Fundamental physics with cold radioactive atoms and molecules

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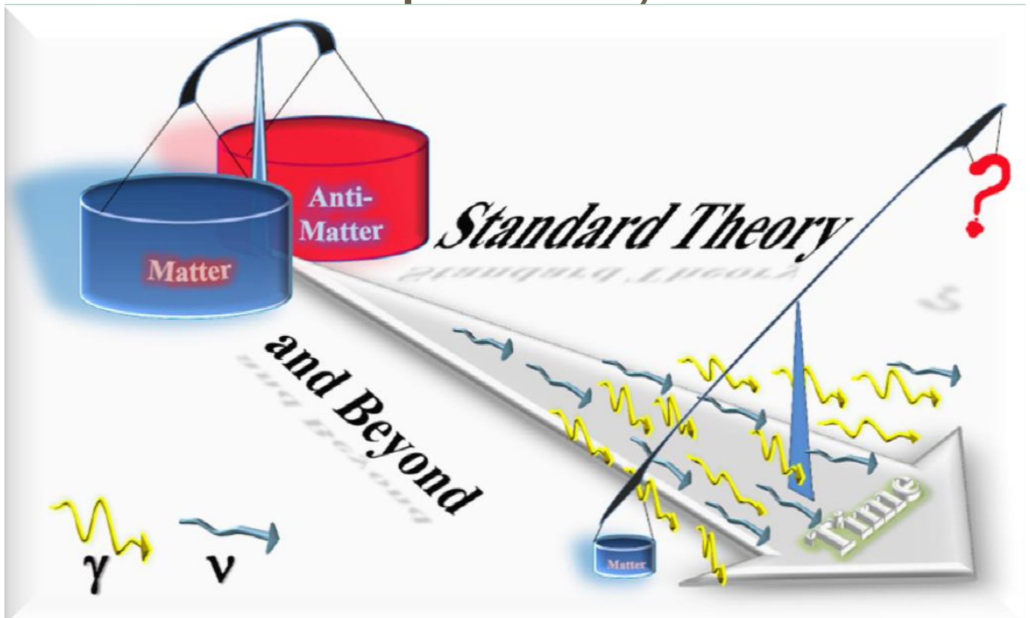
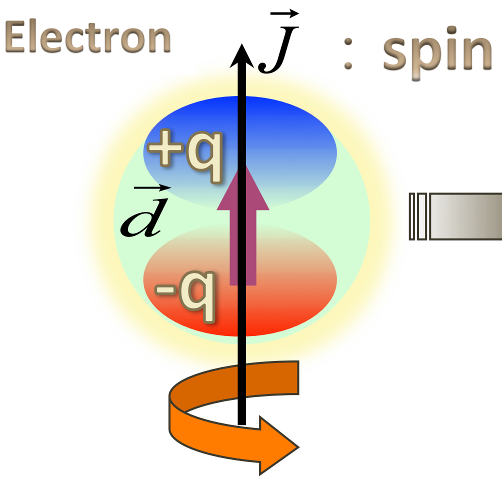
Matter and anti-matter symmetry violation (CPV) in composite system

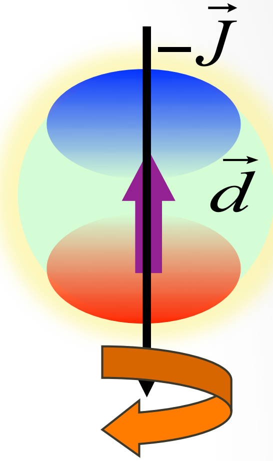


- Standard model of particle physics ～ Best theory we have
- Still large number of open questions:
  particle masses, origin of matter anti-matter asymmetry (CPV) in the universe,
  source of symmetry violation ….
- How these symmetry violations are appeared and amplified in composite sytems such as heavy atoms, molucules
- How to approach BSM with composite systems ～ Electric Dipole Moment (EDM)

Electric dipole moment (EDM)



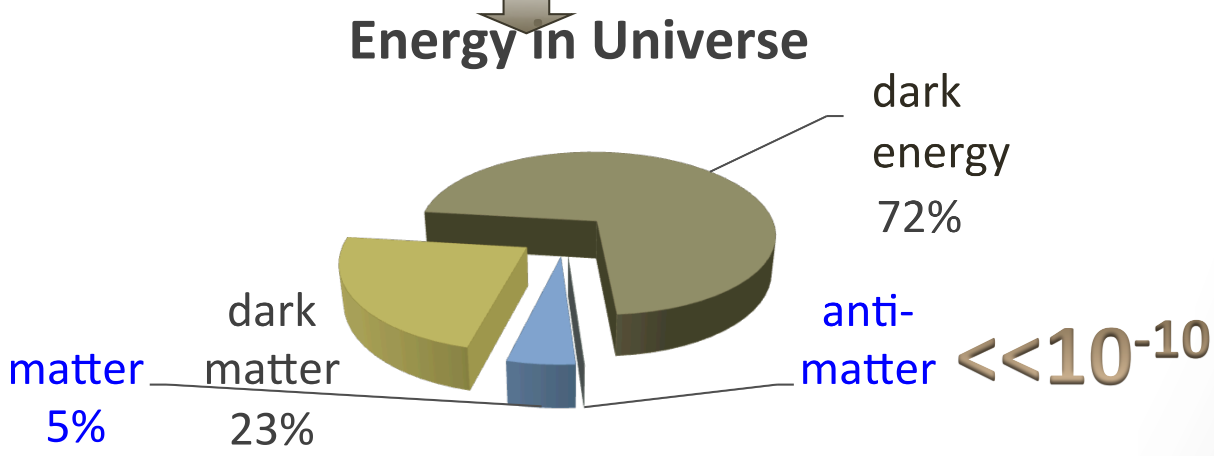
$$\vec{d} = q\vec{r}$$



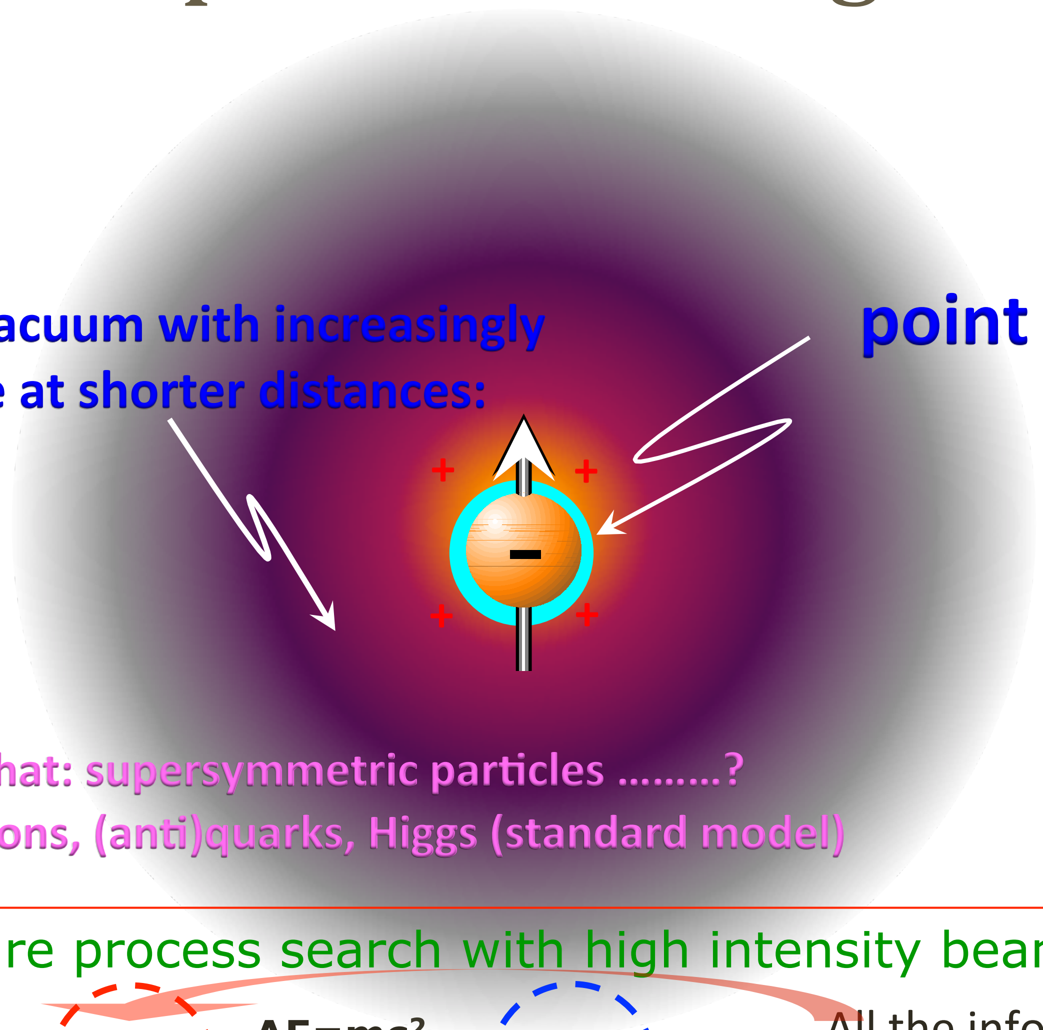
Time reversal ～ symmetry violation

CPT invariance ～ CPT theorem

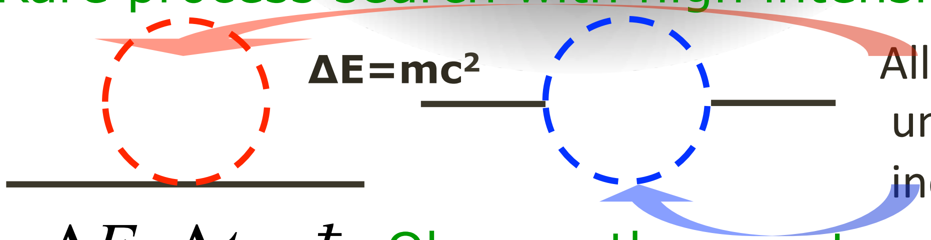
If the electron has an EDM,
Nature has chosen breaking T symmetry, CP violation …



How a point electron gets a structure



Rare process search with high intensity beam



All the information on unknown physics are included in the loop

$\Delta E \cdot \Delta t \approx \hbar$ Observe the quantum fluctuation

Electron EDM

Completely can be neglected at any experimental sensitivity at present

Fourth order electroweak,

F. Hoogeveen:
The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

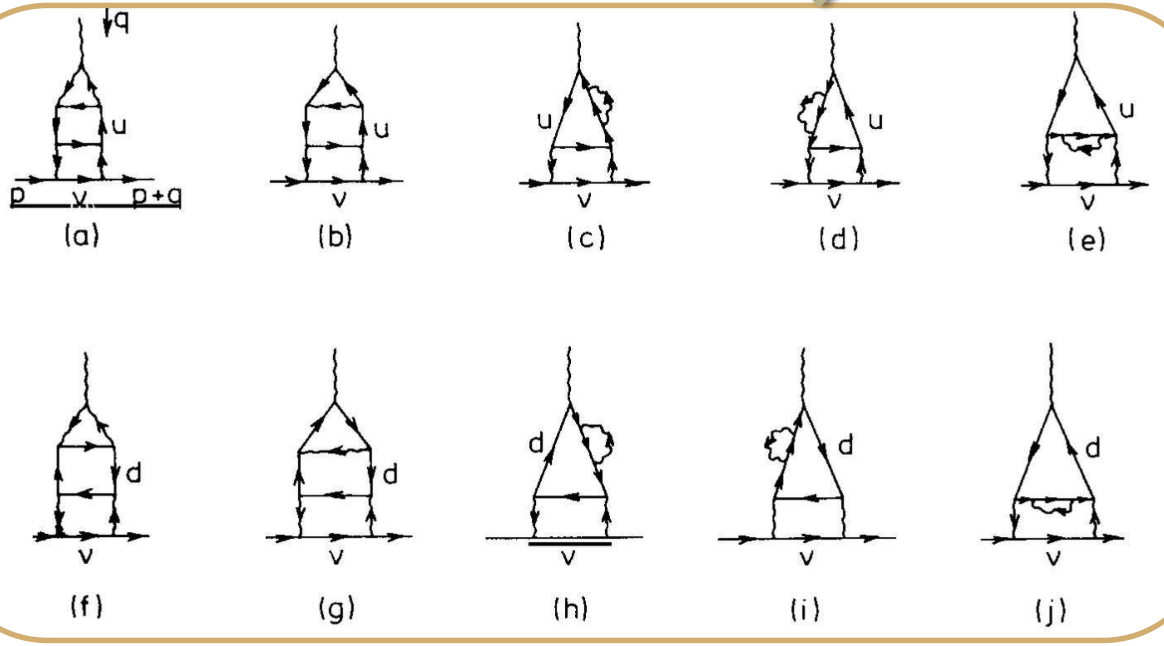


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

$\sim 10^{-37}$ ecm

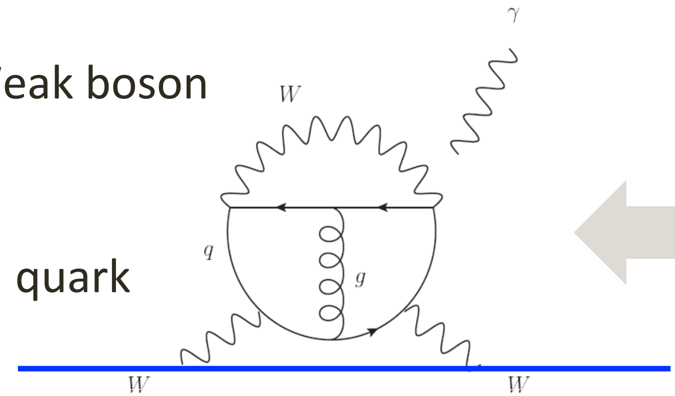
… + new physics?

