Title: Opportunities and Limitations for Warm Rydberg Electric Field Sensors

Speakers: Paul Kunz

Collection: Cold Atom Molecule Interactions (CATMIN)

Date: July 15, 2022 - 2:30 PM

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Abstract: Electric field sensors based on warm vapors of Rydberg atoms have distinguishing features that offer new application possibilities. A single sensor can operate over a wide spectrum of frequencies, from DC to THz, with a consistent instantaneous baseband bandwidth of approximately 10MHz. The sensor head containing the vapor is highly transparent and can be made small relative to the electric field wavelengths, enabling accurate measurements with sub-wavelength spatial resolution. Presently Rydberg sensors rely on the spectroscopic method of electromagnetically induced transparency (EIT) for preparing and probing the atoms, and though simple and effective, this places limits on the sensitivity and instantaneous bandwidth of the sensor. I will discuss these limitations and the optimal EIT parameter regime considering presently available laser technology, and show performance of a promising new prototype vertical external cavity surface emitting laser (VECSEL). Finally, I will present results on recent demonstrations, such as a Rydberg-based spectrum analyzer with sensitivity of -145dBm/Hz and dynamic range >80 dB.

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QUANTUM TECHNOLOGY CENTER

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The University of Texas at Austin
Department of Physics
College of Natural Sciences

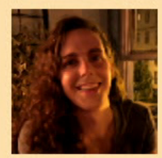
Branch Chief - Fredrik Fatemi

Neutral Atom Team

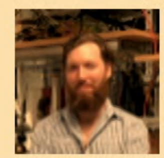
Josh Hill

Kevin Cox

David Meyer



Brie Anderson



Don Fahey

OUTLINE

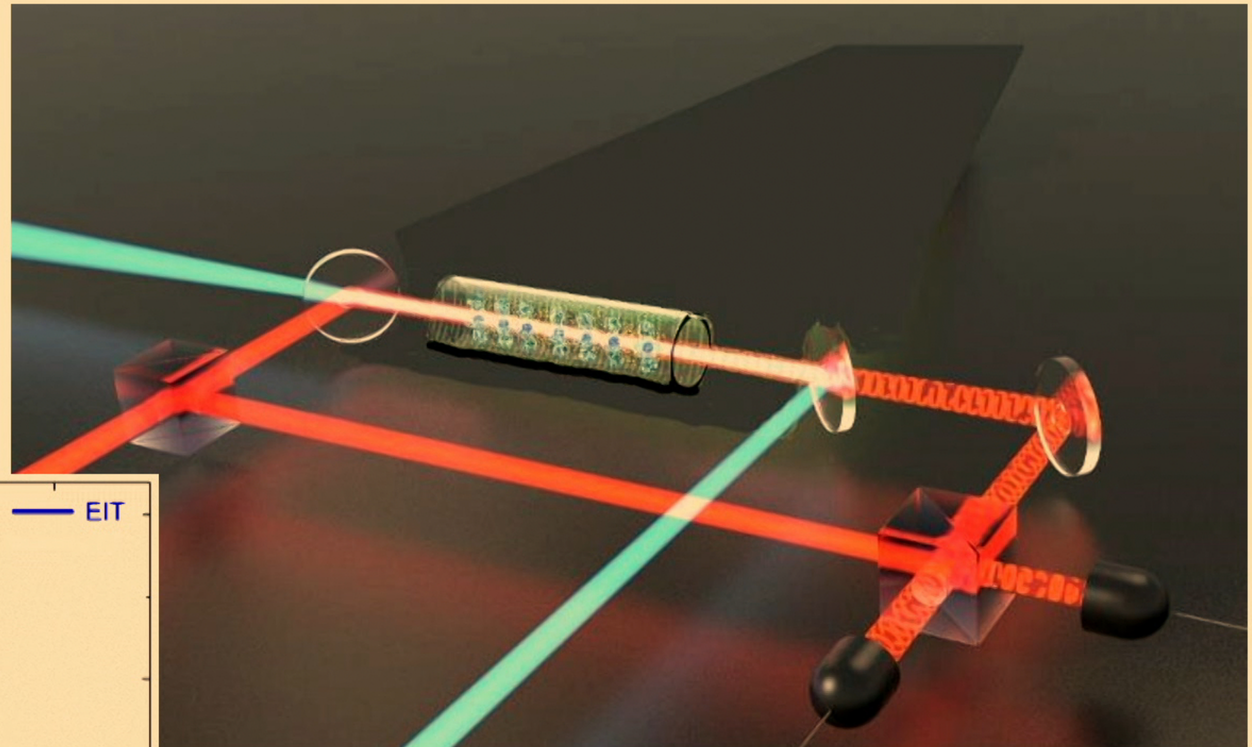
- Rydberg Sensors - Different and maybe useful
- Briefly summarize our early work – Instantaneous Bandwidth
- Sensitivity Calculations & compare with state-of-the-art
- Limitations of EIT spectroscopy probing
- Component development – VECSEL
- Doppler-free Rydberg spectroscopy
- RF-waveguide coupling to Rydberg vapor

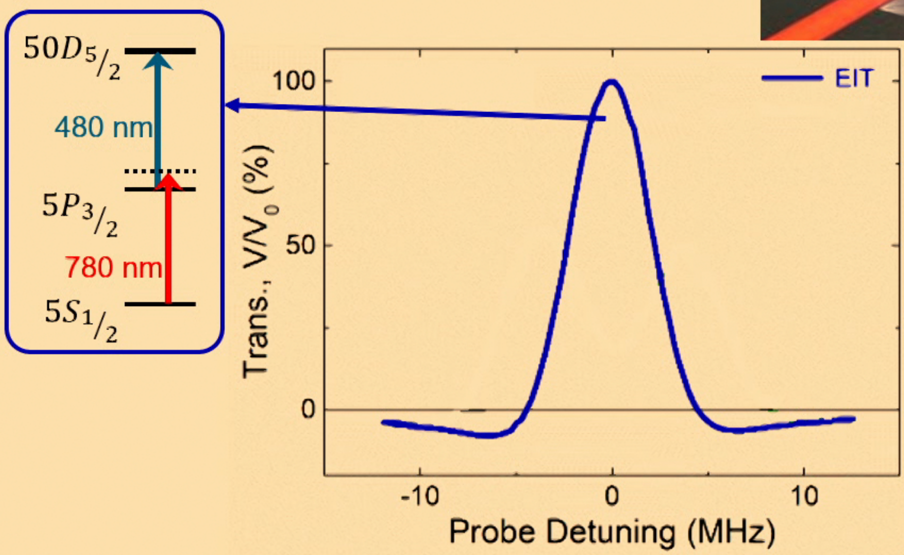
RYDBERG SENSOR - EIT

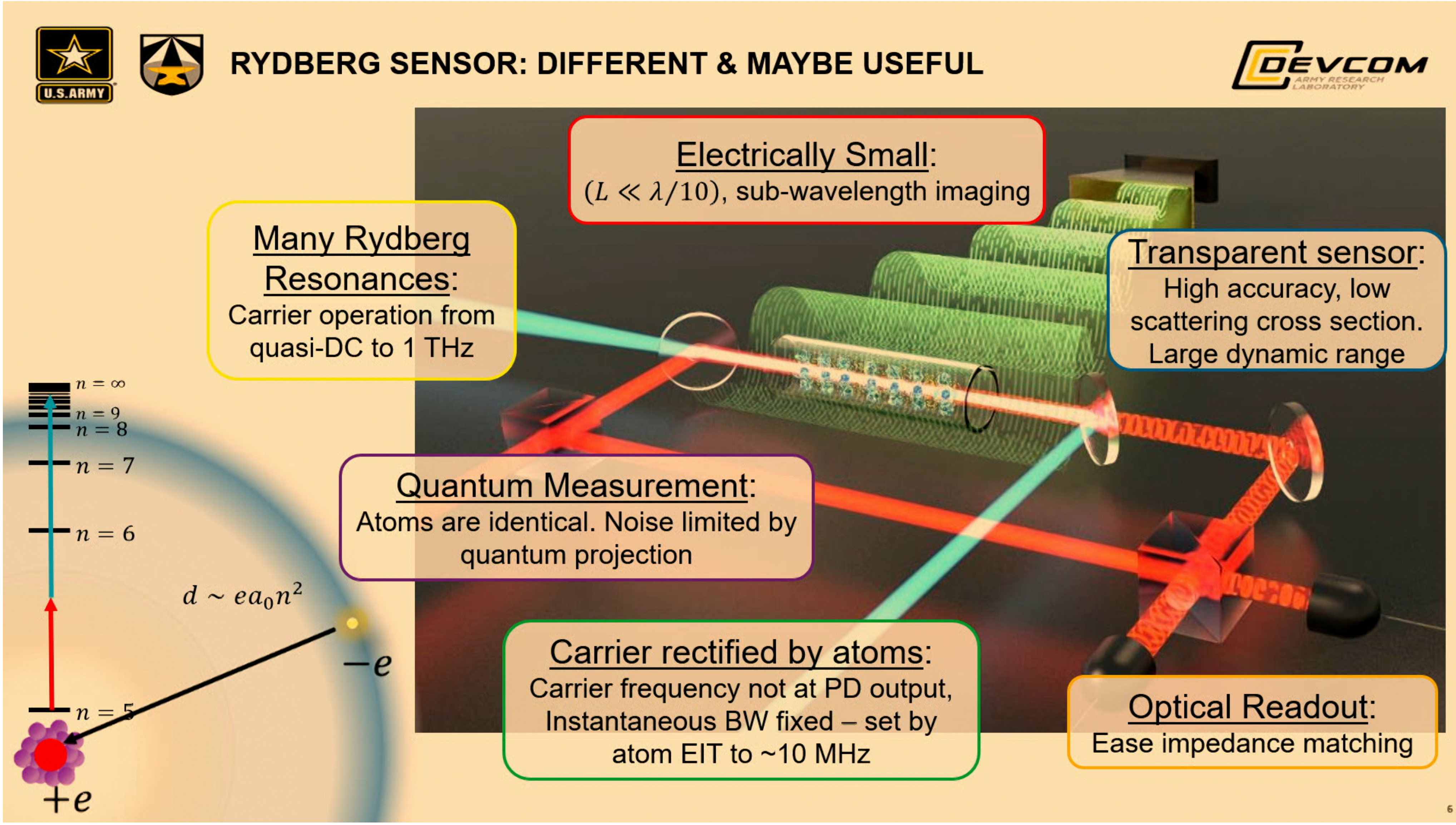
Room temperature atomic vapor

2-Laser Excitation to Rydberg

Electromagnetically Induced Transparency (EIT)







