# *The Physics of Atomic Clocks*

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# *Tutorial Overview*

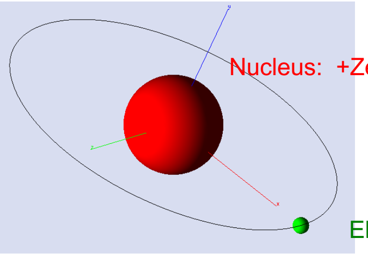
- Atomic physics relevant to clocks
- Physics of key atomic clock techniques
- Key frequency shift effects in clocks
- Some fundamental physics tests using clocks

# ***Atomic Clock Physics***

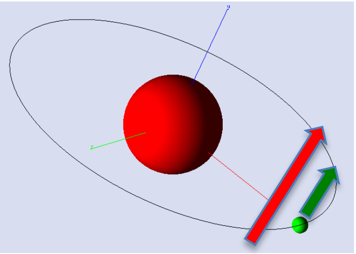
# Basic Microwave Atomic Clock Physics: Atomic Interactions

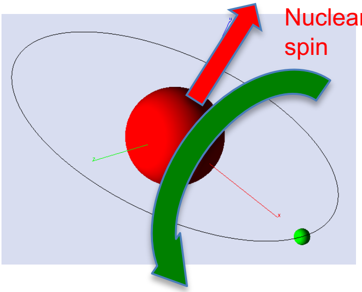
- Hyperfine transitions: 1-40 GHz
- Atomic interactions:
  - **Coulomb** interaction
  - **Fine structure**: electron spin interacts with nuclear electric field (optical)
  - **Hyperfine structure**: nuclear spin interacts with the magnetic field created by the moving electron (microwave)

$$\Delta E = -\frac{1}{4\pi\epsilon_0}\frac{Ze^2}{r}$$



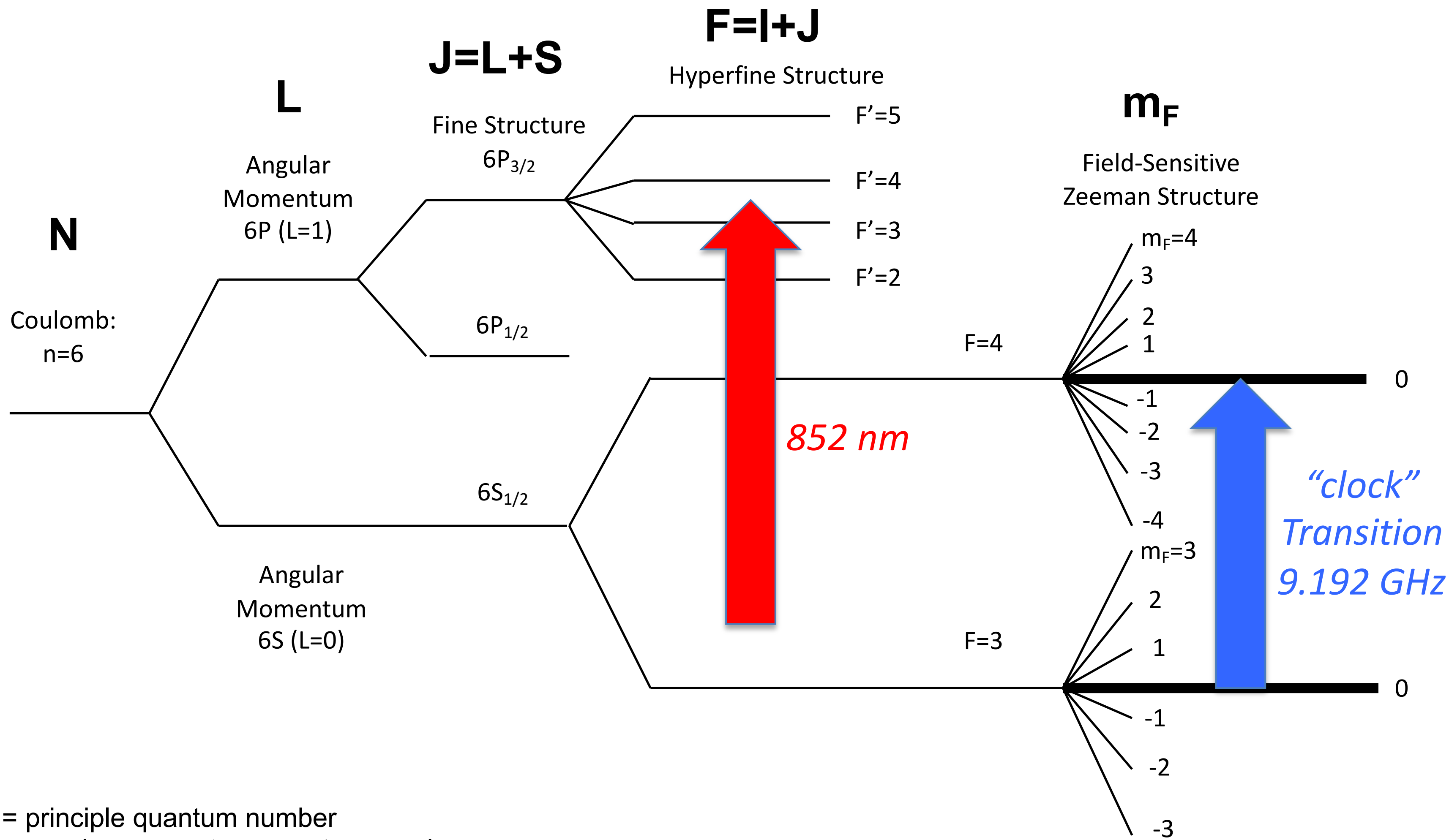

$$\Delta E = -\bar{\mu}_S \cdot \bar{B} = \frac{2\mu_B \bar{s}}{c^2} \cdot (\bar{E} \times \bar{v})$$




$$\Delta E = -\bar{\mu}_N \cdot \overline{B_{el}}$$

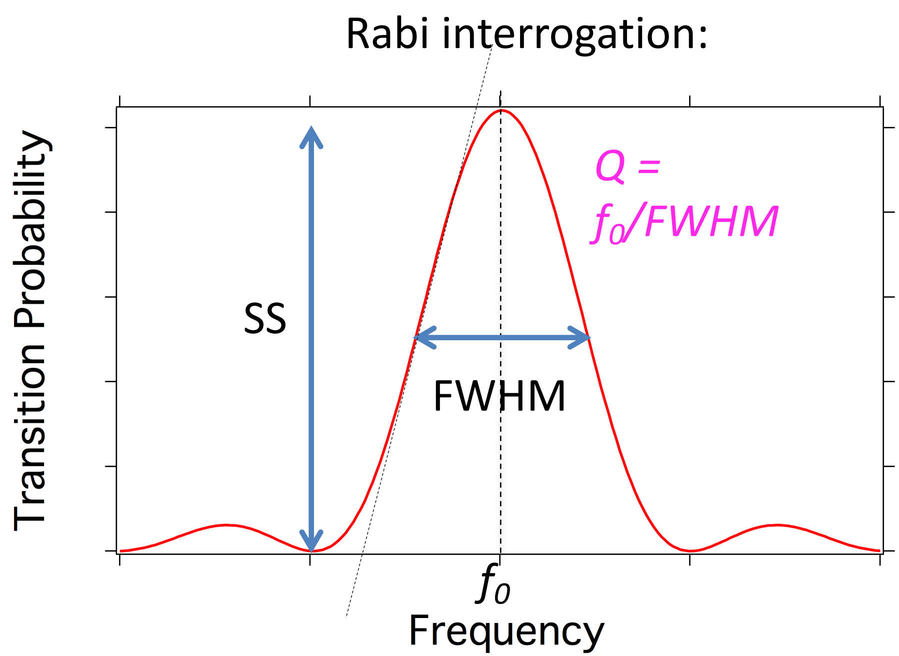
# *Basic Microwave Atomic Clock Physics: Simplified Cesium Atomic Level Structure*




**N** = principle quantum number
**L** = angular momentum quantum number
**S** = electron spin quantum number
**I** = nuclear spin quantum number
**J = L+S**: total electron angular momentum
**F = I + J**: total atomic angular momentum

***Integral F => existence of first-order field-insensitive $m_F$=0 – $m_F$'=0 transition***

# Clock transition line shapes: Clock stability and the Allan Deviation




$$slope = \frac{\pi}{2} \times SS/FWHM$$

$$\sigma(\tau) = \langle \frac{1}{2}[\langle y(t+\tau)\rangle - \langle y(t)\rangle]^2 \rangle^{1/2}$$

$$\sigma(\tau = T_c) = \frac{\Delta f}{f_0} = \frac{\Delta SS}{f_0 \times slope} = \frac{1}{\pi\, SNR\, Q}$$

$$slope = \frac{\pi}{2} \times SS/FWHM$$

$$\Rightarrow \sigma(\tau) \rightarrow \frac{1}{\pi\, SNR\, Q}\sqrt{\frac{T_c}{\tau}} \text{ (White freq.)}$$

$$\sigma(1\, sec) \propto \frac{1}{SNR\, Q}$$

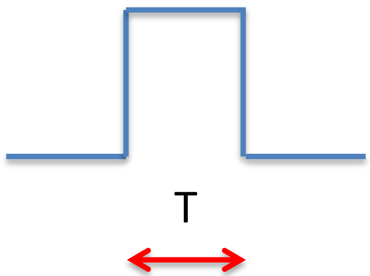
- **SNR** is at SS/2 and is limited by number of atoms
- $\mathbf{f_0}$ is resonance frequency – choice of atom
- **FWHM** is linewidth – measurement time limited

| Example | Q | SNR | Adev (1s) |
|---|---|---|---|
| Rb | 2e7 | 3000 | 2e-11 |
| Cs | 1e7 | 24000 | 5e-12 |
| H-maser | 2e9 | 5000 | 1e-13 |
| $Hg^+$ | 5e12 | 20 | 2e-14 |

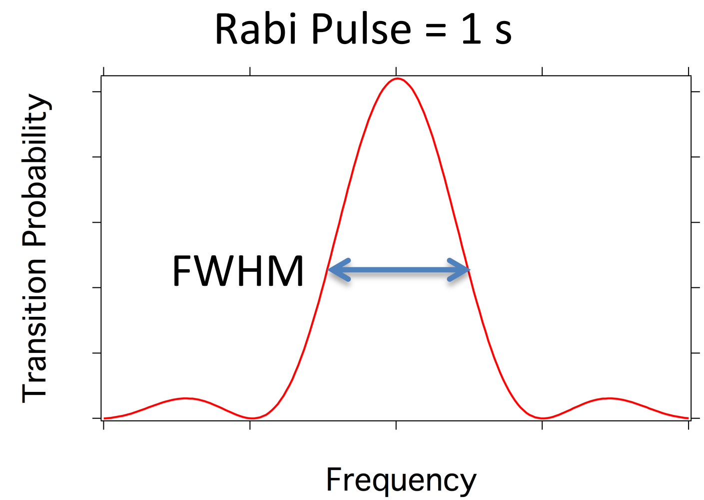
*See NIST Tech. Note 1337, D.B. Sullivan et al., "Characterization of Clocks and Oscillators"*

# *Ramsey vs. Rabi Interrogation*

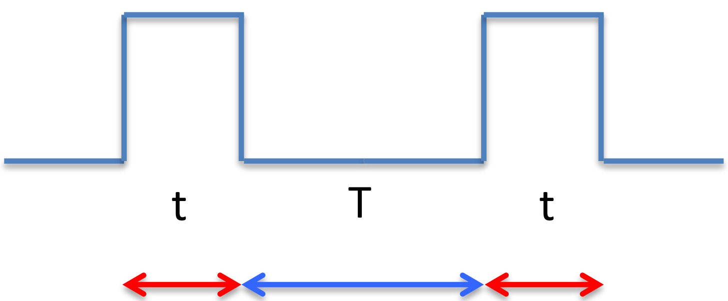
**Rabi**:  microwave pulse on for T

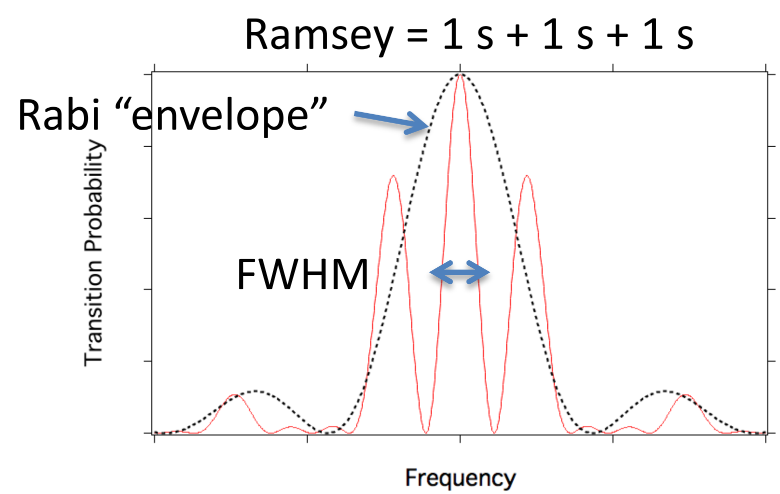



Sinc(x) = sin(x)/x

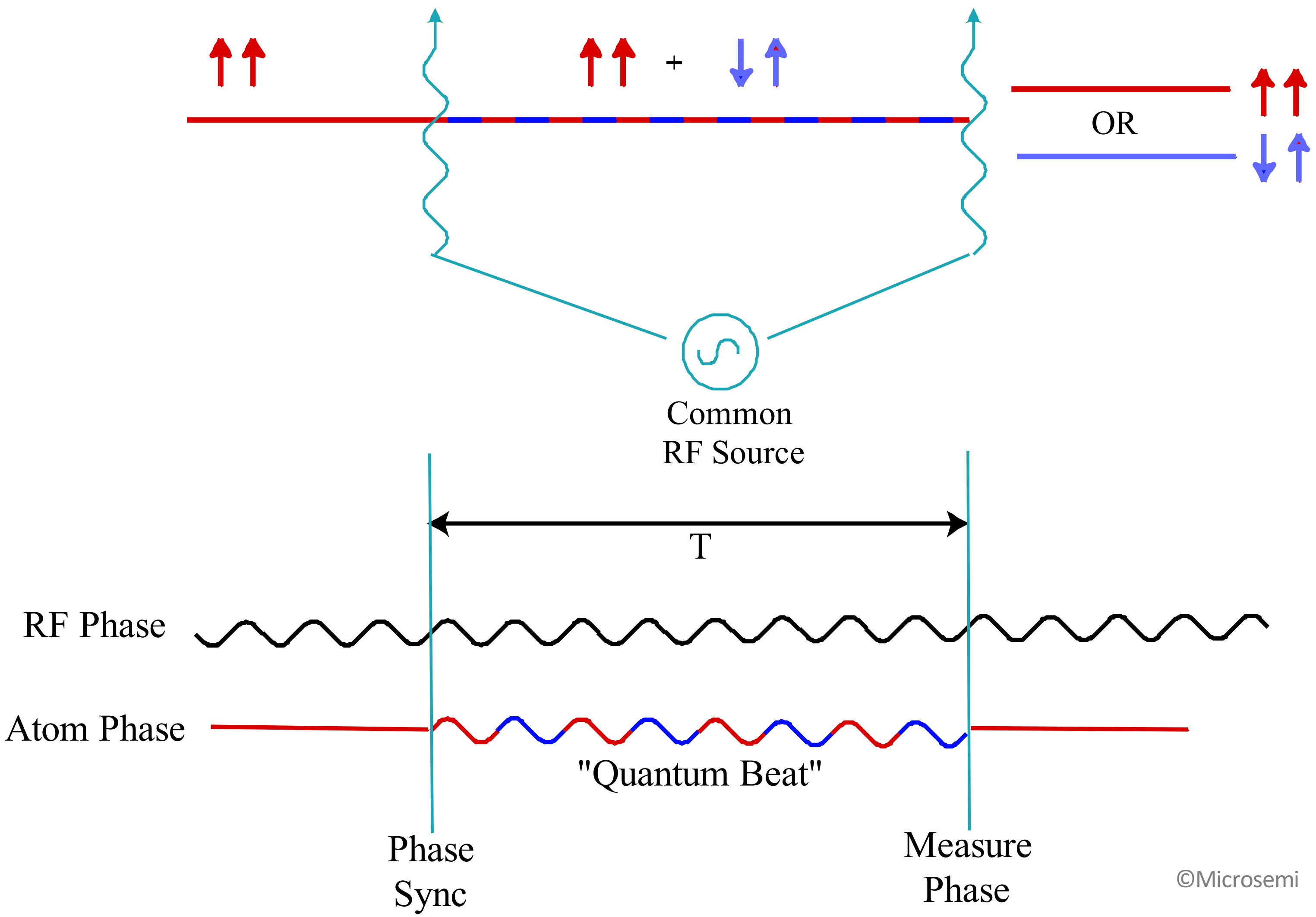



**Ramsey:  a time-domain interferometer**:
two microwave pulses on for t separated by time T



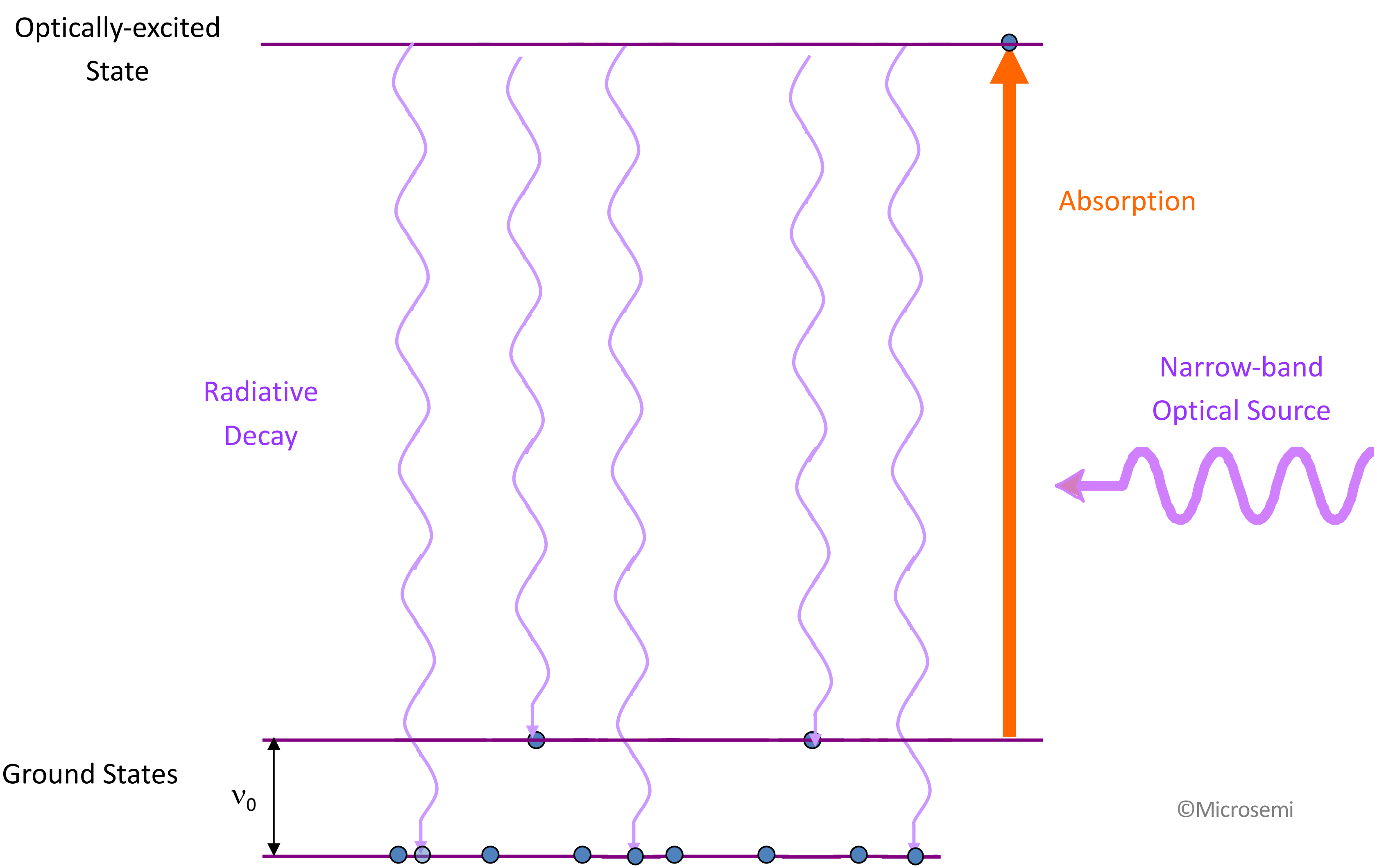
# Basic Microwave Atomic Clock Physics
# Ramsey Separated Oscillatory Fields




