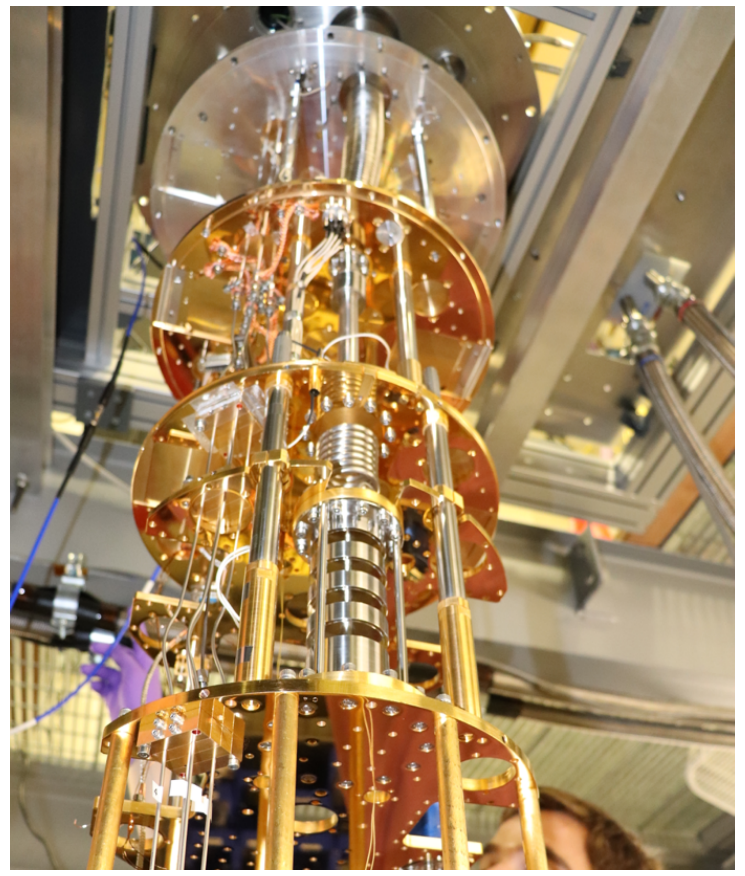
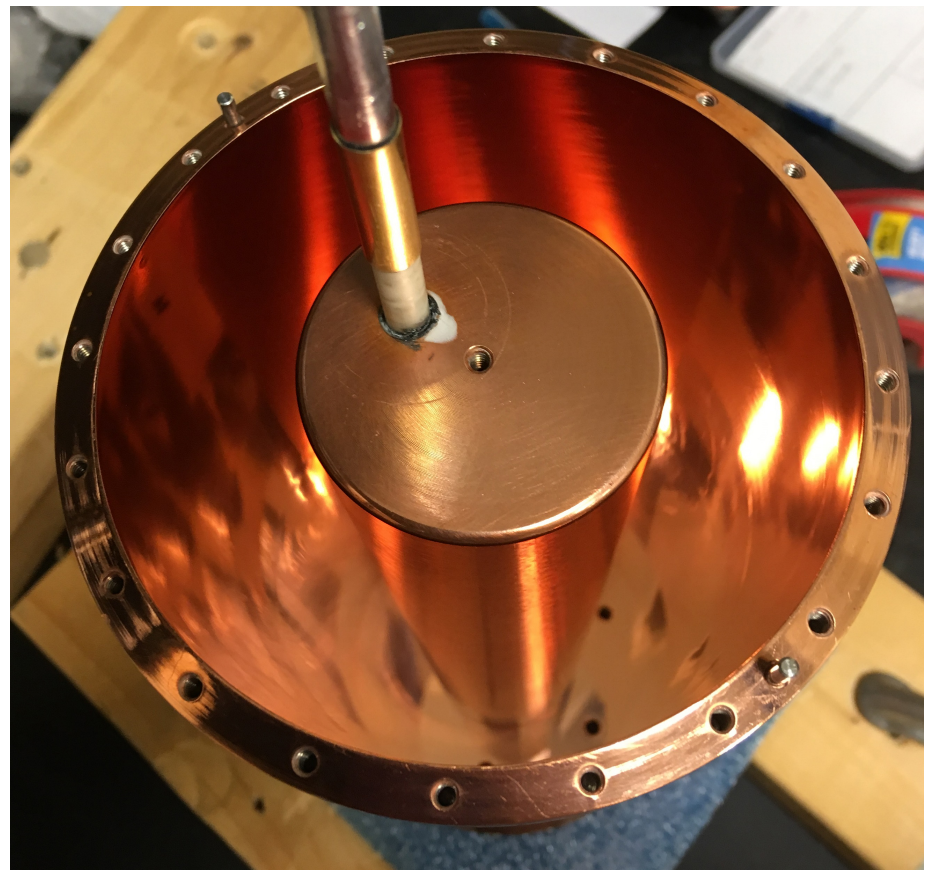
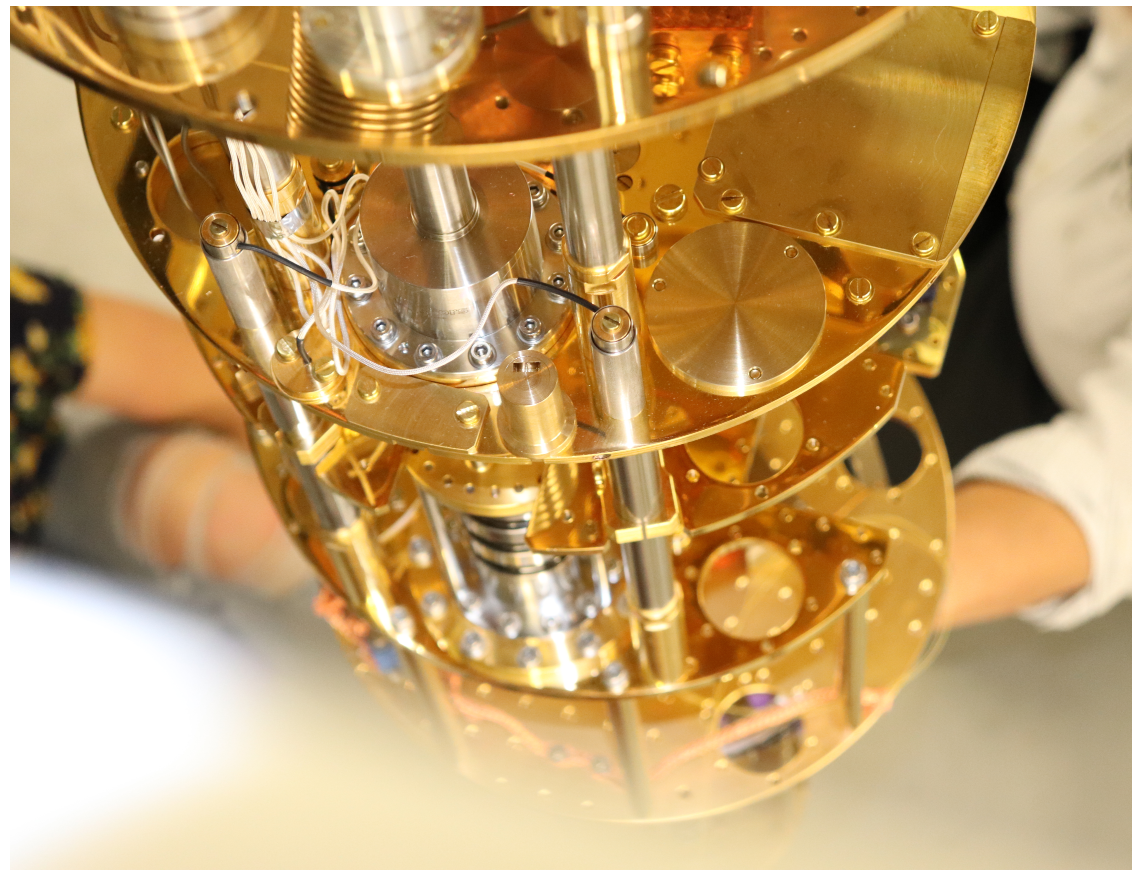
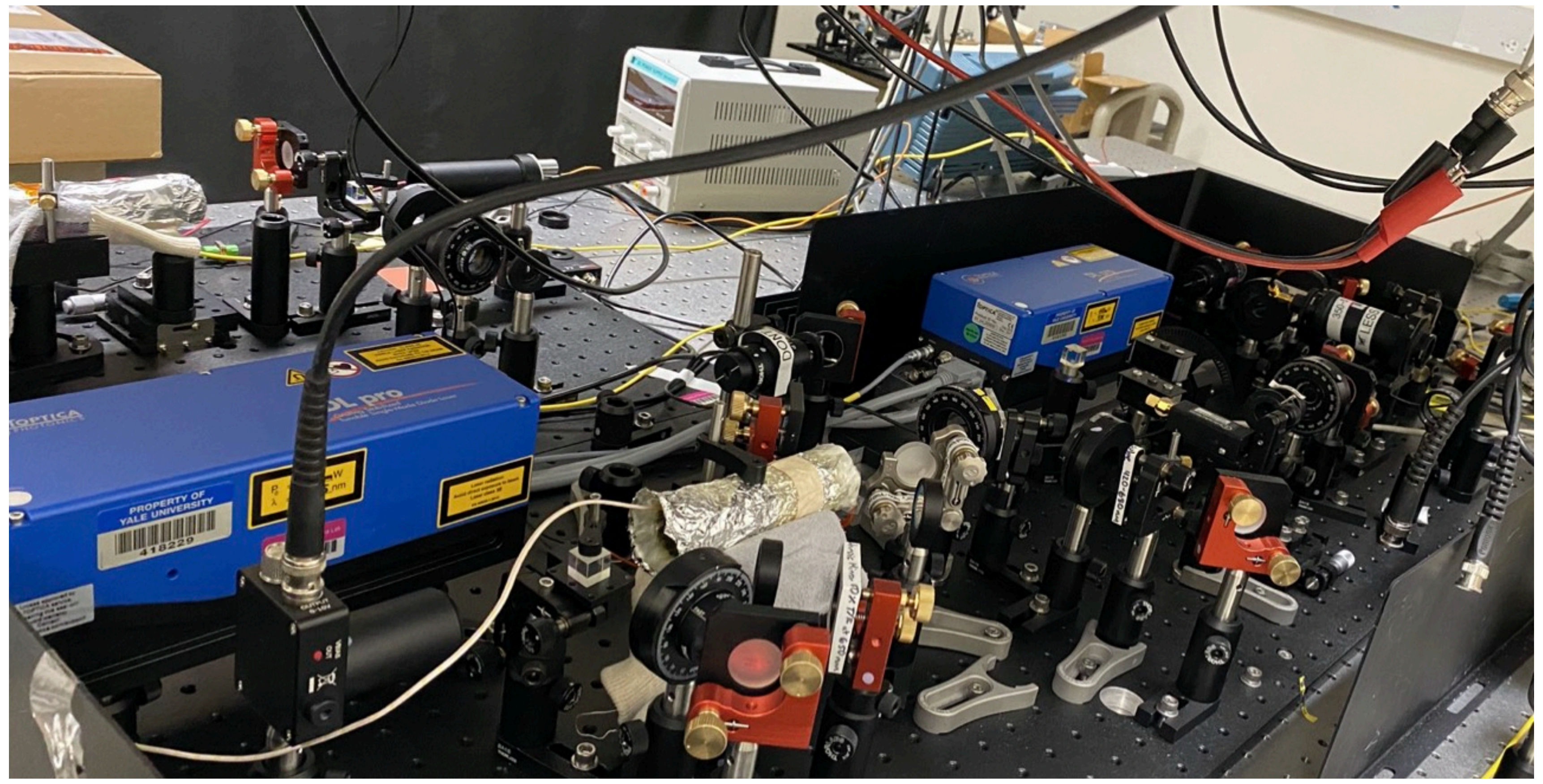