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RYDBERG SENSOR: DIFFERENT & MAYBE USEFUL
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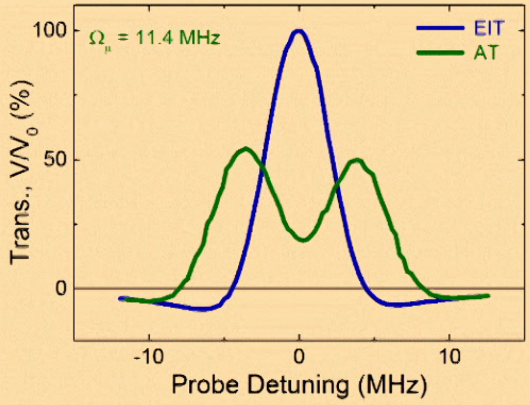
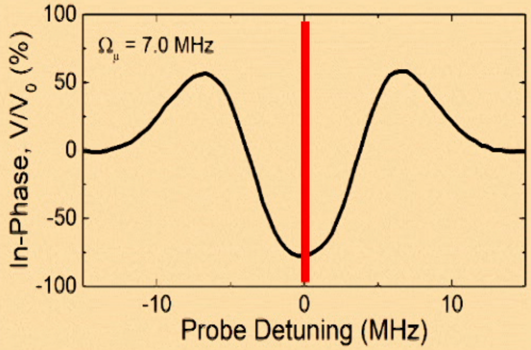
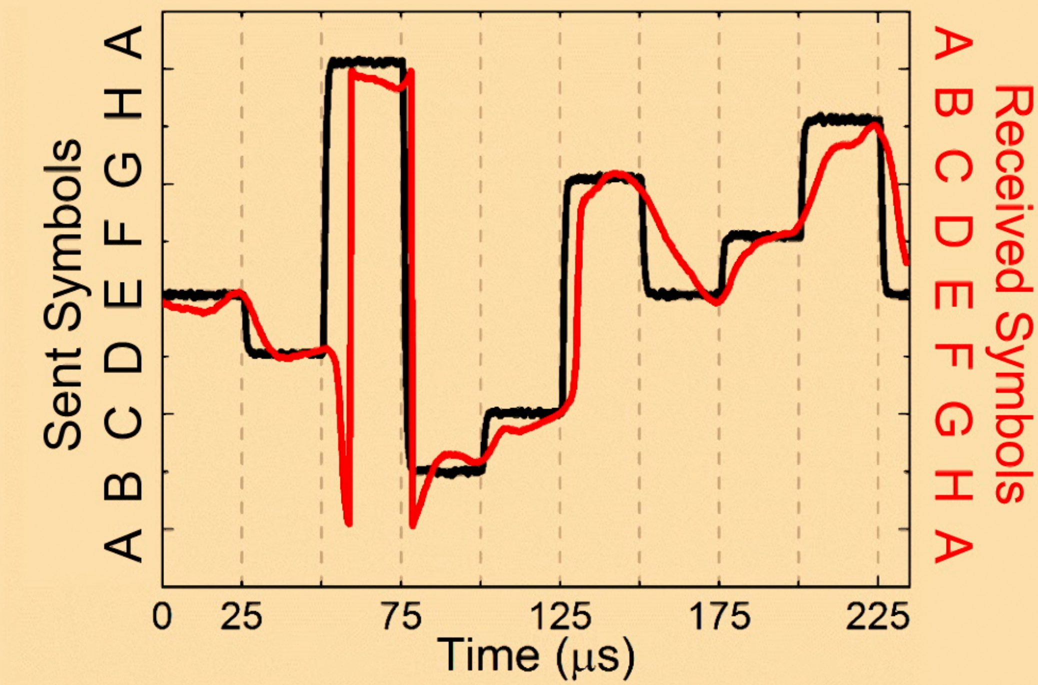
Electrically Small:
$(L \ll \lambda/10)$, sub-wavelength imaging
Many Rydberg Resonances:
Carrier operation from quasi-DC to 1 THz
Transparent sensor:
High accuracy, low scattering cross section.
Large dynamic range
Quantum Measurement:
Atoms are identical. Noise limited by quantum projection
Carrier rectified by atoms:
Carrier frequency not at PD output, Instantaneous BW fixed – set by atom EIT to ~10 MHz
Optical Readout:
Ease impedance matching
$n = \infty$
$n = 9$
$n = 8$
$n = 7$
$n = 6$
$n = 5$
$d \sim e a_0 n^2$
$-e$
$+e$
6

COMMS & STUDY OF BANDWIDTH



Signal = (MW On – MW Off)

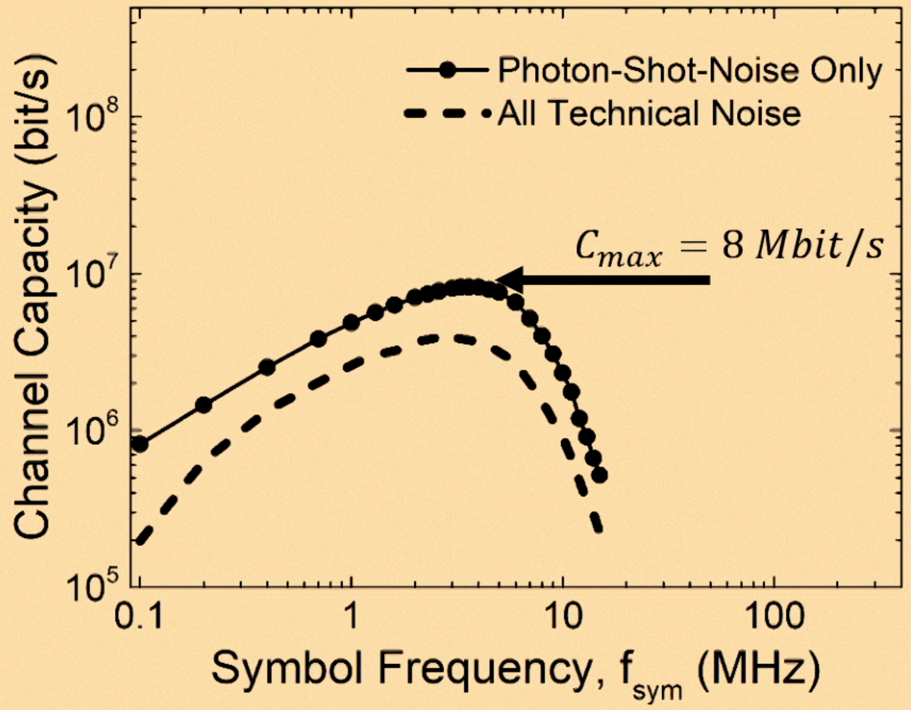




D. Meyer, et al. App. Phys. Lett. (R) 112, 211108 (2018). [arXiv:1803.03545]

RYDBERG CHANNEL CAPACITY

$$Channel\ Capacity = BW \log_2(1 + SNR)$$



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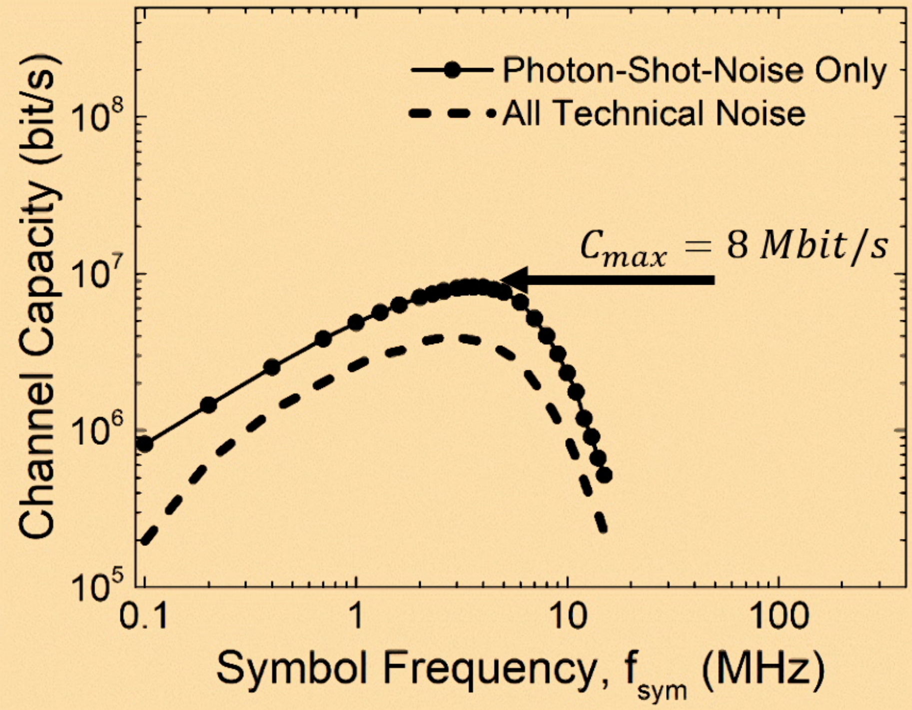
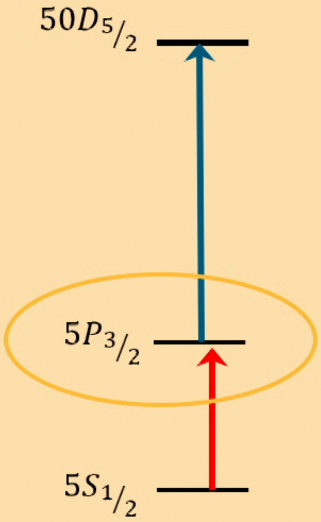
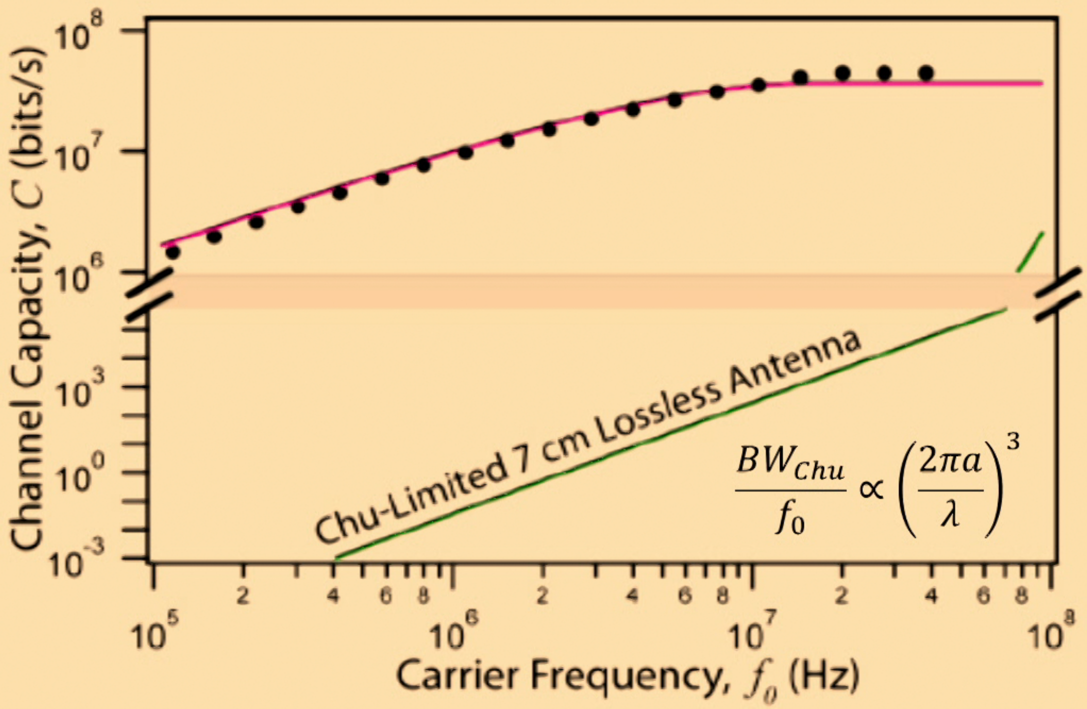




