Searching for the permanent electric dipole moment using laser-cooled francium atoms

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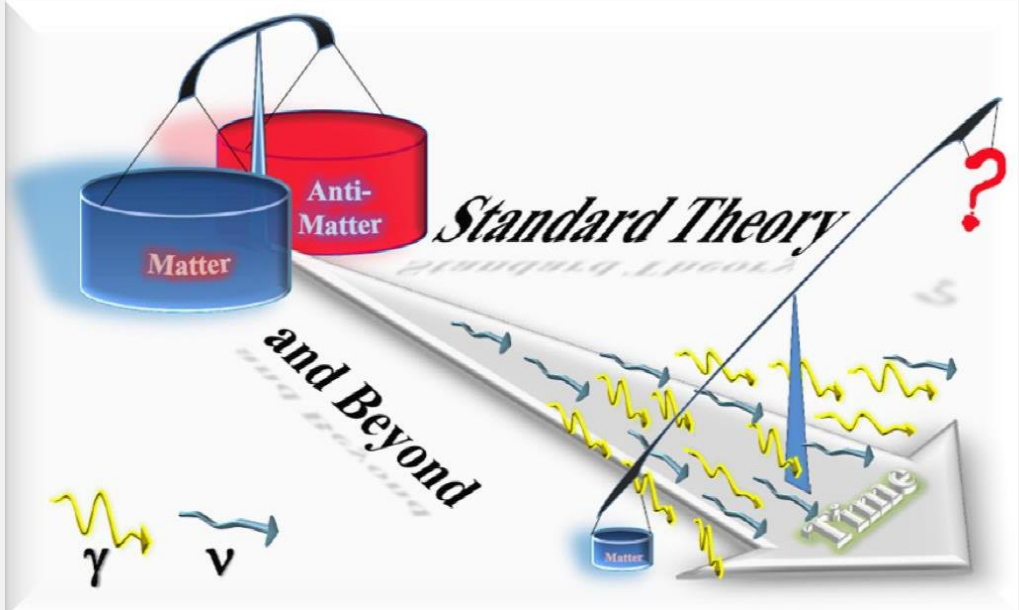
On behalf of the Fr EDM experiment@RIKEN

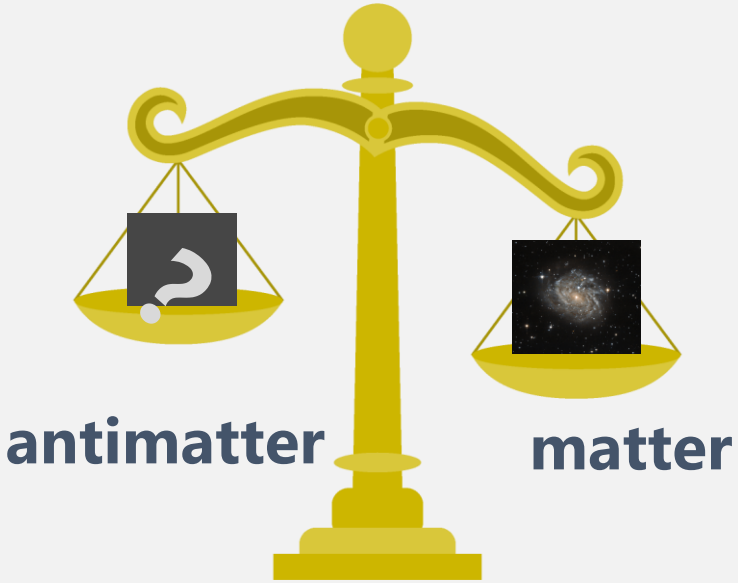
PSI2022

東京大学
THE UNIVERSITY OF TOKYO

RIKEN

Searching for CP violations beyond the SM



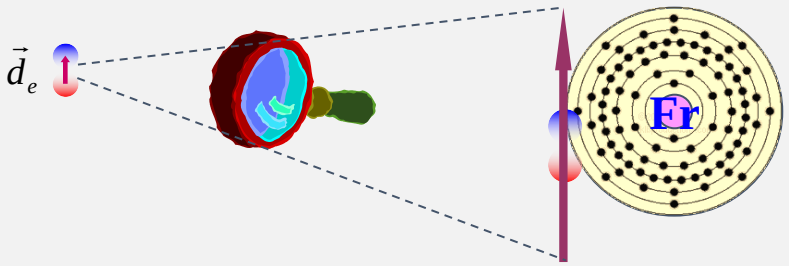


Matter-antimatter asymmetry

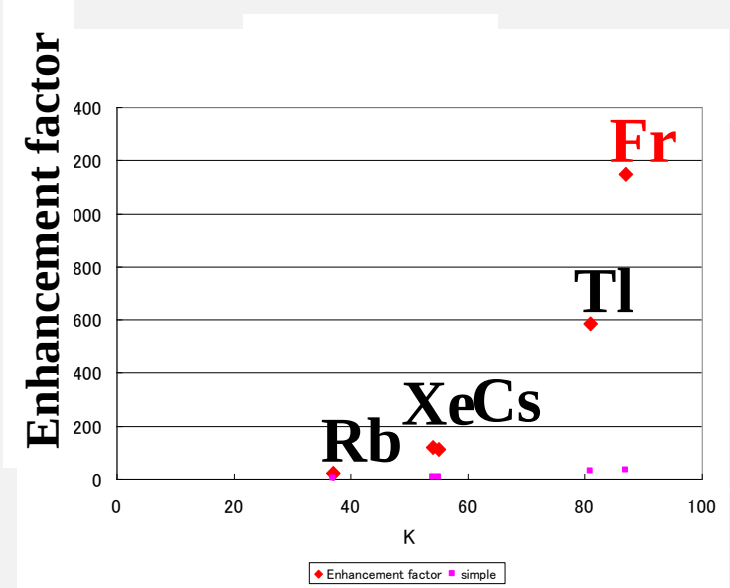
Non-zero Electric Dipole Moment (EDM) : CP violations beyond the SM

Using Fr atoms to search CP violations

Heavy paramagnetic atom : electron/nuclear EDM ~ enhanced

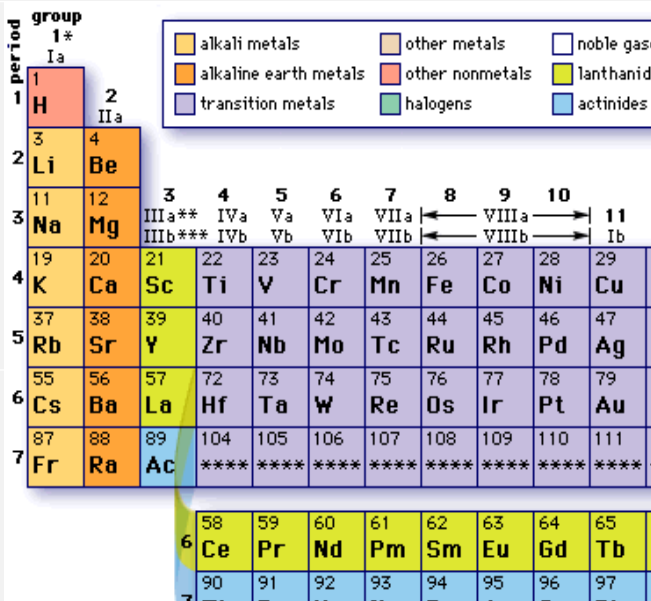


$$K \sim \frac{d_{atom}}{d_e} \sim Z^3 \alpha^2 \sim |\psi_s(0)|^2 V Z^5 \alpha^2 \frac{e}{a_0^{\,2}}$$



Francium (^{210}Fr)

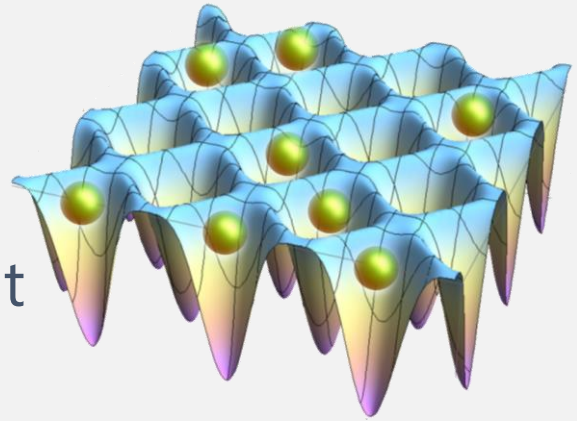
- **Heaviest alkali: atomic number 87**
- **Radioactive isotope (RI) : $t_{1/2}$ ~ 3 min.**
- **Simple atomic structure: -> direct laser cooling**
- **Electron EDM enhancement: 799**
  largest amongst any ground-state atoms

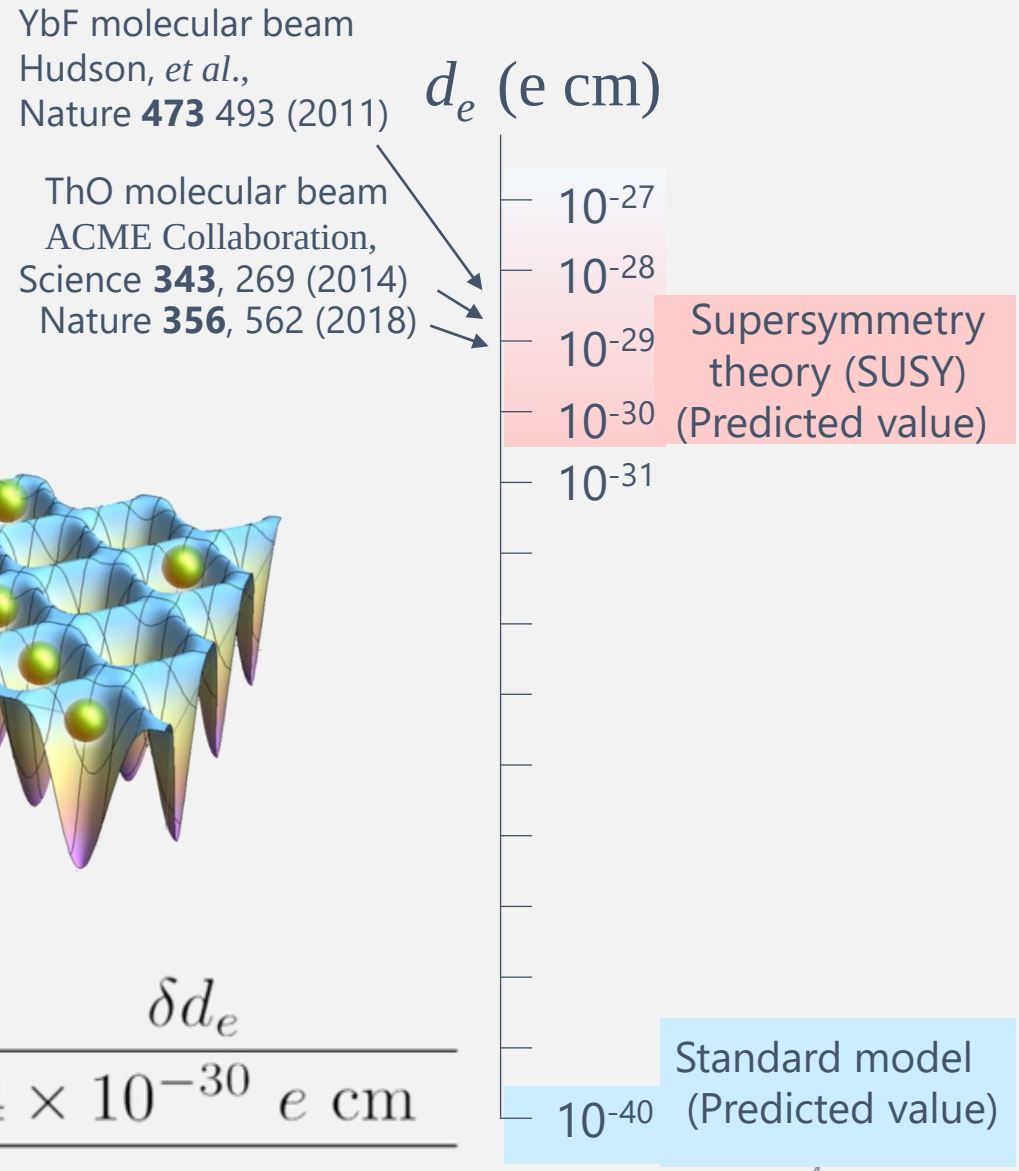


Measurement of Fr EDM using optical lattice

$$\delta d_{atom} \propto \frac{1}{E\,\tau\,\sqrt{N\,m}}$$

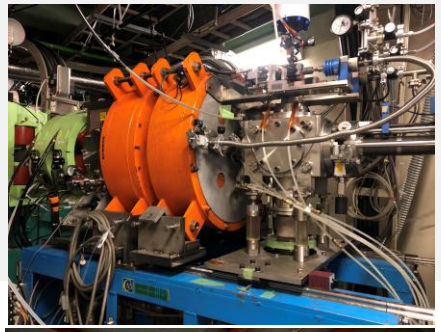
E: Electric field strength
τ: Interaction time
N: Number of particles per measurement
M: Total number of measurements



