QUANTUM ELECTROMAGNETICS
16-20 NOVEMBER

European School of Antennas and Propagation
The EurAAP School

uc3m Universidad Carlos III de Madrid

DIRAQ
DESIGN AND RESEARCH IN RADIOFREQUENCY AND QUANTUM APPLICATIONS

LECTURE 2 · 2 HOURS · ATOMS AS ANTENNAS

# Rydberg sensing and microwave-to-optical conversion

Receiving, converting and counting microwave photons with atoms

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# Plan of the lecture

**01 Rydberg receivers for the RF engineer**

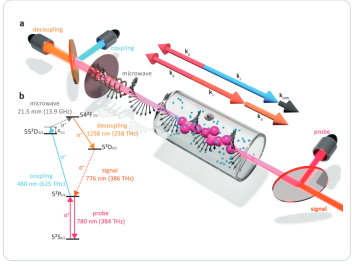
from Autler–Townes field metrology to superheterodyne and all-optical receivers; sensitivity, bandwidth, dynamic range, traceability; case study: the ESA RYDAR breadboard

**02 Microwave-to-optical frequency conversion**

the landscape: electro-optic, optomechanical, magnonic, rare-earth and atomic (Rydberg six-wave mixing) transducers; efficiency, added noise, bandwidth; linking 10 mK qubits to optical fibres

**03 Counting microwave photons at room temperature**

amplification vs. photon counting and the standard quantum limit; thermal-photon radiometry; interaction-enhanced metrology; outlook: cavities, atom arrays, space



# Where we left off



From Lecture 1:

- Rydberg transitions: MHz to THz, dipoles of $10^3\, ea_0$
- EIT turns the Rydberg state into a probe transmission
- An RF field splits the line:

$$E = \frac{h}{d}\frac{\Omega}{2\pi}$$

- Rule of thumb: $ea_0/h = 12.8\,\text{kHz/(V/m)}$

Today's question:

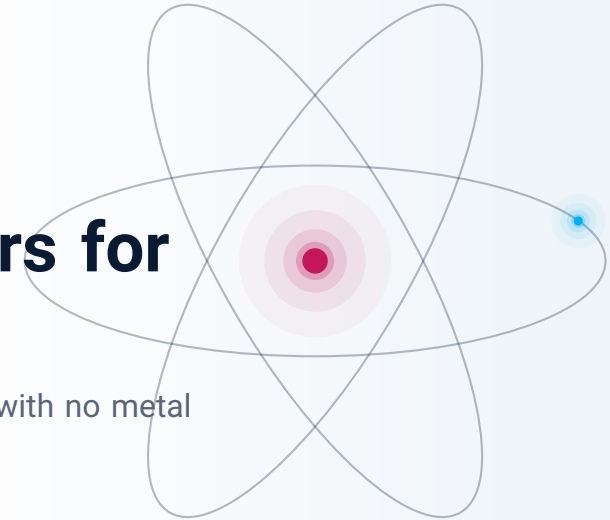
How good is this as a **receiver**, in the units an RF engineer uses, and what does quantum mechanics add that electronics cannot?

Three answers, in order of increasing "quantumness": measure the field, convert the photons, count the photons.

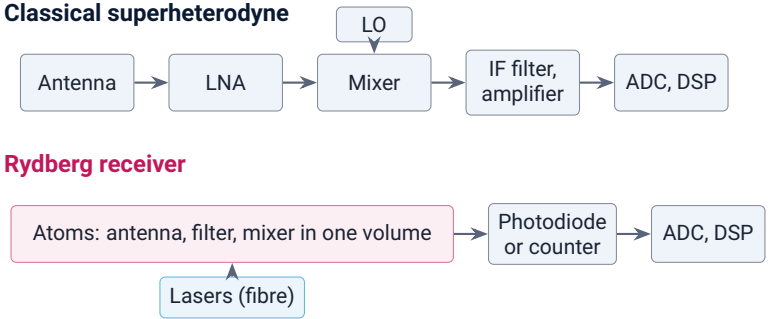
01

# Rydberg receivers for the RF engineer

Measuring fields in absolute units, with no metal antenna



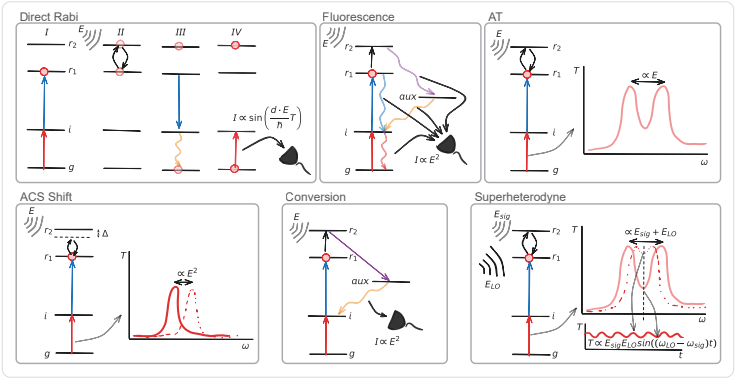
# The same block diagram, redrawn




- No conductor at the sensing point: **nothing to burn out**
- MHz to THz: only the lasers change

- Cost moved to optics: lasers, locks, power
- Bandwidth limited by the atoms

# The zoo of operating modes




Allinson *et al.*, *Rydberg receivers for space applications*, arXiv:2601.20631 (2026)

# Modes compared

| Mode | Strength | Limitation |
|---|---|---|
| Autler–Townes (EIT) | absolute, SI-traceable | strong fields only (EIT width 1–10 MHz) |
| AC-Stark shift | continuous frequency coverage | low sensitivity |
| Superheterodyne | phase; best field sensitivity | needs RF LO; EIT-limited bandwidth |
| All-optical superhet | phase with no RF LO | laser phase noise |
| Fluorescence imaging | spatial imaging, AoA | incoherent: phase lost |
| Upconversion + counting | **bandwidth, no electronic floor** | conversion efficiency |

There is no single best mode. As in classical RF, the application picks the architecture.

Adapted from Allinson *et al.*, arXiv:2601.20631 (2026)

# Translating figures of merit

Rydberg papers quote the **noise-equivalent field**:

$$\mathrm{NEF} \quad \left[\mathrm{V\,m^{-1}\,Hz^{-1/2}}\right]$$

For a short dipole ($G = 3/2$), the power a matched antenna would deliver gives

$$T_n = \frac{\mathrm{NEF}^2}{k_B \Lambda^2}, \quad \Lambda^2 = \frac{8\pi f^2}{\epsilon_0 c^3 G}$$

and then the noise figure

$$F = 10 \log_{10}(1 + T_n/290\,\mathrm{K})$$

At 13.9 GHz:

| NEF (nV/cm/$\sqrt{\mathrm{Hz}}$) | $T_n$ (K) | $F$ (dB) |
|---|---|---|
| 887 | $4 \times 10^7$ | 52 |
| 176 | $2 \times 10^6$ | 38 |
| 3.98 | 850 | 6 |

**For the antenna engineer**

Compare fairly: a dipole has a real aperture. Atoms in a mm-sized beam are not yet a well-matched aperture, so this **penalises** them, and rightly so.

# An antenna in a black body: why $P = k_B T\,\Delta f$



1. Rayleigh–Jeans brightness, per polarisation:

$$B = \frac{k_B T}{\lambda^2} \quad \left[\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}\right]$$

2. Received power, summing all directions:

$$P = \Delta f\, B \oint A_e(\theta, \phi)\, d\Omega$$

3. With $A_e = \dfrac{\lambda^2}{4\pi} G$ and $\oint G\, d\Omega = 4\pi$, the antenna theorem:

$$\oint A_e\, d\Omega = \lambda^2$$

4. The wavelength cancels:

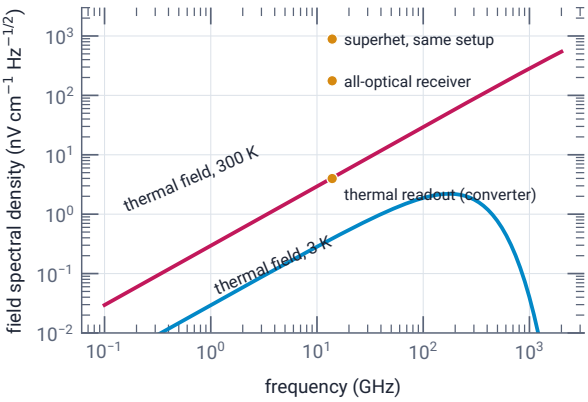
$$P = k_B T\,\Delta f$$

Any lossless antenna, of any shape, delivers the same thermal power. This is Nyquist noise from the sky.

**For the antenna engineer**

$\lambda^2$ of solid-angle-area is **one spatial mode**. Every receiver, atomic or not, is a one-mode device: $k_B T$ per Hz per mode, or $\bar{n}\, hf$ in the quantum case.

# The thermal floor, derived




Black-body energy density per Hz, for $k_B T \gg hf$:

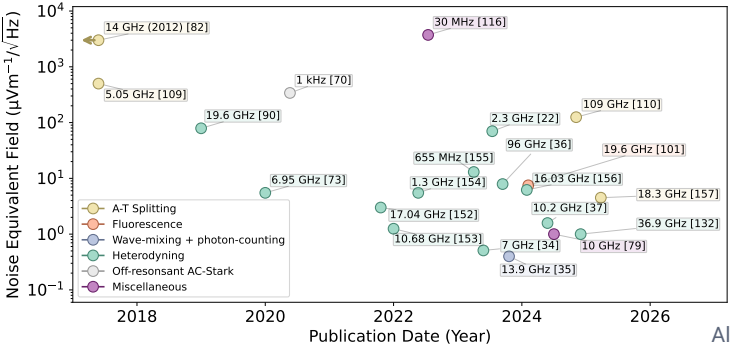
$$u_f = \frac{8\pi f^2}{c^3} k_B T = \epsilon_0 E_{\mathrm{rms}}^2$$

$$E_{\mathrm{th}} = \sqrt{16\pi f^2 k_B T / \epsilon_0 c^3}$$

**Back of the envelope**

13.9 GHz, 300 K: 4.11 nV cm$^{-1}$ Hz$^{-1/2}$ (amplitude, all polarisations). One polarisation: $4.11/\sqrt{3} = 2.37$, which matches $T_n = 300$ K for a dipole.

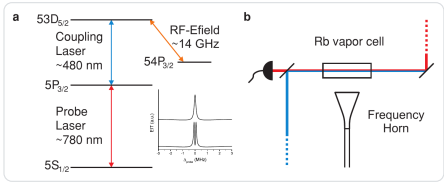
# Progress in sensitivity




- Roughly four decades in NEF since the first vapour-cell demonstrations
- Three jumps: heterodyning, better readout, photon conversion
- Compare methods with care: bandwidth, frequency and definition of *E* differ

Allinson *et al.*, arXiv:2601.20631 (2026)

# 2012: the experiment that started it



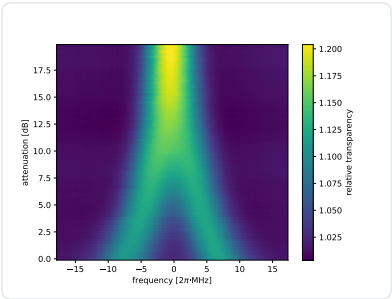

- **Oklahoma / Stuttgart:** EIT in a Rb vapour cell, $53D \rightarrow 54P$ near 14 GHz
- Strong fields: Autler–Townes splitting gives $E$ directly
- Weak fields: 30 μV cm$^{-1}$ Hz$^{-1/2}$, detection down to 8 μV/cm

A table-top cell and two lasers: a new kind of field standard.

Sedlacek *et al.*, Nat. Phys. 8, 819 (2012)

# Autler–Townes metrology: the SI link






EIT spectrum against MW attenuation (our lab)

- Splitting $\propto E$ gives a field in V/m from a frequency measurement
- Uncertainty budget: dipole, frequency axis, **cell perturbation**
- Calibration for all other modes: tie their output to one measured doublet

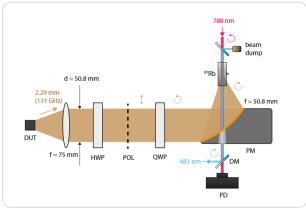
**For the antenna engineer**

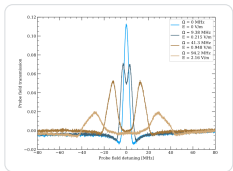
The glass cell is a dielectric resonator: the field inside is not the incident field. Correct for this, or image it.

