Frequency Tunable Atomic Magnetometer based on an Atom Interferometer

D.A. Braje[1], J.P. Davis[2], C.L. Adler[2,3], and F.A. Narducci[2]

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Also thanks to S. A. DeSavage, R. Forster and Z. Switzer

[1] *MIT Lincoln Laboratory, Lexington, MA*
[2] *Naval Air Systems Command, Patuxent River, MD*
[3] *St. Mary's College of Maryland, Saint Mary's City, MD*

LINCOLN LABORATORY
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NAV AIR

$$$$$$$$$$
ONR
NavAir CTO
$$$$$$$$$$

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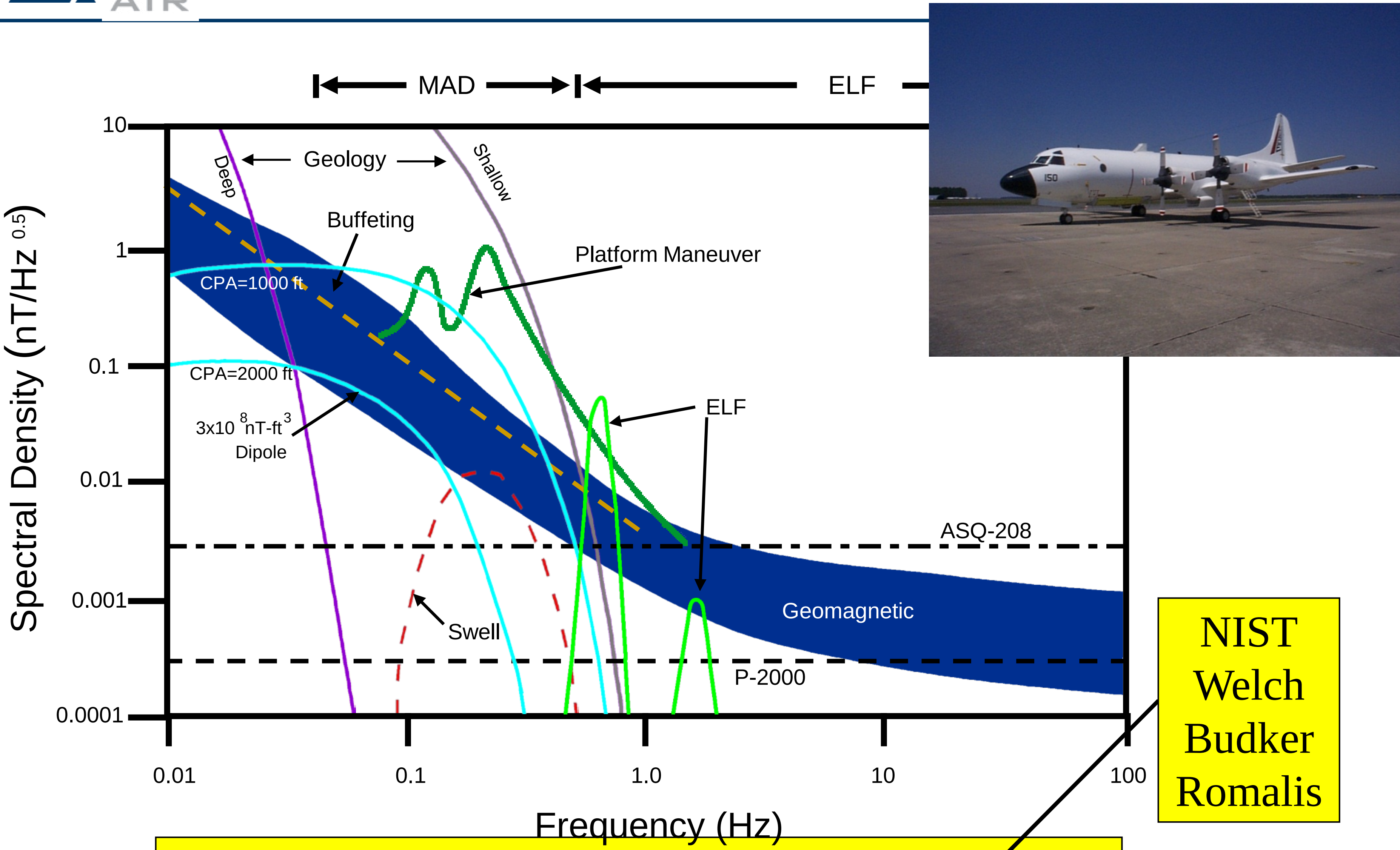
Outline

- **Magnetometry / Gradiometry Motivation**
  - Applications: Remote Sensing, Security, Biomagnetics, Navigation
  - Gradiometry
- **Atom Interferometer Magnetometer**
  - Atom Interferometer Concept
  - NMR Pulse Sequences for Atoms
- **Experimental Results**
  - Clock Transition
  - Ramsey vs. Hahn Echo

This is data

Airborne Magnetic Noise



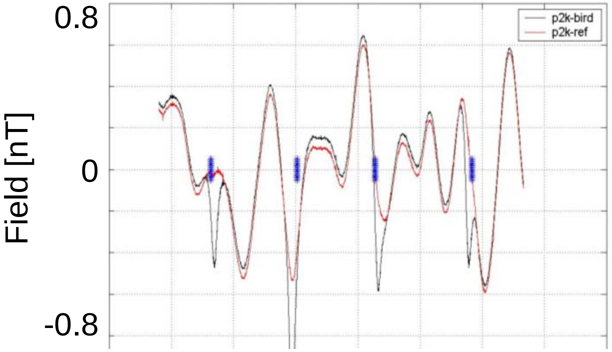
~ fT/Hz$^{1/2}$

NIST
Welch
Budker
Romalis

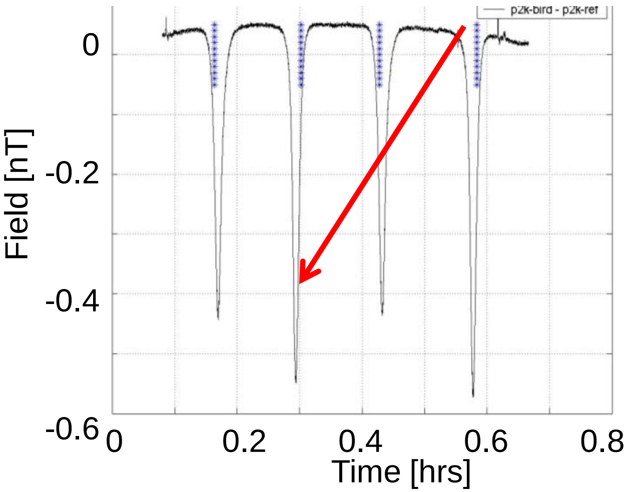
Motivation:

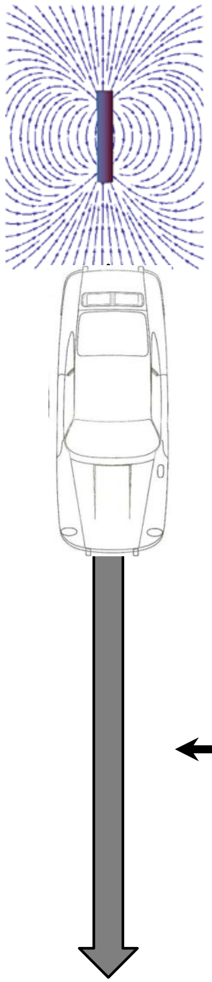
(classical) gradiometer example

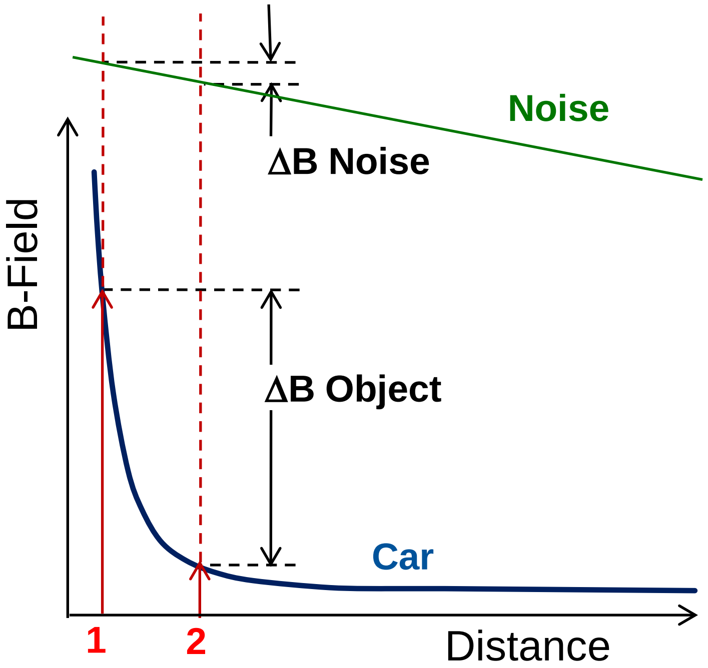
P2000 Gradiometer Test
Memorial Airfield, Chandler AZ
April 27 2003

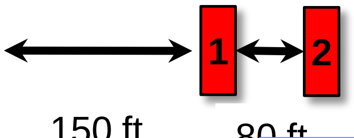


Even an Admiral can see this!









P2000 Sensors

Sensitivity: 500 pT/(80ft)

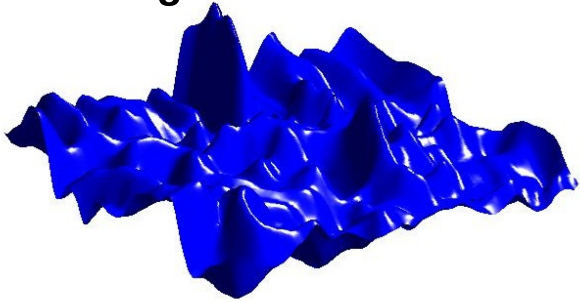
AI Gradiometer Sensitivity: 0.2 pT/m

Atom Interferometry Applications

- **Clocks**
  - Frequency standards
  - Navigation, communication, synchronization
- **Magnetometers**
  - Magnetic anomaly detection (i.e. submarines, unexploded ordinance, mines), detection of dangerous liquids and uranium, biomagnetics, navigation
- **Accelerometers, Gyroscopes**
  - Arrayed for differential acceleration, gravimeters, etc
  - Navigation, seismology, mass anomaly detection (minerals, bunkers, natural resources)
  - Fundamental laws of physics

Language is common to the worlds of NMR and quantum computing

Navigation



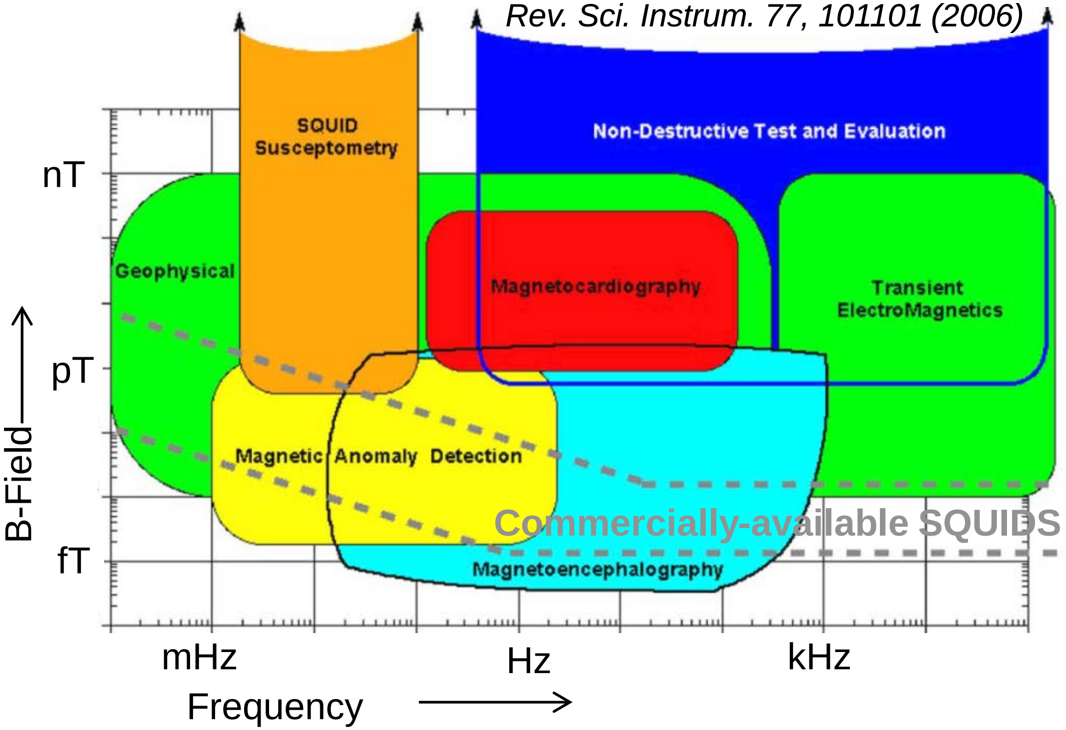
Biomagnetics

Keep Sensitivity; Design Around the Noise

Cannot remove magnetic noise in remote sensing

1. Filter out of band noise
2. Measure magnetic field gradient

   (Gradients used for object location)



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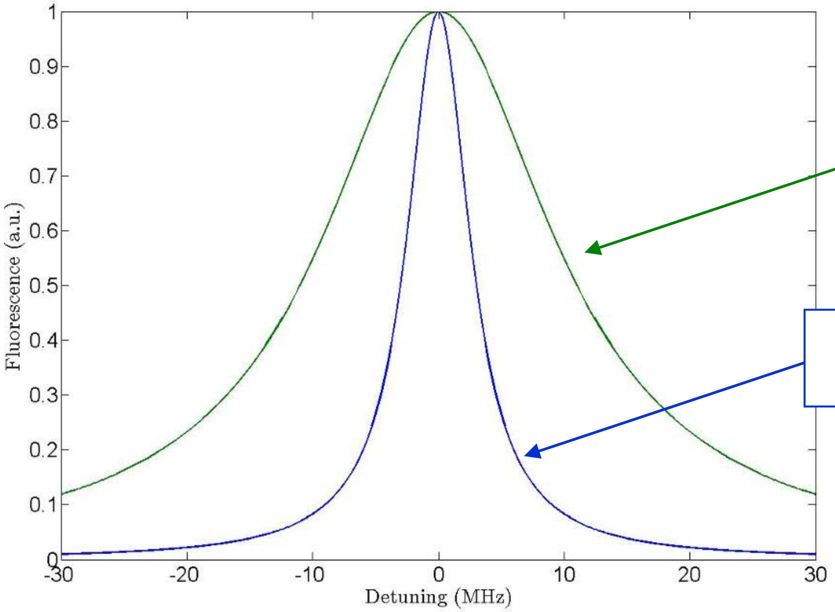
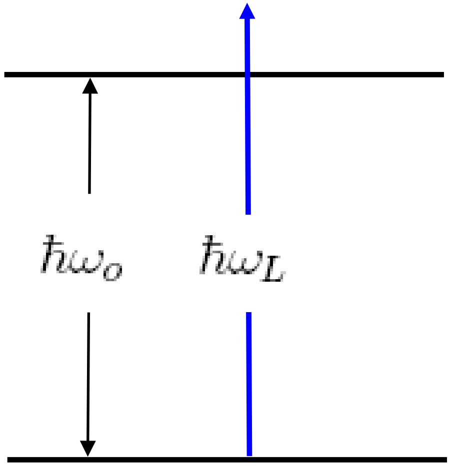
This is data

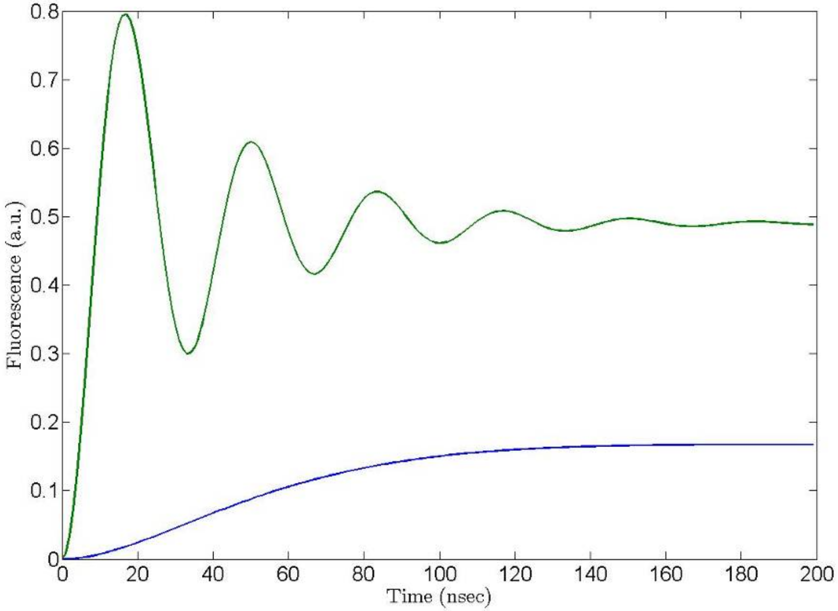
Two level atom reminder



Powerbroadened Linewidth

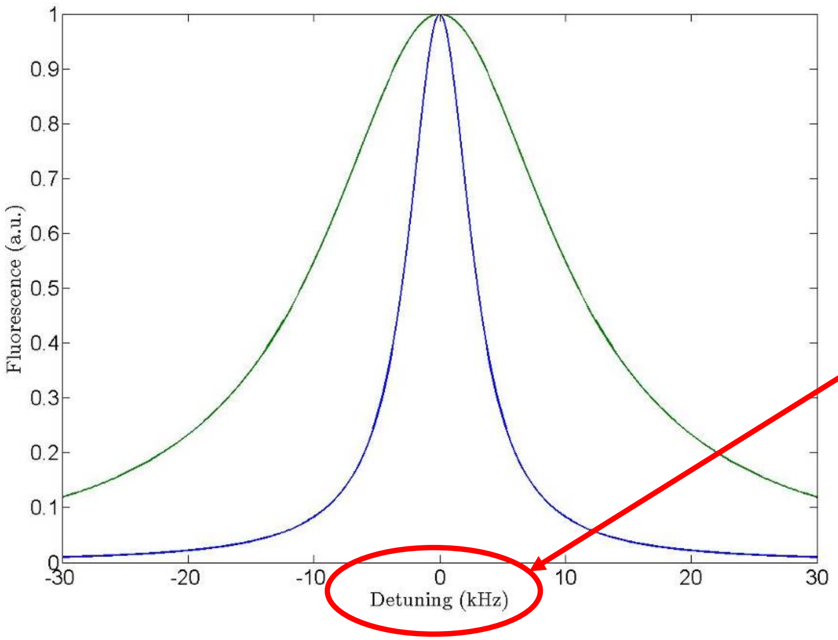
Natural Linewidth

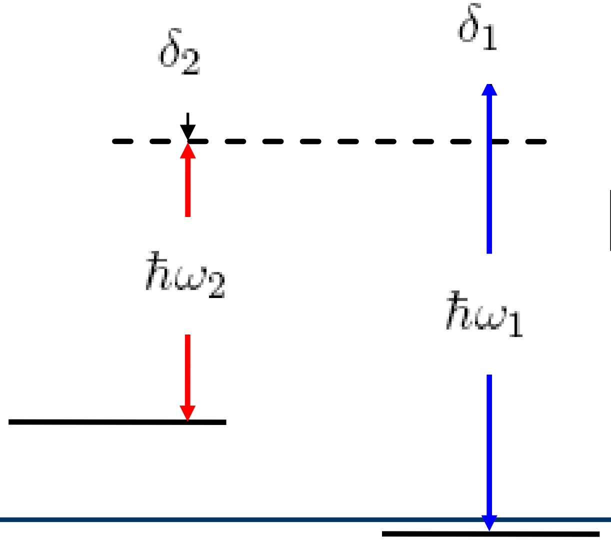


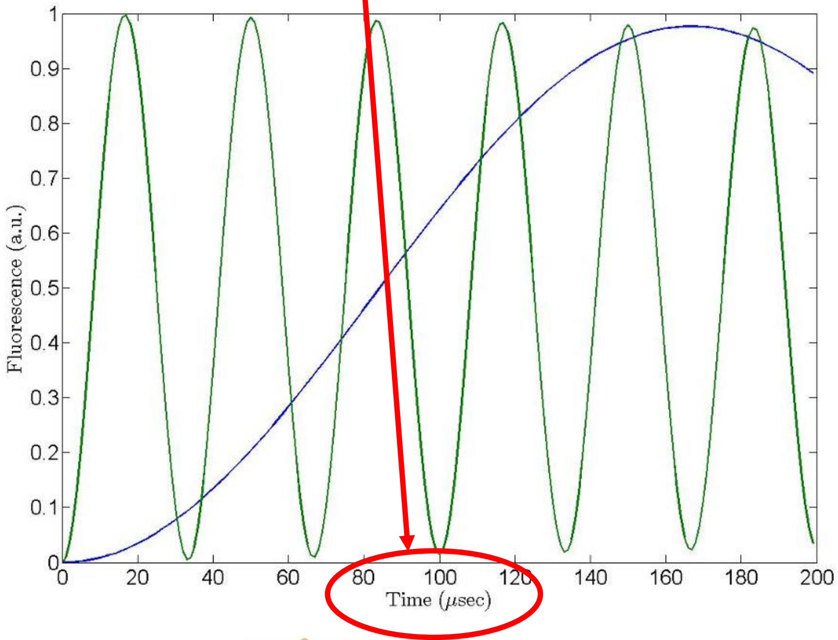


Raman Resonances

Now controlled by ground state decoherence time which can be made very small $\Delta\nu \sim \frac{1}{T_{pulse}}$







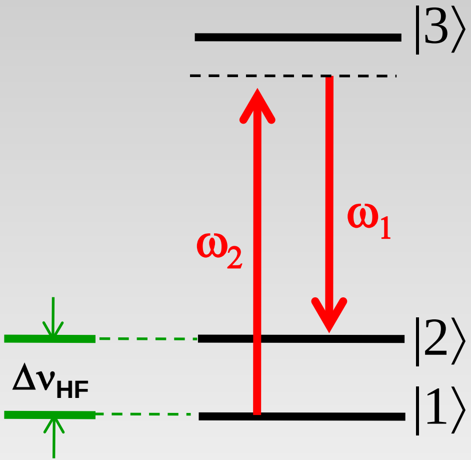
Atom Interferometer:

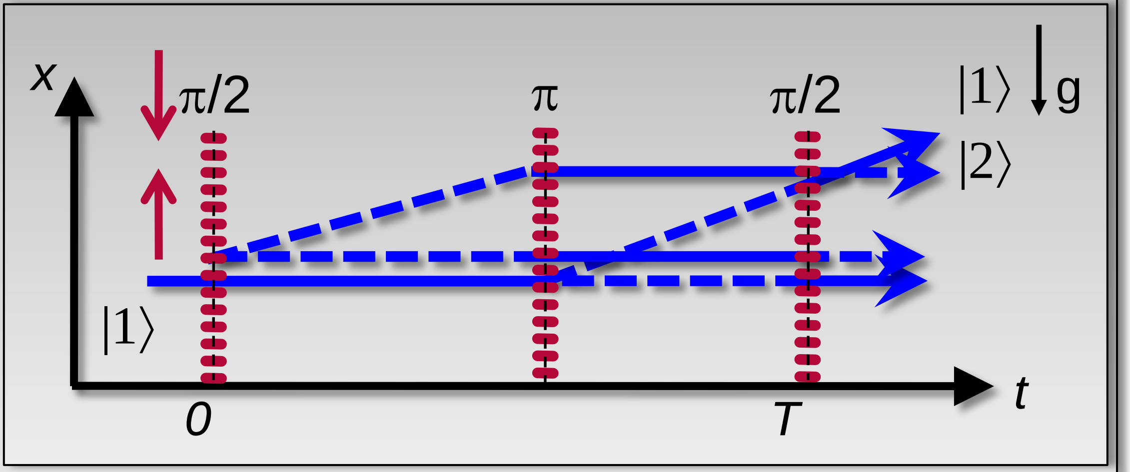
Time Domain

Davis & Narducci, ***JMO*** *55 3173 (2008)*

Zhou et al. ***PRA*** *82 061602 (2010)*

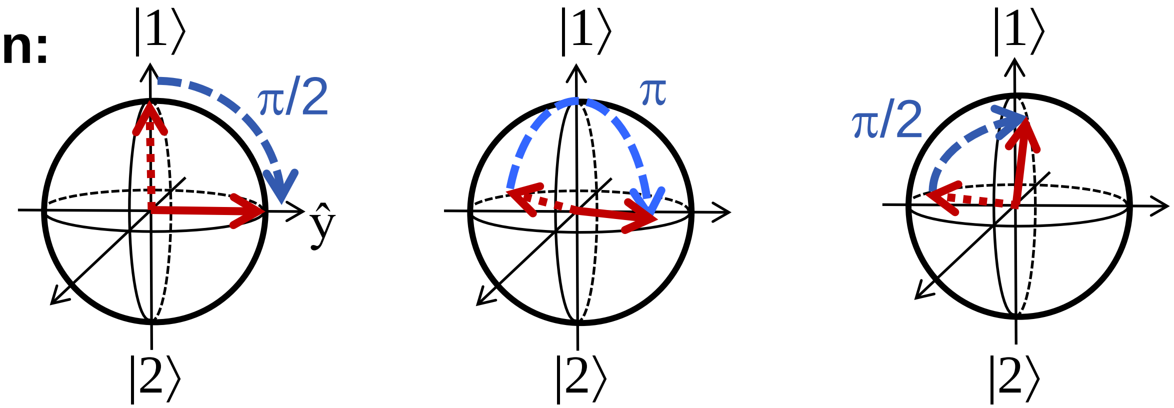
$$\Delta\phi = -\left(\cancel{\vec{k}_1 - \vec{k}_2}\right)gT^2 + \frac{\mu_B}{\hbar}\left(g_{F'}m_{F'} - g_F m_F\right)\left[\int_0^{T/2} B(t)\partial t - \int_{T/2}^{T} B(t)\partial t\right]$$



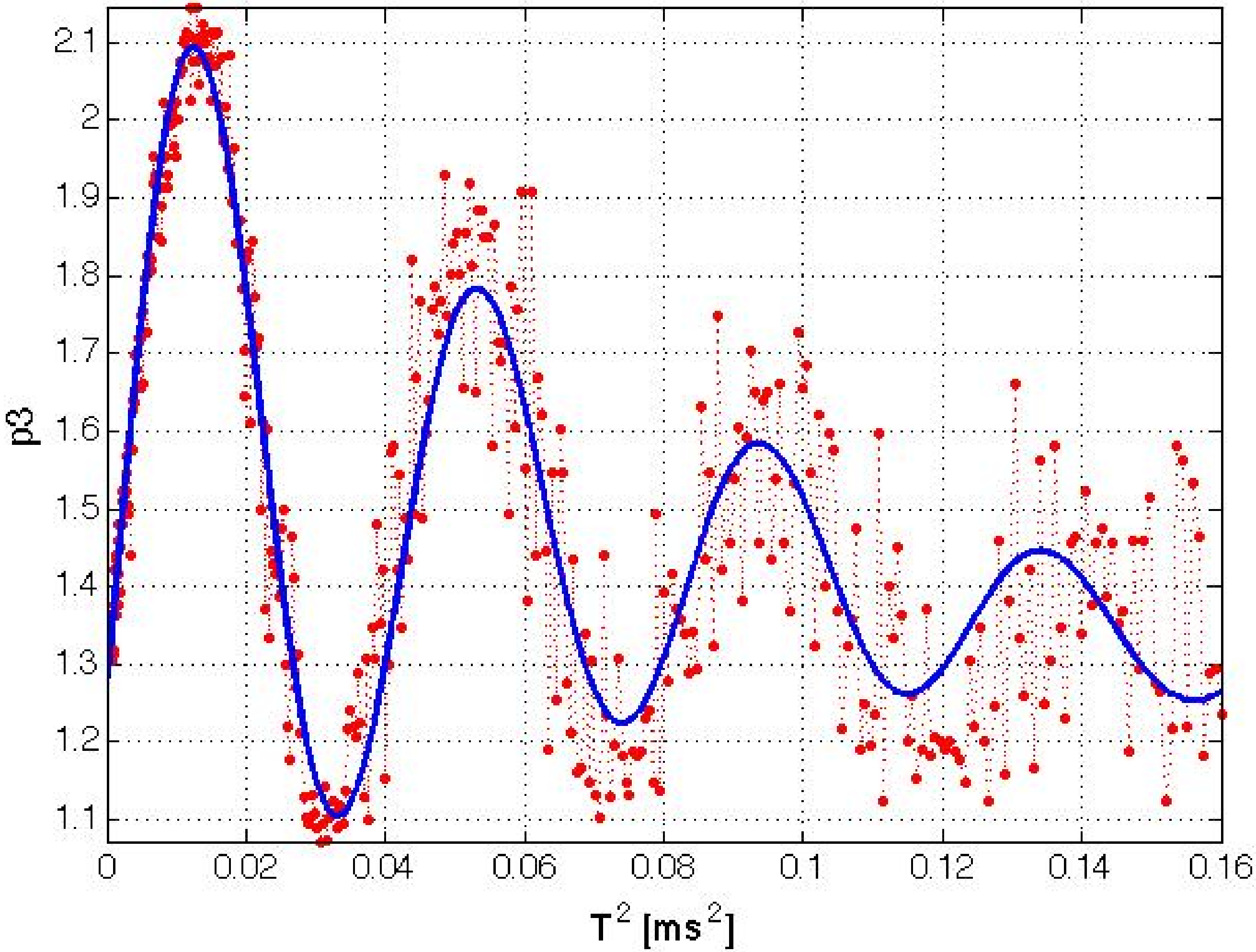


Co-propagating Raman beams:
Doppler-free

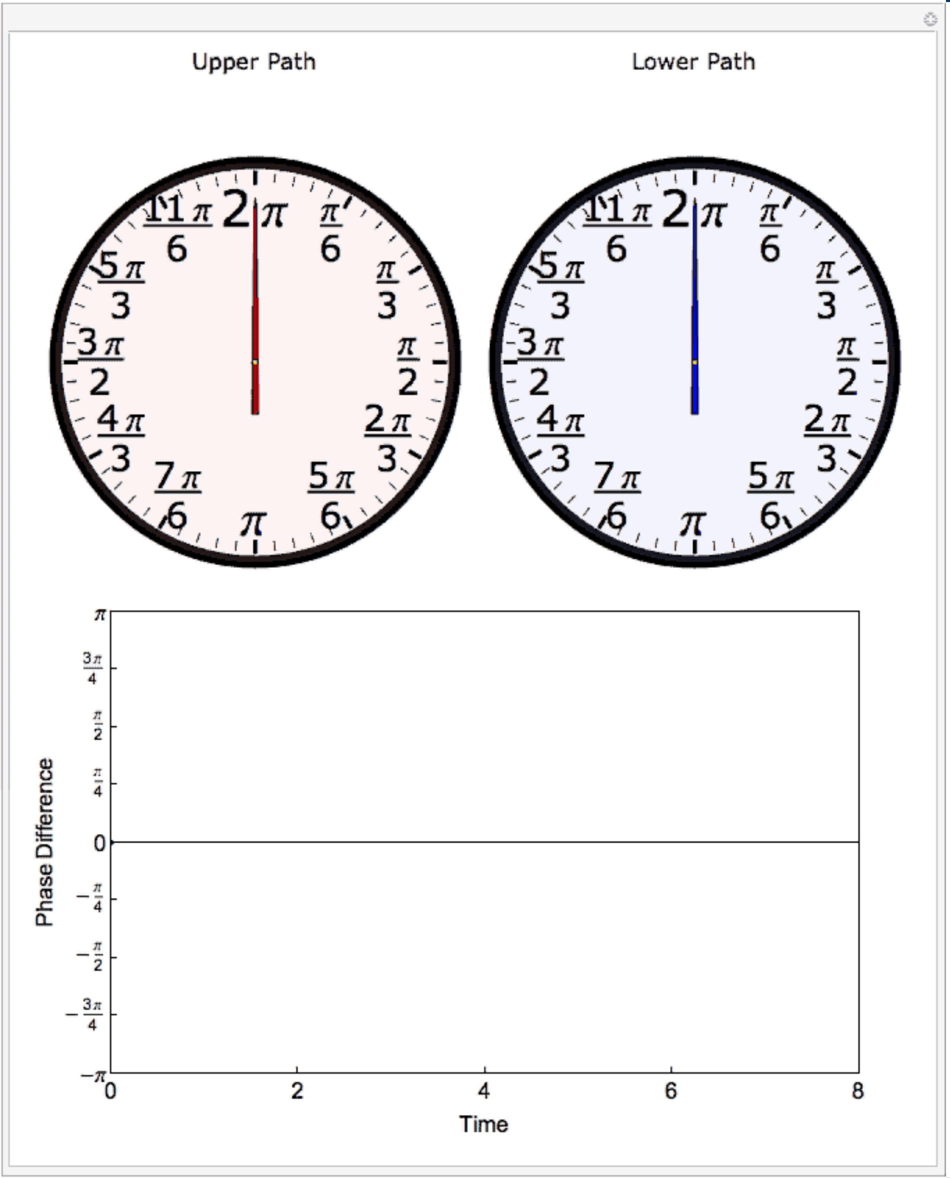
Pseudospin Representation:



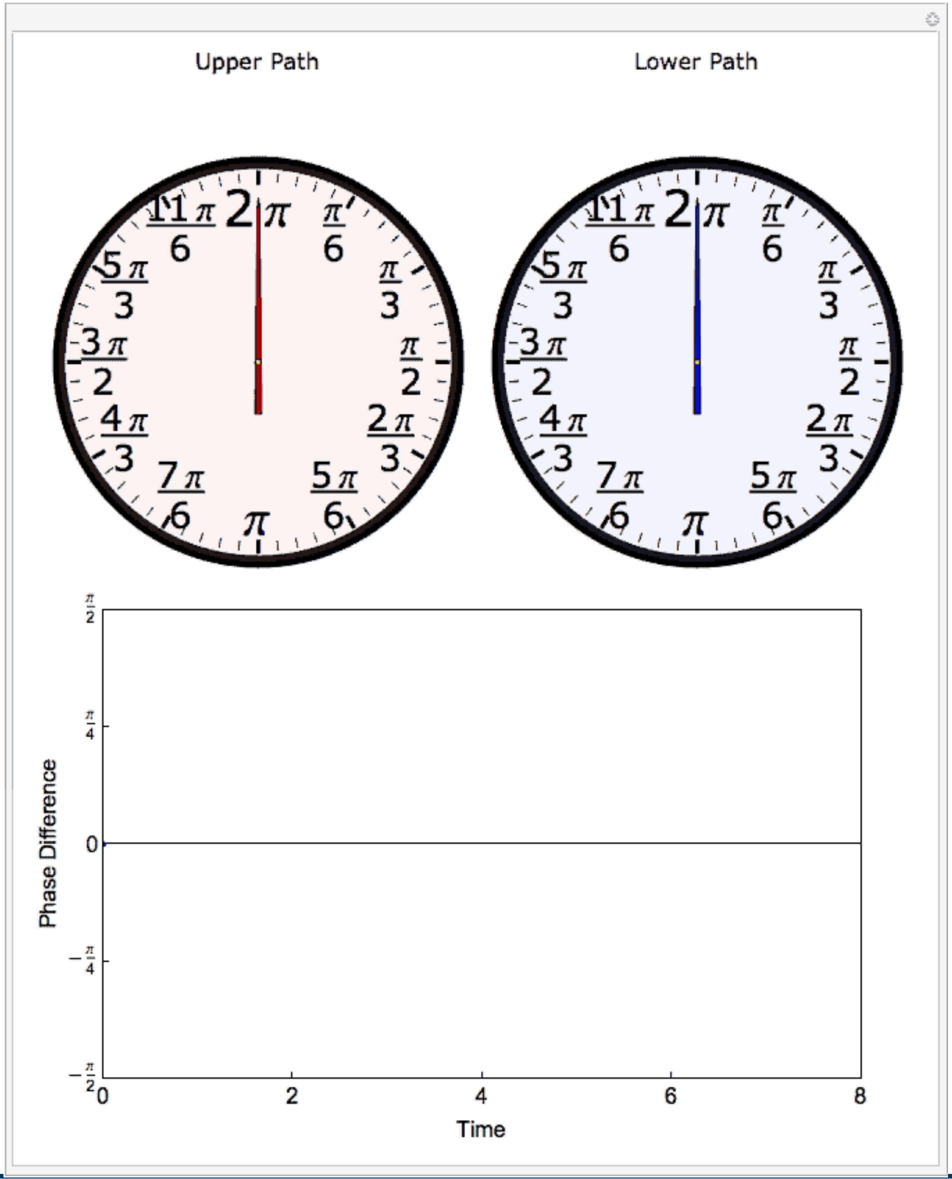
Magnetic Gradient (spin echo) Interferometer…not quite



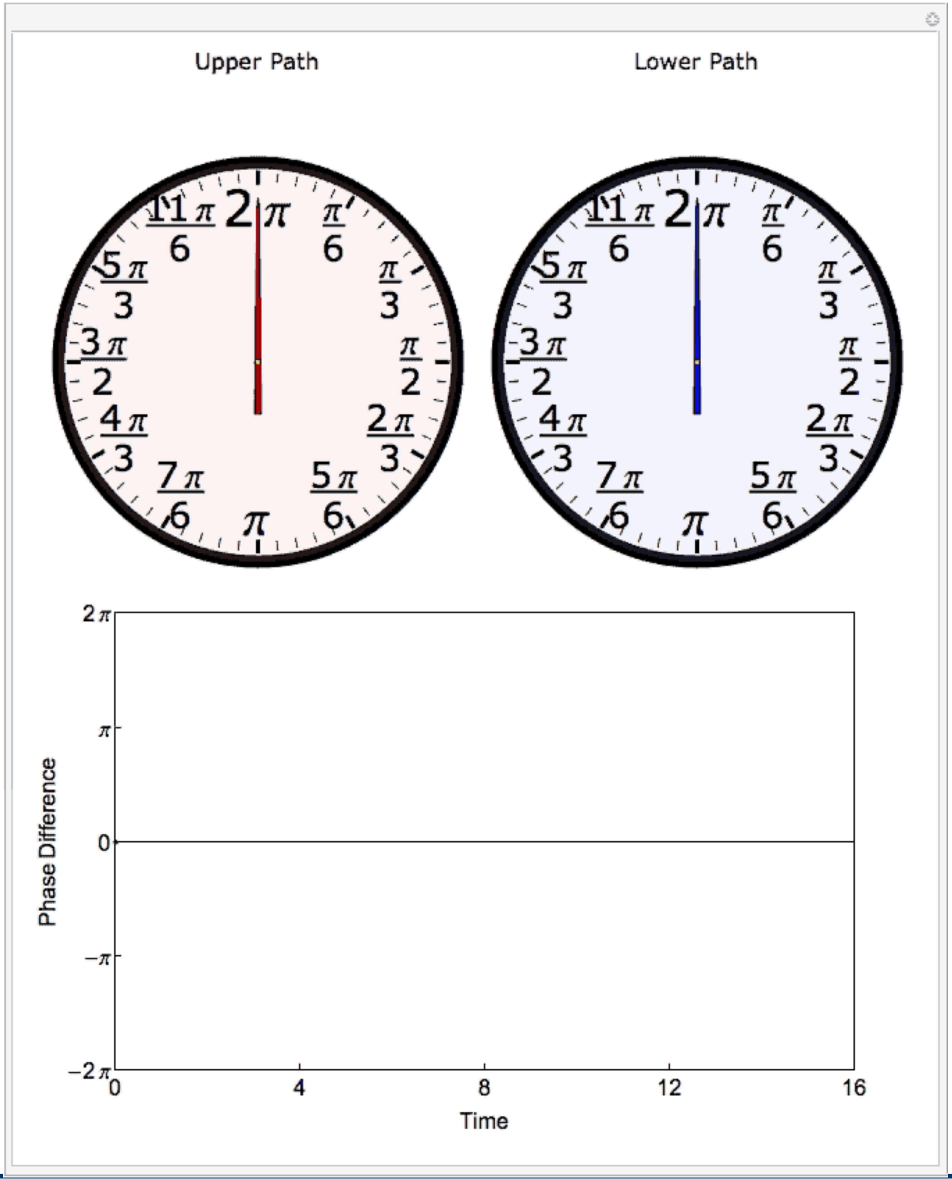
Ramsey (π/2–π/2)


Upper Path
Lower Path
2π
11π/6
π/6
5π/3
π/3
3π/2
π/2
4π/3
2π/3
7π/6
5π/6
π
Phase Difference
π
3π/4
π/2
π/4
0
−π/4
−π/2
−3π/4
−π
0
2
4
6
8
Time

Spin Echo (π/2–π–π/2)

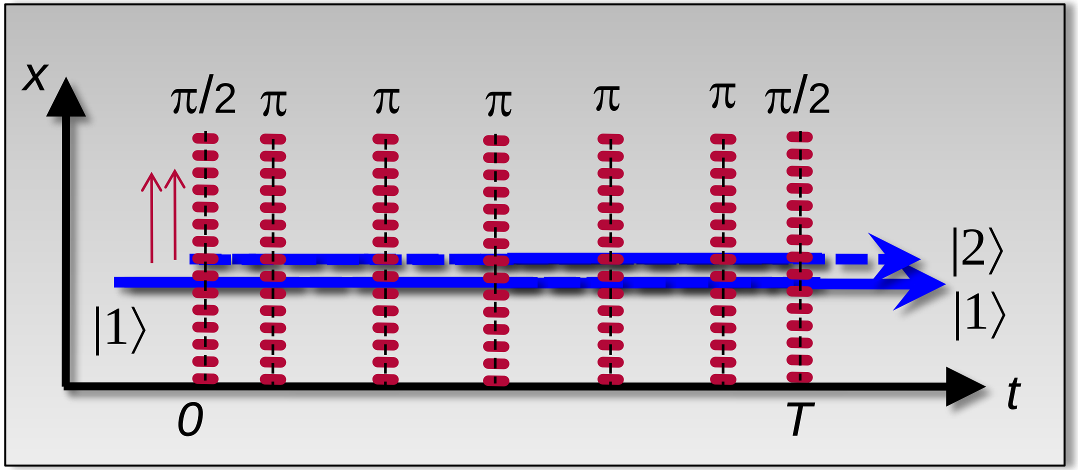


(Unbalanced) Spin echo (π/2–π–π/2)



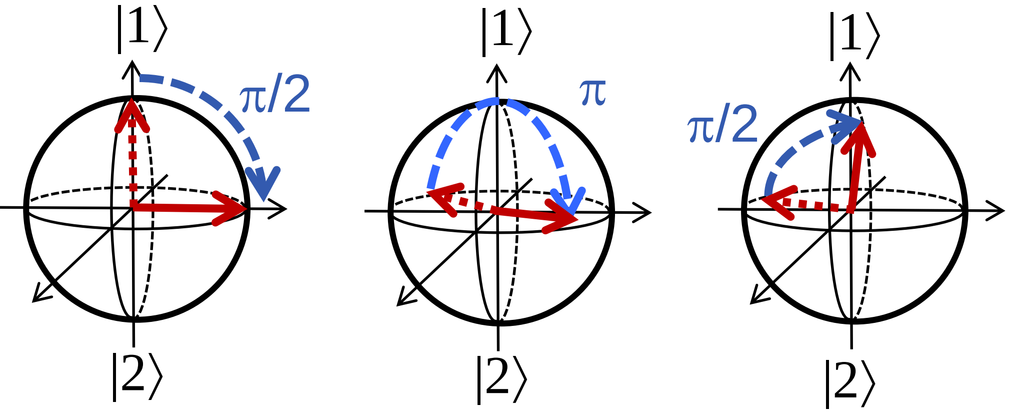
Atom Interferometer:

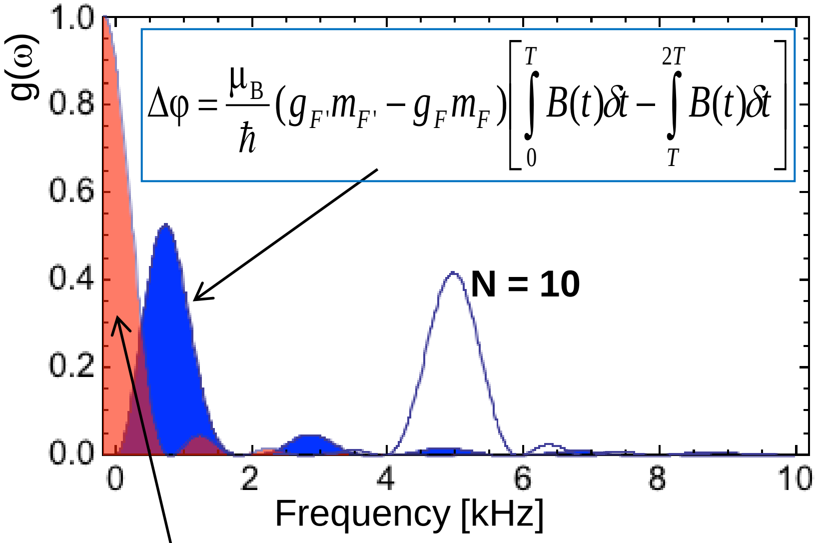
Frequency Domain



Pulse sequence controls interferometer sensitivity to noise

Scanning number of pulses can map out magnetic noise spectral density

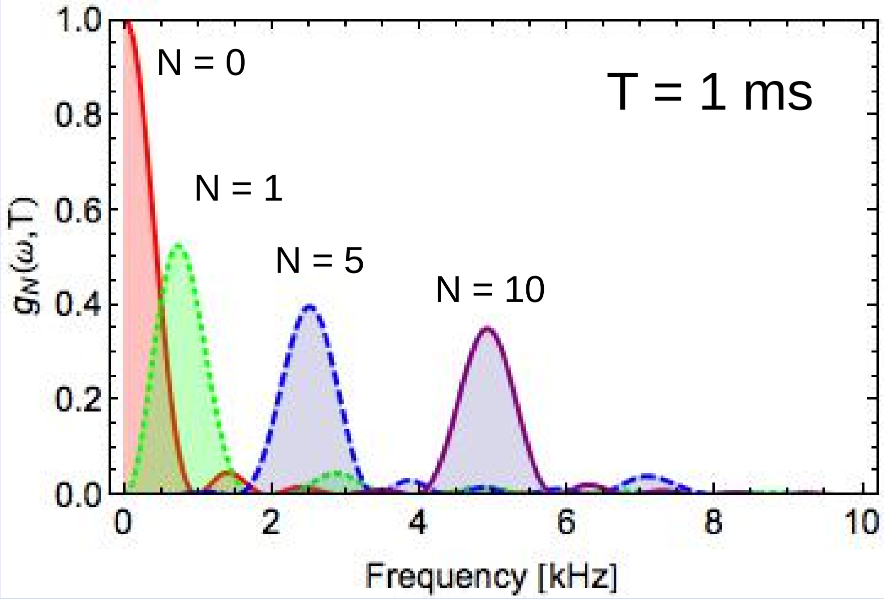


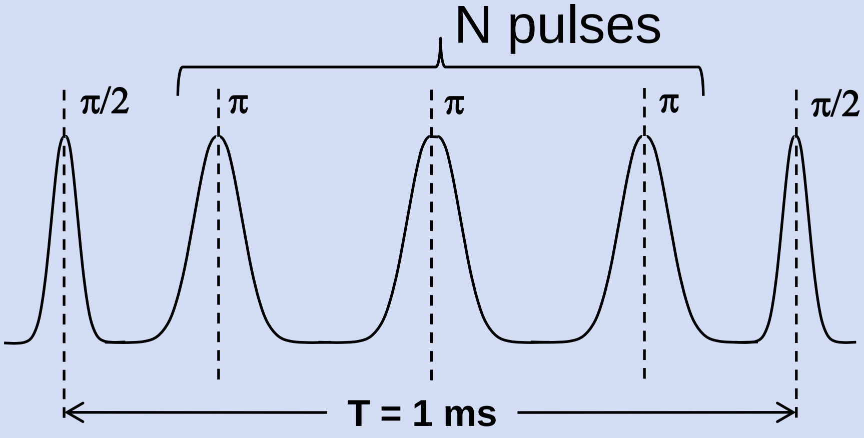


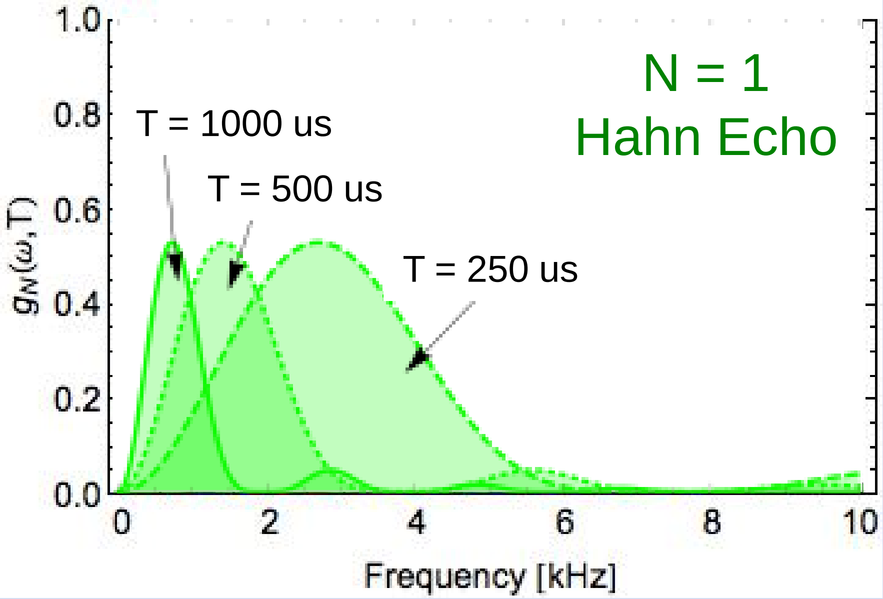
$$\Delta\varphi = \frac{\mu_B}{\hbar}(g_{F'}m_{F'} - g_F m_F)\left[\int_0^T B(t)\delta t - \int_T^{2T} B(t)\delta t\right]$$

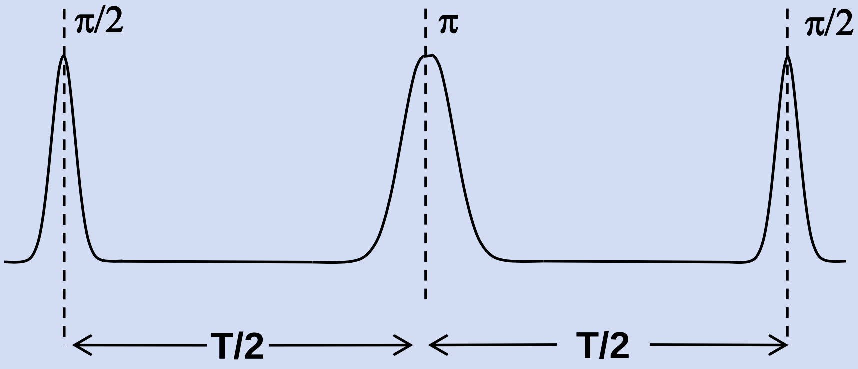
$$\Delta\phi = \frac{\mu_B}{\hbar}(g_{F'}m_{F'} - g_F m_F)\langle B\rangle T$$

Filter Functions Frequency Domain





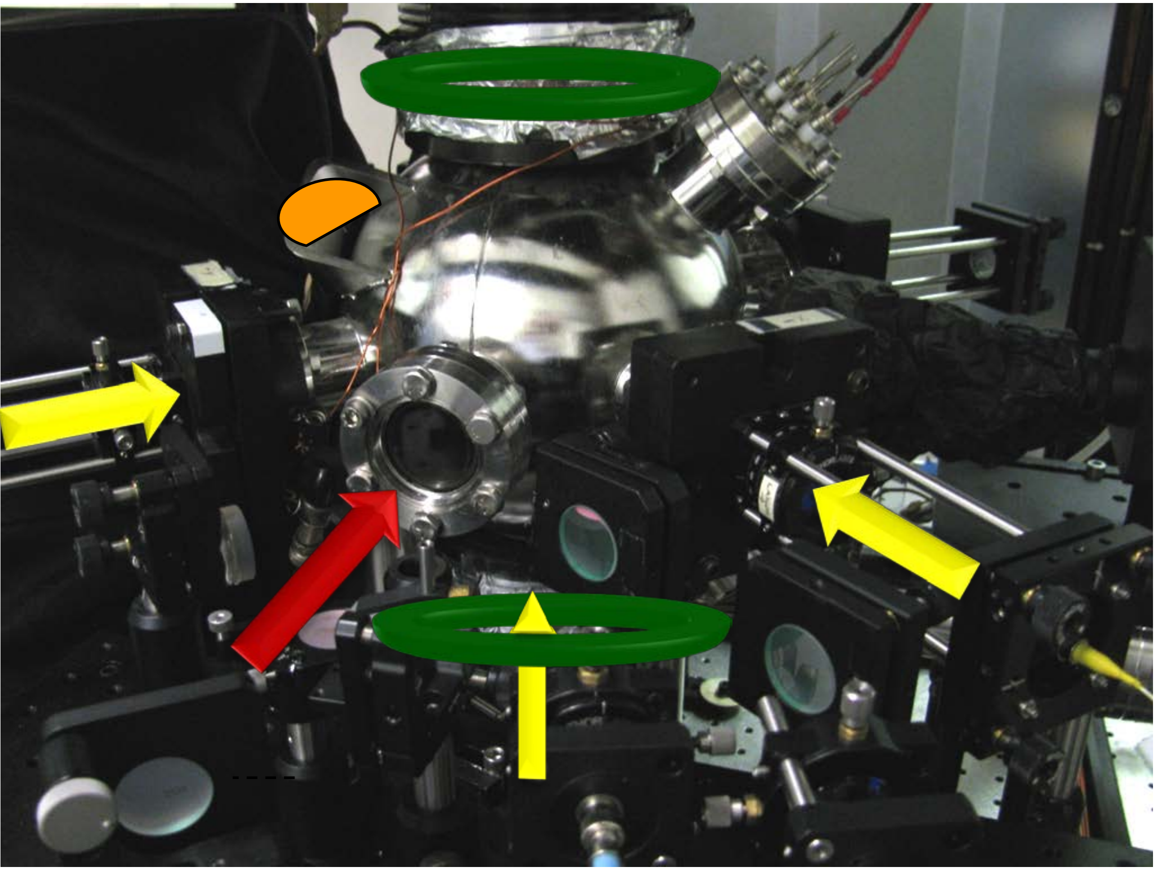




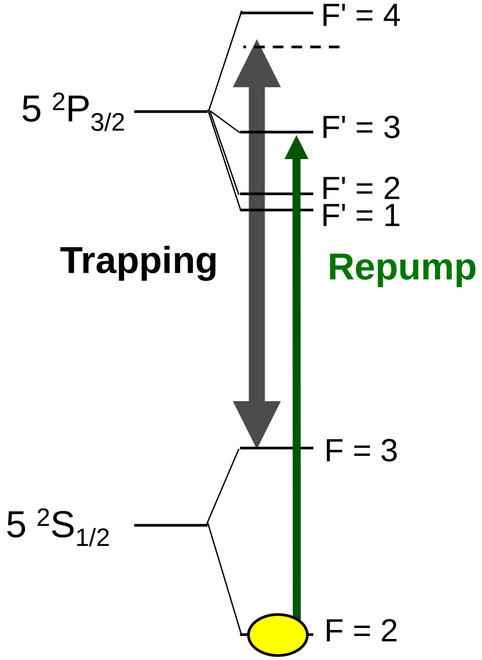
State preparation

✓well defined qubit *✓ initialization*

Unshielded environment and in a metal canister!

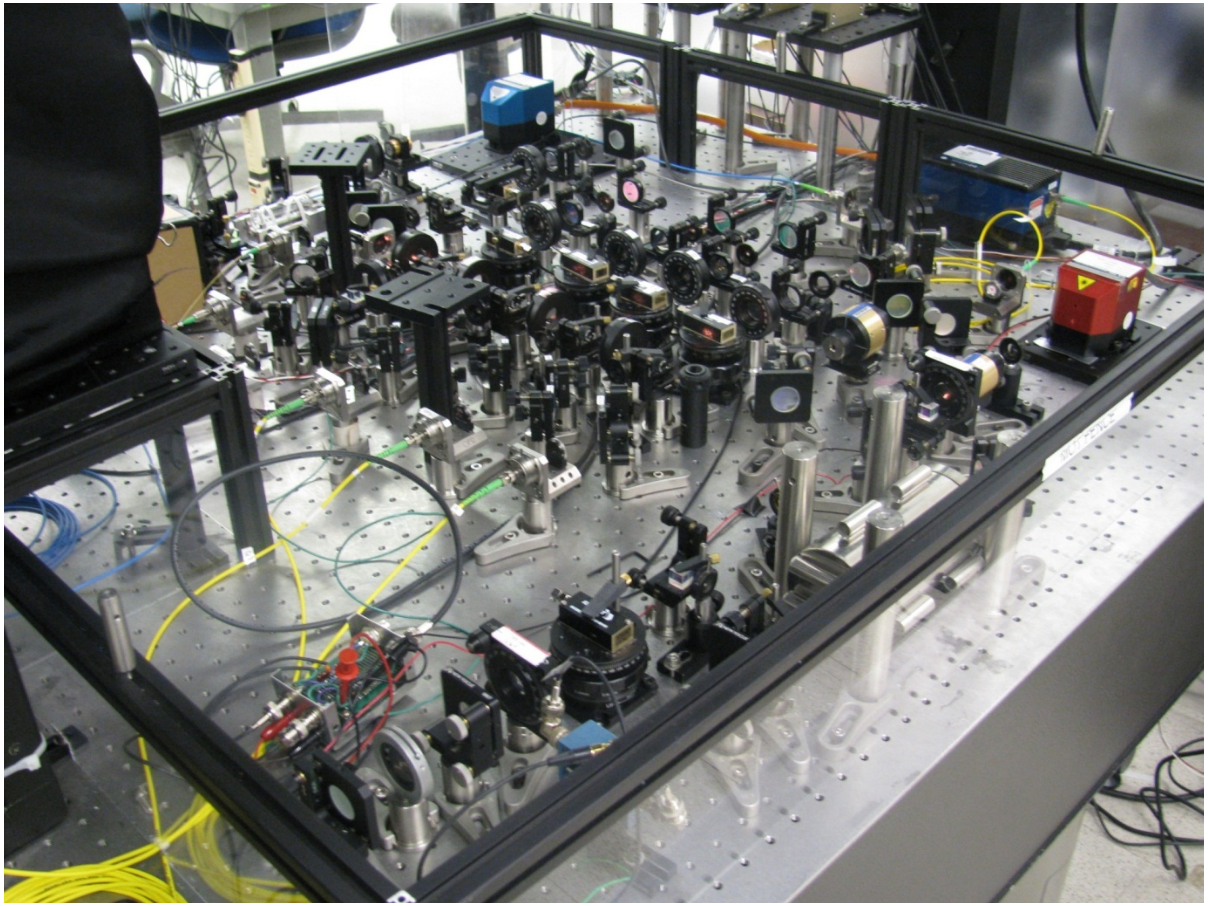


- **Gradient coils**
  - 10 G/cm
- **Trapping lasers:**
  - Amplified (TA7613) New Focus StableWave 7013
  - 2.5 cm beam

