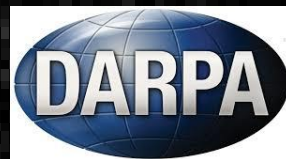


Trapped-Ions, Precision Measurements and Optical Clocks

D. B. Hume, S. M. Brewer, J. S. Chen, C. W. Chou, E. Clements, A. M. Hankin, D. J. Wineland, J. C. Bergquist and D. R. Leibbrandt

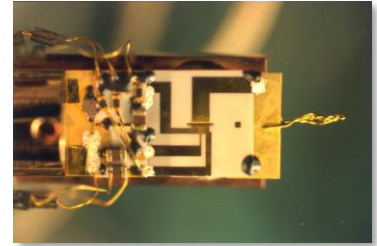
Ion Storage Group
NIST, Boulder

Quantum Sensors for Fundamental Physics
Oxford 10/16/2018



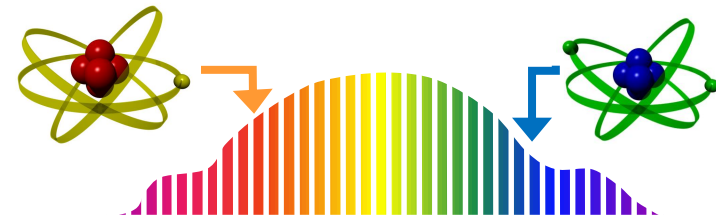
Outline

1. Ions, Ion traps,
Tests of fundamental physics



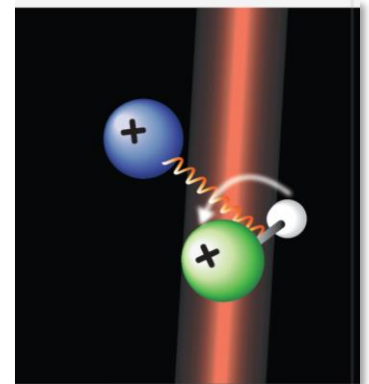
2. Single-ion optical clocks

- Al^+ vs Hg^+ at NIST
- Al^+ vs optical lattice clocks



3. Useful quantum techniques

- Quantum logic spectroscopy
- Correlation spectroscopy



Trapped Ions



Hans Dehmelt

Hans Dehmelt 1988 *Phys. Scr.* **1988** 102

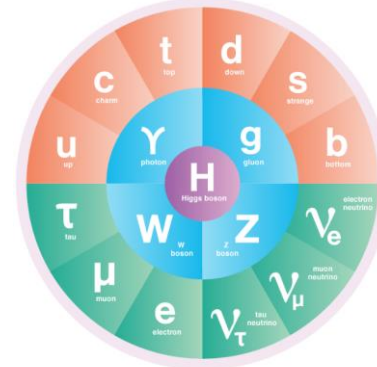


- Quantum-limited experiments
- Long interaction times
- Small relativistic shifts
- Small perturbation from EM fields

+ Strong, controllable interactions between ions

Trapped Ion Species

- Elementary particles (e^- , e^+ , ...)
- Composite particles (p , \bar{p} , ...)
- Atomic ions
 - Singly-ionized (Ca^+ , Al^+ , Yb^+ , ...)
 - Highly-charged (Ar^{14+} , ...)
 - ^{229}Th nucleus
- Molecular ions
 - CaH^+ , N_2^+ , HD^+ , AlH^+ , ...
 - Biological molecules
- Macroscopic particles
 - Water droplets, dust, ...



<https://science.energy.gov/hep/>

● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

PERIODIC TABLE
Atomic Properties of the Elements

FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS¹

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum $c = 299\,792\,458\text{ m}\cdot\text{s}^{-1}$ (exact)

Planck constant $h = 6.626\,070\,15 \times 10^{-34}\text{ J}\cdot\text{s}$ (exact)

elementary charge $e = 1.602\,177\,33 \times 10^{-19}\text{ C}$

electron mass $m_e = 9.109\,383\,56 \times 10^{-31}\text{ kg}$

proton mass $m_p = 1.672\,622 \times 10^{-27}\text{ kg}$

fine-structure constant $\alpha = 1/137.035\,999$

Rydberg constant $R_\infty = 10\,973\,731.500\text{ m}^{-1}$

$\alpha^2 R_\infty$ $13.605\,693\text{ eV}$

$\alpha^2 R_\infty$ $1.002\,177 \times 10^{13}\text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$

Boltzmann constant $k = 1.380\,65 \times 10^{-23}\text{ J}\cdot\text{K}^{-1}$

molar gas constant $R = 8.314\,472\text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$

¹For the most accurate values of these and other constants, visit nist.gov/constants.

Legend: Solids, Liquids, Gases, Artificially Prepared

NIST National Institute of Standards and Technology
U.S. Department of Commerce

Physical Measurement Laboratory www.nist.gov/pml
Standard Reference Data www.nist.gov/srd

1 H Hydrogen 1.008 13.9964	2 He Helium 4.002 14.00307	3 Li Lithium 6.94 15.9948	4 Be Beryllium 9.012 18.9984	5 B Boron 10.81 20.9064	6 C Carbon 12.011 24.0078	7 N Nitrogen 14.007 28.0134	8 O Oxygen 15.999 31.9888	9 F Fluorine 18.998 37.9962	10 Ne Neon 20.180 40.0158	11 Na Sodium 22.990 46.9409	12 Mg Magnesium 24.305 51.9961	13 Al Aluminum 26.982 57.9350	14 Si Silicon 28.086 63.9463	15 P Phosphorus 30.974 70.9069	16 S Sulfur 32.06 78.96	17 Cl Chlorine 35.45 86.9092	18 Ar Argon 39.948 93.9048	19 K Potassium 39.098 99.904	20 Ca Calcium 40.078 100.087	21 Sc Scandium 44.956 102.9055	22 Ti Titanium 47.887 106.42	23 V Vanadium 50.942 110.938	24 Cr Chromium 51.996 114.904	25 Mn Manganese 54.938 118.903	26 Fe Iron 55.845 126.905	27 Co Cobalt 58.933 132.905	28 Ni Nickel 58.693 138.905	29 Cu Copper 63.546 146.909	30 Zn Zinc 65.38 150.926	31 Ga Gallium 69.723 157.47	32 Ge Germanium 72.63 167.227	33 As Arsenic 74.922 174.927	34 Se Selenium 78.971 179.947	35 Br Bromine 79.904 187.901	36 Kr Krypton 83.798 198.906	37 Rb Rubidium 85.468 200.937	38 Sr Strontium 87.62 208.980	39 Y Yttrium 88.906 218.904	40 Zr Zirconium 91.224 223.029	41 Nb Niobium 92.906 226.025	42 Mo Molybdenum 95.94 234.036	43 Tc Technetium 98.906 238.029	44 Ru Ruthenium 101.07 243.04	45 Rh Rhodium 102.905 244.064	46 Pd Palladium 106.42 243.027	47 Ag Silver 107.868 247.807	48 Cd Cadmium 112.411 248.078	49 In Indium 114.818 255.078	50 Sn Tin 118.710 260.104	51 Sb Antimony 121.757 265.075	52 Te Tellurium 127.60 278.101	53 I Iodine 126.905 280.839	54 Xe Xenon 131.29 285.349	55 Cs Cesium 132.91 289.811	56 Ba Barium 137.33 300.904	57 La Lanthanum 138.91 300.905	58 Ce Cerium 140.12 300.905	59 Pr Praseodymium 140.91 300.905	60 Nd Neodymium 144.24 300.905	61 Pm Promethium 144.91 300.905	62 Sm Samarium 150.36 300.905	63 Eu Europium 151.96 300.905	64 Gd Gadolinium 157.25 300.905	65 Tb Terbium 158.93 300.905	66 Dy Dysprosium 162.50 300.905	67 Ho Holmium 164.93 300.905	68 Er Erbium 167.26 300.905	69 Tm Thulium 168.93 300.905	70 Yb Ytterbium 173.05 300.905	71 Lu Lutetium 174.97 300.905	72 Hf Hafnium 178.49 300.905	73 Ta Tantalum 180.95 300.905	74 W Tungsten 183.84 300.905	75 Re Rhenium 186.21 300.905	76 Os Osmium 190.23 300.905	77 Ir Iridium 192.22 300.905	78 Pt Platinum 195.08 300.905	79 Au Gold 196.97 300.905	80 Hg Mercury 200.59 300.905	81 Tl Thallium 204.38 300.905	82 Pb Lead 207.2 300.905	83 Bi Bismuth 208.98 300.905	84 Po Polonium (209) 300.905	85 At Astatine (210) 300.905	86 Rn Radon (222) 300.905	87 Fr Francium (223) 300.905	88 Ra Radium (226) 300.905	89 Ac Actinium (227) 300.905	90 Th Thorium (232) 300.905	91 Pa Protactinium (231) 300.905	92 U Uranium (238) 300.905	93 Np Neptunium (237) 300.905	94 Pu Plutonium (244) 300.905	95 Am Americium (243) 300.905	96 Cm Curium (247) 300.905	97 Bk Berkelium (247) 300.905	98 Cf Californium (251) 300.905	99 Es Einsteinium (252) 300.905	100 Fm Fermium (257) 300.905	101 Md Mendelevium (258) 300.905	102 No Nobelium (259) 300.905	103 Lr Lawrencium (260) 300.905
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Atomic Number, Symbol, Name, Standard Atomic Weight, Ground-state Configuration, Ionization Energy (eV)

<https://www.nist.gov/pml/periodic-table-elements>

Ion Traps

Features:

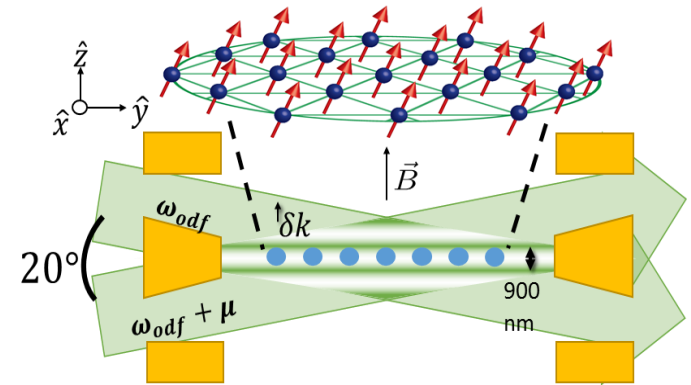
Deep trapping, typ. 300K – 10000 K
Well-controlled environment

- UHV conditions
- Small and/or stable EM fields
- Low temperature

Ion cooling

- Laser cooling
- Resistive cooling
- Buffer gas cooling

Penning Trap High B field



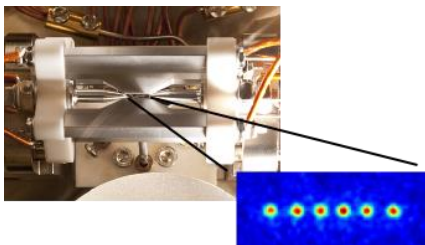
Paul Trap

RF confining fields

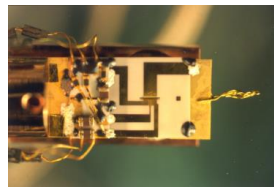
Spherical:



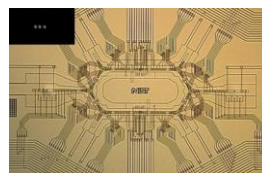
Linear:
Blade



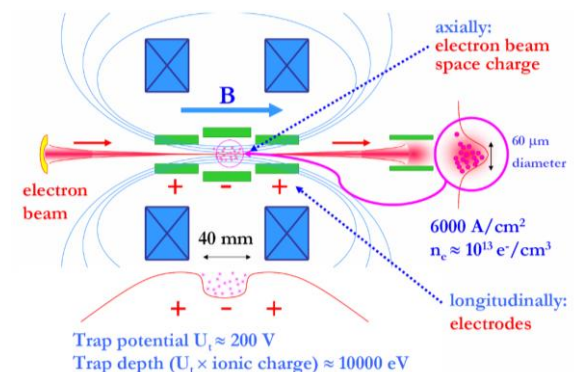
Wafer



Planar



EBIT (Electron Beam Ion Trap) Space charge



Precision Tests of Fundamental Physics

Quantum mechanics

- Linearity
- Randomness
- Bell's inequalities
- Heisenberg limit

Relativity

- Local position invariance
- Lorentz invariance
- Equivalence principle
- Gravitational redshift

Standard model

- g-factor measurements
- Mass measurements
- Tests of quantum electrodynamics
- Electron electric-dipole moment
- Proton radius
- Variation of fundamental constants
($\alpha = e^2/\hbar c$, $\mu = m_e/m_p$)
- Dark matter searches
- Parity non-conservation
- Isotope shifts, King-plot non-linearities
- Anomalous forces, interactions (spin-dependent, spin-independent)

If you want to find the secrets of the universe, think in terms of energy, frequency and vibration. – Nikola Tesla (disputed)

Precision Tests of Fundamental Physics

Quantum mechanics

- Li
- Ra
- Be
- Heisenberg limit

Frequency vs. theory

Gabrielse

Relativity

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- Lorentz invariance
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Precision Tests of Fundamental Physics

Quantum mechanics

- Linearity
- Randomness
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- Heisenberg limit

Frequency vs. time

Godun Wednesday 11:55

Gill Wednesday 9:35

- Local position invariance
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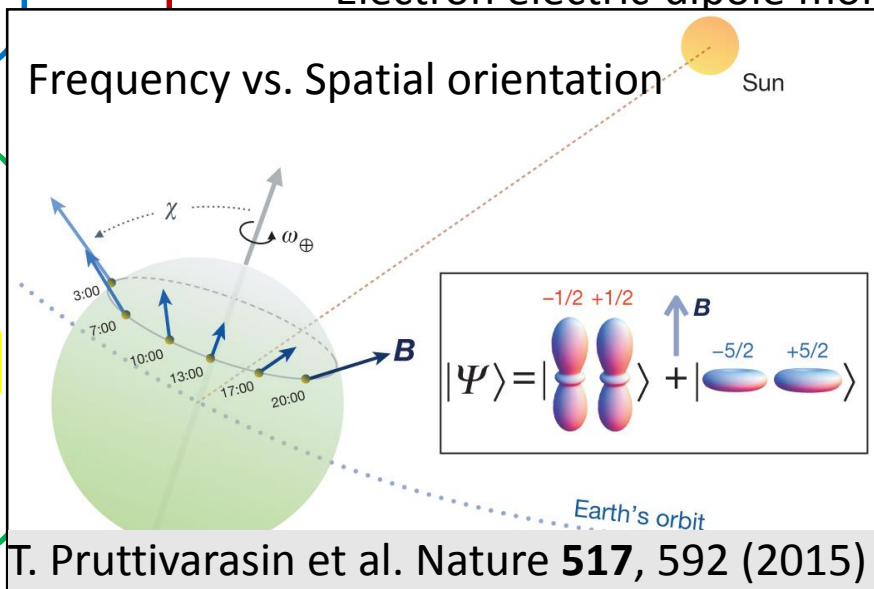
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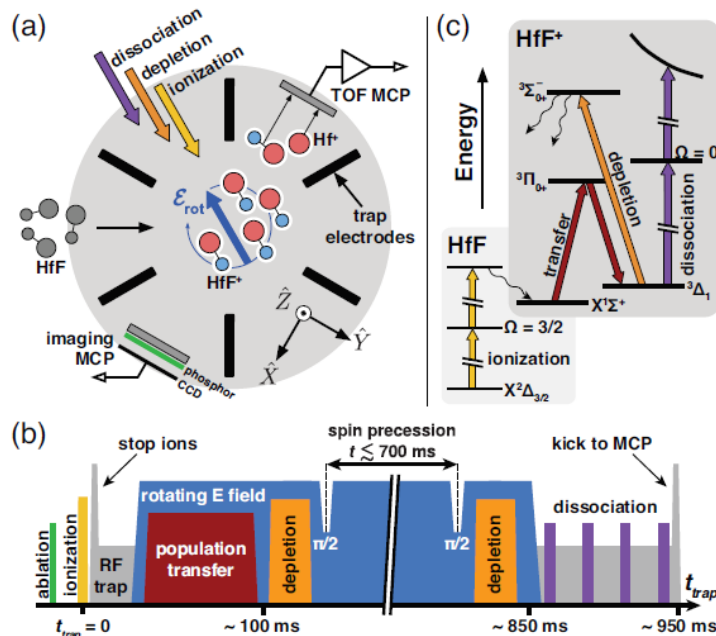
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Precision Tests of Fundamental Physics

Frequency vs. Applied Fields



W. B. Cairncross et al., Phys. Rev. Lett. **119**, 153001 (2017)

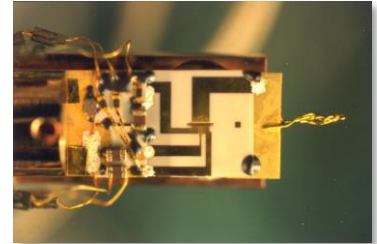
Standard model

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- Mass measurements
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- **Electron electric-dipole moment**
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- Variation of fundamental constants
($\alpha = e^2/\hbar c$, $\mu = m_e/m_p$)
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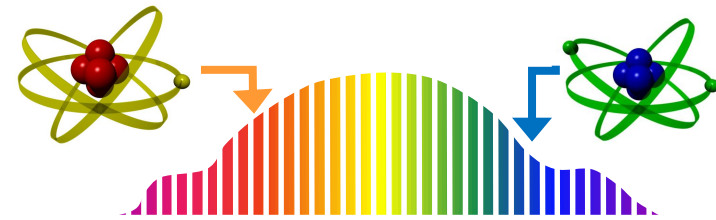
Outline

1. Ions, Ion traps,
Tests of fundamental physics



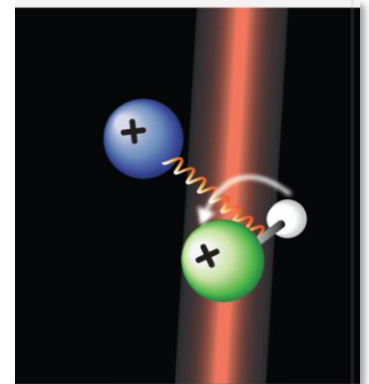
2. Single-ion optical clocks

- Al^+ vs Hg^+ at NIST
- Al^+ vs optical lattice clocks



3. Useful quantum techniques

- Quantum logic spectroscopy
- Correlation spectroscopy



Clock Tests of Fundamental Physics

Quantum mechanics

- Linearity
- Randomness
- Bell's inequalities
- Heisenberg limit

Relativity

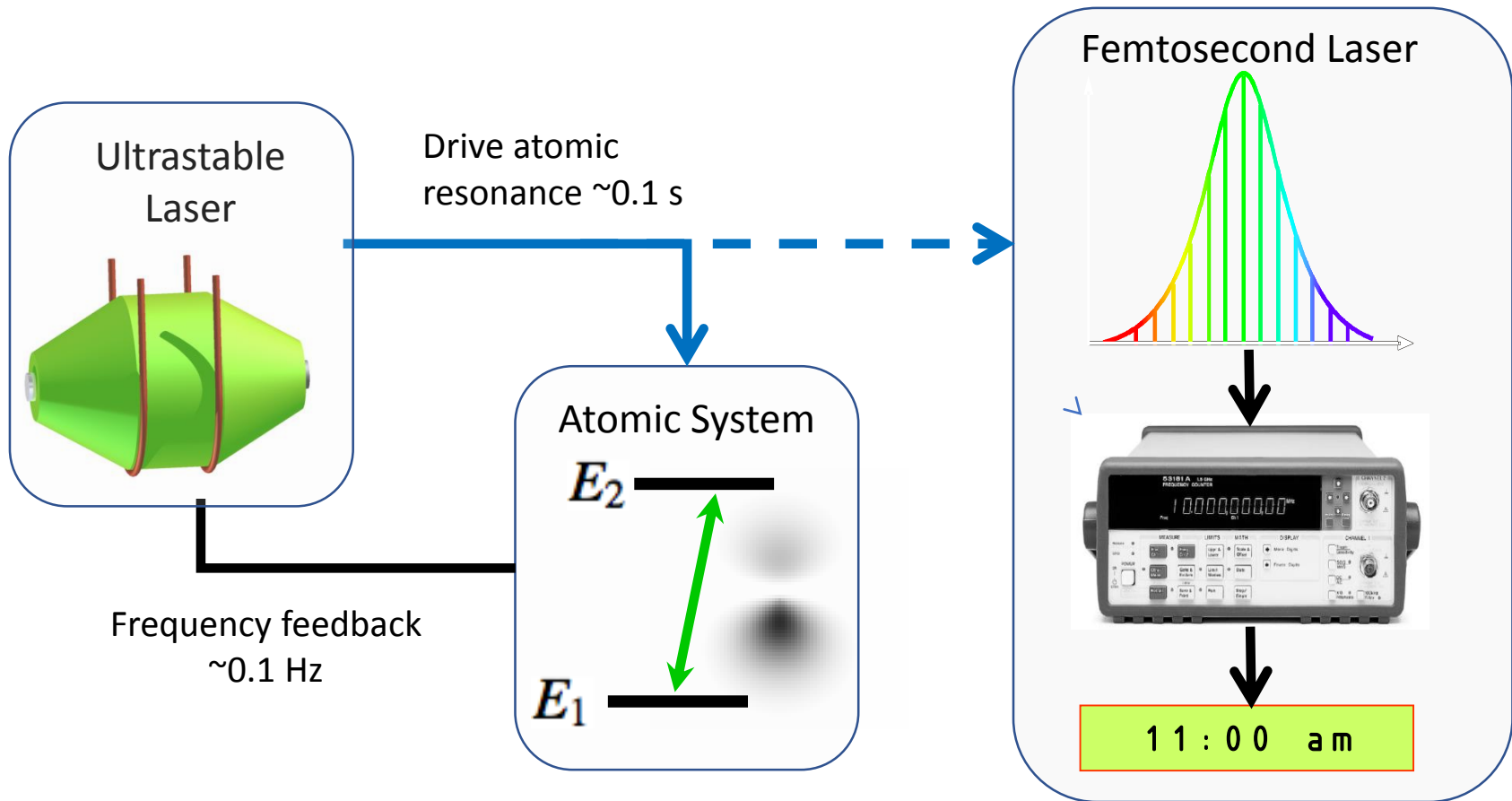
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Principle of Optical Atomic Clocks



