Continuous-wave microwave-to-optical conversion beyond the blackbody radiation noise using room-temperature atoms

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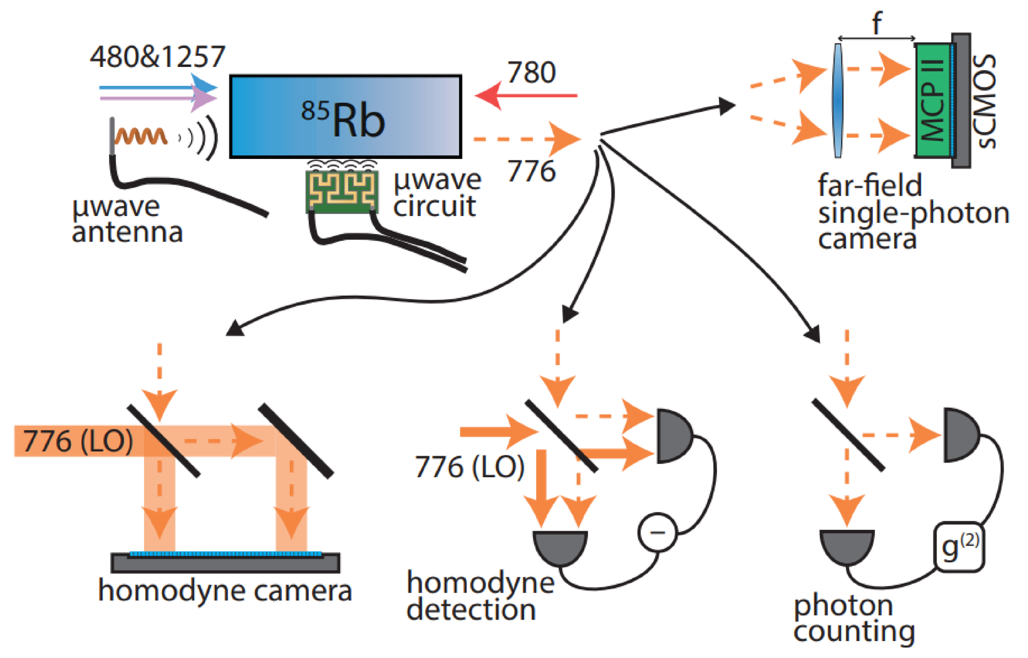
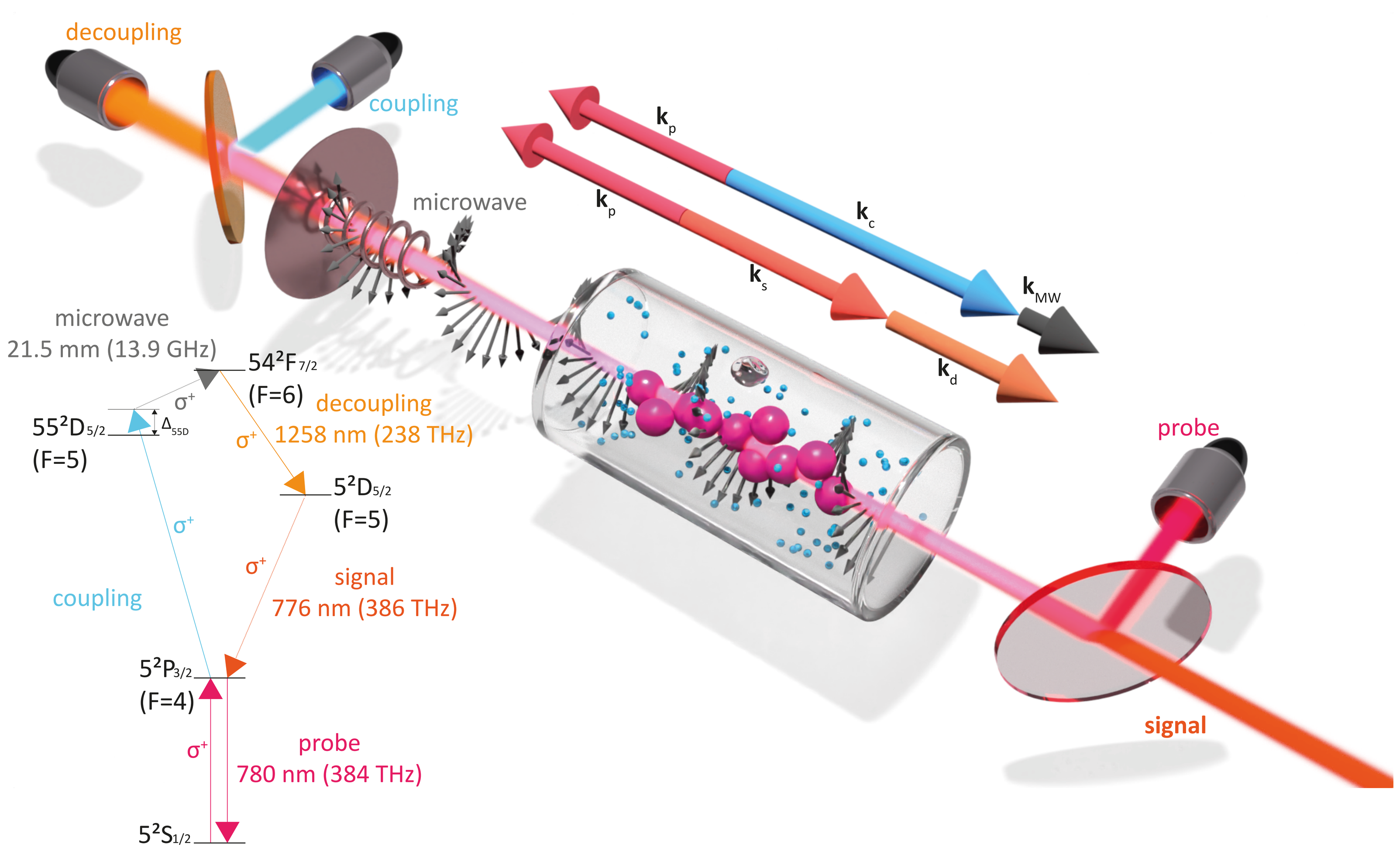
Six-wave mixing upconversion