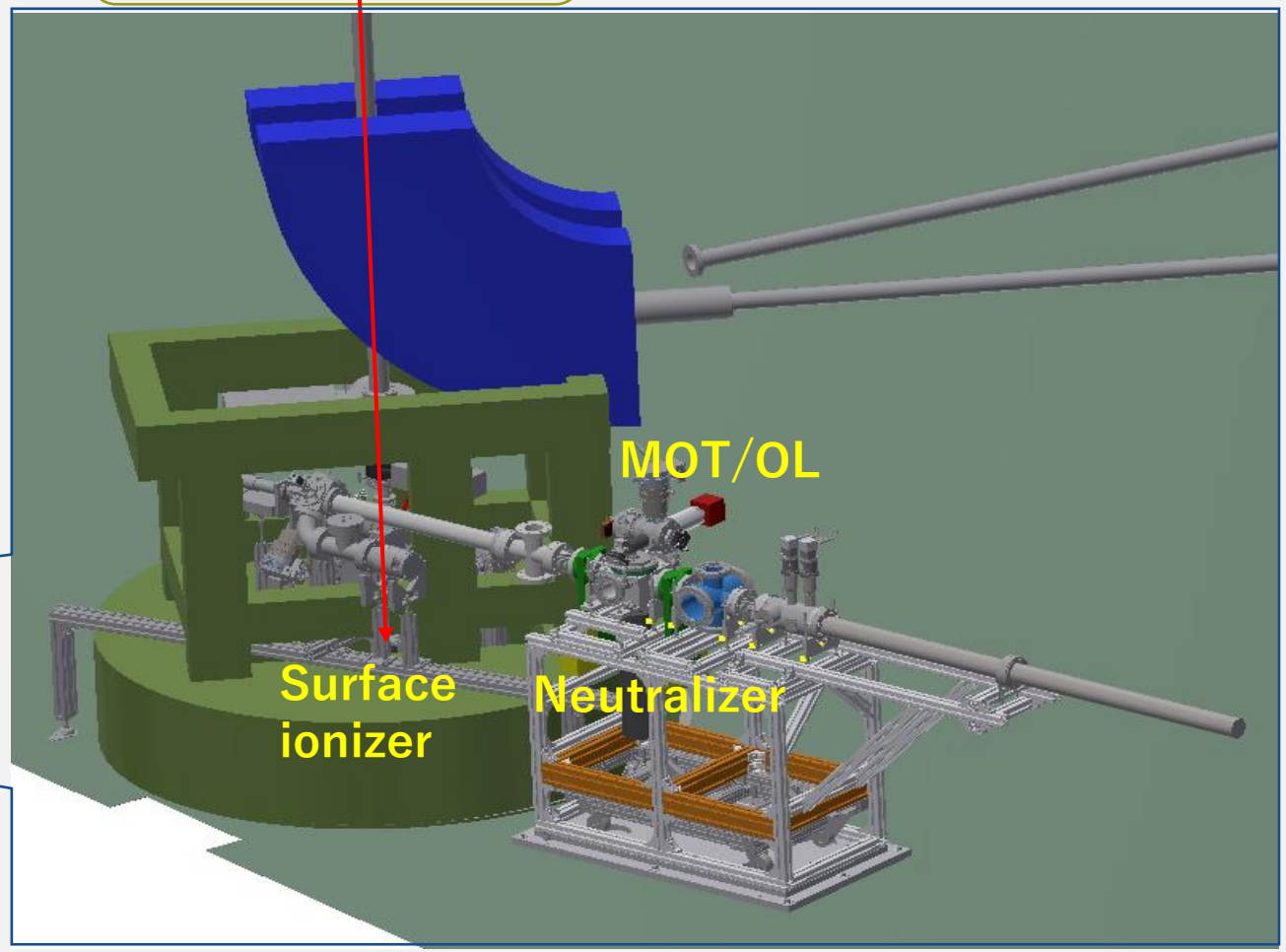


	E	τ	N	n	δd_e
Fr lattice	100 kV/cm	1 s	10^6	10^6	4×10^{-30} e cm

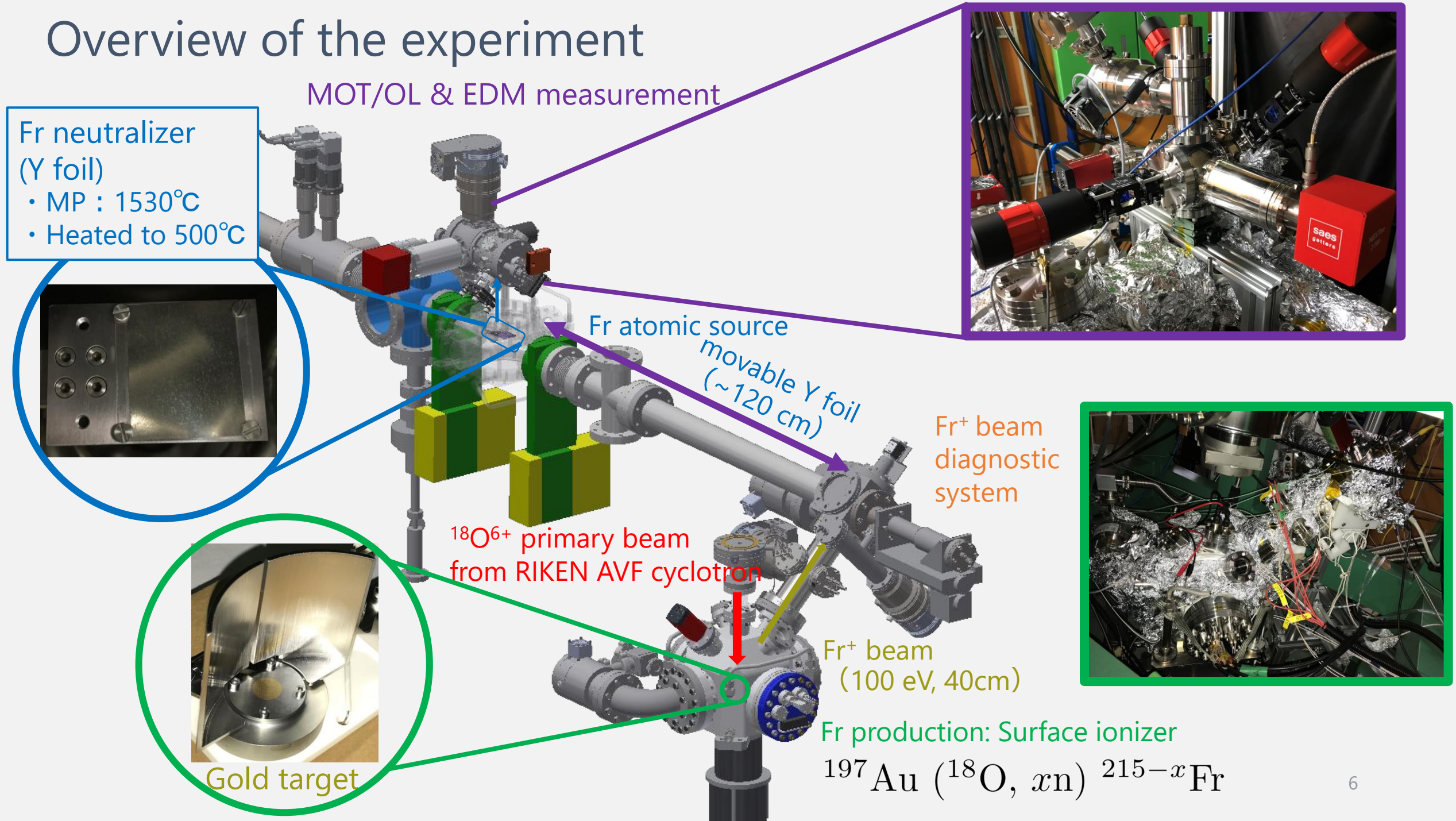
Fr EDM apparatus at RIKEN



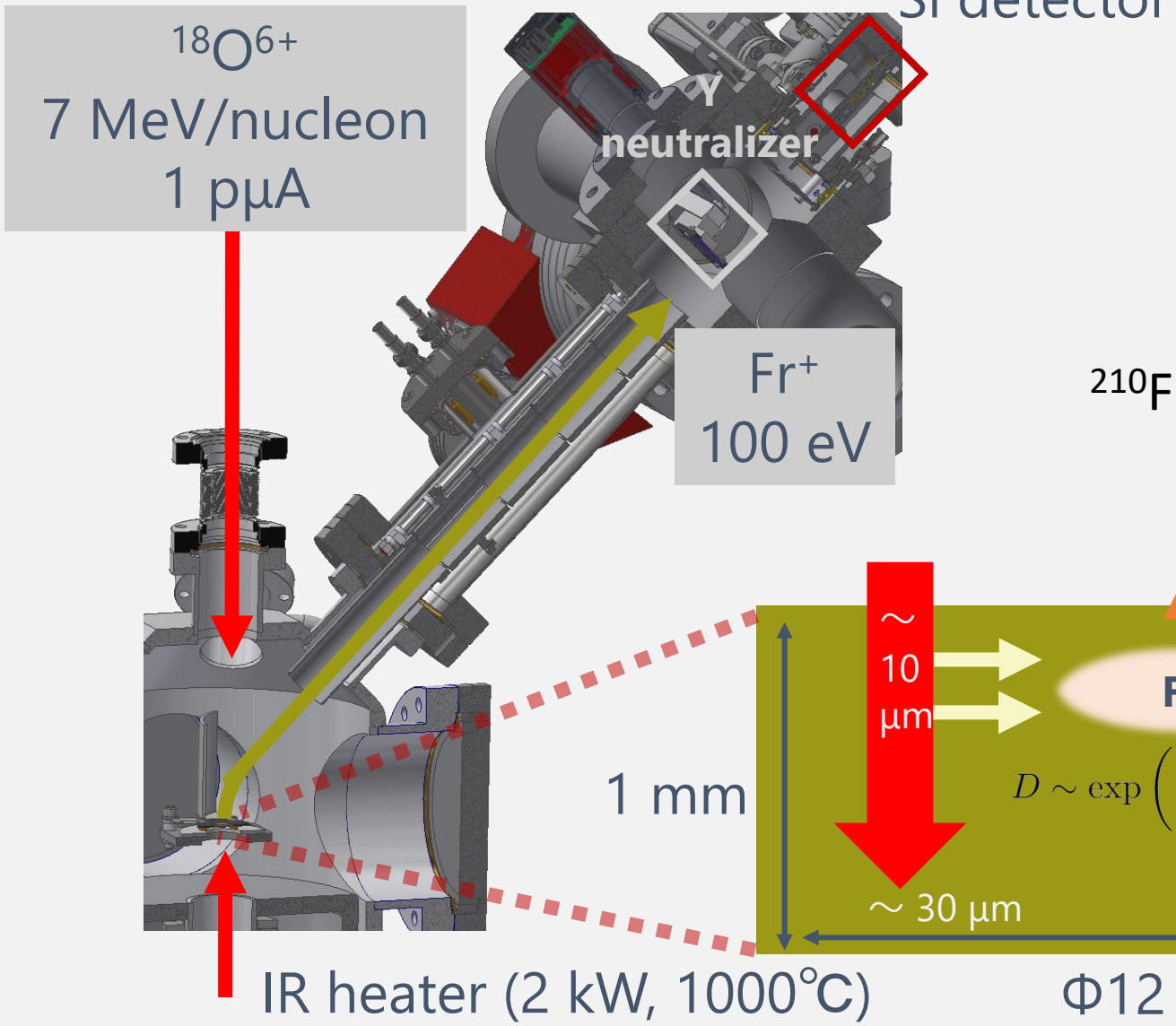
Nuclear fusion reaction : ^{18}O (~100 MeV) + ^{197}Au → $^{215-x}Fr$ + xn

