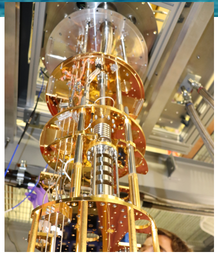
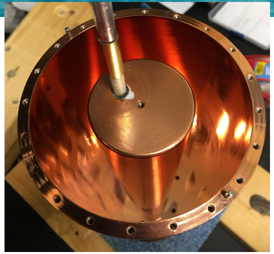
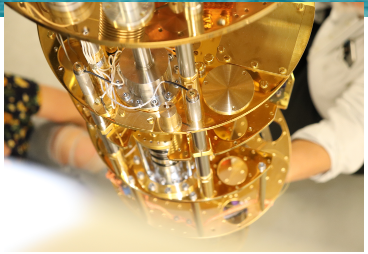
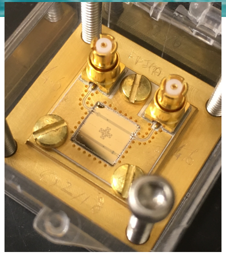
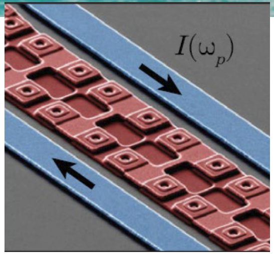
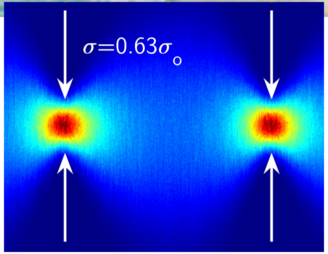
Single-Photon Detection for Axion Haloscopes with RAY



Reina Maruyama, on behalf of Eleanor Graham & RAY
Yale University

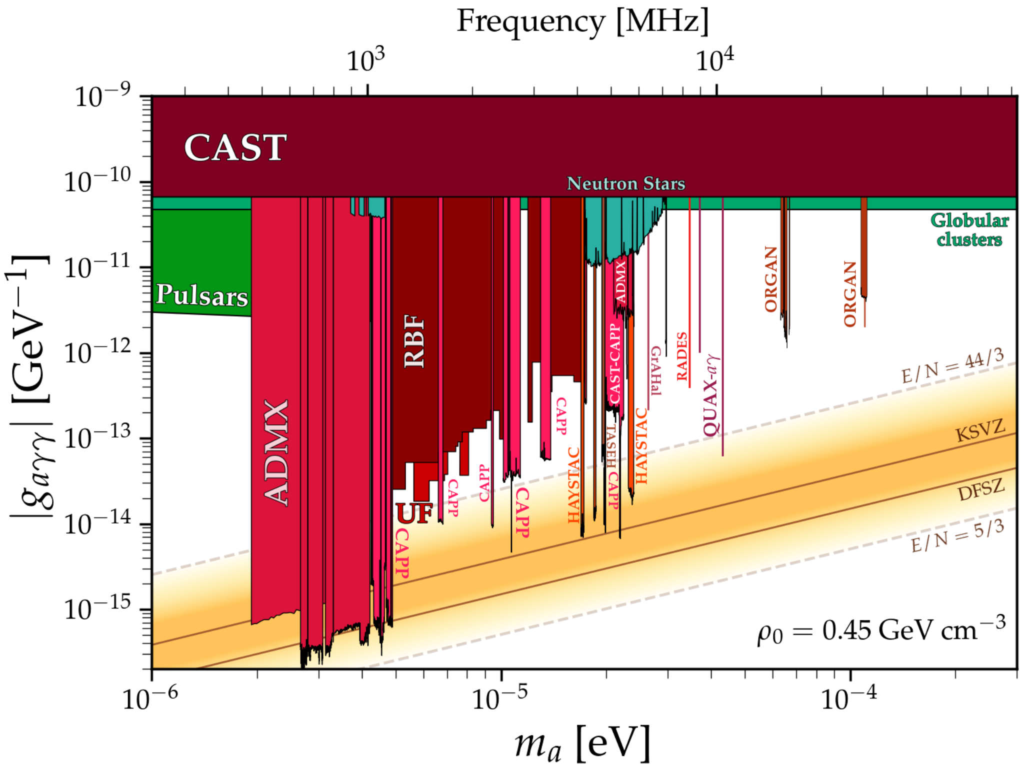
19th Patras Workshop on Axions, WIMPs, and WISPs,
Patras, Greece
September 17, 2024

