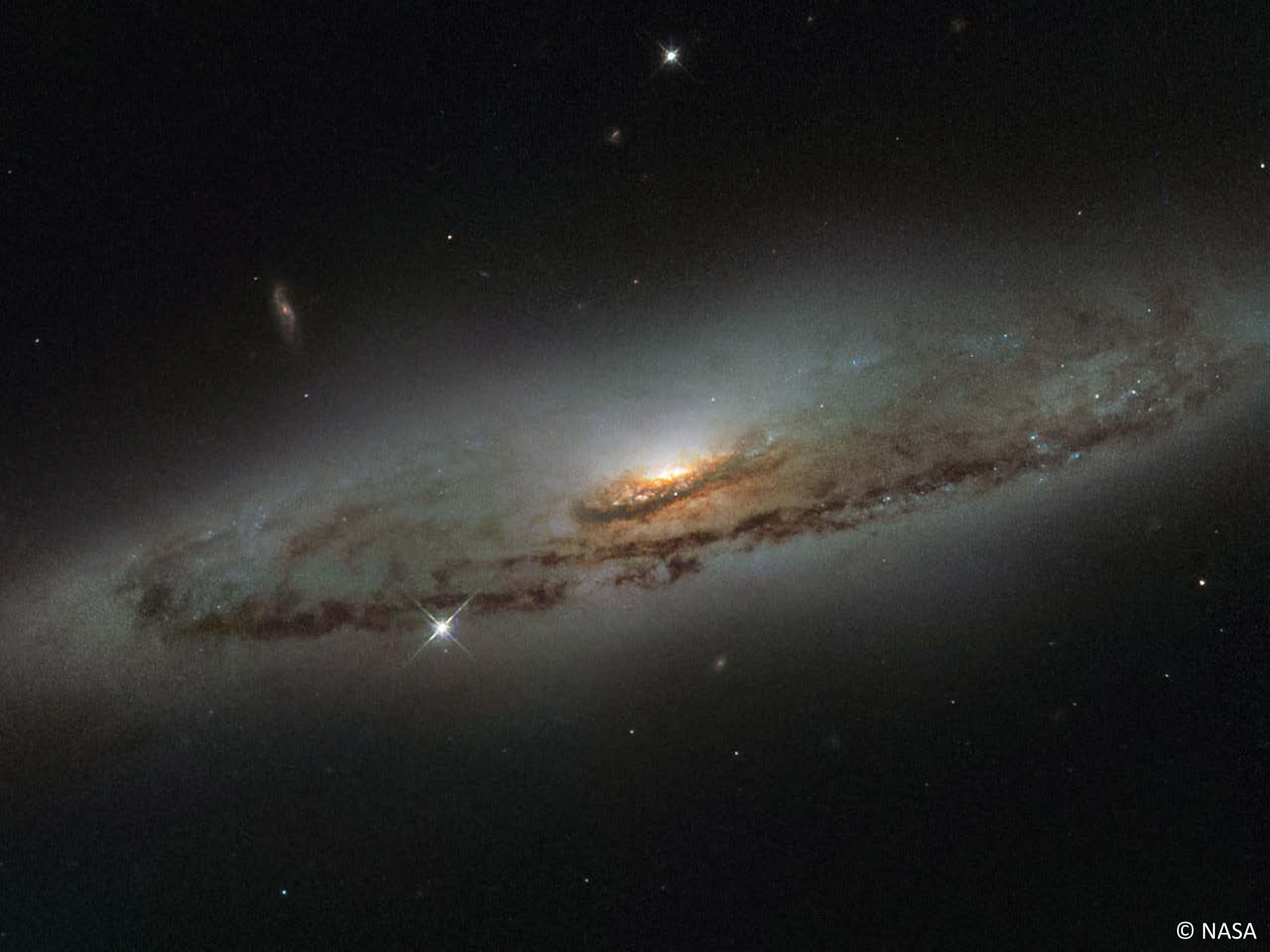
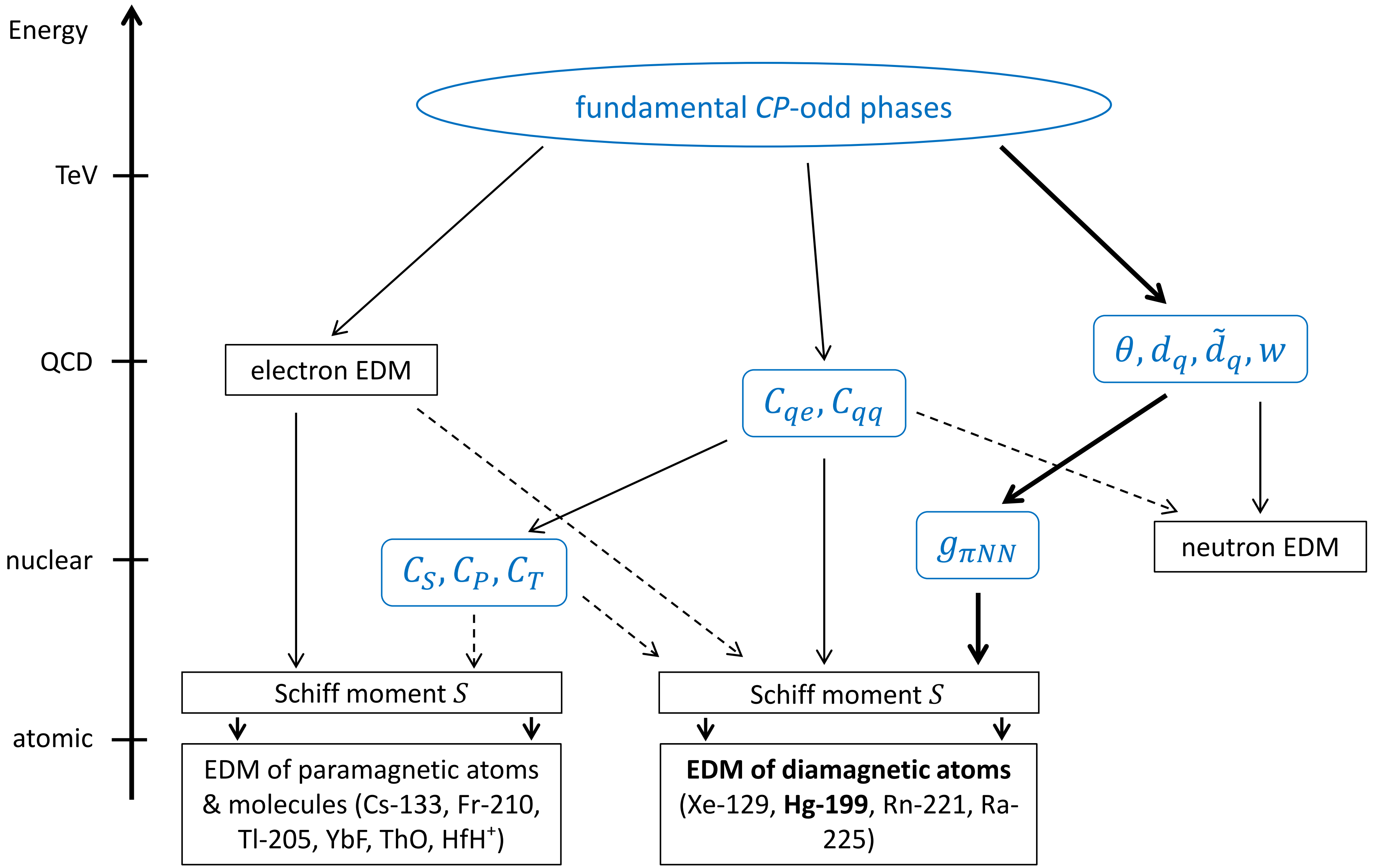
Towards a measurement of the mercury EDM using ultracold atoms

Simon Stellmer
University of Bonn



Mechanisms to generate EDMs



Energy

TeV

QCD

nuclear

atomic

fundamental *CP*-odd phases

electron EDM

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

C_S, C_P, C_T

$g_{\pi NN}$

neutron EDM

Schiff moment S

Schiff moment S

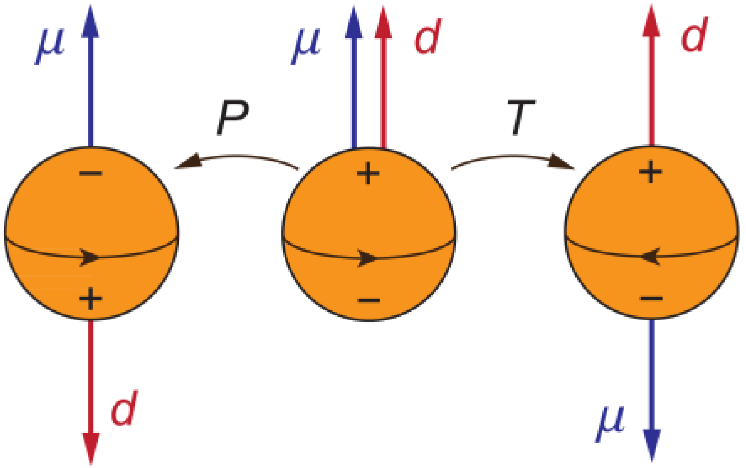
EDM of paramagnetic atoms & molecules (Cs-133, Fr-210, Tl-205, YbF, ThO, HfH$^+$)

EDM of diamagnetic atoms (Xe-129, **Hg-199**, Rn-221, Ra-225)

adapted from M. Pospelov & A. Ritz

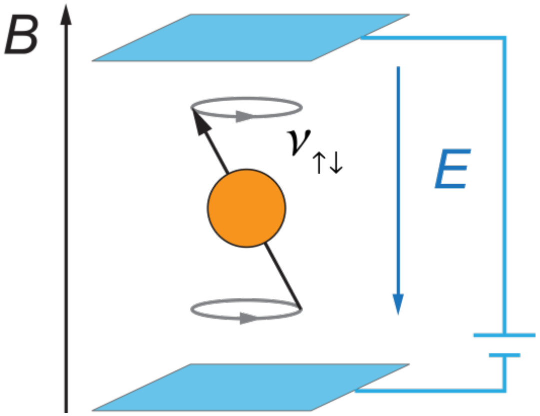
The universal approach to measure EDMs

General idea:



T-violation is equivalent to CP-violation (because of CPT!)

General concept:



Larmor frequency:

$$h\nu = |2\mu B \pm 2dE|$$

Sensitivity:

$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$

The universal approach to measure EDMs: *colder is better*

Sensitivity:

$$\delta d = \frac{\hbar}{2E\,\sqrt{2N\tau T}}$$

next-generation experiments:

neutron EDM	spallation sources:		PSI, ESS Lund, ASS, various other institutes	
	reactor UCNs:		ILL, FRM II, various other institutes	
			Sussex/ILL, 2006	**2.9×10^{-26} e cm**

higher neutron flux, improved cooling in He or D_2, …

(n2EDM @ PSI, CryoEDM @ ILL, FRM II, …)

electron EDM	atoms:	Cs-133	Penn State, Austin Texas, LBNL	
		Tl-205	Berkeley, 2002	1.6×10^{-27} e cm
		Fr-210	CYRIC, Japan	
	molecules:	YbF	Ed Hinds, Imperial College, 2011	**1.0×10^{-27} e cm**
		ThO	ACME collaboration, Harvard/Yale, 2018	**1.1×10^{-29} e cm**
		HfF^+	Cornell/Ye, JILA, 2017	**1.3×10^{-28} e cm**

