Photonic Magnetometry at a (Short) Distance

Chris Sataline

IEEE Reliability Boston Section

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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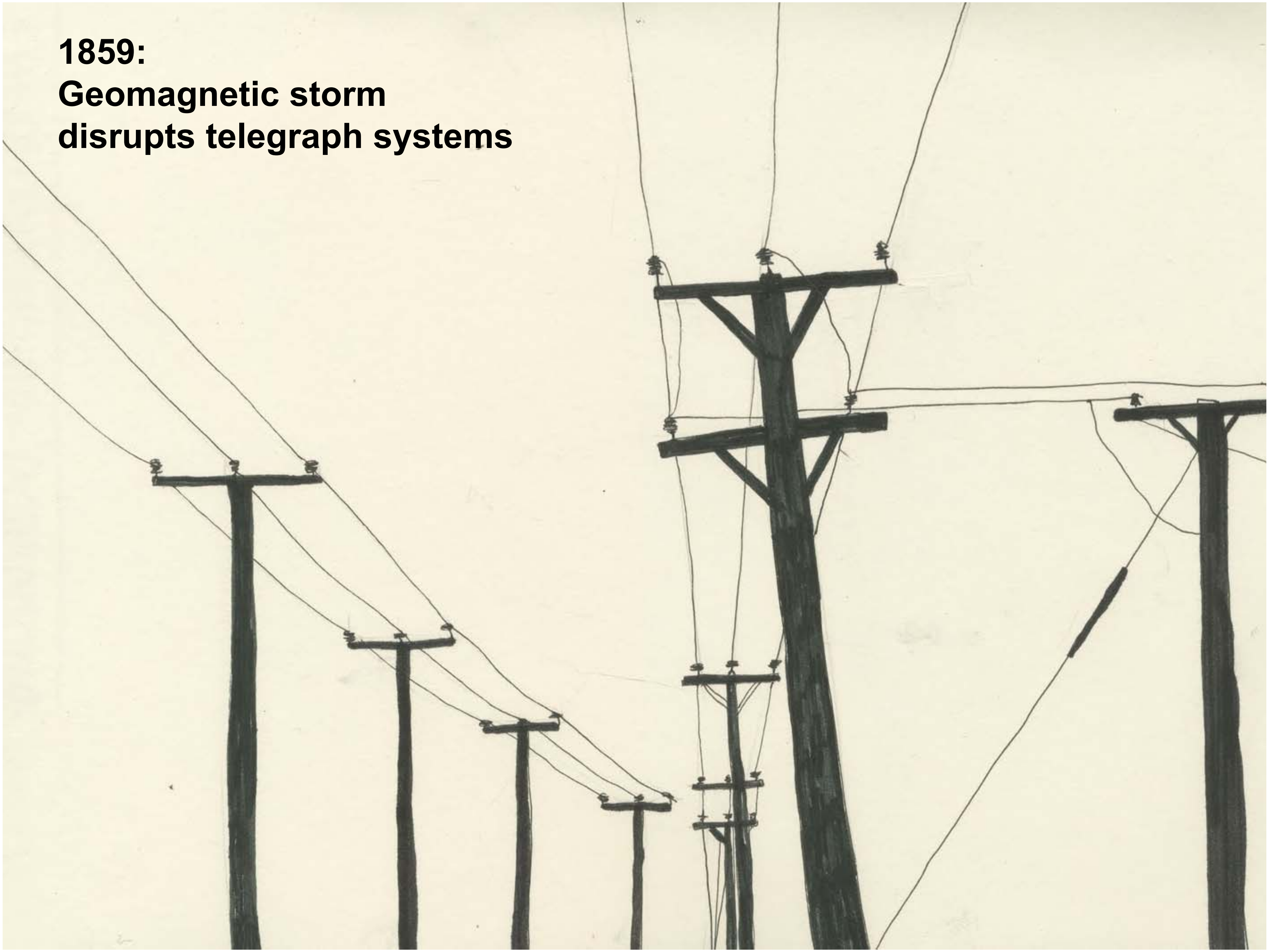

1859:
Geomagnetic storm
disrupts telegraph systems

Space Weather Events

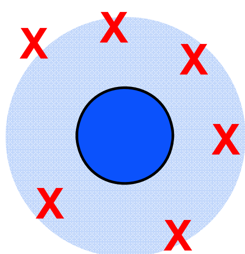
- 1859: Geomagnetic storm takes down telegraph system
- 1972: Lethal doses of energetic particles detected
- 1989: Hydro-Quebec transformer damage takes down Quebec power grid for nine hours (cost: $10M)
- 1997: Coronal mass ejection permanently damages AT&T satellite with estimated cost of $200M

Space weather can damage technology

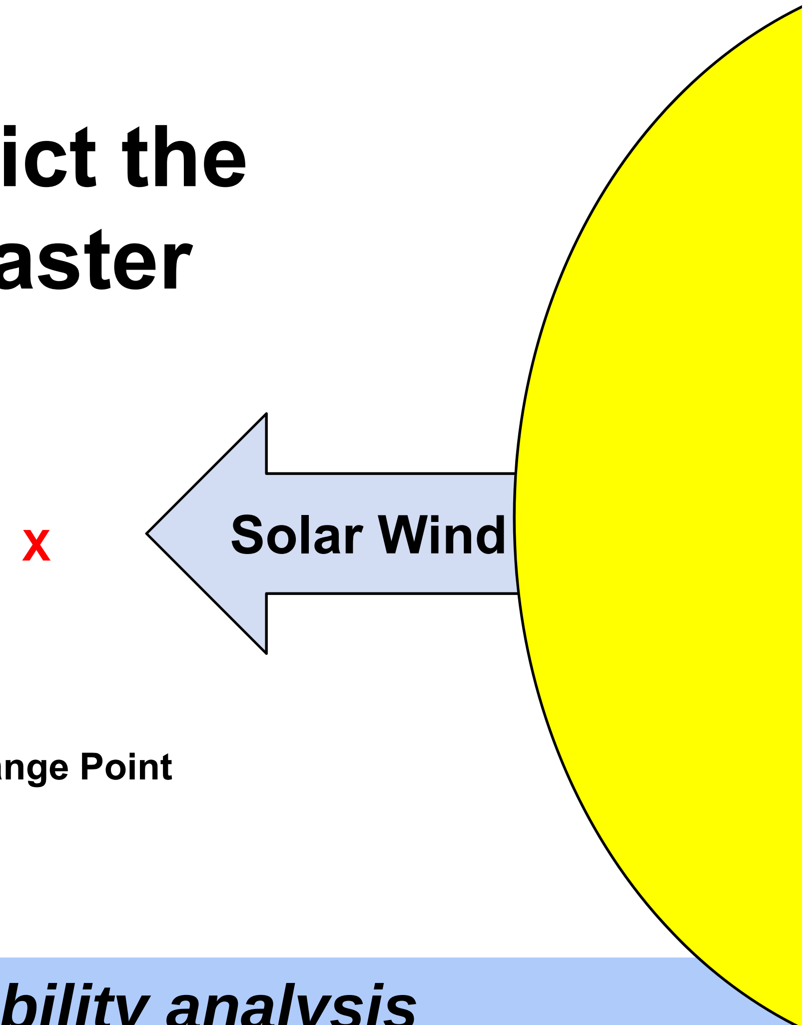
http://en.wikipedia.org/wiki/Space_weather#Examples_of_space_weather_events

Purpose of Space-borne Magnetometry

Understand the interaction



Predict the disaster



Magnetometry aids reliability analysis

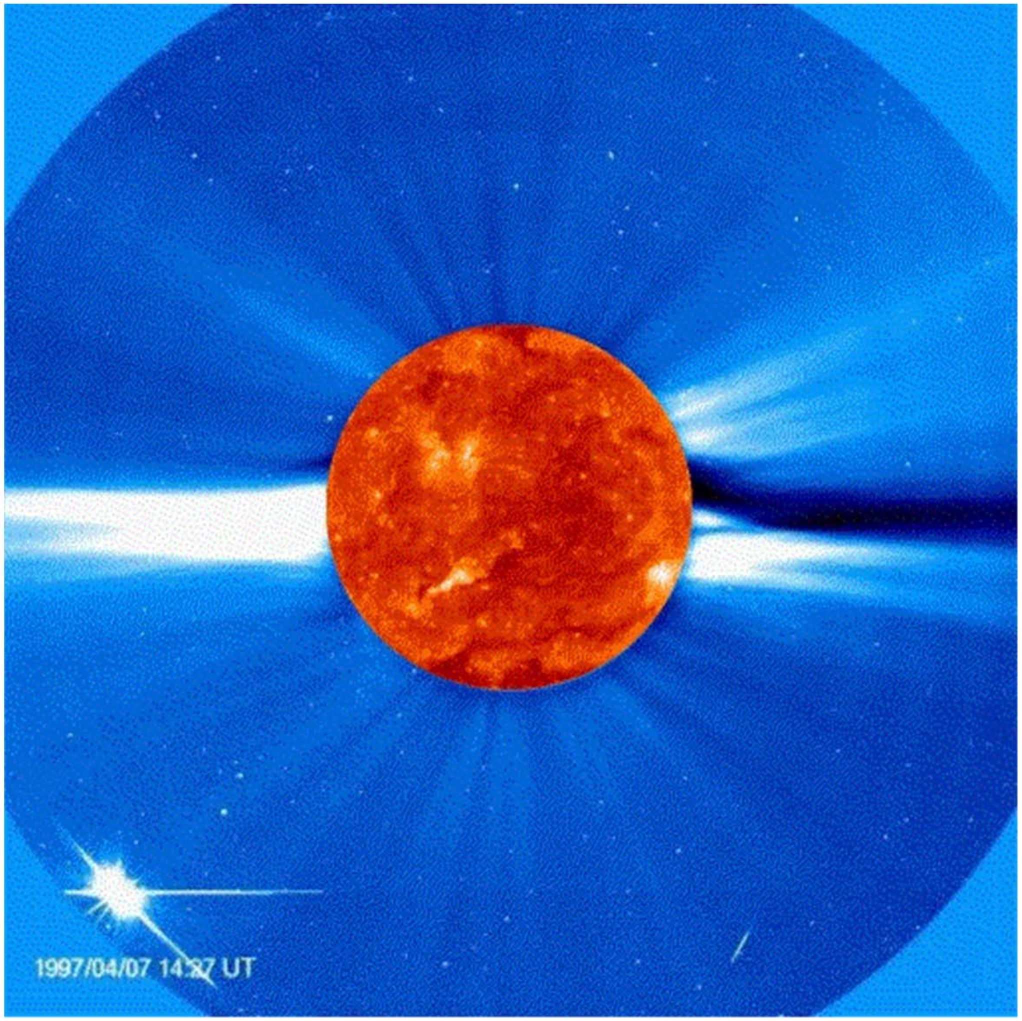
X: Satellite magnetometers

Satellite Death

- Atmospheric drag
- Single event upset
- Differential charging
- Bulk charging

Coronal Mass Ejection (CME)

