Optical witnesses for quantum correlations

in

cavity-driven atomic clouds and other challenges

Strasbourg 2026

Philippe W. Courteille

Research team on interactions between Light & Matter

Organization of the talk

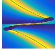
Quantum sensing with cold atoms

Experimental setup & observation of bistability

Towards driven-dissipative spin-squeezing & search for non-invasive witnesses

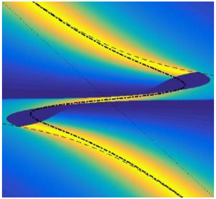
Optically dense clouds in cavities

Gravimetry with continuous monitoring of Bloch oscillations

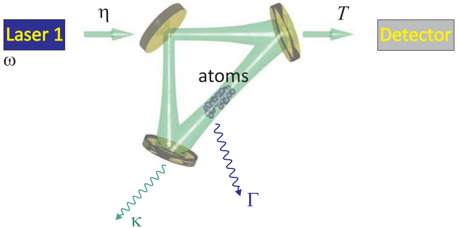


Saturation-induced resonant bistability in cold Strontium

via non-linear interaction with a bad cavity



Dicke model



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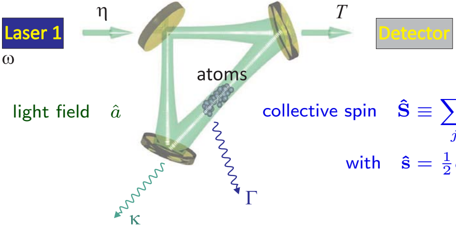

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with $\hat{\mathbf{s}} = \frac{1}{2}\hat{\vec{\sigma}}$

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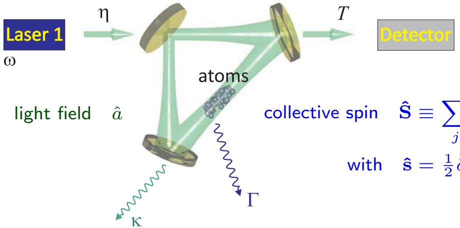

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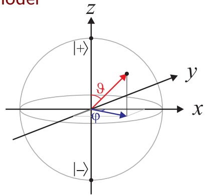
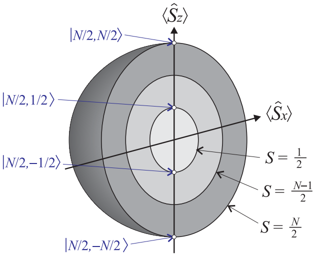
Atoms treated as non-interacting spins

no near field terms, only radiative coupling

coupled spin description $\Rightarrow$ Dicke model





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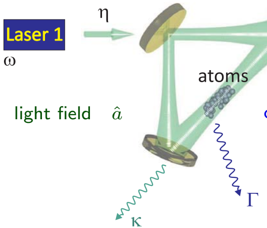

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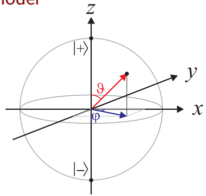
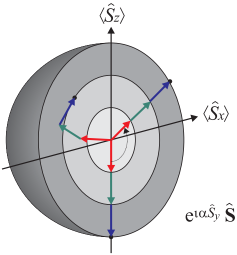
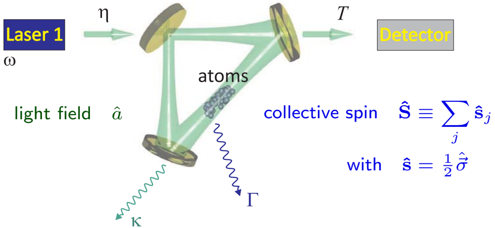




Terms linear in $\hat{S}_{x,y,z}$ *only perform rotations:* $e^{\imath\alpha\hat{S}_z}\ \hat{\mathbf{S}}\ e^{-\imath\alpha\hat{S}_z}$

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

Dicke model



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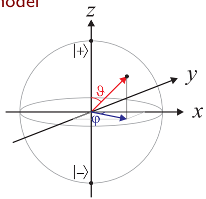

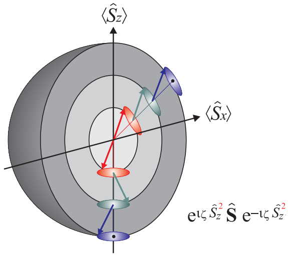

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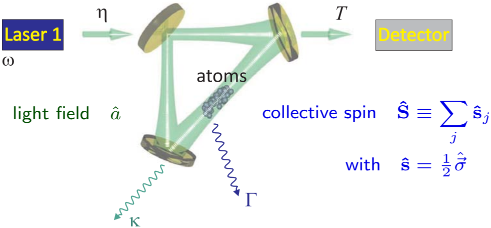
$\Rightarrow$ a coherent spin state always remains a coherent spin state

$\Rightarrow$ 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?



[Norcia, Lewis-Swan, Cline, Bihui Zhu, Rey, Thompson, Science **361**, 259 (2018)]

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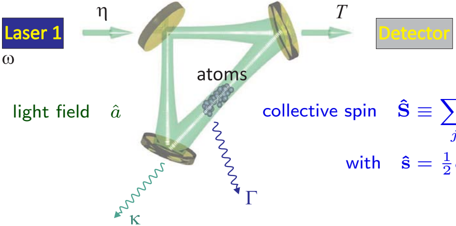

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jump operator for dissipative processes $\hat{\mathfrak{J}} = \kappa\hat{a}$ neglect spontaneous emission $\hat{\mathfrak{J}} = \Gamma\hat{s}_j^- \to 0$

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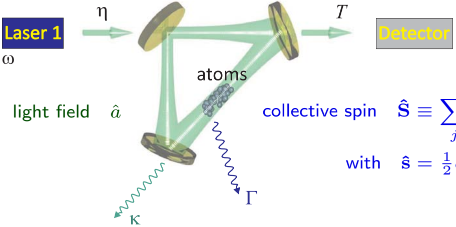

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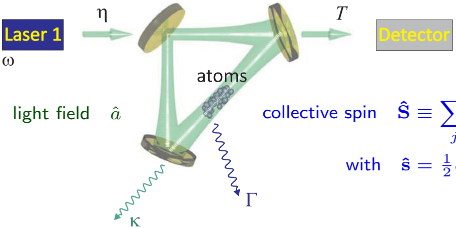

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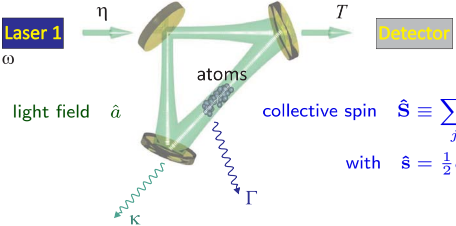

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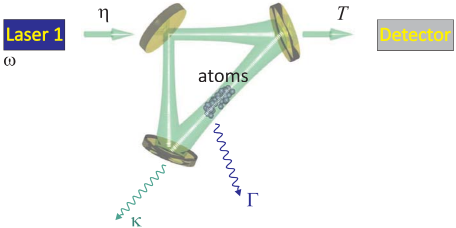
$\uparrow$

Lindbladian $\quad \hat{\mathfrak{L}}\hat{\rho} = \kappa_c(2\hat{S}_-\hat{\rho}\hat{S}_+ - \hat{\rho}\hat{S}_+\hat{S}_- - \hat{S}_+\hat{S}_-\hat{\rho})$ $\qquad$ $\boxed{\simeq \hat{S}_z^2}$

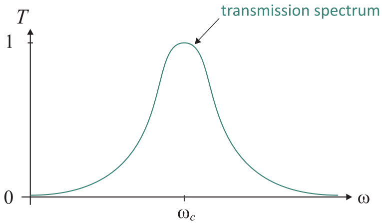
$\implies$ non-linearity induced by feedback can generate entanglement

$\implies$ 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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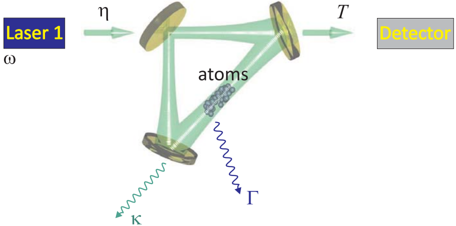

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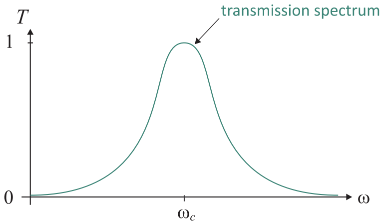

