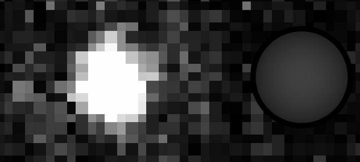
Trapped-Ions, Precision Measurements and Optical Clocks

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. Leibrandt

Ion Storage Group

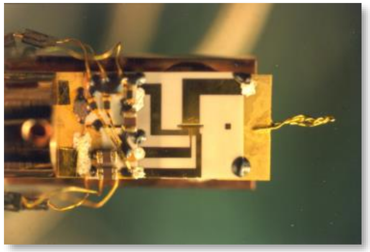
NIST, Boulder



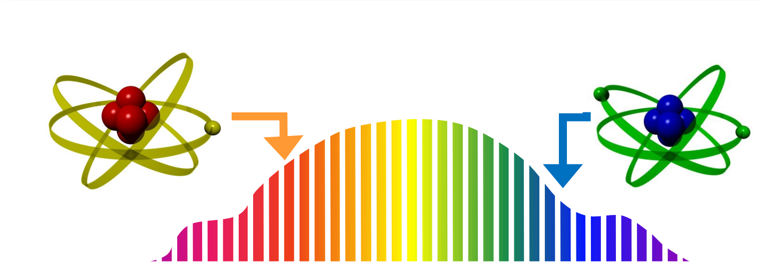
Quantum Sensors for Fundamental Physics
Oxford 10/16/2018

Outline

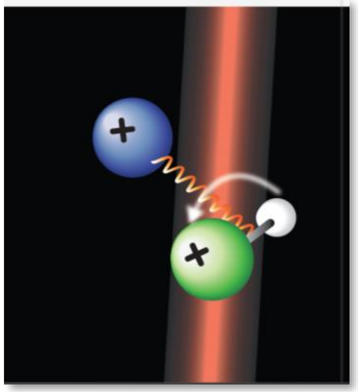
1. Ions, Ion traps,
   Tests of fundamental physics



2. Single-ion optical clocks
   - Al$^+$ vs Hg$^+$ at NIST
   - Al$^+$ vs optical lattice clocks



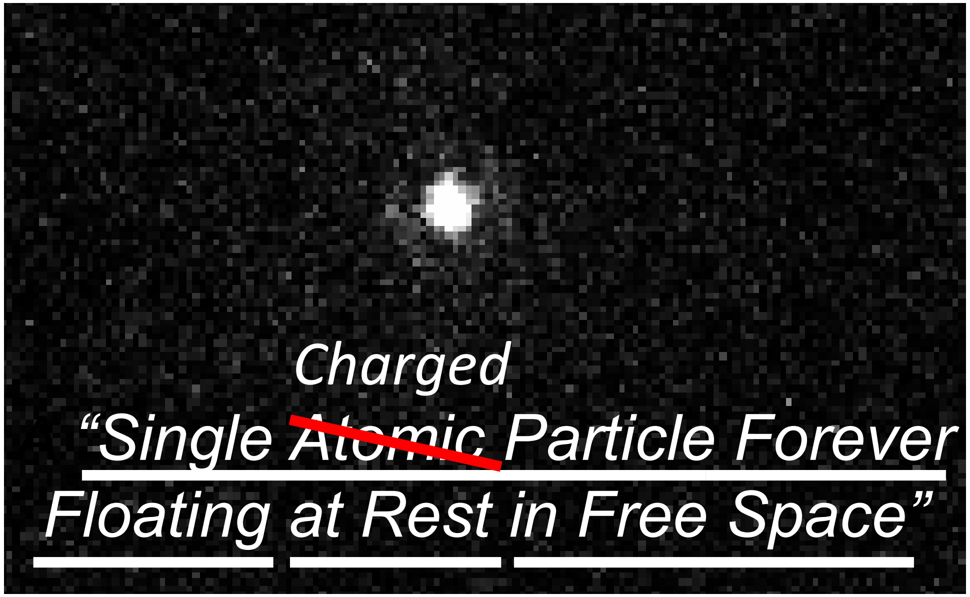
3. Useful quantum techniques
   - Quantum logic spectroscopy
   - Correlation spectroscopy



Trapped Ions

Hans Dehmelt

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



Charged

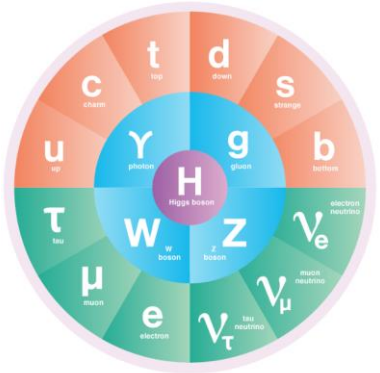
“Single ~~Atomic~~ Particle Forever Floating at Rest in Free Space”

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

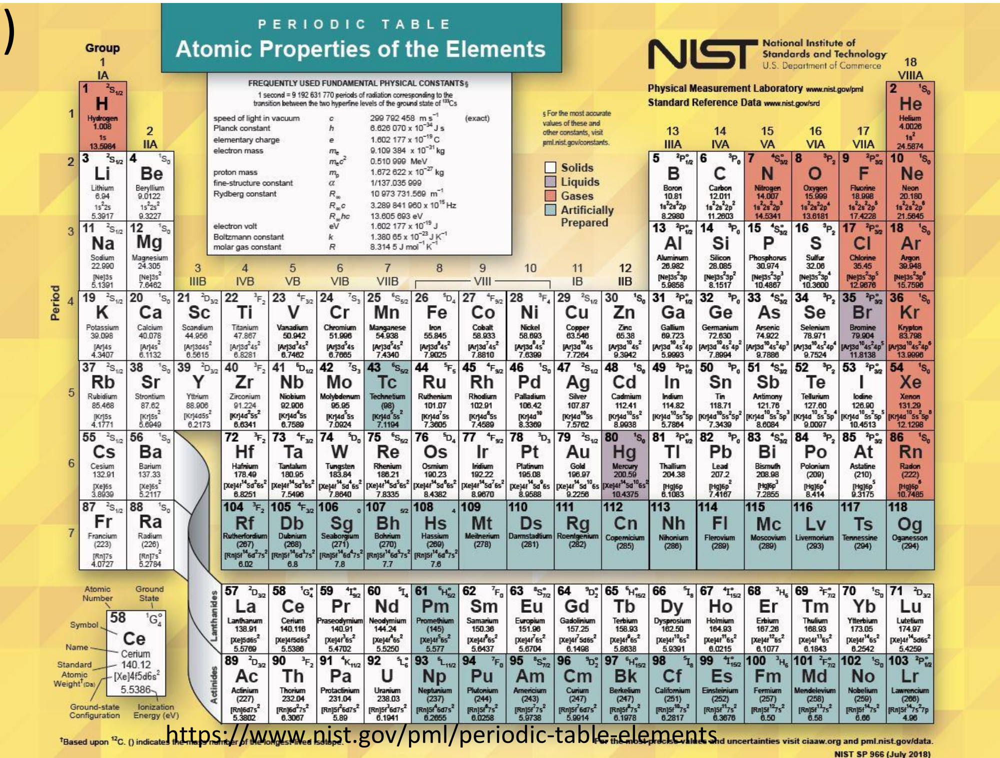
+ Strong, controllable interactions between ions

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/



PERIODIC TABLE

Atomic Properties of the Elements

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

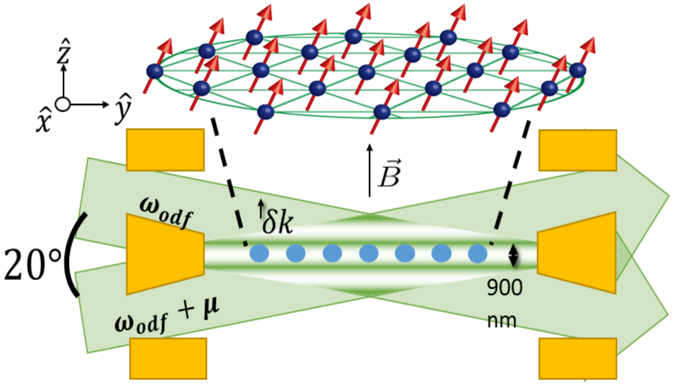
Ion Traps

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

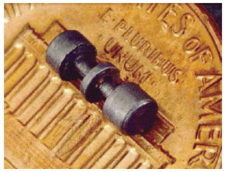
High B field



Paul Trap

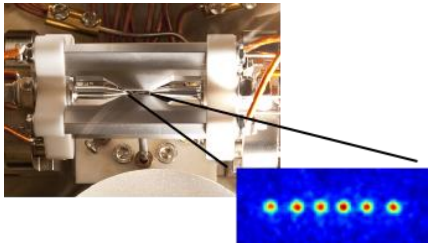
RF confining fields

Spherical:

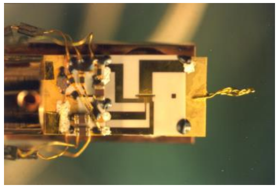


Linear:

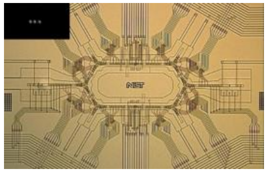
Blade



Wafer



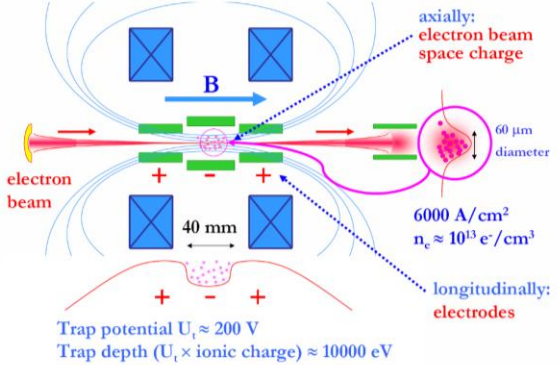
Planar



https://quantumoptics.at/en/research/quantum-information.html

EBIT (Electron Beam Ion Trap)

Space charge



https://www.mpi-hd.mpg.de/pfeifer/page.php?id=90#figure02

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)**

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- Li
- Ra
- Be
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Frequency vs. theory
Gabrielse

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Quantum mechanics

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- Randomness
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Frequency vs. time

Godun Wednesday 11:55

Gill Wednesday 9:35

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nstants

$_p)$

-linearities

ons (spin-

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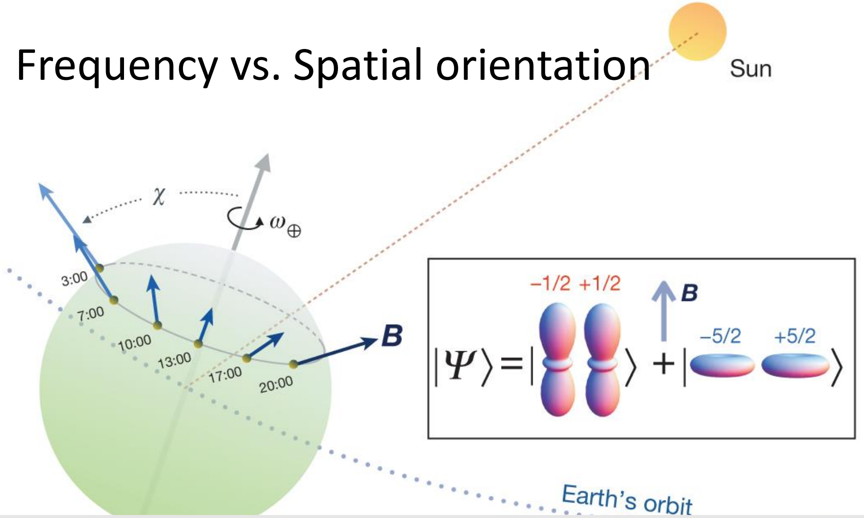
Frequency vs. Spatial orientation



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

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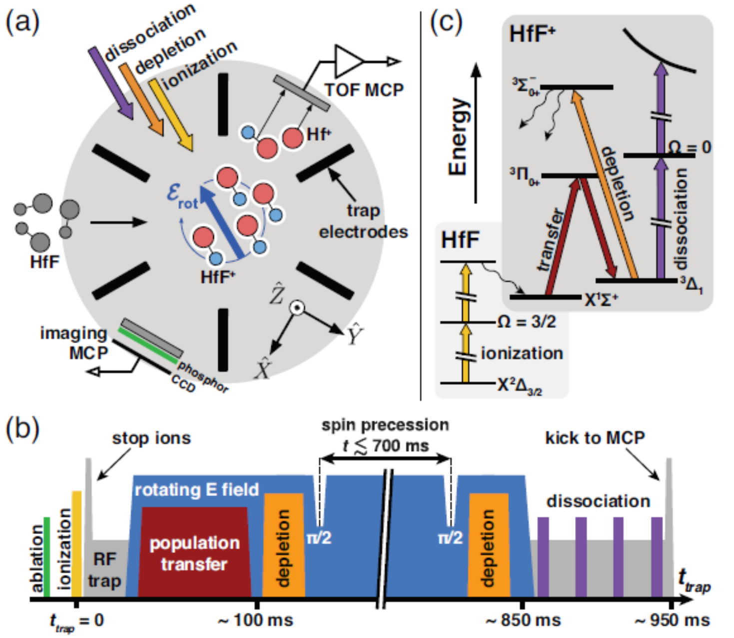
Precision Tests of Fundamental Physics

Frequency vs. Applied Fields



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

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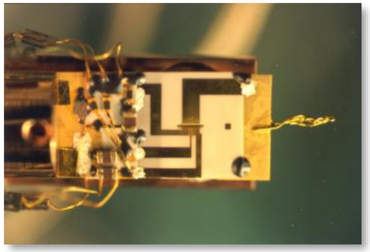

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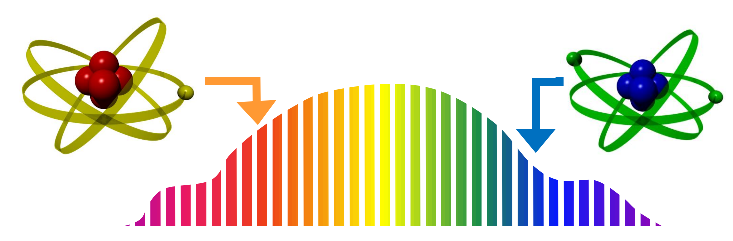

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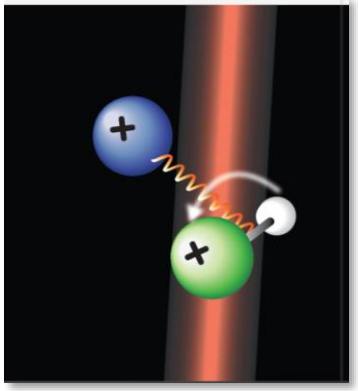

Clock Tests of Fundamental Physics

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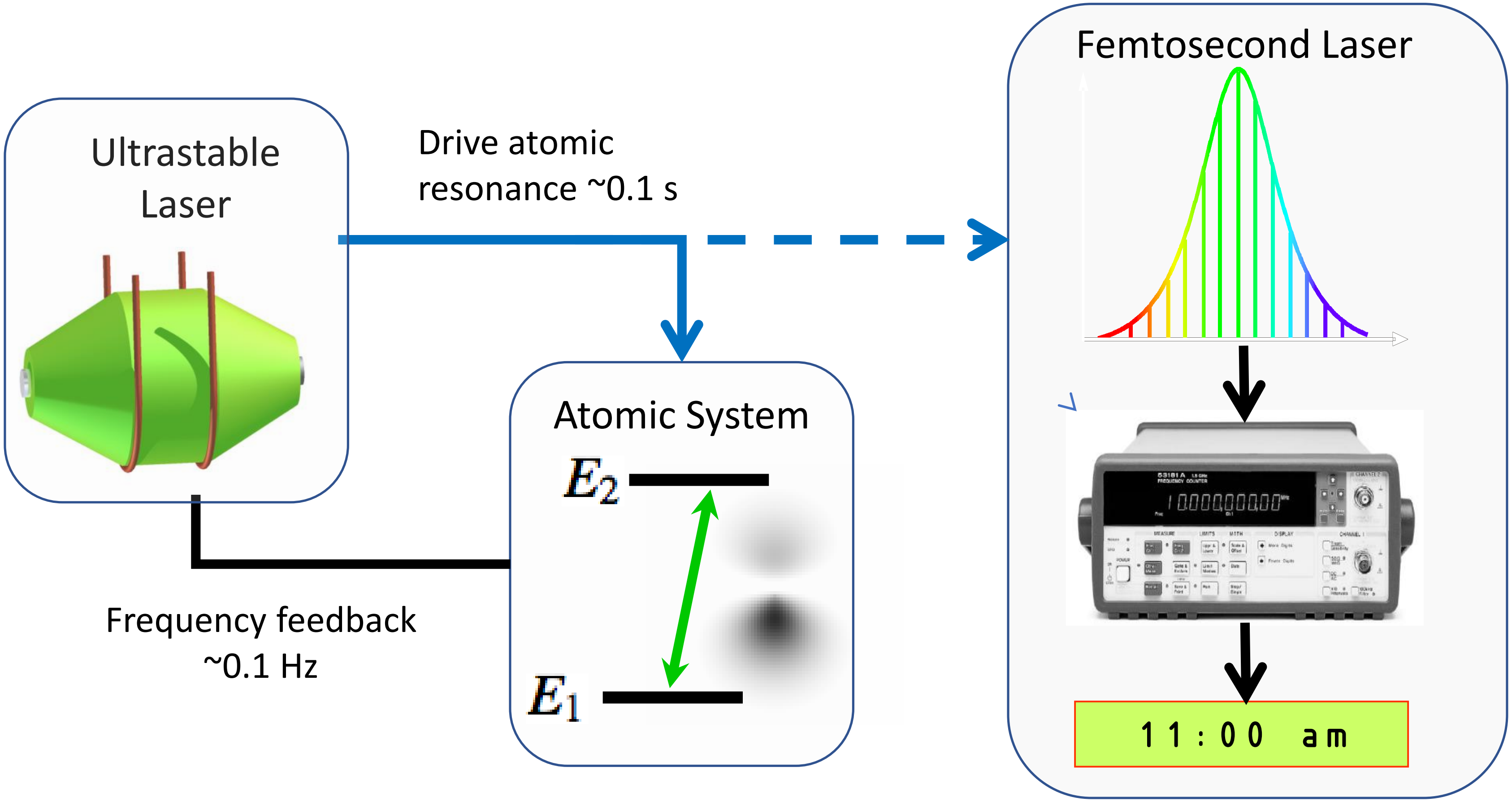
Principle of Optical Atomic Clocks