Clock frequency:
$$f_0 = \frac{E_2 - E_1}{h} \approx 10^{15} \text{ Hz}$$

Clock Performance

$$\frac{f(t)}{f_0} = 1 + \epsilon + y(t)$$

Accuracy Stability

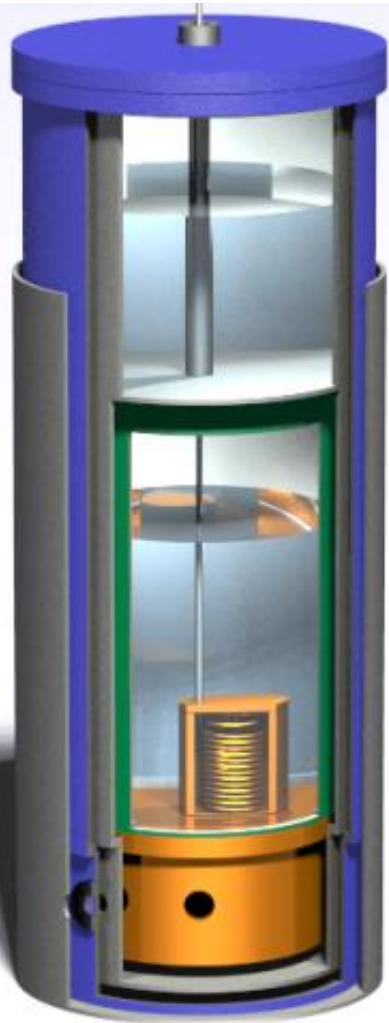
- Systematic uncertainty in clock frequency.
- Two types of shifts
 1. **Field shifts** e.g. Zeeman shift and black body shift
 2. **Motional shifts** e.g. Relativistic Doppler

$$\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} - \frac{\langle \vec{v} \cdot \hat{k} \rangle^2}{2c^2} + \dots$$

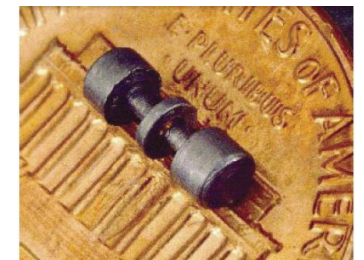
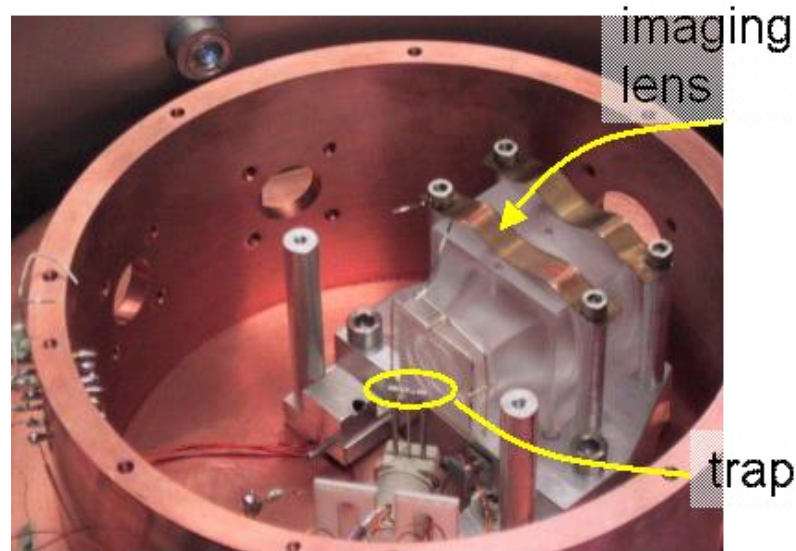
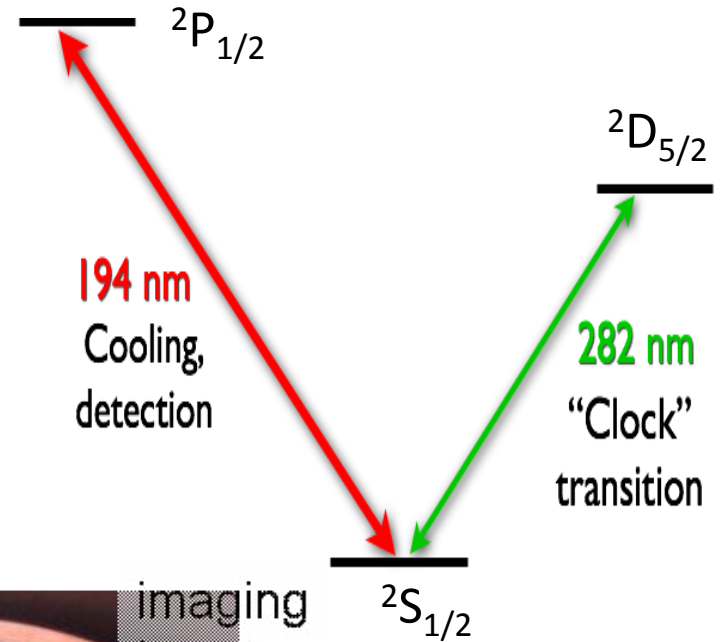
- Average fractional frequency variations
- Typically characterized by the *Allan deviation*:

$$\sigma_y(\tau) \cong \frac{1}{Q} \frac{1}{SNR} \sqrt{\frac{T_C}{\tau}}$$

$^{199}\text{Hg}^+$ system

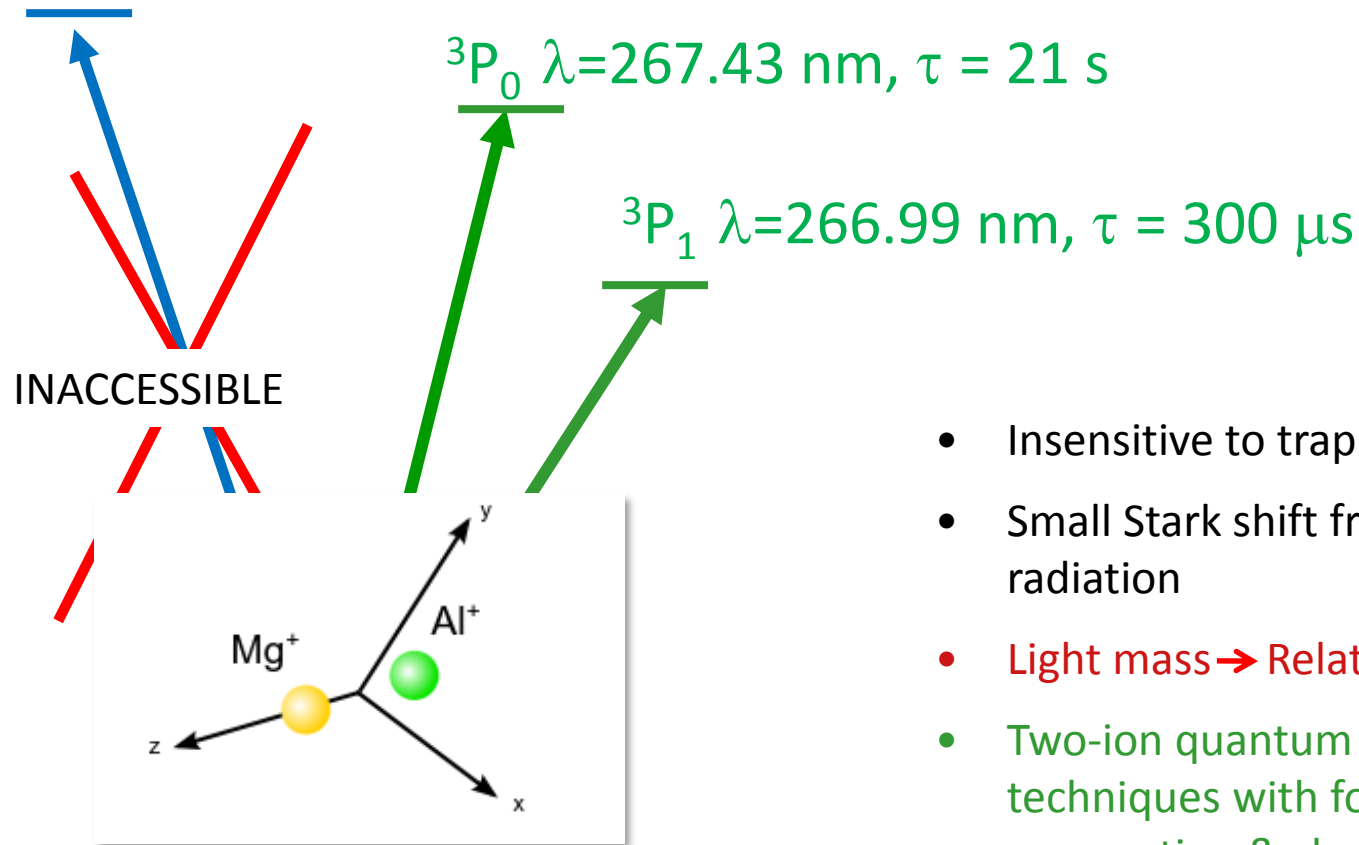


- Spherical Paul Trap
- Cryogenic environment (4 K)
- High sensitivity to variation in the fine structure constant



$^{27}\text{Al}^+$ Atomic System

$^1\text{P}_1$ $\lambda = 167 \text{ nm}$, $\Gamma = 1.5 \text{ GHz}$

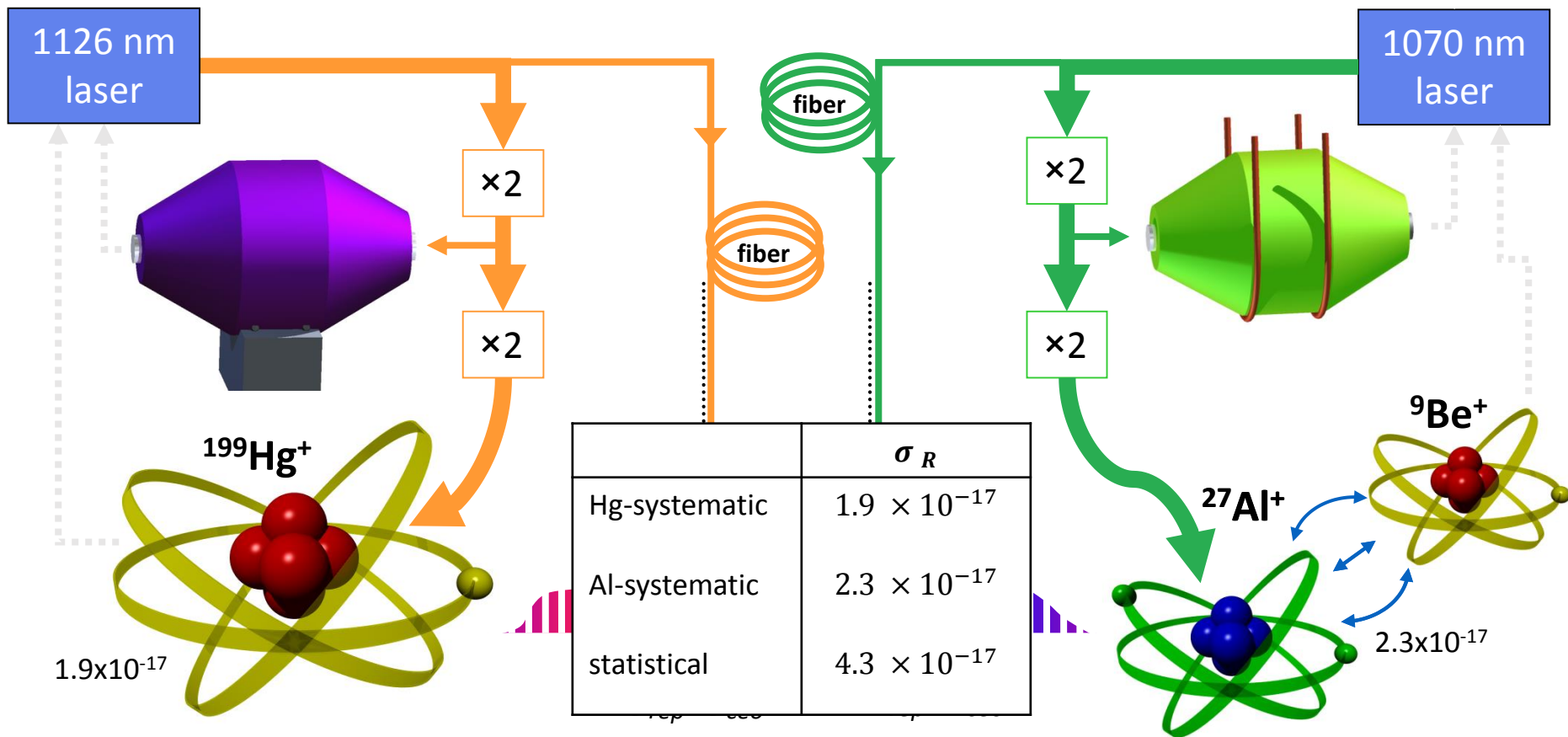


- Insensitive to trapping fields
- Small Stark shift from blackbody radiation
- **Light mass** \rightarrow **Relativistic shifts**
- **Two-ion quantum logic techniques with for cooling, state preparation & clock readout [1]**

[1] D. J. Wineland *et al.*,
Proc. 6th Symp. Freq. Stds. and Metrology, 361 (2001)

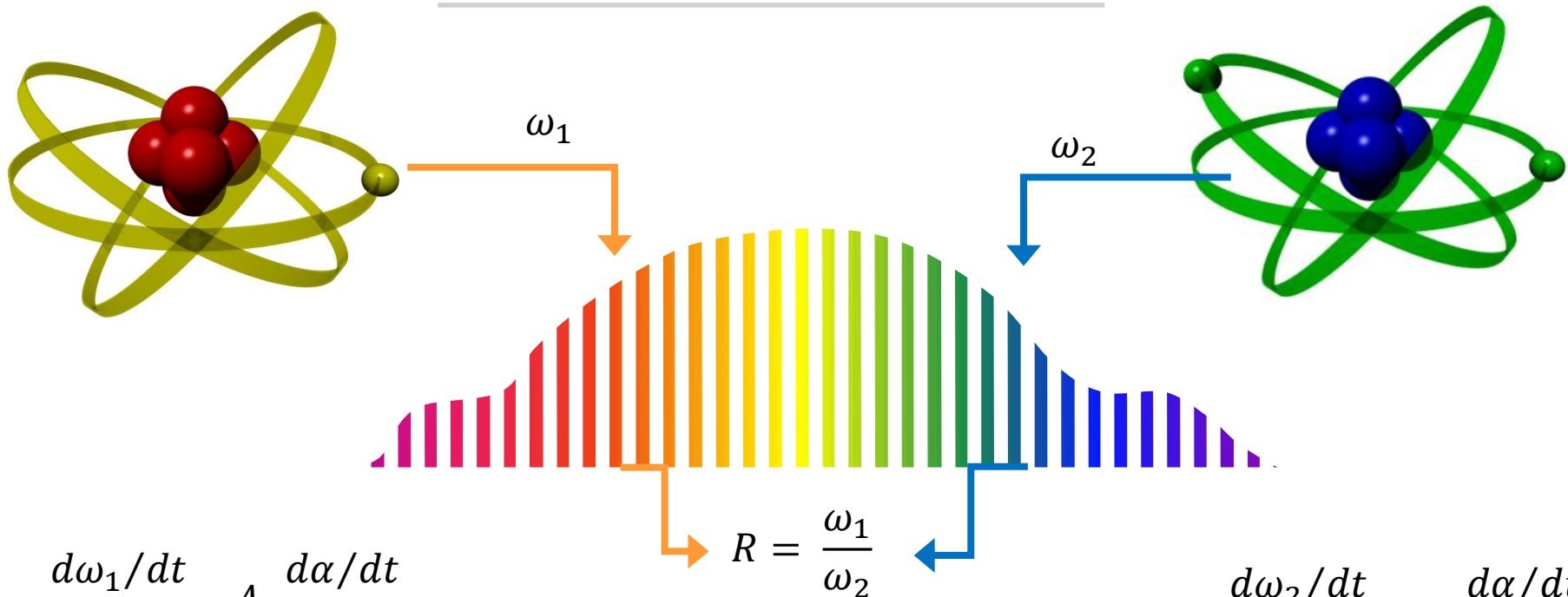
Schmidt *et al.*, Science 309, 749 (2005)

Al⁺/Hg⁺ Comparison



$$R = \frac{\nu_{Al^+}}{\nu_{Hg^+}} = 1.052\,871\,833\,148\,990\,438 \pm 5.5 \times 10^{-17}$$

Measuring $\dot{\alpha}$ with Optical Clocks



$$\frac{d\omega_1/dt}{\omega_1} \sim A_1 \frac{d\alpha/dt}{\alpha}$$

Sensitivity coefficients determined based on atomic structure calculations

$$\frac{d\omega_2/dt}{\omega_2} \sim A_2 \frac{d\alpha/dt}{\alpha}$$

Atom, transition	A
$^{199}\text{Hg}^+, \ ^2S_{1/2} \rightarrow \ ^2D_{5/2}$	- 3.0 [1]
$^{27}\text{Al}^+, \ ^1S_0 \rightarrow \ ^3P_0$	+ 0.0079 [2]
$^{171}\text{Yb}^+, \ ^2S_{1/2} \rightarrow \ ^2D_{3/2}$	+ 0.88 [1]
$^{171}\text{Yb}^+, \ ^2S_{1/2} \rightarrow \ ^2F_{7/2}$	- 5.95 [3]
$^{171}\text{Yb}, \ ^1S_0 \rightarrow \ ^3P_0$	+ 0.31 [4]