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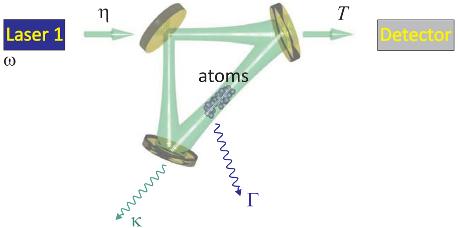

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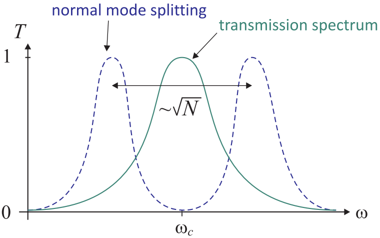

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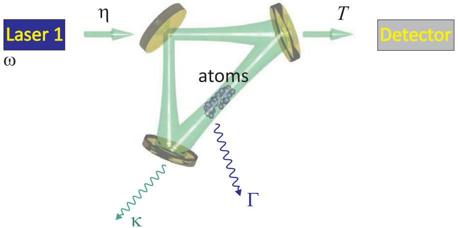

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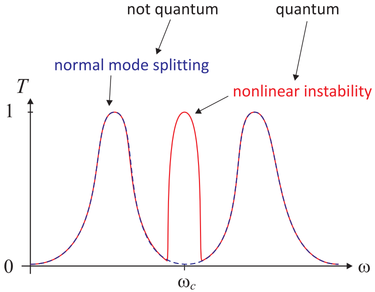
4) verify non-linearity "on-resonance" ($\Delta_c = 0$)



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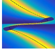

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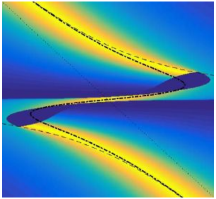
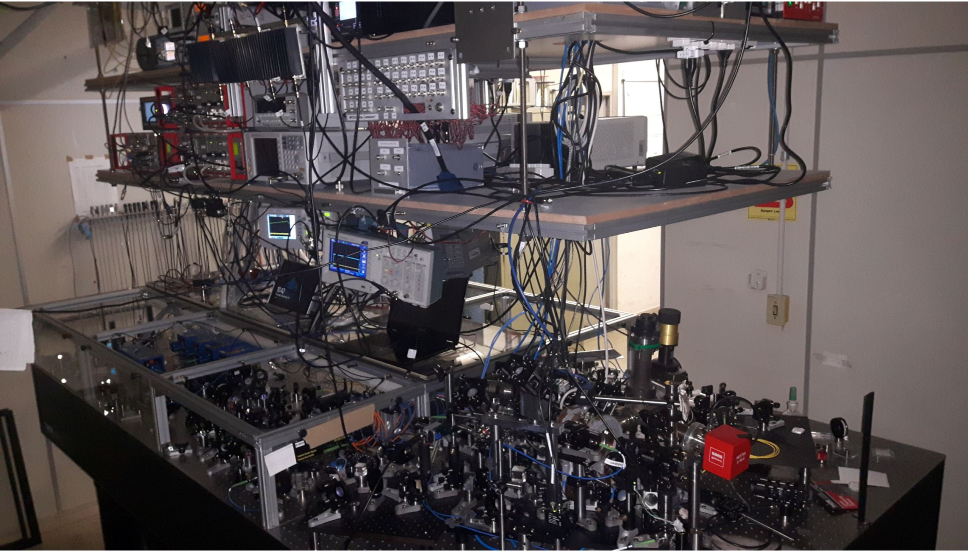


The experiment



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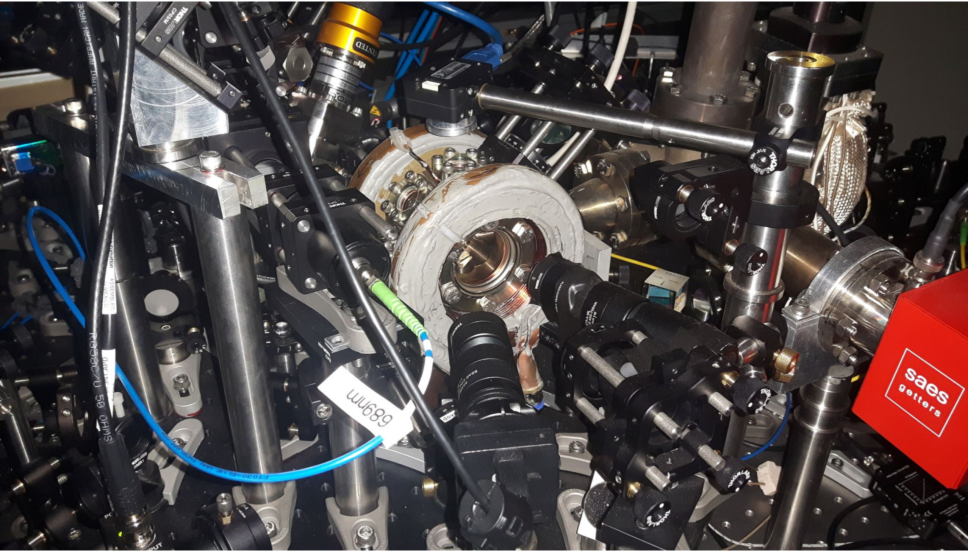
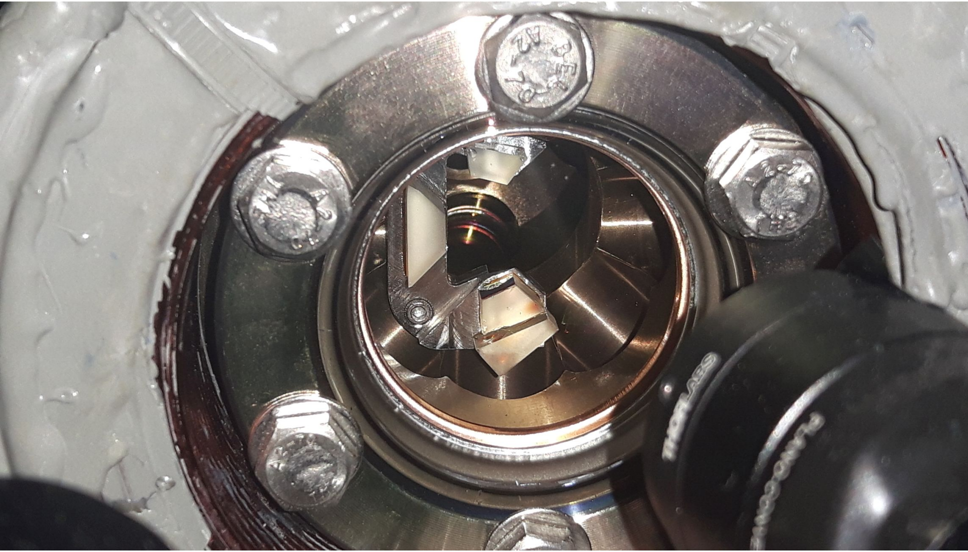


