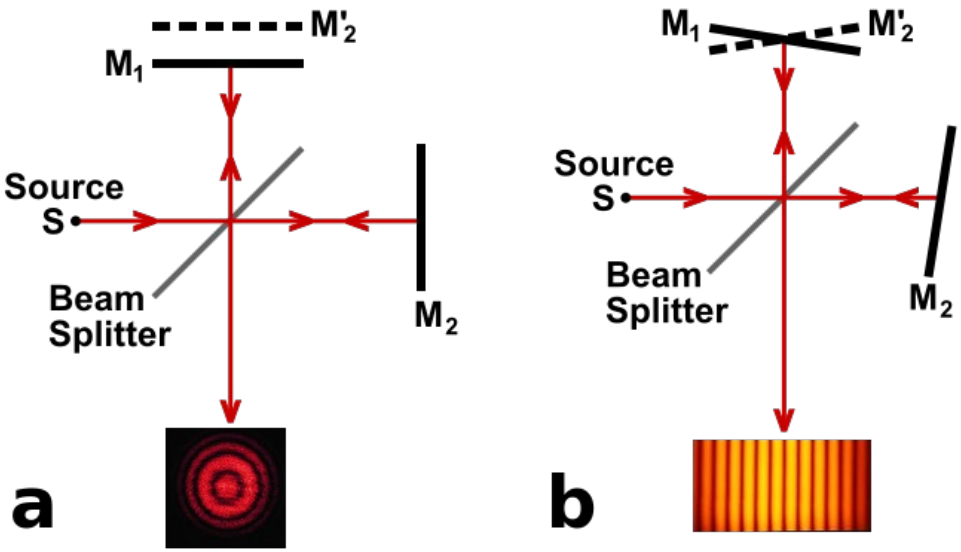
…G. Brooijmans,…. et al, arXiv: 2006.04907

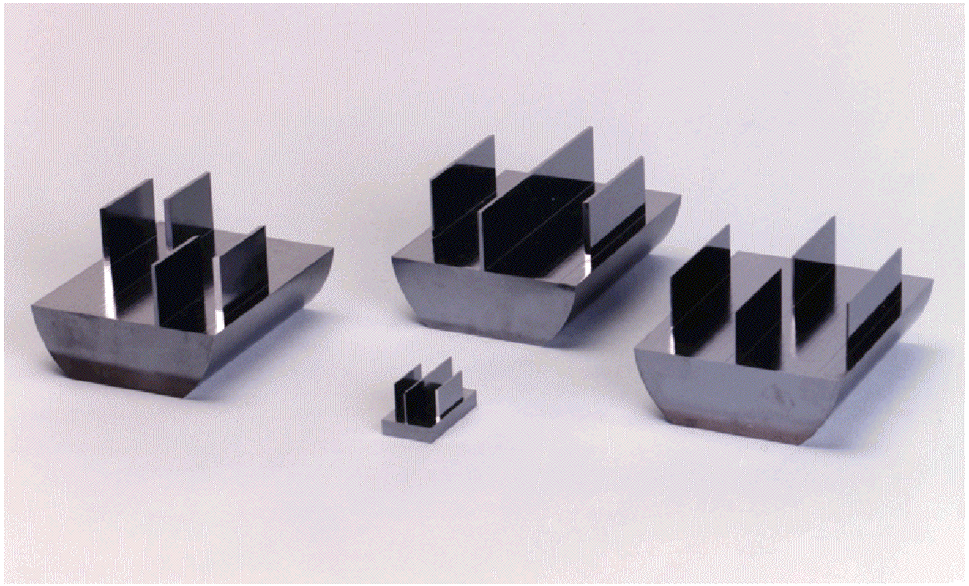
What is a neutron interferometer?

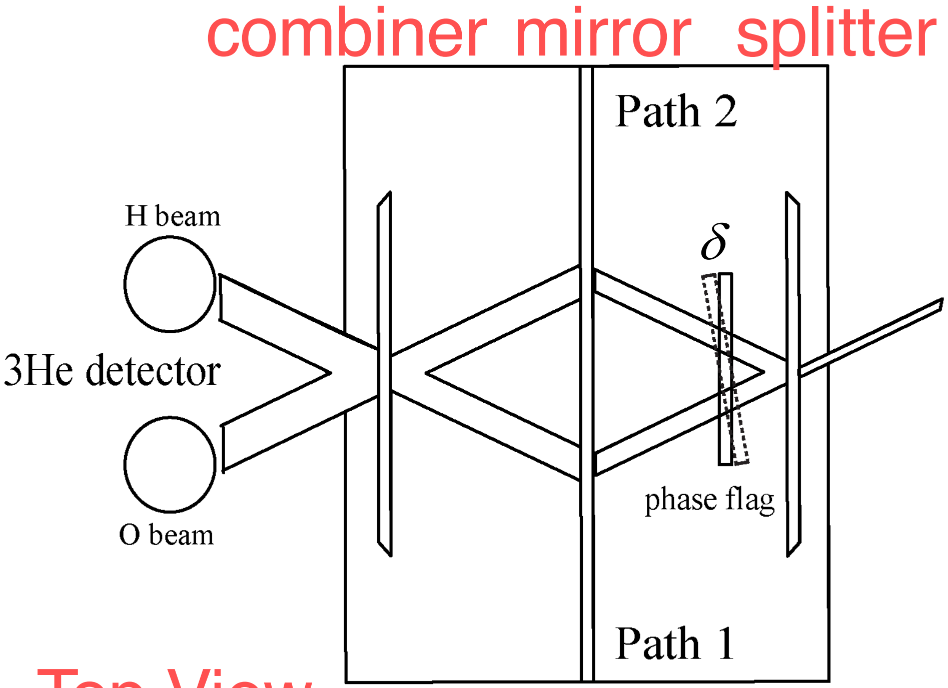
Neutron interferometer is very similar to a light interferometer:

1) Split
2) Reflect
3) Recombine

Michaelson interferometer

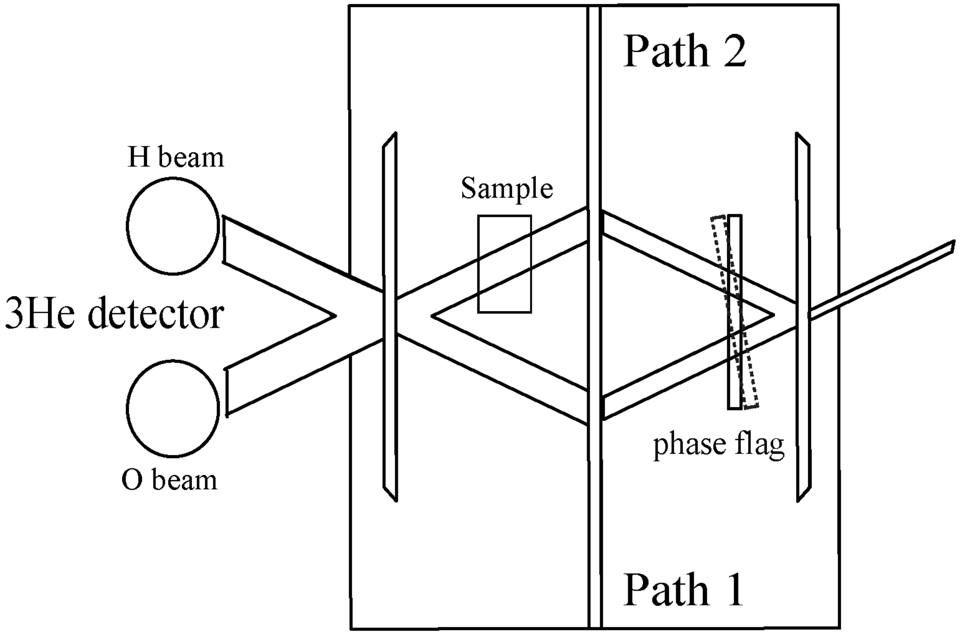






Top View

How it works



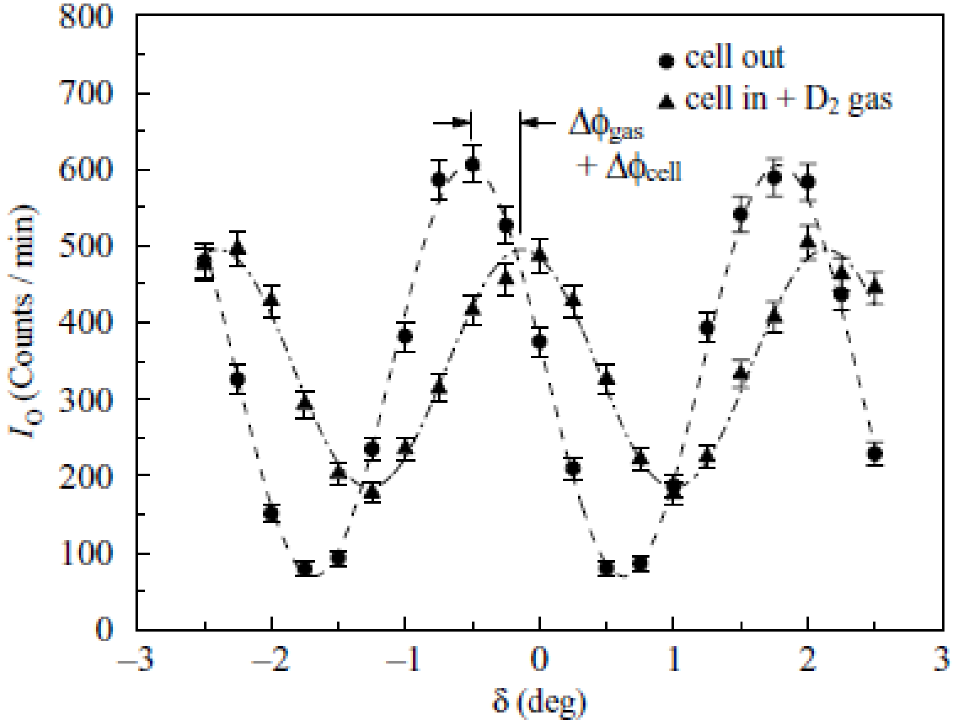
Interference signals:

O beam: $I_0 = A(1 + f\cos(\Delta\Phi))$

H beam: $I_H = B - Af\cos(\Delta\Phi))$

$\Delta\Phi$: phase shift between two paths

f : contrast/visibility



Phase shift from the sample shifts interference pattern.

Plot taken from: Precision neutron interferometric measurements and updated evaluations of the *n*−*p* and *n*−*d* coherent neutron scattering lengths, Phys. Rev. C **67**, 044005

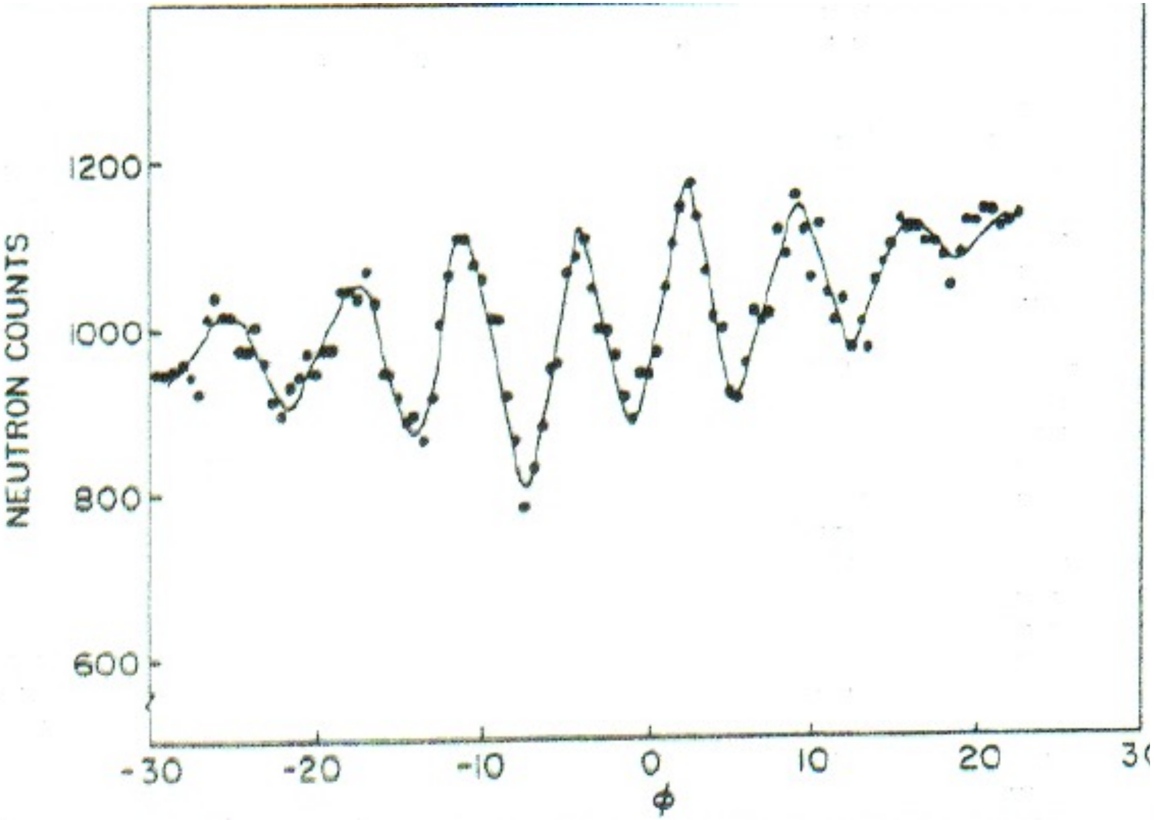
Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121

(Received 14 April 1975)



