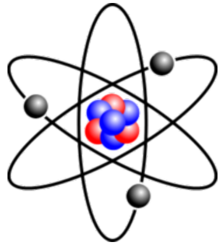
# Rydberg Probes: Can We Transform RF Measurements and Communications ?

NIST

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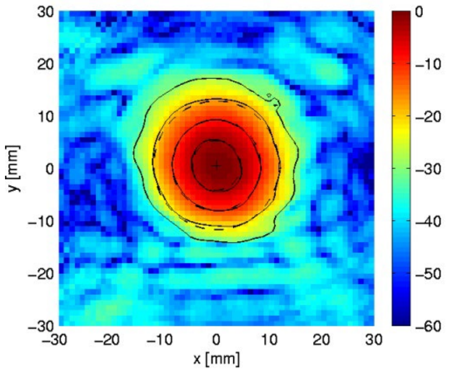
**S. Berweger, A. Rottunno, K. Campbell, M. Jayaseelan**

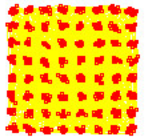
*NIST, Boulder, CO*


*September 2022*

## RF Camera

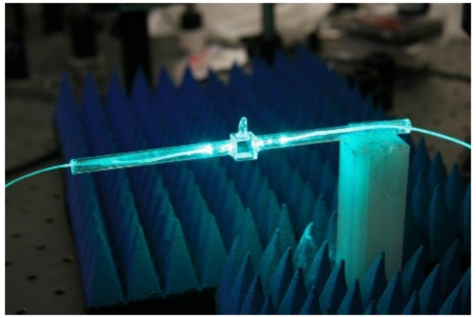


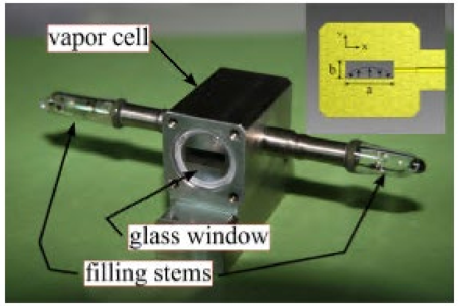

## Receivers

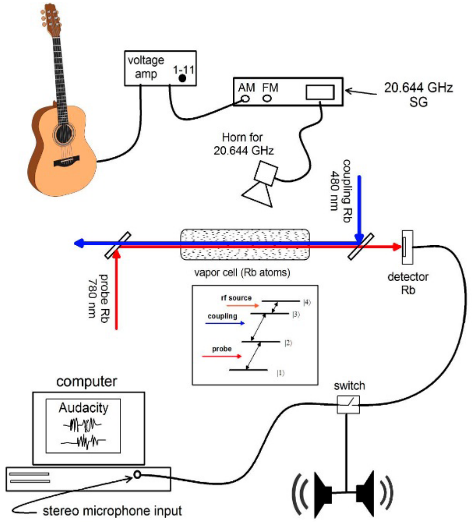


64 QAM
(64 phase states)
6 bits/symbol

## E-field Probes and Power Meters






## Quantum TV and Gaming

# Motivation: Video Streaming-Hot off the Press

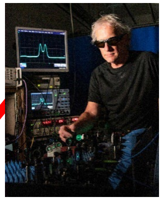
*Prajapati, et al., AVS Quantum Science, August 2022*

One needs motivation to
set through a workshop!

# WHO is National Institute of Standards and Technology (NIST)

**NIST is a Federal Research Laboratory** **NIST's mission:** To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

Me



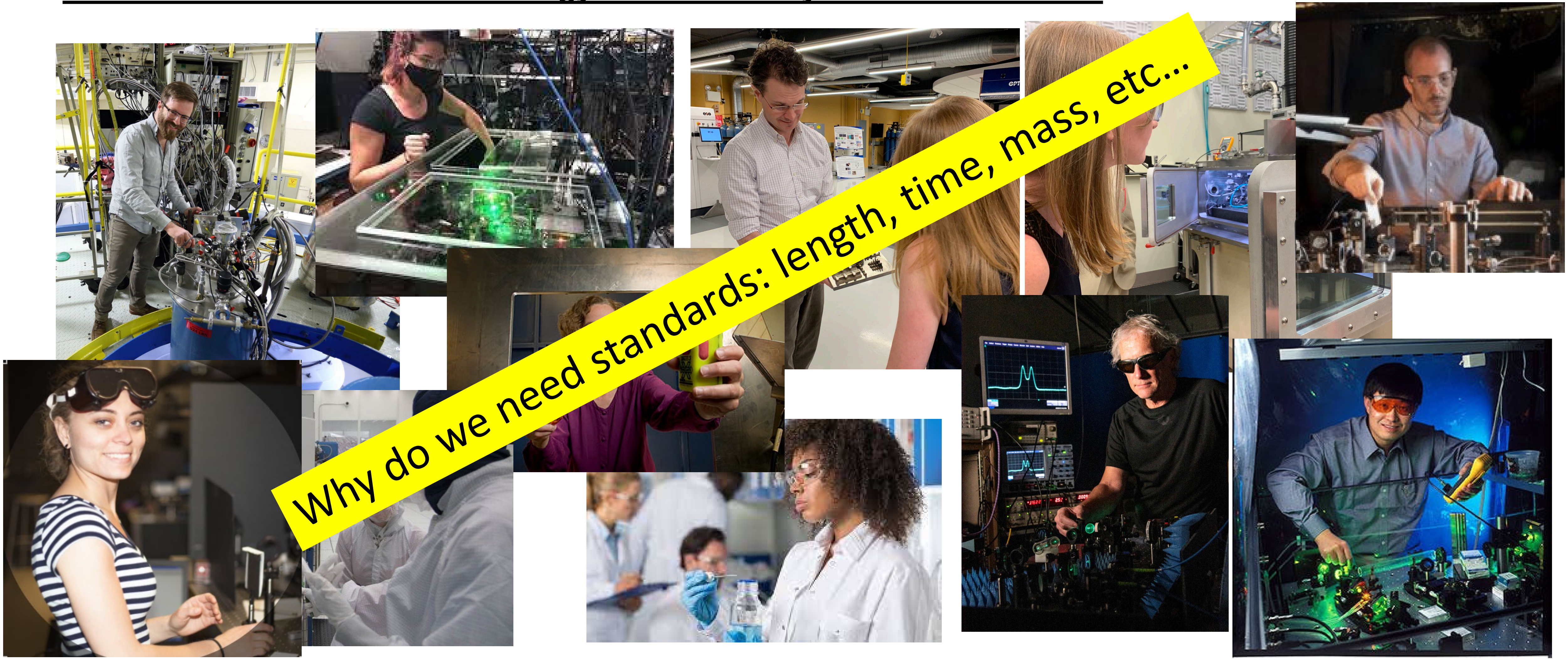
**NIST in Boulder, CO: 600 researchers**

**NIST in Gaithersburg, MD: 2500 researchers**

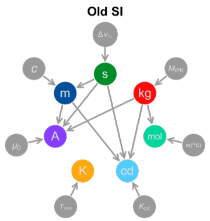
# National Institute of Standards and Technology (NIST)

NIST

**Basically, we kept track of the weights and measures for the country and for the world. Also, we do fundamental research for technology that is 5 to 30 years down the road.**



# International System of Units



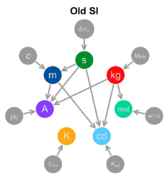


The **International System of Units** (SI, abbreviated from the French Systeme Inernational d'unites: **SI system**) is the modern form of the metric systems and the World's most widely used system of measurement.

**International Bureau of Weights and Measures** (Bureau International des Poids et Measures, BIPM)

Why are pirates responsible for NO metric system in the US?

# Artefact Standards for the World: No MORE




Length (meter stick)

Mass (kg)

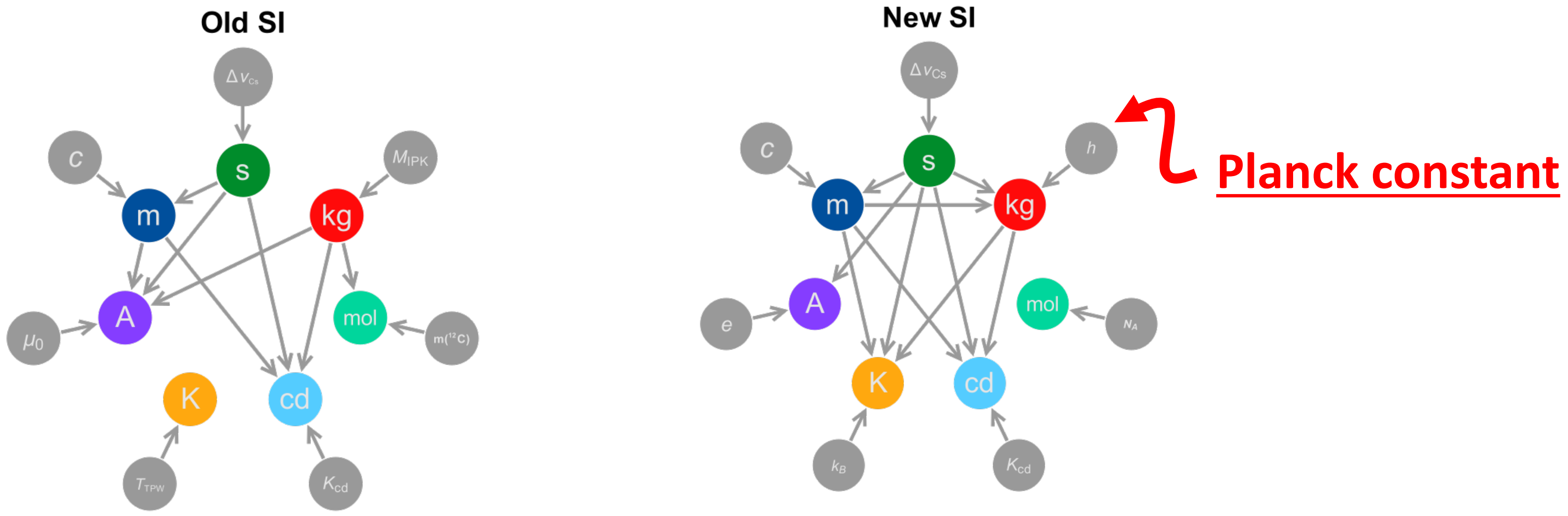
1857 Bushel


This sounds like a good idea.

But, Artefacts Change?

# Re-definition of the SI in 2018

NIST




The world of measurement science is changing rapidly with the SI redefinition planned for 2018.

The key here is that the world moved from artefacts standards to fundamental physical constants.

As a result of the shift towards fundamental physical constants, we can rethink about how SI traceable measurements and calibrations are done.

We propose to transform calibration services and the traceability path for *E-field* and of *RF power* (defined as 100’s MHz to just below THz).

# What are We Trying to Solve

**Calibrating an E-Field Probe**

**Somewhat of a "Chicken-or-Egg" dilemma**

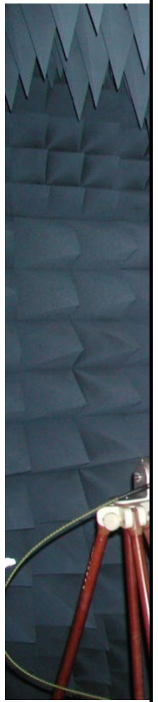
To calibrate a probe, one must place the probe (sensor) in a "known" field.

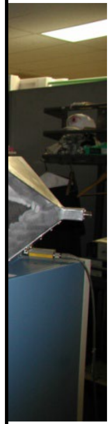
However, to know the field we need a calibrated probe.

# Current Technology for Calibrations

Horn antenna in an anechoic chamber

TEM Cell



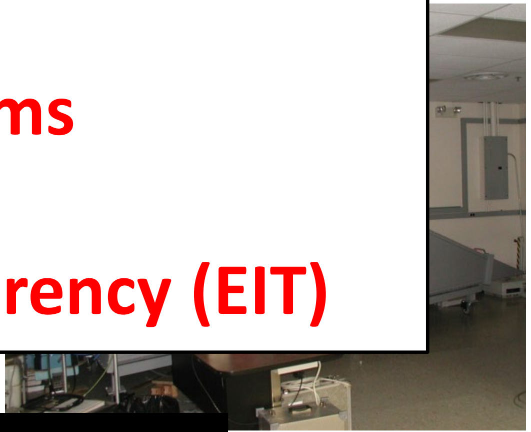


**How will we do Better, by using atoms!**

**Atoms will respond to their environment.**

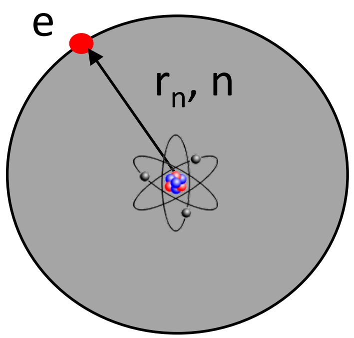
**So, the BIG question is:**
**How do we use the atom to measures E-fields?**

**by Generating Rydbergs Atoms**
**and**
**Electromagnetically Induced Transparency (EIT)**

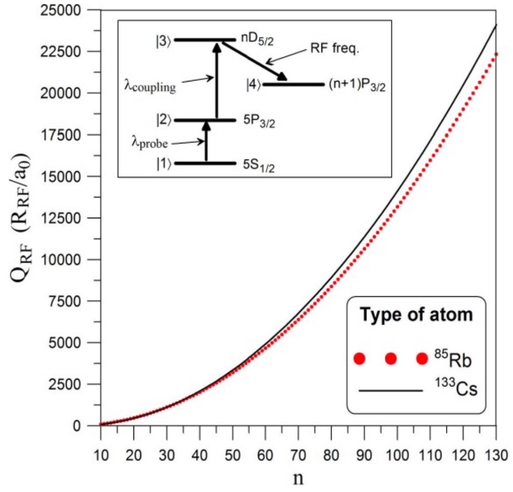


**0.5 dB (or 5%) accuracy**

# Rydberg Atom-Based Technique

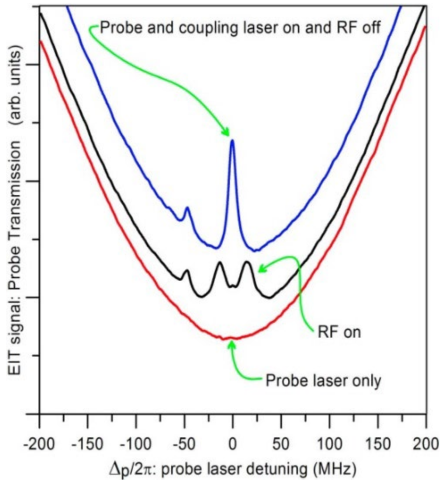



Rydberg atoms are atoms with one electron excited to a very high principal quantum number *n, i.e., $r_n$ is very large*.

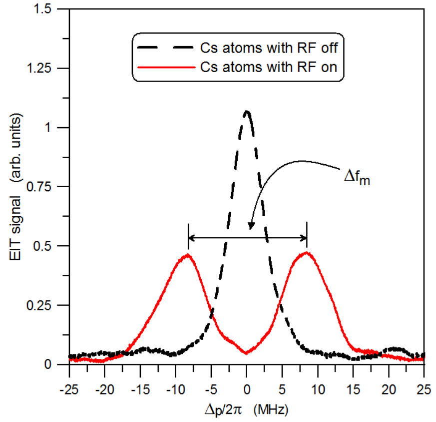



Rydberg states have very large dipole moments: Meaning they are very sensitive to RF E-fields (making for good RF E-field sensors).

So how do we read out the respond of the atom to an electric field?
By <u>electromagnetically induced transparency (EIT)</u>

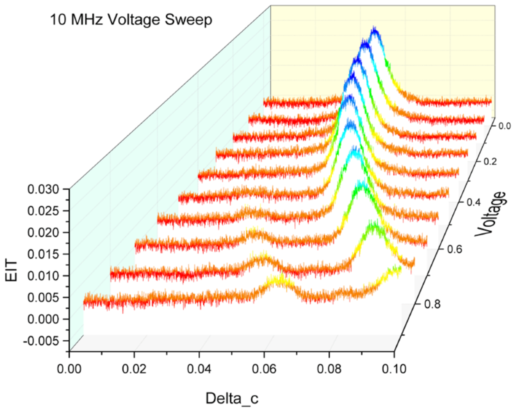



Autler-Townes (AT) splitting




$$|E| = \Delta f \, \frac{\hbar}{\wp}$$

AC Stark shifts

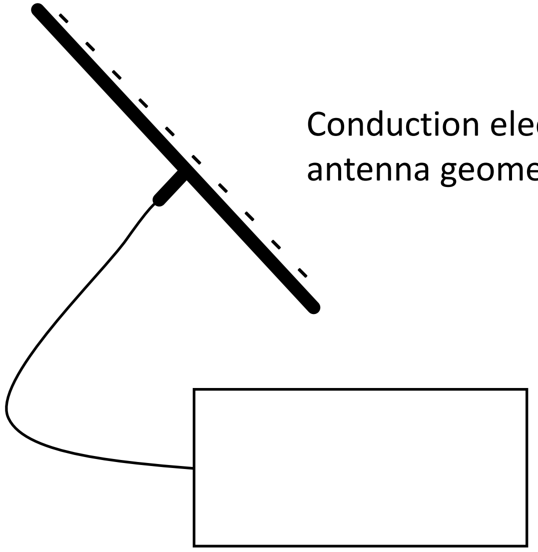



$$|E| = \sqrt{\frac{4\,\Delta f}{\alpha}}$$

# Replace Conventional Techniques with Quantum Based Techniques

**Fundamental Change: Replace Classic Antenna with Rydberg Atoms**

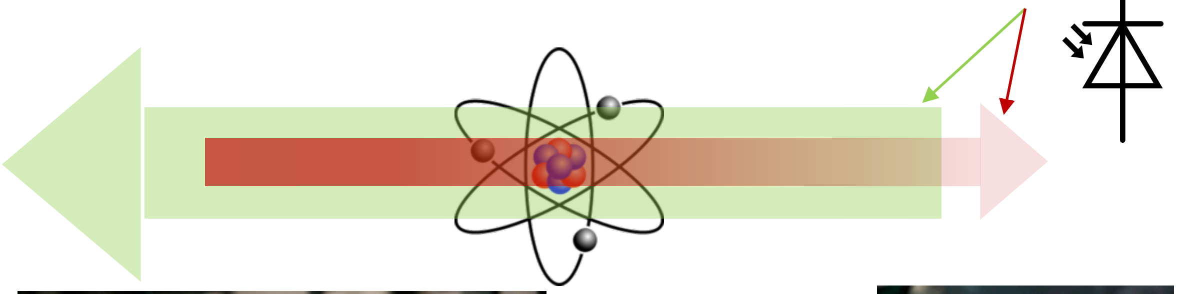
## Classic Antenna or Probe

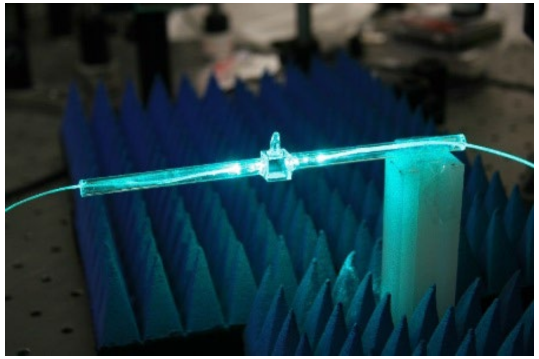


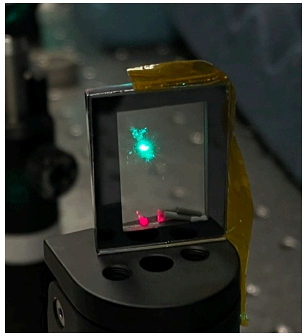
Conduction electrons bound by antenna geometry.

## Rydberg Atom Probe

Atom-bound electrons in a vapor cell have no geometry per se as long as they interact with controlling lasers.





# Historical Perspective - 8 Year History

NIST

Prior to 2010: Many groups investigated E-field interactions with Rydberg atoms

2010: NIST wrote paper discussing using Rydberg atoms for SI measurements of electric fields

2011: DARPA funded two groups on atom-based electric field sensors:

one lead from the University of Oklahoma/Stuttgart: Sedlacek et al., 2012
one lead from of NIST/U. of Michigan: Holloway et al., 2014

2014-Present: G

Because of the success of this program, several groups around the world (including National Metrology Institutes, private companies, universities, and other government laboratories) have started programs in the area of Rydberg atom-based sensors.

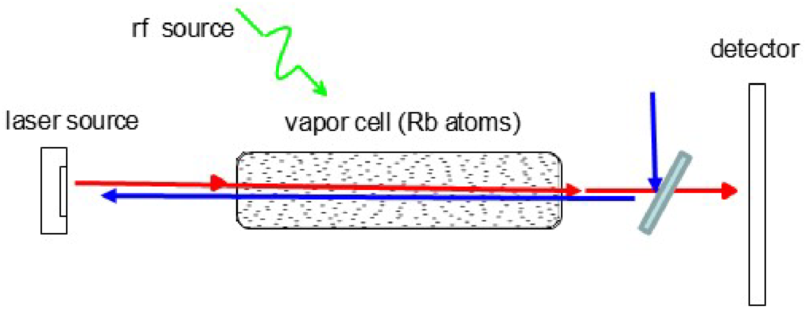
Including: USA, Germany, UK, Canada, China, Japan, South Korea, India, New Zealand, etc..

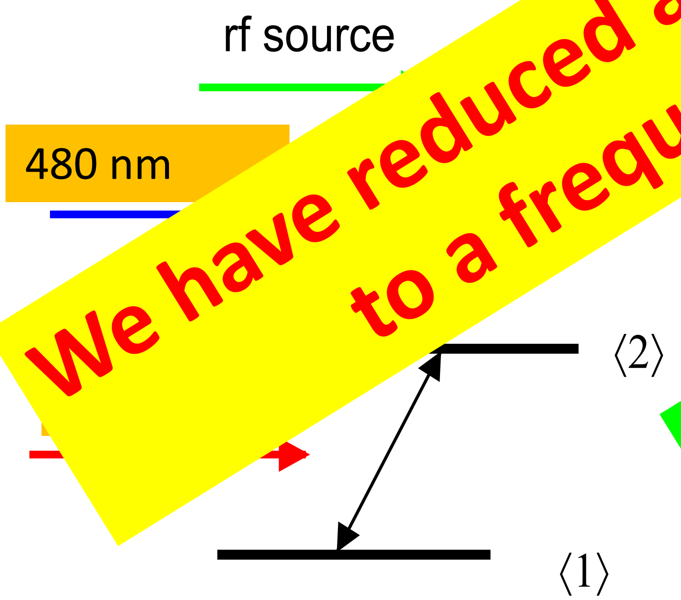
Gov. Labs: NIST, DOD, DOE, National Institute of Metrology (China), NPL (UK), etc..

Universities: U of Michigan, U of Oklahoma, U of Stuttgart, Durham Univ., U of Colorado, U of Maryland, Shanxi University, U College London, U of Ele. Science and Technology, U of Otago, U of Chinese Academy Sciences, Chongqing University, Institute of Laser Spectroscopy, Jiliang University, Jiliang University, Shandong University of Science and Technology, Pusan National University, Beijing Institute of Technology, etc.….

