Pedestrian neutrons

tool and object for fundamental physics

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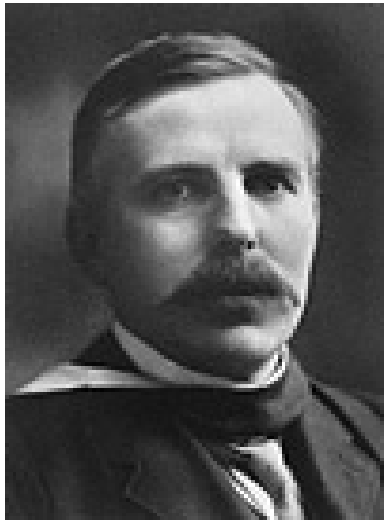
Pisa, 24 July 2019

Topics

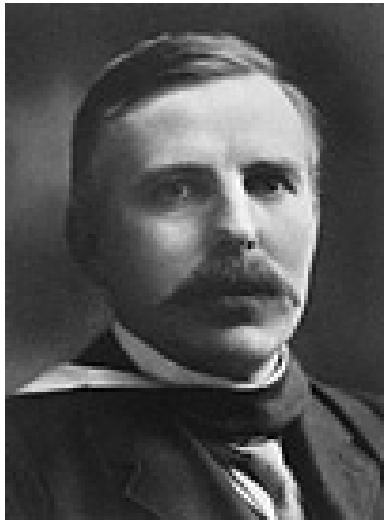
- The impossible particle and how to catch it
- Search for an electric dipole moment of the neutron
- Short-range gravity
- Production of pedestrian neutrons at ILL
- Neutron lifetime
- How to produce more ultracold neutrons?

… and Godfather created the neutron

… and Godfather created the neutron

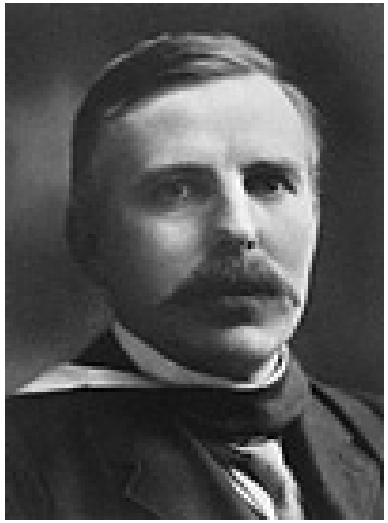


… and Godfather created the neutron



"Such an atom would posses striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and ..."

… and Godfather created the neutron



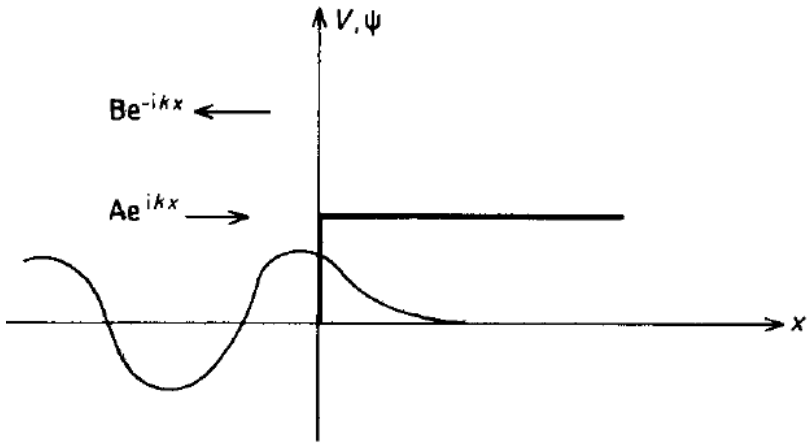
"Such an atom would posses striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and it could not be stored in a closed vessel."

(„Nuclear Constitution of Atoms", Proc. Royal Soc. 1920)

How to store it nevertheless?

Trapping potential #1:

<u>neutron optical potential</u> ***V + iW***



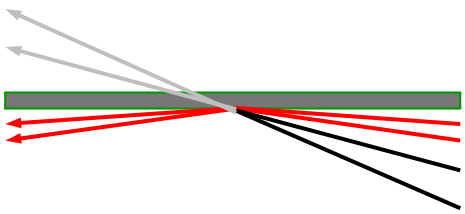
Physical origin:

Interference of incident plane wave with spherically scattered waves in forward direction

$$n = \frac{k'}{k} = \sqrt{1 - \frac{V}{E}}$$

$$V = \frac{2\pi\hbar^2}{m} N a$$

Neutron guides:



Mirror reflection under any angle of incidence

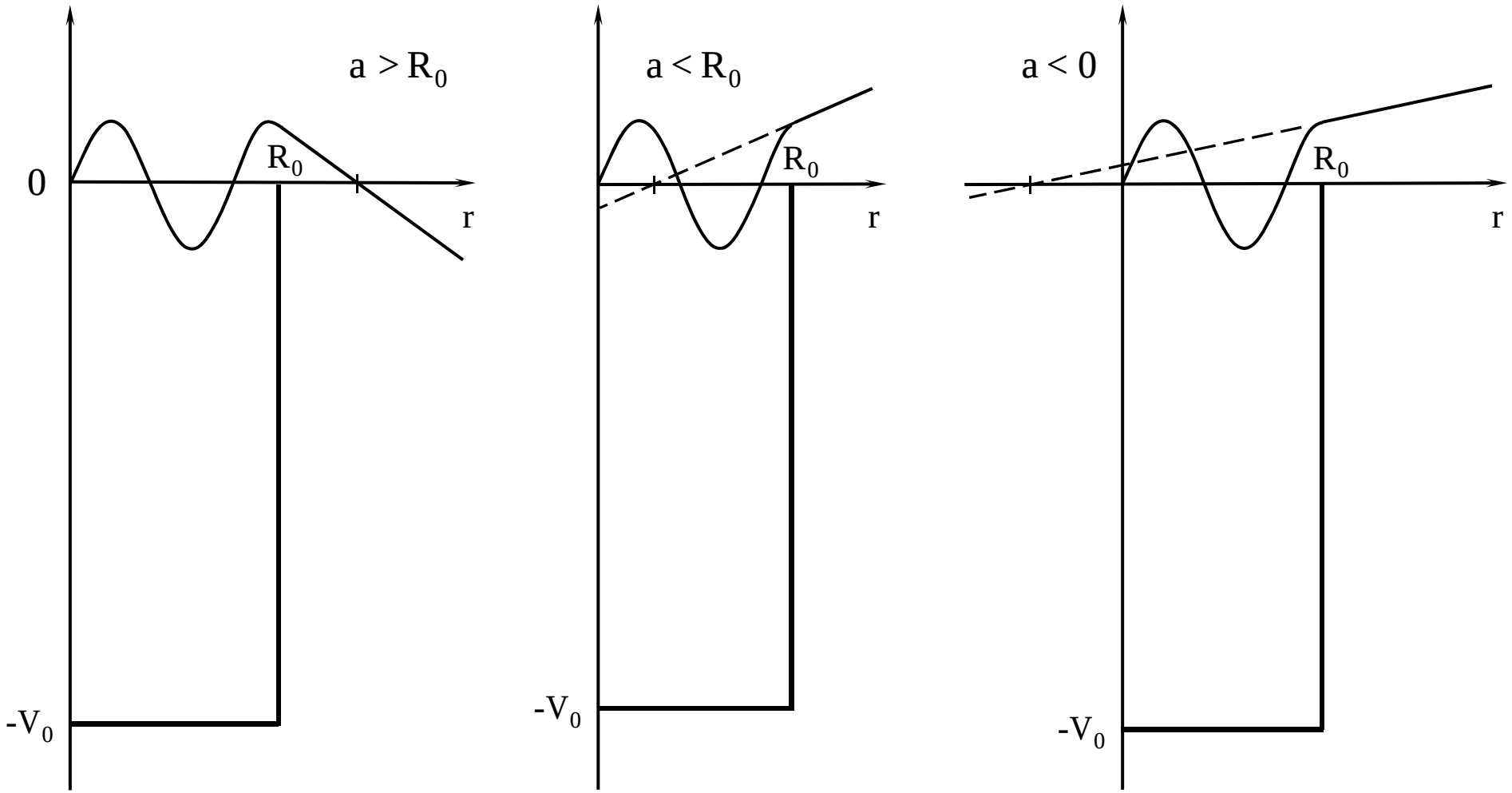
→ ***"UltraCold Neutrons" can be trapped in "neutron bottles"***

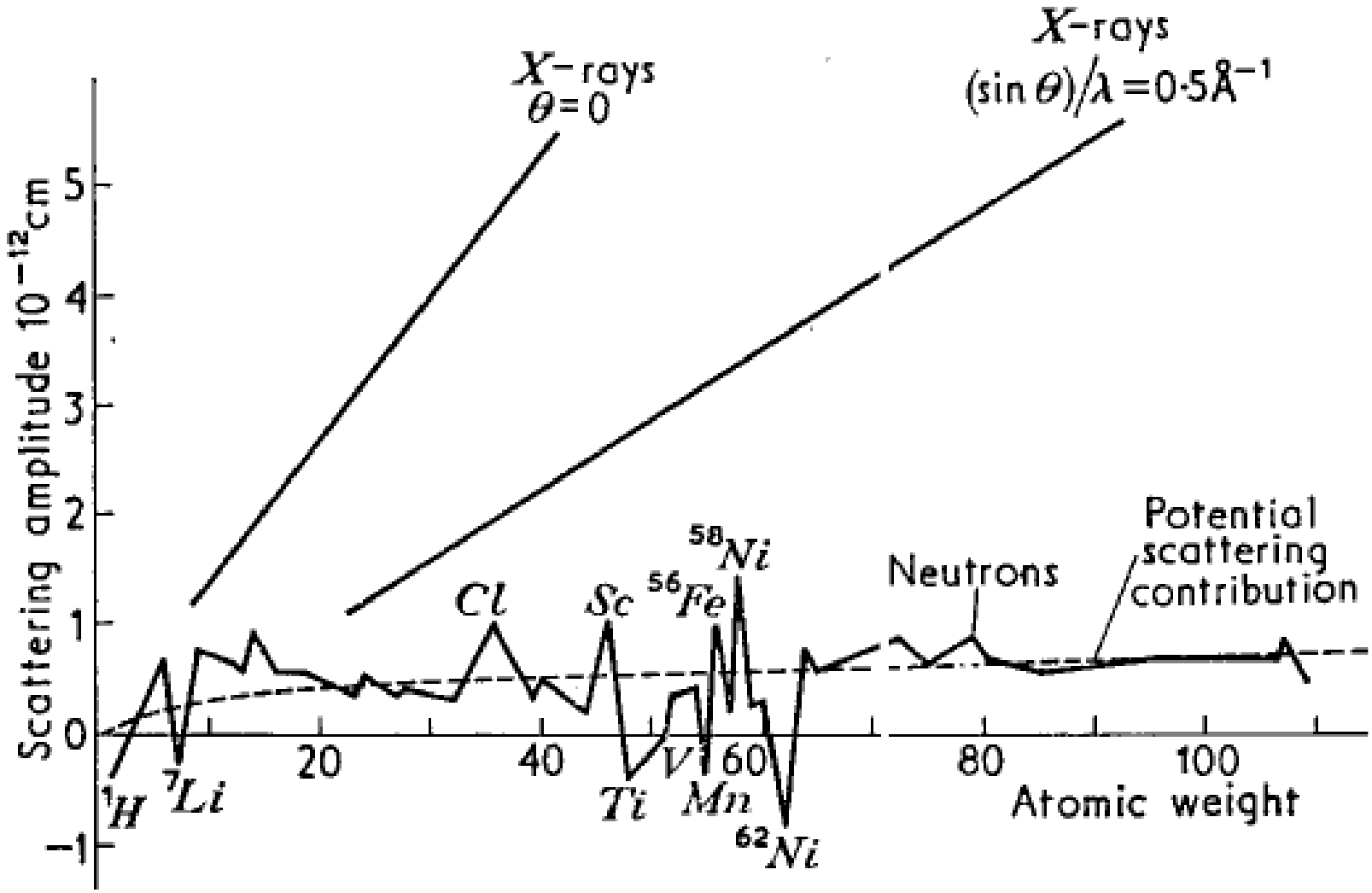
UCN properties of selected materials

Material	N [10^{22} cm^{-3}]	V [neV]	σ_{loss} [barn] *at* 1.8 Å	W/V $\times 10^{-5}$
^{58}Ni	9.0	335	4.4	8.6
BeO	7.25	261	0.66	1.35
Be	12.3	252	0.14	0.5
Al	6.02	54	0.28	2.25
Ti	5.6	-48	5.8	

Low-energy neutron scattering:

only s-waves: $f(\Omega) \rightarrow$ scattering length, i.e., a (complex) number

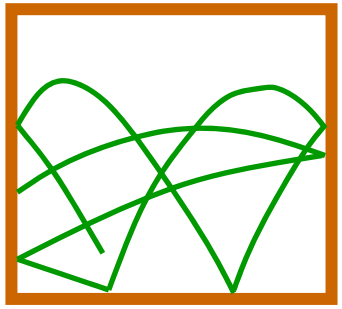



X-rays
θ=0
X-rays
(sin θ)/λ=0·5Å⁻¹
Scattering amplitude 10⁻¹²cm
5
4
3
2
1
0
−1
20
40
60
80
100
Atomic weight
Potential scattering contribution
Neutrons
¹H
⁷Li
Cl
Sc
Ti
V
⁵⁶Fe
Mn
⁵⁸Ni
⁶²Ni

Trapping potential #2:

<u>neutron gravity</u> ***mgz***

for Δz = 1 m: ΔE = 100 neV



Trapping potential #2:

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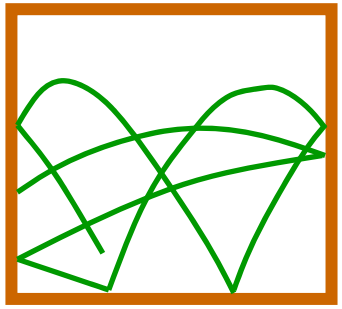
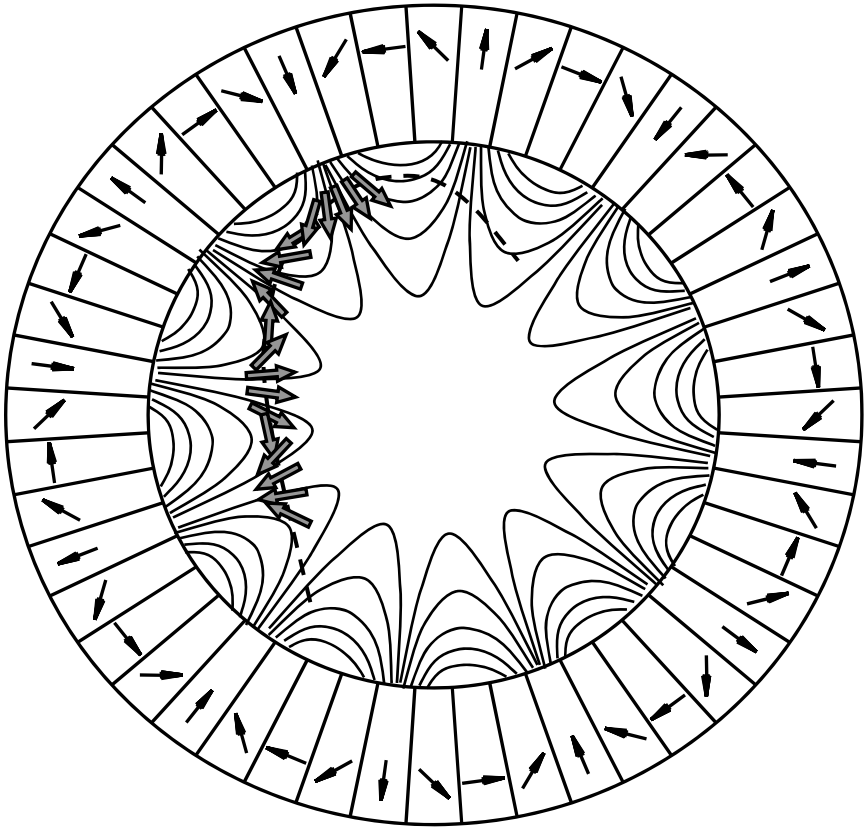


as good for trapping
(if bottle is tall enough):

Trapping potential #3:

magnetic interaction $\pm\mu B$

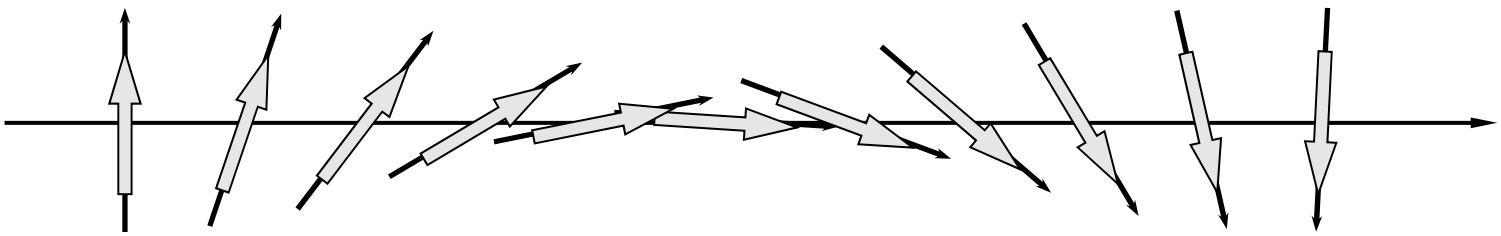


for ΔB = 1 T: ΔE = ± 60 neV

Adiabatic spin transport if

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

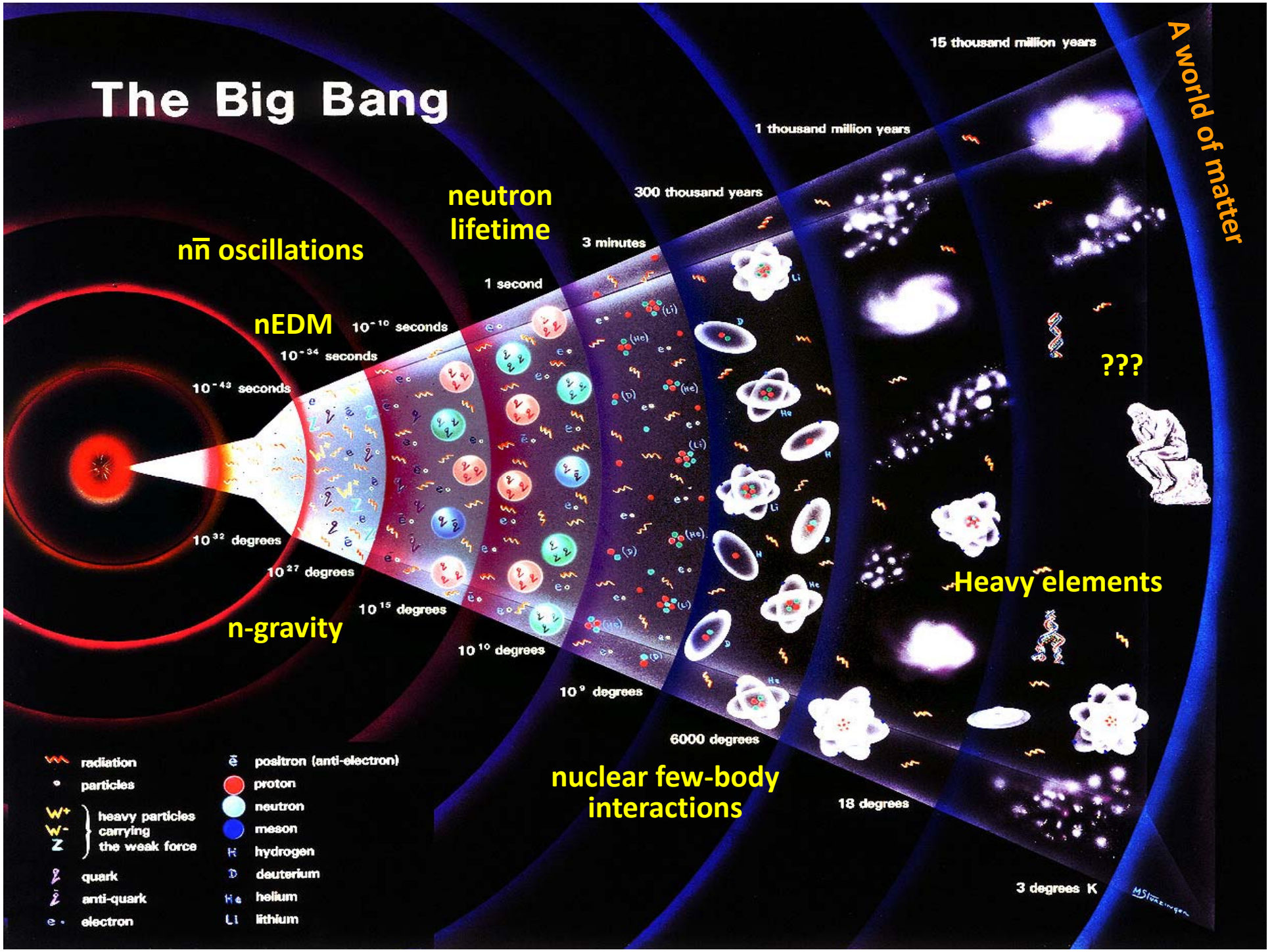
→ mT fields sufficient in typical situations



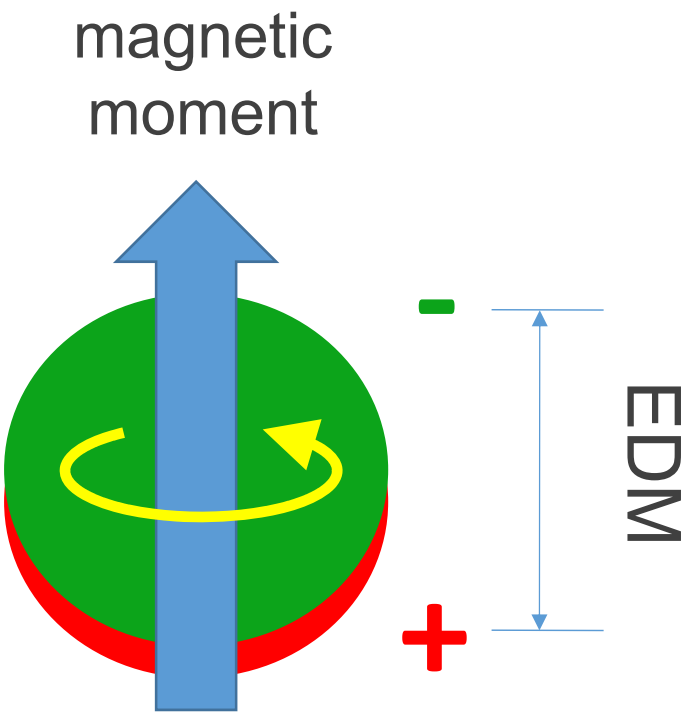
Magnetic gradient fields suppress losses due to wall collisions

Neutron properties (studied with cold and ultracold neutrons):

Property	Symbol	Value
Spin^{Parity}	s^P	$\frac{1}{2}^+$
Mass (relative to ^{12}C mass standard)	m_{n}	1.008 664 915 8(6) u
Mass (absolute units)		939.565 33(4) MeV c^{-2}
Neutron - proton mass difference	$m_{\mathrm{n}} - m_{\mathrm{p}}$	0.001 388 448 9(6) u
		1.293 331 8(5) MeV c^{-2}
Charge	q_{n}	$(-0.4 \pm 1.1) \times 10^{-21}\, e$
Mean-square charge radius	$\langle r_{\mathrm{n}}^2 \rangle$	$-0.116\,1(22)$ fm^2
Electric polarisability	α_{n}	$(9.8^{+1.9}_{-2.3}) \times 10^{-4}$ fm^3
Magnetic moment	μ_{n}	$-1.913\,042\,7(5)\ \mu_N$
		$= -6.030\,773\,8(15) \times 10^{-8}$ eV T^{-1}
Electric dipole moment	d_{n}	$< 2.9 \times 10^{-26}\ e\,\mathrm{cm}$ (90% c.l.)
Mean n$\overline{\mathrm{n}}$-oscillation time of free neutron	$\tau_{\mathrm{n}\overline{\mathrm{n}}}$	$> 8.6 \times 10^7$ s (90% c.l.)
... of bound neutron		$> 1.2 \times 10^8$ s (90% c.l.)
Parameters of β-decay, $\mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \overline{\nu}_{\mathrm{e}}$		
Q-value	Q	0.782 332 9(5) MeV c^{-2}
Mean life time	τ_{n}	885.7(8) s
Ratio of weak coupling constants $g_{\mathrm{A}}/g_{\mathrm{V}}$	λ	$-1.2670\,(30)$
Coefficients of angular correlations:		
neutron spin - electron momentum: $P_{\mathrm{n}} \cdot p_{\mathrm{e}}$	A	$-0.1162\,(13)$
momenta of antineutrino and electron: $p_\nu \cdot p_{\mathrm{e}}$	a	$-0.102\,(5)$
neutron spin - antineutrino momentum	B	$0.983\,(4)$
triple correlation $P_{\mathrm{n}} \cdot (p_{\mathrm{e}} \times p_\nu)$	D	$-0.6\,(10) \times 10^{-3}$
Phase angle between V and A weak currents	ϕ_{VA}	$-180.08\,(10)^0$


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
A world of matter
$n\bar{n}$ oscillations
nEDM
n-gravity
neutron lifetime
nuclear few-body interactions
Heavy elements
???
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e- electron
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

Search for an electric dipole moment of the neutron



Statements well before Lee and Yang 1956 paper:

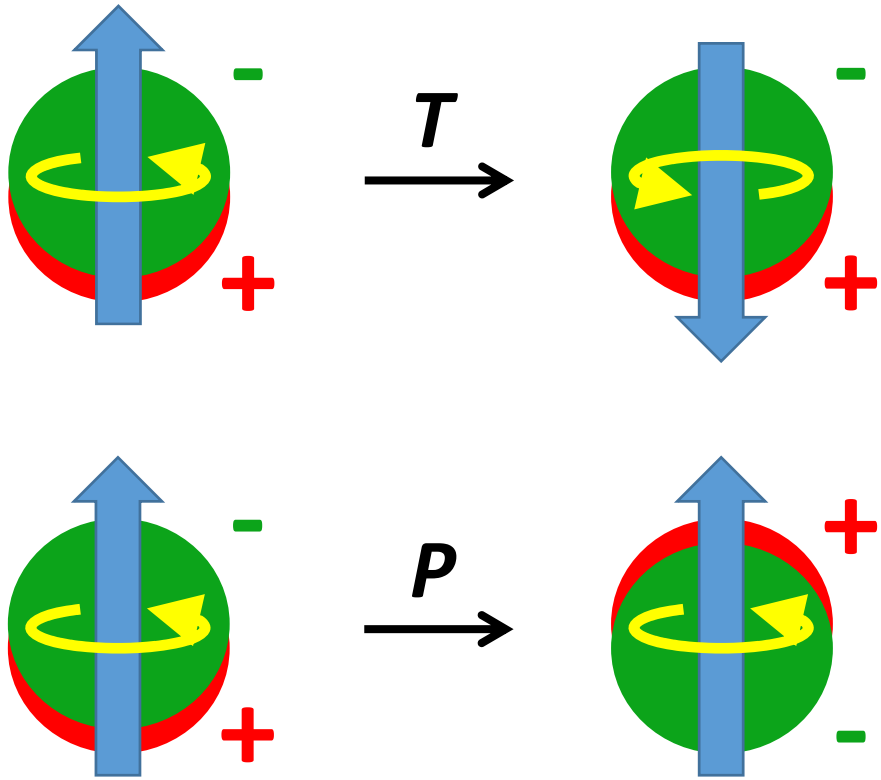
Dirac, Rev. Mod. Phys. 21 (1949) 329:

I donot believe there is any need for physical laws to be invariant under reflections in space and time, although the exact laws of nature so far known have this invariance

Purcell & Ramsey, Phys. Rev. 78 (1950) 807:

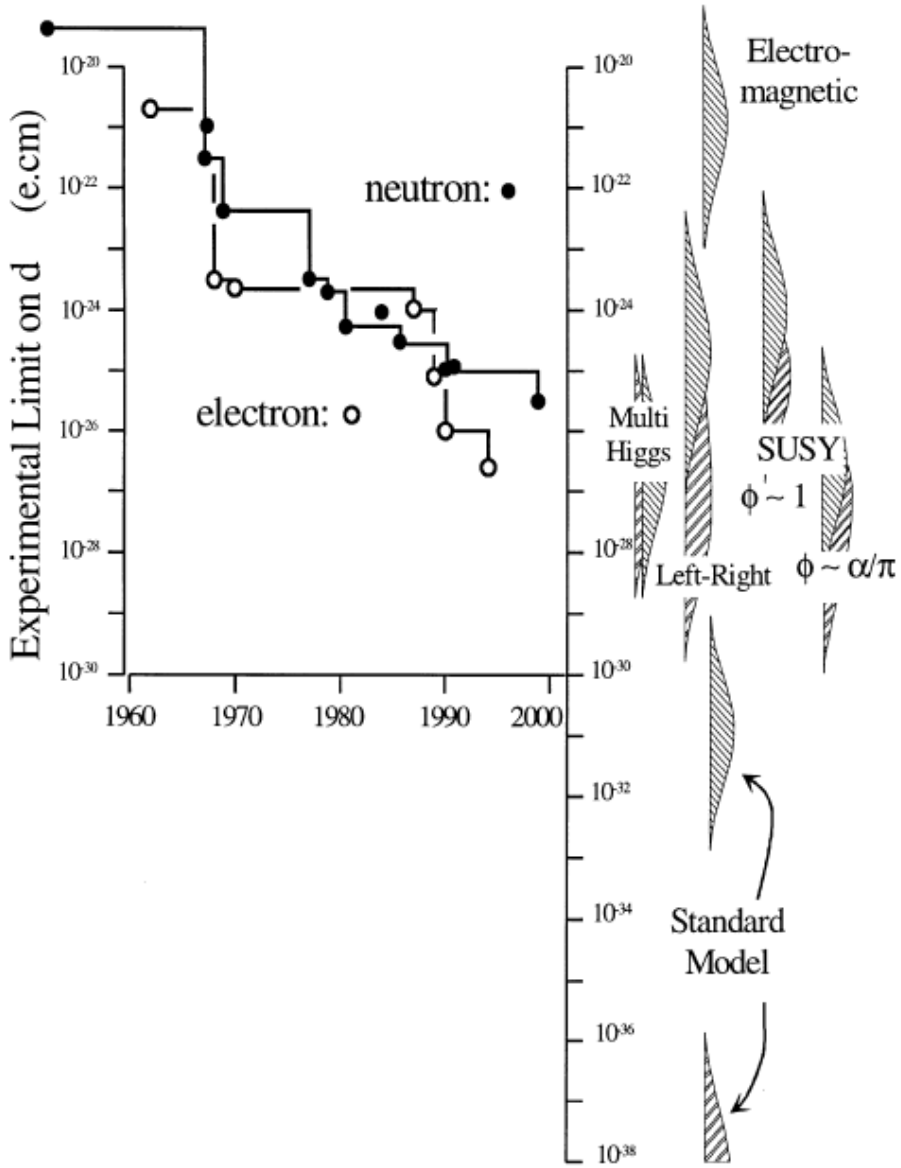
The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle
... becomes a purely experimental matter.

EDM violates fundamental symmetries

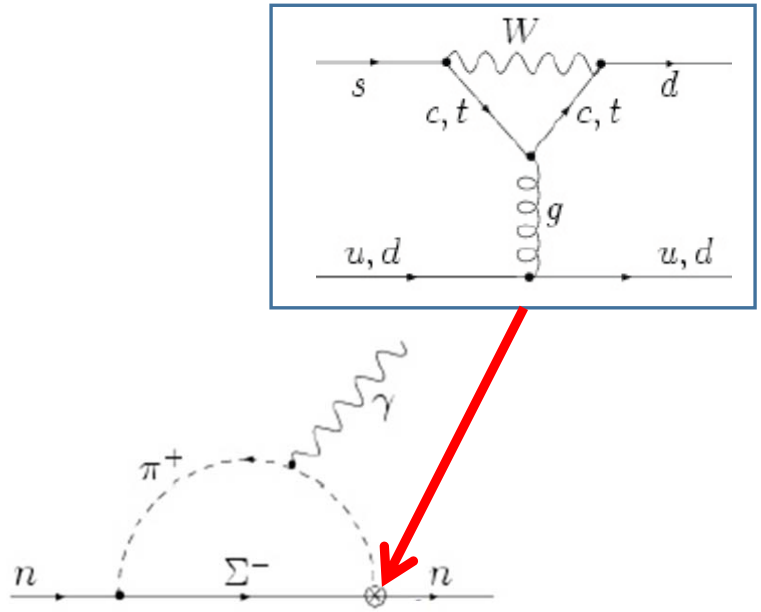


$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

- A non-zero particle EDM violates *T* (time reversal symmetry) and parity *P*
- If we assume *CPT* conservation, also *CP* is violated, which is needed to explain the matter/antimatter asymmetry in the Universe (Sakharov criteria)



Pendlebury and Hinds, NIM A 440 (2000) 471



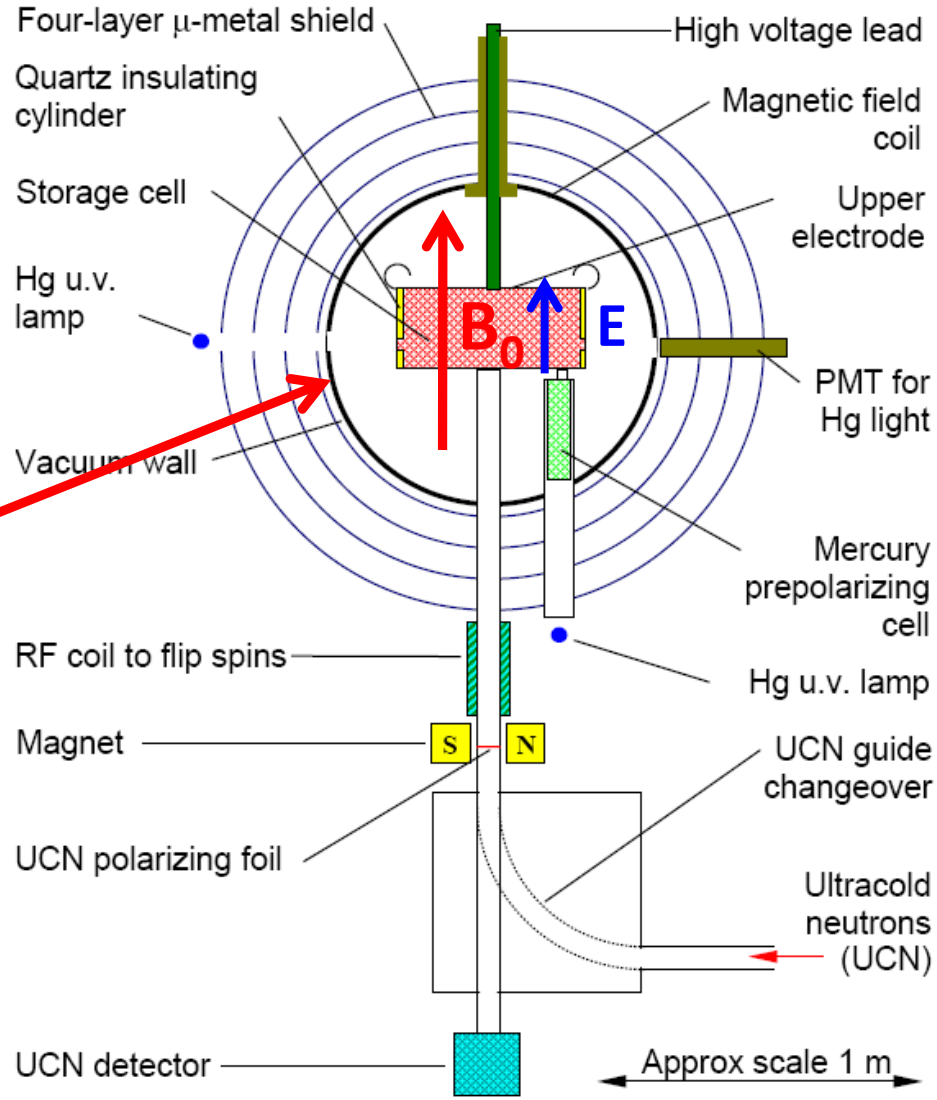
- *CP* violation within the Standard Model (SM) is too weak to explain the matter/antimatter asymmetry in the Universe
- nEDM tiny in the SM (10^{-31} ecm), but large in many beyond-SM theories
- nEDM sensitive probe to search new fundamental forces

How is it measured?

