Quantum Sensing with Rydberg atoms

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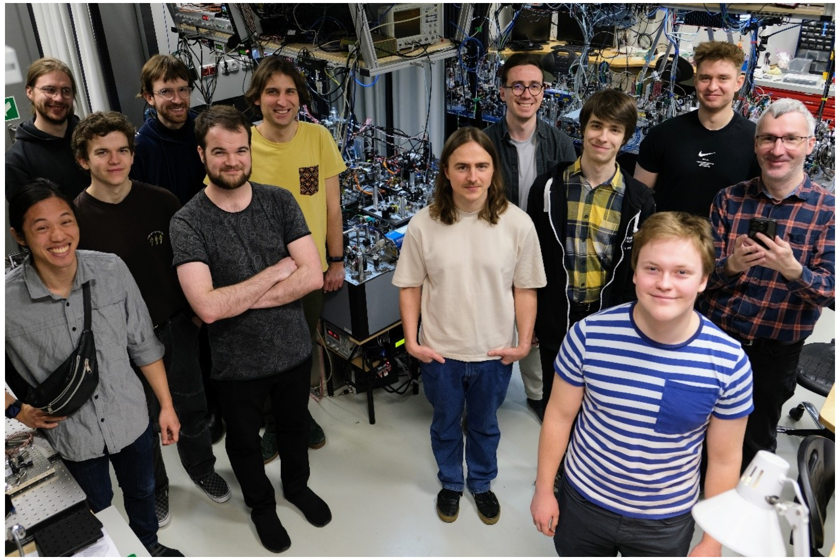
CeNT QOD LAB QOT CENTRE FOR QUANTUM OPTICAL TECHNOLOGIES WYDZIAŁ FIZYKI UNIWERSYTET WARSZAWSKI UNIVERSITY OF WARSAW



www.qodl.eu – lab webpage

NATIONAL SCIENCE CENTRE POLAND

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FENG.02.01-IP.05-0017/23

Sympozjum IFD | Wydział Fizyki UW | 5 grudnia 2025

Michał Parniak

2012-2018

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

UNIVERSITY OF WARSAW

Cold atoms (MOT),
Quantum memories,
Quantum information

2018-2021

Niels Bohr Institutet

UNIVERSITY OF COPENHAGEN

Cavity quantum optomechanics,
hot atoms

2021-

QOT CENTRE FOR QUANTUM OPTICAL TECHNOLOGIES

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Rydberg atoms (hot/cold),
analog optical quantum signal processors (e.g. for superresolution spectroscopy)

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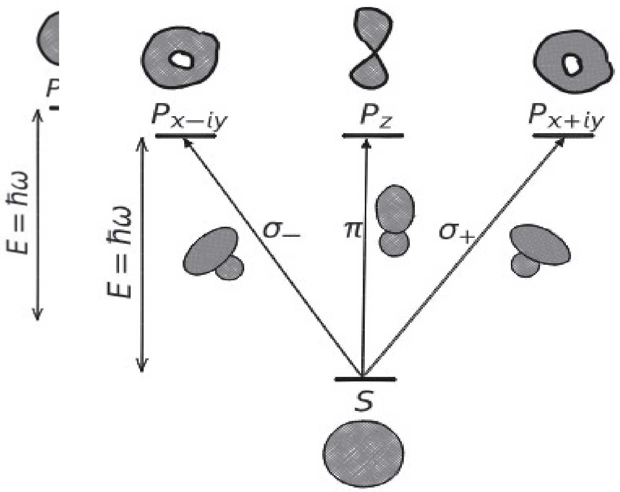
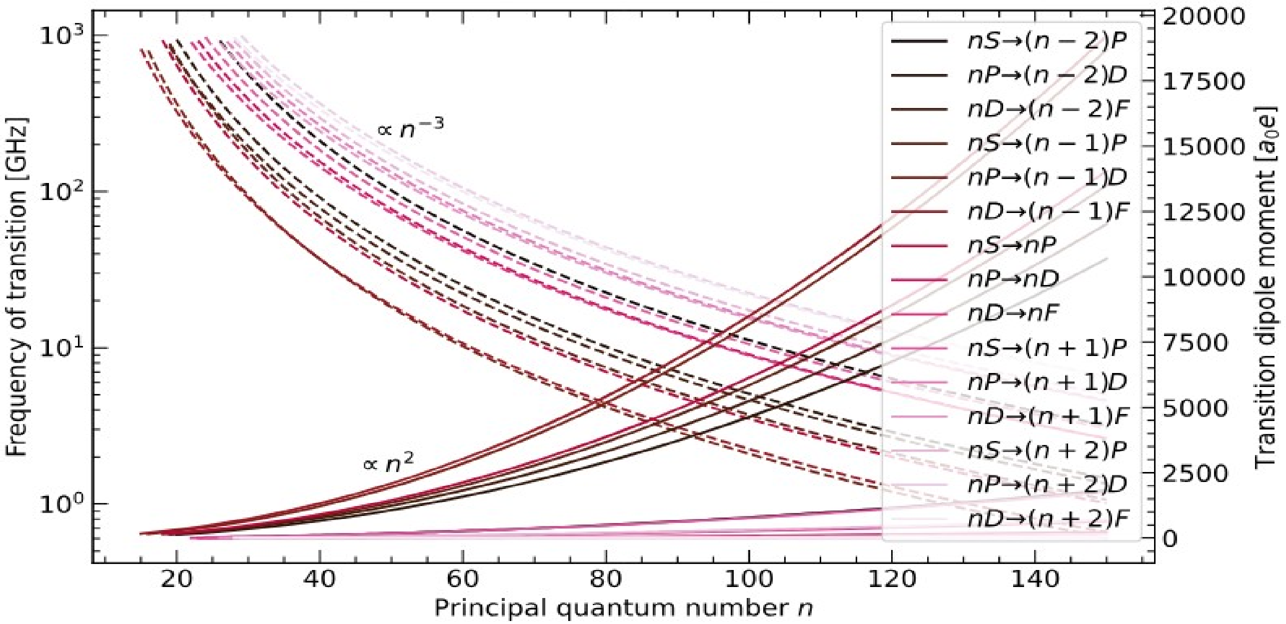
Rydberg atoms

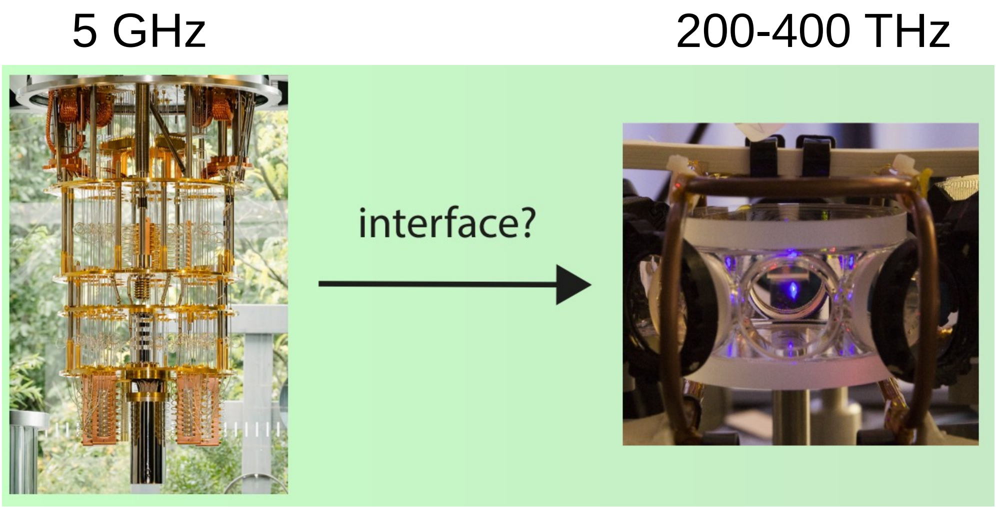
Rydberg atoms

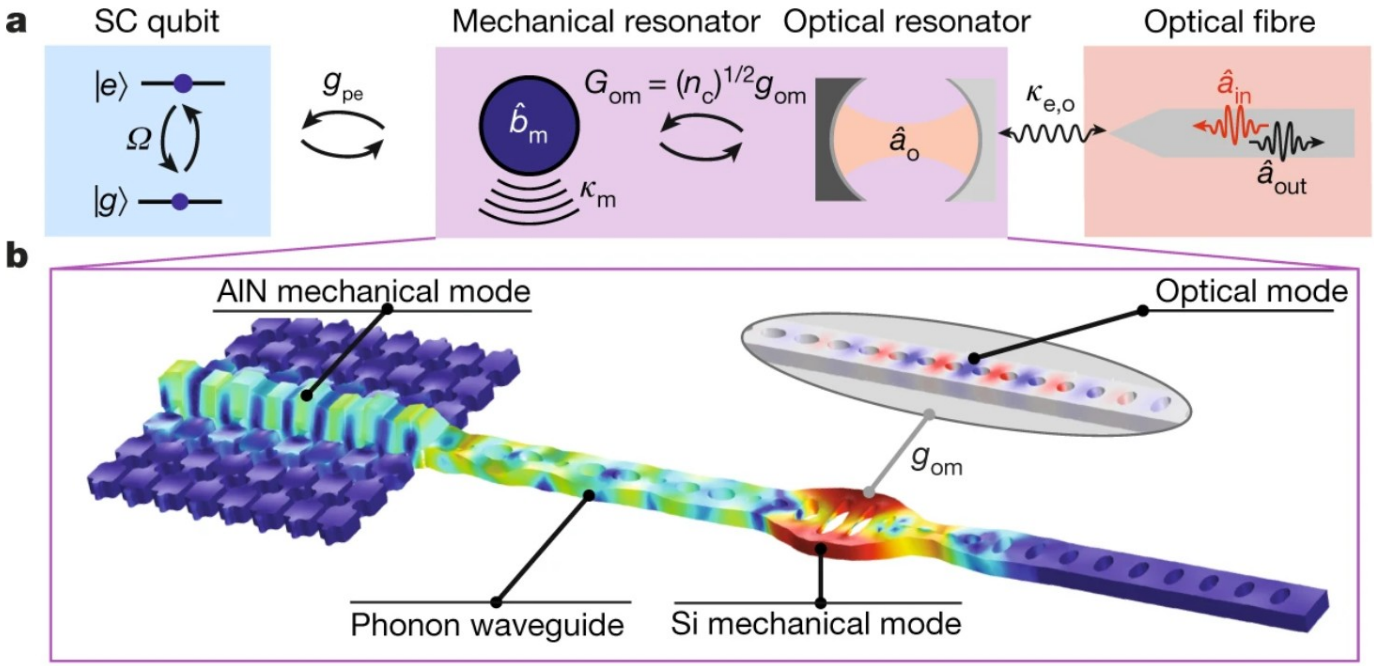
- large principal quantum numbers n ≈ 15-100+
- long state lifetimes τ ≈ 15-200 µs
- long interaction radii ~µm
- microwave (and mm-wave) energy levels transitions Δf ≈ 1000-2 GHz





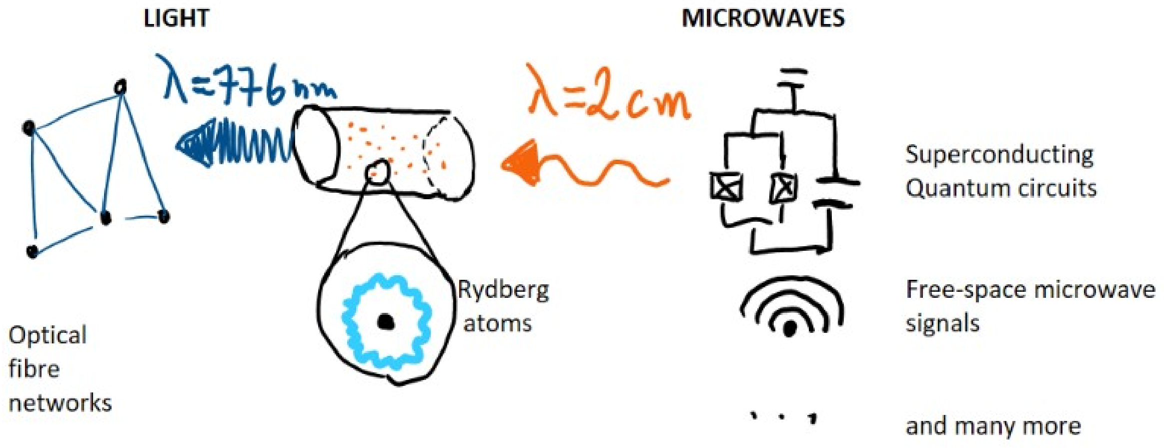
Microwave-optical interface – our original motivation

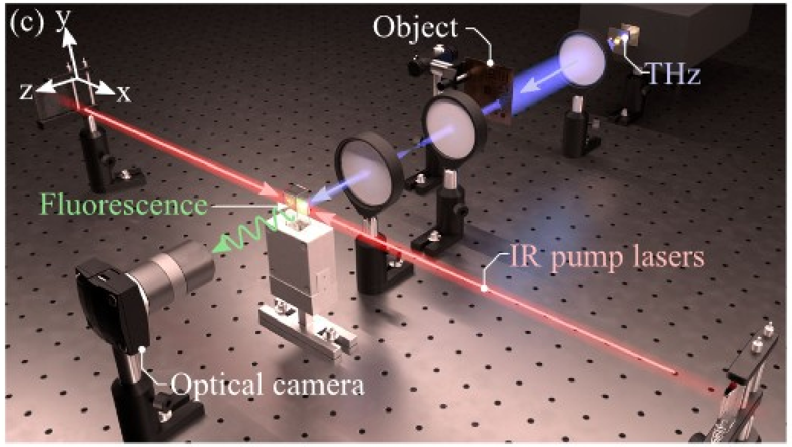




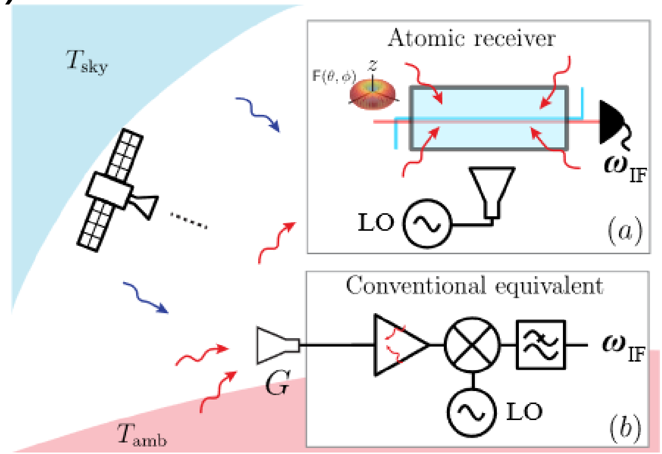
M. Mirhosseini et al. *Nature* **588**, 599–603 (2020)

From transduction to near-term applications





L. A. Downes et al., Phys Rev X 10, 011027 (2020) (Durham)



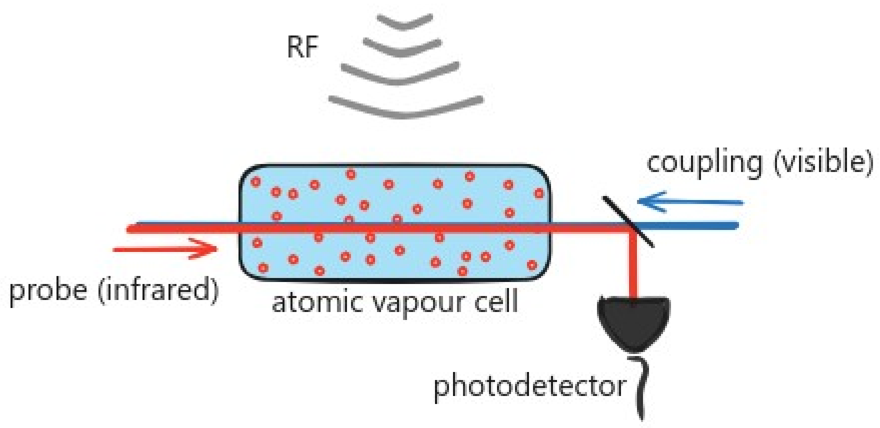
G. Santamaria Botello et al., arXiv:2209.00908 (CU Boulder)

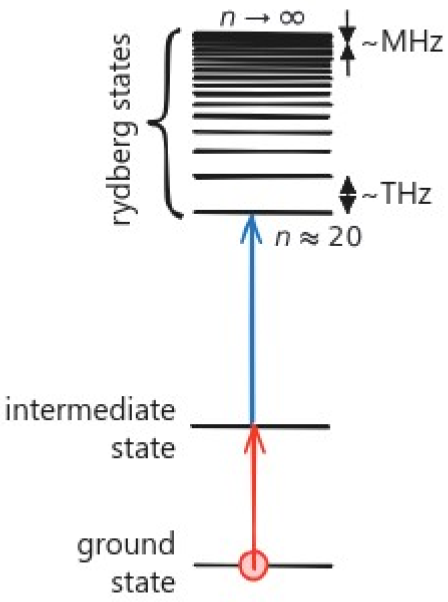
Rydberg electrometry

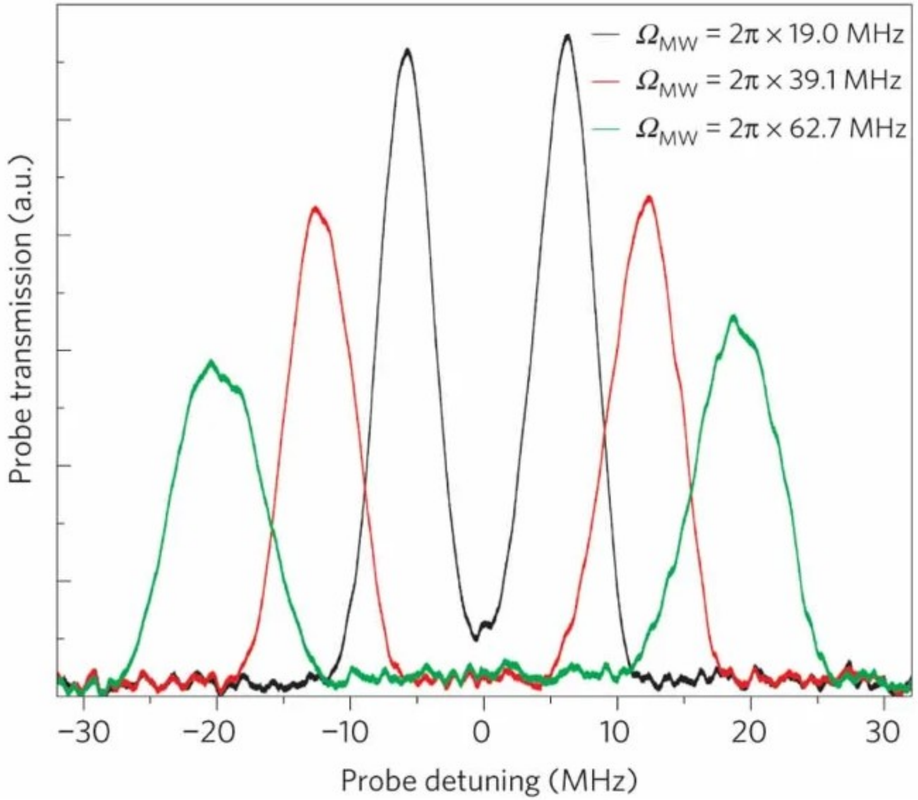
Frequency splitting
- Rabi frequency - **measured with respect to a frequency reference**

$$\Omega = \frac{d_x E_0}{\hbar}$$

Electric field amplitude **E**
Dipole moment **d**



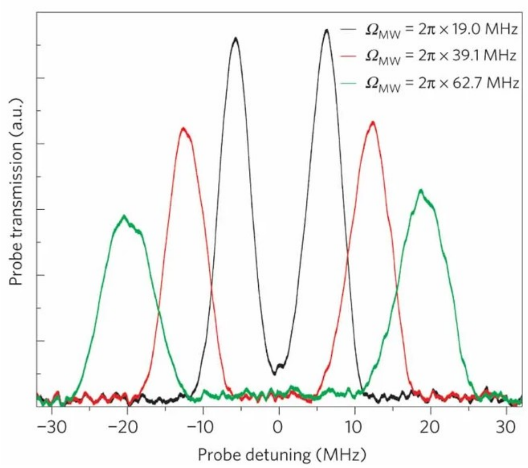




Sedlacek et al., Nature Physics **8**, 819–824 (2012) (Oklahoma/Stuttgart)

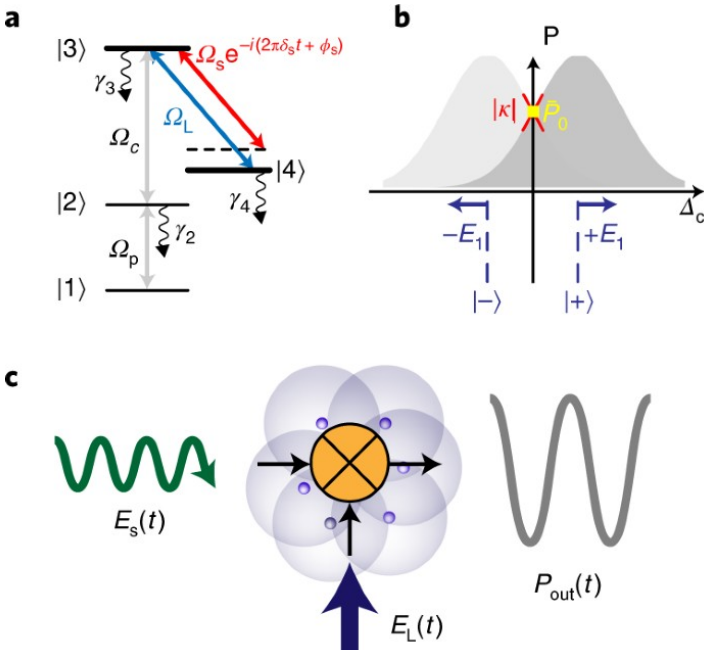
Modes of operation

Autler-Townes



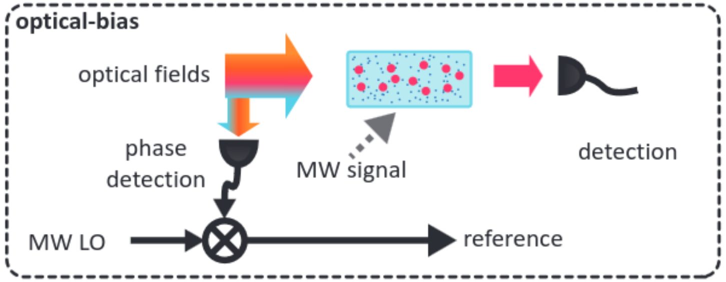
Nature Physics **8**, 819–824 (2012)

