PNPI–ILL–PTI collaboration at ILL reactor in Grenoble and at WWR–M reactor in Gatchina (first part)

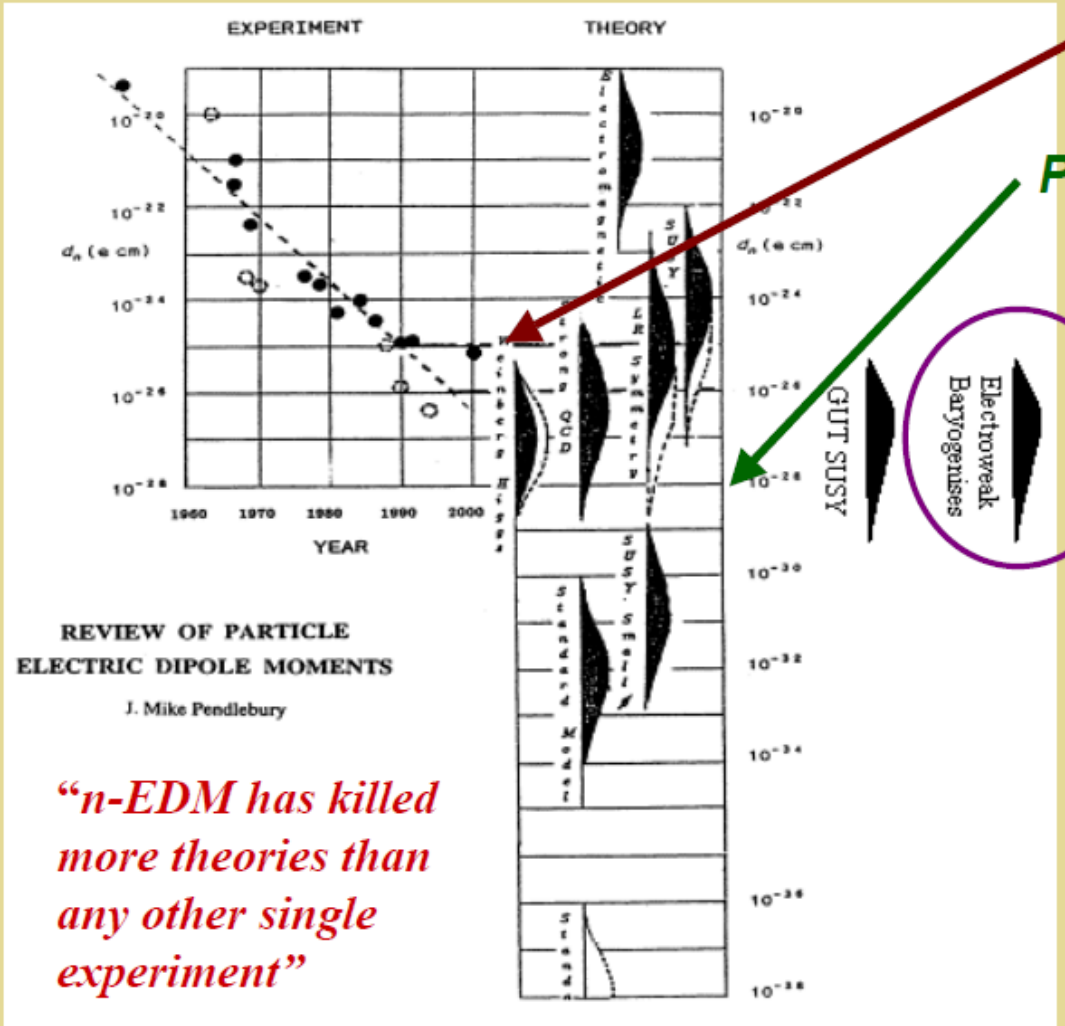
Present status
and
future prospects of the
"Gatchina double chamber EDM spectrometer"

Serebrov A.P.

for Oak Ridge nEDM workshop 11 October 2012

Presented by Peter Geltenbort

EDMs: What We May Learn



"n-EDM has killed more theories than any other single experiment"

Present n-EDM limit

Proposed n-EDM limit

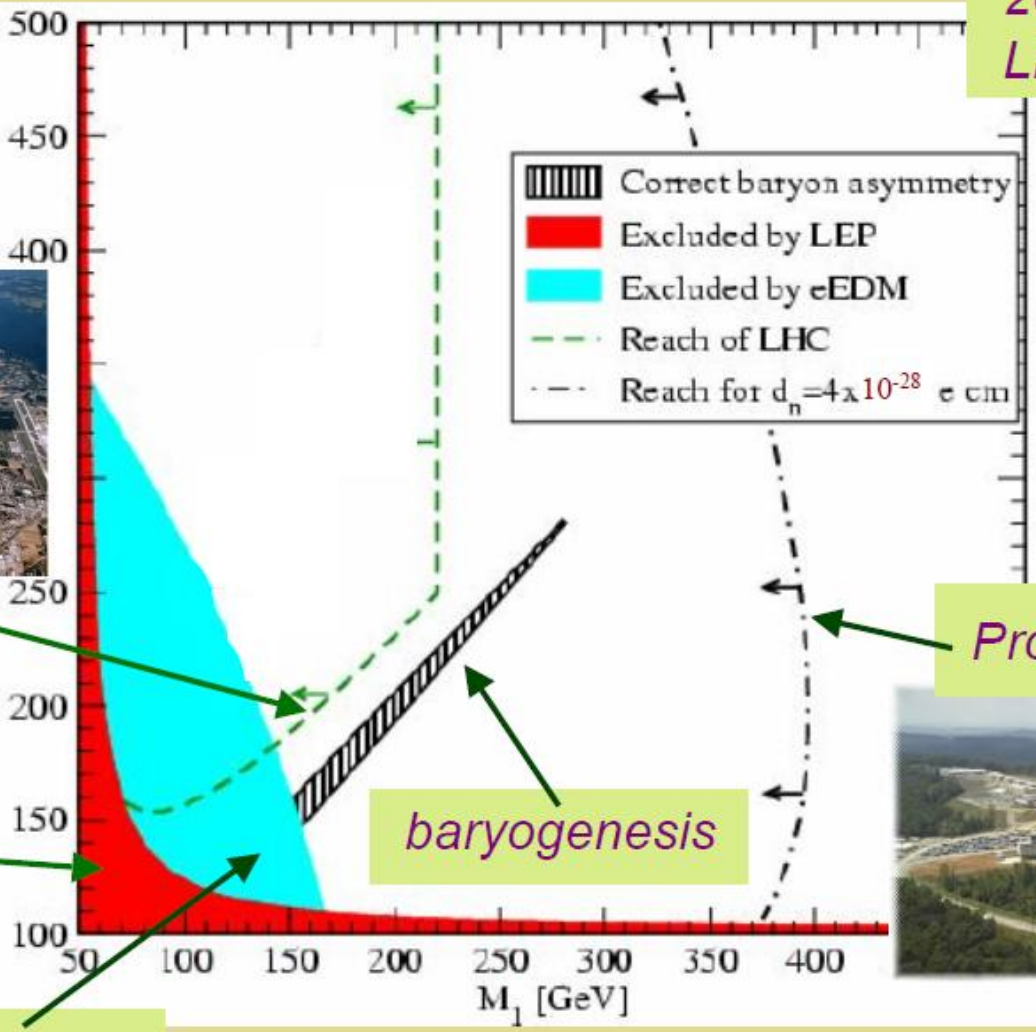
Matter-Antimatter Asymmetry in the Universe:

Theory: How robust ? Can EDMs kill EW baryogenesis ?

MSSM Baryogenesis: EDMs & LHC

2007 NSAC LRP Update

LHC reach



Prospective d_n

baryogenesis

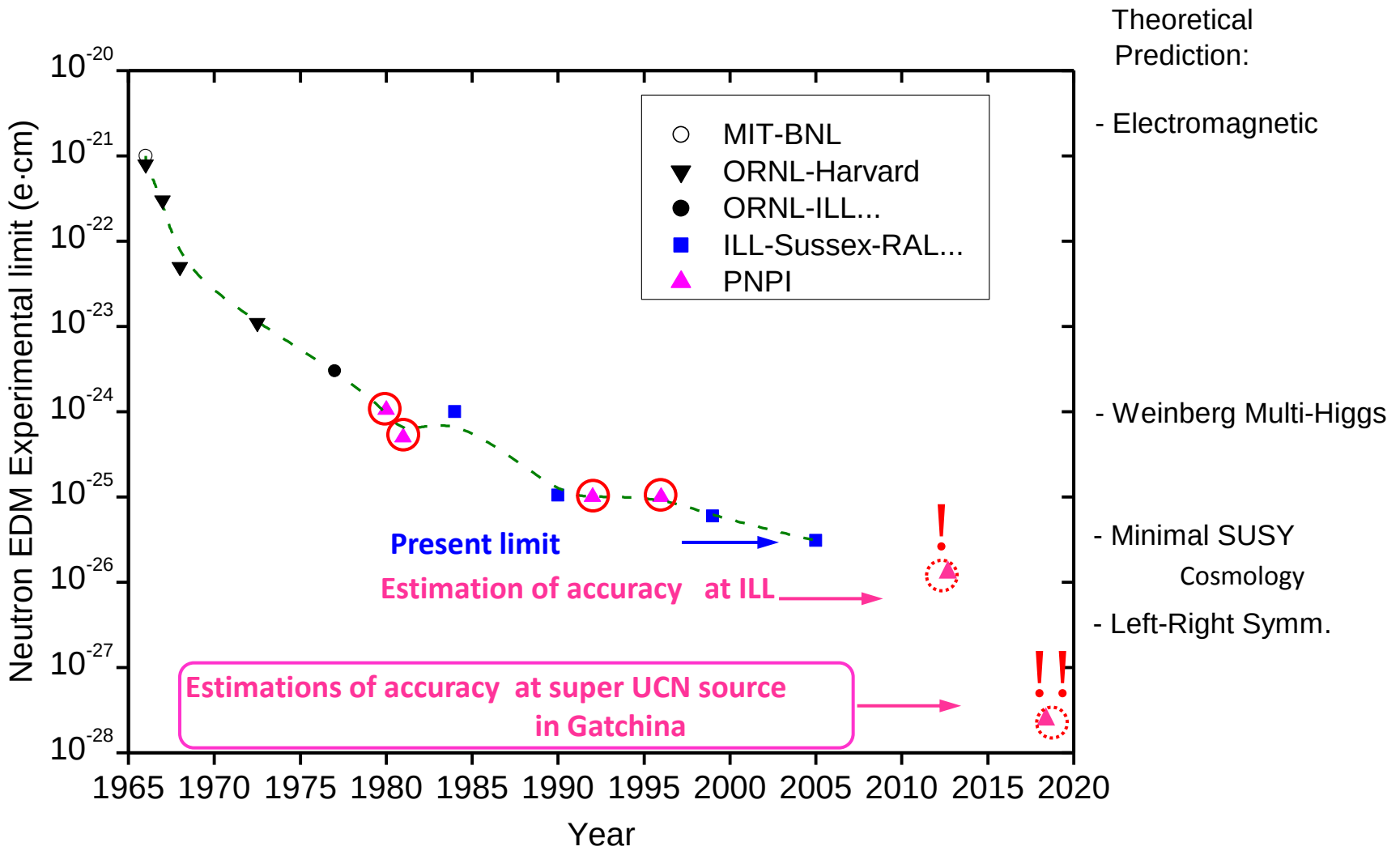
LEP II excl

Present d_e

Cirigliano, Li, Profumo, R-M

History of nEDM measurements

Results and prospects of PNPI-ILL-PTI collaboration



Setting the scene (1)

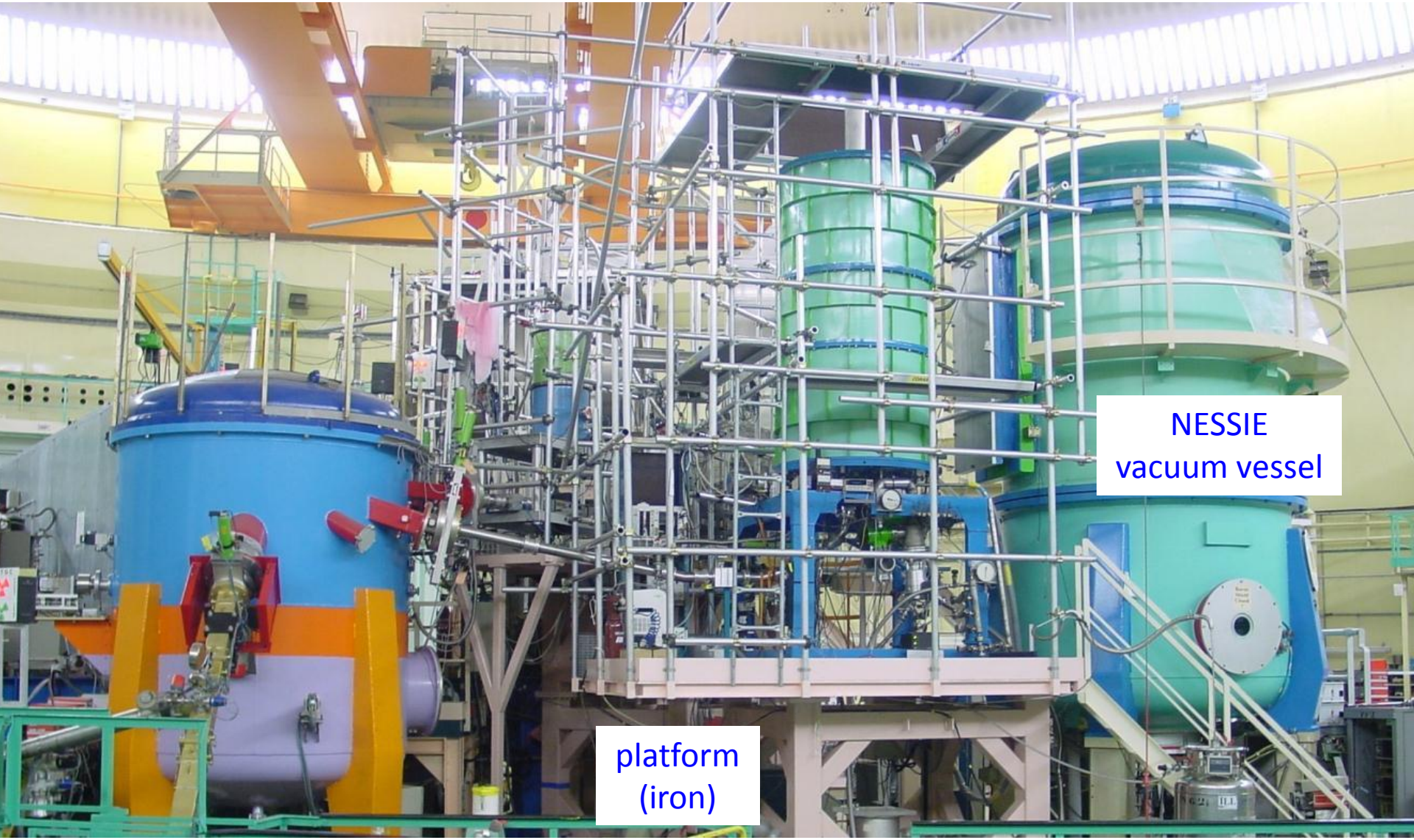
Earth

Europe

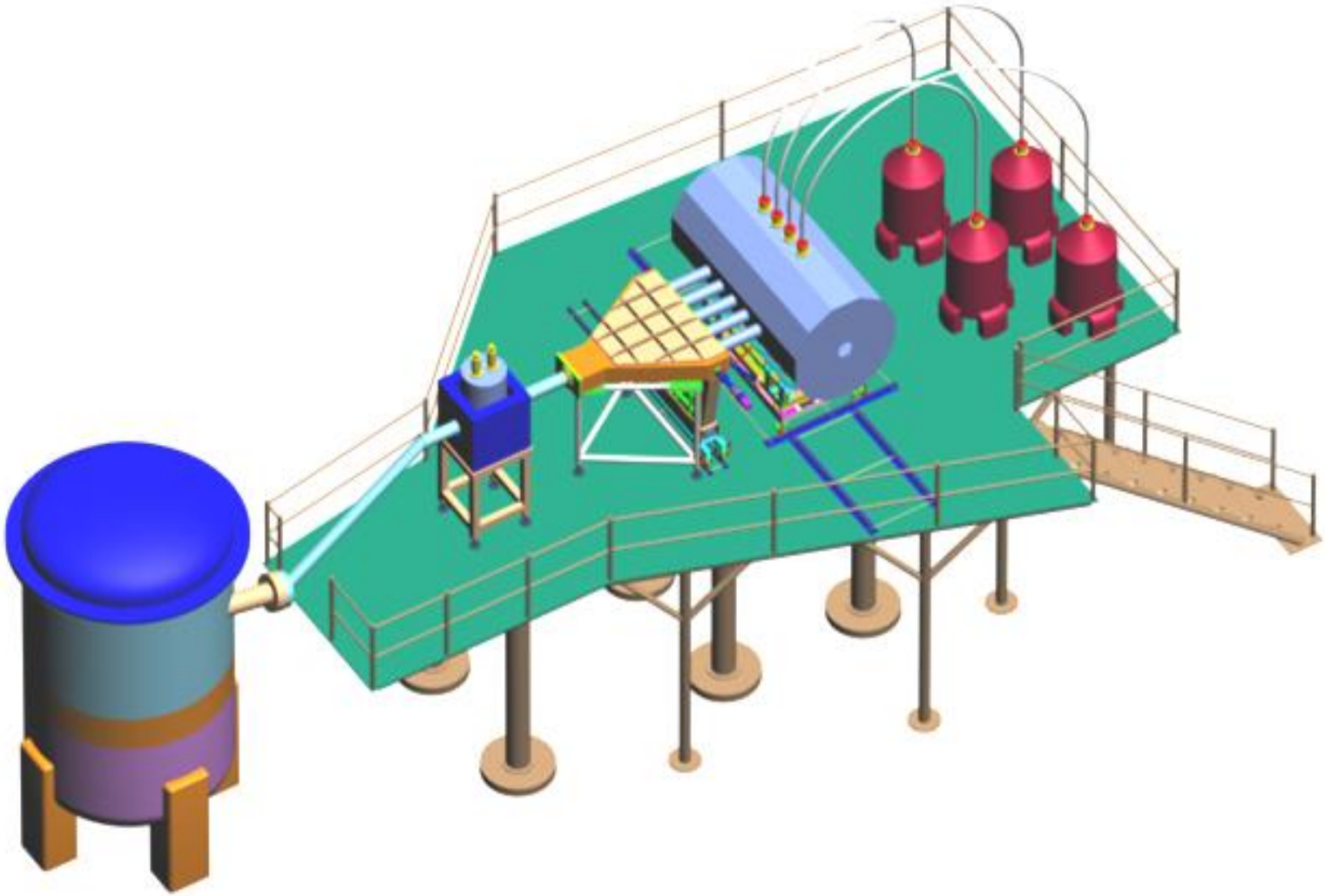
Setting the scene (2)

Setting the scene (3)

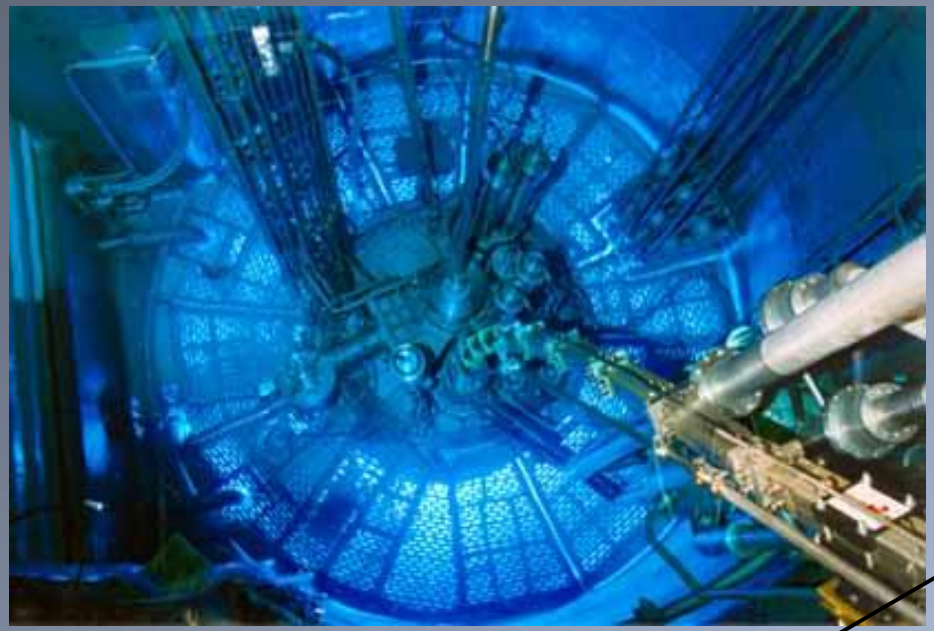
ILL's UCN facilities - PF2/MAM
(in the past)



Layout of the multi-chamber EDM spectrometer
at PF2 (ILL's UCN facility)



