Pushing the boundaries of entanglement with light, atoms and optomechanics

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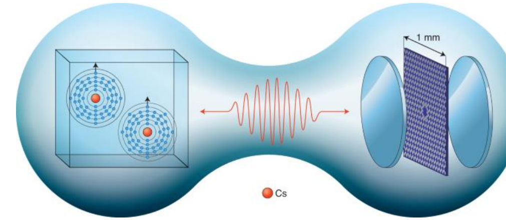
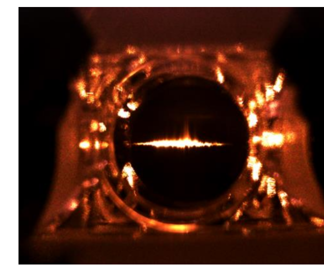
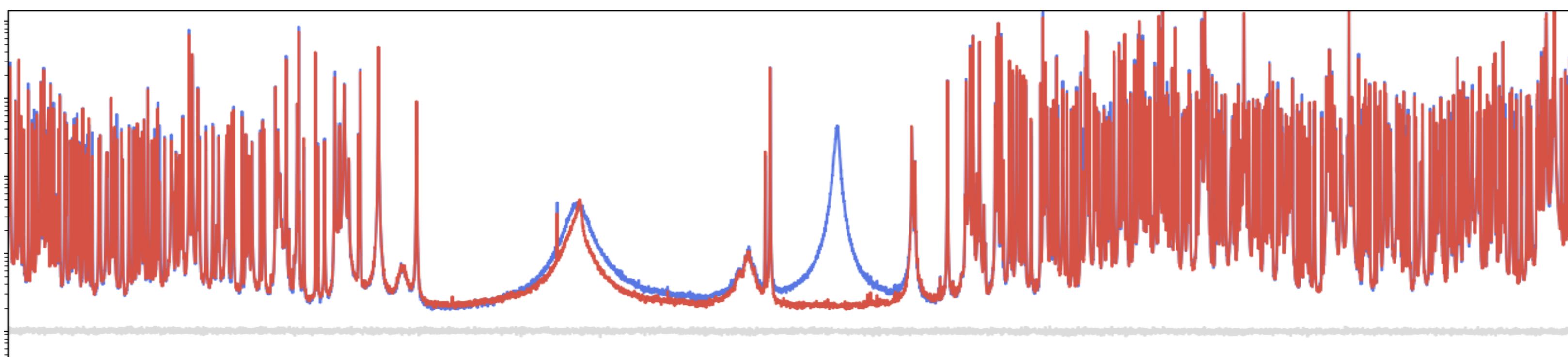






Wojanów, September 7, 2022

Quantum measurements of motion with light

Motion

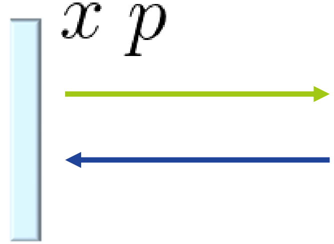
$$\frac{d}{dt}\hat{x} = \frac{\hat{p}}{m}$$

$$\frac{d}{dt}\hat{p} = \hat{f} \qquad \hat{f} = \hat{f}_{th} + \hat{f}_{rp}$$

$$i\Omega\tilde{x} = \frac{1}{m}\frac{\tilde{f}}{i\Omega}$$

$$\tilde{x} = \chi(\Omega)\hat{f}$$

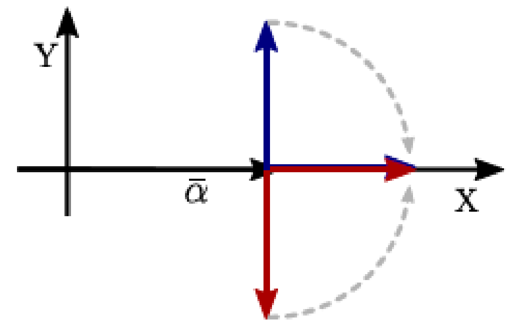
$$\hat{x} \; \hat{p}$$



$$\hat{X}_{out} \; \hat{Y}_{out}$$

$$\hat{X}_{in} \; \hat{Y}_{in}$$

Light



$$X + iY = \alpha e^{i\varphi} = \alpha(1 + i\varphi)$$

$$\varphi \propto \hat{x}/\lambda$$

$$\delta\hat{Y} \propto \alpha\hat{x}$$

$$\hat{f}_{rp} \propto \hat{a}^\dagger\hat{a} = (\alpha + \delta\hat{a}^\dagger)(\alpha + \delta\hat{a}) = |\alpha|^2 + \alpha\hat{X}$$

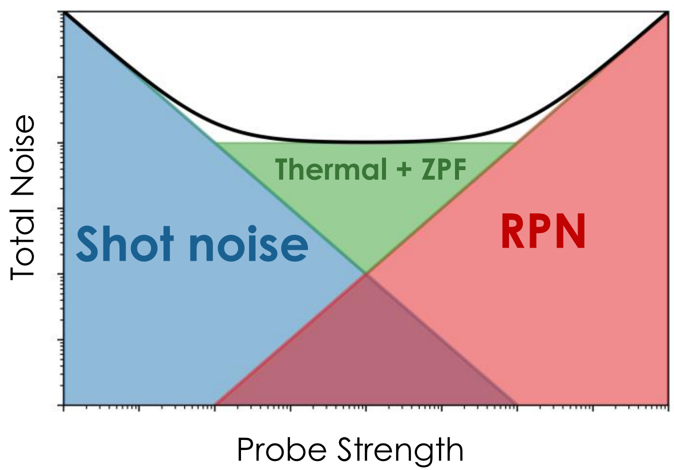
$$\hat{Y}_{out} = \hat{Y}_{in} + \alpha\chi(\Omega)\hat{f}_{th} + \chi(\Omega)\alpha(\alpha\hat{X}_{in})$$

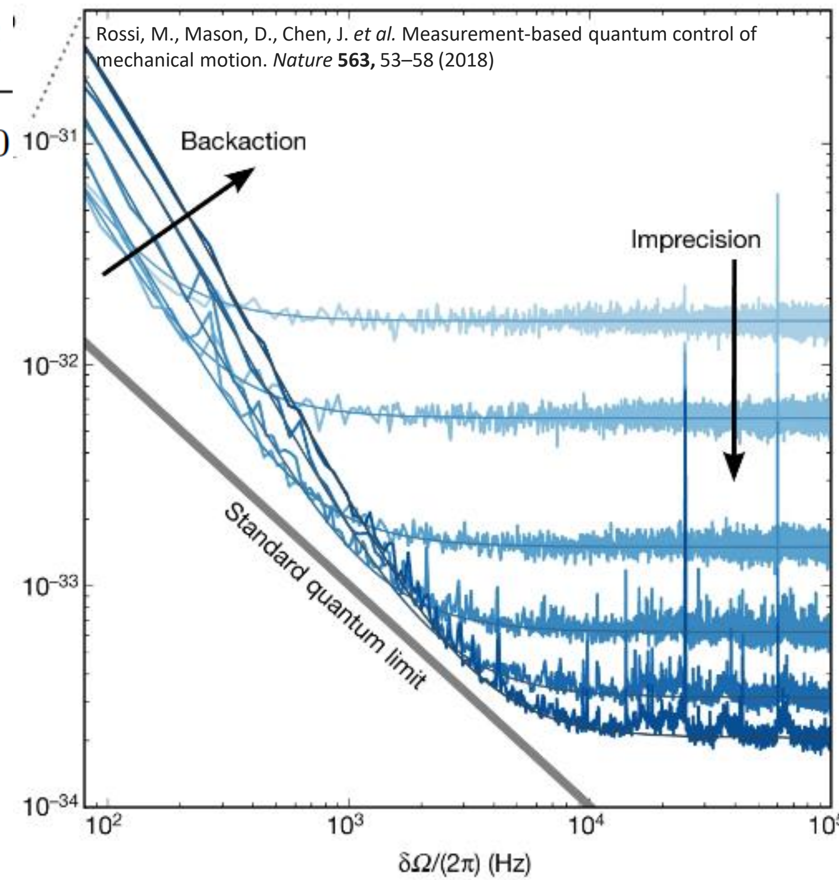
$$\hat{x}_{est} = \hat{Y}_{in}/\alpha + \chi(\Omega)\hat{f}_{th} + \chi(\Omega)\alpha\hat{X}_{in}$$

Caves, Phys. Rev. D **23**, 1693 (1981)

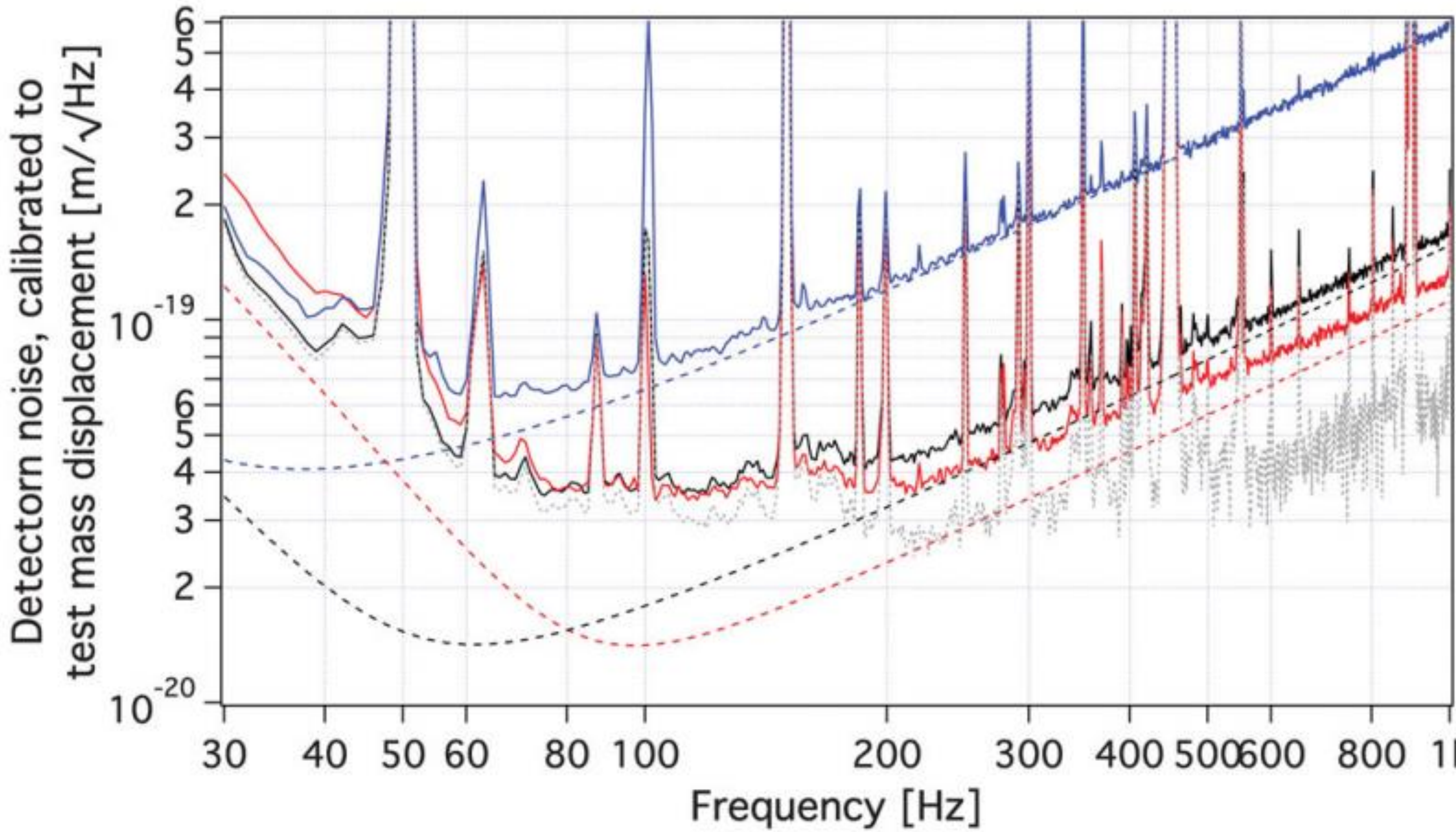
Back-action and standard quantum limit

$$S^x_{\mathrm{tot}} = S^x_{\mathrm{sh}} + S^x_{\mathrm{rp}} = \frac{\hbar\, c^2}{I_0 \omega_0}$$



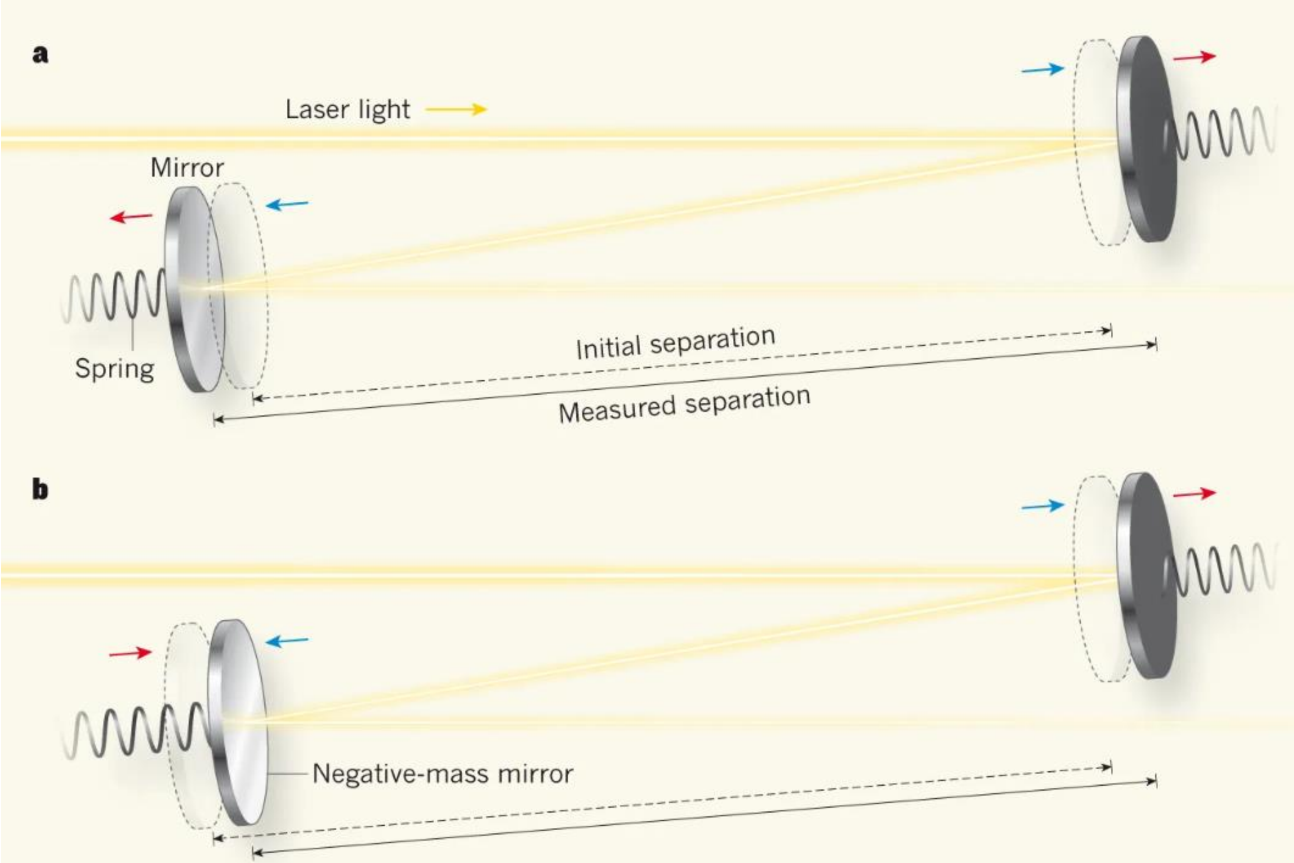


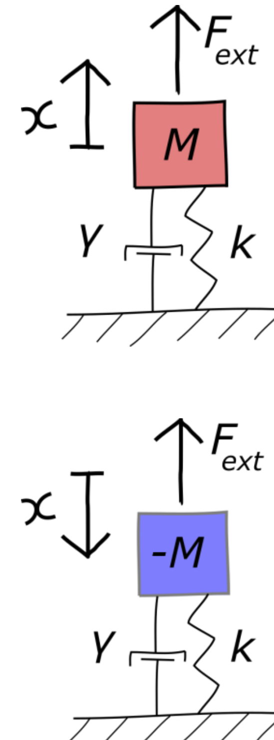
Back-action and shot-noise in GW detector



