原子にEDMを探す

Experimental search for EDM in a diamagnetic atom ^{129}Xe with spin oscillator technique

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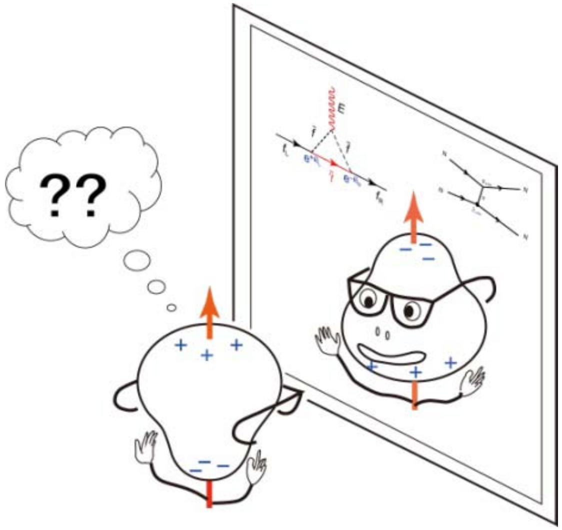
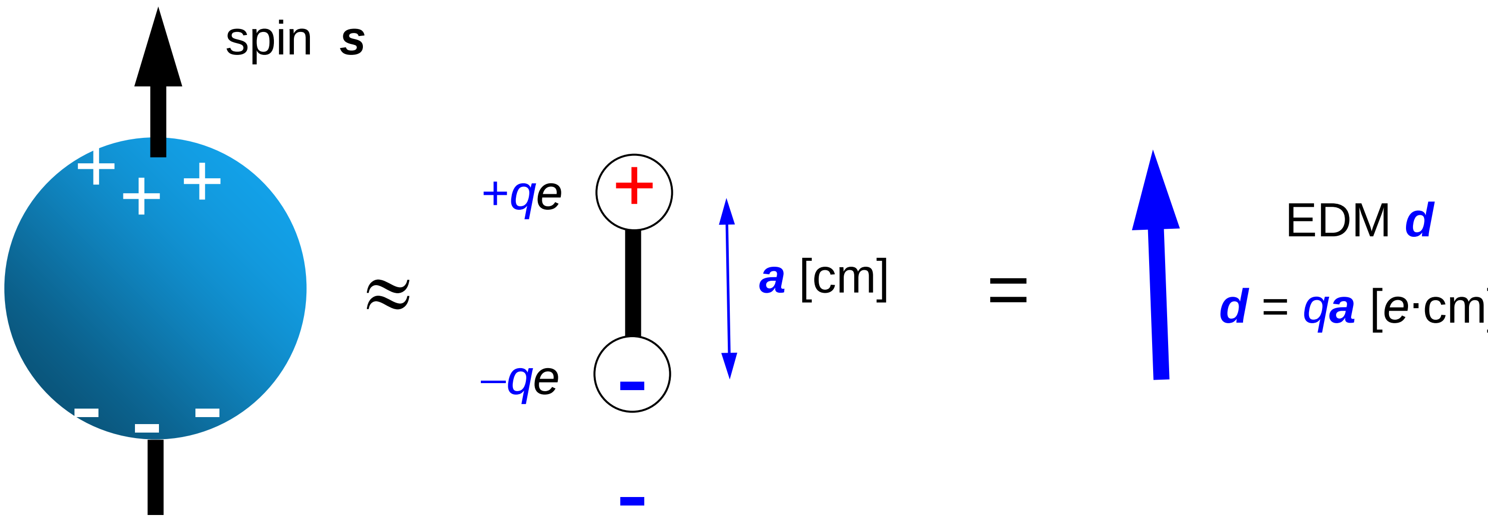
<u>OUTLINE</u>:

1. Why EDM?
2. "Optically coupled" spin oscillator
3. Present status
4. Summary



§ 1 Why EDM?



Neutral particle

or, $$\boldsymbol{d} = \int_{\text{particle}} \rho(\boldsymbol{r})\boldsymbol{r}\,\mathrm{d}^3\boldsymbol{r}$$

● Quantum mechanically, $\boldsymbol{d} \propto \boldsymbol{s}$

$$\boldsymbol{d} = d\,\frac{\boldsymbol{s}}{s}$$

● Field theoretically, its interaction is represented by:

$$\mathscr{L}_{\text{EDM}} = -\frac{i}{2} d\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

$$\mathscr{L}_{\mathrm{EDM}} = -\frac{i}{2} d\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

$$\sigma^{\mu\nu} \equiv \frac{\mathrm{i}}{2}\left[\gamma^{\mu},\gamma^{\nu}\right] = \mathrm{i}\left(\gamma^{\mu}\gamma^{\nu} - g^{\mu\nu}\right)$$

$$F_{\mu\nu} \equiv \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu} = \begin{pmatrix} 0 & E^x & E^y & E^z \\ -E^x & 0 & B^z & -B^y \\ -E^y & -B^z & 0 & B^x \\ -E^z & B^y & -B^x & 0 \end{pmatrix}$$

$$\sigma^{\mu\nu}F_{\mu\nu} = -2\mathrm{i}\left[\boldsymbol{E\sigma B\sigma}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} - \mathrm{i} \quad \cdot \quad \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\right]$$

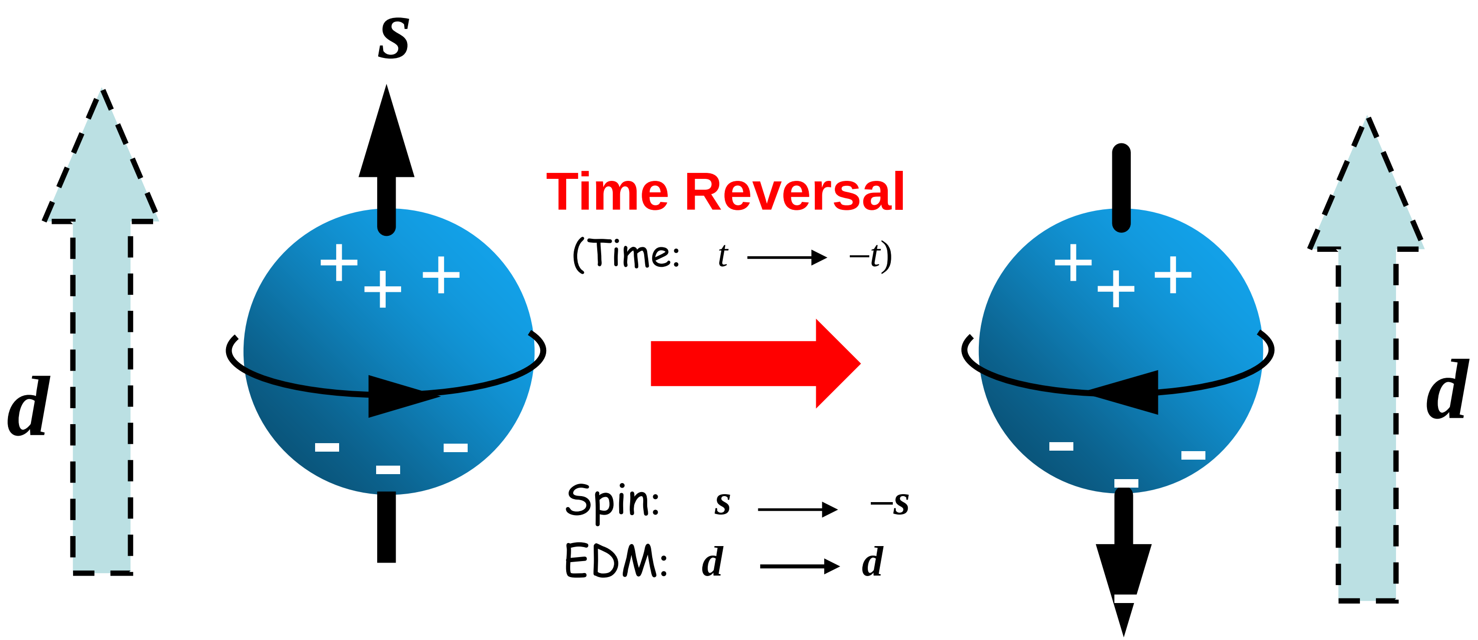
$$\sigma^{\mu\nu}F_{\mu\nu}\gamma_5 = -2\mathrm{i}\left[\boldsymbol{E\sigma B\sigma}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \mathrm{i} \quad \cdot \quad \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\right]$$

$$\psi = \sqrt{E+m}\begin{pmatrix} \phi^s \\ \dfrac{\boldsymbol{\sigma p}}{E+m}\phi^s \end{pmatrix} \rightarrow \sqrt{2E}\begin{pmatrix} \phi^s \\ 0 \end{pmatrix} \qquad (p/m \rightarrow 0)$$

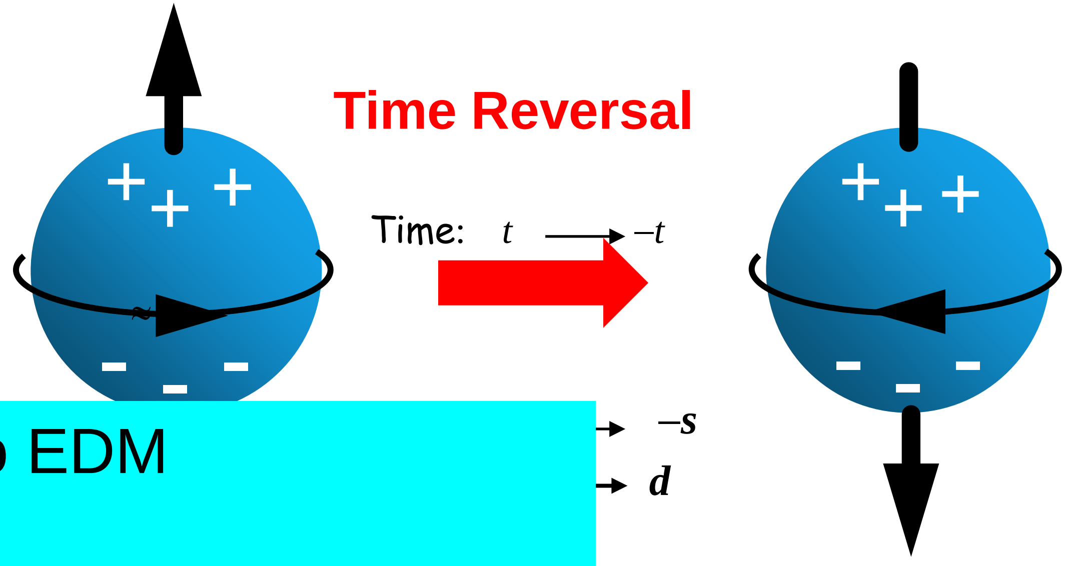
$$\therefore$$

$$\mathscr{L}_{\mathrm{EDM}} \rightarrow -d\boldsymbol{\sigma E} \quad \left(2E\phi^{s\dagger}\phi^s\right)$$

Transformation property of an EDM



Thus... EDM violates T, and hence CP (by CPT theorem)



Non-zero EDM

||

Evidence for an existence of New Physics

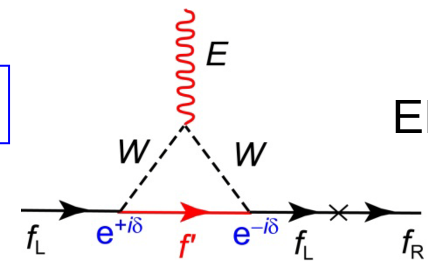
One-loop diagram for EDM

- Standard Model (SM)

  Predicts EDMs that are undetectably small

  -- 10^{-5} times the present limits.

SM

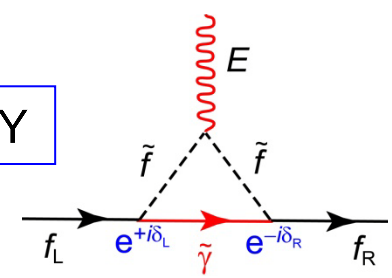


EDM = 0

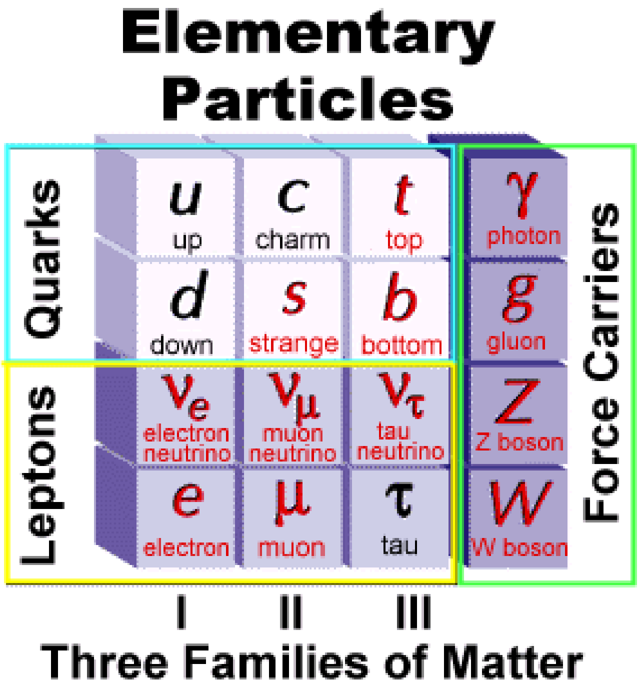
- Theories beyond the SM

  allow sizes of EDM to be reachable with “a-step-forward” experiments

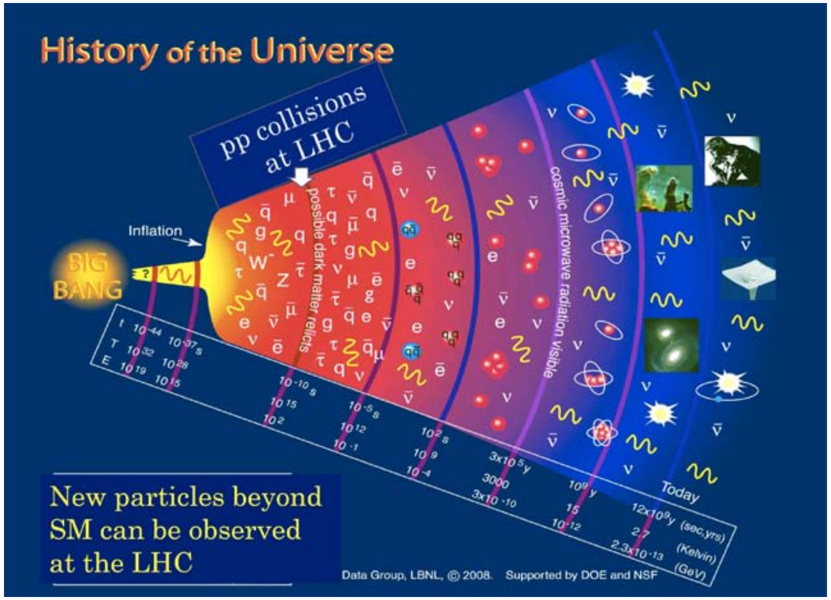
(e.g.) SUSY



Standard Model



Big Bang in Cosmology

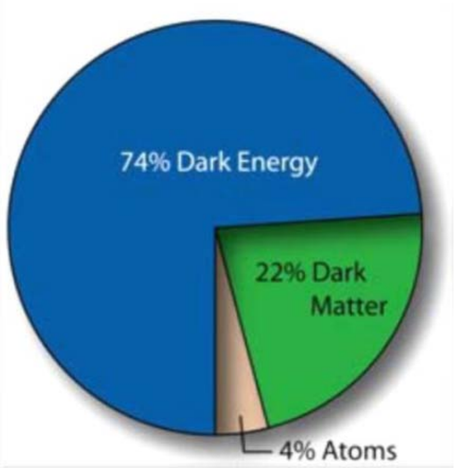


But … we know today that

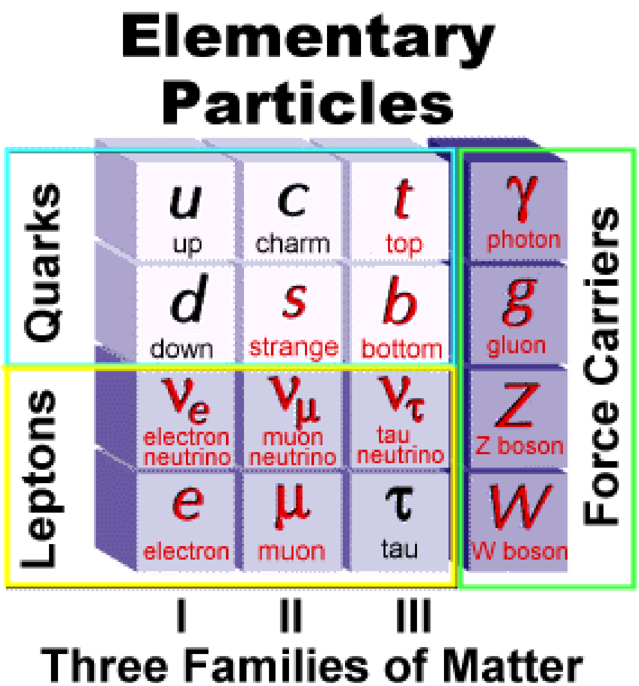
- SM particles share only 4.5 % of the Universe's energy content !

The rest are

- Dark energy 73 %
- Dark matter 22 %



Standard Model



Even further, ….
Formation of matter in the Universe
--- A Puzzle

- CP violation within the SM is too small to explain the predominance of matter over antimatter

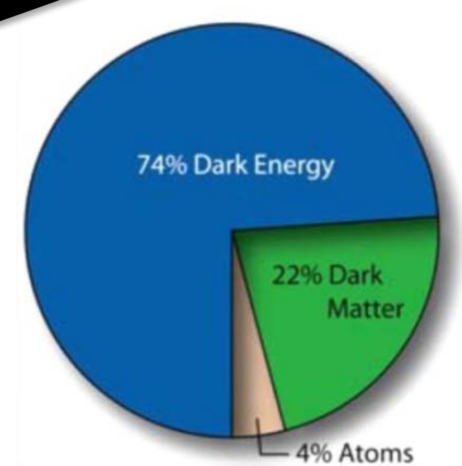
- Extra CP violation is needed !

EDM is an exclusively excellent
<u>NEW PHYSICS indicator</u>,
free from the SM “background”

But … we know today that

- SM particles share only 4.5 %
of the Universe’s energy content !

The rest are
- Dark energy 73 %
- Dark matter 22 %



CP violation in the Standard Model

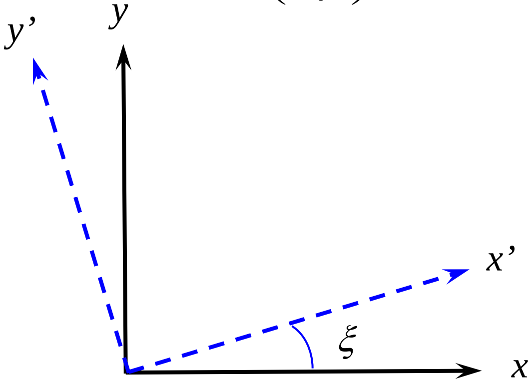
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{13}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{13}} & c_{13}c_{23} \end{pmatrix}$$

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

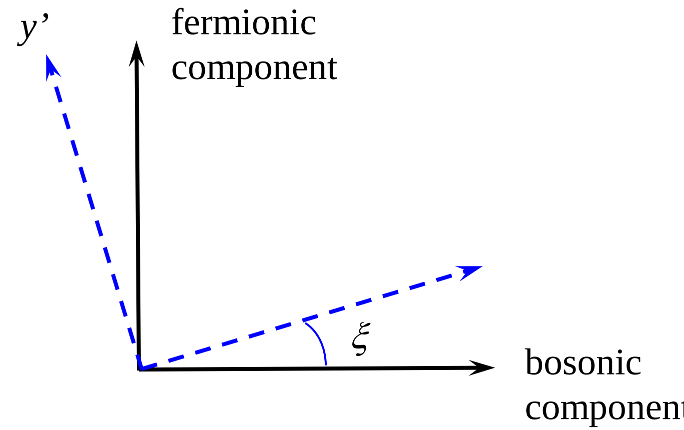
Rotation symmetry

$$\begin{pmatrix} A_x' \\ A_y' \end{pmatrix} = \begin{pmatrix} 1 & \xi \\ -\xi & 1 \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix}$$

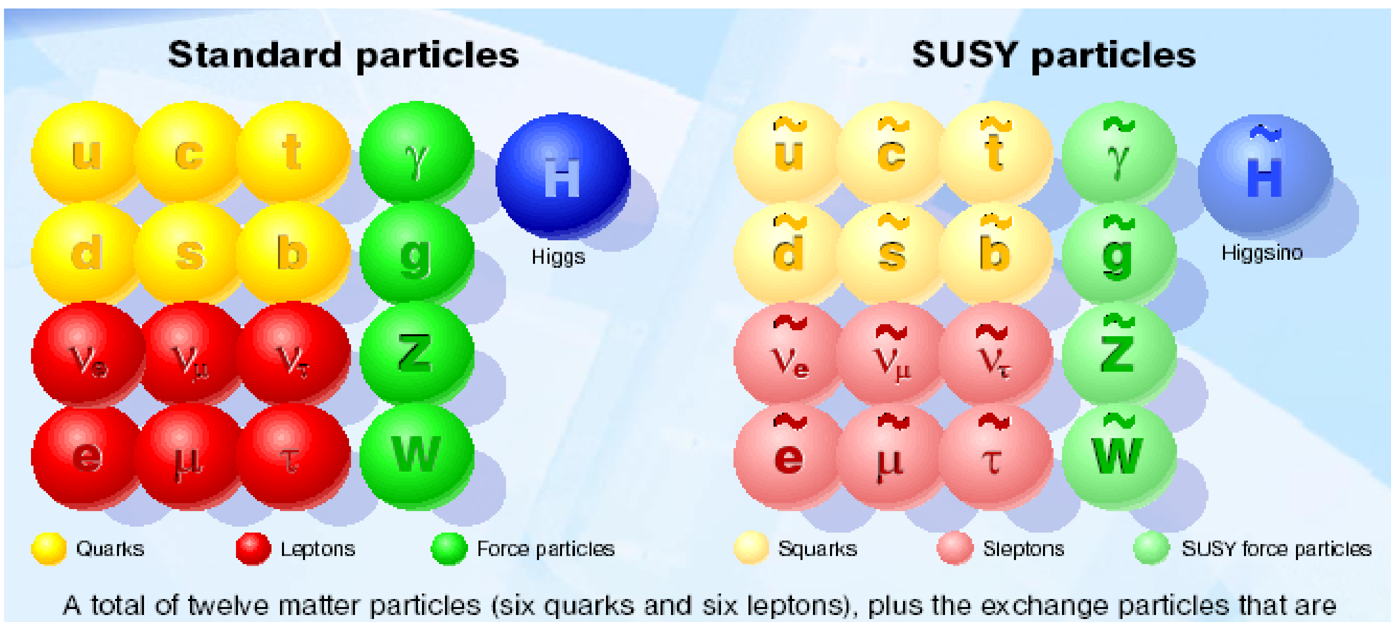


Supersymmetry

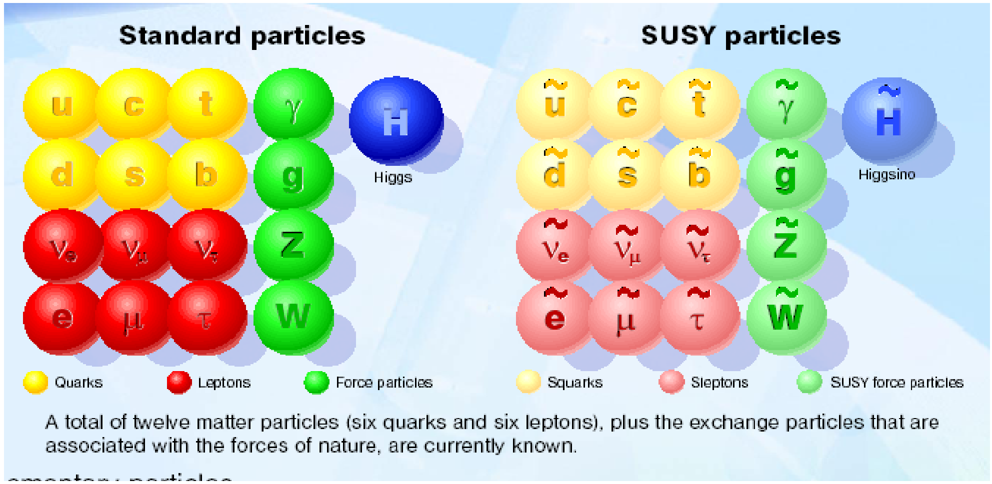
$$\begin{pmatrix} \phi'(x) \\ \chi'(x) \end{pmatrix} = \begin{pmatrix} 1 & \xi \cdot \\ -i\sigma^{\mu} i\sigma_2 \xi^* \partial_{\mu} & 1 \end{pmatrix} \begin{pmatrix} \phi(x) \\ \chi(x) \end{pmatrix}$$



Minimal Supersymmetric Standard Model (MSSM)

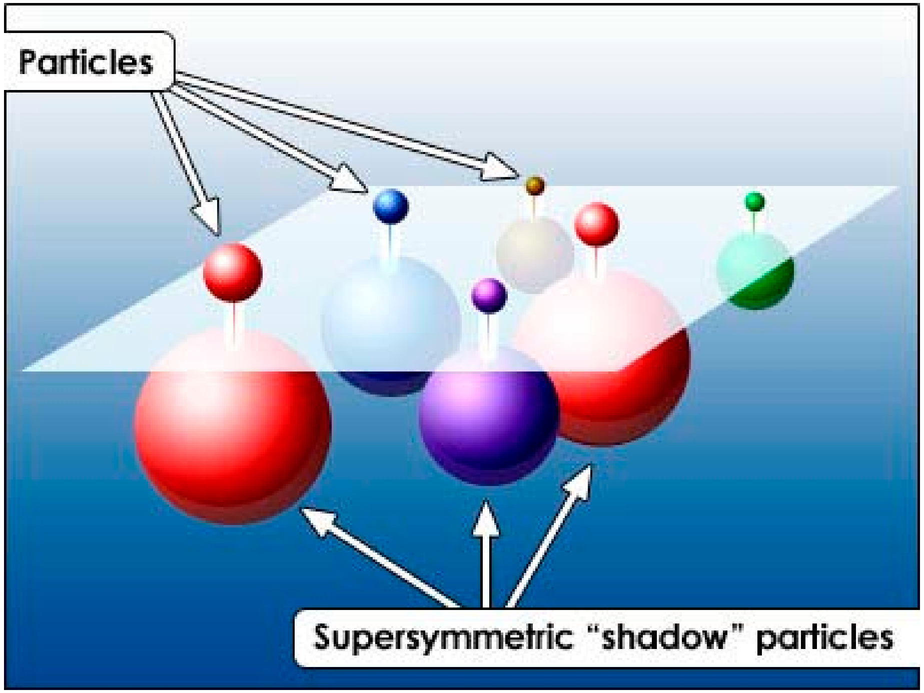


●低エネルギー(E < 100 GeV)(我々の世界)ではSUSYは見掛け上破れている！



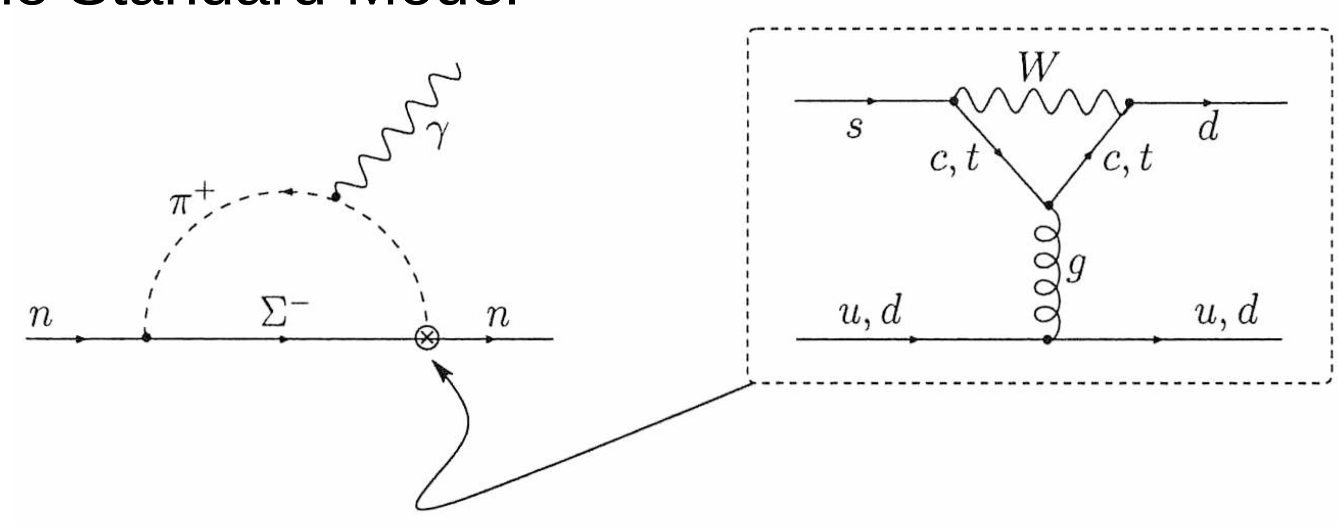
Minimal Supersymmetric Standard Model (MSSM)

