Bistability and spin squeezing in atomic clouds

driven by dissipative cavities

Amsterdam 2025

Philippe W. Courteille

Research team on interactions between Light & Matter

Organization of the talk

Dicke model for atoms in bad cavities

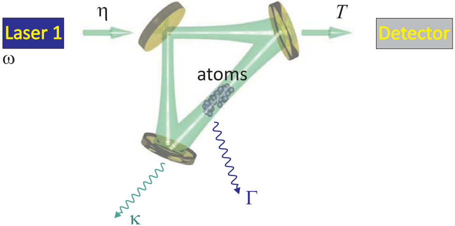
Experimental setup and results

Observation of bistability

Towards driven-dissipative spin squeezing

Search for non-invasive spin squeezing witnesses

Dicke model



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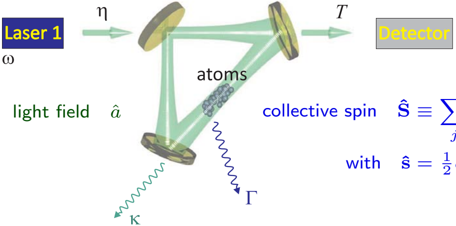

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with $\hat{\mathbf{s}} = \frac{1}{2}\hat{\vec{\sigma}}$

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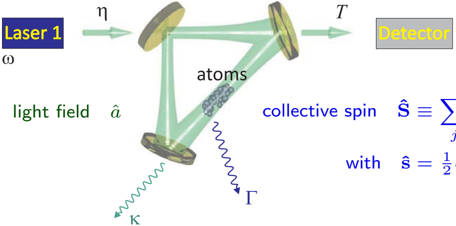

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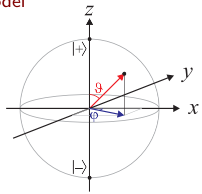
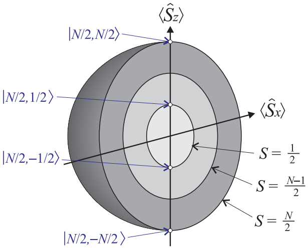
Atoms treated as non-interacting spins

no near field terms, only radiative coupling

coupled spin description $\Rightarrow$ Dicke model





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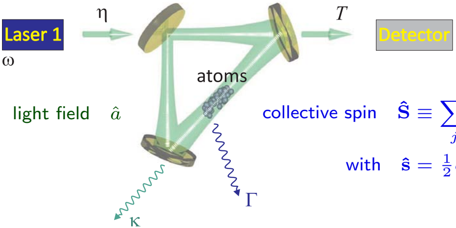

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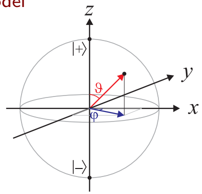
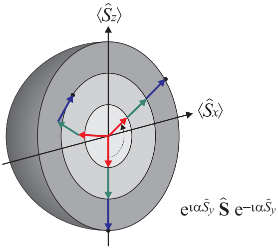
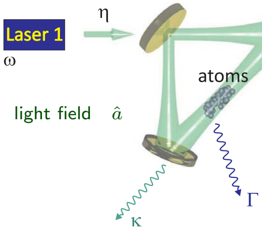




Linear terms $\hat{H} \propto \hat{S}_{x,y,z}$ *only perform rotations:* $e^{\imath\alpha\hat{S}_z}\;\hat{\mathbf{S}}\;e^{-\imath\alpha\hat{S}_z}$

$\Rightarrow$ a coherent spin state always remains a coherent spin state

Dicke model



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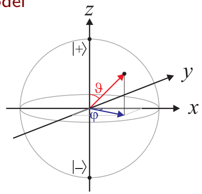

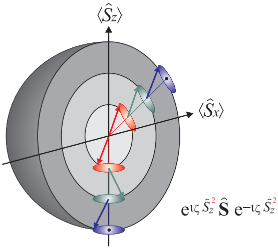

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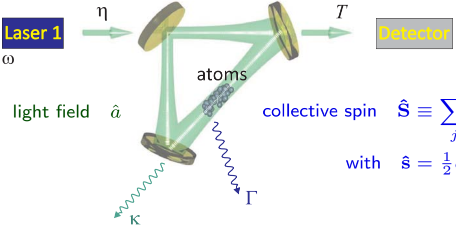
$\Rightarrow$ a coherent spin state always remains a coherent spin state

$\Rightarrow$ no entanglement can be generated by linear spin operators in the Hamiltonian

Spin-squeezing requires non-linear terms: $e^{\imath\zeta \hat{S}_z^2}\ \hat{\mathbf{S}}\ e^{-\imath\zeta \hat{S}_z^2}$

Why bad cavities?



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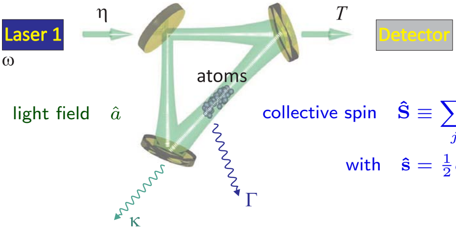

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resonant Dicke model Hamiltonian (*linear*) $\hat{H} = -\imath\eta(\hat{a} - \hat{a}^\dagger) + g(\hat{S}_+\hat{a} + \hat{a}^\dagger\hat{S}_-)$

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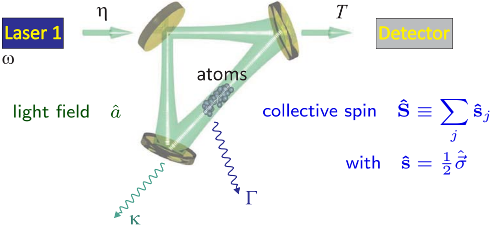

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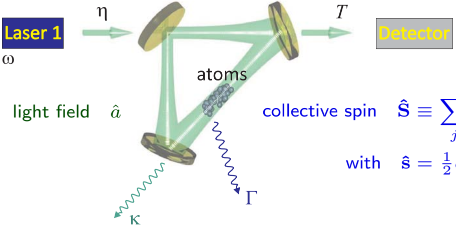

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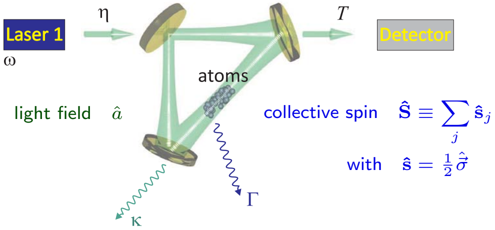