U.S. DEPARTMENT OF ENERGY | Office of Science
QuantiSED

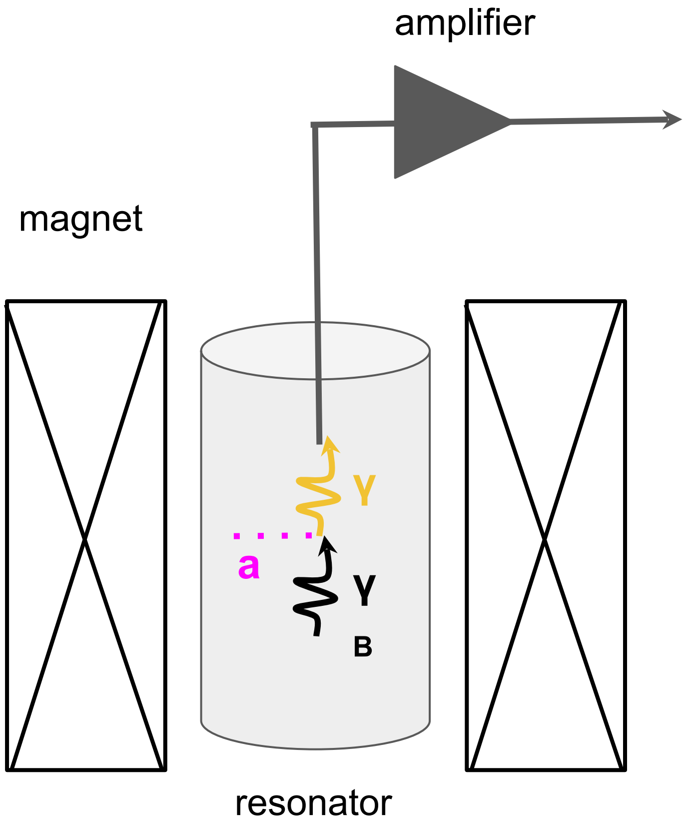
Wright Laboratory

Yale

Haloscope Searches for Axions



https://cajohare.github.io/AxionLimits/

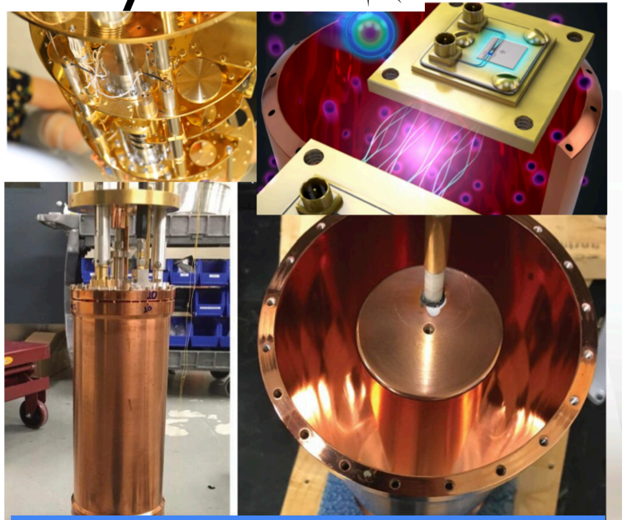


https://axion-dm.yale.edu/

Yale

Axion Searches at Yale

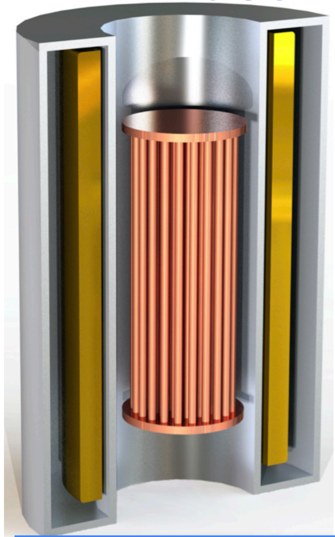
Haystac



See Xiran Bai, Wed. 11:30

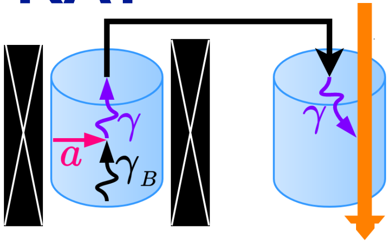
arXiv:2409.08998

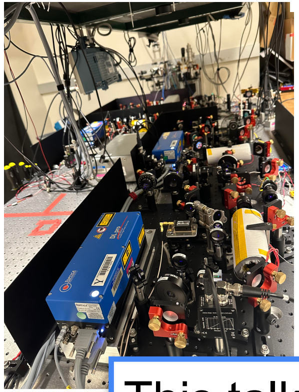
alpha Phase1



Max Silva-Feaver
Wed. 10:45

RAY





This talk

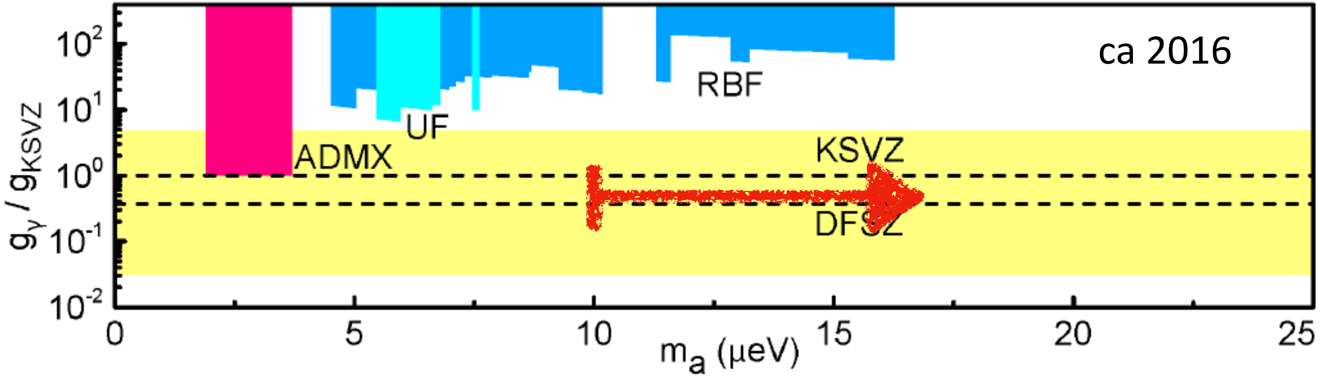
Graham et al.,
PRD 109, 032009 (2024)

When they go low, we go high -M. Obama

- Post-inflation scenarios point to higher masses
- HAYSTAC: Innovation testbed for axion searches > 10 μeV (~2.5 GHz)
- Challenges:
  - Photon detection, noise
  - Scan rate: $V \propto \nu^{-2}$, $\frac{d\nu}{dt} \propto V^2$, $\frac{d\nu}{dt} \propto \nu^{-4}$

Borsanyi et al (2016) PQ symmetry broken after inflation: m_a > 10 μeV

Klaer & Moore (2017); 26.2 ± 3.4 μeV



Buschmann, et al. (2022): 40 μeV [65 ± 6 μeV, q=1; scale invariant spectrum]

* In $\Omega_A \sim f_A^\alpha$, the best fit α = 1.24 ± 0.04
Rather than analytical 1.187

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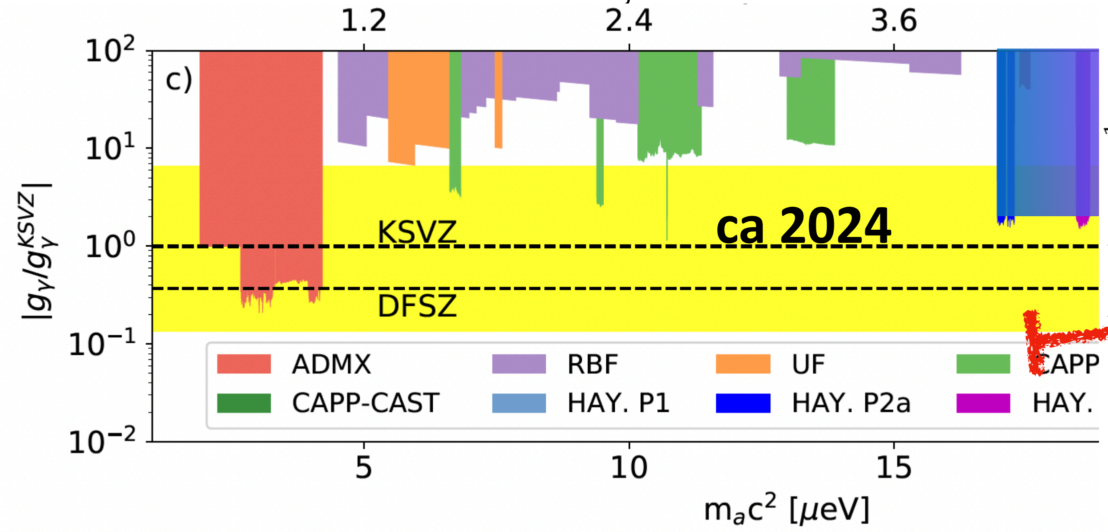
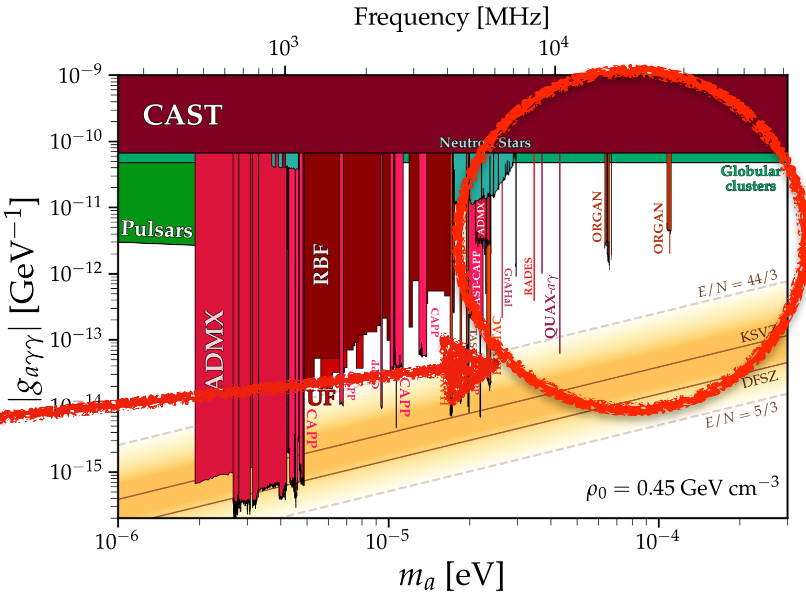