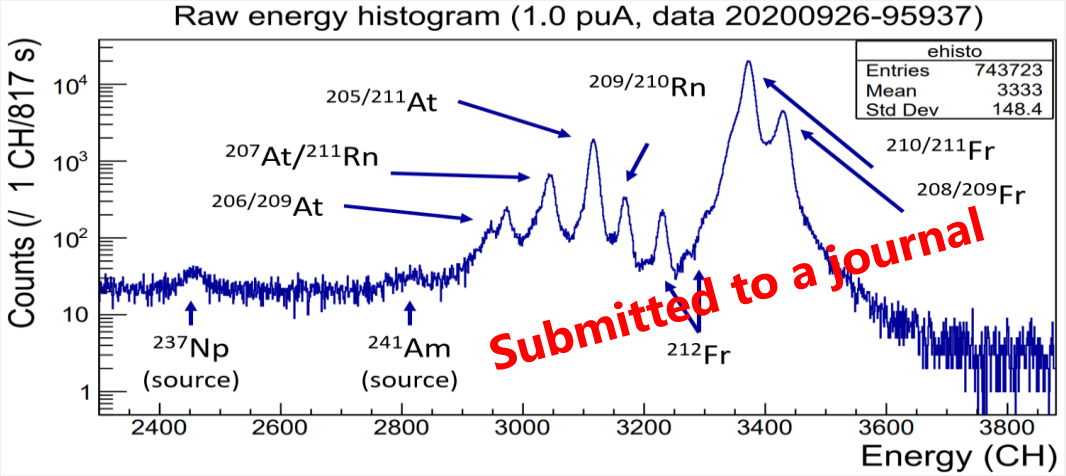


Overview of the experiment



Fr ion beam production & detection



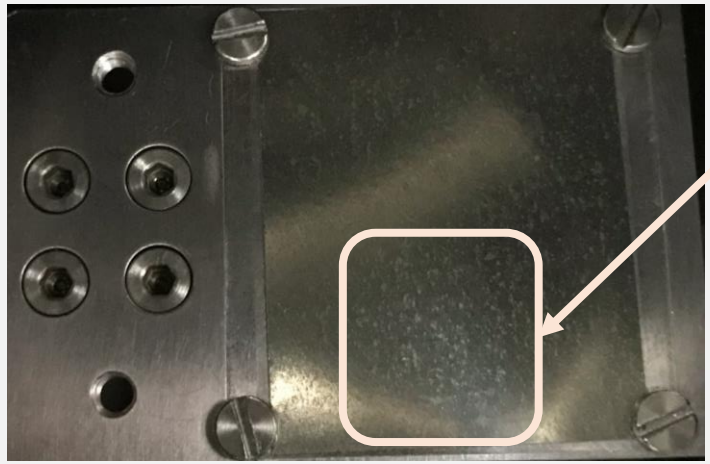


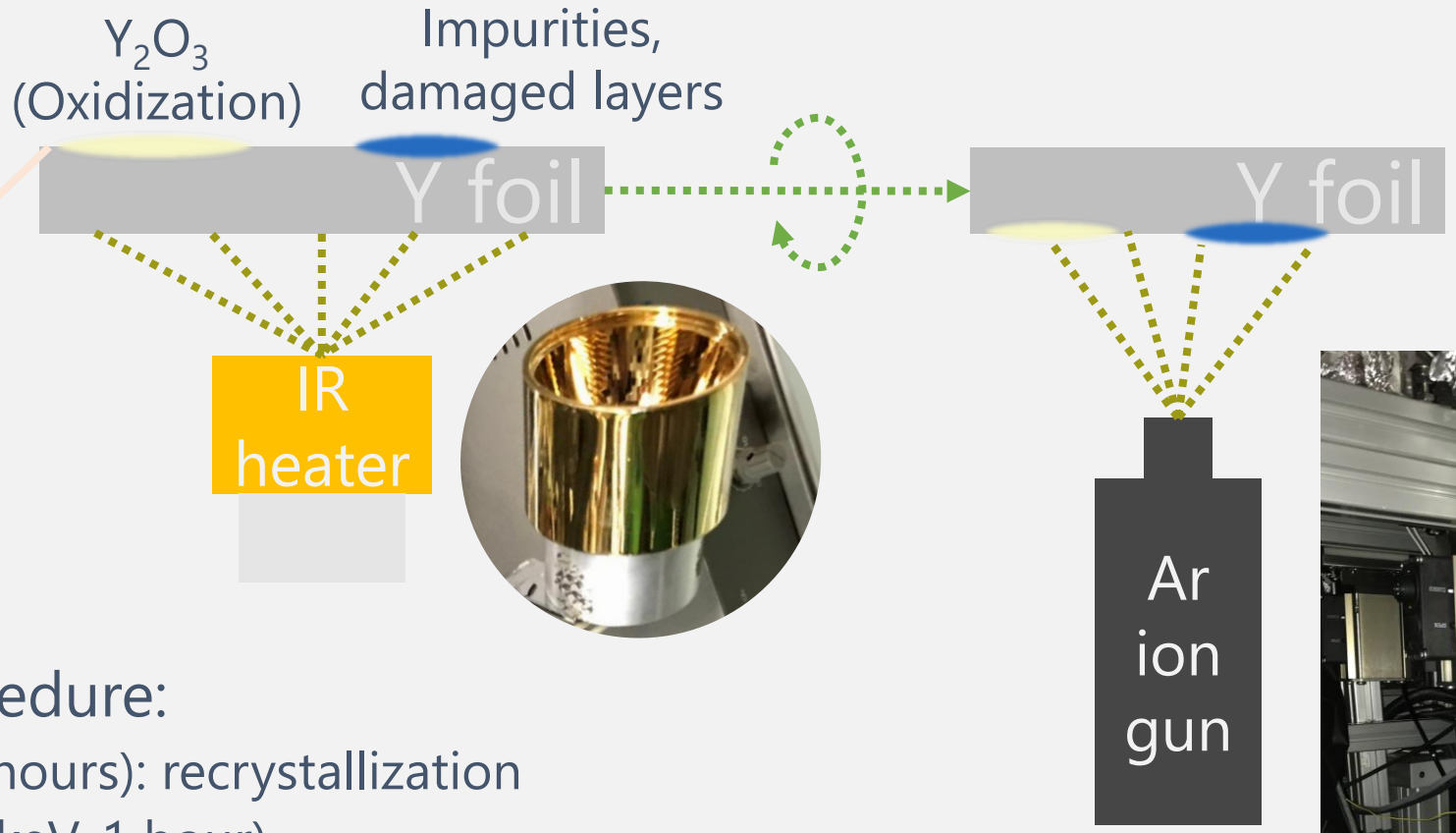
^{210}Fr: 5×10^{6} /s (factor of 10 larger than CYRIC)

$$^{197}\mathrm{Au}\ (^{18}\mathrm{O},\ x\mathrm{n})\ ^{215-x}\mathrm{Fr}$$

Neutralization of Fr^+ ions

- Neutralization efficiency depends on Y surface condition



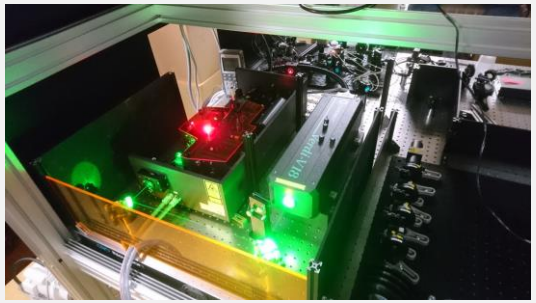


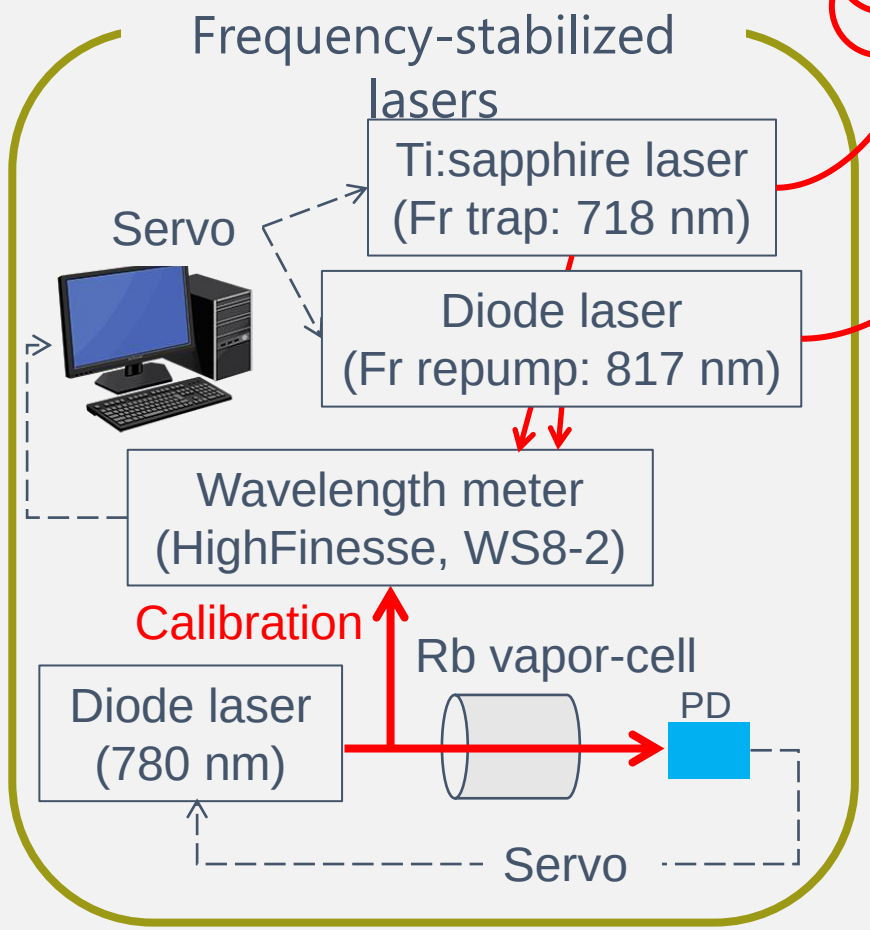
- Surface cleaning procedure:
  - Annealing (750℃, 20 hours): recrystallization
  - Ar ion sputtering (0.5 keV, 1 hour)

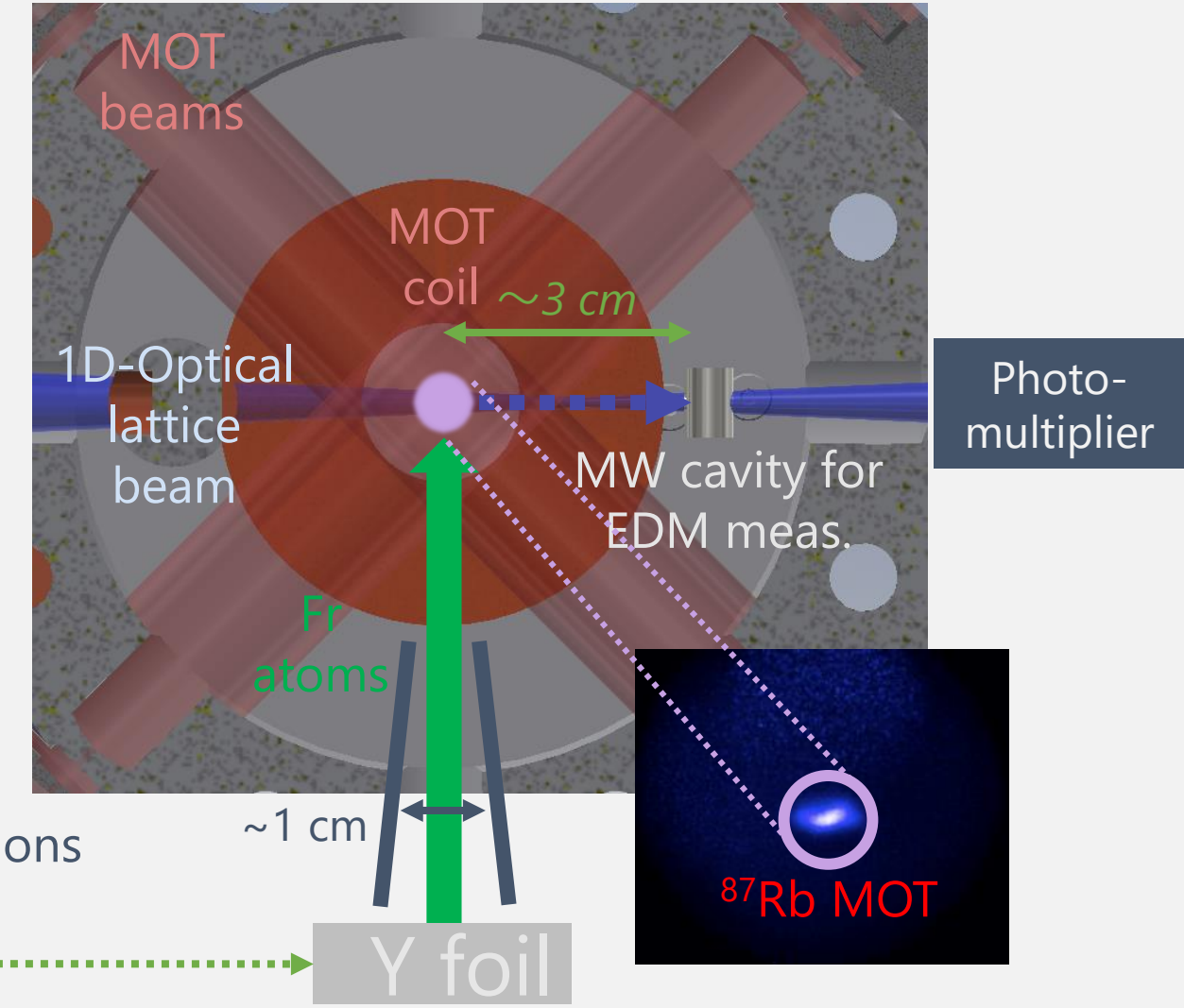
Foord, J. S., *et al.*, Surf. Sci. **94**(1980)339.

Optimization of the neutralization efficiency is still ongoing

Laser setup for magneto optical trap (MOT)







Ready for Fr MOT !

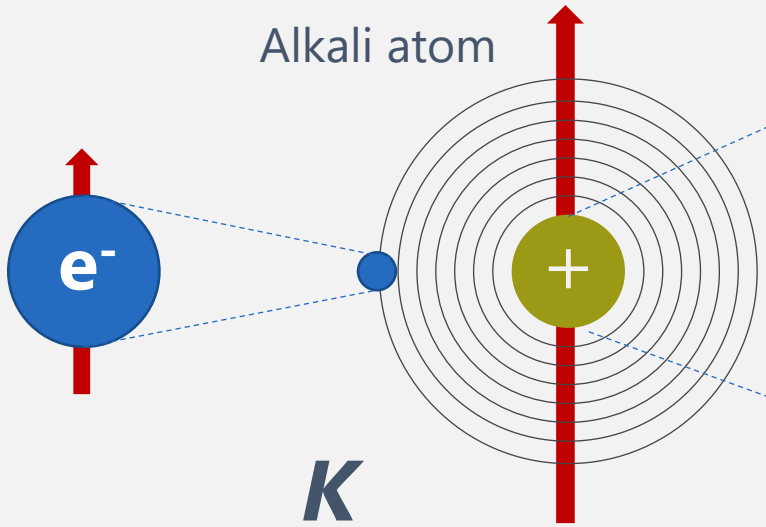
Nuclear EDM measurement using ^{221}Fr

^{210}Fr $T_{1/2}$~3min

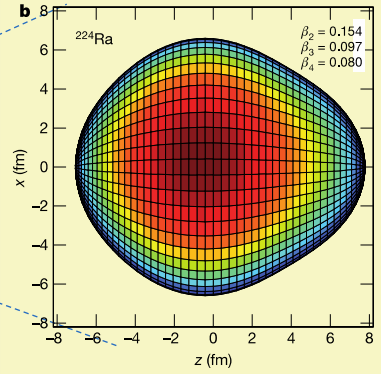
- Heaviest Alkali
- eEDM enhancement

	Rb	Cs	Fr
K	27.5	114	799

Shitara, N., *et al.*, J. High Energ. Phys. **2021**(2021)124.



^{221}Fr $T_{1/2}$~5min



Octupole deformation

	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr
β_2	0.125	0.143	0.129	0.106
β_3	0.100	0.099	0.081	0.100
β_4	0.076	0.082	0.078	0.069
β_5	0.042	0.035	0.024	0.045
β_6	0.018	0.016	0.023	0.020
E_c (keV)	212	221	213	305

S

Spevak, V., N. Auerbach, and V. V. Flambaum.. *Physical Review C* 56.3 (1997): 1357.

