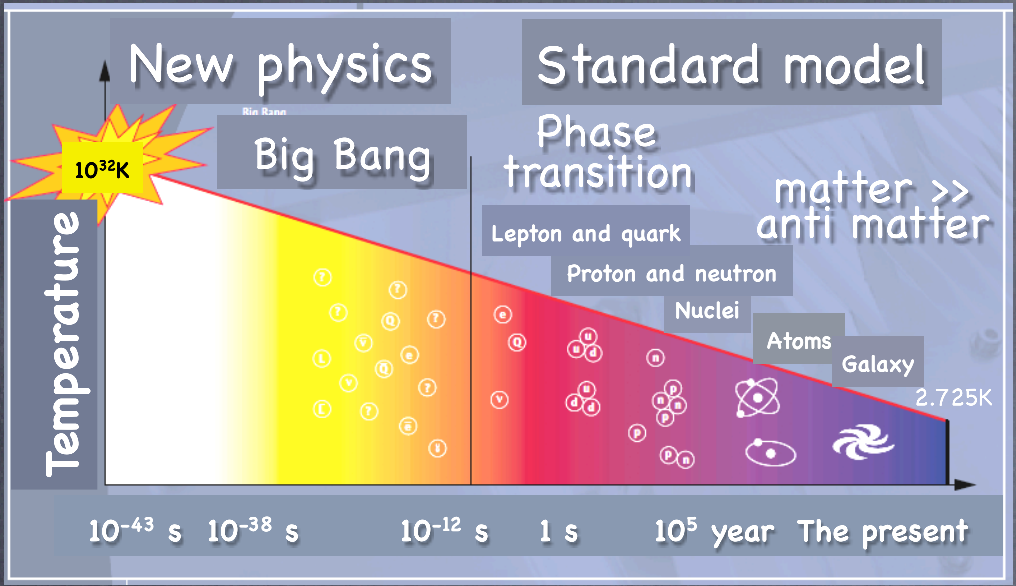
A neutron EDM measurement

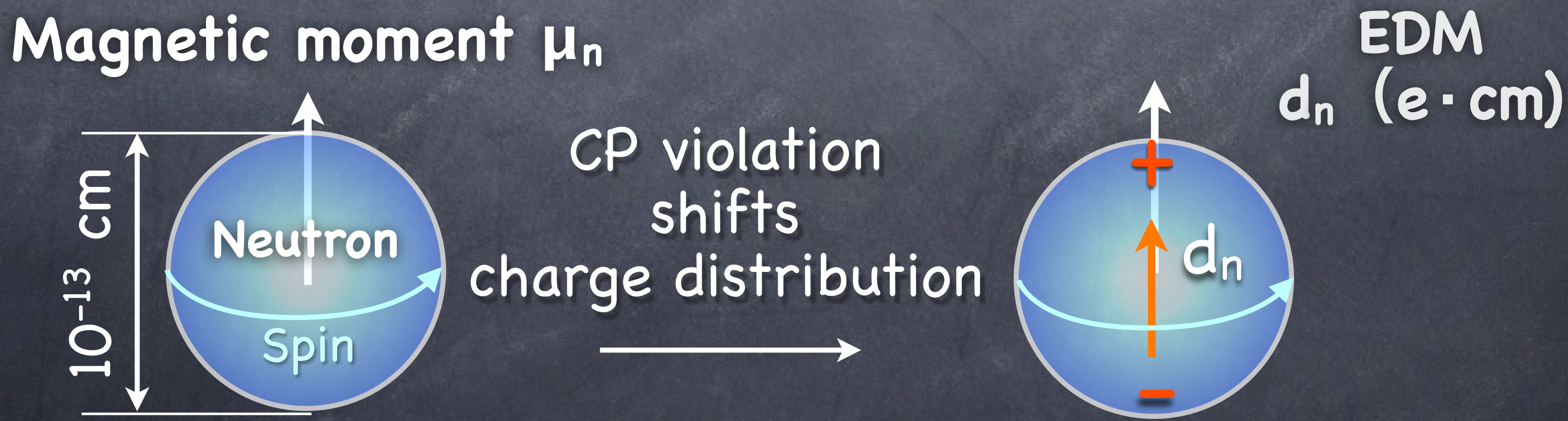
Y. Masuda (KEK), Beihang University, Oct. 15, 2010

1. Why neutron electric dipole moment (EDM)
2. What is ultracold neutron (UCN)
3. EDM measurement
4. Our approach to nEDM

Mystery of baryogenesis



CP violation creates matter
but
Kobayashi Maskawa theory
can't explain the baryon
asymmetry
We need new physics



Our approach to nEDM

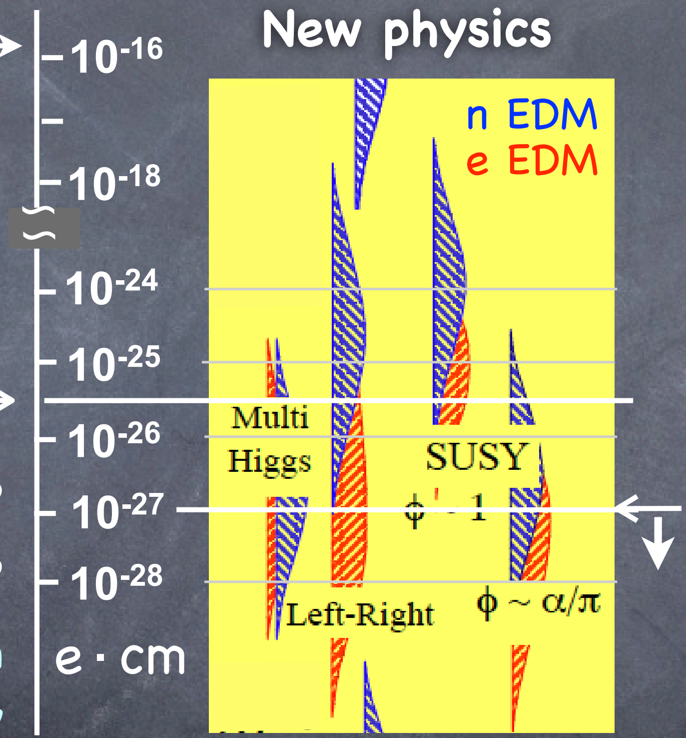
Earth's field ($\mu_n H_o/E$) →

nEDM upper limit →

statistical 1.5×10^{-26}

systematic 0.7×10^{-26}

related with magnetic instability



Statistical < 10^{-27} e · cm

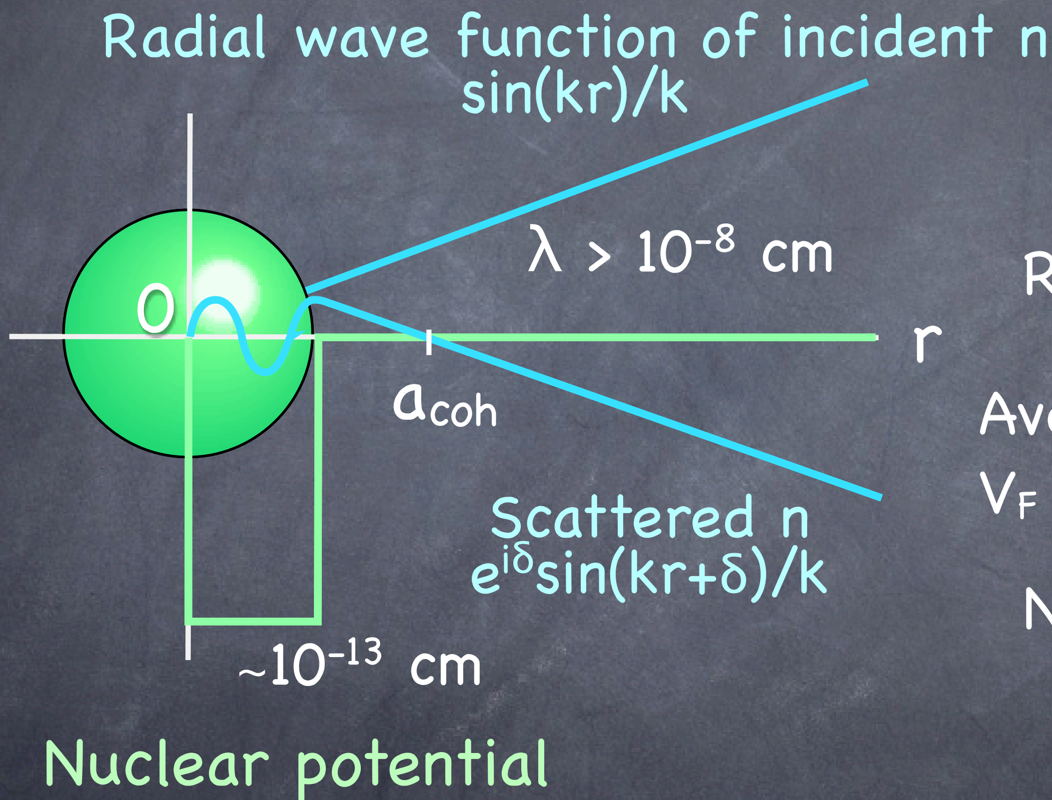
- high density UCN (ultra cold neutron)

Systematic < 10^{-27} e · cm

- new co-magnetometer of buffer gas nuclear spin
- R^2 ×1/10
  - high density UCN
- Spherical coil
- new magnetic shielding