Quantum Measurement Noise in Haloscopes

Zero-point fluctuations in signal amplitude (uncertainty principle)

+

Noise from linear amplifier

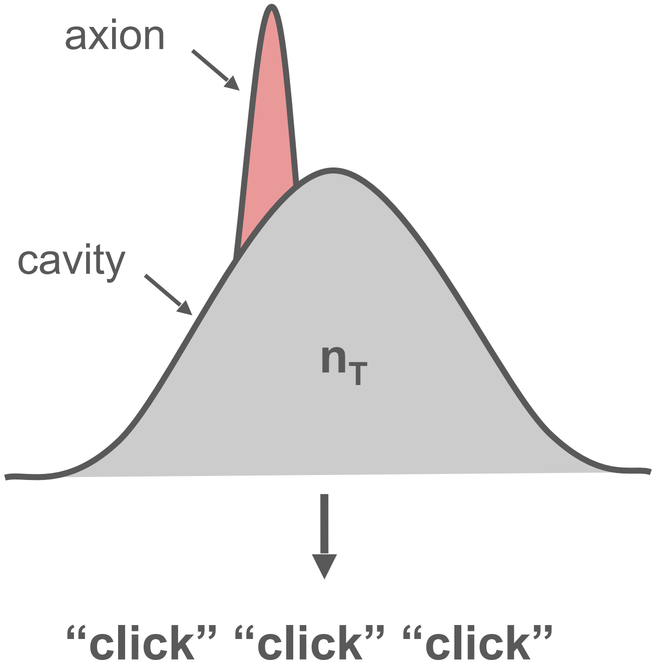
=

The Standard Quantum Limit (SQL)

($N_{SQL} = 1$)

- **Traditional linear receiver:** minimum noise limited by SQL
- **HAYSTAC squeezed-state receiver:** 4 dB squeezing → 2x enhancement relative to SQL-limited axion search
- **Single-photon detector:** equivalent to infinite squeezing, zero measurement noise contribution

Single-Photon Detection for Haloscopes



Best conditions for single-photon detector:

- Cavity bandwidth approaches axion bandwidth
- Thermal background in cavity n_T is small (reduce temperature, increase frequency)

Crossover point where single-photon detector outperforms linear receiver: ~ 10 GHz.

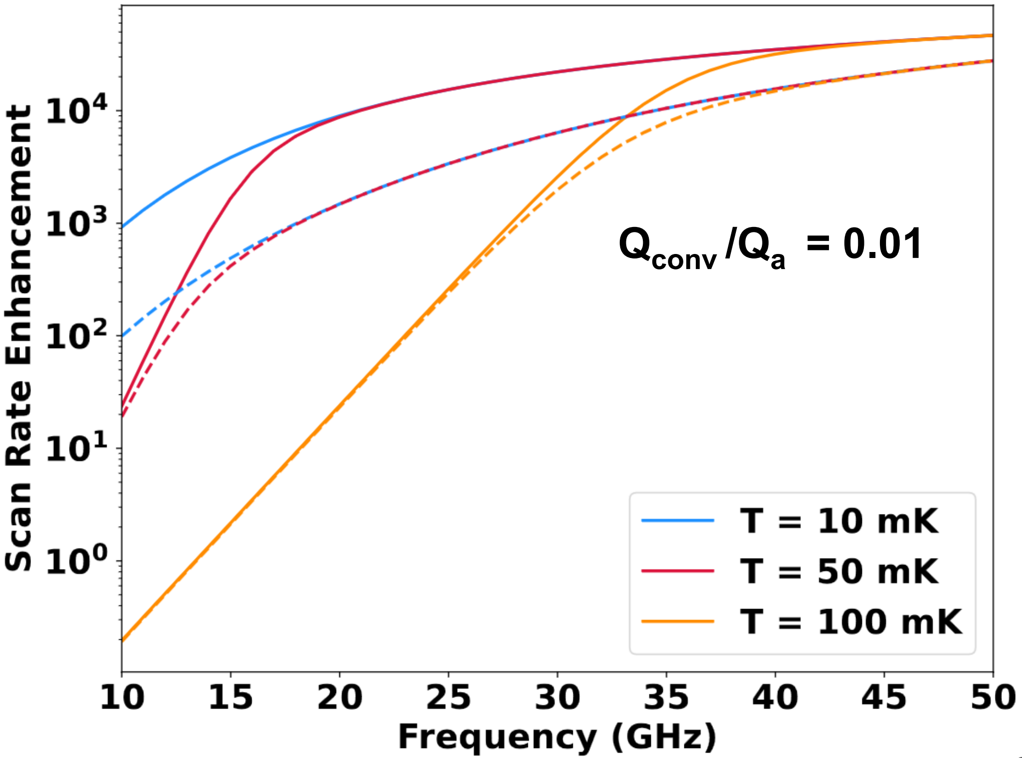
Scan Rate Enhancement: Single-Photon Detectors

Total enhancement:

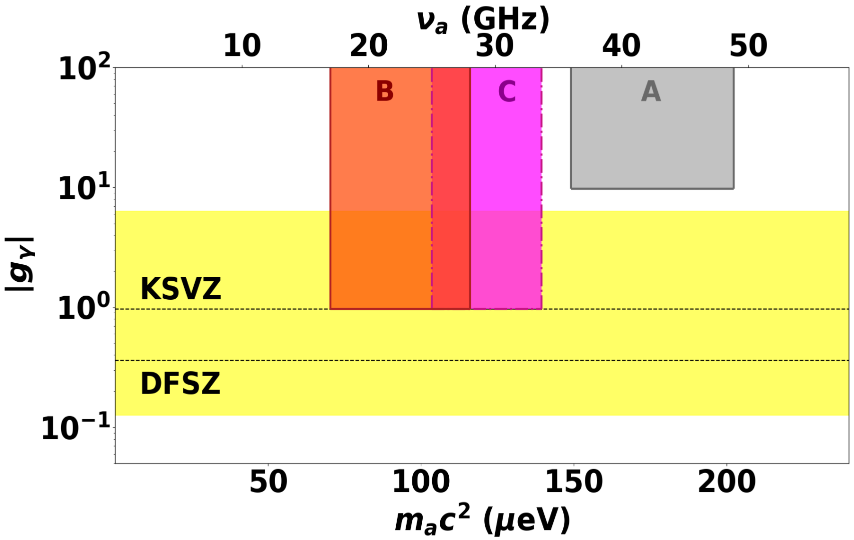
$$E \approx \frac{Q_{\rm conv}}{Q_a} \frac{\Delta\nu_a}{R_{\rm sig} + R_T + R_{\rm RO}}$$

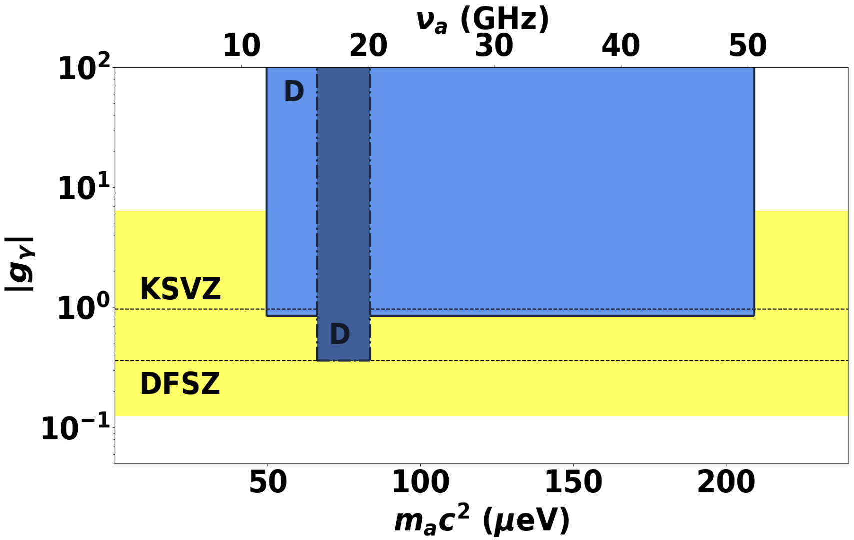
- 10^4 enhancement over linear amp.
- Increase enhancement factor by increasing Q_{conv} to Q_a
- Enhancement largest w/ negligible thermal noise
- Ultimately limited by shot noise

