2^{nd} Conference on Advances in Radioactive Isotope Science (ARIS 2014)
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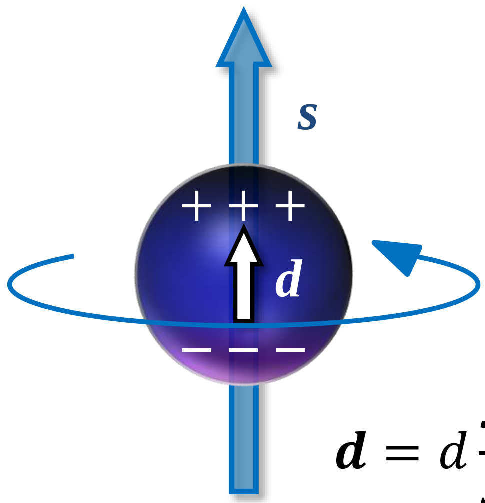
^{129}Xe EDM search experiment using active nuclear spin maser

Tokyo Institute of Technology
Tomoya SATO

EDM, the new physics indicator

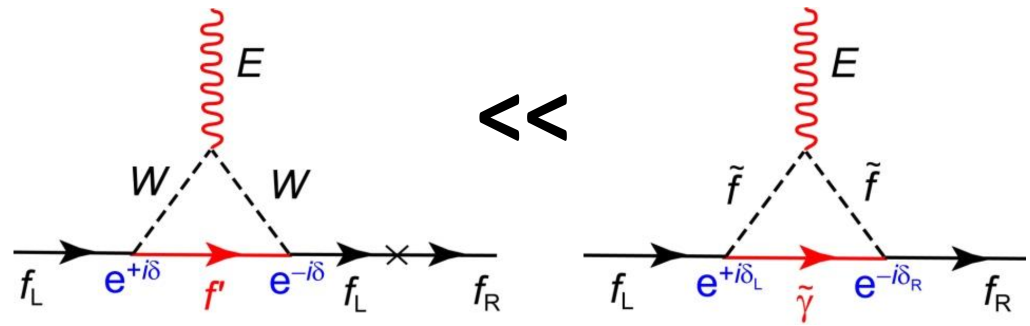
Electric dipole moment



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

T-violation

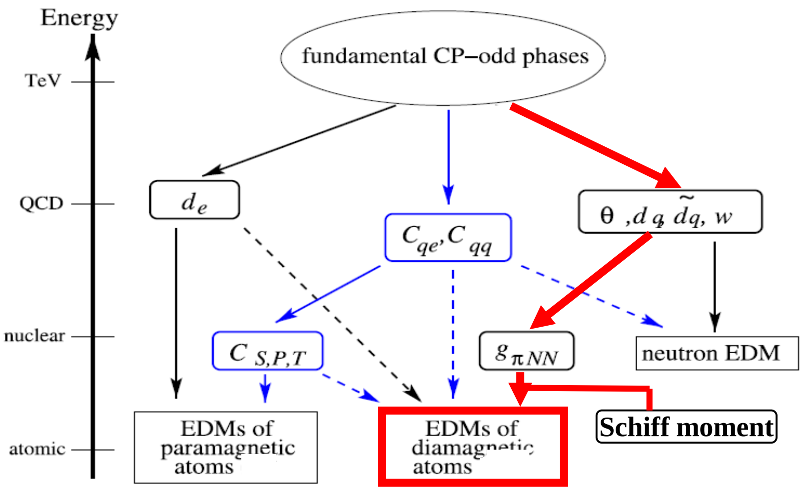
matter Anti-matter



Standard Model Supersymmetry

Discovery of the finite value of the EDM

Discovery of the new physics beyond the SM!!



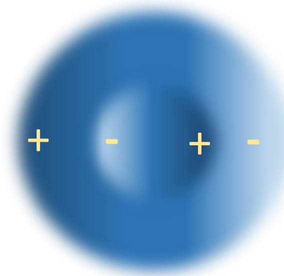
Tl, Fr, Cs··· ^{129}Xe, ^{199}Hg, Rn, Ra···

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

The atomic EDM of the ^{129}Xe

- EDM is generated through the Schiff moment
  (P,T–odd NN interaction, reflect nuclear structure)
- Stable nuclei, huge amount of atoms (∼10^{23})

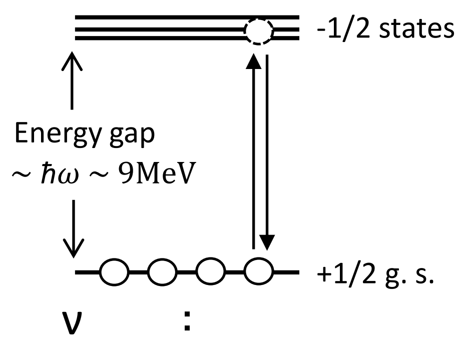
Schiff moment

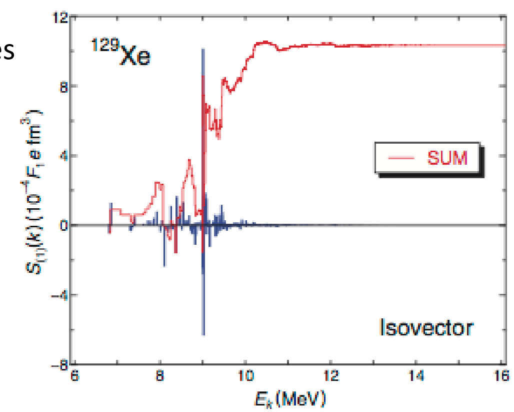


$$\hat{\boldsymbol{S}}_{\rm ch} = \frac{1}{10}\sum_{i=1}^{A} e_i\left(r_i^2 - \frac{5}{3}\langle r^2\rangle_{\rm ch}\right)\boldsymbol{r}_i$$

