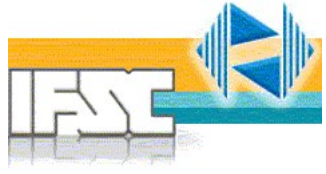
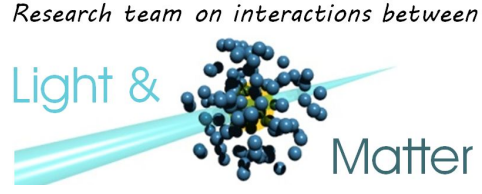
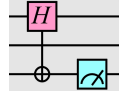
Quantum Sensing with Cold Atoms and Matter Waves

Philippe W. Courteille





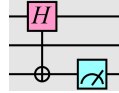
Organization of the talk



Teaser sensing, with atoms, in cavities, quantum sensing 2.0

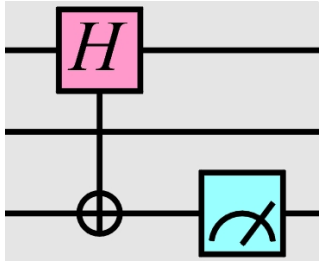
Synchronization of atomic dipoles in bad cavities $\rightarrow$ superradiance, spin-squeezing

Synchronization of matter waves in ring cavities $\rightarrow$ gravimetry in real-time

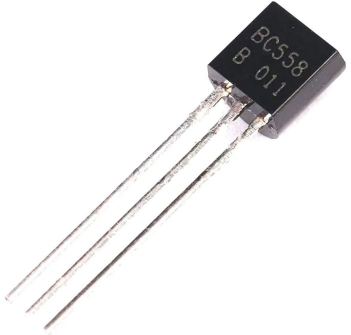


Quantum mechanics

and second generation quantum technologies



Quantum mechanics everywhere



Quantum revolution 1.0

transistor, nuclear energy, laser, atomic clocks, ...

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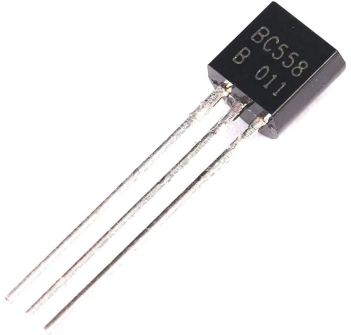

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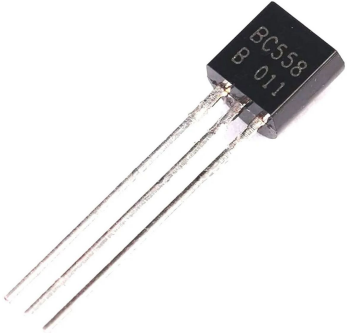

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- QM is correct and complete

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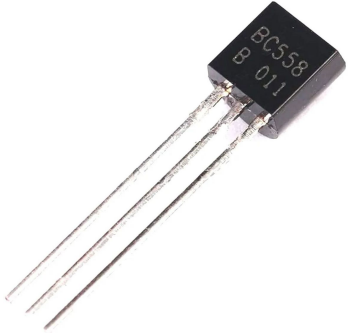

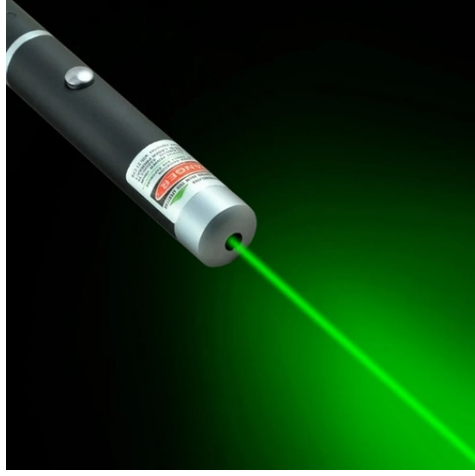

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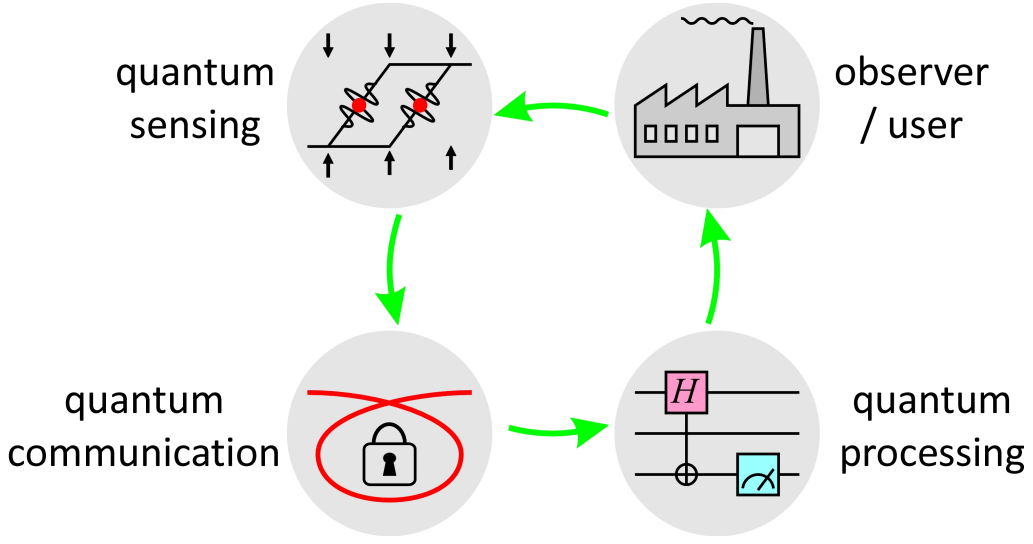
Quantum revolution 2.0

quantum information technologies

Nobel prize 2022



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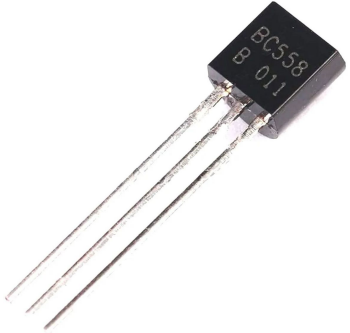

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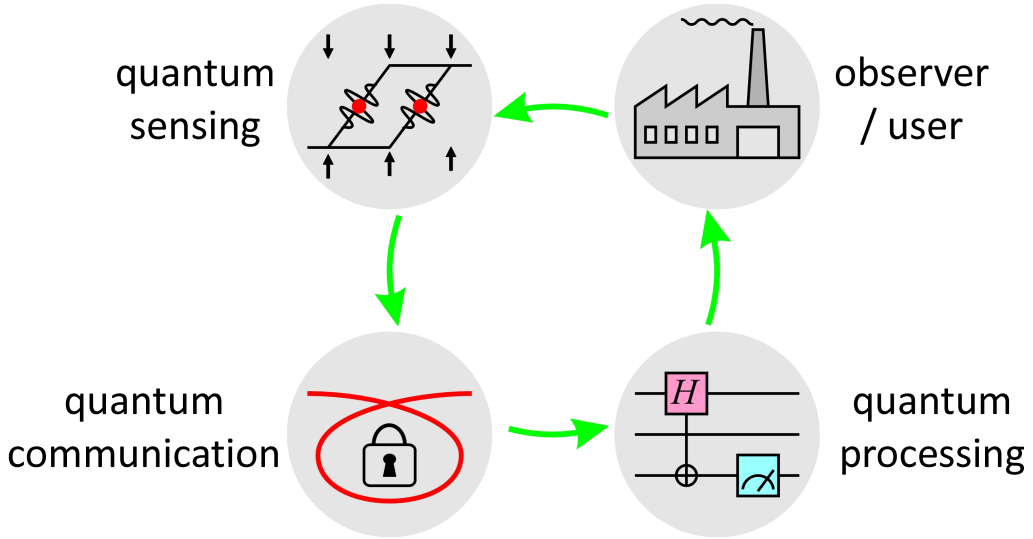

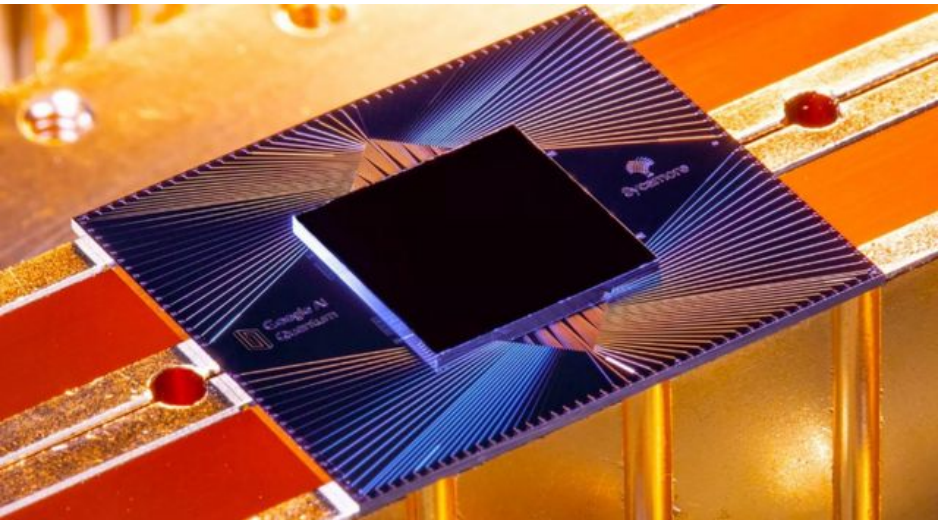

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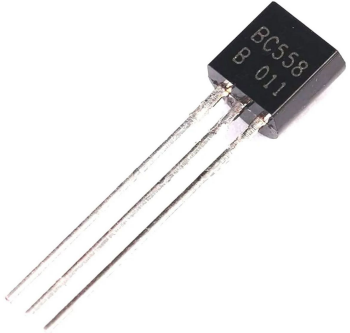