Ultra-cold neutrons (UCN) trapped in an evacuated vessel at room temperature

~ 0.5 m

RAL/SUSSEX/ILL experiment:

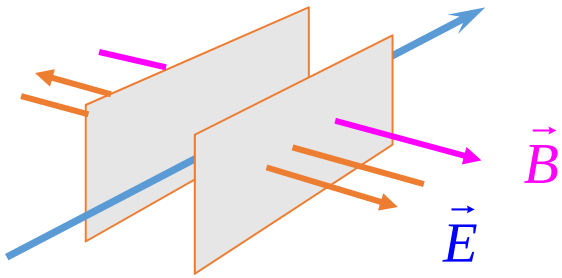


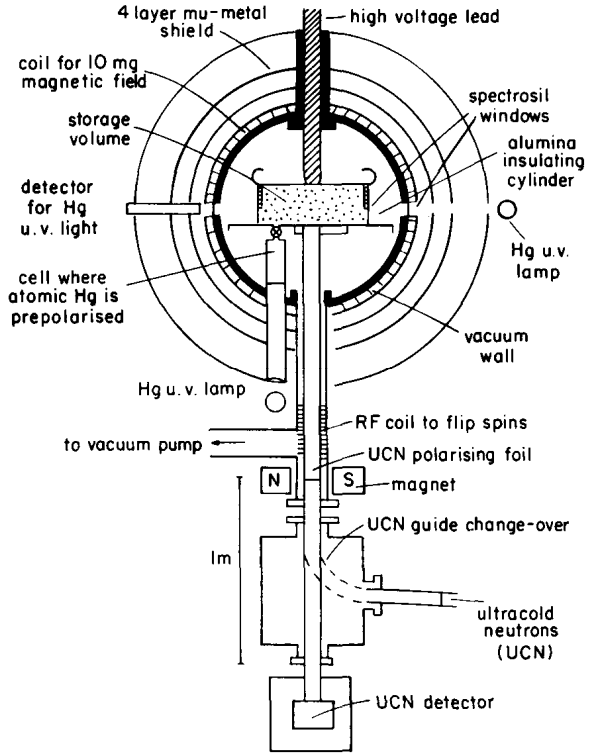
Baker et al., PRL **63** (2006) 131801

Better do in-beam or storage experiment?

Experimental sensitivity:

$$\sigma(d_n) = \frac{h}{4\pi\alpha E T \sqrt{N}}$$





T small ($\cong$ 10 ms)
N large (a few 10^8 s^{-1})

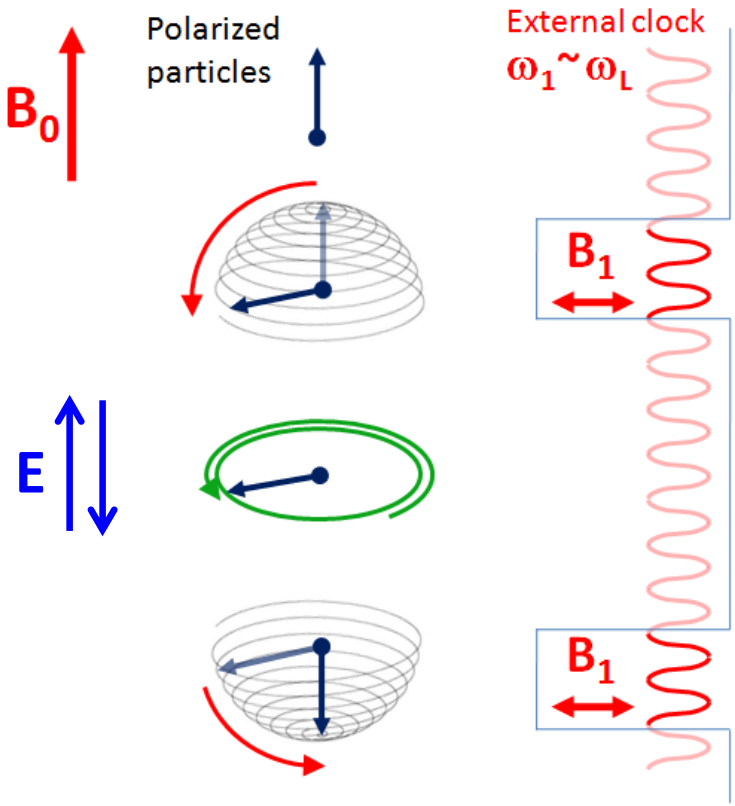
$v \cong$ a few 100 ms^{-1}
$\Rightarrow$ large $\vec{v} \times \vec{E}$ effect

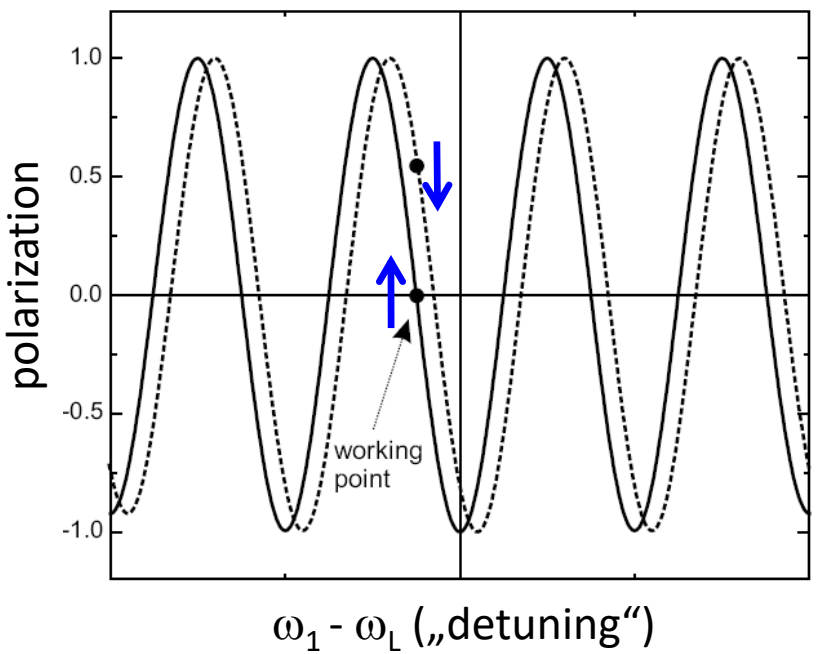
T large ($\cong$ 150 s)
N small ($\cong 10^4$ per filling)

$v \leq 5$ ms^{-1}
$\Rightarrow$ small $\vec{v} \times \vec{E}$ effect

Ramsey's method

Particle beam or trapped particles
(...spin echo)



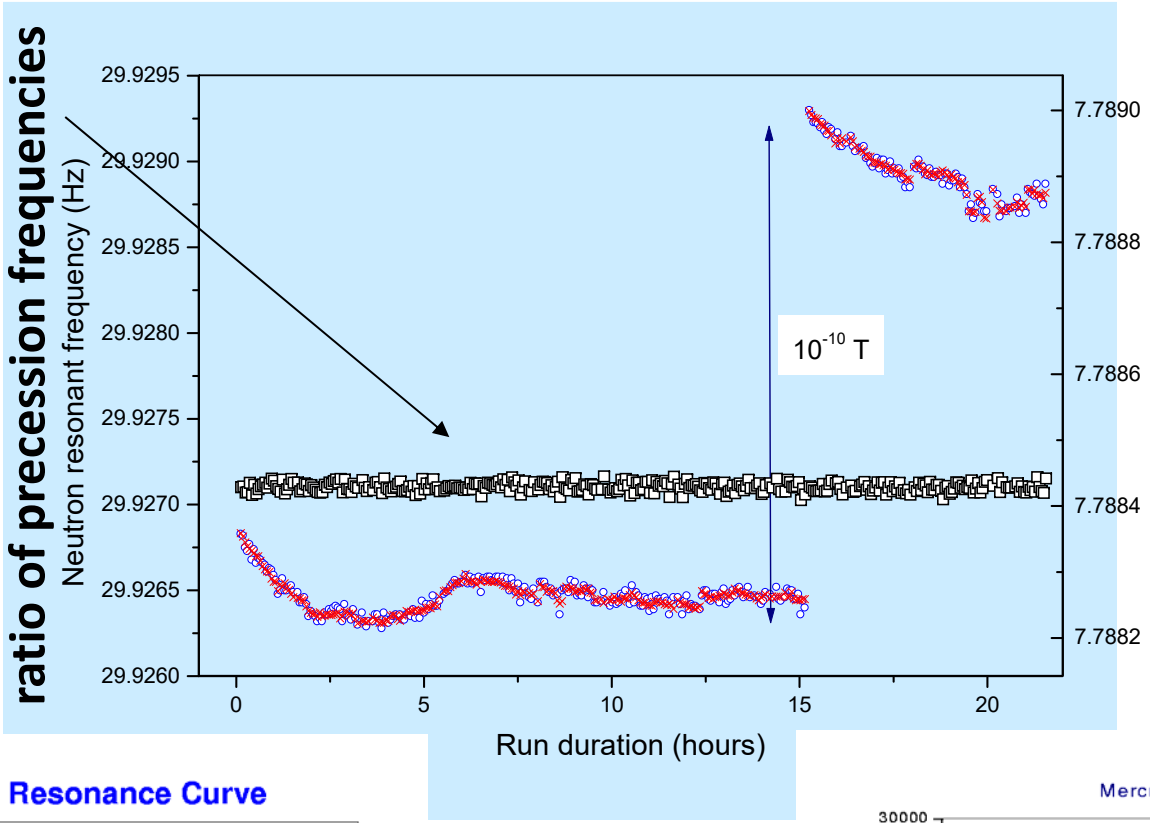


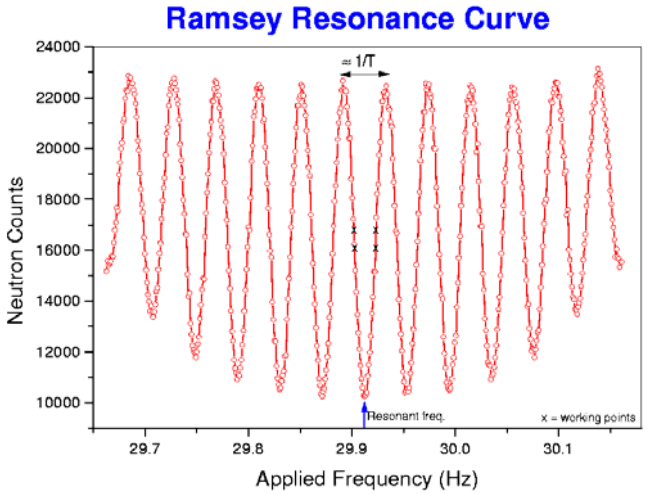
EDM changes frequency:

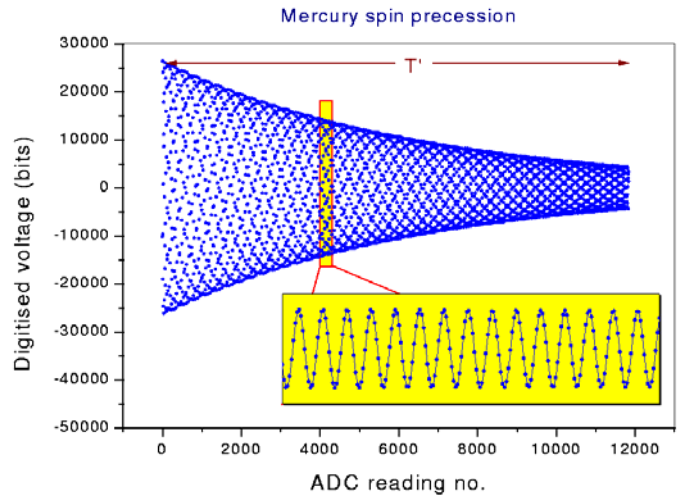
$$\hbar\omega_L \sim \mu_n B \pm d_n E$$

^{199}Hg co-magnetometer for correction of magnetic field drifts

Courtesy
M. v. d. Grinten





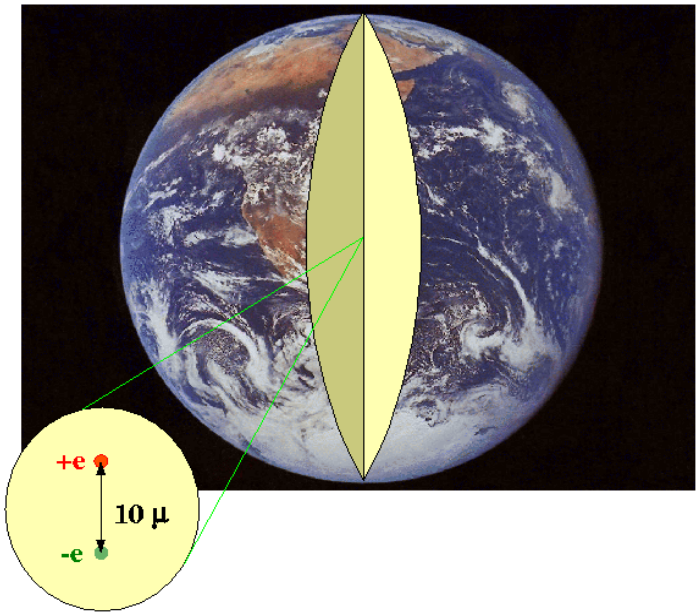


Best result so far (RAL / Sussex / ILL)

$$|d_n| < 2.9 \times 10^{-26} \text{ e cm} \quad (90\% \text{ CL})$$

C.A. Baker et al., PRL **63** (2006) 131801

- 10^{-22} eV spin-dependent interaction
- one spin precession per half year

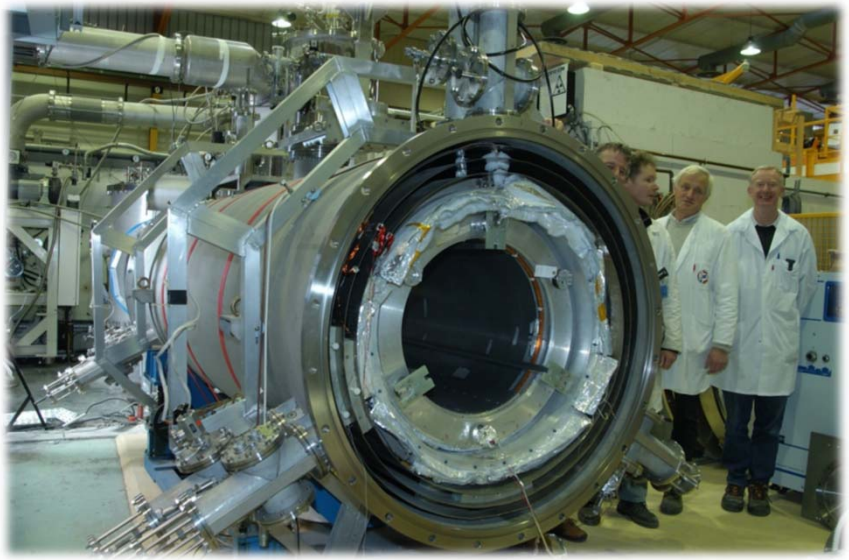


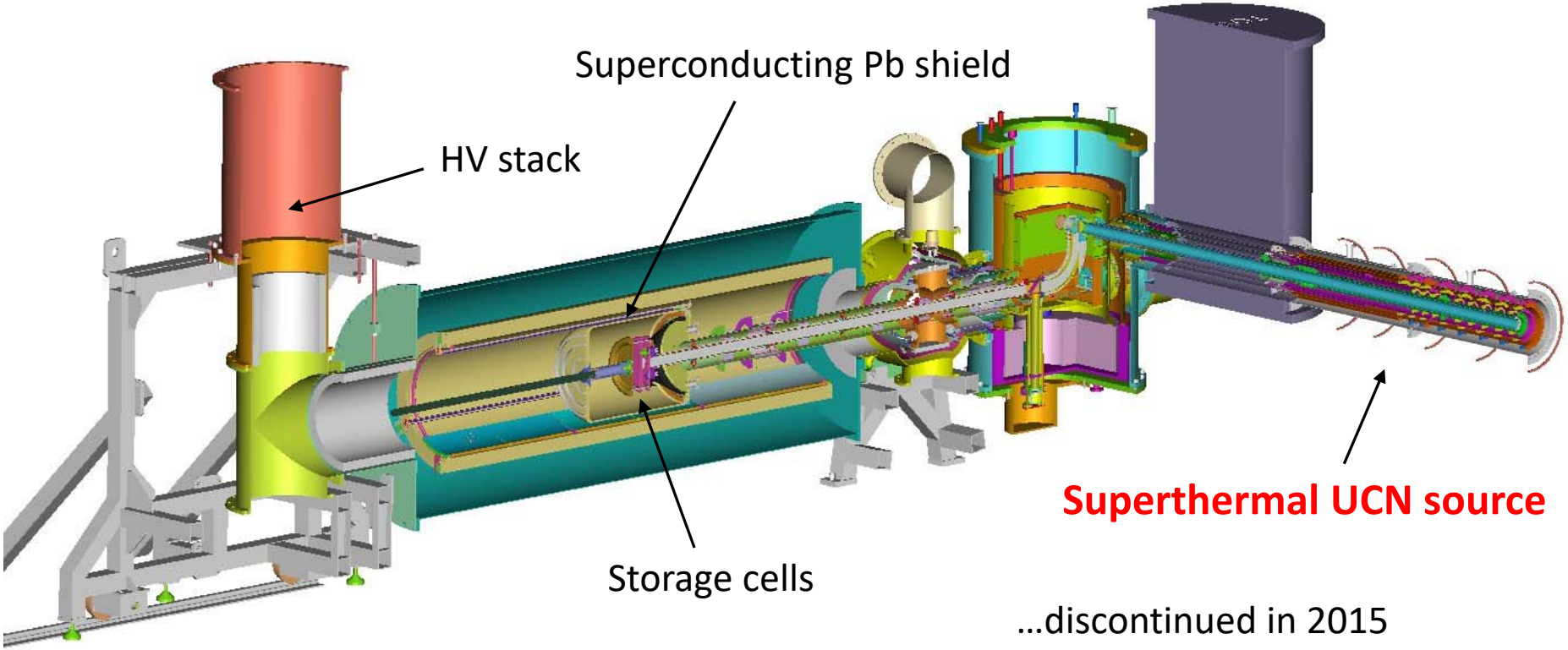
Follow-up experiment:

Cryo-EDM

(Rutherford – Sussex – Kure – Oxford – ILL)

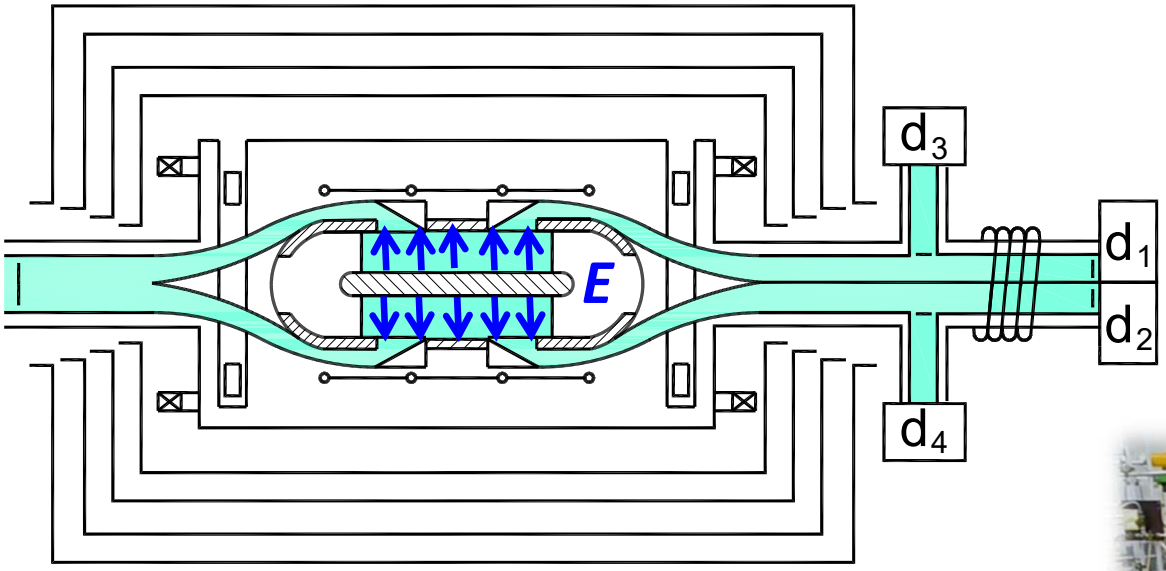
Accuracy goal: 10^{-27} ecm





…discontinued in 2015

Double-chamber EDM experiment (PNPI-ILL)



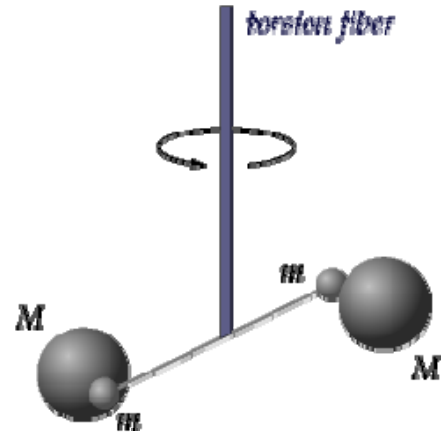
Intermediate result:

$|d_n| < 5.5 \times 10^{-26}$ **e cm** (90% CL)

A. Serebrov et al., JETP Lett. **99** (2014) 4

Several current projects preparing for big improvements:
PSI, Los Alamos, SNS, PNPI, TRIUMF, TUM

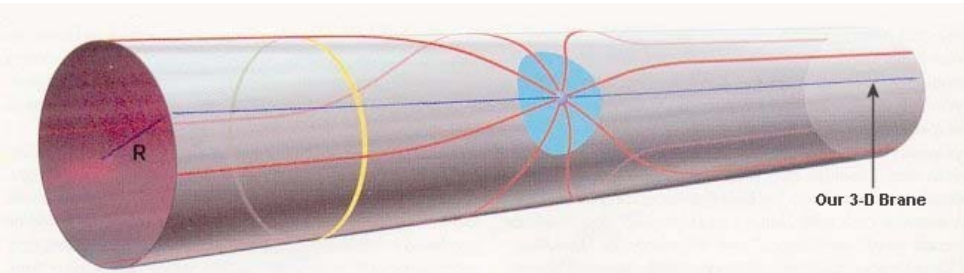
Short-range gravity



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

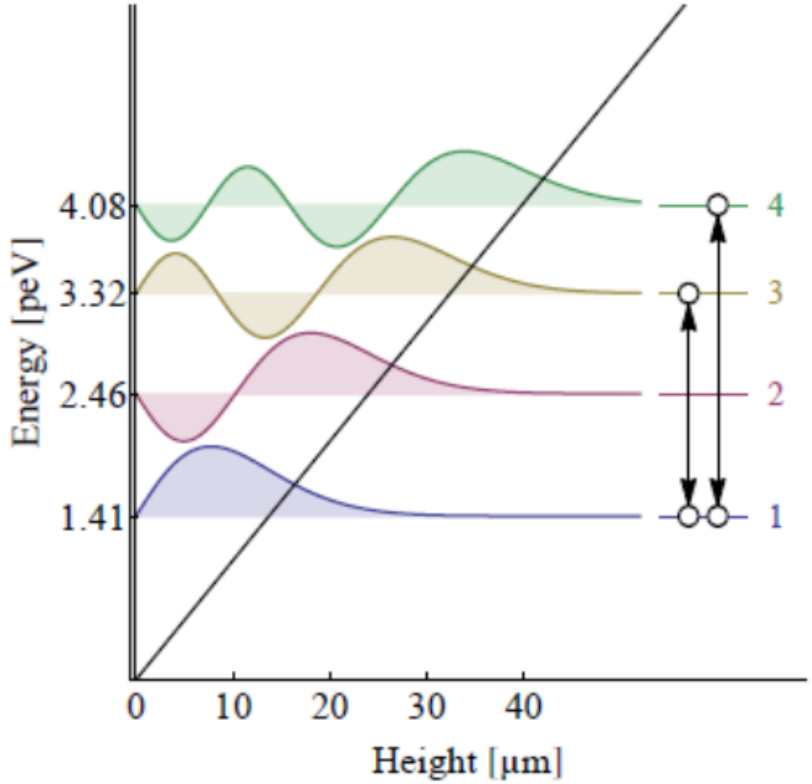
Modification of gravity
with *n* additional dimensions at distances *r* < *R*:

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



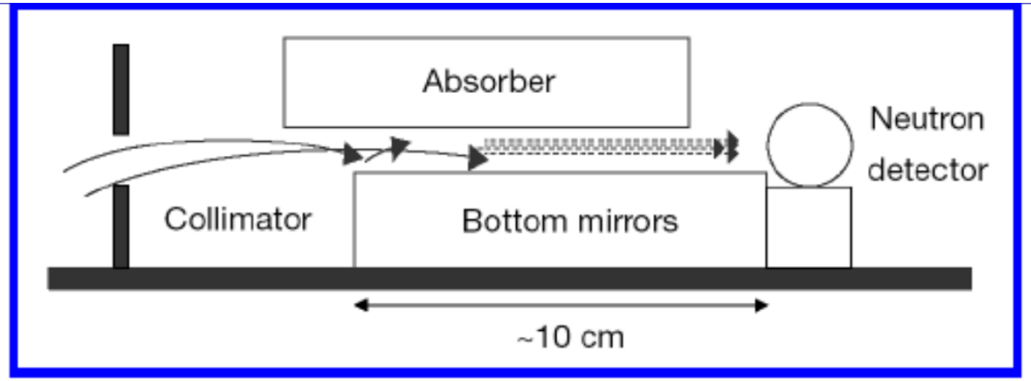
SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines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

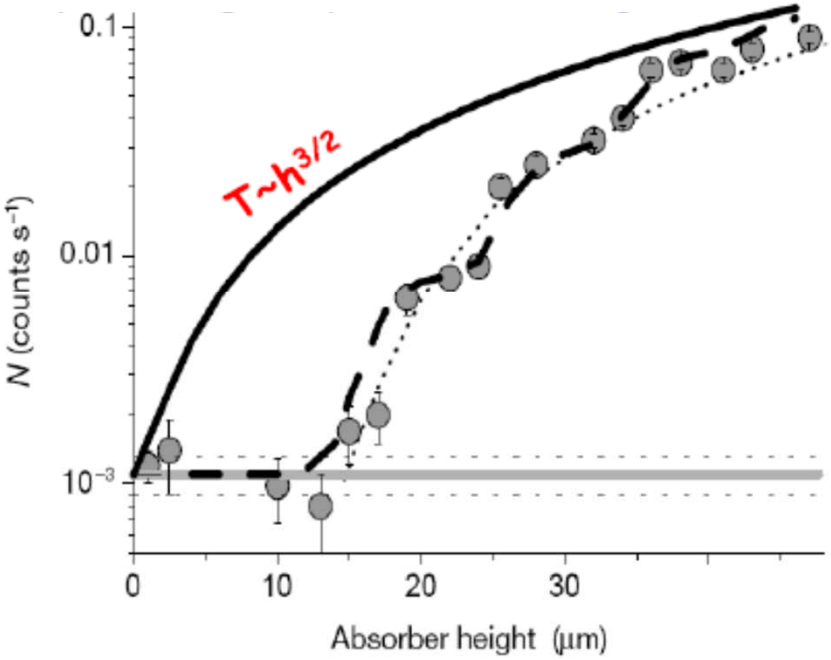
New spectroscopic tool:

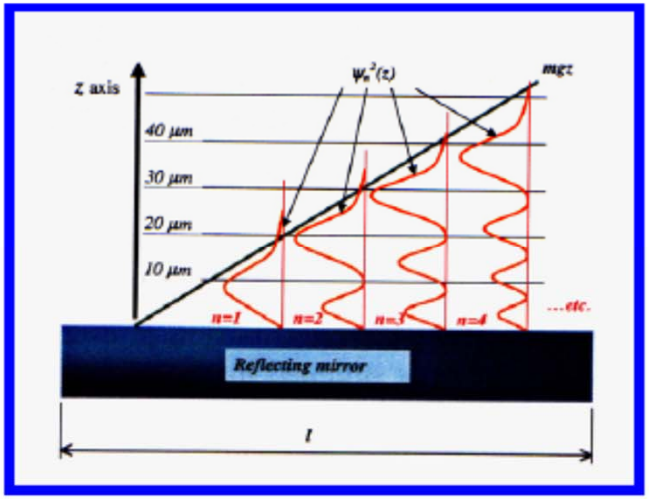


First observations (2002)

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





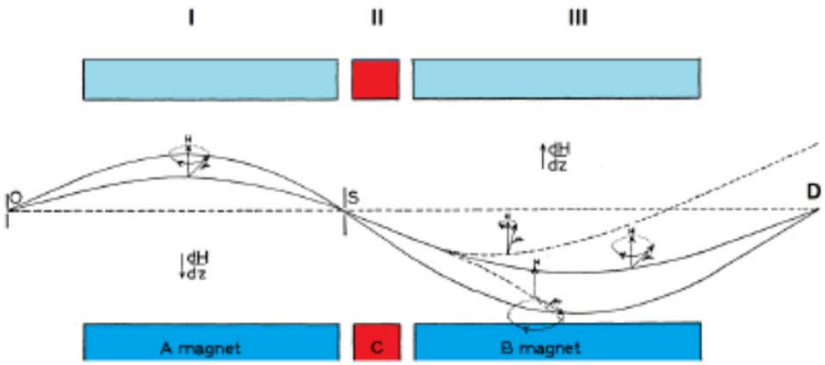


Nesvizhevsky et al., Nature **415** (2002) 299

Rabi-type spectroscopy of gravity

*q*Bounce collaboration (H. Abele, T. Jenke…)

NMR Spectroscopy Technique
to *explore magnetic moments*



3 Regions:

I: 1st State selector/ Polarizer

II: Coupling

– RF field

III: 2nd State Selector / Analyzer

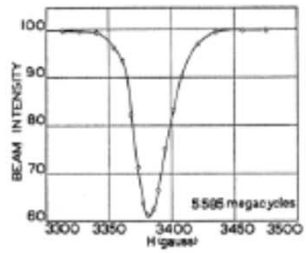
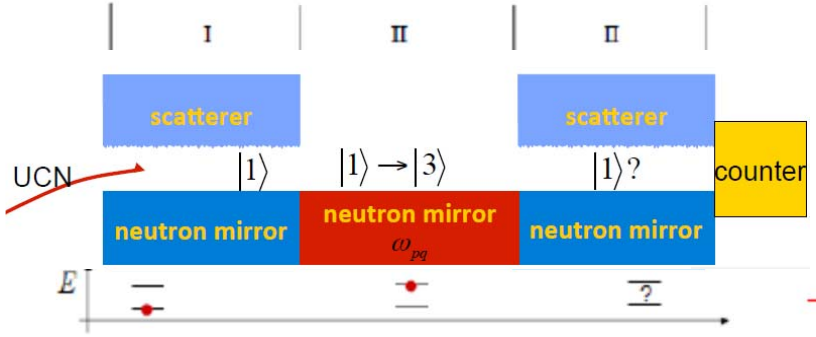


FIG. 4. Resonance curve of the Li^7 nucleus observed in LiCl.

Gravity Resonance Spectroscopy Technique
to *explore gravity*



3 Regions:

I: 1st State selector/ Polarizer

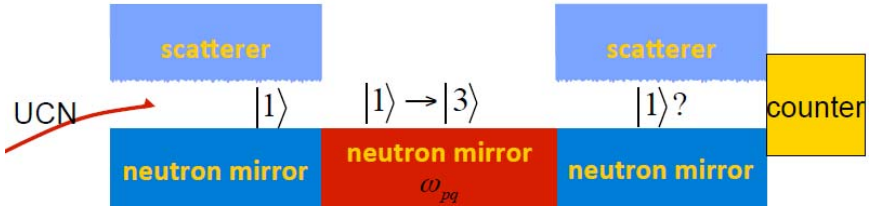
II: Coupling

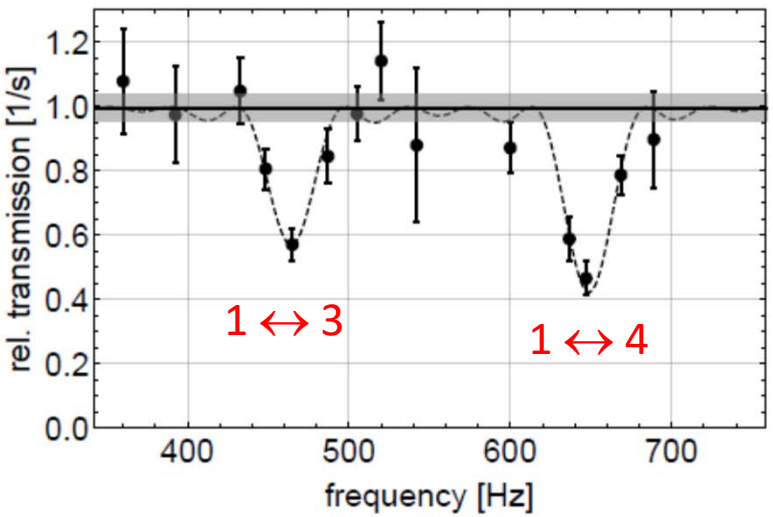
– Vibr. mirror

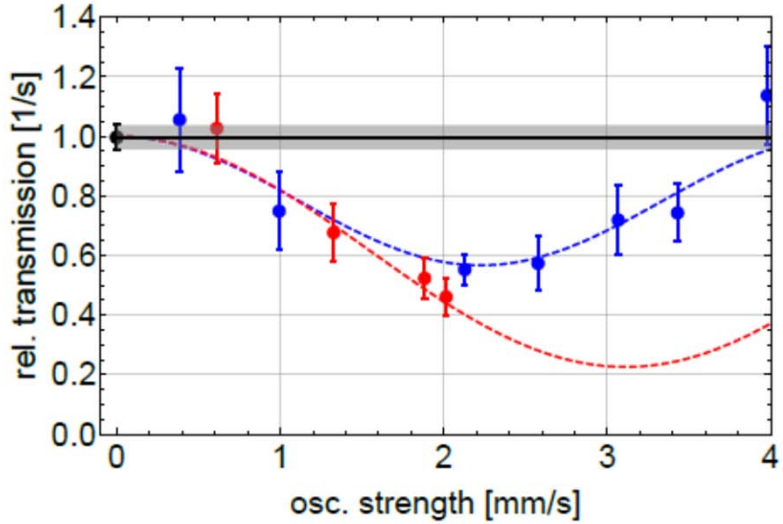
III: 2nd State Selector / Analyzer

Latest results

Cronenberg et al., Nature Phys. 14, 1022 (2018)