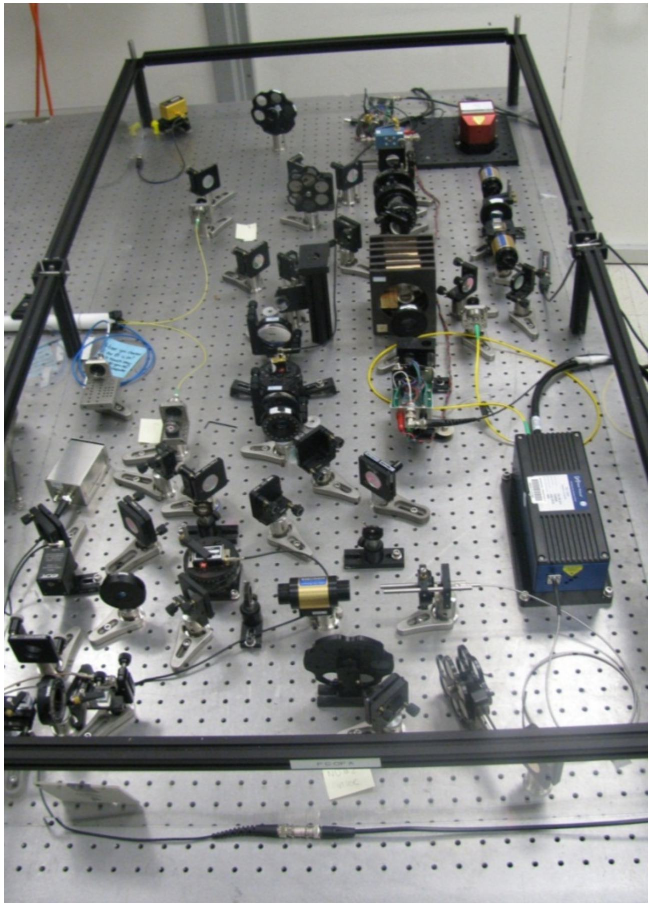


Apparatus

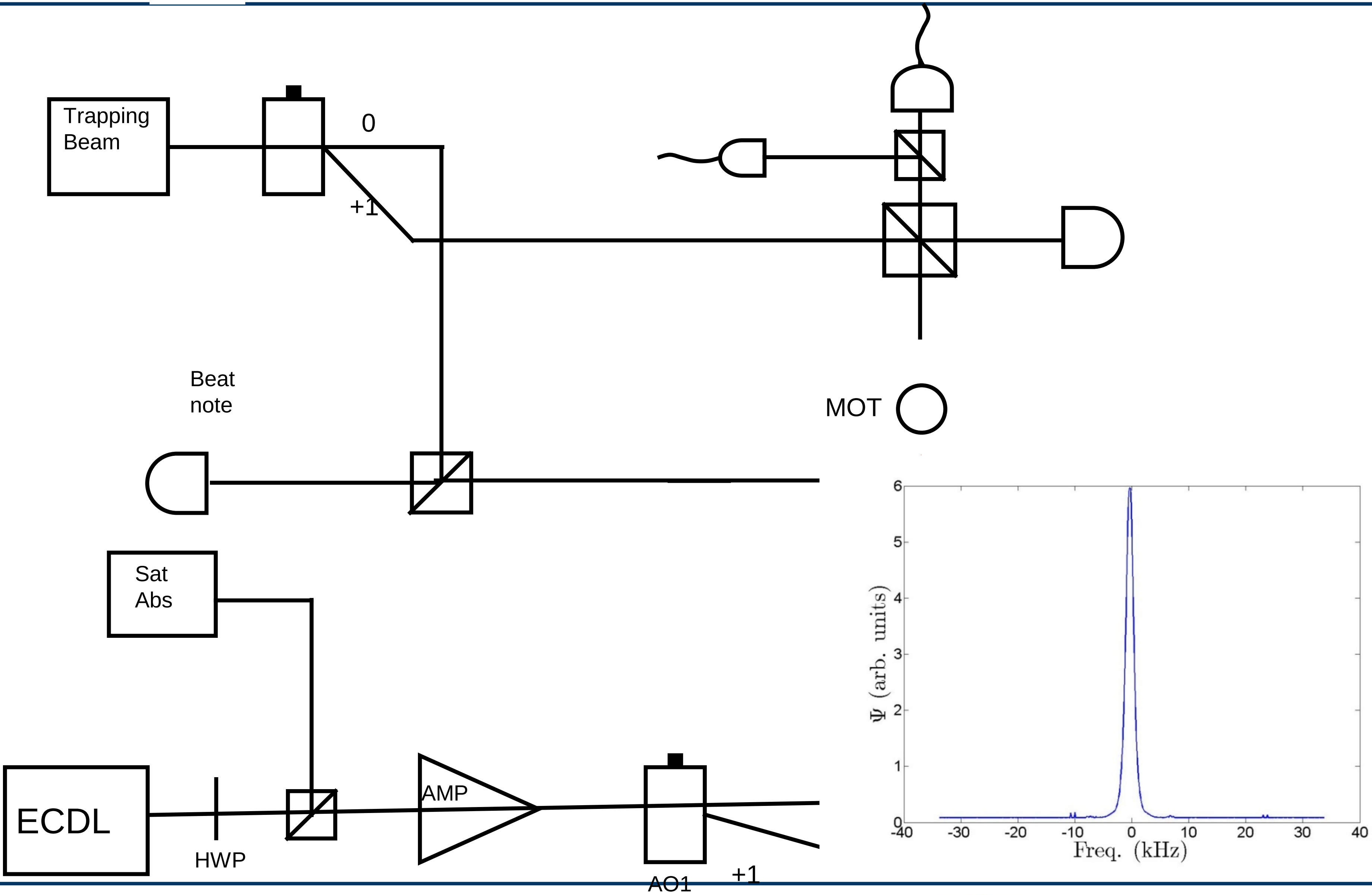
- **Trapping Setup**



- **Raman Lasers**

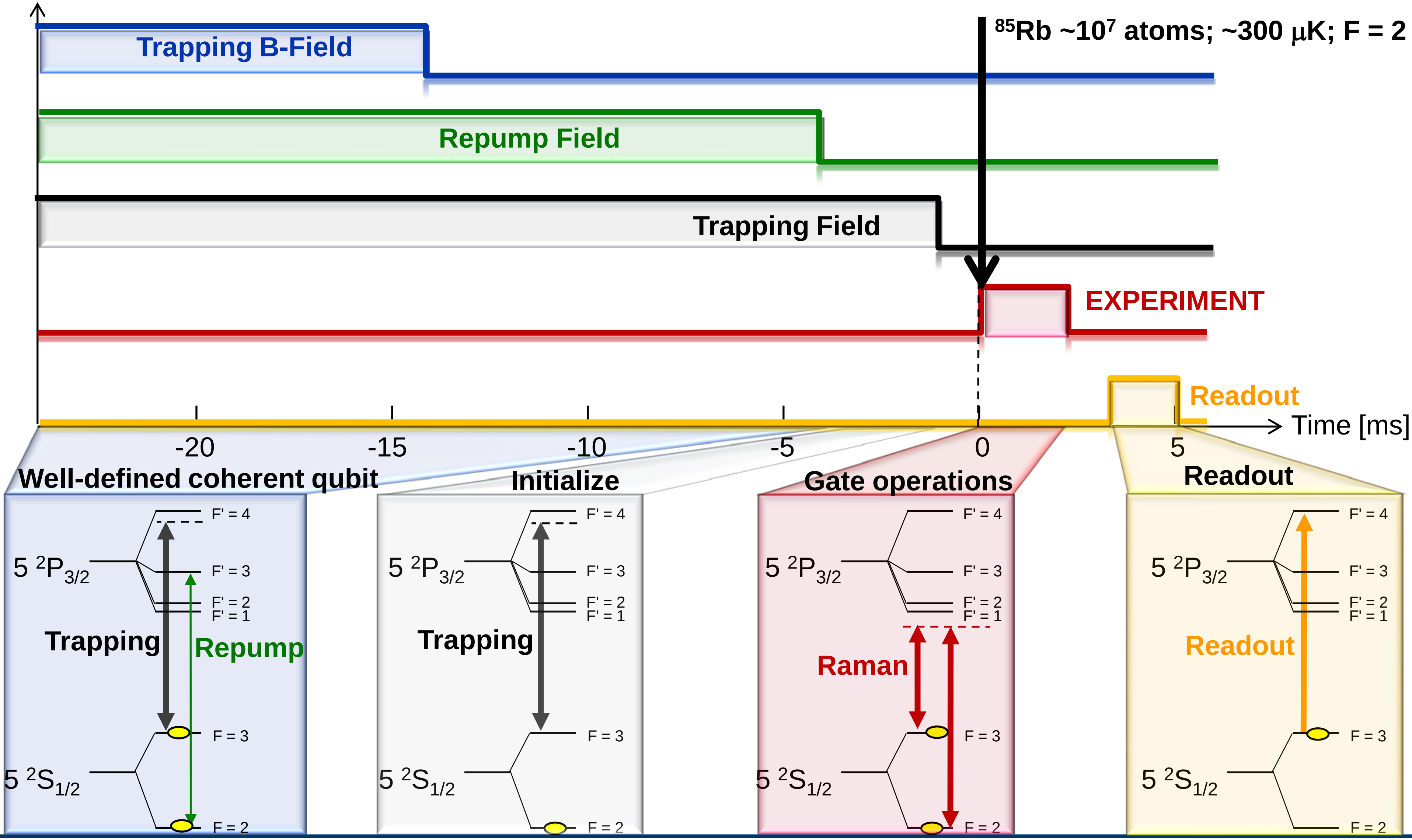


Experimental schematic

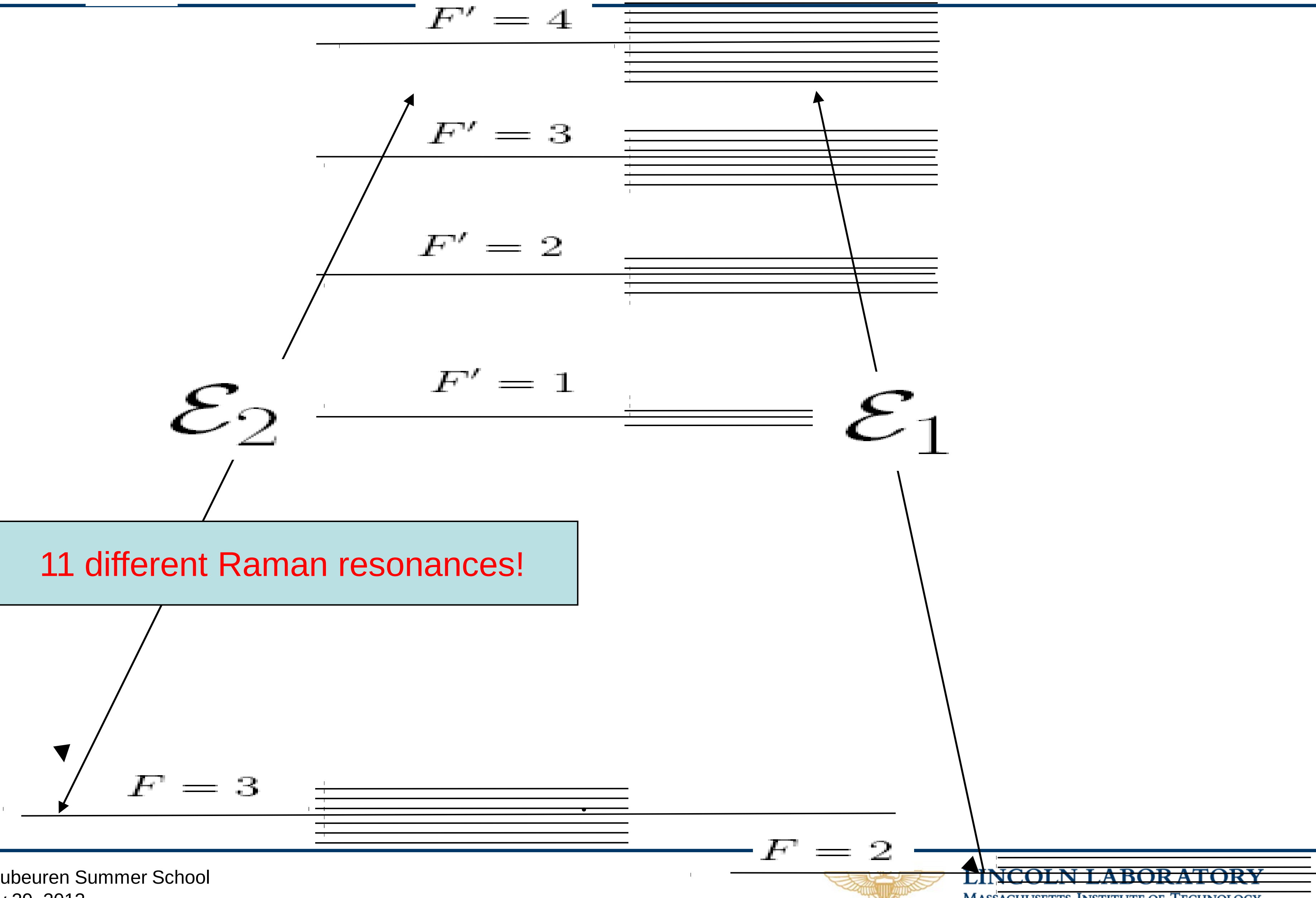


Timing sequence

^{85}Rb ~10^7 atoms; ~300 μK; F = 2

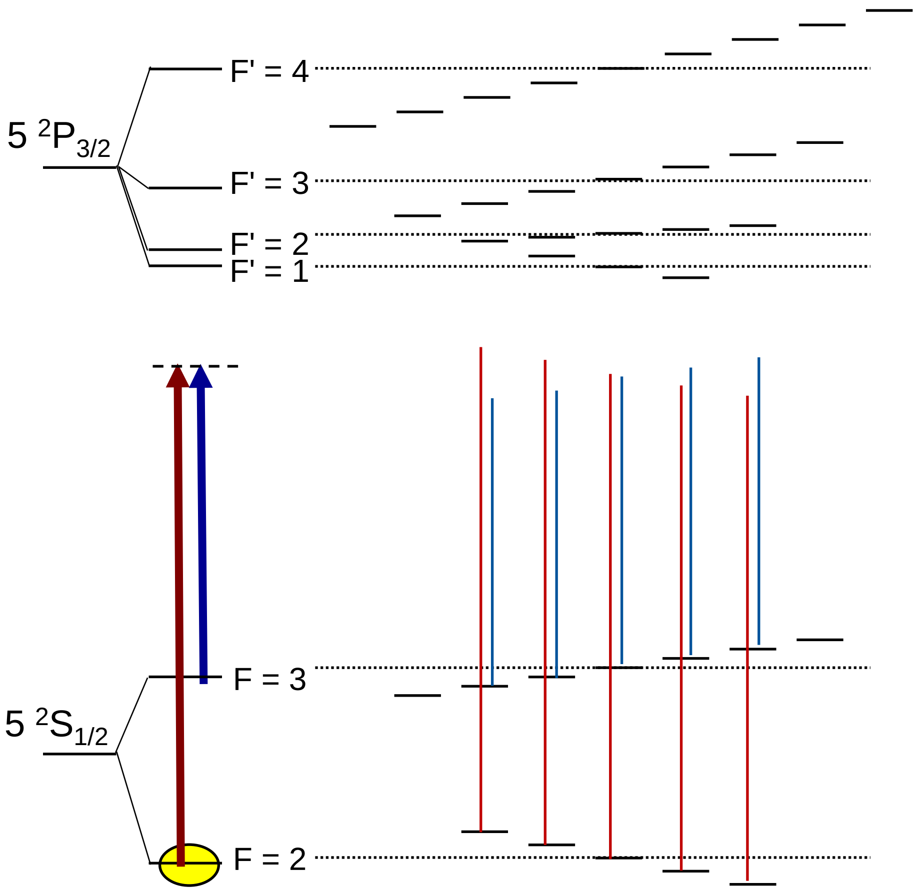


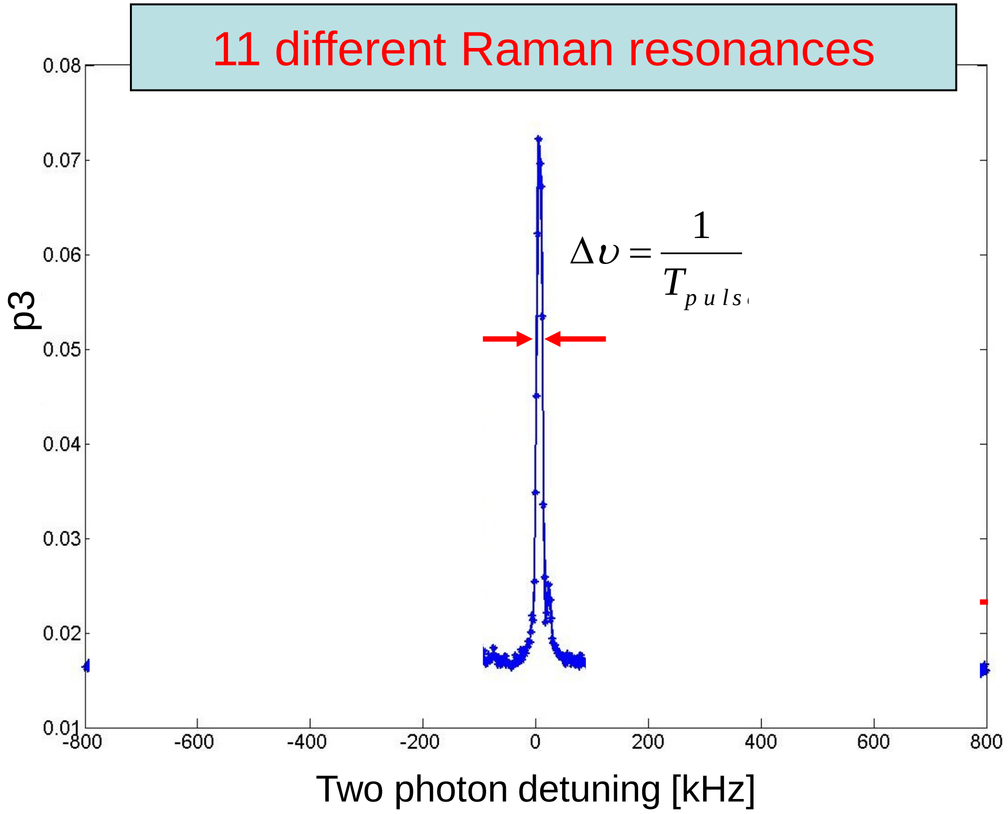
A real atom: ^{85}Rb



11 different Raman resonances!

Raman spectra (arbitrary field)




11 different Raman resonances

$\Delta \upsilon = \frac{1}{T_{puls}}$

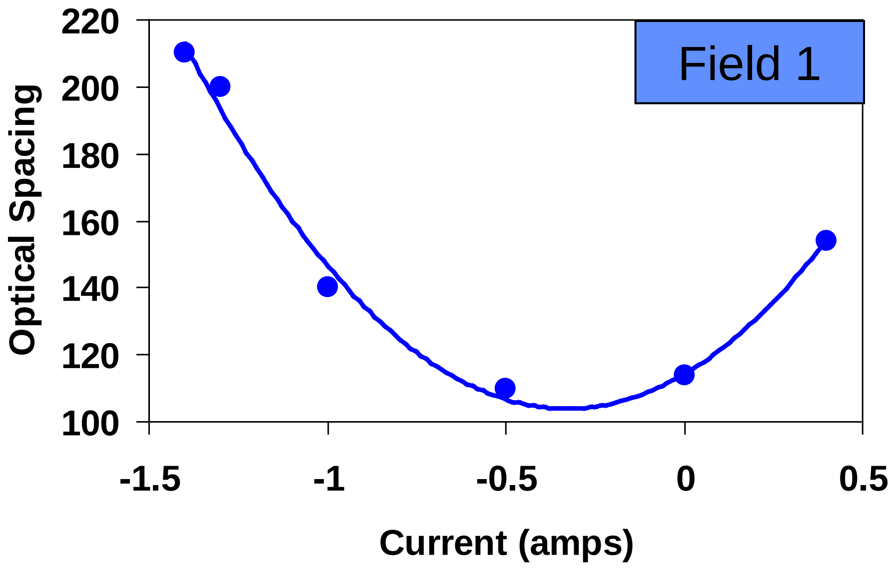
^{85}Rb ~10^7 atoms

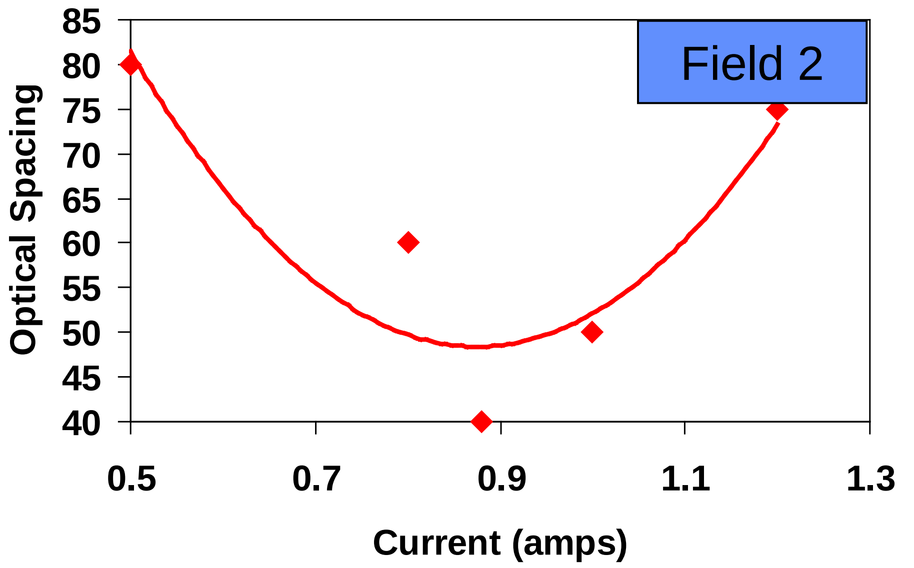
~300 μK

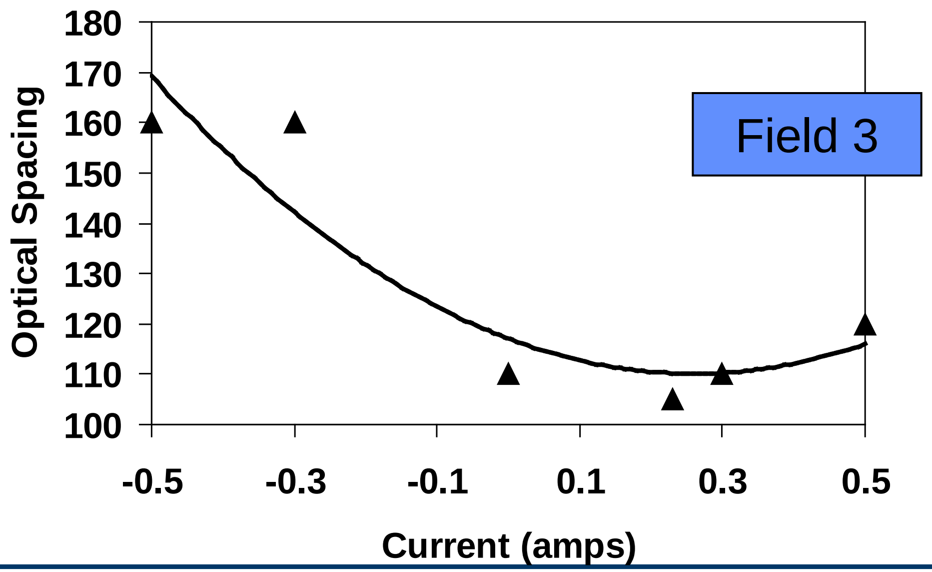
F = 2

$$\delta f = g_F m_F \frac{\mu_B B}{h} \approx 466.5 m_F \mathrm{kHz/G}$$

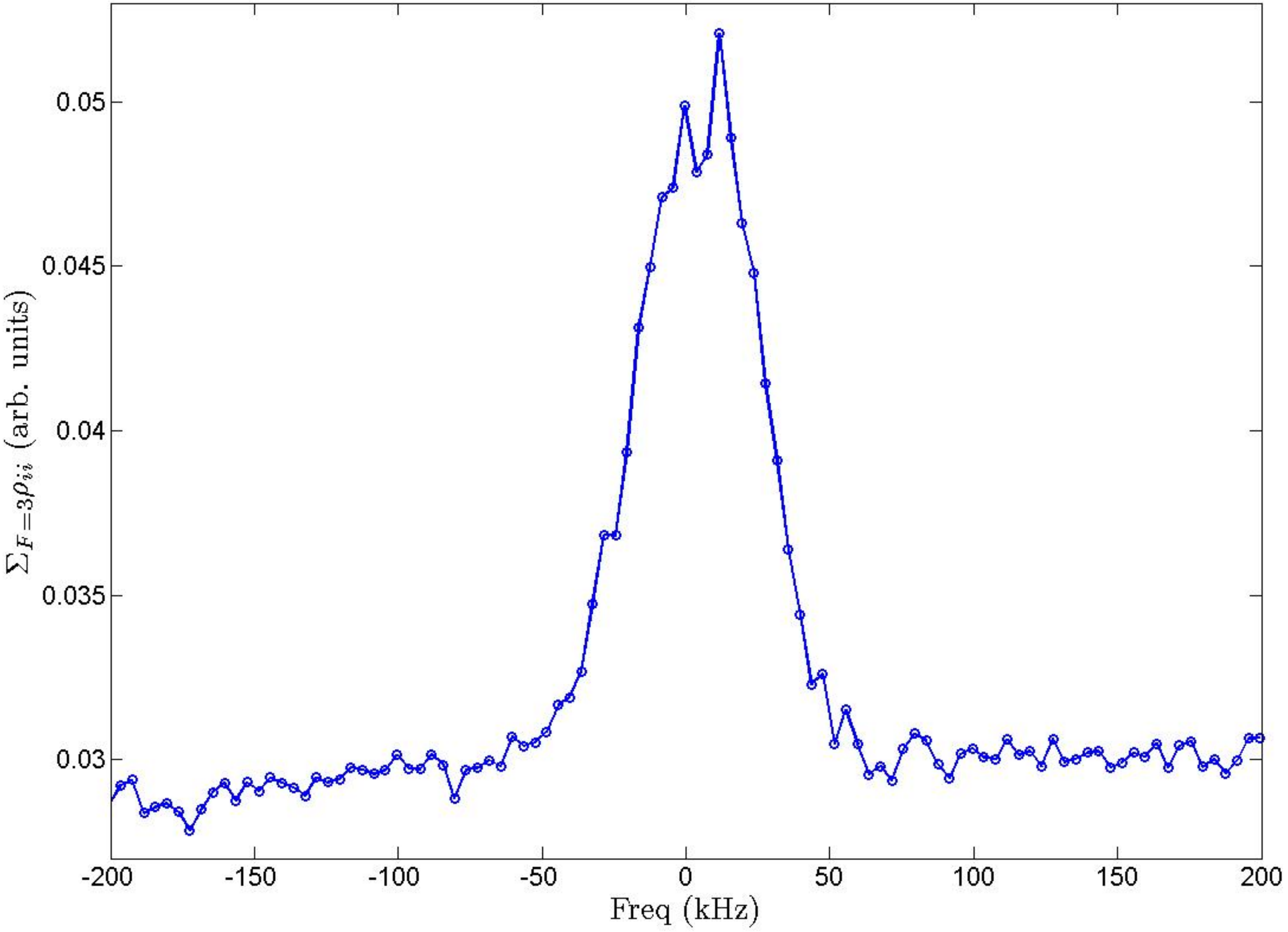
Use to “zero” field around atoms







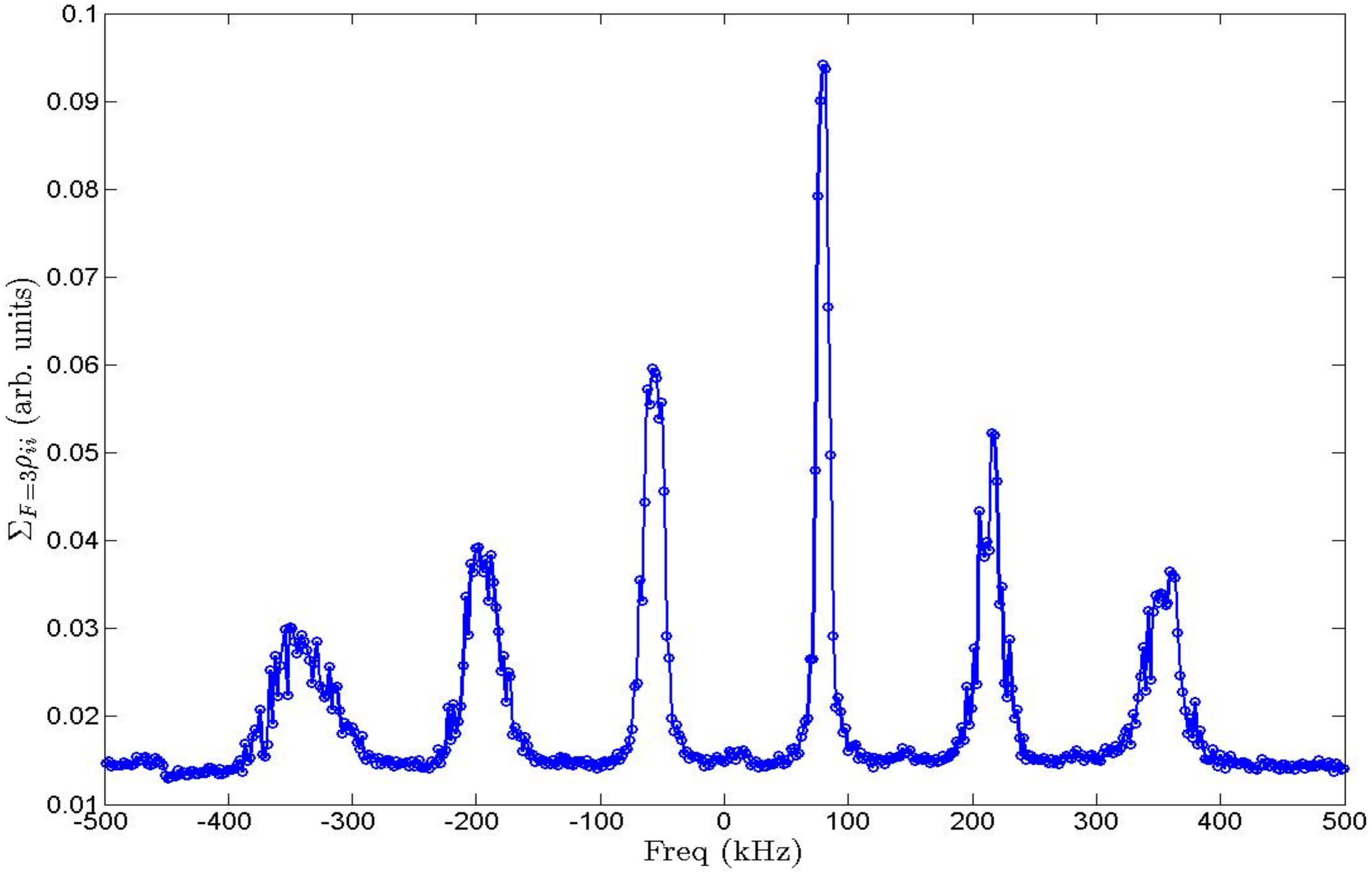
Single Peak


$\Sigma_{F=3}\rho_{ii}$ (arb. units)
0.05
0.045
0.04
0.035
0.03
-200
-150
-100
-50
0
50
100
150
200
Freq (kHz)