- From a shell model point of view

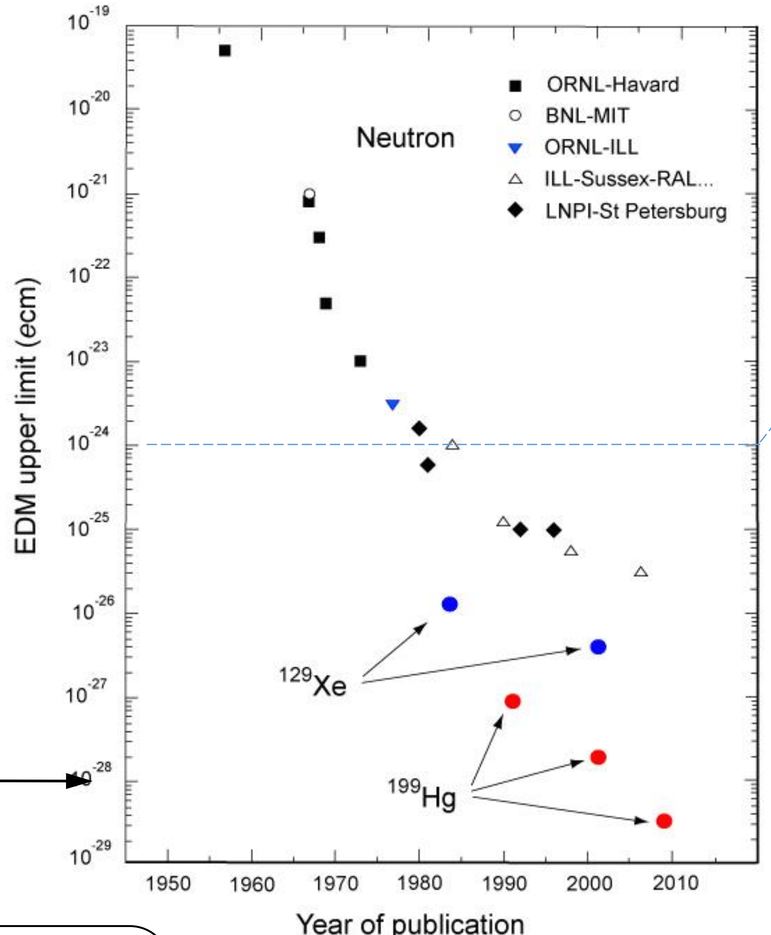
N. Yoshinaga et al.
Phys. Rev. C 87, (2013) 044332



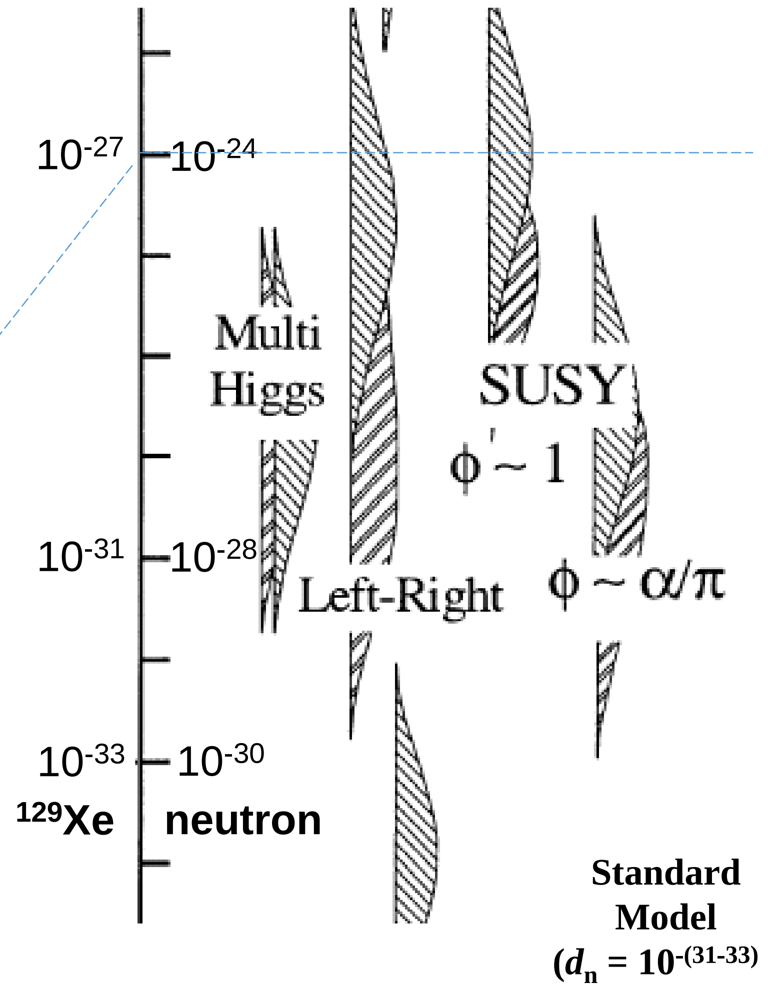


$$S(k) = \sum_{k=1} \frac{\left\langle \frac{1}{2}^+_1 \middle| \hat{S}_{{\rm ch},z} \middle| \frac{1}{2}^-_k \right\rangle \left\langle \frac{1}{2}^-_k \middle| V_\pi^{PT} \middle| \frac{1}{2}^+_1 \right\rangle}{E_1^{(+)} - E_k^{(-)}} + {\rm c.\,c.}$$

Current status of the EDM searches



Prediction value of the EDM



Our target

$|d(^{129}Xe)| = 10^{-28} e\cdot cm$

$E = 10$ kV/cm

● $|d(^{199}Hg)| < 3.1\times 10^{-29}$ *ecm*

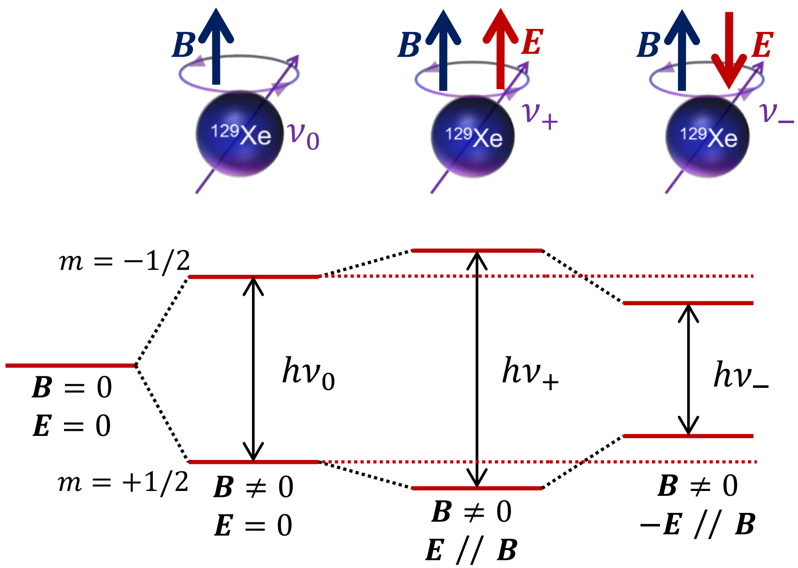
Griffith *et al.*, *PRL* 102 (2009) 101601