What is UCN

very low energy neutrons, nuclear potential becomes repulsive



Fermi potential

$(2\pi\hbar^2/m)\ a_{coh}\ \delta(r)$

Repulsive if a_{coh} is positive

Average potential in material

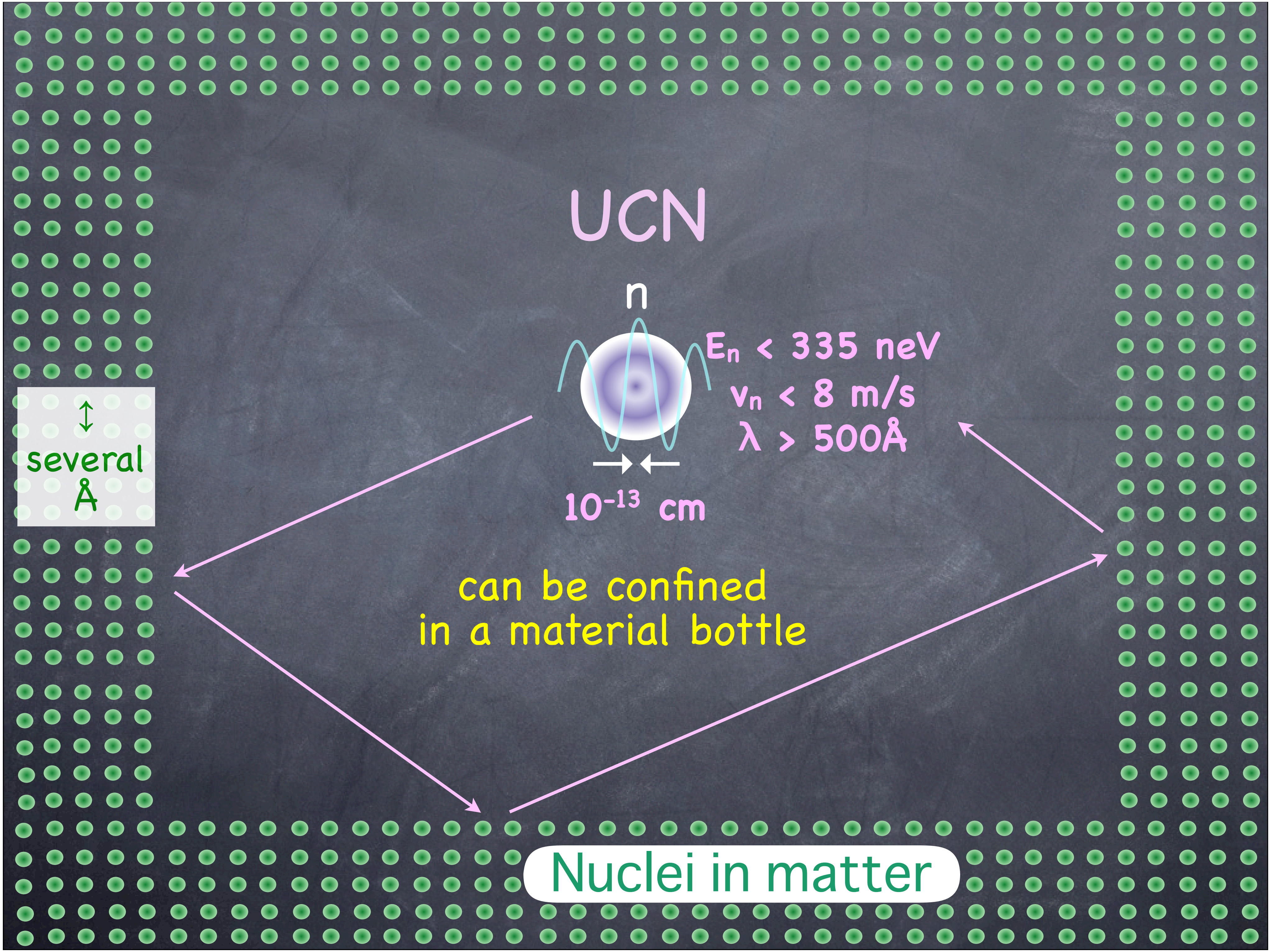
$V_F = (2\pi\hbar^2/m)\ a_{coh}\ N$

N: nuclear number density

335 neV for ^{58}Ni
210 neV for iron

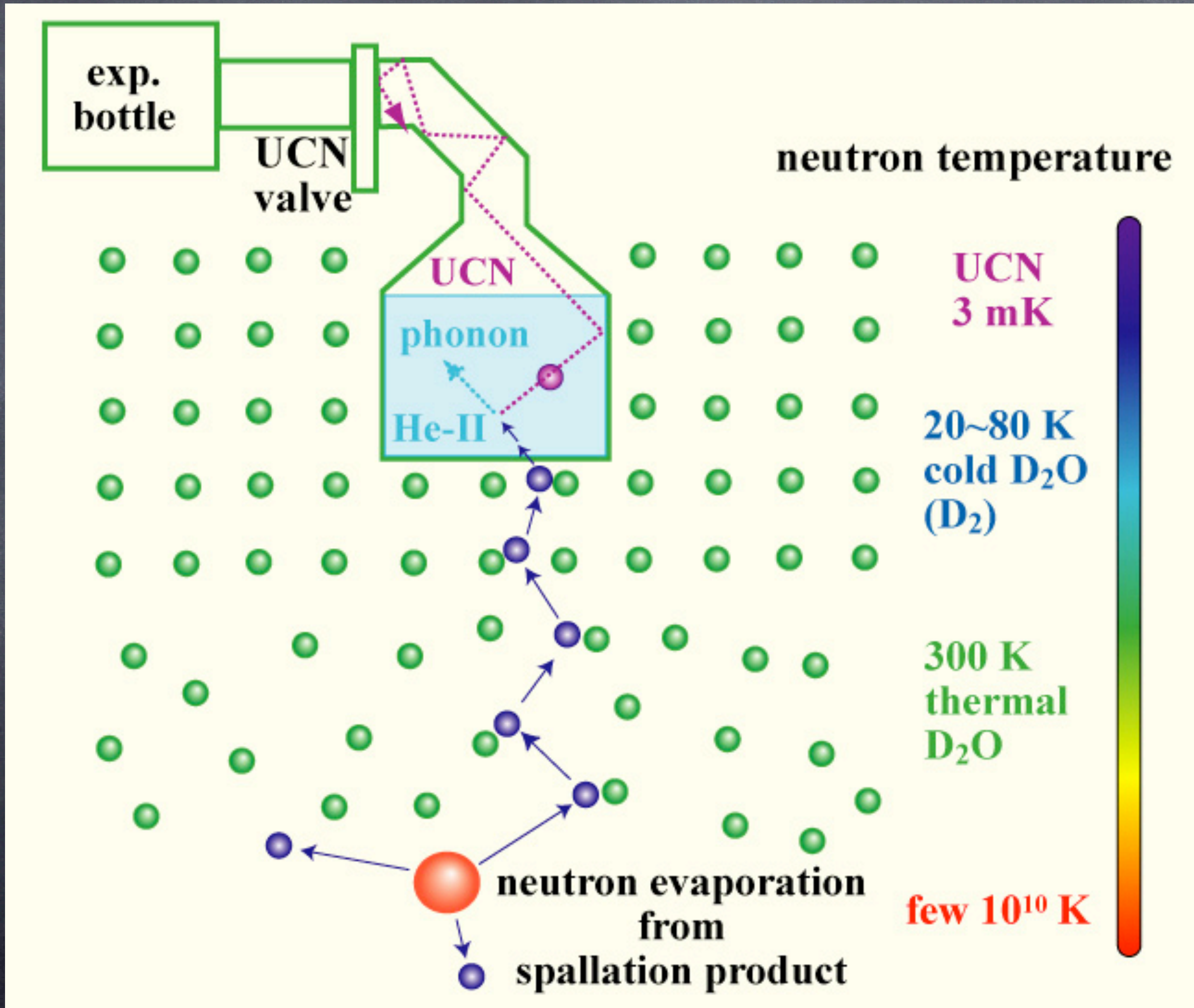
UCN

Neutrons of $E_n < E_c = V_F$, are completely reflected from material surface

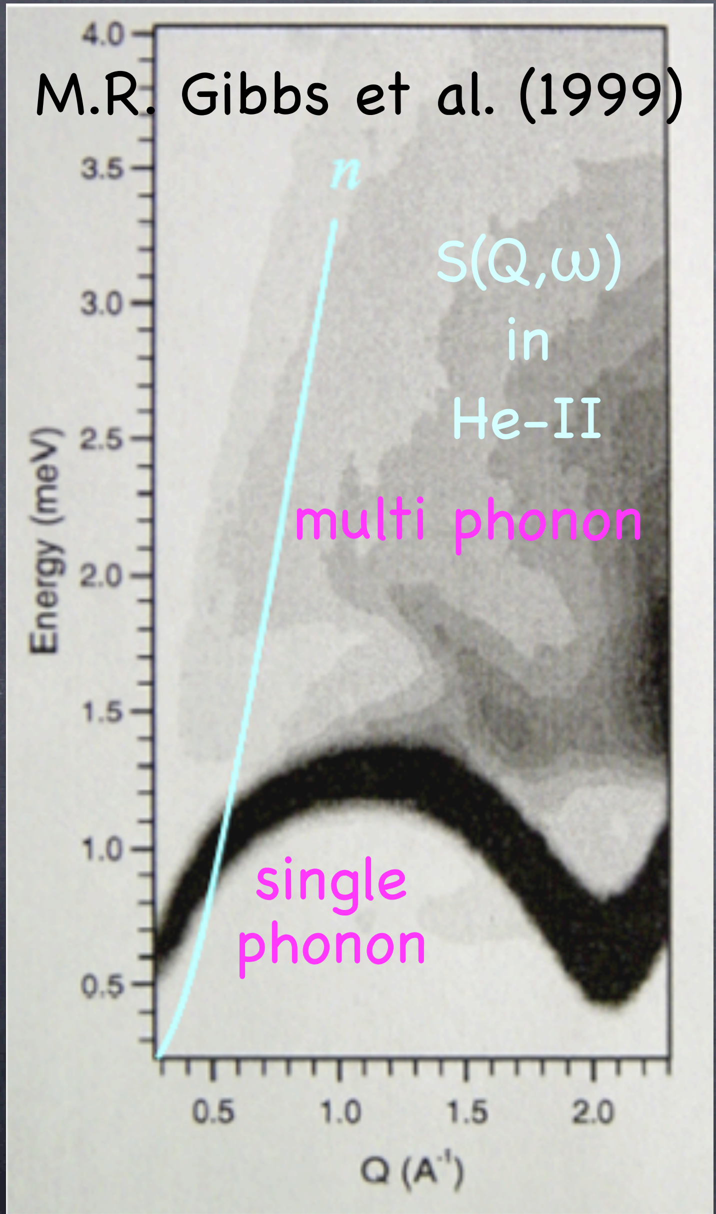


UCN
n
$E_n < 335$ neV
$v_n < 8$ m/s
$\lambda > 500$Å
10^{-13} cm
several Å
can be confined
in a material bottle
Nuclei in matter