Superhet(erodyne)

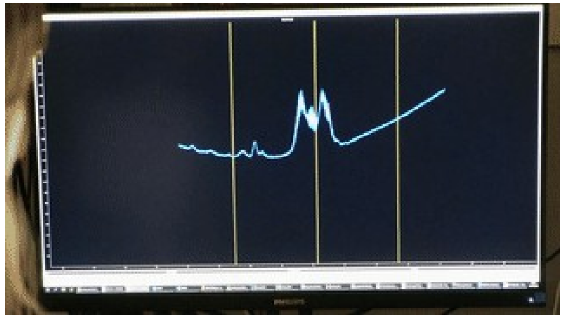


Nature Physics 16, pages 911–915 (2020)

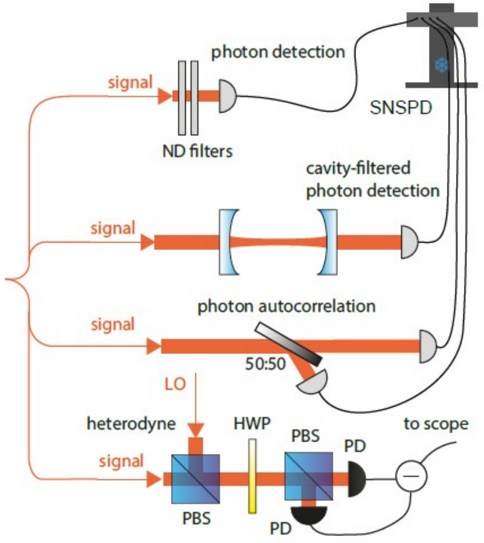
All-optical superhet



Nat. Commun. **16**, 8975 (2025)



Upconversion +photon counting

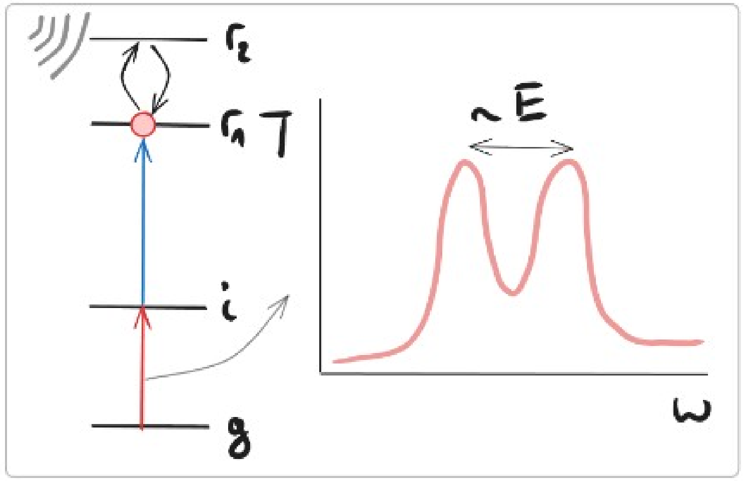


Nature Photonics **18**, 32-38 (2024)

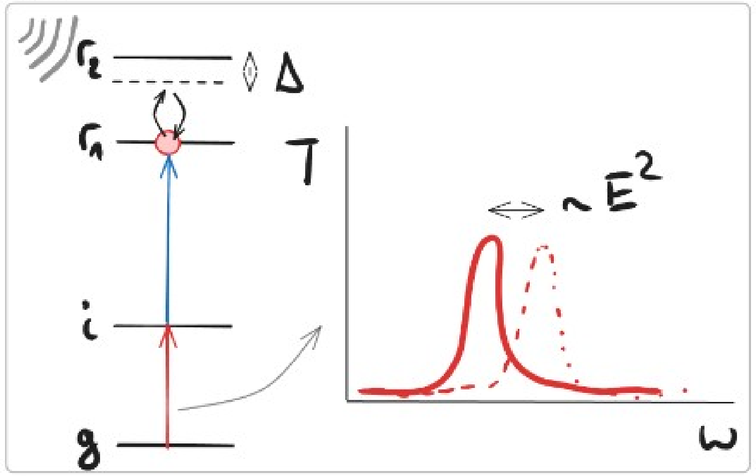
cf. Phys. Rev. A **93**, 042121

Modes of operation – upcoming whitepaper

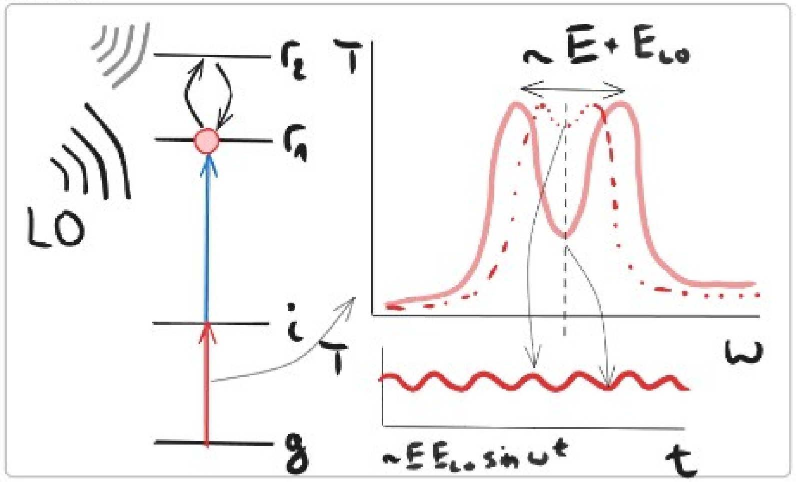
AT



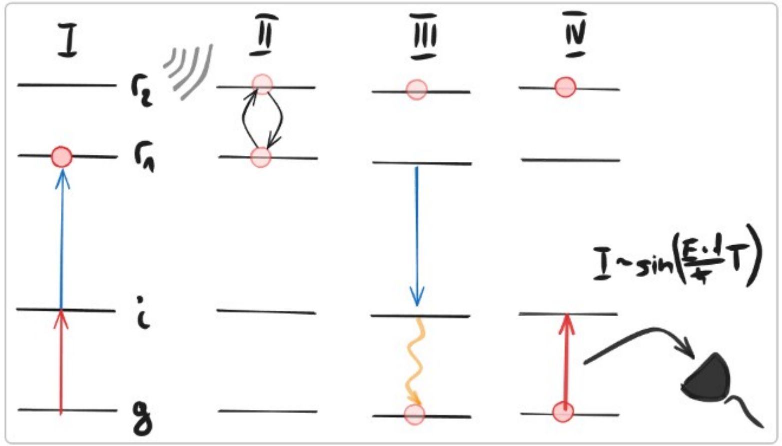
ACS Shift



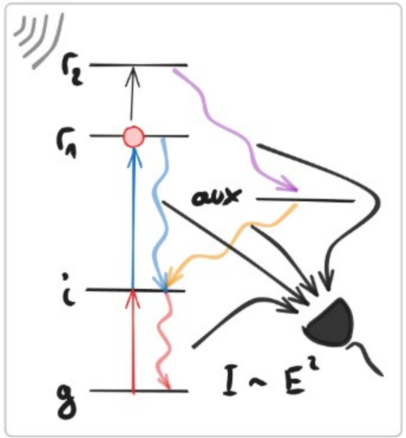
Superheterodyne



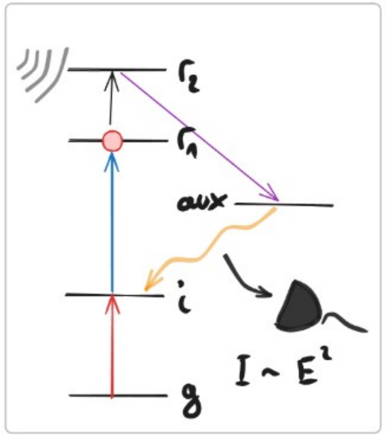
Direct Rabi



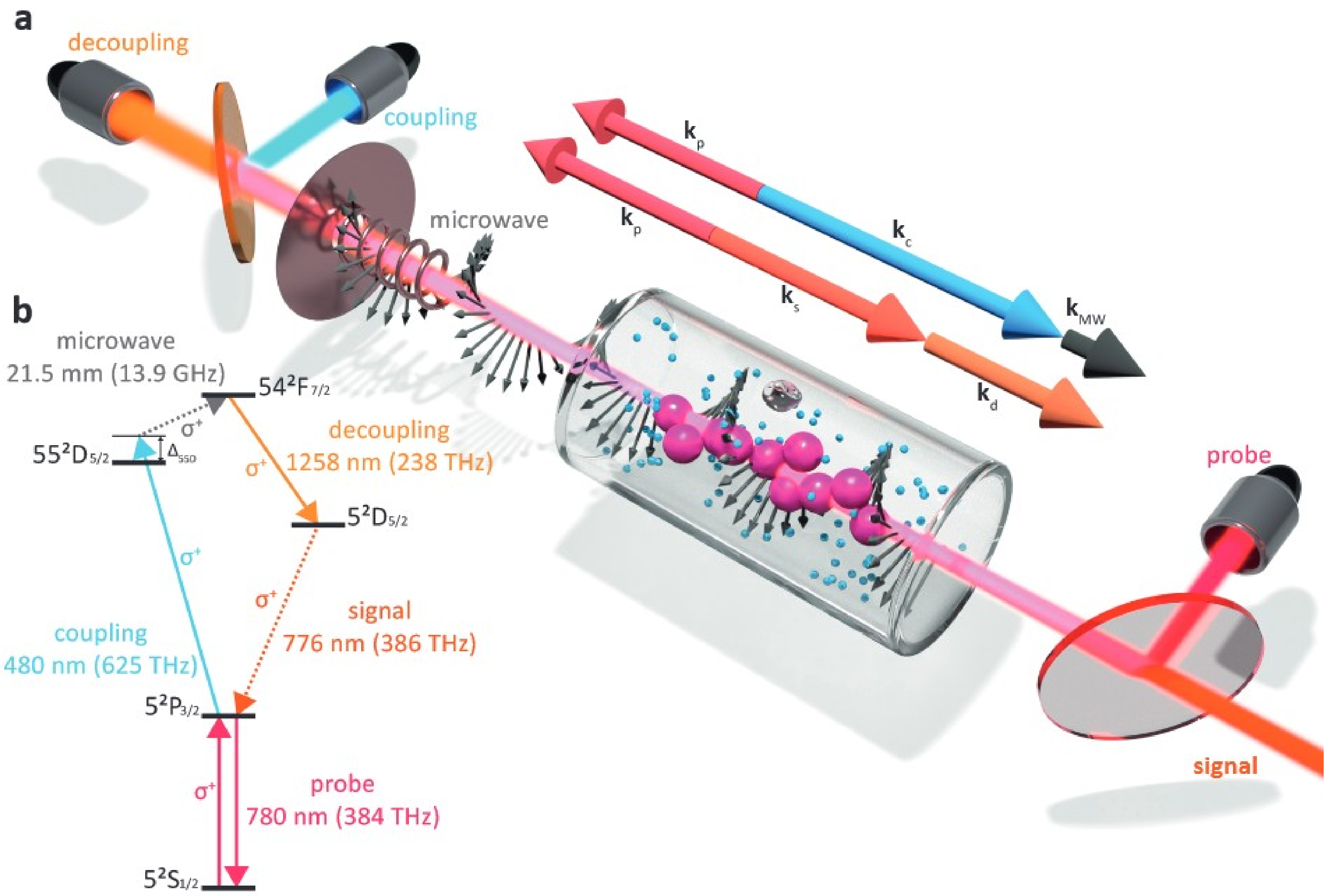
Fluorescence



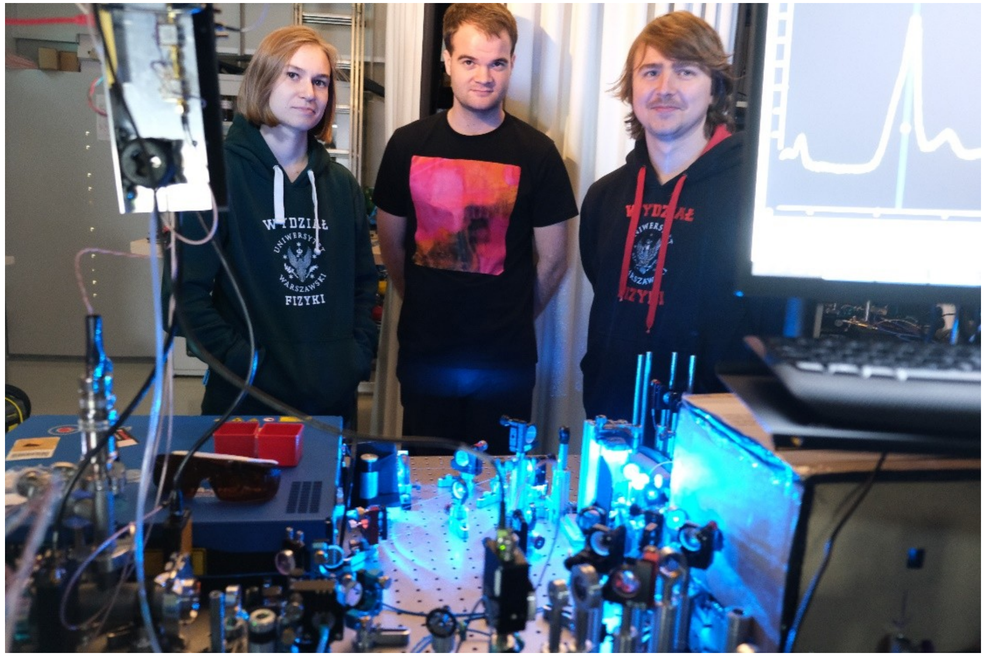
Conversion



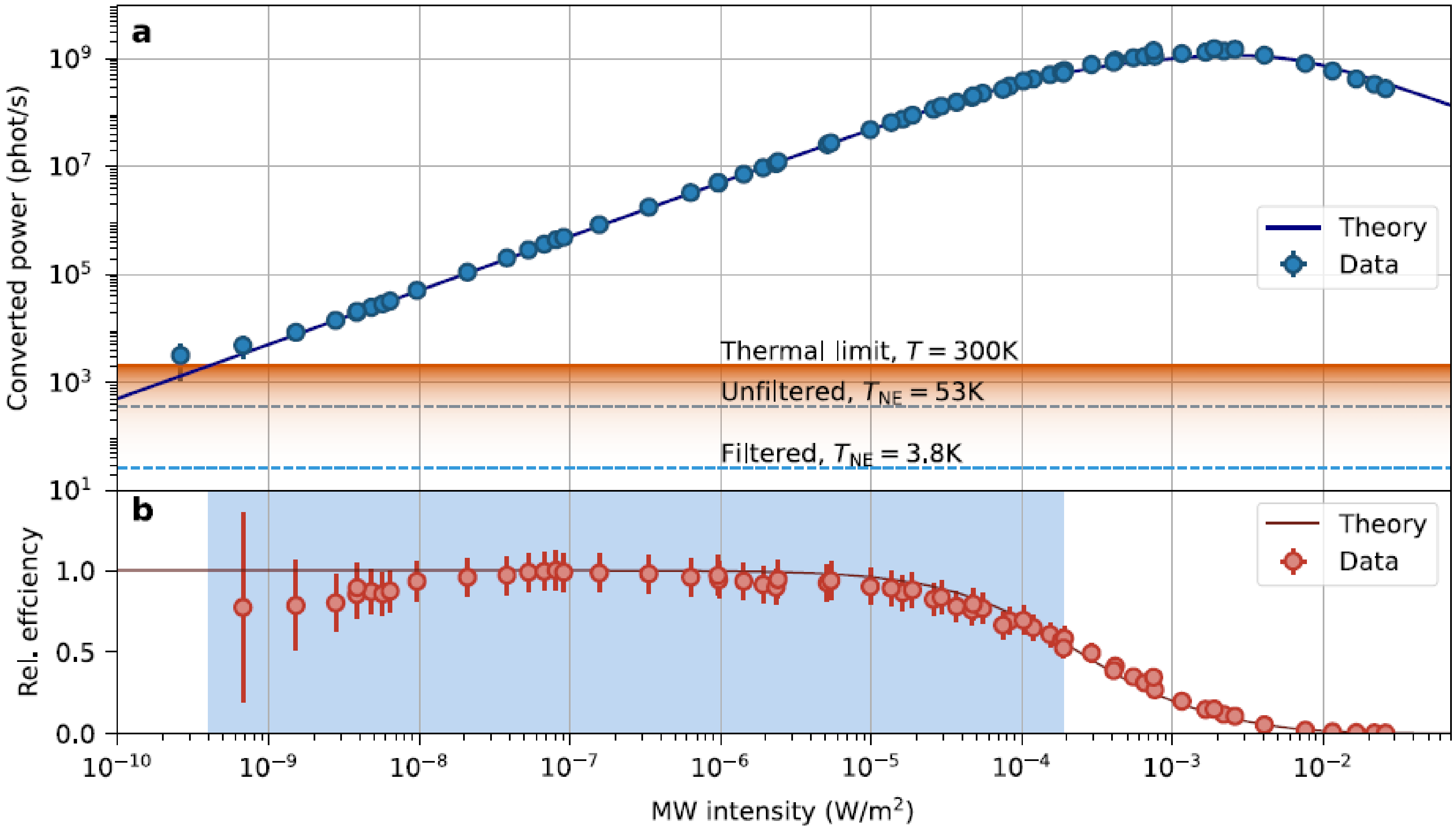
Microwave-to-optical conversion



S. Borówka,
U. Pylypenko, M. Mazelanik, **MP**,
Nature Photonics 18, 32-38 (2024)



Photon counting and efficiency



S. Borówka et al. *Continuous wideband microwave-to-optical converter based on room-temperature Rydberg atoms*, *Nat. Phot.* **18**, 32–38 (2024)

Approaching the thermal limit

Theoretical

4.11 $\mathrm{nVcm^{-1}Hz^{-1/2}}$

Measured

3.98 $\mathrm{nVcm^{-1}Hz^{-1/2}}$

Theory of black-body radiation

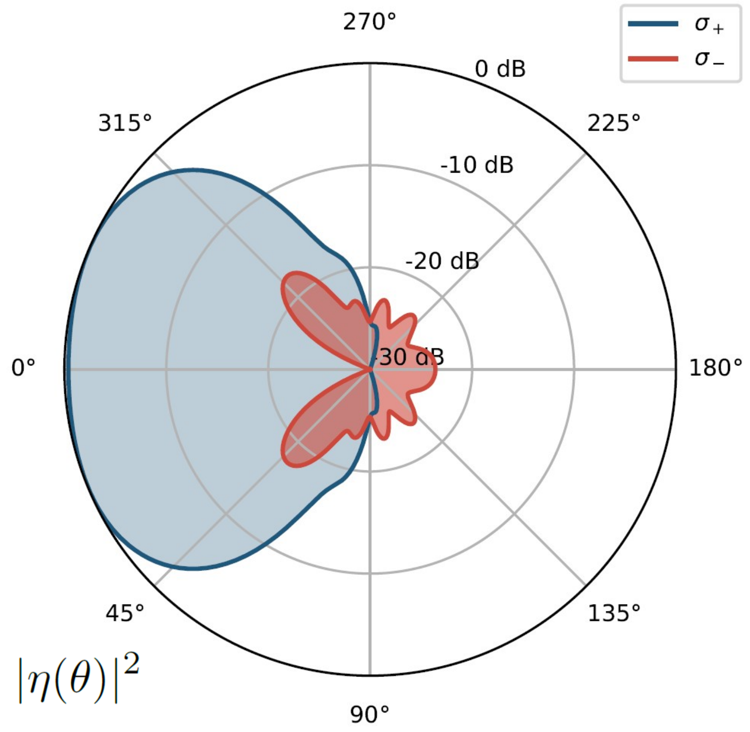
$$\langle E_{\mathrm{eff}}^2\rangle = \frac{\omega^2\langle\mathcal{E}\rangle}{\pi^2 c^3\varepsilon_0}\frac{1}{4\pi}\int_0^{2\pi}\mathrm{d}\phi\int_0^{\pi}\mathrm{d}\theta\,\sin(\theta)|\eta(\theta)|^2,$$

$$\langle\mathcal{E}\rangle = \frac{\hbar\omega}{e^{\hbar\omega/k_{\mathrm{B}}T}-1},$$

$$|\eta(\theta)|^2 = \left(\cos\left(\frac{\theta}{2}\right)^4 + \sin\left(\frac{\theta}{2}\right)^4\right)|\eta_{\mathrm{phm}}(\theta)|^2.$$