*Courtesy of Microsemi*

# ***State selection:***

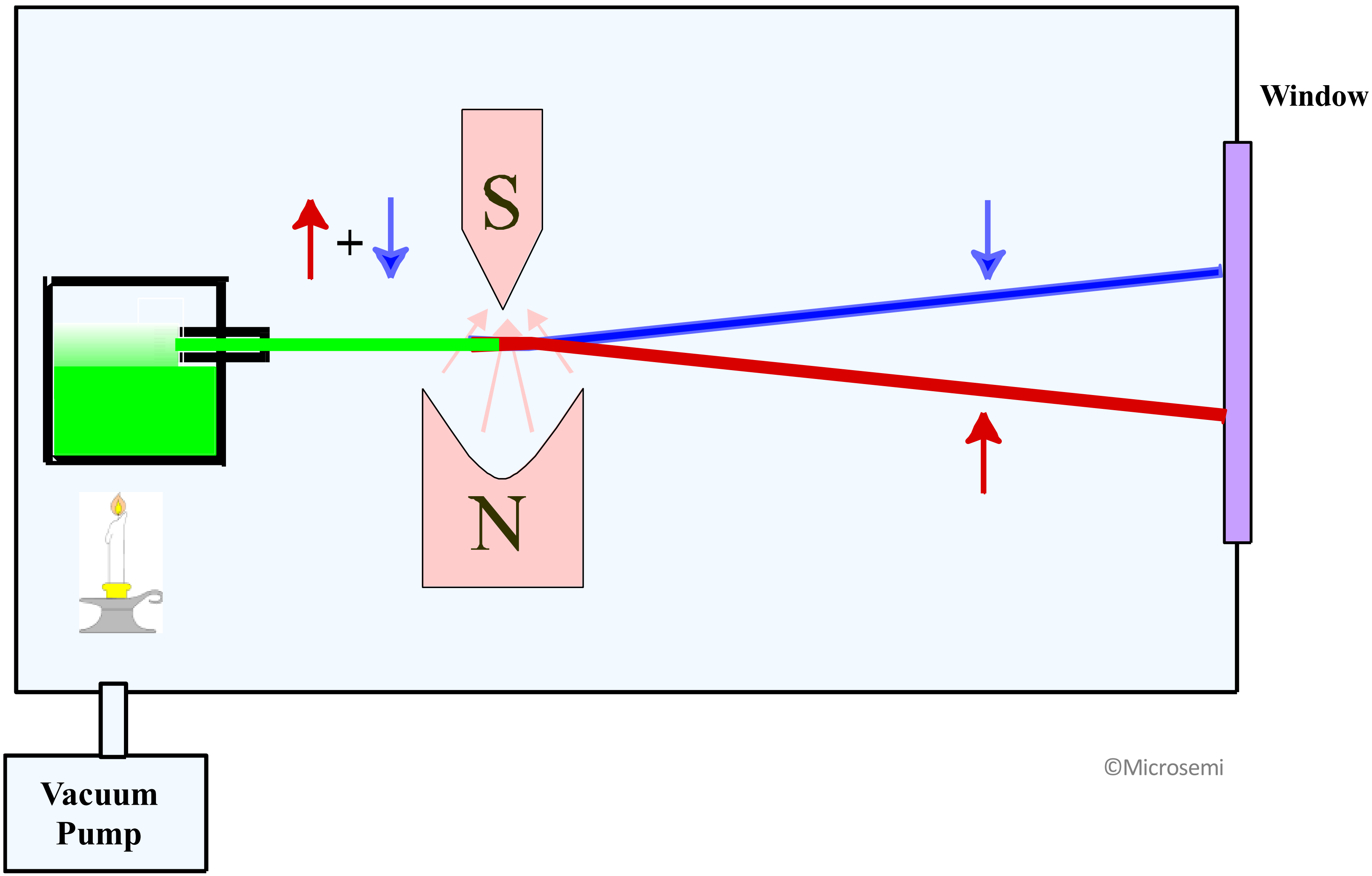
Initialize into the right state using optical pumping






*Courtesy of Microsemi*

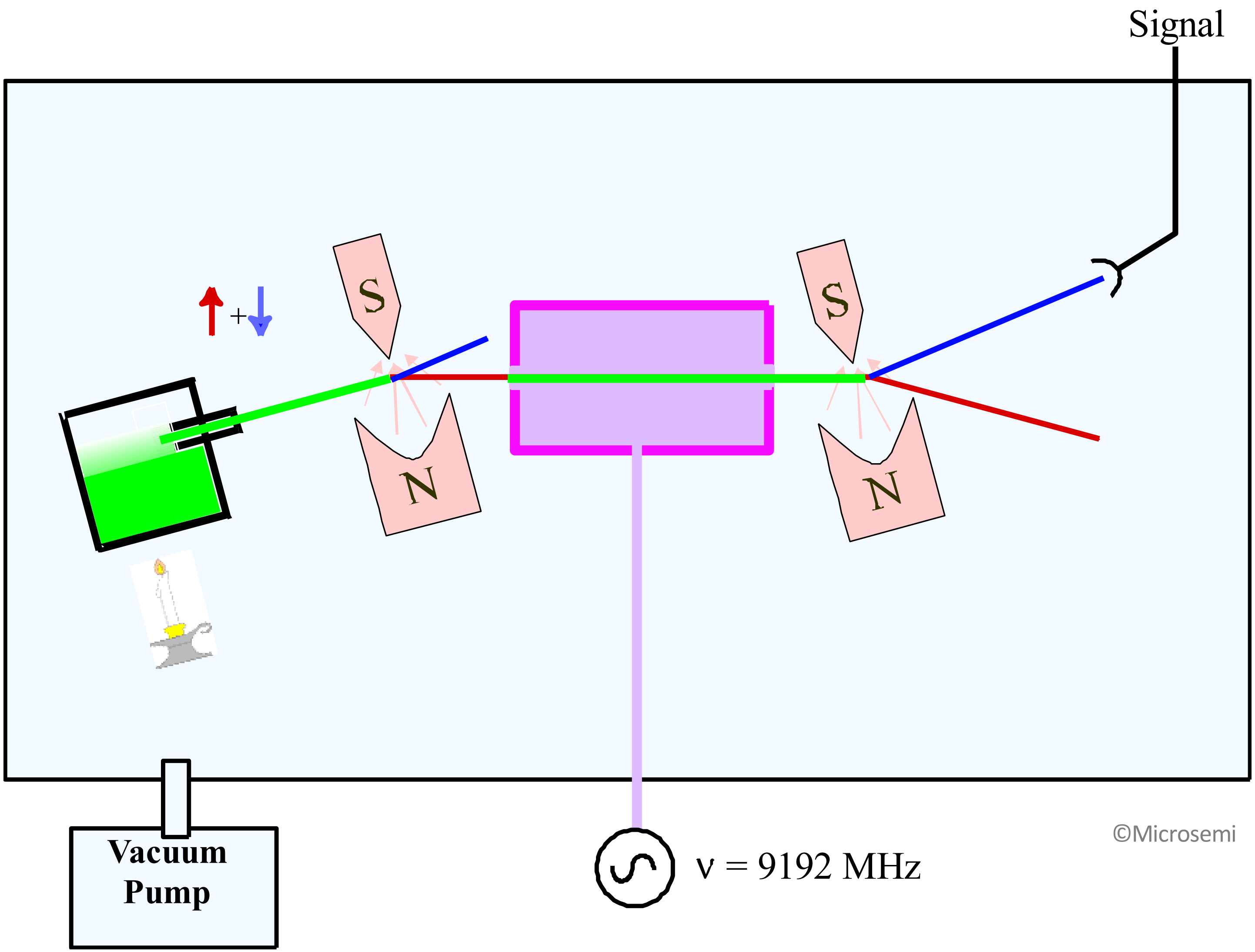
# *Cesium Beam: The Stern Gerlach Effect (magnetic state selection)*






Courtesy of Microsemi

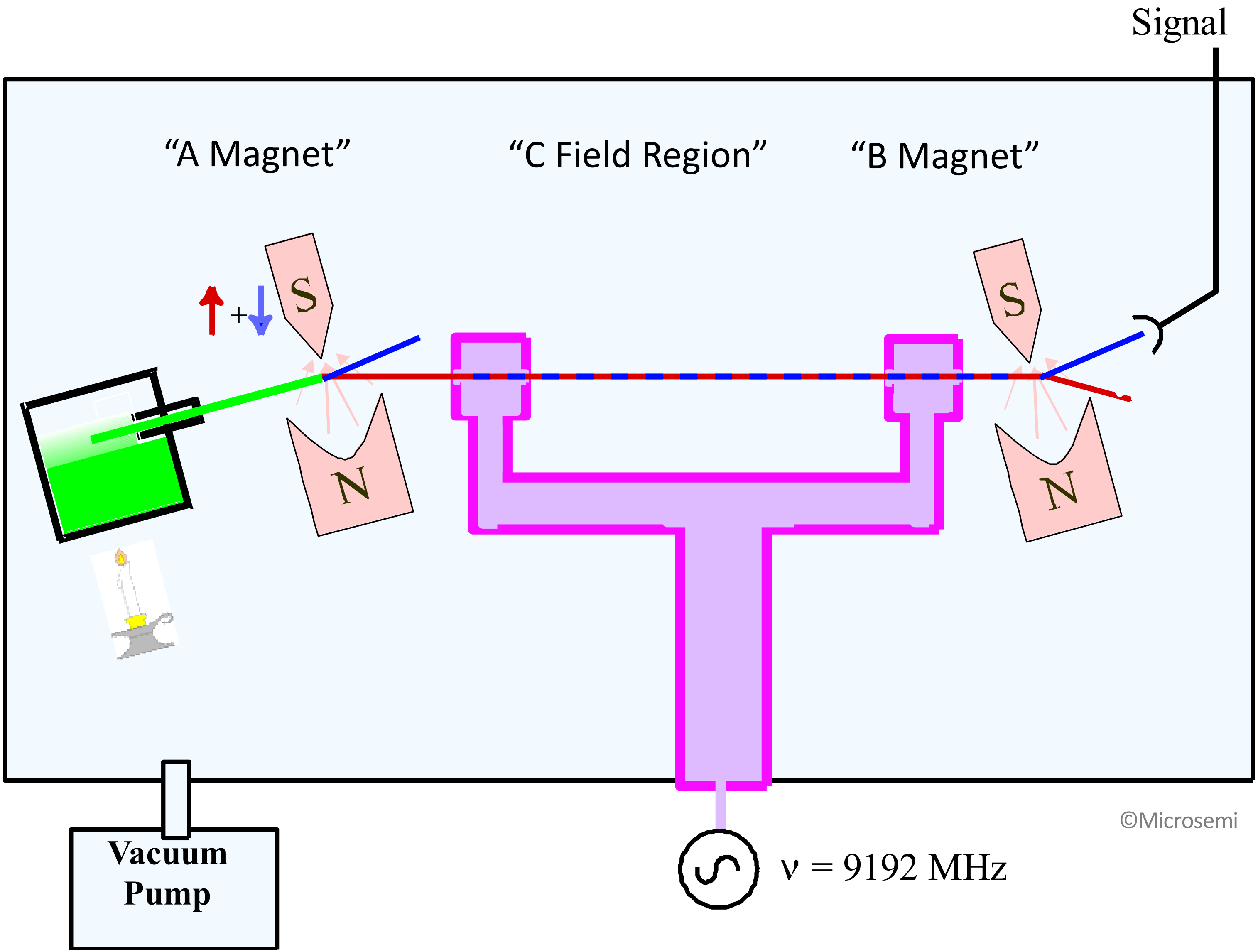
# Rabi Beam Magnetic Resonance






Courtesy of Microsemi

# Ramsey Magnetic Resonance:  Separated Oscillatory Fields

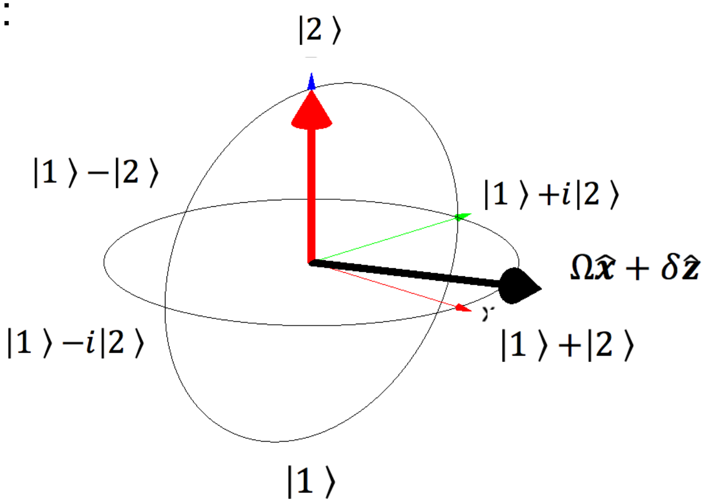


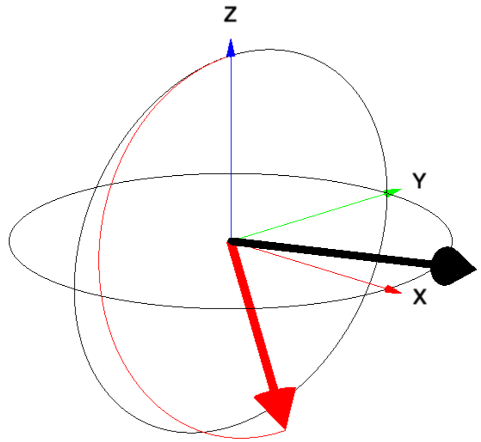



Courtesy of Microsemi

# *The Bloch Sphere: Representing the internal atomic state*

**Rabi** 2 s pi-pulse:




*See Feynman, J. Appl. Phys.* ***28****, 49 (1957)*

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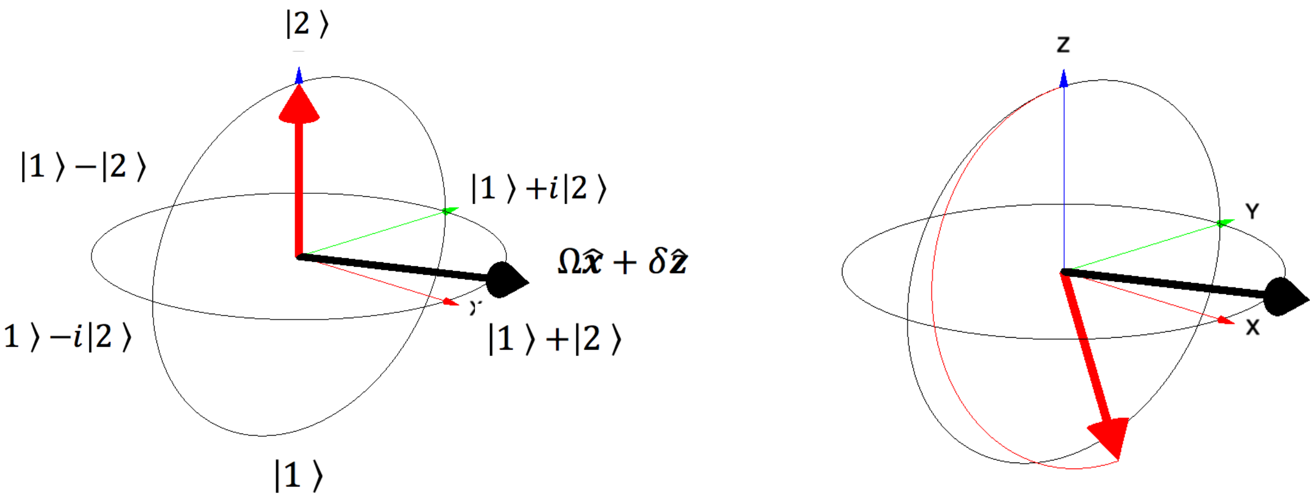
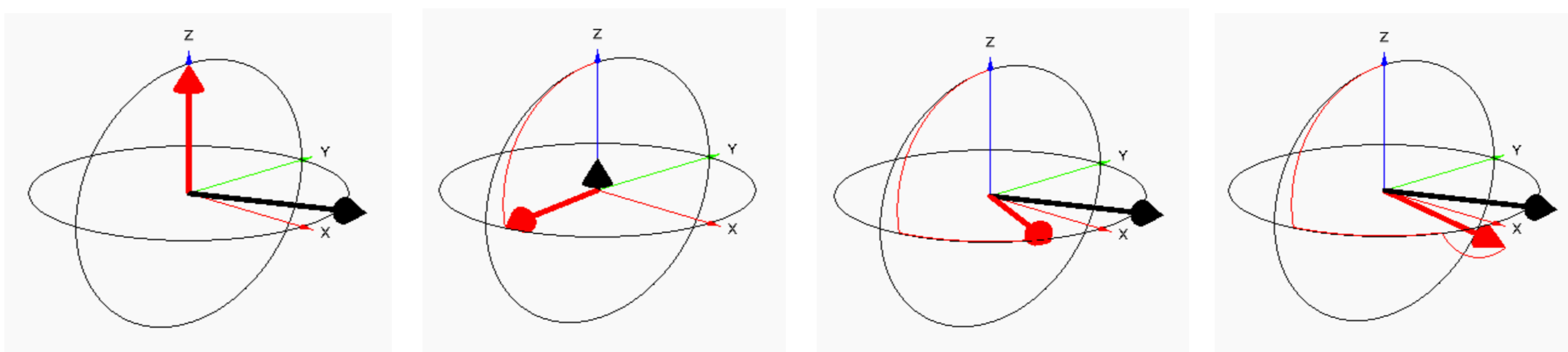