The UCN/VCN facility PF2

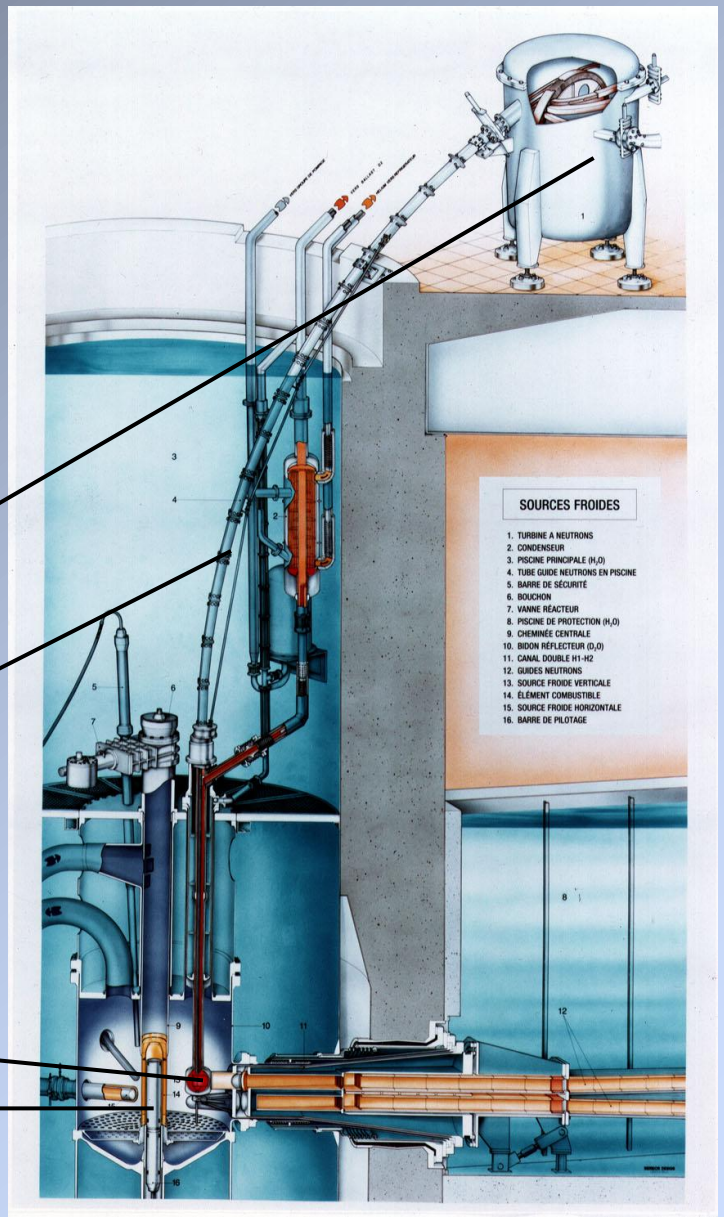


Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

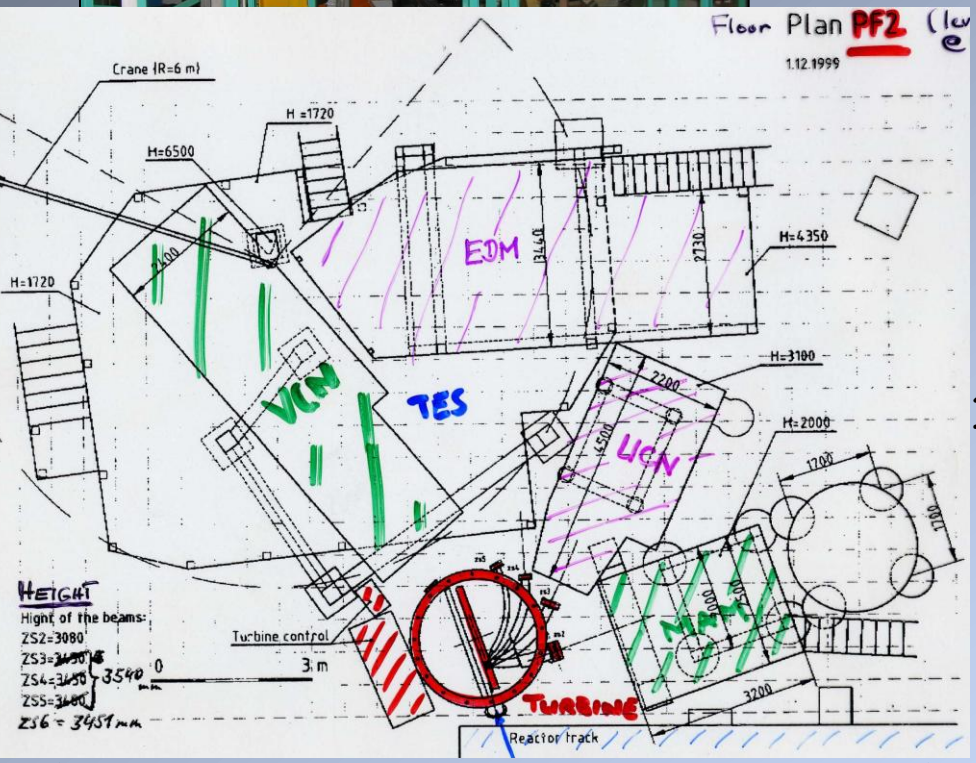
Reactor core



The PF2 beam facility

PF2: Physique Fondamentale 2
2nd installation for fundamental physics

4 positions for Ultracold Neutrons (UCN)



- *MAM*
- *EDM*
- *UCN*

v = 5 ms^{-1}
ρ = ~50 cm^{-3} (at the experiment)

- *TES*

1 position for Very Cold Neutrons (VCN)

- *VCN beam*

v = 50 ms^{-1}
Φ = 10^{8} cm^{-2} s^{-1}

Installation of non-magnetic platform

First experiment on the non-magnetic platform

History of mirror ideas

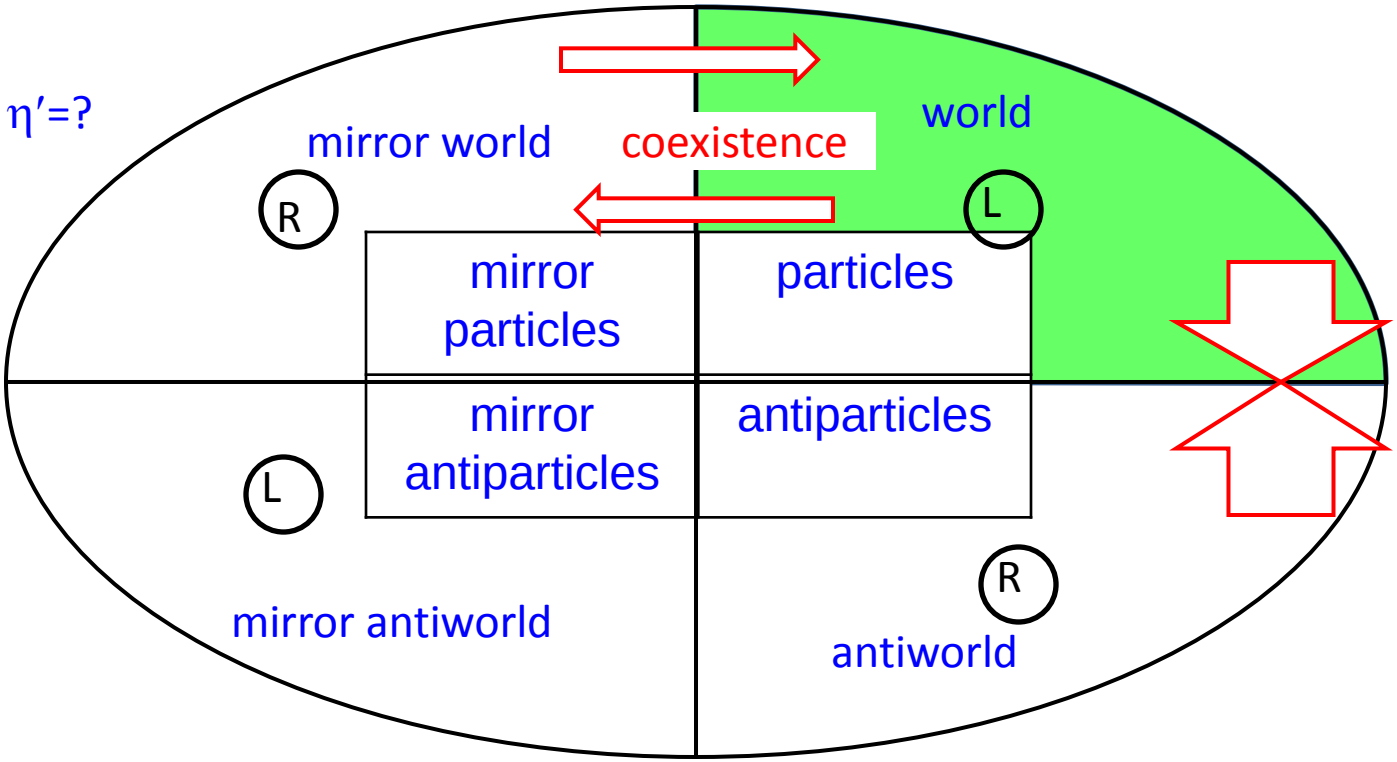
Mirror particles and mirror matter: 50 years of speculation and search

L.B. Okun
ITEP, Moscow, Russia

Review (259 references)
hep-ph/0606202 v2 Dec 2006

Physics-Uspekhi 50 (2007) 380

Coexistence is possible, transitions are complicated



$\eta \approx 6 \cdot 10^{-10}$

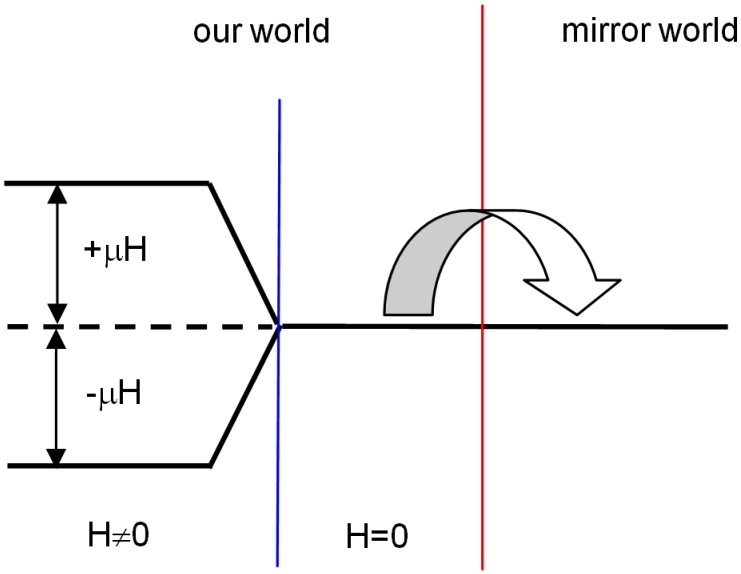
annihilation!!

Coexistence is not possible

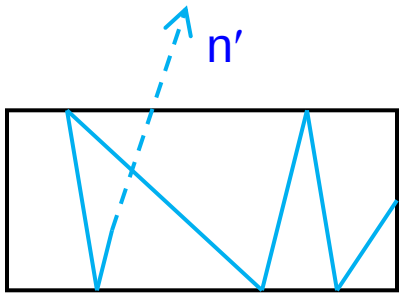
How to observe n-n′ transitions

The evolution of nonrelativistic n-n′ system in the external magnetic field B is described by the effective Hamiltonian :

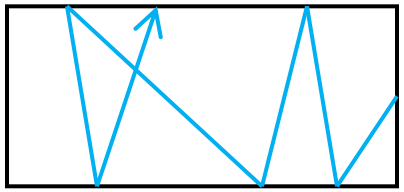
$$H = \begin{pmatrix} m + \frac{P^2}{2m} - i\frac{\Gamma}{2} + \mu(\sigma \cdot B) + V & \delta m \\ \delta m & m' + \frac{P^2}{2m'} - i\frac{\Gamma'}{2} + V' \end{pmatrix}$$



H=0 (H<10^{-4} Gauss)

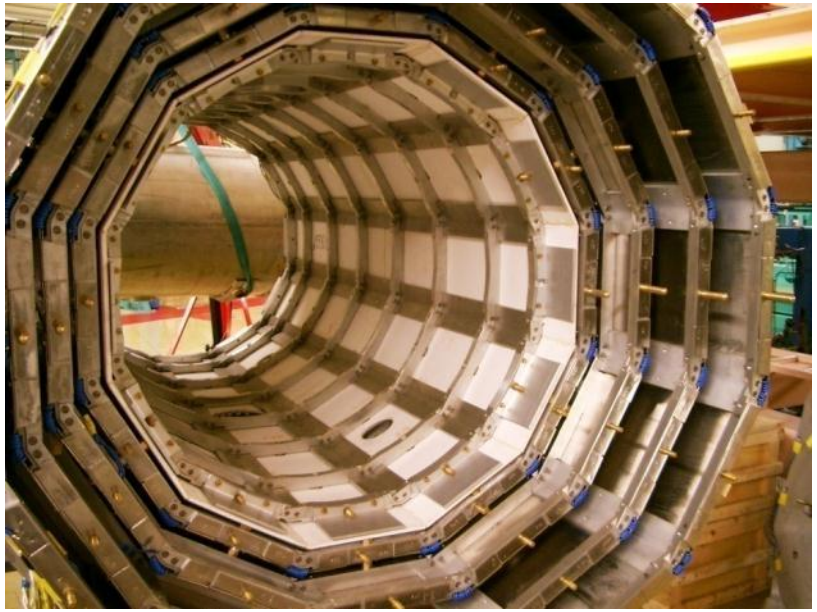


H≠0 (H≈0.2 Gauss)

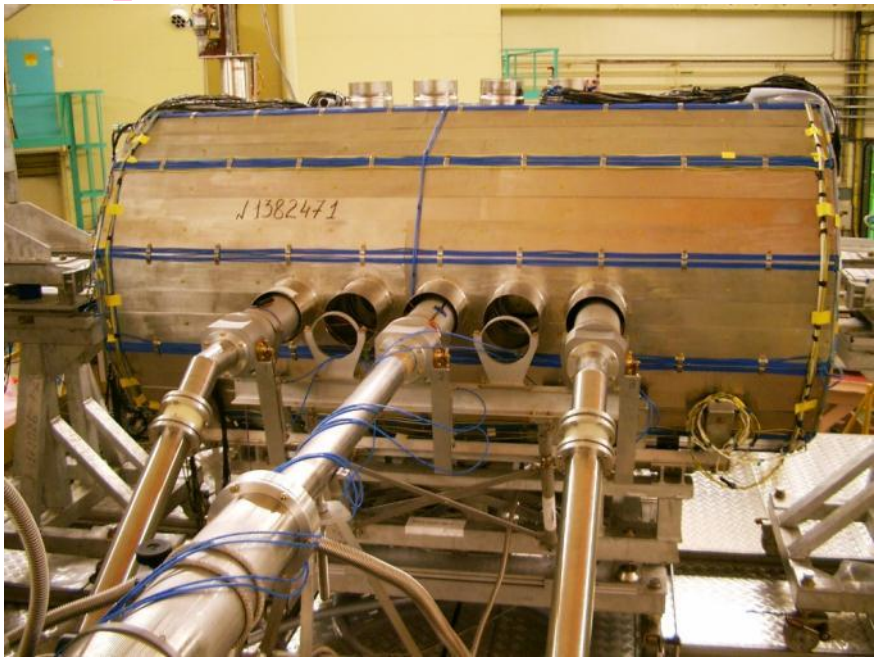


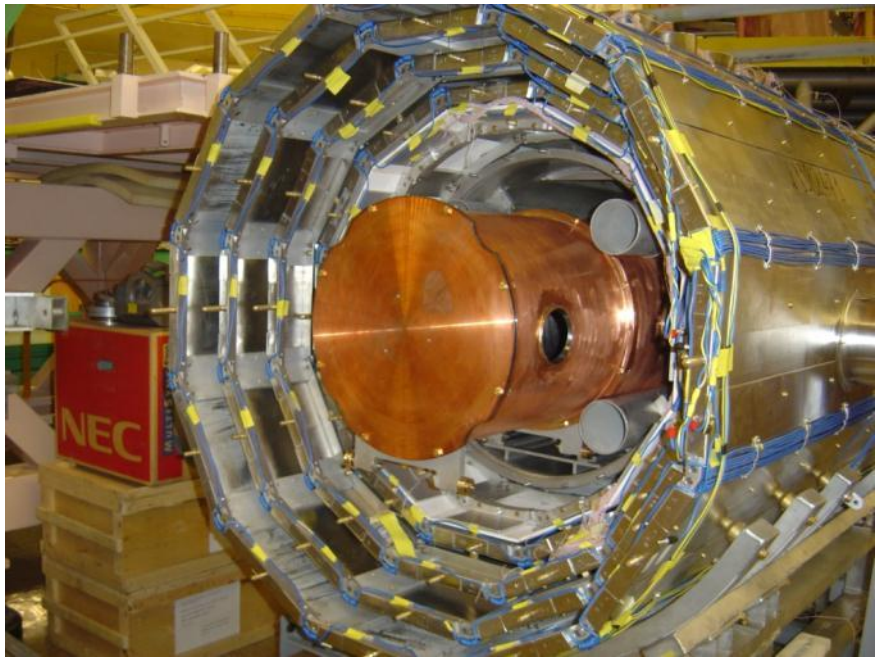
Energy states of ordinary and mirror neutron are degenerated when magnetic field H=0, and transitions are possible. Due to magnetic field energy states of neutron can be shifted and transitions to mirror state will be suppressed.

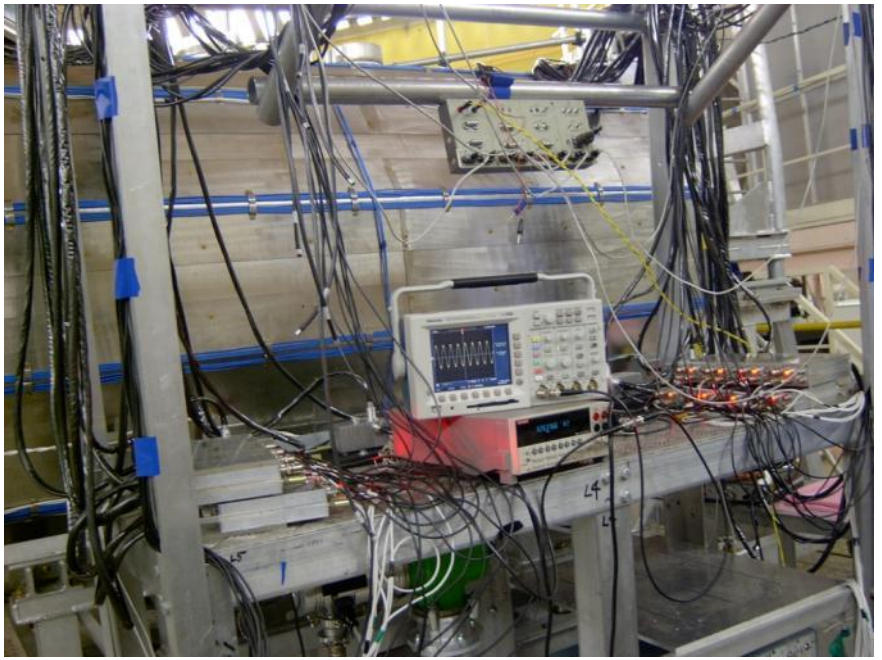
Assembling of magnetic shielding and vacuum chamber of EDM spectrometer



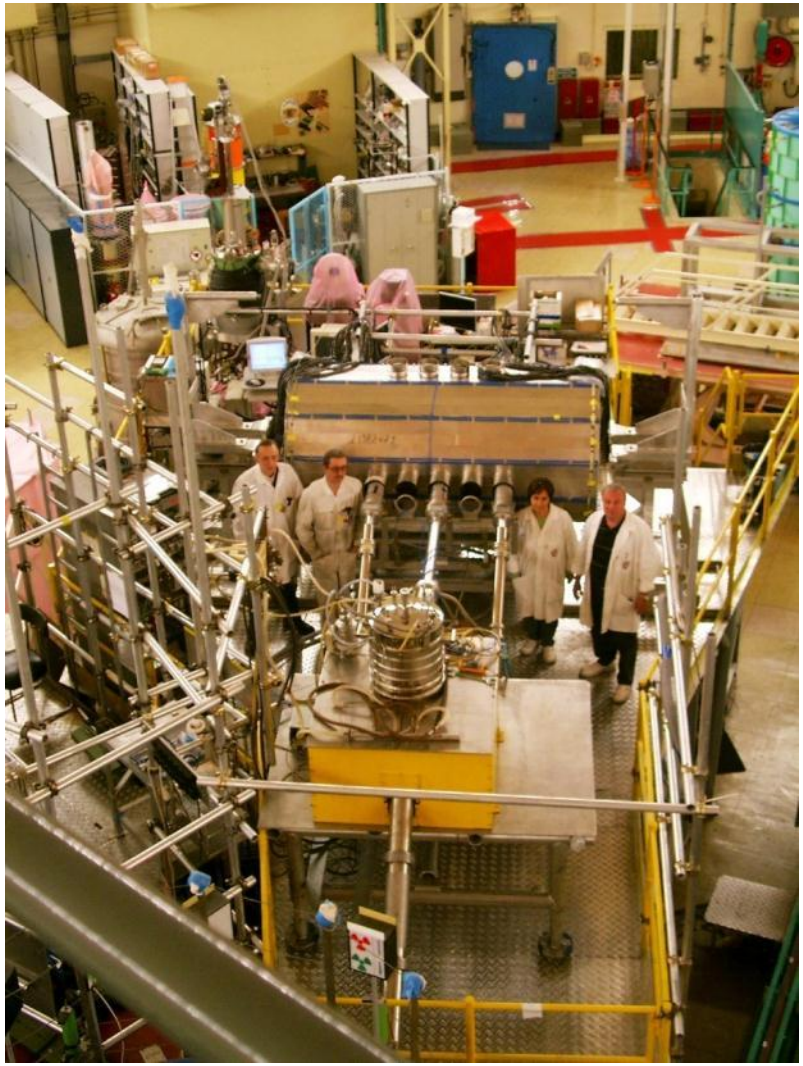
Preparation of n → n′ experiment at ILL







Assembling on the platform



LIMIT ON nn' OSCILLATIONS

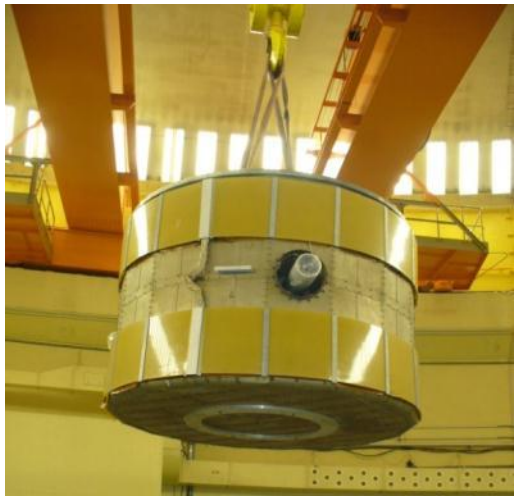
Lee and Yang (LEE 56) proposed the existence of mirror world in an attempt to restore global parity symmetry. See BEREZHIANI 06 for a recent discussion.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 12	95	[29] ALTAREV	09A	CNTR	UCN, scan $0 \leq B \leq 12.5$ μT
>103	95	BAN	07	CNTR	UCN, B field on & off

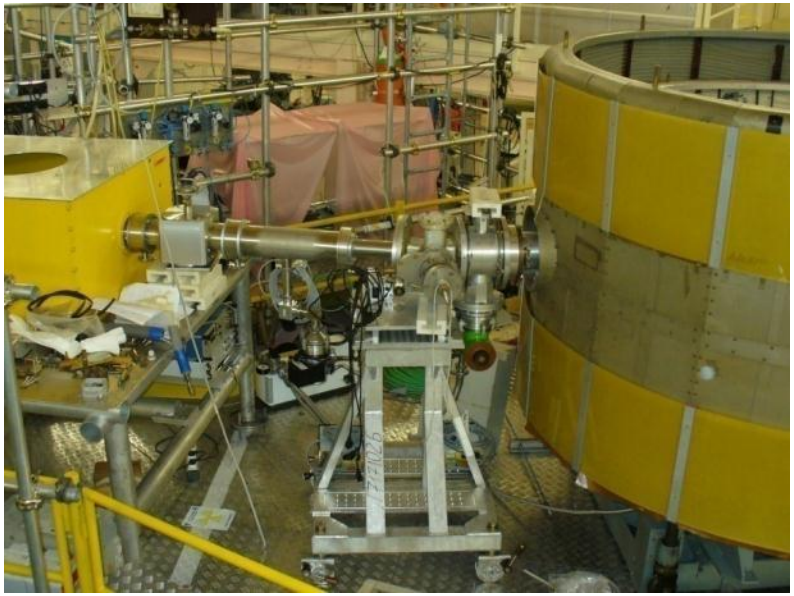
[29] Losses of neutrons due to oscillations to mirror neutrons would be maximal when the magnetic fields B and B' in the two worlds were equal. Hence the scan over B by ALTAREV 09A: the limit applies for any B' over the given range. At $B' = 0$, the limit is 141 s (95% CL).