Earth



X

X: GOES-07

Space Weather Measurements: 1989 geomagnetic storm

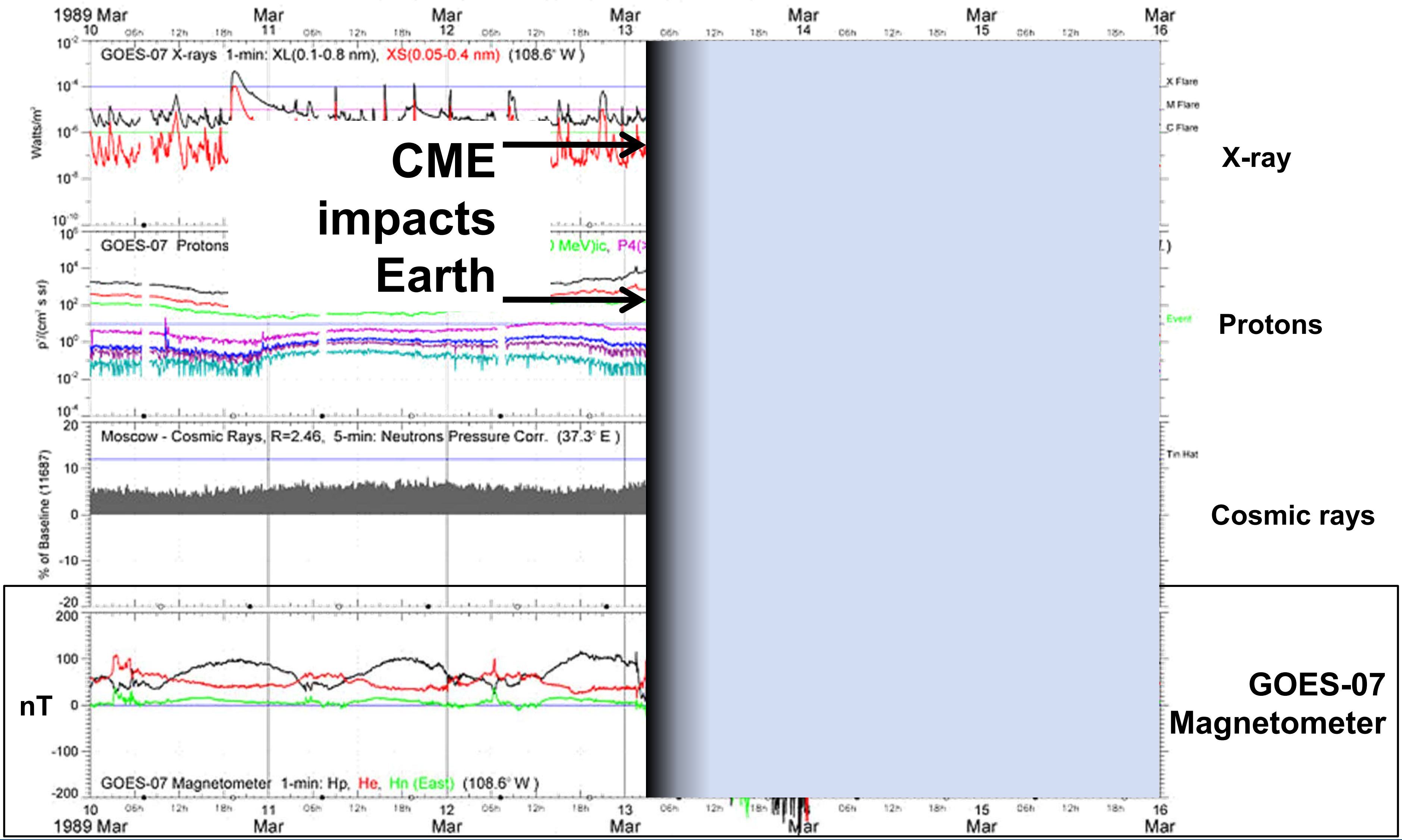
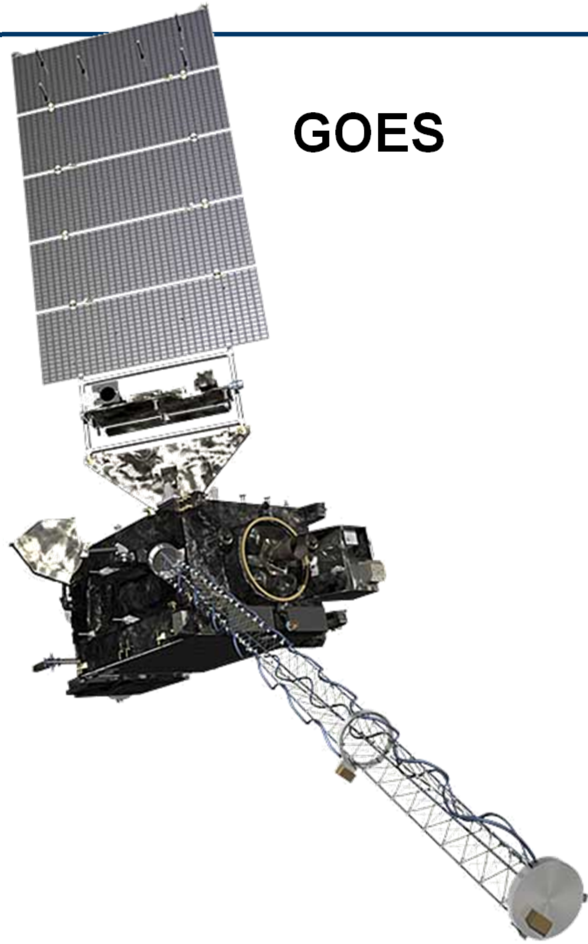
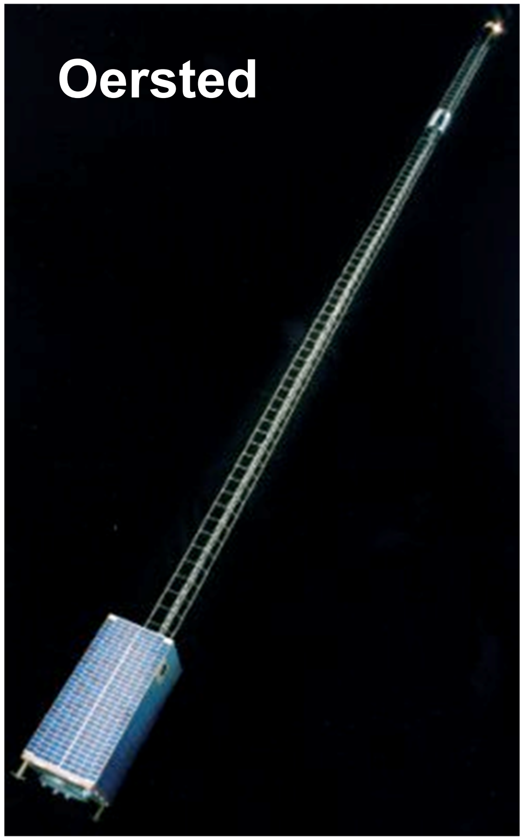


Image: http://en.wikipedia.org/wiki/File:ExtremeEvent_19890310-00h_19890315-24h.jpg

Space Weather Science

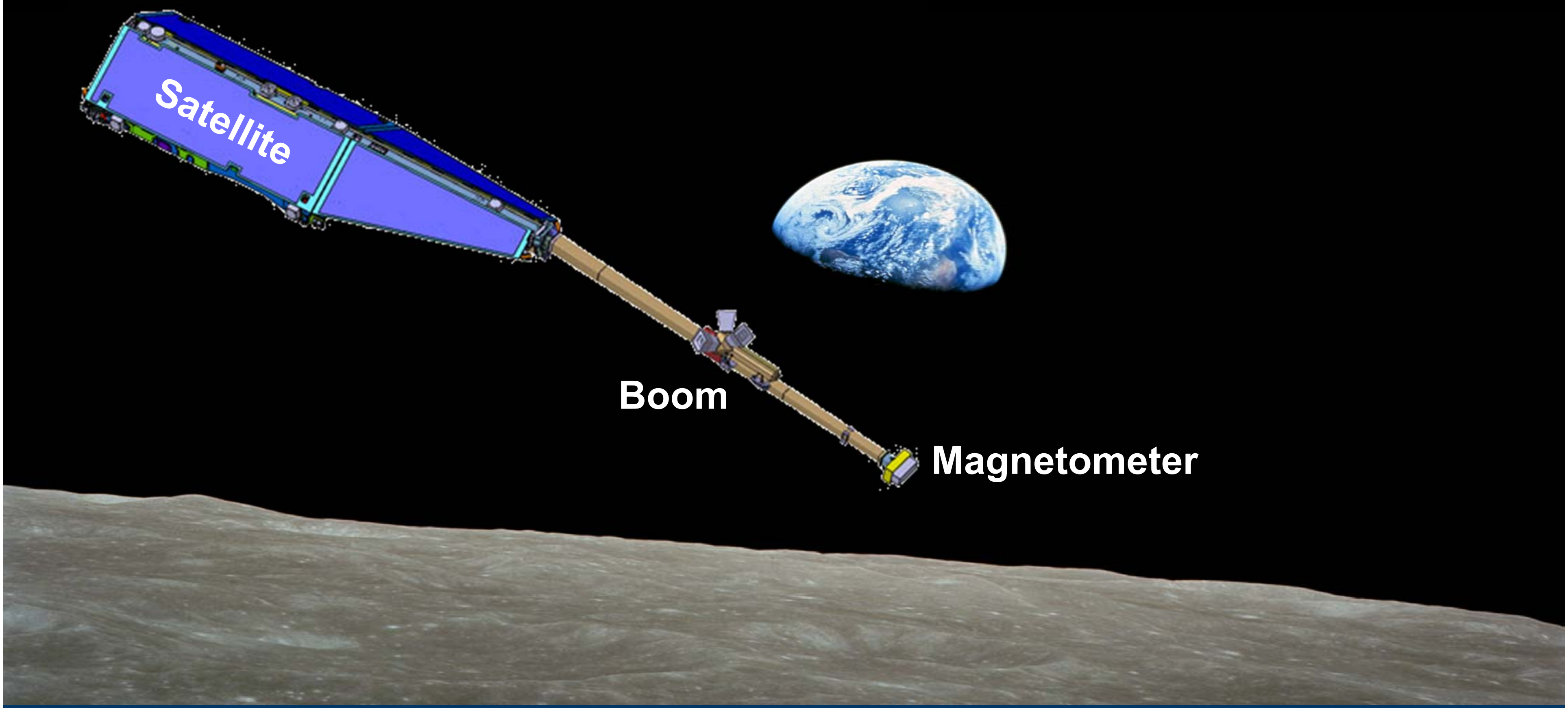




Understanding space weather critical to satellite performance & survival

System Concept

Satellite electromagnetic systems contaminate magnetic field measurement



System Concept

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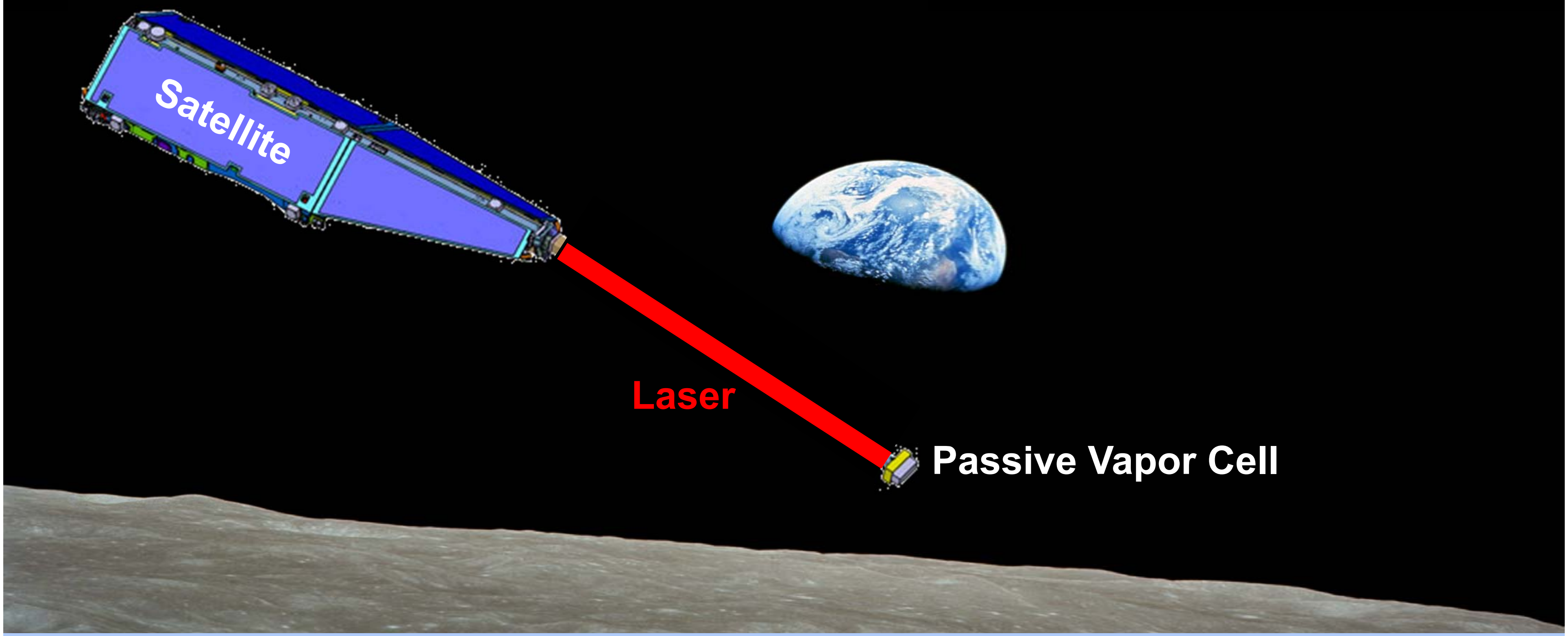
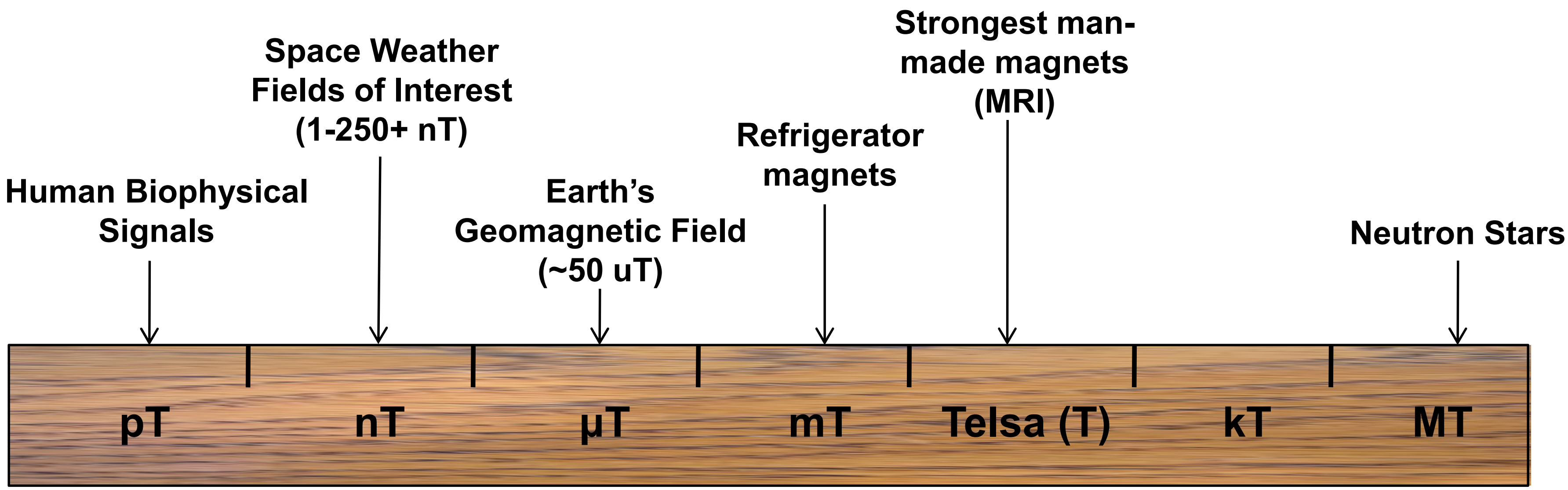


Eliminate isolating boom. Interrogate passive magnetic sensor by laser.