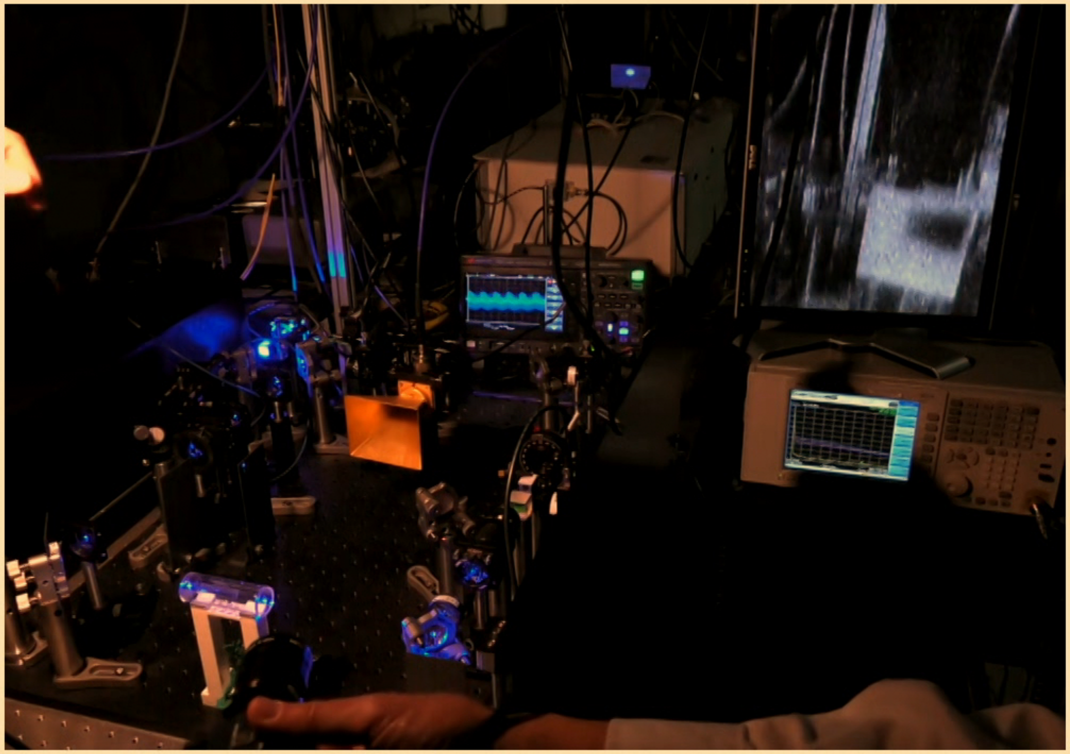
D. Meyer, et al. App. Phys. Lett. (R) 112, 211108 (2018). [arXiv:1803.03545]

ELECTRICALLY SMALL REGIME



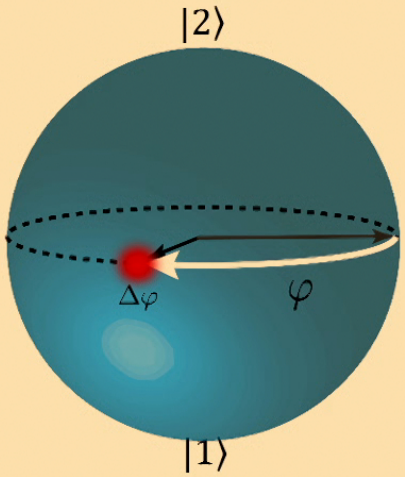
K. Cox, et al., Phys. Rev. Lett. 112, 110502 (2018). [arXiv:1805.09808]

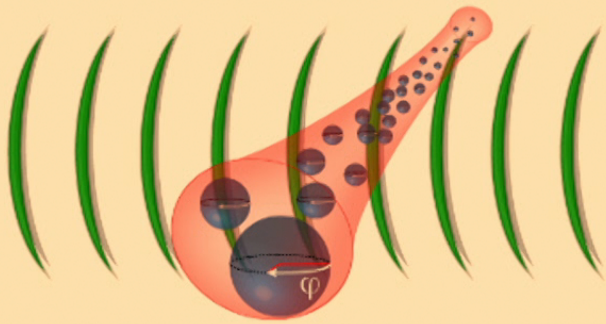
FUN LAB DEMOS



SENSITIVITY – STANDARD QUANTUM LIMIT

minimum detectable field, yielding SNR=1, in one second measurement BW





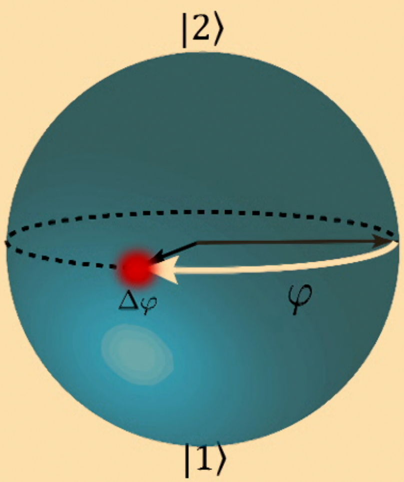
$$SNR = \frac{signal}{noise} = \frac{\varphi}{\Delta\varphi}$$

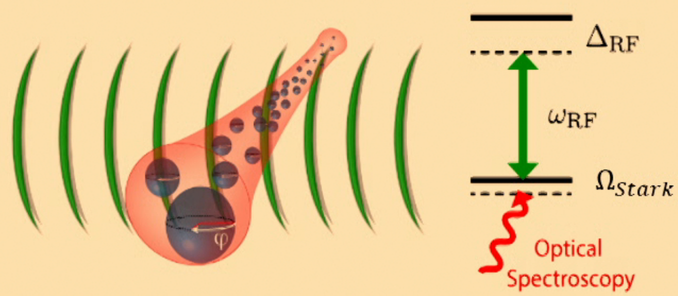
$$= \frac{\Omega_{Stark} \cdot \tau}{\sqrt{\frac{1}{N_{atoms}}}} \cdot \left(\sqrt{\frac{T_2}{\tau}}\right)$$

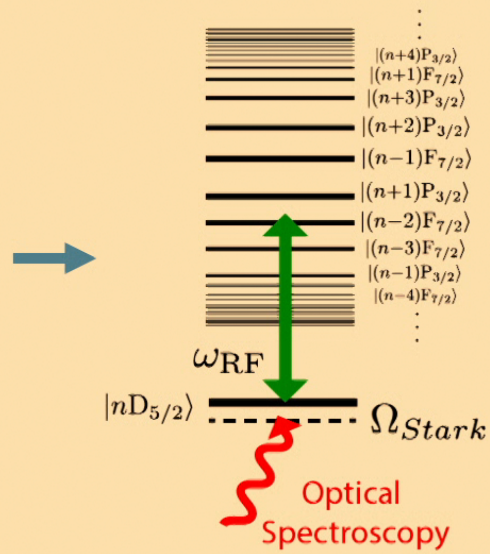
$$= \Omega_{Stark}\sqrt{N_{atoms}\tau T_2}$$

τ - measurement time
T_2 - coherence time

SQL SENSITIVITY OVER WIDE SPECTRUM







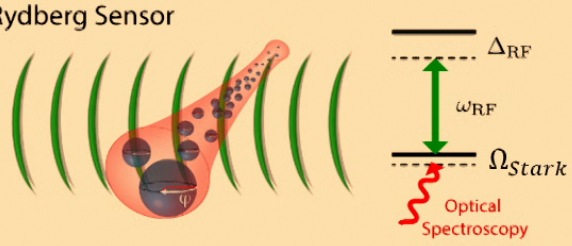
Some complications:

- Not 2-level; many levels

- $\Omega_{Stark} \propto E$ On resonance
- $\Omega_{Stark} \propto E^2$ Off resonance

SENSITIVITY: A COMPARISON

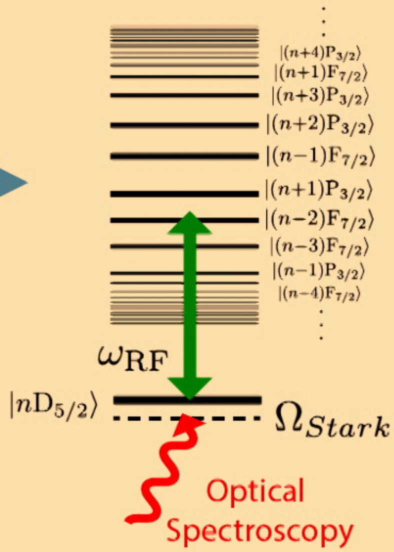
Rydberg Sensor

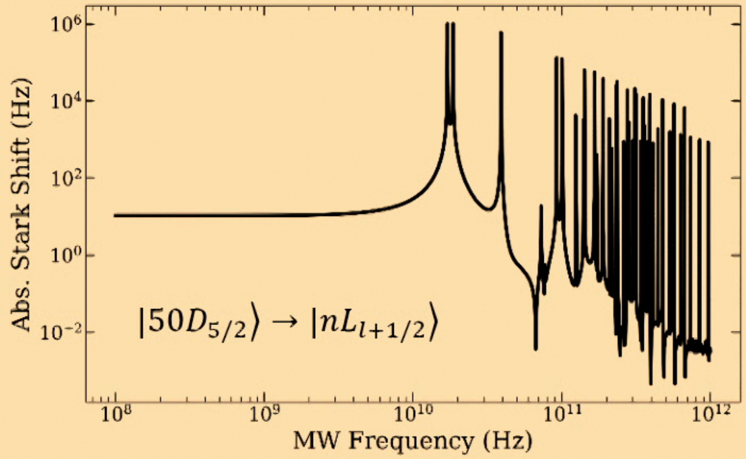


τ - measurement time
T_2 - coherence time

$$SNR = \frac{signal}{noise}$$

$$= \Omega_{Stark}\sqrt{N_{atoms}\tau T_2}$$





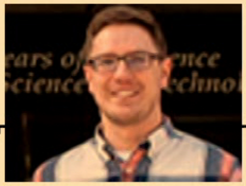
<u>Some complications:</u>

- Not 2-level; many levels
- $\Omega_{Stark} \propto E$ On resonance
- $\Omega_{Stark} \propto E^2$ Off resonance

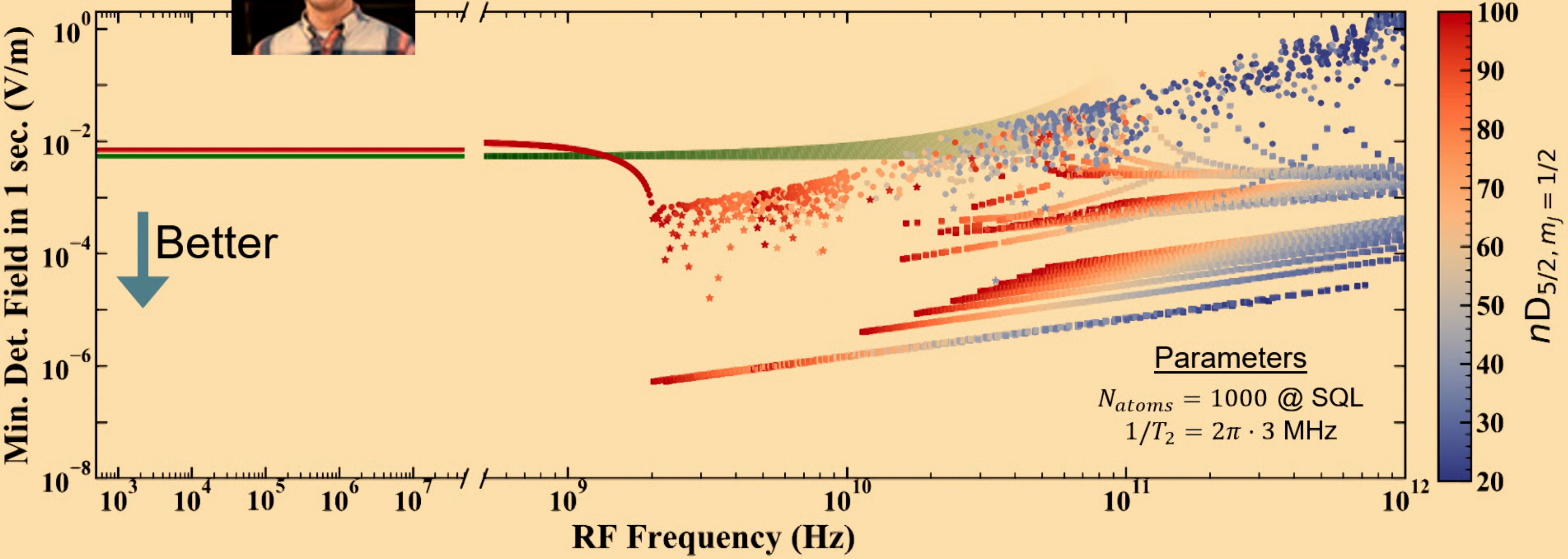
<u>Assume:</u>

- Single target Rydberg (initialization) state
- Field amplitude (0.1V/m)