Go back to EDM

Assembly of double-chamber EDM spectrometer in summer 2008 in the interval between reactor cycles

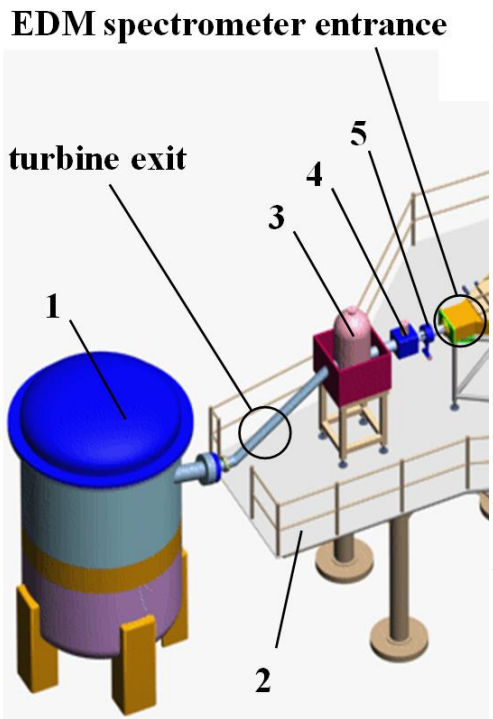


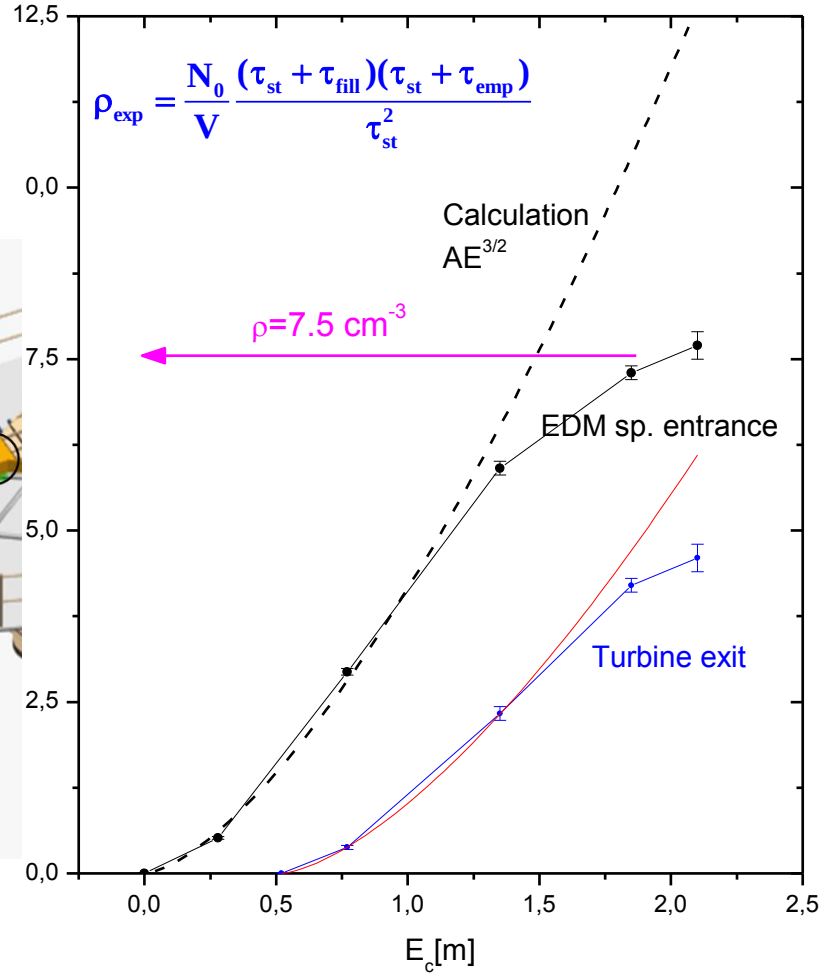
August 2008. Completion of main part of assembly.



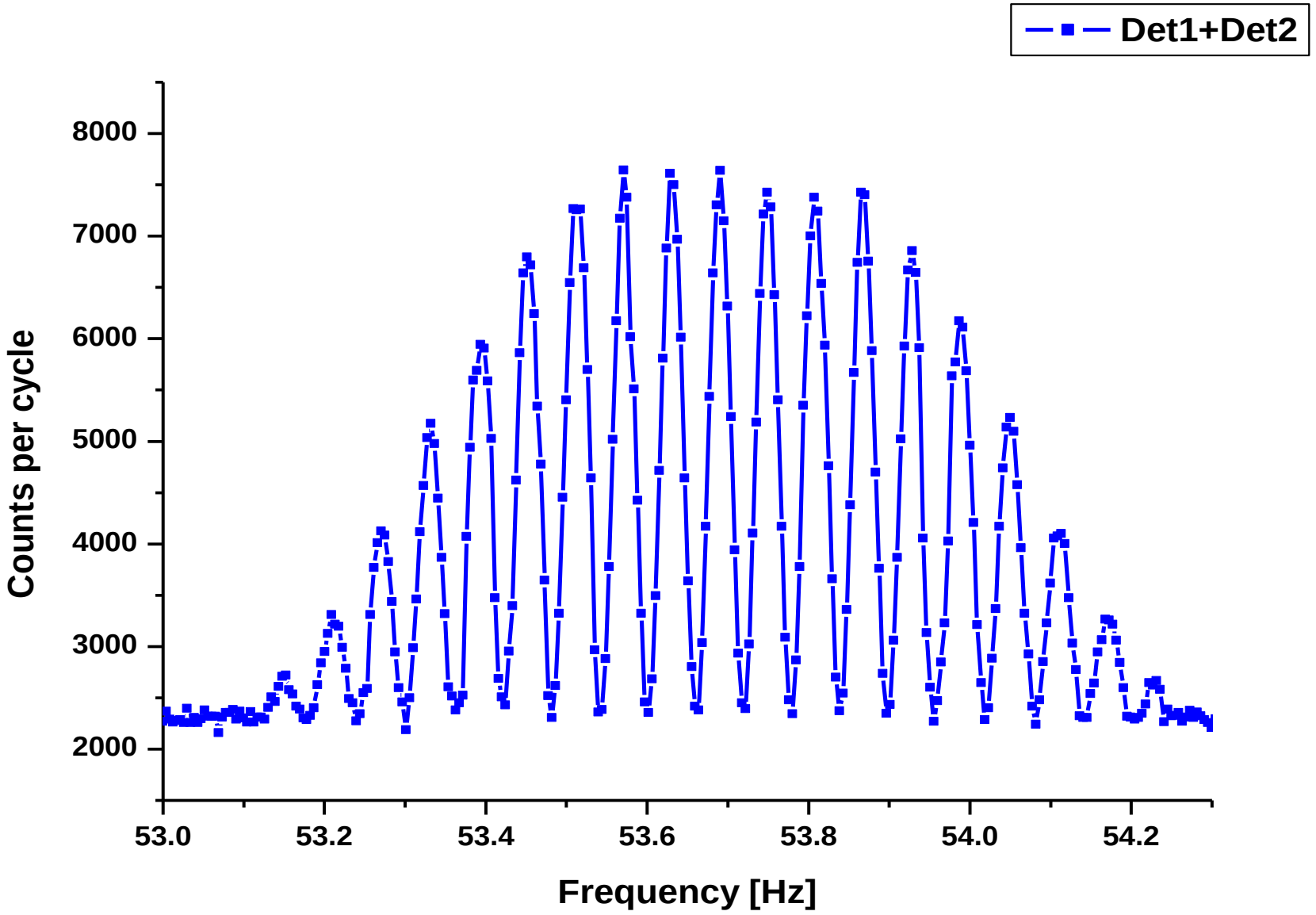
September 2008 - Assembly and testing of detectors, magnetometers and electronics.
October 2008 - Start of the first measurements with the neutrons

Direct measurements of UCN density in the EDM spectrometer entrance and at the UCN turbine exit

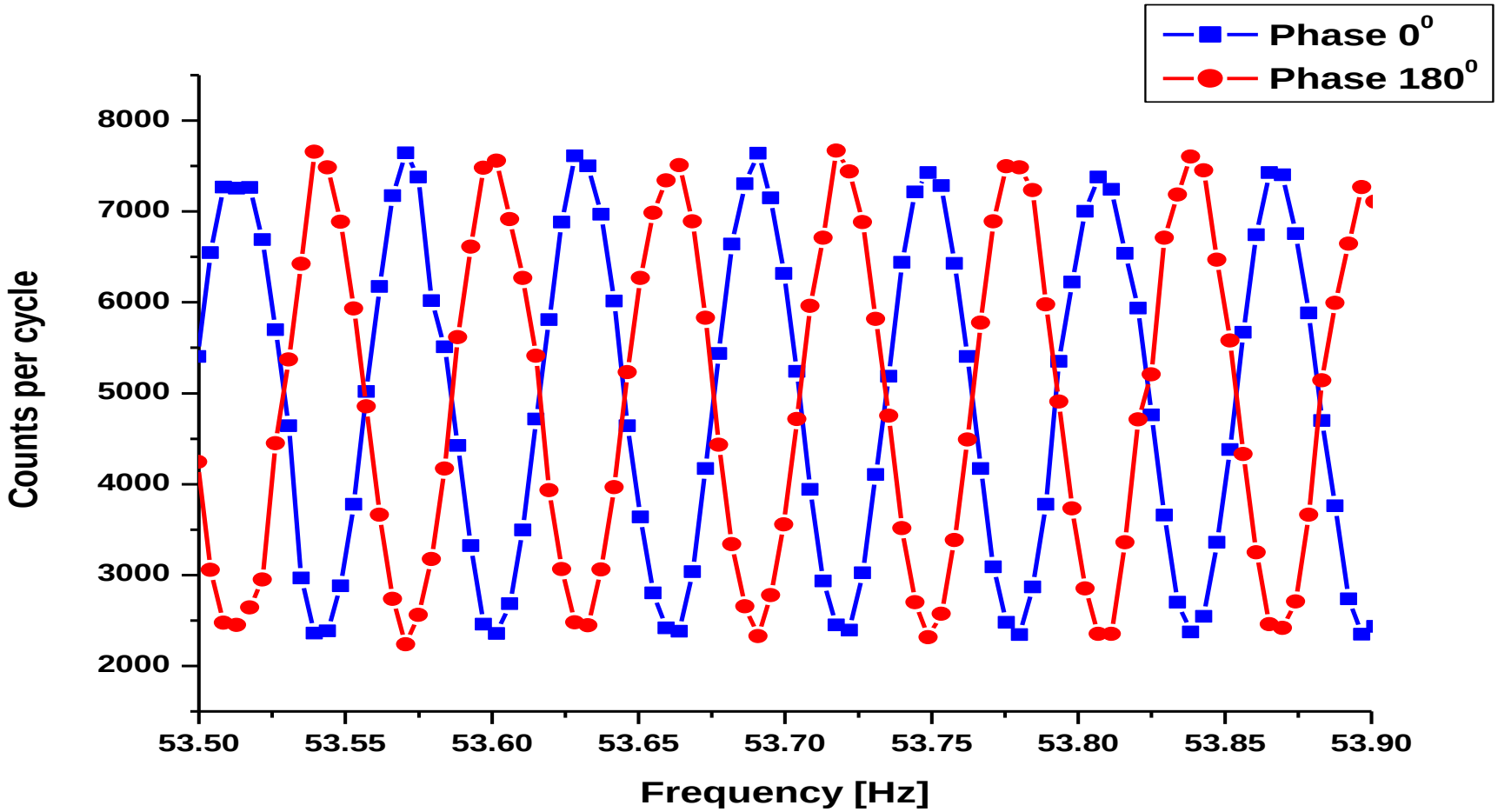




Resonance curve of the double-chamber EDM spectrometer, T(hold)=20s



Resonance curve of the double-chamber EDM spectrometer, T(hold)=20s



First estimation of EDM sensitivity

$(1{,}5 - 2{,}0) \cdot 10^{-25}$ e·cm/day

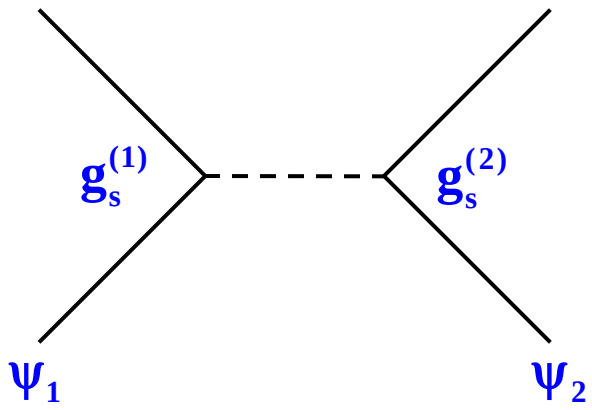
for 20kv/cm , T (hold) = 60s, 4 detectors

High Voltage System was not ready.

We decided to carry out experiment search for possible CP-violating long-range interaction (axion-like interaction) between nucleons

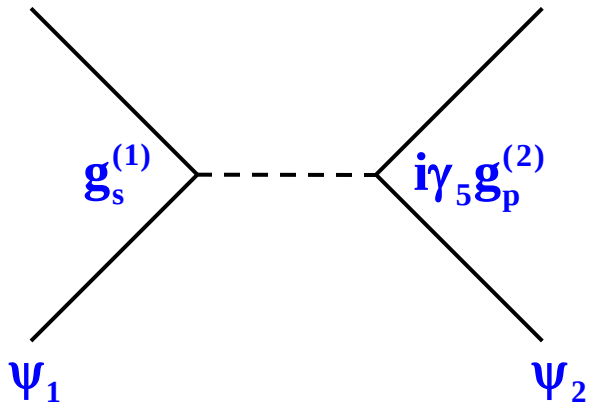
Possible long-range interaction (axion-like interaction) between nucleons

A.A. Anselm JETP Lett. v36 N2 (1982)



$$V(r) = -\frac{g_s^{(1)} g_s^{(2)}}{4\pi r} e^{-\frac{r}{\lambda}}$$

J.E. Moody and Frank Wilczek Phys. Rev. D v30 N1 (1984)



$$V(r) = g_s^{(1)} g_p^{(2)} \frac{\vec{\sigma}_2 \vec{r}}{8\pi M_2} \left[\frac{1}{r\lambda} + \frac{1}{r^2} \right] e^{-\frac{r}{\lambda}}$$

Direct experimental limits for $g_S g_P$ and "axion window" of mass or distance of interaction

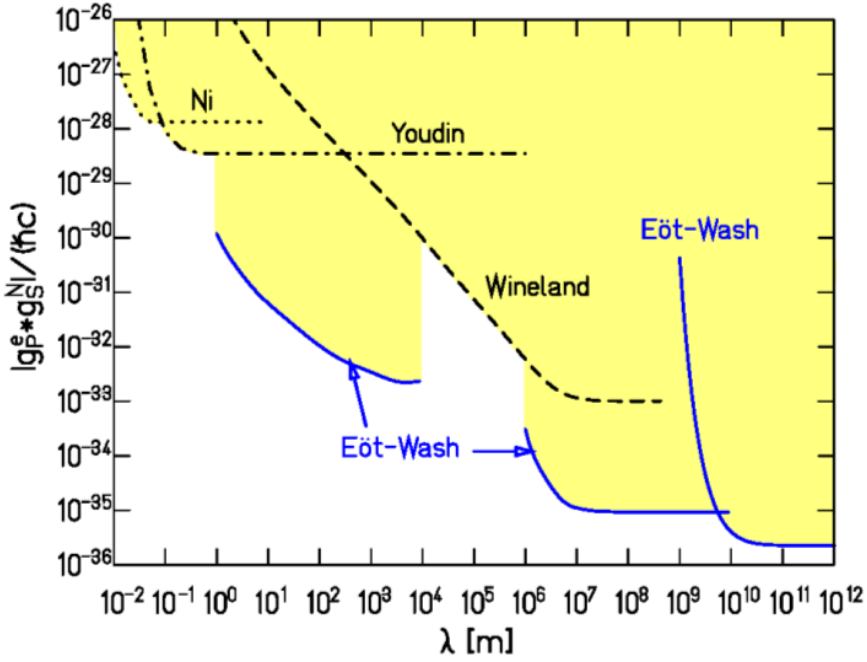


Figure 1: Short-distance gravity upper limits [37] on the product of mass- and spin-vertex couplings as a function of the interaction range λ; the shaded region is excluded at 95% confidence. Figure courtesy E. Adelberger.

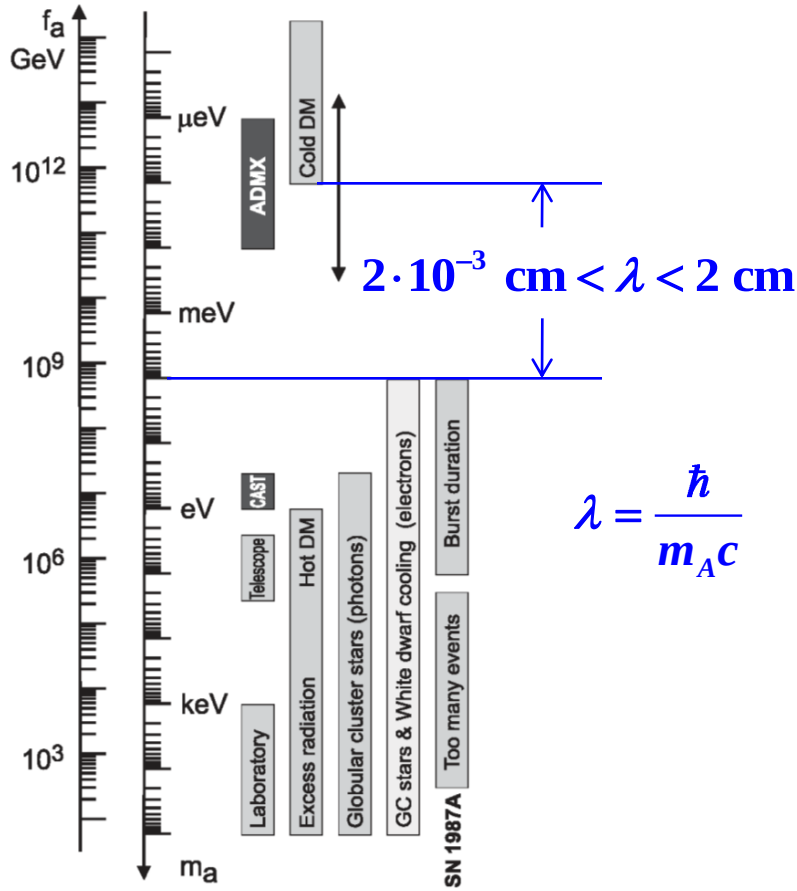
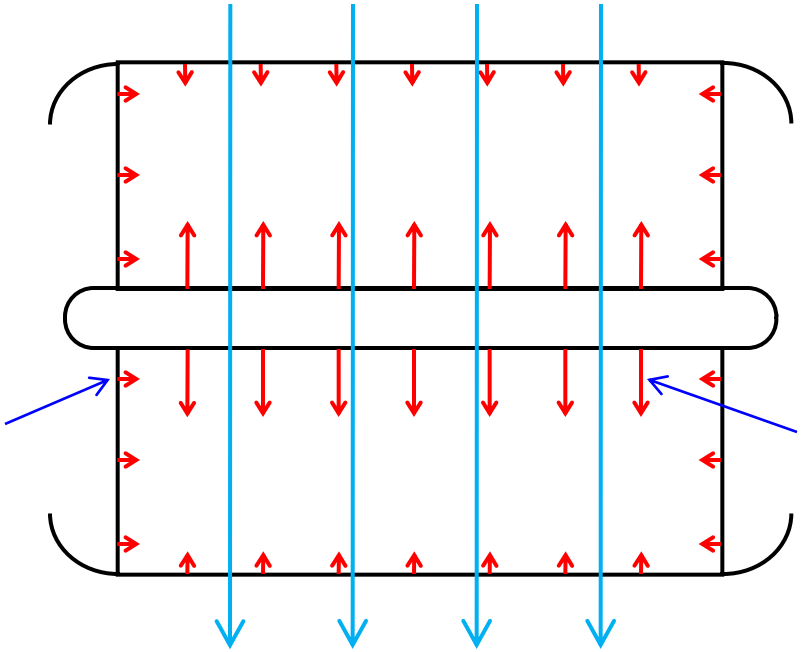


Figure 2: Exclusion and experimental search ranges as described in the text. Limits on coupling strengths are translated into limits on m_A and f_A using $z = 0.56$ and the KSVZ values for the coupling strengths. The "Laboratory" bar is a rough representation of the exclusion range for standard or variant axions. The "GC stars and white-dwarf cooling" range uses the DFSZ model with an axion-electron coupling corresponding to $\cos^2\beta = 1/2$. The Cold Dark Matter exclusion range is particularly uncertain. We show the benchmark case from the misalignment mechanism.