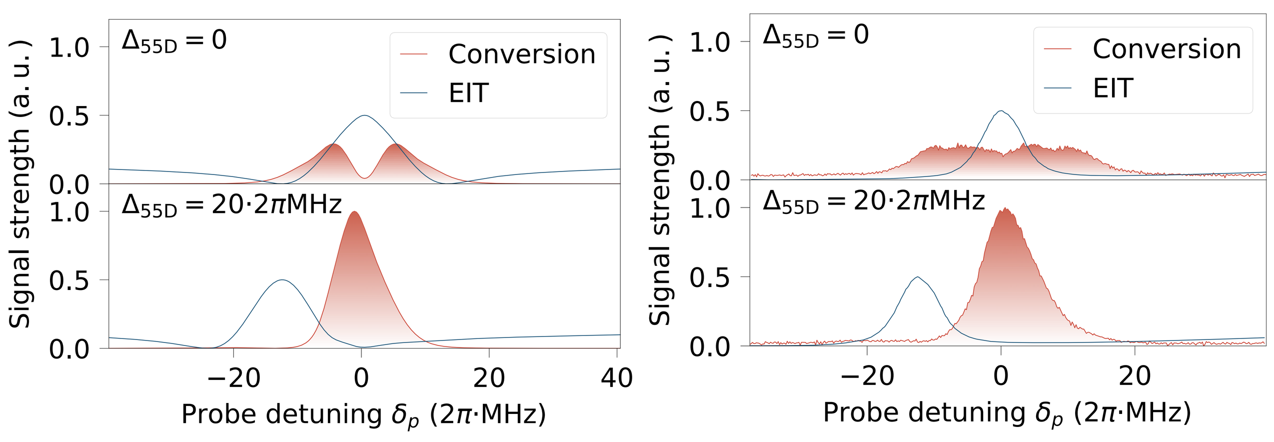
arXiv:2302.08380

Hot-atom vapor for Rydberg sensor/converter for applicable to many scenarios

Six-wave mixing process selected to minimize noise and partially avoid Doppler broadening