A new UCN production



UCN production



UCN density = $P_{UCN} \times \tau_s$

production rate　　storage lifetime

In our He-II at 20 kW

P_{UCN} = $(2\text{~}4)\times10^{-9}\ \Phi_n/cm^3/s$,

Phys.Lett A301(2002)462

= $0.37\text{~}0.73\times10^4$ UCN/cm^3/s

τ_s = 150 s

In Los Alamos SD_2 at 76 kW

P_{UCN} = 4.4×10^4 UCN/cm^3/s,

Phys.Lett B593(2004)55

In PSI SD_2 at 1.2 MW

P_{UCN} = 2.9×10^5 UCN/cm^3/s,

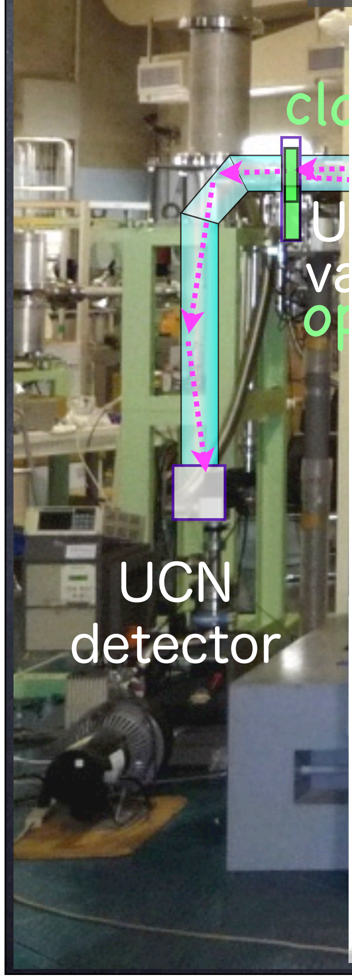
Phys.Rev C71(2005)054601

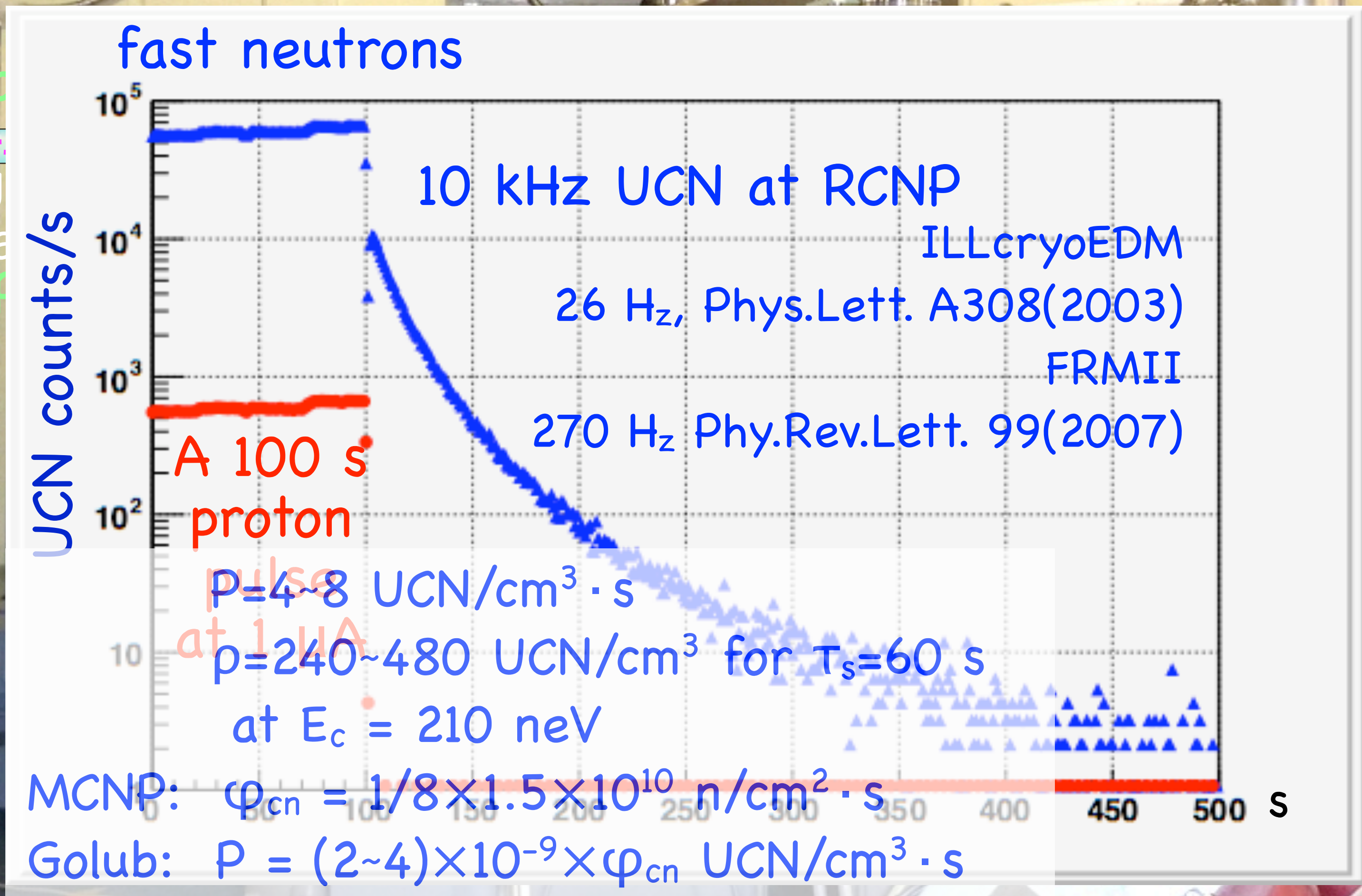
τ_s = 24 ms

UCN production at RCNP

Proton beam power 390 W (av. 100 W)

19 UCN/cm^3 at E_c = 90 neV, P = 4.8 UCN/cm$^3\cdot$s E_c = 210 neV
55   180
30   180 Los Alamos 125 kW (av. 4 kW), SantaFe2009





P=4~8 UCN/cm$^3\cdot$s
ρ=240~480 UCN/cm^3 for τ_s=60 s
at E_c = 210 neV

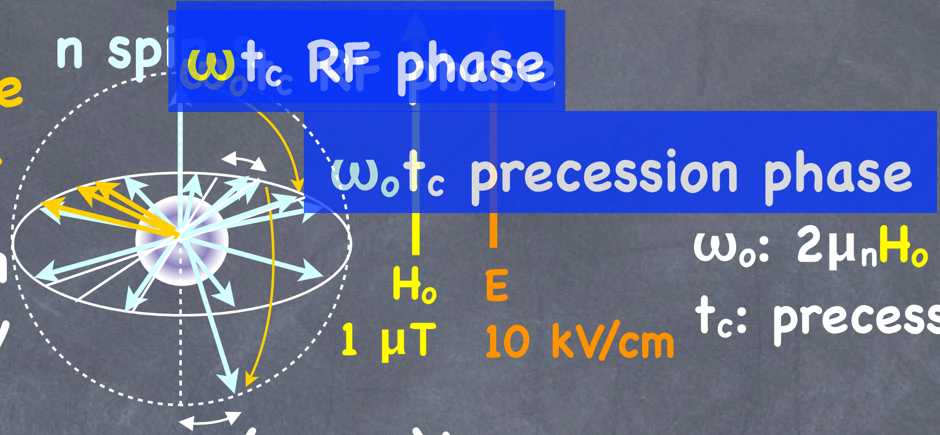
MCNP: φ_{cn} = 1/8×1.5×10^{10} n/cm$^2\cdot$s