Quantum Sensors and Axion Dark Matter Searches

Wright Lab Quantum Sensing Workshop

Quantum Week at Yale

Reina Maruyama
Yale University

April 8, 2022

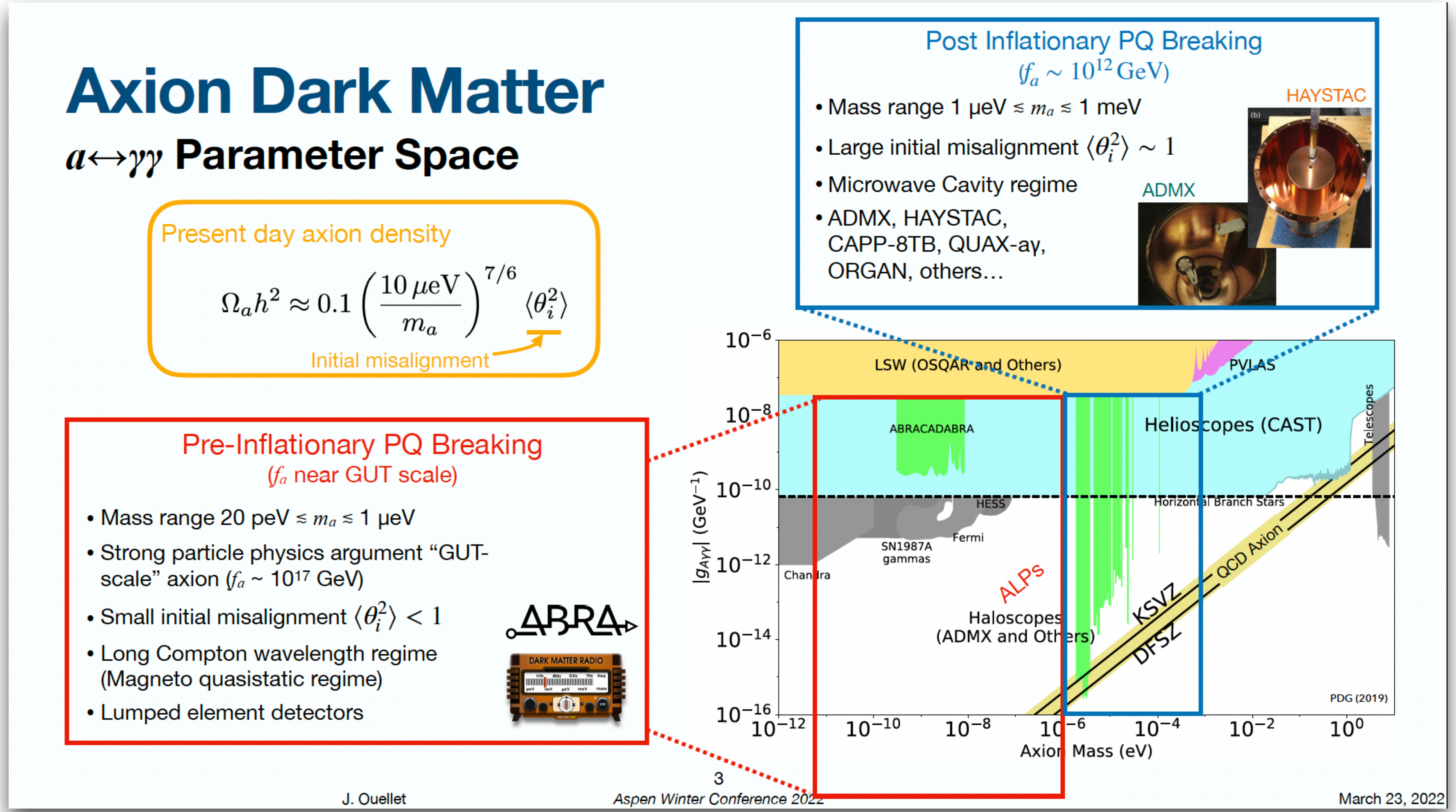
U.S. DEPARTMENT OF ENERGY | Office of Science

QuantiSED

NSF

QISE-NET
QUANTUM INFORMATION SCIENCE AND ENGINEERING NETWORK

Axions are well motivated



Axion searches at Yale

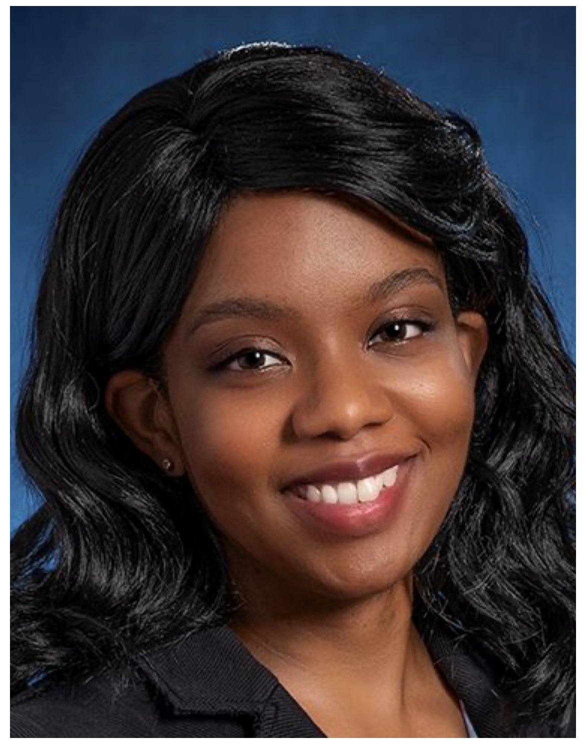
Haystac + Rydberg extension


Steve Lamoreaux


Reina Maruyama


Sid Cahn


James Nikkel


Danielle Speller
-> Johns Hopkins


Mike Jewell

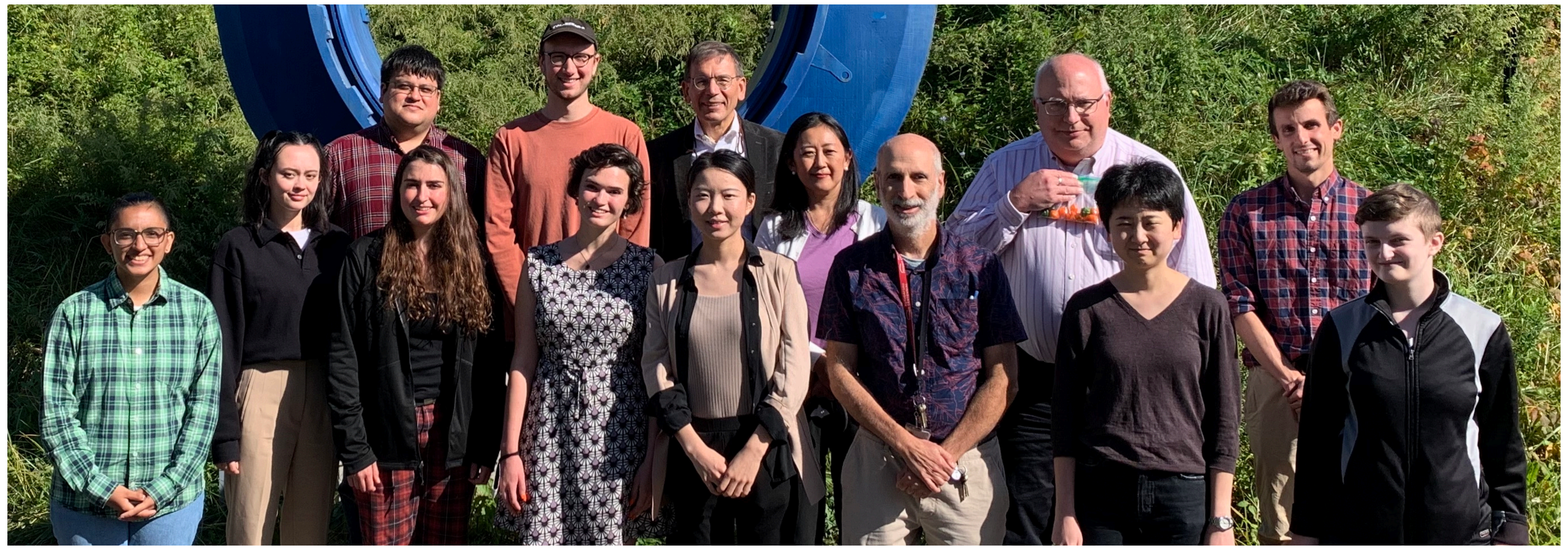

Yuqi Zhu


Sumita Ghosh

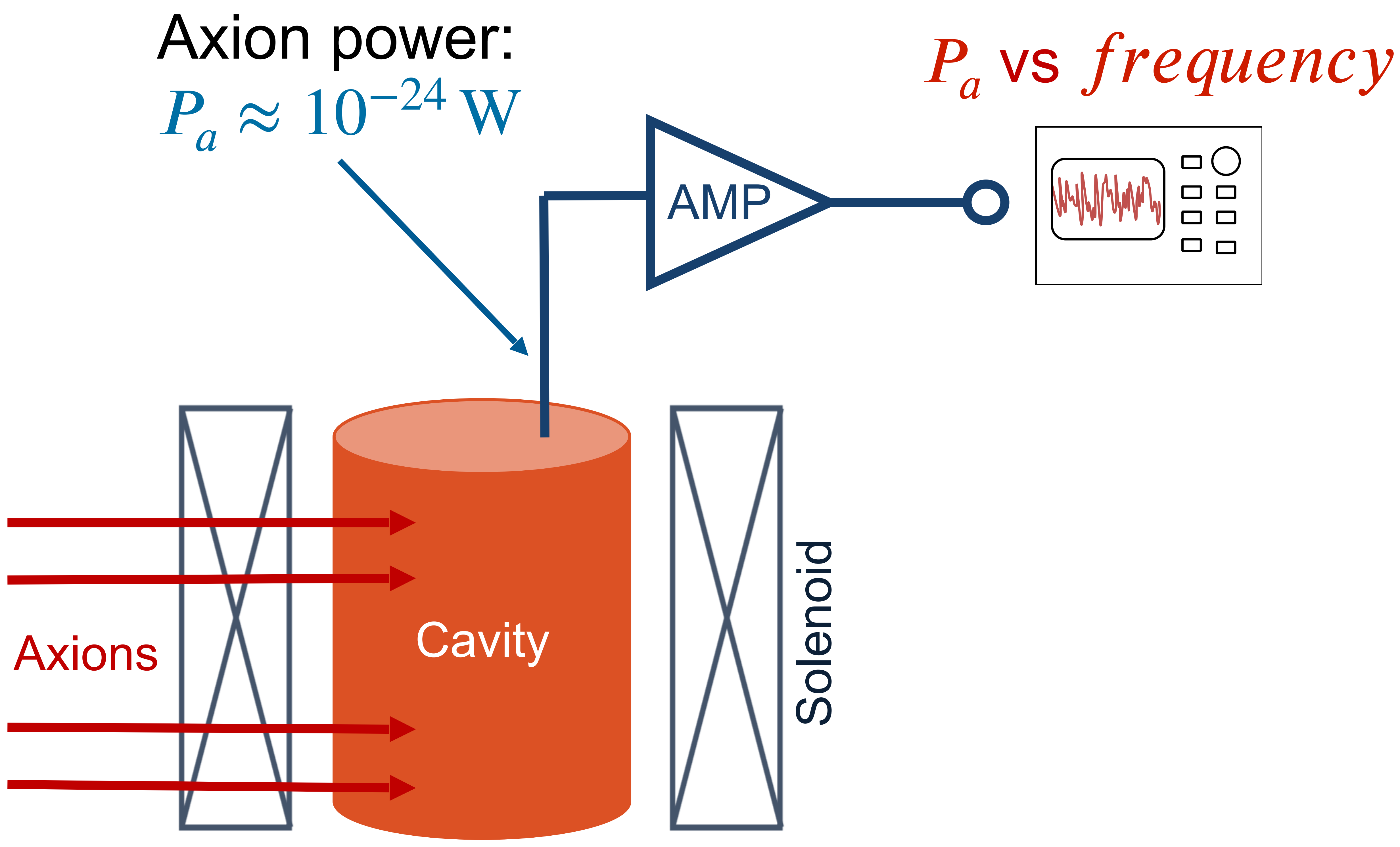

Xiran Bai


Eleanor Graham


Claire Laffan



Basic axion detection principle



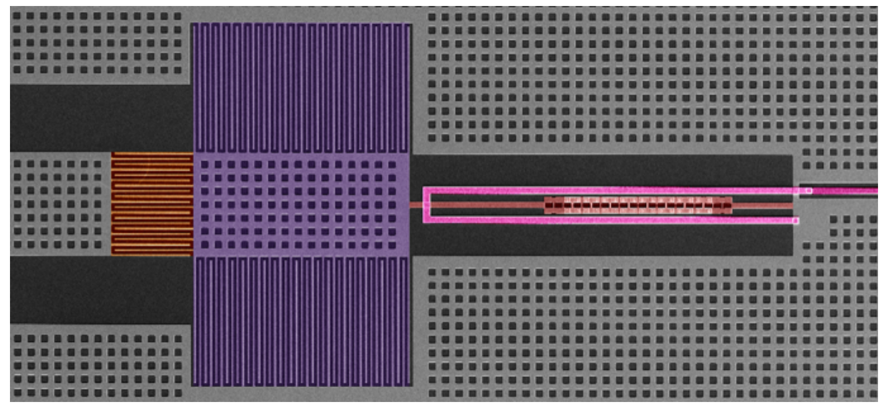
Haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)
HAYSTAC detector: Nucl. Instrum. Methods A 854, 11 (2017)