Selection Rules

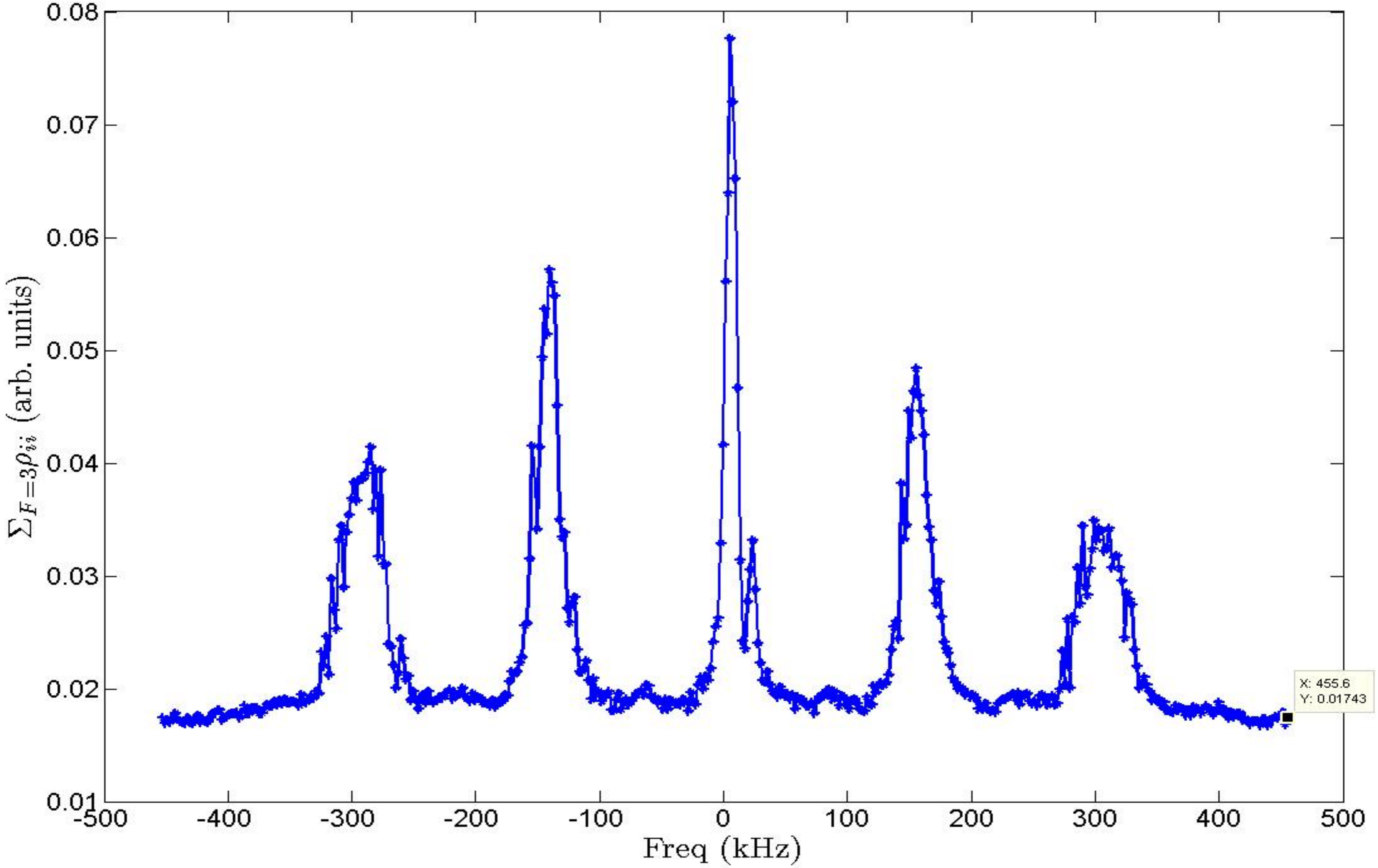
- “*Even*” transitions driven by:
  - $\hat{x} - \hat{y}$ polarization
  - $\hat{\sigma}^+ - \hat{\sigma}^-$ polarization
  - $\Delta m = 0$
- “*Odd*” transitions driven by:
  - $\hat{\sigma}^+ - \hat{z}$, $\hat{\sigma}^- - \hat{z}$, $\hat{x} - \hat{z}$, $\hat{y} - \hat{z}$ polarization
  - $|\Delta m| = 1$
- Here, $\hat{z}$ is defined by the direction of the magnetic field
- g factor between ground states changes sign

Six Peaked Spectrum



Transverse

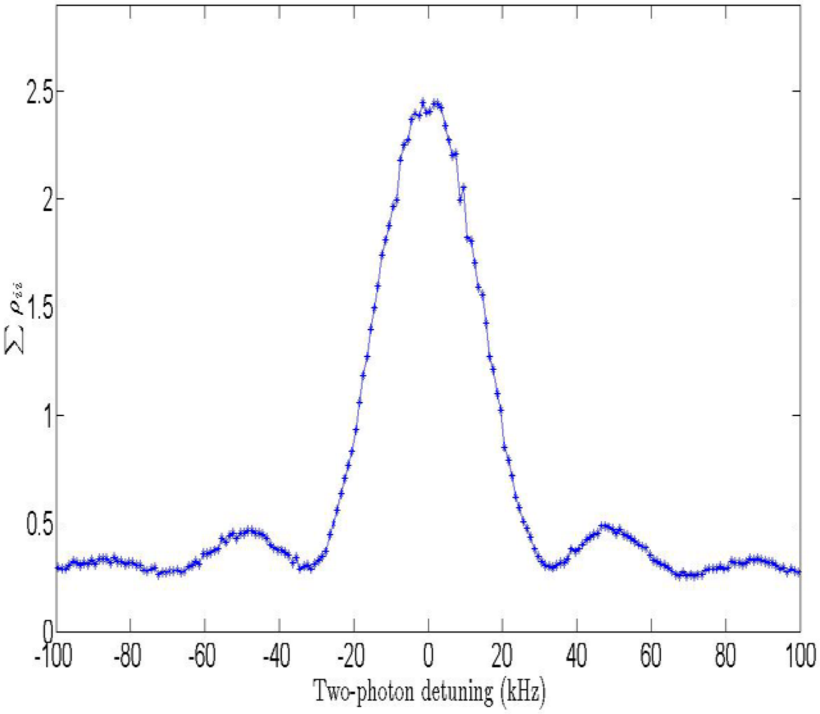
Five Peaked Spectrum



Longitudinal

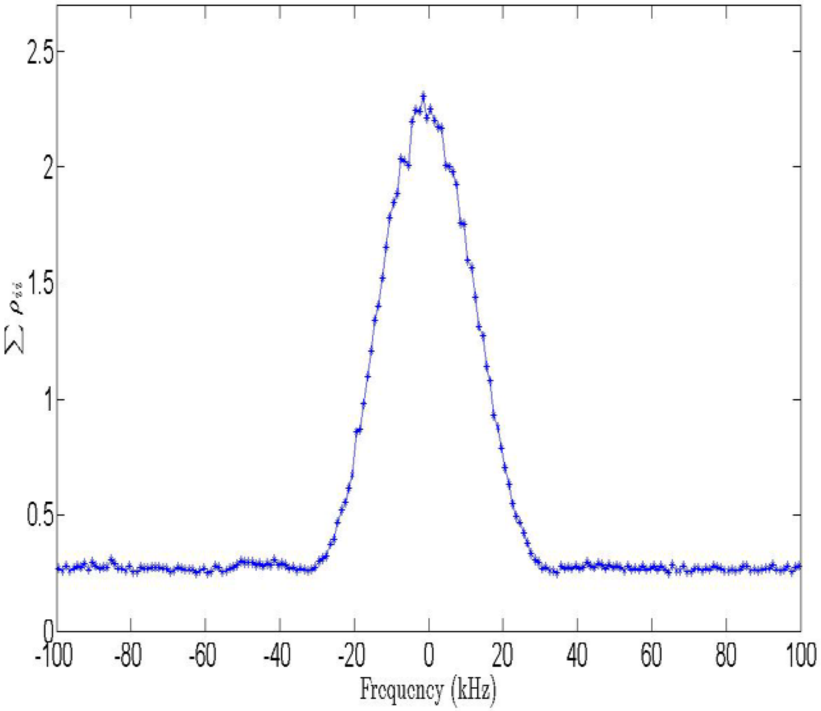
Effect of pulse shape

Square vs Gaussian Pulses

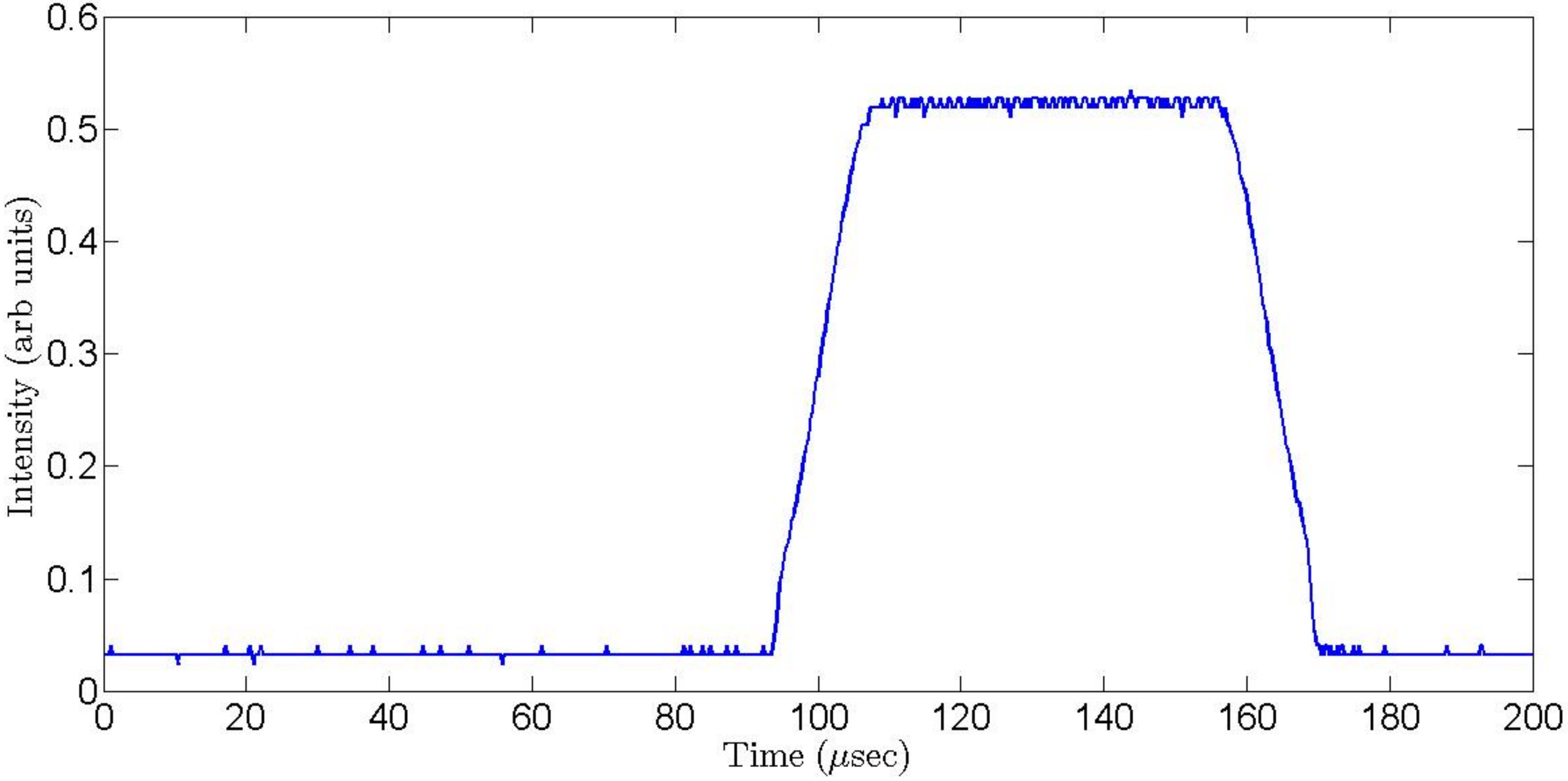


Square Pulse

Gaussian Pulse

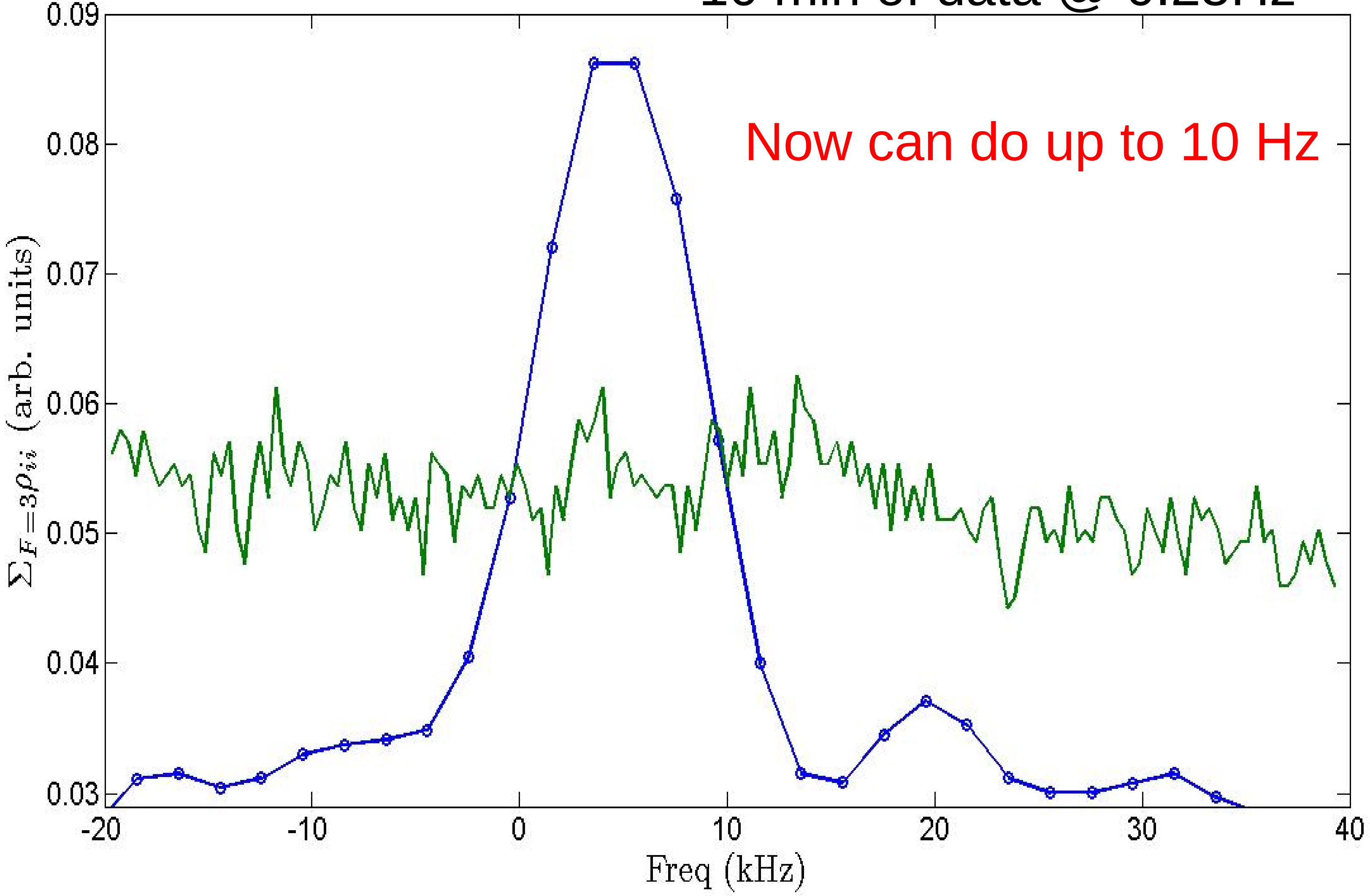


Hybrid Pulse



Crude Magnetometer

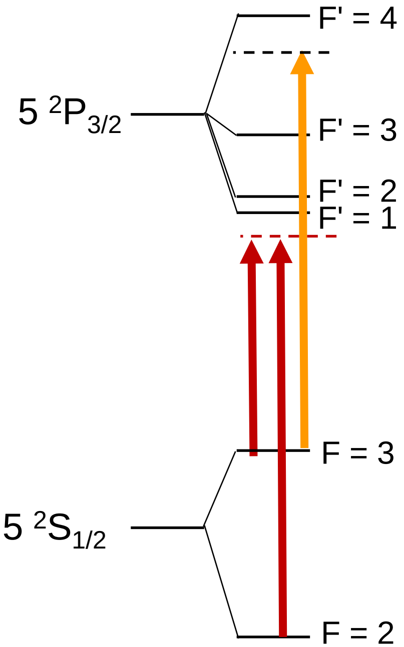
10 min of data @ 0.25Hz

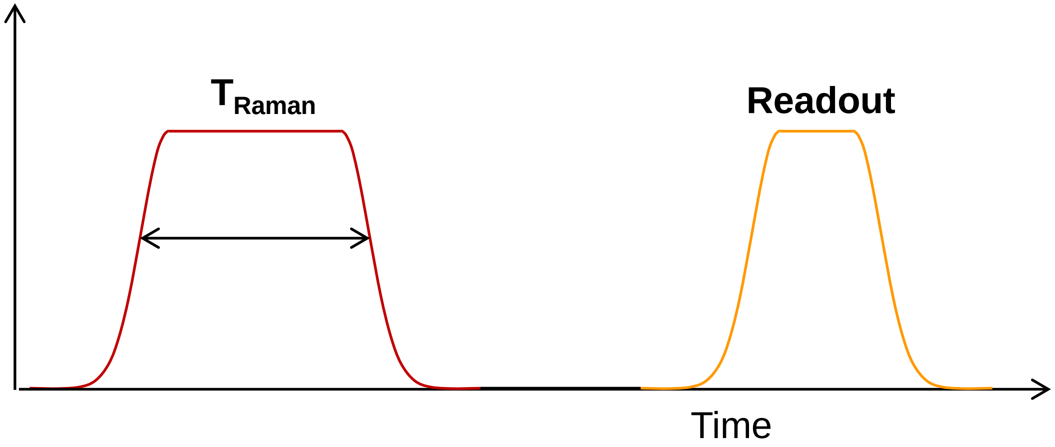


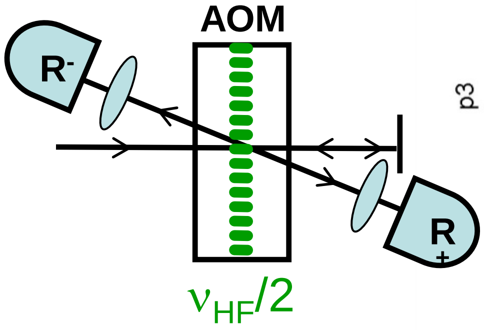
Now can do up to 10 Hz

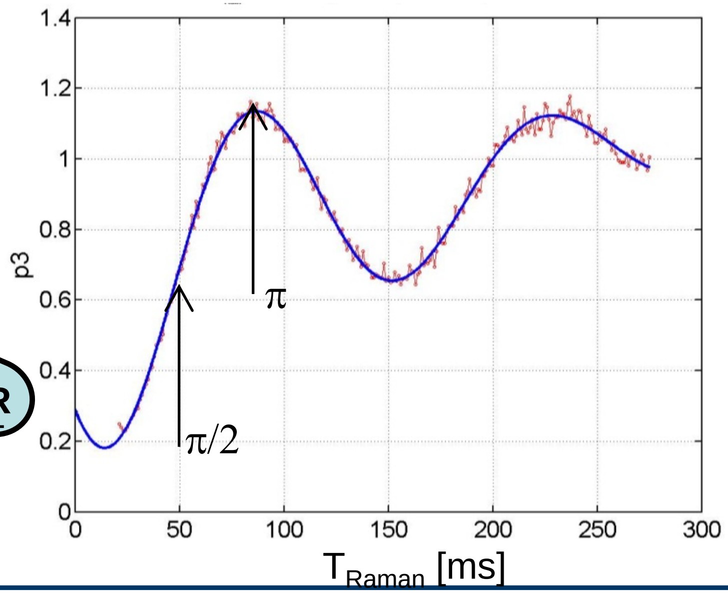
Rabi cycling: m=0 to m'=0 transition

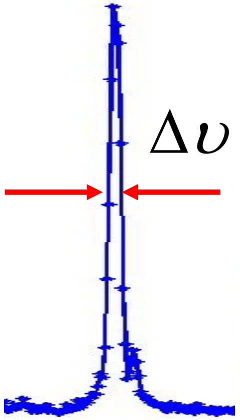
✓ *universal gates* ✓ *ability to read out*