Golub: P = (2~4)×10^{-9}×φ_{cn} UCN/cm$^3\cdot$s

EDM measurement

1st RF π/2 pulse
2nd RF π/2 pulse

for neutron polarimetry



ω_o: $2\mu_n H_o \pm 2d_n E$

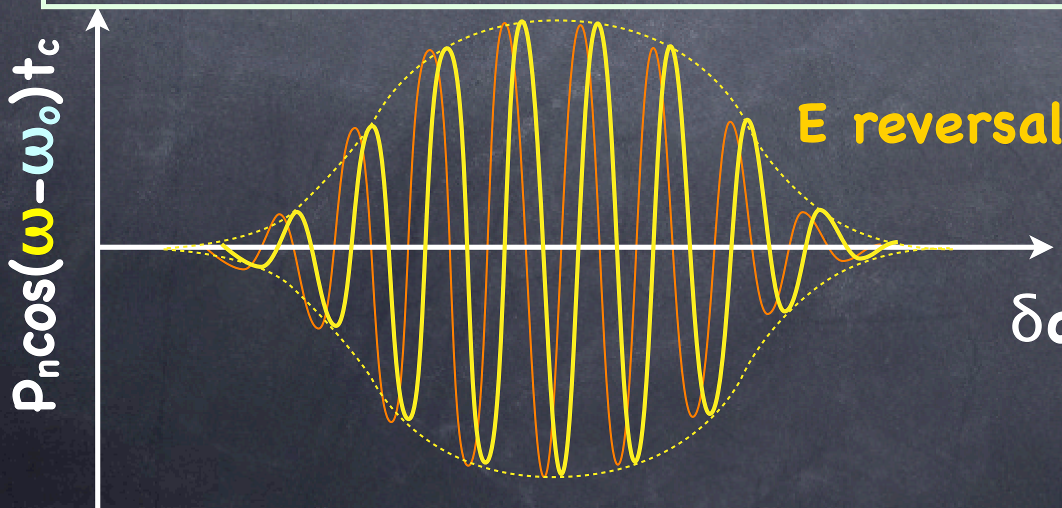
t_c: precession time

Neutron precession

$$S = \exp\{i(\mu \cdot H_0 + d_n \cdot E)/\hbar \cdot t\}$$

μ, $d_n \propto s$

UCN bottle



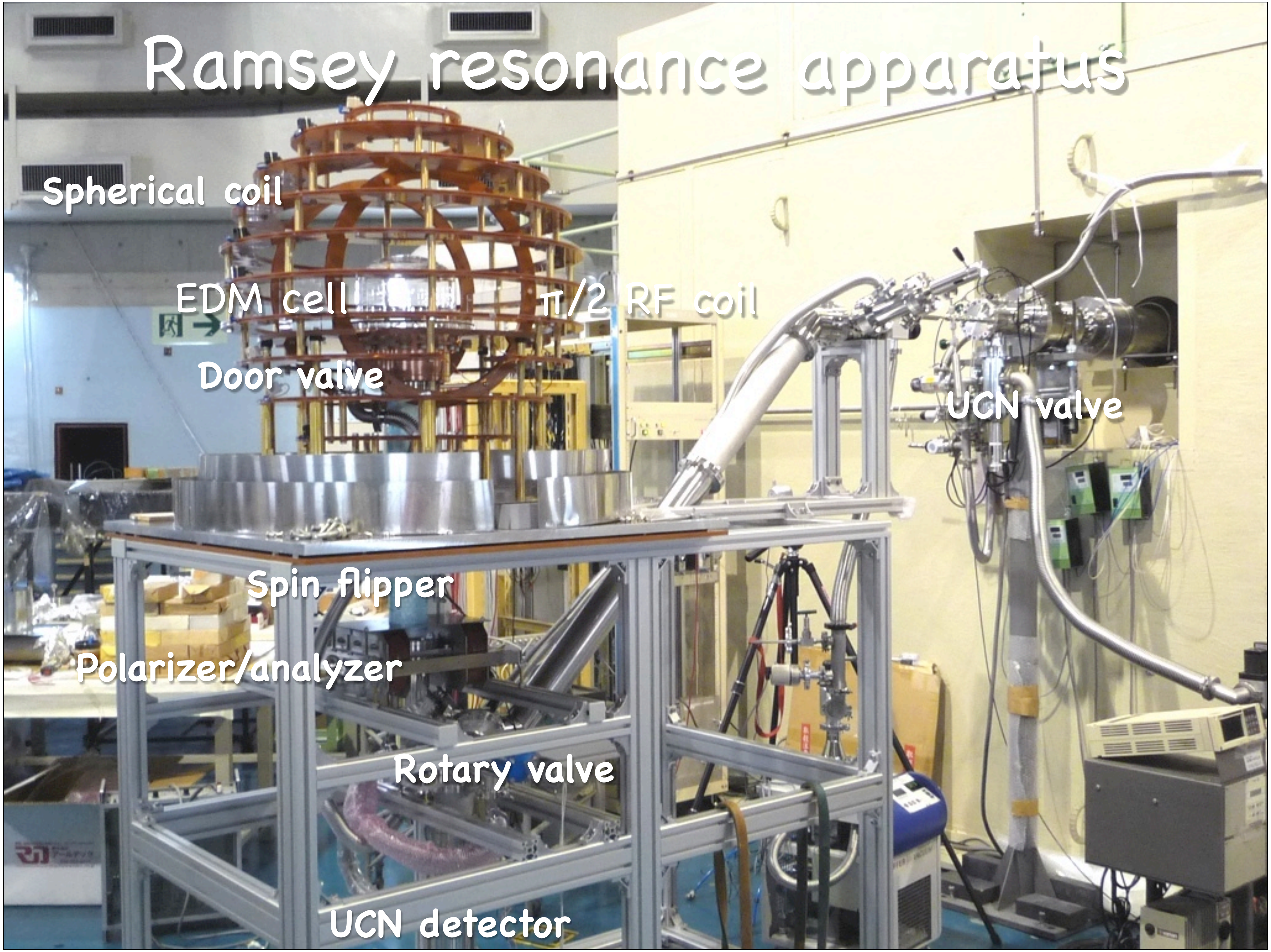
E reversal for extraction of d_n

$$\delta d_{sta} = \hbar/\{2P_n E t_c \sqrt{N}\}$$

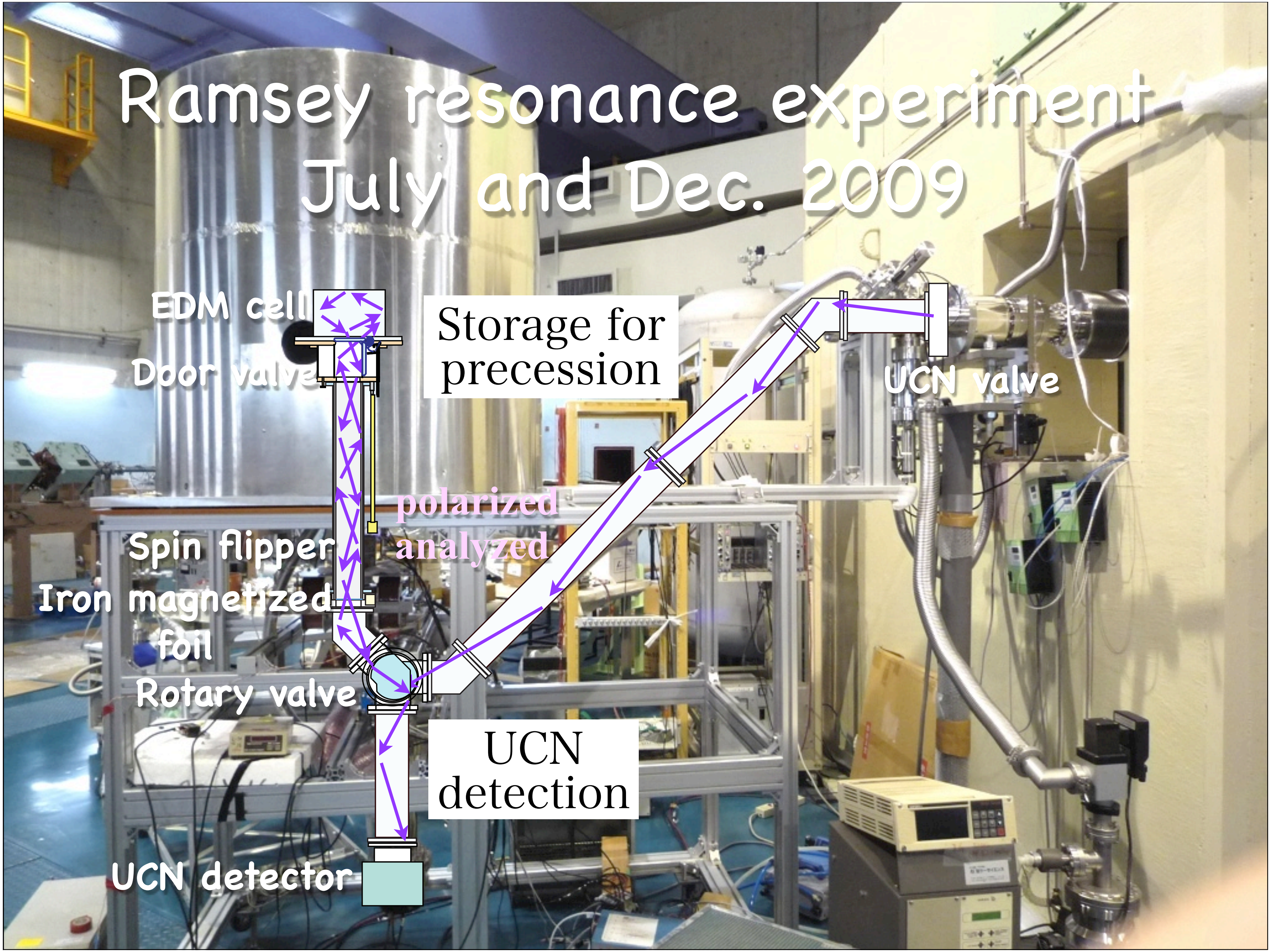
P_n : UCN polarization

N : number of UCN

Ramsey resonance apparatus



Ramsey resonance experiment July and Dec. 2009

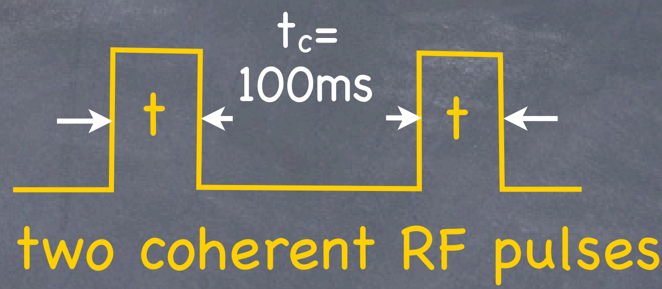


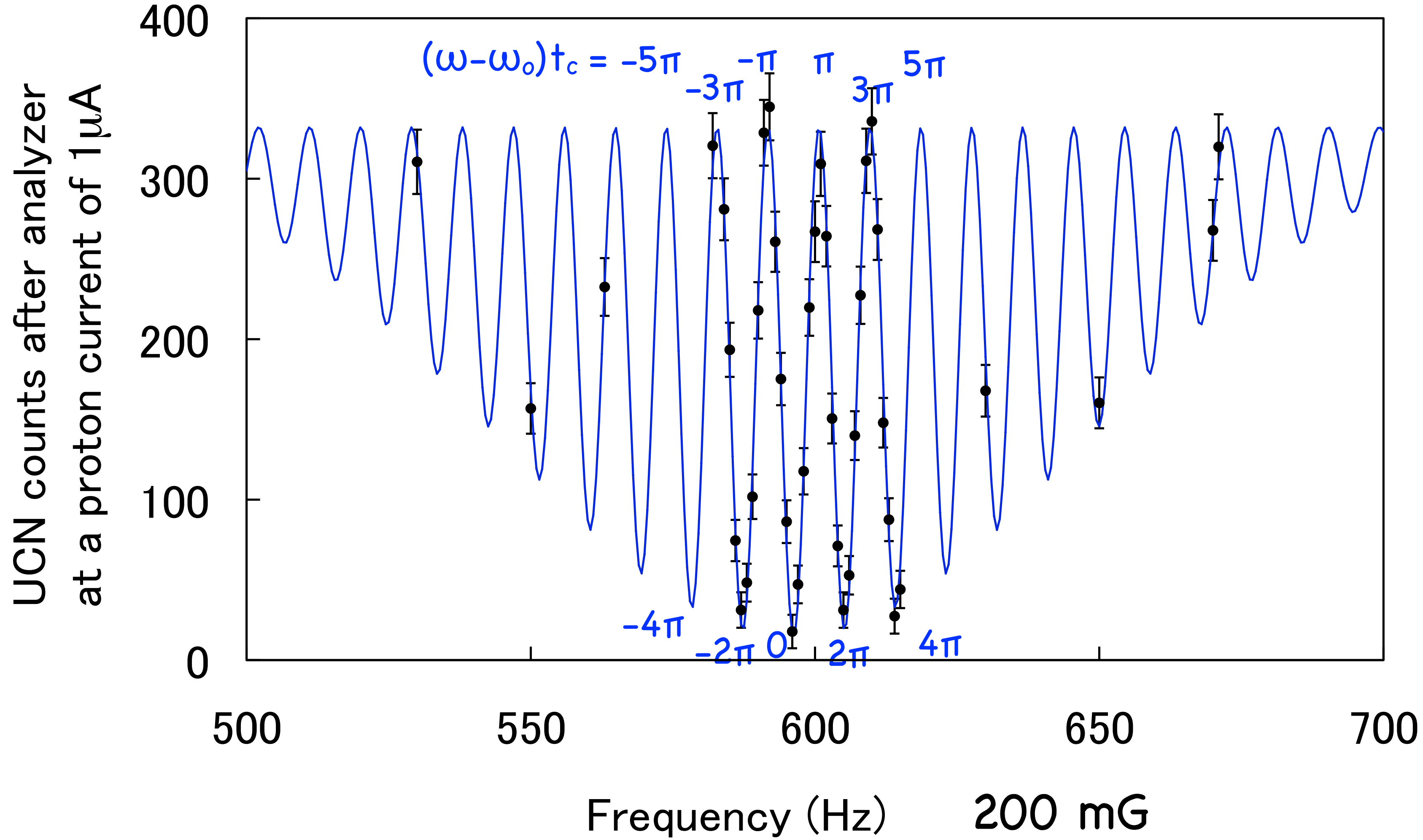
Ramsey resonance 2009

Effect of $P_n\cos(\omega-\omega_o)t_c$

visibility α =

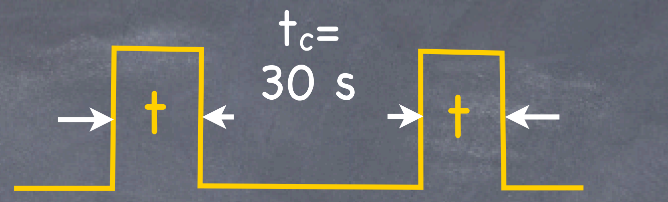
$(N_{max} - N_{min})/(N_{max} + N_{min}) = 0.9$