EDM sources

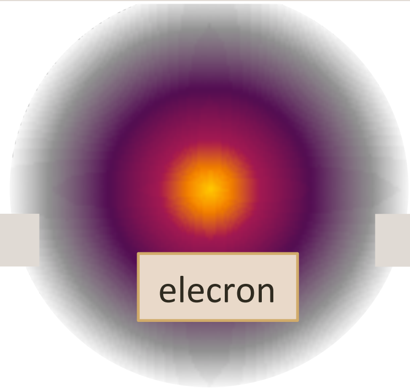
Polarizable vacuum with increasingly rich structure at short distances

Weak boson

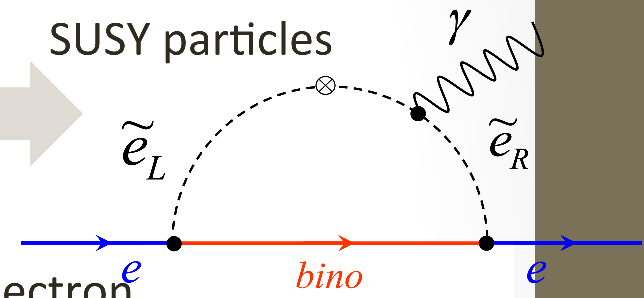
quark



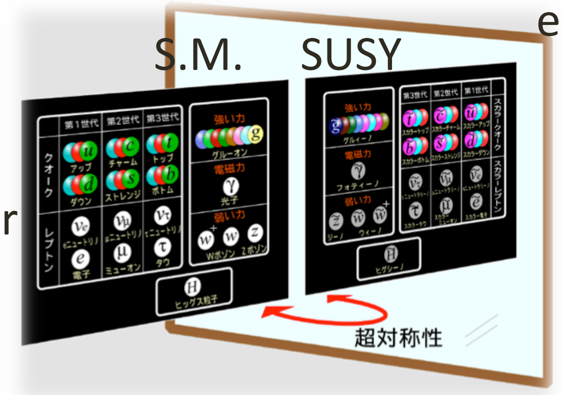
electron



SUSY particles



electron



Standard Model：

EDM ～ appeared in higher order

→ quite small

$$d_e < 10^{-37} e \cdot cm$$

GUT SO(10) etc

Super Symmetry (SUSY)：

EDM ～ appeared from the propagation of SUSY particles

$$d_e \sim \frac{\alpha}{4\pi} \frac{m_\tau}{M_{\tilde{l}}^2} \frac{\mu m_{\tilde{B}}}{M_{\tilde{l}}^2} \sin\theta_\mu \tan\beta$$

EDM small

New physics beyond the standard model

Get the information of the mass of SUSY and CP violating phases

EDM large

Present status of EDM

ThO EDM [±20%]	$\left\|d_e + e(26\,\mathrm{MeV})^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b}\right)\right\| < 8.7 \times 10^{-29} e\,cm$
Neutron EDM [±50%?]	$\left\|e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25d_u) + O(\tilde{d}_s, w, C_{qq})\right\| < 2 \times 10^{-26}\, e\,cm$
Hg EDM [±O(few)?]	$e\|\tilde{d}_d - \tilde{d}_u + \mathcal{O}(d_e, \tilde{d}_s, C_{qq}, C_{qe})\| < 6 \times 10^{-27} e\,\mathrm{cm}$

A precision measurement of the electron's electric dipole moment using trapped molecular ions

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Tanya S. Roussy, Yiqi Ni,§ Yan Zhou, Jun Ye, and Eric A. Cornell
JILA, NIST and University of Colorado, Boulder, Colorado 80309-0440, USA and
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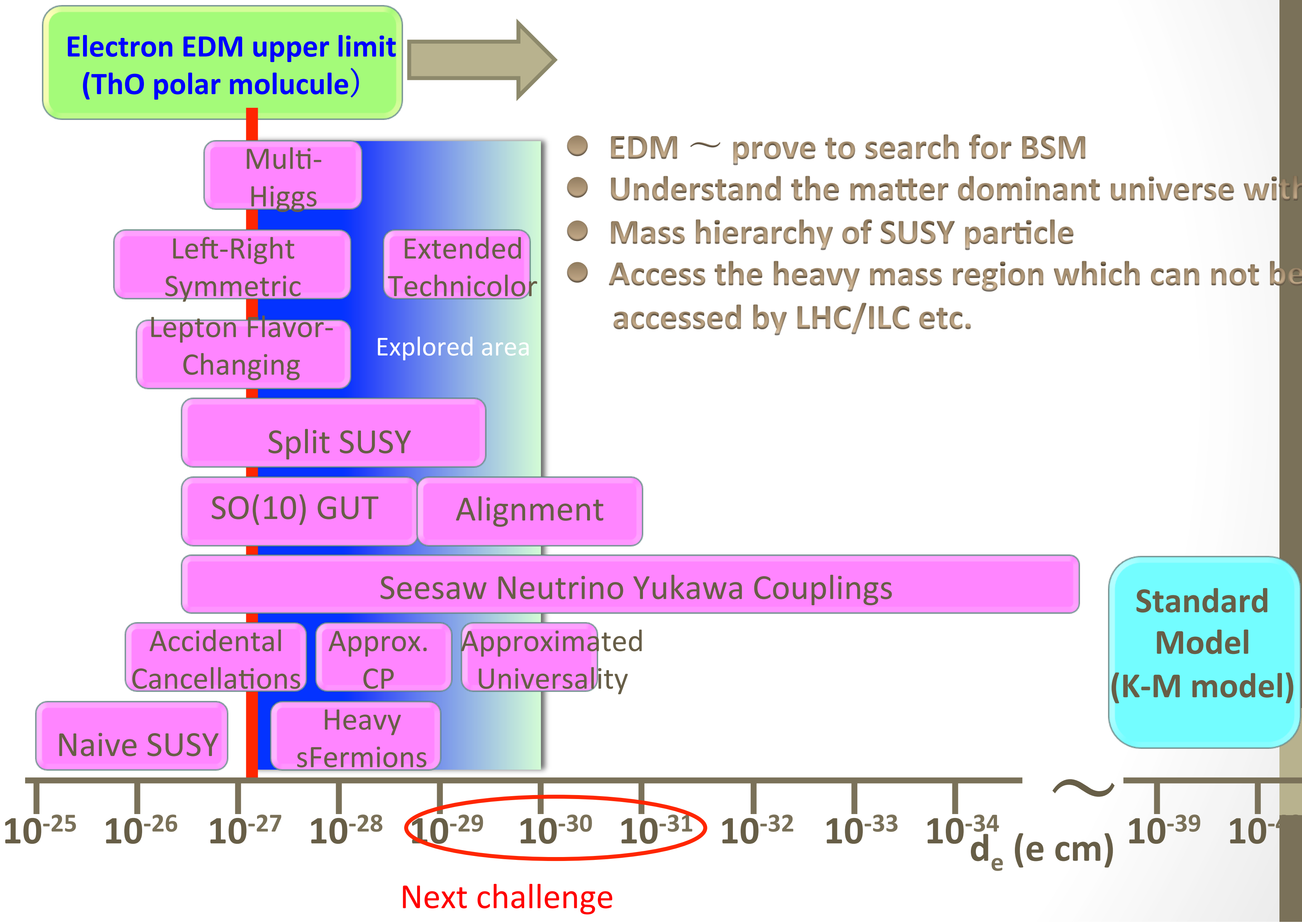
(Dated: April 27, 2017)

We describe the first precision measurement of the electron's electric dipole moment (eEDM, d_e) using trapped molecular ions, demonstrating the application of spin interrogation times over 700 ms to achieve high sensitivity and stringent rejection of systematic errors. Through electron spin resonance spectroscopy on $^{180}\mathrm{Hf}^{19}\mathrm{F}^+$ in its metastable $^3\Delta_1$ electronic state, we obtain $d_e = (0.9 \pm 7.7_{\mathrm{stat}} \pm 1.7_{\mathrm{syst}}) \times 10^{-29}\,e\,\mathrm{cm}$, resulting in an upper bound of $|d_e| < 1.3 \times 10^{-28}\,e\,\mathrm{cm}$ (90% confidence). Our result provides independent confirmation of the current upper bound of $|d_e| < 9.3 \times 10^{-29}\,e\,\mathrm{cm}$ [J. Baron *et al.*, Science **343**, 269 (2014)], and offers the potential to improve on this limit in the near future.

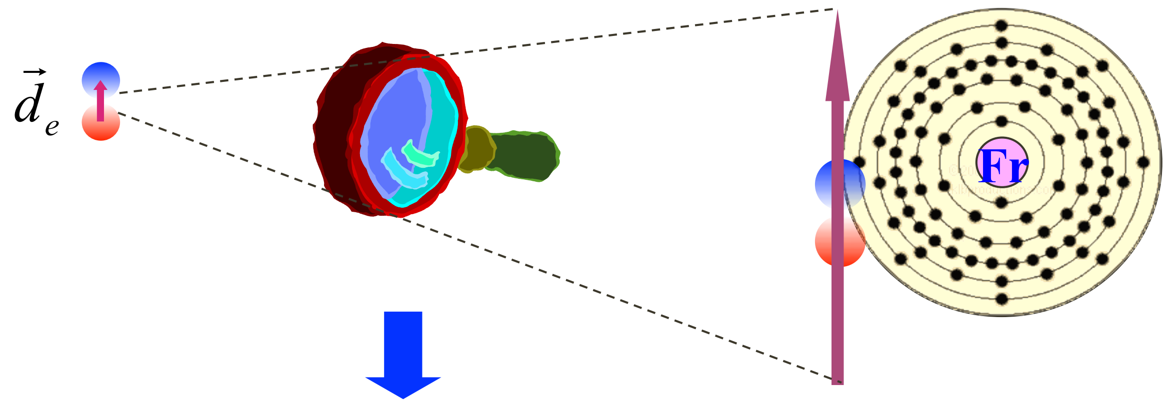
Beyond Standard Model search with EDM

- EDM ～ prove to search for BSM
- Understand the matter dominant universe with EDM
- Mass hierarchy of SUSY particle
- Access the heavy mass region which can not be accessed by LHC/ILC etc.

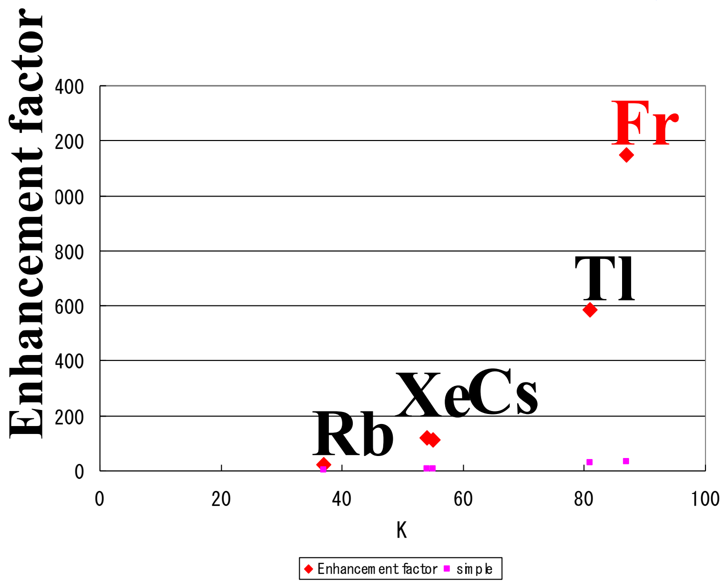


Enhancement of electron EDM

Heavy paramagnetic atom : electron EDM ～ enhanced

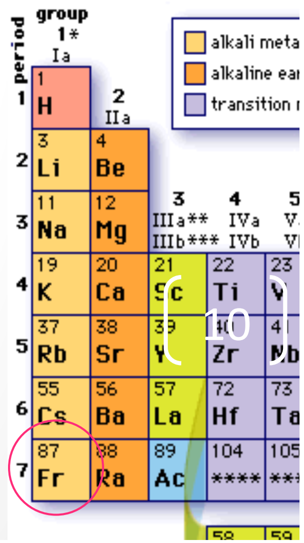


$$K \sim \frac{d_{atom}}{d_e} \sim Z^3\alpha^2 \sim |\psi_s(0)|^2 V Z^5 \alpha^2 \frac{e}{a_0^2}$$



Francium　(^{210}Fr)

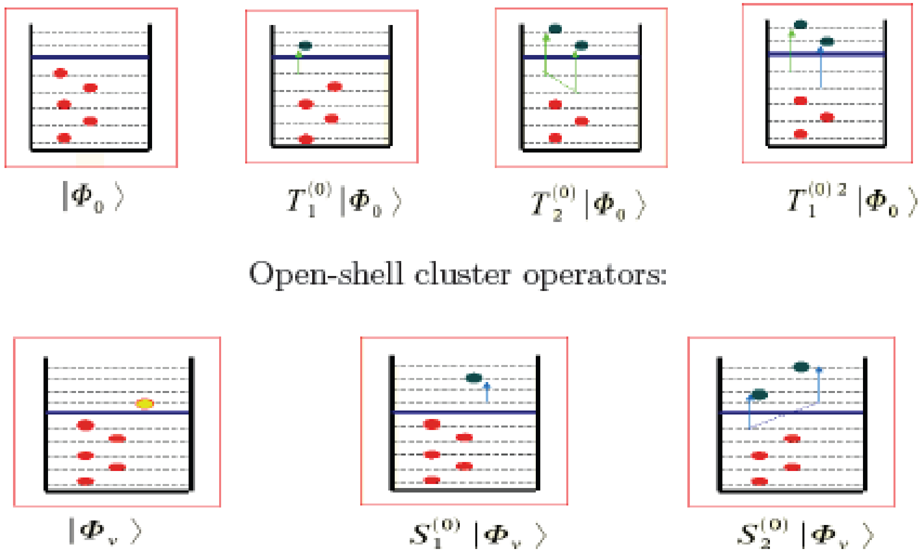
- Heaviest Alkali: atomic number 87
- Radioactive isotope (RI) : $t_{1/2}$ ～ 3 min.
- Atomic structure :simple
- Electron EDM enhancement:　895
  maximum in atom
- Laser cooling: possible

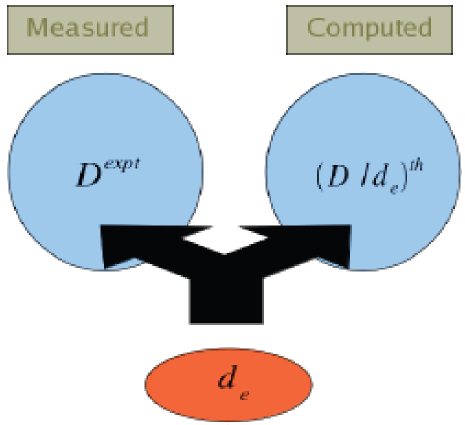


Relativistic Coupled Cluster model

Prof. Das

$$|\Psi_v^{(0)}\rangle = e^{T^{(0)}}\{1 + S_v^{(0)}\}|\Phi_v\rangle$$





d_e X 895

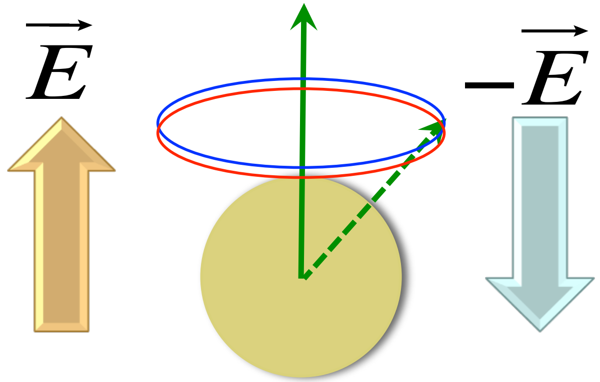
- **Electron correlation : included**
- **Any configurations of electron excitations**
- **Calculation accuracy ~ high**
- **Cs, Rb : ready**
- **Fr calculation ~ enhancement : 895**

Basis set		no. corr.ele./	eEDM EF		% corr.
Name	Details	no. virtuals	Dirac-Fock	CISD	
dyall.cv2z	27s 24p 15d 8f	19/83	784.34	893.44	12.21
		41/113		898.23	12.68
		59/201		900.50	12.90
dyall.cv3z	34s 30p 19d 12f 1g	19/179	789.43	897.19	12.01
dyall.cv4z	38s 35p 24d 19f 4g 1h	19/261	789.64	895.37	11.81

EDM measurement

Measurement of spin precession ← Interaction to external field ← Spin polarization : <J>

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



$$\begin{cases} h\nu_{\uparrow\uparrow} = \mu \cdot B + d \cdot E \\ h\nu_{\uparrow\downarrow} = \mu \cdot B - d \cdot E \end{cases}$$

(1 cycle ~7 year)

$$\Rightarrow \quad \delta\nu \equiv \nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow} = d = \frac{2dE}{h} \approx 4.8\,nHz$$