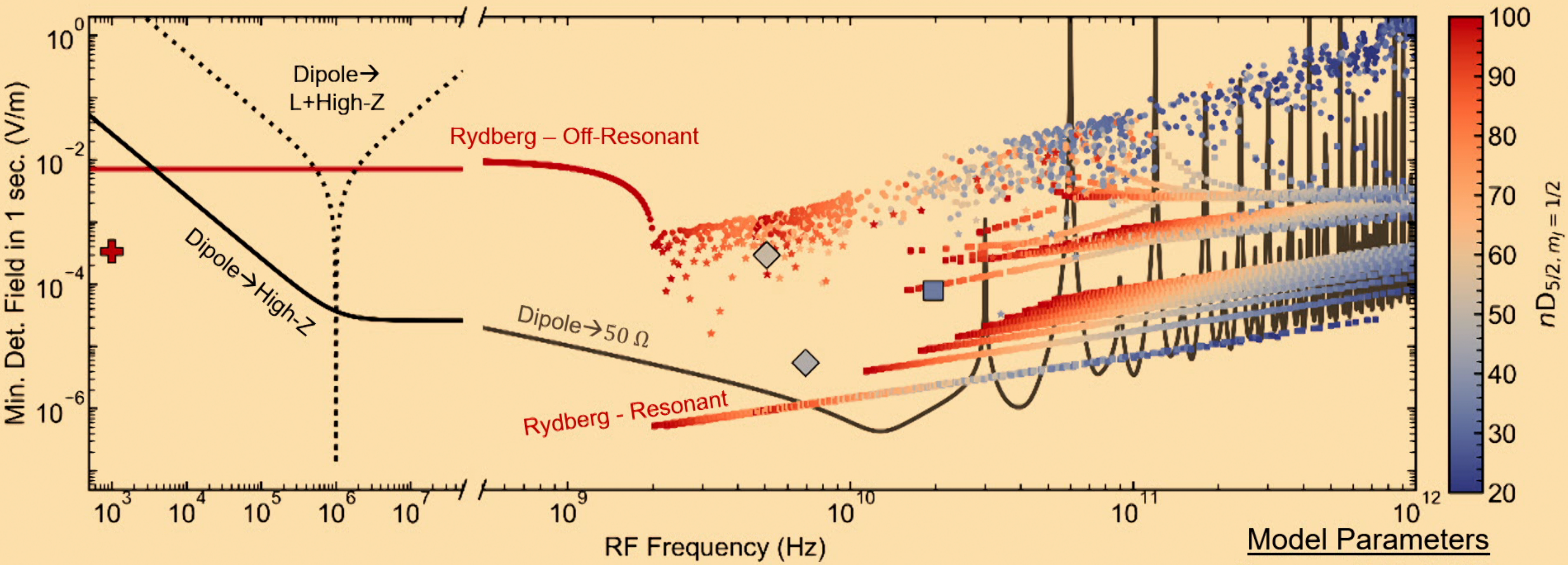
SQL SENSITIVITY OVER WIDE SPECTRUM



D. H. Meyer, et al., J. Phys. B 53, 034001 (2020). [arXiv:1910.00646]



WIDEBAND SENSITIVITY: CURRENT STATUS



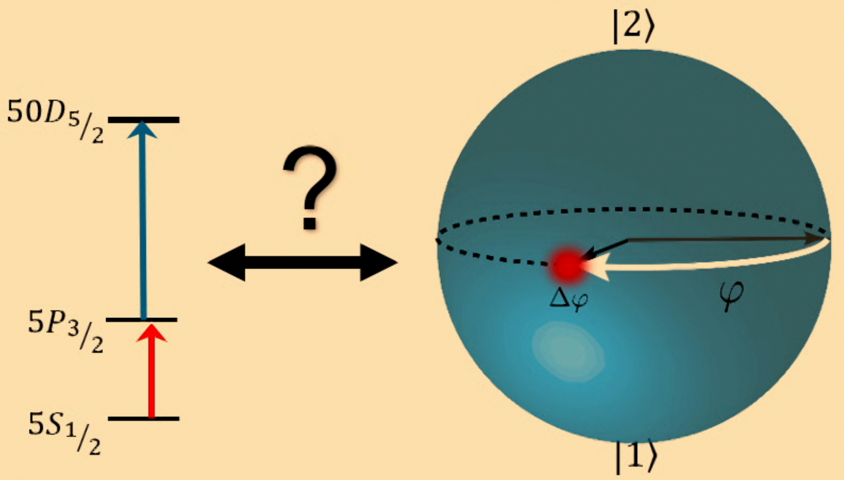
Model Parameters

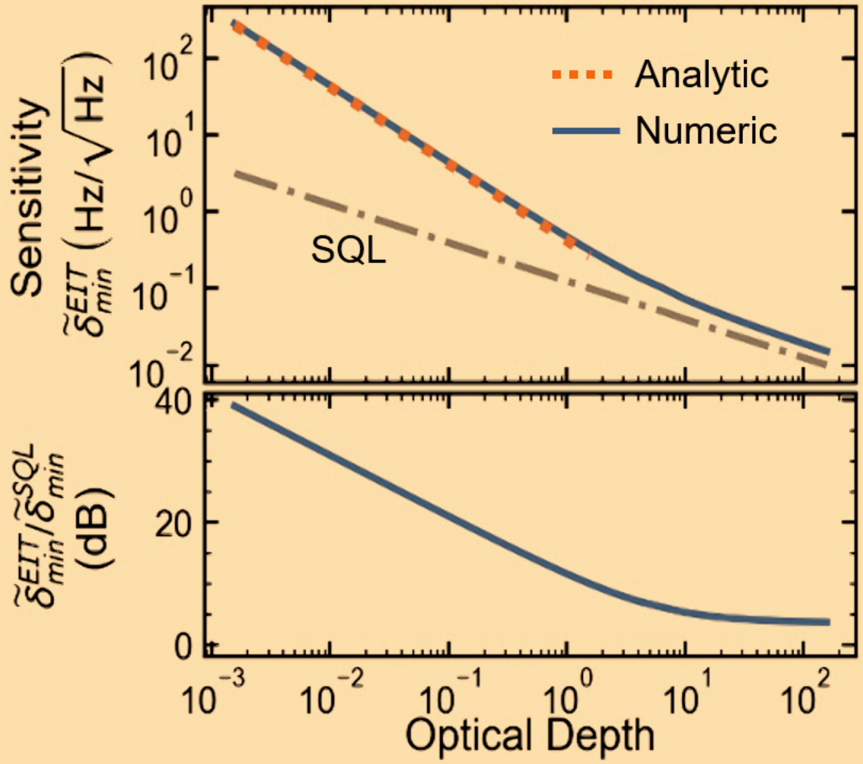
$N_{atoms} = 1000$ @ SQL
$1/T_2 = 2\pi \cdot 3$ MHz
Assume: SQL Readout,
Single tone field

◇ Jing, M., Hu, Y., Ma, J., Zhang, H., Zhang, L., Xiao, L., & Jia, S. *Nature Physics* **16**, 911-915 (2020).
✚ Jau, Y.-Y. & Carter, T. *PRApplied* **13**, 054034 (2020).
■ Gordon, J. A., Simons, M. T., Haddab, A. H. & Holloway, C. L. *AIP Advances* **9**, 045030 (2019).
◇ Kumar, S., Fan, H., Kübler, H., Jahangiri, A. J. & Shaffer, J. P. *Opt. Express, OE* **25**, 8625–8637 (2017).

LIMITS OF EIT

D. Meyer, et al. Phys. Rev. A. 104, 043103 (2021). [arXiv:2105.10494]

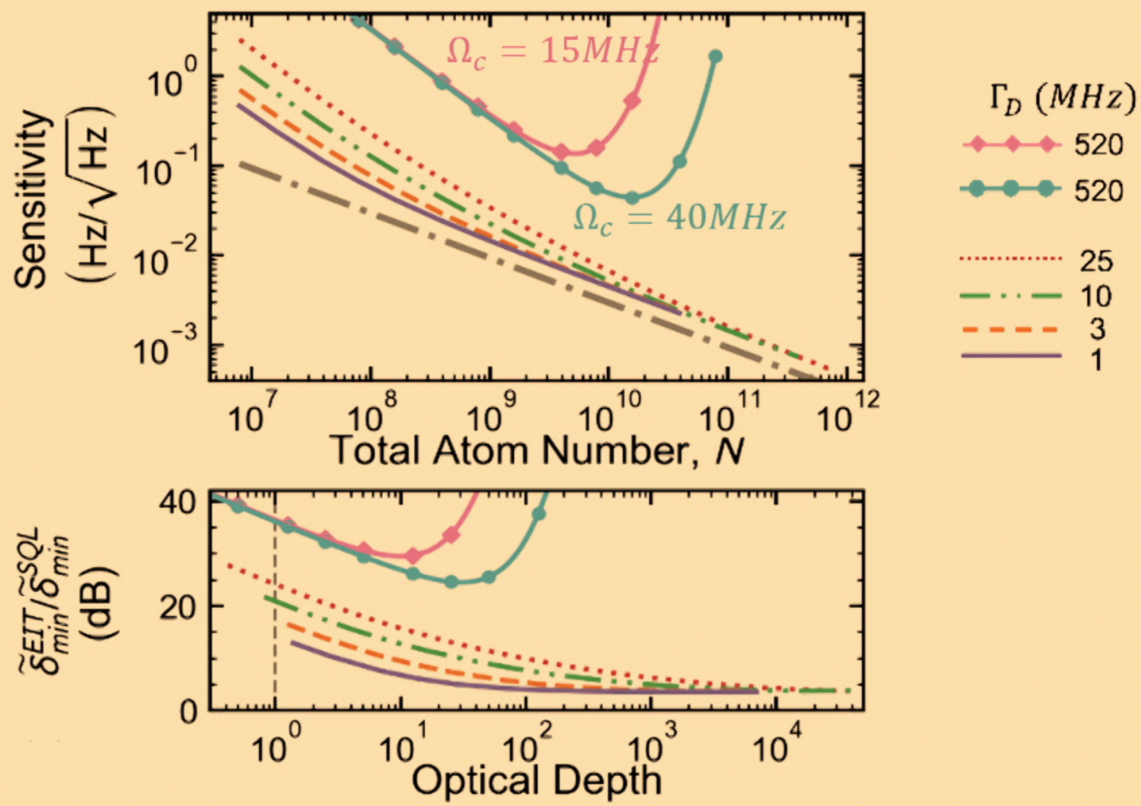




Ans: No, Rydberg EIT can not achieve the Quantum Projection limit (SQL)

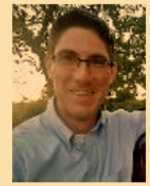
EIT LIMIT WHEN DOPPLER BROADENED

D. Meyer, et al. Phys. Rev. A. 104, 043103 (2021). [arXiv:2105.10494]



- Even worse when Doppler broadened.
- Should explore alternatives to EIT if want to reach Quantum limit of SNR