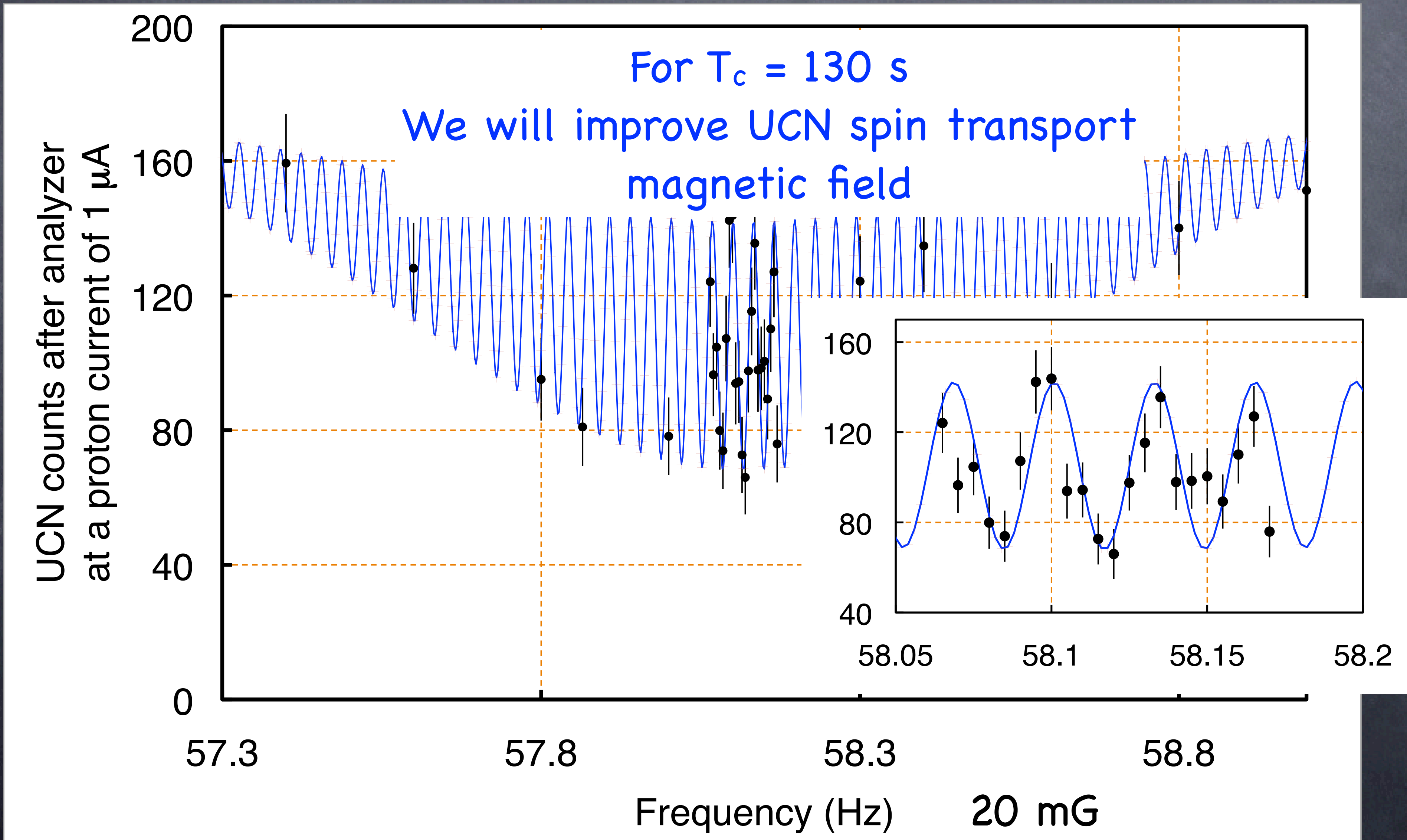




Ramsey resonance 2010

comparable to ILL2006





Magnetometer to correct H_0 variation

Nuclear spin magnetometer

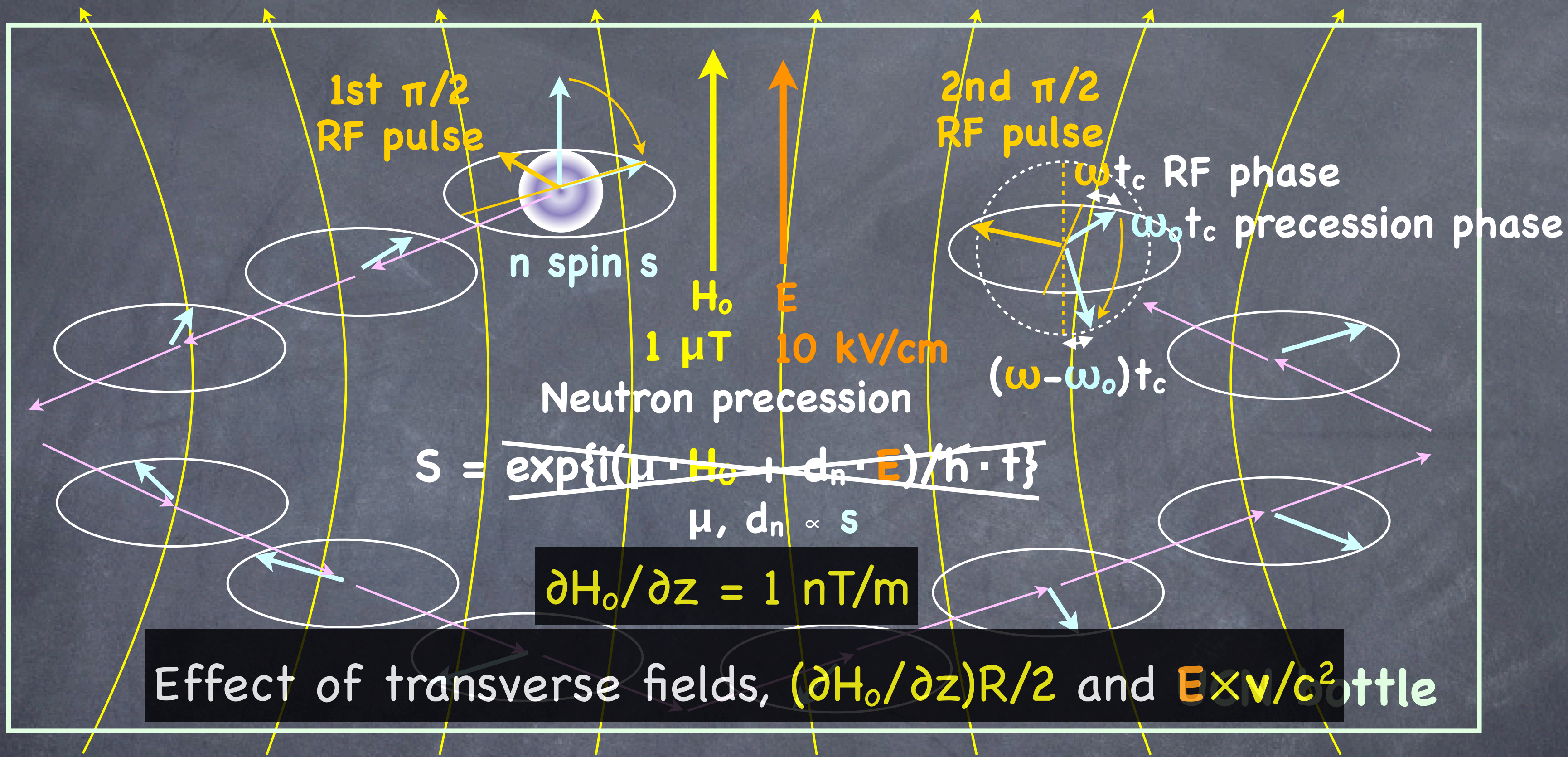
Isotope	J_N	g ($\gamma_N = g\mu_N/\hbar$)	σ_a at 2200 m/s	ρ for $\tau = 1/(\sigma_a \rho v) = 500$ s
^{129}Xe (Ours)	1/2	-0.777	21 b	2.5×10^{14}/cc, SQUID
^{199}Hg (ILL)	1/2	0.5026	2150 b	(3×10^{10}/cc, photon)
n (cryoEDM)	1/2	-1.913		
^{3}He (SNS)	1/2	-2.128	5333 b	10^{12}/cc, SQUID
^{133}Cs (PSI)	7/2	2.579	29 b	

Geometric phase effect GPE:

$$d_{afNn} = -\hbar/4 \cdot \gamma_n J_N \gamma_N (\partial H_{0z}/\partial z) \cdot R^2/c^2$$

$$d_{afn} = -\hbar/2 \cdot J_N (\partial H_{0z}/\partial z)/H_{0z}^2 \cdot v_{xy}^2/c^2$$

Motion induced systematic error



Phase shift arises from the transverse fields,

Bloch Siegert shift,

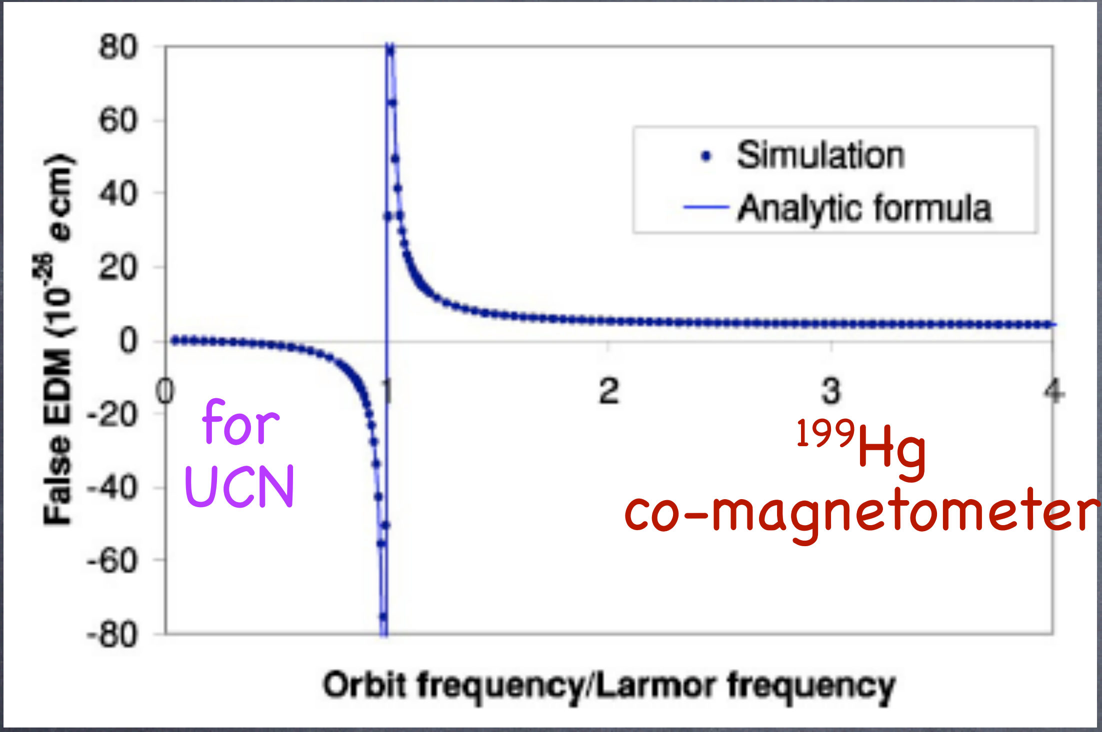
$$[\ (\partial H_0/\partial z)R/2 + E\times v/c^2\ ]^2$$

E dependent cross term Geometric phase effect, GPE

Our approach to
motion induced systematic error, GPE

$d_{afHgn} = \hbar/8|\gamma_n\gamma_{Hg}|$
$\times(\partial H_{0z}/\partial z)\underline{R}^2/c^2$
$\sim 5\times10^{-26}$ e·cm

H_{0z} = 1 μT, $\partial H_{0z}/\partial z$ = 1 nT/m



$d_{afn} \sim 1\times10^{-27}$ e·cm

Pendlebury et al, Phys. Rev. A70(2004),
Golub and Lamoreaux, Phys. Rev. A71(2005)

$d_{afn} \rightarrow 1\times10^{-28}$ e·cm

We proposed
smaller EDM cell with
high density UCN: $\underline{R}^2 \times 1/10$
UCN workshop, TRIUMF
Sep. 13-14, 2007

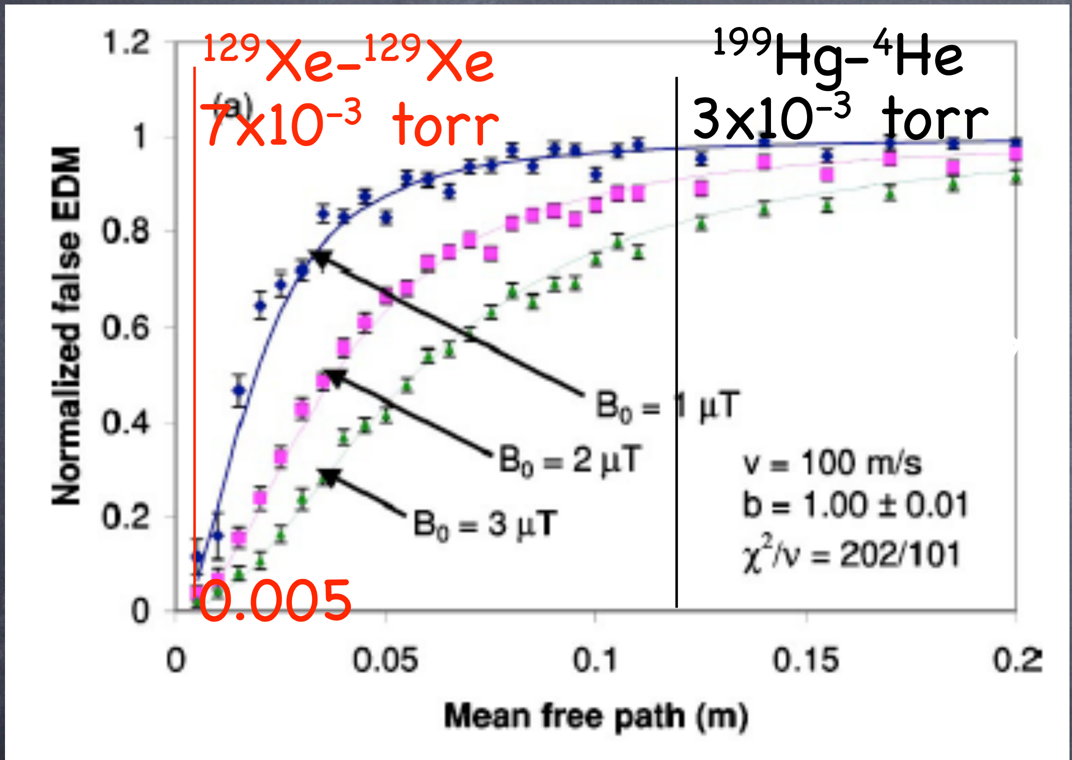
^{129}Xe buffer gas: $\times 1/10$
UCN workshop, Petersburg
June 8-14, 2009

$\underline{< 0.8\times10^{-27} \text{ e}\cdot\text{cm}}$

Decrease $\partial H_{0z}/\partial z$: $\times 1/10$
n and ^{129}Xe

$d_{afXen} \rightarrow 1\times10^{-28}$ e·cm

Short mean free path suppresses motion induced effect



Pendlebury et al (2004)
Barabanov, Golub and Lamoreaux (2006)

GPE by 1/10

^{129}Xe

$\lambda = 1/n\sigma \ll 0.5$ mm

$n = 2.5\times10^{14}$/cc

7×10^{-3} torr

$\sigma_{Xe-Xe} \gg 838Å^2$

Ne Magneto Optical Trap,
Phys.Rev.A78(2008)042712,
σ_{Ne-He} $164Å^2$, σ_{Ne-Ne} $500Å^2$,
σ_{Ne-Ar} $838Å^2$
at thermal energies
between 11 to 27 meV

Develop Pendlebury's approach to GPE

Assuming a cylindrically symmetric field

$R = \gamma_{UCN} H(UCN) / \gamma_{199Hg} H(^{199}Hg) \rightarrow 1 \pm \Delta h \langle \underline{\partial H_{0z}/\partial z} \rangle / H_{0z}$

