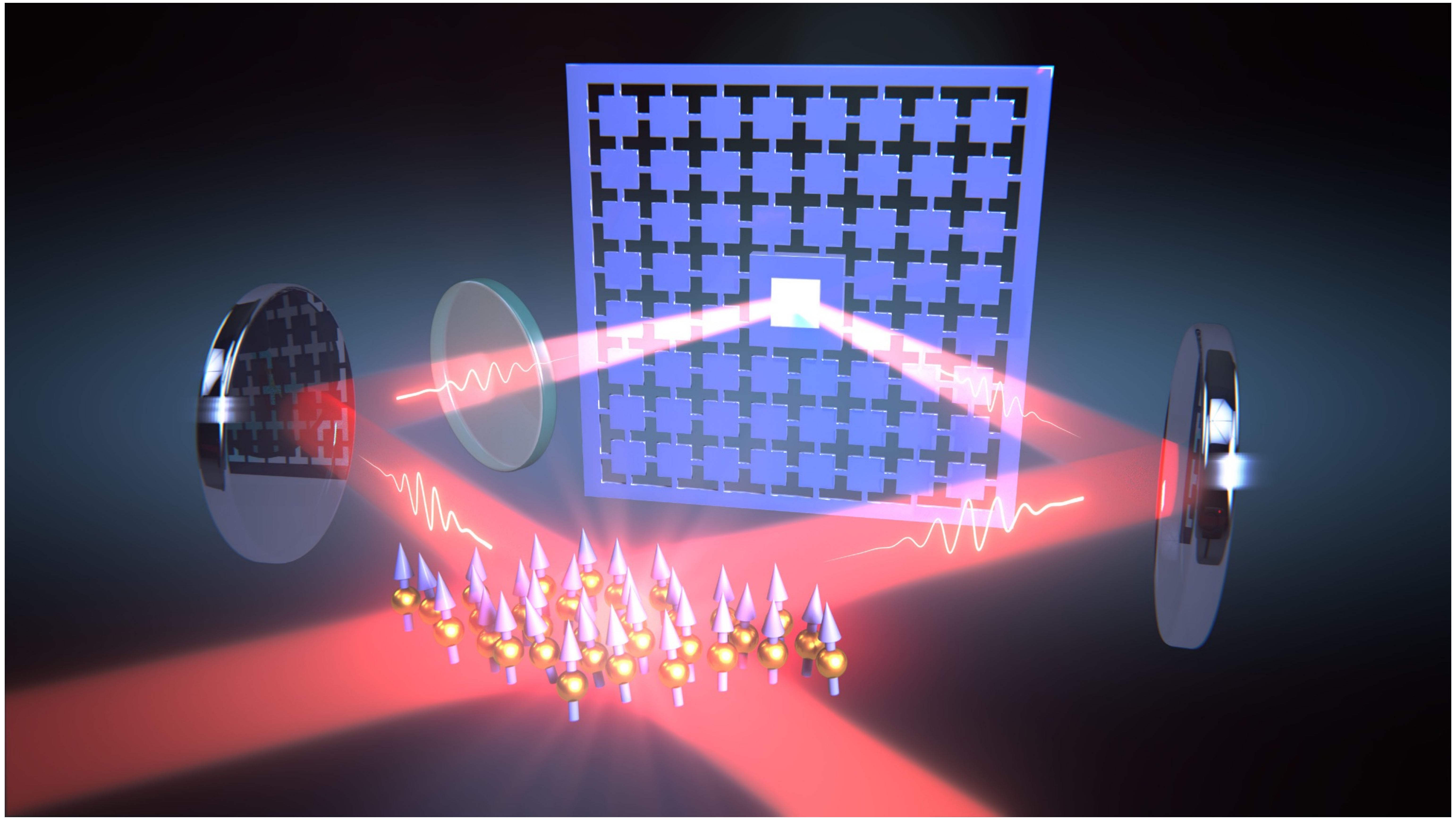
Light-mediated strong coupling between a mechanical oscillator and atomic spins 1 meter apart