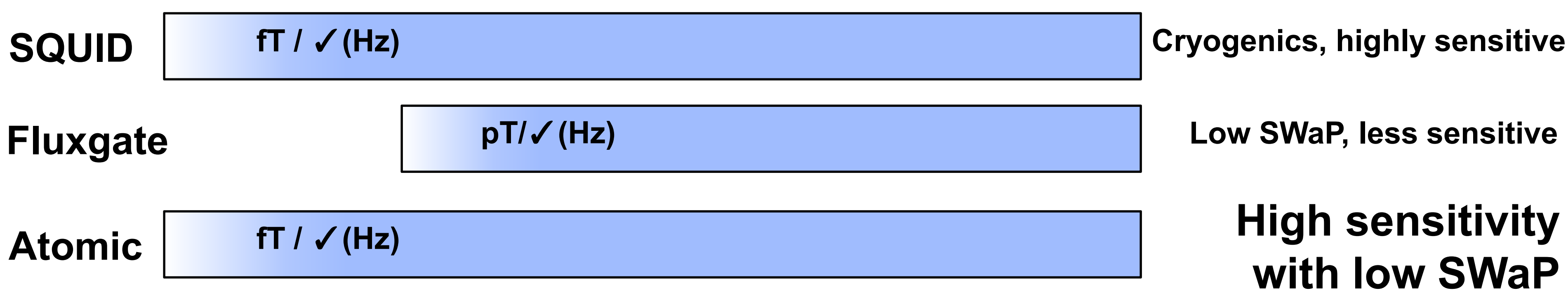
Outline

- Introduction
- **Background Material**
- Experimental
- Results
- Summary

Magnetic Yardstick

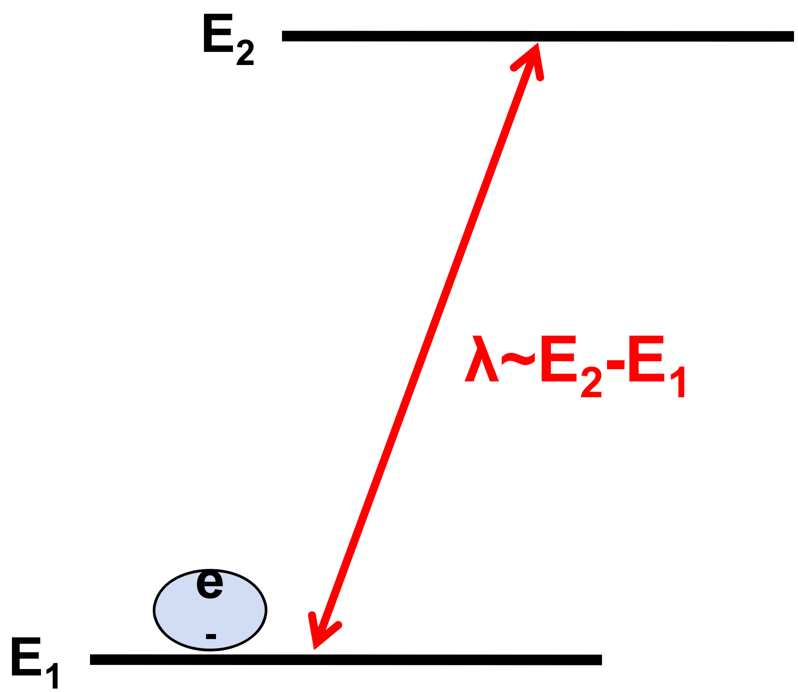


***Magnetometers*:**



Crash Course in Quantum Optics
("Semester in a slide")

Rabi Oscillation



Resonant oscillating electromagnetic field (laser) affects atomic electron distributions

Von Neumann/Liouville Equation

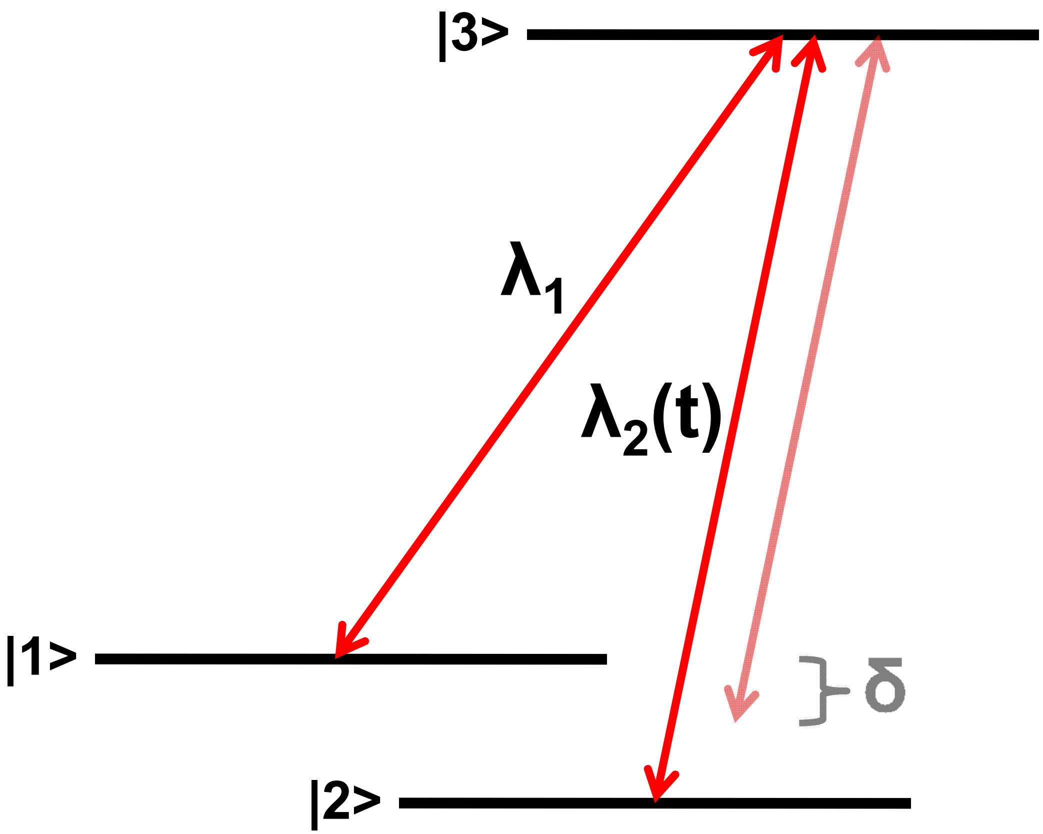
$$i\hbar\dot{\rho} = [H, \rho]$$

$$H = H_{atom} + H_{laser}$$

$$\rho = \text{probability density matrix}$$

Atomic populations evolve according to Hamiltonian

Coherent Population Trapping (CPT)



- Laser lines resonant with two atomic transitions
  - Rabi oscillation
  - Electrons pumped into dark state
  - Dark state: not resonant with either lase field
  - Decrease in atomic absorption
- Sweep λ_2 (sideband) through resonance
  - Absorption varies versus RF sideband frequency

- FM laser spectroscopy

Coherent population trapping produces narrow optical (two-photon) resonances

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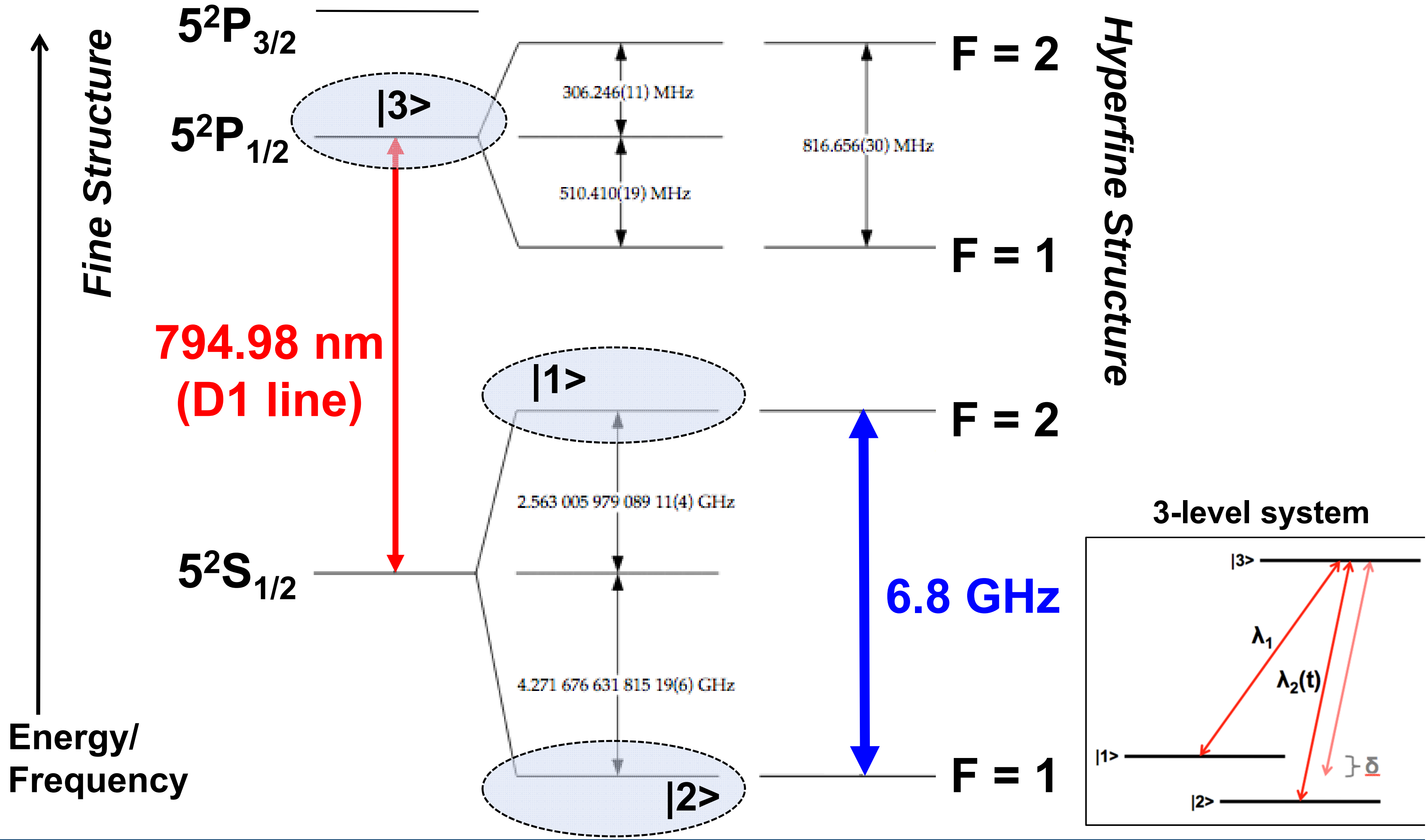
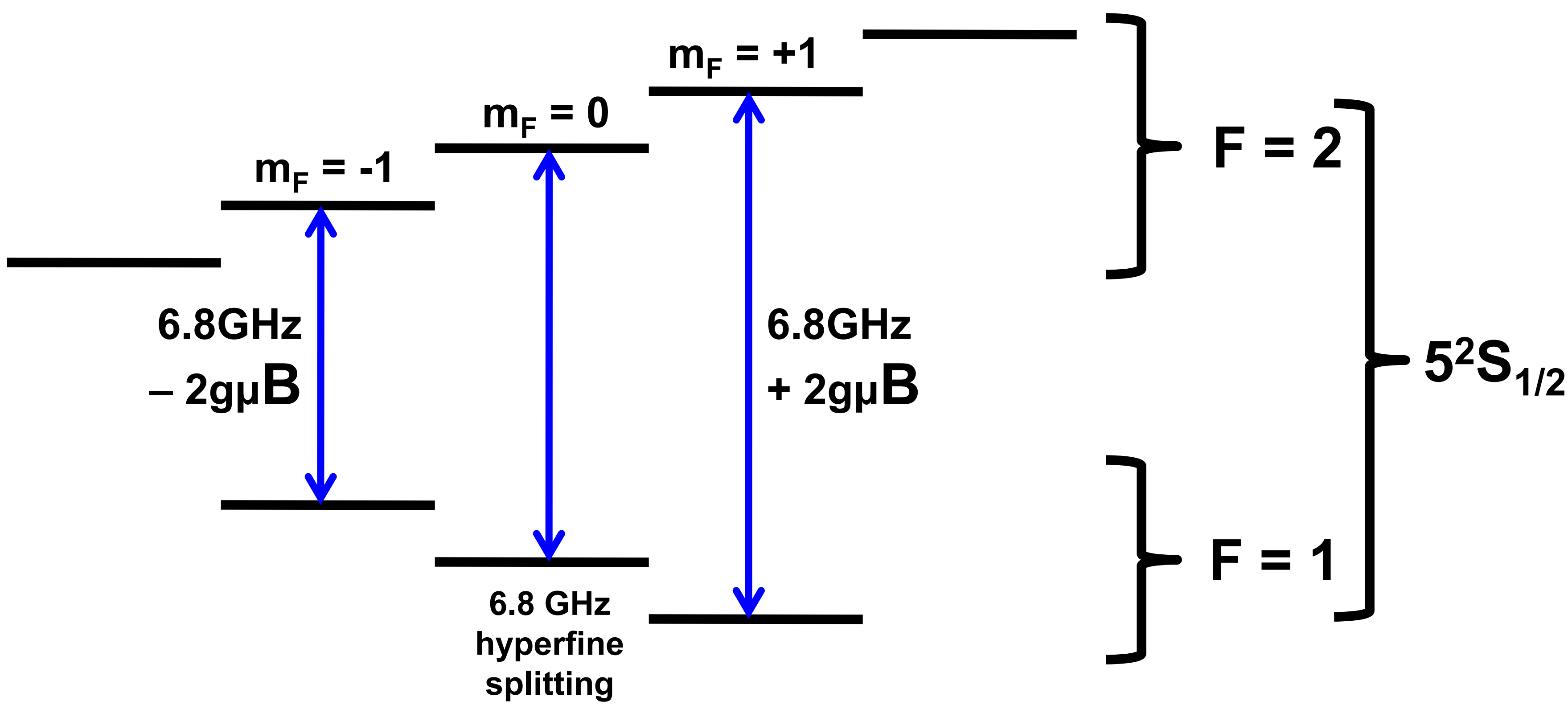
Rubidium-87 Atomic Transitions