ー低エネルギーでの現実の粒子である標準理論の粒子はそれぞれ、自分よりずっと重くて現実には見えない超対称パートナー粒子の影を引きずりながら存在する。

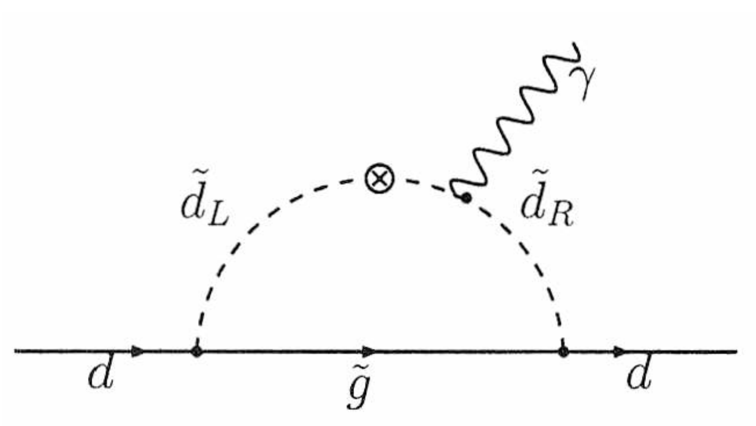


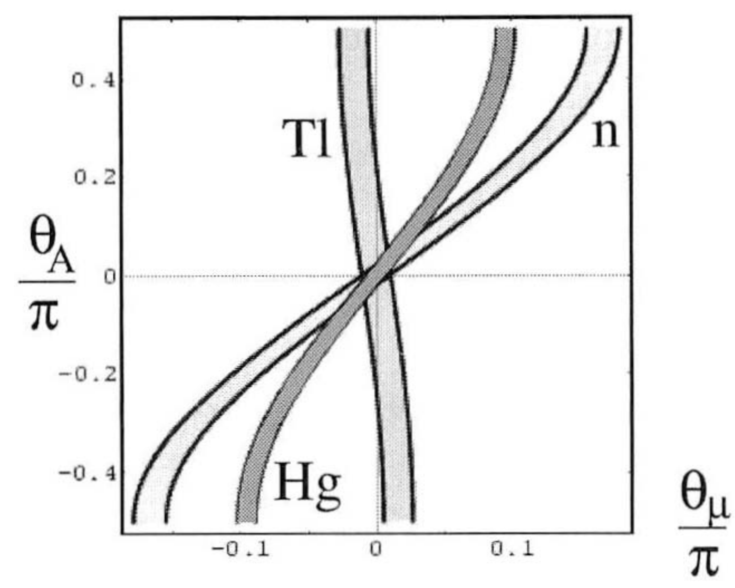
From: CERN Webpage

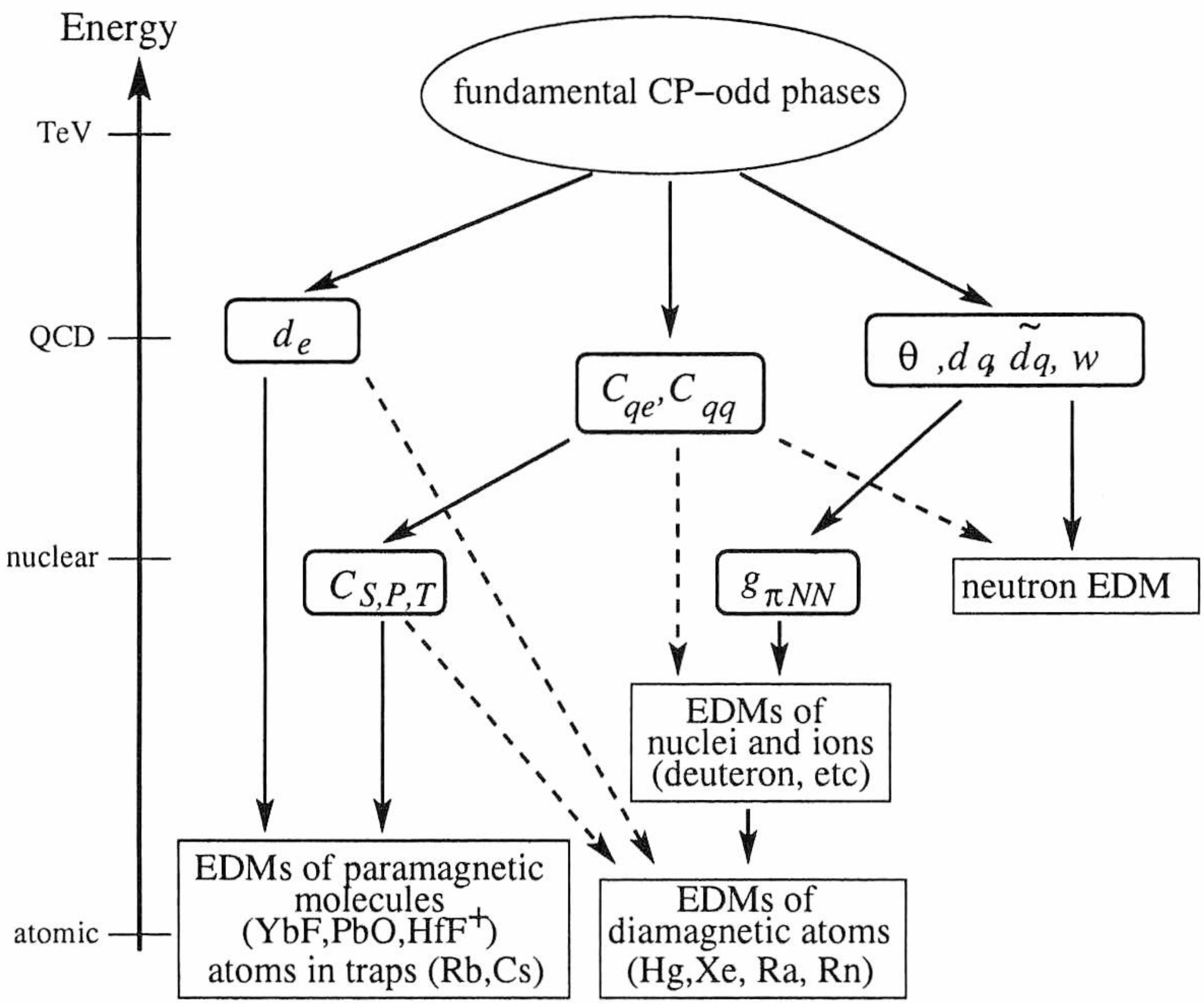
EDM in the Standard Model



EDM in the MSSM







Energy
TeV
QCD
nuclear
atomic
fundamental CP–odd phases
d_e
C_{qe}, C_{qq}
θ , d_q, $\tilde{d}_q$, w
$C_{S,P,T}$
$g_{\pi NN}$
neutron EDM
EDMs of nuclei and ions (deuteron, etc)
EDMs of paramagnetic molecules (YbF,PbO,HfF^+) atoms in traps (Rb,Cs)
EDMs of diamagnetic atoms (Hg,Xe, Ra, Rn)

Sites of EDM searches

- neutron — d_n
- paramagnetic atoms (Tl, Fr, Cs, ...) — d_e
- diamagnetic atoms (^{129}Xe, ^{199}Hg, Rn, Ra, ...) — S_{nucl}
- molecules (TlF, YbF, PbO, ThO, ...) — d_e
- charged particles (μ, p, d, ions, ...) — d_μ, d_p, d_d, d_{nucl}, … d_D

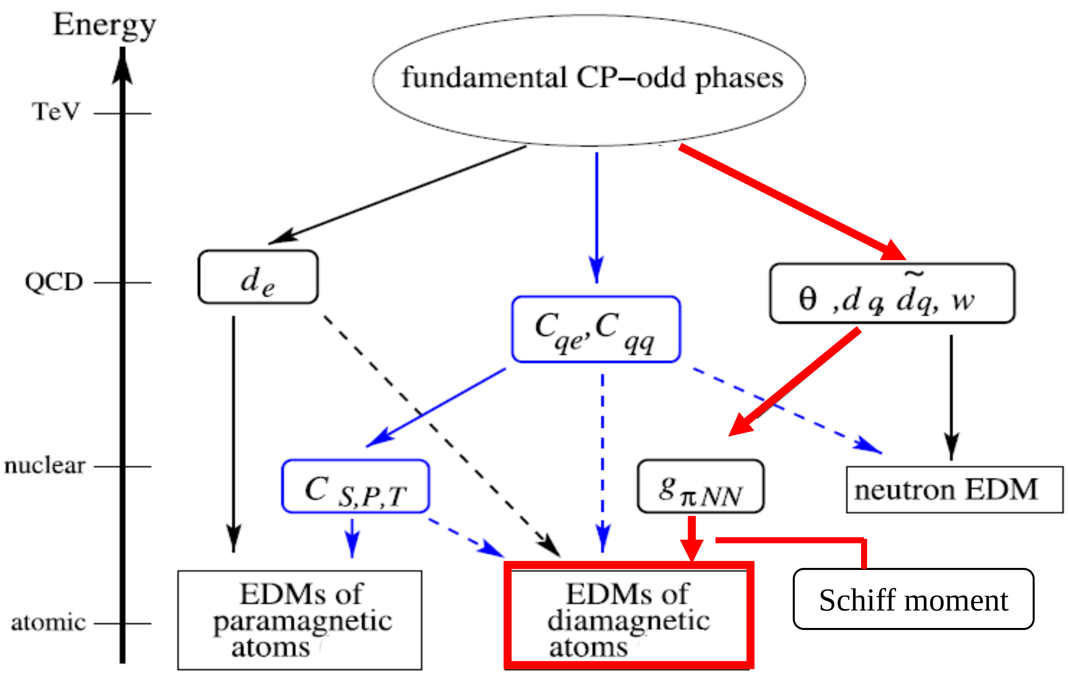
KEK-RCNP

J-PARC/Muon

CYRIC, Tohoku U

The present talk

M. Pospelov and A. Ritz,
Annals of Phys. 318, (2005) 119-169



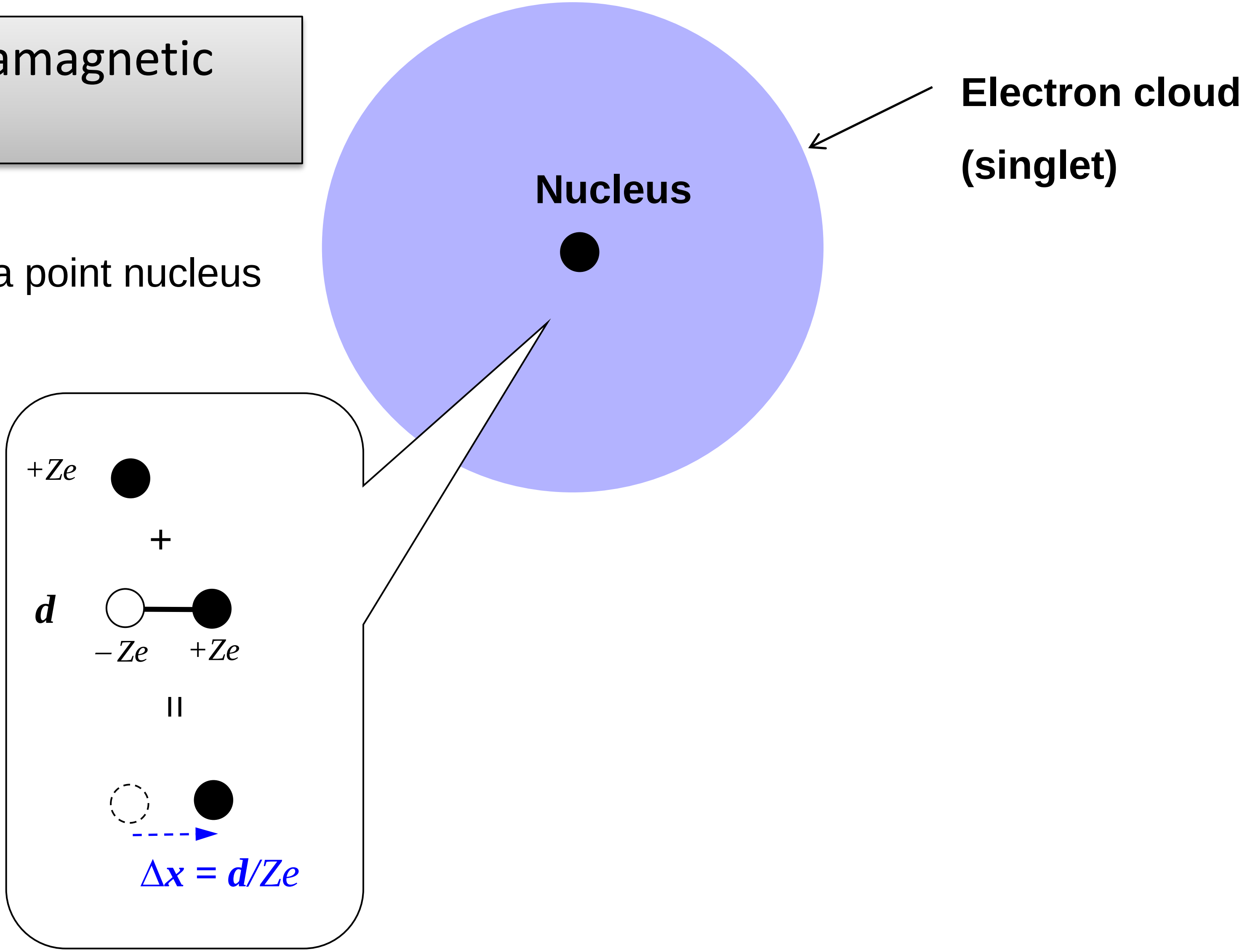
Tl, Fr, Cs… ^{129}Xe, ^{199}Hg, Rn, Ra…

EDM in a ^{129}Xe atom

- stable particle
- macroscopic number of particles
- EDM generated by a nuclear Schiff moment
- P,T-violating NN interaction

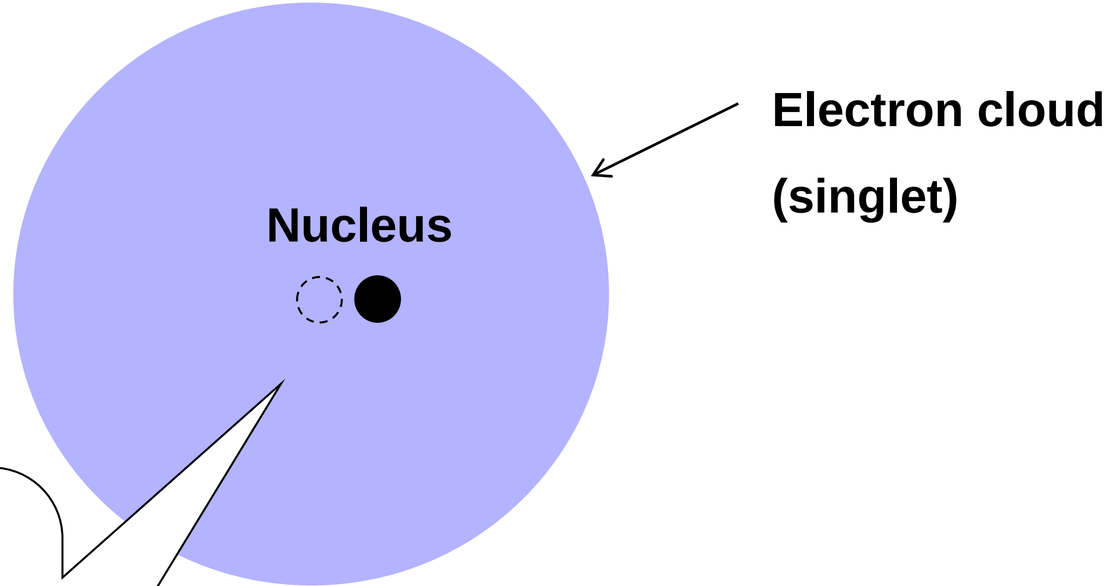
In a diamagnetic atom

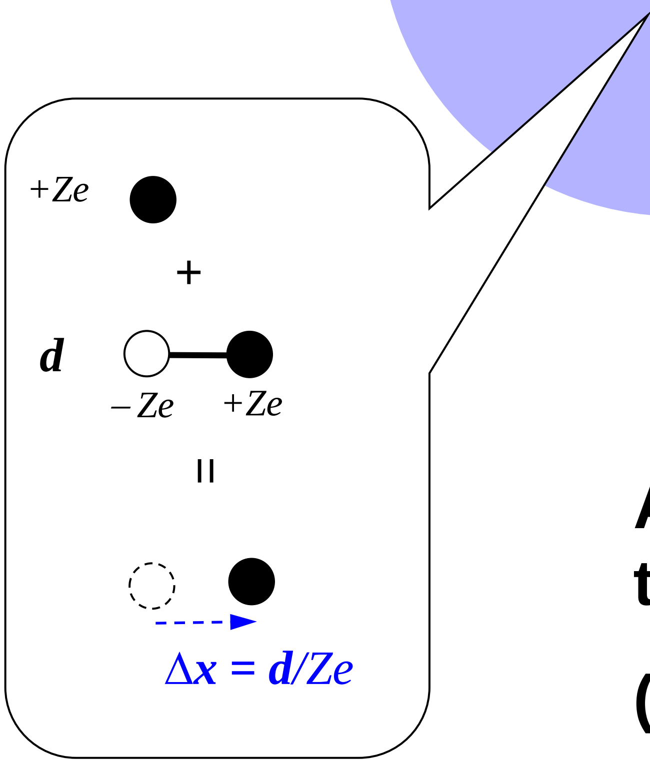
(1) For a point nucleus



In a diamagnetic atom

(1) For a point nucleus



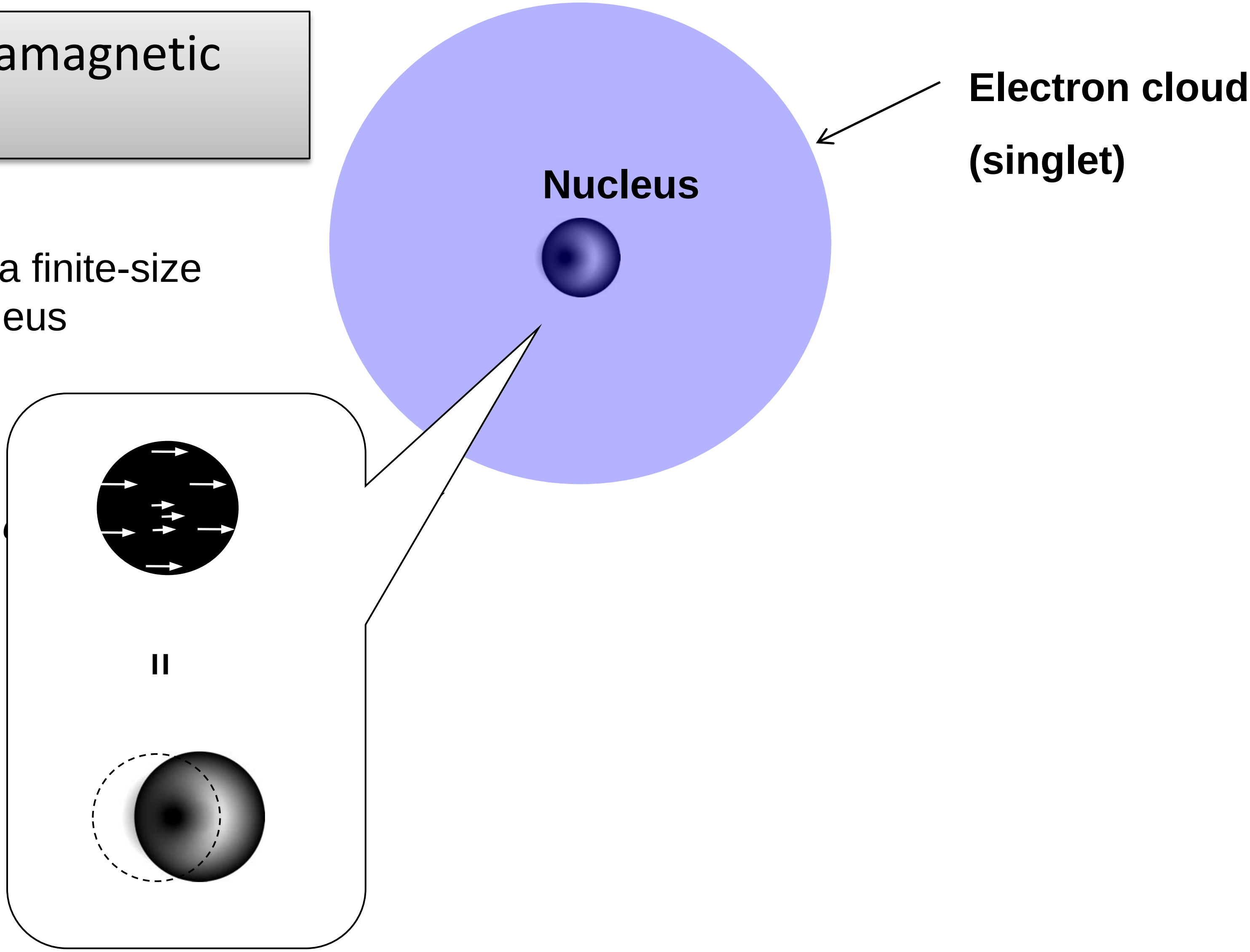


Atomic electrons <u>do not "know"</u> that the nucleus has EDM.

(Schiff’s theorem)

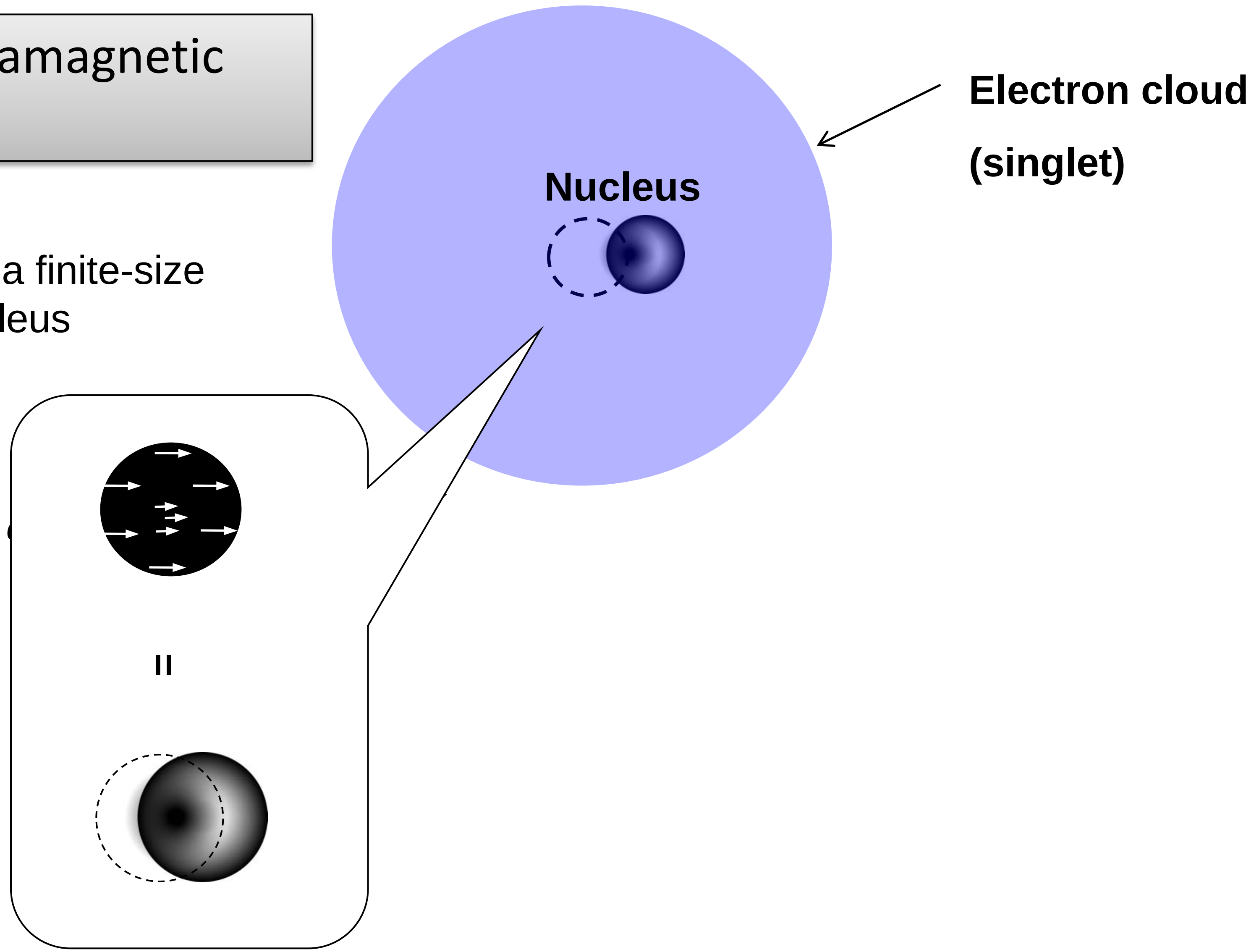
In a diamagnetic atom

(2) For a finite-size nucleus



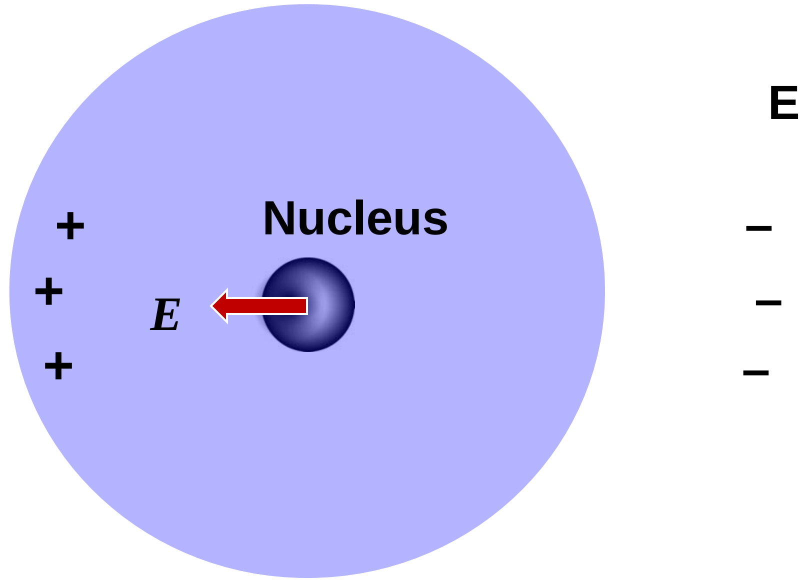
In a diamagnetic atom

(2) For a finite-size nucleus



In a diamagnetic atom

(2) For a finite-size nucleus



Electron cloud

$\boldsymbol{d}_{\text{atom}} \neq 0$

Nontrivial charge distribution in the nucleus generates an EDM in atom:

$$\boldsymbol{d}_{\text{atom}} = \langle \tilde{0} | \hat{\tilde{\boldsymbol{D}}} | \tilde{0} \rangle \qquad \text{where } \boldsymbol{D} = -e \sum_i \boldsymbol{R}_i, \quad |\tilde{0}\rangle \approx |0\rangle + \sum_P \frac{\langle P | -e\varphi_{\text{Schiff}} | 0 \rangle}{E_0 - E_P} |P\rangle$$

$$\approx 2 \sum_P \frac{\langle 0 | \hat{\boldsymbol{D}} | P \rangle \langle P | -e\varphi_{\text{Schiff}} | 0 \rangle}{E_0 - E_P}$$

$$\varphi_{\text{Schiff}} = 4\pi \hat{\boldsymbol{S}} \cdot \nabla \delta(\boldsymbol{R})$$

$$\hat{\boldsymbol{S}} \equiv \frac{1}{10} \left[\int_{\text{nucleus}} \rho(\boldsymbol{r}) \boldsymbol{r} \left(r^2 - \frac{5}{3} \langle r^2 \rangle \right) \mathrm{d}^3 \boldsymbol{r} \right]$$