**Ramsey** 1 s pi/2-pulse, 4 s free, 1 s pi/2-pulse:

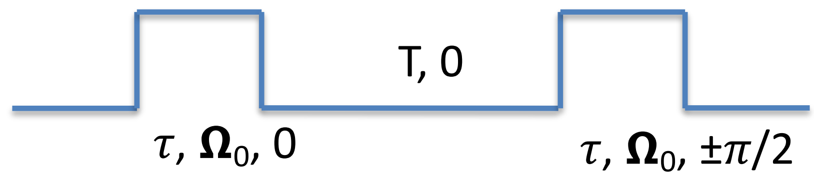



*See Feynman, J. Appl. Phys.* ***28****, 49 (1957)*

# *The Bloch Sphere: Extensions to Ramsey Interrogation*

*- elimination of the interrogation light shift*

**Ramsey (phase modulation):**



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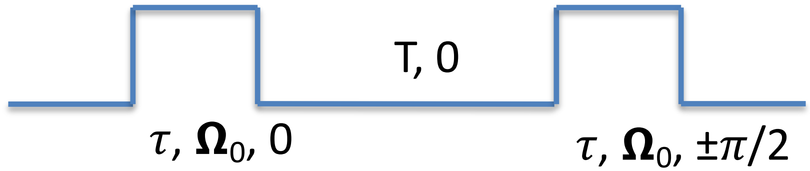
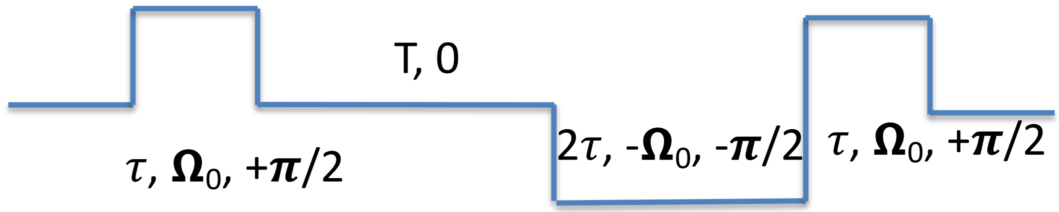
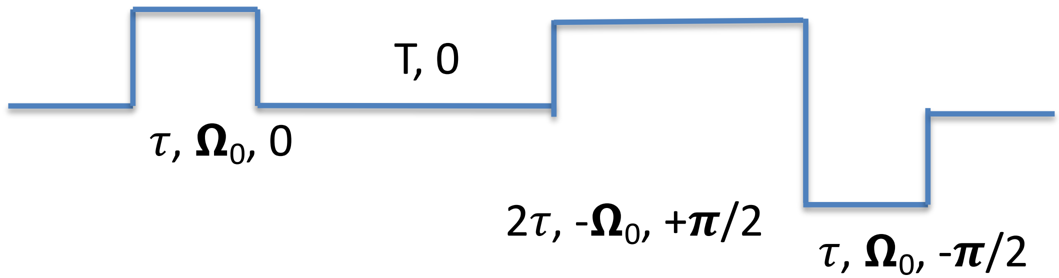


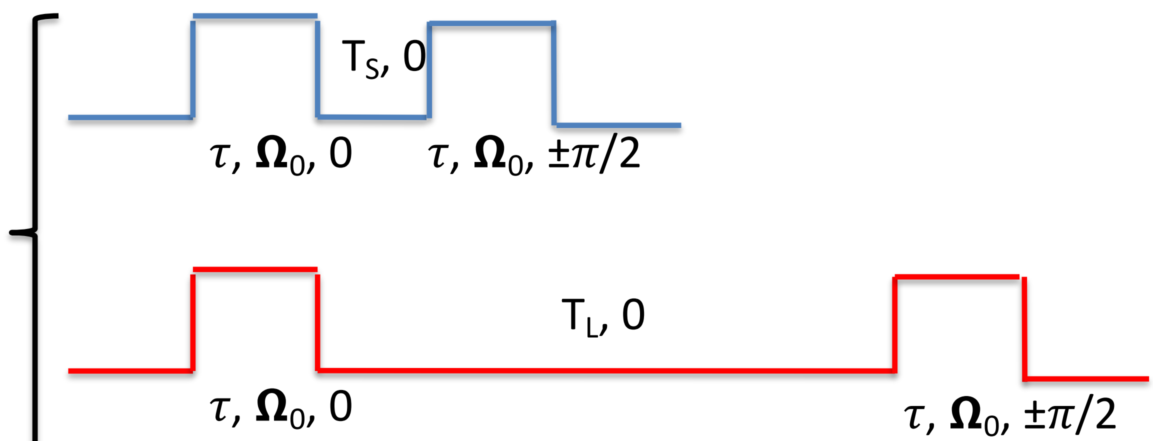

**Hyper- Ramsey:**
*(Yudin, et al., PRA 82, 011804(R) (2010))*



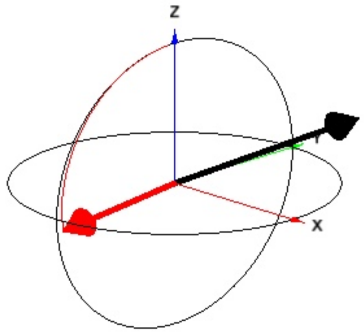

**Modified Hyper- Ramsey:**
*(Hobson, et al., PRA 93, 010501(R) (2016))*

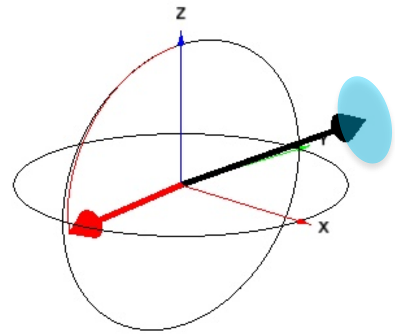


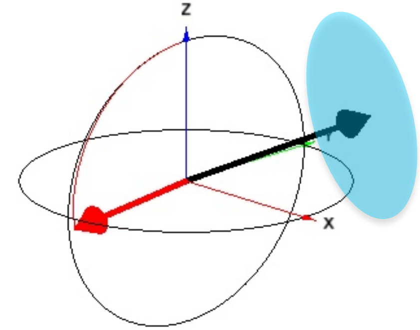

**Auto-Balanced Ramsey:**
*(Samner, et al., ArXiv:1707.02630.v1 [physics.atom-ph] (2017))*

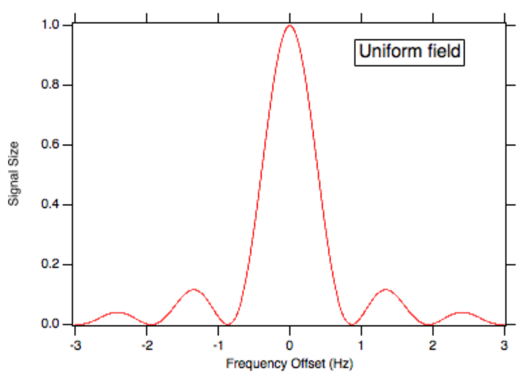


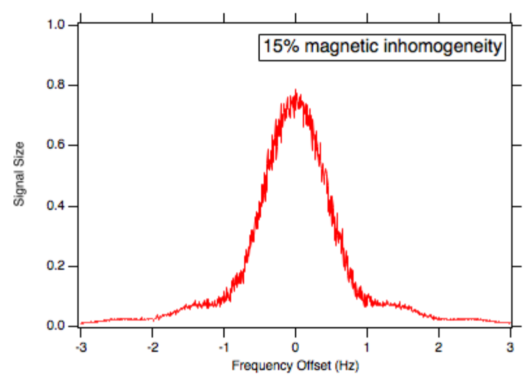
# *The Bloch Sphere and Decoherence*

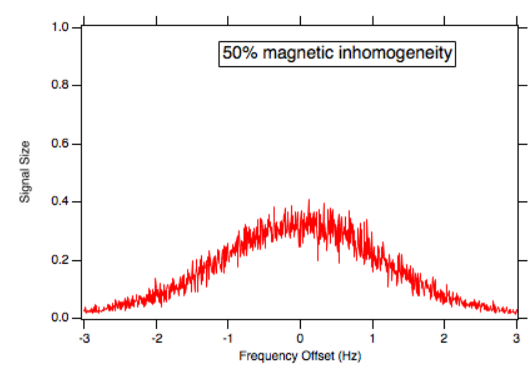


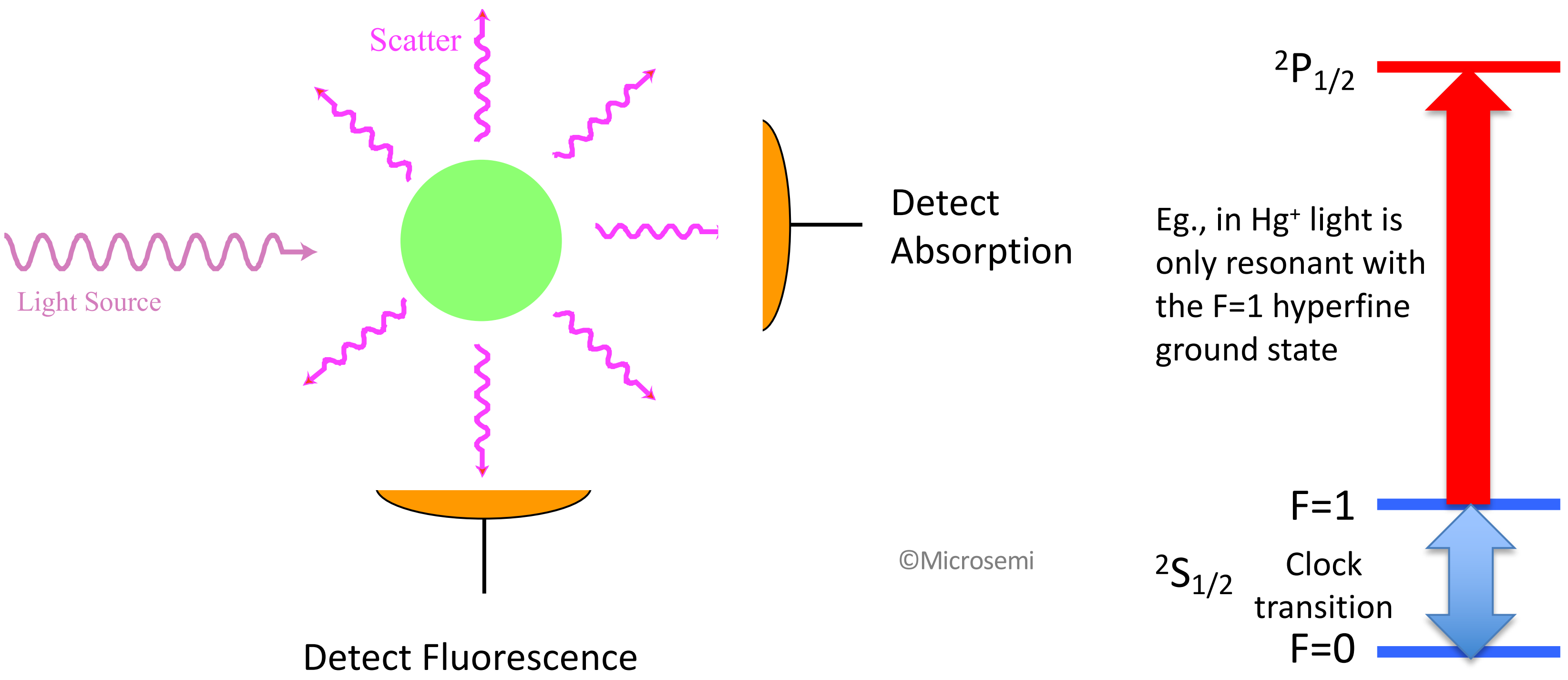



***State detection:***

Determine what state the atom is in by optical scattering



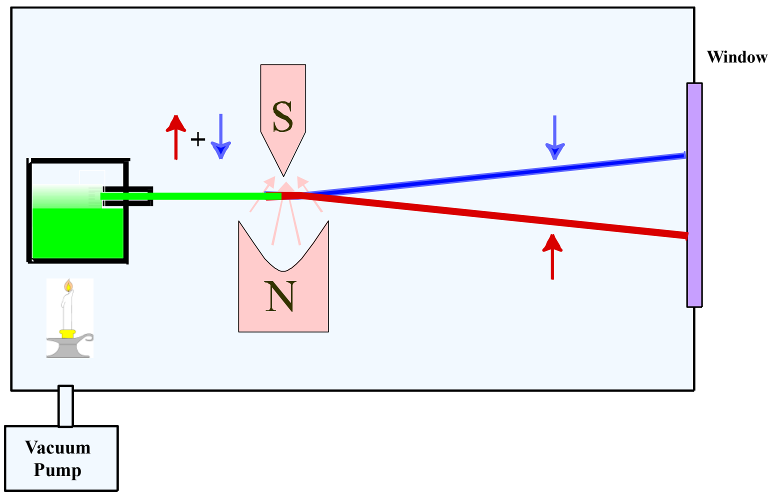


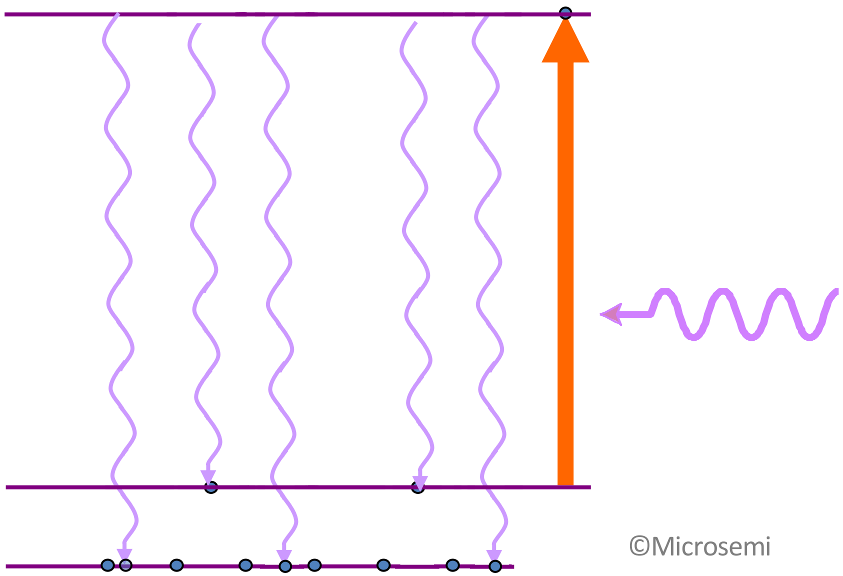

Courtesy of Microsemi

## *The physics of key atomic clock techniques*

- State selection/detection
- CPT
- Masers
- Laser cooling
- Neutral atom traps – MOT
- Neutral atom traps – Optical lattices
- Ion traps

# *State selection: magnetic and optical*

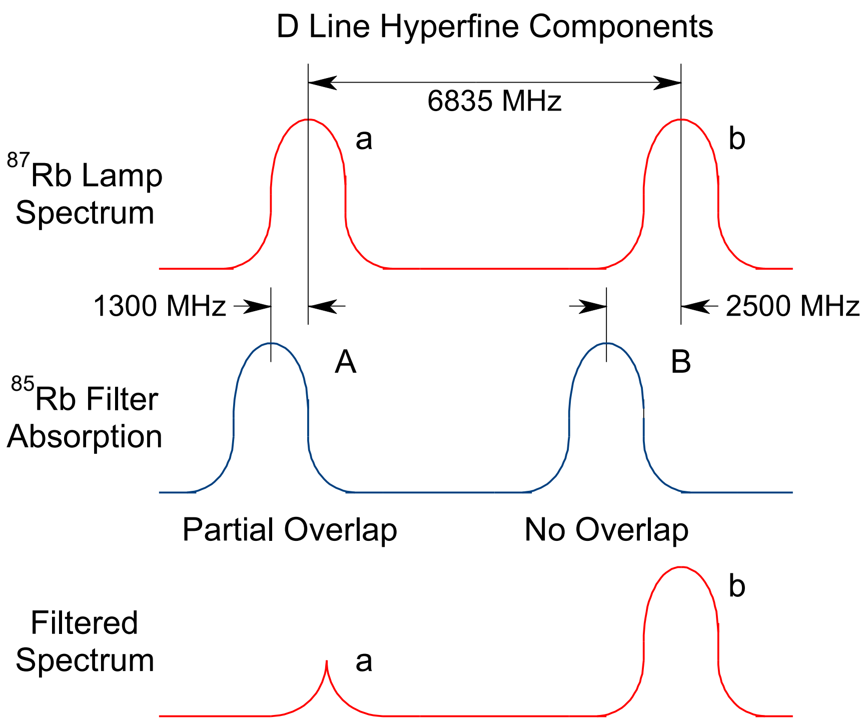


# State selection: Hyperfine filtration in rubidium

***Problem***: a $^{87}$Rb lamp will drive **all** transitions

***Solution***: use a $^{85}$Rb filter




"Fortuitous" overlap between the optical absorption lines of the two naturally-occurring isotopes, $^{85}$Rb and $^{87}$Rb.