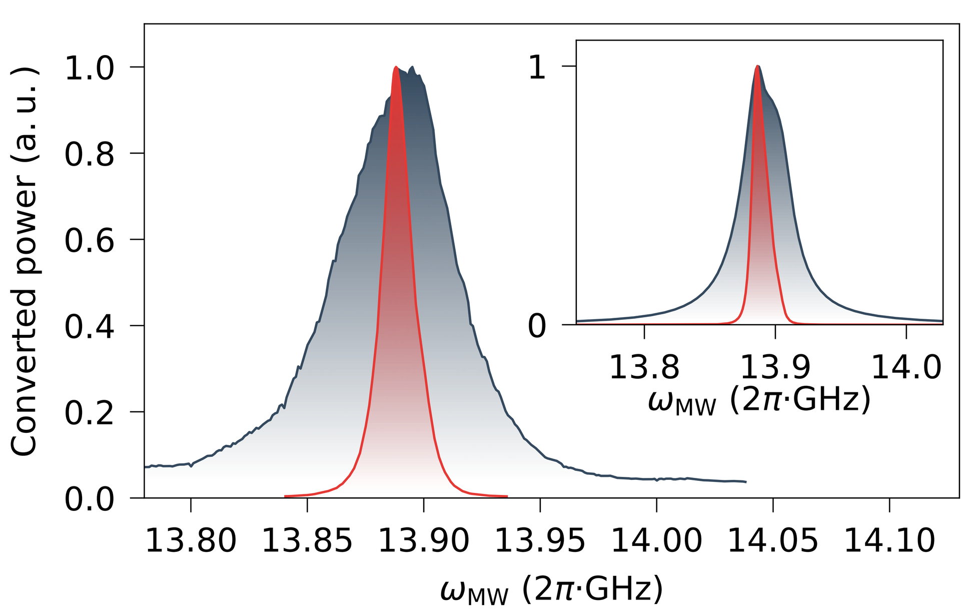






Probe scan reveals optimal conversion off-resonance wrt EIT window.
(cf. Nat. Photonics 16, 291–296 (2022))

Spectroscopic and statistical properties



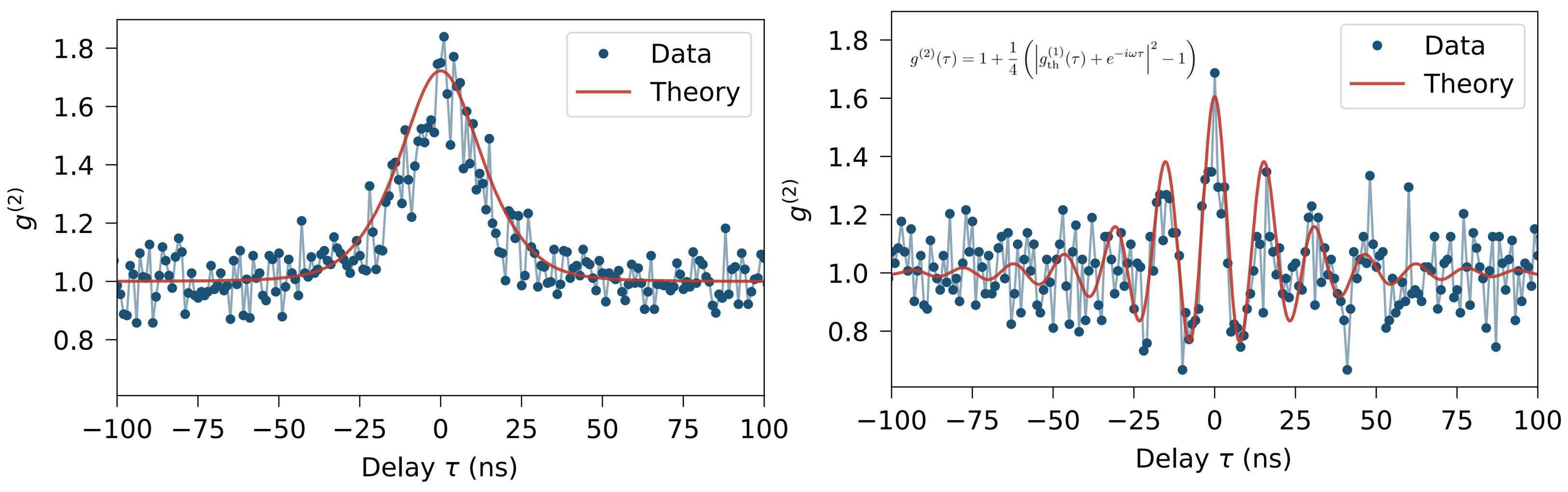
Wiener–Khinchin theorem relates spectrum and the correlation function