Ultrastable Laser

Drive atomic resonance ~0.1 s

Atomic System

E_2

E_1

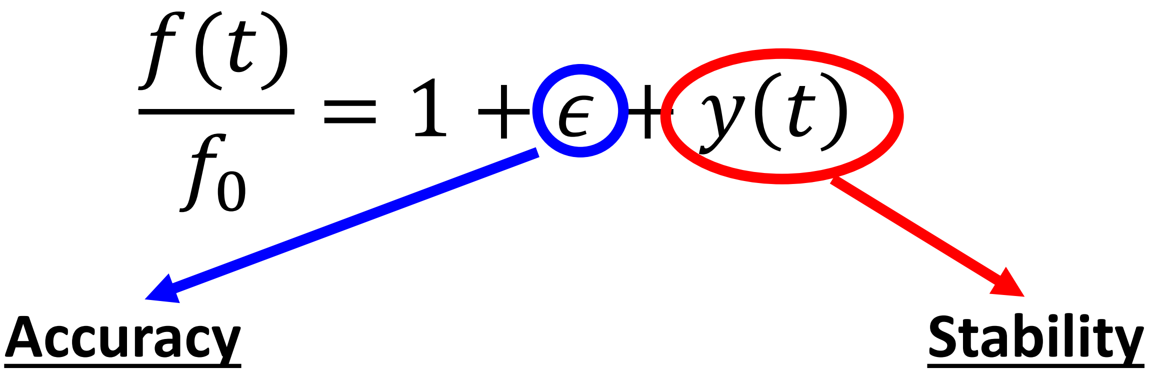
Frequency feedback ~0.1 Hz

Femtosecond Laser

11:00 am

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

Clock Performance



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

Accuracy

- 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

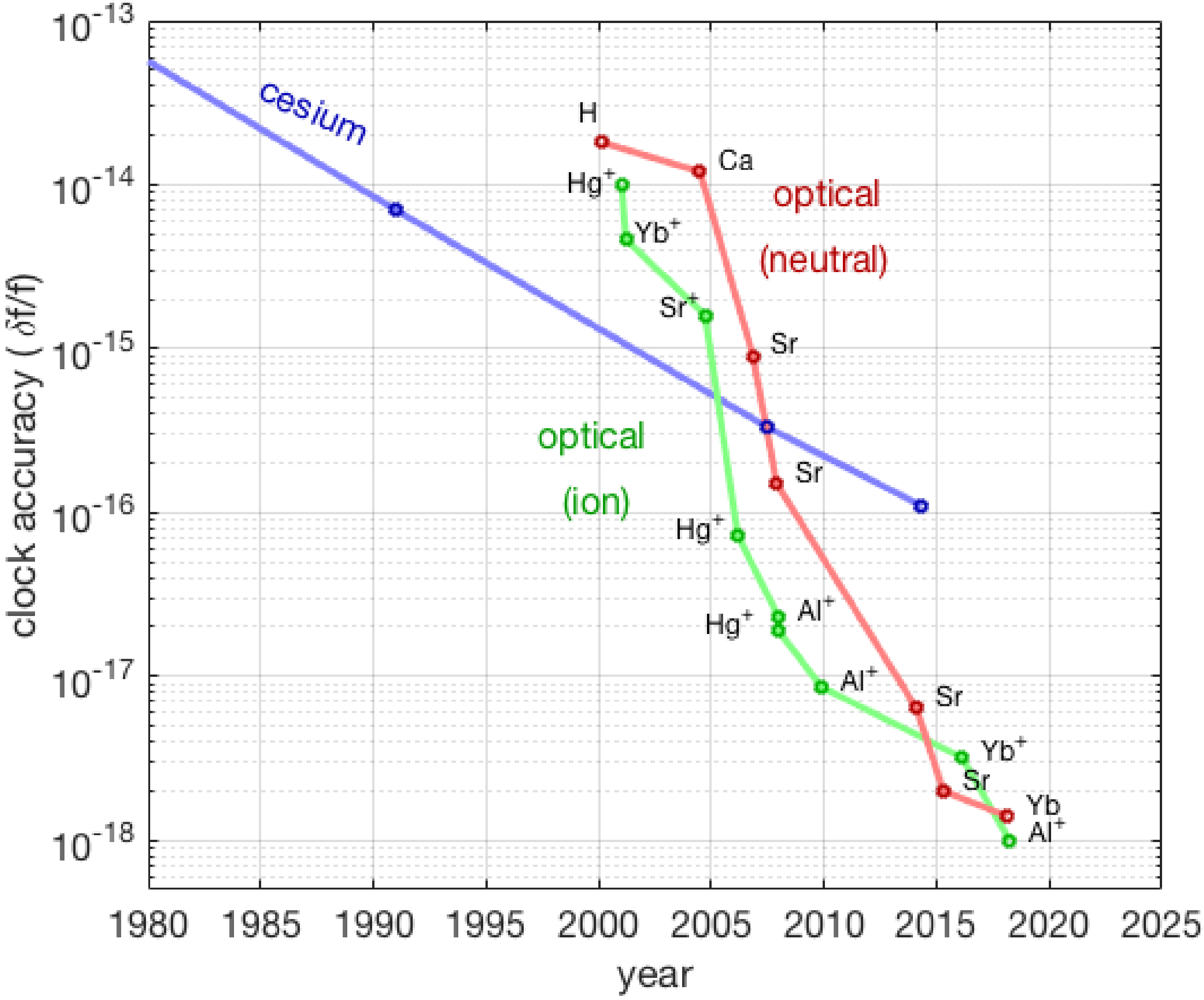
$$\boxed{\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} - \frac{\langle \vec{v} \cdot \hat{k} \rangle^2}{2c^2} + \cdots}$$

Stability

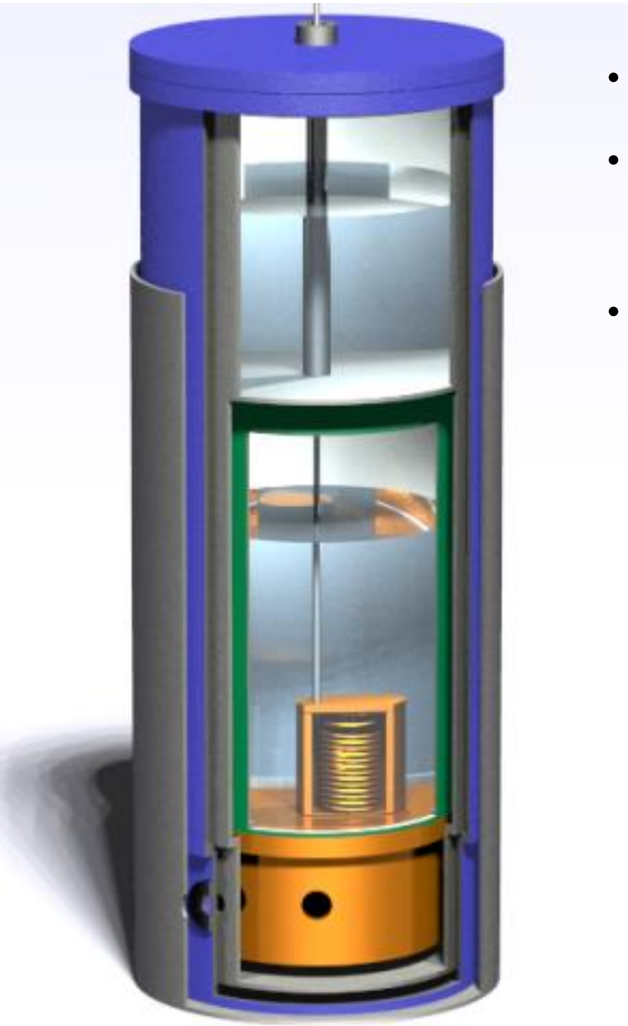
- Average fractional frequency variations
- Typically characterized by the *Allan deviation:*

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

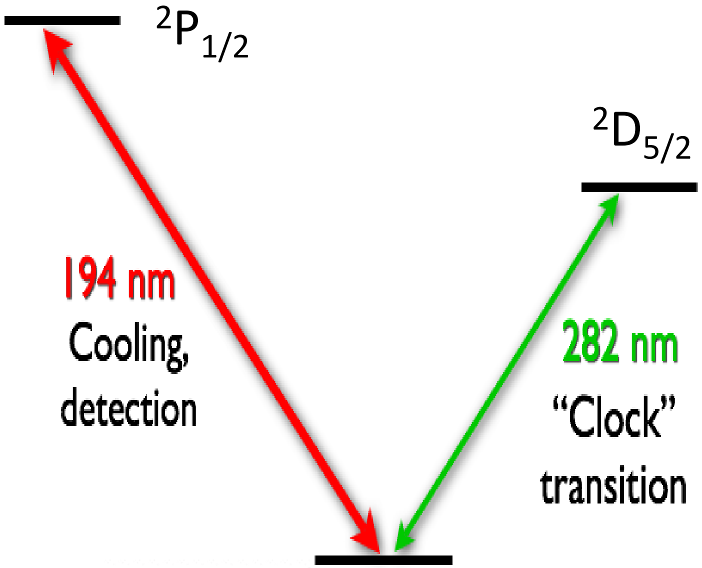
Historical Clock Accuracy

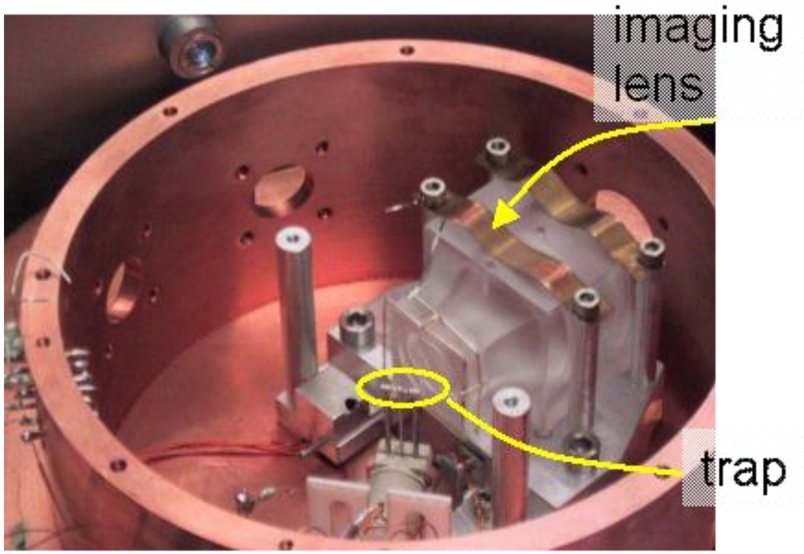


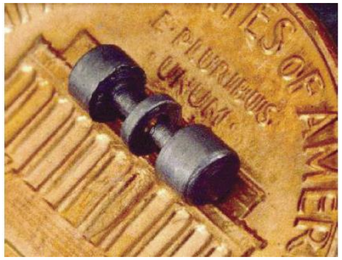
$^{199}Hg^{+}$ system



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



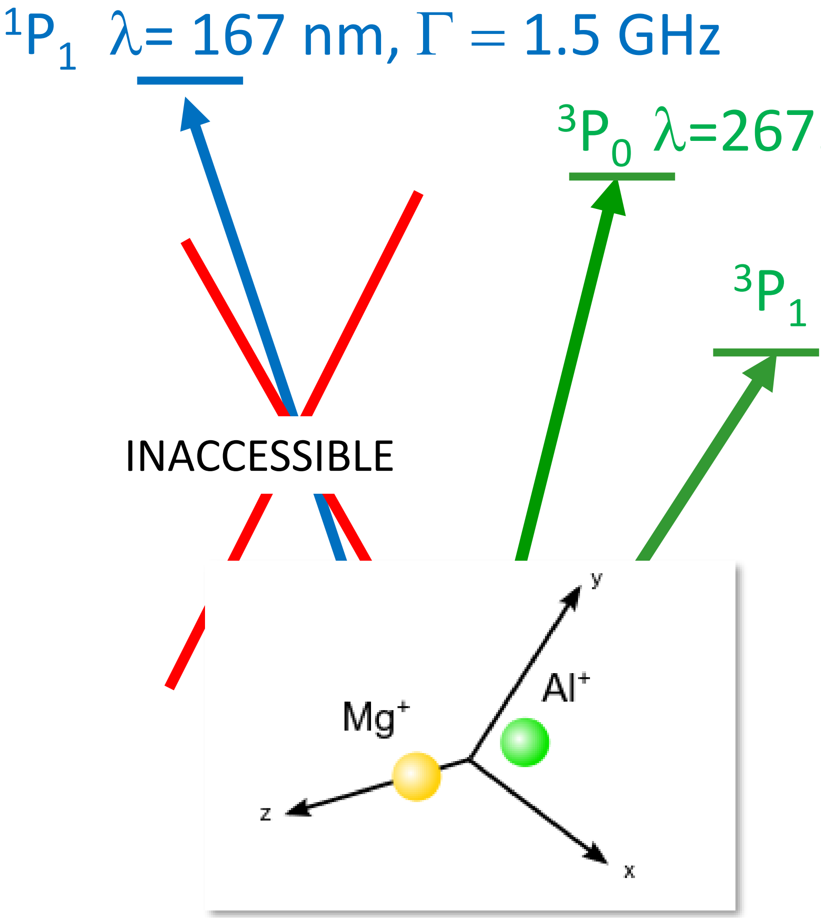




T. Rosenband, *et al.* Science **319**, 1808 (2008)

Diddams et al., Science 293, 825 (2001)

$^{27}Al^+$ Atomic System



$^1P_1$ λ= 167 nm, Γ = 1.5 GHz

$^3P_0$ λ=267.43 nm, τ = 21 s

$^3P_1$ λ=266.99 nm, τ = 300 μs

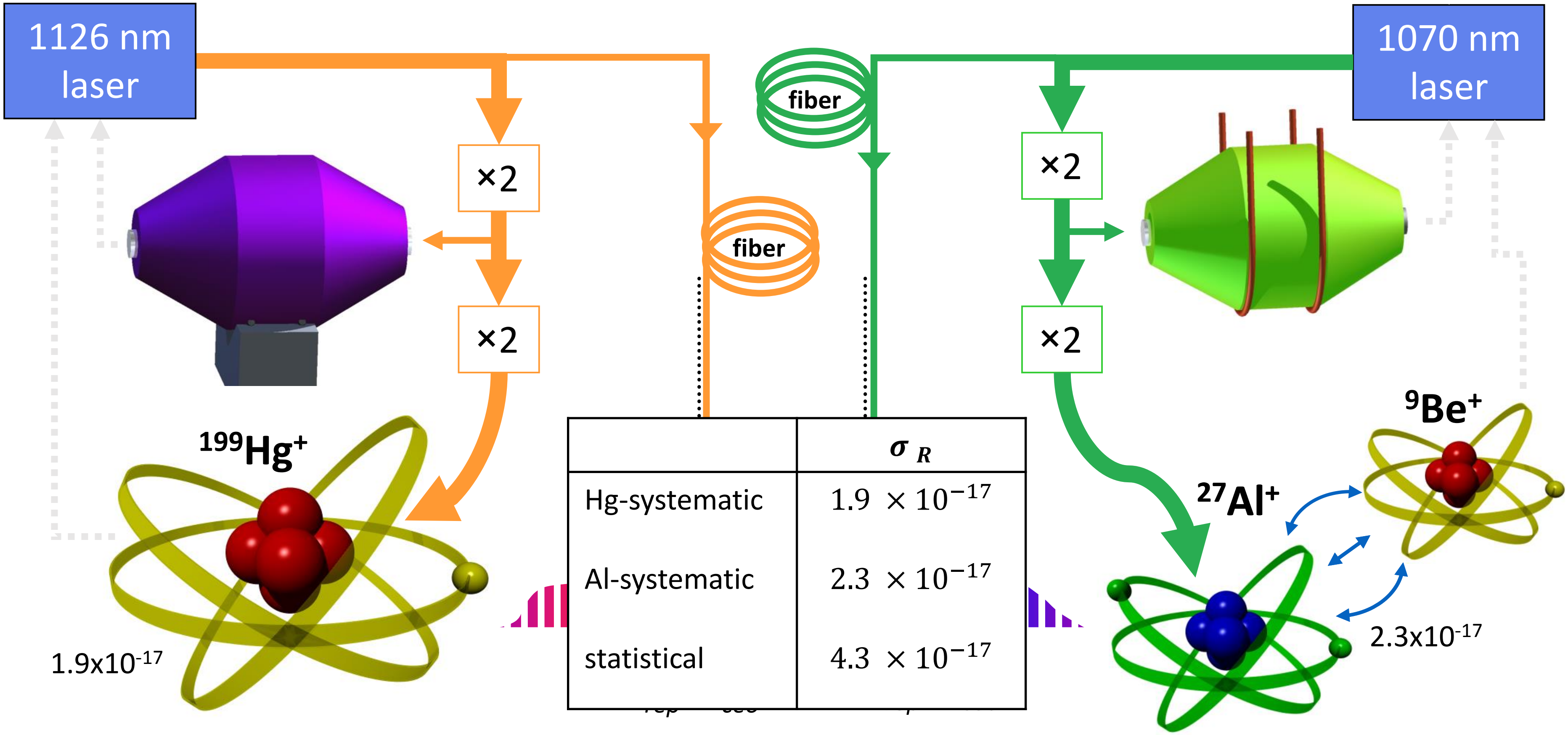
INACCESSIBLE

- Insensitive to trapping fields
- Small Stark shift from blackbody radiation
- Light mass → 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

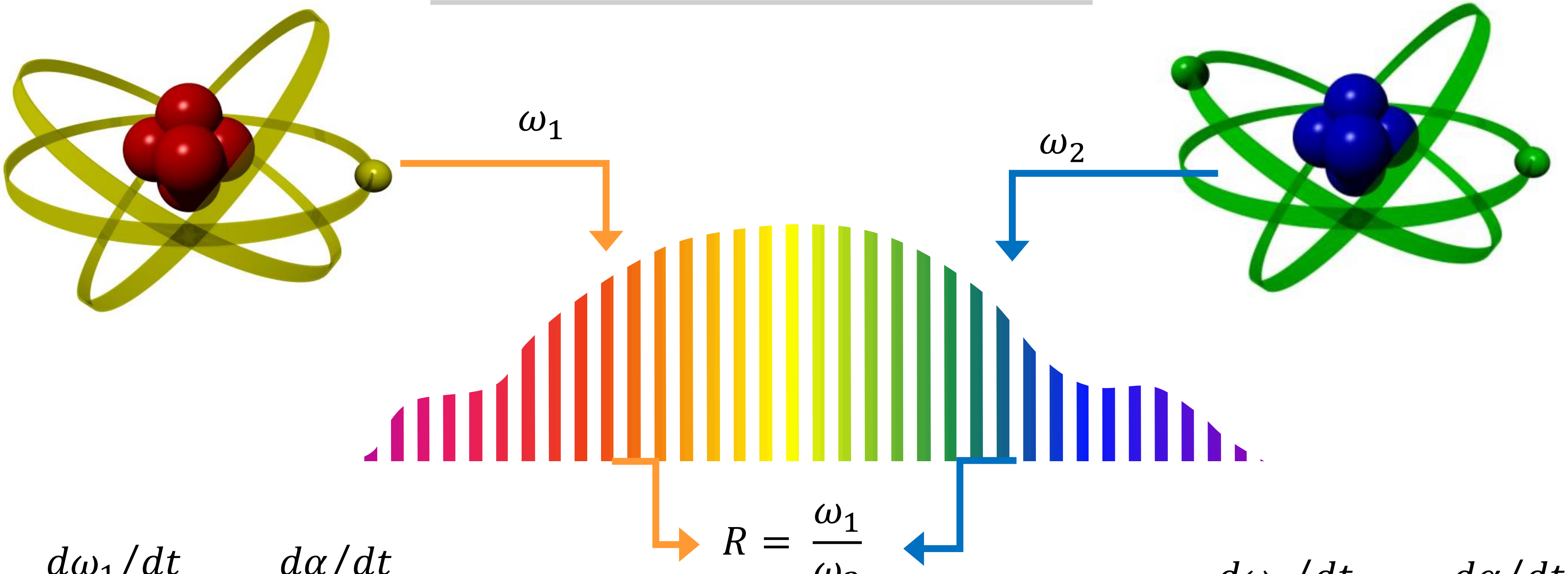


	σ_R
Hg-systematic	1.9×10^{-17}
Al-systematic	2.3×10^{-17}
statistical	4.3×10^{-17}