● $|d(^{129}Xe)| < 4.1\times 10^{-27}$ *ecm*

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

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

- Energy splitting changes due to the EDM



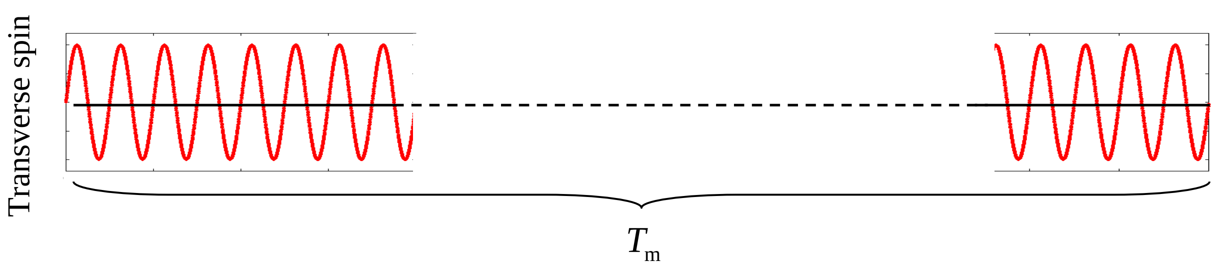
$$\nu_+ = \frac{2\mu B + 2dE}{h}$$

$$\nu_- = \frac{2\mu B - 2dE}{h}$$

$$d = \frac{h\Delta\nu}{4E}$$

$$(\Delta\nu = \nu_+ - \nu_-)$$

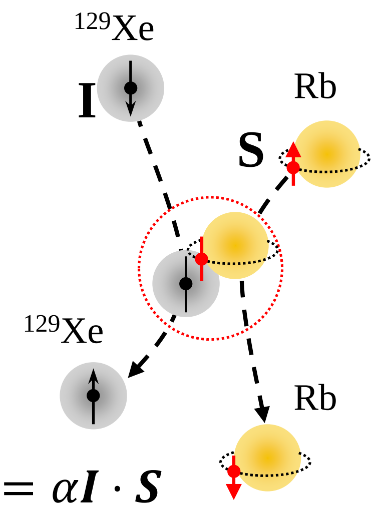
- Consecutive measurement of spin precession (Maser)



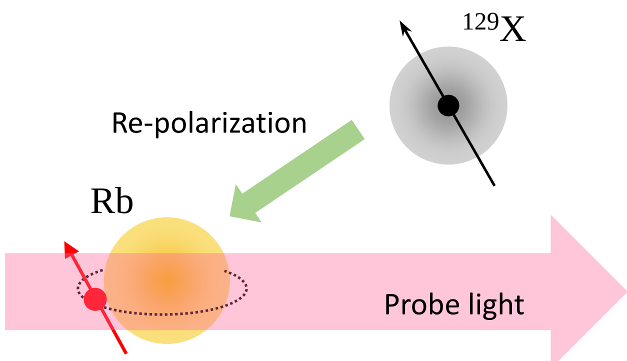
$$\delta\nu_\mathrm{final} \propto \frac{\delta\phi}{T_\mathrm{m}} = T_\mathrm{m}^{-3/2} : \left[\text{Fourier width} : \frac{1}{T_\mathrm{m}}\right] \times \frac{1}{\left[\text{data points} : T_\mathrm{m}\right]^{1/2}}$$

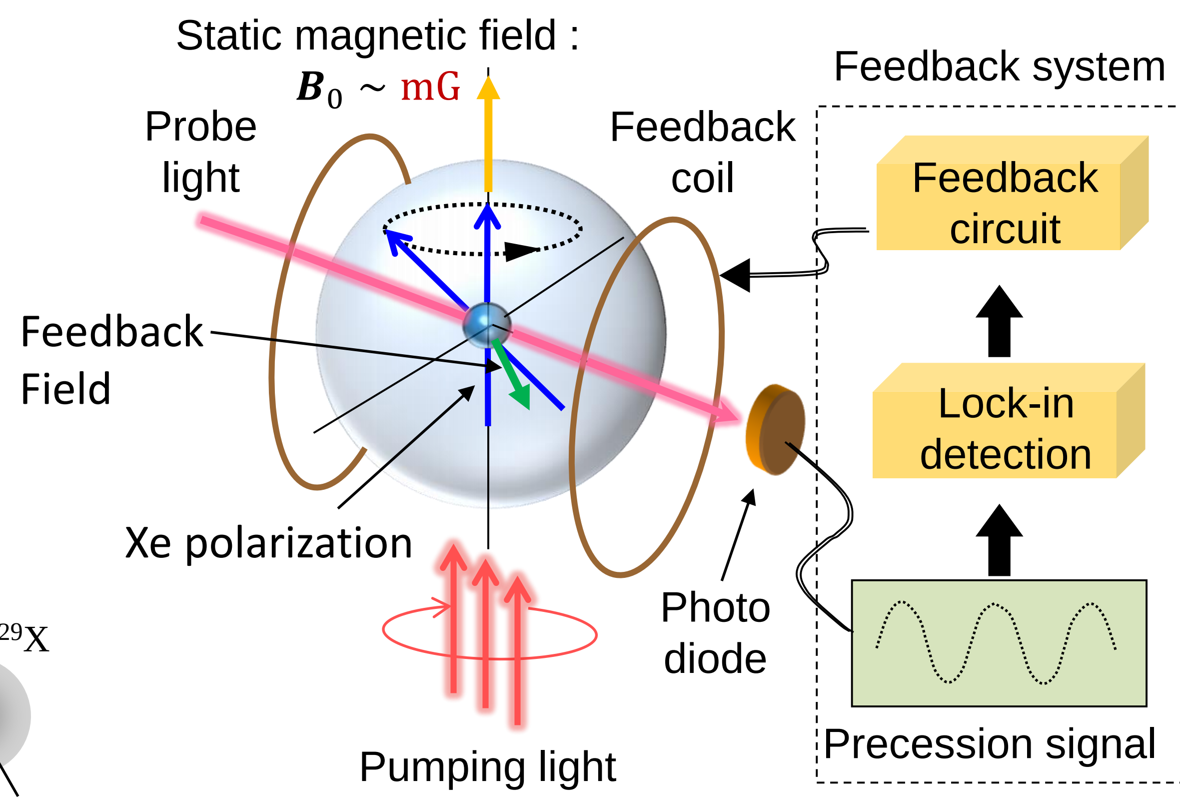
“Optically manipulated” spin maser

with a feedback field generated by optical spin detection



$$H = \alpha \boldsymbol{I}\cdot\boldsymbol{S} = \frac{\alpha}{2}(I_+S_- + I_-S_+) + \alpha I_z S_z$$