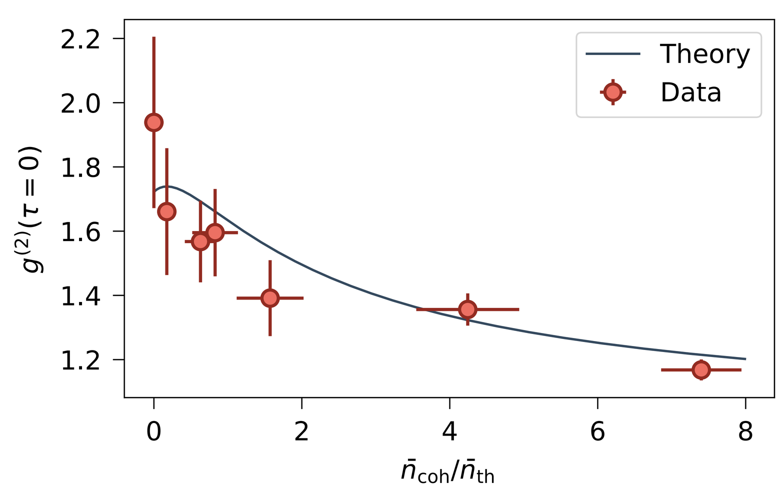
$$g^{(1)}_{\mathrm{th}}(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |S(\omega)|^2 e^{-i\omega\tau}\mathrm{d}\omega$$

We recover the spectrum by measuring transduction function and assuming white noise properties of thermal radiation

$$g^{(2)}(\tau) = 1 + \frac{\left|\bar{n}_{\mathrm{th}} g^{(1)}_{\mathrm{th}}(\tau) + \bar{n}_{\mathrm{coh}} e^{-i\omega\tau}\right|^2 - \bar{n}_{\mathrm{coh}}^2}{(\bar{n}_{\mathrm{th}} + \bar{n}_{\mathrm{coh}} + \bar{n}_{\mathrm{noise}})^2}$$

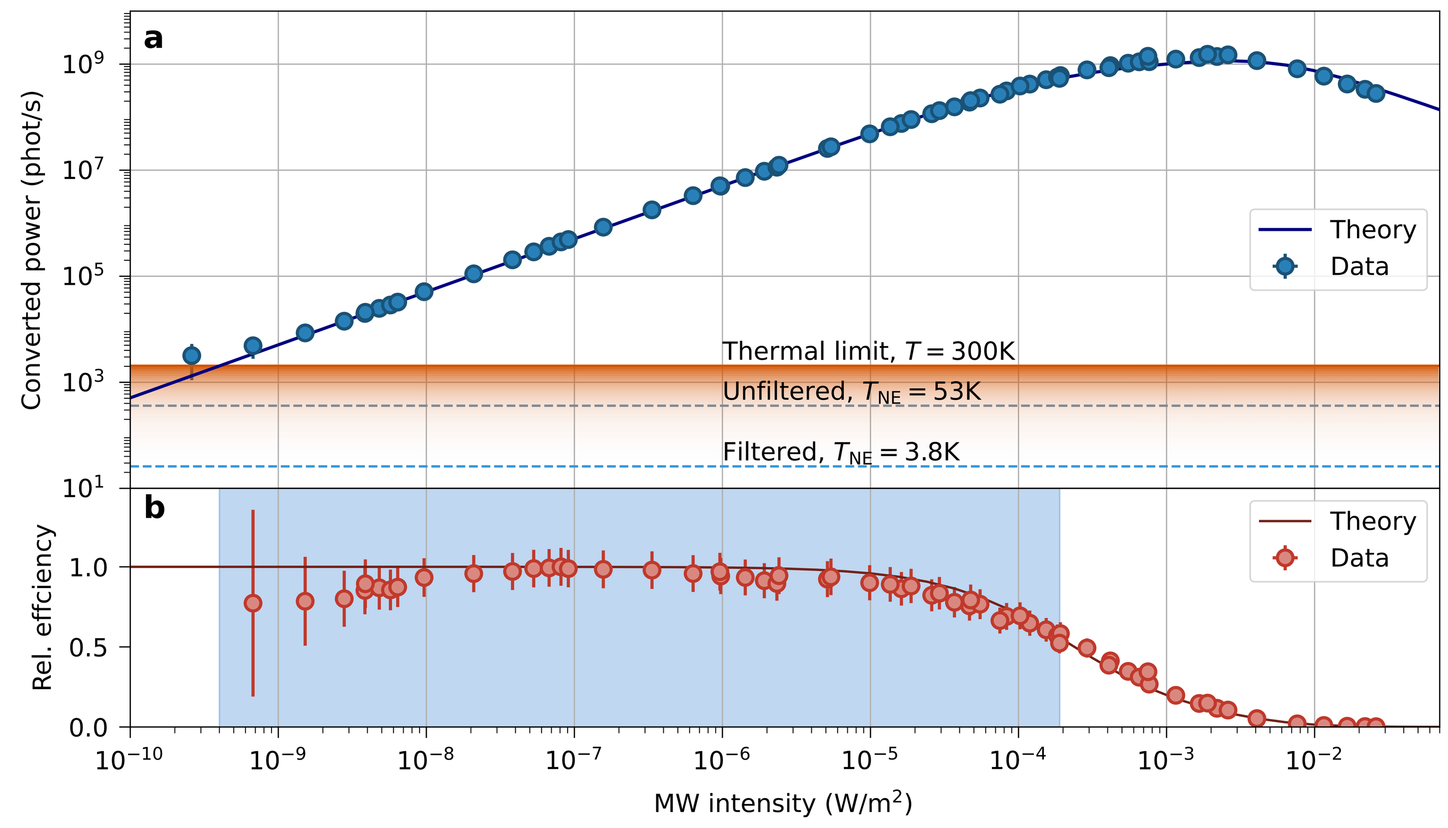
More generally, the second-order correlation function may contain dark noise and coherent compontents