Holloway *et al.*, IEEE TAP 62, 6169 (2014)

# Example: benchmarking automotive radar chips





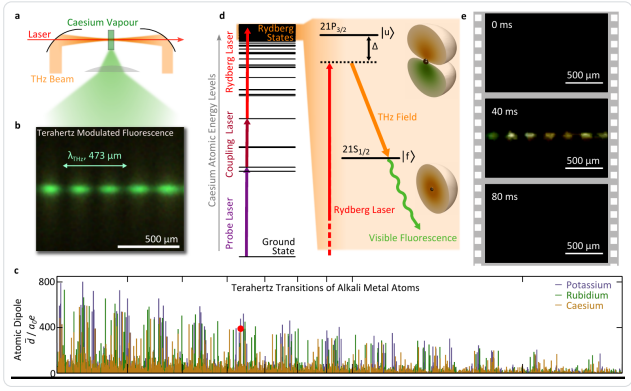




- A 131 GHz radar chip measured in **absolute units**
- 3D-printed lens and wave plates for full polarisation control
- A vapour cell as a traceable transfer standard: no calibrated horn at these frequencies needed



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

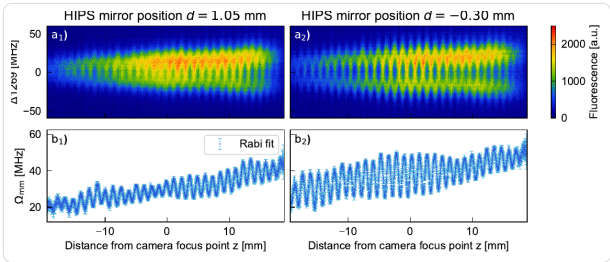
# Imaging terahertz fields with atoms




- **Durham:** a THz beam drives a Rydberg transition in Cs, and atoms fluoresce in the visible
- An ordinary camera sees the THz field **in real time**, without scanning
- Sub-wavelength resolution: the image is formed by the light, not the THz wave

Wade *et al.*, Nat. Photon. 11, 40 (2017)

# Seeing the field: calibrated mm-wave imaging




fluorescence (top) and Rabi frequency (bottom) along the cell, two reflector positions

- Camera images Rydberg fluorescence in a warm vapour
- A decay channel **dark without the mm-wave**: effectively zero background
- Autler–Townes splitting in every pixel: a calibrated **field map**

Standing waves engineered with dielectric reflectors: **the atoms image the cell they sit in**. Ko *et al.*, Opt. Express 34, 25823 (2026)

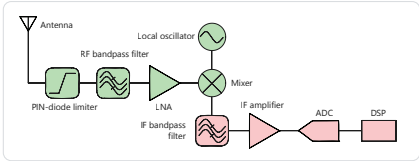
# The atom as a mixer: superheterodyne detection

Strong LO on resonance, weak signal offset by $\delta$:

$$\Omega(t) = \left|\Omega_{\mathrm{LO}} + \Omega_s e^{i(\delta t+\phi)}\right|$$

$$\approx \Omega_{\mathrm{LO}} + \Omega_s \cos(\delta t + \phi)$$

- LO biases the atoms at maximum slope of EIT
- Probe beats at $\delta$: **amplitude and phase** are preserved
- Sensitivity jumps by orders of magnitude




The mixer's nonlinearity is the **dressed atom**. Second picture: LO and coupling laser form a conversion path, and the probe beats with its own converted sideband.

Simons *et al.*, APL 114, 114101 (2019); Gordon *et al.*, AIP Adv. 9, 045030 (2019)

# Superheterodyne, derived: signal = slope $\times$ field

1. Phasor sum of LO and signal, $\Omega_s \ll \Omega_{\mathrm{LO}}$:

$$\left|\Omega_{\mathrm{LO}} + \Omega_s e^{i(\delta t+\phi)}\right| \approx \Omega_{\mathrm{LO}} + \Omega_s \cos(\delta t + \phi)$$

2. Taylor-expand probe transmission around the LO:

$$T(t) \approx T(\Omega_{\mathrm{LO}}) + \frac{\partial T}{\partial \Omega}\,\Omega_s \cos(\delta t + \phi)$$

3. The photodiode sees a beat at $\delta$:

$$\delta P(t) = P_0\,\frac{\partial T}{\partial \Omega}\,\frac{d}{\hbar} E_s \cos(\delta t + \phi)$$

- Output is **linear** in $E_s$, not $E_s^2$
- Amplitude and phase are both kept
- The LO sets the operating point, at maximum slope $\partial T/\partial \Omega$

**For the antenna engineer**

The same as a diode mixer biased by its LO: the conversion gain is the slope of the nonlinearity.

# The photon shot-noise limit, derived

1. Detected probe power $P$, photon flux $P/h\nu$. Counting $N = Pt/h\nu$ photons gives

$$\frac{\delta P}{P} = \frac{1}{\sqrt{N}} = \sqrt{\frac{h\nu}{Pt}}$$

2. Signal from the last slide, $\dfrac{\delta P}{P} = \dfrac{\partial \ln T}{\partial \Omega}\,\delta\Omega$
3. Equate them. With $\delta\Omega = d\,\delta E/\hbar$ and $t = 1\,\mathrm{s}$:

$$\mathrm{NEF}_{\mathrm{shot}} \sim \frac{\hbar}{d}\left|\frac{\partial \ln T}{\partial \Omega}\right|^{-1}\sqrt{\frac{h\nu}{P}}$$

**Back of the envelope**

$P = 10\,\mu\mathrm{W}$ at $780\,\mathrm{nm}$: $\sqrt{h\nu/P} = 1.6 \times 10^{-7}\,\mathrm{Hz}^{-1/2}$.

Slope 10 % per MHz: $1.6\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ in $\Omega/2\pi$.

With $d = 1450\,ea_0$: about $0.9\,\mathrm{nV\,cm^{-1}\,Hz^{-1/2}}$.

Up to factors of order 1. Real receivers sit 1–2 orders above this: slopes are lower, and laser noise adds.

# The projection-noise limit, derived

1. A coherent atom accumulates a phase in time $\tau$:

$$\varphi = \Omega\tau = \frac{dE\tau}{\hbar}$$

2. $N$ independent atoms: binomial statistics limit one measurement to

$$\delta\varphi = \frac{1}{\sqrt{N}}$$

3. Repeat for a total time $t$, gaining $\sqrt{\tau/t}$: $\delta E = \dfrac{\hbar}{d\tau\sqrt{N}}\sqrt{\dfrac{\tau}{t}}$

4. Normalise to $t = 1\,\mathrm{s}$:

$$\mathrm{NEF}_{\mathrm{QPN}} = \frac{\hbar}{d}\frac{1}{\sqrt{N\tau}}$$

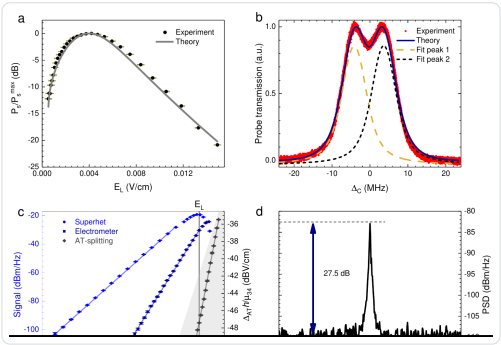
**Back of the envelope**

$N = 10^6$, $\tau = 1\,\mu\mathrm{s}$, $d = 1450\,ea_0$: about $0.09\,\mathrm{nV\,cm^{-1}\,Hz^{-1/2}}$.

Literature versions differ by $2\pi$ and by what counts as $N$: all atoms in the beam, or only the Rydberg ones.

Compare the thermal floor at 300 K: $4\,\mathrm{nV\,cm^{-1}\,Hz^{-1/2}}$ at 14 GHz.

# The atomic superhet: Jing *et al.*



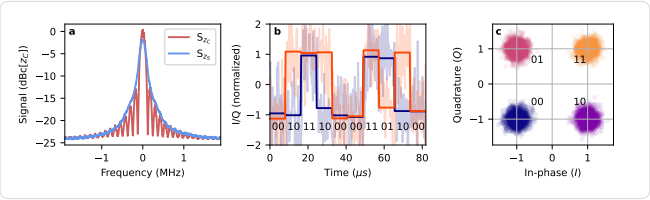

- **Shanxi:** microwave-dressed Rydberg atoms as a quantum mixer
- Sensitivity **55 nV cm$^{-1}$ Hz$^{-1/2}$**
- Linear response over a wide range, far below where Autler–Townes works (panel c)
- Sensitive to phase as well as amplitude

Nearly three orders of magnitude beyond the 2012 result, in the same kind of cell.

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

# Digital communication with atoms






- QAM signals near the 2.4 GHz Wi-Fi band in a warm vapour
- Sensitivity 0.5 μV cm$^{-1}$ Hz$^{-1/2}$
- Channel capacity estimated at 19.3 Mbps with QAM4

**Multi-tone LO:** an atomic transition loop gives an S-band superhet without an LO at the signal frequency.

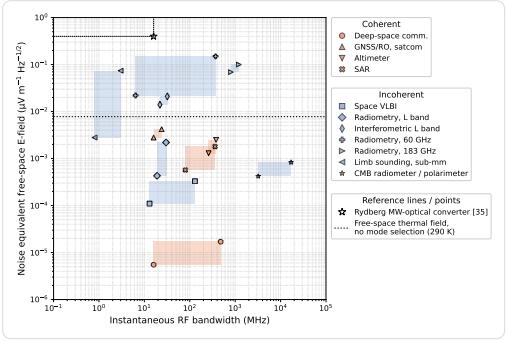
Nowosielski *et al.*, Opt. Express 32, 30027 (2024); Appl. Opt. 64, 5813 (2025)

# What limits bandwidth?

- The atomic response is a low-pass filter on the **envelope**, with corner set by EIT dynamics: typically a few MHz
- A 10 GHz carrier but only MHz of instantaneous band, tunable by lasers
- Faster readout needs stronger lasers

Steady-state models cannot predict bandwidth. The “fractured loop” formalism treats the atom as an interferometer and predicts response, bandwidth and saturation.

Kasza *et al.*, Phys. Rev. A 111, 053718 (2025)




required field sensitivity and bandwidth of space applications

Allinson *et al.*, arXiv:2601.20631 (2026)

# Noise in a Rydberg receiver



## Fundamental

- **Projection noise** of $N$ atoms, coherence time $\tau$:

$$\mathrm{NEF}_{\mathrm{QPN}} = \frac{h}{d}\frac{1}{\sqrt{N\tau}}$$

- **Photon shot noise** of the probe
- **Thermal radiation** at the atoms

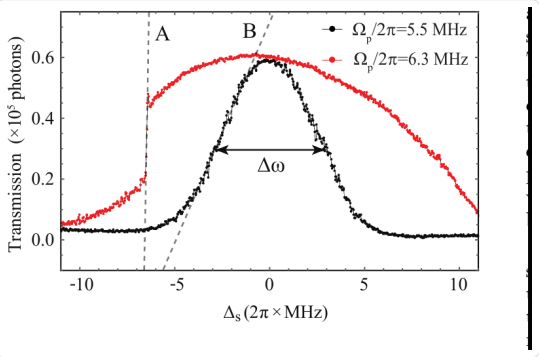
## Technical

- Laser frequency and intensity noise
- Transit noise: atoms crossing the beam
- Photodetector and amplifier noise

Today's receivers sit far above the projection-noise limit, and which $N$ belongs in the formula is itself debated.

Open research question: there is no single quantum limit of Rydberg electrometry, only a landscape of protocol-dependent limits.