Several private companies: Rydberg Technologies, MITRE, SRI, Raytheon, Northrop Grumman, other that I cannot mention, etc.……

# Electromagnetic Induced Transparency (EIT) for SI Traceable Measurements



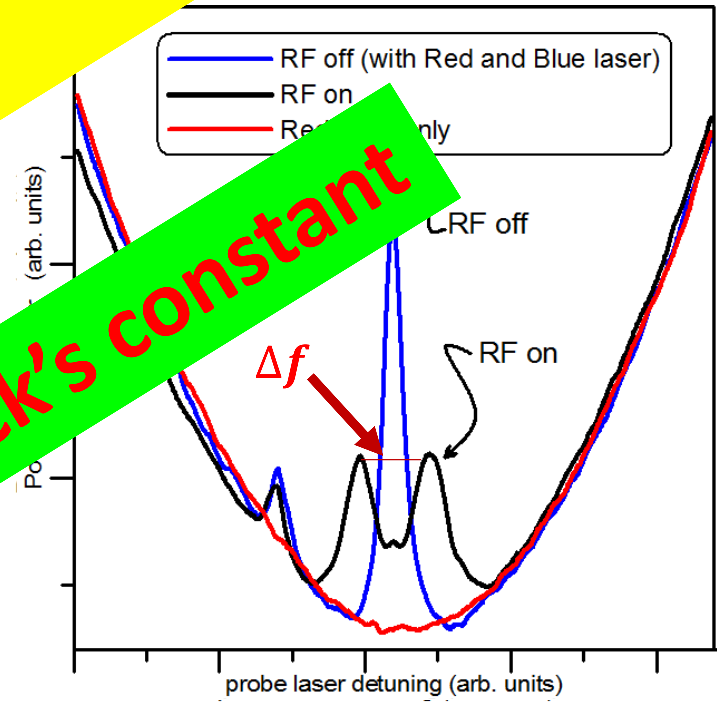




**We have reduced an amplitude measurement to a frequency measurement**

**SI traceable via Planck's constant**

## …robe Laser Response

…gets us high enough that the …ition can be made with RF

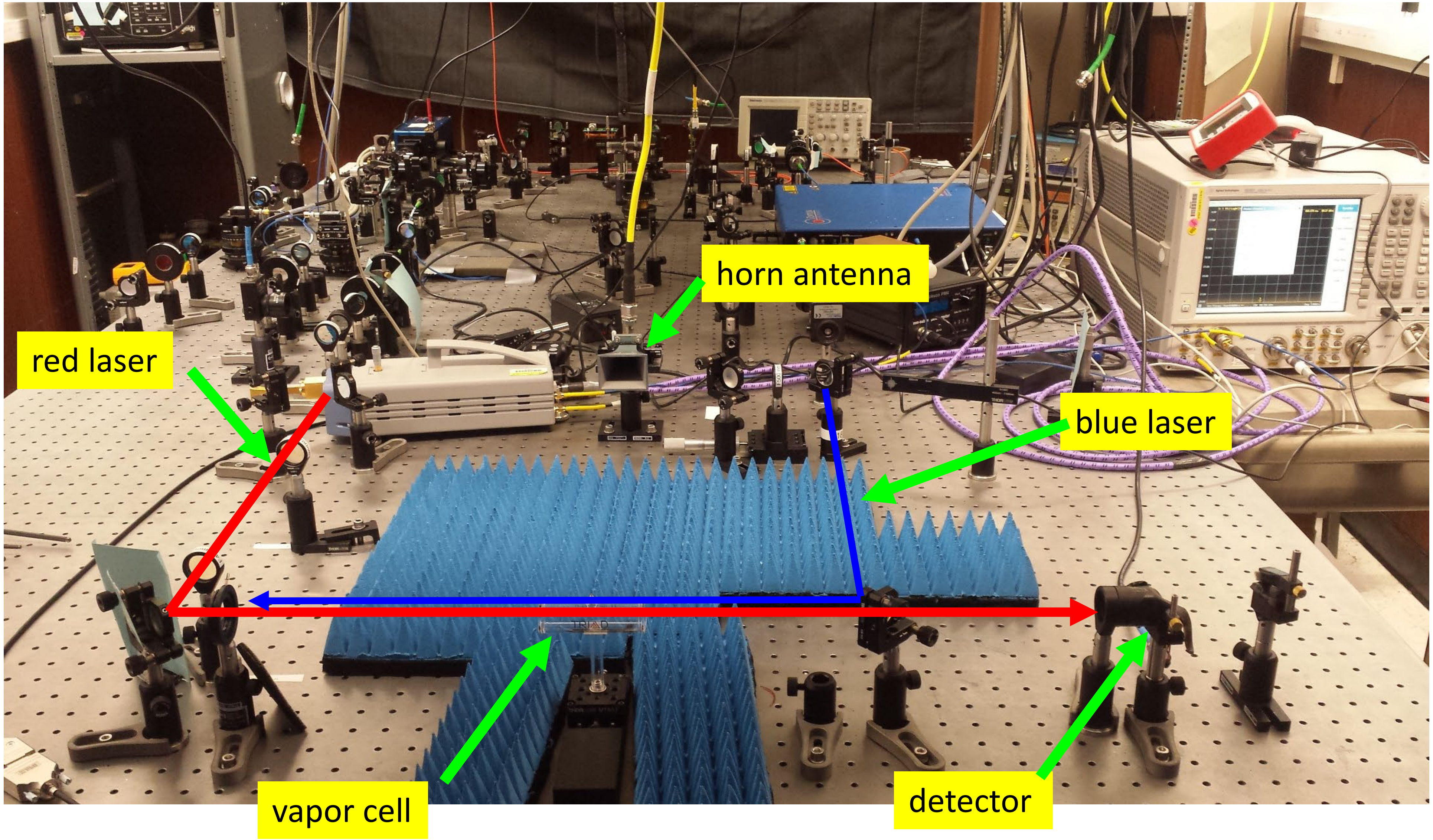



Splitting in the EIT signal

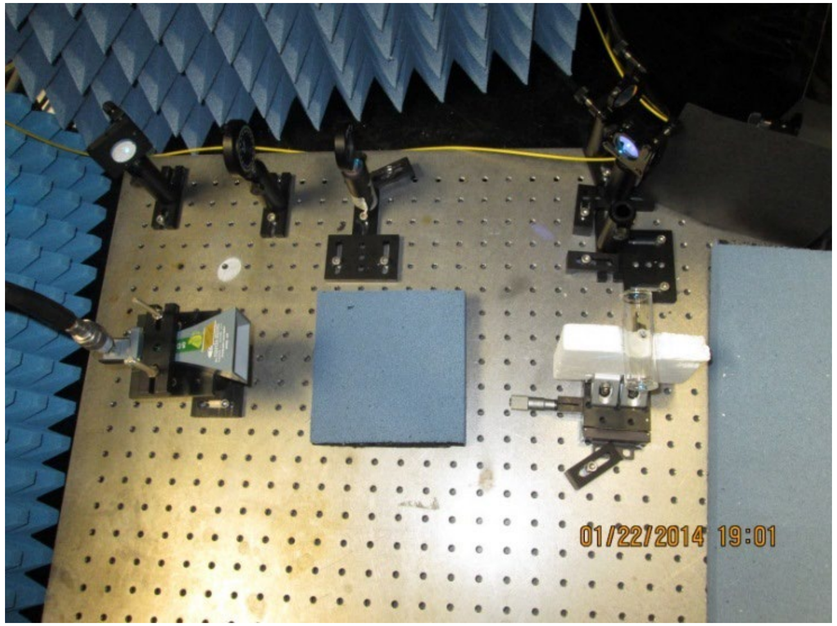
**(Autler-Townes Splitting)**

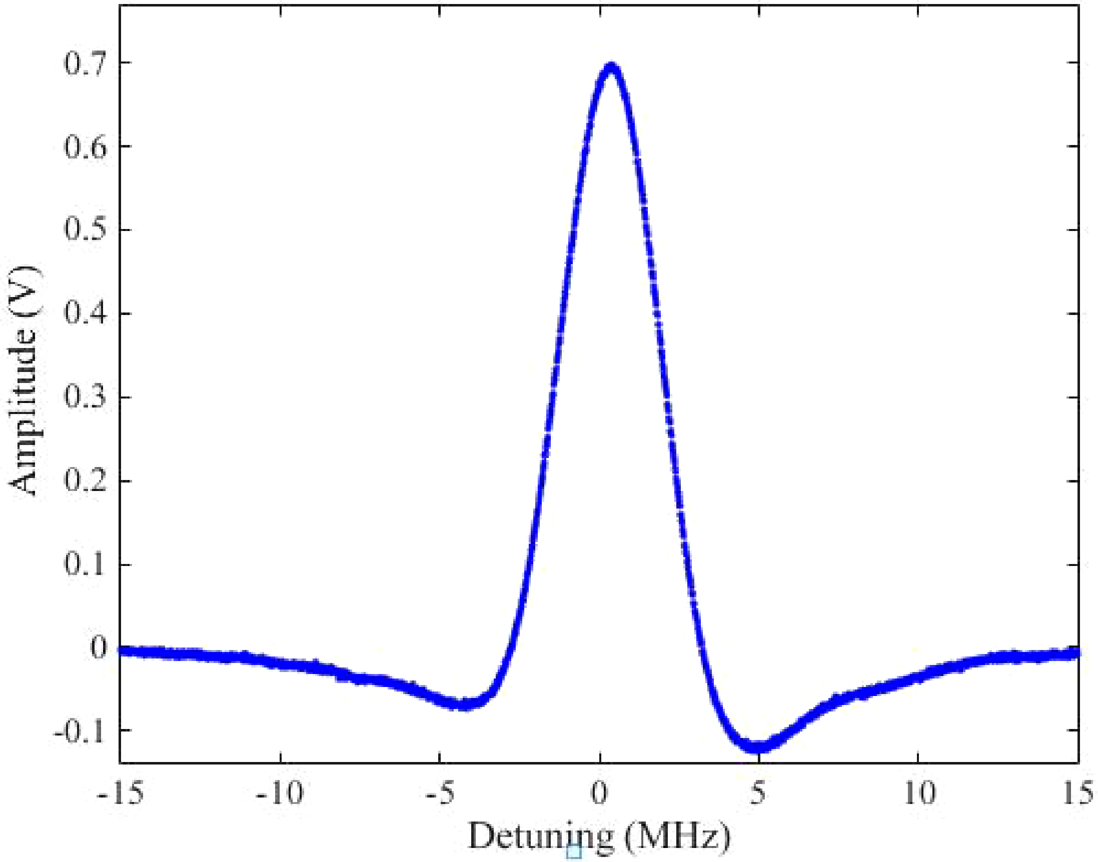
$$\Delta f = |E| \frac{\mathcal{P}}{2\pi\hbar} \quad \rightarrow \quad |E| = 2\pi \Delta f \frac{\hbar}{\mathcal{P}}$$

# Room Temperature Measurement

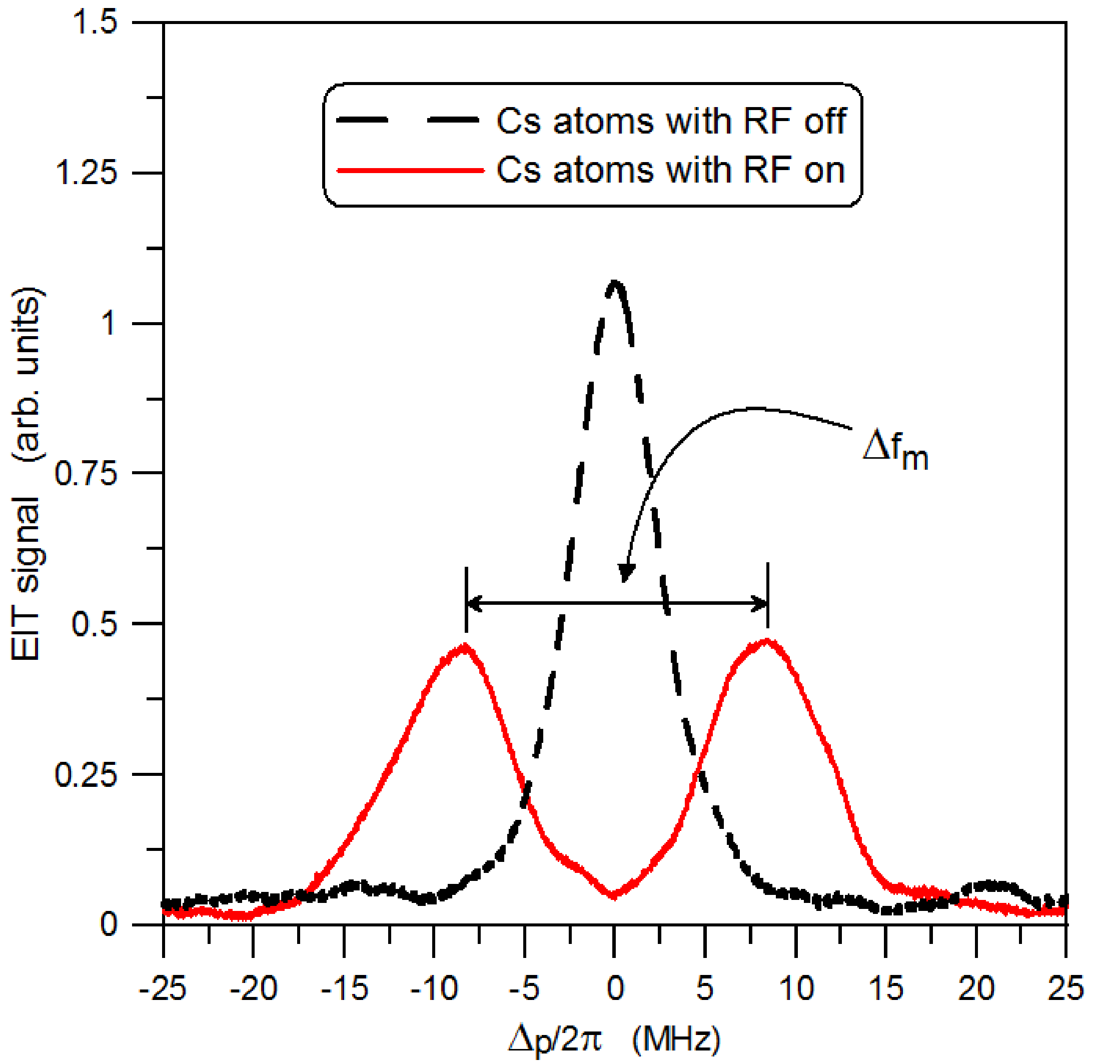


# Signal on the Detector: Typical Experimental Result for the Splitting



# Typical EIT Signal

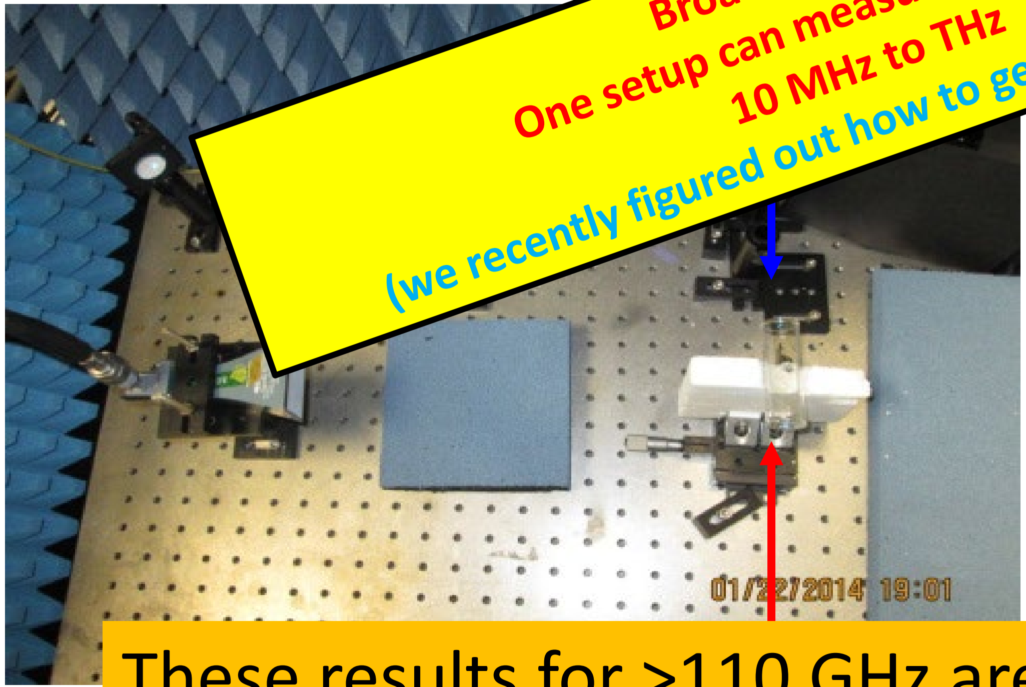


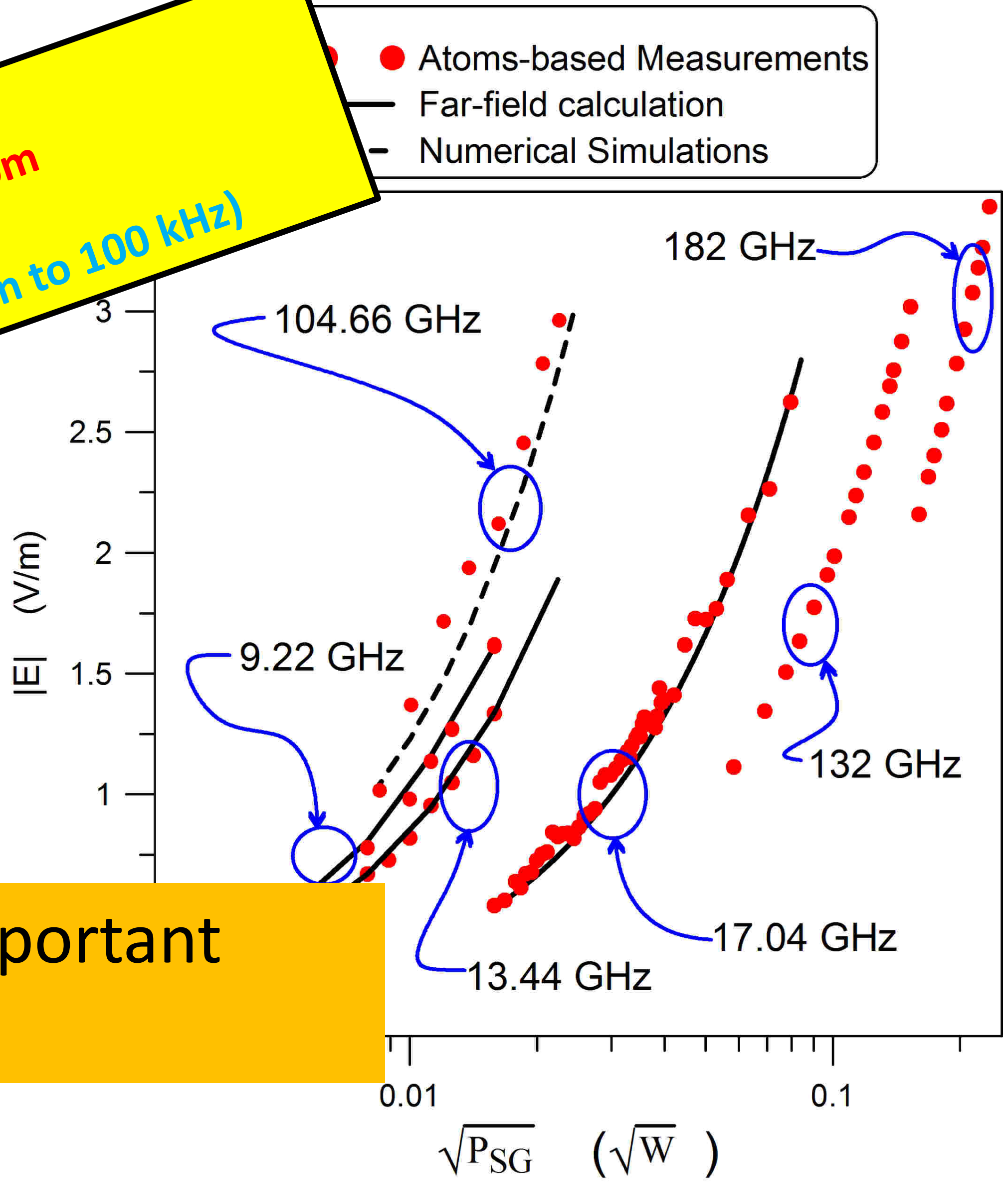
# Correlation to Simulation and Far-field Calculations

Holloway et al., IEEE Trans. AP and EMC, 2014, 2017

$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f$$

**Broadband Sensor:**
**One setup can measure a field from 10 MHz to THz**
(we recently figured out how to get down to 100 kHz)

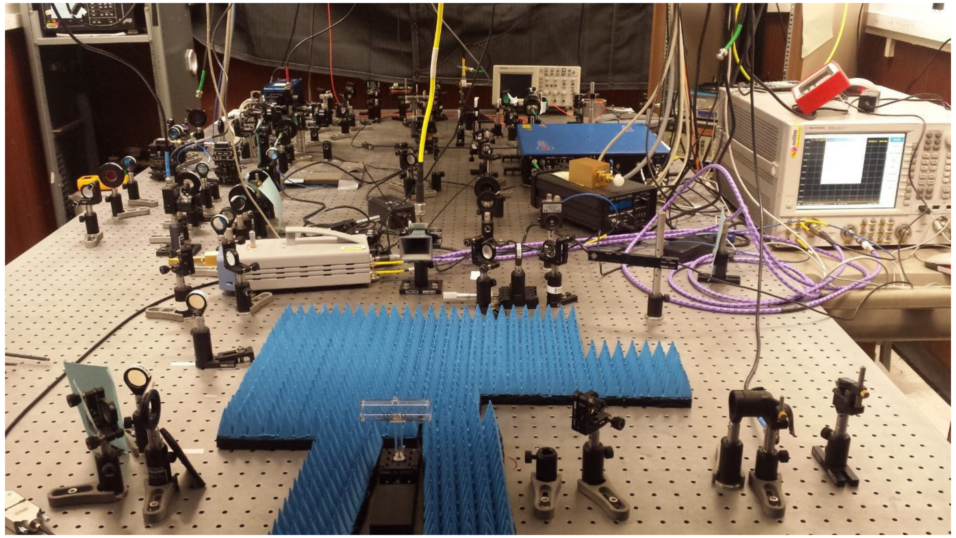


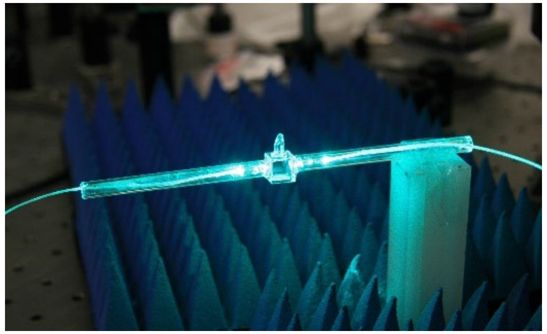


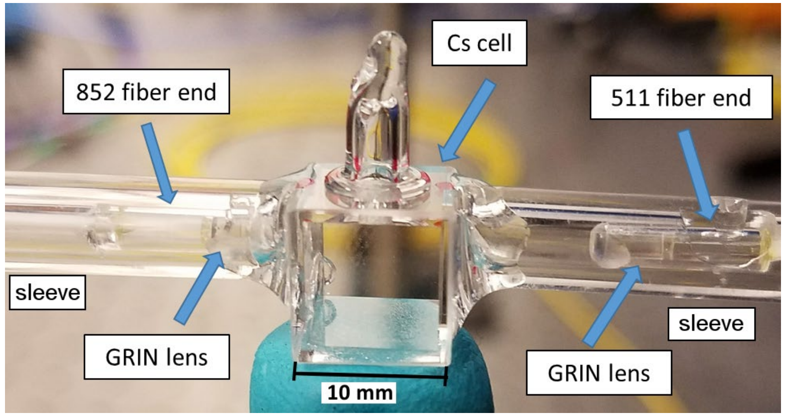

These results for >110 GHz are important from a calibration viewpoint.