Relativistic effects determine sensitivity of clock transitions to $\dot{\alpha}$

[1] V. A. Dzuba and V. V. Flambaum Phys. Rev. A 77, 012515 (2008)

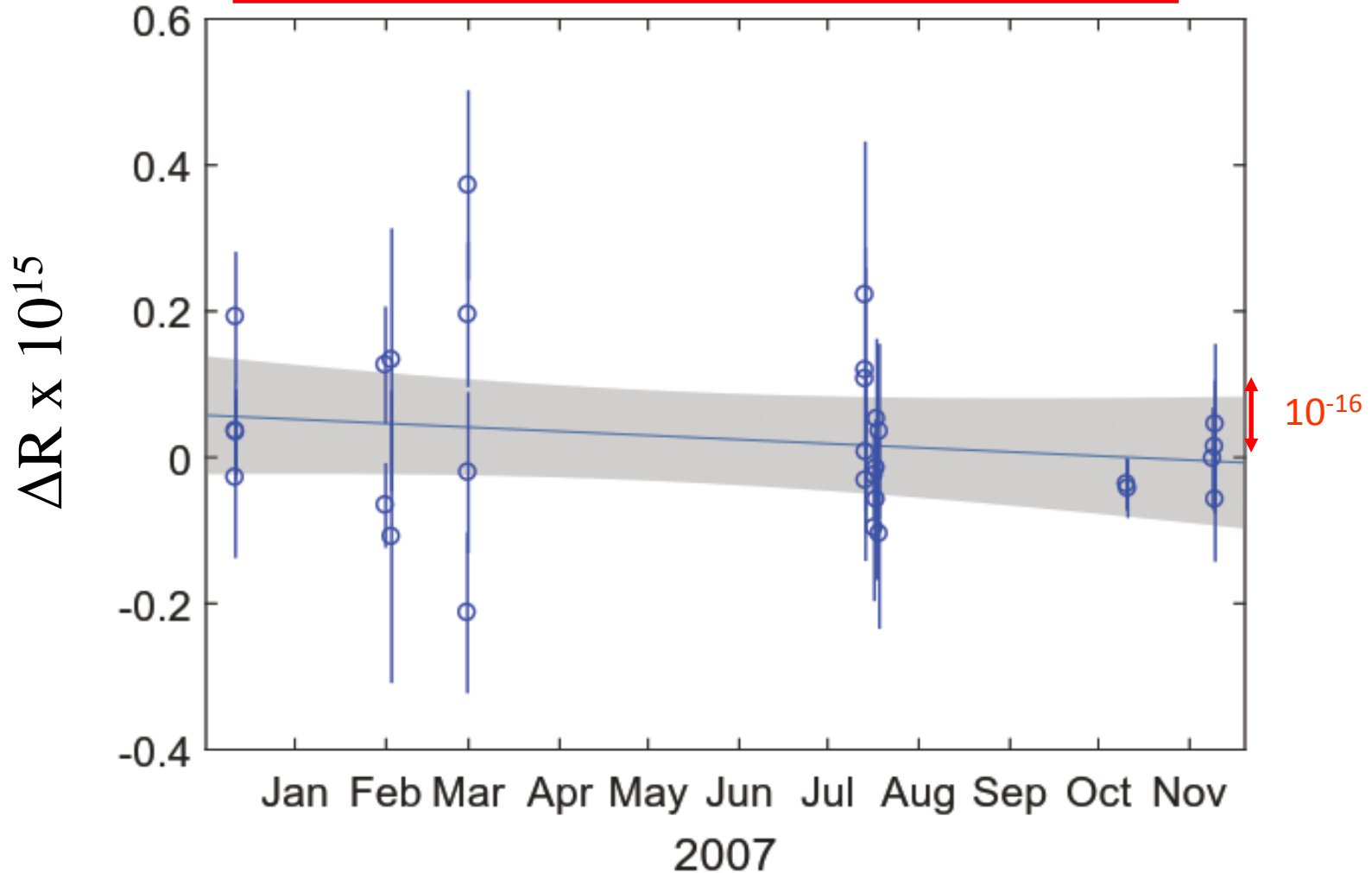
[2] E. J. Angstmann, et al., Phys. Rev. A 70, 014102 (2004)

[3] V. A. Dzuba, V. V. Flambaum, M. V. Marchenko Phys. Rev. A 68, 022506 (2003)

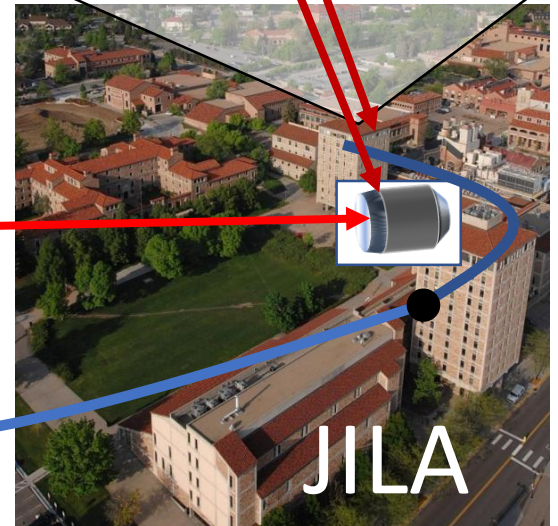
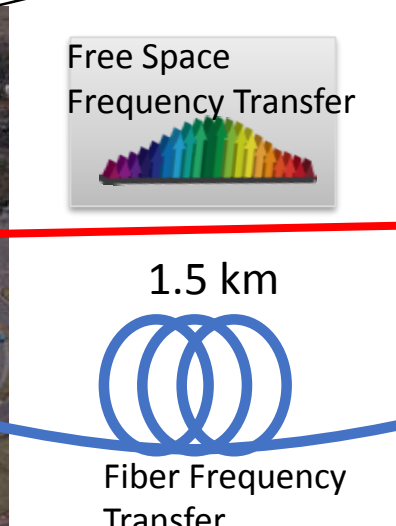
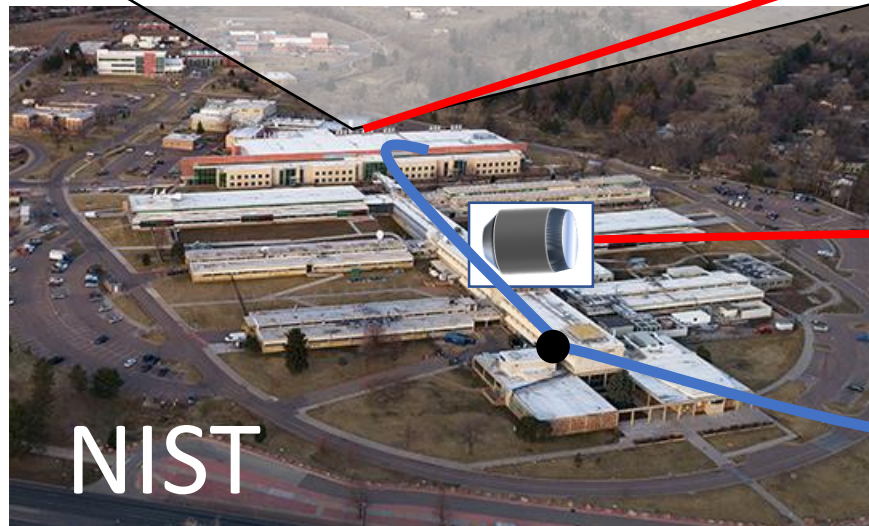
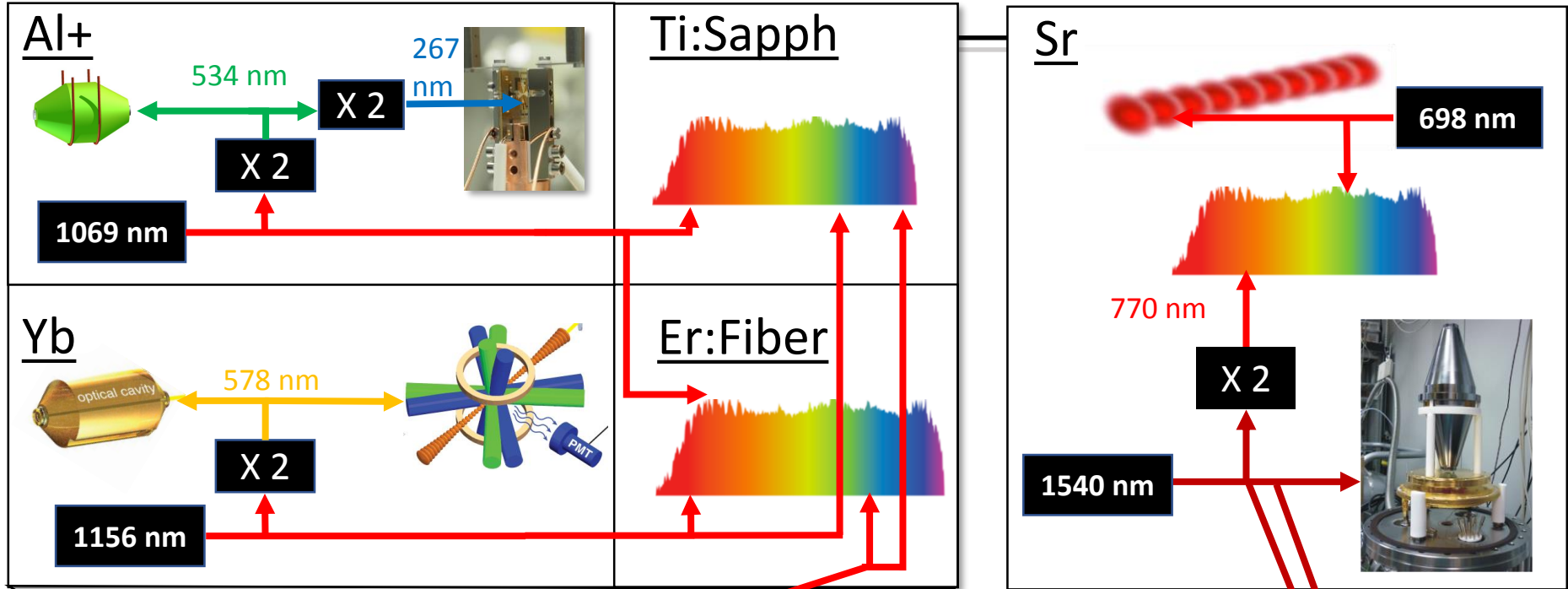
[4] V. A. Dzuba, V. V. Flambaum, Can. J. Phys. 87 15 (2009)

Al⁺/Hg⁺ Comparisons

$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17} / \text{year}$$



Boulder Atomic Clock and Optical Network



The Teams



Al

David Leibrandt
David Hume
Samuel Brewer
Jwo-Sy Chen
Aaron Hankin
Ethan Clements

Yb

Andrew Ludlow
Kyle Beloy
William McGrew
Xiaogang Zhang
Robbie Fasano
Stefan Schafer
Daniele Nicolodi

Sr

Jun Ye
John Robinson
Eric Oelker
Dhruv Kedar
Sarah Bromley
Lindsey Sonderhouse
Colin Kennedy
Tobias Bothwell

Free Space

Nathan Newbury
Laura Sinclair
JD Deschenes
Isaac Khader
Martha Bodine

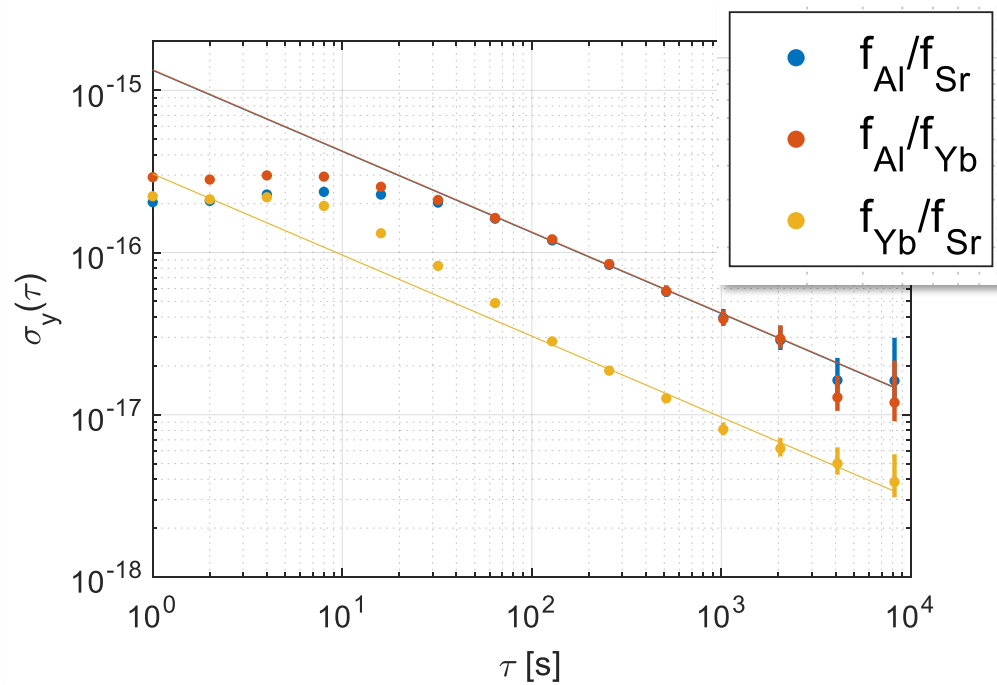
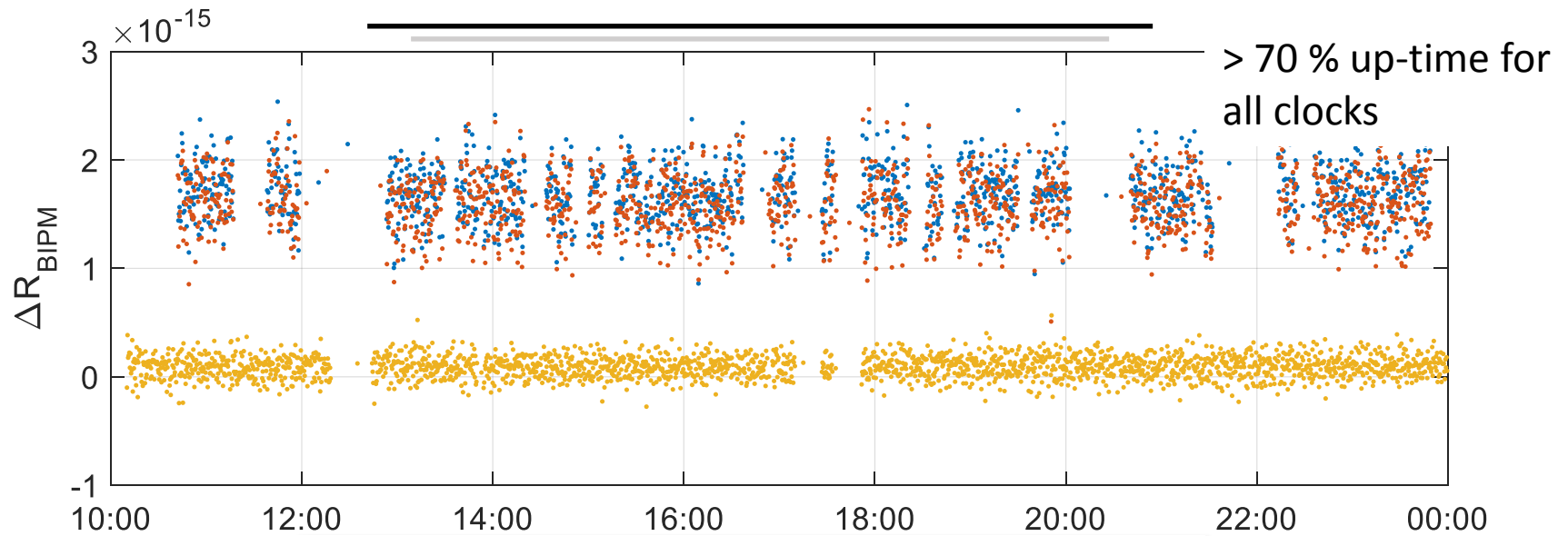
Combs

Scott Diddams
Tara Fortier
Holly Leopardi

Timescale

Jeff Sherman
Jian Yao

Frequency Ratio Measurements

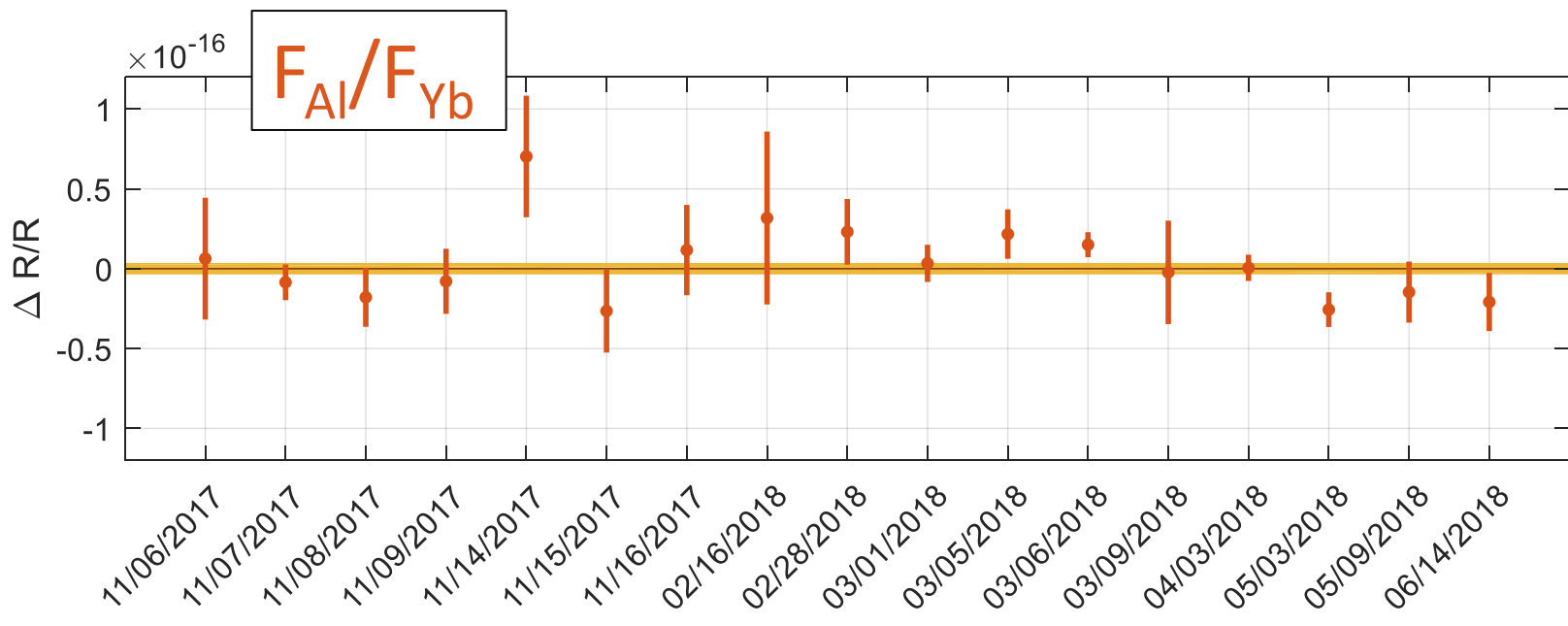
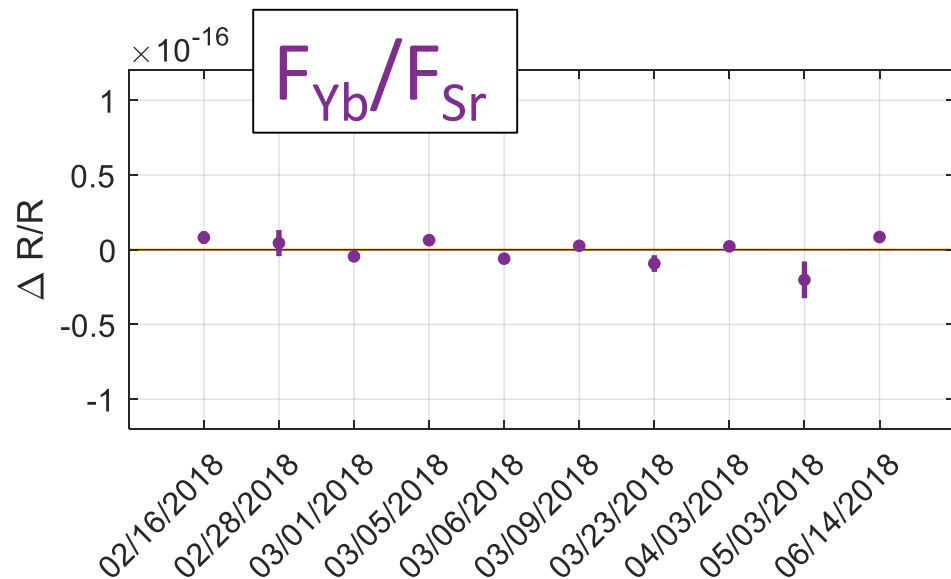
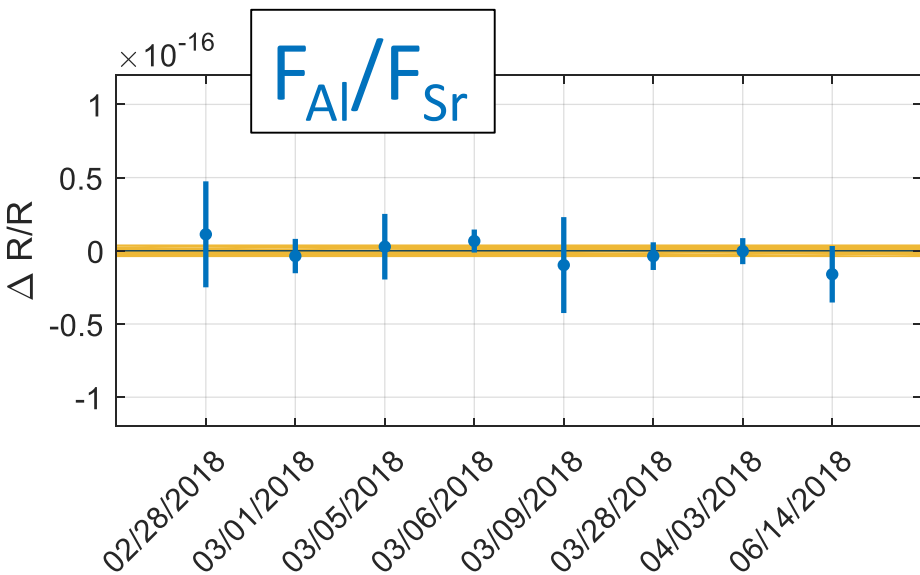