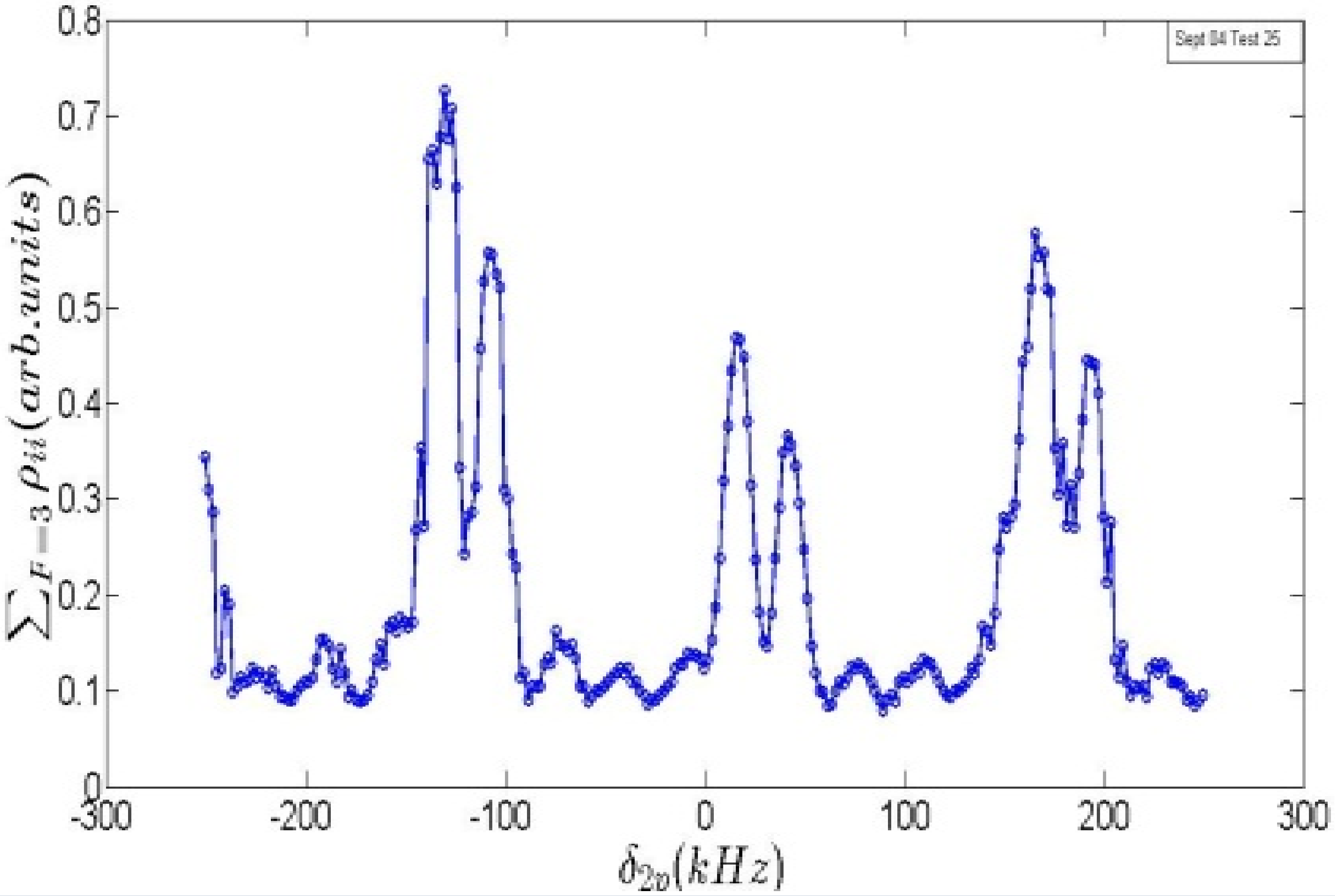




$$\Delta\upsilon = \frac{1}{T_{pulse}}$$

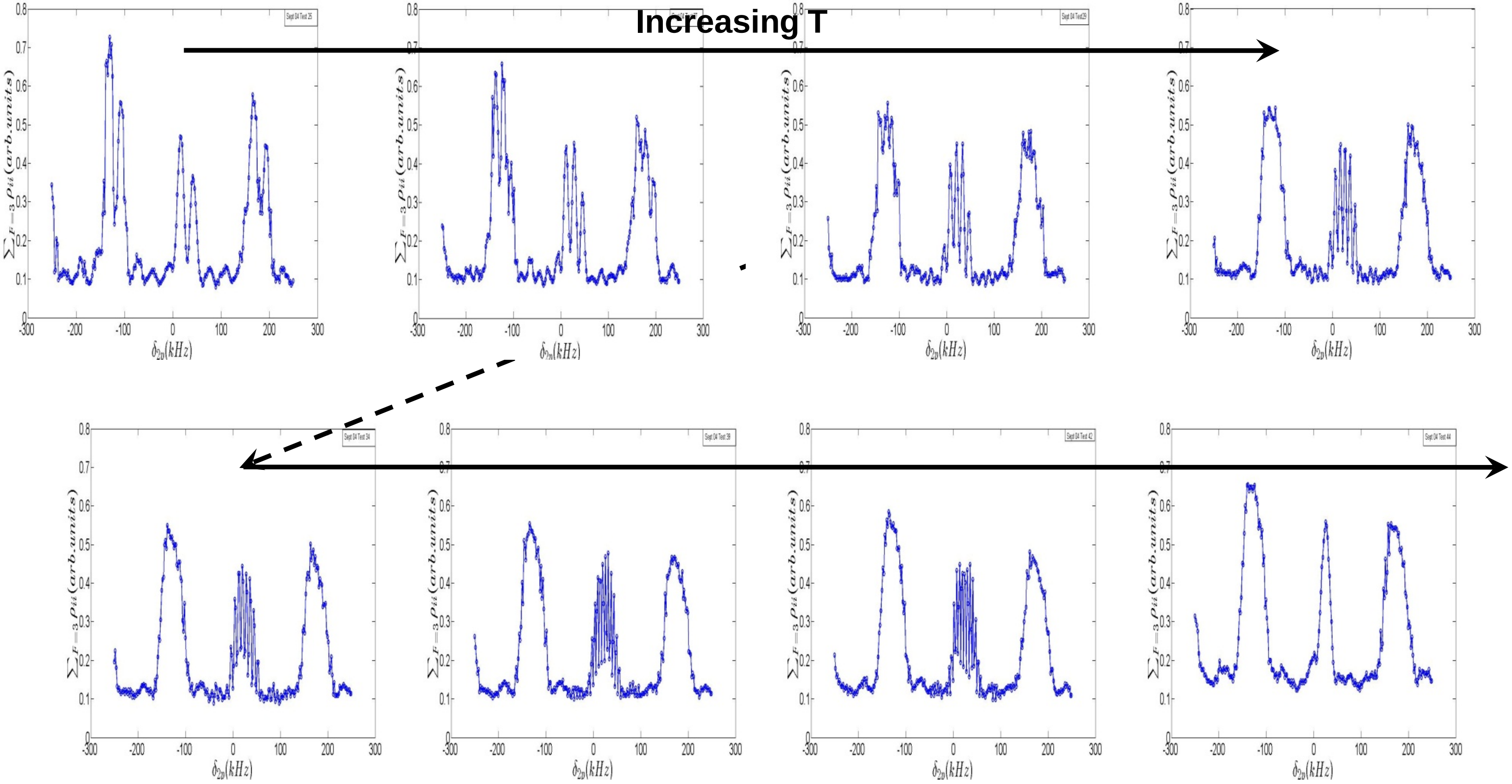
Two photon detuning

Ramsey interference

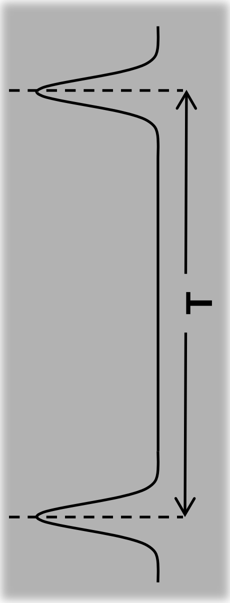


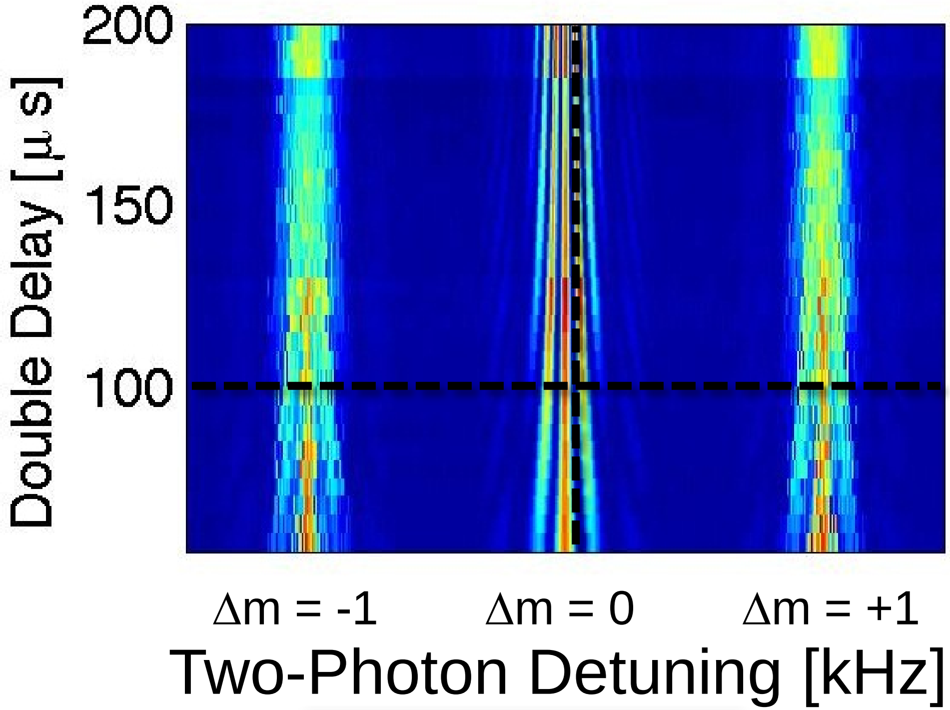
Ramsey vs. double delay

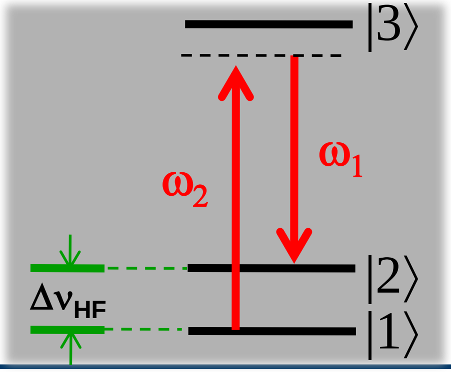
- As time between pulses is lengthened, Ramsey interference disappears.



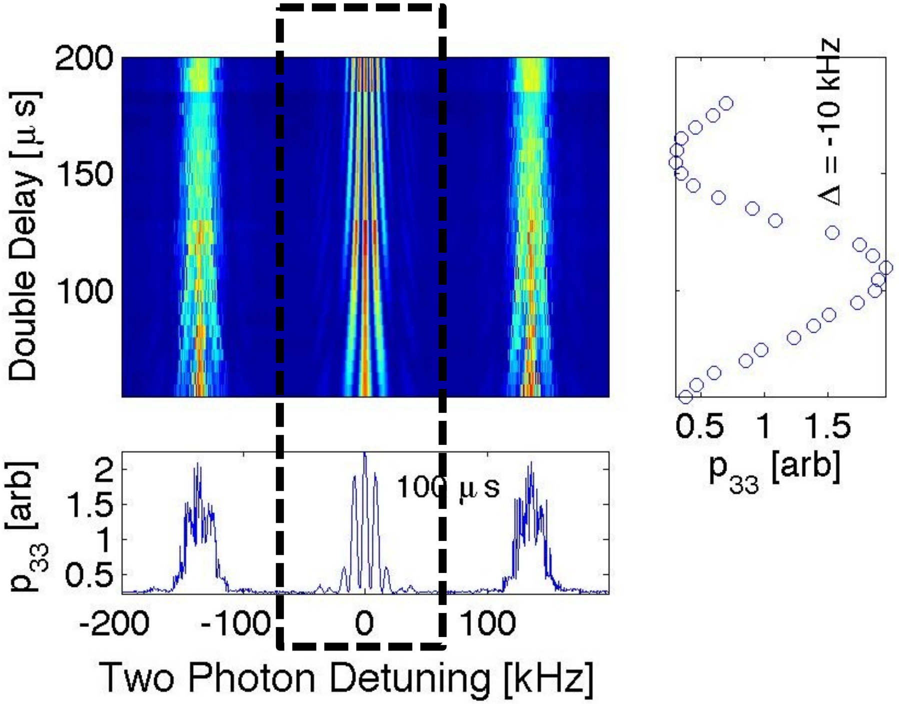
Atom Interferometer Clock Transition

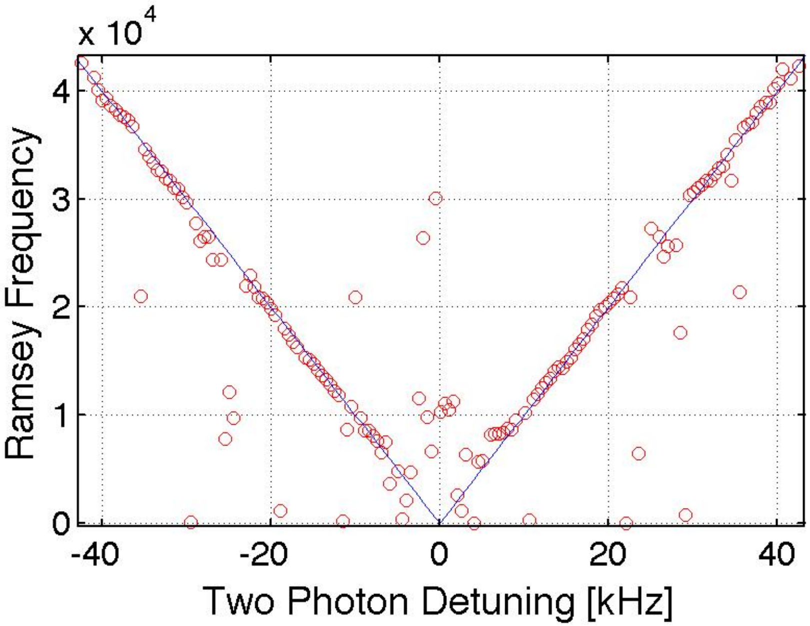






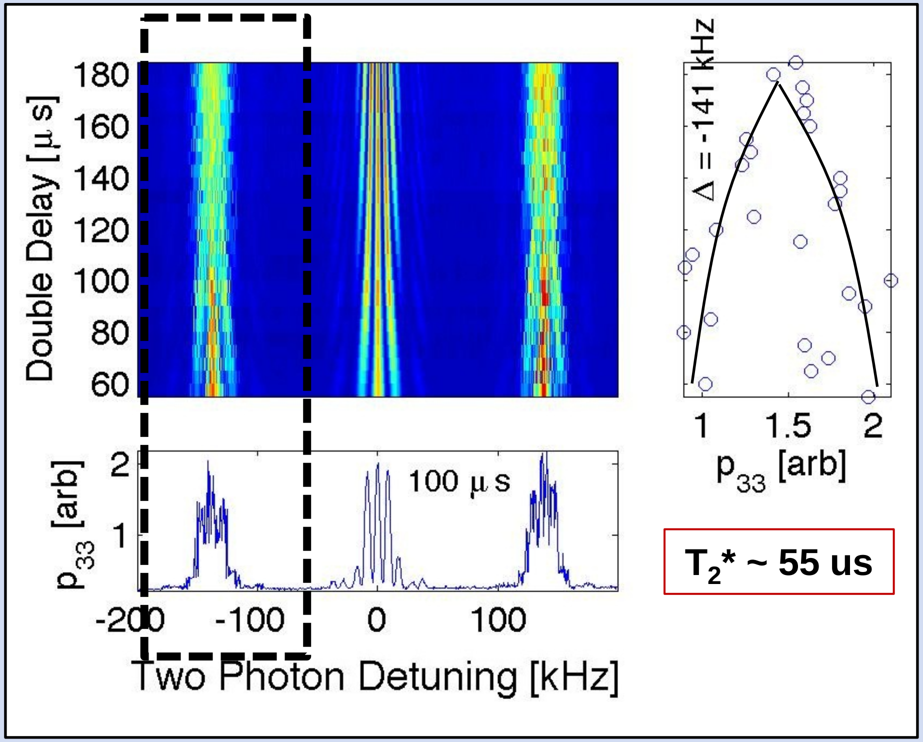
Atom Interferometer Magnetometer





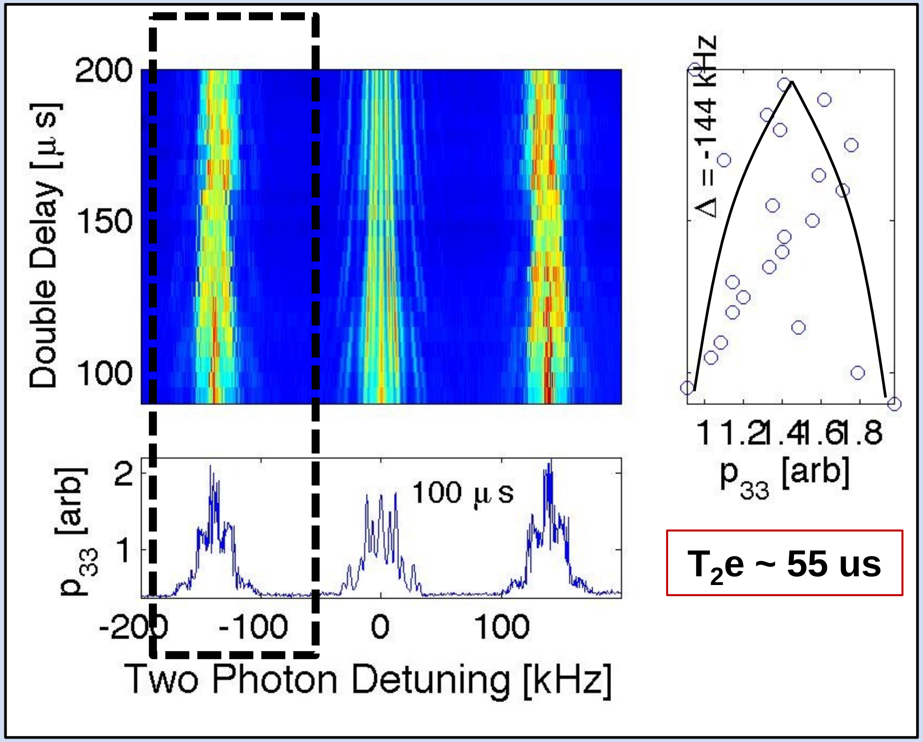
Atom Interferometer Magnetometer

- **Ramsey (Magnetic)**

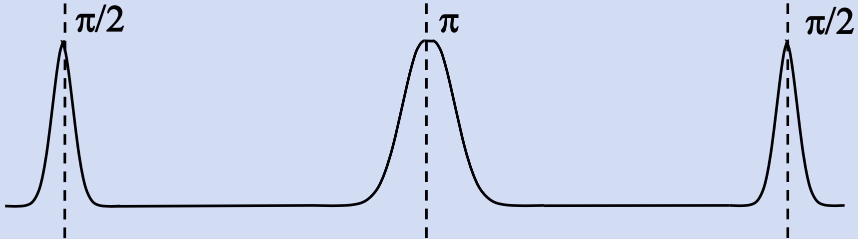


$T_2^* \sim 55$ us

- **Spin Echo (Magnetic)**

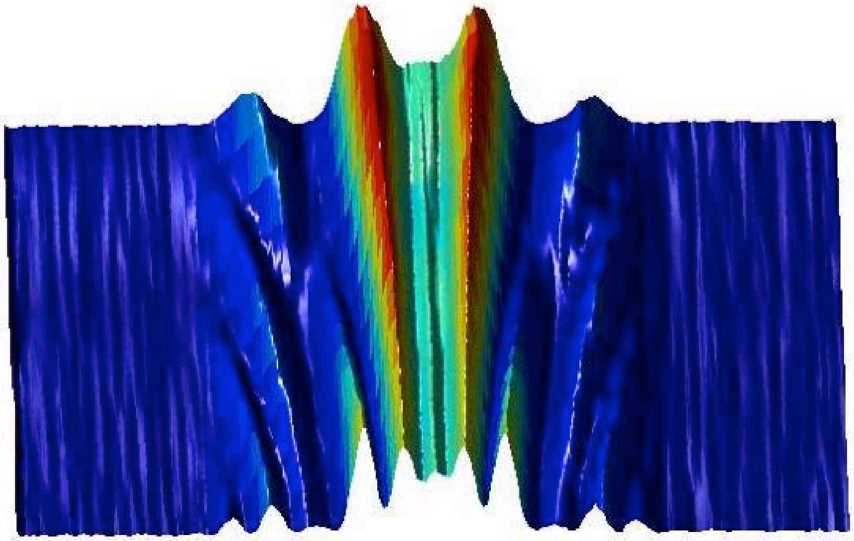


$T_2e \sim 55$ us



Conclusions

- Magnetometry is useful for a broad range of applications from biomagnetics to remote detection
- Atom Interferometry allows NMR like pulse control sequences as a lock-in-amplifier for magnetic signals
- Using these techniques combined with gradiometry, we can detect signals in a magnetically noisy environment



Thank you for your attention!

Questions?