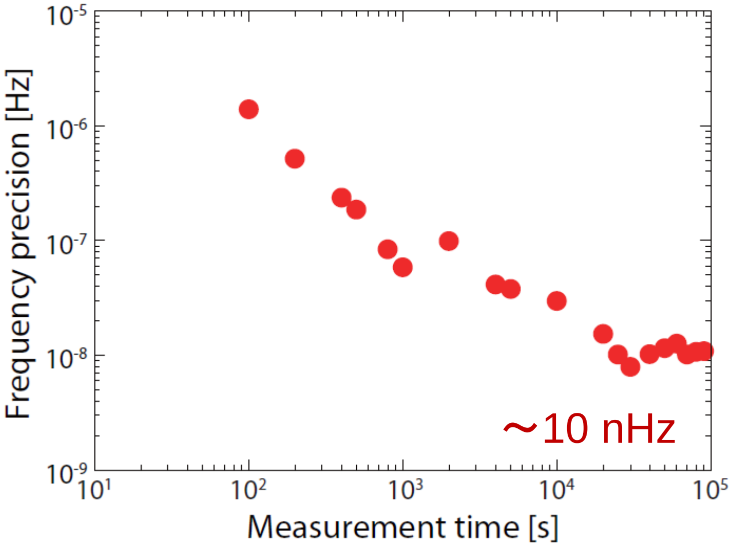


A. Yoshimi *et al.*, Phys. Lett. A 304 (2002) 13.
A. Yoshimi *et al.*, Phys. Lett. A 376 (2012) 1924.

Frequency precision of ^{129}Xe maser

Frequency precision
in one-shot measurement

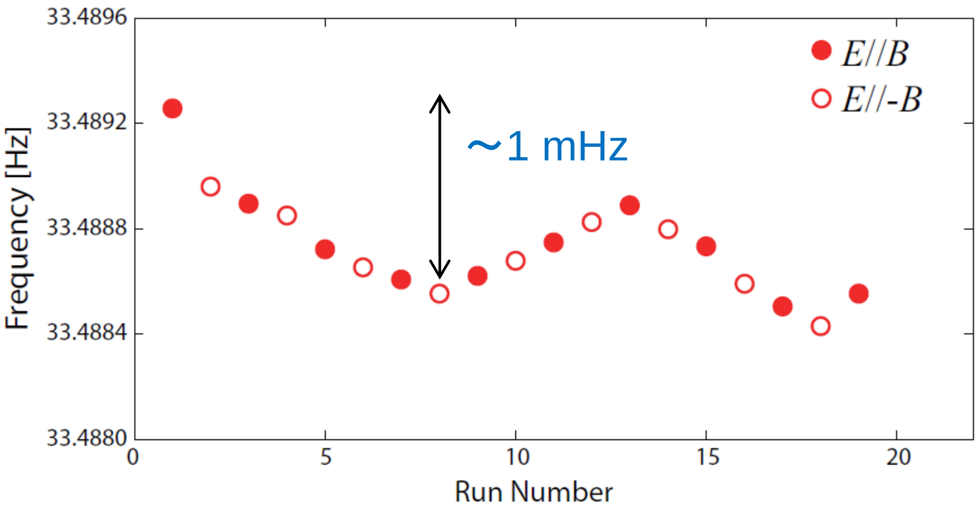
⇨ $\Delta\nu \sim 10$ nHz



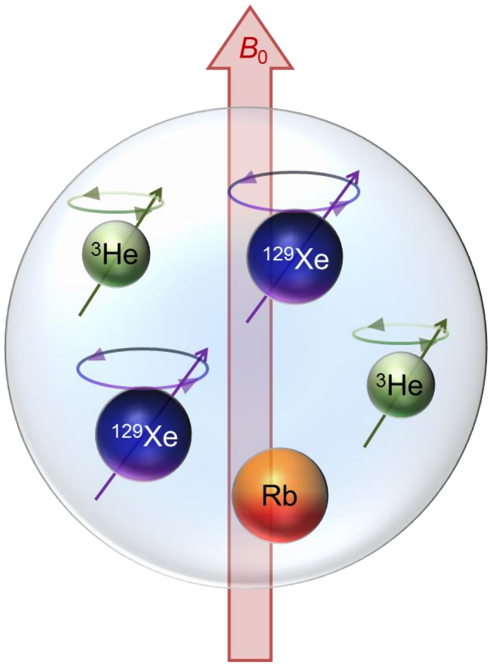
Frequency stability
between repeated
measurements

⇨ $\Delta\nu \sim 1$ mHz

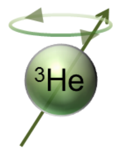
Long term drifts
of the external magnetic field



^{3}He co-magnetometry



- ^{129}Xe frequency: B_0 + EDM



- ^{3}He frequency: B_0

- *in situ* magnetometry
- Negligible EDM in ^{3}He
- Correlation in phase: $\Phi_{\mathrm{Xe}}(t) = \frac{\gamma_{\mathrm{Xe}}}{\gamma_{\mathrm{He}}}\Phi_{\mathrm{He}}(t)$

Contact interaction with pol. Rb atoms

$$\nu(^{129}\mathrm{Xe}) = \frac{\gamma(^{129}\mathrm{Xe})}{2\pi}\{B_0 + \kappa_{\mathrm{Rb-Xe}}[\mathrm{Rb}]P_{\mathrm{Rb}}\} \pm \frac{4d}{h}E$$

EDM factor

Static & Env. mag. field

Freq. shift due to pol. Rb

$$\nu(^{3}\mathrm{He}) = \frac{\gamma(^{3}\mathrm{He})}{2\pi}\{B_0 + \kappa_{\mathrm{Rb-He}}[\mathrm{Rb}]P_{\mathrm{Rb}}\}$$

※^{3}He EDM is assumed to be negligible

Frequency shift of ^{129}Xe/^{3}He due to contact interaction with polarized Rb

$$\Delta\nu \propto \kappa\,[\mathrm{Rb}]\,P_{\mathrm{Rb}}$$

Rb number density

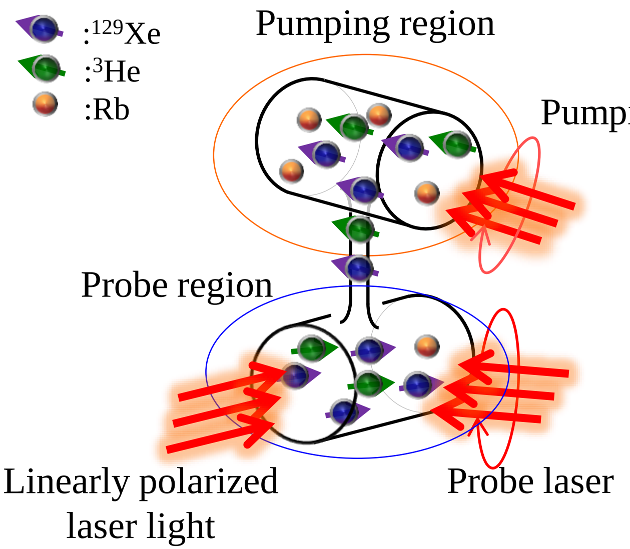
Rb Polarization

$$\begin{cases} \kappa_{0\ \mathrm{Xe-Rb}} = 493(31) & [1] \\ \kappa_{0\ \mathrm{He-Rb}} = 4.52 + 0.00934T & [2] \end{cases}$$

