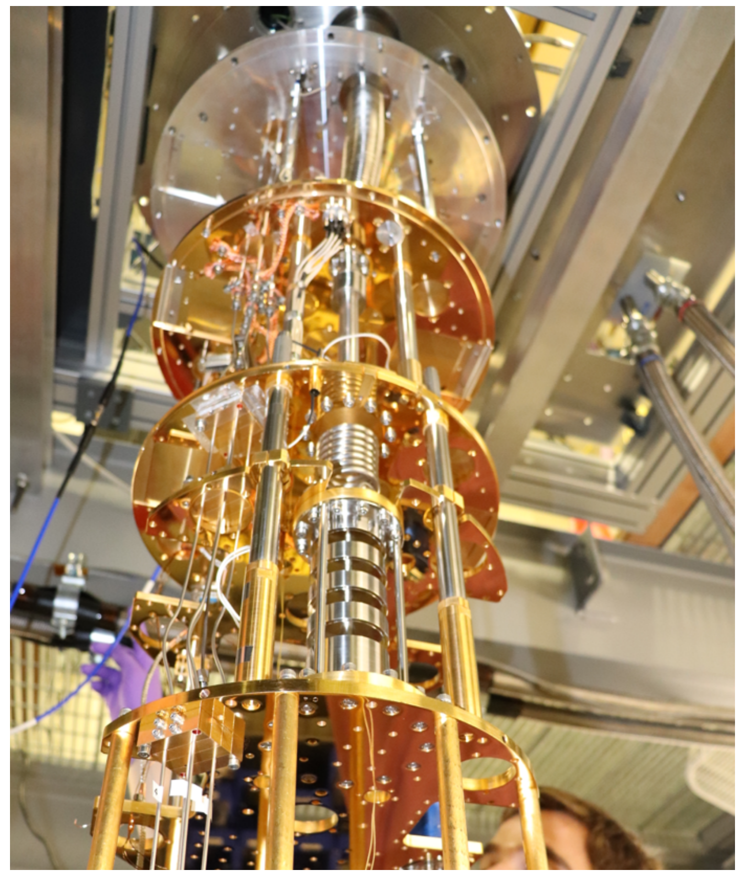

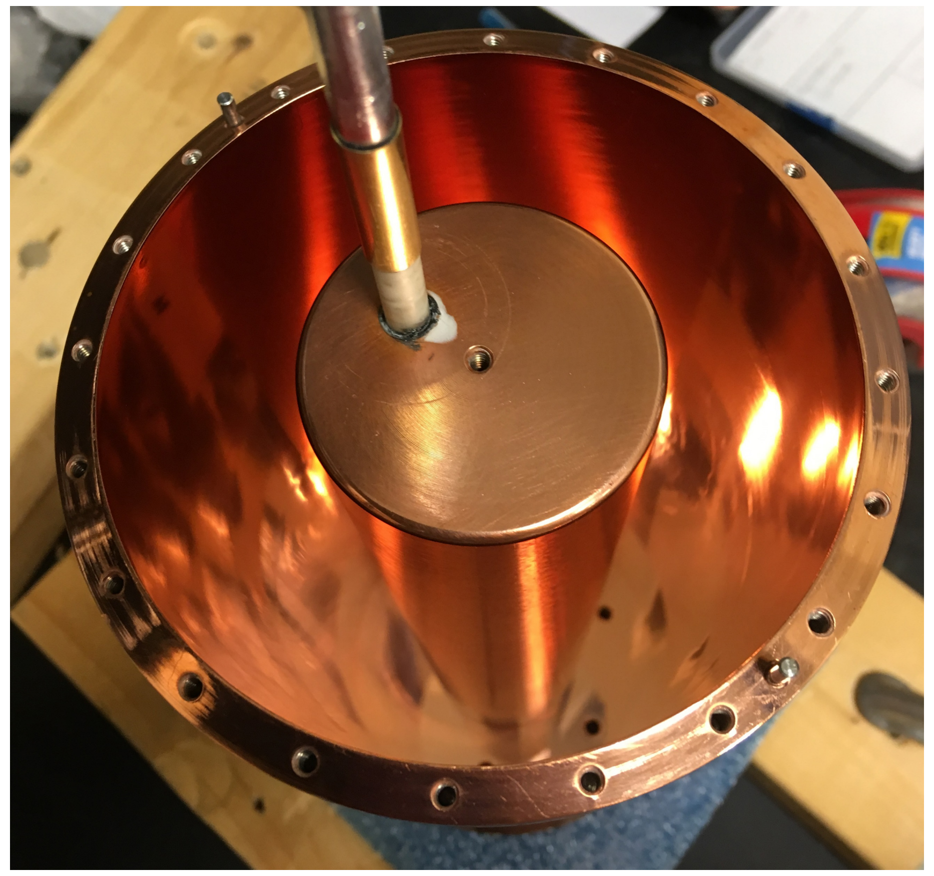

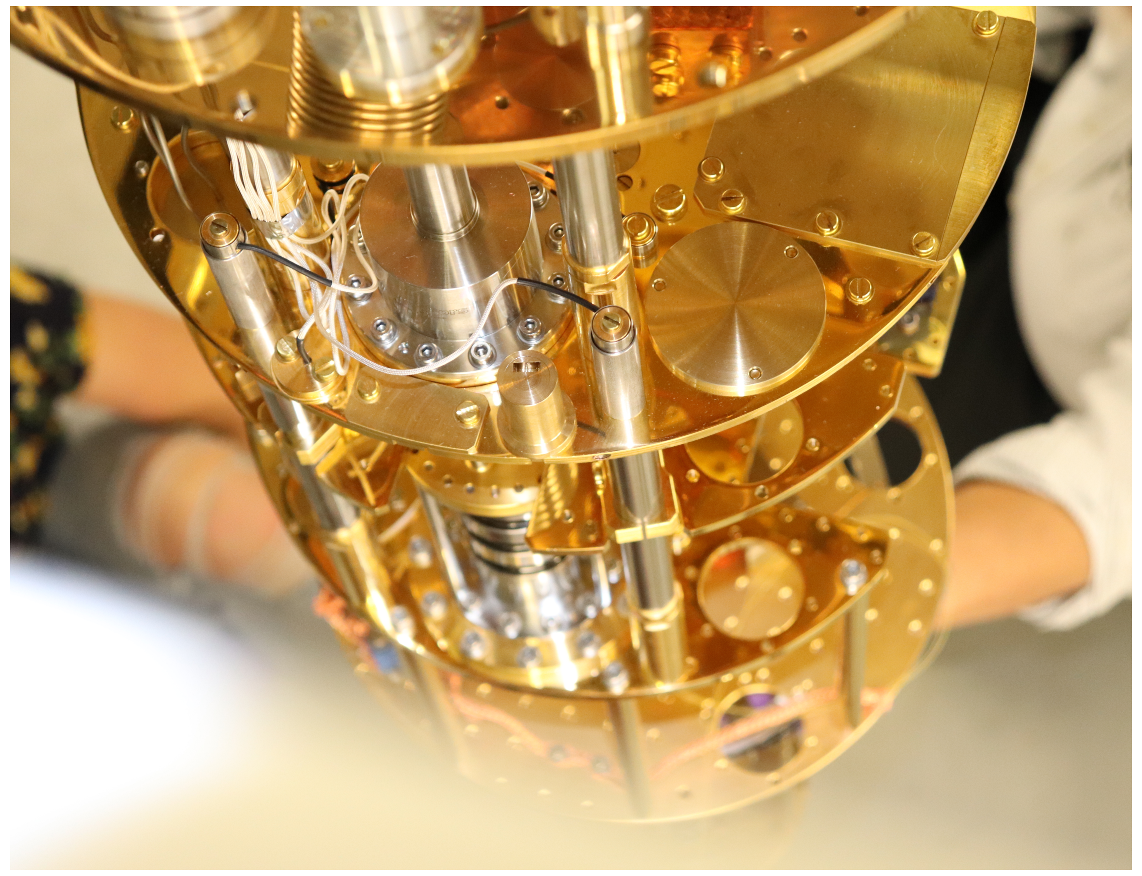

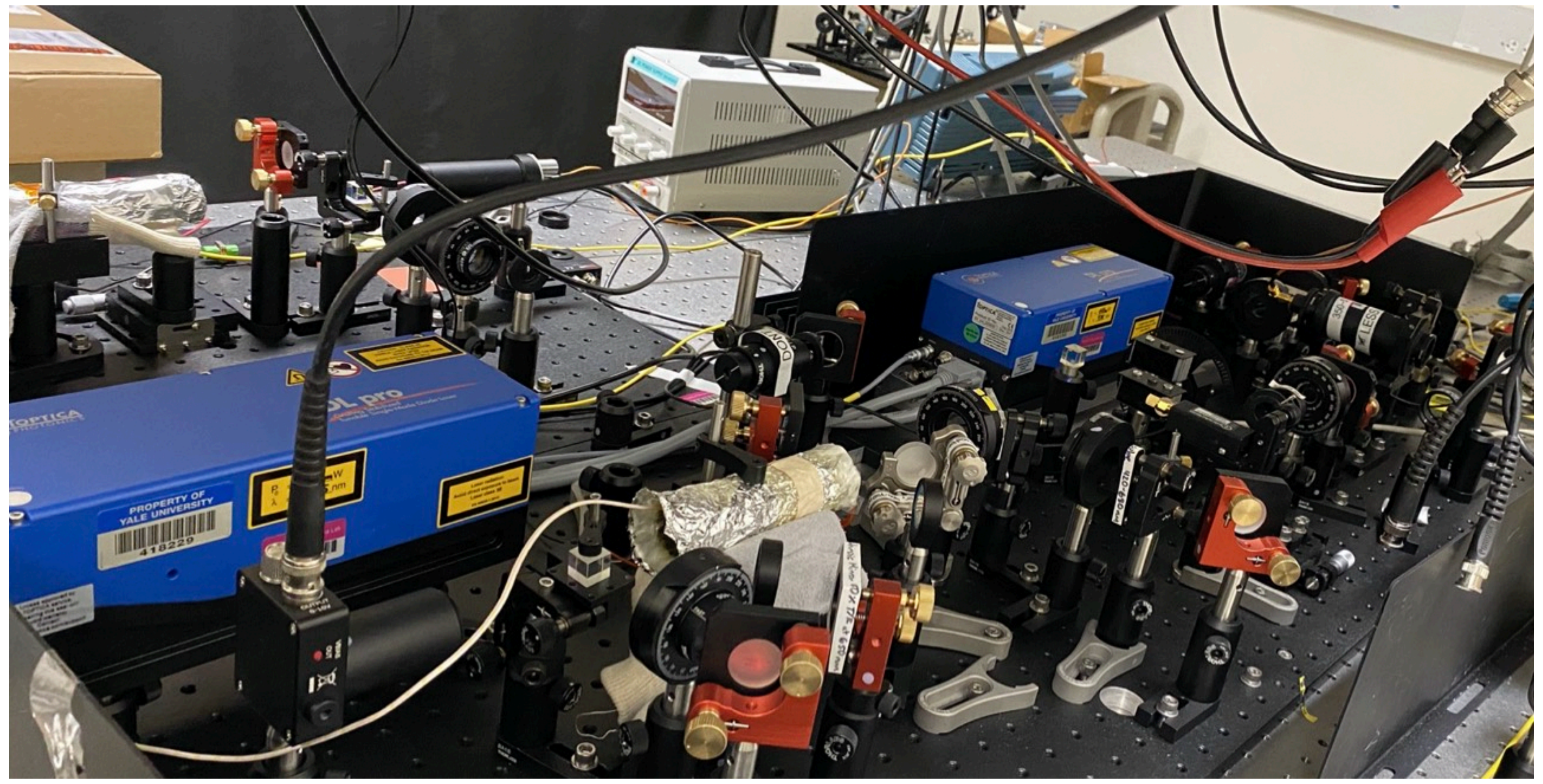

Rydberg Atom-Based Photon Detectors for Axion Searches

New Methods and Ideas at the Frontiers of Particle Physics

Aspen Winter Conference

Reina Maruyama
Yale University
March 23, 2022

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QuantiSED
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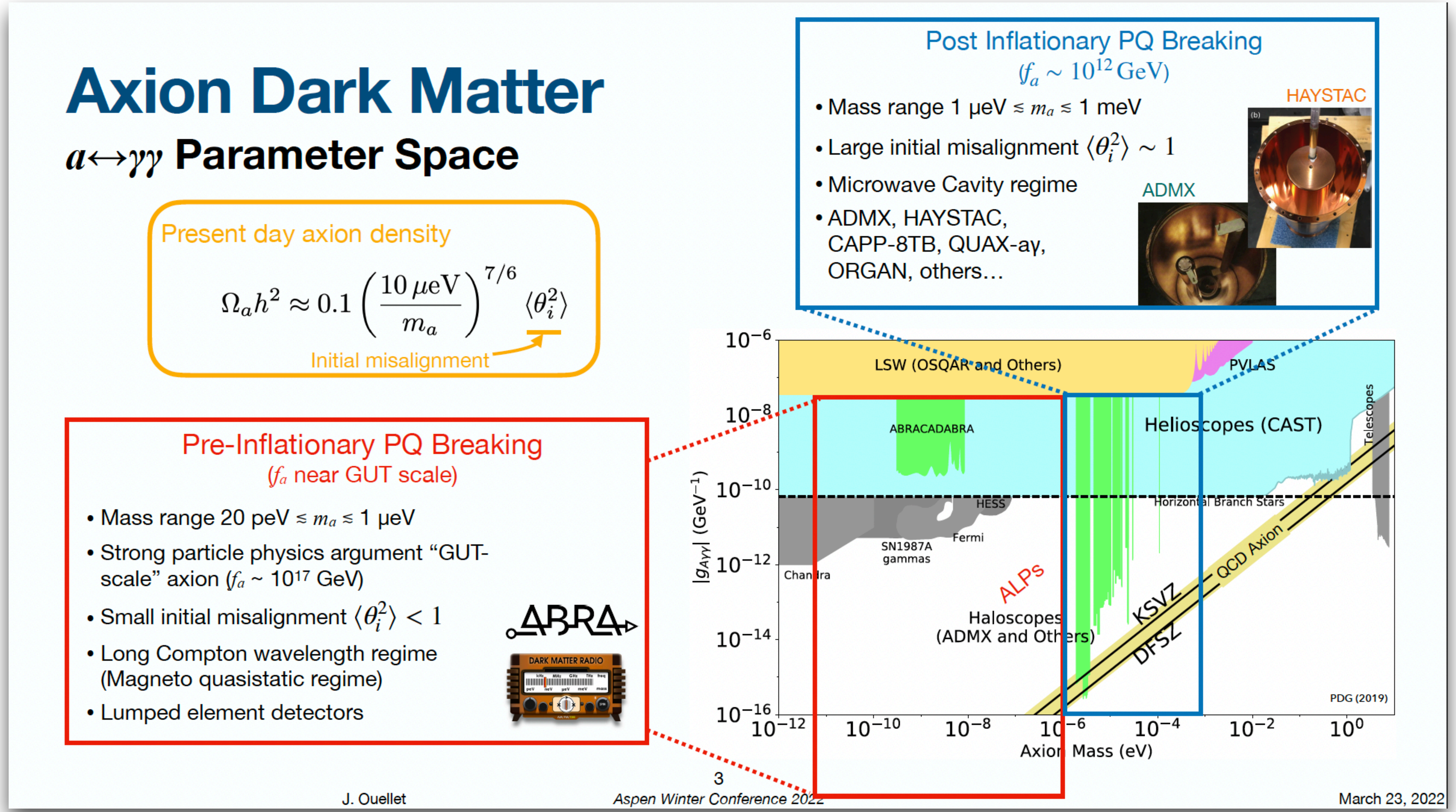
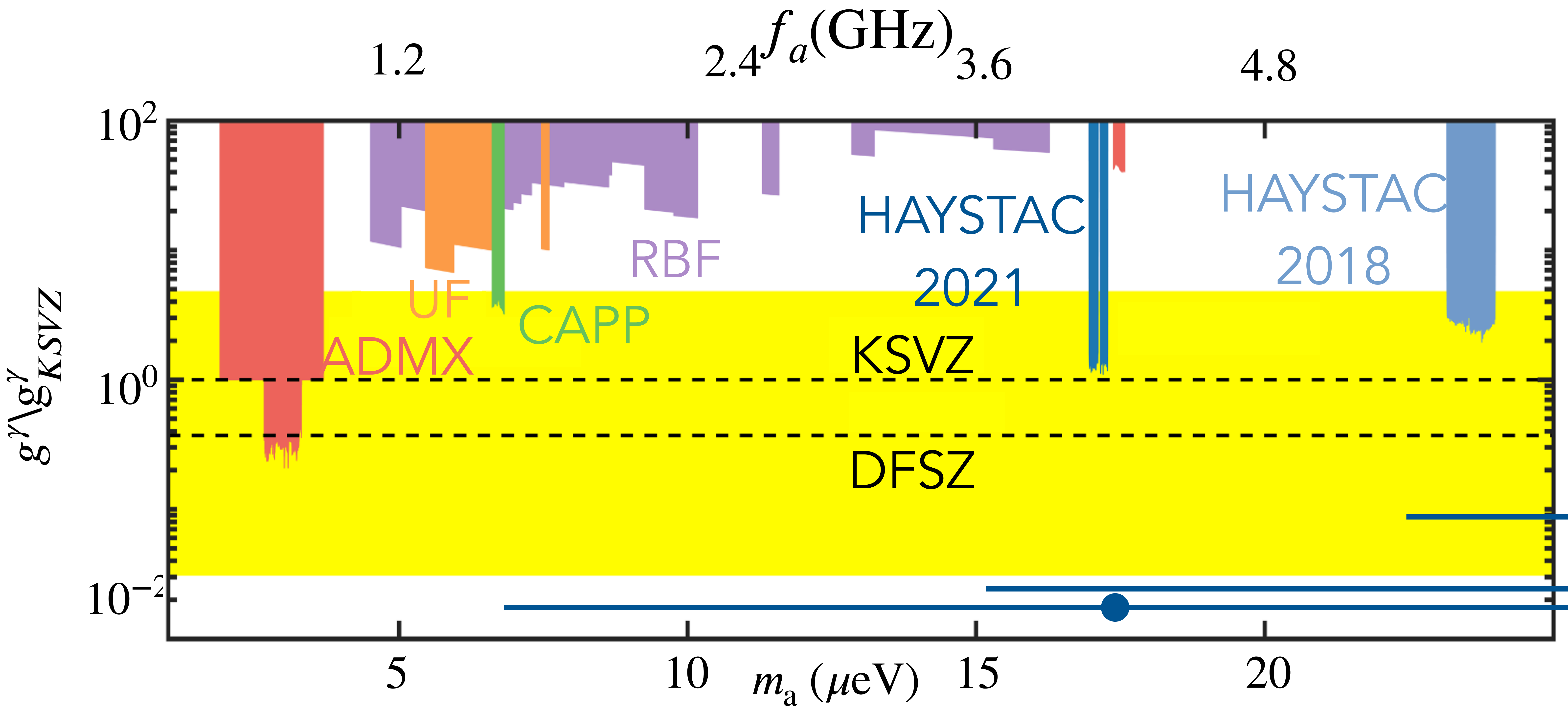
QUANTUM INFORMATION SCIENCE AND ENGINEERING NETWORK