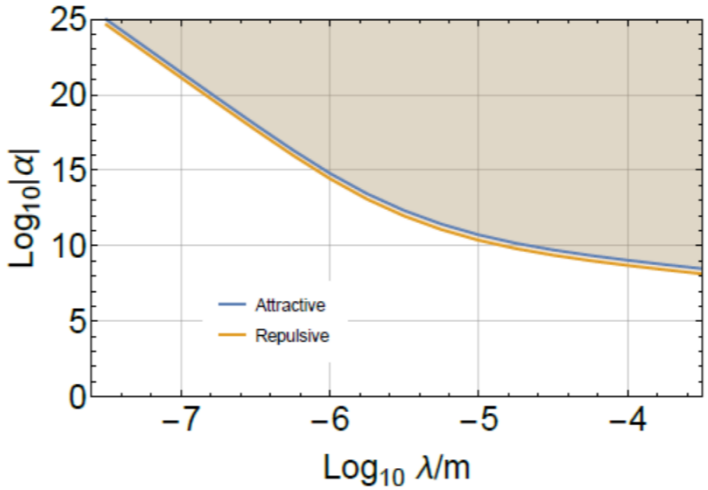




$$f_{13} = 464.1 \pm 1.2 \text{ Hz}$$

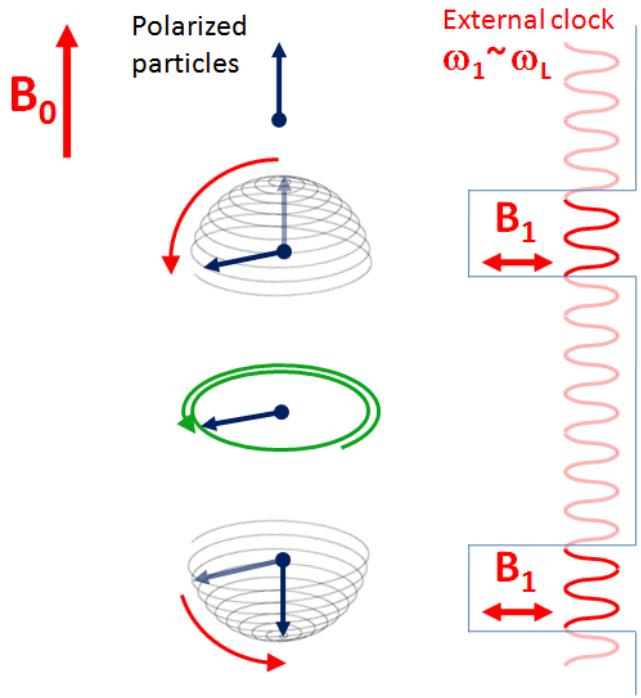
$$f_{14} = 648.8 \pm 1.6 \text{ Hz}$$

$$V(z) = -\frac{GMm}{r}\left(1 + \alpha e^{-z/\lambda}\right)$$



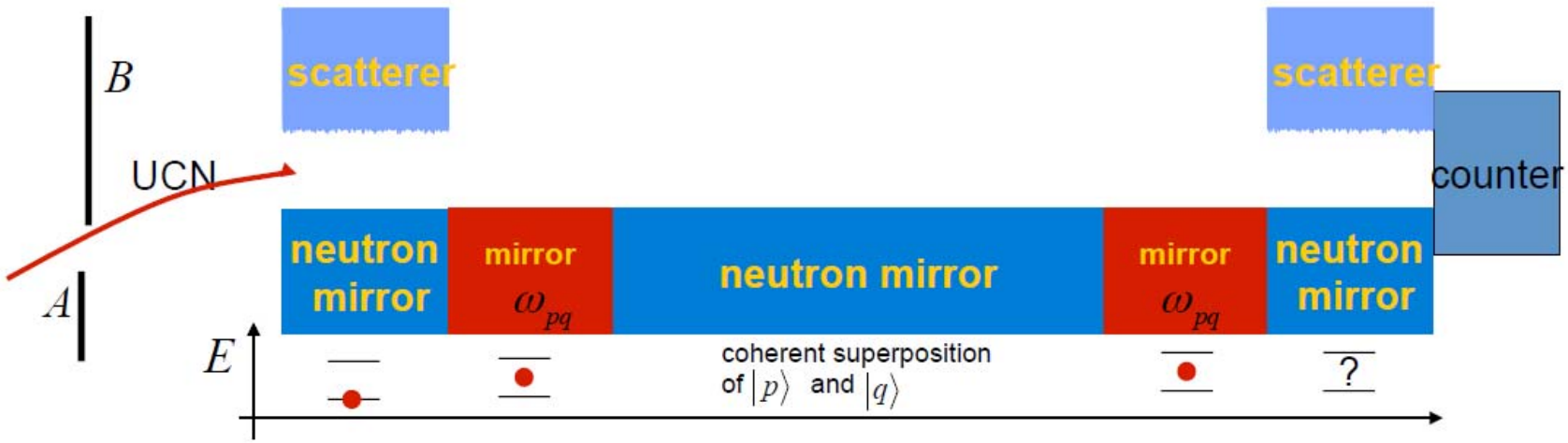
Ramsey spectrometer for gravity states

H. Abele et al., Phys. Rev. D **81** (2010) 065019

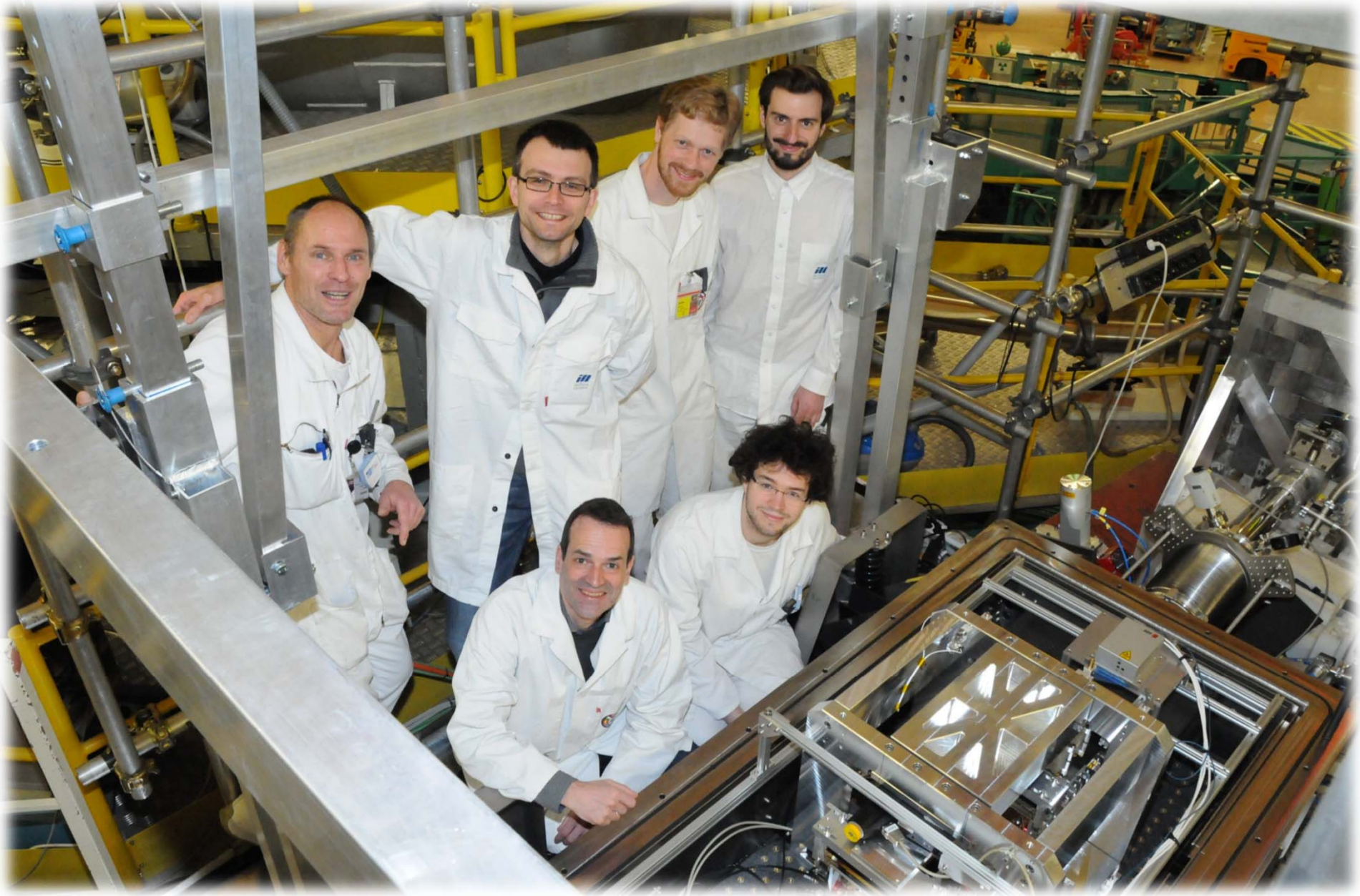


Advantages:

- Long flight path → smaller uncertainty ΔE
- static central mirror for free state evolution



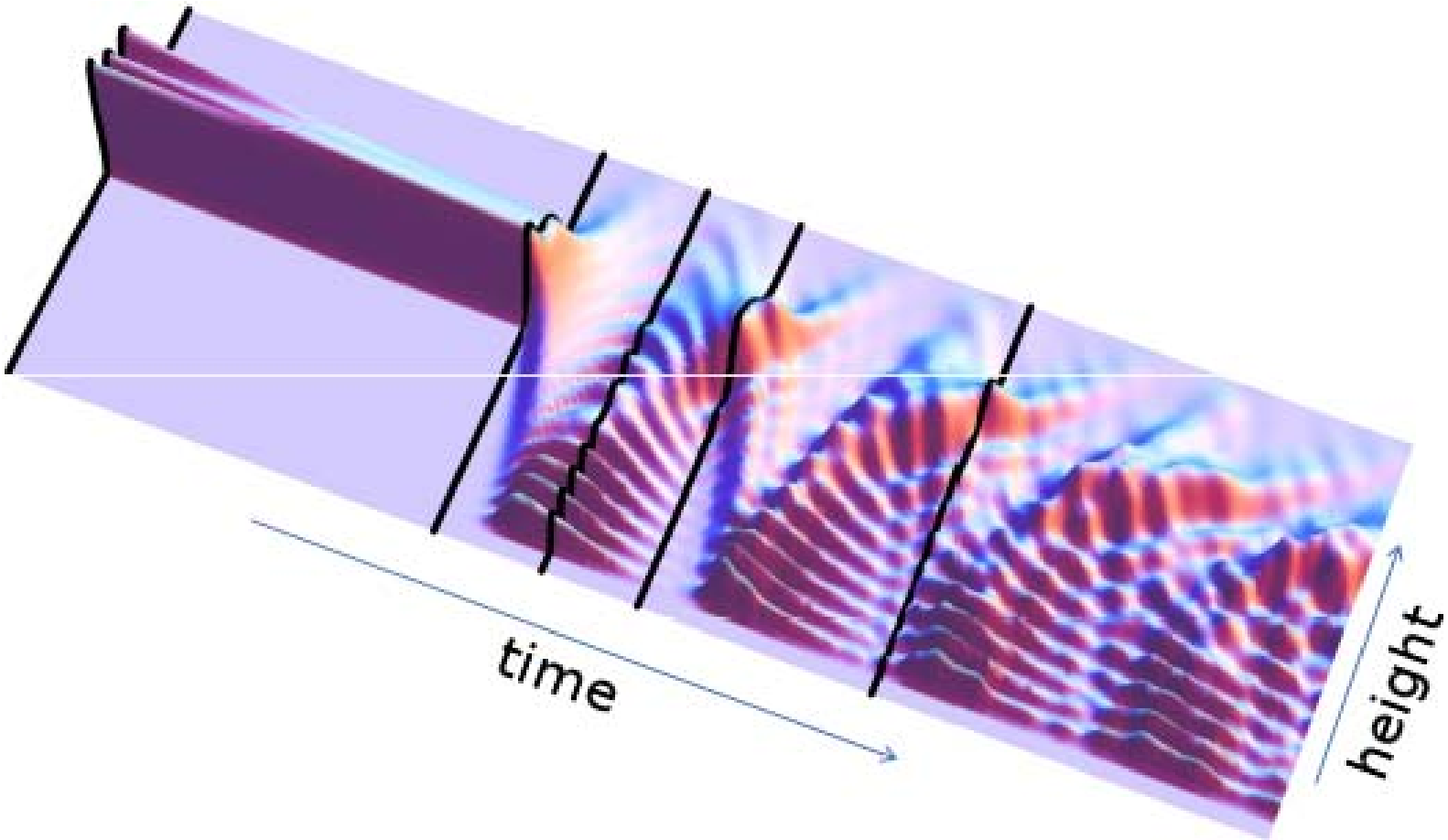
Team of happy experimentalists



Quantum bouncing ball

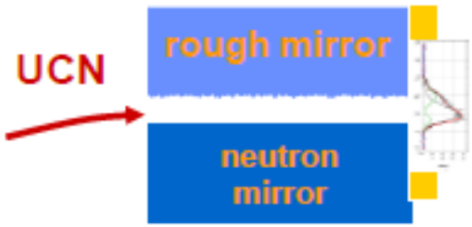
$$\Psi(z,t) = \sum_{n=0}^{\infty} c_n e^{-iE_n t/\hbar} \psi_n(z)$$

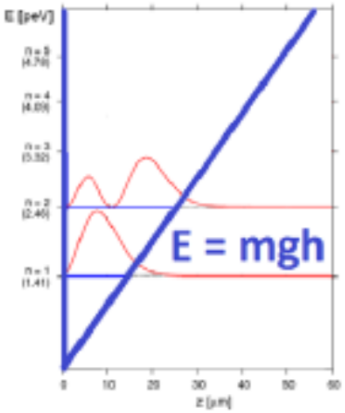
$$\psi_n(z) \sim Ai[\frac{z}{z_0} - \frac{E_n}{E_0}]; c_n = \int_0^{\infty} \Psi(z,0)\psi(z)dz$$

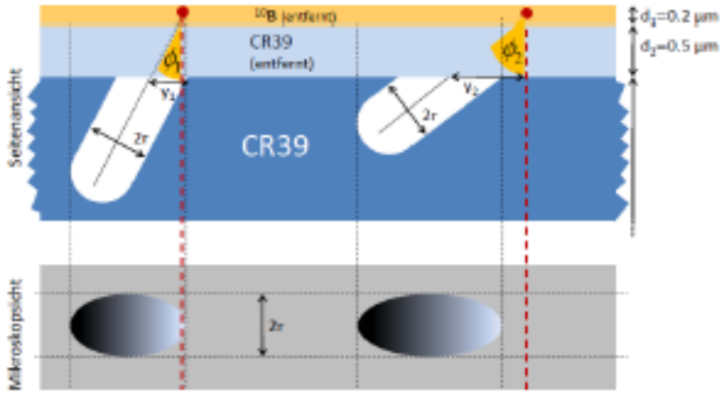


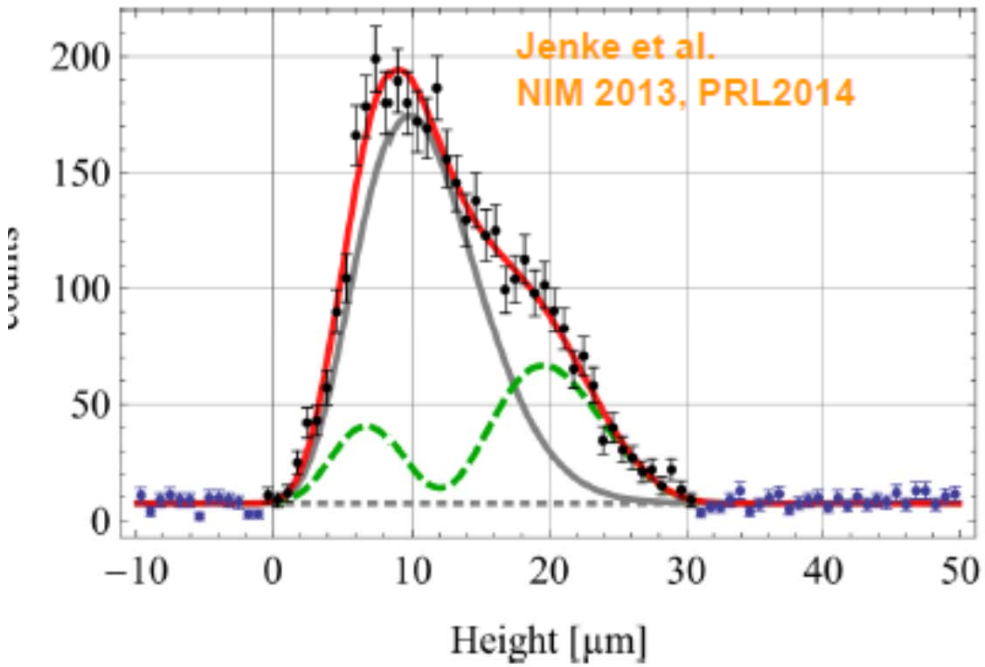
Airy - Quantum States 1 & 2

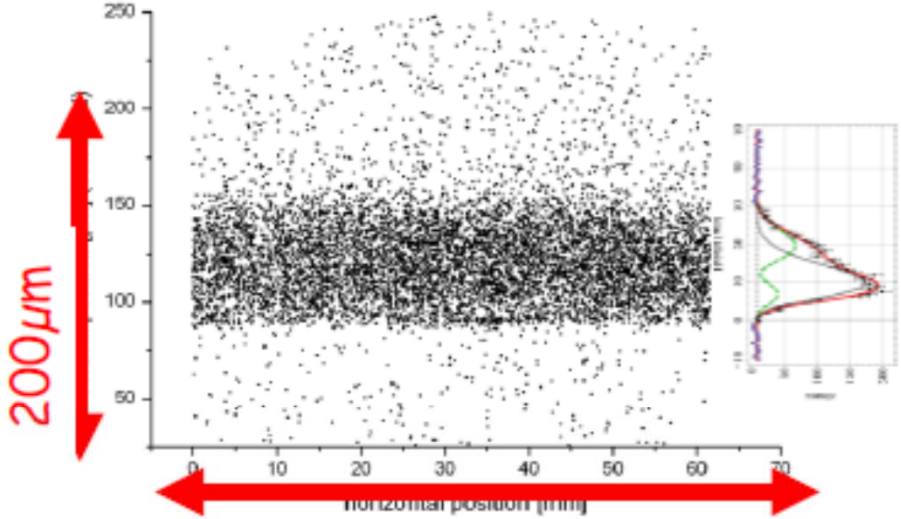
$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha$$





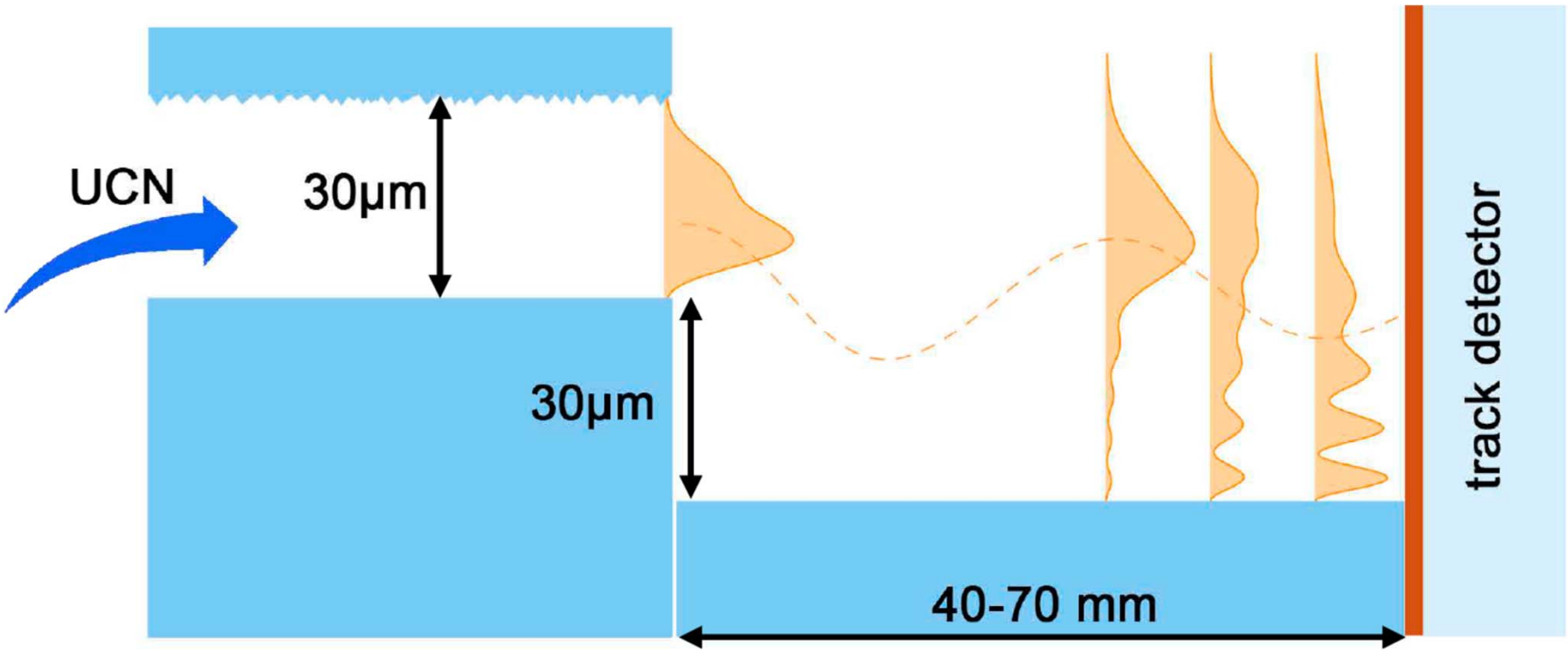






Snapshots of $|\psi|^2$ with 1.5 μm resolution

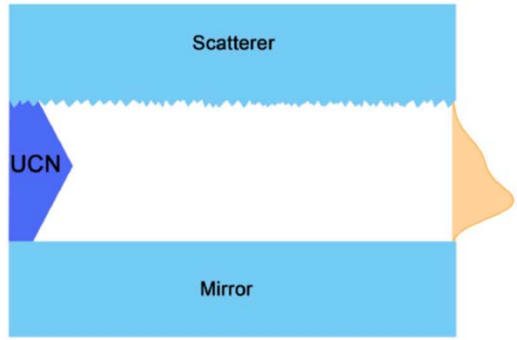
Preliminary results from Ph.D. thesis of Martin Thalhammer, TU Vienna and ILL

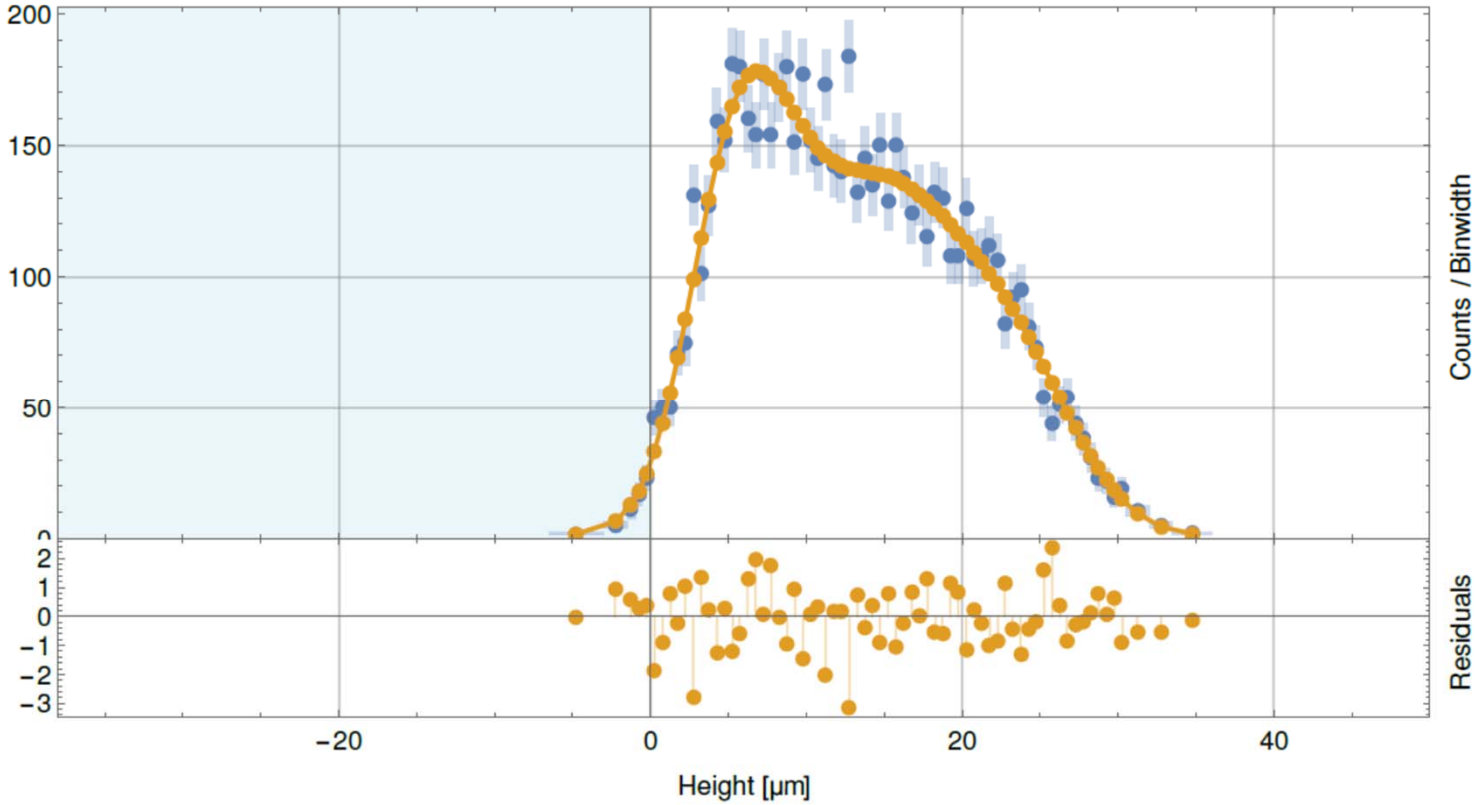


Preparation, L = 0 mm

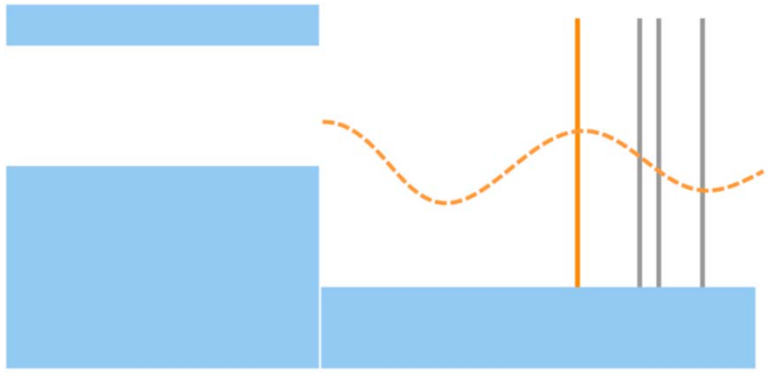
$$|\Psi_l(z,t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

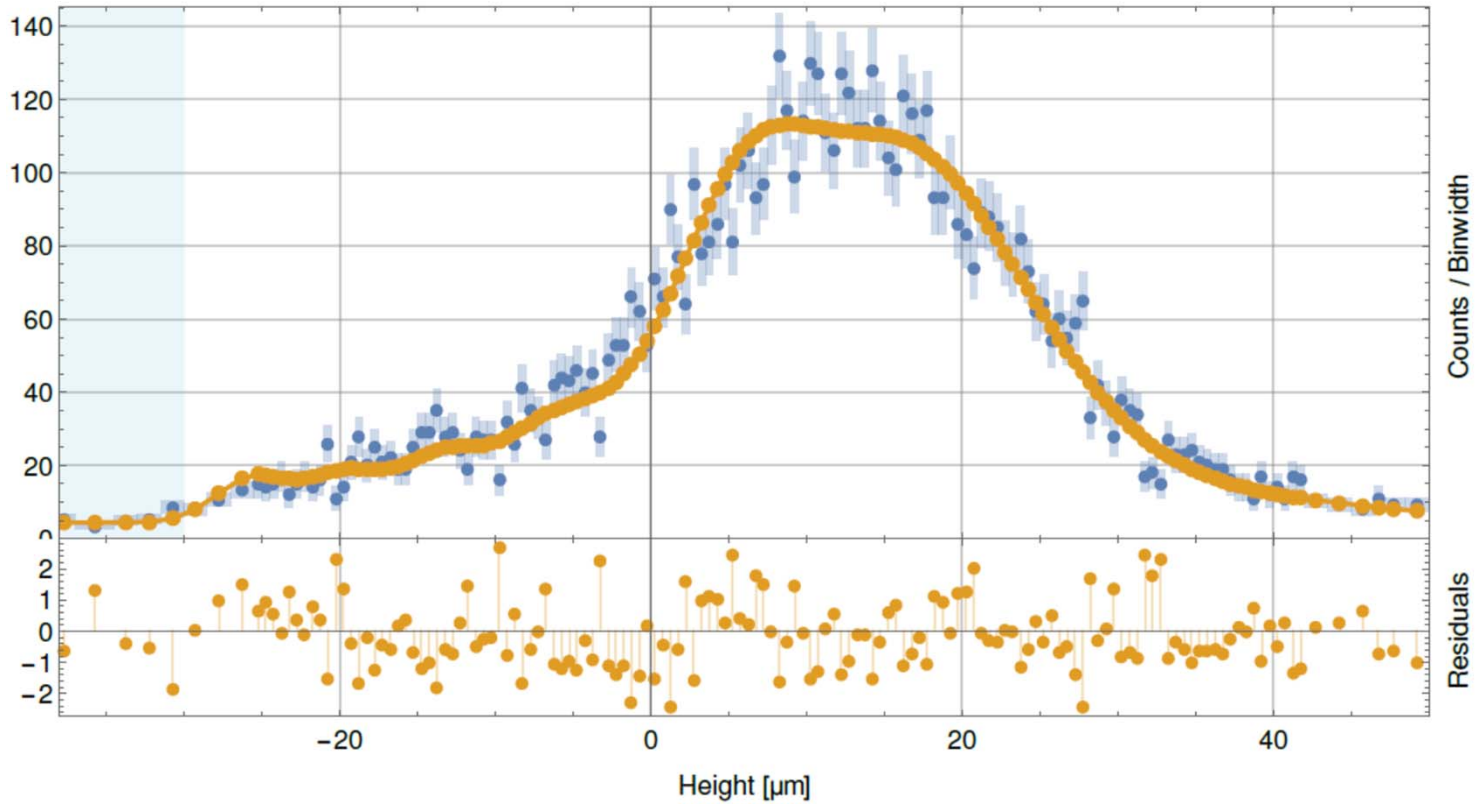
$|c_1|^2 = 45\%$
$|c_2|^2 = 36\%$
$|c_3|^2 = 18\%$
preliminary