Photon counting of upconverted microwave radiation:
- thermal statistics observed
- interference between coherent and thermal field
- transition between thermal and coherent statistics

Reaching the thermal noise



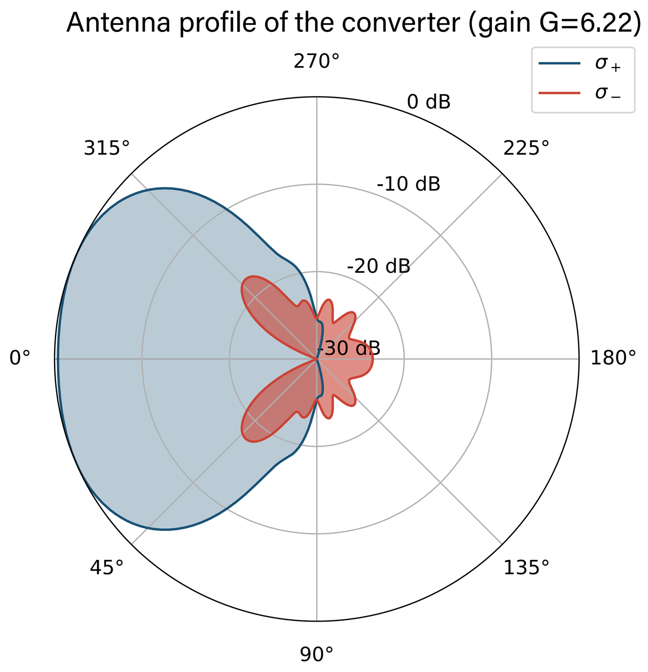
Saturation due to Autler-Townes splitting

A-T splitting also provides fundamental reference for electric field (cf. Nature Physics 8, 819–824 (2012))

1.59 nV cm^{-1} (rad/s)$^{-1/2}$	Measured
1.64 nV cm^{-1} (rad/s)$^{-1/2}$	Calculated

Intrinsic noise (dark background almost 100 times lower than thermal radiation)

Antenna profile of the converter (gain G=6.22)