PRD 109, 032009 (2024)



Single Photons: Axion Sensitivity - 5 years





A: current gen. haloscopes,
e.g. HAYSTAC: Q_{conv}~10^4, 8 T, 100 mK

B: Q_{conv}~10^5, 12 T, 50 mK

C: Q_{conv}~2x10^4, 32 T, 50 mK

D: Plasma Haloscope, 8 T, 50 mK

V_0	1.5 L	Volume at 5 GHz
$C_{mn\ell}$	0.5	Form factor
Q_{det}	10^6	Detection cavity Q
β	1	Coupling factor
η	0.4	Total efficiency
R_{RO}	0.01 ct/s	SFI noise rate

Building a Microwave Single-Photon Detector

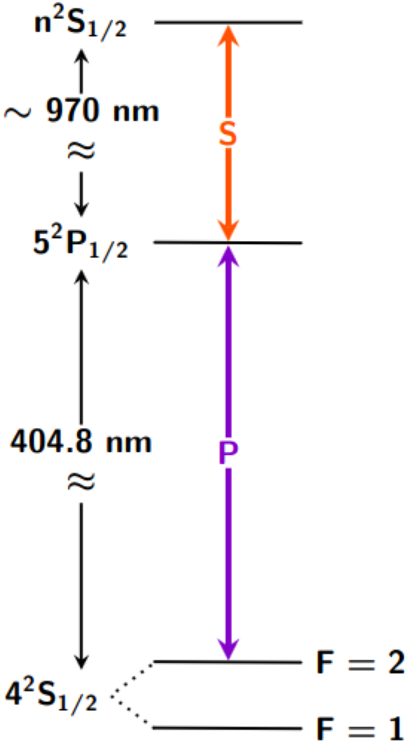
Achieve the required sensitivity by coupling to a quantum system:

Superconducting qubits	Josephson junctions	Rydberg atoms
C. Braggio *et al.*, preprint (2024) A. Dixit *et al.*, Phys. Rev. Lett. **126**, 141302 (2021)	A. L. Pankratov et al., preprint (2024)	T. Haseyama *et al.*, J. Low Temp. Phys. **150**, 549 (2008) [CARRACK] E. Graham *et al.*, Phys. Rev. D **109**, 032009 (2024) This talk!

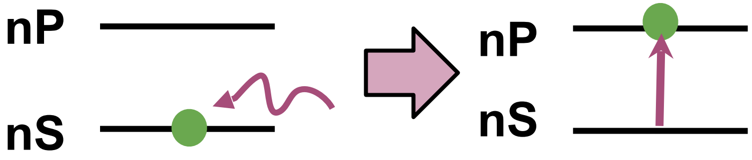
Rydberg atoms: Flexible operating frequency, built-in tuning mechanism.

Rydberg Atom-based Single Photon Detection

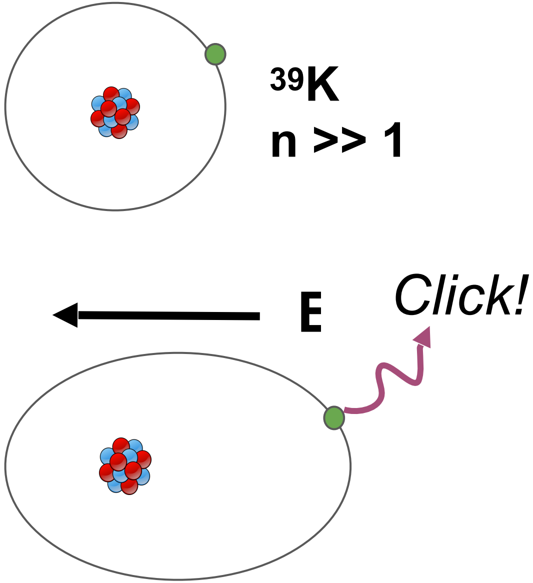
Rydberg state preparation, e.g. ^{39}K



Microwave photons couple to Rydberg transitions



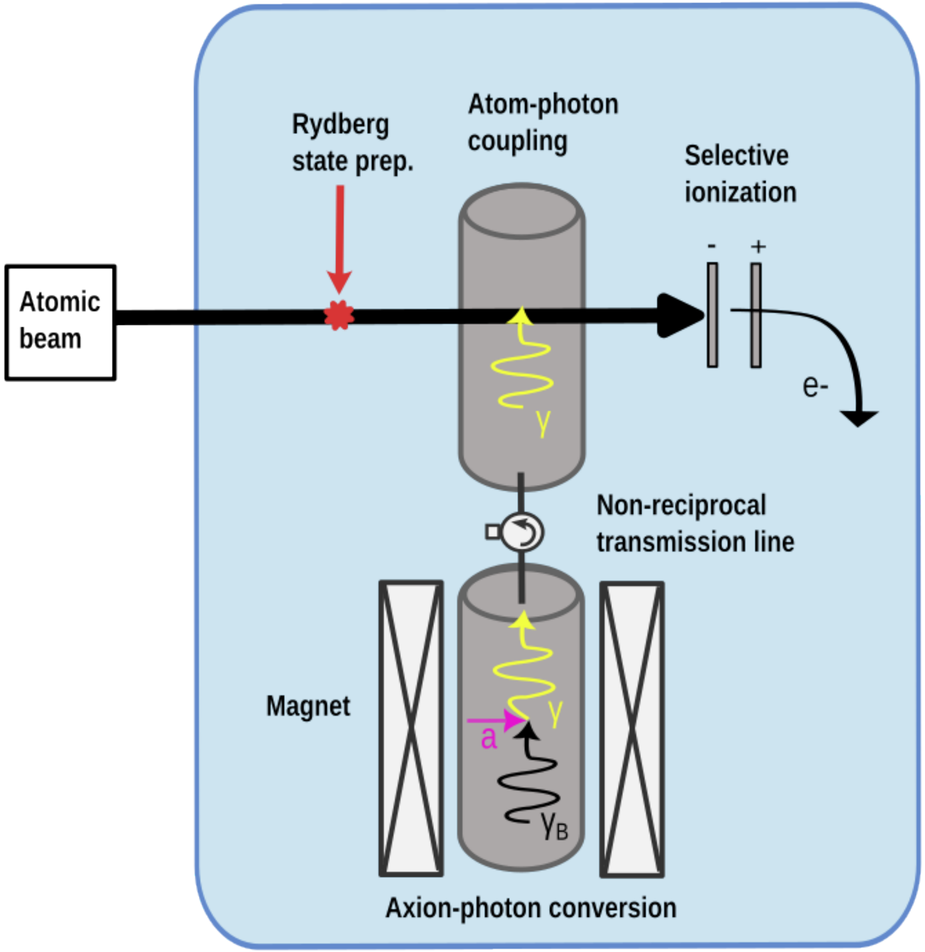
Rydberg atoms have large dipole moments, easily ionized