Also done by H. Rauch et al at Vienna

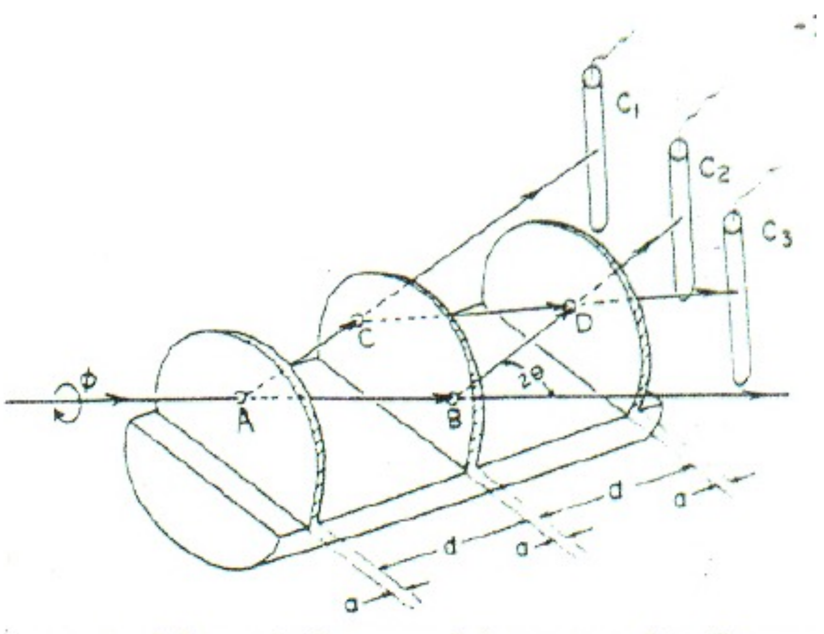
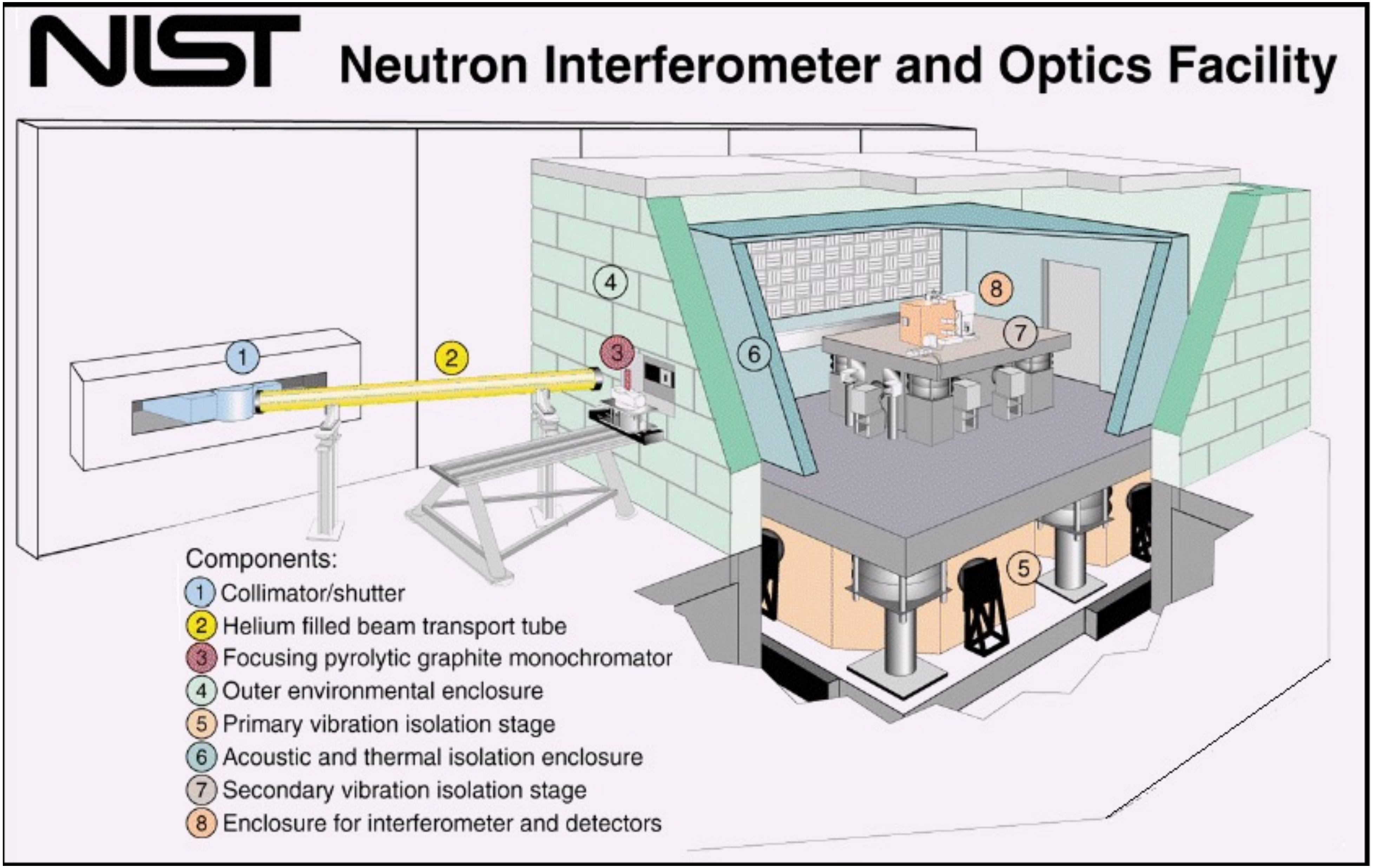


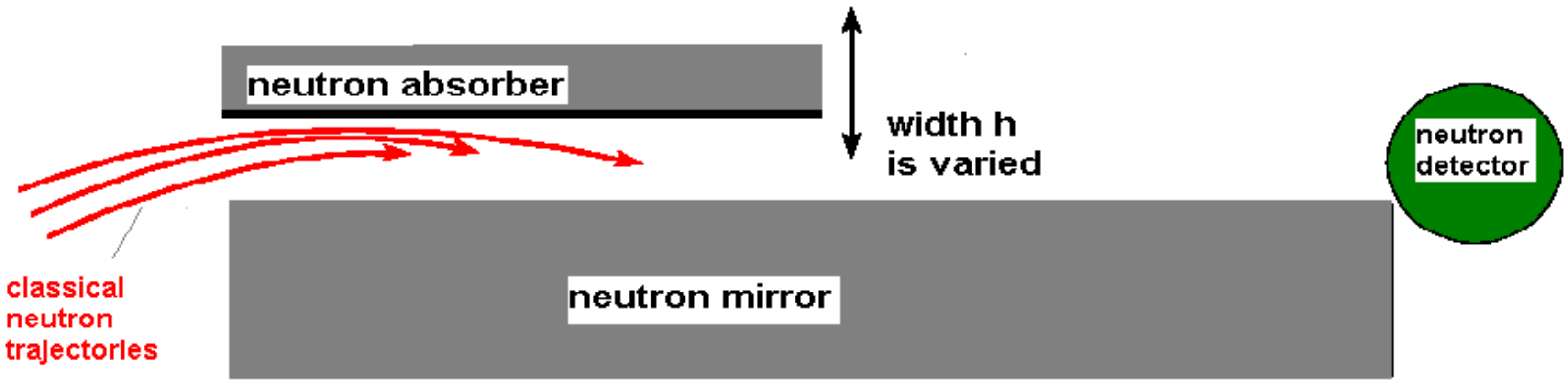
FIG. 1. Schematic diagram of the neutron interferometer and ³He detectors used in this experiment.