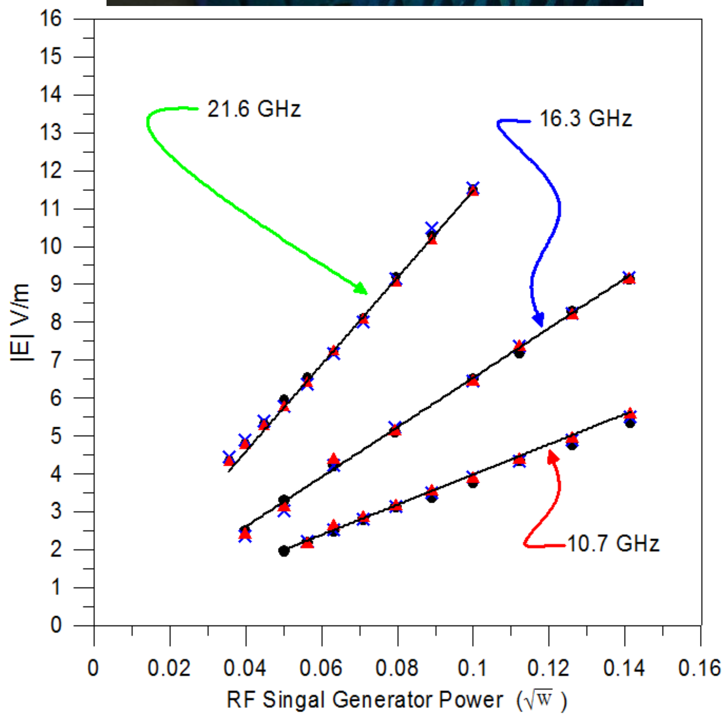
# Fiber-Coupled Probe: Moving Probe OFF Optical Table

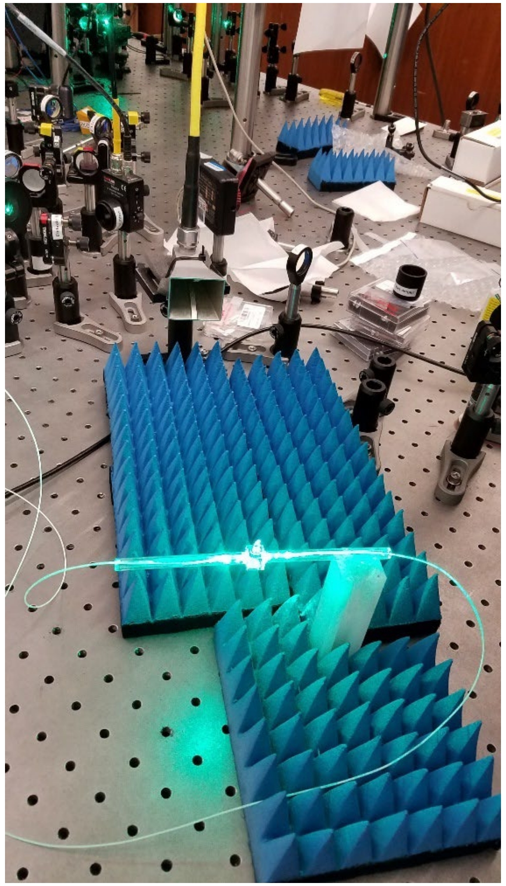
Simons et al., Applied Optics, 2018



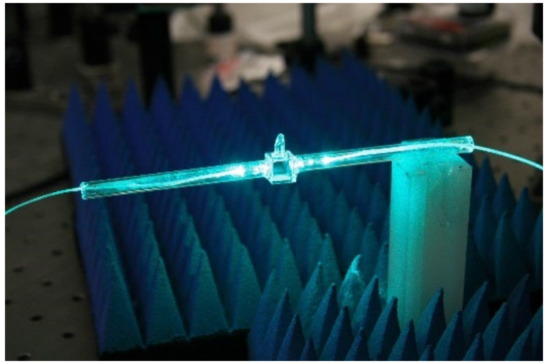


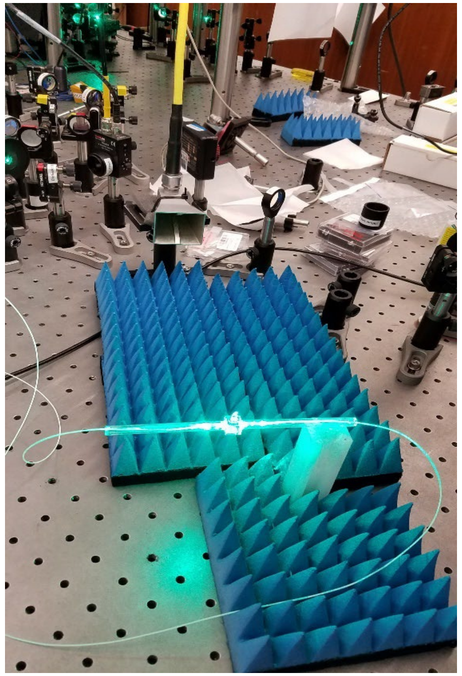


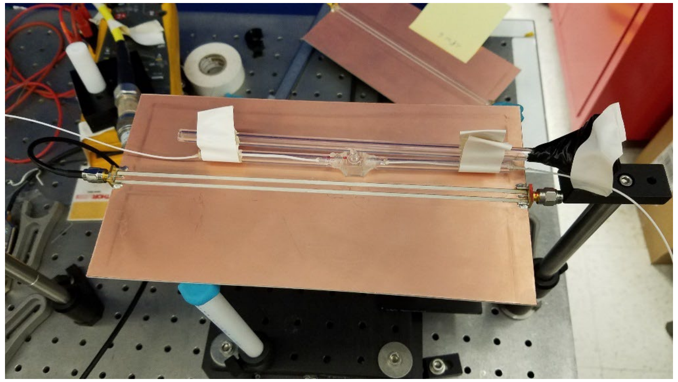



# Fiber-Coupled Cubic Cell (10 mm cube)

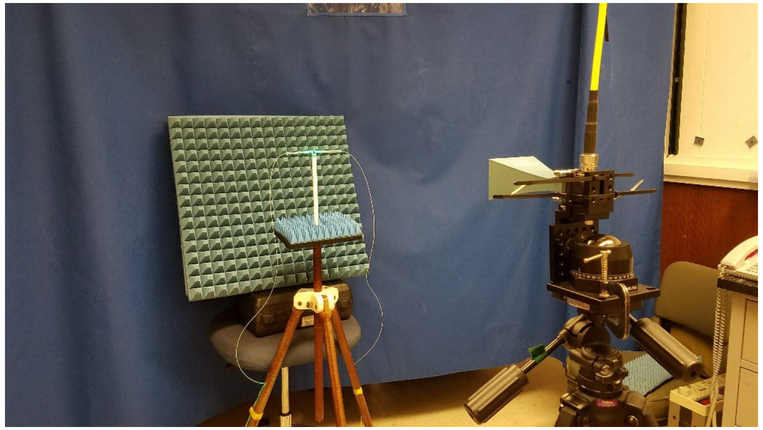




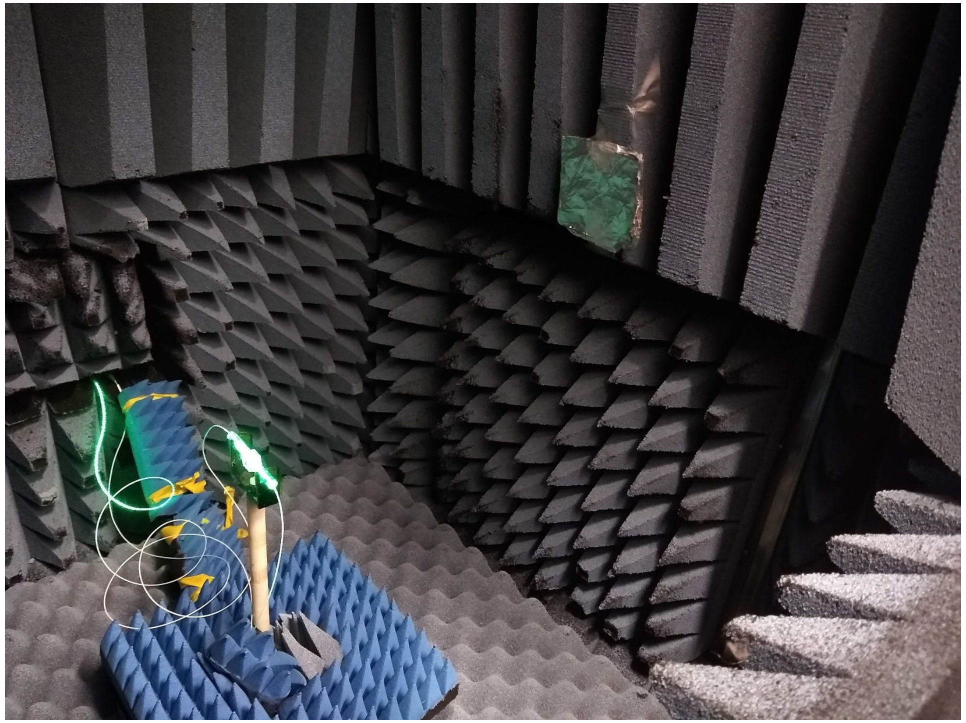
**Printed Circuit Board**



**Antenna Measurement**



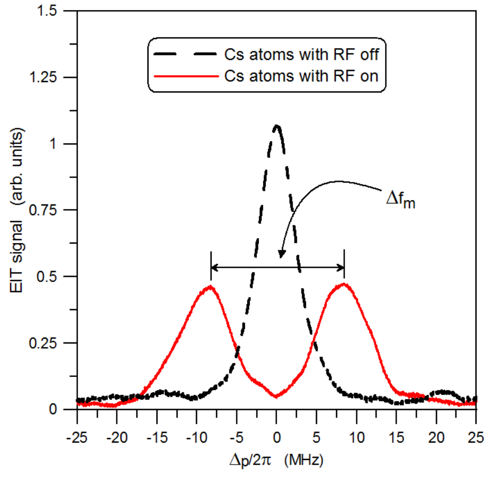
**IoT-Test Chambers (current IMS)**



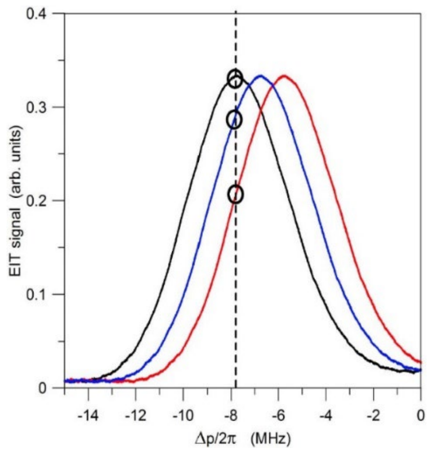
# Communication Receiver: Atom Receiver

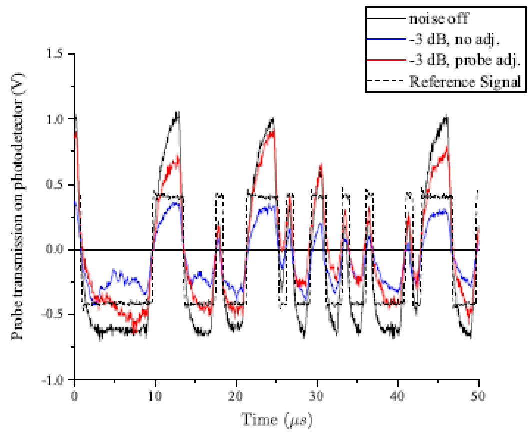
## AM/FM modulation is easy with the atoms!

CW carrier




AM/FM modulated carrier



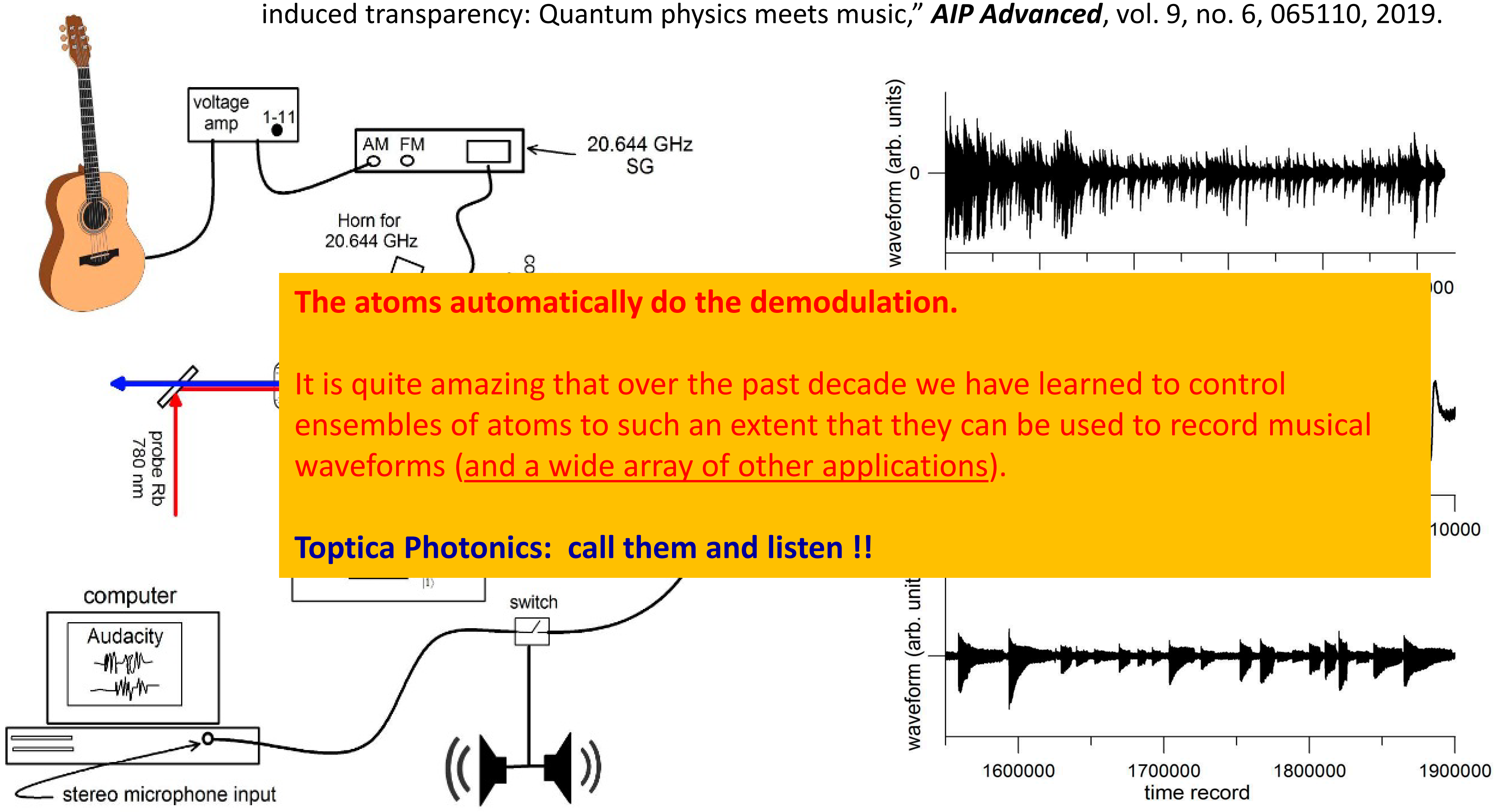




Several groups have demonstrated AM/FM reception:

- Data transmission:
  Song *et. al*, *Opt. Express*, 2019.
  Meyer et. al., *Appl. Phys. Lett.*, 2018.
  Simons et al, 2018.
- Atom Radio: Anderson and Raithel, 2019.
- Guitar Recording: Holloway et. al, *AIP,* 2019.
- Stereo Reception: Holloway et. al, *IEEE APS Mag.*, 2020.

# AM/FM detection----Just For the "FUN" of It: "Real-Time" Guitar Recording

C.L. Holloway, et. al., "A "real-time" guitar recording using Rydberg atoms and electromagnetically induced transparency: Quantum physics meets music," ***AIP Advanced***, vol. 9, no. 6, 065110, 2019.



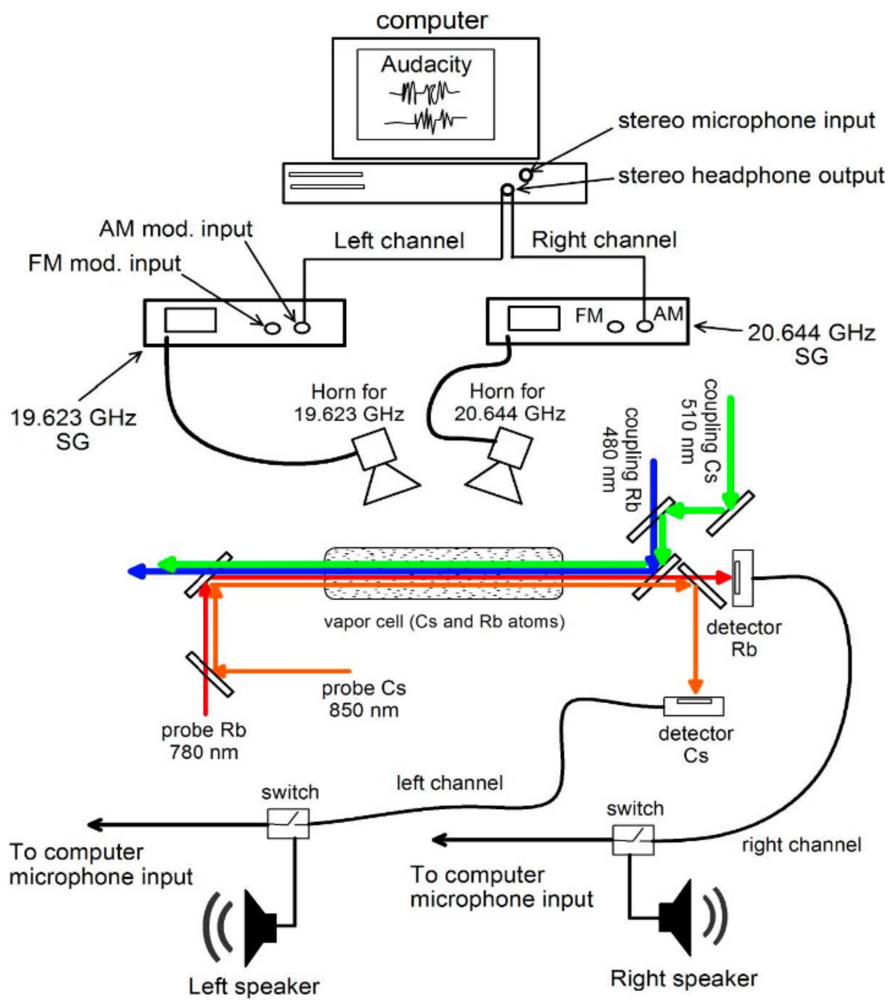

**The atoms automatically do the demodulation.**

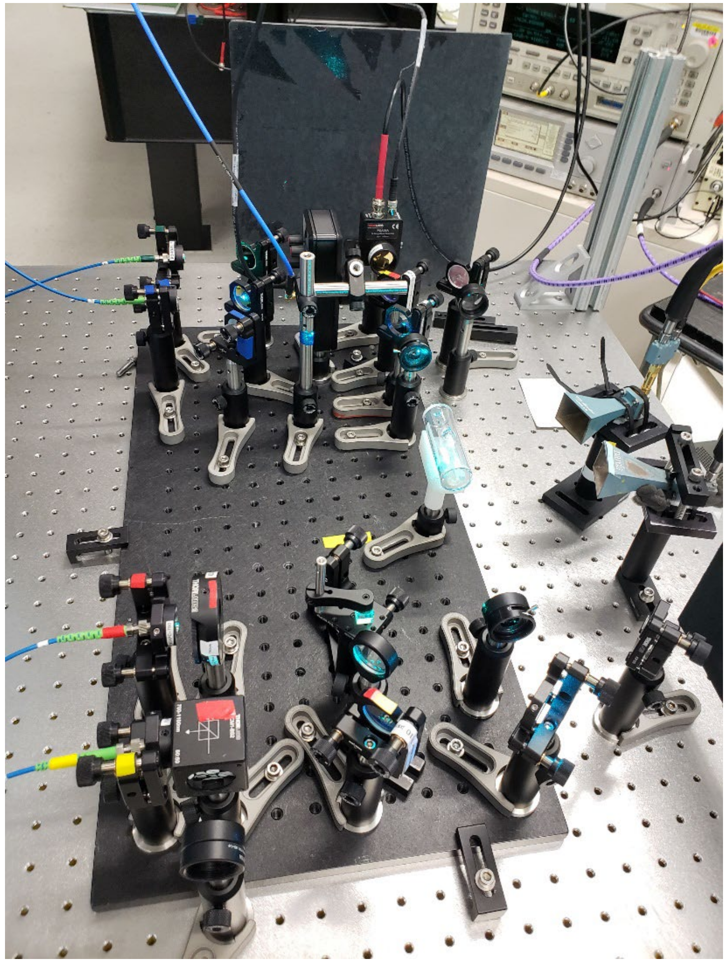
It is quite amazing that over the past decade we have learned to control ensembles of atoms to such an extent that they can be used to record musical waveforms (<u>and a wide array of other applications</u>).

**Toptica Photonics: call them and listen !!**

# Multi-Band/Channel Receiver: Dual Atomic Species for Stereo Reception

Instrumental on Rb atoms
Vocals on Cs atoms

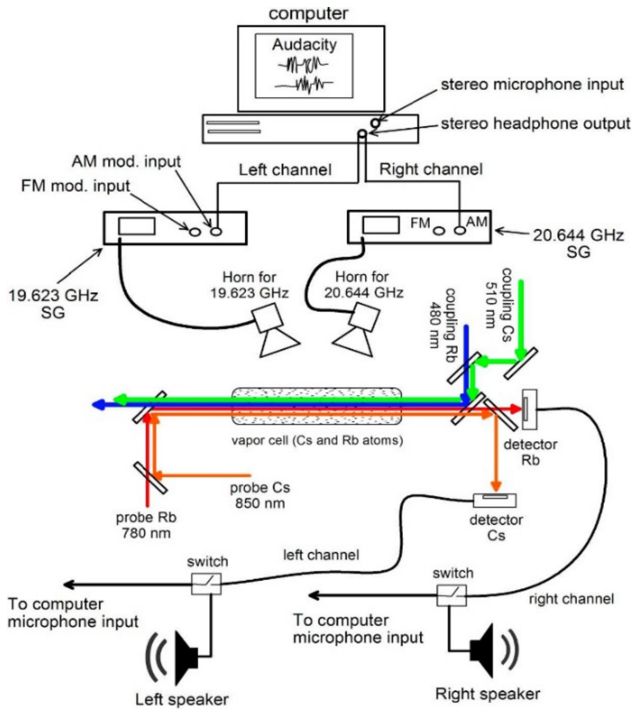


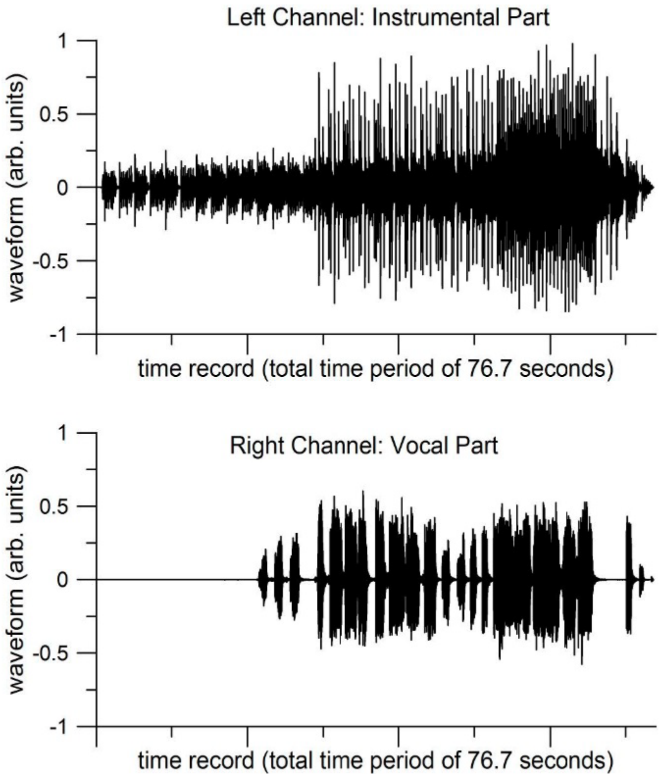
# Dual Atomic Species Stereo Reception

*Holloway et al., IEEE APS Mag., 2021.*

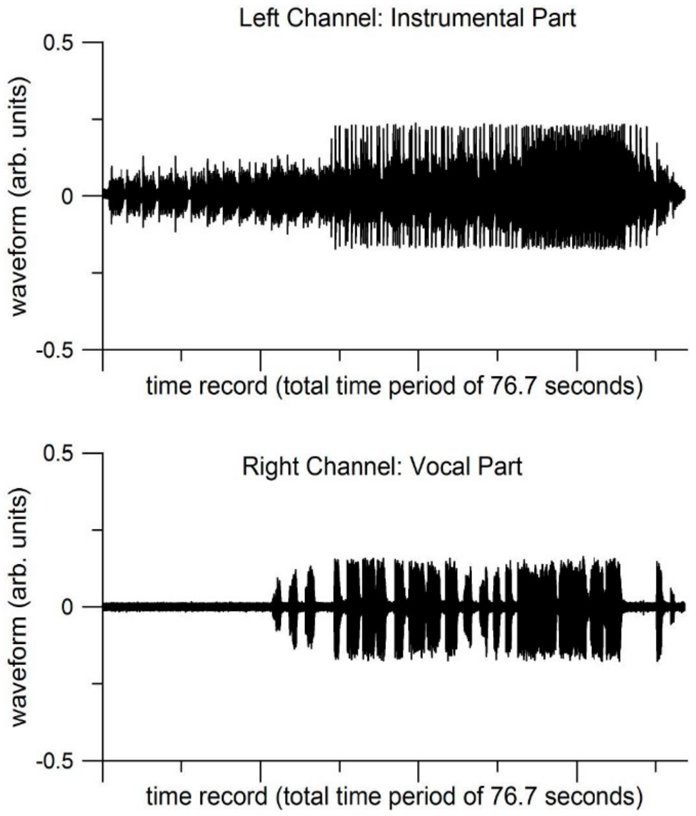
Instrumental on Rb atoms
Vocals on Cs atoms