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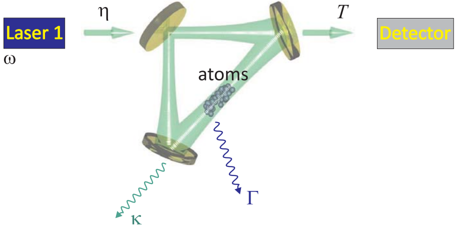
approximated Hamiltonian (*non-linear*) $\hat{H} \simeq U_c\ \hat{S}_+\hat{S}_- \quad \simeq U_c\ \hat{S}_z^2$

dissipation (*non-linear*) $\mathfrak{L}\hat{\rho} = \kappa_c(2\hat{S}_-\hat{\rho}\hat{S}_+ - \hat{S}_+\hat{S}_-\hat{\rho} - \hat{\rho}\hat{S}_+\hat{S}_-)$

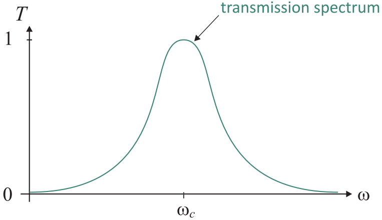
$\Longrightarrow$ non-linearity can generate entanglement

$\Longrightarrow$ spin squeezing and superradiant lasing

Storyboard for an experiment



1) set up an experiment in the 'bad' cavity parameter regime ($\kappa \to \infty$)



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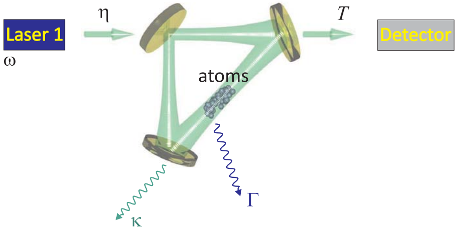

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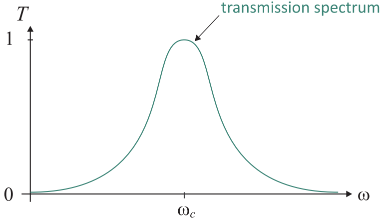
2) take atoms with narrow transitions ($\Gamma \to 0$) and cool them



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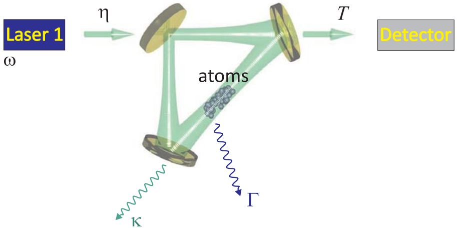

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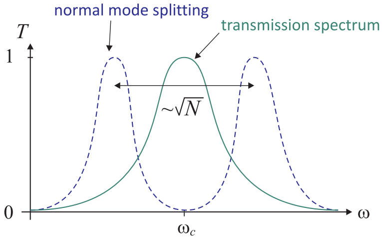

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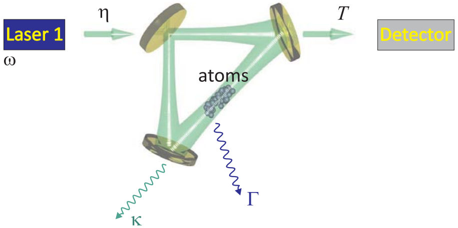

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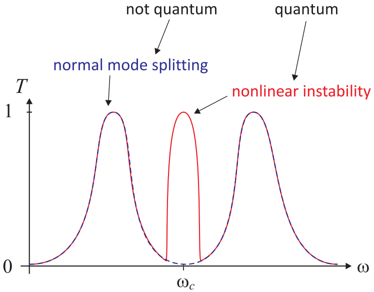
4) verify non-linearity 'on-resonance' ($\Delta_c = 0$)



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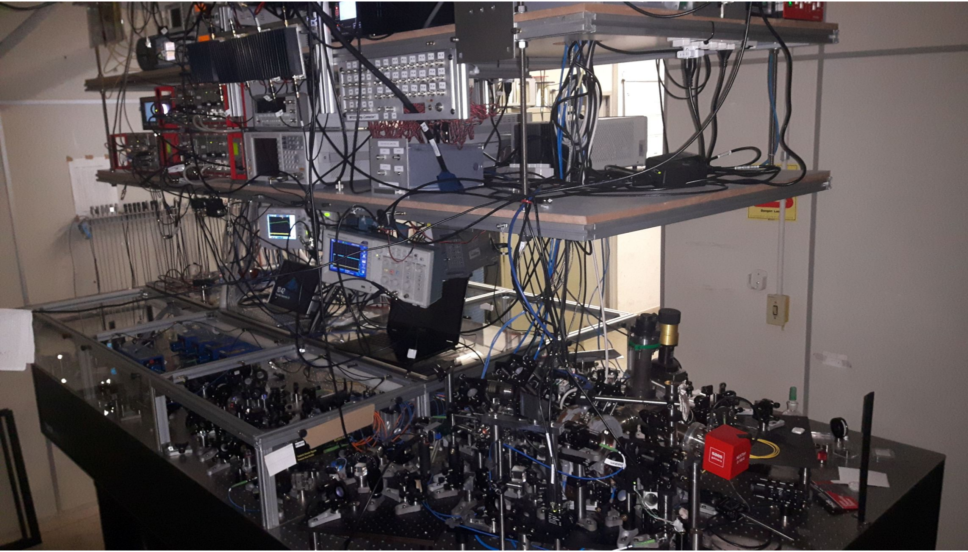
The experiment



