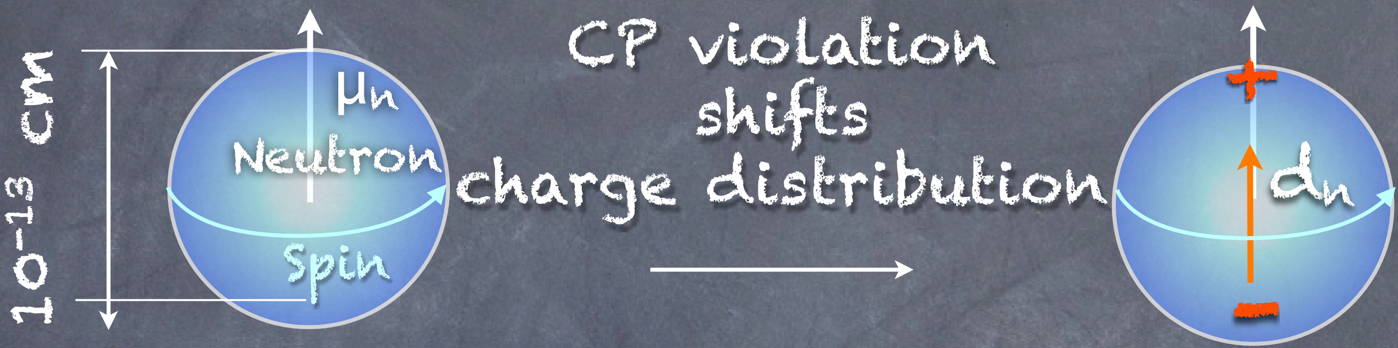
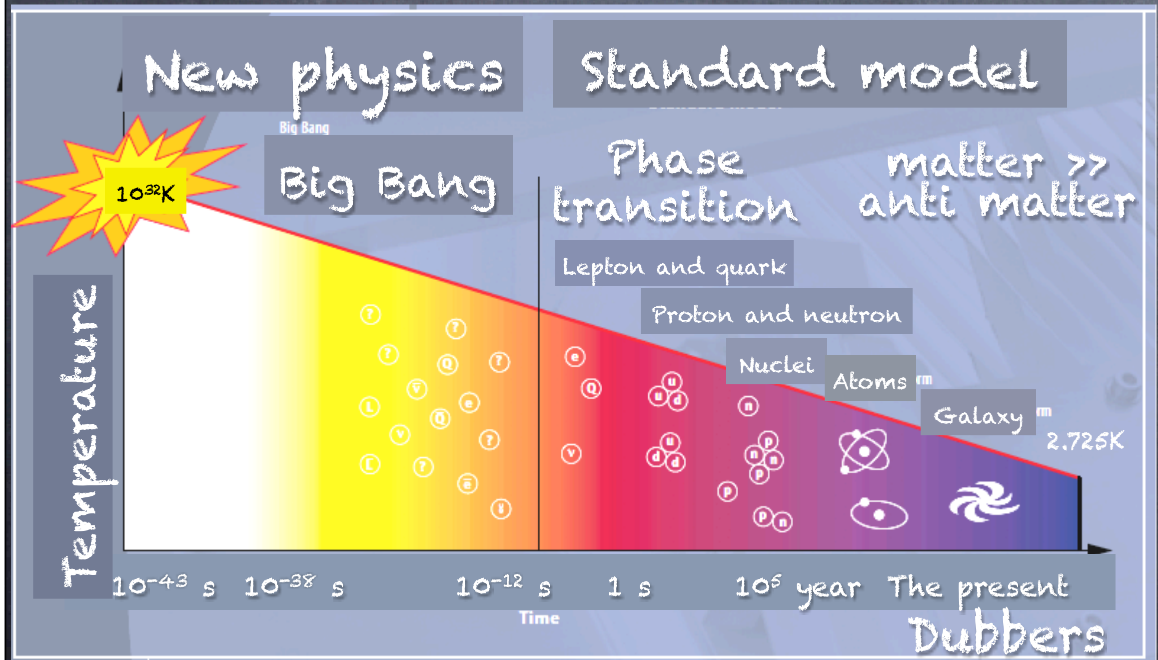
A new EDM measurement with a new generation UCN source

May 22, 2012, ISINN20





Mystery of baryogenesis :