M. Tse et al., Phys. Rev. Lett. **123**, 231107 (2019)
Virgo Collaboration, Phys. Rev. Lett. **125**, 131101 (2020)

BA evasion in a negative mass reference frame





From Baker, C., Bowen, W. „Sensing past the quantum limit", Nature 547, 164–165 (2017) (News and Views article on C. Møller et al., Nature 547, 191–195 (2017))

Evading back action

Negative mass

$$\hat{Y}_{out} = \hat{Y}_{in} + \alpha\chi(\Omega)\hat{f}_{th} + \boxed{\chi(\Omega)\alpha^2\hat{X}_{in}} + \alpha\chi'(\Omega)\hat{f'}_{th} + \boxed{\chi'(\Omega)\alpha^2\hat{X}_{in}}$$

Back action cancellation for

$$\chi(\Omega) = -\chi'(\Omega)$$

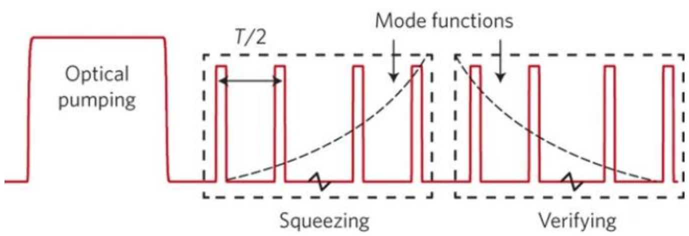
C. B. Møller et al., Nature 547, 191–195 (2017)
W. Wasilewski et al., Phys. Rev. Lett., 104, 133601 (2010)

Quantum correlations

$$\bar{S}_{xx}^{\text{add}}(\Omega) = \bar{S}_{xx}^{\text{imp}} + |\chi_{\text{m}}(\Omega)|^2\bar{S}_{FF}^{\text{qba}}(\Omega) + \boxed{2\text{Re}\left[\chi_{\text{m}}(\Omega)^*\bar{S}_{xF}(\Omega)\right]}$$

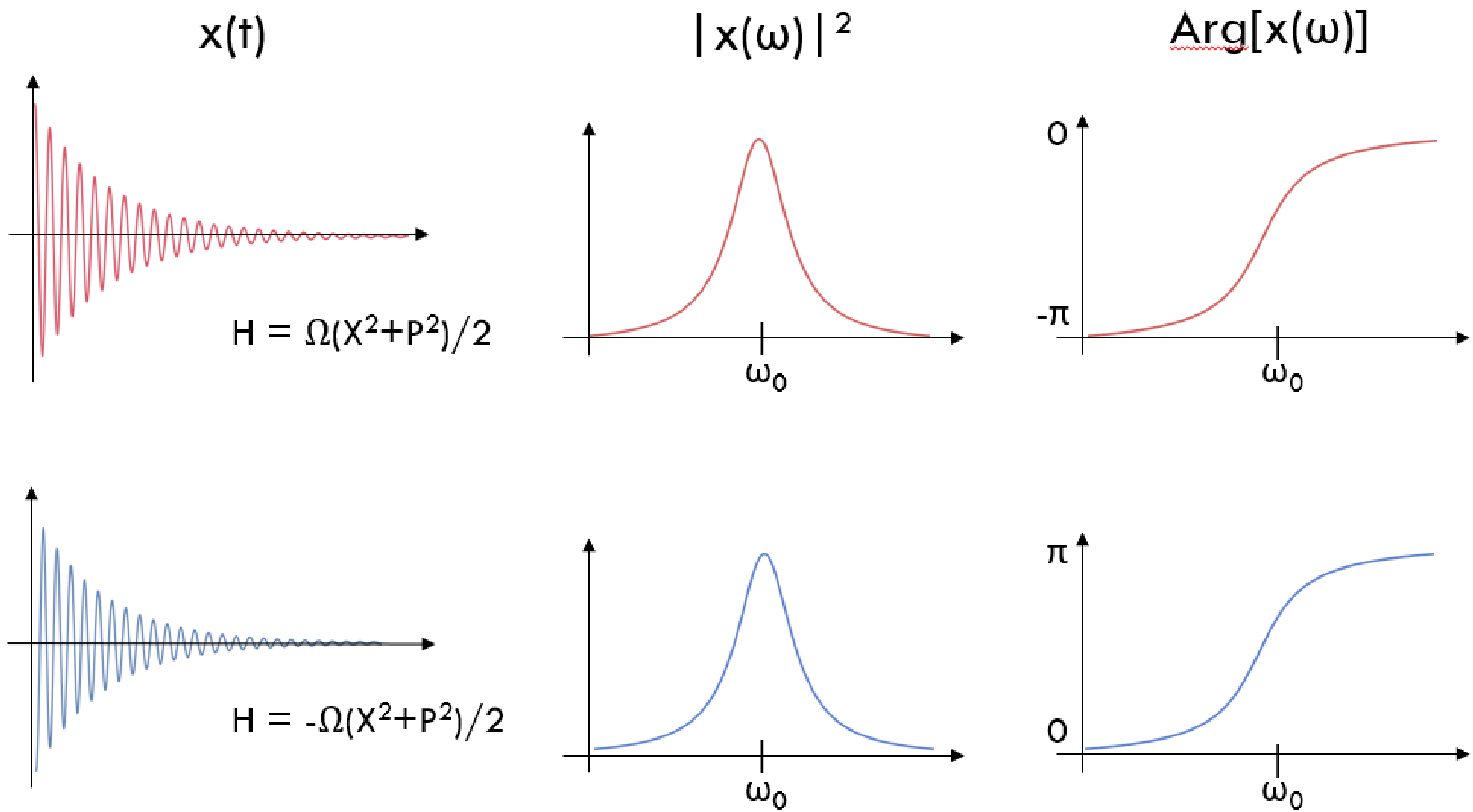
D. Mason et al. ,Nature Physics 15, 745–749(2019)

Stroboscopic measurements

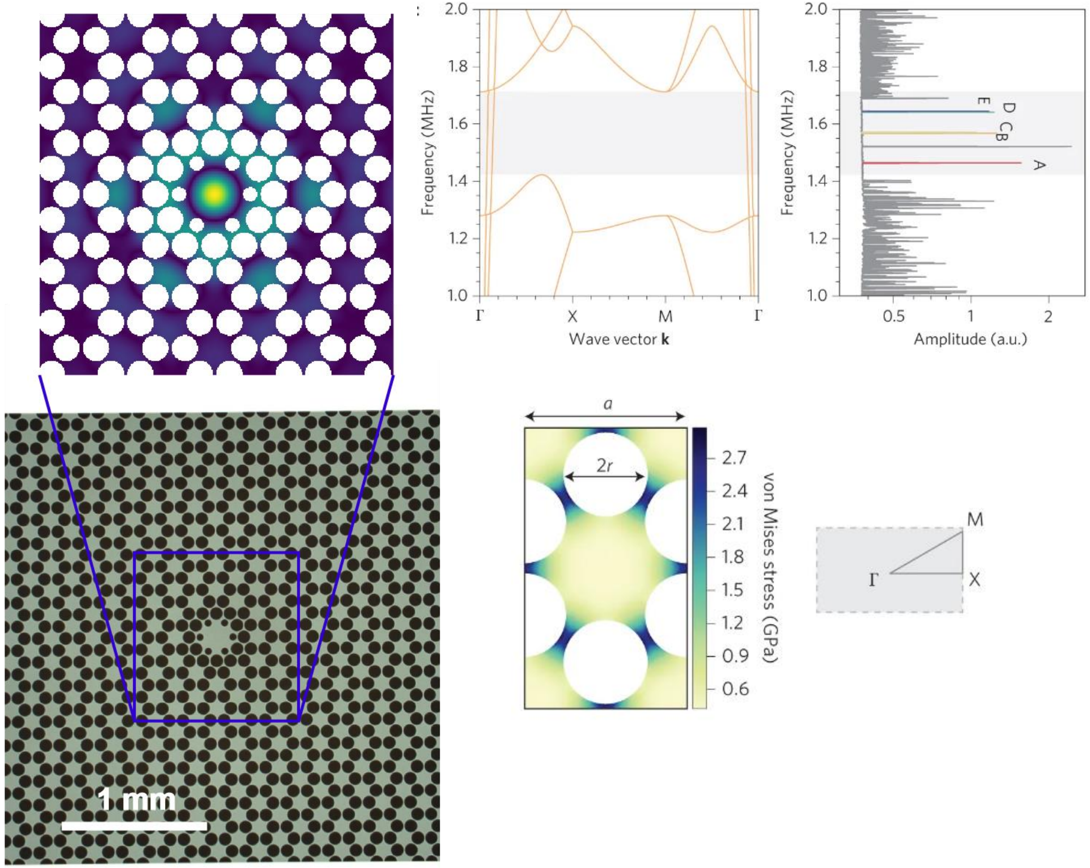


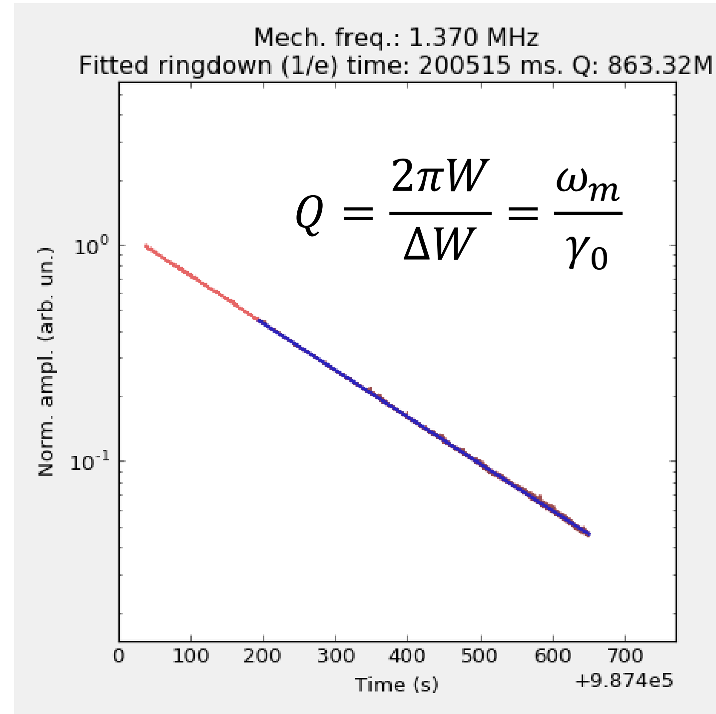
G. Vasilakis et al. Nature Physics 11, 389–392 (2015)

Negative ~~mass~~ susceptibiity



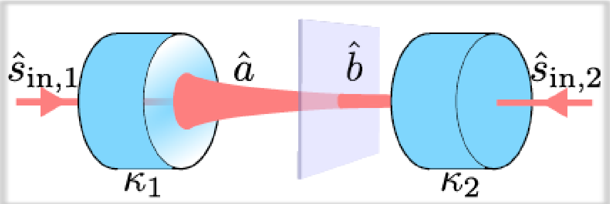
Nanomechanics

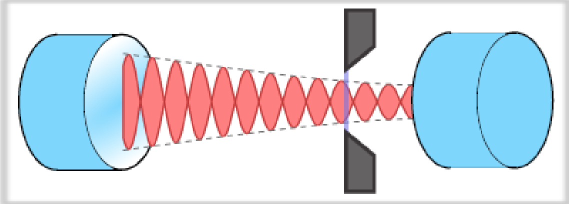


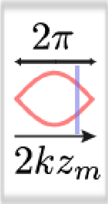


Tsaturyan, Barg, Polzik, Schliesser, Nature Nanotechnology **12**, 776 (2017)

Cavity Optomechanics







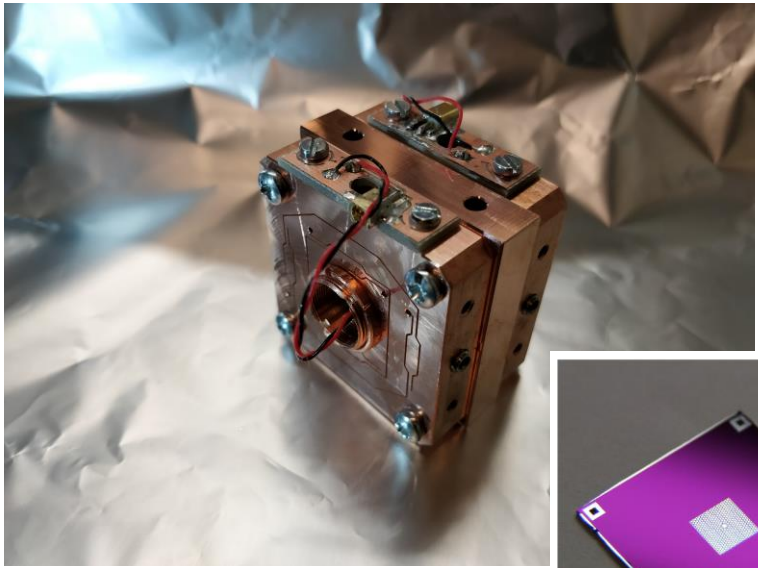
$$\hat{\mathcal{H}} = \hbar\omega_c(\hat{n} + 1/2)$$

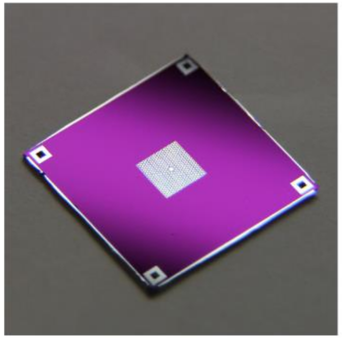
$$\hat{\mathcal{H}} = \hbar\left(\omega_c(0) + \frac{\mathrm{d}\omega_c}{\mathrm{d}q}\bigg|_{q=0} q\right)(\hat{n} + 1/2)$$

$$\hat{\mathcal{H}}_{\mathrm{int}} = \sqrt{2}\hbar g_0 \hat{Q}\hat{n},$$

$$g_0 \equiv G x_{\mathrm{zpf}}.$$

$$\hat{\mathcal{H}}_{int} \propto \hbar g \delta\hat{X}\delta\hat{Q}$$





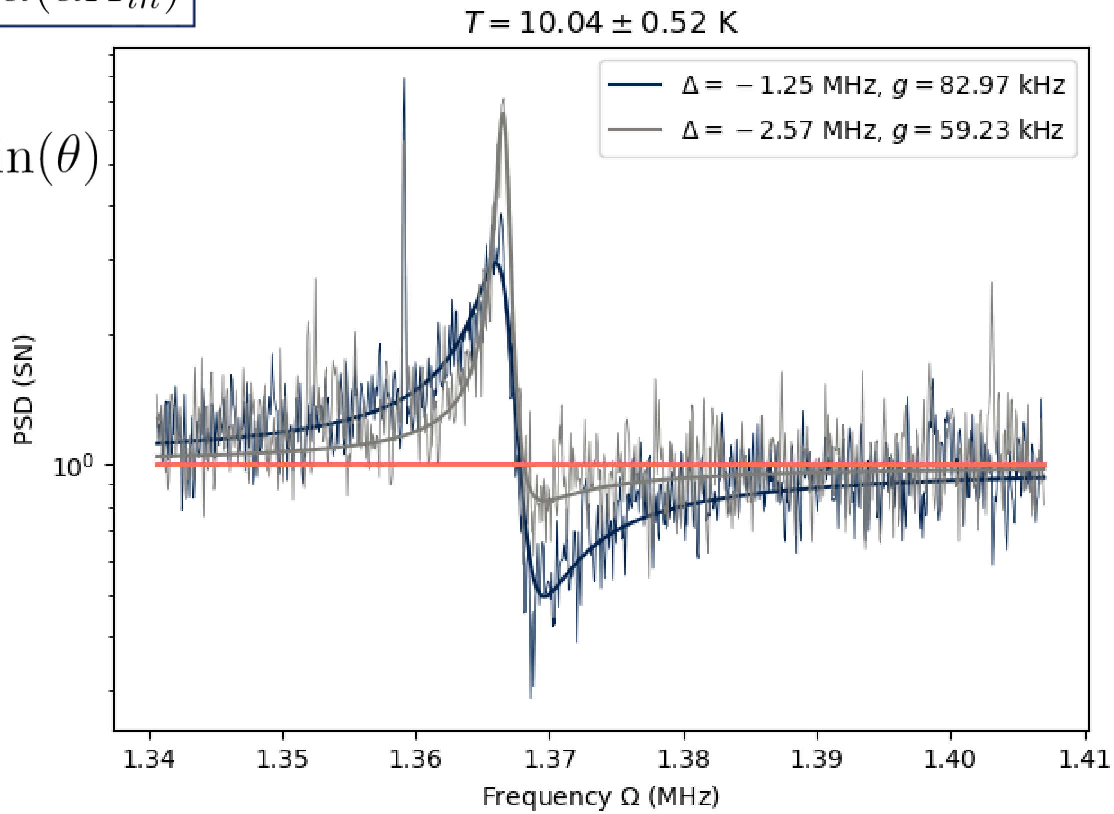
Ponderomotive squeezing

$$\hat{Y}_{out} = \hat{Y}_{in} + \alpha\chi(\Omega)\hat{f}_{th} + \boxed{\chi(\Omega)\alpha(\alpha\hat{X}_{in})}$$