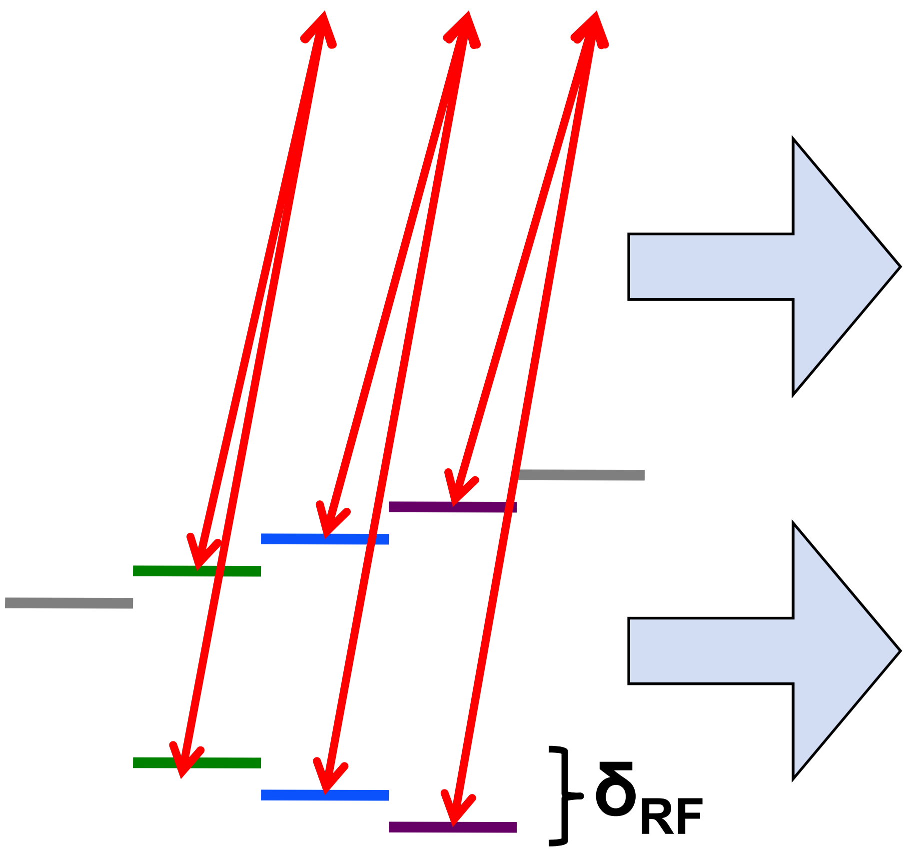


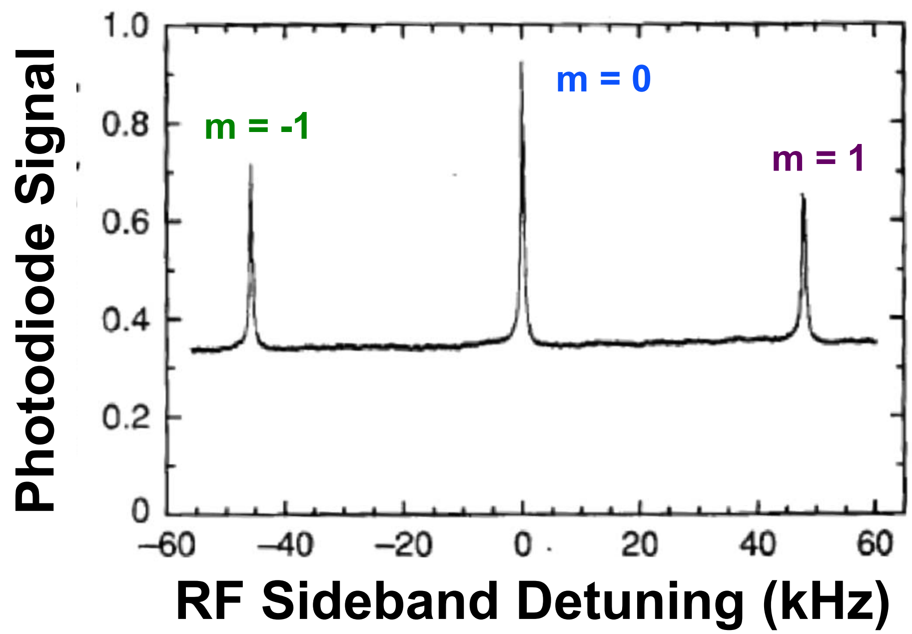
Zeeman Splitting

- **Hyperfine levels contain 2F+1 magnetic sublevels**
- ***Zeeman sublevels shift in external magnetic field***



CPT Magnetometry





Change in magnetic field causes coherent population trapping dark state at different sideband separation

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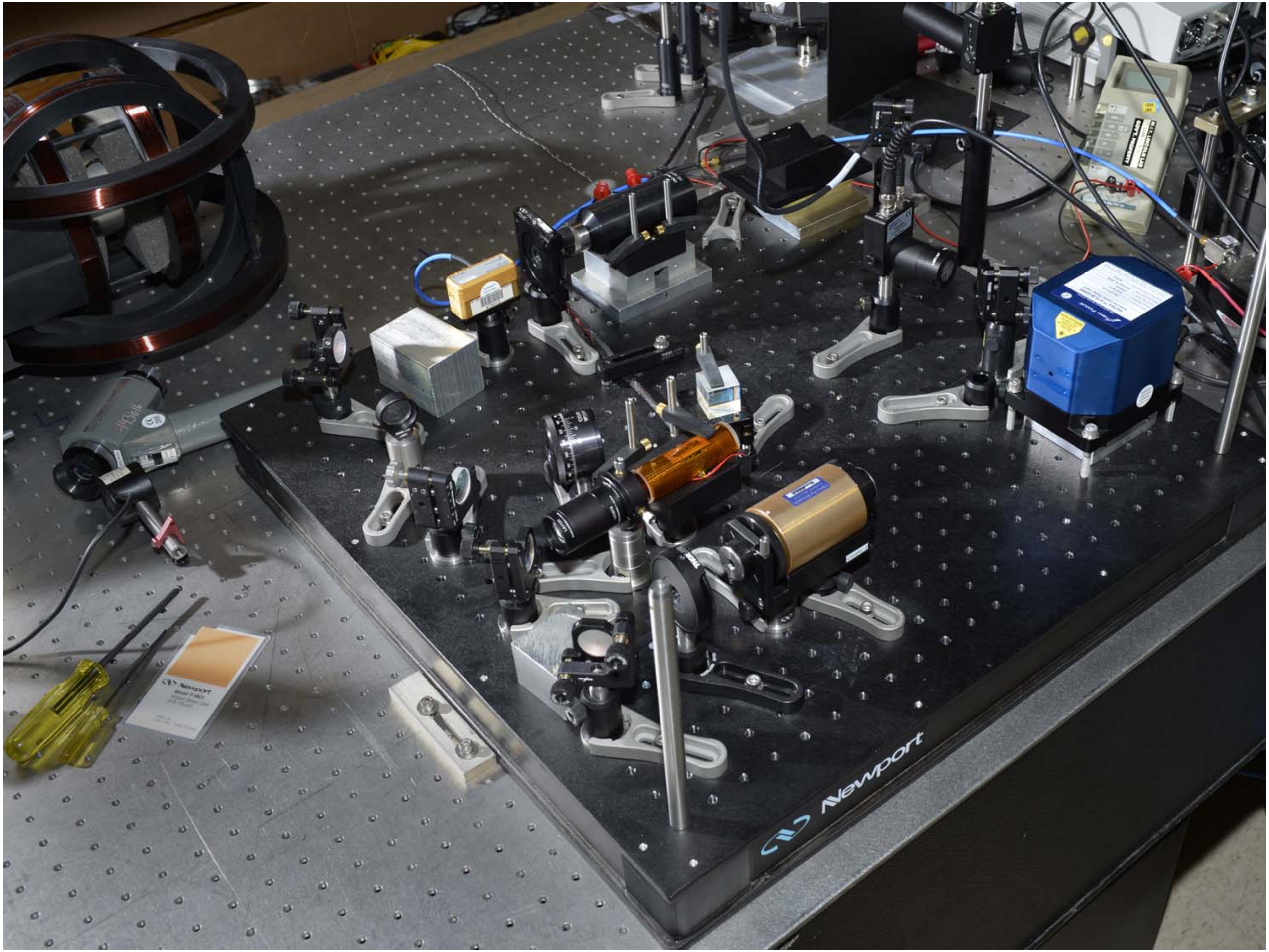
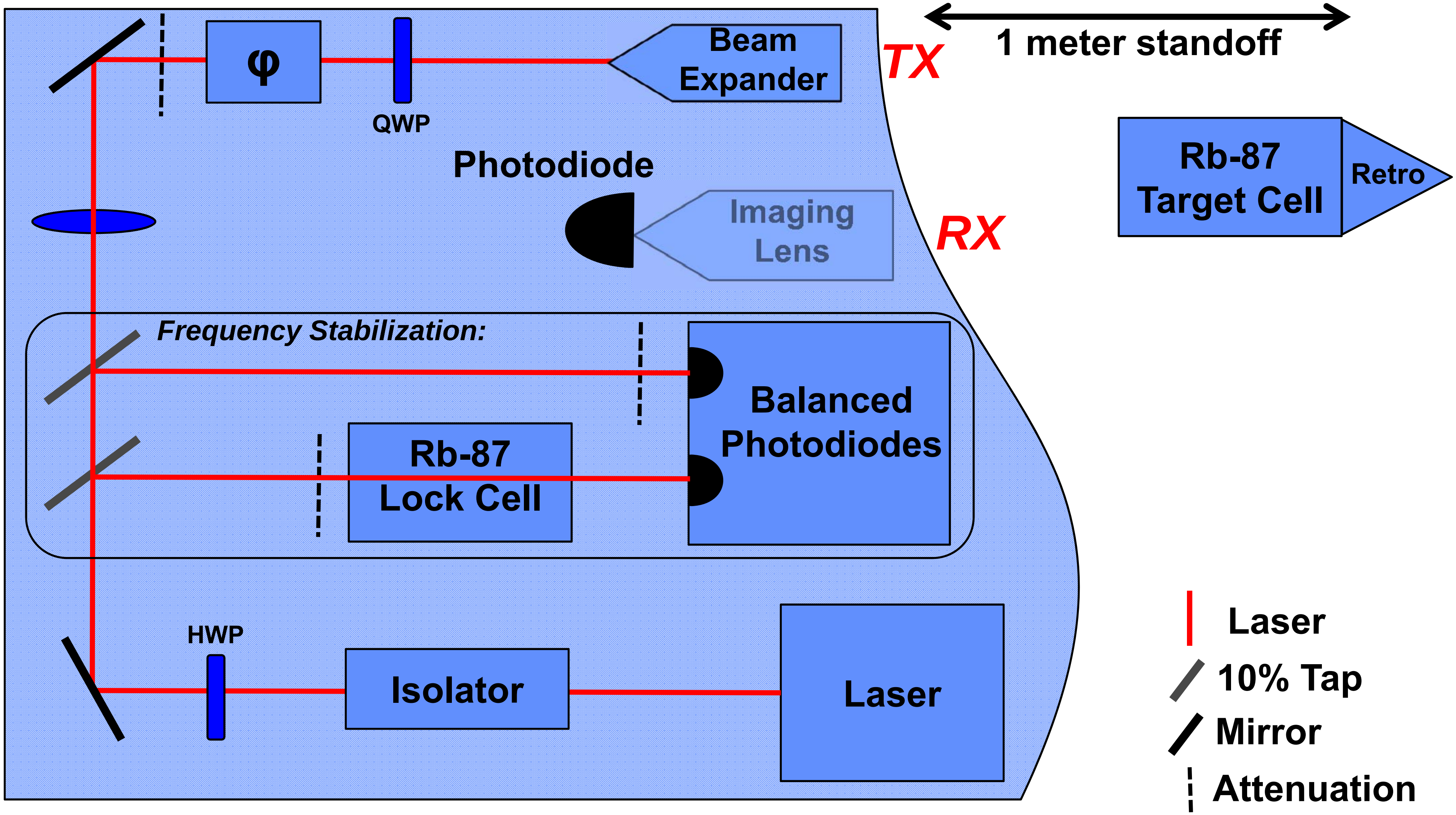
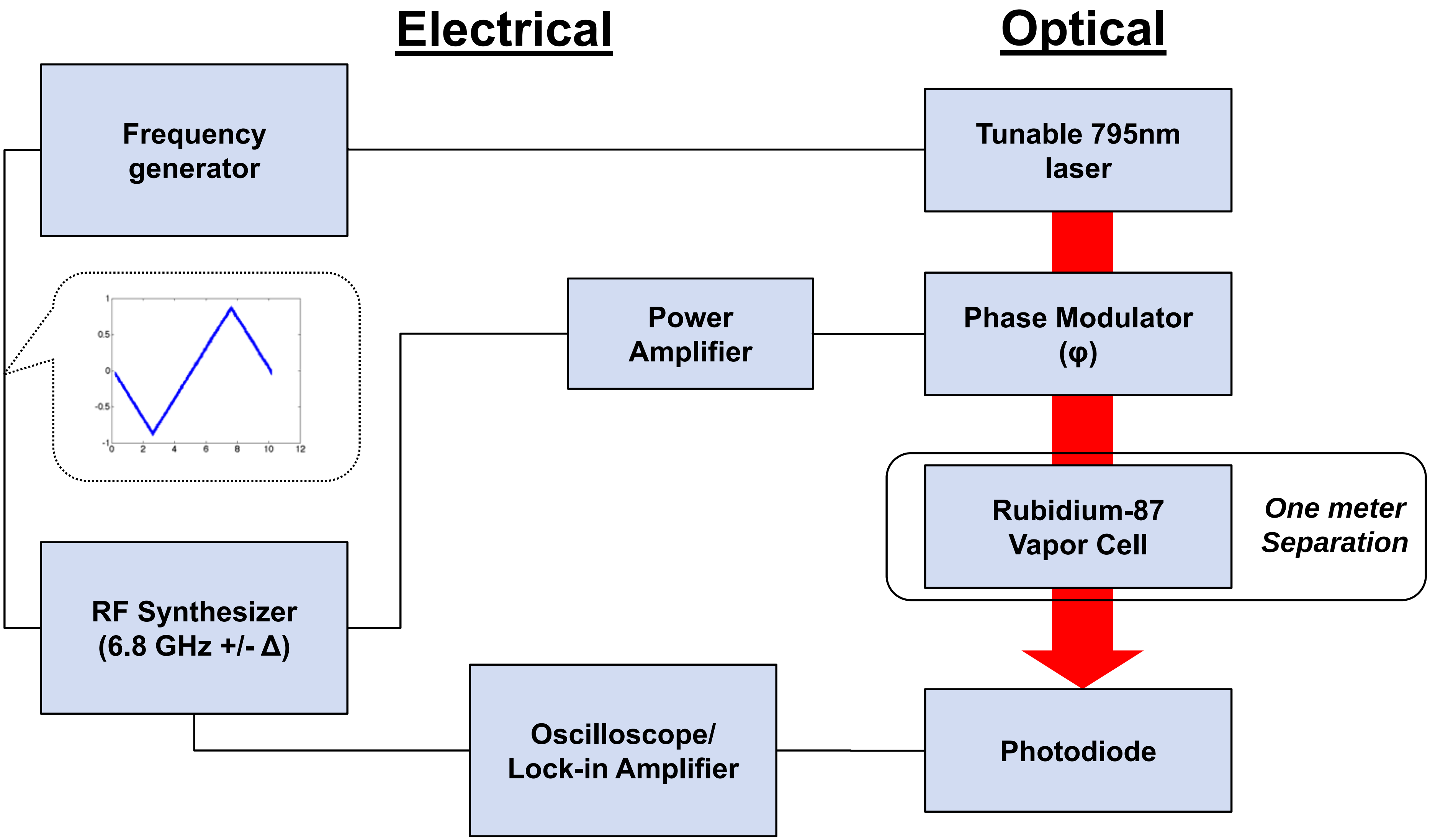