LASER ADVANCES – VECSEL 474nm



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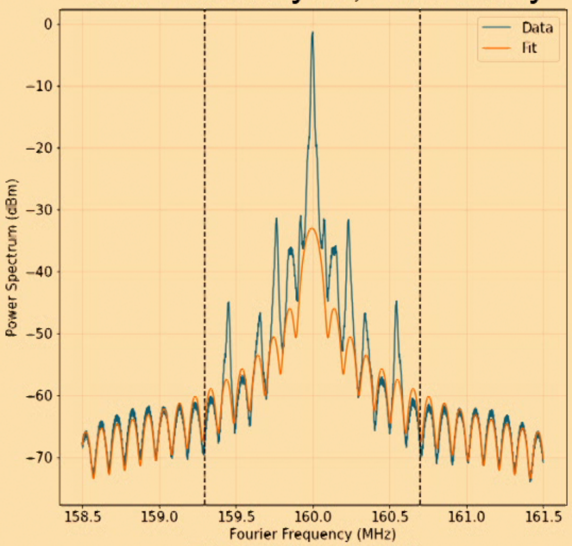
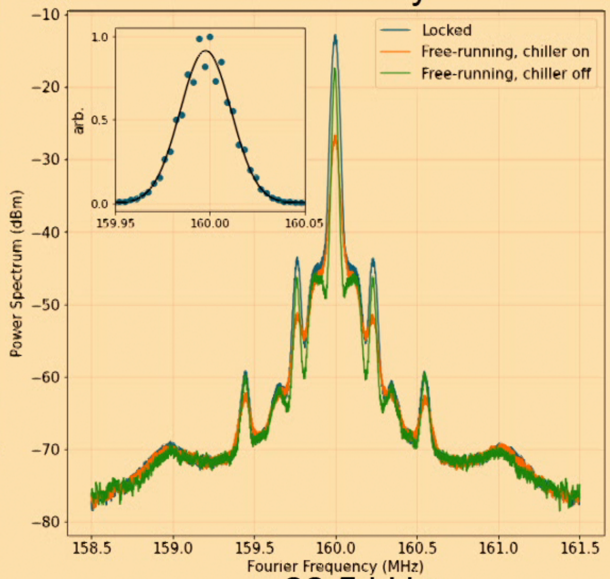
Self-heterodyne, 2km delay



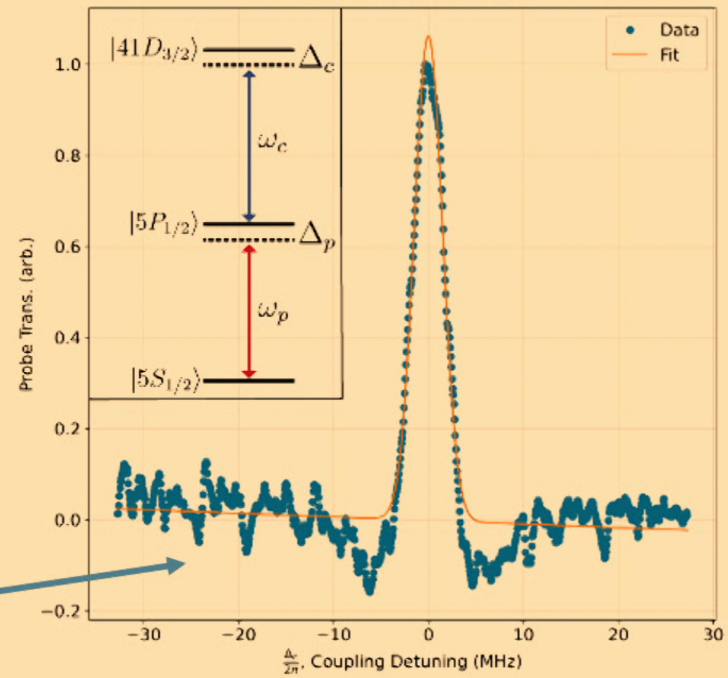
5kHz linewidth
(assuming white noise)

11 km delay



22.5 kHz
Gaussian width

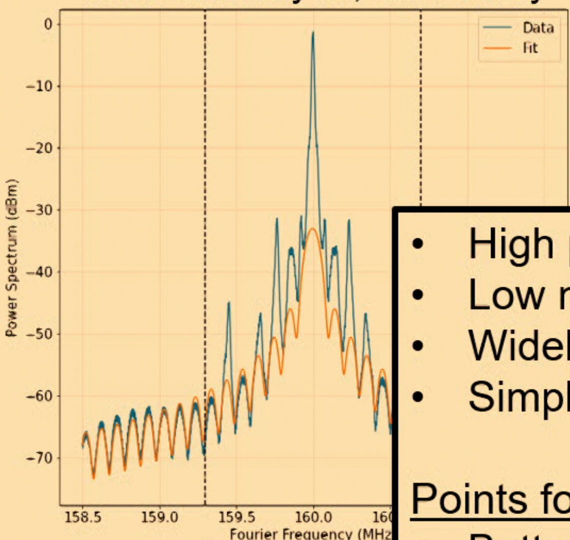
Rydberg EIT



- Measure Rydberg EIT linewidth of 3.5 MHz
- Single sweep in 3.6ms

LASER ADVANCES – VECSEL 474nm

Self-heterodyne, 2km delay



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(assuming white

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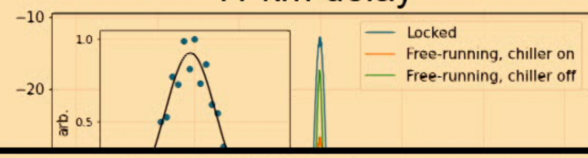

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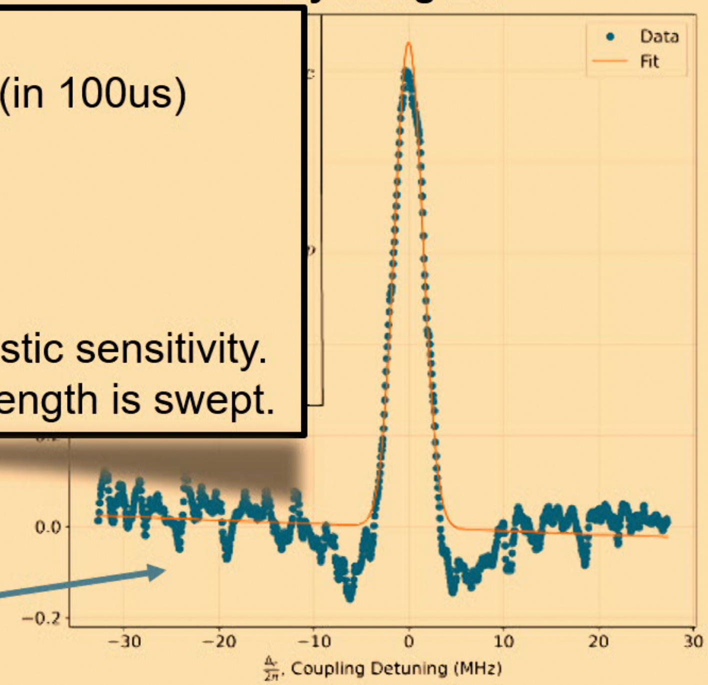
Rydberg EIT

- High power: 1 – 2 W (cw)
- Low noise (*): Lorentzian linewidth 5kHz (in 100us)
- Widely Tunable: 10 nm & can be more
- Simpler / lower cost than doubled ECDL

Points for improvement:

- Better mechanical design to reduce acoustic sensitivity.
- Fix fluctuations in power output as wavelength is swept.

22.5 kHz
Gaussian width



- Measure Rydberg EIT linewidth of 3.5 MHz
- Single sweep in 3.6ms

DOPPLER FREE CONFIGURATION

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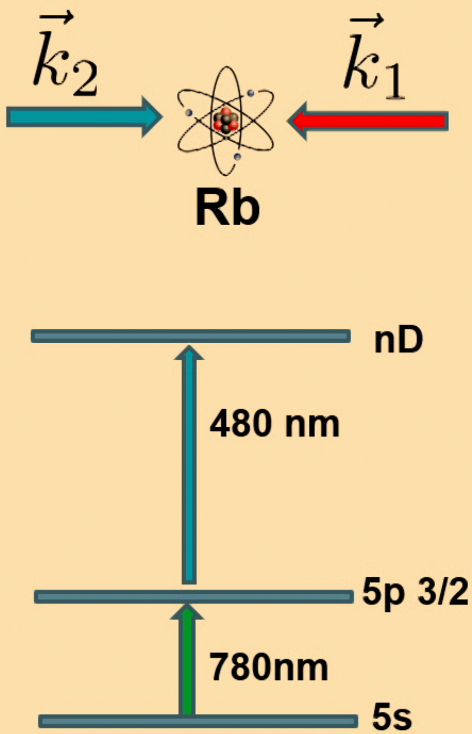
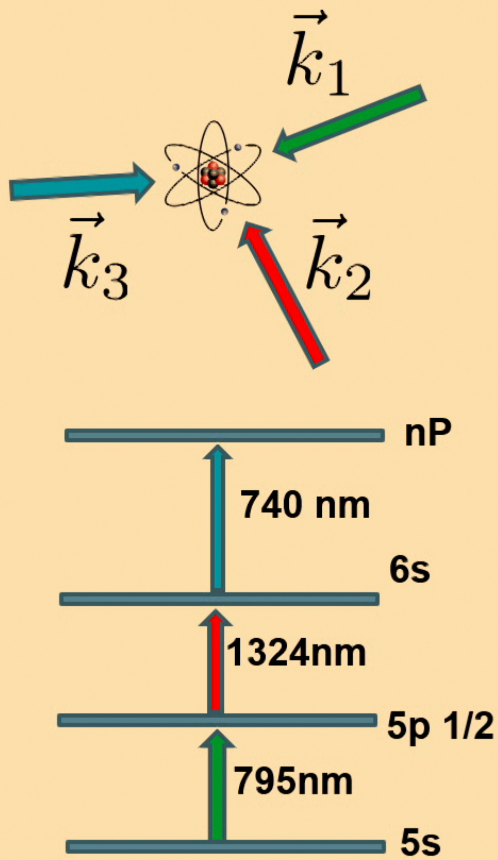
Conventional, not Doppler free