Axions are well motivated



J. Ouellet (Wednesday)

Axions well-motivated @ $m_a > 15\ \mu eV$



Borsanyi et al (2016) PQ symmetry broken after inflation: $m_a > 10\ \mu eV$

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17.4 ± 11 μeV (4.2 ± 1.1 GHz)*

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

Axion searches at Yale

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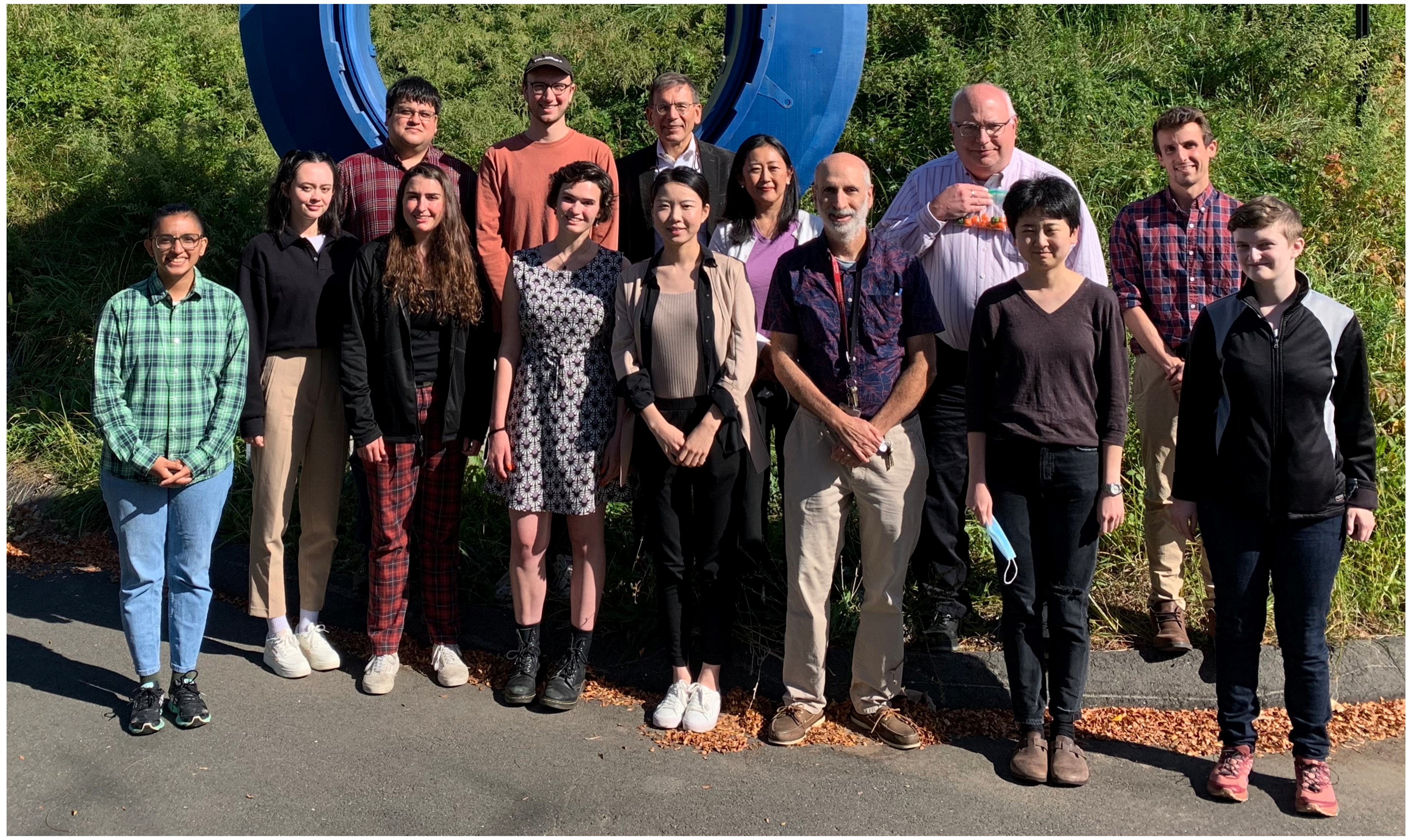
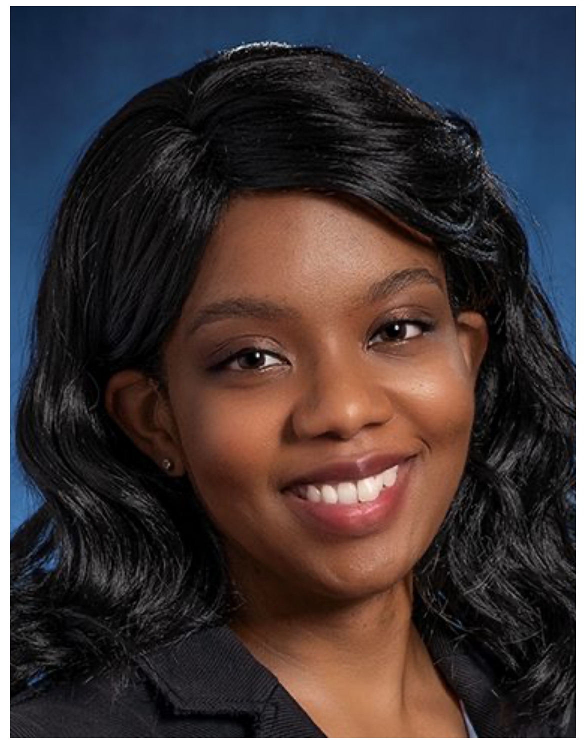
Haystac



Rydberg extension

Reina Maruyama



Danielle Speller
-> Johns Hopkins

Sid Cahn

Yuqi Zhu

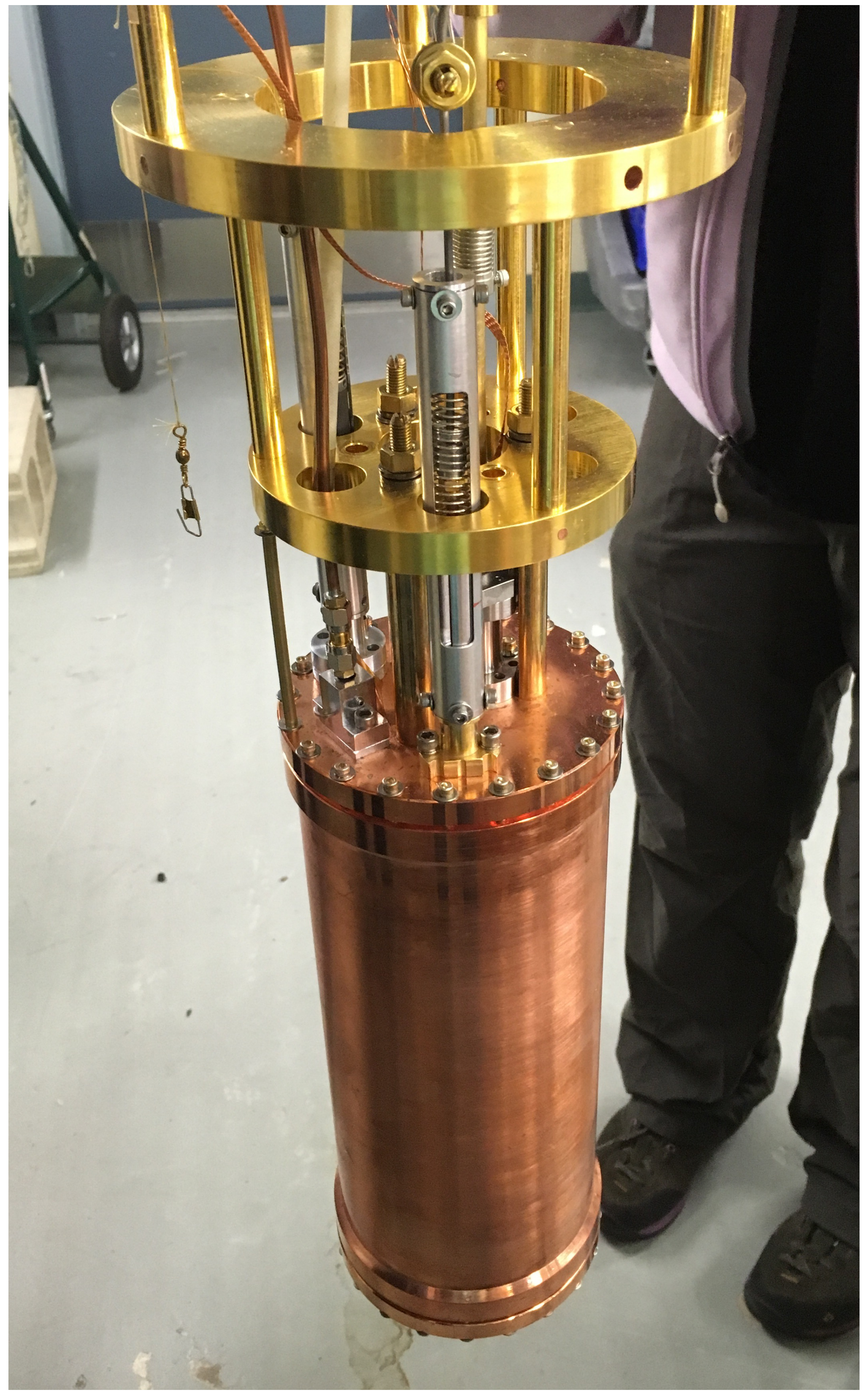
Mike Jewell

Sumita Ghosh

Eleanor Graham

Haloscope Figures of Merit

$f \approx 700$ MHz



$f \approx 5$ GHz

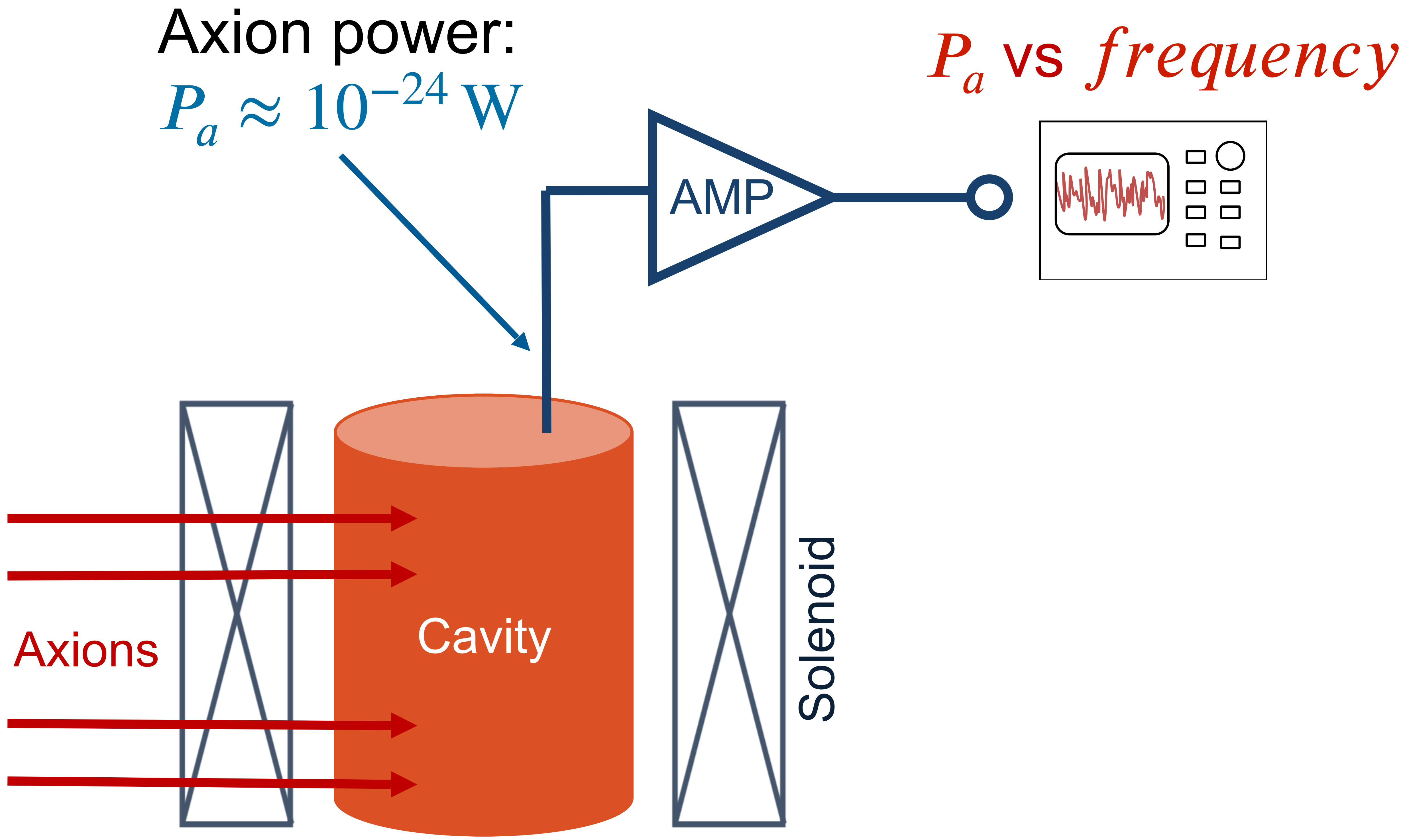
Figures of merit:

- Signal to noise ratio: $\mathrm{SNR} = \frac{P_a}{N_S}\sqrt{\frac{\tau}{\Delta f_a}}$
- Scan rate: $R \propto \int \mathrm{SNR}(f)^2$

Frequency scaling:

- Signal power: $P_a \propto QV$
- Effective scan rate scaling: $R \propto \nu^{-14/3}$

Basic axion detection principle



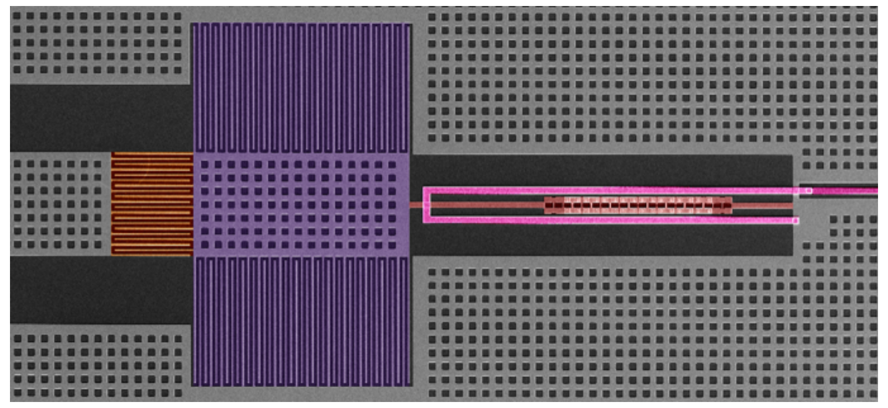
Haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)
HAYSTAC detector: Nucl. Instrum. Methods A 854, 11 (2017)