Schiff moment

●Schiff moment from fundamental sources of CPV

Nuclear structure

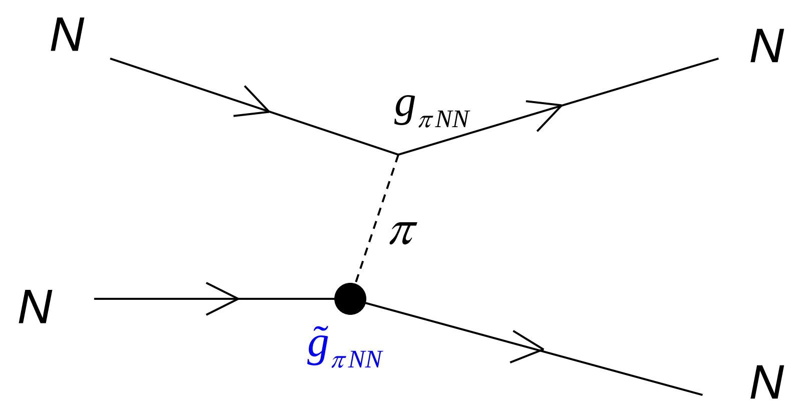
$$\boldsymbol{S} = \left\langle \Psi_{\mathrm{Nucl}} \middle| \hat{\boldsymbol{S}} \middle| \Psi_{\mathrm{Nucl}} \right\rangle$$

where $\Psi_{\mathrm{Nucl}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots, \boldsymbol{r}_A)$ is a solution for the Schroedinger equation

$$\left[\frac{\boldsymbol{p}_k^{\,2}}{2m} + \sum_{j<k}^{A} V(\boldsymbol{r}_j, \boldsymbol{r}_k) \right] \Psi_{\mathrm{Nucl}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots, \boldsymbol{r}_A) = E_0 \Psi_{\mathrm{Nucl}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots, \boldsymbol{r}_A)$$

If $V_{\mathrm{PT}} = 0$, then $S = 0$

Non−zero S is induced by V_{PT}



P-,T-violating pion-mediated NN interaction

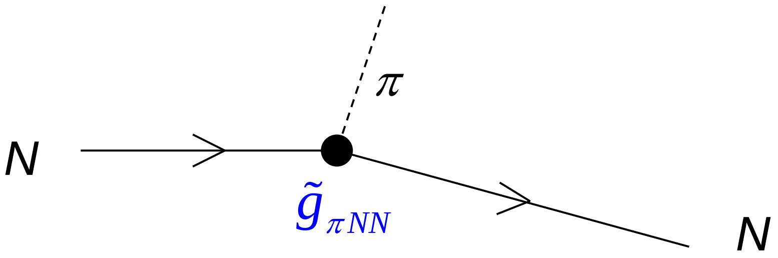
$$V_{\mathrm{PT}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) = -\frac{g m_\pi^{\,2}}{8\pi m_{\mathrm{N}}} \Big\{ (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot(\boldsymbol{r}_1 - \boldsymbol{r}_2) \Big[\bar{g}^{(0)}_{\pi NN} \vec{\tau}_1 \cdot \vec{\tau}_2 - \frac{1}{2} \bar{g}^{(1)}_{\pi NN} (\tau_{1z} + \tau_{2z}) + \bar{g}^{(2)}_{\pi NN} (3\tau_{1z}\tau_{2z} - \vec{\tau}_1 \cdot \vec{\tau}_2) \Big]$$
$$- \frac{1}{2} \bar{g}^{(1)}_{\pi NN} (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\boldsymbol{r}_1 - \boldsymbol{r}_2)(\tau_{1z} - \tau_{2z}) \Big\} \frac{e^{-m_\pi |\boldsymbol{r}_1 - \boldsymbol{r}_2|}}{m_\pi |\boldsymbol{r}_1 - \boldsymbol{r}_2|^2} \left(1 + \frac{1}{m_\pi |\boldsymbol{r}_1 - \boldsymbol{r}_2|} \right)$$

CP-violating effective Lagrangian for the strong interactions of light quarks (up to those of dimension 5):

e.g. [Hisano & Shimizu, PRD70(04)093001]

$$\mathcal{L}_{\mathrm{CPV}} = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G} + \sum_{q=u,d,s}\frac{i}{2}\tilde{d}_q \bar{q} g_s (G\sigma)\gamma_5 q$$

New physics



$$\langle N\pi | i\mathcal{L}_{\mathrm{CPV}} | N \rangle$$

- PCAC
- QCD sun rule
- Baryon mass spectrum

…..

$$\mathcal{L}_{\mathrm{CPV}}^{\pi NN} = \bar{g}^{(0)}_{\pi NN}\bar{N}\tau^a N\pi^a + \bar{g}^{(1)}_{\pi NN}\bar{N}N\pi^0 + \bar{g}^{(2)}_{\pi NN}\left(\bar{N}\tau^a N\pi^a - 3\bar{N}\tau^3 N\pi^0\right)$$

where

$$\bar{g}^{(0)}_{\pi NN} \propto \left(\tilde{d}_u + \tilde{d}_d\right)$$

$$\bar{g}^{(1)}_{\pi NN} \propto \left(\tilde{d}_u - \tilde{d}_d\right)$$

$$\bar{g}^{(2)}_{\pi NN} = 0$$

●Case of ^{199}Hg

[Flambaum *et al.*, 1986]

$$S(^{199}\mathrm{Hg}) = -0.086 g_{\pi NN}\tilde{g}^{(0)}_{\pi NN} - 0.086 g_{\pi NN}\tilde{g}^{(1)}_{\pi NN} + 0.172 g_{\pi NN}\tilde{g}^{(2)}_{\pi NN} \quad e\ \mathrm{fm}^3$$

[Dmitriev *et al.*, 2003]

$$S(^{199}\mathrm{Hg}) = -0.0004 g_{\pi NN}\tilde{g}^{(0)}_{\pi NN} - 0.055 g_{\pi NN}\tilde{g}^{(1)}_{\pi NN} + 0.009 g_{\pi NN}\tilde{g}^{(2)}_{\pi NN} \quad e\ \mathrm{fm}^3$$

With SkO' interaction,
[de Jesus & Engel, 2005]

$$S(^{199}\mathrm{Hg}) = -0.0010 g_{\pi NN}\tilde{g}^{(0)}_{\pi NN} + 0.074 g_{\pi NN}\tilde{g}^{(1)}_{\pi NN} + 0.018 g_{\pi NN}\tilde{g}^{(2)}_{\pi NN} \quad e\ \mathrm{fm}^3$$

[Ban, Dobaczewski, Engel and Shukla. 2010]

$$S(^{199}\mathrm{Hg}) = 0.016 g_{\pi NN}\tilde{g}^{(0)}_{\pi NN} - 0.006 g_{\pi NN}\tilde{g}^{(1)}_{\pi NN} + 0.019 g_{\pi NN}\tilde{g}^{(2)}_{\pi NN} \quad e\ \mathrm{fm}^3$$

Hartree-Fock-Bogoliubov calc. with SLy4 interaction
modified to include CP-odd π-exch. *NN* int.

"The calculations presented here are more sophisticated and inclusive than any yet attempted, but it may very well be that still more sophistication is required."

● Case of ^{129}Xe

- Work by Flambaum, Khriplovich, Sushkov, 1985

- New calculation is strongly anticipated !

^{129}Xe *vs.* ^{199}Hg

Previous calculation [Flambaum, Khriplovich, Sushkov, 1985]

$$d(^{129}\mathrm{Xe}) = 6.7 \times 10^{-26}\ \eta\ e\mathrm{cm}$$

$$d(^{199}\mathrm{Hg}) = 4.0 \times 10^{-25}\ \eta\ e\mathrm{cm}$$

× 6

$$(d_{\mathrm{n}} = -5 \times 10^{-23}\ \eta\ e\mathrm{cm})$$

But, ….

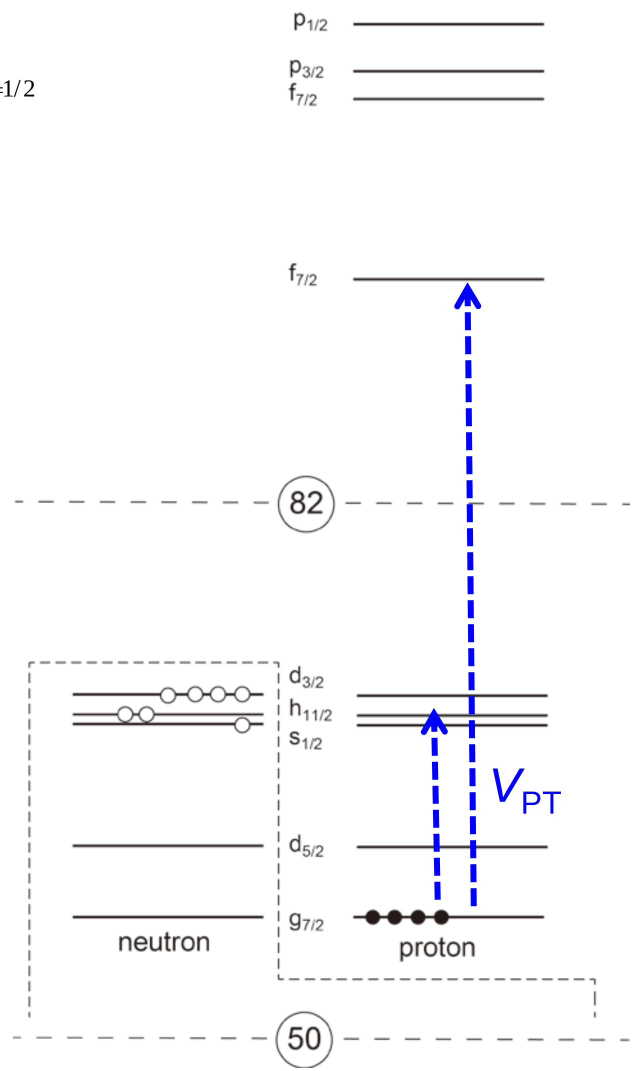
●Case of ^{129}Xe (nuclear structure consideration)

A simple-minded g.s. wave function:

$$\left| {}^{129}\mathrm{Xe},\ 1/2^+ \right\rangle \approx \left| \nu\left(\left(\mathrm{d}_{3/2}{}^{-4}\right)^{0^+} \left(\mathrm{h}_{11/2}{}^{-2}\right)^{0^+} \mathrm{s}_{1/2}{}^{-1} \right)^{1/2^+} \otimes \pi\left(\mathrm{g}_{7/2}{}^{4}\right)^{0^+} \right\rangle^{J=1/2}$$

$$S = \sum_i \frac{\langle \mathrm{g.s.} | \hat{S}_z | i \rangle \langle i | \hat{V}_{\mathrm{PT}} | g.s. \rangle}{E_{g.s.} - E_i}$$

$$\hat{S}_z \equiv \frac{1}{10} e \left(r_{\mathrm{p}}{}^2 z_{\mathrm{p}} - \frac{5}{3} \left\langle r^2 \right\rangle_{\mathrm{ch}} z_{\mathrm{p}} \right)$$



^{129}Xe (Z=54, N=75)

●Case of ^{129}Xe (nuclear structure consideration)

A simple-minded g.s. wave function:

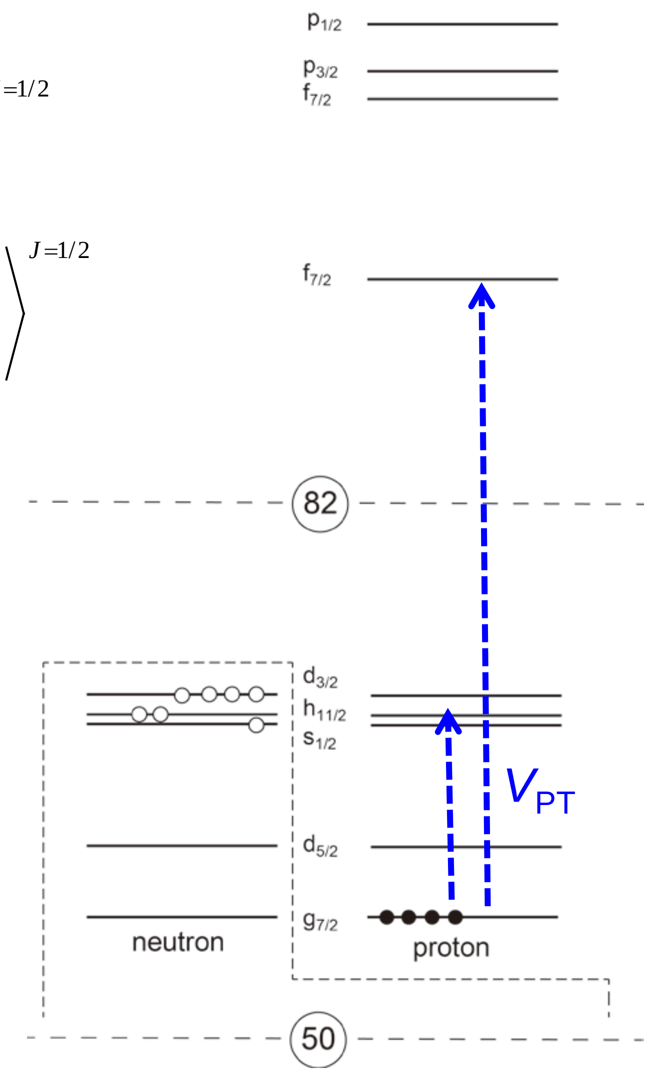
$$\left|{}^{129}\mathrm{Xe},\ 1/2^{+}\right\rangle \approx \left|\nu\left(\left(\mathrm{d}_{3/2}{}^{-4}\right)^{0^+}\left(\mathrm{h}_{11/2}{}^{-2}\right)^{0^+}\mathrm{s}_{1/2}{}^{-1}\right)^{1/2^+}\otimes\pi\left(\mathrm{g}_{7/2}{}^{4}\right)^{0^+}\right\rangle^{J=1/2}$$

$$+\alpha\left|\nu\left(\left(\mathrm{d}_{3/2}{}^{-4}\right)^{0^+}\left(\mathrm{h}_{11/2}{}^{-2}\right)^{2^+}\mathrm{s}_{1/2}{}^{-1}\right)^{3/2^+}\otimes\pi\left(\mathrm{g}_{7/2}{}^{4}\right)^{2^+}\right\rangle^{J=1/2}$$

$$+\ (\text{others} \ldots.)$$

$$S = \sum_i \frac{\langle \mathrm{g.s.}|\hat{S}_z|i\rangle\langle i|\hat{V}_{\mathrm{PT}}|g.s.\rangle}{E_{g.s.} - E_i}$$

$$\hat{S}_z \equiv \frac{1}{10}e\left(r_{\mathrm{p}}{}^2 z_{\mathrm{p}} - \frac{5}{3}\left\langle r^2\right\rangle_{\mathrm{ch}} z_{\mathrm{p}}\right)$$

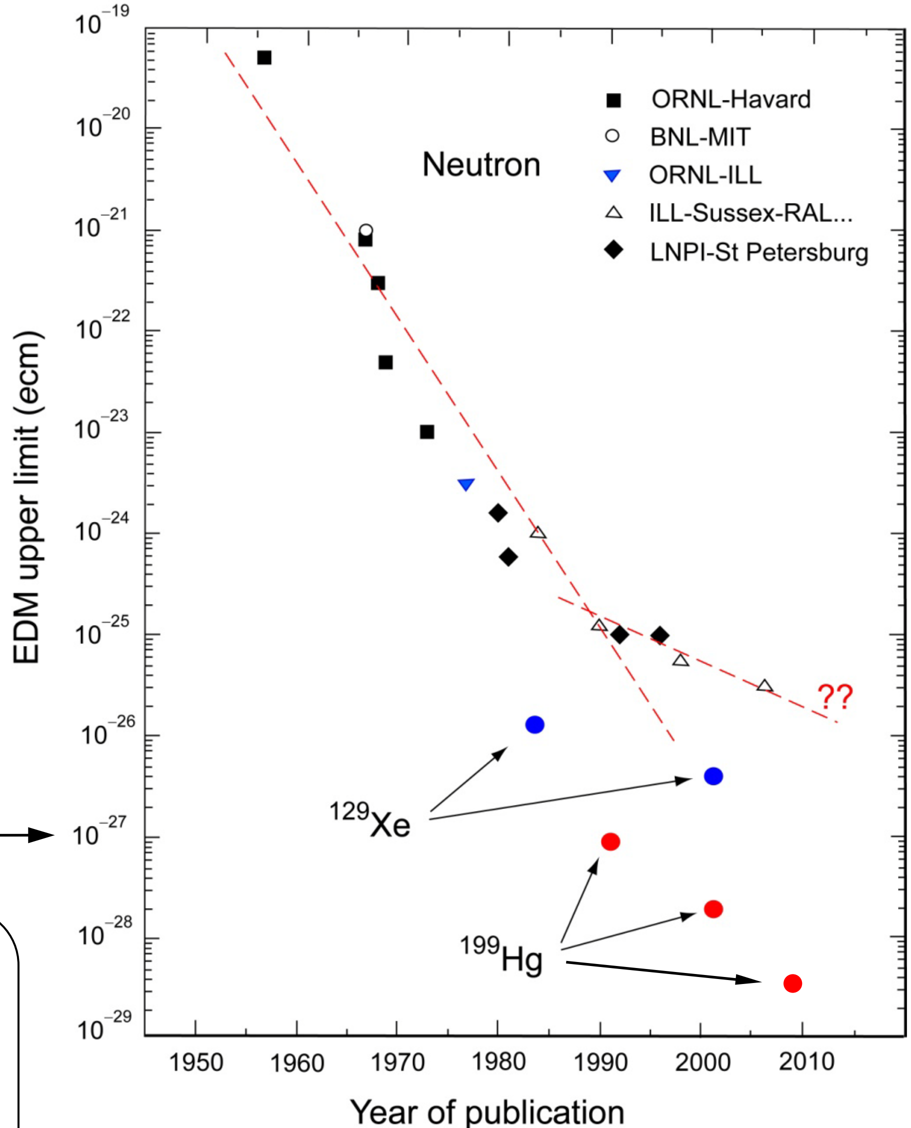


^{129}Xe (Z=54, N=75)

●Shell-model calculation of the ^{129}Xe Schiff moment is presently under way, by N. Yoshinaga and co-workers (Saitama U.)

$d = 10^{-27}$ $e\cdot$cm
$E = 10$ kV/cm

$\Delta\nu = 10$ nHz
($\Delta\omega \approx 1^\circ$ /day)



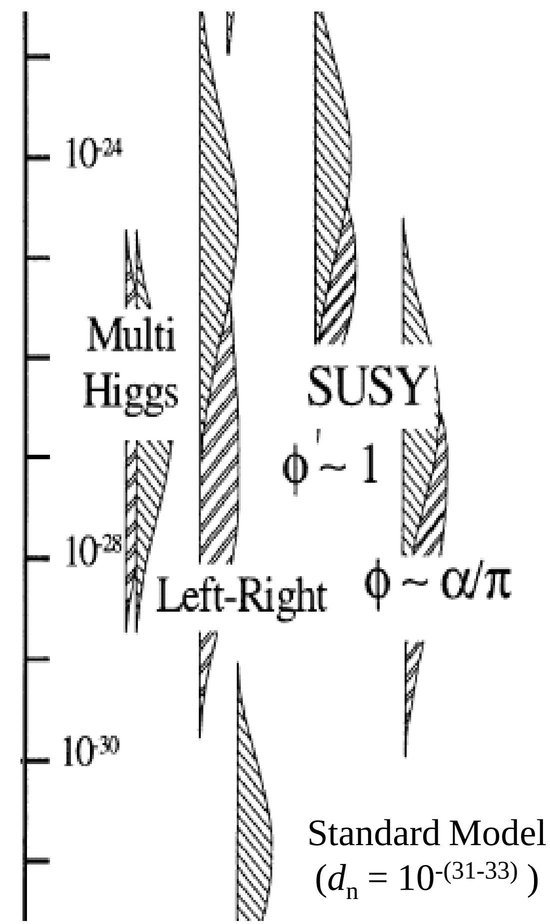
● $d(^{199}Hg) < 3.1 \times 10^{-29}$ $e$cm

Grifith *et al.*, *PRL* **102** (2009) 101601

● $d(^{129}Xe) < 4.1 \times 10^{-27}$ $e$cm

Rosenberry and Chupp, *PRL* **86** (2001) 22

Neutron EDM predicted values



[Pendlebury and Hinds, *NIM* A **440** (00) 471]

Natural size of an EDM

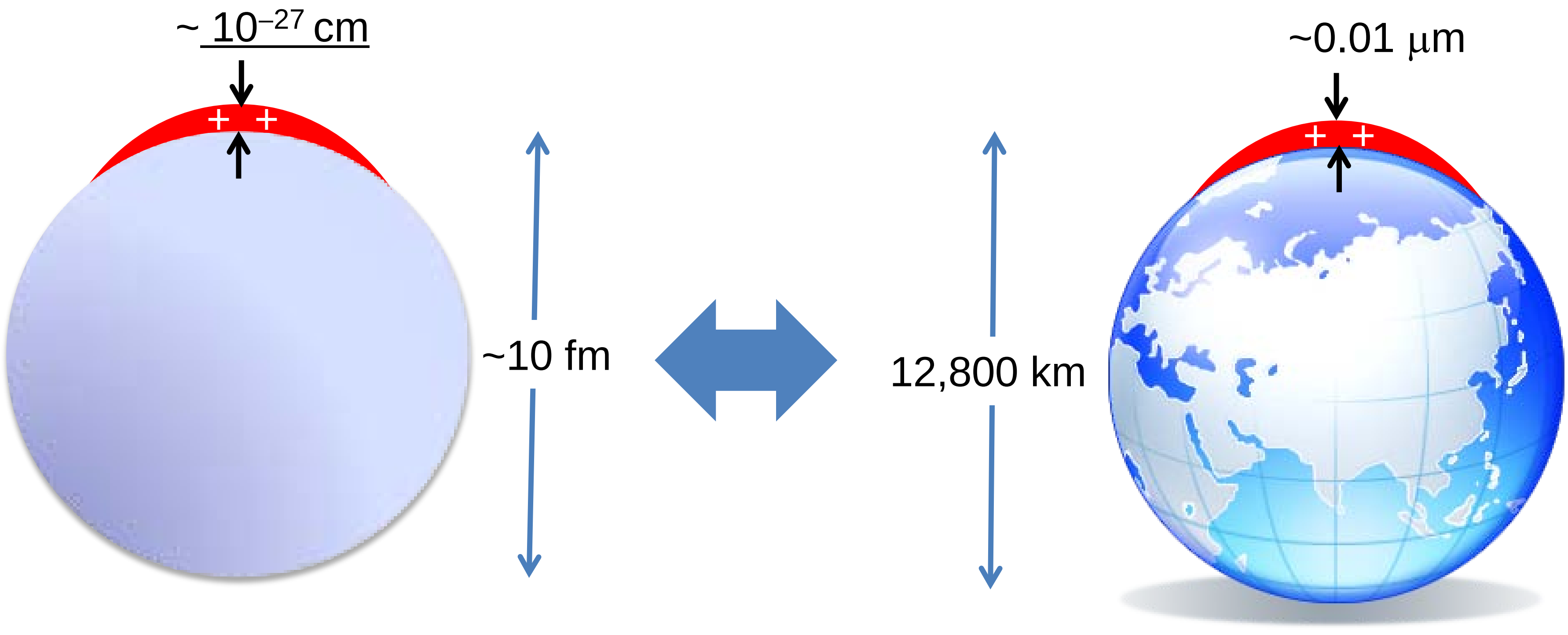
$$d \sim e\cdot[\text{distance}]\cdot[\text{weak force}]\cdot[\text{CP}]$$

$$\sim e\cdot 10^{-13}\ \text{cm} \quad\cdot\quad 10^{-7} \quad\cdot\ 10^{-3}$$

$$\sim 10^{-23}\ e\cdot\text{cm}\ (?)$$

$$d_n < 10^{-26}\ e\cdot\text{cm}$$

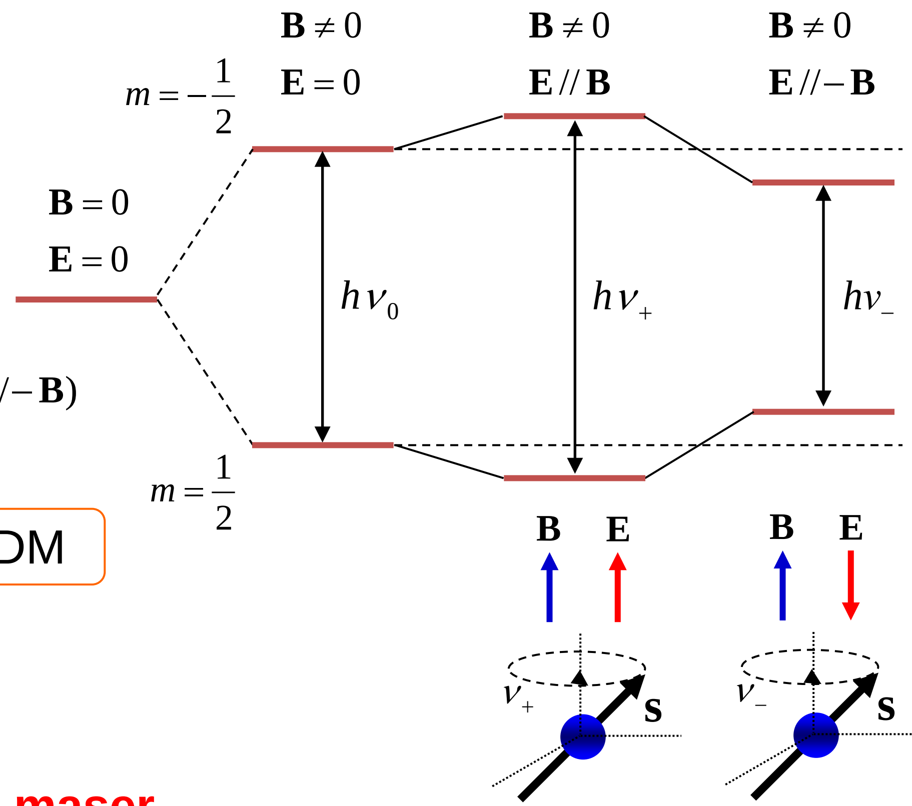
$d \sim 10^{-27}\, e\cdot\text{cm}$ という大きさ