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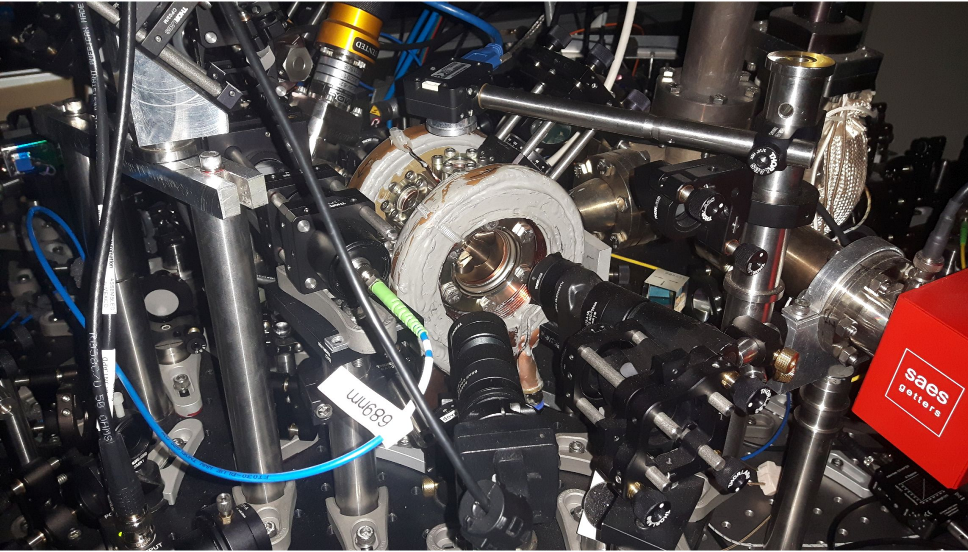
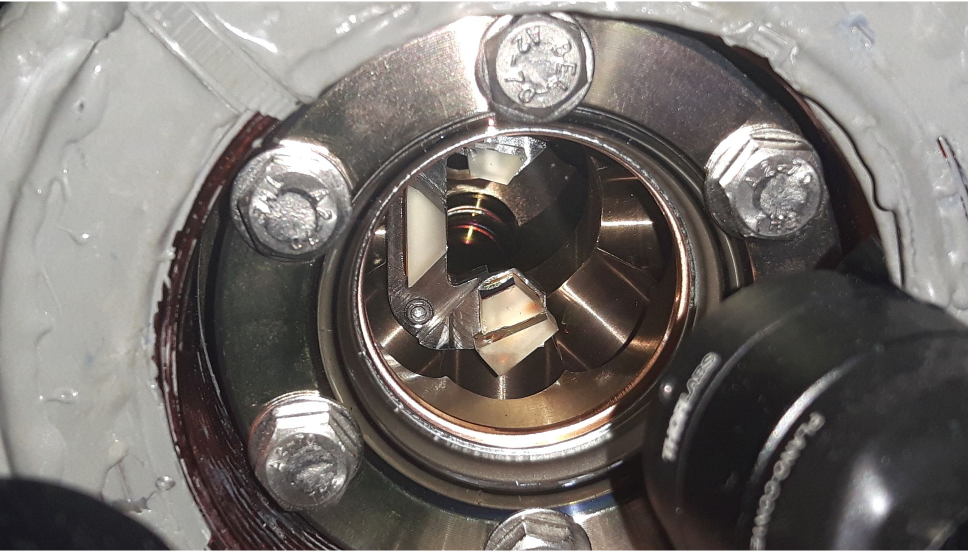


The experiment

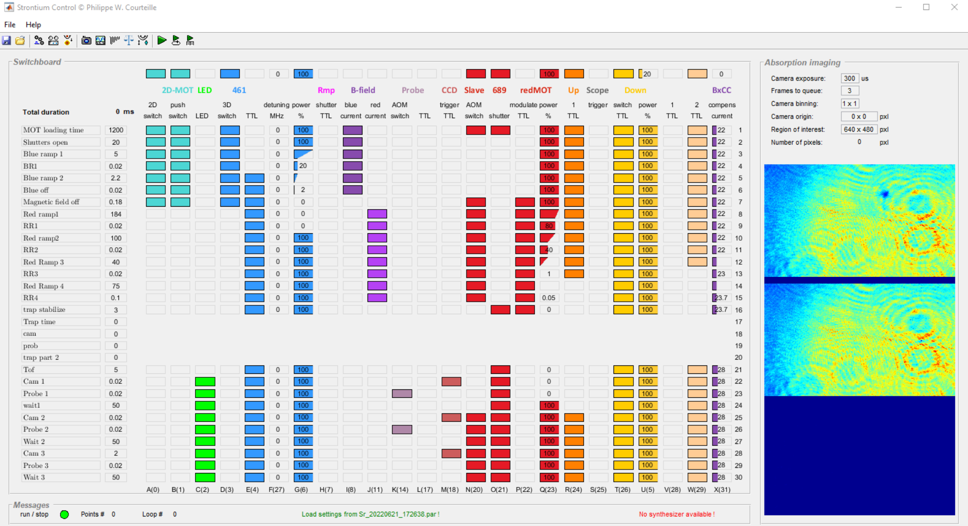
strontium $\Gamma = 7.5\,\mathrm{kHz}$

cavity decay $\kappa = 4.3\,\mathrm{MHz}$



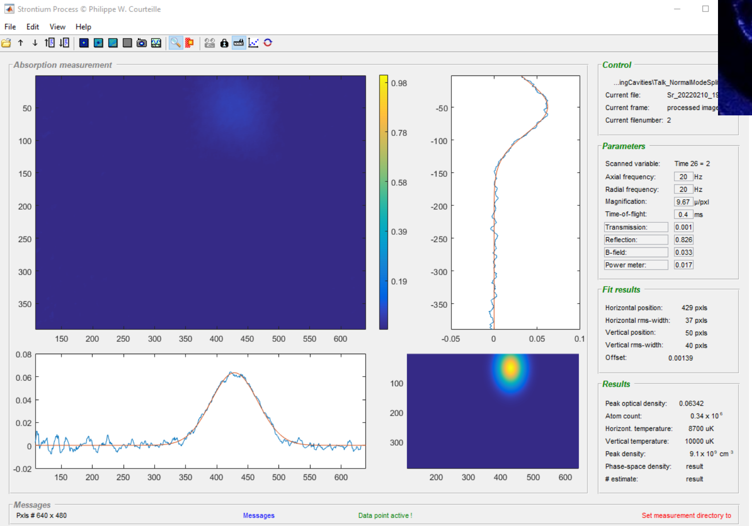
Experimental procedure & state of the art