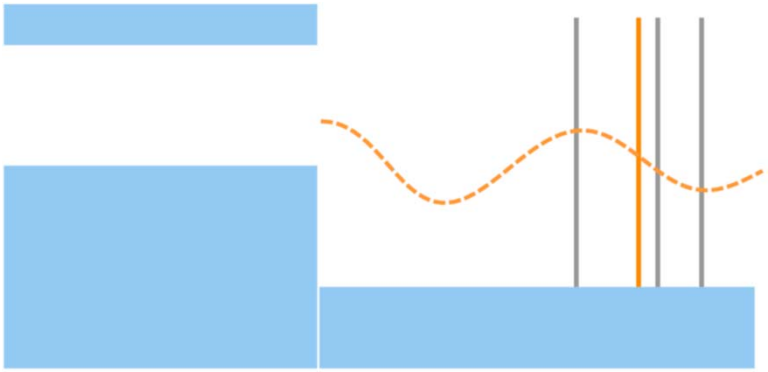


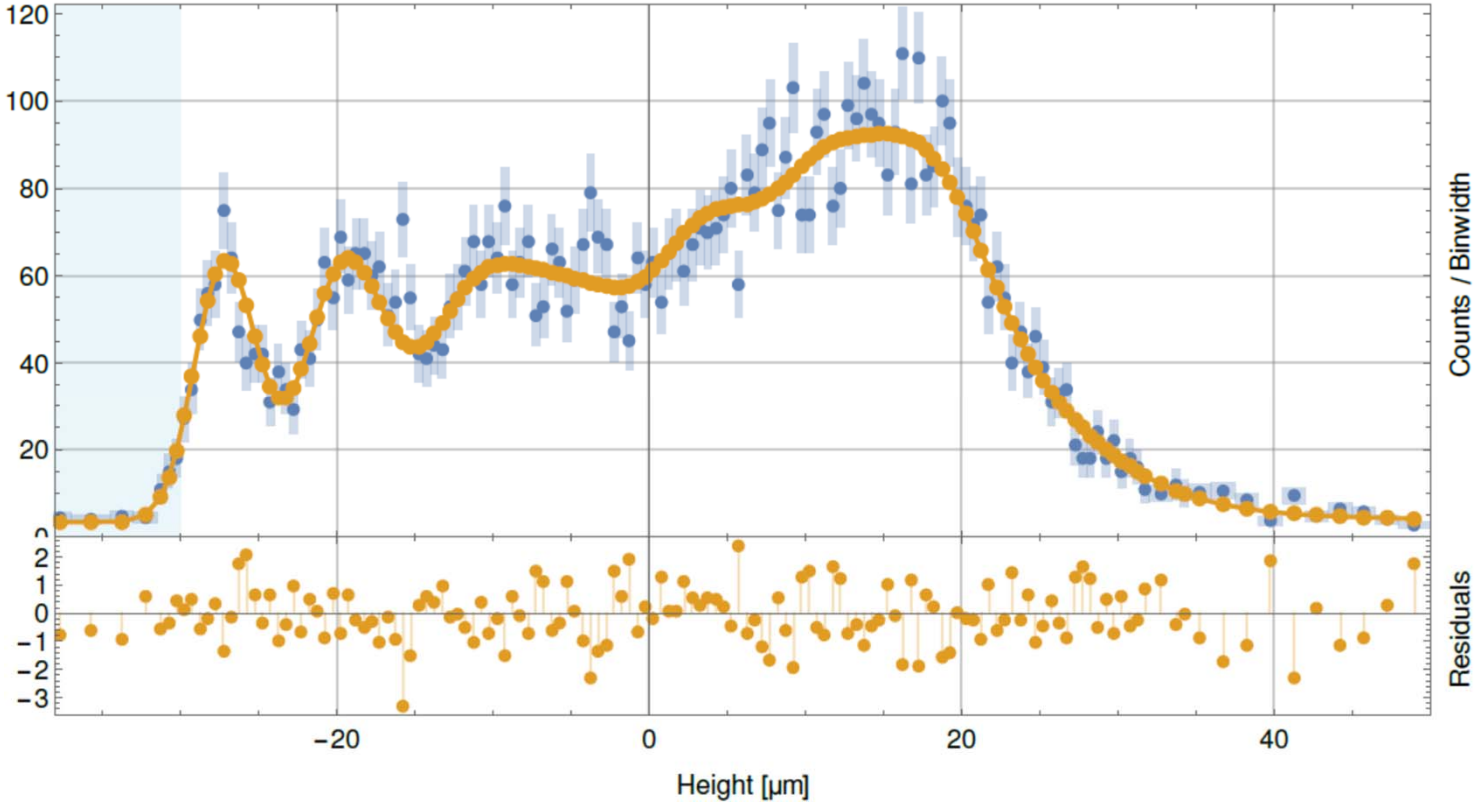
2nd turning point L = 41 mm



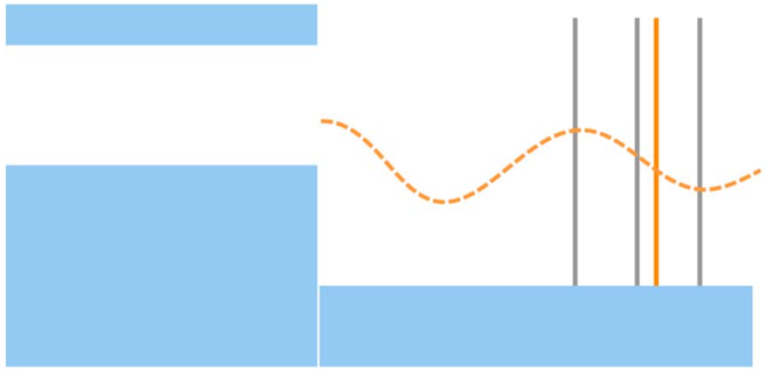


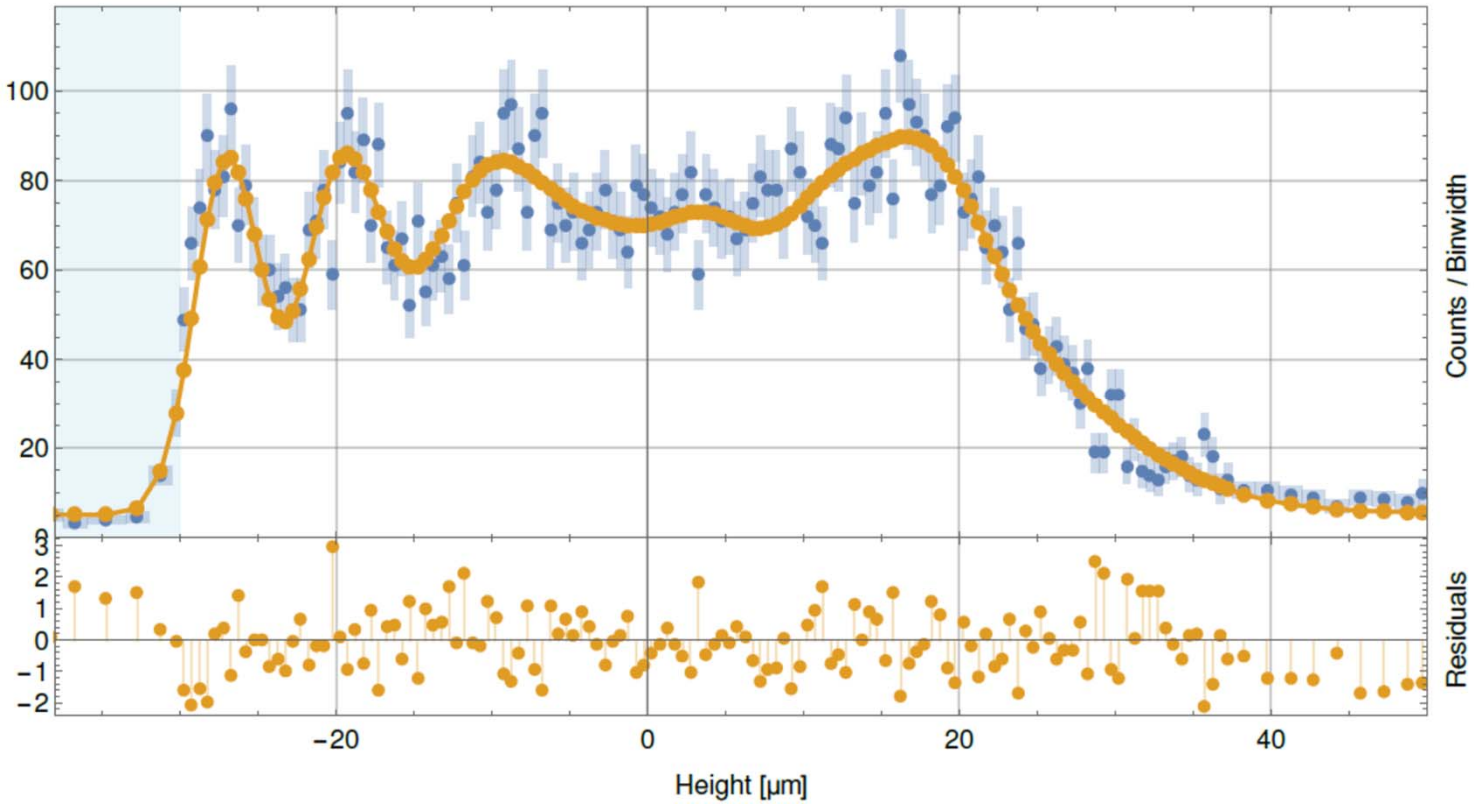
again falling, *L* = 51 mm



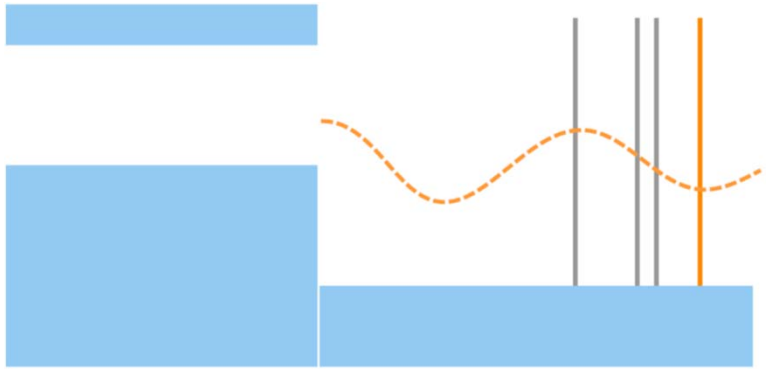


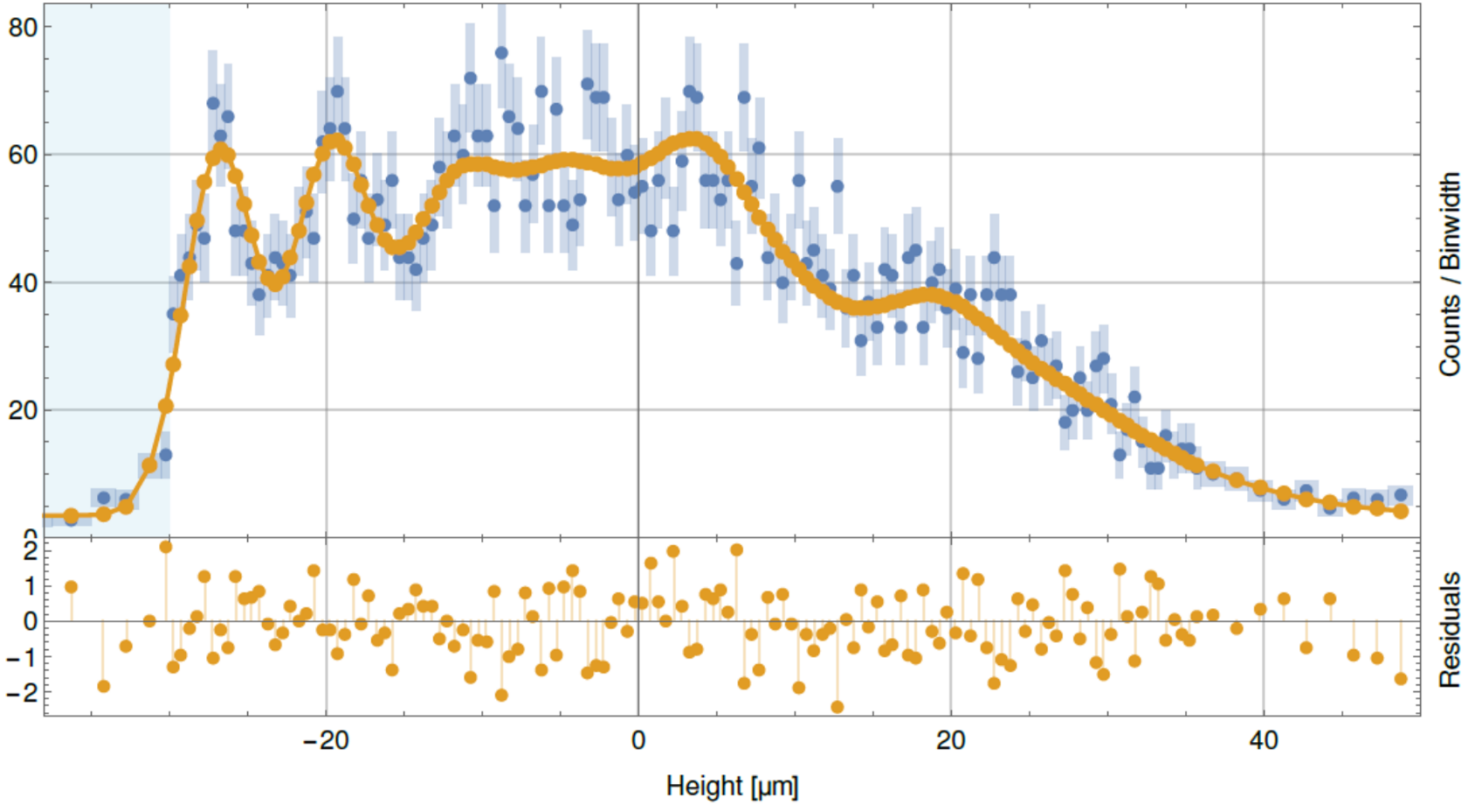
still falling, *L* = 54 mm



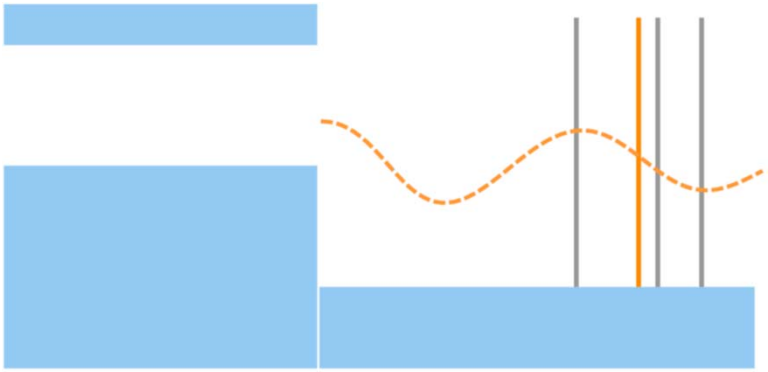


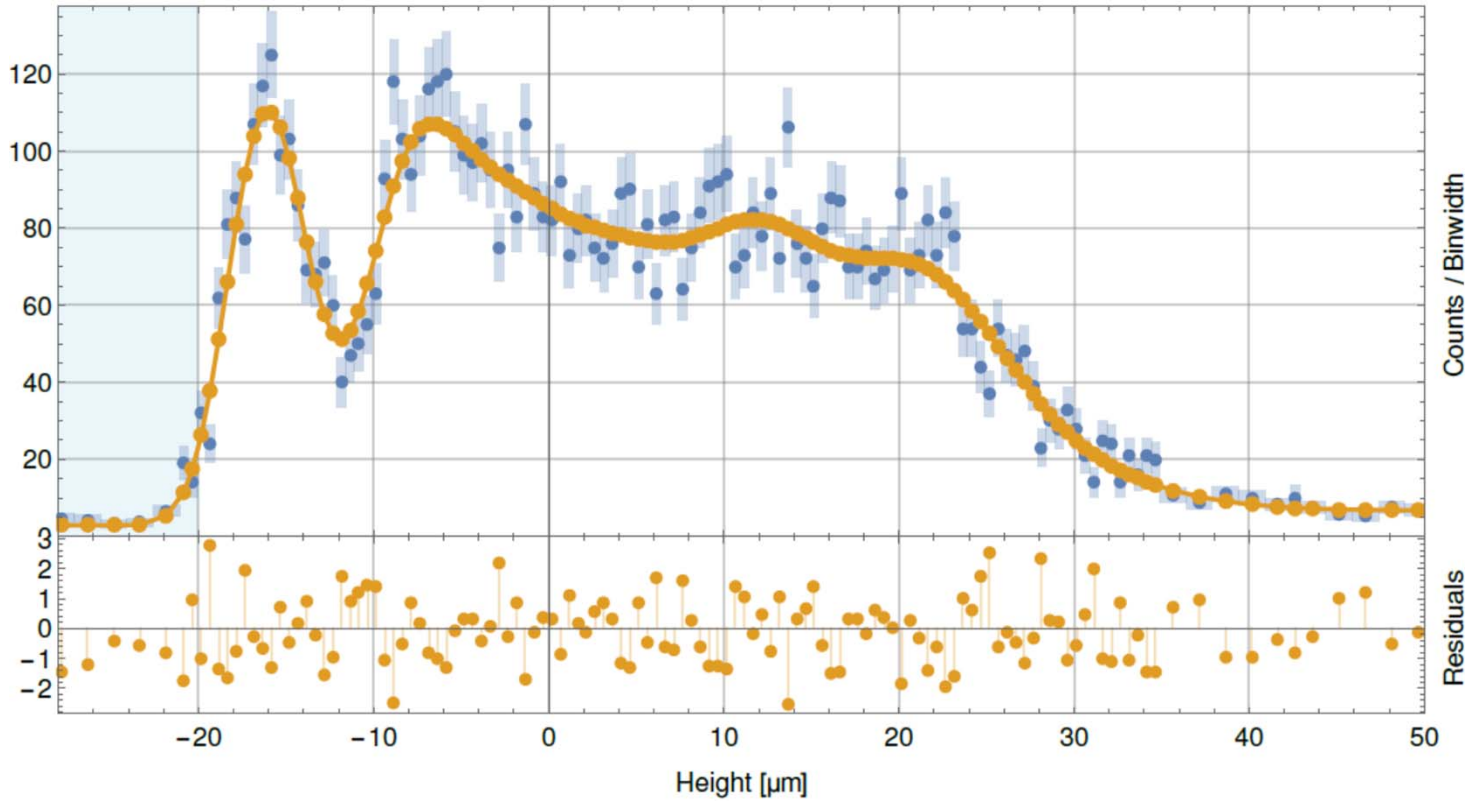
“lowest” point, *L* = 61 mm





only 20 μm step, *L* = 51 mm





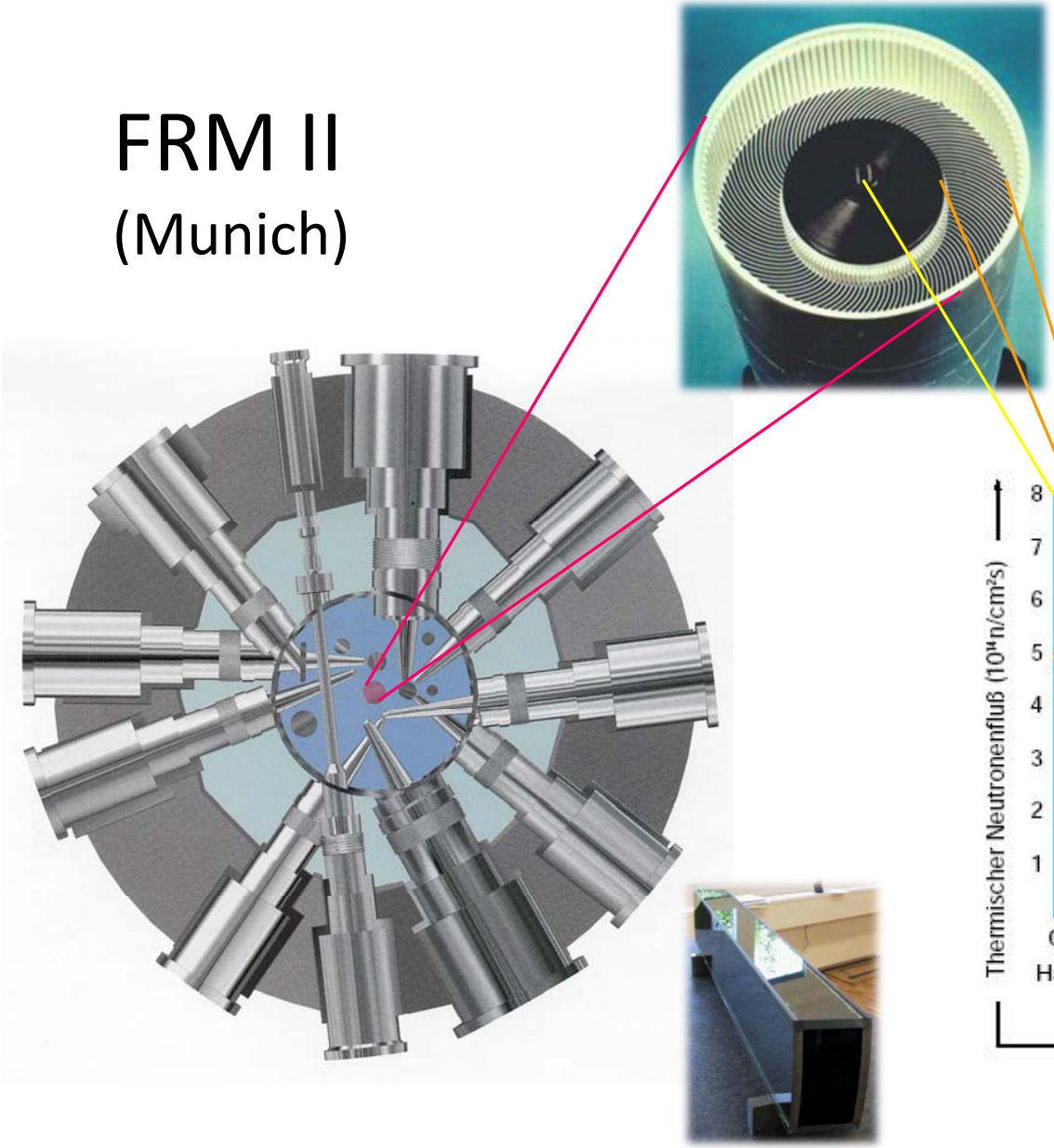
From where do we get our neutrons?

Reactor sources:

Spallation sources:

Neutron production at research reactors

FRM II
(Munich)



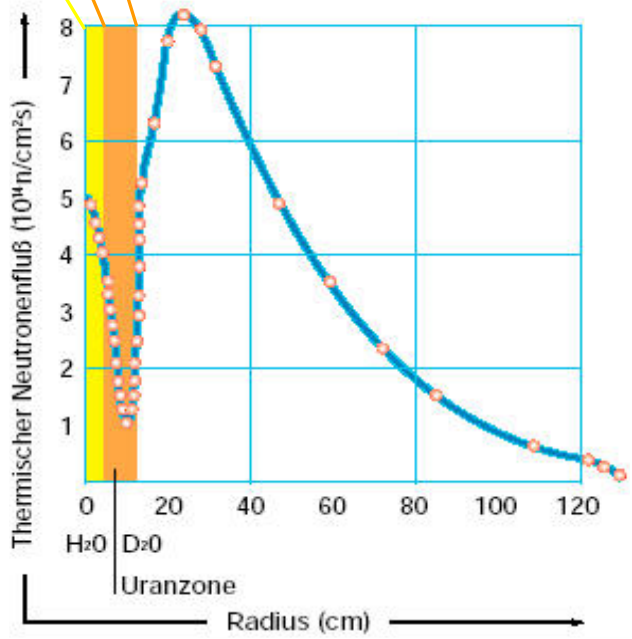
Thermal neutrons:

$E_{kin} \sim 25$ meV

$v \sim 2200$ m/s

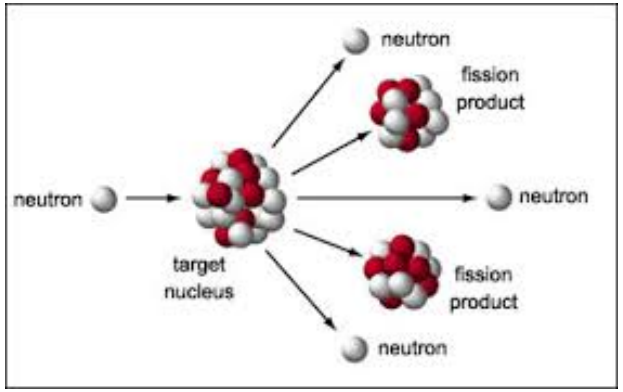
$\lambda \sim 1.8$ Å

$T \sim 300$ K



Nuclear fission

in fuel element



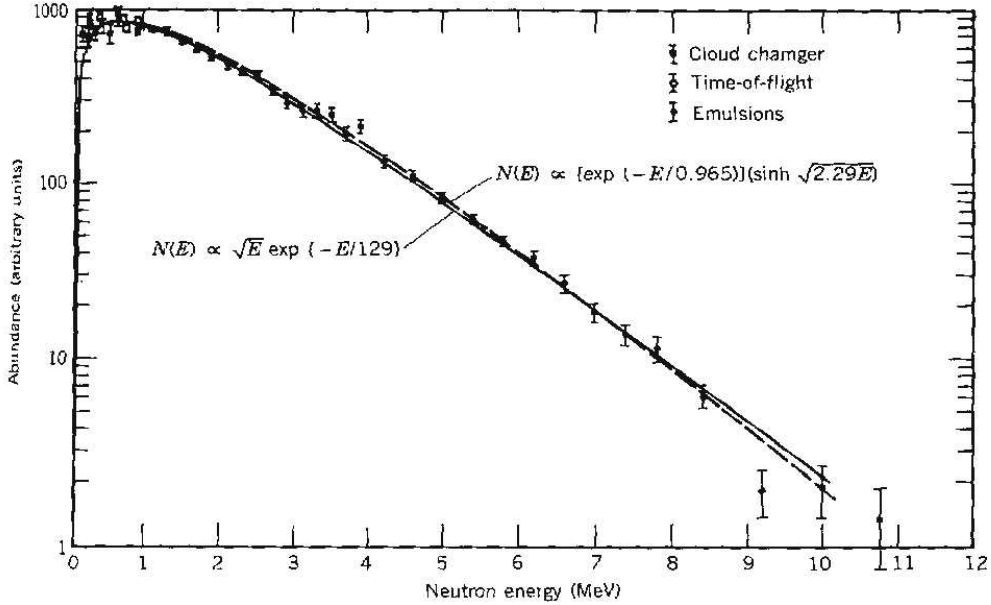
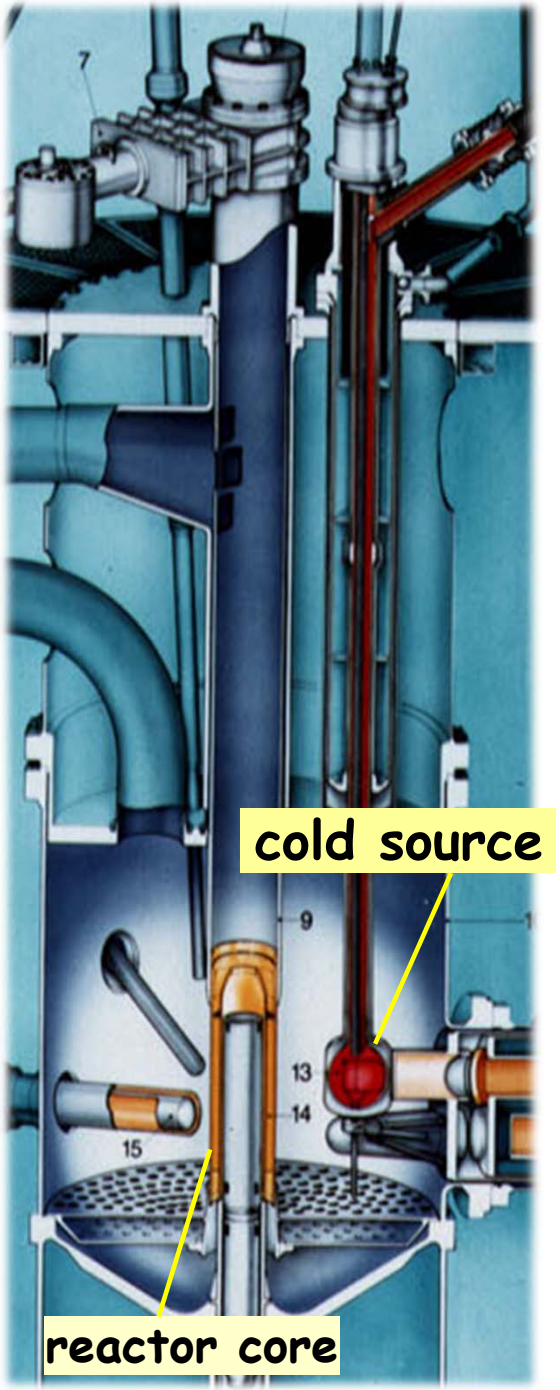


Figure 13.13 Energy spectrum of neutrons emitted in the thermal-neutron fission of ^{235}U. From R. B. Leachman, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Vol. 2 (New York: United Nations, 1956), p. 193.

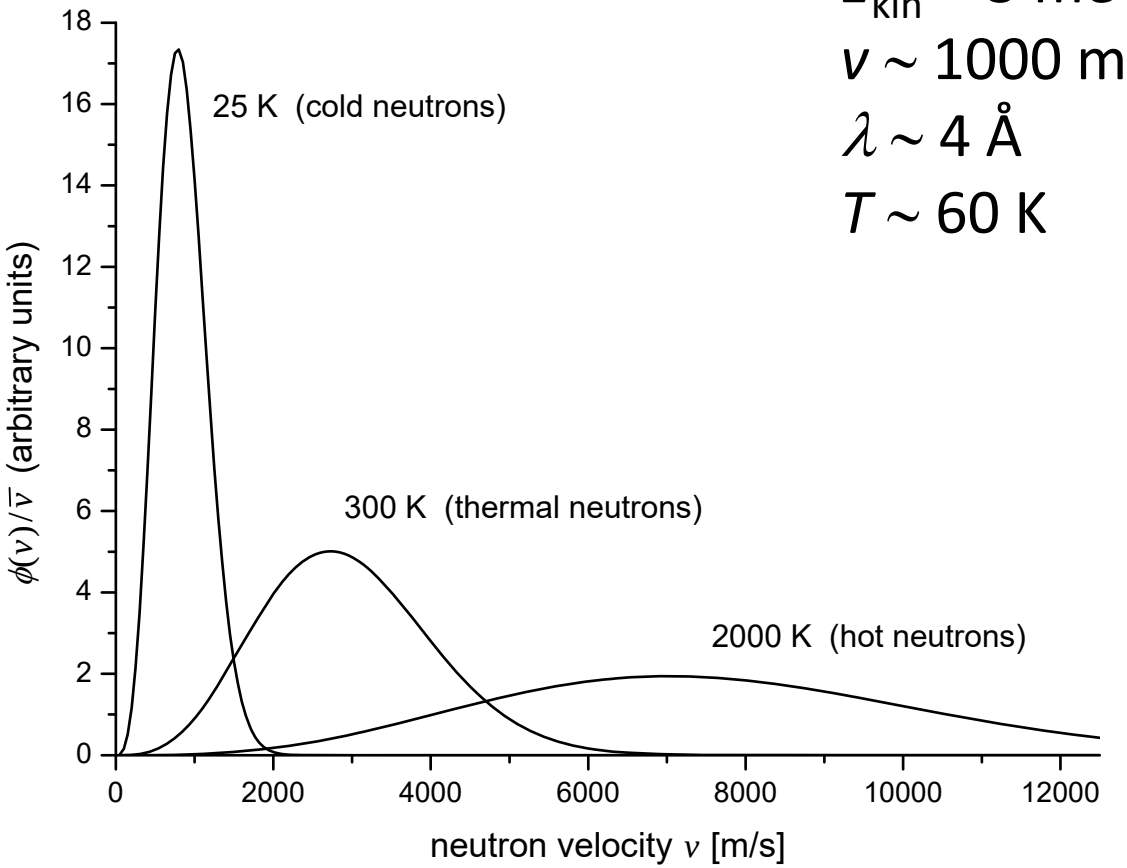
ILL

(Grenoble)



Moderation

in heavy-water reflector and cold source (liq. D_2)



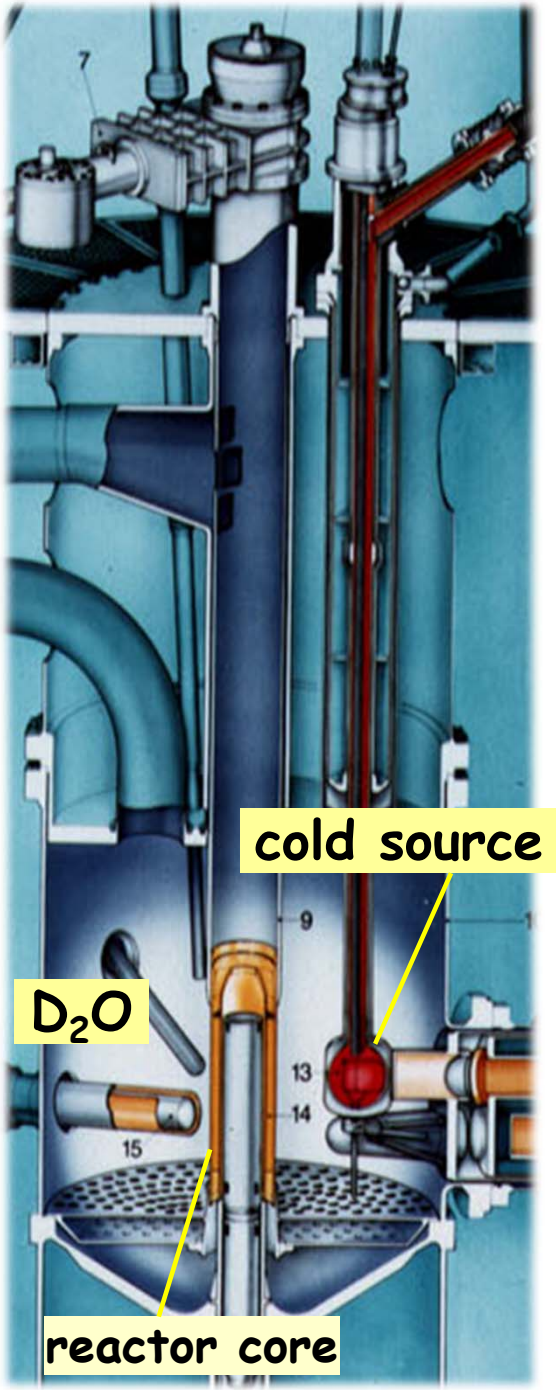
Cold neutrons:

$E_{kin} \sim 5$ meV

$v \sim 1000$ m/s

$\lambda \sim 4$ Å

$T \sim 60$ K



(Ultra)cold neutron production at ILL

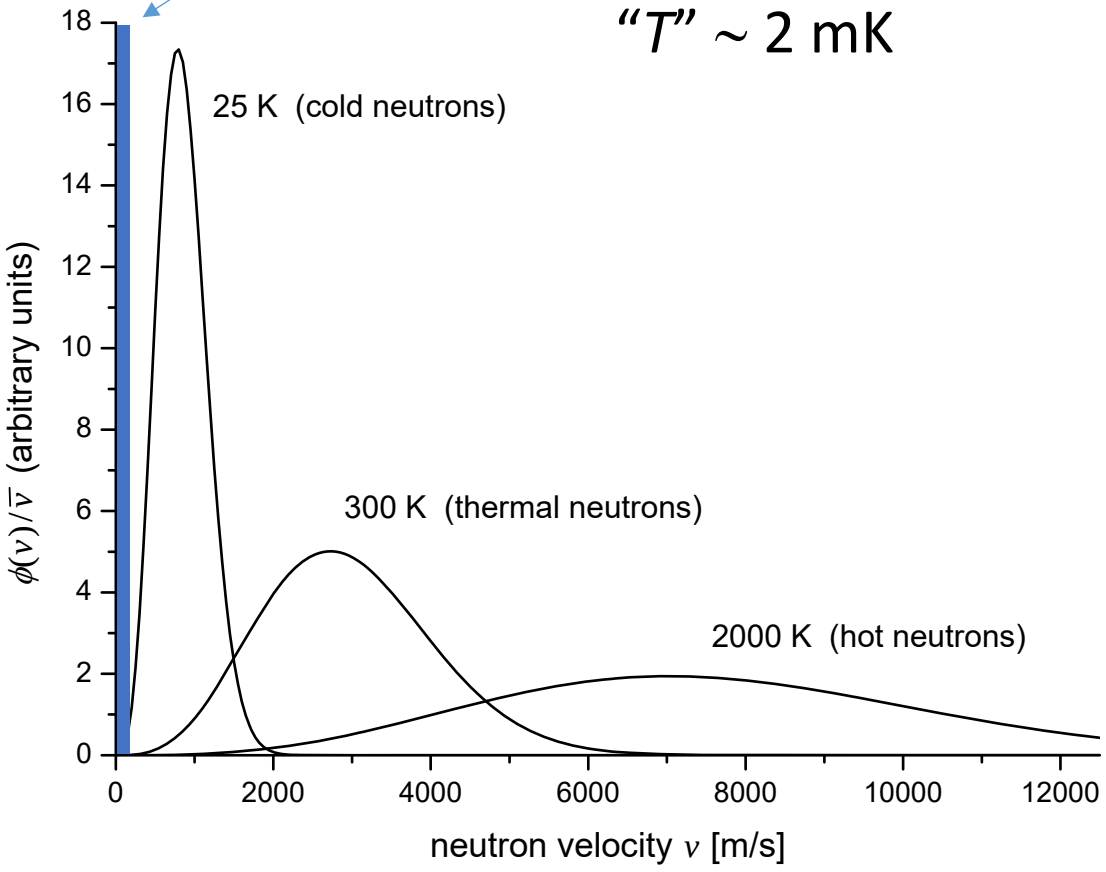
Ultracold neutrons:

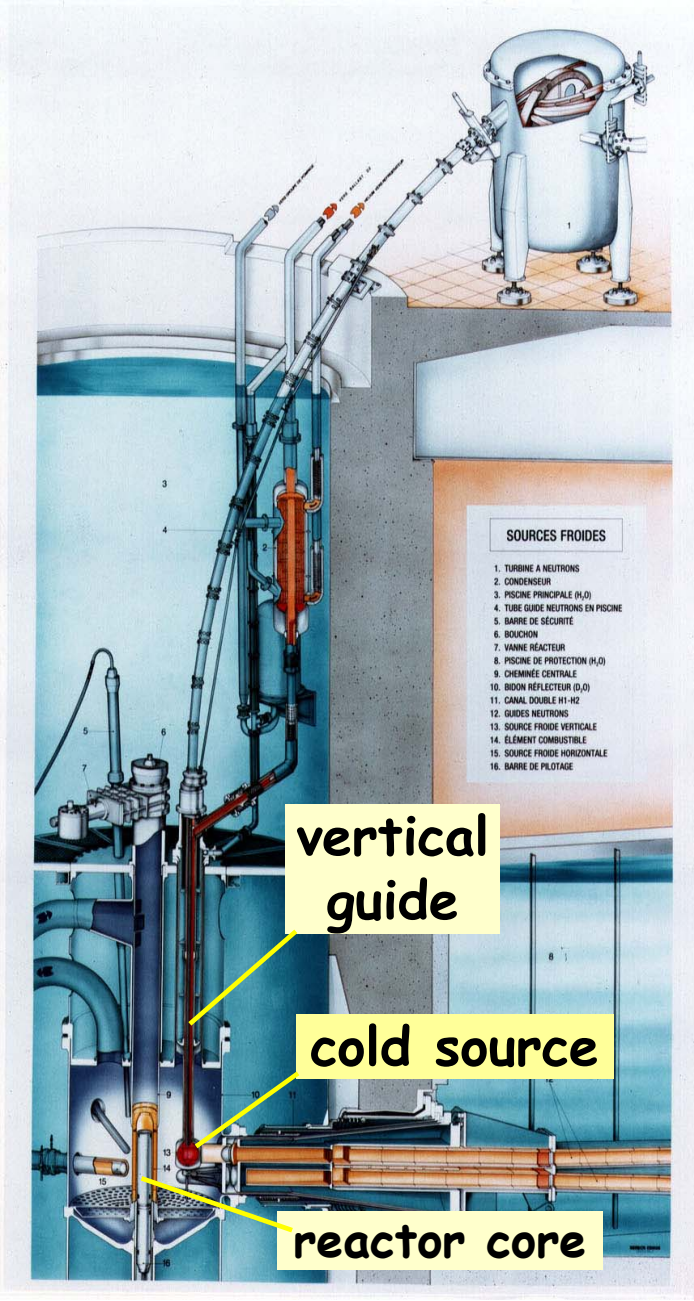
$E_{kin} < 3\times10^{-7}$ eV

$v < 7$ m/s

$\lambda > 600$ Å

"T" ~ 2 mK





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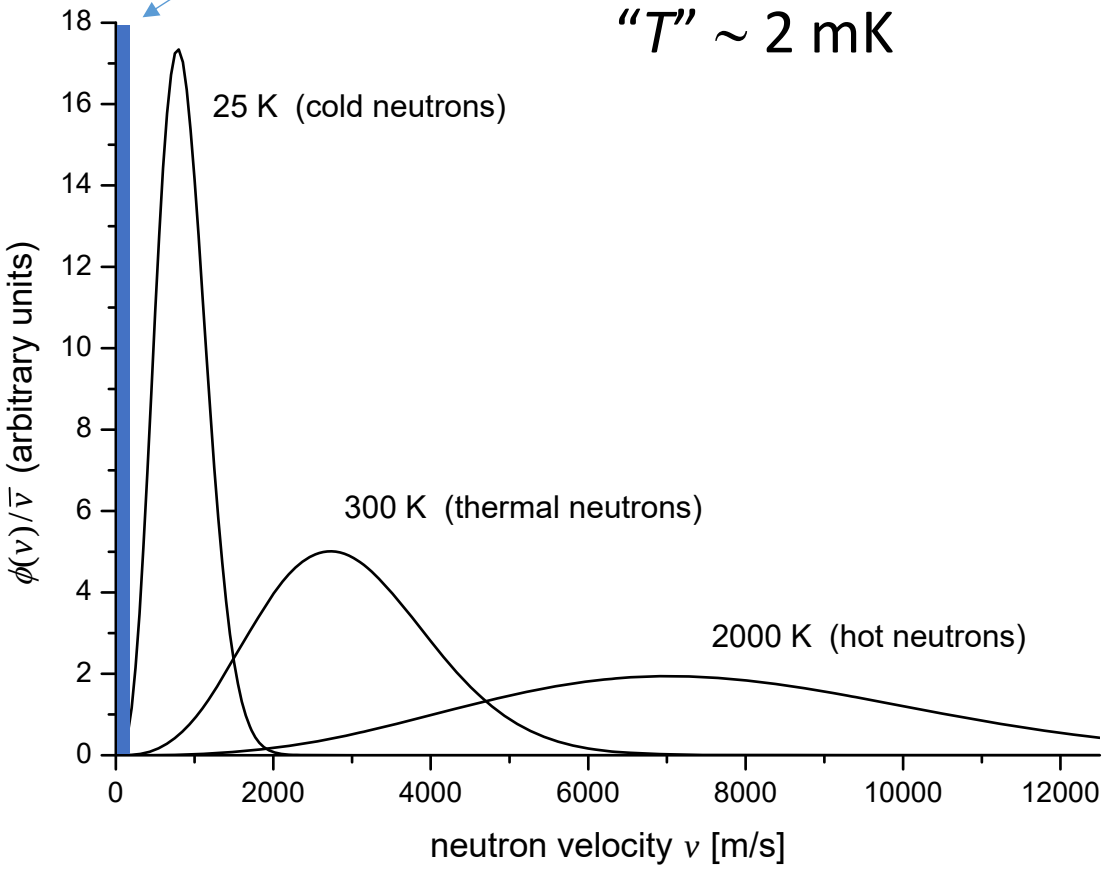
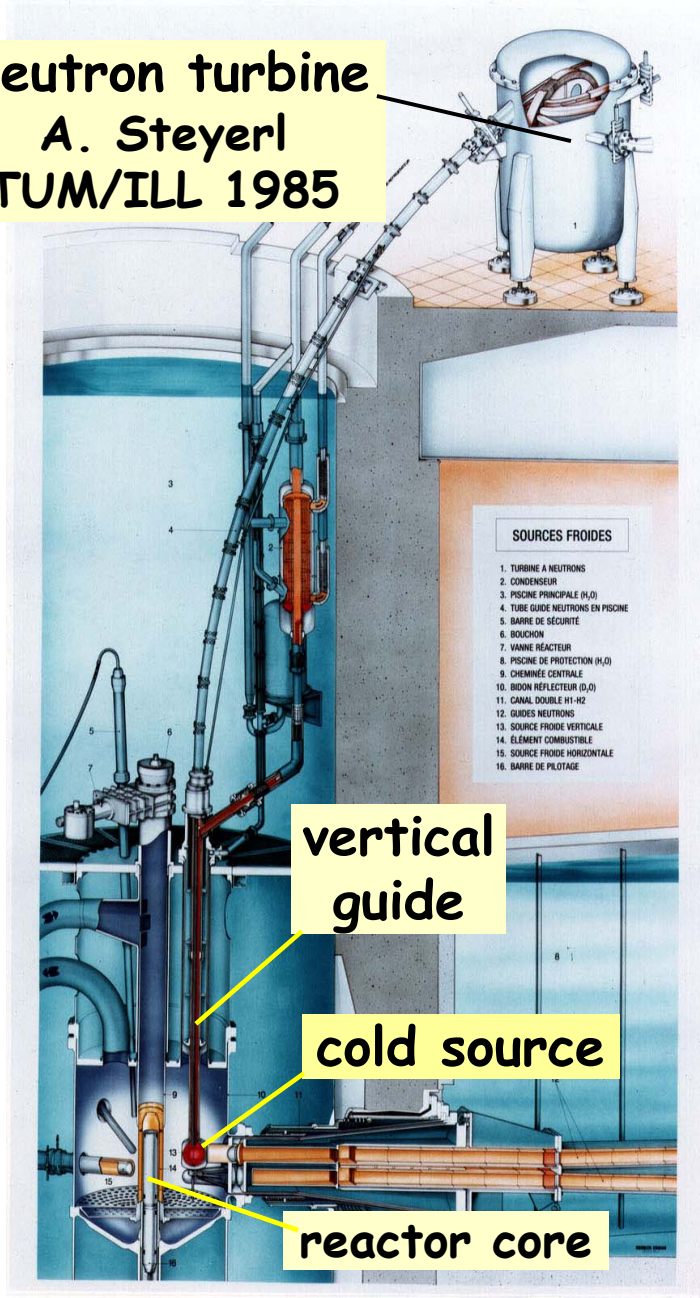
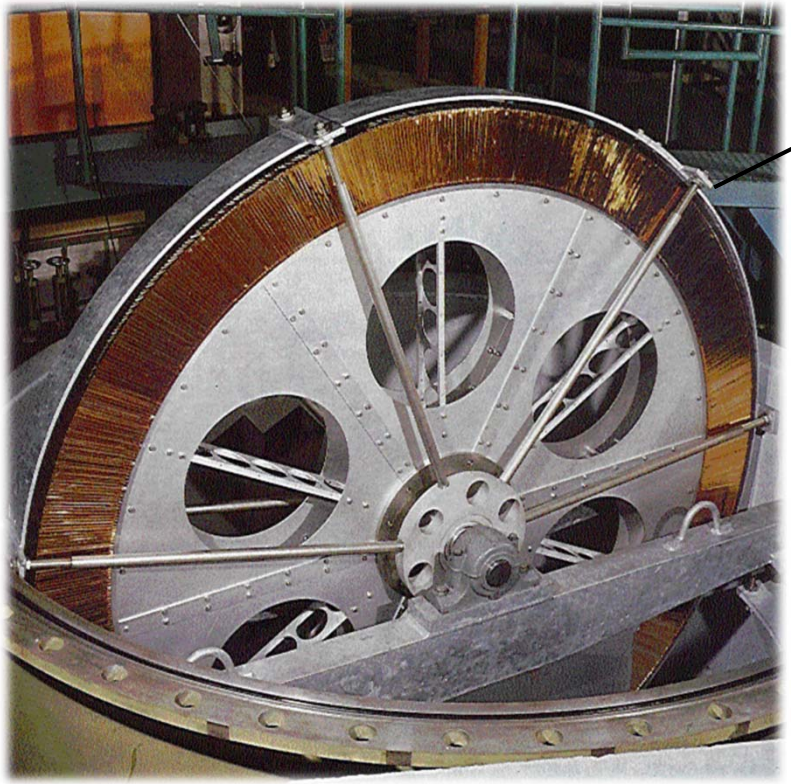