Polarization

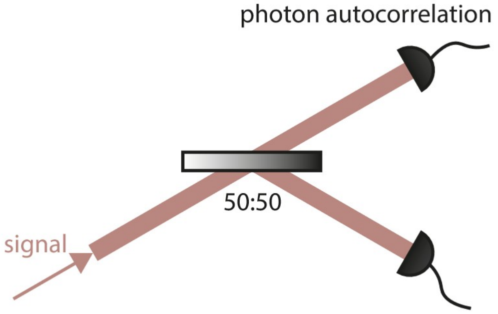
Phase matching

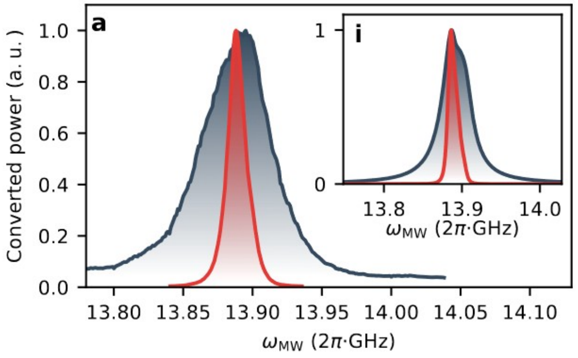


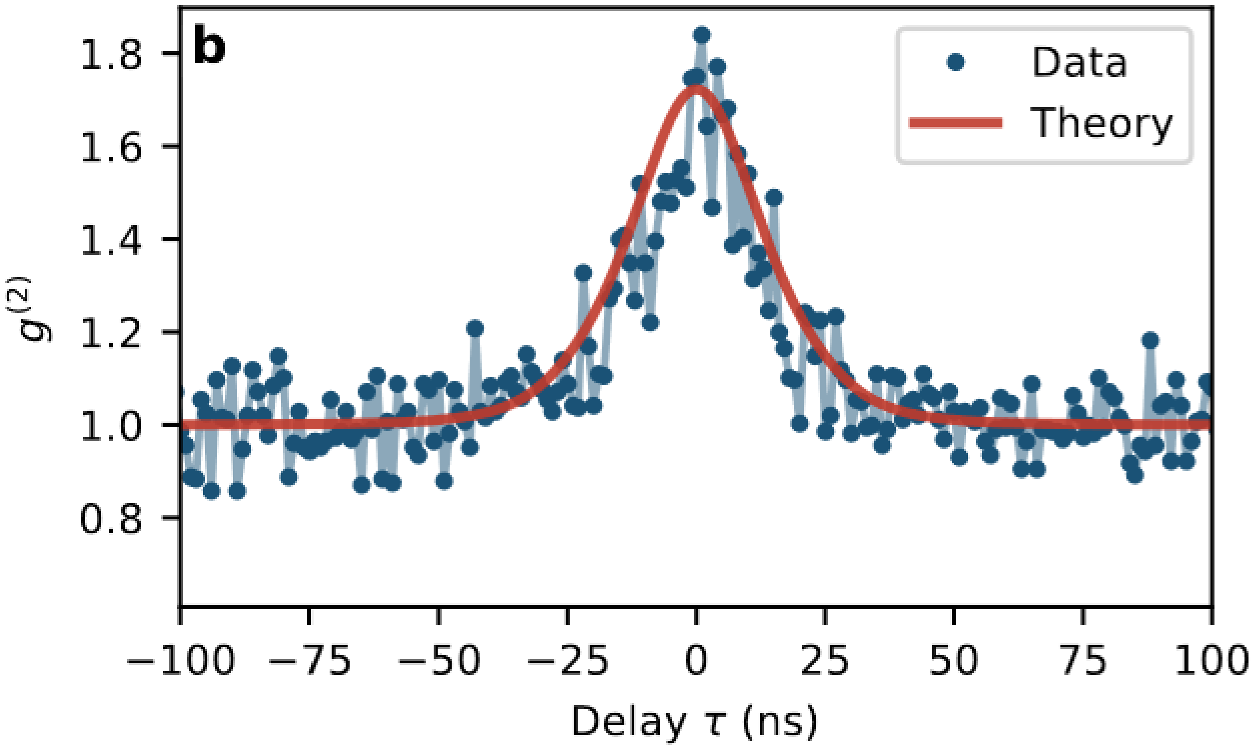
$|\eta(\theta)|^2$

S. Borówka et al. *Continuous wideband microwave-to-optical converter based on room-temperature Rydberg atoms*, *Nat. Phot.* **18**, 32–38 (2024)

Second-order correlation







Wiener-Khinchin theorem!

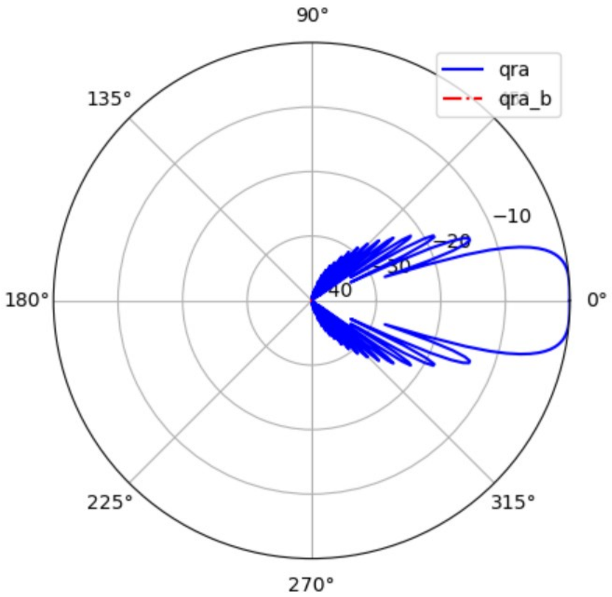
$$g_{\text{th}}^{(1)}(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |S(\omega)|^2 e^{-i\omega\tau}\mathrm{d}\omega,$$

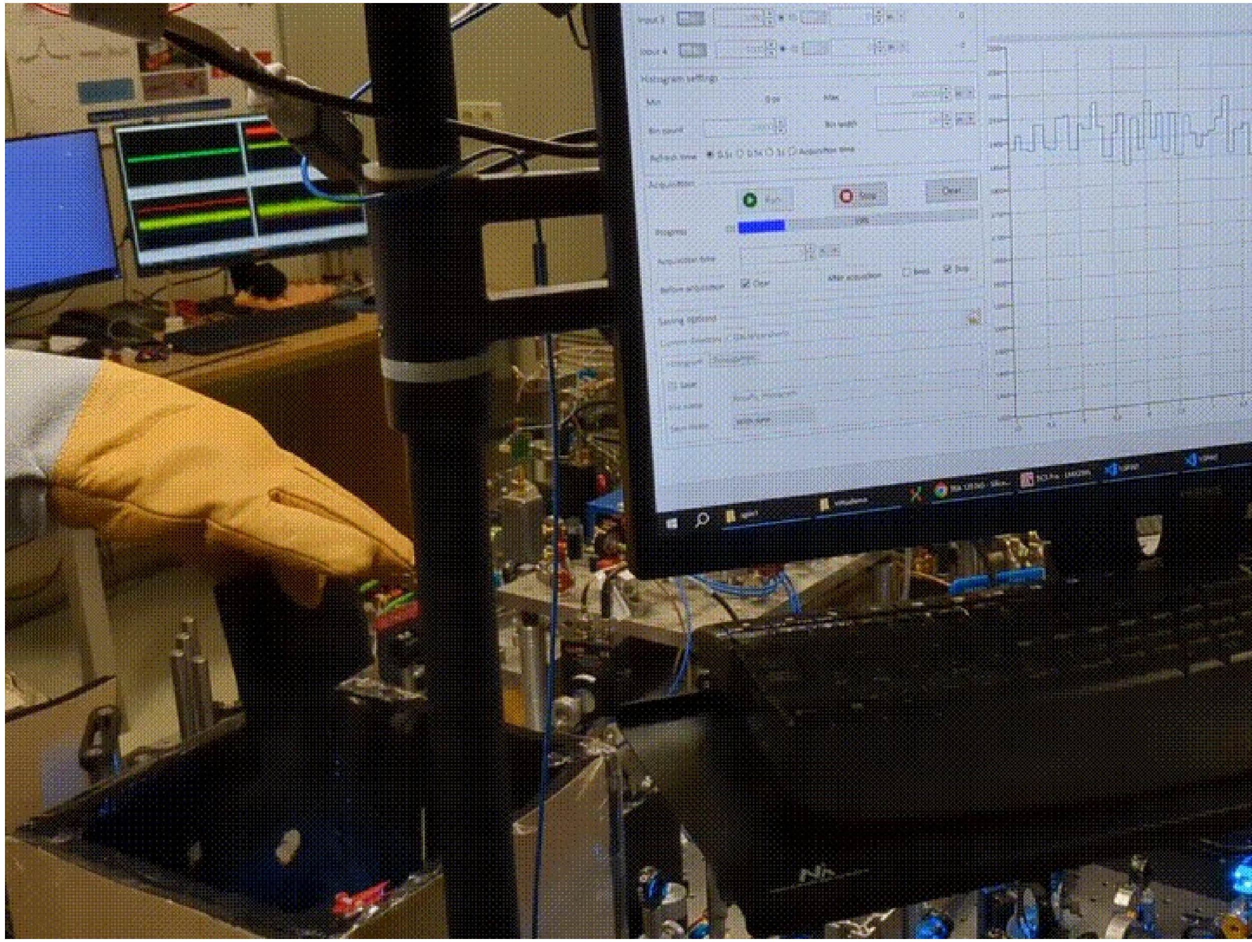
$$g^{(2)}(\tau) = 1 + \frac{1}{4}\left(\left|g_{\text{th}}^{(1)}(\tau) + e^{-i\omega\tau}\right|^2 - 1\right),$$

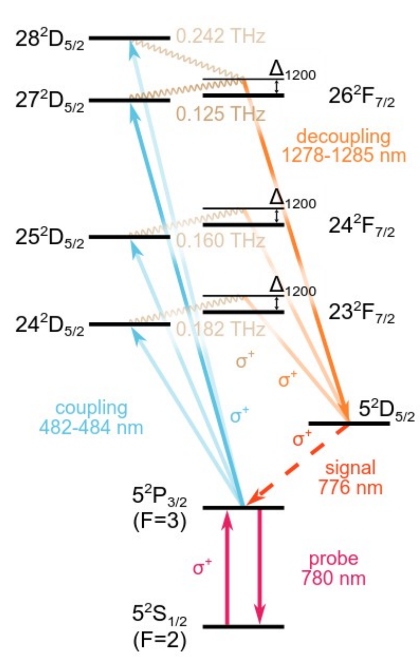
S. Borówka et al. *Continuous wideband microwave-to-optical converter based on room-temperature Rydberg atoms*, *Nat. Phot.* **18**, 32–38 (2024)

Conversion @130 GHz

Rydberg transition
34D to 32F

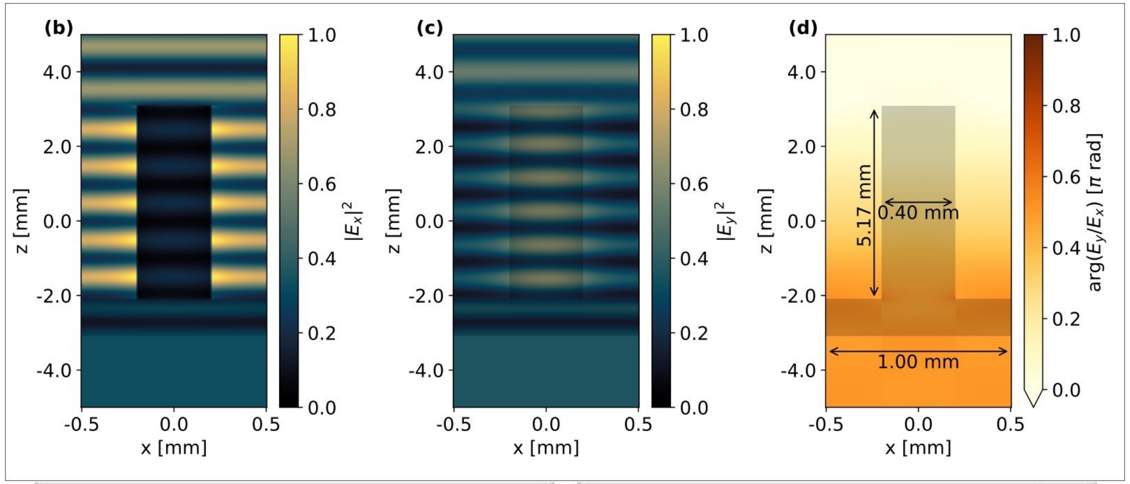


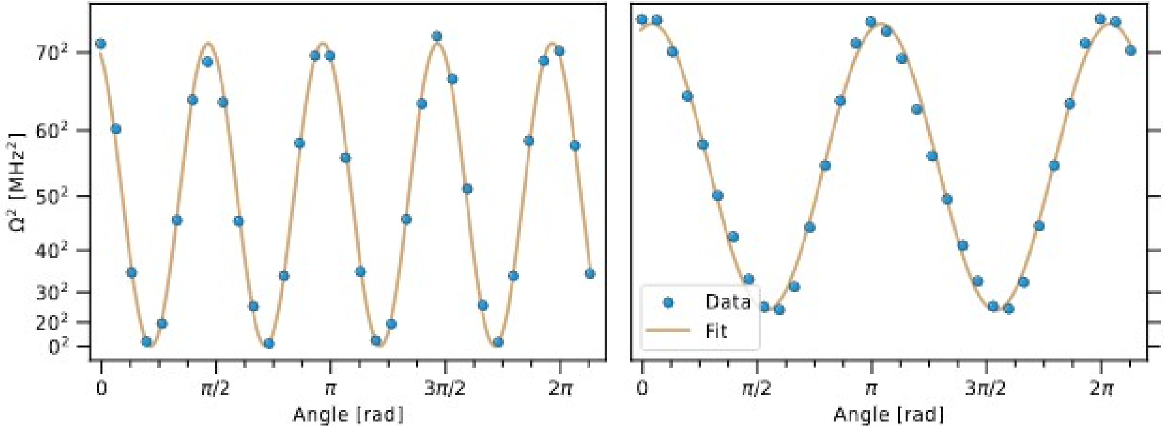


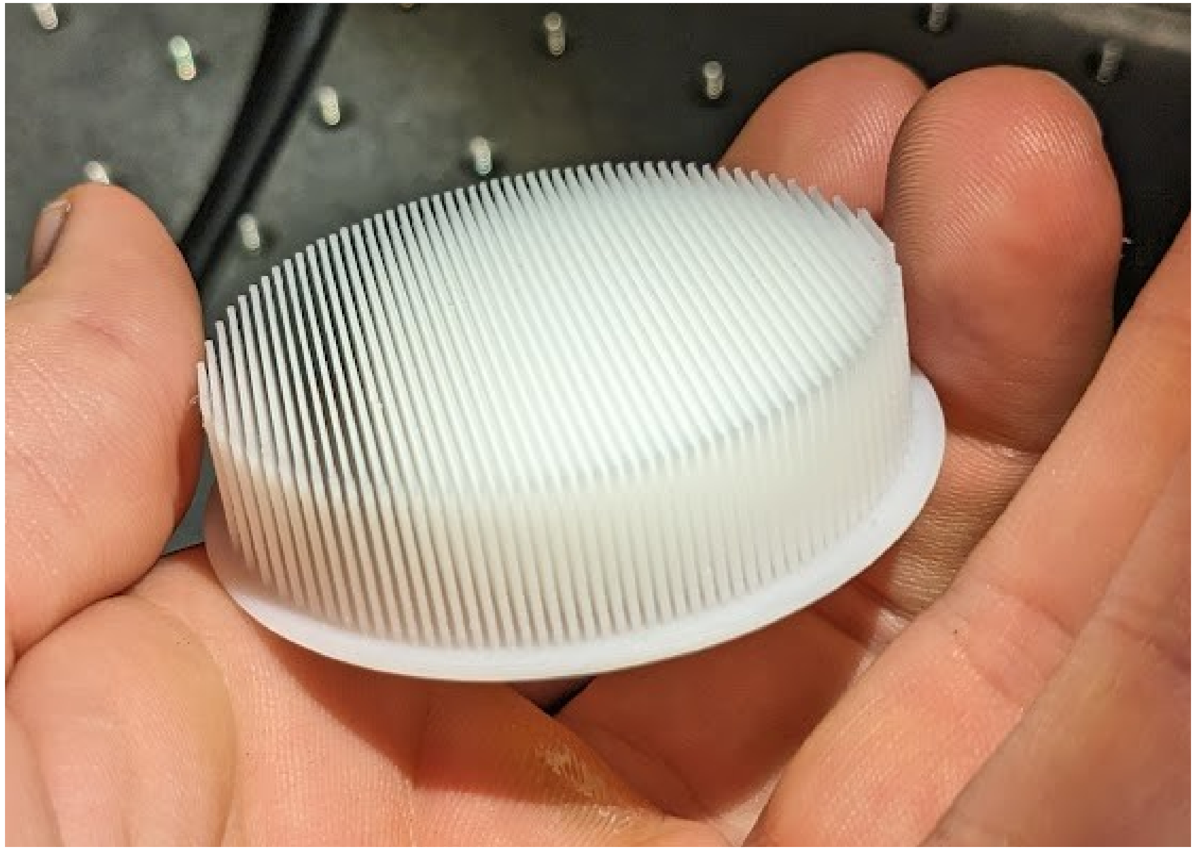


Sebastian Borówka, et al. Phys. Rev. Applied **22**, 034067 (2024)

THz "photonics"



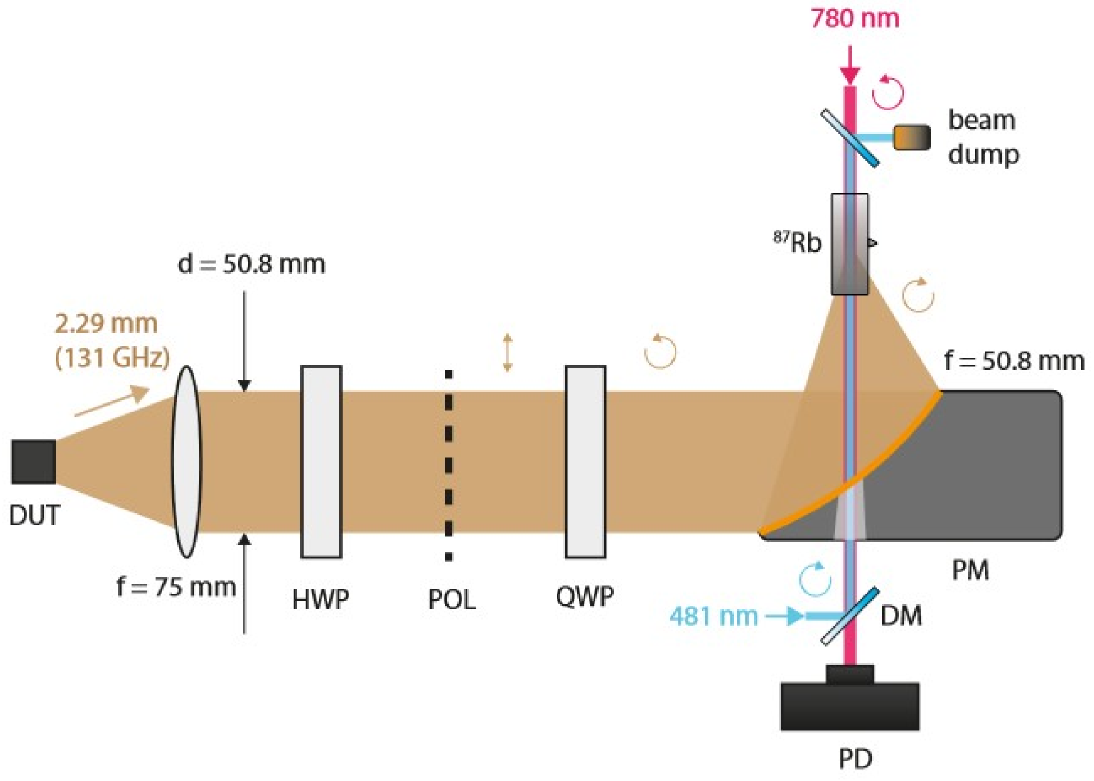


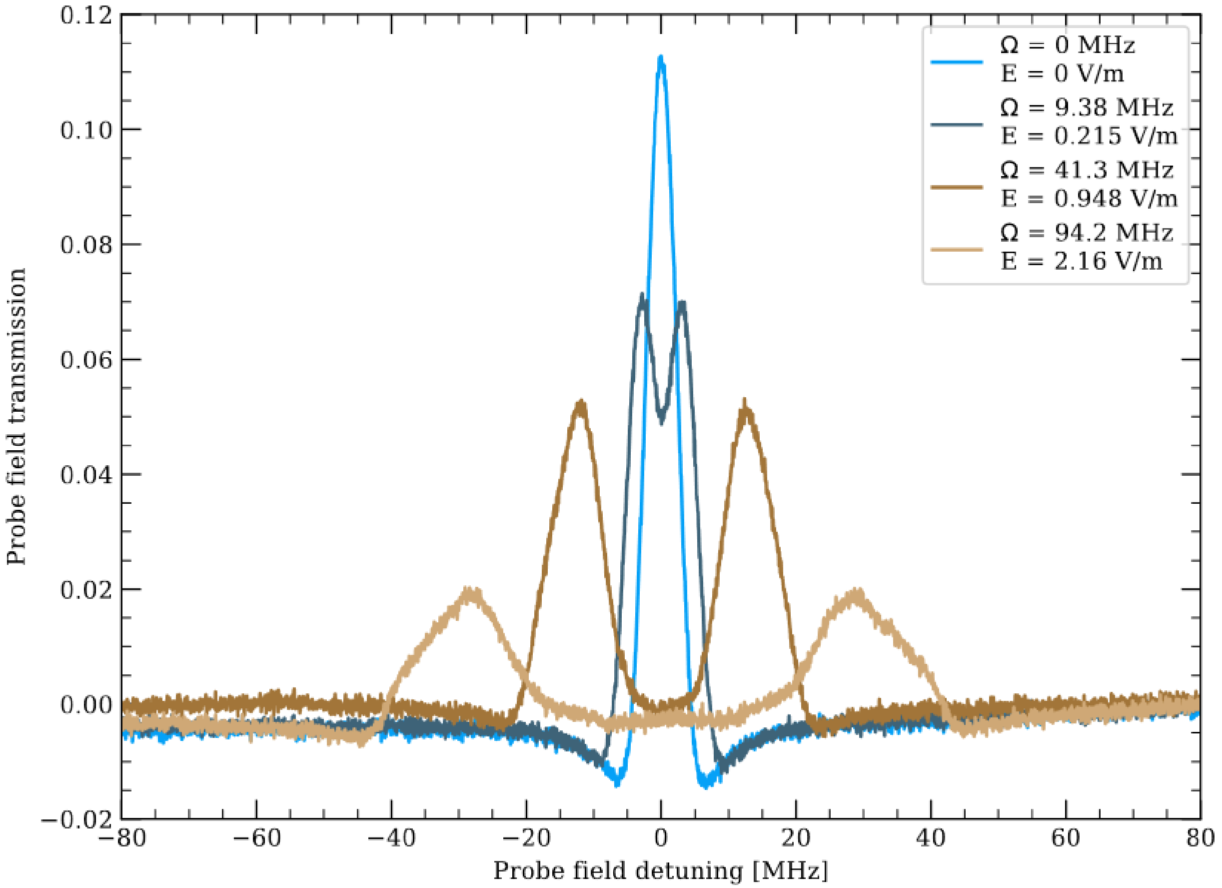


Computed using https://github.com/flexcompute/tidy3d

Sebastian Borówka, et al. Phys. Rev. Applied **22**, 034067 (2024)