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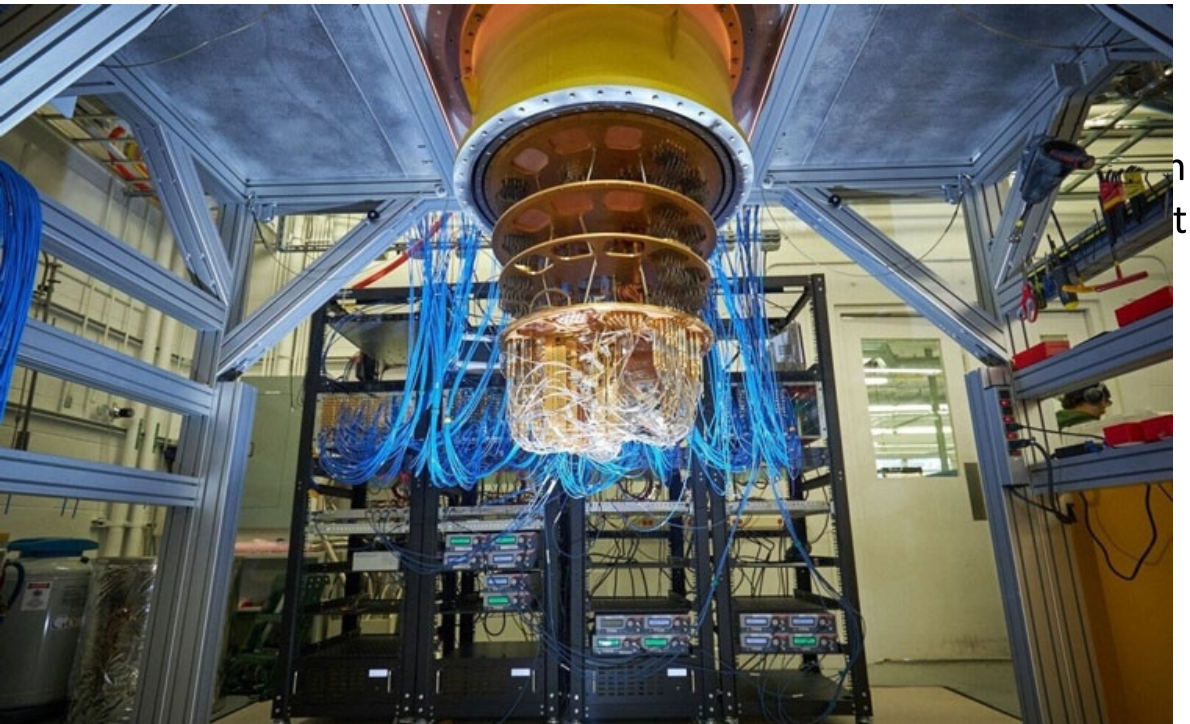
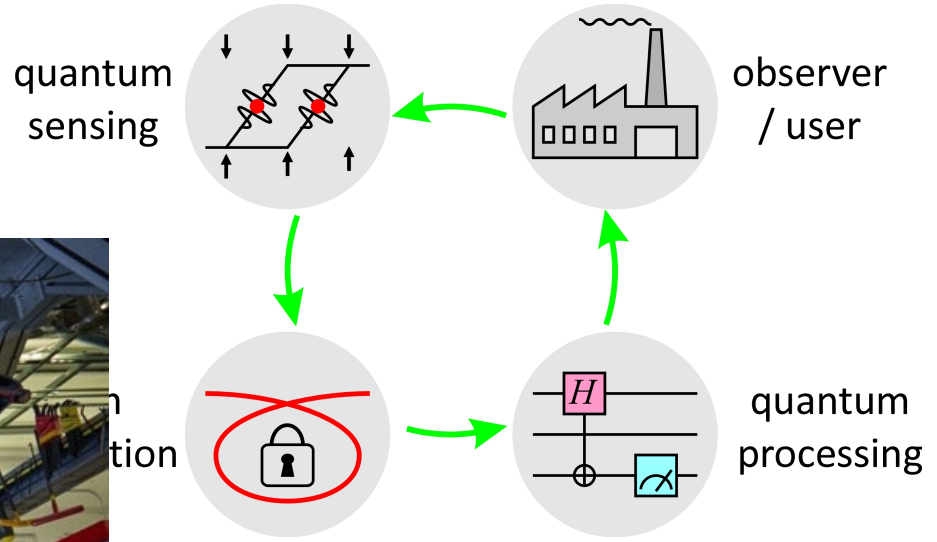
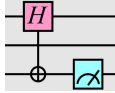




Private sector



IBM Q

Google AI

intel

AT&T

accenture

aws

Amazon Braket

Microsoft

Quantum Computer

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Microsoft Quantum Computer

AOSense
Sensors for a Quantum World

μQUANS

AQT

GWR Instruments

KIPP & ZONEN
SINCE 1830

PQS 1 PAR Quantum Sensor

The National Quantum Initiative Act

law signed by **EX**-president Trump on Dec. 21, 2018

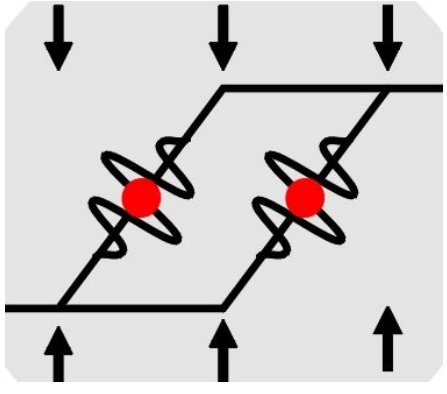
⟨quantum|gov⟩

Nondefense AI and QIS R&D Summary: Fiscal Years 2020 - 2021

	FY2020 Budget Proposal*	FY2020 Enacted Estimate**	FY2021 Budget Proposal
Artificial Intelligence	$973.5 Million	$1.118 Billion	$1.503 Billion
Quantum Information Science	$435 Million***	$579 Million	$699 Million

[https://doi.org/10.1088/2058-9565/ab0441]

Quantum sensing with atoms & light



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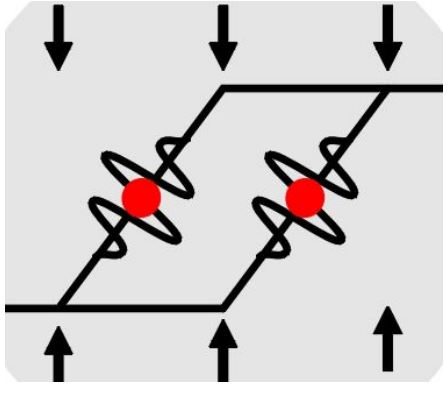

What is a sensor?

'device generating & providing information on events or changes in its environment' (Wikipedia)

time, gravitation, gravity gradients, accelerations and rotations, electric and magnetic fields, temperature, ...

Sensors everywhere

smartphone, 5G, autonomous driving, ...

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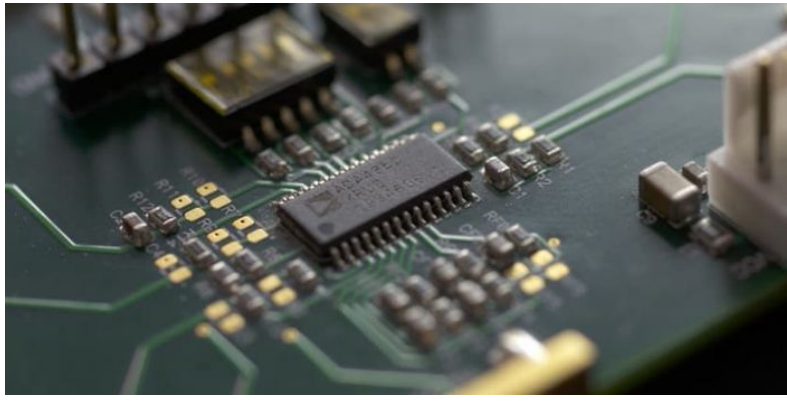
In fundamental science

measure weak forces with high sensitivity, strong forces with great accuracy!

What is a quantum sensor?

'measurement device exploiting quantum correlations in order to enhance sensitivity and resolution'

e.g. quantum superpositions or entanglement (Wikipedia)



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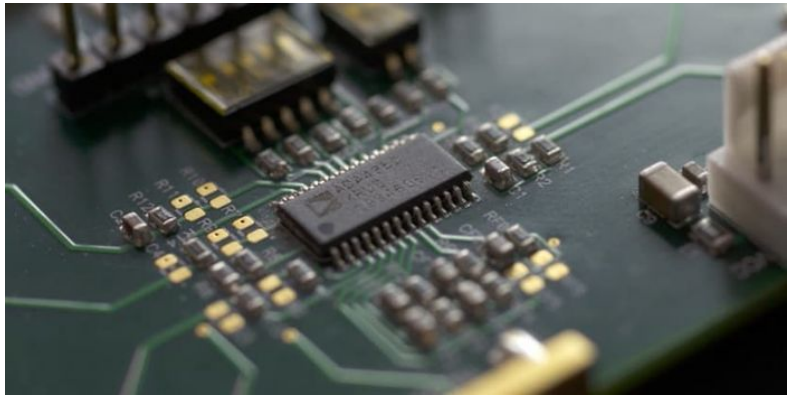
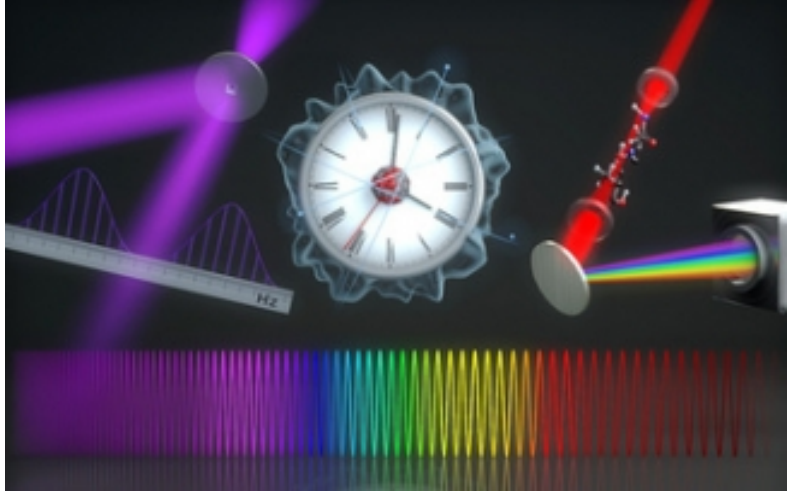


Advantages of quantum sensors

- precision & sensitivity
- speed
- robustness
- integrability, ...

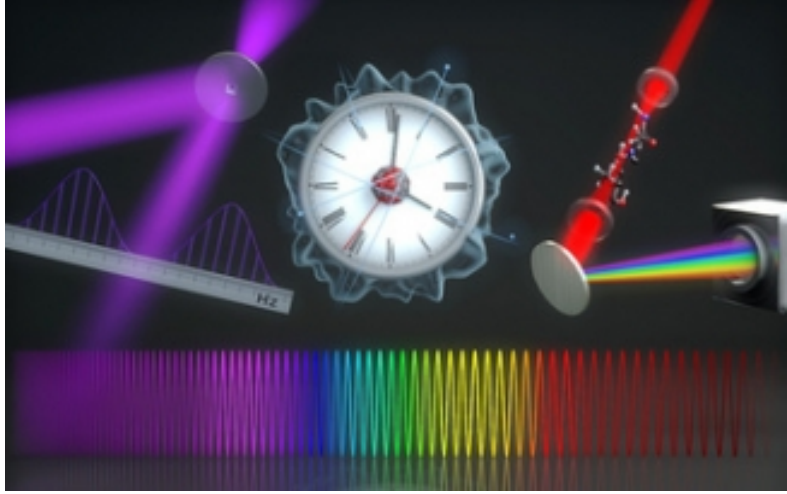
What is an atomic quantum sensor?



atoms are 'quantum', some have ultra-narrow resonances

imprecision of best atomic clock: $2.5 \cdot 10^{-19} = 0.000\ 000\ 000\ 000\ 000\ 000\ 25$

What is an atomic quantum sensor?



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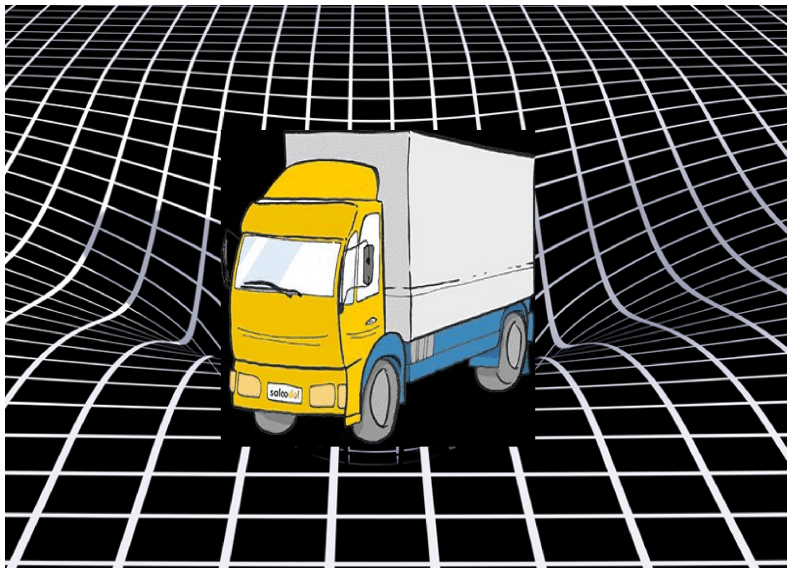
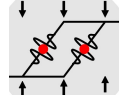
imprecision of best gravimeter: 10^{-9} $\longrightarrow$ measure deformation of gravity field caused by a truck

some projects in Brazil

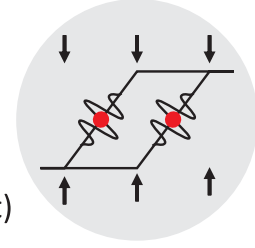


What is a quantum sensor 2.0?