Original Waveform

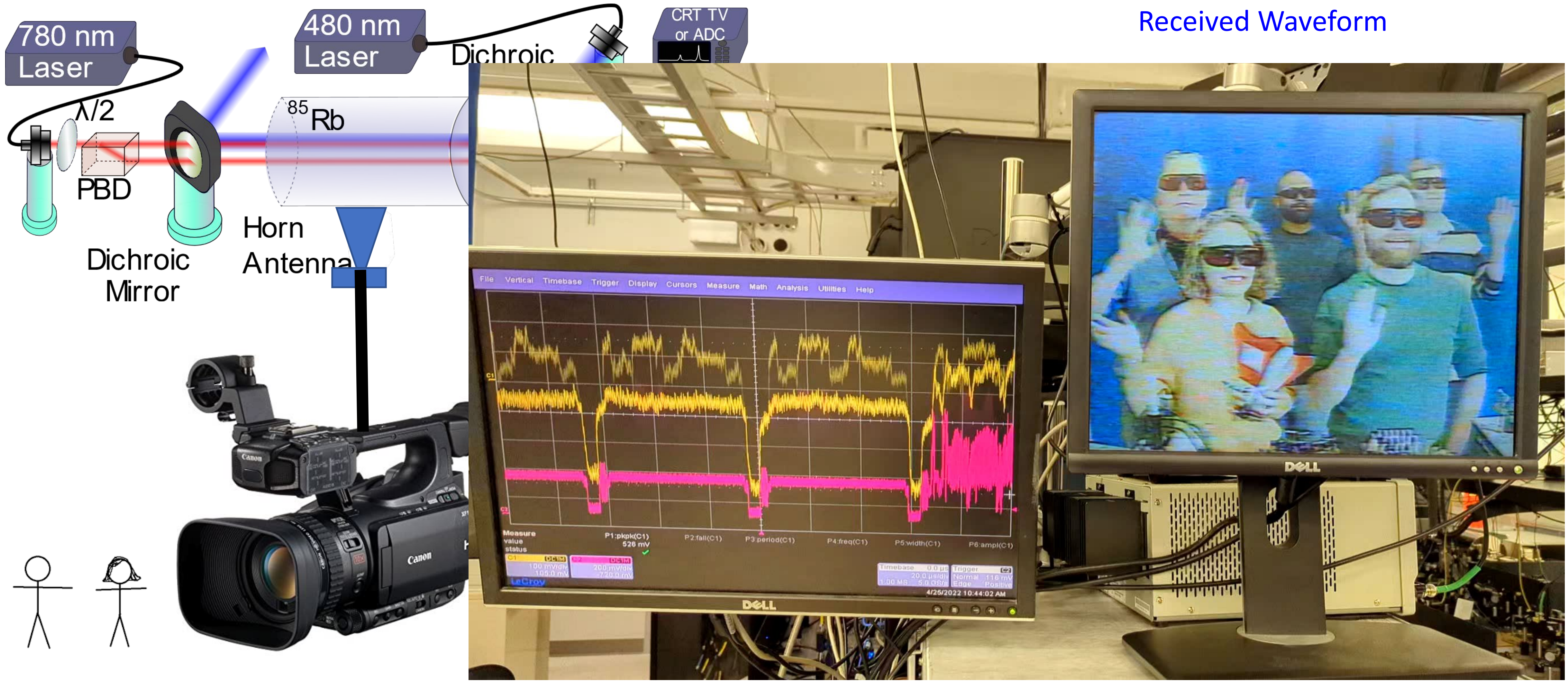



Received Waveform



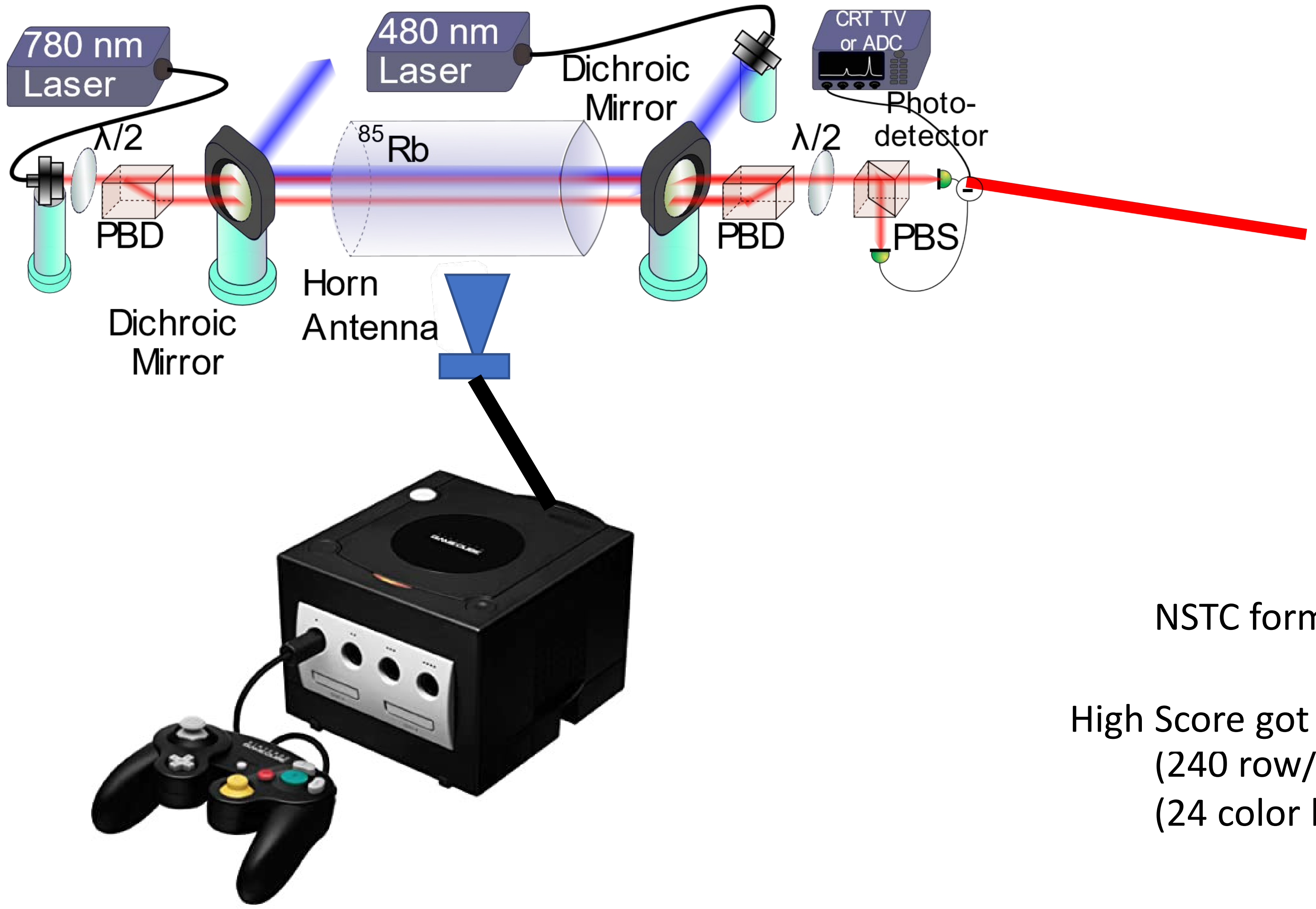

**AM/FM Stereo Receiver**

# Video Streaming with Quantum Sensors




*Prajapati, et al., AVS Quantum Science, August 2022*

# TV and Gaming with Quantum Sensors




NSTC format video signals

High Score got to be FIRST author on Paper
(240 row/frames) x (640 pixel/row) x (60 frames/s) x (24 color bits/pixel) = 221 Mbits/s

# *MORE:* Historical Perspective - 8 Year History

Amplitude: Most of this work was toward amplitude of the E-field by NIST and a few others.

Polarization: [Sedlacek et al., APL, 2013].

AM/FM Reception is possible.

The missing link was "phase" !

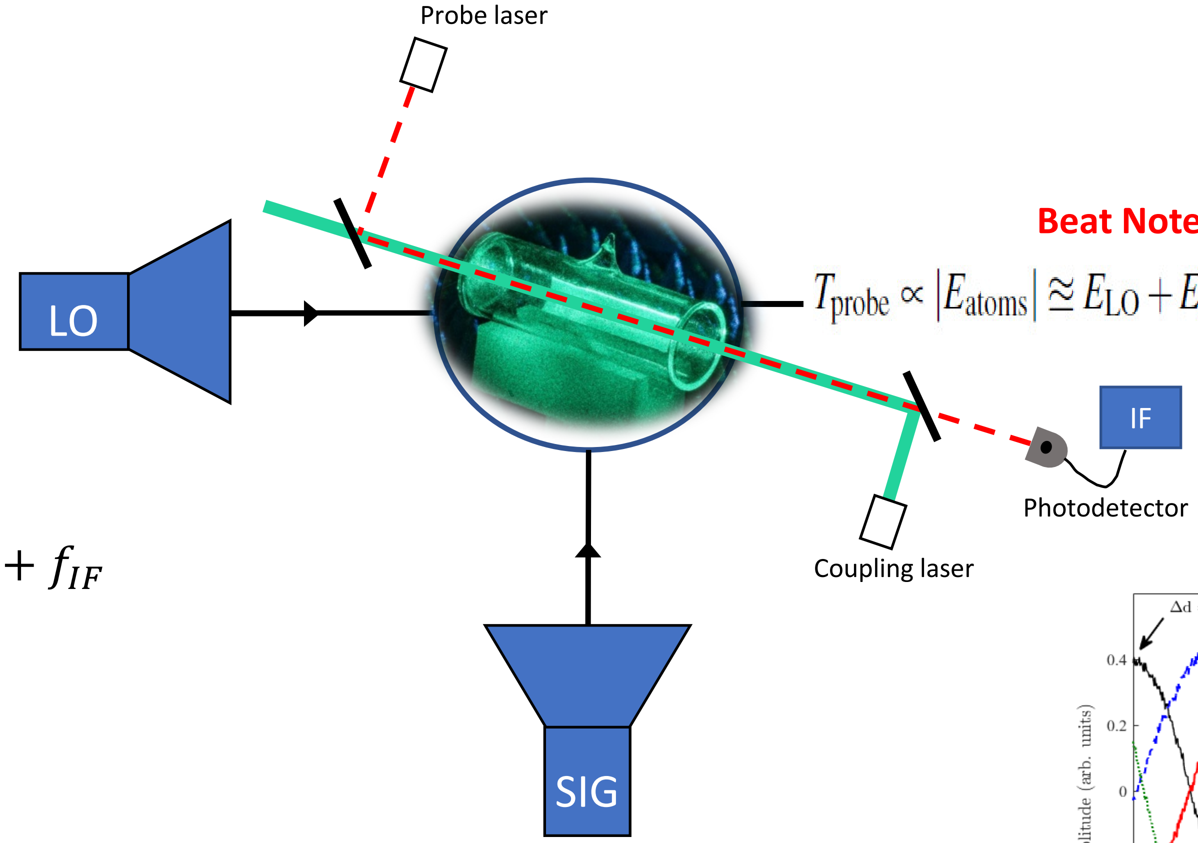
Phase: NIST-[Simons et al., APL, 2019].

We can now ***fully characterize*** a radio frequency field, in that the amplitude, phase, and polarization of the field can be determined in one compact quantum-based sensor.

We can now start looking at a wide array of applications.

# *Phase Measurements : Rydberg Atom-Based Mixer*

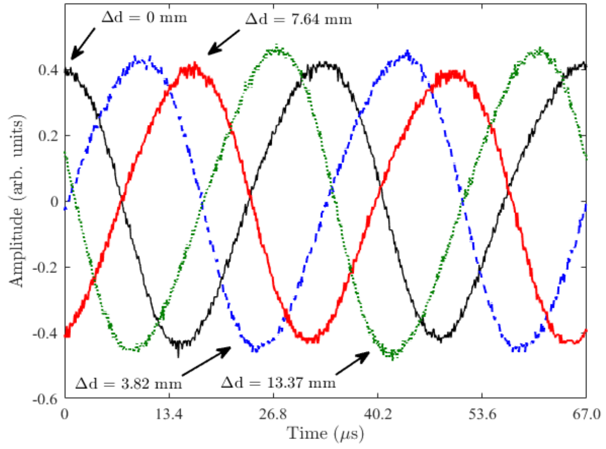
*Simons et al., APL, 2019*



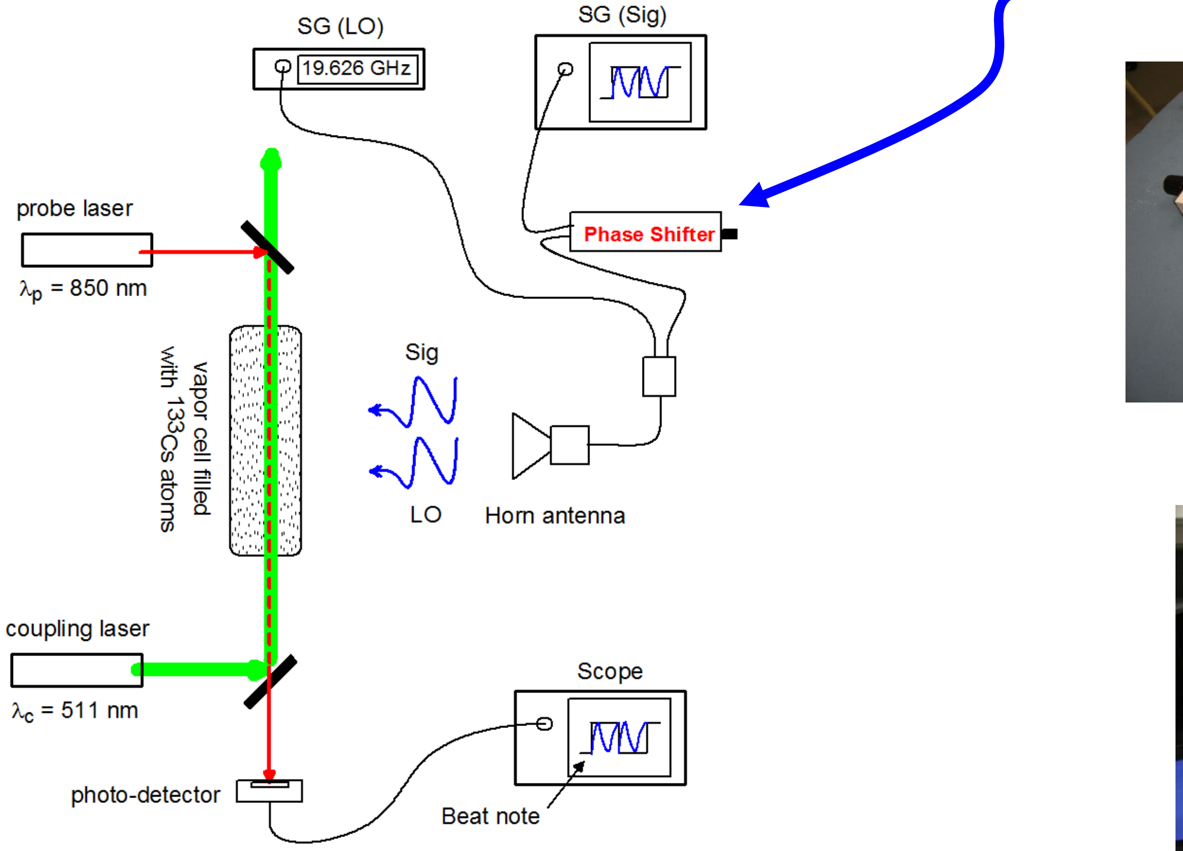

$$T_{\text{probe}} \propto |E_{\text{atoms}}| \approx E_{\text{LO}} + E_{\text{SIG}} \cos(\Delta\omega\, t + \Delta\phi)$$

$$f_{SIG} = f_{LO} + f_{IF}$$

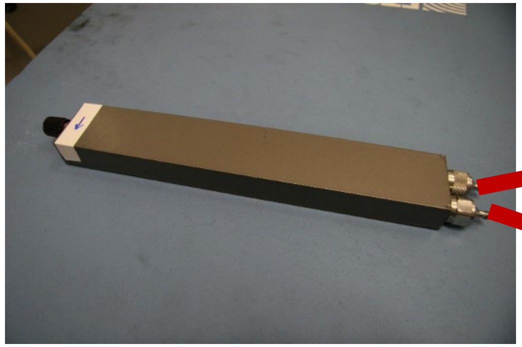
**Beat Note**



# Measuring the Phase of a Phase Shifter



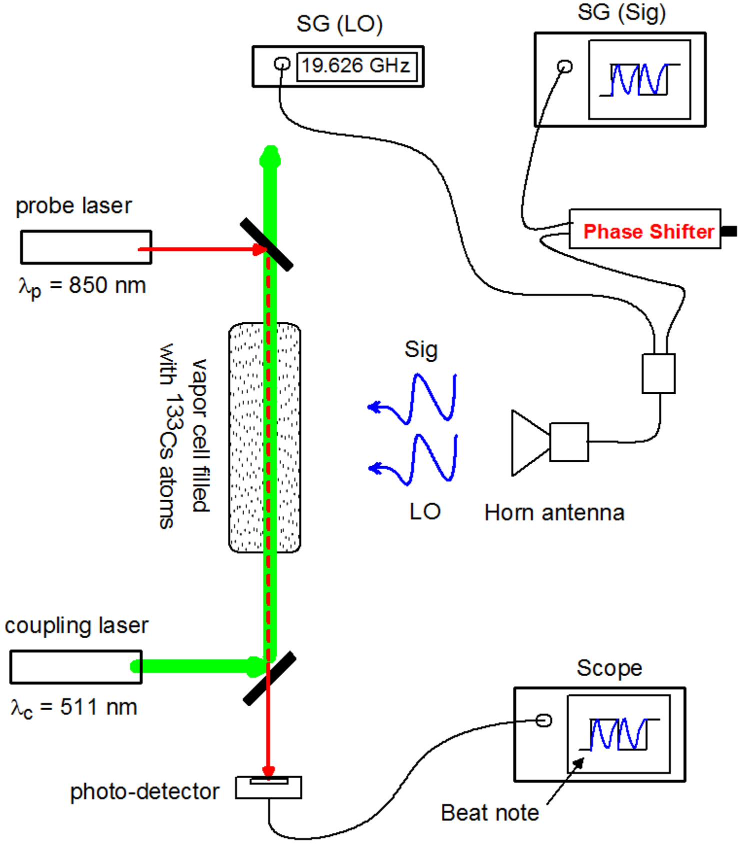

**Variable Phase Shifter**



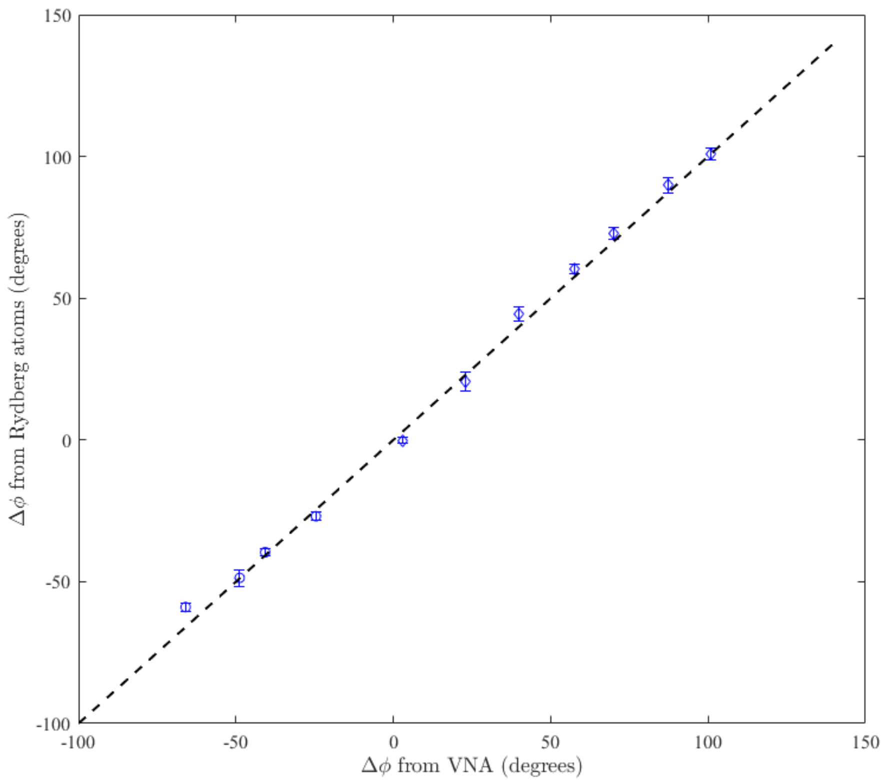
Vector Network Analyzer

# Measuring the Phase of a Phase Shifter

*Simons et al., APL, 2019*




**CW carrier: Phase Shift**

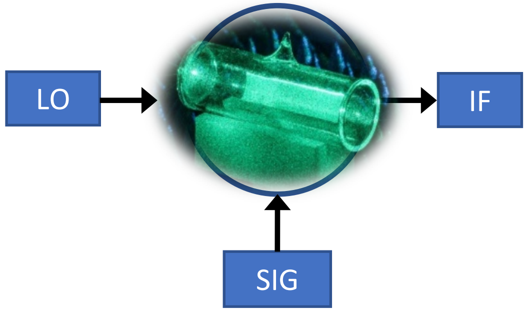



**About 1 degree resolution!**

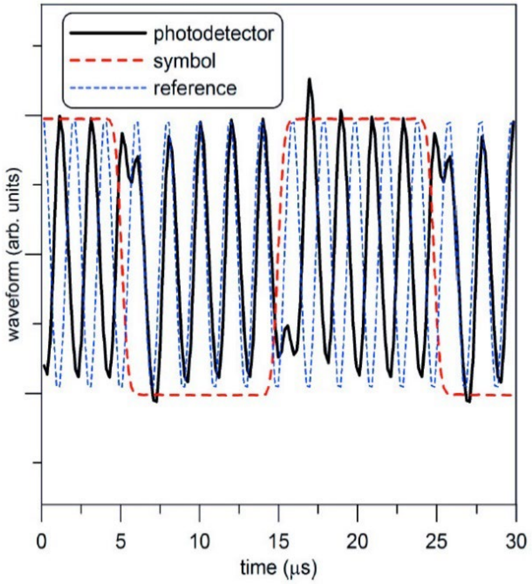
# Phase Modulation for Communications (Phase Modulated Carrier)

*Holloway et al., IEEE AWPL, 2019*

2047 symbols steam




BPSK (Binary Phase Shift Keying)



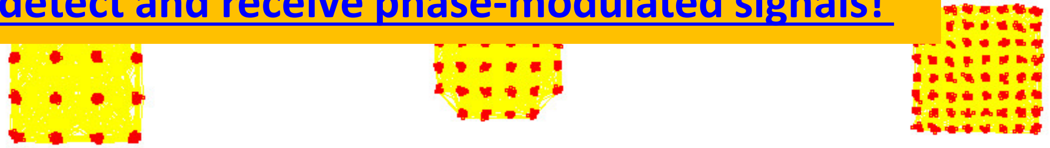

What is the Advantage?

No down-conversion circuity is needed:

**The atoms do the down-conversion automatically.**

**We can detect and receive phase-modulated signals!**

s)



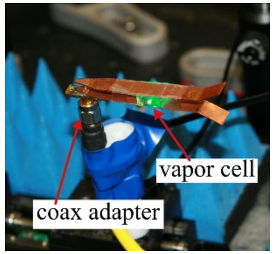
16 QAM
(16 phase states)
4 bits/symbol

32 QAM
(32 phase states)
5 bits/symbol

64 QAM
(64 phase states)
6 bits/symbol

# Cell Phone detection

# Sensor/Receiver




We need to keep in mind that the Rydberg atom-based receiver/sensor, in effect, replaces the receiving antenna and front-end components and electronics that are used in a conventional receiver system.

For example, the Rydberg atoms perform some of the same functions as both antennas and demodulators all in one, so this needs to be considered when comparing with traditional systems.

Fully characterize the RF E-field in one compact vapor cell:

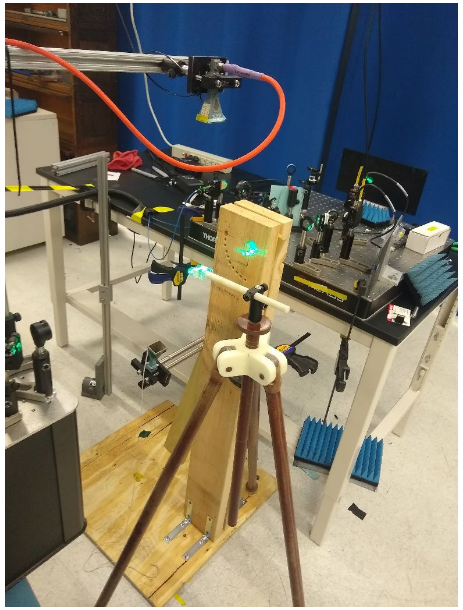
- Magnitude
- Phase
- Polarization

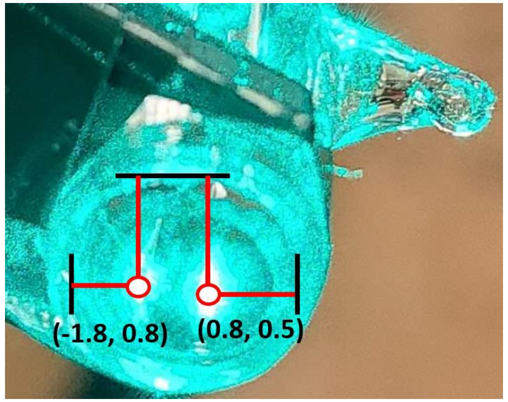
1. Detection of fields and modulated signals
2. Direction of arrival
3. Vector fields
4. Waveform characterization (CHIRP signals)
5. DC to THz detection
6. Very Weak fields / Very Strong fields

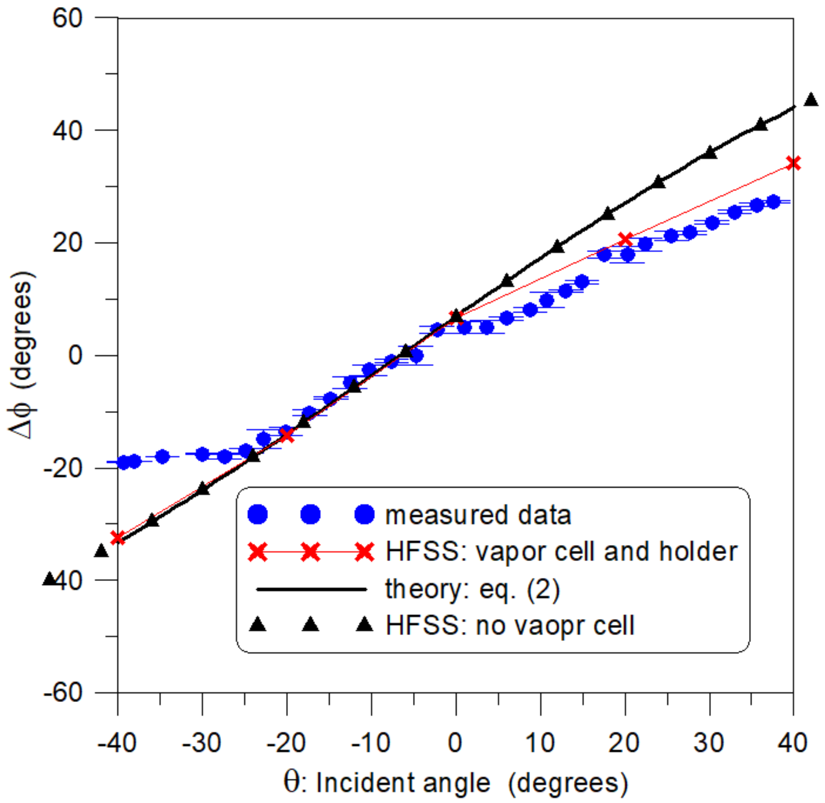
# Proof-of-Concept Angle-of-Arrival Measurements with Rydberg Sensor

*Robinson et al., APL, 2021*

**The angle-of-arrival can be determined by measuring the phase-difference between the two locations where the laser beams are located.**





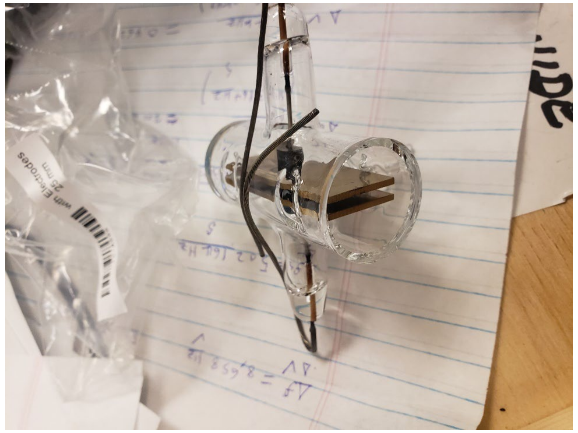




- These results show proof-of-concept for measuring angle-of-arrival of an RF source.
- While discrepancies between theory and measurements are seen, these results show that it is possible to determine the angle-of-arrival.
- It is believed that the discrepancies between theory and measurements is due to RF internal cell resonances, causing additional phase shifts (different for different cell sizes).
- We think we have ways of correcting or calibrating out these discrepancies.