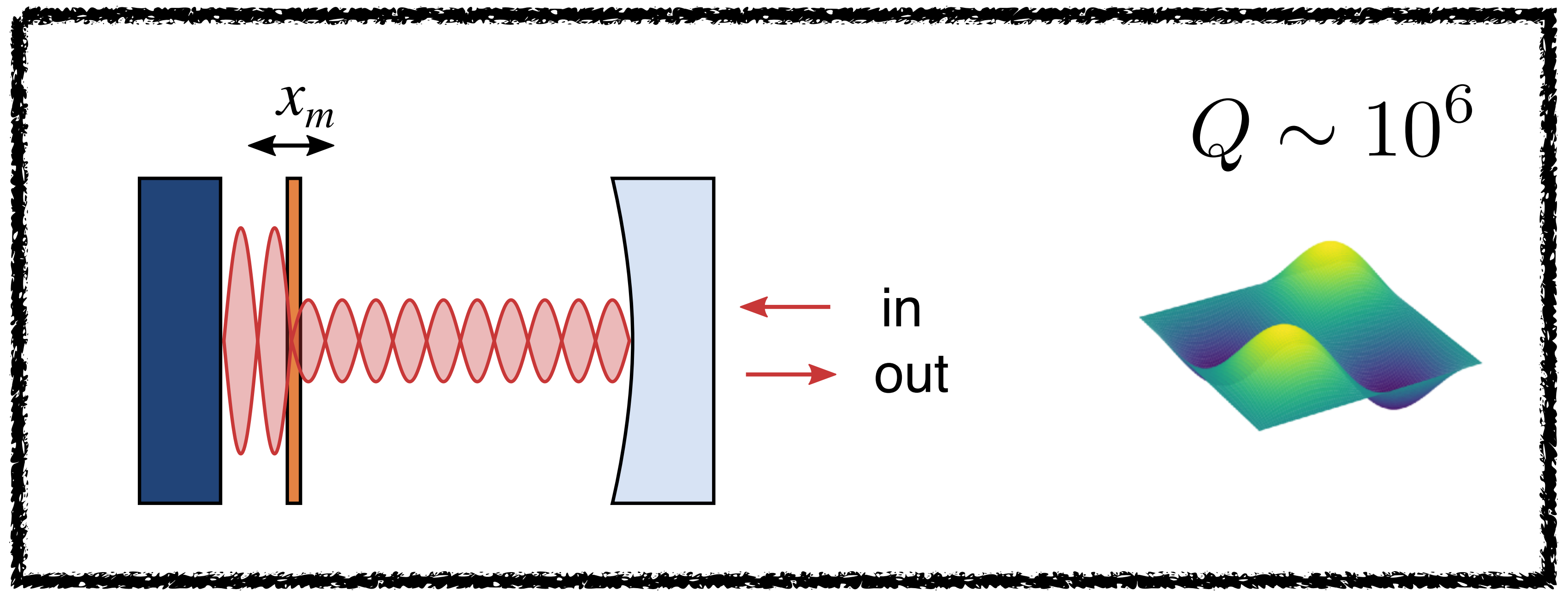


Manel Bosch Aguilera, Gian-Luca Schmid, Chun Tat Ngai, Maryse Ernzer, Thomas Karg, Baptiste Gouraud and Philipp Treutlein