NIST Neutron Interferometry facility



Classical/QM Bouncing Neutrons

Classical View



neutron absorber

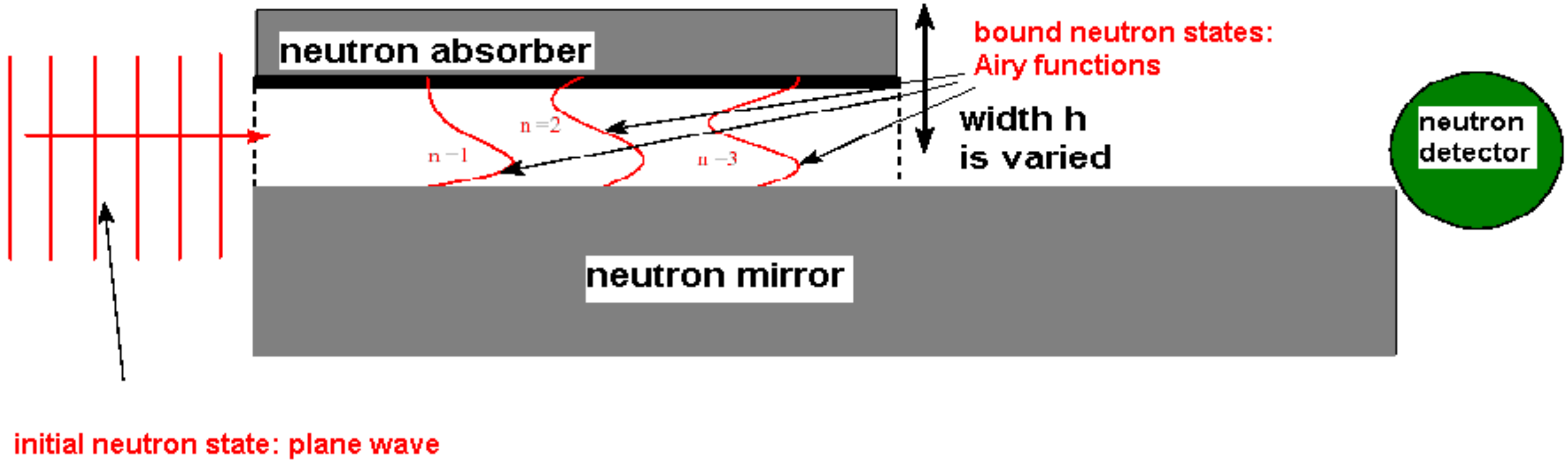
width h
is varied

neutron detector

classical
neutron
trajectories

neutron mirror

Quantum View



neutron absorber

bound neutron states:
Airy functions

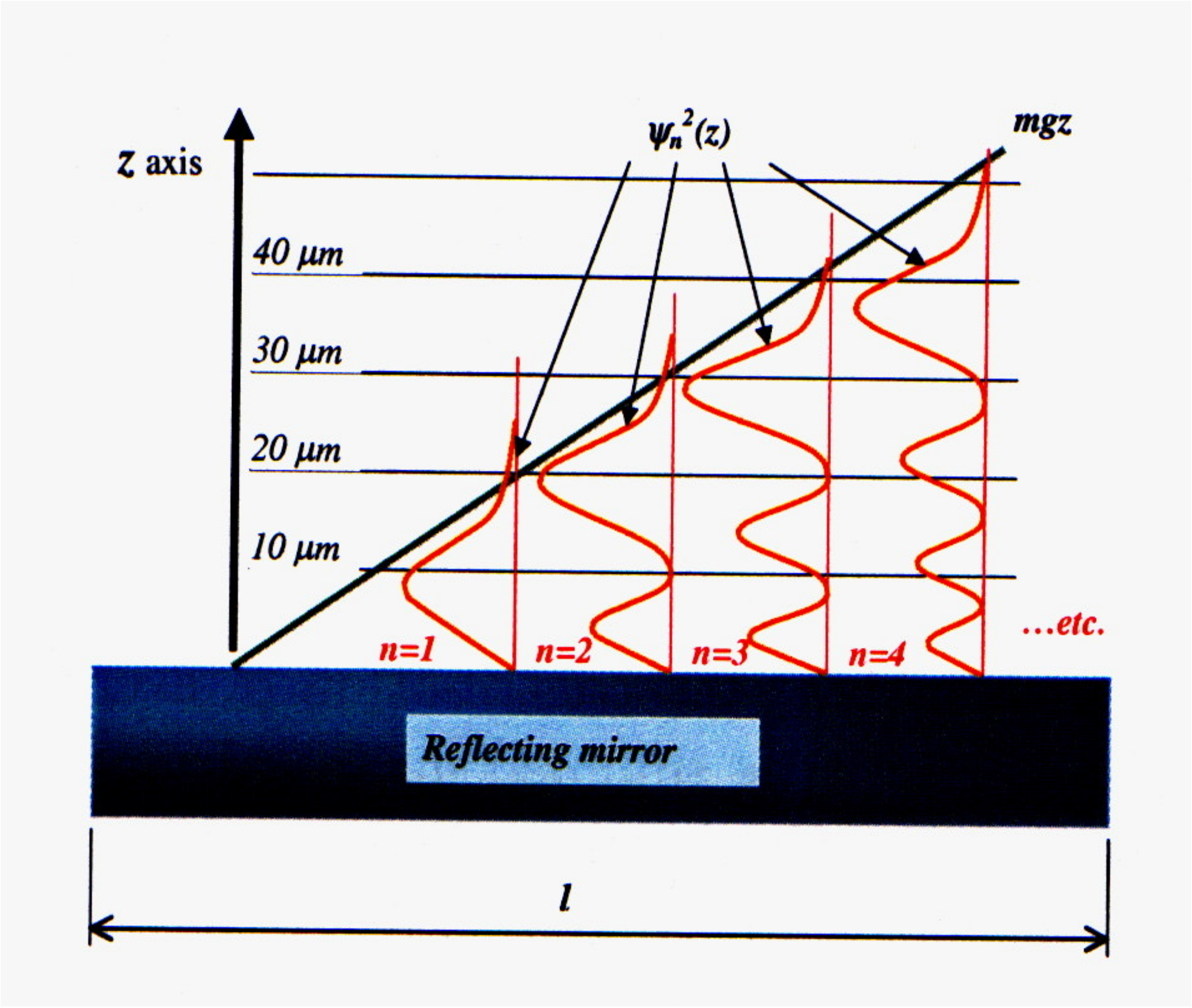
width h