# Sensing at a critical point




probe transmission near and far from the critical point

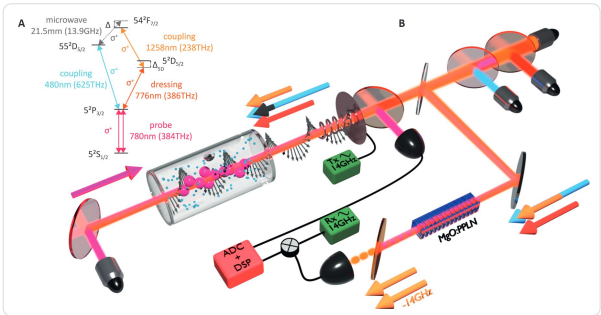
- **USTC / Durham:** a Rydberg vapour operated at a non-equilibrium phase transition
- Near criticality, Fisher information is **three orders of magnitude** larger than for independent atoms
- Sensitivity 49 nV cm$^{-1}$ Hz$^{-1/2}$

Interactions as a **resource**. A Rydberg analogue of a transition-edge sensor is one open direction.

Ding *et al.*, Nat. Phys. 18, 1447 (2022)

# Removing the RF local oscillator



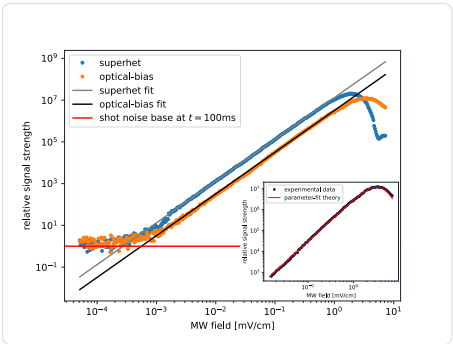



- A superhet needs an LO horn next to the cell: not truly all-optical
- **Optical bias**: two extra lasers close a loop through the Rydberg levels, and the loop's own optical field acts as LO
- The price: phase noise of **all** lasers enters directly

Borówka *et al.*, Nat. Commun. 16, 8975 (2025)

# Optical bias: performance






superhet and optical-bias response against MW field

**176**

nV/cm/$\sqrt{\text{Hz}}$ optical bias

**887**

nV/cm/$\sqrt{\text{Hz}}$ superhet, same setup

- 13.9 GHz; reliable up to 3.5 mV/cm
- Phase noise cancelled in real time with a reference: **+35 dB** SNR
- QAM signals received with no metal near the atoms

# Why atoms are hard to kill



## Strong signals

- An LNA has a damage threshold. Atoms have none in the same sense: overload saturates the response and recovers
- Out-of-band fields barely couple: resonance acts as a built-in filter

## Other unique features

- Dielectric sensor head: low-signature, minimal field perturbation
- One volume, several bands at once
- Polarisation from selection rules

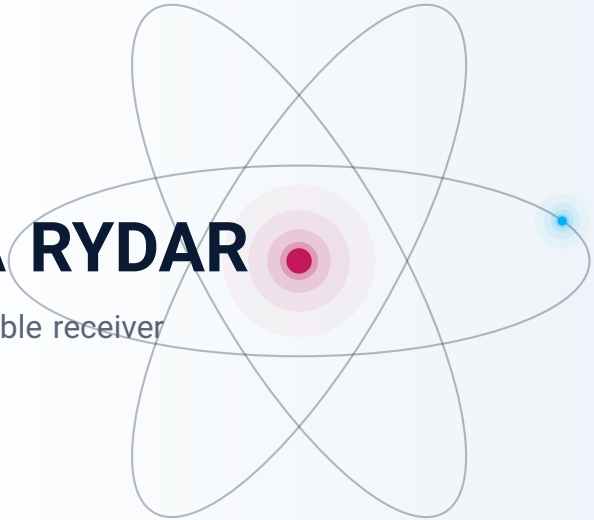
## Honest weaknesses

- Sensitivity against an LNA with a good antenna: atoms still lose
- Size, weight, power of laser systems
- Bandwidth of MHz, not GHz
- Temperature control and lifetime of cells

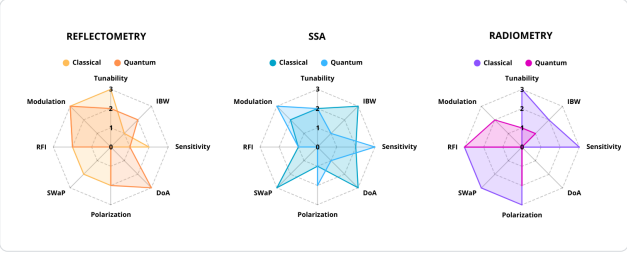
Do not sell atoms as a better LNA. Sell them where the **combination** of properties is the requirement.

# Case study: ESA RYDAR

From an optical table to a field-testable receiver



# RYDAR: finding the application first




classical against quantum capabilities, three candidate missions

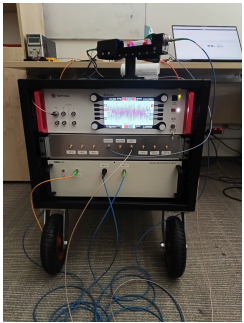
ESA contract, 20 months. UWRC (prime) with Thales Alenia Space Italia.

Candidates:

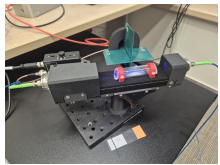
- GNSS reflectometry
- Microwave radiometry
- **Space situational awareness**

SSA won: it needs agility over widely spaced bands, tolerance of strong interference, and polarimetry.

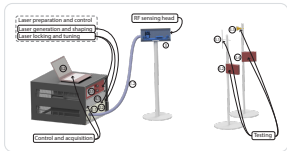
# RYDAR: from optical table to breadboard



19-inch rack



fibre-pigtailed sensor head



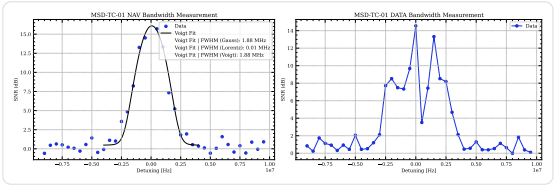

**1.55 kg**
sensor head, max.

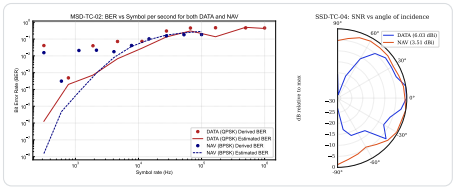
**1.63 L**
sensor head, max.

- Rb cell; 780 nm and 480 nm lasers, locked to atomic lines
- Optical engine separated from the head by fibres
- Software-defined demodulation

# RYDAR: test campaign






**28/31**

requirements met fully or partly

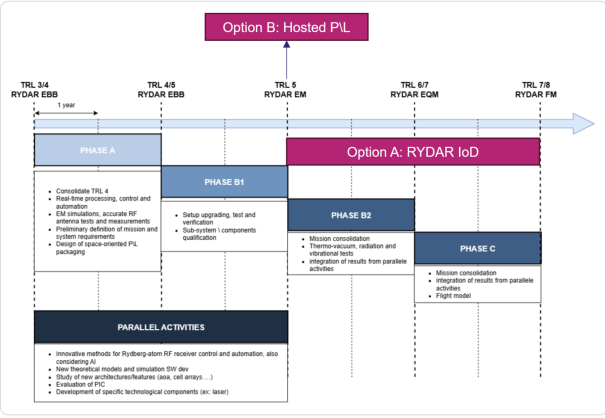
**$>$57 dB**

dynamic range (1 s)

- **Simultaneous** NAV (1.2–1.5 GHz) and DATA (20.64 GHz), no reconfiguration
- BPSK, QPSK with BER $< 10^{-3}$, several Mbit/s
- Polarisation angle reconstructed
- Field sensitivity 154–370 μV m$^{-1}$ Hz$^{-1/2}$

RYDAR final report, executive summary (UWRC, Thales Alenia Space Italia, ESA, 2026)

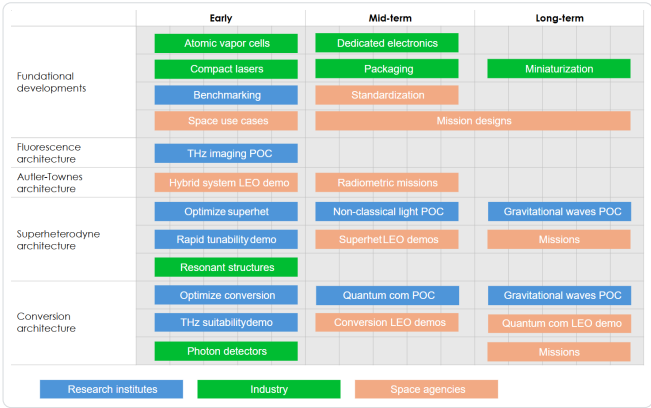
# From breadboard to orbit




- TRL 2 to **TRL 3–4**
- **Hosted payload** (3–4 years): sensor head as secondary payload
- **In-orbit demonstrator** (5–6 years): dedicated quantum receiver

Critical technologies: compact 480 nm lasers, space-grade frequency locking, micro-machined cells with thermal management.

# The ESA community roadmap




- Whitepaper from an ESA-led community effort, following a 2024 workshop at ESA
- Maps architectures to missions: radiometry, radar, communications, metrology
- Good first read for anyone joining the field

Allinson *et al.*, arXiv:2601.20631 (2026)

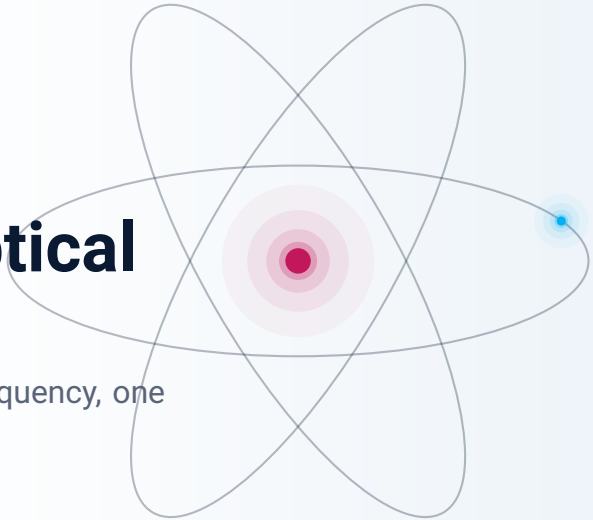
# Break

Next: instead of measuring the field, convert the photons

02

# Microwave-to-optical conversion

Over four orders of magnitude in frequency, one photon at a time



# Why convert microwaves to light?



## Quantum networks

- Superconducting qubits: 5 GHz, 10 mK
- Fibres: 193 THz, 300 K, low loss
- One 5 GHz photon is 21 μeV. One thermal fluctuation at 300 K is 1000 times that
- Link fridges with light: a **modular quantum computer**

## Sensing

- Optical detectors count single photons with near-zero dark rate. Microwave detectors cannot
- Convert first, count later
- Tolerates much higher noise and lower efficiency than quantum links

**Back of the envelope**

Frequency ratio: $193\,\text{THz}/5\,\text{GHz} \approx 4 \times 10^4$. A transducer must bridge this gap with a nonlinearity, while adding less than one photon of noise.

# What a transducer has to do

Any coherent converter is a two-port built on one idea: **a nonlinearity plus a strong pump**.

- Microwave photon: $\hat{b}$. Optical photon: $\hat{a}$
- Pump supplies the energy difference and sets the coupling $g = g_0\sqrt{n_{\mathrm{pump}}}$
- Red pump: beam-splitter

$$H = \hbar g(\hat{a}^\dagger \hat{b} + \hat{a}\hat{b}^\dagger)$$

- Blue pump: two-mode squeezer, which generates microwave–optical entanglement

Three numbers matter:

- **Efficiency** $\eta$: direct quantum transfer needs $\eta > 1/2$
- **Added noise** $N_{\mathrm{add}} \ll 1$ photon
- **Bandwidth**: sets the qubit rate

The common enemy: the pump needed for coupling heats the mK stage, which raises the noise.