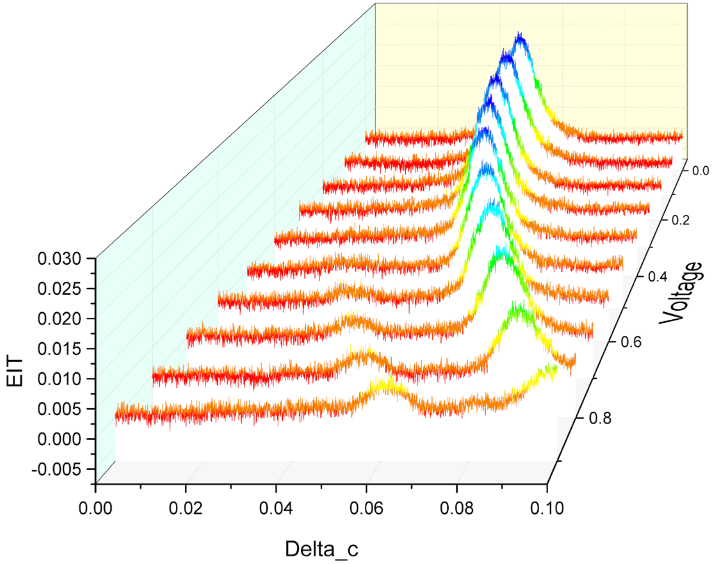
# SI Traceable AC/DC Voltage Standards

*Holloway, et al., AVS Quantum Sciences, 2022*

**Electrodes in Vapor Cell**



**AC/DC Stark shifts**




$$|E| = \sqrt{\frac{4\,\Delta f}{\alpha}}$$

$$V = |E|\ d$$

While a Rydberg atom-based approach will not have the uncertainties of the benchtop Josephson voltage standard at 1 V, Rydberg based voltage standards offer the possibility of compact, room temperature, cheap (SWAP-C) alternatives for a large range of AC/DC voltages.

Amplitude: 1V – 10V, but possibly could be extended to 1000V at reduced accuracy. This is limited by the choice of Rydberg state and level mixing that occurs at elevated voltage.

Uncertainty: Probably 1e-5 fractional uncertainty, and 1e-7 long-term stability, limited by fringing fields.

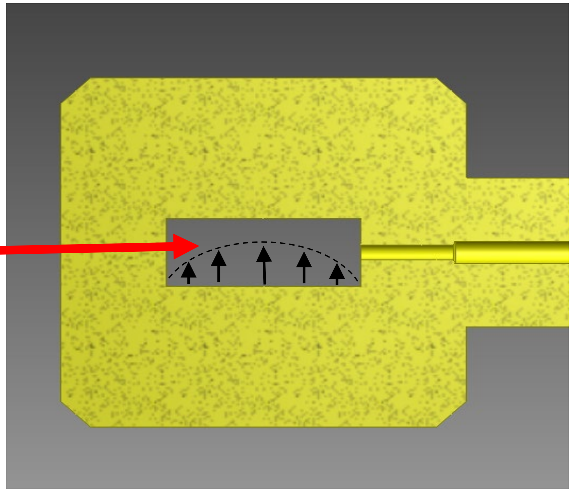
# Traceable RF Power Measurements

TE$_{10}$ mode in rectangular waveguide

only allowed mode at measurement frequency

$$\vec{E} = E_0 \sin\frac{\pi x}{a}\left\{e^{-j\beta z} + \Gamma e^{j\beta z}\right\}\hat{y}$$

½ sinusoid in x, constant in y, partial standing wave in z



Transmitted Power

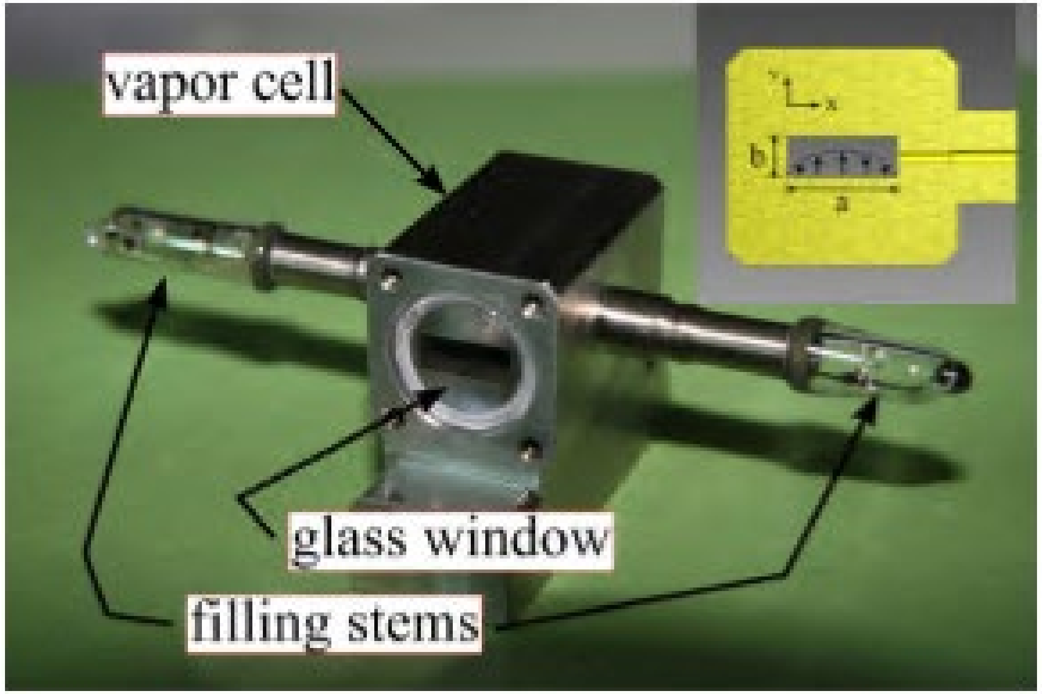
$$P_{trans} = E_0^2\frac{ab}{4}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{1-\left(\frac{c}{2af}\right)^2}$$

Depends on $E$, physical constants ($\varepsilon_0$, $\mu_0$, $c$), and geometry ($a$,$b$)

We measure E with the Rydberg atoms and power is traceable to Planck's constant.

# Traceable RF Power Measurements

*Holloway, et al., APL, 2018*

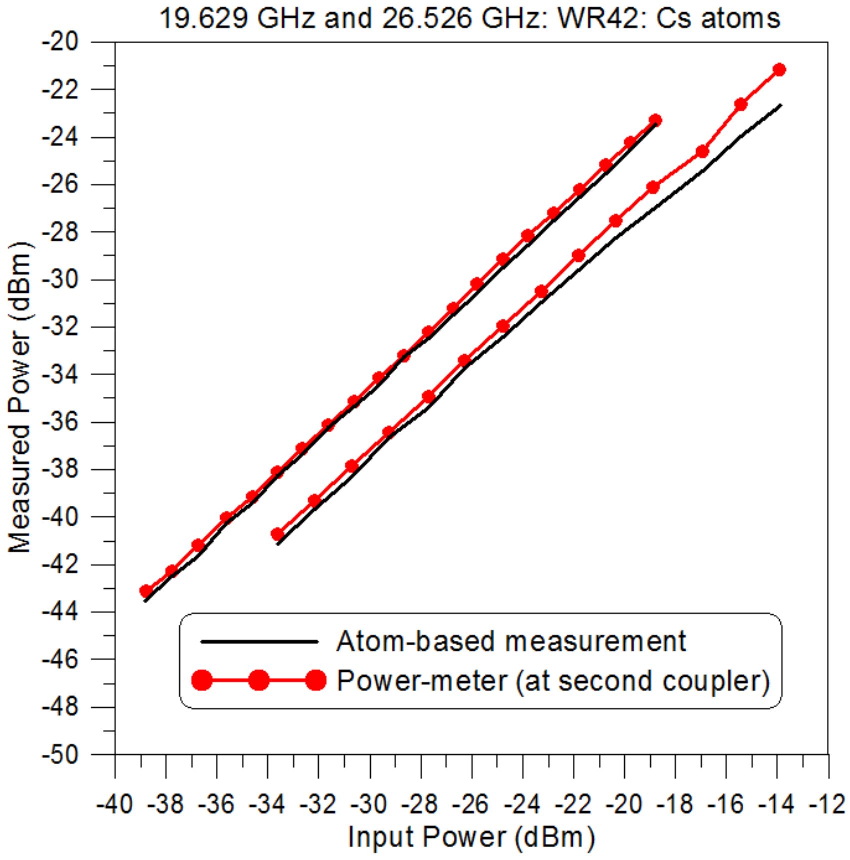



TE$_{10}$ mode in rectangular waveguide

$$\vec{E} = E_0 \sin\frac{\pi x}{a}\{e^{-j\beta z} + \Gamma e^{j\beta z}\}\,\hat{y}$$

Transmitted Power

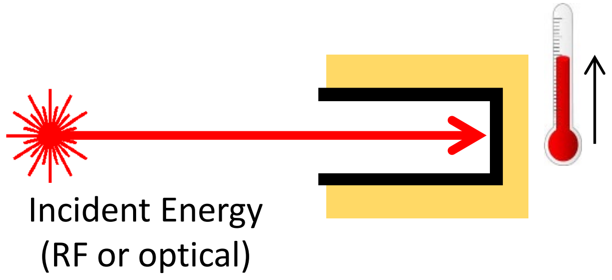
$$P_{trans} = E_0^2 \frac{ab}{4}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{1-\left(\frac{c}{2af}\right)^2}$$



# New Paradigm for RF Power (Calibrated Source)

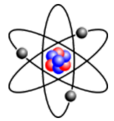
**Current State of the Art**

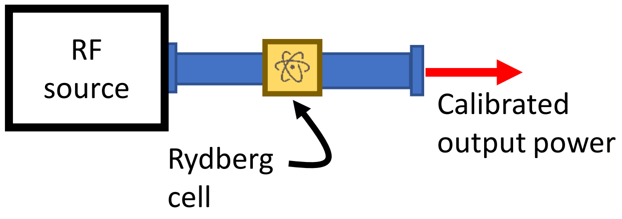
- Energy meter
- Absorption-based
- Energy $\propto \Delta T$
- Calibration through the power meter



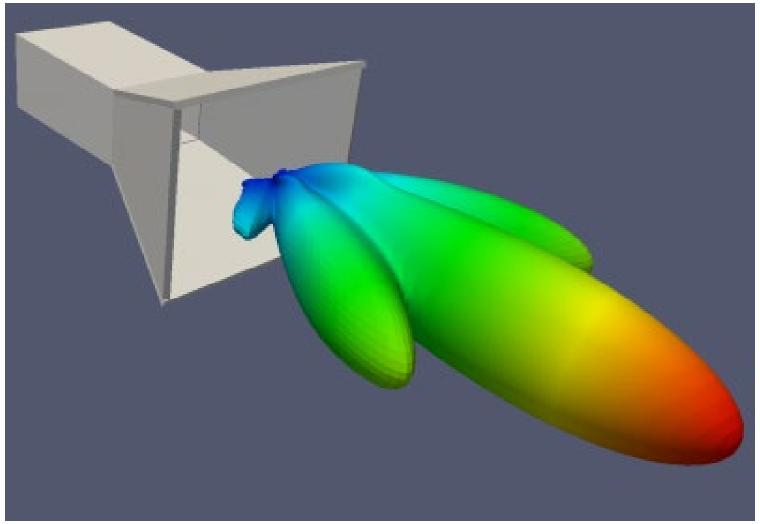

**Outcome after IMS: Real-time "*in situ*" traceability**

In Situ RF (Rydberg cell)



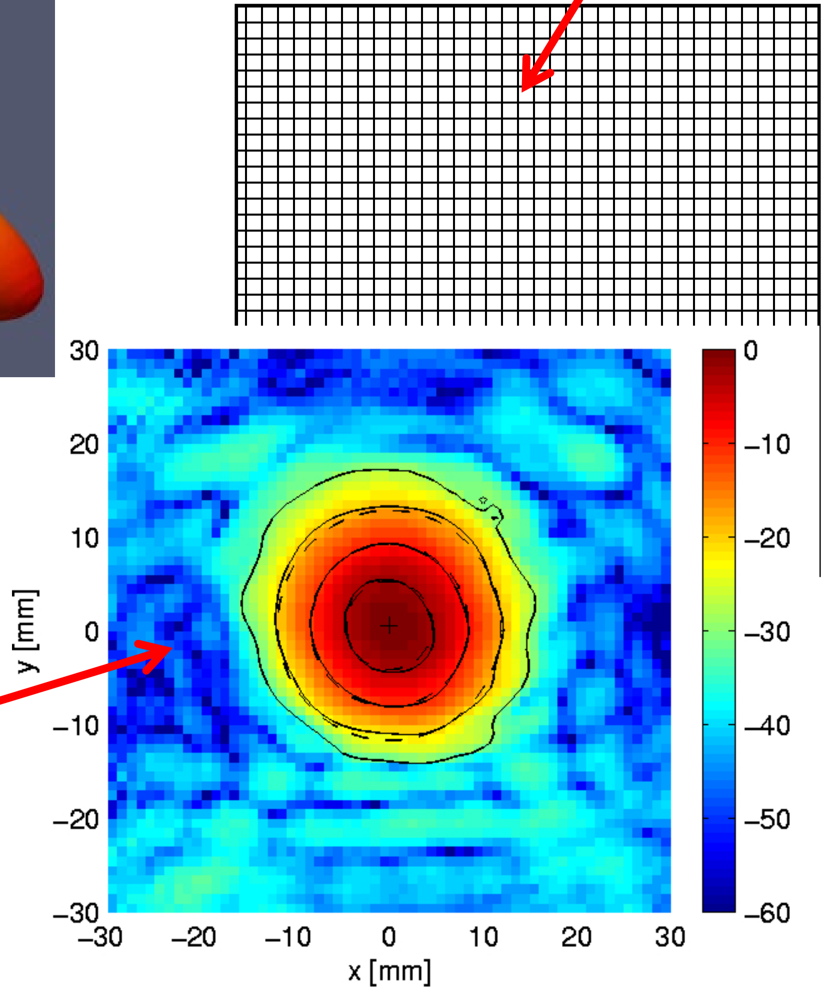


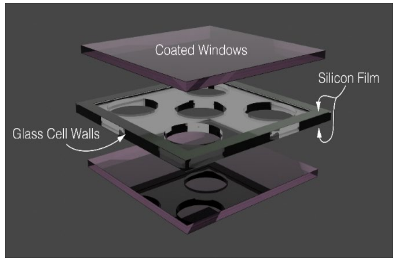
# RF Atomic-Vapor Cell (AVC) Camera

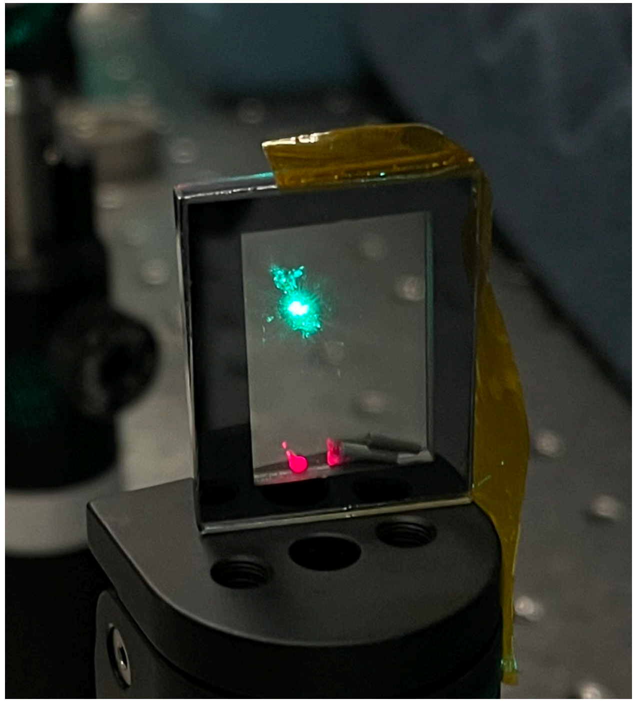


AVC array

Vapor cell pixel



RF Image

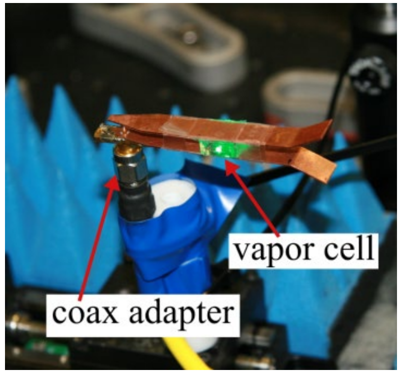
RF AVC Camera

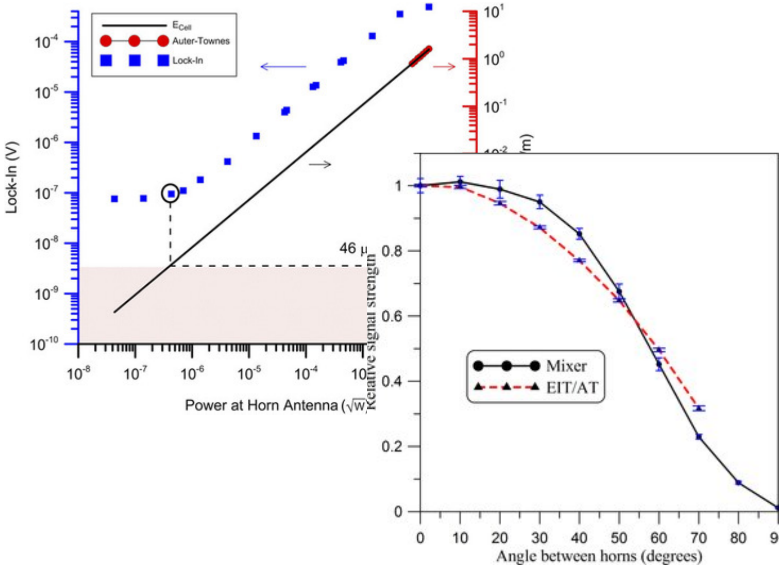
or

**RF Beam Profiler**

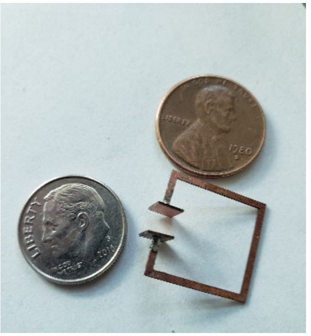
# Embedded Sensor Head: Weak Field Detection and Waveform Analyzer

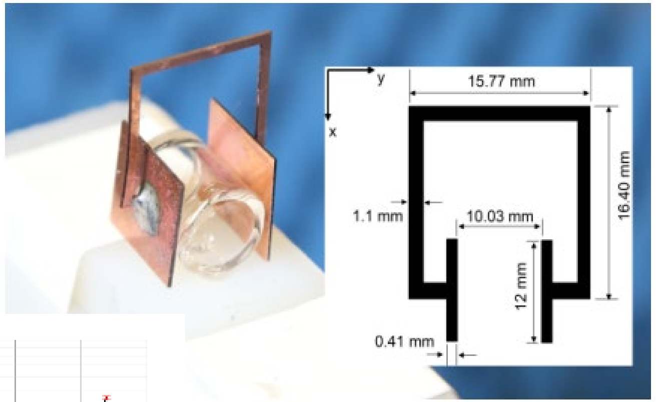
Simons et al., IEEE Access, 2019

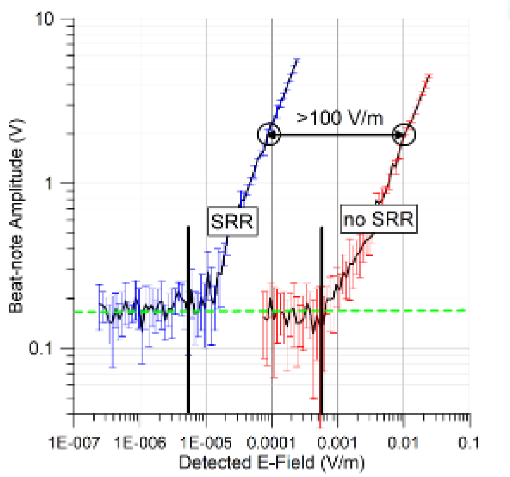



Holloway et al., APL, 2022



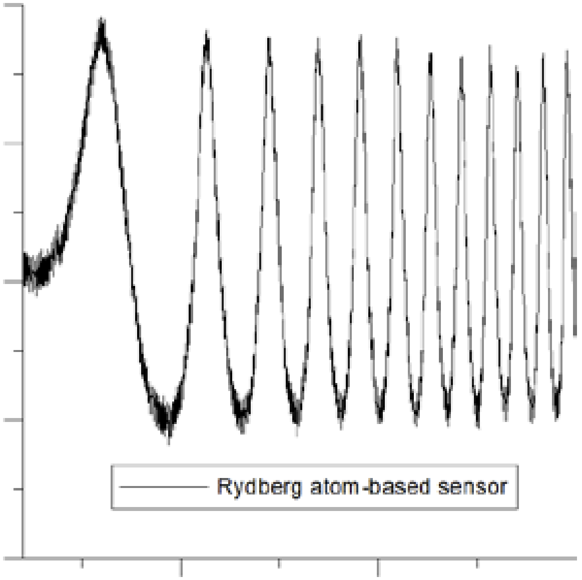



Field Enhancement

**New Recorded Sensitivity by NIST:**
**3 μ V/m Hz$^{-1/2}$**

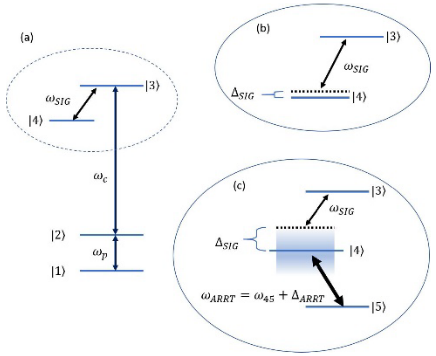
Waveform Analyzer:
CHIRP waveform

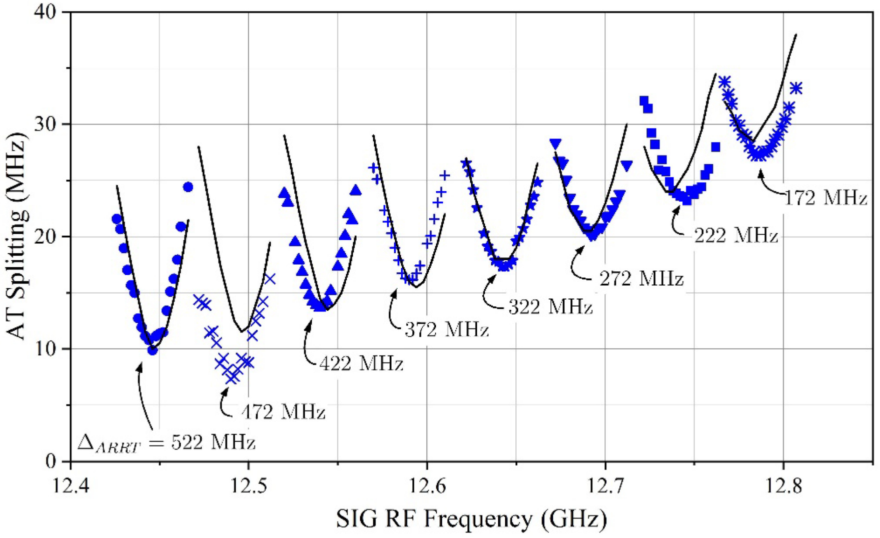


# Rydberg Engineering Through State Dressing : Continuous Frequency and Weak Fields

Simons, et al., *“Continuous radio frequency electric-field detection through adjacent Rydberg resonance tuning”* PRA, August 2021

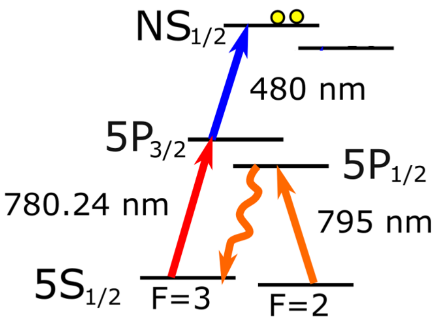
By using a second RF source we can “dress” (or tune) the Rydberg state to detect any RF frequency.