[1] Z. L. Ma *et al.*, Phys. Rev. Lett. 106, 193005 (2011)

[2] M. V. Romalis *et al.*, Phys. Rev. A 58, 3004 (1998)

Reduction of the pol. Rb atoms



$\Delta\nu_{Xe/He}$ (Maser frequency shift)
$\propto \kappa_{Xe/He}$ (Coefficient) $\times$ [Rb] $\times$ P_{Rb}

- Double cell geometry
- Linearly polarized laser light

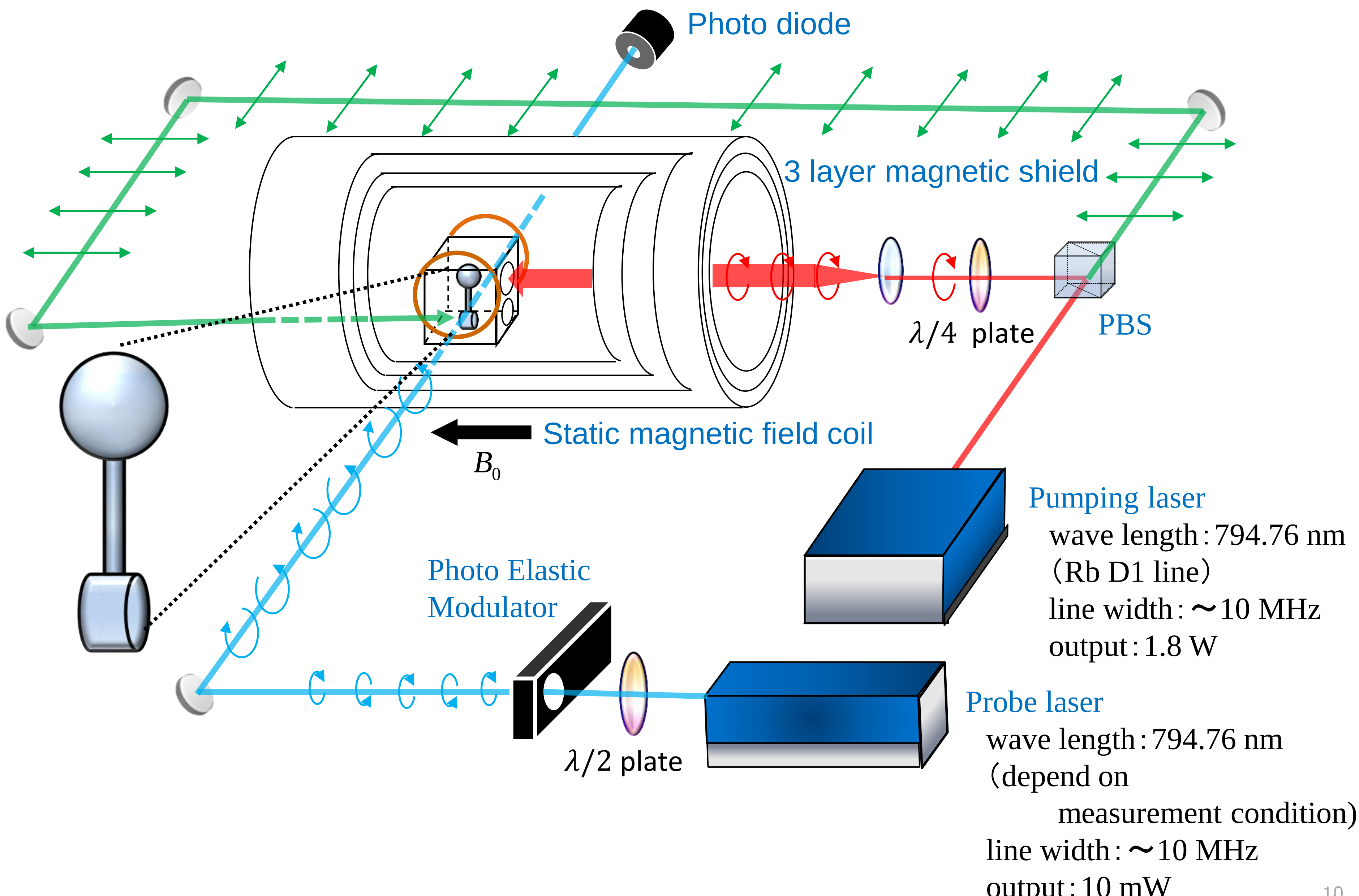
Advantages

- Reduce P_{Rb} at probe section
- Different temperature at pumping & probe sections