UNI BASEL

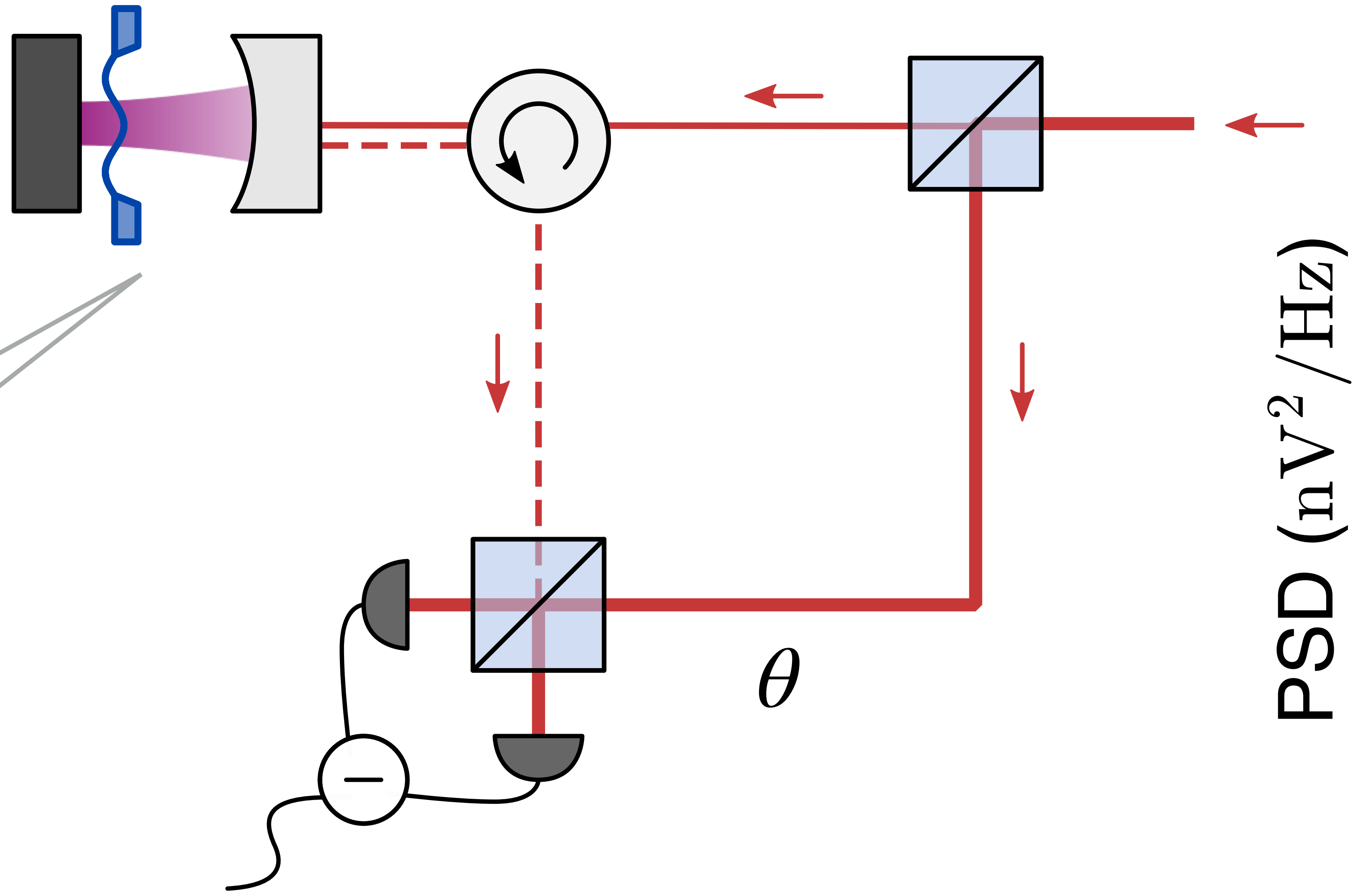
Cavity optomechanics

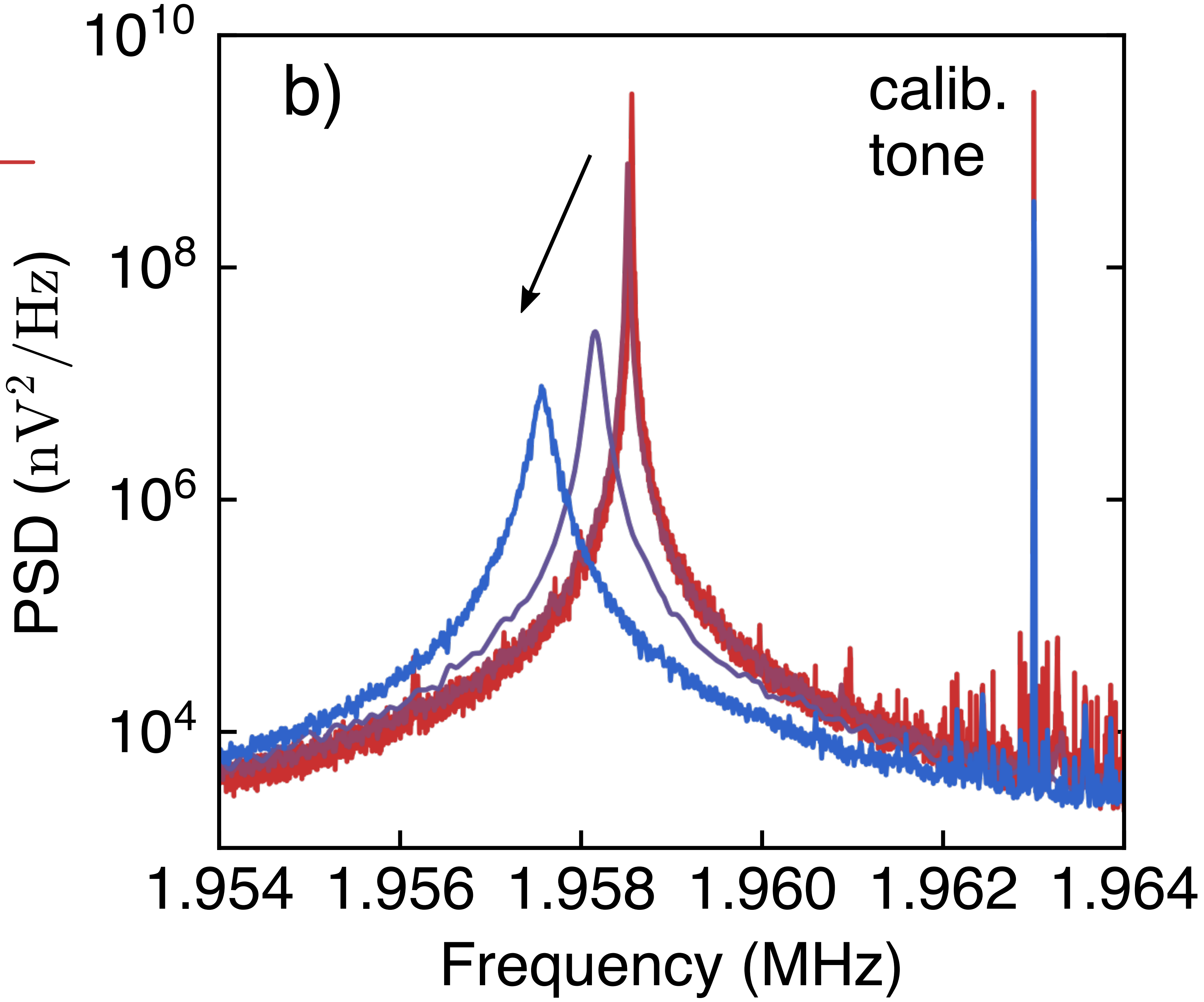
Coupling between light and mechanical oscillator (membrane) through radiation pressure:



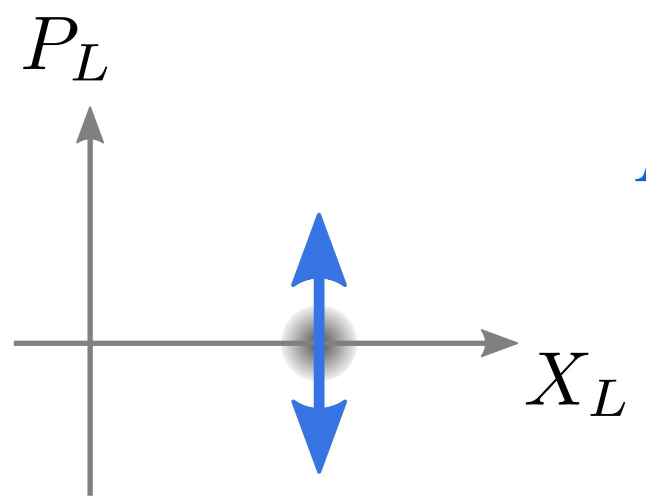
$\Omega_m/2\pi$	1.96 MHz
$\kappa/2\pi$	65 MHz
$g_0/2\pi$	200 Hz
η_c	0.9

