Atomic Clocks : Primary Frequency Standards at NIST

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NIST – Time and Frequency Division

Outline

- Atomic Clocks - general
- Primary Frequency Standard
  - Beam Standards
  - Laser-Cooled Primary Standards
- Systematic Frequency Shifts in Primary Frequency Standards
- Possible Future – PARCS space clock
- Certain Future – optical clocks

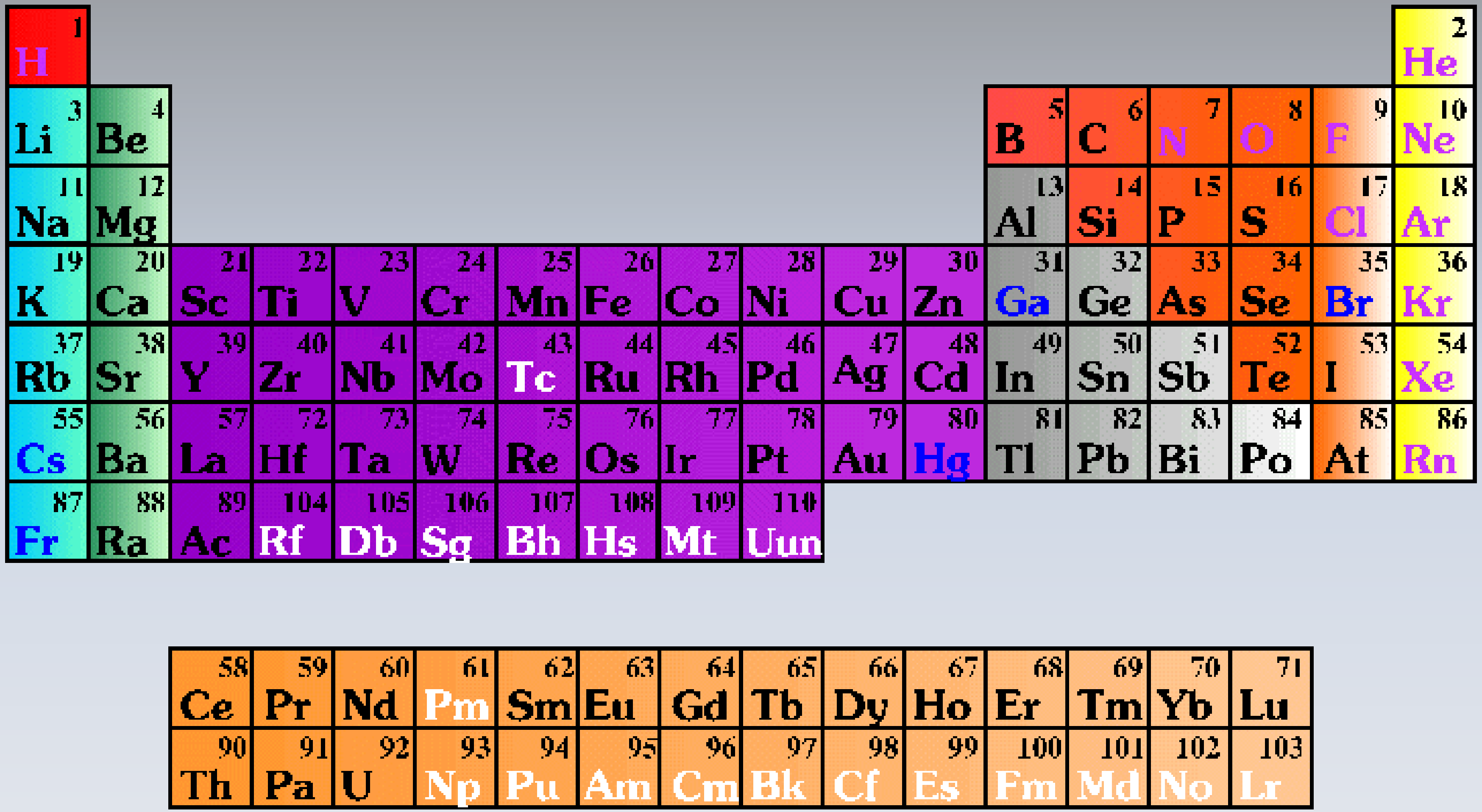
Acknowledgements

Tom Heavner, Jon Shirley and Tom Parker - the rest of the NIST-F1 team

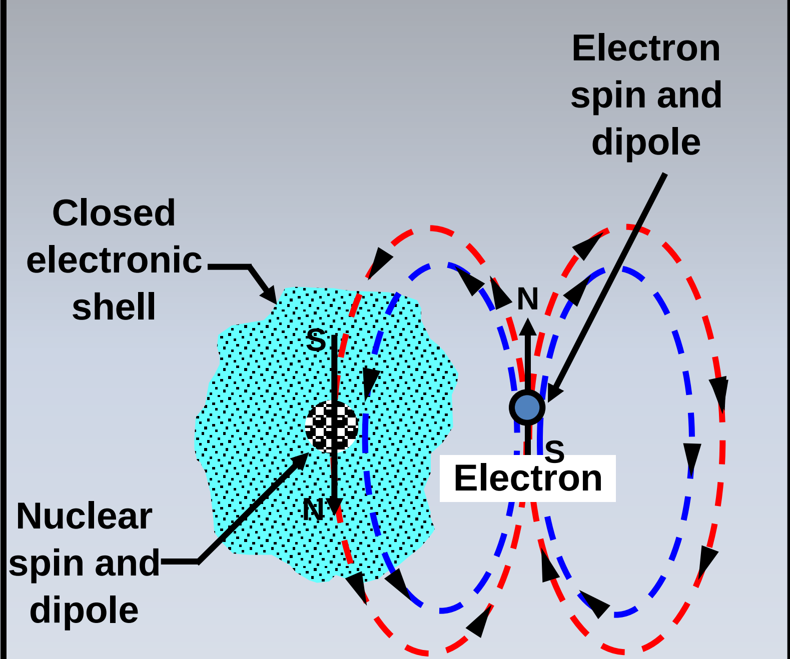
Filippo Levi and Coworkers at IEN (Torino)

Atomic Clocks - General

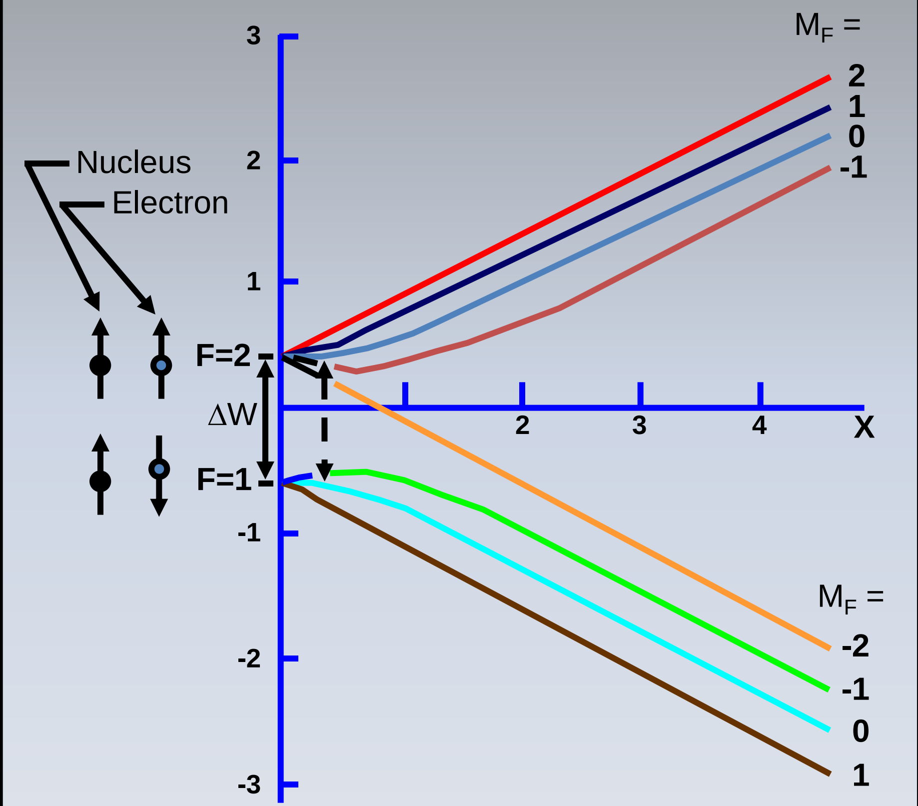
The Elements



An Energy View of an Atom

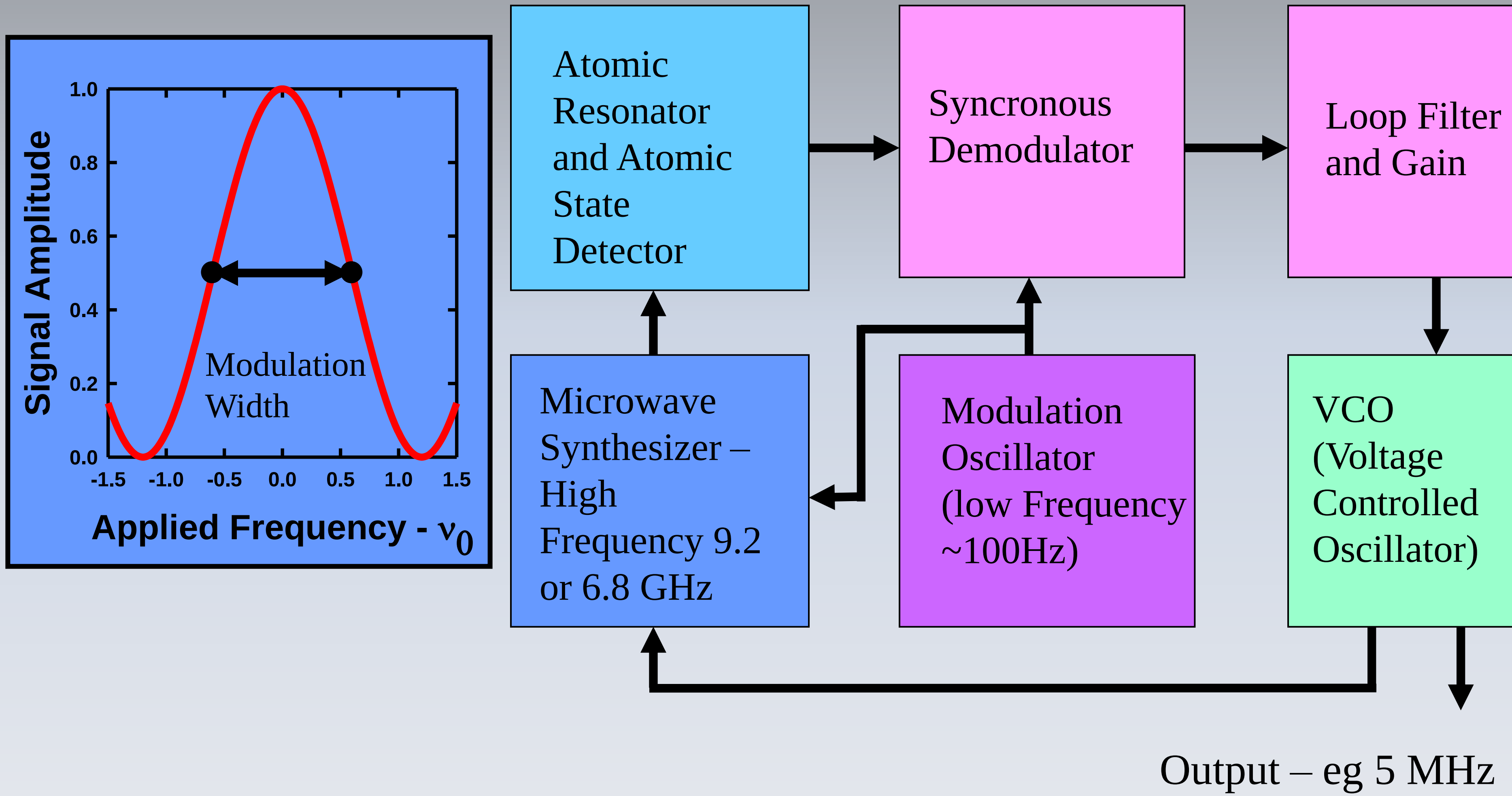


Hydrogen-like (or alkali) atoms



Hyperfine structure of ^{87}Rb, with nuclear spin I=3/2, $\nu_0 = \Delta W/h$=6,834,682,605 Hz and $X=[(-\mu J/J) + (\mu I/I)]H_0/\Delta W$ calibrated in units of 2.44×10^3 Oe.

Block Diagram – simplified a little



A Little Quantum Mechanics

- The allowed states (configurations) of an atom have discrete (quantized) energies, in the long run, atoms are only allowed to exist in these quantized states (these are the only stable states)
- Atoms of the same element (and isotope) are indistinguishable, for example, all cesium 133 atoms are the same
- Energy and Frequency are equivalent, $E=h\nu$ where h is Plank's constant
- Atoms move between their allowed energy levels by absorbing or emiting a photon of the correct frequency for the difference between the beginning and ending energies.

- The "rules" just given explain the high long term stability of atomic frequency standards. The atoms behave (define the frequency) the same way tomorrow that they do today and did yesterday. In an ideal atomic standard this would be rigorously true, in the real world the atoms interact with their environment and experience slight frequency shifts.
- These shifts are typically caused by things like
  - Less than perfect magnetic shielding
  - Collisions between atoms
  - Gravitational effects
  - Thermal radiation
  - Electronics drifts
  - etc

Microwave Field

- The change in state (up to down) is driven by an microwave field
- The interaction is between the electron and the field…essentially the electron is "flipped"
- The "clock" transition is, to first order, not shifted by a magnetic field, but requires that the magnetic field of the microwaves be parallel to the C-field (quantization axis)

Definition of the SI second

The ***second*** is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.[1]

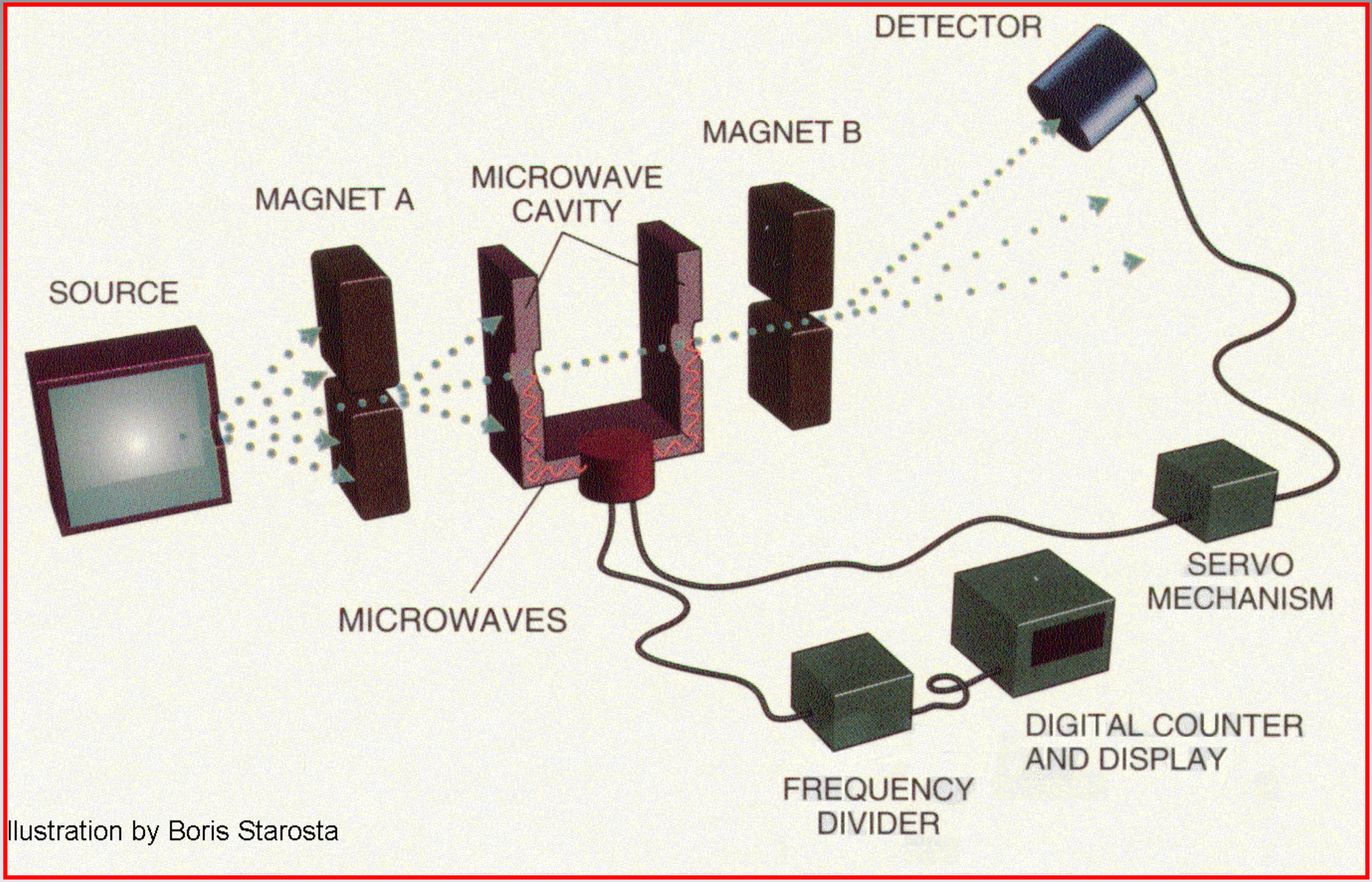
This definition refers to a cesium atom

at rest at a temperature of 0 K (absolute zero)