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

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

Enhancement factor : maximum

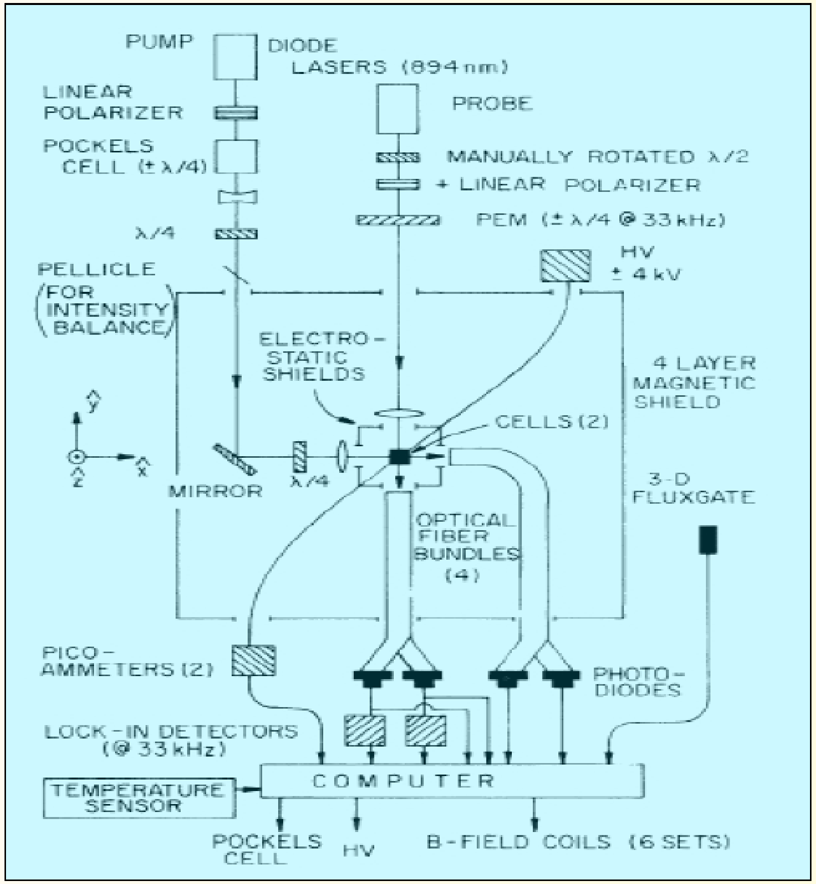
Electric field

Trapped number

Coherence time: Long

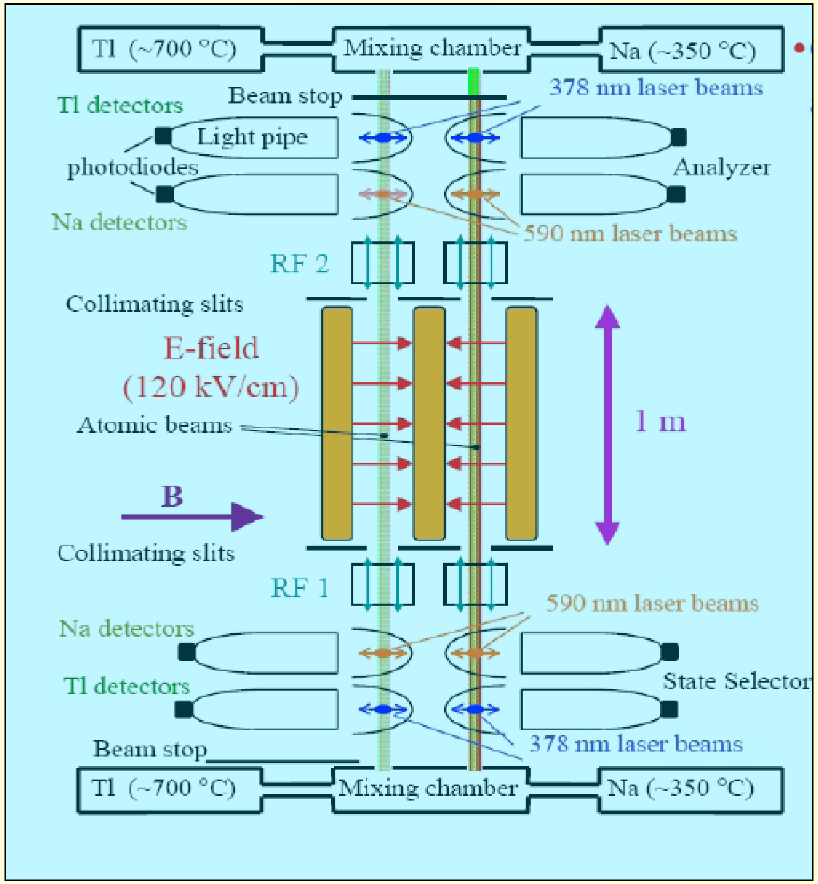
e-EDM experiment with cell and atomic beam

Cs EDM CELL experiment
(Phys. Rev. Lett., 63,965, 1989)



Result: $d_e = (-1.5 \pm 5.7) \times 10^{-26}\, e\,cm$

Berkeley Tl EDM BEAM experiment
(Phys. Rev. Lett., 88, 071805, 2002)



Result: $d_e = (6.9 \pm 7.4) \times 10^{-28}\, e\,cm$, which yields a limit $|d_e| < 1.6 \times 10^{-27}\, e\,cm$ at 90% CL.

Limitations of cell and collinear beam experiment

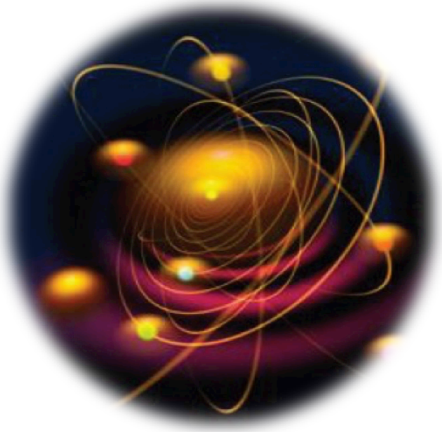
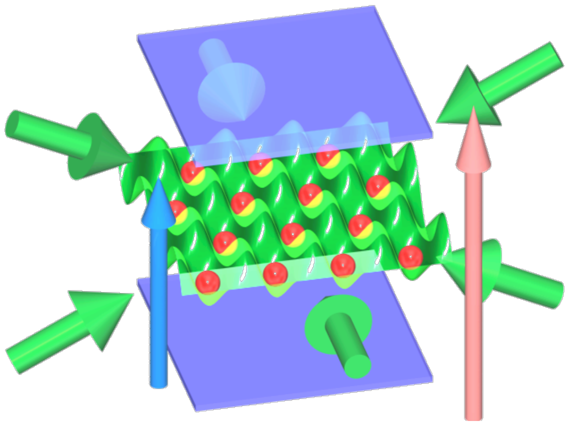
Measurement accuracy and systematic errors in EDM experiments

- Interaction time : short
- Uniform external field ~ difficult to realize in the long electrode
- Motional magnetic fields, $B_m = \frac{v \times E}{c^2}$
- Misalignment of static magnetic field B_0 with static electric field E; cause a component of B_m to lie along B_0
- Magnetic field B_E, generated by leakage and/or changing currents, inaccuracy of high voltage electric field reversals, correlated with E
- Geometric phase shifts generated by complicated field gradients

↓

Laser cooled and trapped atoms ~ one of the candidates to overcome these difficulties

EDM with cooled/trapped atom

Francium (^{210}Fr) RI		Laser trap (ODT and lattice) Trapped atom
	×	

- Heaviest Alkali
- $T_{1/2}$～3 min. : enough for online exp.
- Laser cooling/trapping : possible

⇓

- EDM enhancement : largest （～895）

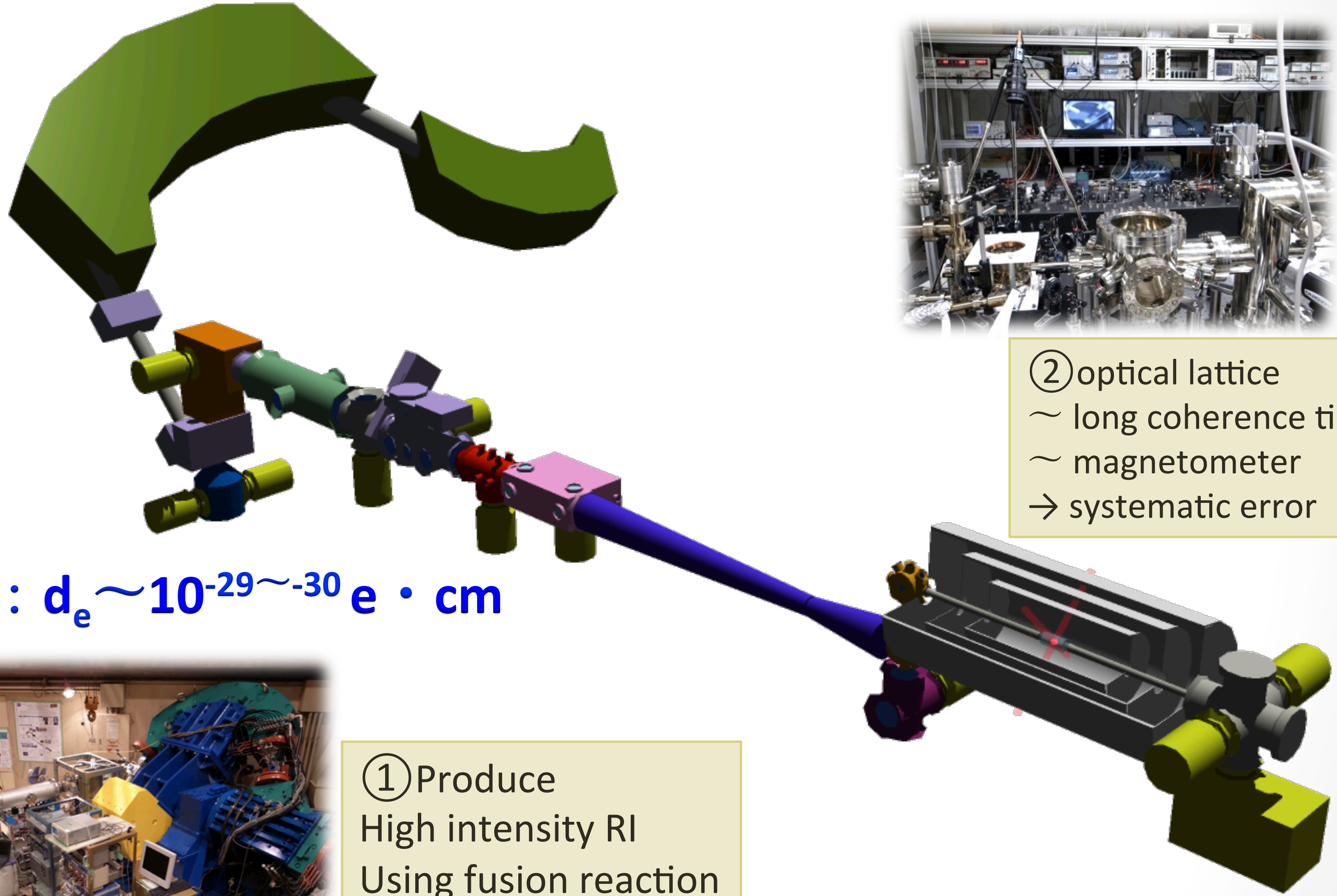
- Cooled atom
- Interaction between atoms ～ weak
- High vacuum ～ high electric field

⇓

- Long coherence time ～ sec. order

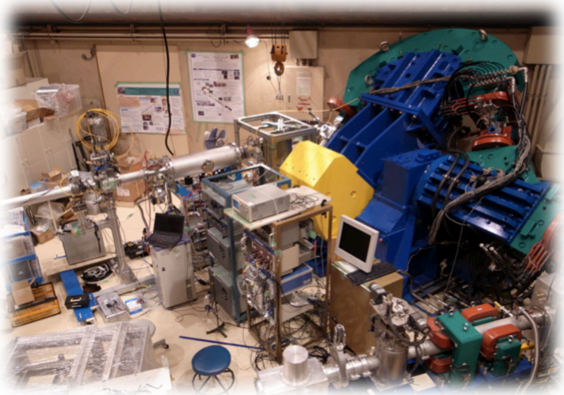
Accuracy : $\frac{895(Fr)}{114(Cs)} \times \sqrt{\frac{1(trap)}{10^{-3}(beam)}} > 100$ Times improved

Fr EDM search with optical lattice at CYRIC



②optical lattice
～ long coherence time
～ magnetometer
→ systematic error

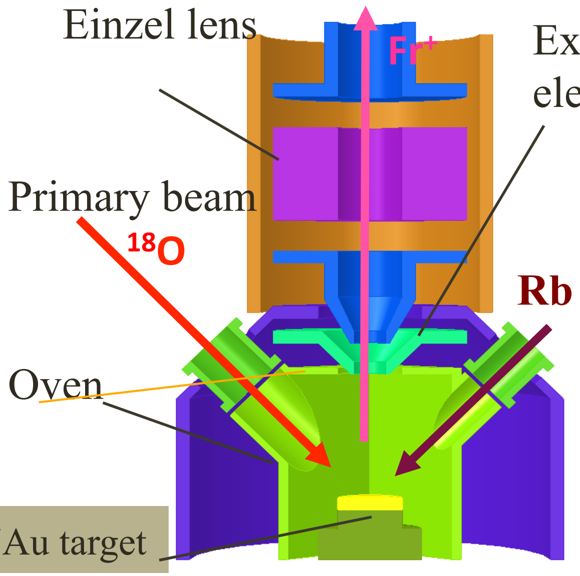
goal：d_e～$10^{-29～-30}$ e・cm

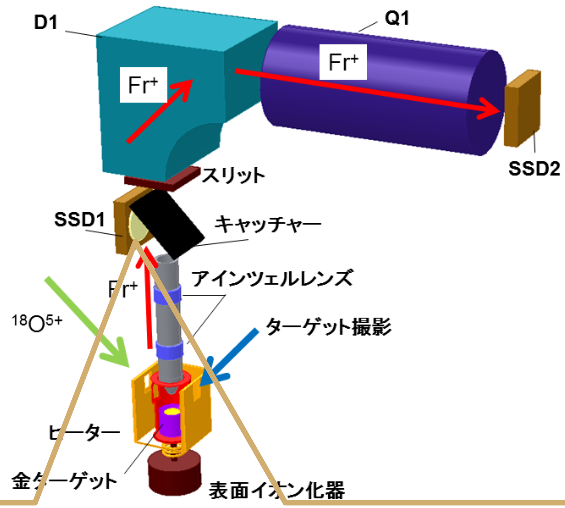


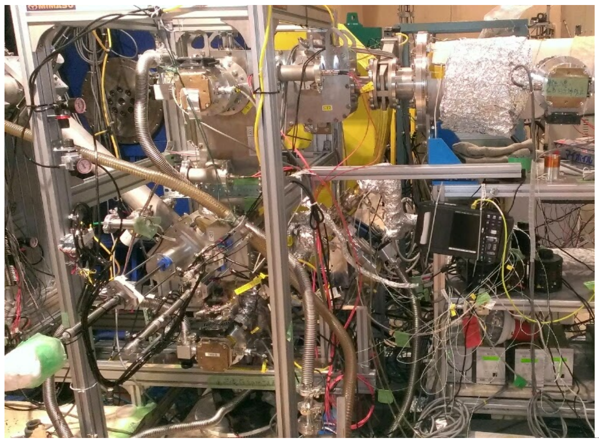
①Produce
High intensity RI
Using fusion reaction

