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Hybrid entanglement between hot atoms and a cryogenic membrane

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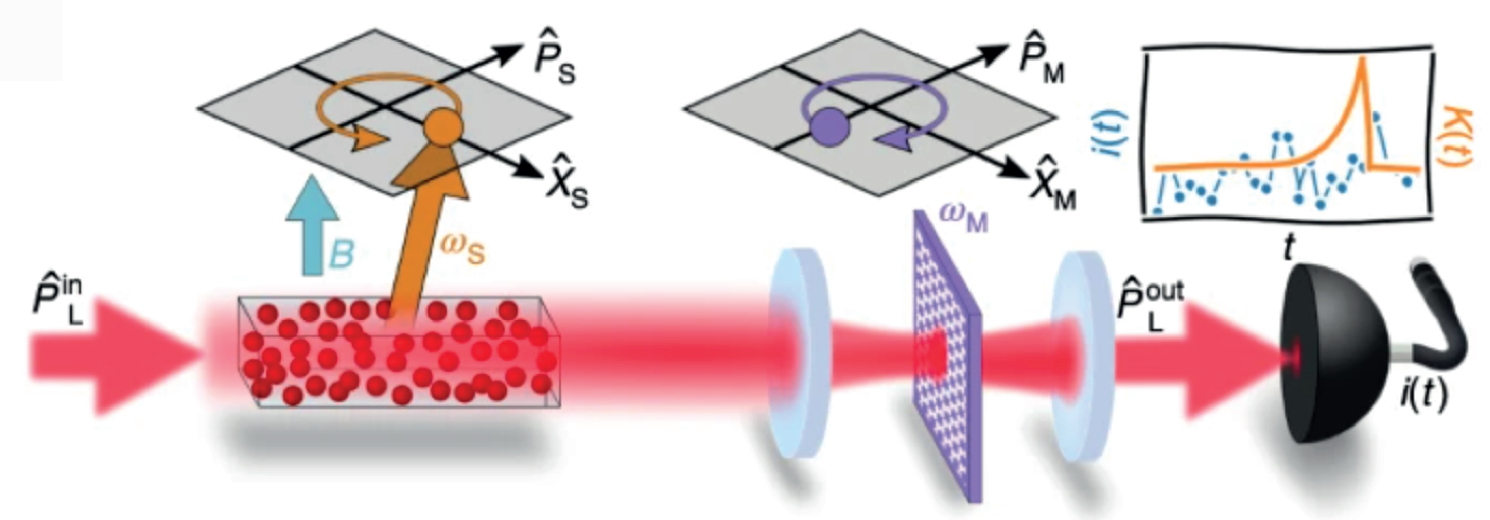
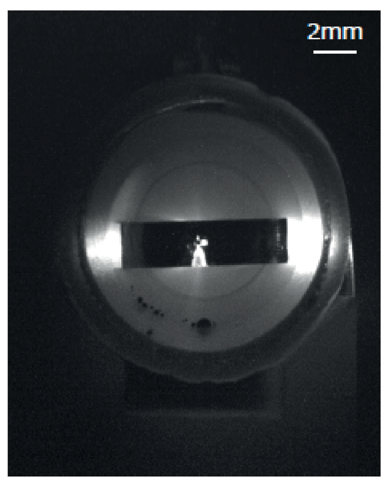
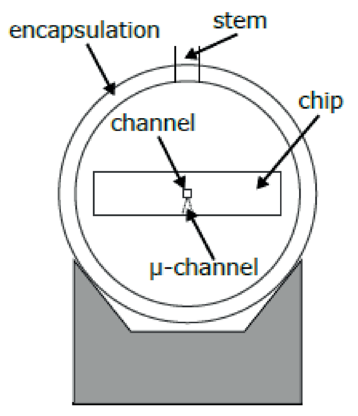