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

T. Rosenband, *et al.* Science **319**, 1808 (2008)

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



$$R = \frac{\omega_1}{\omega_2}$$

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

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

Sensitivity coefficients determined based on atomic structure calculations

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

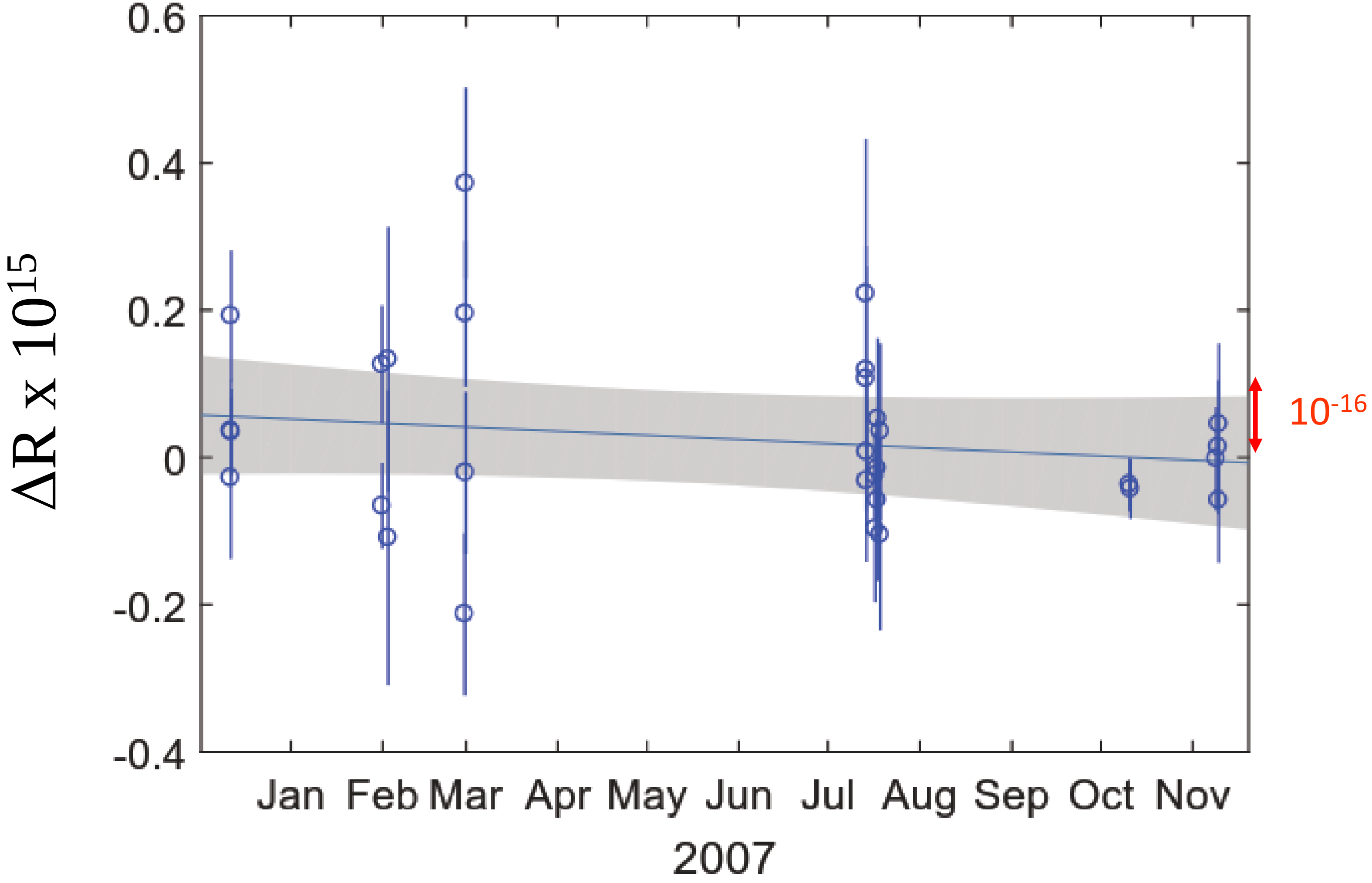
[2] E. J. Angstmann, et al., Phys. Rev. A 70, 014102 (2004)

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

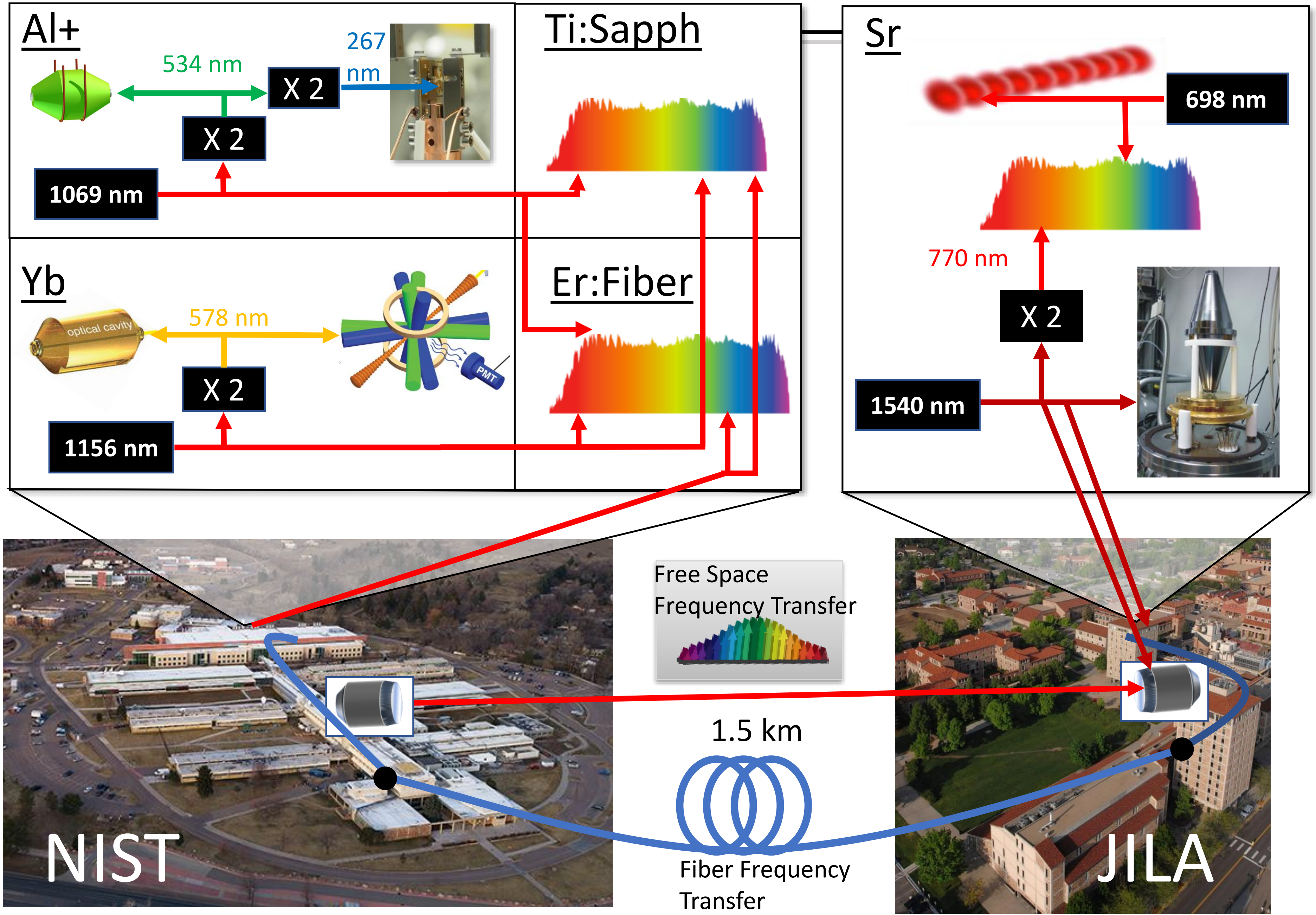
[4] V. A. Dzuba, V. V. Flambaum, Can. J. Phys. 87 15 (2009)

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

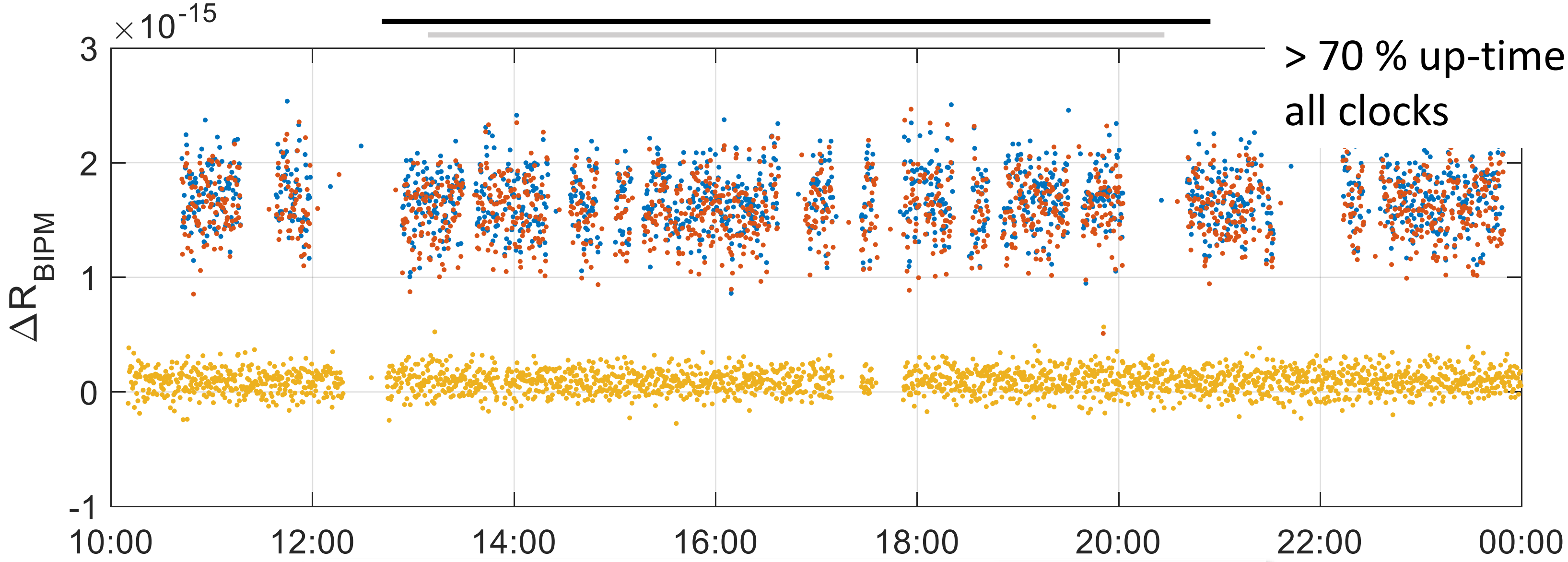
Sr
Jun Ye
John Robinson
Eric Oelker
Dhruv Kedar
Sarah Bromley
Lindsey Sonderhouse
Colin Kennedy
Tobias Bothwell

Free Space
Nathan Newbury
Laura Sinclair
JD Deschenes
Isaac Khader
Martha Bodine

Combs
Scott Diddams
Tara Fortier
Holly Leopardi

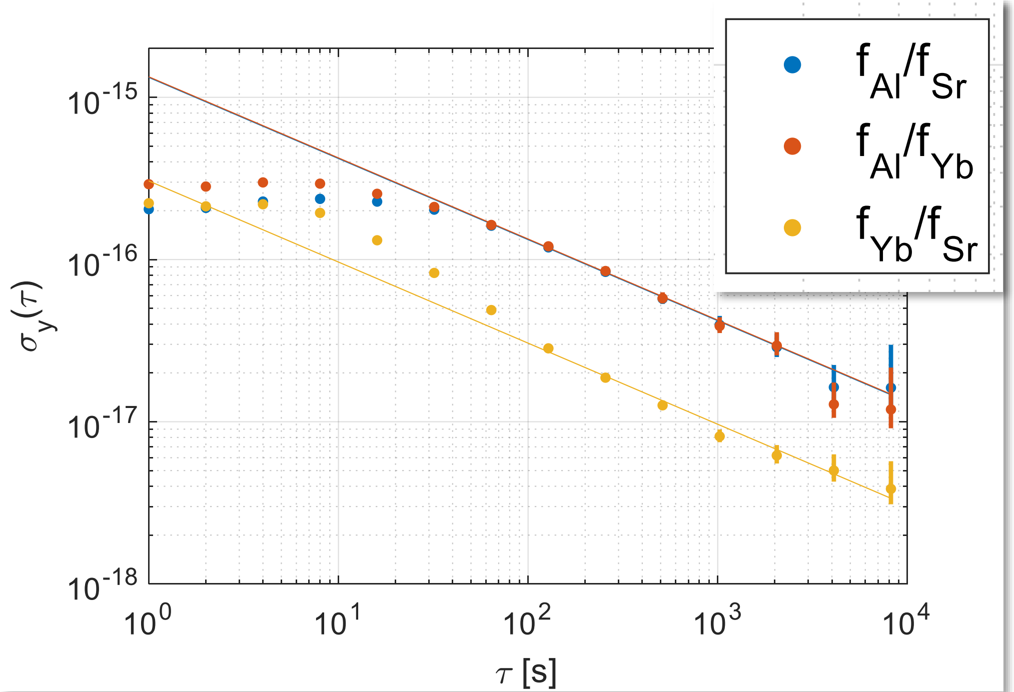
Timescale
Jeff Sherman
Jian Yao

Frequency Ratio Measurements



> 70 % up-time for all clocks

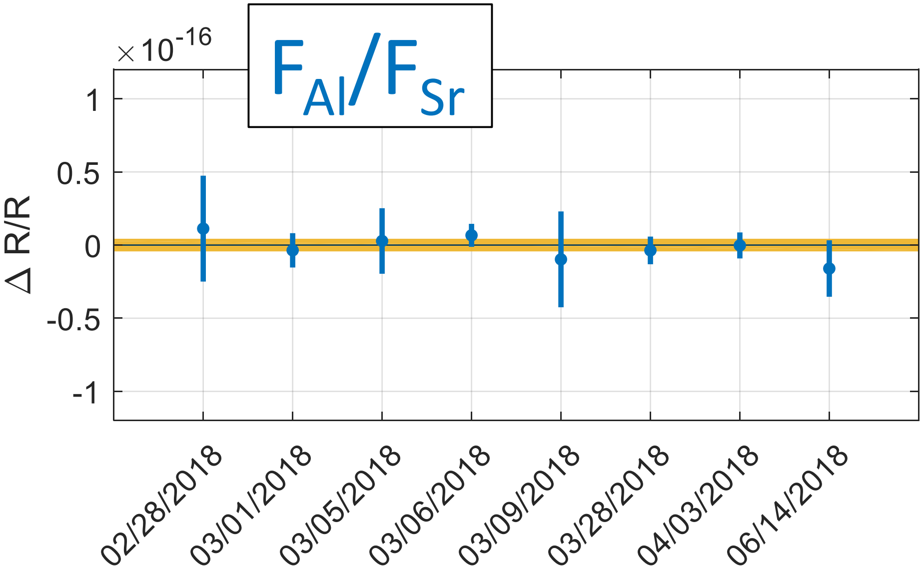
Mar 06, 2018

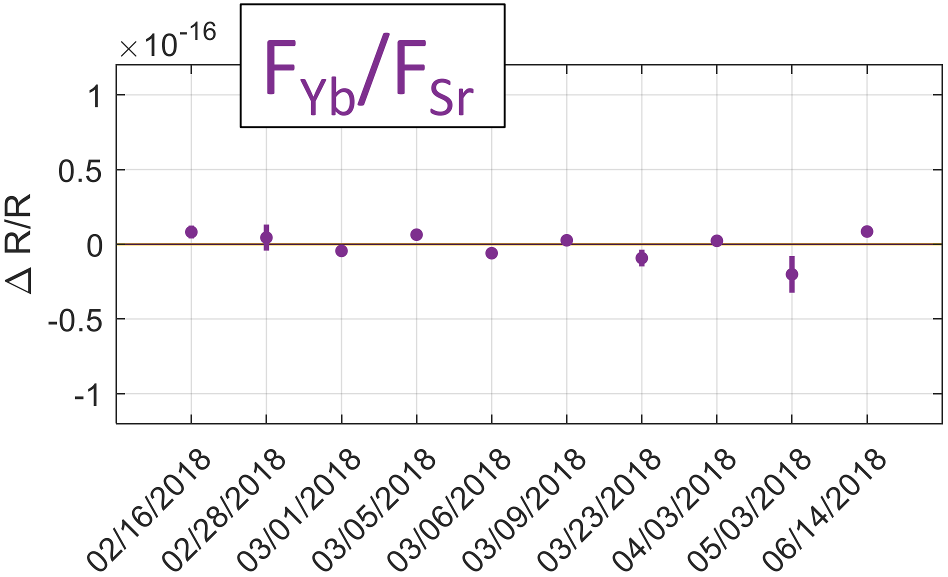


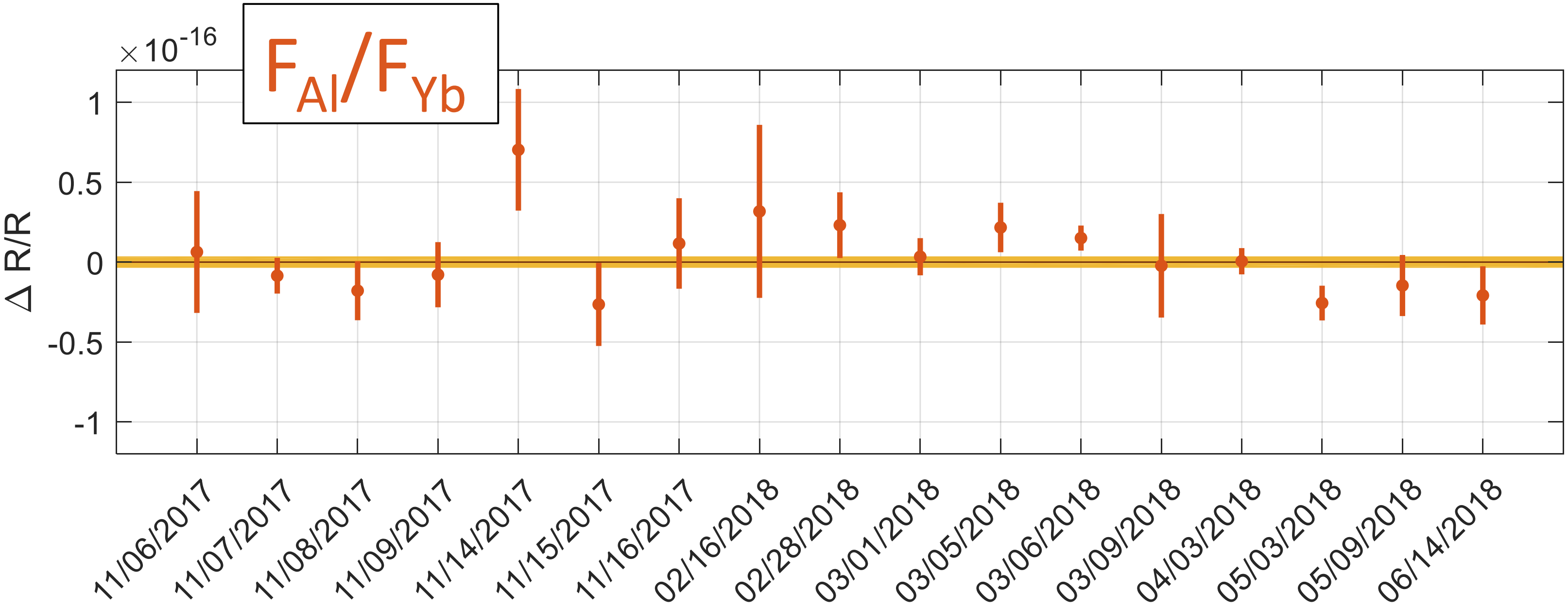
Al clock stability
1.3×10^{-15} @ 1s

Yb/Sr stability
3.1×10^{-16} @ 1s

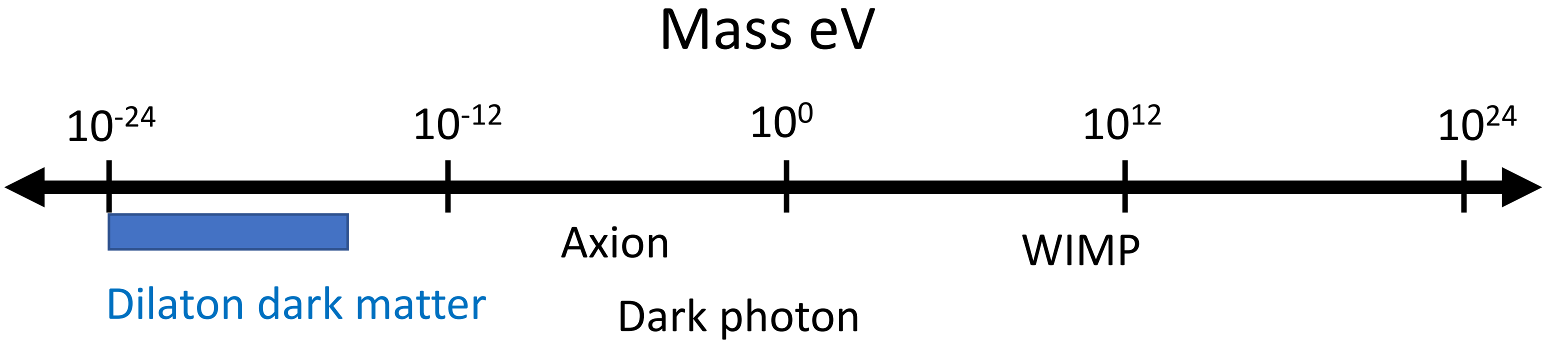
Ratios Day by Day







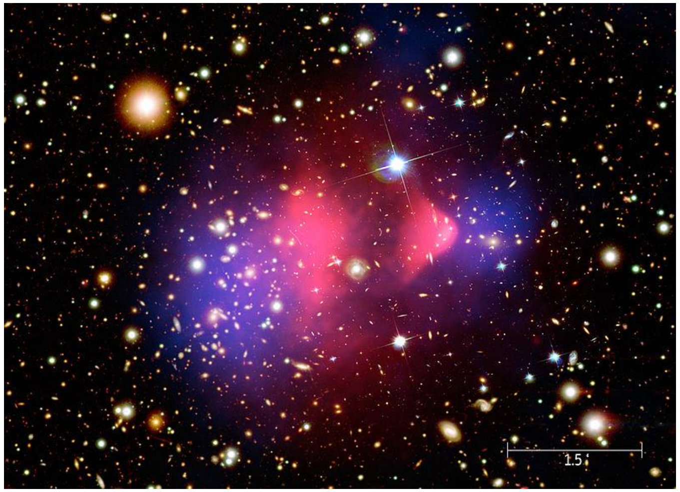
Dark Matter as an Ultralight Particle



Dilaton dark matter
Fuzzy dark matter
Wave dark matter
Ultralight bosonic dark matter
Ultralight virialized fields
…