is varied

neutron detector

neutron mirror

initial neutron state: plane wave

Neutron Probability Distributions Above the Mirror

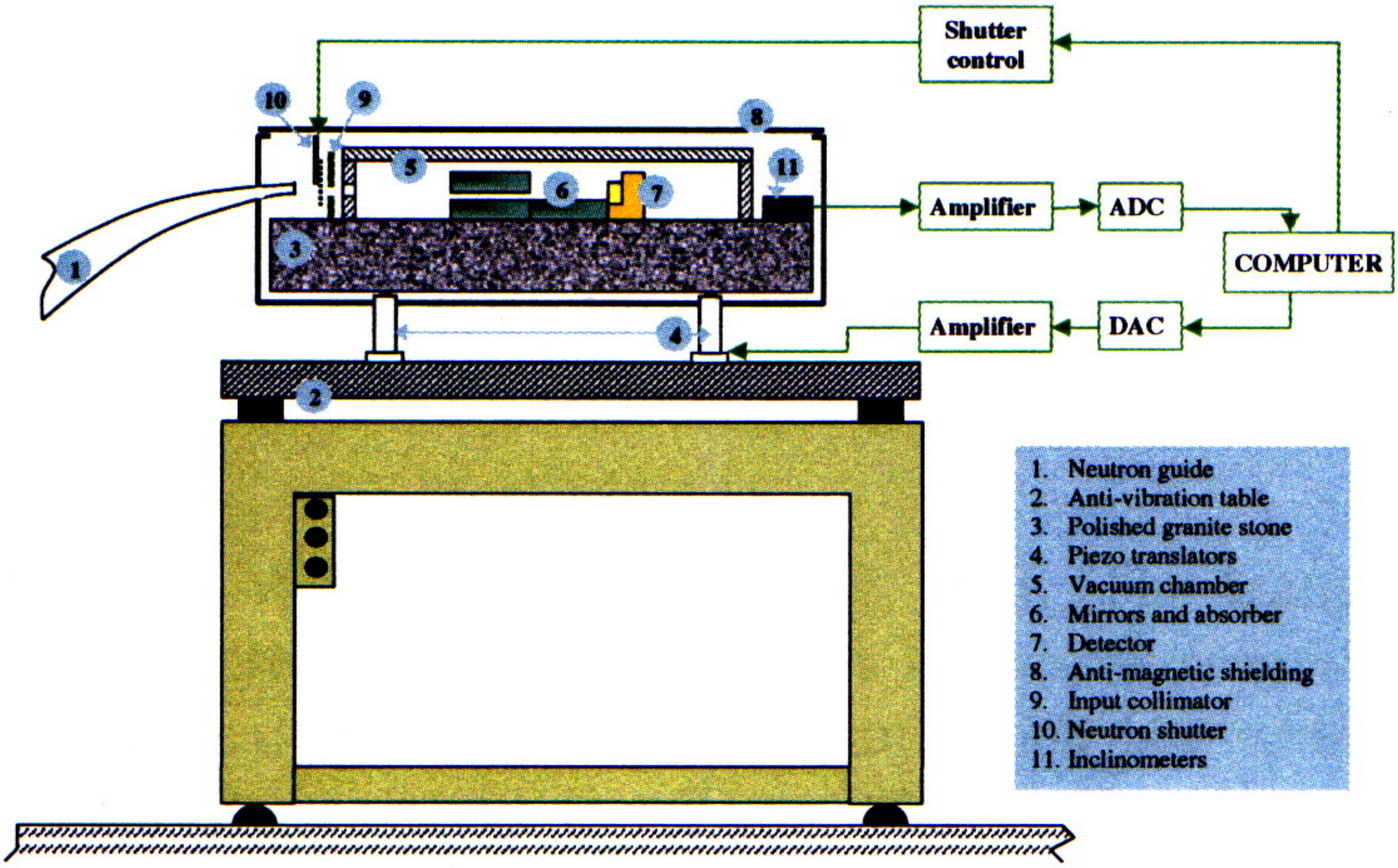


Combo. of reflection from mirror+gravity gives bound states

Linear potential V=mgz. Airy functions solve Schrodinger eqn.

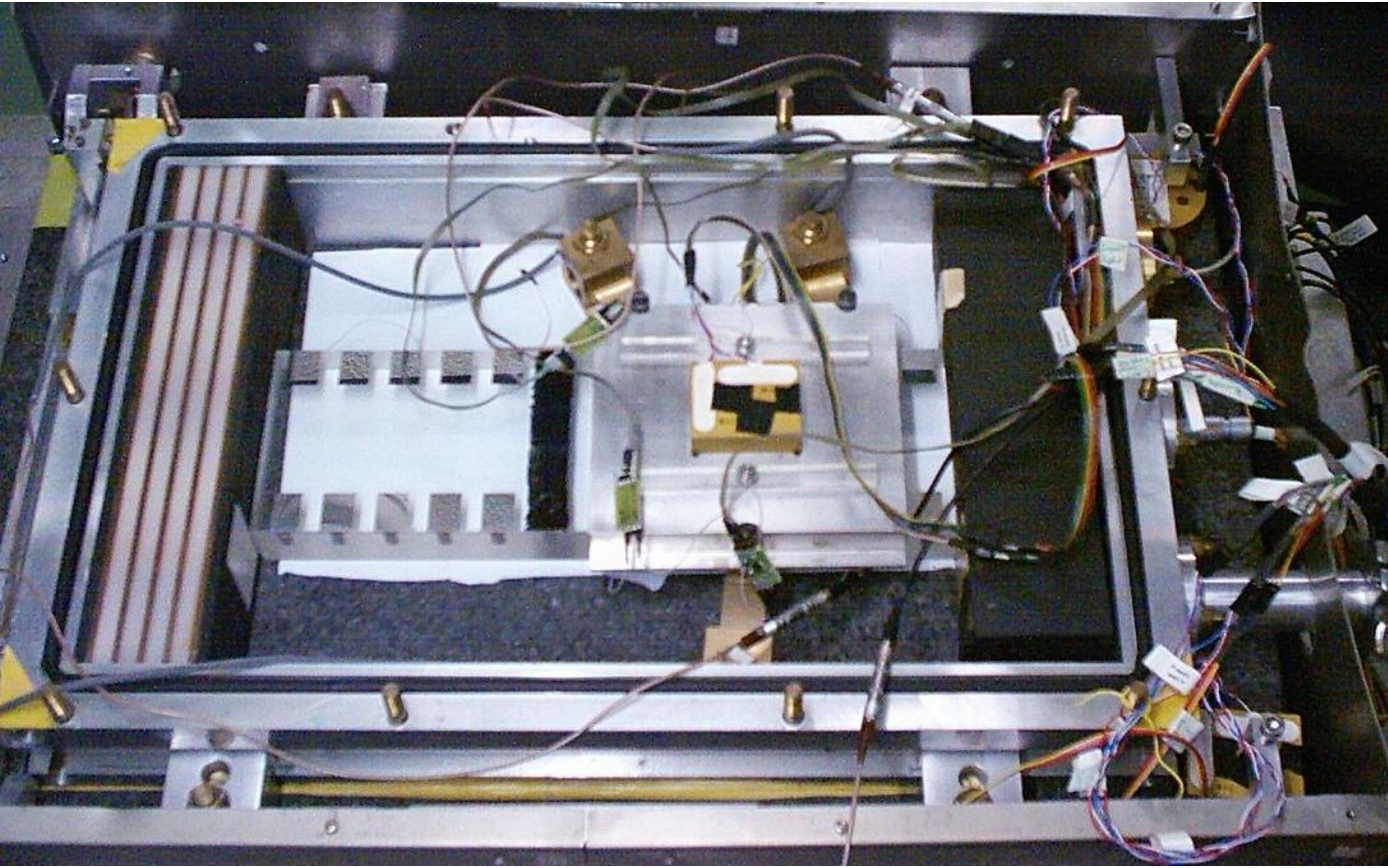
A quantum bouncing ball!