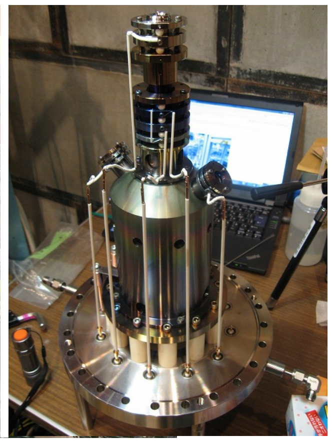
Fr production ： surface ionizer

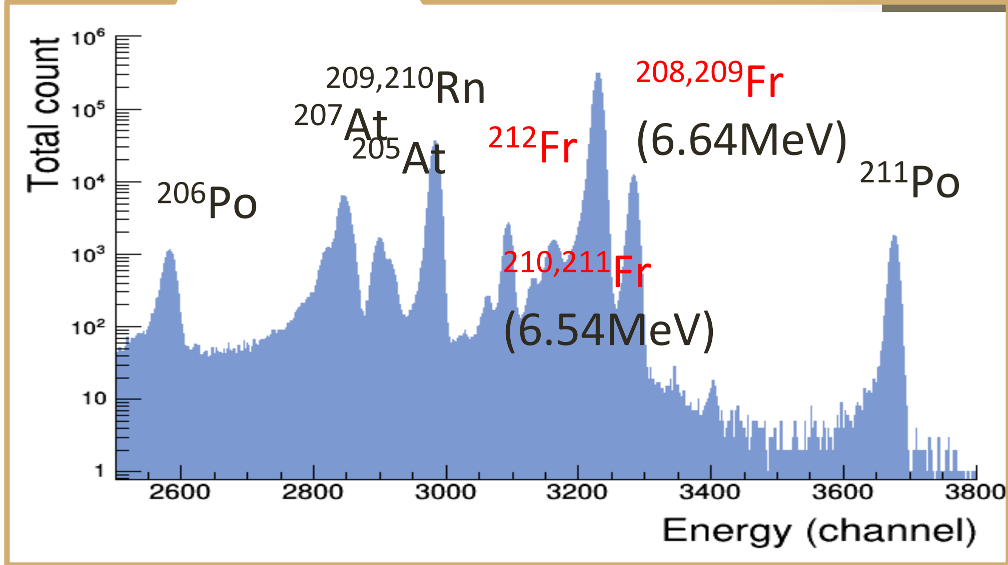
- **Fusion reaction ： ^{18}O(beam 100MeV)+^{197}Au(target)→^{210}Fr+5n**
- **10^6 Fr+/sec＠200nA realized**
- **Extraction efficiency ～30% ：　advantage of molten target**



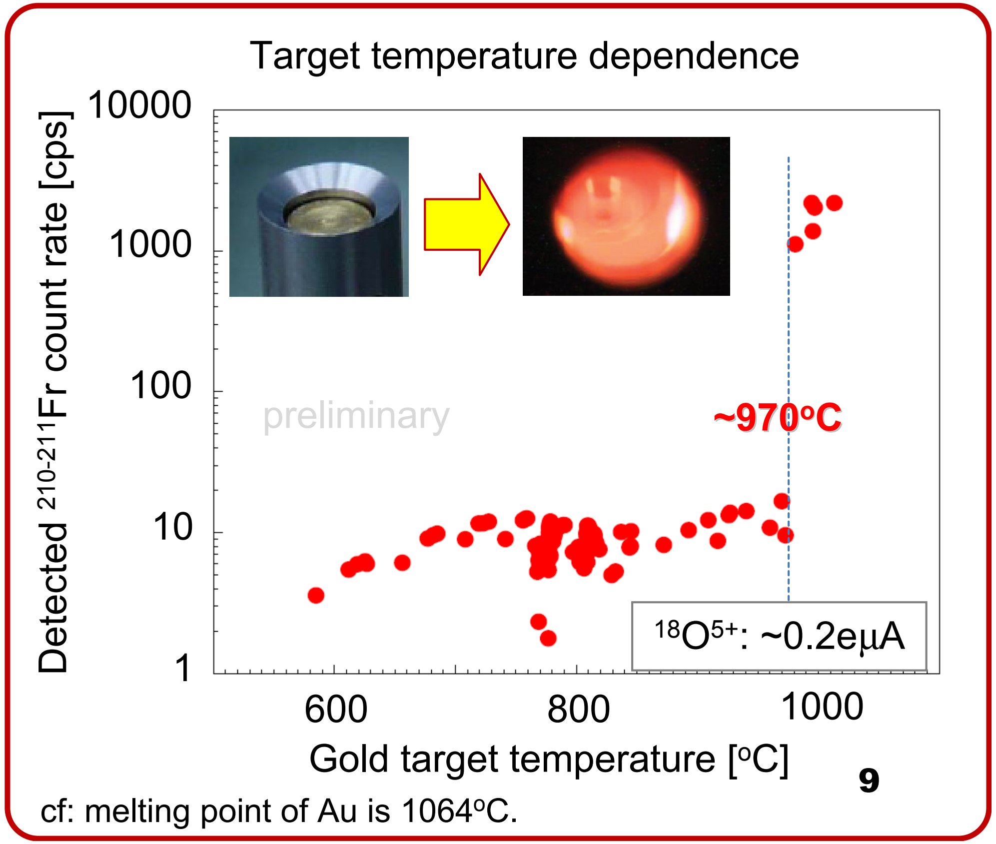


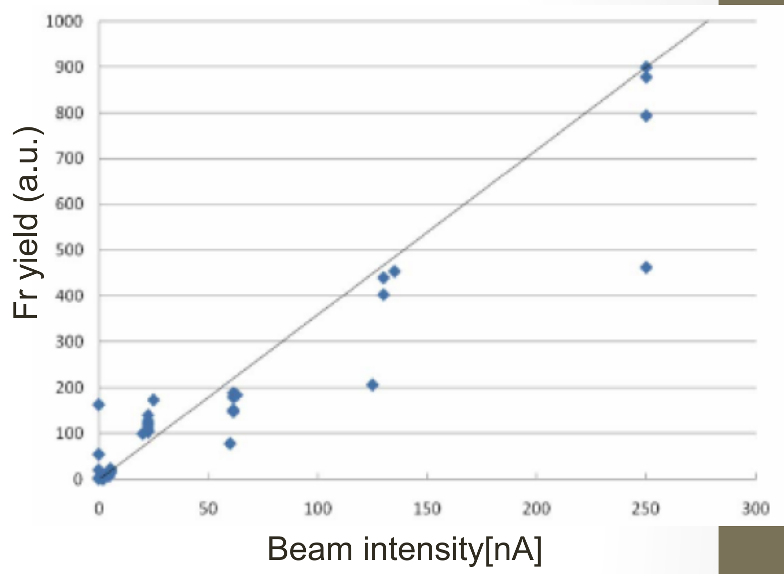






Surface ionizer with molten target

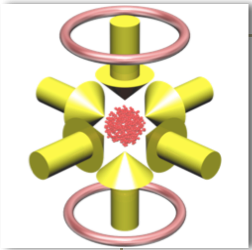




	Fr yield	Primary beam
CYRIC	～ 10^6 /s	^{18}O (0.2uA, 100MeV)
LNL（Italy）	> 0.7~2x10^6 /s	^{18}O (2.0uA, 100MeV)
TRIUMF（Canada）	8.5x10^7 /s (^{210}Fr) ⇒ ～10^9 /s (^{210}Fr) at present	p (2uA, 500MeV)
ISOLDE (CERN)	1.9x10^9 /s (^{210}Fr) 3.9x10^9 /s (^{212}Fr)	p (1uA, 600MeV) p (1uA, 600MeV)

- **S.I with molten target ~ succeeded**
- **Extraction efficiency ~ 30% high**
- **will be increased**
  ～ 10^7 Fr^+/s@0.2 uA

Required confinement technique

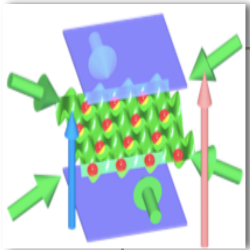


Magneto Optical Trap (MOT)

- Temperature : 65 uK ~ 210 uK
- Life time : a few 10 seconds
- Accumulate the Fr

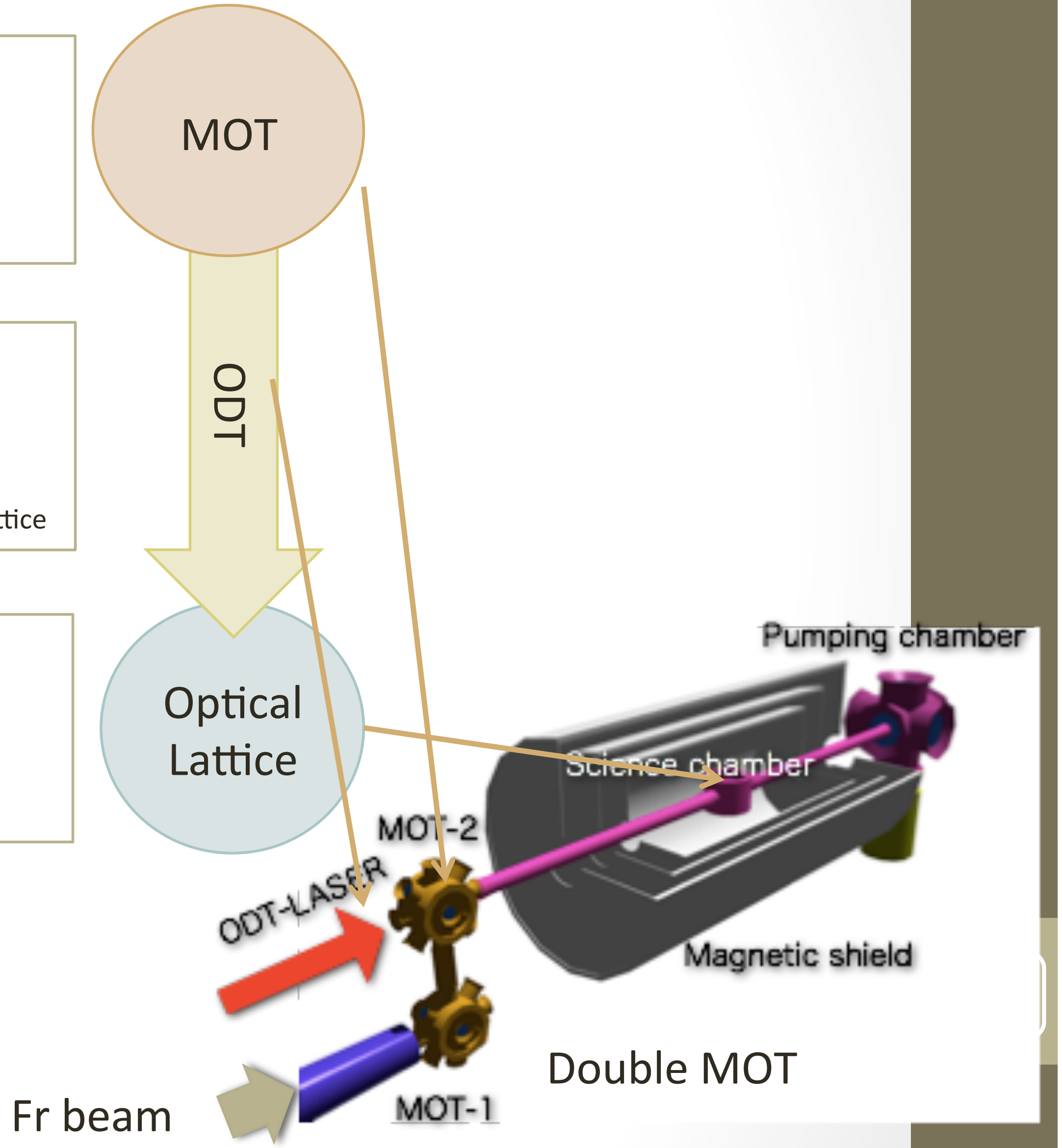
Optical Dipole Trap (ODT)

- Temperature : ~65uK
- Life time : > 10 seconds
- EDM measurement (1st phase)
- Optical tweezer to load to the optical lattice



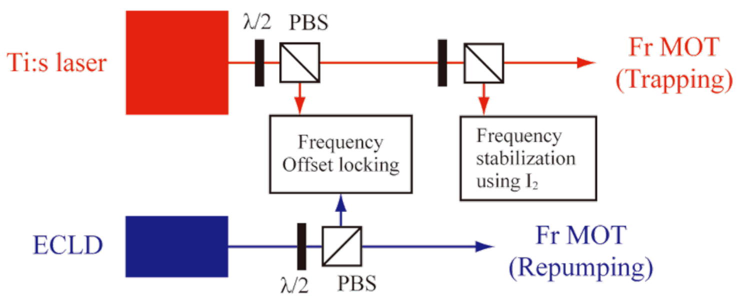
Optical Lattice (OL)

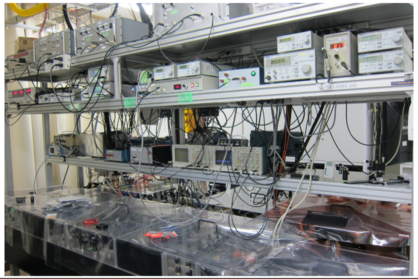
- Temperature : < 65 uK
- Life time: > 10 seconds
- EDM measurement
- Magnetometer