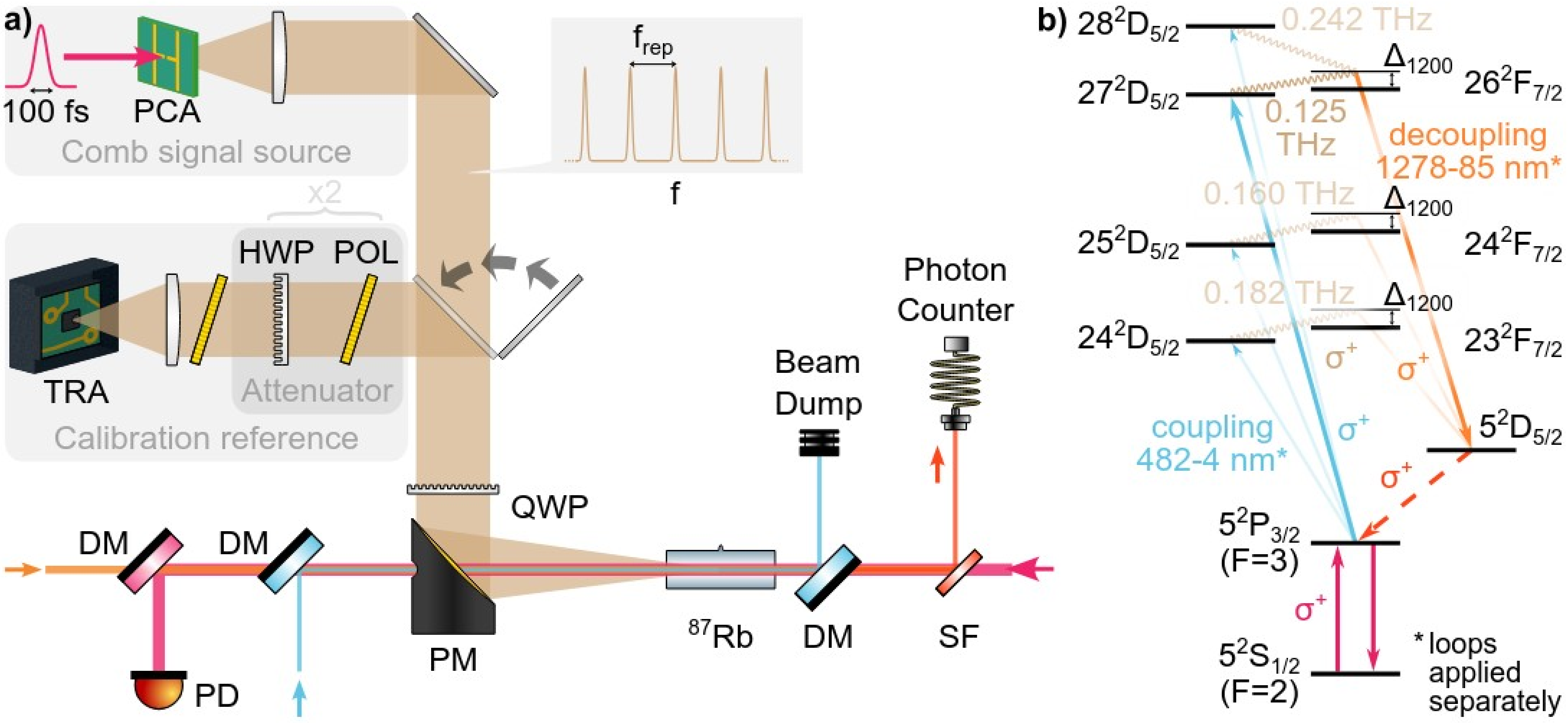
Callibration of a chip source for automotive applications (TRA120)





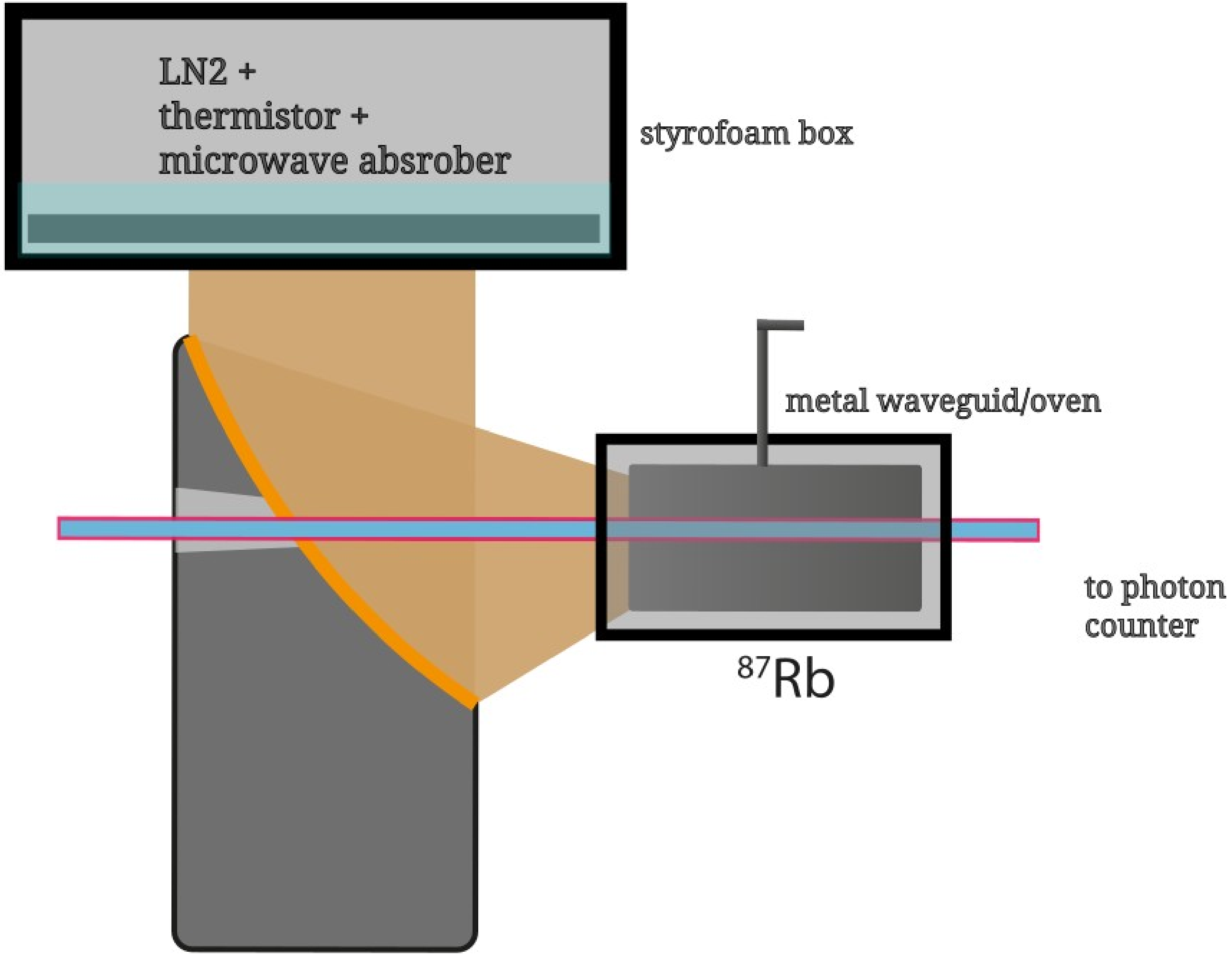
Sebastian Borówka, et al. Phys. Rev. Applied **22**, 034067 (2024)

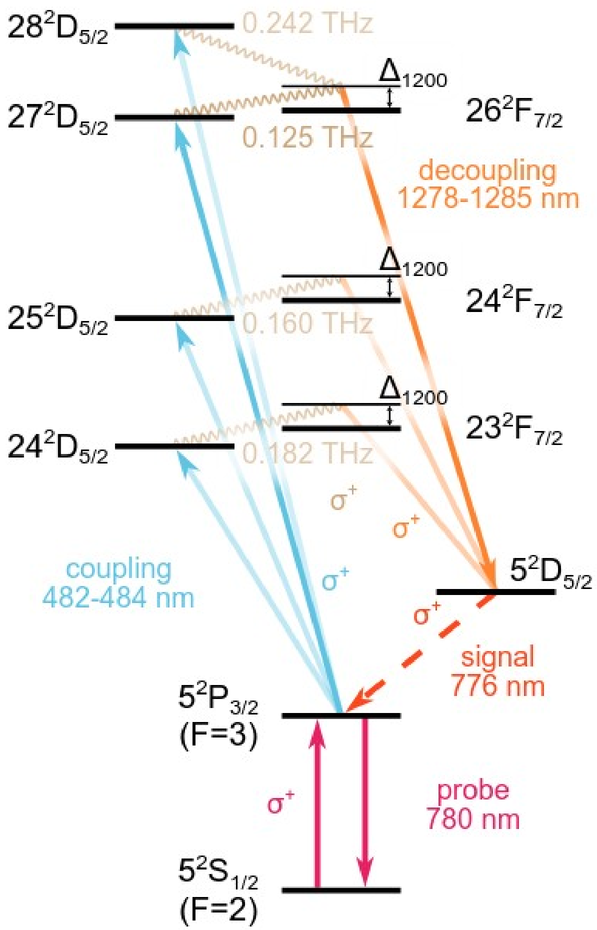
Detecting a Terahertz frequency comb



W. Krokosz et al, https://arxiv.org/pdf/2508.20698, accepted in Optica

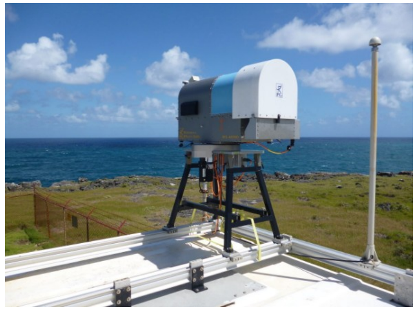
Quantum radiometer setup





Radiometer & quantum radiometer

Conventional radiometer



https://en.wikipedia.org/wiki/Microwave_radiometer#/media/File:Microwaveradiometerbardabos.jpg

$$\mathrm{SNR} = \frac{T_{sig}}{T_{sys}}\sqrt{\Delta\nu\Delta t}$$

$$\Delta T = T_{sys}/\sqrt{\Delta\nu}$$

Practical limitations: gain fluctuations, statistical fluctuations, ...

$$T_{\mathrm{sys}} = T_{\mathrm{cmb}} + \Delta T_{\mathrm{source}} + T_{\mathrm{atm}} + T_{\mathrm{spillover}} + T_{\mathrm{rcvr}} + \ \ldots$$

Quantum limit

Assuming

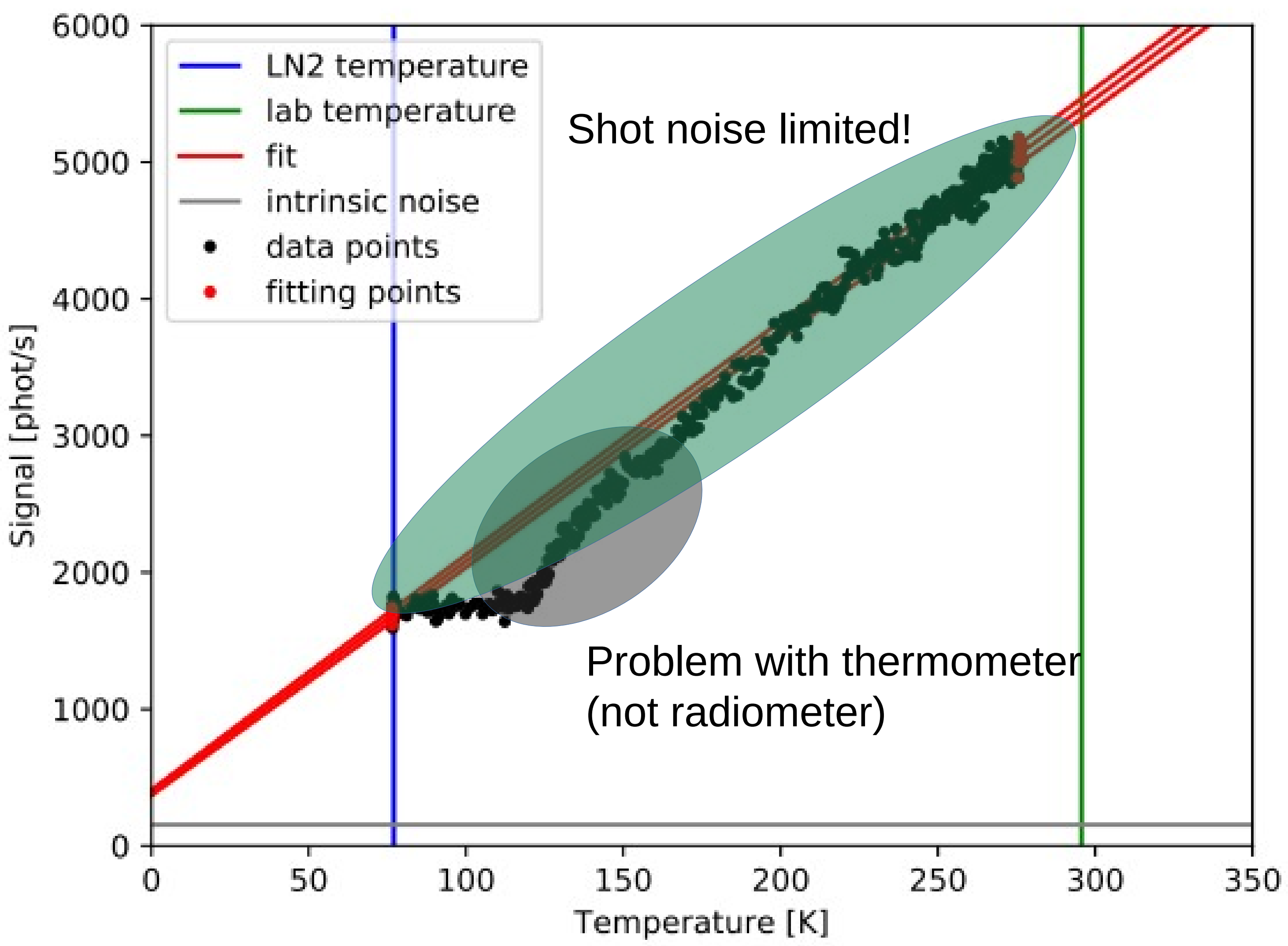
$$\Delta t \gg \ 1/\Delta\nu$$

$$\Delta T = T_{sig}\sqrt{\frac{h\nu}{kT_{sig}}}/\sqrt{\Delta\nu}$$

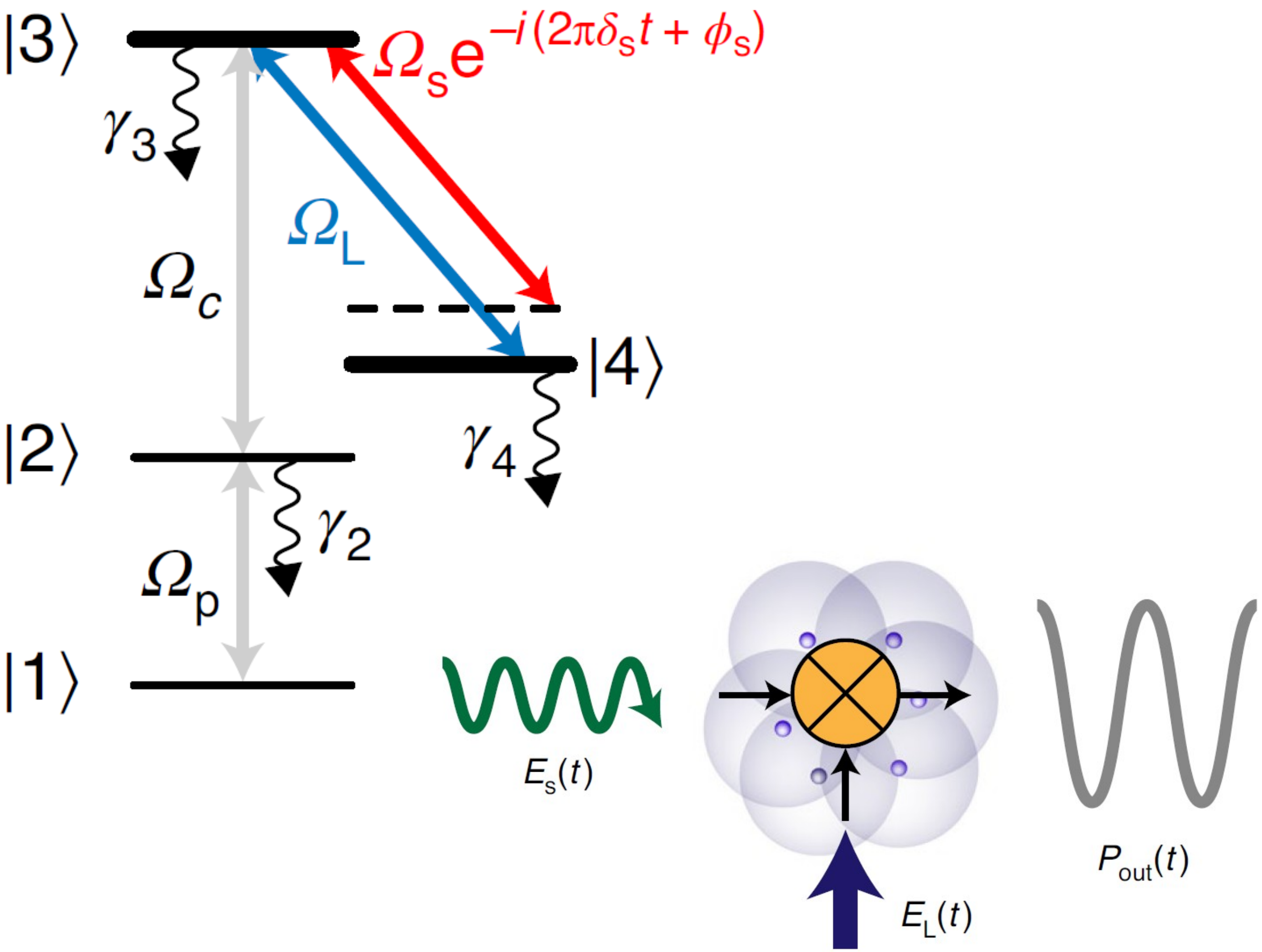
$$T_Q$$

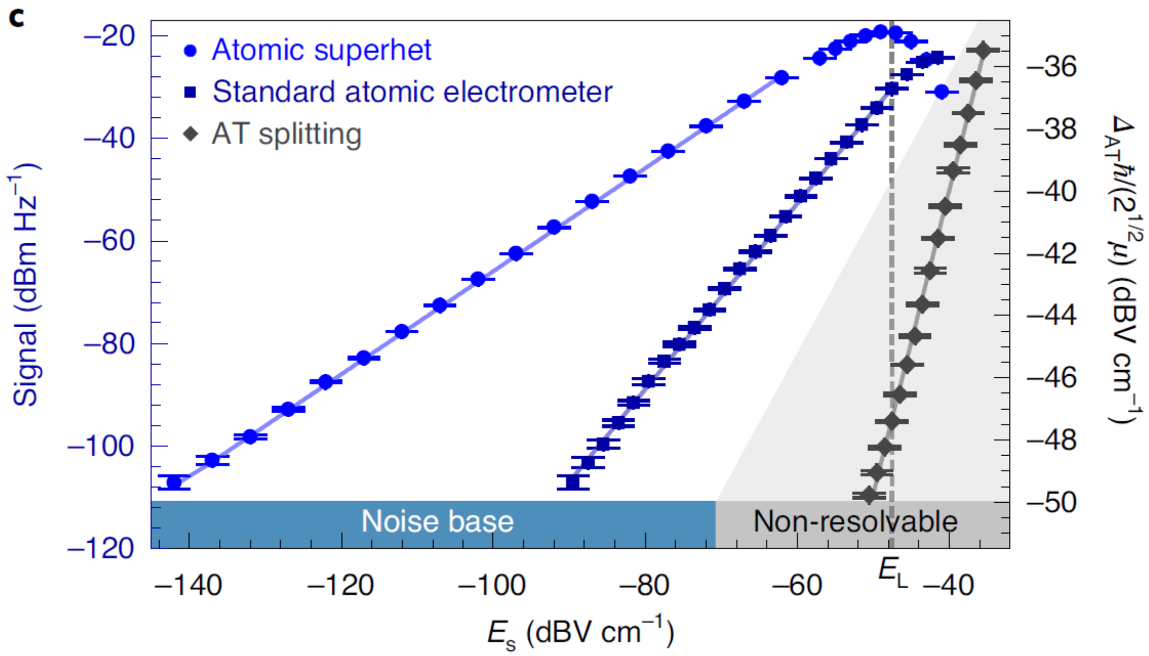
Practical limitations: added noise, finite efficiency, measurement time, ...