Experimental Apparatus

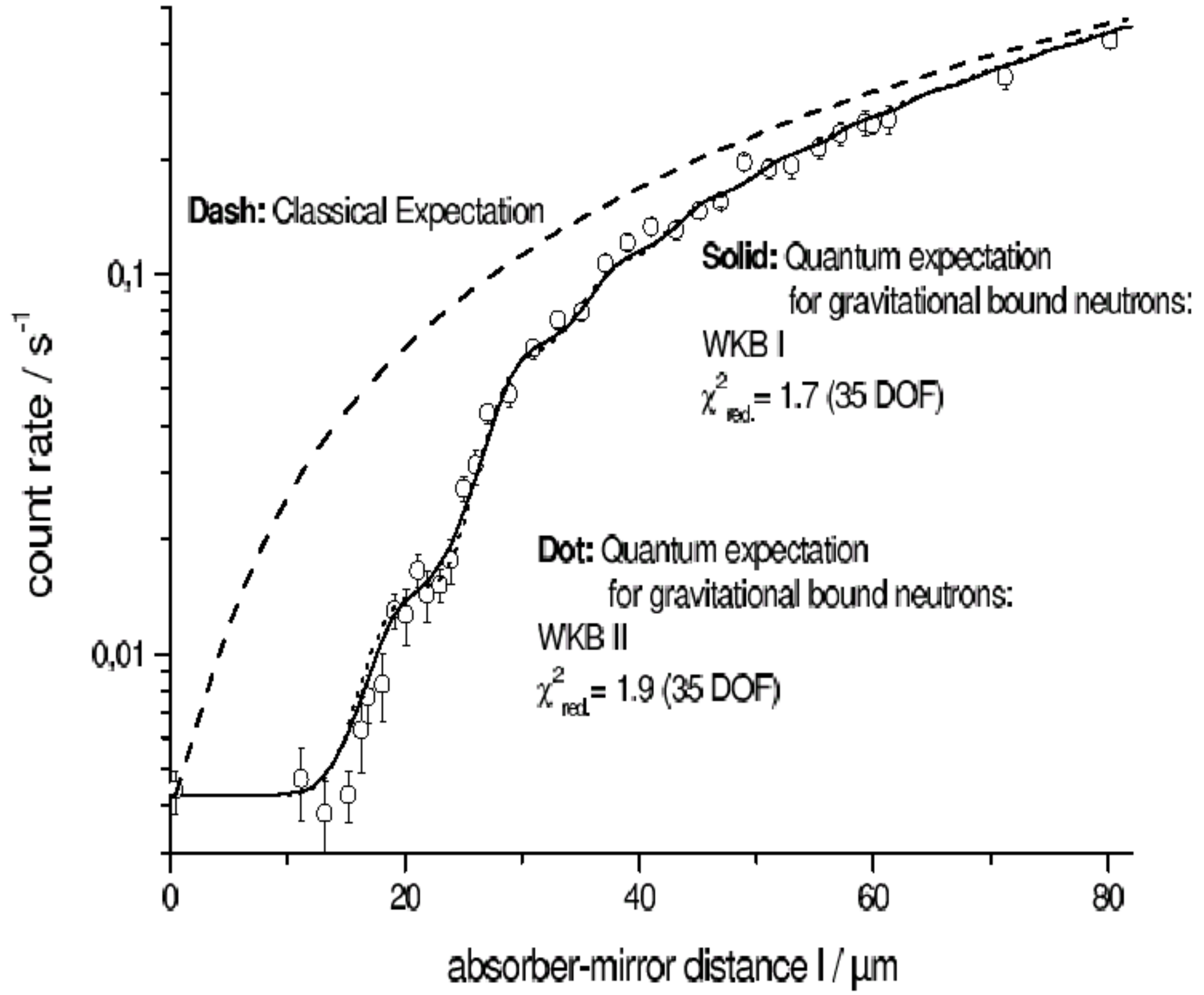


1. Neutron guide
2. Anti-vibration table
3. Polished granite stone
4. Piezo translators
5. Vacuum chamber
6. Mirrors and absorber
7. Detector
8. Anti-magnetic shielding
9. Input collimator
10. Neutron shutter
11. Inclinometers

the Experimental Apparatus: Top View



Observation/Comparison to Theory

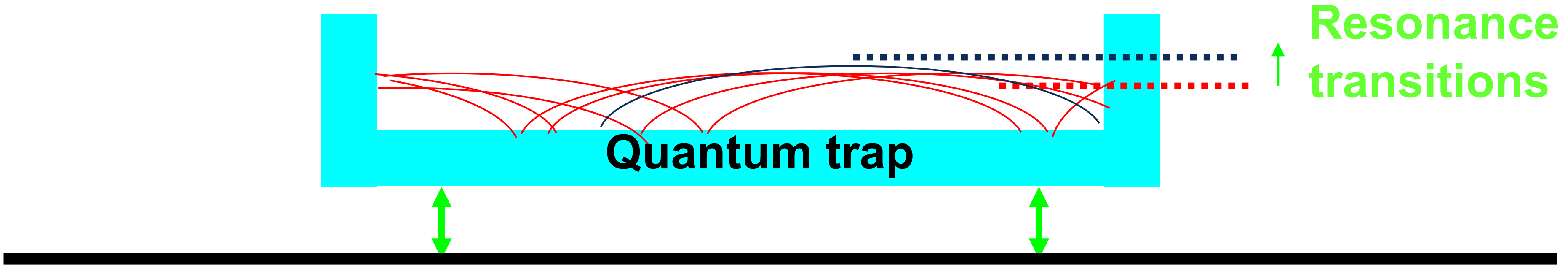


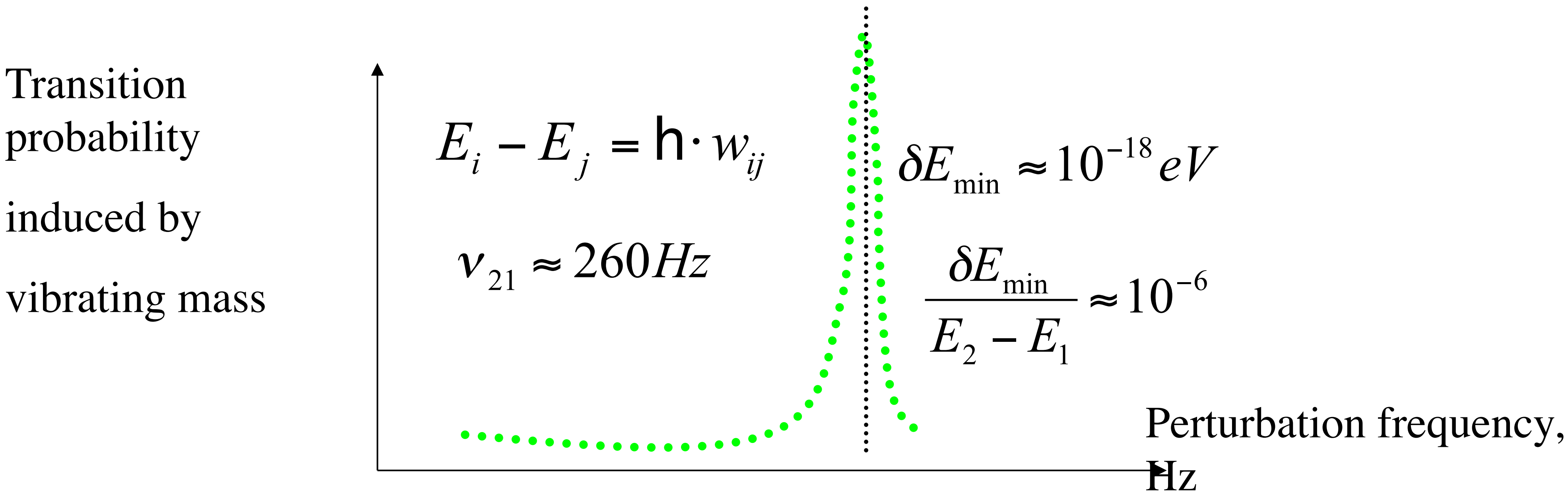
Applications in fundamental physics

- Search for extra fundamental forces at short distances of 1 nm - 10 µm

-Verification of electrical neutrality of neutrons

-Search for dark energy fields (chameleons, symmetrons,…)





$$E_i - E_j = h \cdot w_{ij}$$

$$\nu_{21} \approx 260 Hz$$

$$\delta E_{\min} \approx 10^{-18} eV$$

$$\frac{\delta E_{\min}}{E_2 - E_1} \approx 10^{-6}$$

V.V.Nesvizhevsky

Conclusions

Slow neutrons can address many interesting scientific questions in nuclear/particle/astrophysics and cosmology

Neutron decay: test of weak interaction theory, input for Big Bang nucleosynthesis