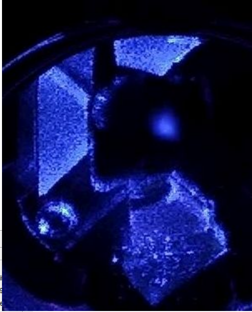
experimental control



Experimental procedure & state of the art

trapping atoms in the blue MOT: $N = 10^6$ $T = 5\,\mathrm{mK}$





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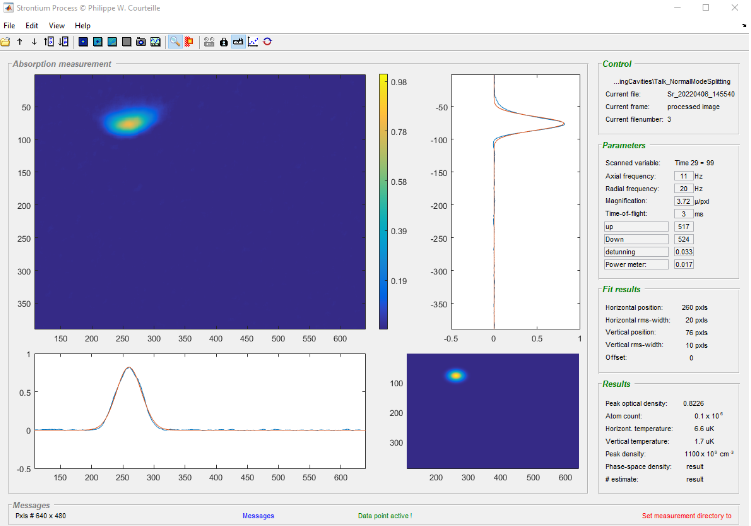
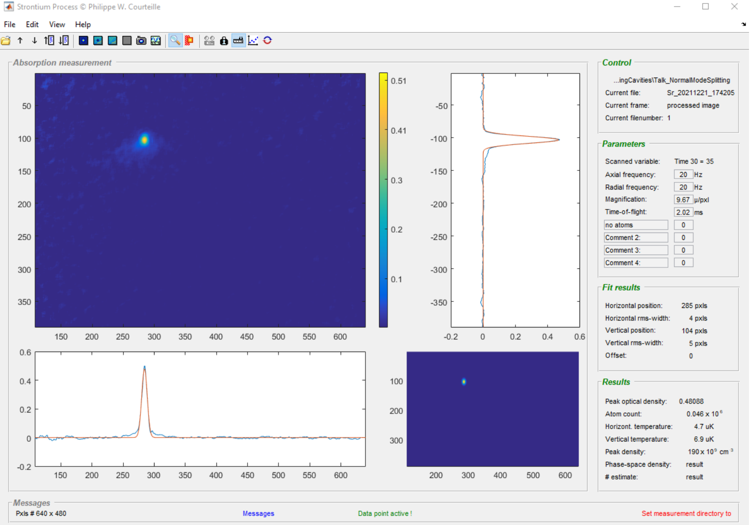
cooling atoms in the red MOT



Experimental procedure & state of the art

cooling atoms in the red MOT: $N = 2 \cdot 10^5 \qquad T = 1\,\mu\mathrm{K}$



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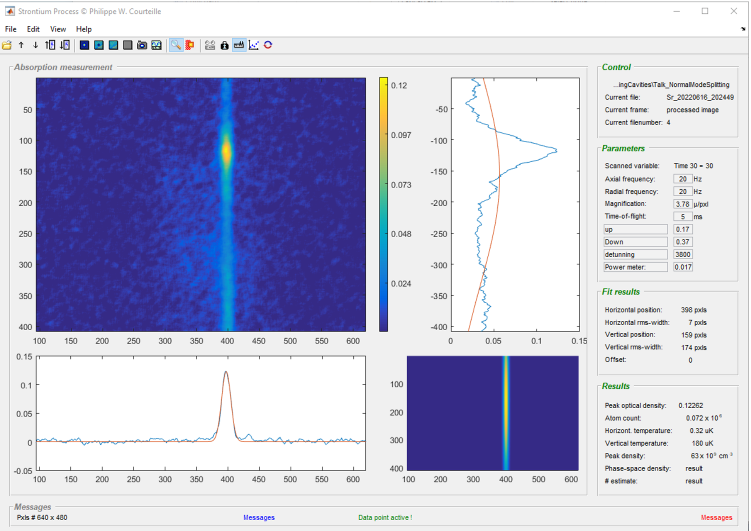

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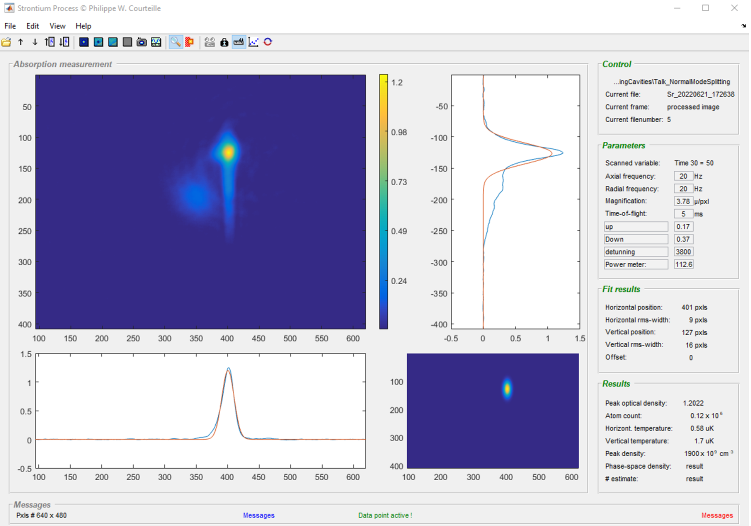
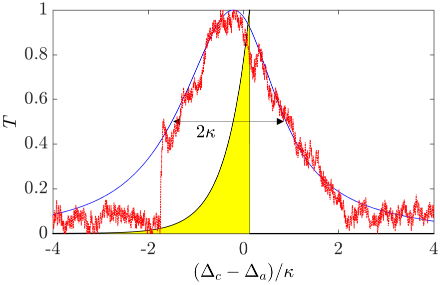
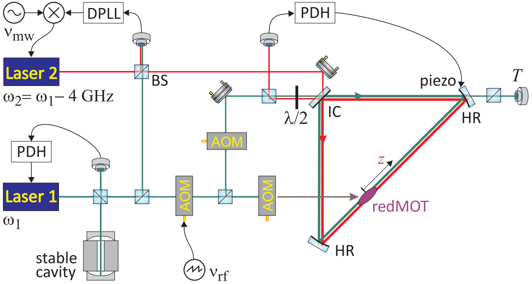