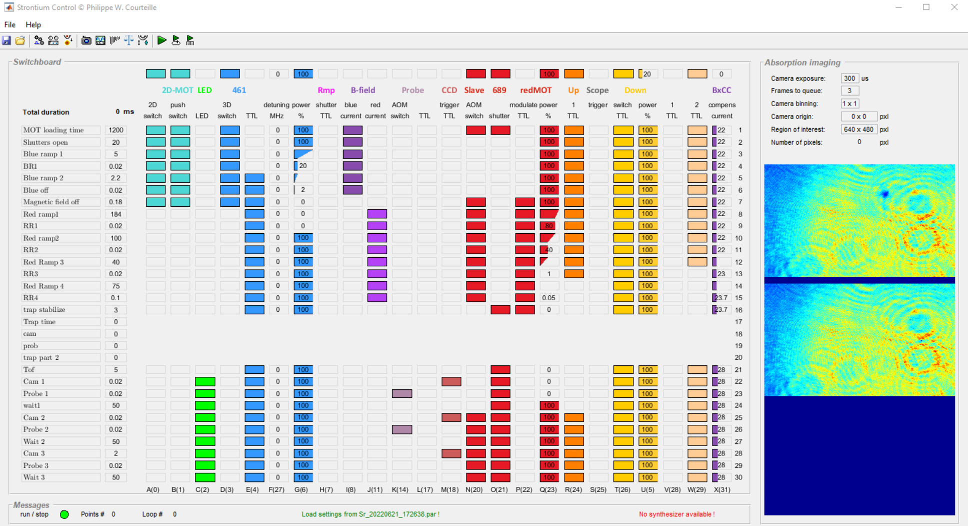
The experiment

strontium $\Gamma = 7.5\,\mathrm{kHz}$ cavity decay $\kappa = 4.3\,\mathrm{MHz}$



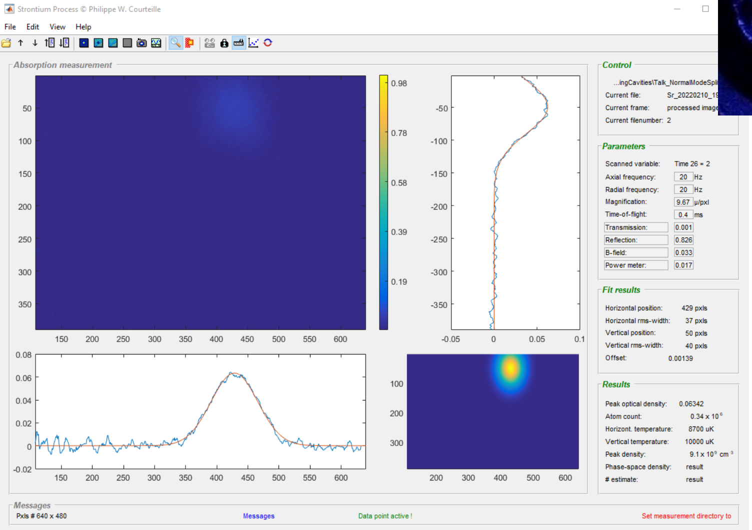
Experimental procedure & state of the art

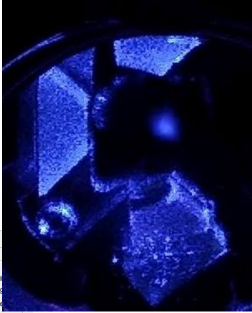
experimental control



Experimental procedure & state of the art

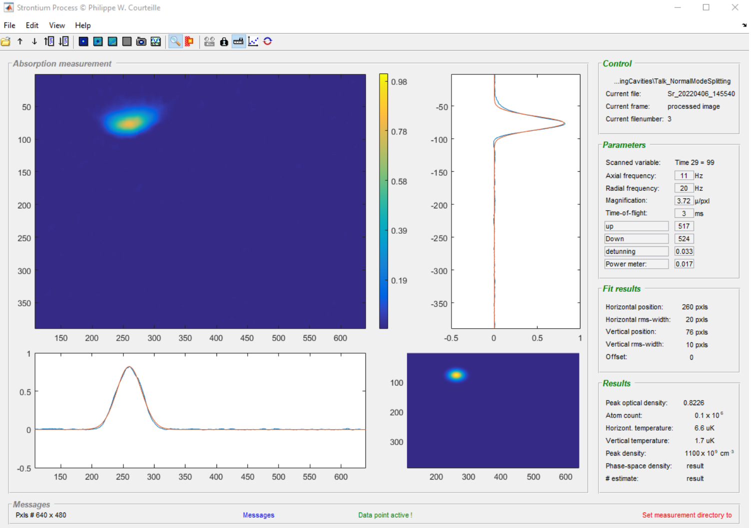
trapping atoms in the blue MOT: $N = 10^6$ $T = 5\,\mathrm{mK}$





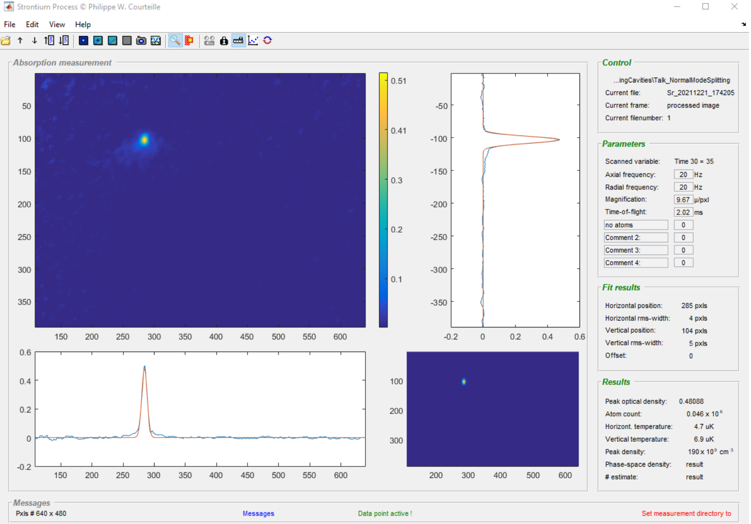
Experimental procedure & state of the art

cooling atoms in the red MOT



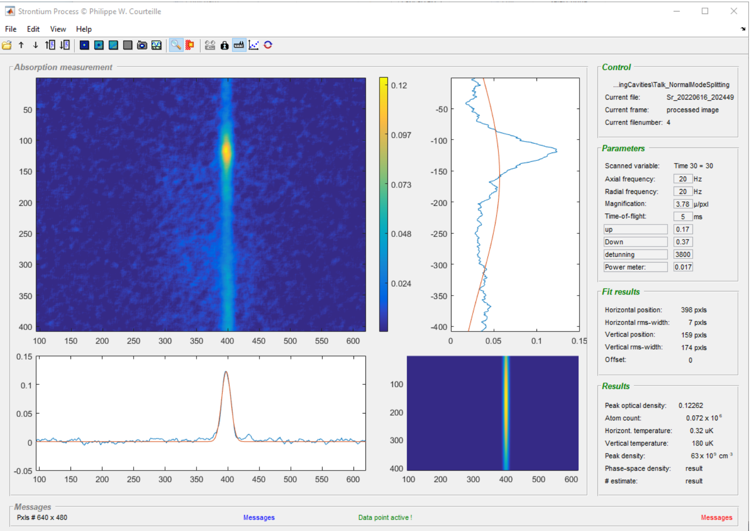
Experimental procedure & state of the art

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



Experimental procedure & state of the art

transferring atoms to the ring cavity mode via magnetic field ramp



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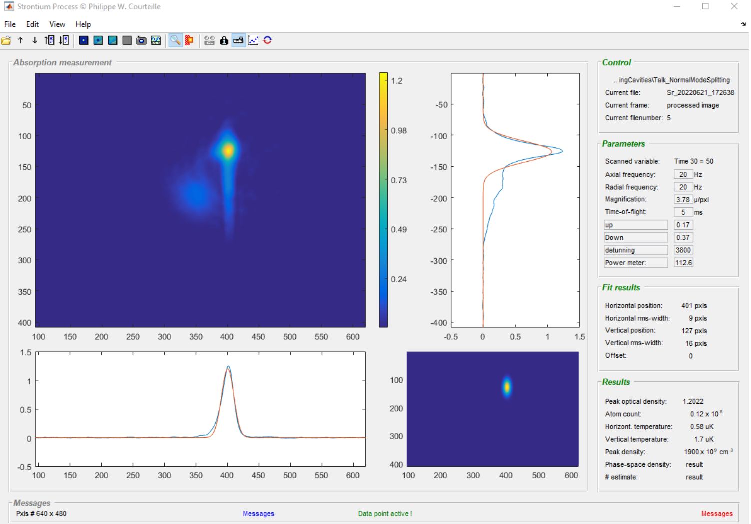
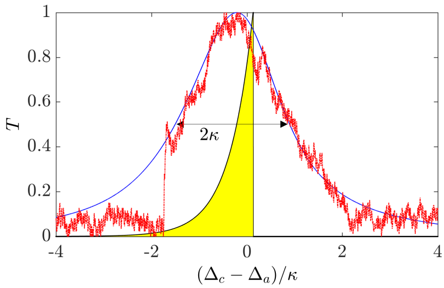
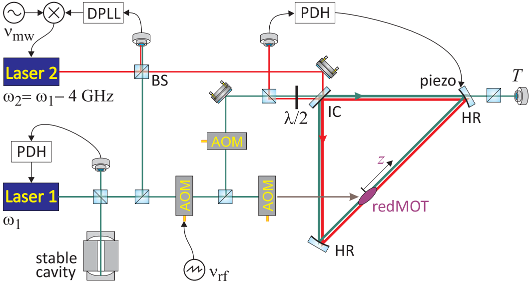