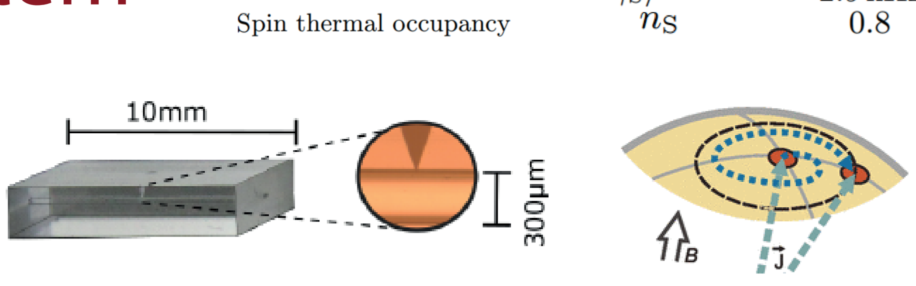
We generate entanglement of a collective spin of a Cs hot atomic ensemble and a phononic crystal SiN membrane resonator.
The entanglement is enabled by a collective continous measurement under the conditions of **quantum back-action evasion**.
Back-action is evaded by engineering the atomic ensemble to act as a **negative-mass oscillator**, which leads to cancellation of back-action effect of strong proble light.

Atomic spin system

Decoherence rate in the dark	$\gamma_{S0,dark}/2\pi$	450 Hz
Effective linewidth	$\gamma_S/2\pi$	2.9 kHz
Spin thermal occupancy	n_S	0.8