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

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

Geometry-corrected thermal noise of the electric field

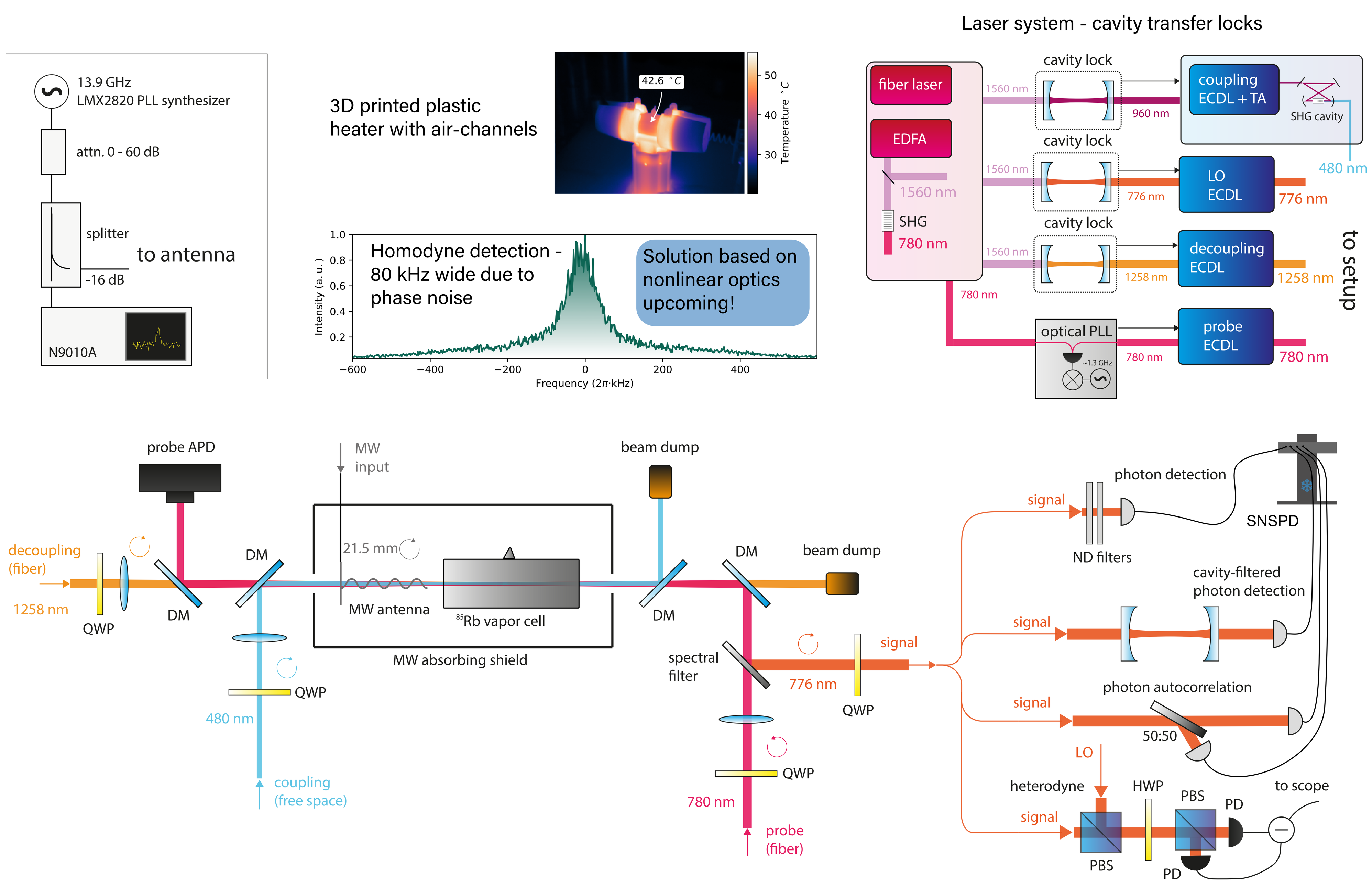
$$|\eta(\theta)|^2 = \left(\cos\left(\frac{\theta}{2}\right)^4 + \sin\left(\frac{\theta}{2}\right)^4\right)|\eta_{\mathrm{phm}}(\theta)|^2$$

$$\chi_\theta = E_p E_p^* E_c E_d^* E_{\mathrm{MW}}(\theta)$$

$$\eta_{\mathrm{phm}}(\theta) = \int_{-L/2}^{L/2}\mathrm{d}z\int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\rho\mathrm{d}\rho\chi_\theta u_s^*$$