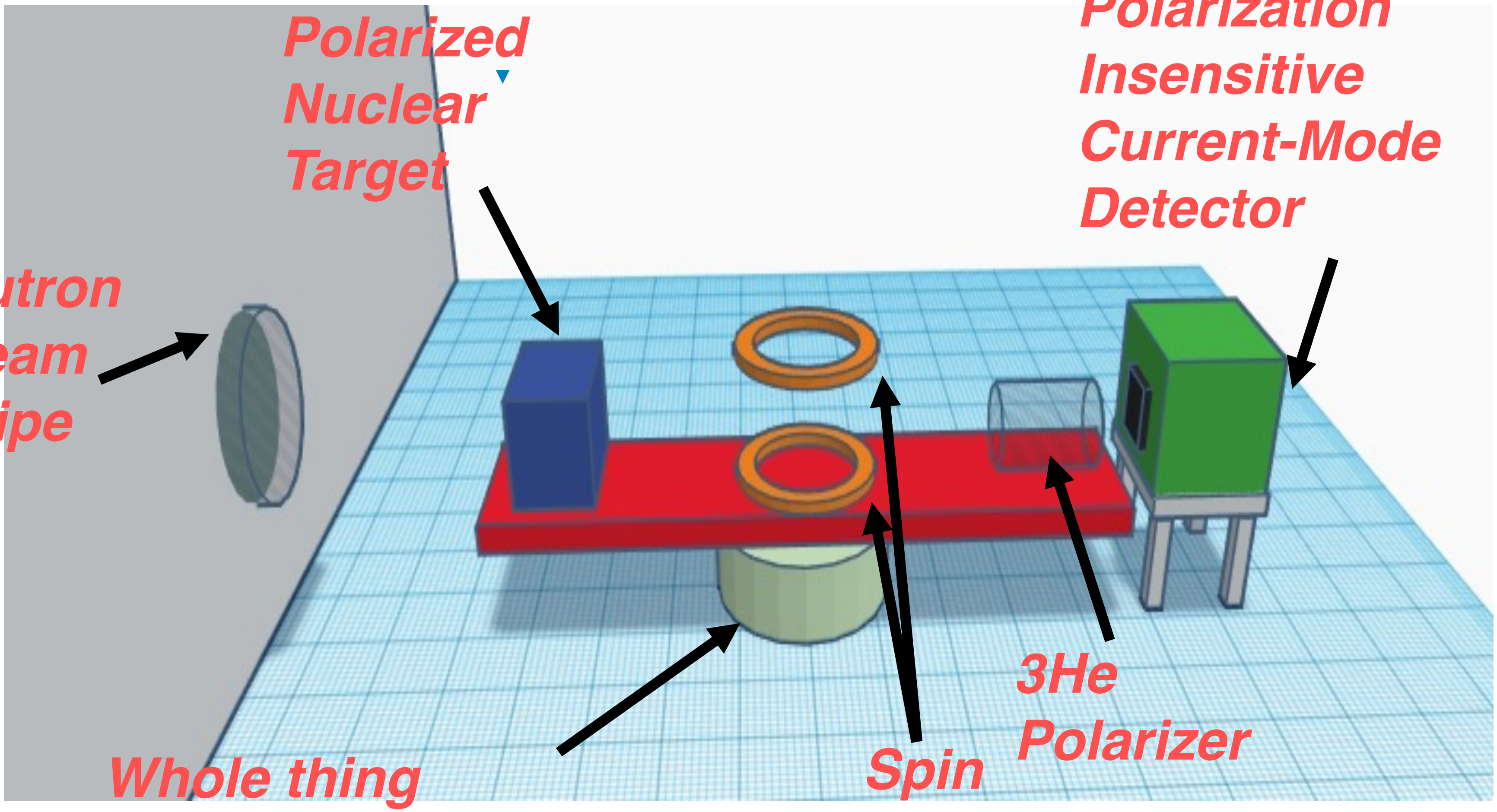
Neutron time reversal tests: search for new physics, could help explain the matter-antimatter asymmetry of the universe

Neutron/antineutron oscillations: sensitive search for baryon number violation

Neutron interferometry/gravity: shows that gravity produces quantum interference, search for dark energy fields,…

How Do We “Reverse Time”?

If we can experimentally reverse all of the vectors that are odd under the T transformation and reverse the initial and final states, this would be equivalent!