Most current quantum sensors use single-atom quantum superpositions

today: individual atoms can be observed $\longrightarrow$ emergence of quantum jumps, ...



quantum sensor(qubit)

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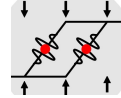

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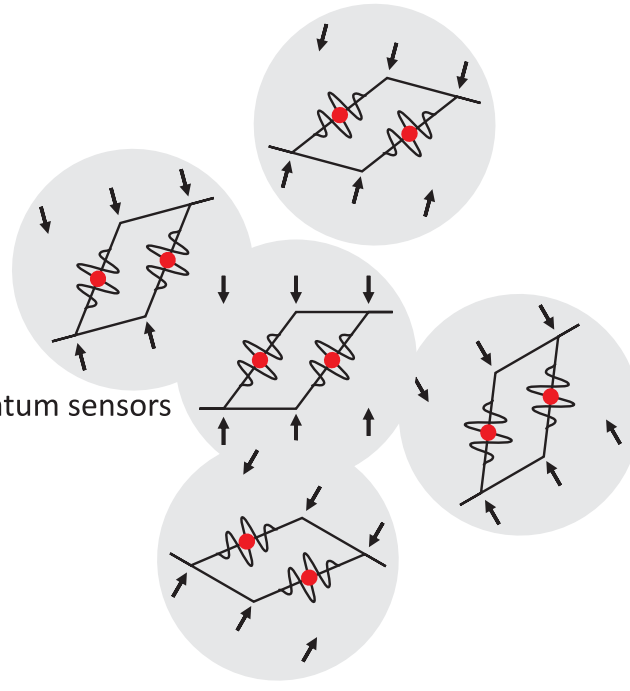
For good signal-to-noise $\longrightarrow$ *observe many atoms simultaneously*

Standard Quantum Limit / shot noise $(\propto \sqrt{N}^{-1})$



sample of quantum sensors

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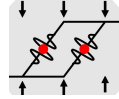

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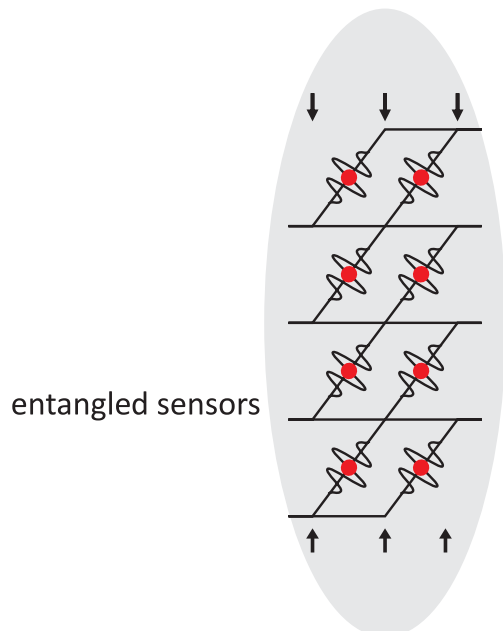
Entangled qubits allow precision beyond SQL (Nobel prize 2022)

Heisenberg limit $(\propto N^{-1})$ and beyond

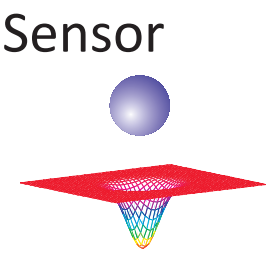
spin squeezing, squeezed light for gravitational wave detection



[Bouyer, Kasevich, PRA **96**, R1083 (1997) *Heisenberg-limited spectroscopy with degenerate Bose-gases*]

Quantum sensing using cavities?

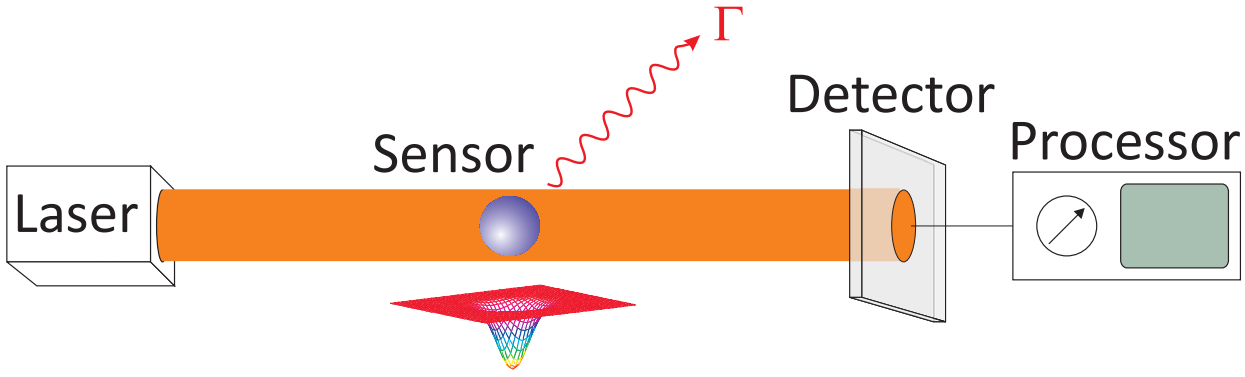
Atoms as sensor



Quantum sensing using cavities?

Atoms as sensor , light as detector

light interacts with the atoms and carries the information to the detector



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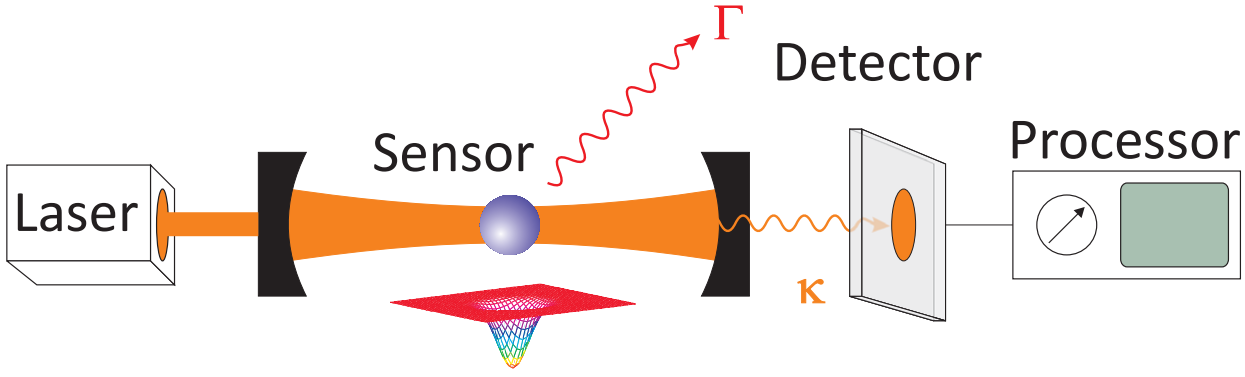


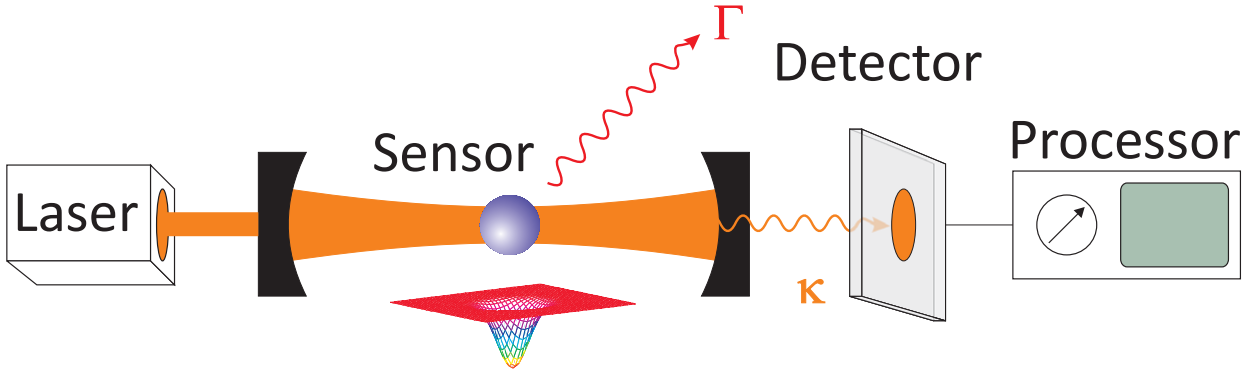
Quantum sensing using cavities?

Atoms as sensor , light as detector

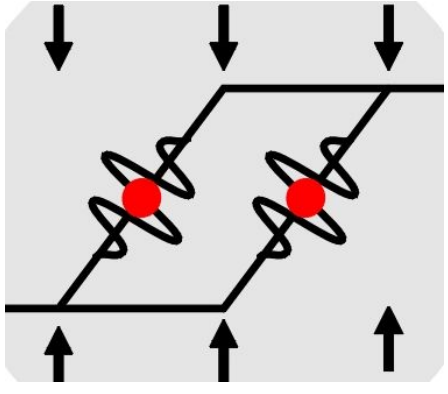
light interacts with the atoms and carries the information to the detector

for coherent interaction $\longrightarrow$ use bad cavities $(\kappa \gg \Gamma)$

- isolate single light mode
- collective coupling of atoms $(g\sqrt{N} \gg \kappa)$ $\longrightarrow$ precondition for quantum correlation



Quantum projection noise



Classical projection noise

Probability to be in $|$  $\rangle$ *or* $|$  $\rangle$

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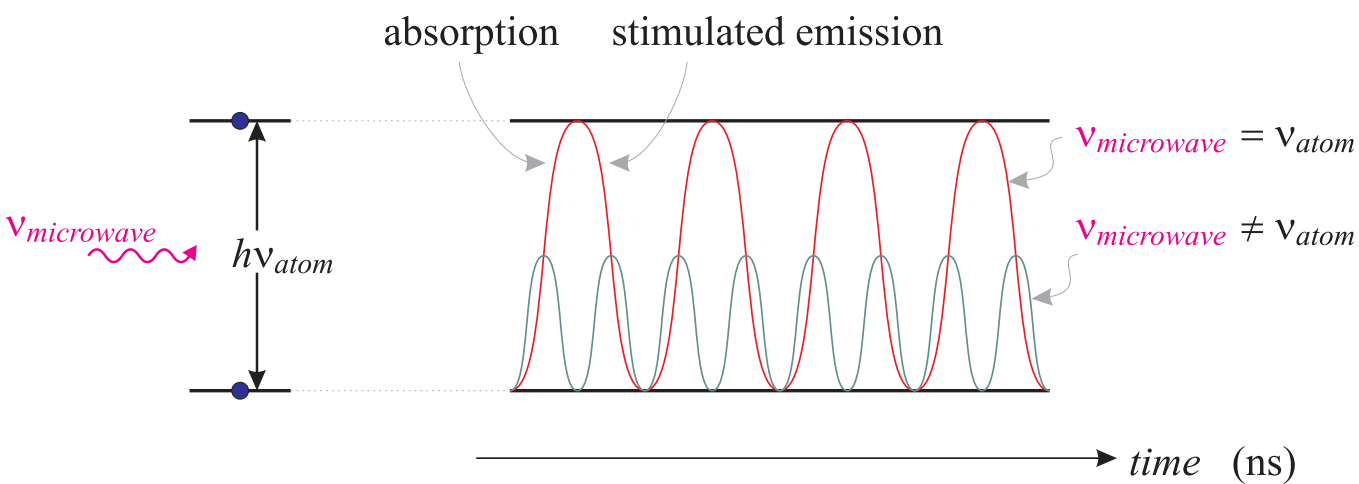
Probability to be in $|\quad + \quad\rangle + |\quad - \quad\rangle$