Additional effective magnetic field in EDM spectrometer

$$V(z) = \pm 5.2 \cdot 10^5 \left[\text{eV/cm}\right] \lambda \left[\text{cm}\right] e^{-\frac{z}{\lambda}} g_S g_P = \pm \mu_n H_{eff} \qquad \mu_n = 6 \cdot 10^{-12} \left[\text{eV/G}\right]$$

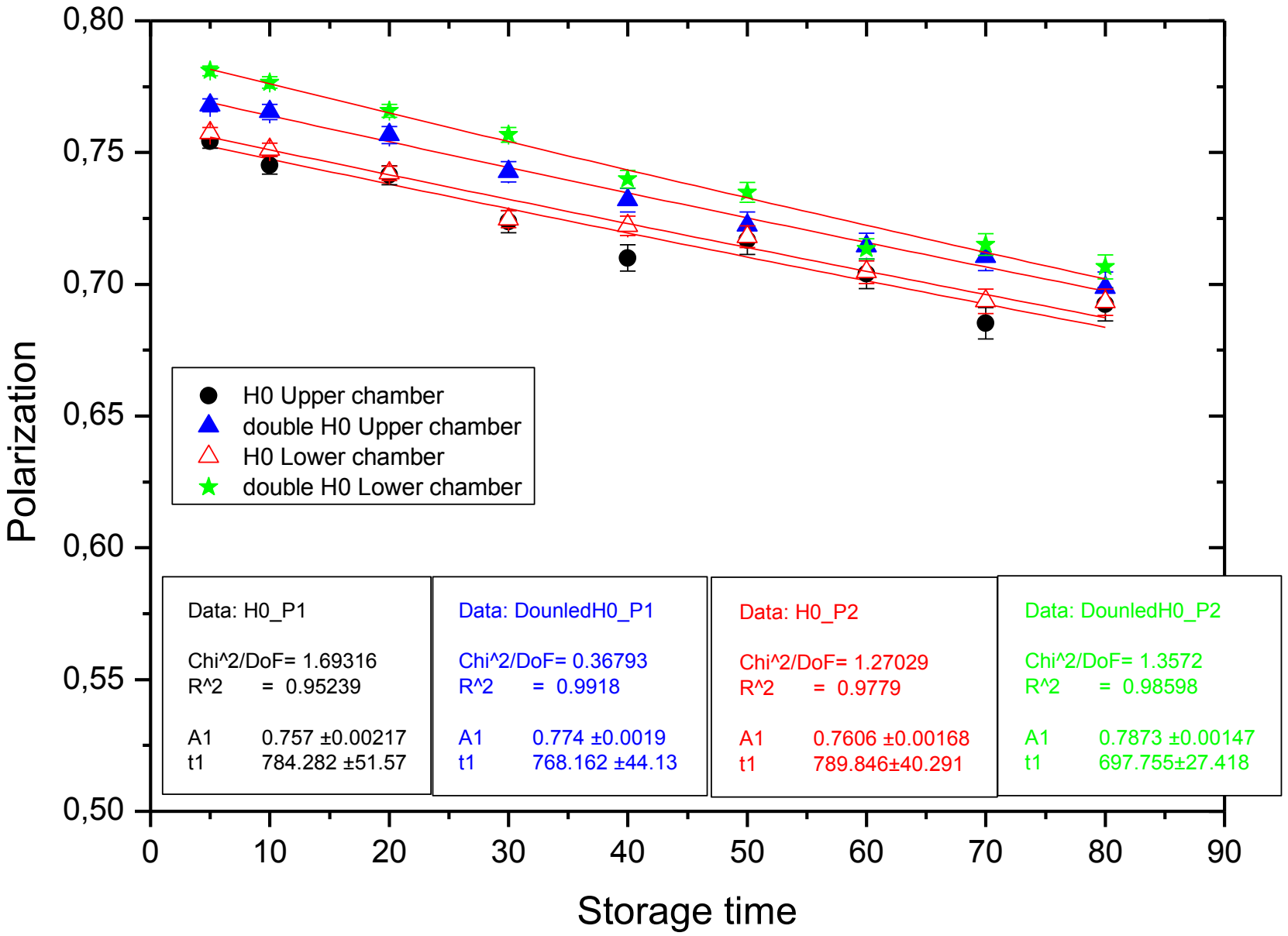
$$H_{eff} = \frac{5.2 \cdot 10^5 \lambda e^{-\frac{z}{\lambda}} g_S g_P}{\mu_n} = 8.7 \cdot 10^{16} \left[\text{G/cm}\right] \lambda \left[\text{cm}\right] g_S g_P e^{-\frac{z}{\lambda}}$$



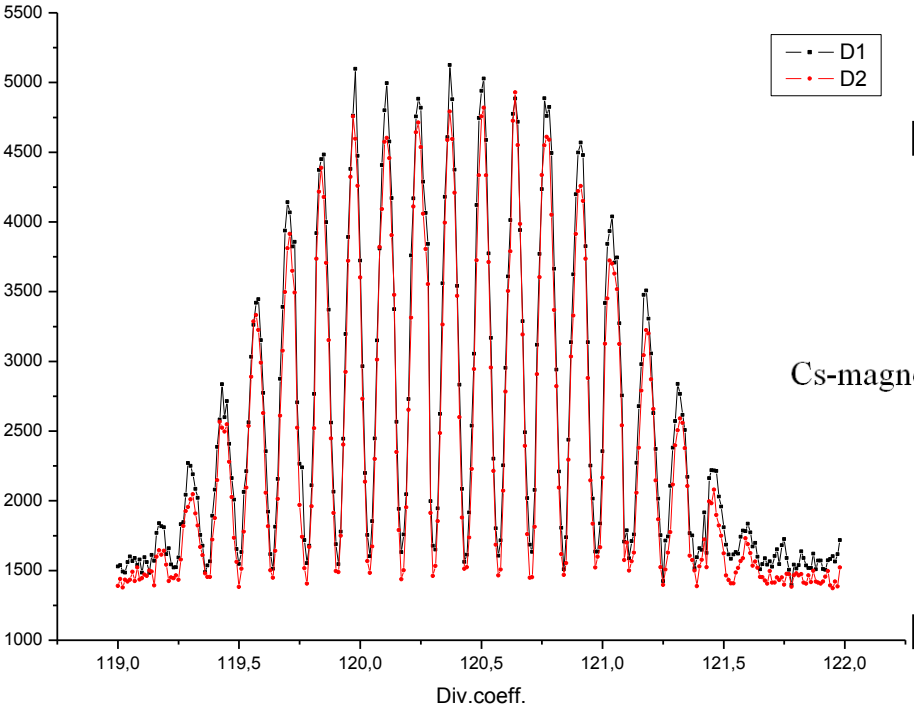
UCN depolarization on vertical walls
A. Serebrov
(arxiv:0902.1056)

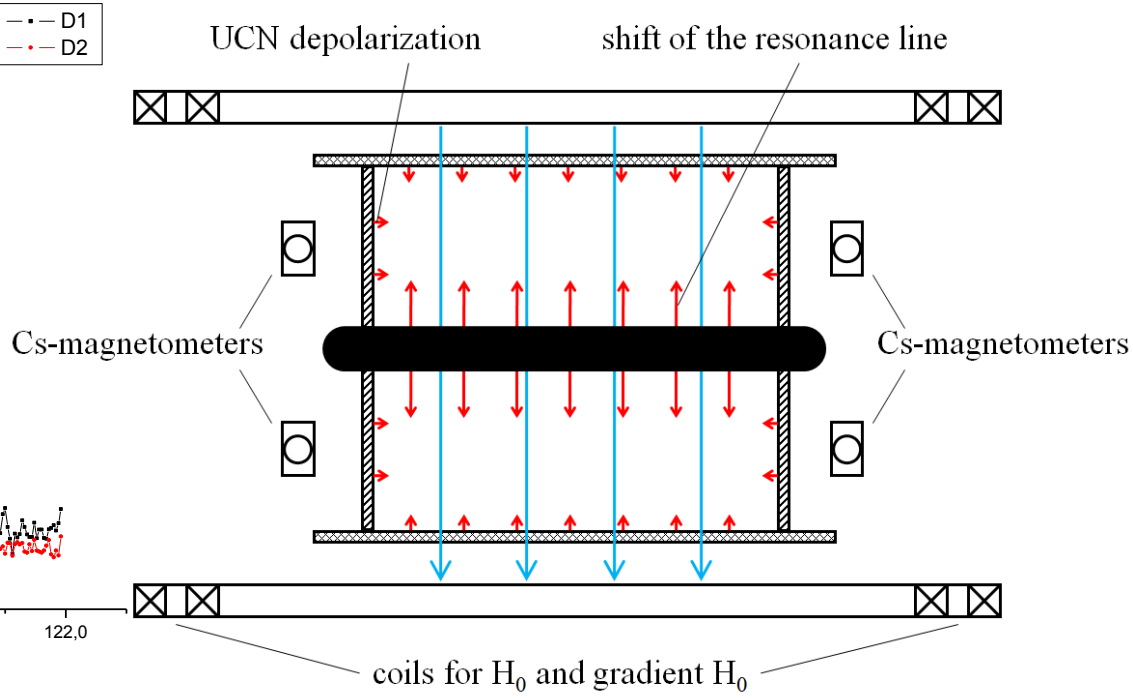
shift of resonances on horizontal walls
O. Zimmer
(arxiv:0810.3215)

Measurement of UCN depolarization in EDM spectrometer



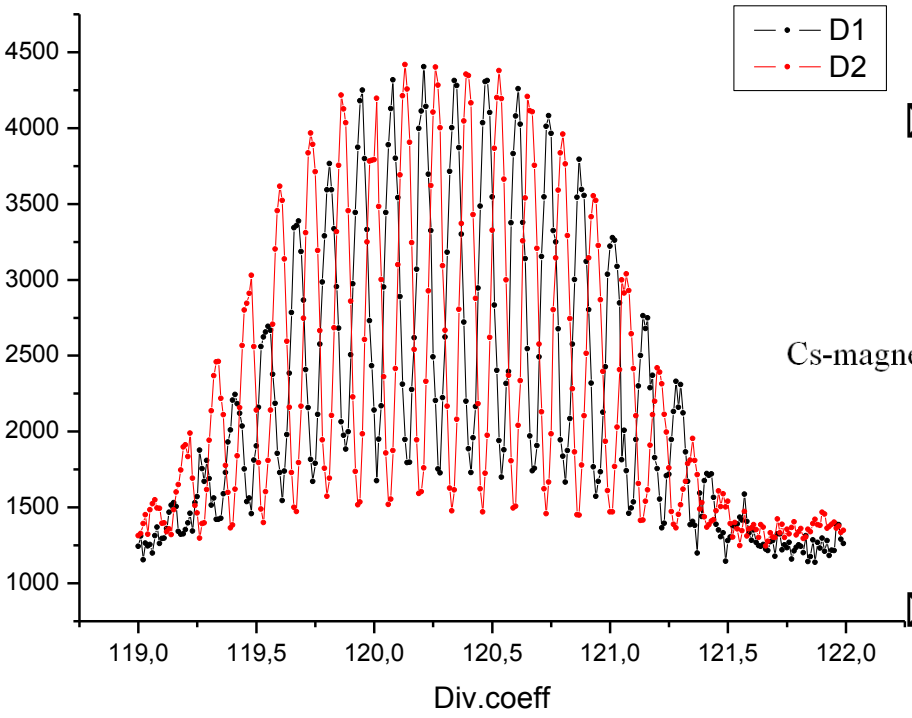
Measurement of resonance shift at the change of direction of magnetic field in EDM spectrometer

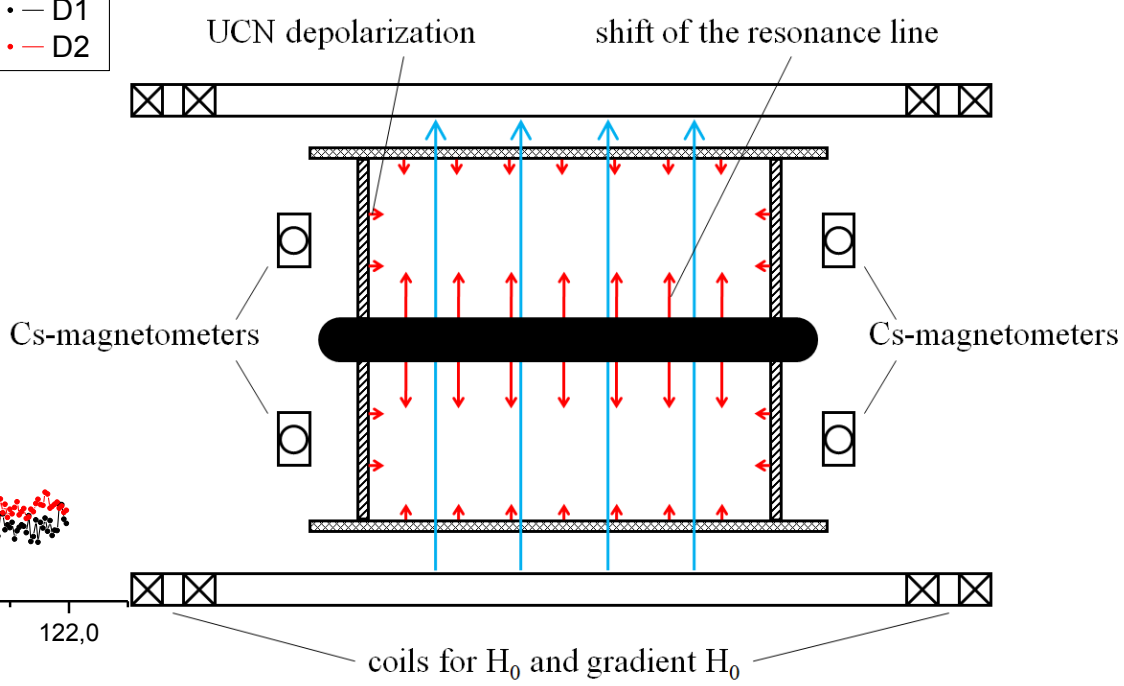




magnetic field down

Measurement of resonance shift at the change of direction of magnetic field in EDM spectrometer

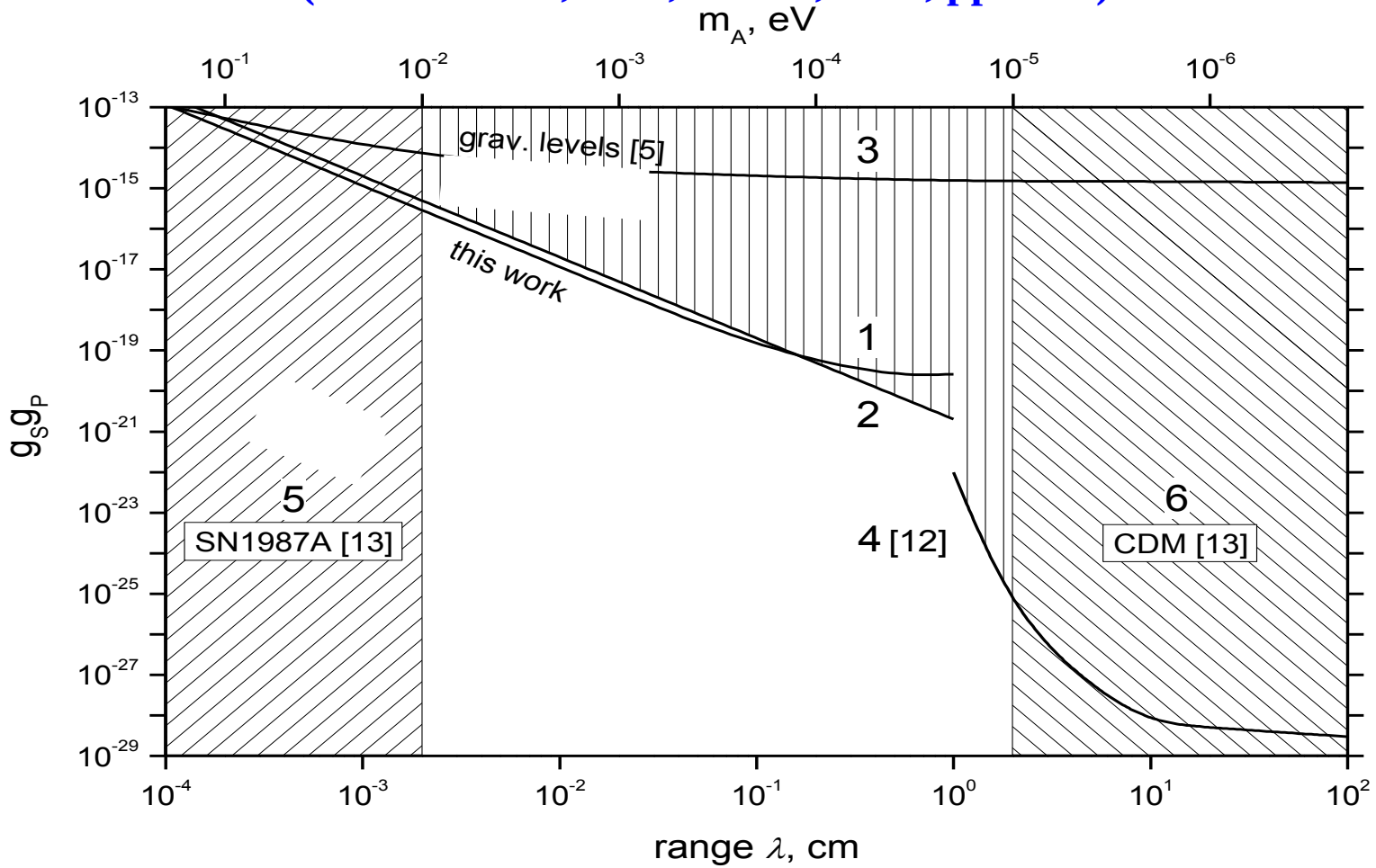




magnetic field up

Result of measurements

(JETP Letters, 2010, Vol. 91, no. 1, pp. 6-10)



1 – UCN depolarization (this work); 2 – shift of resonance (this work); 3 – gravitational levels [5]; 4 – [12]; 5 – astrophysical restriction of axion mass [13]; 6 – cosmological restriction of axion mass in model of cold dark matter [13]. On the upper horizontal axis the mass range of intermediate boson (axion) is shown in correspondence with formula $\lambda = \hbar / m_A c$

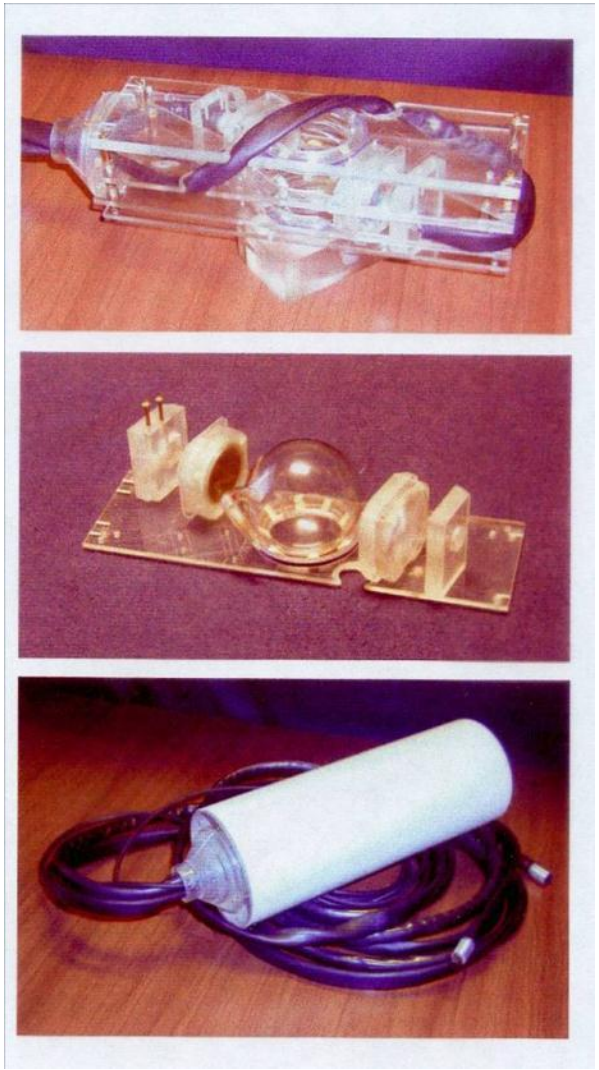
Axion Limits from *T*-violating Medium-Range Forces

The limit is for the coupling $g = g_p\ g_s$ in a T-violating potential between nucleons or nucleon and electron of the form $V = \frac{g\hbar^2}{8\pi m_p}(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\ (\frac{1}{r^2} + \frac{1}{\lambda r})\ e^{-r/\lambda}$, where g_p and g_s are dimensionless scalar and pseudoscalar coupling constants and $\lambda = \hbar/(m_A c)$ is the range of the force.