Electron EDM in paramagnetic atoms

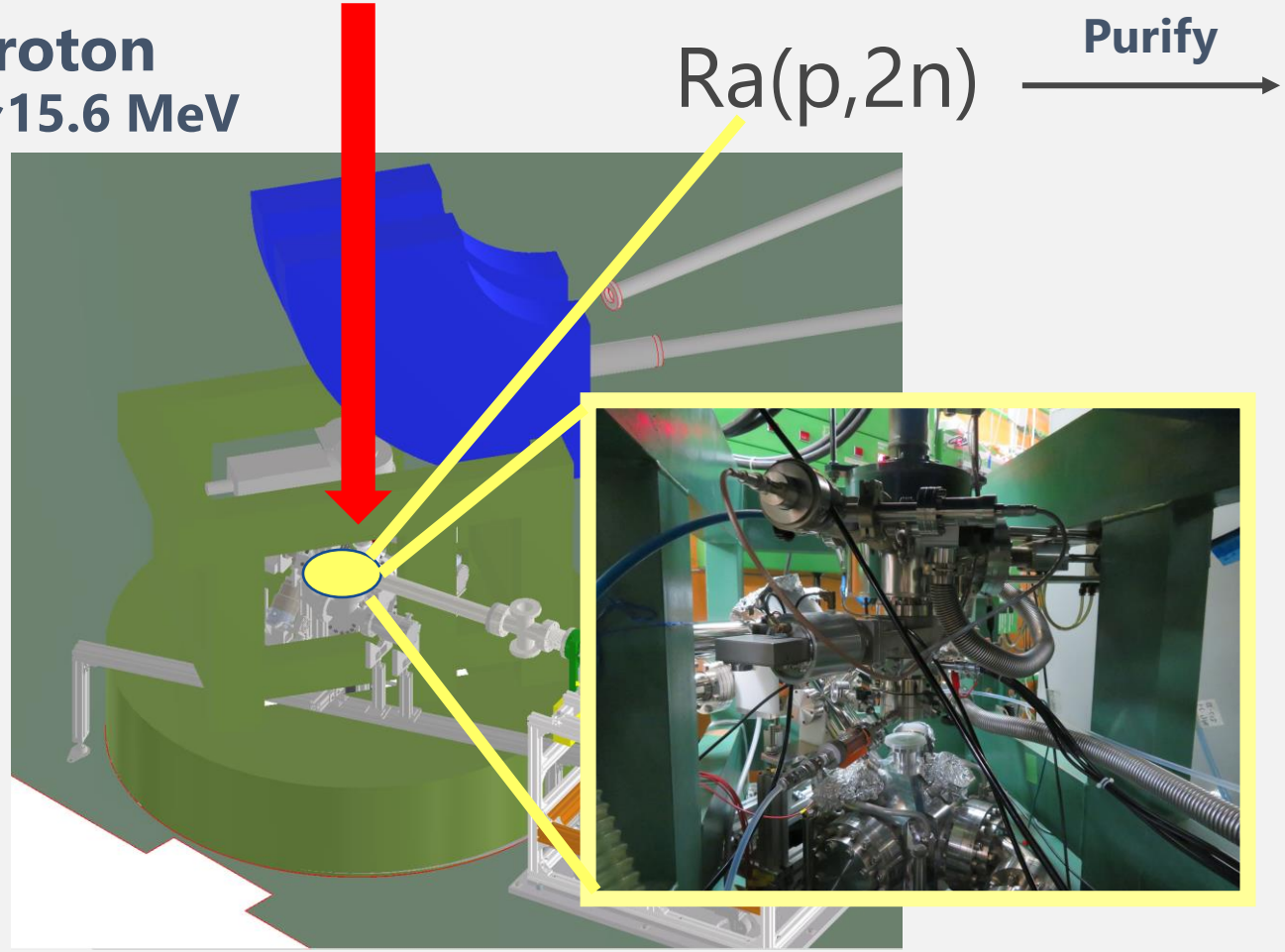
$$d_{\text{atom}} = K d_e + R C_{S,P,T} + S$$

Sandars, P.G.H., Phys. Lett. **22**(1966)290.

^{221}Fr produced from the alpha decay of ^{225}Ac

RIKEN AVF cyclotron

Proton
~15.6 MeV



Ra(p,2n) $\xrightarrow{\text{Purify}}$ ^{225}Ac $\xrightarrow{\alpha}$ ^{221}Fr

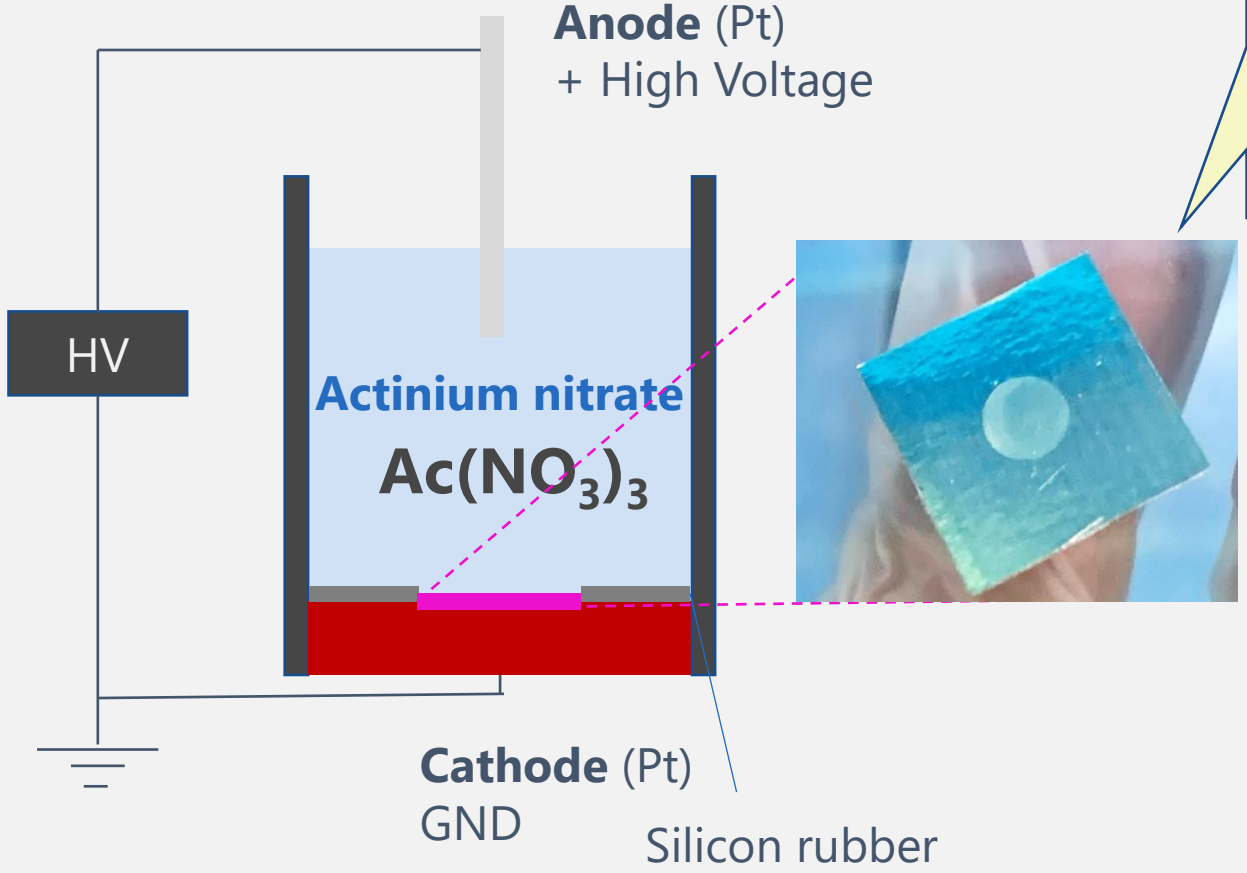
α-emittion
~ 5.8 MeV

$T_{1/2}$ ~10.0 d

bring to the RIBF hot lab

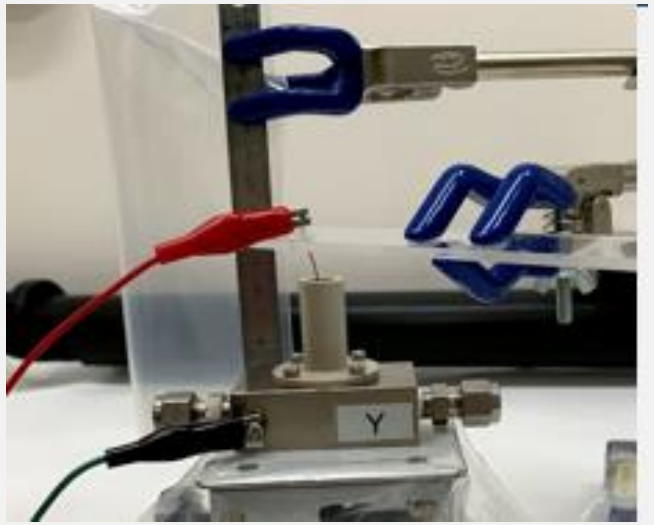
Making ^{221}Fr Source @ RIBF hot lab

Molecular Plating Method



Molecular plating method in 2021

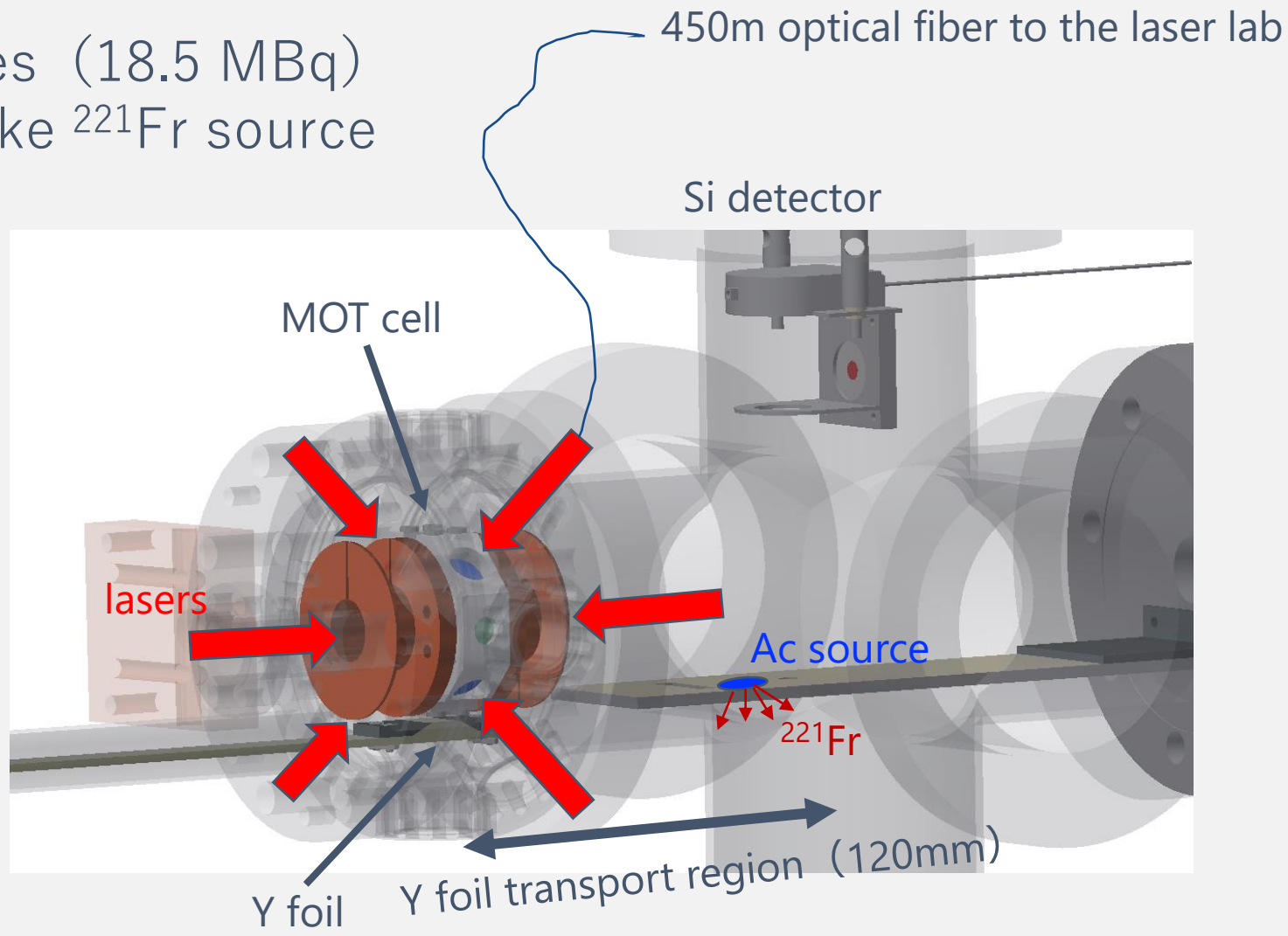
Achieved **77.9%** efficiency,
with **20.4 MBq**



^{221}Fr MOT@RIBF hot lab

Plan of FY2022

①1/Nov: ^{225}Ac arrives（18.5 MBq）
②Several days：Make ^{221}Fr source
③^{221}Fr MOT



Summary

- Aiming for the EDM measurement using ^{210}Fr and ^{221}Fr ($d \sim 10^{-30}$ e cm) .