Newport

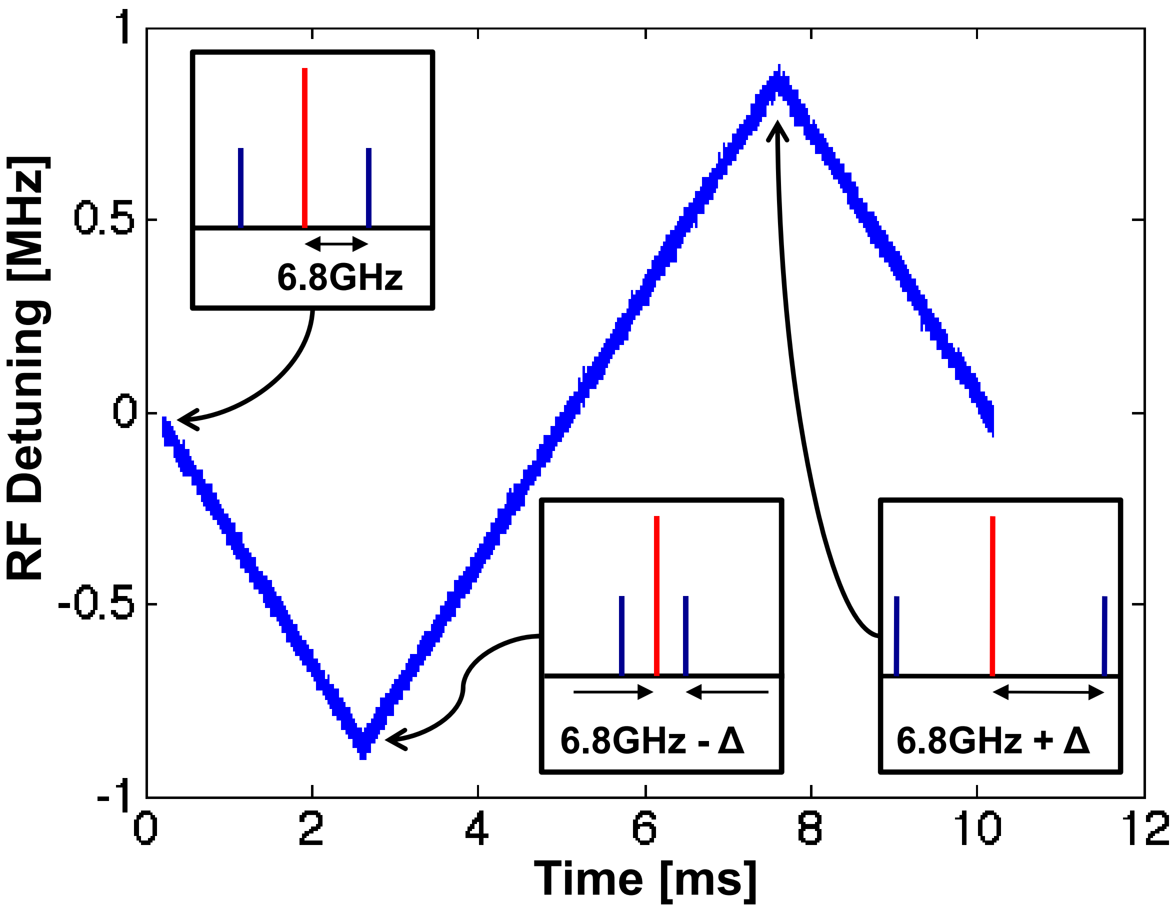
Transmit and Receive Optical System



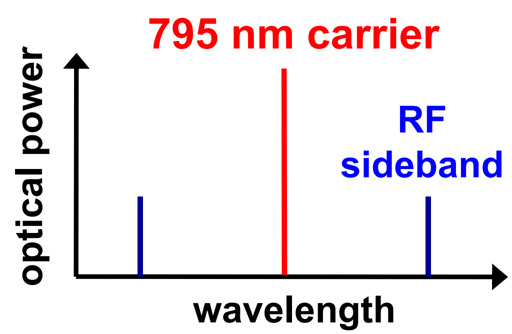
System Block Diagram



RF Sideband Modulation



- **Center wavelength fixed on D1 optical transition**
- **Phase modulator creates RF sidebands**
- **Phase modulation frequency swept through Δ = 900 kHz detuning**



Sweep RF sideband through two-photon resonance

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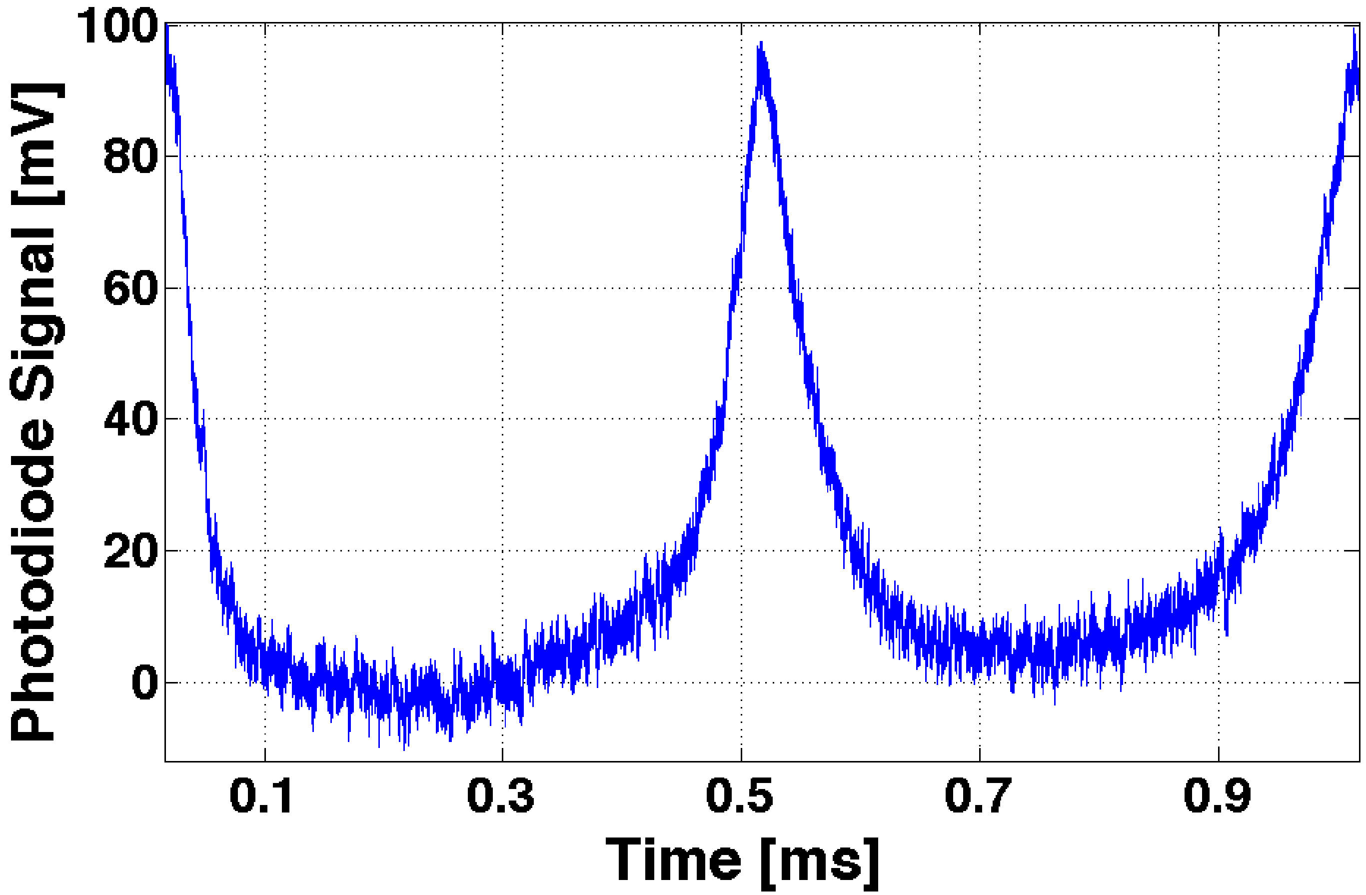
Basic CPT Data

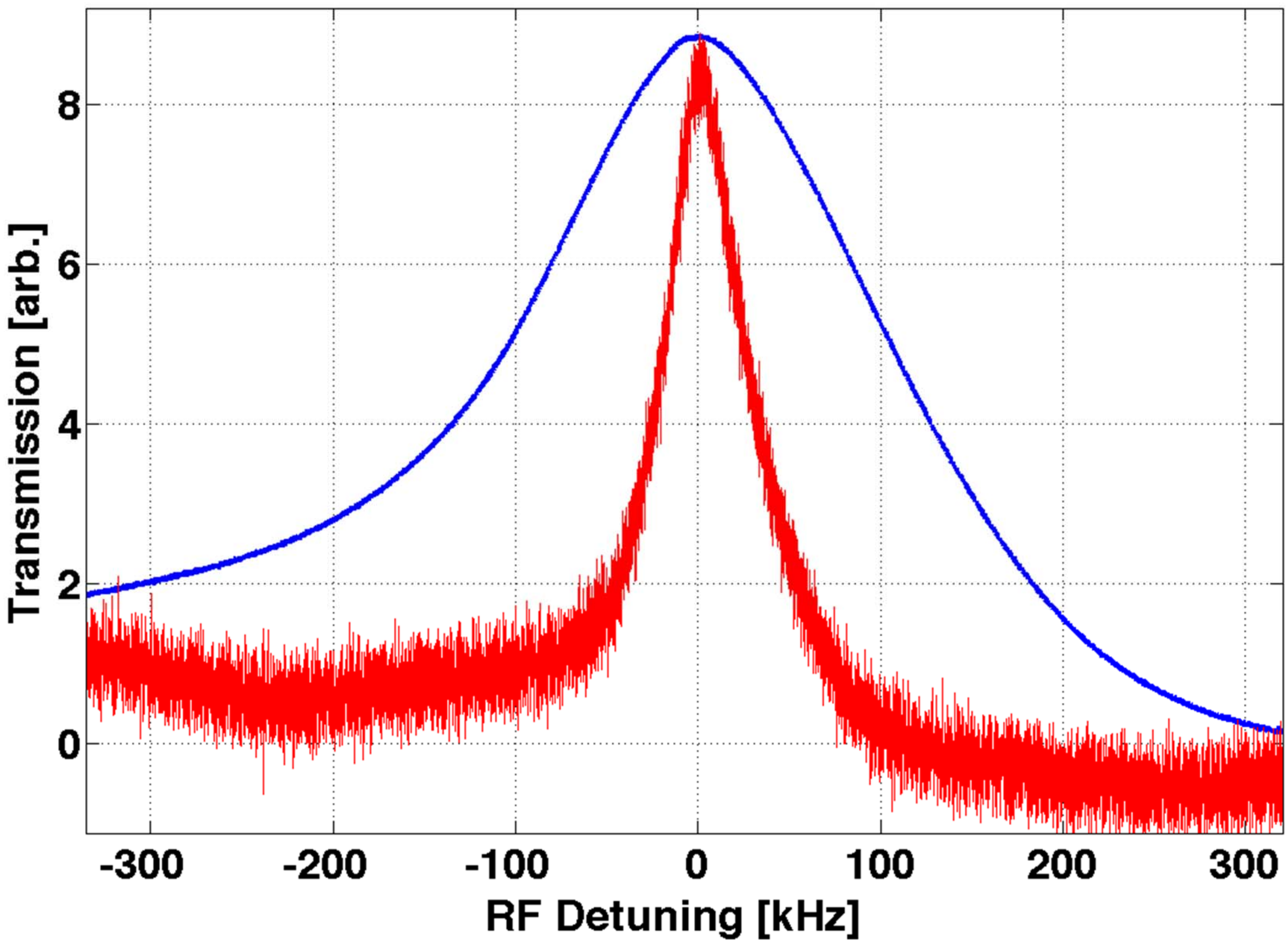


("No" magnetic field, Zeeman sublevels degenerate)

Narrow linewidths enable small frequency shift measurement

Magnetic Environment

- **Blue curve**
  - **Broadened from magnetic environment in laboratory**
- **Red curve**
  - **Narrower linewidth with less averaging**
  - **Facilitates "ideal" system characterization**