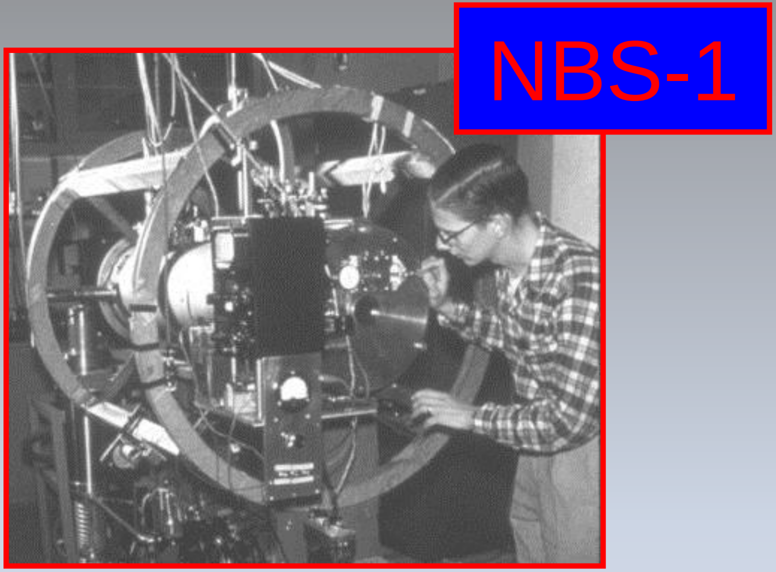
The ground state is defined at ***zero electric and magnetic fields***.

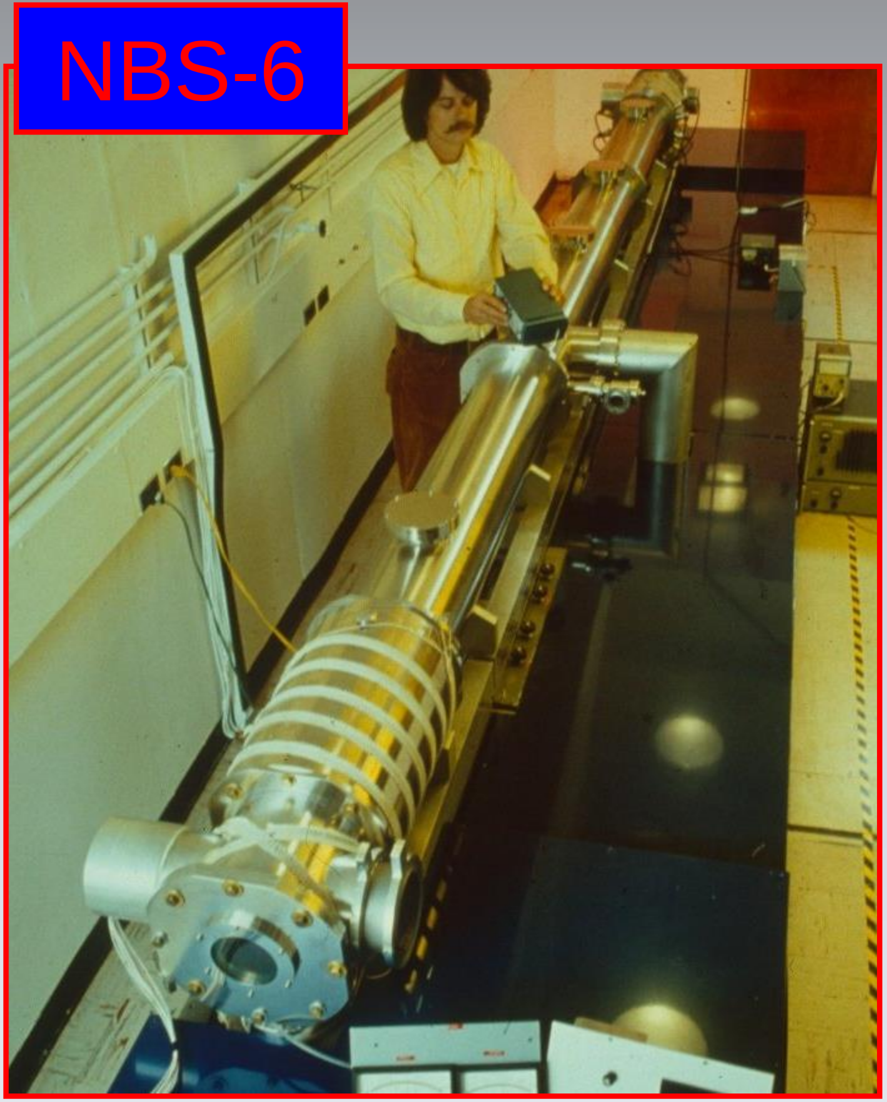
Must also correct for ***gravitational effects*** – clocks are corrected to the reference geoid (sea-level)

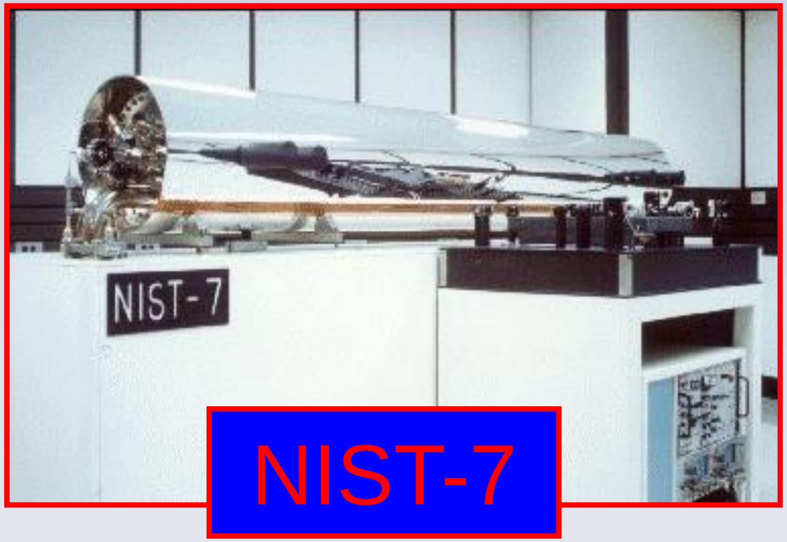
Magnetically Selected Thermal Beam



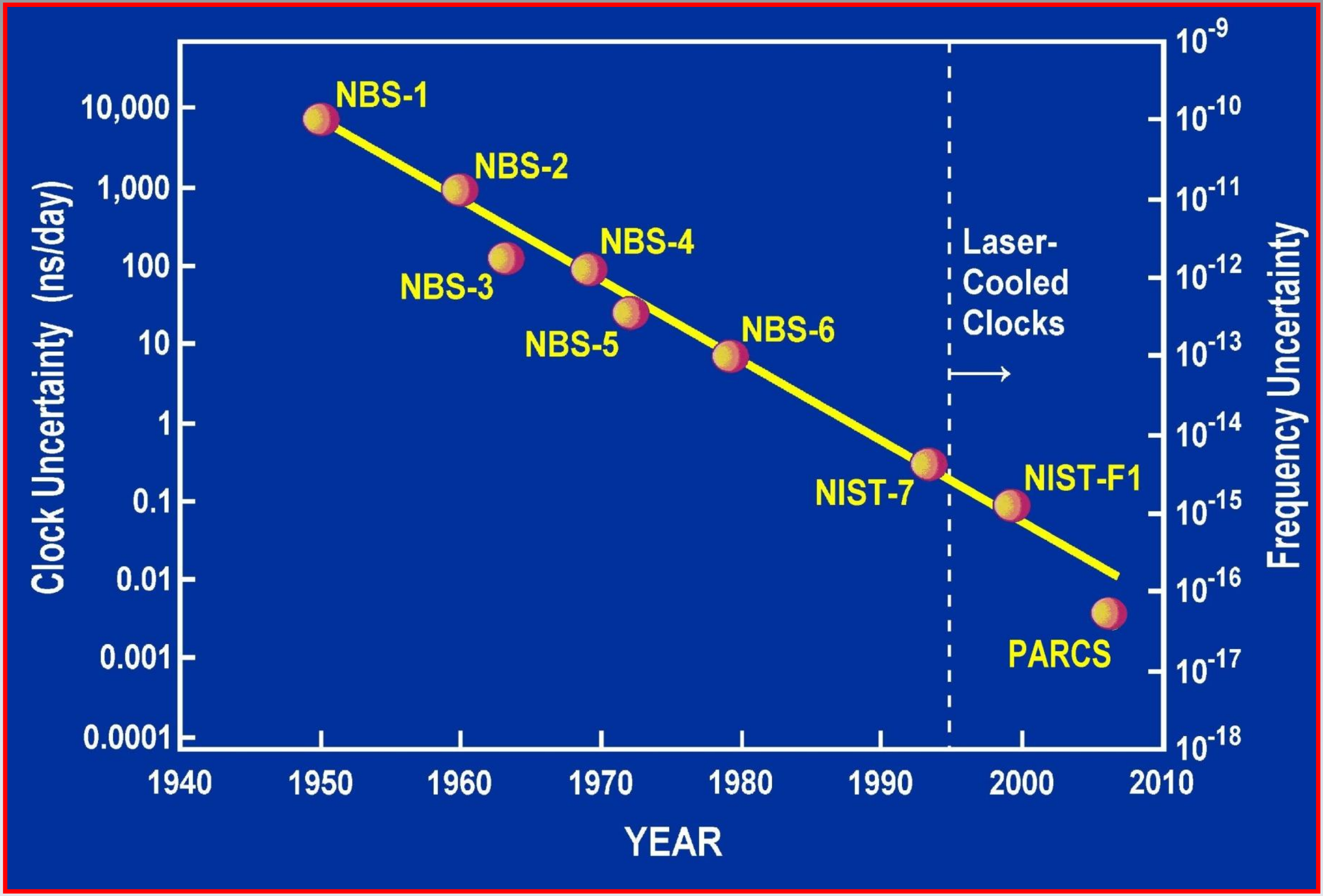
Thermal Cesium Beam Clocks at NIST







NIST Standards vs Time



NIST-F1,F2
Cesium Fountain Primary Frequency Standards

T

Clock Performance

Clock Stability is given by:

$$\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

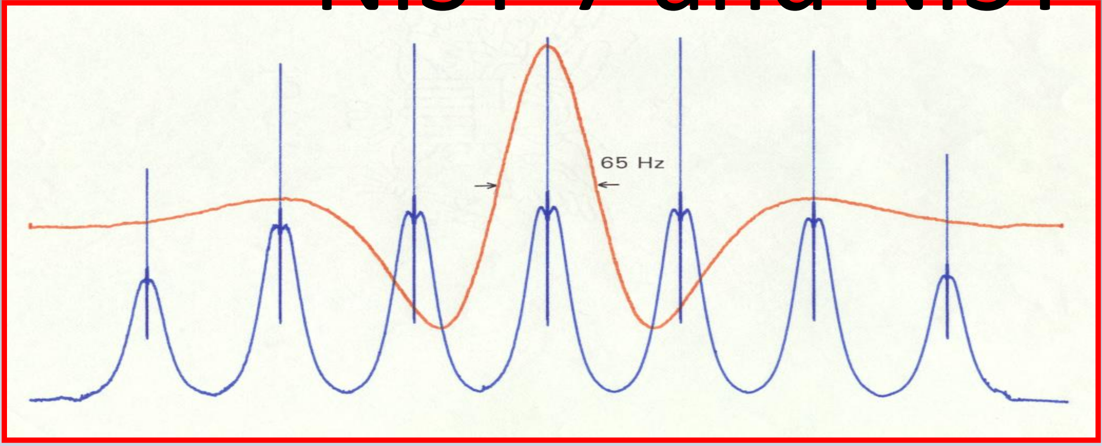
Atomic Line Q

Signal to Noise

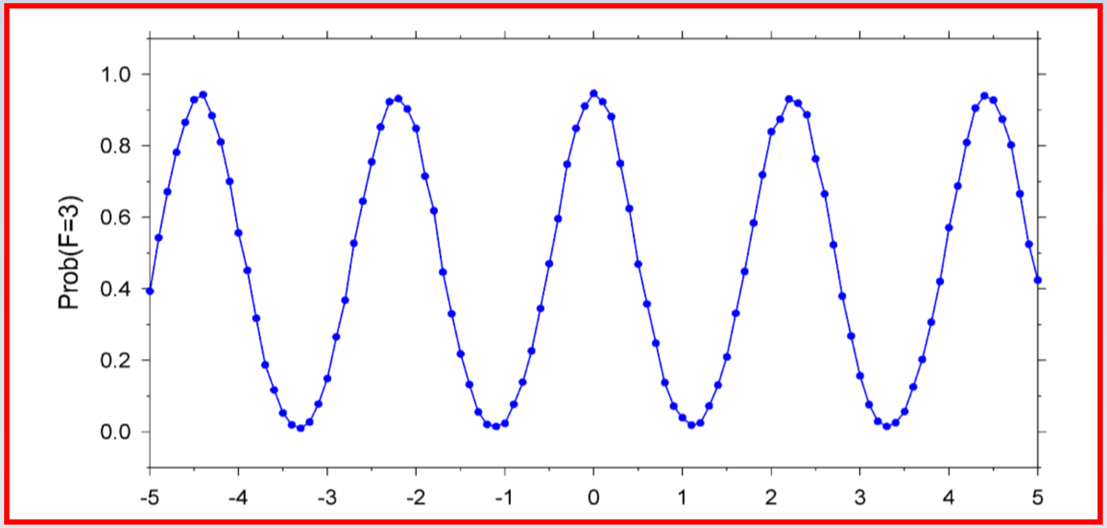
Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease $\Delta\omega = 1/T_{Ramsey}$)
- Increase The Frequency of the Clock Transition
- Improve the S/N