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

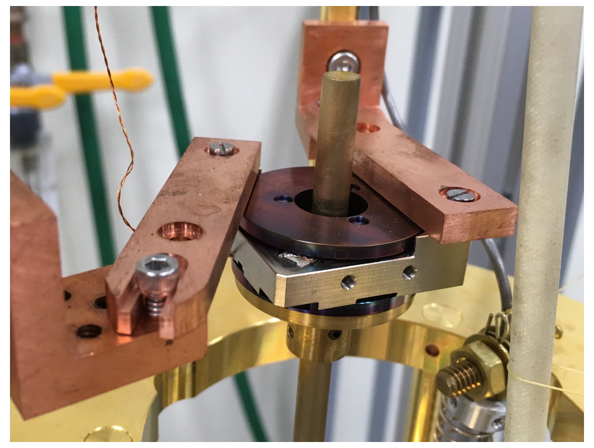
- High Q cavity: $Q = \dfrac{f_c}{\Delta f_c}$
- Low noise amplifier
- Tunable: $h f_a \approx m_a c^2$
- Large magnet: $\boldsymbol{B} = 8$ T
- Cryogenic: $T = 60$ mK

Haystac

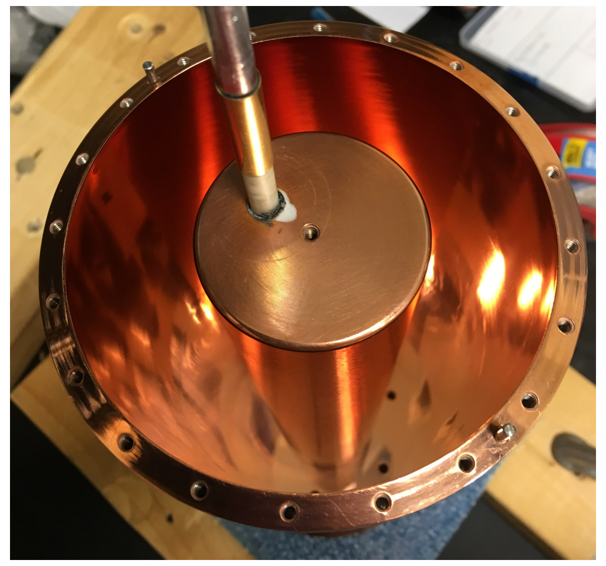
HAYSTAC Experiment



Quantum amplifiers



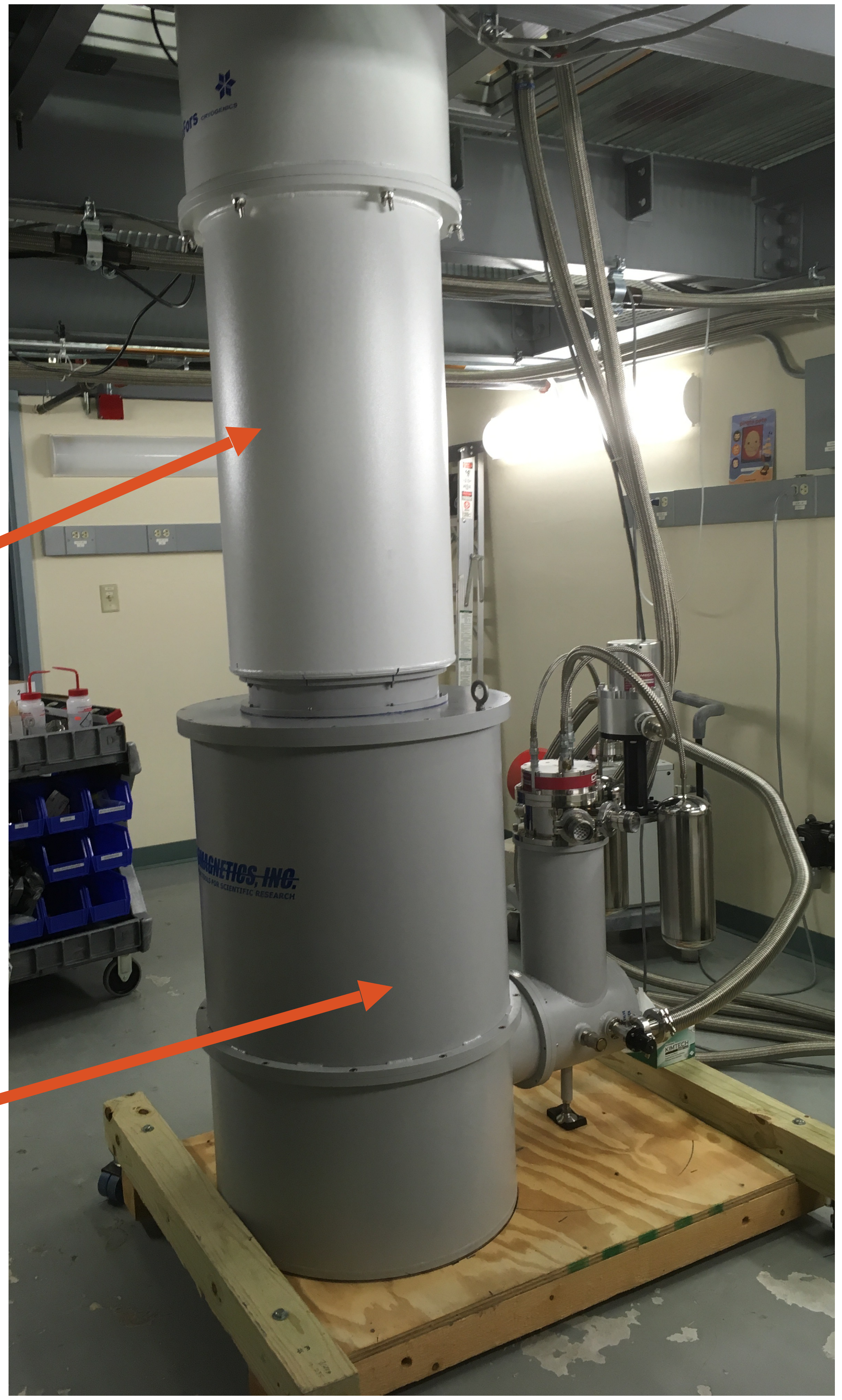
Piezoelectric tuning



Microwave cavity

Cryostat
operating temp
~60 mK

9 T magnet



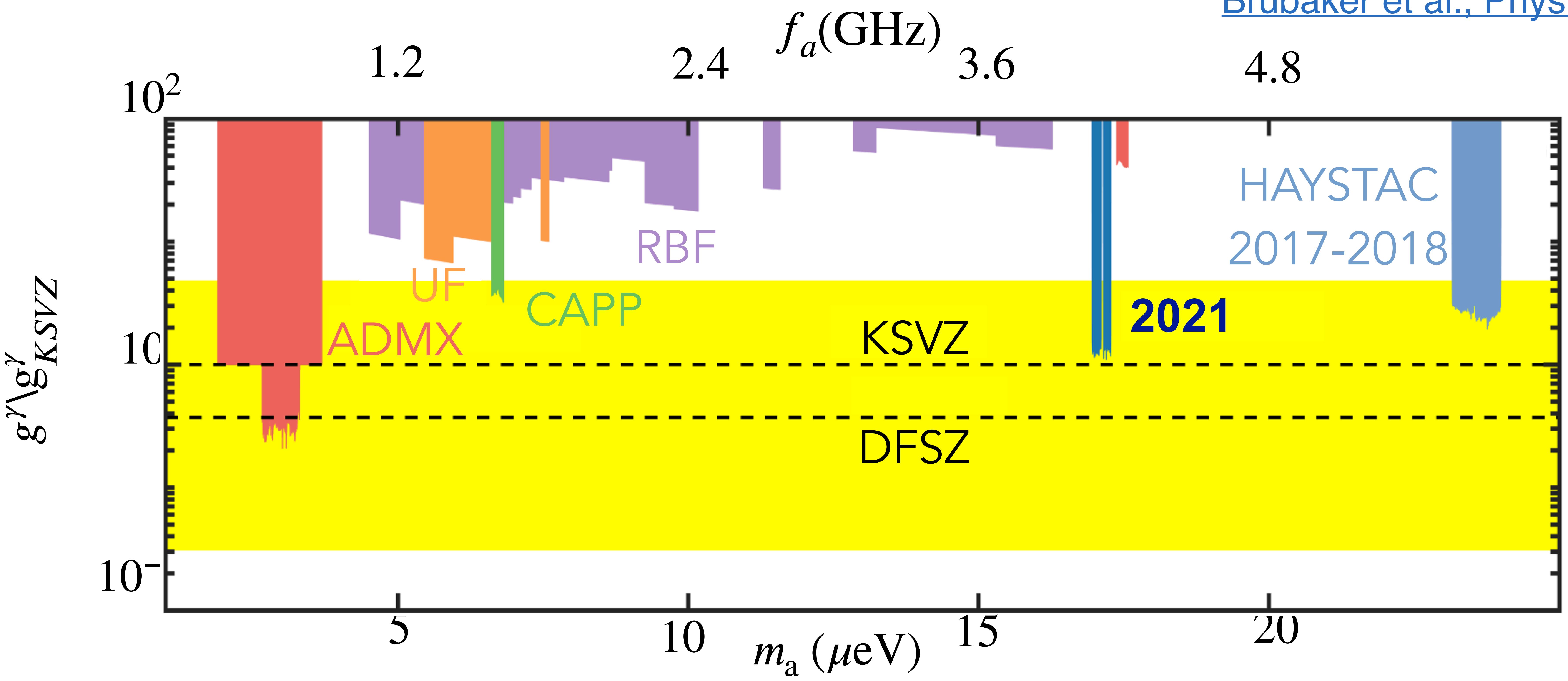
HAYSTAC results

Haystac

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

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

Buschman, et al. (2021): 40 μeV [65 ± 6 μeV, q=1; scale invariant spectrum]

Klaer & Moore (2017); 26.2 ± 3.4 μeV (6.3 ± 0.8 GHz)

Buschman, Foster & Safdi (2019): **25.2 ± 11 μeV (6.1 ± 2.7 GHz)**
17.4 ± 11 μeV (4.2 ± 1.1 GHz)*