laser cooling & magneto-optical trapping of molecules

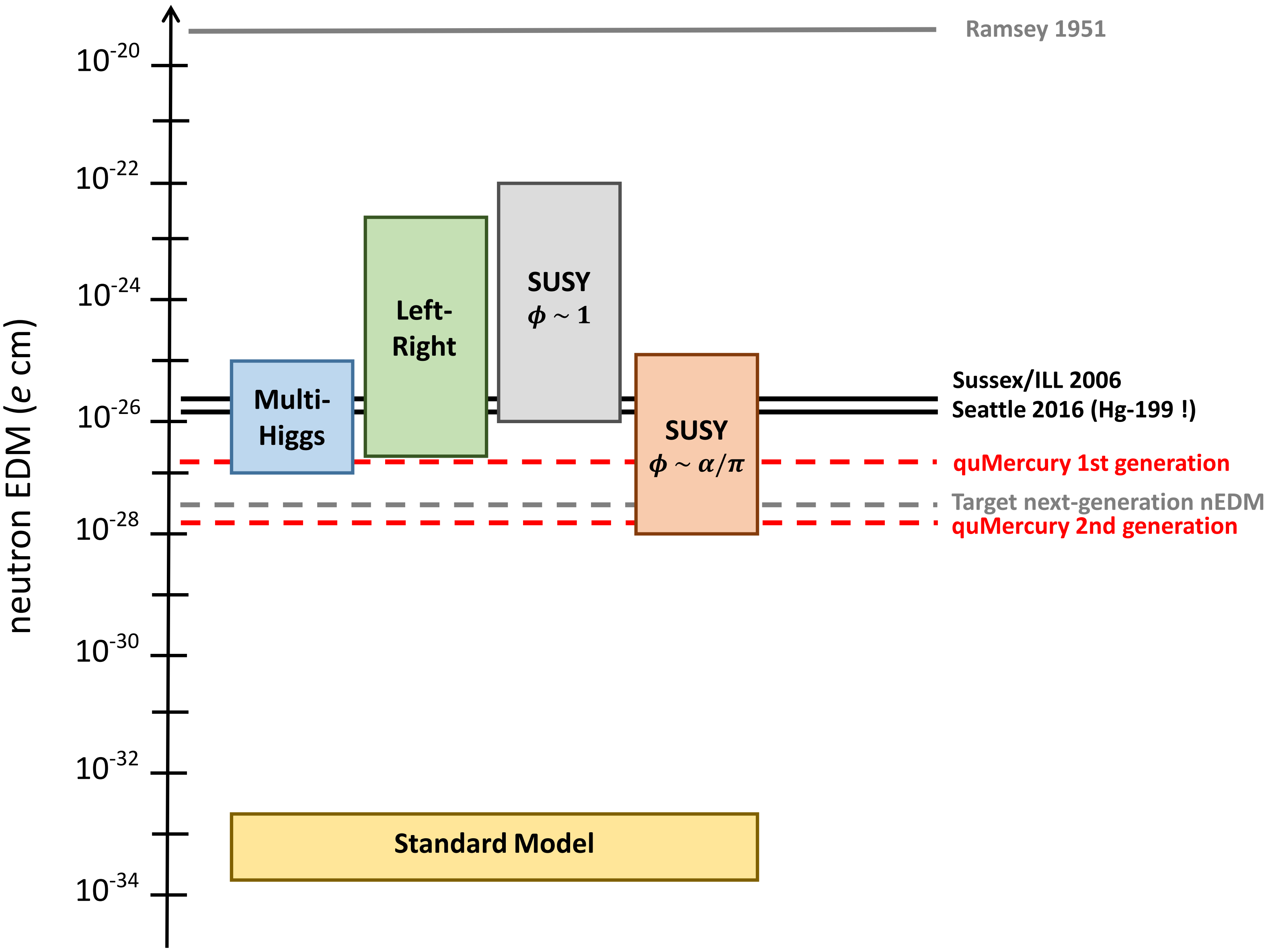
(Imperial, Yale, ACME, JILA, …)

atomic EDM	thermal:	Hg-199	Fortson/Heckel, Seattle, 2016	**7.4×10^{-30} e cm**
		Rn-221	Chupp, TRIUMF	
	MOT:	Ra-225	Argonne, 2016	1.4×10^{-23} e cm
	liquid:	Xe-129	Chupp, U of Michigan, 2001	7.0×10^{-28} e cm

ultracold atoms:

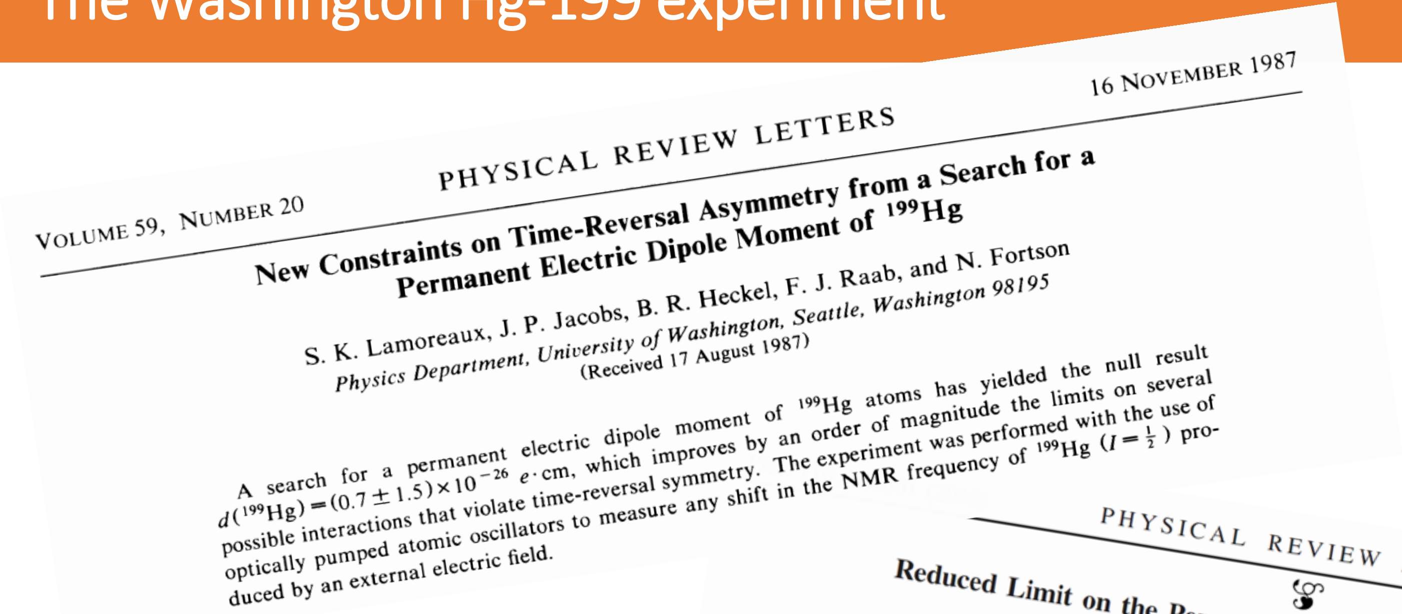
Radium-225 (Argonne)

Excluding beyond-SM thories (example: neutron EDM)



adapted from Ed Hinds group

The Washington Hg-199 experiment



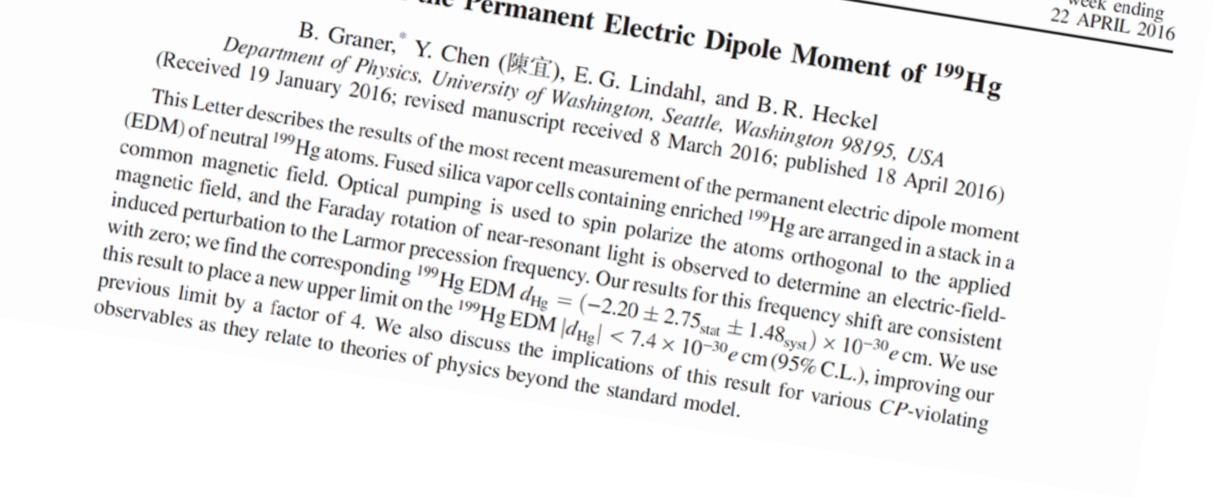
VOLUME 59, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1987

New Constraints on Time-Reversal Asymmetry from a Search for a Permanent Electric Dipole Moment of ^{199}Hg

S. K. Lamoreaux, J. P. Jacobs, B. R. Heckel, F. J. Raab, and N. Fortson
Physics Department, University of Washington, Seattle, Washington 98195

(Received 17 August 1987)

A search for a permanent electric dipole moment of ^{199}Hg atoms has yielded the null result $d(^{199}\mathrm{Hg}) = (0.7 \pm 1.5) \times 10^{-26}$ $e \cdot$cm, which improves by an order of magnitude the limits on several possible interactions that violate time-reversal symmetry. The experiment was performed with the use of optically pumped atomic oscillators to measure any shift in the NMR frequency of ^{199}Hg ($I = \frac{1}{2}$) produced by an external electric field.



PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

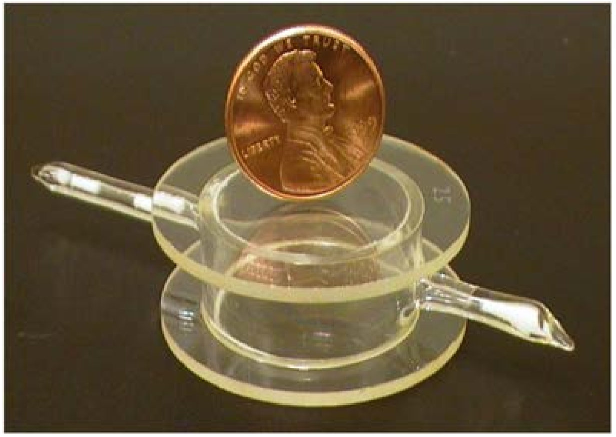
Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

B. Graner,* Y. Chen (陳宜), E. G. Lindahl, and B. R. Heckel
Department of Physics, University of Washington, Seattle, Washington 98195, USA

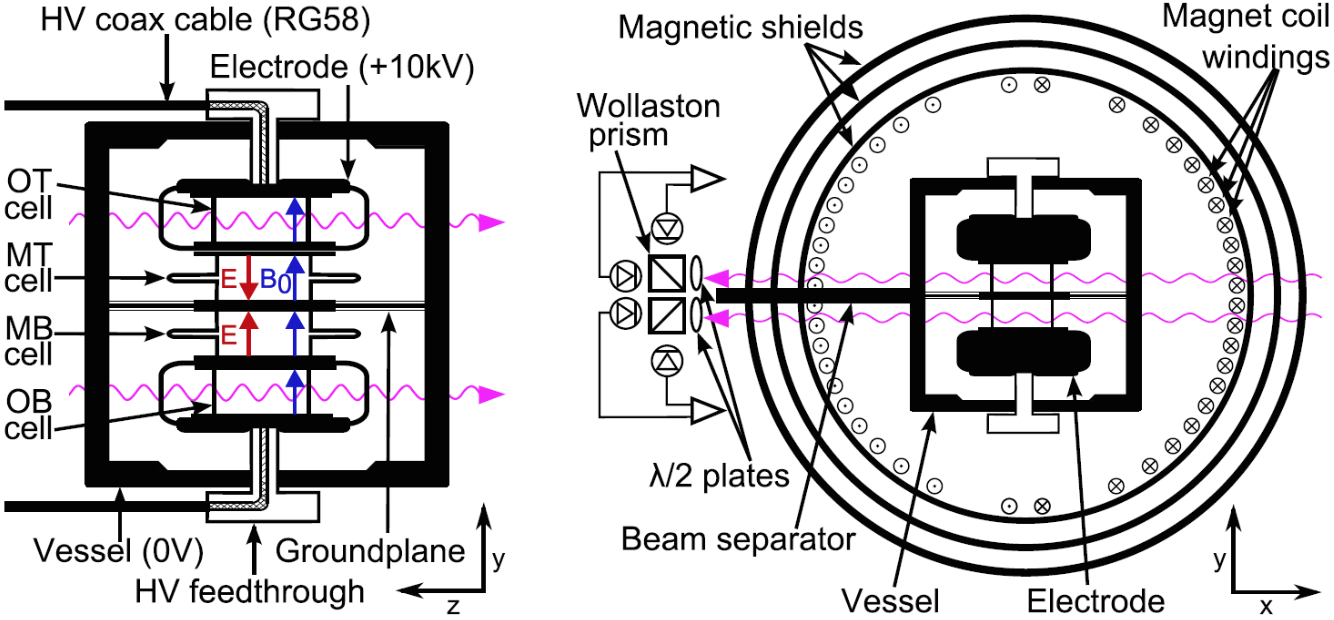
(Received 19 January 2016; revised manuscript received 8 March 2016; published 18 April 2016)

This Letter describes the results of the most recent measurement of the permanent electric dipole moment (EDM) of neutral ^{199}Hg atoms. Fused silica vapor cells containing enriched ^{199}Hg are arranged in a stack in a common magnetic field. Optical pumping is used to spin polarize the atoms orthogonal to the applied magnetic field, and the Faraday rotation of near-resonant light is observed to determine an electric-field-induced perturbation to the Larmor precession frequency. Our results for this frequency shift are consistent with zero; we find the corresponding ^{199}Hg EDM $d_{\mathrm{Hg}} = (-2.20 \pm 2.75_{\mathrm{stat}} \pm 1.48_{\mathrm{syst}}) \times 10^{-30}\,e\,$cm. We use this result to place a new upper limit on the ^{199}Hg EDM $|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}\,e\,$cm (95% C.L.), improving our previous limit by a factor of 4. We also discuss the implications of this result for various *CP*-violating observables as they relate to theories of physics beyond the standard model.