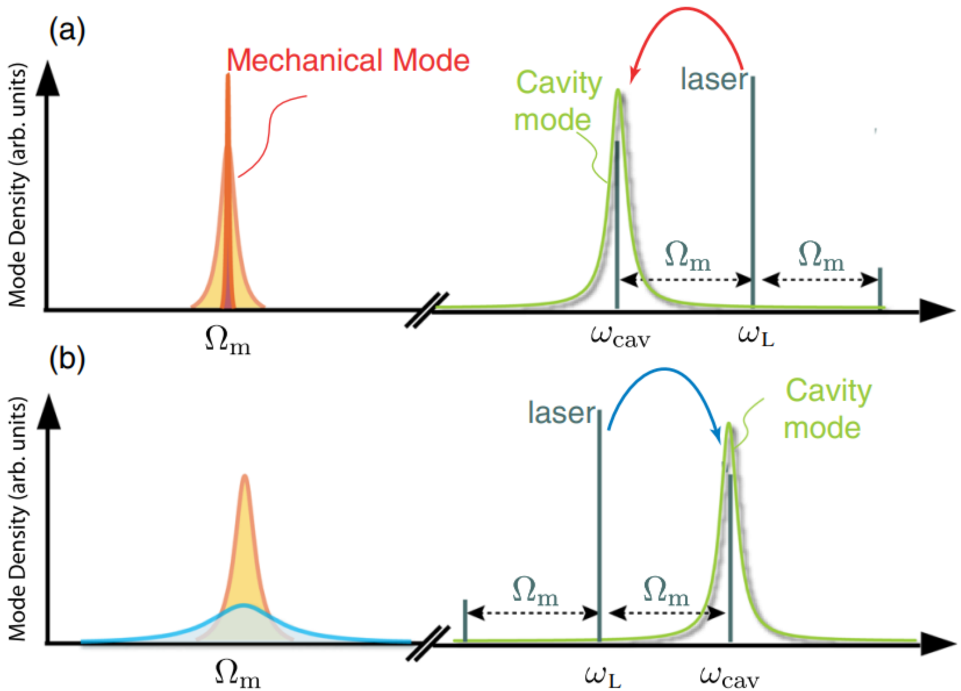
$$\hat{X}_{out} = \boxed{\hat{X}_{in}}$$

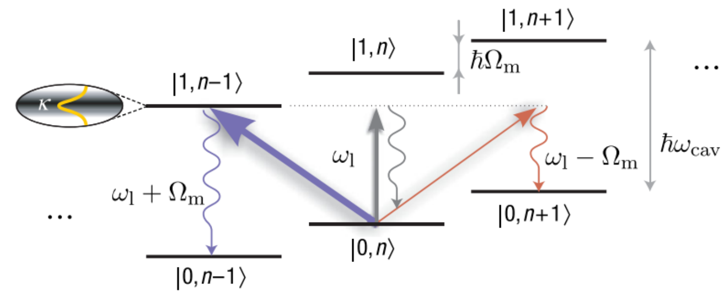
$$\hat{X}_{meas} = \hat{X}_{out}\cos(\theta) + \hat{Y}_{out}\sin(\theta)$$

Easily 4-5 dB of squeezing, limited by detection and outcoupling loss



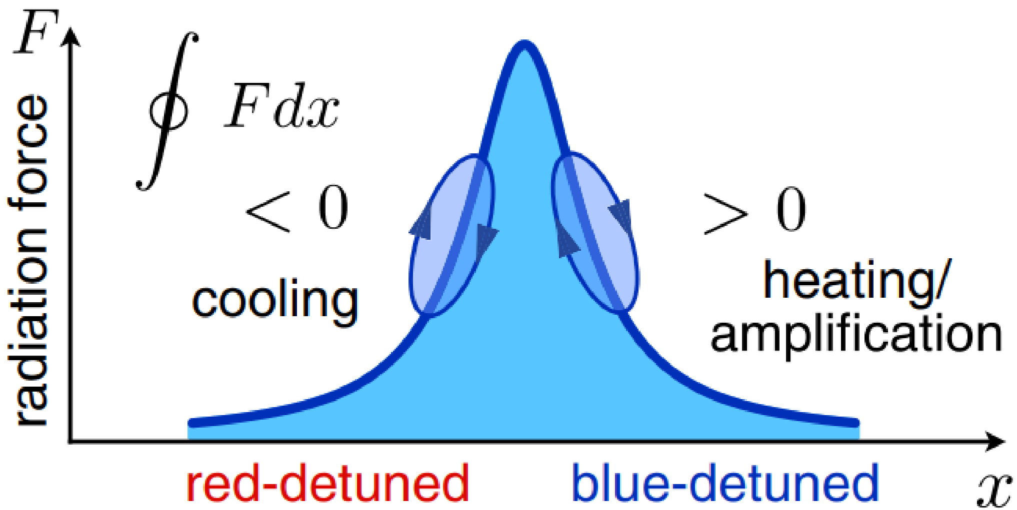
Sideband cooling





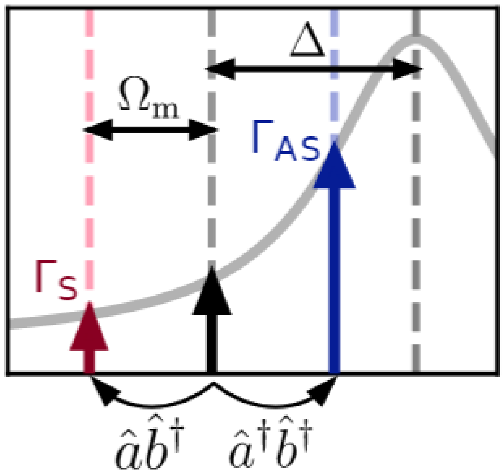
Rev. Mod. Phys. **86**, 1391 (2014)

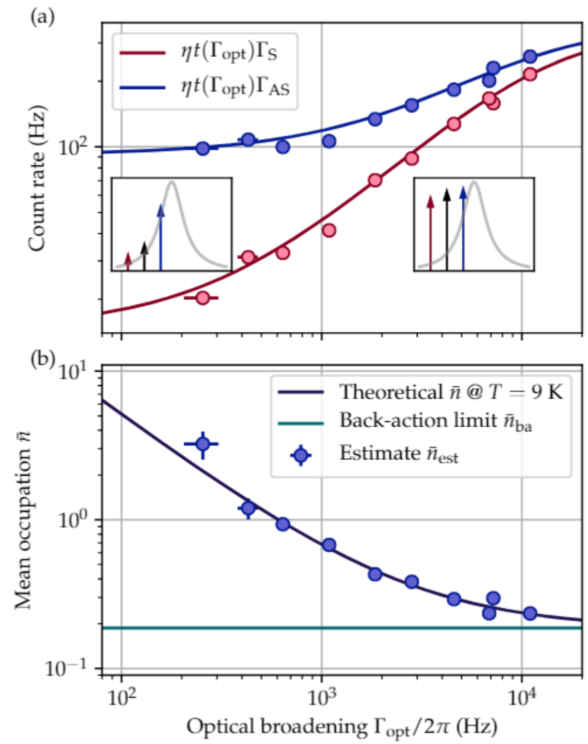
Classical picture of cooling

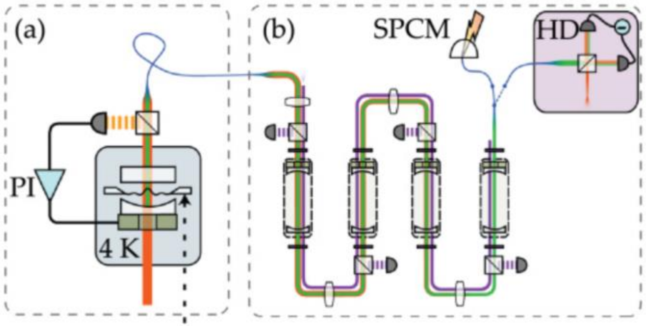


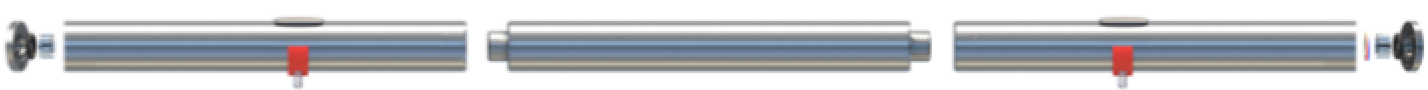
Rev. Mod. Phys. **86**, 1391 (2014)

Our experiment



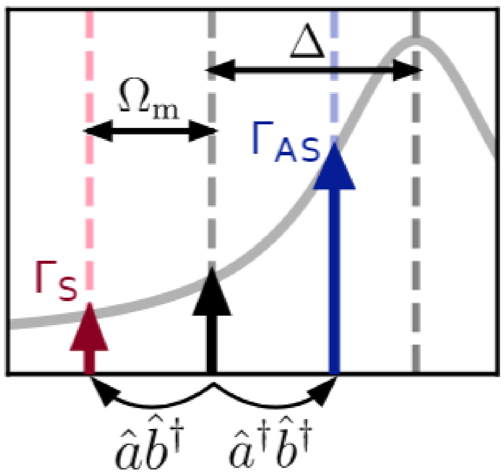






I. Galinskiy, Y. Tsaturyan, MP, E. S. Polzik, Optica 7, 718 (2020)

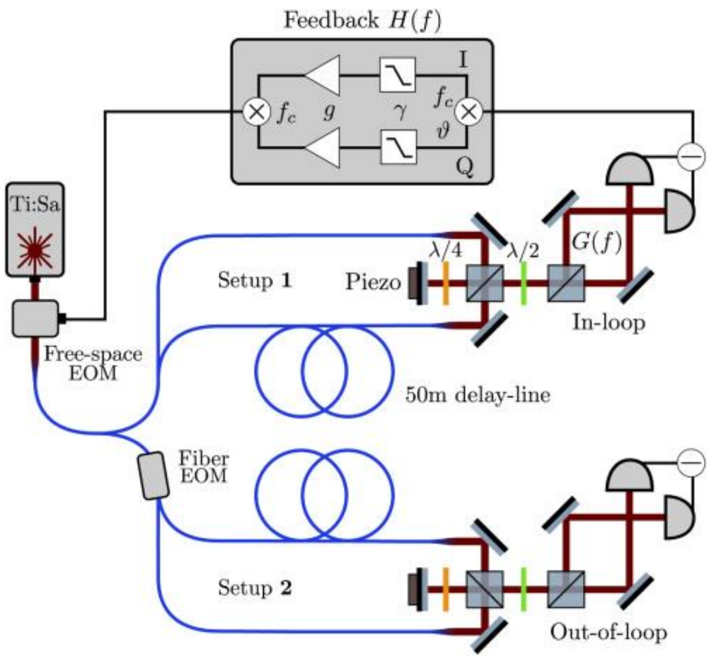
Sideband thermometry with cooling beam

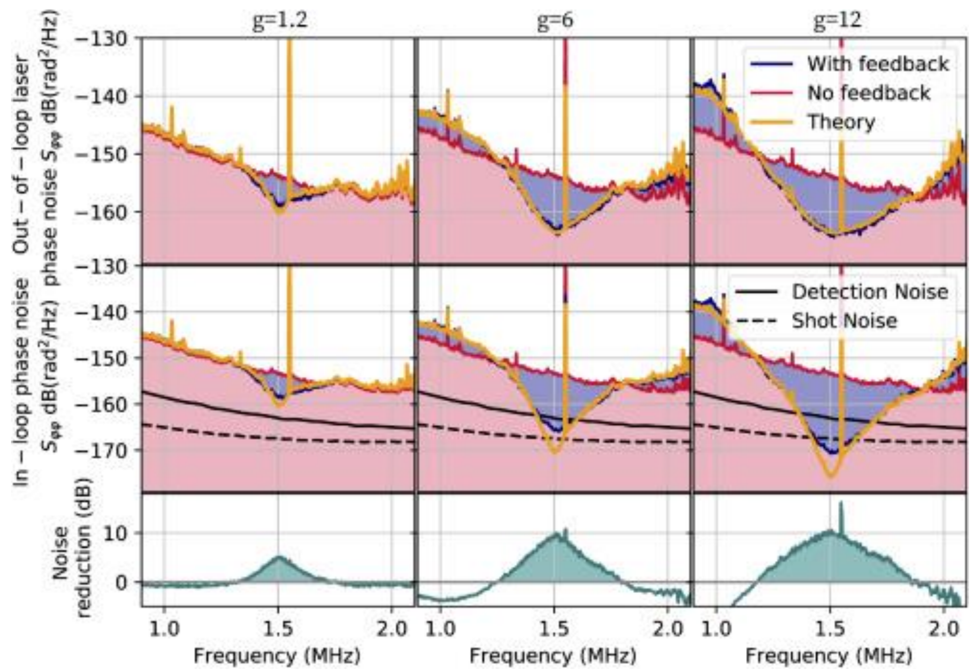


$$\bar{n}_{est} = \frac{RA_+}{A_- - RA_+}$$
$$= \frac{R((\Delta + \Omega_m)^2 + \kappa^2/4)}{((\Delta - \Omega_m)^2 + \kappa^2/4) - R((\Delta + \Omega_m)^2 + \kappa^2/4)},$$

I. Galinskiy, Y. Tsaturyan, MP, E. S. Polzik, Optica 7, 718 (2020)

Even colder – removing laser noise

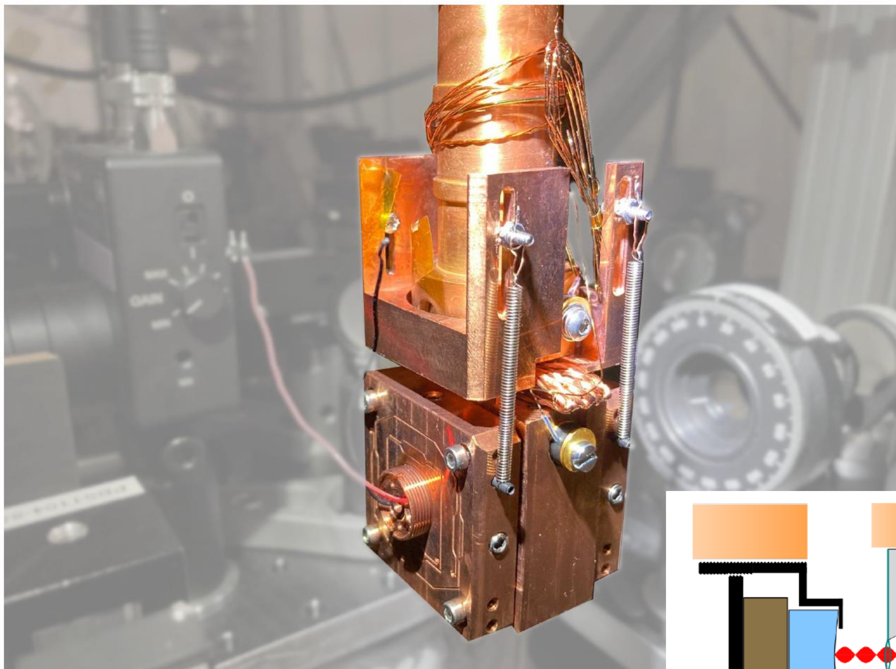


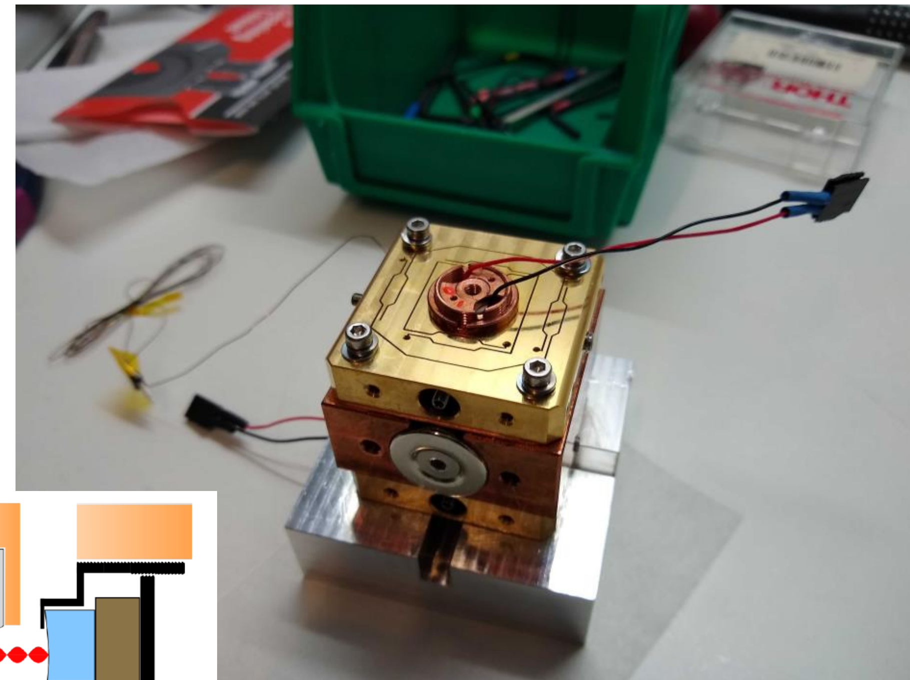


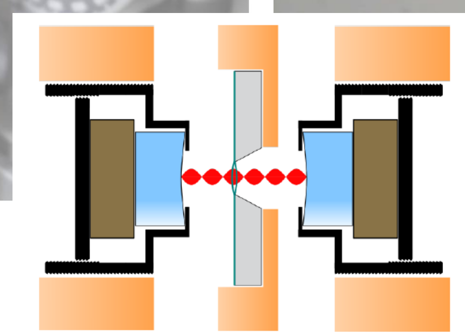
$$\bar{n} \approx \sqrt{\frac{\bar{n}_{\mathrm{th}}\Gamma_{\mathrm{m}}}{g_0^2}\Omega_{\mathrm{m}}^2\bar{S}_{\varphi\varphi}(\Omega_{\mathrm{m}})}$$