Detection of an EDM

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

Energy levels for a spin 1/2
(for a case of μ > 0, d > 0)



Energy shift upon an *E*-field reversal

E // B

$$H = -\mu B - dE$$

E // −B

$$H = -\mu B + dE$$

⬇

Shift in a precession frequency

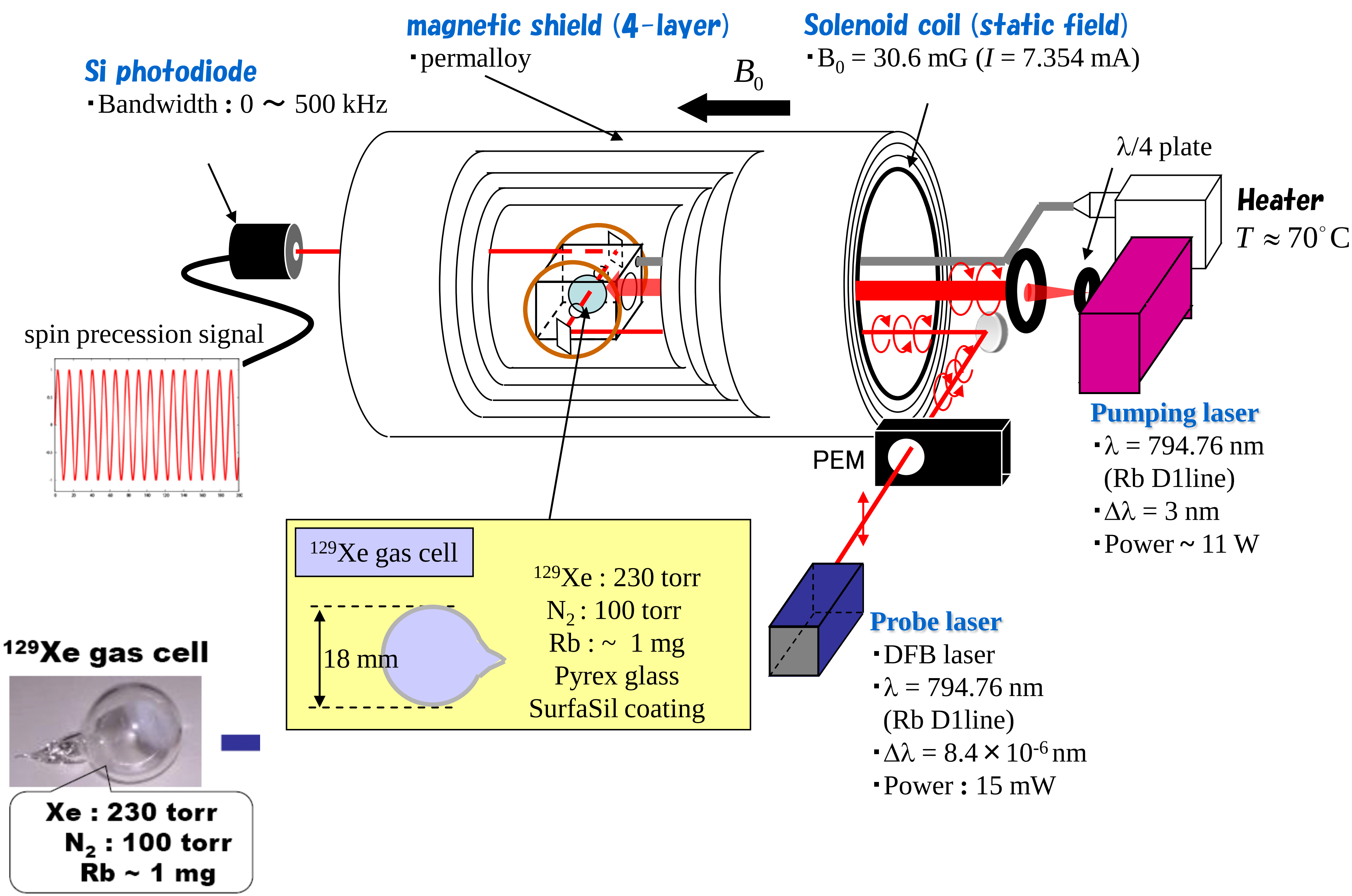
$$\nu_+ = \frac{2\mu B + 2dE}{h} \; (\mathbf{E} // \mathbf{B}) \qquad \nu_- = \frac{2\mu B - 2dE}{h} \; (\mathbf{E} // -\mathbf{B})$$

the difference ⇒ signal of an EDM

$$\Delta\nu = \nu_+ - \nu_- = \frac{4dE}{h}$$

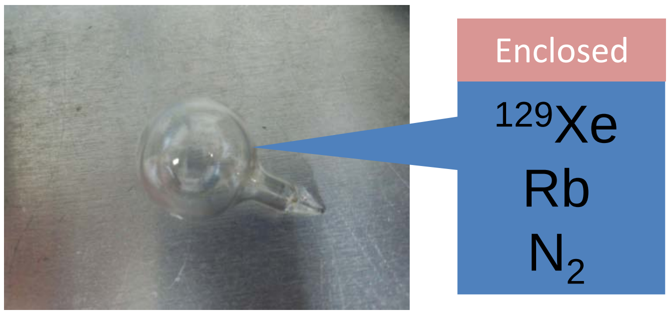
Desires long precession times => Spin maser

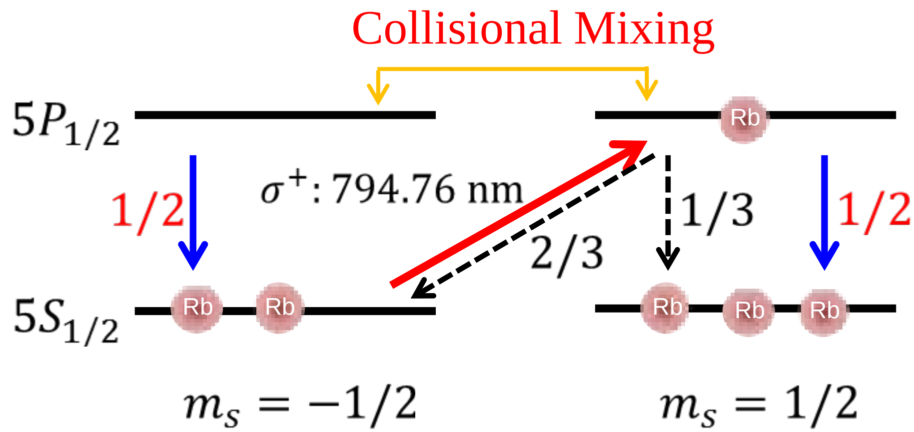
Setup for the spin oscillator experiment



Production of Polarization

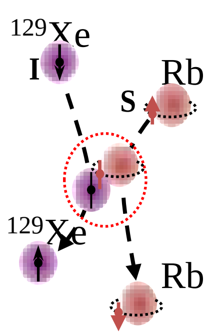
Optical pumping





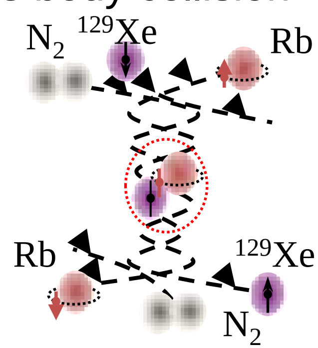
Spin exchange interaction in Rb-Xe

2 body collision



$\tau \sim 10^{-12}$

3 body collision



$\tau \sim 10^{-7}$

$$P_{\mathrm{Xe}} = \frac{\gamma_{se}^{\mathrm{Xe}}}{\gamma_{se}^{\mathrm{Xe}} + \Gamma_{sd}^{\mathrm{Xe}}} P_{\mathrm{Rb}}$$

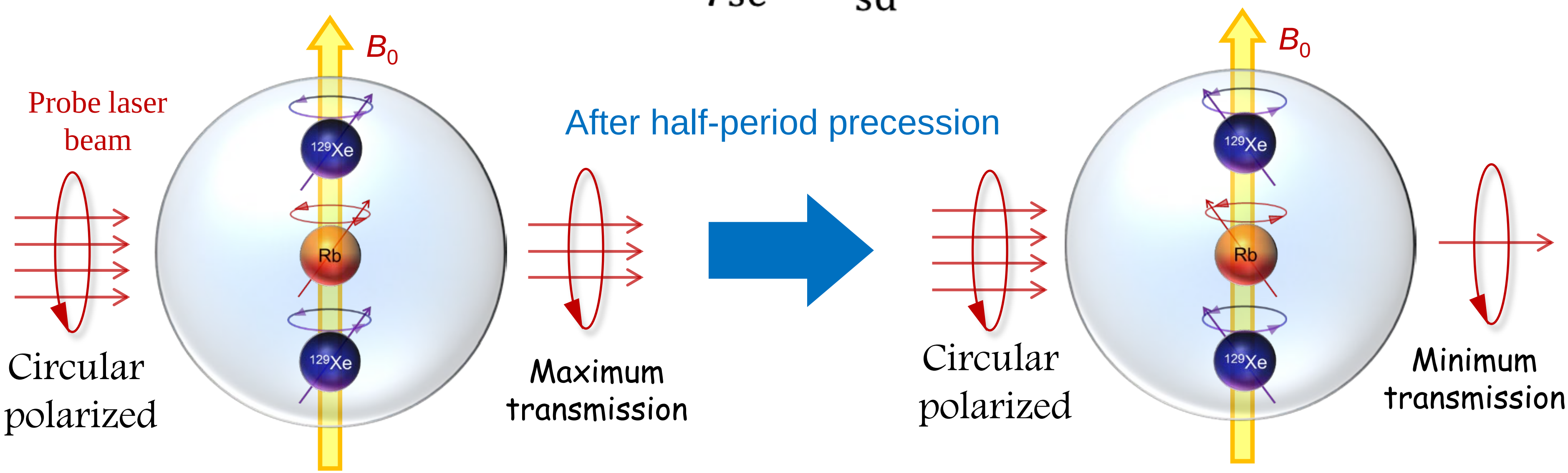
- P_{Xe}: Polarization of Xe
- P_{Rb}: Polarization of Rb
- $\gamma_{se}^{\mathrm{Xe}}$: Spin exchange ratio
- $\Gamma_{sd}^{\mathrm{Xe}}$: Relaxation ratio

W. Happer, Rev. Mod. Phys. 44 (1972) 169.

Optical Spin Detection

Transverse polarization of ^{129}Xe transfer to Rb : Re-polarization

$$P_{\mathrm{Rb}} = \frac{\gamma_{\mathrm{se}}}{\gamma_{\mathrm{se}} + \Gamma_{\mathrm{sd}}} P_{\mathrm{Xe}}$$



Spin oscillator

- ^{129}Xe polarization vector $\boldsymbol{P} = \langle \boldsymbol{I} \rangle / I$
- Applied field $\boldsymbol{B}_0 = (B_x, B_y, B_0)$

- $\boldsymbol{P}$ follows the Bloch equations:

$$\dot{\boldsymbol{P}} = -\gamma \boldsymbol{B} \times \boldsymbol{P} - \frac{1}{T_{1,2}} \boldsymbol{P}$$

or,

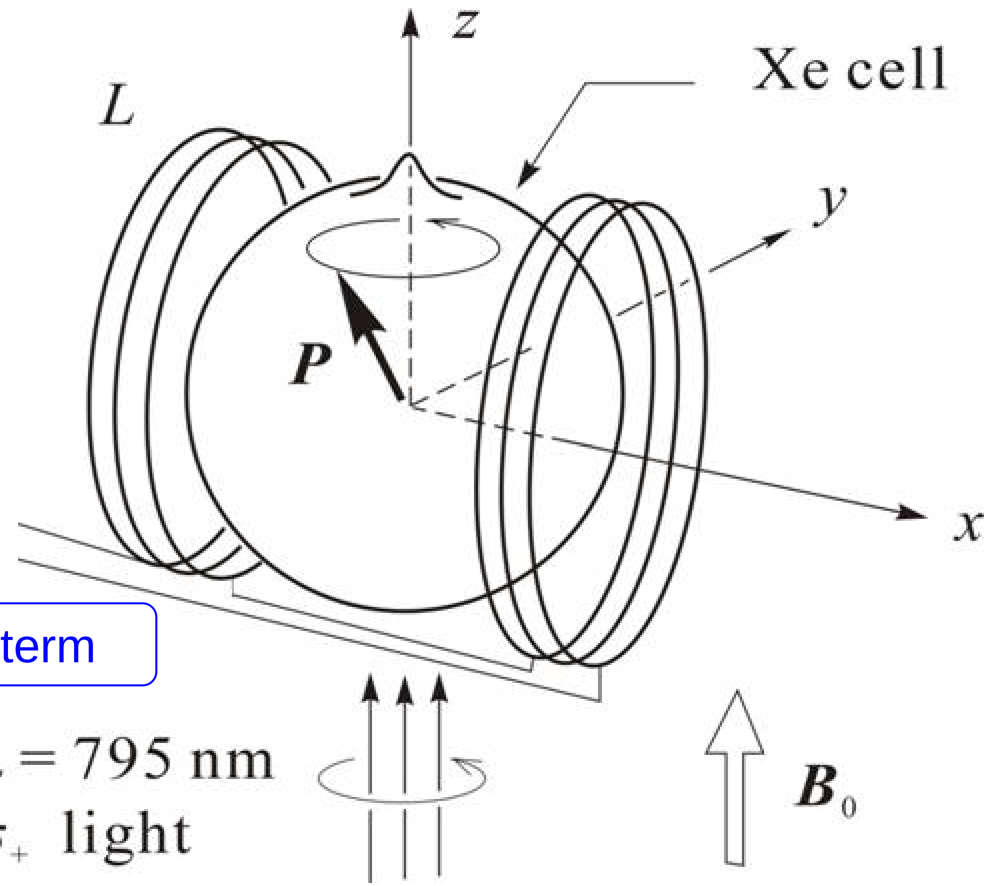
$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = \gamma \left(P_y B_0 - P_z B_y \right) - \frac{P_x}{T_2},$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \gamma \left(P_z B_x - P_x B_0 \right) - \frac{P_y}{T_2},$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = \gamma \left(P_x B_y - P_y B_x \right) - \frac{P_z}{T_1} + \left(P_0 - P_z \right) G.$$

relaxation term

Pumping term

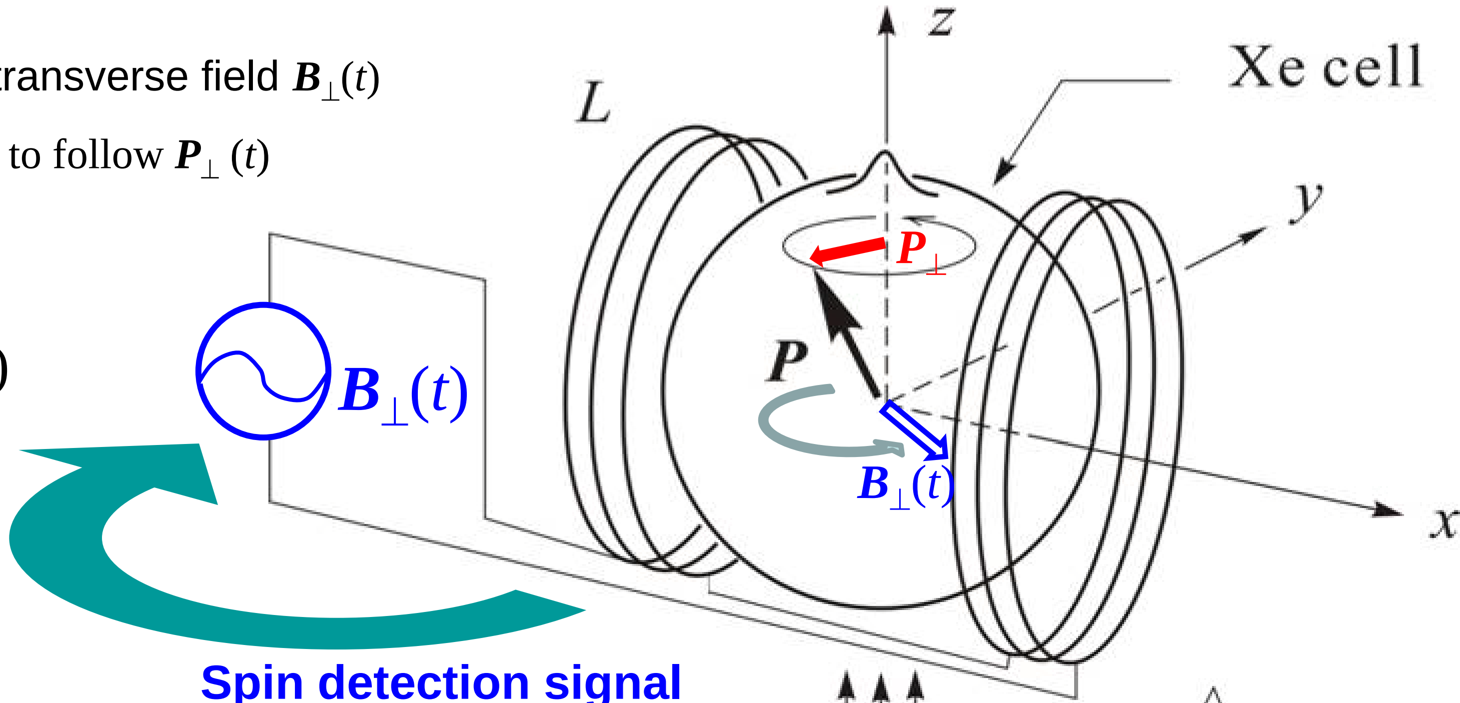


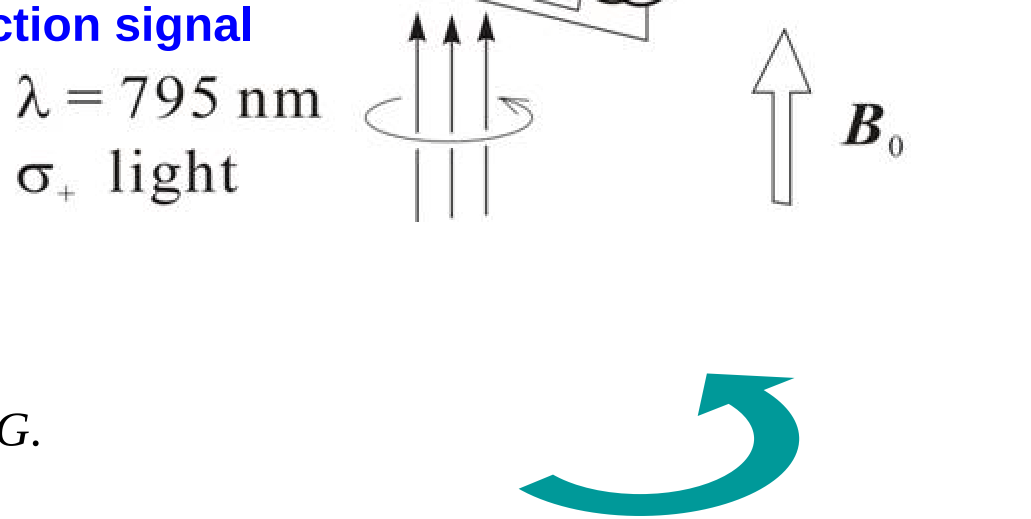
Spin oscillator

- Now we apply a transverse field $\boldsymbol{B}_{\perp}(t)$ which is organized to follow $\boldsymbol{P}_{\perp}(t)$

$$B_x(t) \propto P_y(t)$$

$$B_y(t) \propto -P_x(t)$$





$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = \gamma\left(P_y B_0 - P_z B_y\right) - \frac{P_x}{T_2},$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \gamma\left(P_z B_x - P_x B_0\right) - \frac{P_y}{T_2},$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = \gamma\left(P_x B_y - P_y B_x\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G.$$

$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = -\omega_0 P_y + \alpha P_z P_x - \frac{P_x}{T_2}, \qquad (1)$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \omega_0 P_x + \alpha P_z P_y - \frac{P_y}{T_2}, \qquad (2)$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = -\alpha\left(P_x P_x + P_y P_y\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G. \qquad (3)$$

$$\left(\begin{aligned} B_x &\equiv \frac{\alpha}{\gamma} P_y \\ B_y &\equiv -\frac{\alpha}{\gamma} P_x \\ \omega_0 &\equiv -\gamma B_0 \end{aligned} \right)$$

Taking (1) + i (2) and setting $P_x(t) + iP_y(t) \equiv e^{i\omega_0 t}\tilde{P}_\perp(t)$

$$\frac{\mathrm{d}\tilde{P}_\perp}{\mathrm{d}\,t} = \left(\alpha P_z - \frac{1}{T_2}\right)\tilde{P}_\perp, \qquad (4)$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = -\alpha\left|\tilde{P}_\perp\right|^2 - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G. \qquad (3')$$

<u>The steady state solutions</u> (namely solutions under $\frac{\mathrm{d}\tilde{P}_\perp}{\mathrm{d}\,t} = 0$ and $\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = 0$)

- Trivial solution: $\tilde{P}_\perp^{\,\mathrm{eq}} = 0, \quad P_z^{\,\mathrm{eq}} = \frac{GT_1}{GT_1 + 1} P_0$

- Non-trivial solution: $\left|\tilde{P}_\perp\right|^{\mathrm{eq}} = \sqrt{\frac{G}{\alpha}\left(P_0 - \frac{1 + 1/GT_1}{\alpha T_2}\right)}, \quad P_z^{\,\mathrm{eq}} = \frac{1}{\alpha T_2}.$

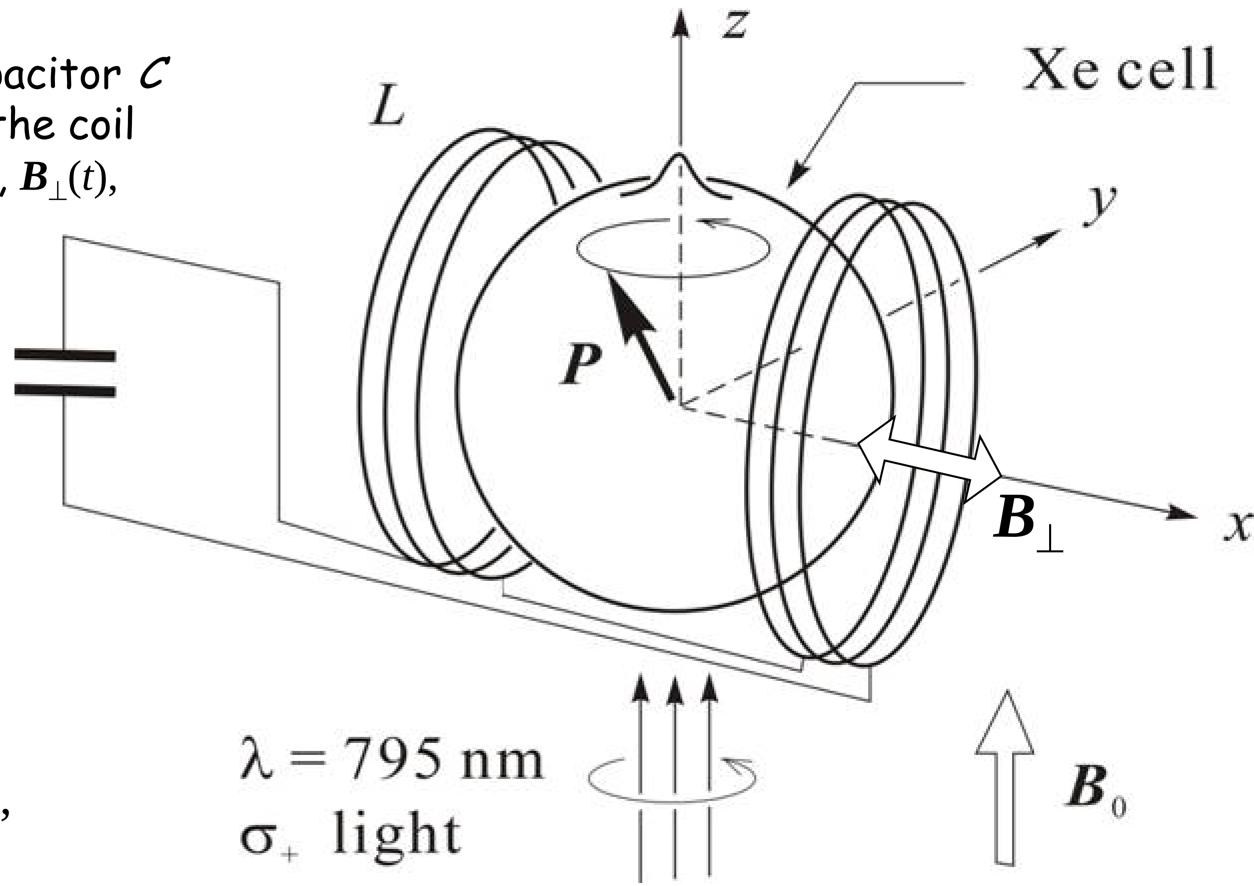
(Natural) spin maser

[T.E. Chupp *et al*, *Phys. Rev. Lett.* **72** (94) 2363]
[M.A. Rosenberry and T.E. Chupp, *Phys. Re. Lett.* **86** (2001) 22]