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

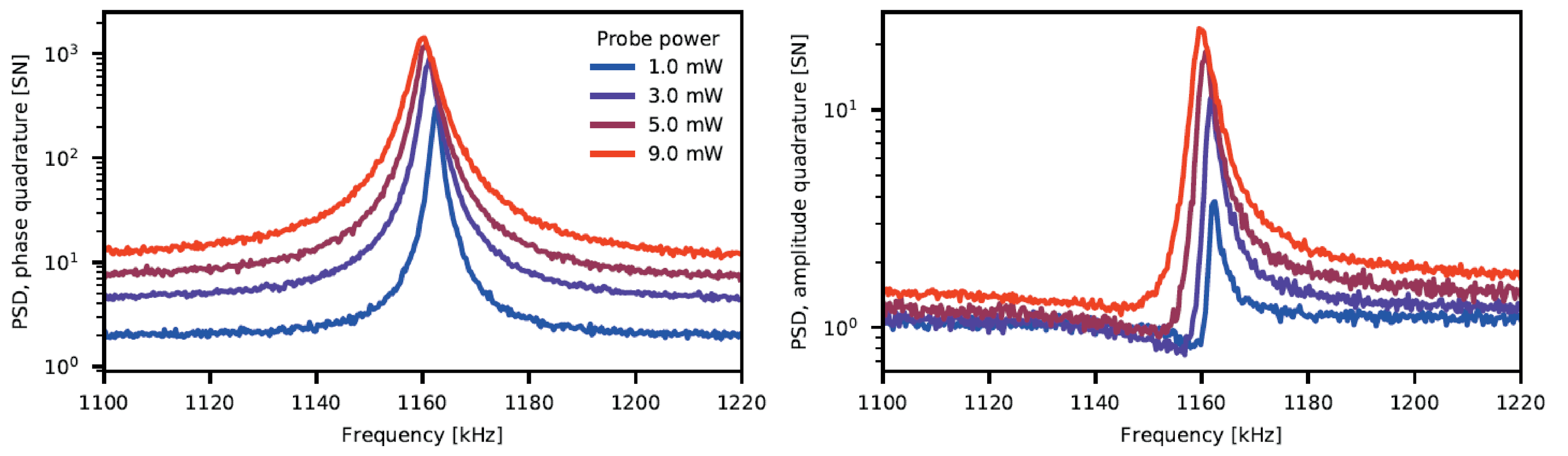
$$\hat{X} = \hat{J}_z/\sqrt{|J_x|}$$

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

Magnetic field transverse to propagation direction

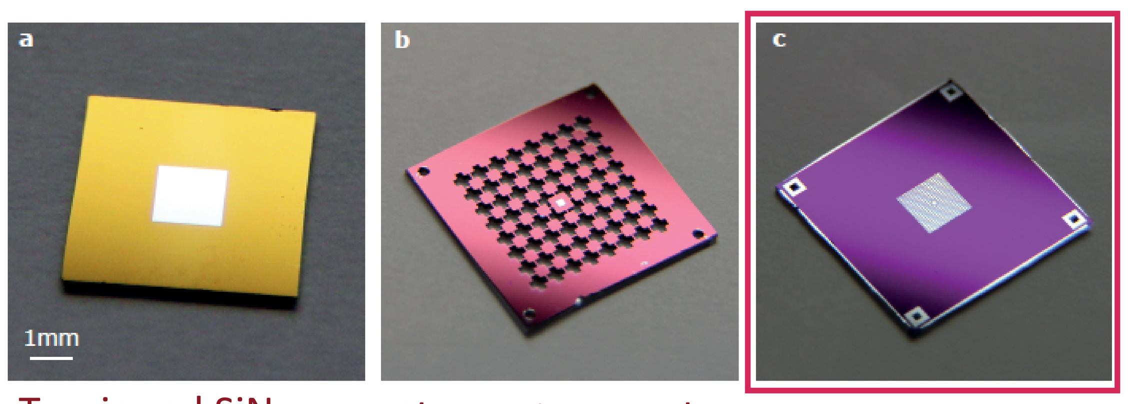
Off-resonant polarization rotation interaction

Polarization rotates due to spin <-> AC-Stark shifts rotate spin



Collective spin oscillator features narrow natural linewidth and high quantum cooperativity. For example, significant squeezing of light can be generated via interference of shot noise and back-action noise

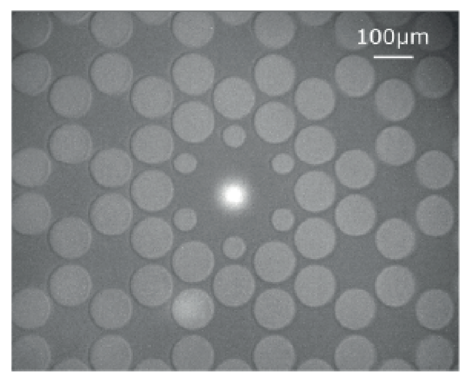
Nanomechanical oscillator



Tensioned SiN membrane inside Si frame

Phononic crystal in Si frame

Phononic crystal in SiN structure



Gaussian cavity mode overlaps with defect mechanical mode

Cavity resonance shift with membrane positon
<->
light pressure on the membrane

Intrinsic damping rate	$\gamma_{M0}/2\pi$	2.1 mHz
Total cavity linewidth	$\kappa/2\pi$	4.2 MHz
Single photon coupling rate	$g_0/2\pi$	6×10^1 Hz
Quantum cooperativity	C_q^M	15
Mean occupancy	n_M	~ 2

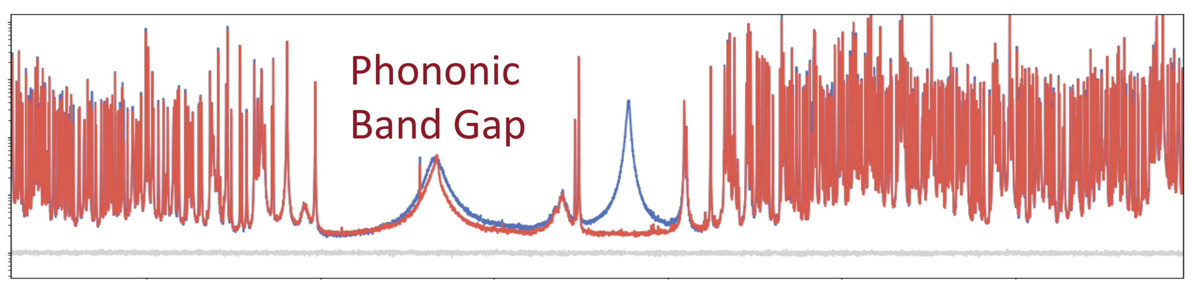
$$\hat{\mathcal{H}} = \hbar\omega_c(\hat{n}+1/2)$$