MP, I. Galinskiy, T. Zwettler, E. S. Polzik, Optics Express 29, 6935 (2021)

Even deeper in the ground state?



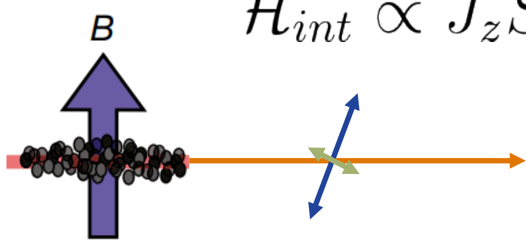




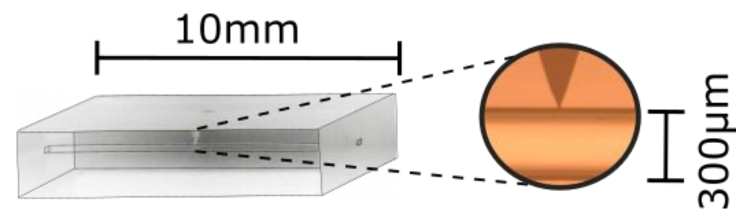
Spin oscillator

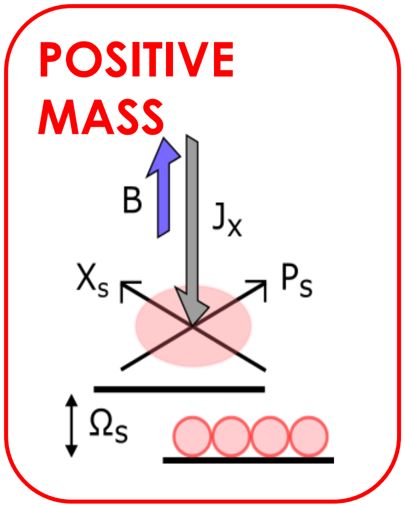
Paramagnetic Faraday rotation coupling

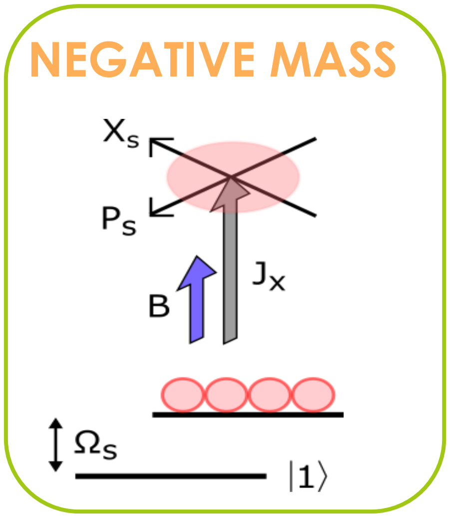
$$\hat{\mathcal{H}}_{int} \propto \hat{J}_z \hat{S}_z$$

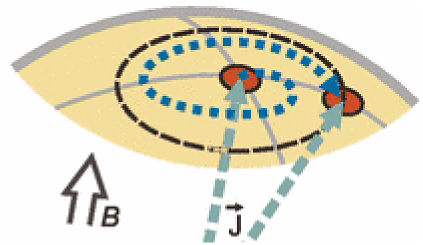


Large atomic spin along **x**
Probing spin fluctuations along **z**



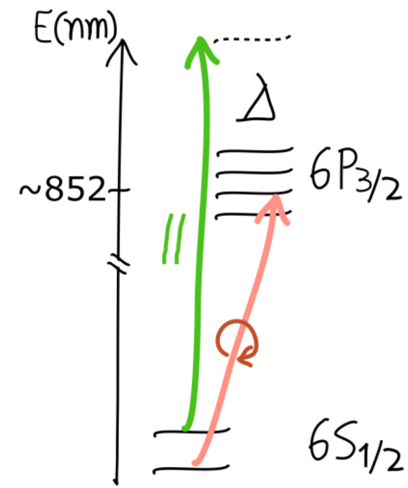






$$\hat{X} = \hat{J}_z / \sqrt{|J_x|}$$

$$\hat{P} = \hat{J}_y / \sqrt{|J_x|}$$

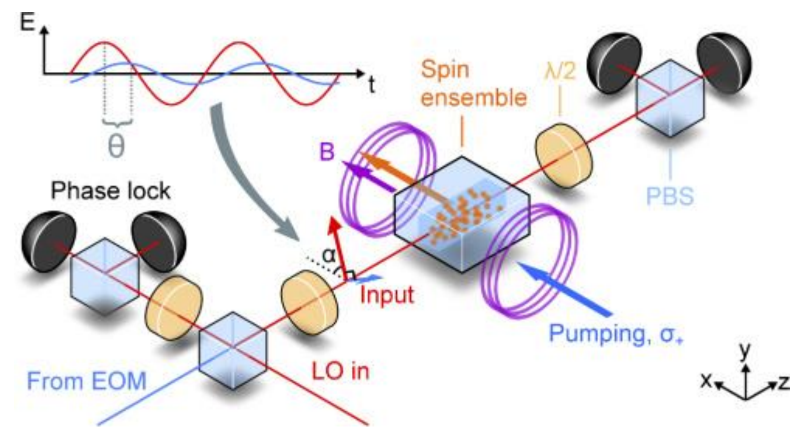


R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Setup and interaction

$$\hat{H}_S^{(i)}/\hbar = \pm\omega_S \hat{F}_x^{(i)} + g_S \Big[a_0 \hat{S}_0 + a_1 \hat{S}_z \hat{F}_z^{(i)} +$$
$$2a_2 \Big[\hat{S}_0 (\hat{F}_z^{(i)})^2 - \hat{S}_x ((\hat{F}_x^{(i)})^2 - (\hat{F}_y^{(i)})^2) - \hat{S}_y (\hat{F}_x^{(i)} \hat{F}_y^{(i)} + \hat{F}_y^{(i)} \hat{F}_x^{(i)}) \Big] \Big],$$

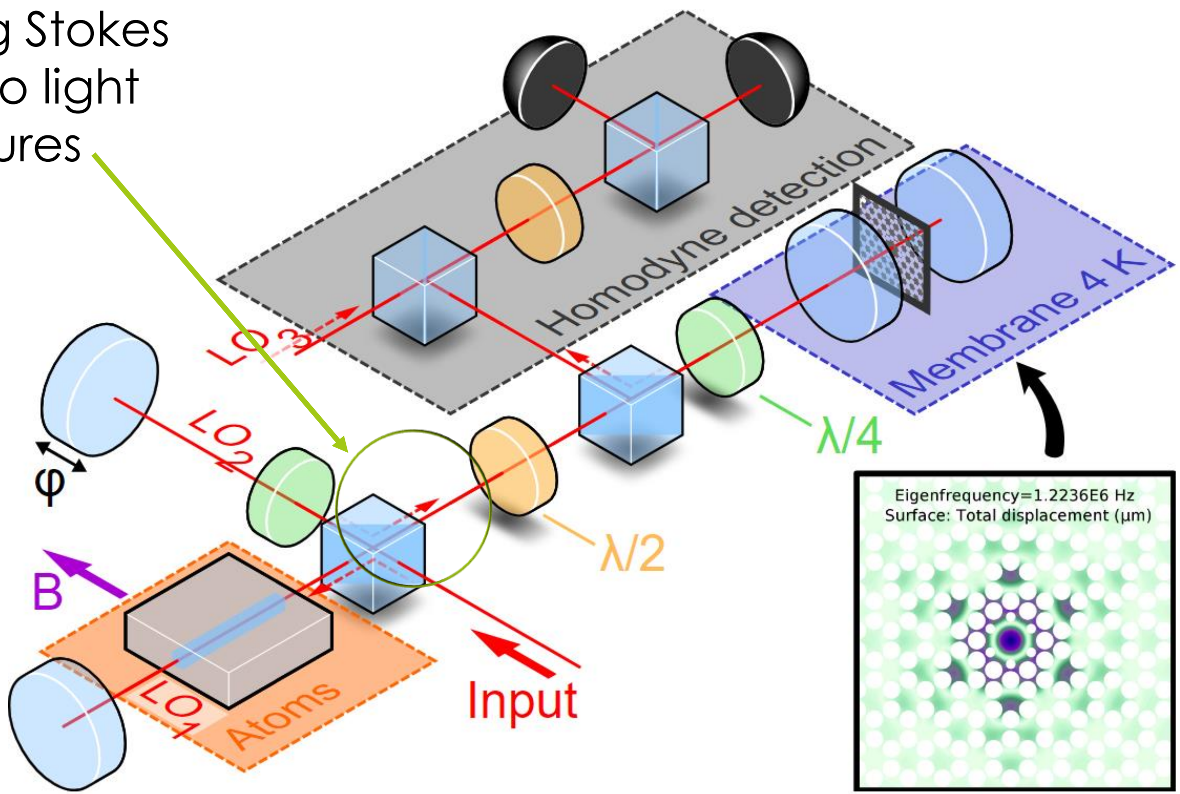
$$\hat{H}_S/\hbar = \mp \frac{\omega_S}{2} (\hat{X}_S^2 + \hat{P}_S^2) - 2\sqrt{\Gamma_S} \left(\hat{X}_S \hat{X}_L + \zeta_S \hat{P}_S \hat{P}_L \right).$$



R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

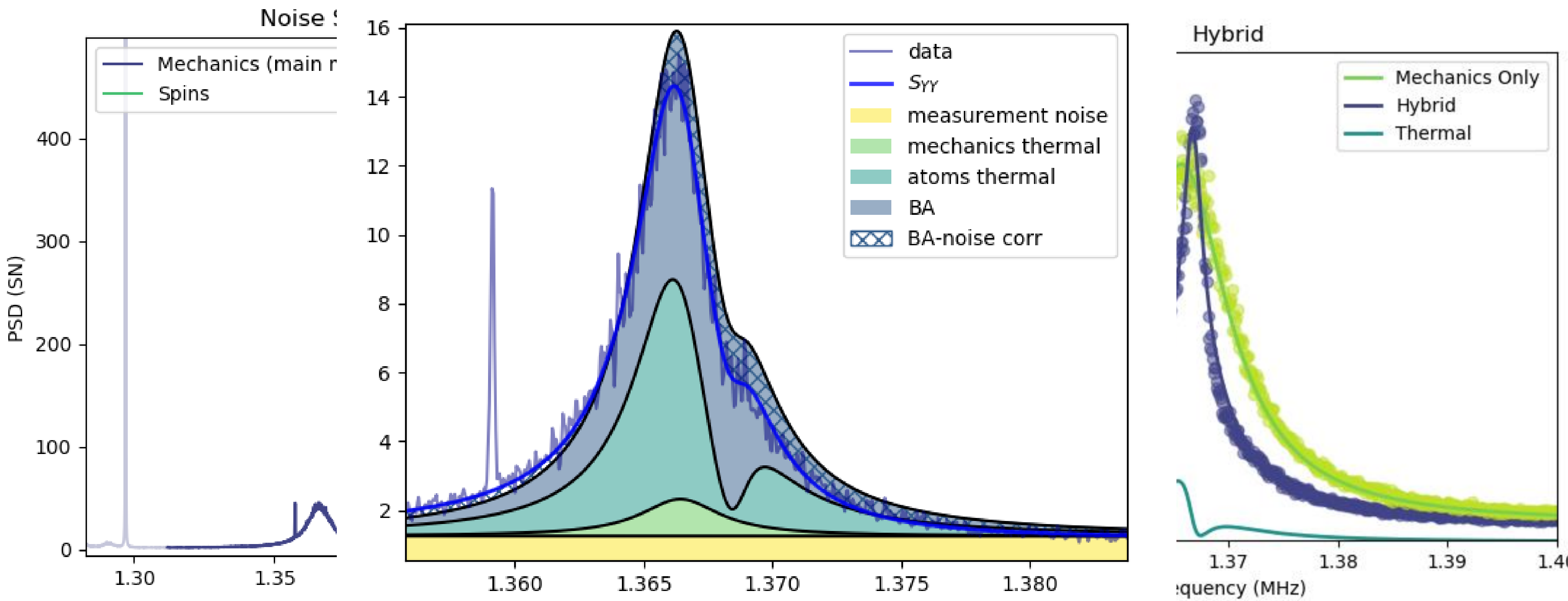
Hybrid setup

Mapping Stokes vectors to light quadratures



R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Quantum back-action evasion



R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

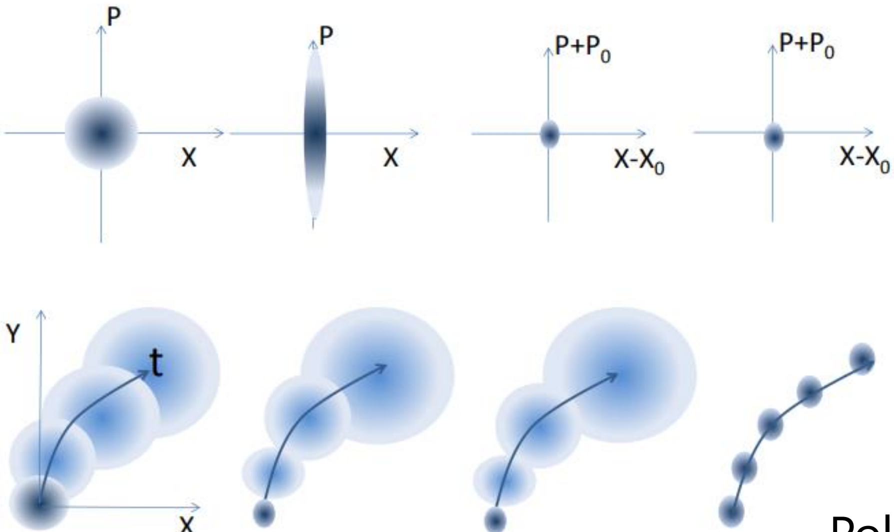
Trajectory in the negative-mass reference frame

Free mass

$$(X - X_0)(dt) = (X - X_0)(0) + (\dot{X} - \dot{X}_0)dt = (X - X_0)(0) + (P \mp P_0)/m dt$$

Harmonic Oscillator

$$X(t) - X_0(t) = (X(0) - X_0(0))\cos(\omega t) + (P(0) \mp P_0(0))\sin(\omega t)$$



$$[X - X_0, P + P_0] = 0$$

Polzik&Hammerer, Ann. Phys. 527, A15 (2015)