$$\hat{H}_{\text{int}} = -\hbar G \hat{X}_{\text{m}} \hat{c}^\dagger \hat{c}$$





Phase modulation



$$P_L^{(\text{out})} \propto X_m$$

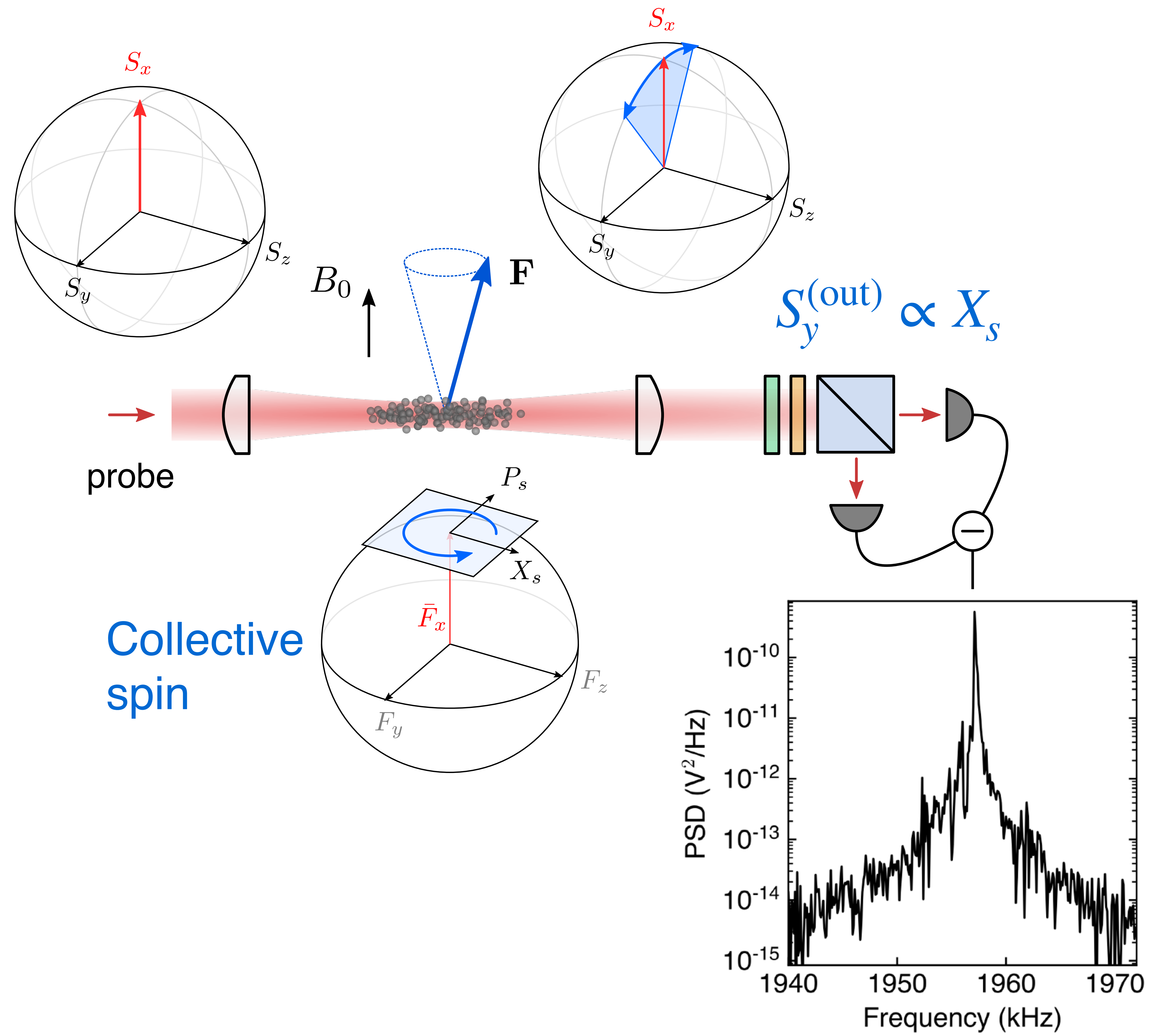
$$\hat{H}_{\text{int}} = \hbar\sqrt{4\Gamma_{\text{m}}}\hat{X}_{\text{m}}\hat{X}_{\text{L}}$$

Thompson et al., Nature (2008); Purdy et al. Science (2013); Nielsen et al. PNAS (2017)

Atom-light interaction

Coupling between light and atomic spin through Faraday interaction:

$$\hat{H}_{\text{int}} = \hbar\sqrt{4\Gamma_{\text{s}}}\hat{F}_z\hat{S}_z$$



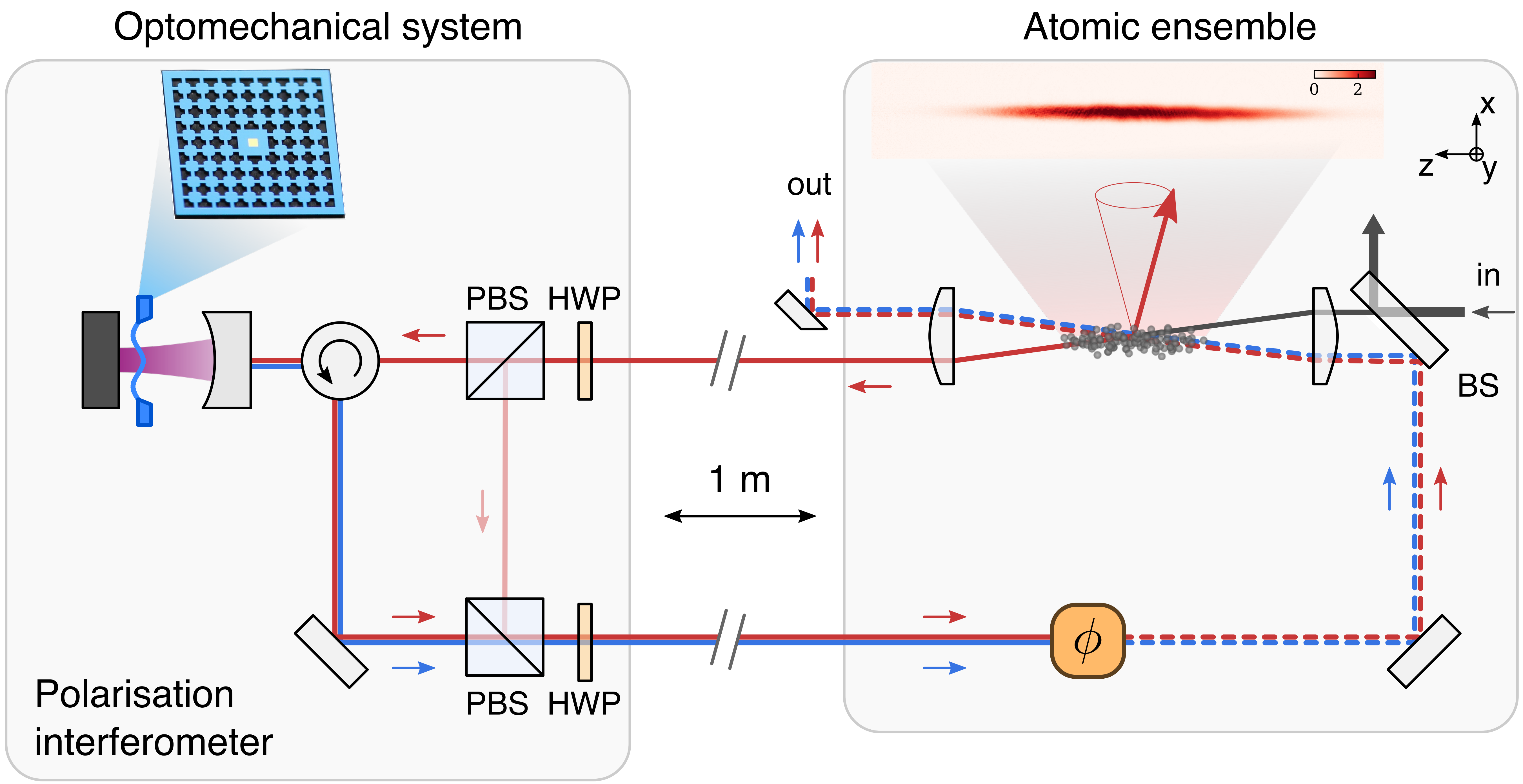
Holstein-Primakoff approximationn

$$\hat{S}_x \simeq S_x \quad \text{and} \quad \hat{F}_x \simeq F_x$$

$$\hat{H}_{\text{int}} \propto \hbar\sqrt{4\Gamma_{\text{s}}}\hat{X}_{\text{S}}\hat{P}_{\text{L}}$$

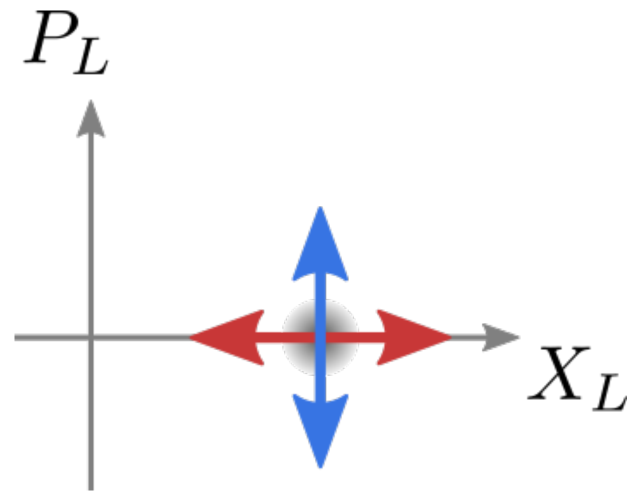
Hammerer, Sørensen & Polzik, RMP 82, 1041 (2010)

Spin-membrane coupling scheme



Membrane $H_m = 2\hbar\sqrt{\Gamma_m} X_m X_L$

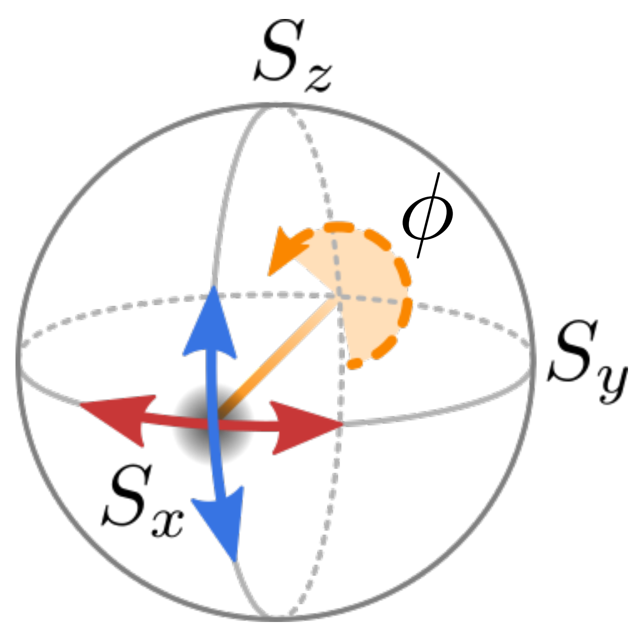
$H_s = 2\hbar\sqrt{\Gamma_s} X_s P_L$ **Spin**