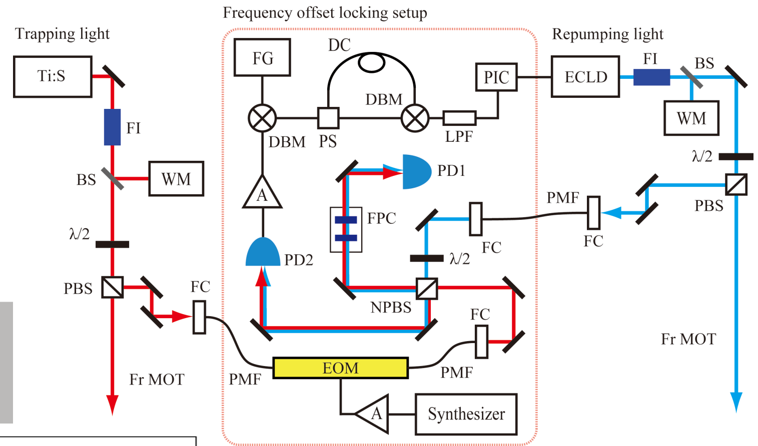
Status of Fr MOT

Magneto-Optical trapping

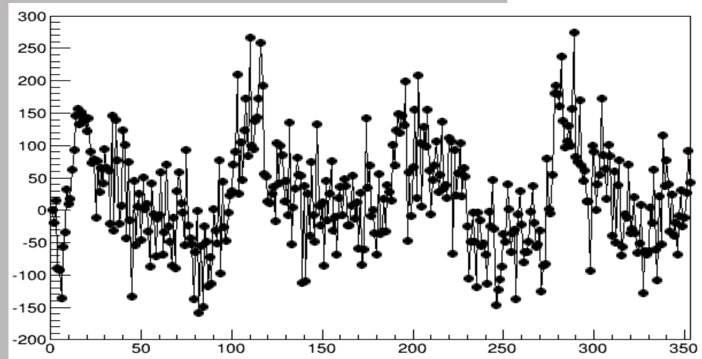


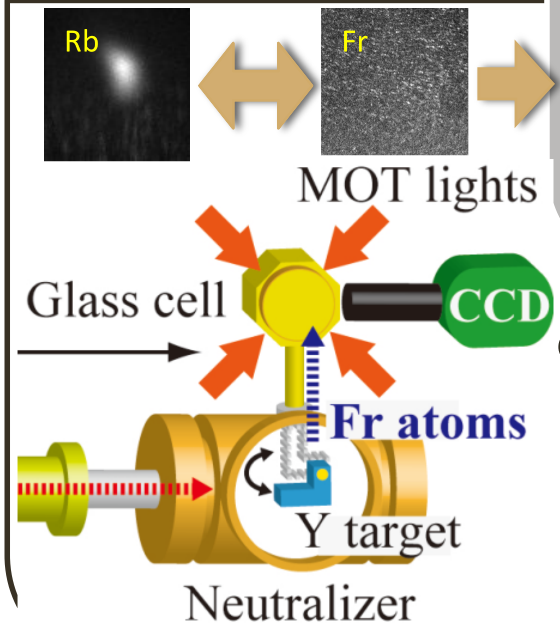


Frequency offset locking

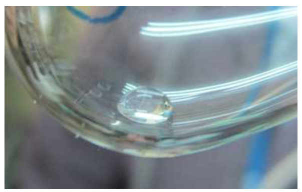


Fr MOT signal



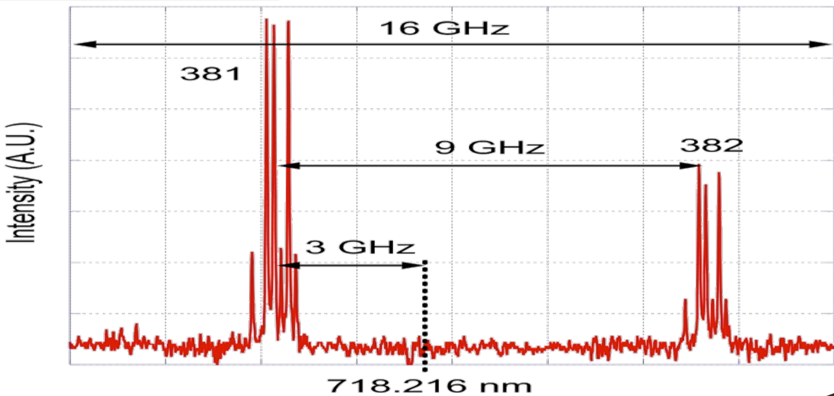


Coating and LID
to increase Fr



Frequency stabilization

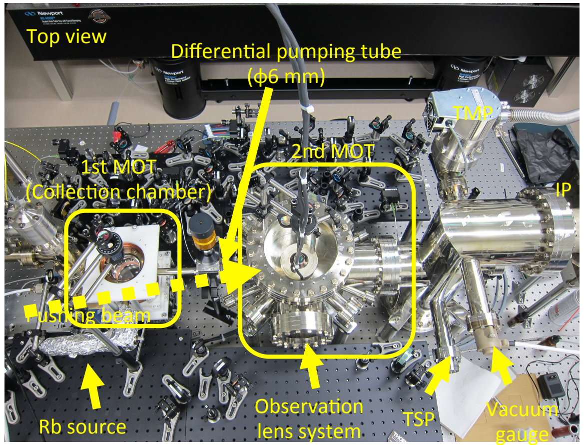
Iodine molecule cell (718 nm transition: B3Π0u ← X1Σg)

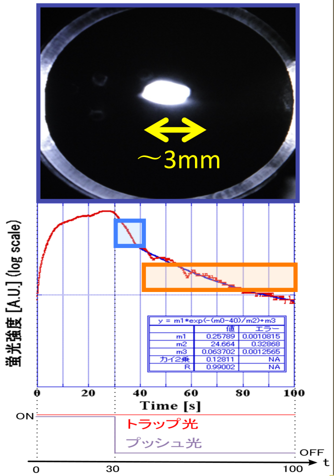


Optical lattice EDM

Magneto-Optical Trap

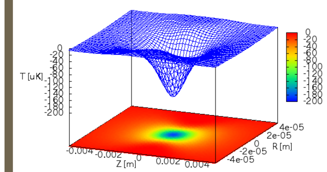
- Double MOT



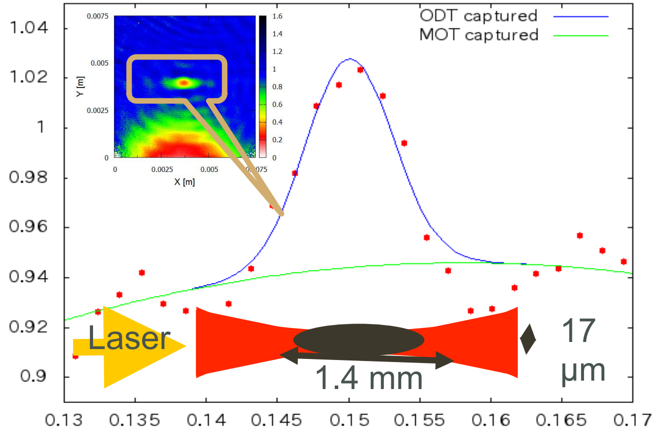


Optical Dipole force Trap

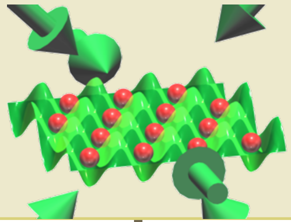
- Same technique as optical lattice
- Extend to the optical lattice with the standing wave



Trap potential
～11 mK

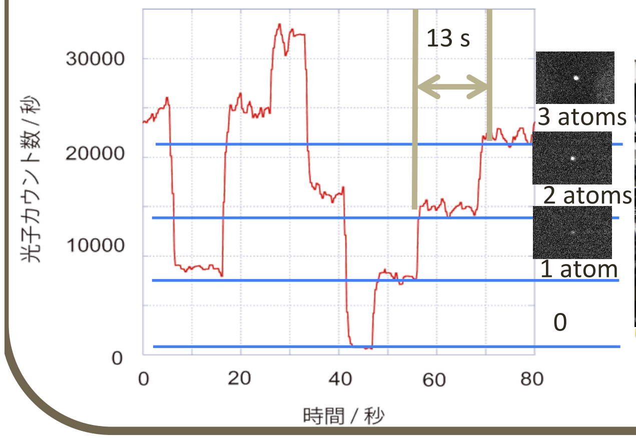


Optical Lattice

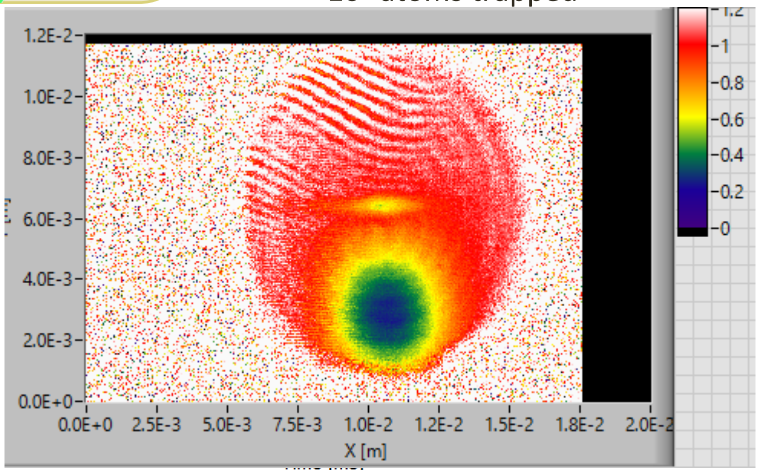


Single atom trap

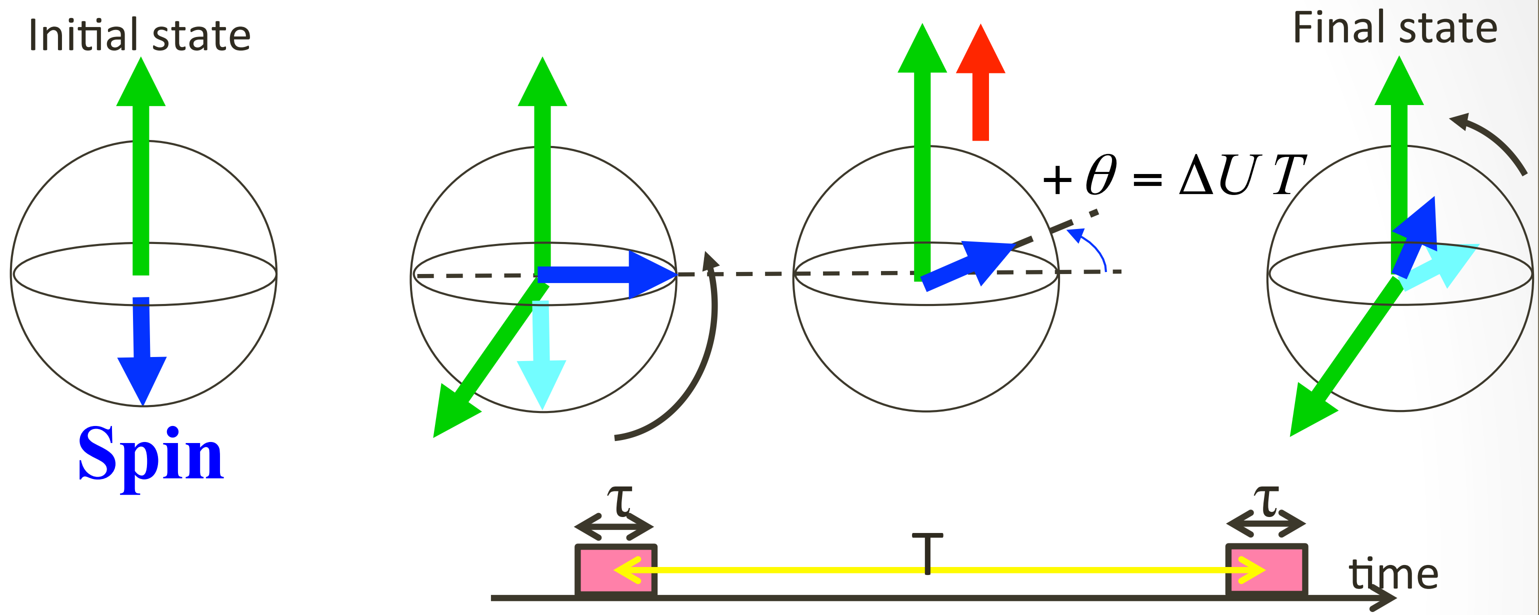
- Long interaction time ～　10 s
- EDM measurement accuracy : improved

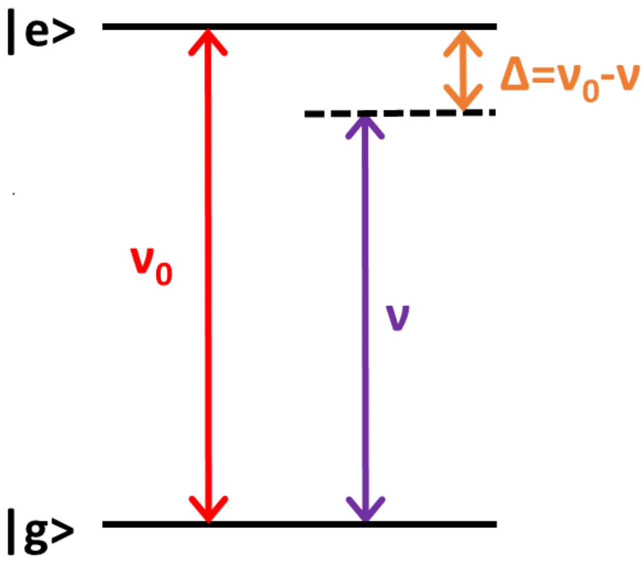


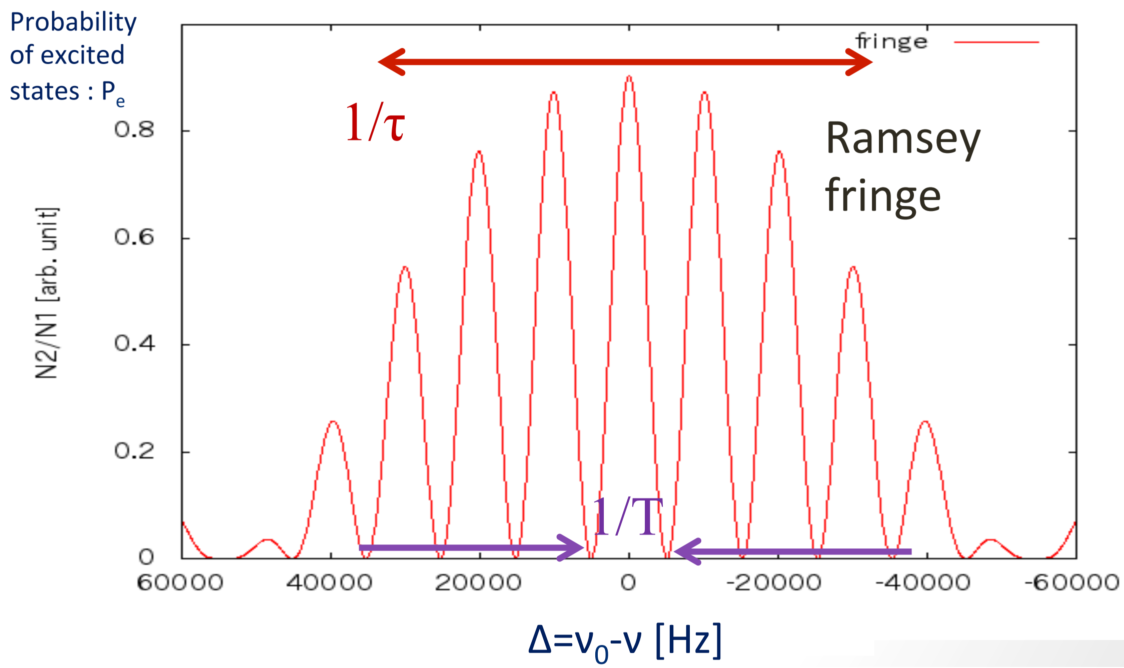
- 1 dimensional optical lattice
- ～20 uK
- ～10^6 atoms trapped