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Other experiments-then

**"…~~could be~~ interesting.
But it's ~~not~~ fundamental
enough"** → **maybe**

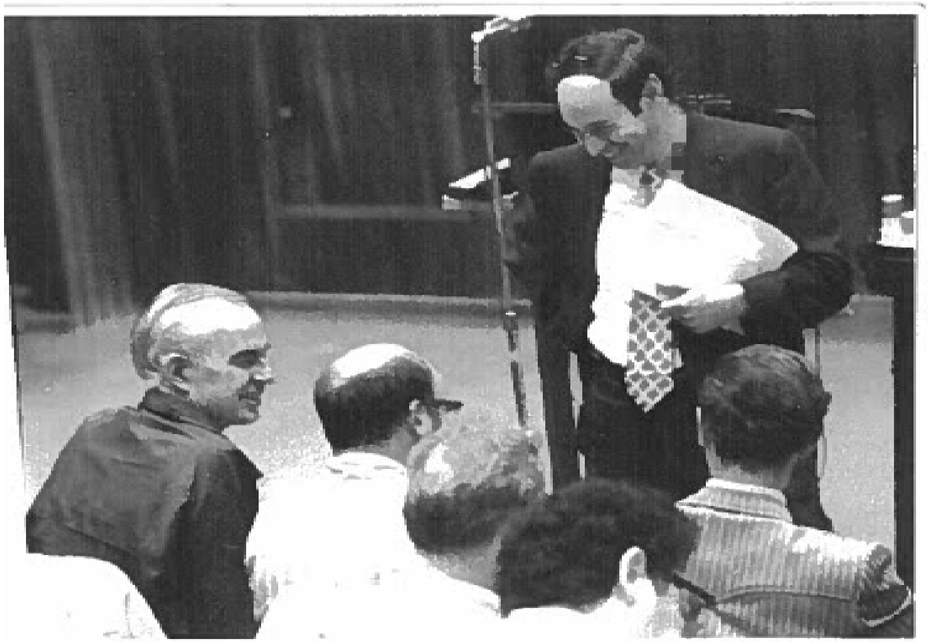
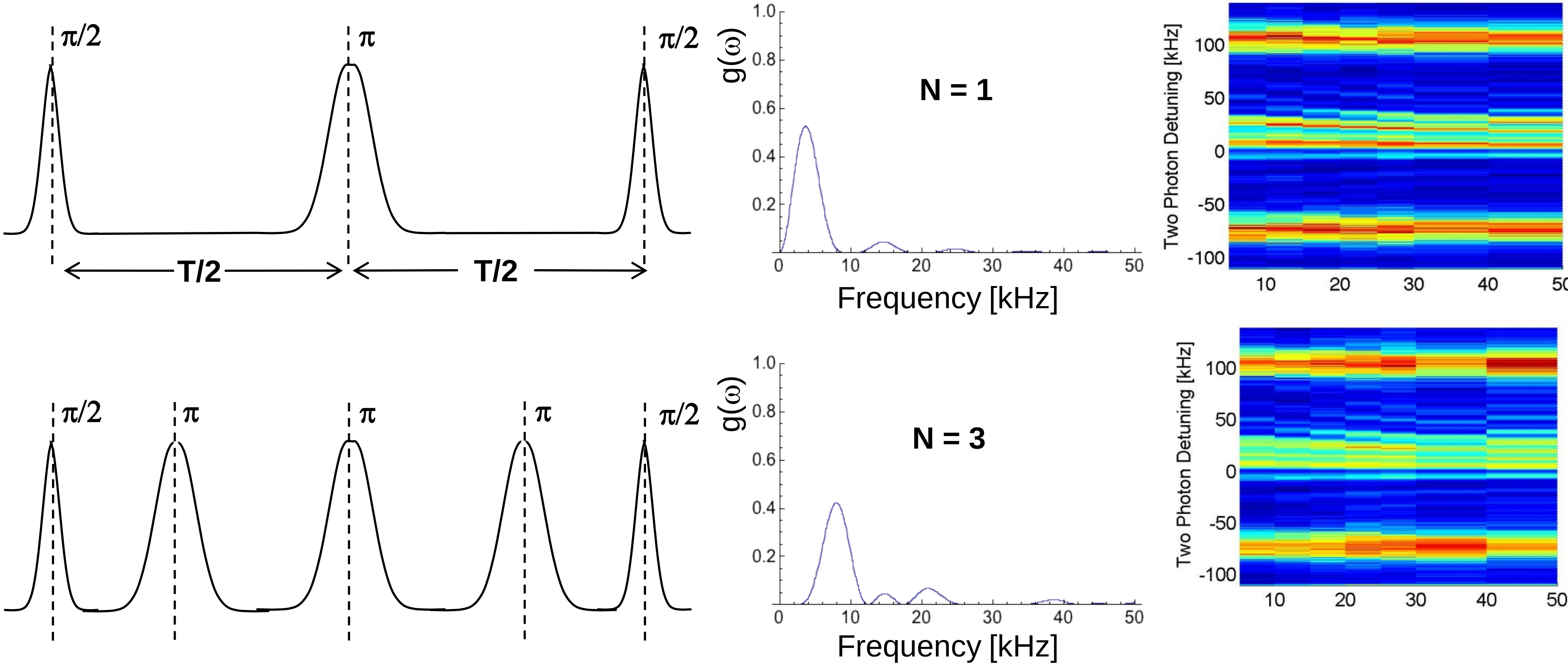


Photo courtesy J. Mandel

**Leonard Mandel
1927-2001**

Bonus Material

Multiple Pulse Interferometer Sequences

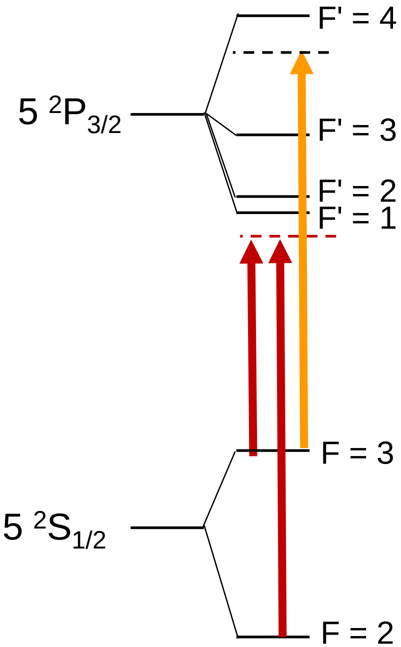


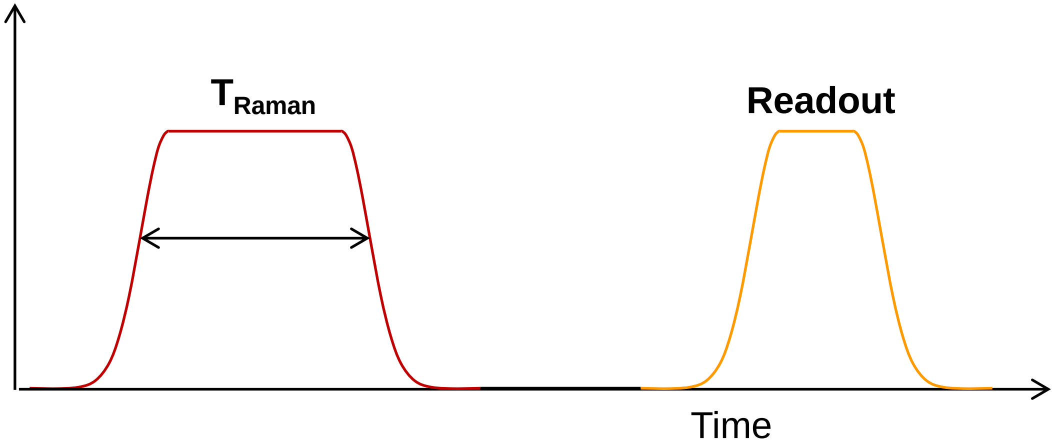
NMR: Carr Purcell *PR* 94 **630** (1954)
Ions: Biercuk *Nature* **458** 996 (2009)
Atoms: Davidson PRL 105,053201 (2010)
NV Centers: Lukin, Rugar, Cappellaro …
Superconductors: Bylander *Nature Phys* **565** 1994 (2011)

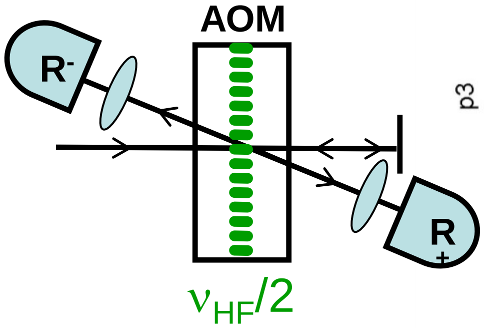
transition

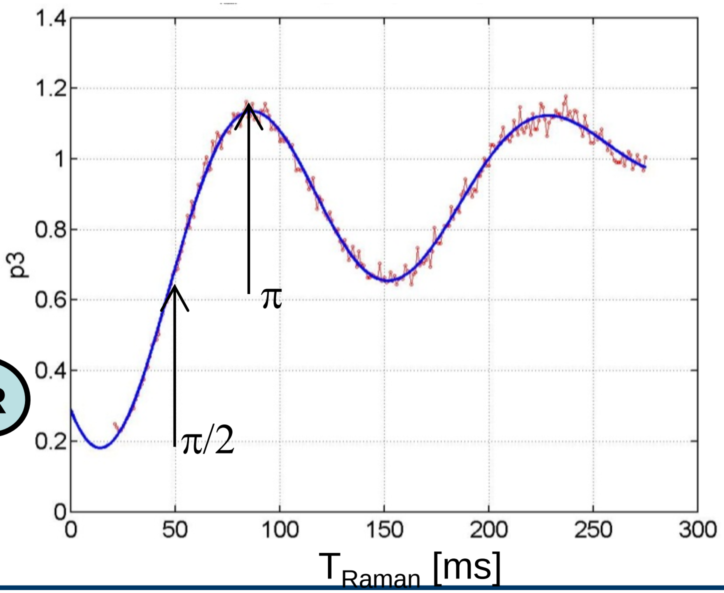
✓ universal gates

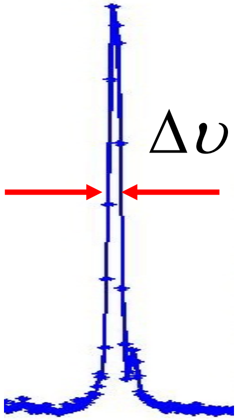
✓ ability to read out











$$\Delta\upsilon = \frac{1}{T_{pulse}}$$

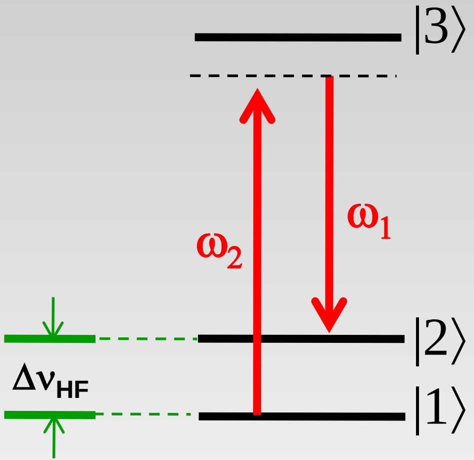
Two photon detuning

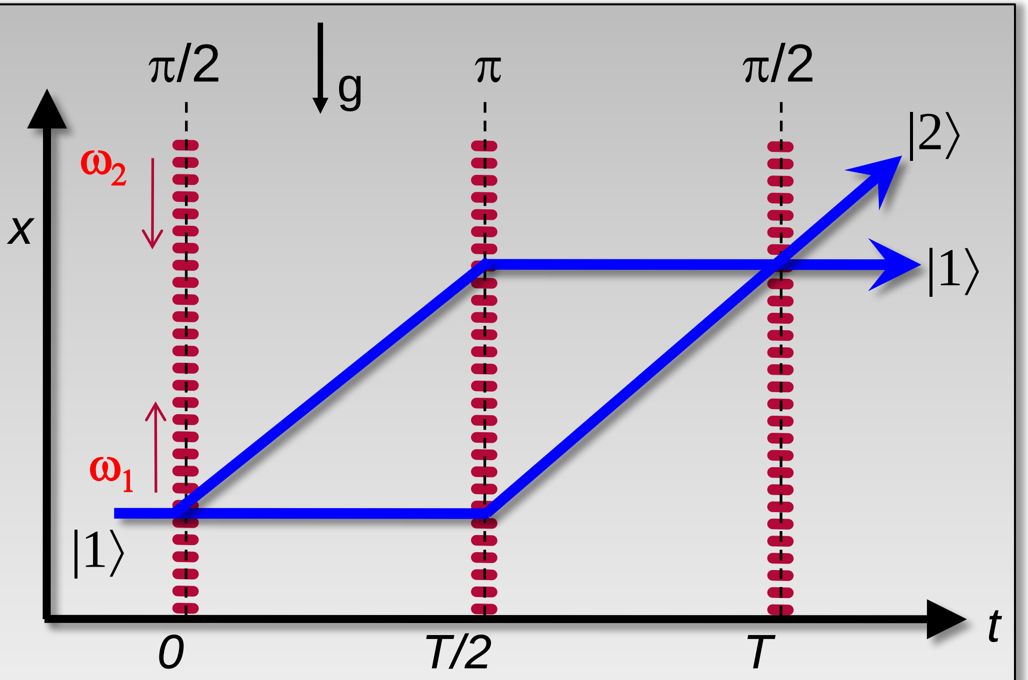
Atom Interferometer

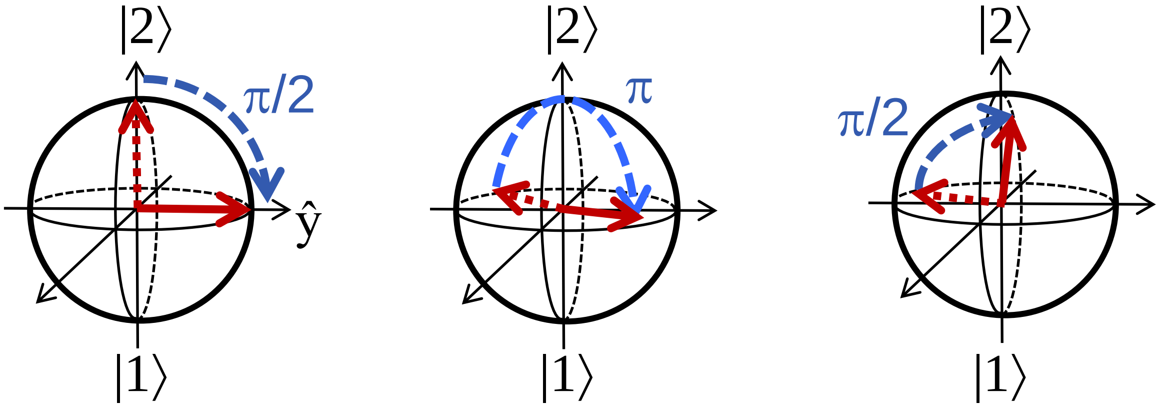
Davis & Narducci, ***JMO*** *55 3173 (2008)*

Zhou et al. ***PRA*** *82 061602 (2010)*

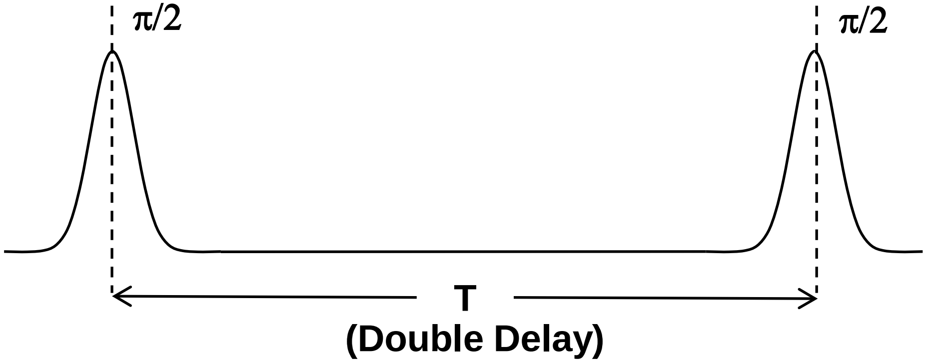
$$\Delta\phi = -\left(\vec{k}_1 - \vec{k}_2\right) g T^2 + \frac{\mu_B}{\hbar}\left(g_{F'} m_{F'} - g_F m_F\right)\left[\int_0^{T/2} B(t)\partial t - \int_{T/2}^{T} B(t)\partial t\right]$$

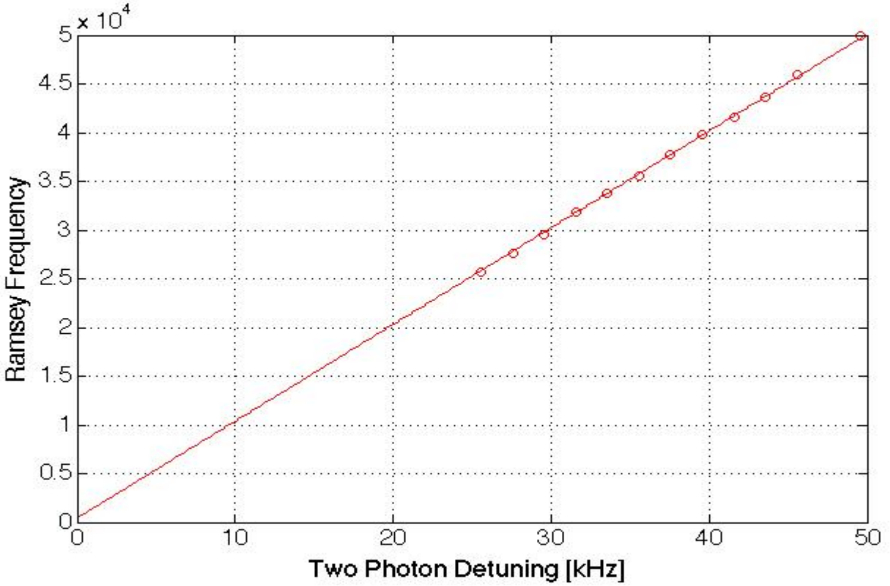


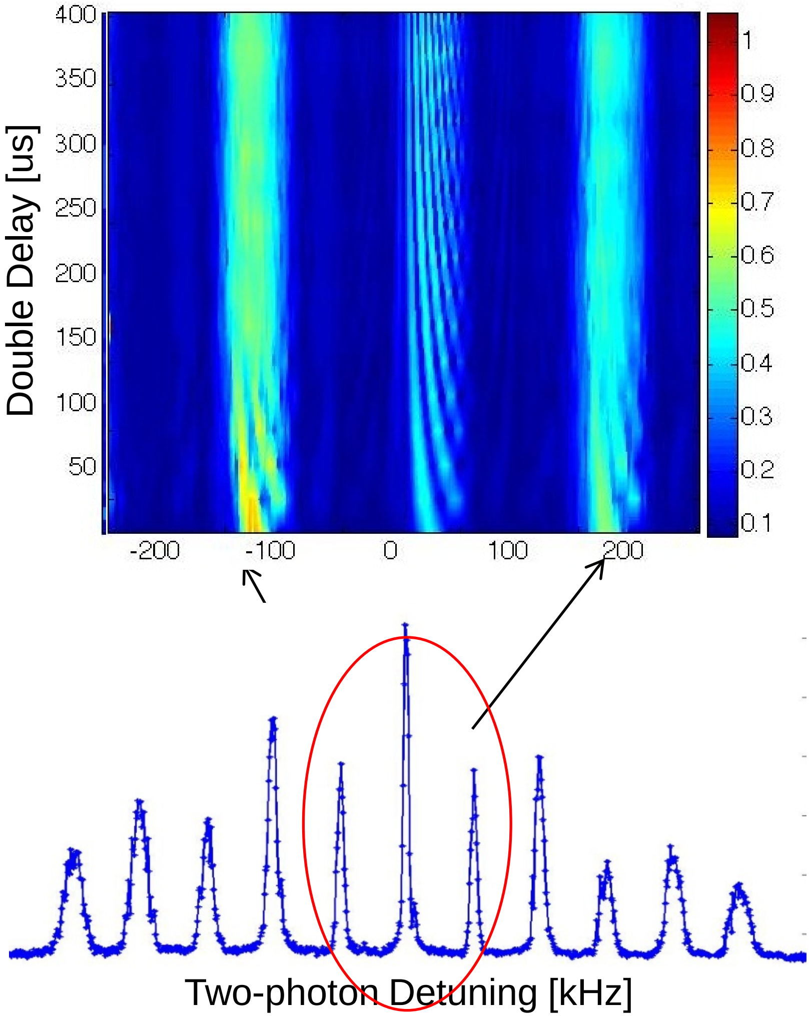




Magnetically sensitive Ramsey interferometer

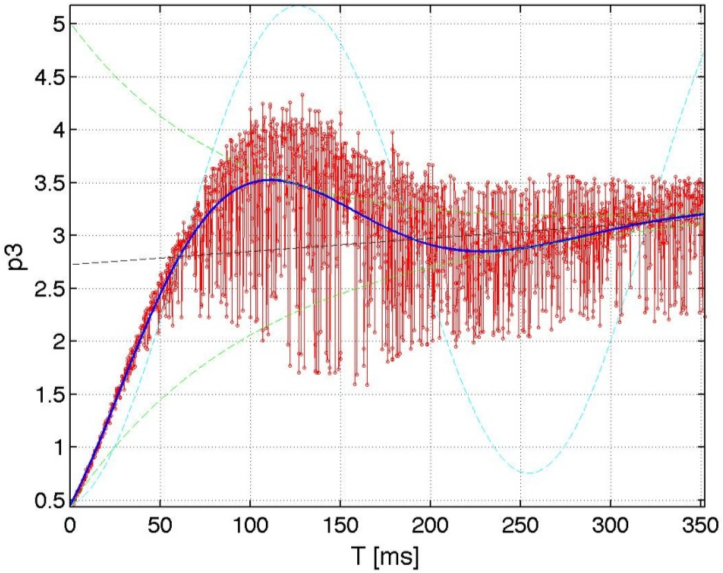






Atom Interferometer Magnetometer

- **Rabi flopping in a magnetically noisy environment:**



Sensitivity

$$\Delta\phi = -\frac{\mu_B}{\hbar}\left(m_{F'}g_{F'} - m_F g_F\right)\frac{dB(r_o)}{dr}\Delta r T$$