Interaction of interest: $\mathcal{L} \supset g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$

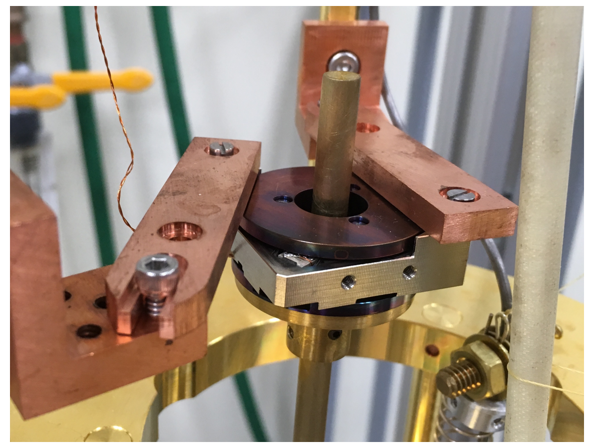
- High Q cavity: $Q = \dfrac{f_c}{\Delta f_c}$
- Low noise amplifier
- Tunable: $hf_a \approx m_a c^2$
- Large magnet: $\boldsymbol{B} = 8\ \mathrm{T}$
- Cryogenic: $T = 60\ \mathrm{mK}$

Haystac

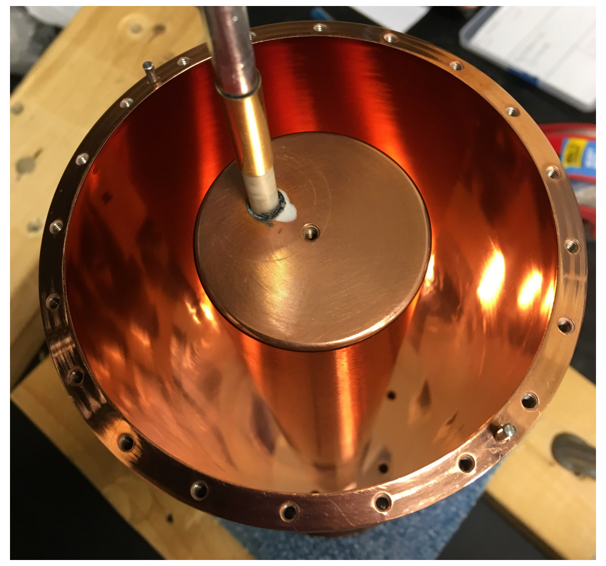
HAYSTAC Experiment



Quantum amplifiers



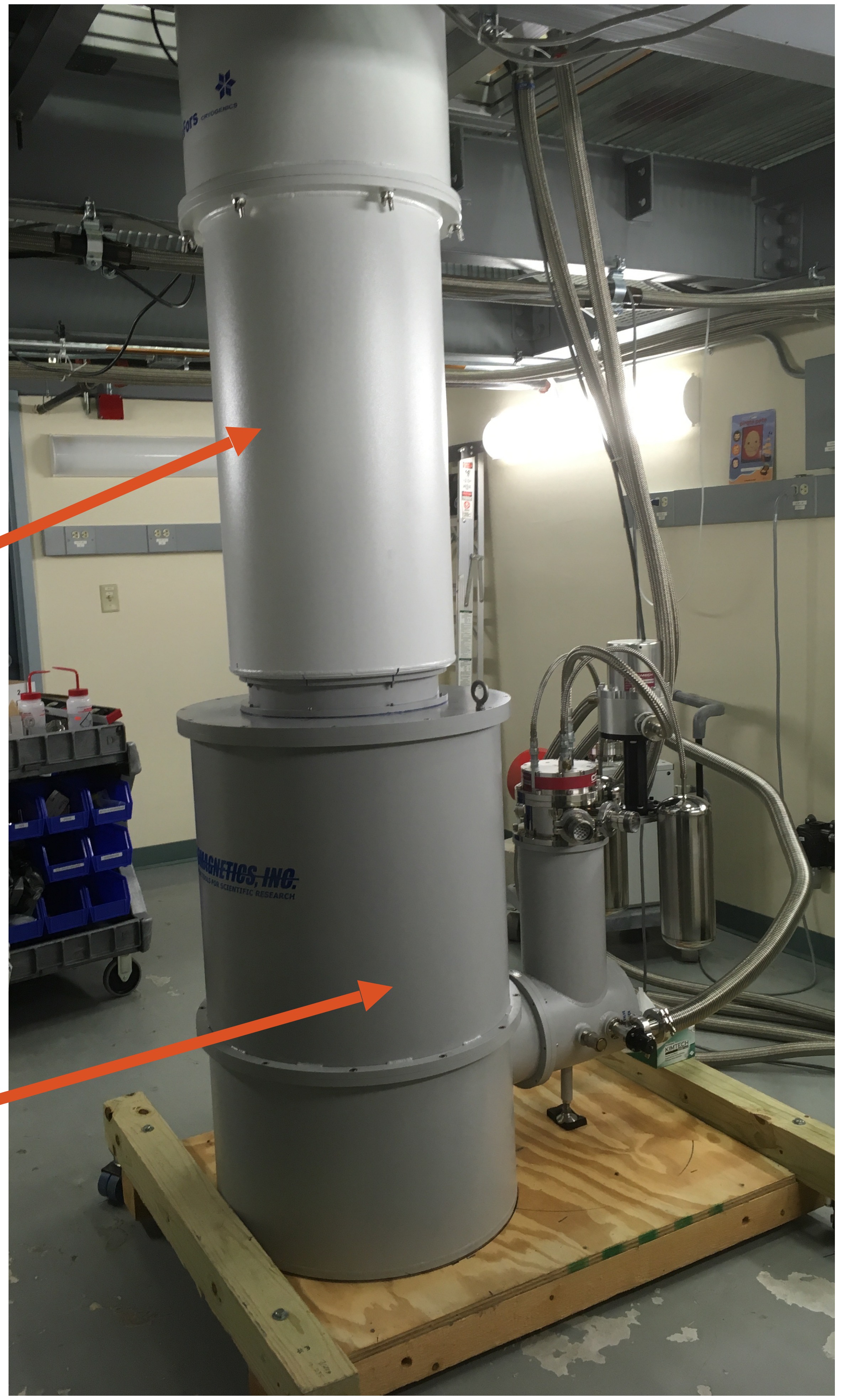
Piezoelectric tuning



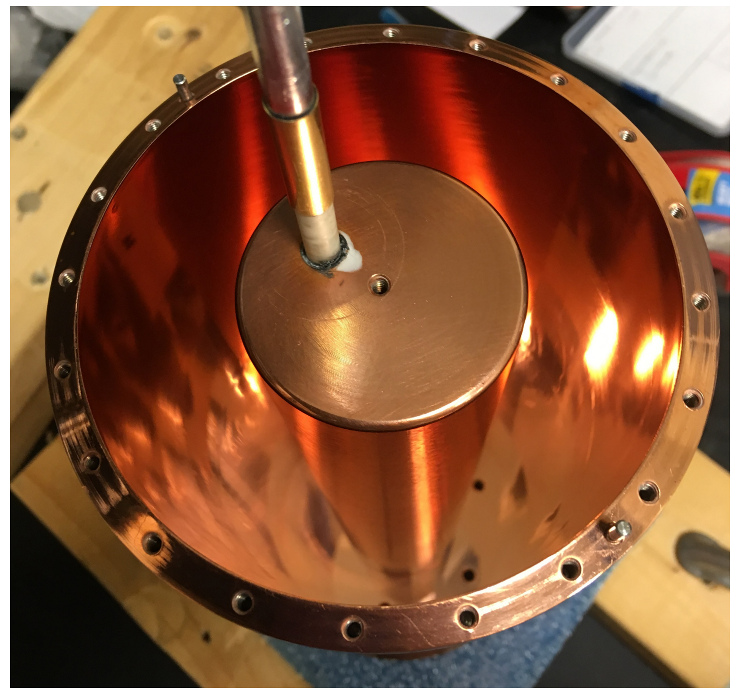
Microwave cavity

Cryostat
operating temp
~60 mK

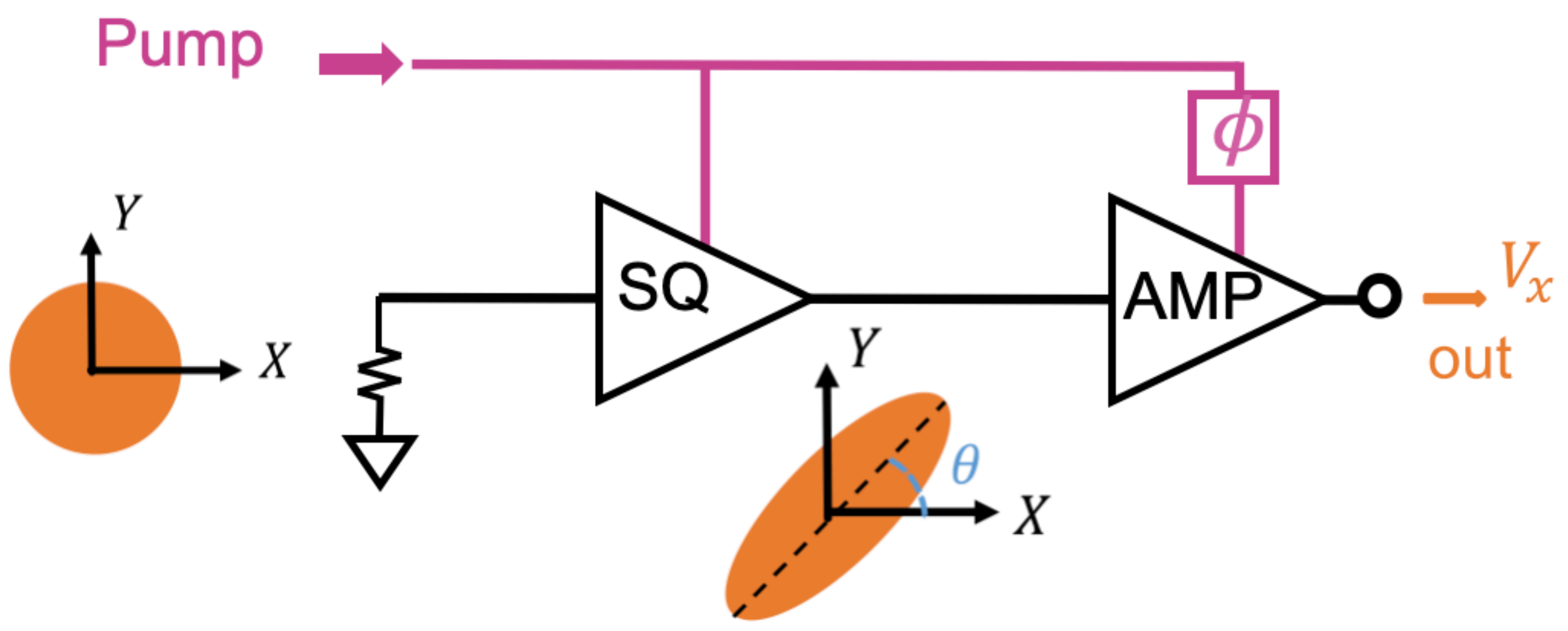
9 T magnet

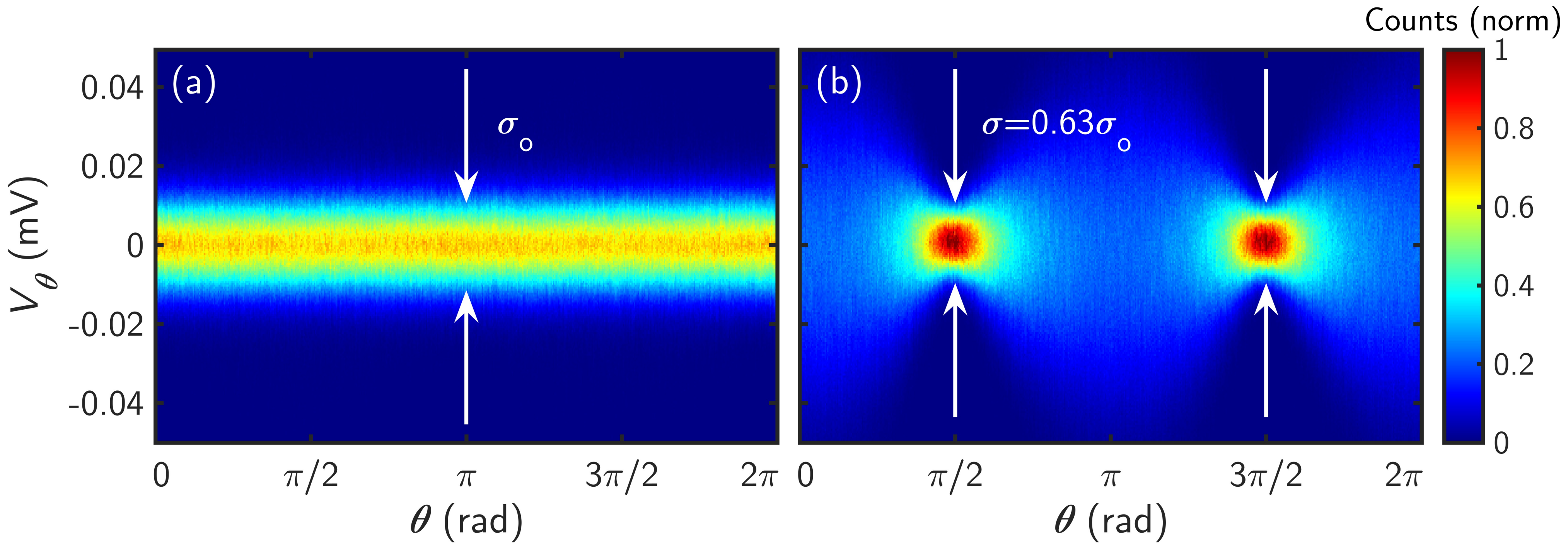


HAYSTAC Axion Experiment



- First dark matter exclusion enhanced by quantum squeezing
- Most sensitive axion search > 10 μeV
- Josephson Parametric Amplifier source squeezed states
- Squeezed state receiver operation
- -4dB noise reduction
- x2 speedup



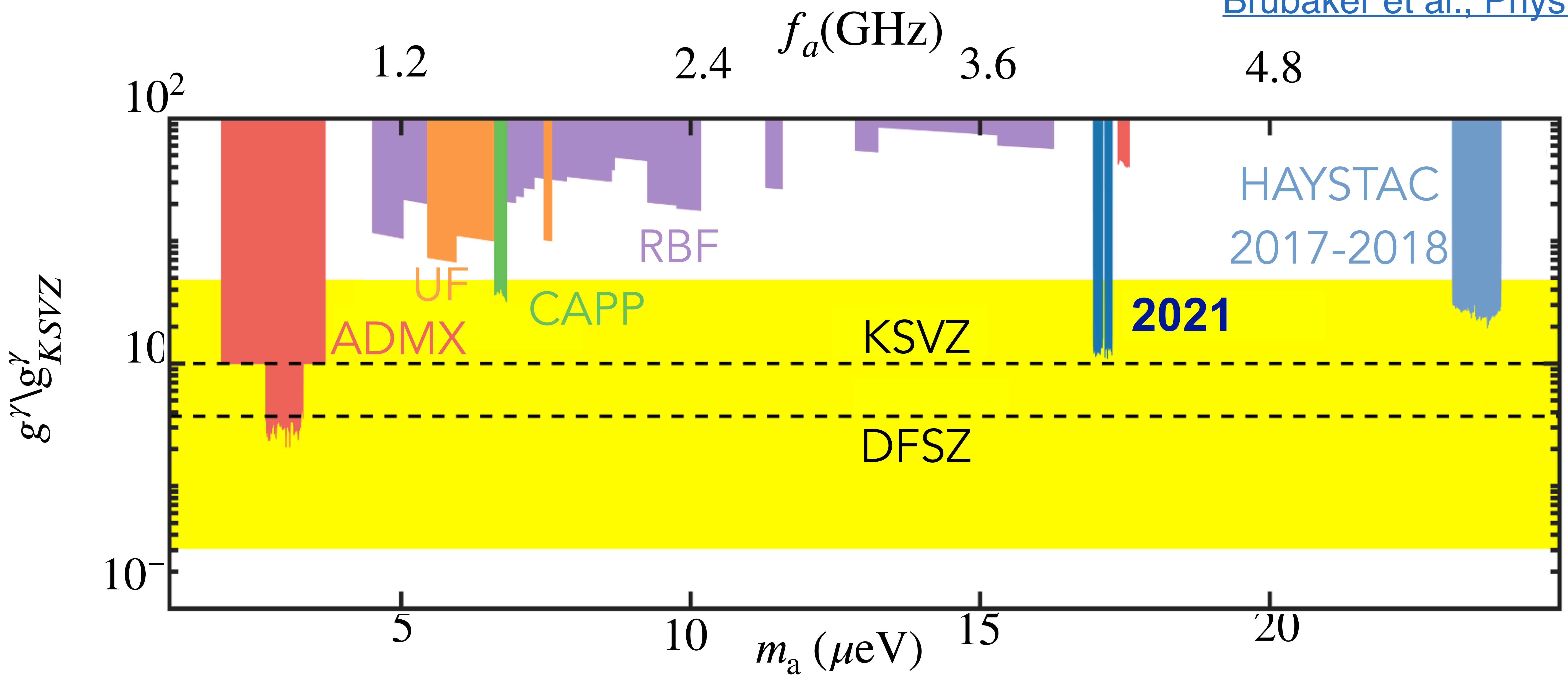


HAYSTAC results

Backes et al., *Nature*, 590, 238–242 (2021)