* 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

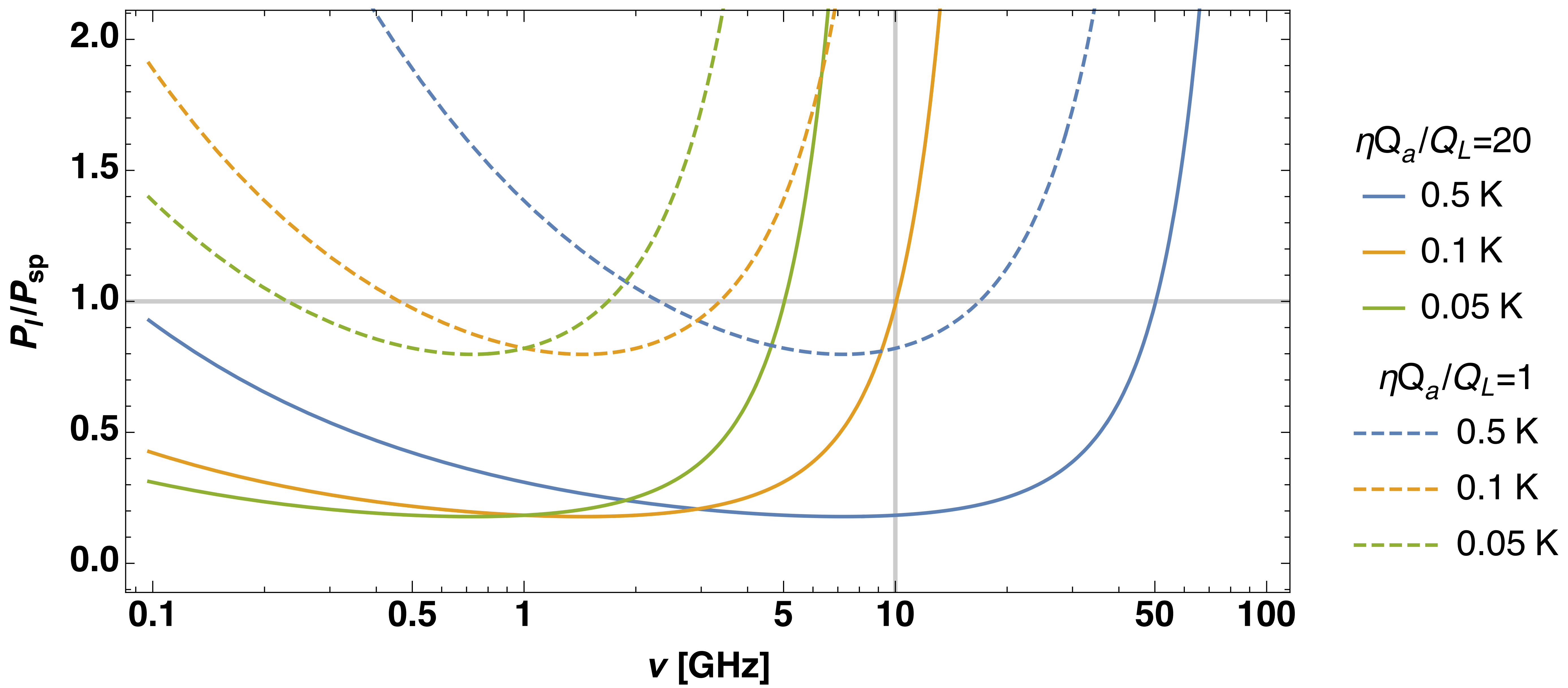
Linear amplifier

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

Single-photon detector

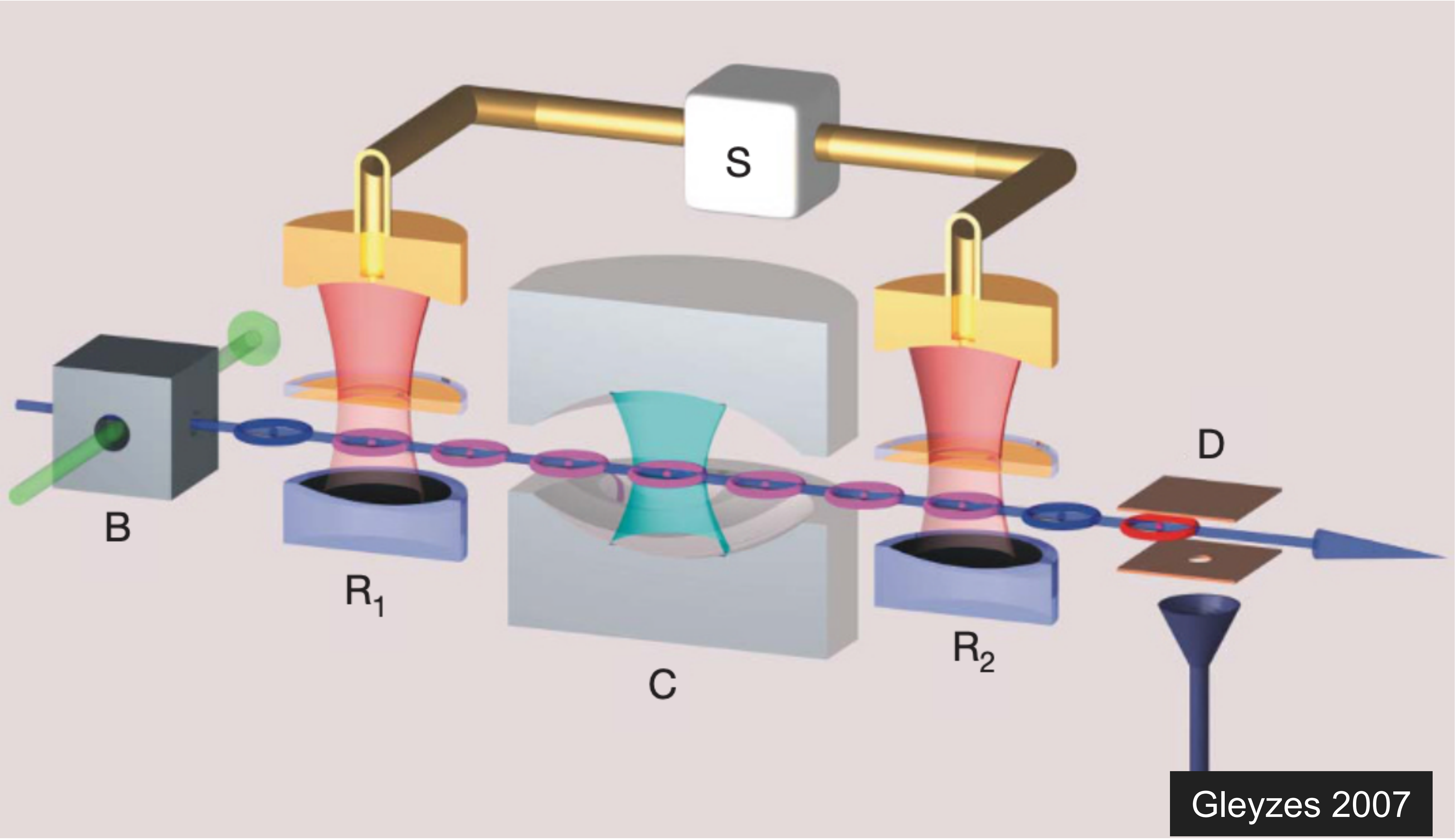
- shot noise due to BBR
  $P_{sp} = h\nu\sqrt{\frac{\eta \bar{n}_{\text{BBR}}\Gamma}{\tau_{\text{int}}}}$
  (η: efficiency, $\Gamma = 2\pi\nu/Q_L$ decay rate)
- only sensitive to amp.