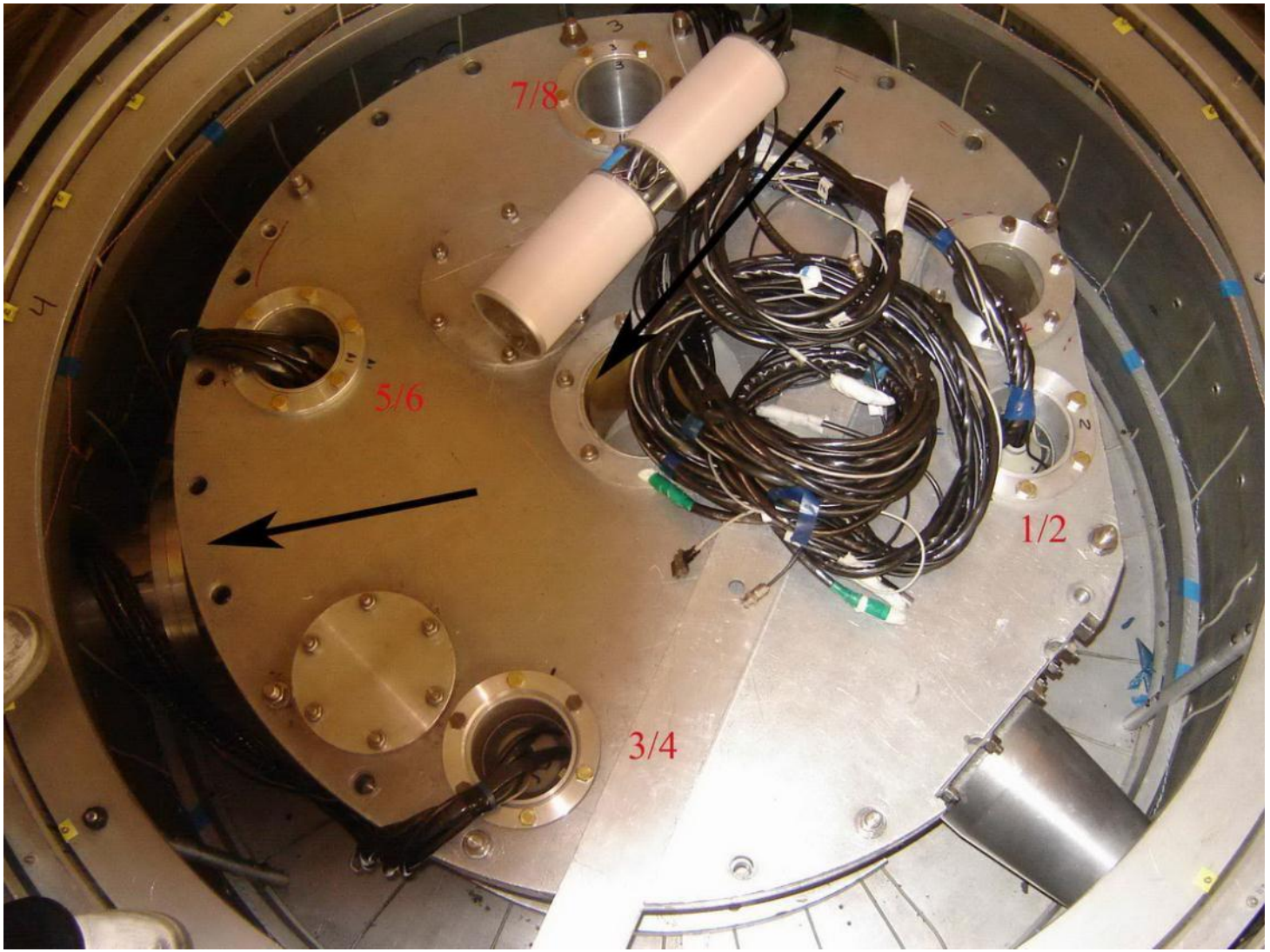
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[245] HOEDL	11		torsion pendulum
	[246] PETUKHOV	10		polarized ^{3}He
	[247] SEREBROV	10		ultracold neutrons
	[248] IGNATOVICH	09	RVUE	ultracold neutrons
	[249] SEREBROV	09	RVUE	ultracold neutrons
	[250] BAESSLER	07		ultracold neutrons
	[251] HECKEL	06		torsion pendulum
	[252] NI	99		paramagnetic Tb F_3
	[253] POSPELOV	98	THEO	neutron EDM
	[254] YOUDIN	96		
	[255] RITTER	93		torsion pendulum
	[256] VENEMA	92		nuclear spin-precession frequencies
	[257] WINELAND	91	NMR	

Again go back to EDM

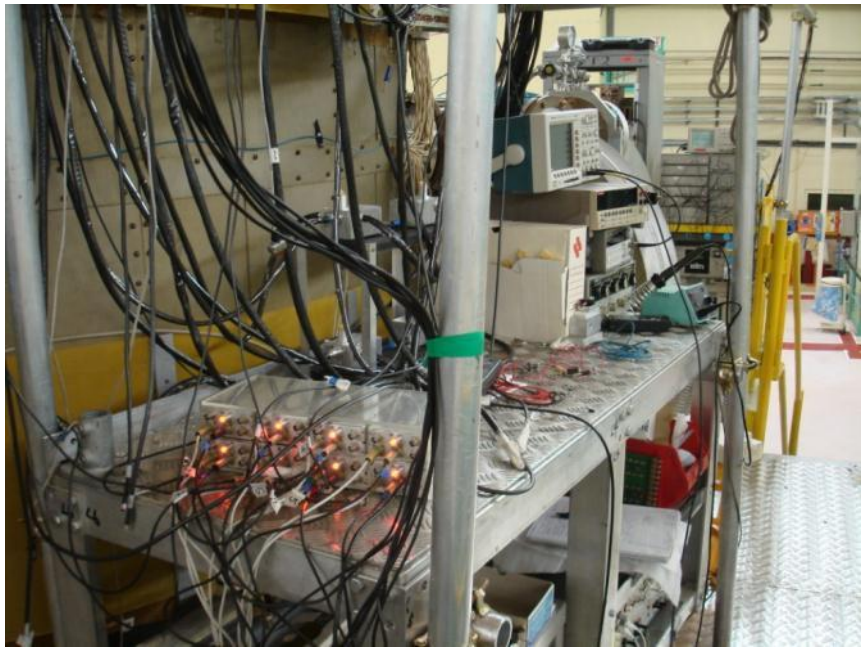
Preparation of Cs-magnetometers at PTI

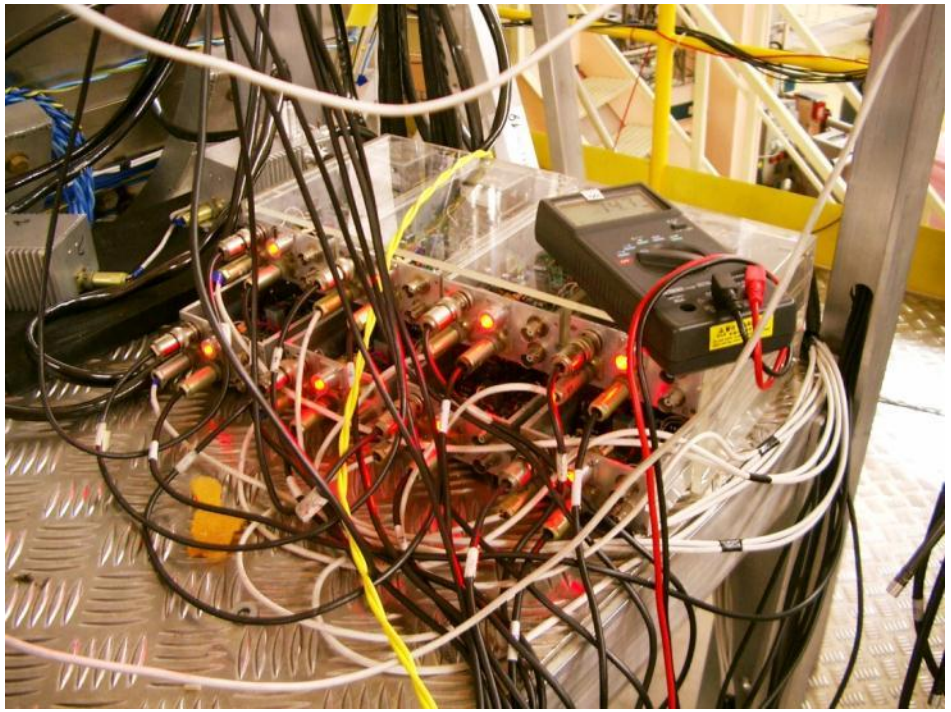


8 (4x2)Cs-magnetometers inside EDM spectrometer



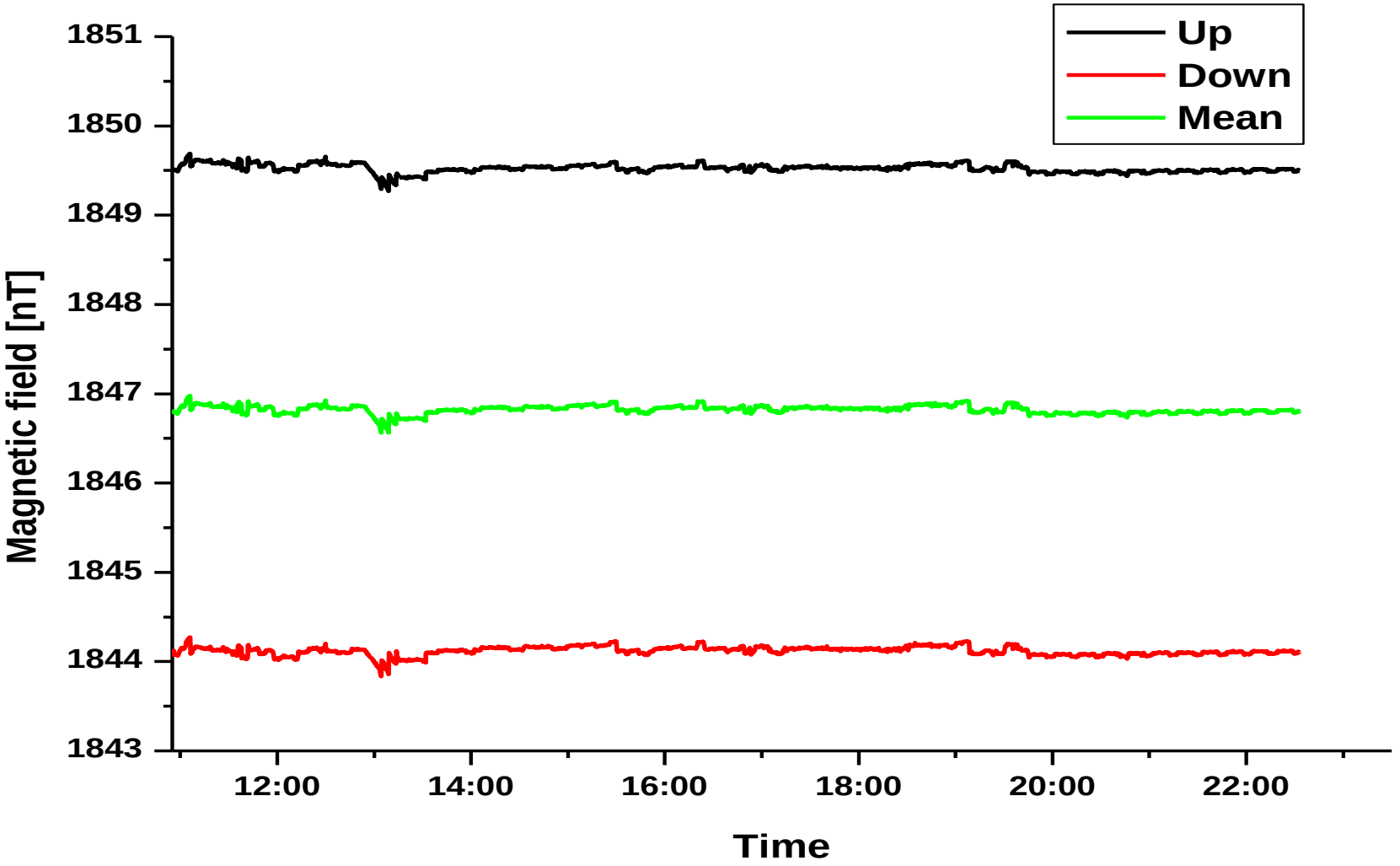
System of optical pumping with light guides



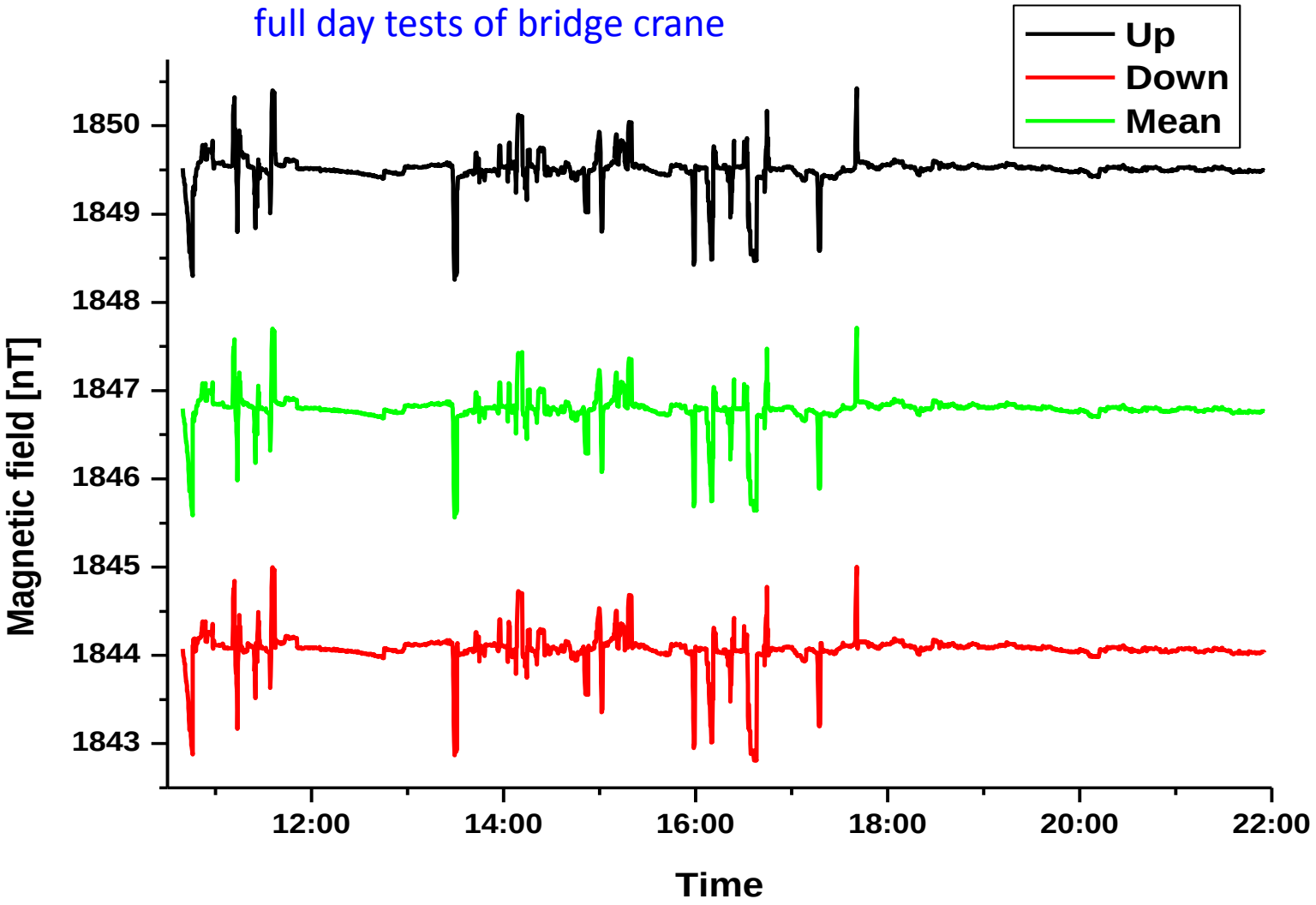


Stabilization of magnetic field during resonance measurements (system of stabilization of resonance conditions + feedback by means of current coils)

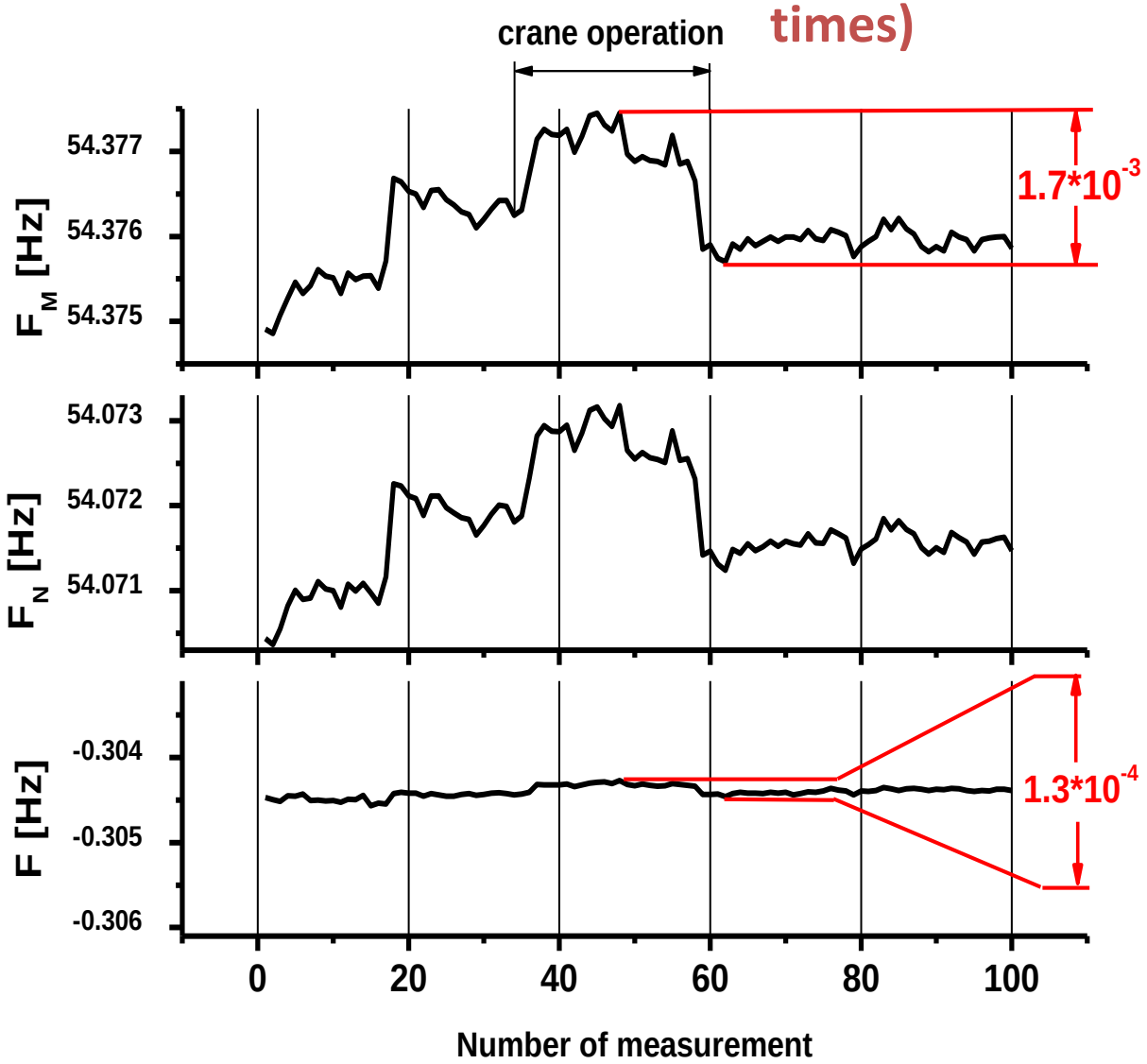
quiet magnetic situation



Stabilization of magnetic field during resonance measurements (system of stabilization of resonance conditions + feedback by means of current coils)



The influence of external magnetic fluctuations on stability of resonance conditions in a spectrometer.
(factor of stabilization by mean of 8 Cs-magnetometers is about 10 – 15 times)