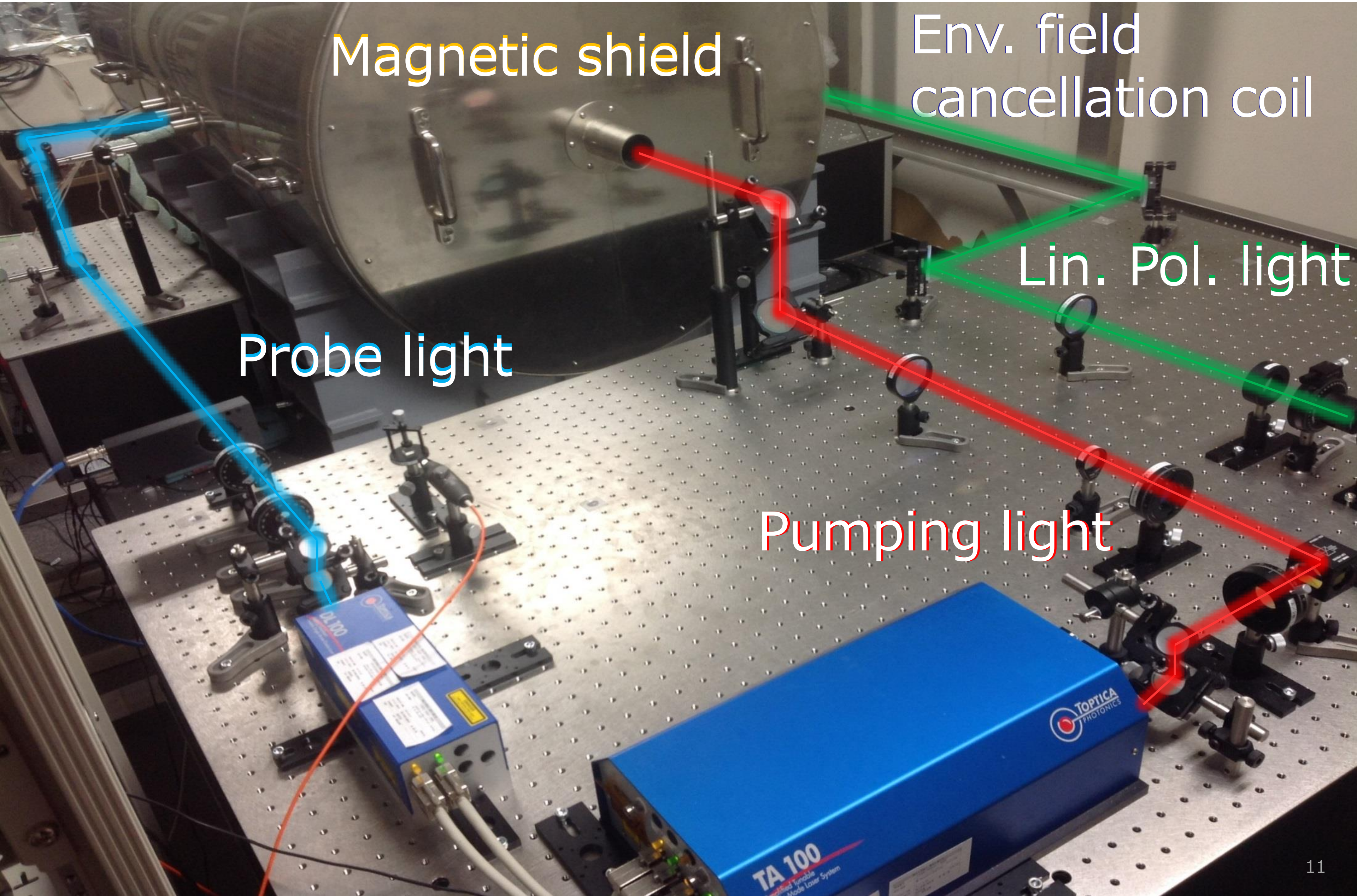
Difficulties

- Reduction of P (^{129}Xe) as diffusion
- Reduction of maser signal due to reduced P_{Rb}