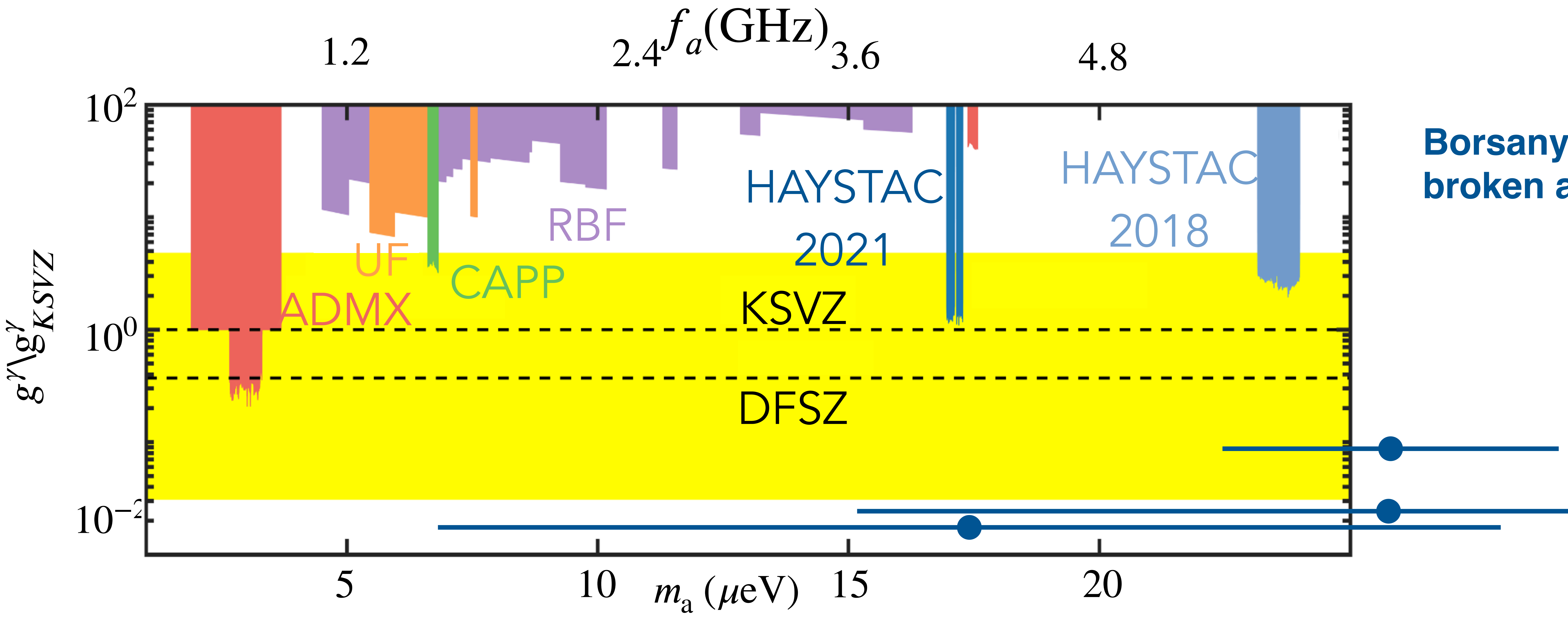
Zhong et al., Phys. Rev. D **97** 092001 (2018)

Brubaker et al., Phys. Rev. Lett. 118 061302 (2017)



- dark matter exclusion enhanced by quantum squeezing
- sensitive axion search, dipping into KSVZ $> \mathbf{10\ \mu eV}$
- New data 2020 – 2021, stay tuned

Axions well-motivated @ $m_a > 15$ μeV



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

Single photon detectors

- Single photon detectors have lower noise at higher frequencies Lamoreaux et al., 2013

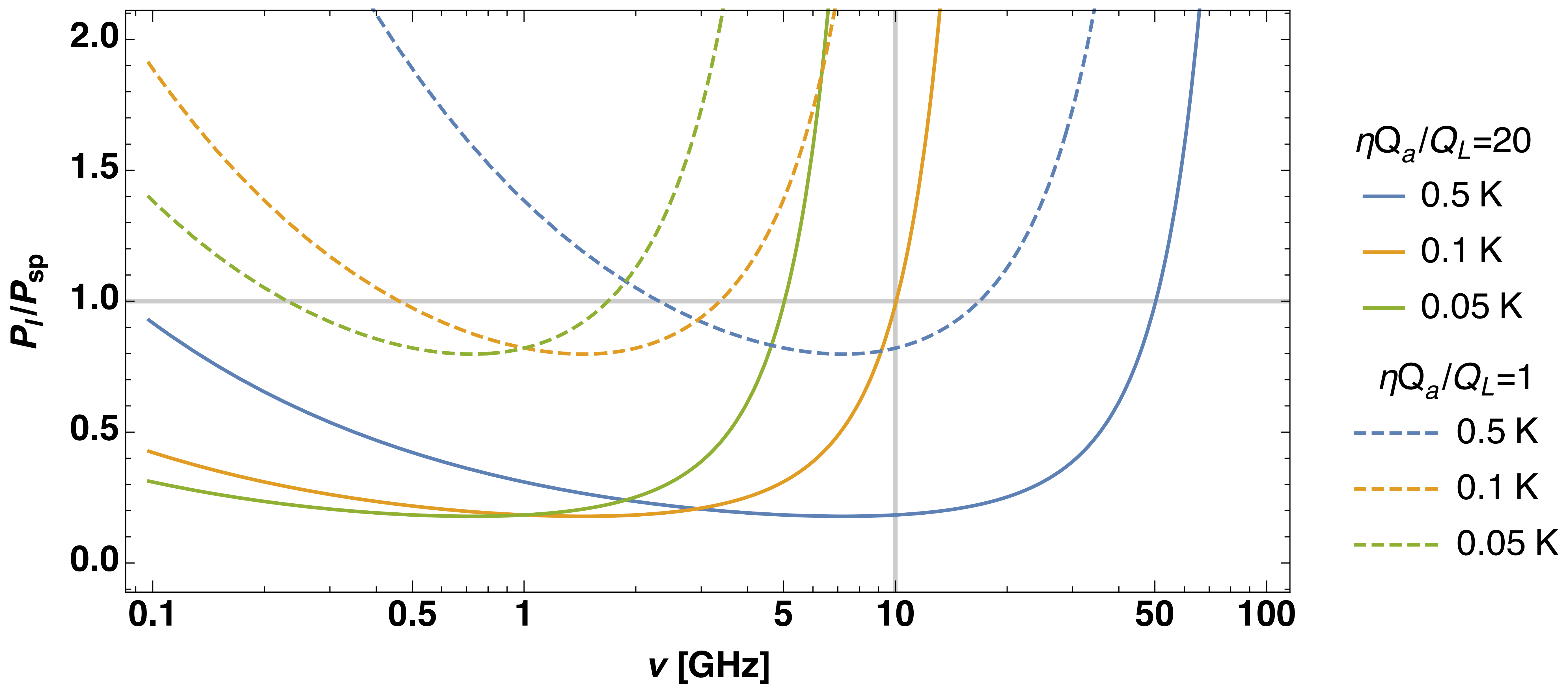
Linear amplifier

- low-T Dicke radiometer eq.
  $P_l = h\nu(\bar{n}_{\rm BBR} + 2 \times \frac{1}{2})\sqrt{\frac{\Delta\nu_a}{\tau_{\rm int}}}$
  ($\bar{n}_{\rm BBR} = \frac{1}{e^{h\nu/k_BT}-1}$, 1/2: zero-point fluctuations)
- sensitive to amplitude and phase

Single-photon detector

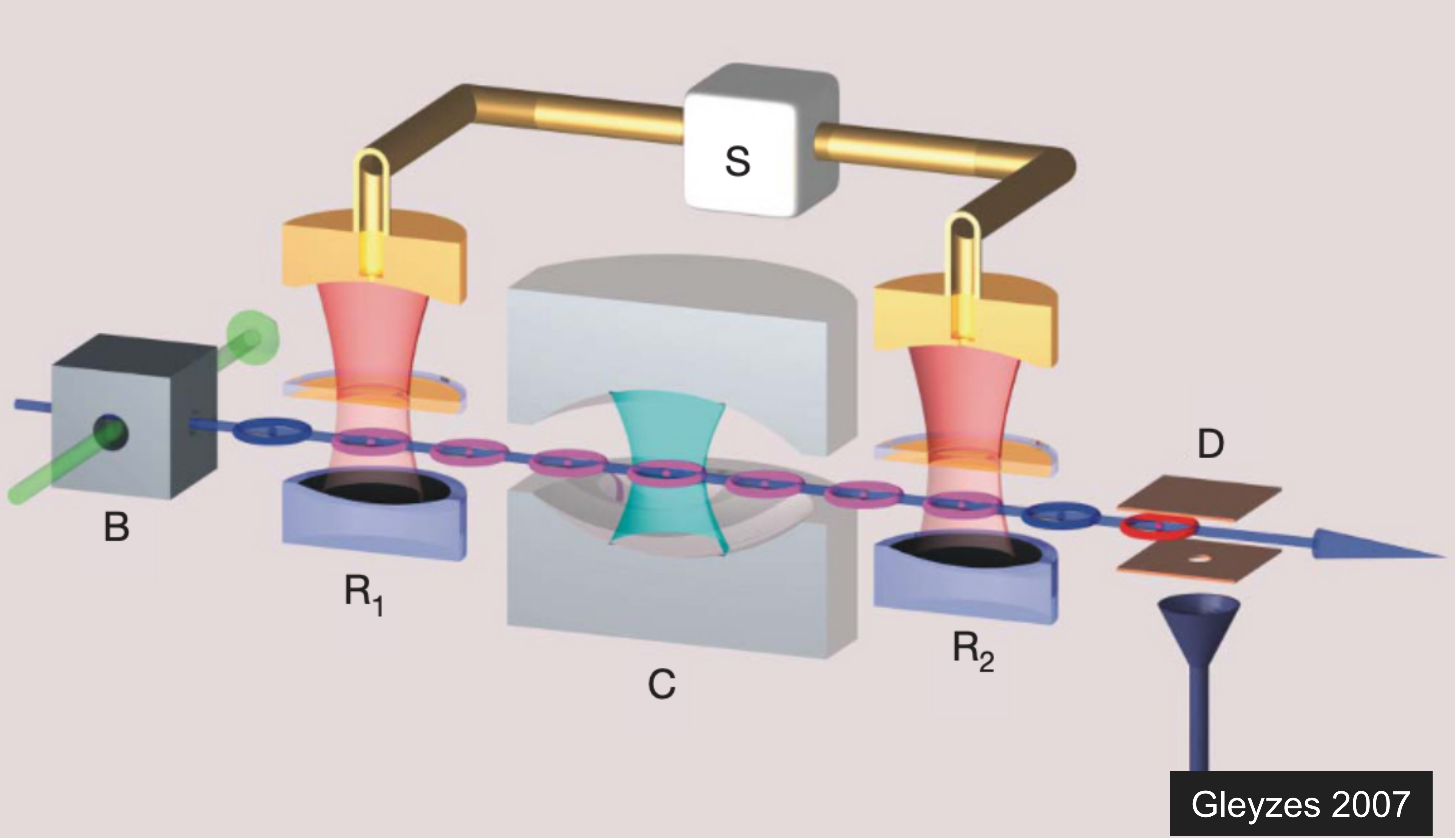
- shot noise due to BBR
  $P_{sp} = h\nu\sqrt{\frac{\eta\bar{n}_{\rm BBR}\Gamma}{\tau_{\rm int}}}$
  (η: efficiency, $\Gamma = 2\pi\nu/Q_L$ decay rate)
- only sensitive to amp.

$$\frac{P_l}{P_{sp}} = \frac{\bar{n}_{\rm BBR}+1}{\sqrt{\bar{n}_{\rm BBR}}}\sqrt{\frac{Q_L}{2\pi\eta Q_a}}$$