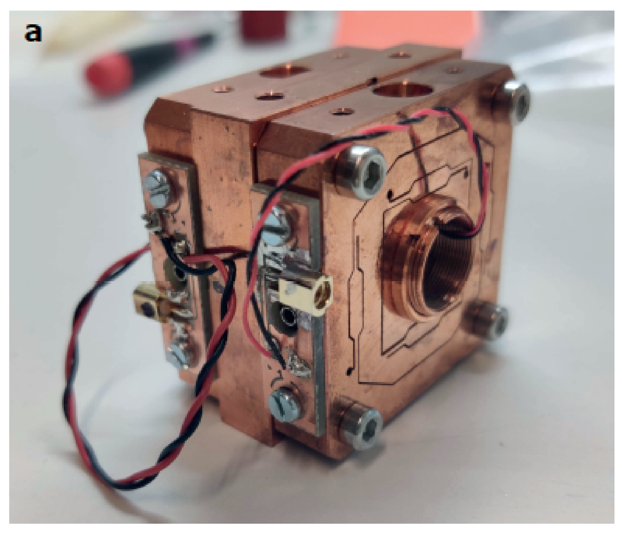
$$\hat{\mathcal{H}} = \hbar\left(\omega_c(0) + \left.\frac{d\omega_c}{dq}\right|_{q=0} q\right)(\hat{n}+1/2)$$

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

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

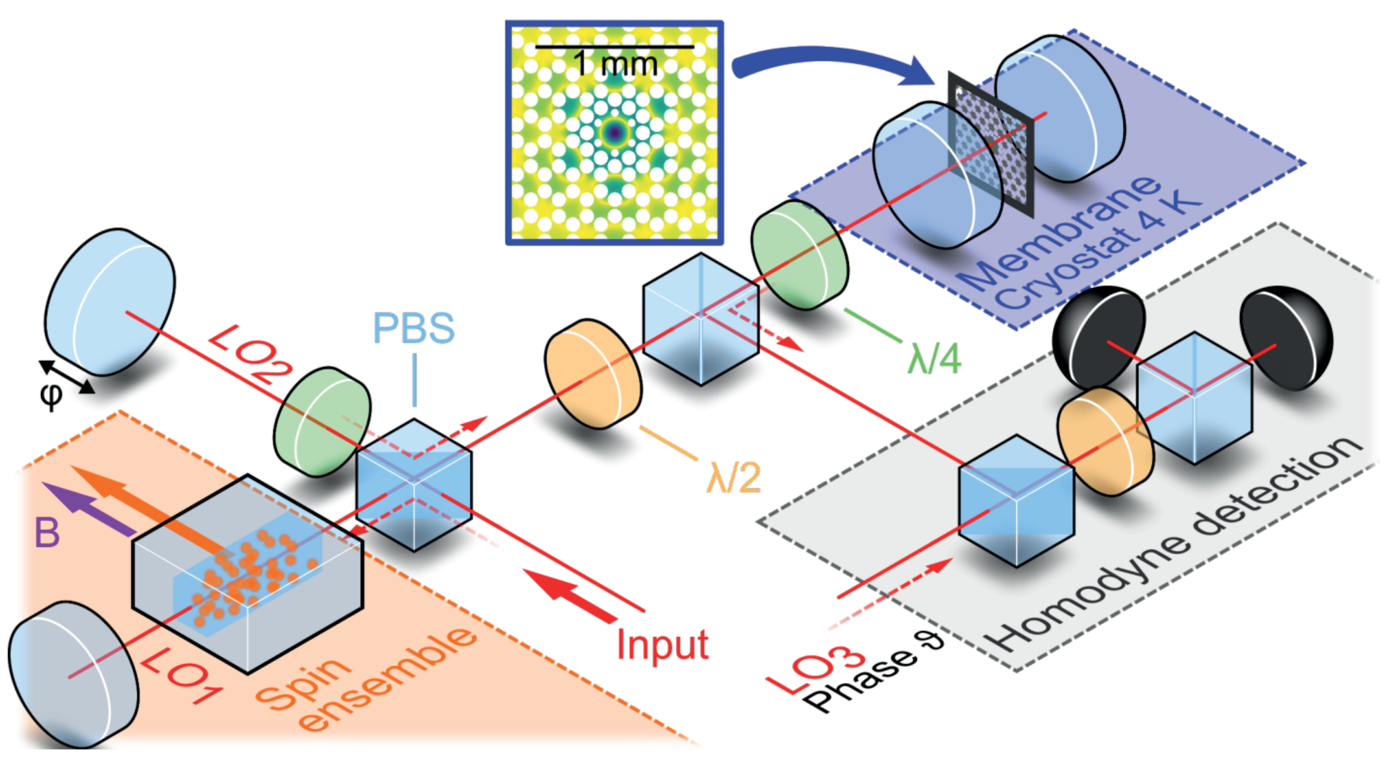
$$\hat{\mathcal{H}}_{int} \propto \hbar g \delta\hat{X}\delta\hat{Q}$$