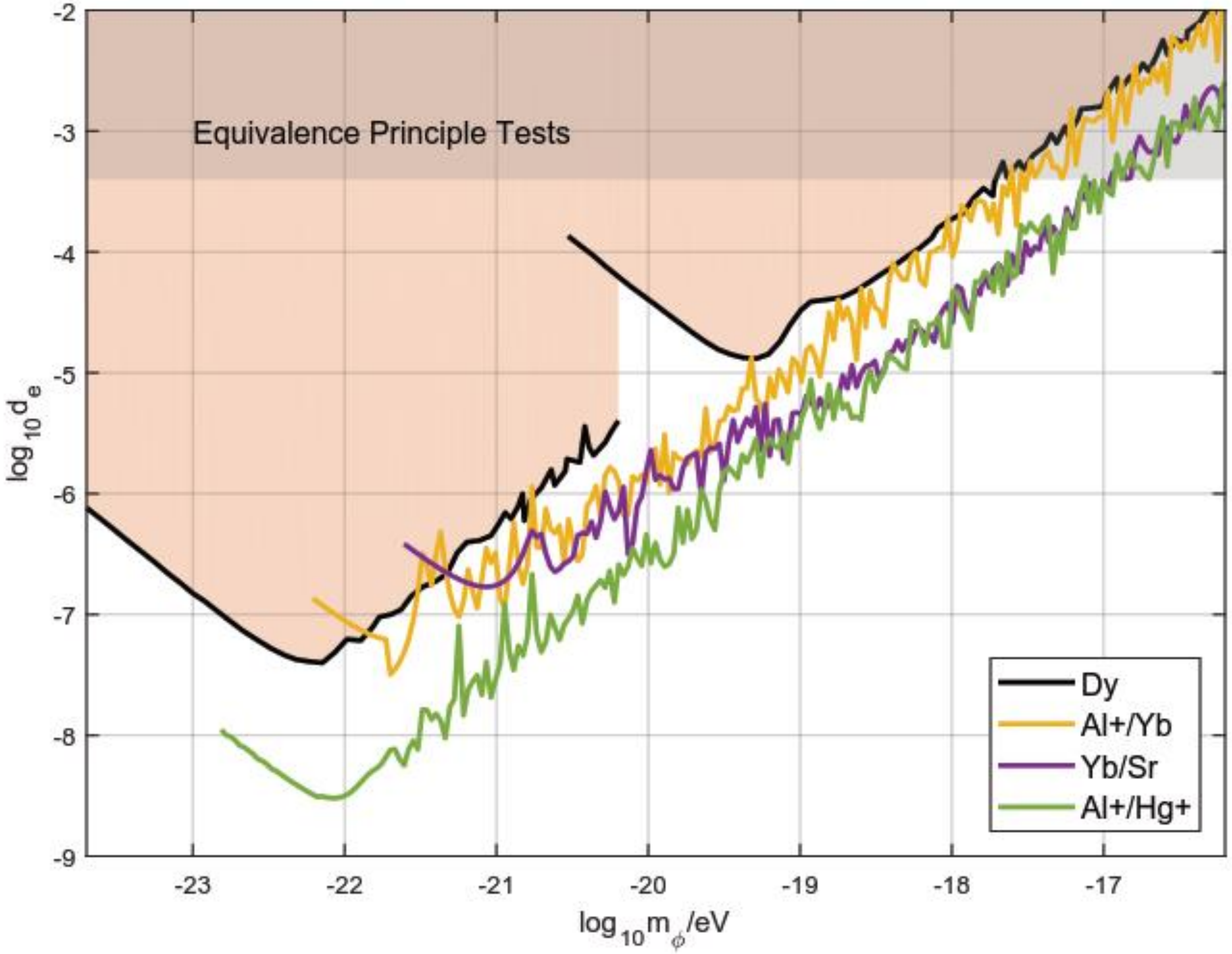
If it is an ultralight particle, what we DO know:

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

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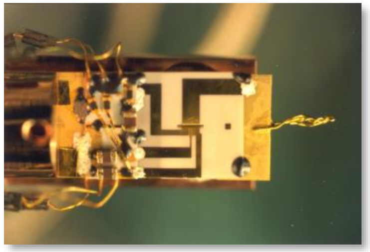

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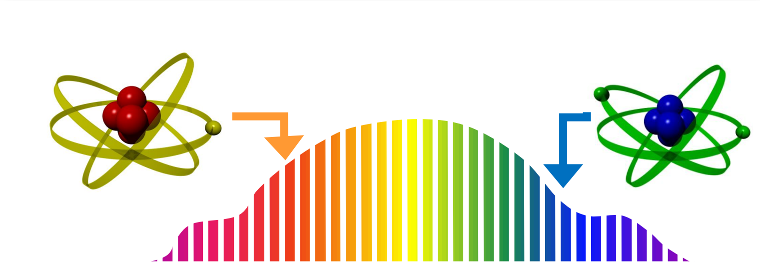

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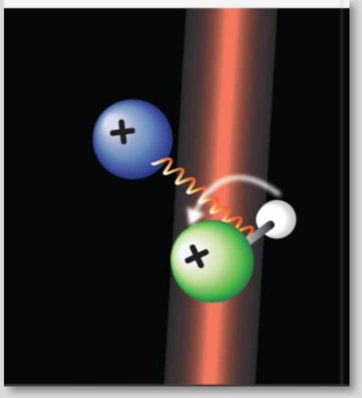
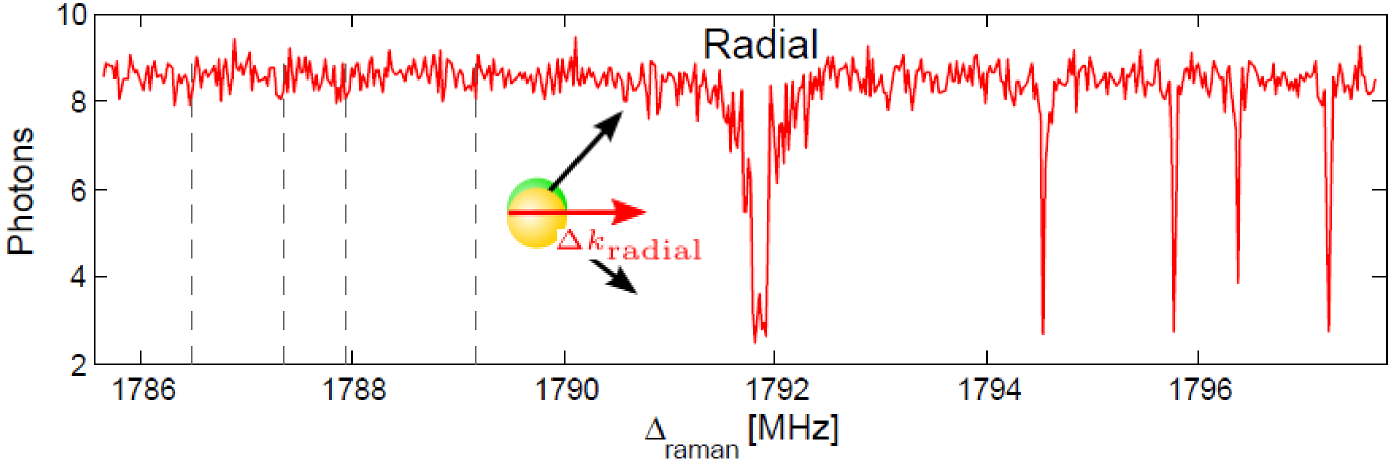
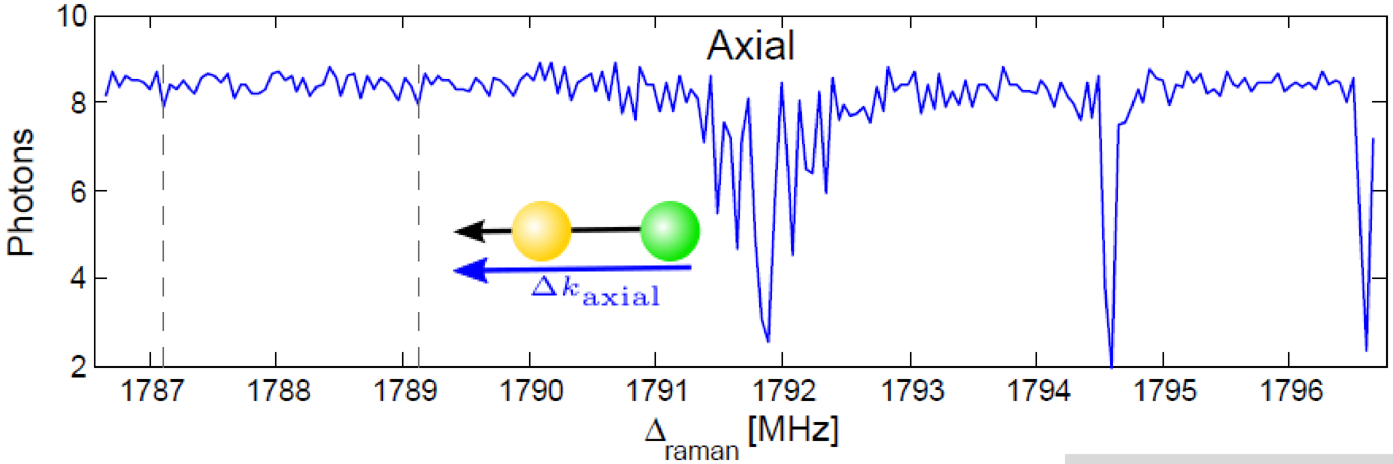


Quantum Logic Spectroscopy





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

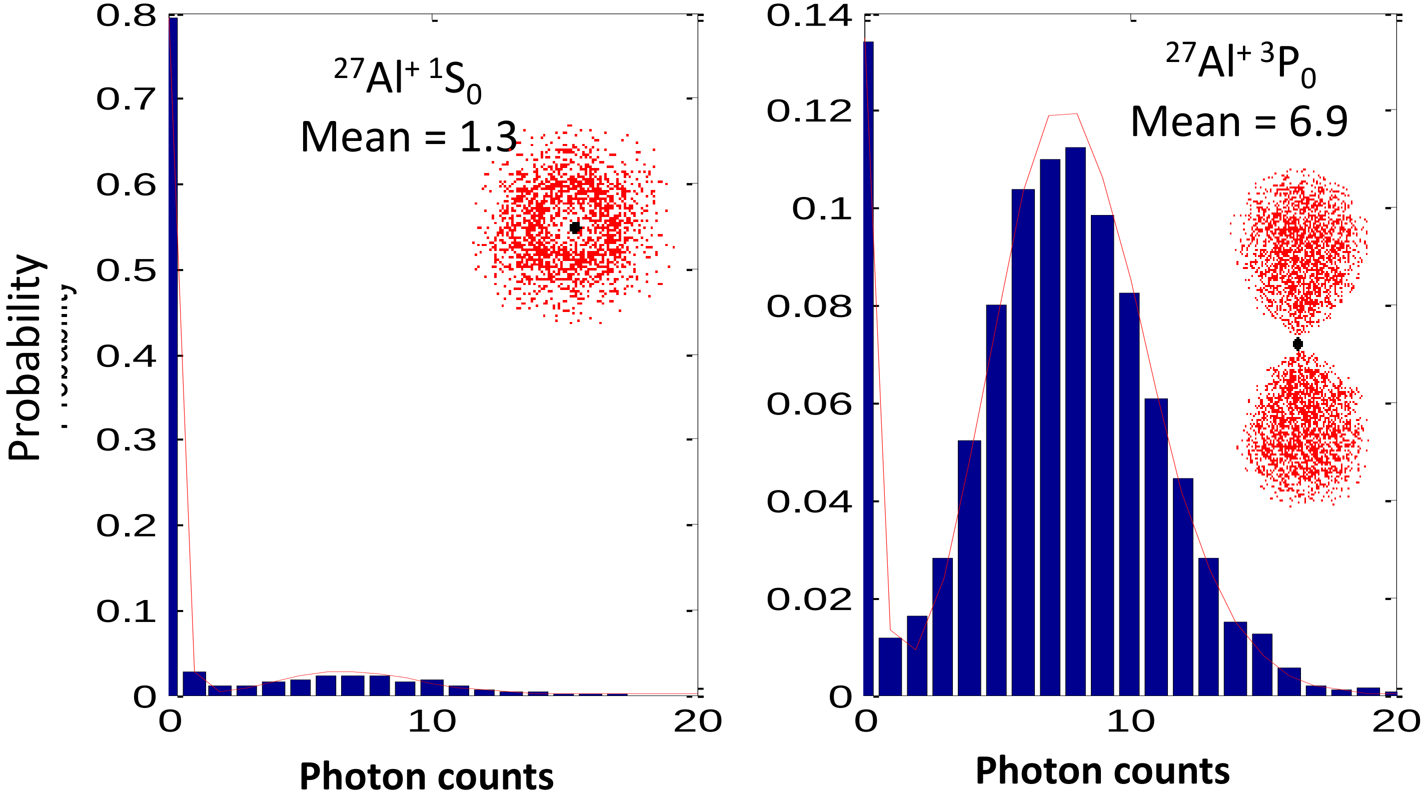
Monroe et al., PRL 75, 22, 4011 (1995)

Typical mode frequencies: 2.7 – 7.2 MHz

Al$^+$ quantum-assisted readout

QND

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)

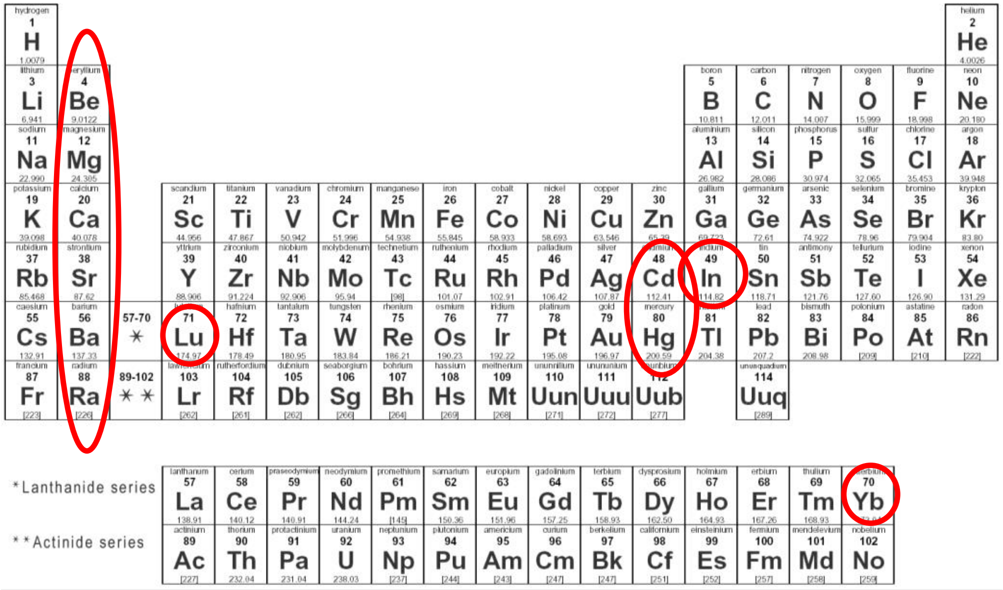
P.O. Schmidt, *et al.*
Science **309**, 749 (2005)

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

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

Generalizing to New Atomic Systems

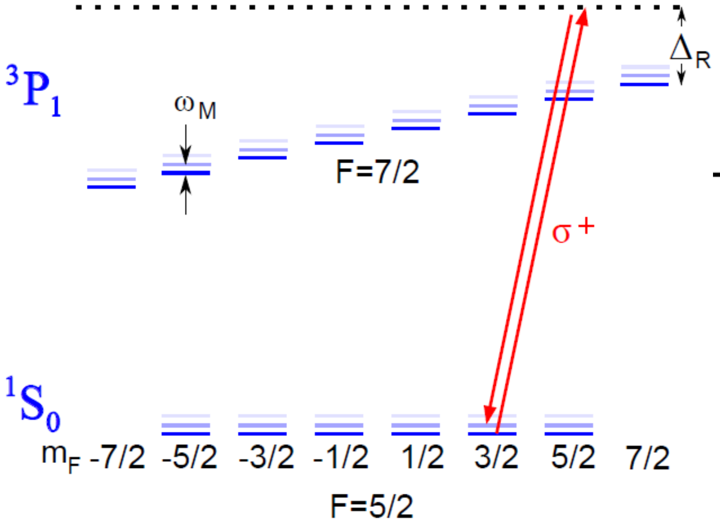
- Applications
  - Variations of fundamental constants (α, μ)
  - Parity Nonconservation
  - Electron EDM
  - Comparing with astrophysical data
  - The ideal clock?
  - The ideal qubit?