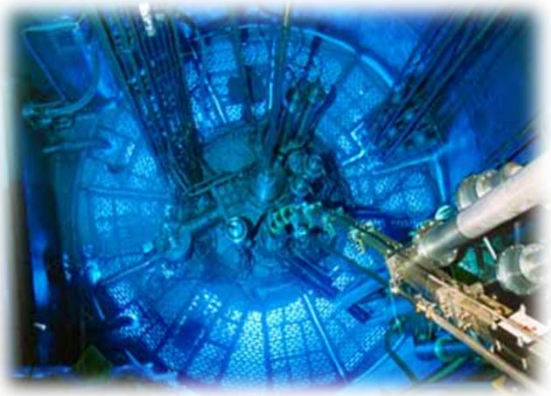


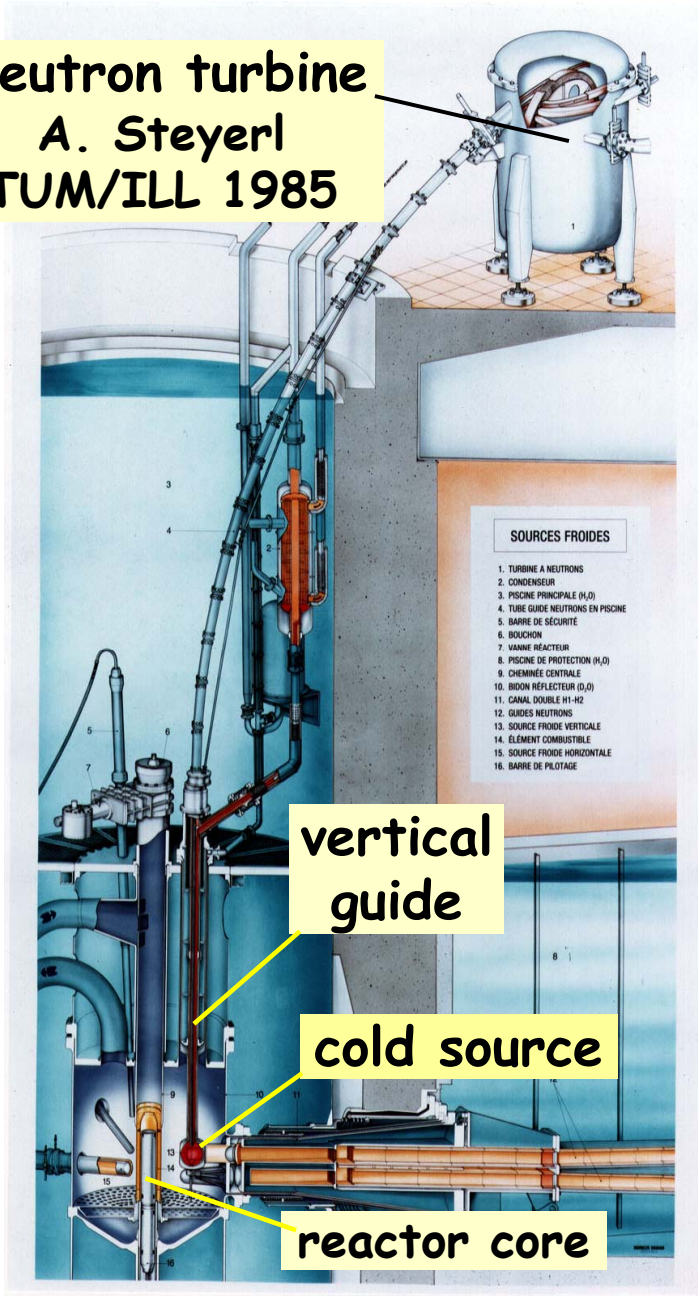
((Ultra)cold) neutron production at ILL

~ 20 cm^{-3}

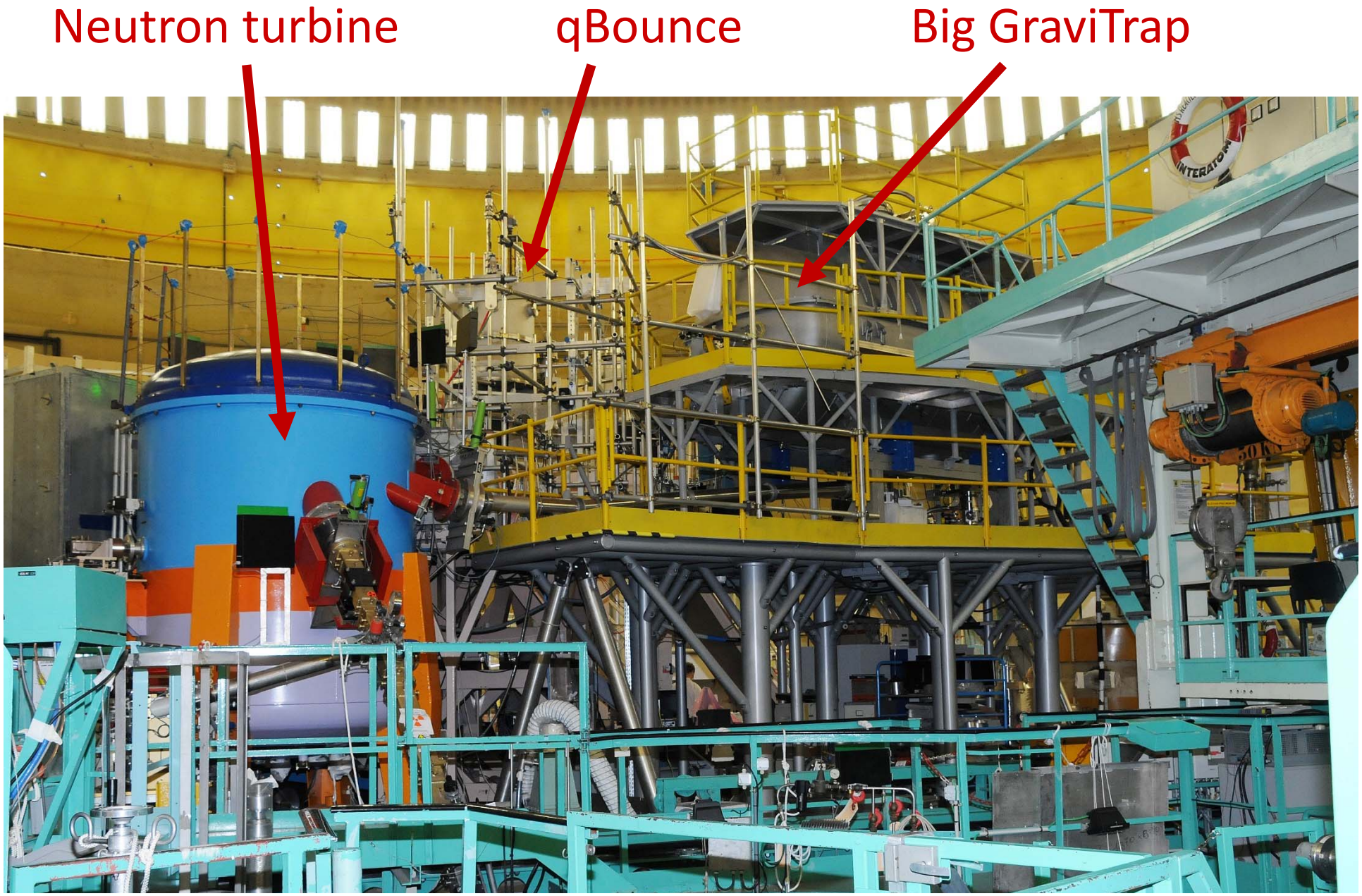


Neutron turbine
A. Steyerl
TUM/ILL 1985





Instruments on “level D” at ILL



Big bang nucleosynthesis and the neutron lifetime

10^{-6} s (100 MeV) quarks & gluons form nucleons

$n + e^+ \leftrightarrow p + \nu$, $n + \nu \leftrightarrow p + e$, $n \rightarrow p + e + \nu$

$$\frac{[\mathrm{n}]}{[\mathrm{p}]} = \exp\left(-\frac{\Delta mc^2}{kT}\right)$$

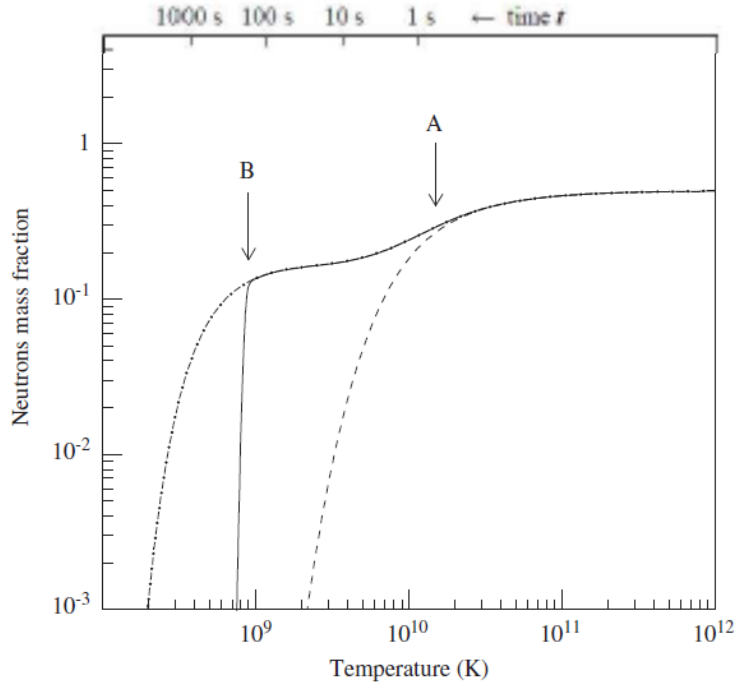
1 s (1 MeV) neutrinos decouple $\Rightarrow$ neutrons decay

$n \rightarrow p + e + \nu$, $p + n \leftarrow d + \gamma$

3 min (0.1 MeV) deuterons become stable

$p(n,\gamma)d$, $d(d,n)^3He$, $d(d,p)^3H$, $^3He(n,\gamma)^4He$ ...

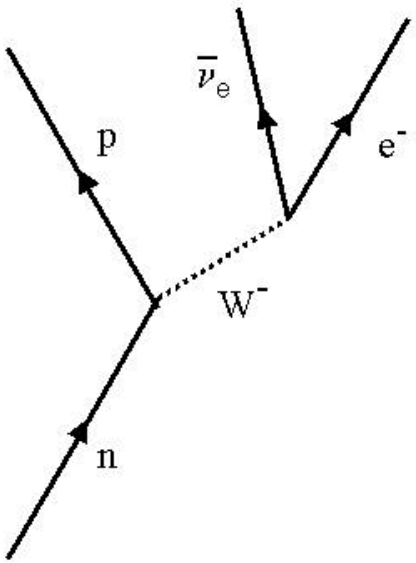
after 30 min **primordial abundances of light elements:**



^{1}H	**75%**
^{4}He	**25%**
^{2}H	**30ppm**
^{3}He	**13ppm**
^{7}Li	**4×10^{-10}**

A. Coc, NIM A **611** (2009) 224
Cyburt et al. Rev. Mod. Phys **88** (2016) 015004-1
Steven Weinberg, "The first three minutes"

Impact for nuclear and particle physics



$\rightarrow g_A$ and g_V

(axial-vector and vector weak formfactors of the nucleon, from neutron lifetime and beta asymmetry)

$\rightarrow$ important cross sections

of 1st generation semileptonic weak interactions, e.g.:

primordial neutrino reactions	$\mathbf{n + e^+ \leftrightarrow p + \bar{\nu}_e}$
solar fusion	$\mathbf{p + p \rightarrow d + e^+ + \nu_e}$
neutrino detection	$\mathbf{\bar{\nu}_e + p \rightarrow n + e^+ \ldots}$

V_{ud} determination and test of CKM unitarity

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

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

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

Marciano & Sirlin PRL 96 (2006) 032002

$\lambda = g_A / g_V$

(from β asymmetry)

$g_V = G_F V_{ud}$

uncertainty due to radiative corrections:

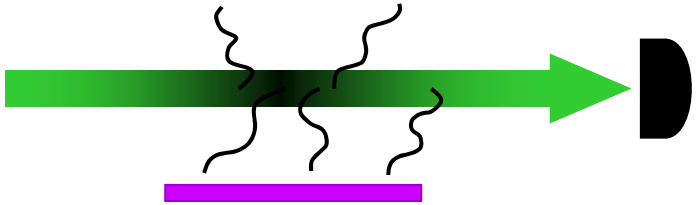
$\delta |V_{ud}|^2_{RC} = 3.8 \times 10^{-4}$ $\rightarrow$ request $\delta\tau_n < 0.3$ s

How can we measure the neutron lifetime?

- **In-beam experiments:**
  - measure radioactivity of a neutron beam:

$$\frac{dN}{dt} = -\frac{N}{\tau_{\mathrm{n}}} = -\frac{\rho V}{\tau_{\mathrm{n}}}$$

$E_n \approx$ a few meV

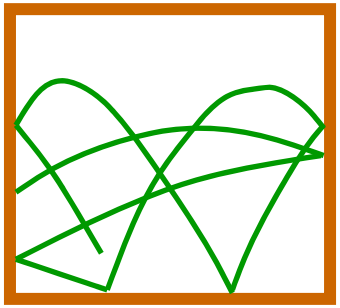


  - needs absolute knowledge of $\frac{dN}{dt}$, ρ, V and detection efficiency

- **UCN trapping experiments:**
  - measure decrease of neutron number directly:

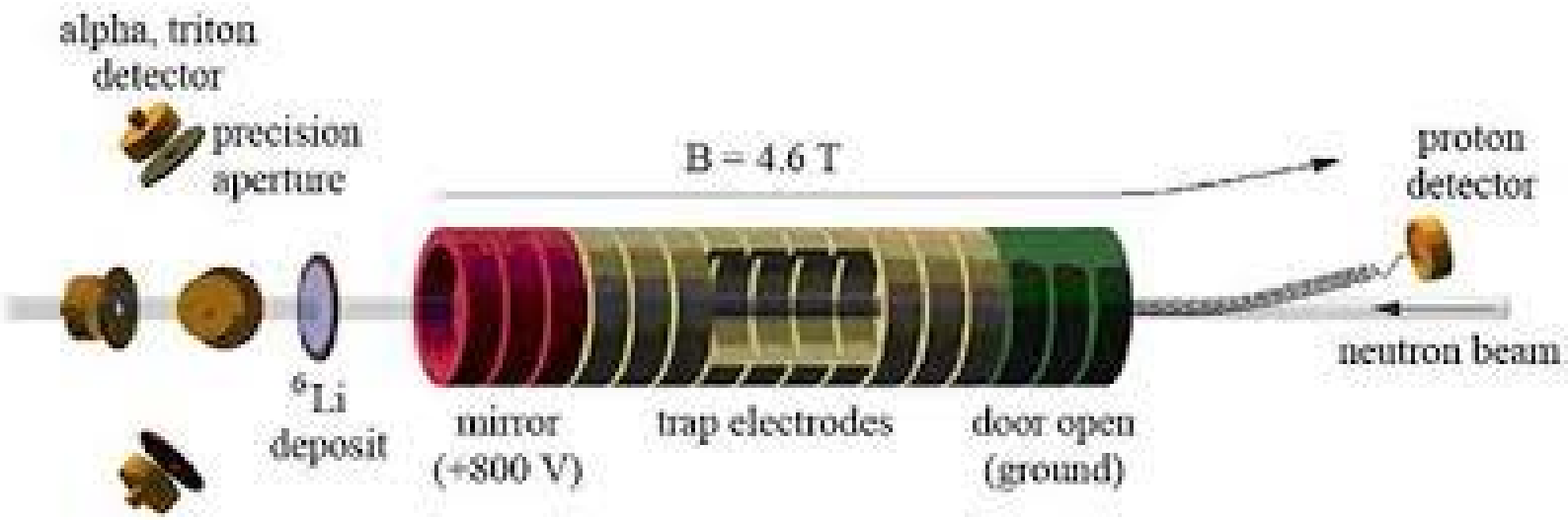
$$N(t) = N(0)\exp\left(-\frac{t}{\tau}\right)$$

E_n < 250 neV



  - no absolute determinations, but: $\tau^{-1} = \tau_{\mathrm{n}}^{-1} + \tau_{\mathrm{loss}}^{-1}$

The NIST in-beam neutron lifetime experiment

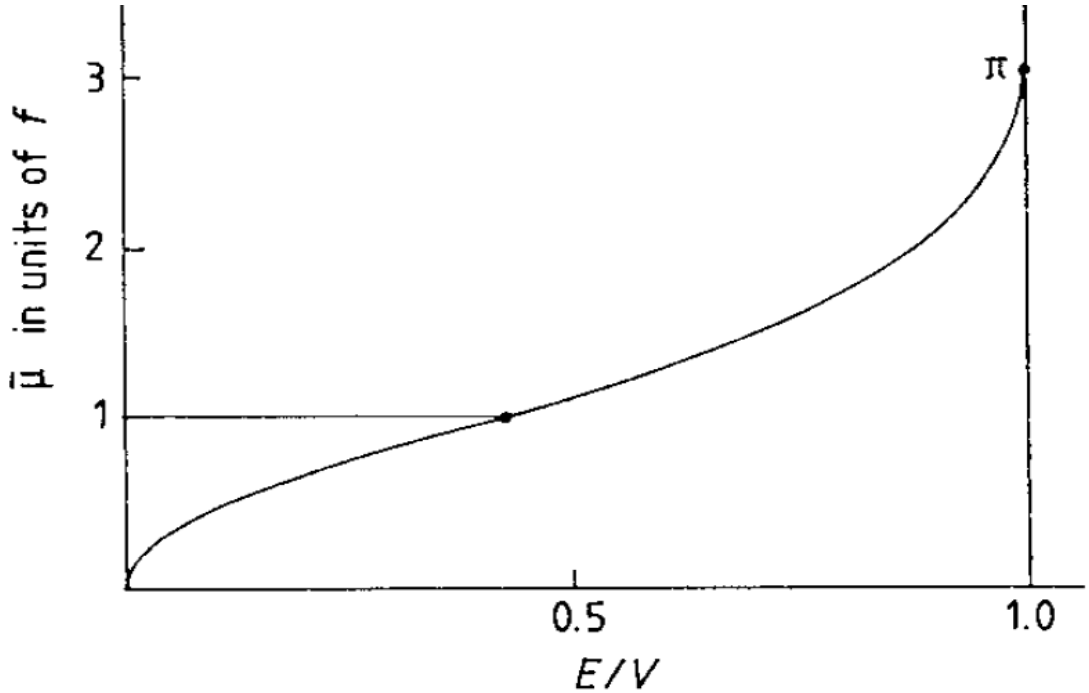


Trap of variable length, electrode distances used for blinding

$\tau_n = (887.7 \pm 1.2_{stat} \pm 1.9_{sys})$ s A.T. Yue et al., Phys. Rev. Lett 111, 222501 (2013)

Loss per wall collision for trapped UCN gas:

$$\overline{\mu}(E) = 2f\left[\frac{V}{E}\arcsin\left(\sqrt{\frac{E}{V}}\right) - \sqrt{\frac{V}{E}-1}\right]$$



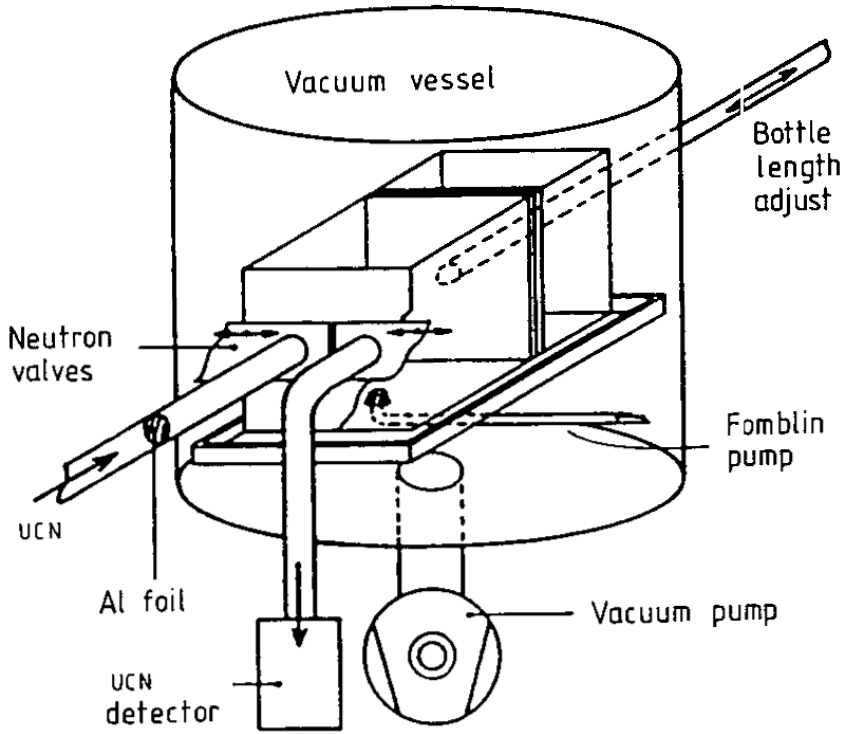
$f = W/V$

Not sufficiently under control for reliable calculation

→ need experimental strategy

The liquid-wall trap of Walter Mampe

- Liquid surfaces (fomblin oil)
- Modulation of losses via well-defined variation of the ratio surface/volume
- Extrapolation: volume $\rightarrow \infty$
- <u>Result:</u>



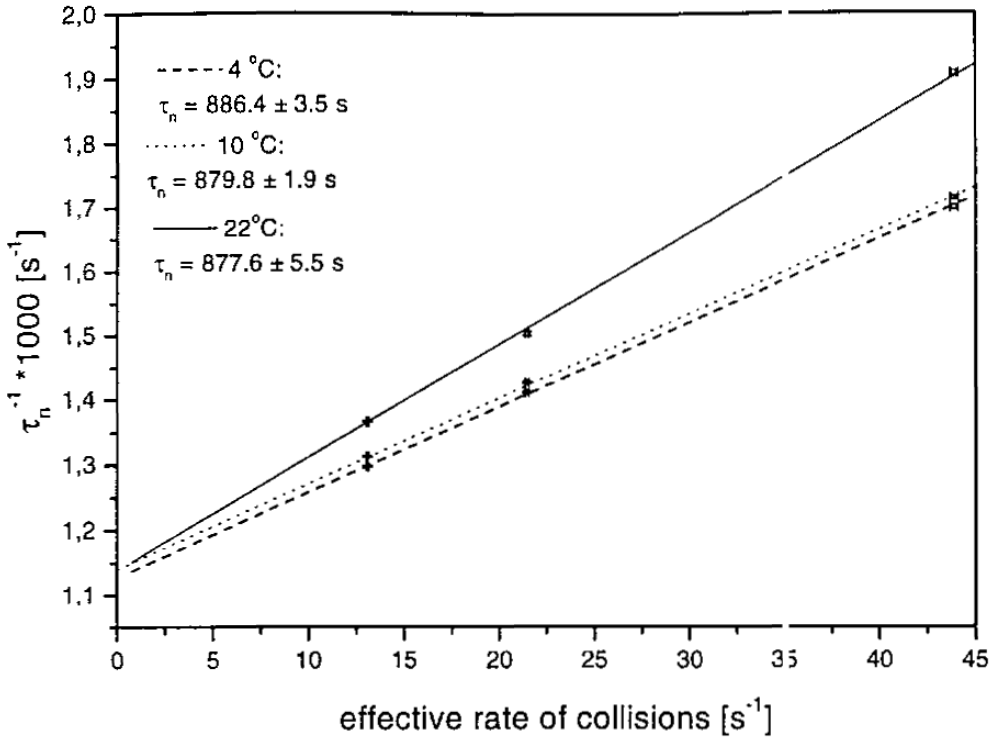
τ_n = 887.6 ± 3 s W. Mampe et al., Phys. Rev. Lett. 63 (1989) 593

- <u>Result of follow-up experiment MAMBO II:</u>

880.7 ± 1.8 s A. Pichlmaier et al. Phys. Lett. B 693 (2010) 221

The liquid-wall trap of Walter Mampe

- Liquid surfaces (fomblin oil)
- Modulation of losses via well-defined variation of the ratio surface/volume
- Extrapolation: volume → ∞
- <u>Result:</u>

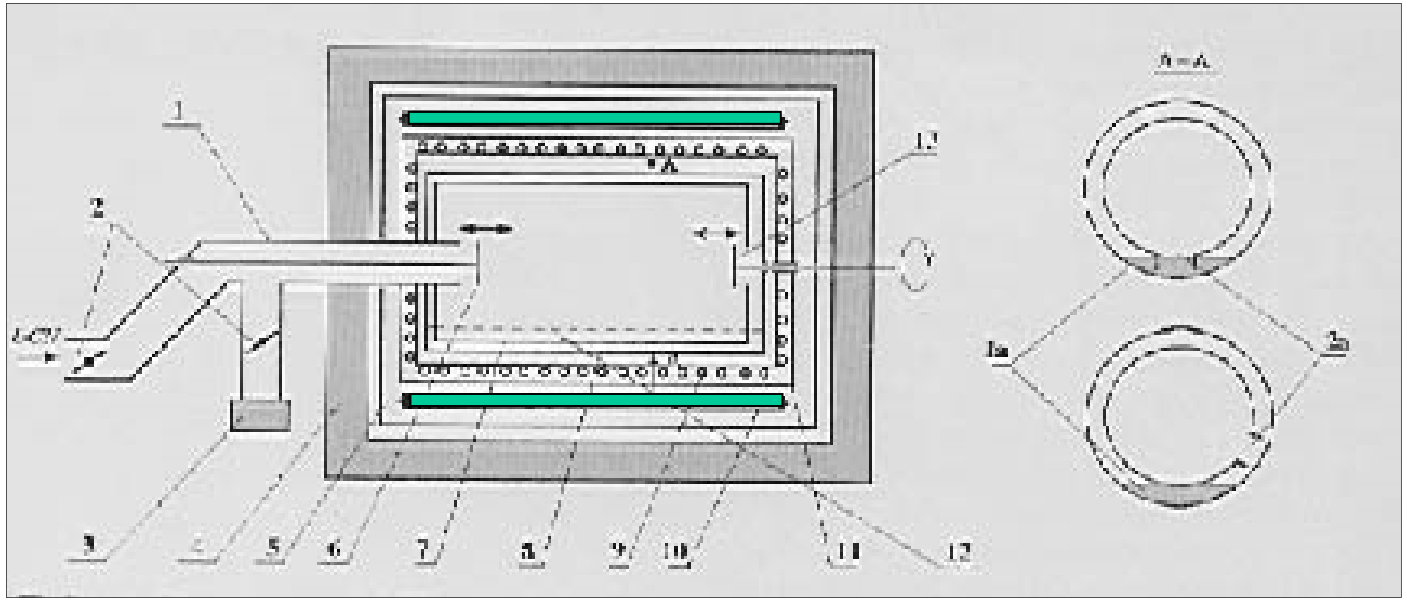


τ_n = 887.6 ± 3 s W. Mampe et al., Phys. Rev. Lett 63 (1989) 593

- <u>Result of follow-up experiment MAMBO II:</u>

880.7 ± 1.8 s A. Pichlmaier et al. Phys. Lett. B 693 (2010) 221

Experiment with detection of upscattered neutrons



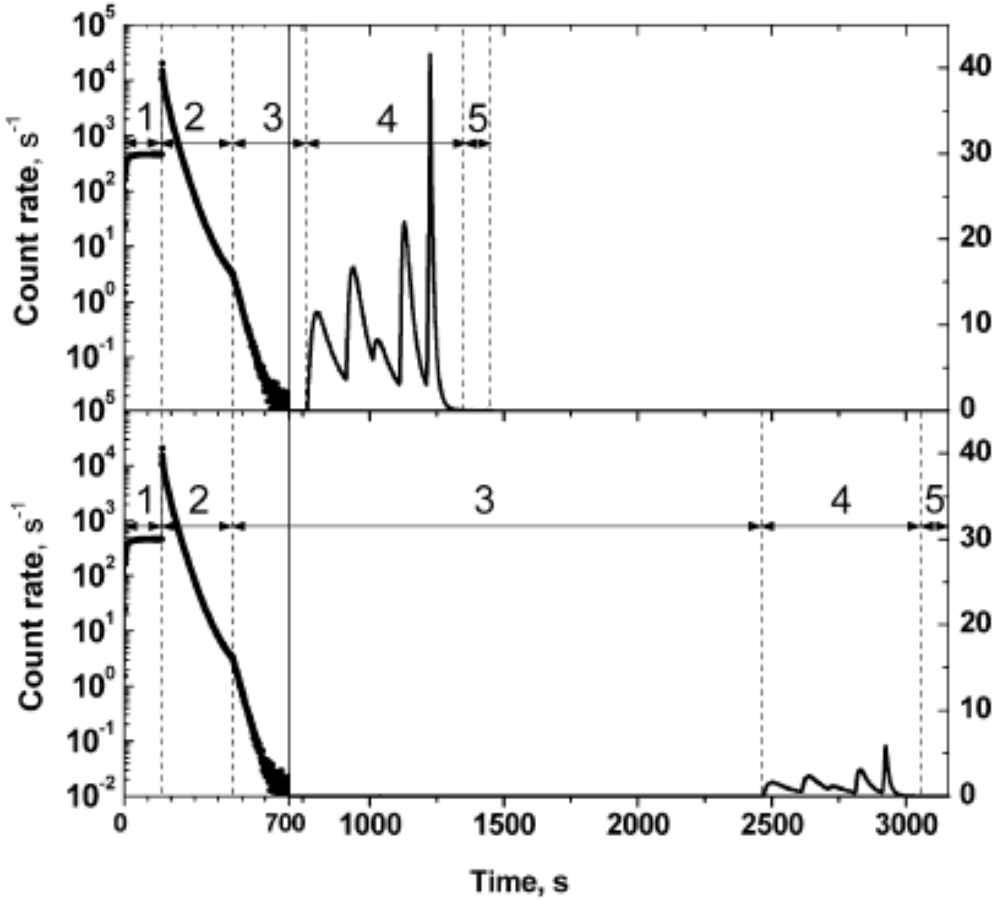
- Liquid surfaces (fomblin oil)
- <u>Result (+ revision):</u>

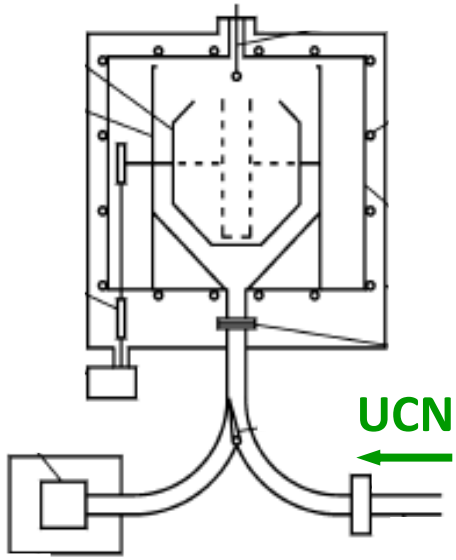
$\tau_n = 885.4 \pm 0.9_{stat} \pm 0.4_{syst}$ s Arzumanov et al., Phys. Lett. B 483 (2000) 15

$881.6 \pm 0.8_{stat} \pm 1.9_{syst}$ s Arzumanov et al. JETP Lett. 95 (2012) 224

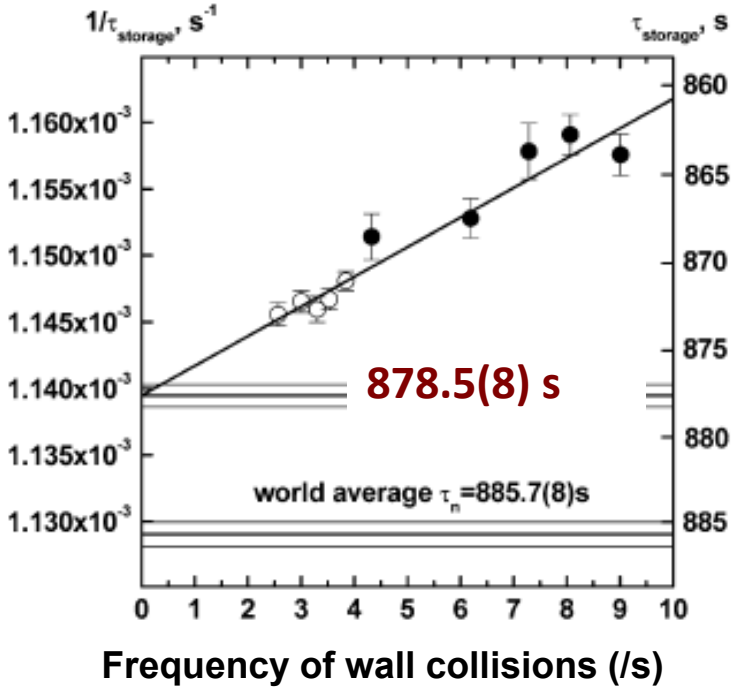
Neutron lifetime experiment **GraviTrap** with low-*T* „fomblin“ oil coated walls

A. Serebrov et al., PLB **605** (2005) 72





$$\tau_{\text{storage}}^{-1} = \tau_{\text{n}}^{-1} + \tau_{\text{loss}}^{-1}$$



Successor experiment Big GraviTrap

(during installation in 2014 at ILL)

Job (installation) done...