**Carver & Alley 1958**

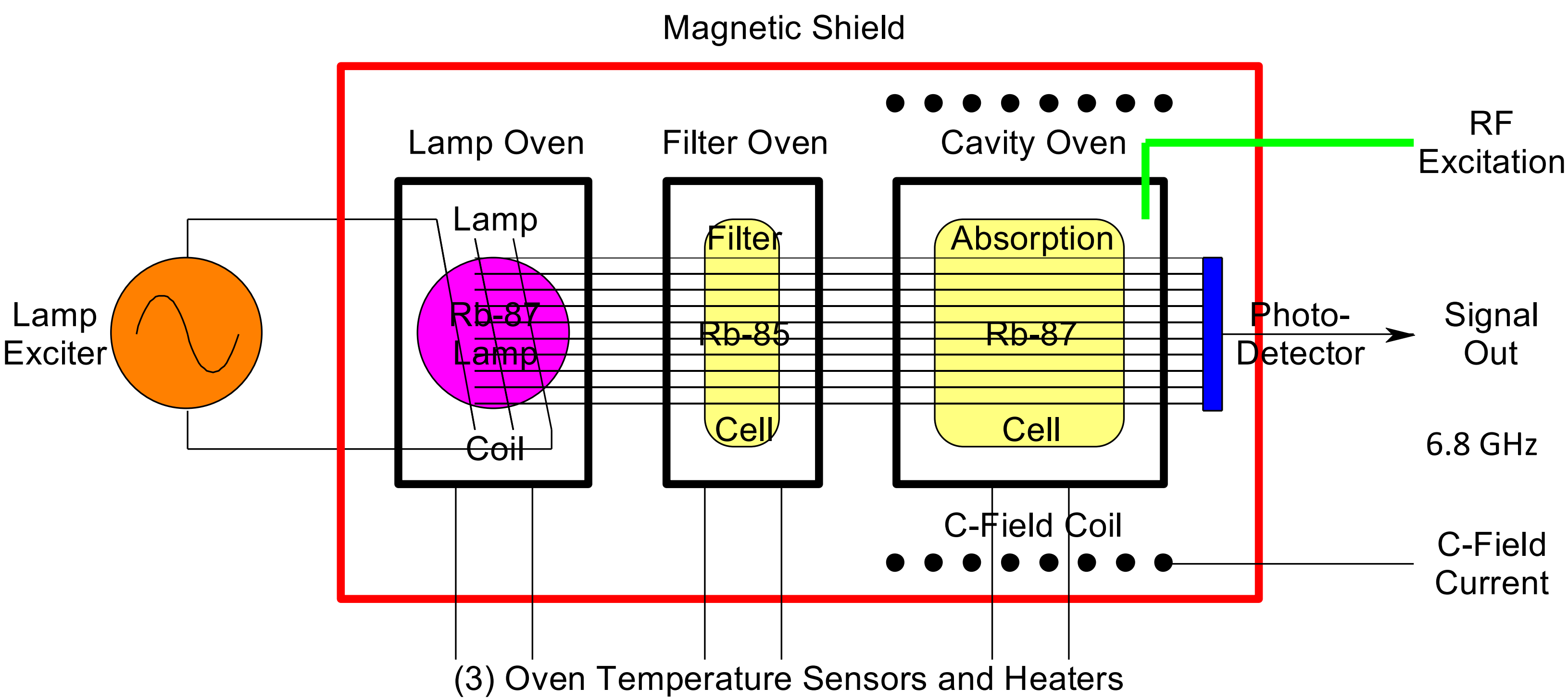
**Isotopic Filtering of Rubidium 87 D Lines**

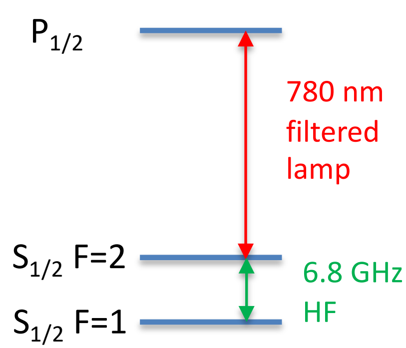




*Courtesy of WJ Riley 2002 PTTI Tutorial*

# Rb Gas Cell Physics Package



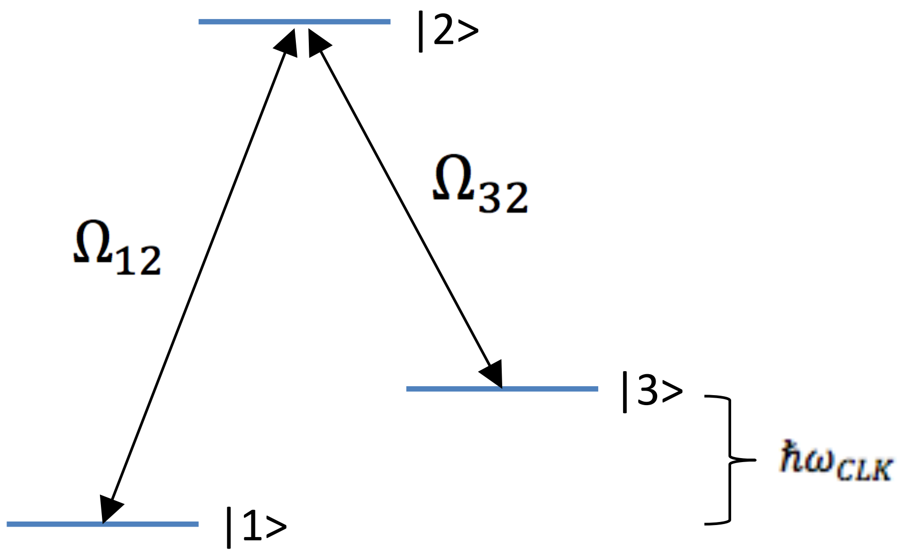








*Courtesy of WJ Riley 2002 PTTI Tutorial*

# *Coherent Population Trapping*




*Total Hamiltonian:* $H = H_A + H_L + H_I$

*New Eigenstates:*

$$\psi_1 = \frac{1}{\sqrt{\Omega_{12}^2 + \Omega_{32}^2}}(\Omega_{12}|1\rangle + \Omega_{32}|3\rangle)$$

$$\psi_2 = \frac{1}{\sqrt{\Omega_{12}^2 + \Omega_{32}^2}}(\Omega_{12}|1\rangle - \Omega_{32}|3\rangle)$$

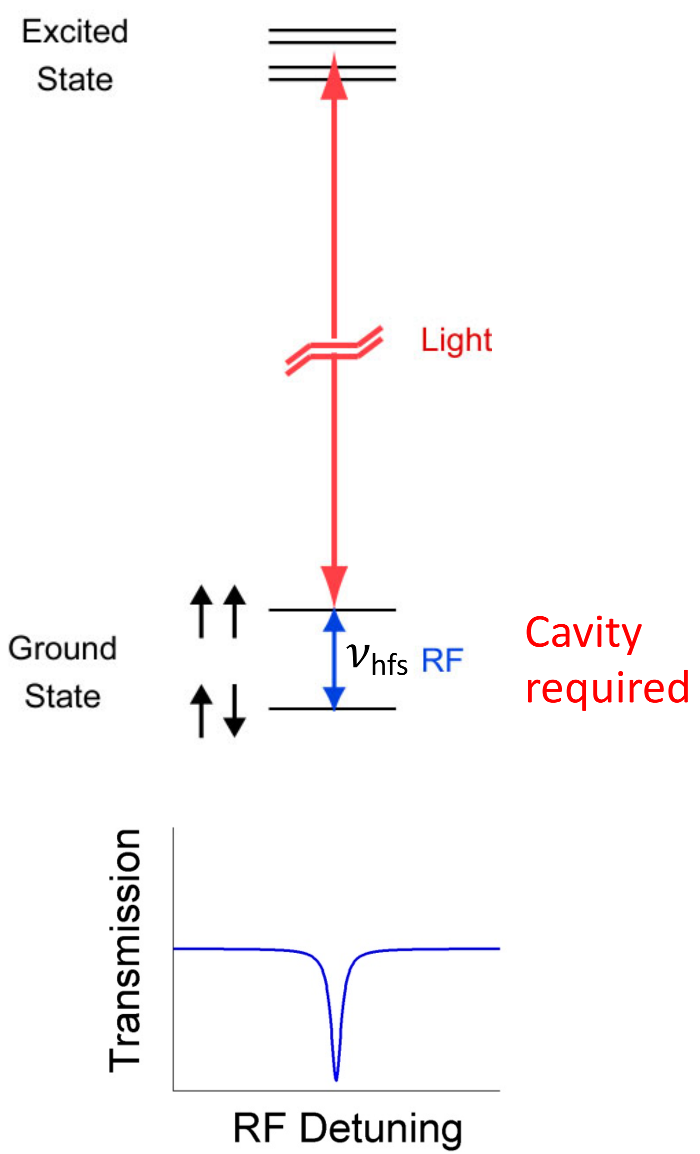
$$\langle 2|H|\psi_1\rangle = \mathrm{d}_{12}\Omega_{12} + \mathrm{d}_{32}\Omega_{32}$$

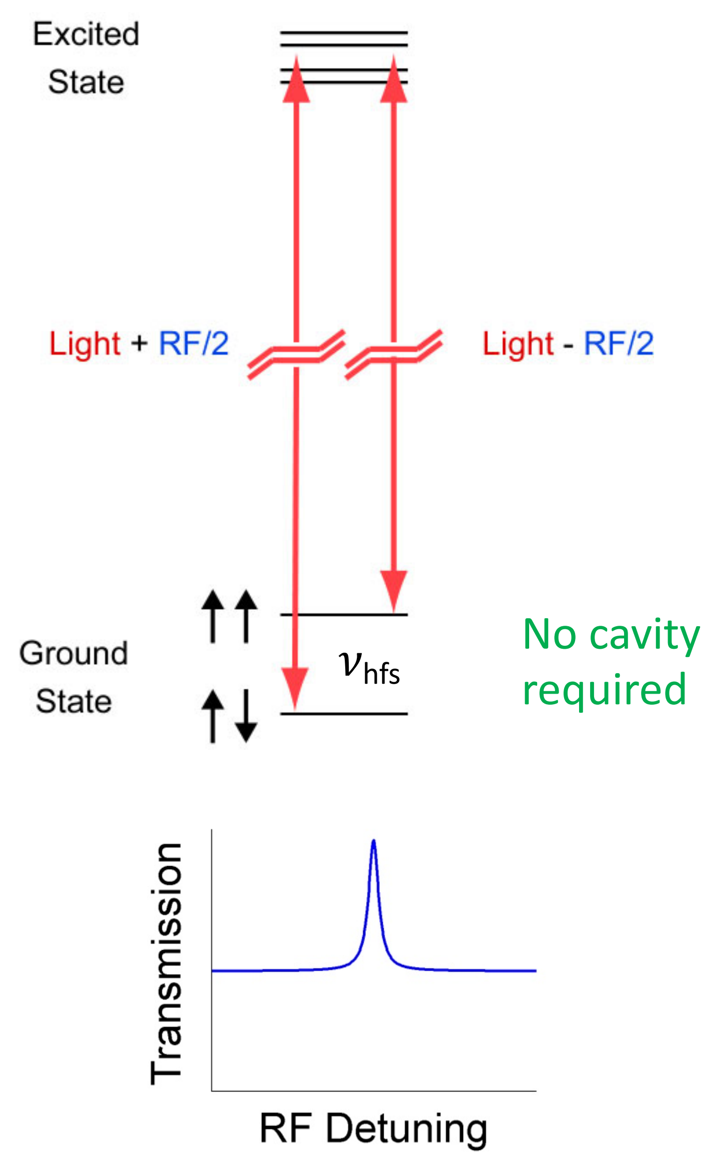
$$\langle 2|H|\psi_2\rangle = \mathrm{d}_{12}\Omega_{12} - \mathrm{d}_{32}\Omega_{32}$$ ⇒ 0 !

**With proper intensities $\psi_2$ is dark (not coupled to |2>) and $\omega_{12}$-$\omega_{32}$ = $\omega_{CLK}$**

# *RF vs. CPT Interrogation*

"Coherent Population Trapping":
$\Delta f = \nu_{hfs}$ -> "dark state" -> transmission






*Courtesy of Microsemi*

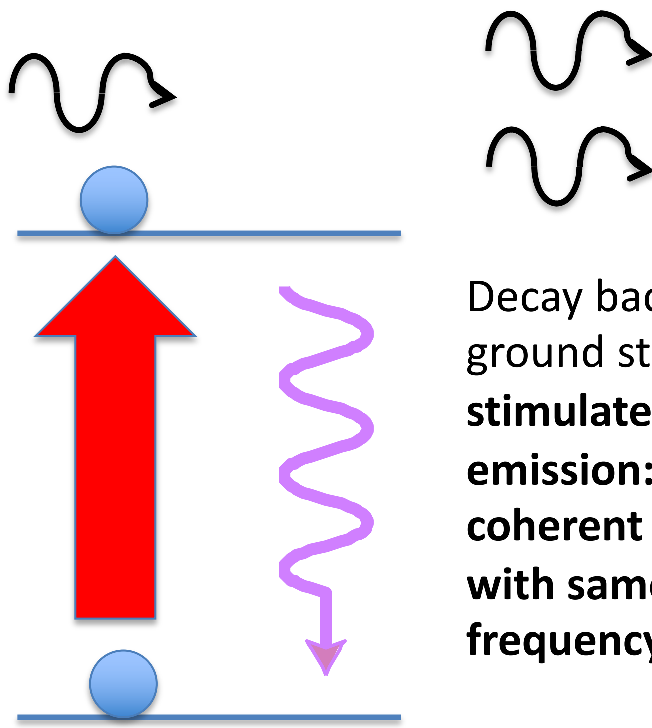
# ***Microwave Amplification of Stimulated Emission Radiation: The Maser***

(Microwave counterpart to laser)

*Meta-stable **upper** hyperfine ground state*

Magnetic state selection creates population inversion

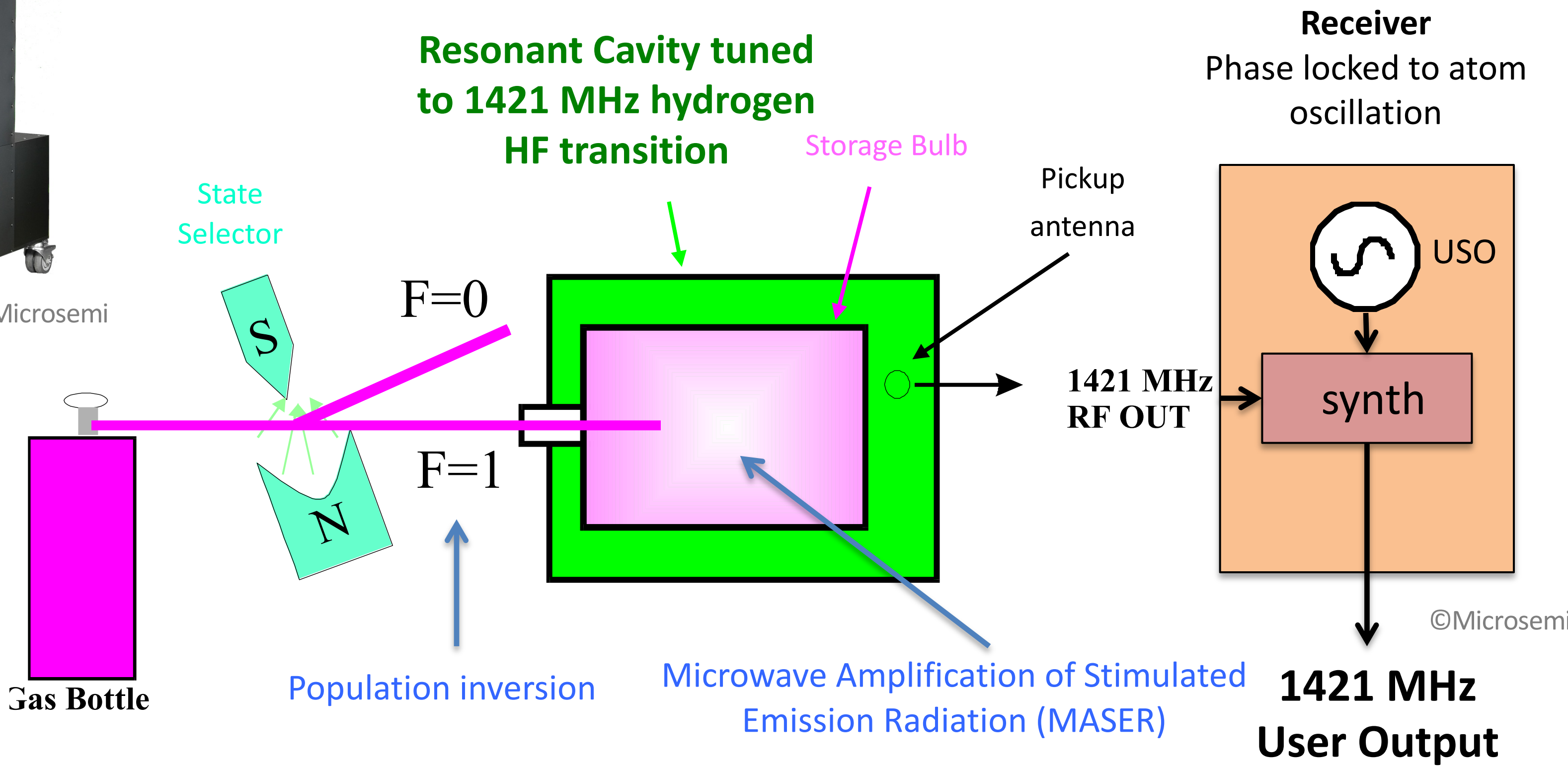
*Meta-stable **lower** hyperfine ground state*



Decay back to ground state by **stimulated emission: coherent photons with same frequency**

# *Active Hydrogen Maser*


**Microsemi Model MHM2010**

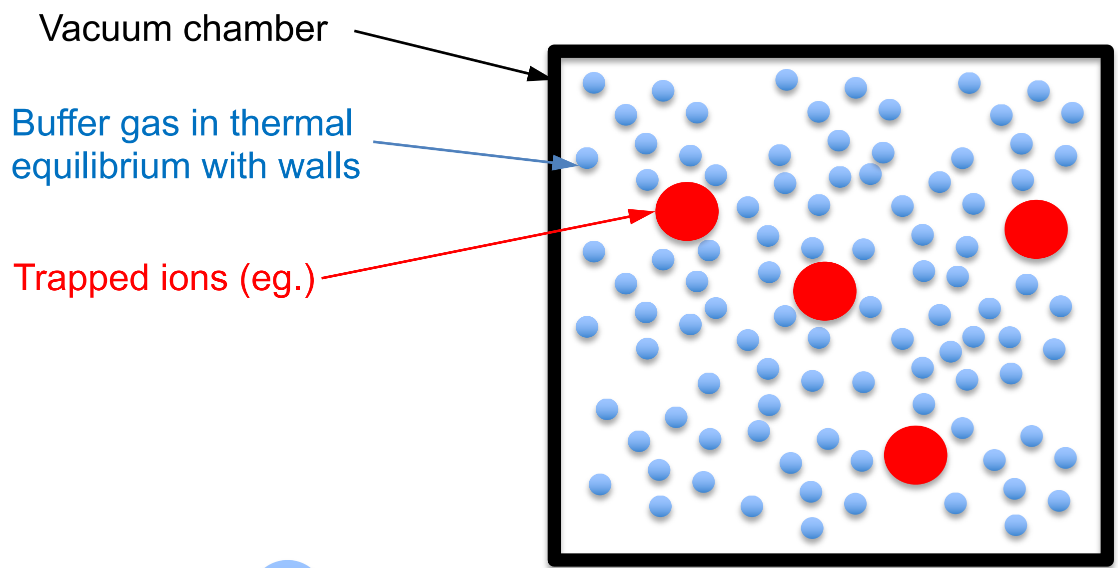


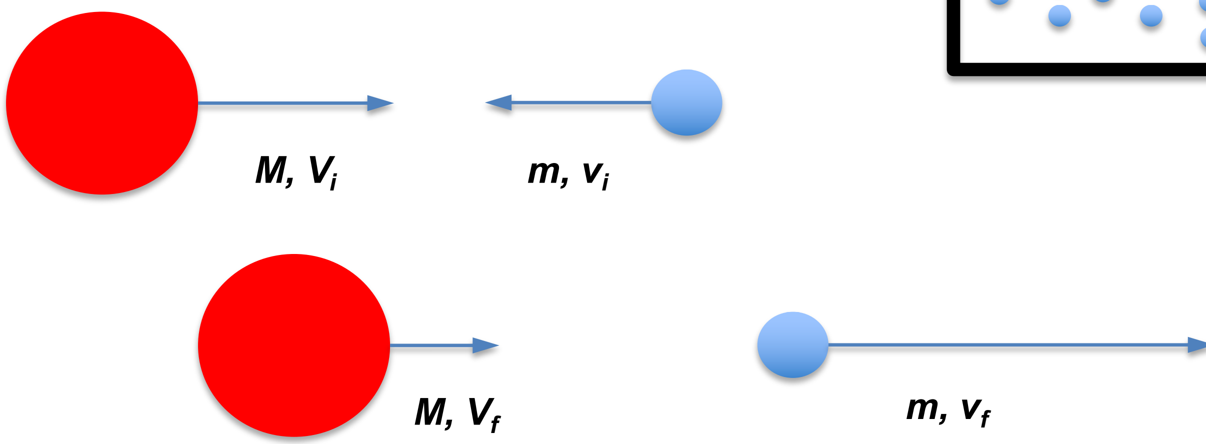

- Active Device analogous to laser
- Excellent short term stability ($10^{-13}$ at 1 s, $10^{-15}$ at 1000 s)
- Drifts with cavity/wall properties: $10^{-15}$ /day typical
- Lamb-Dicke Confinement: no 1st order Doppler