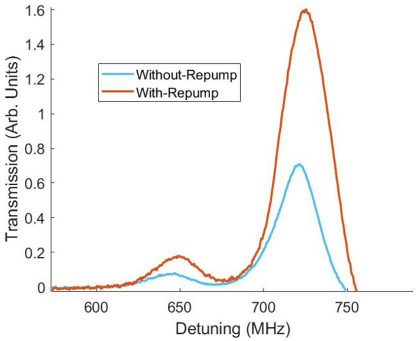


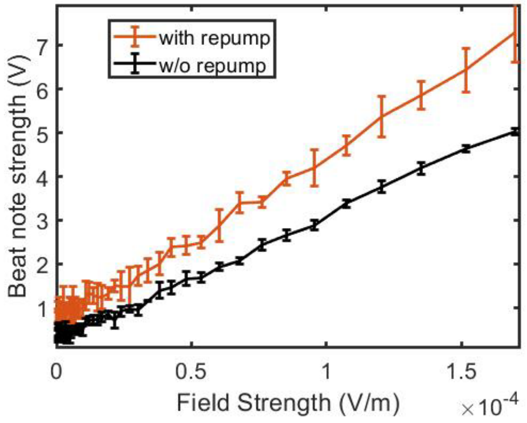




## Optical Repumping: Weak Field Detection

Prajapati, et al., APL, 2021



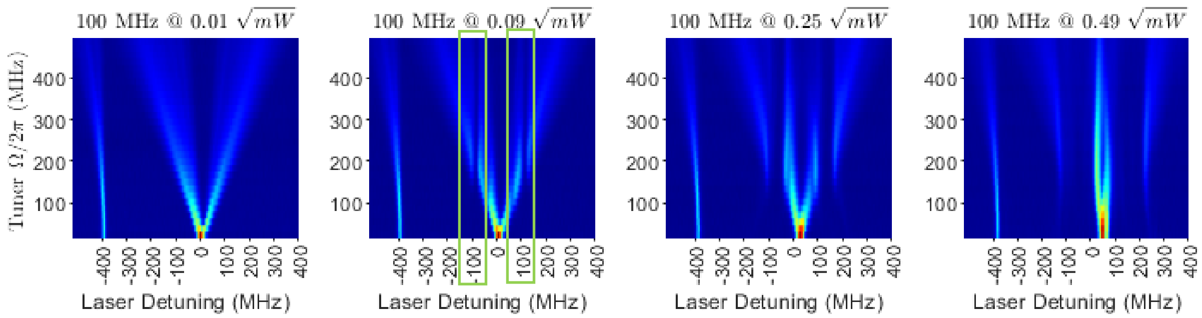



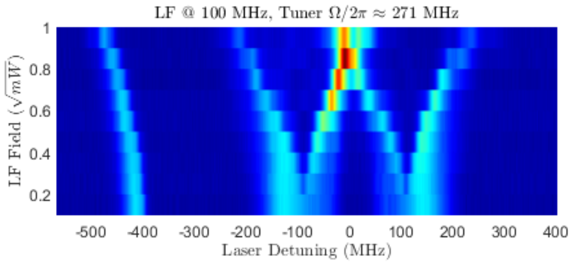




**New Recorded Sensitivity:**
**3 μ V/m Hz$^{-1/2}$**

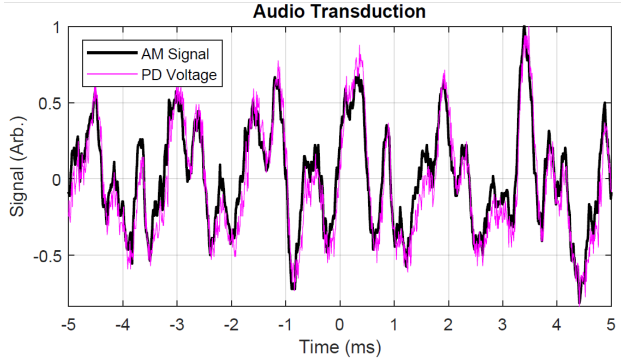
# Rydberg Engineering: “Low-Frequency” detection

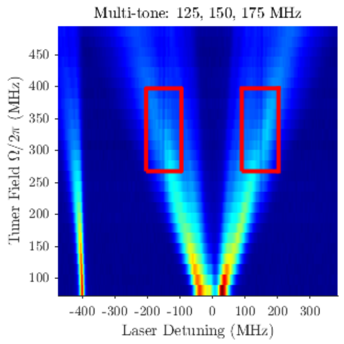
- Idea: Tune splitting $\Omega_{tuner}$ to match applied Low Frequency $\omega_{LF}$
- Measure $|E_{LF}|$ via non-linear “Floquet” sideband states’ absorption dip
- Enables new experiments:
  - DC field component (at half frequency)
  - Multiple tones “Spectrum analyzer”
  - Audio transmission: AM mod on LF field
- Takeaways:
  - Receives long waves in a cm-sized sensor
  - Far off-resonant Low Frequency fields are made “pseudo-resonant” using tuning field

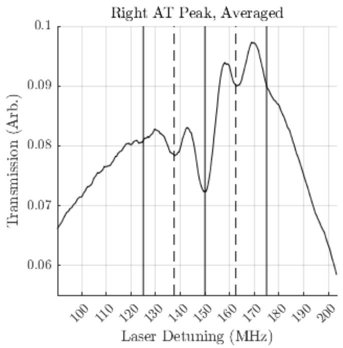


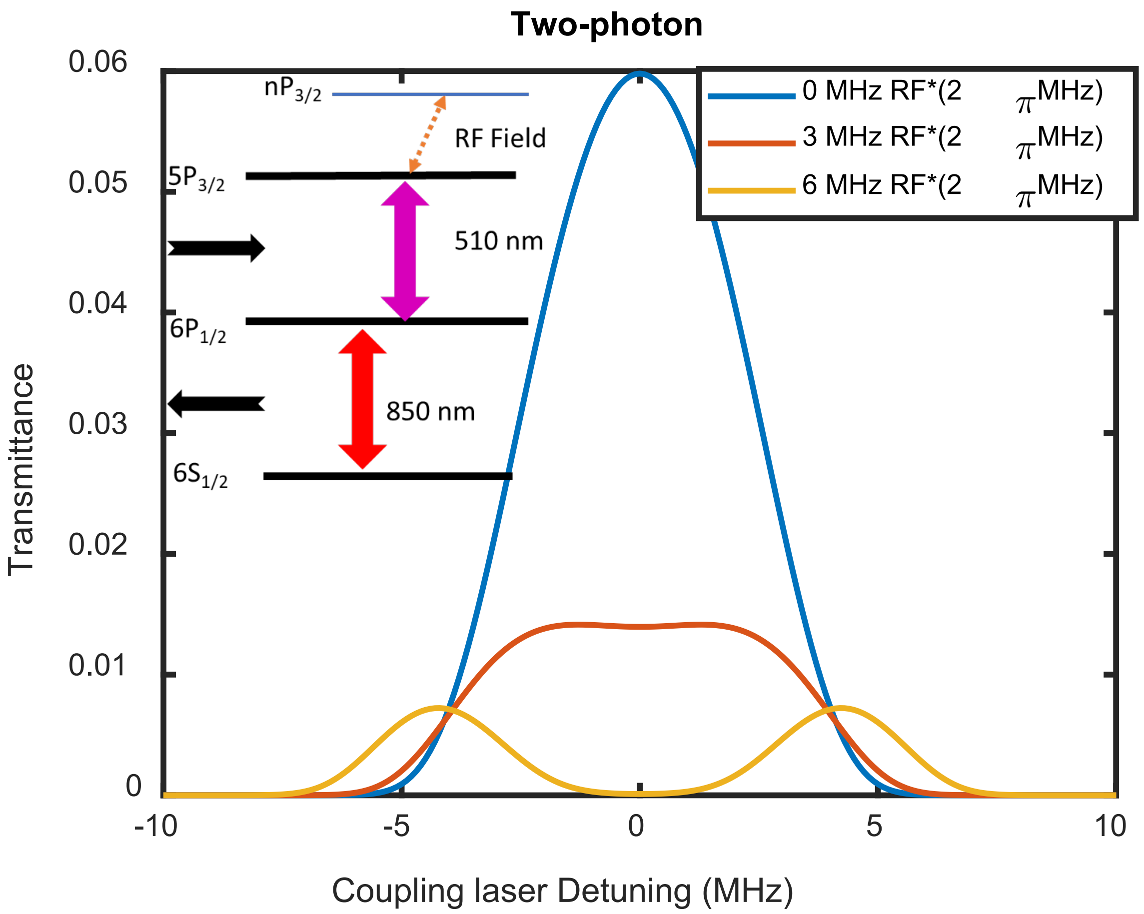

Non-linear LF splitting at constant $\Omega_{tuner}$ splitting

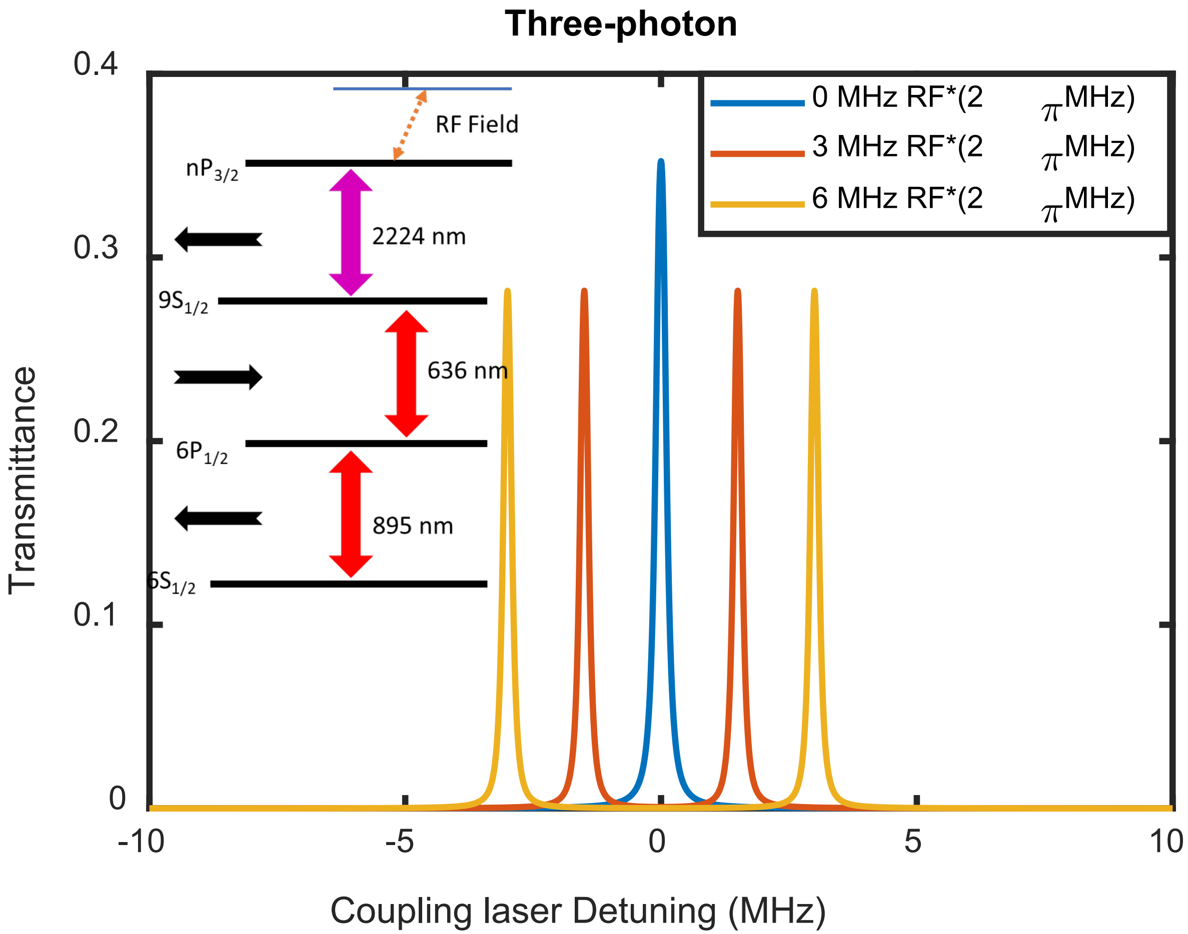


# Two photon vs. three photon approach

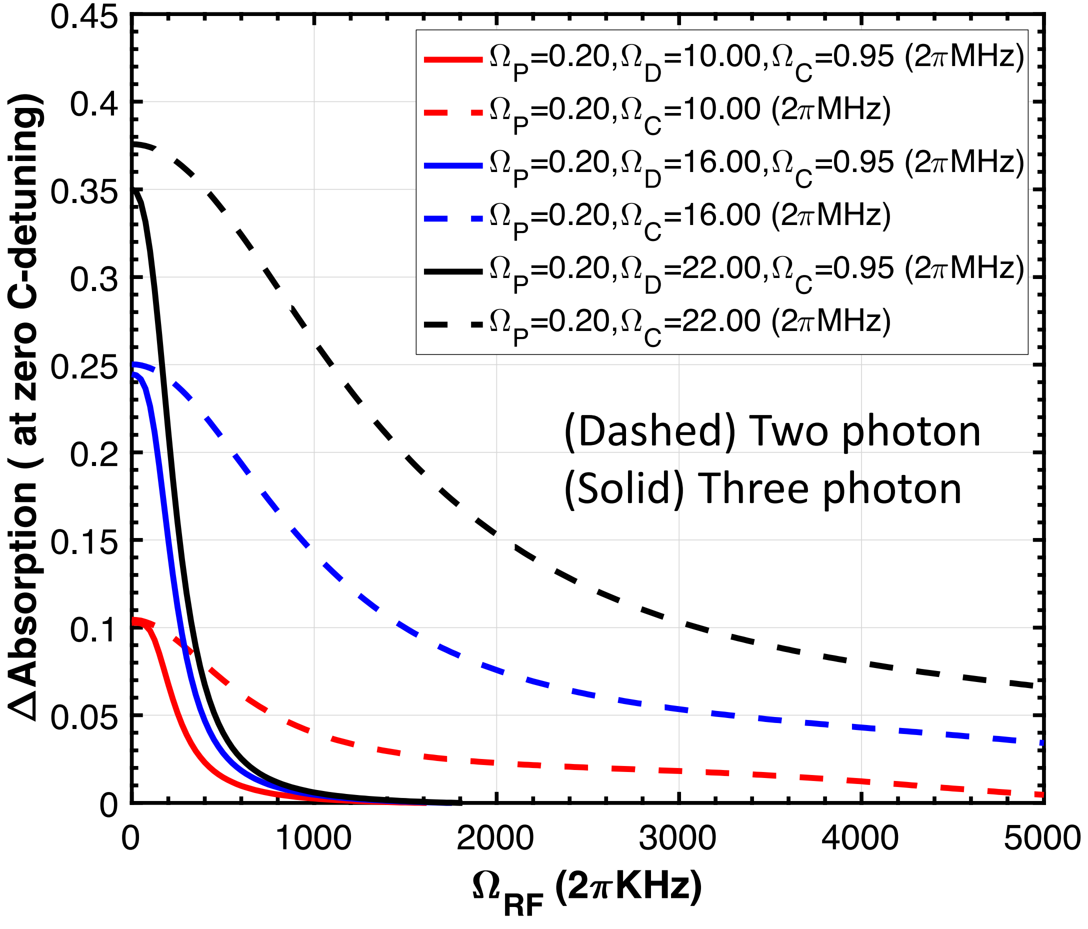


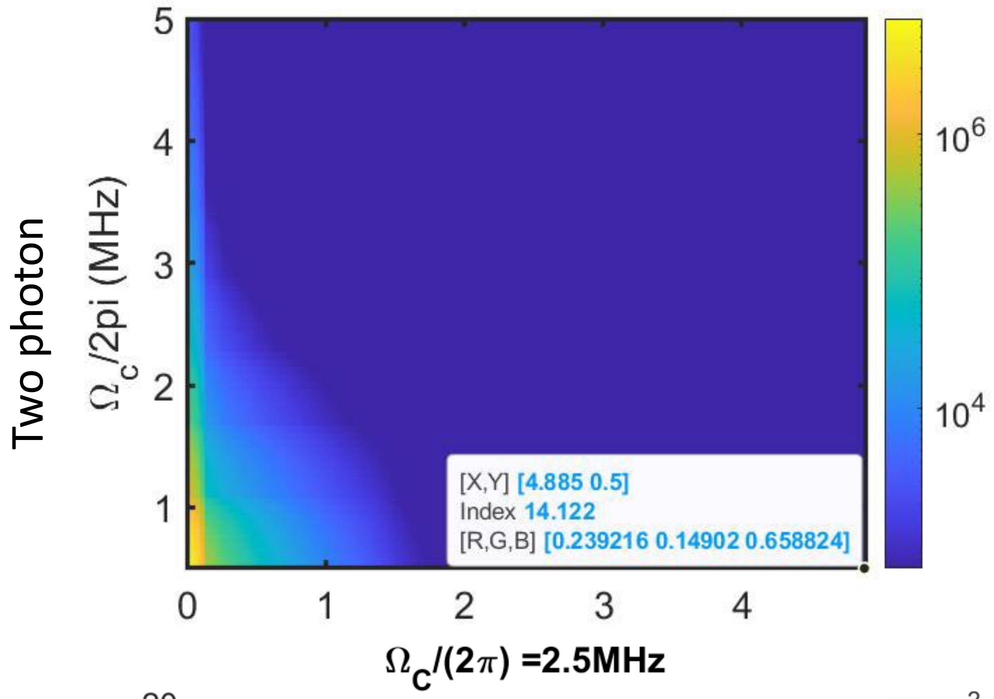



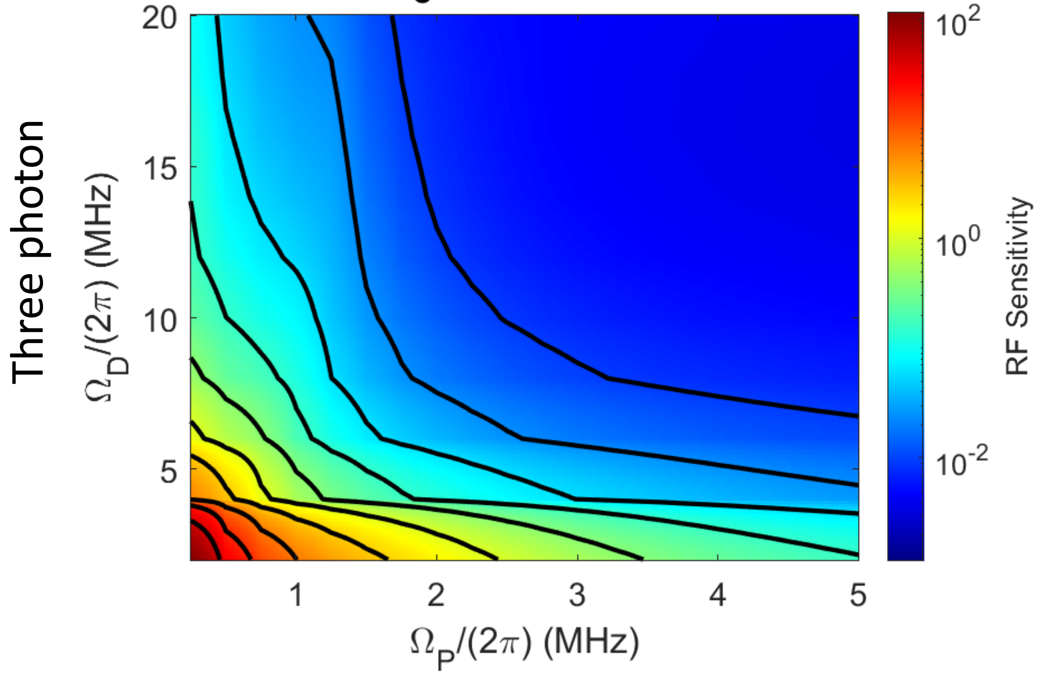

$$Doppler\ resid_2 = \frac{|k_{850} - k_{510}|}{|k_{850}|} \cdot \gamma_{12} = 0.667 \cdot \gamma_{12}$$

$$Doppler\ resid_3 = \frac{|k_{895} - k_{636} + k_{2224}|}{|k_{850}|} \cdot \gamma_{12} = 0.0048 \cdot \gamma_{12}$$

# Sensitivity Estimation

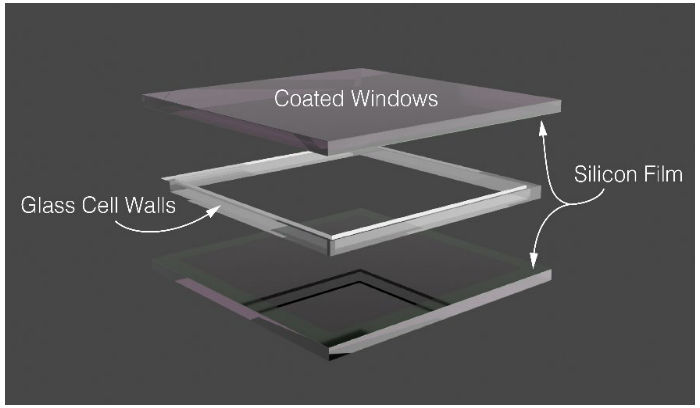


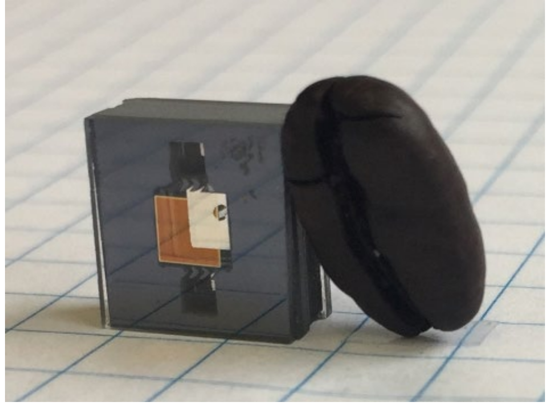



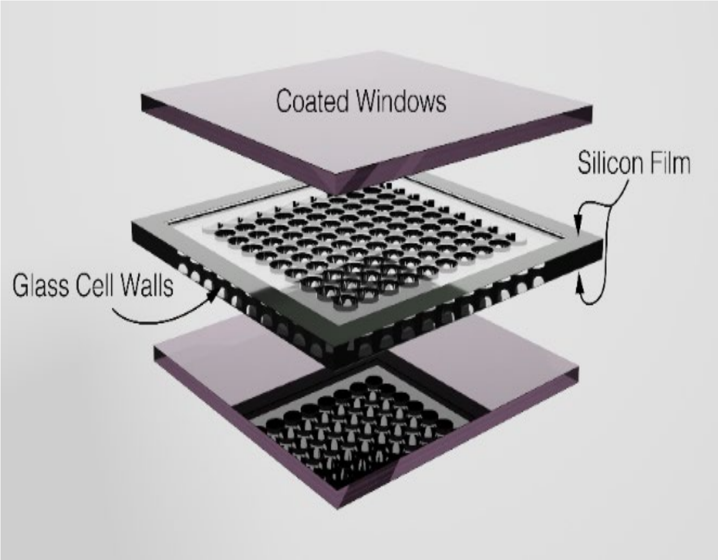



# Development of Technologies for Commercialization

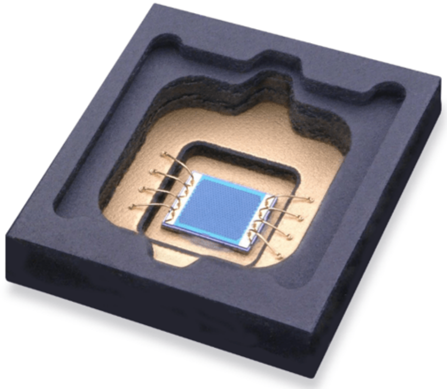
## Miniaturize Vapor Cells






## Miniaturize Visible Lasers (blue and/or green)



# Field Sensors, Receivers, and Imaging

Over the past few years, great progress has been made in using Rydberg atoms for electrical field sensors.
Because of the success of this program, several groups around the world (including National Metrology Institutes, private companies, universities, and other government laboratories) have started programs in the area of Rydberg atom-based sensors.