- ^{210}Fr project
  - Development of the Fr production apparatus started since 2018.
  - Succeeded 5×10^{6}/s ^{210}Fr ion beam production in 2020 ($\times$10 than CYRIC)
  - Neutralizer and MOT were installed and observed ^{87}Rb MOT in 2021.
  - Ready for ^{210}Fr MOT

- ^{221}Fr project
  - ^{221}Fr generator (^{225}Ac) is developed in 2021.
  - ^{221}Fr MOT apparatus developed in Sep/2022.
  - Ready for ^{221}Fr MOT

Thank you for your attention

- Fr-EDM collaboration@RIKEN

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M. Fukase
D. Uehara

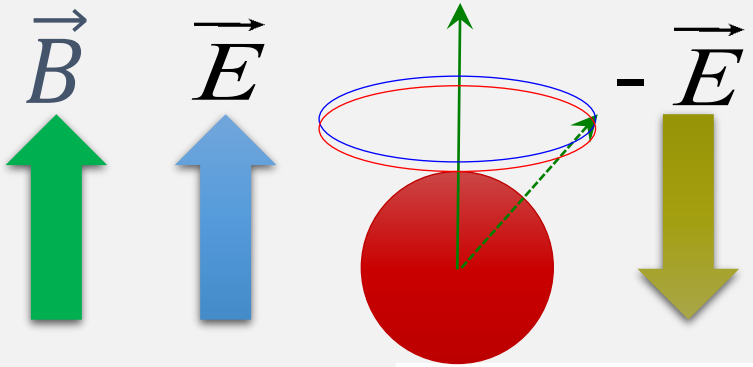
Paul Scherrer Institute
K. S. Tanaka

Backup Slides

EDM measurement

Spin polarisation : <J> → Interaction with external field → Measurement of spin precession

$$\frac{d\langle \vec{J} \rangle}{dt} = \left(m\vec{B} + d\vec{E}\right) \times \langle \hat{J} \rangle$$



$$\begin{cases} h\nu_{++} = m\times B + d\times E \\ h\nu_{--} = m\times B - d\times E \end{cases}$$

(1 cycle ~7 year)

$$\Rightarrow \quad d\nu \propto \nu_{++} - \nu_{--} = d = \frac{2dE}{h} \approx 4.8\,nHz$$

$$\text{where } d = 10^{-28}\, e\times cm, \quad E = 100\,kV/cm$$

$$\delta d = \frac{\hbar}{2e} \times \frac{1}{K} \times \frac{1}{E} \times \frac{1}{\sqrt{N \times t \times T}}$$

- K: Enhancement factor : maximum
- E: Electric field
- N: Trapped number
- T: Coherence time: Long

Current upper limit : eEDM

Standard Model

$$d_e \sim 8 \times 10^{-41}\ e\ \mathrm{cm}$$

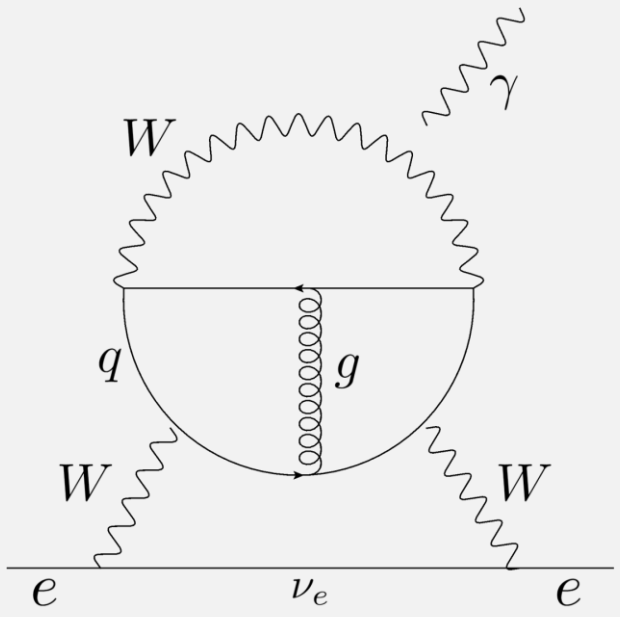
SUSY

$$d_e \sim 5 \times 10^{-31}\ e\ \mathrm{cm}$$

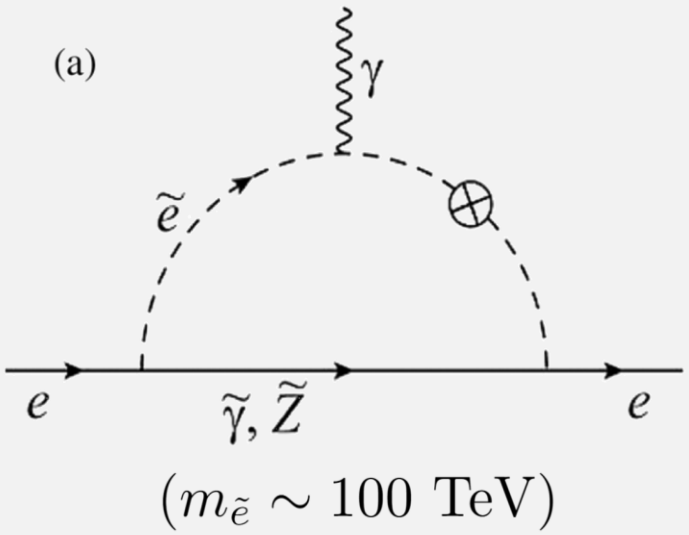
Current upper limit

$$|d_e| < 1.1 \times 10^{-29} e\ \mathrm{cm}$$

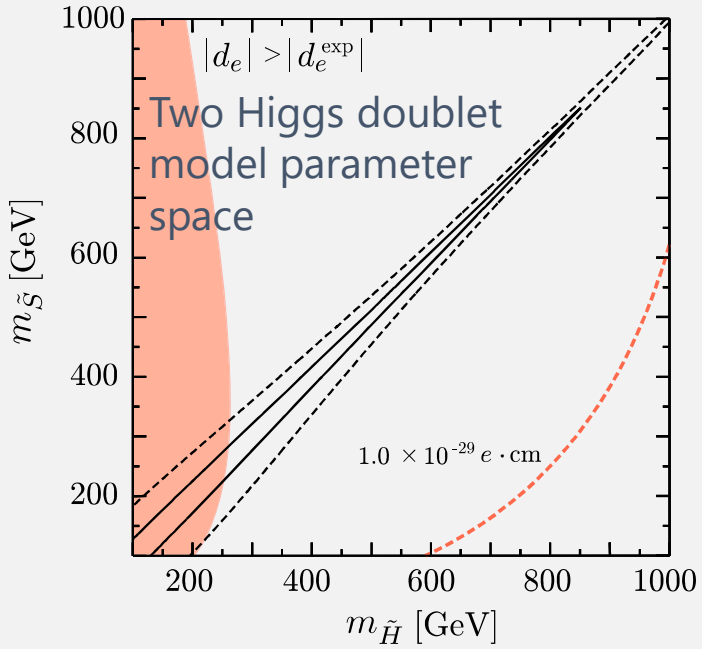
ACMEII, Nature (2018)



Fukuyama, T., Int. J. Mod. Phys. A **27**(2012)1230015.

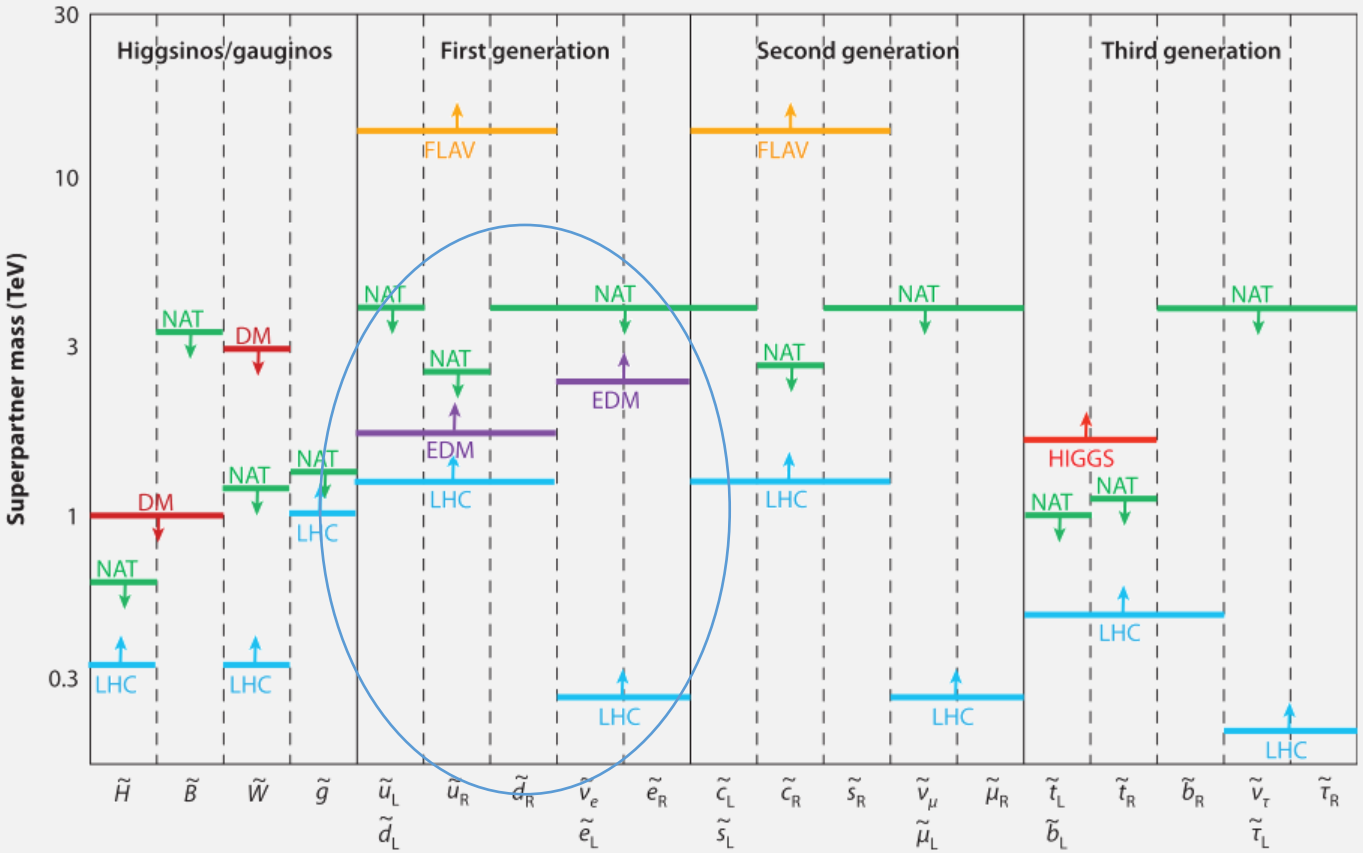


Safronova, M. S. *et al.*, Rev. Mod. Phys. **90** (2018)025008.



Fuyuto, K. *et al.*, Phys. Lett. B **755**(2016)491.

SUSY mass



- e EDM with Fr atoms ～ sensitive to the colorless SUSY particles
- LHC: hadron collider, and not so sensitive to colorless particles
- Fr EDM ～ can explore the mass scale > TeV region : 10^{-30} ecm

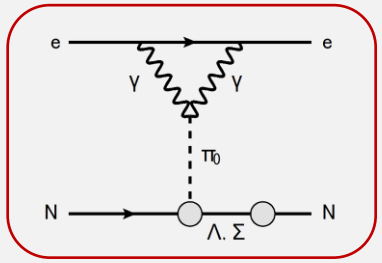
CP violation effect in ThO/Ra/Fr

In quantum many body systems
EDM and CP violating interactions can be extracted

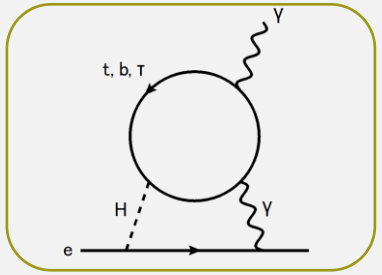
d_e | $C_{s\text{-}ps}$ (CPV int.)