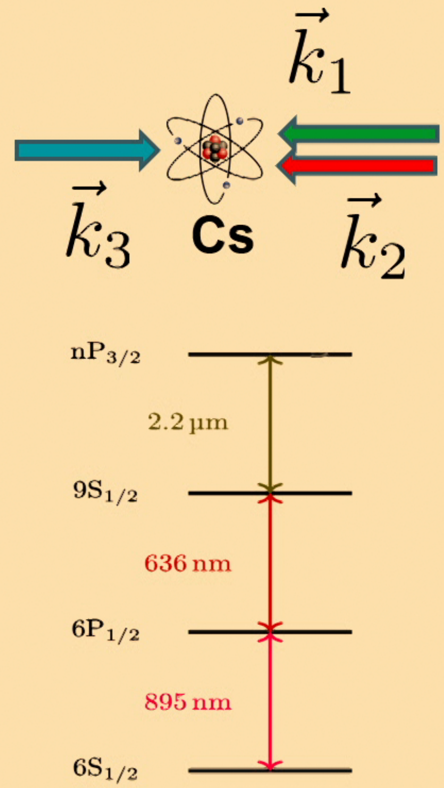


Doppler-free

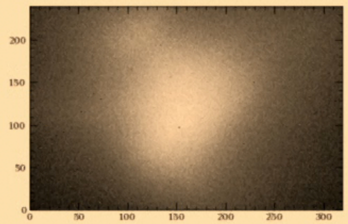


Collinear Doppler-free

J. Shaffer group



ADDRESS ALL VELOCITIES – MORE RYDBERGS



500nm shortpass

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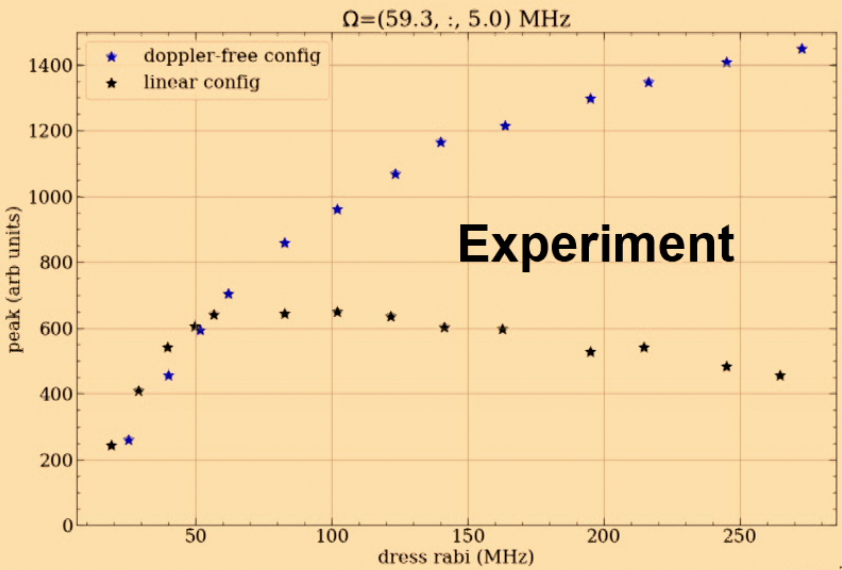
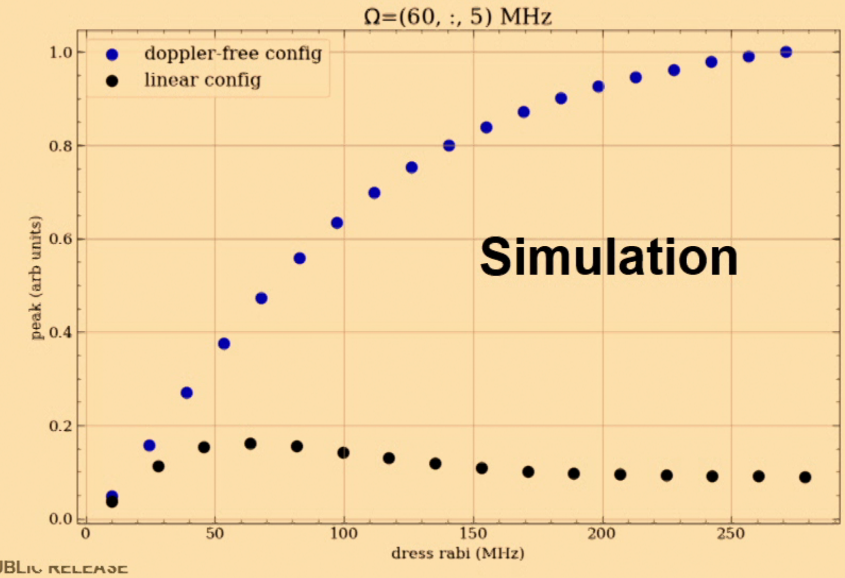