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

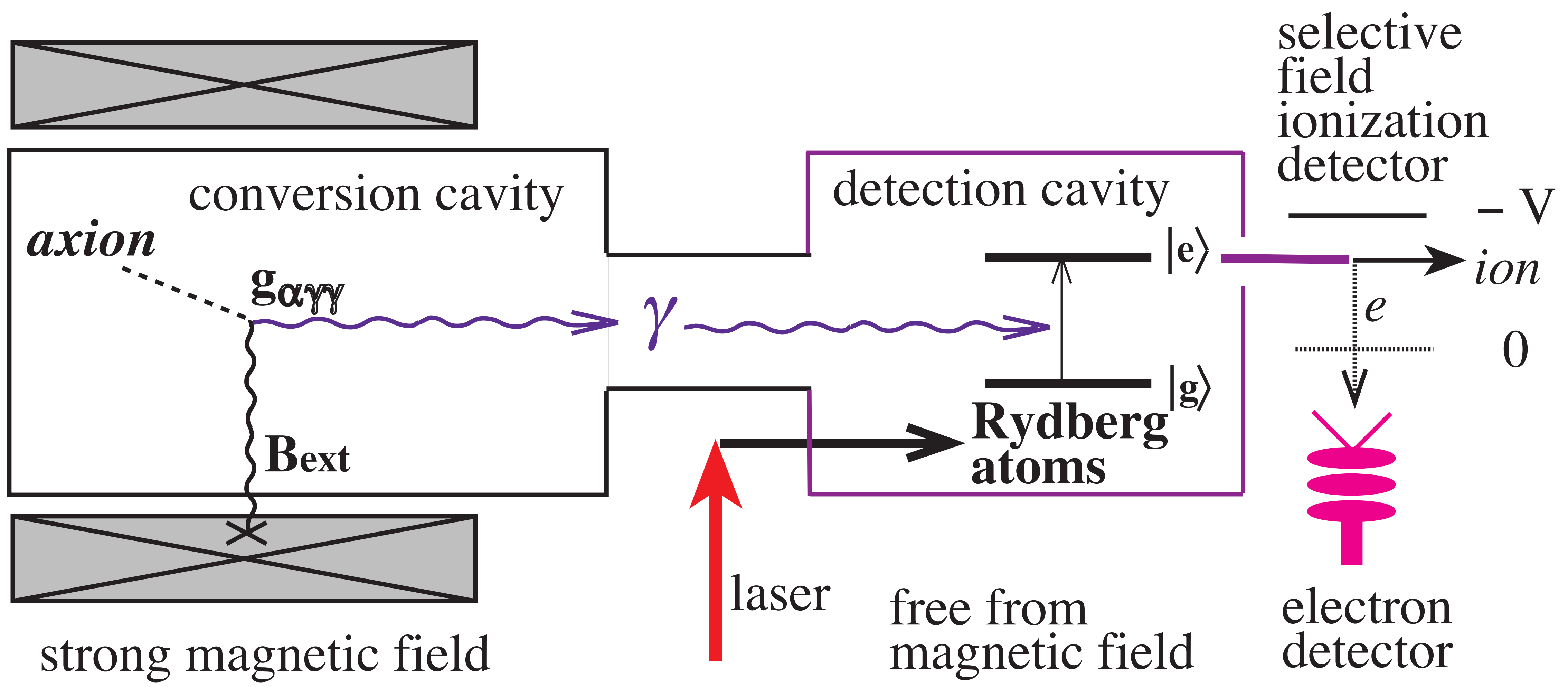


Rydberg atoms as microwave detectors

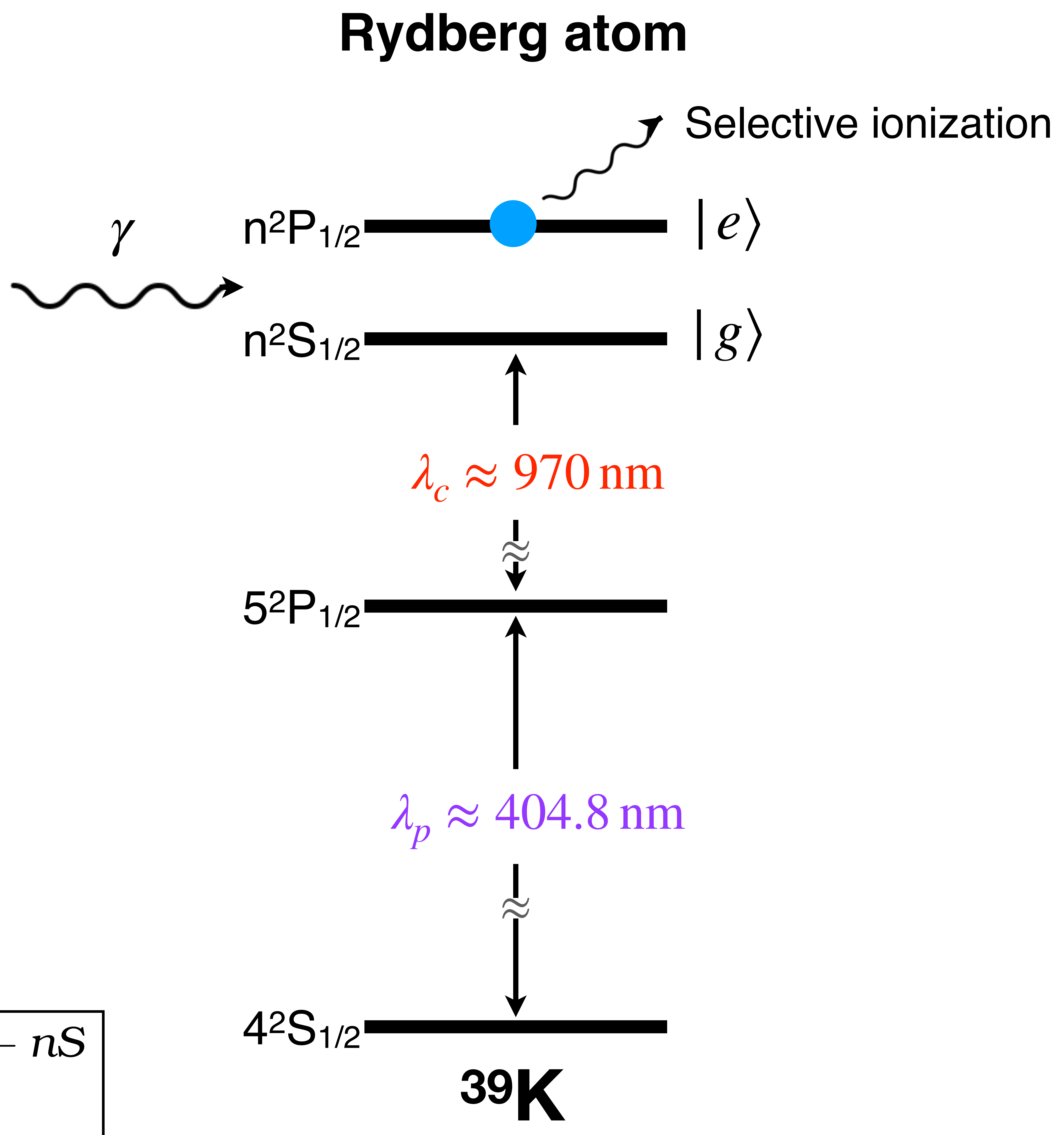
- Rydberg atoms:
  - Highly excited valence e^-
  - Couple strongly to 10 - 1000 GHz
- Applications:
  - Vapor-cell electrometry
    - e.g. Stuttgart; Sediacek et al., 2016
  - Single-atom cavity QED: ENS
  - **CARRACK axion search**



Basic principle

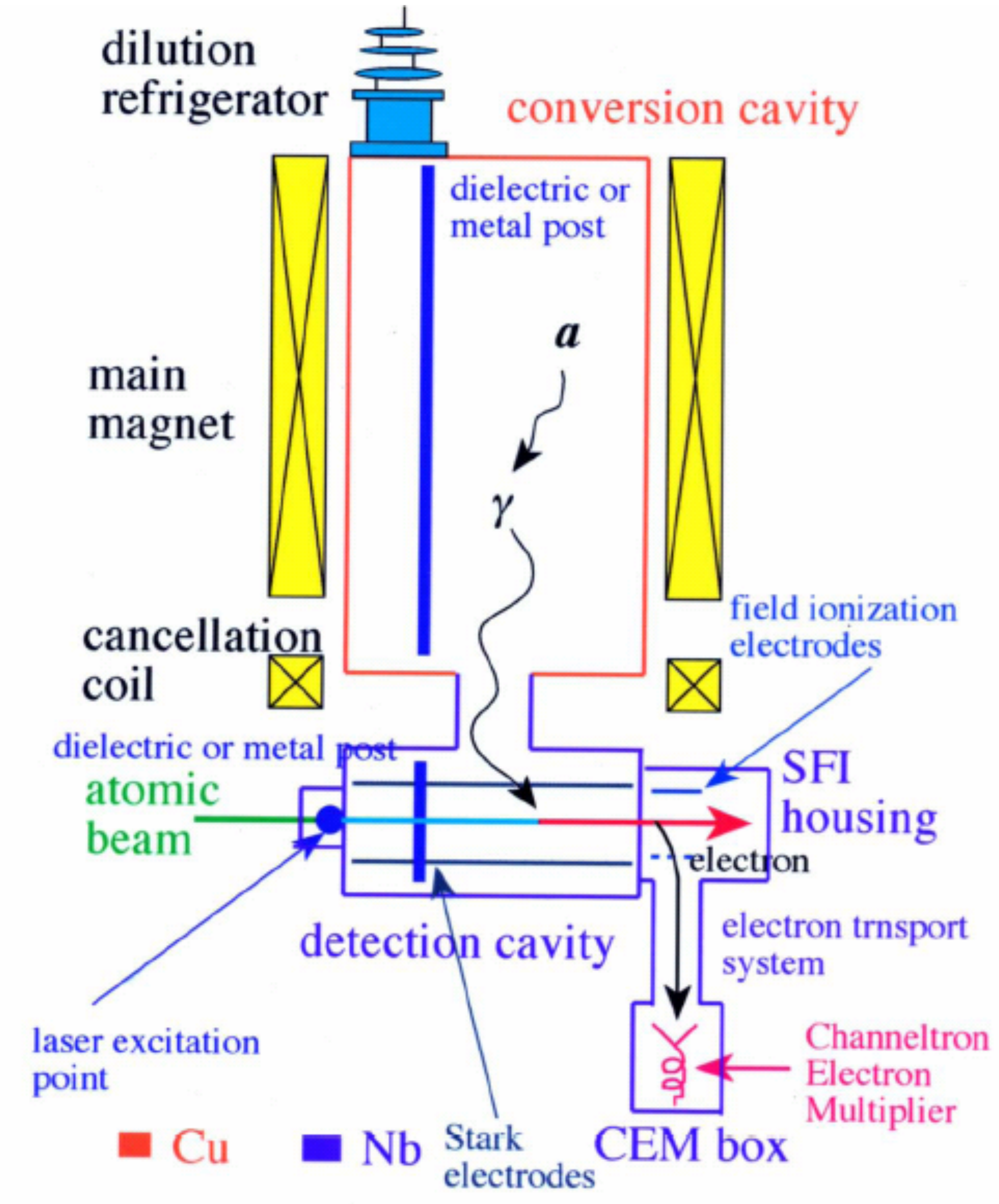


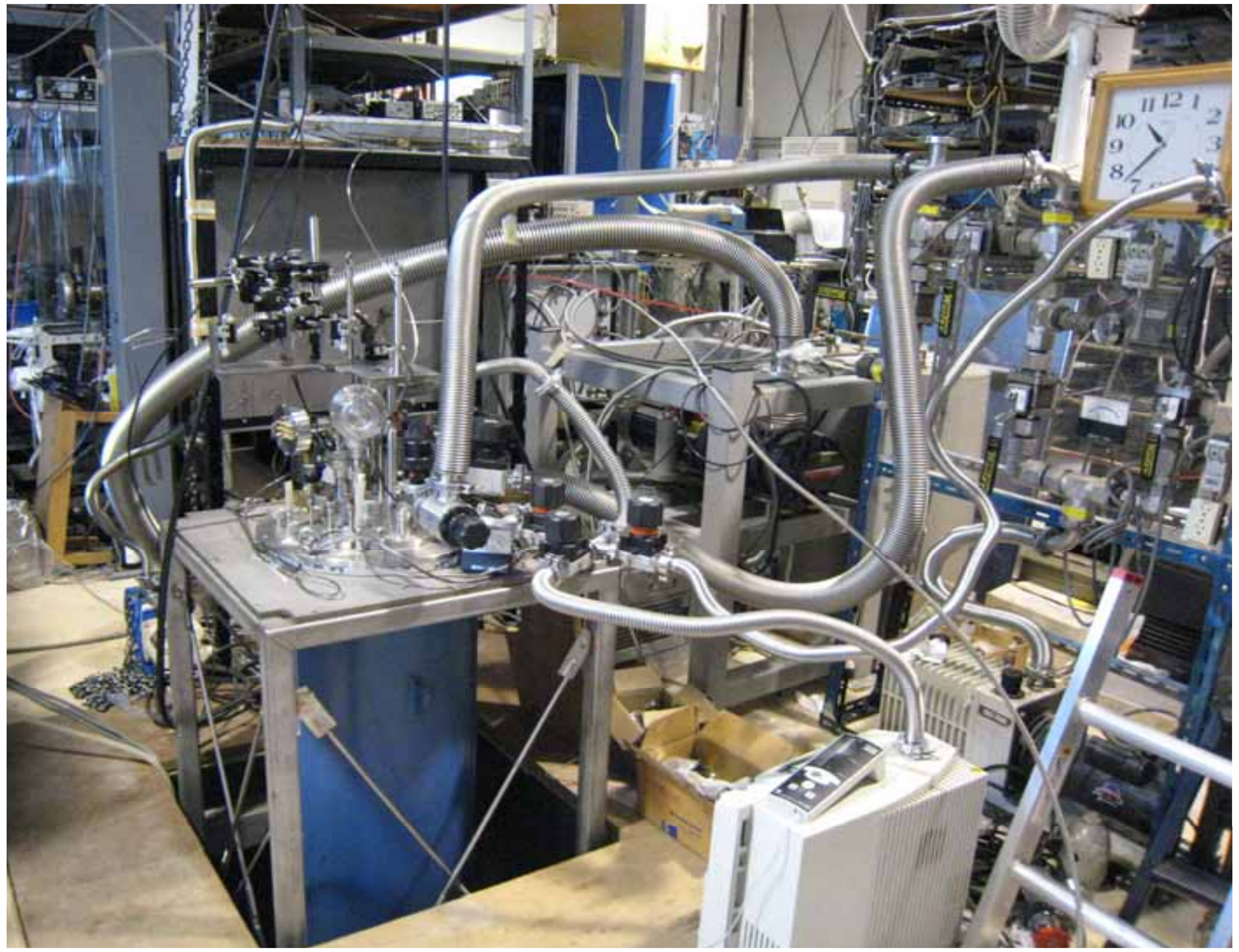
alternative: $4S - 4P_{3/2} - nS$
@767 nm, 457 nm