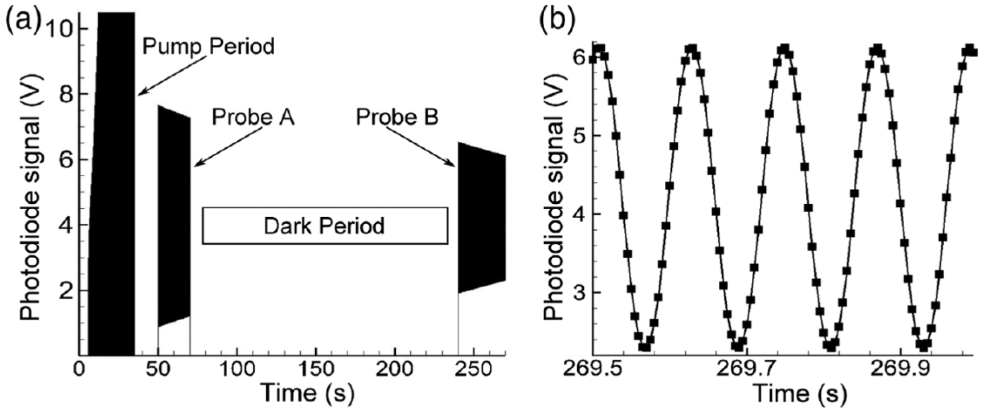
5000-fold improvement
over 30 years !

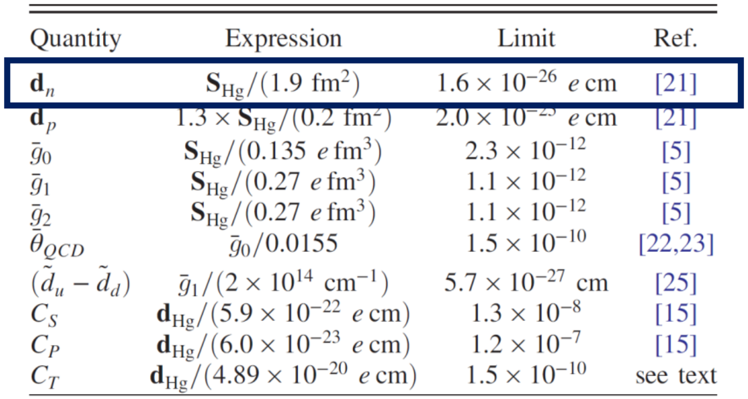


The Washington Hg-199 experiment



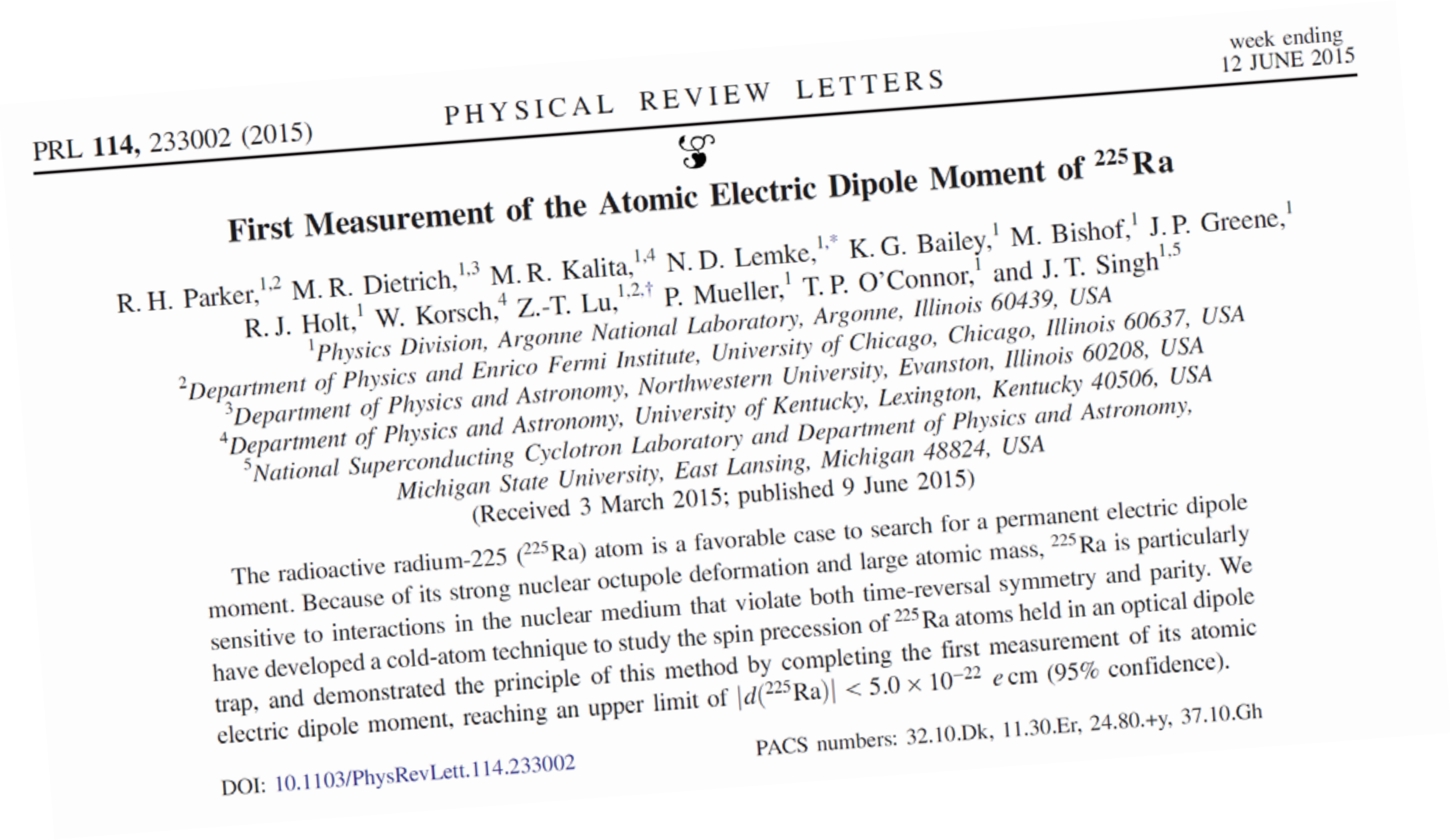
Phys. Rev. Lett. 116, 161601 (2016)





Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{\mathrm{Hg}}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e\,\mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{\mathrm{Hg}}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e\,\mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{\mathrm{Hg}}/(0.135\ e\,\mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22,23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\ \mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[25]
C_S	$\mathbf{d}_{\mathrm{Hg}}/(5.9 \times 10^{-22}\ e\,\mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{\mathrm{Hg}}/(6.0 \times 10^{-23}\ e\,\mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{\mathrm{Hg}}/(4.89 \times 10^{-20}\ e\,\mathrm{cm})$	1.5×10^{-10}	see text

The Argonne Ra-225 experiment: laser-cooled atoms!



PRL **114,** 233002 (2015) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2015

First Measurement of the Atomic Electric Dipole Moment of ^{225}Ra

R. H. Parker,[1,2] M. R. Dietrich,[1,3] M. R. Kalita,[1,4] N. D. Lemke,[1,*] K. G. Bailey,[1] M. Bishof,[1] J. P. Greene,[1]
R. J. Holt,[1] W. Korsch,[4] Z.-T. Lu,[1,2,†] P. Mueller,[1] T. P. O'Connor,[1] and J. T. Singh[1,5]

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Michigan State University, East Lansing, Michigan 48824, USA

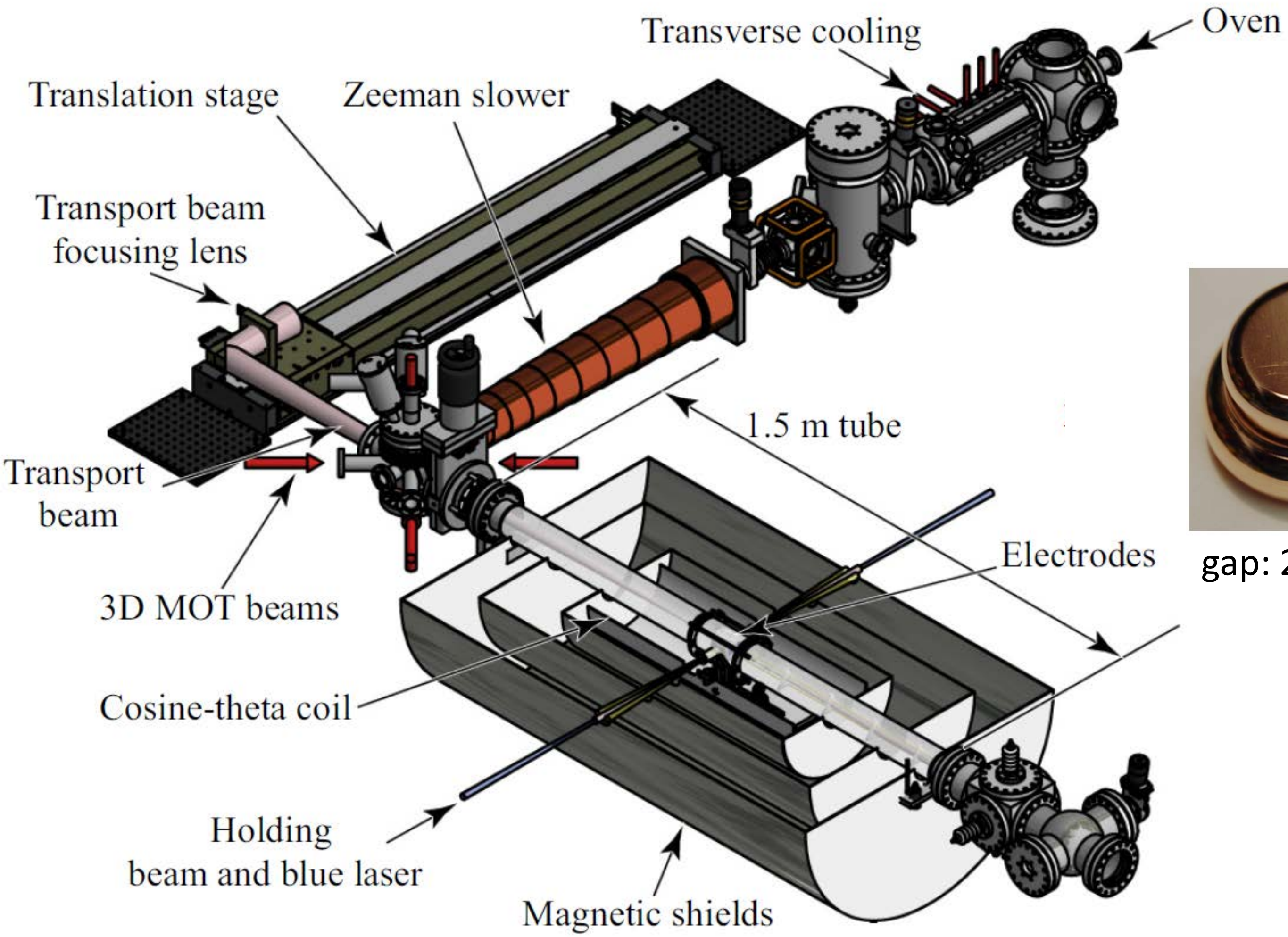
(Received 3 March 2015; published 9 June 2015)

The radioactive radium-225 (^{225}Ra) atom is a favorable case to search for a permanent electric dipole moment. Because of its strong nuclear octupole deformation and large atomic mass, ^{225}Ra is particularly sensitive to interactions in the nuclear medium that violate both time-reversal symmetry and parity. We have developed a cold-atom technique to study the spin precession of ^{225}Ra atoms held in an optical dipole trap, and demonstrated the principle of this method by completing the first measurement of its atomic electric dipole moment, reaching an upper limit of $|d(^{225}\mathrm{Ra})| < 5.0 \times 10^{-22}$ e cm (95% confidence).