*Courtesy of Microsemi*

# Buffer gas cooling

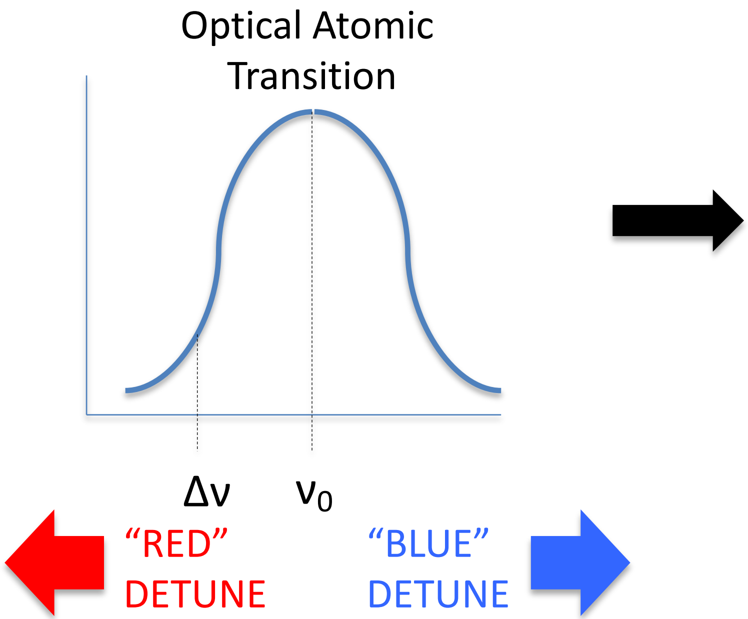


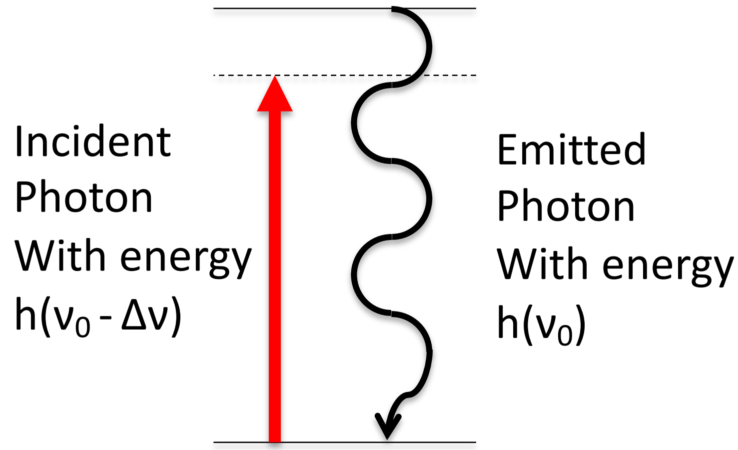




***Conservation of momentum and energy => (to be completed)***

# Laser Cooling

***(S. Chu, C. Cohen-Tannoudji, and W.D. Phillips Nobel prize 1997)***



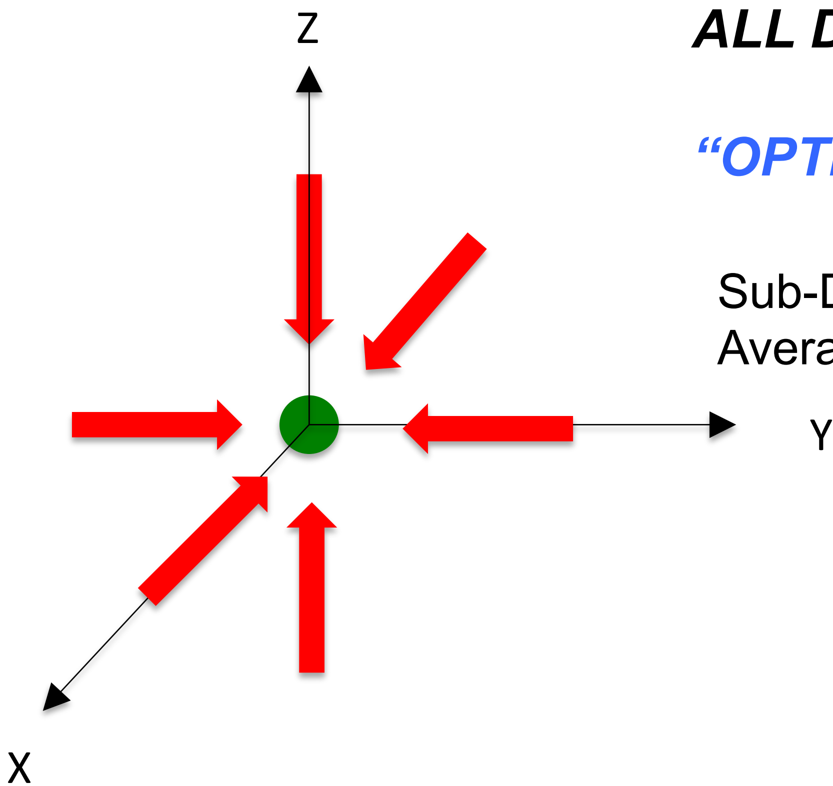

Atom traveling towards laser absorbs only "red-detuned" light

***Net effect:***

- Atom emits more energy than it absorbs
- atom slows down in 1D

# Laser Cooling

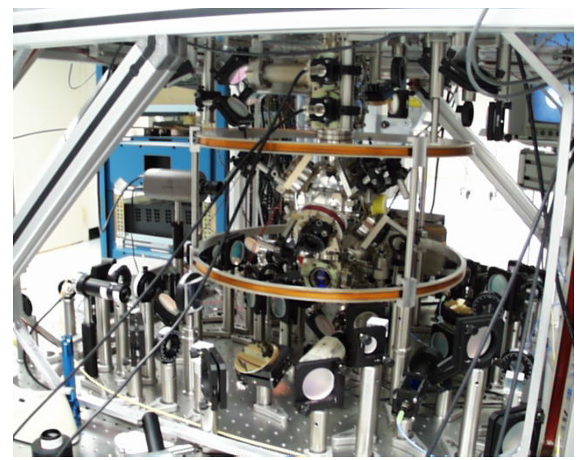
Now add "red-detuned" lasers in all three directions




***ALL DIRECTIONS SLOWED BY LIGHT:***

***"OPTICAL MOLASSES"***

Sub-Doppler cooling -> ~ 1 uK
Average velocity ~ 1 cm/s



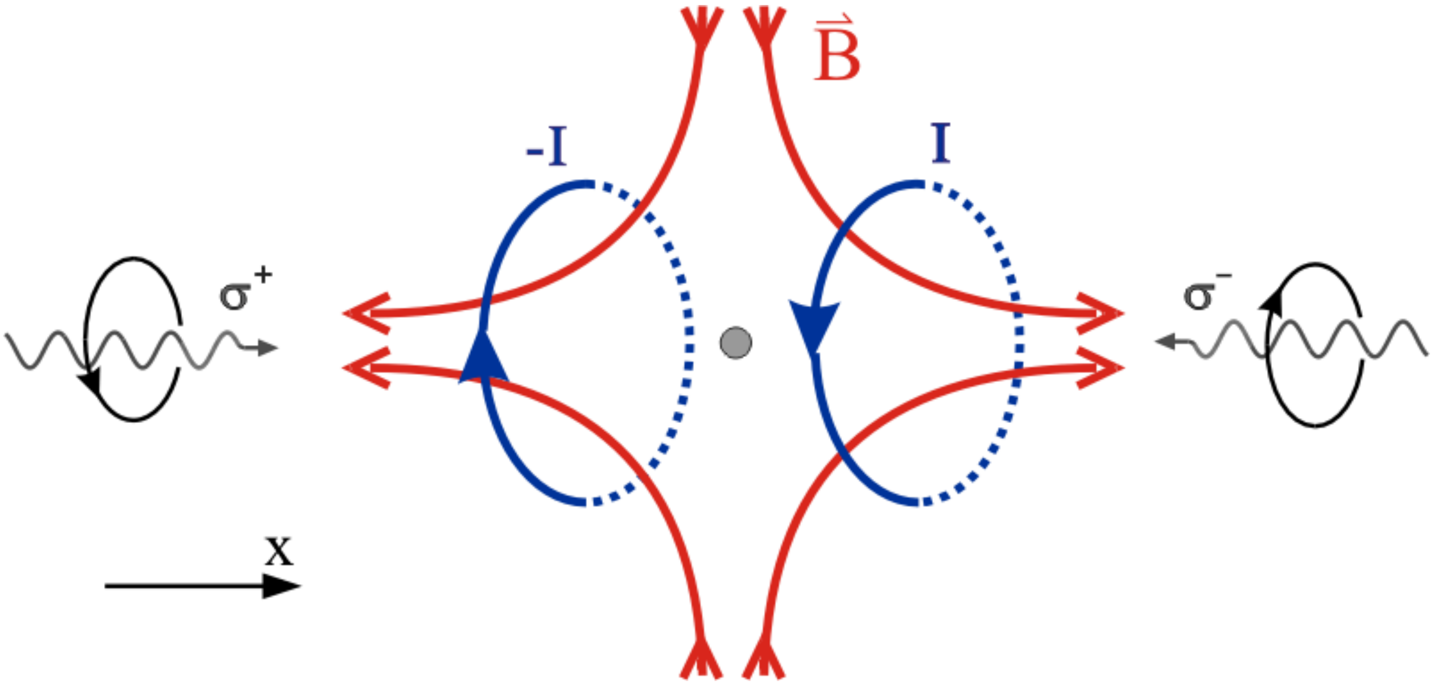
*USNO*

Note: by unbalancing opposing beams, can move atoms

# *Laser Cooling: Motivation*

- Atom confinement for O(s) instead of O(ms)
- Reduce Doppler effect
- Enables trapping and in-situ interrogation
- Enables moving atom ensembles over macroscopic distances
  - Atomic fountains

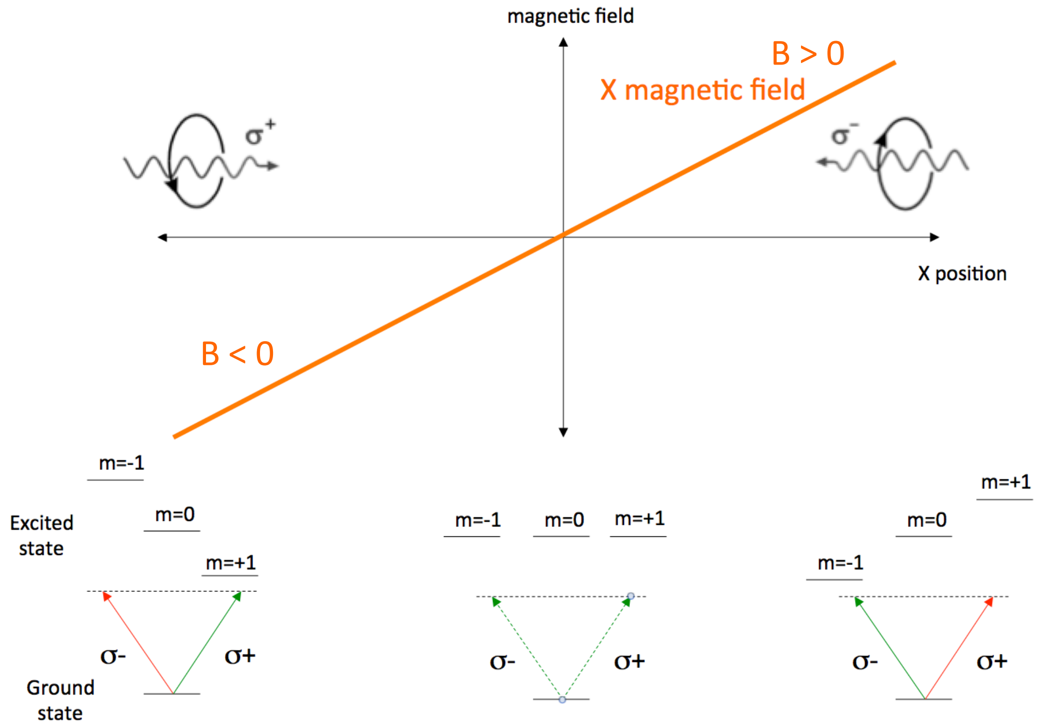
# *Neutral Atom Trapping – The MOT*




Wikicommons

***Magnetic Field + Circularly Polarized Light***
***= Position-dependent restoring force***
***= Magneto-Optic Trap (MOT) !***

# *Neutral Atom Trapping – The MOT*




$$\Delta E = g_F \mu_B B m_F$$

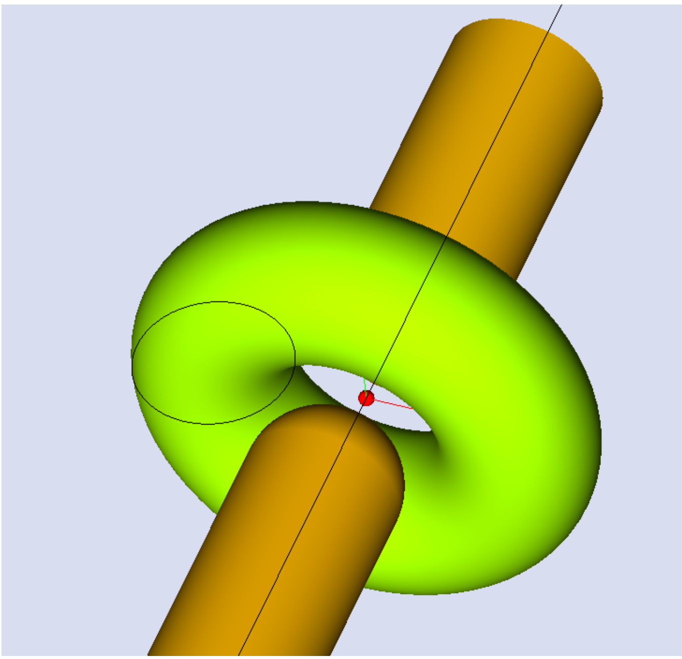
- Combine detuning, polarization, Zeeman shift: **create a position-dependent restoring force**
- Circular polarization drives only **$\Delta m = \pm 1$ Zeeman transitions**
- Strong field away from geometric center shifts transition into resonance with laser
  - => **light restoring pressure proportional to distance from center**
- Weak field in center:  laser off resonance – little or no interaction with atoms
- Atoms localized and laser-cooled in 1D
- Extend to 3D with additional beams:  Magneto Optical Trap (MOT)

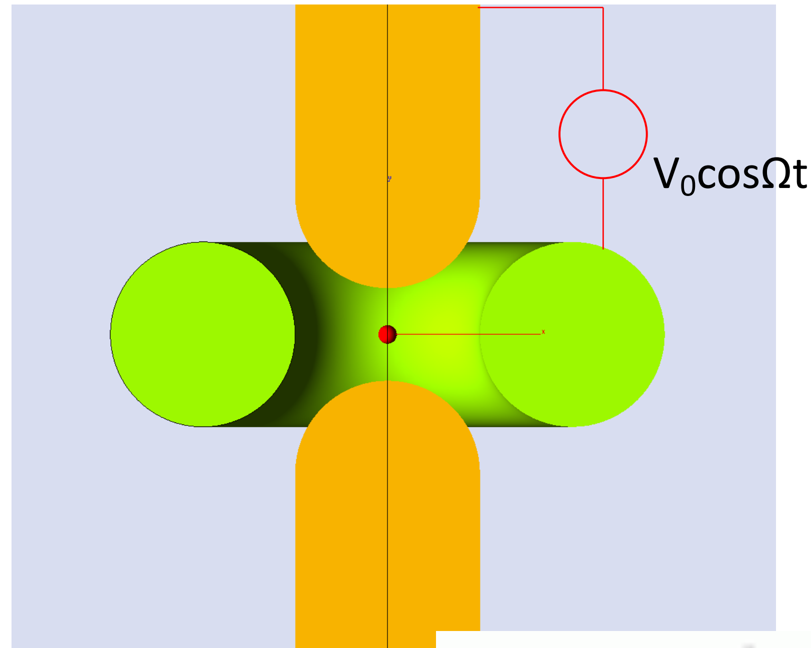
# *Neutral atom trapping: optical lattices*

(to be completed)

# *Ion Trapping: The quadrupole Paul Trap*

***(Hans Dehmelt and Wolfgang Paul, Nobel Prize, 1989*)***

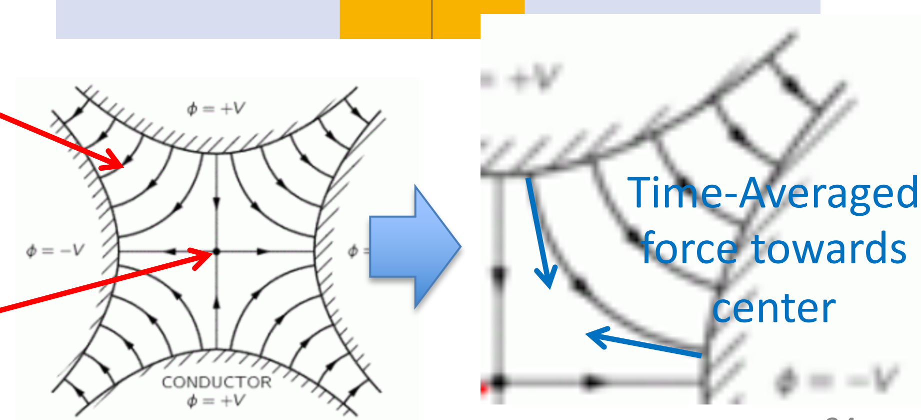





Typical well depth: several eV
(room temperature is 1/40 eV)