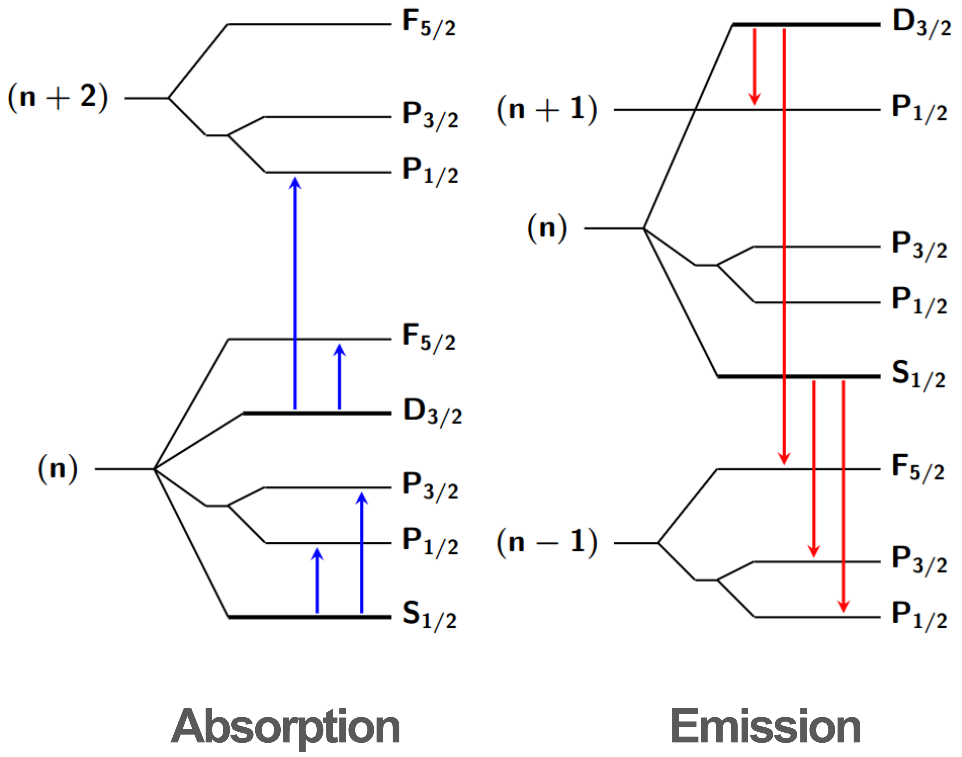
RAY Axion Search Concept

Detection sequence:

1. Axion-photon conversion in magnetic field
2. Photon transported away from magnetic field into detection cavity
3. Rydberg atom couples to photon in detection cavity
4. Ionization readout of Rydberg atom – was a photon detected?



Frequency Tuning



Three ways of tuning transition frequency:

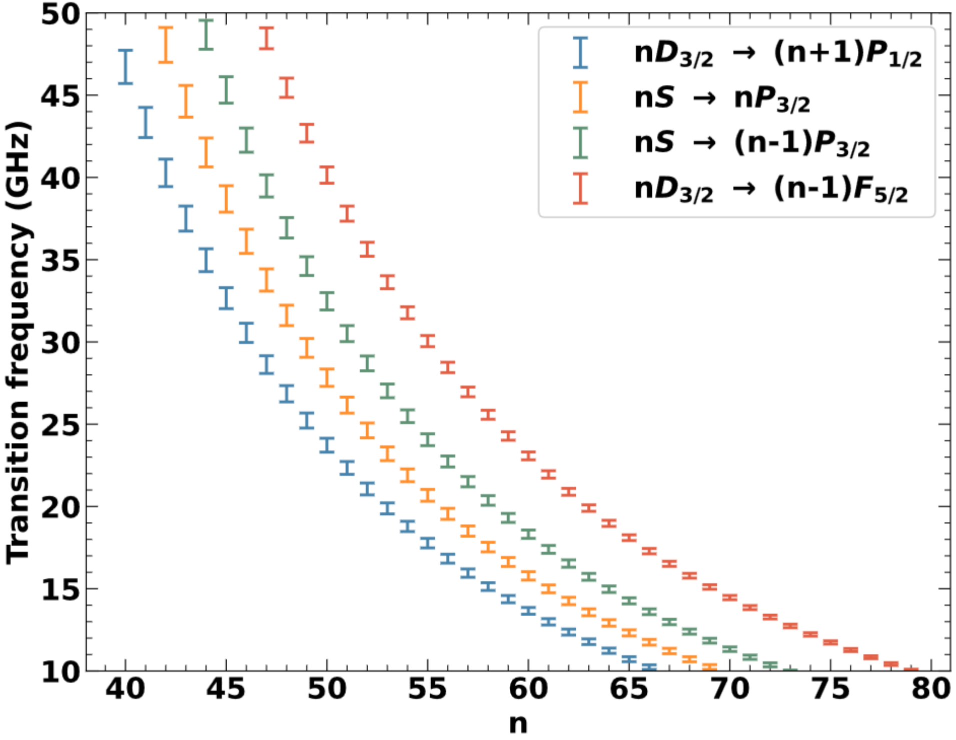
1. Vary n of starting state
2. Vary type of transition
3. Apply magnetic or electric field (Zeeman or Stark tuning)

Zeeman tuning
field: ~ 100 G
tuning range: ~ 100 MHz

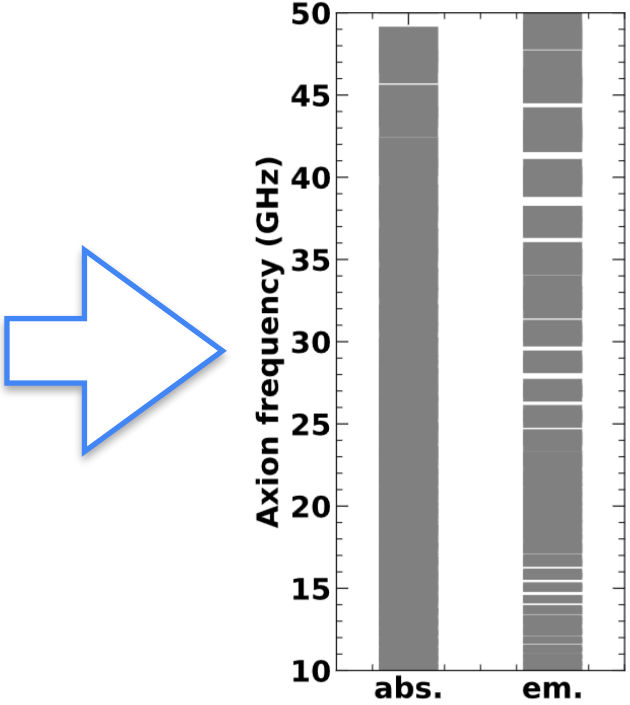
Solution: use different states

Frequency Coverage with Rydberg Atoms

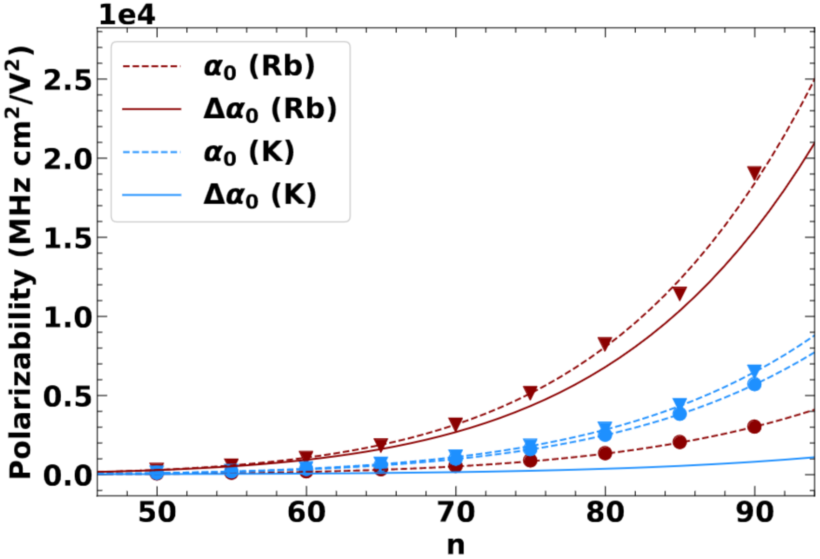
Zeeman tuning for individual transitions in K