CP violation creates matter

but

Standard model

can't explain the baryon asymmetry

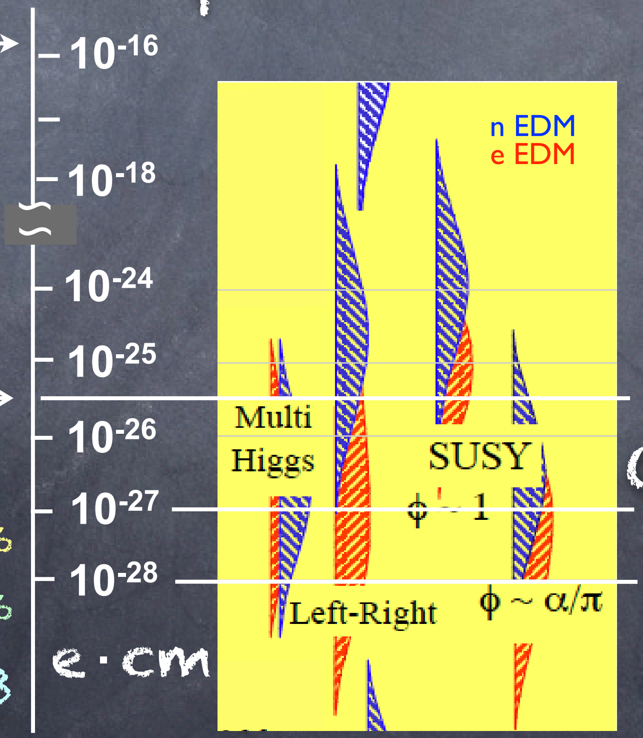
KEK-RCNP EDM measurement

Y. Masuda, S. Jeong, Y. Watanabe, T. Adachi, S. Kawasaki, K.Matsuta,
M. Mihara, K. Hatanaka, R. Matsumiya, and K. Asahi

New physics predicts EDM

Earth's field ($\mu_n H_o/E$) →

EDM upper limit →



Ours

statistical 1.5×10^{-26}
systematic 0.7×10^{-26}
related with B

statistical
high density UCN

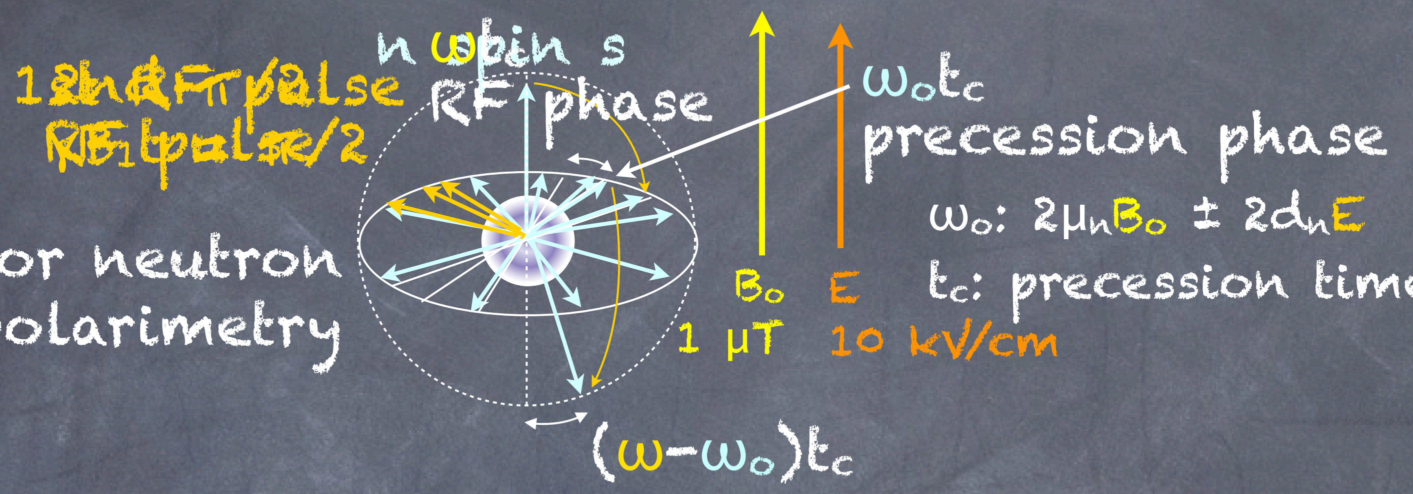
10^{-27} e·cm

10^{-28} e·cm

systematic
new magnetometer

10^{-28} e·cm

EDM measurement

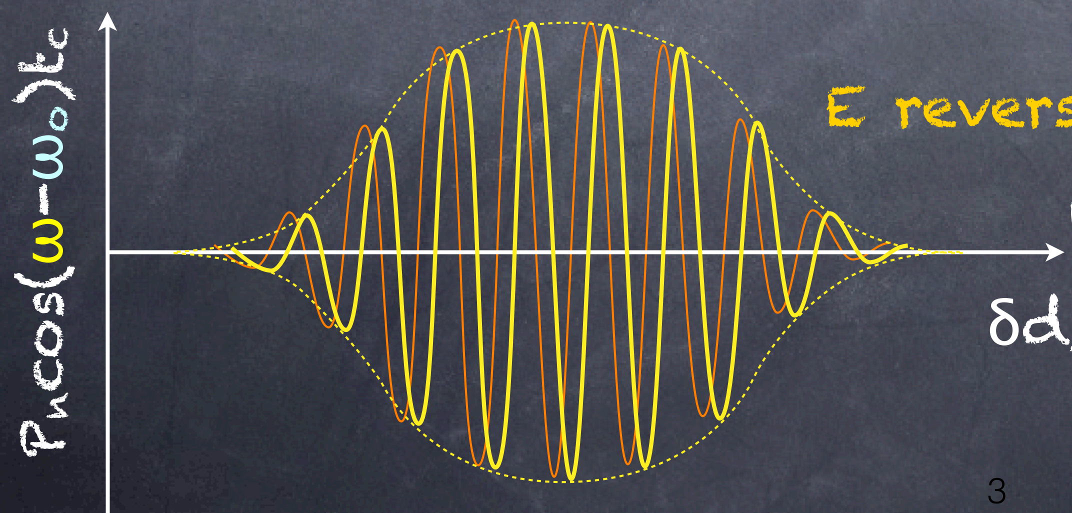


Neutron precession

$$S = \exp\{i(\mu \cdot B_0 + d_n \cdot E)/\hbar \cdot t\}$$

$\mu, d_n \propto s$

UCN bottle



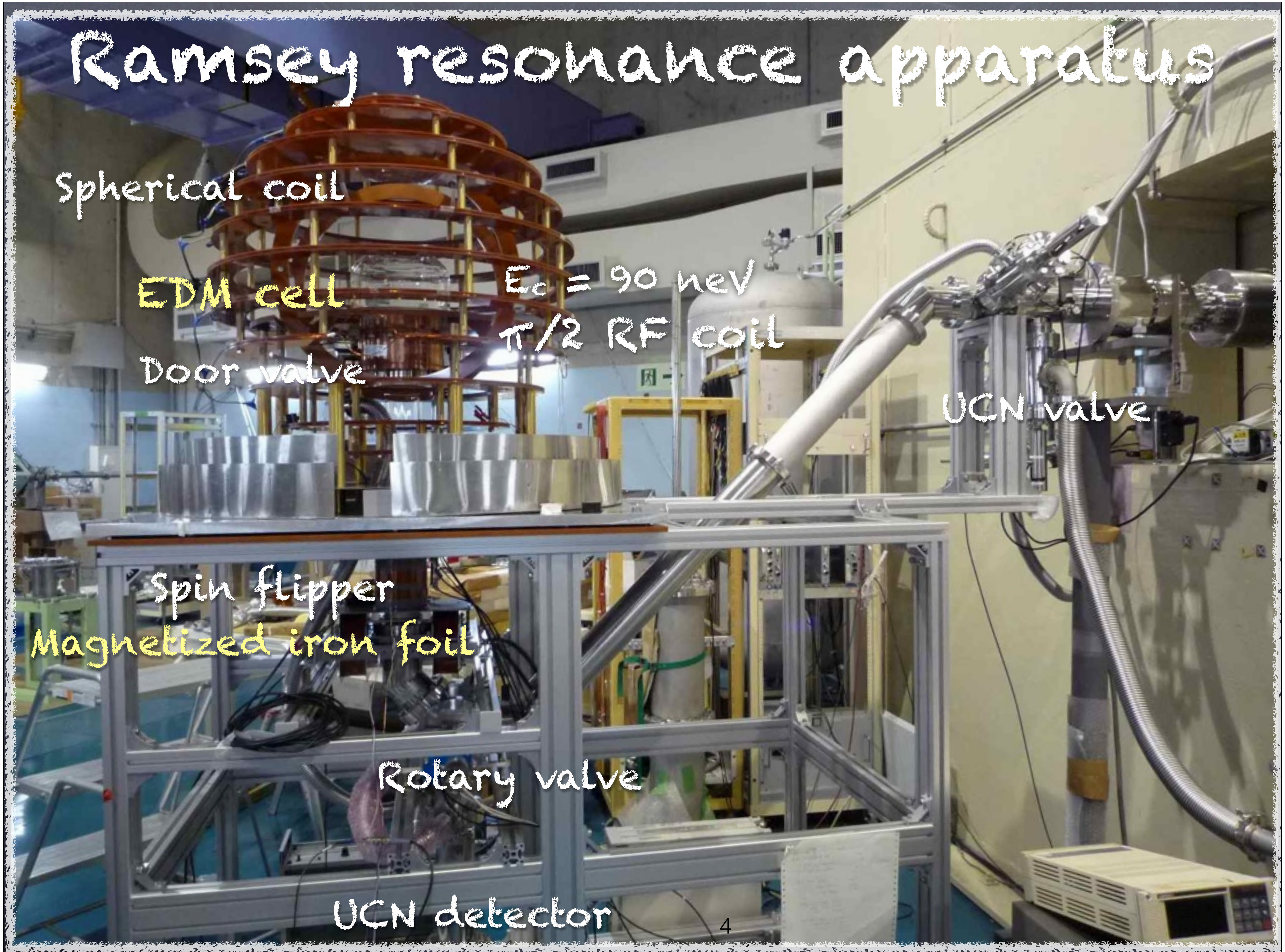
E reversal for extraction of d_n

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

P_n : UCN polarization

N : number of UCN

Ramsey resonance apparatus



UCN production for EDM

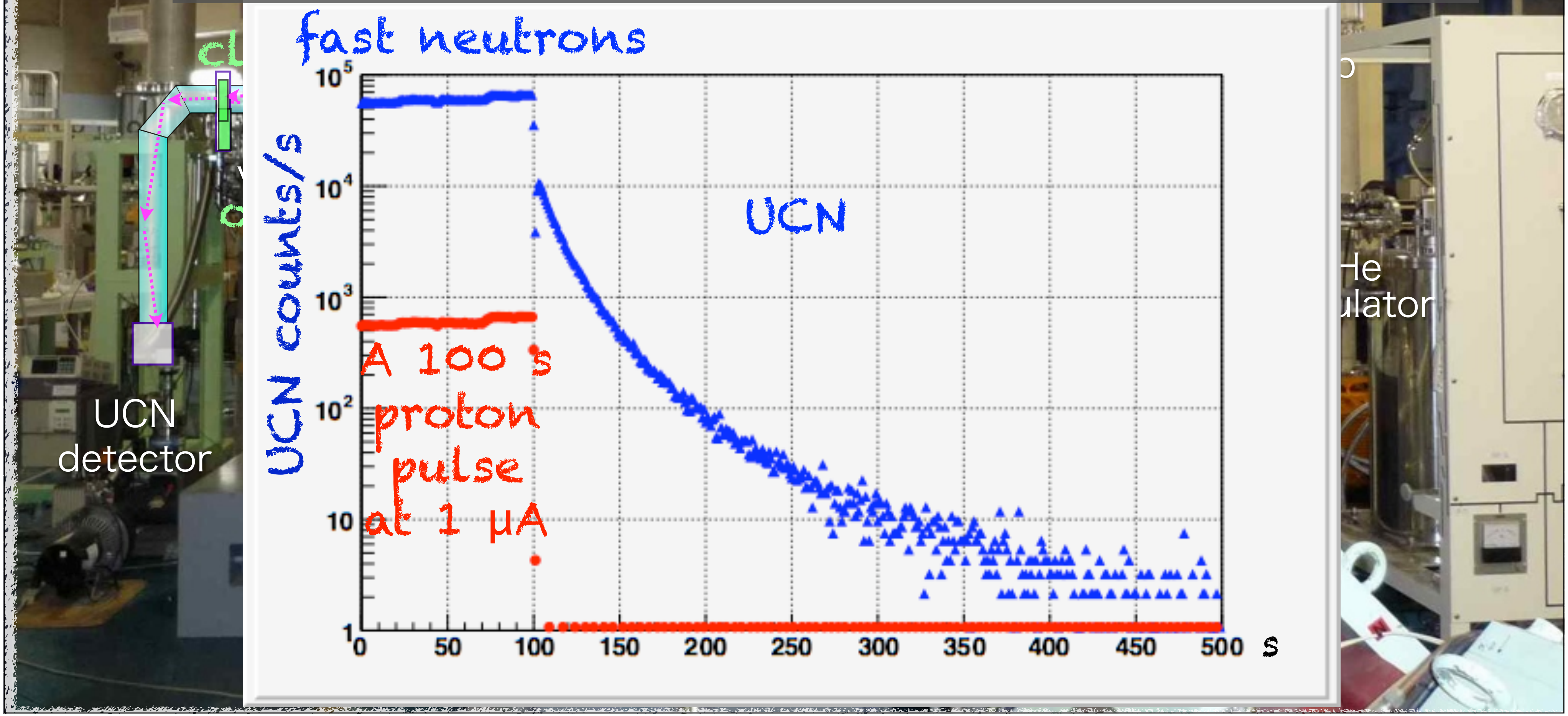
T_s = 81 s — Phys. Rev. Lett. 108(2012)134801