Conditional entanglement scheme

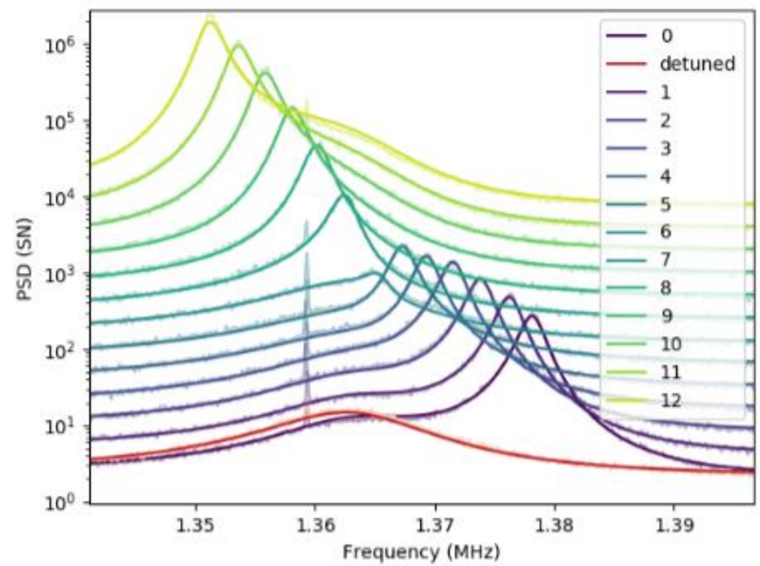
$$\hat{P}_L^{\mathrm{out}} = \alpha \hat{X}_M + \beta \hat{X}_S + \hat{P}_L^{\mathrm{in}},$$

$$\hat{p}_L^{\mathrm{out}} = \mathrm{Re}(\alpha)\hat{x}_M - \mathrm{Im}(\alpha)\hat{p}_M + \mathrm{Re}(\beta)\hat{x}_S \mp \mathrm{Im}(\beta)\hat{p}_S + \hat{p}_L^{\mathrm{in}}$$
$$-\hat{x}_L^{\mathrm{out}} = \mathrm{Im}(\alpha)\hat{x}_M + \mathrm{Re}(\alpha)\hat{p}_M + \mathrm{Im}(\beta)\hat{x}_S \pm \mathrm{Re}(\beta)\hat{p}_S - \hat{x}_L^{\mathrm{in}}$$

$$\hat{x}_{\mathrm{EPR}} = \frac{\sqrt{\Gamma_{\mathrm{m}}}\hat{\tilde{x}}_{\mathrm{m}} + \sqrt{\Gamma_{\mathrm{s}}}\hat{\tilde{x}}_{\mathrm{s}}}{\sqrt{(\Gamma_{\mathrm{m}} + \Gamma_{\mathrm{s}})/2}}$$

$$\hat{p}_{\mathrm{EPR}} = \frac{\sqrt{\Gamma_{\mathrm{m}}}\hat{\tilde{p}}_{\mathrm{m}} - \sqrt{\Gamma_{\mathrm{s}}}\hat{\tilde{p}}_{\mathrm{s}}}{\sqrt{(\Gamma_{\mathrm{m}} + \Gamma_{\mathrm{s}})/2}}$$

$$\mathrm{var}(\hat{x}_{\mathrm{EPR}}) = \frac{\Gamma_m \overbrace{\mathrm{var}(\hat{\tilde{x}}_m)}^{1/2} + \Gamma_s \overbrace{\mathrm{var}(\hat{\tilde{x}}_s)}^{1/2}}{\Gamma_{\mathrm{EPR}}} = 1$$



R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Wiener filtering

$$\hat{y} = \hat{x} + \hat{n}.$$

$$\vec{x}(t) = \int_{-\infty}^{t} K(t - t' \ldots$$

$$\hat{x}(t) = \underbrace{\int_{-\infty}^{t} \mathrm{d}t' K(t - \ldots}_{\vec{x}(t)}$$

$$\langle \hat{R}(t)\hat{y}(t') + \hat{y}(t')\hat{R}(\ldots$$

$$C_{xy}(t) - \int_{0}^{\infty} \mathrm{d}t' K(\ldots$$

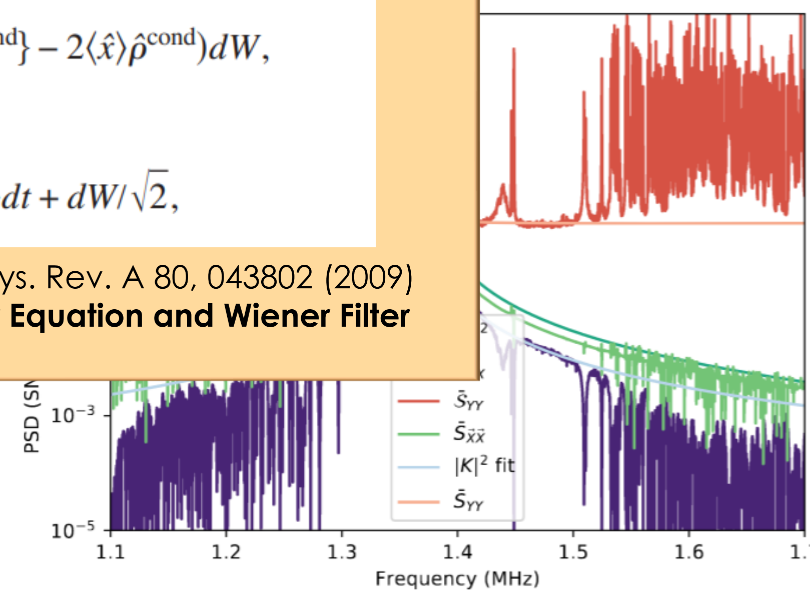
$$V_c = \langle \hat{R}(0)^2 \rangle = \underbrace{\langle \hat{x}(0)^2 \rangle}_{V_u} - \langle \hat{\vec{x}}(0)^2 \rangle$$

$$\begin{pmatrix} C_{yy}(t_0) & C_{yy}(t_1) & C_{yy}(t_2) & \cdots & C_{yy}(t_N) \\ C_{yy}(t_1) & C_{yy}(t_0) & C_{yy}(t_1) & \cdots & C_{yy}(t_{N-1}) \\ C_{yy}(t_2) & C_{yy}(t_1) & C_{yy}(t_0) & \cdots & C_{yy}(t_{N-2}) \\ \ldots & & & & (t_0) \end{pmatrix} \underbrace{\begin{pmatrix} K(t_0) \\ K(t_1) \\ K(t_2) \\ \vdots \\ K(t_N) \end{pmatrix}}_{\mathbf{K}} = \underbrace{\begin{pmatrix} C_{xy}(t_0) \\ C_{xy}(t_1) \\ C_{xy}(t_2) \\ \vdots \\ C_{xy}(t_N) \end{pmatrix}}_{\mathbf{C}_{xy}}$$

$$d\hat{\rho}^{\mathrm{cond}} = -\frac{i}{\hbar}[H_{\mathrm{sys}}, \hat{\rho}^{\mathrm{cond}}]dt - \frac{\alpha^2}{4\hbar^2}[\hat{x},[\hat{x},\hat{\rho}^{\mathrm{cond}}]]dt + \frac{\alpha}{\sqrt{2}\hbar}(\{\hat{x},\hat{\rho}^{\mathrm{cond}}\} - 2\langle\hat{x}\rangle\hat{\rho}^{\mathrm{cond}})dW,$$

$$d\hat{y} = \frac{\alpha}{\hbar}\langle\hat{x}\rangle dt + dW/\sqrt{2},$$

H. Muller-Ebhart et al., Phys. Rev. A 80, 043802 (2009)
Linking Stochastic Master Equation and Wiener Filter

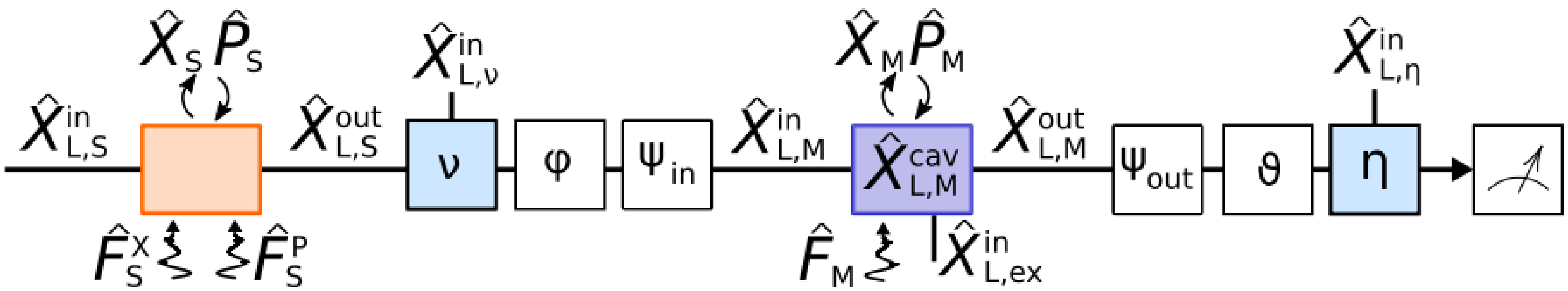


R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Full quantum noise spectra

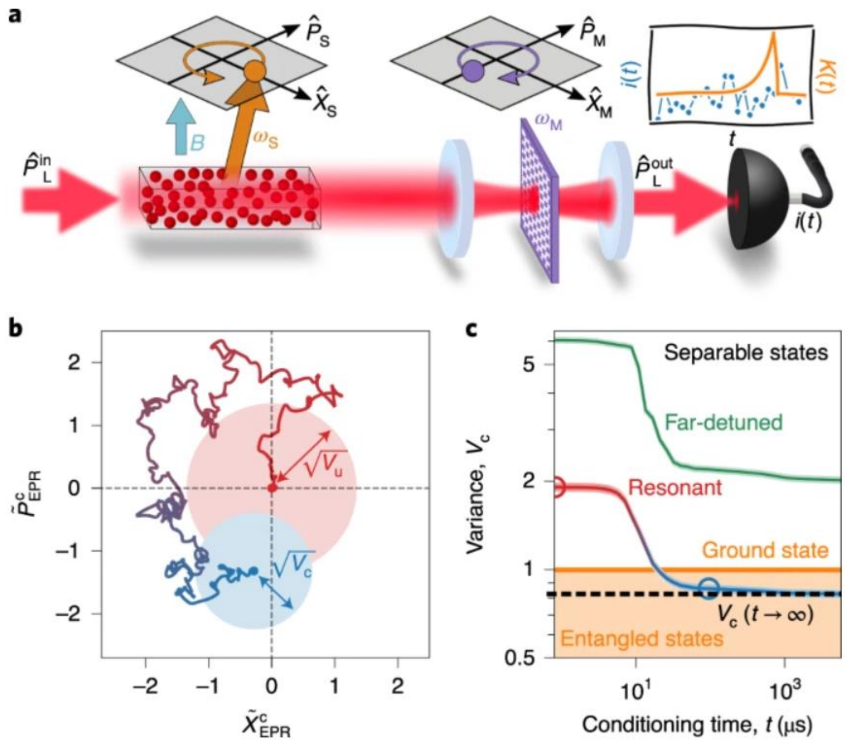
$$\hat{P}_{\mathrm{L}}^{\mathrm{out}} = \hat{P}_{\mathrm{L}}^{\mathrm{in}\,\prime} + \sqrt{\eta}\left(\sqrt{\Gamma_{\mathrm{M}}}\hat{X}_{\mathrm{M}} - \sqrt{\nu\Gamma_{\mathrm{S}}}\hat{X}_{\mathrm{S}}\right)$$

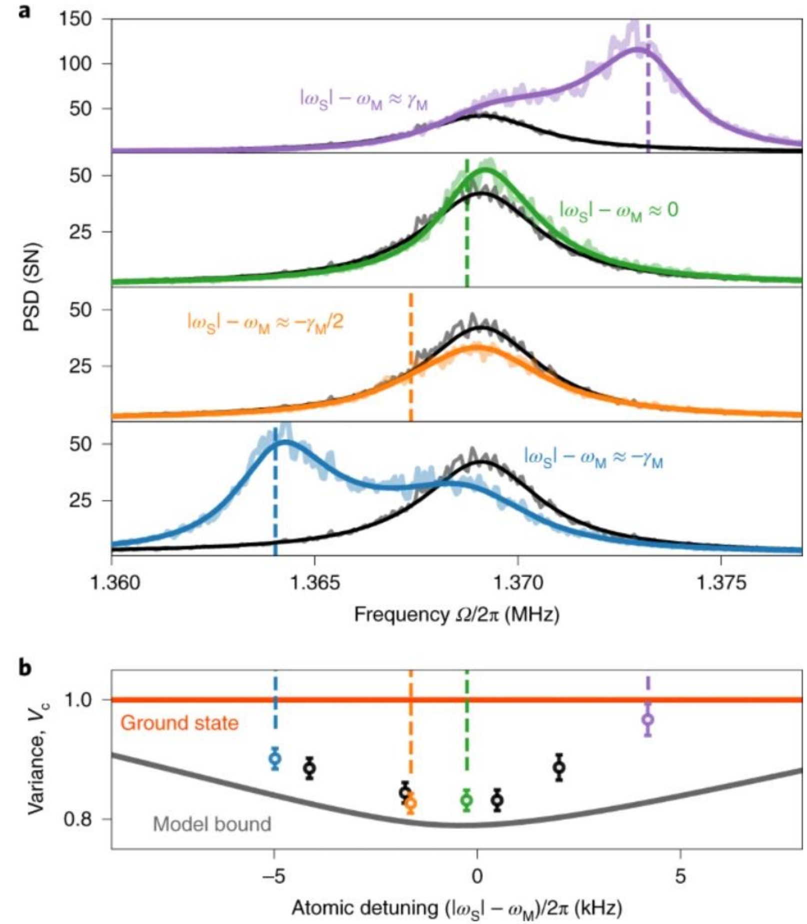
$$\approx \hat{P}_{\mathrm{L}}^{\mathrm{in}\,\prime} + \sqrt{\eta}\,(\; - \sqrt{\nu}\left[\frac{\chi_{\mathrm{S}}}{\chi_{\mathrm{S0}}}\Gamma_{\mathrm{M}}\chi_{\mathrm{M}} + \frac{\chi_{\mathrm{M}}}{\chi_{\mathrm{M0}}}\Gamma_{\mathrm{S}}\chi_{\mathrm{S}}\right] 2\hat{X}_{\mathrm{L,S}}^{\mathrm{in}}$$
$$+\sqrt{\Gamma_{\mathrm{M}}}\chi_{\mathrm{M}}[\hat{F}_{\mathrm{M}} + \sqrt{(1-\nu)\Gamma_{\mathrm{M}}}2\hat{X}_{\mathrm{L},\nu}] - \frac{\chi_{\mathrm{M}}}{\chi_{\mathrm{MS}}}\sqrt{\nu\Gamma_{\mathrm{S}}}\chi_{\mathrm{S}}\hat{F}_{\mathrm{S}}\;),$$