DOI: 10.1103/PhysRevLett.114.233002 PACS numbers: 32.10.Dk, 11.30.Er, 24.80.+y, 37.10.Gh

Theory: Phys. Rev. A **59**, 4547 (1999)

The Argonne Ra-225 experiment: laser-cooled atoms!



gap: 2.3 mm, 15 kV

MOT: 1000 atoms @ 40 μK
Dipole trap: 50 atoms at 50 μK

Phys. Rev. Lett. 114, 233002 (2015)

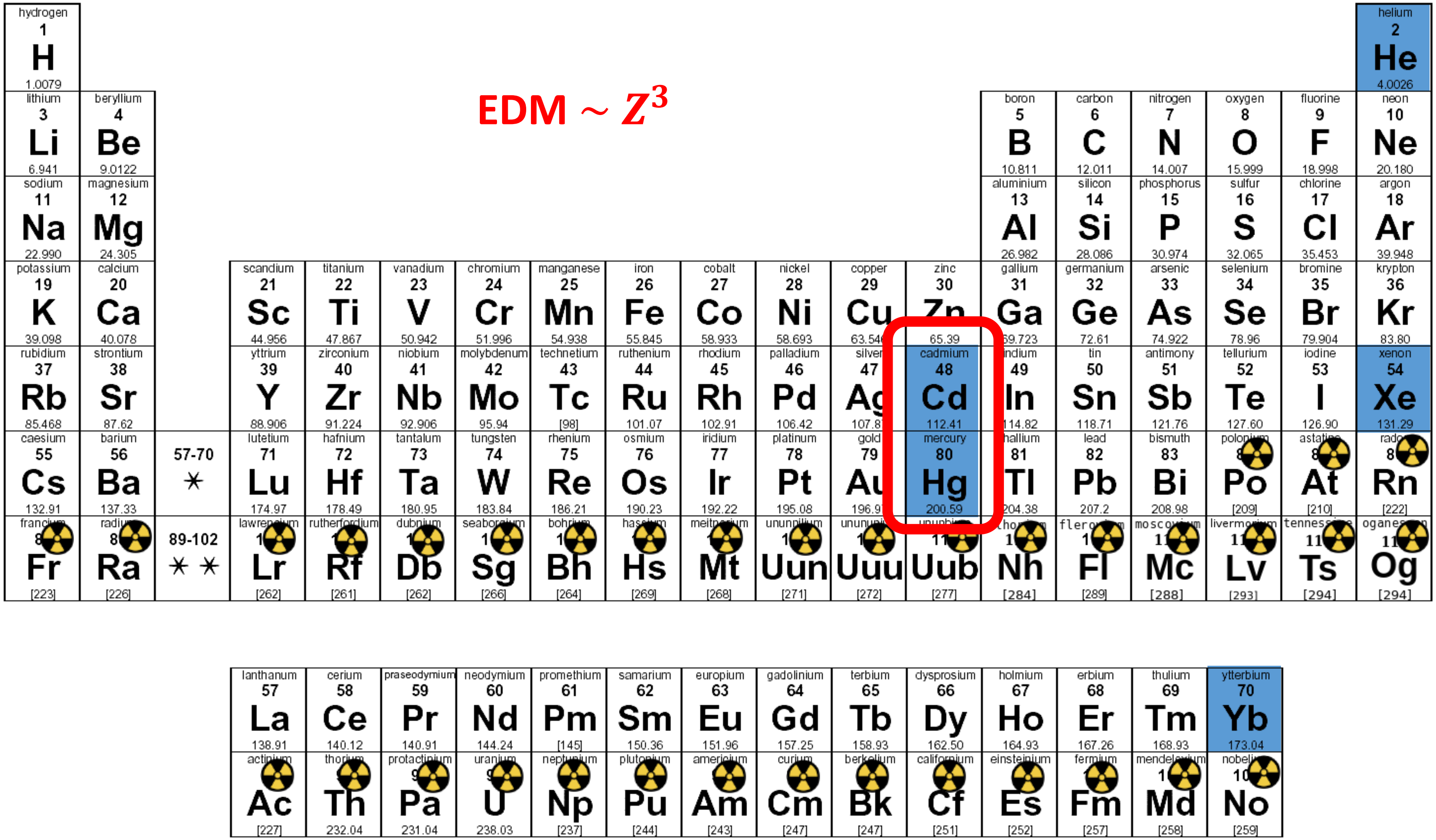
Our approach

QUANTUM METROLOGY
quMercury

- atomic EDM measurements with (non-radioactive) laser-cooled atoms
- find ways to improve sensitivity by using quantum phenomena

Choice of the atomic species

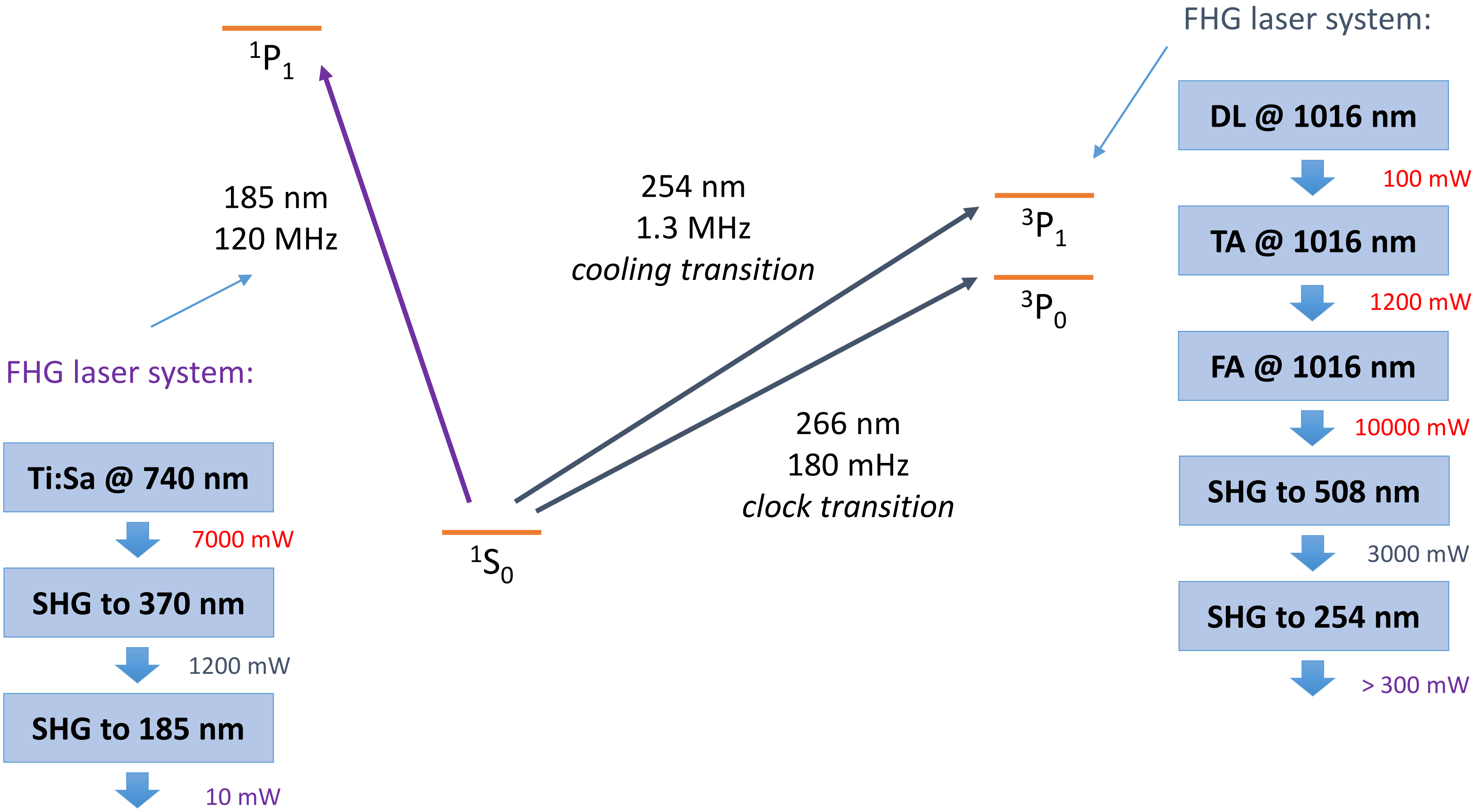
EDM $\sim Z^3$



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.54	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.8	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.9	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 8 Po [209]	astatine 8 At [210]	radon 8 Rn [222]
francium 8 Fr [223]	radium 8 Ra [226]	89-102 * *	lawrencium 1 Lr [262]	rutherfordium 1 Rf [261]	dubnium 1 Db [262]	seaborgium 1 Sg [266]	bohrium 1 Bh [264]	hassium Hs [269]	meitnerium Mt [268]	ununnilium 1 Uun [271]	ununu 1 Uuu [272]	ununbium 11 Uub [277]	nihonium 1 Nh [284]	flerovium 1 Fl [289]	moscovium 11 Mc [288]	livermorium 11 Lv [293]	tennessine 11 Ts [294]	oganesson 11 Og [294]

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium Ac [227]	thorium Th 232.04	protactinium 9 Pa 231.04	uranium 9 U 238.03	neptunium Np [237]	plutonium Pu [244]	americium Am [243]	curium Cm [247]	berkelium Bk [247]	californium Cf [251]	einsteinium Es [252]	fermium 1 Fm [257]	mendelevium 1 Md [258]	nobelium 10 No [259]

Mercury: a 2-electron atom



$^1P_1$

185 nm
120 MHz

FHG laser system:

Ti:Sa @ 740 nm

7000 mW

SHG to 370 nm

1200 mW

SHG to 185 nm

10 mW

$^1S_0$

254 nm
1.3 MHz
cooling transition

$^3P_1$

$^3P_0$

266 nm
180 mHz
clock transition

FHG laser system:

DL @ 1016 nm

100 mW

TA @ 1016 nm

1200 mW

FA @ 1016 nm

10000 mW

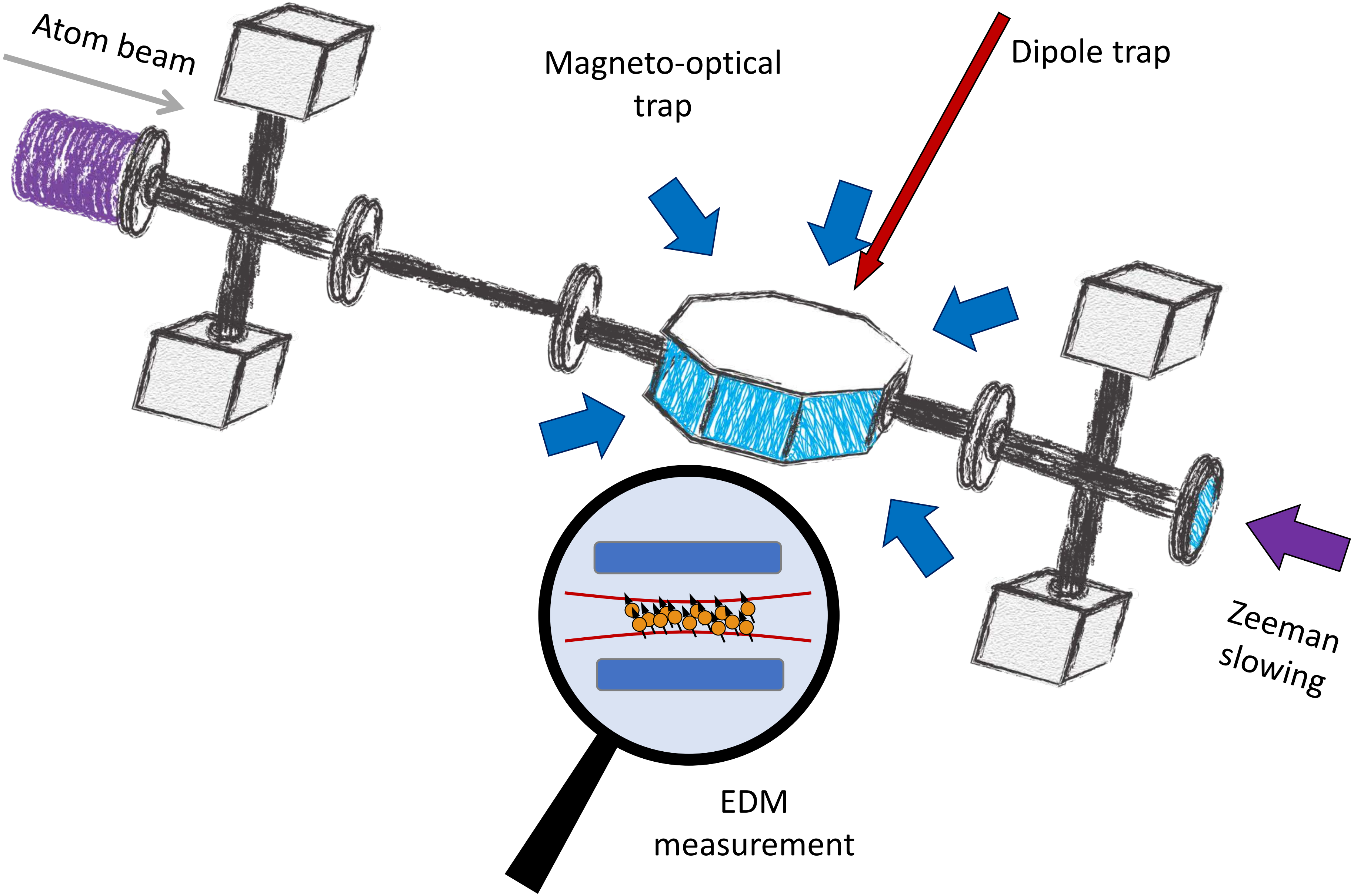
SHG to 508 nm

3000 mW

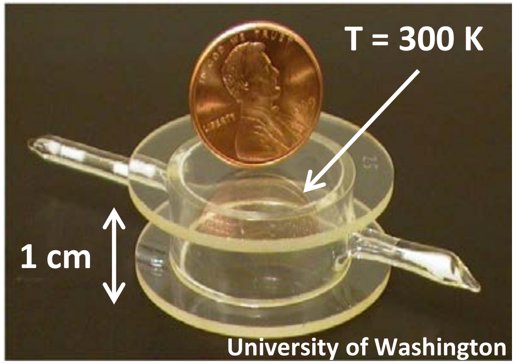
SHG to 254 nm

> 300 mW

The experimental setup

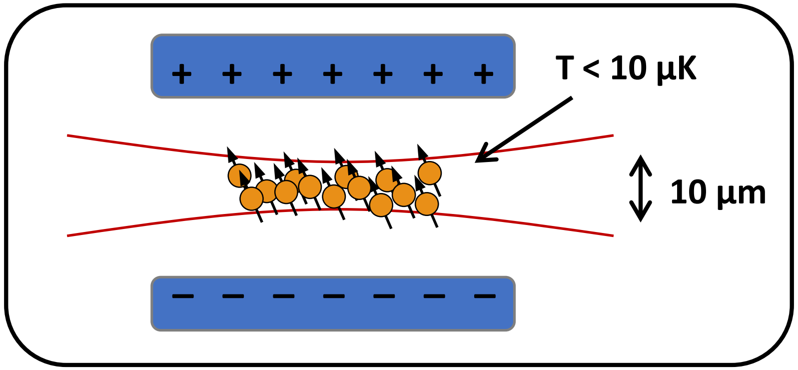


Taking a classical experiment into the quantum world



2016 Seattle Hg-199 EDM experiment:

$|d_{Hg}| < 7.4 \times 10^{-30}\ e$ cm



quMercury Hg-199 EDM experiment

improve control:
- no spin decoherence from collisions with the walls
- no $E \times v$ effect from movement of the atoms
- size reduces from 1 cm to a few 10 μm: homogeneous fields
- in-vacuum electrodes: no leakage currents, much higher fields

improve sensitivity by at least a factor 10, **conservative estimate: $\delta d = 7 \times 10^{-31}\ e$ cm**