- If the coil is coupled to a capacitor *C* forming a resonating circuit, the coil produces a transverse *B* field, $\mathbf{B}_{\perp}(t)$,

$$B_x(t) \propto P_y(t)$$

$$B_y(t) \propto -P_x(t)$$



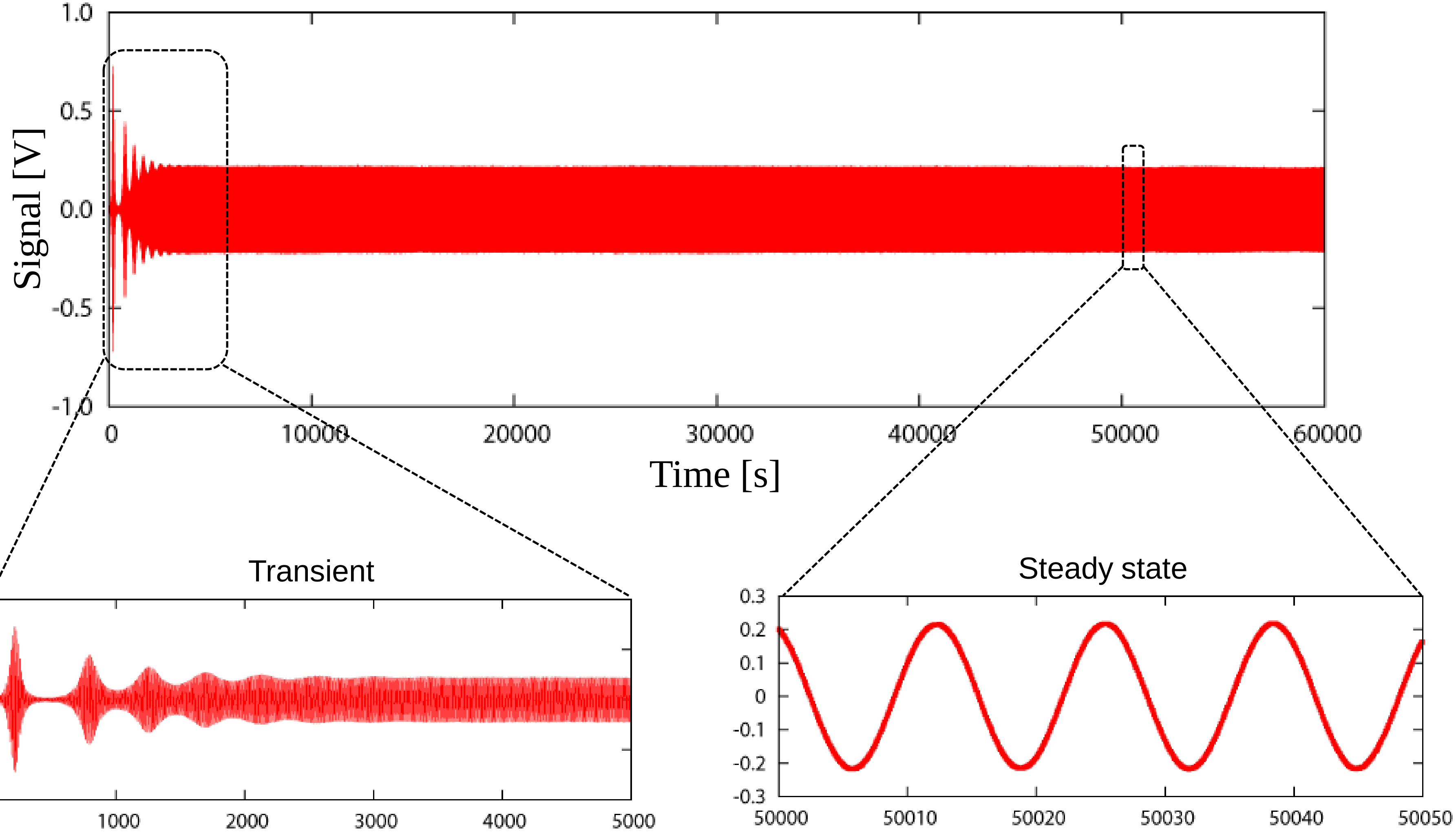
$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = \gamma\left(P_y B_0 - P_z B_y\right) - \frac{P_x}{T_2},$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \gamma\left(P_z B_x - P_x B_0\right) - \frac{P_y}{T_2},$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = \gamma\left(P_x B_y - P_y B_x\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G.$$

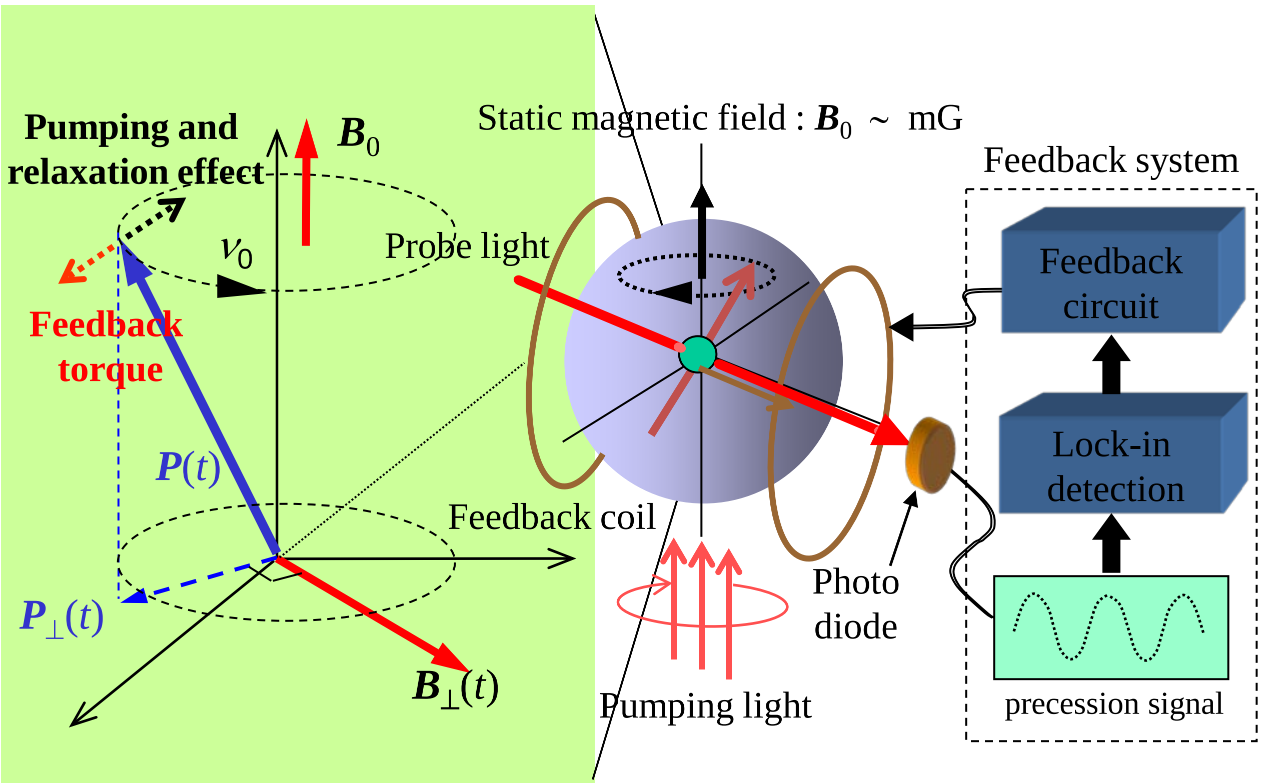
Spin oscillator signal

B_0 = 28.6 mG (I_0 = 7.0 mA) => ν_0 = 33.7 Hz



Spin oscillator

"Optically coupled" spin maser
with a feedback field generated according to optical spin detection



①[129]Xe nuclear spin polarization by optical pumping

↓

② Optical detection of the spin precession

↓

③Generation of a feedback field

↓

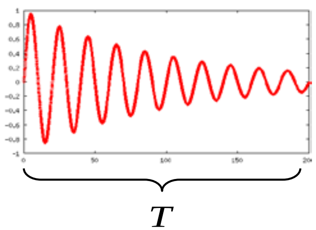
④Self-sustained spin precession

Realization of maser oscillation at very low fields (≤ mG)

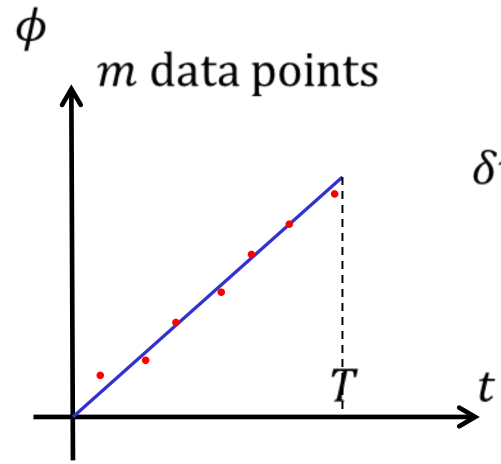
Suppression of drifts in the B_0 field => Suppression of drifts in ν

Precision of Precession Frequency

Single-shot measurement



$$\delta\nu' \propto \frac{1}{T^{3/2}}$$

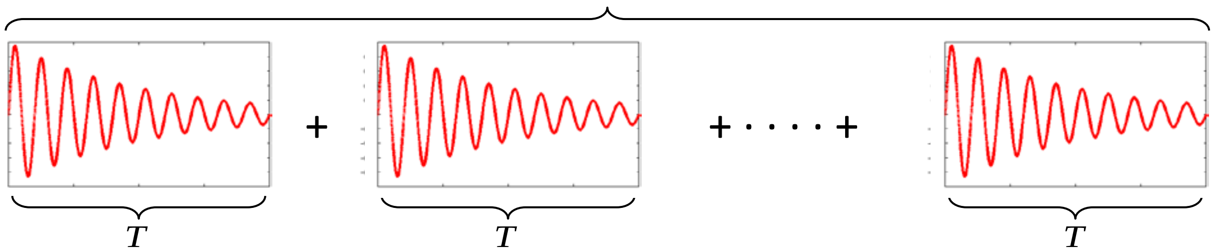


$$\delta\nu' \propto \frac{\delta\phi}{T\sqrt{m}} \propto \frac{1}{T^{3/2}}$$

$$(\because m \propto T)$$

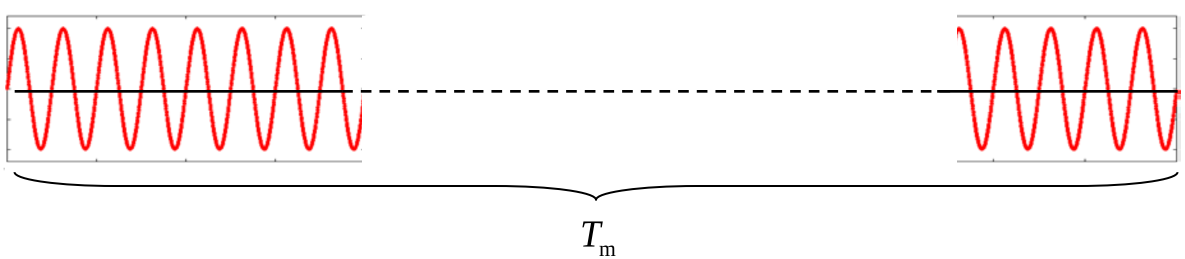
$T_m = nT$

Multi-shot measurement

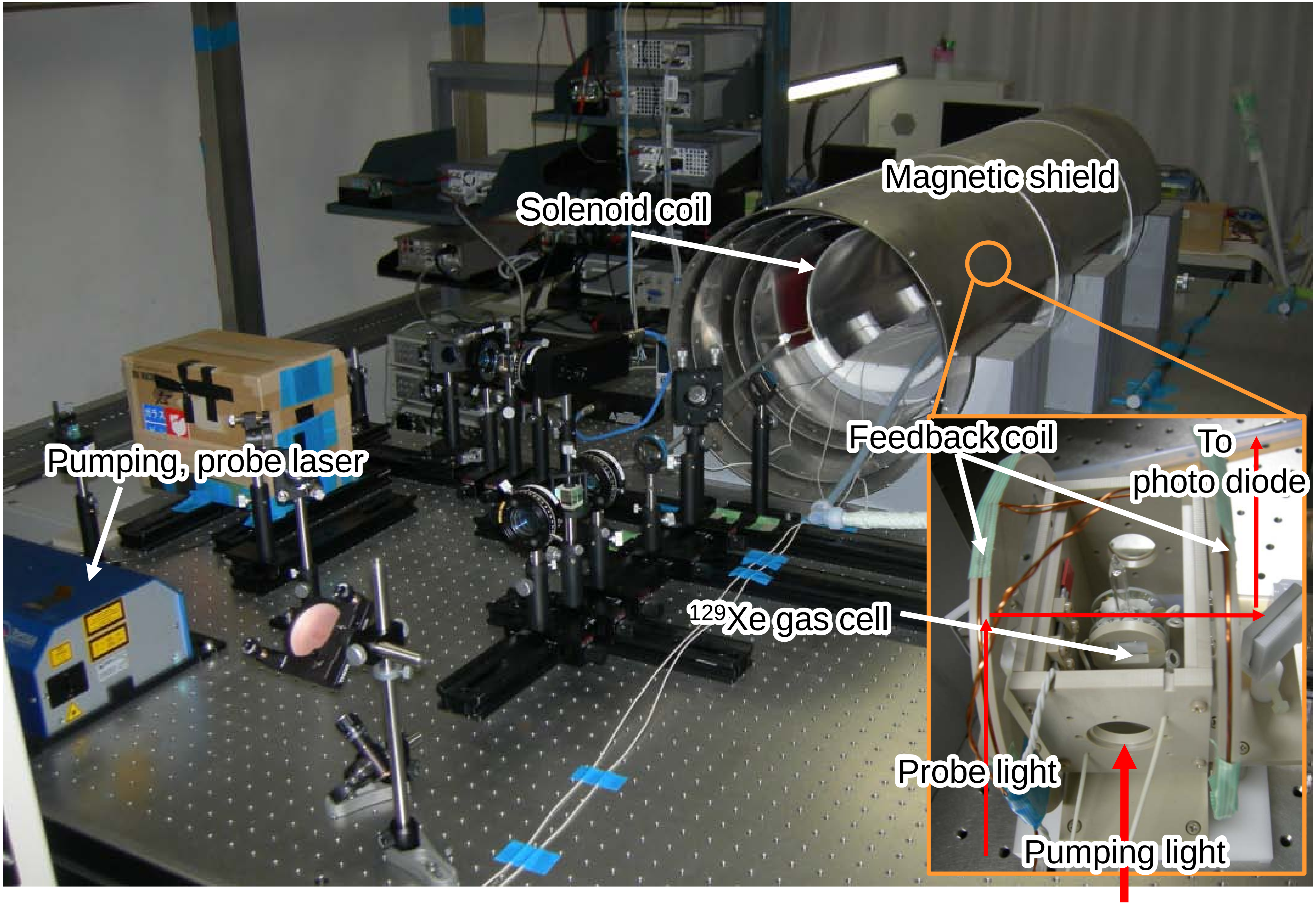


$$\delta\nu = \frac{\delta\nu'}{\sqrt{n}} \propto \frac{1}{T_m^{1/2}T}$$

Long-term measurement

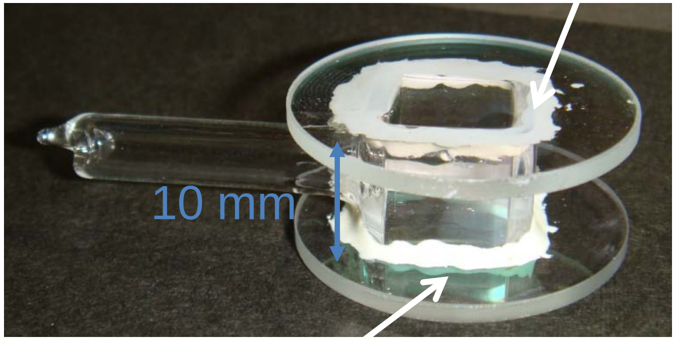


$$\delta\nu \propto \frac{1}{T_m^{3/2}}$$


Magnetic shield
Solenoid coil
Pumping, probe laser
Feedback coil
To
photo diode
^{129}Xe gas cell
Probe light
Pumping light

EDM cell

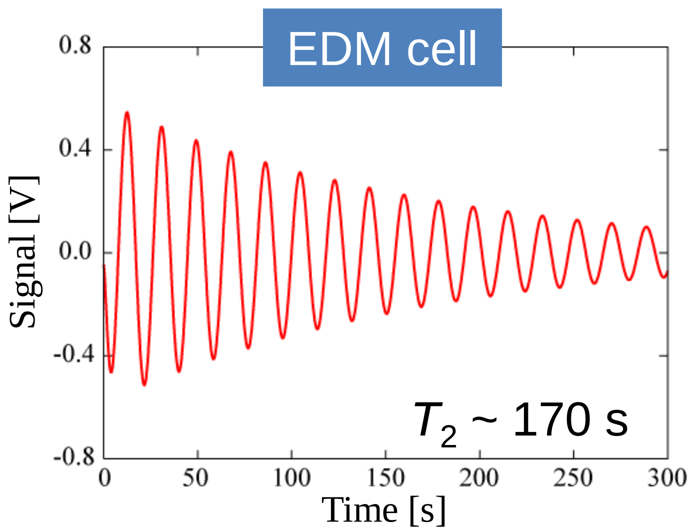
Torr seal

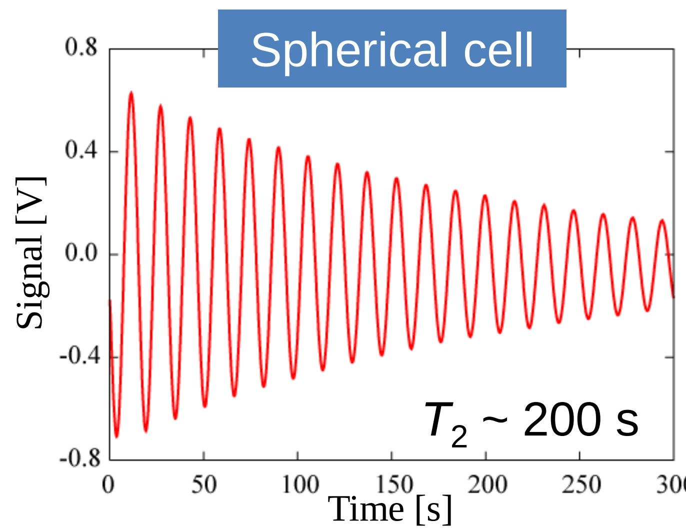


ITO conductive coating

EDM cell
- ^{129}Xe : ~ 200 torr
- N_2 : ~ 100 torr
- Rb ~ 1 mg
- SurfaSil coating
- size: 10 mm × 10 mm × 10 mm

^{129}Xe free spin precession





<u>Relaxation time comparable to that of spherical cell</u>

Maser operation applying E_0

● Major sources of frequency drift

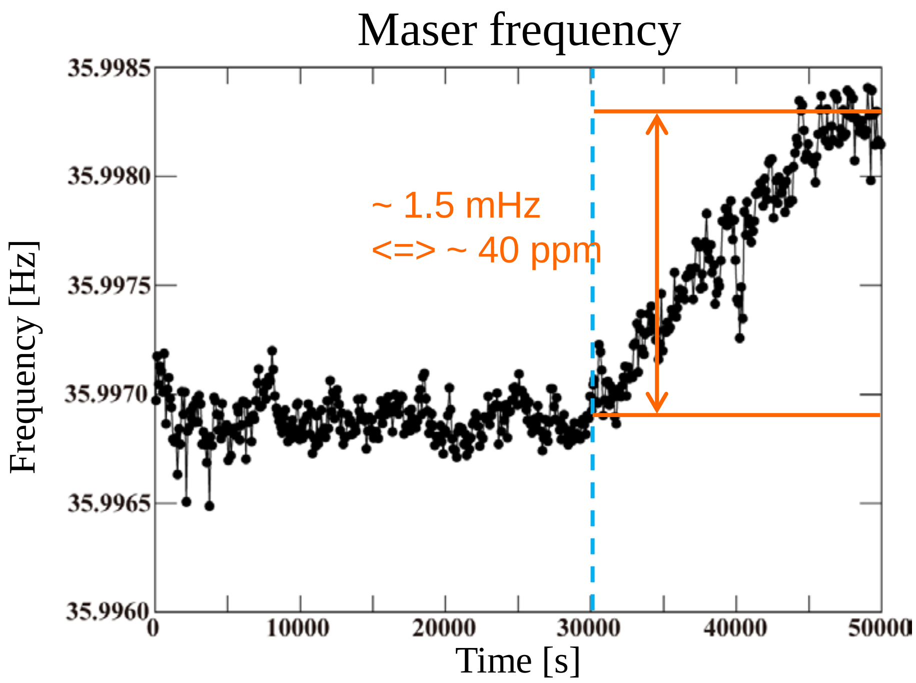
(1) Solenoid current I_0

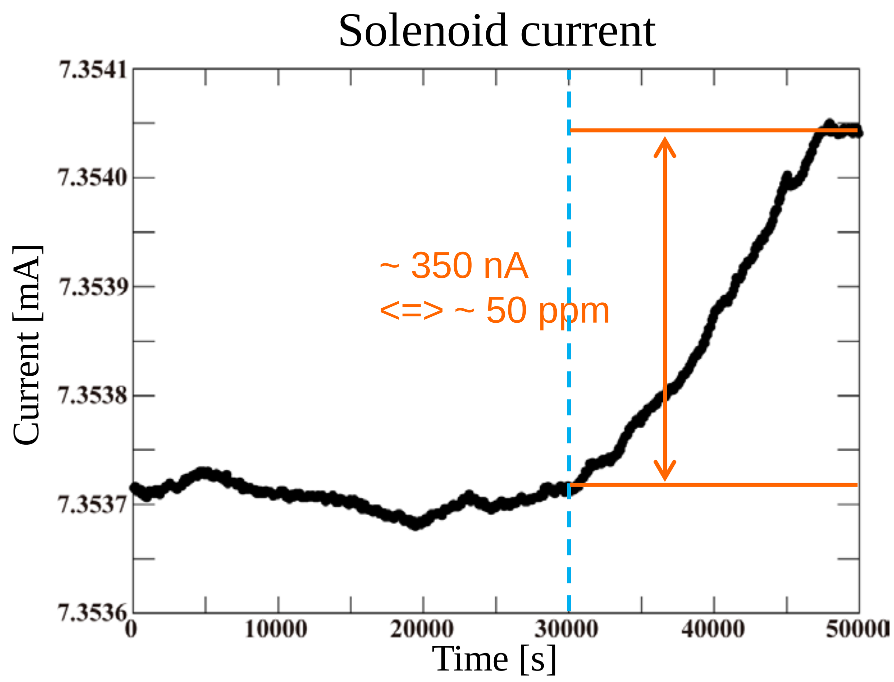
(2) Cell temperature

(3) Environmental field

(4) Other sources

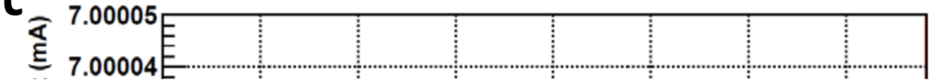
$\nu_0 - I_0$ correlation



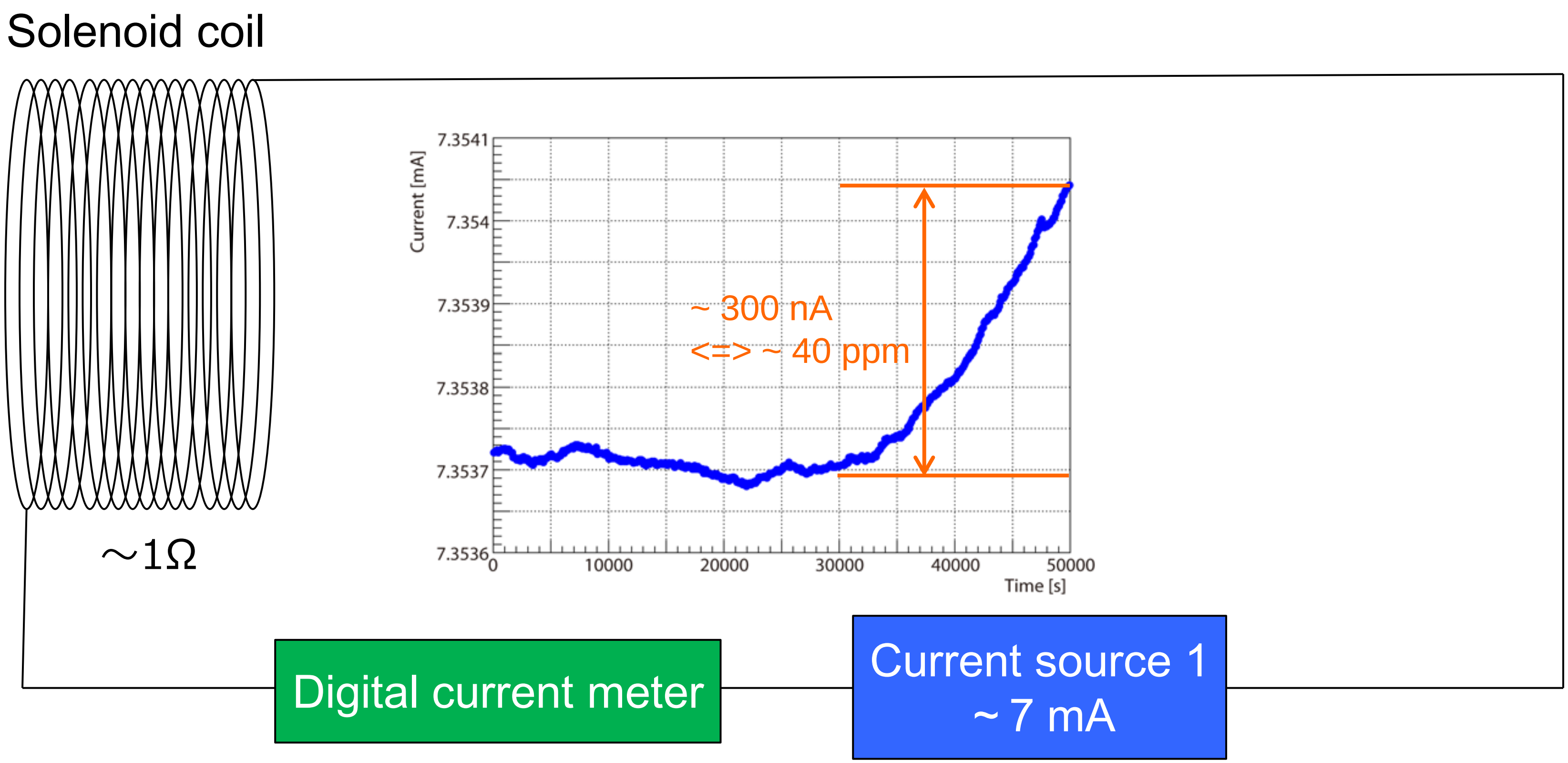


The solenoid current drift induces the frequency drift.