Normal mode splitting

scanning laser frequency which pumps the cavity





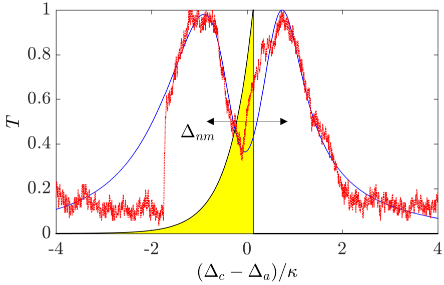
[Rivero, Beli, Armijo, da Silva, Kessler, Shiozaki, Teixeira, Courteille, Appl. Phys. B **128**, 44 (2022)]

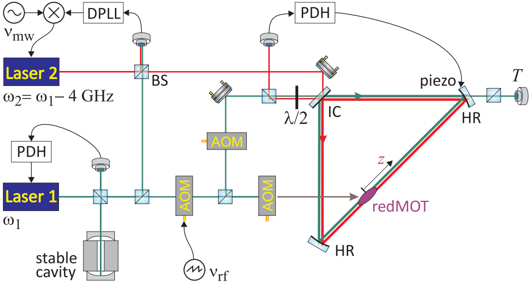
[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

Normal mode splitting

scanning laser frequency which pumps the cavity

$$\Gamma \ll \kappa \ll g\sqrt{N} \equiv \Delta_{nm}$$





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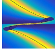
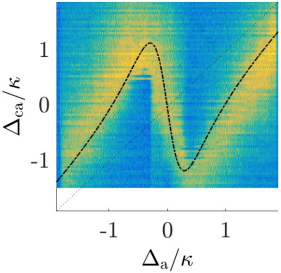
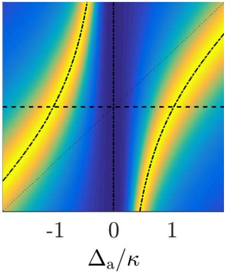
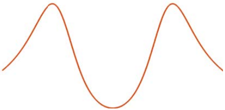


Normal mode splitting $\equiv$ 1D photonic band gap

avoided crossing $+$ instable feature







$$\Delta_{ca} \equiv \Delta_a - \Delta_c$$

$$\Delta_c = \frac{Ng^2 \Delta_a}{\Delta_a^2 + \Gamma^2/4}$$

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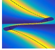

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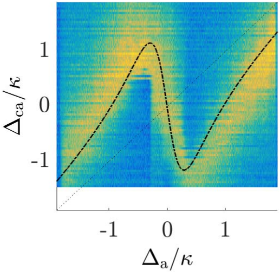

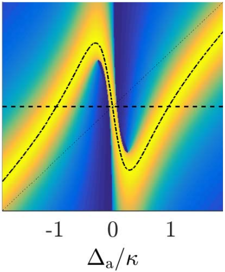

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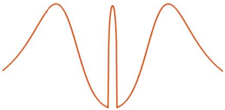

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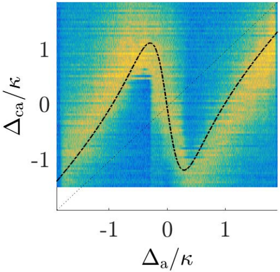

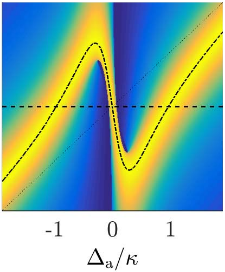

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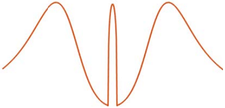
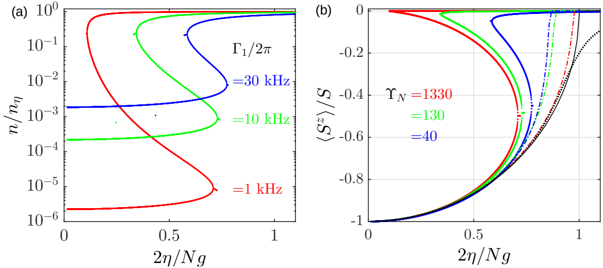


adiabatic elimination only near $\Delta_a = 0$

Steady state behavior within mean field

bistability curve for $\Delta_\mathsf{a} = 0 = \Delta_\mathsf{c}$ and $\langle \hat{S}_\pm \hat{S}_z \rangle = \langle \hat{S}_\pm \rangle \langle \hat{S}_z \rangle$ and $\frac{d}{dt}\hat{a} = 0 = \frac{d}{dt}\hat{\mathbf{S}}$

cavity transmission | atomic inversion



normalized cavity pump rate

[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

[Leppenen and Shahmoon, arXiv:2404.02134]

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bistability curve for $\Delta_\mathrm{a} = 0 = \Delta_\mathrm{c}$ and $\langle \hat{S}_\pm \hat{S}_z \rangle = \langle \hat{S}_\pm \rangle \langle \hat{S}_z \rangle$ and $\frac{d}{dt}\hat{a} = 0 = \frac{d}{dt}\hat{\mathbf{S}}$

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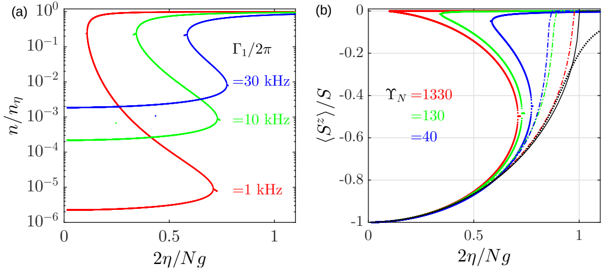


normalized cavity pump rate

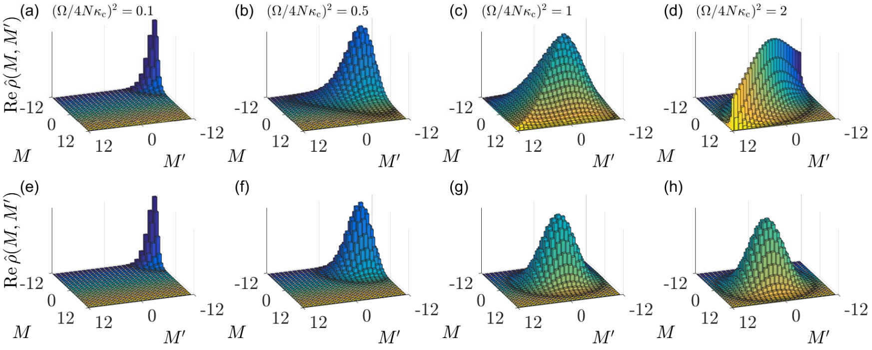
cooperativity $\Upsilon_N = \frac{Ng^2}{\kappa\Gamma} = \frac{N\kappa_c}{\Gamma} = \frac{\text{collective decay}}{\text{single-atom decay}}$