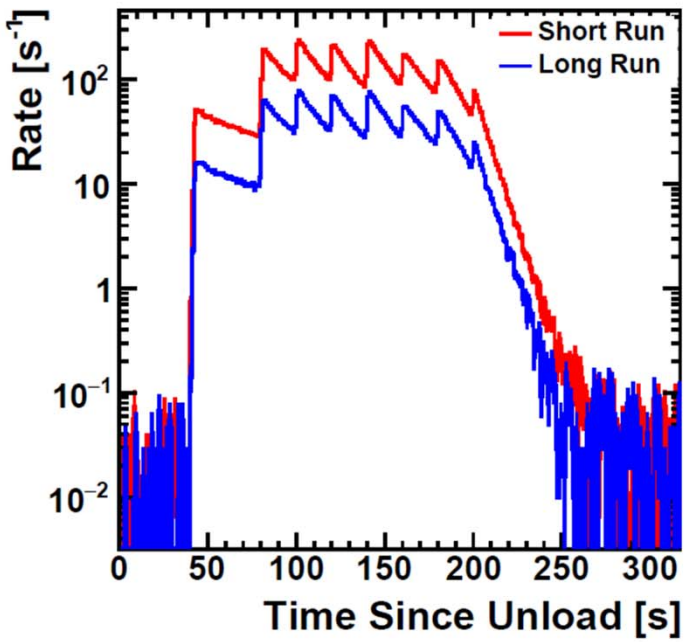
Work on trap preparation

First result (measurements to be continued with colder trap):

Serebrov et al., PRC 97, 055503 (2018):

$\tau_n = (881.5 \pm 0.7 \pm 0.6)$ s

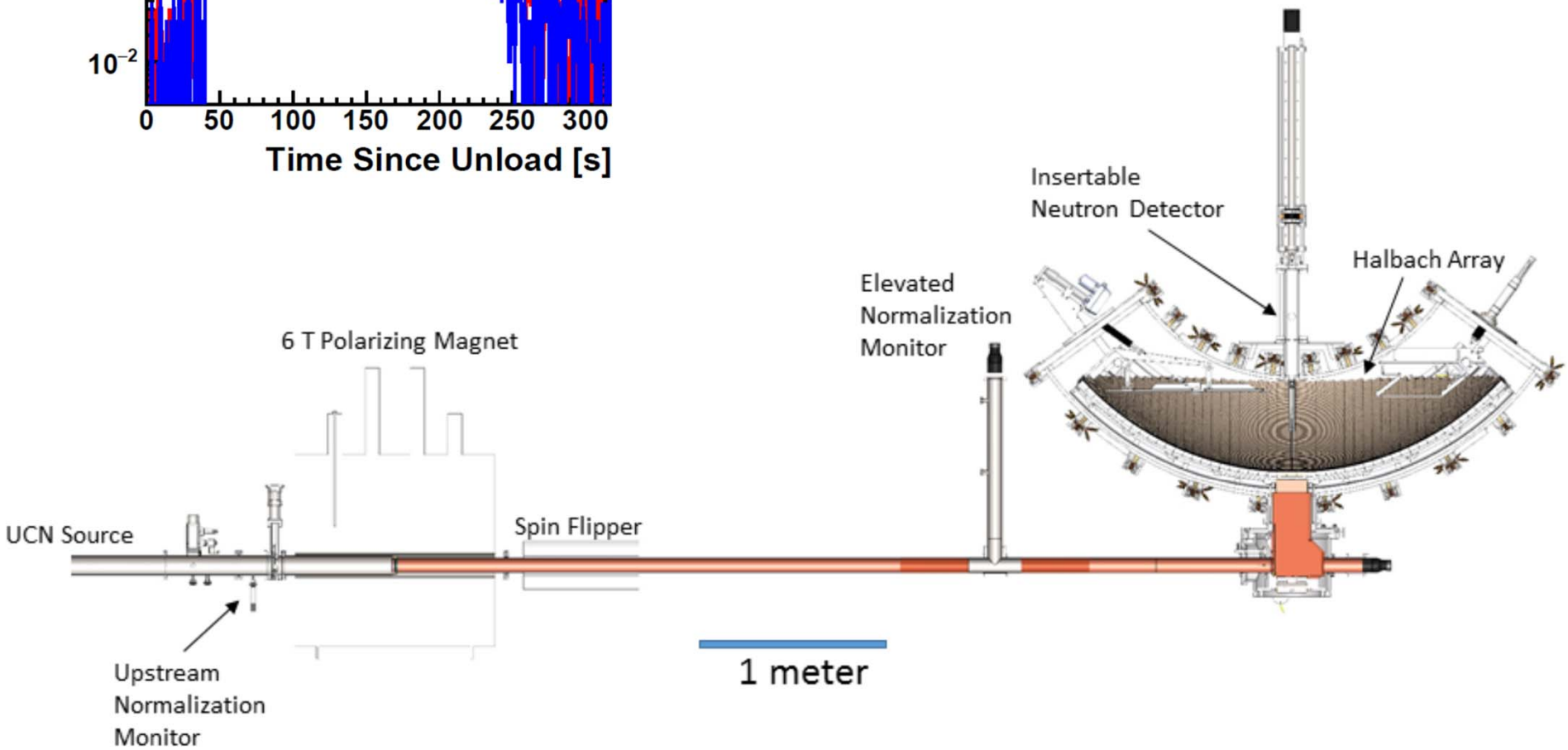
UCN τ ("fill and kill")

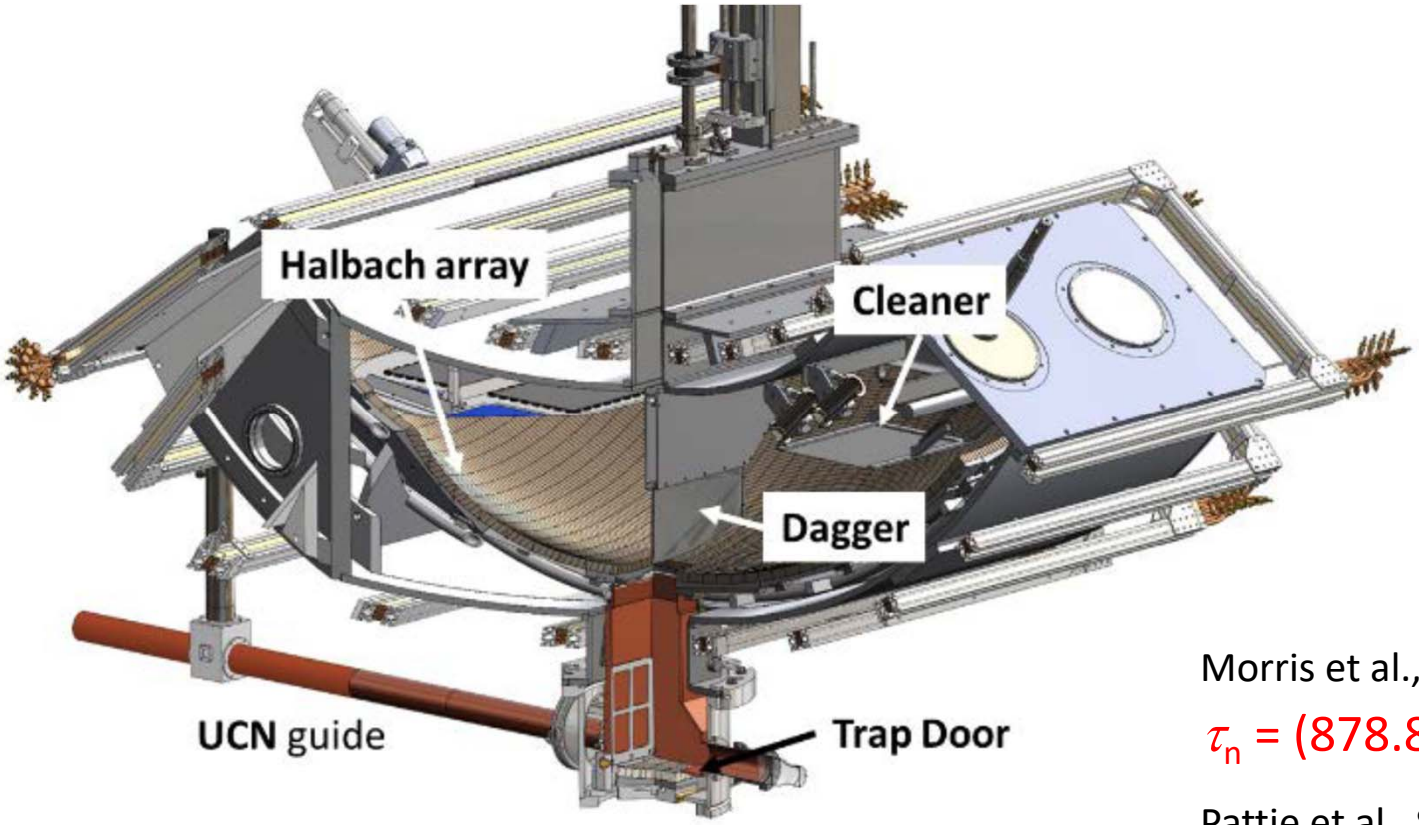


done at Los Alamos

magneto-gravitational trapping

asymmetric trap $\rightarrow$ chaotic trajectories





Morris et al., arXiv:1610.04560:

τ_n = (878.8 ± 2.6 ± 0.6) s

Pattie et al., Science 360, 627 (2018) (arXiv:1707.01817):

τ_n = (877.7 ± 0.7 + 0.3/-0.1) s

+ triple blind analysis

– no monitoring of depolarised UCNs

Statement in first arXiv version:

"…is the first measurement of τ_n that does not require corrections larger than the quoted uncertainties" but:

The neutron storage ring NESTOR

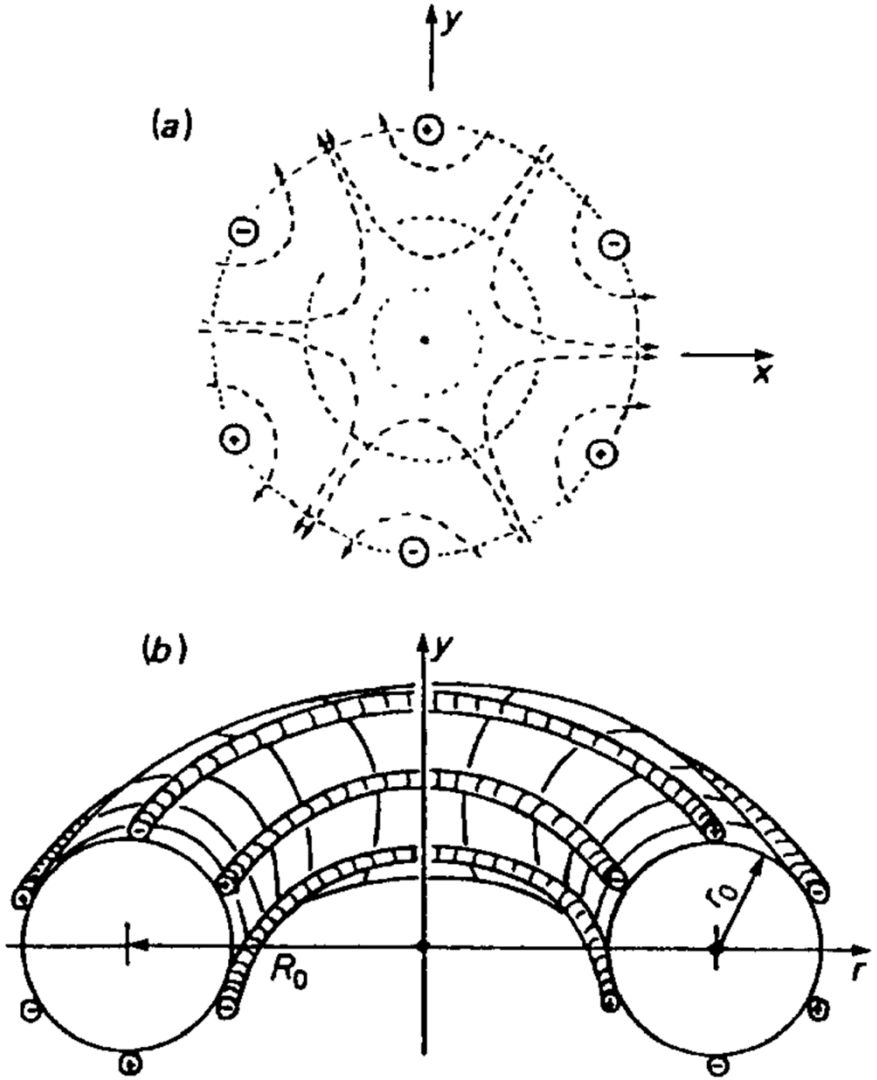
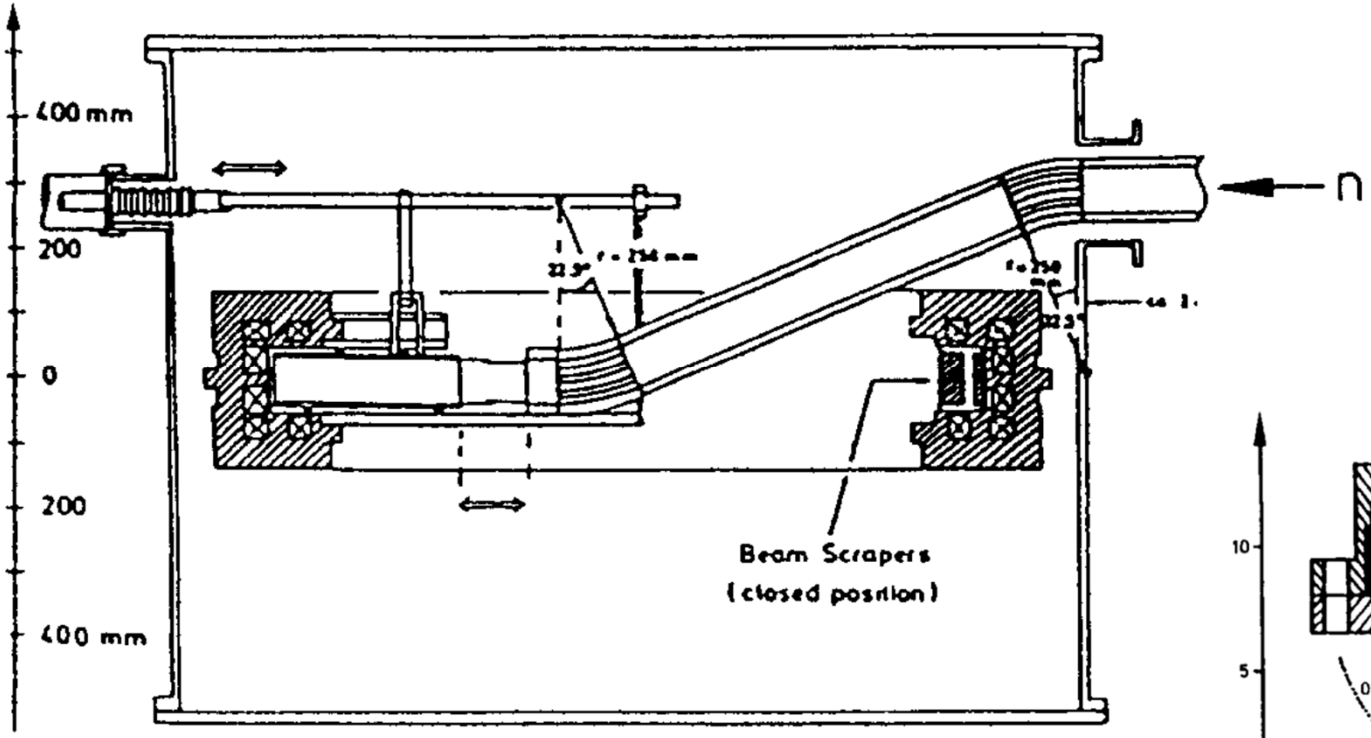
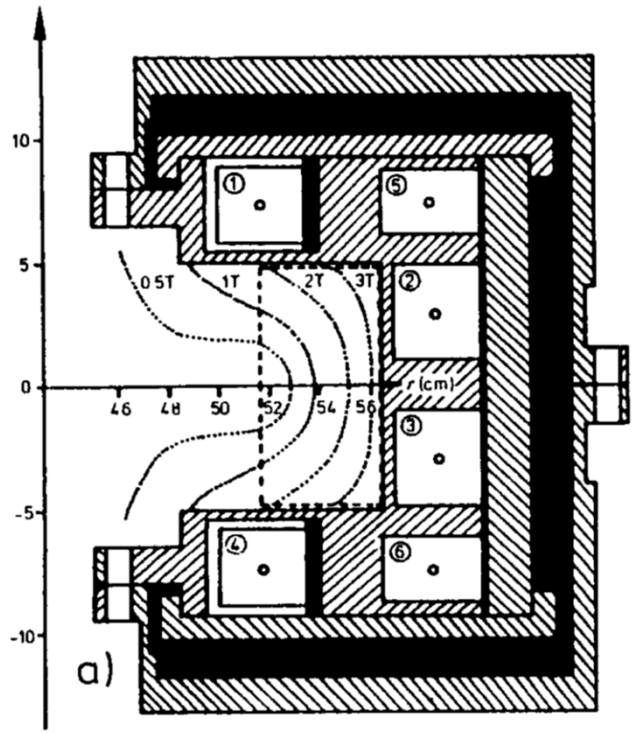


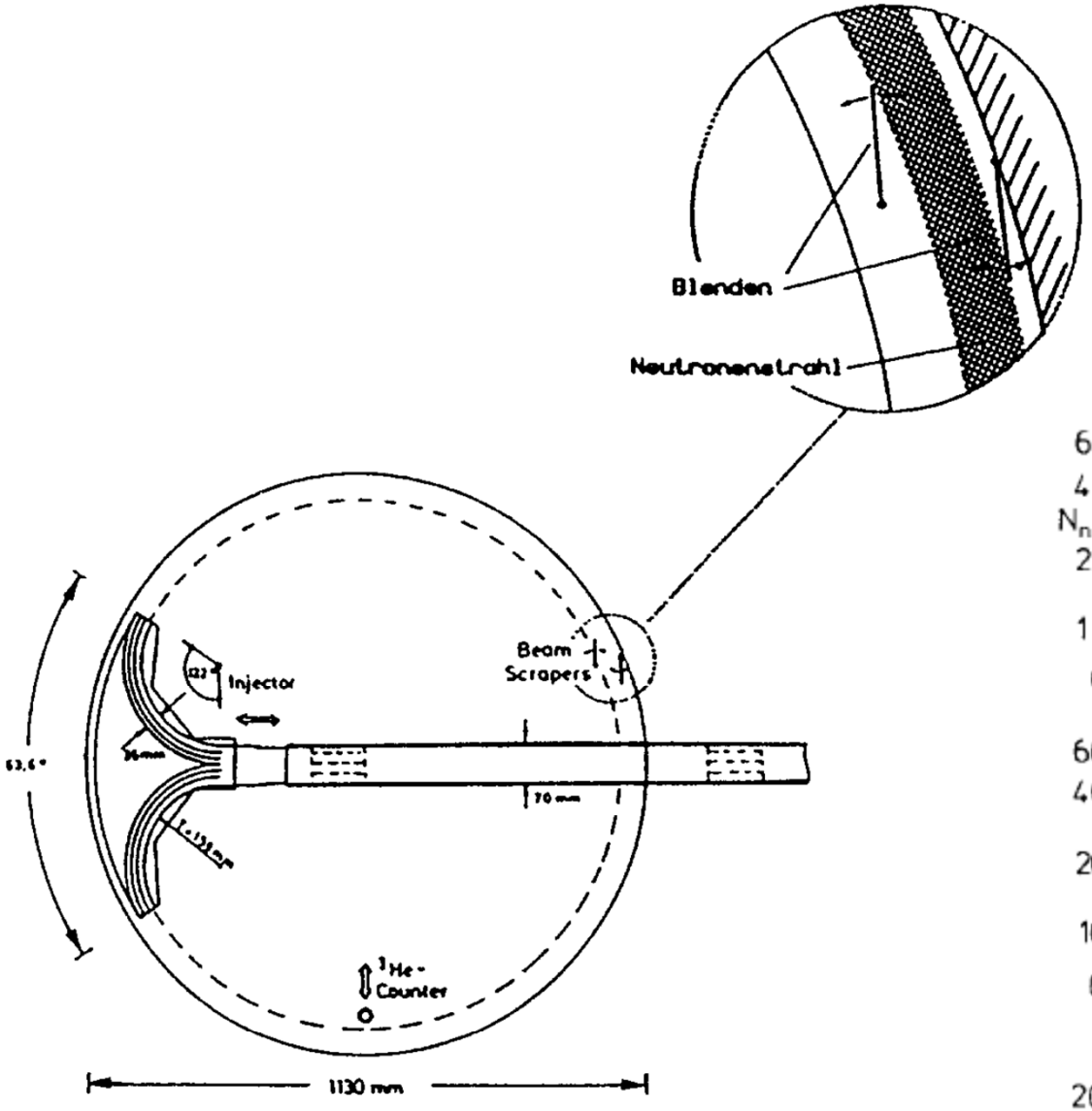
Fig. 2 Field lines and magnetic induction B of a linear sextupole (a) and of a sextupole torus (b).

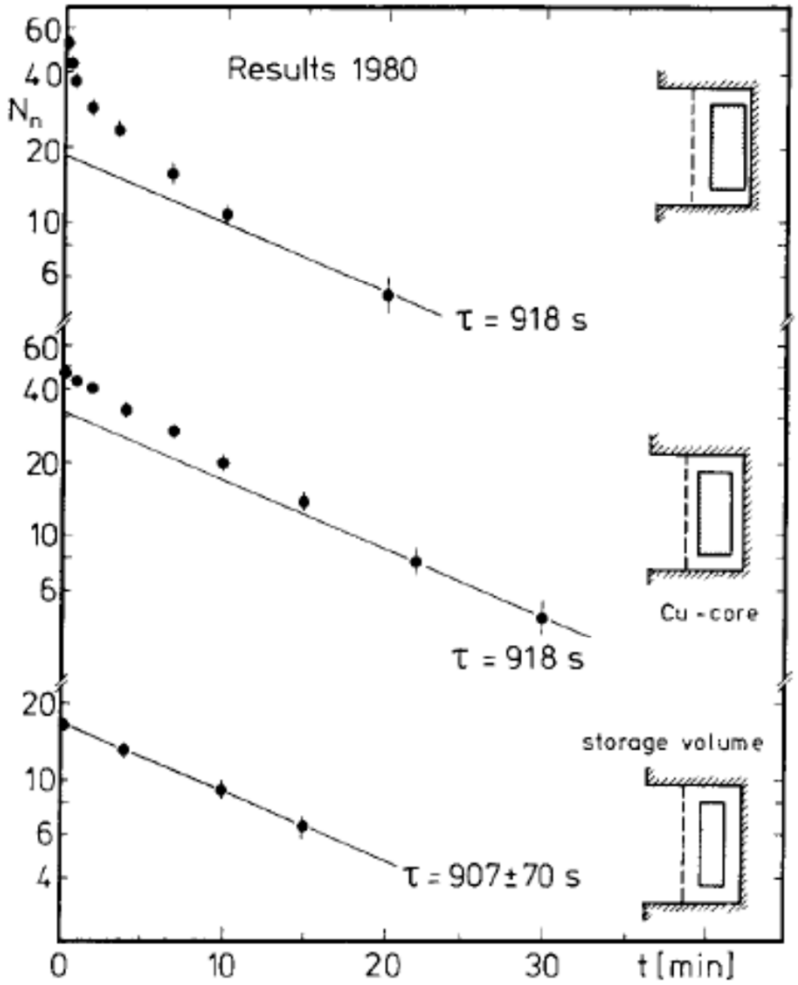
<u>Principle:</u> balance of centrifugal and Stern-Gerlach forces In a magnetic sextupole ring

NESTOR: the real device






Blenden
Neutronenstrahl
Injector
Beam Scrapers
70 mm
^{3}He - Counter
1130 mm


Results 1980
N_n
τ = 918 s
τ = 918 s
τ = 907 ± 70 s
Cu - core
storage volume
t [min]

F. Anton, W. Paul, W. Mampe, L. Paul and S. Paul

NIM A **284** (1989) 101

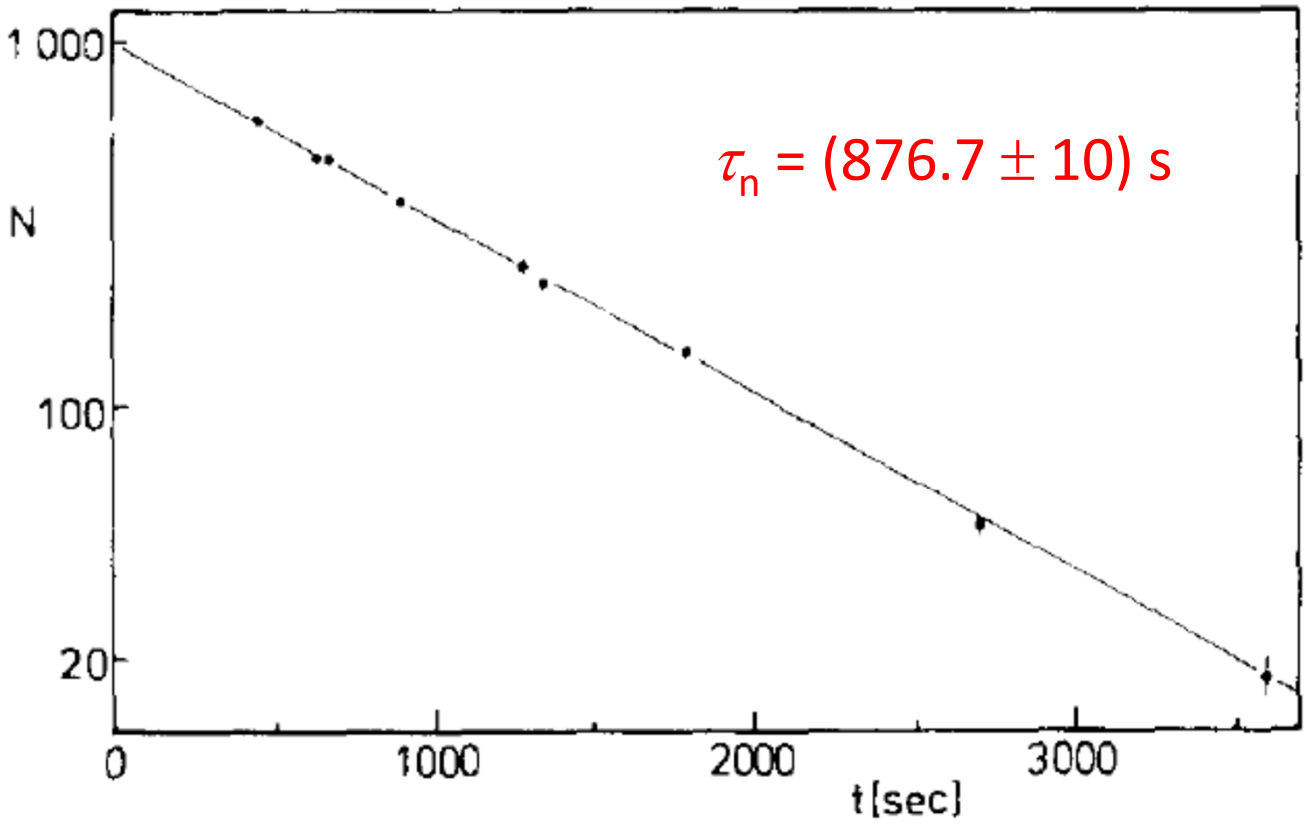


Fig. 12. Neutron lifetime in the storage ring. The diagram contains all data normalized to $N = 1000$.

...no corrections larger than the quoted uncertainties

F. Anton, W. **Paul**, W. Mampe, L. **Paul** and S. **Paul**

NIM A **284** (1989) 101

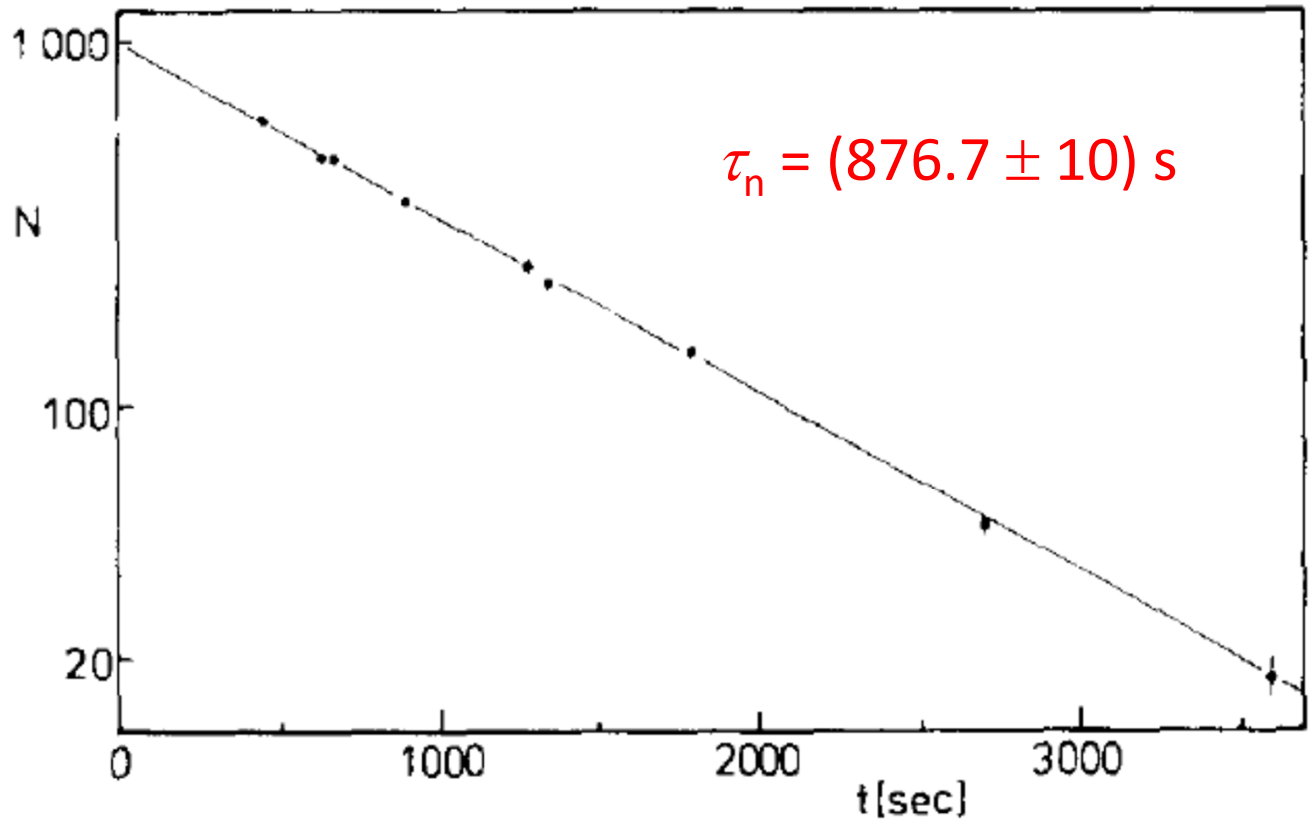
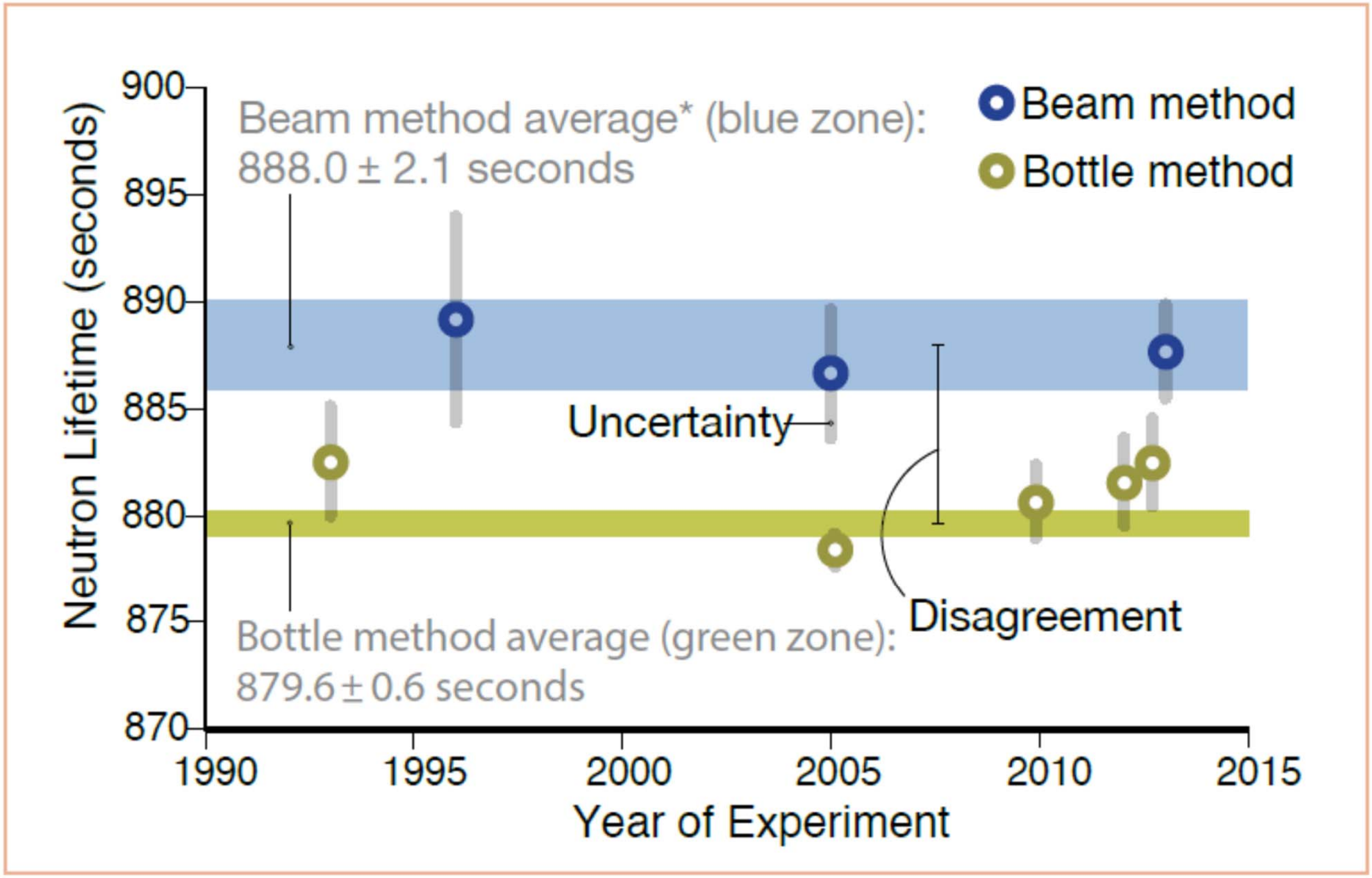


Fig. 12. Neutron lifetime in the storage ring. The diagram contains all data normalized to $N = 1000$.