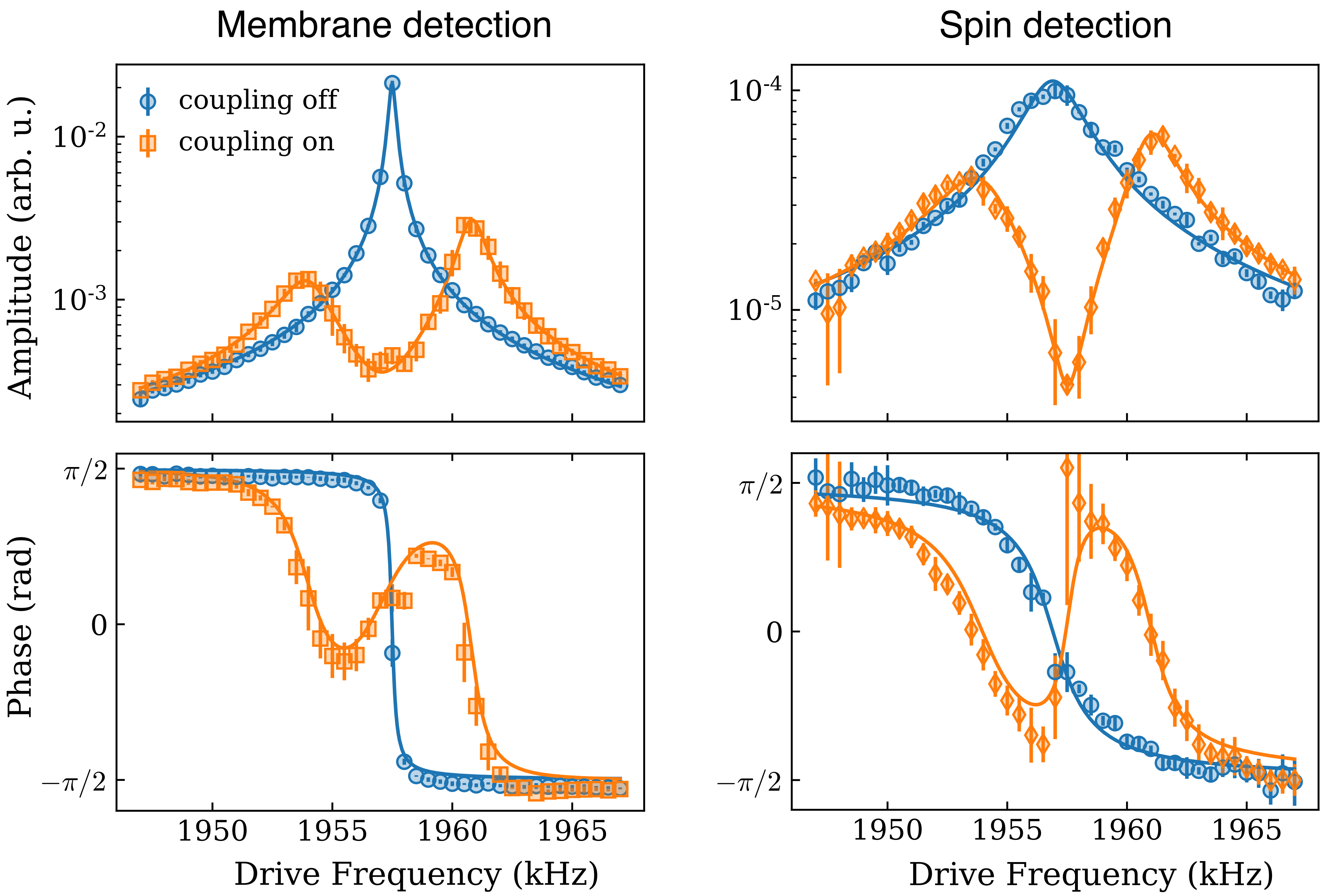
$$\phi = \pi$$

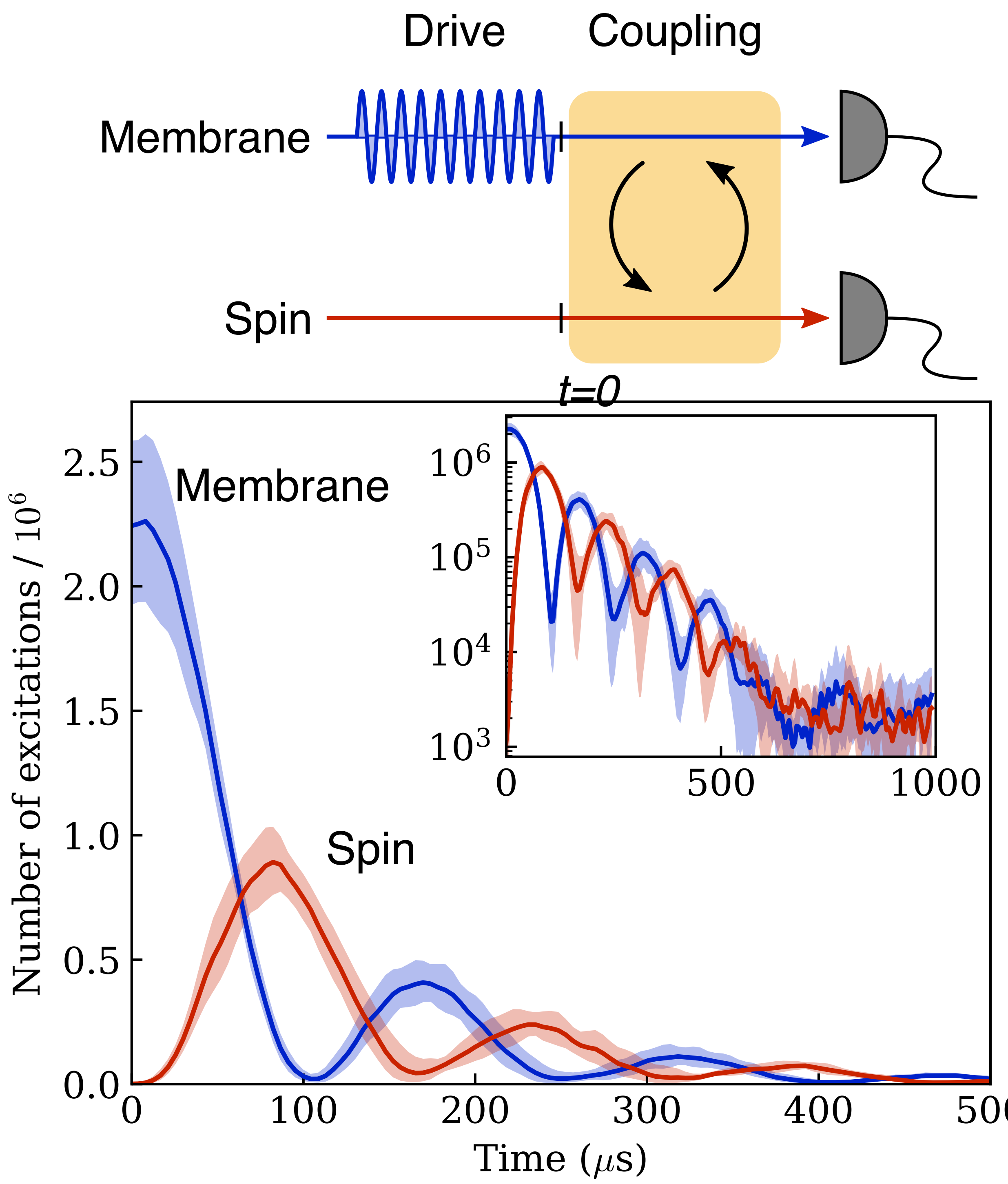
$$H_{\text{eff}} = 2\hbar g X_m X_s$$

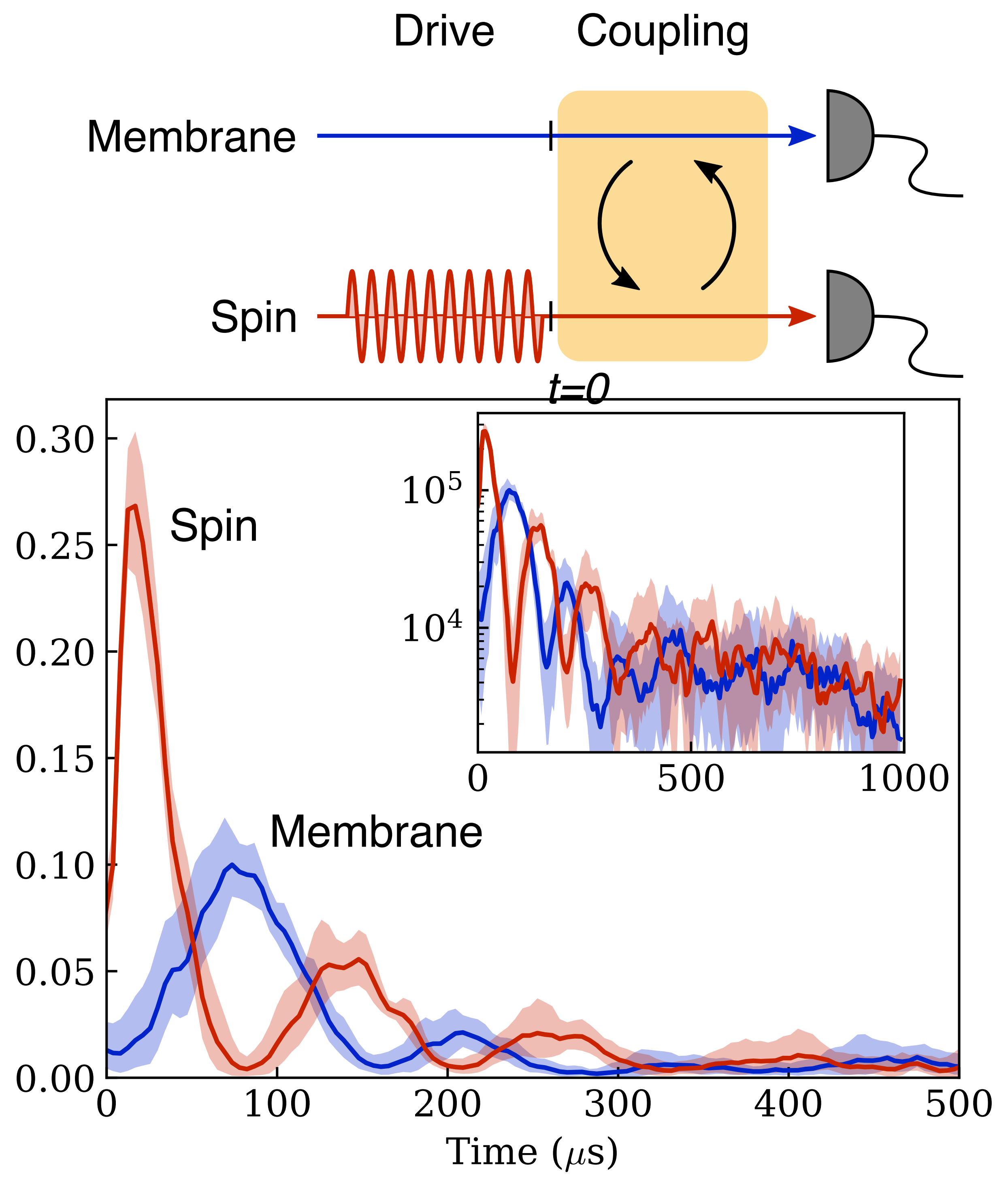
$$g = (\eta^2 + \eta^4)\sqrt{\Gamma_m \Gamma_s}$$



Spin-membrane strong coupling experiments (I)