Zeeman tuning for all transitions



Atom Choice: K vs Rb



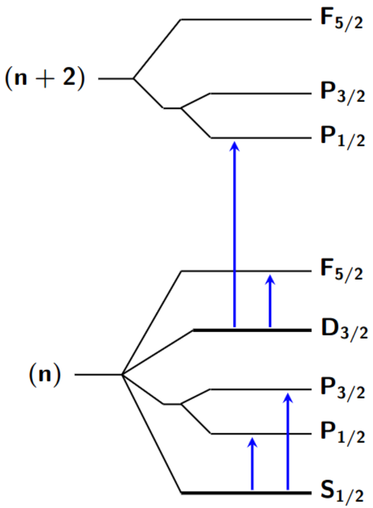
Polarizability:

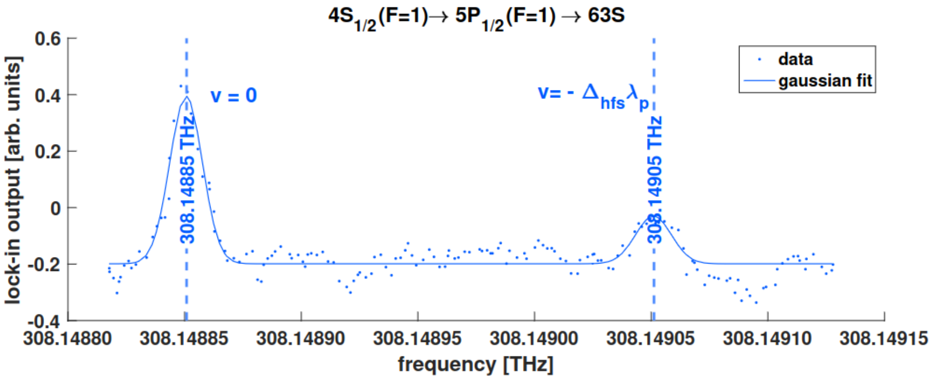
K is less sensitive to stray electric fields compared to Rb

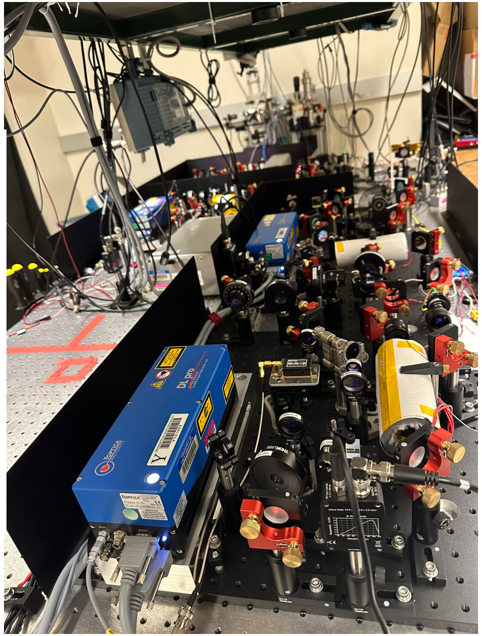
Why do we care?

Stray E fields in the detection cavity can interfere with atom-photon coupling (observed by CARRACK)

Preparing Rydberg Atoms

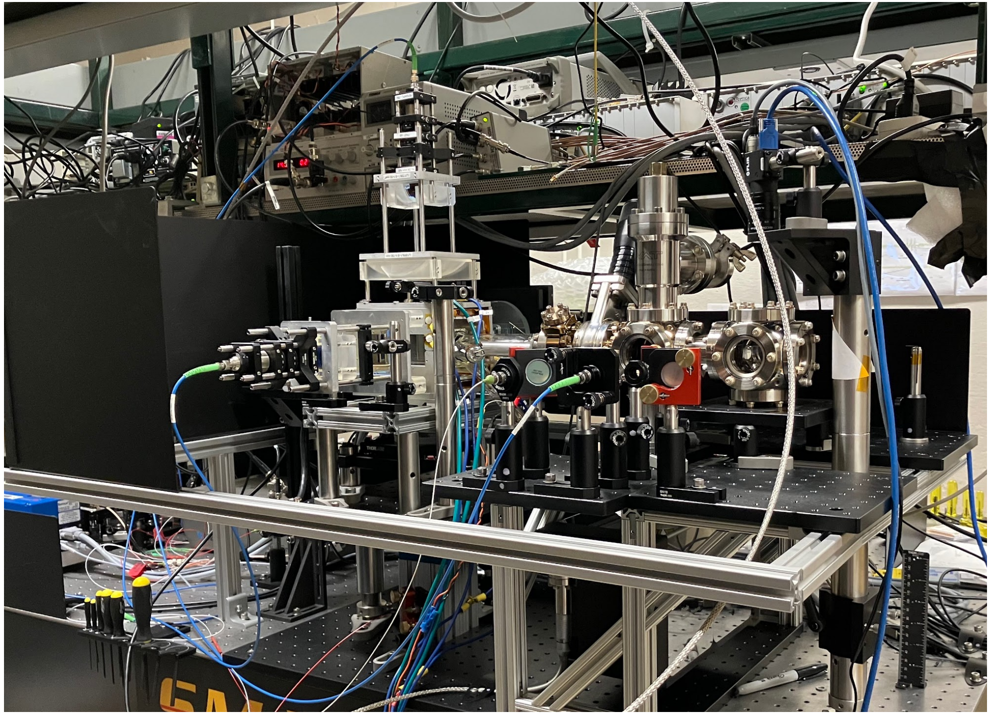


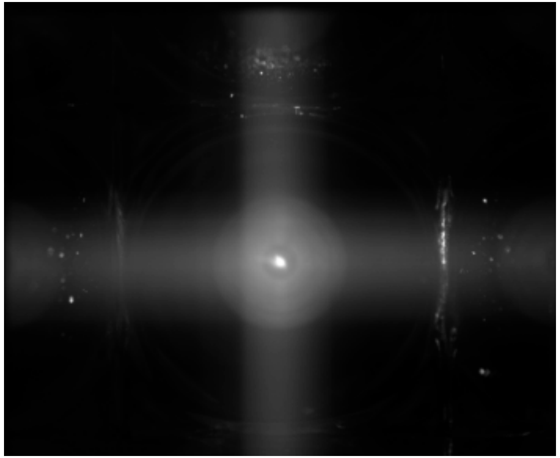




[Y. Zhu, S. Ghosh, S. B. Cahn, M. J. Jewell, D. H. Speller, RHM , PRA 105, 042808 (2022).]