240 s 390W proton irradiation

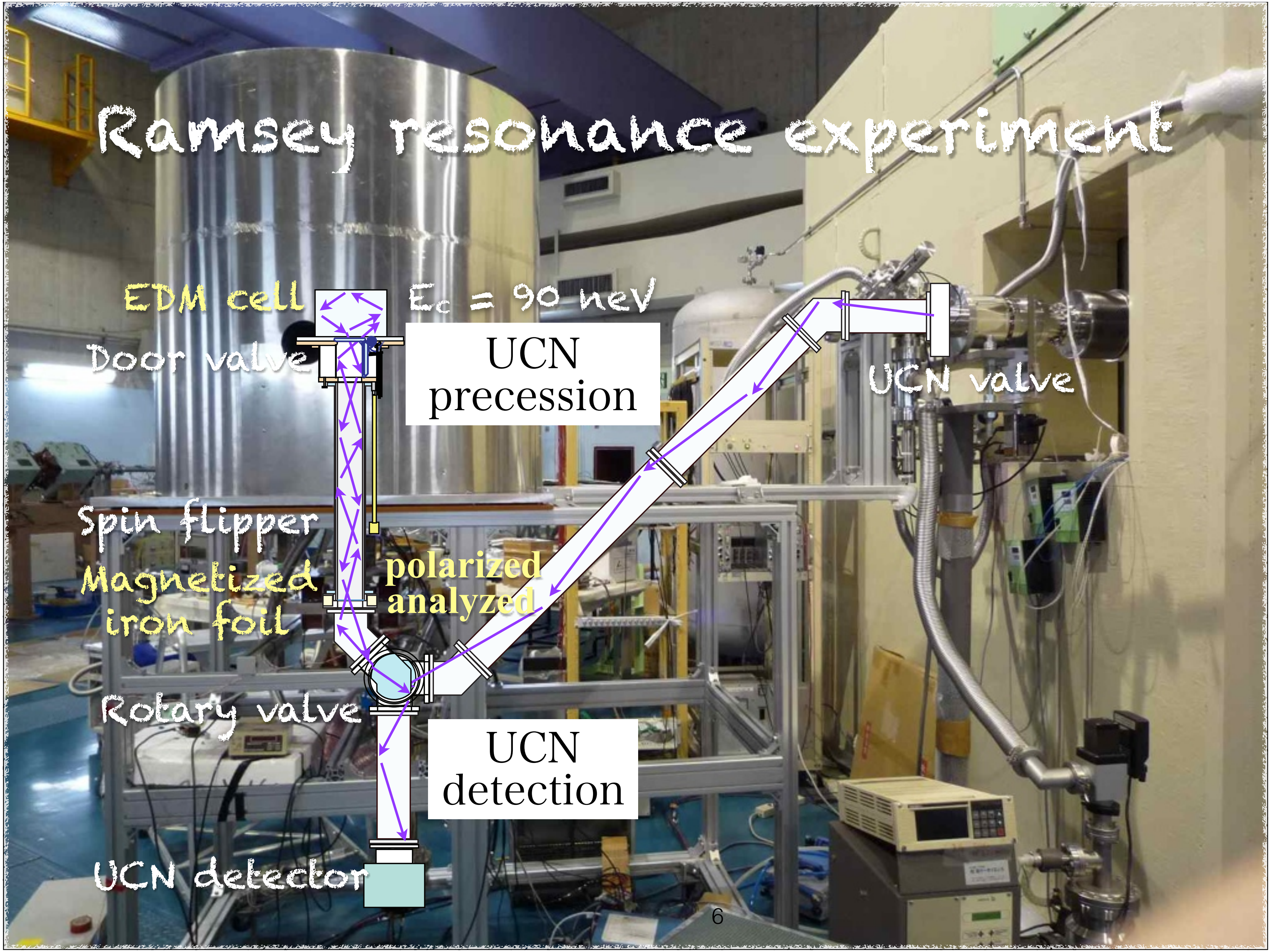
26 UCN/cm^3 at E_c = 90 neV, P = 4 UCN/cm^3·s at E_c = 210 neV