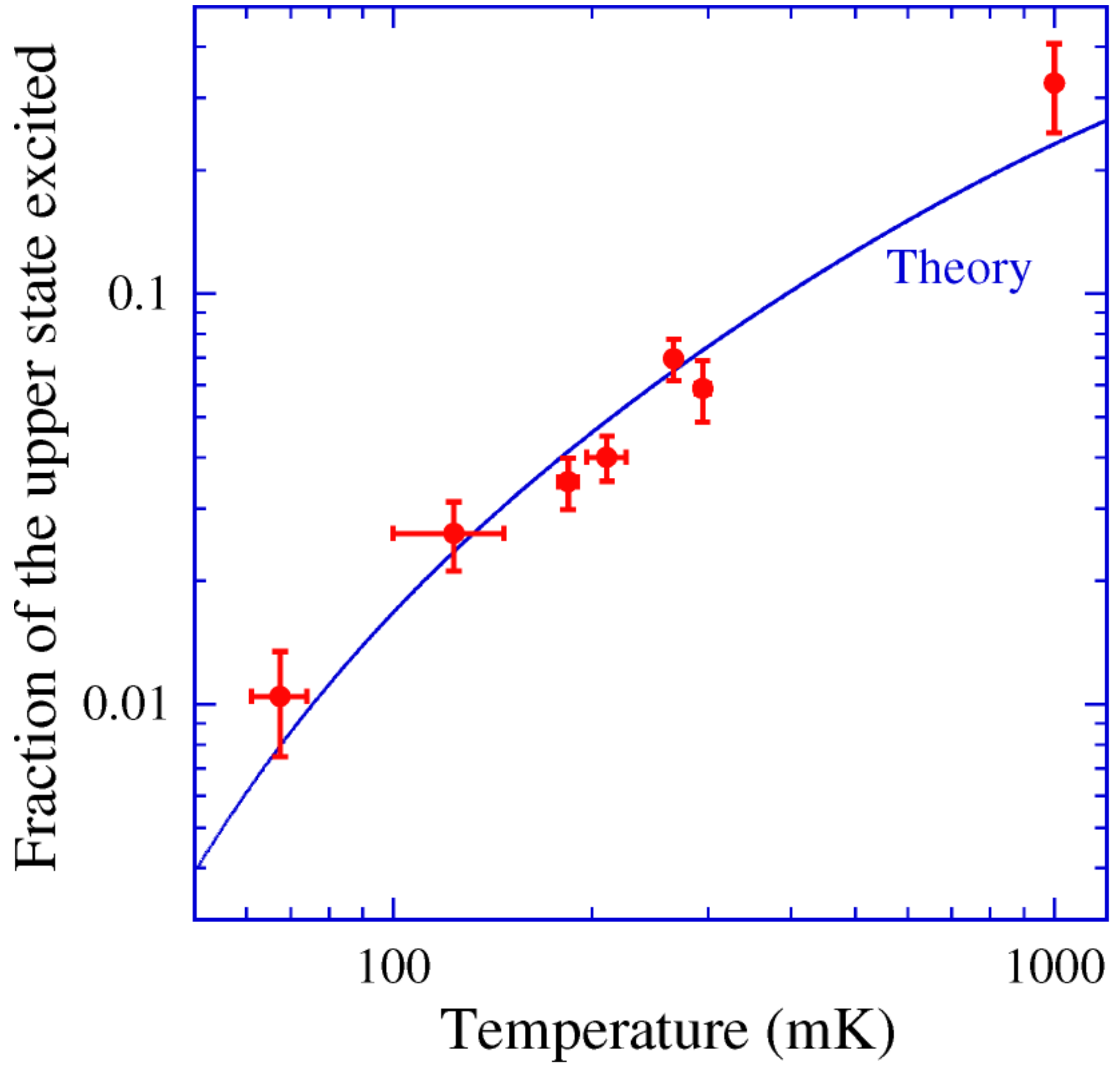
CARRACK

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

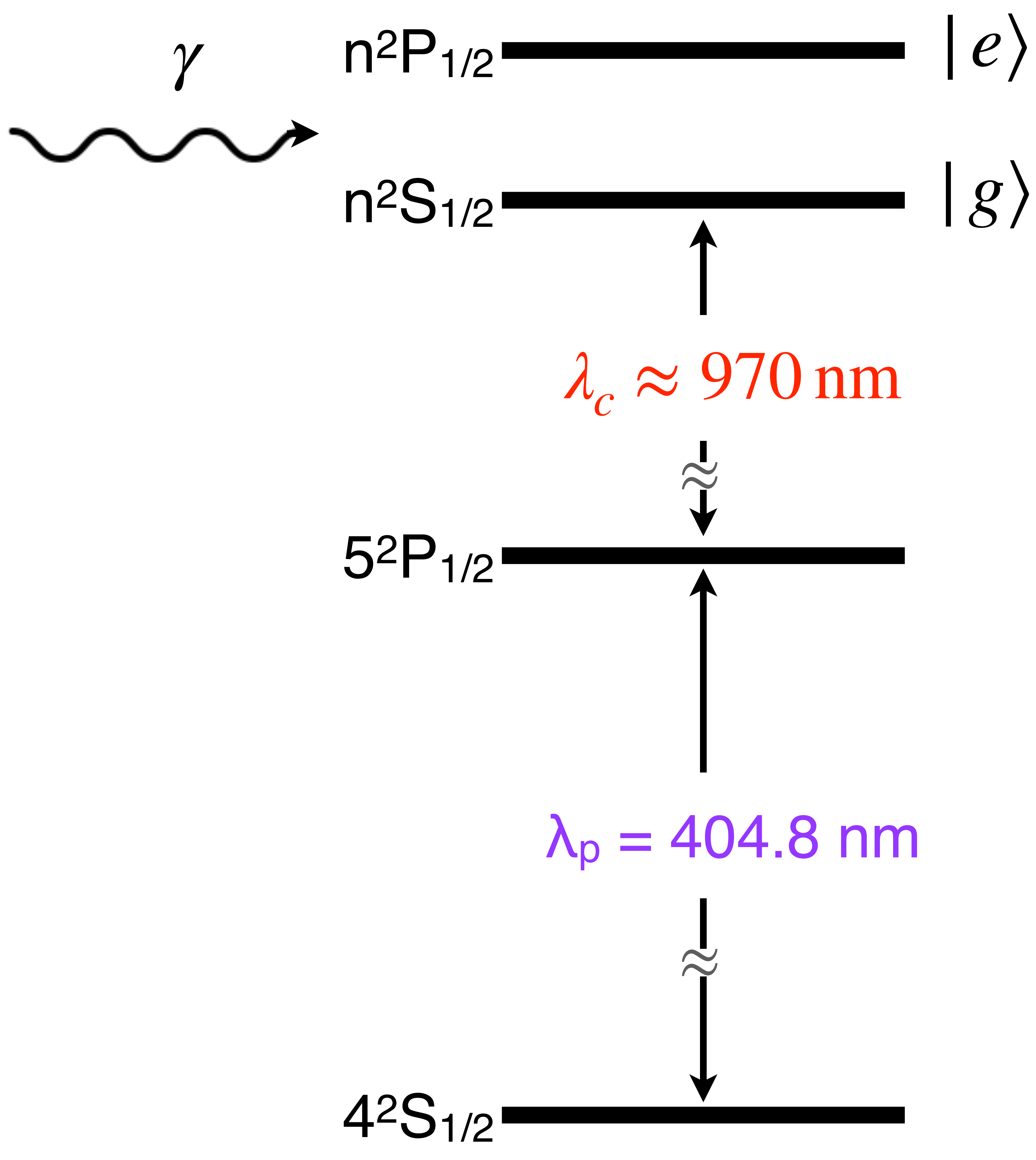




Black body radiation

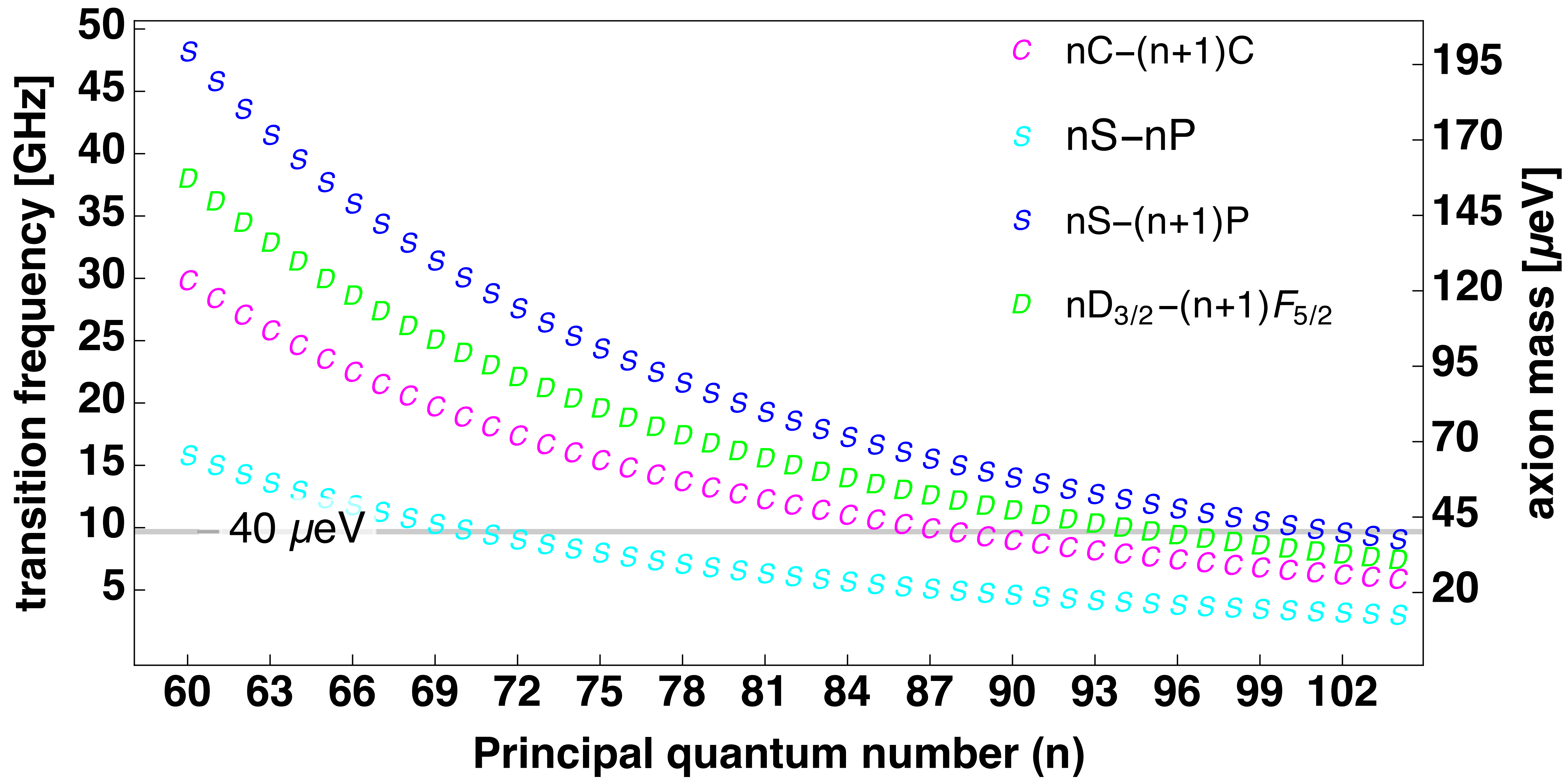


"Tuning" Rydberg atoms



Coarse-tuning: *n* Fine-tuning: Zeeman/Stark

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

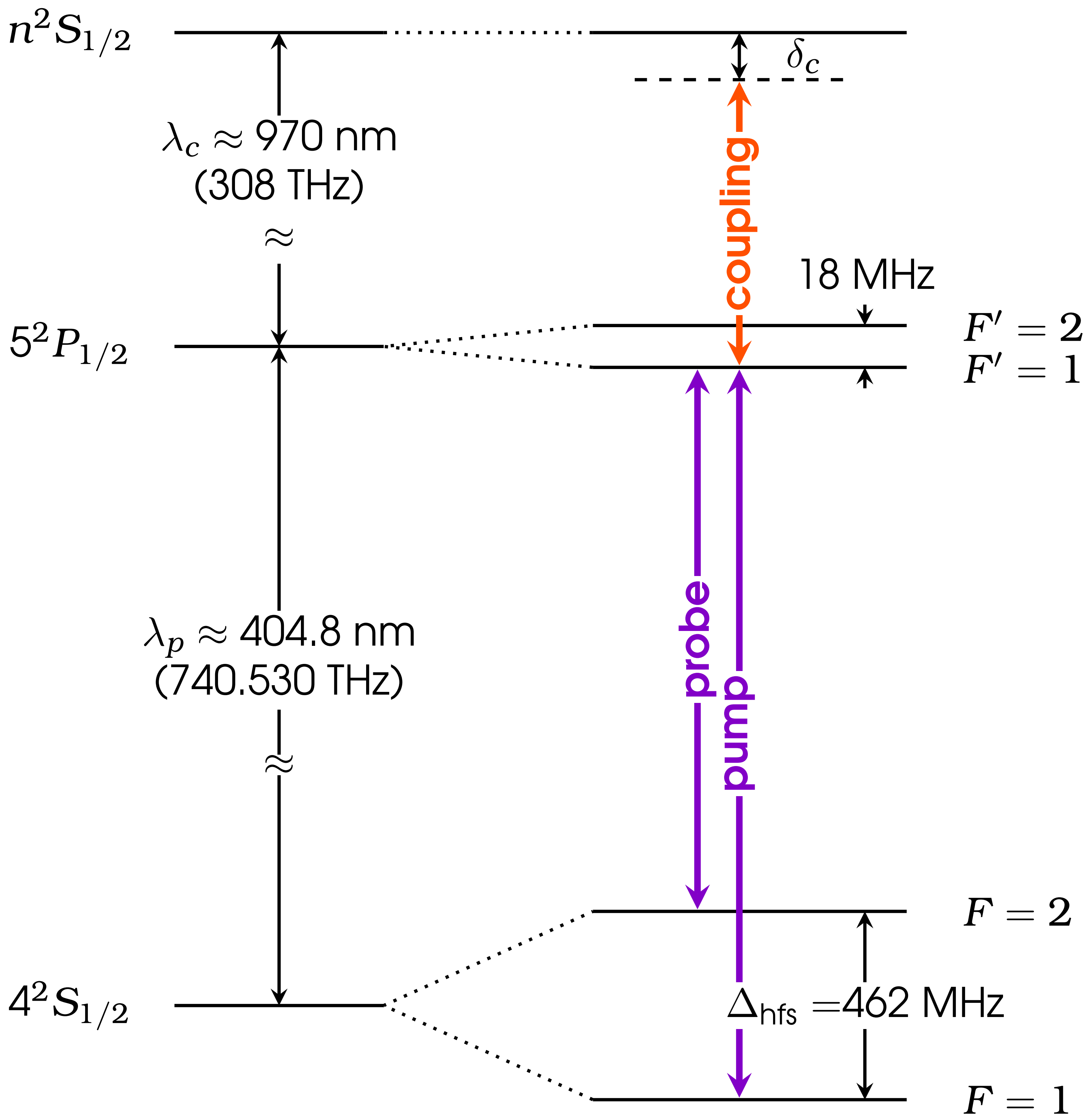


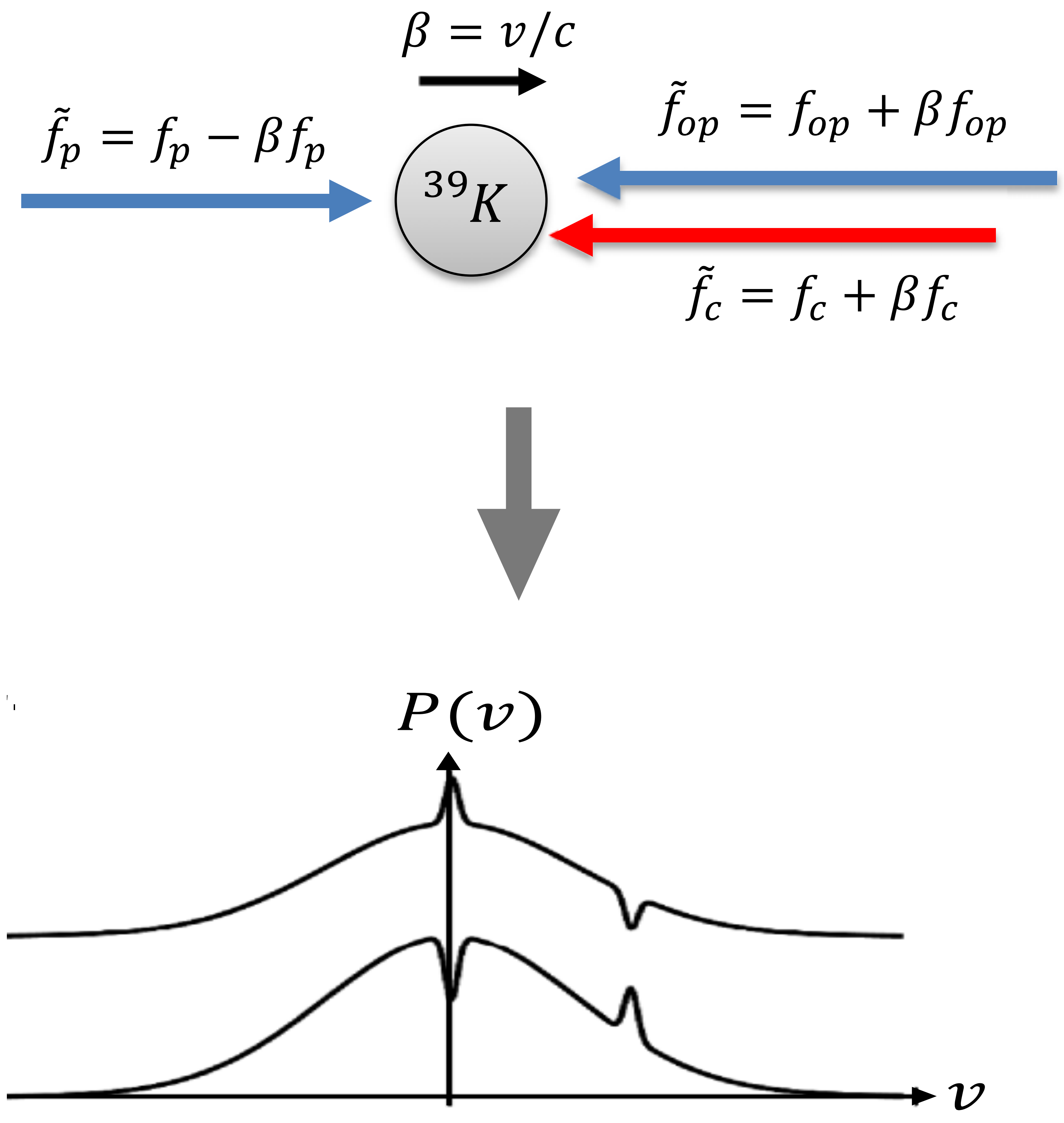
For m_a = 40 μeV ≈ 10 GHz*:

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

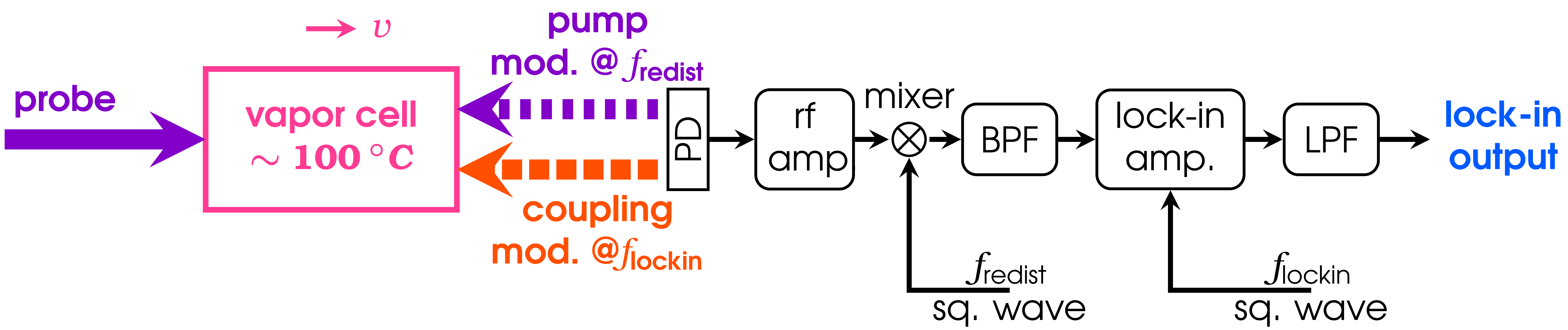
Rydberg spectroscopy

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

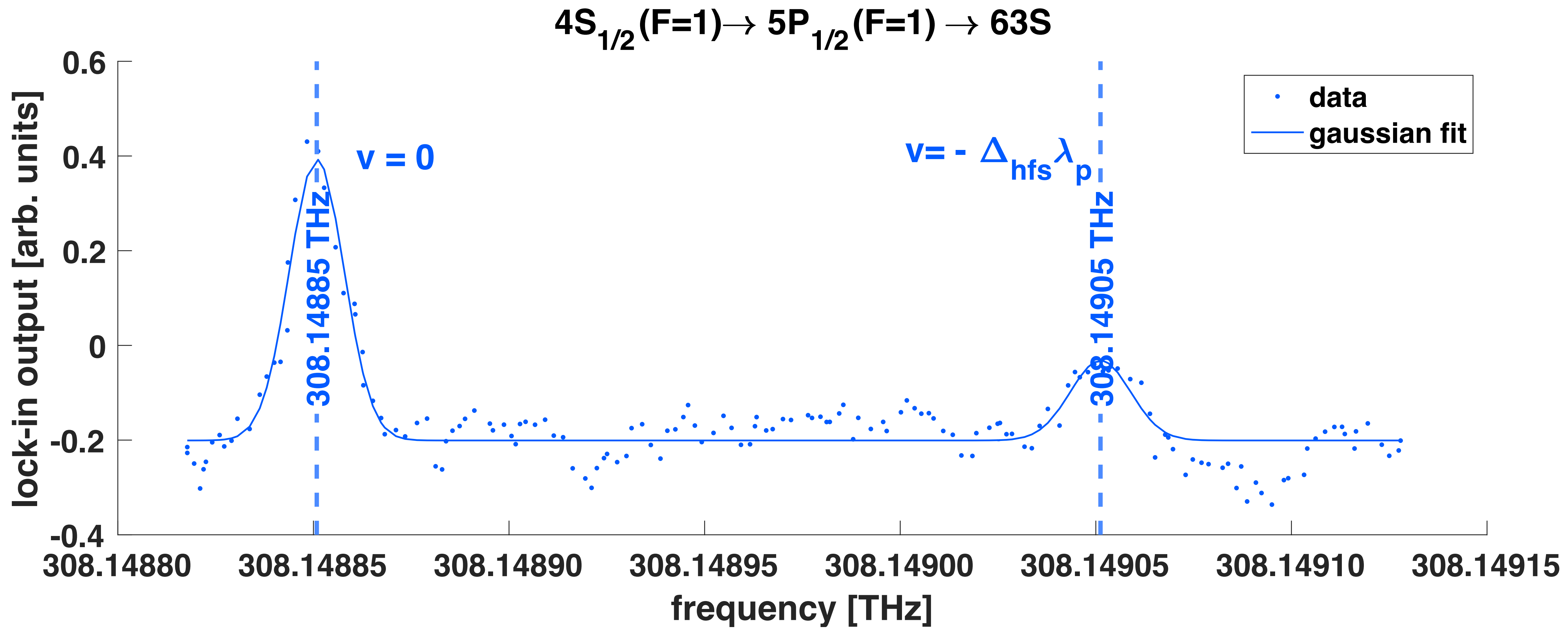




EIT Setup

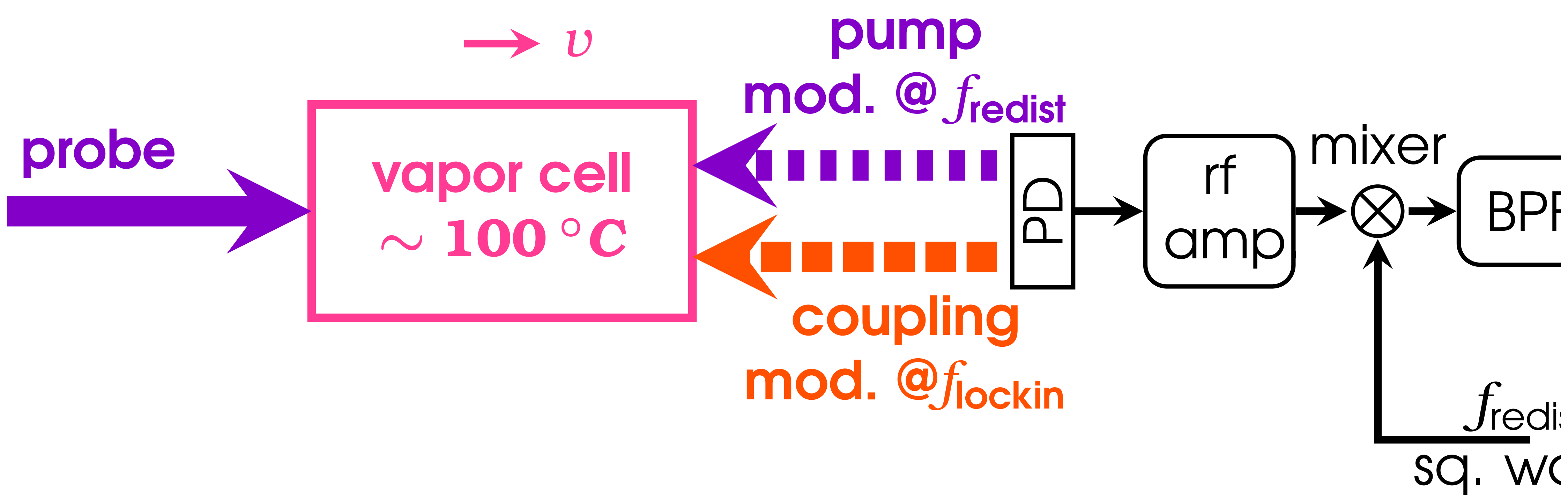


→ v
pump
mod. @ f_{redist}
probe
vapor cell
~ 100 °C
coupling
mod. @f_{lockin}
PD
rf
amp
mixer
BPF
lock-in
amp.
LPF
lock-in
output
f_{redist}
sq. wave
f_{lockin}
sq. wave