$\Delta h = h_{av}(UCN) - h_{av}(^{199}Hg) = 3$ mm

$(\partial H_{0z}/\partial z)$: 3 nT/m → 0.3 nT/m

n and co-magnetometer GPEs ×1/10

^{129}Xe is better

No earth's rotation effect on the frequency ratio

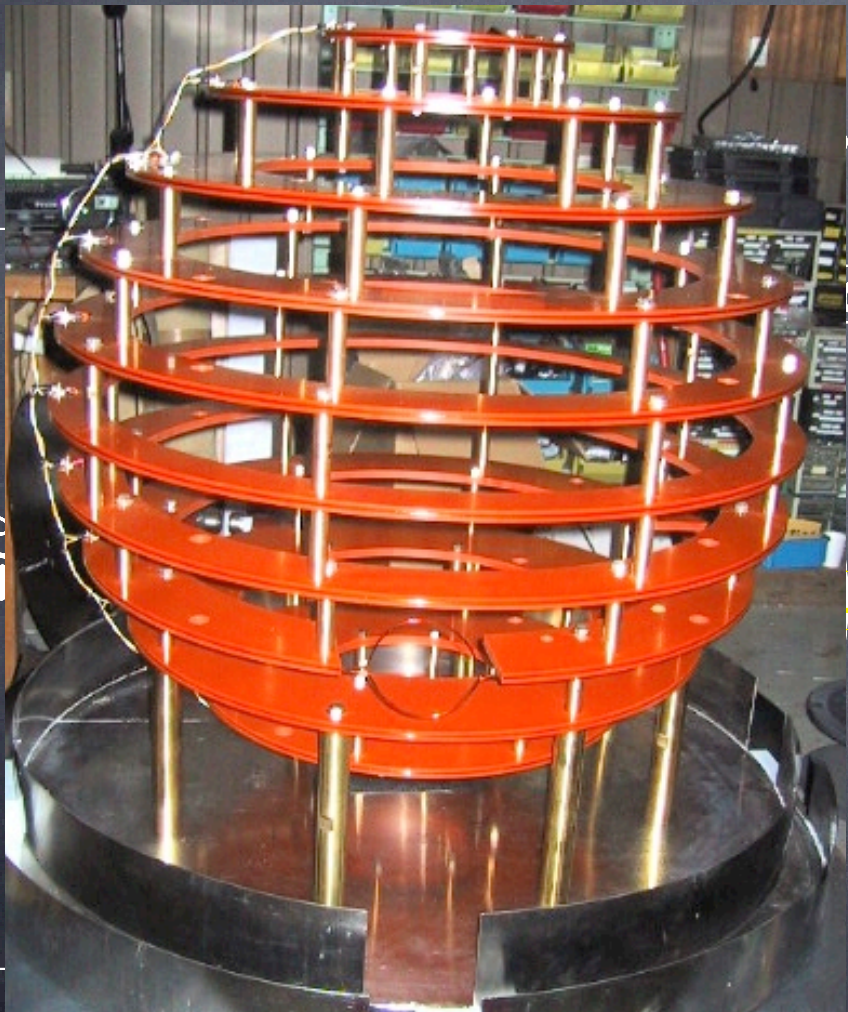
($d_{rot} = 2.5\times10^{-26}$ e·cm for ^{199}Hg)

sign of γ_{129Xe} same as γ_n

PRL 98 (2007) 149101

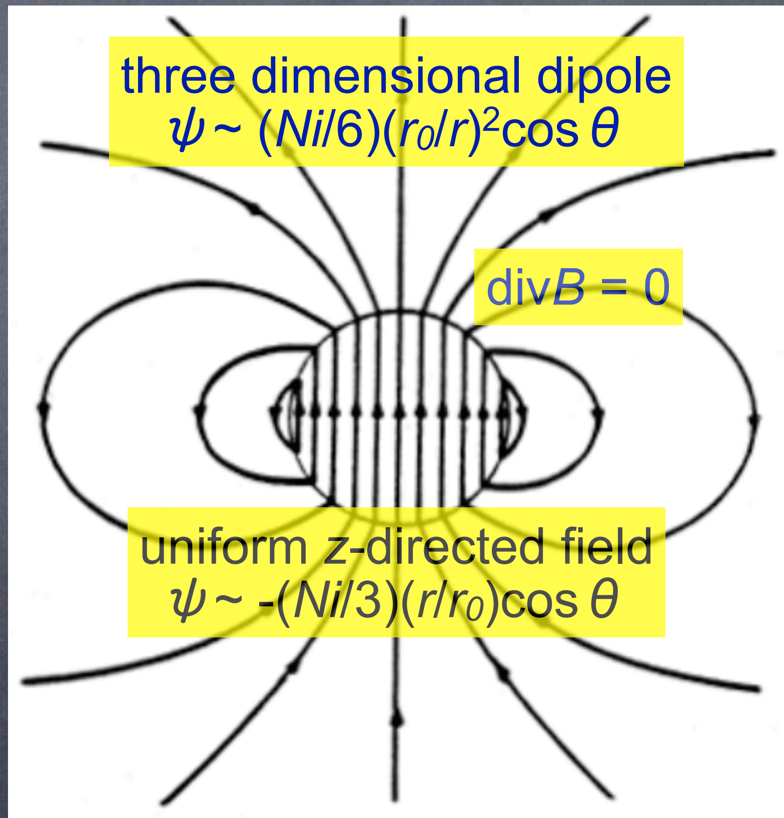
Spherical coil has cylindrical symmetry

compact apparatus



$2r_0$

dz



10^{-4} setting and current fine tuning

World's nEDM project

	H_0 field	magnetometer	magnetic shielding	EDM cell	UCN density
KEK-RCNP	*spherical coil*	*^{129}Xe buffer gas co-magnetometer*	*Finemet?/ superconductor*	*small* T = 300 K	*5800**
Sussex RAL	solenoid	n at E = 0 magnetometer	μ metal superconductor	large T ~ 0.5 K	1000
SNS	truncated cosθ coil	^{3}He co-magnetometer	Metglass/ superconductor	large T ~ 0.5 K	150
PSI	truncated cosθ coil	Cs multi-magnetometer	μ metal	large T = 300 K	1000

* UCN density at the EDM experiment port of E_c = 90 neV

Statistical uncertainty $\delta d_{sta} = \hbar/\{2\alpha E t_c \sqrt{N}\}$

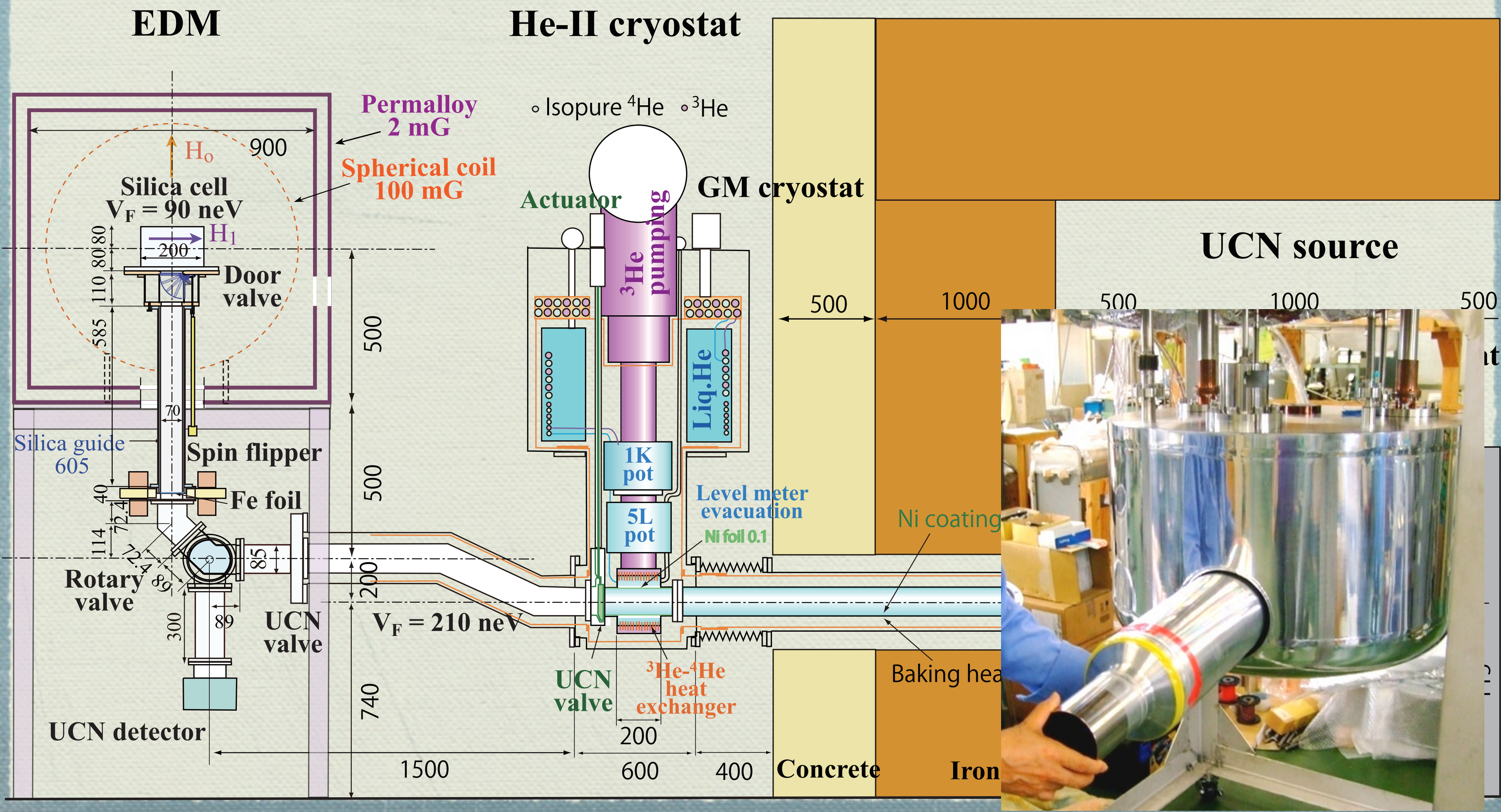
	α	E kV/cm	T_c s	Number of UCN /batch	σ_d e.cm/day
ILL 2006	0.7	10	130	1.4×10^4 in 21 L	34×10^{-26}
4kW RCNP	0.9	12	130	1.1×10^6 in 3.1 L	2.5×10^{-26}
20kW TRIUMF	0.9	12	130	6.4×10^6 in 3.1 L	1×10^{-26}

Horizontal He-II UCN source at 20 kW
5800 UCN/cm^3 at E_c = 90 neV
Efficient UCN polarization of 5T magnet