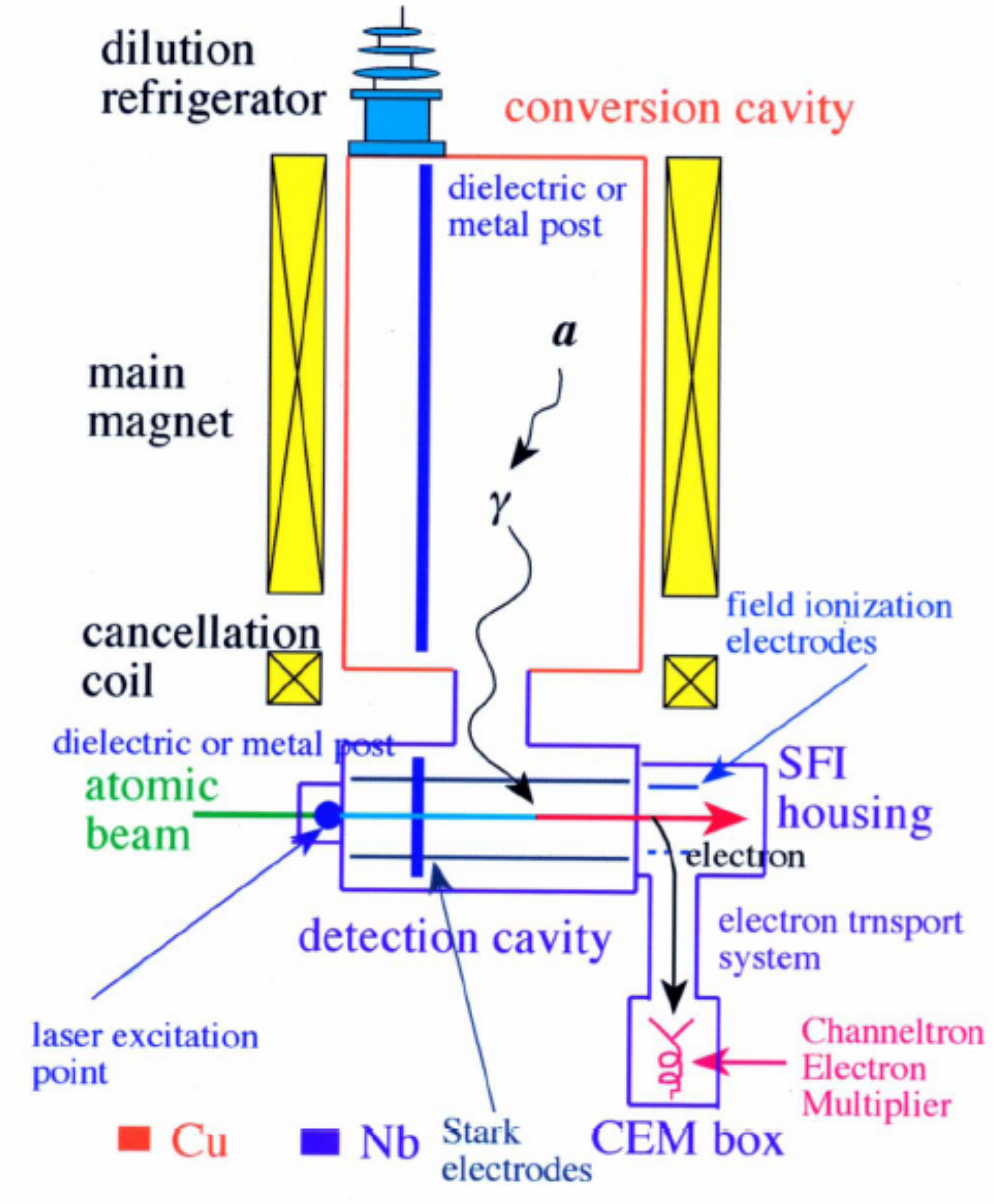
Rydberg atoms as microwave detectors

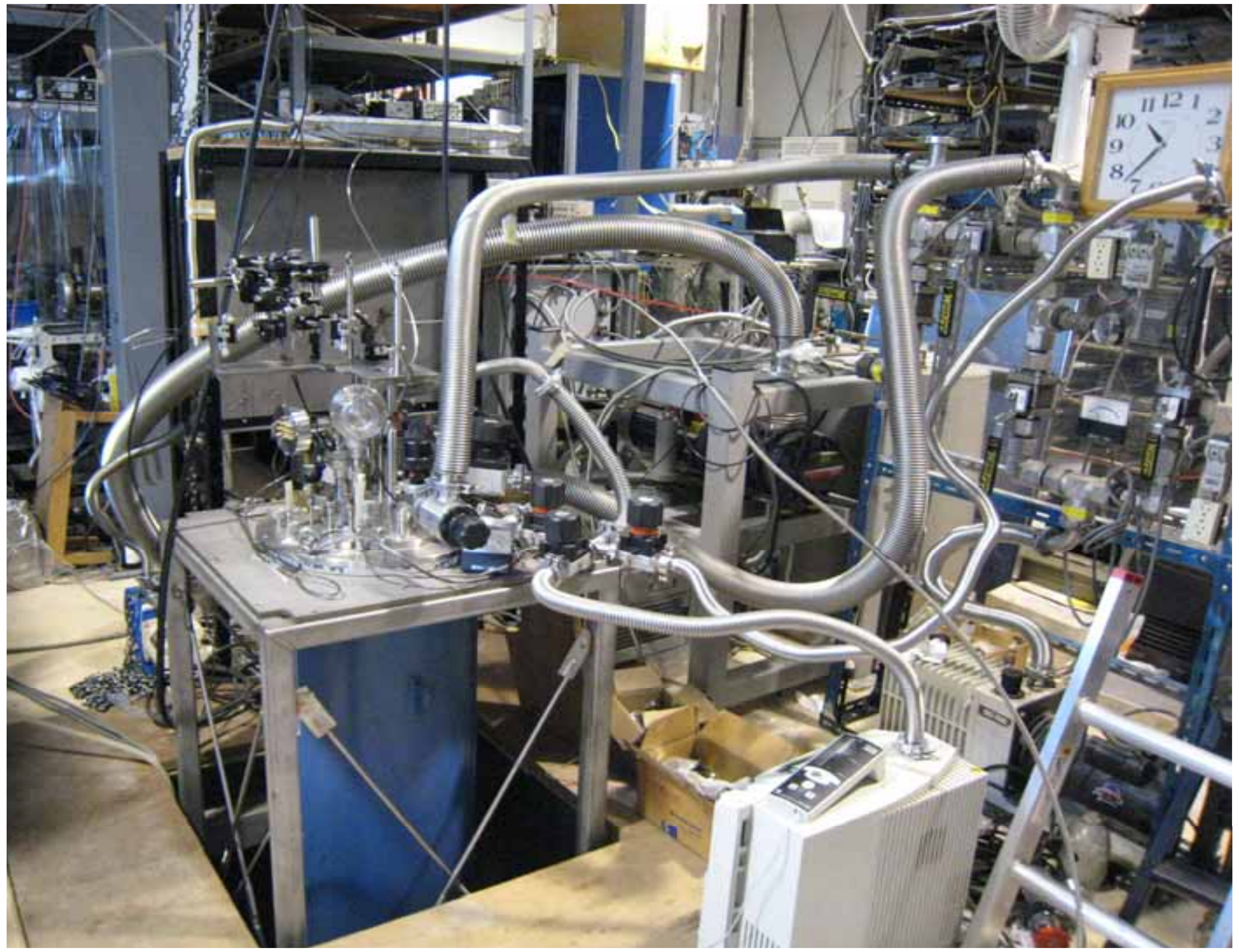
- Rydberg atoms:
  - Highly excited valence e^-
  - Couple strongly to 10 - 1000 GHz
- Applications:
  - Vapor-cell electrometry
    - e.g. Stuttgart; Sediacek et al., 2016
  - Single-atom cavity QED: ENS
  - **CARRACK axion search**



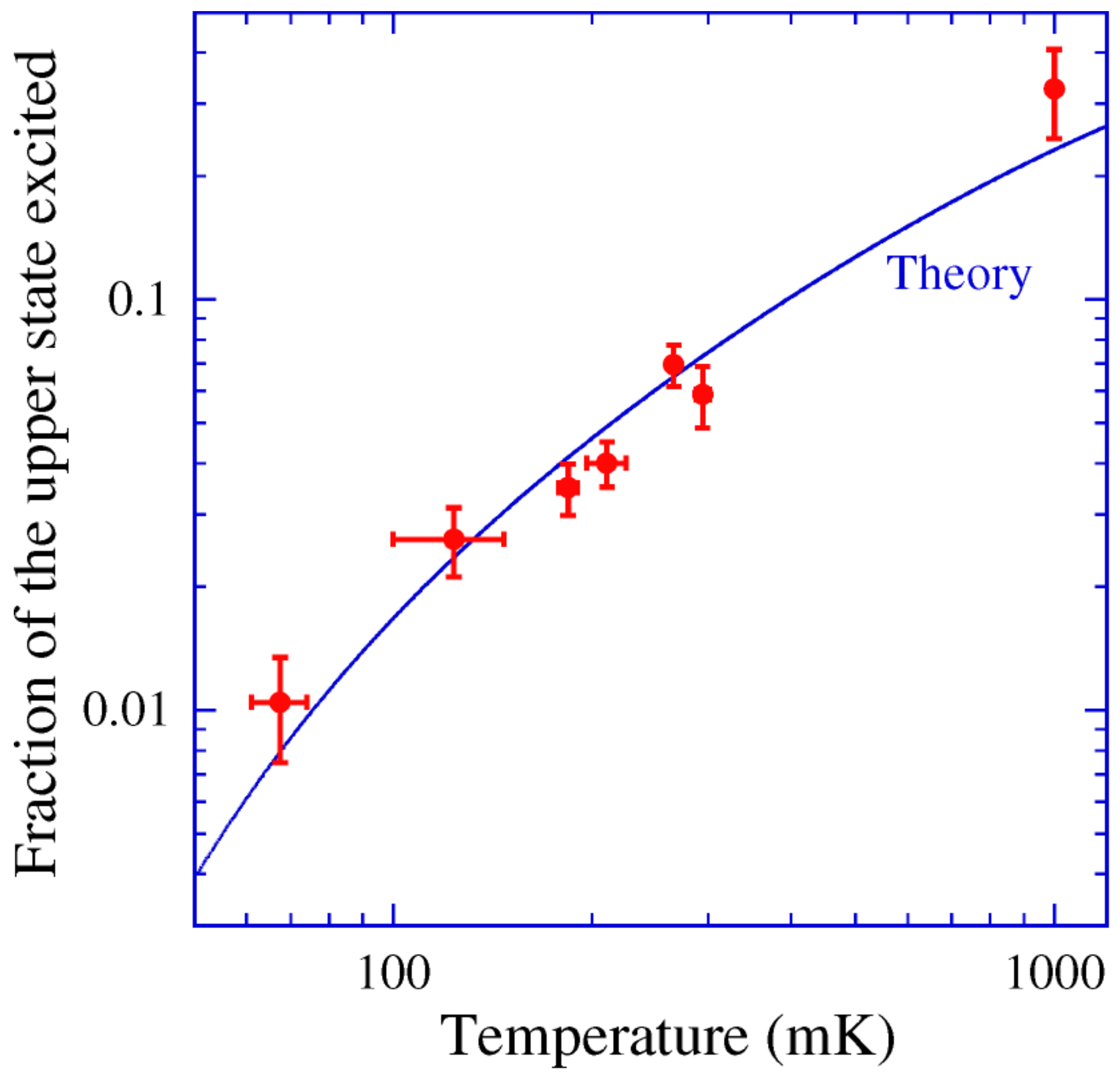
CARRACK

Imai, PANIC 2008
Tada, PLA 349 (2006) 488

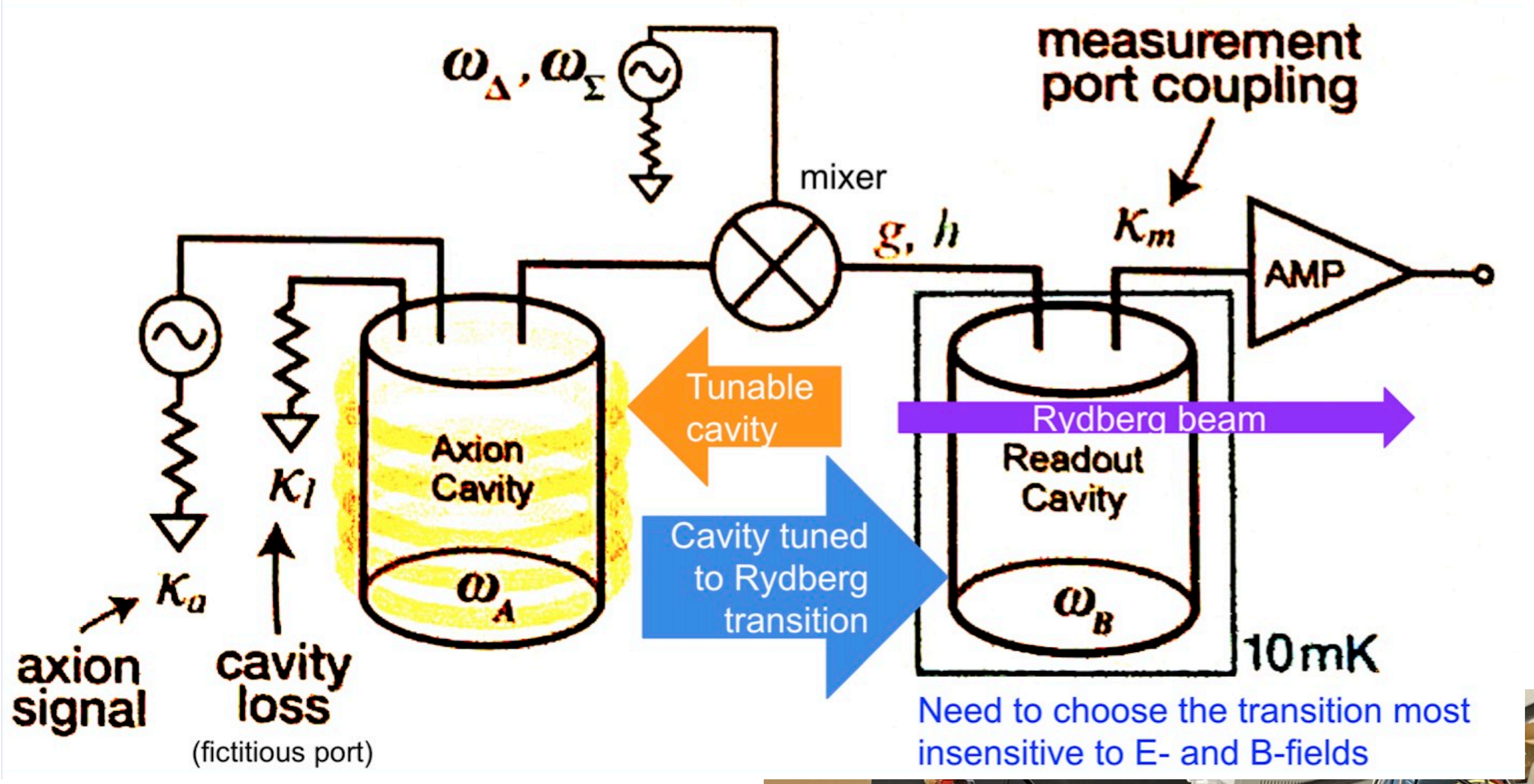


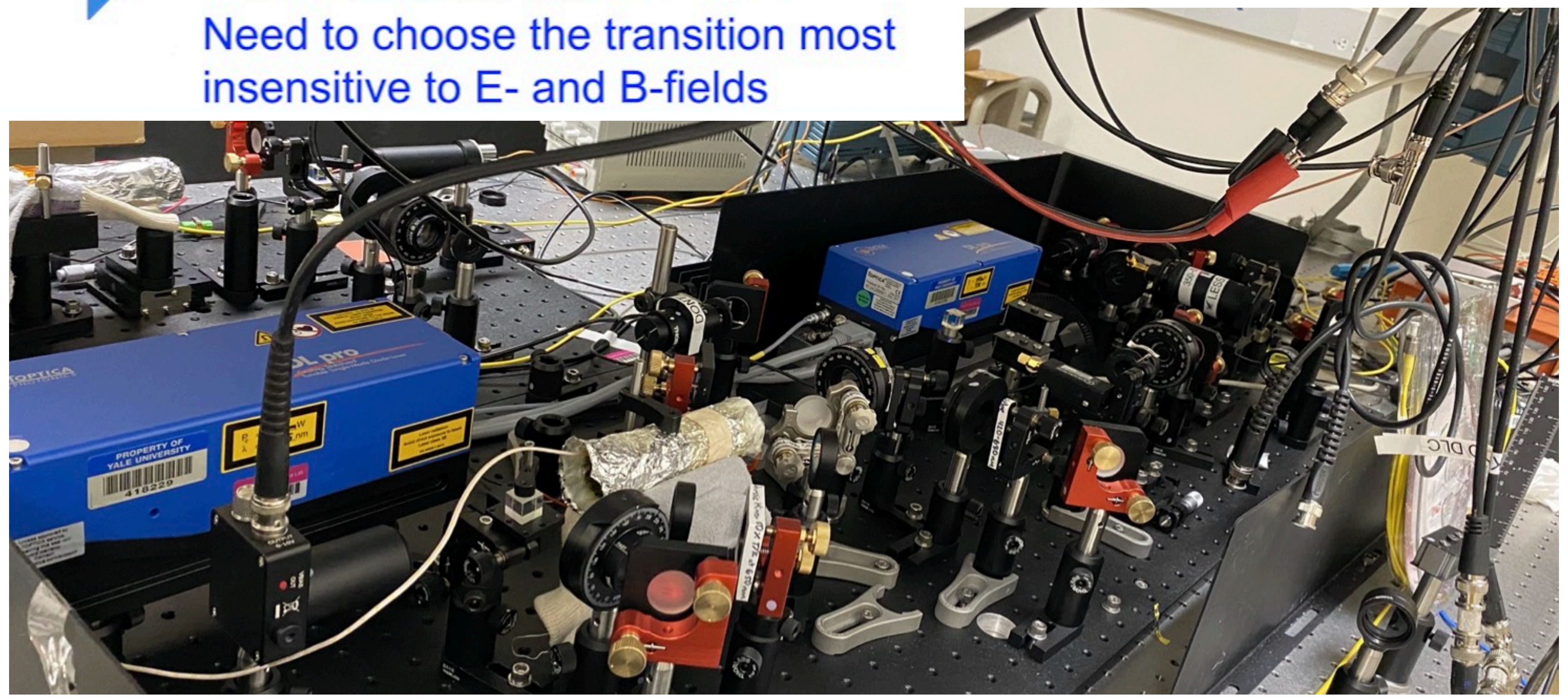


Black body radiation



Rydberg atom single photon detectors





Rydberg atoms at Yale:

- 10 – 50 GHz (40–200μeV)
- Rydberg atom detection
- Single photon counting
- Recall CARRACK, but for higher mass