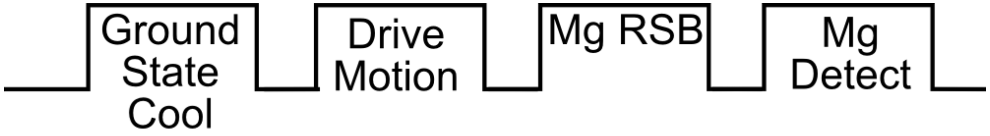


State detection that does not depend on details of the atomic structure

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

``Quantum Jumps´´ between Zeeman States





Ground State Cool

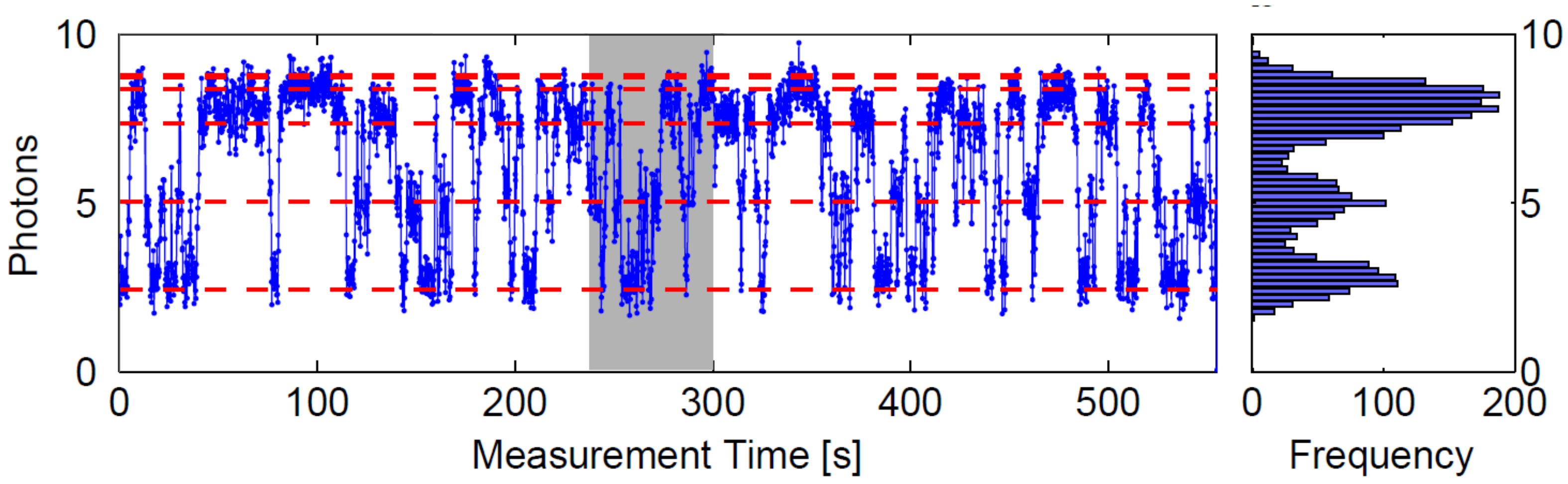
Drive Motion

Mg RSB

Mg Detect

Coherent state amplitude:

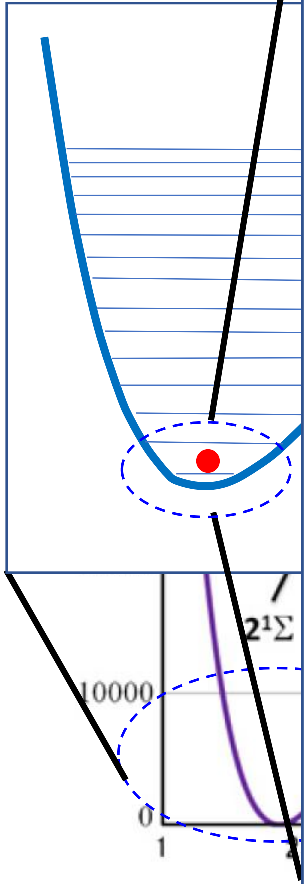
$$|\beta^{(m)}| = \frac{\eta\left(\Omega_0\langle\tfrac{5}{2},m;1,1|\tfrac{7}{2},m+1\rangle\right)^2 t_d}{|\Delta_m|}$$

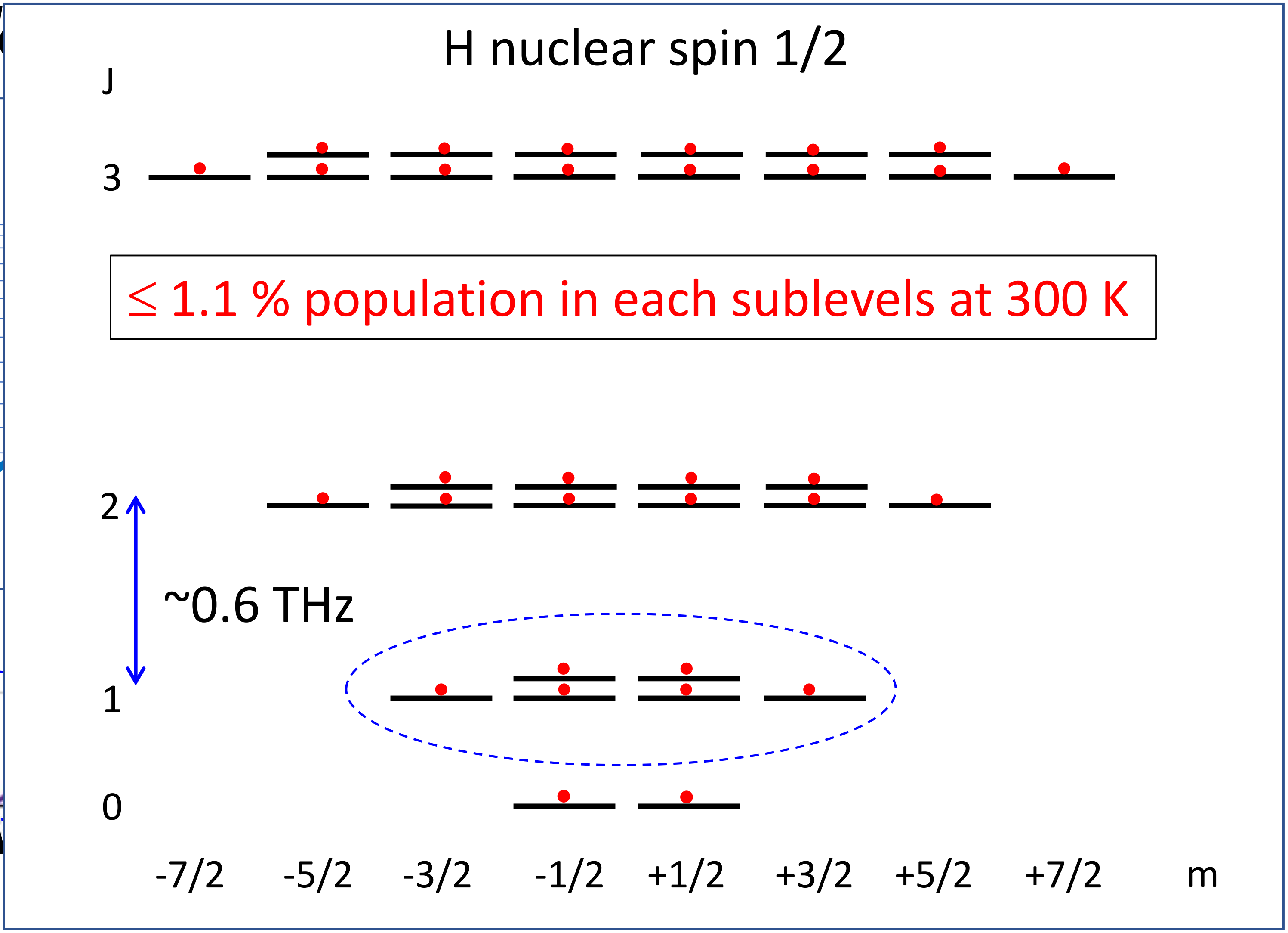


Hume PRL, **107**, 243902 (2011)

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

- Ro



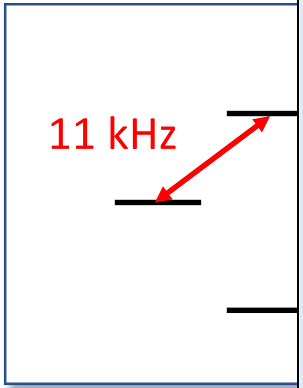


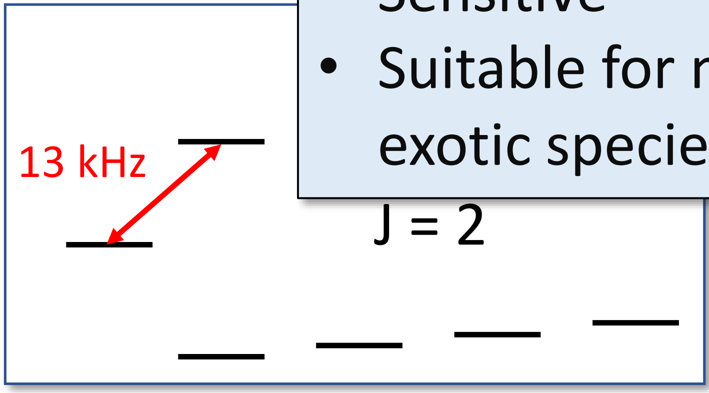
$\leq$ 1.1 % population in each sublevels at 300 K

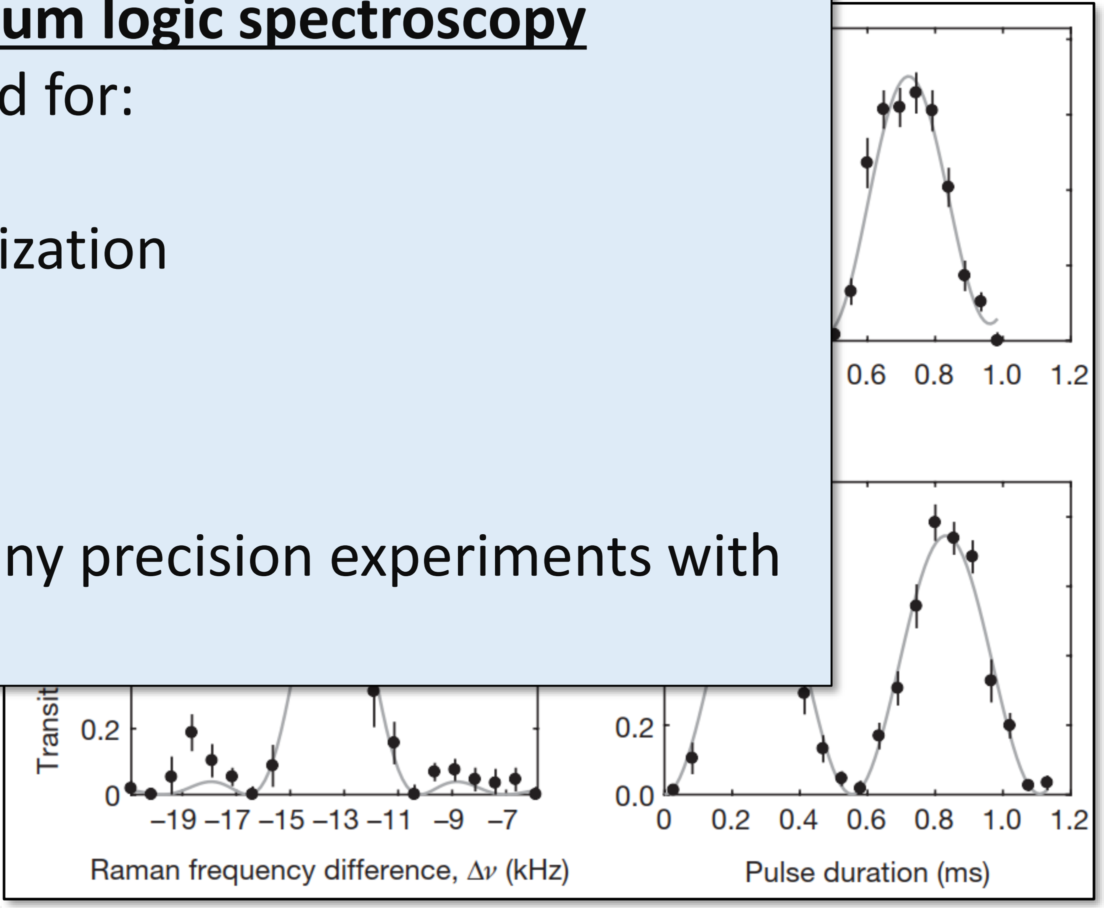
M. Abe et al., Chem. Phys. Lett. 521, 31 (2012)

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

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

Correlation Spectroscopy: Projection Noise Limit

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

Oscillation frequency

Atom number

Free-evolution period

Total measurement duration

- 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

Chwalla et al., App. Phys. B **89** 483 (2007)

Chou, *et al.*, PRL **106**, 160801 (2011)

Marti et al., PRL **120**, 103201 (2018)