RF electric field

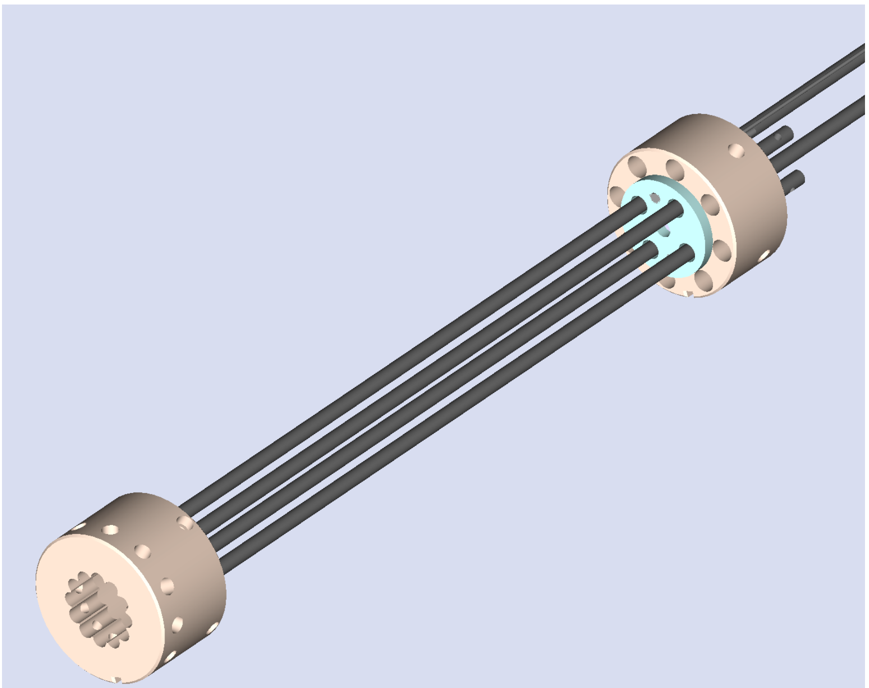
Ions seek region of weakest field

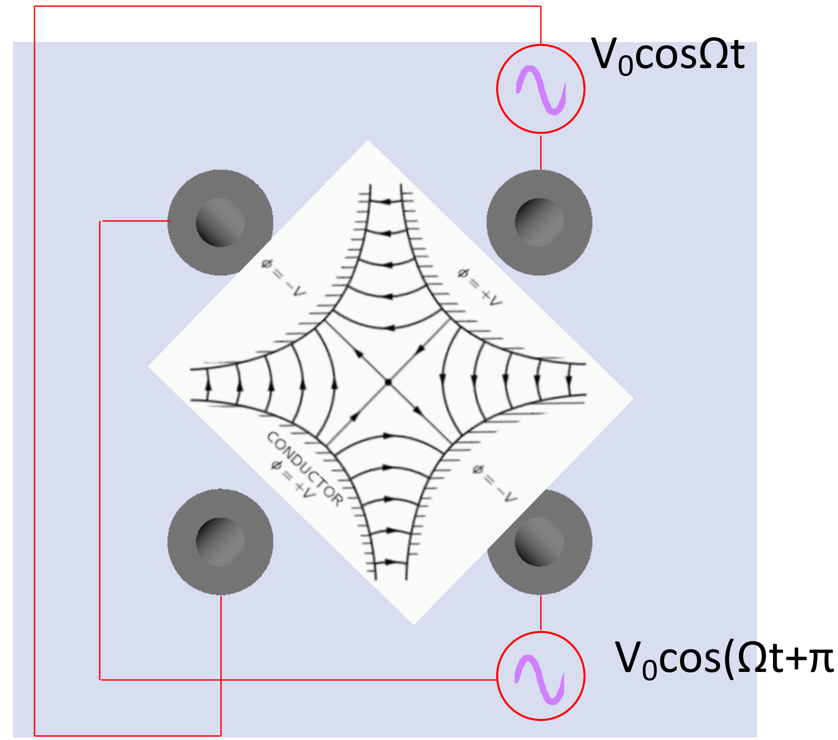





*Normal Ramsey shared this Nobel prize for his invention of the method of separated oscillatory fields

# Ion Trapping:
# The quadrupole linear ion trap*



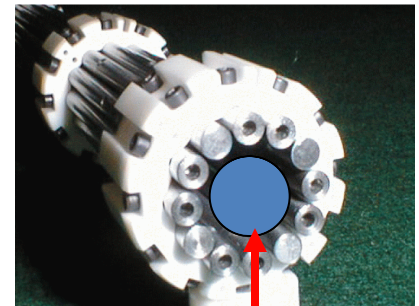



Number of ions scales up linearly $$N_{lin} = \frac{3}{5}\left(\frac{L}{R_{sph}}\right) N_{sph}$$

*J.D. Prestage, G.J. Dick, and L. Maleki J. Appl. Phys. 66, 1013 (1989)

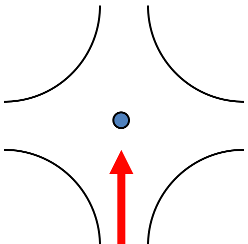
# *Ion Trapping:*
# *The The Multi-pole linear ion trap*

Multi-pole (12)
RF Trap



Field-"free"
Region in a
volume

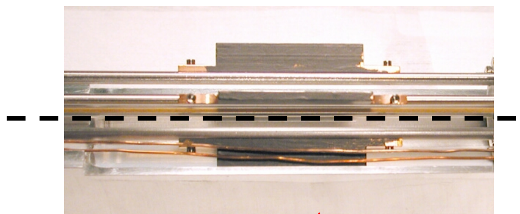
Spherical
Quadrupole
RF Trap



Field-free region at one
point in center of trap

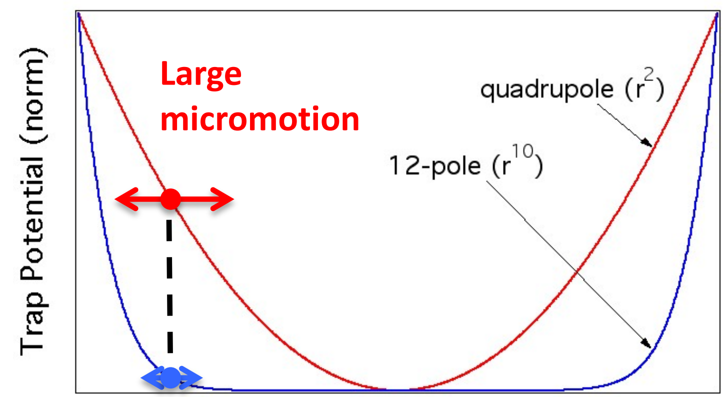
*H.G. Dehmet, Bull. Am. Phys. Soc. 18, 1521 (1973)*

Linear
Quadrupole
RF Trap



Field-free
region
on a line

*J.D. Prestage, G.J. Dick, and L. Maleki, J. Appl. Phys. 66, 1013 (1989)*




*J.D. Prestage, R.L. Tjoelker, and L. Maleki, Proceedings of the 1999 Joint EFTF-FCS*

# *Ion trapping: simulations*

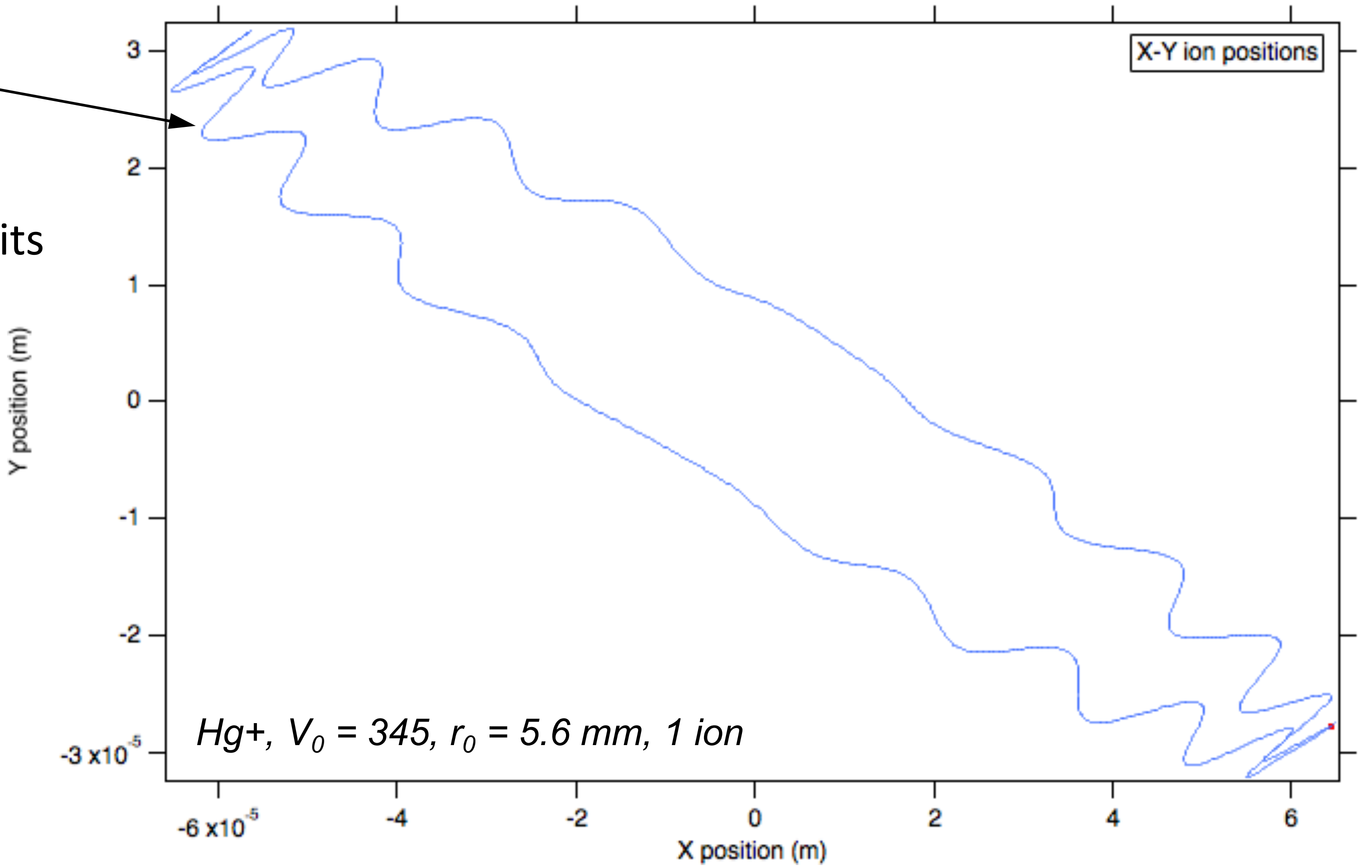
Single ion equations of motion: The Mathieu equations

$$\ddot{x} + \frac{e}{mr_0^2}(U - V cos\Omega t) = 0, \qquad \ddot{y} - \frac{e}{mr_0^2}(U - V cos\Omega t)$$

Micromotion
- $f_m = f_{trap\text{-}drive}$

Secular motion = orbits
- $f_s$ ~ 0.1 – 1 MHz

**Movie!**

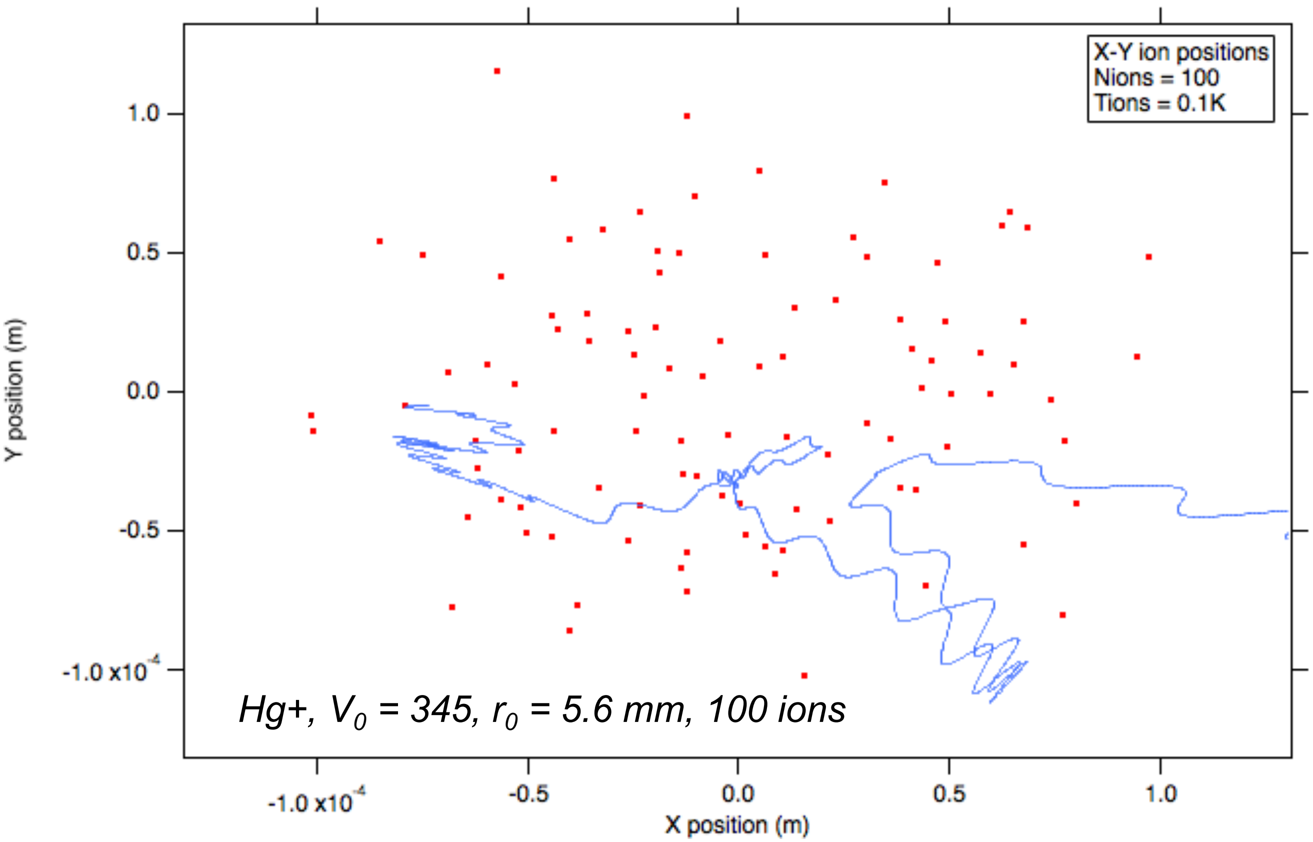


# *Ion trapping: simulations*

Many ions - add Coulomb interactions

$$\ddot{x}_i + \frac{e}{mr_0^2}(U - V cos\Omega t) - \sum_{j\neq i}\frac{1}{4\pi\epsilon_0 m}\frac{e^2}{x_{ij}^2} = 0$$

**Movie!**



# *Ion trapping: simulations*

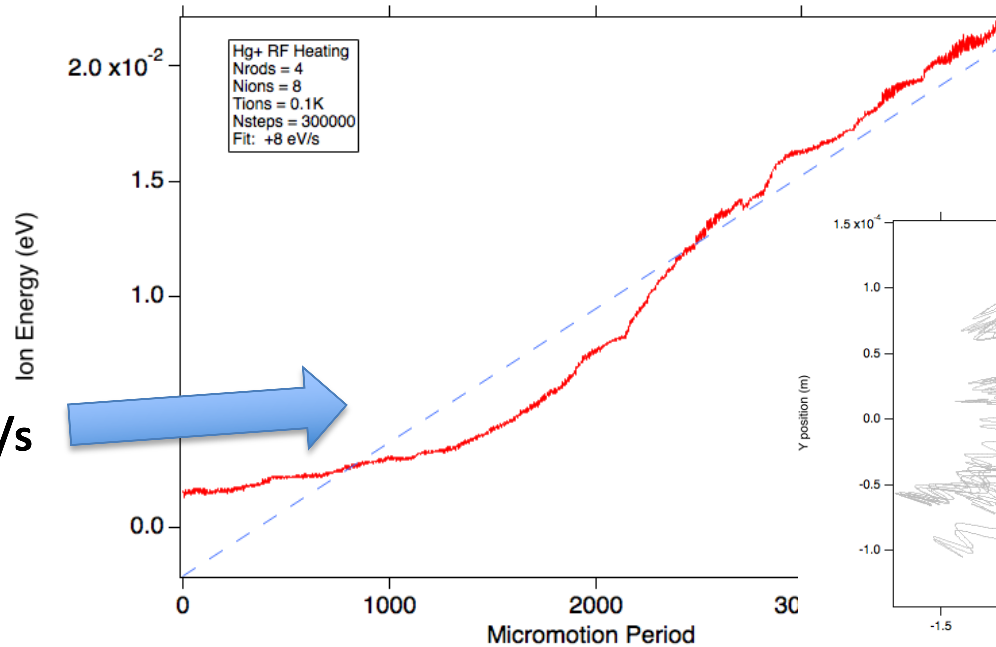
## Many ions – RF heating

### How does RF heating work?

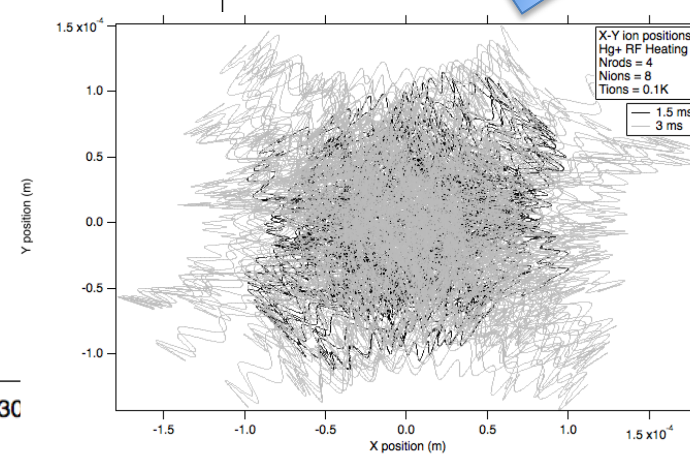
- Only present when there are more than one ion experiencing collisions
- Consider collision where $v_{ion} = 0$ *(Cetina, et al., PRL 109, 253201 (2012))*
- $V_{ion} = v_{sec} + v_{micro} \Rightarrow v_{sec} = -v_{micro}$
- Conservative potential: $v_{ion} = v_{sec} = 0$
- RF trap field has done work on the ion during the collision

Nions = 8 Hg+
Quadrupole trap
T ions initial = 0.1K
Total time ~ 3 ms
Trap freq. = 1.4 MHz
Sec. freq. ~ 60 kHz