# The efficiency formula, derived

Input–output equations on resonance, input on mode $b$, decay $\kappa_a, \kappa_b$:

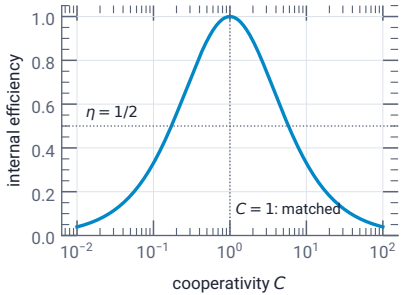
$$\dot{\hat{b}} = -\tfrac{\kappa_b}{2}\hat{b} - ig\hat{a} + \sqrt{\kappa_{b,\mathrm{e}}}\,\hat{b}_{\mathrm{in}}, \quad \dot{\hat{a}} = -\tfrac{\kappa_a}{2}\hat{a} - ig\hat{b}$$

Steady state: $\hat{a} = -\dfrac{2ig}{\kappa_a}\hat{b}$, then

$$\hat{b} = \frac{2}{\kappa_b}\,\frac{\sqrt{\kappa_{b,\mathrm{e}}}\,\hat{b}_{\mathrm{in}}}{1+C}, \quad C = \frac{4g^2}{\kappa_a\kappa_b}$$

Output $\hat{a}_{\mathrm{out}} = \sqrt{\kappa_{a,\mathrm{e}}}\,\hat{a}$ gives

$$\eta = \left|\frac{\hat{a}_{\mathrm{out}}}{\hat{b}_{\mathrm{in}}}\right|^2 = \eta_a\eta_b\,\frac{4C}{(1+C)^2}, \quad \eta_i = \frac{\kappa_{i,\mathrm{e}}}{\kappa_i}$$




**For the antenna engineer**

Peak at $C = 1$: **impedance matching**. Over-coupling reflects the signal.

# Why $\eta > 1/2$? A no-cloning argument



1. A lossy transducer is a beam-splitter with the environment:

$$\hat{a}_{\text{out}} = \sqrt{\eta}\,\hat{b}_{\text{in}} + \sqrt{1-\eta}\,\hat{v}$$

2. The lost part goes to the other port:

$$\hat{e}_{\text{out}} = \sqrt{1-\eta}\,\hat{b}_{\text{in}} - \sqrt{\eta}\,\hat{v}$$

3. If $\eta < 1/2$, the environment holds a **better** copy than the receiver

4. Then a perfect decoder for the receiver would also work for the environment, which would clone the state. Impossible:

quantum capacity $= 0$ for $\eta \leq 1/2$

Below 1/2, the link can still carry **classical** data or herald entanglement: useful, but different.

**For the antenna engineer**

Classical links survive loss by amplification. Quantum links cannot: an amplifier adds noise, as we will derive in Part 3.

# Five ways to build the bridge

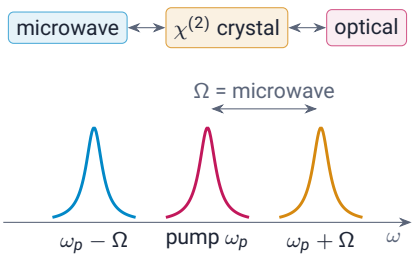


| Platform | Intermediate | Nonlinearity | Coupling |
|---|---|---|---|
| Electro-optic | none | $\chi^{(2)}$ (Pockels) | $\hat{a}^\dagger \hat{a}_p \hat{b}$ |
| Opto-electro-mechanical | phonon, MHz | radiation pressure, capacitance | $\hat{a}^\dagger \hat{a}\, \hat{x}$, $\hat{b}^\dagger \hat{b}\, \hat{x}$ |
| Piezo-optomechanical | phonon, GHz | piezoelectric, photoelastic | $\hat{b}^\dagger \hat{c}$, $\hat{a}^\dagger \hat{a}\, \hat{x}$ |
| Magnonic | magnon | Faraday effect | $\hat{b}^\dagger \hat{m}$, $\hat{a}^\dagger \hat{a}_p \hat{m}$ |
| Rare-earth / Rydberg atoms | atomic levels | atomic resonance | multi-wave mixing |

Direct conversion is simple but weak. An intermediate excitation can couple strongly to each side, but it brings its own thermal noise.

# Electro-optic: the mechanism






triply resonant: optical mode spacing equals the microwave frequency

The refractive index follows the applied field:

$$H = \hbar g_0 \left(\hat{a}_+^\dagger \hat{a}_p \hat{b} + \text{h.c.}\right)$$

Pump $\hat{a}_p \to \alpha$ gives a beam-splitter with $g = g_0\alpha$.

- Same physics as a telecom electro-optic modulator, in resonators
- $g_0$ is tiny, so cavities must have high $Q$ on **both** sides
- No intermediate mode: wide bandwidth, tens of MHz

Blue pump: microwave–optical entanglement, Sahu *et al.*, Science 380, 718 (2023)

# Electro-optic: how large is the coupling?



1. Pockels effect: $\Delta n = \frac{1}{2} n^3 r E$
2. An optical cavity shifts with the index:

$$\frac{\delta\omega}{\omega} = -\frac{\Delta n}{n}$$

3. Single microwave photon: use the vacuum field in mode volume $V$,

$$E_{\mathrm{vac}} = \sqrt{\frac{\hbar\Omega}{2\epsilon_0\epsilon_r V}}$$

4. Combine (with field overlap $\zeta \leq 1$):

$$g_0 = \frac{1}{2}\zeta\omega n^2 r E_{\mathrm{vac}}$$

**Back of the envelope**

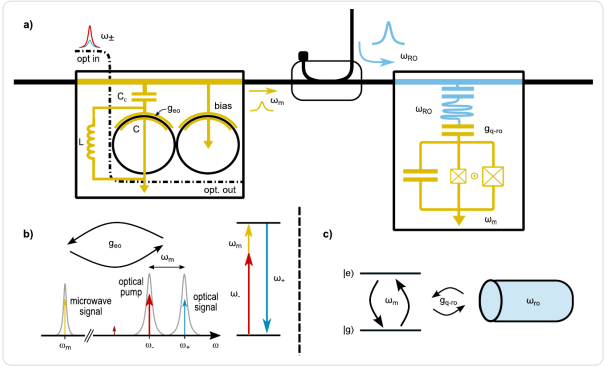
$LiNbO_3$: $n = 2.2$, $r = 30\,\mathrm{pm/V}$, $\epsilon_r = 28$. 10 GHz, $V = 10^{-11}\,\mathrm{m}^3$:

$E_{\mathrm{vac}} \approx 0.04\,\mathrm{V/m}$, so $g_0/2\pi \sim 500\,\mathrm{Hz}$.

Tiny, against $\kappa/2\pi \sim$ MHz. Hence the need for high-$Q$ resonators and pump powers that heat the fridge.

# Electro-optic: driving a qubit with light

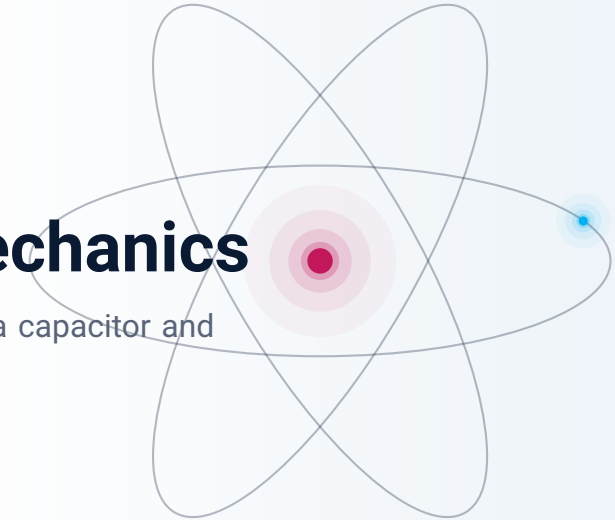





- Thin-film $LiNbO_3$ with a superconducting resonator, 14 mK
- Optical pump and signal generate a microwave field that drives a qubit: **Rabi oscillations from light**
- $\eta = 1.18 \times 10^{-2}$, $N_{\mathrm{add}} < 0.12$, 30 MHz

Bulk $LiNbO_3$: $\eta = 1.5 \times 10^{-2}$, 0.41 noise photons, 24 MHz (Sahu *et al.*, Nat. Commun. 13, 1276, 2022).

Warner *et al.*, Nat. Phys. 21, 831 (2025)



# Opto-electro-mechanics

One vibrating membrane between a capacitor and an optical cavity

# Light pushes on matter

A cavity whose length depends on displacement $x$:

$$\omega_c(x) \approx \omega_c - Gx, \quad G = \omega_c/L$$

$$H = \hbar\omega_c \hat{a}^\dagger\hat{a} + \hbar\Omega_m \hat{c}^\dagger\hat{c} - \hbar g_0\, \hat{a}^\dagger\hat{a}\,(\hat{c} + \hat{c}^\dagger)$$

$g_0 = Gx_{\mathrm{zpf}}$: frequency shift per zero-point motion.

Add a strong drive, $\hat{a} \to \bar{\alpha} + \delta\hat{a}$, and keep first order:

$$H_{\mathrm{int}} = -\hbar g(\delta\hat{a} + \delta\hat{a}^\dagger)(\hat{c} + \hat{c}^\dagger), \;\; g = g_0\bar{\alpha}$$

**Back of the envelope**

1 mW on a mirror: force $2P/c = 6.7$ pN, about the weight of a 0.1 mm water droplet.

A cavity recycles the light and boosts this by its finesse.

**For the antenna engineer**

The capacitor is the electrical twin: $\omega_{LC}(x)$ depends on the plate gap, so an $LC$ circuit obeys the **same Hamiltonian** with $\hat{a} \to \hat{b}$.

# The electrical twin: a capacitor with a moving plate

1. *LC* resonance, gap-dependent capacitance:

$$\omega_e(x) = \frac{1}{\sqrt{LC(x)}}$$

2. Expand in displacement:

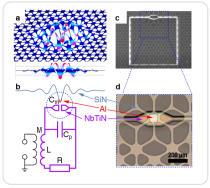
$$\omega_e(x) \approx \omega_e - G_e x, \quad G_e = \frac{\omega_e}{2}\frac{1}{C}\frac{\partial C}{\partial x}$$

3. Parallel plates, gap $d$, participation $\beta = C_m/C_{\text{total}}$:

$$G_e \approx \frac{\beta\,\omega_e}{2d}$$

4. Same form as optics, with $G_o = \omega_o/L$:

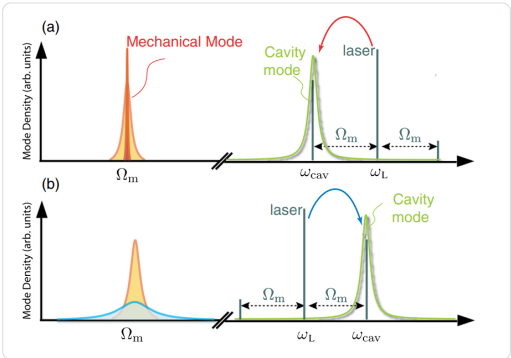
$$H = -\hbar\left(G_o \hat{a}^\dagger \hat{a} + G_e \hat{b}^\dagger \hat{b}\right)\hat{x}$$




A cavity length and a capacitor gap do the same job. One membrane does both: that is the transducer.

Small gaps give large $G_e$: tens of nm to µm are used.