- **SI traceable electric-field probe**
- **SI traceable power calibration**
- **Blackbody radiation detection**

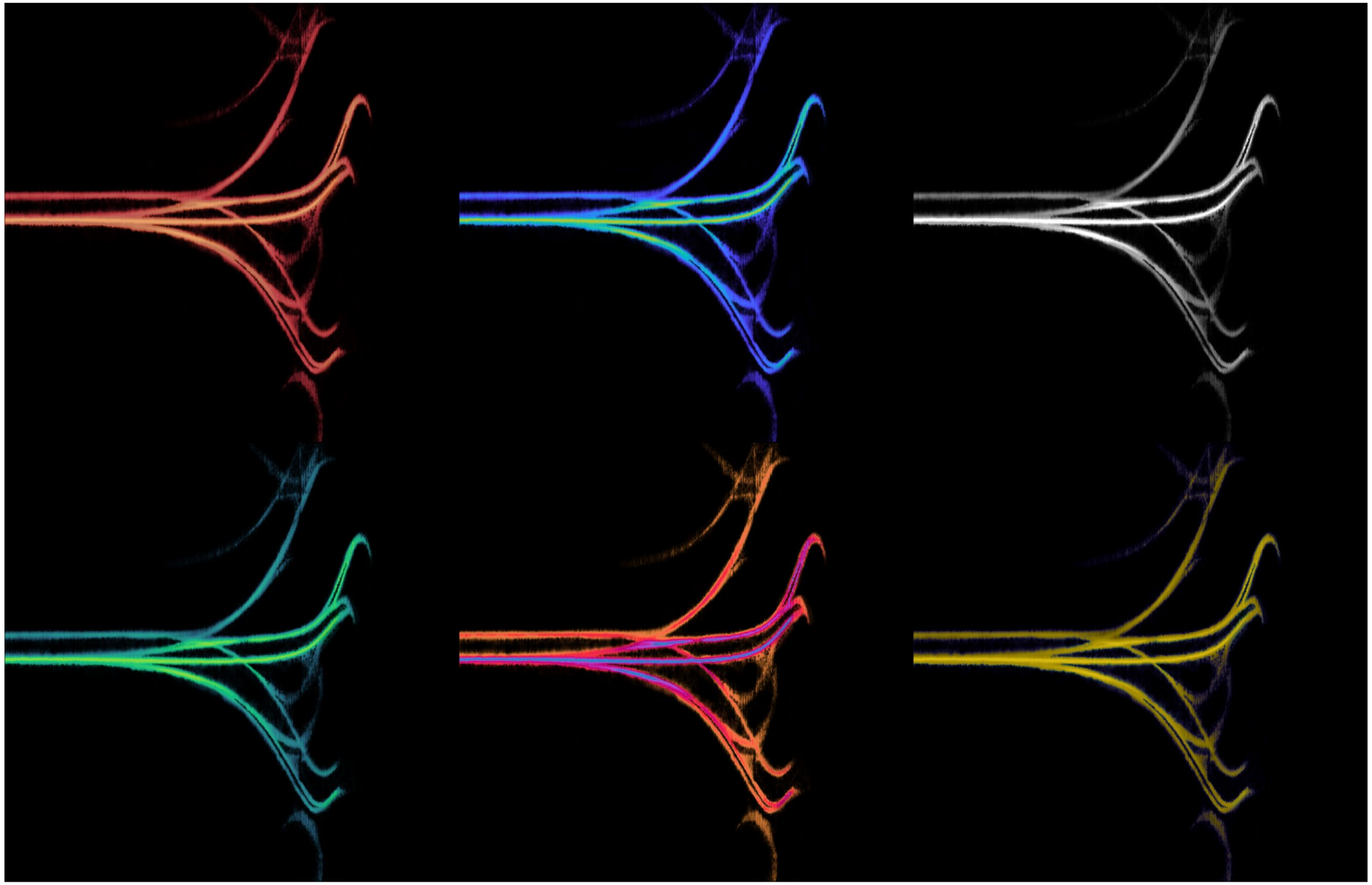
- **Atom-based receivers/antennas**
  **AM/FM**
  **BPSK, QPSK, QAM signals**

- **RF imaging and visualization technology (RF camera)**
- **Near-field imaging**
- **Sub-wavelength imaging**

- **Voltage standards**
- **Plasma sensors**
- **Waveform/Spectrum Analyzer**
- **Atomic thermal field sensing and measurement (blackbody radiation calibrations)**
- **Measuring noise sources**
- **Video Streaming and Recording music**

# Rydberg Art

## Autler-Townes Splitting in Rydberg Atoms from Extreme RF Fields



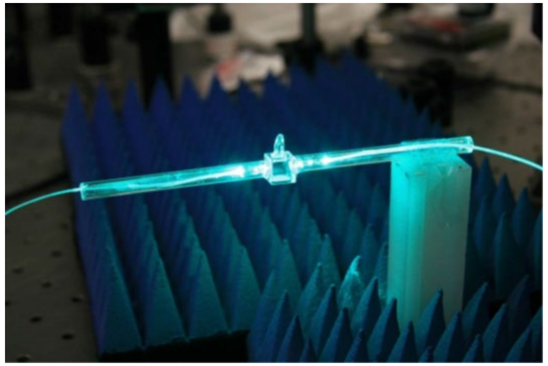
Chris Holloway, Matt Simons, Aly Artusio-Glimpse, Nik Prajapati, Drew Rotunno, Sam Berweger ▪
19 March 2022 ▪ christopher.holloway@nist.gov ▪

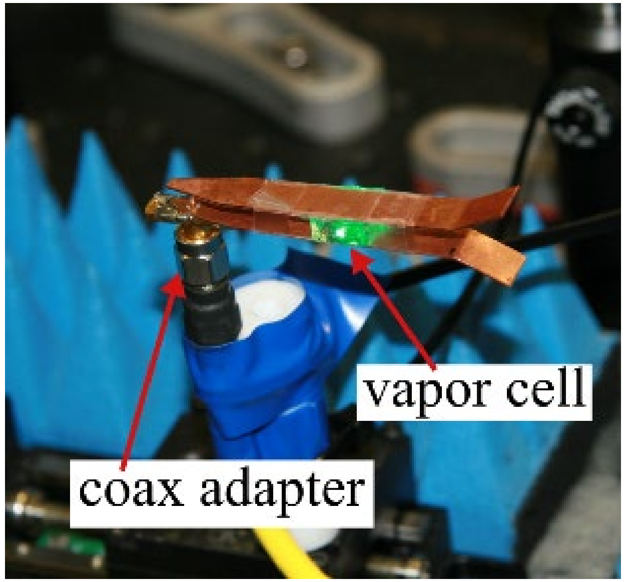
# Summary

## Fundamentally new approach for E-field and Power measurements

**E-Fields**

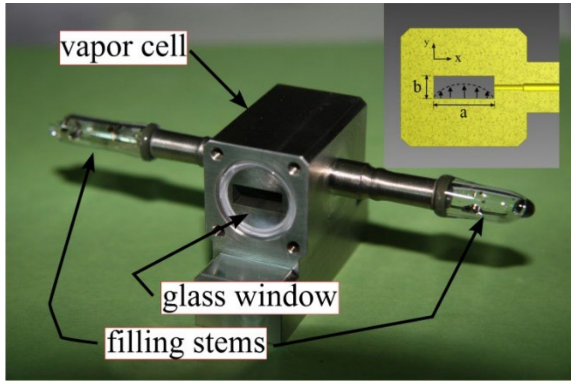
- **Broadband probe/sensor: 10 MHz-to-500 GHz (possibly to 1 THz)**
- Will allow direct SI units linked RF electric field (*E*-field) measurements
- Would provide RF field measurements independent of current techniques
- Very small and compact probe: fiber-coupled atom-based probe
- Measure *weak* and *large* E-field strengths over a large range of frequencies :
  < 1 μV/m and > 10 kV/m:






**Power**

- SI traceable Power measurements
- Calibrations above 110 GHz
- Real-time power calibrations




**Unique and Unforeseen Applications**

# Perseverance

*Quote from Nobel Laureate* for inspiration for early career scientists

“There is no success like Failure,
but Failure is no success at ALL”
*-Bob Dylan*

[To be successful:, you need to adapt, be willing to do and learn new things, and take every opportunity that comes your way.]


=

=


# Acknowledgments


DARPA

ARMY

NIST Embedded Standards Program

Amy Robinson, NIST/CU

Josh A. Gordon NIST

G. Raithel from University of Michigan

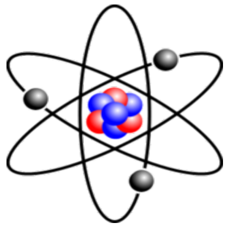
D. Anderson from Rydberg Technologies

<u>others</u>:  Marc Kautz, Kyle A. Rogers, Abdulaziz H. Haddab, Tom Crowley , etc…….

Various postdocs and students at U. of Colorado, U. of Michigan, U of Oklahoma

# ??? Questions ???

**Bottom-line: Rydberg Atoms are “cool” and we can do “cool” things with them, leading to many unforeseen applications.**



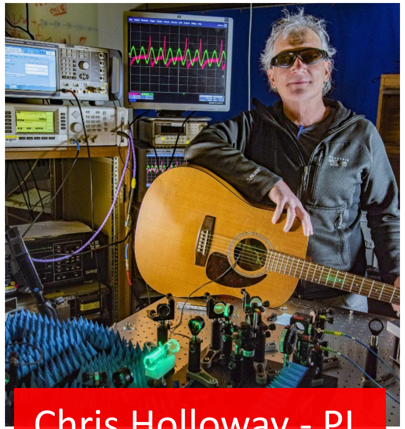
Atom: Cs or Rb

Matt Simons Physicist

Nik Prajapati - Postdoc

Maitreyi Jayaseelan- Postdoc

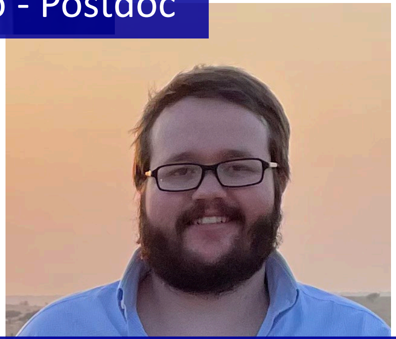
Andrew Rotunno - Postdoc



Chris Holloway - PI

Aly Artusio-Glimpse Physicist

Sam Berweger Physicist



Kaleb Campbell- Postdoc

**Call if you want to join the team!**

# Journal Publications


1. Holloway, et al. , "Sub-Wavelength Imaging and Field Mapping via electromagnetically induced transparency and Autler-Townes Splitting In Rydberg Atoms," *Applied Physics Letters*, vol.1 104, 244102, 2014.
2. Holloway, et al., "Broadband Rydberg Atom-Based Electric-Field Probe/Sensor: From Self-Calibrated Measurements to Sub-Wavelength Imaging," *IEEE Trans. on Antenna and Propagation*, vol. 62, no. 12, 6169-6182, 2014.
3. Gordon, et al., "Millimeter-Wave Detection via Autler-Townes Splitting In Rubidium Rydberg Atoms", *Applied Physics Letters*, vol. 105, 024104, 2014.
4. Anderson, et al., "Two-photon transitions and strong-field effects in Rydberg atoms via EIT-AT," Applied Physics Review, vol. 90, 043419, 2014.
5. Fun et al. "Effect of Vapor Cell Geometry on Rydberg Atom-based Radio-frequency Electric Field Measurements", *Physical Review Applied*, vol. 4, 044015, 2015.
6. Anderson et al., "Optical measurements of strong microwave fields with Rydberg atoms in a vapor cell", *Physical Review Applied*, 5, 034003, 2016.
7. Simons et al., "Using frequency detuning to improve the sensitivity of electric field measurements via electromagnetically induced transparency and Autler-Townes splitting in Rydberg atoms", *Applied Physics Letters*, 108 174101, 2016.
8. Simons, et al. "Simultaneous use of Cs and Rb Rydberg atoms for dipole moment assessment and RF electric field measurements via electromagnetically induced transparency", J. Appl. Phys., 102, 123103, 2016.
9. Holloway, et al., "Atom-Based RF Electric Field Metrology: From Self-Calibrated Measurements to Sub-Wavelength and Near-Field Imaging", *IEEE Trans. on Electromagnetic Compat., Special Issue of Near-Field Imaging*, vol. 59, no. 2, pp. 717-728, April 2017.
10. Holloway, et al., "Electrical Field Metrology for a New SI: A Study of Systematic Measurement Uncertainties in Electromagnetically Induced Transparency in Atomic Vapor", *J. of Applied Physics*, May, 2017.
11. Anderson, et al., "Optical measurements of plasma fields using Rydberg atoms on electromagnetically induced transparency", J. of Applied Phys, 2018.
12. Simons, et al., "Electromagnetically Induced Transparency (EIT) and Autler-Townes (AT) splitting in the Presence of Band-Limited White Gaussian Noise"', *J. of Applied Physics*, vol. 123, 203105, 2018.
13. Holloway, et al., "A New Quantum-Based Power Standard: Using Rydberg Atoms for a SI-Traceable Radio-Frequency Power Measurement Technique in Rectangular Waveguides", *Applied Phys. Letters*, vol. 113, 094101, 2018.
14. Simons, et al., "Fiber-coupled vapor cell for a Rydberg atom-based electric field sensor", *Applied Optics*, vol. 57, no. 22, pp. 6456-6460, 2018.
15. Simons, et al, "A Rydberg Atom-Based Mixer: Measuring the Phase of a Radio Frequency Wave," *Applied Physics Letters*, vol. 114, 114101, 2019.
16. Gordon, et al., "Weak Electric-Field Detection with Sub-1 Hz Resolution at Radio Frequencies Using a Rydberg Atom-Based Mixer, *AIP Advanced*, vol. 9, 045030, 2019.
17. Holloway, et al., Detecting and Receiving Phase-Modulated Signals with a Rydberg atom-based receiver., *IEEE AWPL*, vol. 18 (9), 1853-1857, 2019.
18. Holloway, et al. "Quantum Physics Meets Music: A ``Real-Time" Guitar Recording Using Rydberg-Atoms and Electromagnetically Induced Transparency," *AIP Advanced*, vol. 9, 065110, 2019.
19. Simons, et al., "Embedding a Rydberg Atom-Based Sensor into an Antenna for Phase and Amplitude Detection of Radio-Frequency Fields and Modulated Signals," IEEE Access, 2019.
20. N. Prajapati, et al., ``Enhancement of electromagnetically induced transparency-based Rydberg-atom electrometry through population repumping", *Applied Physics Letters*, 119, 214001, 2021.
21. Robinson, et al., "Atomic Spectra in a Six-Level Scheme for Electromagnetically Induced Transparency and Autler-Townes Splitting in Rydberg Atoms", Phys. Rev. A, 2021.
22. Simons, et al., "Continuous radio frequency electric field detection through adjacent Rydberg resonance tuning", *Phys. Rev. A*, 104, 032824, 2021.
23. Robinson et al., "Determining the angle-of-arrival of a radio-frequency source with a Rydberg atom-based sensor, *Applied Phys. Letters*, vol. 118, 114001, 2021.
24. Simons, et al., "Rydberg atom-based sensors for radio-frequency electric field metrology, sensing, and communications", Measurement: Sensors, 18, 100273, 2021.
25. Prajapati, et al., "Enhancement of electromagnetically induced transparency-based Rydberg-atom electrometry through population repumping", Applied Physics Letters, 119, 214001, 2021.
26. Holloway, et al., "Rydberg-atom sensors for quantum-based voltage measurements", *AVS Quantum Science*, vol. 4, 034401, 2022.
27. Artusio-Glimpse, et al., "Modern RF Measurements with Hot Atoms", IEEE Microwave Magazine, vol. 23, no. 5, 44-56, May 2022.
28. Holloway, et al., ''Rydberg atom-based field sensing enhancement using a split-ring resonator," *Applied Phys. Letts.*, May 2022.
29. Prajapati, et al., "TV and Video Game streaming with a Quantum Receiver: A study on a Rydberg atom-based receiver's bandwidth and reception clarity," *AVS Quantum Science*, vol. 4, 035001, 2022. .

# Conference Publications

NIST

**Rydberg-Atom Sensor Papers:**

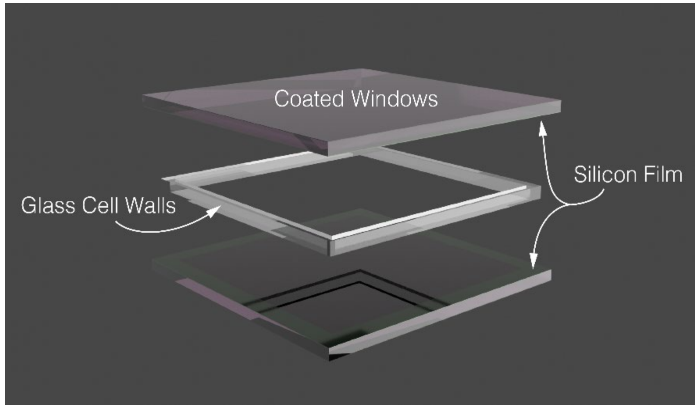

1. Gordon, et al, "Quantum-Based SI Traceable Electric-Field Probe," Proc of *2010 IEEE International Symposium on Electromagnetic Compatibility*, July 25-30, 321-324, July 2010.
2. Holloway, et al., "Broadband Rydberg Atom Based Self-Calibrating RF E-Field Probe", *2014 XXXIth URSI General Assembly and Scientific Symp*., Beijing, China, Aug, 2014.
3. Holloway, et al., "Atom-Based RF Electric Field Measurements: An Initial Investigation of the Measurement Uncertainties", *EMC 2015: Joint IEEE International Symposium on Electromagnetic Compatibility and EMC Europe*, Dresden, Germany, pp. 467-472, 2015.
4. Holloway, et al., "Atom-Based RF Field Probe: From Self-Calibrated Measurements to Sub-Wavelength Imaging", *IEEE NANO 2015: 15th International Conference on Nanotechnology*, Rome, Italy, 2015.
5. Simons, et al., "Atom-based RF electric field metrology above 100 GHz", *SPIE: Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications*, Feb, 2016.
6. Holloway, et al., "Using Cs and Rb Rydberg Atoms Simultaneously for SI-Traceable RF Electric-Field Metrology via Electromagnetically Induced Transparency", *EMC Europe 2016*, Aug. 2016.
7. Holloway, et al., "Development of A New Atom-Based SI Traceable Electric-Field Metrology Technique", *AMTA*, 2017.
8. Holloway, et al., "Development and Applications of a Fiber-Coupled Atom-Based Electric Field Probe", *EMC Europe 2018*, Amsterdam, NL, Aug. 2018.
9. Simons, et al., "An investigation of the uncertainties in the EIT/AT based approach for E-field metrology", *EMC Europe 2018*, Amsterdam, NL, Aug. 2018.
10. Anderson, et al., "High-resolution antenna near-field imaging and sub-THz measurements with a small atomic vapor-cell sensing element", *GSMM18*, Boulder, Co, 2018.

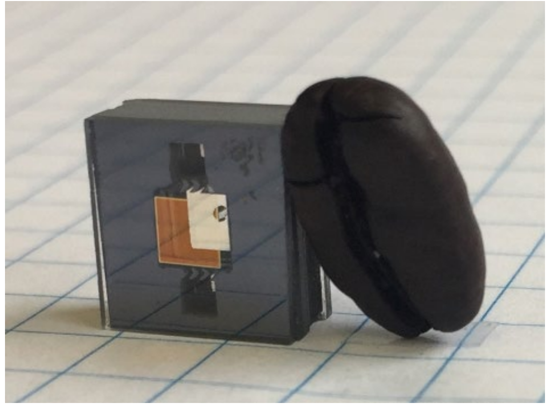

**RF Radiation Pressure papers:**

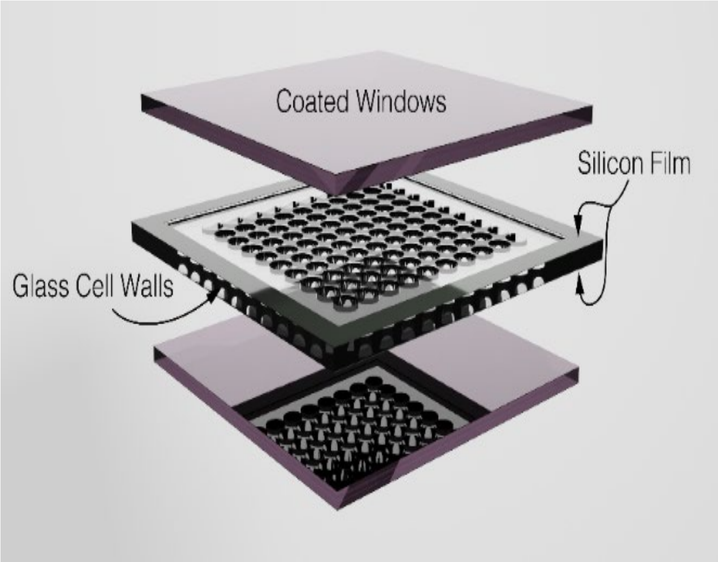

1. Holloway, et al., "Measurement of Radio-Frequency Radiation Pressure: The Quest for a NEW SI Traceable Power Measurement", *EMC Europe 2018*, Amsterdam, NL, Aug. 2018.
2. Artusio-Glimpse, et al., "Measurement of Radio-Frequency Radiation Pressure", *CPEM*, July 8-13, 2018.
3. Ryger, et al., "MEMS non-absorbing electromagnetic power sensor employing the effect of radiation pressure", Eurosensors 2018, Sept 9-12, Graz, Austria, 2018