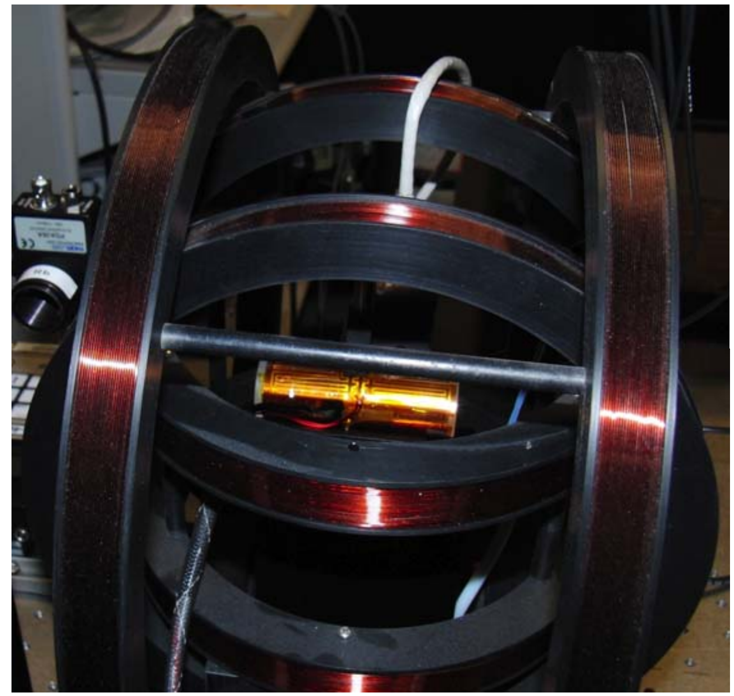


Magnetic Field Control

μ-Metal

- High magnetic susceptibility alloy shields contents from external magnetic fields
- Used only for system characterization

Helmholtz Coils



- Current through symmetric coils forms uniform field in center
- 3-axis control
- Used for producing artificial magnetic fields

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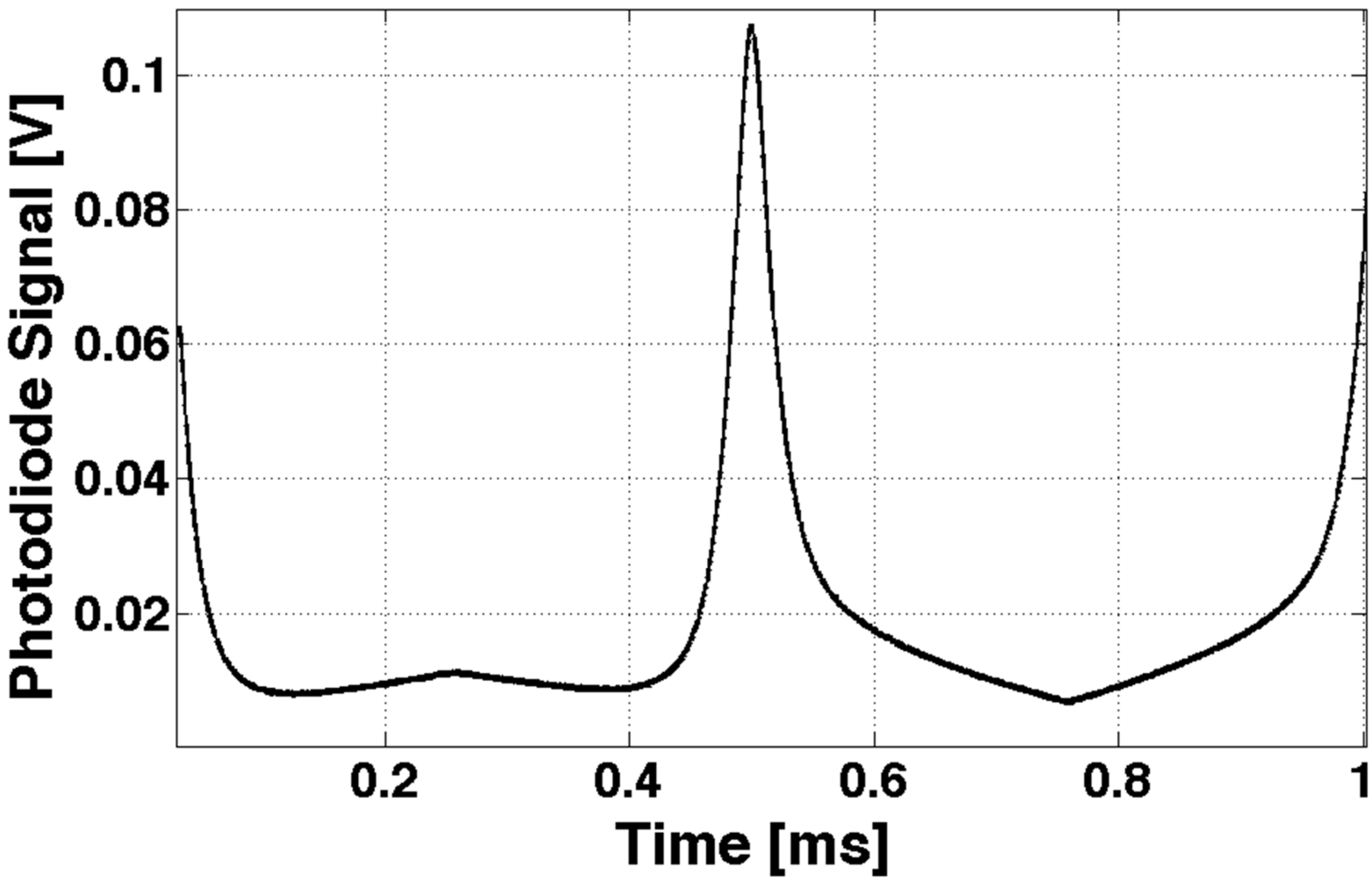
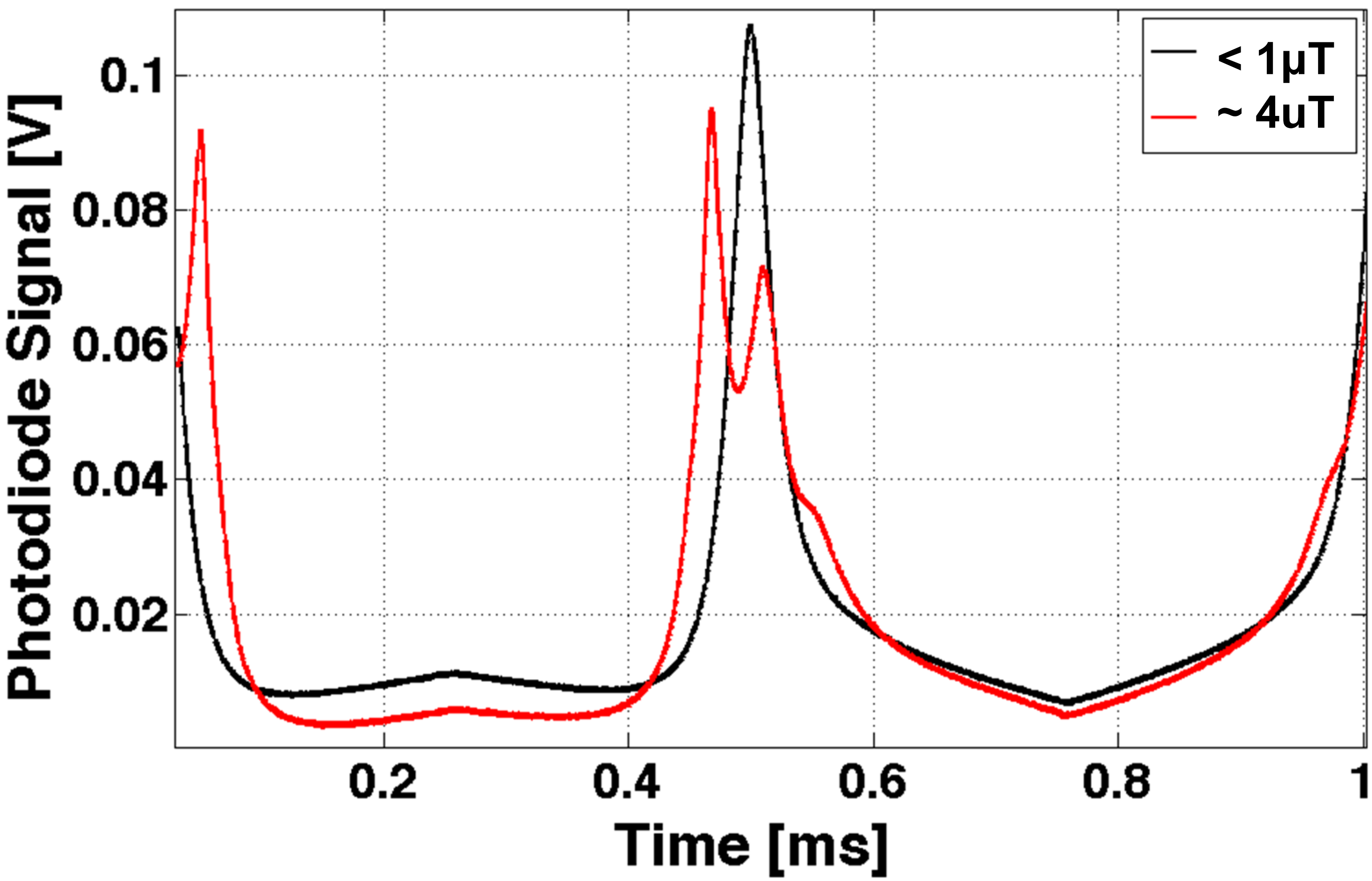
No Magnetic Field