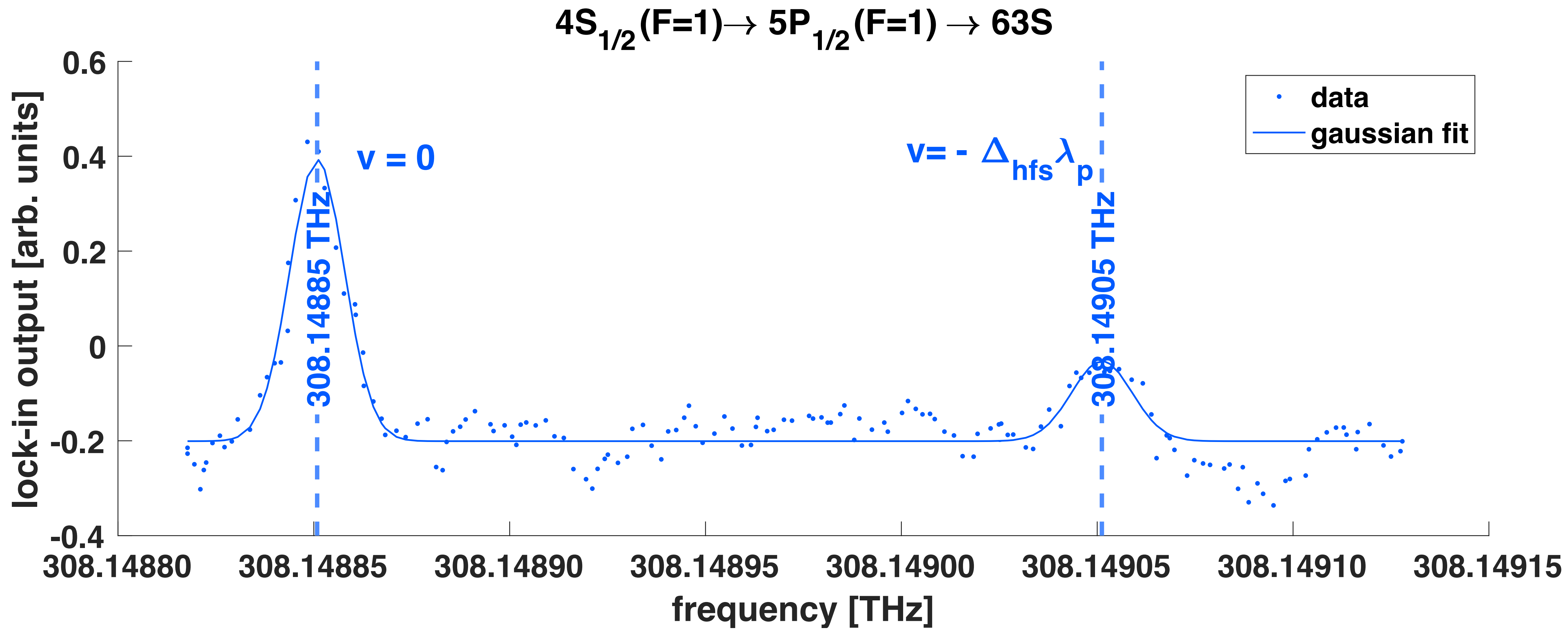


$4S_{1/2}(F=1) \rightarrow 5P_{1/2}(F=1) \rightarrow 63S$
lock-in output [arb. units]
0.6
0.4
0.2
0
-0.2
-0.4
v = 0
v= - $\Delta_{hfs}\lambda_p$
308.14885 THz
308.14905 THz
data
gaussian fit
308.14880
308.14885
308.14890
308.14895
308.14900
308.14905
308.14910
308.14915
frequency [THz]

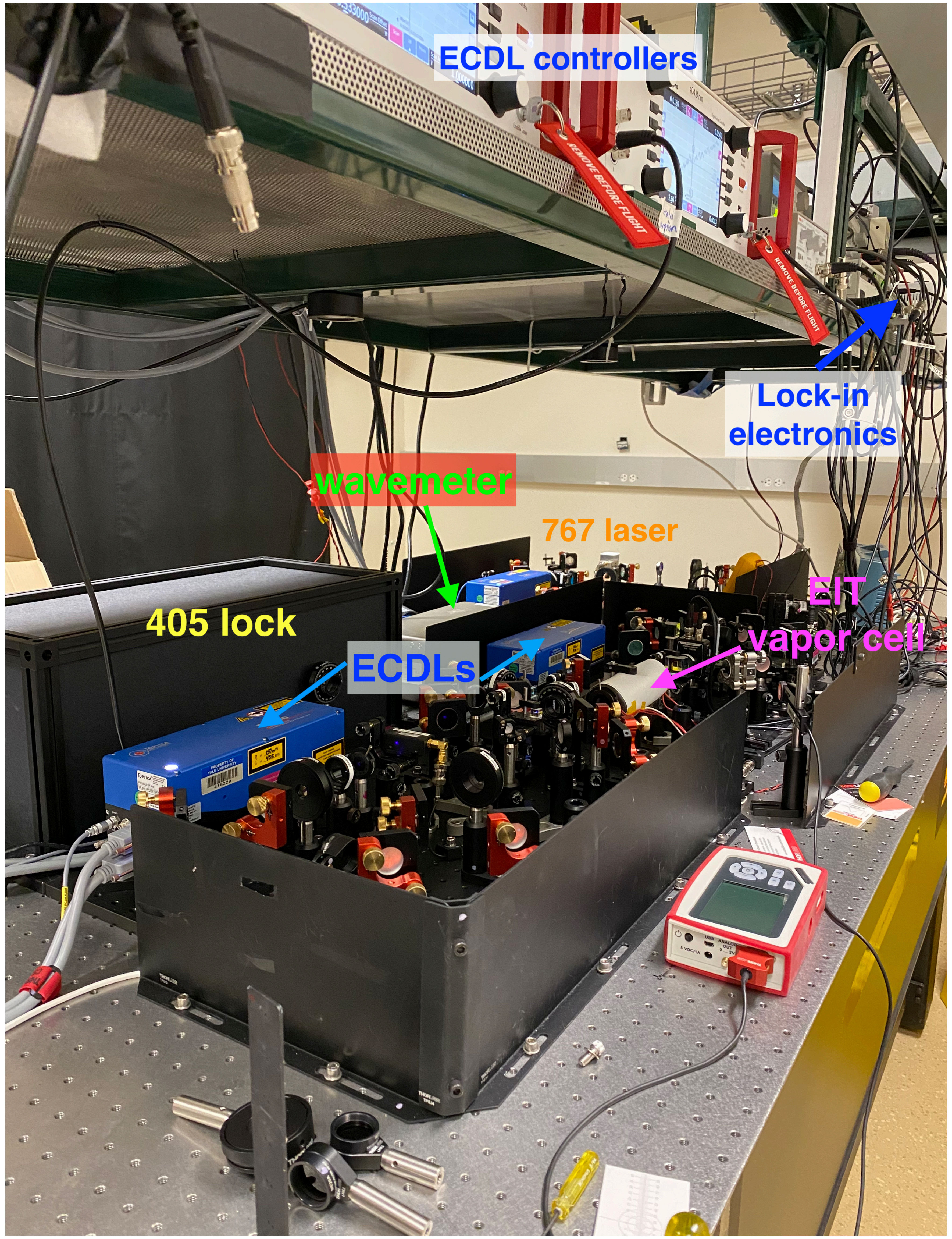
EIT Setup



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



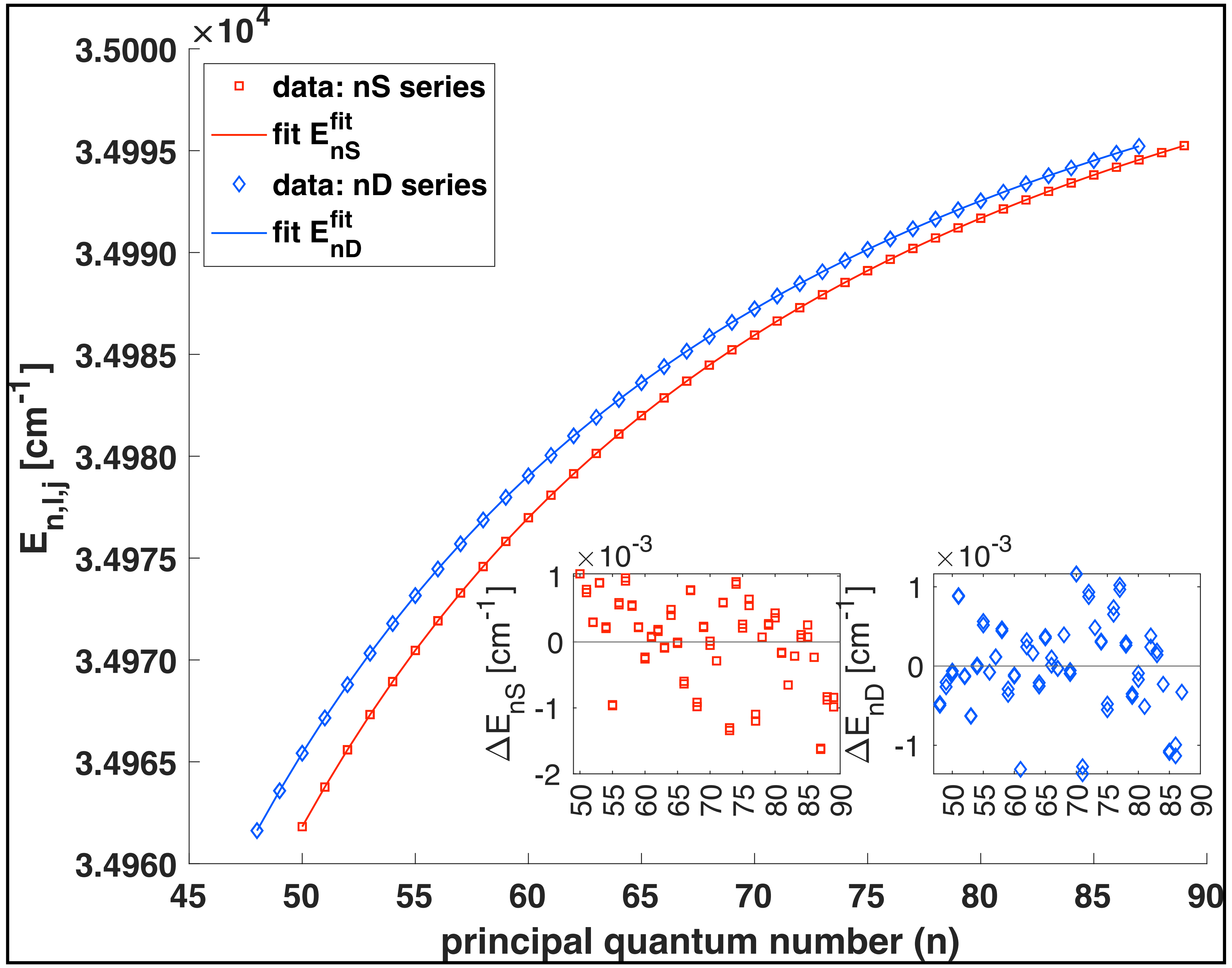
$4S_{1/2}(F=1) \rightarrow 5P_{1/2}(F=1) \rightarrow 63S$
lock-in output [arb. units]
0.6
0.4
0.2
0
-0.2
-0.4
v = 0
v= - $\Delta_{hfs}\lambda_p$
308.14885 THz
308.14905 THz
data
gaussian fit
308.14880
308.14885
308.14890
308.14895
308.14900
308.14905
308.14910
308.14915
frequency [THz]



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

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