$\rho_{UCN} \propto E_c^{3/2}$

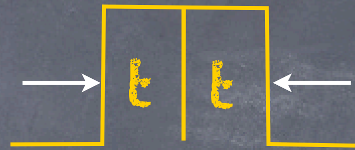
will be increased in the new source



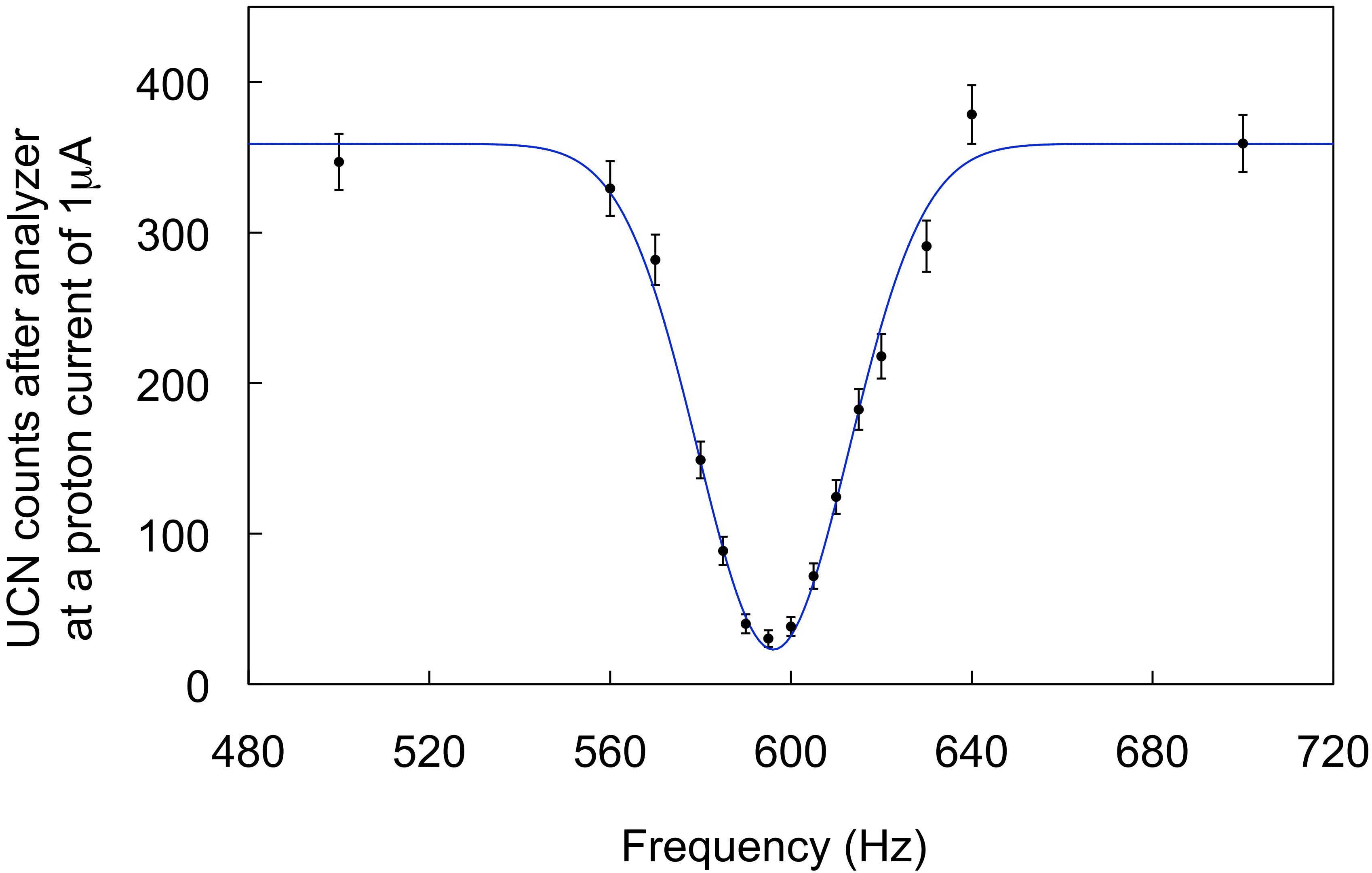
Ramsey resonance experiment



UCN NMR in EDM cell

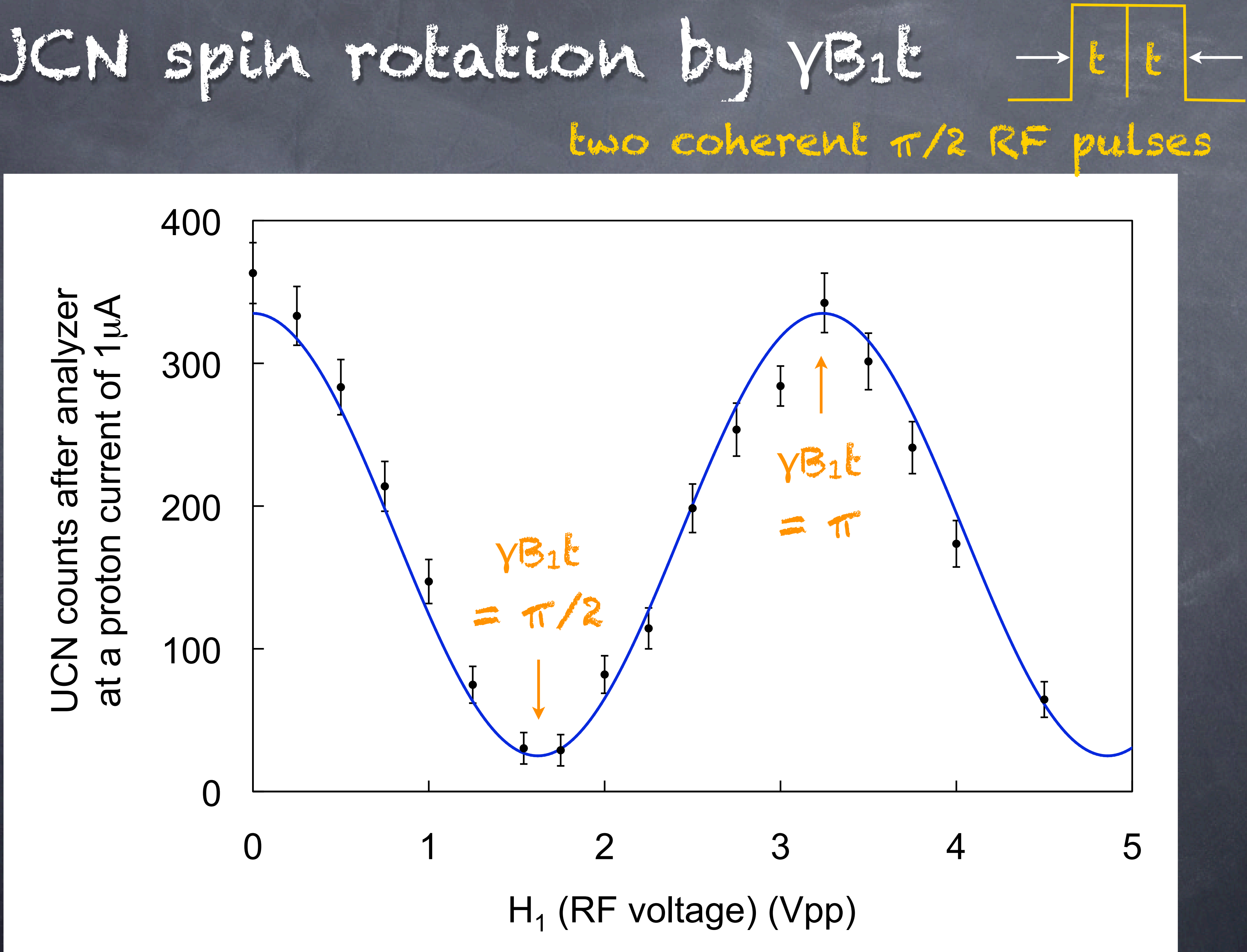


two coherent π/2 RF pulses



UCN spin rotation by $\gamma B_1 t$

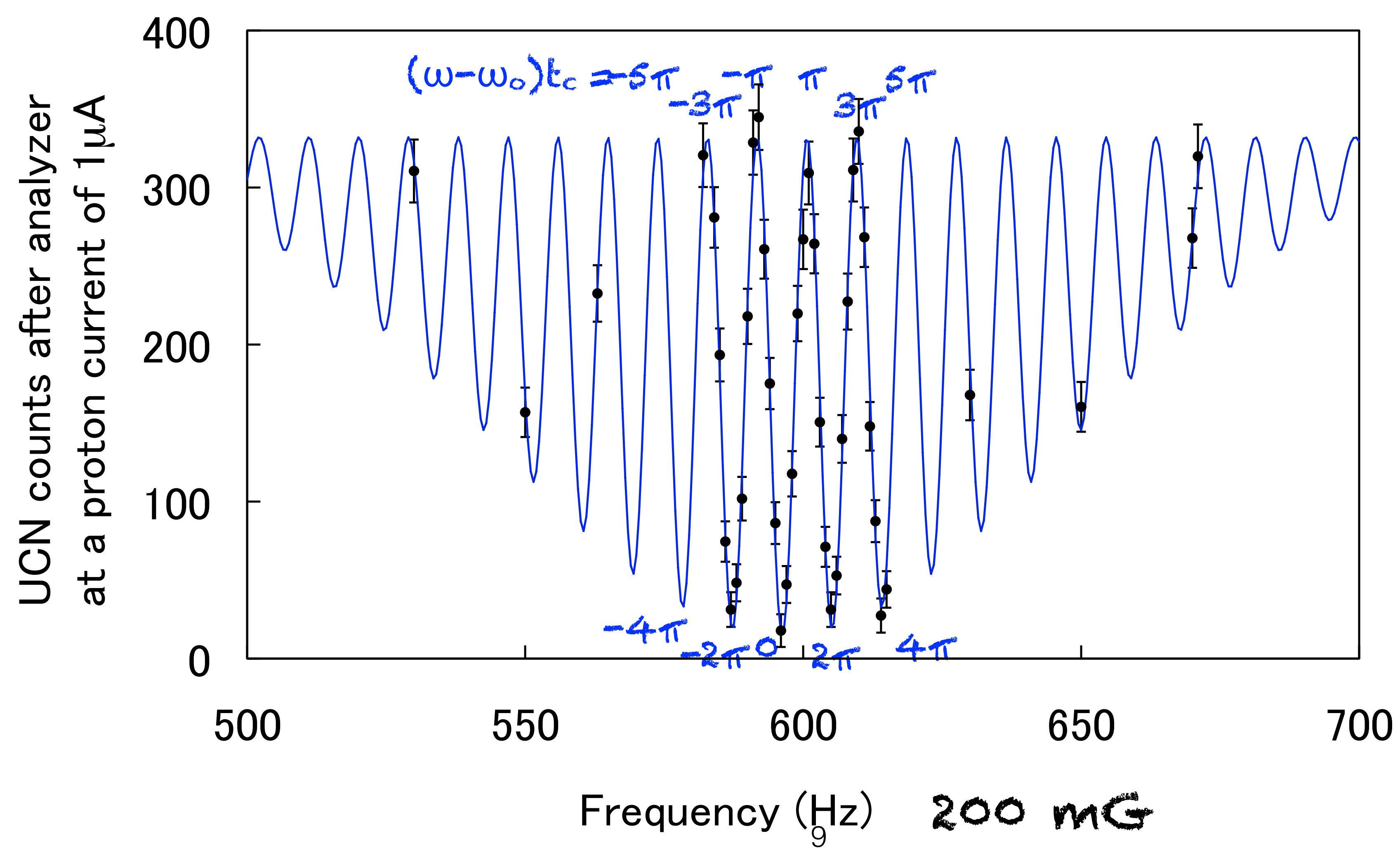
two coherent $\pi/2$ RF pulses



Ramsey resonance

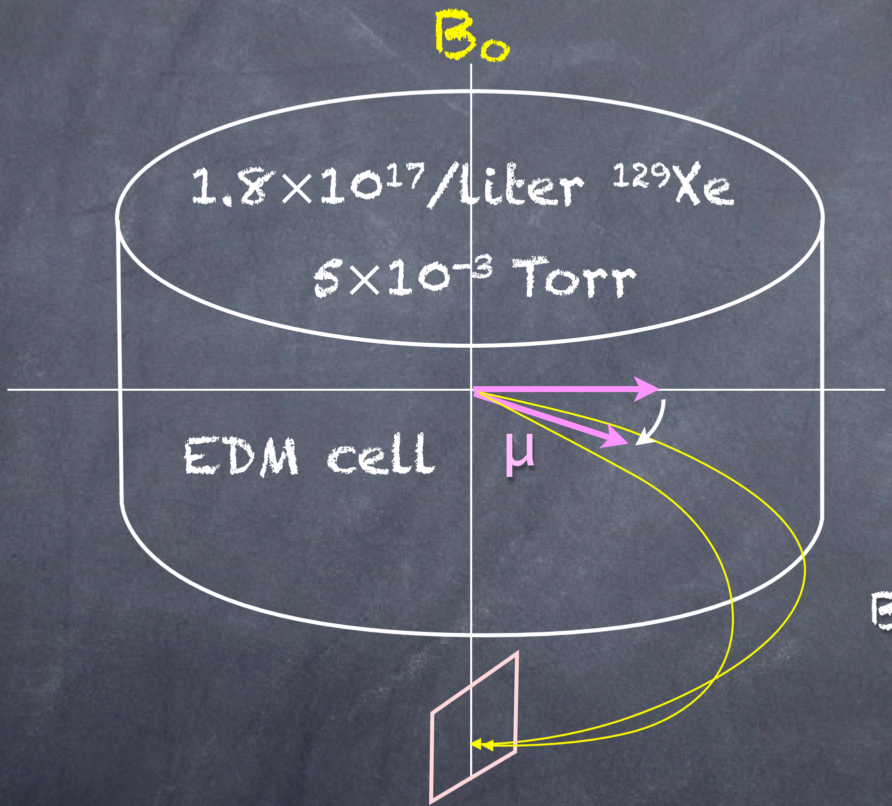
visibility α =
$(N_{max} - N_{min})/(N_{max} + N_{min}) = 0.9$