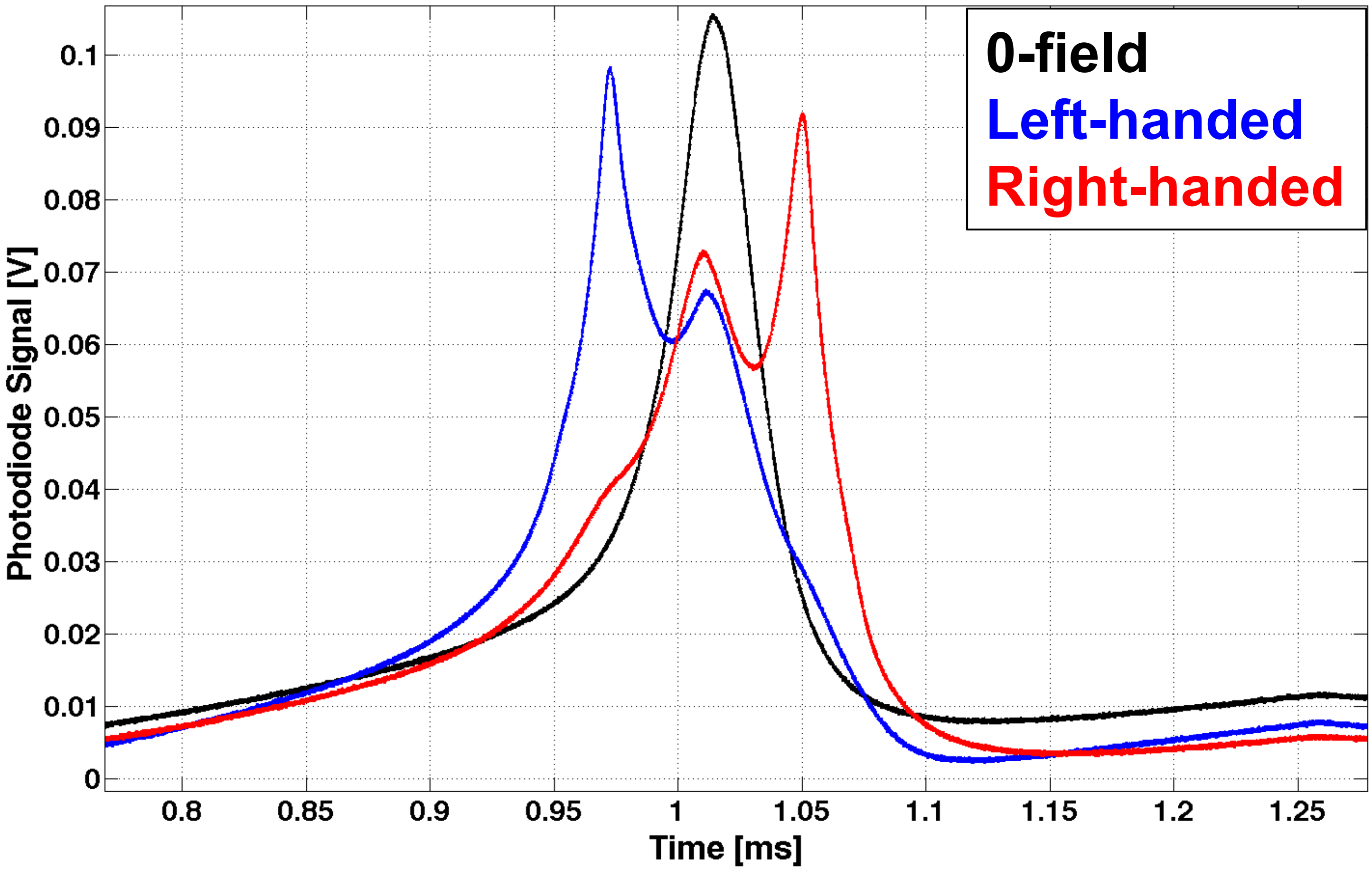


Magnetic Field



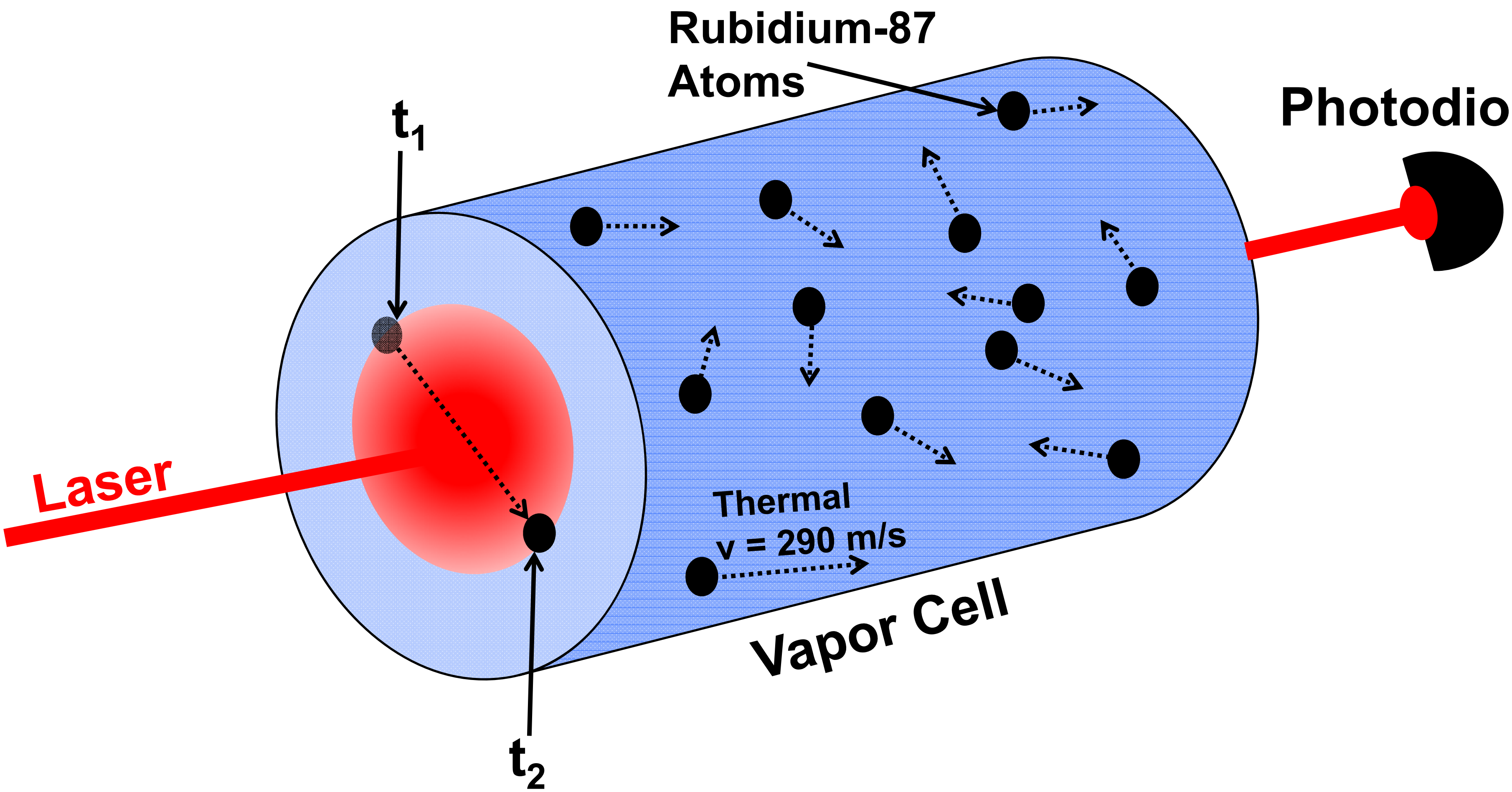
Magnetic field causes measureable Zeeman shift

Polarization Effects



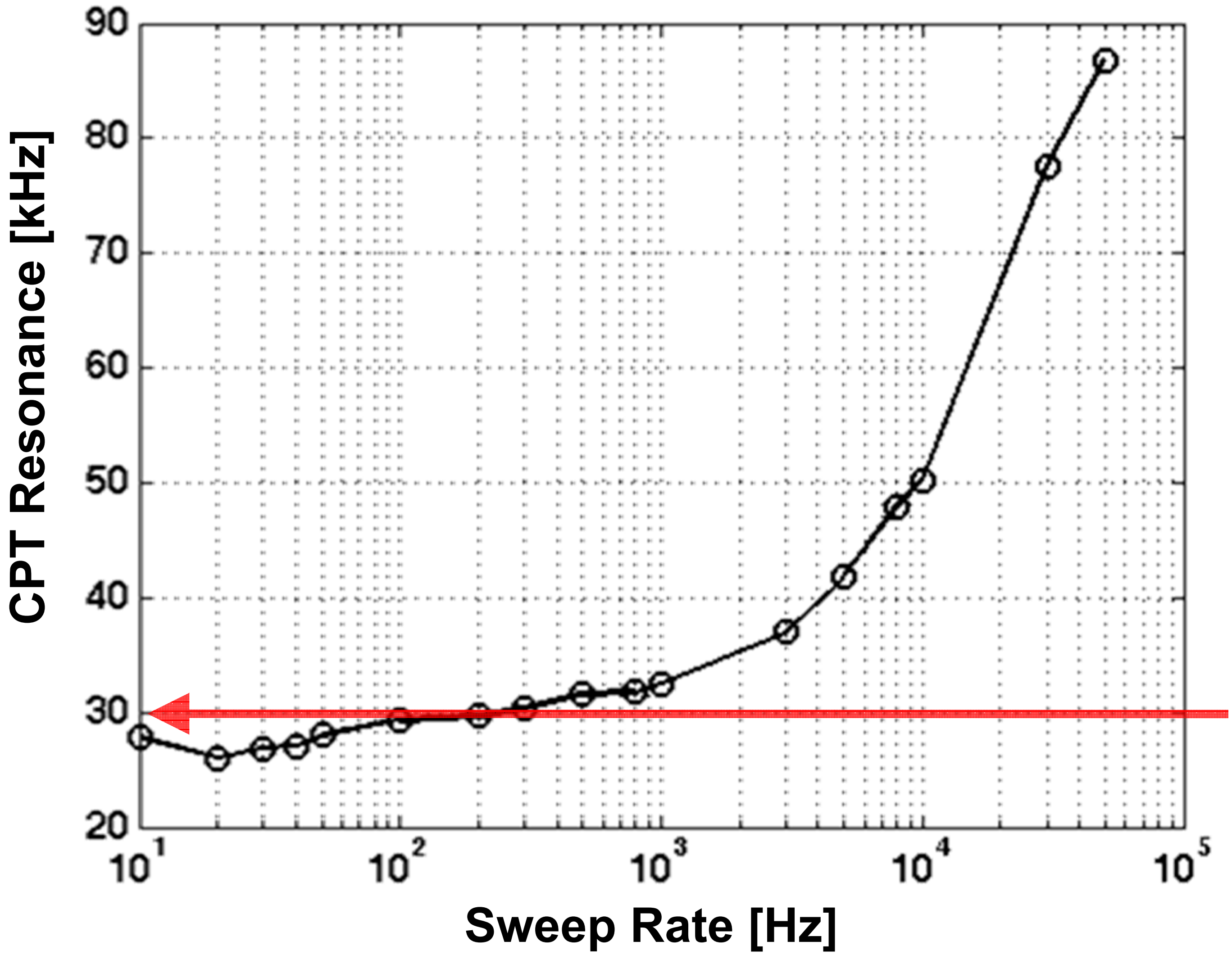
Dipole matrix elements squared: 1/2, 1/4, 1/12

Transit-Time Broadening



Measurement time limited by atoms' path through laser

Transit-Time Limited Linewidth

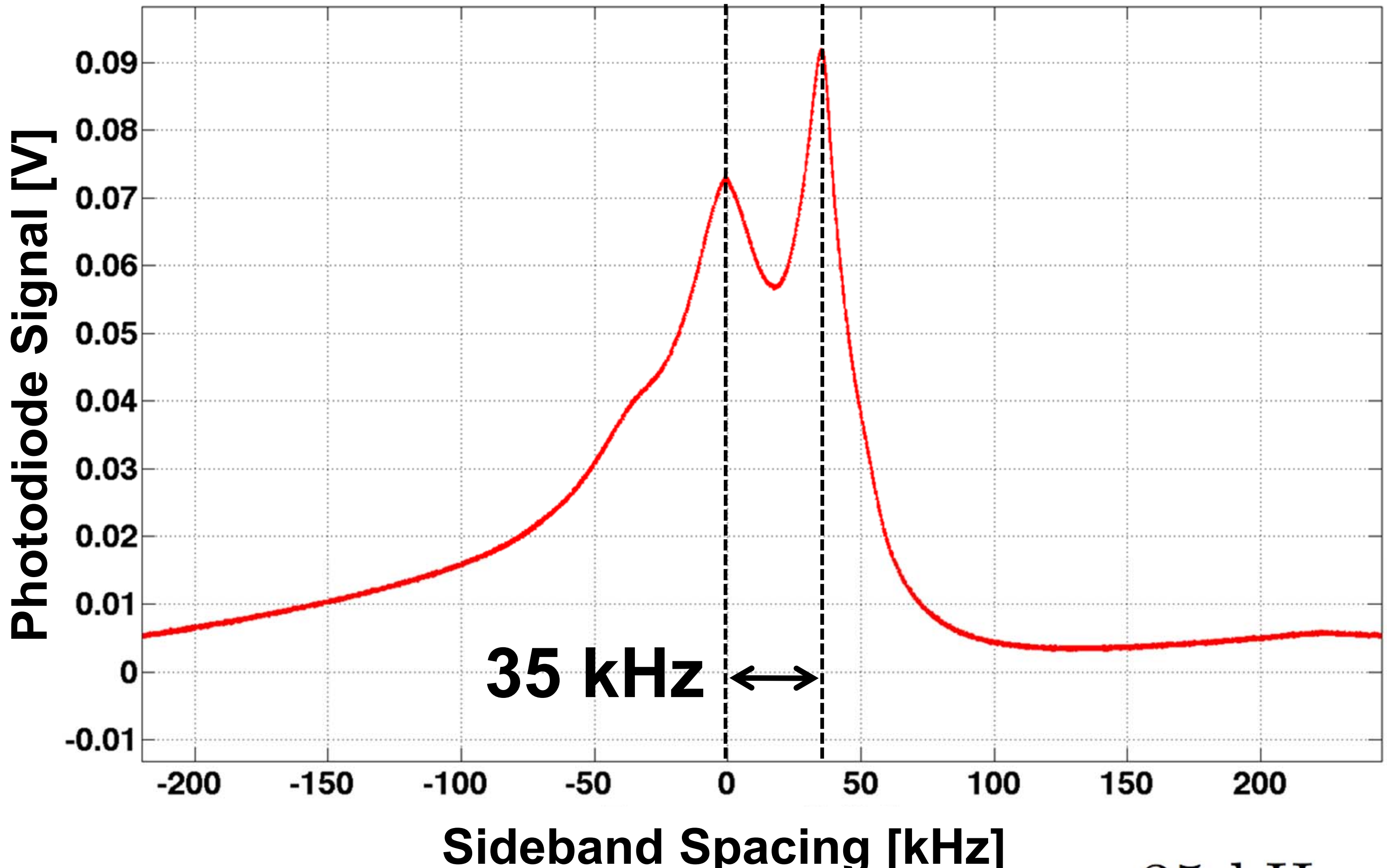


- Minimum CPT linewidth: **30 kHz**
- Optimal sweep rate: **100 Hz**

~1 cm beam width, Rb thermal velocity (290 m/s) matches theory*

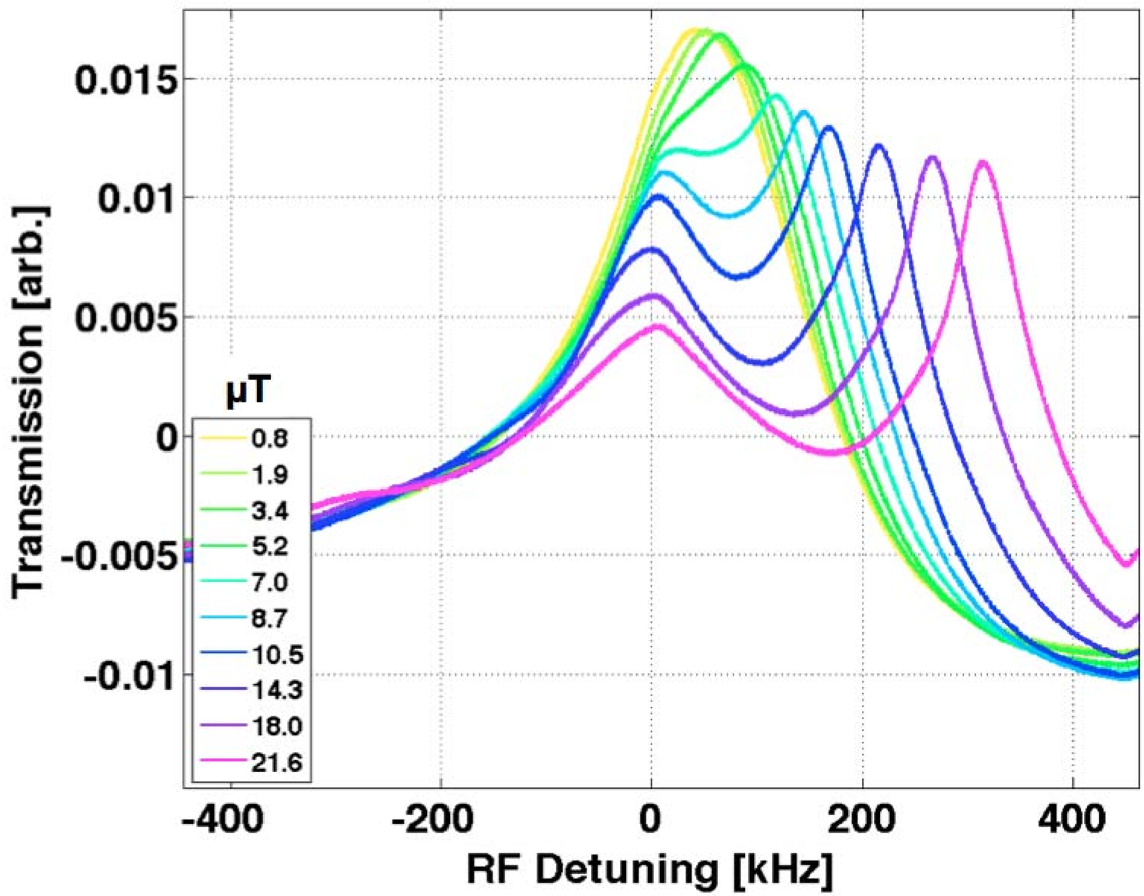
* Schmidt, et al. Phys. Rev. A, 53, R27, 1996