Basic principle

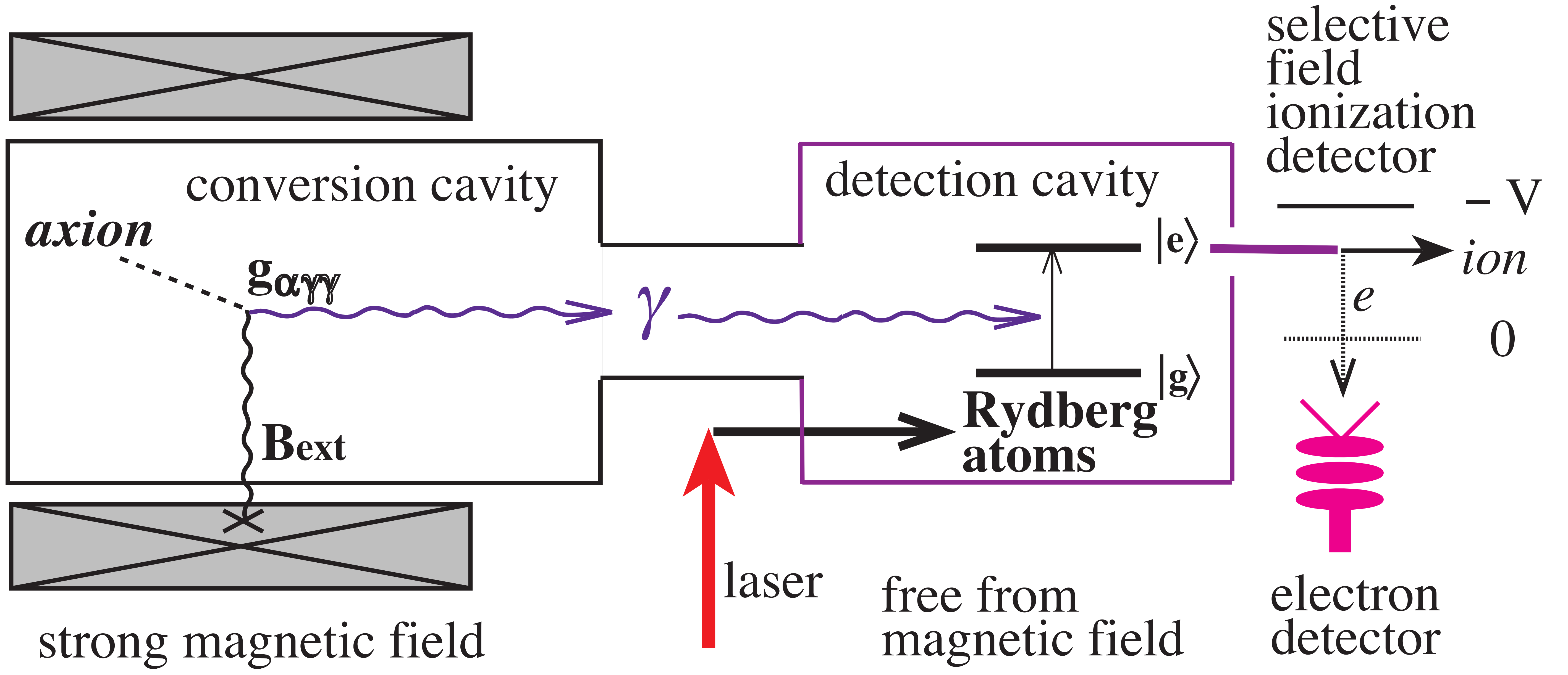
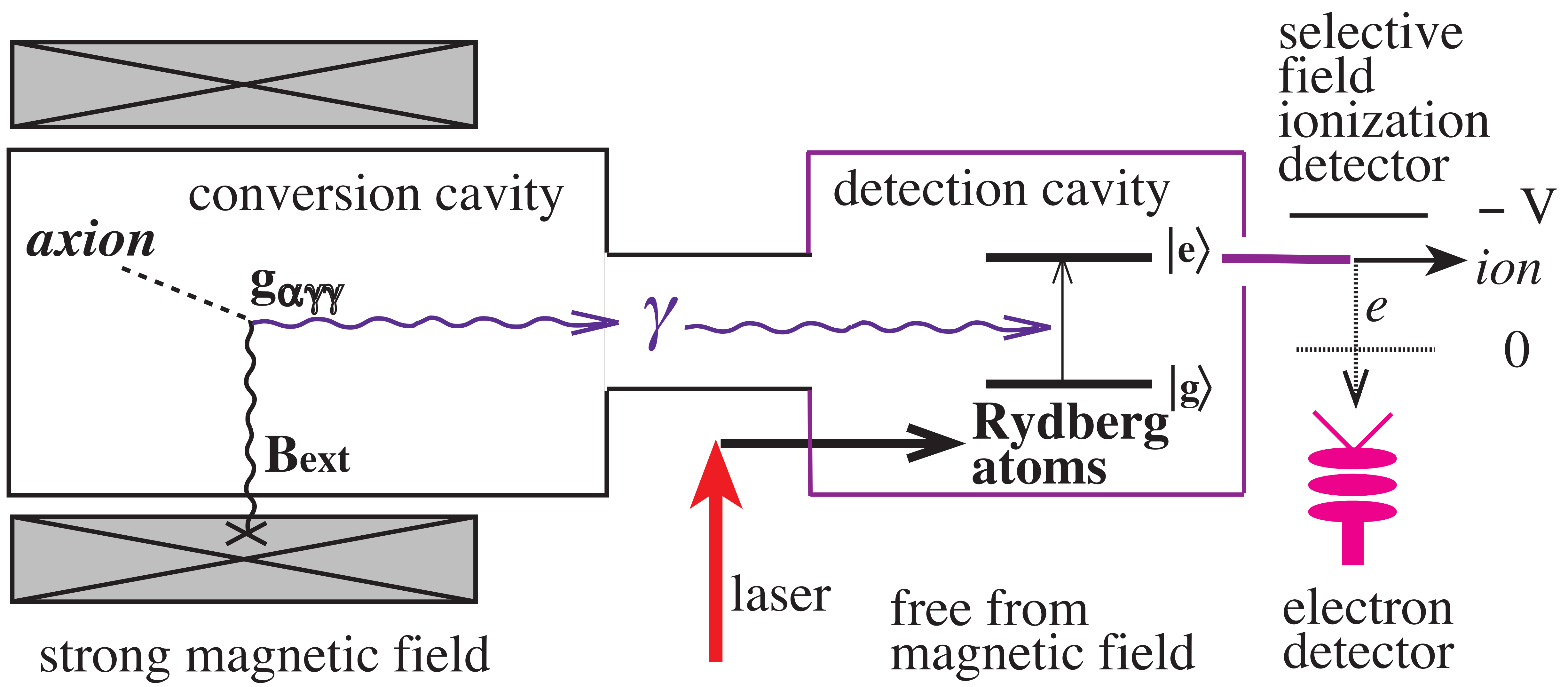
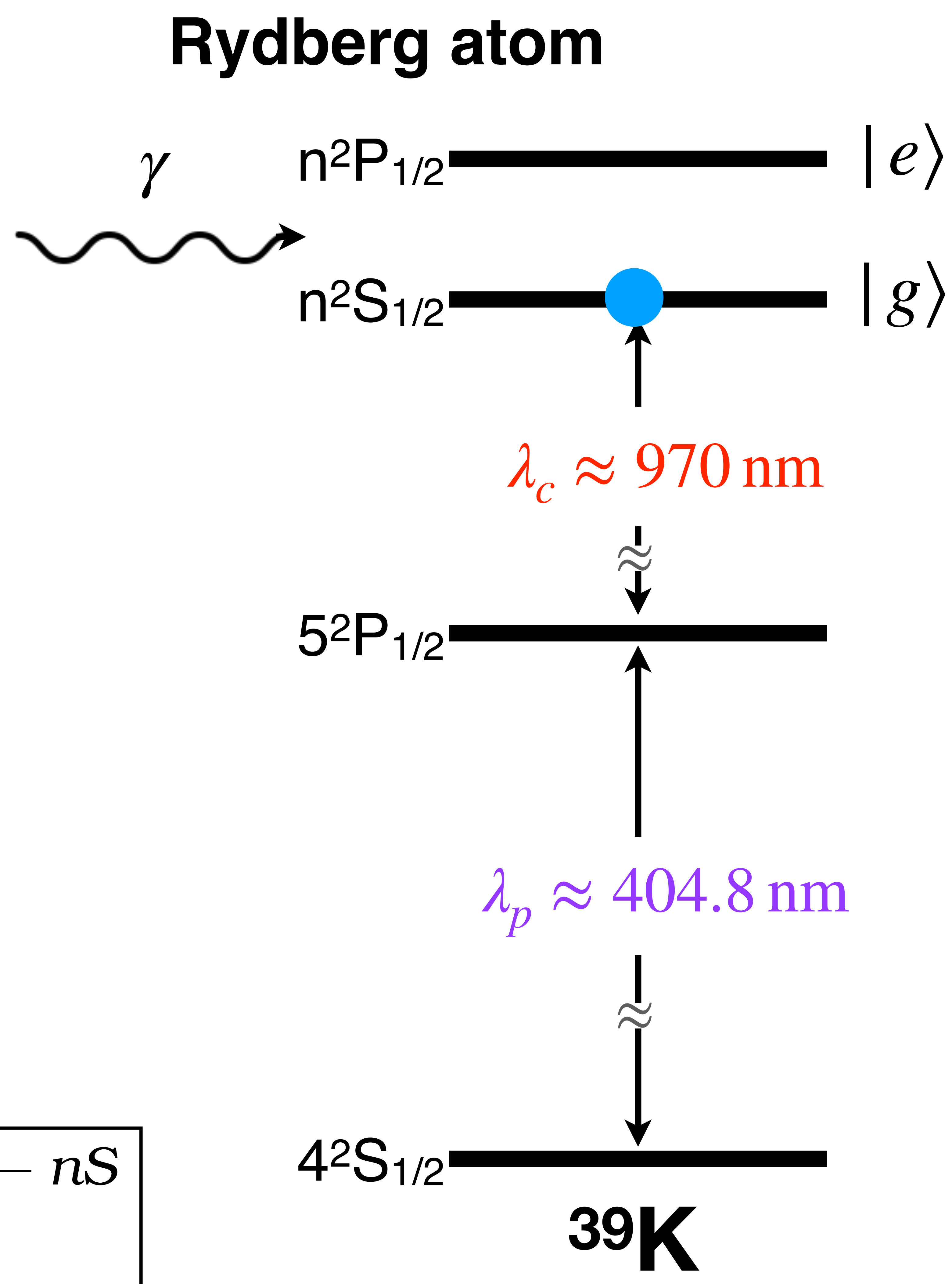