two coherent $\pi/2$ RF pulses



^{129}Xe spin magnetometer

Upon E reversal



^{129}Xe magnetization

$P_{129Xe} = 0.5$

$B = 0.4$ pT
in the EDM cell

Rb-^{129}Xe
van der Waals
molecule

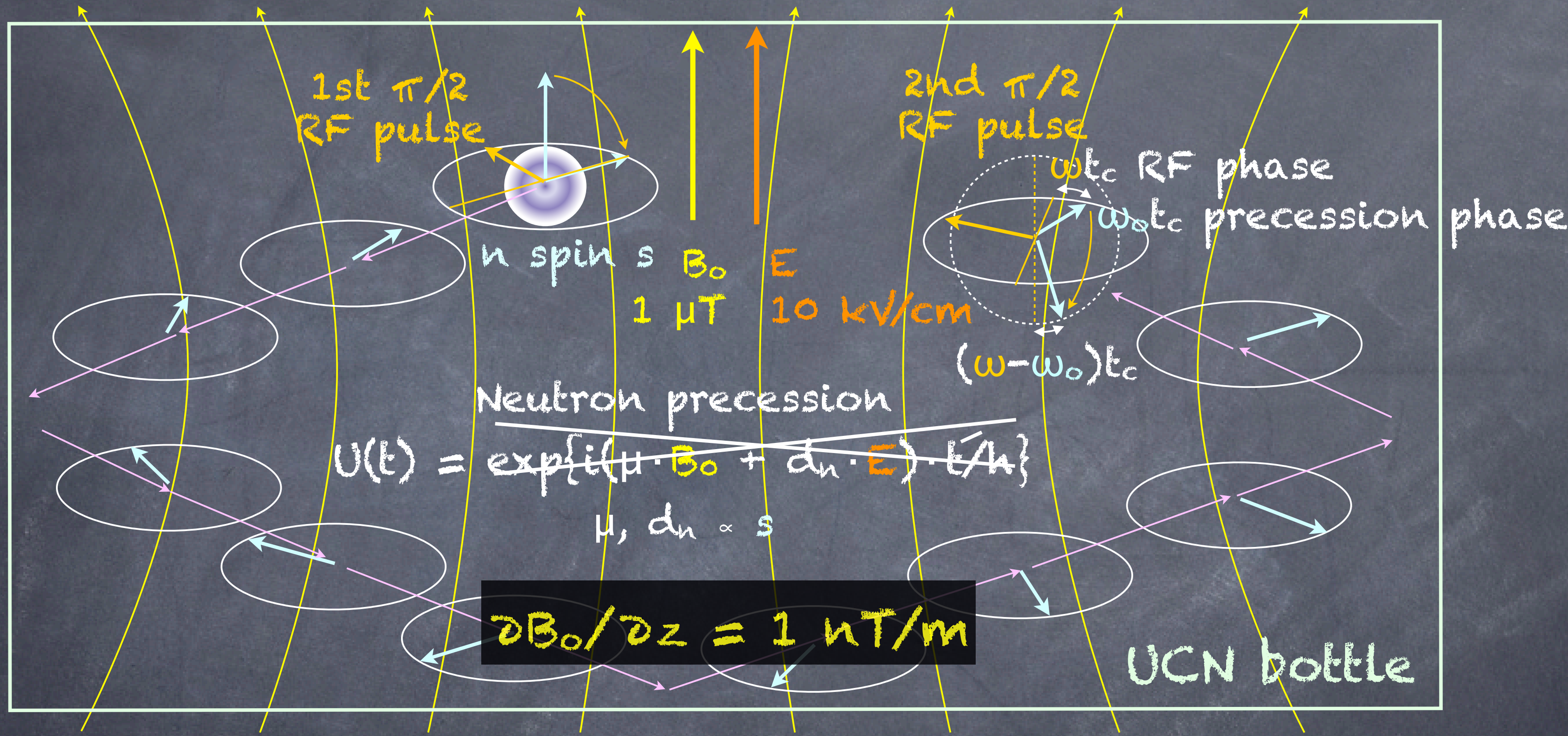
$B = 0.15$ pT
at 0.1 m
from the center

SQUID 1fT, $5\mu\Phi_0/\sqrt{Hz}$

B_0 monitor by nuclear spin precession

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, Rb-Xe
^{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)



Geometric phases arise from the transverse fields,

$B_{0r} = (\partial B_0/\partial z)r/2$, $B_v = E \times v/c^2$

Pendlebury, Phys. Rev. A70(2004)032102.
Lamoreaux, Phys. Rev. A71(2005)052115.

Effect of time dependent interaction

$$U(t) = \exp(-iH_0 t/\hbar)$$
$$H_0 = -\boldsymbol{\mu}\cdot\boldsymbol{B}_0 - \boldsymbol{d}_n\cdot\boldsymbol{E}$$

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$$H = H_0 + V(t)$$

$$V(t) = -\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t) = -\gamma\boldsymbol{s}\cdot(\boldsymbol{B}_v(t) + \boldsymbol{B}_{0r}(t))$$

$$\boldsymbol{B}_v = \boldsymbol{E}\times\boldsymbol{v}/c^2 \quad \boldsymbol{B}_{0r} = -(\partial B_{0z}/\partial z)\boldsymbol{r}/2$$

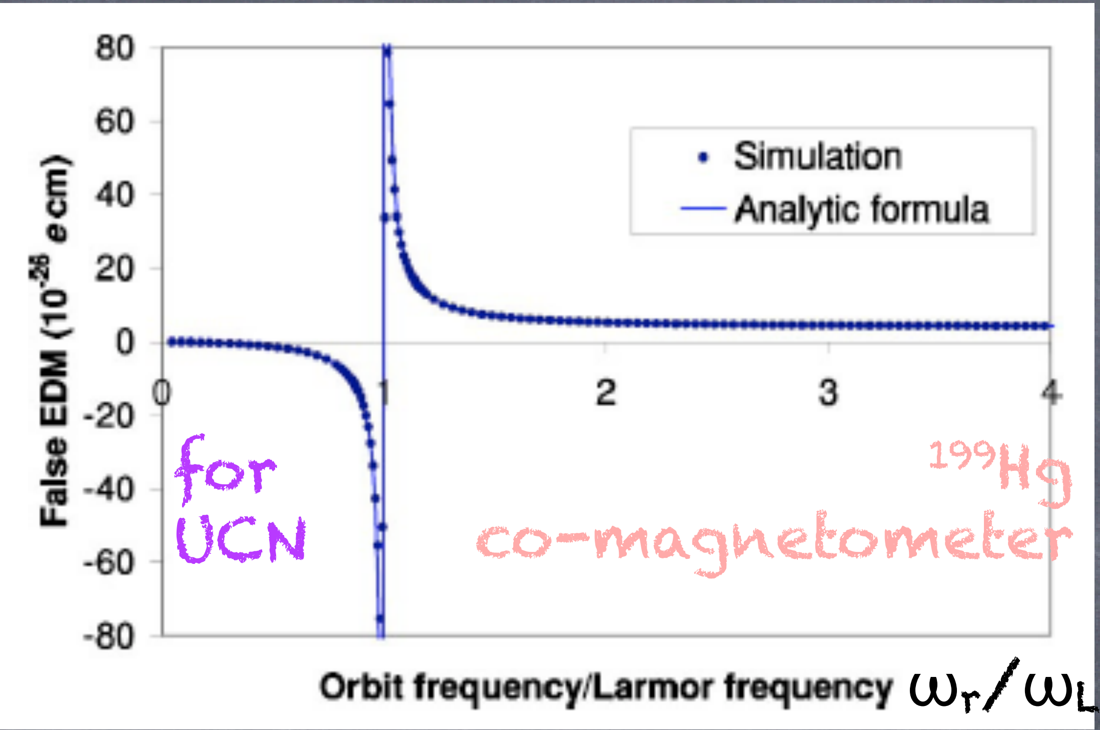
$$U_I(t) = 1 + \left(\frac{-i}{\hbar}\right)\int_0^t dt' V_I(t') + \left(\frac{-i}{\hbar}\right)^2 \int_0^t dt' \int_0^{t'} dt'' V_I(t')V_I(t'') + \cdots$$

$$V_I(t) = \exp(iH_0 t/\hbar)\{-\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t)\}\exp(-iH_0 t/\hbar)$$

$$U_I(t) = 1 + \frac{is_z}{\hbar}\frac{1}{4}\gamma^2\frac{E}{c^2}\frac{\partial B_{0z}}{\partial z}\int_0^t dt' \int_0^{t'} d\tau \cos(\omega_0\tau)$$
$$\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

GPE problem

$$\int_0^t d\tau \cos(\omega_0 \tau)\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$



$d_{afn} = -\hbar/4 \cdot (\partial B_{0z}/\partial z)/B_{0z}^2 \cdot v_{xy}^2/c^2$

~ 1×10^{-27} e·cm

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

~ 5×10^{-26} e·cm

Pendlebury, Phys. Rev. A70(2004)032102.
Lamoreaux, Phys. Rev. A71(2005)052115.