Mar 06, 2018

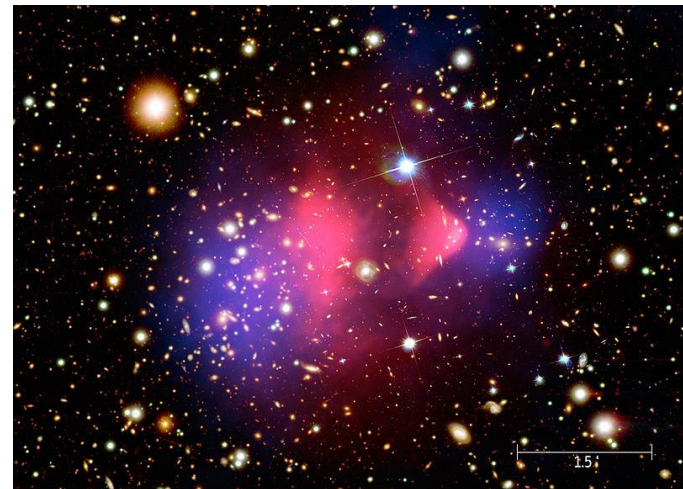
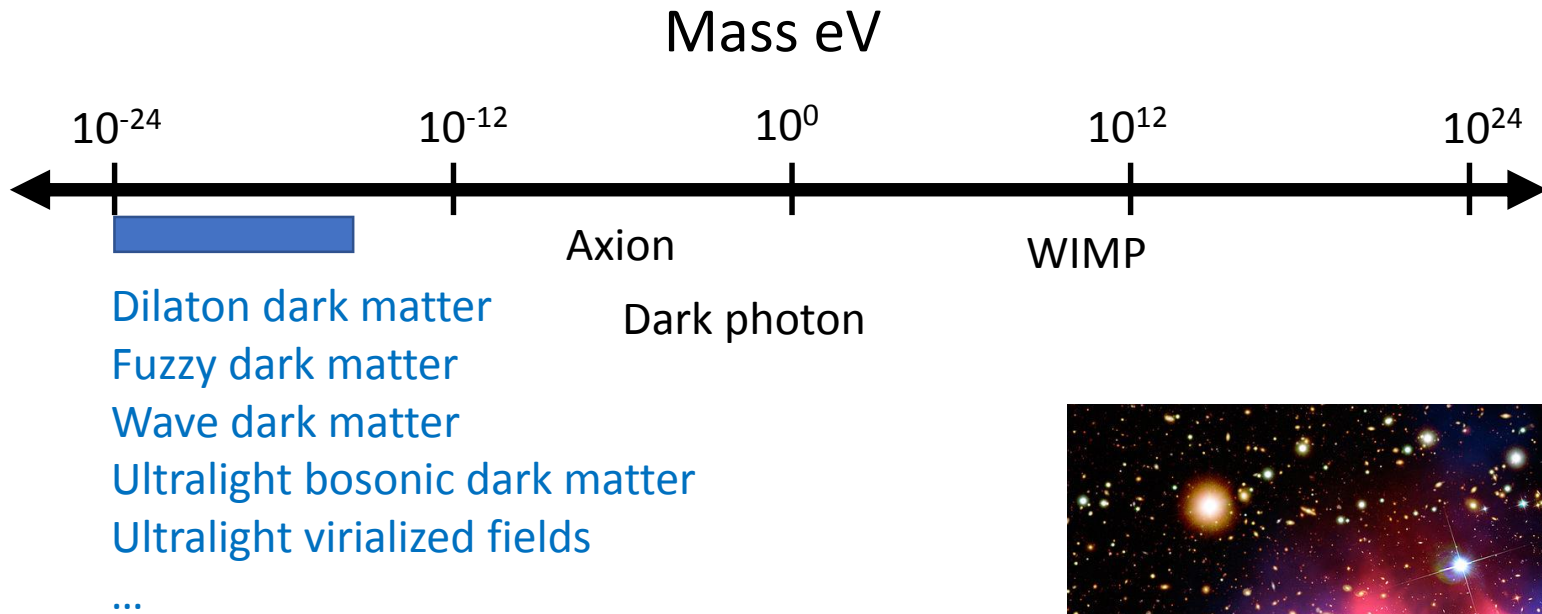
Al clock stability
 1.3×10^{-15} @ 1s

Yb/Sr stability
 3.1×10^{-16} @ 1s

Ratios Day by Day



Dark Matter as an Ultralight Particle

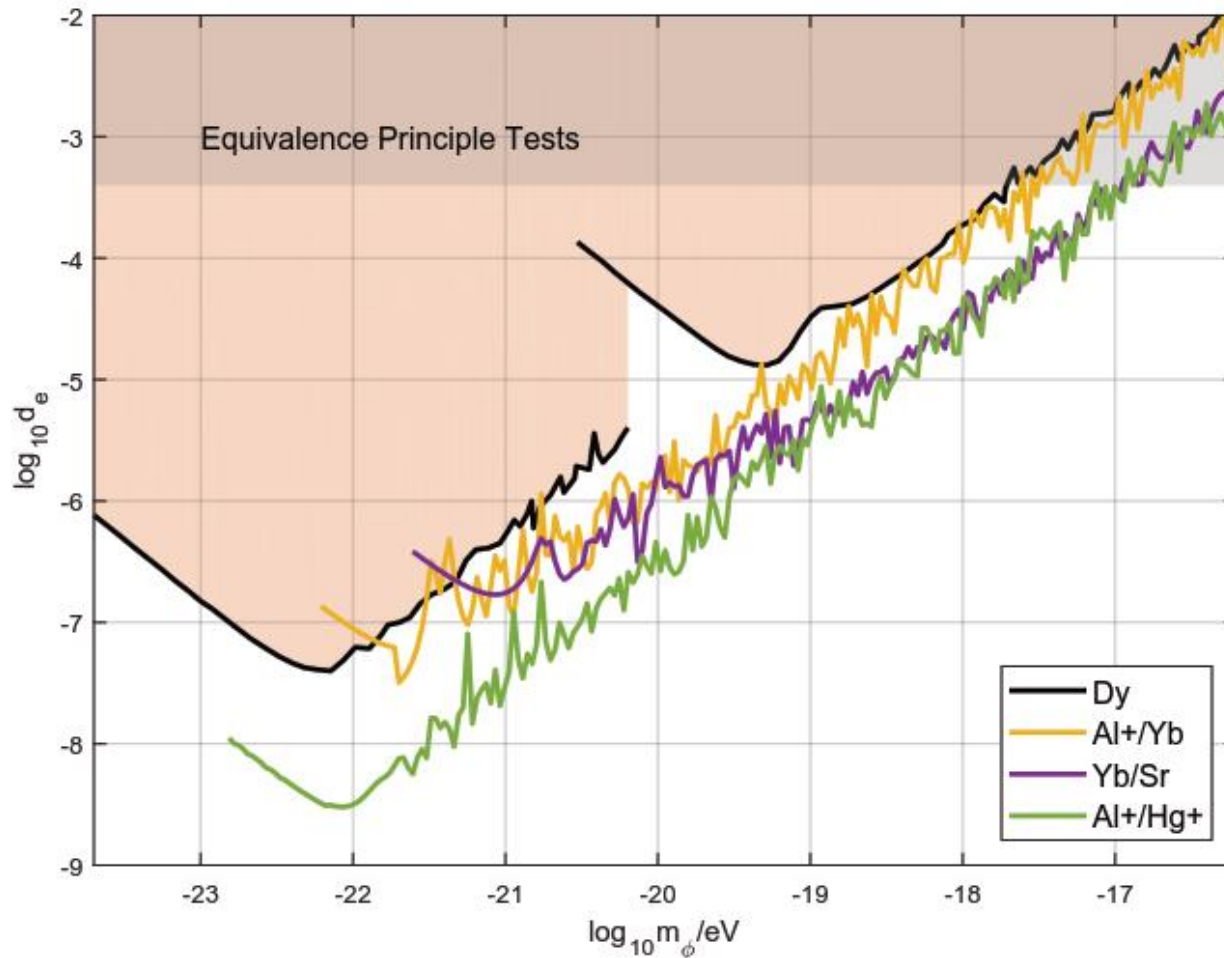


If it is an ultralight particle,
what we DO know:

- de Broglie wavelength shorter than size scale of a galaxy
- Bosonic (as many as 10^{100} particles in a single mode)
- Density: $\sim 0.3 \text{ GeV/cm}^3$
- Acts like a scalar field oscillating at the Compton frequency
- Coherence time $\sim 10^6 \times$ Oscillation period

Ultralight Dark Matter Constraints

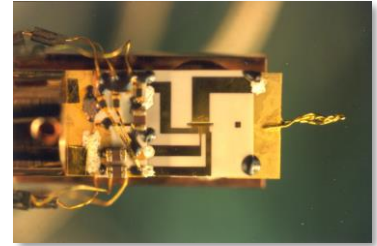
$$\omega_{DM} = \frac{m_\phi c^2}{\hbar}$$



See also: **Tilburg et al., PRL 115, 011802 (2015)** and **Hees et al., PRL 117, 061301 (2016)**

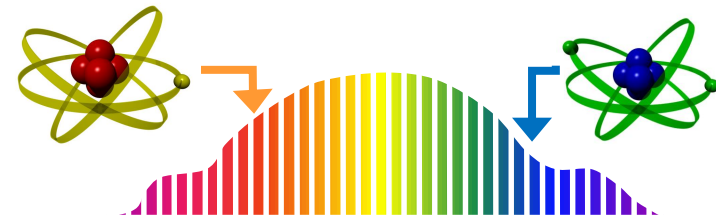
Outline

1. Ions, Ion traps, Tests of fundamental physics



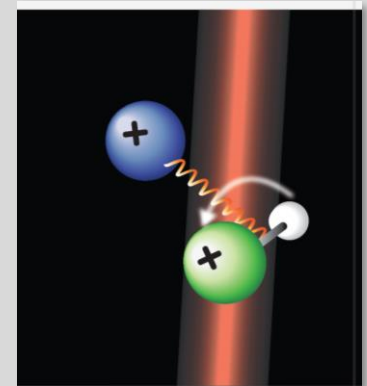
2. Single-ion optical clocks

- Al^+ vs Hg^+ at NIST
- Al^+ vs optical lattice clocks

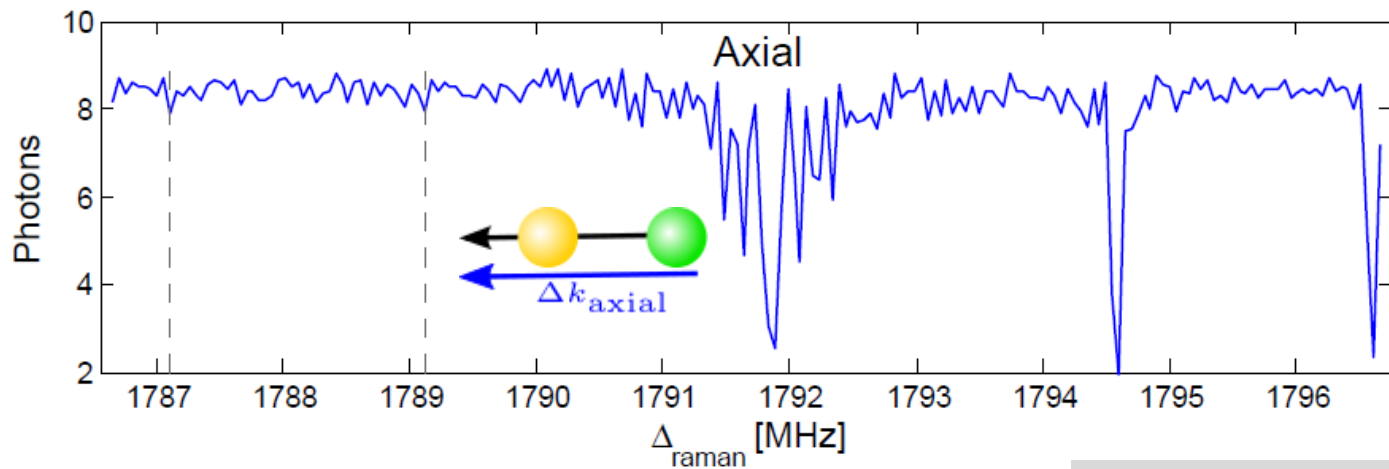
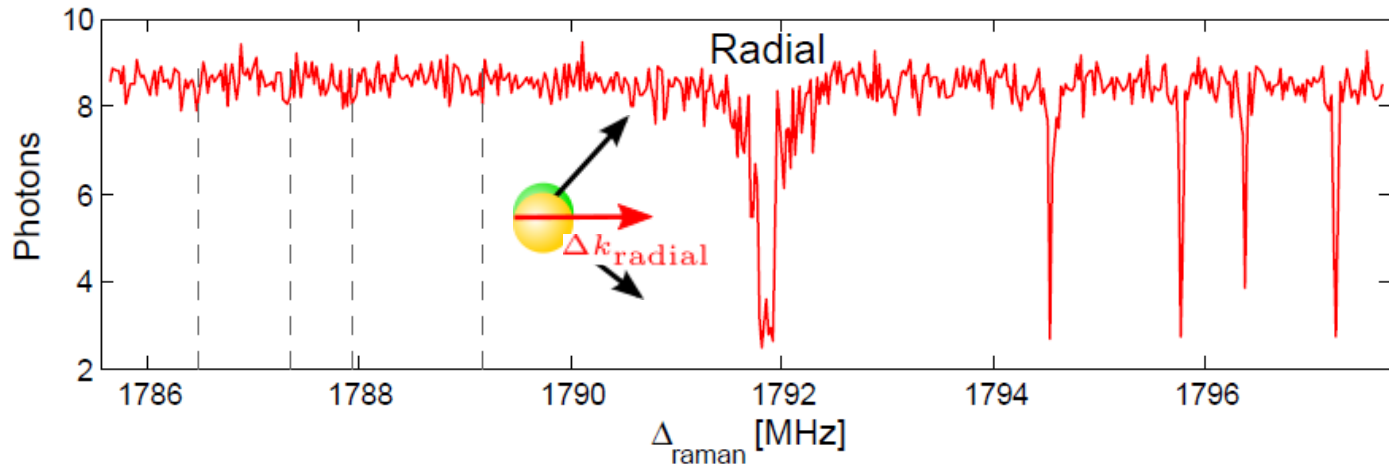


3. Useful quantum techniques

- Quantum logic spectroscopy
- Correlation spectroscopy



Quantum Logic Spectroscopy

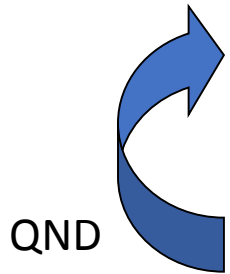


Typical mode frequencies: 2.7 – 7.2 MHz

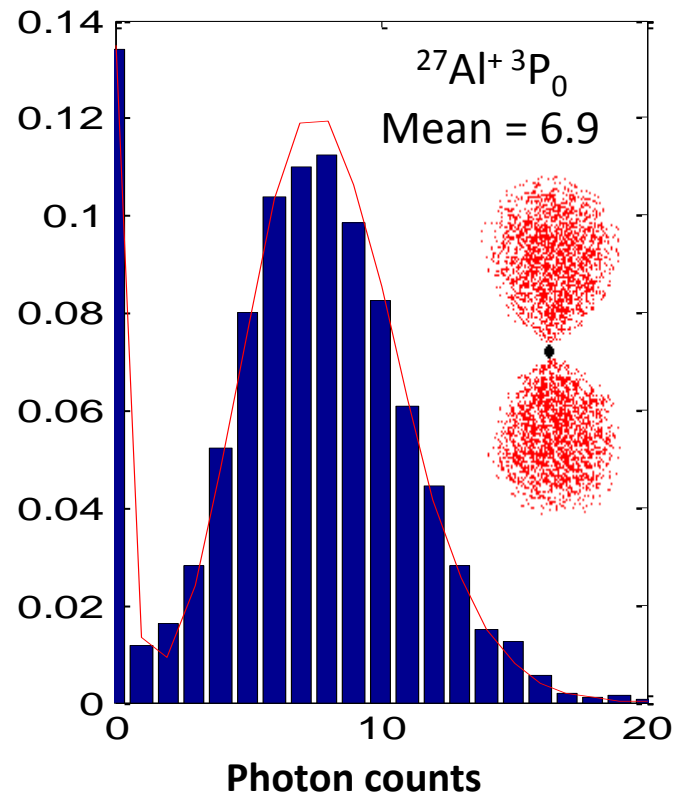
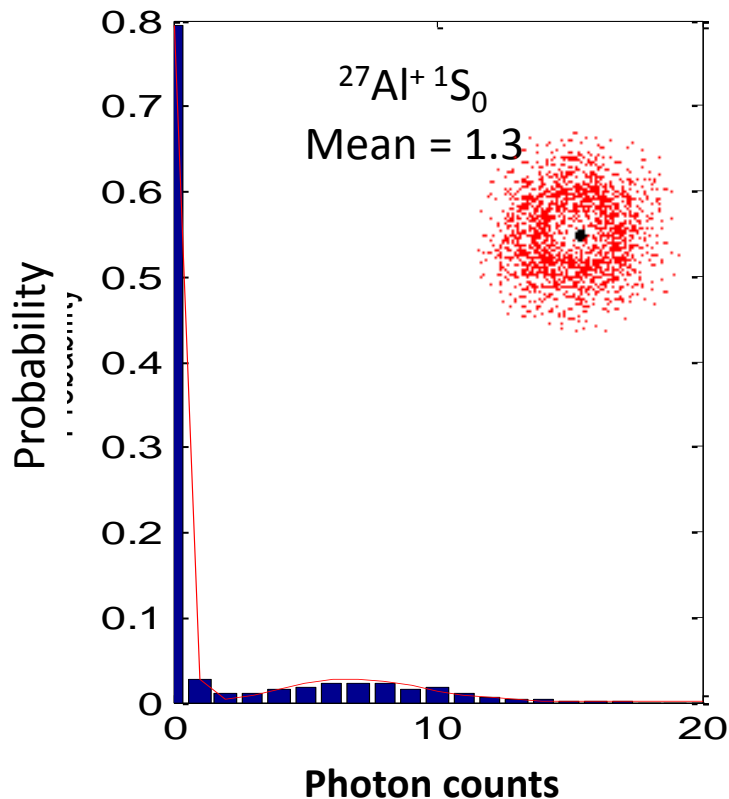
Diedrich et al., PRL 62, 4, 403 (1989)