Normal mode splitting

scanning laser frequency which pumps the cavity





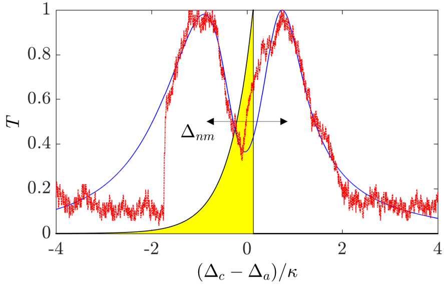
[Rivero, Beli, Armijo, da Silva, Kessler, Shiozaki, Teixeira, Courteille, Appl. Phys. B **128**, 44 (2022)]

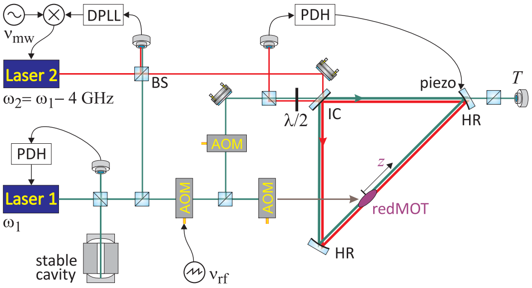
[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

Normal mode splitting

scanning laser frequency which pumps the cavity

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





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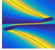
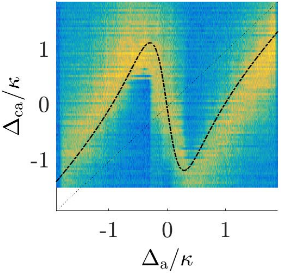
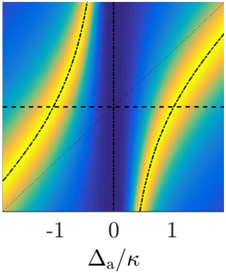
Normal mode splitting $\equiv$ 1D photonic band gap



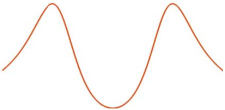
avoided crossing $+$ instable feature



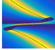


$$\Delta_{\mathrm{ca}} \equiv \Delta_{\mathrm{a}} - \Delta_{\mathrm{c}}$$

$$\Delta_{\mathrm{c}} = \frac{N g^2 \Delta_{\mathrm{a}}}{\Delta_{\mathrm{a}}^2 + \Gamma^2/4}$$



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



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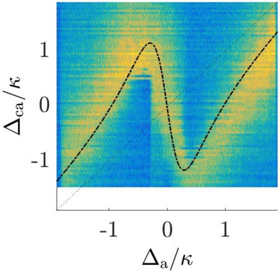
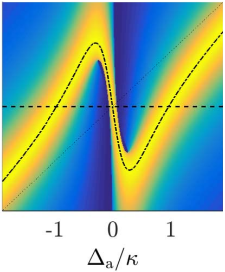
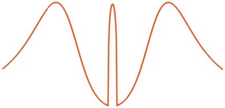




$$\Delta_{ca} \equiv \Delta_a - \Delta_c$$

$$\Delta_c = \frac{N g^2 \Delta_a}{\Delta_a^2 + \Gamma^2/4 + \Omega_\eta^2/4}$$



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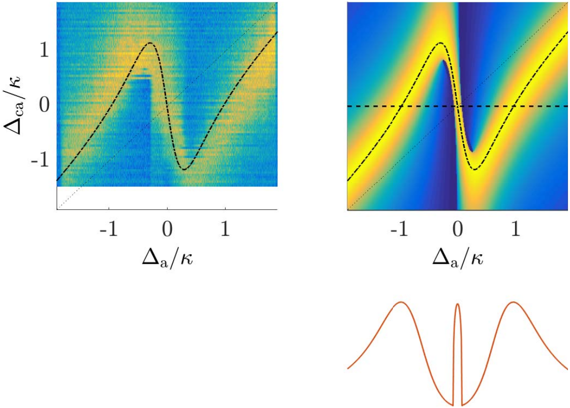
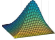


$$\Delta_{\rm ca} \equiv \Delta_{\rm a} - \Delta_{\rm c}$$

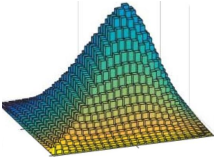
$$\Delta_{\rm c} = \frac{N g^2 \Delta_{\rm a}}{\Delta_{\rm a}^2 + \Gamma^2/4 + \Omega_\eta^2/4}$$

adiabatic elimination only near $\Delta_a = 0$



Route to steady state spin-squeezing

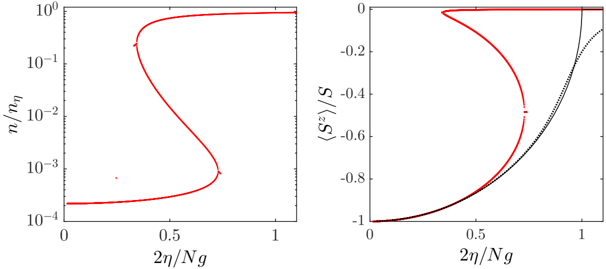
and search for spin-squeezing witnesses



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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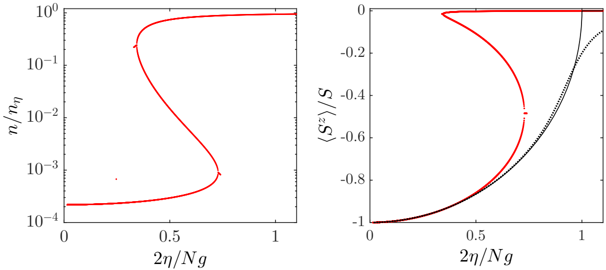


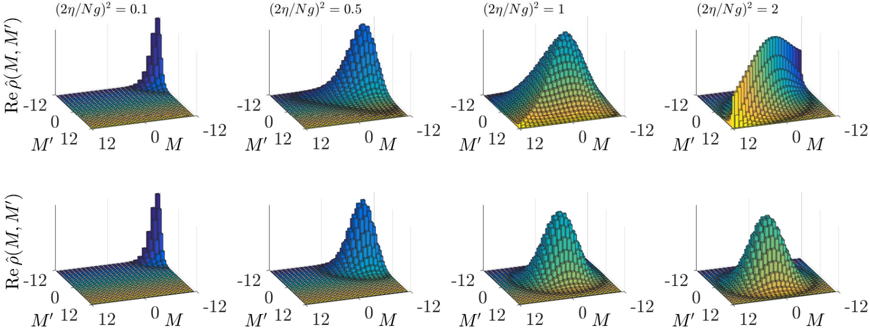
normalized cavity pump rate

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

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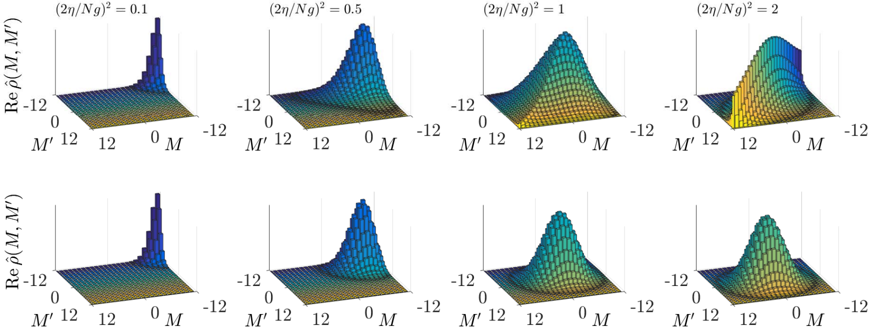

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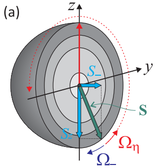
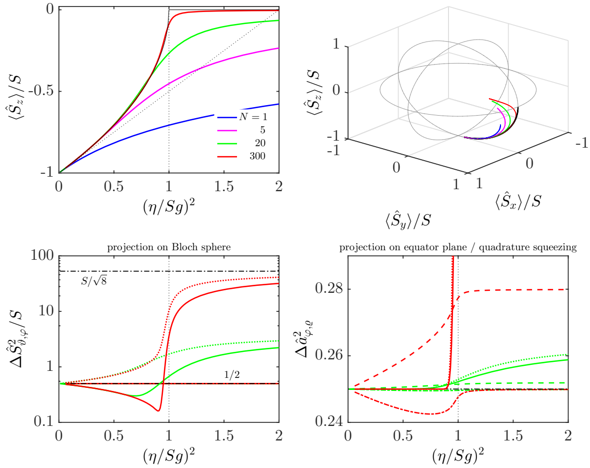