**HEATING: 8 eV/s**




Increasing orbital extent from 1.5 ms to 3.0 ms

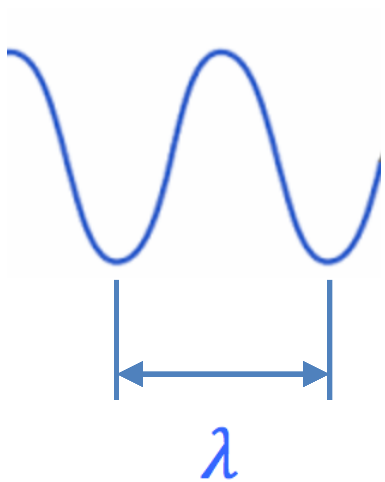


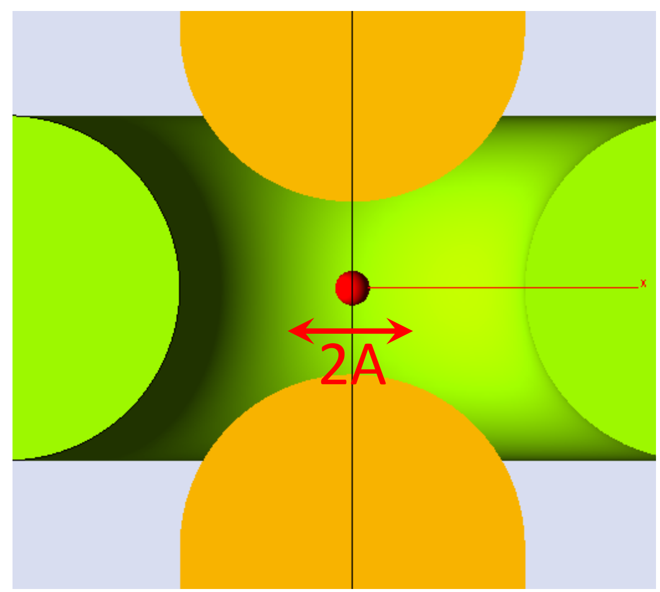
# *Ion trapping: motivation*

- Eliminate “end-to-end” effects
- Can extend confinement almost indefinitely
- very long interrogation times possible
- No wall effect !
- Eliminate the first order Doppler effect: **Lamb-Dicke Confinement**

$$A < \frac{\lambda}{2\pi}$$

Clock transition
microwave radiation



## *Key frequency shift effects in atomic clocks*

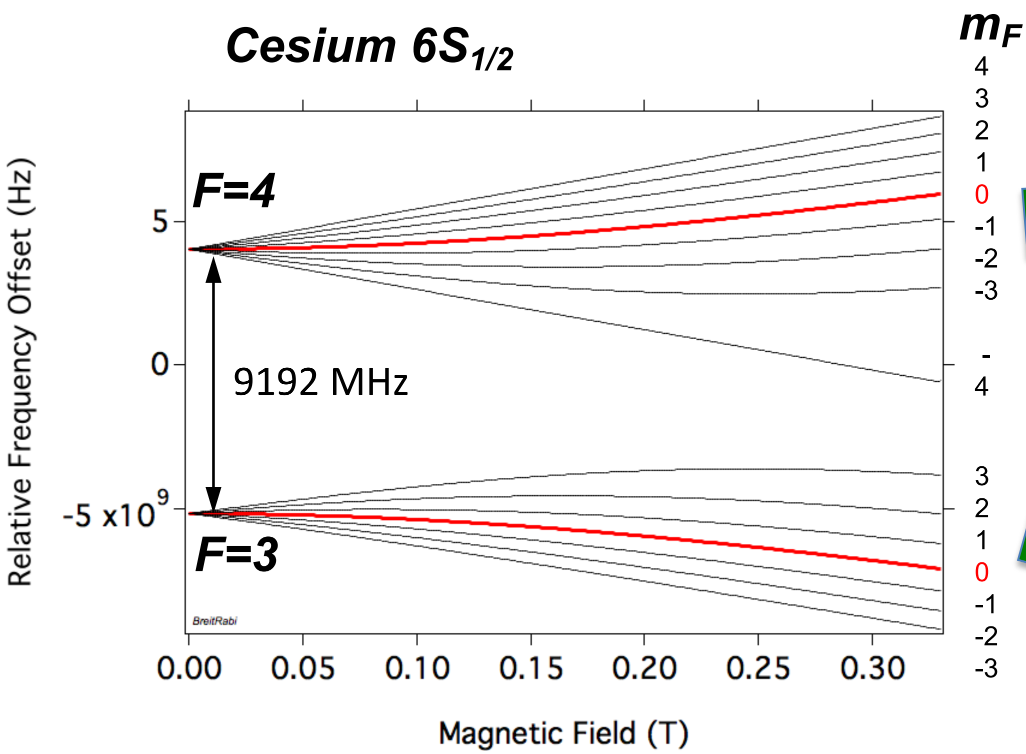
- Magnetic
- Electric
- Collisional
- Doppler
- Gravitational

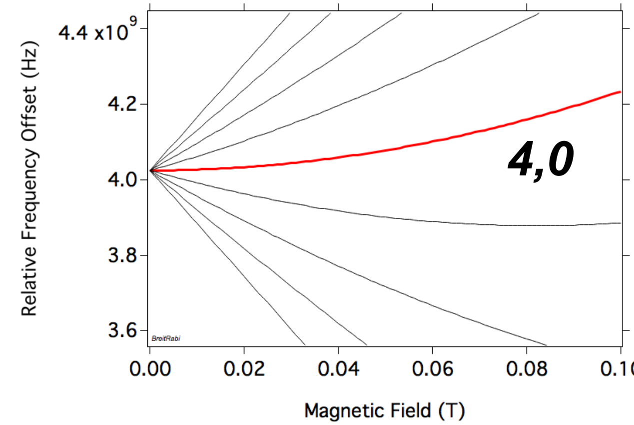
# *Magnetic effects: Zeeman shifts (1st and 2nd order)**

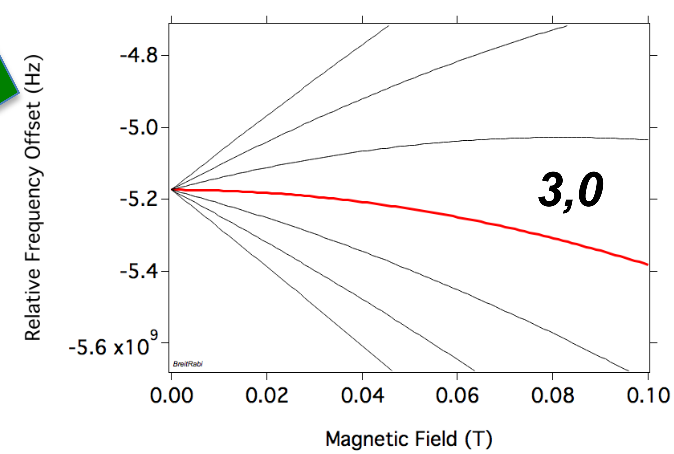
The Breit-Rabi forumula:

$$\Delta E(F,M) = -\frac{h\Delta\nu}{2(2I+1)} - g_I' \mu_B B M \pm \frac{1}{2} h\Delta\nu \times \left\{1 + \frac{4M}{2I+1}x + x^2\right\}^{1/2}$$

$$x = \frac{(g_J + g_I')\mu_B B}{h\Delta\nu}$$




****See "Elementary Atomic Structure", 2nd Edition, by G.K. Woodgate, Oxford University Press, eq. 9.80, p. 193***

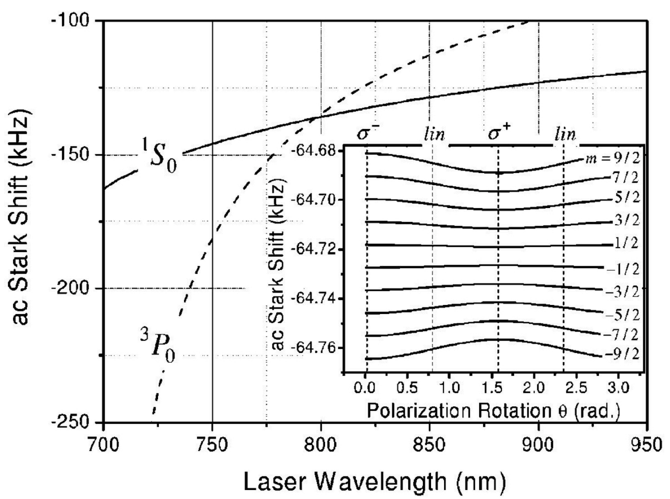
# *Electric effects: AC Stark (light) shift to first order*

$$\Delta\nu^{E1} = (\Delta\kappa^s + \Delta\kappa^v m_F \xi \overrightarrow{e_k} \cdot \overrightarrow{e_B} + \Delta\kappa^t \beta) U_0$$

***Field magnitude:***
- Scalar light shift
- Magic wavelength[1]

***Field alignment:***
- Vector light shift[2]
- Alignment of k rel. to B

***Field orientation:***
- tensor light shift[2]
- Orientation of E rel. to B
- Magic angle




2-photon: $\Delta\nu^{hyper} = \Delta\kappa^h (U_0/E_r)^2$

Higher pole: $\Delta\nu^{M1/E2} = \Delta\kappa^{M1/E2}\sqrt{U_0}$


1. *H. Katori, et al., PRL **91**, 173005 (2003)*
2. *P.G. Westergaard, , Phys. Rev. Lett. **106**, 210801 (2011)*

# *Electric effects: AC Stark (light) shift to higher order*

**Hyperpolarizability**

- 2 photon effect
- Can't zero it out
- Operate with low trap field

$$\Delta\nu^{hyper} = \Delta\kappa^{h}(U_0/E_r)^2$$

**Higher trap field poles**

- Magnetic dipole or electric quadrupole
- Also can't zero out
- Operate with low trap field

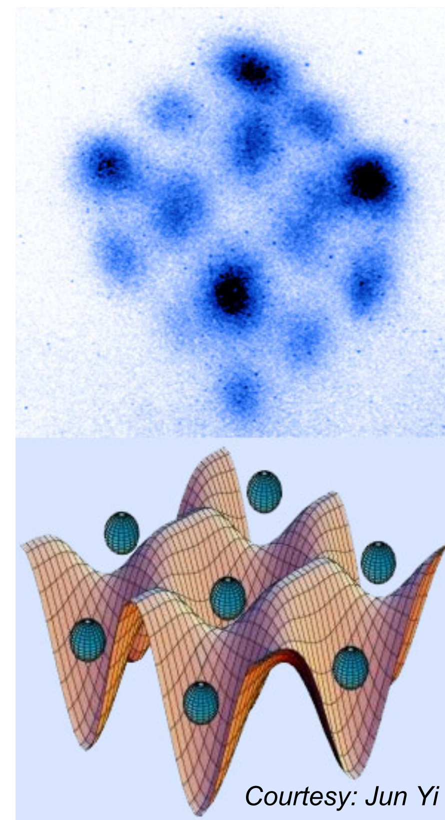
$$\Delta\nu^{M1/E2} = \Delta\kappa^{M1/E2}\sqrt{U_0}$$

*P.G. Westergaard, , Phys. Rev. Lett.* ***106****, 210801 (2011)*

# *Collision shifts – ultra-cold*

- S-wave collisions vs. room temperature
- Glancing collisions!
- Bosonic vs. Fermionic species

(to be completed)

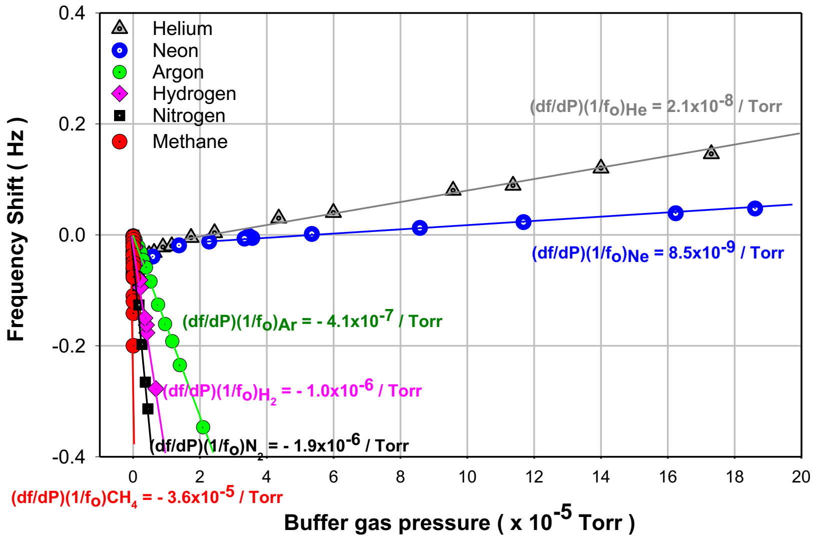


*Courtesy: Jun Yi*

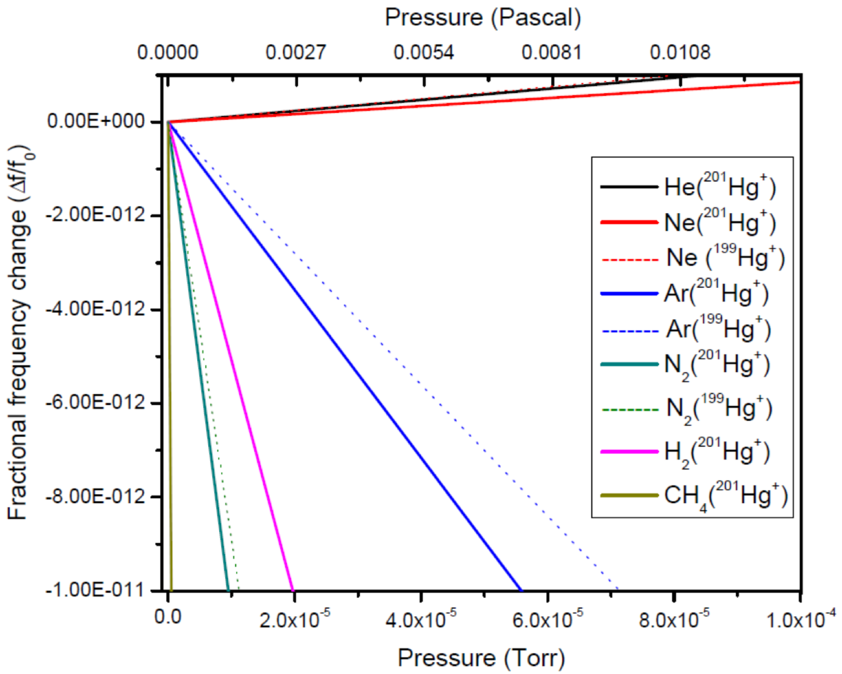
# Collision shifts – room temperature

$$\frac{\Delta f}{f} = K_i P_i$$

eg., in Hg+ (hyperfine), $K_{H2}$ = 3e-6/torr, $K_{CH4}$ = 1e-5/torr, $K_{He}$ = 1e-8/torr
=> If $\Delta P_{CH4}$ = 1e-10 torr, $\Delta f/f$ = 1e-15 !!




S.K. Chung, et al., Proc. IEEE IFCS (2004)




L. Yi, et al., Proc. IEEE IFCS (2012)

# *Doppler shifts – 1st and 2nd order*

- First order:
  - Lamb-Dicke confinement

$$\frac{\Delta f}{f} = \frac{v}{c}$$

- Second order:
  - Laser cool to zero point
  - Multi-pole traps
  - Compensation schemes

$$\frac{\Delta f}{f} = -\frac{3k_B T}{2mc^2}\left(1 + \frac{2}{3}\frac{1}{k-1}\right)$$

(to be completed)

# *Gravitational shifts*

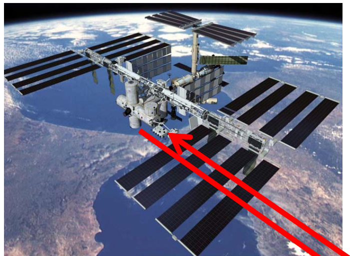
- Gravitational red shift

(to be completed)

## *Overview of fundamental physics tests with atomic clocks*

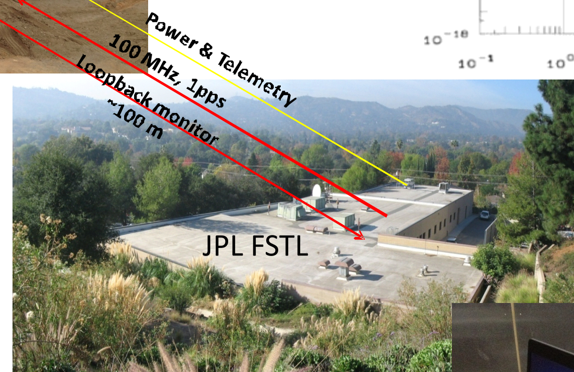
- Fundamental constants
- Compare different atomic species
- Compare mechanical and atomic standards
- Isotopic effects
- Gravitational waves
- VLBI
- Dark energy and precision ranging
- Occultation studies

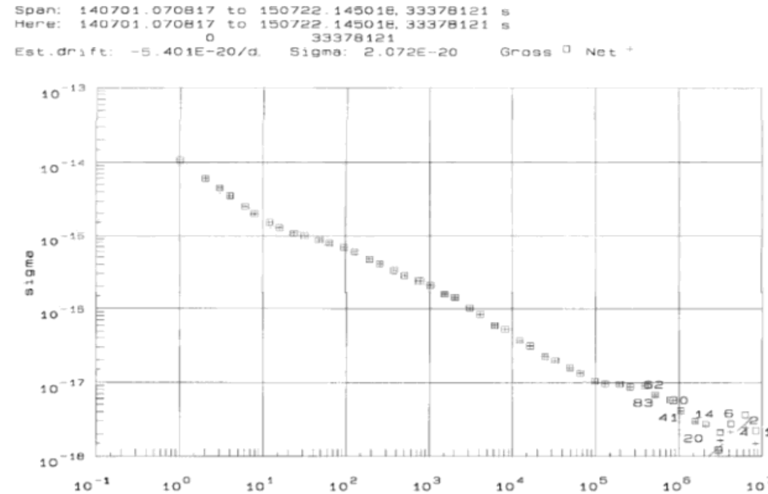
# *Gravitational red shift: Atomic Clock Ensemble in Space Mission (ACES)- JPL reference*