# Sidebands: choosing what the drive does




Moving mirror modulates light at $\Omega_m$. In the **resolved-sideband** regime ($\kappa < \Omega_m$), the cavity selects one sideband:

- **Red drive**, $\Delta = -\Omega_m$: anti-Stokes enhanced

$$H = -\hbar g(\delta \hat{a}^\dagger \hat{c} + \delta \hat{a}\, \hat{c}^\dagger)$$

beam-splitter: **cooling**, state swap

- **Blue drive**, $\Delta = +\Omega_m$: Stokes enhanced

$$H = -\hbar g(\delta \hat{a}^\dagger \hat{c}^\dagger + \delta \hat{a}\, \hat{c})$$

two-mode squeezing: **entanglement**

Aspelmeyer, Kippenberg, Marquardt, RMP 86, 1391 (2014)

# Sideband cooling, derived

1. Golden rule: the cavity line at the scattered frequency sets the rates,

$$A_{\mp} = \frac{g^2\kappa}{(\Delta \pm \Omega_m)^2 + \kappa^2/4}$$

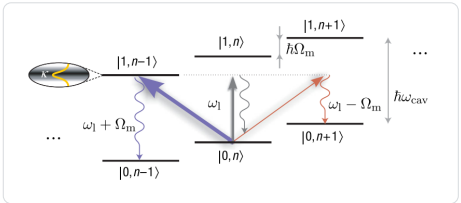
2. Red drive, $\Delta = -\Omega_m$, with $\kappa \ll \Omega_m$: $A_- = \dfrac{4g^2}{\kappa}$, $A_+ \approx \dfrac{g^2\kappa}{4\Omega_m^2}$

3. Phonon rate equation, $\Gamma = A_- - A_+$:

$$\dot{\bar{n}} = -\Gamma\bar{n} + A_+ + \gamma_m\bar{n}_{\mathrm{th}}$$

4. Steady state, strong drive:

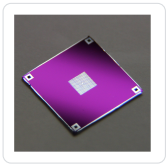
$$\bar{n}_{\mathrm{min}} \approx \frac{A_+}{\Gamma} \approx \left(\frac{\kappa}{4\Omega_m}\right)^2$$

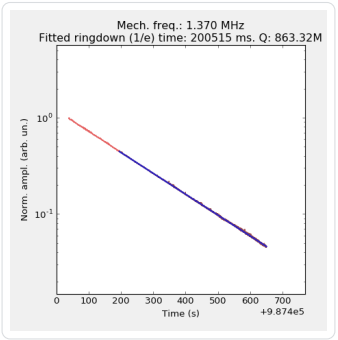



Each anti-Stokes photon removes one phonon. Ground state is reachable if $\kappa < \Omega_m$.

Same mathematics as laser cooling of a trapped ion.

# Ultracoherent membranes






ringdown: $Q = 8.6 \times 10^8$ at 1.37 MHz, a 200 s decay

- Stressed SiN, mm size, nm thick
- Phononic crystal: **soft clamping** confines the mode to a defect

**Back of the envelope**

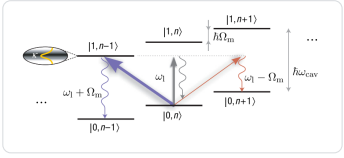
Coherent if $Qf > k_B T/h$.

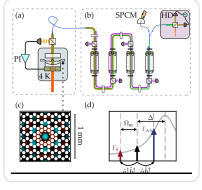
Here $Qf = 1.2 \times 10^{15}$ Hz,

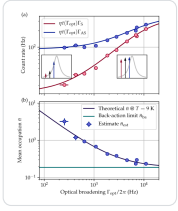
and at 300 K $k_B T/h = 6 \times 10^{12}$ Hz.

Thermal decoherence $\gamma_m \bar{n}_{\mathrm{th}}$ sets the transducer's noise. Tsaturyan *et al.*, Nat. Nanotech. 12, 776 (2017)

# Counting phonons in a membrane




- Membrane-in-the-middle at 1.5 MHz, cascaded Fabry–Pérot filters, single-photon counter
- Raman ratio $\Gamma_S/\Gamma_{AS} \propto (\bar{n}+1)/\bar{n}$: **quantum thermometer**
- $\bar{n} = 0.23 \pm 0.02$ phonons

Galinskiy, Tsaturyan, Parniak, Polzik, Optica 7, 718 (2020); photon–phonon correlations: Galinskiy *et al.*, PRL 133, 173605 (2024)

# One oscillator, two cavities: the derivation



1. Two red drives. Equations on resonance, mechanics $\hat{c}$, input on the microwave side:

$$\dot{\hat{c}} = -\tfrac{\gamma_m}{2}\hat{c} - ig_o\hat{a} - ig_e\hat{b}$$

$$\dot{\hat{b}} = -\tfrac{\kappa_e}{2}\hat{b} - ig_e\hat{c} + \sqrt{\kappa_e}\,\hat{b}_{\mathrm{in}}$$

$$\dot{\hat{a}} = -\tfrac{\kappa_o}{2}\hat{a} - ig_o\hat{c}$$

2. Cavities are fast: set $\dot{\hat{a}} = \dot{\hat{b}} = 0$:

$$\hat{a} = -\frac{2ig_o}{\kappa_o}\hat{c}, \quad \hat{b} = \frac{2\hat{b}_{\mathrm{in}}}{\sqrt{\kappa_e}} - \frac{2ig_e}{\kappa_e}\hat{c}$$

3. Insert into $\dot{\hat{c}} = 0$, with $\Gamma_i = 4g_i^2/\kappa_i$:

$$\hat{c} = \frac{-2i\sqrt{\Gamma_e}\,\hat{b}_{\mathrm{in}}}{\gamma_m + \Gamma_o + \Gamma_e}$$

4. Output $\hat{a}_{\mathrm{out}} = \sqrt{\kappa_o}\,\hat{a}$. With cooperativities $C_i = \Gamma_i/\gamma_m$:

$$\eta = \left|\frac{\hat{a}_{\mathrm{out}}}{\hat{b}_{\mathrm{in}}}\right|^2 = \frac{4\Gamma_e\Gamma_o}{(\gamma_m + \Gamma_e + \Gamma_o)^2} = \frac{4C_eC_o}{(1 + C_e + C_o)^2}$$

# One oscillator, two cavities: what it means



- Best at $C_e = C_o \gg 1$: **balanced** ports
- Bandwidth $\approx \gamma_m(1 + C_e + C_o)$: narrow, typically kHz
- Added noise $\sim \bar{n}_{\mathrm{th}}/C$: need $C \gg \bar{n}_{\mathrm{th}}$

**Back of the envelope**

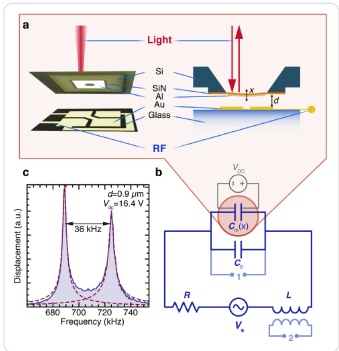
Bagci *et al.*: $C_{\mathrm{em}} \approx 6800$ at room temperature: effective noise temperature $T/C \approx 40\,\mathrm{mK}$. Next slide.

Microwaves and light never meet. Each talks only to the phonon, which passes the signal on.

**For the antenna engineer**

The phonon is a low-frequency IF stage between two carriers. Its $Q$ decides how quiet this IF stage is.

# Radio waves to light, at room temperature

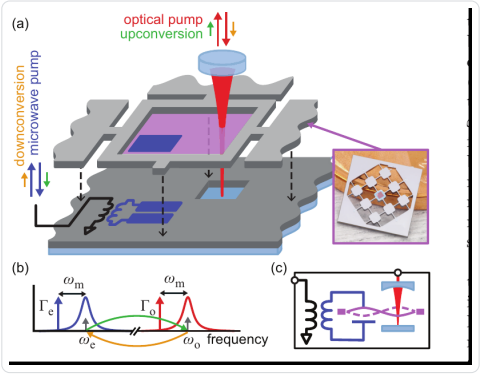



- **Copenhagen, 2014:** a metallised SiN membrane forms a capacitor of an *LC* circuit, and is read out by a laser
- 0.72 MHz mechanical mode, tuned into resonance by a bias voltage
- Added noise $T_m/C_{\mathrm{em}} \approx 40$ mK, with $C_{\mathrm{em}} \approx 6800$, at room temperature
- Limit of $5\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$, about $-210$ dBm/Hz, near 1 MHz

A room-temperature RF preamplifier made of light and a drum.

Bagci *et al.*, Nature 507, 81 (2014)

# Microwave to light at the quantum level




**JILA line of experiments:**

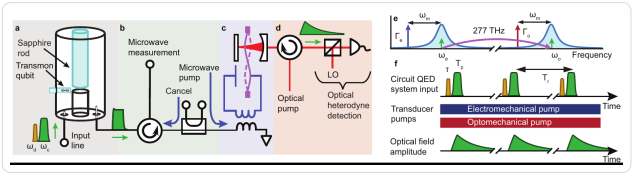
- 2014: bidirectional conversion, Andrews *et al.*, Nat. Phys. 10, 321
- 2018: $\eta = 47\,\%$ below 100 mK, 38 noise photons with feedforward (Higginbotham, Nat. Phys. 14, 1038)
- 2022: mechanics sideband-cooled to its ground state: $\eta = 47\,\%$, $N_{\mathrm{add}} = 3.2$, continuous operation

Highest efficiency among mK solid-state transducers. Weak point: kHz bandwidth.

Brubaker *et al.*, Phys. Rev. X 12, 021062 (2022)

# Reading a qubit with light, and the electrical twin

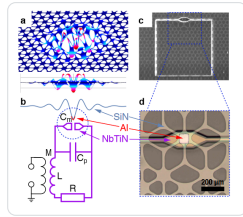





Transmon state read out optically through a membrane transducer.

Low back-action: the light never reaches the qubit.

Delaney *et al.*, Nature 606, 489 (2022)




Copenhagen: soft-clamped membrane,

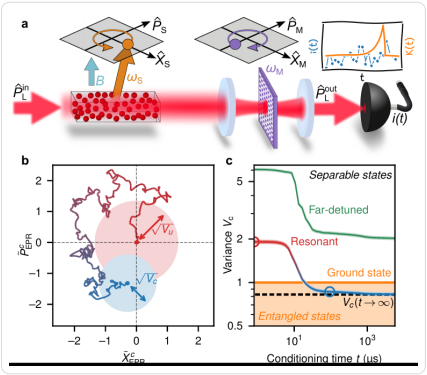
$Q > 10^9$ at 30 mK, cooled electrically to

$\bar{n} = 0.76 \pm 0.16$

Seis *et al.*, Nat. Commun. 13, 1507 (2022)

# Hybrid quantum systems: a membrane meets atoms





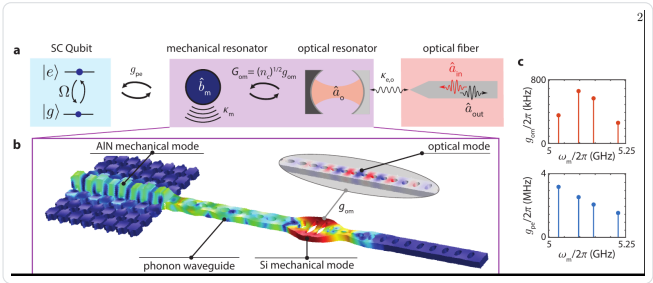

- A mm-size membrane and $10^9$ Cs spins, in separate setups, linked by light
- Spin oscillator as an effective **negative mass**: back-action evasion
- Entanglement of motion and spin: EPR variance $0.83 \pm 0.02 < 1$

Atoms and mechanics speak the same language of oscillators and light. Rydberg ensembles, membranes and cavities are part of one toolbox.

Thomas, Parniak *et al.*, Nat. Phys. 17, 228 (2021)

# Piezo-optomechanics: GHz phonons on a chip

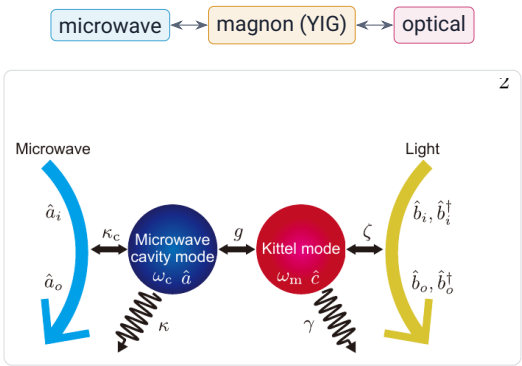
qubit, 5 GHz ↔ GHz phonon ↔ optical photon




- Piezoelectric AlN drives a phonon in a silicon optomechanical crystal
- Phonon frequency equals the microwave: no frequency mismatch on that side
- Transmon excitation turned into a telecom photon
- $\eta = 8.8 \times 10^{-6}$, $N_{\mathrm{add}} = 0.57$, 15 mK

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

# Magnons: spins in a ferromagnet

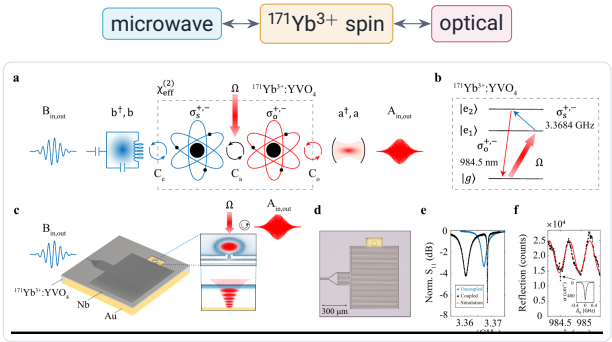



- Collective spin wave (Kittel mode) in a YIG sphere: very strong coupling to microwaves
- Faraday effect couples it to light
- Works at room temperature, with GHz tuning by a magnet

The optical side is the bottleneck: $\eta \sim 10^{-10}$ in 2016, and $\sim 10^{-8}$ by 2020, so optical cavities are the key.