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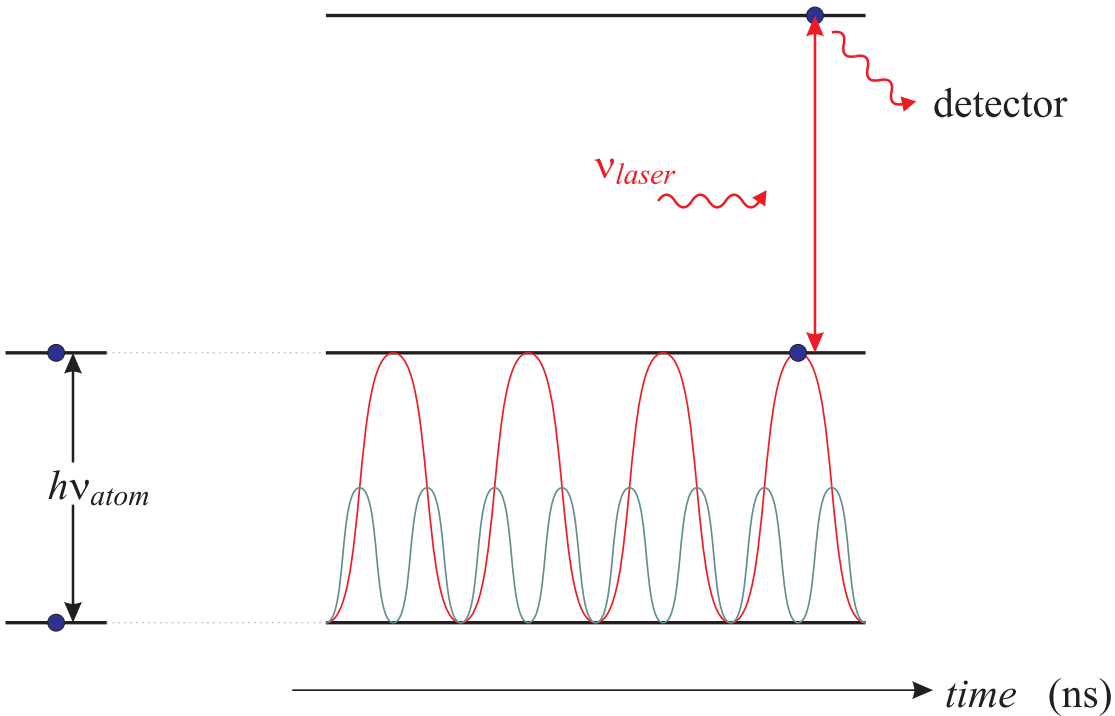
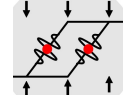


Projection noise in a two-level system



Probability to be in $|+\rangle$ *or* $|-\rangle$ $\quad p_+ = \langle \hat{P}_+ \rangle = |\langle + | \psi \rangle|^2 = 1 - p_-$

[Itano *et al.*, PRA **47**, 3554 (1993)]

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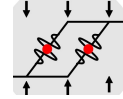

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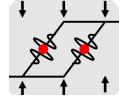

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Task $\quad$ find out p_+ via N repeated measurements $\quad P_{N,r,+} = \binom{N}{r} p_+^{\,r} (1-p_+)^{N-r}$

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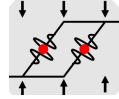

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Expectation value and variance

$$\bar{r} = \sum_{r=0}^{N} r P_{N,r,+} = N p_+$$

$$(\Delta r)^2 = \sum_{r=0}^{N} (r - N p_+)^2 P_{N,r,+} = N p_+ p_-$$

$$\Longrightarrow \quad \frac{\bar{r}}{\Delta r} \propto \sqrt{N}$$

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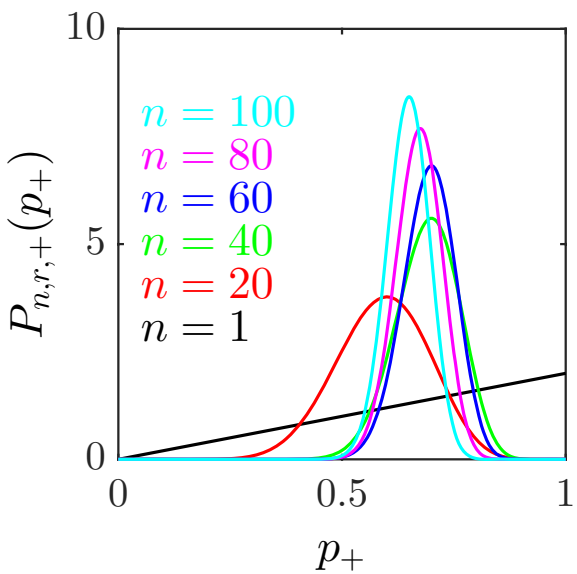
Task $\quad$ find out p_+ via N repeated measurements $\quad P_{N,r,+} = \binom{N}{r} p_+^{\,r} (1-p_+)^{N-r}$

Expectation value and variance

$$\bar{r} = \sum_{r=0}^{N} r P_{N,r,+} = N p_+$$

$$(\Delta r)^2 = \sum_{r=0}^{N} (r - N p_+)^2 P_{N,r,+} = N p_+ p_-$$

$$\Longrightarrow \quad \frac{\bar{r}}{\Delta r} \propto \sqrt{N}$$



[Itano *et al.*, PRA **47**, 3554 (1993)]

[Kitagawa *et al.*, PRA **47**, 5138 (1994)]

[Wineland *et al.*, PRA **50**, 67 (1994)]

Projection noise in a two-level system

Probability to be in $|+\rangle$ *or* $|-\rangle$ $\quad p_+ = \langle \hat{P}_+ \rangle = |\langle +|\psi\rangle|^2 = 1 - p_-$

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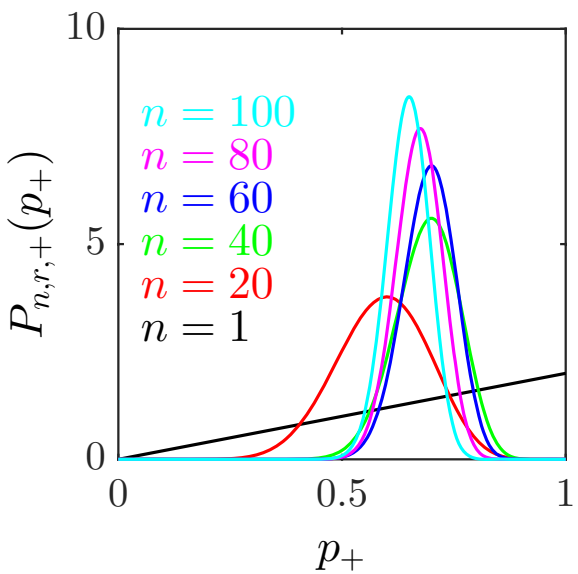

$p_+ = 0.6$

[Itano *et al.*, PRA **47**, 3554 (1993)]

[Kitagawa *et al.*, PRA **47**, 5138 (1994)]

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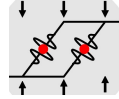
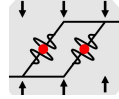
Projection noise in a Rabi experiment



Tentative π-pulse $(t = \frac{\pi}{\Omega})$*, then projection on energy eigenstate*

$$p_+(t) = \rho_{++} = \frac{\Omega^2}{G^2} \sin^2 \frac{Gt}{2} \quad , \quad G \equiv \sqrt{\Delta^2 + \Omega^2}$$

Projection noise in a Rabi experiment



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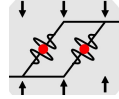

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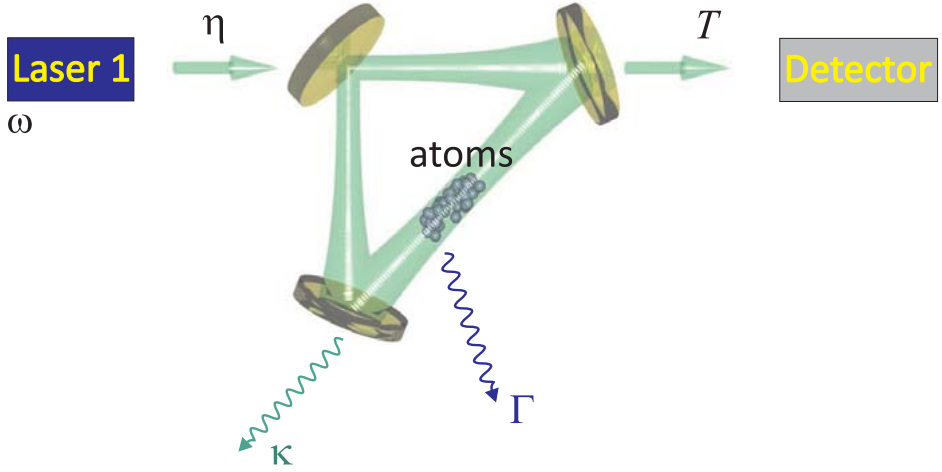
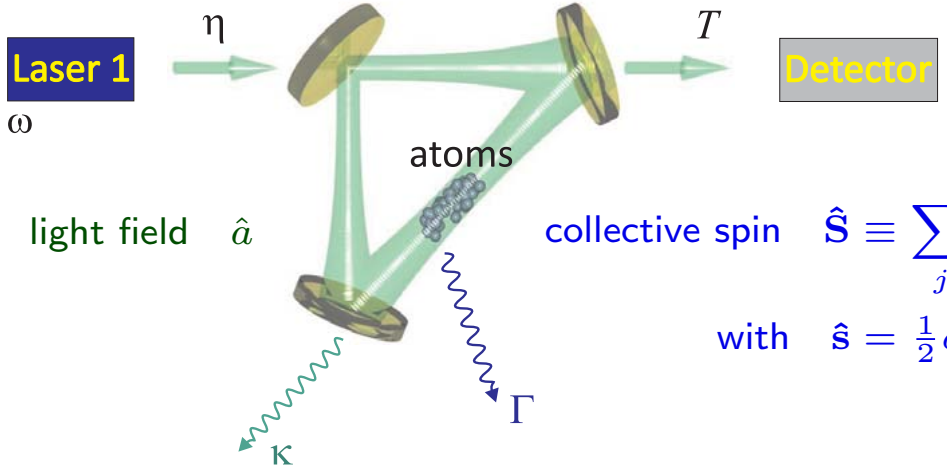
- fundamental uncertainty in the determination of clock parameters
- analogous to shot noise from photonic energy discretisation

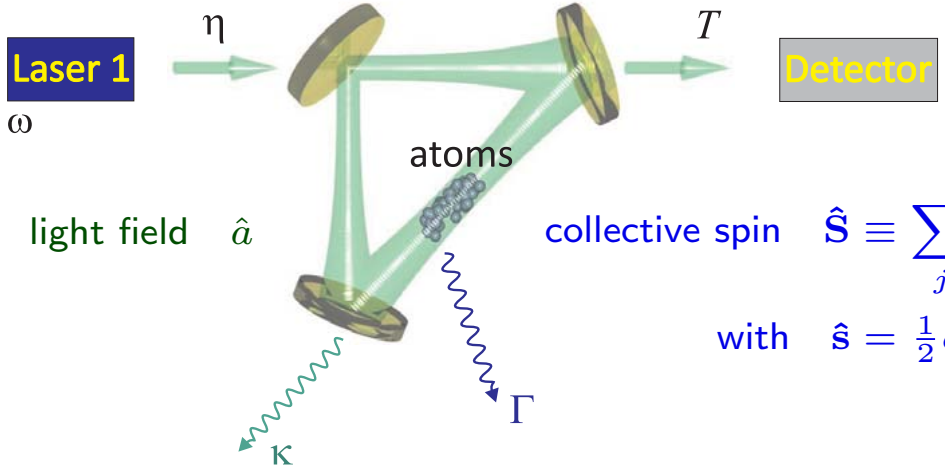
Dicke model



Dicke model


η
T
Laser 1
Detector
ω
atoms
light field $\hat{a}$
collective spin $\hat{\mathbf{S}} \equiv \sum_j \hat{\mathbf{s}}_j$
with $\hat{\mathbf{s}} = \frac{1}{2}\hat{\vec{\sigma}}$
Γ
κ