$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$

field E:	30 keV on a 0.5-mm gap
atom number N:	10^8 atoms
vacuum lifetime τ:	300 s
measurement time T:	3 months

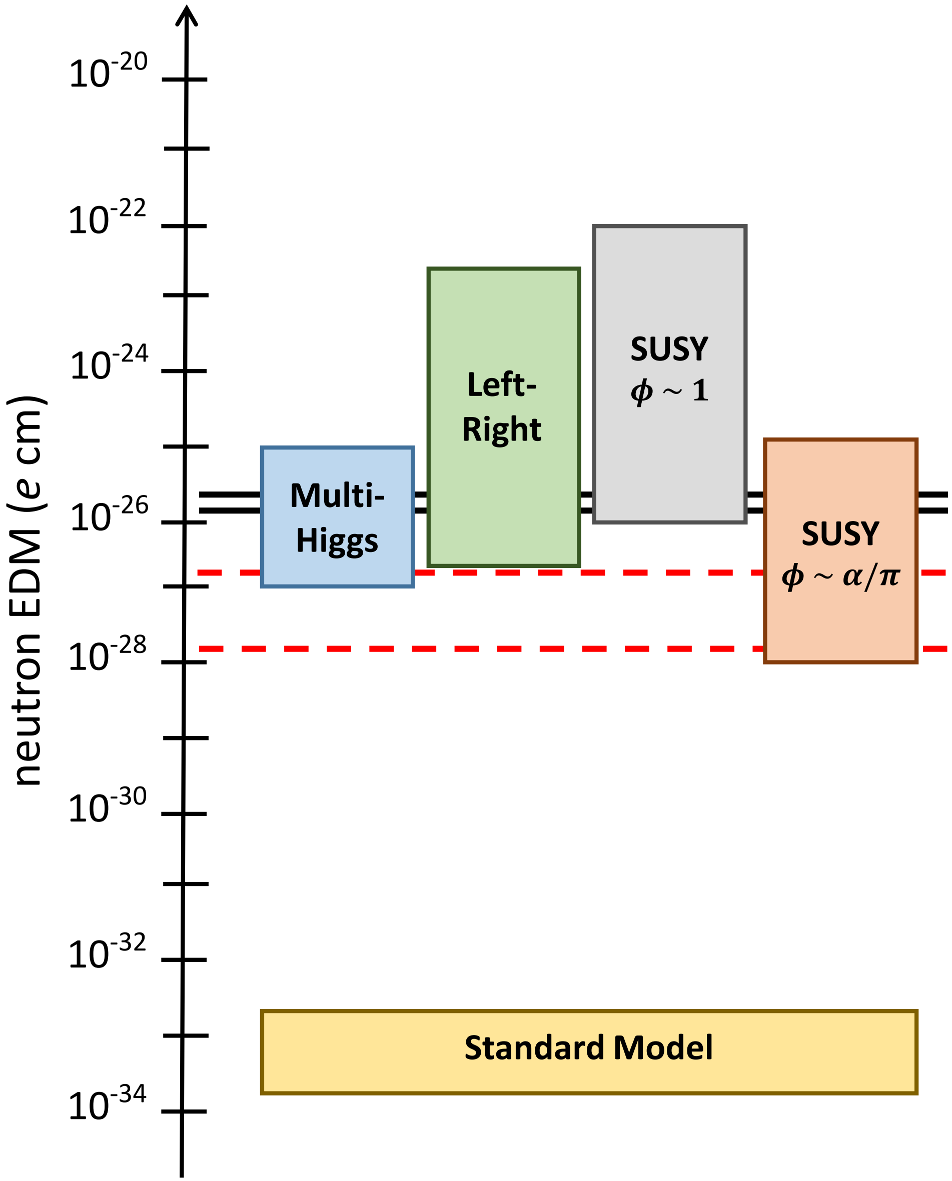
explore benefits of quantum nature:
- **Heisenberg scaling** through entanglement?
- state engineering (squeezing, decoherence-free subspace)?
- matter-wave interference?

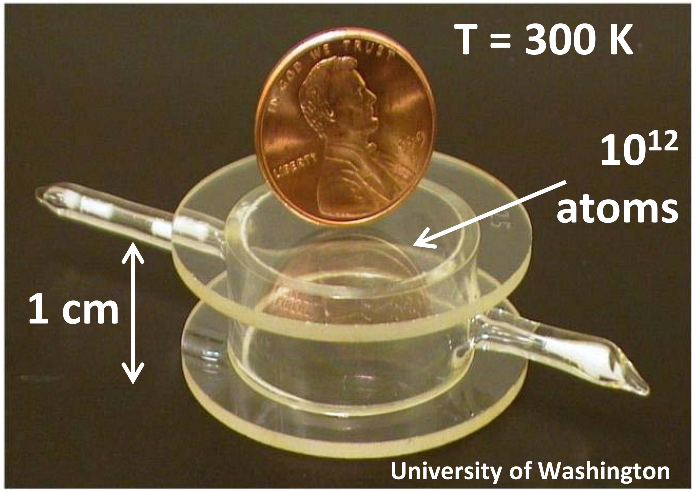
Expected sensitivity of the quMercury experiment

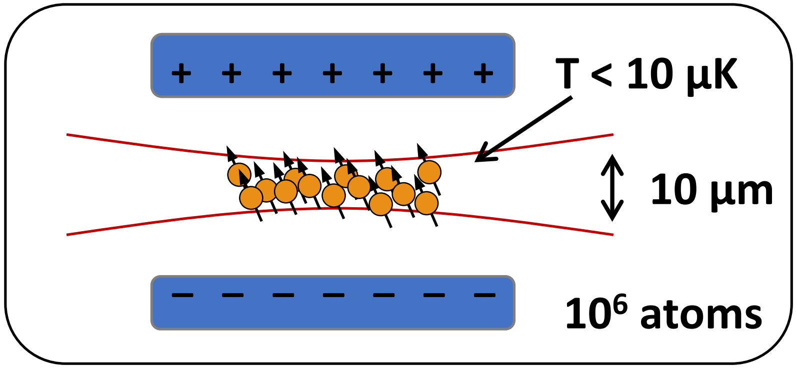
$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$

	Seattle (2016)	quMercury			
		first try	**after 5 years**	2nd generation	Heisenberg
voltage	15 kV	10 kV	**30 kV**	30 kV	30 kV
electrode gap	1.1 cm	0.5 mm	**0.5 mm**	0.2 mm	1 mm
E-field	13.6 kV/cm	200 kV/cm	**600 kV/cm**	1500 kV/cm	300 kV/cm
spin decoherence τ	100 s	100 s	**300 s**	300 s	100 s
atom number N	2 x 10^{14}	10^{6}	**10^{8}**	10^{9}	10^{6}
measurement time T	10 months	3 months	**3 months**	6 months	3 months
sensitivity δd	**7.4 x 10^{-30} *e* cm**	1.5 x 10^{-28} *e* cm	**7.6 x 10^{-31} *e* cm**	7.1 x 10^{-32} *e* cm	2.6 x 10^{-32} *e* cm
comments	Nominal δd of 2 x 10^{-33} *e* cm not reached because of leakage currents.	Already six orders of magnitude better than Rn-221 and Ra-225 experiments in a dipole trap.	**Improves Seattle experiment by factor 10.**	Improves Seattle experiment by factor 100.	

Expected sensitivity of the quMercury experiment

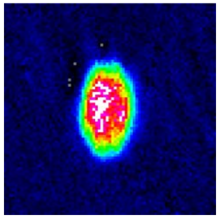




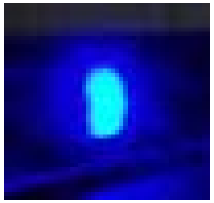


Current status...

Laser cooling is a powerful tool



BEC

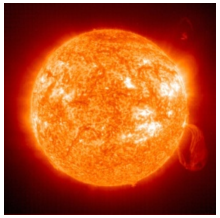


MOT

(Scientific American)

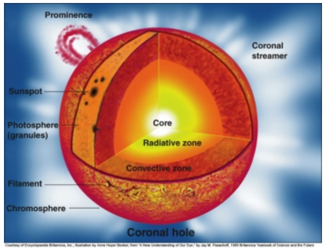
superfluid He

(wikipedia)



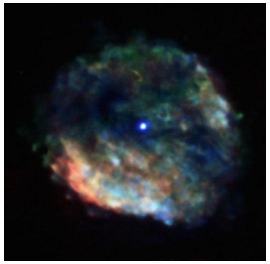
sun surface

(Encycl. Brit.)



sun core

(NASA, Chandra)