Suppression of current drift
=> Construction of new stabilized current source

Introduct  t source

○ Previous current source



● Major sources of frequency drift

(1) Solenoid current I_0

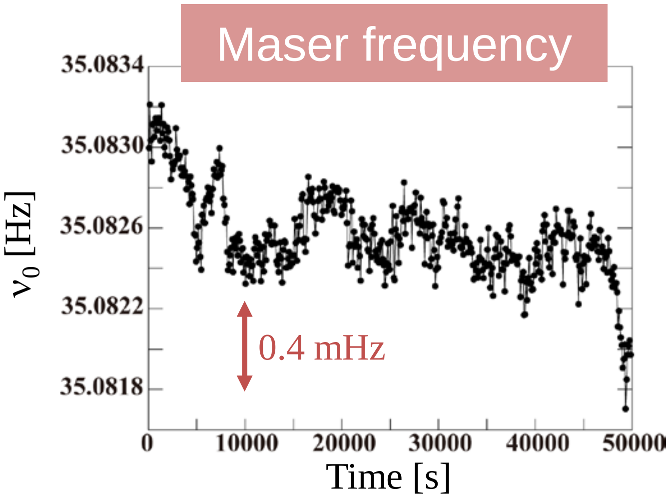
→ New stabilized current source

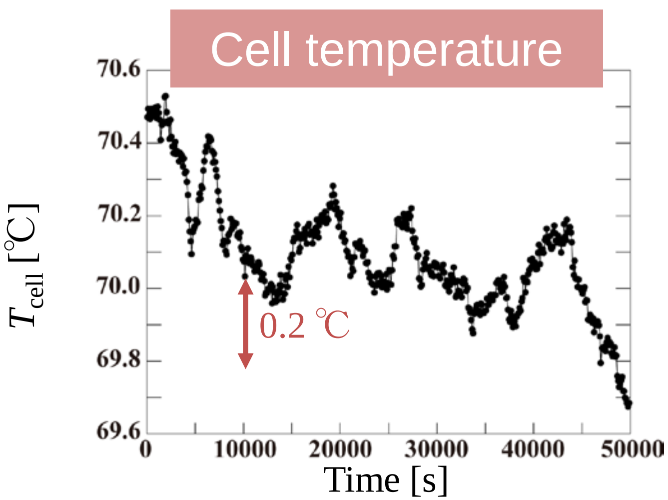
(2) Cell temperature

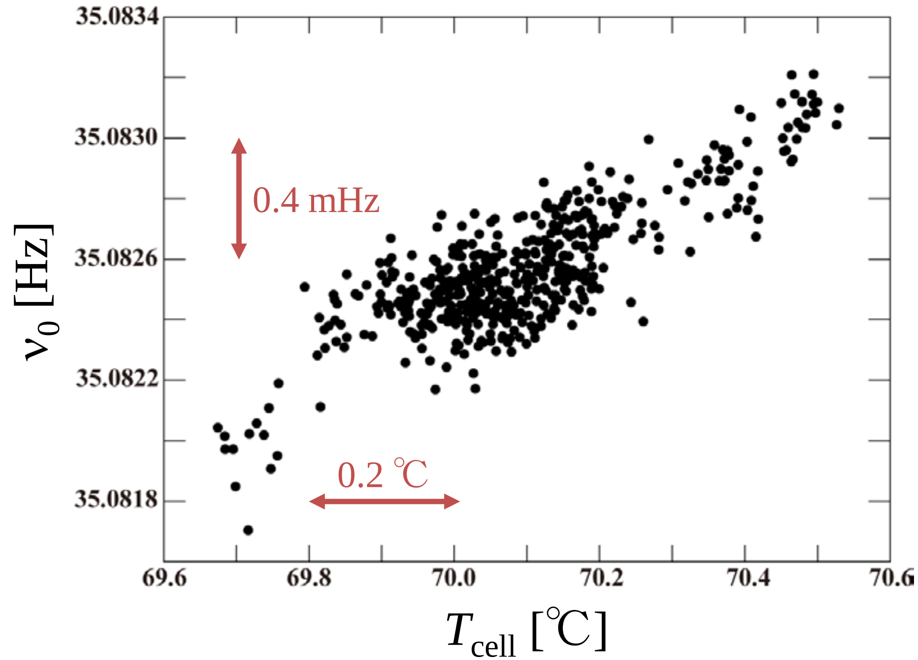
(3) Environmental field

(4) Other sources

$\nu_0 - T_{cell}$ correlation







Frequency shift of ^{129}Xe due to Rb magnetization

$$\Delta|\nu_{\mathrm{Xe}}| = -\frac{1}{h}\frac{\mu_{\mathrm{Xe}}}{I_{\mathrm{Xe}}}\frac{8\pi}{3}\mu_B g_s \kappa_{\text{Xe-Rb}}[\mathrm{Rb}]\langle S_z\rangle$$

S. Schaefer et al., PRA39 (1989) 5613.

$$\rightarrow \delta(\Delta|\nu_{\mathrm{Xe}}|) \sim 1.6\ \mathrm{mHz}/^{\circ}\mathrm{C}\ \ (T_{\mathrm{cell}} = 70\ ^{\circ}\mathrm{C},\ P_{\mathrm{Rb}} = 0.2)$$

Xe frequency shift due to Rb magnetization
: proportional to Rb density [Rb]

=> Drift of frequency shift in Xe
: [Rb] drift

=> Low cell temperature
: suppuration of frequency drift
due to temperature drift

➡ Maser operation
under low cell temperature (~ 50℃)

● Major sources of frequency drift

(1) Solenoid current I_0

→ New stabilized current source

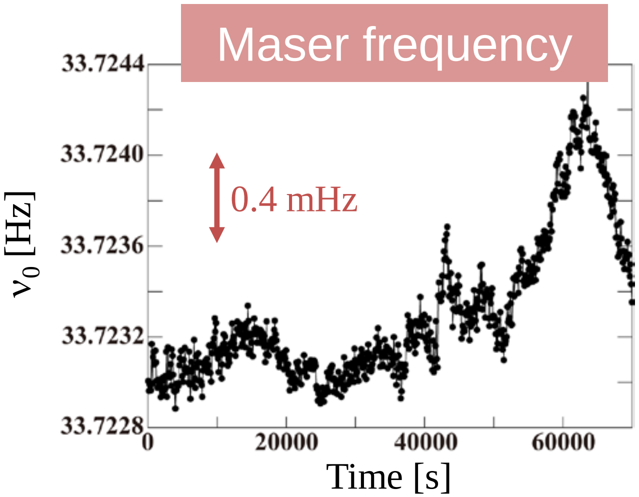
(2) Cell temperature

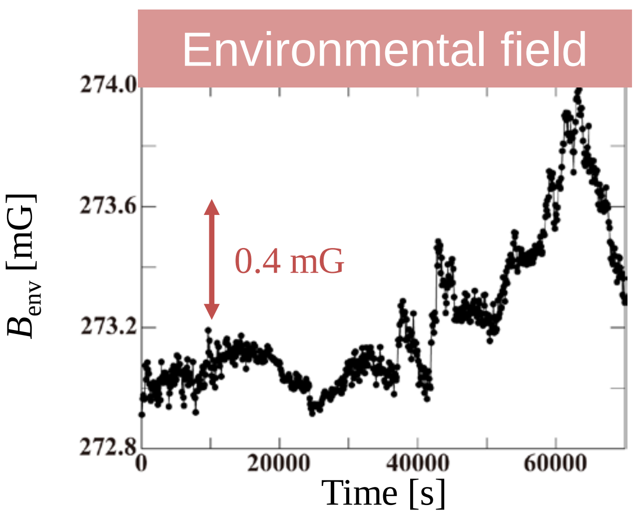
→ Operation at low cell temperature (~50℃)

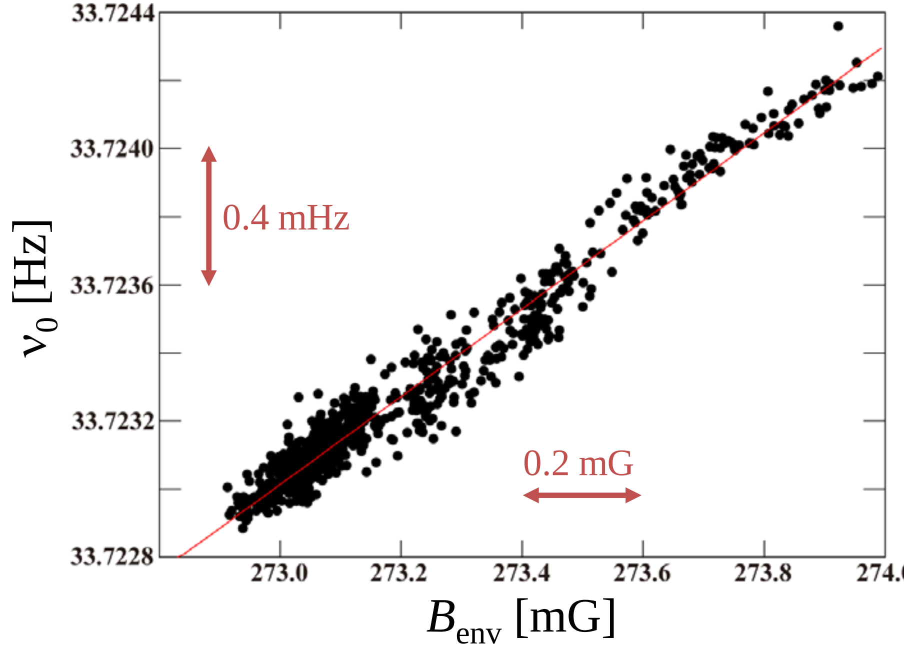
(3) Environmental field

(4) Other sources

$\nu_0 - B_{env}$ correlation







B_{env} fluctuation => B_0 fluctuation

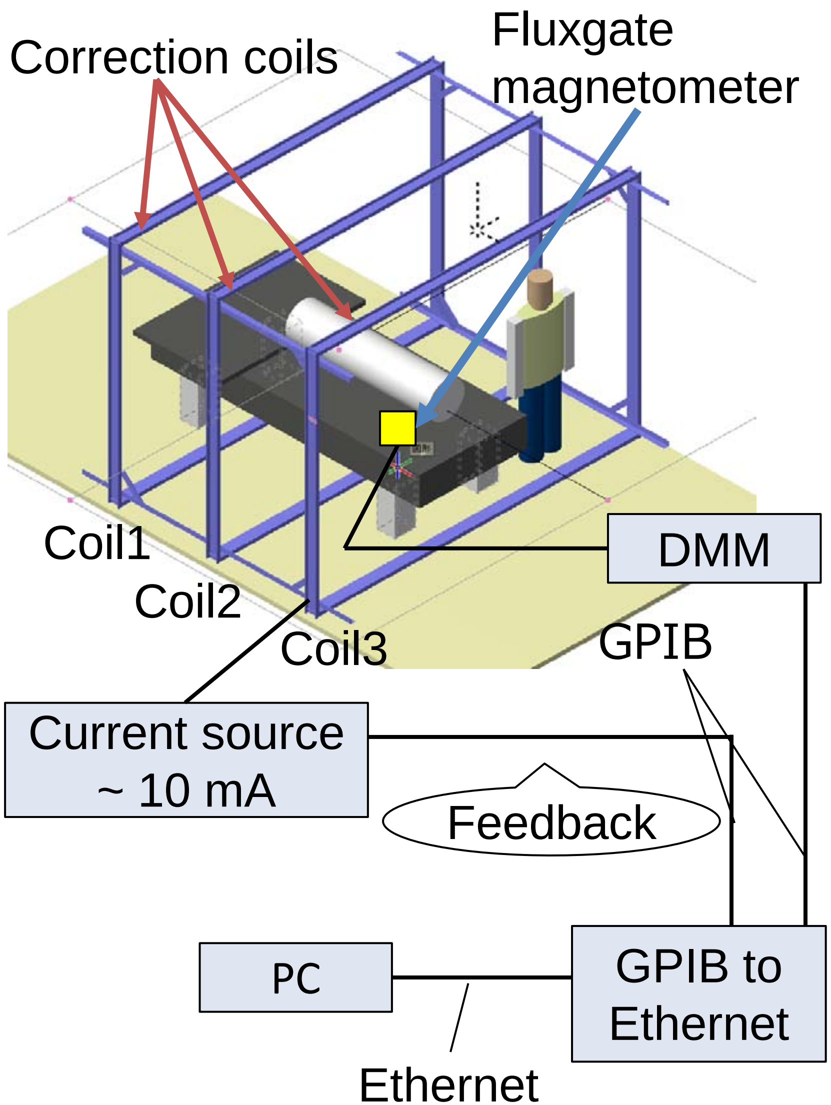
Shielding factor (SF) : $\sim 10^3$, $\Delta B_{env} = 0.1$ mG

=> $\Delta \nu_0 \sim 0.12\ \mu$Hz

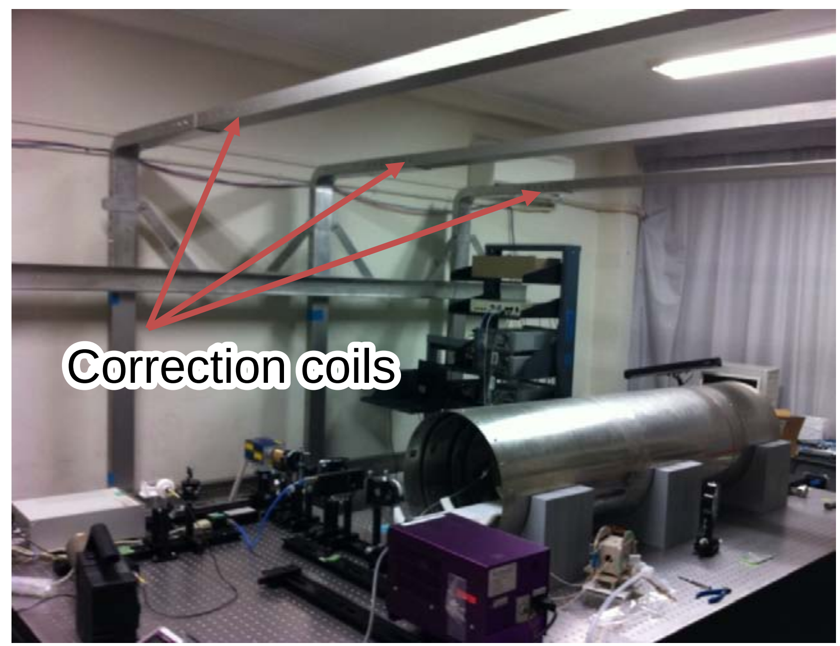
B_{env} stabilization system construction

Environmental field stabilization system

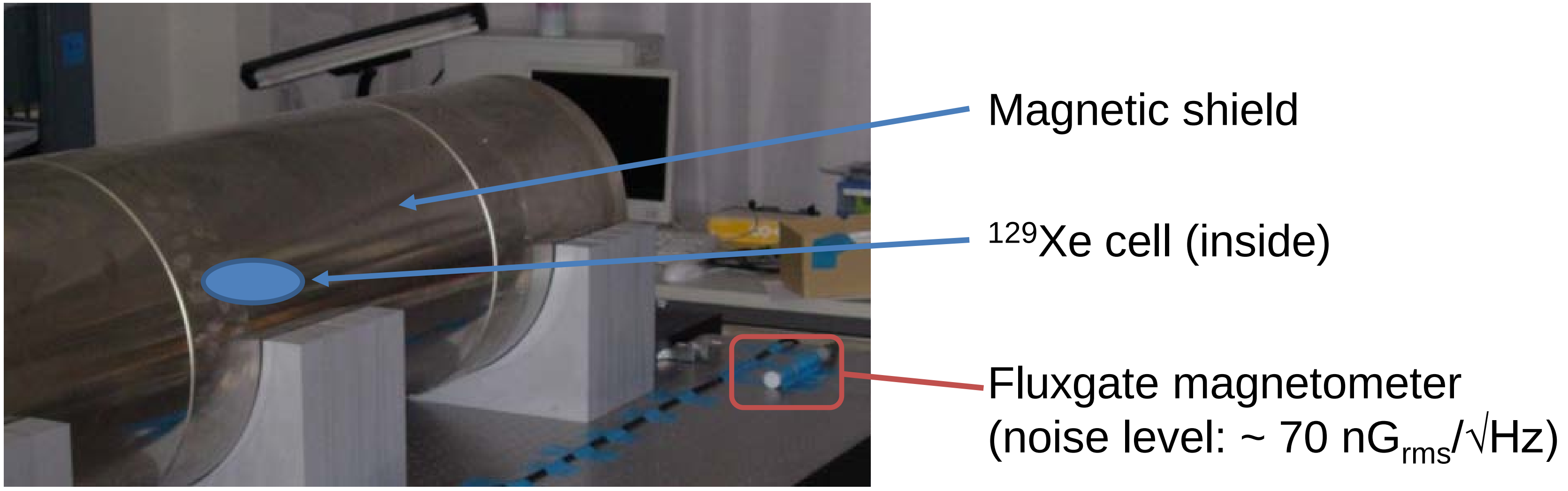
for detail see: T. Nanao's poster

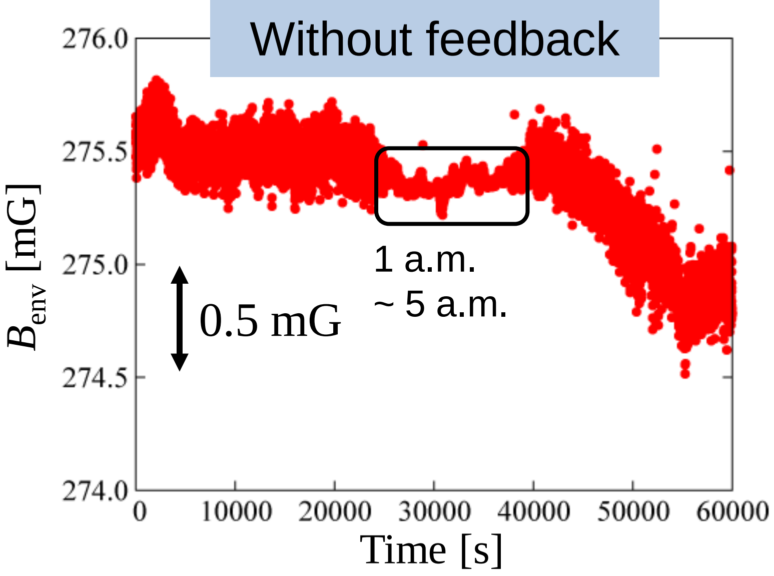


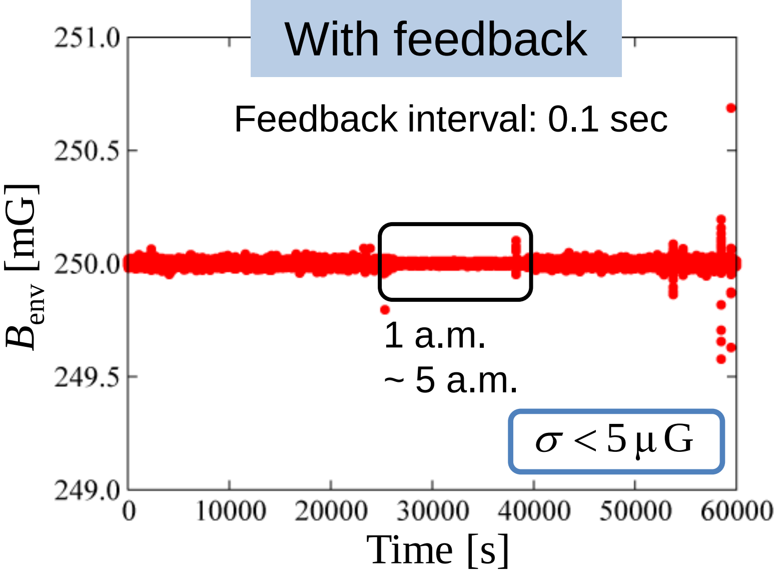
- B_{env} measurement
  - fluxgate magnetometer
    noise level: ~ 70 $nG_{rms}/\sqrt{Hz}$
- Correction coils
  - Coli1,3: ~ 88 A•turn
  - Coil2 : ~ 26 A•turn



Feedback outside the shield







Suppression of short term fluctuation and long term drift

● Major sources of frequency drift

(1) Solenoid current I_0

→ New stabilized current source

(2) Cell temperature

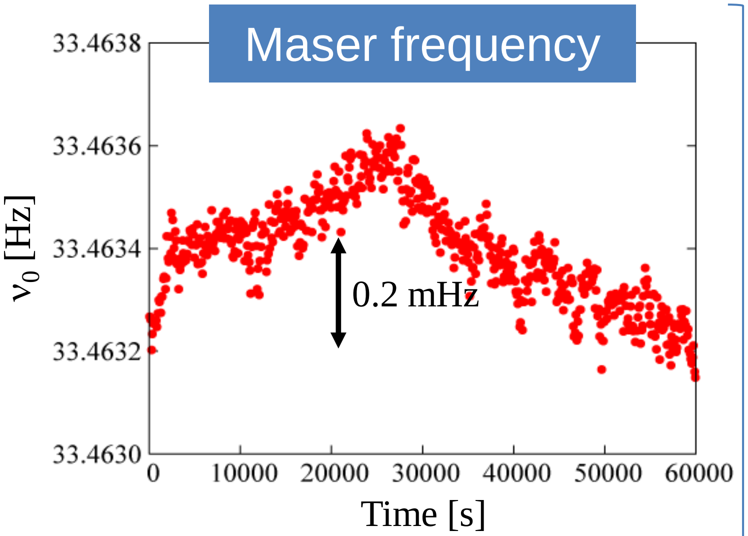
→ Operation at low cell temperature (~50℃)

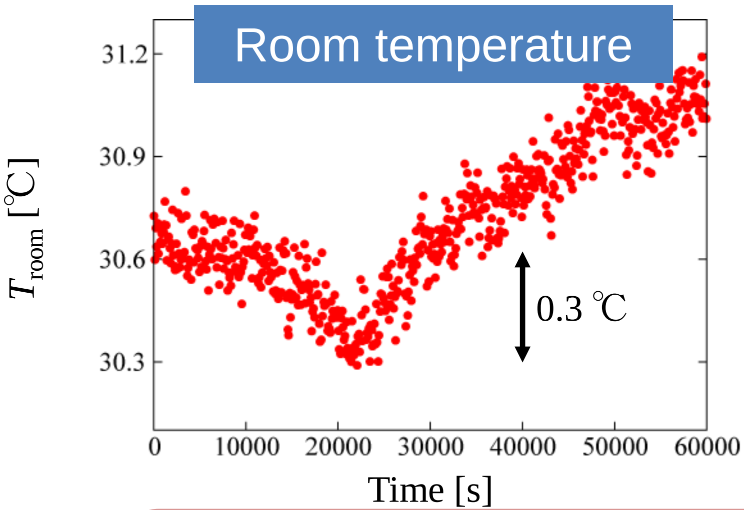
(3) Environmental field

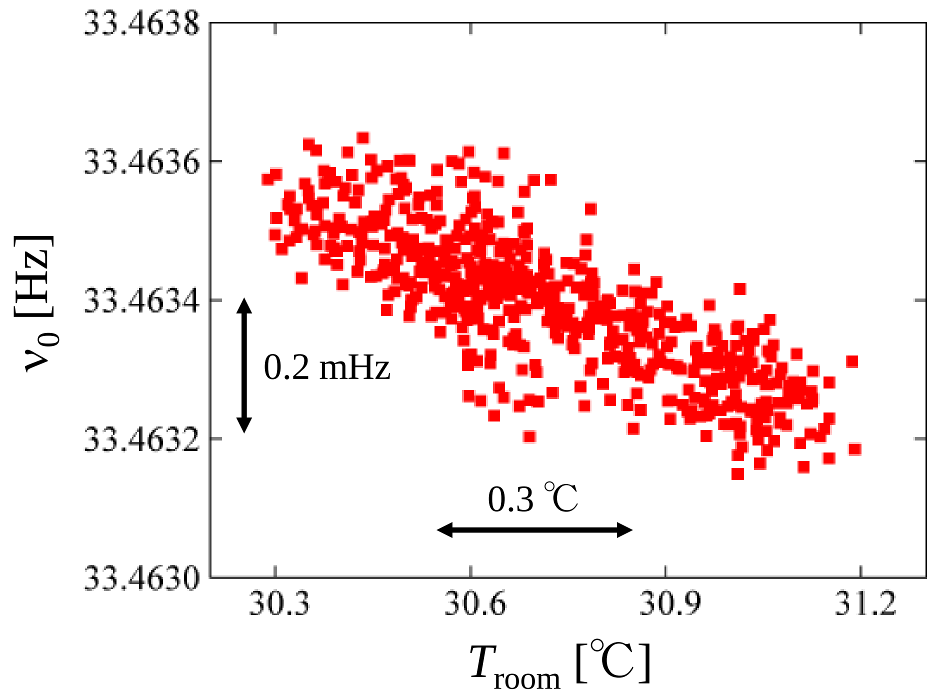
→ Field compensation system

(4) Other sources

$\nu_0 - T_{room}$ correlation





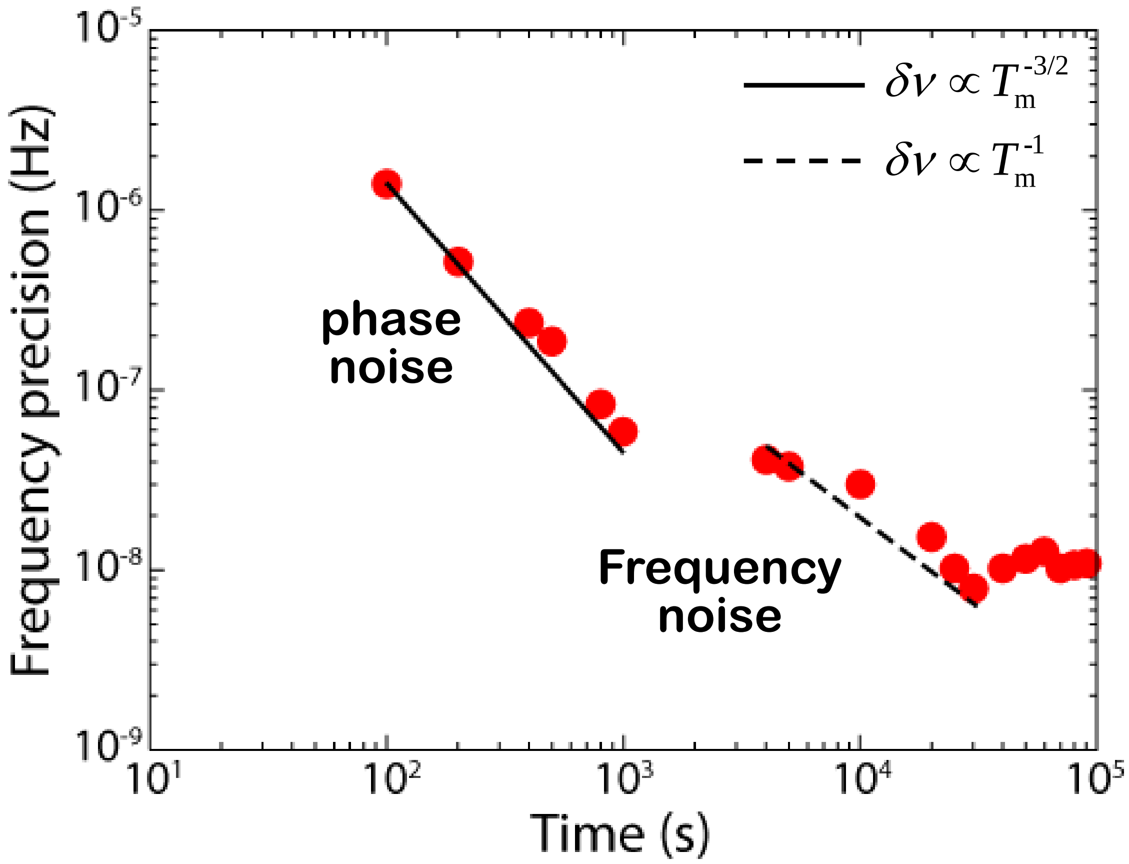


Room temperature T_{room} fluctuation
→ Shielding factor of magnetic shield fluctuation
→ Maser frequency fluctuation

- Temperature stabilization around the shield
- Measurement of local magnetic field applied to ^{129}Xe nucleus,

← ^{3}He co-magnetometer or Rb magnetometer
(the next presentation by Prof. Yoshimi)