Polarized Nuclear Target

Polarization Insensitive Current-Mode Detector

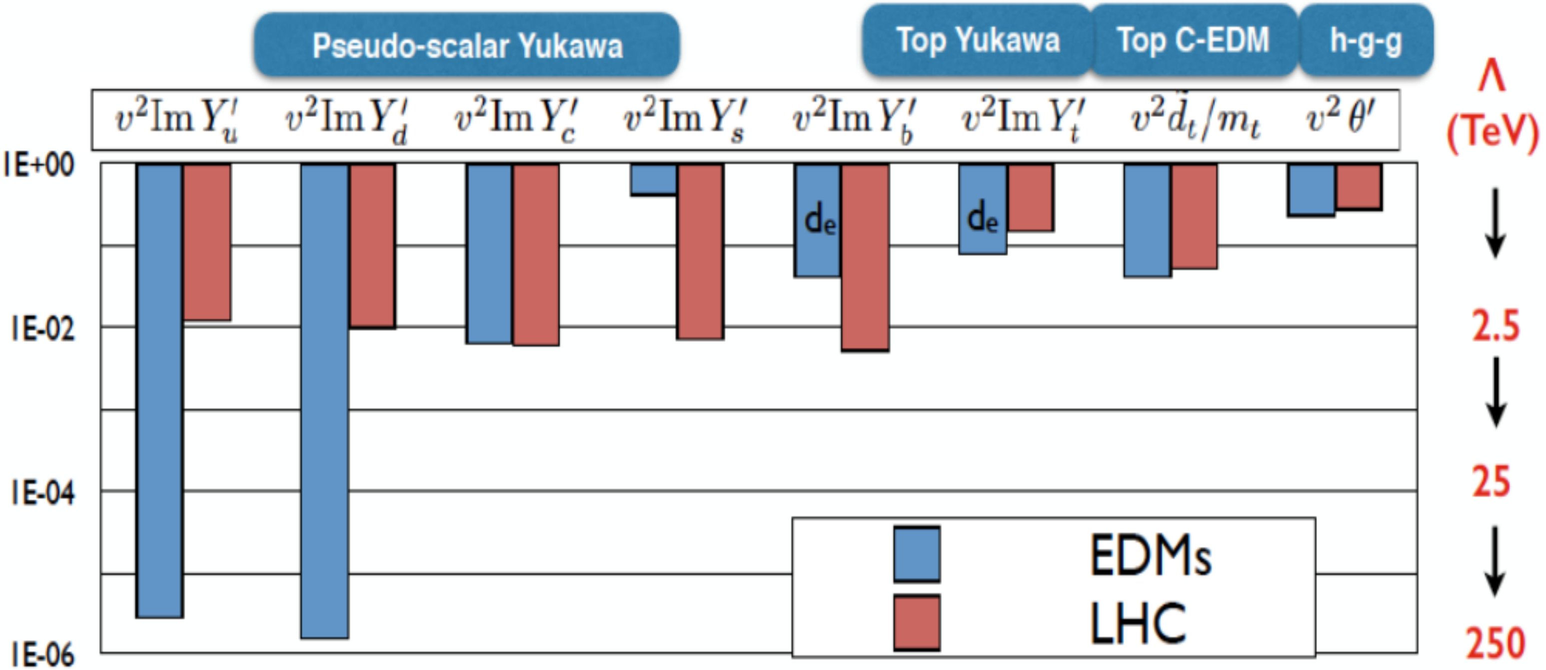
Neutron beam pipe

3He Polarizer

Whole thing mounted on a rotation stage

Spin Flipper Coils

CP/T Scientific reach: example

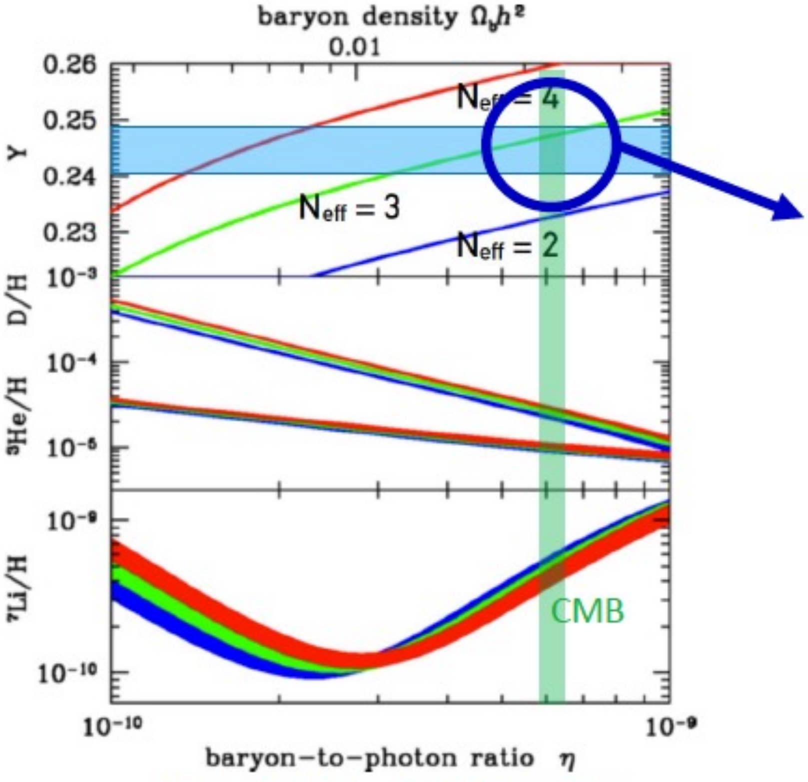


- Neutron EDM is teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

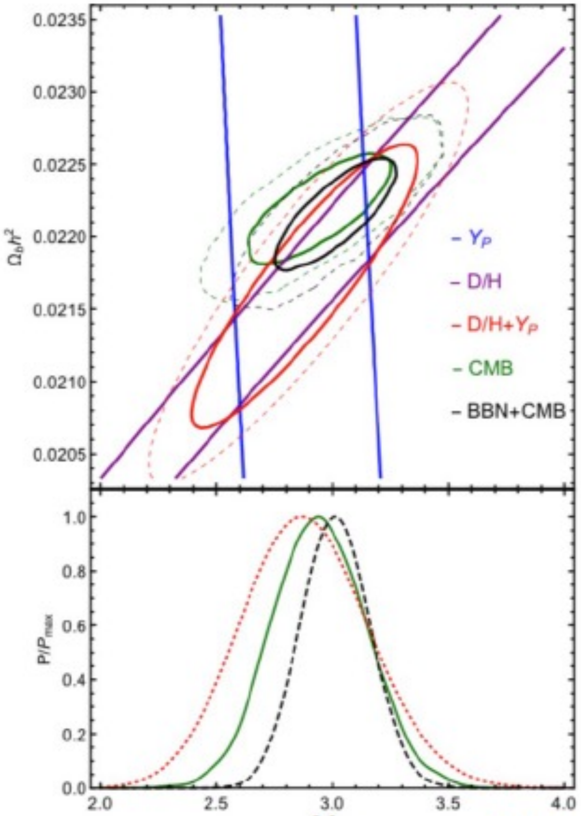
V. Cirigliano, talk at Grenoble workshop on Particle Physics at Neutron Sources PPNS-2018

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

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

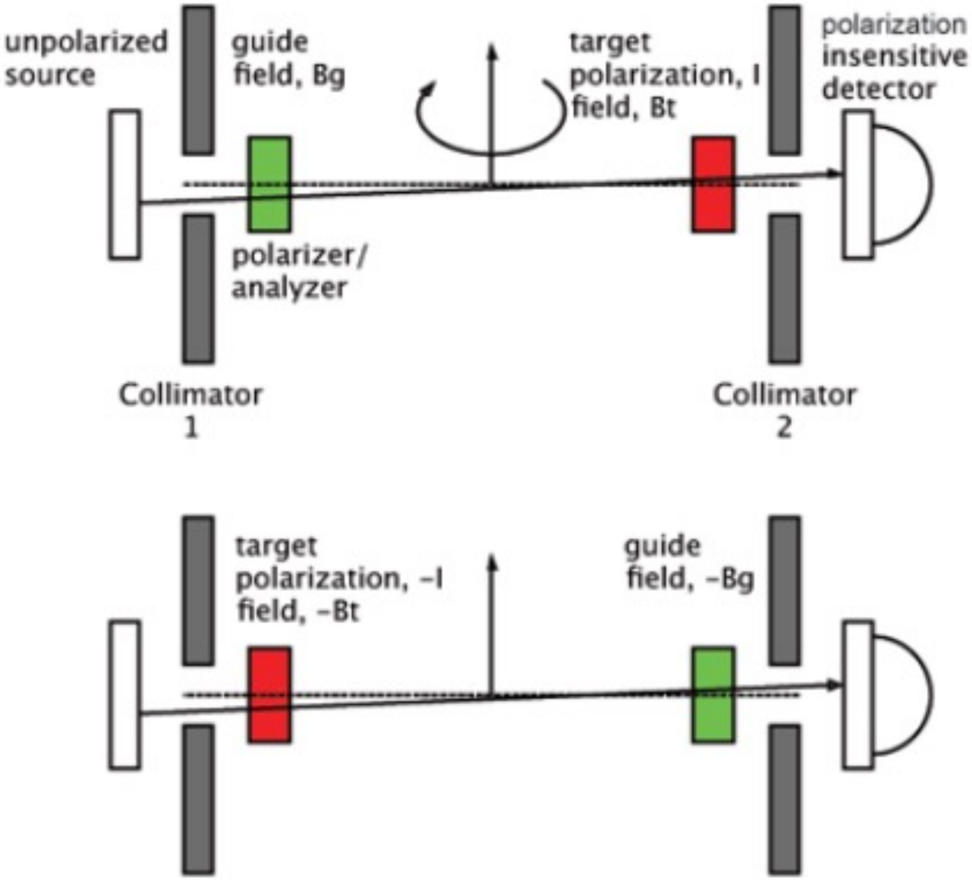


Rev. Mod. Phys. 88, 015004 (2016)



Physics Reports 754, 1-66 (2018)

EDITORS' SUGGESTION Phys. Rev. C (2015)
Search for time reversal invariance violation in neutron transmission
J. David Bowman and Vladimir Gudkov



The authors analyze a novel null test to search for time reversal invariance in a model neutron transmission experiment. The proposed experimental procedure involves nuclear reactions and is sensitive to the neutron-nucleus interactions. The approach could significantly increase the discovery potential compared to the limits of present experiments.

Classical Theory of Weak Decay

Standard Model for neutron decay:

$$H = \frac{G_F}{\sqrt{2}} V_{ud} \quad \bar{p}\left\{\gamma_\mu\left(1+\lambda\gamma_5\right)+\frac{\mu_p-\mu_n}{2m_p}\sigma_{\mu\nu}q^\nu\right\}n \quad \bar{e}\gamma^\mu\left(1-\gamma_5\right)\nu_e$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = U_{CKM}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

Unitarity of CKM matrix

Expression for neutron lifetime in Standard Model

$$\tau^{-1} = V_{ud}^2 G_F^2 (1+3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$