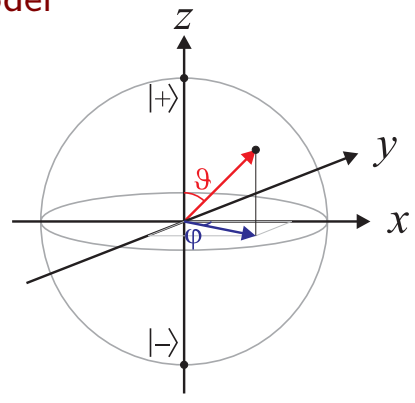
Dicke model

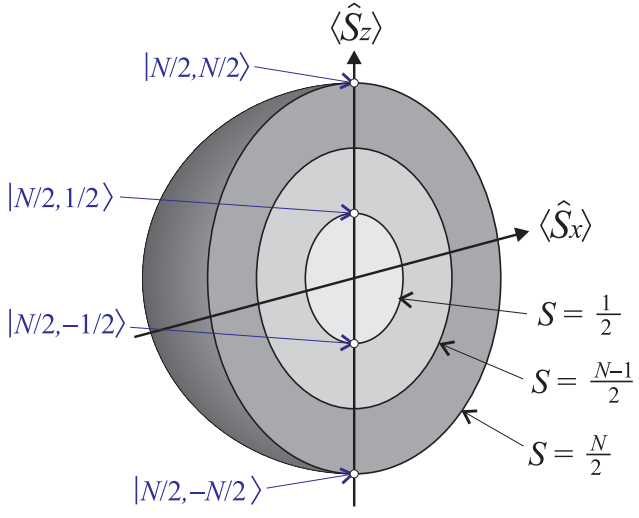


Atoms treated as non-interacting spins

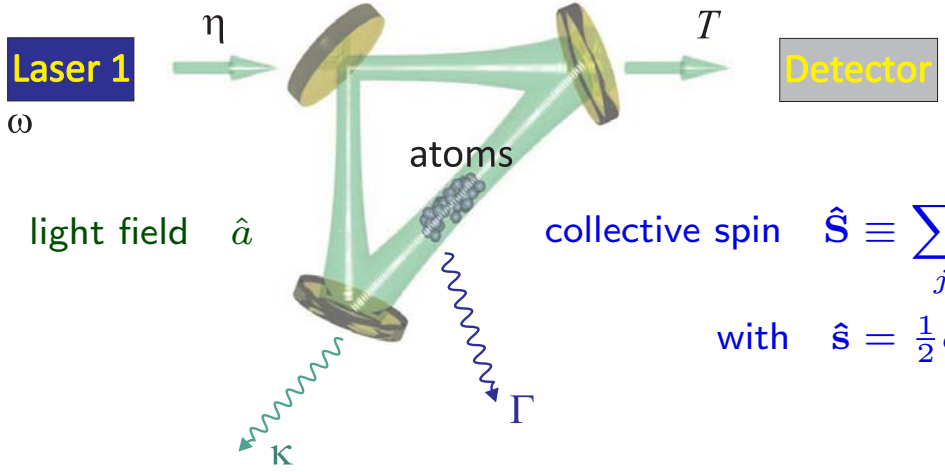
no near field terms, only radiative coupling

coupled spin description ⇒ Dicke model





Dicke model



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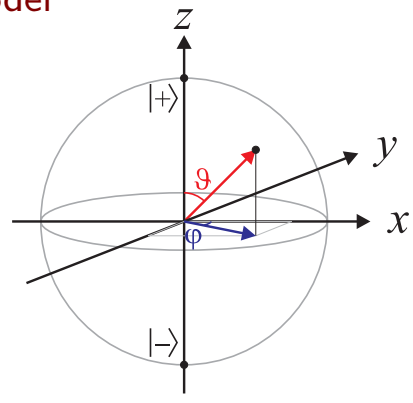
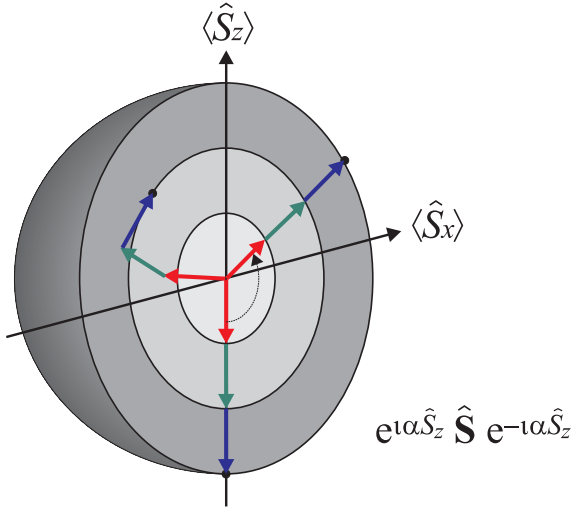
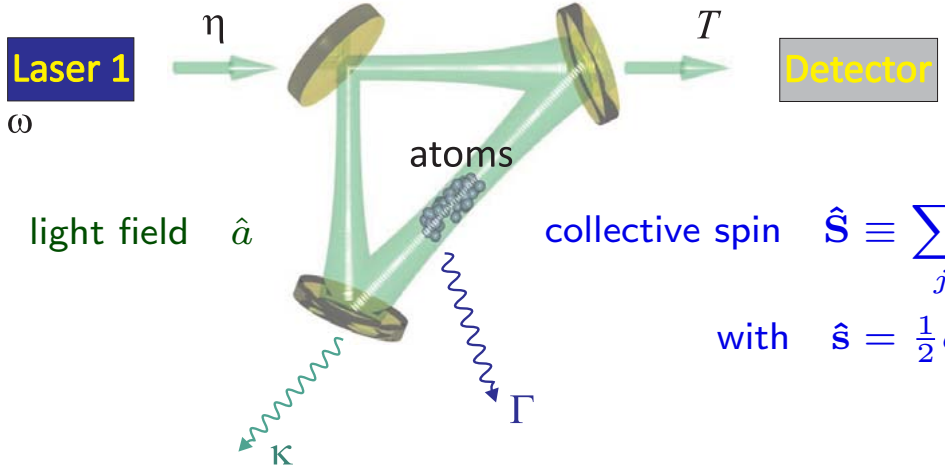




Terms linear in $\hat{S}_{x,y,z}$ only perform rotations: $e^{\imath\alpha\hat{S}_z}\ \hat{\mathbf{S}}\ e^{-\imath\alpha\hat{S}_z}$

⇒ a coherent spin state always remains a coherent spin state

Dicke model



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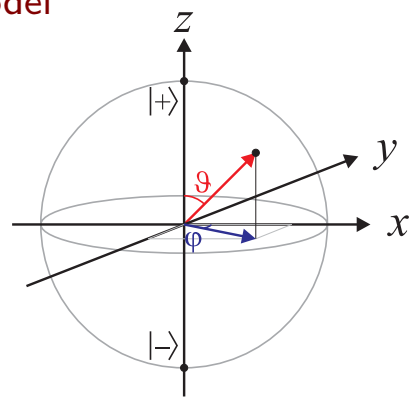
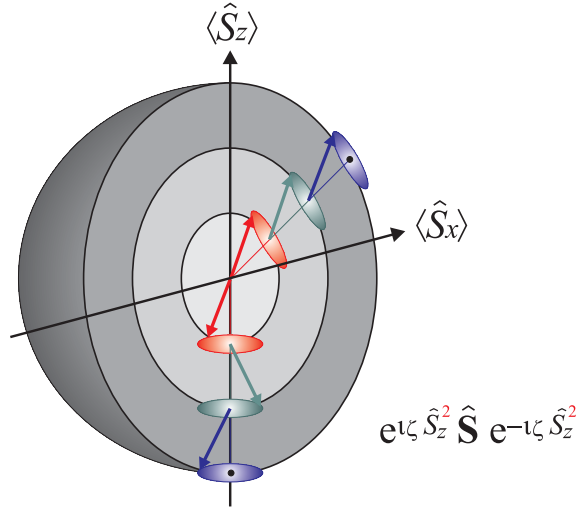




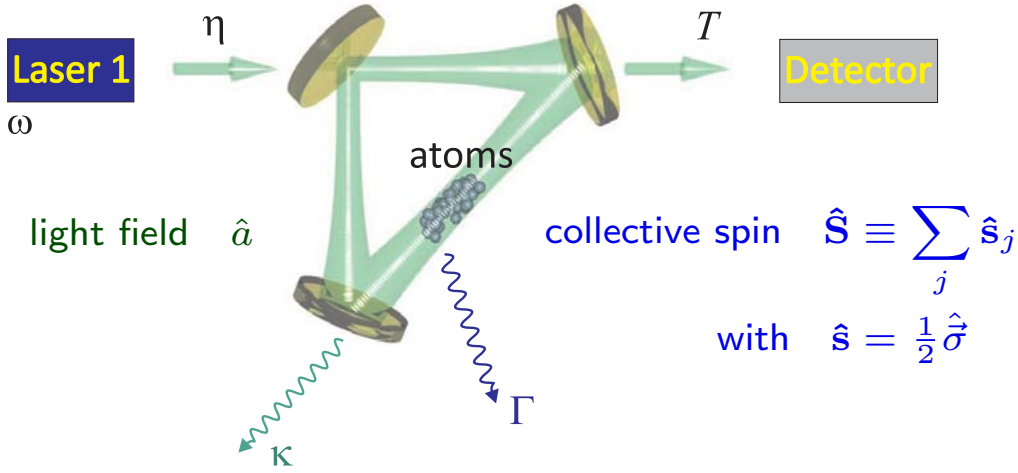
Terms linear in $\hat{S}_{x,y,z}$ only perform rotations: $e^{\imath\alpha\hat{S}_z}\ \hat{\mathbf{S}}\ e^{-\imath\alpha\hat{S}_z}$

⇒ a coherent spin state always remains a coherent spin state

⇒ 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)]

[Salvi, Poli, Vuletić, Tino, PRL 120, 033601 (2018)]

[Haonan Liu, Jäger, Touzard, Shankar, Holland, Nicholson, PRL **125**, 253602 (2020)]

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

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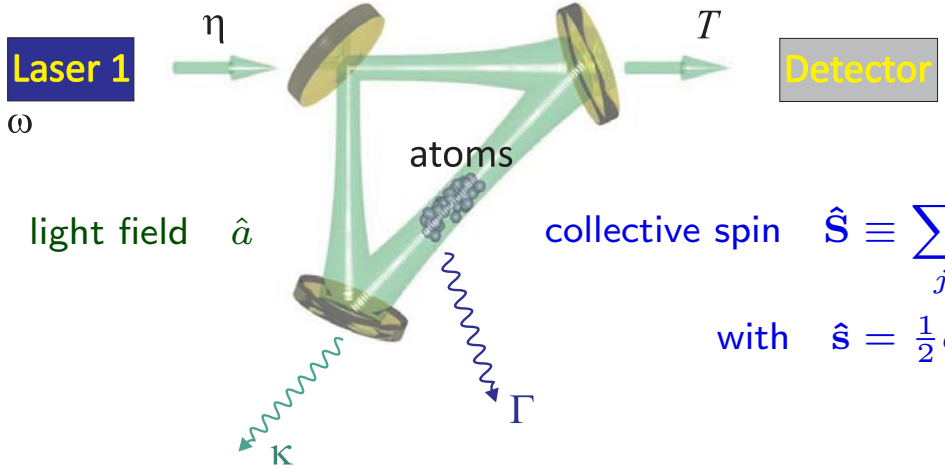

resonant Dicke model Hamiltonian $\hat{H} = -\imath\eta(\hat{a} - \hat{a}^\dagger) + g(\hat{S}_+\hat{a} + \hat{a}^\dagger\hat{S}_-)$