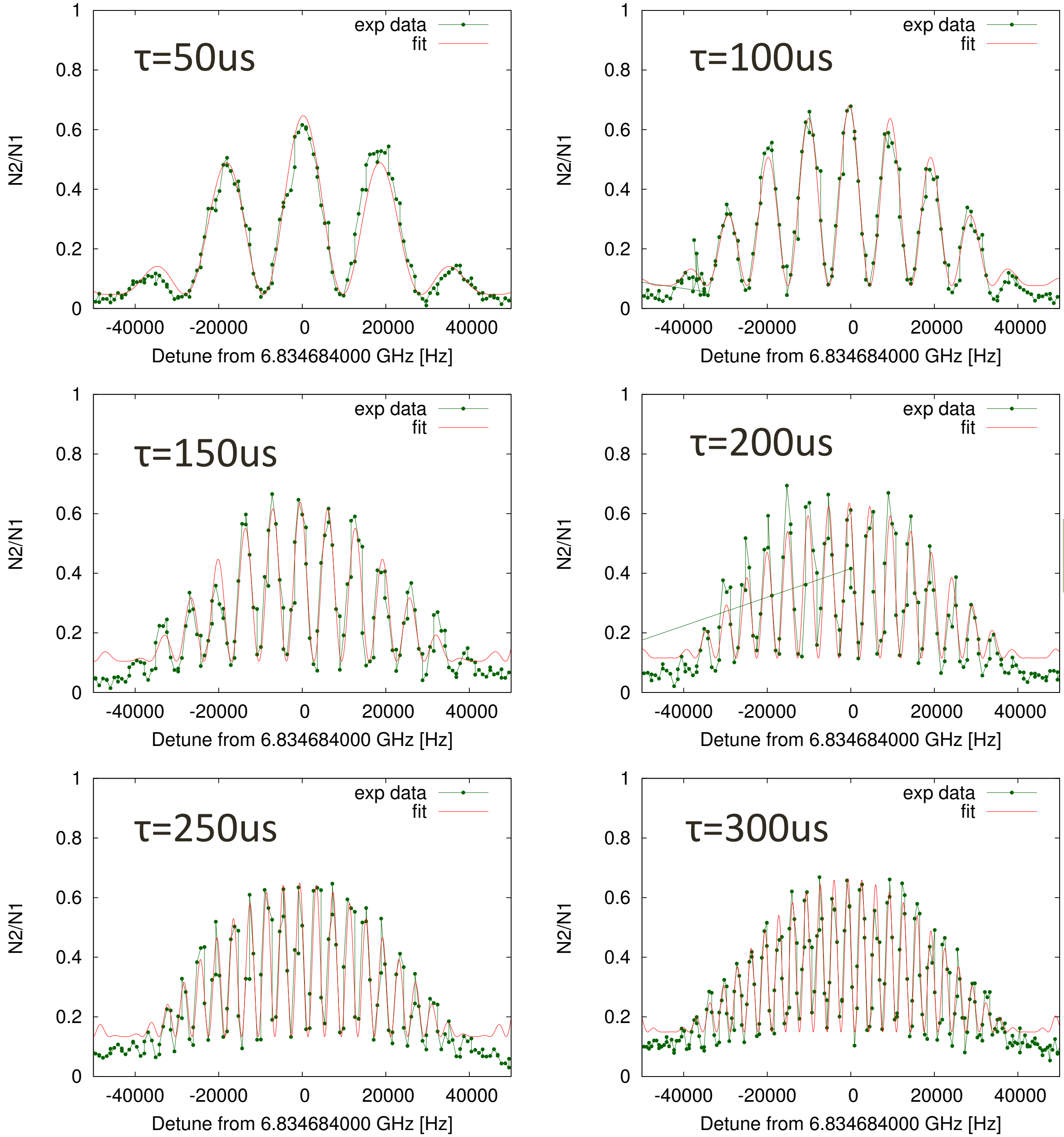
Ramsey interferometry



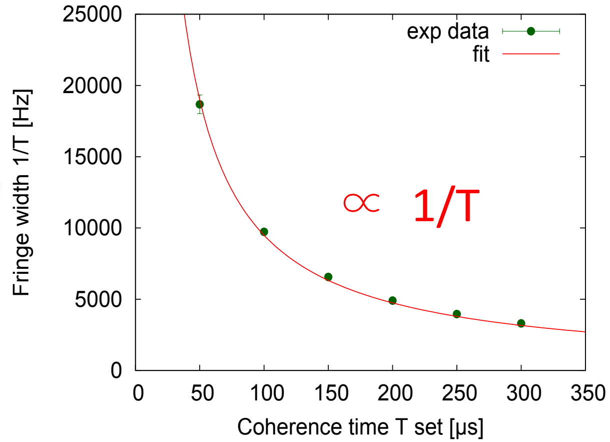




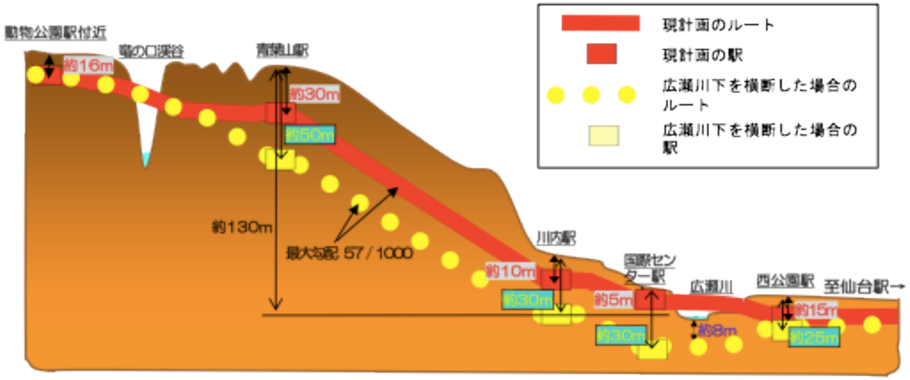
Results on Ramsey fringe for Rb atoms

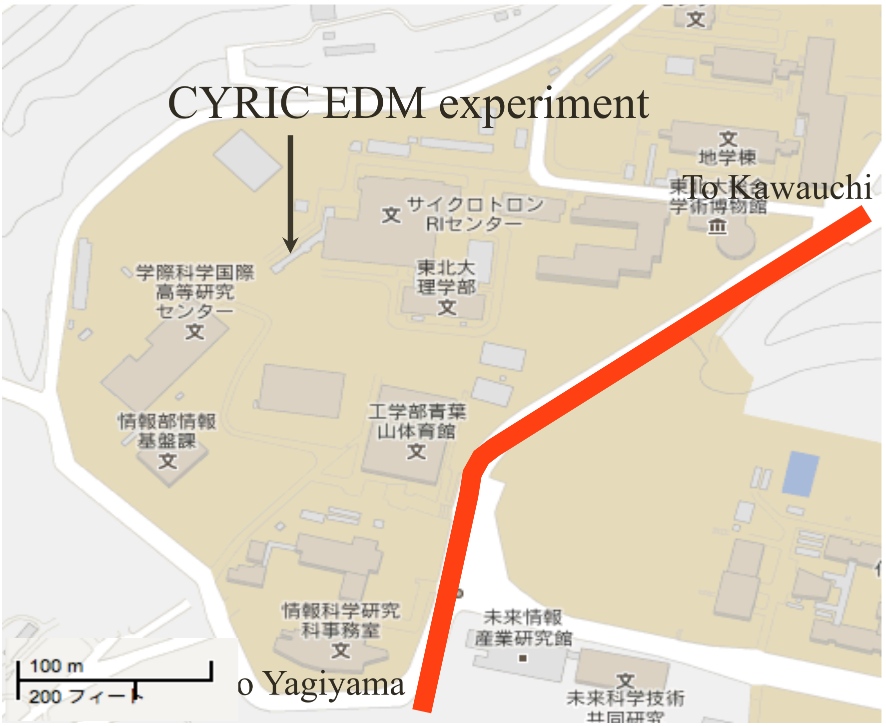


Frequency resolution

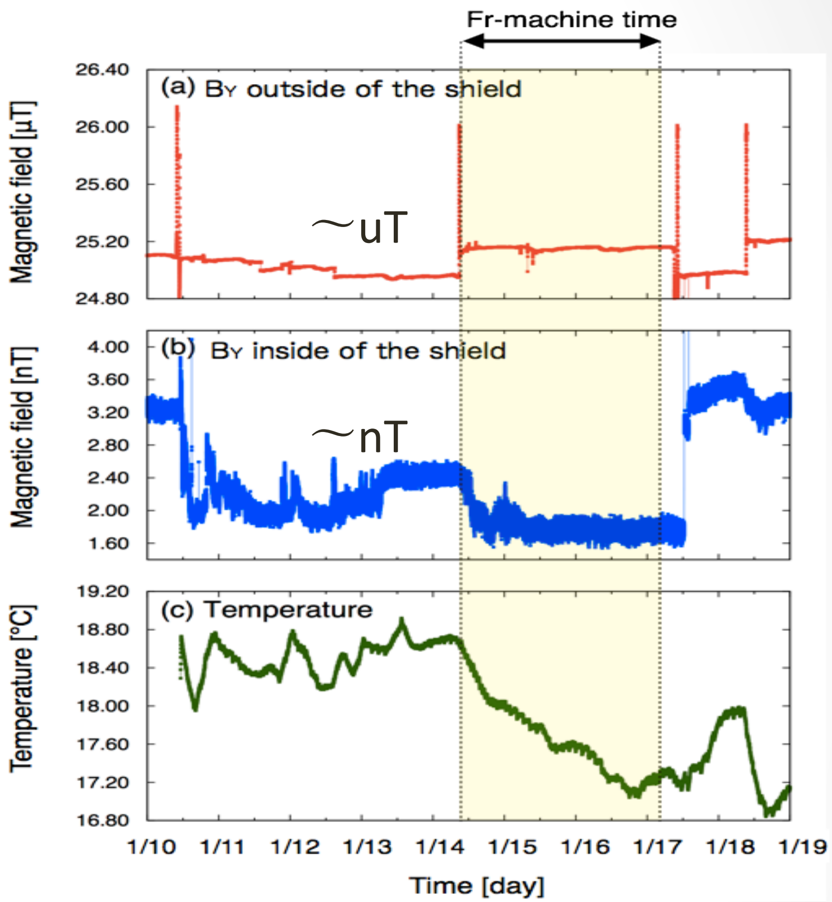


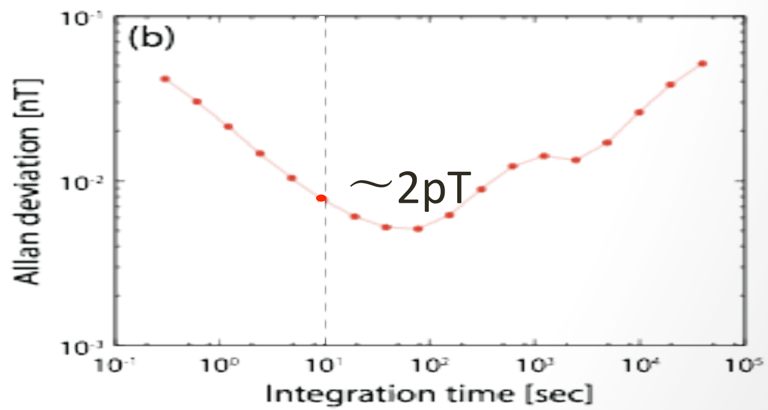
Magnetic field effects from subway





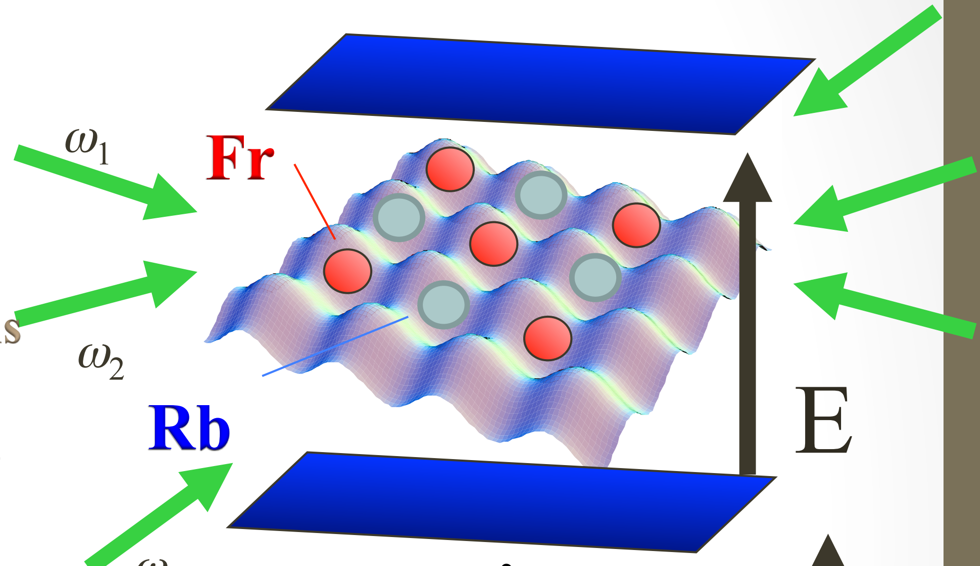
Station located at 150 m from EDM experimental room





Fr/Rb co-magnetometer with optical lattice

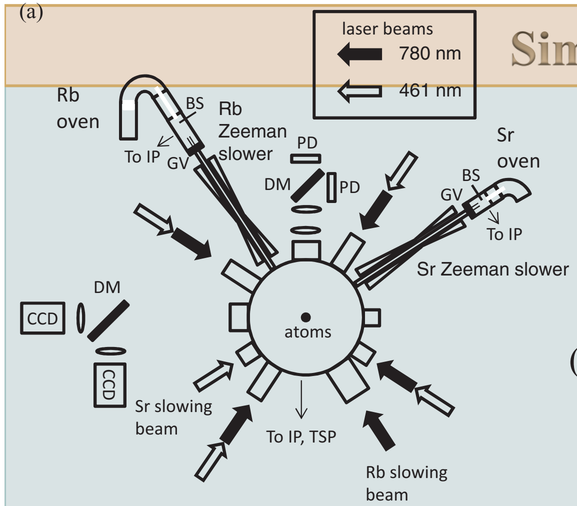
- Natural extension of ODT (1 dim.)
- 3 dim. standing wave
- Blue detuned optical lattice
  ~ photon scattering rate : 0.2/s
- Reduce the interaction between atoms
  ~ reduce the depolarization
- Long coherence time ~ realized ~ sec.
- Can be used for co-magnetometer



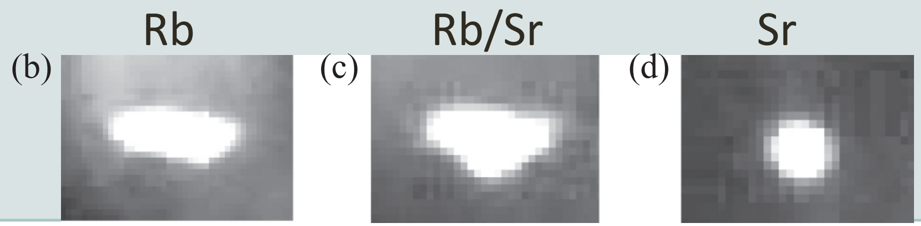
$$U(\mathbf{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(\mathbf{r})(\Delta \equiv \omega - \omega_0)$$