Monroe et al., PRL 75, 22, 4011 (1995)

Al⁺ quantum-assisted readout



1. Cool to motional ground-state with logic ion
2. Depending on Al⁺ clock state, add one vibrational quantum via Al⁺
3. Detect vibrational quantum with logic ion



D. J. Wineland, *et al.*
*Proc. 6th Symp. Freq. Stds.
and Metr.* (2001)

P.O. Schmidt, *et al.*
Science **309**, 749 (2005)

T. Rosenband, *et al.*
PRL **98**, 220801 (2007)

D. B. Hume, *et al.*
PRL **99**, 120502 (2007)

Generalizing to New Atomic Systems

- Applications

- Variations of fundamental constants (α , μ)
- Parity Nonconservation
- Electron EDM
- Comparing with astrophysical data
- The ideal clock?
- The ideal qubit?

hydrogen 1 H 1.0079	helium 2 He 4.0026																																																																																		
lithium 3 Li 6.941	beryllium 4 Be 9.0122																																																																																		
sodium 11 Na 22.990	magnesium 12 Mg 24.305																																																																																		
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 65.38	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	cesium 55 Cs 132.91	barium 56 Ba 137.33	lanthanum 57 La 138.905	cerium 58 Ce 140.12	praseodymium 59 Pr 140.908	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 173.05	lutetium 71 Lu 174.967	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 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]	francium 87 Fr [223]	radium 88 Ra [226]	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

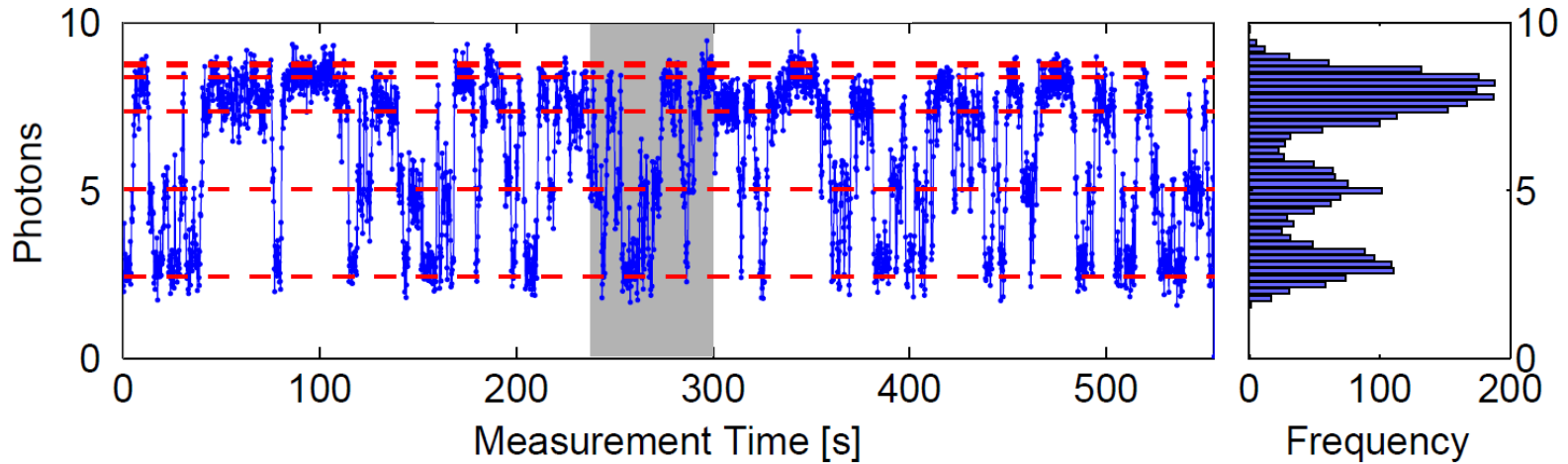
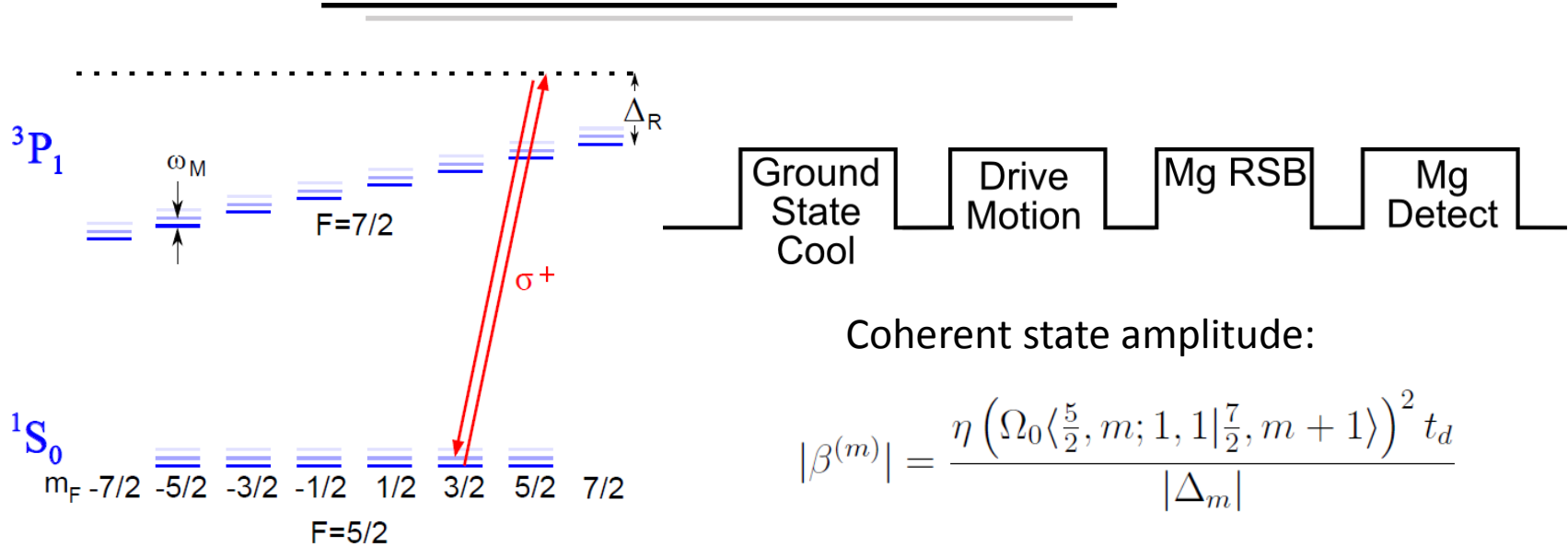
* Lanthanide series

** Actinide series

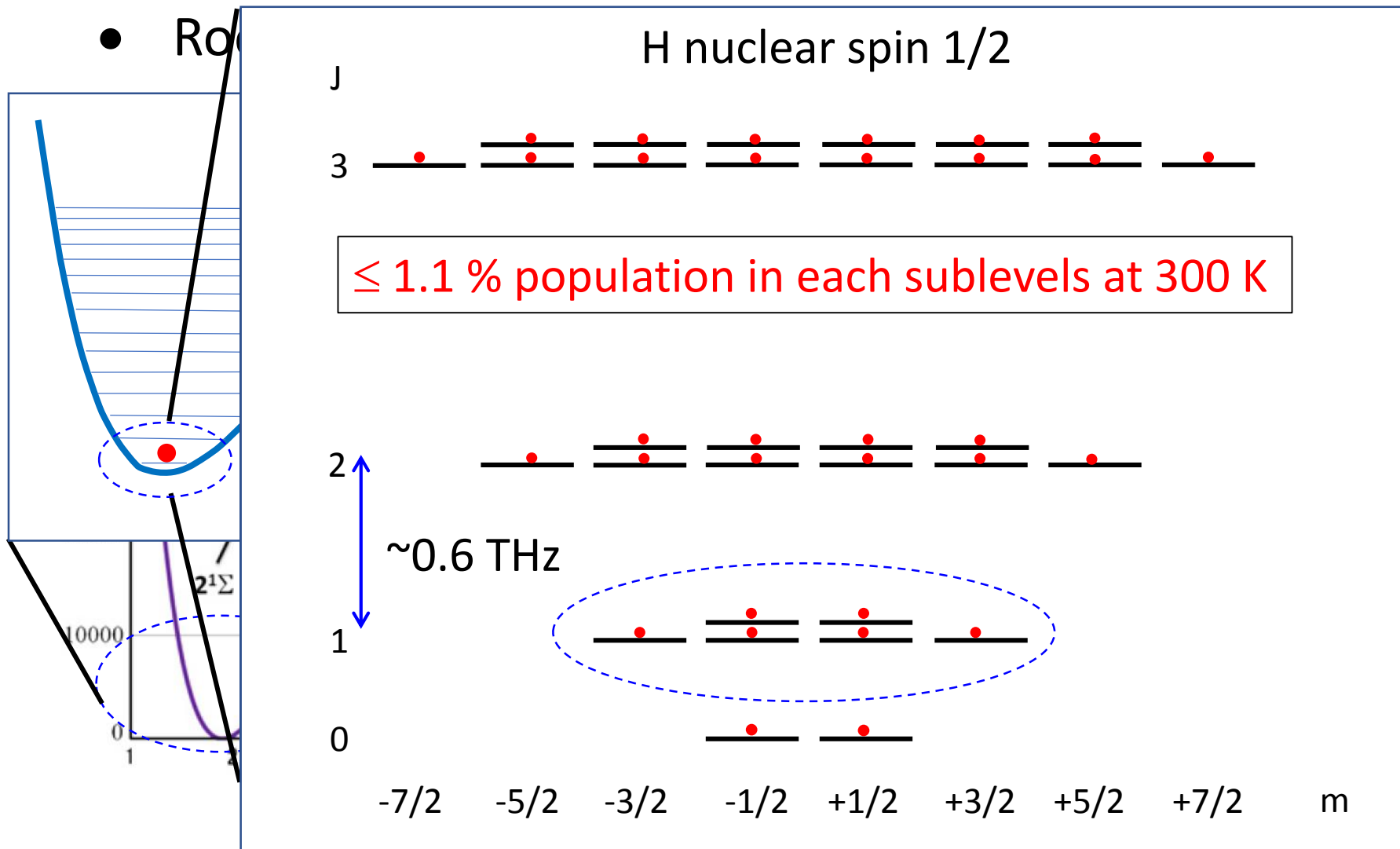
State detection that does not depend on details of the atomic structure

- Off-resonant interactions for projective detection
- Broadband source for spectroscopy

“Quantum Jumps” between Zeeman States



$^{40}\text{CaH}^+$: Test bed for Molecular Ion Spectroscopy



Coherent Spectra from a Single Molecule

Optical Pumping

Projective
State Preparation

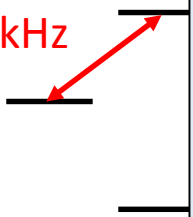
Experiment Pulse

Detection

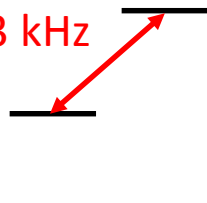
Summary: Quantum logic spectroscopy

- “Logic ion” used for:
 - Cooling
 - State initialization
 - Detection
- Flexible
- Sensitive
- Suitable for many precision experiments with exotic species

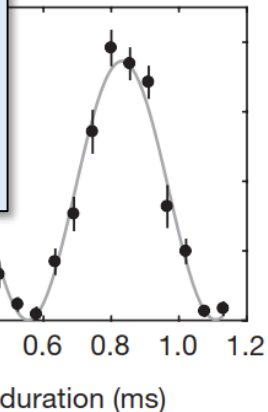
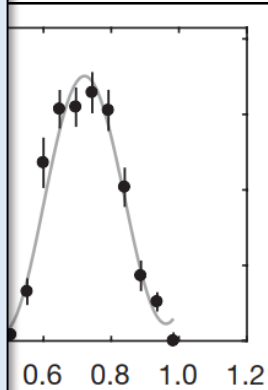
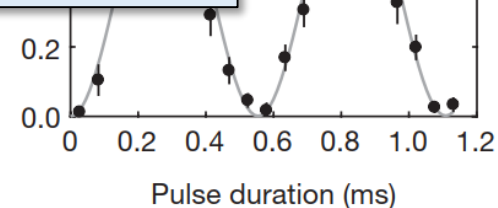
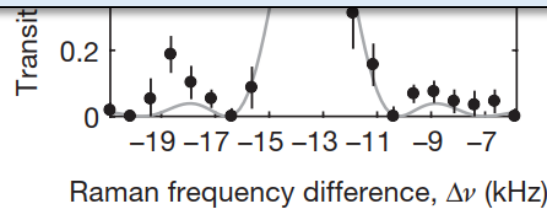
11 kHz



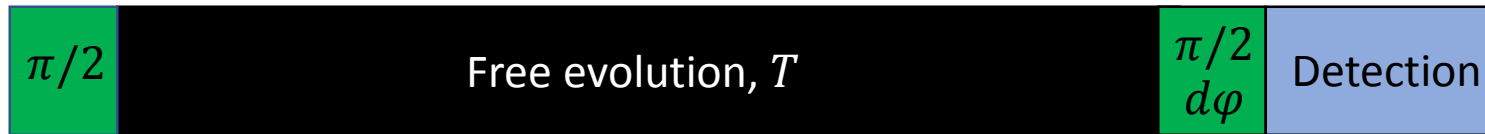
13 kHz



$J = 2$



Correlation Spectroscopy: Projection Noise Limit



$$\sigma_{y,proj}(\tau) = \frac{1}{\omega \sqrt{NT\tau}}$$

Oscillation frequency ω
Atom number N
Free-evolution period T
Total measurement duration τ

- Free evolution period (i.e. Ramsey probe time) limited by laser coherence
- **Idea: probe two ions simultaneously with same laser**
 - Laser noise is common mode
 - Simultaneous measurements insensitivity to noise during dead-time