Dicke phase transition

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

$\dot{\hat\rho} = \imath[\hat\rho, \hat H] + \mathfrak{L}\hat\rho$ with $\hat H = \frac{\imath\eta g}{\kappa}\hat S_x$ and $\mathfrak{L}\hat\rho = \frac{g^2}{\kappa}(2\hat S_-\hat\rho\hat S_+ - \hat S_+\hat S_-\hat\rho - \hat\rho\hat S_+\hat S_-)$



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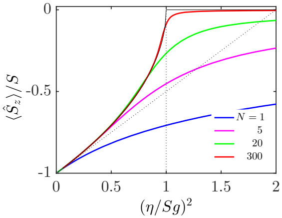
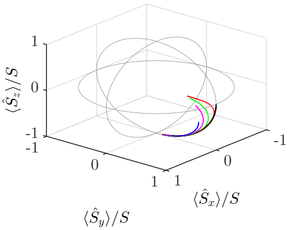
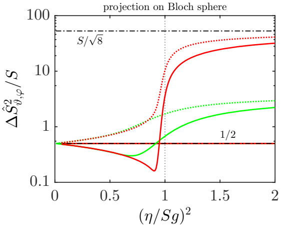
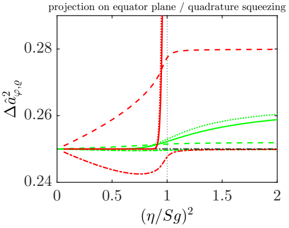








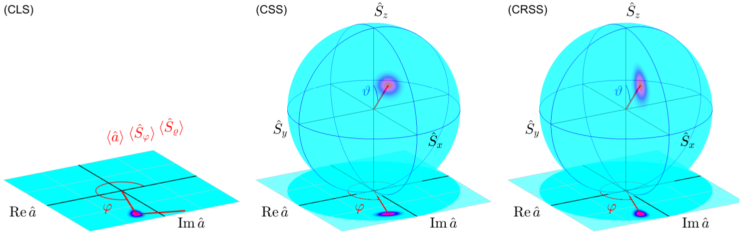
driven-dissipative spin-squeezing

light squeezing

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]

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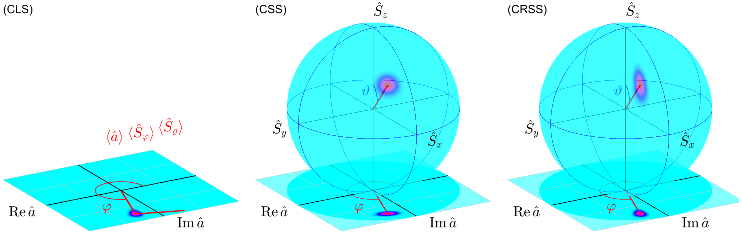

optical spin-squeezing witness?

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

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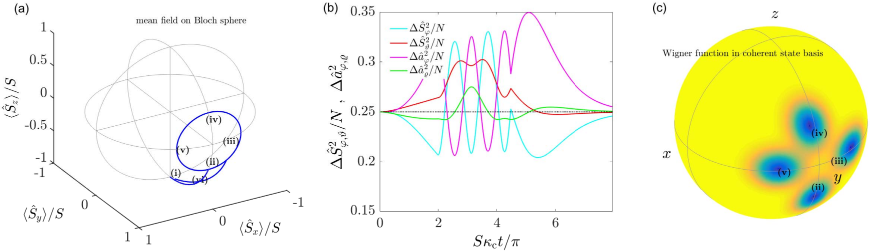
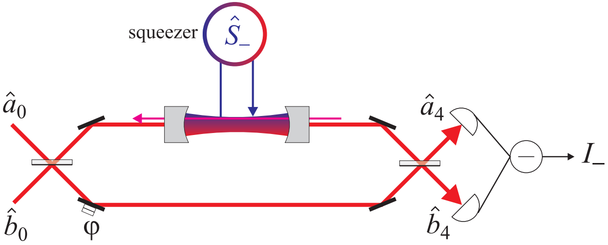
[Song, Rey, Thompson et al., Science Adv. **11**, eadu5799 (2025)]

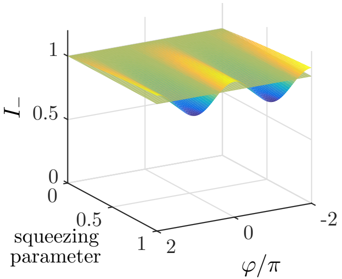
Optical spin-squeezing witness

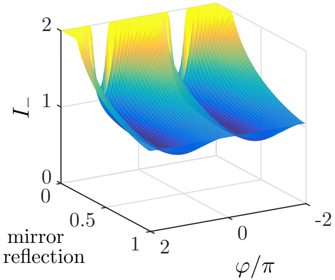
rotation pulse for squeezing axis works, but only for times short compared to $\kappa_c = \frac{g^2}{\kappa} \approx (2\pi)\, 20\,\mathrm{Hz}$



Homodyne detection

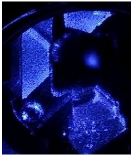






contrast reduction due to losses

Quintessence for bistability



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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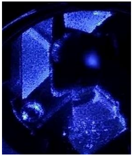

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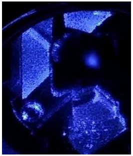

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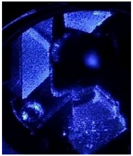

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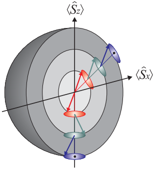
To do:

drive atoms into spin-squeezed steady state

find optical spin-squeezing witnesses

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



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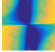
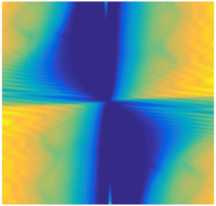
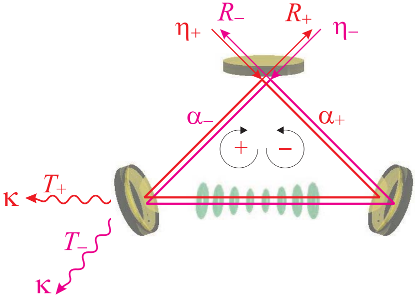


Optically dense clouds in optical lattices

Cavity models breaking down



Optically dense clouds in optical lattices

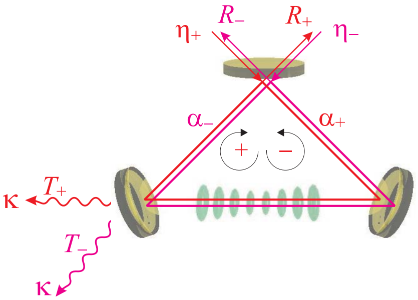


atom numbers $N \approx 200000$

lattice sites $N_s \approx 300$

optical density $OD = \frac{6N}{k^2 w^2} \approx 3$

Optically dense clouds in optical lattices



atom numbers $N \approx 200000$

lattice sites $N_s \approx 300$

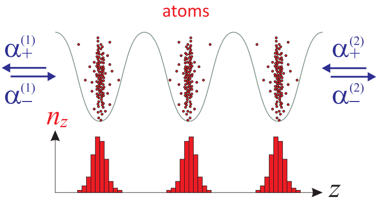
optical density $OD = \frac{6N}{k^2 w^2} \approx 3$

$\Longrightarrow$ absorption and multiple scattering

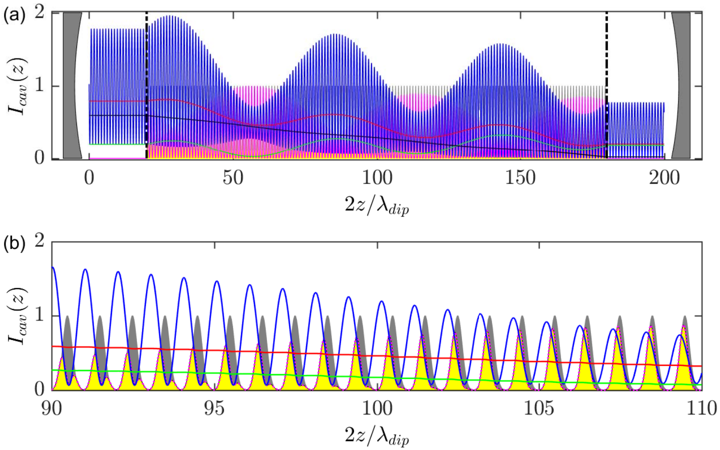
$\Longrightarrow$ cavity concept invalid (no valid cavity mode function)