Atom Beam: 2D MOT



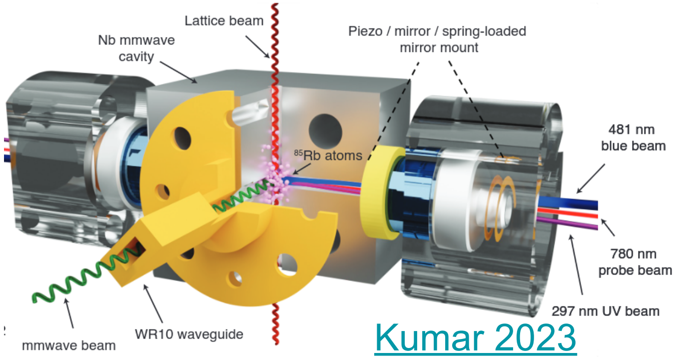


Photon Detection Cavity:

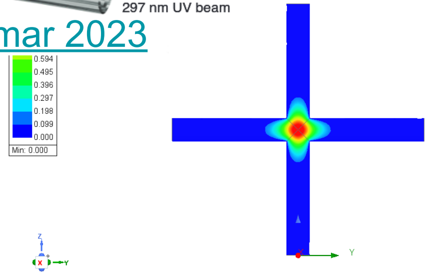
Kumar et al., Nature 615 614-619 (2023)
Suleymanzade et al, Appl. Phys. Lett. 116, 104001 (2020)

Requirements:

- High quality factor $Q > 10^6$
- Mode volume ~ $0.1\ \lambda^3$
- Way for atoms to enter cavity

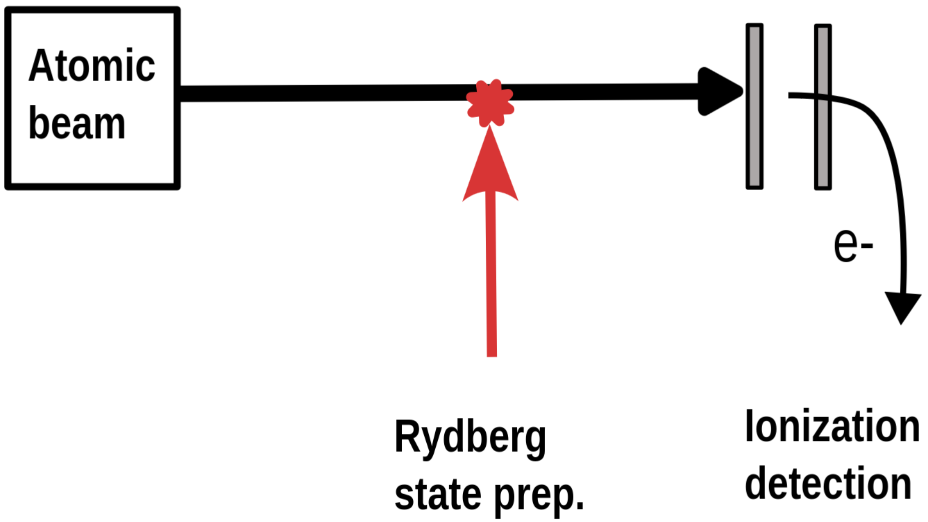


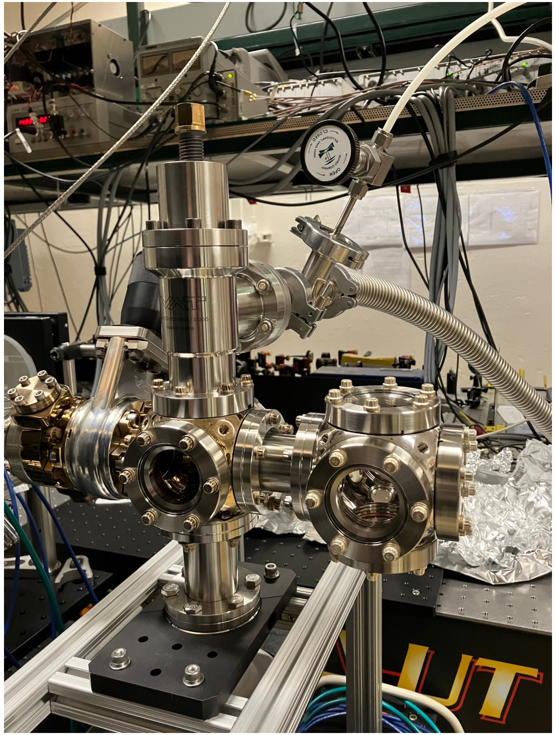
Kumar 2023



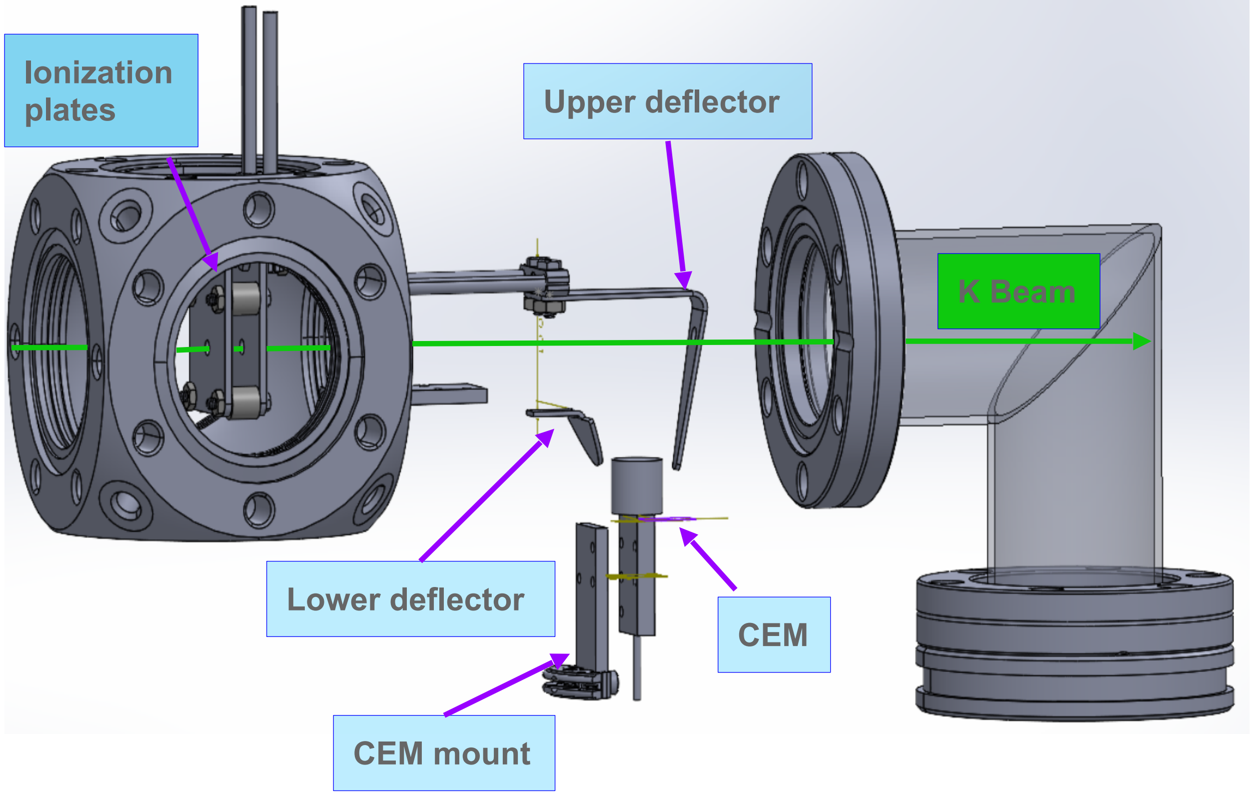
Type	ν (GHz)	V (λ^3)	Q	Atom coupling
Coplanar waveguide resonator [82]	19.6	$\sim 10^{-6}$	2.3×10^3	yes, Rydberg He beam
Superconducting coplanar waveguide resonator [83]	2.9 – 5	$\sim 10^{-6}$	3×10^5	not demonstrated
Superconducting rectangular/cylindrical cavity [84]	7.7–11.4	0.1	$10^6 - 10^8$	not demonstrated
Fabry-Perot cavity [85]	51	260	4.2×10^{10}	yes, Rydberg Rb beam
Superconducting seamless cavity [86, 87]	98.2	0.14	3×10^7	yes, trapped Rydberg Rb