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

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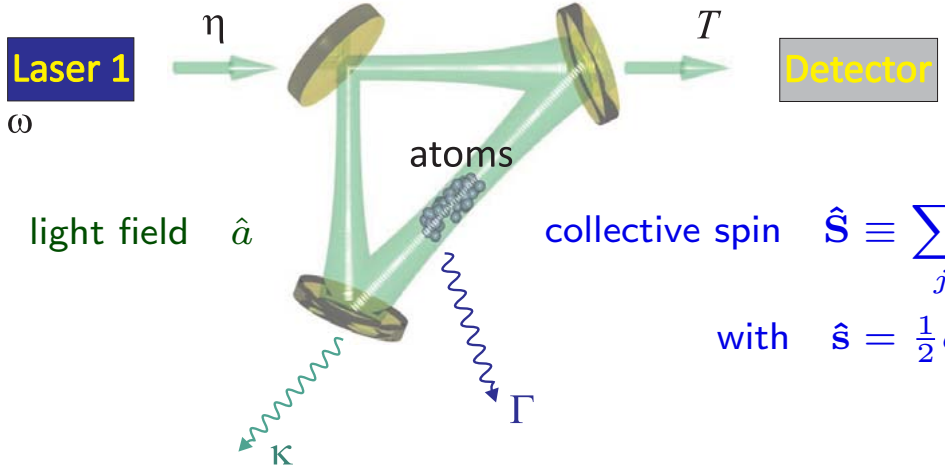

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Bad-cavity limit: $\kappa \gg \Gamma$ $\implies$ *adiabatic slaving of cavity dynamics* $\implies$ *eliminate* $\hat{a}$ *from Hamiltonian*

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

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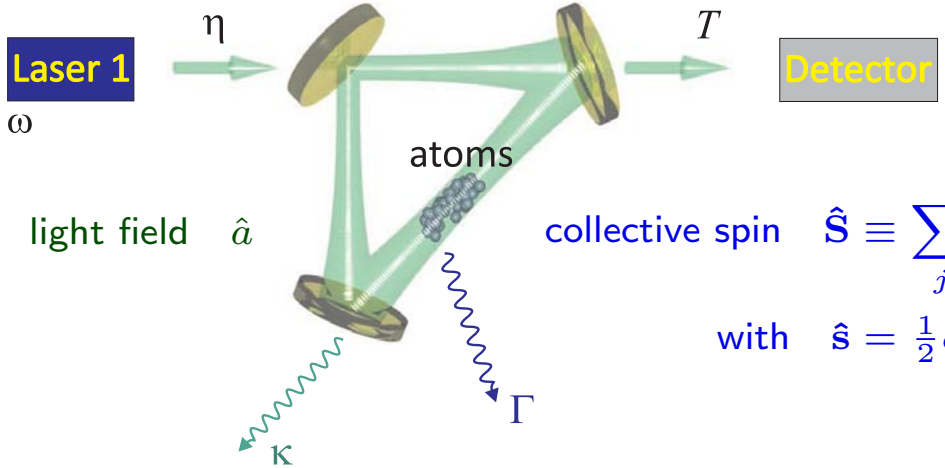

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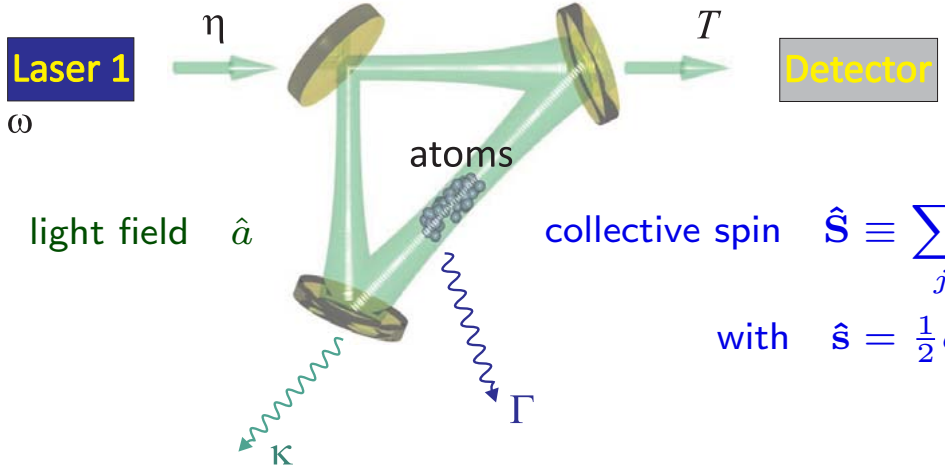

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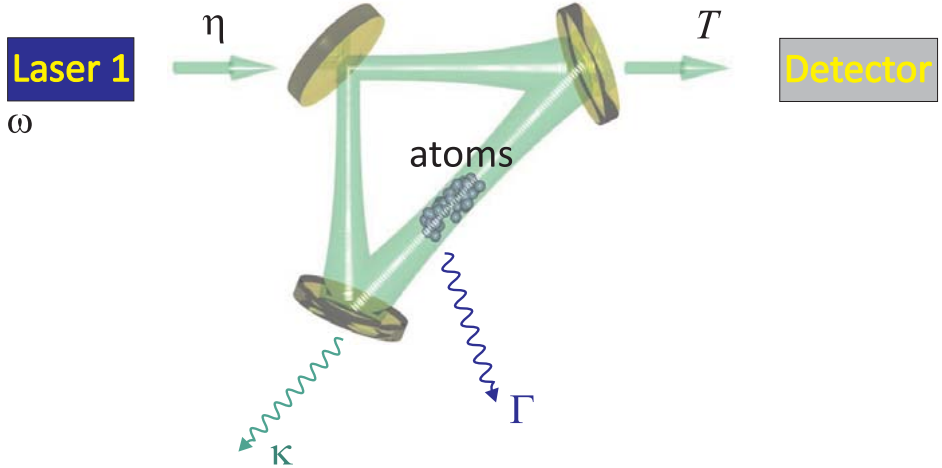
approximated Hamiltonian $\hat{H} \simeq U\ \hat{S}_+\hat{S}_- \quad \simeq U\ \hat{S}_z^2$

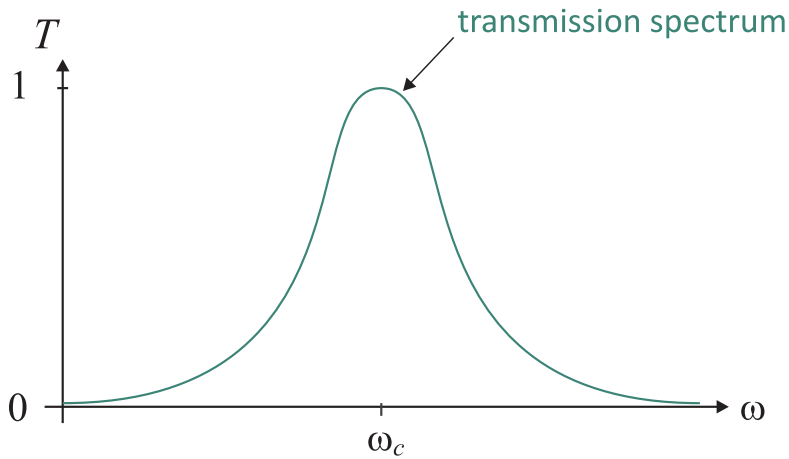
$\Longrightarrow$ non-linearity can generate entanglement

$\Longrightarrow$ 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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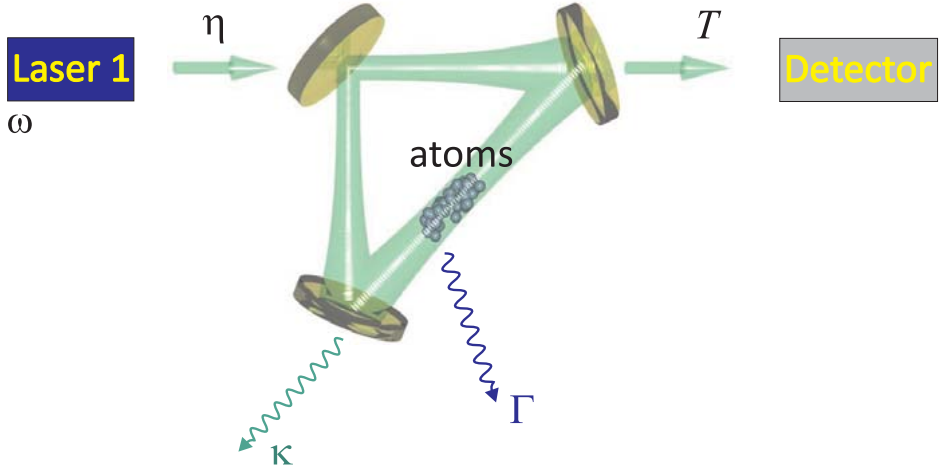
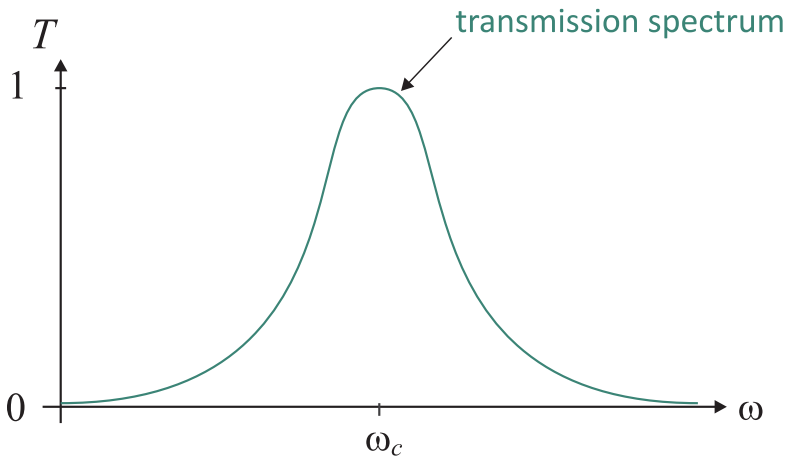


1) set up an experiment in the 'bad' cavity parameter regime ($\kappa \to \infty$)

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



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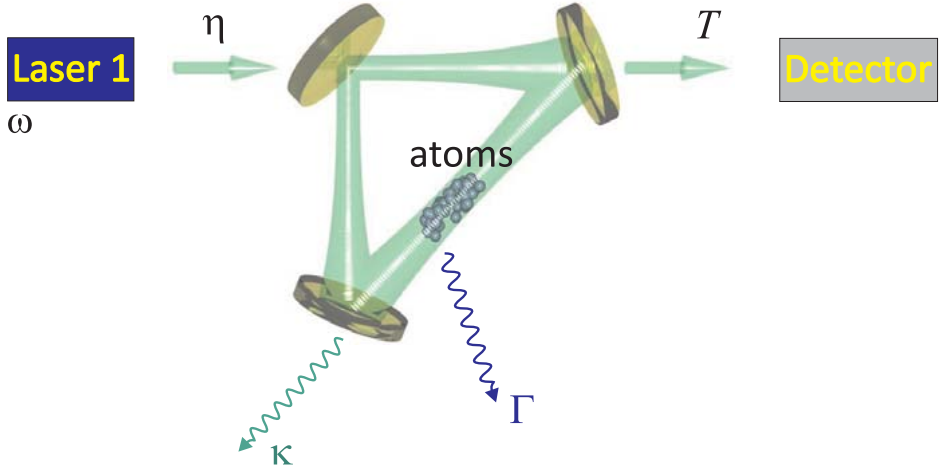
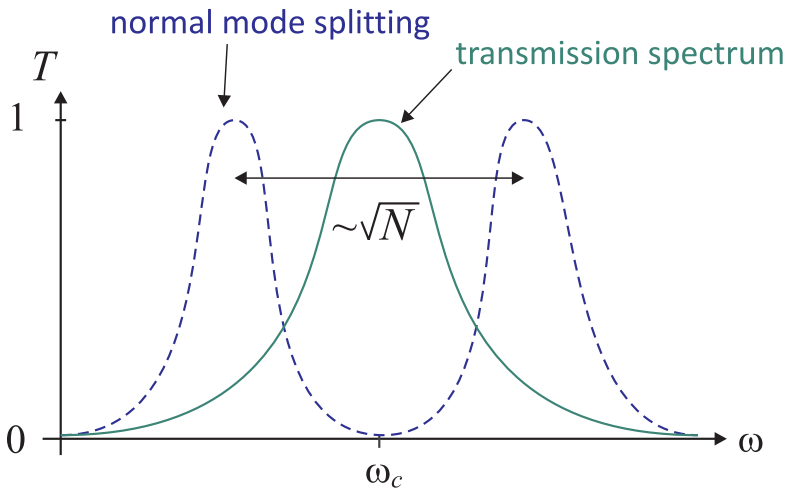