Hisatomi *et al.*, PRB 93, 174427 (2016); Zhu *et al.*, Optica 7, 1291 (2020)

# Rare-earth ions: an atom frozen in a crystal




- Ions with both optical and microwave transitions: **atoms that do not move**
- Three-level scheme, similar in spirit to Rydberg mixing
- Yb:$YVO_4$ on chip: $\eta = 7.6 \times 10^{-3}$, $N_{\mathrm{add}} = 1.24$, 0.5 MHz, no optical cavity
- Limited by the inhomogeneous linewidth

Xie *et al.*, Nat. Phys. 21, 931 (2025);
Bartholomew *et al.*, Nat. Commun. 11, 3266 (2020)

# Transducer platforms compared

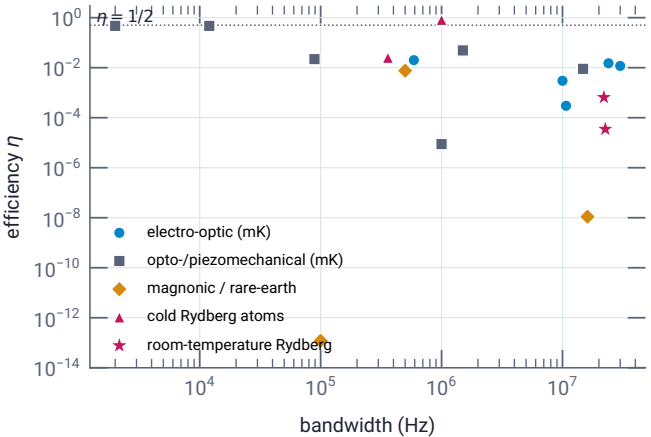


| Platform | Efficiency $\eta$ | Added noise | Bandwidth | Temperature |
|---|---|---|---|---|
| Electro-optic ($LiNbO_3$) | $1.2 \times 10^{-2}$ | $< 0.12$ | 30 MHz | 14 mK |
| Piezo-optomechanical | $2.2 \times 10^{-2}$ | 0.94 | 89 kHz | 30 mK |
| Electro-optomechanical (membrane) | 0.47 | 3.2 | 2 kHz | 40 mK |
| Magnonic (YIG) | $1.1 \times 10^{-8}$ | not reported | 16 MHz | 300 K |
| Rare-earth ($Yb:YVO_4$) | $7.6 \times 10^{-3}$ | 1.24 | 0.5 MHz | $< 1$ K |
| **Cold Rydberg**, free space | 0.82 | – | 1 MHz | µK atoms |
| **Cold Rydberg**, mm-wave cavity | $2.5 \times 10^{-2}$ (internal 0.58) | 0.6 | 360 kHz | 5 K environment |
| **Hot Rydberg** (this lecture) | next slides | thermal-limited | 16 MHz | 300 K |

No platform yet has all three: $\eta > 1/2$, $N_{\mathrm{add}} \ll 1$ and MHz bandwidth. Efficiency definitions also differ between rows.

Solid state: Sekine *et al.*, npj Nanophotonics 3, 42 (2026). Tu *et al.*, Nat. Photon. 16, 291 (2022). Kumar *et al.*, Nature 615, 614 (2023)

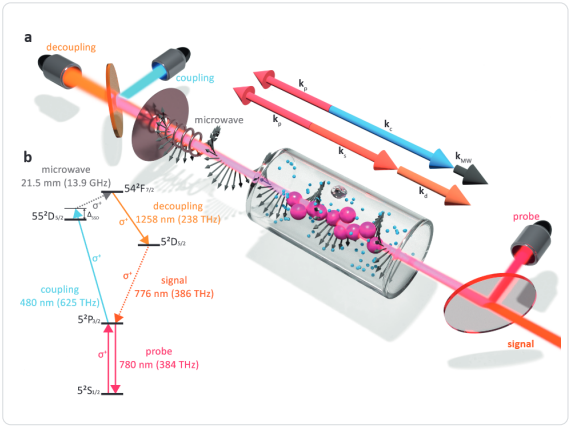
# The landscape in one plot




- Clear split: solid-state platforms cooled to mK; atoms in free space
- Atoms bring their own **identical, narrow** resonators
- Room-temperature stars: per-mode efficiency of free-space thermal detection, a stricter definition

Selected results; values from Sekine *et al.* (2026), Tu (2022), Kumar (2023), Jastrzębski *et al.* (2026)

# Rydberg six-wave mixing



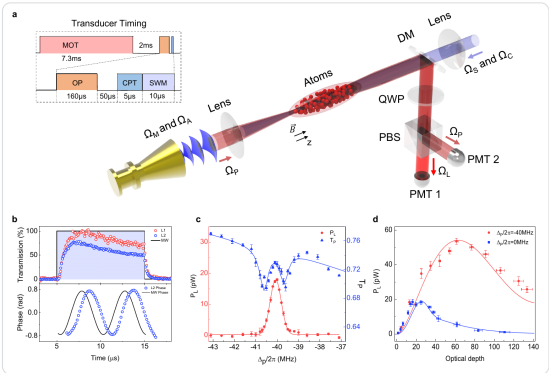

Closed loop of six fields in Rb:

$$\nu_s = \nu_c + f_{\mathrm{MW}} - \nu_d$$

- $5S \xrightarrow{\text{probe}} 5P \xrightarrow{\text{coupling}} 55D \xrightarrow{\text{MW}} 54F \xrightarrow{\text{decoupling}} 5D$
- Signal $5D \rightarrow 5P$ at 776 nm, and the **probe again** closes the loop to $5S$: six fields
- $625 - 238 \approx 387$ THz: the probe cancels
- Fully **coherent**: amplitude and phase of the MW are copied to the signal

Borówka *et al.*, Nat. Photon. 18, 32 (2024)

# Cold atoms: record conversion efficiency




- **Tu *et al.*:** off-resonant six-wave mixing in a long, thin cold-atom cloud
- $\eta = 82 \pm 2\,\%$, about 1 MHz bandwidth
- **Kumar *et al.*:** mm-wave resonator, optical cavity, 5 K: internal $\eta = 58(11)\,\%$, 360 kHz, 0.6 added photons

First cold-atom conversion: Han *et al.*, PRL 120, 093201 (2018); Vogt *et al.*, PRA 99, 023832 (2019)

Tu *et al.*, Nat. Photon. 16, 291 (2022); Kumar *et al.*, Nature 615, 614 (2023)

# Six-wave mixing, derived: from atoms to signal

1. Perturbation theory around the loop: each field gives Rabi frequency over $D_i = \Gamma_i/2 - i\Delta_i$. The probe enters twice:

$$\rho_s \propto \frac{|\Omega_p|^2\,\Omega_c\,\Omega_{\mathrm{MW}}\,\Omega_d^*}{\prod_i D_i}$$

2. The coherence radiates (slowly-varying envelope):

$$\partial_z E_s = \frac{ik_s}{2\epsilon_0} P_s, \quad P_s = 2N d_s \rho_s\, e^{i\Delta k z}$$

3. Integrate along the cell, length $L$:

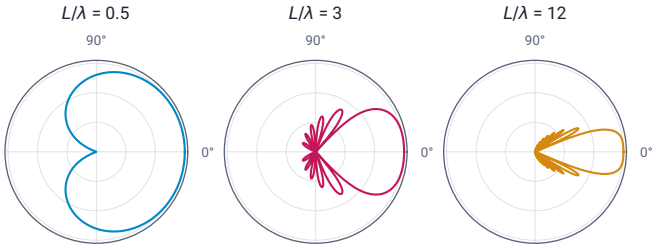
$$E_s(L) \propto \int_0^L e^{i\Delta k z} dz \;\propto\; L\,\mathrm{sinc}\frac{\Delta k L}{2}$$

$$\eta \propto (NL)^2\,\mathrm{sinc}^2(\Delta k L/2)$$

- **Linear** in $\Omega_{\mathrm{MW}}$: phase is copied, conversion is coherent
- $|\Omega_p|^2$: probe phase cancels, so $\mathbf{k}_p$ drops out of phase matching
- Efficiency grows as $(NL)^2$ while $\eta \ll 1$

Steady state, no cavity, no cryostat: the atoms are a $\chi^{(5)}$ medium with resonant enhancement.

# Phase matching is an array factor




line-source pattern $\mathrm{sinc}^2\left[(L/\lambda)(1-\cos\theta)\right]$, 30 dB range

Efficient only if

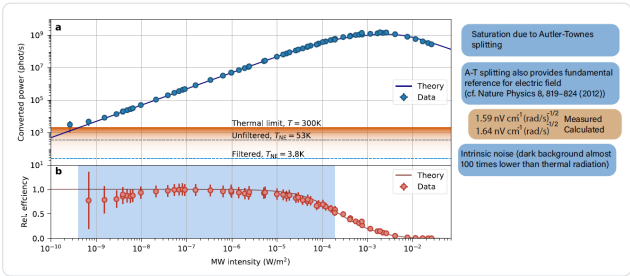
$$\mathbf{k}_s = \mathbf{k}_c + \mathbf{k}_{\mathrm{MW}} - \mathbf{k}_d$$

Along a long cell,
$\Delta k(\theta) = k(1-\cos\theta)$.

**For the antenna engineer**

Each atom is an element and laser phases set the progressive excitation: an **end-fire travelling-wave line source**, with the pattern steered by beam angles. Real patterns also depend on Gaussian beams and Gouy phase, as in our Nature Photonics model.

# Room-temperature conversion: results




Borówka *et al.*, Nat. Photon. 18, 32 (2024)

**57 dB**
dynamic range

**16 MHz**
bandwidth

- Continuous-wave, free space, 13.9 GHz
- Theory reproduces response and saturation
- Photon counting reaches the **thermal limit**: measured 3.98 nV cm$^{-1}$ Hz$^{-1/2}$, predicted 4.11

# We are seeing thermal photons

With no MW source connected, photons still arrive:

- 85 % thermal radiation of the room
- 13 % fluorescence of optics, 2 % other
- Noise-equivalent temperature 53 K, down to 3.8 K with a filter cavity

Test of the statistics, Hanbury Brown–Twiss:

$$g^{(2)}(\tau) = 1 + \left(g^{(2)}(0) - 1\right) e^{-2\tau/\tau_0}$$

$$g^{(2)}(0) = 1.868 \pm 0.035, \quad \tau_0 = 26.0(15)\,\text{ns}$$

**Back of the envelope**

Bandwidth 16 MHz implies coherence time of order $1/\pi\Delta f \approx 20$ ns. The bunching width **is** the conversion band, by the Wiener–Khinchin theorem.

The Hanbury Brown–Twiss effect of 1956, seen for **microwave photons** in free space, at room temperature, with a single-photon counter.

# How efficient is it, really?

- Interaction region: ∼100 µm beams. Field: $\lambda \sim$ cm
- Area-normalised efficiency (photons out per photons through the beam): measured $3.1 \pm 0.4\,\%$, predicted $2.8 \pm 1.6\,\%$
- Per free-space mode it is much smaller

## Per-mode efficiency [unpublished]

$$\eta_{\mathrm{mode}} = \frac{\sigma}{A_{\mathrm{mode}}}, \quad A_{\mathrm{mode}} = \frac{\lambda \ell}{4\pi}$$

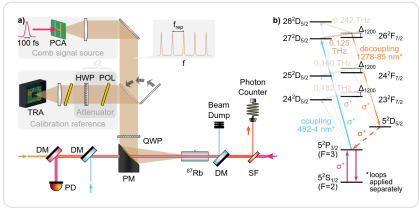
$\sigma$: conversion cross-section, $\ell$: length of the ensemble. Its transverse size drops out.