Frequency precision
under stabilized I_0, B_{env} and low T_{cell}

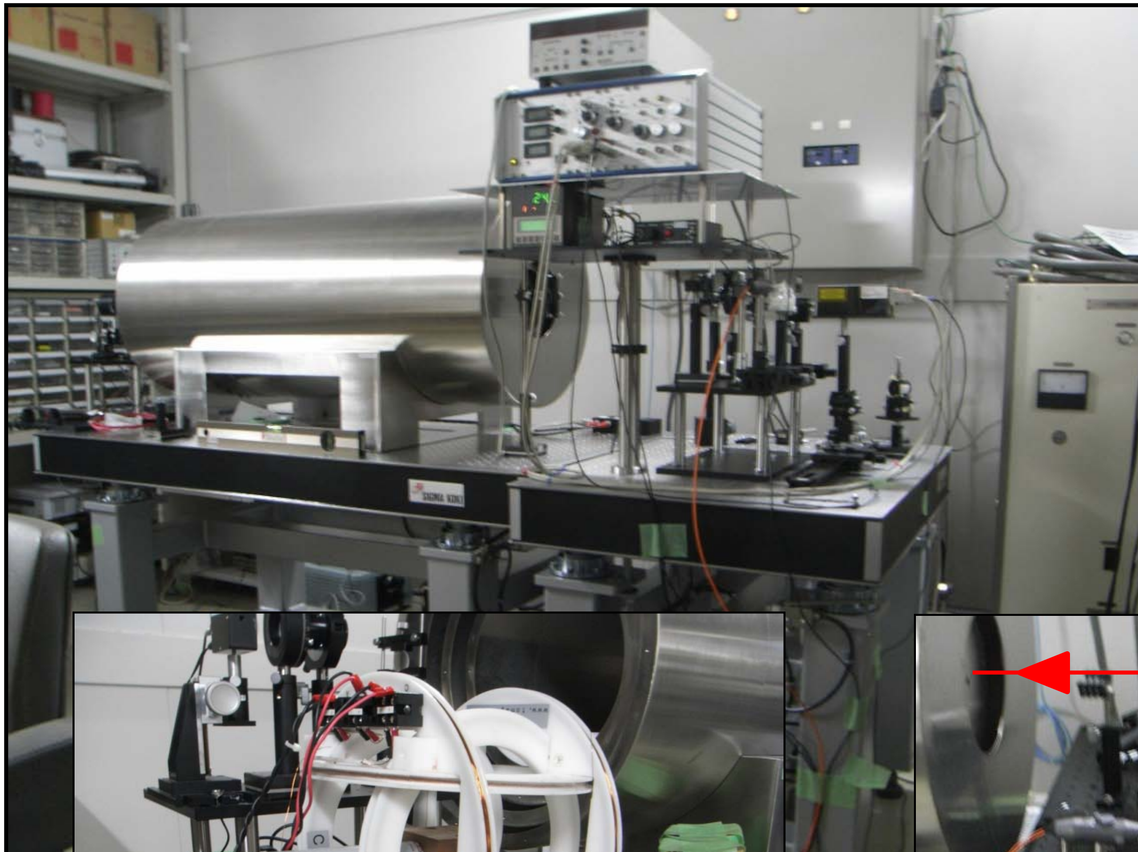


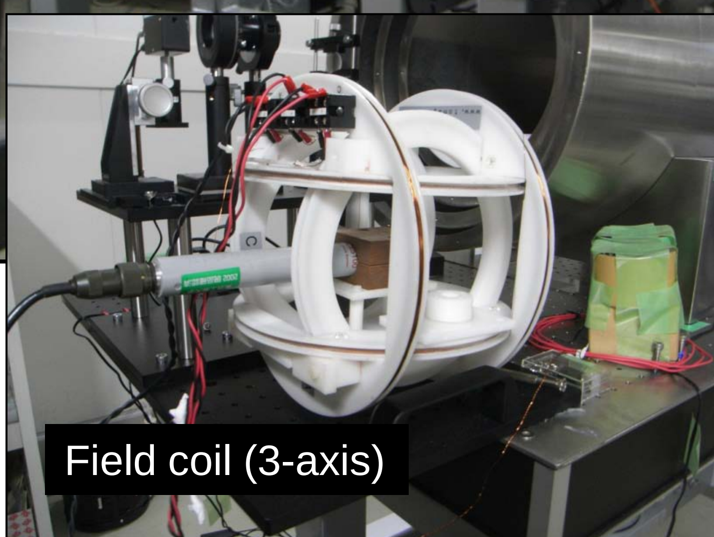
$$\delta\nu = \frac{\sqrt{12\sigma_\phi^2 \Delta t}}{2\pi} T_m^{-3/2}$$

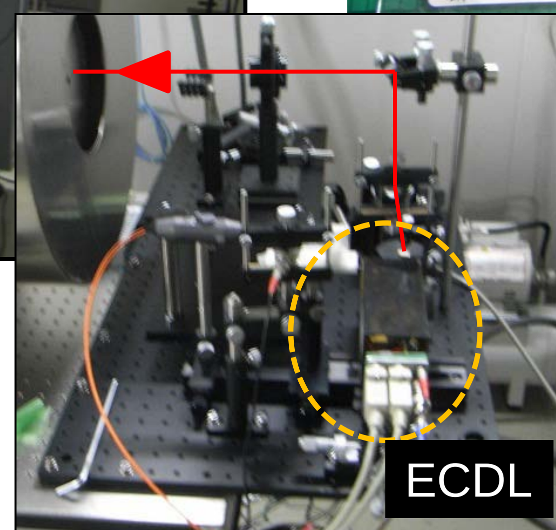
$\delta\nu$ = 7.9 nHz

$\delta d = 8 \times 10^{-28}$ $e$cm (with 10 kV/cm)

Development of high-precision magnetometer using nonlinear magnet-optical rotation (NMOR)



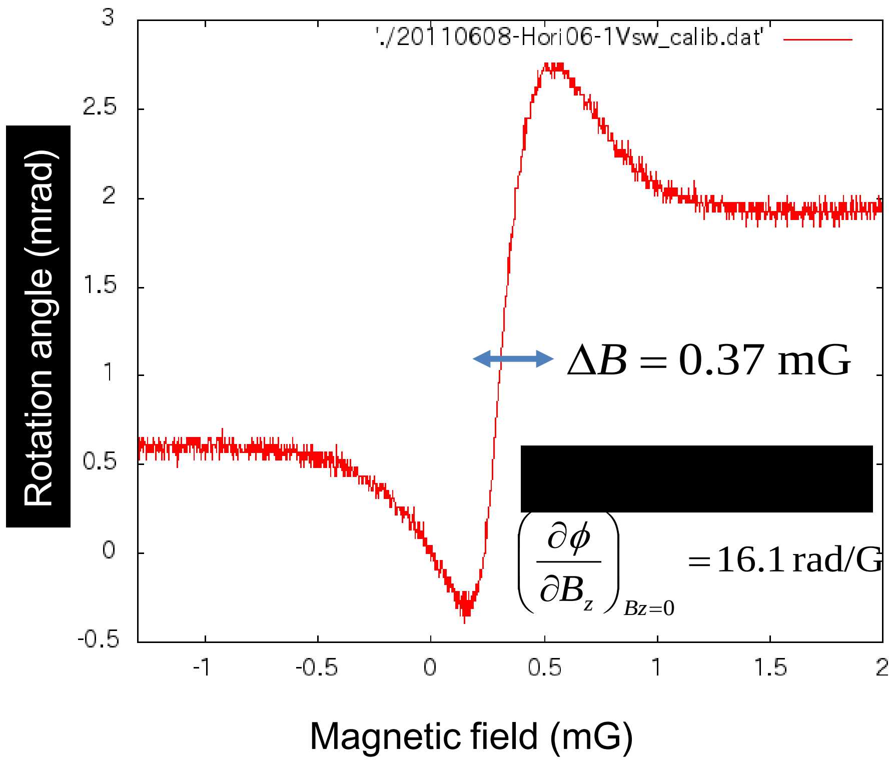


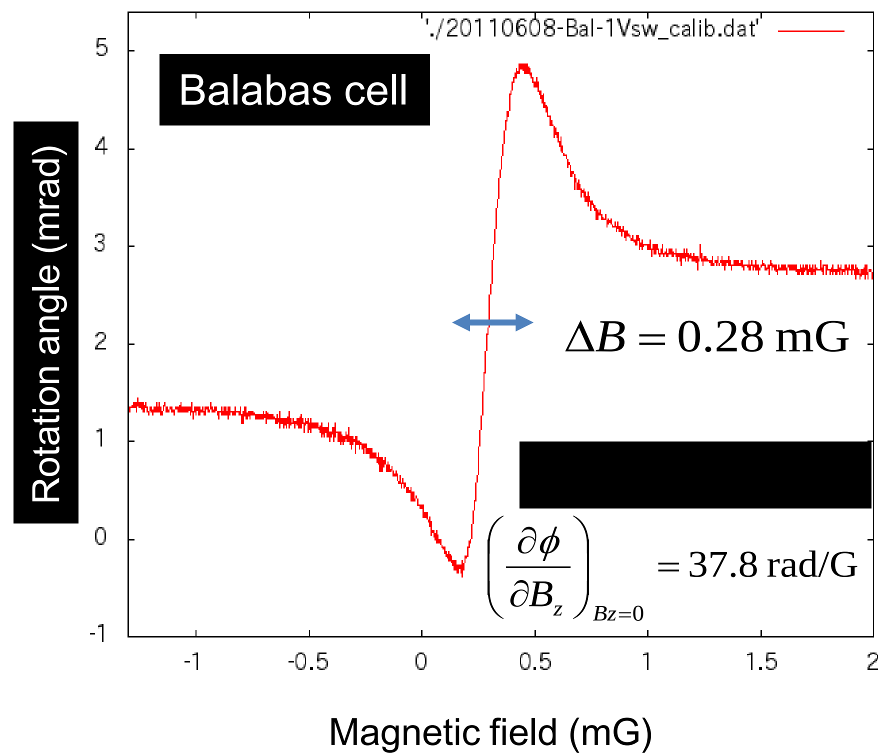


Rb cell with Paraffin coating:
commercial paraffin mixture
(Paraflint) $(CH_2)n$

The cell made by Prof. M.V. Balabas : φ60 mm, T1 ~2s.

Thanks to Prof. Hatakeyama (Tokyo Univ. Agri. Tech.)



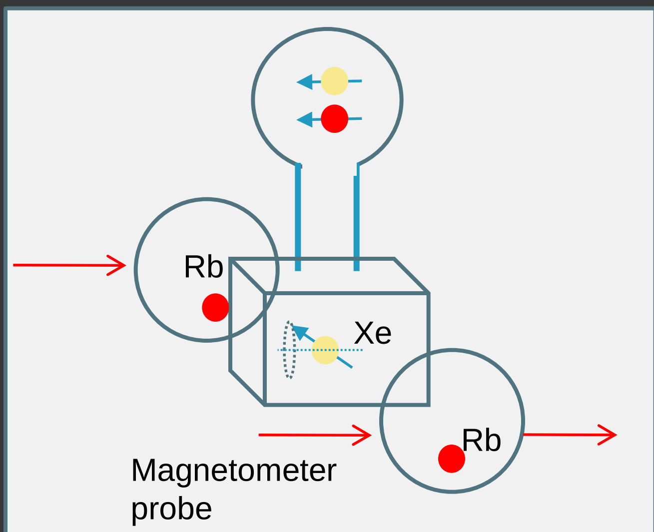


No large difference in NMOR width

→ Wall performance does not limit the width → residual field…

Magnetometer for Low freq-Spin maser EDM experiment

(1) High sensitivity magnetometers



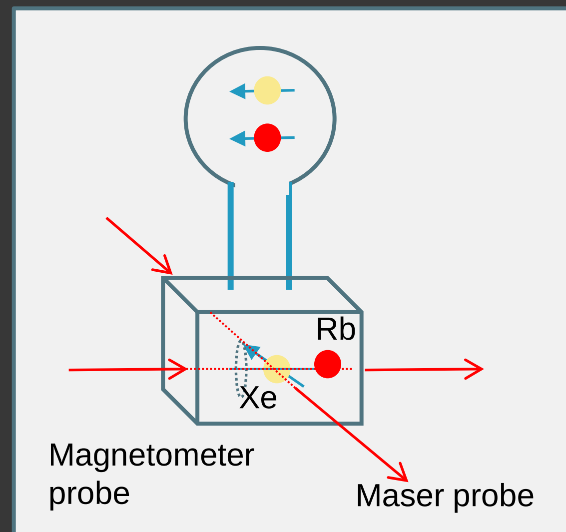
- Not comagnetometer
- Rb magnetometer near maser cell
- Only Xe and Rb (small, and not pol)

$$\delta B = 10^{-11}\ \mathrm{G}/\sqrt{\mathrm{Hz}}$$

100 s –run (if constant):

$$\delta B = 10^{-12}\ \mathrm{G}$$

(2) Rb comagnetometer



- Comagnetometer of Rb
- Only Xe and Rb (small, and not pol)

- Probrem of

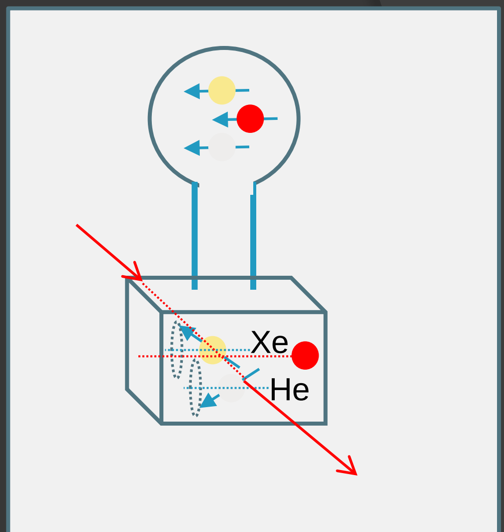
Rb – Xe interaction ?

(→ Low density Xe gas ?)

Polarizability problem

$$\delta B = ?\ \mathrm{G}/\sqrt{\mathrm{Hz}}$$

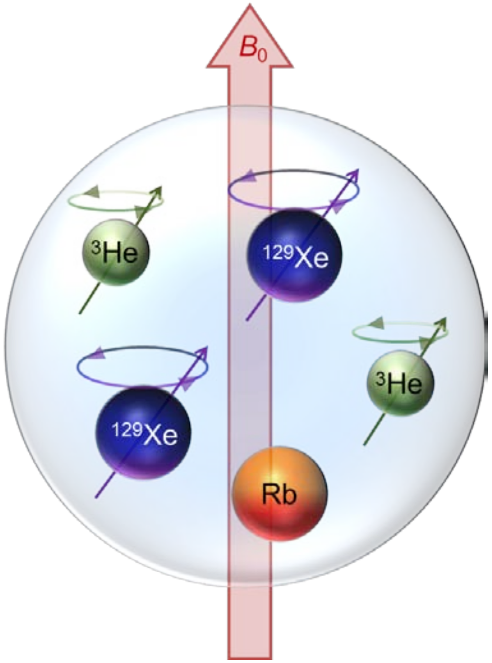
(3) 3He comagnetometer



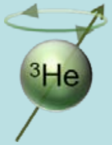
- Comagnetometer of 3He
- S/N for He precession for laser probing .

^{3}He Co-magnetometer

Scheme of ^{3}He Co-magnetometer



EDM measurement



Monitor and stabilize B_0

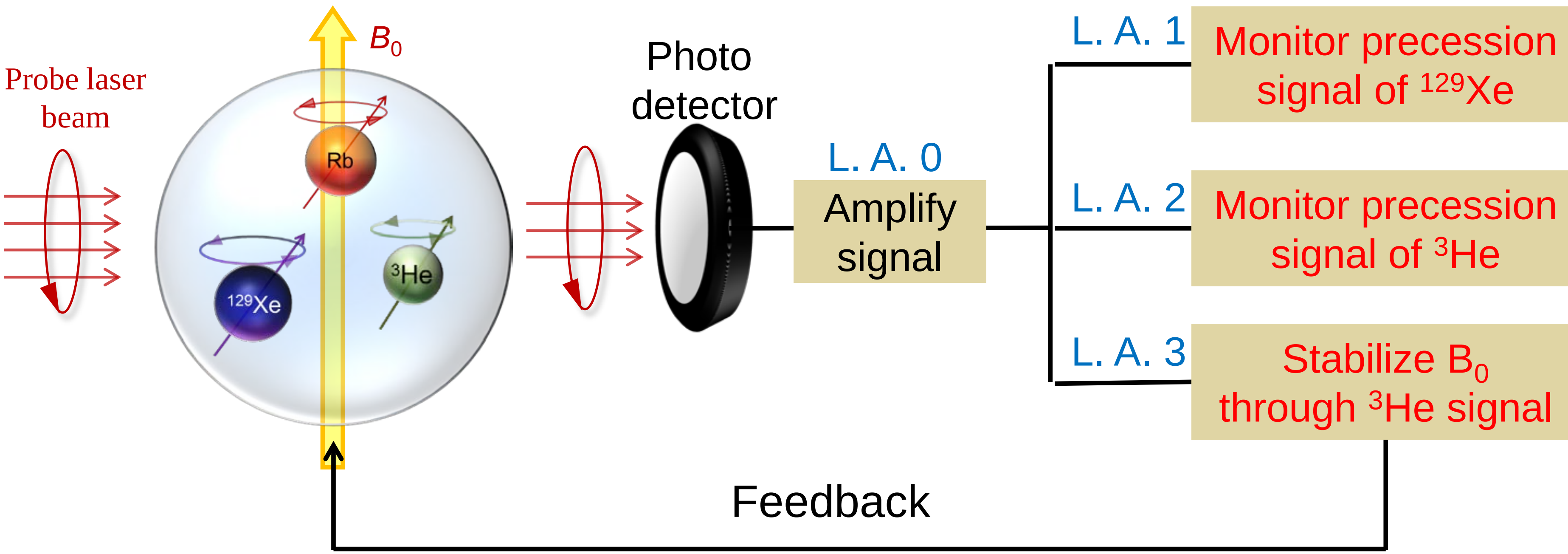
EDM is roughly proportional to Z^2

➡ Negligible EDM in ^{3}He

Monitor & stabilize B_0

➡ Suppress systematic uncertainty

Principles of ^{3}He co-magnetometer



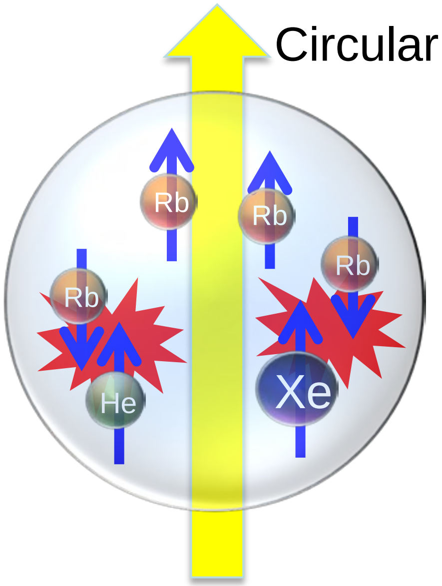
$$\phi_{Xe}(t) = \gamma_{Xe} \underline{B_0} t \quad \longrightarrow \quad \phi_{Xe}(t) = \frac{\gamma_{Xe}}{\gamma_{He}} \phi_{He}(t)$$

$$\phi_{He}(t) = \gamma_{He} B_0 t$$

$$\Leftrightarrow \quad B_0 = \frac{\phi_{He}(t)}{\gamma_{He} t}$$

Enable to measure precession signal of ^{129}Xe under locked B_0

Production of Polarization of ^{3}He



$$P_{He} = P_{Rb} \frac{\gamma_{se}^{He}}{\gamma_{se}^{He} + \Gamma_{sd}^{He}} [1 - \exp\{-(\gamma_{se}^{He} + \Gamma_{sd}^{He})t\}]$$

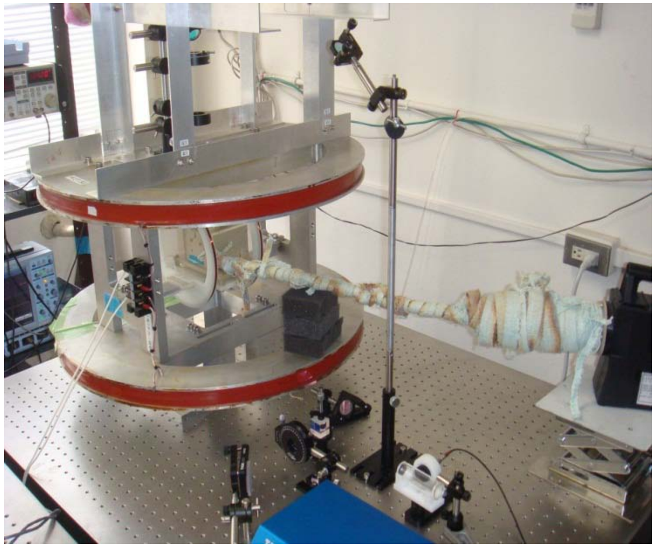
γ_{se}^{He} : spin exchange ratio

Γ_{sd}^{He} : relaxation ratio

GE180 cell :
Low magnetic impurity
Low leakage of ^{3}He

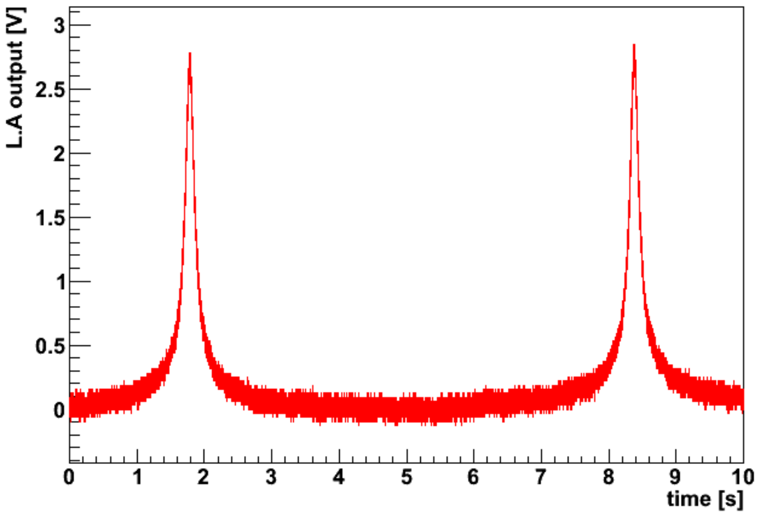
Enclosed
^{129}Xe : 50 Torr
N_2 : 100 Torr
He : 470 Torr
Rb : ~1 mg

Production of Polarization of $^{3}He/^{129}Xe$ cell



Checked by AFP-NMR measurement

(Adiabatic Fast Passage
Nuclear Magnetic Resonance)