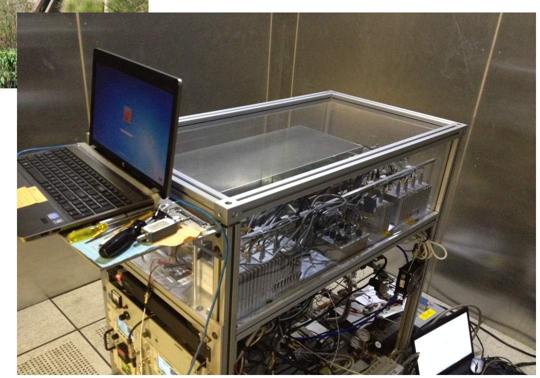
ISS clocks

ACES ground terminal

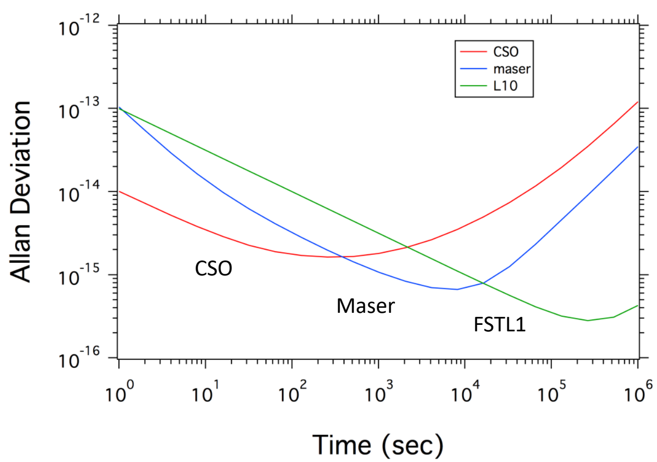


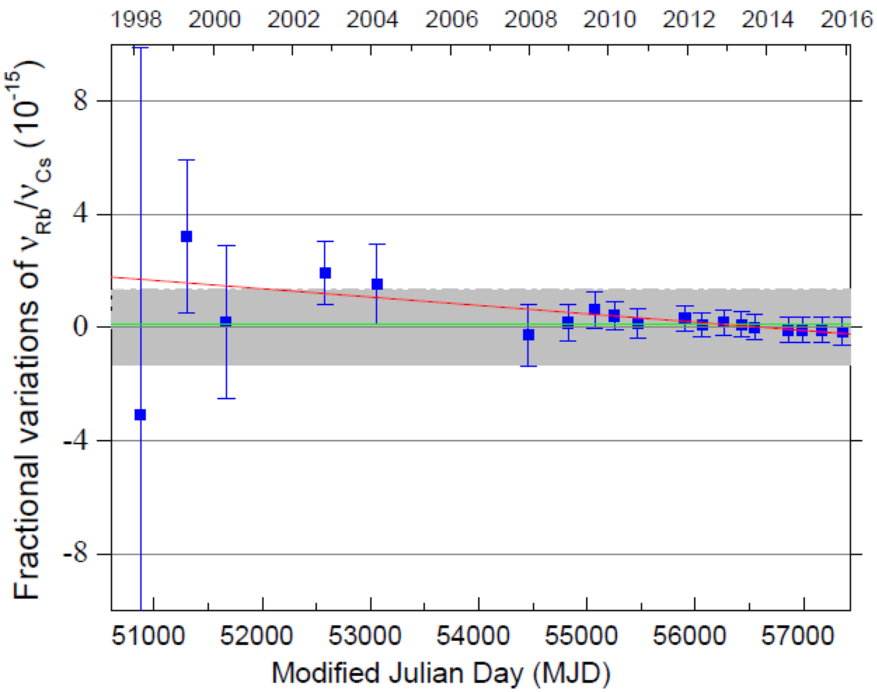

JPL link noise: 1 year ADEV $3x10^{-18}$ noise floor



H-maser LO – Hg+ reference



# Rb/Cs: search for time variation in fundamental constants




*Phys. Rev. Lett. 109, 080801 (2012)*

Weighted least-squares fit to a line

$$\frac{d}{dt}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-10.7 \pm 4.9) \times 10^{-17}\, yr^{-1}$$

$\Rightarrow$ limit on a potential variation of fundamental constants :

With QED calculations: *J. Prestage, et al., PRL (1995), V. Dzuba, et al., PRA (1999)*

$$\frac{d}{dt}\ln\left(\frac{g_{Rb}}{g_{Cs}}\alpha^{-0.49}\right) = (-10.7 \pm 4.9) \times 10^{-17}\, yr^{-1}$$

With QCD calculations: *T.H. Dinh, et al., PRA79 (2009)*

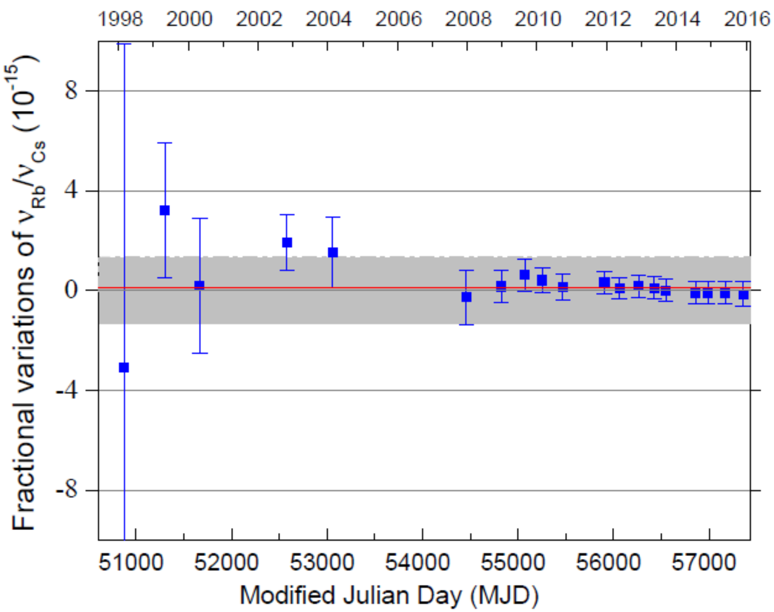
$$\frac{d}{dt}\ln\left[\alpha^{-0.49}(m_q/\Lambda_{QCD})^{-0.021}\right] = (-10.7 \pm 4.9) \times 10^{-17}\, yr^{-1}$$

*Slide courtesy J. Guéna, SYRTE*

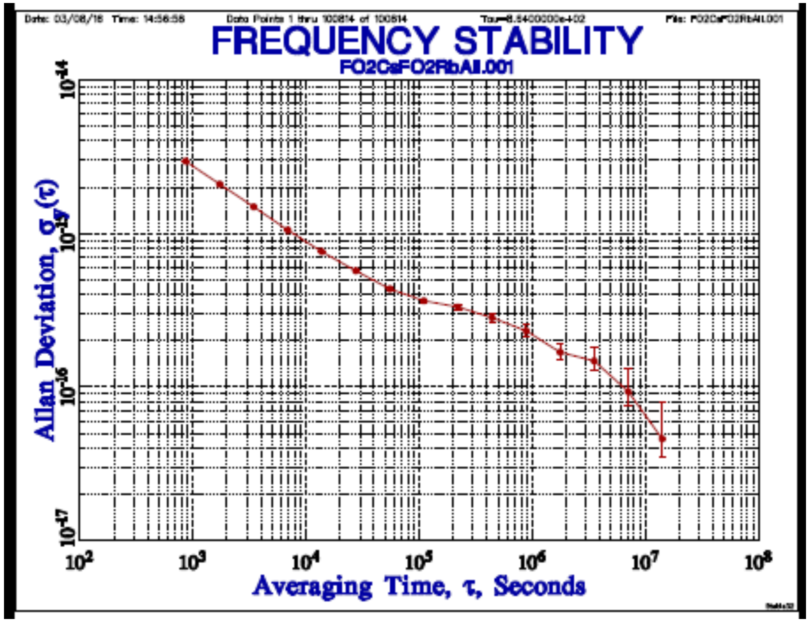
# Fundamental Physics with Rb/Cs fountains (SYRTE)

- 16 years of $^{87}$Rb ground state hyperfine frequency measurements against Cs : FO2-Rb against FO1 or FOM, and since 2009 against FO2-Cs operated simultaneously.

- Feb. to Aug. 2012 measurement
  6 834 682 610.904 312 (3) Hz ($\pm 4.4 \times 10^{-16}$)
  $\Rightarrow$ recommended value of Rb hf frequency




*Phys. Rev. Lett. 109, 080801 (2012)*




FO2Cs – FO2Rb long term comparison (Dec. 2009 – Feb. 2016)

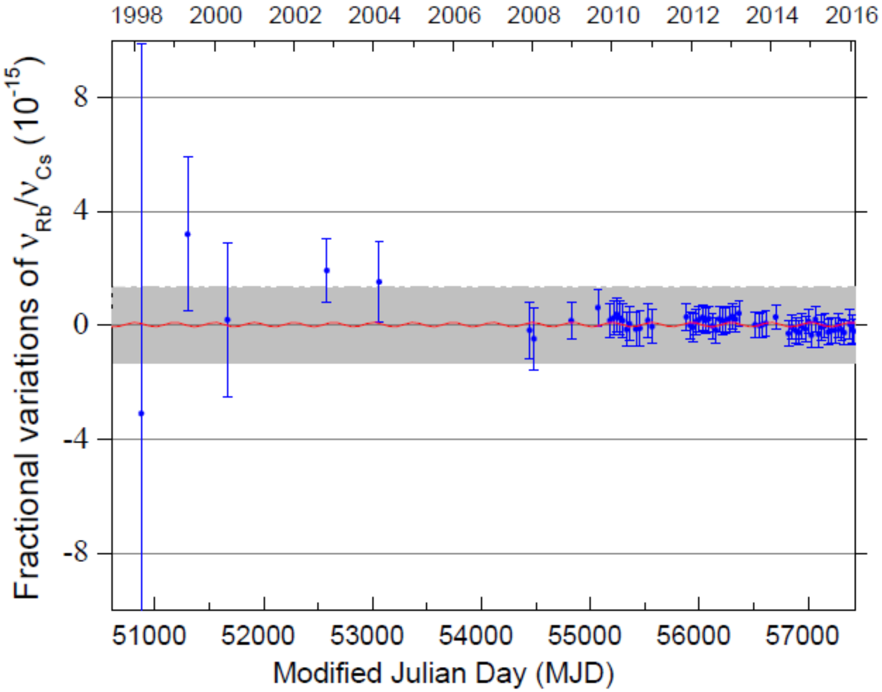
average difference $1.1 \times 10^{-16}$

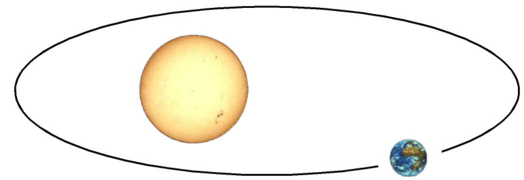
statistical unc. down to $4.8 \times 10^{-17}$



*Slide courtesy J. Guéna, SYRTE*

# Rb/Cs: search for annual variations



$$\frac{\Delta U(t)}{c^2} \simeq -\frac{GM_\odot}{c^2 a}\epsilon \cos[\Omega(t - t_{perihelion})]$$

$$d\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = C + (0.8 \pm 0.9)\times 10^{-16}\cos[\Omega_\oplus(t - t_{perihelion})]$$

$$c^2\frac{d}{dU}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-4.7 \pm 5.3)\times 10^{-7}$$

- **Differential redshift test**

$$d\nu/\nu = (1+\beta)dU/c^2$$

$$\beta(^{87}Rb) - \beta(^{133}Cs) = (-4.7 \pm 5.3)\times 10^{-7}$$

- **Variation of constants with gravity**

$$c^2\frac{d}{dU}\ln\left(\frac{g_{Rb}}{g_{Cs}}\alpha^{-0.49}\right) = (-4.7 \pm 5.3)\times 10^{-7}$$

$$\frac{d}{dt}\ln\left(\alpha^{-0.49}(m_q/\Lambda_{QCD})^{-0.021}\right) = (-4.7 \pm 5.3)\times 10^{-17}\,yr^{-1}$$

# Fundamental Physics with Ion Clocks: $^{201}$Hg+/$^{199}$Hg+ Dual Isotope Clock

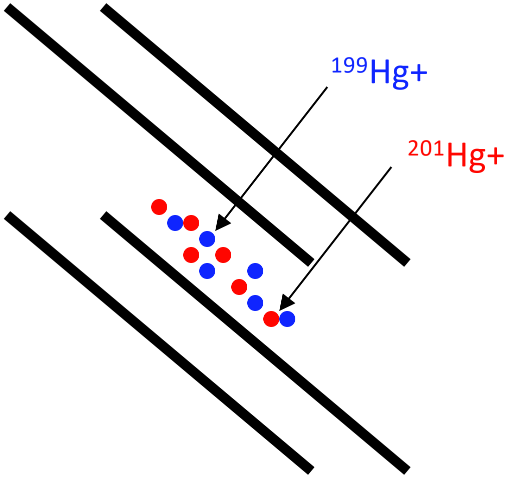
- HF clocks: depend on $\alpha$, $\mu$ via $A \propto (m_e e^4/\hbar^2)[\alpha^2 F_{rel}(Z\alpha)](\mu m_e/m_p)$
    - some ambiguity
- Direct optical clock comparisons depend only on $\alpha$
- $\mu \propto m_q/\Lambda_{QCD}$ *
- $B_{201} \approx -B_{199}$ **:

$$\frac{\partial}{\partial t}\ln\frac{f_{201}}{f_{199}} = \left[B_{201} - B_{199}\right]\frac{\partial}{\partial t}\ln\left(\frac{m_q}{\Lambda_{QCD}}\right)$$

- $B_{201}-B_{199} \approx 0.2$ - *BIG!*
- Would provide a stand-alone independent limit on $m_q/\Lambda_{QCD}$ variation

**Dual isotope clock will reduce systematic sensitivity in difference measurement:**

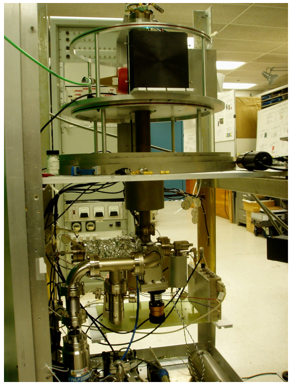
- Simultaneous measurement
- Measurement in same location



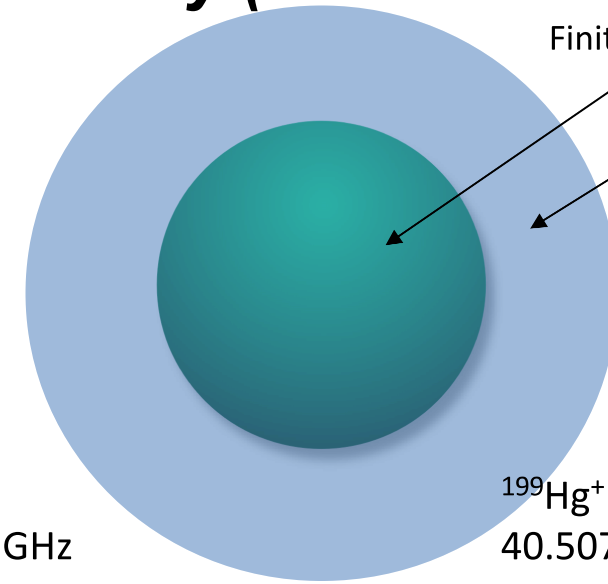

*V.V. Flambaum and A.F. Tedesco, Phys. Rev. C 73, 055501 (2006)

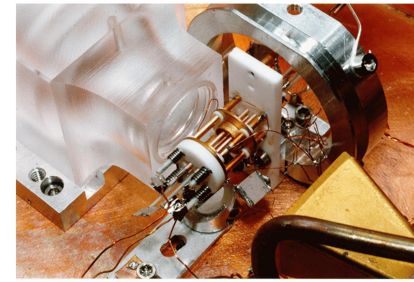
**S.N. Lea, to be published in the Eur. Phys. J ST.

# *Fundamental Physics with Ion Clocks: Hyperfine Anomaly (Bohr-Weisskopf Effect*)*



*E.A. Burt, JPL*



*Courtesy J. Bergquist, NIST*

$^{201}Hg^{+}$ HF clock:
29.9543658213(17) GHz

(E.A. Burt, et al., PRA 79, 062506 (2009))

$^{199}Hg^{+}$ HF clock:
40.507347996841590(41) GHz

(D.J. Berkeland, et al., PRL 80, 2089 (1998))

Point nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = \left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2}$$

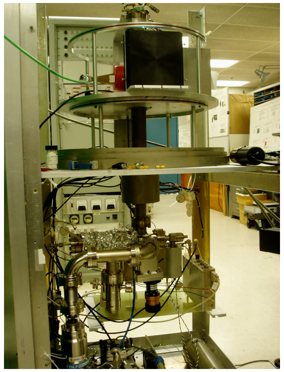
Finite nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = (1+\Delta)\left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2}$$

HF anomaly

**A. Bohr and V.F. Weisskipf, PR 77, 94 (1950)*

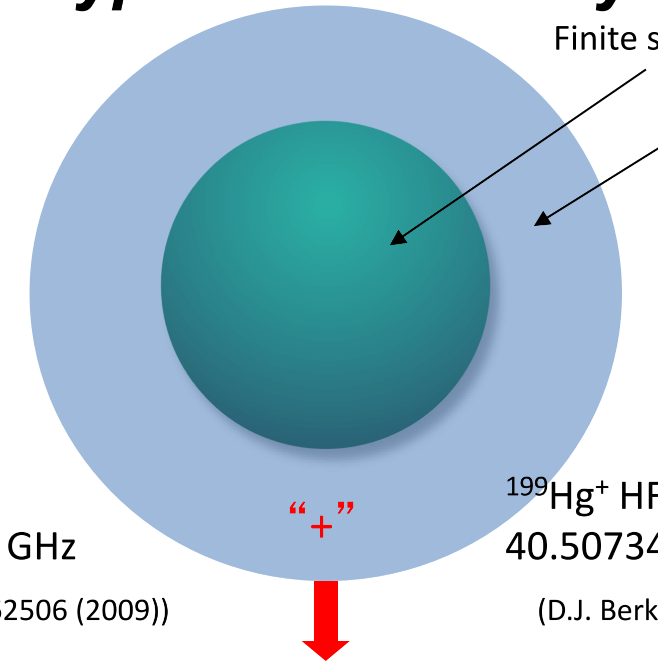
# *Fundamental Physics: The Hyperfine Anomaly*

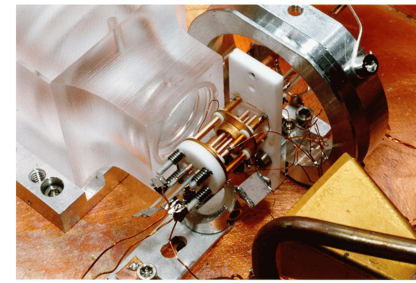


*E.A. Burt, JPL*

$^{201}Hg^{+}$ HF clock:
29.9543658213(17) GHz

(E.A. Burt, et al., PRA 79, 062506 (2009))



*Courtesy J. Bergquist, NIST*

$^{199}Hg^{+}$ HF clock:
40.50734799684159(41) GHz

(D.J. Berkeland, et al., PRL 80, 2089 (1998))

$$\frac{\Delta f_1}{\Delta f_2} = (1+\Delta)\left(\frac{\mu_{I1}/I_1}{\mu_{I2}/I_2}\right)\frac{F_1}{F_2} \qquad \frac{f_{201}}{f_{199}} = -0.739479805577(3)$$

$$\Delta\left(S_{1/2}, {}^{199}\mathrm{Hg}^{+}, {}^{201}\mathrm{Hg}^{+}\right) = -0.0016257(5)$$

E.A. Burt, et al., PRA 79, 062506 (2009)

Previous values Hg: -0.001627(19), *(Reimann and McDermott, PRC 7, 2065 (1973))*
$Hg^{+}$: -.0034 to +0.0056 *(Grandinetti, et al., (1986))*

- Value now limited by knowledge of $\mu_I$
- Agrees with neutral value: valence screening has minimal effect

# *Selected Textbook References (see specific slides for journal references)*


Atomic Physics

- "Elementary Atomic Structure", 2nd Edition, G.K. Woodgate, Oxford (1986)
- "Atomic Physics", C.J. Foot, Oxford (2005)

Trapping and Cooling of Atoms

- "Laser Cooling and Trapping", H.J. Metcalf and P. van der Straten, Springer (1999)

Atomic Clocks

- "The Quantum Physics of Atomic Frequency Standards", J. Vanier and C. Audoin, CRC Press
- "The Quantum Physics of Atomic Frequency Standards – Recent Developments", J. Vanier and C. Tomescu, CRC Press (2016)

Clock Characterization

- "Characterization of Clocks and Oscillators", NIST Technical Note 1337, D.B. Sullivan et al.