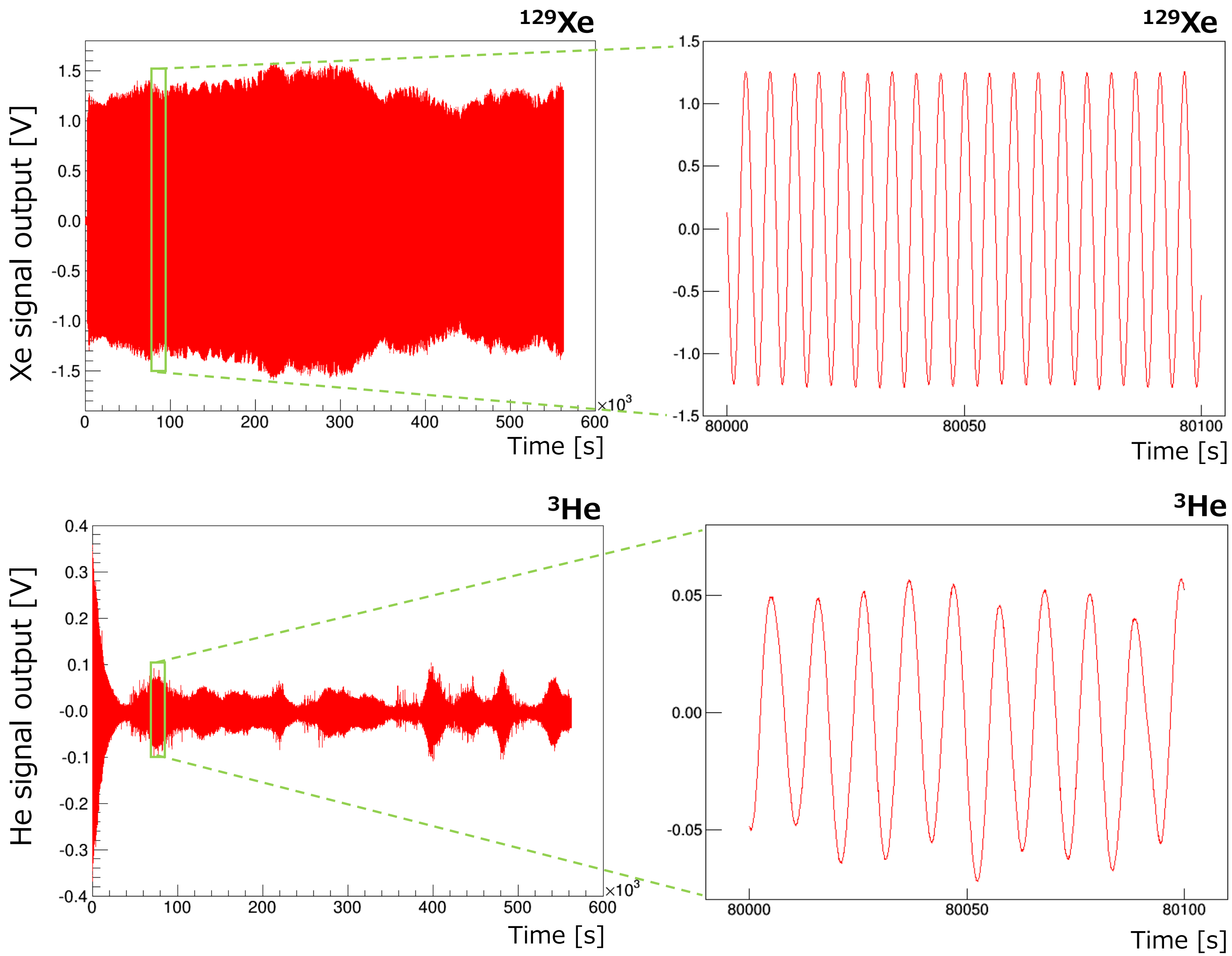
Experimental setup



Experimental setup



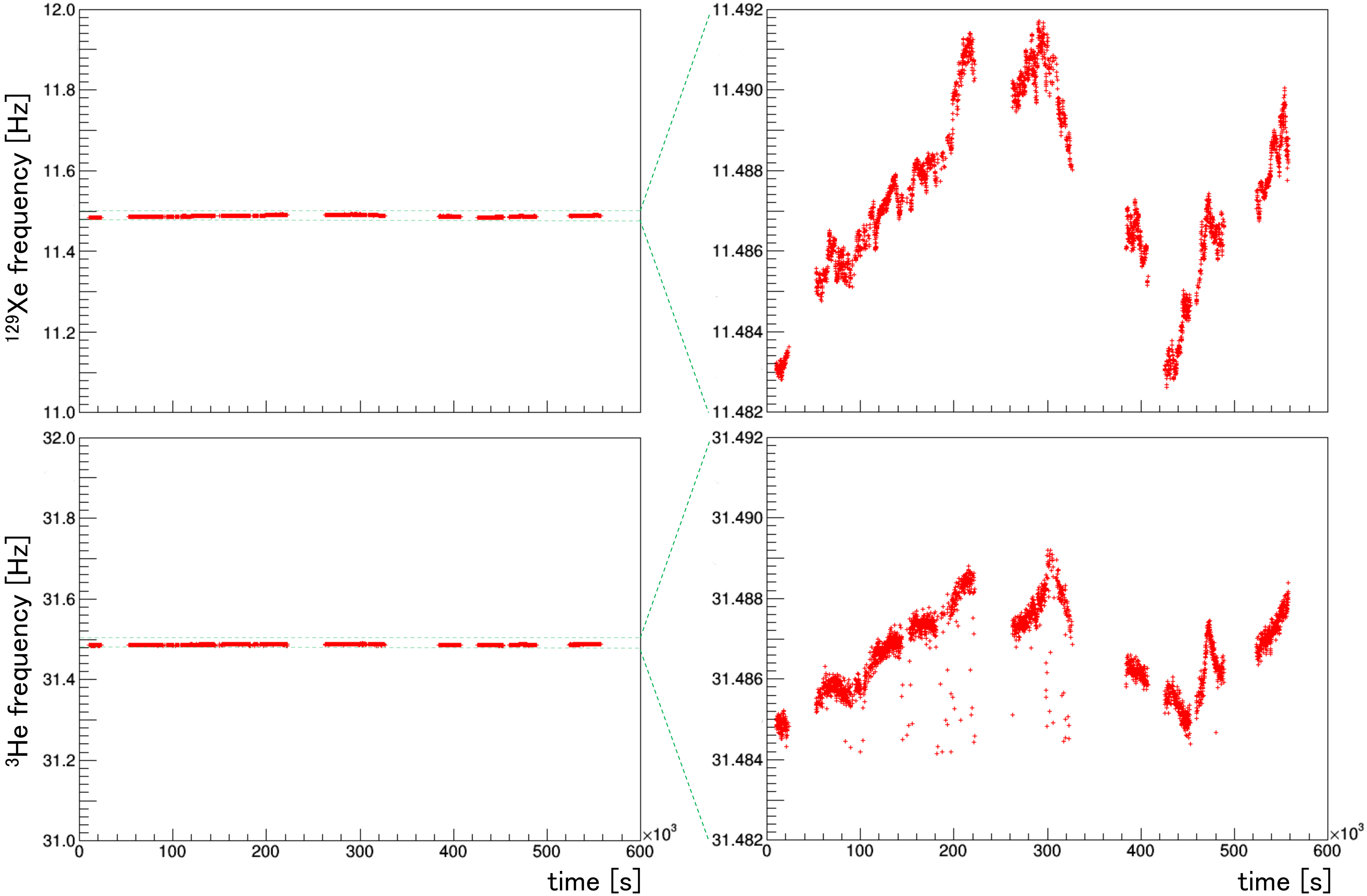
Dual spin maser with double cell geometry



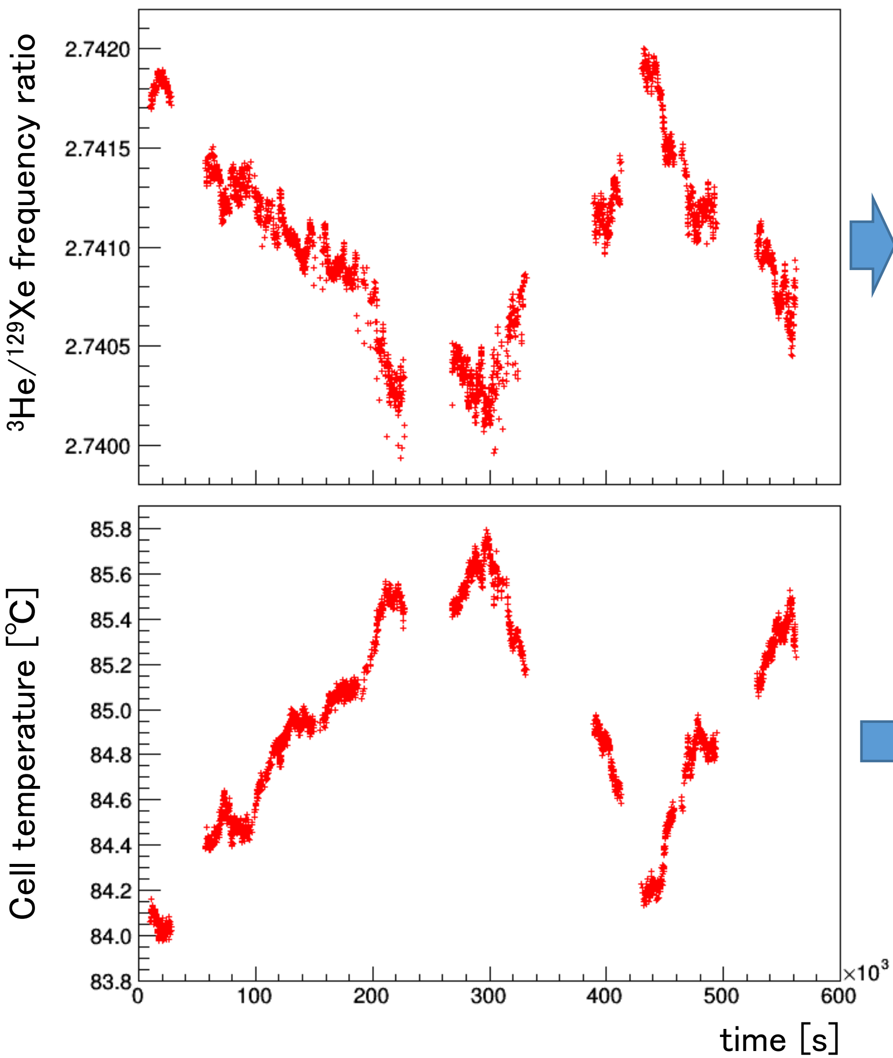
First trial of $^{129}Xe/^{3}He$ dual spin maser with double cell geometry