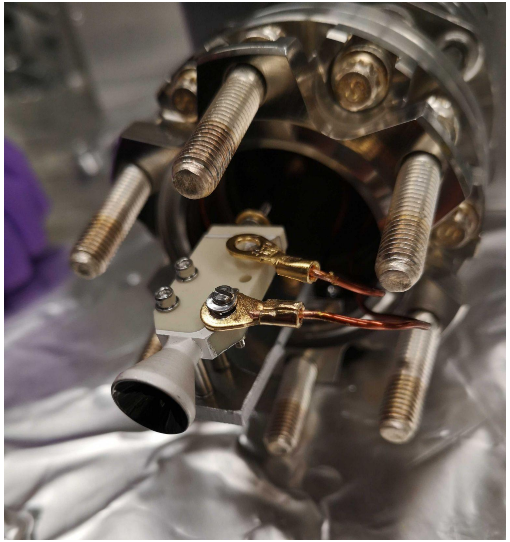
Detecting Ionized Electrons: Selective Field Ionization

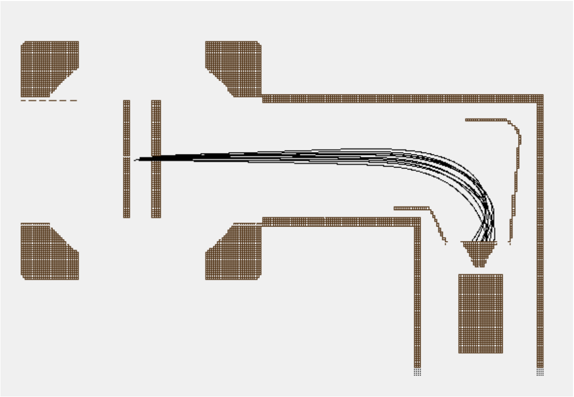




Ionization Detection of Rydberg Atoms

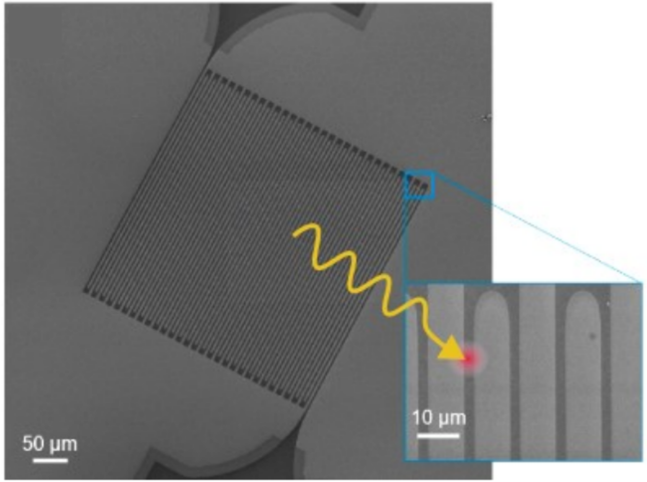




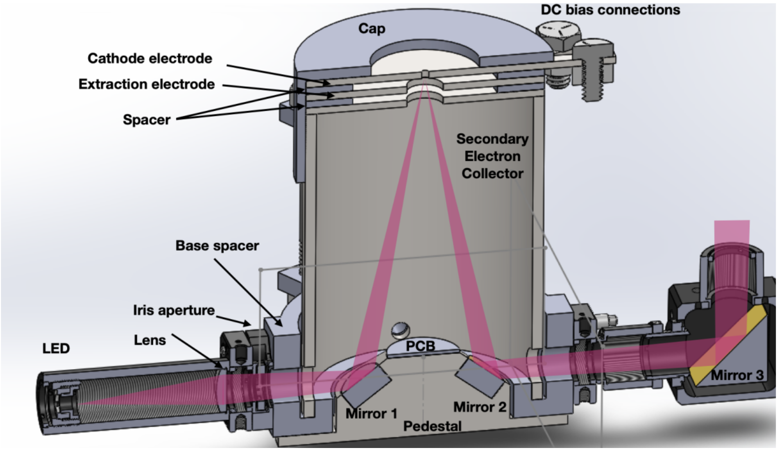


State Readout: SNSPDs for Electron Detection

RAY's electron detector will need to be **cryo-compatible**, **high-efficiency**, and **low-dark-count**.



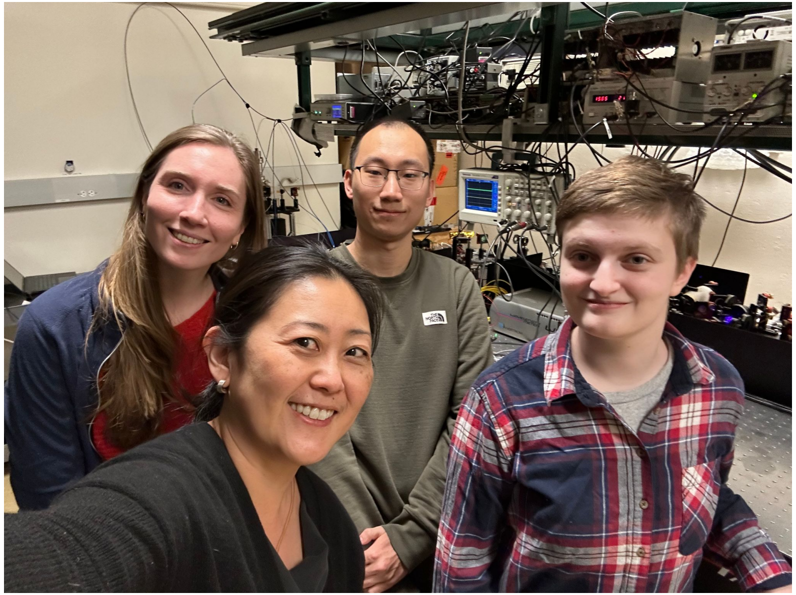
(Dip Joti Paul)



(Stewart Koppell)

We are collaborating with the Berggren group at MIT to develop electron-sensitive Superconducting Nanowire Single Photon Detectors (SNSPDs) for RAY.

RAY: Rydberg/Axions at Yale



Prof. Reina Maruyama (PI)

Prof. Charles Brown (Yale)

Prof. Danielle Speller (JHU)

Dr. Mike Jewell

Dr. Sabrina Zacarias

Benjia Li

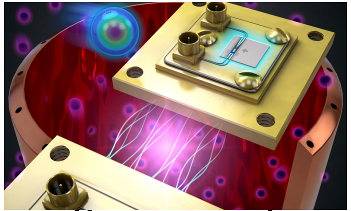
Eleanor Graham

Xiran Bai

Eunice Beato

Building a microwave single-photon detector for dark matter searches.

Conclusions



- New results and exciting developments for dark matter searches
- Developments in and out of Axion world
  - Rapid advances in quantum science
  - new experiments, new parameter space
  - New ideas, new people, new discovery
- Compelling case for axions at higher masses
  - Rydberg atoms offer possibility to extend search to high mass