Radiometry during warm-up



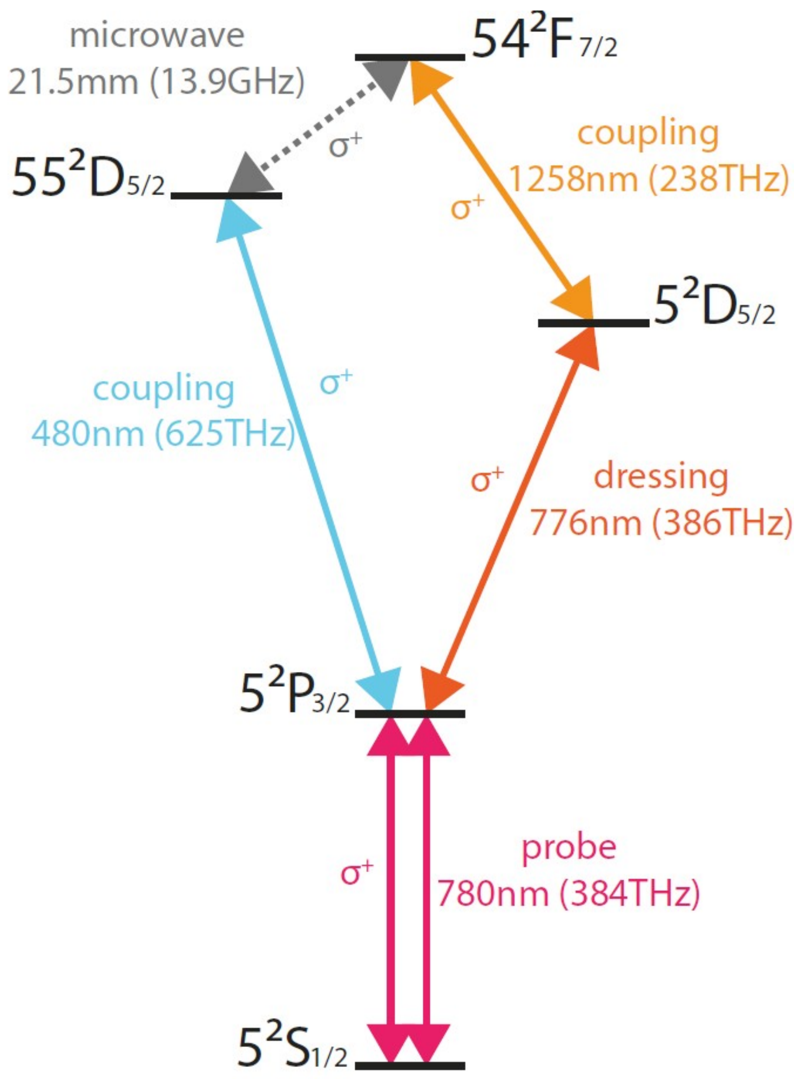
Phase sensitive detection – microwave mixer

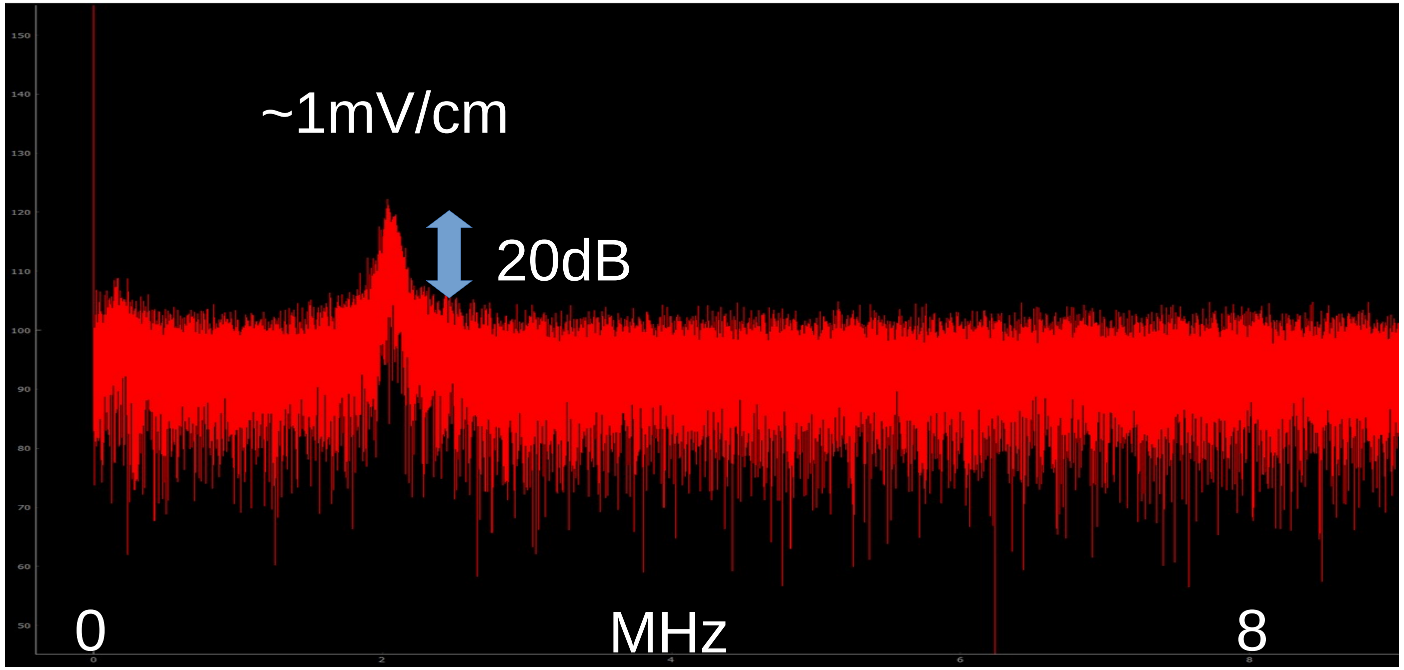




M. Jing et al. *Nat. Phys.* **16**, 911–915 (2020)

All optical superheterodyne – optically biased detection

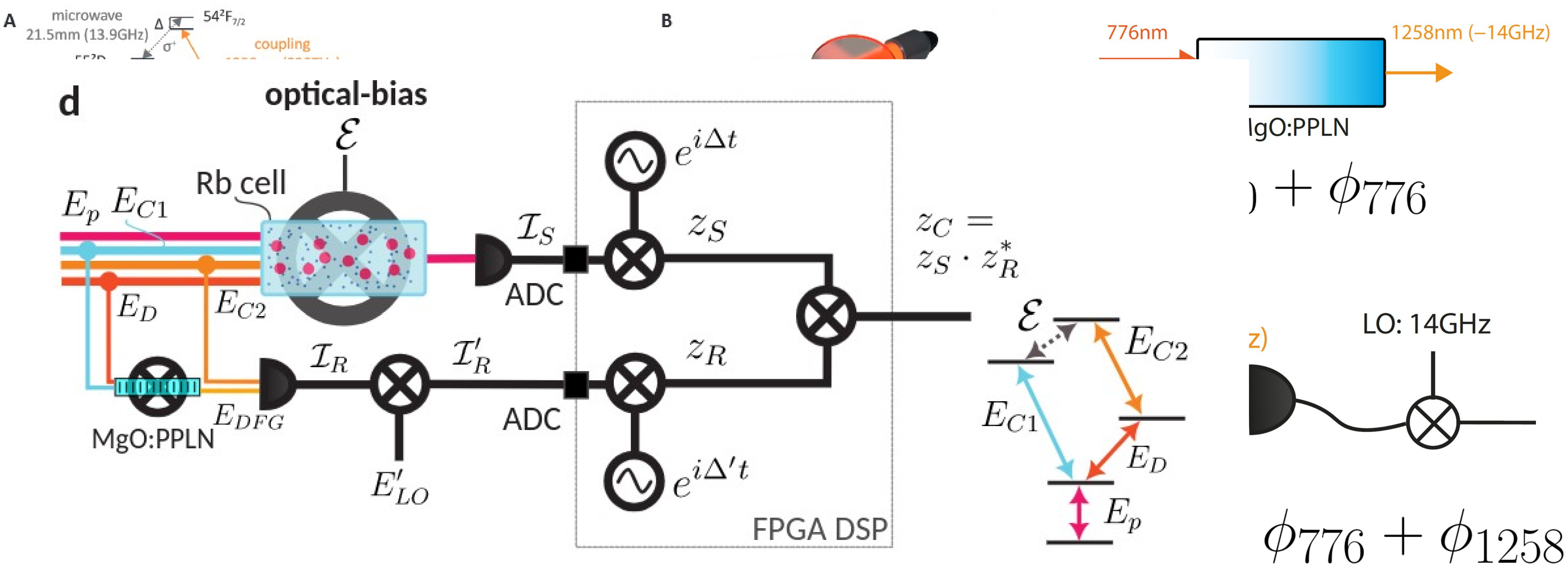




$$\phi = \phi_{480} + \phi_{776} + \phi_{1258}$$

Laser phase fluctuations transferred to the signal :(
Can we solve it without investing in ultra-stable lasers?

Noise-compensated detection

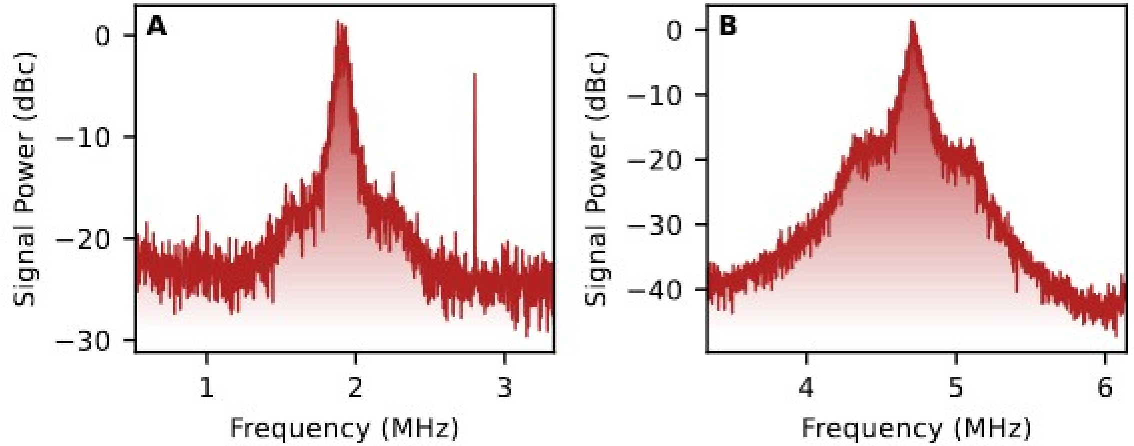


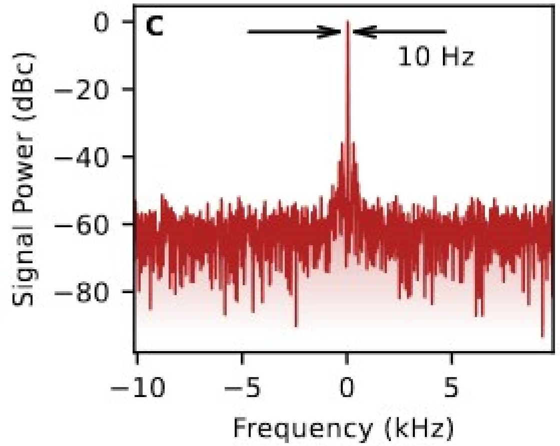
S. Borówka, M. Mazelanik, W. Wasilewski, M. Parniak, **Nature Communications 16, 8975 (2025**

Phase compensation and sensitivity comparison

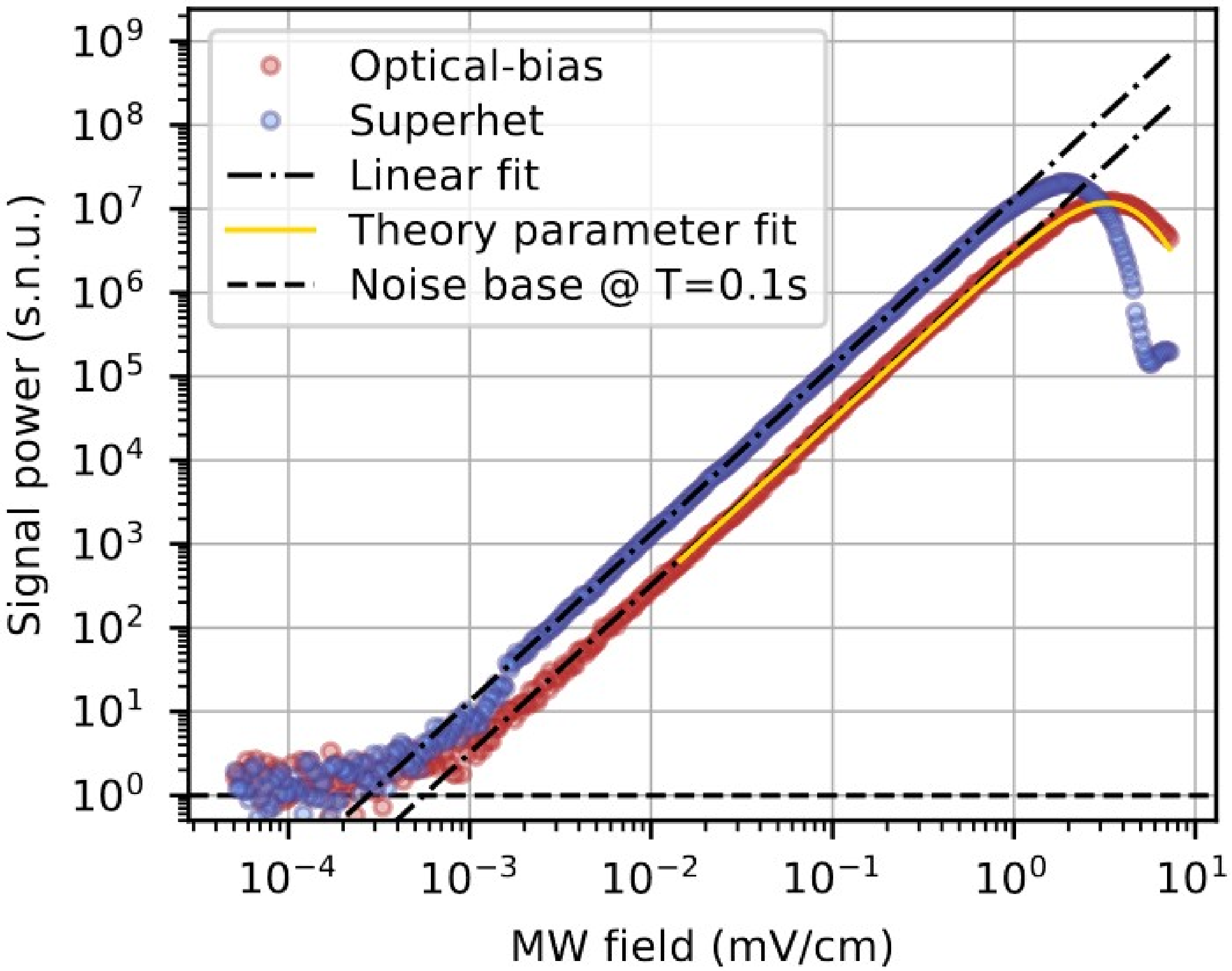
signal

reference



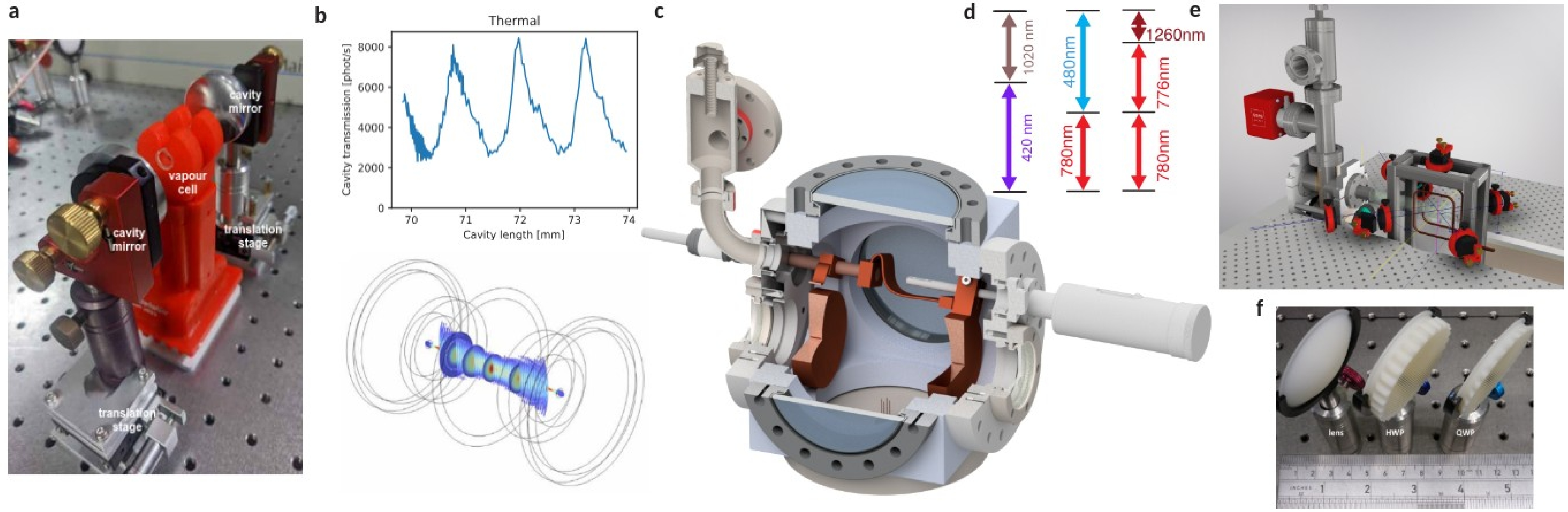


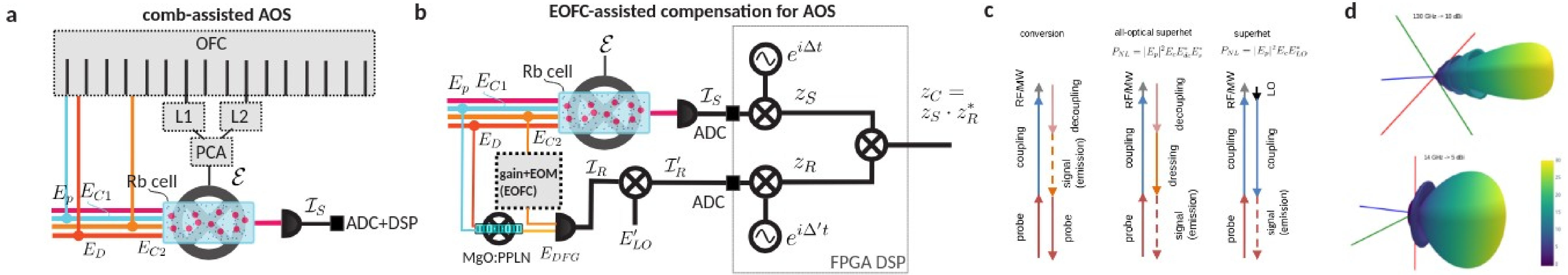
Improvement from
20dB to 60dB SNR



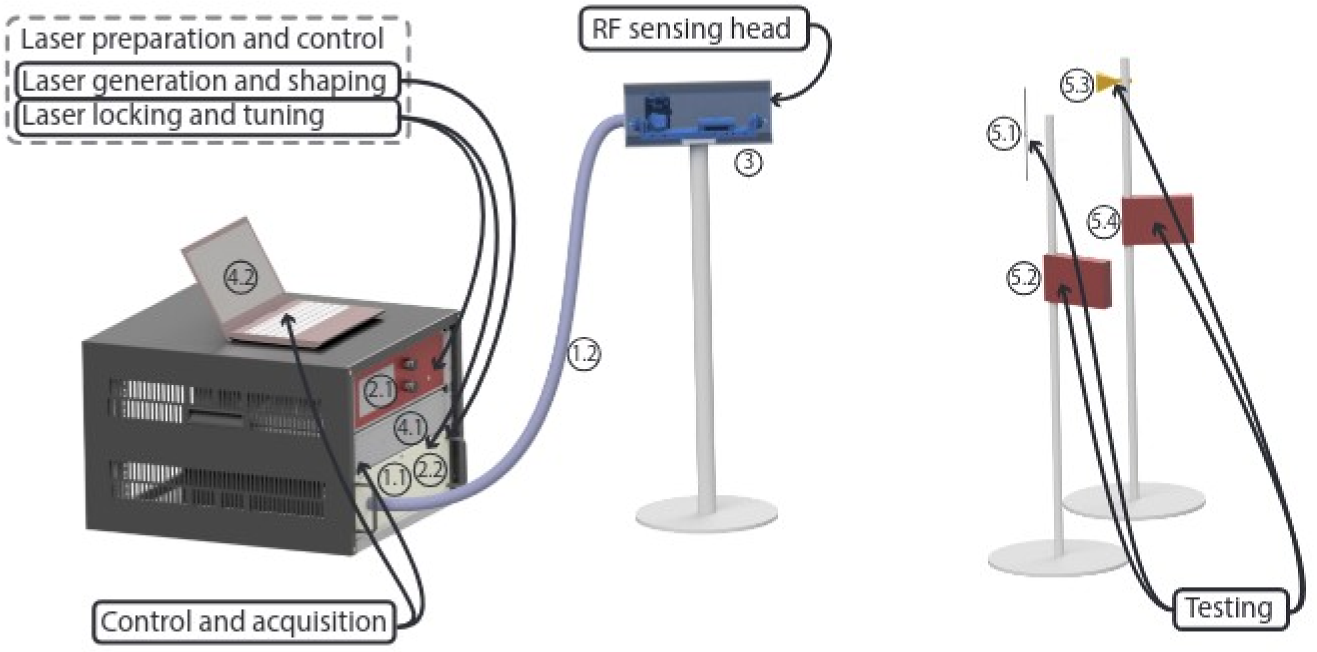
S. Borówka, M. Mazelanik, W. Wasilewski, M. Parniak, **Nature Communications 16, 8975 (2025**