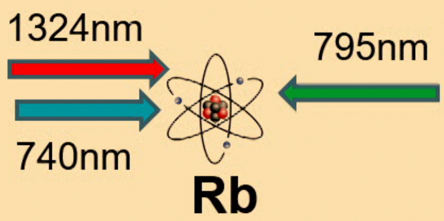


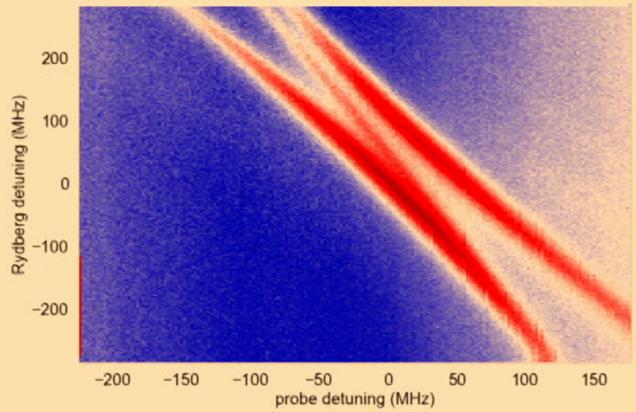
QUALITATIVE SIM & EXPERIMENT AGREEMENT

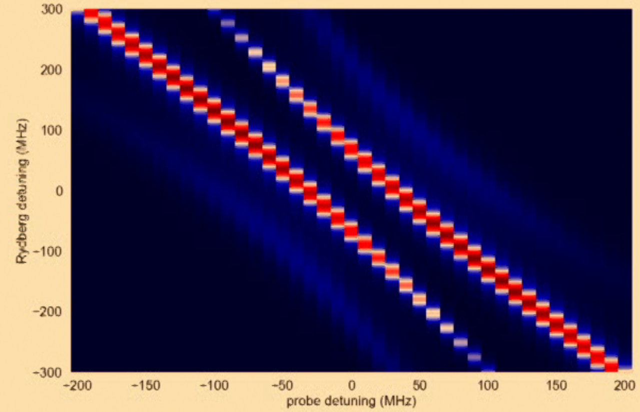
Experiment

Simulation

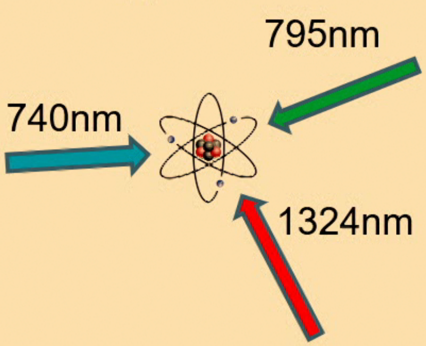
Non-Doppler Free

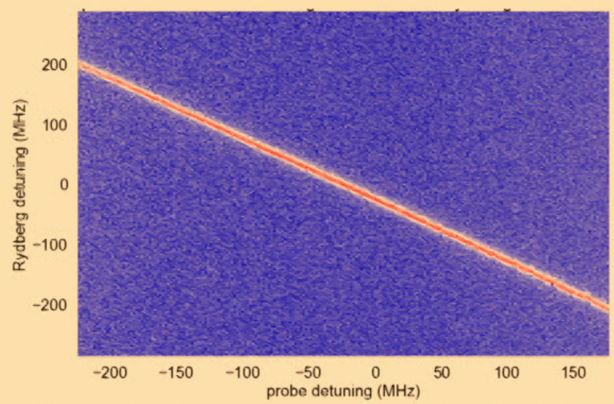


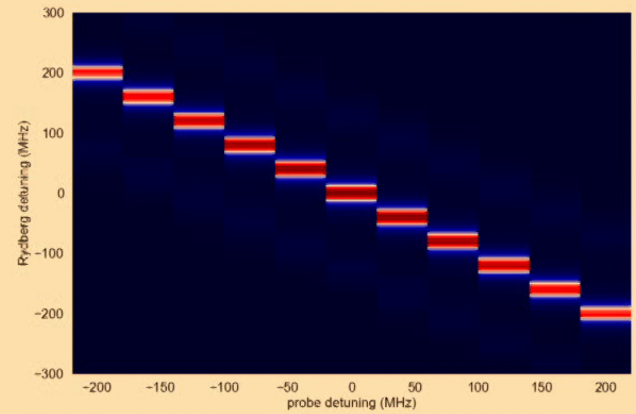




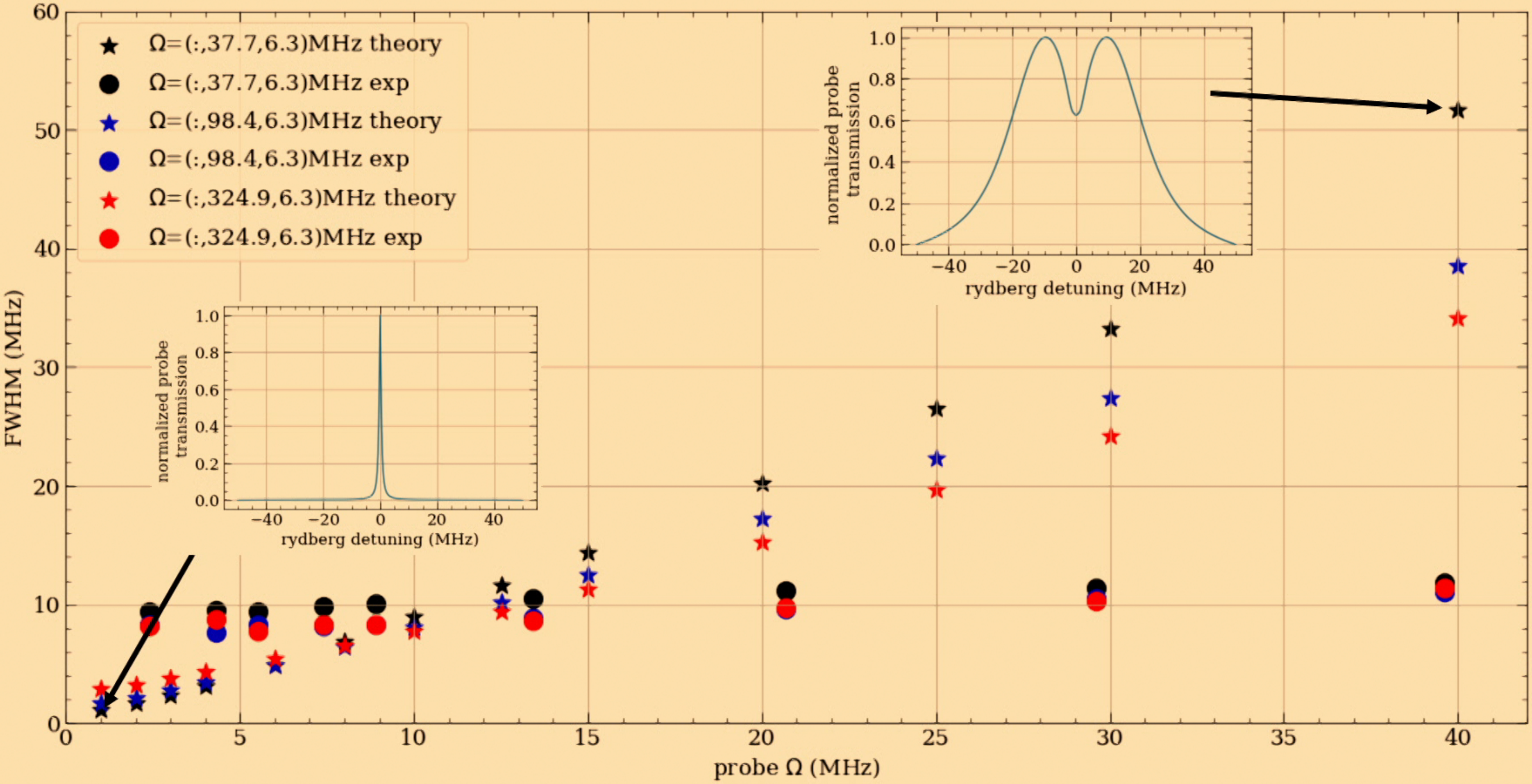
Doppler Free



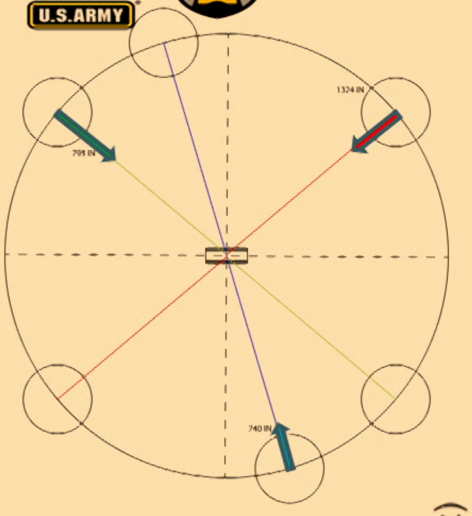


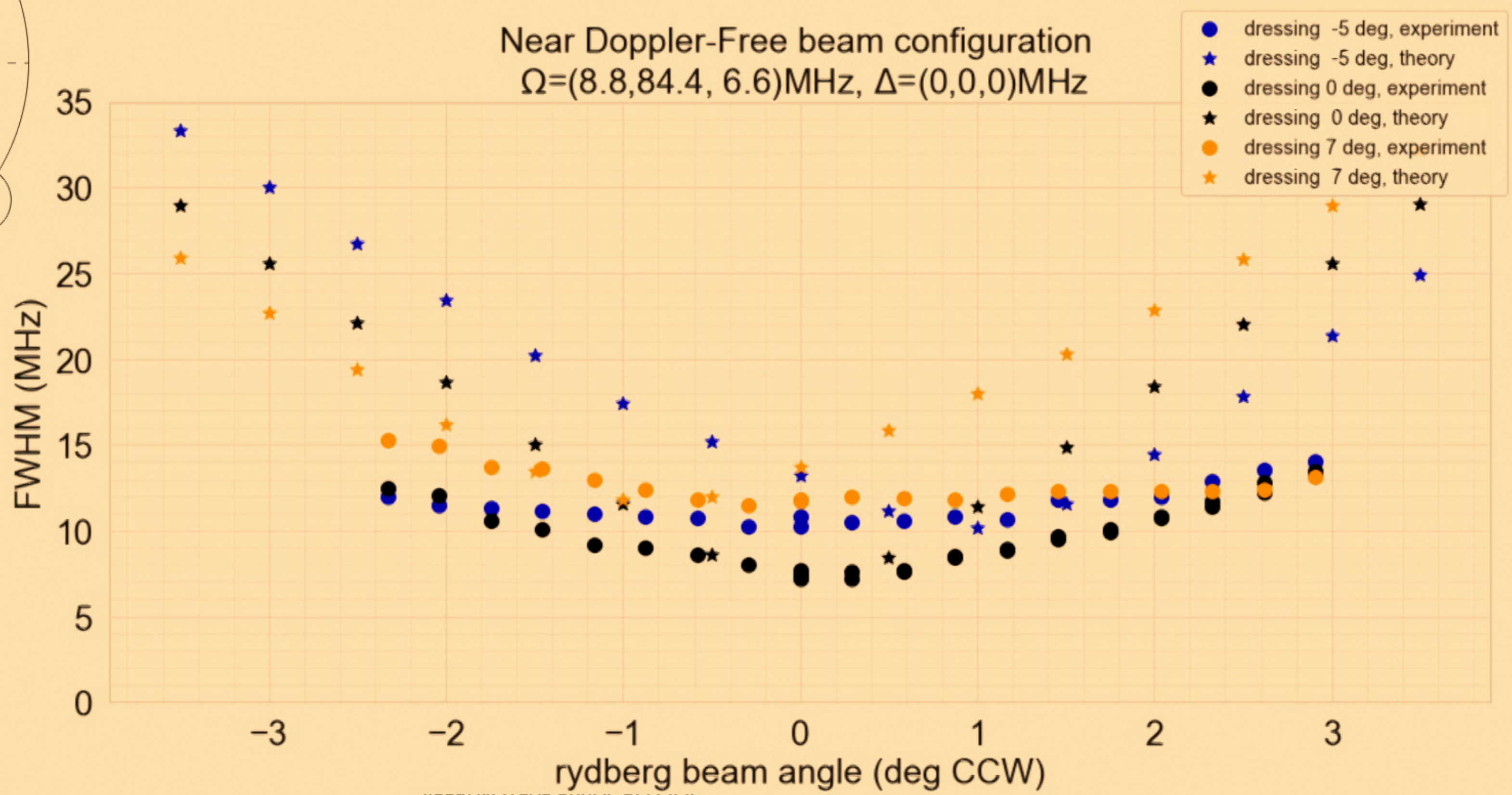


POWER BROADENING, AND NOT



ANGULAR DEPENDANCE

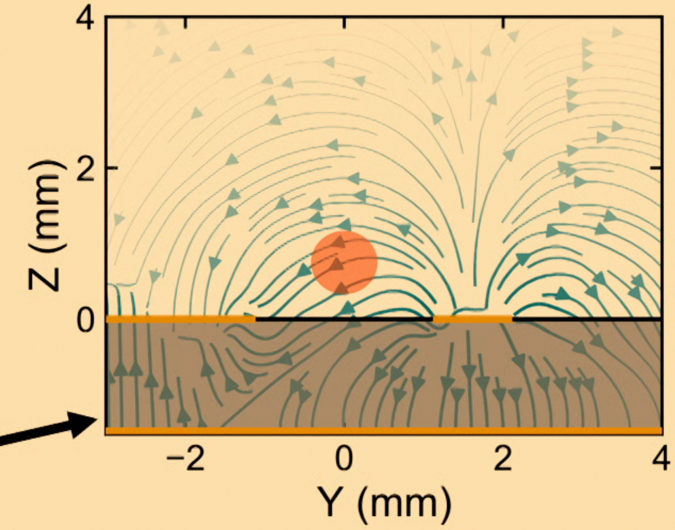


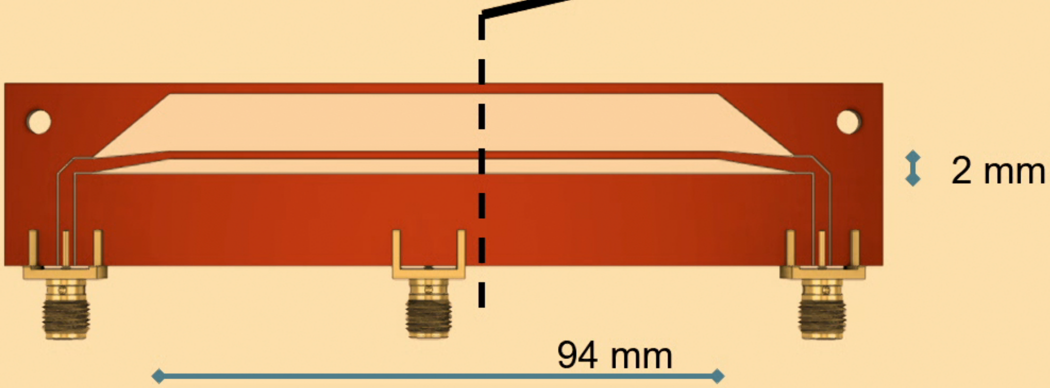


CAN WE DO BETTER?

Concentrate the field to sub-wavelength evanescent mode

Dr. Kevin Cox





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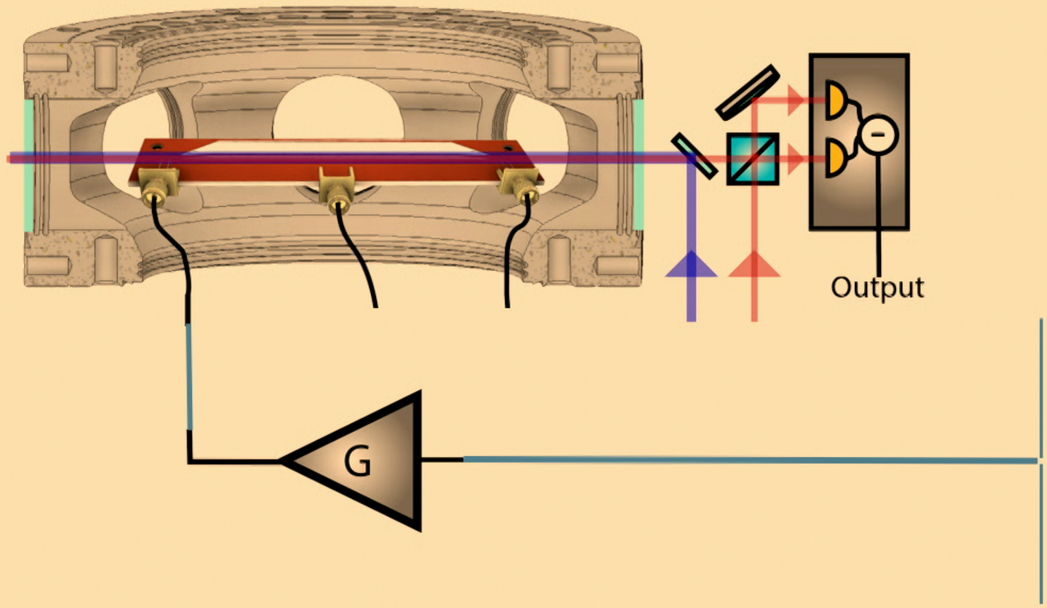
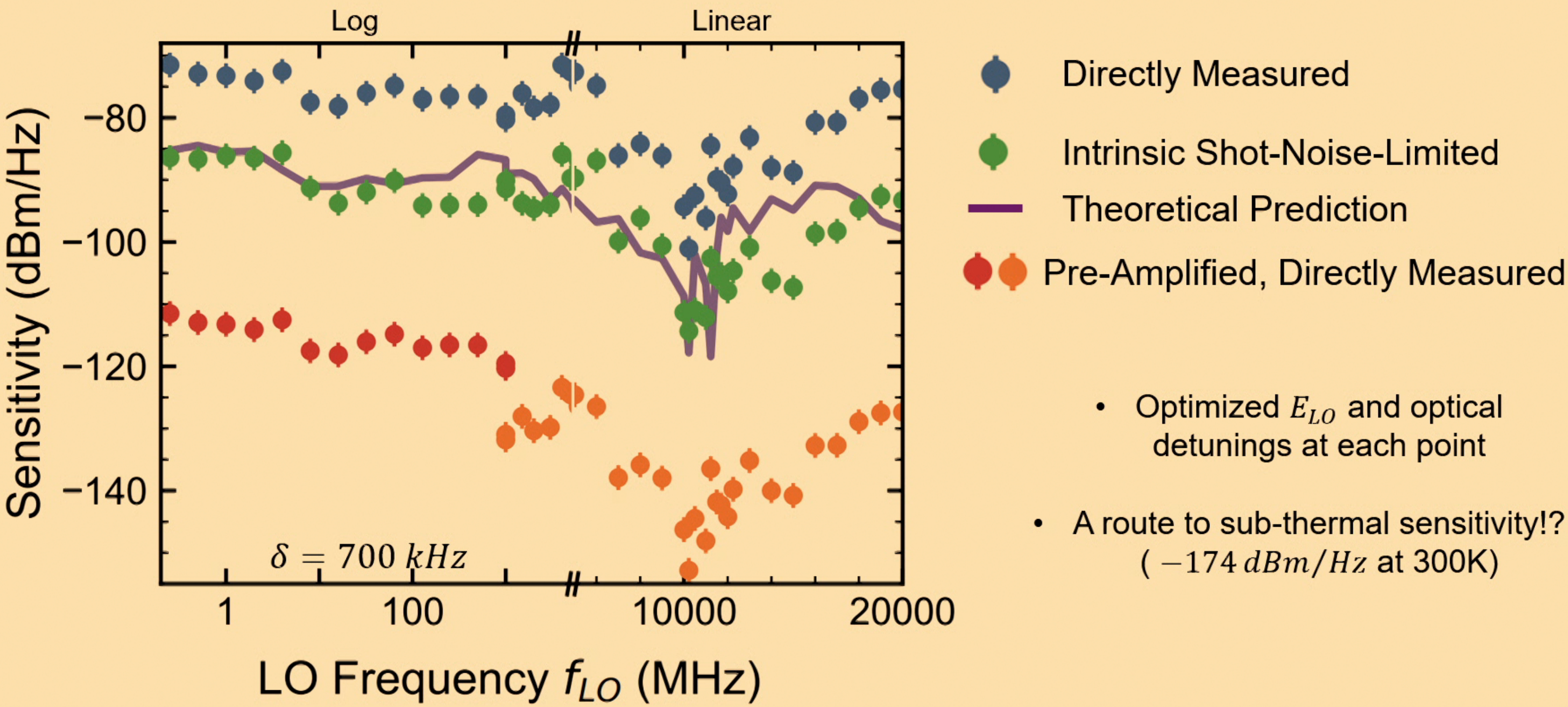
WAVEGUIDE-COUPLED RYDBERG SENSOR