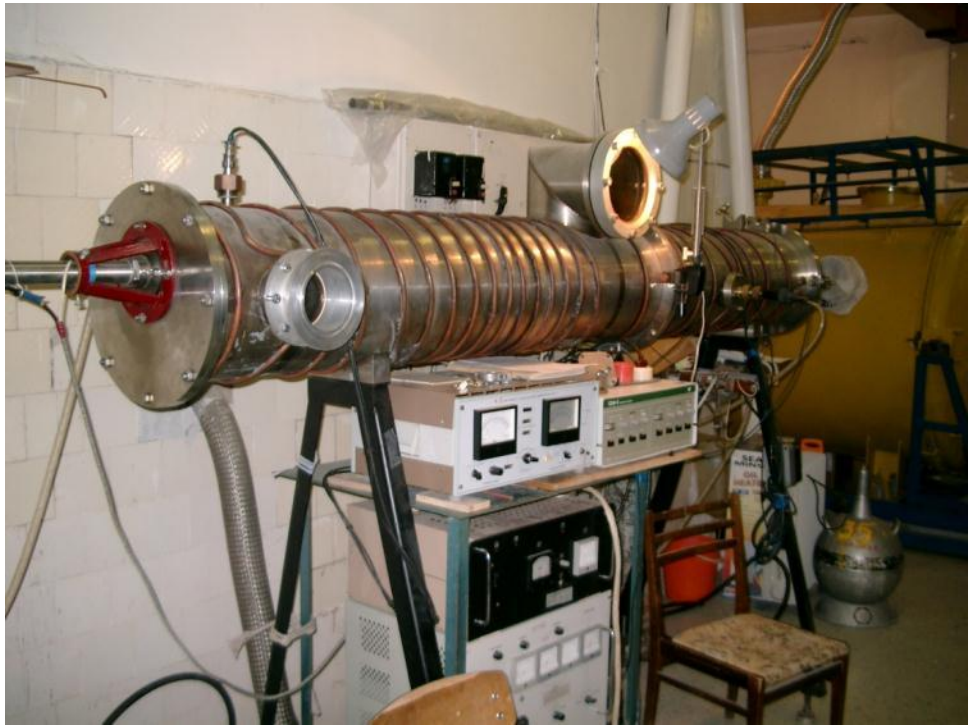


a)FM is the average frequency measured by means of eight Cs magnetometers;

b) FN is the frequency measured by the additional Cs magnetometers in working volume;

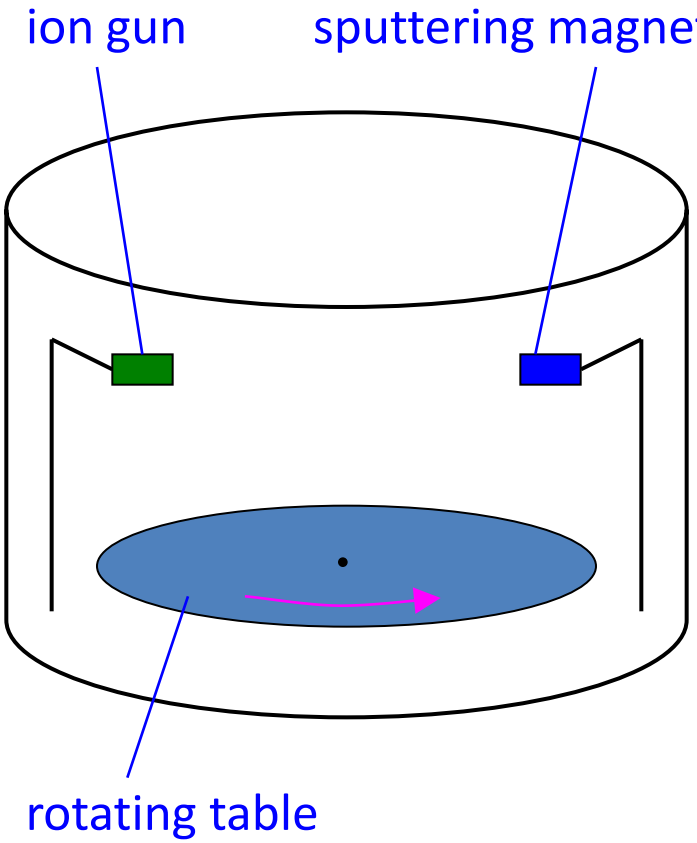
Difference FN – FM.

For reduction of UCN losses the neutron guides and storage chambers (glass-ceramics rings and electrodes) were sent to PNPI where their surfaces were cleaned and freshly coated with 58Ni-Mo and BeO, Be, respectively.



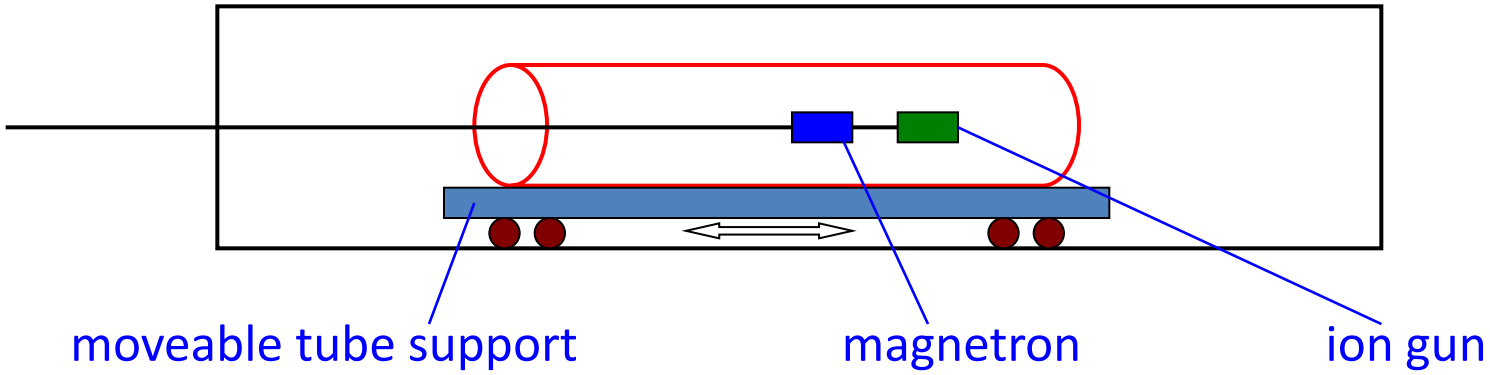
PNPI installations for coating of neutron guides and storage chamber.

Coating facilities at PNPI (installation for coating of flat surface of UCN guides and electrodes ($Ni^{58}Mo$, Be) and cylindrical surface of UCN trap (BeO)

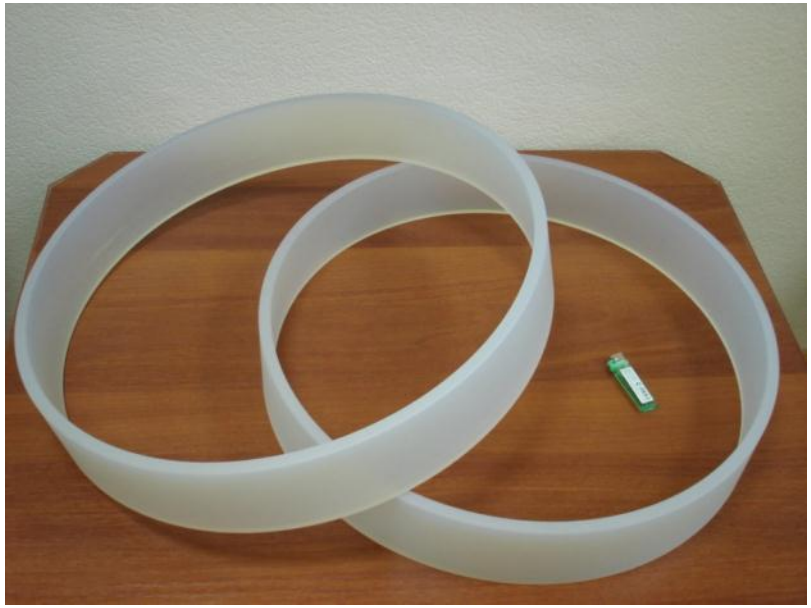


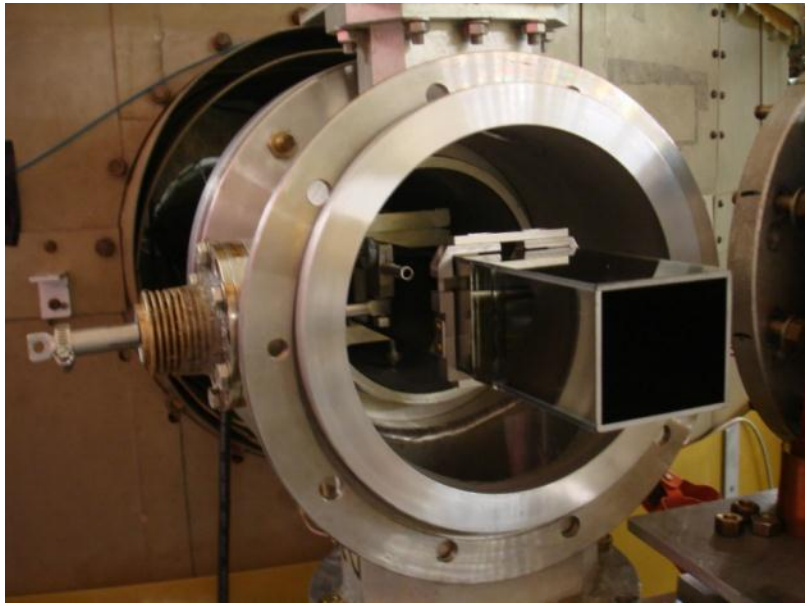
Near installation
A.Kharitonov, E.Siber, O.Rozhnov

Coating facilities at PNPI (installation for coating of cylindrical UCN guides inside ($Ni^{58}Mo$, Be))



Near installation
M.Lasakov, A.Vasiliev

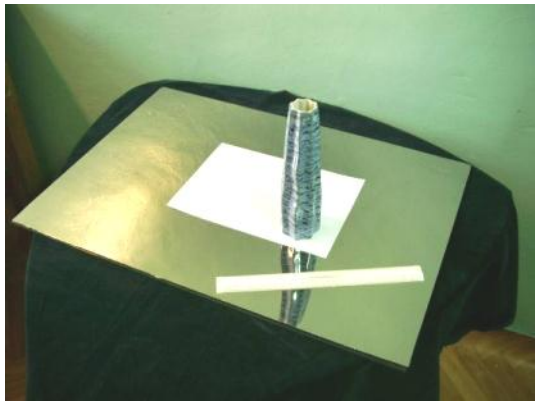




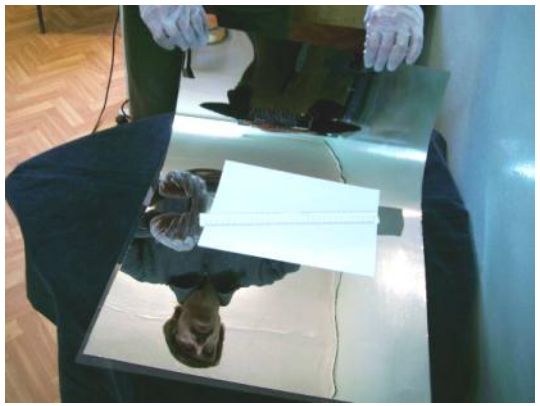
Glass ceramics rings (insulators) and new entrance guide after coating by BeO and 58Ni-Mo

UCN guide with a big diameter (replica technology)

Installation for coating of $Ni^{58}Mo$ on the float glass



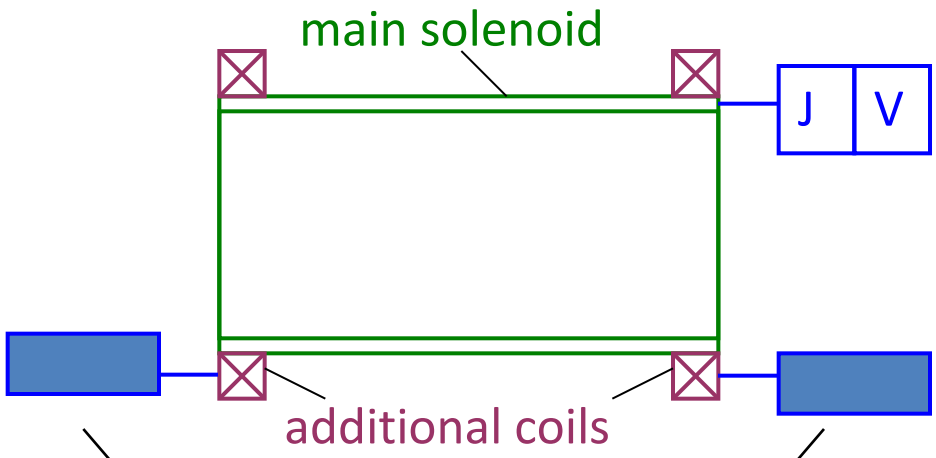
foil after separation from glass (size 700x470 mm^2)



preparation of a UCN guide

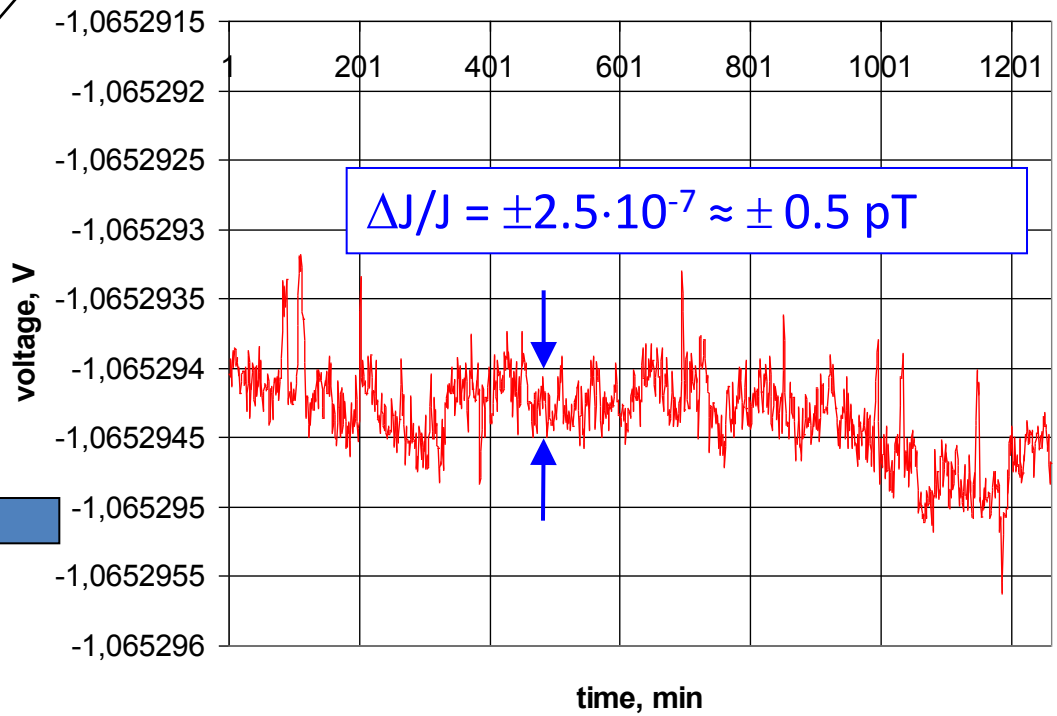
UCN guides of different diameters

Electronics for magnetic field generation



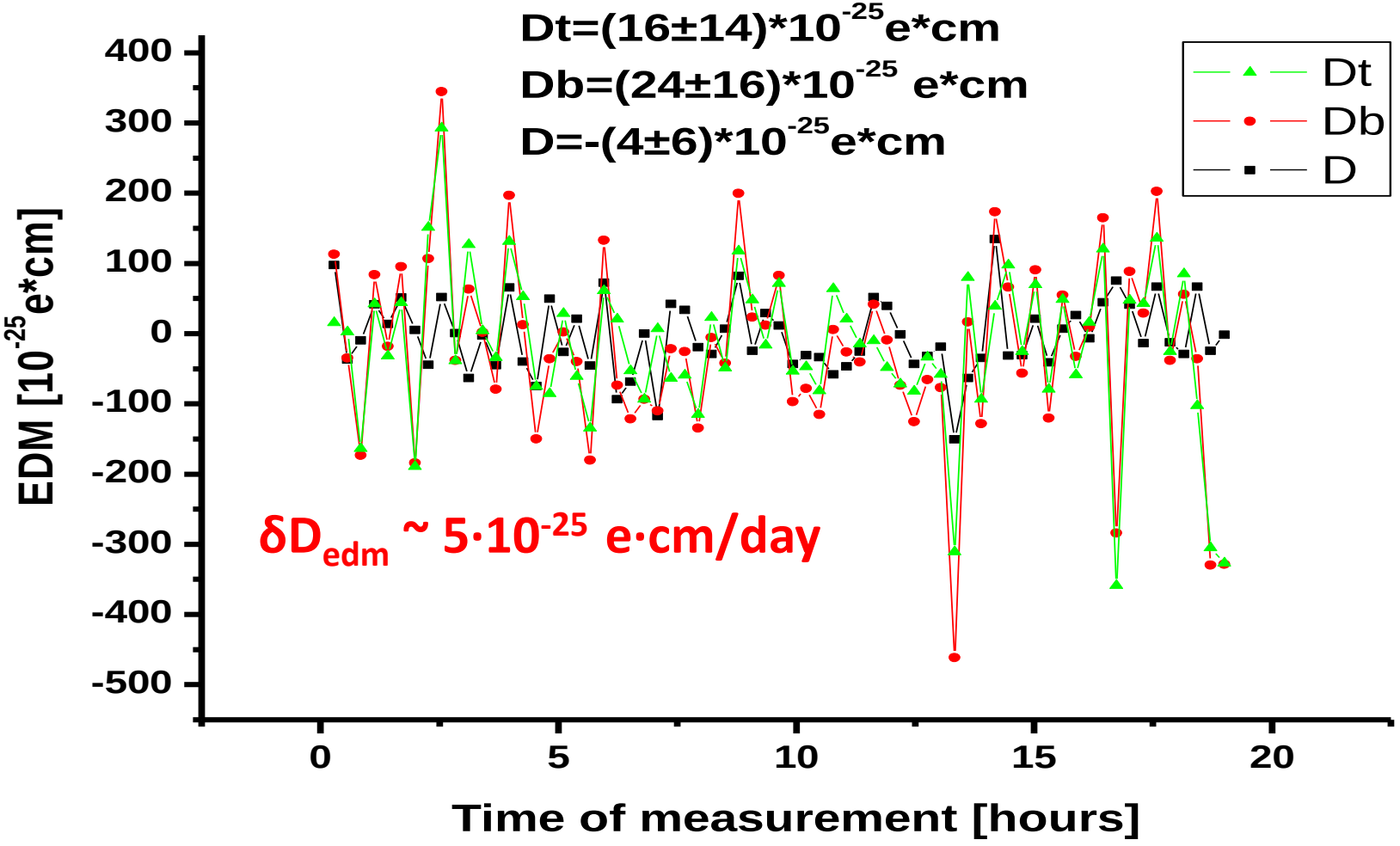
$\Delta J/J = \pm 1 \cdot 10^{-7} \approx \pm 0.2$ pT

$\Delta J/J = \pm 2.5 \cdot 10^{-7} \approx \pm 0.5$ pT



The recent measurement of EDM sensitivity

Direct measurement of sensitivity of EDM spectrometer with UCN density 3-4 ucn/cm^3 (MAM position) with electric field 10 kV/cm and T(hold) = 65 s



New result with HV
(+_)175kV/ 8.7cm = 20kV/cm

Corrected measurement of sensitivity of EDM spectrometer with UCN density 3-4 ucn/cm^3 (MAM position) with new electric field 20 kV/cm and T(hold) = 65 s