Ramsey Resonance in NIST-7 and NIST-F1

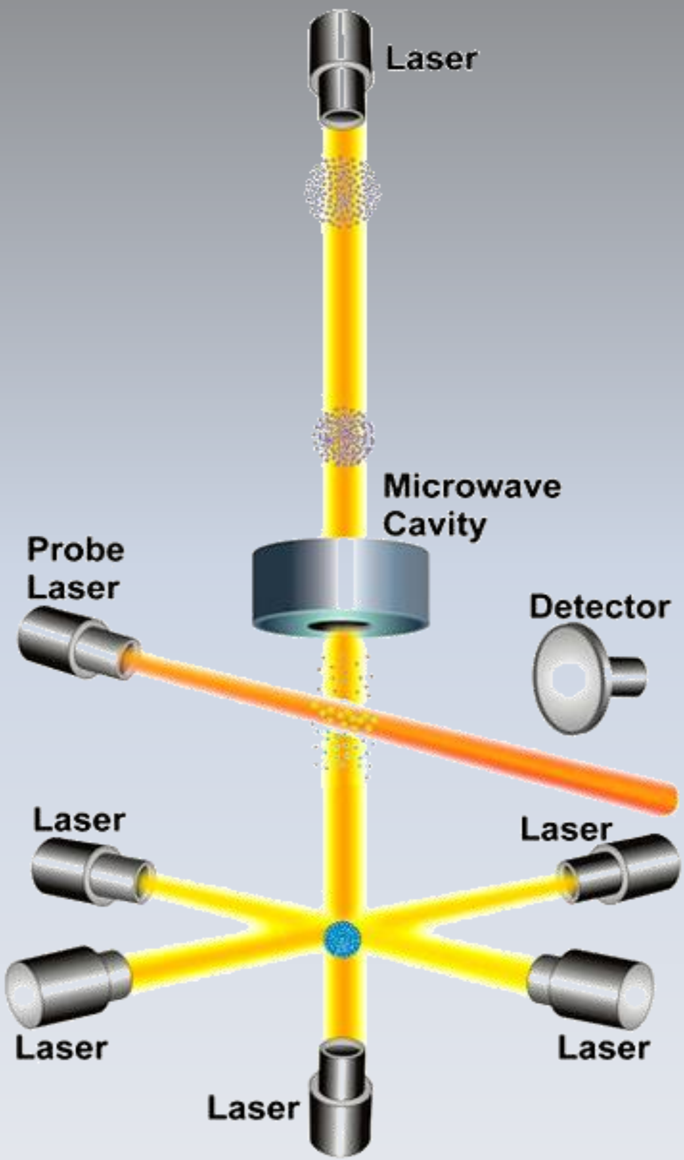


NIST-7
65Hz Linewidth



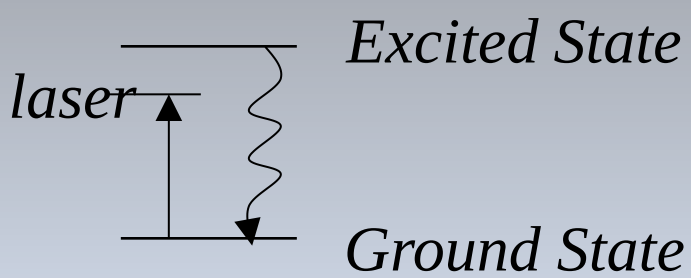
NIST-F1
1 Hz Linewidth

Cesium Fountain Schematic

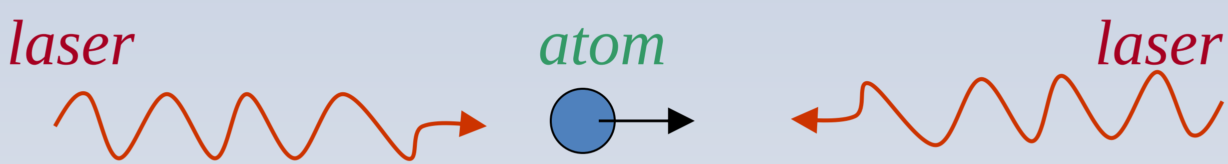


- Load and launch≈10^7 Cs atoms in 300 ms. Atoms are all in | F= 4, m_F >.
- State Selection π-pulse moves atoms in | F = 4, m_F =0> $\rightarrow$ | F = 3, m_F = 0>.
- Optical pulse removes remaining | F = 4, m_F ≠0> atoms, leaving a pure | F = 3, m_F = 0> sample.
- Ramsey spectroscopy atoms. (SOF on way UP and way DOWN.)
- Detection region measures populations in | F = 4, m_F =0> and | F = 3, m_F = 0>.

Laser Cooling I
Doppler Cooling



Laser is de-tuned to the red of the ground-to-excited state transition

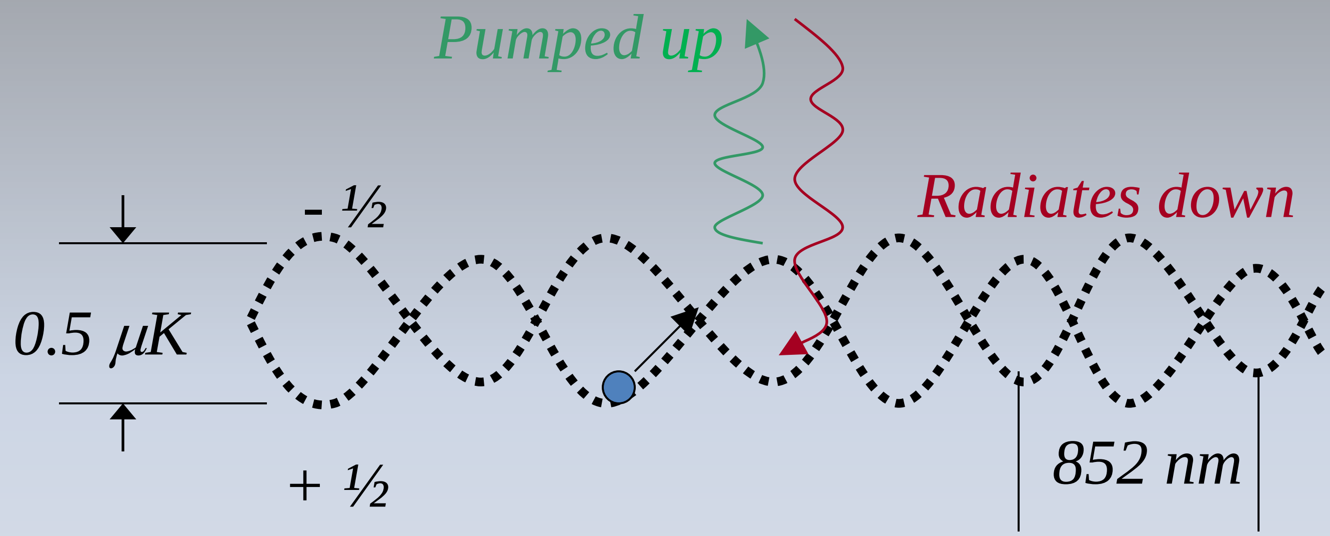


As an atom moves toward the laser, it is Doppler-shifted into resonance -- it absorbs a photon and is "kicked" backwards. It re-emits the photon in a random direction. Net result is cooling.

Cooling limit ~ 120 μK for Cs.

Velocity ~ 9 cm/s

Laser Cooling II
Sisyphus Cooling

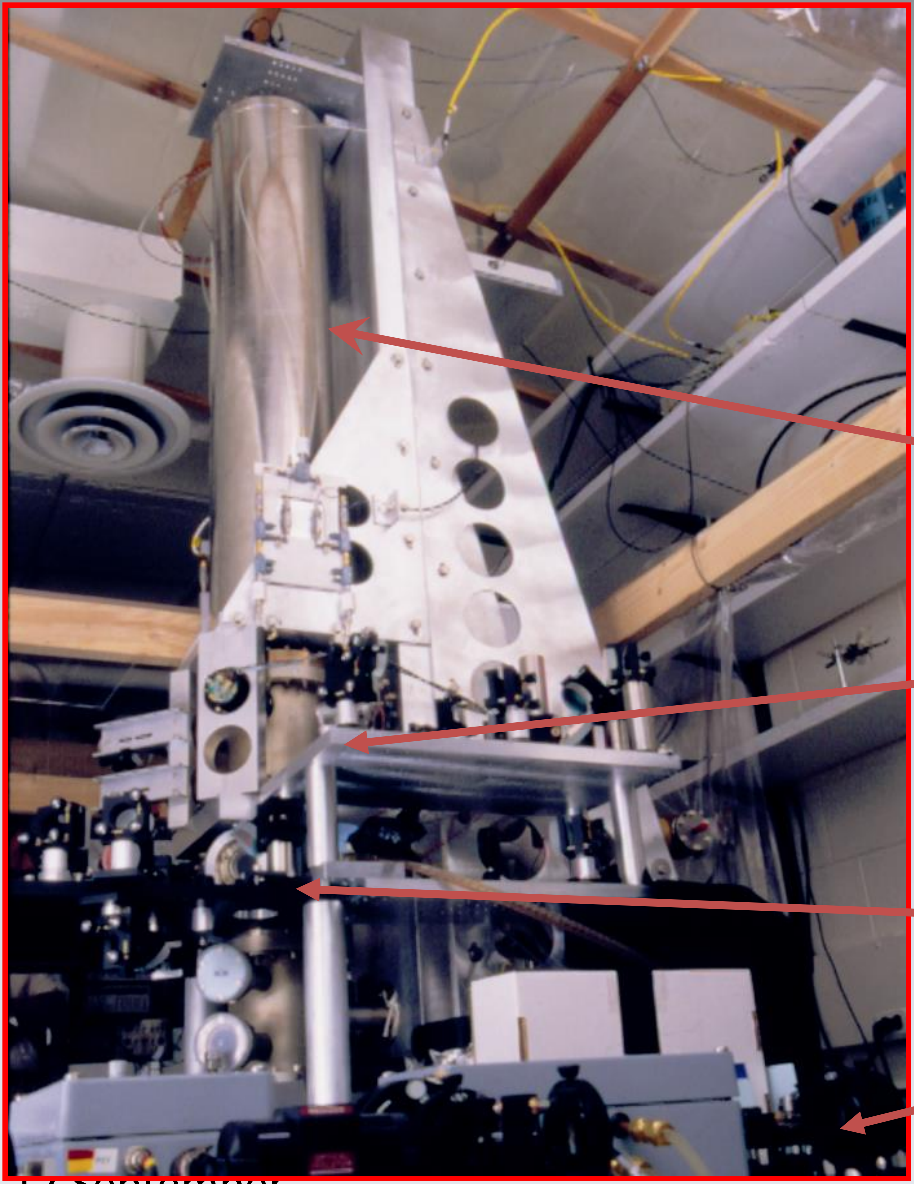


Polarization of the Ground State by light shift from optical standing wave

1. Suppose atom m= |+½> has v to the right 2. De-tuning and light shift => absorb at top 3. Radiates to |-½>, down to the bottom 4. Up the hill again

Cooling limit ~ 0.5 μK, Velocity ~ 0.5 cm/s

U.S. Primary Frequency Standard



NIST-F1

Magnetic Shields: Microwave Cavities and Flight Tube are Inside

Detection Region

Cs Optical Molasses Region

Optical Bench: Lasers, etc.

NIST-F1 Error Budget Today

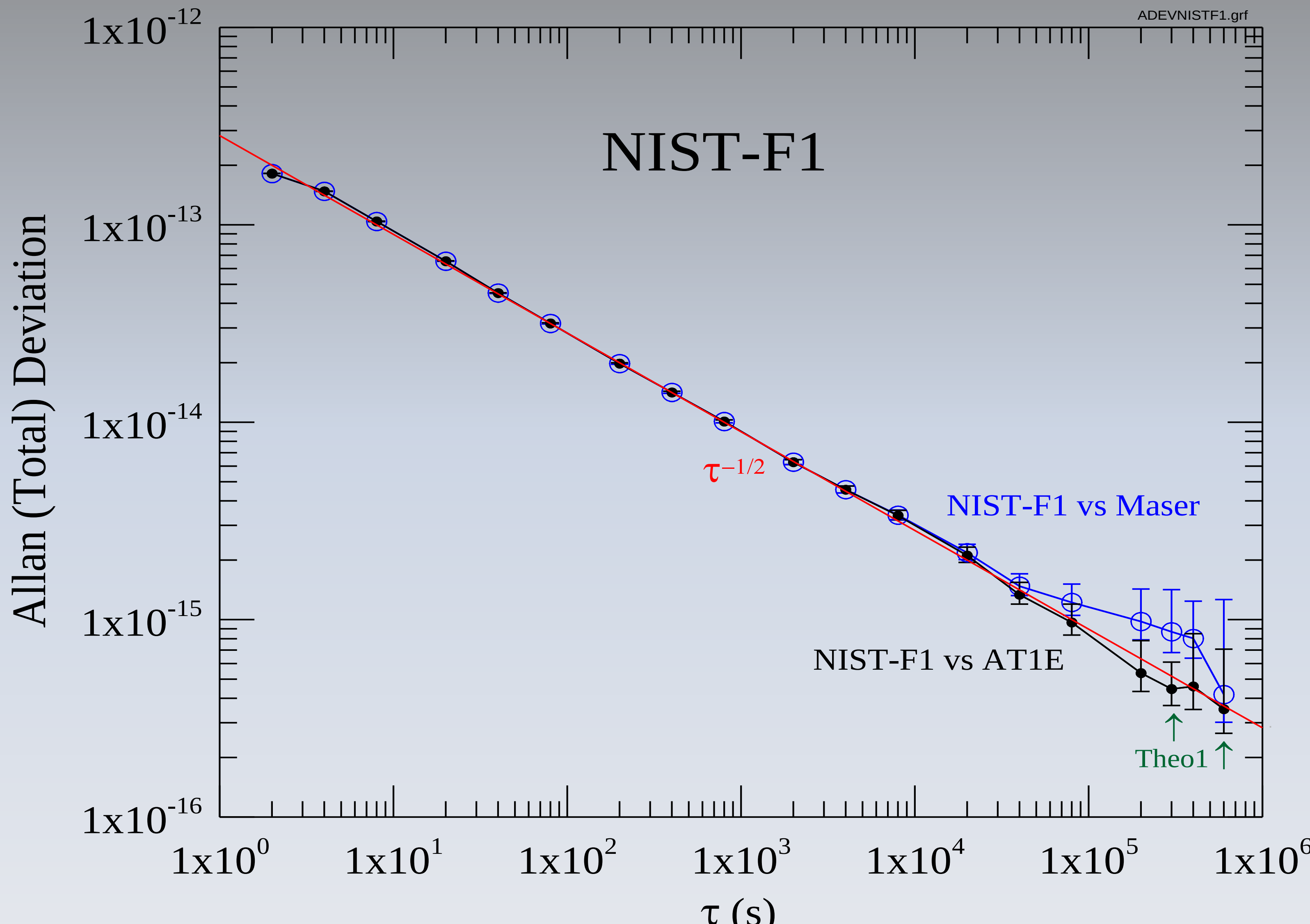
Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+180.25	0.01
Blackbody	-22.98	0.28
Microwave Effects	-0.026	0.12
Spin Exchange (density =8)	0.0 (-0.56)	0.06 (0.16)
AC Zeeman (heaters)	0.05	0.05
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Second-Order Doppler	0.02	0.02
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	$3x10^{-3}$	$3x10^{-3}$
Integrator offset	0	0.01
	Total Type B Standard Uncertainty (including Spin Exchange)	0.30 (0.34)

Dominant Uncertainty

Dominant Uncertainty

Dominant Uncertainty

ADEV NIST-F1 vs AT1E



Blackbody Shift

$$\frac{\delta\nu}{\nu_0} = \beta\left(\frac{T}{T_0}\right)^4\left(1+\varepsilon\left(\frac{T}{T_0}\right)^2\right) \quad \beta = -(1.710 \pm 0.006)\times 10^{-14}$$

- This uncertainty (±1K) dominates NIST-F1 budget
- At 300K the uncertainty in the calculated value of β amounts to almost 10^{-16}
- Calculation and measurement of DC Stark shift
- Direct measurement of AC stark has been problematic with results varying at the 10^{-15} level….difficult measurement….NO measurements at 10^{-16} level

Unlikely to get well below 10^{-16} with room temperature fountains

Microwave Shifts

- Neglecting Blackbody these are the dominant uncertainty in NIST-F1
- Frequency accuracy at $\frac{\delta\nu}{\nu} \approx 10^{-16}$ requires ~1 μradian phase control on the interrogating signal.
- Enters into the standard in a number of ways, leakage, cavity phase, spurs etc.
- These will probably be the ultimate limiting systematic effects on microwave standards

Mature Standard

- 45+ evaluations
- Limited by Blackbody
- Highly Reliable
- Probably won't improve