R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

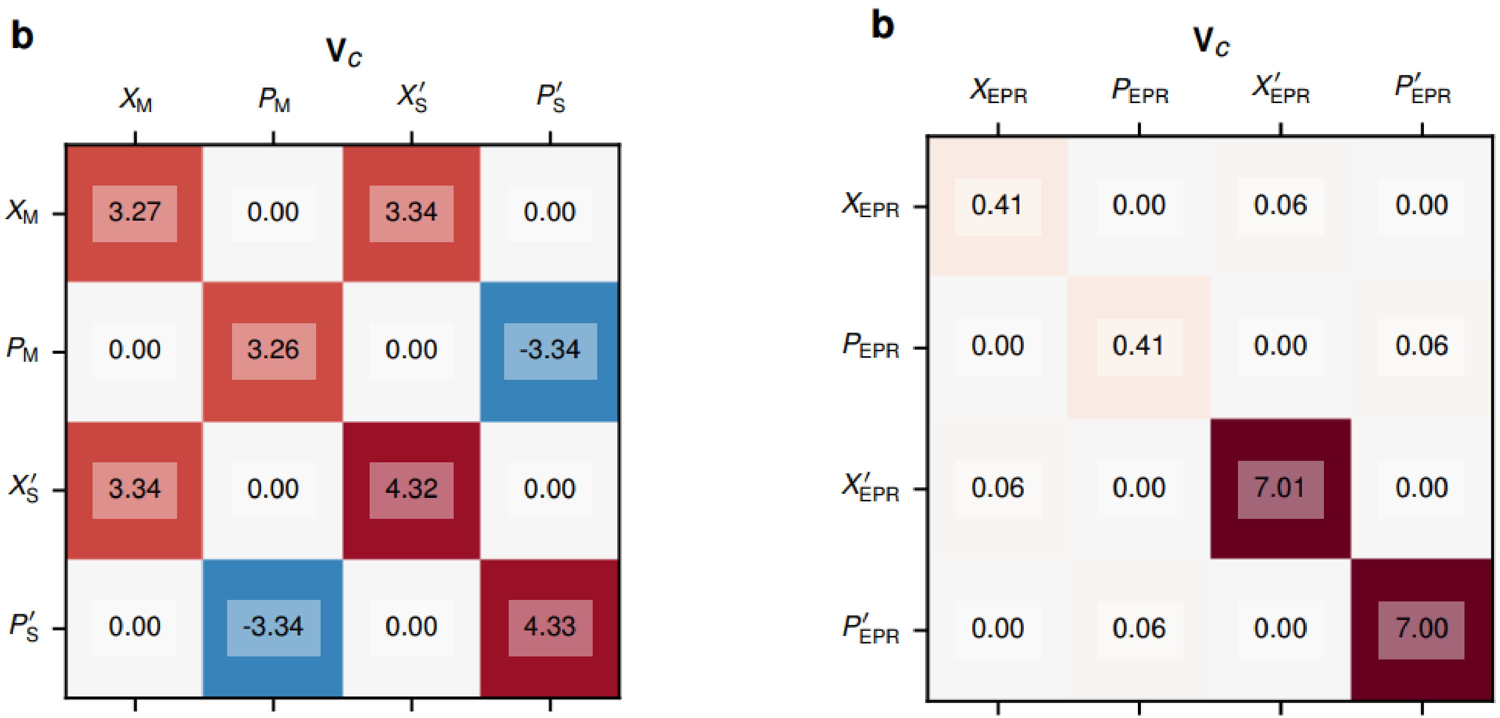
Final result





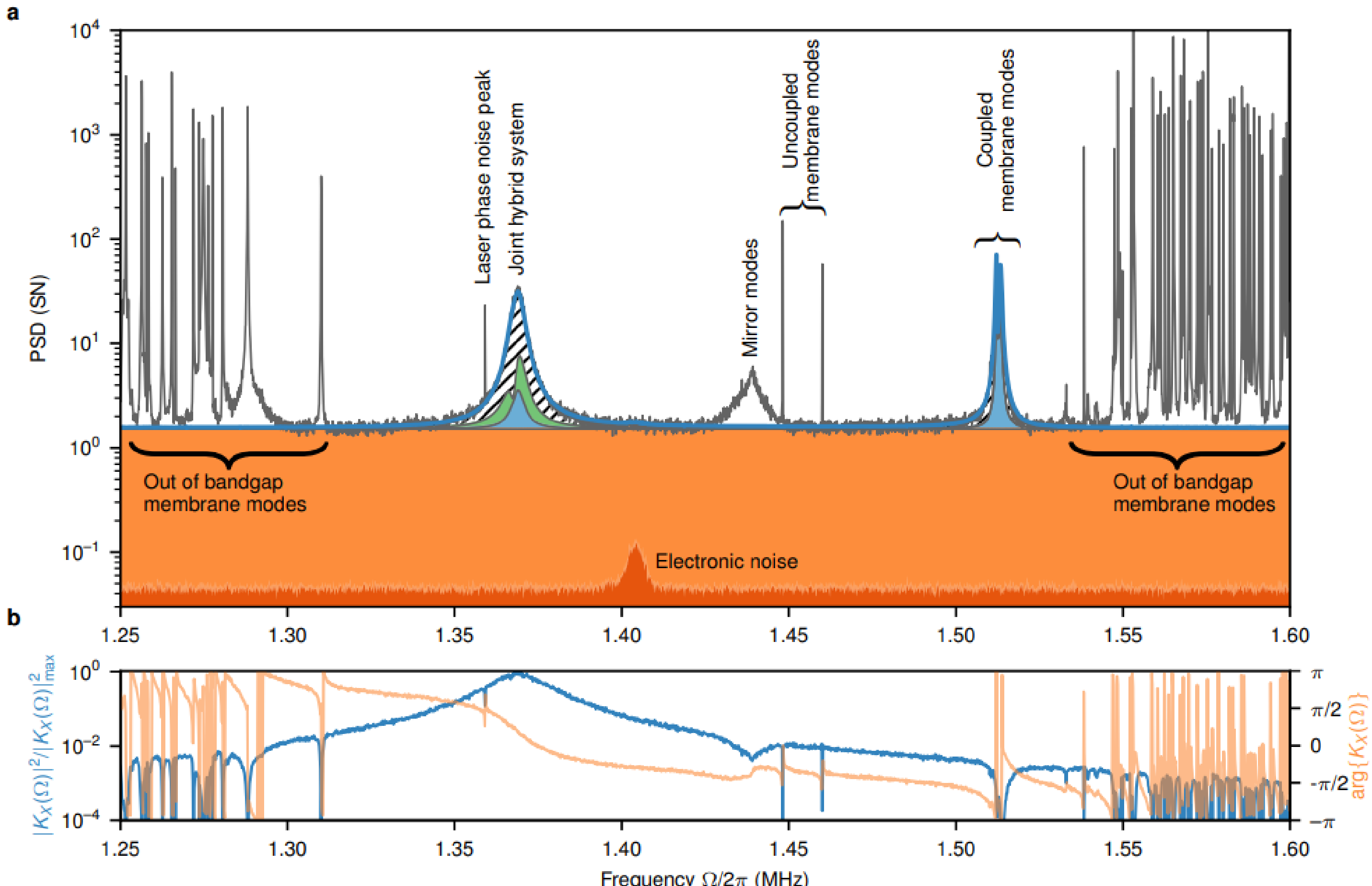
R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Covariance



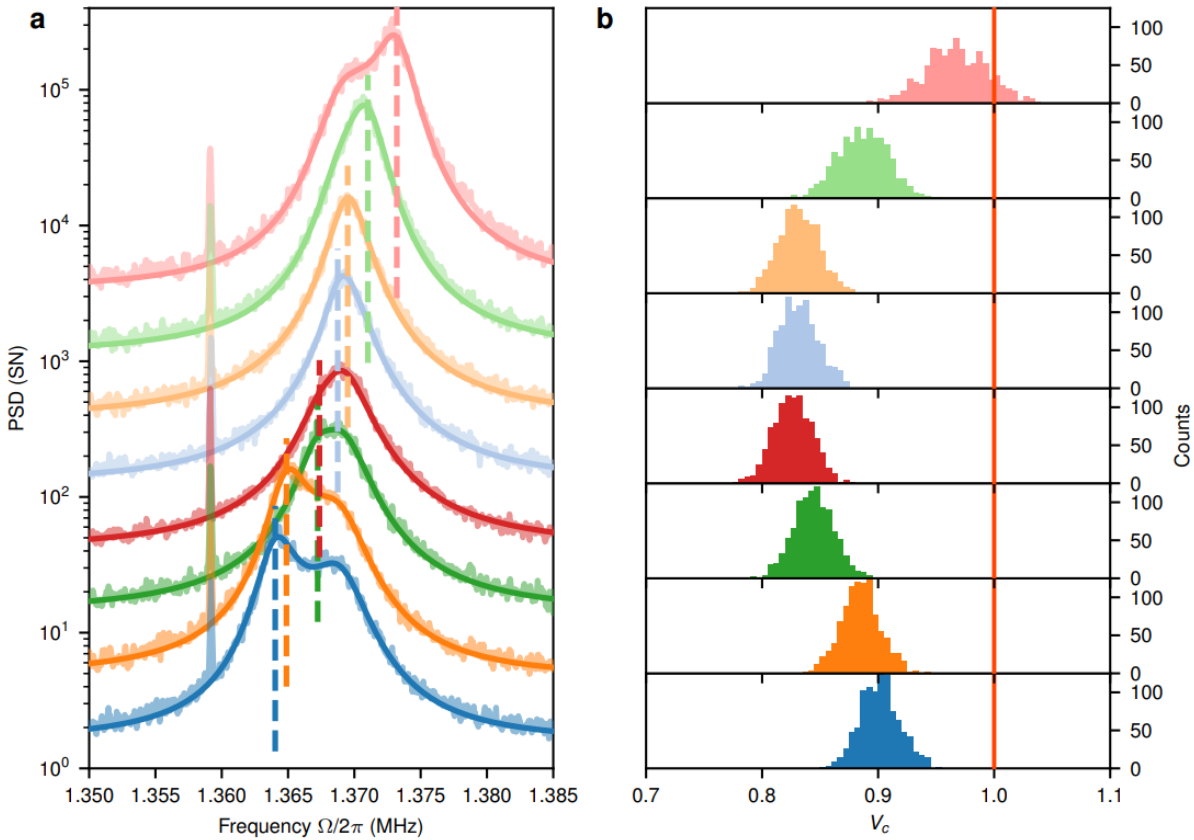
R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Filtering technicalities



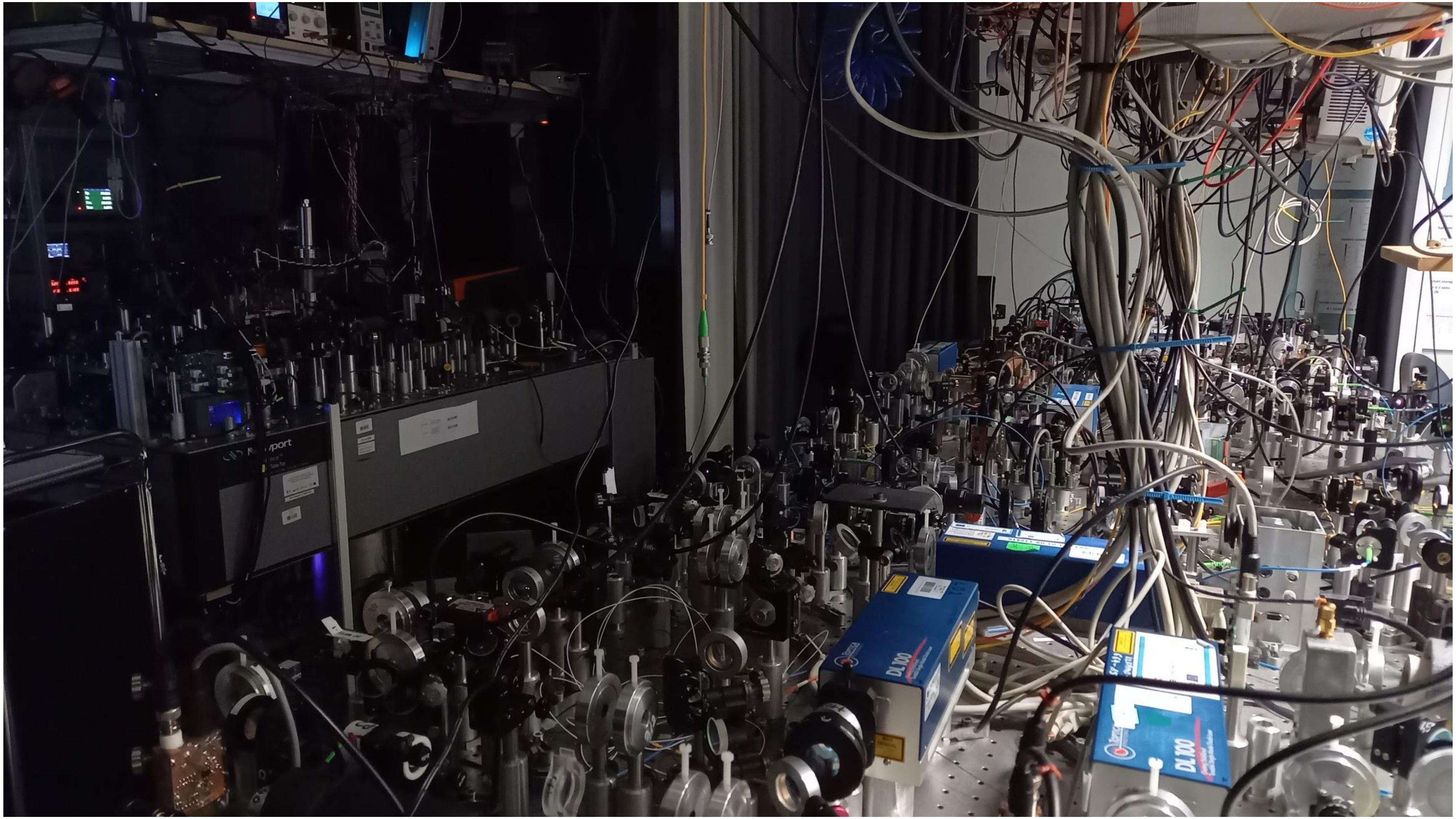
R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Callibrations and uncertainties