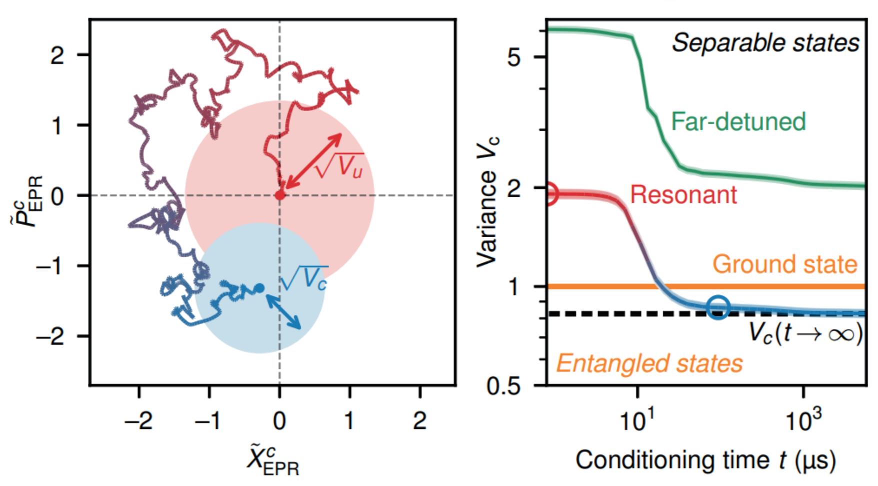


Multi-degree-of-freedom cavity assembly inside a LHe cryostat

Hybrid Entanglement



Spin and mechanical systems are connected via light. Polarization rotation signal from spins is converted to phase quadrature signal directed towards OM cavity.