The cryogenic fountain: NIST-F2

Blackbody shift dominant in NIST-F1

⇓

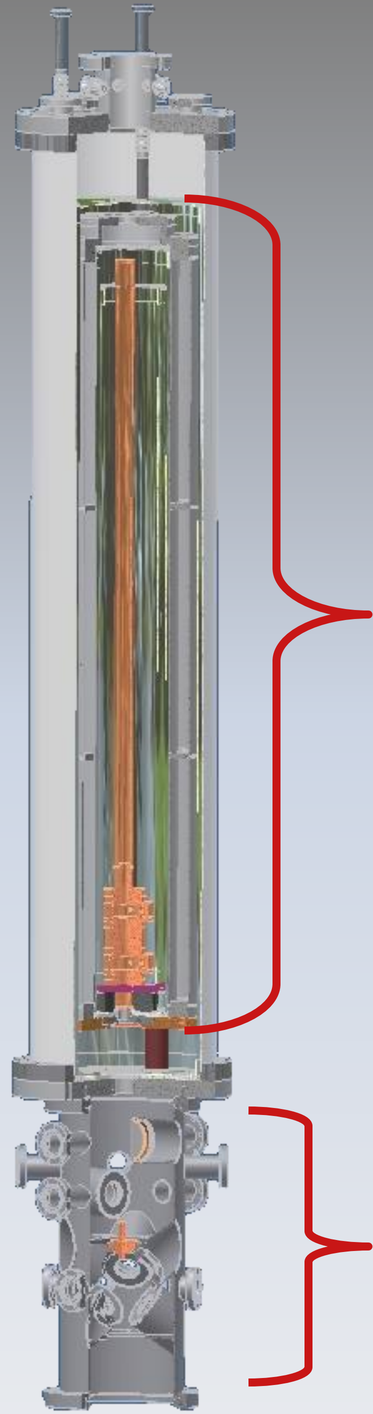
NIST-F2 has cryogenic (~80K) Ramsey cavity and drift region

⇓

Blackbody reduced to about $1\times10^{-16.}$

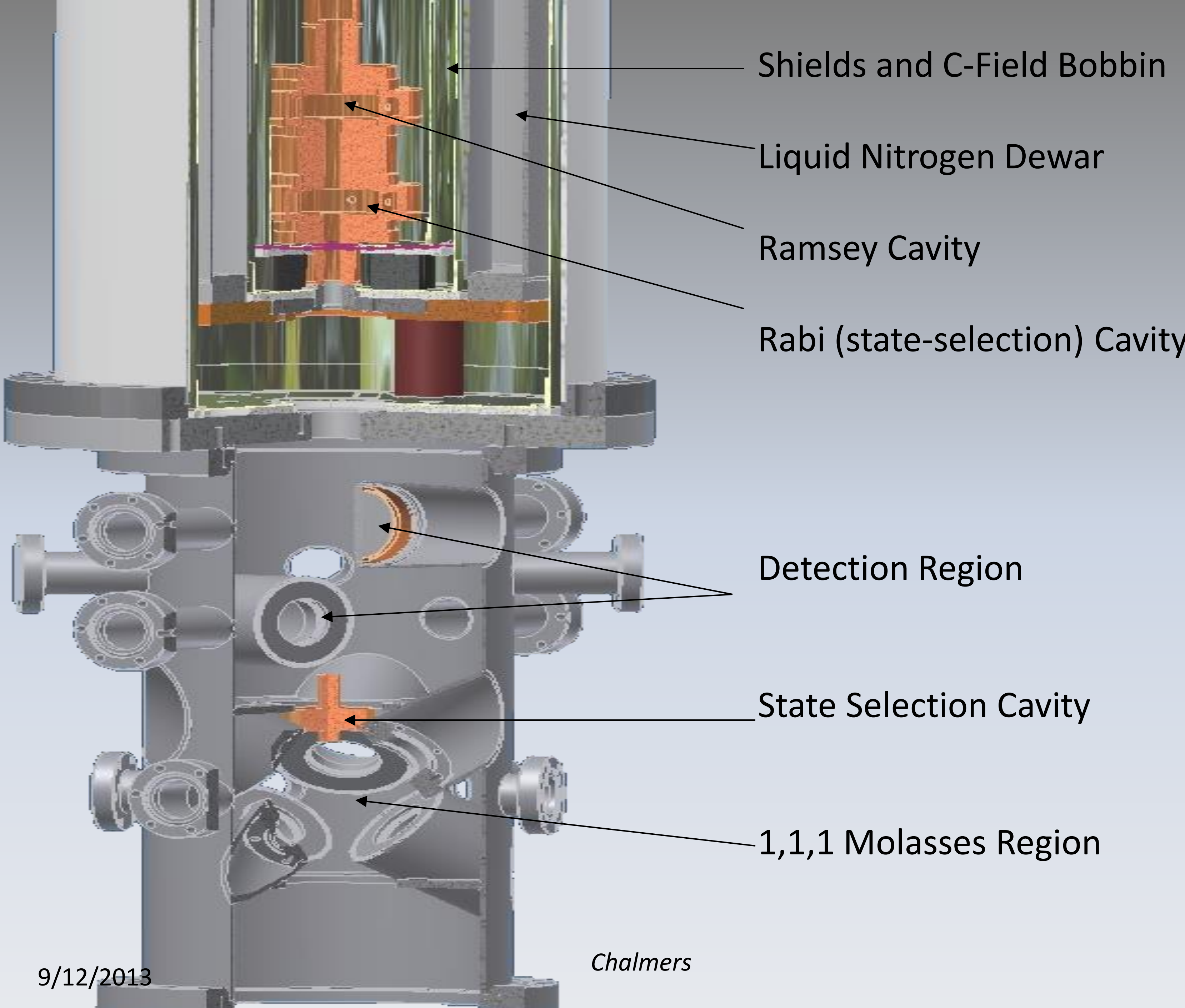
This is the total shift: a 1K error yields an uncertainty of 5×10^{-18}.

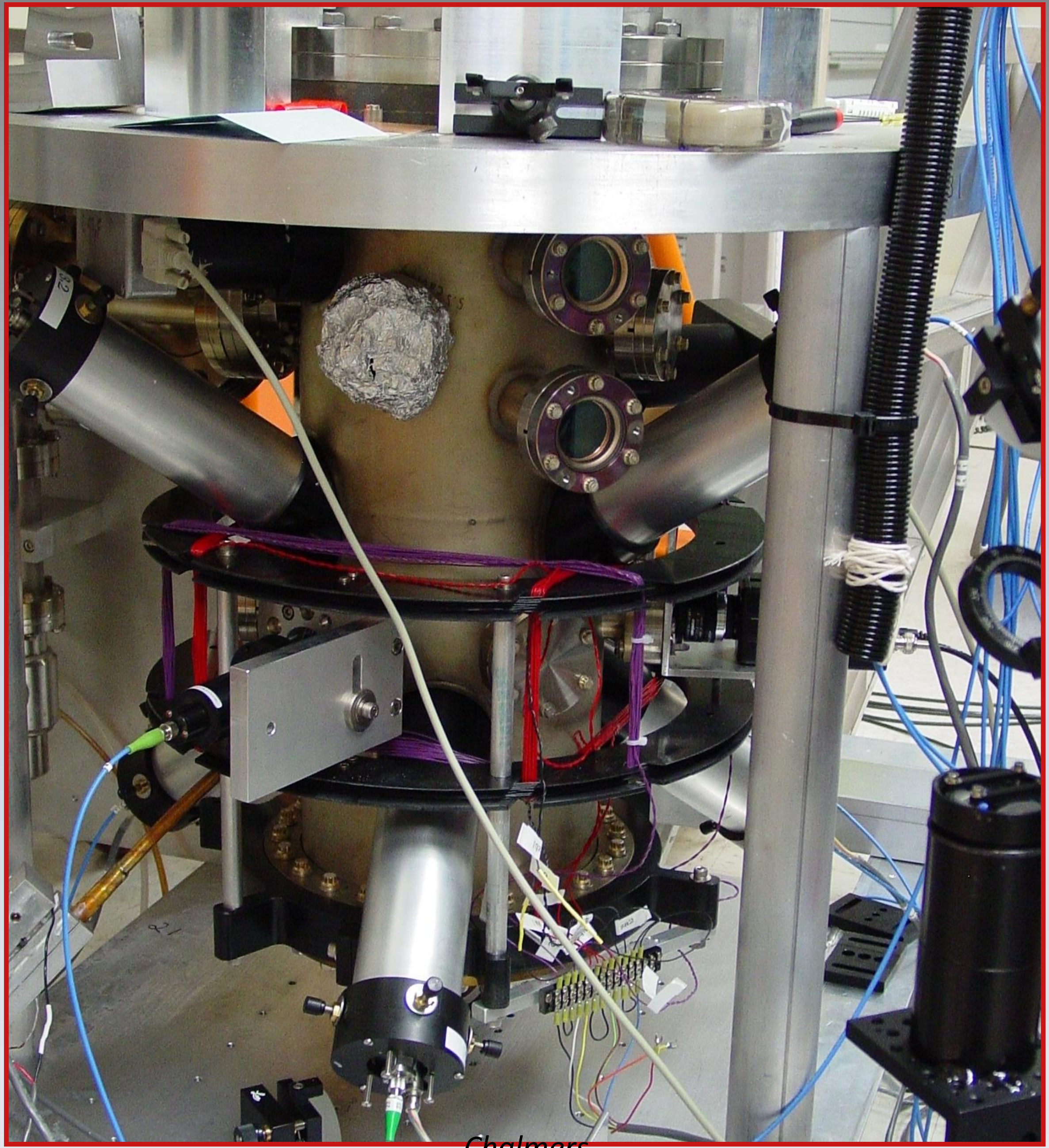
NIST-F2 Physics Package



Cryogenic (80K) Region with Ramsey microwave cavity C-field, magnetic shields and drift region

Room-temperature molasses collection and launch region with detection region above molasses region

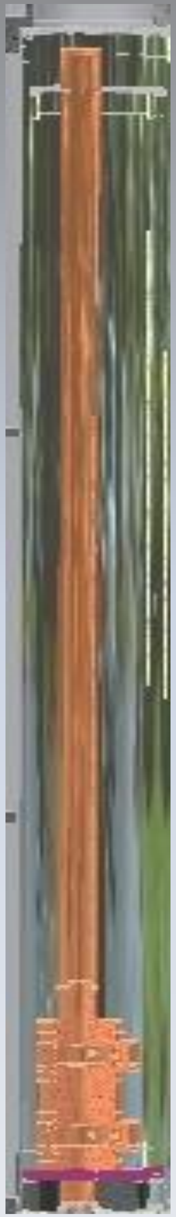

Shields and C-Field Bobbin
Liquid Nitrogen Dewar
Ramsey Cavity
Rabi (state-selection) Cavity
Detection Region
State Selection Cavity
1,1,1 Molasses Region



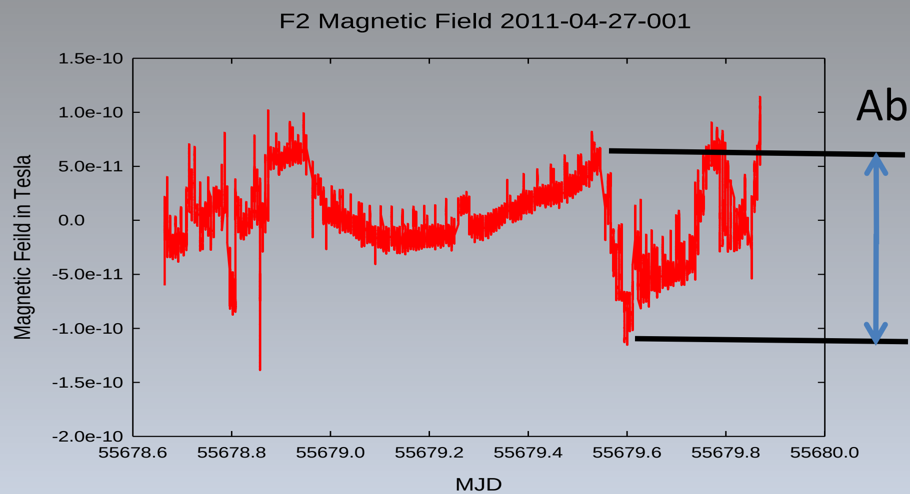
Microwave Structure

Very Similar to NIST-F1

- Cavities tuned to resonance at 80K
  - 4 feed cavity, feeds balanced to -60dB
  - Feeds balanced to within 100 μradians
  - Q is ~ 30K
  - Resonance width in Kelvin similar to room temp
- Drift Region (above Ramsey)
  - Below Cutoff for all modes except TE_{11}
  - Anti-resonant for TE_{11} at 9.192 GHz and 80K
- All microwaves FM far (~5 MHz) off resonance when atoms are below the Ramsey cavity