Meyer et al. Phys. Rev. Applied **15**, 014053 (2021)



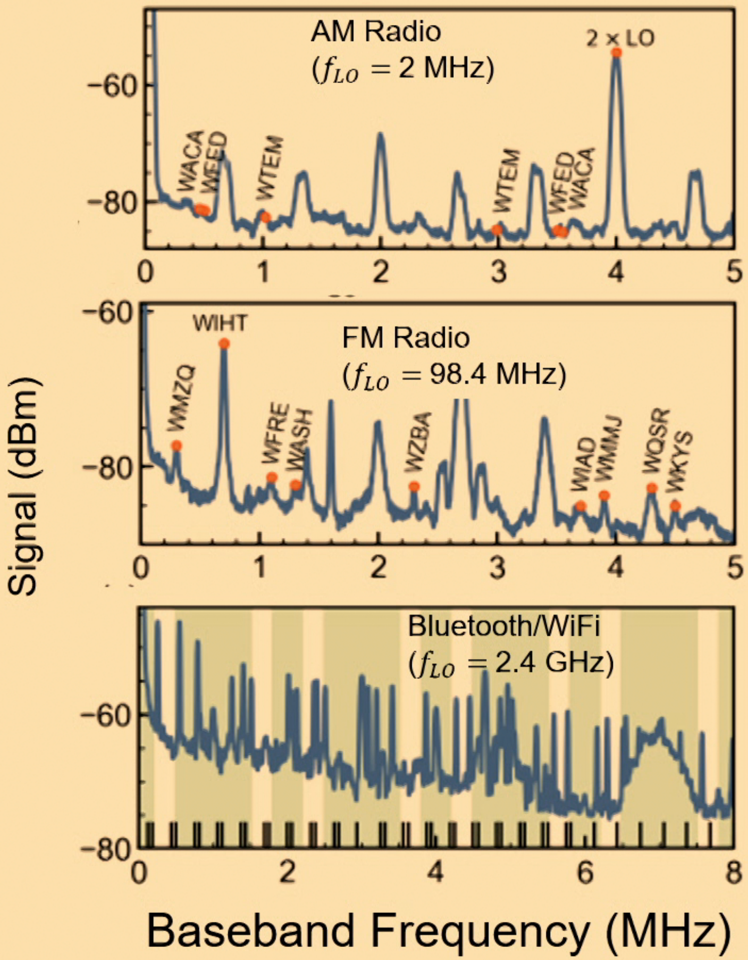
Allows use of other standard RF front-end components (antennas, amplifiers, etc) that provide spatial/spectral filtering and gain

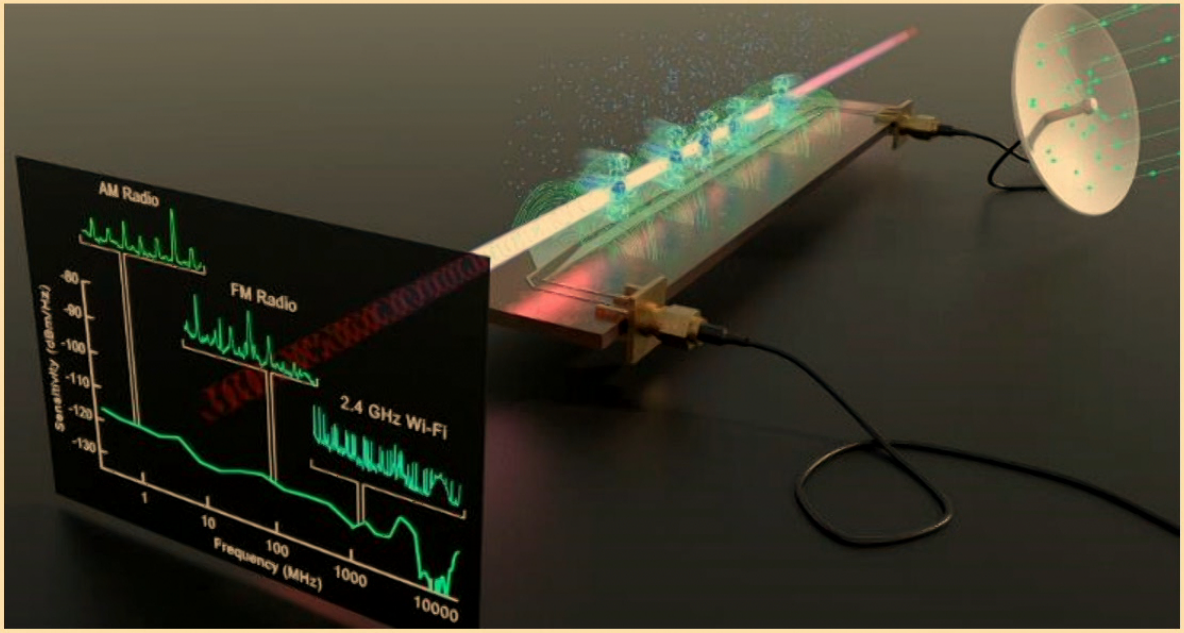
WIDEBAND PERFORMANCE



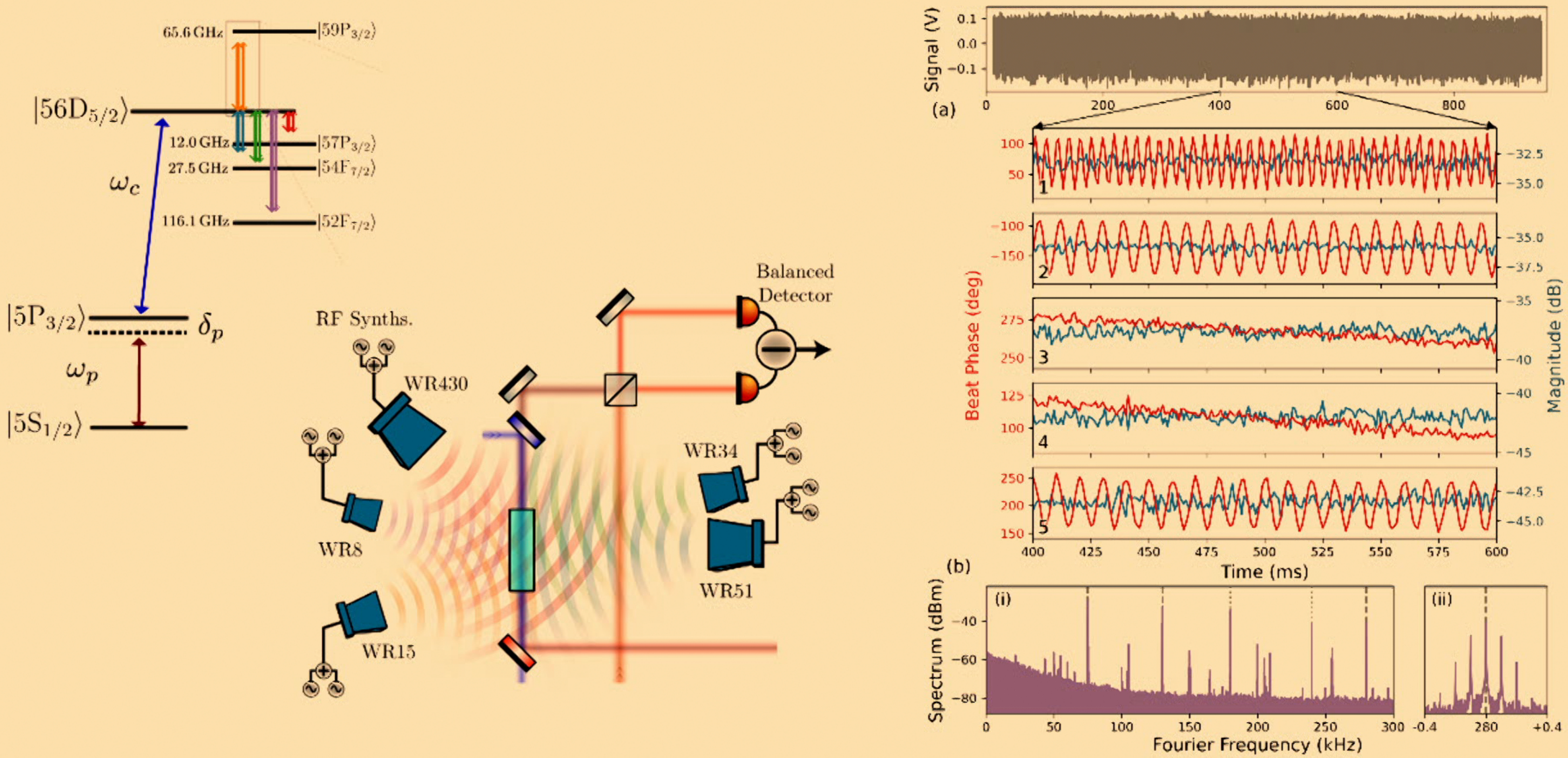
- Optimized E_{LO} and optical detunings at each point
- A route to sub-thermal sensitivity!? ($-174\,dBm/Hz$ at 300K)

MEASURE SIGNALS BROADCAST FROM OUTSIDE OF LAB

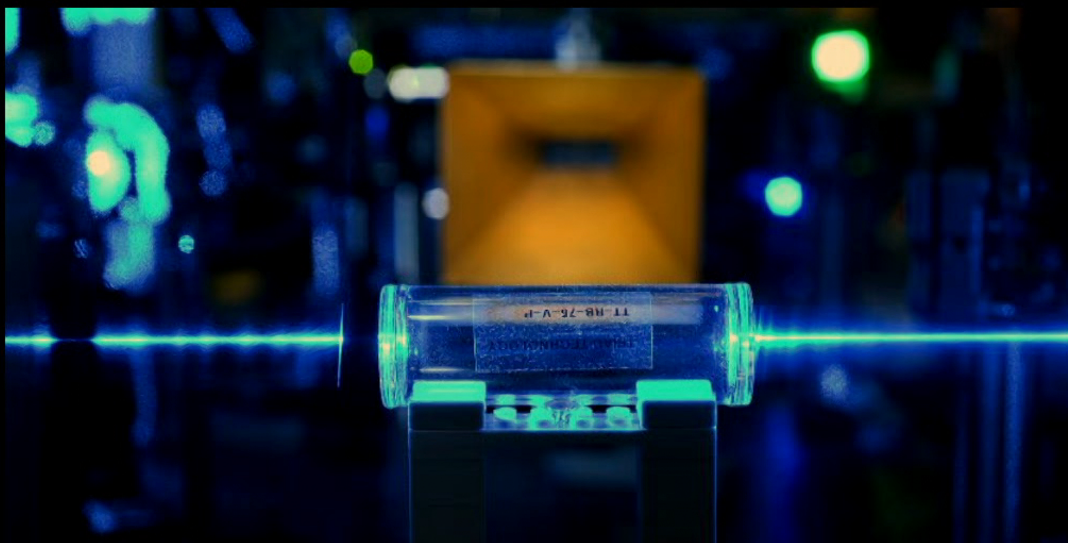




SIMULTANEOUS MEASUREMENT OF SIGNALS ON WIDELY DISPARATE TONES



Thank You



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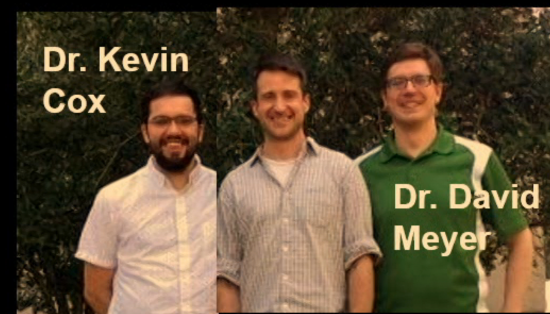

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