Figure from Tada et al, 2001

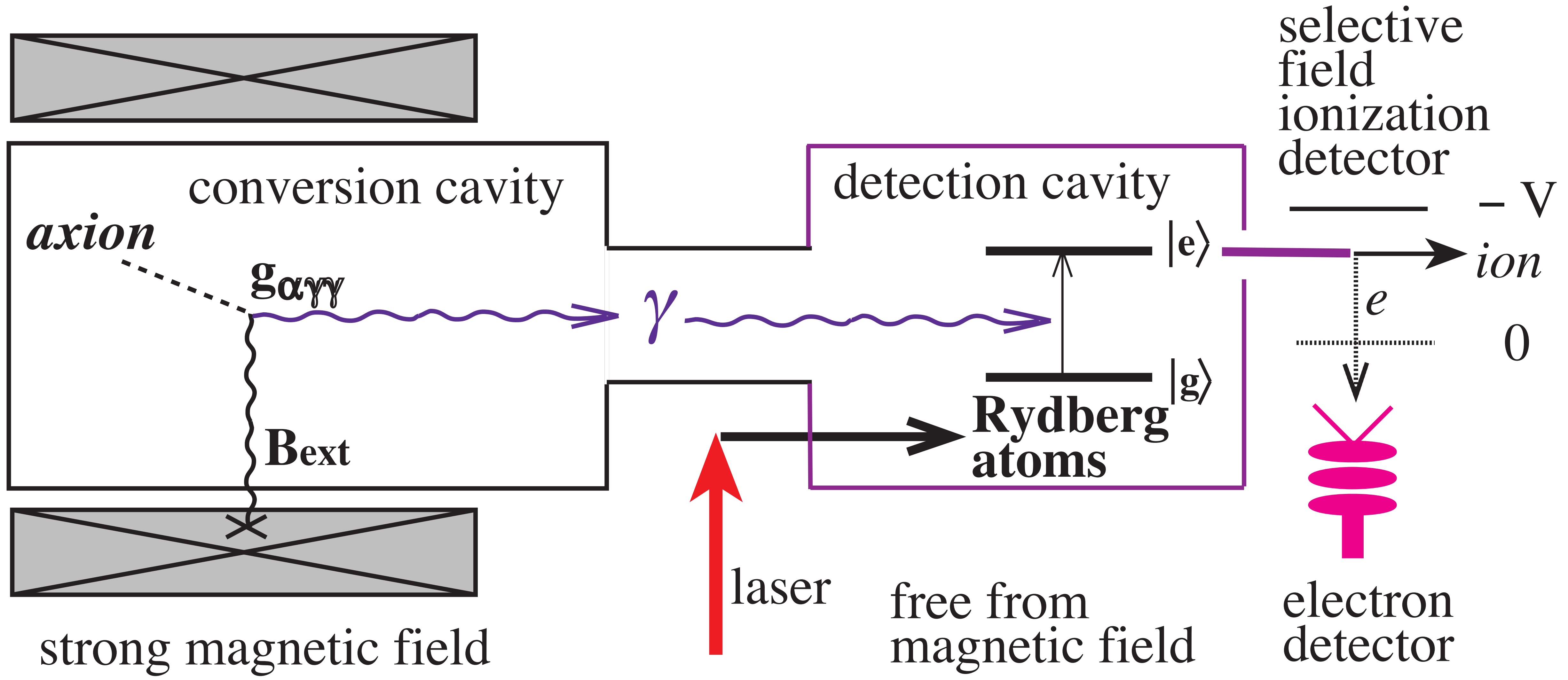
Basic principle



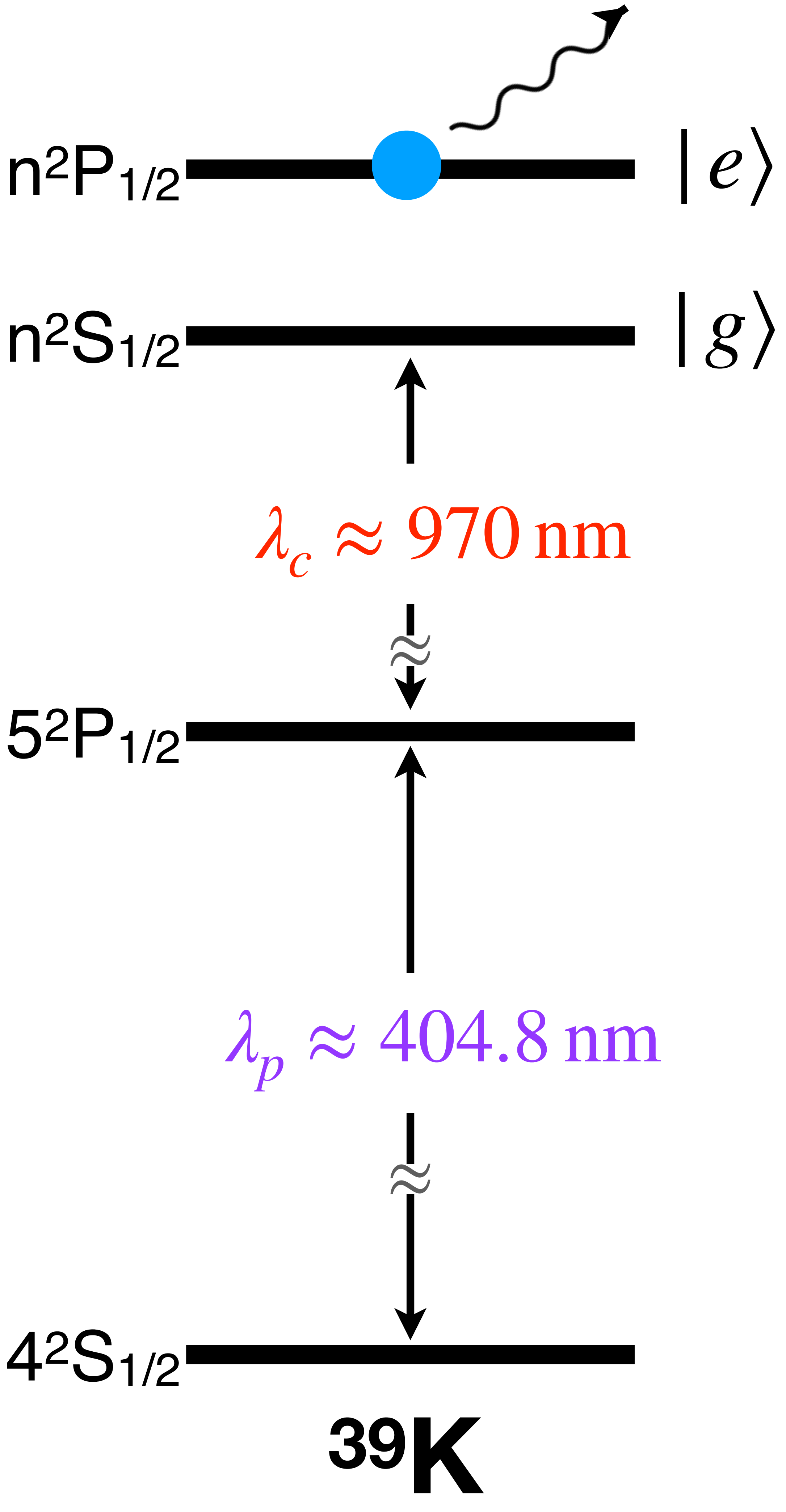


alternative: $4S - 4P_{3/2} - nS$
@767 nm, 457 nm

Basic principle

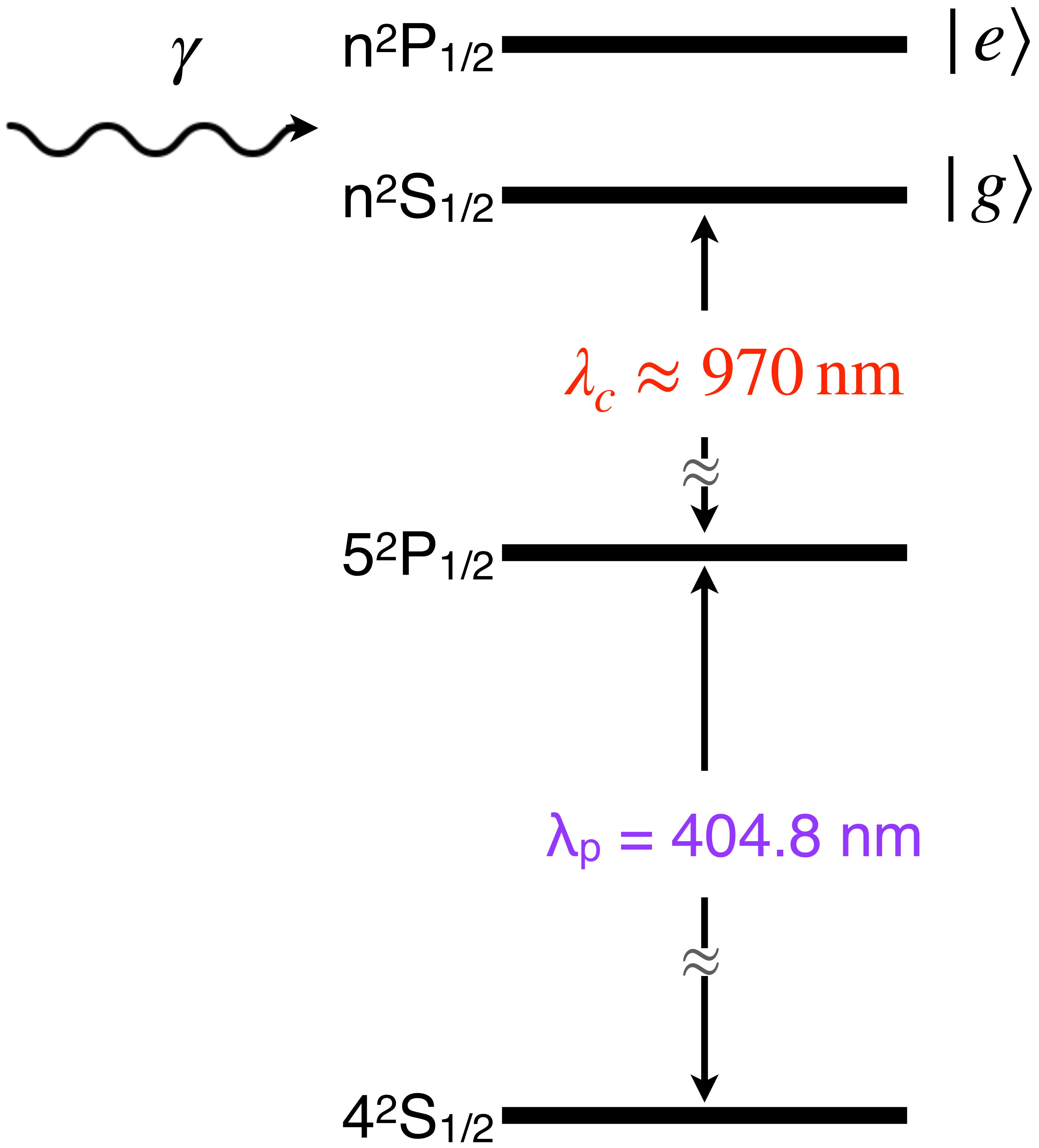


Selective ionization



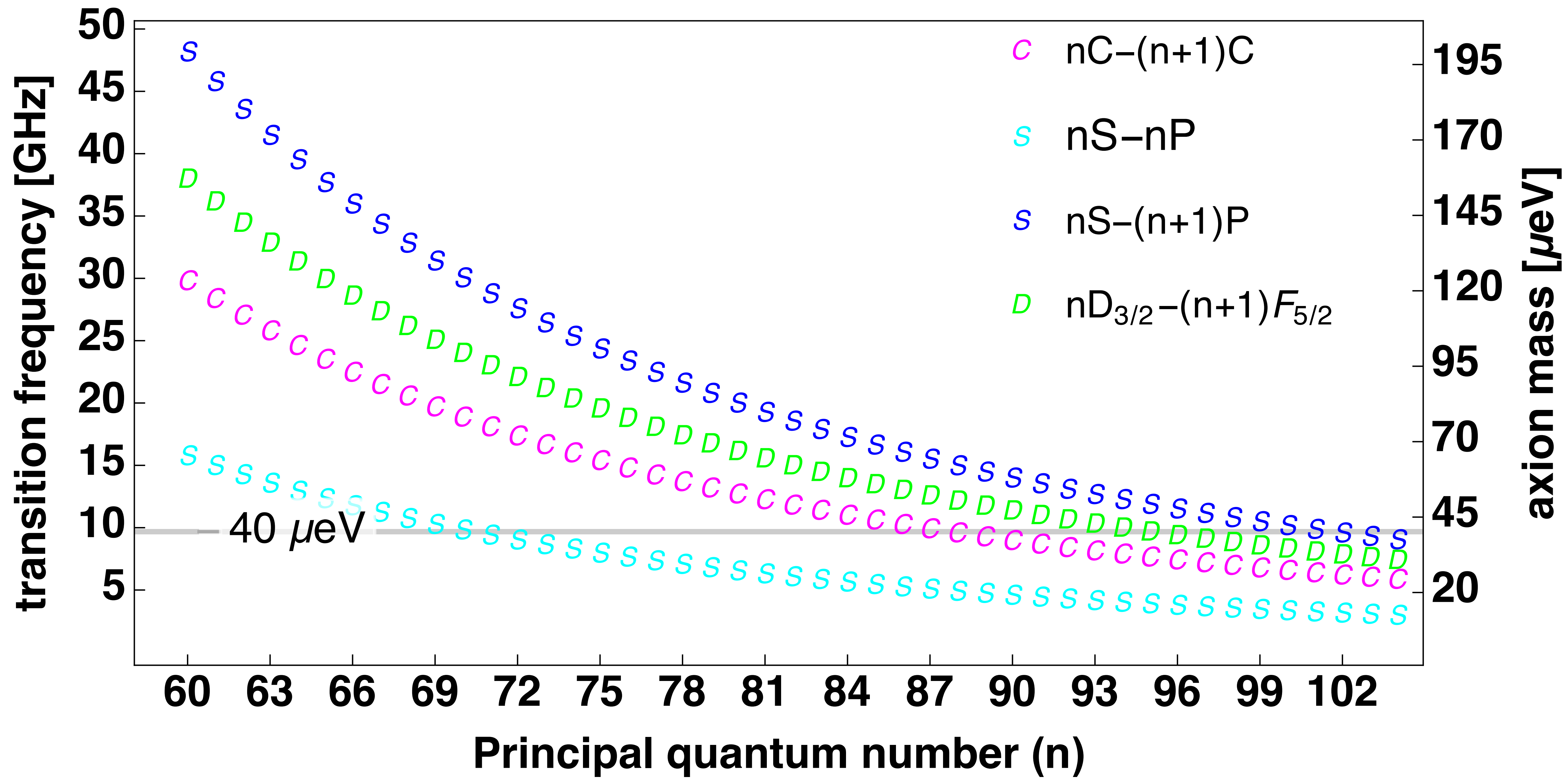
alternative: $4S - 4P_{3/2} - nS$
@767 nm, 457 nm

“Tuning” Rydberg atoms



Coarse-tuning: *n;* Fine-tuning: Zeeman shifting

nC (circular, *l* = |*m*| = *n* − 1); *nS* (*l* = 0); *nD* (*l* = 3)

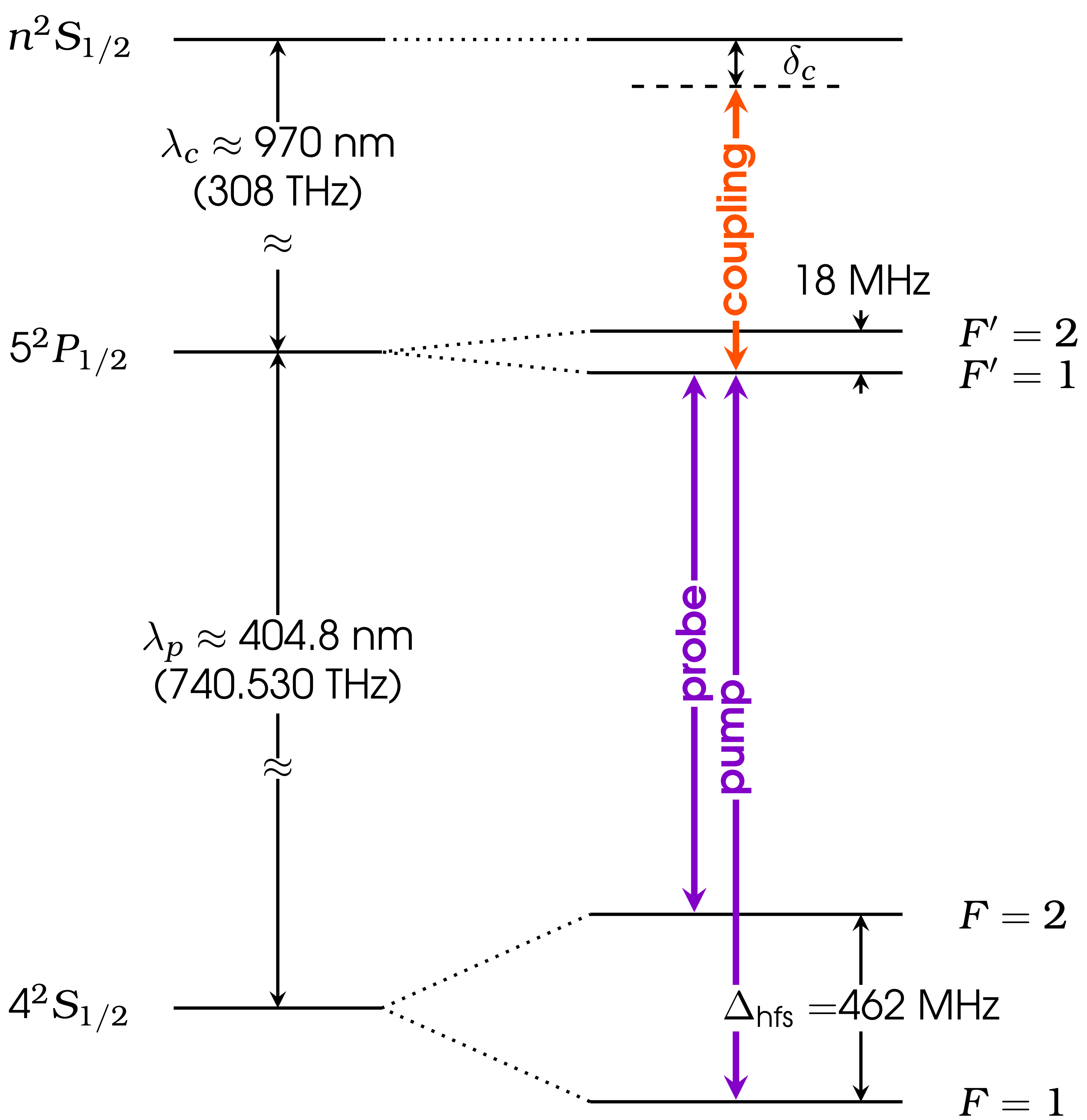


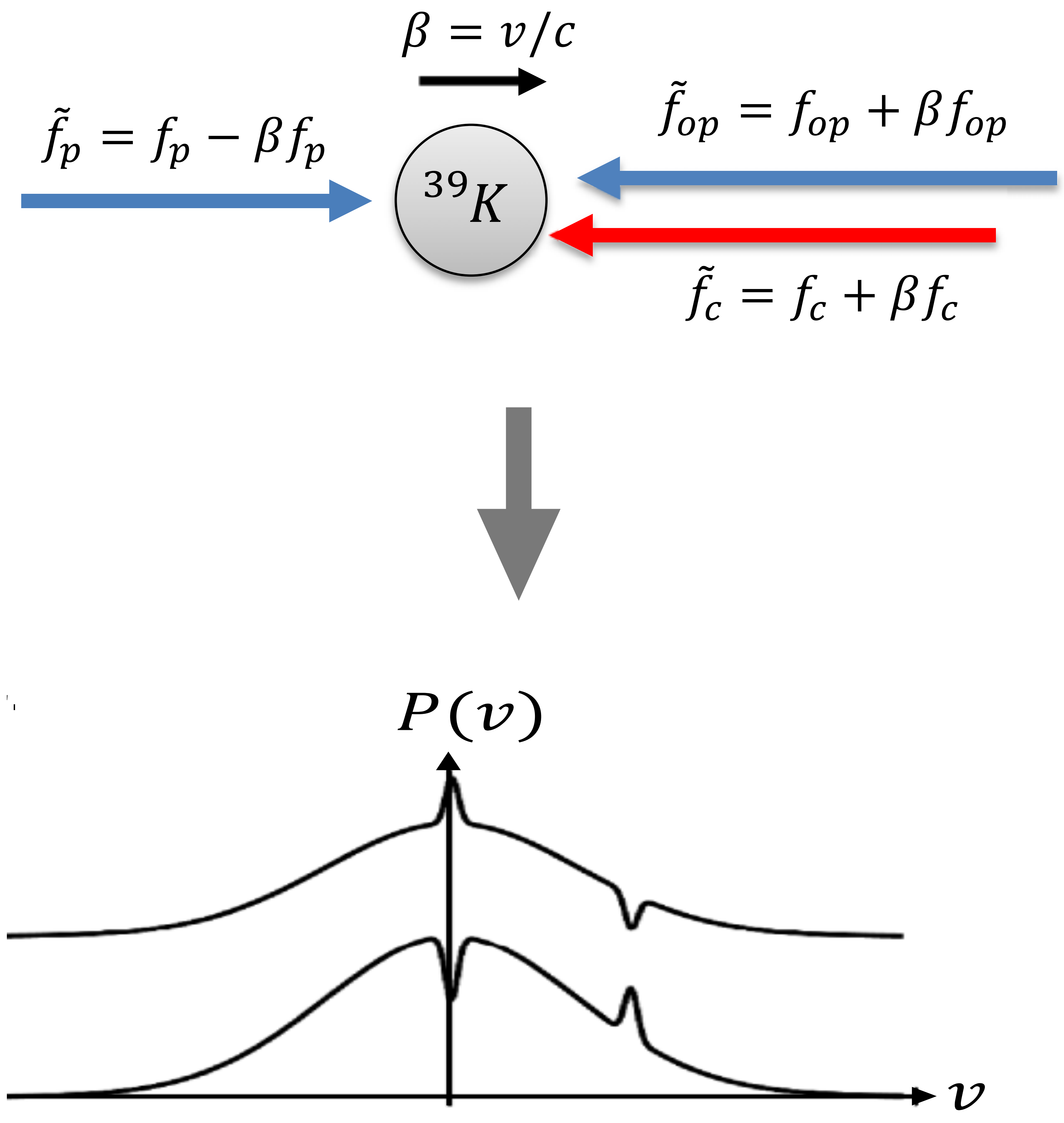
For m_a = 40 μeV ≈ 10 GHz*:

101*S* (and 70*S*), 95$D_{3/2}$, and 87*C*

Rydberg spectroscopy

- **Goal:** identify the *n* ~ 50 – 90 transitions for 970 nm
- **Detection:** electromagnetically induced transparency (EIT)