[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

[Leppenen and Shahmoon, arXiv:2404.02134]

Beyond mean field without spontaneous emission

driven-dissipative steady state density matrix in Dicke basis



corresponding coherent spin state

Beyond mean field without spontaneous emission

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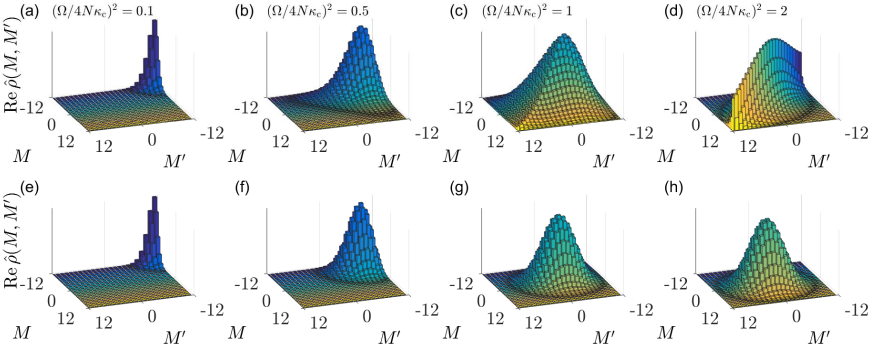
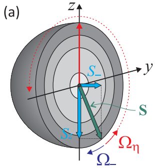


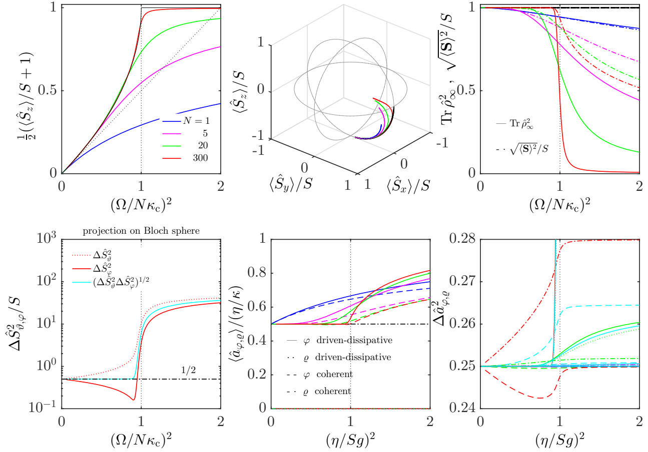
corresponding coherent spin state



Dicke phase transition

non-linearity provided by **collective dissipation + pumping** rather than Hamiltonian evolution

$$\dot{\hat{\rho}} = \imath[\hat{\rho}, \hat{H}_{\mathrm{ad}}] + \mathfrak{L}\hat{\rho} \quad \text{with} \quad \hat{H}_{\mathrm{ad}} = \frac{\imath\eta g}{\kappa}\hat{S}_x \quad \text{and} \quad \mathfrak{L}\hat{\rho} = \frac{g^2}{\kappa}(2\hat{S}_-\hat{\rho}\hat{S}_+ - \hat{S}_+\hat{S}_-\hat{\rho} - \hat{\rho}\hat{S}_+\hat{S}_-)$$



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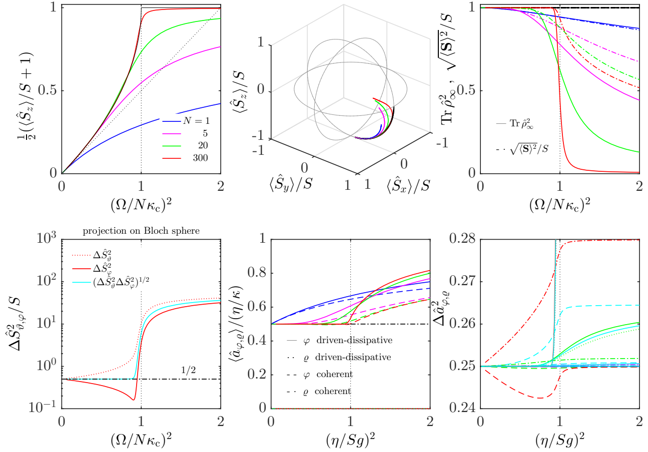
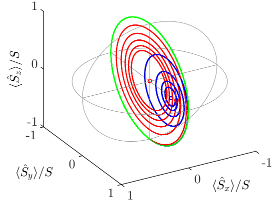
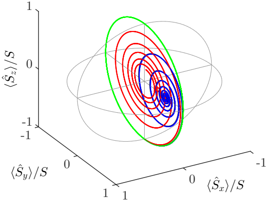


dissipative spin-squeezing and light squeezing

Impact of spontaneous emission

spontaneous emission recovers steady state excitation





[Song, Rey, Thompson et al., SciAdv2025,11,eadu5799]

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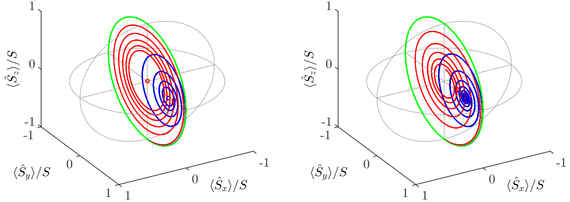
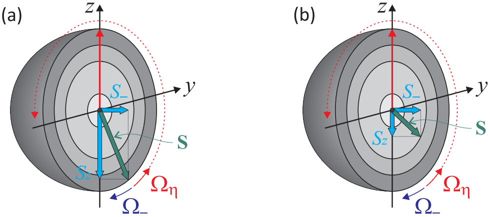


driven-damped rigid rotor flipping over

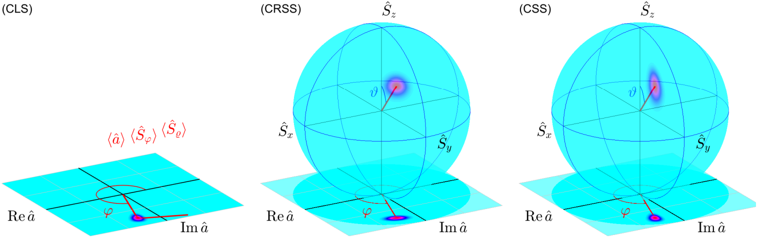


[Song, Rey, Thompson et al., SciAdv2025,11,eadu5799]