...no corrections larger than the quoted uncertainties

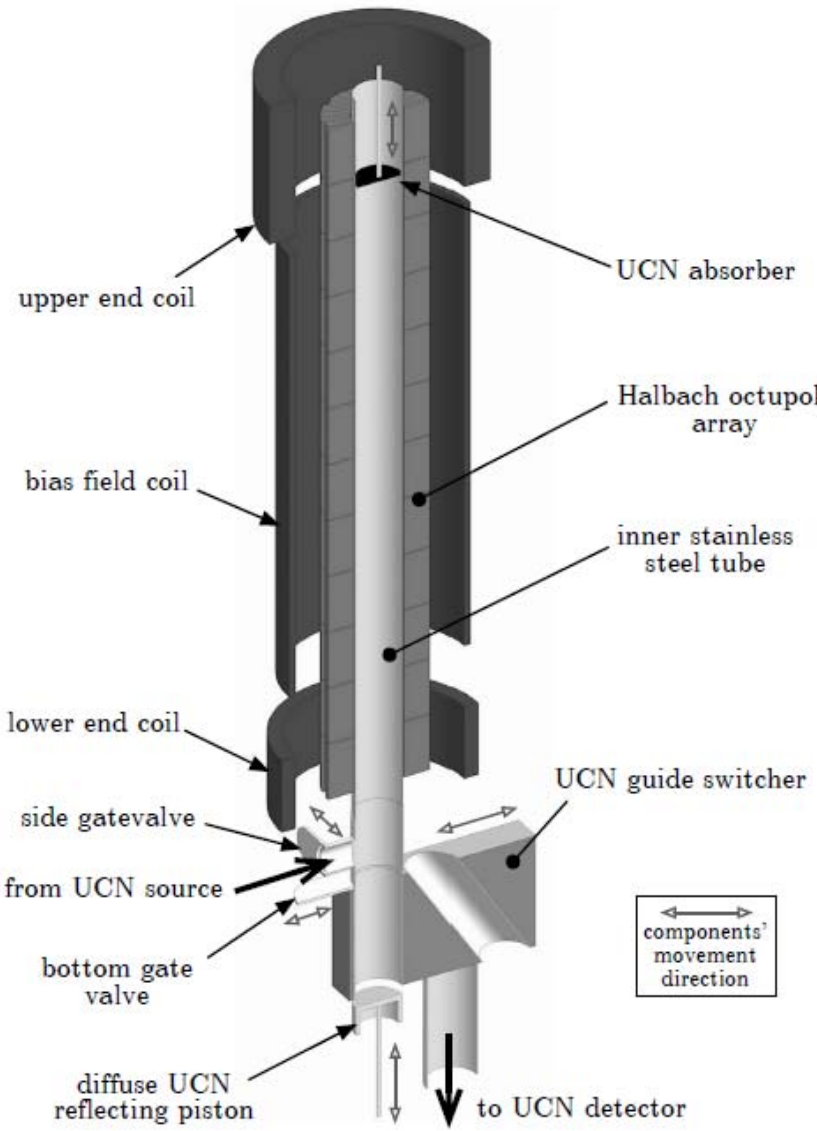
Current situation

G. Greene and P. Geltenbort, Sci. Am. **314** (2016) 36

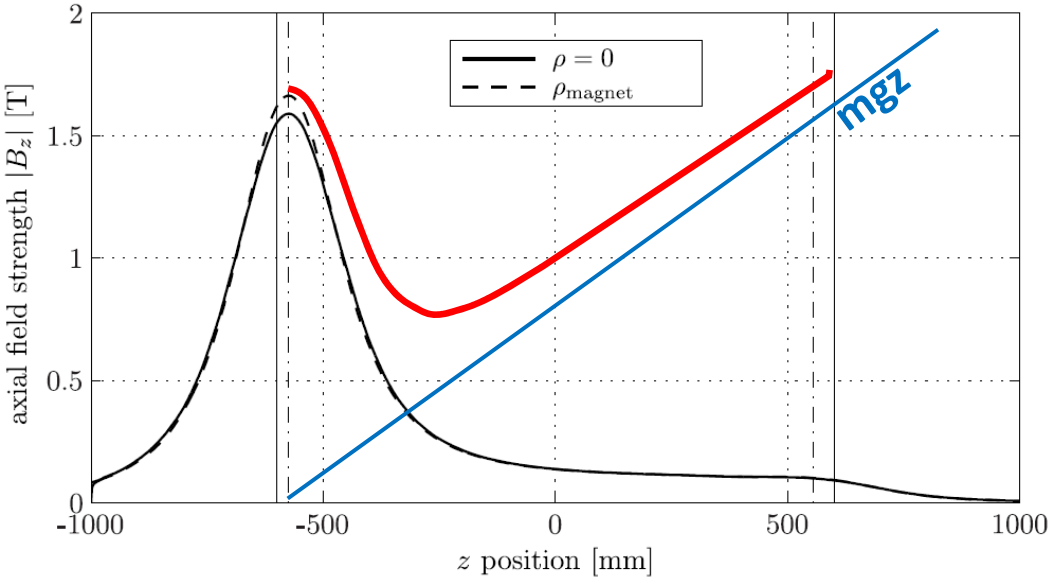


HOPE – Halbach OctuPole neutron lifetime Experiment

PhD works Loris Babin, Felix Rosenau, Fabien Lafont, Kent Leung

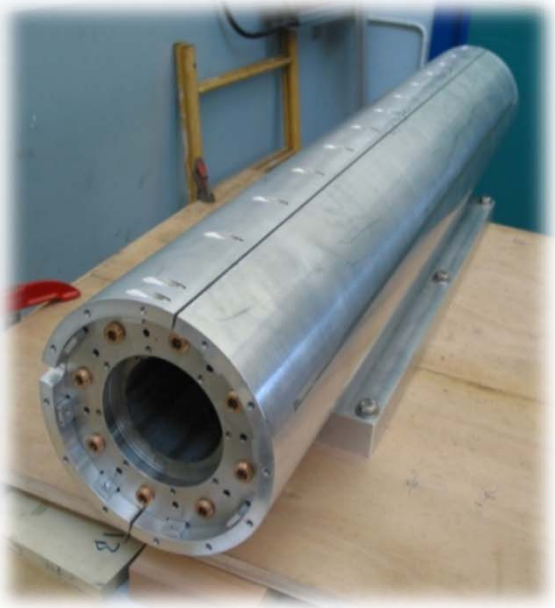


- magneto-gravitational trap
- $V_{eff} \approx 2$ l
- trap depth 47 neV
- counting the dead & survivors
- depolarisation monitoring
- employs a new UCN source

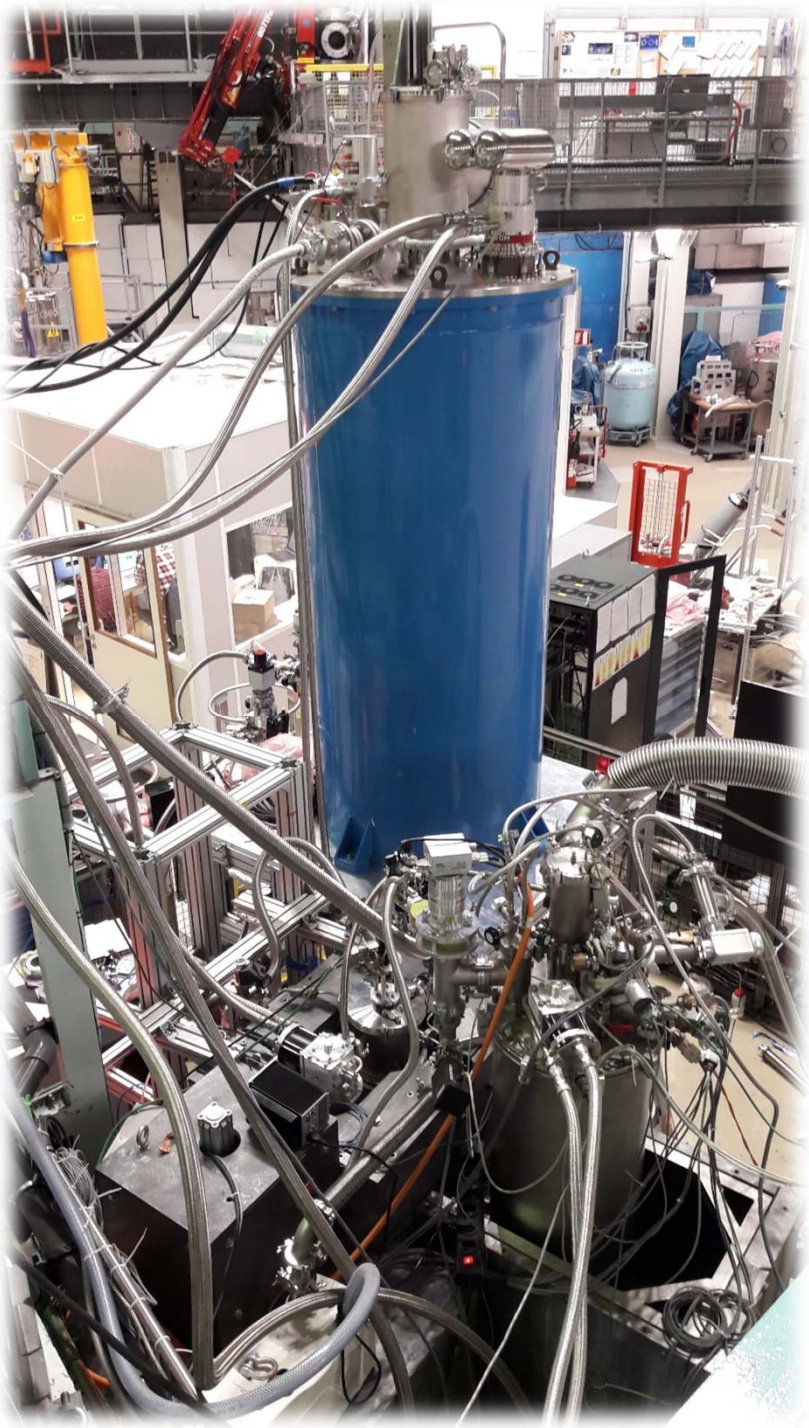


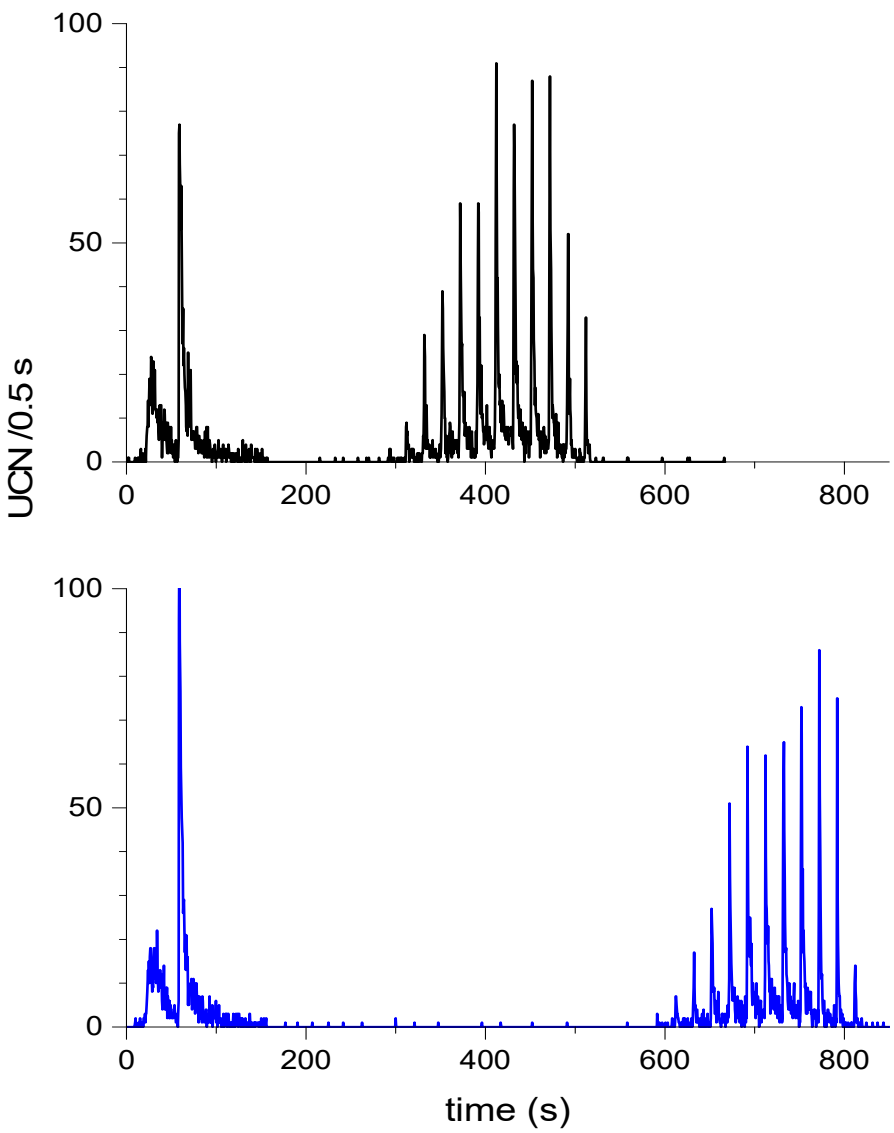
Halbach octupole radial trap

- $B(r) = B_R(r/R)^3$
- 32 magnet slices
- B_R = 1.35 T (NdFeB)



12 8-pole modules + hands & forces = magnetic trap



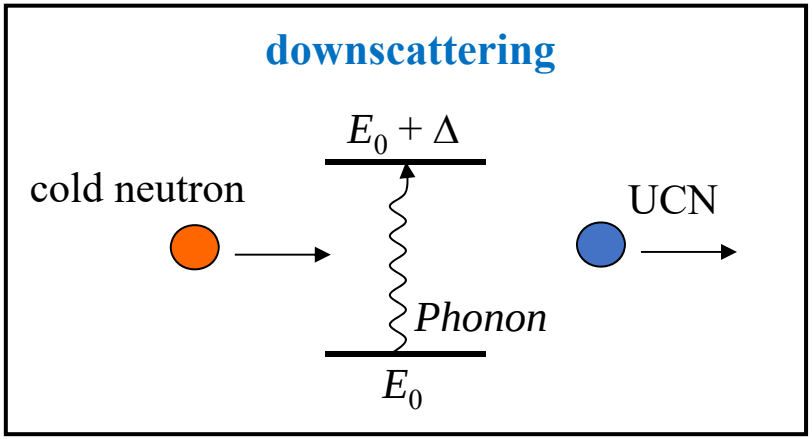


Exp. established statistical sensitivity at SUN-2 prototype UCN source:

0.7 s /50 days

How to produce more ultracold neutrons?

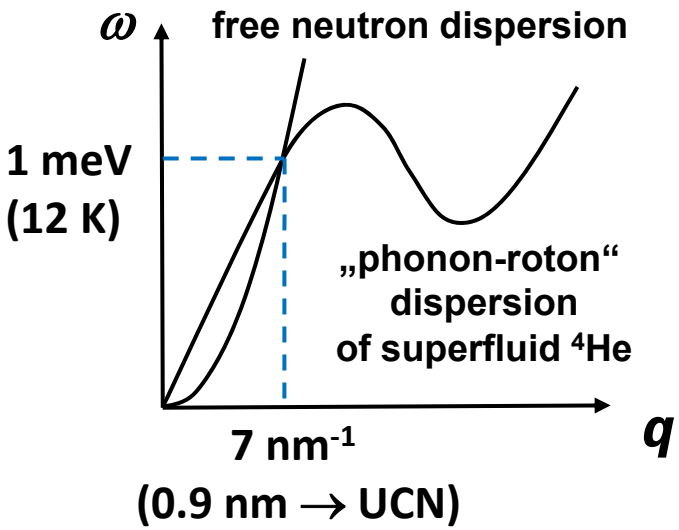
UCN sources based on neutron **conversion**:

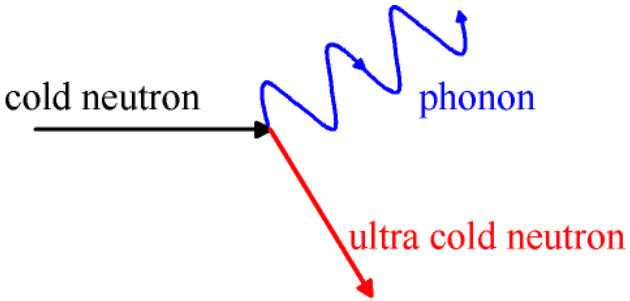


	solid Deuterium sD_2:	superfluid helium-4:
• temperature:	5 K	0.5 K (1.3 K)
• spin effects	para-D_2 content < 1%	spin-0
• UCN storage lifetime	$\approx$ 0.15 s	$\rightarrow \tau_n \approx$ 880 s
• mesoscopic structure	single crystal – crystallites	homogeneous liquid
• implementation	in-pile	in beam (in-pile)

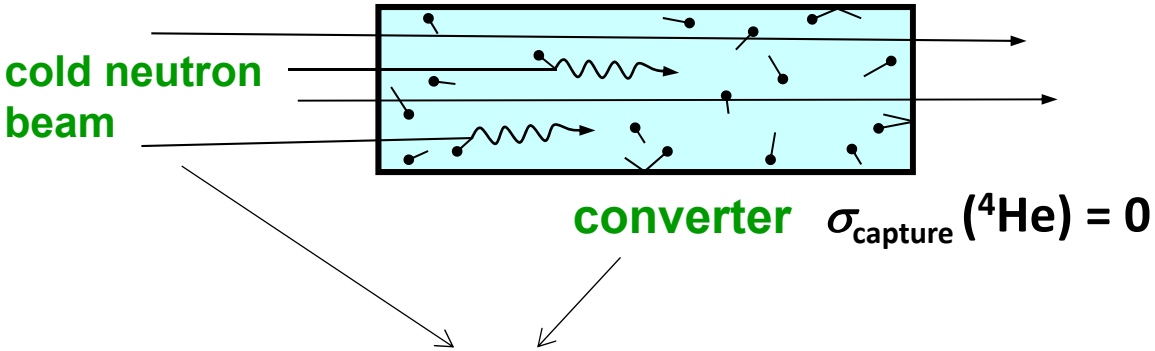
UCN production in superfluid He

R. Golub, J.M. Pendlebury, PL **53A** (1975) 133





T [K]	τ_{max} [s]
1	100
0.8	310
0.7	510
0.5	820
0	880



$$\rho_{UCN} = P\tau$$

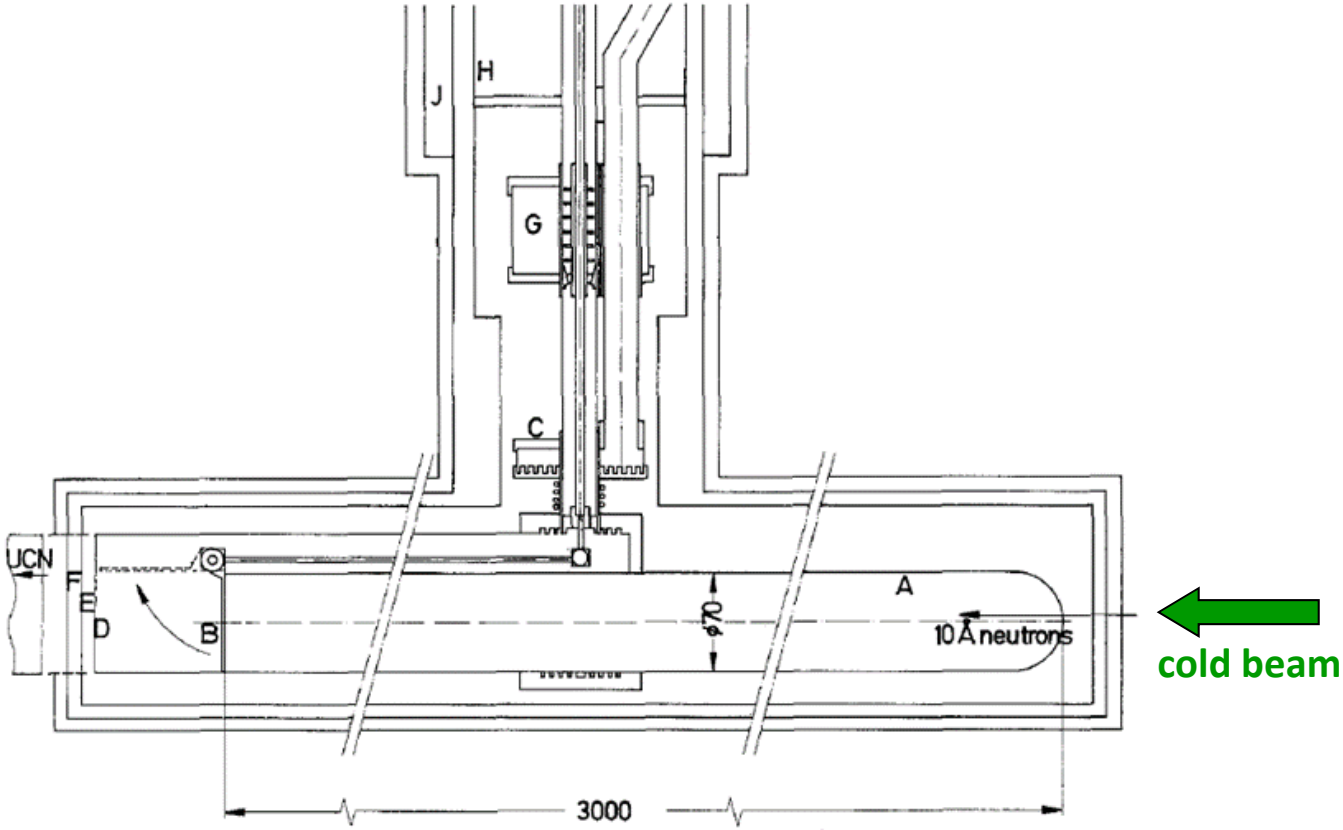
$$\tau^{-1} = \tau^{-1}_{decay} + \tau^{-1}_{upscattering} + \tau^{-1}_{capture} + \tau^{-1}_{wall\ losses}$$

→ **need T < 0.5 - 0.6 K and low-loss walls**

UCN accumulation and extraction?

Factor 50 missing in an experiment at ILL in the 1980's

→ „one cannot extract UCNs accumulated in superfluid helium"

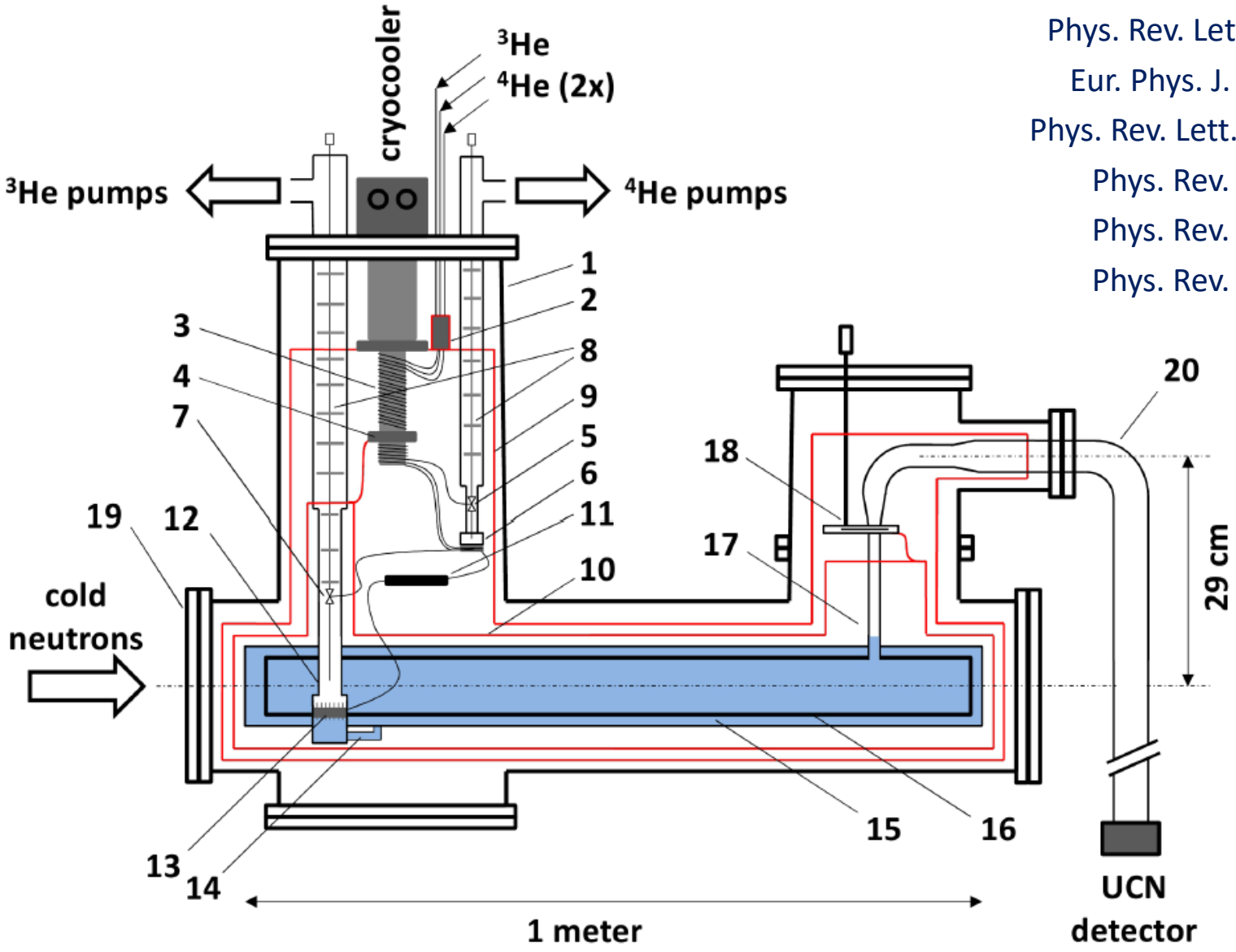


A.I. Kilvington *et al.*, PL A **125** (1987) 416

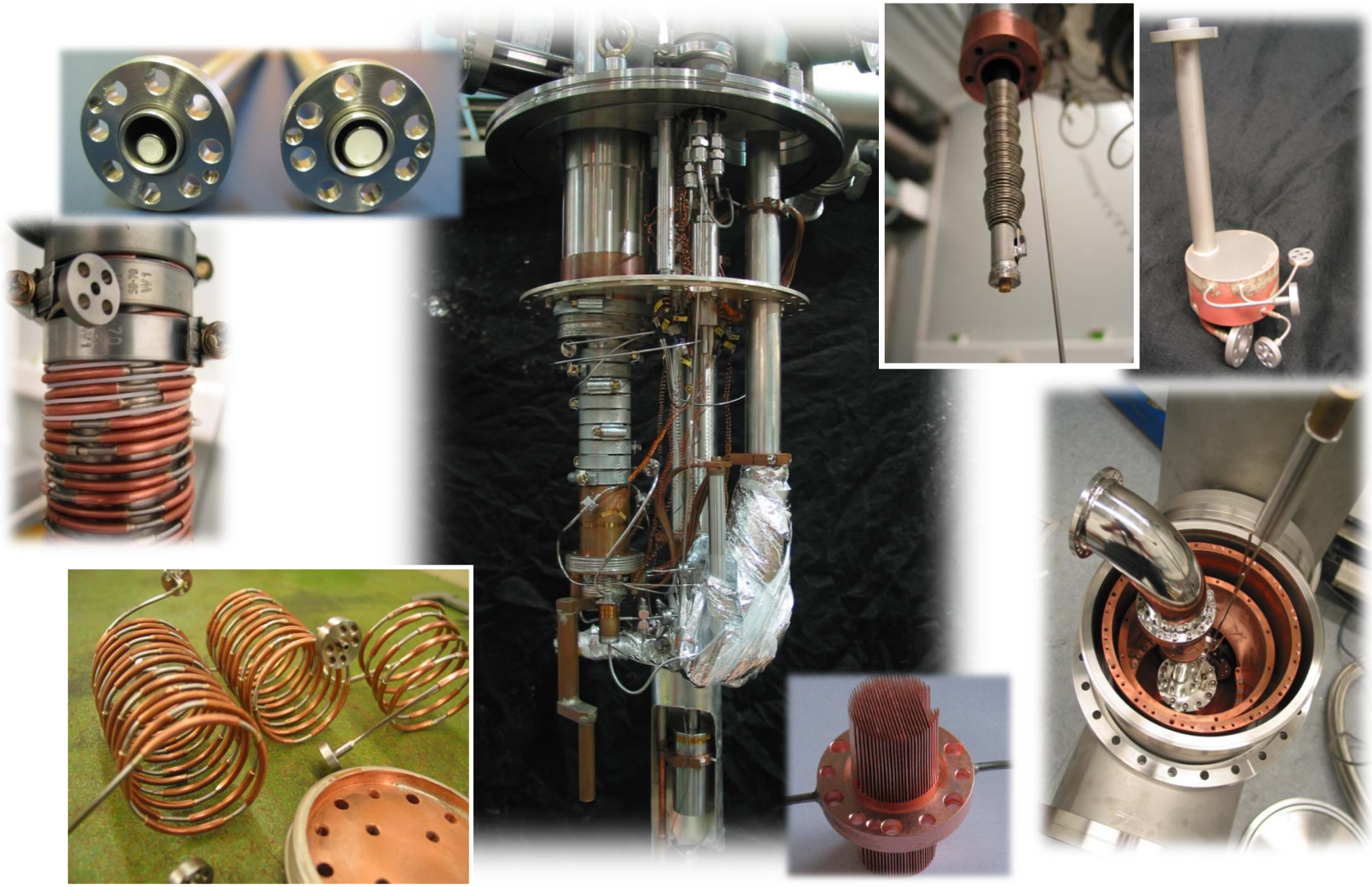
Superfluid-He UCN source development (2004+)

window- and gap-less vertical UCN extraction

Cryogenics **46** (2006) 799___
Phys. Rev. Lett. **99** (2007) 104801
Eur. Phys. J. C **67** (2010) 589___
Phys. Rev. Lett. **107** (2011) 134801
Phys. Rev. C **90** (2014) 015501
Phys. Rev. C **92** (2015) 024004
Phys. Rev. C **93** (2016) 025501

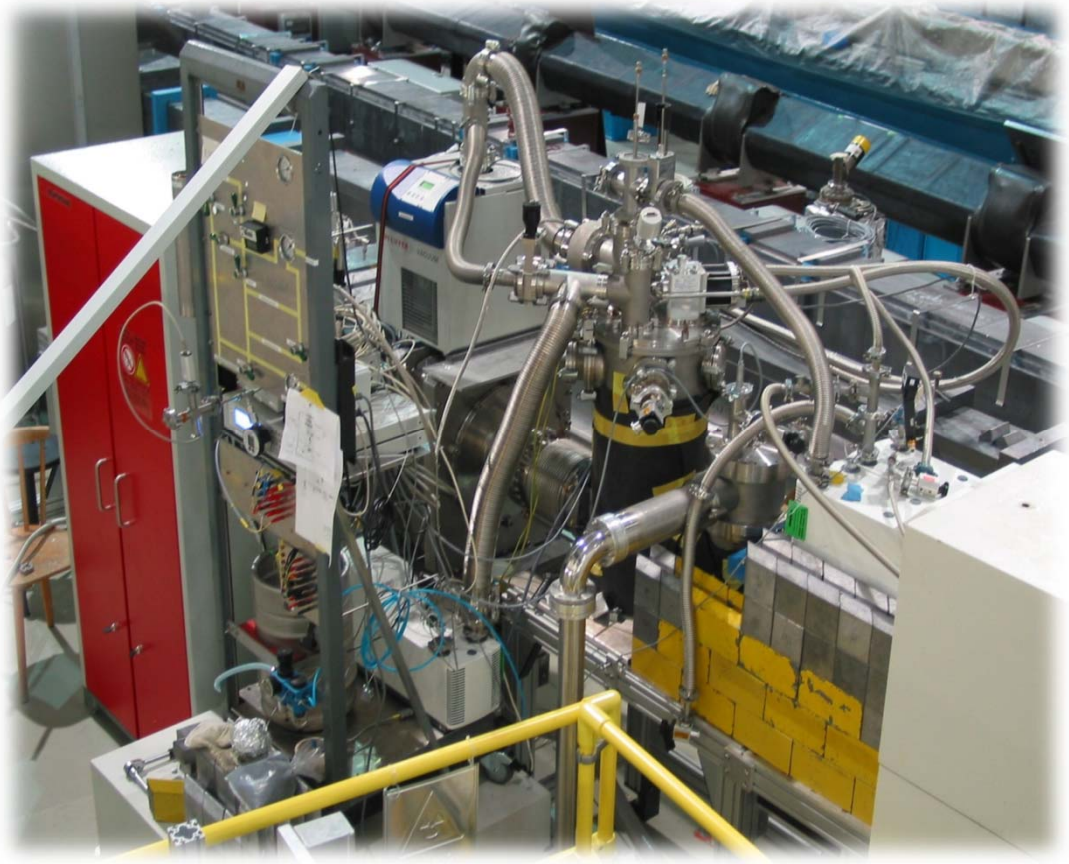


Superfluid-He UCN source development (2004+)



Superfluid-He UCN source development (2004+)

2007 (TUM): Implementation at the neutron beam at the research reactor FRM II

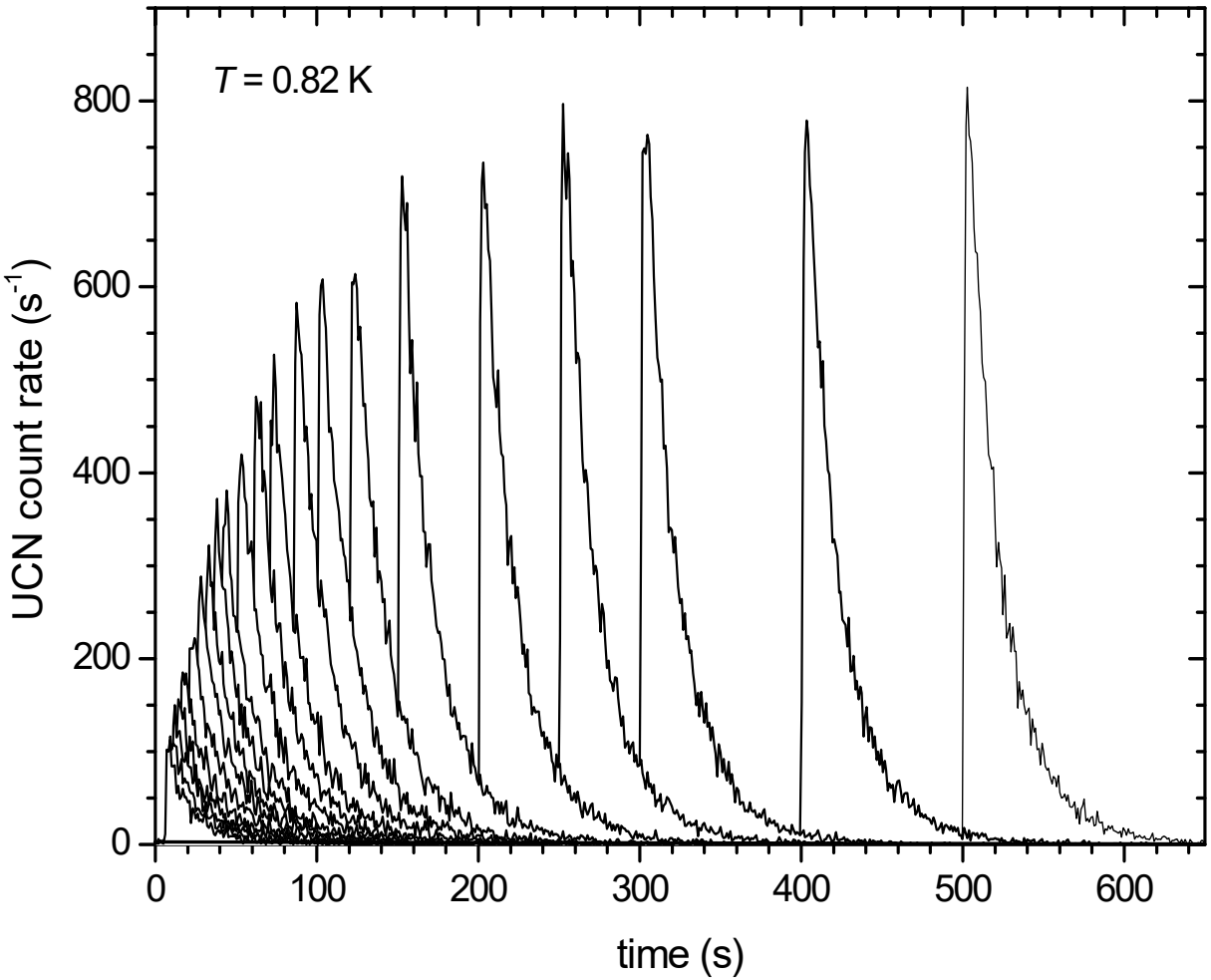


f. l. t. r.: Hans Friedrich Wirth,
Karsten Baumann, Bea Franke

Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

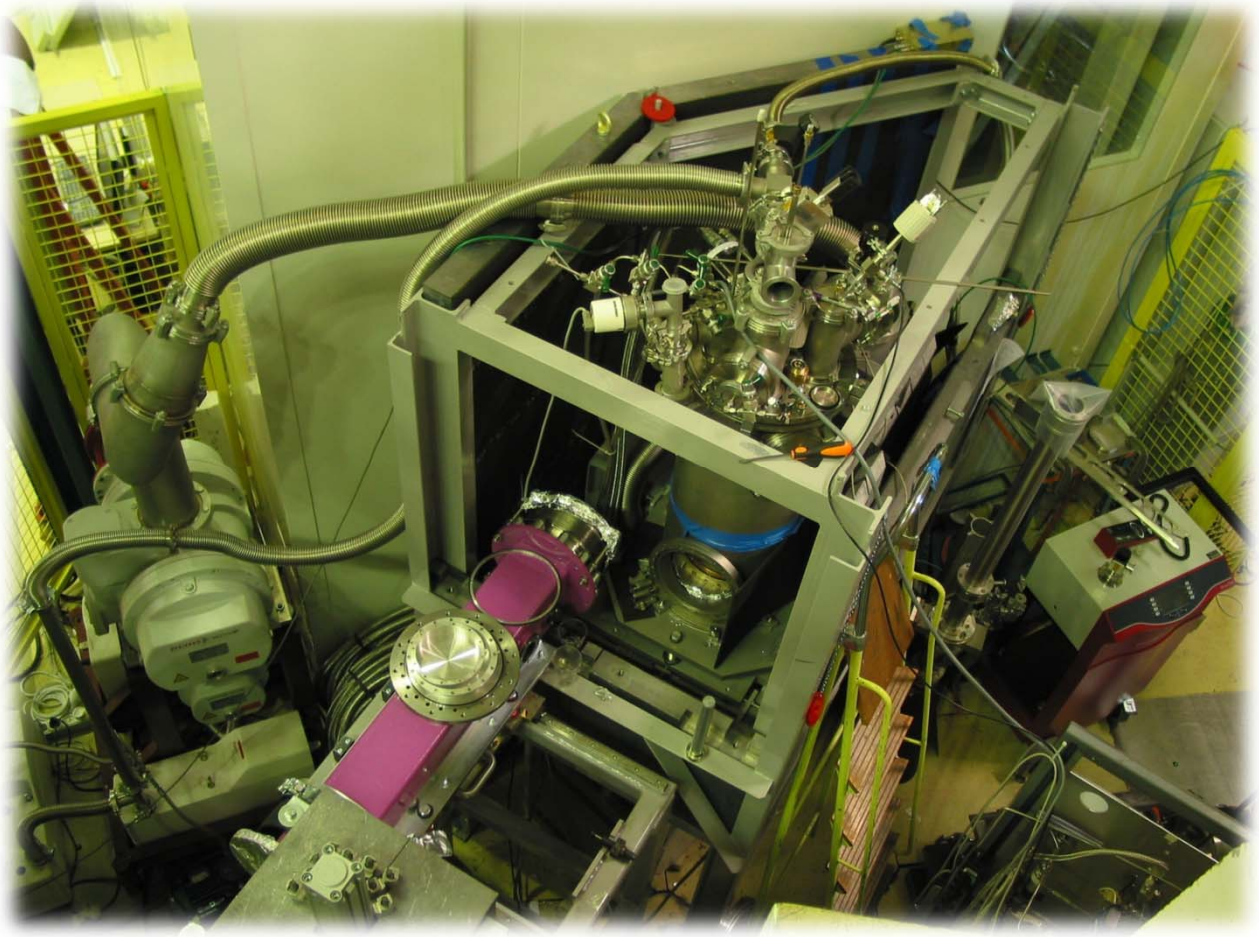
PRL **99** (2007) 104801, EPJ C **67** (2010) 589



Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): Transfer to ILL, upgrade, installation and troubleshooting

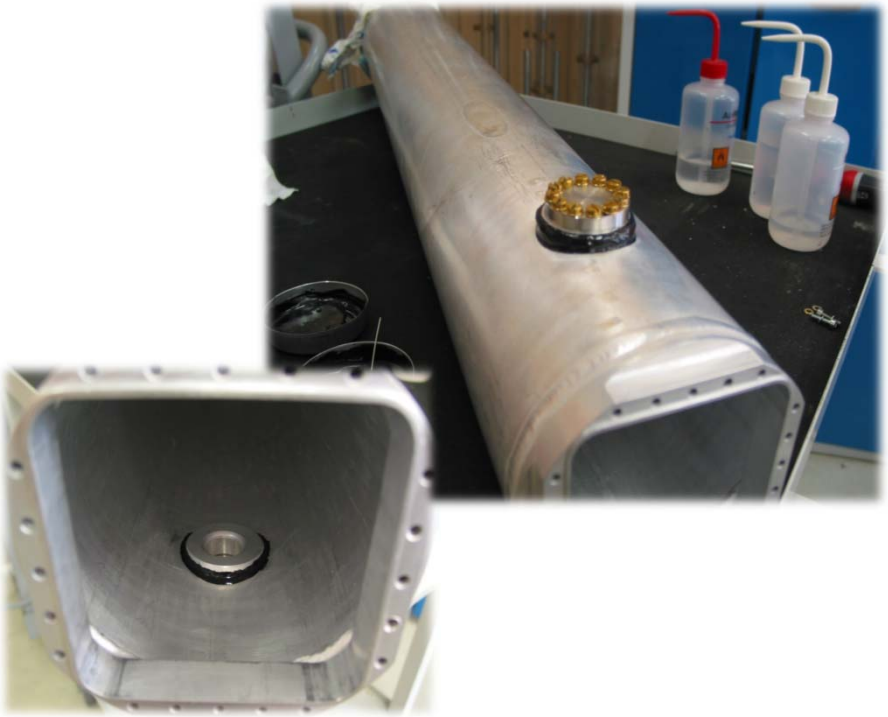


Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): Transfer to ILL, upgrade, installation and troubleshooting