$\Longrightarrow$ Open Dicke Model (ODM) no longer valid

$\Longrightarrow$ use Transfer Matrix Model (TMM)



Intracavity intensity



[Deutsch, Spreeuw, Rolston, Phillips, PRA **52**, 1394 (1995)]

[Slama, von Cube, Kohler, Zimmermann, Courteille, Phys. Rev. A **73**, 023424 (2006)]

[Schilke, Zimmermann, Courteille, Guerin, Nature Phot. **6**, 101 letter (2012)]

[Samoylova, Piovella, R. Bachelard, Ph.W. Courteille, Opt. Comm. **312**, 94 (2014)]

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

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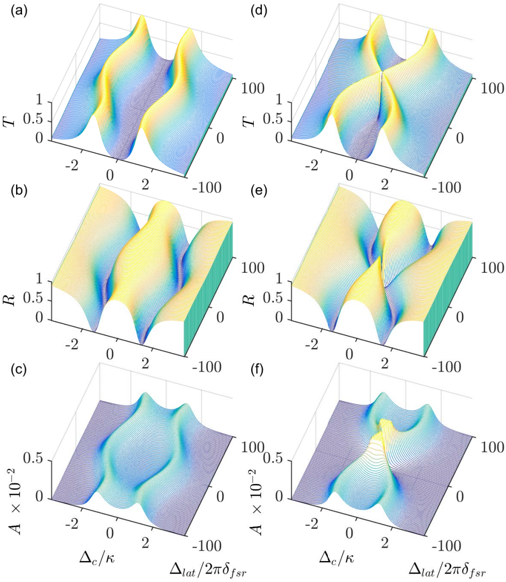

linear cavity

left/right: atoms sit at antinodes/nodes

$OD < 1 \;\Rightarrow\;$ ODM = TMM

[Courteille, Rivero, de França, Pessoa, Teixeira, Slama, Phys. Rev. A **111**, 013310 (2025)]

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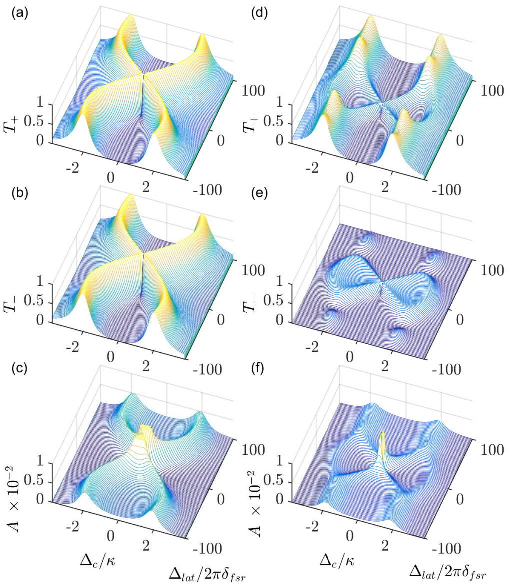

ring cavity

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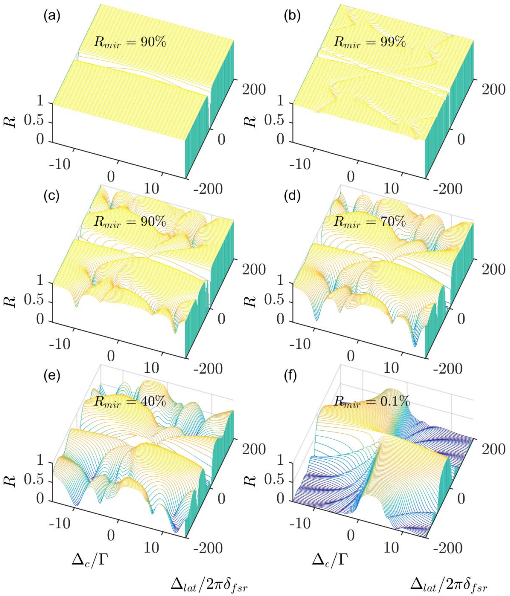

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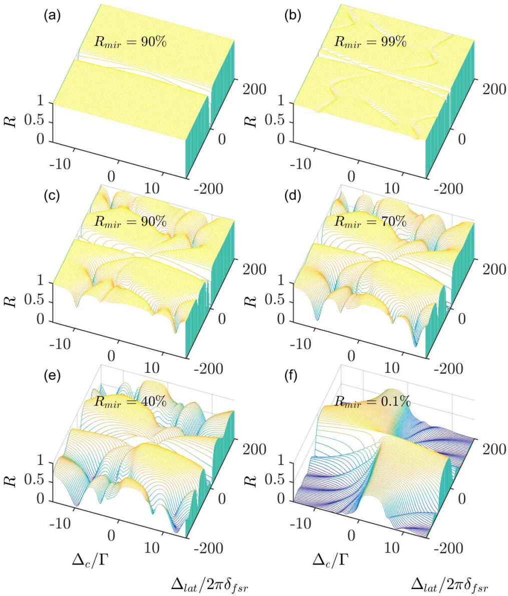


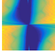
linear cavity

$OD > 1 \;\Rightarrow\;$ ODM $\neq$ TMM

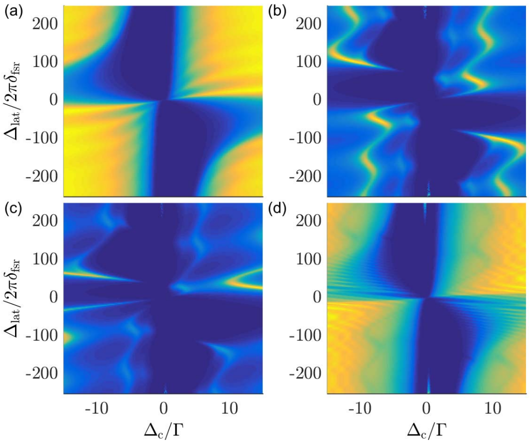
$\Rightarrow$ appearance of photonic bandgap

$\Rightarrow$ notion of cavity mode function fails

[Courteille, Rivero, de França, Pessoa, Teixeira, Slama, Phys. Rev. A **111**, 013310 (2025)]



Dense cloud with macroscopic boundary conditions



cavity = filter for specific reflection paths

[Courteille, Rivero, de França, Pessoa, Teixeira, Slama, Phys. Rev. A **111**, 013310 (2025)]

Quintessence for dense clouds

need a full quantum model working at any '$I_{\rm sat}$' and 'OD'

[Courteille, Rivero, de França, Pessoa, Teixeira, Slama, Phys. Rev. A **111**, 013310 (2025)]

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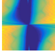

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ODM and TMM neglect direct photon exchange via radiation modes $(\mathbf{k}, \lambda)$

$$\hat{H}_{\rm Ising} = \sum_{i \neq j} \Delta_{ij} \hat{\sigma}_j^+ \hat{\sigma}_i^-$$

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treat mirrors as macroscopic boundaries $\Longrightarrow$ cooperative environment shaping $g_{\mathbf{k}\lambda}$

$$\hat{H} = \hbar\sum_{\mathbf{k},\lambda}\sum_j (\hat{\sigma}_j^+ e^{-\imath k z_j} + \hat{\sigma}_j^- e^{\imath k z_j})(g_{\mathbf{k}\lambda}\hat{a}_{\mathbf{k}\lambda} + g^*_{\mathbf{k}\lambda}\hat{a}^\dagger_{\mathbf{k}\lambda})$$

[Courteille, Rivero, de França, Pessoa, Teixeira, Slama, Phys. Rev. A **111**, 013310 (2025)]

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need a full quantum model working at any 'I_{sat}' and 'OD'

ODM and TMM neglect direct photon exchange via radiation modes $(\mathbf{k}, \lambda)$

$$\hat{H}_{\mathrm{Ising}} = \sum_{i \neq j} \Delta_{ij} \hat{\sigma}_j^+ \hat{\sigma}_i^-$$

treat mirrors as macroscopic boundaries $\implies$ cooperative environment shaping $g_{\mathbf{k}\lambda}$

$$\hat{H} = \hbar \sum_{\mathbf{k},\lambda} \sum_j (\hat{\sigma}_j^+ e^{-\imath k z_j} + \hat{\sigma}_j^- e^{\imath k z_j})(g_{\mathbf{k}\lambda} \hat{a}_{\mathbf{k}\lambda} + g_{\mathbf{k}\lambda}^* \hat{a}_{\mathbf{k}\lambda}^\dagger)$$