2 atom Ramsey experiment

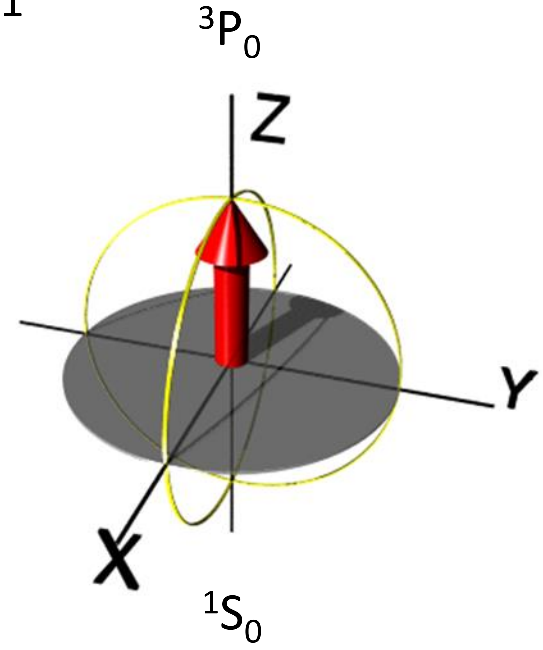
$\pi/2$

Free evolution, T

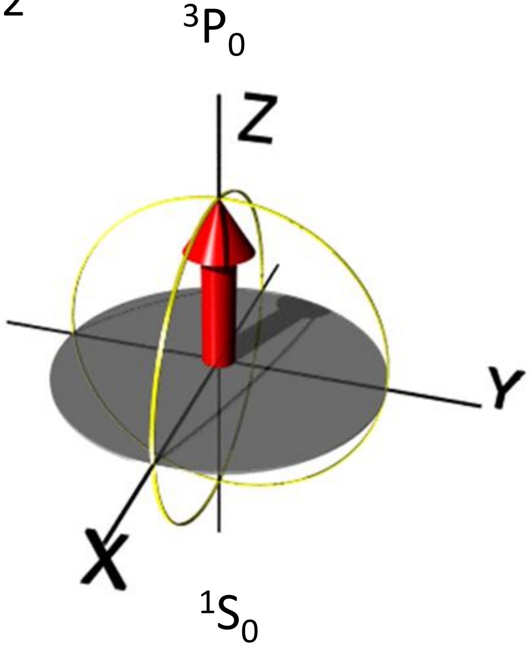
$\pi/2$
$d\varphi$

Detection

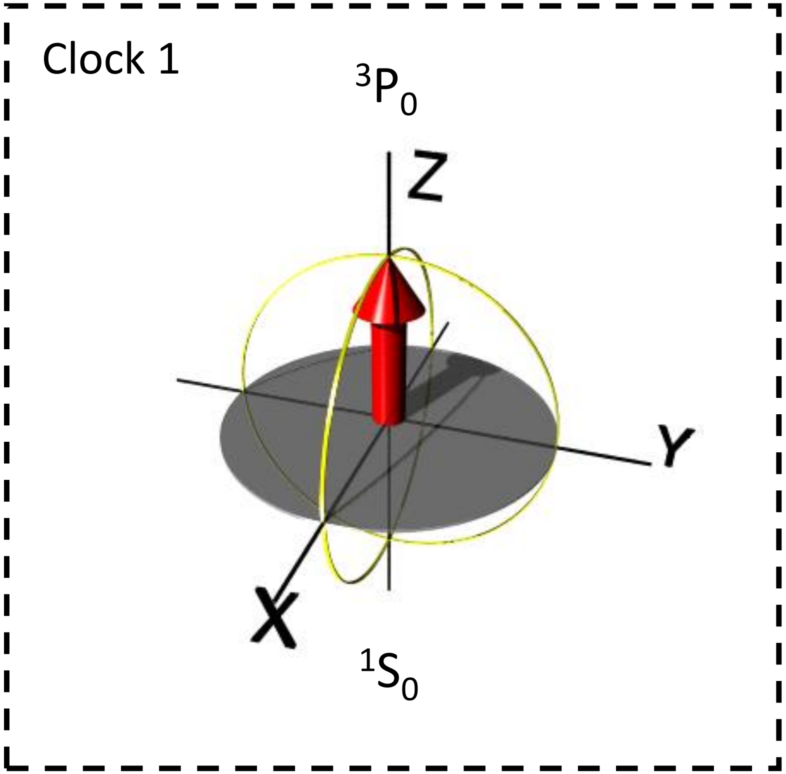
Clock 1

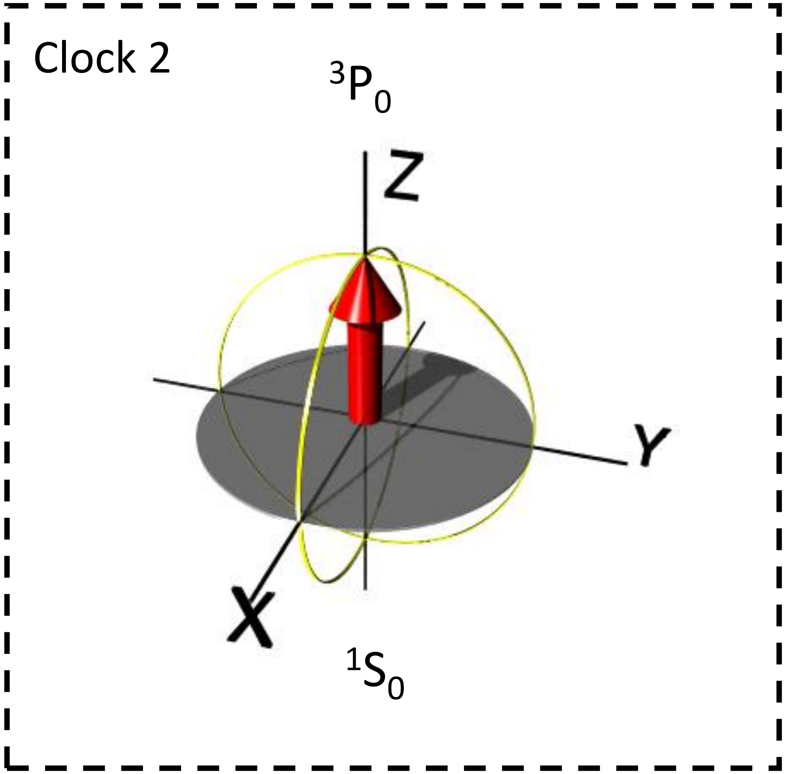


Clock 2



2 atom Ramsey experiment


Clock 1


Clock 2

2 atom Ramsey experiment

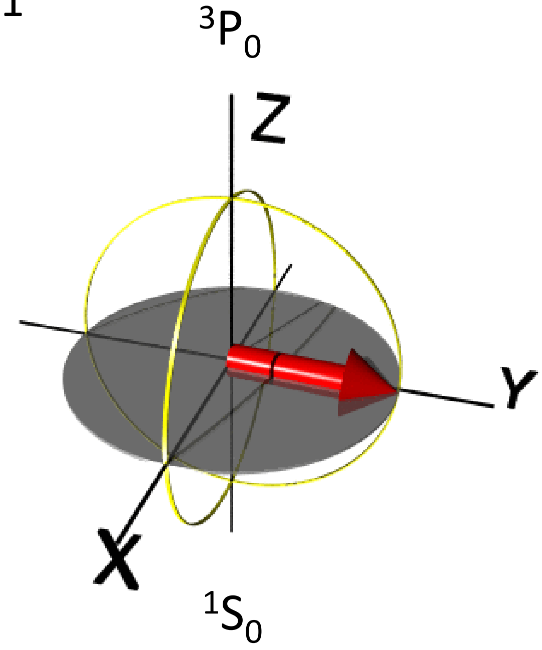
$\pi/2$

Free evolution, T

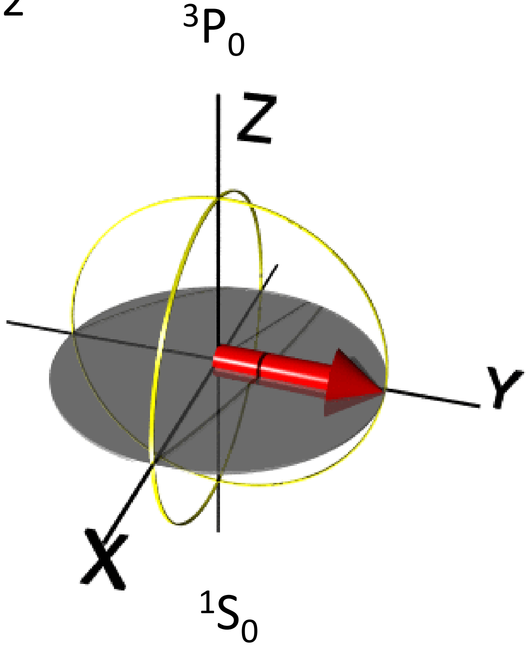
$\pi/2$ $d\varphi$

Detection

Clock 1



Clock 2



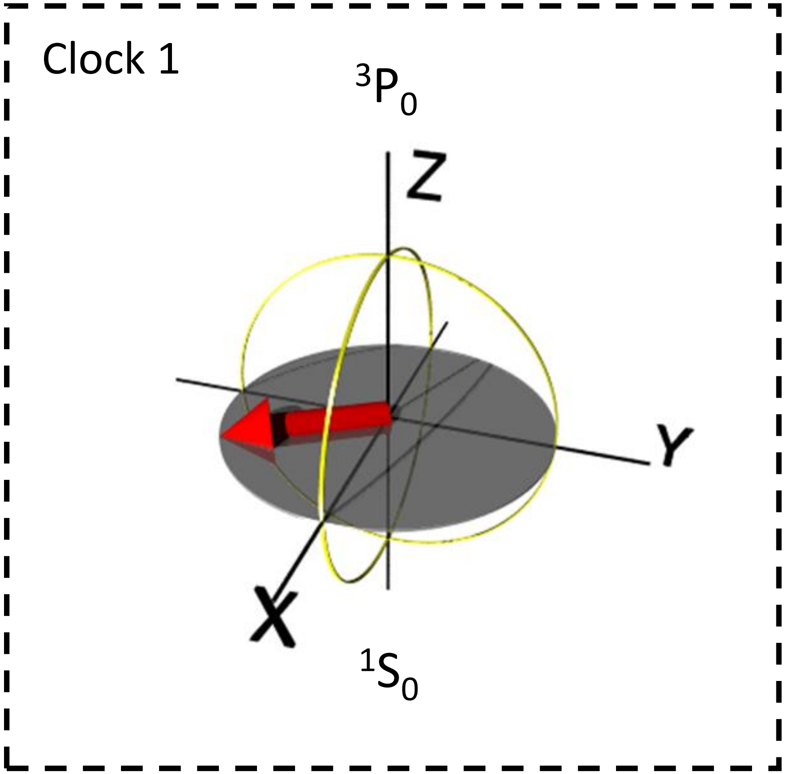
2 atom Ramsey experiment

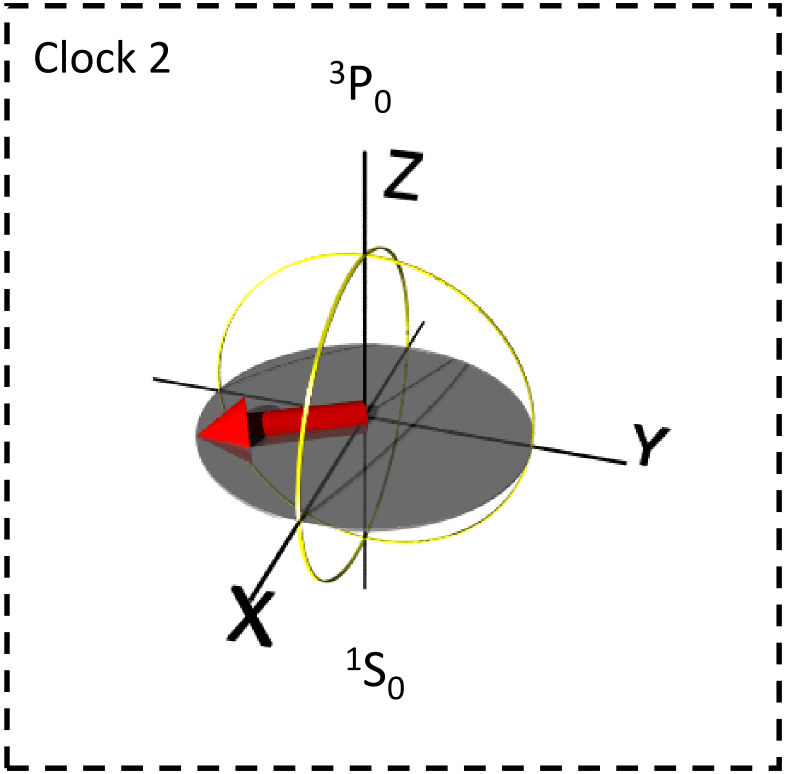
$\pi/2$

Free evolution, T

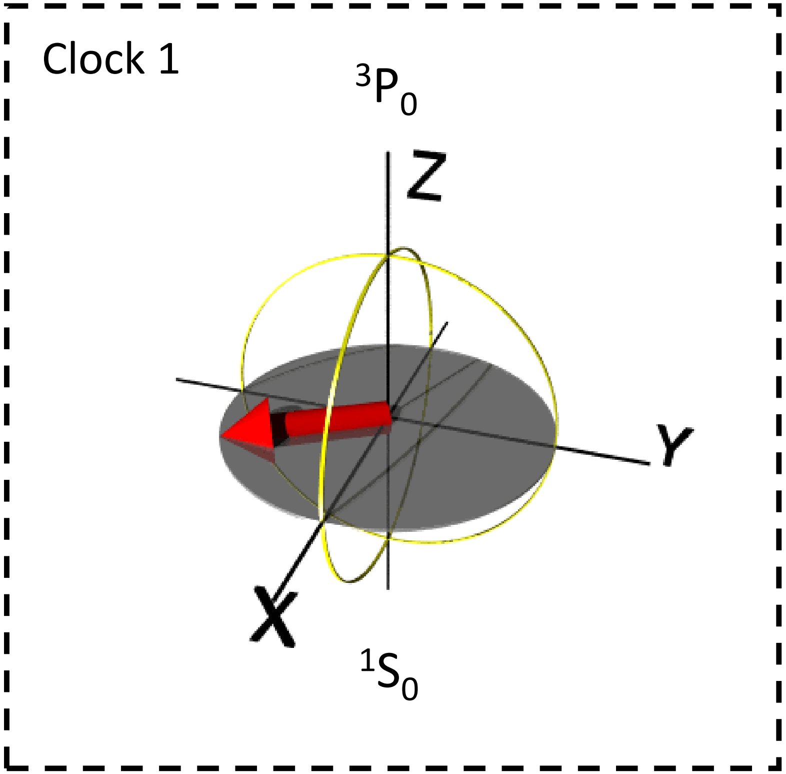
$\pi/2$
$d\varphi$

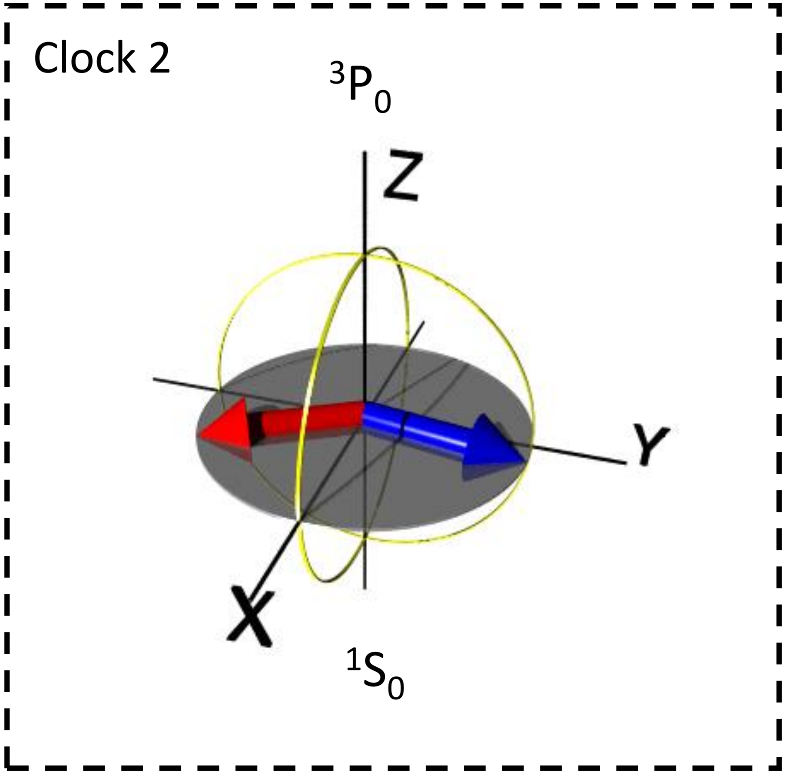
Detection





2 atom Ramsey experiment

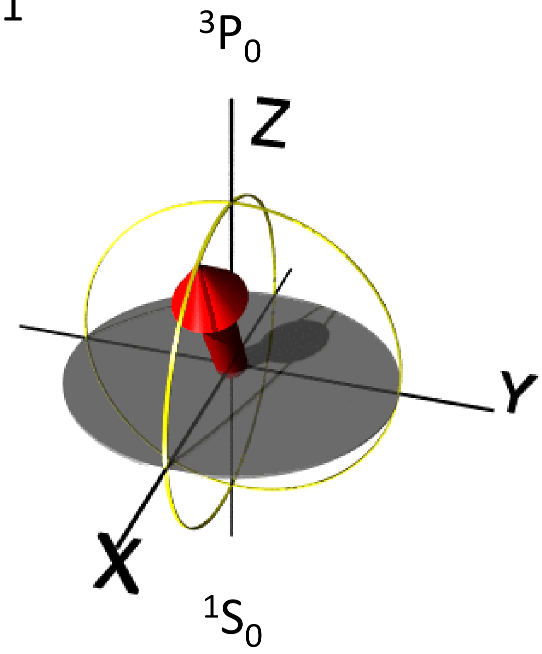




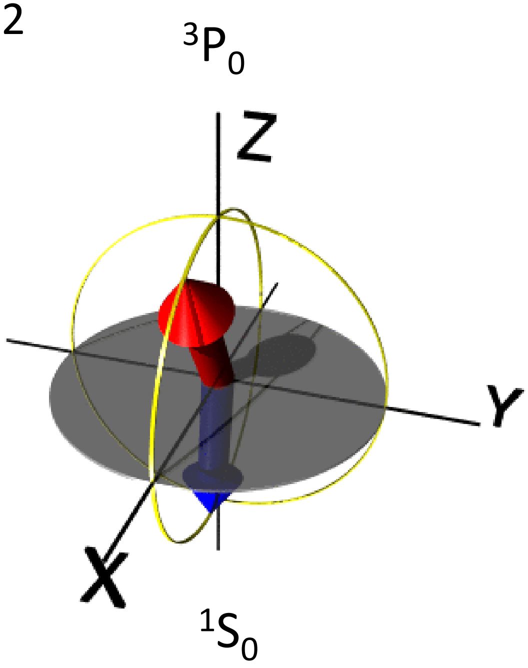
2 atom Ramsey experiment

$\pi/2$ | Free evolution, T | $\pi/2$ $d\varphi$ | Detection

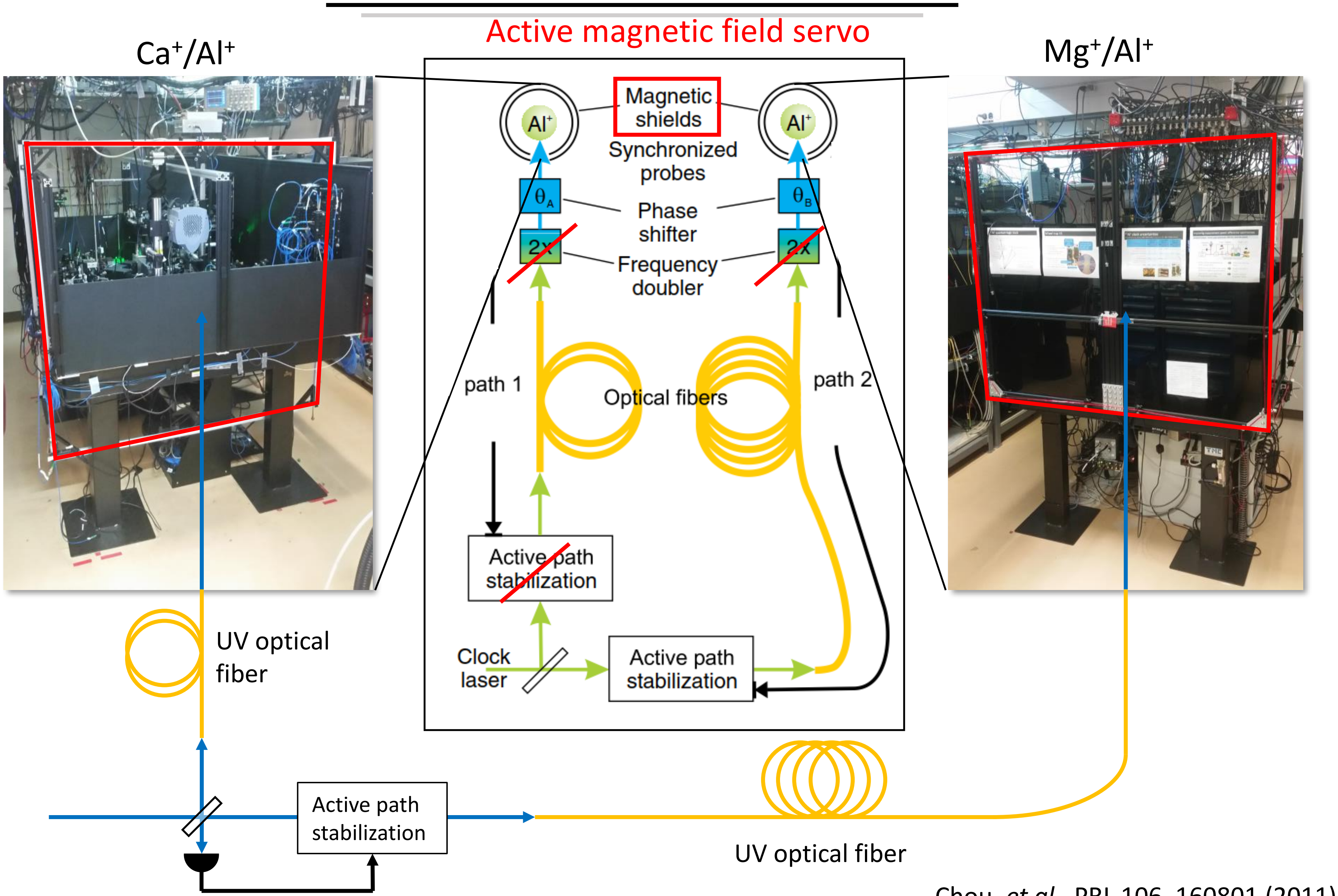
Clock 1



Clock 2



Correlation Spectroscopy between 2 Clocks

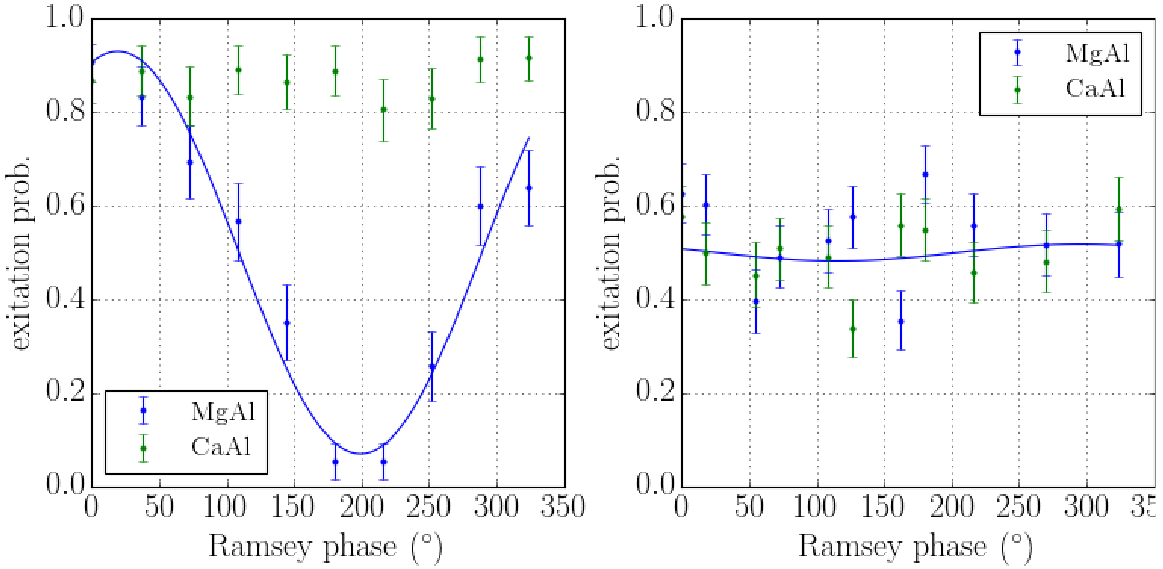


Chou, *et al.*, PRL 106, 160801 (2011)

UV Optical Coherence at 1 s

T = 0.05 s

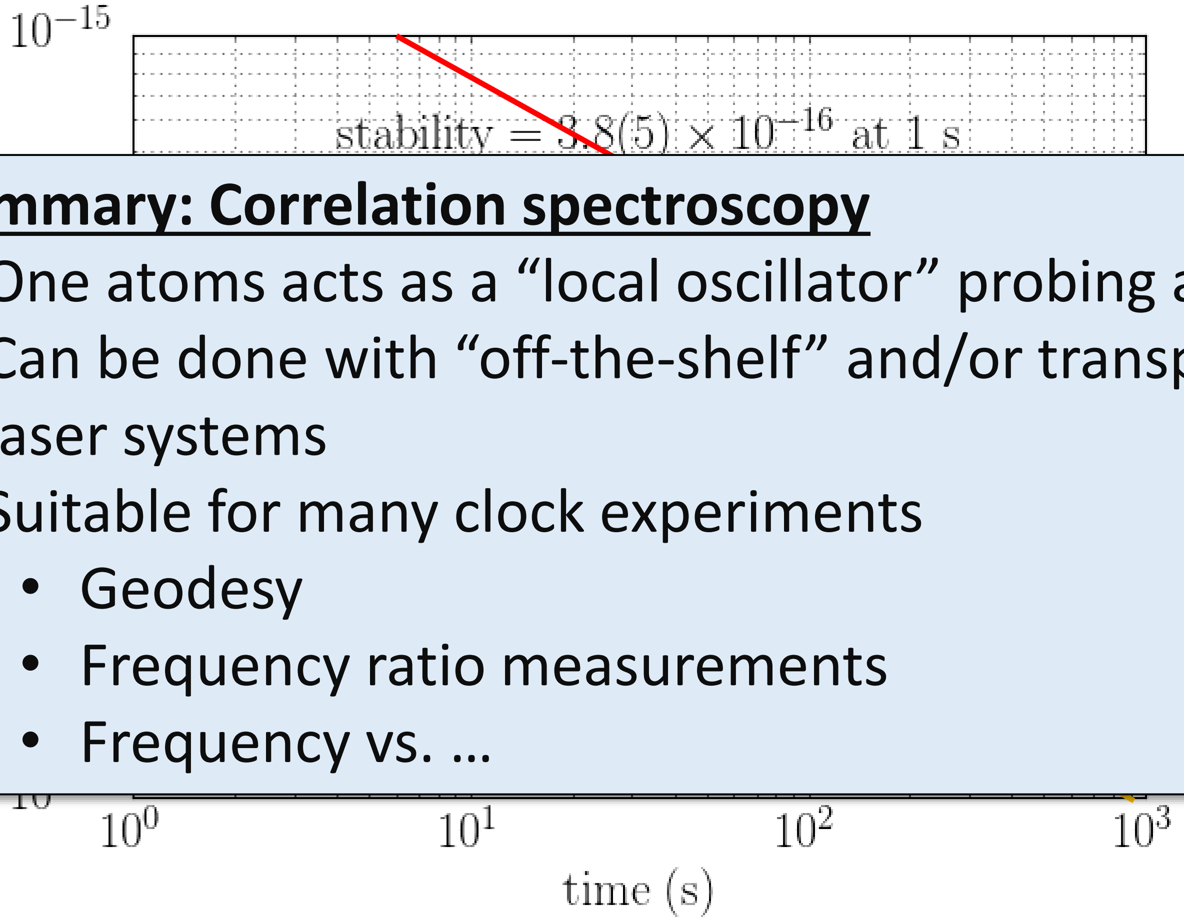
T = 1 s



Within laser
coherence time

Laser – Atom
coherence lost

Correlation Spectroscopy Stability



Summary: Correlation spectroscopy

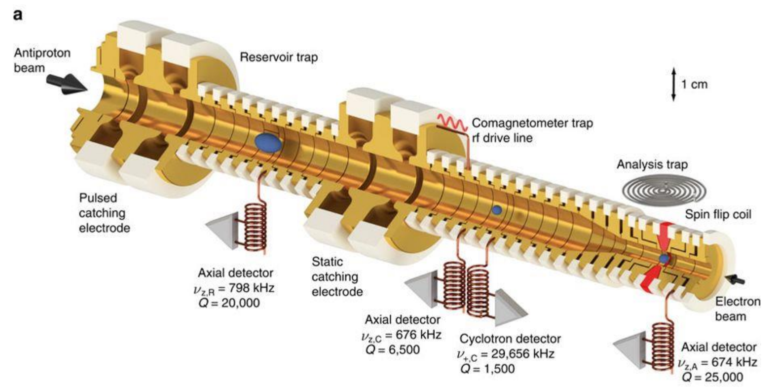
- One atoms acts as a “local oscillator” probing another
- Can be done with “off-the-shelf” and/or transportable laser systems
- Suitable for many clock experiments
  - Geodesy
  - Frequency ratio measurements
  - Frequency vs. …

-Al
ent

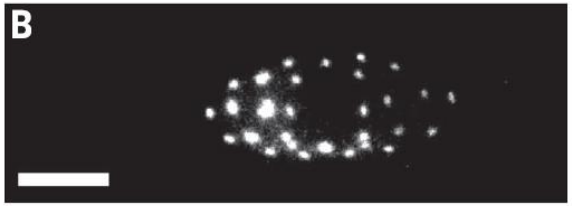
ion in
ime!