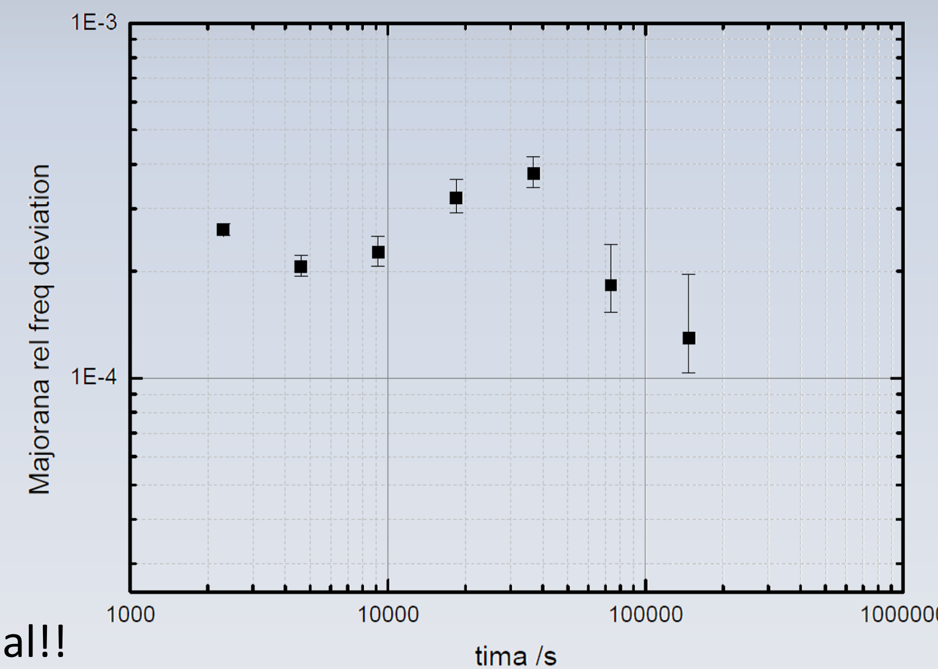


Magnetic Field vs time

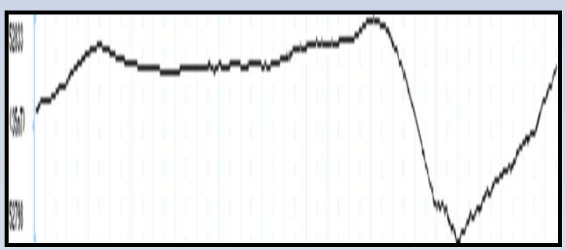


About 1 Ramsey Fringe on |3,1⟩ to |4,1⟩ line

INRIM-F2 Magnetic Field Stability – Similar at NIST



35 nT

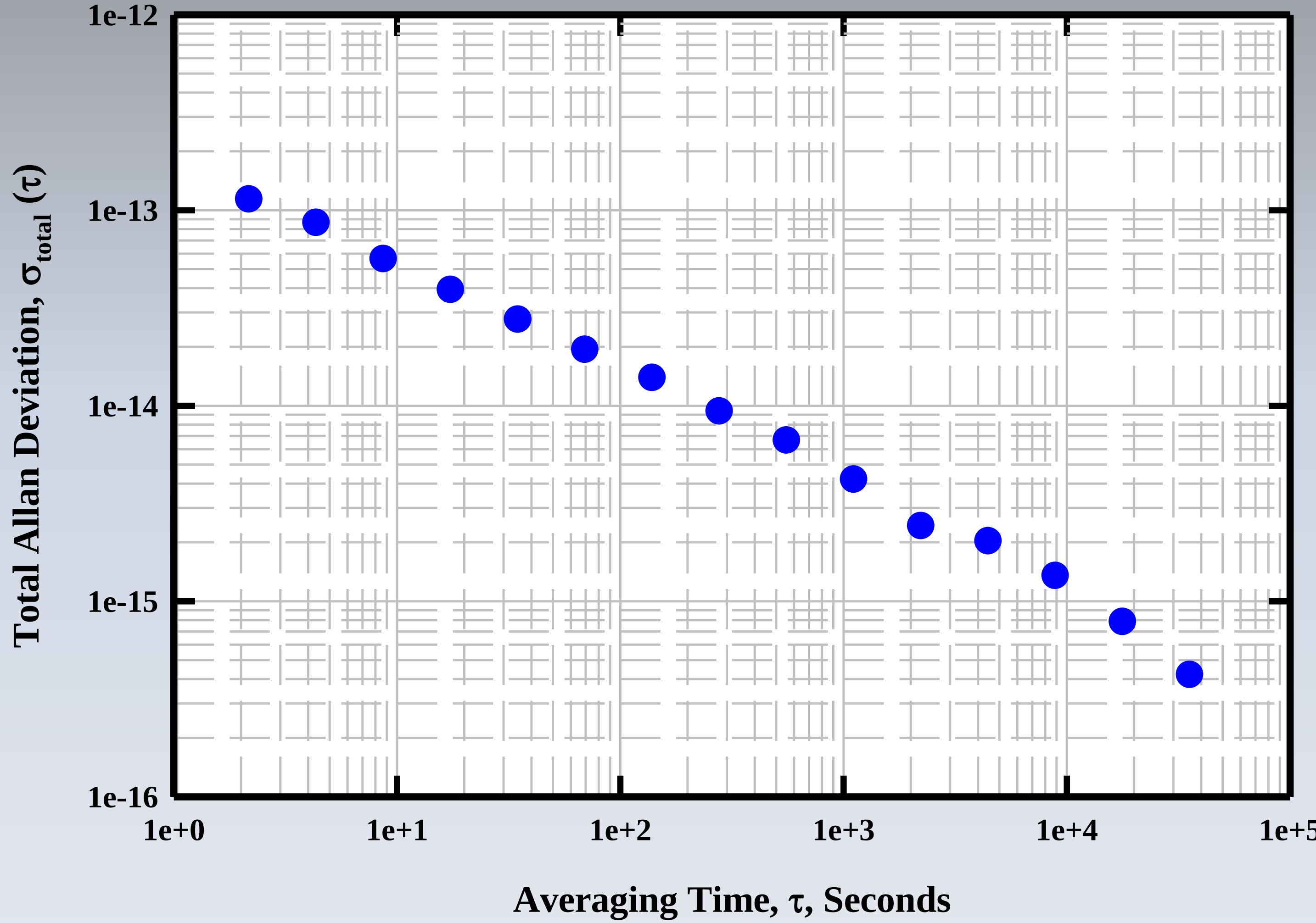


From USGS 24 Hours: Stop is 21:30 UTC April 28, 2011

Data is from the USGA Boulder monitoring site

Conclusion - NIST-F2 is a really expensive sundial!!

NIST-F2 Stability – high density June 2010



NIST-F2 Error Budget Today

Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.15	0.03
Second-Order Zeeman	+287.178	0.03
Blackbody	-0.096	0.005
Microwave Effects	-0.0025	0.10
Spin Exchange (density =10)	0.0 (0.07)	0.01 (0 .18)
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Second-Order Doppler	0.00	0.01
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	$3x10^{-3}$	$3x10^{-3}$
Integrator offset	0	0.01
Total Type B Standard Uncertainty 0.11 (Including Spin Exchange) 0.20		

Dominant Uncertainty

Dominant Uncertainty

Comparing F1 & F2

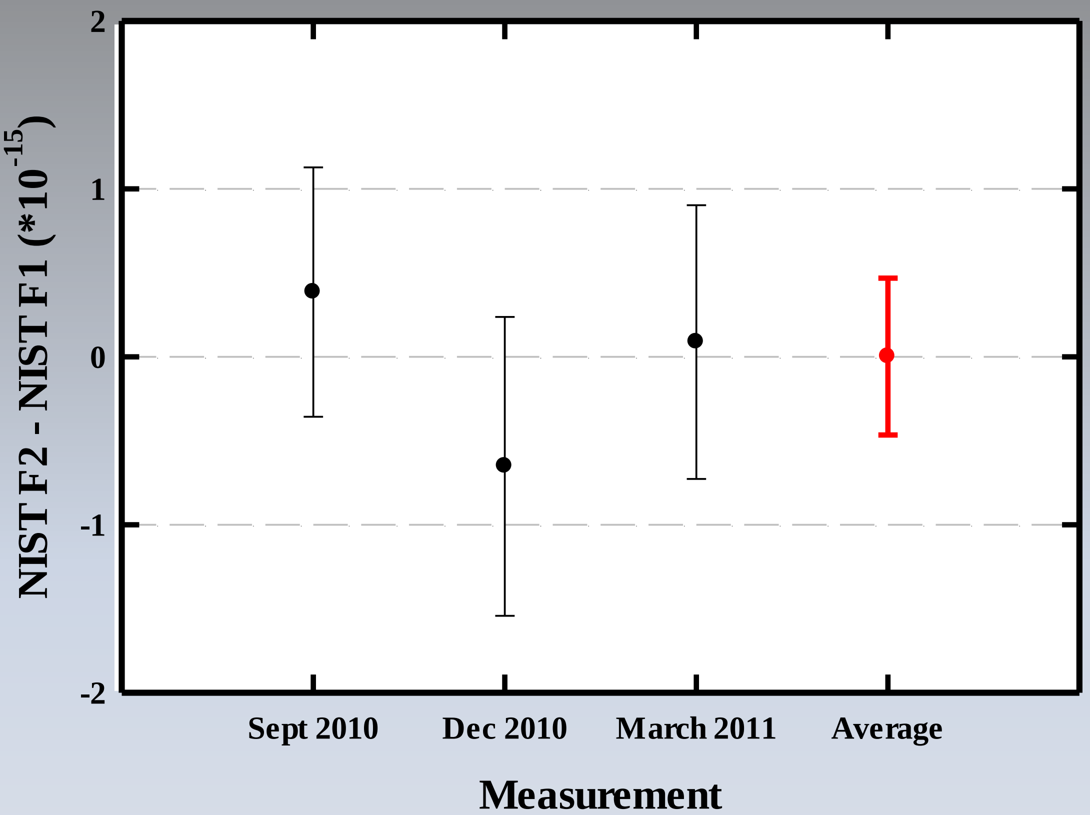
- Comparison of F1 and F2 is a measurement of the Blackbody shift of F1…..among other things!
- Uncertainty table looks quite different for comparison vs evaluation. Common mode rejection of several systematic frequency shifts (eg – Gravity)

Scheme is to operate F1 and F2 concurrently – since we are running F1 anyway, get an eval. for F1 and report to BIPM.

Measure the same maser using F1 and F2, subtract the data to remove the maser.

Correct for everything except the blackbody, the difference is the frequency shift associated with F1 blackbody.

Measuring the Blackbody Shift in NIST-F1



F2- F1 both corrected for all known systematic frequency shifts. The weighted average (in red) constitutes our best measurement of the blackbody shift. The result ($Blackbody_{measured}$ –$Blackbody_{theory}$) = $(0.02 \pm 0.40 \pm 0.29)\times 10^{-15}$ level, the best to date.

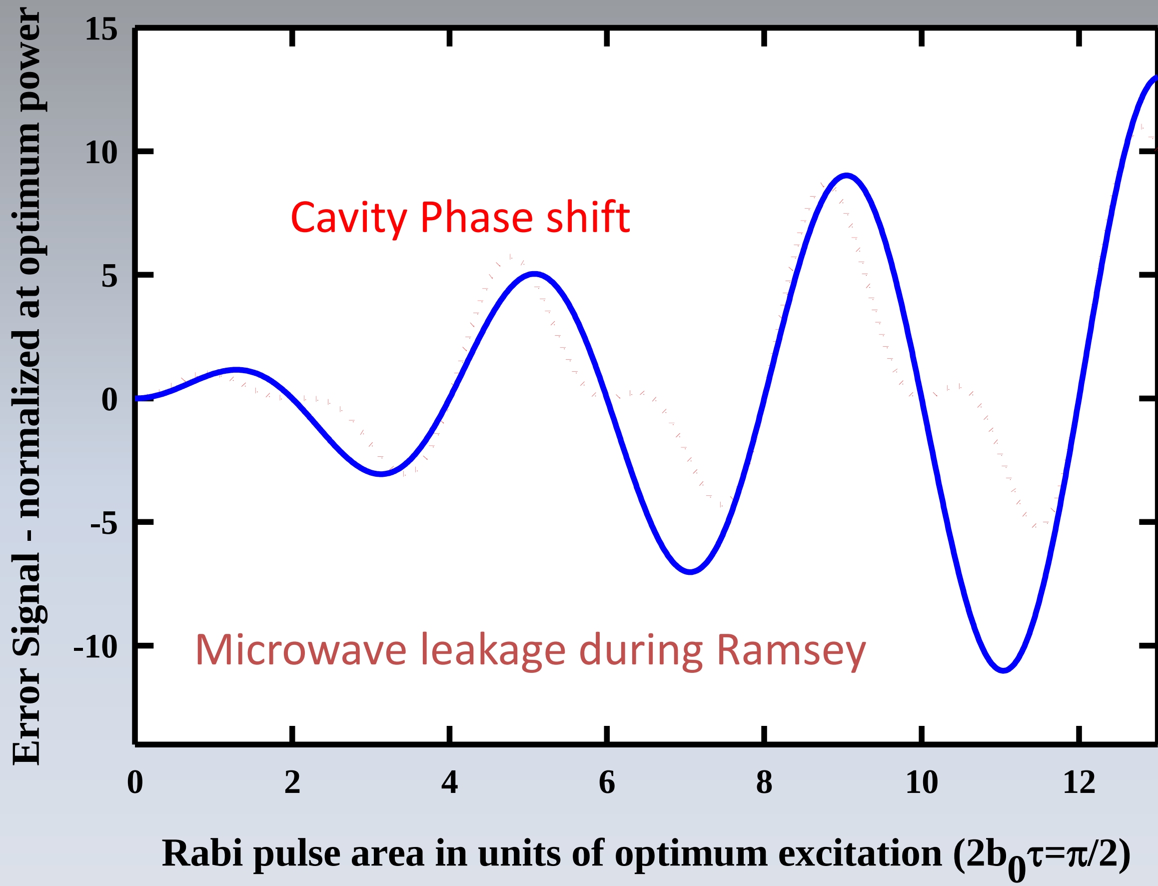
(Note – result is given as result ± Type A uncertainty ± Type B uncertainty – uncertainties are 1σ)

Conclusions

- Next Generation cesium fountains at NIST and INRIM should contribute to TAI at the high 10^{-17} level (eventually), and the low 10^{-16} level very soon.
- NIST-F2 cryogenic fountain should be beginning operation (contributing to TAI very shortly)

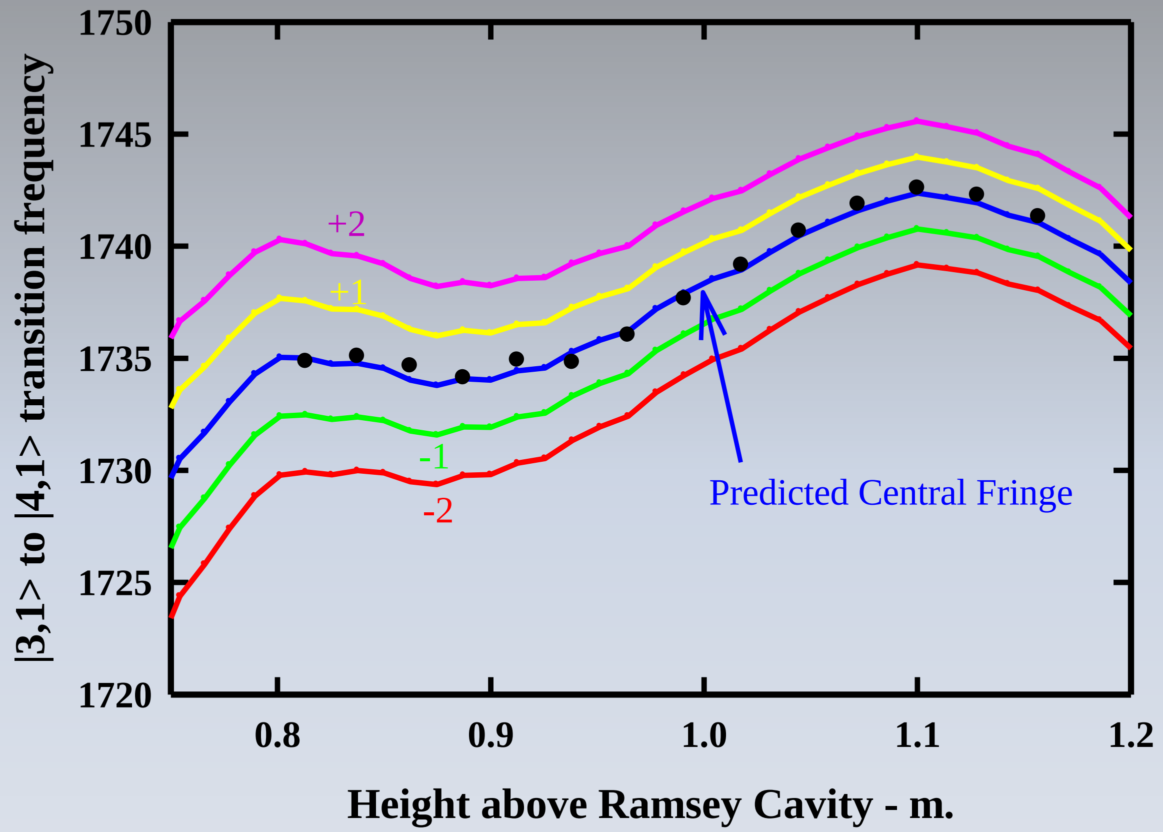
ANYTHING AFTER HERE IS SPARE

Cavity Phase and Leakage



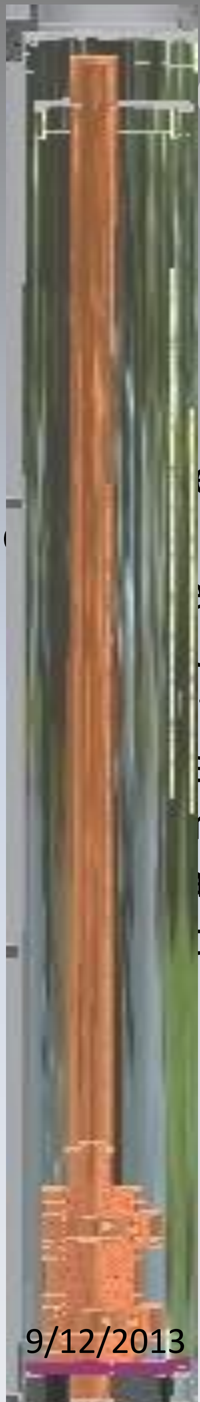
Leakage below the Ramsey cavity in NIST-F1…
..maximum at optimum power and multiples thereof.