We can measure the nEDM of 10^{-27} ~ 10^{-28} e.cm
for the study of new physics

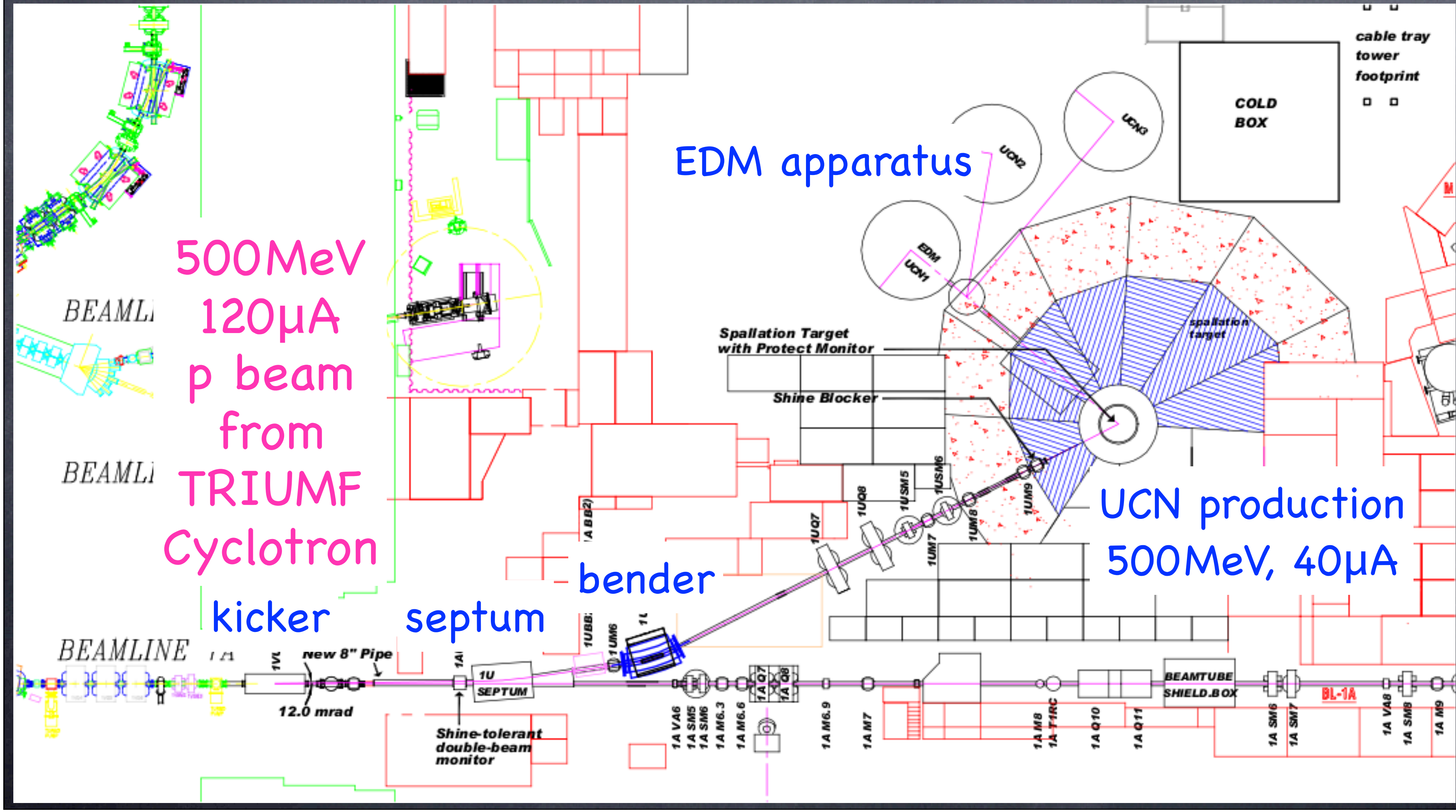
Horizontal UCN source

for more efficient UCN production and transport to exp.



Japan-Canada nEDM project

UCN are produced by a 20 kW p beam



World's UCN projects

	source type	E_c neV	τ_s s	ρ_{UCN} /cm^3 source	ρ_{UCN} /cm^3 exp.
Ours 20kW	spallation He-II(D_2O)	210	150	5×10^4 (11L)	5800* (90neV)
ILL 60 MW	n beam He-II	250	150	**	1000 (250neV)
SNS 1 MW	n beam He-II	134	500	**	150
LANL 125kW	spallation SD2	250	1.6	**	30* (180 neV)
PSI 1 MW	spallation SD2	250	6	2000 (2m^3)	1000 (250neV)
Munich 20 MW	reactor SD2	250	**	1×10^4	**

* ρ at experimental port, ** no number

Present collaborators:

Y. Masuda, T. Adachi, S.C. Jeong, S. Kawasaki,
Y. Watanabe (KEK), K. Asahi (TIT)
K. Matsuta, M. Mihara, D. Nishimura (Osaka)
K. Hatanaka, R. Matsumiya (RCNP)

I. Tanihata (RCNP, Beihang University)

J. Martin, C. Bidinosti (Winnipeg)
L. Buckman, C. Davis, A. Konaka, L. Lee, A. Miller,
D. Ramsay, W. van Oers (TRIUMF), S. Page (Manitoba)
Momose (UBC), E. Korkmaz (UNBC), M. Barnes (CERN)

R. Golub, E. Korobkina (North Carolina)

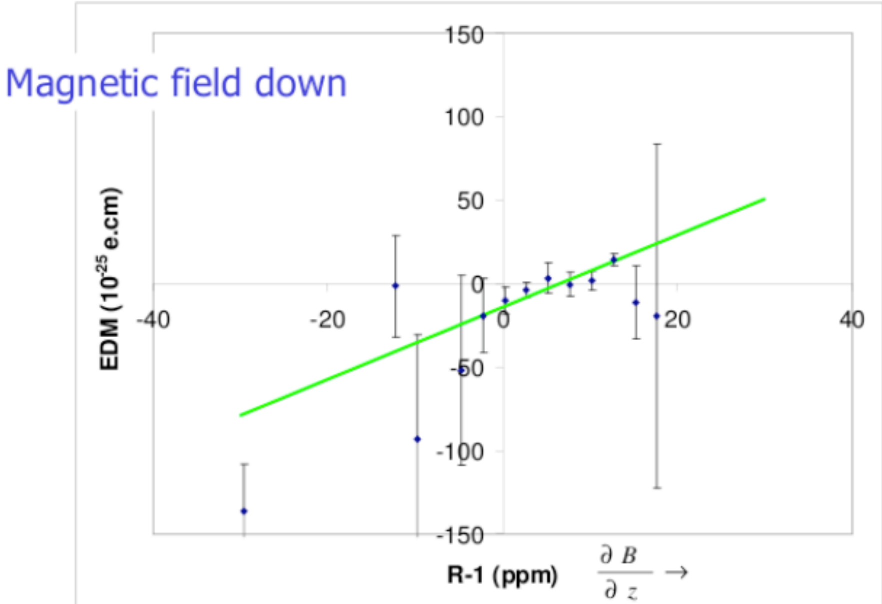
Thanks

Develop Pendlebury's approach to GPE

Assuming a cylindrically symmetric field

$$R = \gamma_{UCN} H(UCN)/\gamma_{199Hg} H(^{199}Hg) \rightarrow 1 \pm \Delta h \underline{\langle \partial H_{0z}/\partial z \rangle} / H_{0z}$$

$$\Delta h = h_{av}(UCN) - h_{av}(^{199}Hg) = 3 \text{ mm}$$



false EDM (GP) effect

GPE correction

$$d_{afHgn} = \hbar/8 |\gamma_n \gamma_{Hg}| \underline{(\partial H_{0z}/\partial z)} R^2/c^2$$

$(\partial H_{0z}/\partial z)$: 3 nT/m → 0.3 nT/m

For ^{199}Hg Earth's rotation effect on the frequency ratio.

$d_{rot} = 2.5 \times 10^{-26}$ e · cm

sign of γ_{199Hg} is opposite to γ_n

PRL 98 (2007) 149101

^{129}Xe is not serious

γ_{129Xe} same as γ_n

Systematic errors at ILL

	$\times 10^{-27}$ e.cm	
1 Door cavity dipole	-5.6 ±2.0	Non-cylindrical symmetry 1) dipole field of remnant magnetization 2) quadrupole component of truncated cosθ coil
2 Other dipole fields	0.0 ±6.0	
3 Quadrupole difference	-1.3 ±2.0	
4 **v**×**E** translational	0.0 ±0.03	
5 **v**×**E** rotational	0.0 ±1.0	Deviation from gas like motion
6 Second-order **v**×**E**	0.0 ±0.02	
7 Hg light shift (geo phase)	3.5 ±0.8	
8 Hg light shift (direct)	0.0 ±0.2	
9 Uncompensated B drift	0.0 ±2.4	Failure of magnetic shielding
10 Hg atom EDM	-0.4 ±0.3	
11 Electric forces	0.0 ±0.4	
12 Leakage currents	0.0 ±0.1	
13 AC fields	0.0 ±0.01	
Total	-3.8 ±7.2	

Systematic errors at ILL

	$\times 10^{-27}$ e.cm
1 Door cavity dipole	-5.6 ±2.0
2 Other dipole fields	0.0 ±6.0
3 Quadrupole difference	-1.3 ±2.0
4 **v**×**E** translational	0.0 ±0.03
5 **v**×**E** rotational	0.0 ±1.0
6 Second-order **v**×**E**	0.0 ±0.02
7 Hg light shift (geo phase)	3.5 ±0.8
8 Hg light shift (direct)	0.0 ±0.2
9 Uncompensated B drift	0.0 ±2.4
10 Hg atom EDM	-0.4 ±0.3
11 Electric forces	0.0 ±0.4
12 Leakage currents	0.0 ±0.1
13 AC fields	0.0 ±0.01
Total	-3.8 ±7.2

Buffer gas.
Remnant magnetization is removed by magnetometers.
Quadrupole component is removed in a spherical coil.

Deviation from gas like motion

Failure of magnetic shielding

Systematic errors at ILL

	$\times 10^{-27}$ e.cm
1 Door cavity dipole	-5.6 ±2.0
2 Other dipole fields	0.0 ±6.0
3 Quadrupole difference	-1.3 ±2.0
4 **v**×**E** translational	0.0 ±0.03
5 **v**×**E** rotational	0.0 ±1.0
6 Second-order **v**×**E**	0.0 ±0.02
7 Hg light shift (geo phase)	3.5 ±0.8
8 Hg light shift (direct)	0.0 ±0.2
9 Uncompensated B drift	0.0 ±2.4
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12 Leakage currents	0.0 ±0.1
13 AC fields	0.0 ±0.01
Total	-3.8 ±7.2

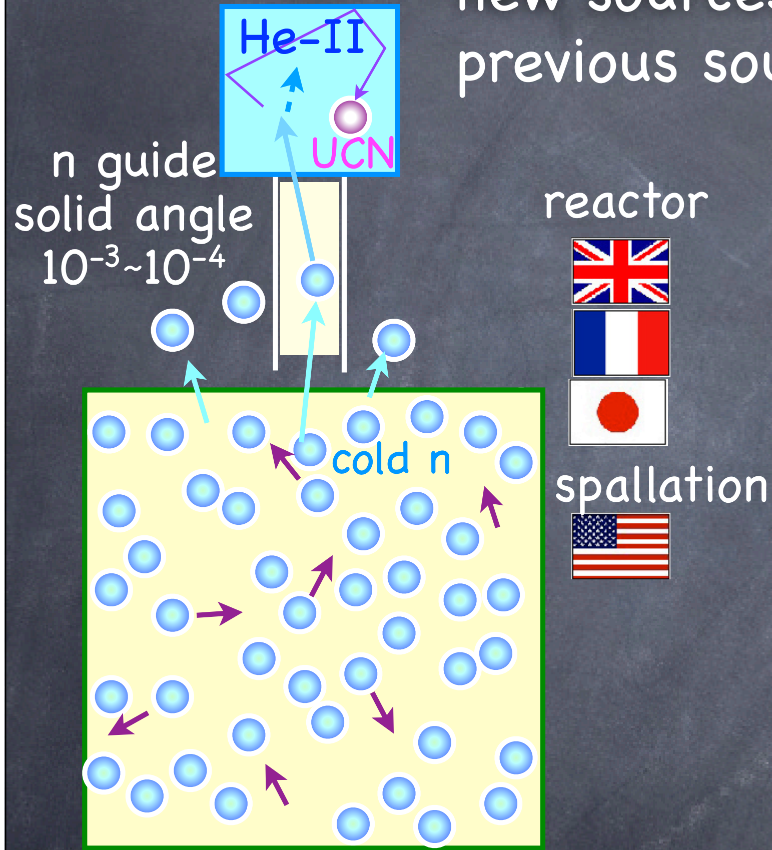
Buffer gas.
Remnant magnetization is removed by magnetometers.
Quadrupole component is removed in a spherical coil.