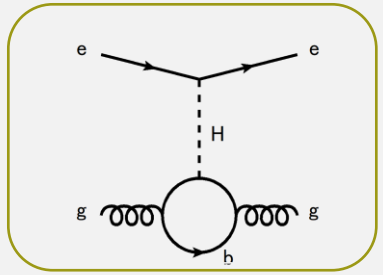
Standard model

10^{-38} ecm

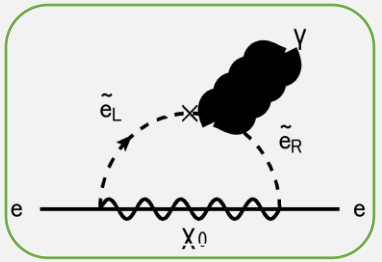


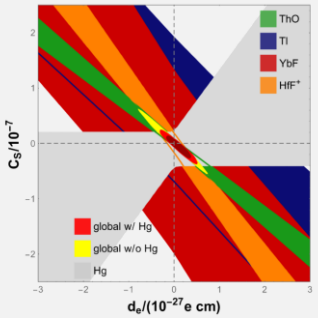
Double Higgs model



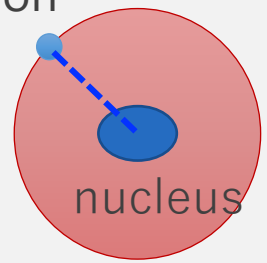


Super Symmetry model





electron

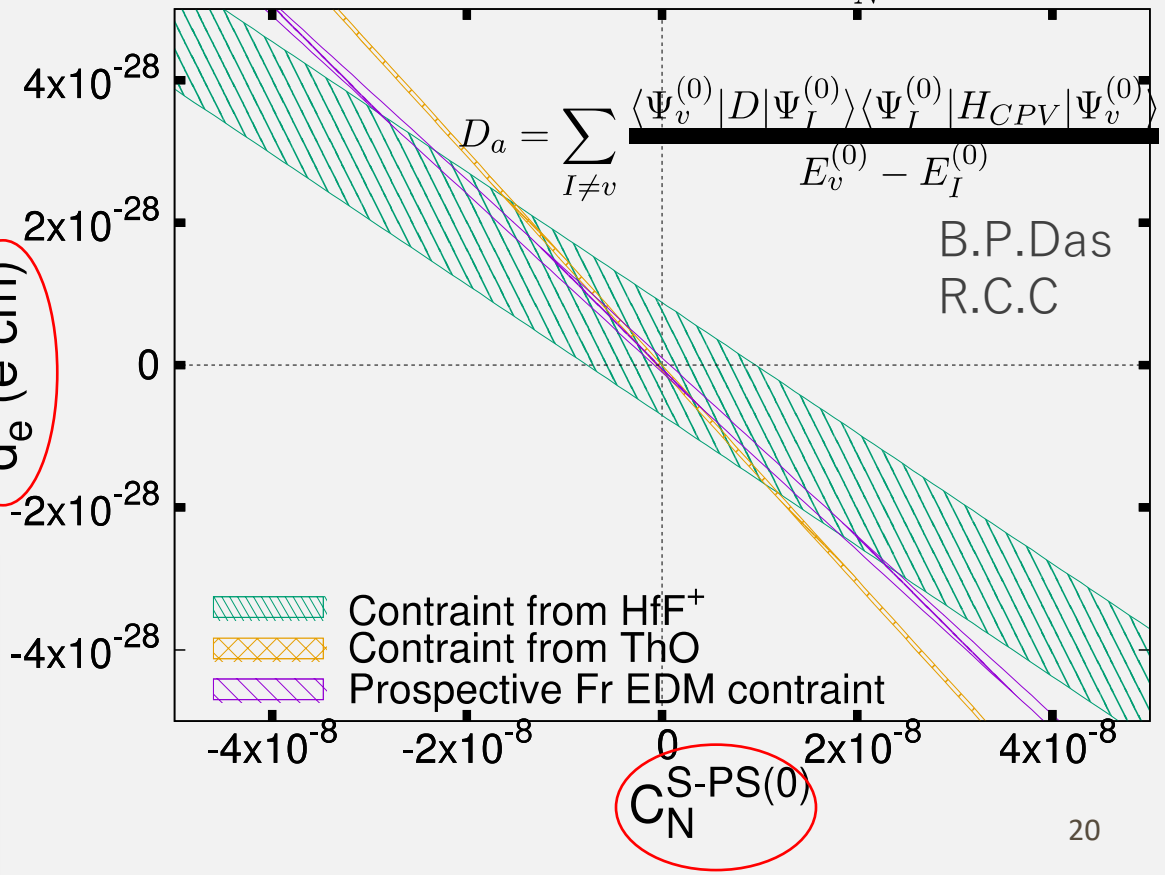


$d_A = K \cdot d_e + R \cdot C_{s\text{-}ps}$

$d_e + (R/K) \cdot C_{s\text{-}ps}$

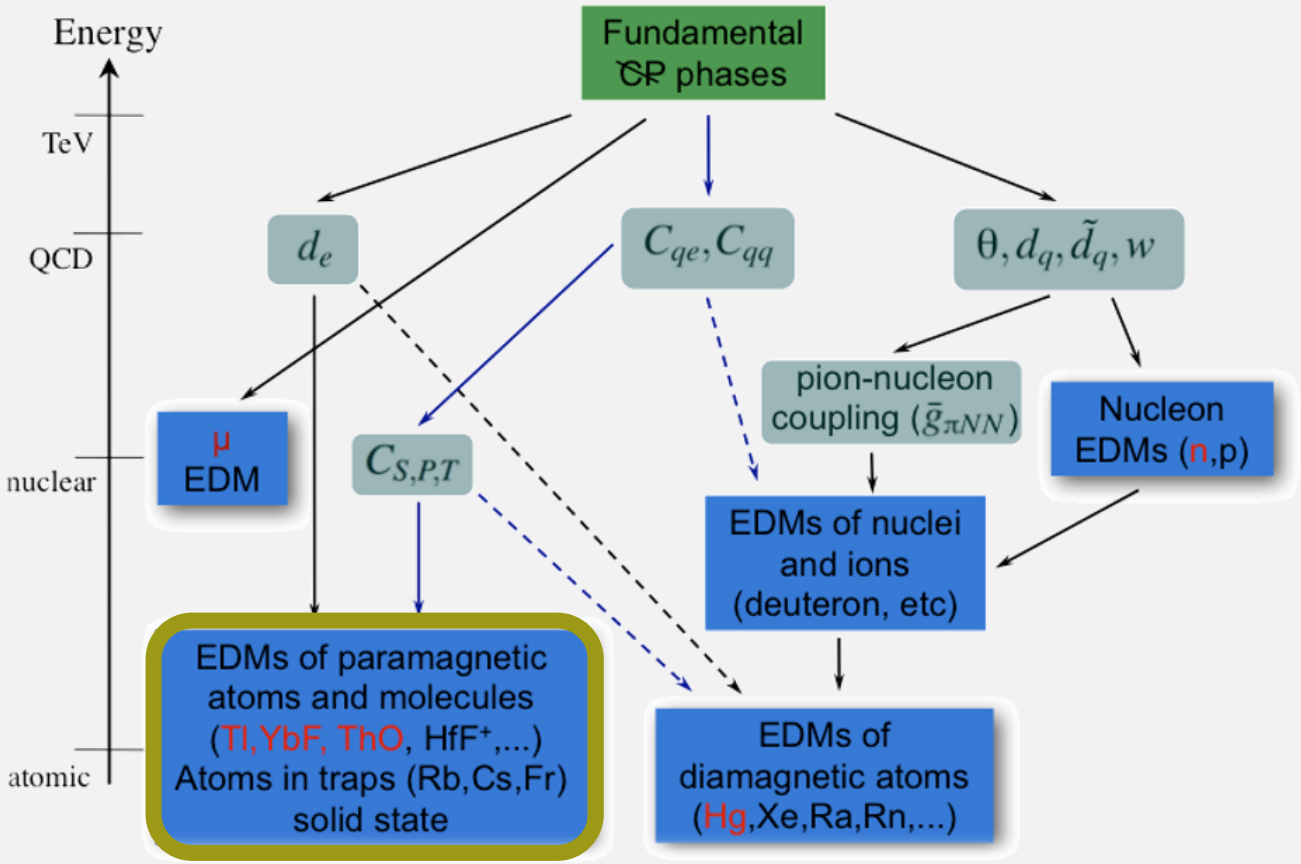
Nuclear/atomic structure

$$D_a = 799\, d_e + 10.5 \times 10^{-18}\, C_N^{S-PS(0)}\, e\,\mathrm{cm}$$



EDM and CP violating interactions in atoms

Source of the CP violation in the EDM



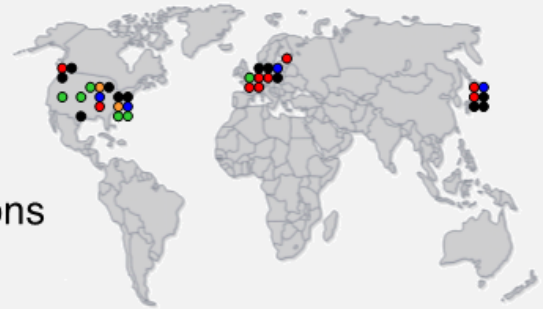
Particle cooling technique ~ in progress

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

Neutrons ~200
- @ILL
- @ILL,@PNPI
- @PSI
- @FRM-2
- @RCNP,@TRIUMF
- @SNS
- @J-PARC

Molecules ~50
- YbF@Imperial
- PbO@Yale
- ThO@Harvard
- HfF+@JILA
- WC@UMich
- PbF@Oklahoma

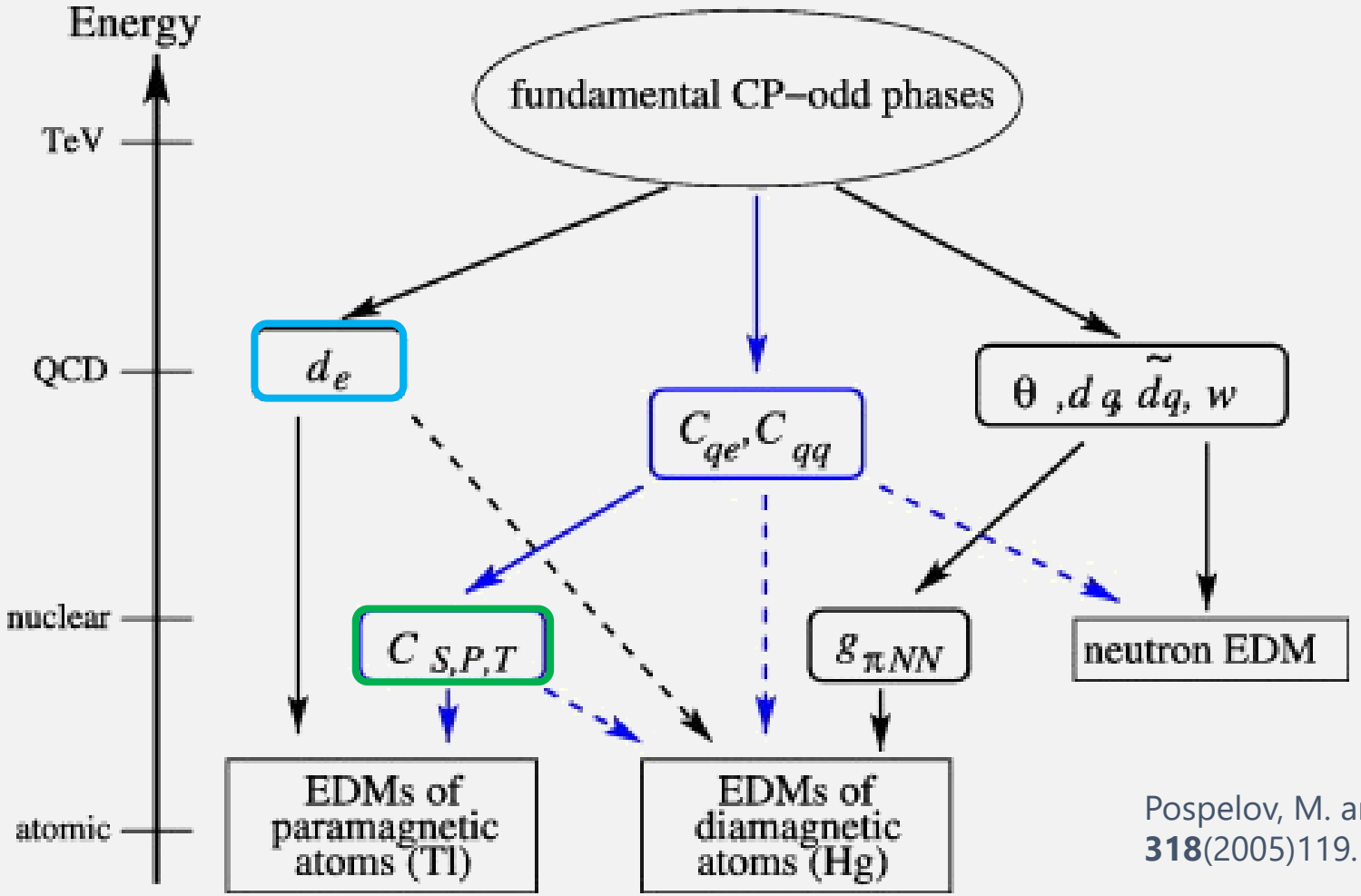
Atoms ~100
- Hg@UWash
- Xe@Princeton
- Xe@TokyoTech
- Xe@TUM
- Xe@Mainz
- Cs@Penn
- Cs@Texas
- Fr@ CNS・RIKEN
- Rn@TRIUMF
- Ra@ANL
- Ra@KVI
- Yb@Kyoto



Ions-Muons ~200
- @BNL
- @FZJ
- @FNAL
- @JPARC

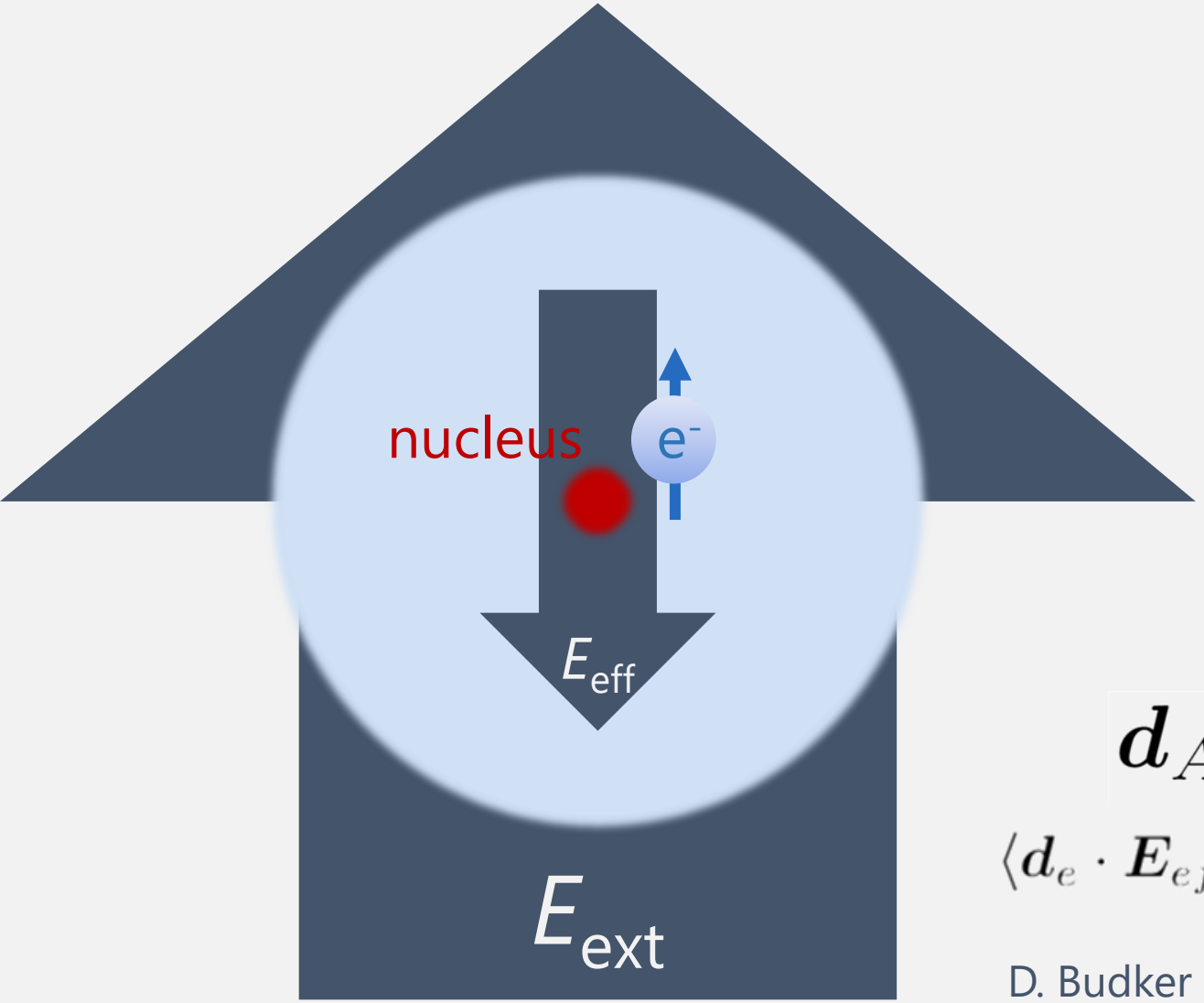
Solids ~10
- GGG@Indiana
- ferroelectrics@Yale

EDM and CP violating interactions in atoms



Pospelov, M. and Ritz, A., Ann. Phys. **318**(2005)119.