$$\sigma_\phi = \frac{1}{C}\sqrt{\frac{1}{N}}$$

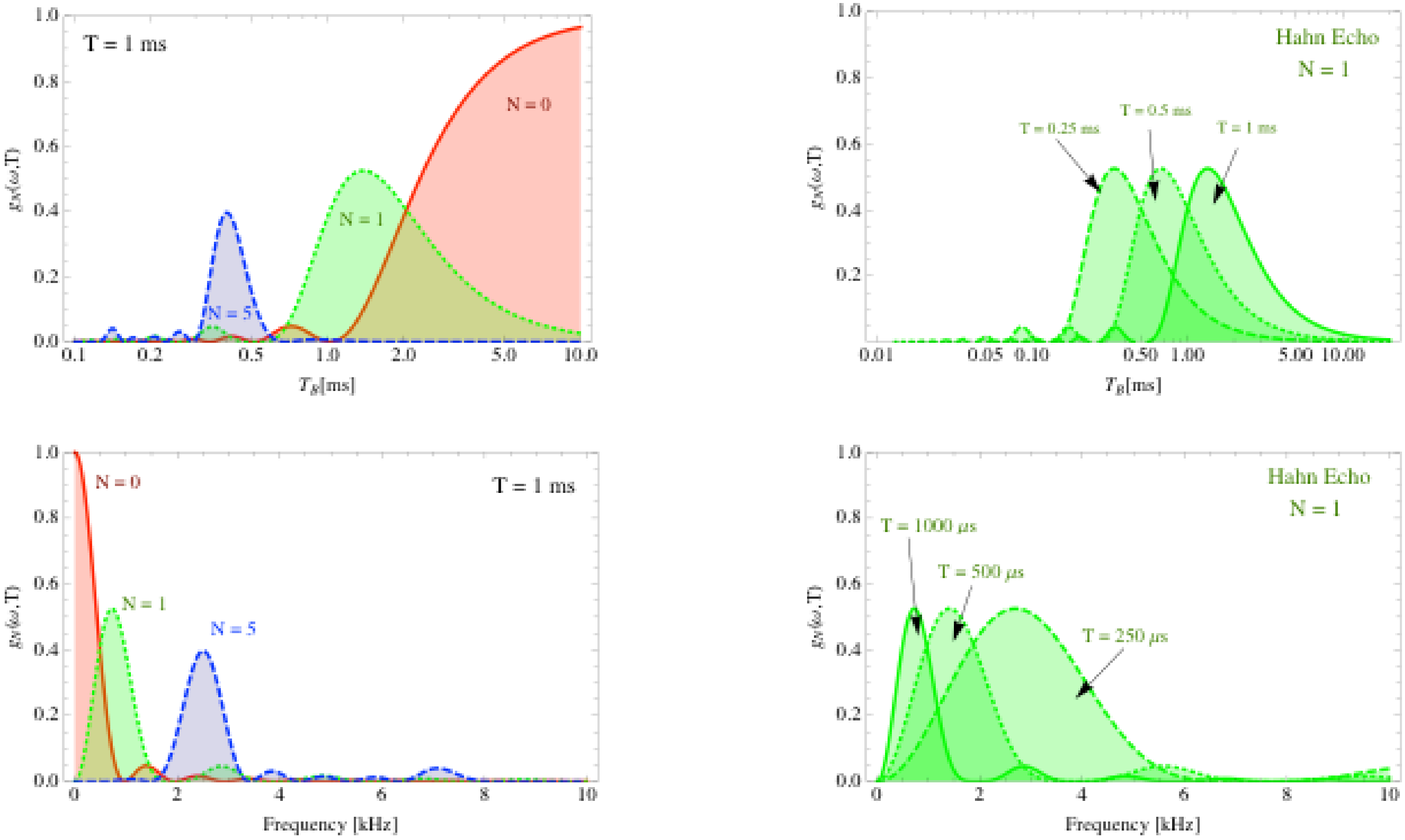
For SNR=1 we have $\sigma_\phi = \Delta\phi$

$$\left(\frac{dB}{dr}\right)_{min} = \frac{1}{C\sqrt{N}}\cdot\frac{1}{\mu_B/\hbar}\cdot\frac{1}{(m_{F'}g_{F'} - m_F g_F)}\cdot\frac{1}{\mathrm{v}T^2}$$

$$= \frac{2}{\sqrt{10^9}}\cdot\frac{1G}{8.8\times 10^6\ Hz}\cdot\frac{1T}{10^4 G}\cdot\frac{1}{2/3}\cdot\frac{1}{(50\ m/s)(10^{-2}\ sec)^2}$$

$$= \quad .2pT/m$$

Filter Functions Time / Frequency Domain

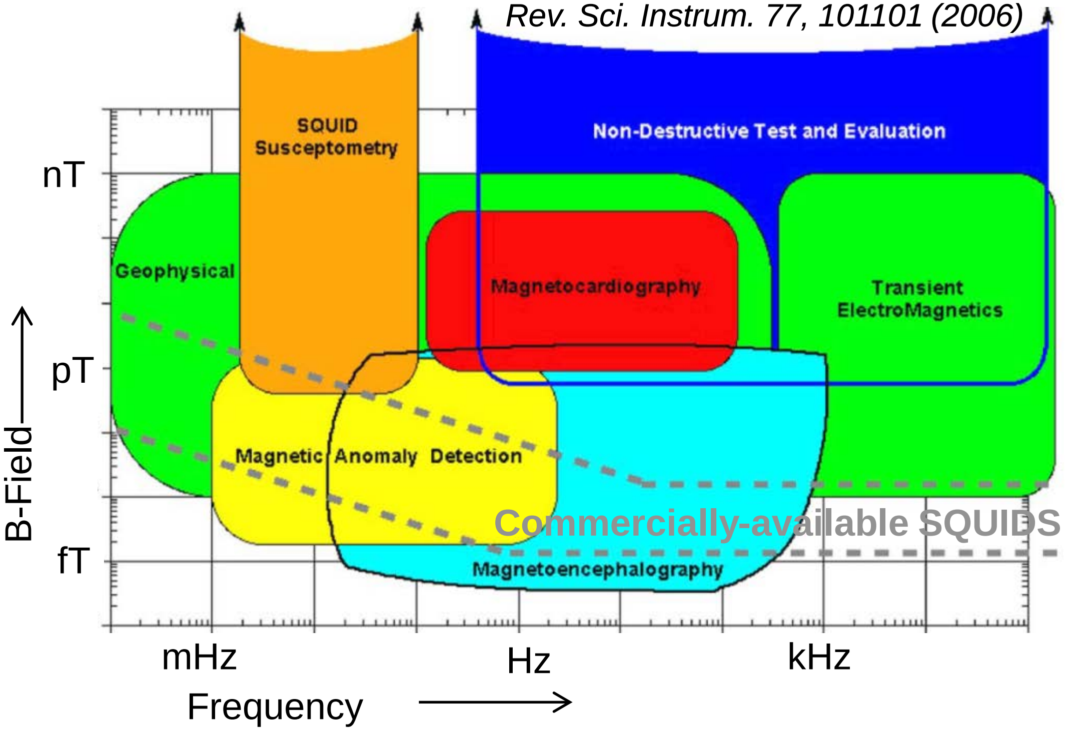


Keep Sensitivity; Design Around the Noise

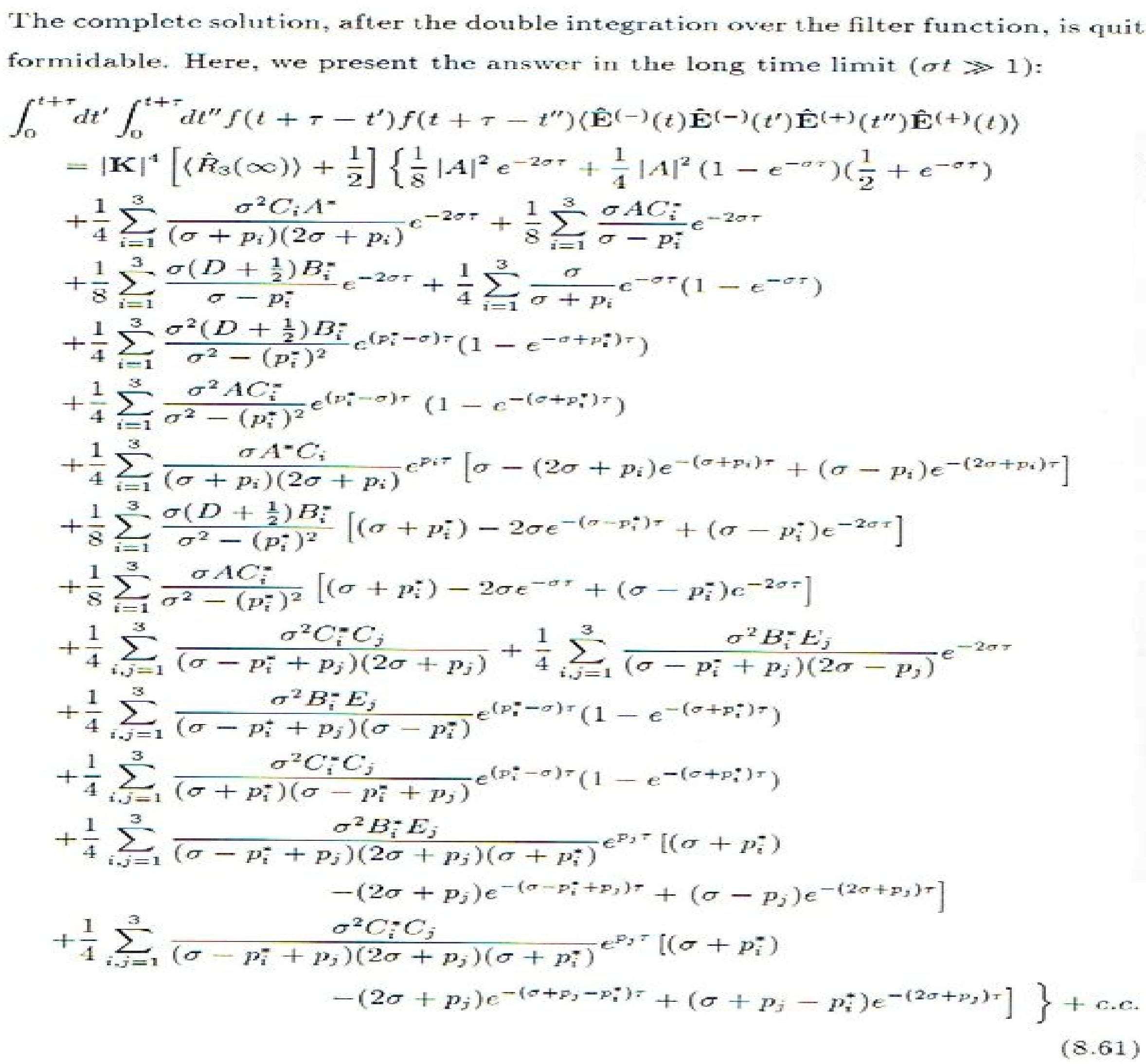
Cannot remove magnetic noise in remote sensing

1. Filter out of band noise
2. Measure magnetic field gradient

   (Gradients used for object location)



Homecoming



The complete solution, after the double integration over the filter function, is quite formidable. Here, we present the answer in the long time limit ($\sigma t \gg 1$):

$$
\begin{aligned}
&\int_0^{t+\tau} dt' \int_0^{t+\tau} dt'' f(t+\tau-t') f(t+\tau-t'') \langle \hat{\mathbf{E}}^{(-)}(t) \hat{\mathbf{E}}^{(-)}(t') \hat{\mathbf{E}}^{(+)}(t'') \hat{\mathbf{E}}^{(+)}(t) \rangle \\
&\quad = |\mathbf{K}|^4 \left[\langle \hat{R}_3(\infty) \rangle + \frac{1}{2} \right] \left\{ \frac{1}{8} |A|^2 e^{-2\sigma\tau} + \frac{1}{4} |A|^2 (1 - e^{-\sigma\tau})(\frac{1}{2} + e^{-\sigma\tau}) \right. \\
&\quad + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma^2 C_i A^*}{(\sigma + p_i)(2\sigma + p_i)} e^{-2\sigma\tau} + \frac{1}{8} \sum_{i=1}^{3} \frac{\sigma A C_i^*}{\sigma - p_i^*} e^{-2\sigma\tau} \\
&\quad + \frac{1}{8} \sum_{i=1}^{3} \frac{\sigma (D + \frac{1}{2}) B_i^*}{\sigma - p_i^*} e^{-2\sigma\tau} + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma}{\sigma + p_i} e^{-\sigma\tau} (1 - e^{-\sigma\tau}) \\
&\quad + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma^2 (D + \frac{1}{2}) B_i^*}{\sigma^2 - (p_i^*)^2} e^{(p_i^* - \sigma)\tau} (1 - e^{-\sigma + p_i^*)\tau}) \\
&\quad + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma^2 A C_i^*}{\sigma^2 - (p_i^*)^2} e^{(p_i^* - \sigma)\tau} (1 - e^{-(\sigma + p_i^*)\tau}) \\
&\quad + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma A^* C_i}{(\sigma + p_i)(2\sigma + p_i)} e^{p_i \tau} \left[\sigma - (2\sigma + p_i) e^{-(\sigma + p_i)\tau} + (\sigma - p_i) e^{-(2\sigma + p_i)\tau} \right] \\
&\quad + \frac{1}{8} \sum_{i=1}^{3} \frac{\sigma (D + \frac{1}{2}) B_i^*}{\sigma^2 - (p_i^*)^2} \left[(\sigma + p_i^*) - 2\sigma e^{-(\sigma - p_i^*)\tau} + (\sigma - p_i^*) e^{-2\sigma\tau} \right] \\
&\quad + \frac{1}{8} \sum_{i=1}^{3} \frac{\sigma A C_i^*}{\sigma^2 - (p_i^*)^2} \left[(\sigma + p_i^*) - 2\sigma e^{-\sigma\tau} + (\sigma - p_i^*) e^{-2\sigma\tau} \right] \\
&\quad + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 C_i^* C_j}{(\sigma - p_i^* + p_j)(2\sigma + p_j)} + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 B_i^* E_j}{(\sigma - p_i^* + p_j)(2\sigma - p_j)} e^{-2\sigma\tau} \\
&\quad + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 B_i^* E_j}{(\sigma - p_i^* + p_j)(\sigma - p_i^*)} e^{(p_i^* - \sigma)\tau} (1 - e^{-(\sigma + p_i^*)\tau}) \\
&\quad + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 C_i^* C_j}{(\sigma + p_i^*)(\sigma - p_i^* + p_j)} e^{(p_i^* - \sigma)\tau} (1 - e^{-(\sigma + p_i^*)\tau}) \\
&\quad + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 B_i^* E_j}{(\sigma - p_i^* + p_j)(2\sigma + p_j)(\sigma + p_i^*)} e^{p_j \tau} \left[(\sigma + p_i^*) \right. \\
&\qquad\qquad \left. - (2\sigma + p_j) e^{-(\sigma - p_i^* + p_j)\tau} + (\sigma - p_j) e^{-(2\sigma + p_j)\tau} \right] \\
&\quad + \frac{1}{4} \sum_{i,j=1}^{3} \frac{\sigma^2 C_i^* C_j}{(\sigma - p_i^* + p_j)(2\sigma + p_j)(\sigma + p_i^*)} e^{p_j \tau} \left[(\sigma + p_i^*) \right. \\
&\qquad\qquad \left. \left. - (2\sigma + p_j) e^{-(\sigma + p_j - p_i^*)\tau} + (\sigma + p_j - p_i^*) e^{-(2\sigma + p_j)\tau} \right] \right\} + \text{c.c.}
\end{aligned}
\tag{8.61}
$$

Leonard Mandel
1927-2001

Photo courtesy J. Mandel

17 years later

Bulletin of the American Physical Society

2013 Joint Meeting of the APS Division of Atomic, Molecular & Optical Physics and the CAP Division of Atomic, Molecular & Optical Physics, Canada
Volume 58, Number 6

Monday–Friday, June 3–7, 2013; Quebec City, Canada

Session K1: Poster Session II (4:00 - 6:00PM)
4:00 PM–4:00 PM, Wednesday, June 5, 2013
Room: 400A

Abstract: K1.00030 : Optical Coherence of the Fluorescence of a Driven Single-Atom with Slow and Fast Light Media

Authors:

Tony Abi-Salloum
(Physics and Astronomy Dept. Widener University, Chester, Pa. 19013)

Jon Davis
(Naval Air Systems Command, Patuxent River, Md. 20670)

Frank Narducci
(Naval Air Systems Command, Patuxent River, Md. 20670)

Other experiments-then

“…could be interesting. But it’s not fundamental enough”

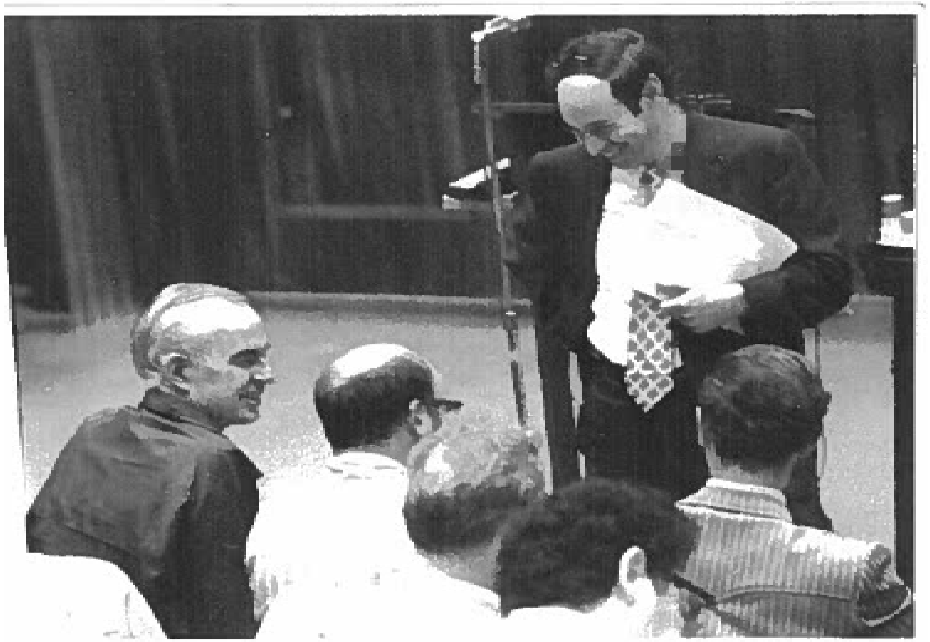
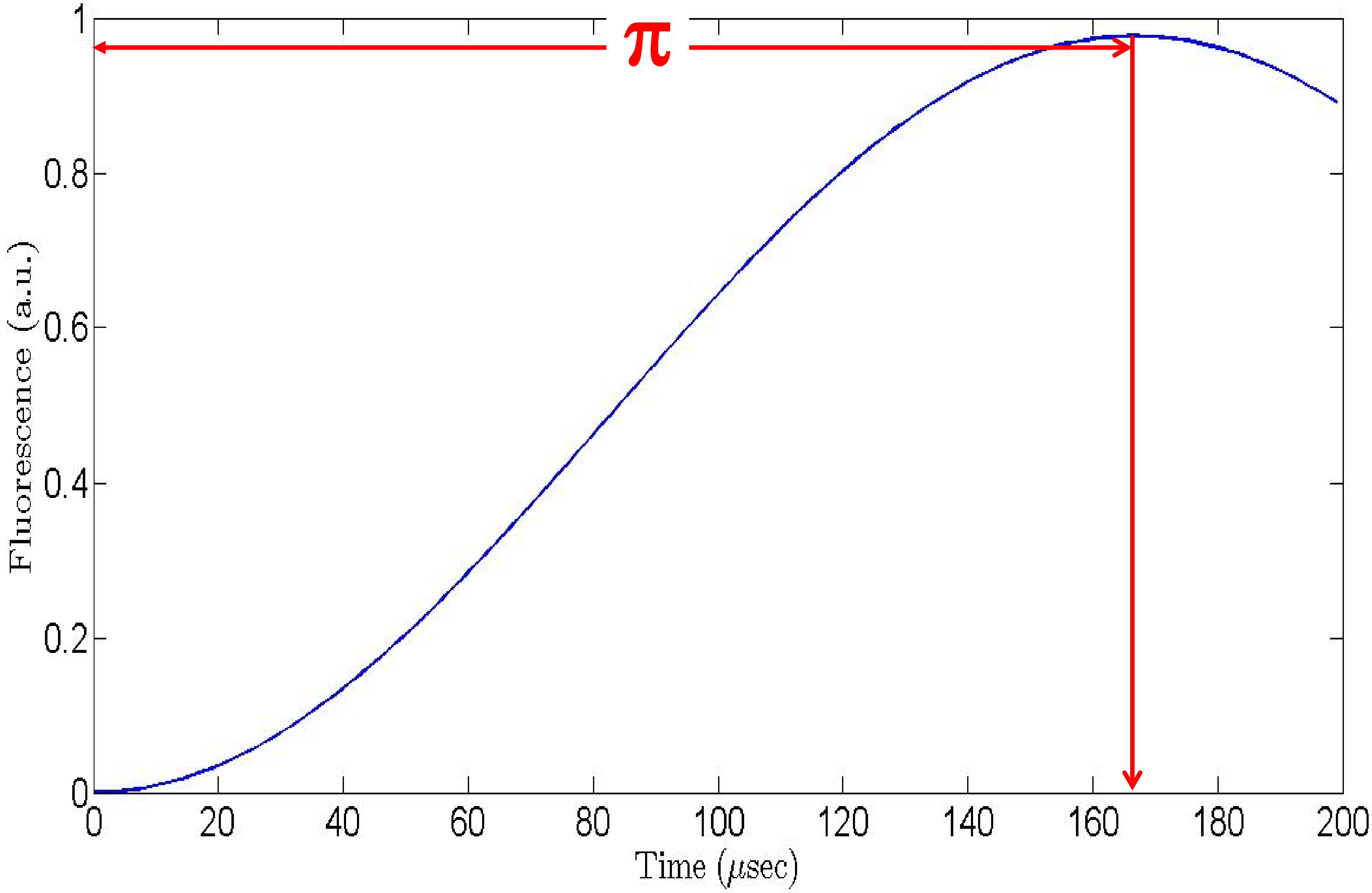


Photo courtesy J. Mandel

Leonard Mandel
1927-2001

Definition of π pulse



Definition of π/2 pulse