BeO ceramics, Be windows

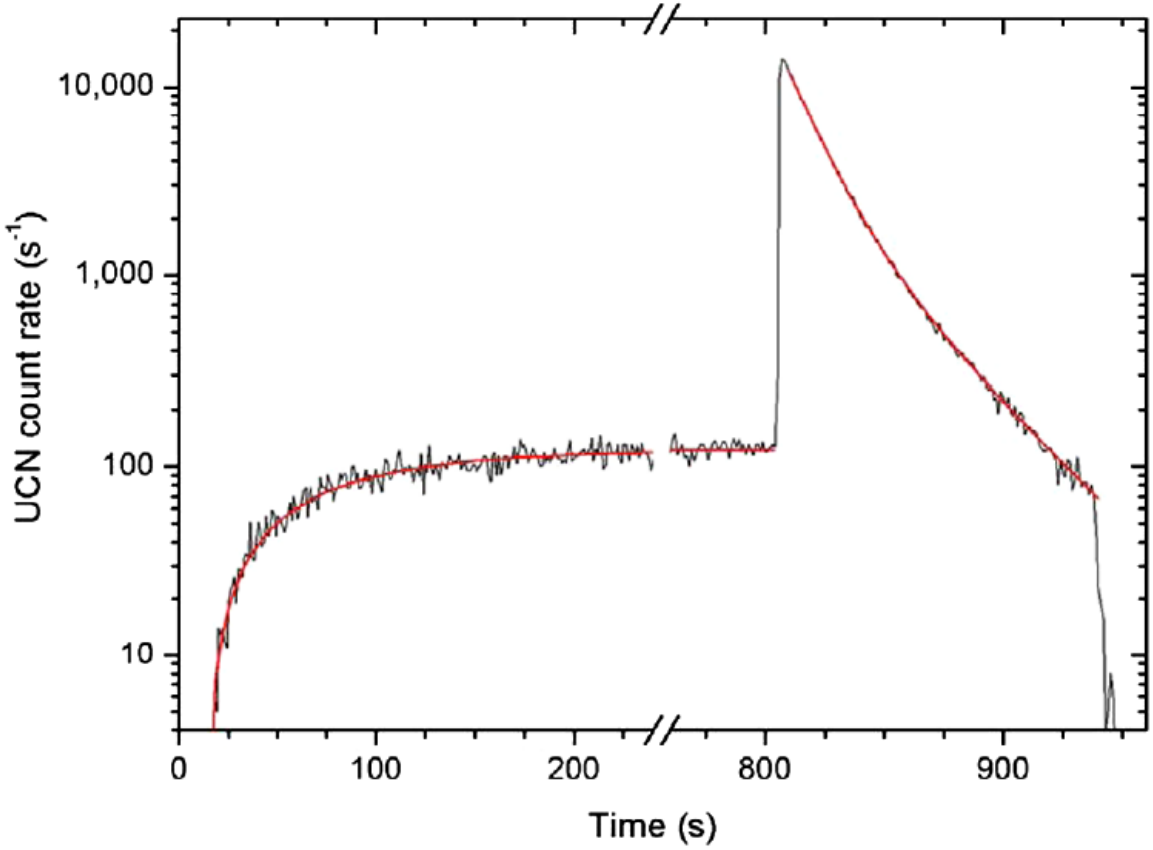


Leak cured with Stycast 2850 FT,
...30 cooldowns since

Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

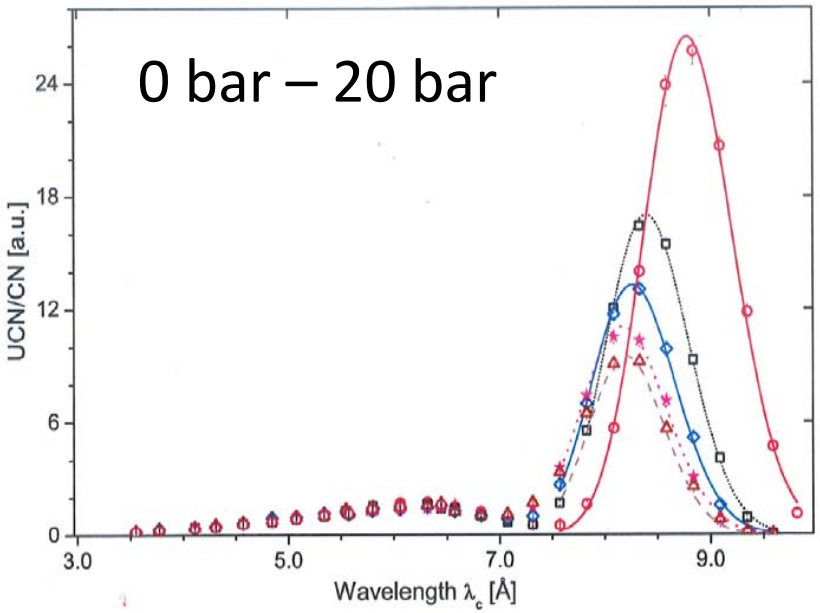
2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (**55/ccm**)



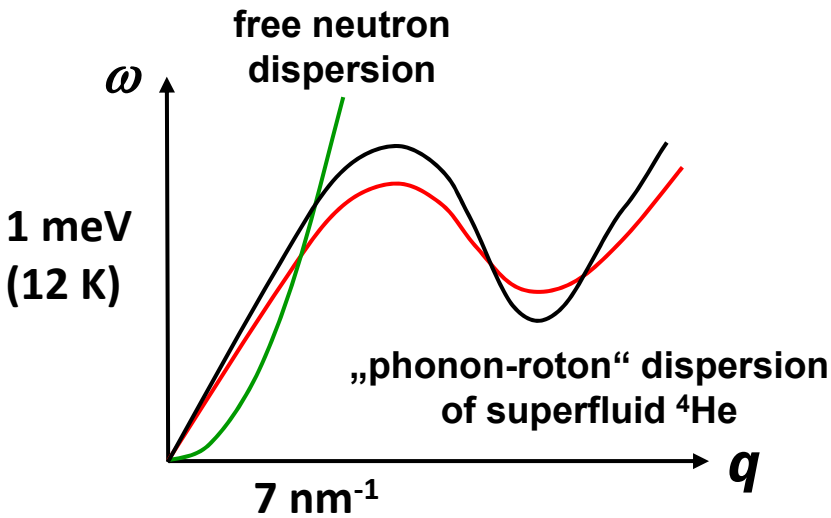
PRL **107** (2011) 134801 **(PRL highlight)**

UCN production in pressurized He-II (@PF1b)

Schmidt-Wellenburg et al., PRC **92** (2015) 024004



f. l. t. r.:
Philipp Schmidt-Wellenburg
Amel Rahli, Torsten Soldner,
Kent Leung



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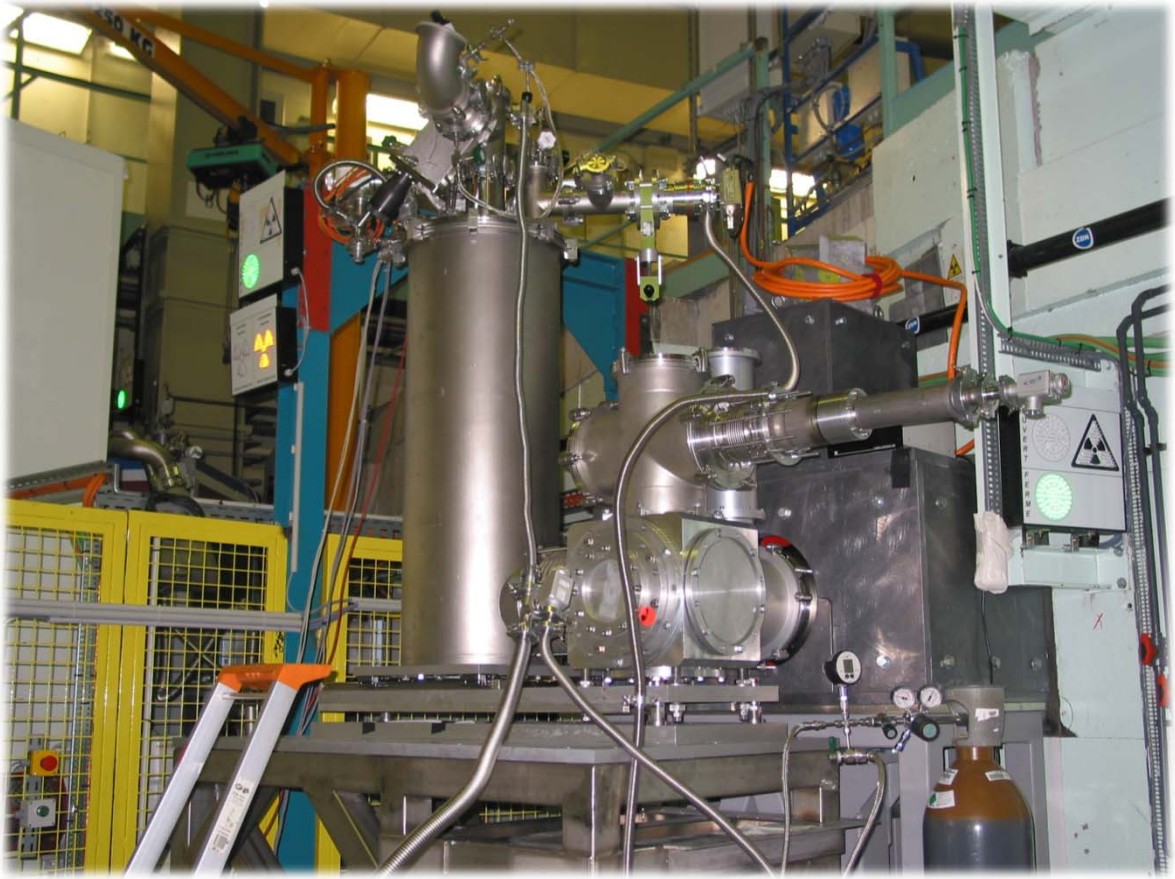

Superfluid-He UCN source development (2004+)

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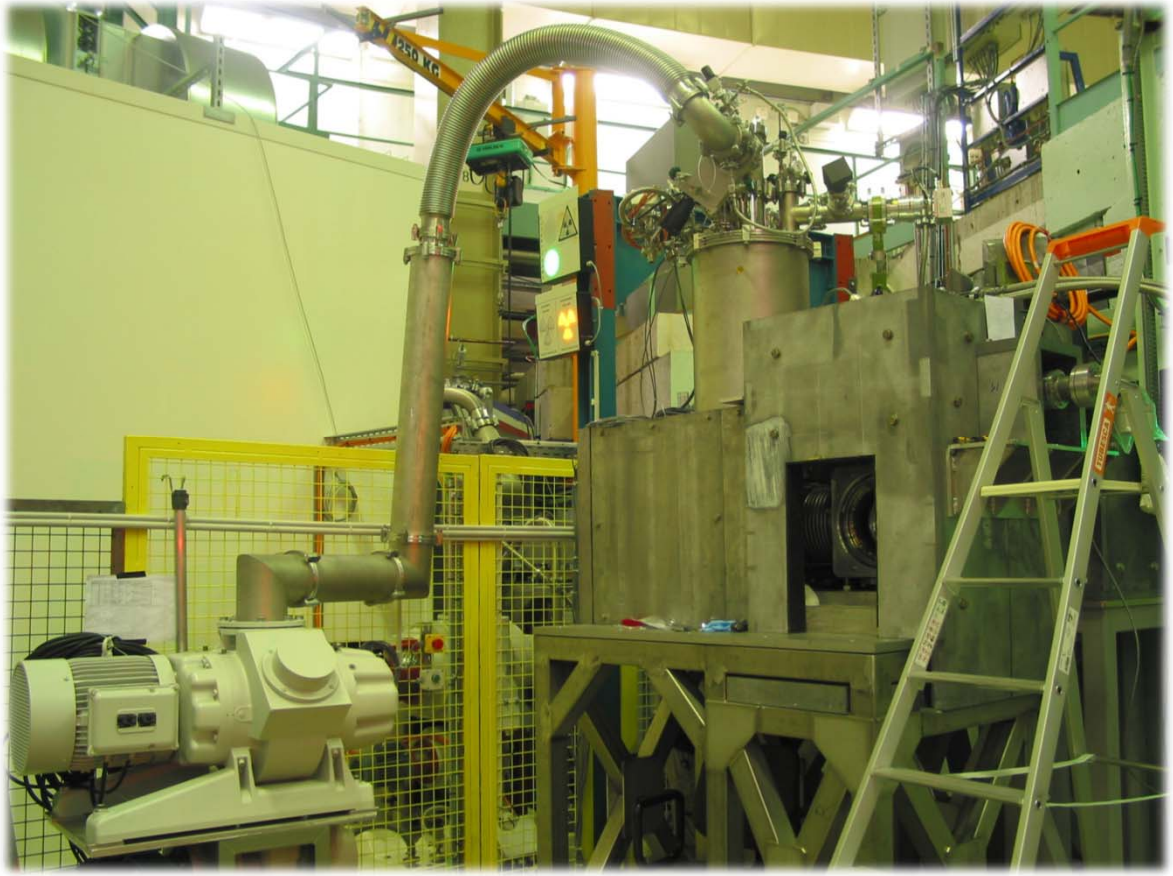

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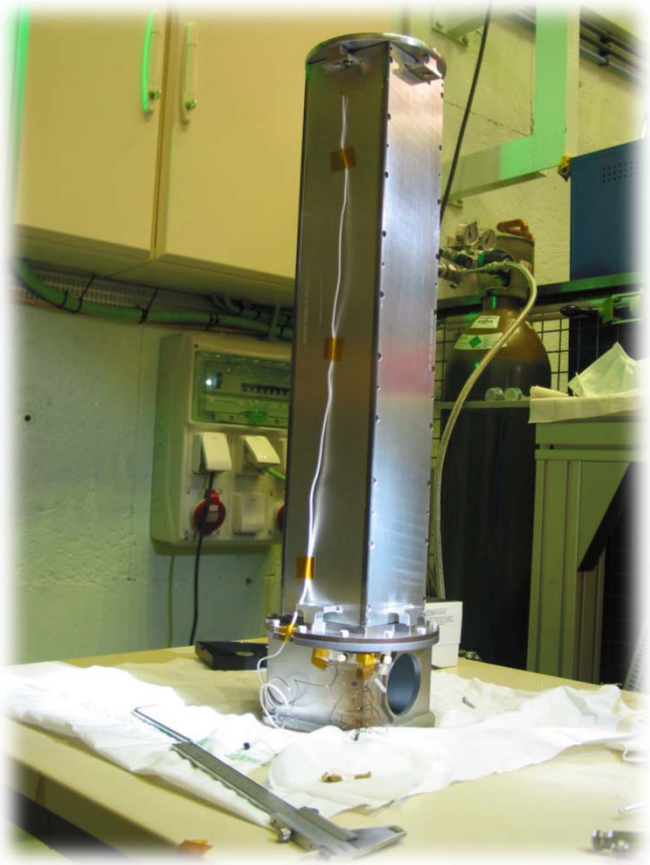

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Superfluid-He UCN source development (2004+)

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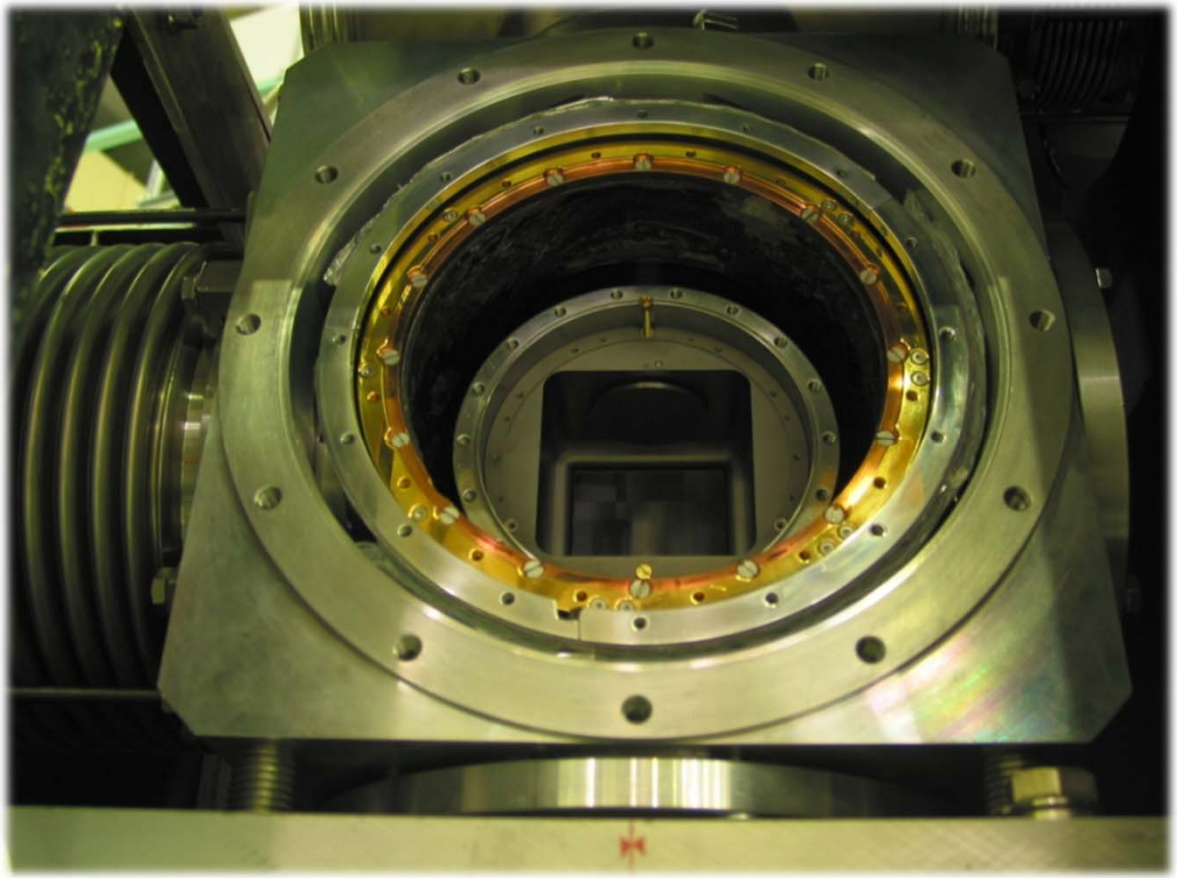
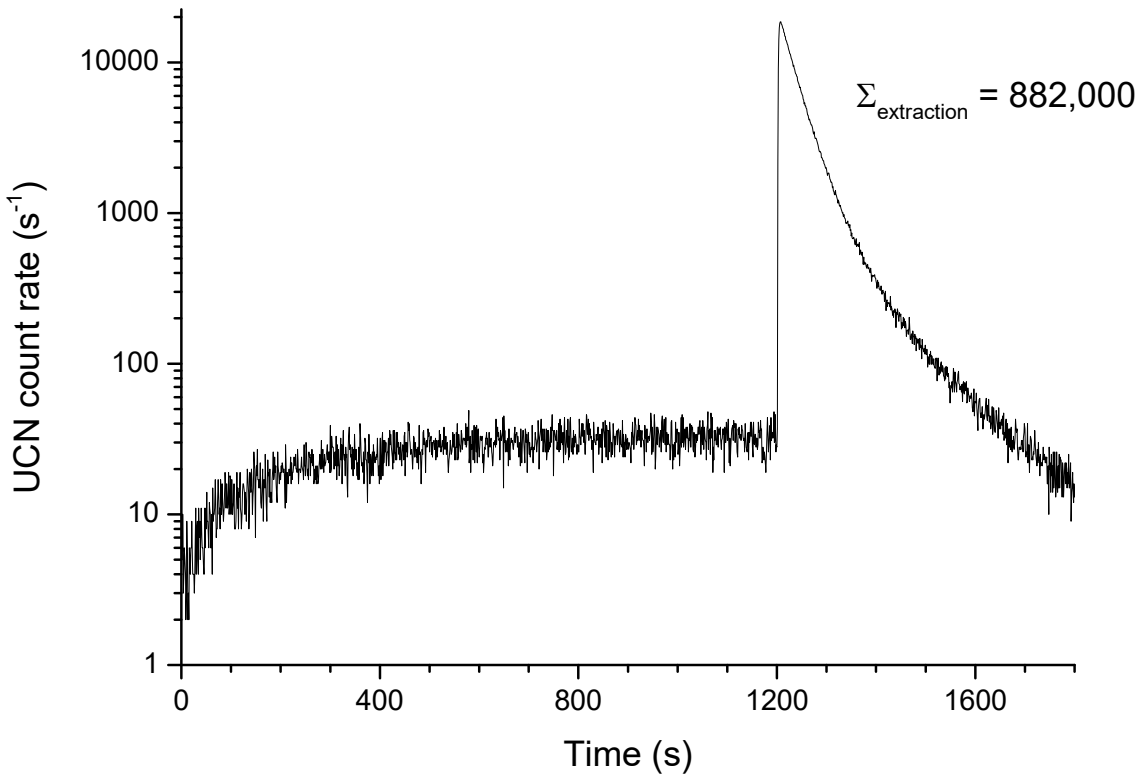


Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (55/ccm)

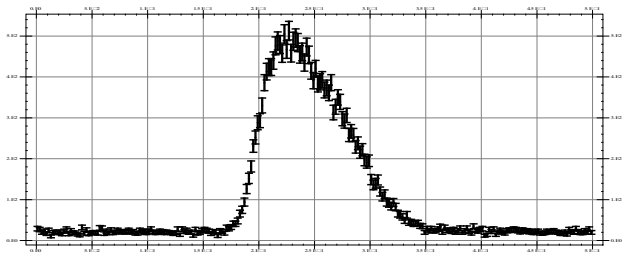
2015 (ILL): 882000 UCNs from 4-l converter of 2nd prototype SUN-2 (**220/ccm**)



UCN ToF spectra:

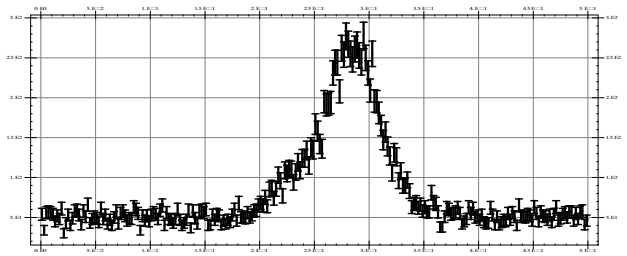
Open converter

v(max) = 5.1 m/s, $E_{||}$ = 144 neV



200 s accumulation

v(max) = 3.9 m/s, $E_{||}$ = 81 neV



Superfluid-He UCN source development (2004+)

2007 (TUM): First demonstration of windowless extraction of accumulated UCNs from converter of 1st prototype source at FRM2

2010 (ILL): 274000 UCNs extracted from 5-l converter of SUN-1 (55/ccm)

2015 (ILL): 882000 UCNs from 4-l converter of 2nd prototype SUN-2 (220/ccm)

2014+ (ILL): Design and construction of SuperSUN UCN-source user facility

User facility **SuperSUN**

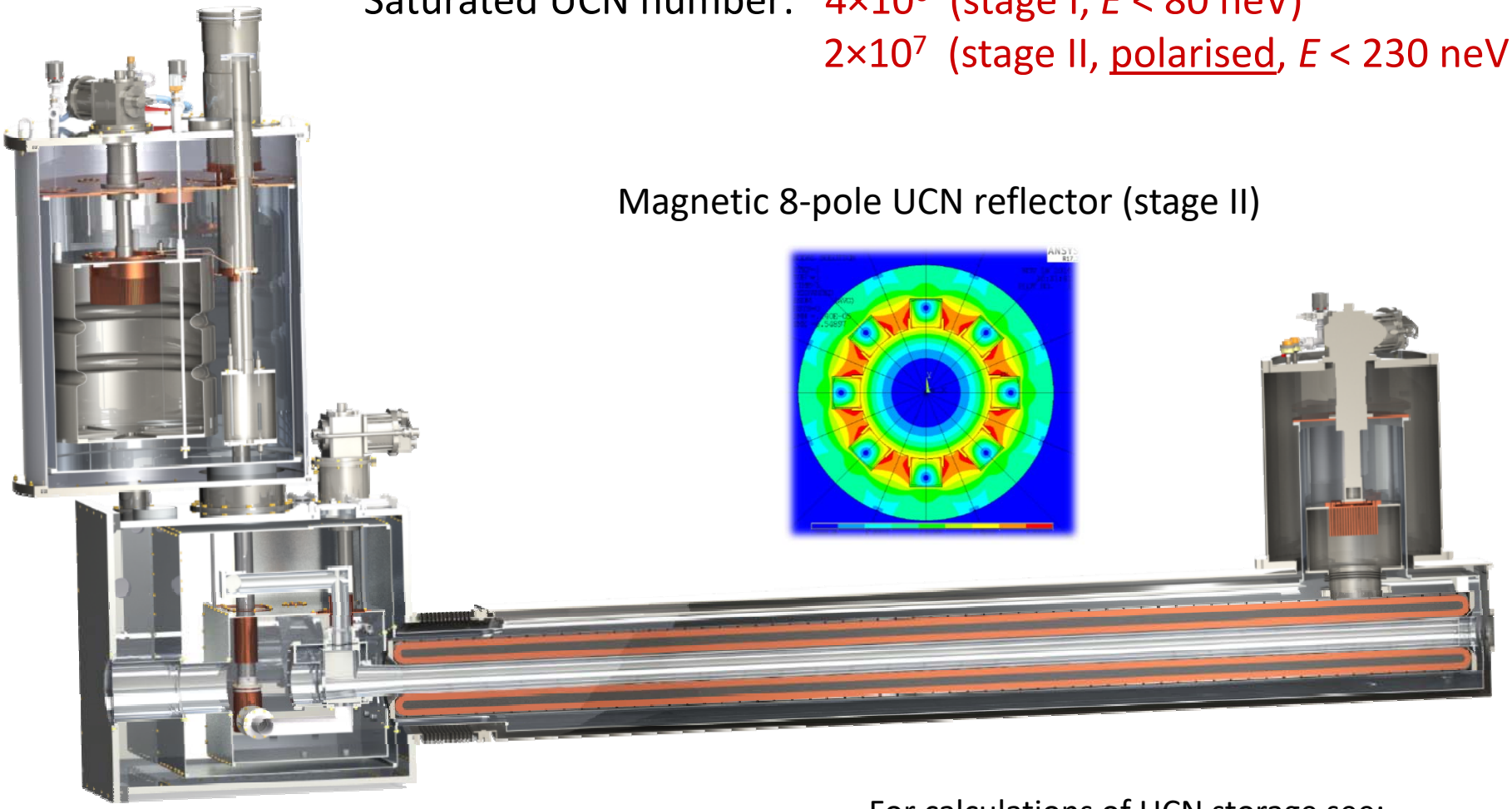
under construction

Converter volume: 12 liters

Saturated UCN number: 4×10^6 (stage I, $E < 80$ neV)

2×10^7 (stage II, polarised, $E < 230$ neV)

Magnetic 8-pole UCN reflector (stage II)



For calculations of UCN storage see:

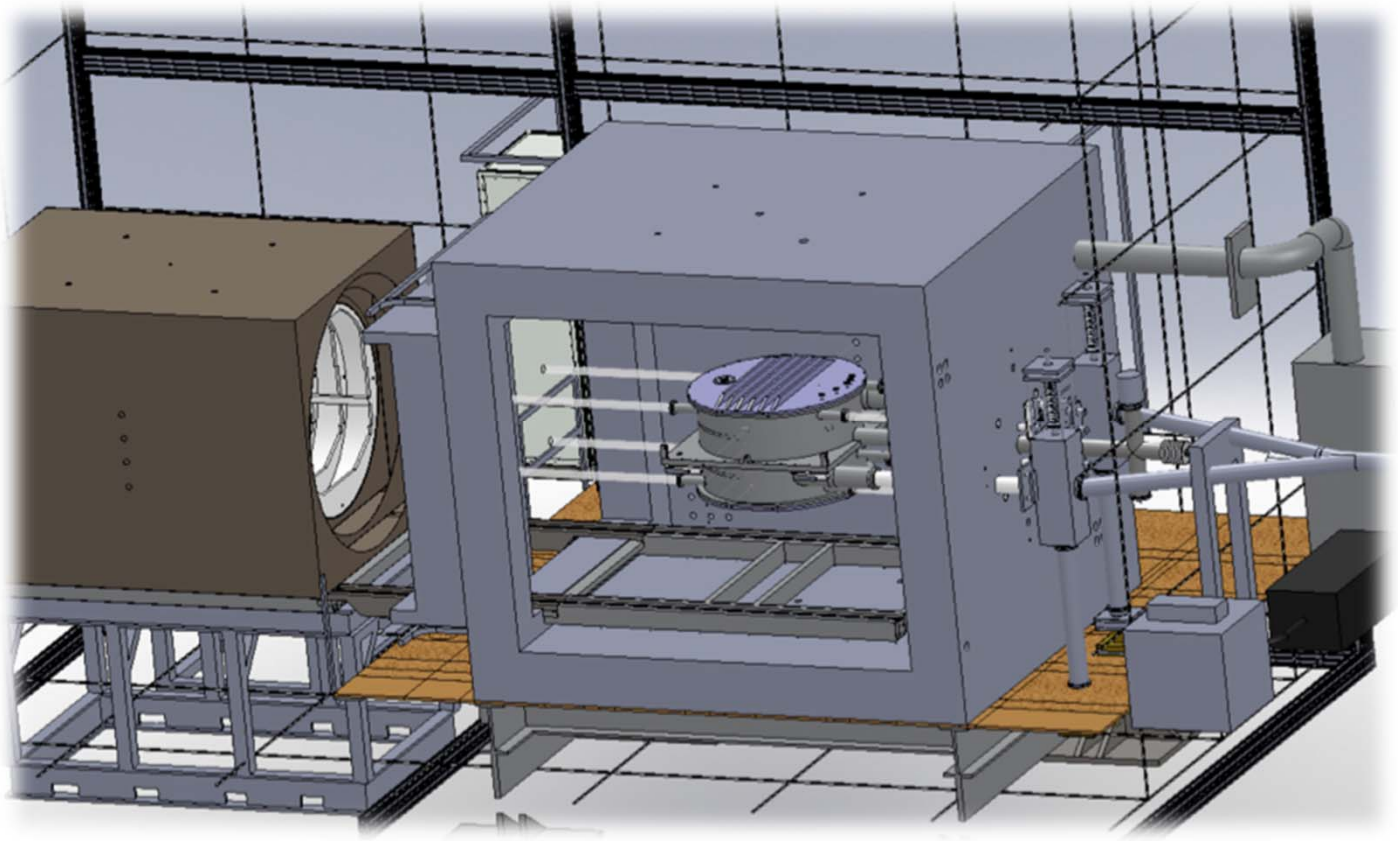
Zimmer & Golub, Phys. Rev. C **92** (2015) 015501

Octagonal neutron guide for SuperSUN

PanEDM experiment, TUM, ILL, PNPI, RAL,...

Peter Fierlinger

Cut through the apparatus:

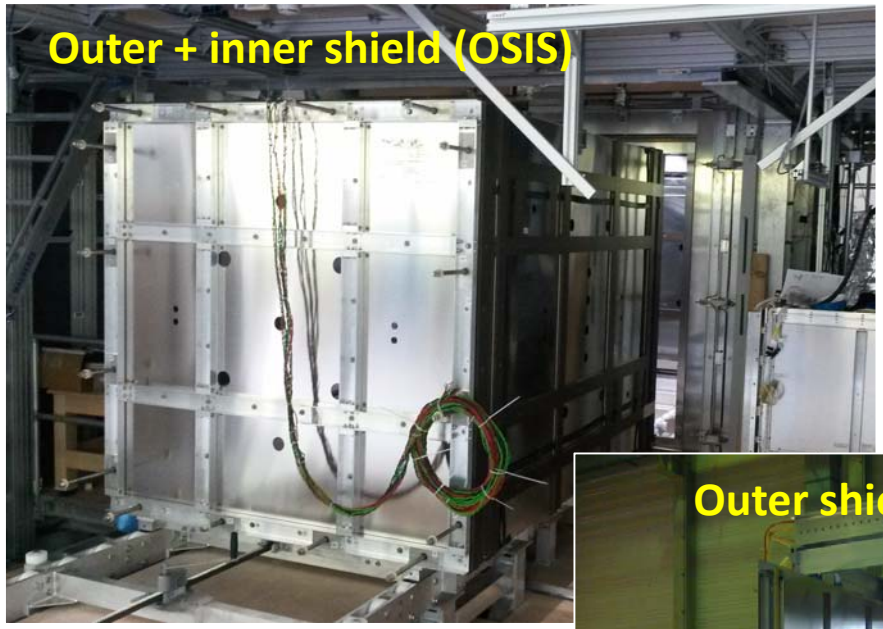


… can be separated in two independent magnetically shielded rooms

Magnetic shields of PanEDM

Peter Fierlinger

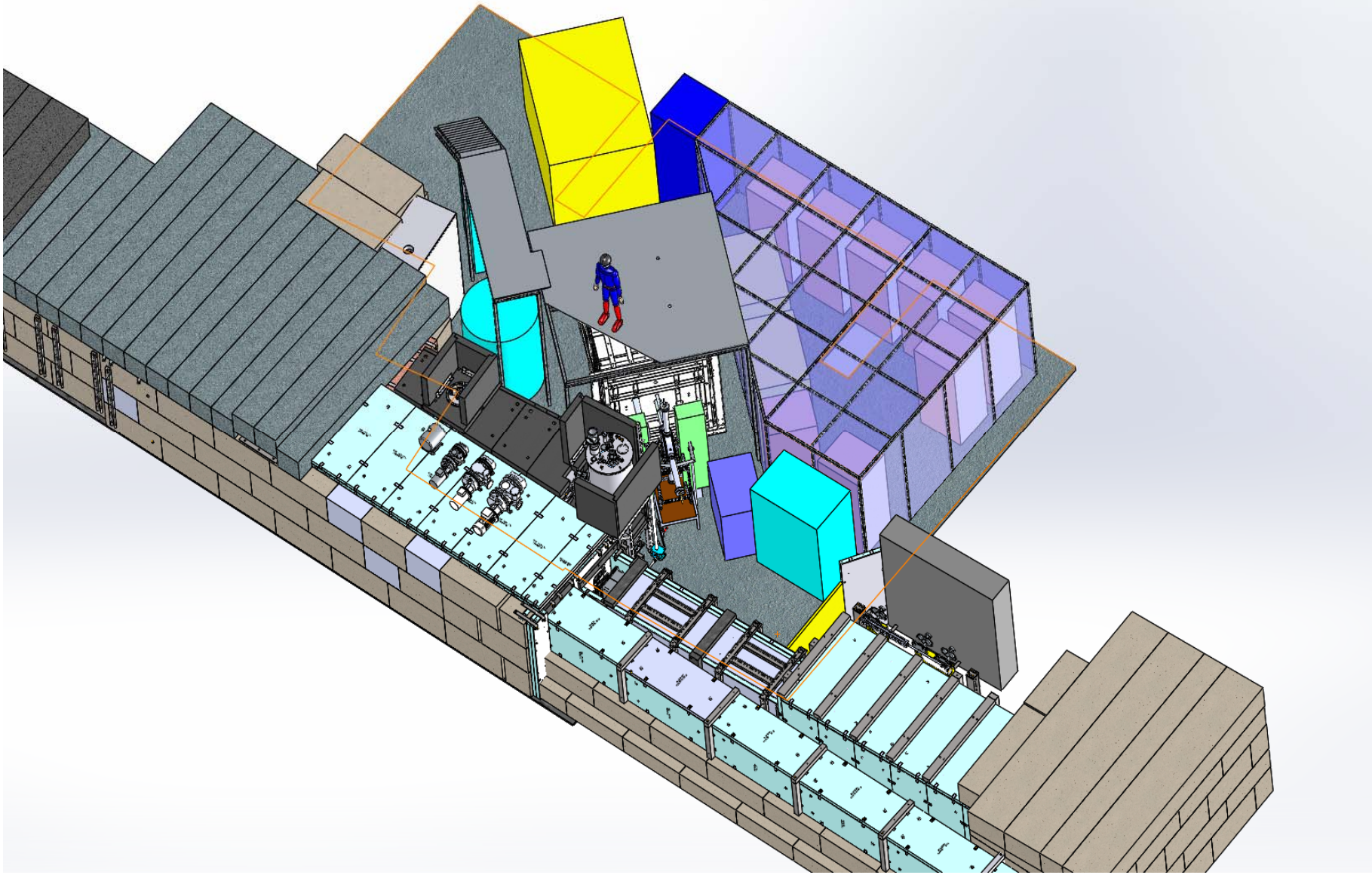
Passive SF: > 6 Millions @ 1 mHz
SF of inner shield alone: > 70.000 @ 1 mHz, 1µT excitation



I. Altarev et al., arXiv:1501.07408
I. Altarev et al., arXiv:1501.07861

PanEDM @ SuperSUN @ ILL

	Stage I	Stage II
Sensitivity (1 σ) 100 days	**1.9×10^{-27} ecm**	**4.2×10^{-28} ecm**
Limit (90% C.L.) 100 days	**3.0×10^{-27} ecm**	**7.0×10^{-28} ecm**




Merci de votre attention!

The neutron and its role in cosmology and particle physics

D. Dubbers and M. G. Schmidt,

Rev. Mod. Phys. **83**, 1111 (2011)