2 atom Ramsey experiment

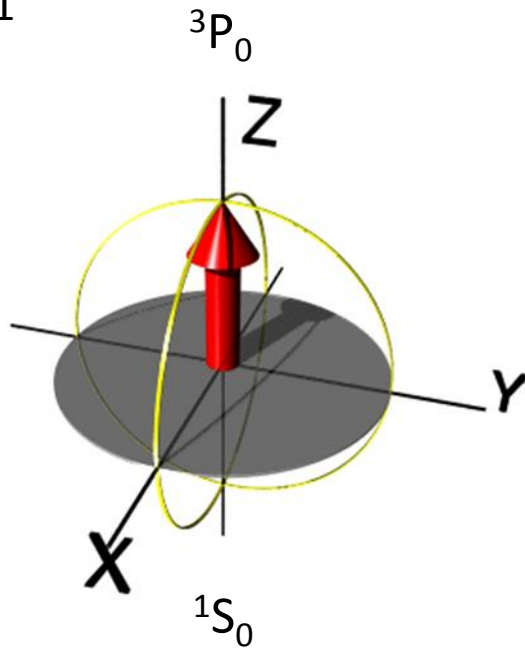
$\pi/2$

Free evolution, T

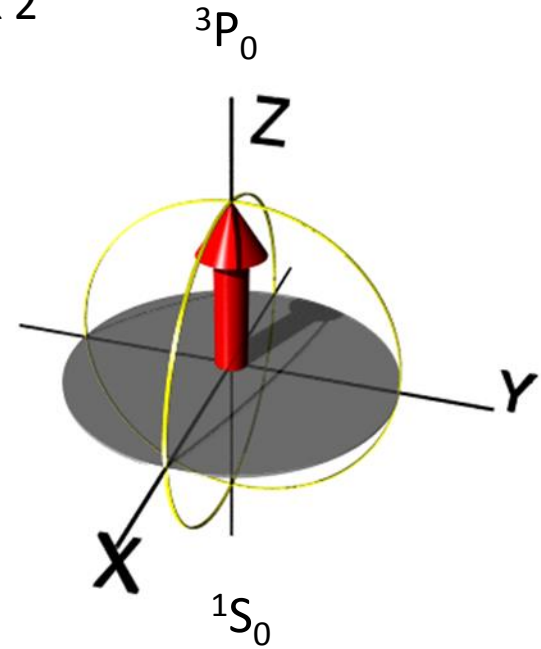
$\pi/2$
 $d\phi$

Detection

Clock 1



Clock 2



2 atom Ramsey experiment

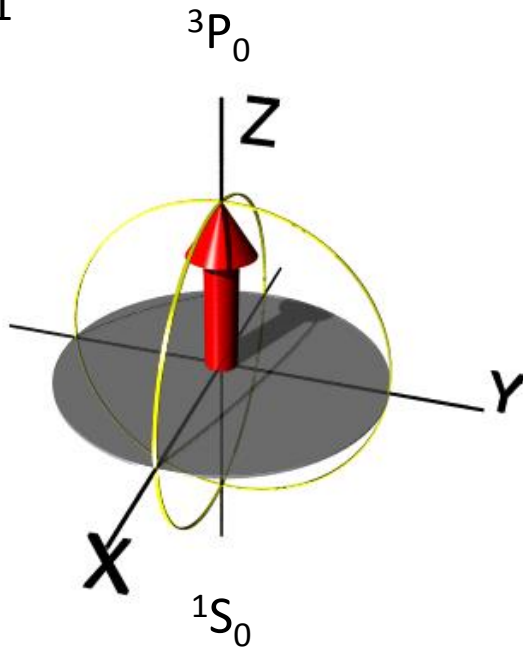
$\pi/2$

Free evolution, T

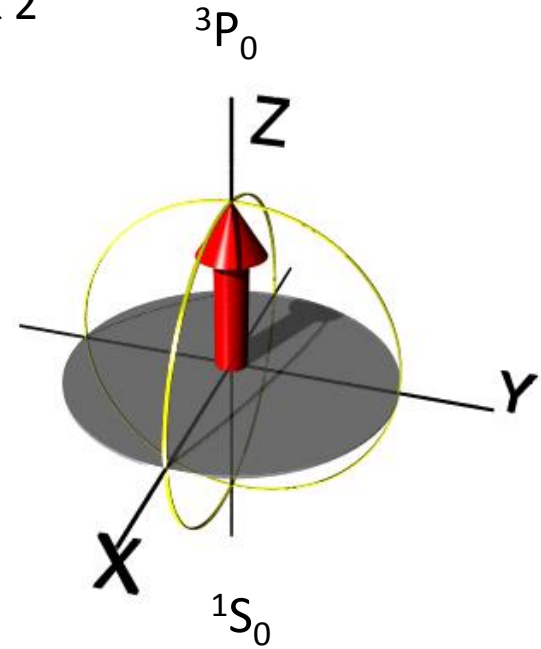
$\pi/2$
 $d\phi$

Detection

Clock 1



Clock 2



2 atom Ramsey experiment

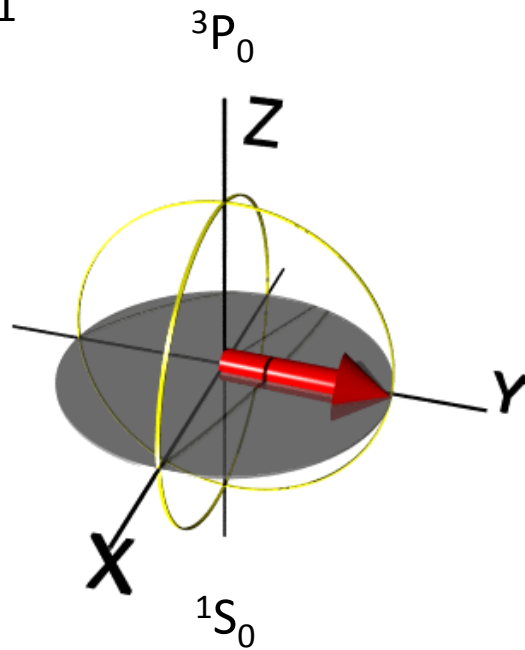
$\pi/2$

Free evolution, T

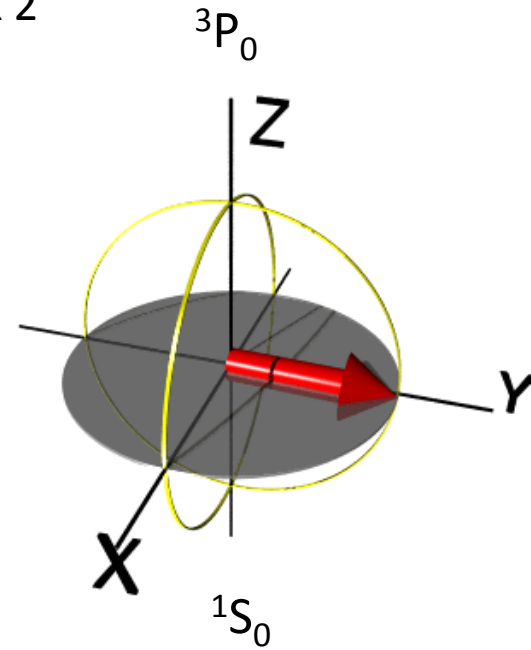
$\pi/2$
 $d\phi$

Detection

Clock 1



Clock 2



2 atom Ramsey experiment

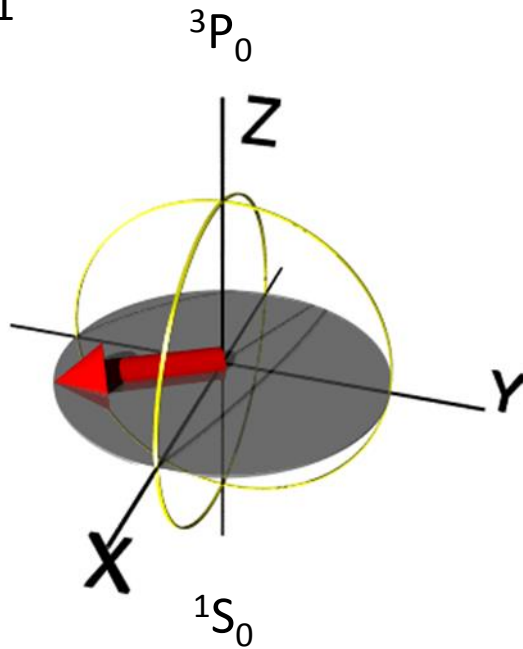
$\pi/2$

Free evolution, T

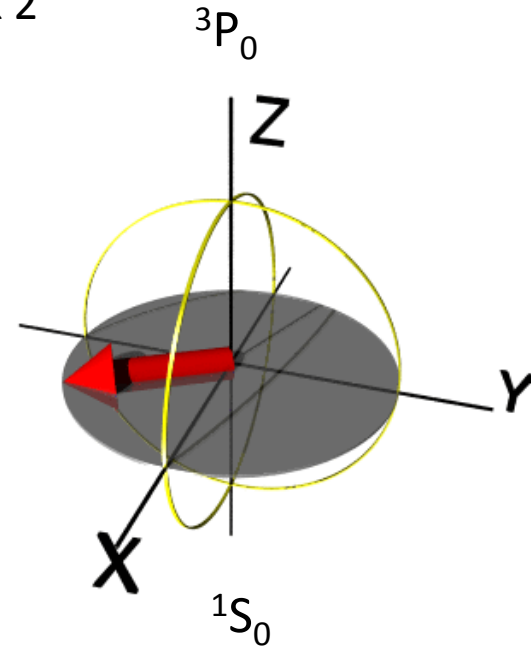
$\pi/2$
 $d\varphi$

Detection

Clock 1



Clock 2



2 atom Ramsey experiment

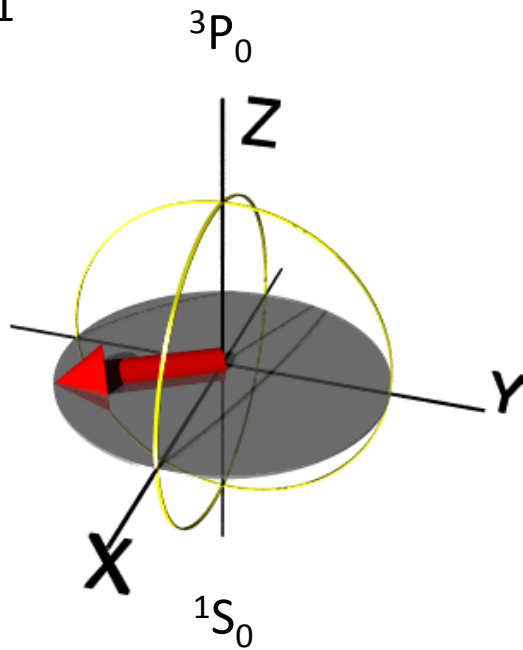
$\pi/2$

Free evolution, T

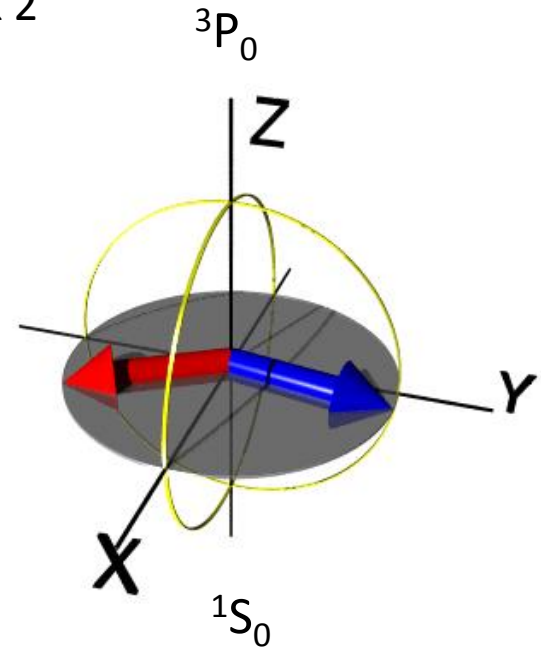
$\pi/2$
 $d\varphi$

Detection

Clock 1



Clock 2



2 atom Ramsey experiment

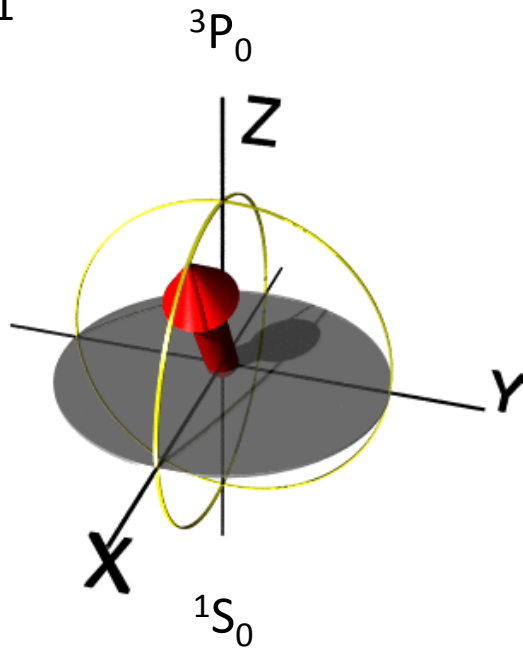
$\pi/2$

Free evolution, T

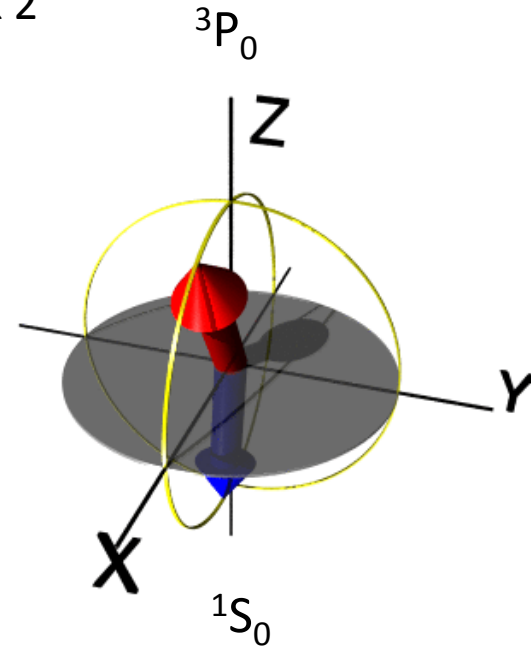
$\pi/2$
 $d\varphi$

Detection

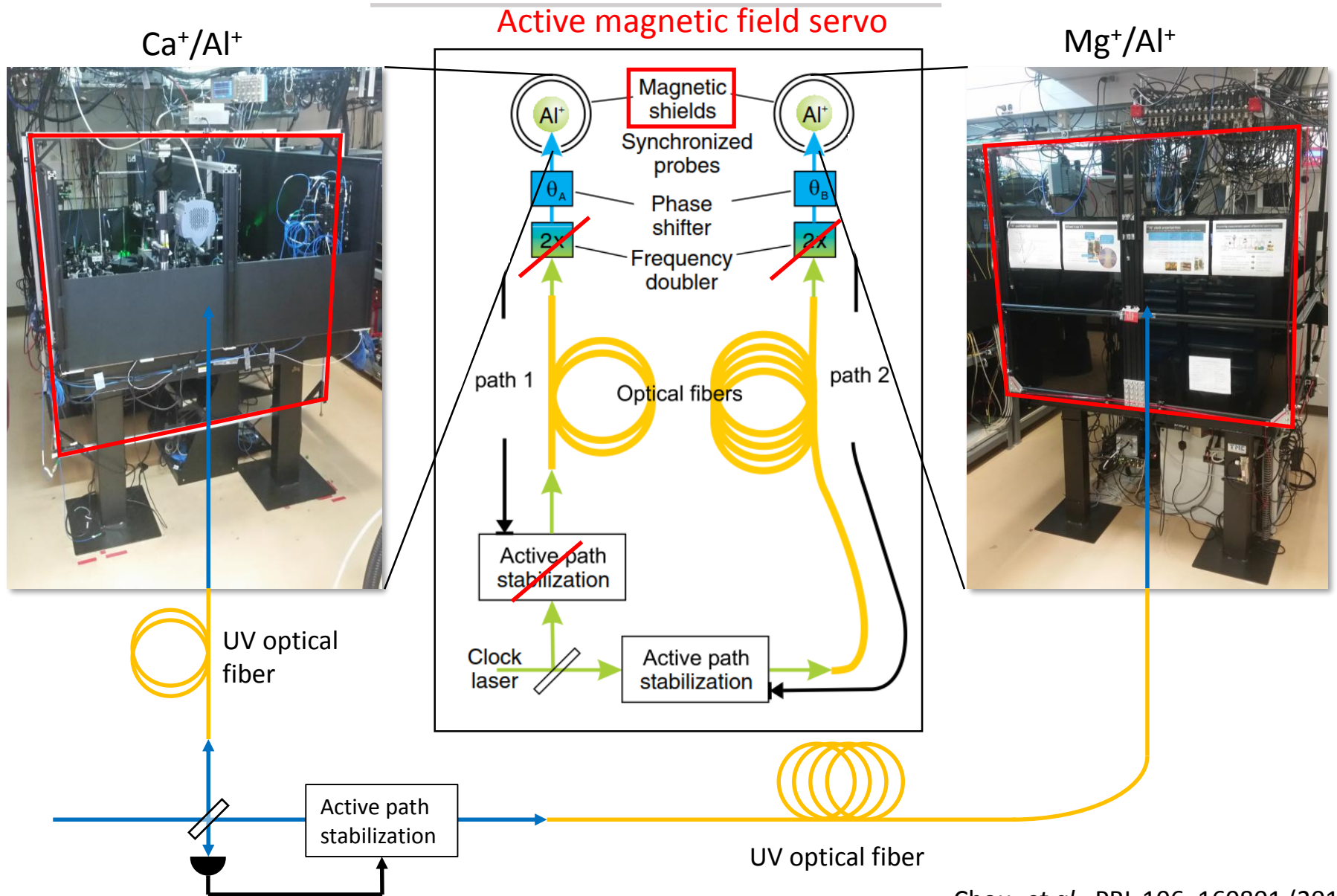
Clock 1



Clock 2

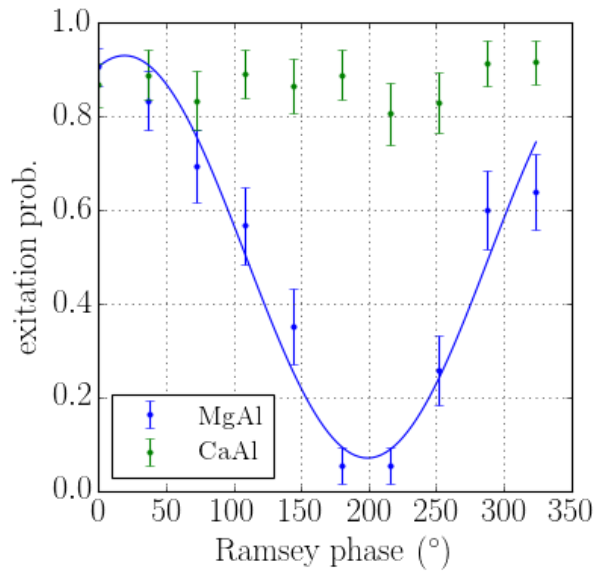


Correlation Spectroscopy between 2 Clocks



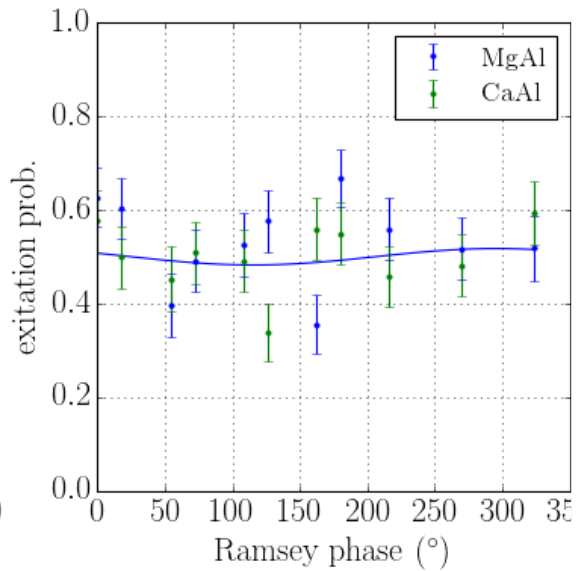
UV Optical Coherence at 1 s

T = 0.05 s



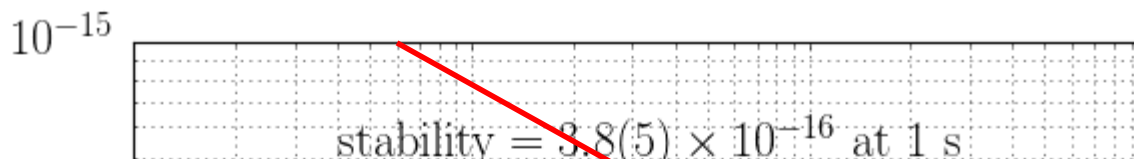
Within laser
coherence time

T = 1 s



Laser – Atom
coherence lost

Correlation Spectroscopy Stability



Summary: Correlation spectroscopy

- One atoms acts as a “local oscillator” probing another
- Can be done with “off-the-shelf” and/or transportable laser systems
- Suitable for many clock experiments
 - Geodesy
 - Frequency ratio measurements
 - Frequency vs. ...

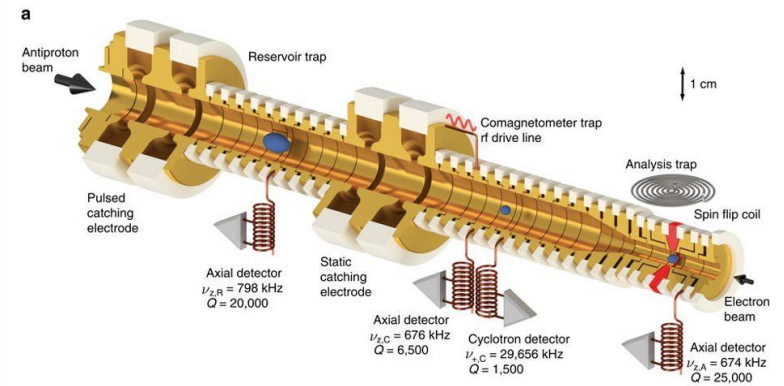
-Al
ent

ion in
time!

10⁻¹⁵
10⁰ 10¹ 10² 10³
time (s)

Trends in Trapped Ion Experiments

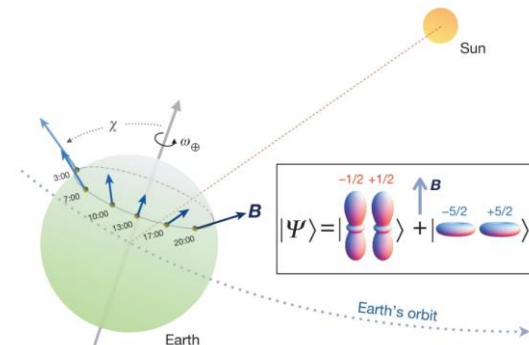
- Expansion of quantum control and precision measurement to new previously inaccessible systems (low, medium and high energies)
 - new atomic systems, molecules, antimatter, highly-charged ions
- Precision measurements adopting techniques from quantum information processing
 - Quantum-enhanced metrology, dynamical decoupling, quantum logic spectroscopy
- Identifying new targets for precision measurements in ion traps for fundamental physics
 - Lorentz invariance, dark matter, King-plot nonlinearities, . . .



H. Nagahama et al., *Nat. Comm.* **8**, 14084 (2017)



Schmoeger et al. *Science* **347**, 1243 (2015)

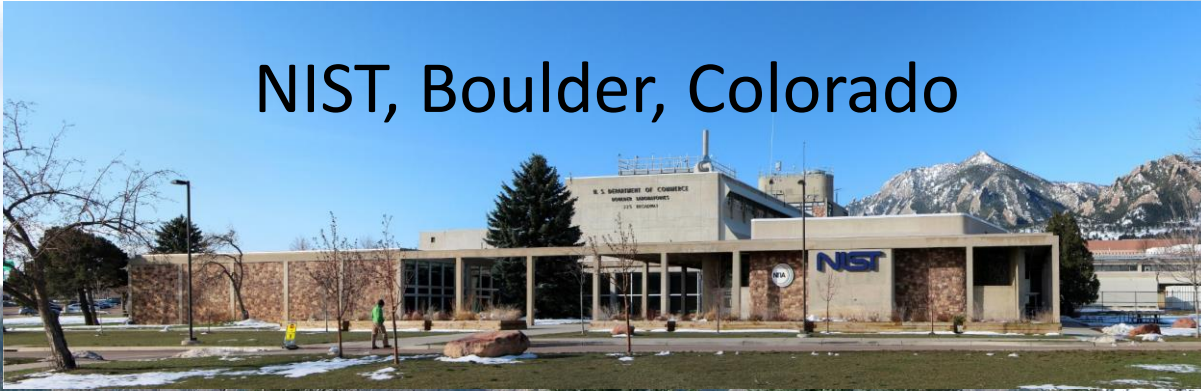


T Pruttivarasin et al. *Nature* **517**, 592-595 (2015)

Thanks!