Solution for GPE problem

$$\int_0^t d\tau \cos(\omega_0\tau)\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

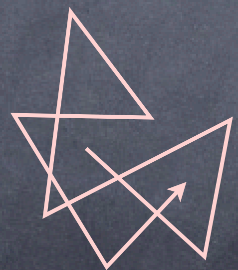
^{129}Xe buffer gas

$\lambda = 1/n\sigma \ll 0.7$ mm

$n = 1.8\times10^{14}$/cc at 5×10^{-3} torr

$\sigma_{Xe-Xe} \gg 838 Å^2$

random walk



r(t) does not change so much

v(t−τ) changes rapidly

$\langle r(t)v(t-\tau)\rangle \to \ll 1$

$d_{afHgn} \sim$ <u>5×10^{-26} e·cm</u>

<u>$d_{afXen} \to < 1\times10^{-28}$ e·cm</u>

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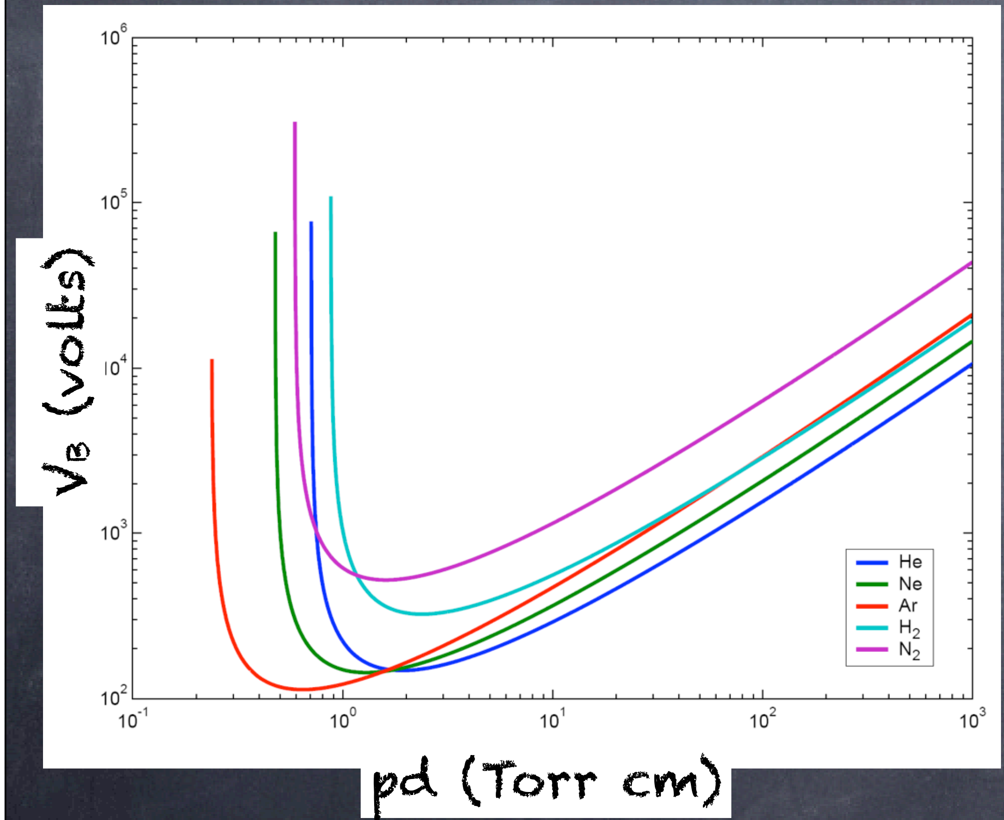
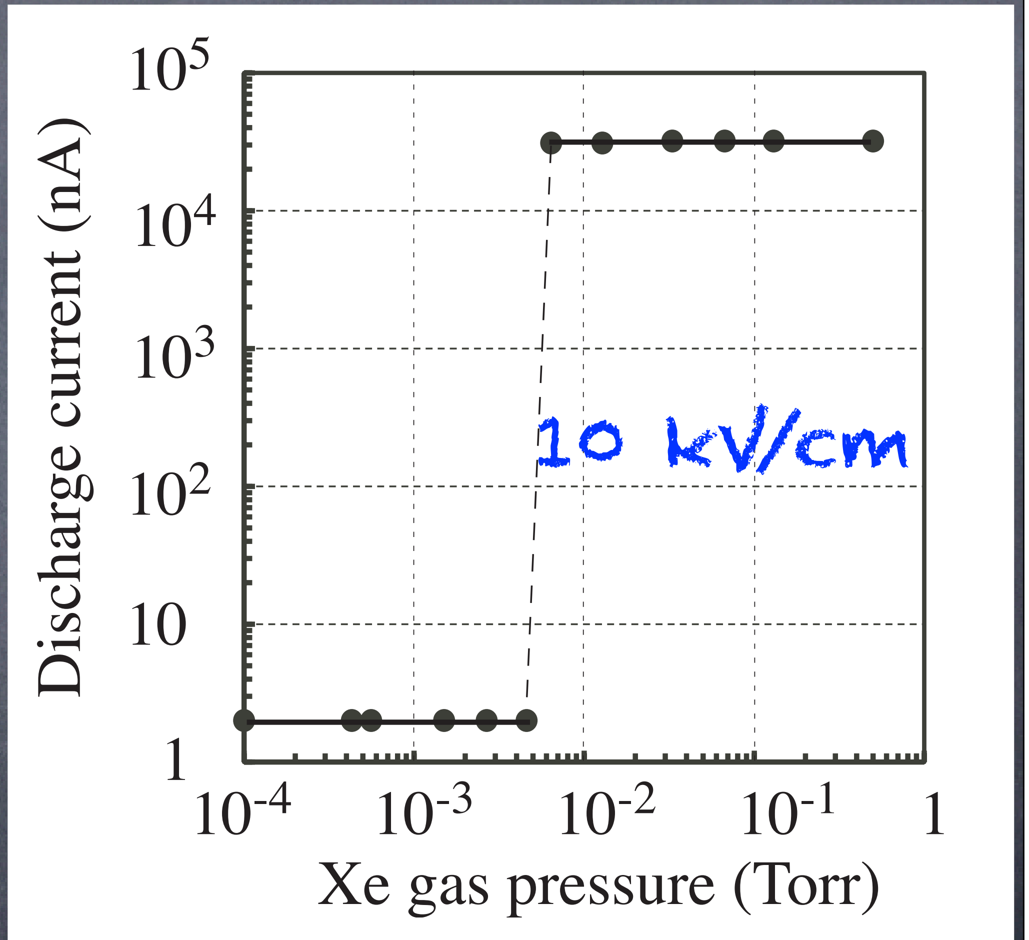
High voltage break down at 5×10^{-3} torr ?

Paschen's law





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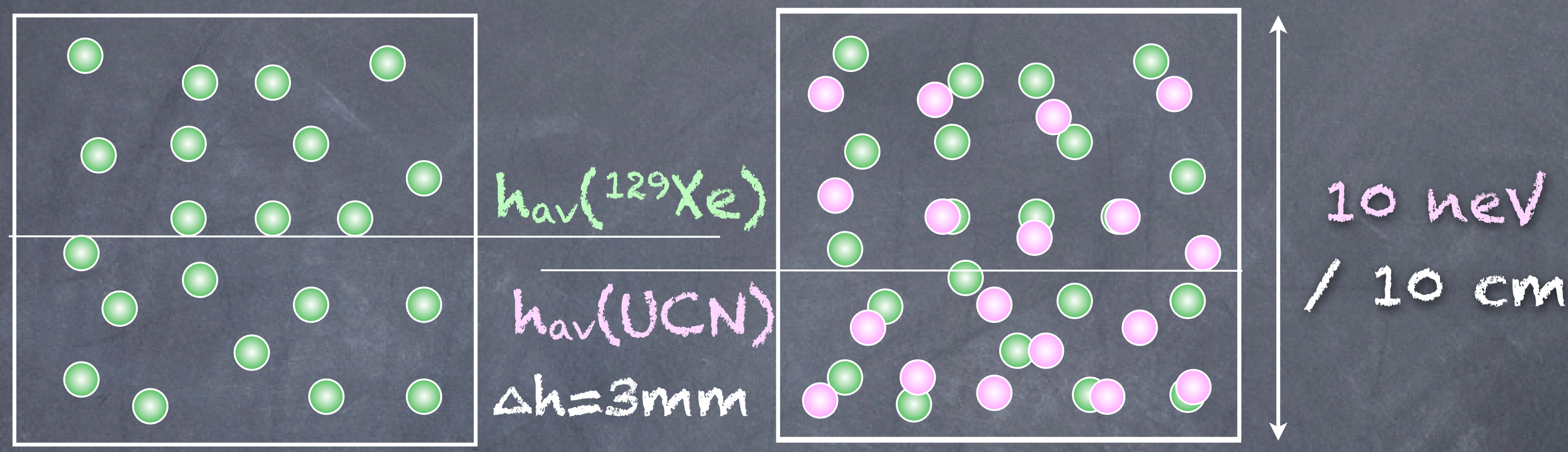
Field gradient control