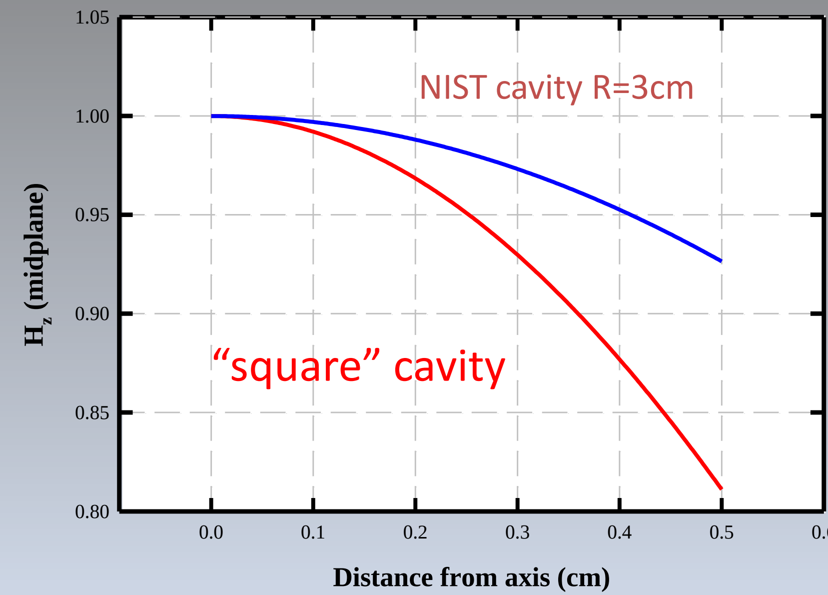
NIST-F2 Zeeman Correction

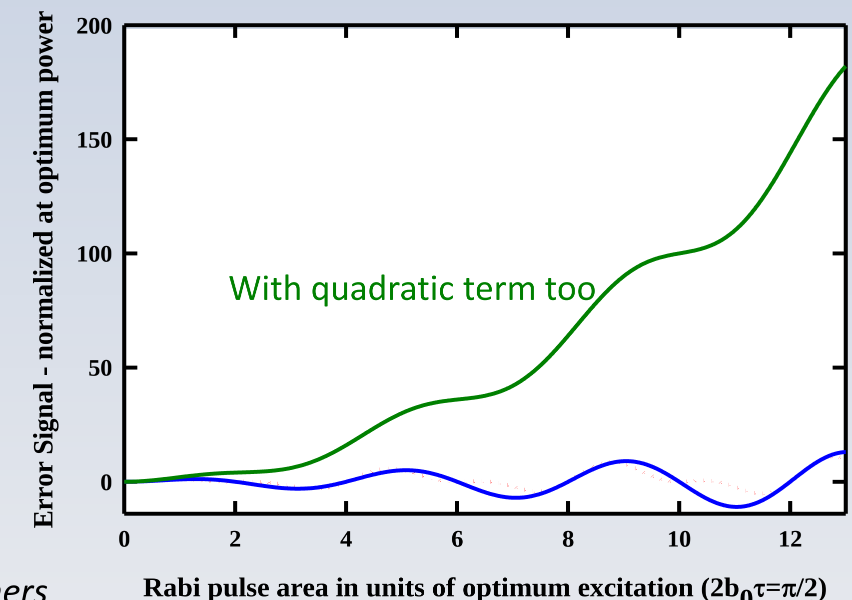


Predicted-Measured Fringe Position = -0.067±0.04 fringes eakage - cont

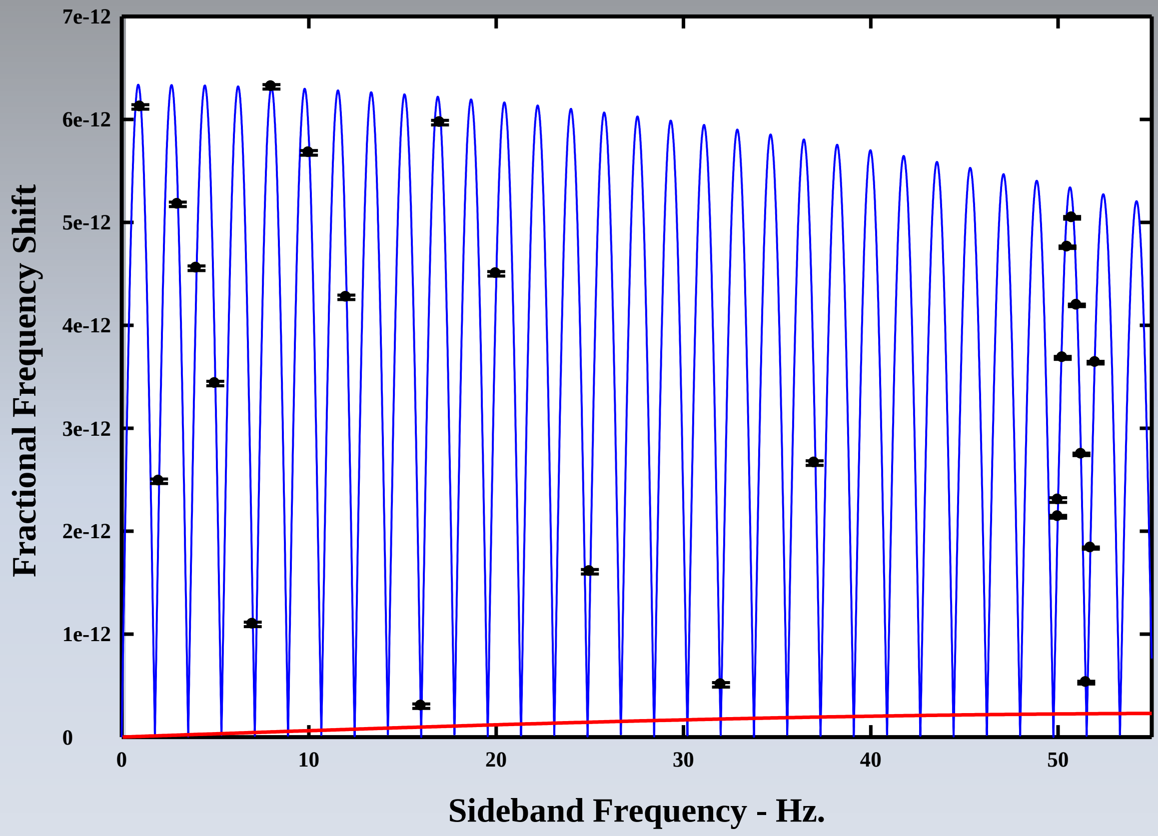
e on NIST-F1 allows
to propagate tube is
ed from leakage by
utoff chokes at each
the tube is cut to be
esonant at 9.1926
no leakage allowed
aves are far detuned
ter resonance.







Spurs



Much larger than predicted by previous theory

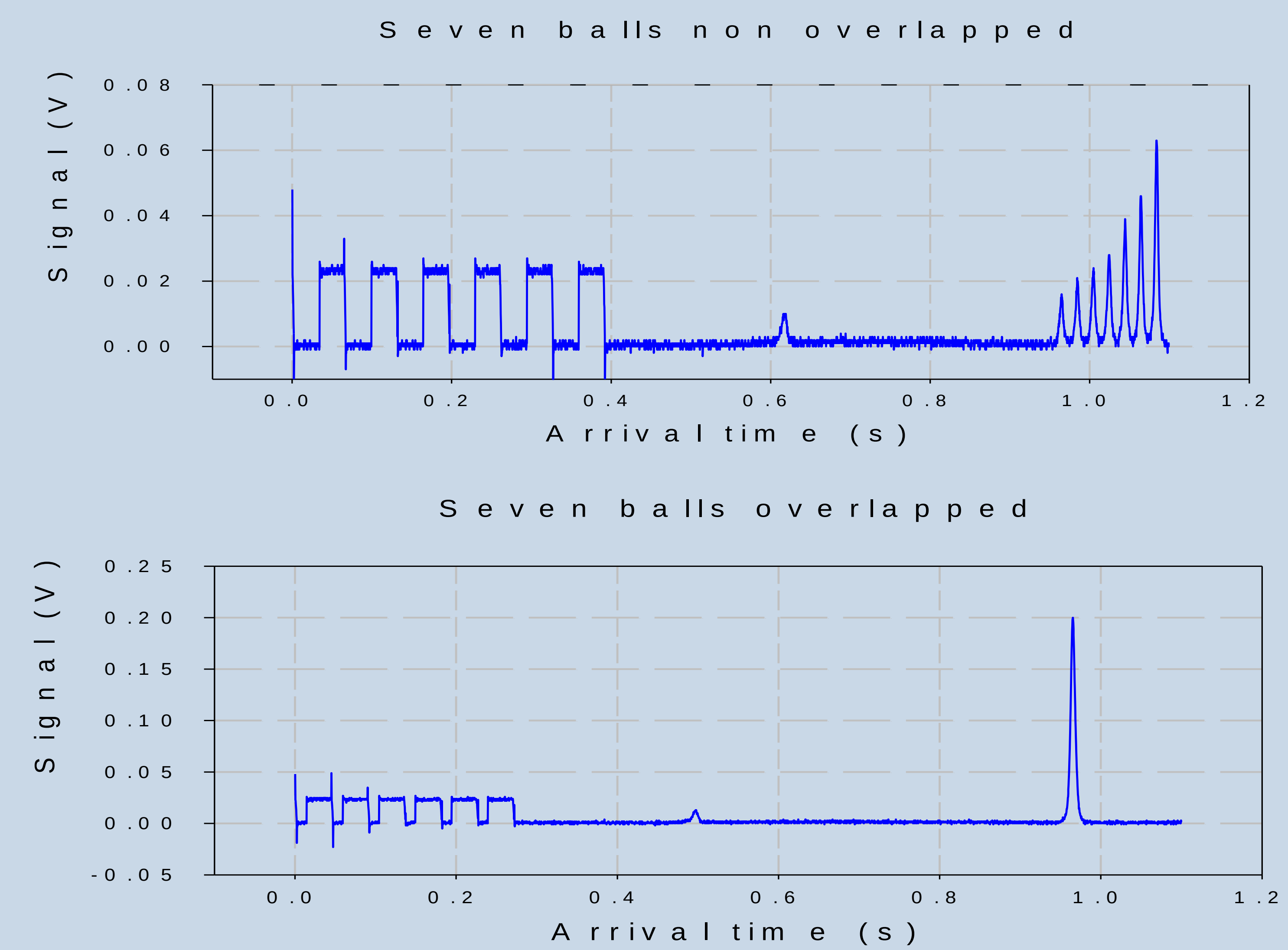
–

pulsed standards are different!

Generic Problems in the Realization of the second

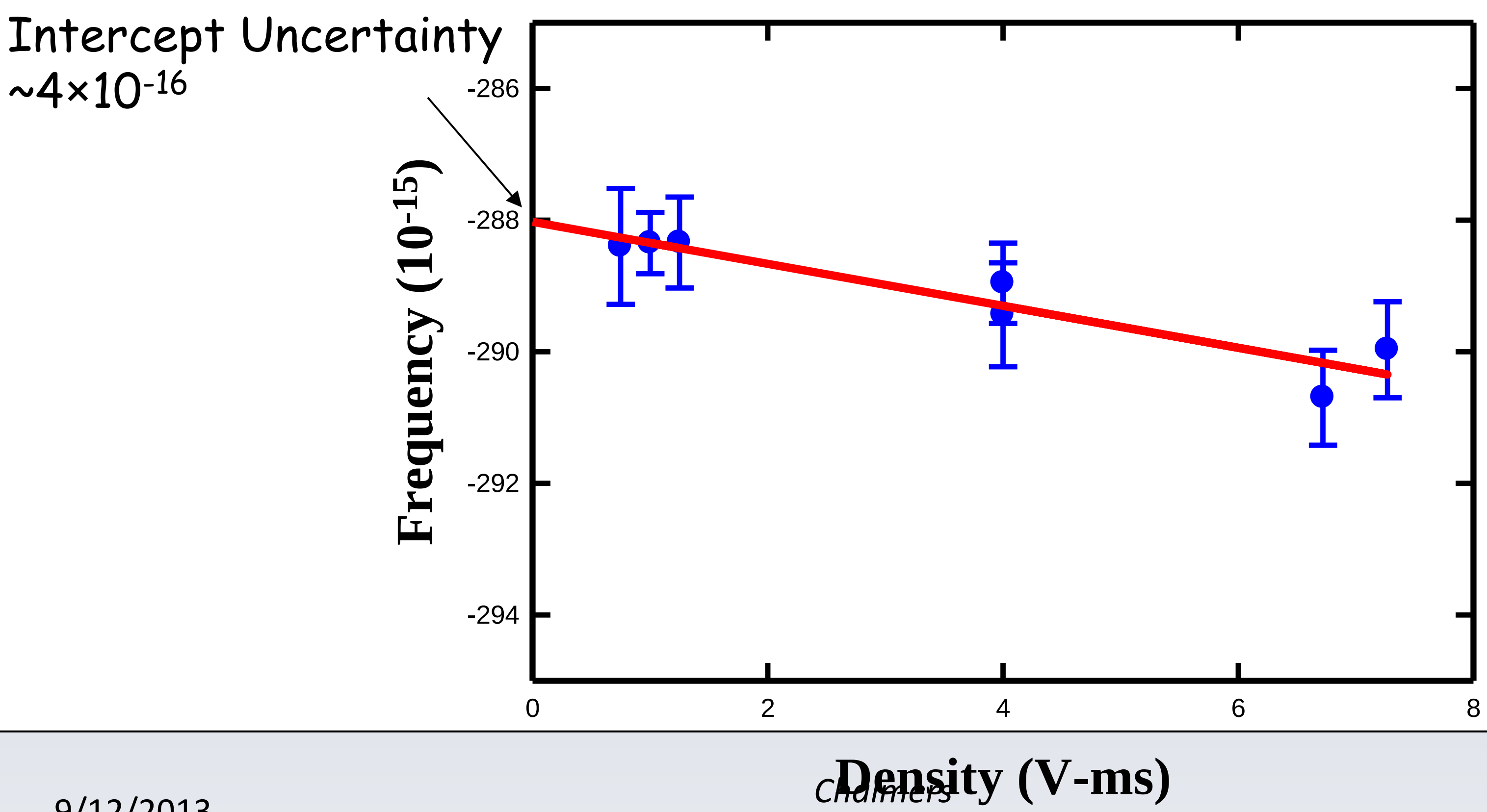
- Collision Shift (a different approach in the next talk)
- Blackbody Shift
- Microwave Effects

Actual Multi-toss Data



Collision Shift

- Frequency Shift proportional to Cesium Density (everything else held constant) so, vary density and extrapolate to zero density



Blackbody

- Radiation associated with non-zero temperature peak at about 10μm (room temp)
- Frequency shift is relatively large ~$2 \cdot 10^{-14}$ at room temperature
- Shift goes like T^4
- Shift is about $3 \cdot 10^{-16}$/°C!
- Temperature Uncertainty is mainly due to leakage of room temperature radiation
- Final Uncertainty is Assigned 1C ~ $\delta f/f = 2.8 \cdot 10^{-16}$

Clock Performance

Clock (in)Stability is given by:

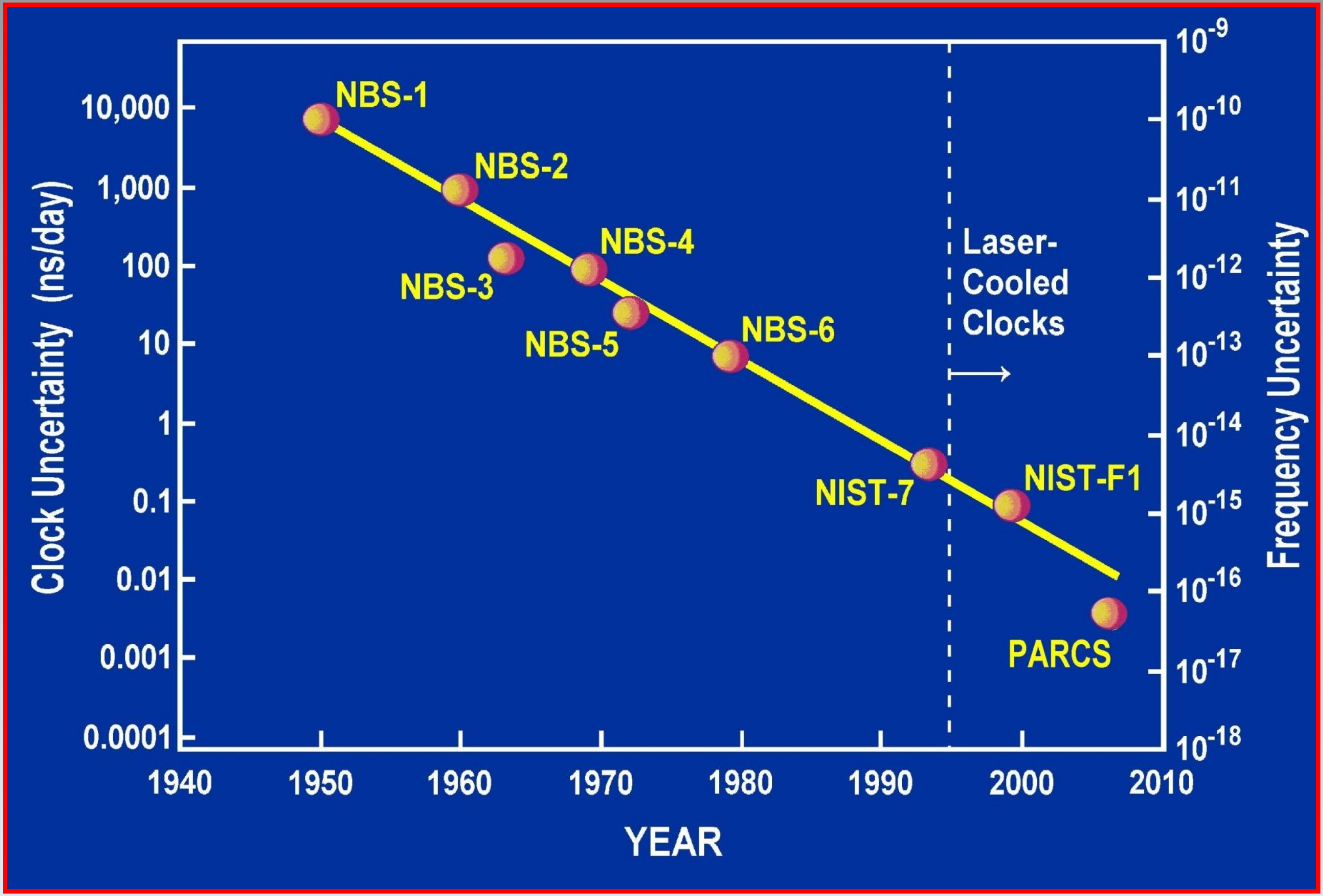
$$\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

Atomic Line Q   Signal to Noise

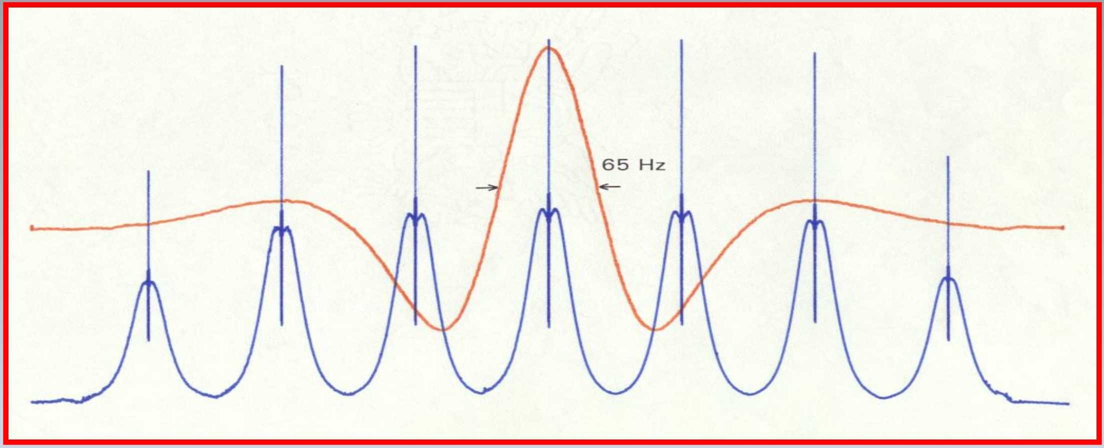
Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease $\Delta\omega = 1/T_{Ramsey}$)
- Increase The Frequency of the Clock Transition
- Improve the S/N

NIST Standards vs Time

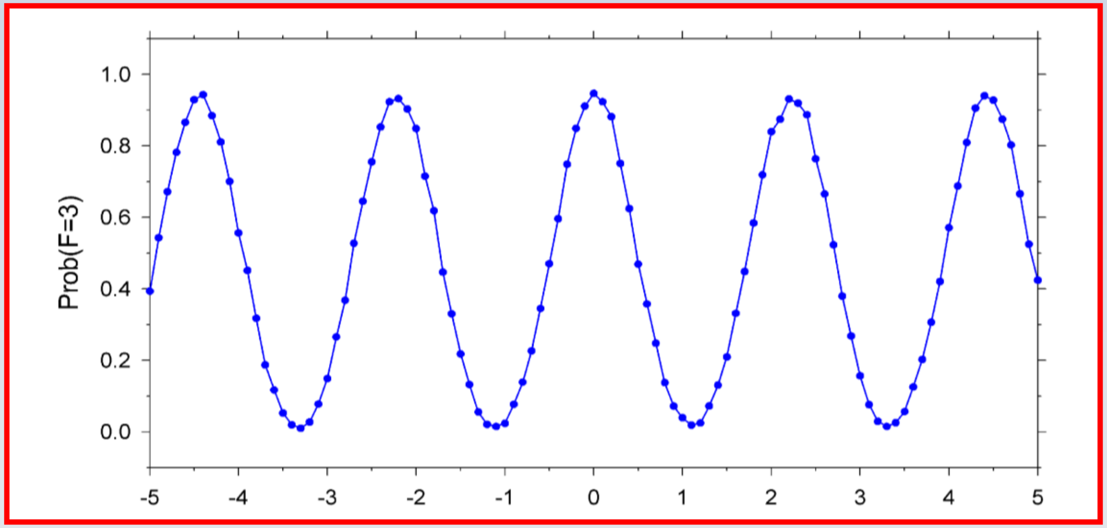


Ramsey Resonance in NIST-7 and NIST-F1



NIST-7

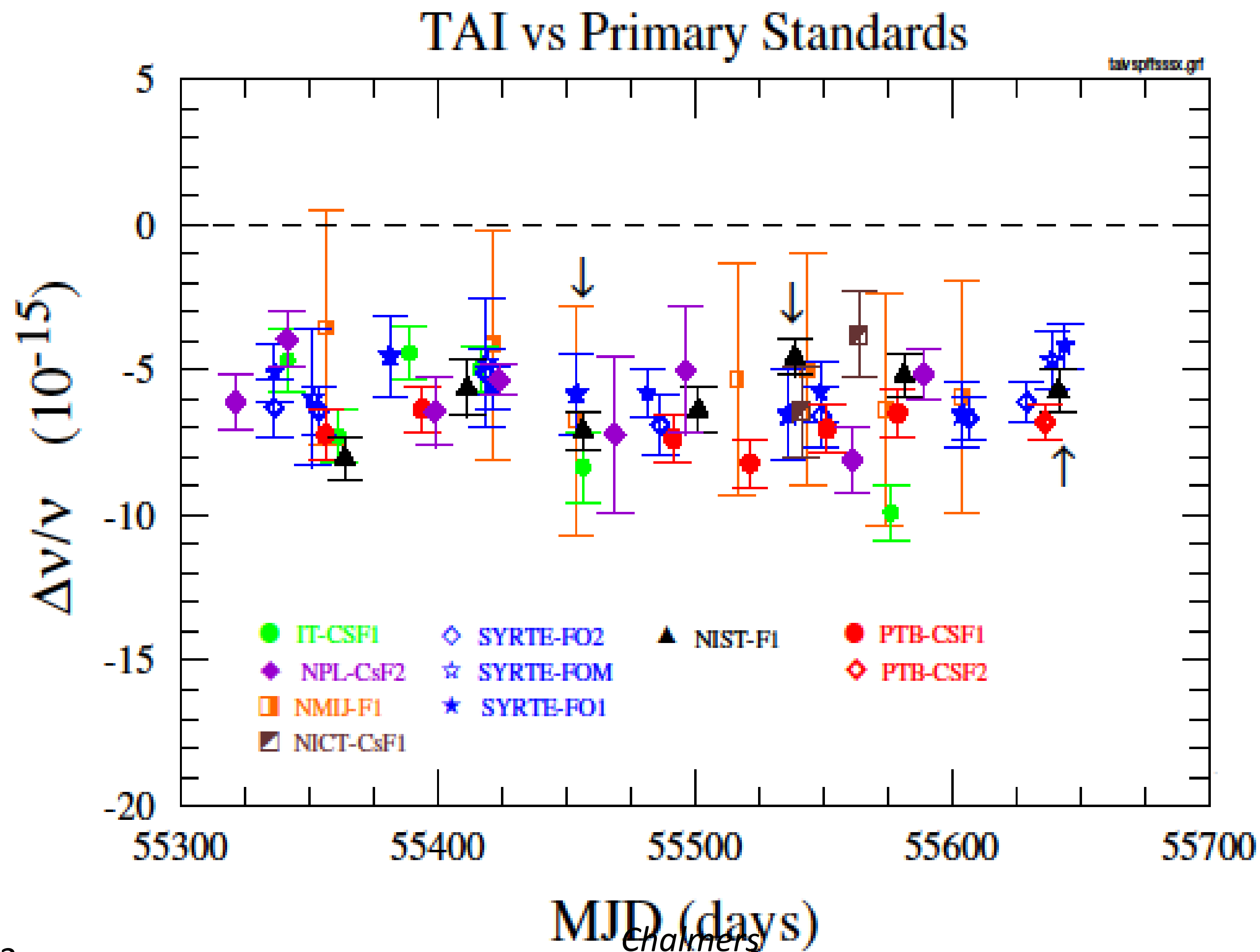
65Hz Linewidth



NIST-F1

1 Hz Linewdith

F1 Evals used compared to TAI



Clock Performance

Clock (in)Stability is given by:

$$\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

Atomic Line Q

Signal to Noise

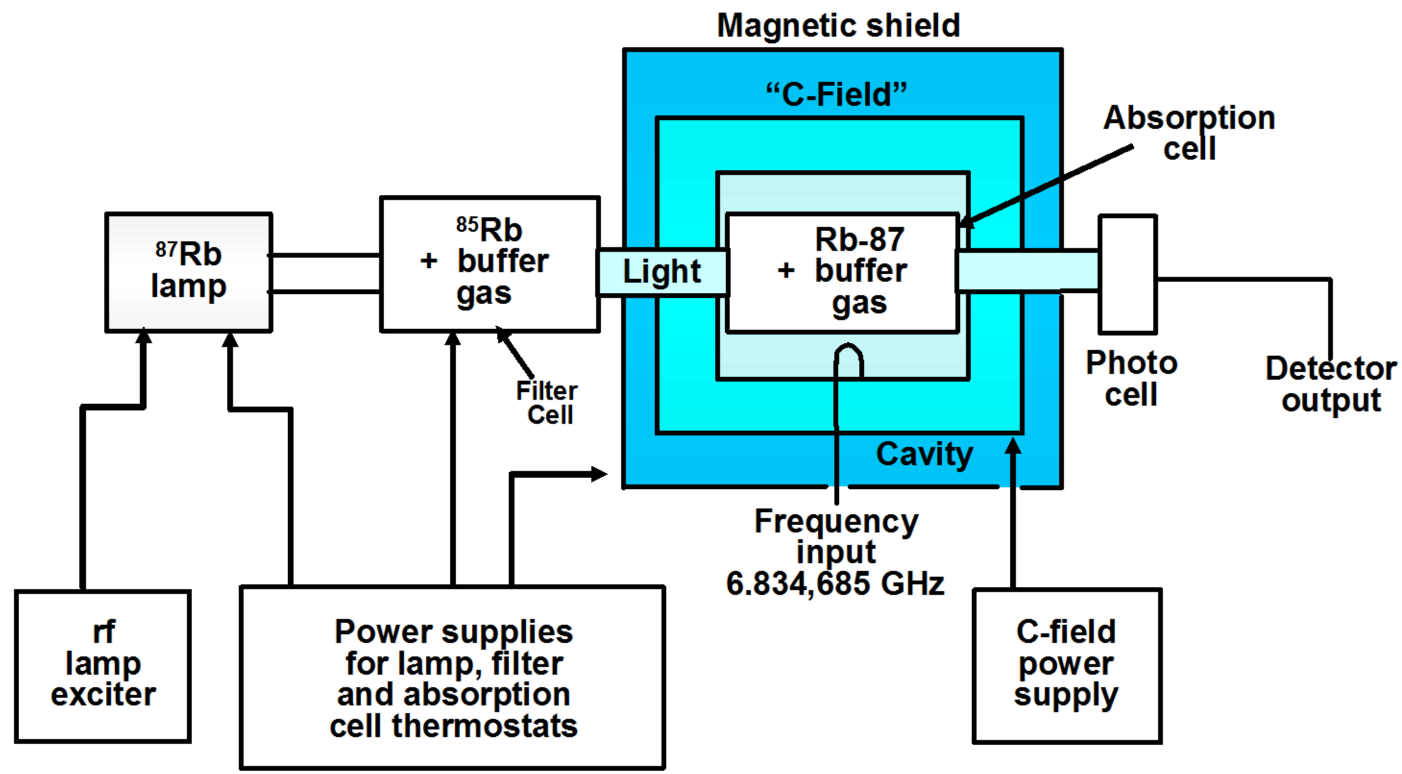
Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease $\Delta\omega = 1/T_{Ramsey}$)
- Increase The Frequency of the Clock Transition
- Improve the S/N

Commercial Atomic Clocks

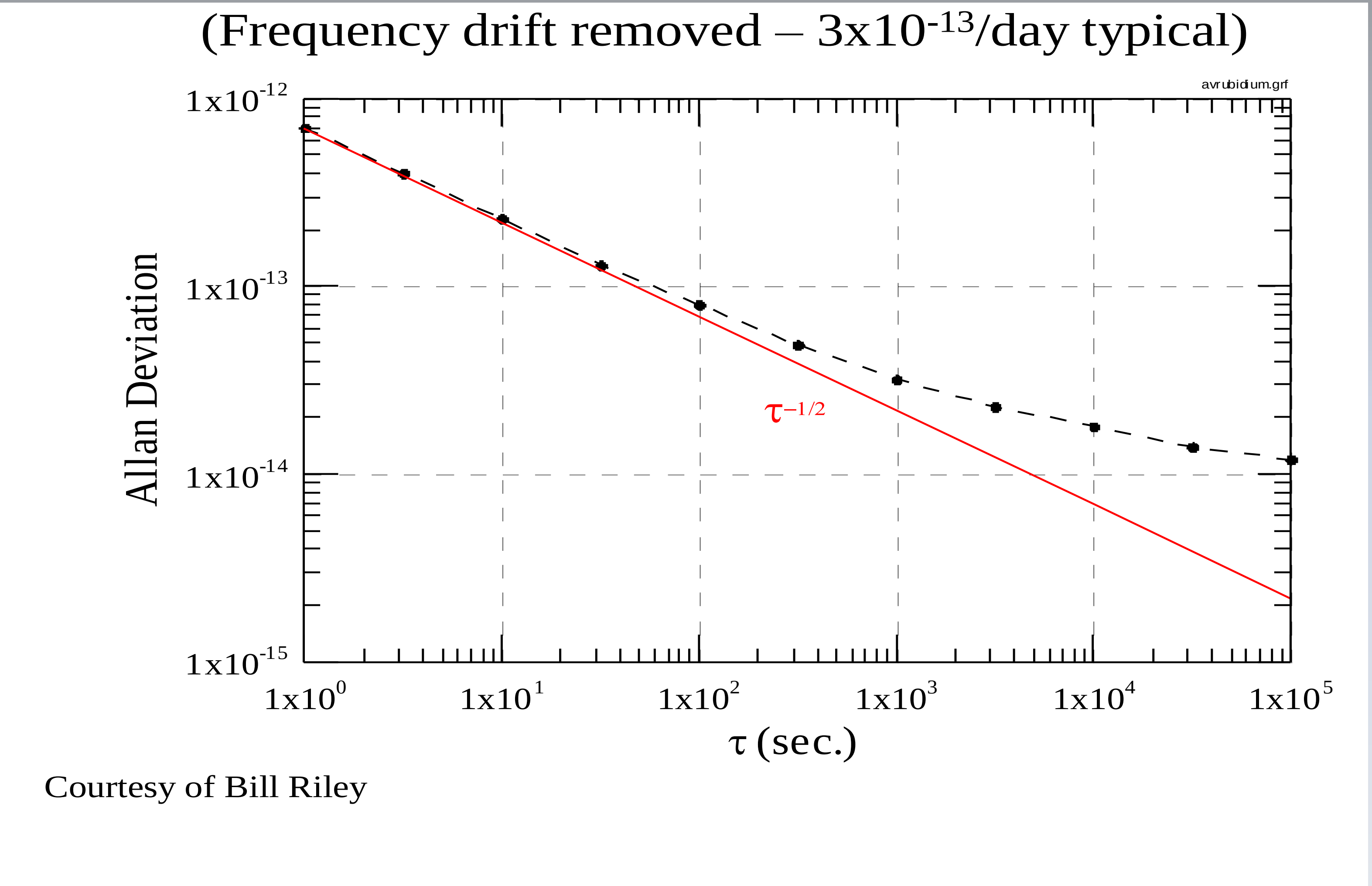
- Commercial Atomic Clocks come in three basic flavors – Cesium beam clocks, Rubidium cell clocks and Hydrogen masers
- All atomic clocks depend on the same basic quantum mechanical principals just discussed