Study UCN motion

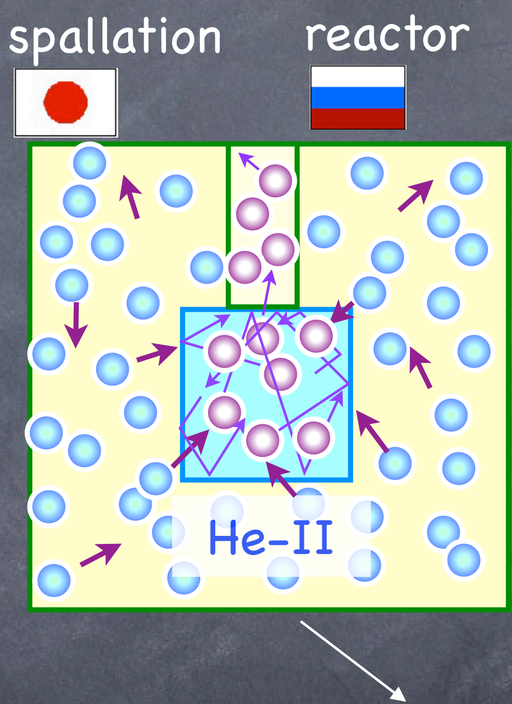
Study superparamagnetic material/superconductor

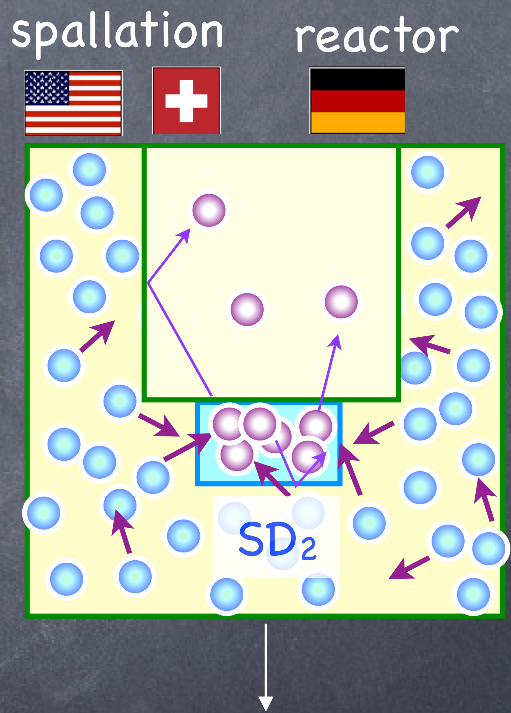
World status of new UCN sources

new sources: phase space density increases
previous souces: phase space density does not increase



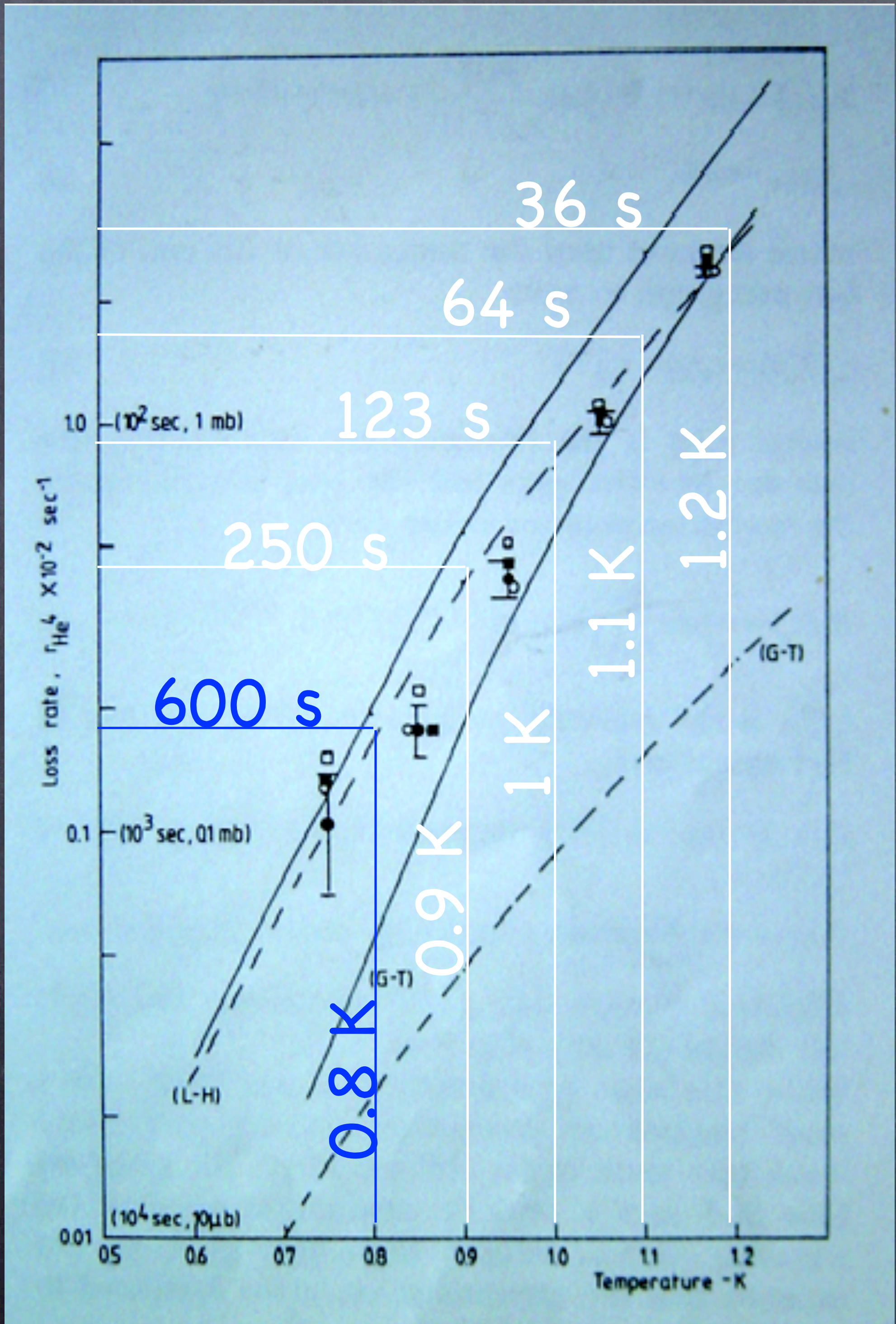
Cold n source





UCN density ρ_{UCN}	high	middle
production rate P_{UCN}	small	high
loss $1/\tau_s$	small	high
extraction loss ε_{ext}	small	high

Storage time τ_s



He-II [Golub et al. (1983)]

phonon up-scattering, $1/\tau_{ph} \propto T^7$

$\tau_s = 1/\{1/\tau_{ph} + 1/\tau_\beta + 1/\tau_w\} = 150$ s

τ_{ph}= 600 s at 0.8 K

τ_β = 886 s (β decay)

τ_w = ~300 s (wall loss)

SD_2 [Phys.Rev.C71(2005)054601]

$\tau_s = 1/\{1/\tau_{ph} + 1/\tau_{o\text{-}p} + 1/\tau_a\} = 24$ ms

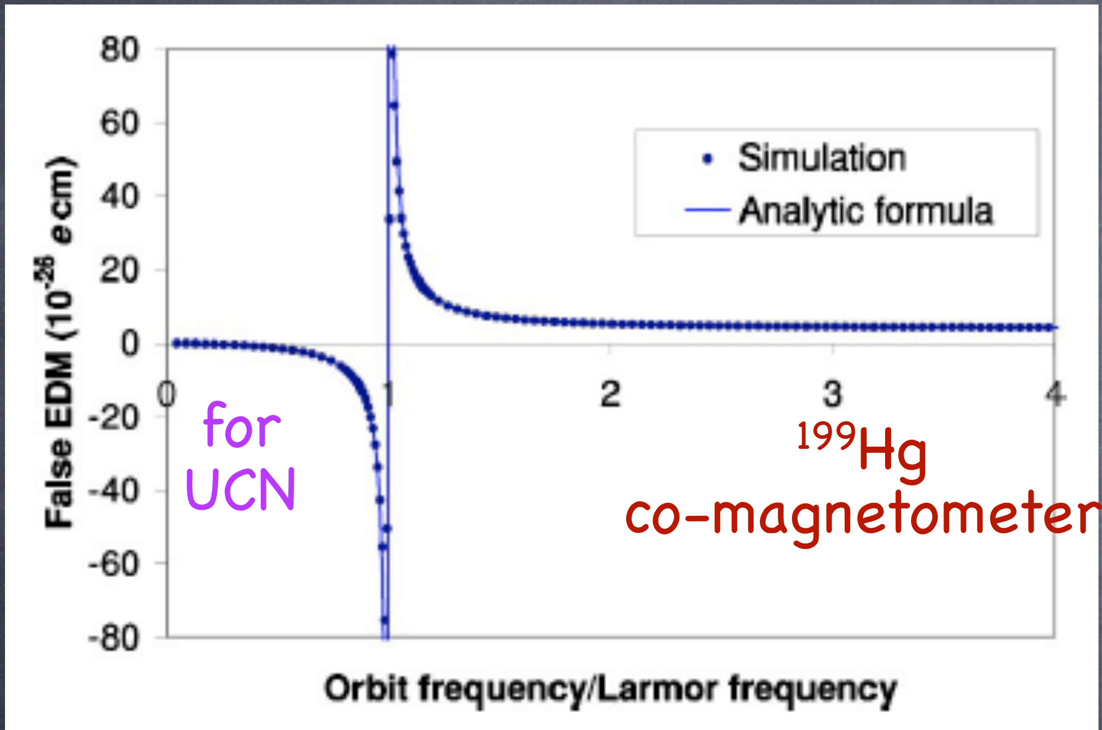
τ_{ph} = 40 ms at 8 K

$\tau_{o\text{-}p}$ = 100 ms

τ_a = 150 ms

Motion induced systematic error

Geometric Phase Effect (GPE)



$$d_{afHgn} = \hbar/8|\gamma_n\gamma_{Hg}| \times(\partial H_{0z}/\partial z)\underline{R}^2/c^2$$

$$\sim 5\times10^{-26}\ e\cdot cm$$

$H_{0z} = 1\ \mu T$, $\partial H_{0z}/\partial z = 1\ nT/m$

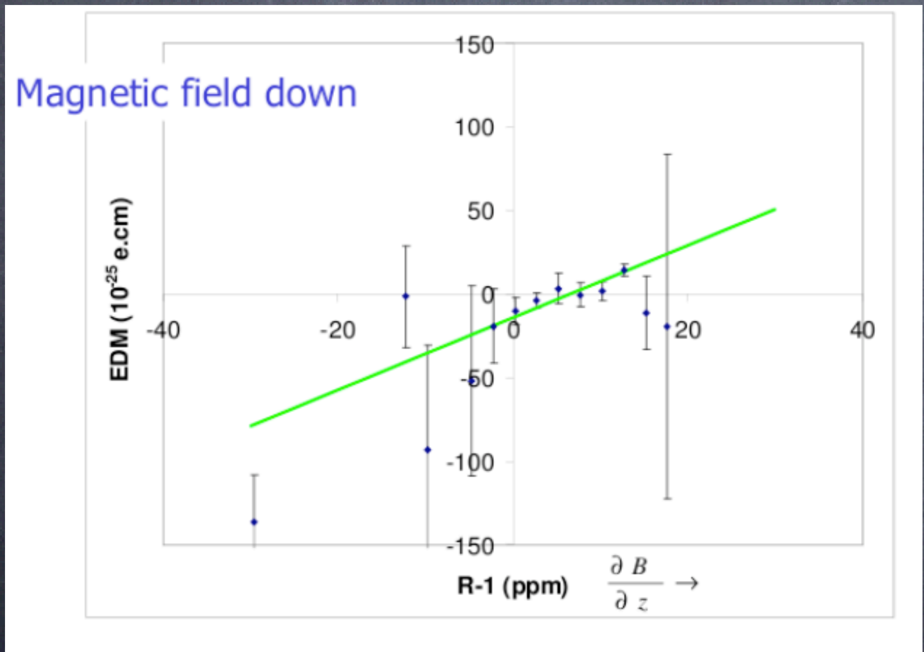
$d_{afn} \sim 1\times10^{-27}\ e\cdot cm$

Pendlebury et al, Phys. Rev A70(2004),
Golub and Lamoreaux, Phys. Rev A71(2005)

Pendlebury's approach to GPE

$R = \gamma_{UCN} H(UCN)/\gamma_{199Hg} H(^{199}Hg) \rightarrow 1 \pm \Delta h \underline{\langle \partial H_{0z}/\partial z \rangle} / H_{0z}$

$\Delta h = h_{av}(UCN) - h_{av}(^{199}Hg) = 3\ \mathrm{mm}$



false EDM (GP) effect

GPE correction

$d_{afHgn} = \hbar/8 |\gamma_n \gamma_{Hg}| \underline{(\partial H_{0z}/\partial z)}\, R^2/c^2$