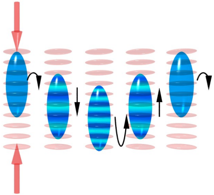
JCM with 1 atom breaks down for Purcell factor $\gg 1$

$$OD = \sigma_0 n_{\mathrm{at}} N_{\mathrm{s}} \frac{\lambda_{\mathrm{lat}}}{2} = \frac{6N}{k^2 w^2} = \frac{\pi \Upsilon_N}{F} > 1$$

[Blaha, Rauschenbeutel, Volz, JOSA B **41**, C222 (2024)]

Matter wave Bloch oscillations

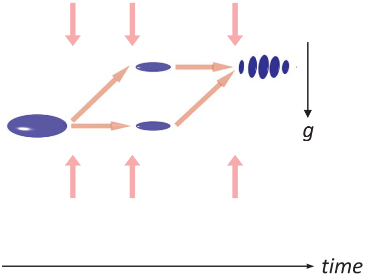
for inertial sensing



Gravimetry with Bose-Einstein condensates

differential phase shift of de Broglie waves

$\longrightarrow$ matter wave interferometers



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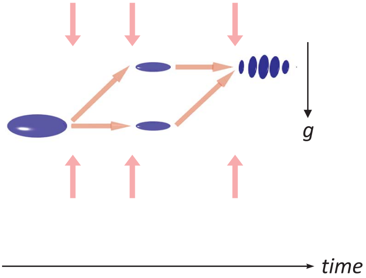
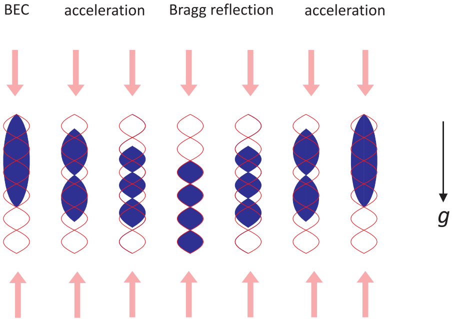


matter wave Bloch oscillations in a periodic potential

- wavelength $\lambda_{\mathrm{dB}} = \frac{h}{mv}$



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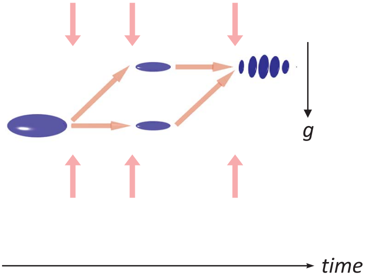
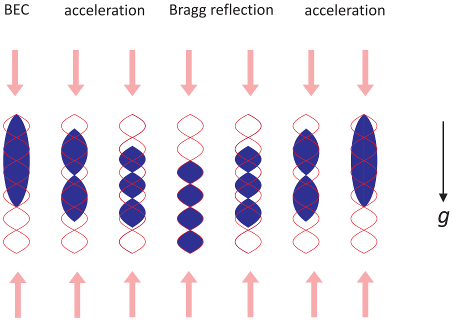


matter wave Bloch oscillations in a periodic potential

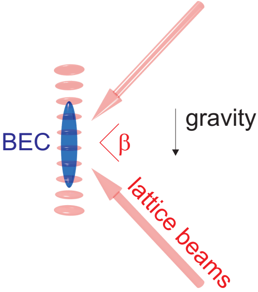
- wavelength $\lambda_{\mathrm{dB}} = \frac{h}{mv}$
- frequency $\nu_{\mathrm{Bloch}} = \frac{mg}{2\hbar k}$

$\longrightarrow$ measure gravity g



[Ben Dahan, Peik, Castin, Salomon, PRL **76**, 4508, (1996)]

Continuous monitoring Bloch oscillations in a cavity



[Samoylova, Piovella, Robb, Bachelard, Courteille, Opt. Exp. **23**, 14823 (2015)]
[Samoylova, Piovella, Hunter, Robb, Bachelard, Courteille, Las. Phys. Lett. **11**, 126005 (2014)]

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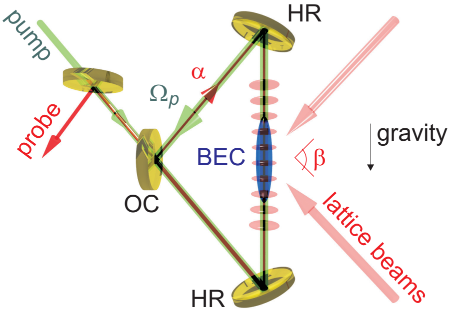

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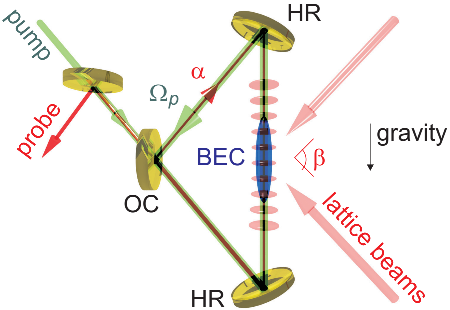
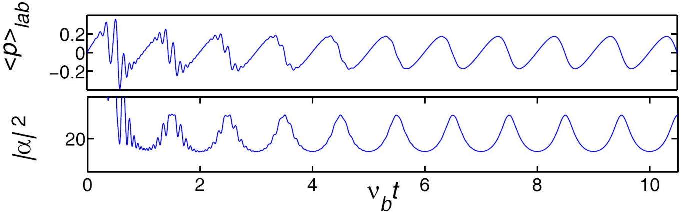




$N = 8 \cdot 10^4$

$\kappa = 160\omega_{\text{rec}}$

$U_0 = 0.04\omega_{\text{rec}}$

$W_0 = 80U_0$

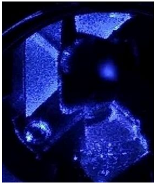
[Samoylova, Piovella, Robb, Bachelard, Courteille, Opt. Exp. **23**, 14823 (2015)]

[Samoylova, Piovella, Hunter, Robb, Bachelard, Courteille, Las. Phys. Lett. **11**, 126005 (2014)]

Quintessence

Done:

- 200000 atoms cooled down to single-photon recoil limit



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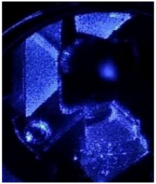
- 200000 atoms cooled down to single-photon recoil limit
- confinement in an optical lattice sustaining 1 trapped state



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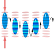

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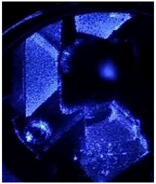
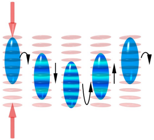


To do:

search for signatures of Bloch oscillations in light modes



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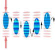

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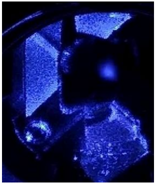
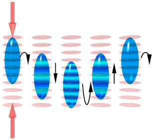


To do:

search for signatures of Bloch oscillations in light modes

continuous monitoring of gravity



CONCLUSION

The team

Raul Teixeira, Dalila Rivero, Gustavo de França, Claudio Pessoa, Thiago da Silva

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

FAPESP

CAPES

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de ciência e tecnologia

CONCLUSION

Linearity of quantum mechanics

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Linearity of quantum mechanics

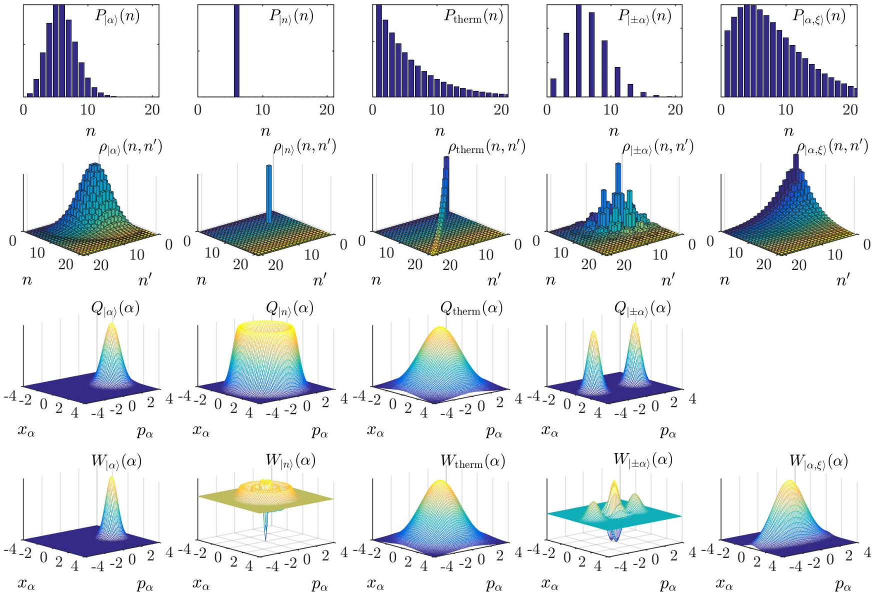
QM is a Lie algebra $\implies$ linearity $\implies$ our universe is a quantum computer