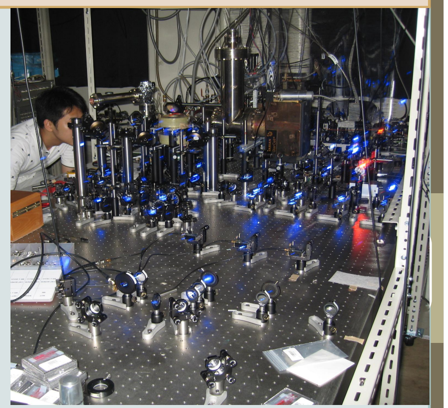
Trap potential of optical lattice

Simultaneous MOT of Rb and Sr ~ succeeded

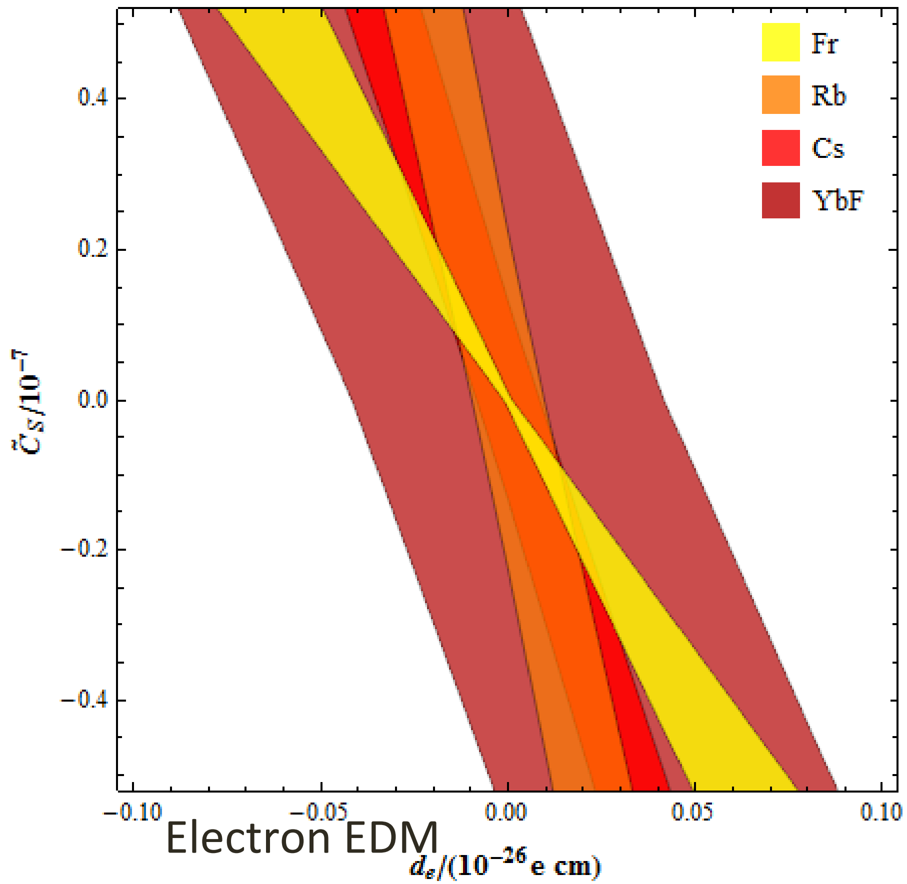


- First step for Fr/Rb trapping at the same time
- Basic technique to locate Fr and Rb to each cite
  ⇒ co-magnetometer





Status of electron EDM



Electron EDM

By Dr. Martin Jung

- Fr: CYRIC~ **trapped Fr EDM**
- Rb: Penn. State Univ., USA
- Cs: LBNL, California, USA
- YbF: Imperial College London
- ThO: Harvard, USA

Observables : $d_x = K \cdot d_e + R \cdot Cs$

- e-EDM: d_e
- Electron-nucleon (quark) CP-odd interaction : Cs
- K,R: enhancement factor

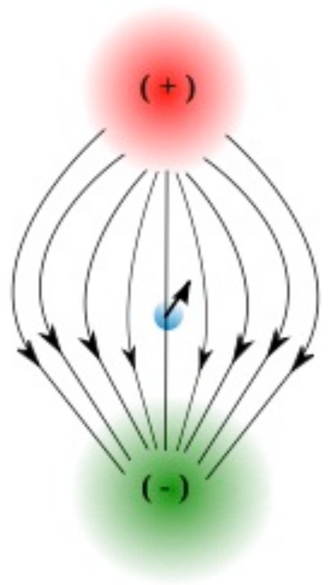
Fr EDM

10^{-29} ecm

- Long coherence time : 1 – 10 s
- Enhancement factor : 895

Polar molecule EDM

Polar molecules (e.g. ThO [Harvard/Yale], YbF [Imperial])
[Baron et al ‘13, Hudson et al ’11]



$$\Delta E_{\mathrm{ThO}} \sim \mathcal{E}_{\mathrm{eff}}(E_{\mathrm{ext}})d_e + \mathcal{O}(C_S)$$

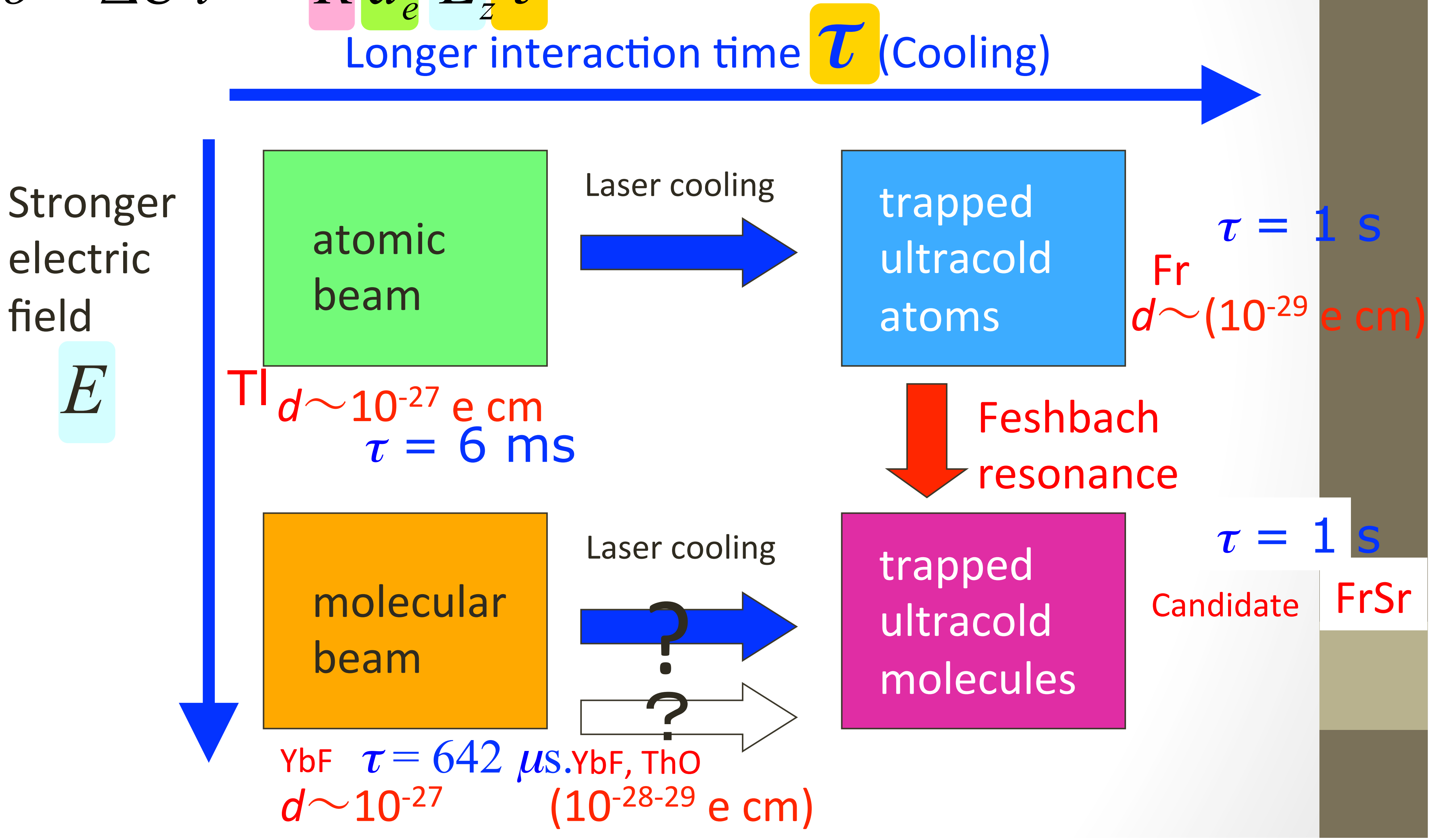
Nonlinear function of E_{ext}

$$\text{“}d_{\mathrm{YbF}}\text{”} \sim 10\alpha^2 Z^3 \frac{\mu_{\mathrm{nuc}}}{m_e} d_e + \mathcal{O}(C_S)$$

[Sandars; Sushkov & Flambaum, ’78]

Possibility of Fr-Sr polar molecules

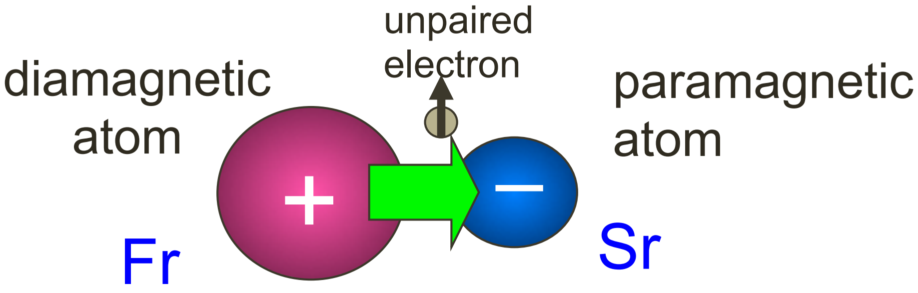
$$\theta \propto \Delta U\, t = -R\, d_e\, E_z\, \tau$$



One possibility :

ultracold polar molecules
associated with Feshbach resonance / photoassociation

paramagnetic molecule (radical)



effective field
4.2 GV/cm → calculation
-M. Abe, G. Gopakumar, M. Hada
-H. S. Nataraj, Y. Sakemi

Fr atom : Alkali atom with the largest R
Sr atom : Laser cooling below 1 μK

e-EDM sensitivity

$$\delta d_e = \frac{1}{|P|E_{eff}} \frac{\hbar}{\tau} \times \frac{1}{\sqrt{N}} \times \frac{1}{\sqrt{n}}$$

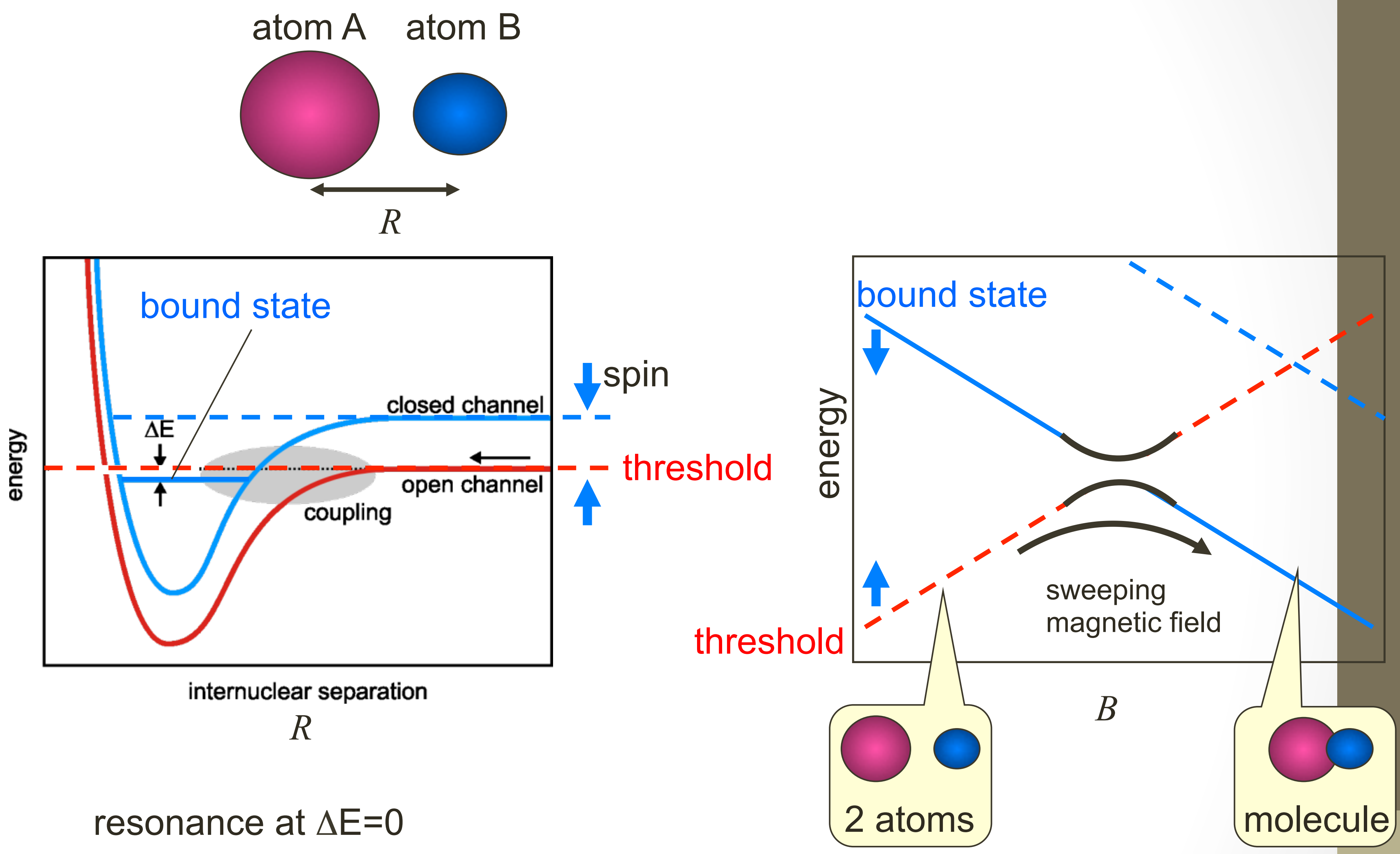
one measurement
δd1

P : polarization of the system
E_{eff} : effective electric field
τ : interaction time
N : number of molecules
$n = T/\tau$: number of measurement
T : total measurement time

Interaction time of ultracold trapped molecules is elongated to be more than 1 s, which is much longer than that of conventional atomic and molecular beam experiment.