Coherently radiating spin-squeezed states

$$\hat{a}_{\varphi,\varrho} = \hat{c} - \imath \frac{g}{\kappa} \hat{S}_{\varrho,\varphi}$$

$$\Delta \hat{a}^2_{\varphi,\varrho} - \frac{1}{4} = \frac{g^2}{\kappa^2} (\Delta \hat{S}^2_{\varrho,\varphi} + \frac{1}{2} \langle \hat{S}_z \rangle)$$



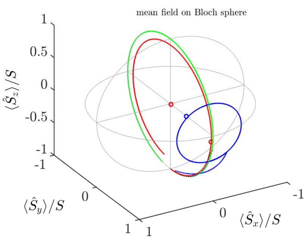
[Wang, Wu et al., New J. Phys. **16**, 063039 (2014)]

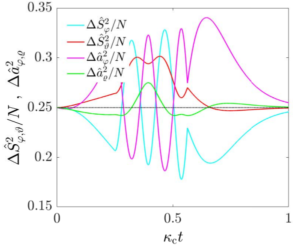
[Somech, Leppenen, Shahmoon, et al., PRA **108**, 0203725 (2023) & PRX Quantum **5**, 010349 (2024) & arXiv:2404.02134]

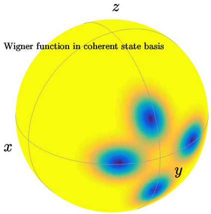
[Song, Rey, Thompson et al., Science Adv. **11**, eadu5799 (2025)]

Pulsed spin-squeezing witness

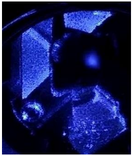
rotation pulse for squeezing axis works, but only for times short compared to $\kappa_c = \frac{g^2}{\kappa} \approx (2\pi)\,20\,\mathrm{Hz}$







Quintessence



Done:

- bistability observed on resonance with a 'bad cavity'! $\Longrightarrow$ non-linearity

[Meiser et al., PRL **102**, 163601 (2009)]

[Debnath, Zhang, Mølmer, PRA **98**, 063837 (2018)]

[Rosario, Santos, Piovella, Kaiser, Cidrim, R. Bachelard, PRL 133, 050203 (2024)]

[recent work of groups of Vuletic, Schleier-Smith, Thompson, Rey, ...]

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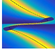

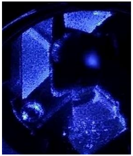

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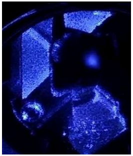

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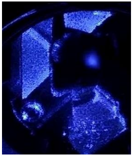

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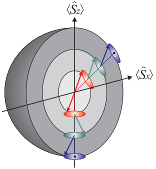
To do:

understand role of quantum fluctuations in the phase transition

find optical spin-squeezing witnesses

generate inversion $> 50\%$ (e.g. via optical pumping) for light amplification



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The team

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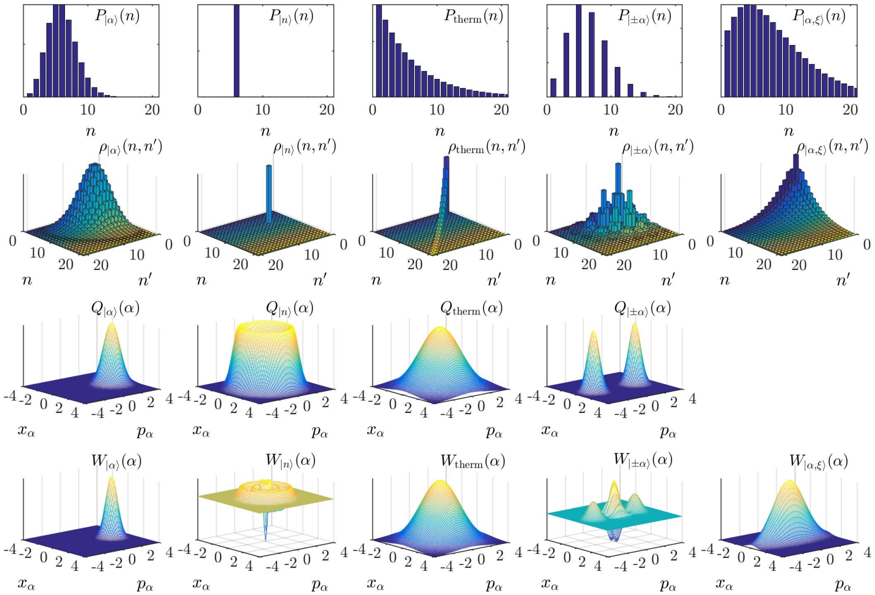
Ana Cipris, Matheus Rodrigues, Daniel Coelho, Felipe Brambila, Thales Pereira

FAPESP

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

inct
institutos nacionais de ciência e tecnologia

Representation of particular states of light



CONCLUSION

Beyond mean field: Coherently radiating spin-squeezed state

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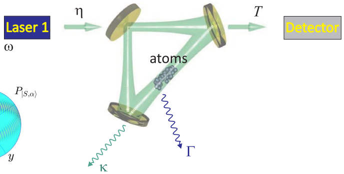

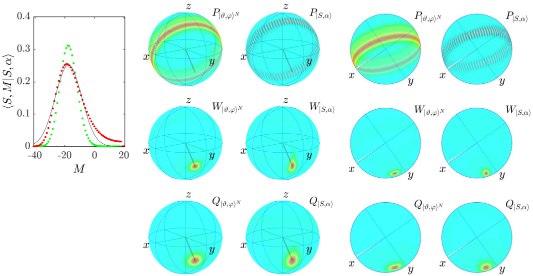

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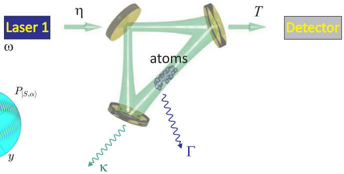