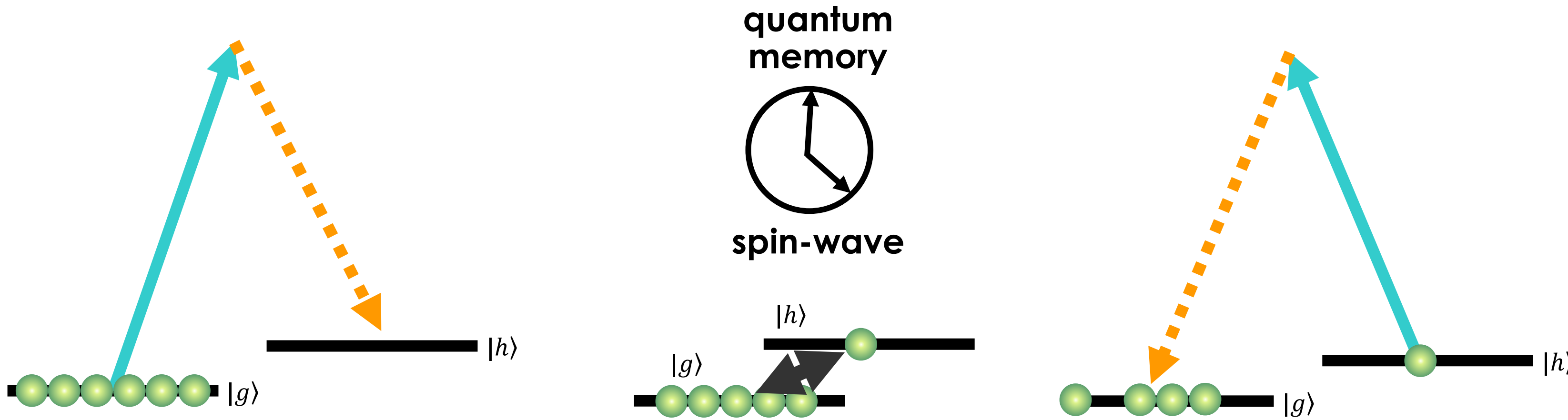


R. A. Thomas, MP, et al., *Nature Physics* **17**, 228–233 (2021)

Centre for Quantum Optical Technologies

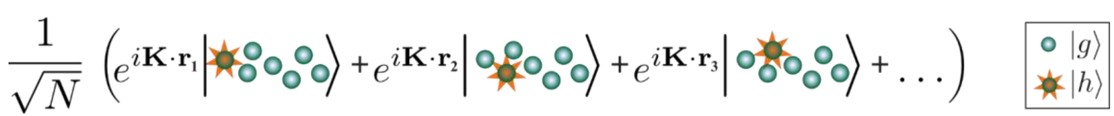


Raman interface

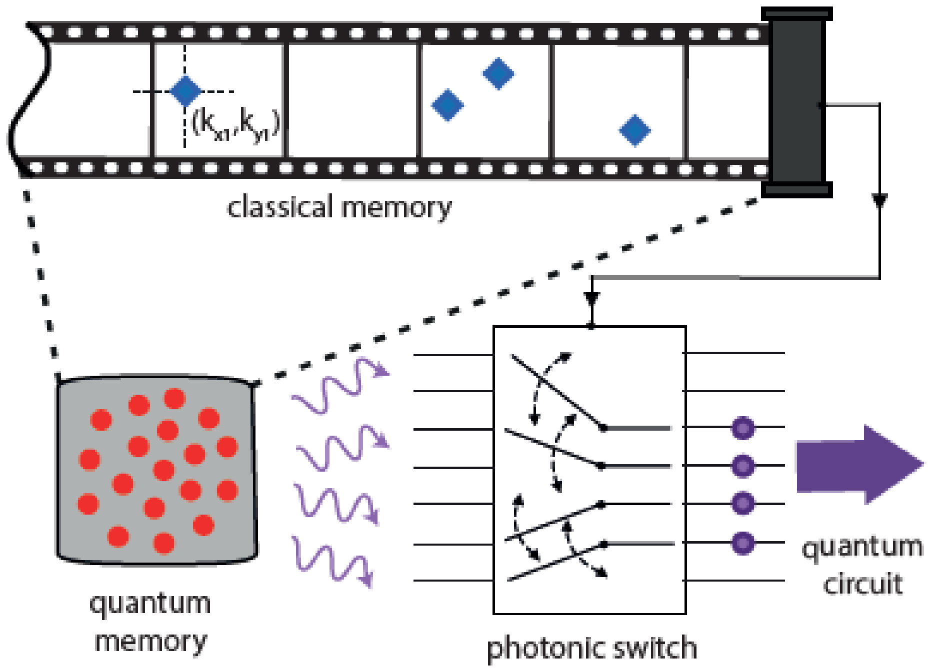


two-mode squeezed state creation via off-resonant **Raman scattering**

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

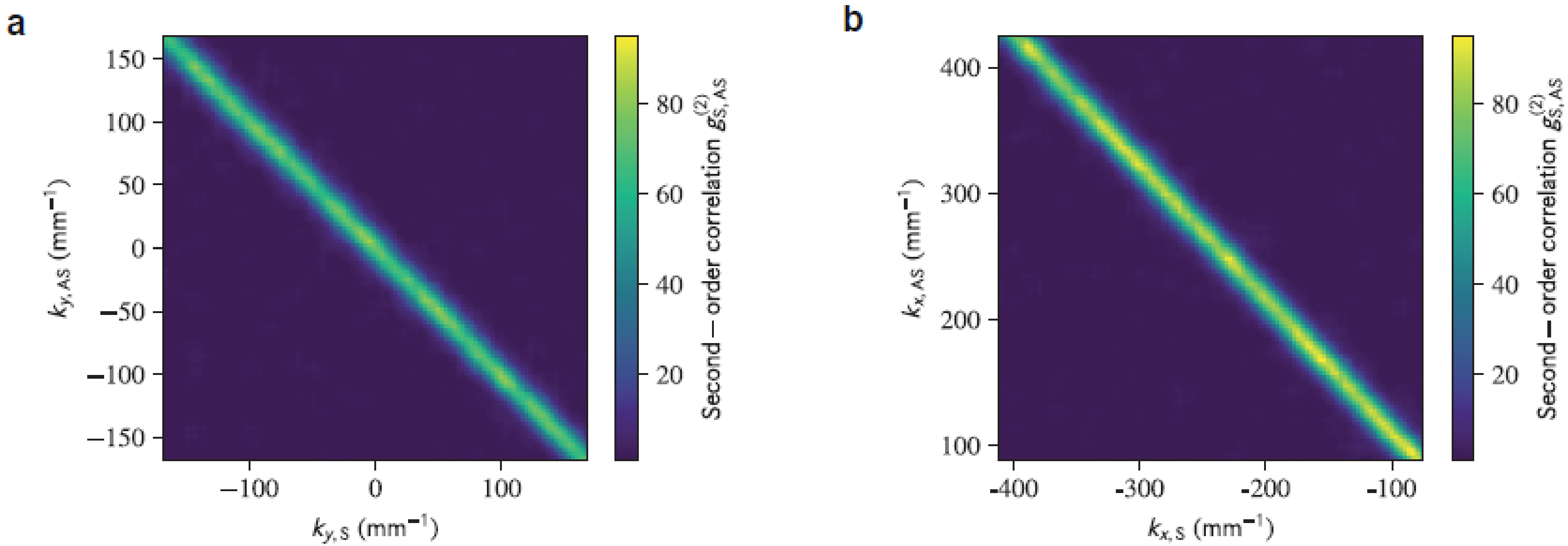


Deterministic single and multi-photons



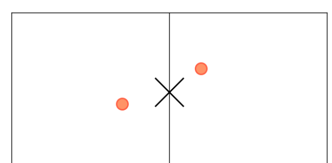
MP, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, Nat. Commun **8**, 2140 (2017)

Photon number correlations



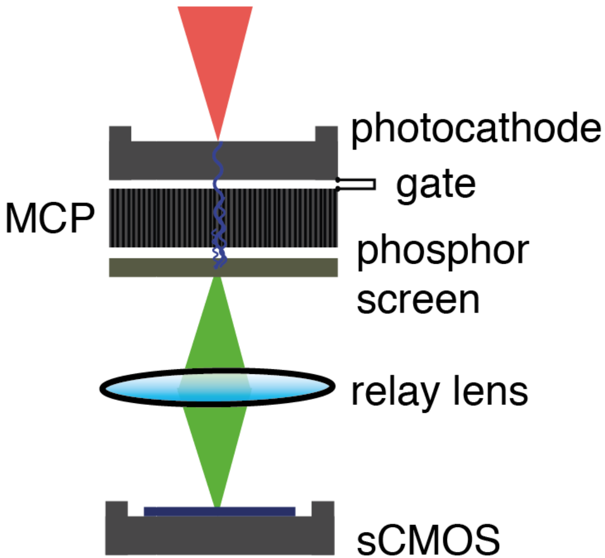
non-classical correlations

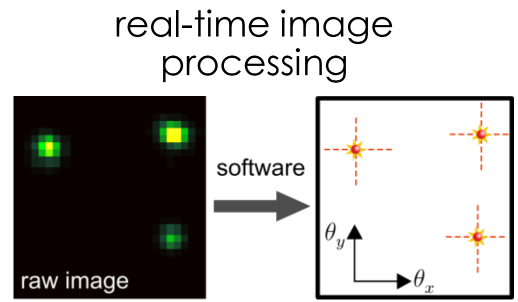
$$g^{(2)} = \frac{\langle n_S n_{AS} \rangle}{\langle n_S \rangle \langle n_{AS} \rangle} = 72 \pm 5 \gg 2$$

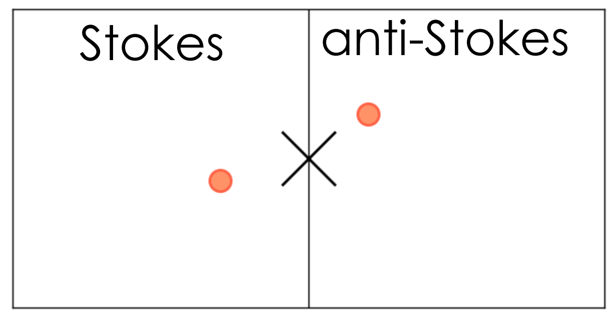


Nat. Commun **8**, 2140 (2017)

I-sCMOS camera







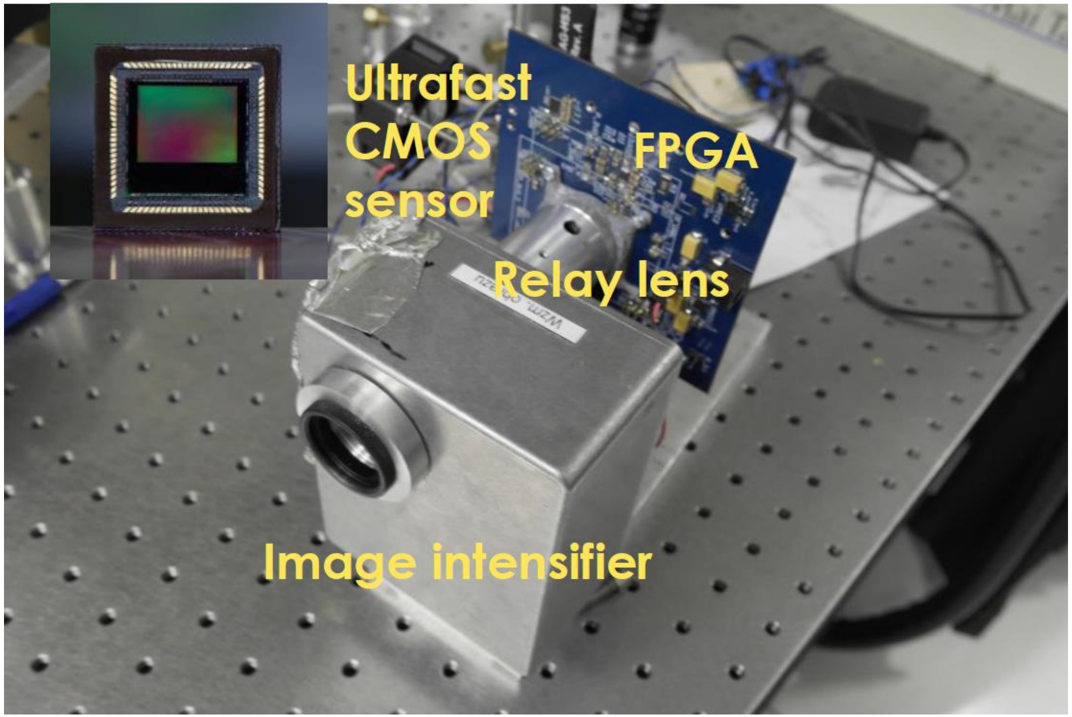
MP, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, Nat. Commun. **8**, 2140 (2017)

New system

Custom FPGA data processing

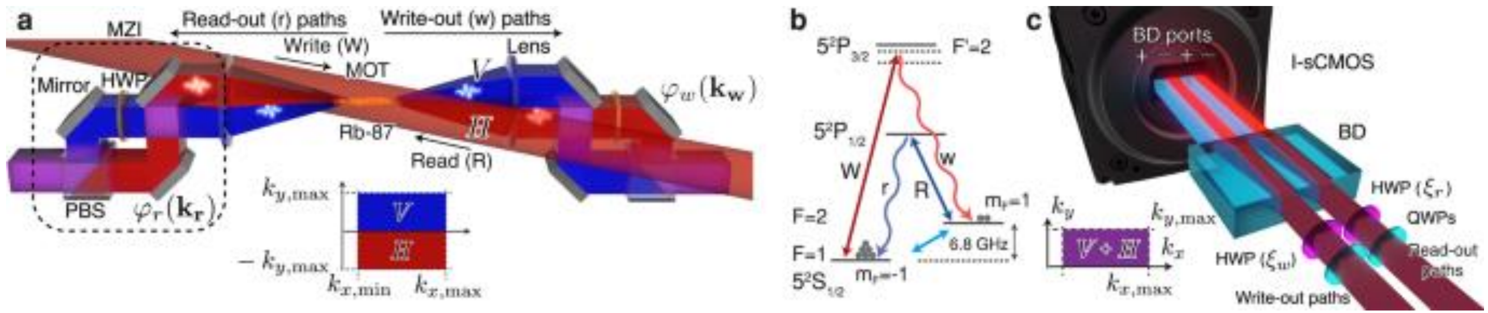
New custom high-voltage gating module

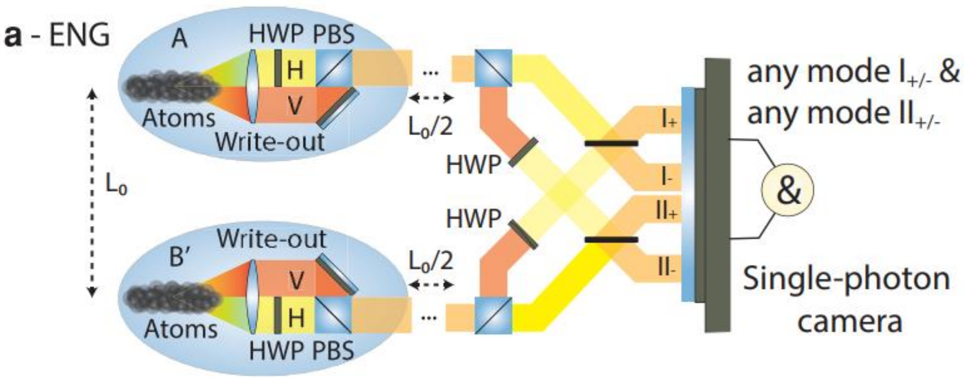
Now 100.000 frames per second, **~10 microseconds from detection to information**

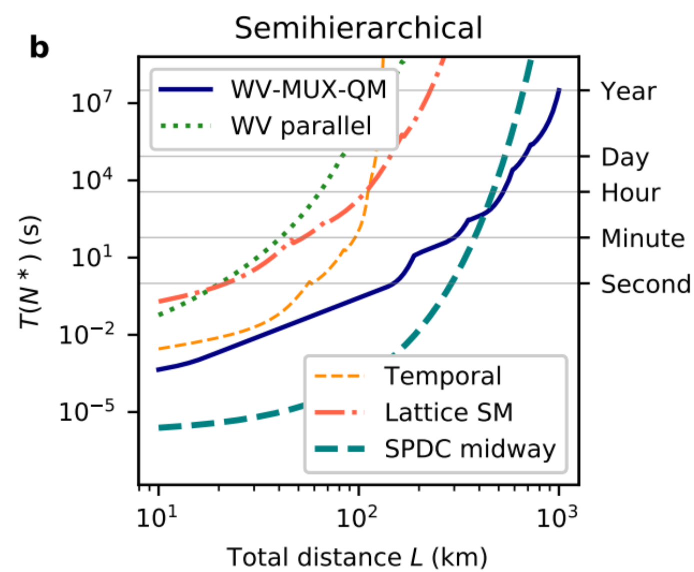


Optics Letters 46, 3009 (2021)

Many Bell states for multiplexed quantum repeaters

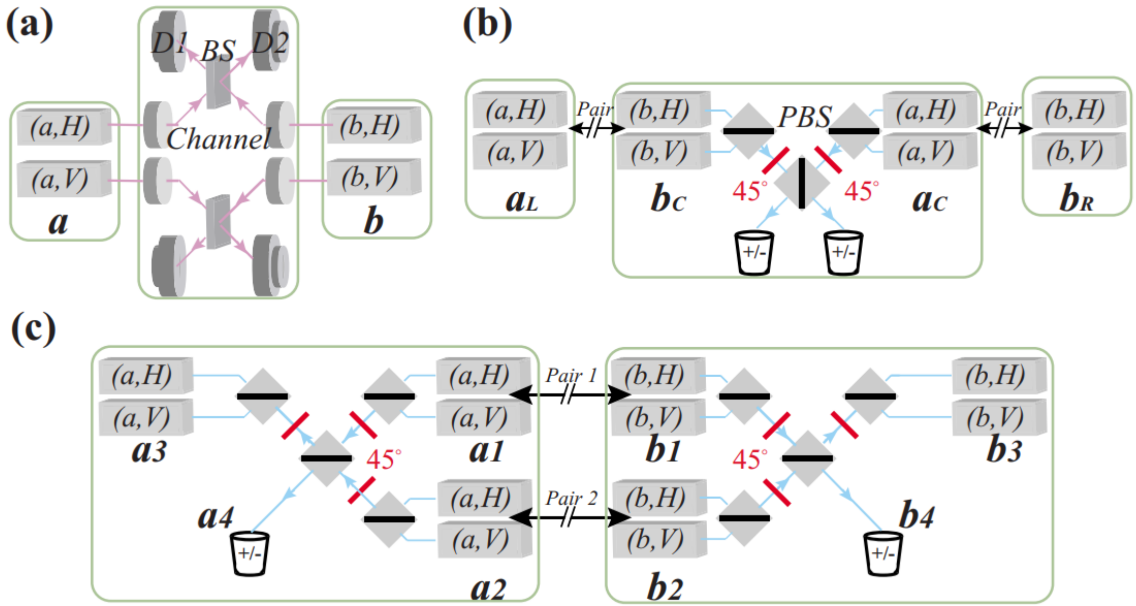






Communications Physics **4**, 46 (2021)
& New J. Phys. 23, 053012 (2021)

Quantum repeater



PHYSICAL REVIEW A **76**, 012301 (2007)

Fast and robust approach to long-distance quantum communication with atomic ensembles