$V(\mathbf{r})$ is an artifact [just like $n_{\mathrm{rfr}}(\mathbf{r})$ in optics or $\Phi(\mathbf{r})$ and $\mathbf{A}(\mathbf{r})$ in E-dynamics]

need to break down physical processes into momentum-conserving collisions $\implies$ microscopic description of V

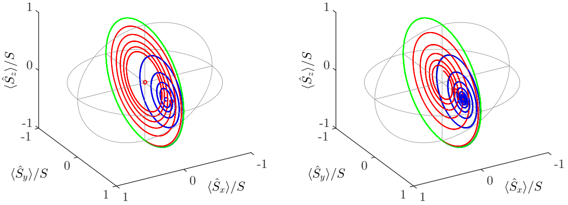
Space is homogeneous $\implies$ momentum always conserved

Representation of particular states of light



Impact of spontaneous emission

spontaneous emission recovers steady state excitation



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

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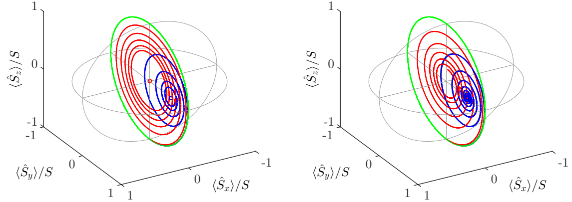
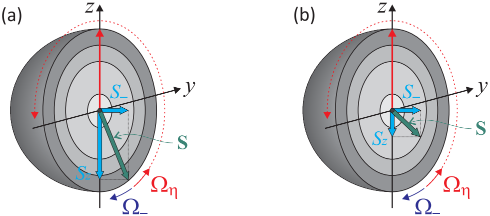


driven-damped rigid rotor flipping over



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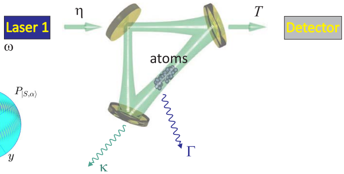
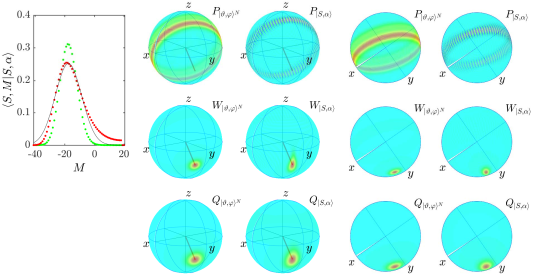
CONCLUSION

Beyond mean field: Coherently radiating spin-squeezed state

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





[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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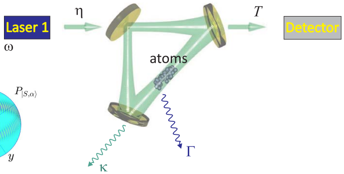
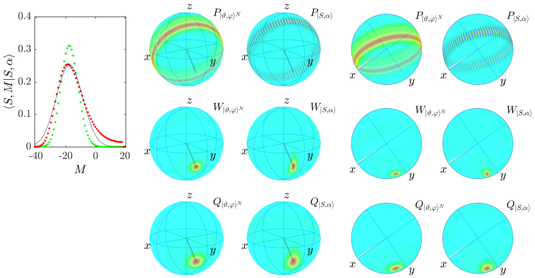
$$\hat{S}_-|ss\rangle \simeq \alpha|ss\rangle \quad \& \quad [\hat{S}_-, \hat{H}_{\text{eff}}] = 0 \quad \Leftrightarrow \quad 0 = \frac{d}{dt}\hat{\rho} = \frac{d}{dt}|ss\rangle\langle ss|$$





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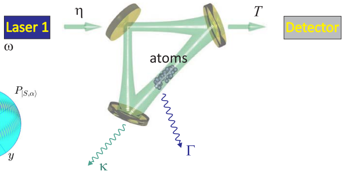
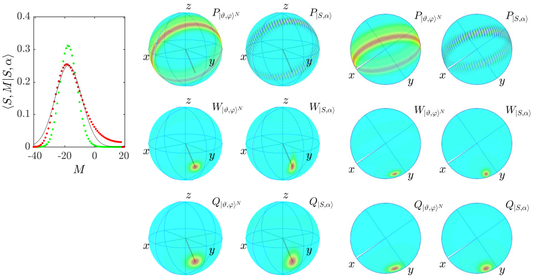


P-, Wigner, and Q-function of CSS and CRSS



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)]
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Spin-squeezing near a Dicke phase transition

CONCLUSION

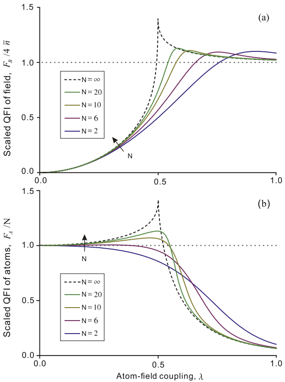


Figure 1. Scaled quantum Fisher information of the bosonic field $F_B/(4\bar{n})$ (a) and that of the atoms F_A/N (b) as a function of the coupling strength λ for a finite number of atoms $N = 2$, 6, 10, and 20, as indicated by the arrow. Horizontal dotted lines: the classical (or shot-noise) limit for 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 $\omega = \omega_0 = 1$.

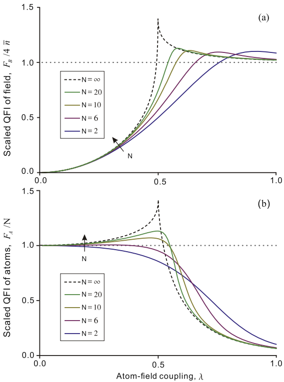
RWA, no dissipation

Quantum Fisher information and squeezing parameter

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

CONCLUSION

Spin-squeezing near a Dicke phase transition



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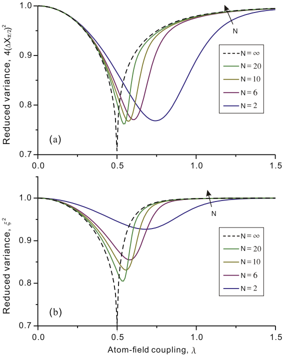

Figure 3. Degree of quadrature squeezing for the field mode $4(\Delta\hat{X}_{\pi/2})^2$ (a), and that of spin squeezing for the atoms ξ^2 (b) against the coupling strength λ for the number of atoms $N = 2$, 6, 10, and 20, as indicated by the arrow. Dashed lines: analytical results in the thermodynamic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

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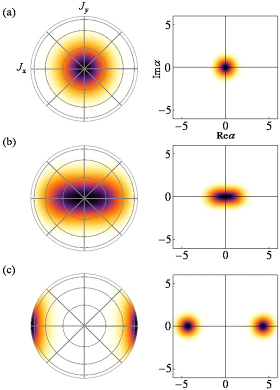
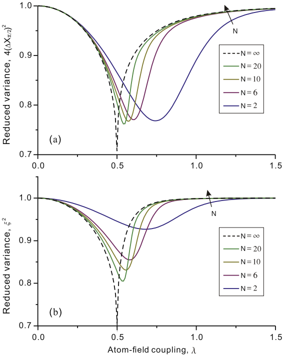


Figure 2. Quasi-probability distributions $Q_A(\theta, \phi)$ (left panel) and $Q_B(\alpha)$ (right panel) of the ground state of the Dicke Hamiltonian with $N = 20$ and the atom-field coupling strength $\lambda = 0$ (a), 0.54 (b), and 1 (c). The axes on the Bloch sphere (top view from the south pole) 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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