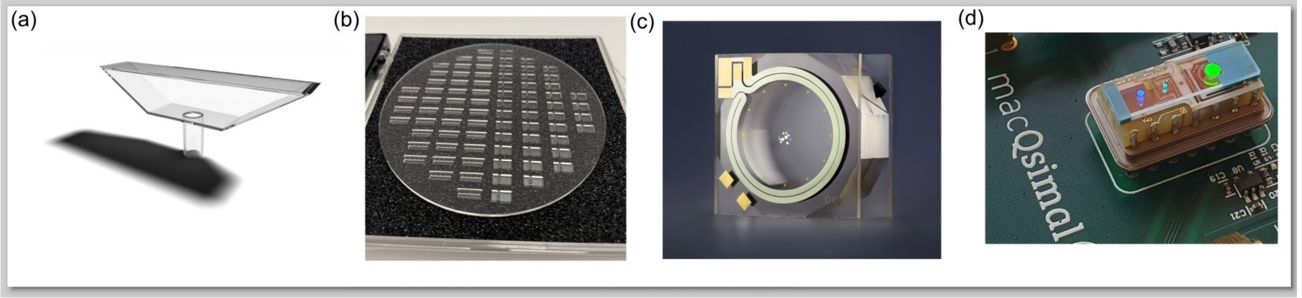
QURA Outlook: new protocols, fundamental limits, cavity (Q)ED

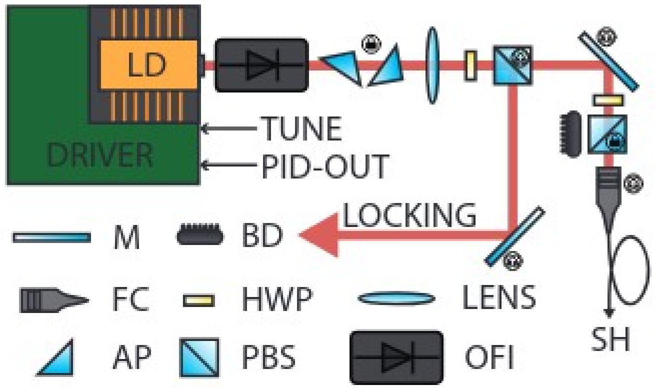


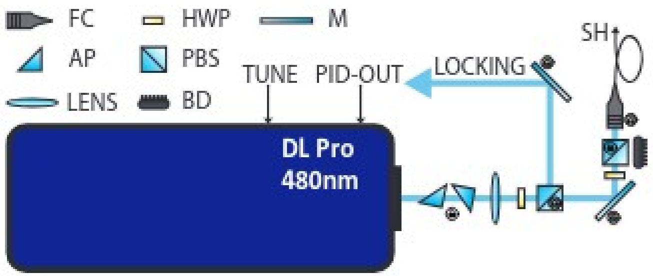


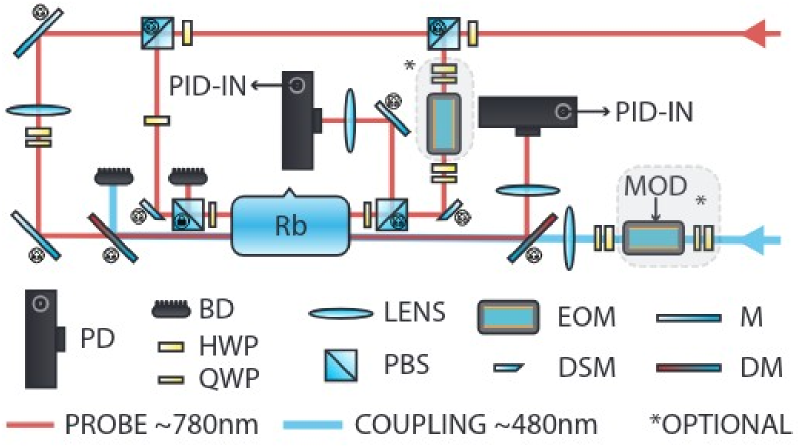
Applications outlook







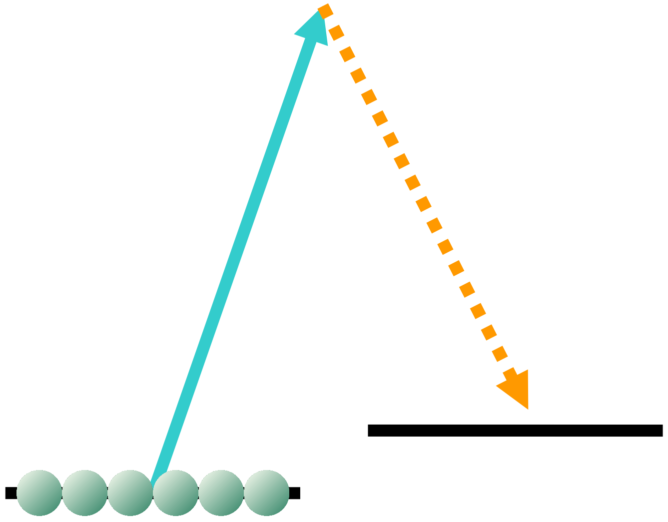




Microwave sensing with cold Rydberg atoms

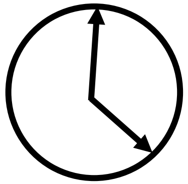
- No Doppler Broadening
- Atoms stay in the interaction region
- No collisions
- Precise controll of the atomic state
- Experimental sequence – non-steady-state dynamics

Collective excitations in the ground state - interface

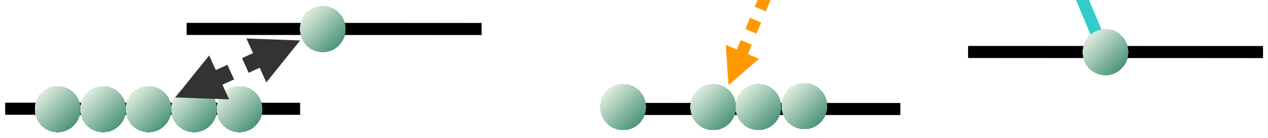


two-mode squeezed state
creation via off-resonant **Raman scattering**

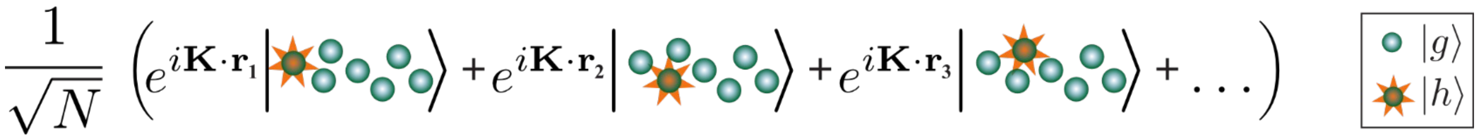
quantum memory



spin-wave

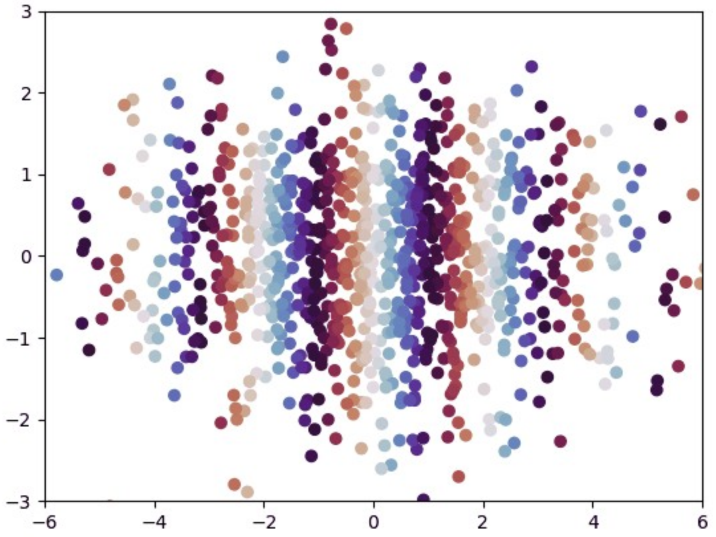


readout stage after storage time results in **anihilation of spin-wave**



M. Parniak et al., Nature Communications 8, 2140 (2017)

Spin-wave storage and readout



$$\tau = \left(|\boldsymbol{k}| \sqrt{\frac{k_B T}{m}} \right)^{-1}$$

Classical analogue
Spatially-dependent atomic coherence

$$\hat{\rho}(\mathbf{r}) = \frac{1}{1+|\beta(\mathbf{r})|^2} \begin{pmatrix} 1 & \beta(\mathbf{r}) e^{i\mathbf{K}\cdot\mathbf{r}} \\ \beta^*(\mathbf{r}) e^{-i\mathbf{K}\cdot\mathbf{r}} & |\beta(\mathbf{r})|^2 \end{pmatrix}.$$

$$\tilde{\mathbf{P}} = n\mathrm{Tr}(\rho\hat{\mathbf{d}}),$$

$$2i\frac{\partial \mathbf{A}}{\partial z} = -\frac{\omega}{c\epsilon_0}\mathbf{P}.$$

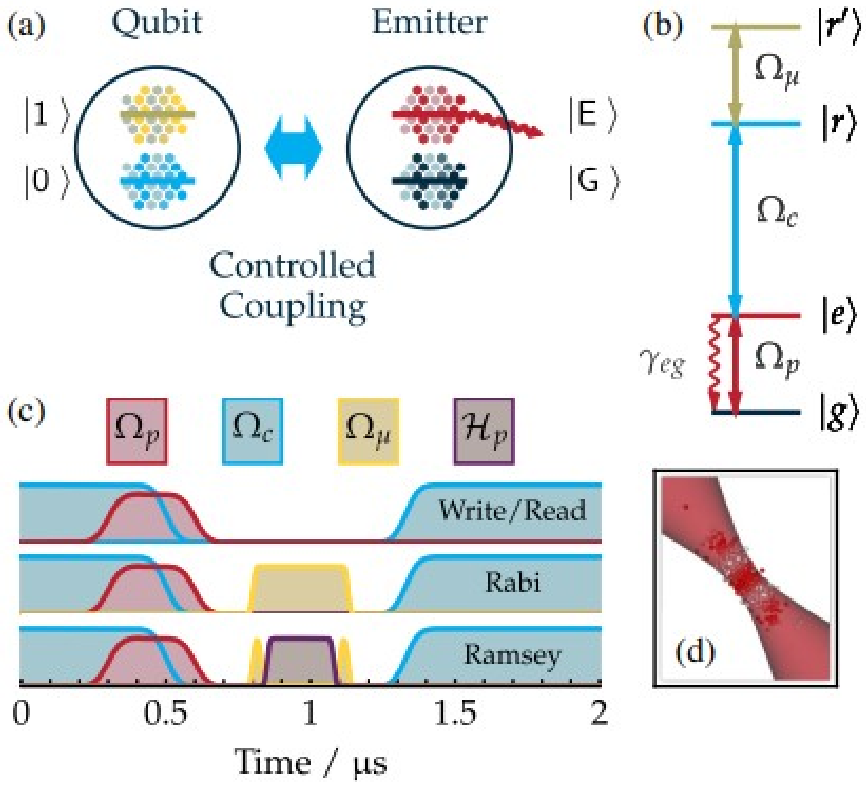
Result: directionial emission due to phase matching
But also: decay due to atomic motion

Collective Rydberg qubits

- quantum information is distributed over many atoms
- direct readout in a well-defined spatial mode

$$|0\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_r t)} |g_1, g_2, \ldots, r_j, \ldots, g_N\rangle$$

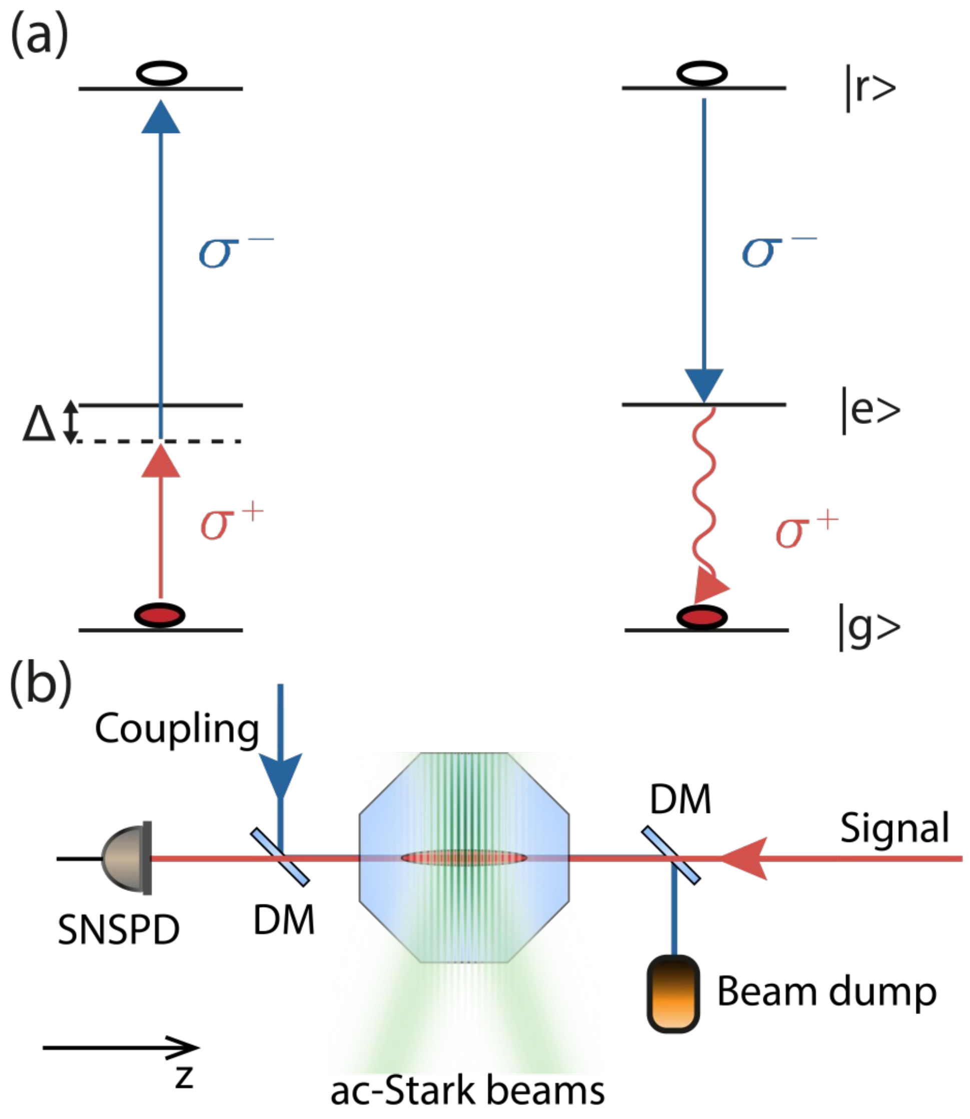
$$|1\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_{r'} t)} |g_1, g_2, \ldots, r'_j, \ldots, g_N\rangle$$

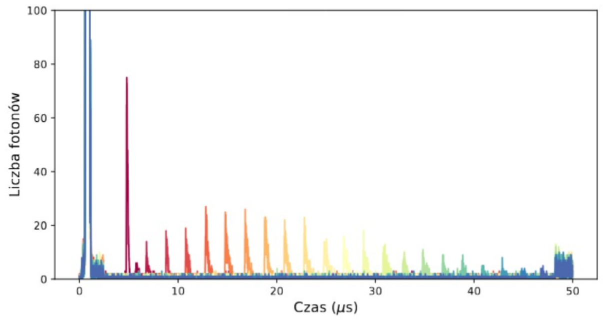


Collectively Encoded Rydberg Qubit

Nicholas L. R. Spong, et al., Phys. Rev. Lett. **127**, 063604

EIT preparation and retrieval

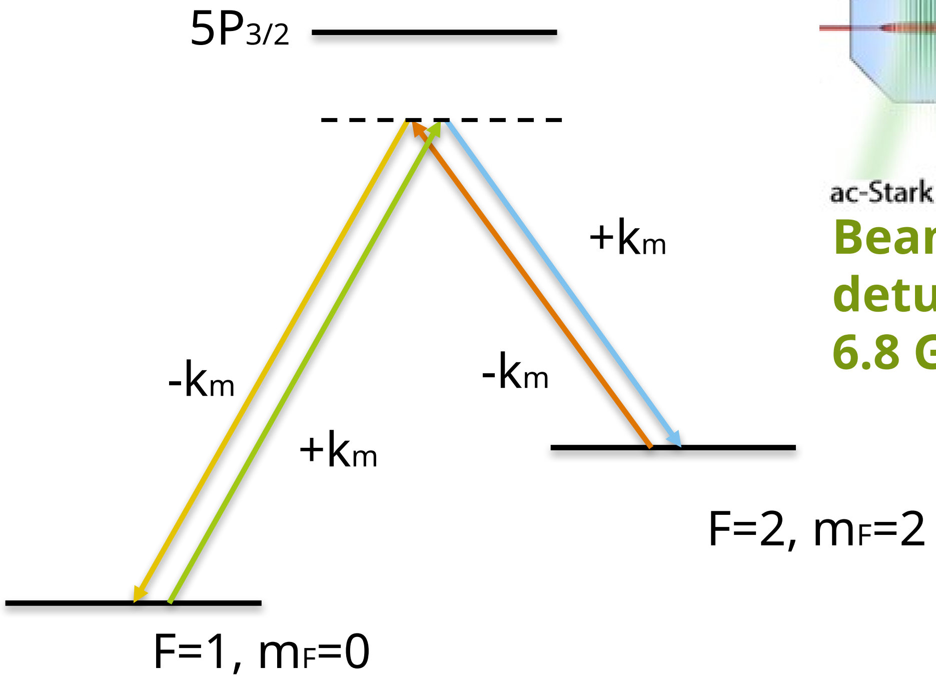


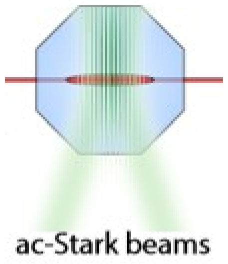


S. Kurzyna, B. Niewelt, W. Wasilewski, M. Mazelanik, M. Parniak
arXiv:2402:06513, Quantum 8, 1431 (2024)

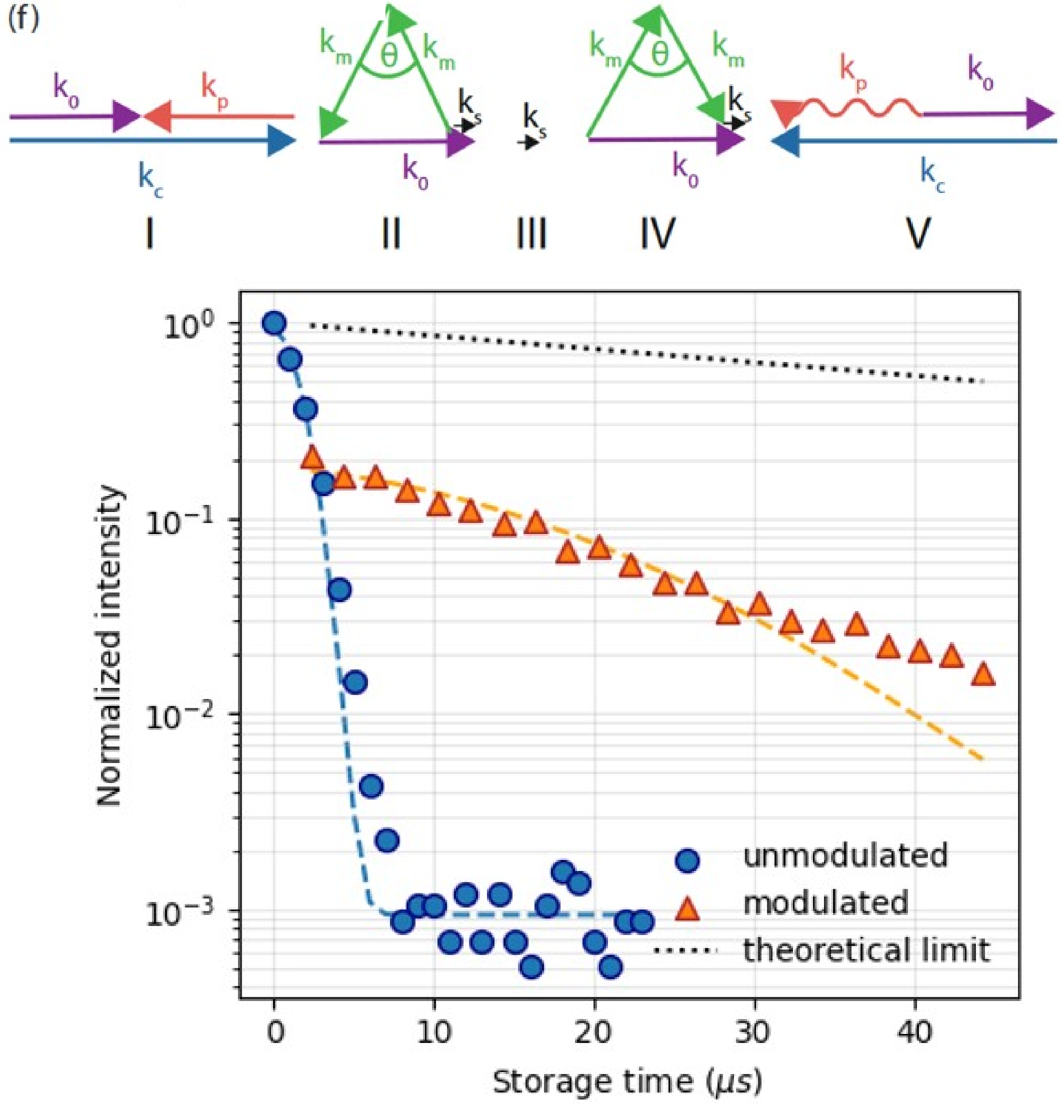
Spin-wave freezing

two-Photon Rabi oscillation/Raman transition between hyperfine states with simultaneous momentum transfer