NIST, Boulder, Colorado



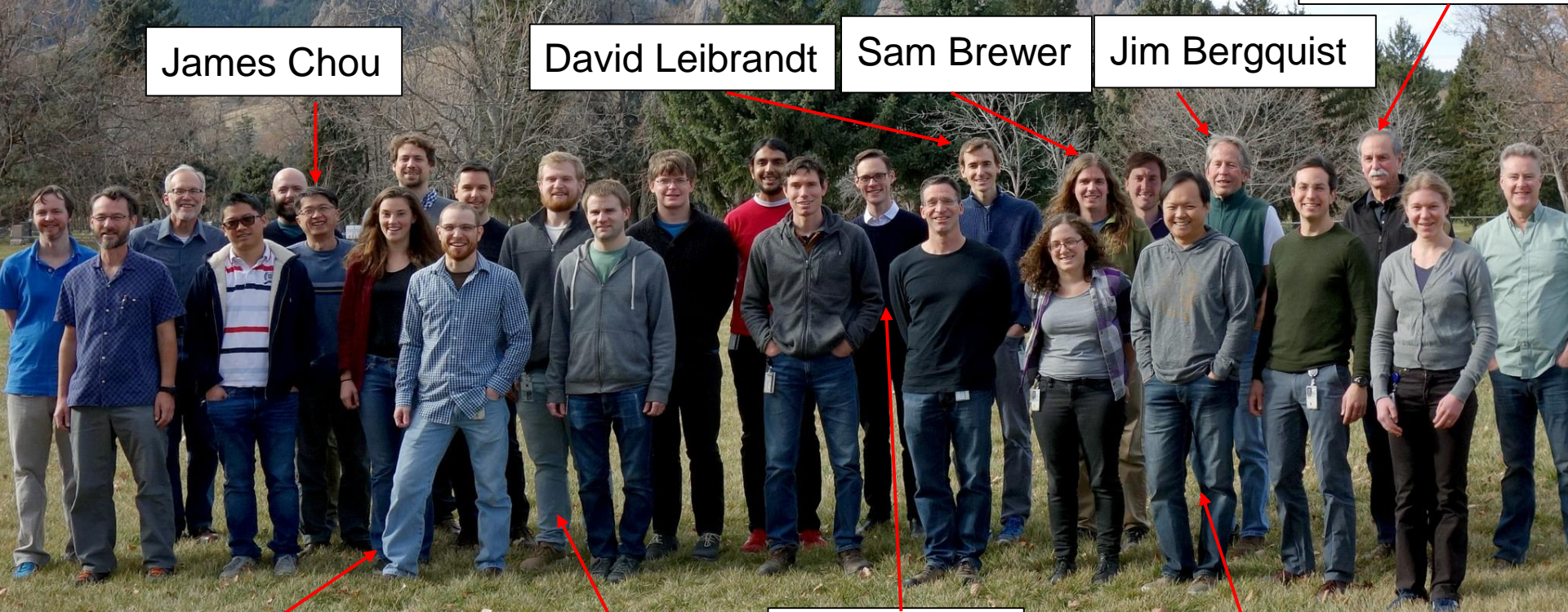
David Wineland

James Chou

David Leibrandt

Sam Brewer

Jim Bergquist



Aaron Hankin

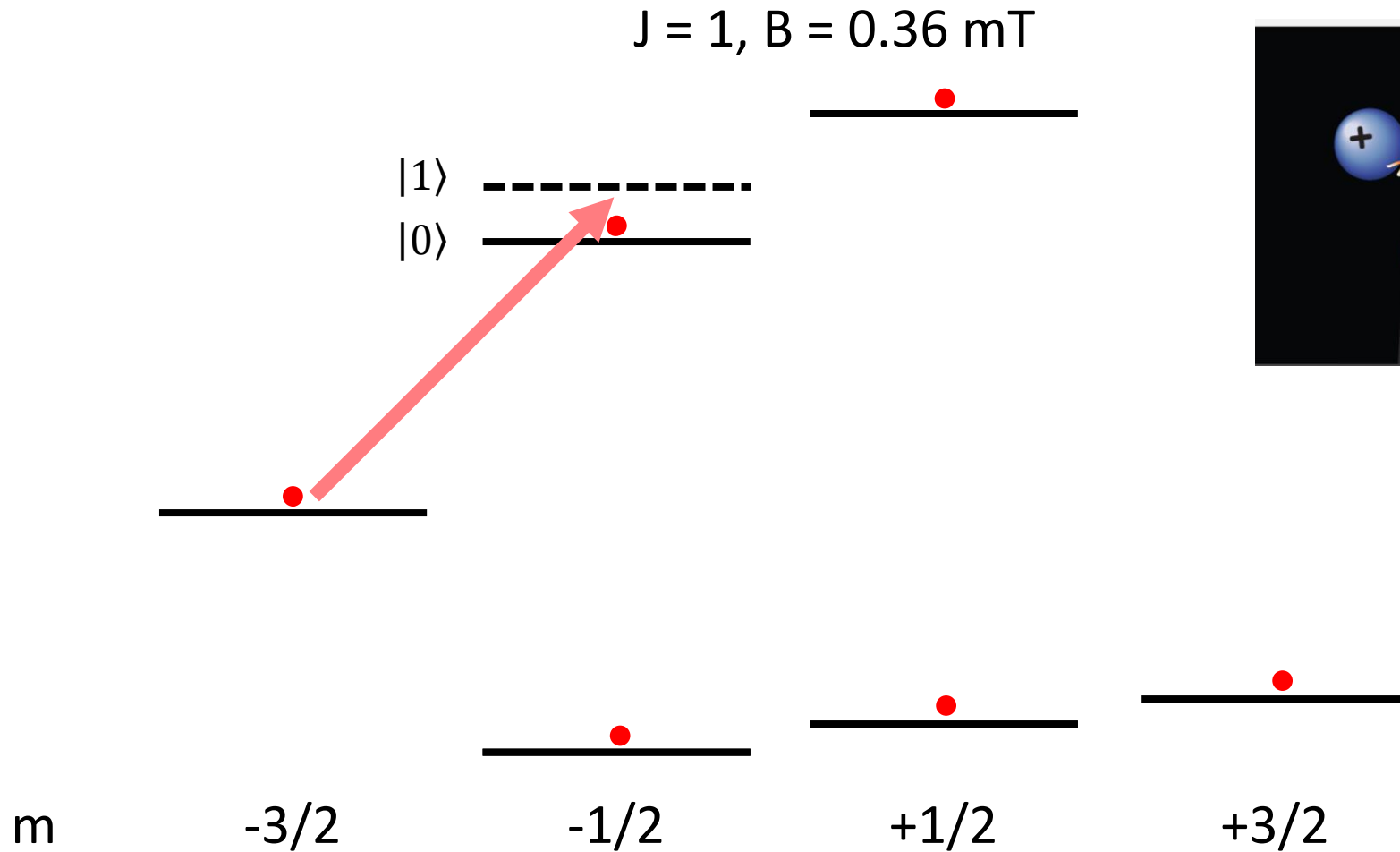
Ethan Clements

Tom Hardy

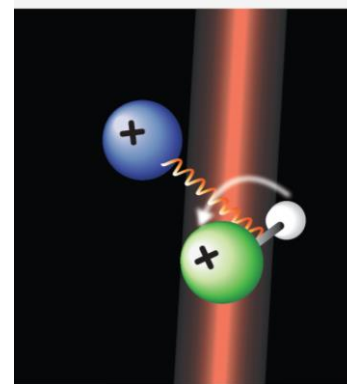
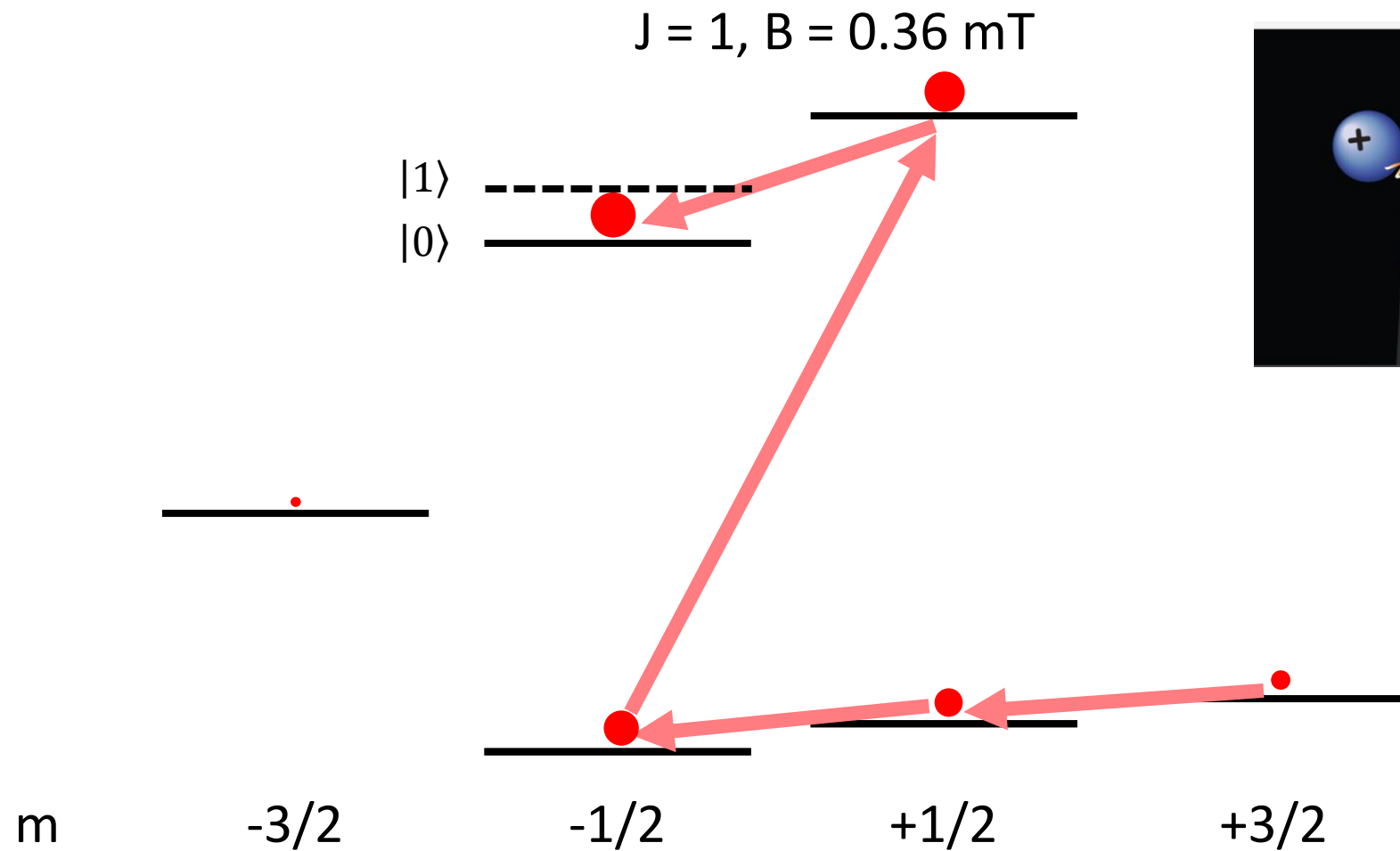
Jwo-Sy Chen

Backup Slides

CaH⁺ Optical Pumping

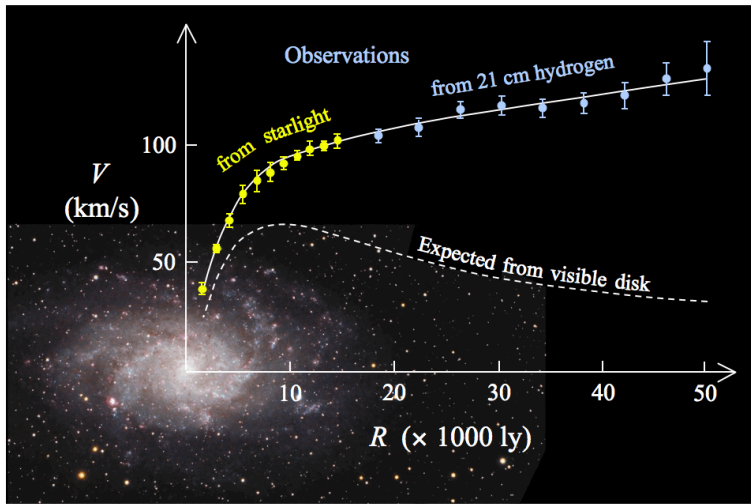


CaH+ Optical Pumping

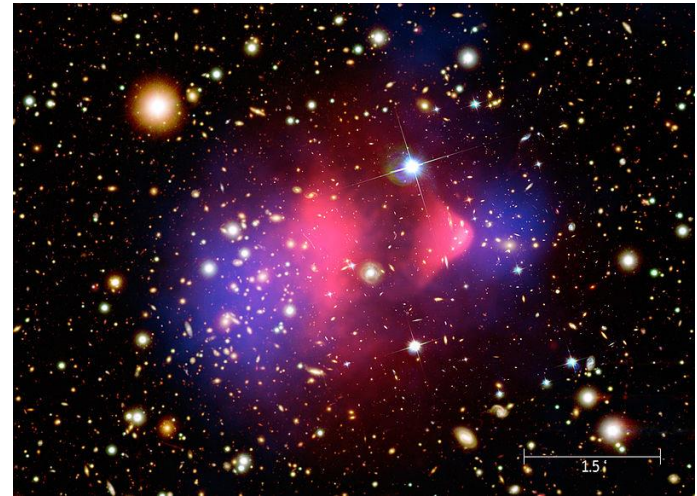


Dark Matter

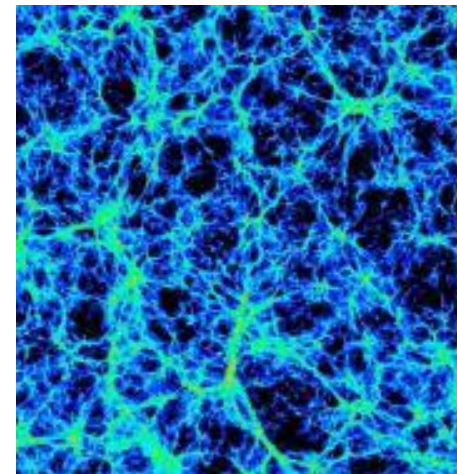
Galactic Rotation Curves



Gravitational Lensing

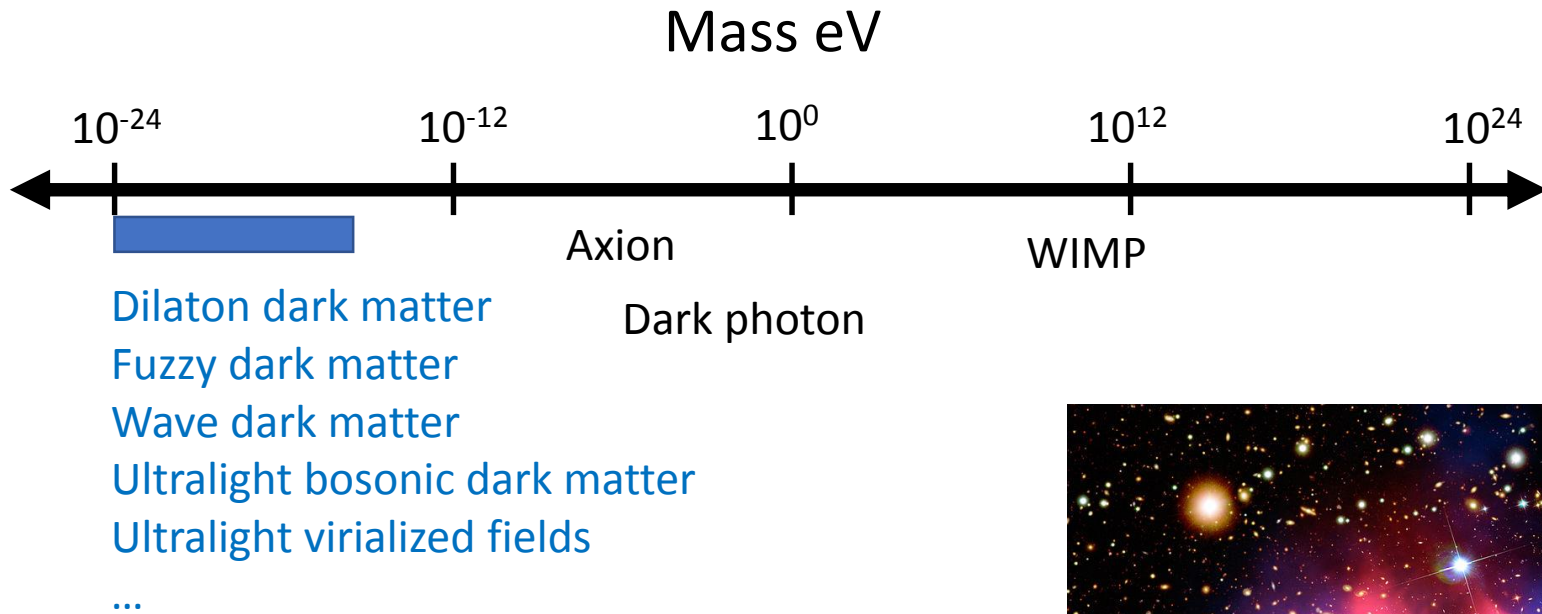


Large-Scale Structure Formation



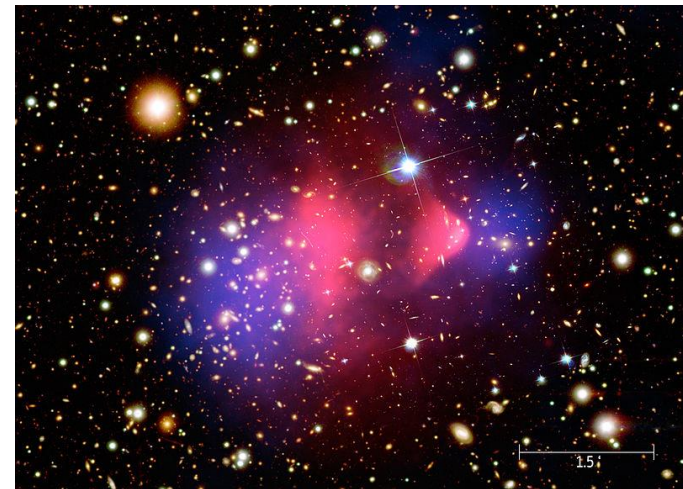
- Multiple, consistent lines of evidence indicate predominance of dark matter over normal matter
- No direct observation on Earth