Electron EDM enhancement in alkali atoms



$$E_{int} \sim \frac{Ze}{r^2} \sim \frac{Z^3 e}{{a_0}^2}$$

$$d_e E_{eff} \sim \beta^2 \left(d_e E_{int}\right)$$

$$\beta \sim Z\alpha$$

$$\psi \sim A e^{-\frac{Zr}{a_0}}$$

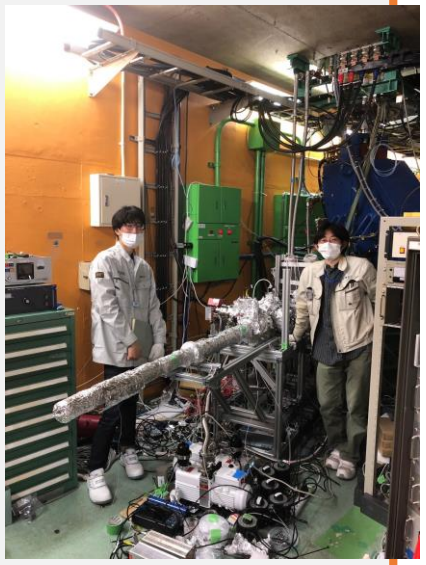
$$A \sim \sqrt{\frac{Z}{\pi {a_0}^3}} \rightarrow \left|\psi(r \sim 0)\right|^2 \propto Z$$

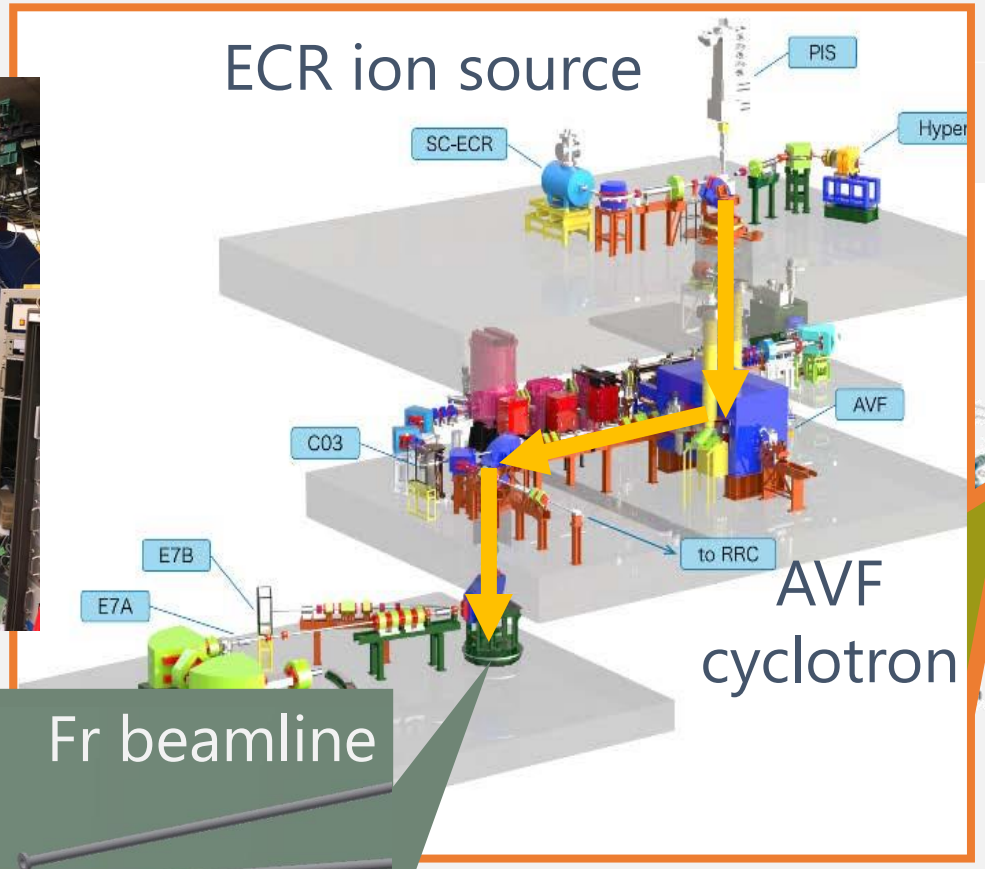
$$\boldsymbol{d}_A \cdot \boldsymbol{E}_{ext} = \langle \boldsymbol{d}_e \cdot \boldsymbol{E}_{eff} \rangle$$

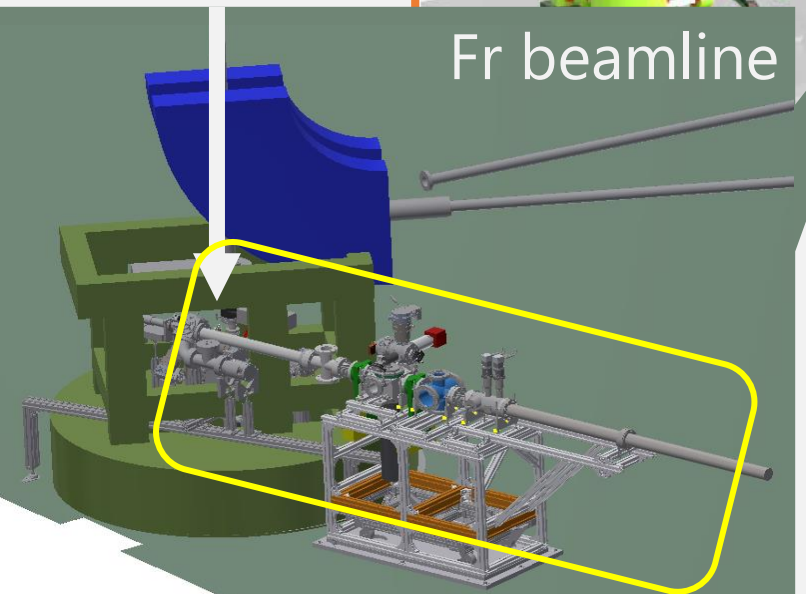
$$\langle \boldsymbol{d}_e \cdot \boldsymbol{E}_{eff} \rangle \sim V_{atom} \left|\psi(r \sim 0)\right|^2 d_e E_{eff} \propto Z^3 d_e$$

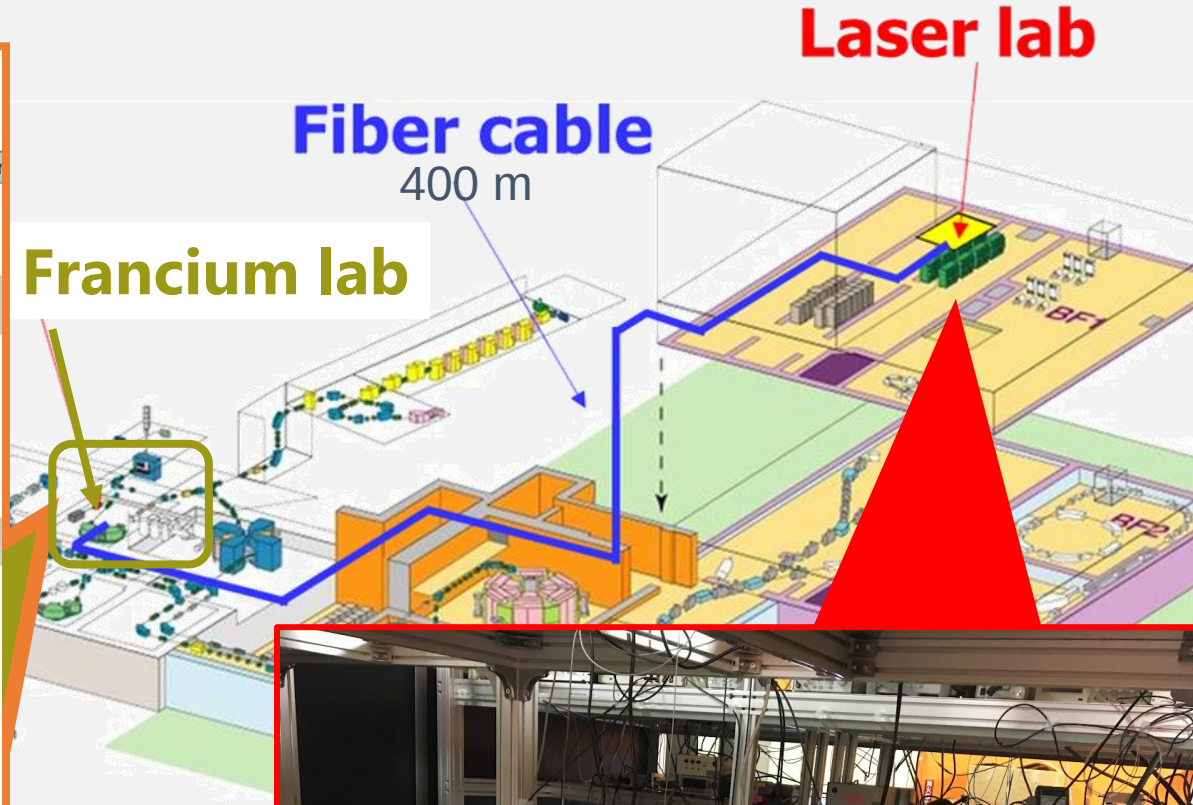
D. Budker *et al.*,
"Atomic Physics: An Exploration through Problems and Solutions" (2008)

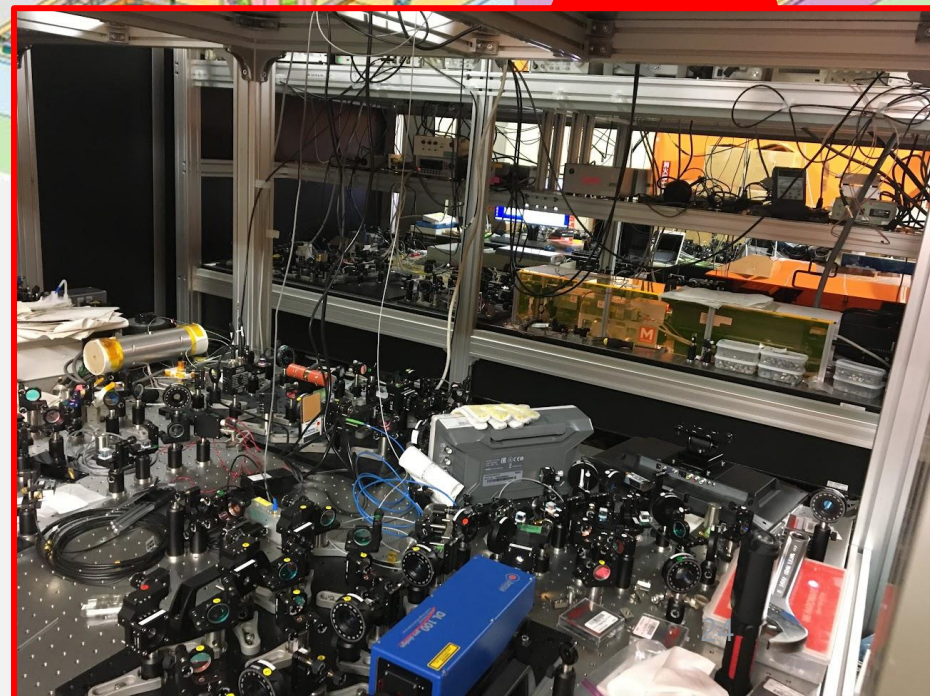
Experimental overview at RIKEN RIBF











Fr trapping and co-magnetometer

- Cold Fr source with MOT (Magneto-Optical Trap) ~ technique established
- Dual atoms co-magnetometer

$$H = -\mu \frac{\boldsymbol{s}}{|\boldsymbol{s}|} \cdot \boldsymbol{B} - d \frac{\boldsymbol{s}}{|\boldsymbol{s}|} \cdot \boldsymbol{E}$$

Magnetic field shift measurement

Dual atoms co-magnetometer (Rev. Sci. Inst. 89 (2018) 123111)