1) set up an experiment in the 'bad' cavity parameter regime ($\kappa \to \infty$)

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

3) put them into a 'bad' cavity and prove that they are interacting $\Longrightarrow$ check normal-mode spectra



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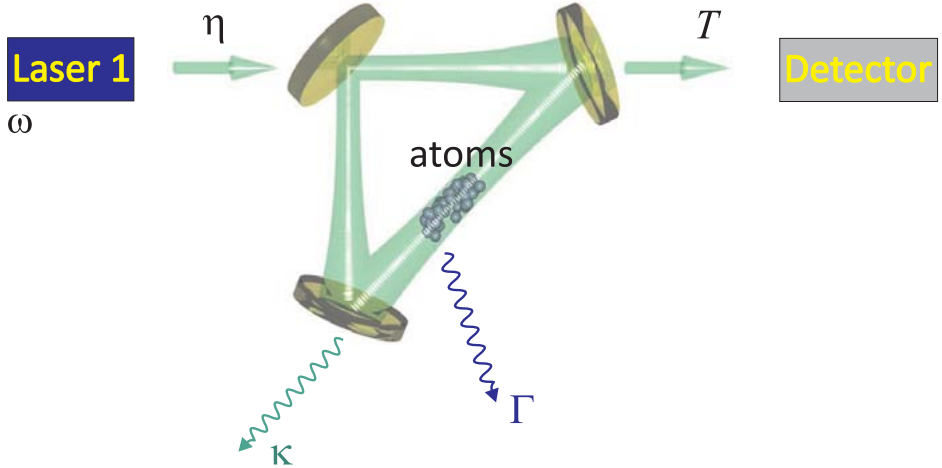

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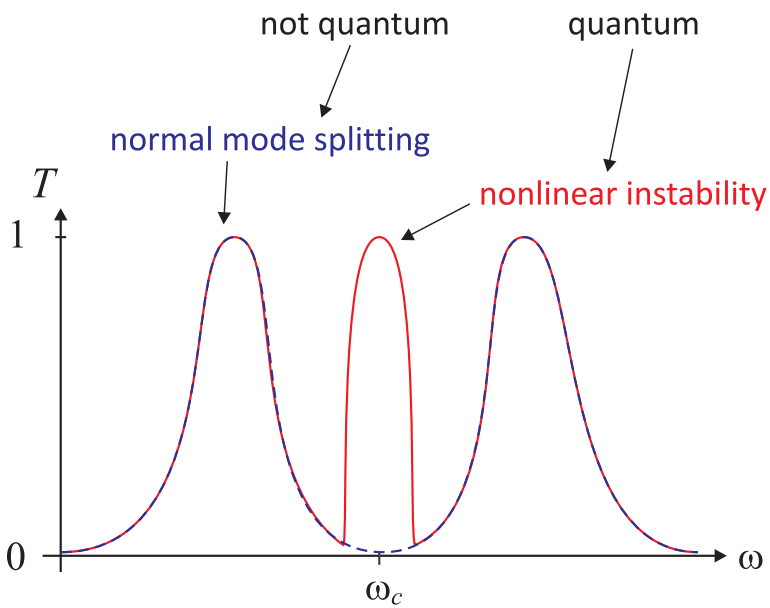
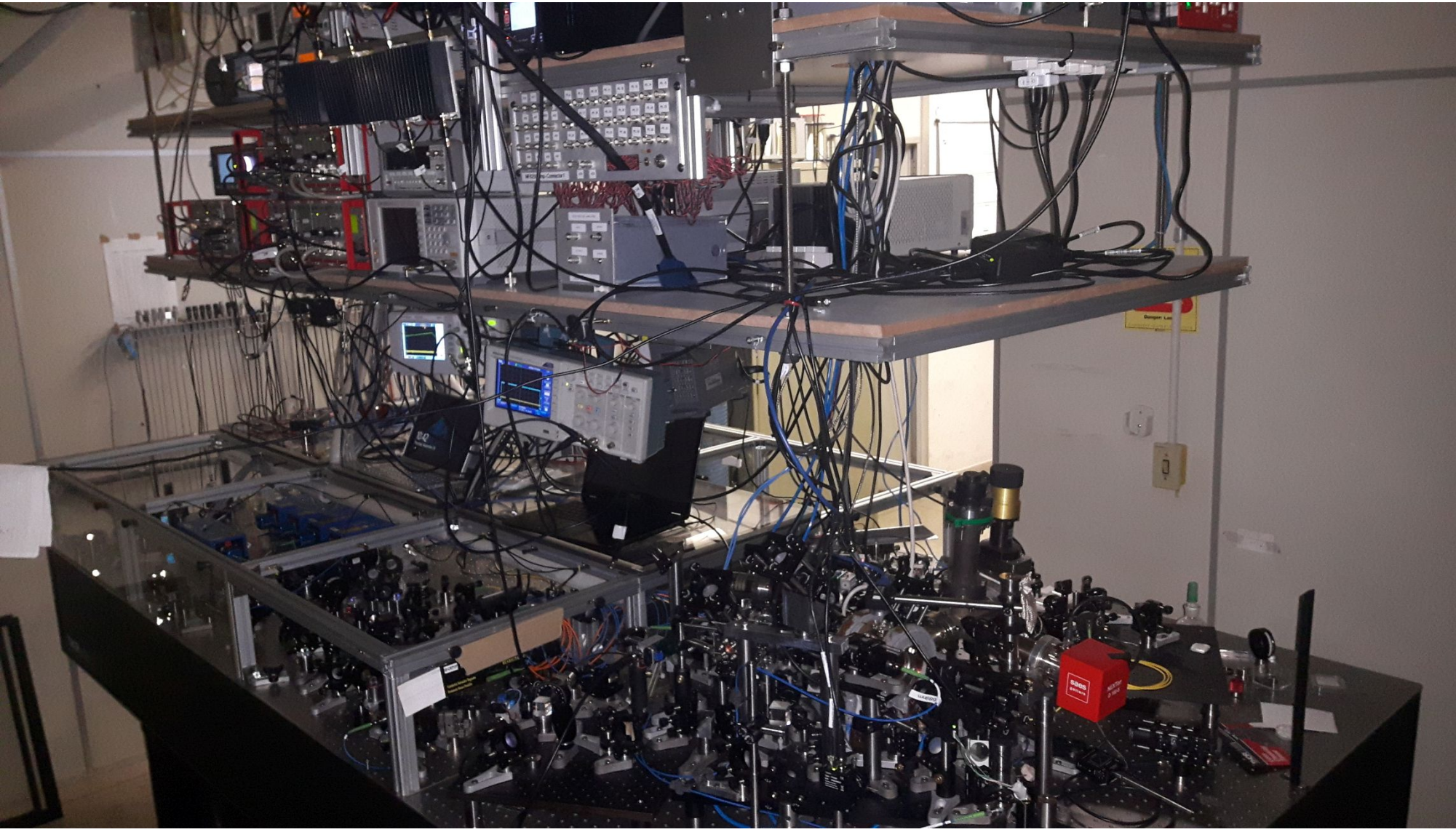
4) verify non-linearity 'on-resonance' ($\Delta_c = 0$)



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

The experiment



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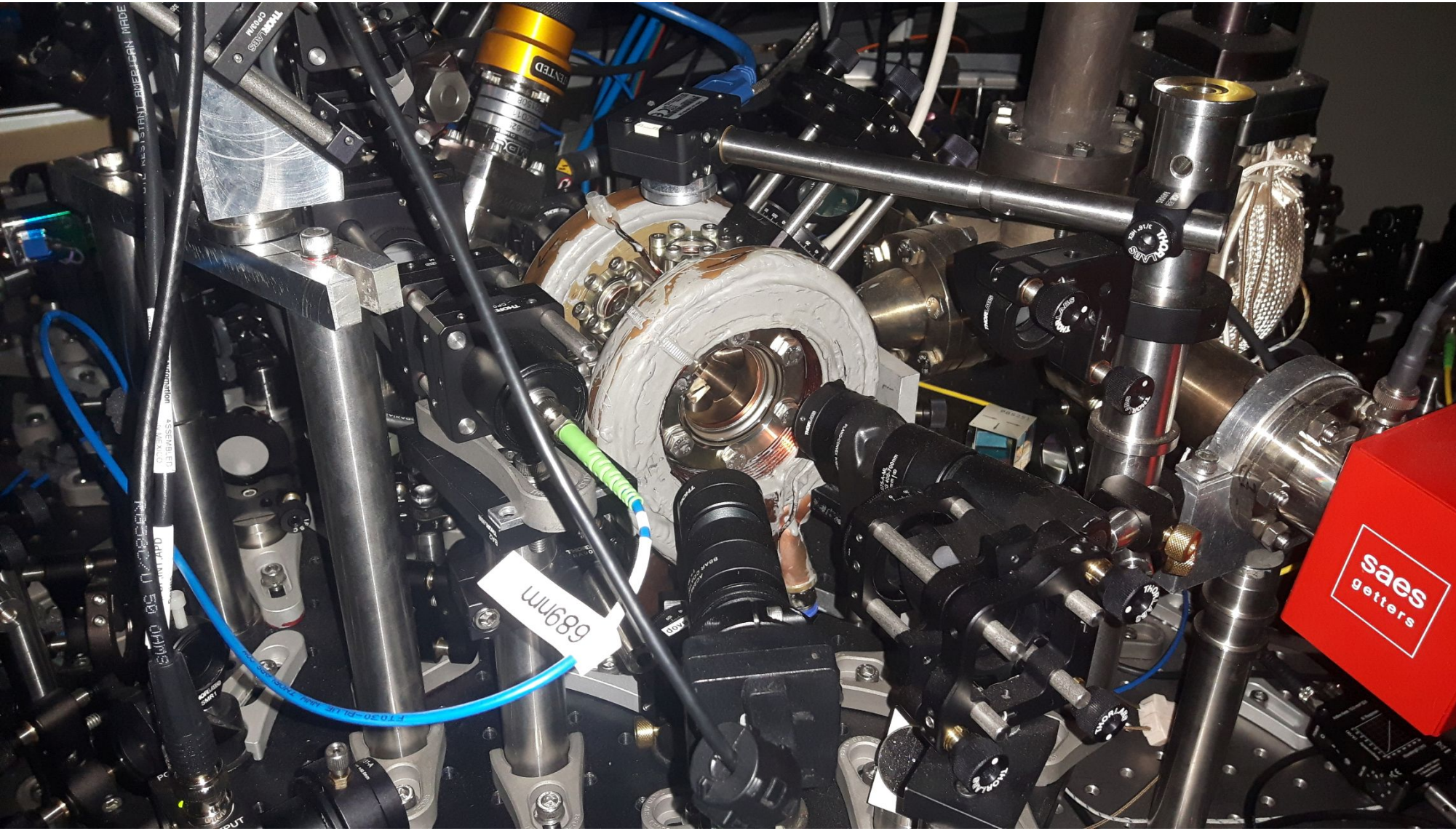
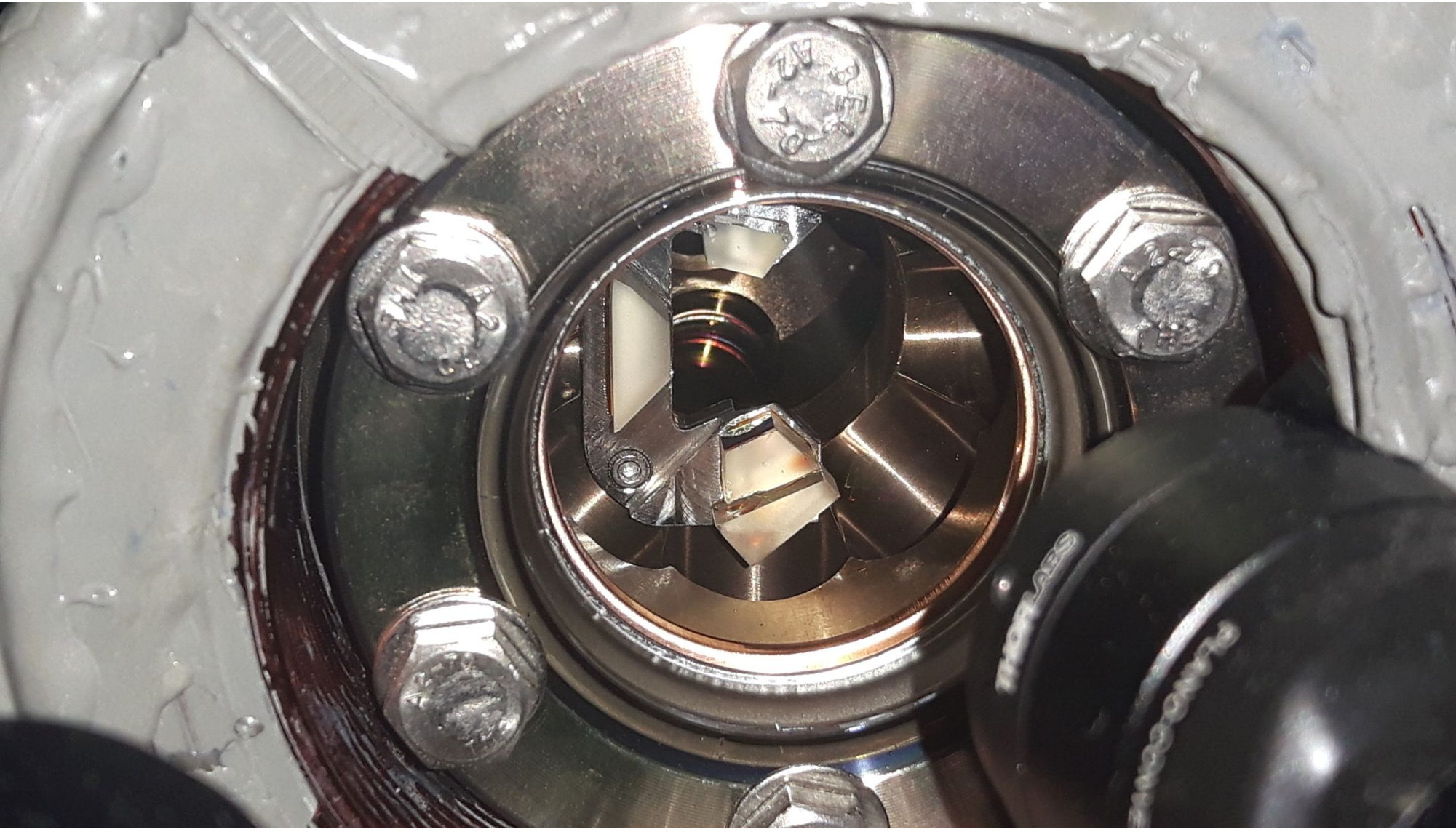