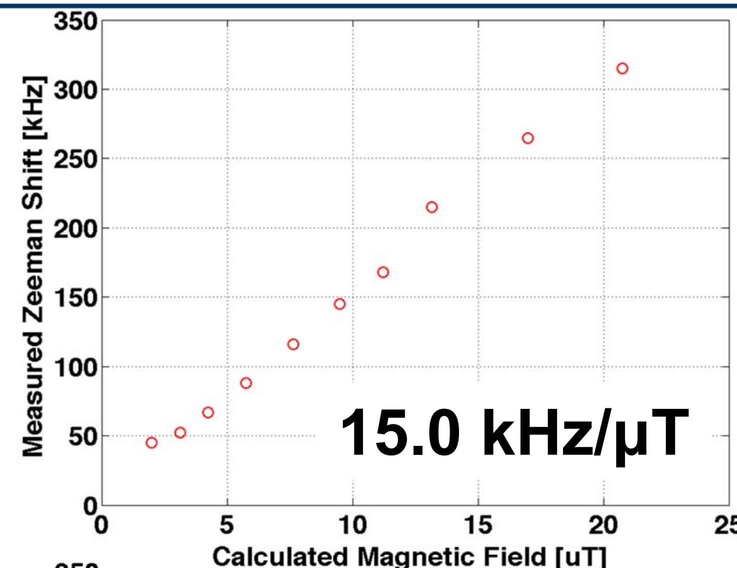
Field Determination

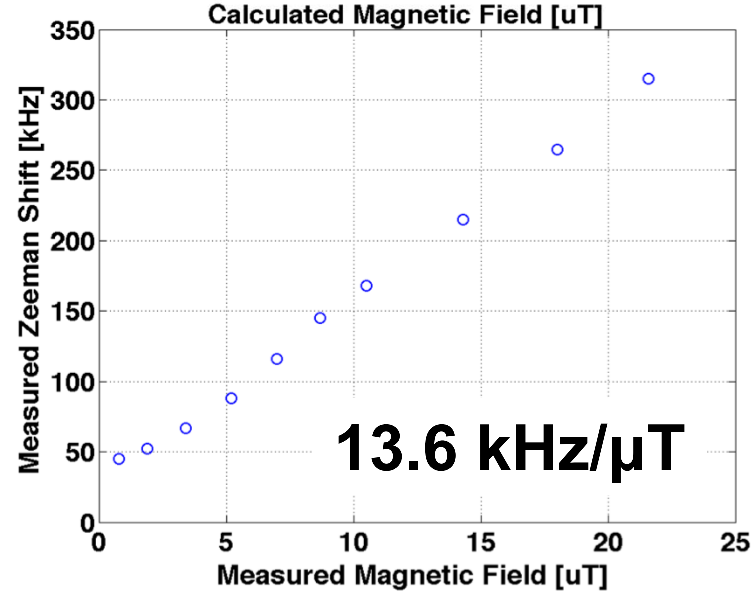


$$\frac{35\ \text{kHz}}{2 \cdot 7\ \text{kHz}/\mu\text{T}} = 2.5\mu\text{T}$$

1-meter Magnetometry







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Summary

- CPT magnetometry testbed established
- Sensitivity matches theory (unbuffered vapor, 30 kHz)
- 1 meter standoff measurements
- Zeeman shift tracks prediction (7 kHz/μT)

Future Work

- **Peak finding algorithm**
  - **Sensitivity better than quoted**
- **Buffer gas improvements**
  - **Helium at ~10 torr**
  - **Better sensitivity**
- **VCSEL**
  - **Direct current injection modulation up to 10 GHz**
  - **Control over sideband conversion efficiency**
- **Gradiometry**
  - **Removes common mode noise**
  - **CCD imaging capability**
- **Time-varying fields**

Questions

Backup Slides

Atomic Structure

- Fine structure
  - Relativistic corrections
  - Spin-orbit coupling
    - J = L + S
- Hyperfine structure
  - Electron spin/nuclear spin coupling
    - F = J + I

Rubidium-87 (alkali metal)

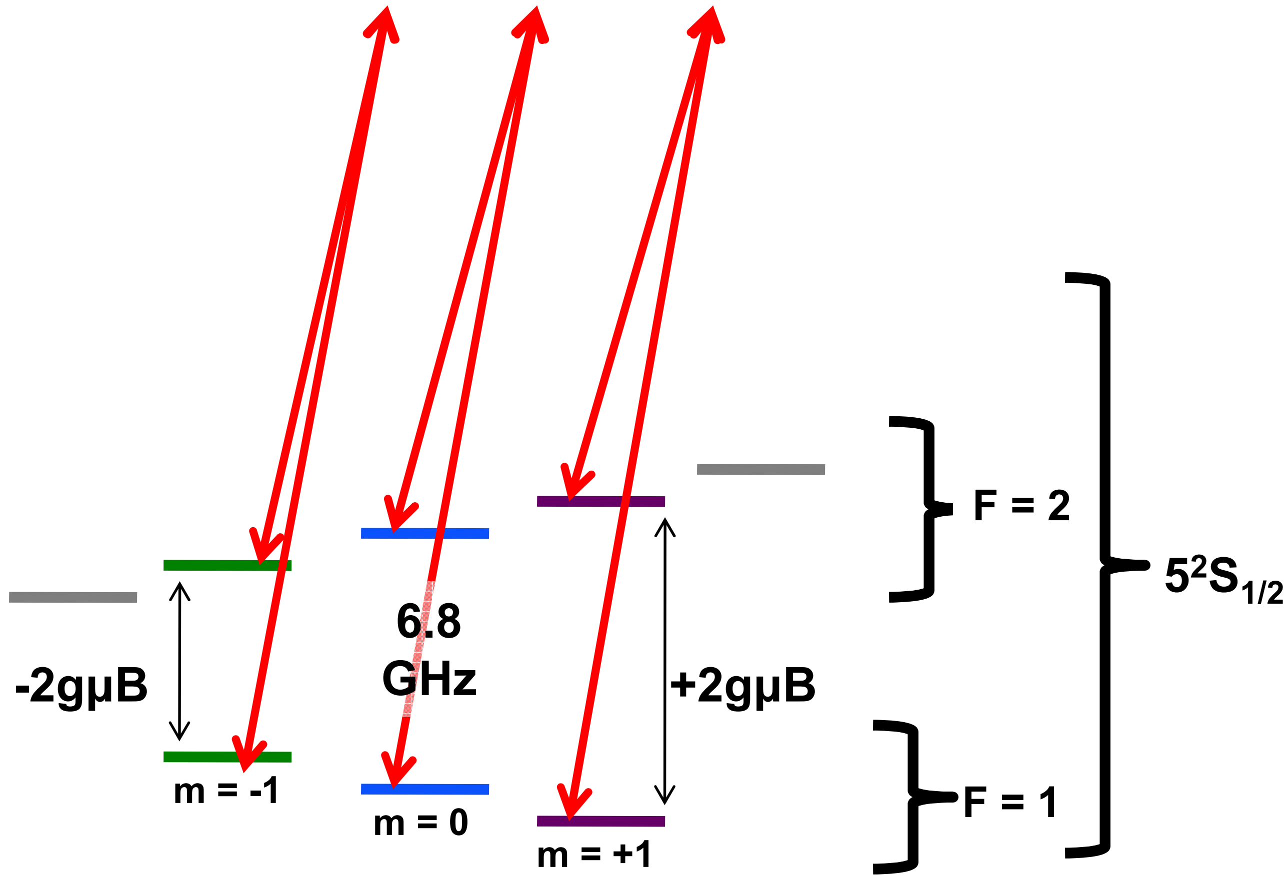
Atomic number 37, nuclear spin I = 3/2

e^- configuration: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 5s^1$

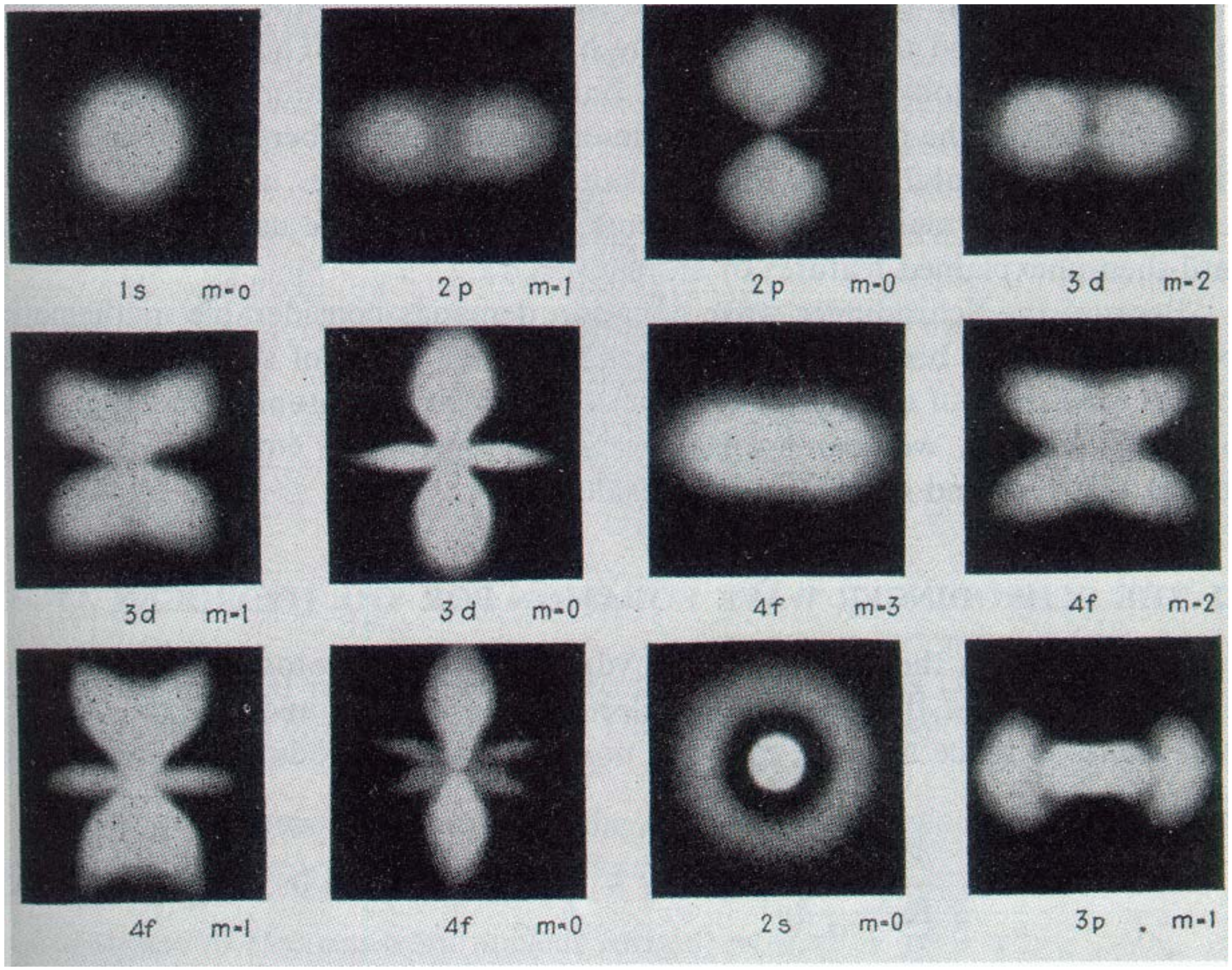
Valence e^- ground state: 5s ("s" ➔ L=0)

Fine structure ground state: J = 0+½ ➔ $5S_{1/2}$

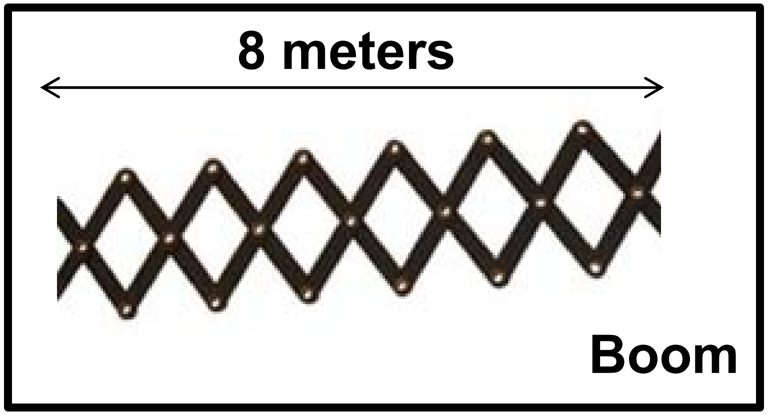
Hyperfine ground state: F = {3/2 + ½, 3/2 – ½ } = {2,1}


6.8
GHz
-2gμB
+2gμB
m = -1
m = 0
m = +1
F = 2
F = 1
$5^2S_{1/2}$

Electron Cloud Distributions

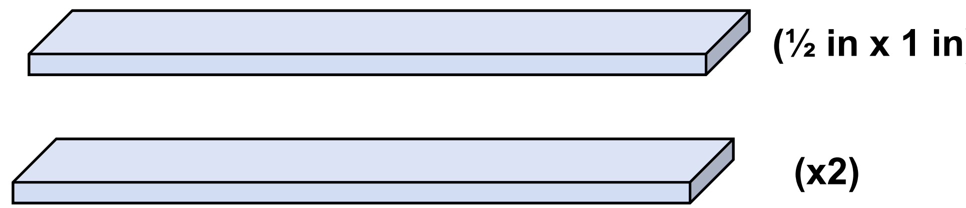


Boom Expense



Model: (8 m) * Scissor Geometry =

(315 inches) * (1.4) = 441 in



Total Volume: ~440 in^3

Density: 0.0748 lb/in^3

Total Weight: 33 lb

- **Aluminum Beryllium metal alloy (AlBeMet)**
  - Low weight
  - High stiffness

Satellite launch cost (to LEO): x $5000 per pound

Raw material costs: x $409 per pound

Lightweight 8 meter boom (w/o design): **$178,500**