^{129}Xe: v_{129Xe} 240 m/s

UCN: v_{UCN} 5 m/s



$$\omega_{129xe} = \gamma_{129xe} B(h_{129Xe}),\quad \omega_n = \gamma_n B(h_n)$$

Assuming cylindrical symmetry

$$(\omega_n/\gamma_n)/(\omega_{129Xe}/\gamma_{129Xe}) = 1 + \delta\gamma + \delta z(\partial B_{0z}/\partial z)/B_{0z}$$

Precision g factor measurement

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$(\omega_n/\gamma_n)/(\omega_{129Xe}/\gamma_{129Xe}) = 1 + \delta\gamma + \delta z(\partial B_{0z}/\partial z)/B_{0z}$

The value of $\delta\gamma$ can be obtained with 10^{-7}
in a 3 cm hight cell
at B_{0z} = 50 μT, $\partial B_{0z}/\partial z$ = 5 nT/m
the effect of residual magnetization is small.

The uncertainty of 10^{-7} is much smaller than ^{199}Hg.

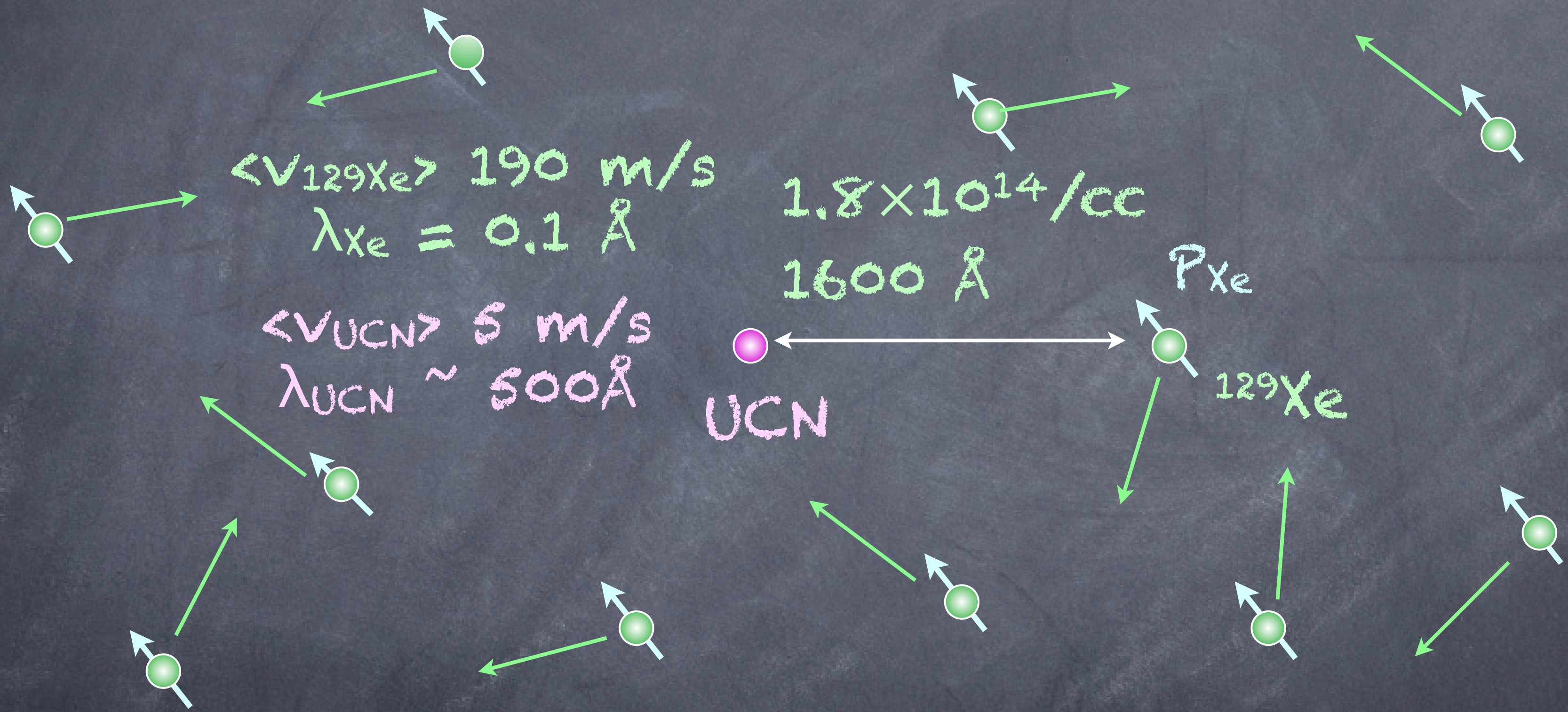
ω_n/ω_{129Xe} in the EDM cell → $\partial B_{0z}/\partial z$ ×1/10

$d_{afn} = -\hbar/4 \cdot (\partial B_{0z}/\partial z)/B_{0z}^2 \cdot v_{xy}^2/c^2$ → < 1×10^{-28} e·cm

Effect of ^{129}Xe pseudo magnetism ?

$0.4\ nT > B_{or} = 0.1\ nT$

spin dependent coherent scattering



Even if coherence remain,
time variation of B_p, ω_{129Xe} and $E\times v/c^2$, ω_r are out of

Rotating field originated from nuclear forth

$$B_{xy}(t) = \exp(-\frac{is_z\omega_r t}{\hbar}) B_v(0) \exp(\frac{is_z\omega_r t}{\hbar}) + \exp(-\frac{is_z\omega'_0 t}{\hbar}) B_p(0) \exp(\frac{is_z\omega'_0 t}{\hbar})$$

$$V_I(t) = -\frac{\mu B_v}{\hbar}[\exp\{\frac{is_z(\omega_0 - \omega_r)t - \delta}{\hbar}\} s_x \exp\{\frac{-is_z(\omega_0 - \omega_r)t + \delta}{\hbar}\}]$$
$$-\frac{\mu B_p}{\hbar}[\exp\{\frac{is_z(\omega_0 - \omega'_0)t}{\hbar}\} s_x \exp\{\frac{-is_z(\omega_0 - \omega'_0)t}{\hbar}\}]$$

ω_r : $E \times v/c^2$ rotation, $\omega'_0 = \omega_{129Xe}$, $\omega_0 = \omega_n$, δ: phase at $\pi/2$

$$\delta\omega = (\gamma_n^2 B_v B_p / 2t)[\{1/(\omega_0 - \omega_0') + 1/(\omega_0 - \omega_r)\}$$
$$\times \{1/(\omega_0' - \omega_r)\}\{\sin((\omega_0' - \omega_r)t - \delta) + \sin\delta\}$$
$$-(\gamma_n^2 B_v B_p / 2t)[\{1/(\omega_0 - \omega_0')\}\{1/(\omega_0 - \omega_r)\}$$
$$\times \{\sin((\omega_0 - \omega_r)t - \delta) + \sin((\omega_0 - \omega'_0)t + \delta)\}]$$

These oscillating term $< 10^{-28}$ e·cm

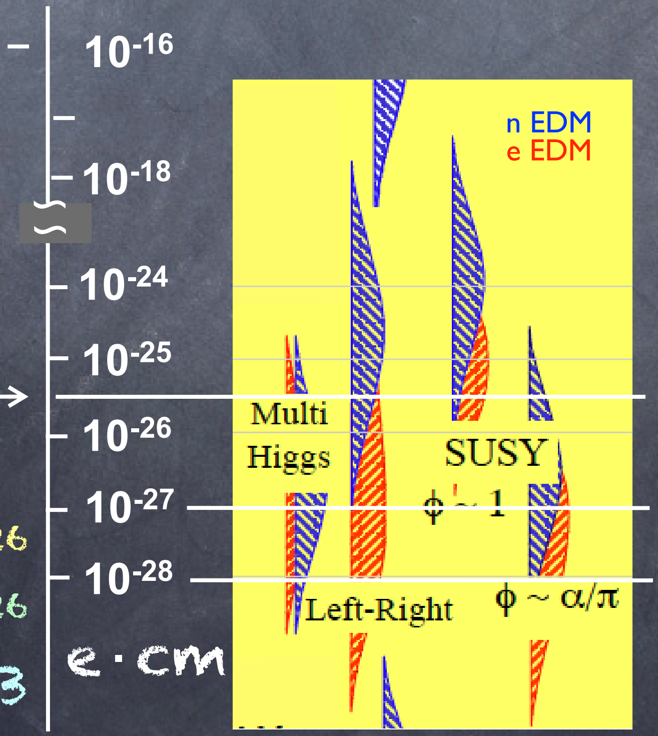
KEK-RCNP EDM measurement

magnetic field	magnetometer	EDM cell	UCN polarization	polarized UCN density
spherical coil Finemet	^{129}Xe comagnetometer	E_c = 90 neV	90%	600* UCN/cm^3