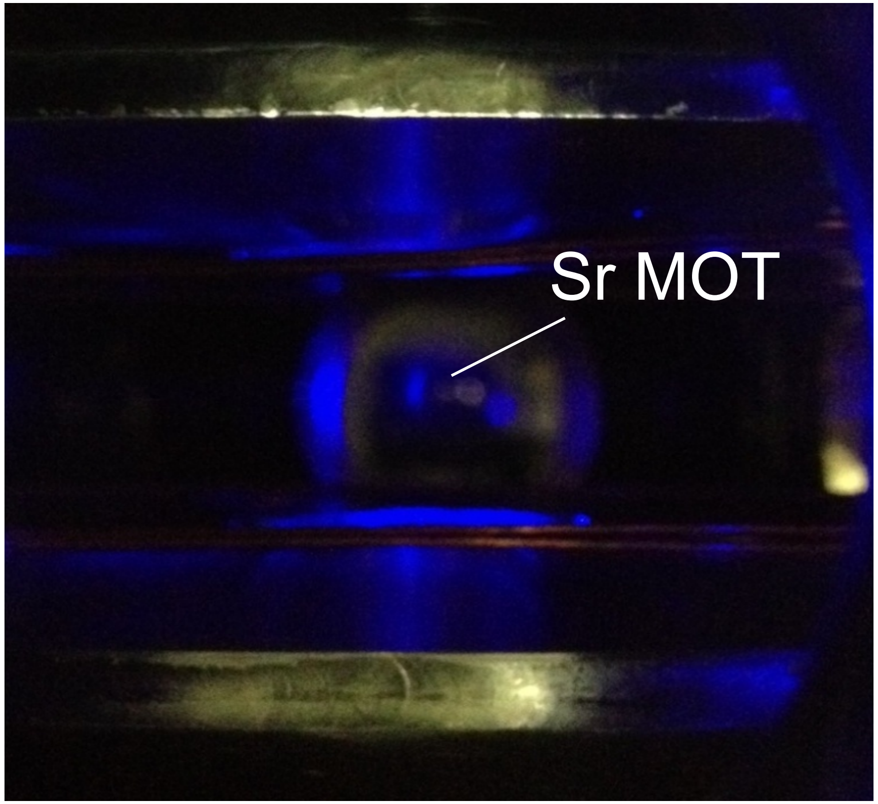
	E_{eff} (GV/cm)	t (ms)	N
ThO	80	1	10^5
FrSr	4	1000	10^5

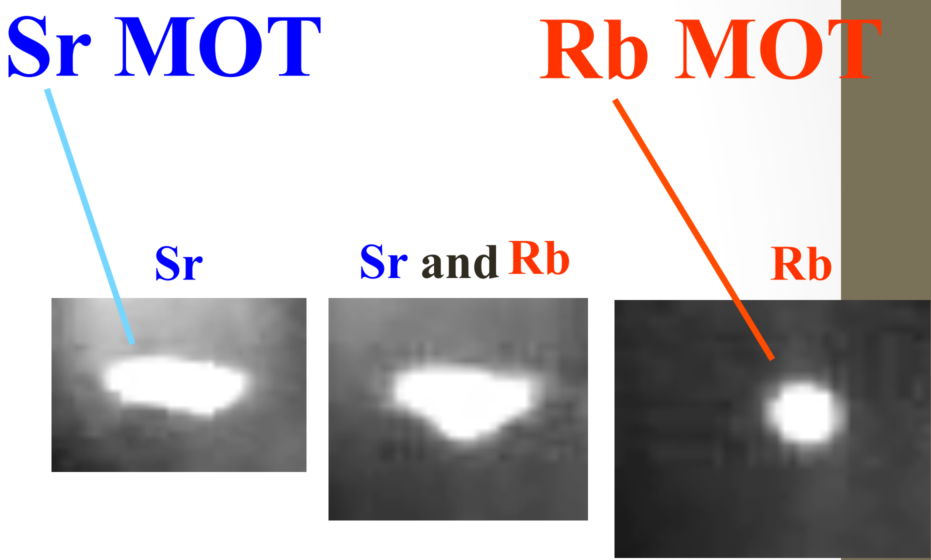
Association/dissociation of molecules near Feshbach resonance



Different spin states can be tuned due to Zeeman effect in the hyperfine level.
The energy of the molecular state, which is bound state of closed channel, coincides with the free atom threshold at the resonance peak.
Molecules are associated (or dissociated) by a slow magnetic-field sweep across the resonance by sweeping the magnetic field.

Simultaneous MOT of Rb and Sr





461 nm

- Slowing beam 2.3 mW
  detuning -820 MHz

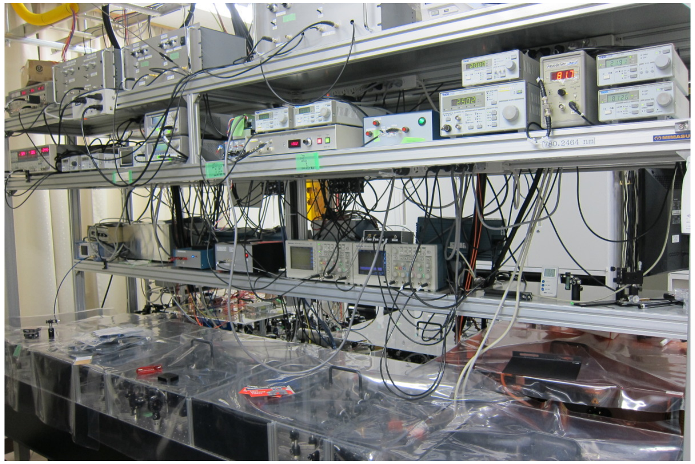
- MOT beam ϕ 16 mm
  10 mW
  detuning -40 MHz

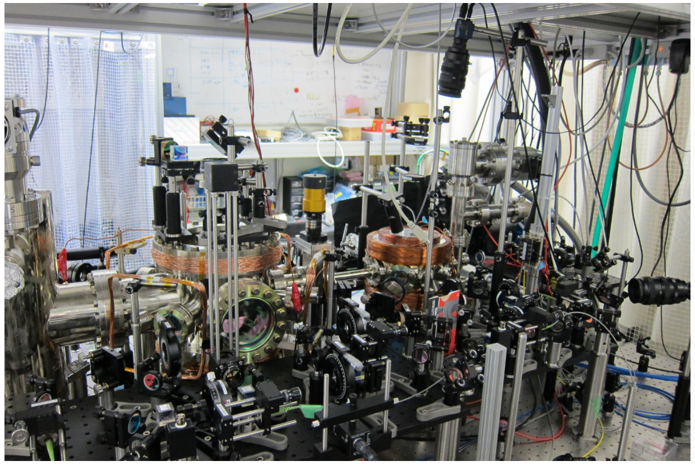
N_{Sr} = 1 x 10^6 atoms

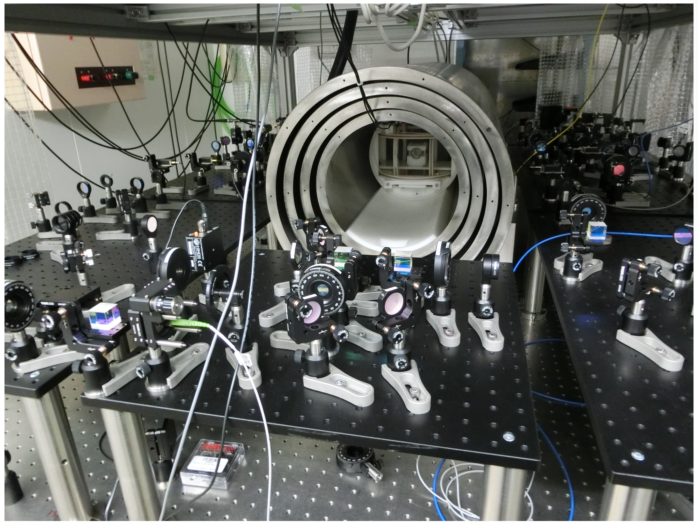
N_{Rb} = 10^8 atoms @ 90 G/cm^2

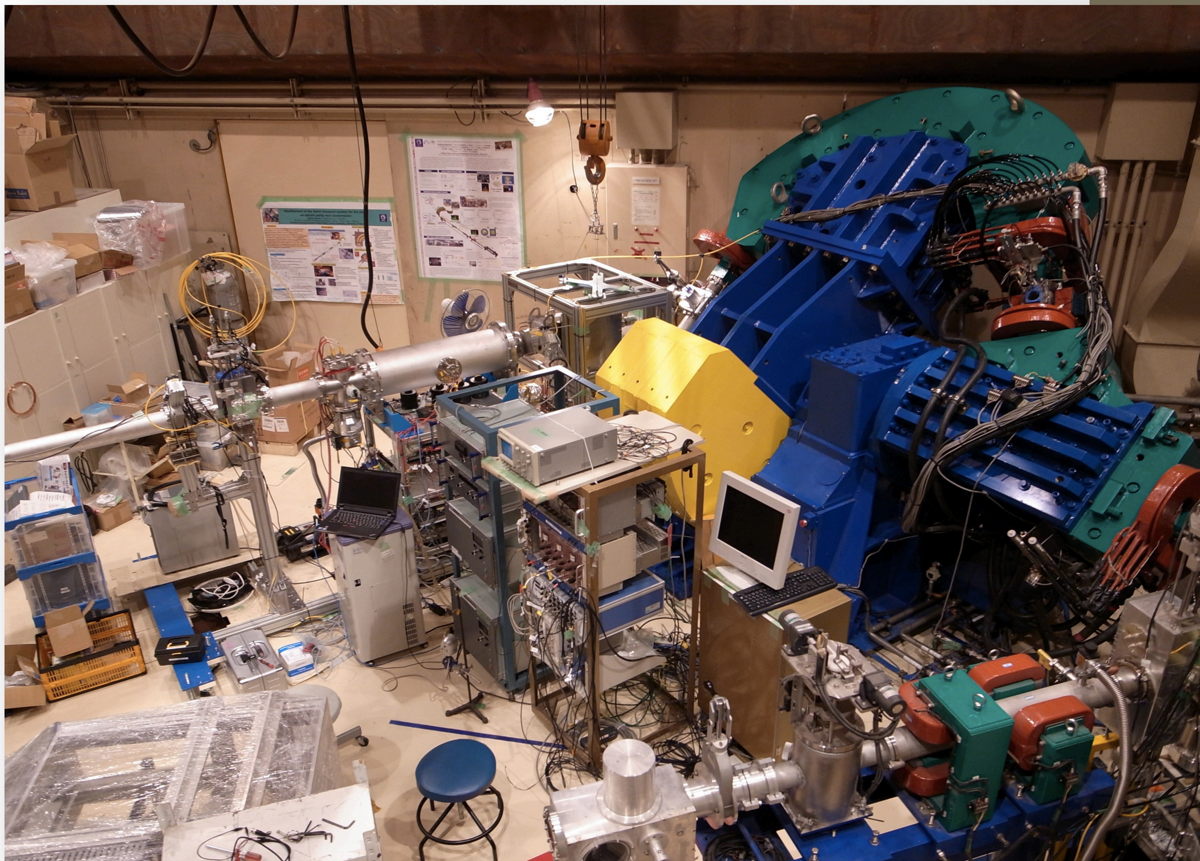
Sr Oven 430℃

（A smaller Rb cloud is a reference for Sr position）



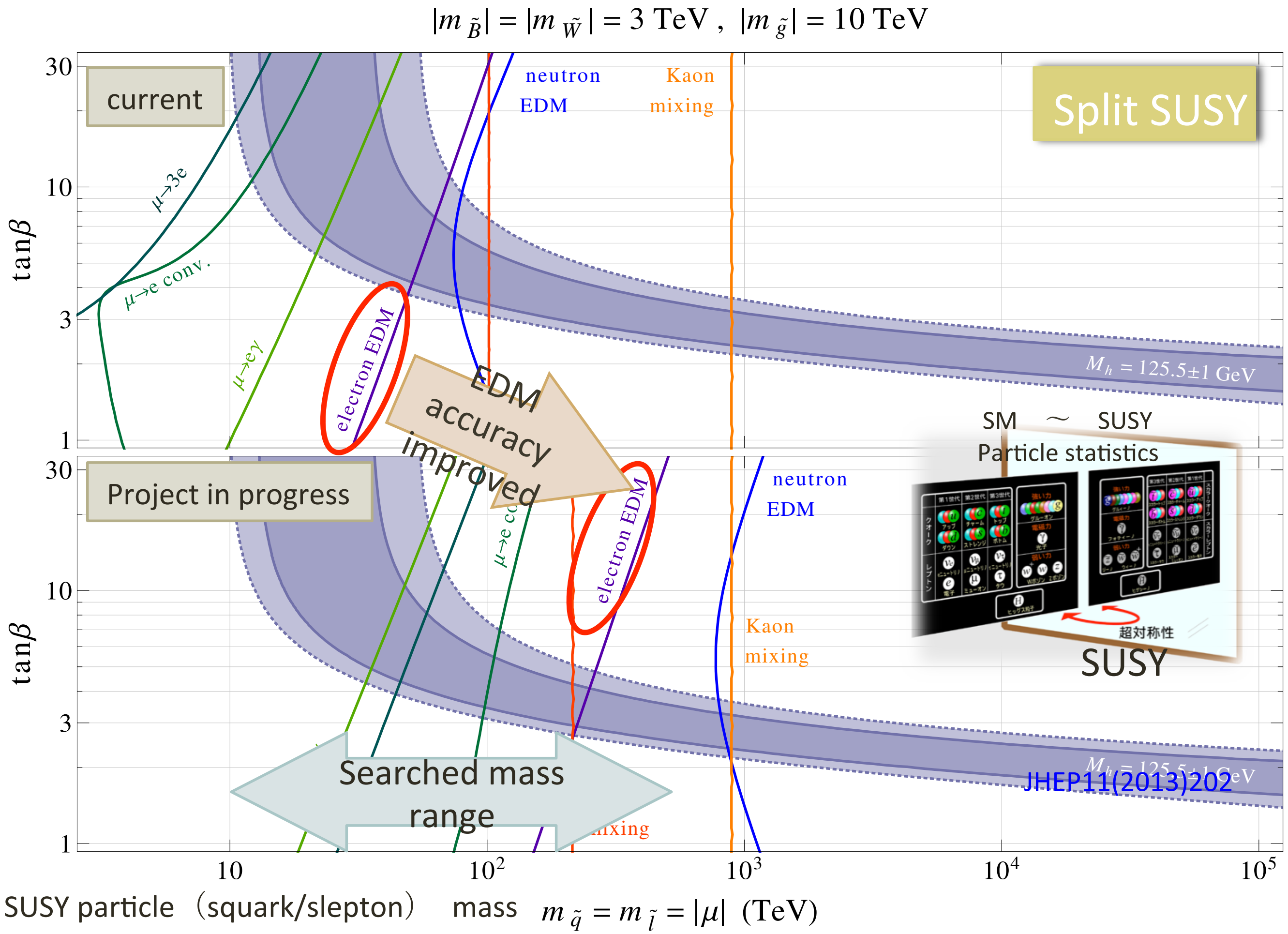


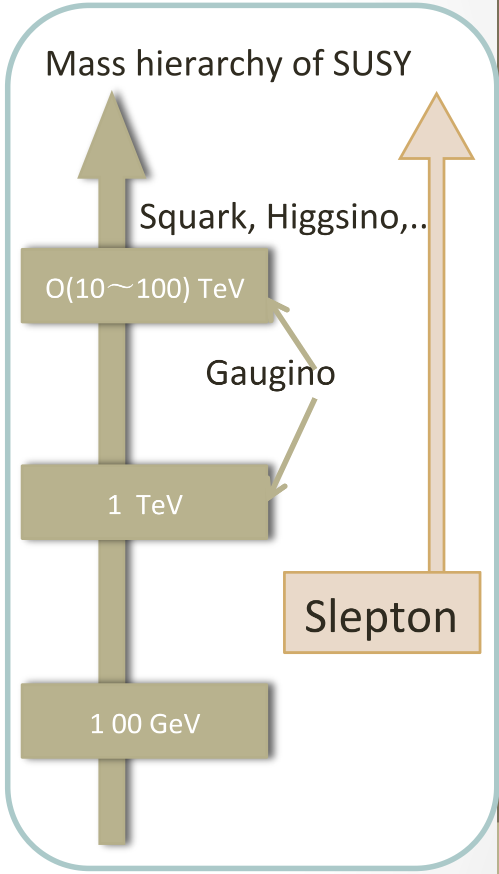




EDM test measurement to evaluate the systematic error :
will be started within 2 years

EDM and mass hierarchy





e-EDM can search the mass range in O（10〜100） TeV
Sensitive to colorless SUSY particles

Summary

- Optical lattice with RI ～ effective for accurate EDM measurement
- EDM: 10^{-29} e・cm search ⇒ BSM search with 10～500 TeV mass scale
- Higgs mass ～126 GeV → suggesting heavy SUSY mass
- Electron EDM ～ sensitive to color less SUSY particle
  ⇔ compliment to hadron collider at LHC
- Get the information on the mass hierarchy of SUSY particles
  (slepton,squark,gaugino..)
- Fr-EDM search : will be started within 2 years