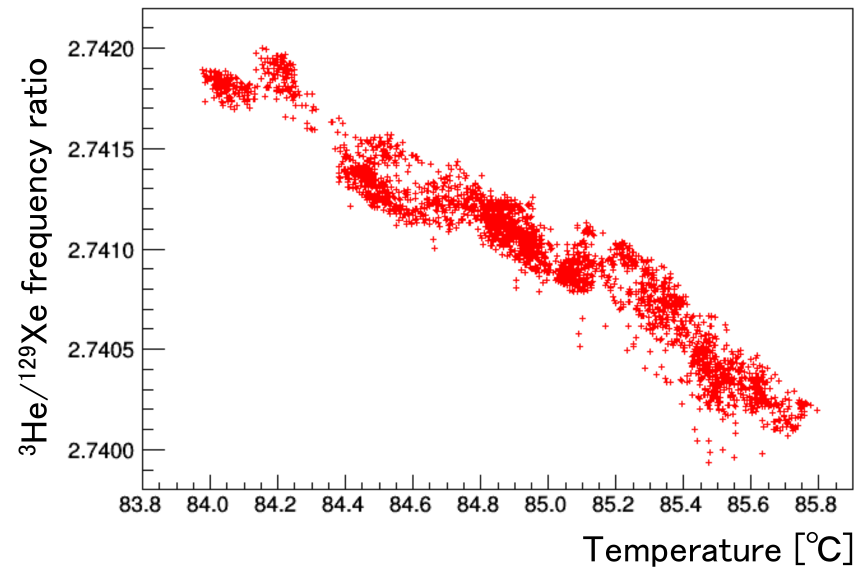
$^{129}Xe/^{3}He$ frequency analysis (1)

Maser frequencies (stable region, 100s averaged)



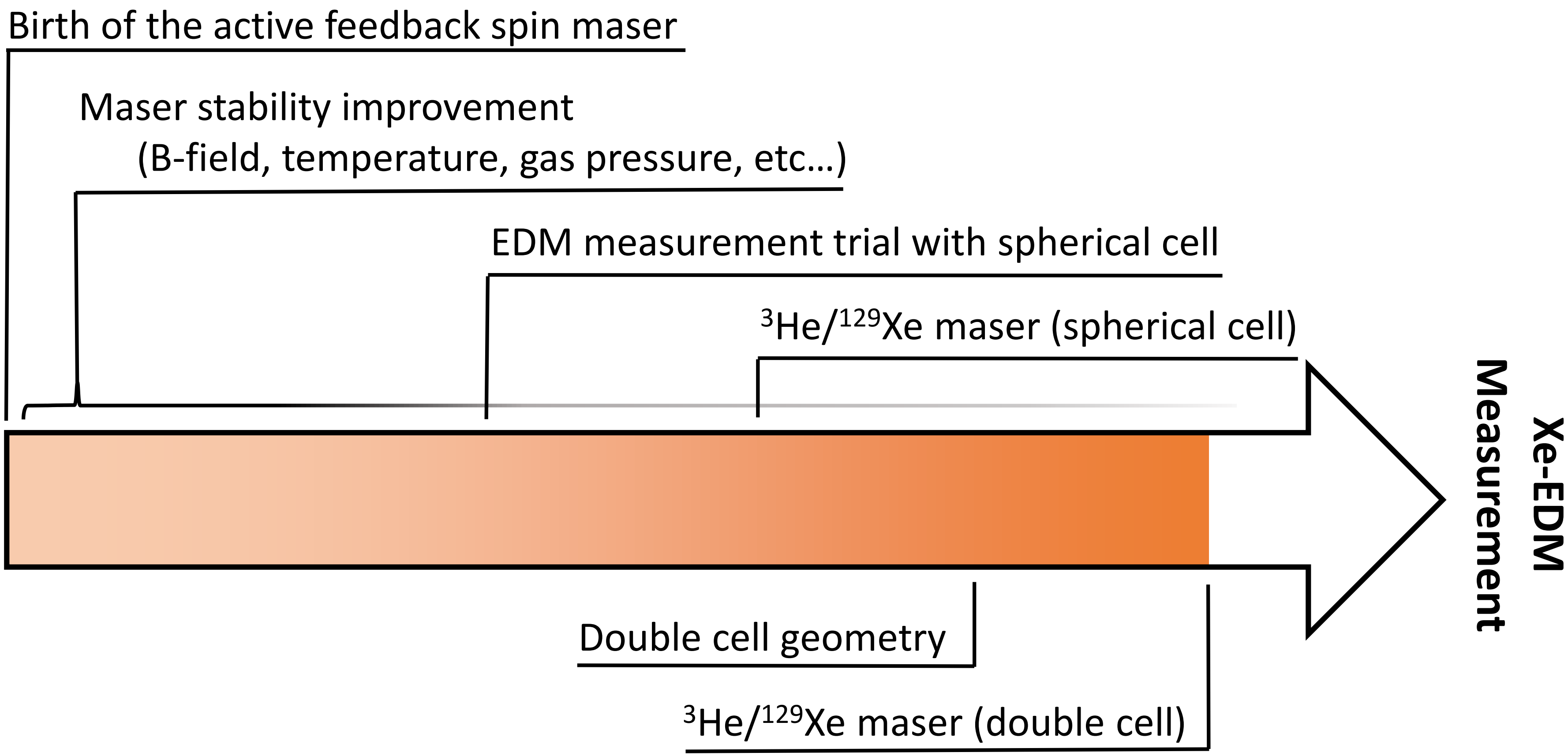
$^{129}Xe/^{3}He$ frequency analysis (2)





verification is continued.

Towards measurement of Xe-EDM



Remaining (on going) steps

- Verification of ^{3}He co-magnetometry
- Development of EDM cell with transparent electrodes

Summary and future plan

- Search for ^{129}Xe EDM aiming at 10^{-28} *e*cm region
- Active nuclear spin maser
  - ✓ Optical detection of spin + Artificial feedback
- Development
  - ✓ ^{3}He co-magnetometry (reduce B-field fluctuation)
  - ✓ Double-cell geometry (minimize interaction with pol. Rb)
  - ✓ Dual spin masers of ^{129}Xe/^{3}He using double cell
- Future outlook
  - ✓ Evaluation of systematic uncertainty
  - ✓ EDM cell (with Electrode) development
  - ✓ EDM measurement

Collaborators

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