Trends in Trapped Ion Experiments

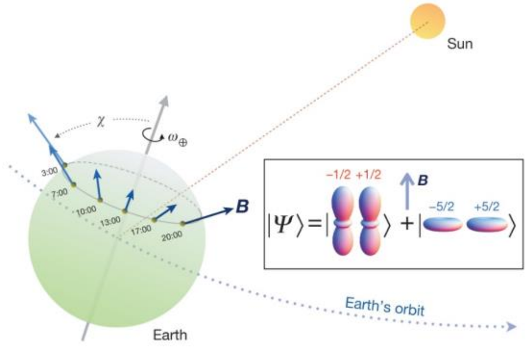
- Expansion of quantum control and precision measurement to new previously inaccessible systems (low, medium and high energies)
  - new atomic systems, molecules, antimatter, highly-charged ions
- Precision measurements adopting techniques from quantum information processing
  - Quantum-enhanced metrology, 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)

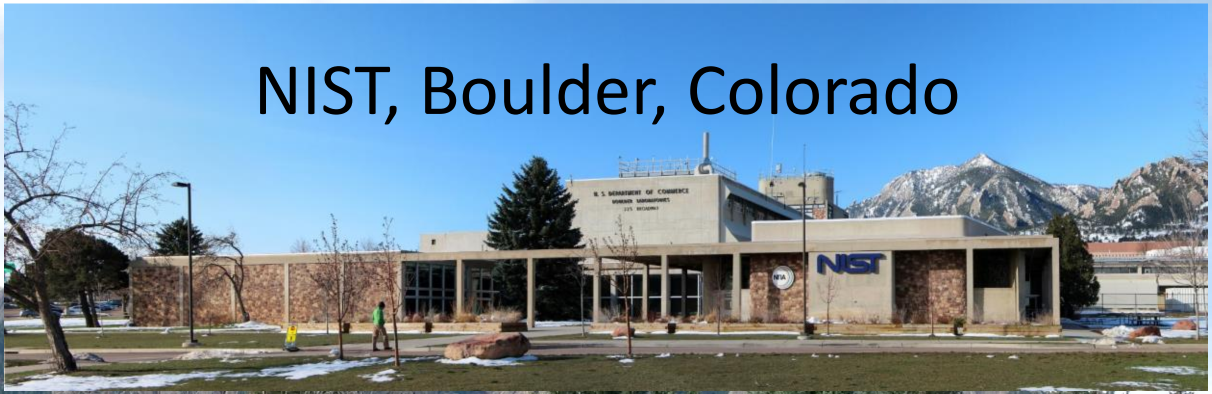


Schmoeger *et al. Science* **347**, 1243 (2015)

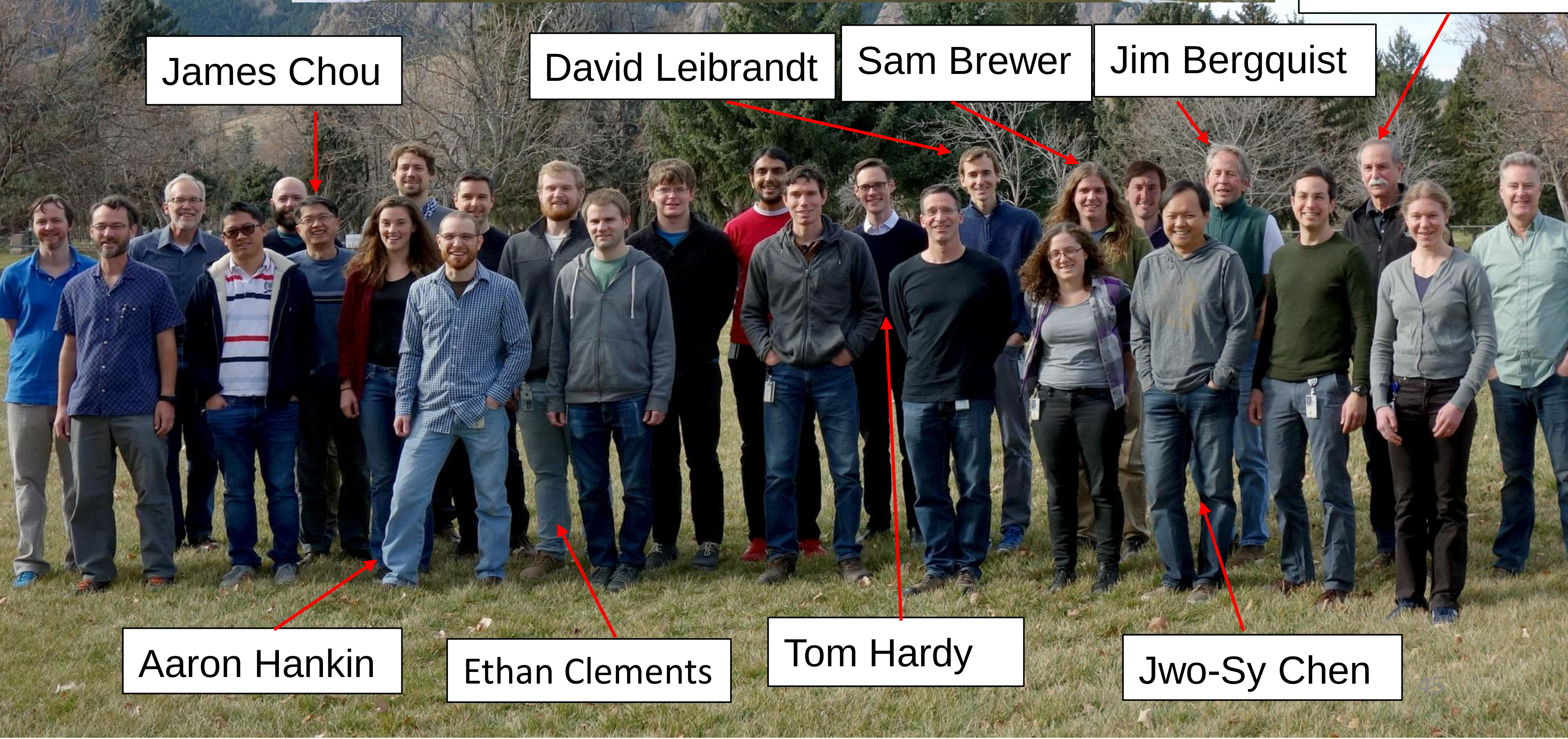


T Pruttivarasin *et al. Nature* **517**, 592-595 (2015)

Thanks!



NIST, Boulder, Colorado



James Chou

David Leibrandt

Sam Brewer

Jim Bergquist

David Winelan

Aaron Hankin

Ethan Clements

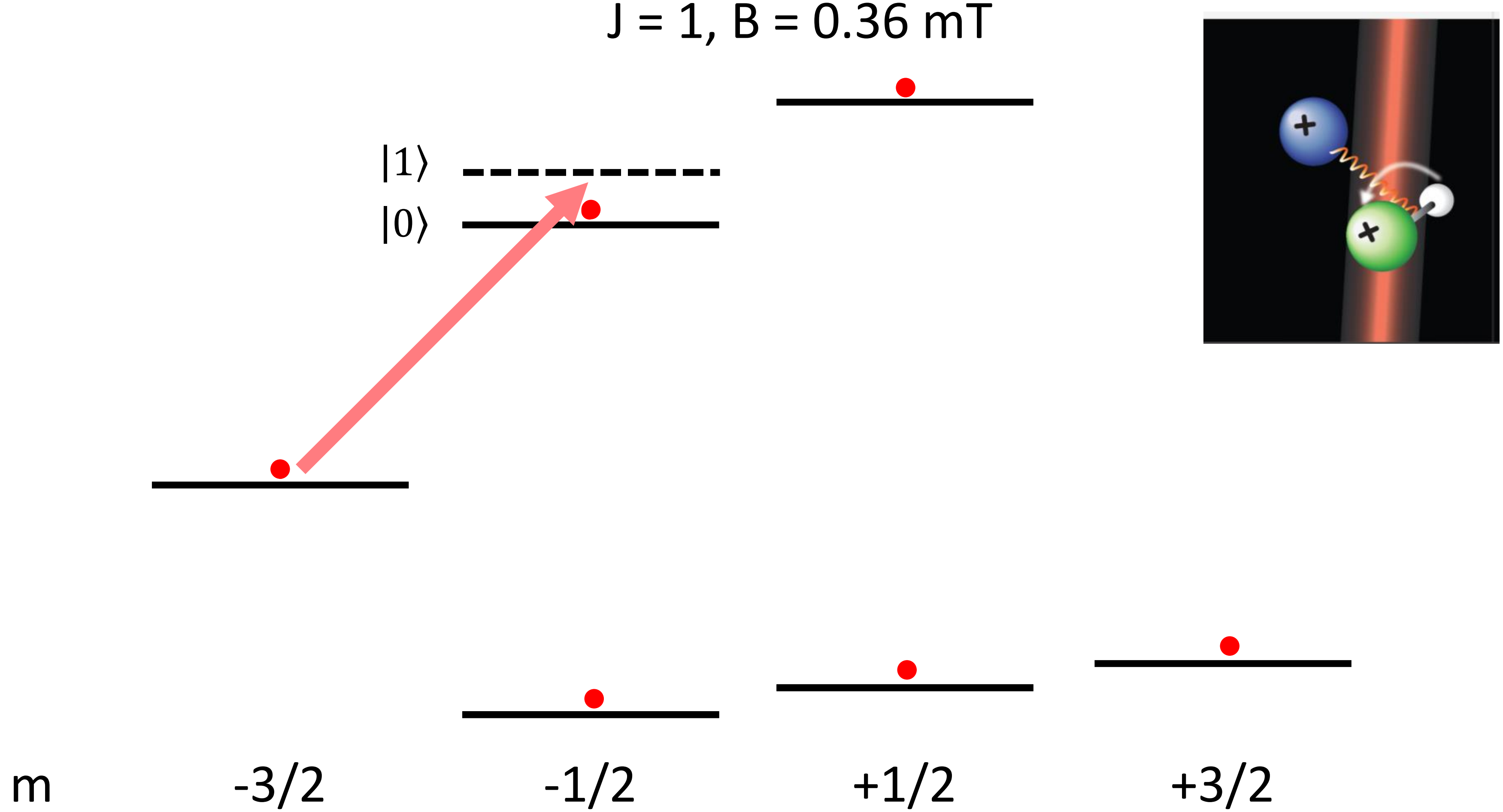
Tom Hardy

Jwo-Sy Chen

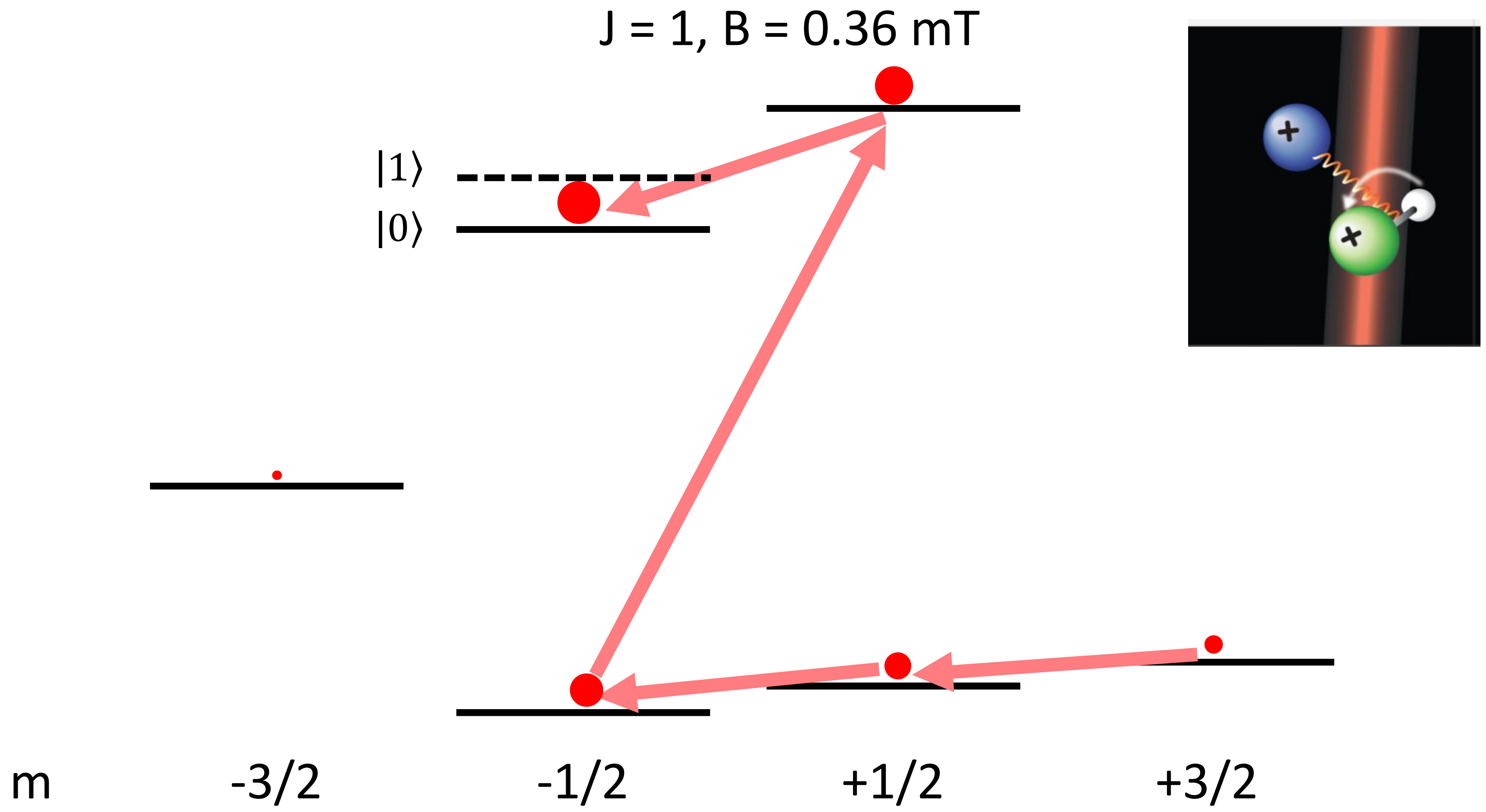
Backup Slides

CaH+ Optical Pumping

J = 1, B = 0.36 mT

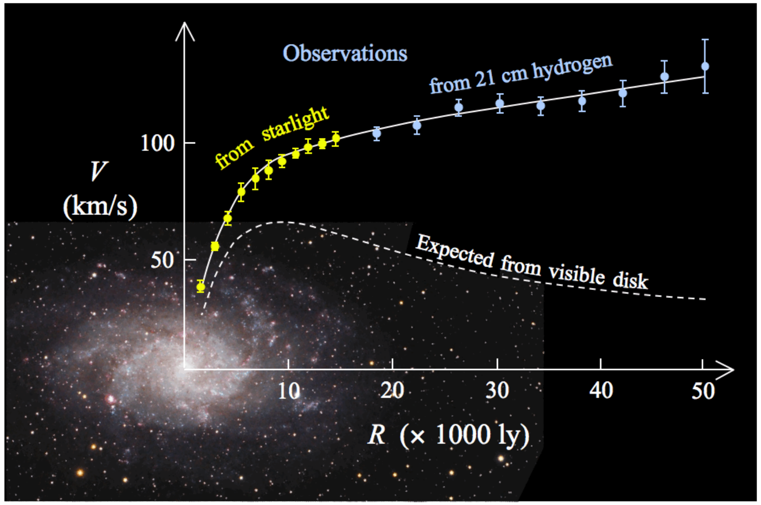


CaH+ Optical Pumping

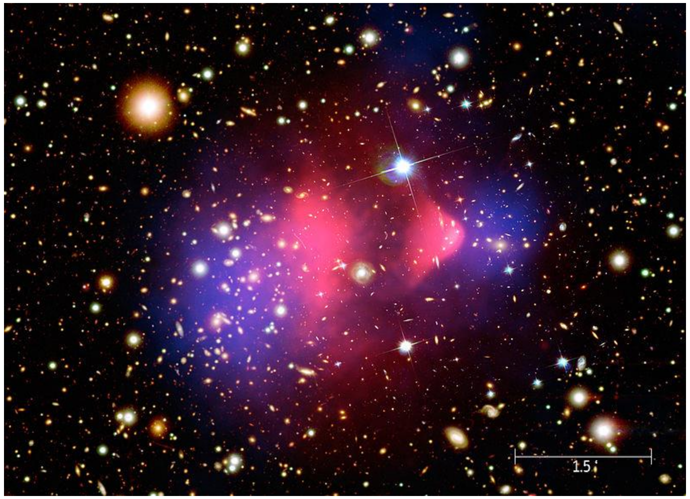


Dark Matter

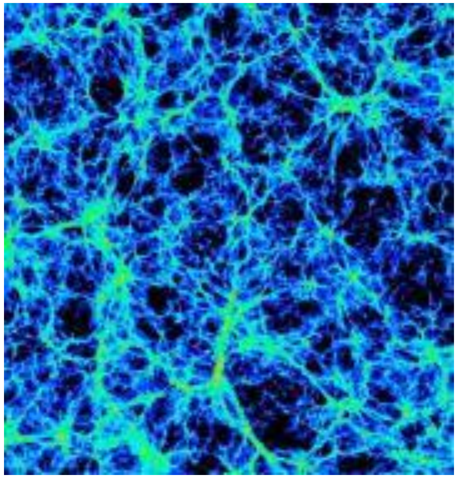
Galactic Rotation Curves



Gravitational Lensing

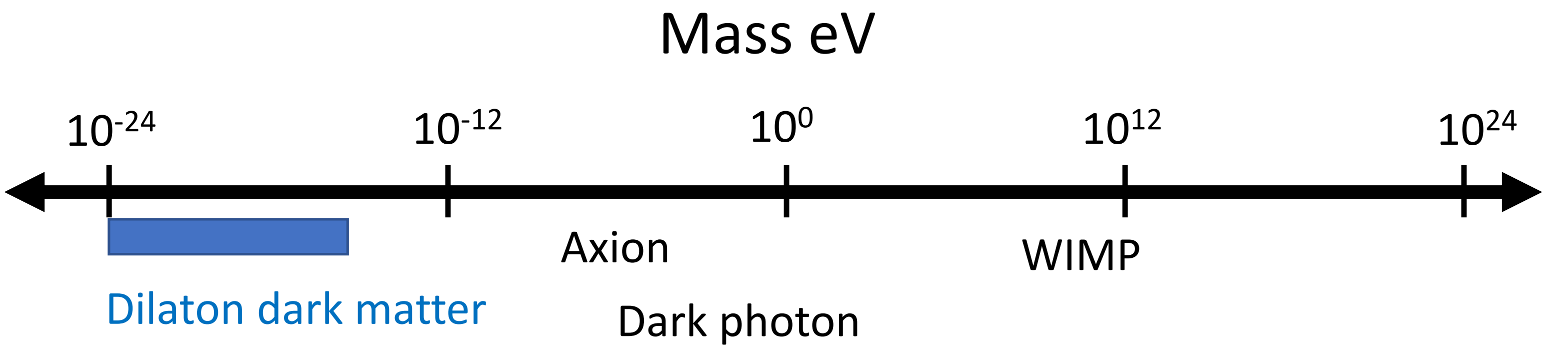


Large-Scale Structure Formation

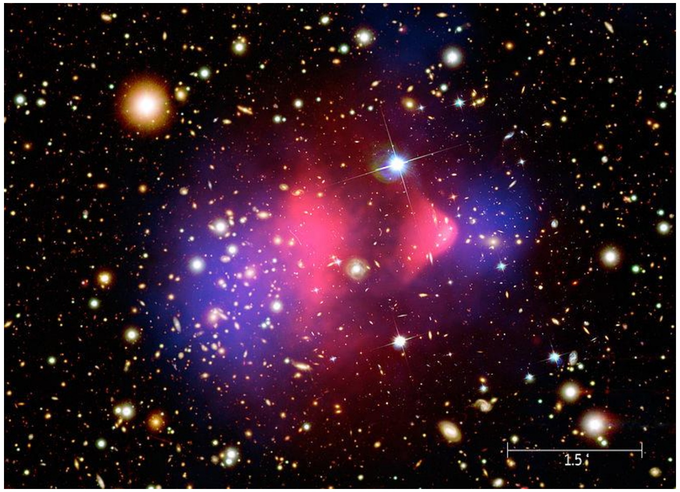


- Multiple, consistent lines of evidence indicate predominance of dark matter over normal matter
- No direct observation on Earth