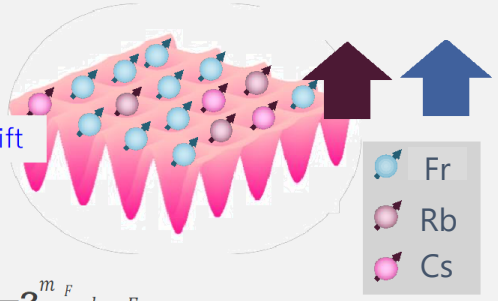
- Rb/Cs atoms trapped simultaneously
- Zeeman shift/Vector light shift accurate measurement

$$\hbar\nu = \Delta E_1(F, m_F) - \Delta E_2(F, m_F)$$

$$= -2 m_F g_F \mu_B B \quad : \text{Zeeman shift}$$

$$- \alpha^{(1)}(F;\omega) \frac{m_F}{F} \frac{\theta_I \sin\varphi}{\varepsilon_0 c} \quad : \text{Vector light shift}$$

$$- 2 \frac{m_F}{F} d_{Fr} E \quad : \text{Shift from EDM}$$



$$\hbar\nu_{Fr} = -2 m_{Fr} g_{Fr} \mu_B B - \alpha^{(1)}_{Fr}(F_{Fr};\omega) \frac{m_{Fr}}{F_{Fr}} \frac{\theta_I \sin\varphi}{\varepsilon_0 c} - 2 \frac{m_F}{F_{Fr}} d_{Fr} E$$

$$\hbar\nu_1 = -\Delta_1 g_1 \mu_B B - \alpha^{(1)}_1(F_1;\omega) \frac{\Delta_1}{F_1} \frac{\theta_I \sin\varphi}{2\varepsilon_0 c}$$

$$\hbar\nu_2 = -\Delta_2 g_2 \mu_B B - \alpha^{(1)}_2(F_2;\omega) \frac{\Delta_2}{F_2} \frac{\theta_I \sin\varphi}{2\varepsilon_0 c}$$

$$\hbar\nu_1 = -\gamma_1 B - \sqrt{1}\,\theta_I \sin\varphi$$

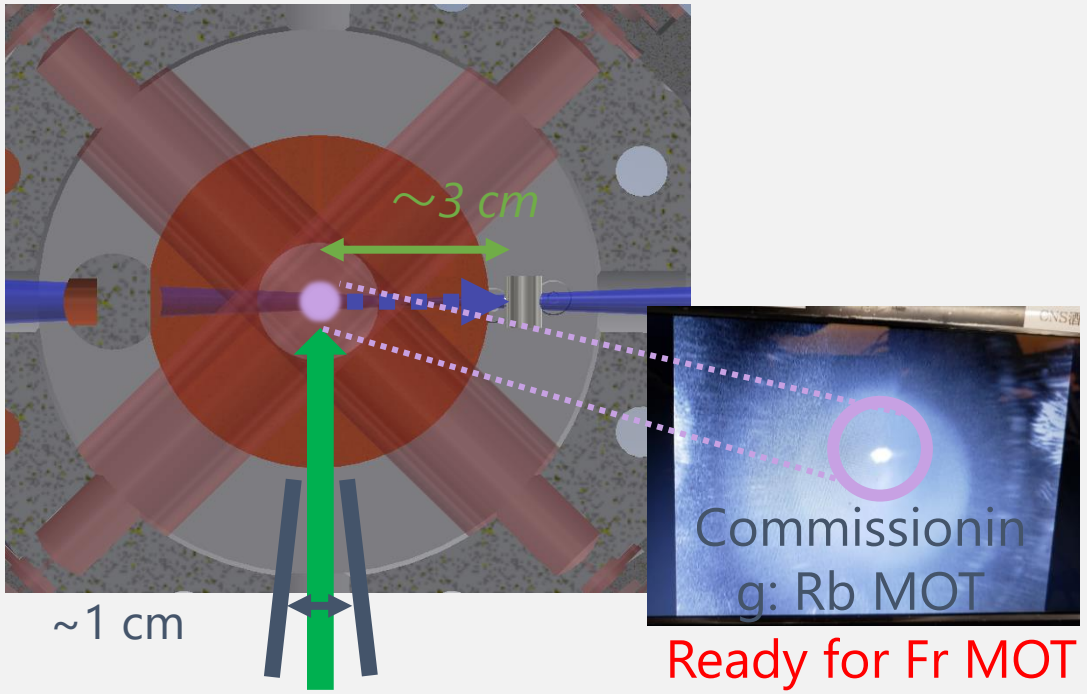
$$\hbar\nu_2 = -\gamma_2 B - \sqrt{2}\,\theta_I \sin\varphi$$

$$B = -\frac{\sqrt{2}\nu_1 - \sqrt{1}\nu_2}{\gamma_1\sqrt{2} - \gamma_2\sqrt{1}}$$

$$\theta_I \sin\varphi = -\frac{\gamma_2\nu_1 - \gamma_1\nu_2}{\gamma_1\sqrt{2} - \gamma_2\sqrt{1}}$$

Cold Fr source

Laser cooled Fr ~ stable supply
Laser frequency stabilization
Offset locking of trapping and repumping laser



Ready for Fr MOT

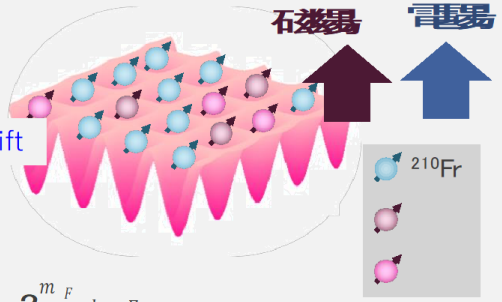
Dual atoms co-magnetometer

$$\hbar\nu = \Delta E_1(F, m_F) - \Delta E_2(F, -m_F)$$

$$= -2 m_F g_F \mu_B B \quad : \text{Zeeman shift}$$

$$- \alpha^{(1)}(F;\omega) \frac{m_F}{F} \frac{\theta I \sin\varphi}{\varepsilon_0 c} \quad : \text{Vector light shift}$$

$$- 2 \frac{m_F}{F} d_{Fr} E \quad : \text{Shift from EDM}$$



$$\hbar\nu_{Fr} = -2 m_{Fr} g_{Fr} \mu_B B - \alpha^{(1)}_{Fr}(F_{Fr};\omega) \frac{m_{Fr}}{F_{Fr}} \frac{\theta I \sin\varphi}{\varepsilon_0 c} - 2 \frac{m_F}{F_{Fr}} d_{Fr} E$$

$$\hbar\nu_1 = -\Delta m_1 g_1 \mu_B B - \alpha^{(1)}_1(F_1;\omega) \frac{\Delta m_1}{F_1} \frac{\theta I \sin\varphi}{2\varepsilon_0 c}$$

$$\hbar\nu_2 = -\Delta m_2 g_2 \mu_B B - \alpha^{(1)}_2(F_2;\omega) \frac{\Delta m_2}{F_2} \frac{\theta I \sin\varphi}{2\varepsilon_0 c}$$

$$\hbar\nu_1 = -\gamma_1 B - \Gamma_1 \theta I \sin\varphi$$

$$\hbar\nu_2 = -\gamma_2 B - \Gamma_2 \theta I \sin\varphi$$

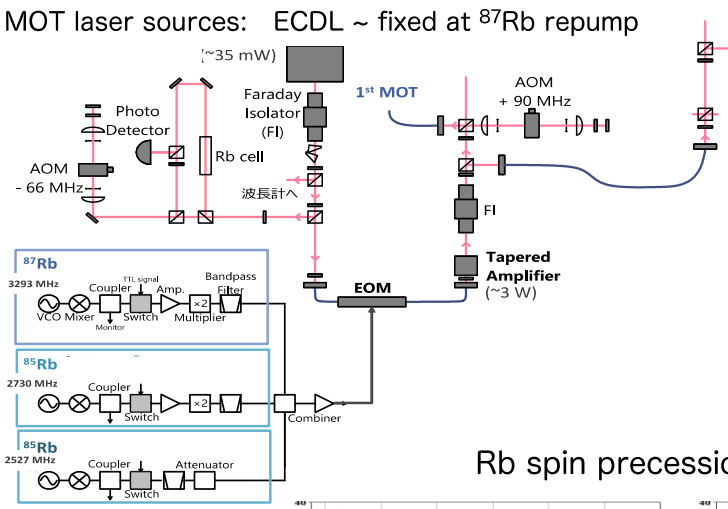
$$B = -\frac{\Gamma_2 \nu_1 - \Gamma_1 \nu_2}{\gamma_1 \Gamma_2 - \gamma_2 \Gamma_1}$$

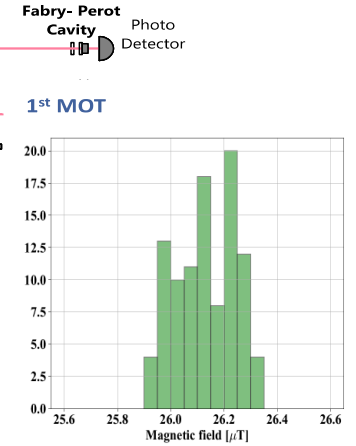
$$\theta I \sin\varphi = -\frac{\gamma_2 \nu_1 - \gamma_1 \nu_2}{\gamma_1 \Gamma_2 - \gamma_2 \Gamma_1}$$

Dual atoms co-magnetometer (Rev. Sci. Inst. 89 (2018) 123111)

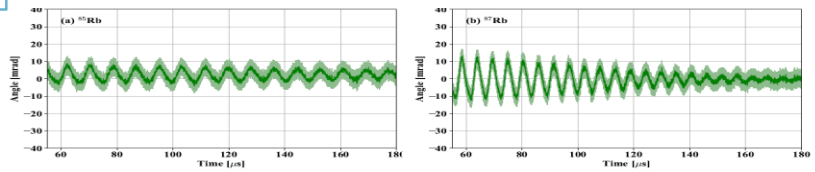
- ^{85}Rb/^{87}Rb atoms trapped simultaneously
- Zeeman shift/Vector light shift accurate measurement

MOT laser sources: ECDL ~ fixed at ^{87}Rb repump





Rb spin precession

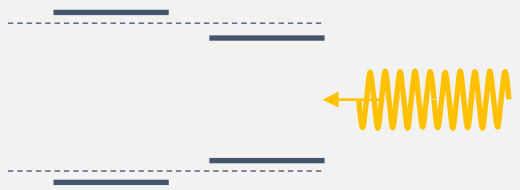


Magnetic field measurement accuracy ~0.1 uT achieved

Predicted systematic errors

Energy shift	Shift item	Systematic error (10^{-29} ecm)	This project
Zeeman shift	magnetic field	1.34	dual species magnetometer
	applied current	1.34 x 10^{-5}	
	leakage current	0.04	
	Johnson noise	4.6 x 10^{-5}	
Vector light shift	polarization	0.46	dual species magnetometer
Atom collision shift	collision	0.14	optical lattice
	shift in OL	1.6 x 10^{-7}	
Geometrical phase		4.6 x 10^{-6}	cooling
Black body radiation		9.2 x 10^{-4}	cooling

Ultra-precise spectroscopy



$B \uparrow\downarrow E_{DC}$ $B \uparrow\uparrow E_{DC}$

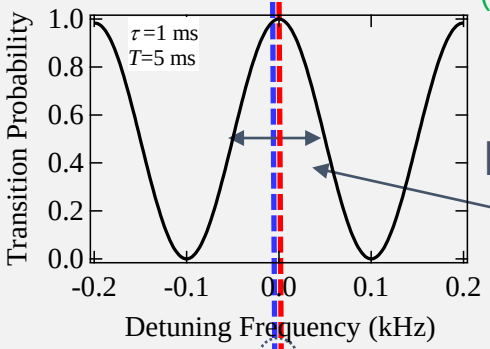
$$\mathcal{H} = -\boldsymbol{d}_{\text{atom}} \cdot \boldsymbol{E}_{DC} - \boldsymbol{\mu} \cdot \boldsymbol{B}$$

$$\hbar\omega_{\uparrow\downarrow} = Rd_e E_{DC} - \mu B$$

$$\hbar\omega_{\uparrow\uparrow} = Rd_e E_{DC} - \mu B$$

$$\Delta\omega_{\text{EDM}} = \omega_{\uparrow\downarrow} - \omega_{\uparrow\uparrow} = \frac{2Rd_e E_{DC}}{\hbar}$$

$\Delta\omega_{\text{EDM}}$ $\frac{\Delta\omega_{\text{EDM}}}{2\pi} \sim 10^{-8}\text{Hz}$ (RE_{DC} ~ 80 MV/cm, d_e~10^{-30})

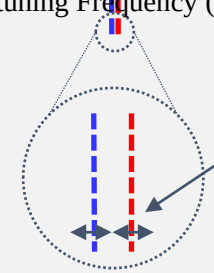


Ramsey fringe

Linewidth $1/2T$

$\sim 10^{-2}\text{Hz}$

(T~10 s)



$$\Delta\omega_{\text{RES}} = \frac{1}{V(T)T\sqrt{Nm}}$$

$\Delta\omega_{\text{EDM}} \sim \Delta\omega_{\text{RES}}$

$$d_e \sim \frac{\hbar}{2RE_{DC}V(T)T\sqrt{Nm}}$$

- Enhancement factor : R
- Static electric field : E_{DC}
- Number of atoms : N
- Number of measurements : m
- Interaction time : T
- Visibility : $V(T)$

electron EDM (eEDM)

YbF molecular beam
Hudson, *et al.*,
Nature **473** 493 (2011)

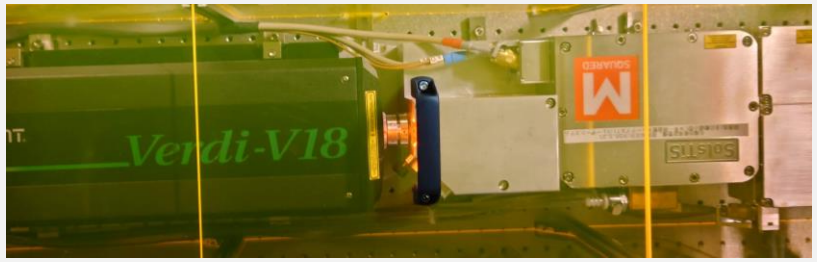
ThO molecular beam
ACME Collaboration,
Science **343**, 269 (2014)
Nature **356**, 562 (2018)

Supersymmetry theory (SUSY) (Predicted value)

Standard model (Predicted value)

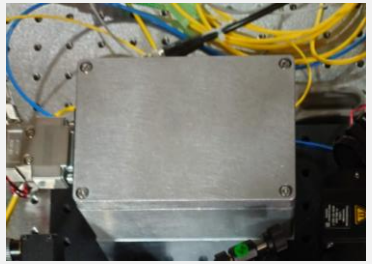
Light source

Light source



Ti:sapphire laser
Verdi (Coherent) + SolsTiS
(M SQUARED LASERS) 700-1000 nm

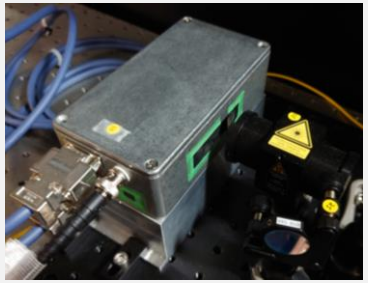
Linewidth： < 70 kHz
Maximum output：1.5 W



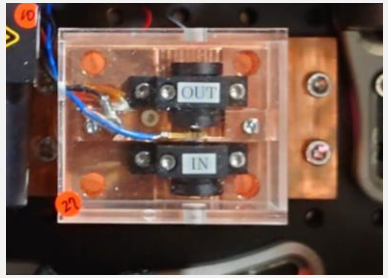
LD：
Eagleyard
EYP-RWE-0840
810-860 nm

Homemade interference-filter-type ECDL

Linewidth： ~420 kHz
Maximum output: 90 mW



+



Homemade
Littrow-type ECDL + TA

Linewidth： ~530 kHz
Maximum output: 1.6 W

DFB laser
(TOPTICA Photonics)

Linewidth： < 70 kHz
Maximum output： 45 mW

Energy level diagram