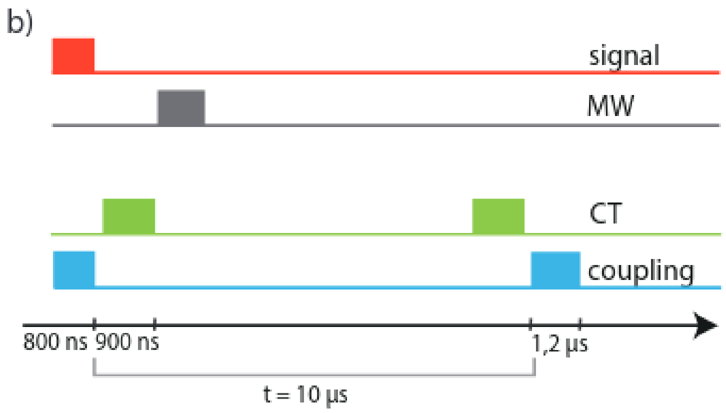




Beams detuned by 6.8 GHz



Rydberg Rabi oscillations



Probe power

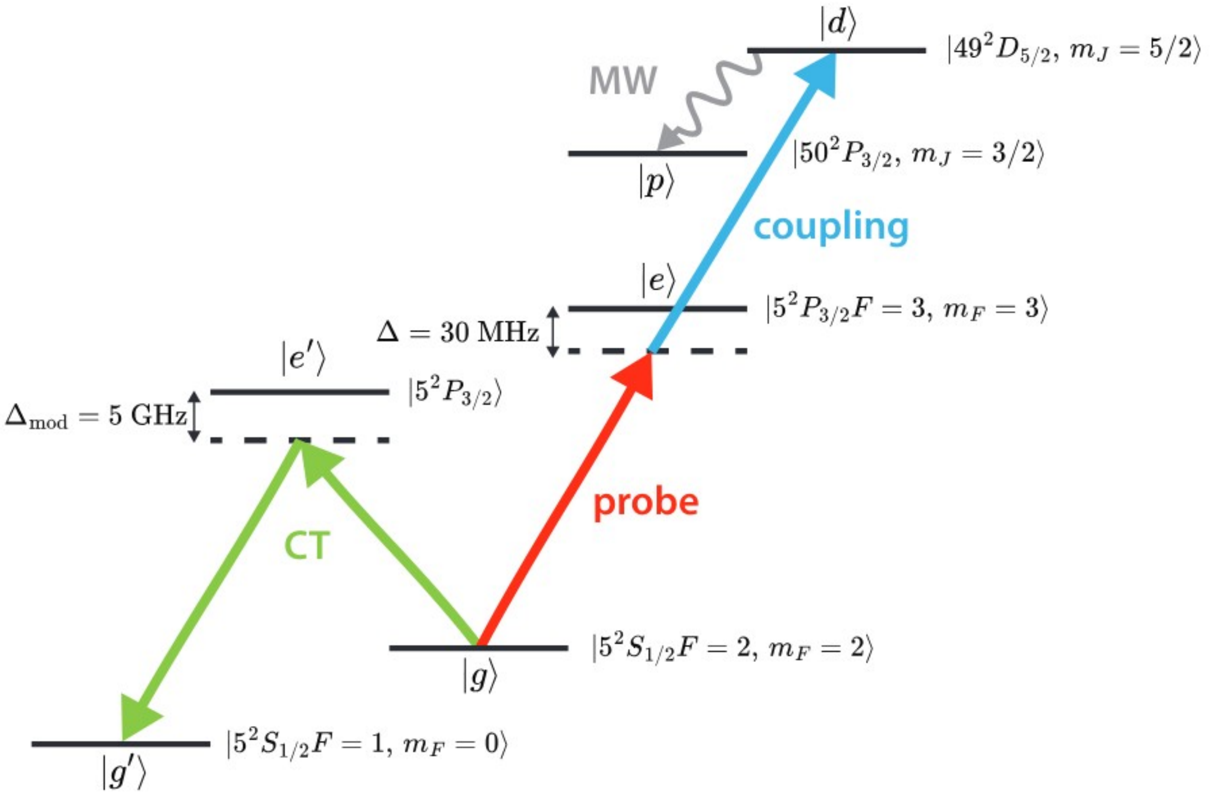
Ω = 2π × 0.39 MHz, 1/Γ = 1.45 us, Rydberg number = 34.88

p orbital state, “p” mode

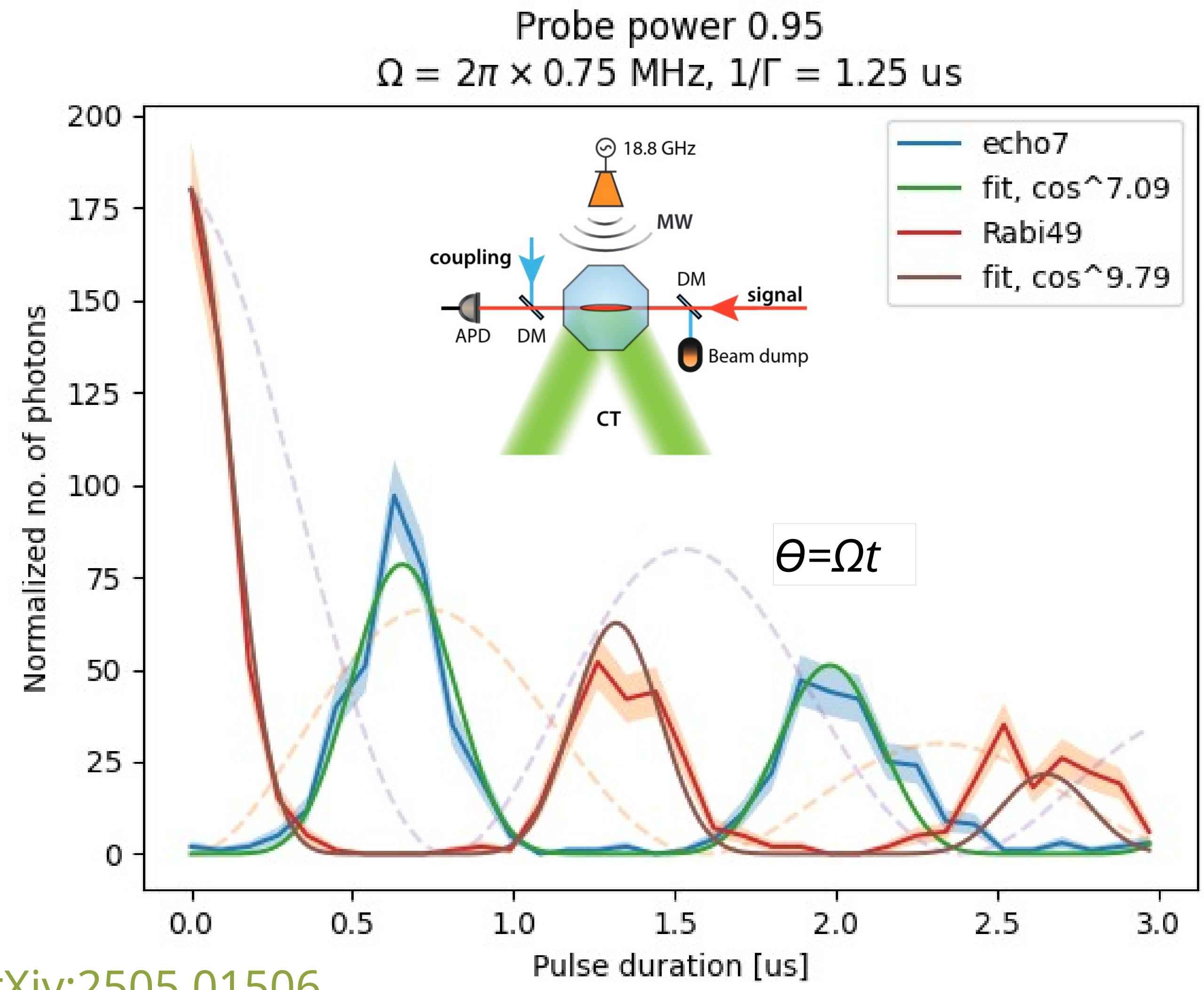
$$|0\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_r t)} |g_1, g_2, \ldots, r_j, \ldots, g_N\rangle$$

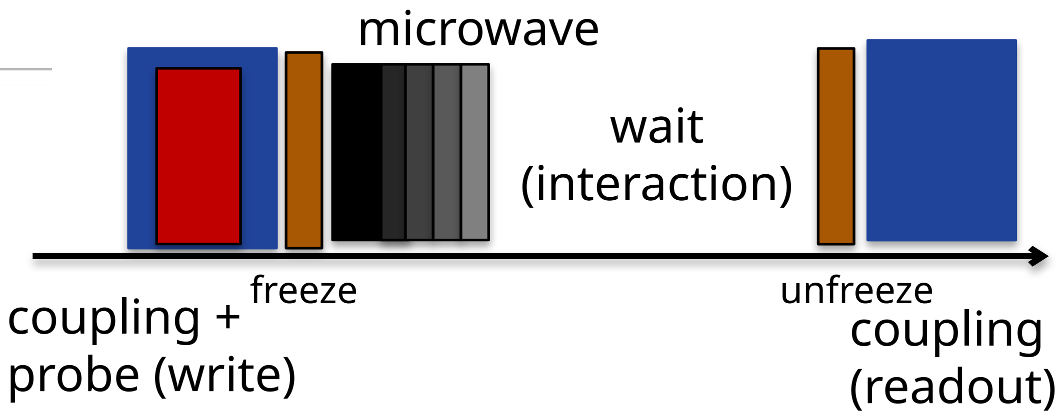
$$|1\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(\boldsymbol{k}\cdot\boldsymbol{R}_j - \omega_{r'} t)} |g_1, g_2, \ldots, r'_j, \ldots, g_N\rangle$$

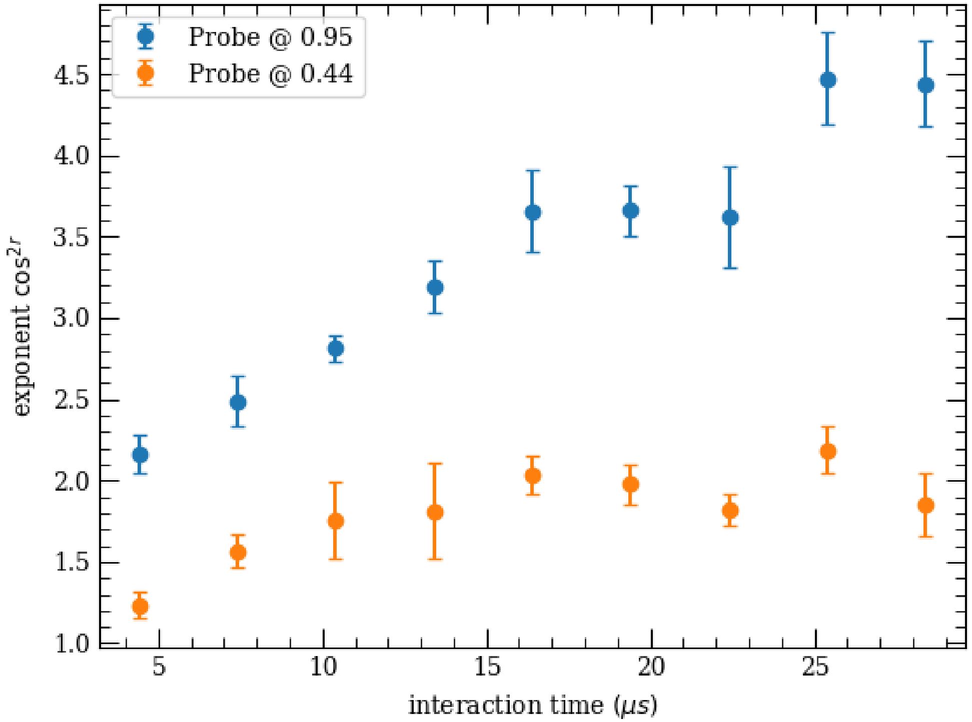
d orbital state, “d” mode



E-field metrology attempt

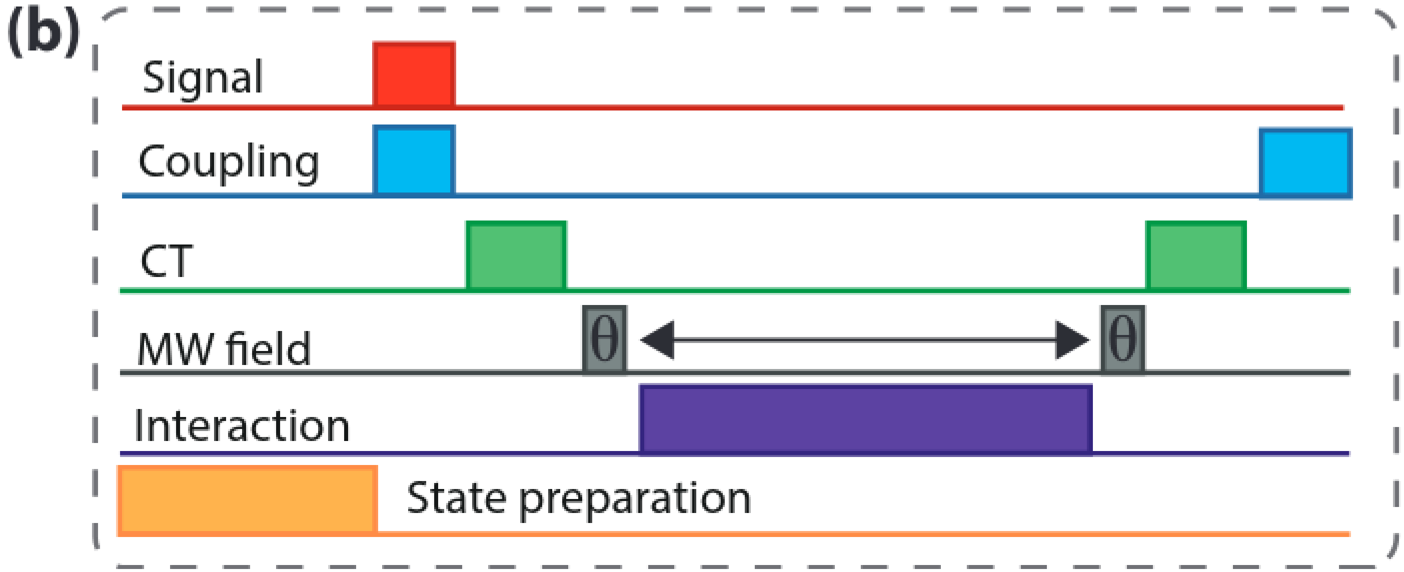


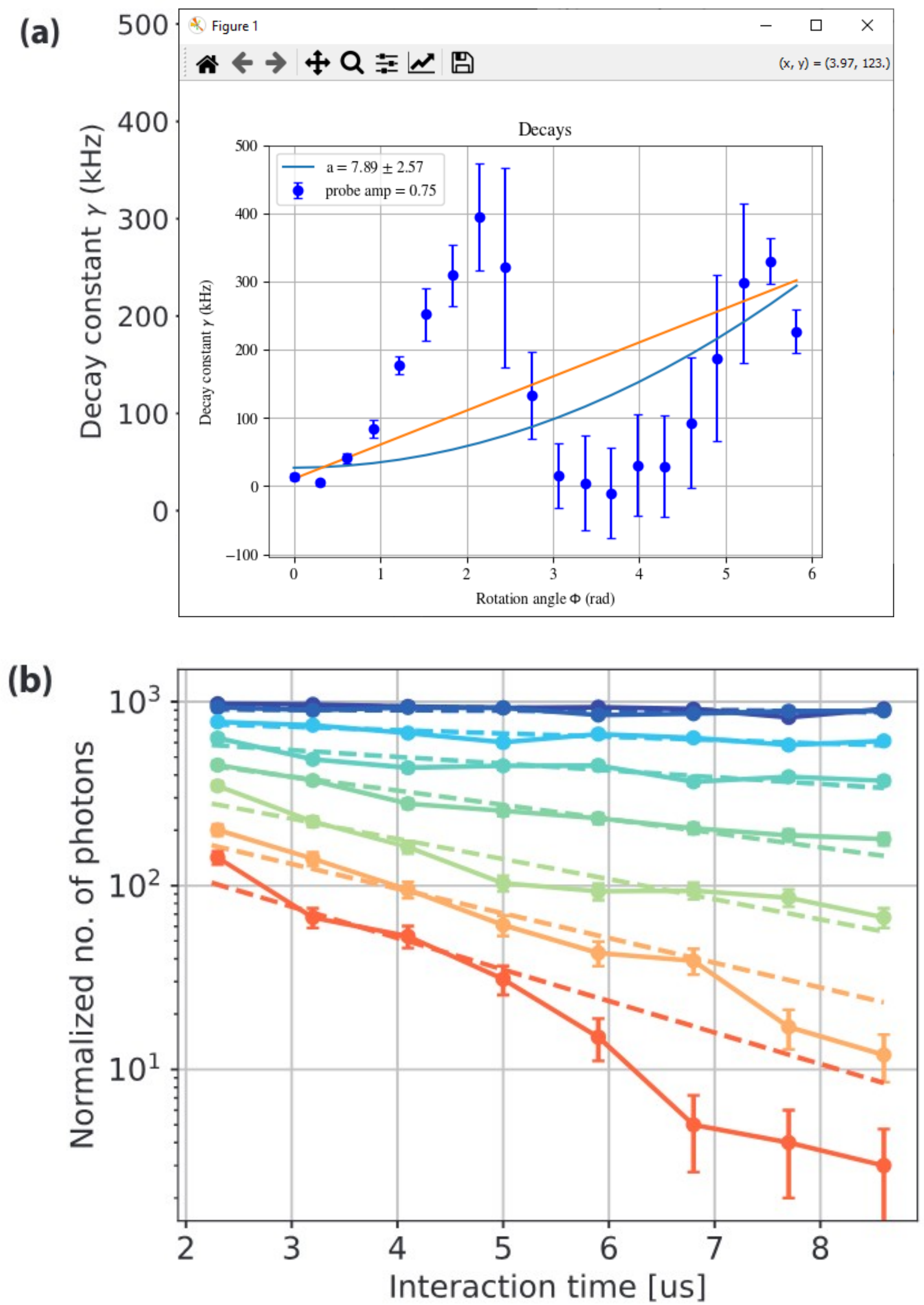




arXiv:2505.01506

Understanding the many-body decoherence





arXiv:2505.01506

Understanding the many-body decohe

$$V(R,\theta) = \frac{C_3}{\ldots}\frac{3\cos(2\theta)+1}{\ldots}$$

$$\hat{H} = \sum_{\mu<\nu} \hat{\sigma}^{\mu}_{dp}\hat{\sigma}^{\nu}_{pd}V^{\mu\nu}_{dip} + h.c.$$