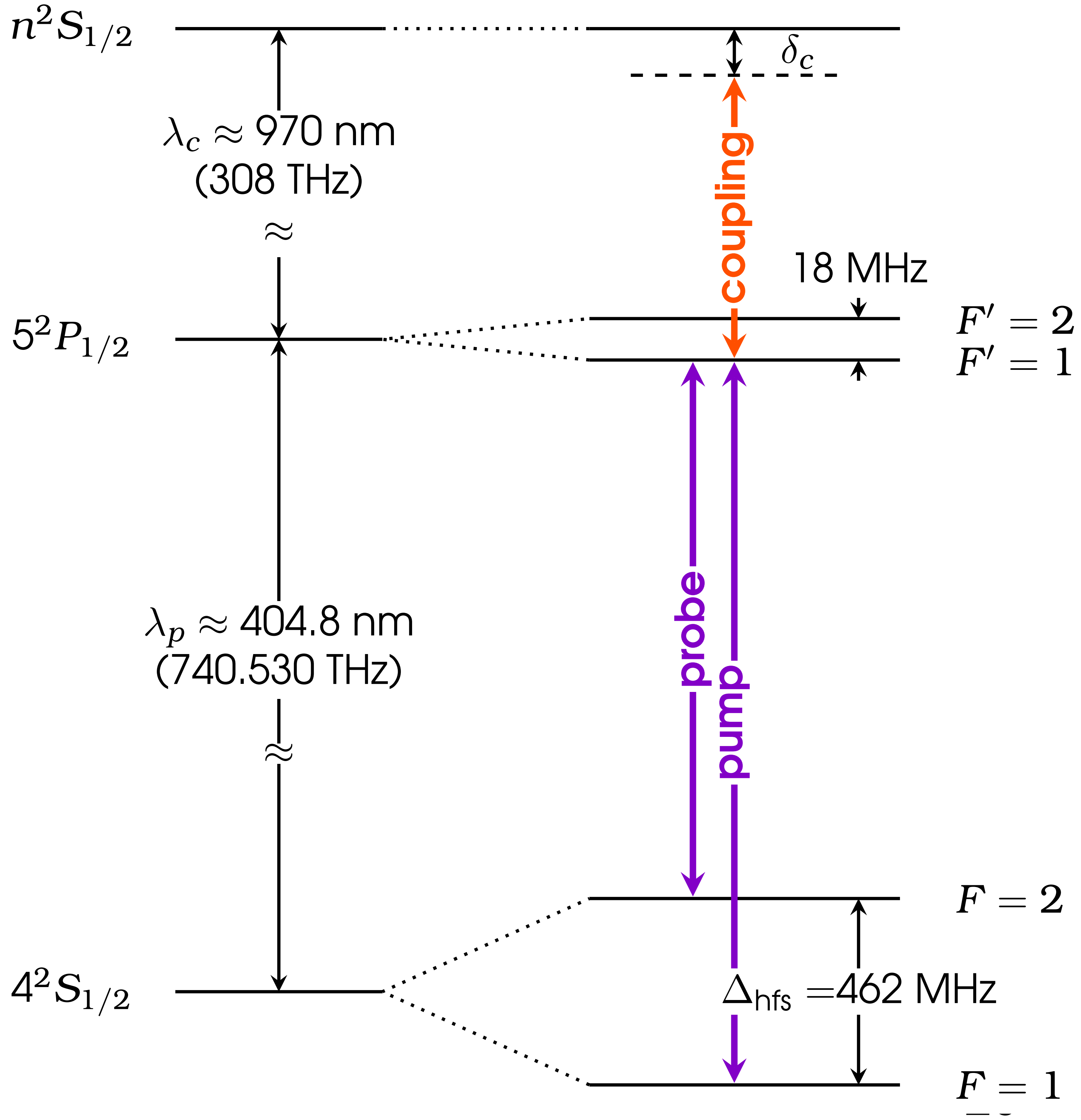


Rydberg spectroscopy

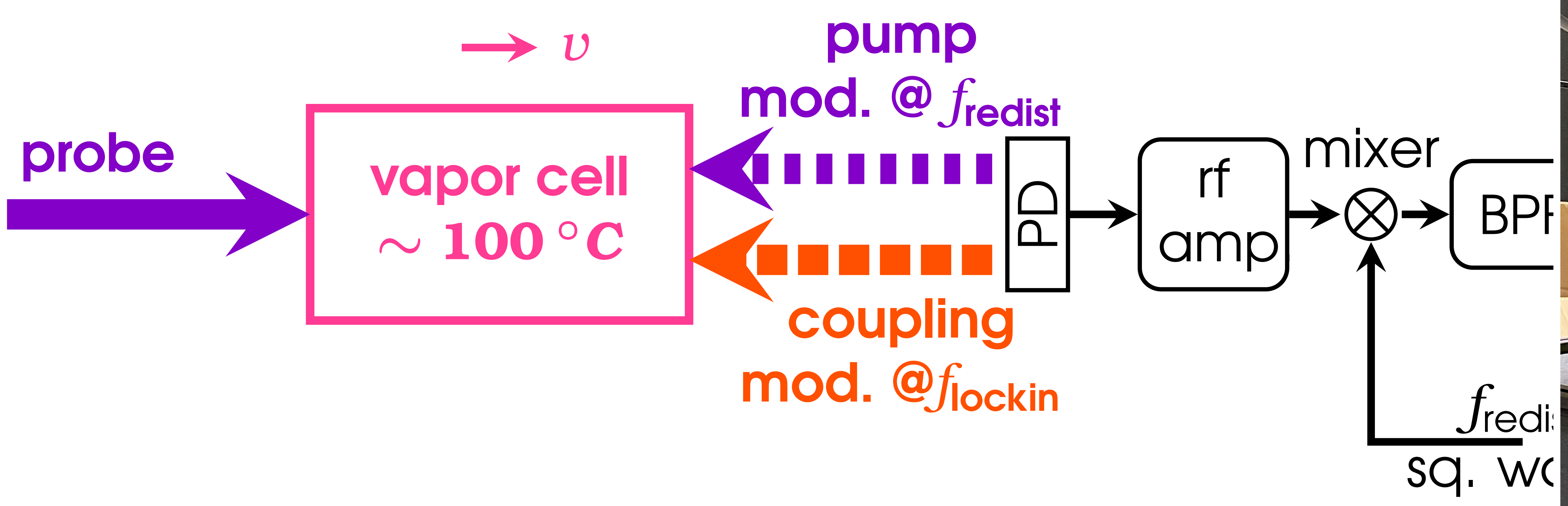
- **Challenge:** inverted ladder system $\lambda_p = 405 < \lambda_c = 970$ nm
  - Same sign between one-photon & two-photon Doppler shift

    $$-k_p v \text{ vs. } -(k_p v - k_c v)$$

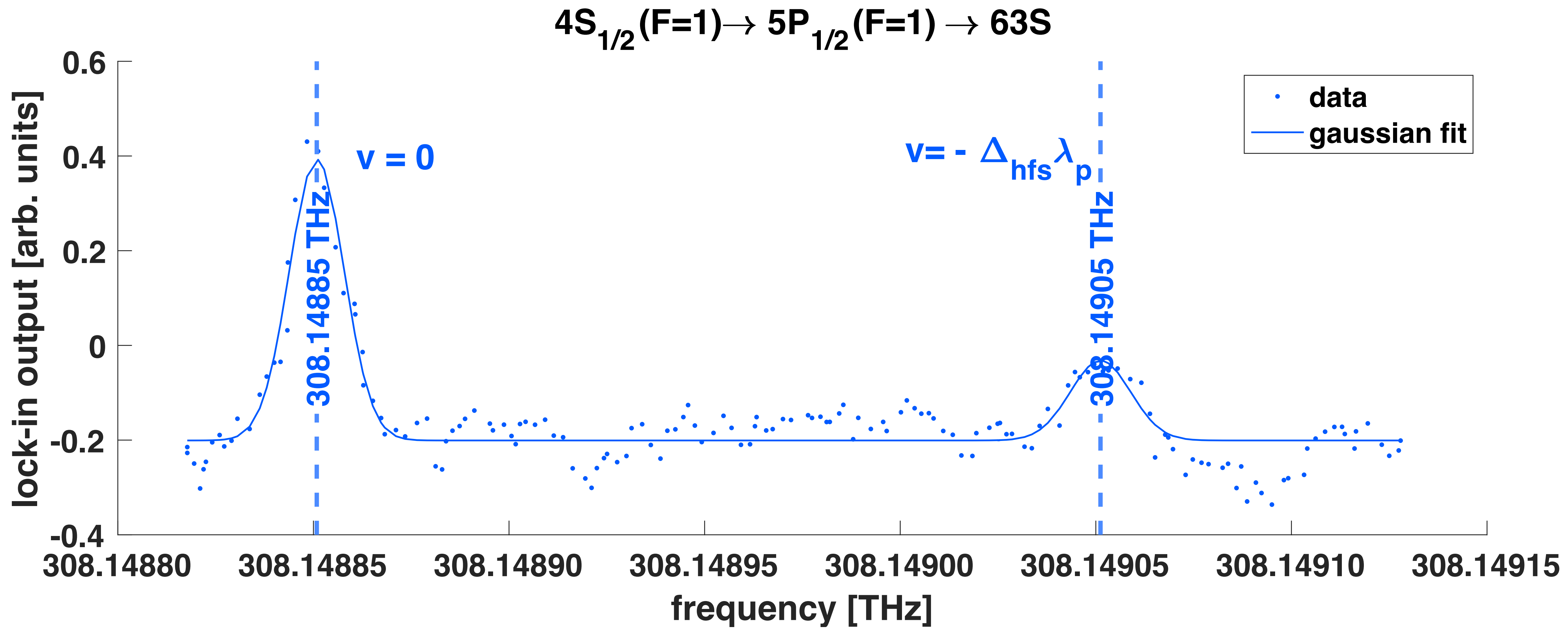
  $\Rightarrow$ no transparency window (Boon et al, 1999, Urvoy et al, 2013)
- **Solution:** velocity selective EIT (Xu, DeMarco, 2016)



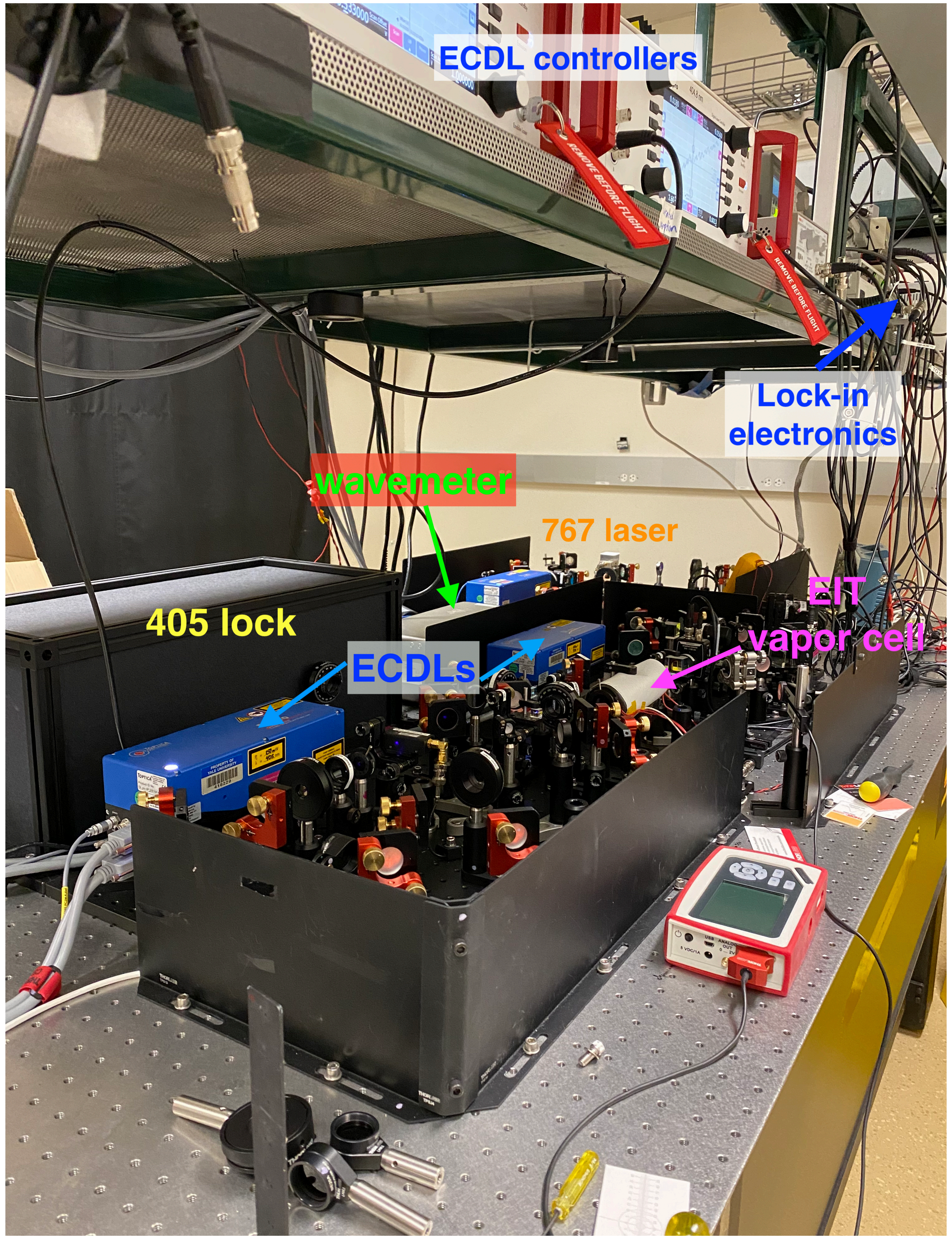
EIT Setup



probe
vapor cell
~ 100 °C
→ v
pump
mod. @ f_{redist}
coupling
mod. @f_{lockin}
PD
rf amp
mixer
BPF
f_{redi}
sq. wa



$4S_{1/2}$(F=1)→ $5P_{1/2}$(F=1) → 63S
data
gaussian fit
v = 0
v= - $\Delta_{hfs}\lambda_p$
308.14885 THz
308.14905 THz
lock-in output [arb. units]
frequency [THz]
0.6
0.4
0.2
0
-0.2
-0.4
308.14880
308.14885
308.14890
308.14895
308.14900
308.14905
308.14910
308.14915

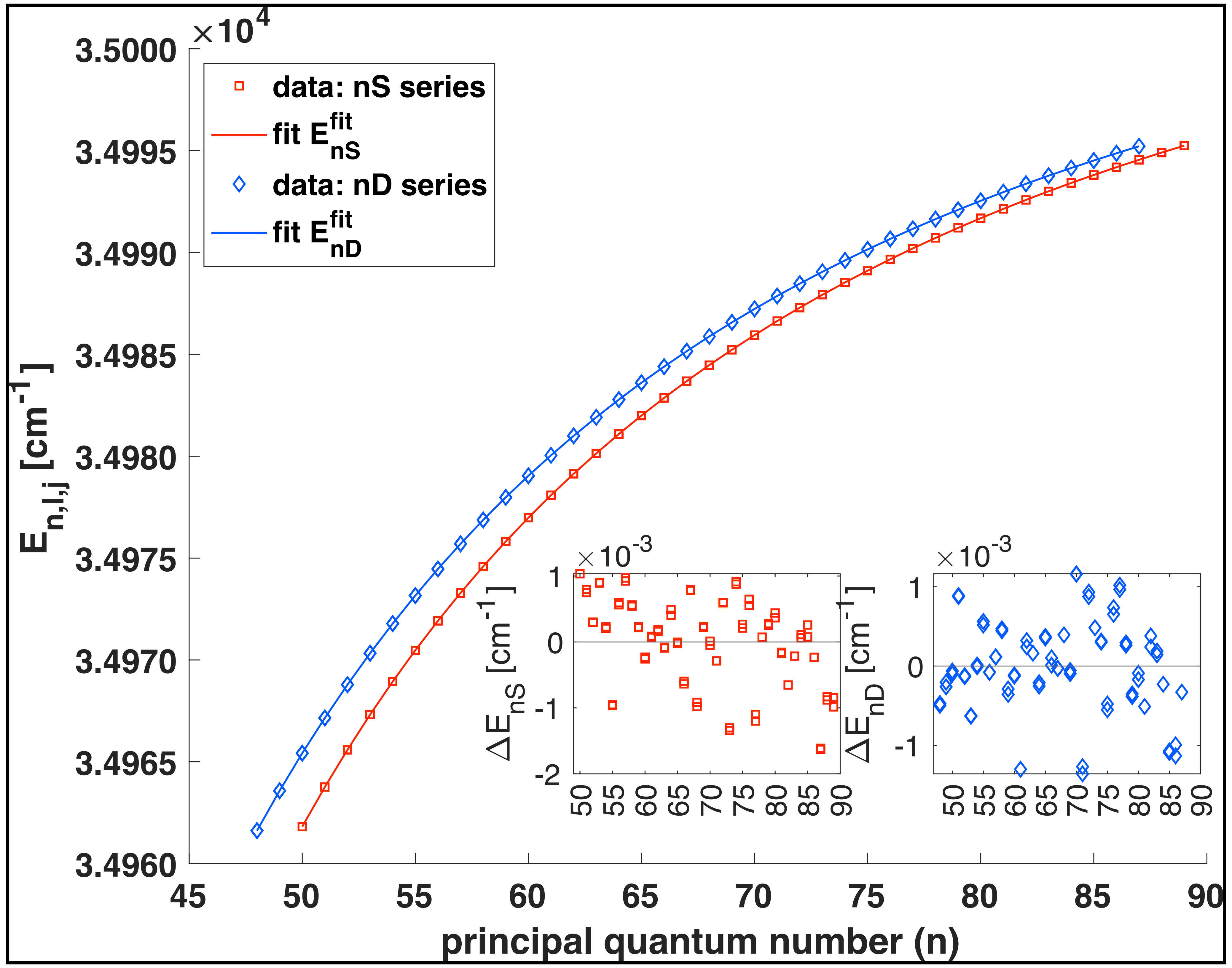


ECDL controllers
Lock-in electronics
wavemeter
767 laser
405 lock
ECDLs
EIT vapor cell

n = 47 to 90 identified

- ~80 transitions identified between n = 47 - 90
- 70 of the 80 newly observed Ryd. levels
- Enable access to ~5 – 50 GHz

  (m_a ~ 20 – 200 μeV)



YZ, S. Ghosh, S.B. Cahn, M.J. Jewell, D. H. Speller, RHM, arxiv:2112.04614

Conclusions

- HAYSTAC continues to scan 4 – 10 GHz
- Compelling case for axions at higher masses
- Rydberg atoms give us access to axion @ 10 – 1000 GHz/40 – 4000 μeV
- Effort @ Yale focus on 10 - 50 GHz
- $n \sim 50 - 90$ Rydberg leves observed
- Stay tuned