Rubidium Clocks

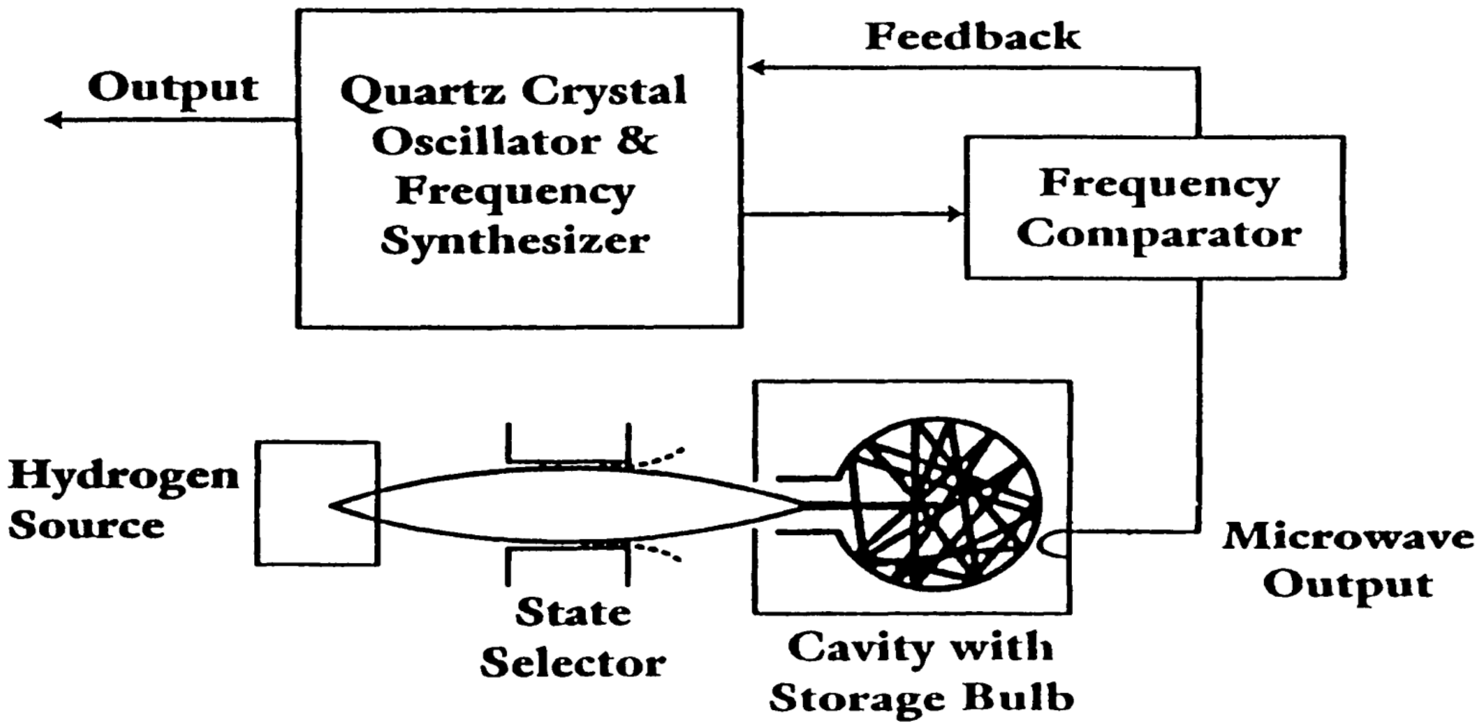


Adapted from figure by John Vig

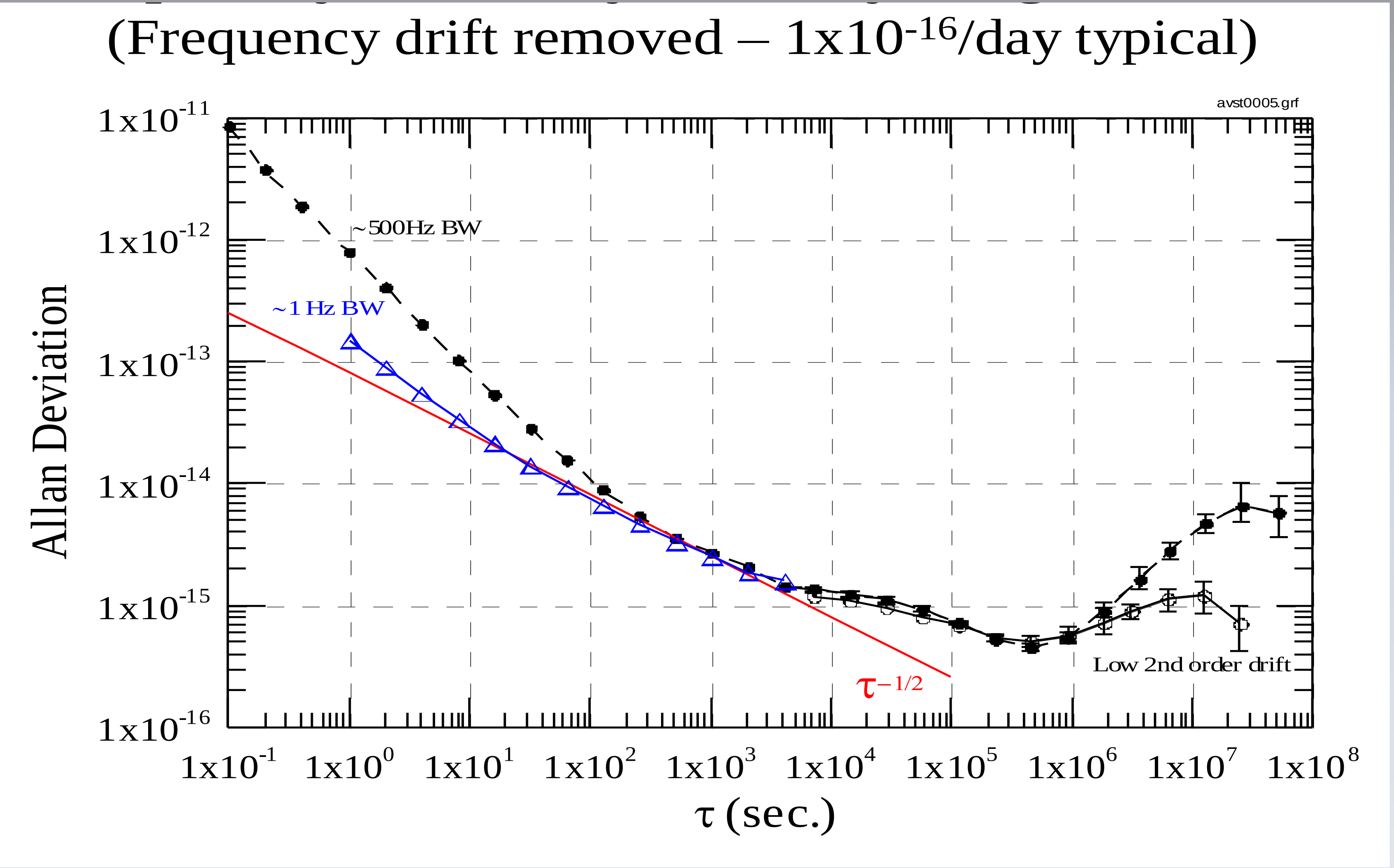
Rubidium - Stability



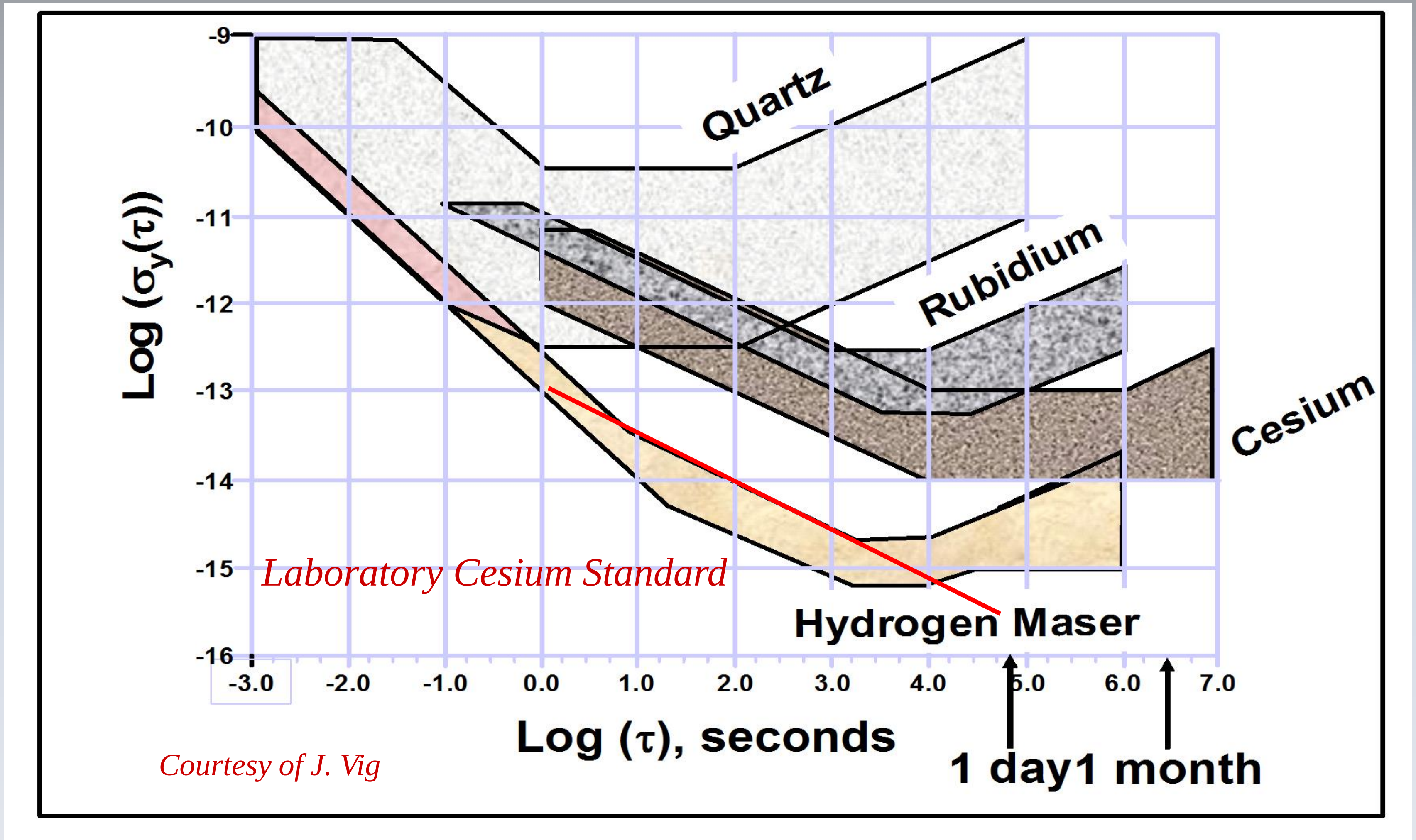
Hydrogen Maser



Hydrogen Maser - Stability



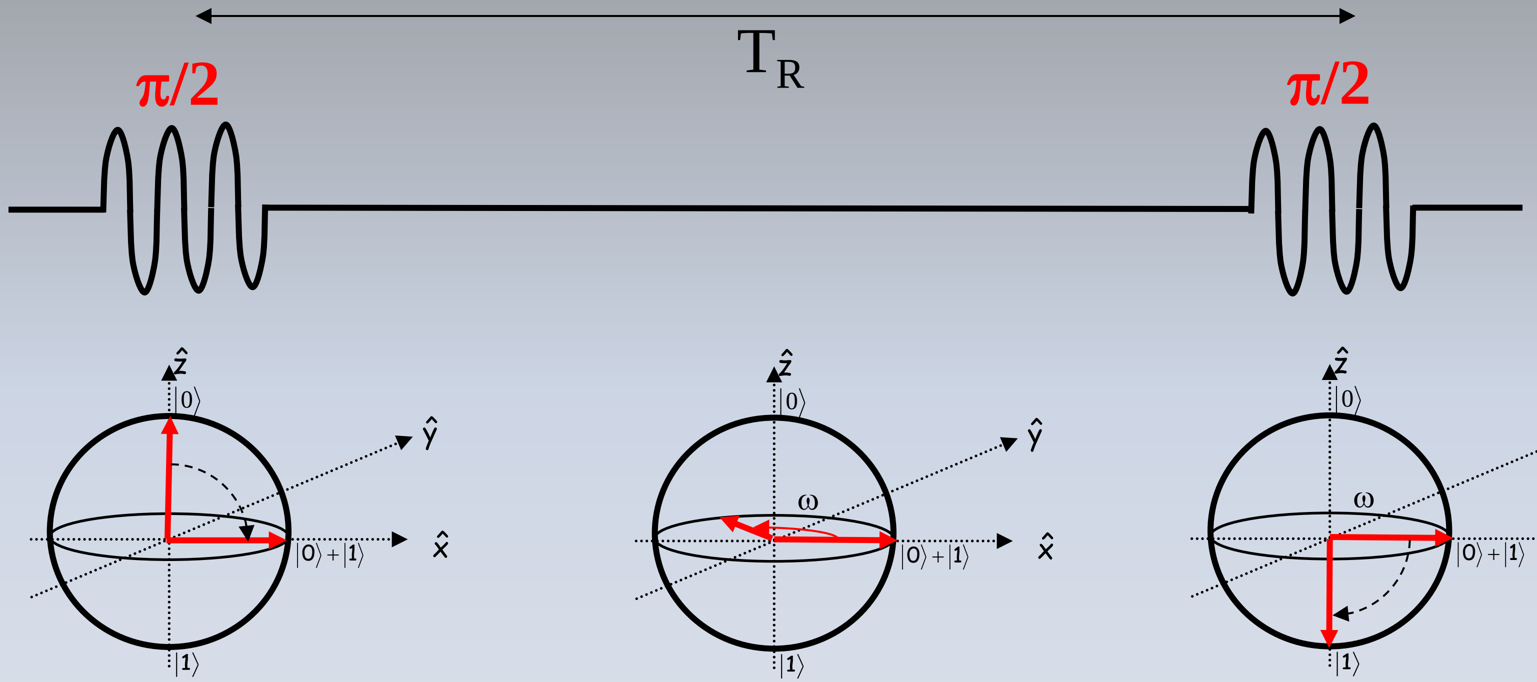
Stability of Various Commercial Clocks



Commercial Atomic Clocks

- Sizes from ~10 cm^3 to 10^6 cm^3
- Power from ~100mW to 100 W
- Stability (1s) from $\delta f/f \sim 10^{-9}$ to $\delta f/f \sim 10^{-13}$
- Price from ~$1k to $250k (not space qualified if you want space qualified x 10)
- Stability at 1 year $\delta f/f \sim 10^{-9}$ to $\delta f/f \sim 3*10^{-15}$

Ramsey's method of separated oscillating fields



The final projection depends on the relative phase between the superposition and the microwave field!