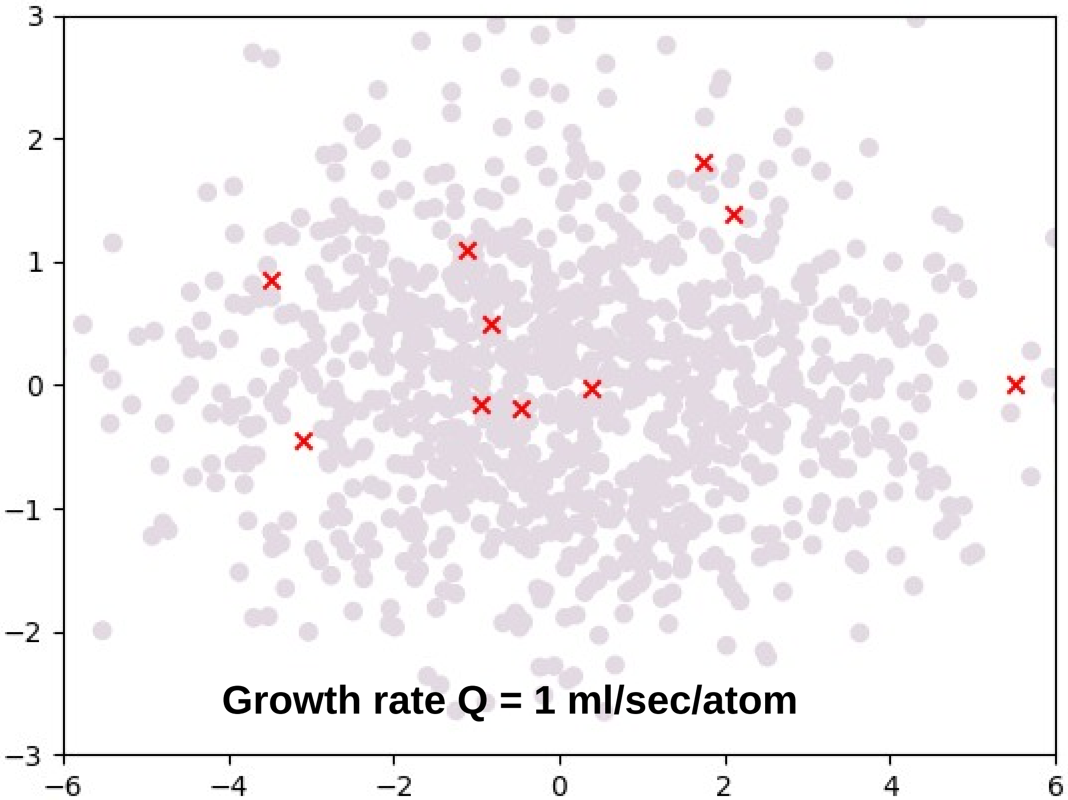
$$\Psi\left(\begin{array}{c|c} \xi & 0 \\ \mu & \end{array}\right) = \psi(\xi)\psi(\mu)$$

$$i\hbar\dot{\Psi}\left(\begin{array}{c|c} \xi & t \\ \mu & \end{array}\right) = V(\xi-\mu)\Psi\left(\begin{array}{c|c} \mu & t \\ \xi & \end{array}\right) \overset{\text{sym.}}{=} V(\xi-\mu)\Psi\left(\begin{array}{c|c} \xi & t \\ \mu & \end{array}\right)$$

$$\Psi\left(\begin{array}{c|c} \xi & t \\ \mu & \end{array}\right) = \exp\left(-\frac{it}{\hbar}V(\xi-\mu)\right)\Psi\left(\begin{array}{c|c} \xi & 0 \\ \mu & \end{array}\right)$$

$$\langle \hat{d}^{\dagger}\hat{d}\rangle = \frac{1}{N}\sum_{i,j}\langle\Psi|\,\hat{\sigma}^{i}_{dg}\hat{\sigma}^{j}_{gd}\,|\Psi\rangle =$$

$$\frac{1}{N^3}\sum_{k,l,m}\Psi^{*}\left(\begin{array}{c|c} \xi_k & t \\ \mu_m & \end{array}\right)\Psi\left(\begin{array}{c|c} \xi_l & t \\ \mu_m & \end{array}\right)\frac{1}{\sqrt{p(\xi_k)p(\xi_l)p(\mu_m)}}$$



$$\ldots \mathcal{V} \ldots \quad 9\sqrt{3}\ \hbar$$

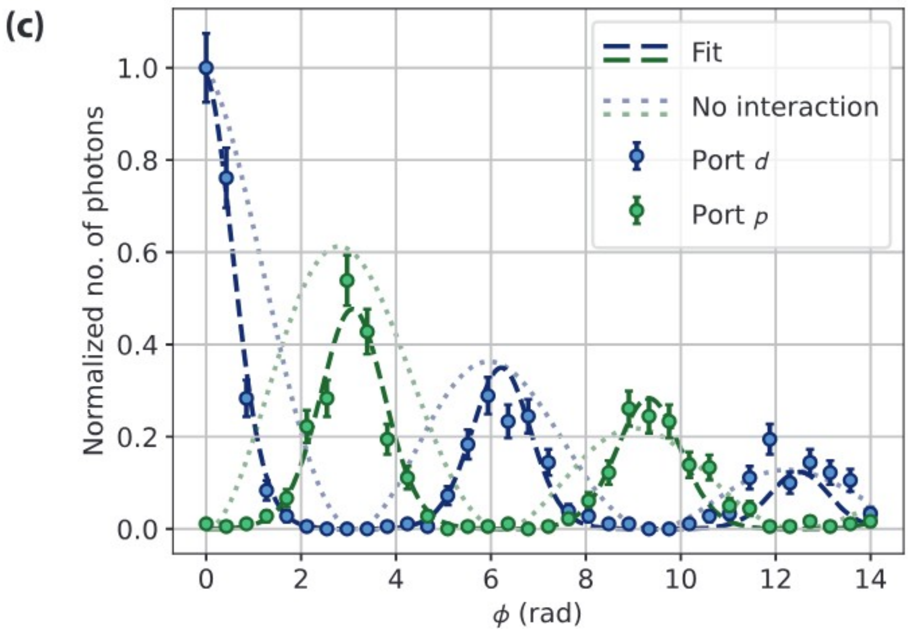
$$\langle \hat{d}^{\dagger}\hat{d}\rangle \approx \left(1-\frac{2Q}{\mathcal{V}}t\right)^{n} \approx \exp\left(-n\frac{2Q}{\mathcal{V}}t\right)$$

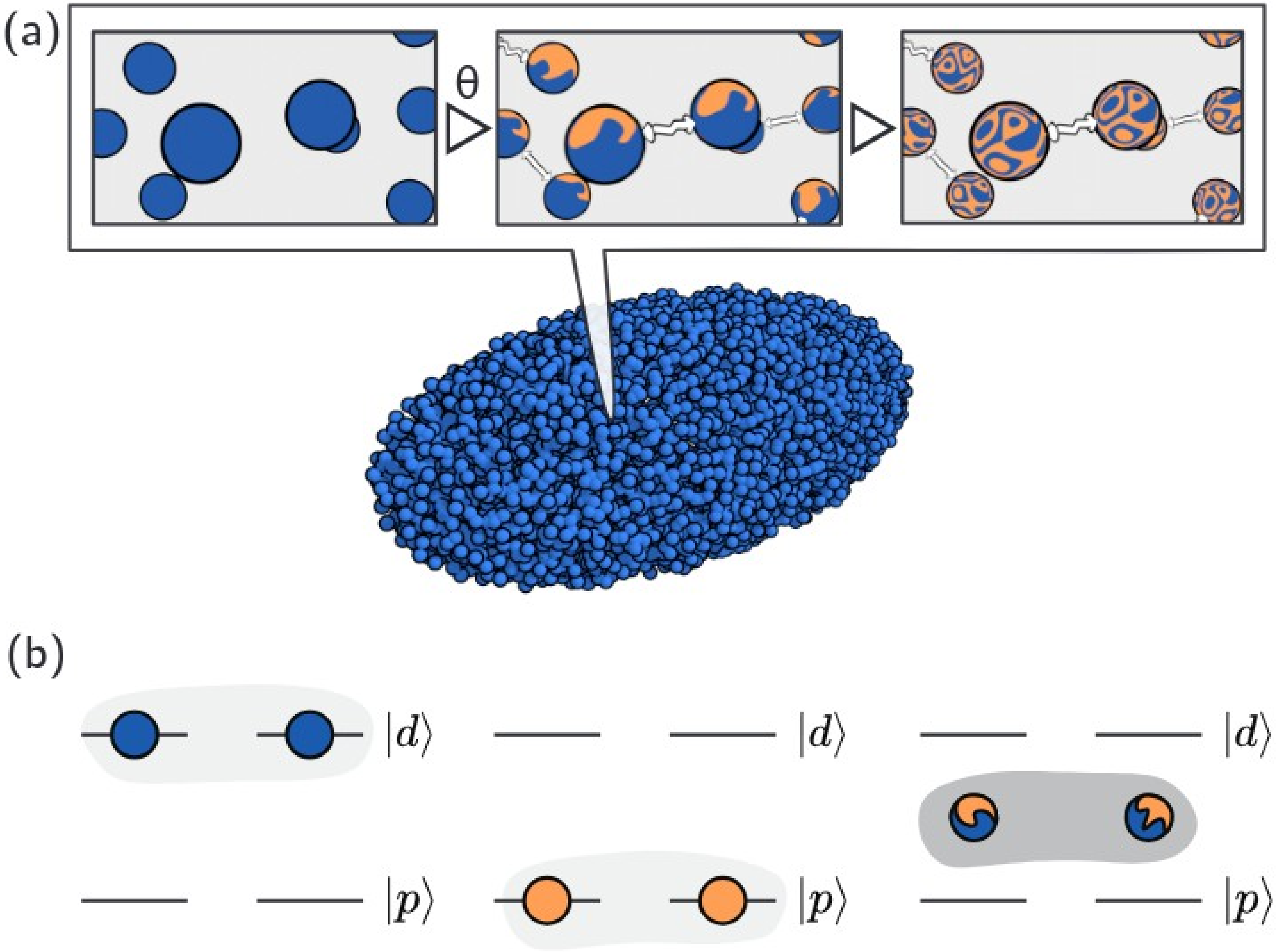
arXiv:2505.01506

excellent agreement with experimental decay rate = 2 kHz per 1 Rydberg atoms

Dipole interaction

$$\begin{cases} \langle \hat{d}^\dagger \hat{d} \rangle = n_0 \cos(\theta/2)^2 \exp\left(-n_0 \sin(\theta/2)^2 \gamma\tau\right) \\ \langle \hat{p}^\dagger \hat{p} \rangle = n_0 \sin(\theta/2)^2 \exp\left(-n_0 \cos(\theta/2)^2 \gamma\tau\right) \end{cases}$$



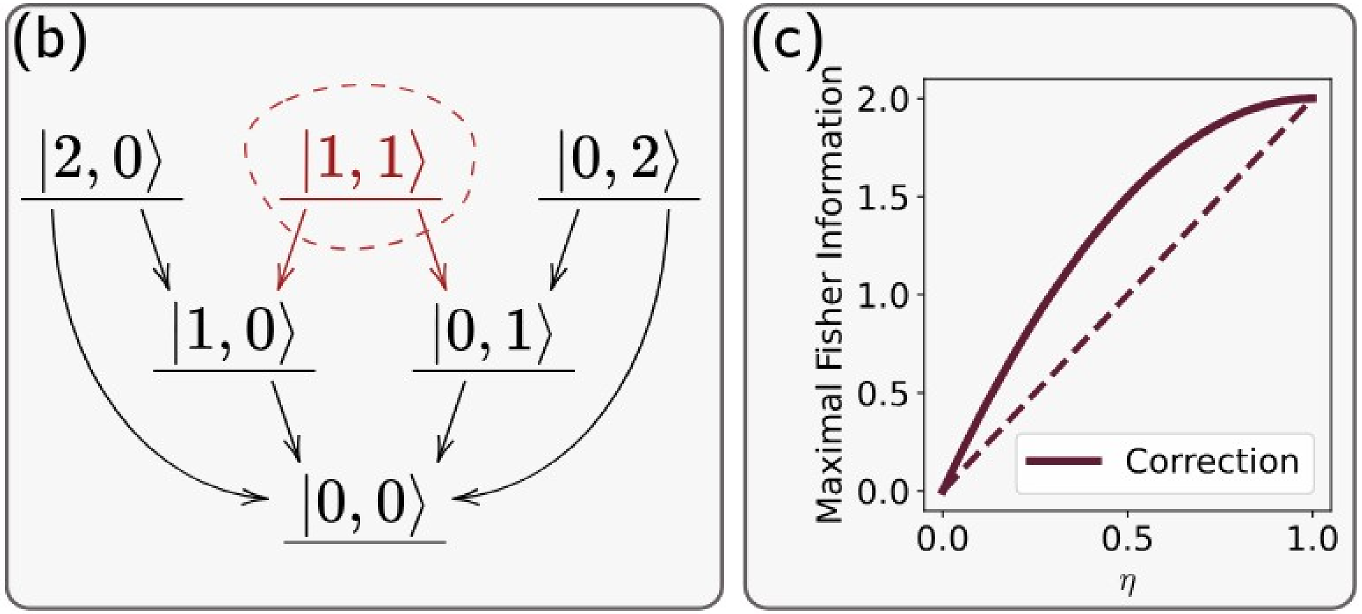


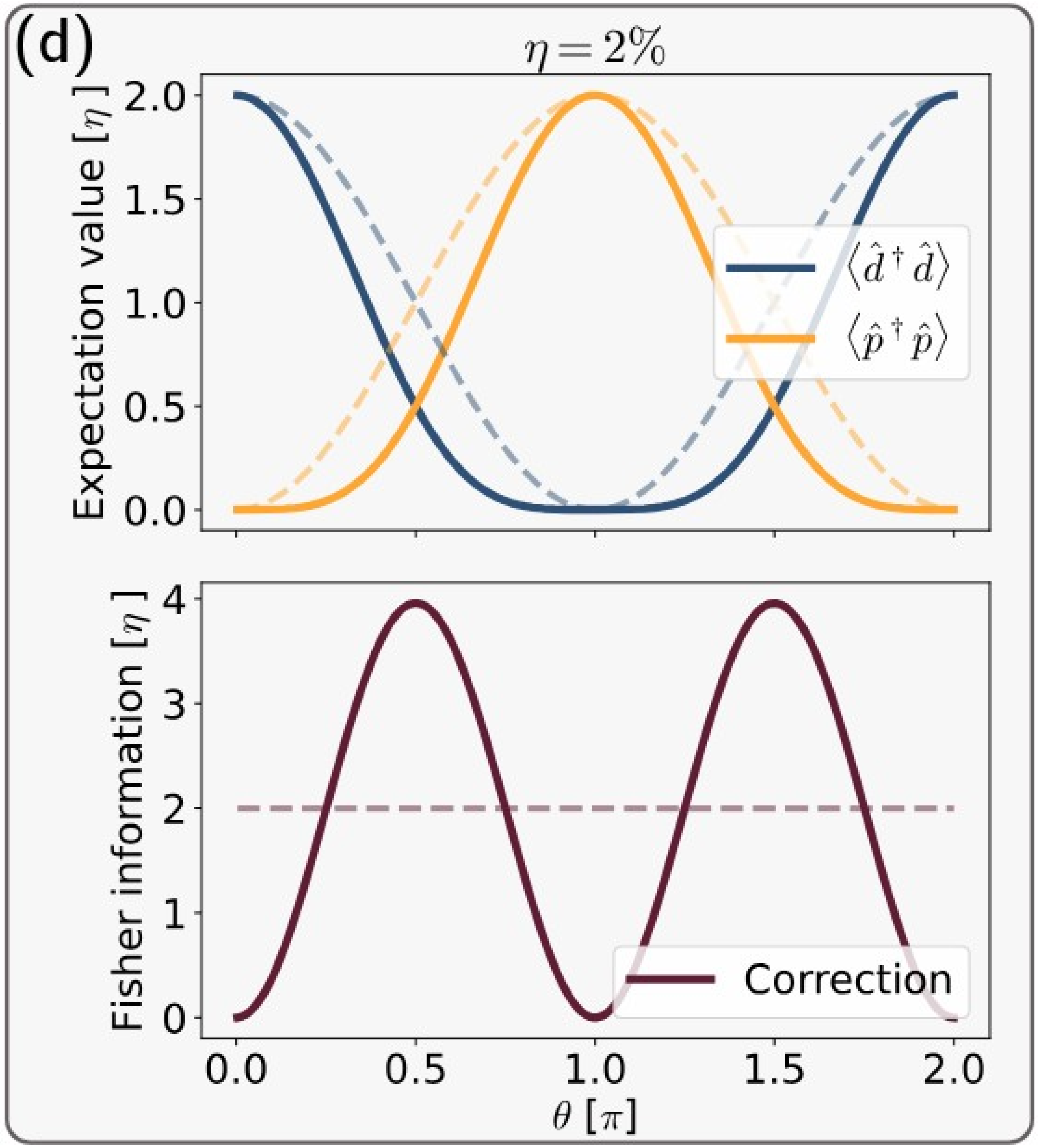
$$\hat{K}_{k,m} = \hat{p}^k \hat{d}^m \sqrt{\frac{(e^{\gamma\tau\hat{d}^\dagger\hat{d}} - 1)^k (e^{\gamma\tau\hat{p}^\dagger\hat{p}} - 1)^m}{k!m!}} e^{-\gamma\tau\hat{d}^\dagger\hat{d}\hat{p}^\dagger\hat{p}}$$

arXiv:2505.01506

The case of
2 photons (or Rydberg magnons)
Enhancing Fock-space distinguishibility

$$|\psi\rangle = \cos^2\left(\frac{\theta}{2}\right)|2,0\rangle + \frac{i}{\sqrt{2}}\sin(\theta)\,|1,1\rangle - \sin^2\left(\frac{\theta}{2}\right)|0,2\rangle$$



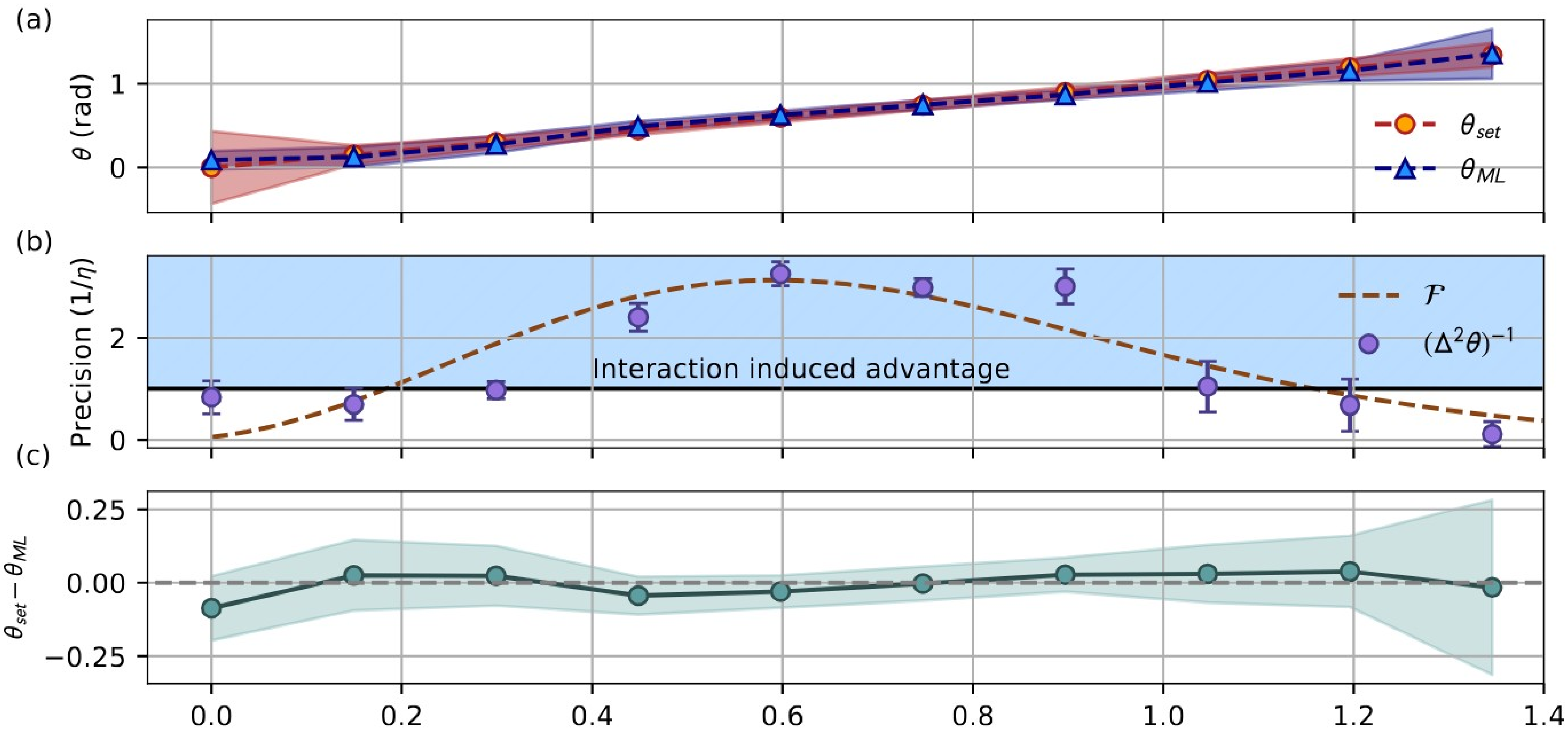


For 2 photons, it's optimal!
(assuming no amplification is allowed)

theory work with R. Demkowicz-Dobrzański

arXiv:2505.01506

Demonstration of interaction-induced advantage

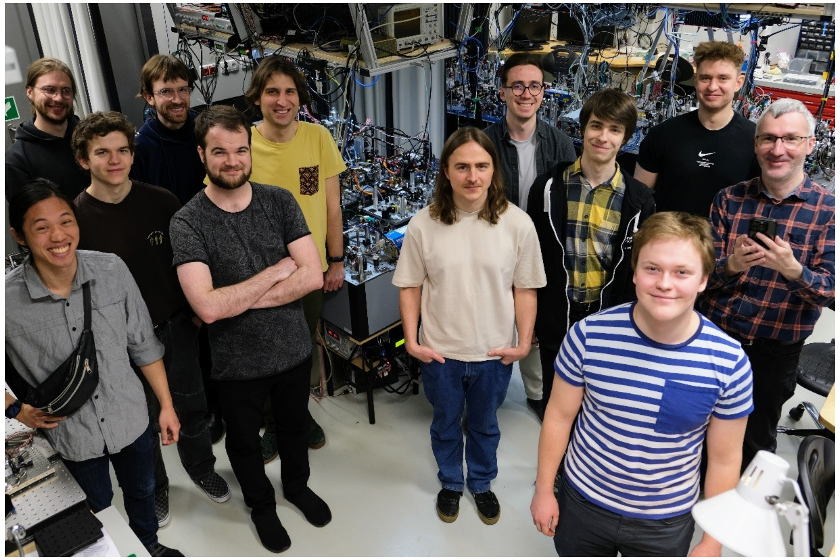


Θ (rad)

arXiv:2505.01506

Thank You

Faculty of Physics – Optics Division – optics.fuw.edu.pl
QOT Centre for Quantum Optical Technologies - qot.uw.edu.pl



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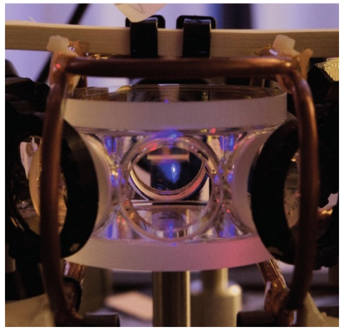

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