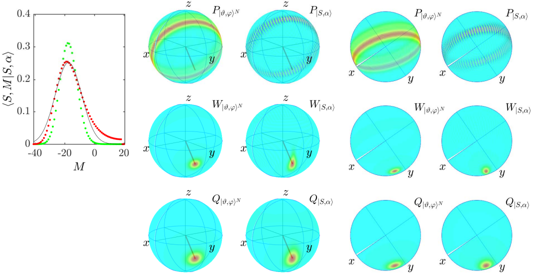

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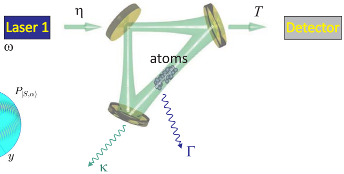
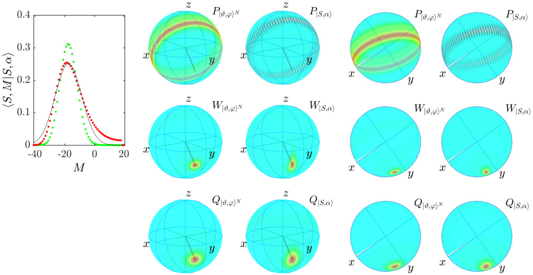


P-, Wigner, and Q-function of CSS and CRSS



light scattered by a collective spin: $\hat{a}^\dagger = \hat{a}_0^\dagger + G\hat{S}_-$

[Wang, Wu et al., New J. Phys. **16**, 063039 (2014)]
[Somech, Leppenen, Shahmoon, et al., PRA **108**, 0203725 (2023) & PRX Quantum **5**, 010349 (2024) & arxXiv:2404.02134]
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Quantum Fisher information

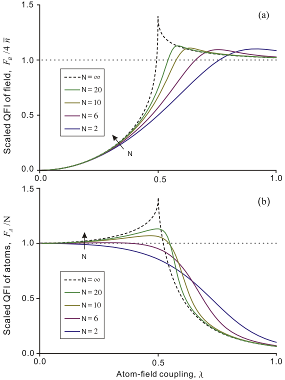

Figure 1. Scaled quantum Fisher information of the bosonic field $F_B/(4\bar{n})$ (a) and that of the atoms F_A/N (b) as a function of the coupling strength λ for a finite number of atoms $N = 2, 6, 10$, and 20, as indicated by the arrow. Horizontal dotted lines: the classical (or shot-noise) limit for the field mode $F_B = 4\bar{n}$ (with mean number of bosons $\bar{n}$) and that of the atoms $F_A = N$. Dashed lines: analytical results of the QFI in the thermodynamic limit (i.e., $N = \infty$). For each state $\hat{\rho}_{A,B}$, the derivative of the QFI has a singularity at the critical point λ_{cr}. Other parameter: the critical coupling $\lambda_{cr} \equiv \sqrt{\omega\omega_0}/2 = 1/2$ on resonant condition $\omega = \omega_0 = 1$.

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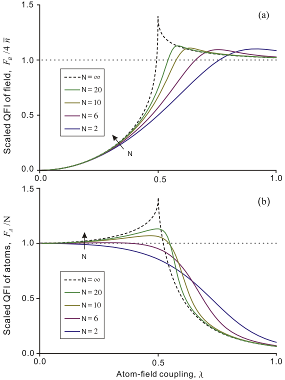

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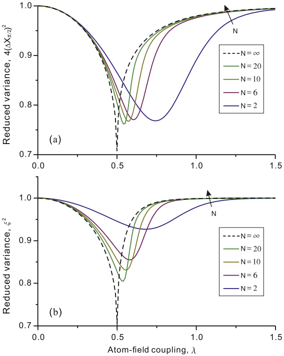

Figure 3. Degree of quadrature squeezing for the field mode $4(\Delta\hat{X}_{\pi/2})^2$ (a), and that of spin squeezing for the atoms ξ^2 (b) against the coupling strength λ for the number of atoms $N = 2$, 6, 10, and 20, as indicated by the arrow. Dashed lines: analytical results in the thermodynamic limit (i.e., $N = \infty$). The local minimum of the reduced variances indicates quadrature squeezing of $\hat{\rho}_{AB}$ at the critical point $\lambda_{cr} = 0.5$ (on resonance, as figure 1).

[Wang, Wu et al., New J. Phys. **16**, 063039 (2014)]

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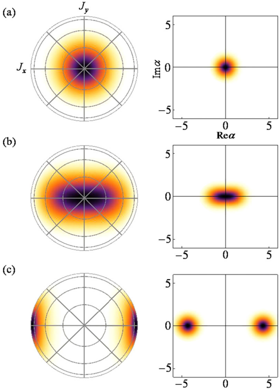
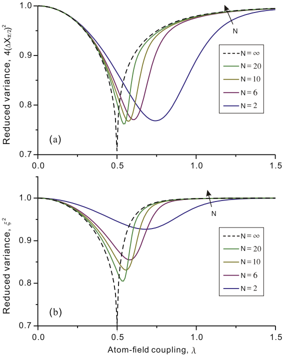


Figure 2. Quasi-probability distributions $Q_A(\theta, \phi)$ (left panel) and $Q_B(\alpha)$ (right panel) of the ground state of the Dicke Hamiltonian with $N = 20$ and the atom-field coupling strength $\lambda = 0$ (a), 0.54 (b), and 1 (c). The axes on the Bloch sphere (top view from the south pole) are given by $J_{x,y,z} = \langle \hat{J}_{x,y,z} \rangle$, while for that of the field mode, Re $\alpha = \langle \hat{X}_0 \rangle$ and Im $\alpha = \langle \hat{X}_{\pi/2} \rangle$. The expectation values are taken with respect to the coherent states $|\theta, \phi\rangle$ and $|\alpha\rangle$, respectively. Other parameters: the critical coupling $\lambda_{cr} = 1/2$, the same as in figure 1. The density of Q_A is normalized by its maximal value [44, 45], i.e., $Q_{A,\max} = 1$ (a), 0.557 (b), and 0.5 (c).



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