Quantum back-action evasion

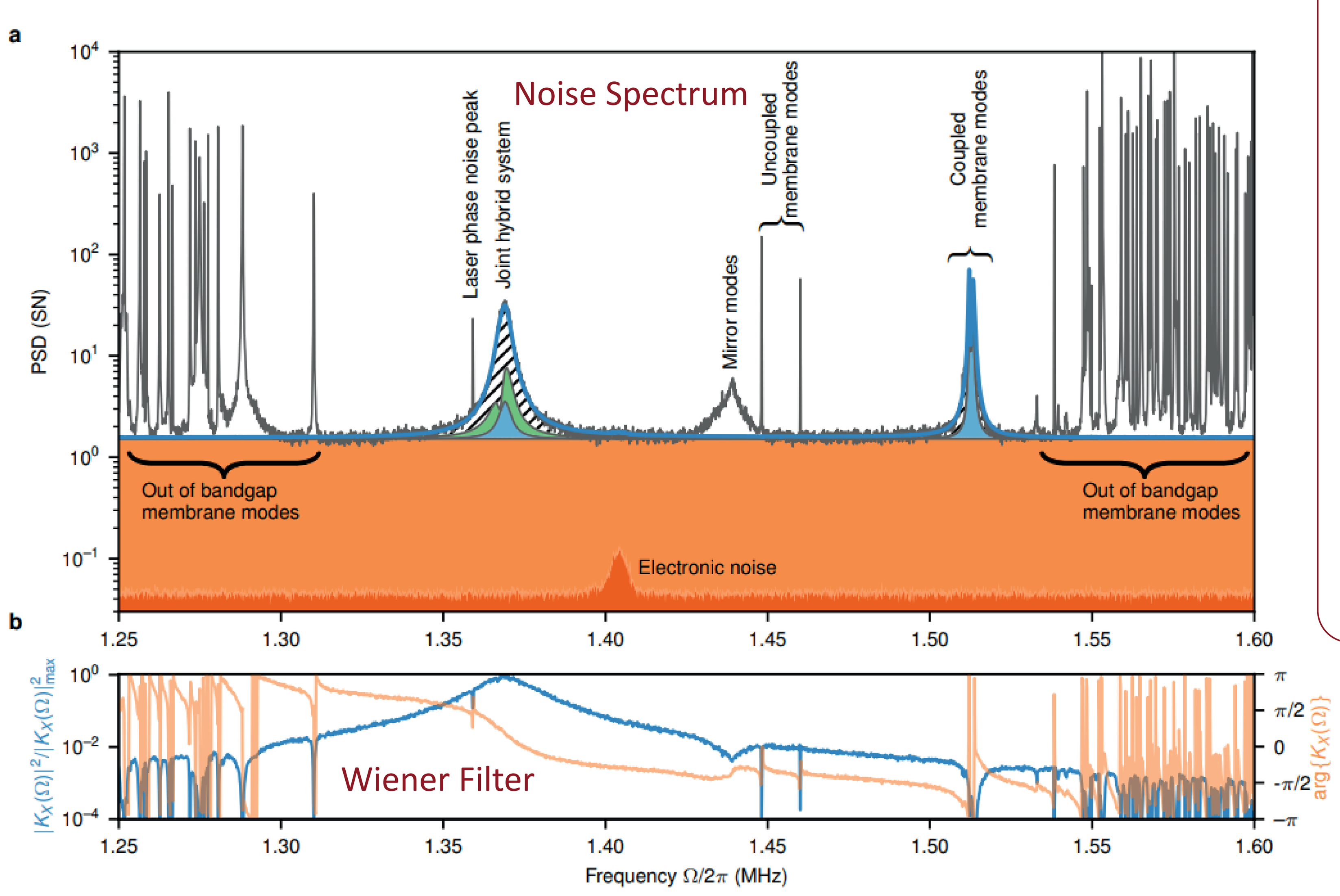
Measurement of two systems

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

Back action cancellation for

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

Consequence:
- noiseless trajectory in an EPR subspace
- projection of joint state on an entangled state via measurment