* 3000 UCN/cm^3 at TRIUMF

Earth's field ($\mu_n H_0 / E$)

EDM upper limit



statistical 1.5×10^{-26}
systematic 0.7×10^{-26}
related with B

statistical

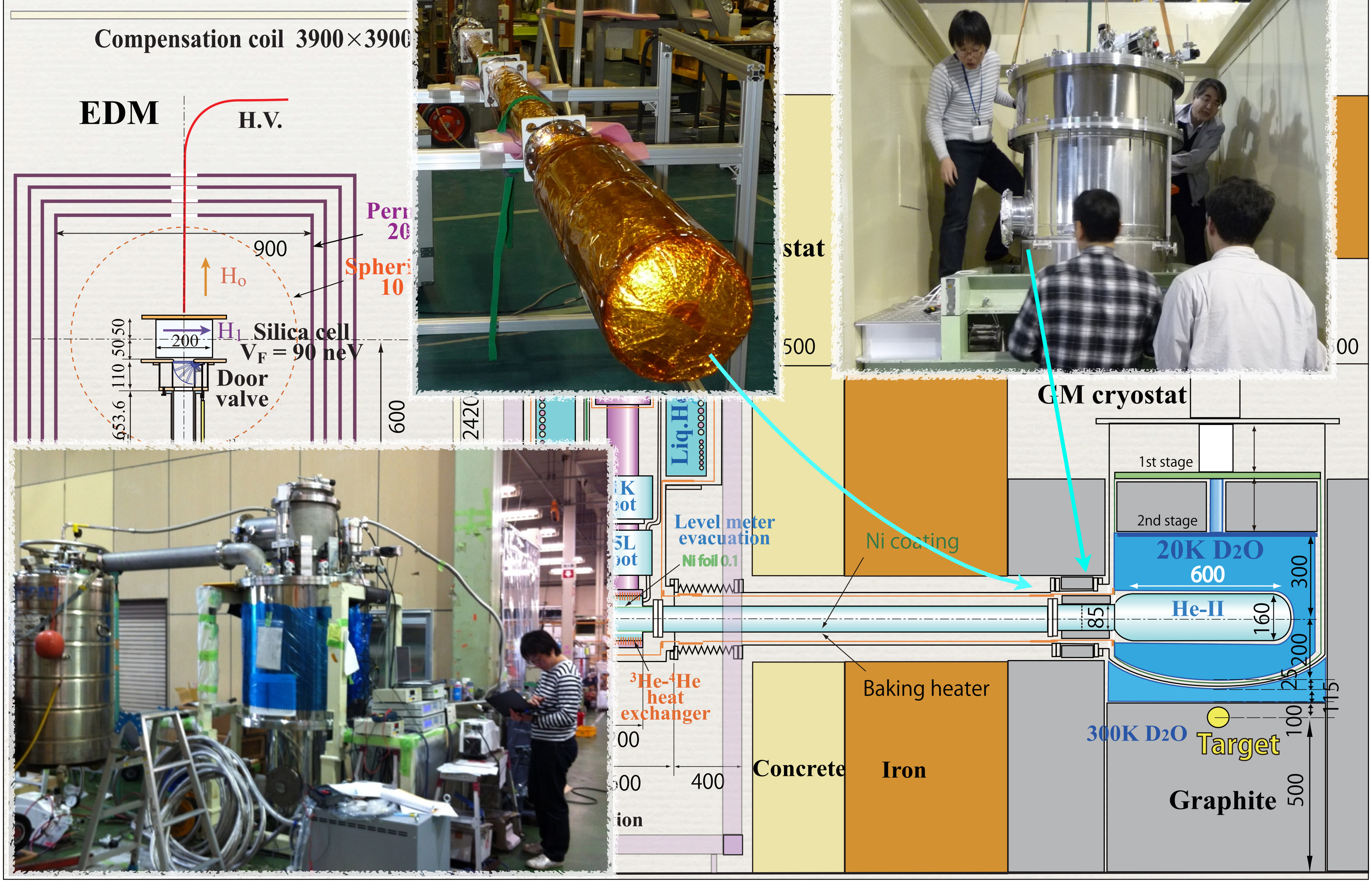
10^{-27} e·cm

10^{-28} e·cm

systematic

10^{-28} e·cm

We are constructing the apparatus



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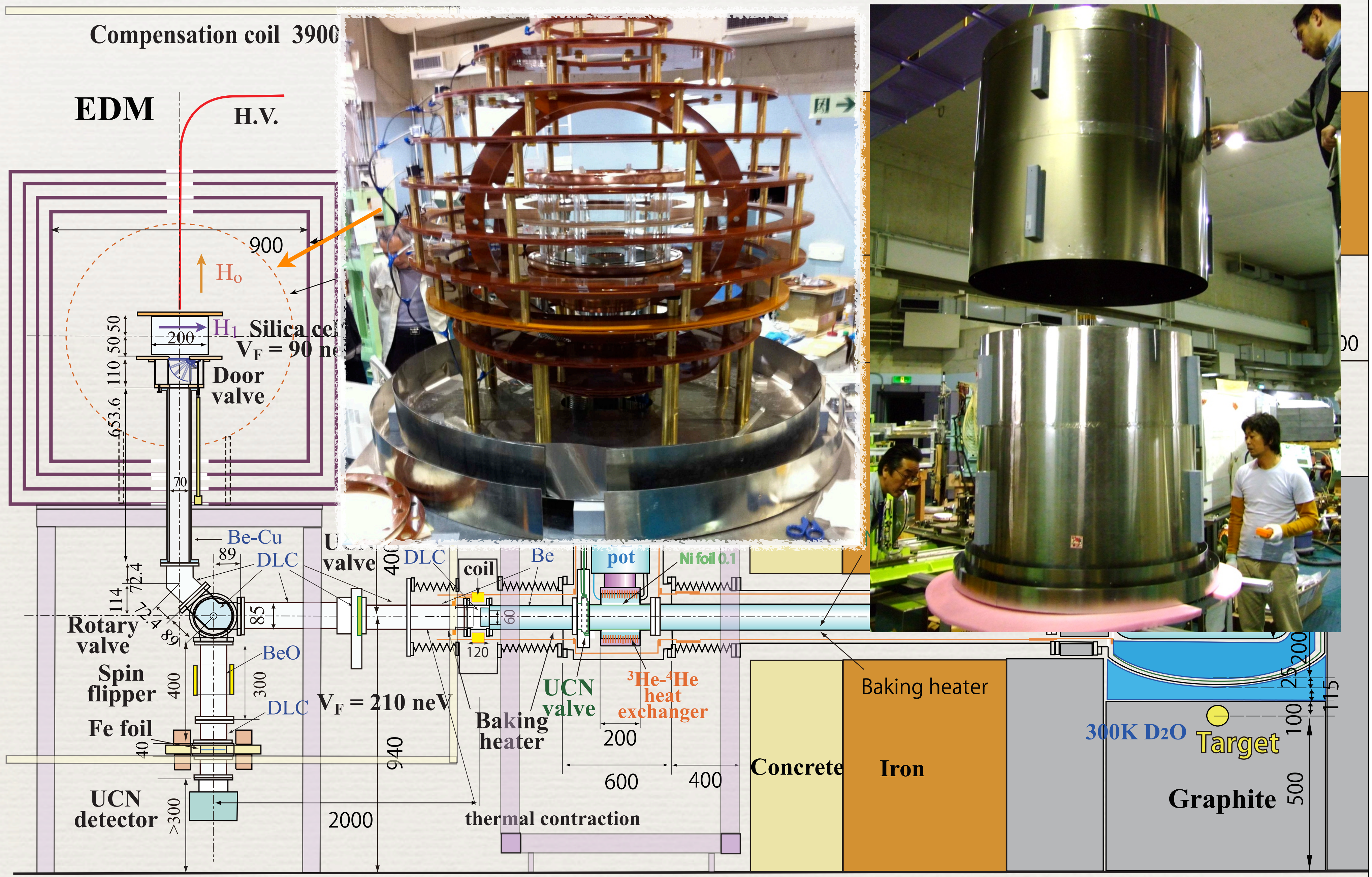

Thanks