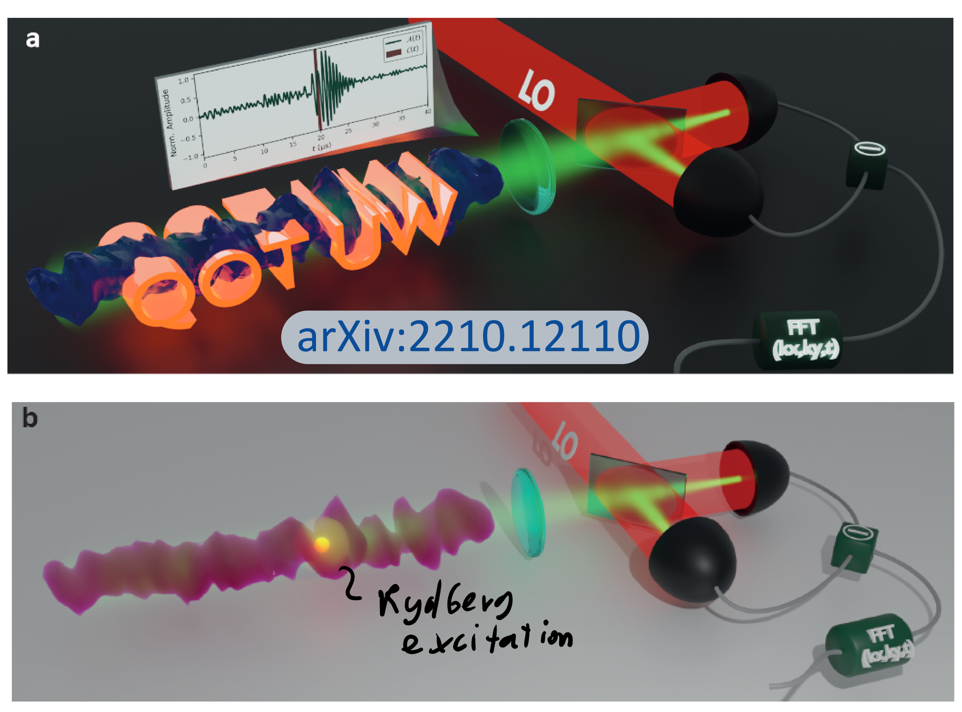
Corrections due to phase matching (including Gouy phases!)

Full experimental setup

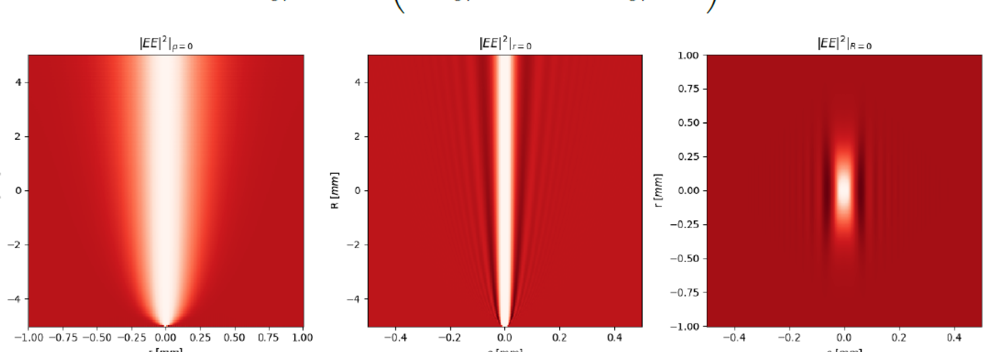


Prospects

Rydberg polaritons in Gradient Echo Memory



$$\frac{\partial EE}{\partial R} = C_D\left(\frac{\partial^2 EE}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial EE}{\partial\rho}\right) - \left(C_{VR}V(r,\rho) - C_{Vr}\frac{\partial^2 V(r,\rho)}{\partial r^2}\right)EE + C_r\frac{\partial^2 EE}{\partial r^2} + C_{Vr}\left(\frac{\partial^2 EEV(r,\rho)}{\partial r^2} - 2\frac{\partial(EE\frac{\partial V(r,\rho)}{\partial r})}{\partial r}\right).$$



Other References:
A. Kumar et al., Nature 615, 614–619 (2023) - Rydberg-atom converter in cryogenic environment
M. Parniak et al., Nature Communications 8, 2140 (2017) - multimode quantum memory based on Rb atoms
S. Borówka et al., Applied Optics 61, 8806-8812 (2022) - Rydberg-atom FM and AM microwave receiver/simple scenario but with much less sensitivity
G. Santamaria-Botello et al., arXiv:2209.00908 - comparison of noise temperatures of Rydberg-atom receivers

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