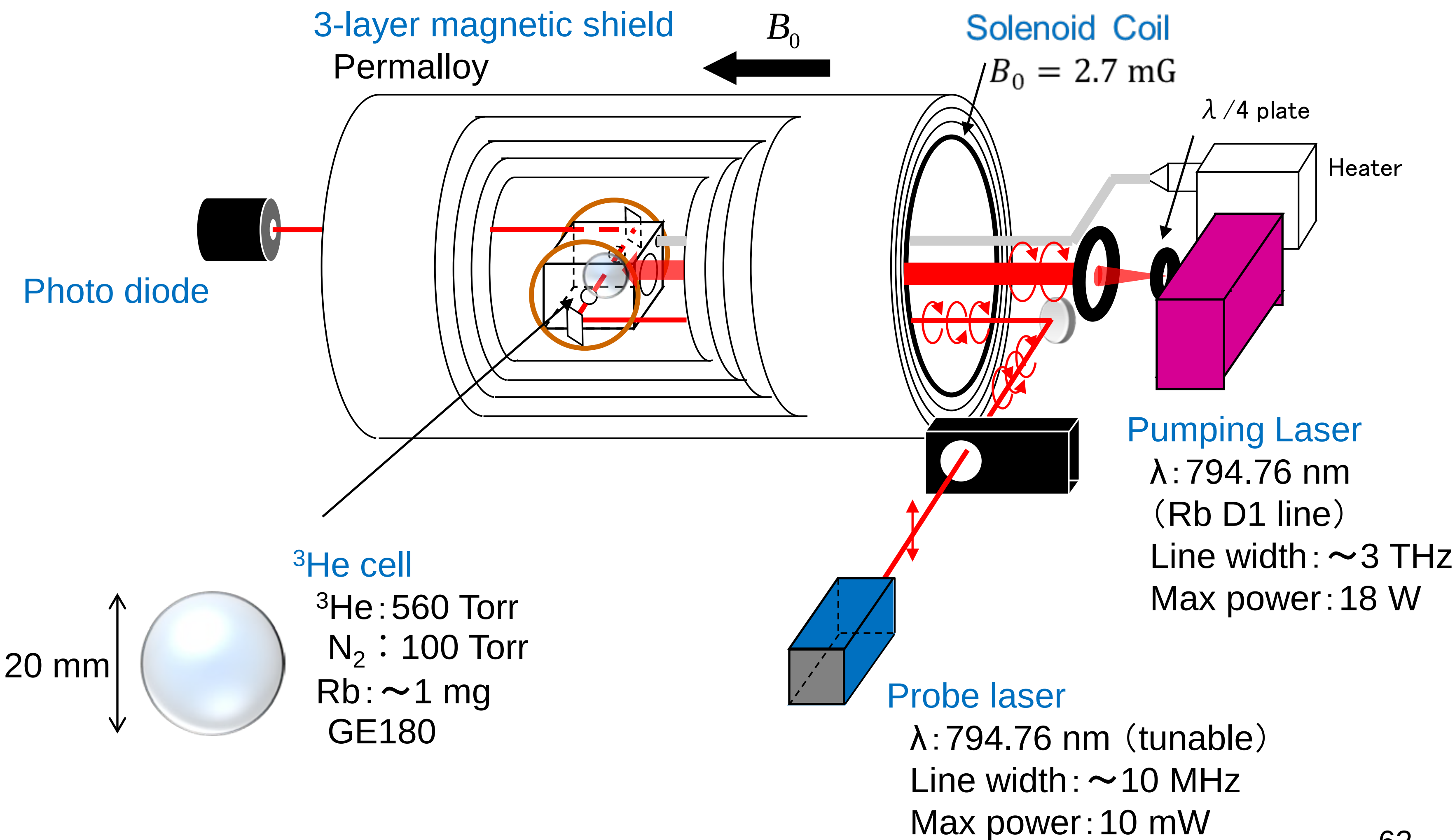
Typically

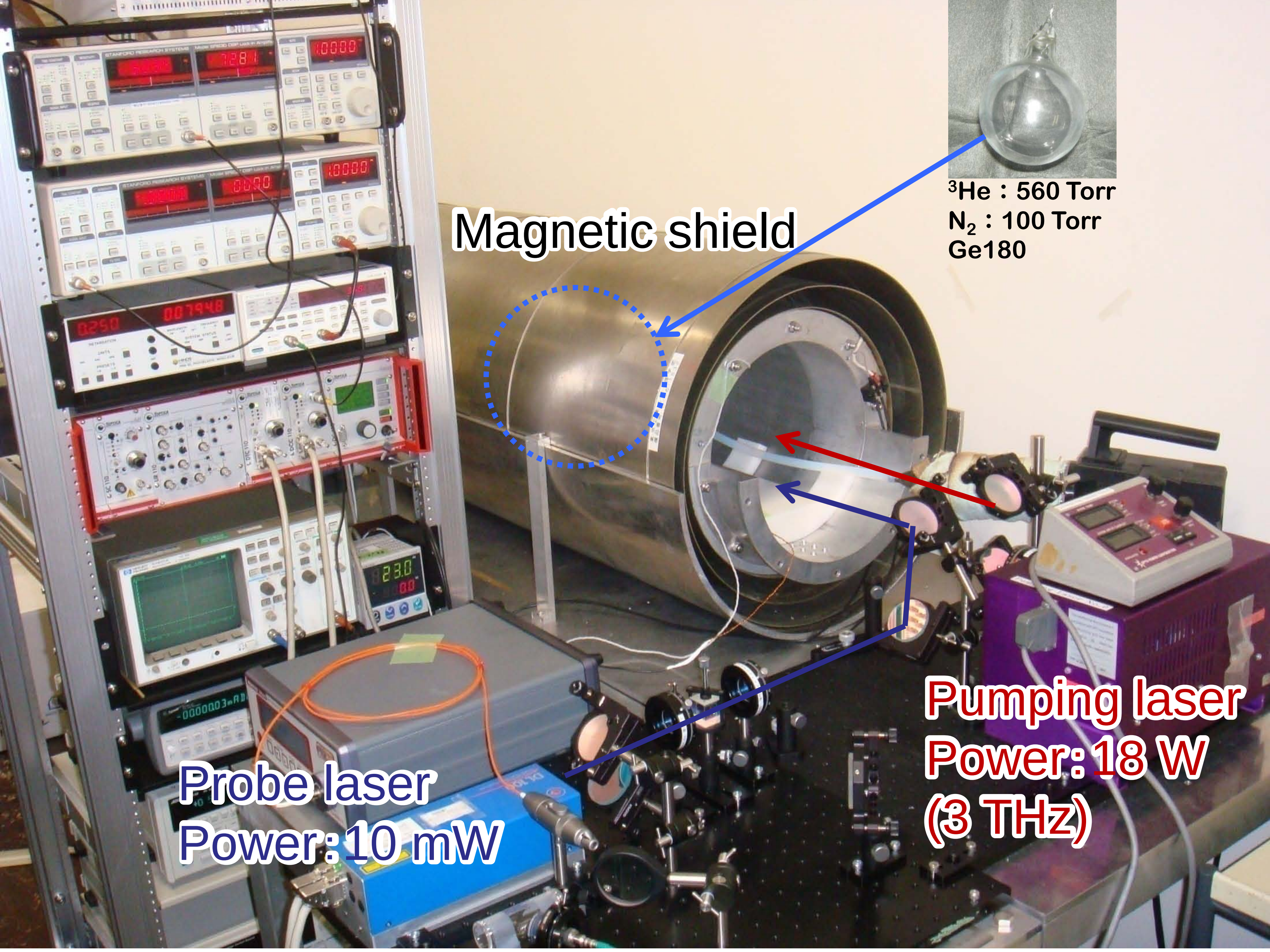
$P(^{3}He) = \sim 3\ \%$

$T_1(^{3}He) = 100$ hours

@ 100 ℃

Experimental setup for ^{3}He maser oscillation test

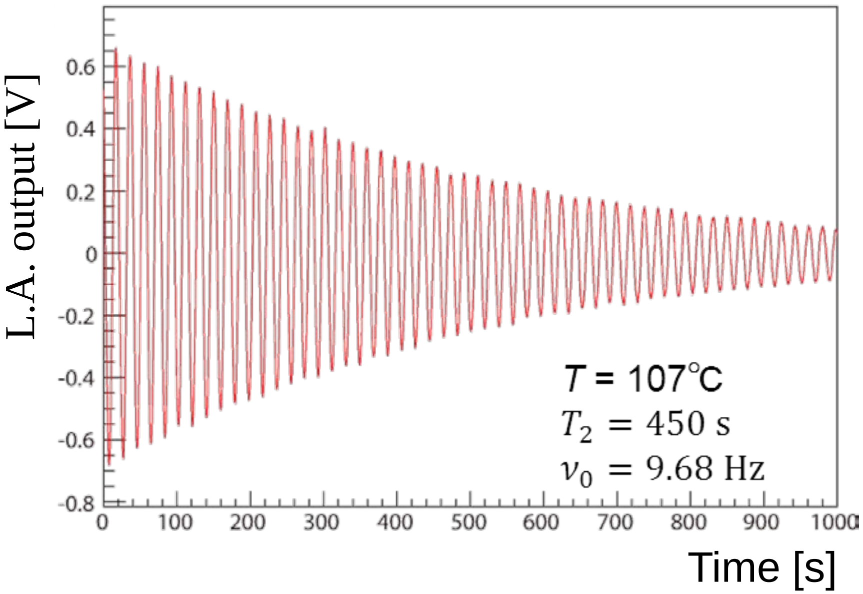




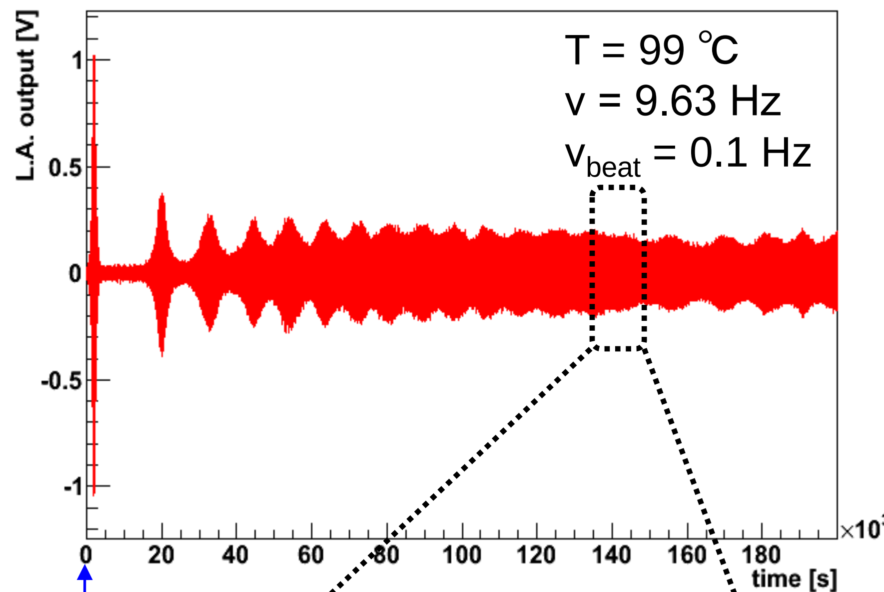
Magnetic shield
^3He : 560 Torr
N_2 : 100 Torr
Ge180
Pumping laser
Power: 18 W
(3 THz)
Probe laser
Power: 10 mW

Maser Oscillation of ^{3}He

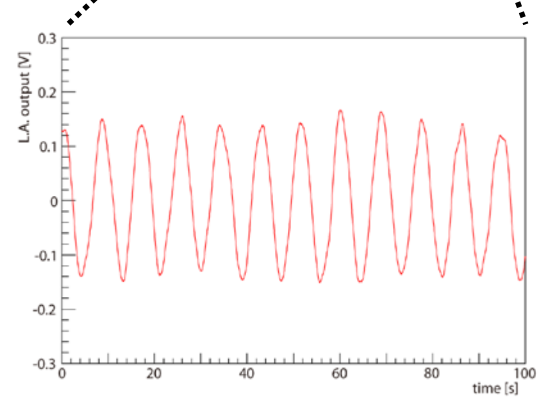
Free induction decay



Maser oscillation

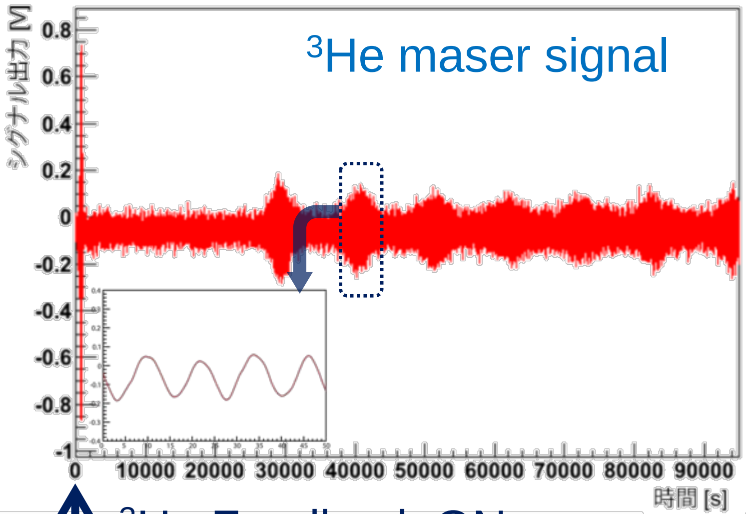


Feedback ON

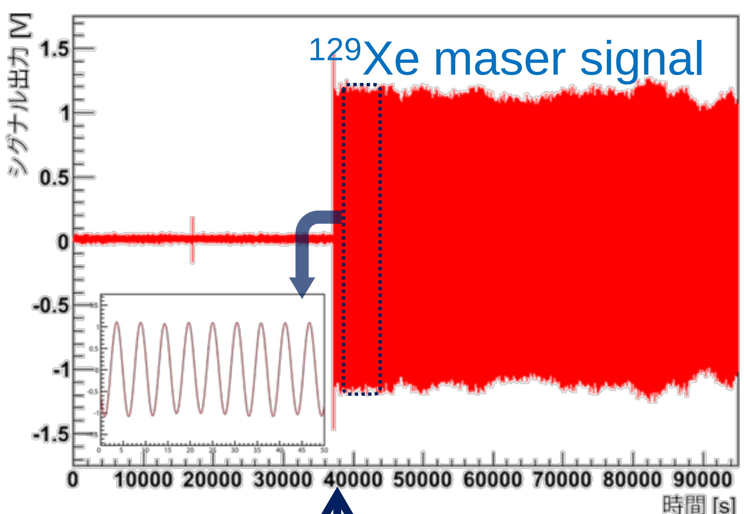


Succeeded in optical detection

Concurrent operation of $^{129}Xe/^{3}He$



↑ ^{3}He Feedback ON



↑ ^{129}Xe Feedback ON

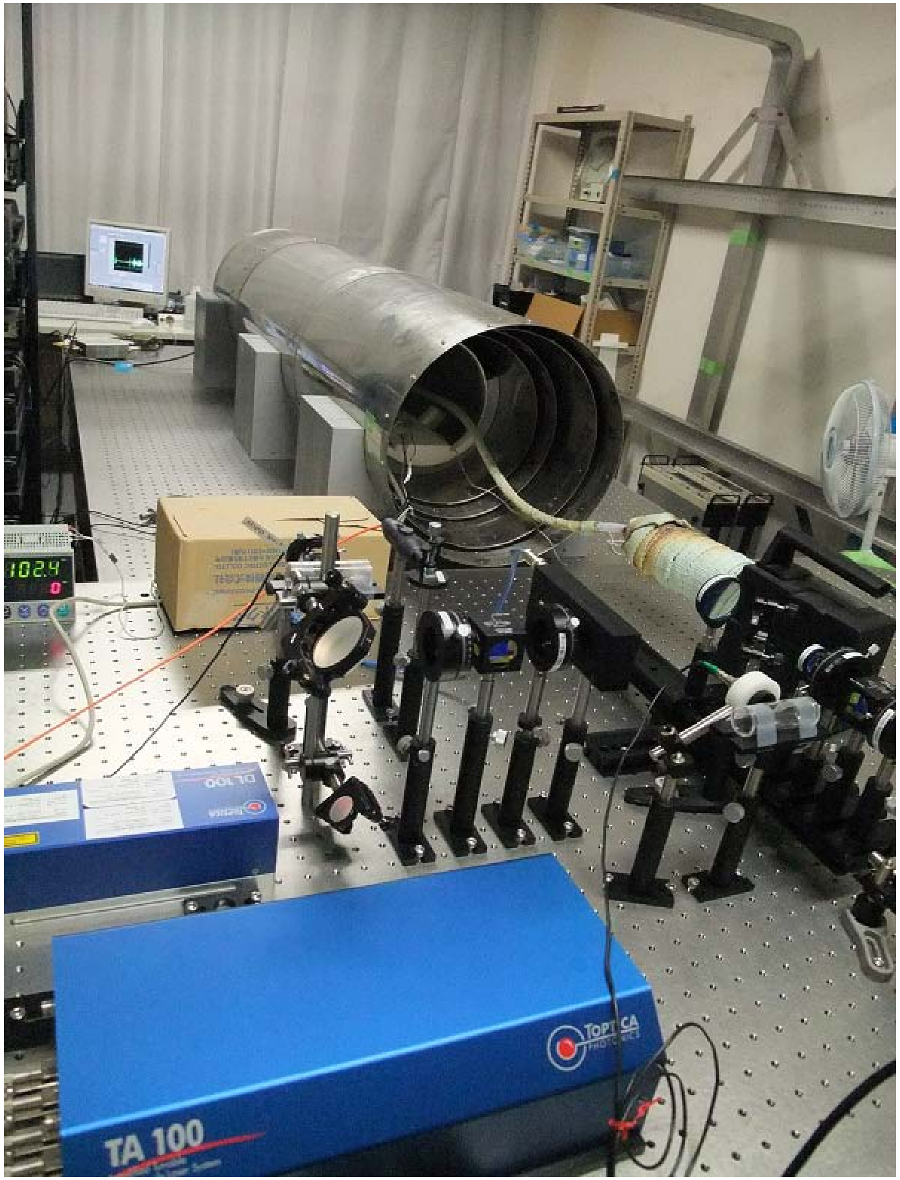
(Preliminary) Freq. Precision

$$\Delta\nu_{\mathrm{He}} \sim 600\ \mathrm{nHz}$$
$$\Delta\nu_{\mathrm{Xe}} \sim 50\ \mathrm{nHz}$$

(For 100 s average)

Enclosed
^{129}Xe : 10 Torr
N_2 : 100 Torr
He : 470 Torr
Rb : ~1 mg

Experimental setup for EDM measurement



Major improvement

TADFB laser
Power : 1 W, Width : 10 MHz

Vibration isolated table

Stabilization of Env. field

Stabilization of static field

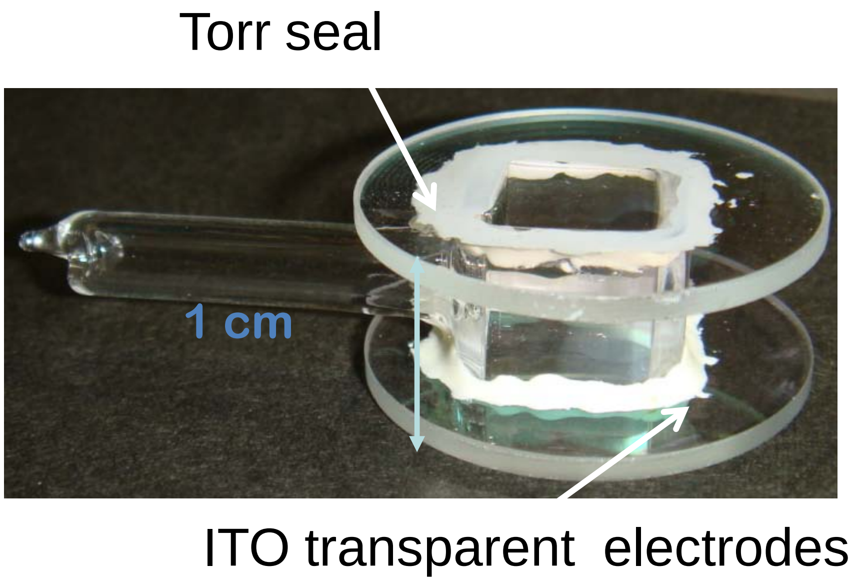
Present aim

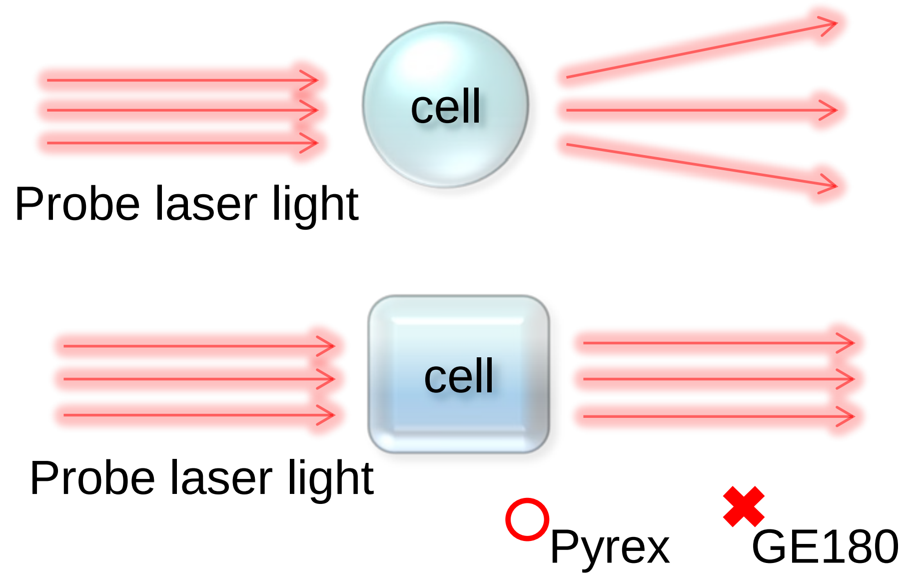
$\delta\nu(^{129}\mathrm{Xe}) \sim < 10\ \mathrm{nHz}$

$\delta\nu(^{3}\mathrm{He}) \sim < 10\ \mathrm{nHz}$

Future Perspective

$^{129}Xe/^{3}He$ cell for EDM measurement





・Gas pressure

^{129}Xe	:	1 Torr
^{3}He	:	470 Torr
N_2	:	100 Torr
Rb	:	～1 mg

・Pyrex cubic shaped glass

・SurfaSil coating

New magnetic shield

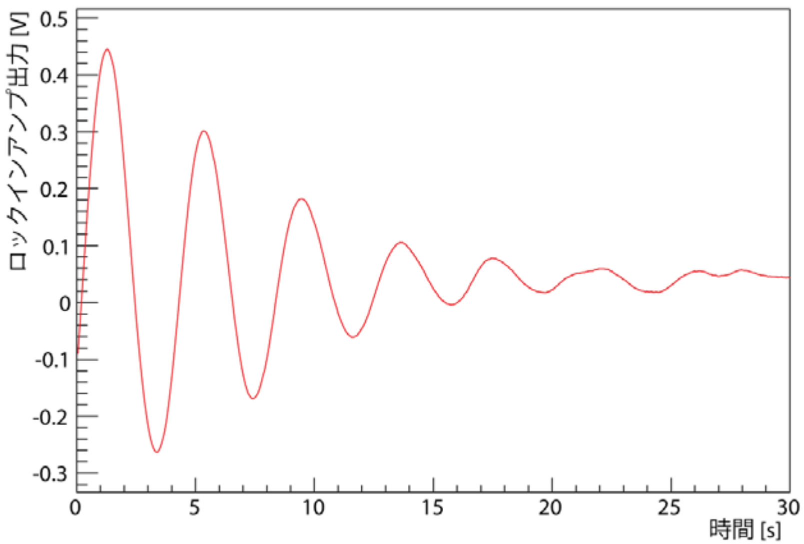
New 3-layer magnetic shield

- Outer: 800mmΦ × 1300mm × 2mm^t
- Middle: 600mmΦ × 1000mm × 2mm^t
- Inner: 400mmΦ × 680mm × 2mm^t
- Caps for each layer

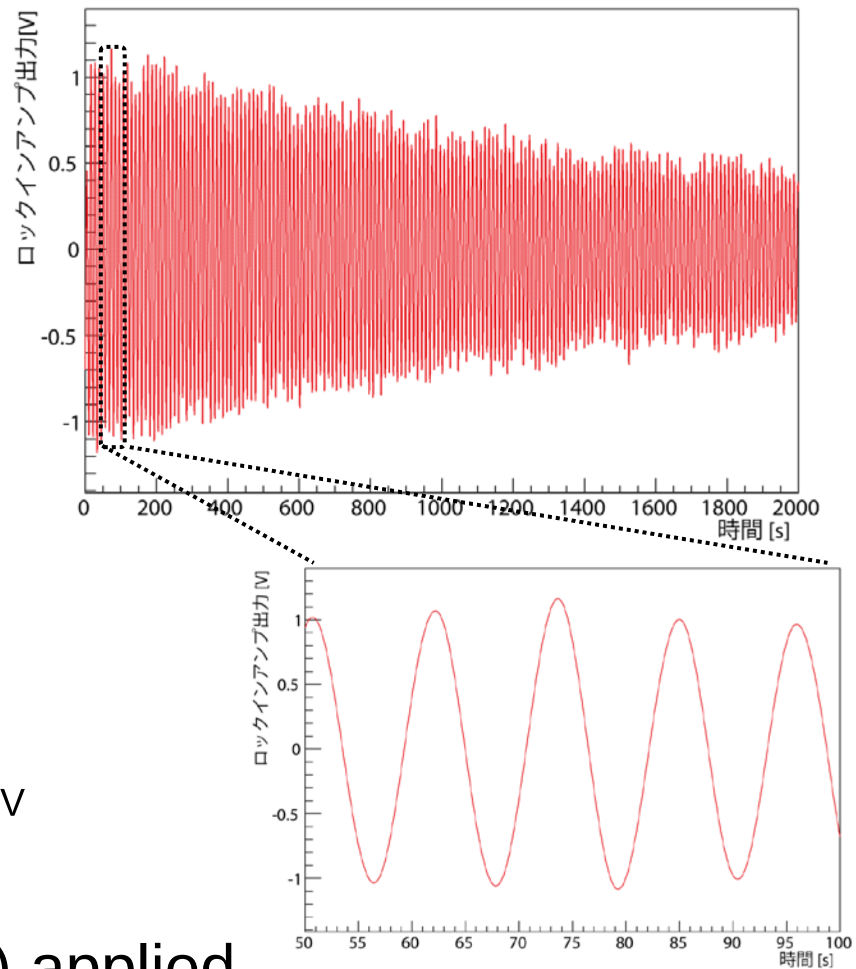
Residual field
$|B|$ < few 10 μ Gauss
Shielding factor ～ 10^4
Cf.) ～ 10^3 for old one

$^{129}Xe/^{3}He$ double spin detection

Xe



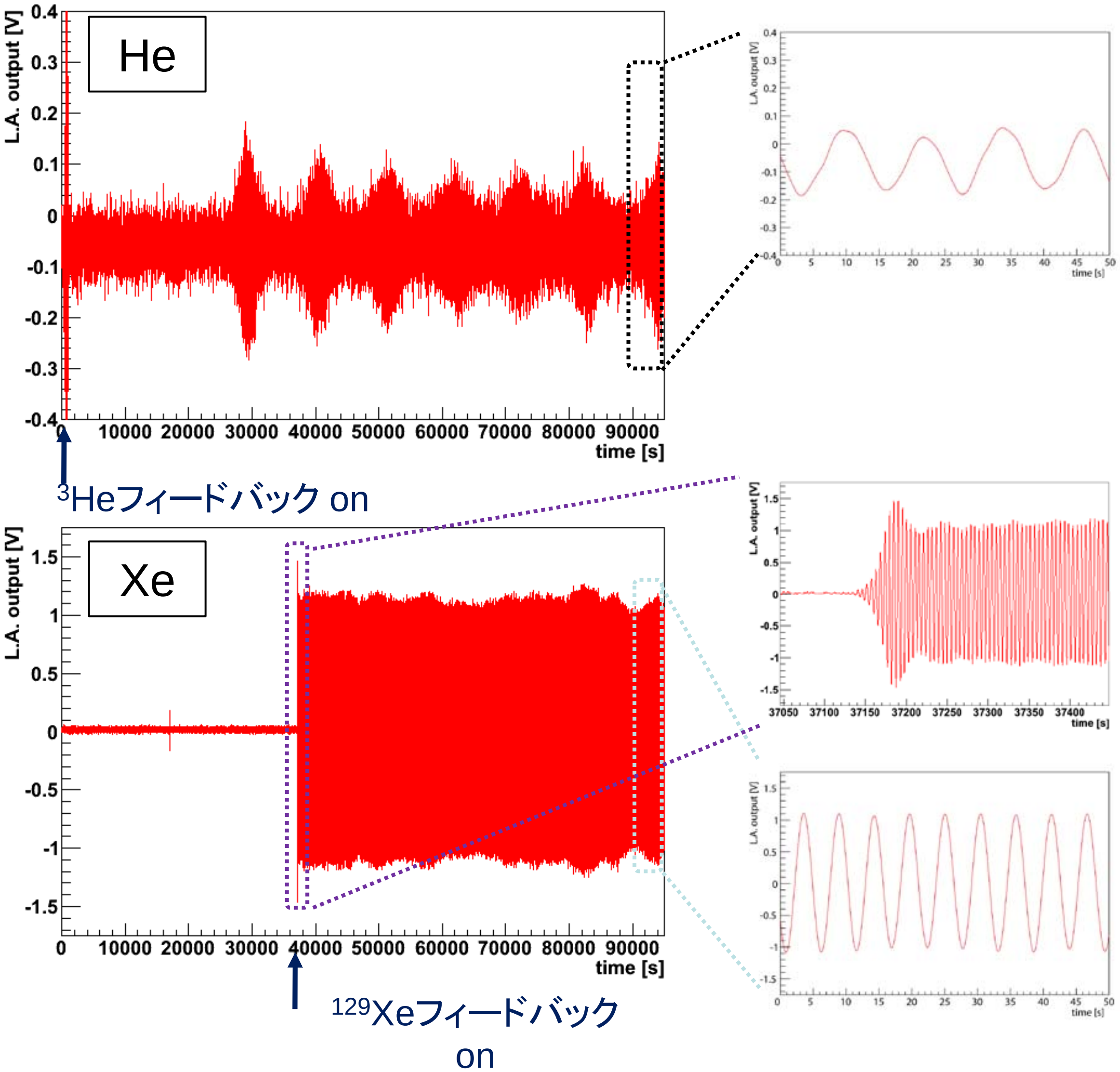
He



Temperature：103 ℃
Xe：10 Torr、He：470 Torr
$T_2(^{129}Xe)$～7 s、$T_2(^{3}He)$～2000 s
$\nu(^{129}Xe)$～4.0 Hz、$\nu(^{3}He)$～10.7 Hz
[Lock-in]　T.C. (^{129}Xe)：300 ms、T.C. (^{3}He)：1 s
[signal before ampl]　$V(^{129}Xe)$～250μV、$V(^{3}He)$～25μV

Pulses with $\nu(^{129}Xe)$ and $\nu(^{3}He)$ applied.
⇒Double spin detection
⇒$^{129}Xe/^{3}He$ double spin maser

Operation of a ^{129}Xe/^{3}He double-spin maser



Temperature：103 ℃
Xe：10 Torr
He：470 Torr
N_2：100 Torr

$\nu_{feedback}$ (^{129}Xe)= 3.75 Hz
ν_{beat} (^{129}Xe)∼ 0.2 Hz
$\nu_{feedback}$ (^{3}He)= 10.53 Hz
ν_{beat} (^{3}He)∼ 0.1 Hz

[Lock-in amplifier]
Time const (^{129}Xe)：300 ms
Time const (^{3}He)：1 s
[signal before amplification]
V(^{129}Xe)∼250μV
V(^{3}He)∼2.5μV

Summary

- Precession of ^{129}Xe spins is maintained for unlimitedly long times, by application of a feedback field generated from optically detected spins. The merit of this optically coupled spin maser as a scheme for the EDM search is the capability of operation at very low B_0 fields, as mG or below.
- Sources of frequency drifts have been identified, and steps taken to overcome them, such as (1) the current source renewal, (2) adoption of low cell temperatures, (3) installation of a field compensation system, and (4) development of a Rb NMOR magnetometer and ^{3}He co-magnetometer.
- Frequency precision presently reached is **7.9 nHz**, which corresponds to an EDM sensitivity of 8×10^{-28} ecm (E=10kV/cm).
- EDM cell equipped with transparent electrodes was prepared.
- ^{3}He co-magnetometer is being developed, and recently the operation of a ^{3}He/^{129}Xe double-spin maser has been tested.