L. Jiang,[1] J. M. Taylor,[1,2] and M. D. Lukin[1]
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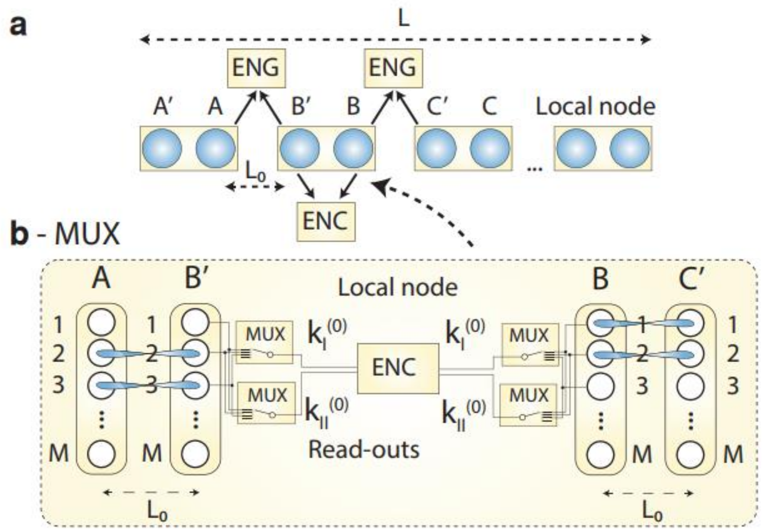
[2]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 27 November 2006; revised manuscript received 3 April 2007; published 2 July 2007)

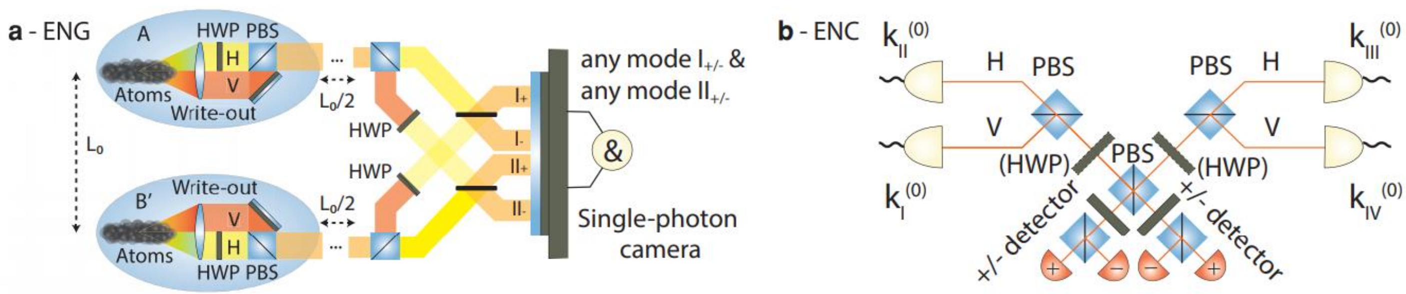
Quantum repeater with multiplexing



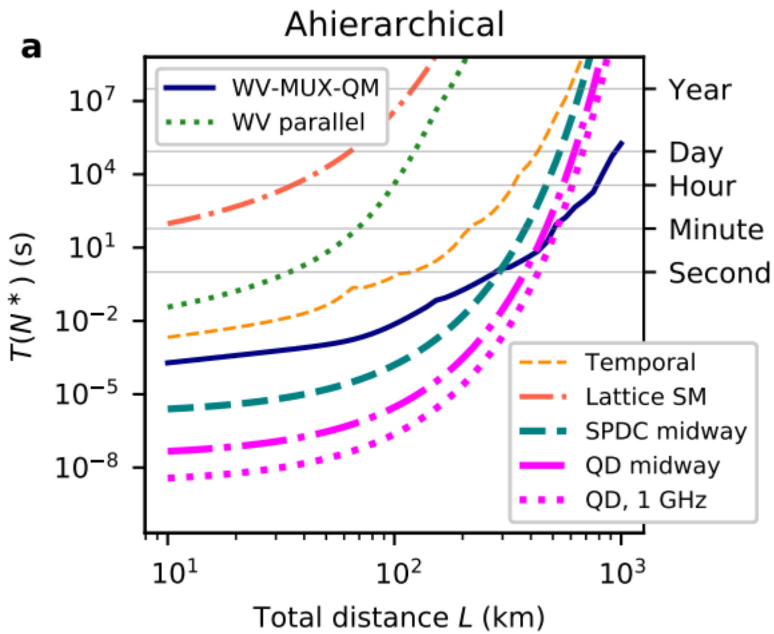
Communications Physics **4**, 46 (2021)
& New J. Phys. 23, 053012 (2021)

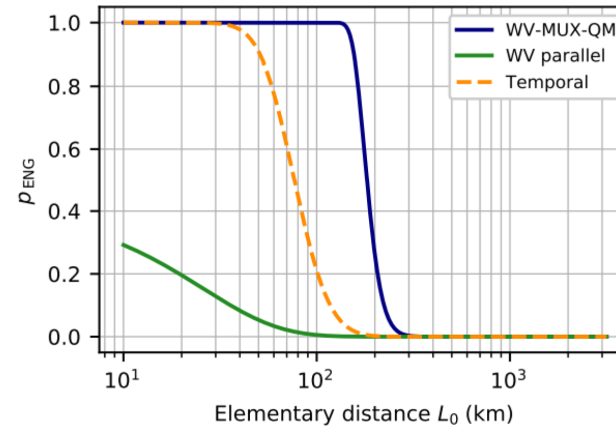
$$p_g^{(\text{parallel})} = 1 - (1 - p_1)^M.$$

$$p_g = 1 - (1 - p_1)^{M^2}.$$



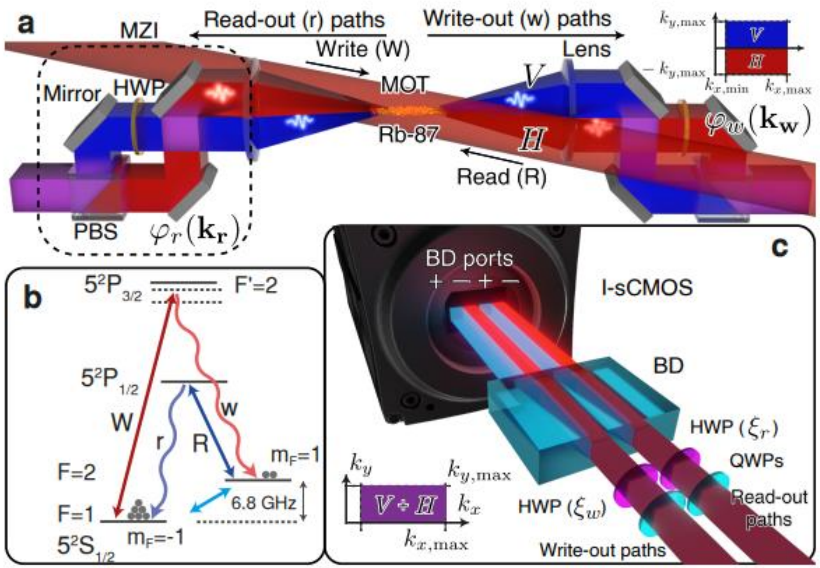
Performance of the quantum repeater

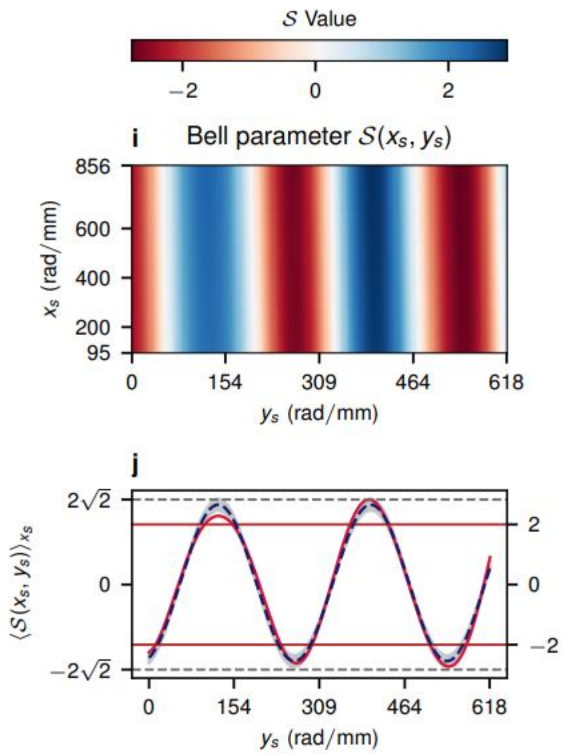




Communications Physics **4**, 46 (2021)
& New J. Phys. 23, 053012 (2021)

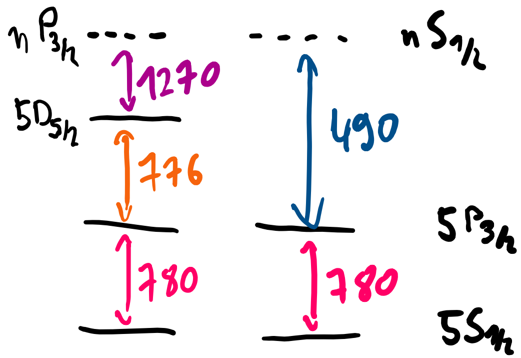
Towards experimental repeater

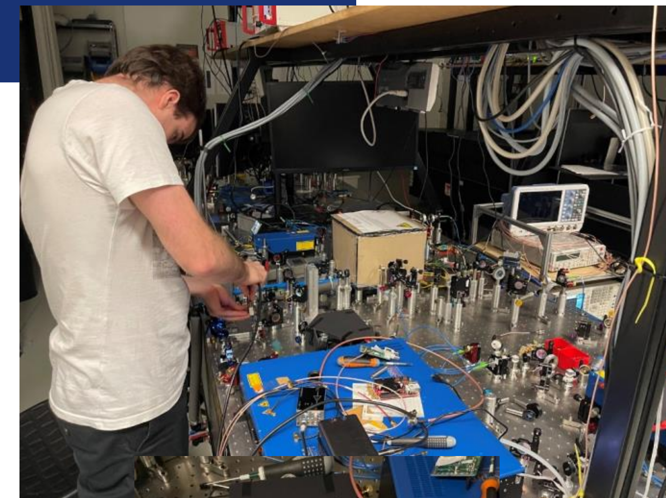


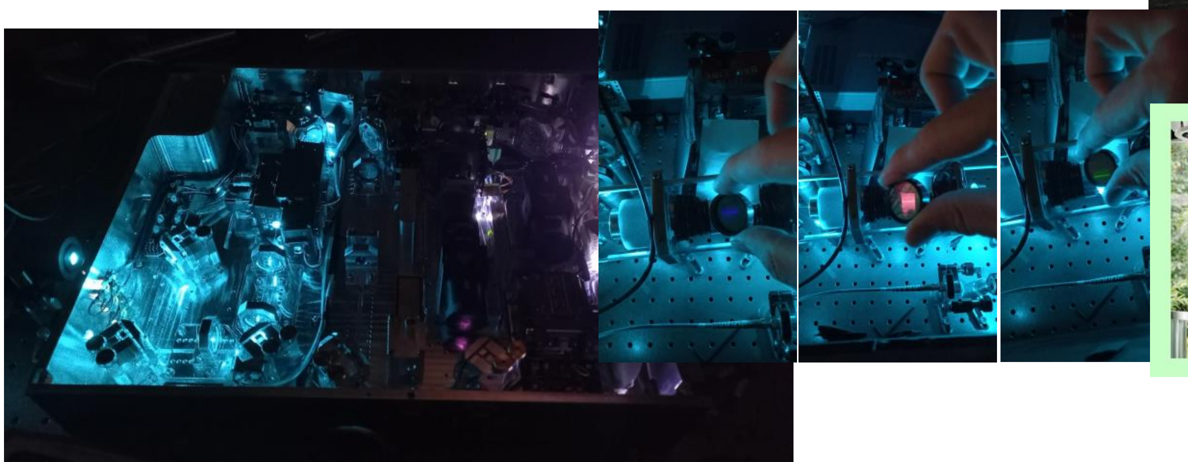


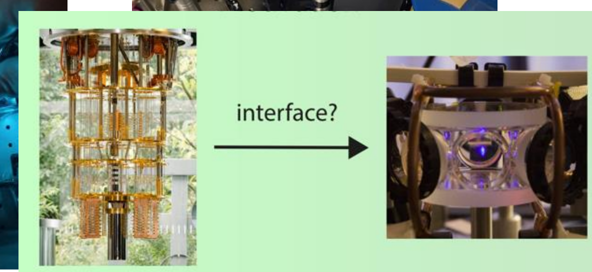
Communications Physics **4**, 46 (2021)
& New J. Phys. 23, 053012 (2021)

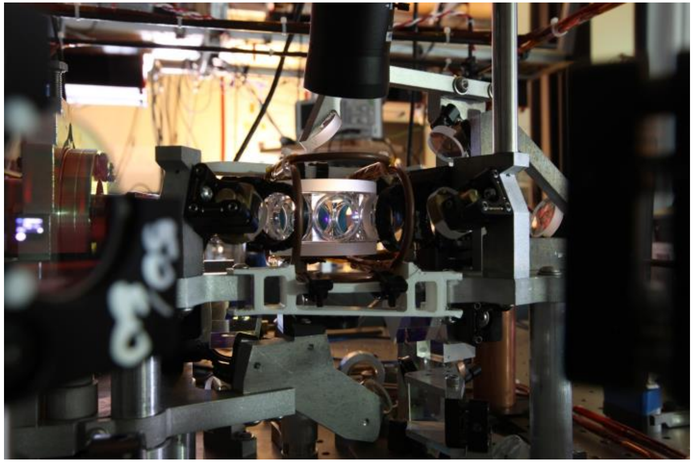
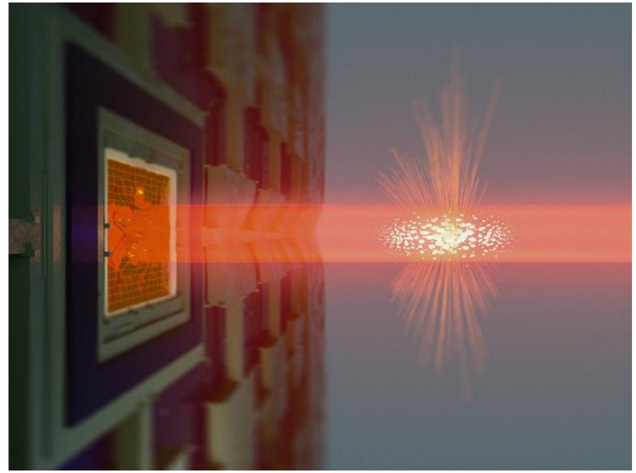
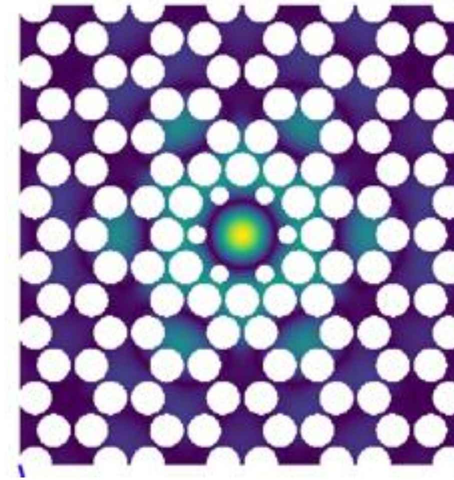
New Rydberg experiment









Hybrid Project:
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Theory with: Emil Zeuthen
Membranes:
Yeghishe Tsaturyan, Albert Schliesser

Lead: Eugene S. Polzik

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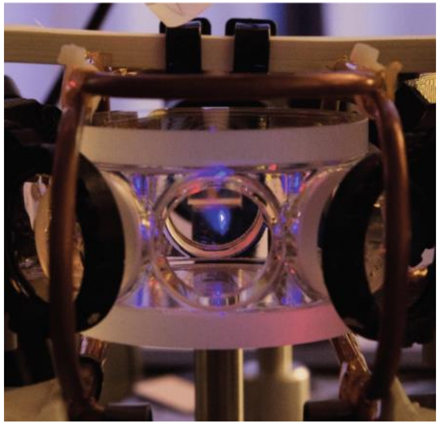
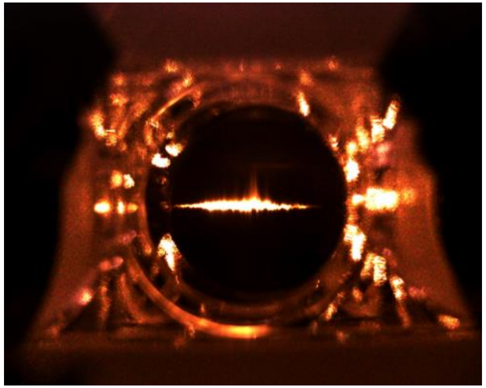
Thank You





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Adam Leszczyński (graduated)

Engineering support:
Tomasz Kowalczyk

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