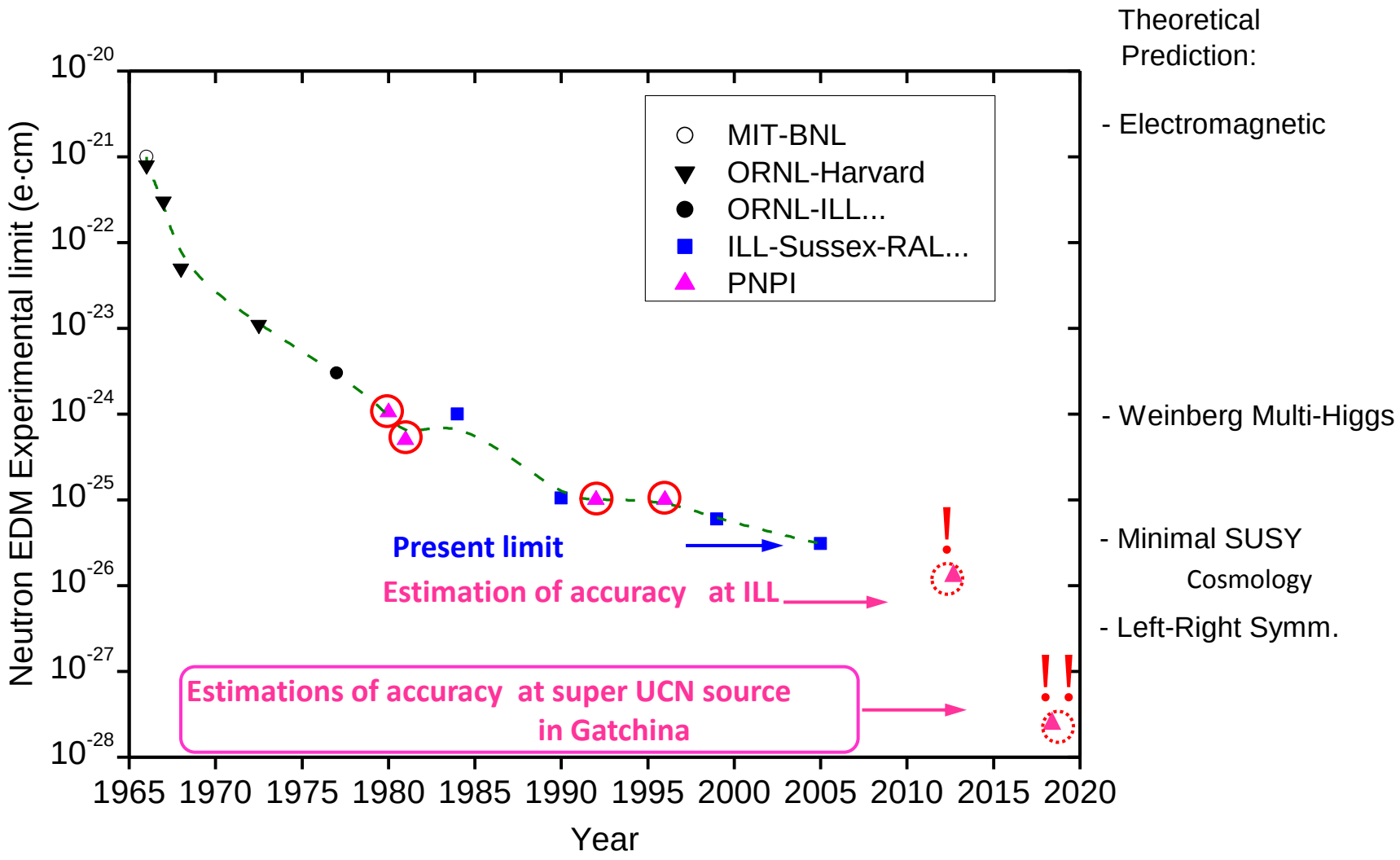
$\rho_{ucn\ at\ entrace} \sim 3\text{-}4$ ucn/cm^3,

$\delta D_{edm} \sim 2.5 \cdot 10^{-25}$ e·cm/day

Upper limit of sensitivity :

$2.5 \cdot 10^{-26}$ e·cm/100 days

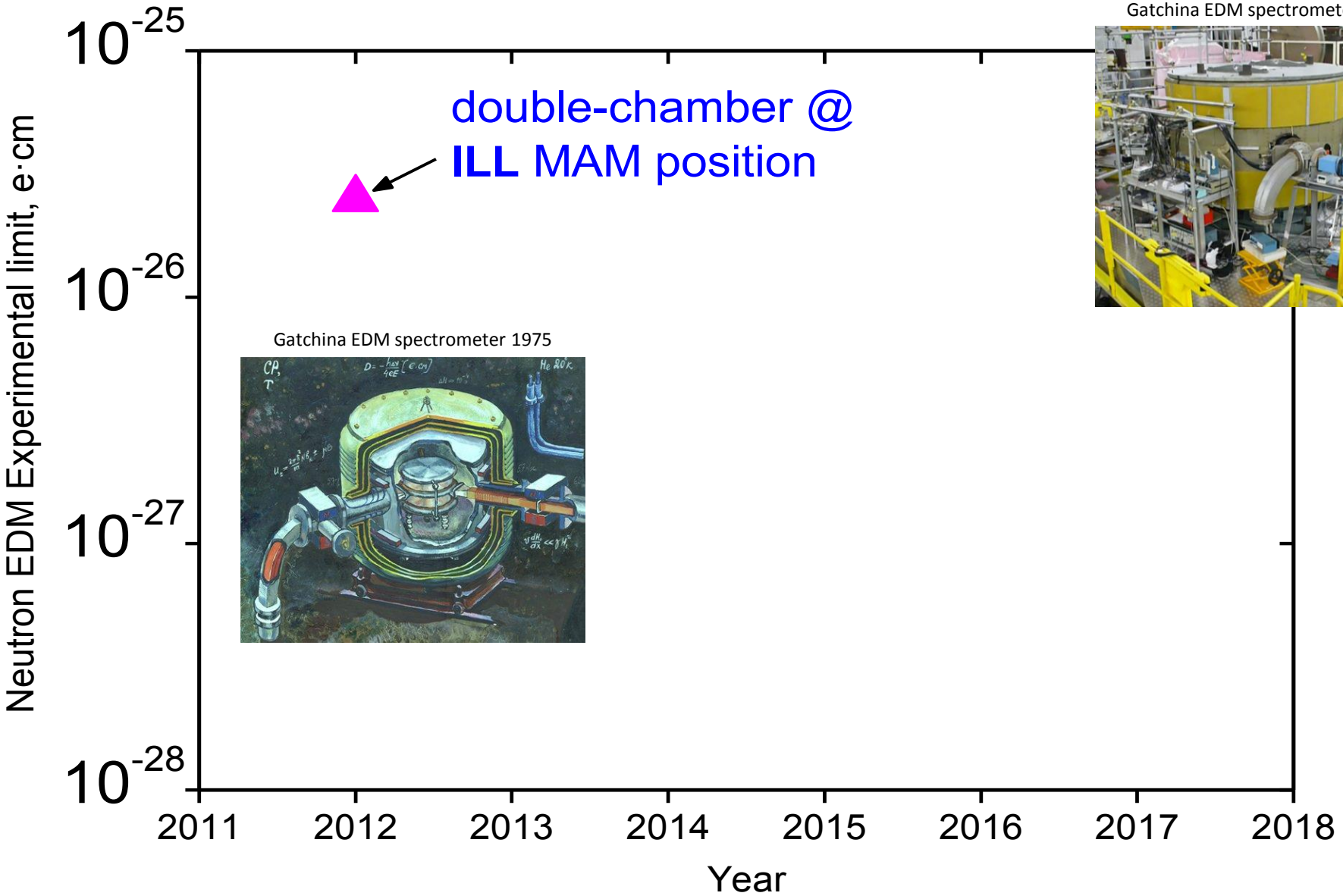
History of nEDM measurements. Results and prospects of PNPI-ILL-PTI collaboration



PNPI-ILL-PTI collaboration

Prospects to increase sensitivity of EDM measurements

Gatchina EDM spectrometer at ILL



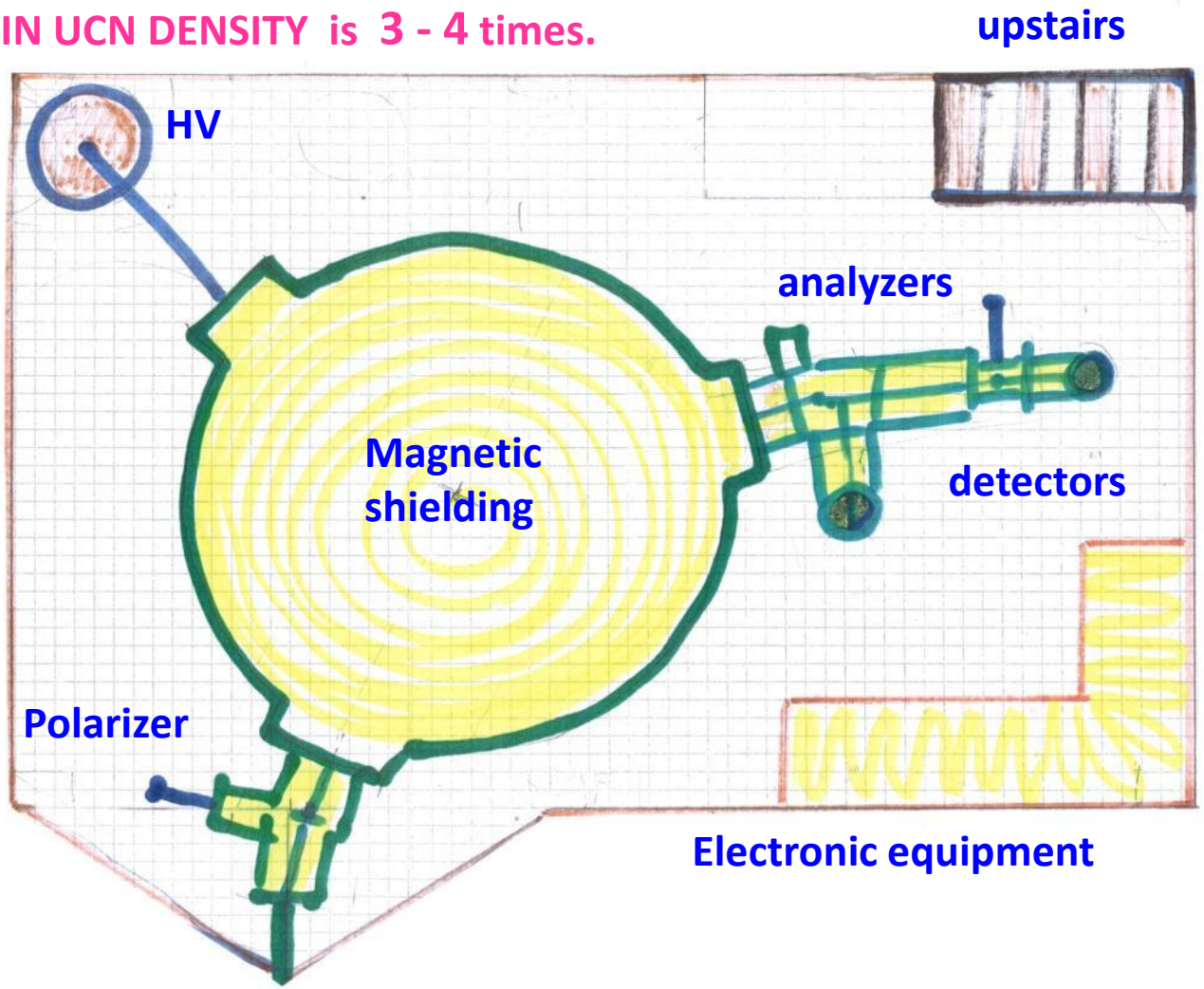
Gatchina EDM spectrometer 1975

PF2 position EDM

EDM spectrometer on the position EDM PF2

(legs of platform have to be cut (1.3 m))

GAIN FACTOR IN UCN DENSITY is 3 - 4 times.



EDM sensitivity at PF2 position "EDM"

2013 - 2014. **New position at PF2 (EDM instead of MAM) Factor in UCN density is about 3 – 4 times in respect to MAM position.**

$\rho_{ucn\ at\ entrace} \sim 20$ ucn/cm^3,

$\delta D_{edm} \sim 1 \cdot 10^{-25}$ e·cm/day

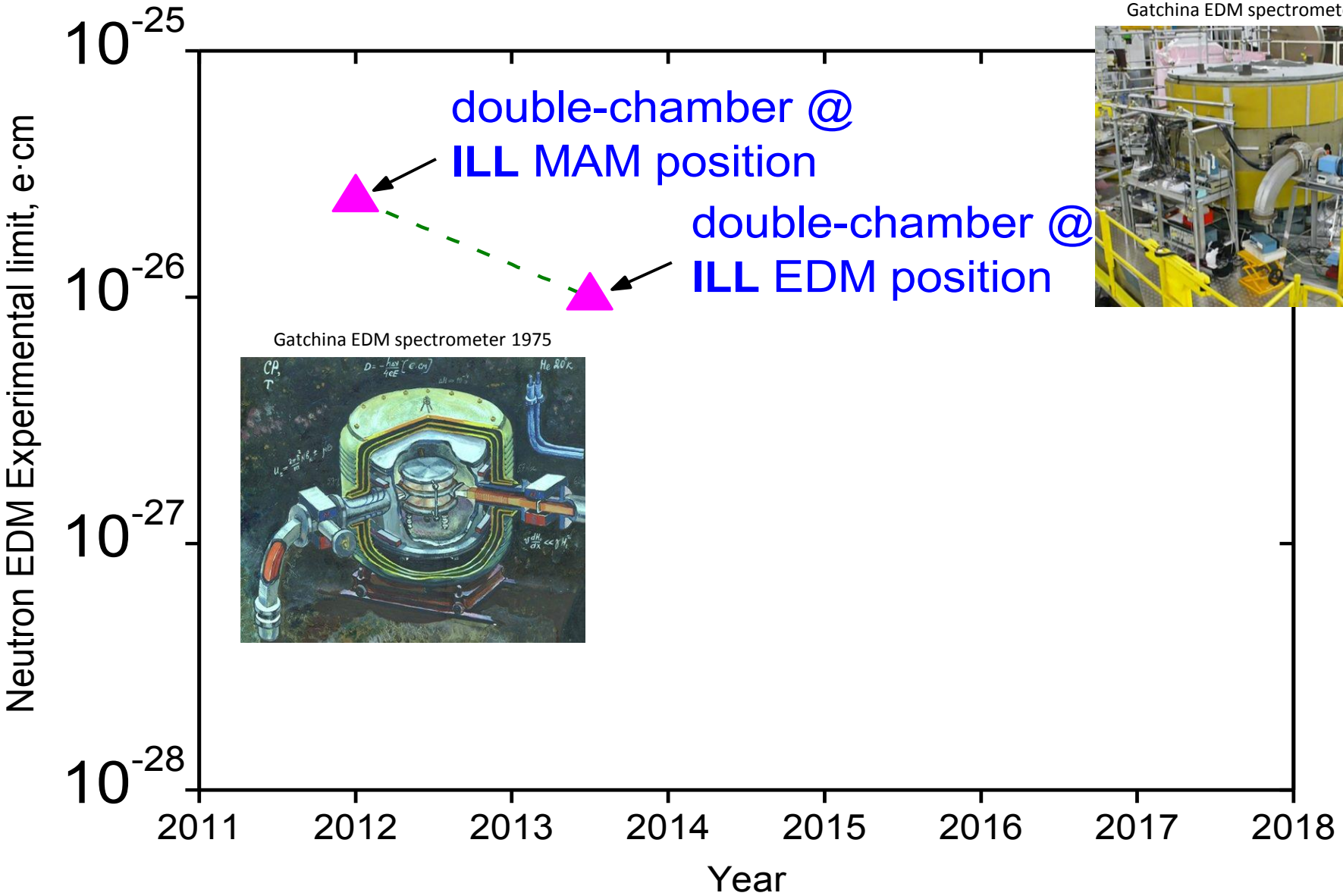
Upper limit of sensitivity :

$1 \cdot 10^{-26}$ e·cm/100 days

PNPI-ILL-PTI collaboration

Prospects to increase sensitivity of EDM measurements

Gatchina EDM spectrometer at ILL



Gatchina EDM spectrometer 1975

Status of He-II UCN source developments at ILL

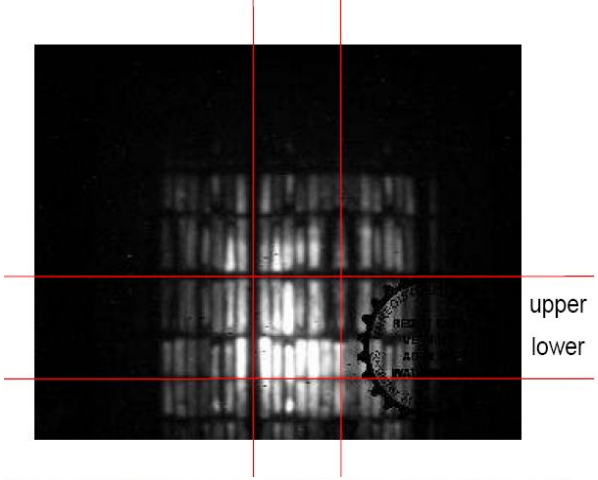
M. Fertl, S. Ivanov, K. Leung, F. Martin, S. Mironov, F. Piegsa, F. Rosenau, P. Schmidt-Wellenburg, M. Simson, Oliver Zimmer

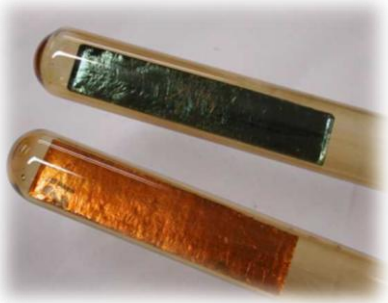
Cryo-EDM meeting, RAL 25 June 2012

He-II UCN sources at H172

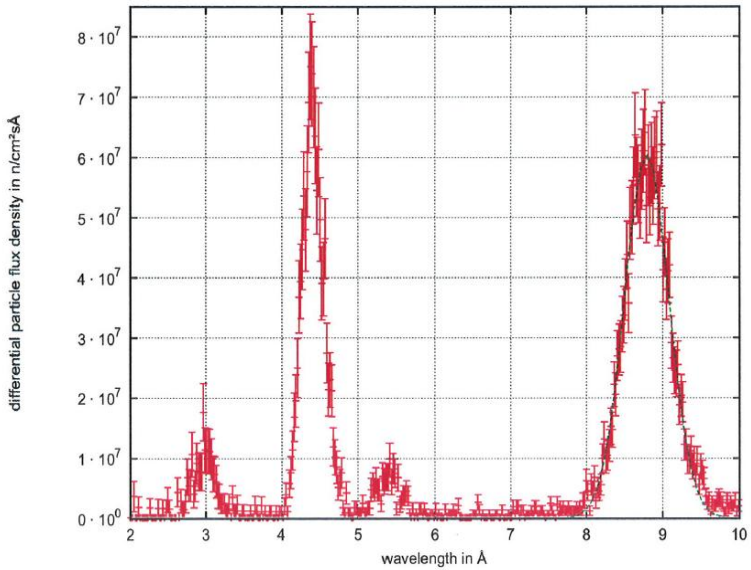
H172a and H172b secondary 0.9 nm beams:

Bragg reflection off stage-I /-II intercalated graphite





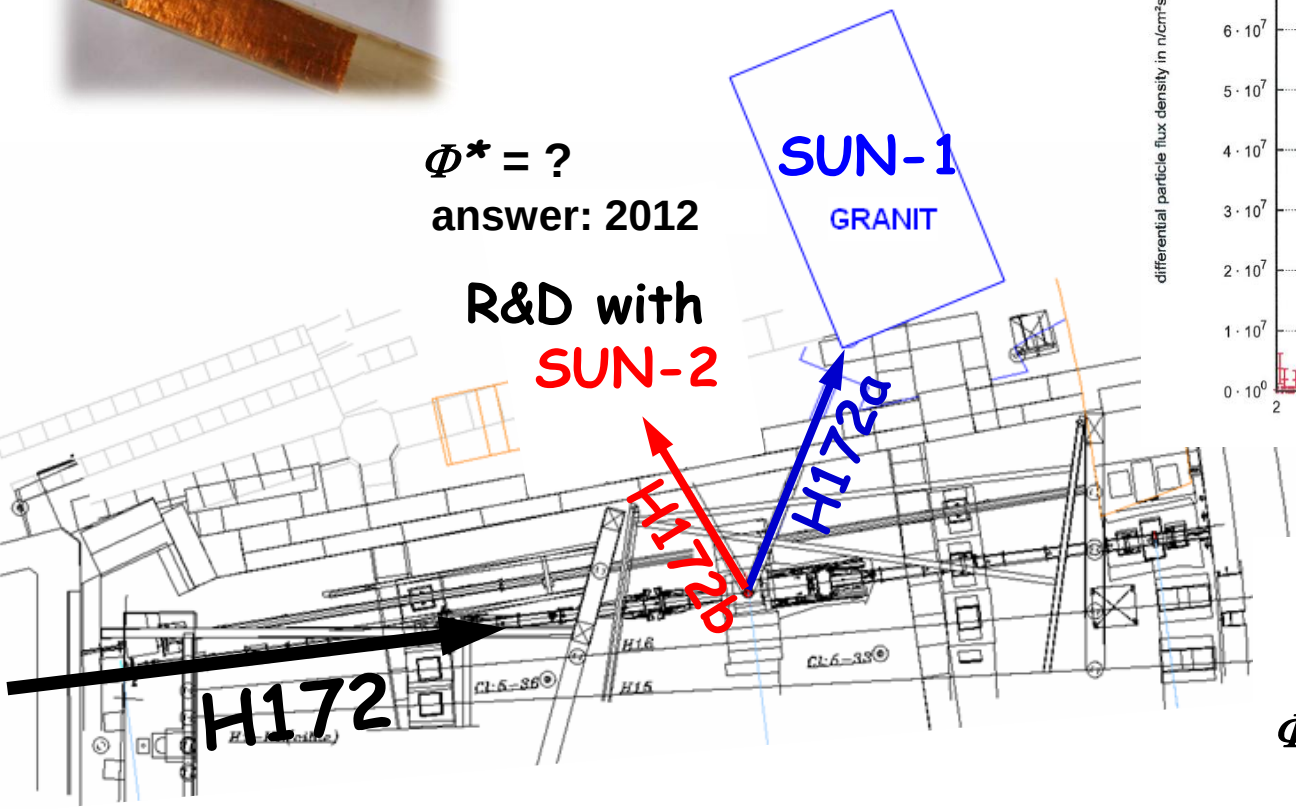
$\Phi^* = 9\times10^8/cm^2snm$



$\Phi^* = ?$

answer: 2012

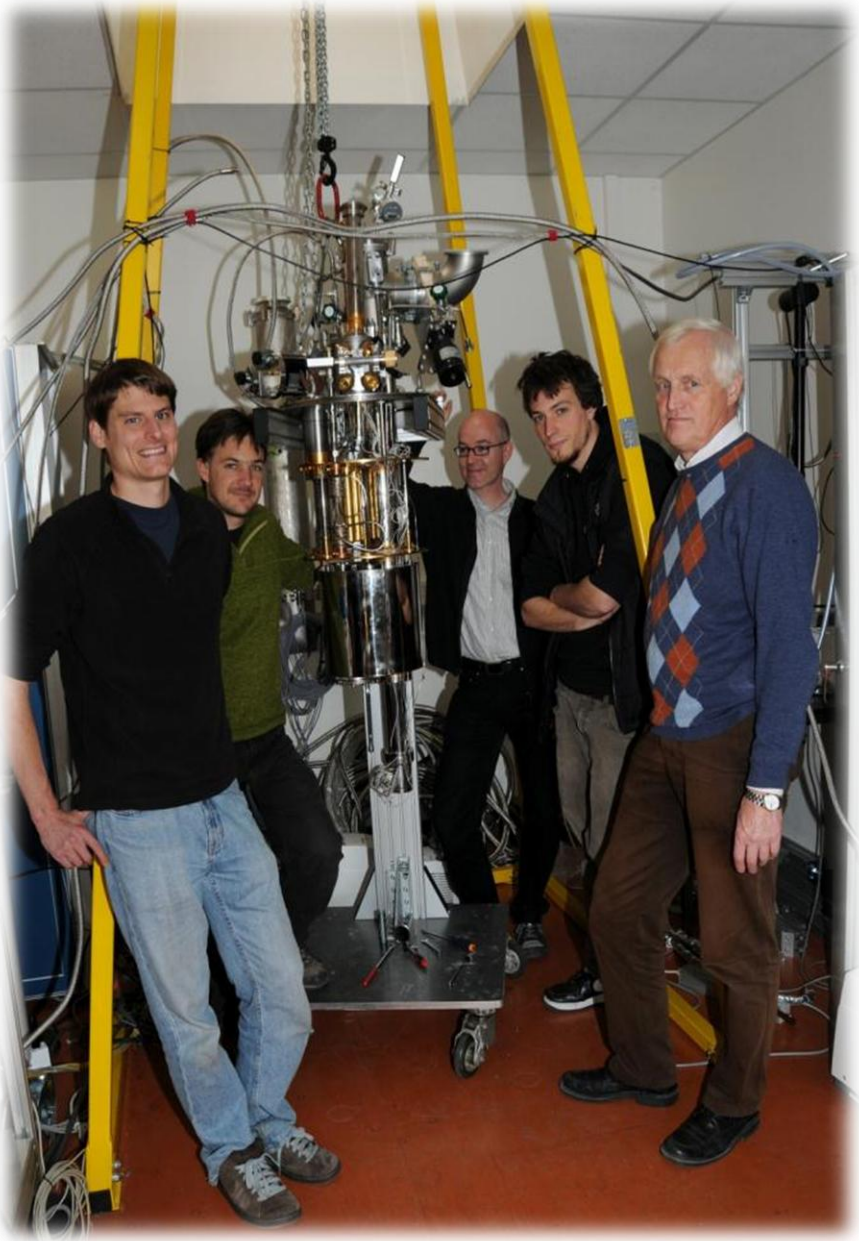
R&D with SUN-2



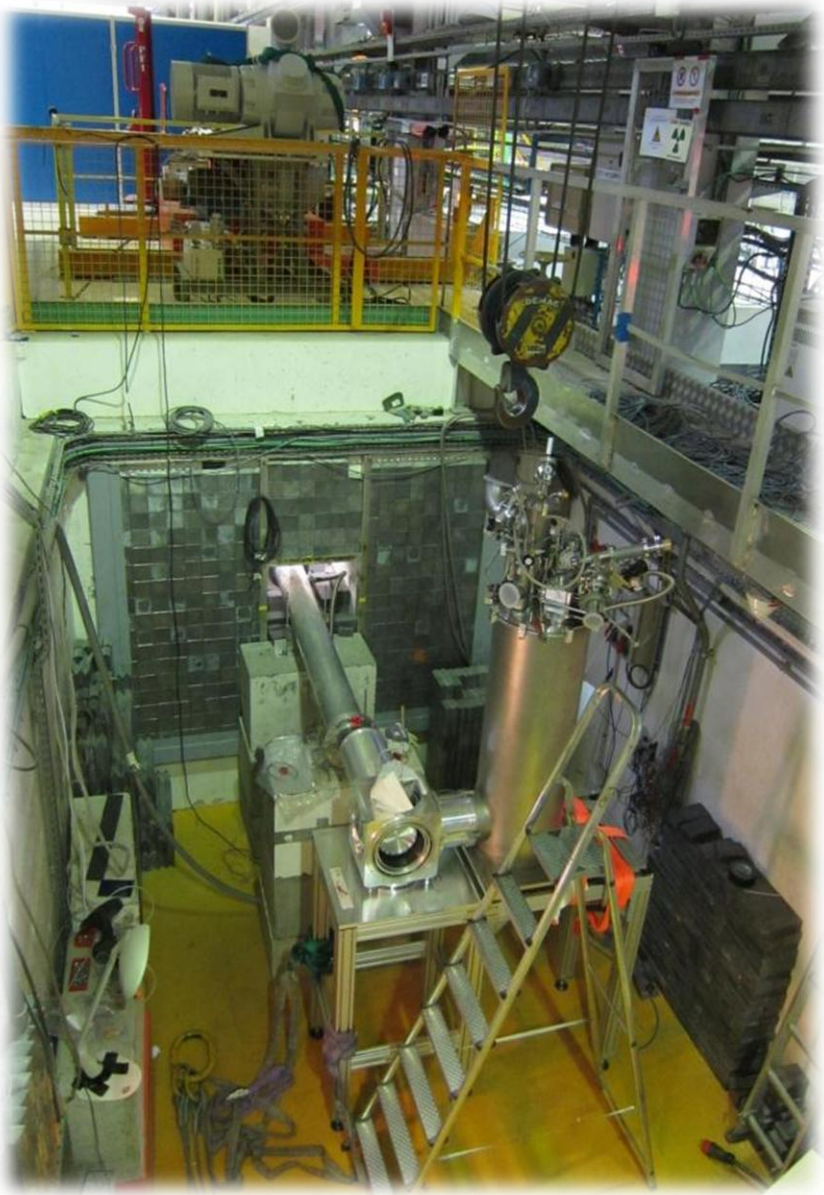
primary beam:

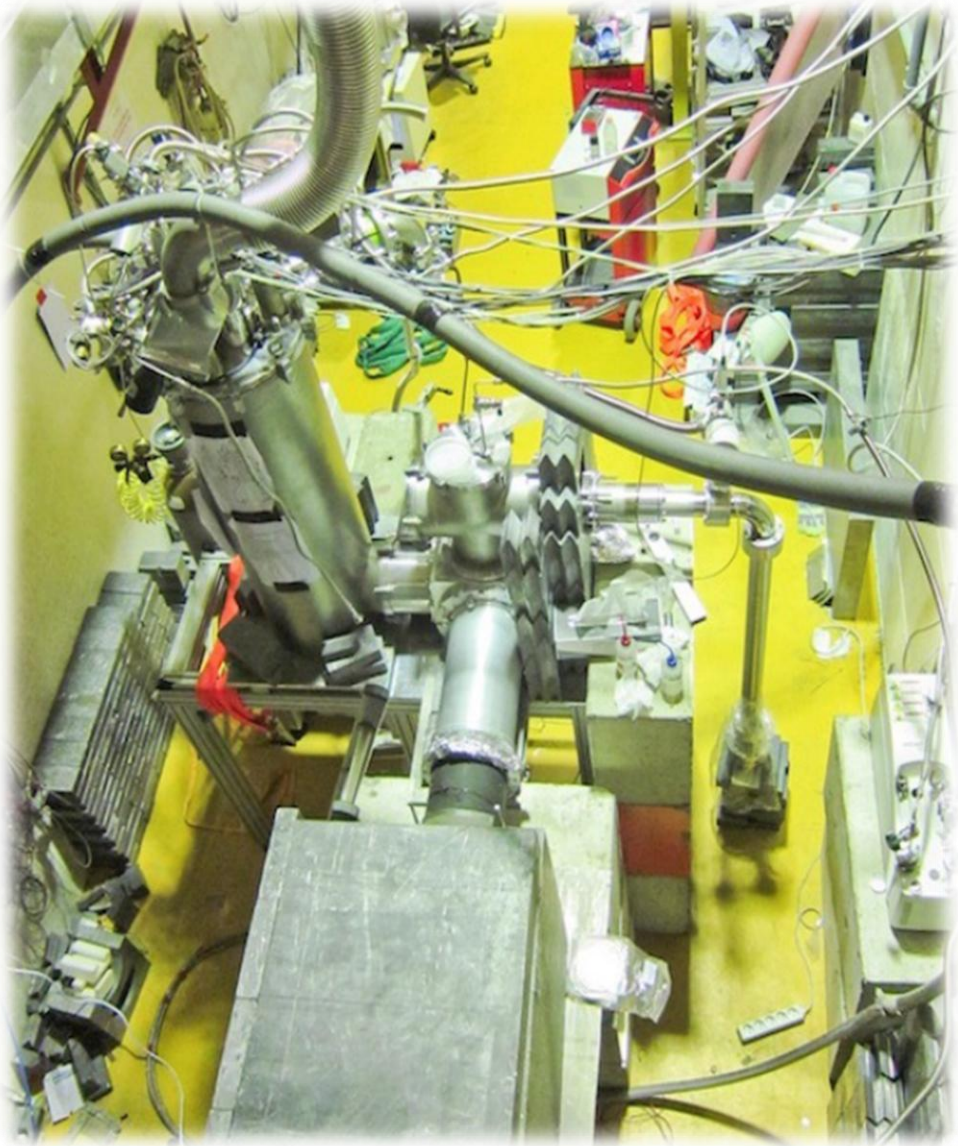
$\Phi^* = 5.7\times10^9/cm^2snm$

SUN-2 people and cooling „tower“

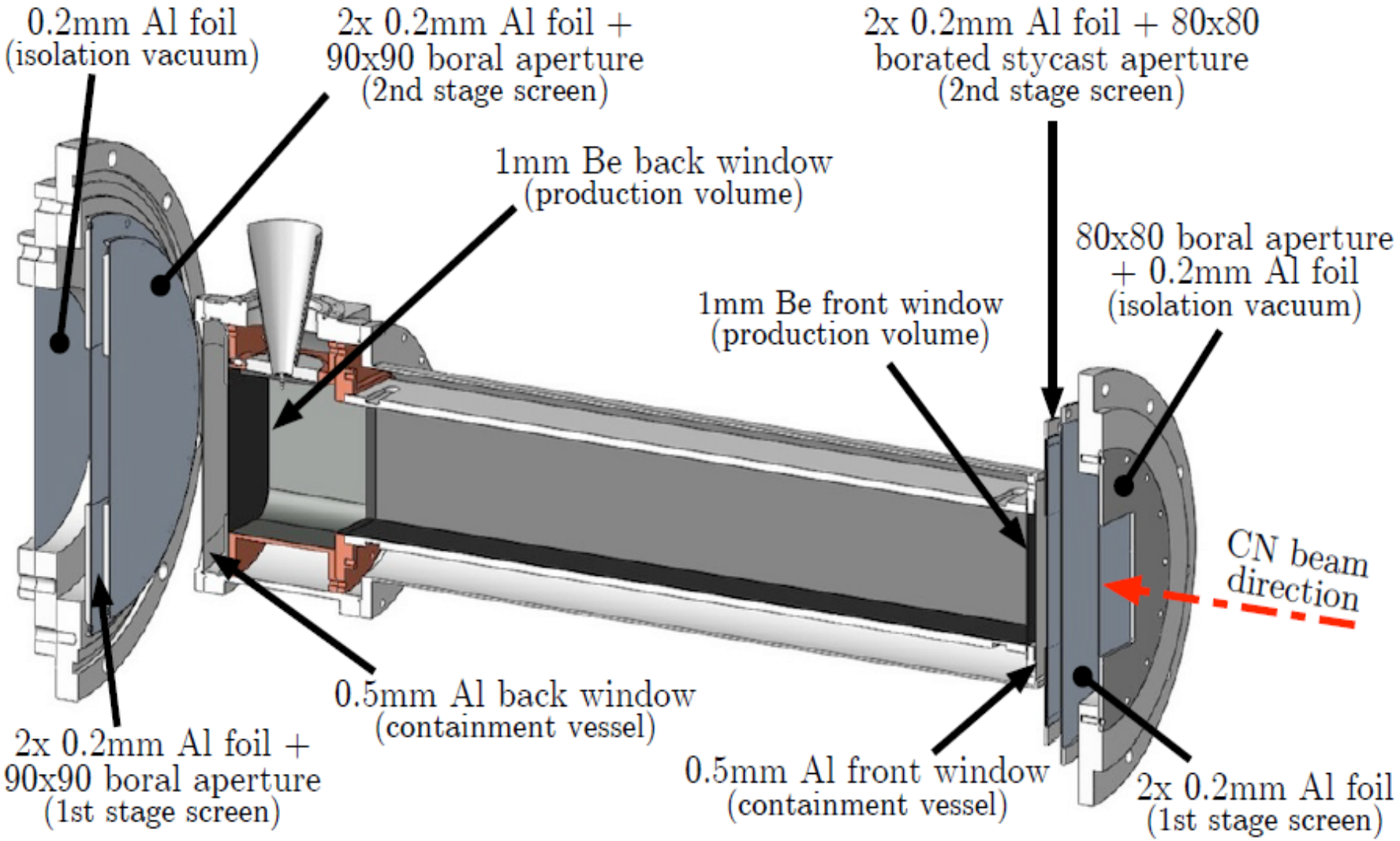


SUN-2 @ white cold beam PF1b (2011)

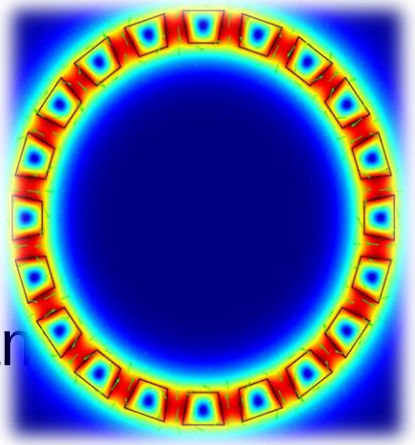




Schematics of converter vessel



Room for improvement of 55/cm³:



SuperSUN:

SUN-2 cryostat + magnetic reflector (+ direct bear

	achieved (SUN-1)	SuperSUN ultimate	gain	
Φ^* [cm^{-2}s^{-1}nm^{-1}]	9×10^8	5.7×10^9	6.3	primary beam
UCN storage τ [s]	67	800	× 11.9	magnetic reflector
Wall potential			× 1.6	
Divergence loss			× 1.4	
Polarization		0.5	× 0.5	magnetic reflector

H172b: (1 – 3) × **730/cm³** polarised = 84

H172 direct beam: **4600/cm³** polarised

EDM sensitivity at new position H172B, UCN source with superfluid He at ILL.

2015. New position at H172B, UCN source with superfluid He at ILL. Factor in UCN density is about 10 times in respect to PF2 EDM position.

$\rho_{ucn\ at\ entrace} \sim 200$ ucn/cm^3,

$\delta D_{edm} \sim 3.5 \cdot 10^{-26}$ e·cm/day

Upper limit of sensitivity :

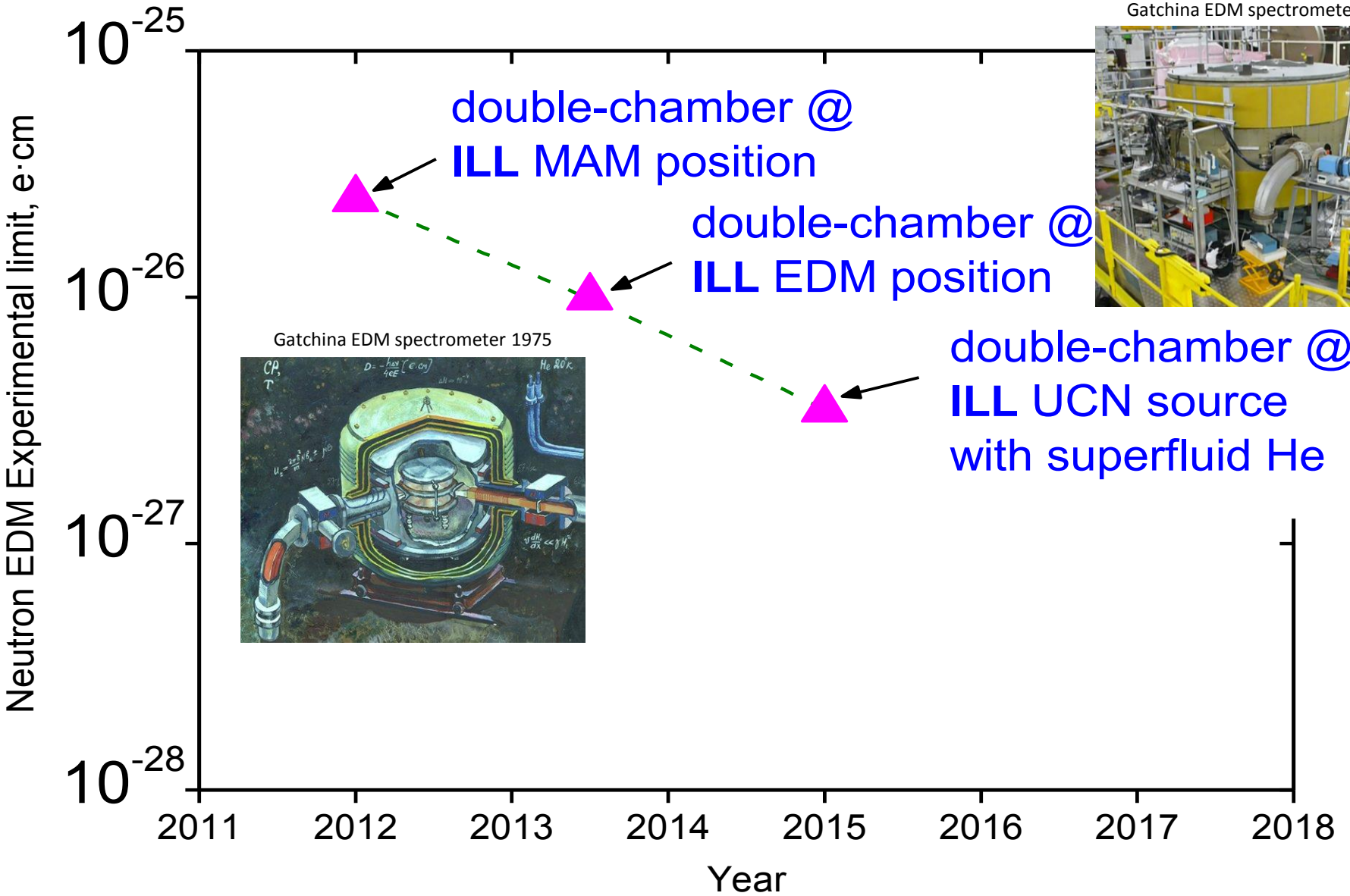
$3.5 \cdot 10^{-27}$ e·cm/100 days

PNPI-ILL-PTI collaboration

Prospects to increase sensitivity of EDM measurements

Gatchina EDM spectrometer at ILL

Gatchina EDM spectrometer 1975



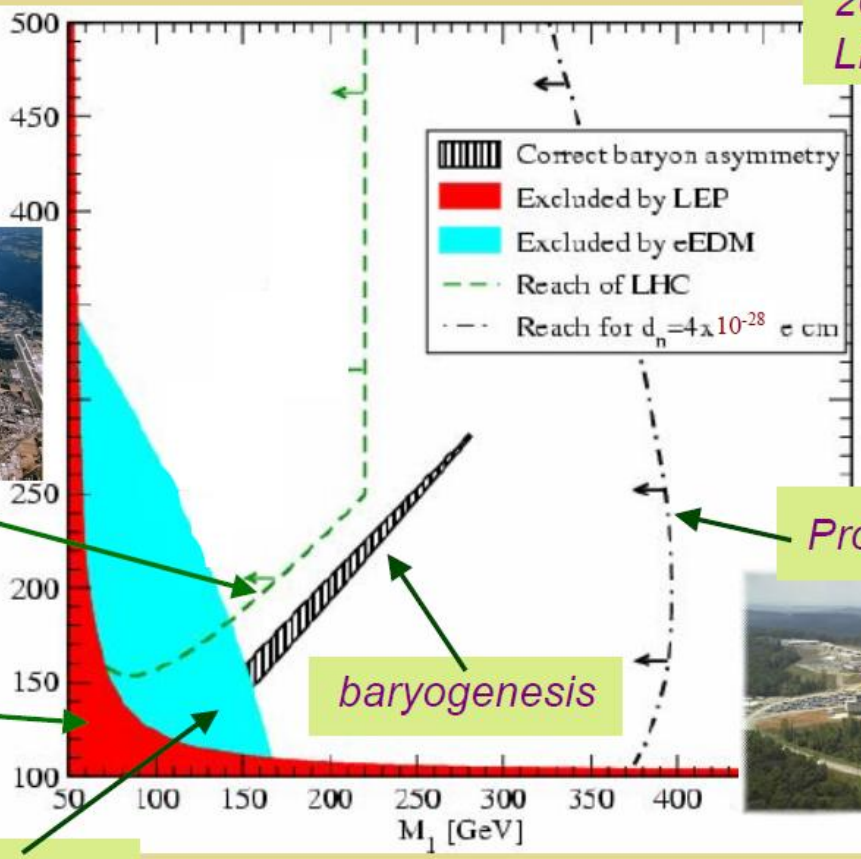
Friendly Competition: GATCHINA - OAK RIDGE (Orlova Роща – Oak Роща)

Роща (roscha) it means in russian a small forest

MSSM Baryogenesis: EDMs & LHC

Orlova Роща

Oak Роща



Best regards from Russia

Anatolii Serebrov