- Independent spectroscopies:

  $\gamma_m = 2\pi \times 0.3$ kHz $\qquad \gamma_s = 2\pi \times 4$ kHz

- Normal mode splitting: $2g = 2\pi \times 6.1$ kHz

- Asymmetry due to propagation delay: $\tau = 13$ ns

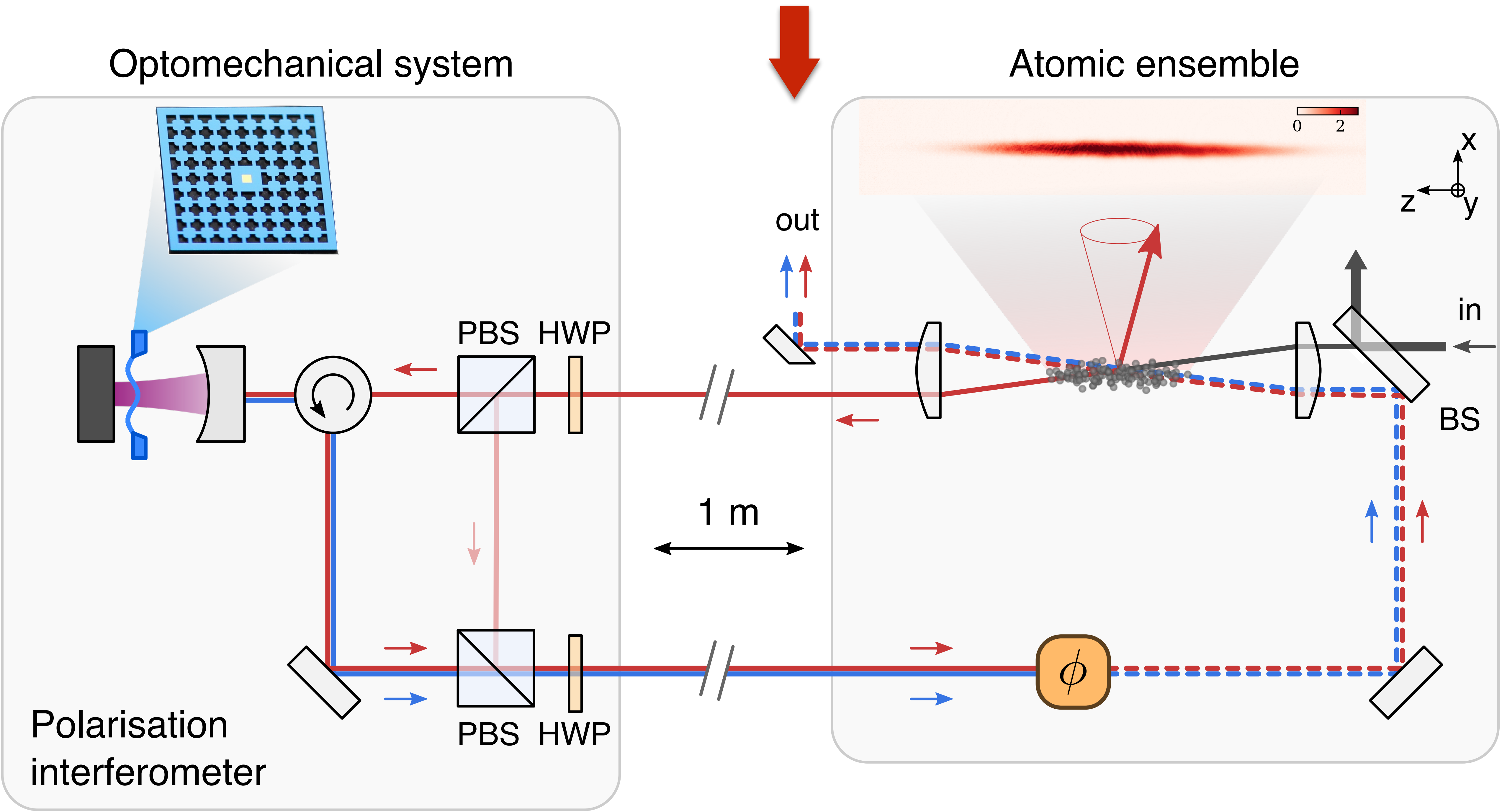
Steady state occupation below thermal bath