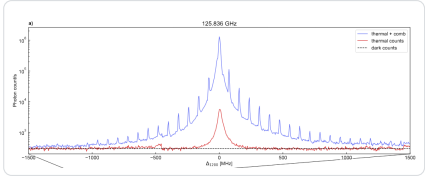
**For the antenna engineer**

This is the familiar antenna statement. A sub-wavelength collector has an effective aperture set by $\lambda$, not by its physical area. Quoting $\sigma$ over beam area flatters any small sensor.

Headline efficiencies from different groups are not comparable until they use the same reference mode. Ask before you compare.

# Towards mm-waves and terahertz




- Same scheme, lower *n*: individual lines of a THz comb, 0.125 THz to 0.242 THz
- Octave-spanning, MHz selectivity, tuned by lasers
- Field calibrated against atomic constants
- Sensitivity 45.2 fW cm$^{-2}$ Hz$^{-1/2}$ per comb mode, at room temperature

Krokosz *et al.*, Optica 12, 1854 (2025)

# What is missing for qubit links?



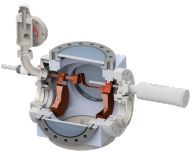
## Hot atoms today

- Thermal background of 300 K: $\bar{n} \approx 450$ photons per mode at 13.9 GHz
- Low per-mode efficiency
- Perfect for sensing, not for qubits

## The cold-atom route

- Tu *et al.*: 82 %, about 1 MHz
- Kumar *et al.*: 0.6 added photons, with a superconducting resonator

The hard part is **mode matching**: bringing a microwave mode and an atomic ensemble together, without heating the cryostat with lasers.

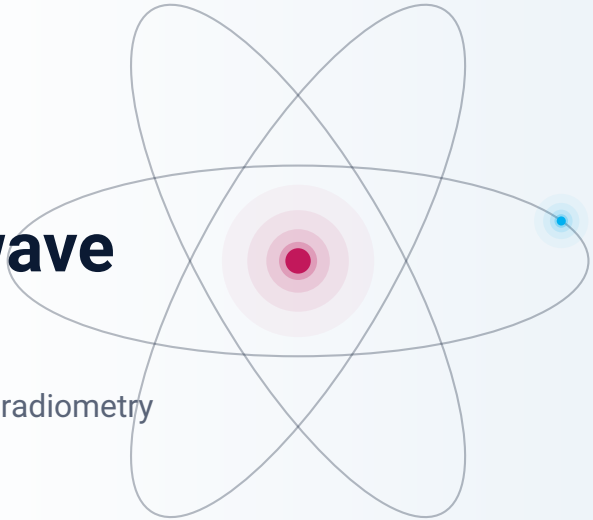


QURA: cavity in vacuum with high optical access

03

# Counting microwave photons

Room-temperature photon counting, radiometry and quantum limits



# Amplifiers vs. photon counters



## Linear amplifier

- Measures both quadratures $\hat{X}, \hat{P}$
- They do not commute, so noise is unavoidable:

$$N_{\mathrm{add}} \geq \tfrac{1}{2}\left(1 - 1/G\right)$$

- Standard quantum limit, Haus & Mullen, Caves
- Link to Tuesday's lecture: TWPAs approach this

## Photon counter

- Measures $\hat{n} = \hat{a}^\dagger \hat{a}$
- Phase is discarded
- Vacuum has **zero variance**: no quantum penalty
- Limited by efficiency and dark counts

For weak incoherent signals, phase is useless: paying a quantum of noise to measure it is a bad deal.

Caves, PRD 26, 1817 (1982); Lamoreaux *et al.*, PRD 88, 035020 (2013)

# The amplifier's quantum of noise, derived

1. Try a noiseless amplifier: $\hat{a}_{\mathrm{out}} = \sqrt{G}\,\hat{a}$
2. Check the commutator:

$$[\hat{a}_{\mathrm{out}}, \hat{a}^{\dagger}_{\mathrm{out}}] = G \neq 1$$

Not a valid bosonic mode: **forbidden**

3. Add a noise mode to repair it:

$$\hat{a}_{\mathrm{out}} = \sqrt{G}\,\hat{a} + \sqrt{G-1}\,\hat{b}^{\dagger}$$

$$[\hat{a}_{\mathrm{out}}, \hat{a}^{\dagger}_{\mathrm{out}}] = G - (G-1) = 1$$

4. With $\hat{b}$ in vacuum, input-referred noise:

$$N_{\mathrm{add}} = \tfrac{1}{2}\left(1 - \frac{1}{G}\right) \xrightarrow{G \gg 1} \tfrac{1}{2}$$

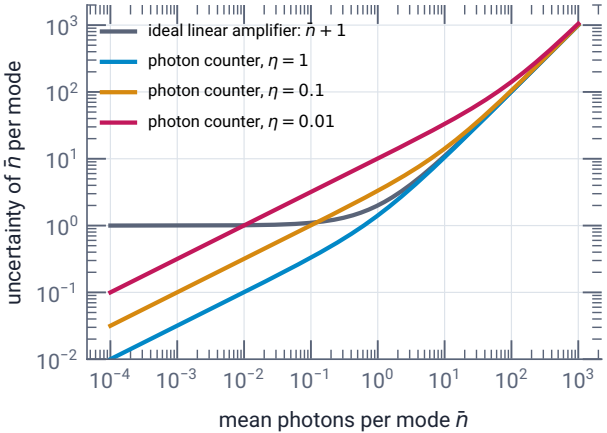
The noise is not an engineering defect. It is required by the commutator, because the amplifier preserves both quadratures.

**Back of the envelope**

$T_{\mathrm{SQL}} = hf/2k_B$: 0.12 K at 5 GHz, 3 K at 126 GHz.

A photon counter measures only $\hat{n}$. It preserves no phase, so it owes no such debt.

# When does counting win?



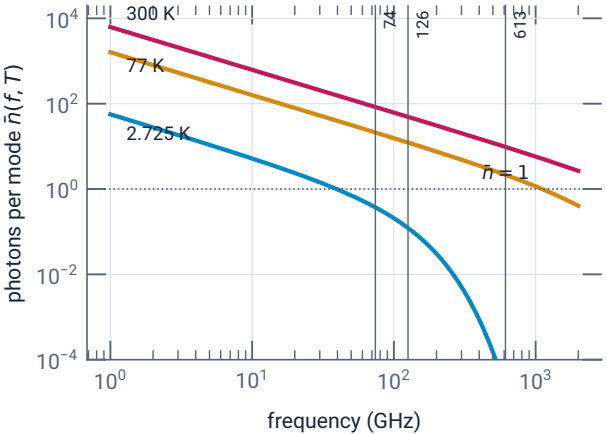

Uncertainty of mean occupation $\bar{n}$, per mode:

$$\delta_{\mathrm{amp}} = \bar{n} + 1, \quad \delta_{\mathrm{count}} = \sqrt{\bar{n}^2 + \bar{n}/\eta}$$

- $\bar{n} \gg 1$: both reach $\bar{n}$, the thermal noise itself
- $\bar{n} \ll 1$: counter wins by $\sqrt{\eta/\bar{n}}$, if $\eta > \bar{n}$

Even a lossy counter beats an **ideal** amplifier at low enough occupation.

# Thermal photons per mode




$$\bar{n} = \frac{1}{e^{hf/k_B T} - 1} \approx \frac{T}{T_Q}, \quad T_Q = \frac{hf}{k_B}$$

- Quantum temperature scale: 0.24 K at 5 GHz, 6.0 K at 126 GHz, 29 K at 613 GHz
- Sky at THz or cold targets: few photons per mode
- Above ∼100 GHz, classical front-ends get hard, and counting gets attractive

# Radiometry: from kelvins to photons

## Classical (Dicke)

$$\Delta T = \frac{T_A + T_{\mathrm{Rx}}}{\sqrt{B\tau}}$$

- Uncooled mm-wave front-ends: $T_{\mathrm{Rx}} \sim$ 500–3 000 K
- Gain drift needs calibration loads

## Photon counting

$$\Delta T = \sqrt{\frac{T_A T_Q}{\eta\, \Delta f\, \tau}}$$

- Noise scales as $\sqrt{T_A}$: Poissonian counts
- No added amplifier noise
- Figure of merit: $\eta\, \Delta f$

**Back of the envelope**

Counted rate $\bar{n}_A = \eta\, \Delta f\, \bar{n} = G\, T_A$, gain $G = \eta\, \Delta f / T_Q$. At 126 GHz we measure $G =$ 110 photons/s/K: tens of thousands of counts per second from a room-temperature target.

# The radiometer equation, derived



**Classical**

1. Noise power in band $B$ fluctuates by its own size in each coherence time $1/B$
2. Time $\tau$ holds $B\tau$ independent samples, so averaging gives $1/\sqrt{B\tau}$
3. Power is proportional to $T_A + T_{\mathrm{Rx}}$:

$$\Delta T = \frac{T_A + T_{\mathrm{Rx}}}{\sqrt{B\tau}}$$

**Photon counting,** $\eta\bar{n} \ll 1$

1. Modes in time $\tau$: $\Delta f\,\tau$, each with $\bar{n} \approx T_A/T_Q$
2. Counts $N = \eta\,\Delta f\,\tau\,T_A/T_Q$, with shot noise $\sqrt{N}$
3. Convert: $\Delta T = T_A/\sqrt{N}$:

$$\Delta T = \sqrt{\frac{T_A T_Q}{\eta\,\Delta f\,\tau}}$$

With $T_{\mathrm{Rx}} = 0$ the two are equal at $\eta\,T_A/T_Q = 1$. Counting pays when $T_{\mathrm{Rx}}$ is large: its penalty is $\eta$, not additive noise.

# Thermal statistics and bunching, derived



1. One mode at temperature $T$: Boltzmann weights give a geometric distribution:

$$P(n) = \frac{\bar{n}^n}{(1+\bar{n})^{n+1}}$$

2. Variance $\langle \Delta n^2 \rangle = \bar{n}^2 + \bar{n}$: wave noise plus shot noise
3. Hence $g^{(2)}(0) = \dfrac{\langle n^2 \rangle - \langle n \rangle}{\langle n \rangle^2} = 2$
4. At delay $\tau$, for a chaotic field:

$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$$

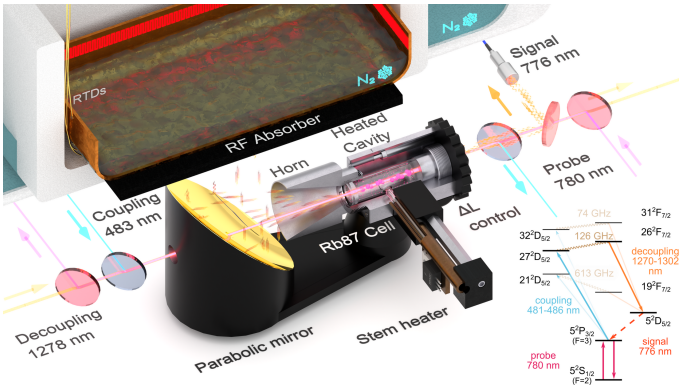
5. Wiener–Khinchin: $g^{(1)}$ is the Fourier transform of the spectrum

Measure the conversion band, Fourier-transform it, square it, and you predict the photon correlation with **no free parameter**.

**Back of the envelope**

A Lorentzian band of FWHM $\Delta f$ gives $g^{(1)} = e^{-\pi \Delta f |\tau|}$. Then $\Delta f = 16\,\text{MHz}$ gives $1/\pi\Delta f = 20\,\text{ns}$.