Wiener filtering and conditional variance

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

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

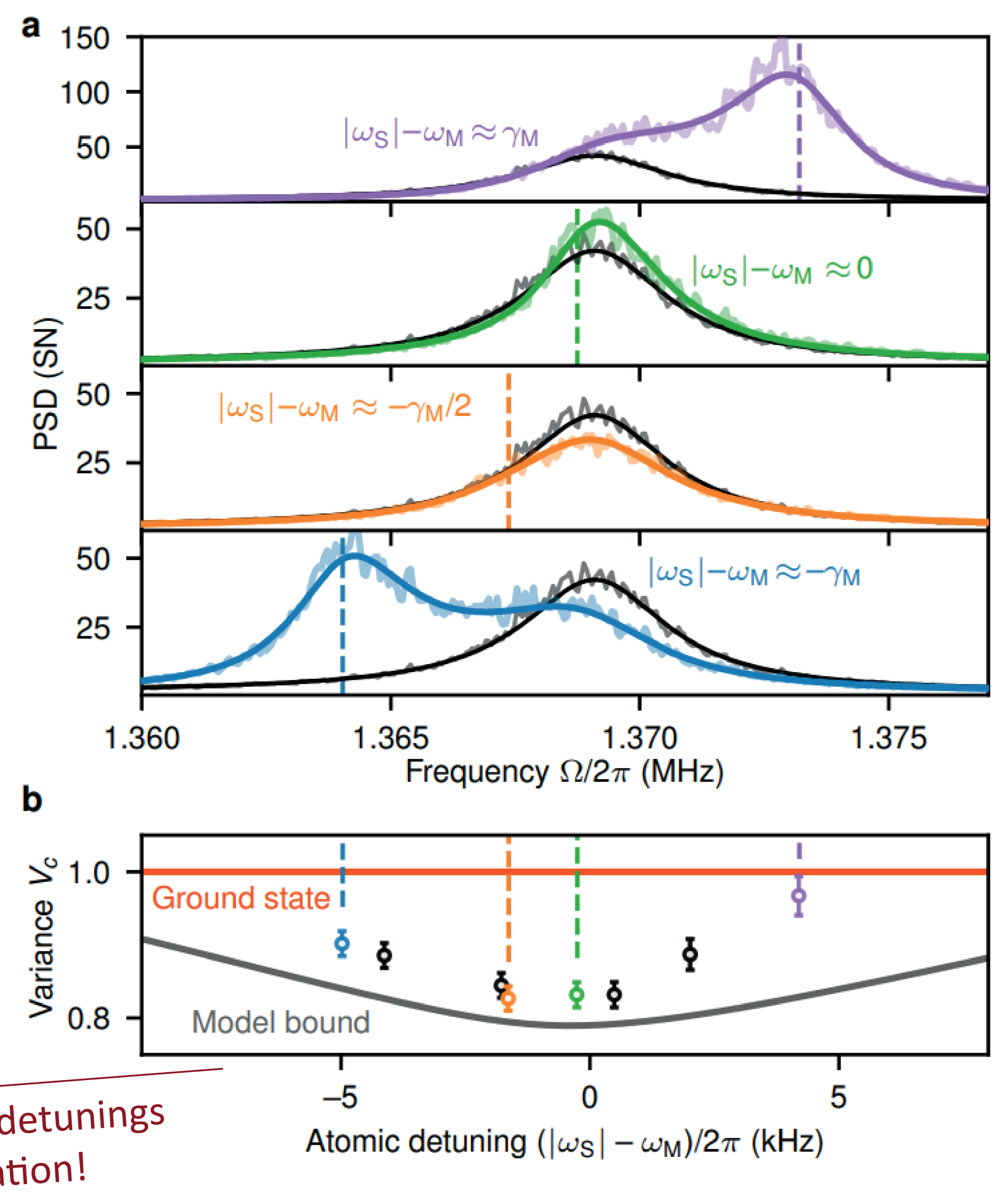
$$\hat{x}(t) = \underbrace{\int_{-\infty}^{t} dt' K(t-t')\hat{y}(t')}_{\vec{x}(t)} + \hat{R}(t)$$

$$\langle \hat{R}(t)\hat{y}(t') + \hat{y}(t')\hat{R}(t)\rangle = 0 \ \forall_{t'<t}$$

$$C_{xy}(t) - \int_0^\infty dt' K(t')C_{yy}(t-t') = 0 \ \forall_{t>0}$$

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

See also [Phys. Rev. A 80, 043802 (2009)]



Entanglement observed for various detunings thanks to optimized tracking/estimation!

Phonon counting thermometry: Optica 7, 718-725 (2020)
Classical Noise Cancellation: Optics Express 29, 6935-6946 (2021)
Hot Atoms Workshop 2021/online

Back-action cancellation for metrology:
Nature 547, 191-195 (2017)
Phys. Rev. Lett. 121, 031101 (2018)

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