Dark Matter as an Ultralight Particle



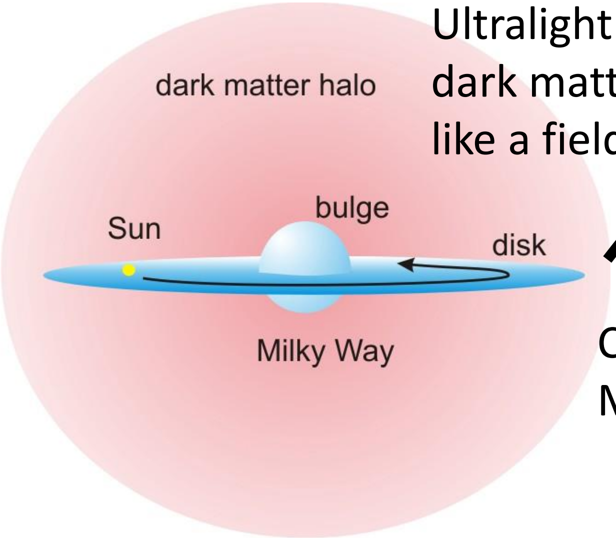
Dilaton dark matter
Fuzzy dark matter
Wave dark matter
Ultralight bosonic dark matter
Ultralight virialized fields
…



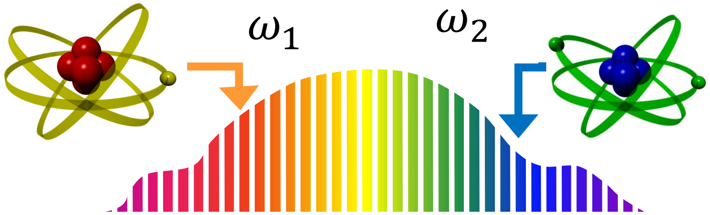
If it is an ultralight particle, what we DO know:

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

Searching for Dark Matter with Clocks



Ultralight ($1\text{x}10^{-25}$ – 10 eV) dark matter particles act like a field ϕ



Coupling to Standard Model Particles

$$R(t) = \frac{\omega_1(t)}{\omega_2(t)}$$

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

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

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

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

A. Arvanataki et al.,Phys. Rev. D **91**, 015015 (2015)

Y. V. Stadnik and V. V. Flambaum, Phys. Rev. Lett. **115**, 201301 (2015)

A. Derevianko and M. Pospelov., Nature Phys. **10**, 933 (2014)

Y. V. Stadnik and V. V. Flambaum, PRA **93**, 063630 (2016)

Dark Matter Field Coupling to α

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

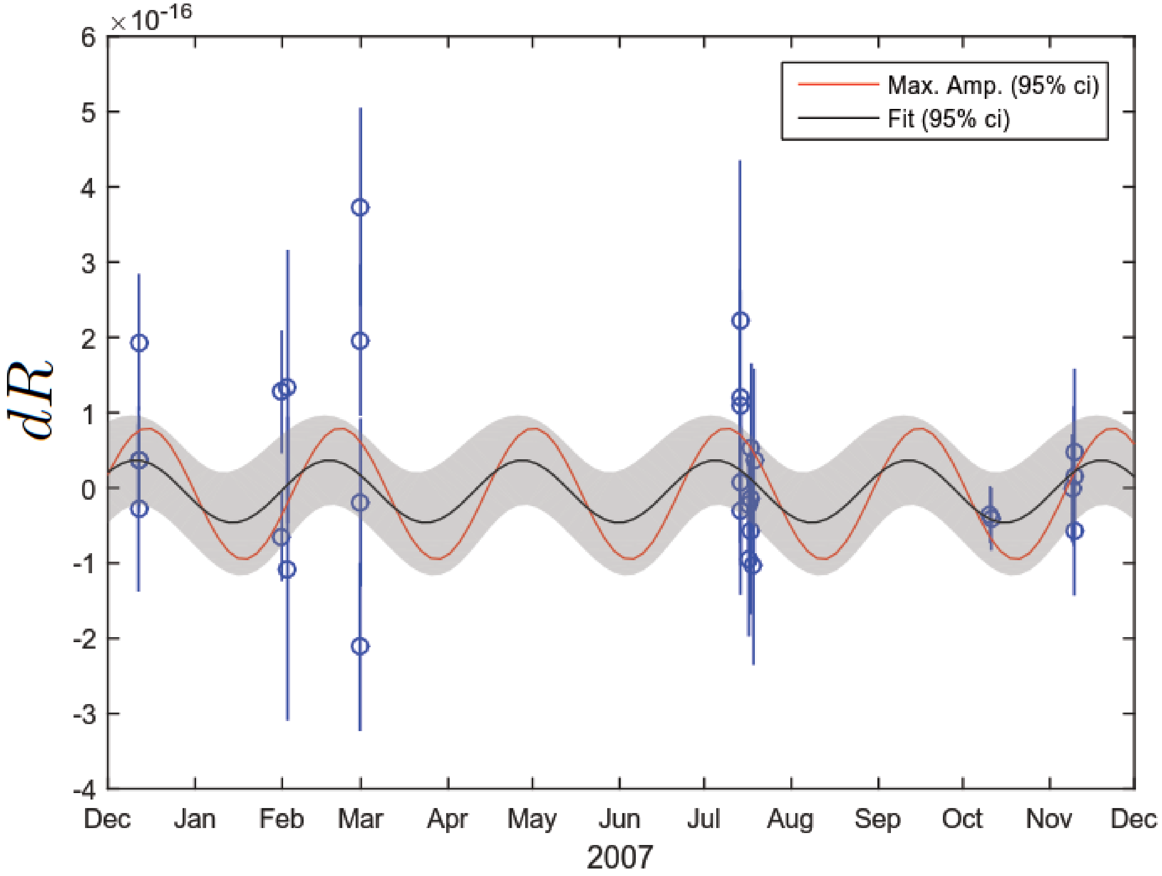
$$\omega_{DM} = \frac{m_\phi c^2}{\hbar}$$

- Amplitude of the oscillation dR depends on:
  - Dark matter density ρ_{DM}

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

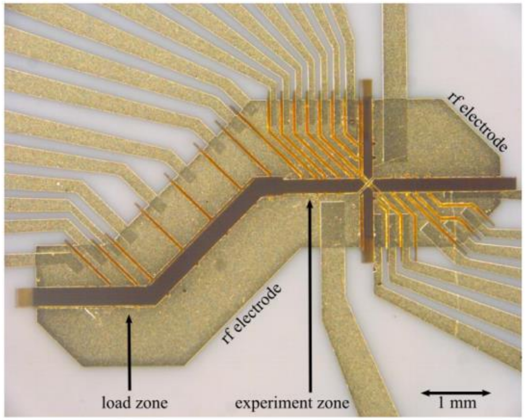
  - Coupling coefficient d_e

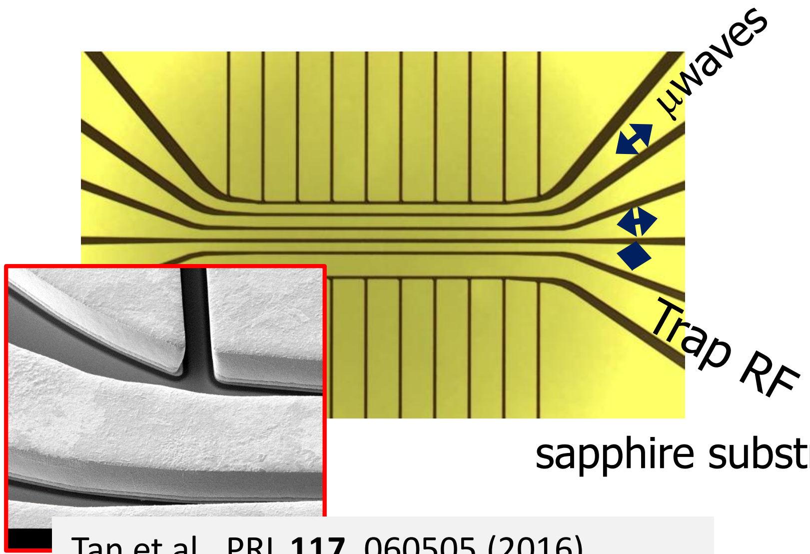
$$R = R_0 + dR\sin(\omega_{DM}t + \phi_{DM})$$



Other work in the Ion Storage Group

Quantum information processing

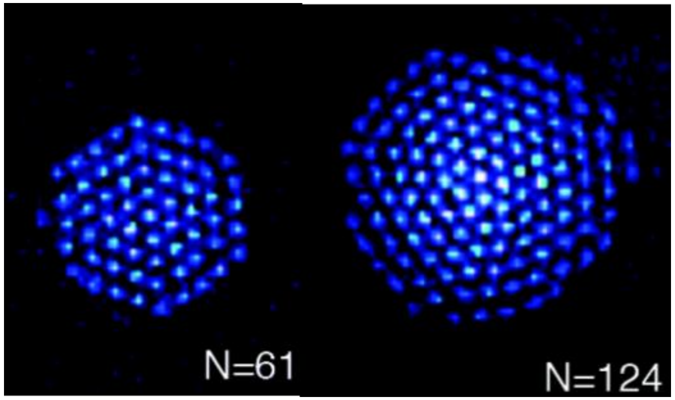




sapphire substrate

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

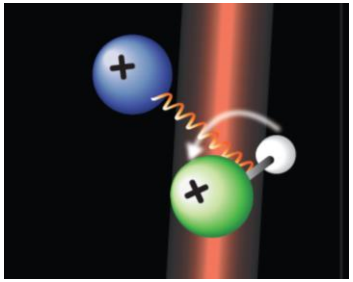
Penning Trap Experiments



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

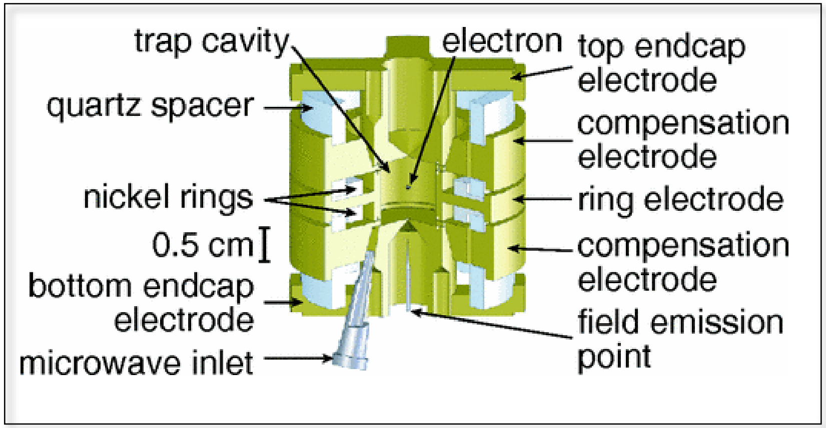
Sources	Fractional Uncertainty (10^{-18})		
	Shift	Uncertainty	Previous clock
Time-dilation: Excess micromotion	-4.7	0.6	-9.0(6.0)
Time-dilation: Secular motion	-1.8	0.3	-16.3(5.0)
BBR shift	-2.6	0.3	-9.0(3.0)
Cooling light shift	0.0	0.0	-3.6(1.5)
Quadratic Zeeman shift	-925.9	0.6	-1079.9(0.7)
Linear 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



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

- Theory

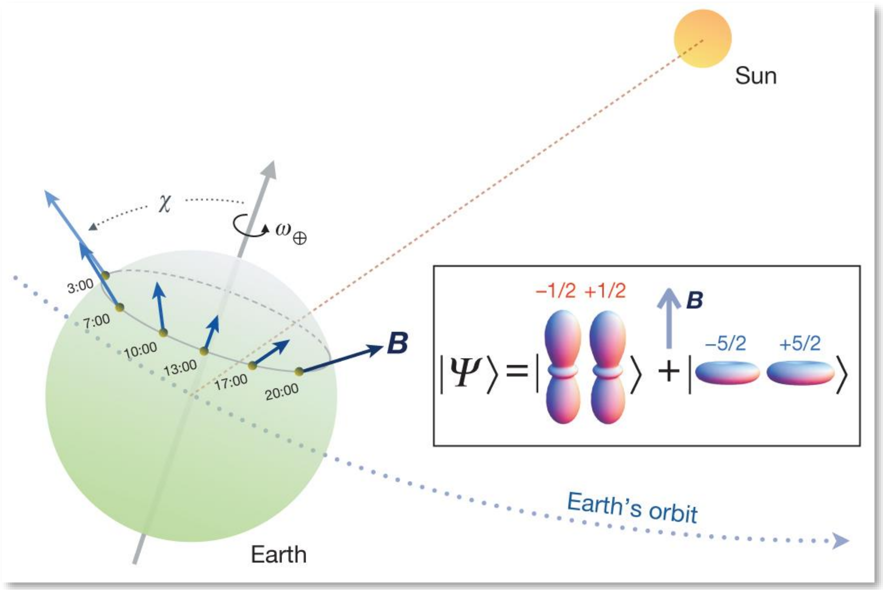
$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

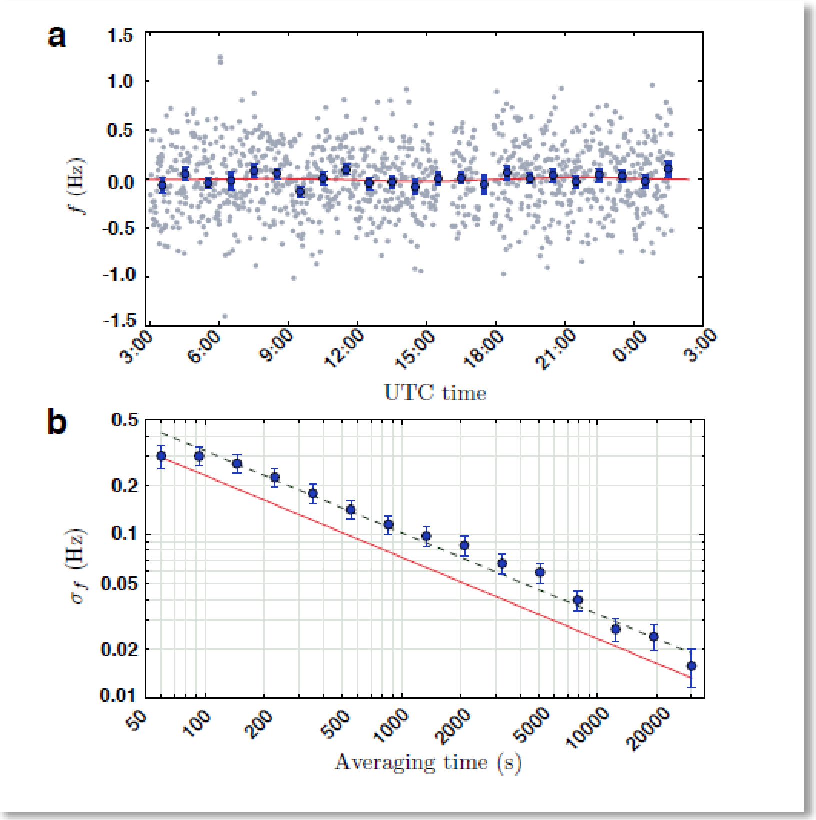
  - Taking α from independent measurements, this is a test of QED
  - Alternately, assuming calculated coefficients and corrections from QED, this is a measurement of α

Hanneke et al., Phys. Rev. Lett. 100, 120801

Test of Lorentz Invariance

Frequency vs. Spatial Orientation



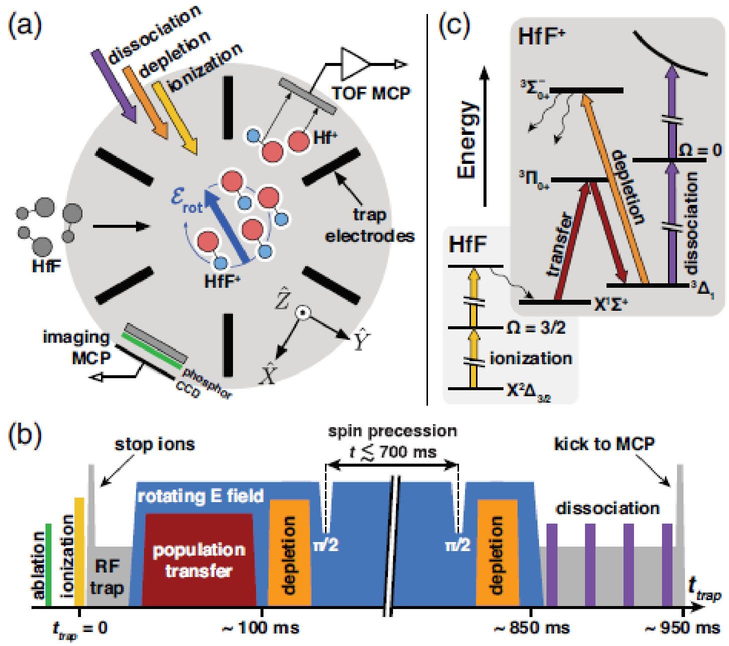


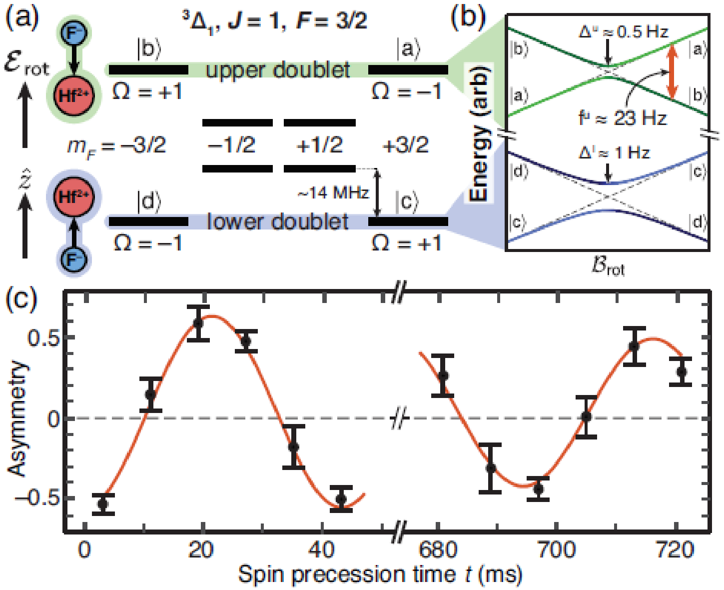
Use a decoherence free subspace of 2 Ca+ ions for long probe times

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

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

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