neutron star core

temperature

1 nK
1 μK
1 mK
1 K
10^3 K
10^6 K
10^9 K
10^{12} K
10^{15} K

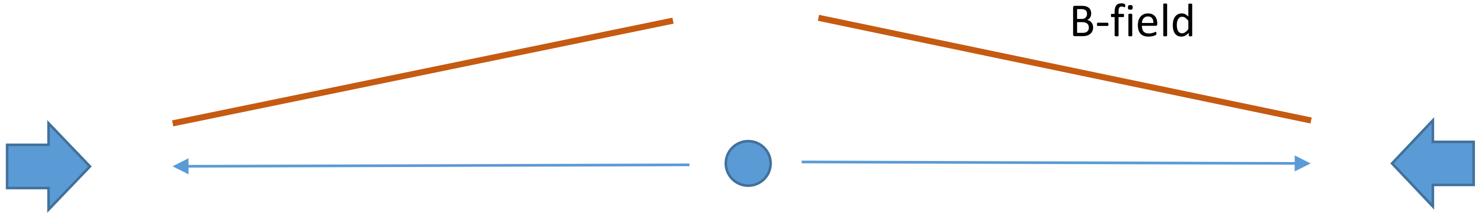
x 1 / 1 000 000 000 000

x 1 000 000 000 000

laser cooling

evaporative cooling

Laser cooling

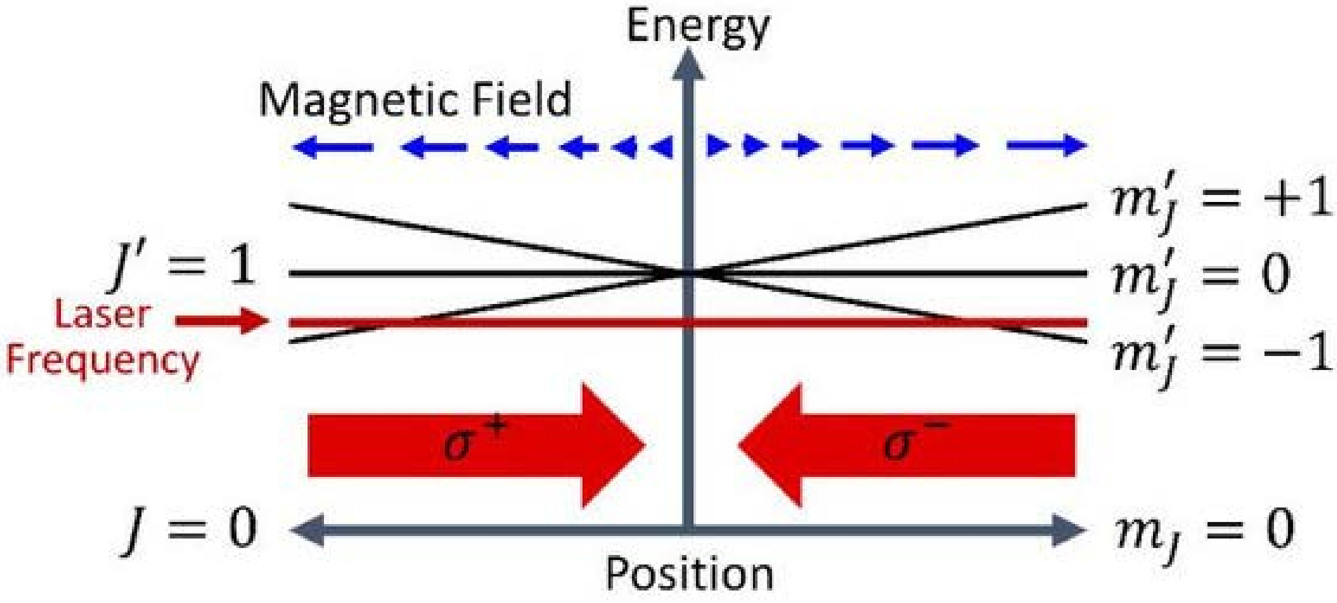


B-field

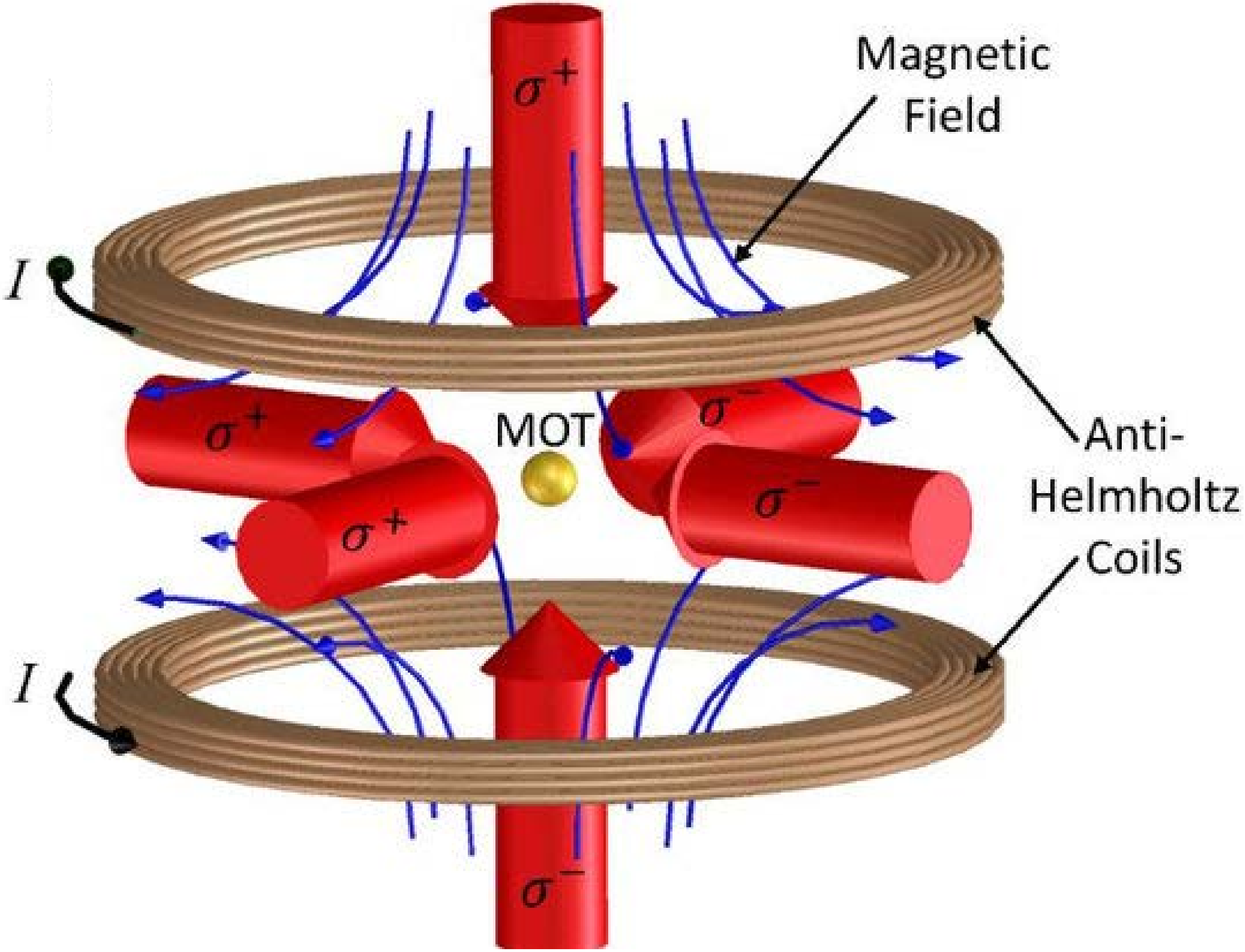
laser light

Dopper shift

+ Zeeman shift = Zeeman slower



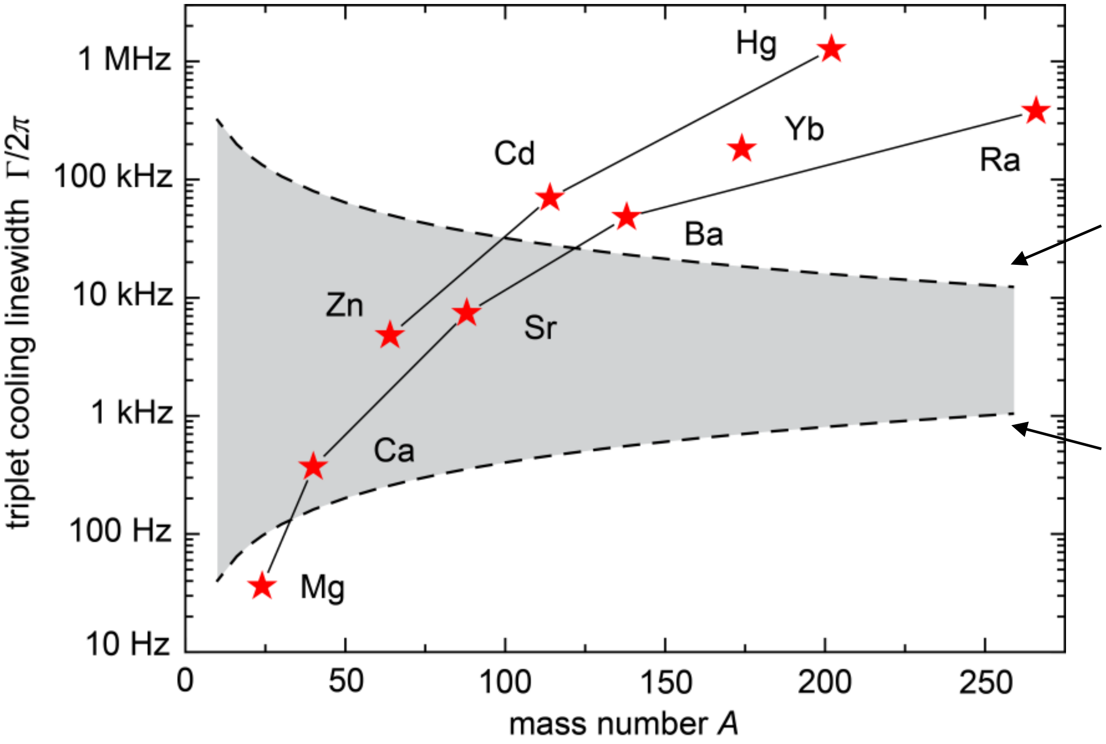
Magneto-optical trap



$$T_D = \hbar\Gamma/(2k_B)$$

… but we can do better: sub-Doppler cooling

Narrow-line cooling

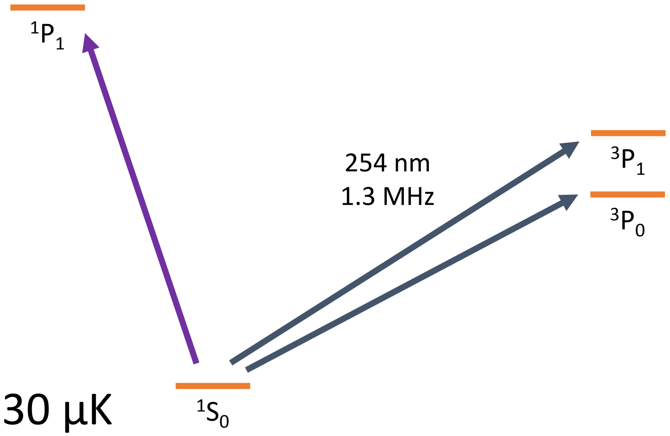


Doppler limit = recoil limit

max. optical force = gravity

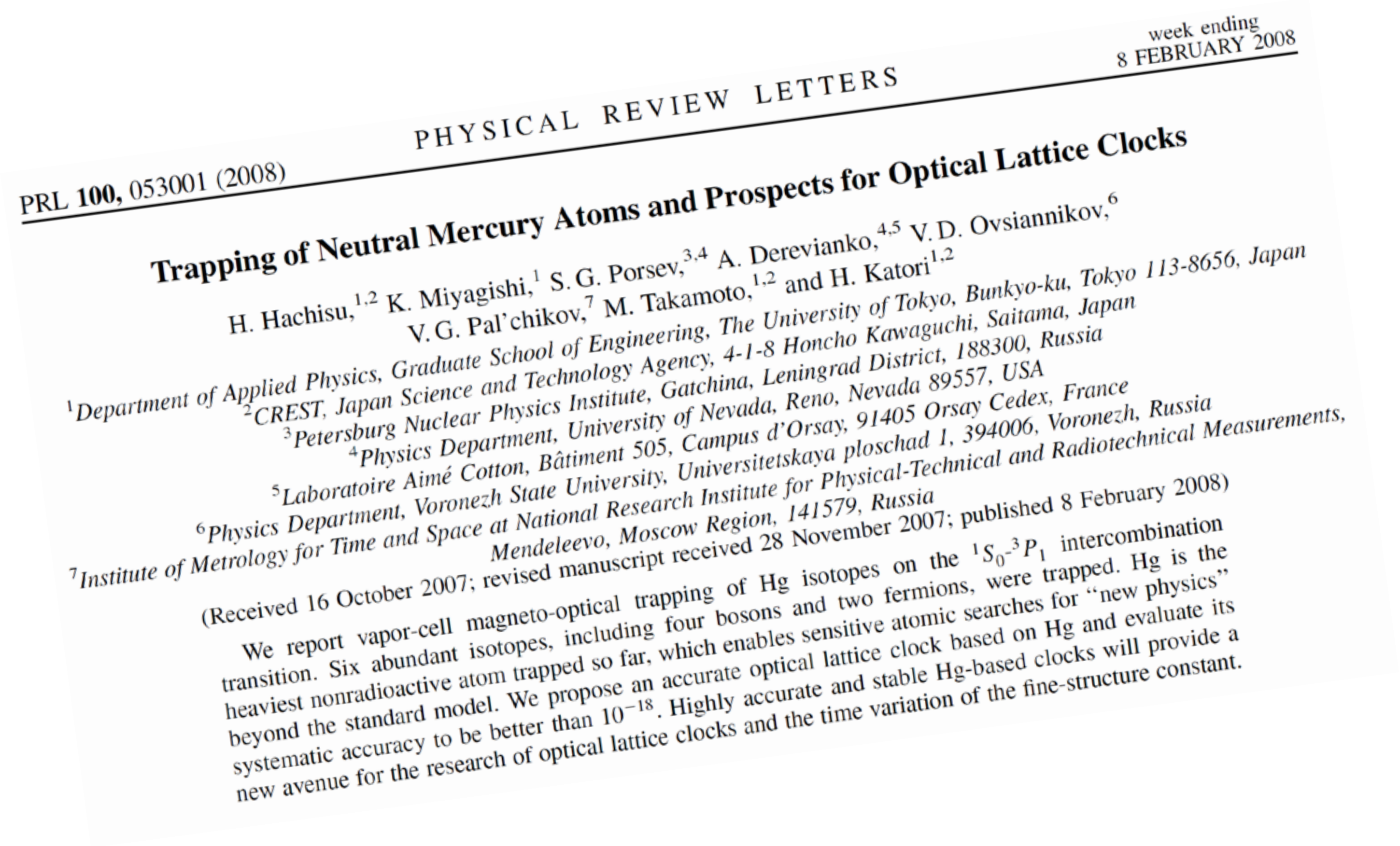
$$T_D = \hbar\Gamma/(2k_B)$$

$$T_r = \hbar^2 k^2/(k_B m)$$



Hg Doppler temperature: 30 μK

Magneto-optical trapping of Hg



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Trapping of Neutral Mercury Atoms and Prospects for Optical Lattice Clocks