# Development of Technologies for Commercialization

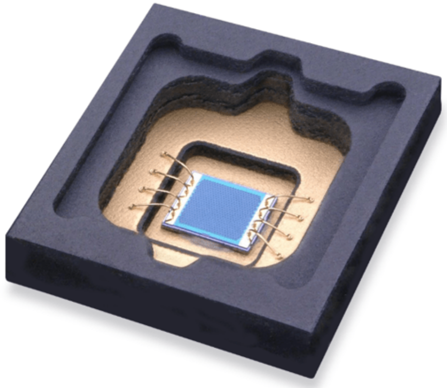
## Miniaturize Vapor Cells



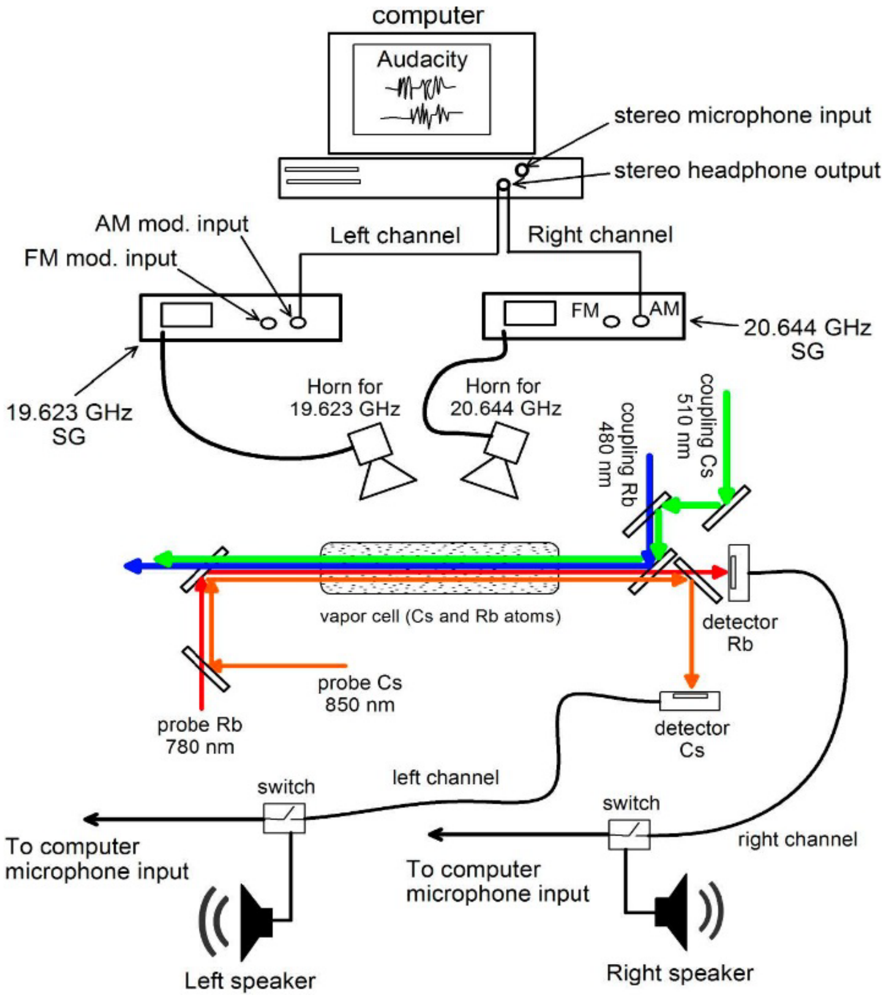


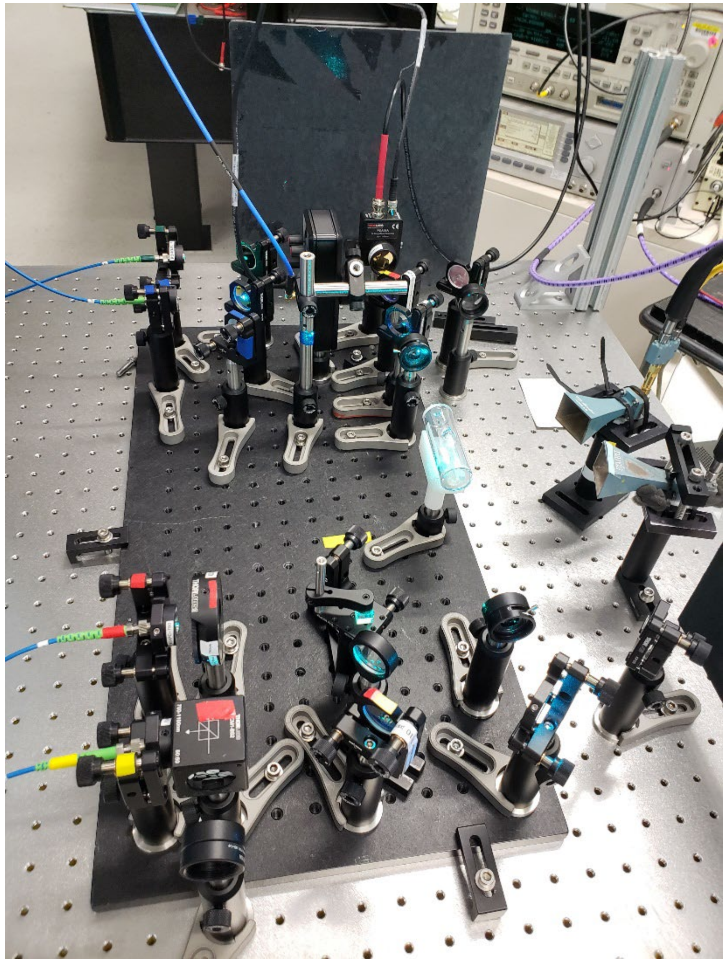

## Miniaturize Visible Lasers (blue and/or green)



# Multi-Band/Channel Receiver: Dual Atomic Species for Stereo Reception

Instrumental on Rb atoms
Vocals on Cs atoms

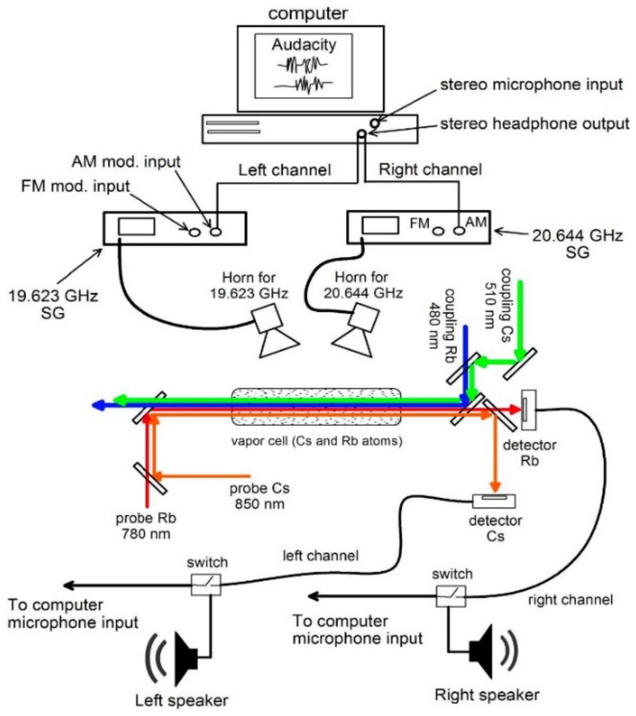


# Dual Atomic Species Stereo Reception

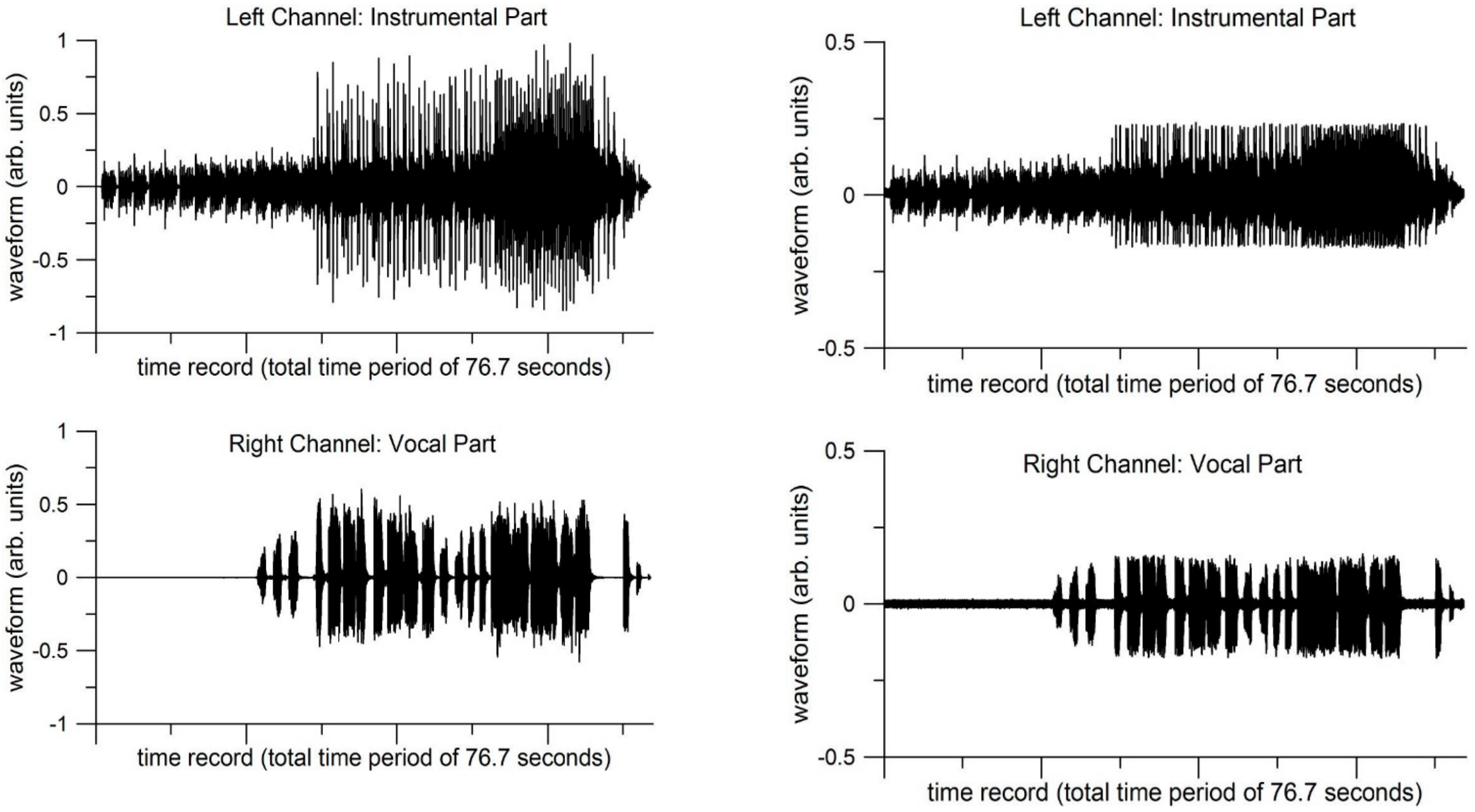
*Holloway et al., IEEE APS Mag., 2021.*

Instrumental on Rb atoms
Vocals on Cs atoms



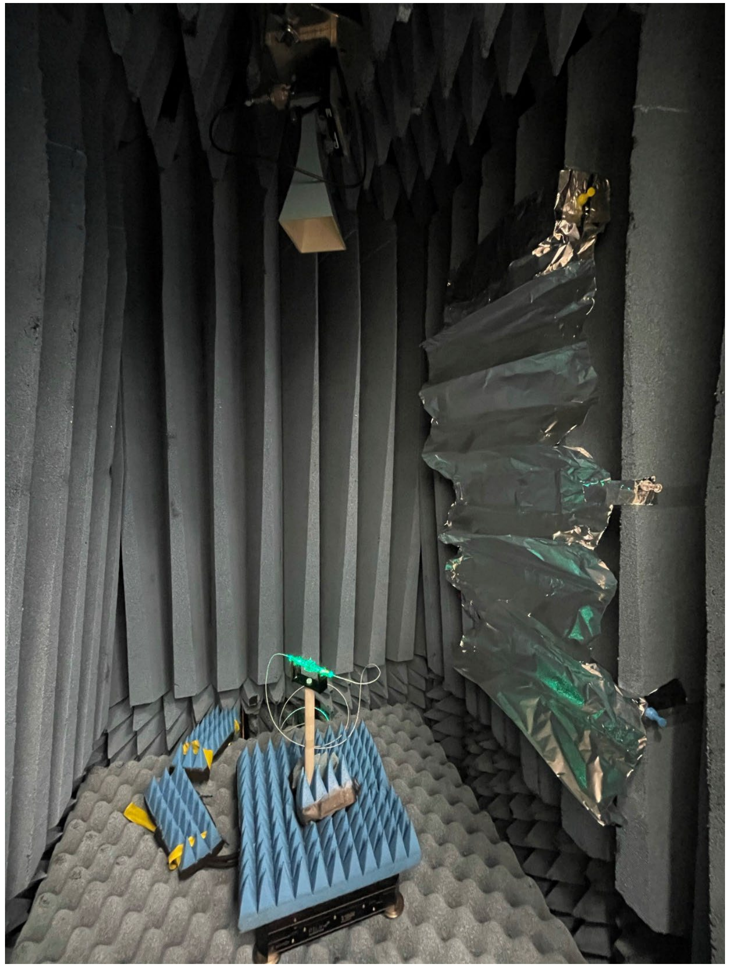

Original Waveform

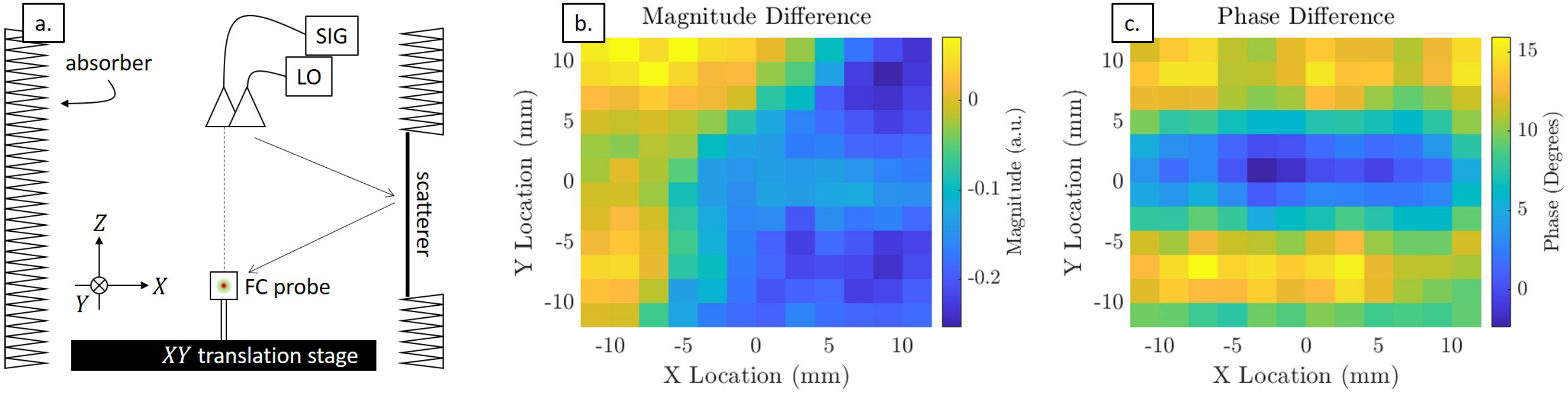
Received Waveform




**AM/FM Stereo Receiver**

# IoT: Chamber Characterization

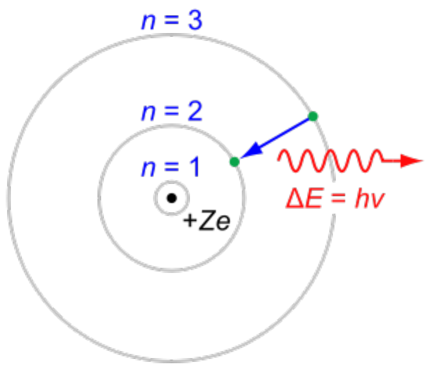




# A Little Atomic Physics: The Hydrogen Atom

Bohr Model

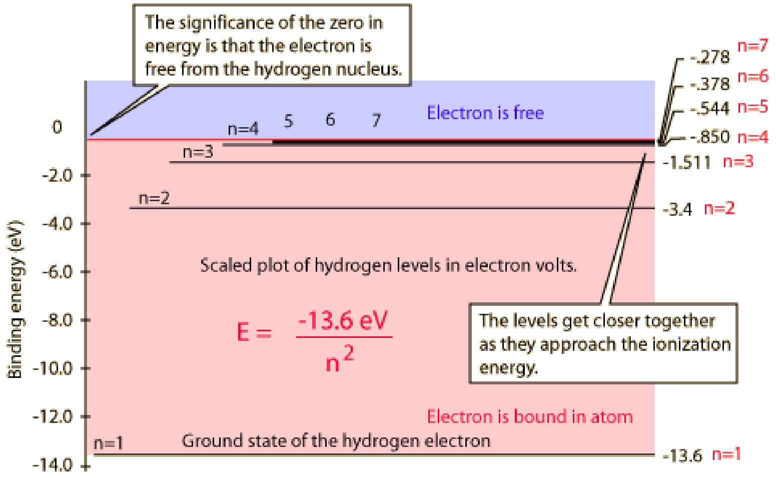
1. Electrons orbit the nucleus in discrete radii.
2. The ground state is n=1
3. Need to supply or released energy (or photons) to change state (or orbit)




$\Delta E = h\nu$ where h=6.62607x10$^{-34}$ m$^2$kg/s and is Planck's constant

$$h\nu = -13.6\left[\frac{1}{ni^2} - \frac{1}{nf^2}\right]\ eV$$

$$\frac{1}{\lambda} = R_H\left[\frac{1}{ni^2} - \frac{1}{nf^2}\right]\ 1/m$$ $R_H$=1.0973731x10$^{-7}$ m$^{-1}$




**Transition from ground state: n=1 to n=2**

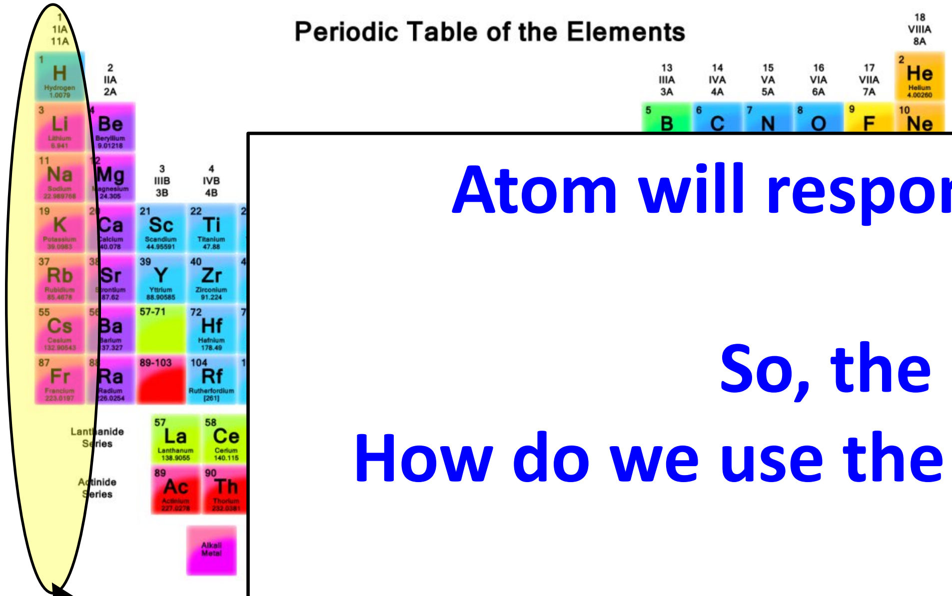
λ=121.6 nm (f=2x10$^{15}$ Hz) : $\Delta E = h\nu$ = 10.2 eV

Energy in a 20 GHz photon:

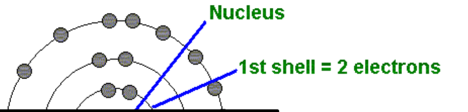
$\Delta E = h\nu$ = 8.27x10$^{-5}$ eV

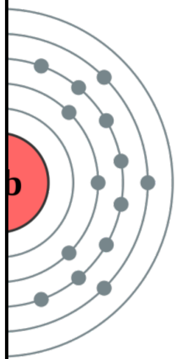
Ground state: photons at RF to lower THz will not change the state (or orbit)

# Alkali Atoms and Rydberg Atoms




Sulfur



**Atom will respond to their environment.**

**So, the BIG question is:**

**How do we use the atom to measures E-fields?**

**by Generating Rydbergs Atoms**

**and**

**Electromagnetically Induced Transparency (EIT)**

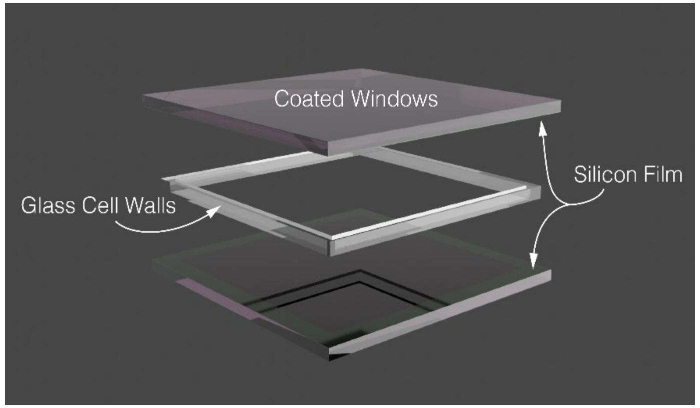
- We can used theoretical calculations of the hydrogen atom to predict interactions
- This is especially true for Rydberg Atoms (excited atoms to a very large n)

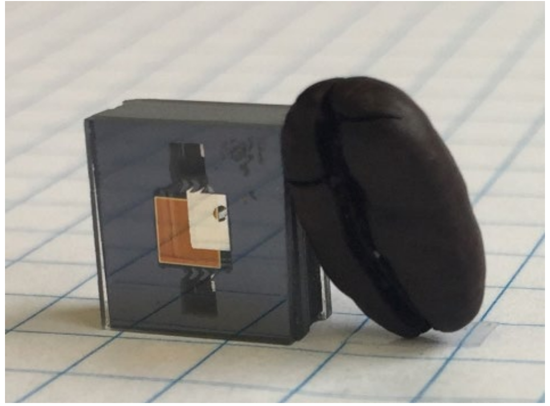
one electron in outer shell

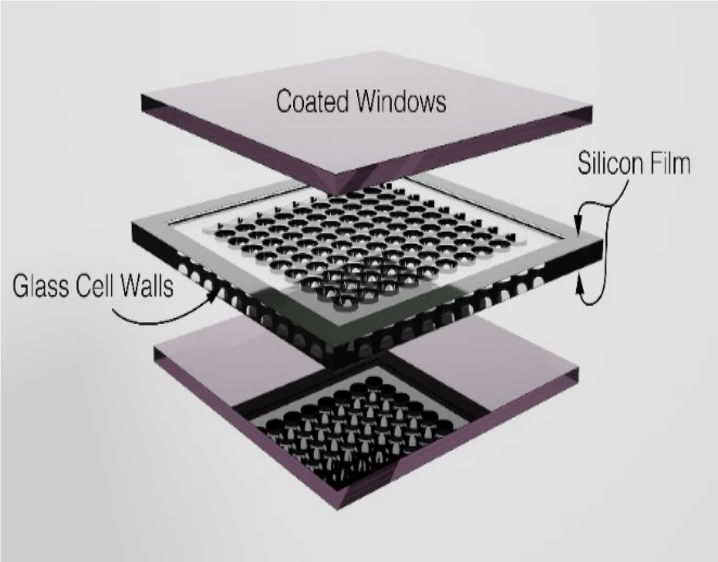
*ground state: n=5*

# Development of Technologies for Commercialization

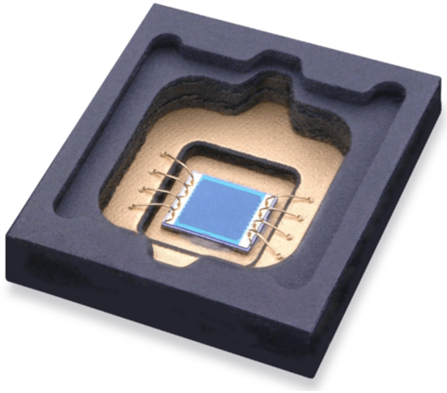
## Miniaturize Vapor Cells





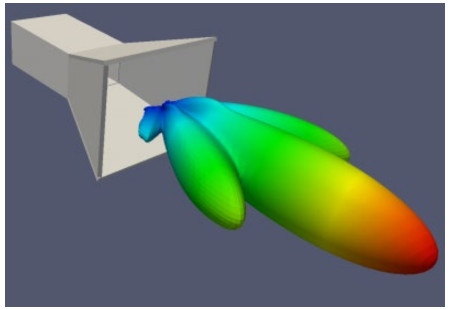

## Miniaturize Visible Lasers (blue and/or green)

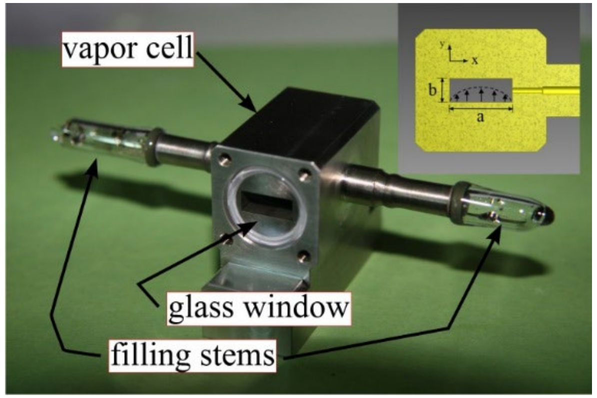


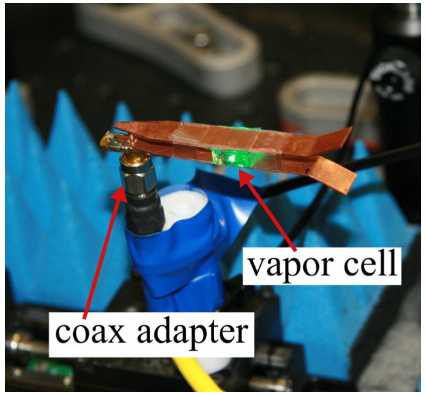
# Applications

- <u>New SI Traceable Power Calibration</u>
- Atom-based receivers/antennas
- Quantum RF imaging and visualization technology (RF camera)
- Quantum-enabled medical imaging and diagnostics
- Plasma sensors
- Atomic DC/AC voltage and current references
- Atomic thermal field sensing and measurement (blackbody radiation calibrations)
- Single microwave photon detection
- Quantum storage of radio frequency, microwave, and THz photons using slow light effects in Rydberg gases. (Quantum encrypted Rydberg atom quantum receivers from 1 GHz to 1 THz)
- Waveguide Power Measurements: Power Calibrations
- Sub-wavelength imaging
- Near-field imaging
- Measuring Noise sources

<u>And many other unforeseen applications.</u>



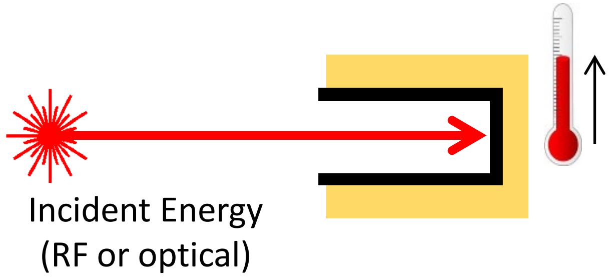


# *New Paradigm for RF Power (Calibrated Source)*

**Current State of the Art**

- Energy meter
- Absorption-based
- Energy $\propto \Delta T$
- Calibration through the power meter




**Outcome after IMS: Real-time "*in situ*" traceability**

In Situ RF (Rydberg cell)