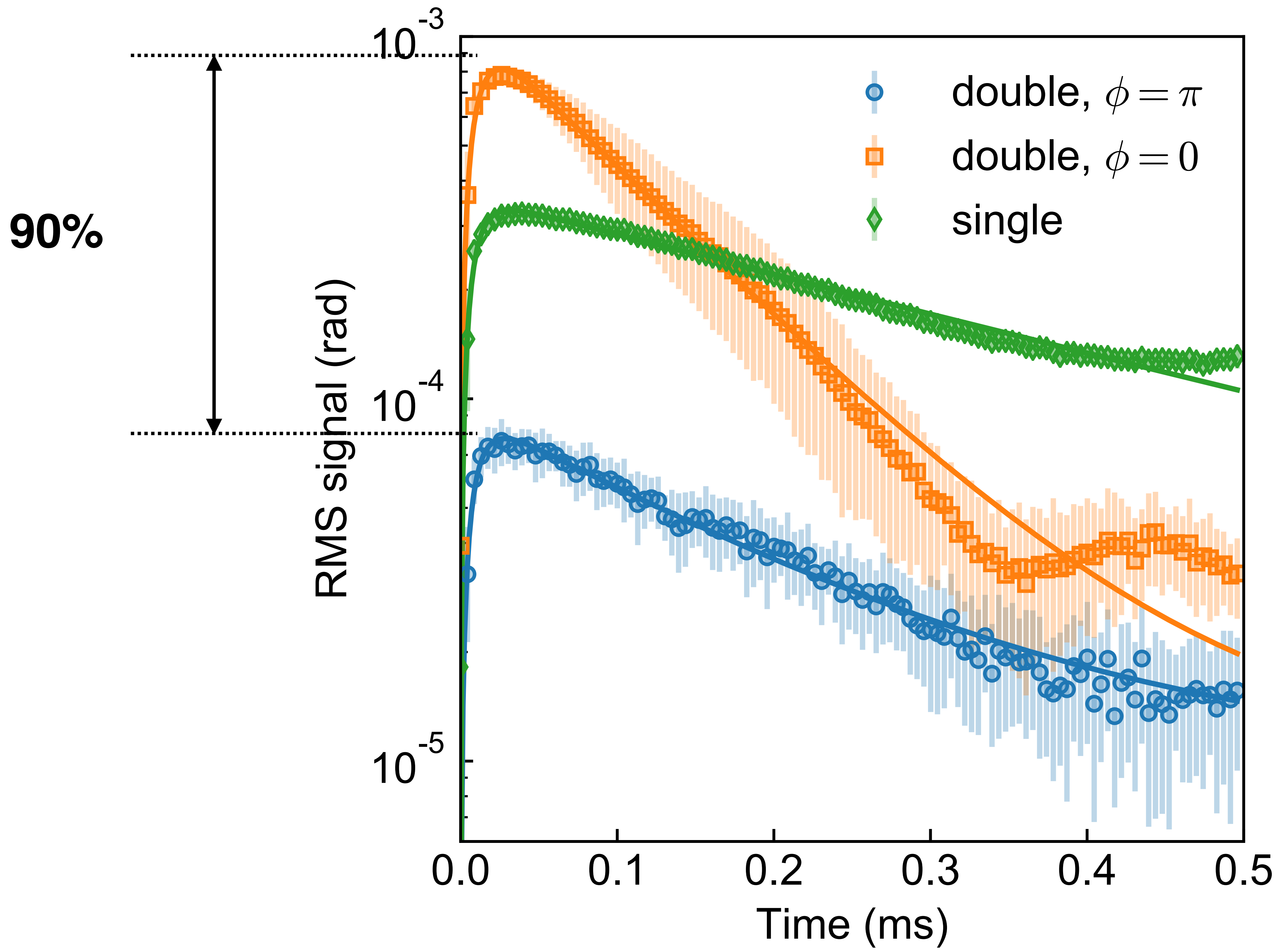
T. M. Karg et al., Science **369**, 174 (2020)

Spin-membrane strong coupling experiments (II)

Double pass in spin system

Coupling to environment due to information leakage can be highly suppressed by tuning the phase of the loop, thanks to a destructive interference of the spin signal in the output field





T. M. Karg et al., Science **369**, 174 (2020)