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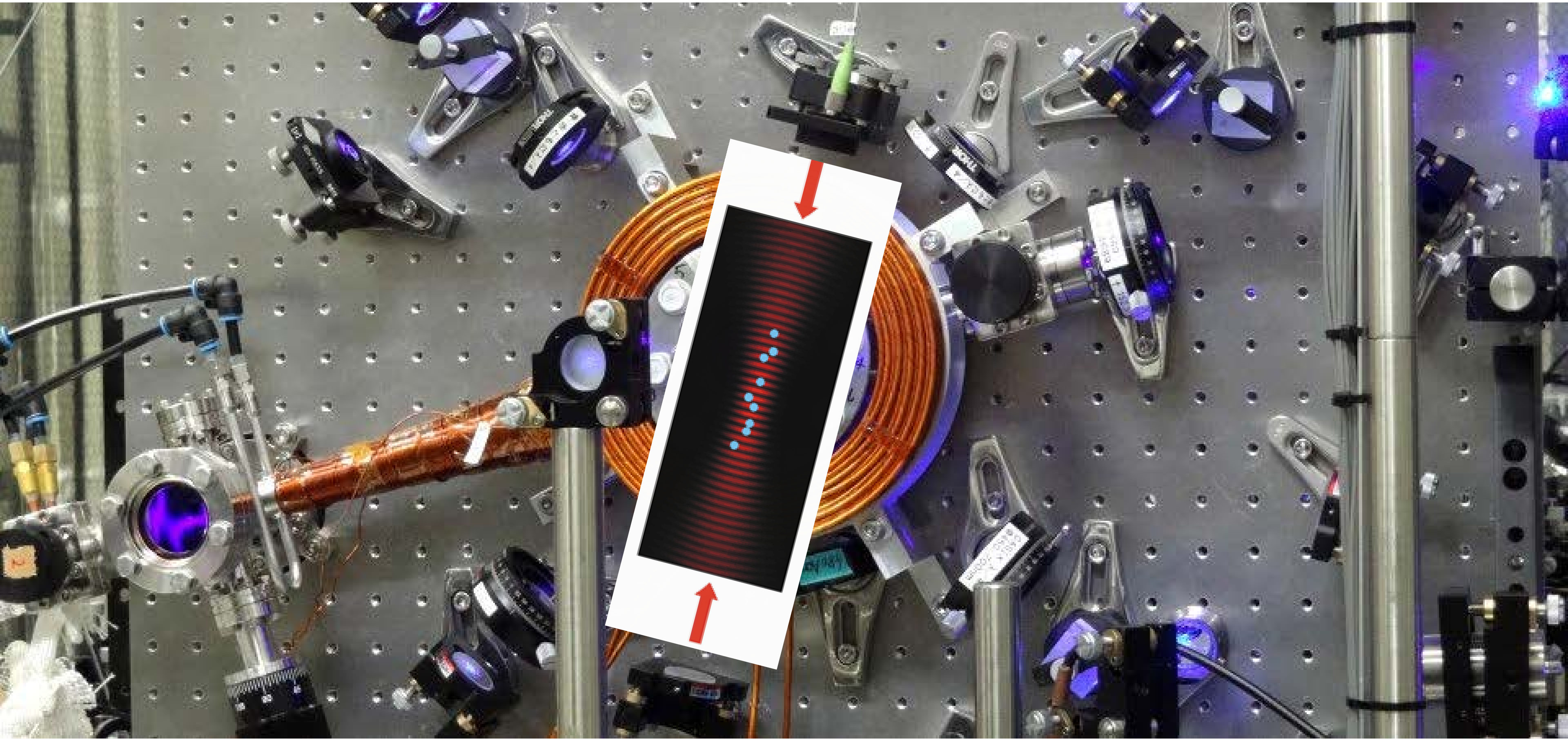
We report vapor-cell magneto-optical trapping of Hg isotopes on the $^1S_0$-$^3P_1$ intercombination transition. Six abundant isotopes, including four bosons and two fermions, were trapped. Hg is the heaviest nonradioactive atom trapped so far, which enables sensitive atomic searches for "new physics" beyond the standard model. We propose an accurate optical lattice clock based on Hg and evaluate its systematic accuracy to be better than 10^{-18}. Highly accurate and stable Hg-based clocks will provide a new avenue for the research of optical lattice clocks and the time variation of the fine-structure constant.

Katori group in 2008:
500,000 atoms of Hg-199 at 50 µK

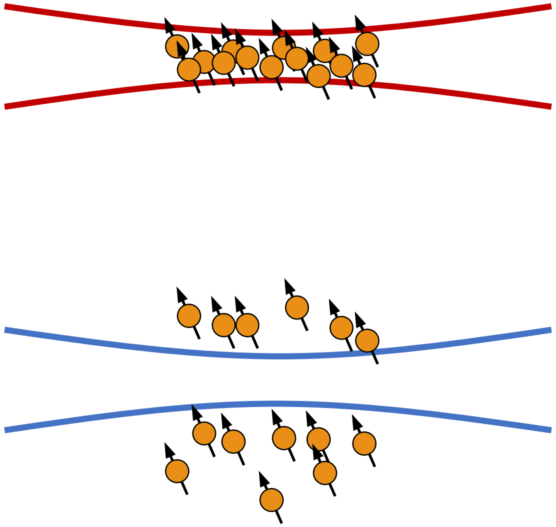
Optical clocks with mercury



Katori group, RIKEN (Sr lattice clock)

Optical dipole traps

NP 2018:
Arthur Ashkin
optical tweezers



$$U_{\text{dip}}(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\omega_0 - \omega} + \frac{\Gamma}{\omega_0 + \omega}\right) I(\mathbf{r})$$

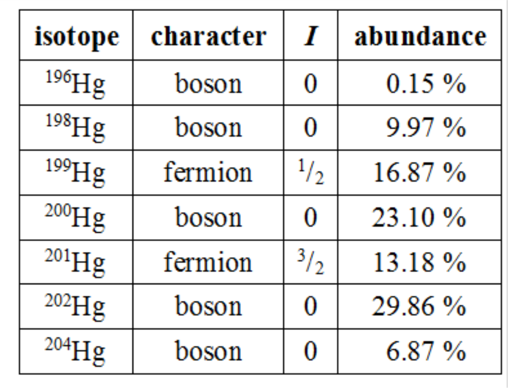
resonance frequency of the atom

frequency of the laser

Scattering properties are important (and unknown)

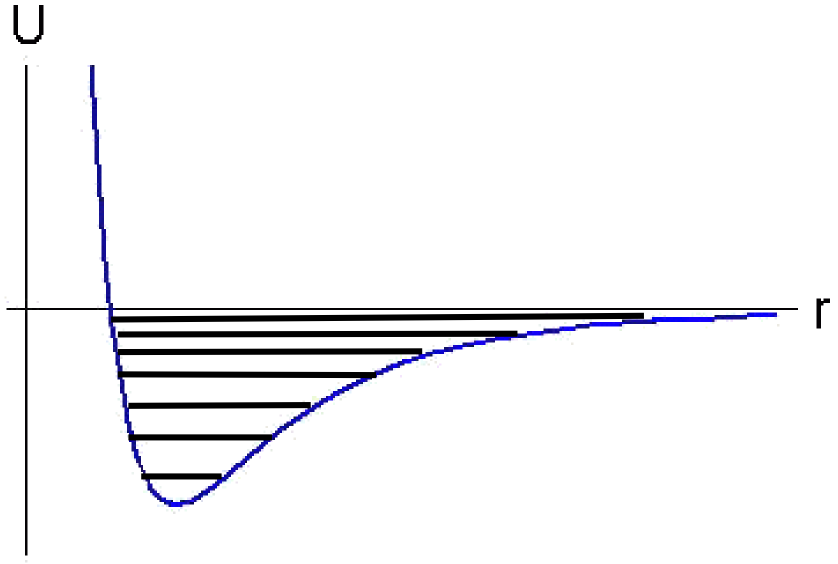
Evaporative cooling...

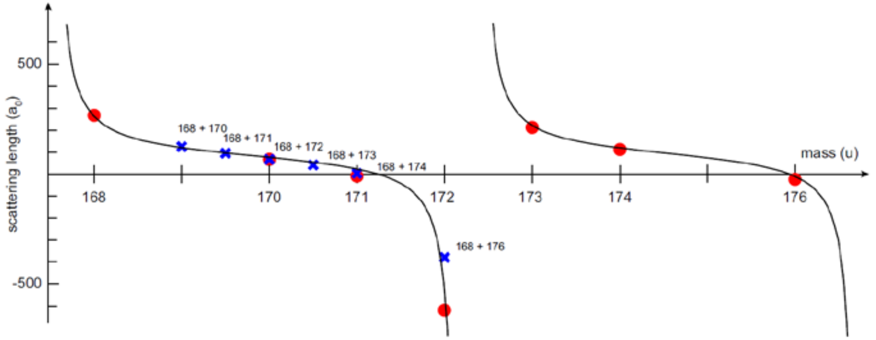
- is an efficient way to increase phase space density
- relies on re-thermalization of the atoms
- works only within a certain range of scattering properties



isotope	character	I	abundance
^{196}Hg	boson	0	0.15 %
^{198}Hg	boson	0	9.97 %
^{199}Hg	fermion	$^1/_2$	16.87 %
^{200}Hg	boson	0	23.10 %
^{201}Hg	fermion	$^3/_2$	13.18 %
^{202}Hg	boson	0	29.86 %
^{204}Hg	boson	0	6.87 %

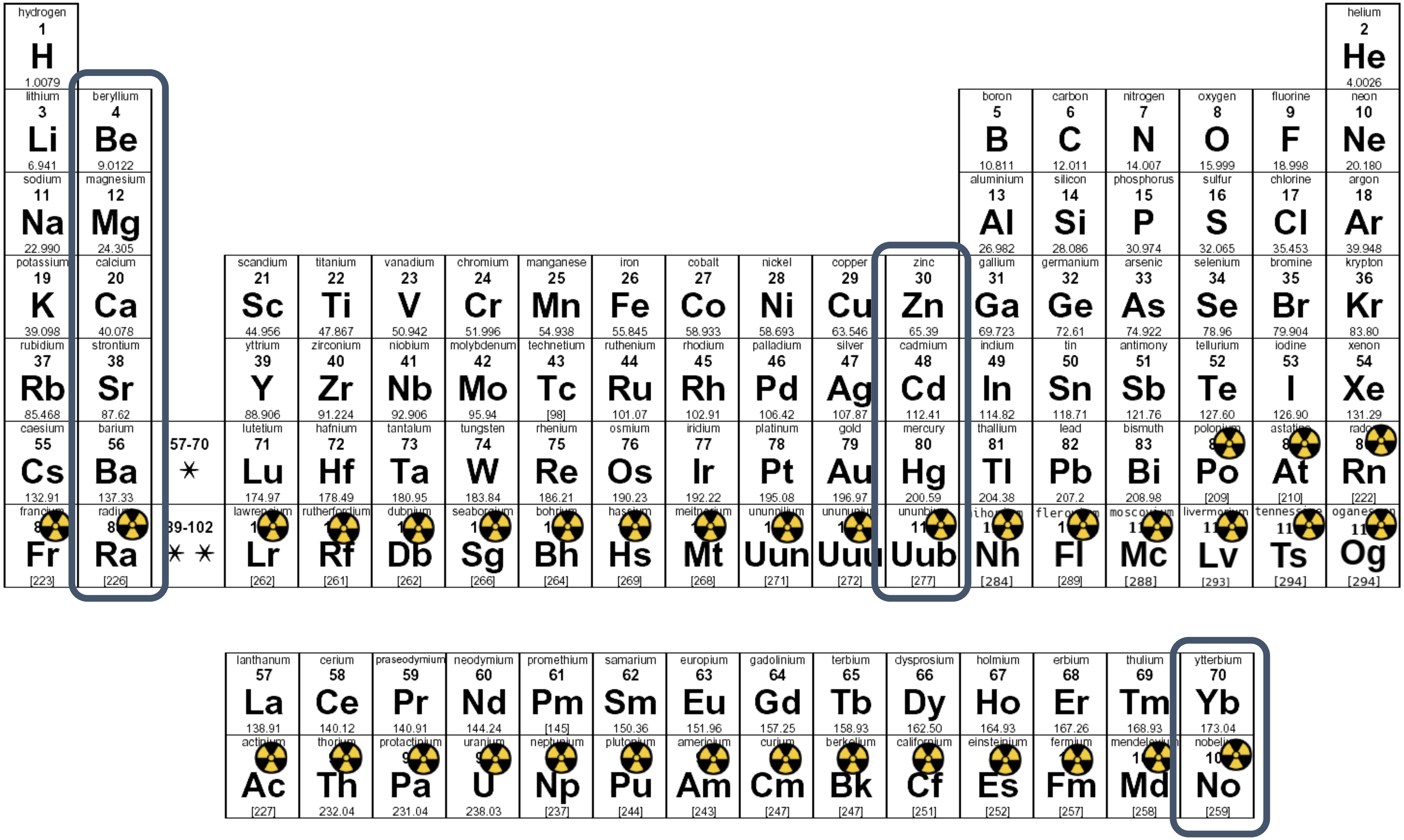
scattering cross section: $\sigma = 4\pi\, a_s^2$