Dark Matter as an Ultralight Particle

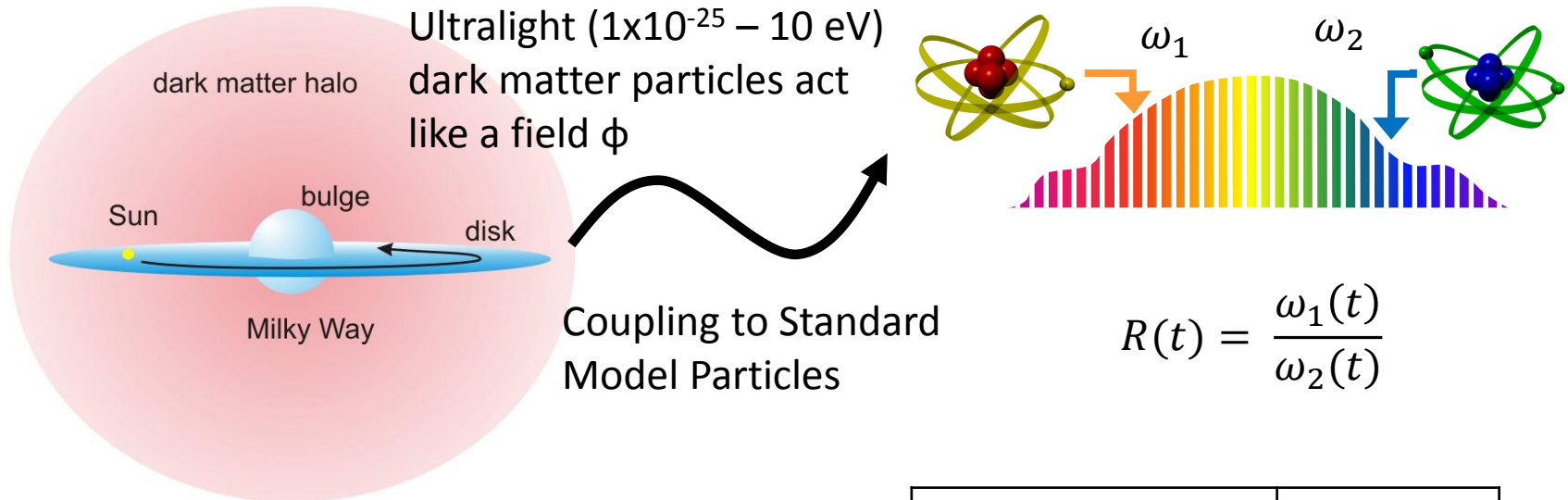


If it is an ultralight particle,
what we DO know:

- de Broglie wavelength shorter than size scale of a galaxy
- Bosonic (as many as 10^{100} particles in a single mode)
- Density: $\sim 0.3 \text{ GeV/cm}^3$
- Acts like a scalar field oscillating at the Compton frequency
- Coherence time $\sim 10^6 \times$ Oscillation period



Searching for Dark Matter with Clocks



$$\frac{d\omega_1/dt}{\omega_1} = A_1 \frac{d\alpha/dt}{\alpha}$$

$$\frac{d\omega_2/dt}{\omega_2} = A_2 \frac{d\alpha/dt}{\alpha}$$

$$\frac{dR/dt}{R} = (A_1 - A_2) \frac{d\alpha/dt}{\alpha}$$

Atom, transition	A
$^{199}\text{Hg}^+, {}^2S_{1/2} \rightarrow {}^2D_{5/2}$	- 3.0
$^{27}\text{Al}^+, {}^1S_0 \rightarrow {}^3P_0$	+ 0.0079
$^{171}\text{Yb}^+, {}^2S_{1/2} \rightarrow {}^2D_{3/2}$	+ 0.88
$^{171}\text{Yb}^+, {}^2S_{1/2} \rightarrow {}^2F_{7/2}$	- 5.95
$^{171}\text{Yb}, {}^1S_0 \rightarrow {}^3P_0$	+ 0.31
$^{87}\text{Sr}, {}^1S_0 \rightarrow {}^3P_0$	+0.06

Dark Matter Field Coupling to α

- Leads to oscillation of the value of α , at the Compton frequency

$$\omega_{DM} = \frac{m_\phi c^2}{\hbar}$$

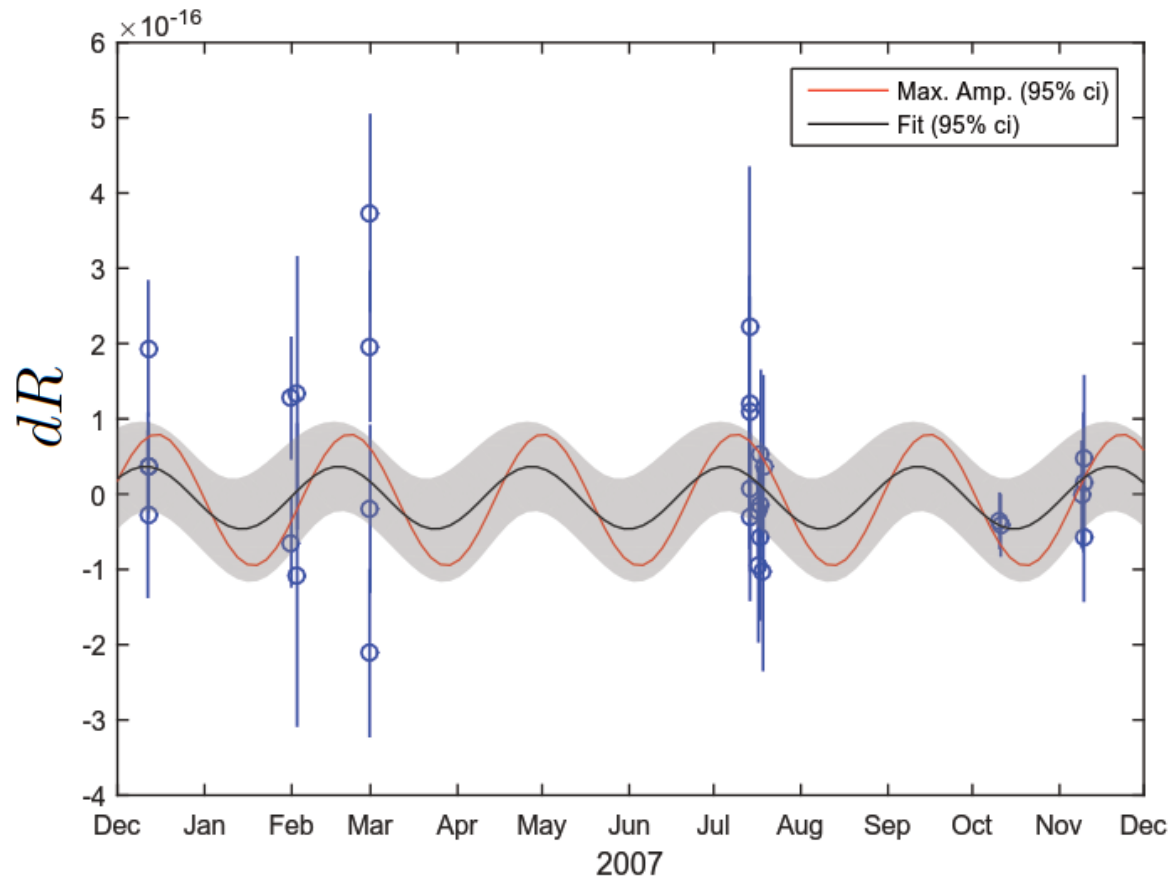
- Amplitude of the oscillation dR depends on:

- Dark matter density ρ_{DM}

$$\rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3}$$

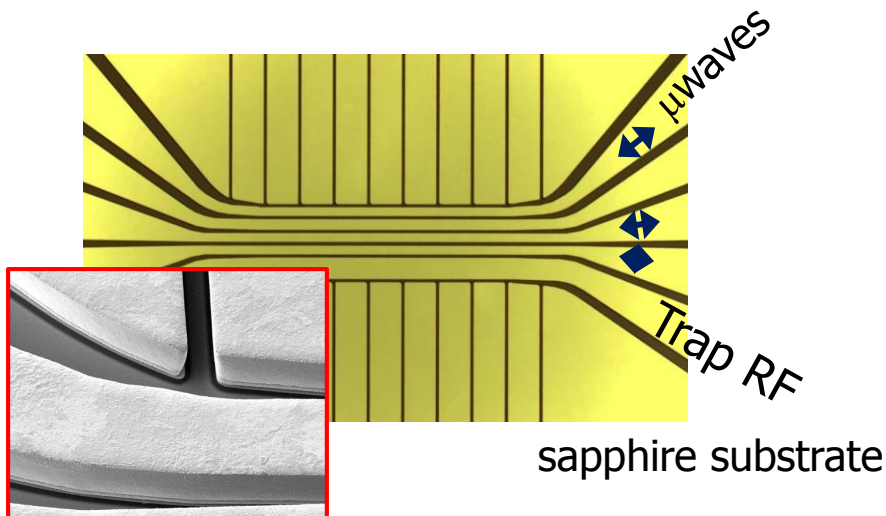
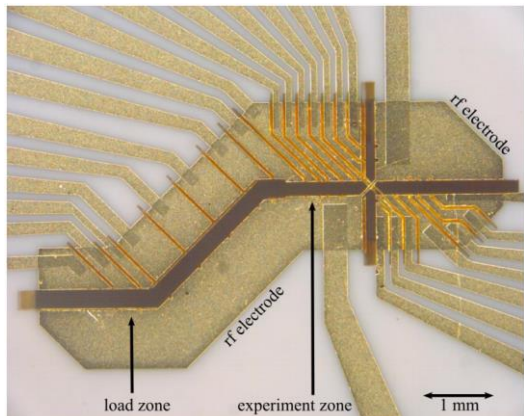
- Coupling coefficient d_e

$$R = R_0 + dR \sin(\omega_{DM} t + \phi_{DM})$$



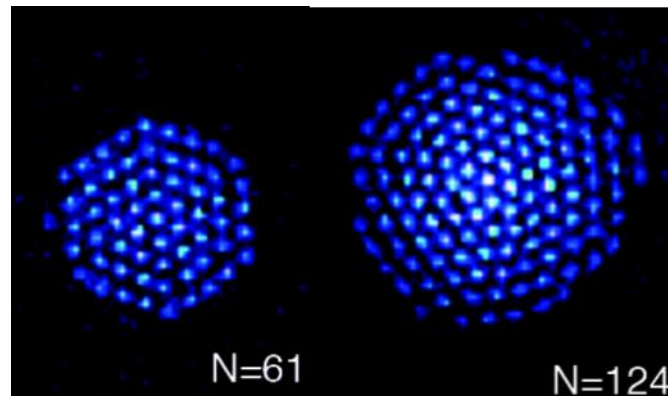
Other work in the Ion Storage Group

Quantum information processing



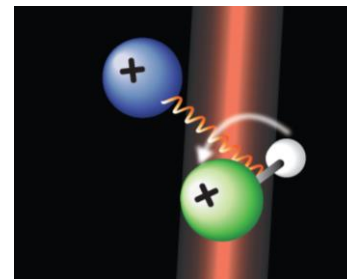
Tan et al., PRL **117**, 060505 (2016)
Ospelkaus et al., Nature **476**, 181 (2011)
10/16/2018

Penning Trap Experiments



Bohnet et al., Science **352**, 6291 (2017)
Gilmore et al., PRL **118**, 263602 (2017)

Molecular Spectroscopy



Chou et al., Nature **545**, 203 (2017)

Al⁺ Clock Uncertainty Budget

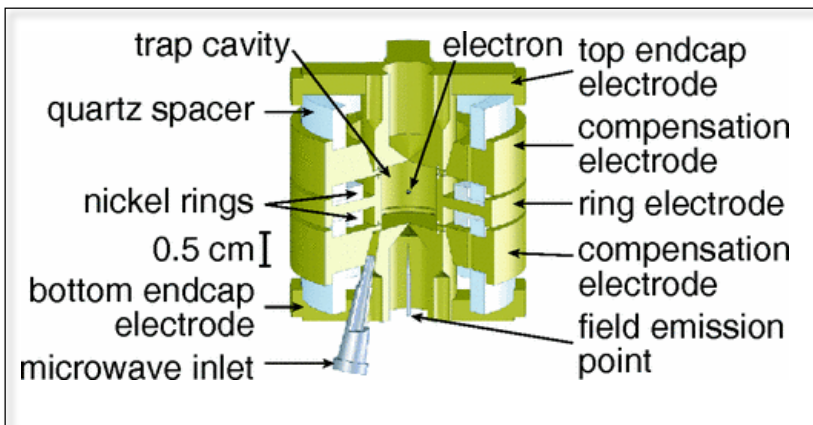
Sources	Fractional Uncertainty (10^{-18})		
	Shift	Uncertainty	Previous clock
Time-dilation: Excess micromotion	-4.7	0.6	-9.0(6.0)
Time-dilation: Secular motion	-1.8	0.3	-16.3(5.0)
BBR shift	-2.6	0.3	-9.0(3.0)
Cooling light shift	0.0	0.0	-3.6(1.5)
Quadratic Zeeman shift	-925.9	0.6	-1079.9(0.7)
Linear Doppler shift	0.0	0.2	0.0(0.3)
Clock light shift	0.0	0.2	0.0(0.2)
Background gas collision	0.0	0.3	0.0(0.5)
AOM phase chirp	0.0	< 0.1	0.0(0.2)
Total	-935.0	1.0	-1117.8(8.6)

Frequency vs. Theory

Example: Measurement of the electron magnetic moment

- Experiment

Single electron in a Penning trap



- Theory

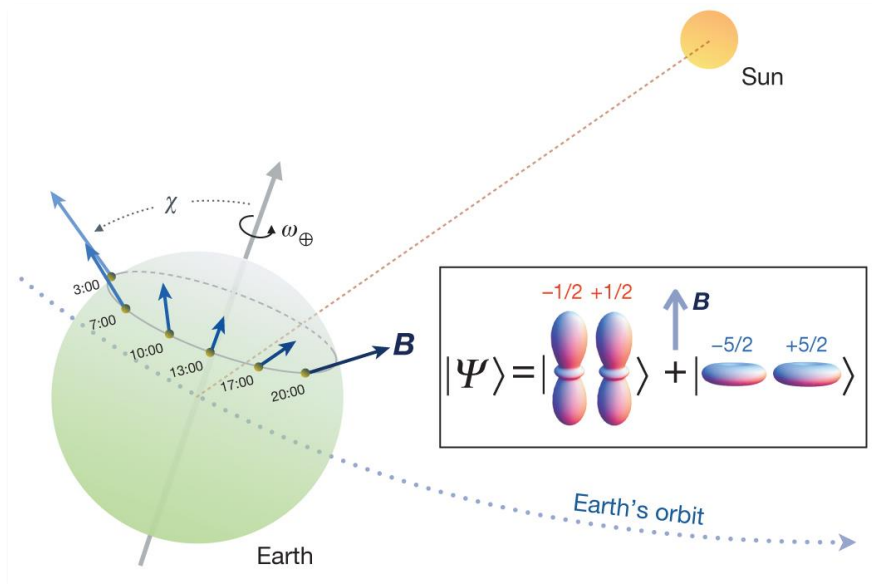
$$\frac{g}{2} = 1 + C_2 \left(\frac{\alpha}{\pi}\right) + C_4 \left(\frac{\alpha}{\pi}\right)^2 + C_6 \left(\frac{\alpha}{\pi}\right)^3 + C_8 \left(\frac{\alpha}{\pi}\right)^4 + C_{10} \left(\frac{\alpha}{\pi}\right)^5 + \dots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}$$

- Taking α from independent measurements, this is a test of QED
- Alternately, assuming calculated coefficients and corrections from QED, this is a measurement of α

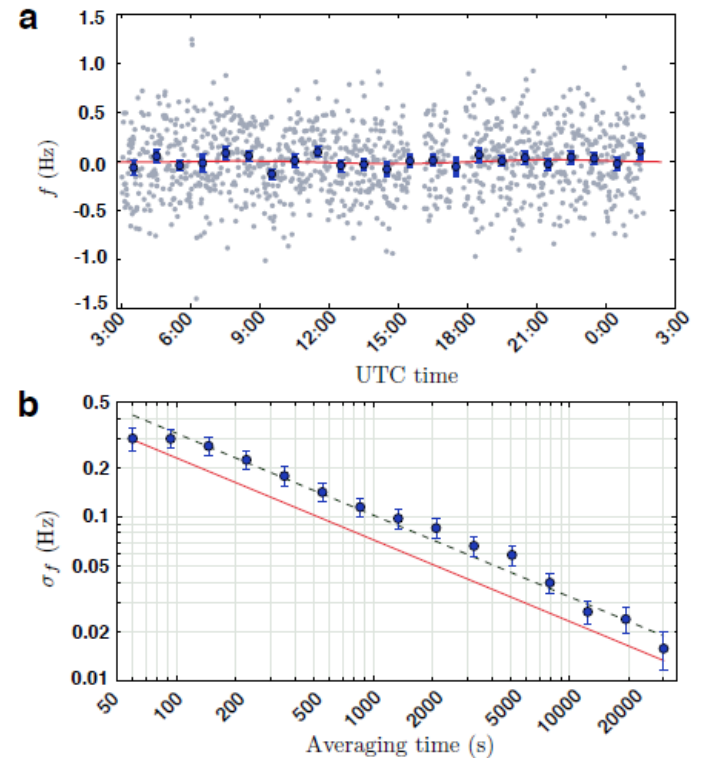
$$\frac{g}{2} \simeq 1 + \frac{\bar{\nu}_a - \bar{\nu}_z^2/(2\bar{f}_c)}{\bar{f}_c + 3\delta/2 + \bar{\nu}_z^2/(2\bar{f}_c)} + \frac{\Delta g_{cav}}{2}$$

Test of Lorentz Invariance

Frequency vs. Spatial Orientation

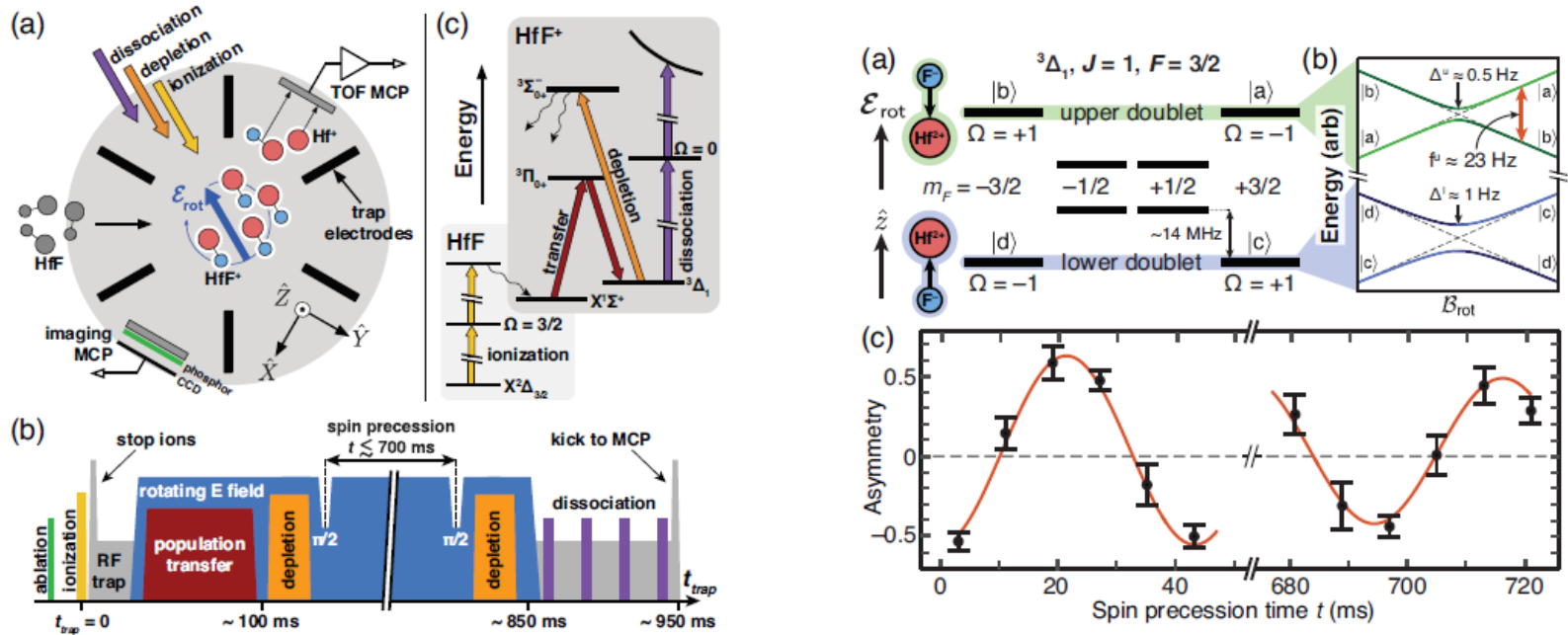


Use a decoherence free subspace of 2 Ca⁺ ions for long probe times



Electron EDM

Frequency vs. Applied Fields



- HfF+ ions in an octupole ion trap
- Electric field in molecule enhanced from 10 V/cm to 23 GV/cm