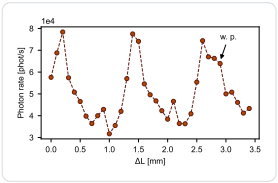
# The multiband Rydberg radiometer




- $^{87}$Rb, three lasers, signal at 776 nm to an SNSPD
- Off-axis parabola with a through-hole: collinear phase matching and a view of an external target
- Tunable one-sided **horn cavity**
- 74, 126 or 613 GHz: same hardware, different laser detunings

Jastrzębski, Borówka, Krokosz, Mazelanik, Wasilewski, Parniak, *Quantum shot noise limited multiband radiometer enabled by Rydberg atoms* (2026)

# An antenna problem: the horn cavity

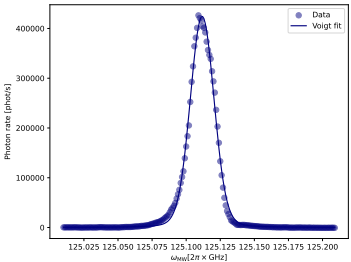



measured (top) and FEM (bottom) **[unpublished]**

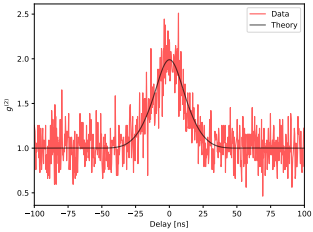
- Resonant one-sided cavity with a horn, tuned by a threaded plug
- Photon rate oscillates with period $\approx \lambda/2$
- Full-wave FEM of cell, cavity and horn reproduces the period and contrast
- Cooperativity: a few % of power lost in glass and Rb film decides how much of the radiation comes from the target

Quantum sensors still need antenna engineers. **The biggest gains now are electromagnetic.**

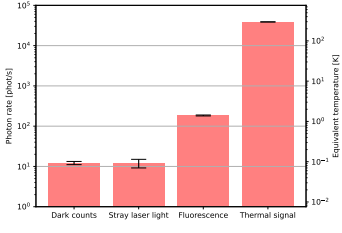
# The counted photons are thermal




band: $\Delta f_{\mathrm{FWHM}} = 20.6\,\mathrm{MHz}$




$g^{(2)}(0) \to 2$, parameter-free theory

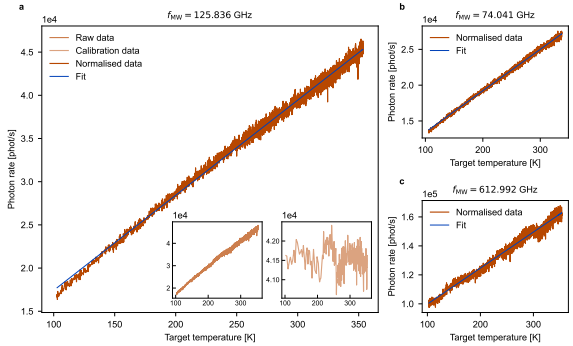



noise budget, laser on/off

- Band measured with a tunable source. Wiener–Khinchin then predicts the bunching curve with **no free parameter**
- Non-thermal contributions: dark counts, stray light, fluorescence. Together $T_{\mathrm{noise}} \approx 1.6\,\mathrm{K}$

# Measuring a defined target





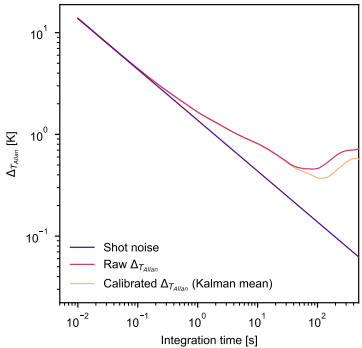

- Target scanned from 106 to 347 K
- Linear response: $\bar{n}_A = G(T_{\mathrm{tg}} + T_0)$
- $T_0$: radiation not from the target



125.8 GHz: $\chi = 0.84$, so 84 % of the signal comes from the target

# Stability: shot-noise-limited operation






Allan deviation, 86 K target, 125.836 GHz, 4.5 h record

- Follows photon shot noise up to $\sim$ 100 ms: 4.44 K measured, 4.35 K shot-noise limit
- Reference calibration extends averaging beyond 30 s
- Minimum $\Delta T = 0.37\,\mathrm{K}$ at 110 s
- No cryogenics, no LNA

# Radiometric parameters across bands

| | $f_{\mathrm{MW}}$ [GHz] | | | |
|---|---|---|---|---|
| | 74.041 | 125.836 | 612.992 | |
| Photon rate $\bar{n}_A$ at 297 K | 25 000 | 39 000 | 149 000 | phot/s |
| Gain $G$ | 58 | 110 | 249 | phot/s/K |
| Cooperativity $\chi$ | 0.69 | **0.84** | 0.50 | |
| Non-thermal noise $T_{\mathrm{noise}}$ | 1.34 | 1.56 | 4.1 | K |
| $\Delta T$ at 100 ms (shot limit) | 6.92 (6.23) | 4.44 (4.35) | 5.71 (3.68) | K |
| Min. Allan $\Delta T$ (at $t$) | 0.53 (108 s) | **0.37** (110 s) | 1.65 (60 s) | K |
| Quantum efficiency $\eta$ | $1.3 \times 10^{-5}$ | $3.5 \times 10^{-5}$ | $6.5 \times 10^{-4}$ | |
| Equivalent $T_{\mathrm{Rx}}$ | 14 000 | 8 300 | 22 000 | K |

One device, almost a decade of frequency. Not yet competitive in $T_{\mathrm{Rx}}$, but there is a long way up: $\eta$ can grow by orders of magnitude.

# Where the next orders of magnitude come from



## Efficiency $\eta$

- Higher-$Q$ resonator around the cell
- Better mm-wave/optical mode matching
- Higher density without bistability

## Bandwidth $\Delta f$

- Stronger probe: above 100 MHz, at some cost in $\eta$

## Cooperativity $\chi$

- Cell glass with lower mm-wave loss
- Narrower field of view

## Systematics

- Fluorescence floor: spectral and spatial filtering
- Autler–Townes cross-calibration: counts tied to SI field units

Goal: room-temperature noise competitive with cooled electronics, across many bands, from one sensor head.

# Fisher information in one slide

1. Outcomes with probabilities $p_i(\theta)$, $\nu$ repetitions. Cramér–Rao:

$$\Delta\theta \geq \frac{1}{\sqrt{\nu\mathcal{F}}}, \quad \mathcal{F} = \sum_i \frac{(\partial_\theta p_i)^2}{p_i}$$

2. One atom, rotated by $\theta$: $p = \sin^2(\theta/2)$

$$\mathcal{F} = \frac{(\partial_\theta p)^2}{p(1-p)} = 1$$

3. $N$ independent atoms: $\mathcal{F} = N$, the standard quantum limit
4. Each is detected with efficiency $\eta$:

$$\mathcal{F} = \eta N$$

An entangled $N$-atom state reaches $\mathcal{F} = N^2$, but losing one particle destroys it:

$$\mathcal{F} \sim \eta^N N^2$$

**The problem:** quantum advantage is exponentially fragile. Real detectors have $\eta \ll 1$.

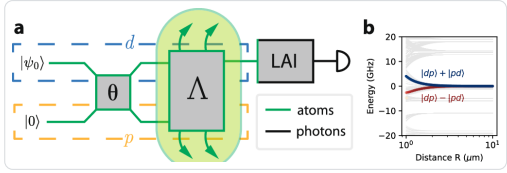
Our experiment asks: can interactions protect the information before it is lost?

# Metrology with interactions: the problem

Quantum enhancements are fragile:

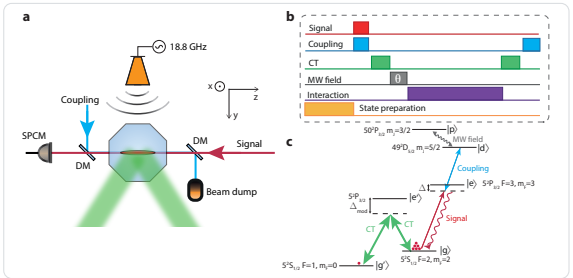
- Entangled probes are hit hard by **detection loss**
- Fisher information $\mathcal{F}$ sets the precision: Cramér–Rao $\Delta\theta \geq 1/\sqrt{\nu\mathcal{F}}$
- With loss $\eta$ per particle, advantage usually disappears

**Idea:** process the information **before** it reaches the lossy detector. A Rydberg interaction provides a built-in nonlinear "pre-measurement".




Kurzyna *et al.*, Nat. Commun. 17, 9013 (2026)

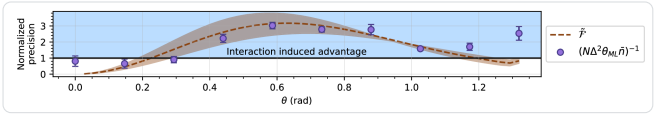
# Metrology with interactions: the experiment

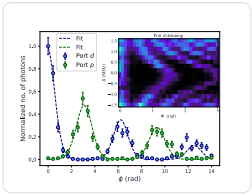



- Cold Rb cloud; collective Rydberg excitations stored as spin waves
- 18.8 GHz pulse rotates them between two Rydberg states
- Dipolar interaction couples the excitations: losses become **information-preserving**
- Readout as photons in two ports

Two excitations are the simplest non-trivial case, and for them the scheme is shown to be optimal without amplification.

# Metrology with interactions: the result




**3.3×**
Fisher information

**39**
nV/cm/$\sqrt{\text{Hz}}$

- Precision 44 μV/cm in a single shot
- Advantage comes from **interaction**, not from reducing loss
- Sensing and quantum processing in the same atoms

# Outlook: quantum antennas






European Research Council
Established by the European Commission

**ERC Starting Grant**

**QURA**

2027–2031

**Goal:** reach the **fundamental limits** of microwave and mm-wave detection with Rydberg atoms, and design devices that **surpass state-of-the-art electronics**.

**Protocols & limits**

superhet, all-optical, photon counting, pulsed and transition-edge sensing

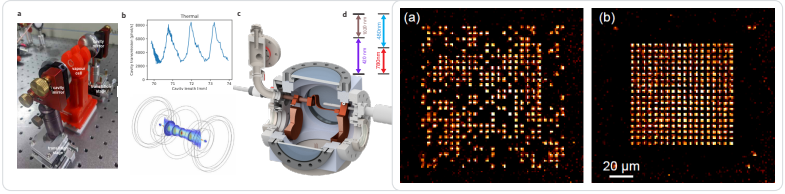
**Quantum control**

atoms in a cavity: cooling and converting microwave photons

**Ultimate sensors**

sky radiometer for CMB photons; entangled antenna arrays

# Outlook: three directions


a
b
c
d
Thermal
Cavity
Lens
Vibration
Isolator
Cavity
Lens
Vacuum
Chamber
Cavity
Lens
Vacuum
Chamber
Cavity
Lens
Vacuum
Chamber

# Summary



### 01 Receivers

Absolute field metrology, atomic mixers and all-optical receivers. Real strengths: traceability, multiband, resilience. Real weaknesses: sensitivity, SWaP, bandwidth. RYDAR took this off the optical table.

### 02 Conversion

Six-wave mixing maps MW photons to light, coherently, at room temperature. Phase matching is an array factor. Always check how efficiency is defined.

### 03 Counting

Counters avoid the amplifier's quantum of noise. A room-temperature radiometer is shot-noise limited across 74–613 GHz. Interactions protect quantum advantage from loss.

Atoms are not better antennas. They are **different** antennas: quantum, calibrated, and read out with light.

# Further reading



**Rydberg sensing**

- G. Allinson *et al.*, arXiv:2601.20631 (2026)
- J. A. Sedlacek *et al.*, Nat. Phys. 8, 819 (2012)
- M. Jing *et al.*, Nat. Phys. 16, 911 (2020)
- H. Fan *et al.*, J. Phys. B 48, 202001 (2015)
- C. G. Wade *et al.*, Nat. Photon. 11, 40 (2017)
- D.-S. Ding *et al.*, Nat. Phys. 18, 1447 (2022)

**Transduction**

- A. Sekine *et al.*, npj Nanophotonics 3, 42 (2026)

**Our work**

- Nat. Photon. 18, 32 (2024): conversion
- Nat. Commun. 16, 8975 (2025): optical bias
- Optica 12, 1854 (2025): THz comb
- Nat. Commun. 17, 9013 (2026): interactions
- All papers: www.qodl.eu/publications

# Thank you!

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**www.qodl.eu** **qot.uw.edu.pl** **qura.space**

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