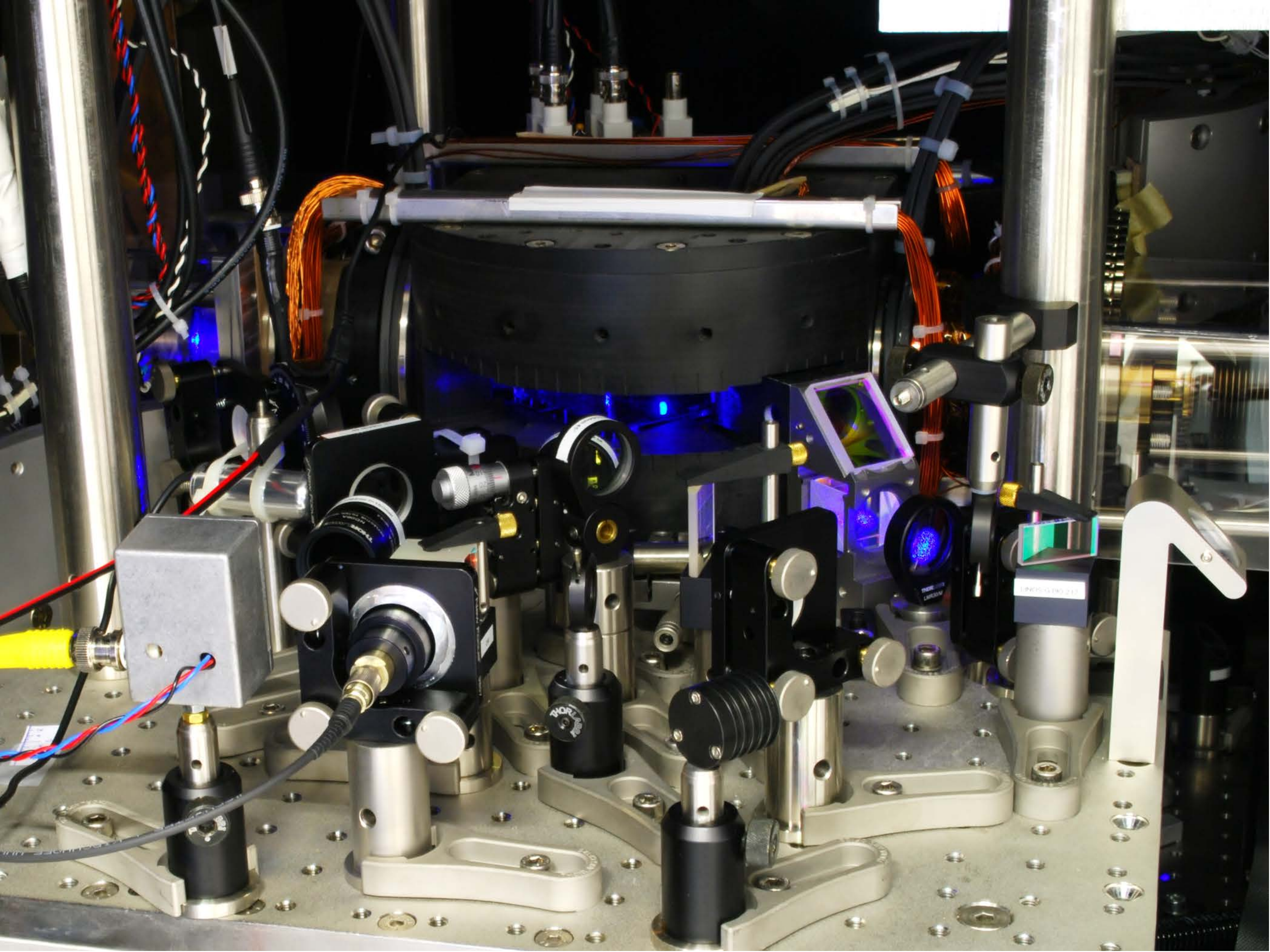
mass scaling in Yb

Strontium, very similar to mercury



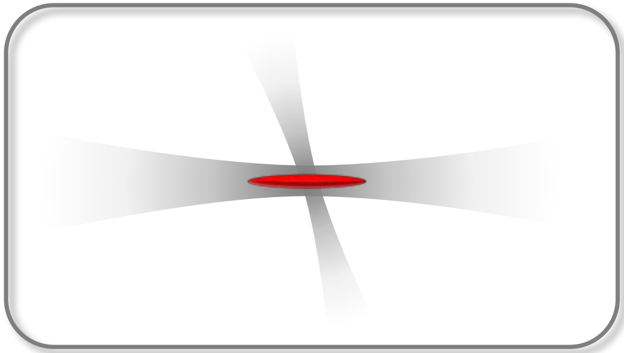
hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium ☢ 8 **Po** [209]	astatine ☢ 8 **At** [210]	radon ☢ 8 **Rn** [222]
francium ☢ 8 **Fr** [223]	radium ☢ 8 **Ra** [226]	89-102 * *	lawrencium ☢ 1 **Lr** [262]	rutherfordium ☢ 1 **Rf** [261]	dubnium ☢ 1 **Db** [262]	seaborgium ☢ 1 **Sg** [266]	bohrium ☢ 1 **Bh** [264]	hassium ☢ **Hs** [269]	meitnerium ☢ 1 **Mt** [268]	ununnilium ☢ 1 **Uun** [271]	unununium ☢ 1 **Uuu** [272]	ununbium ☢ 11 **Uub** [277]	nihonium ☢ 1 **Nh** [284]	flerovium ☢ 1 **Fl** [289]	moscovium ☢ 11 **Mc** [288]	livermorium ☢ 11 **Lv** [293]	tennessine ☢ 11 **Ts** [294]	oganesson ☢ 11 **Og** [294]

lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
actinium ☢ **Ac** [227]	thorium ☢ **Th** 232.04	protactinium ☢ 9 **Pa** 231.04	uranium ☢ 9 **U** 238.03	neptunium ☢ **Np** [237]	plutonium ☢ **Pu** [244]	americium ☢ **Am** [243]	curium ☢ **Cm** [247]	berkelium ☢ **Bk** [247]	californium ☢ **Cf** [251]	einsteinium ☢ **Es** [252]	fermium ☢ 1 **Fm** [257]	mendelevium ☢ 1 **Md** [258]	nobelium ☢ 10 **No** [259]

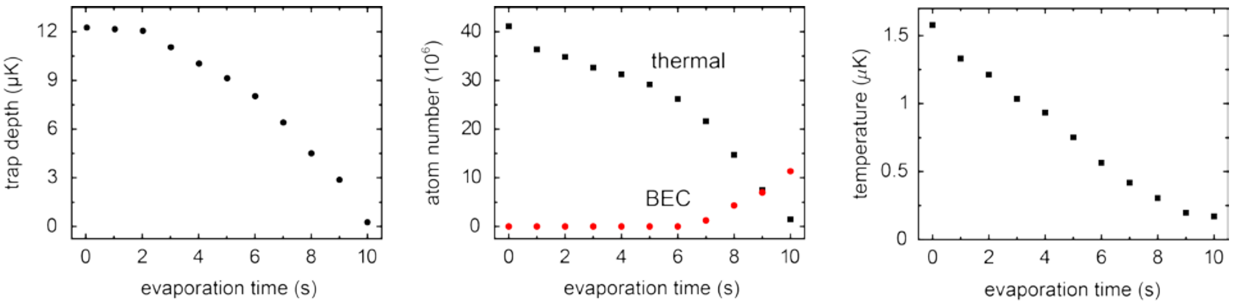

THORLABS

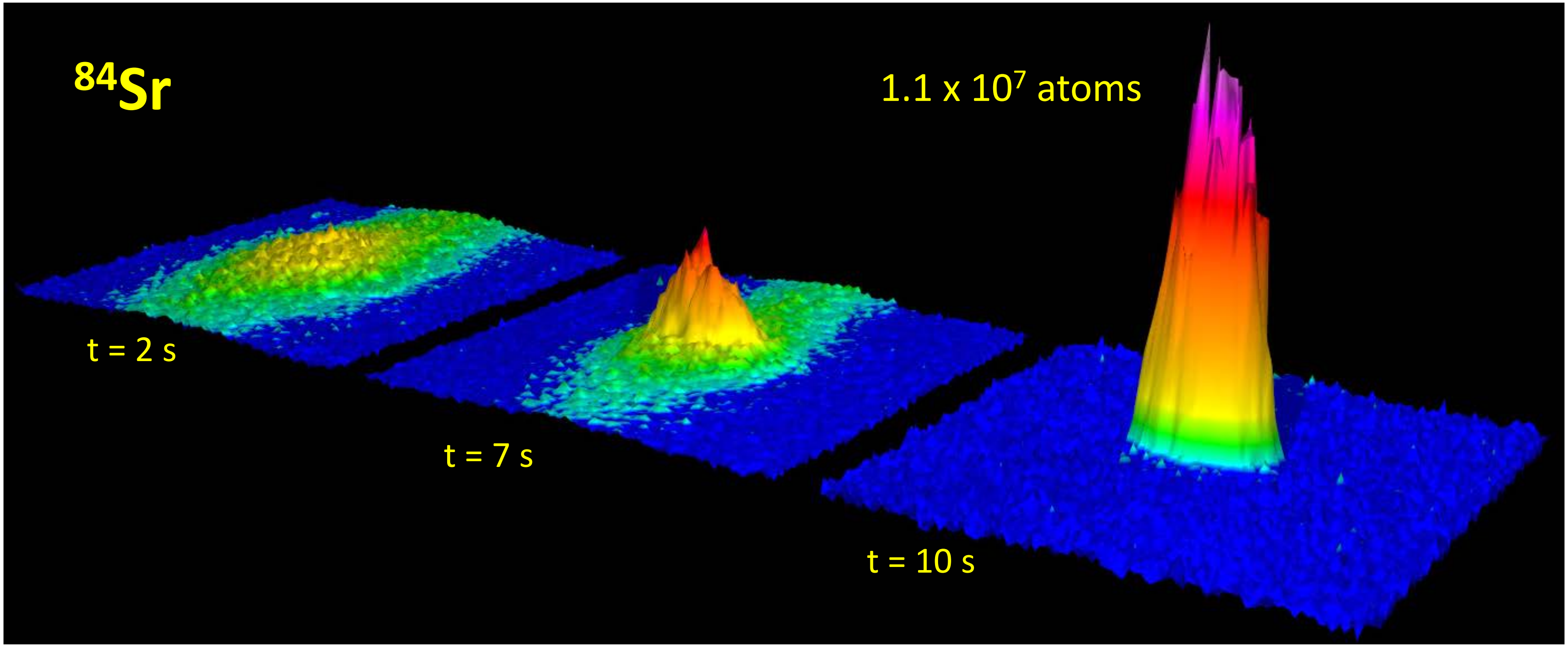
Bose-Einstein condensation of Strontium

loading of the dipole trap



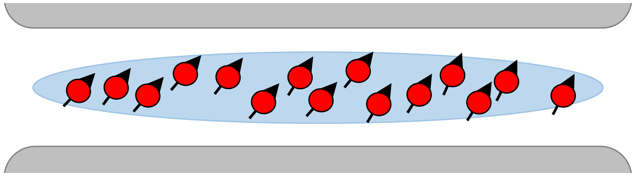
evaporation



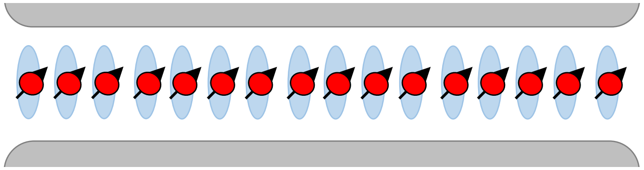


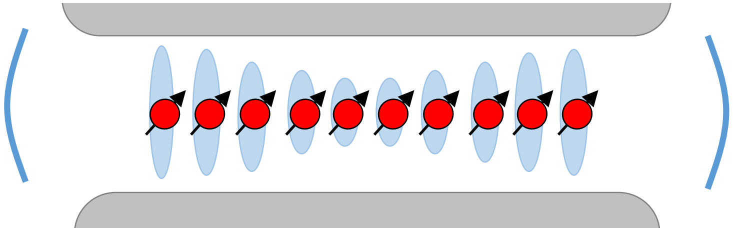
Is there an advantage of quantum-degenerate atoms?

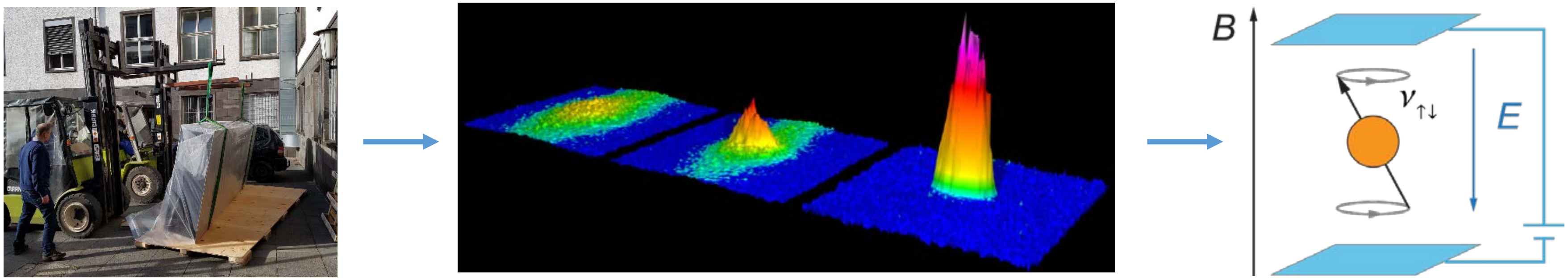
$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$



?







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