The experiment

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

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

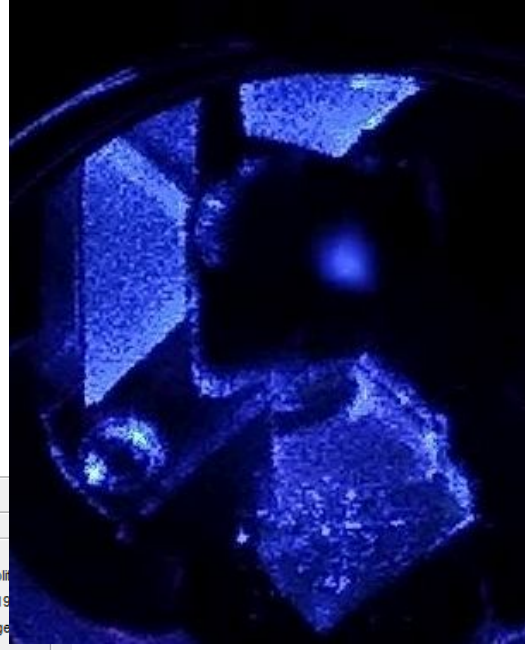


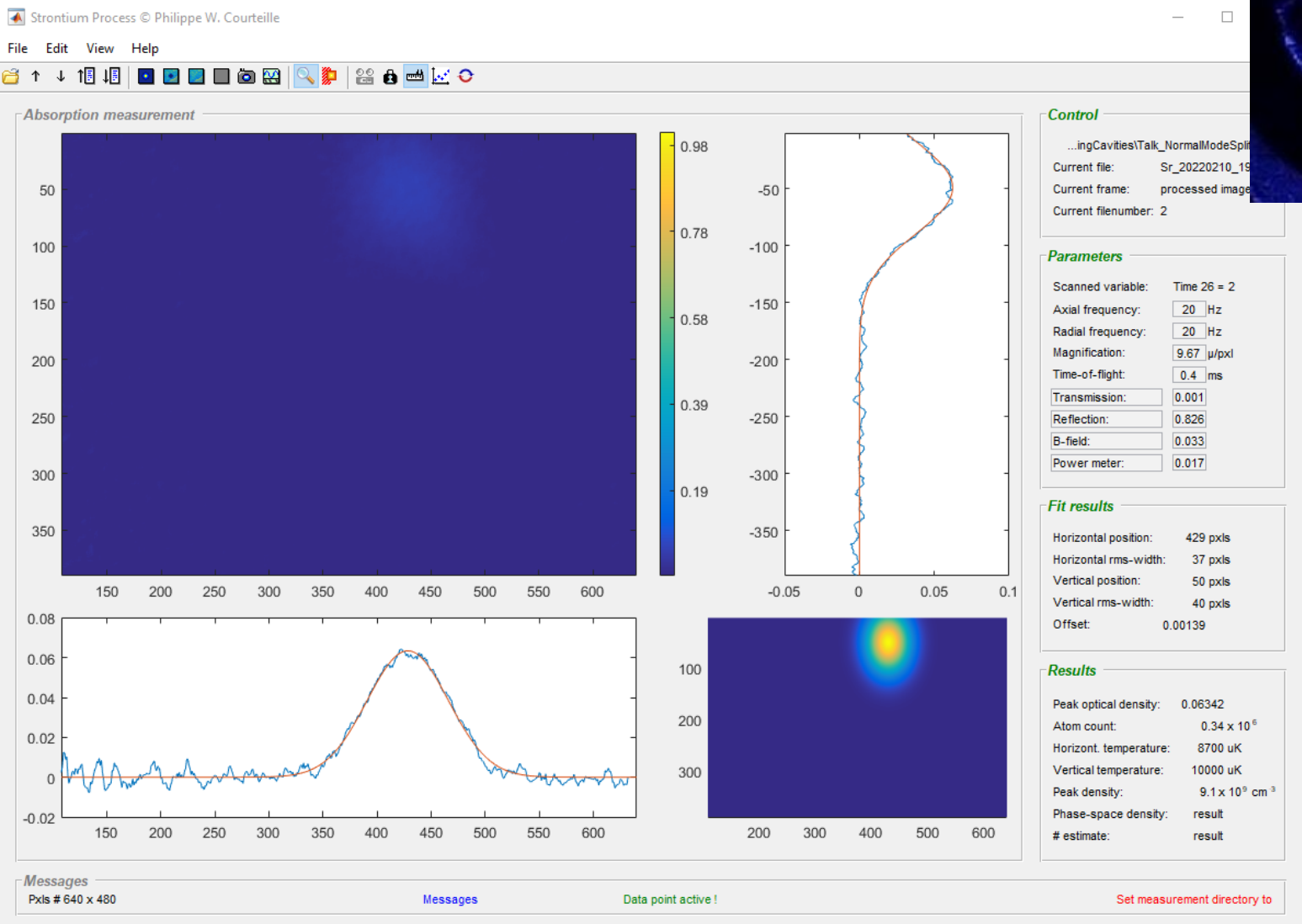
Experimental procedure & state of the art

experimental control

Experimental procedure & state of the art

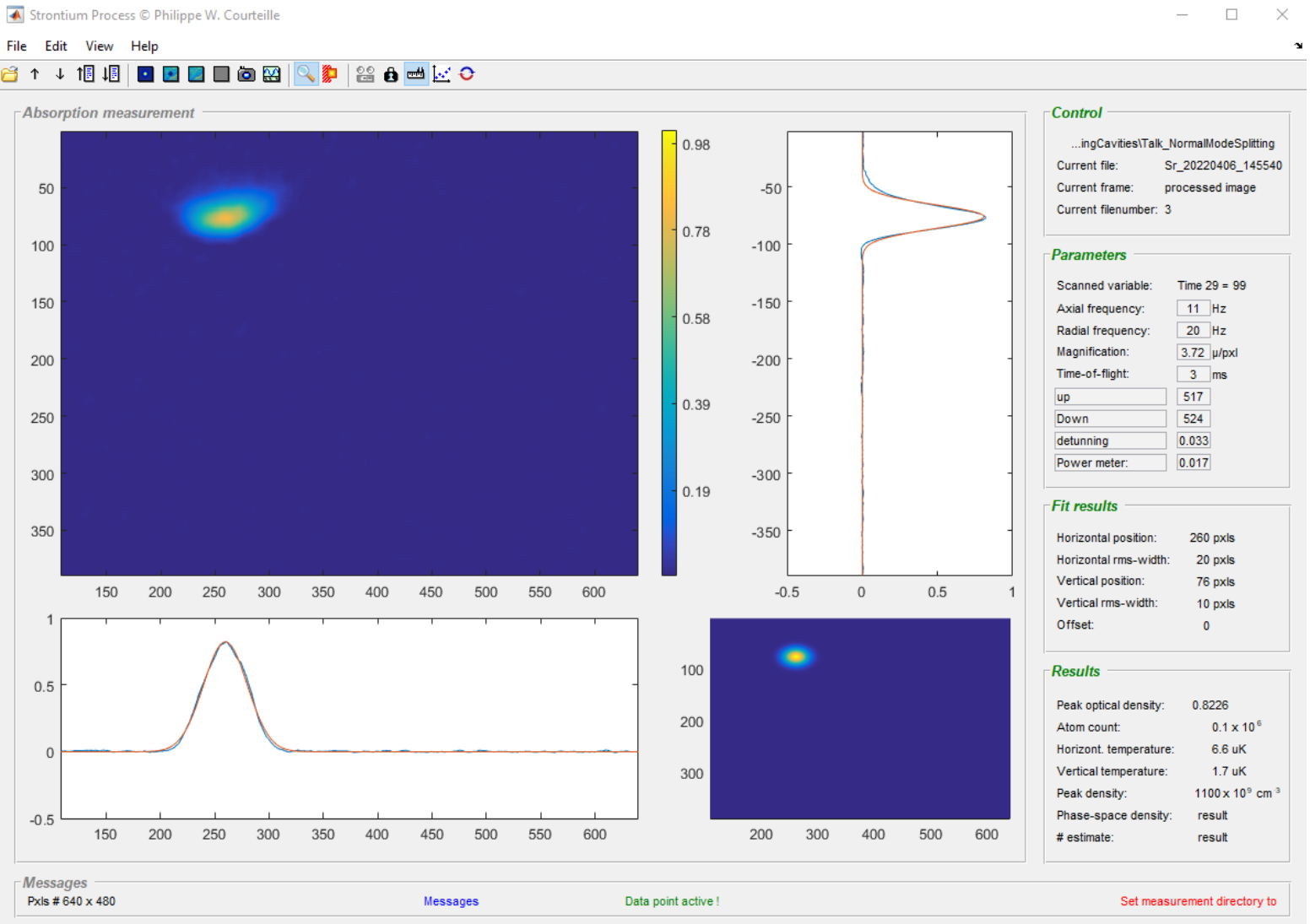
trapping atoms in the blue MOT: $N = 10^6$ $T = 5\,\mathrm{mK}$





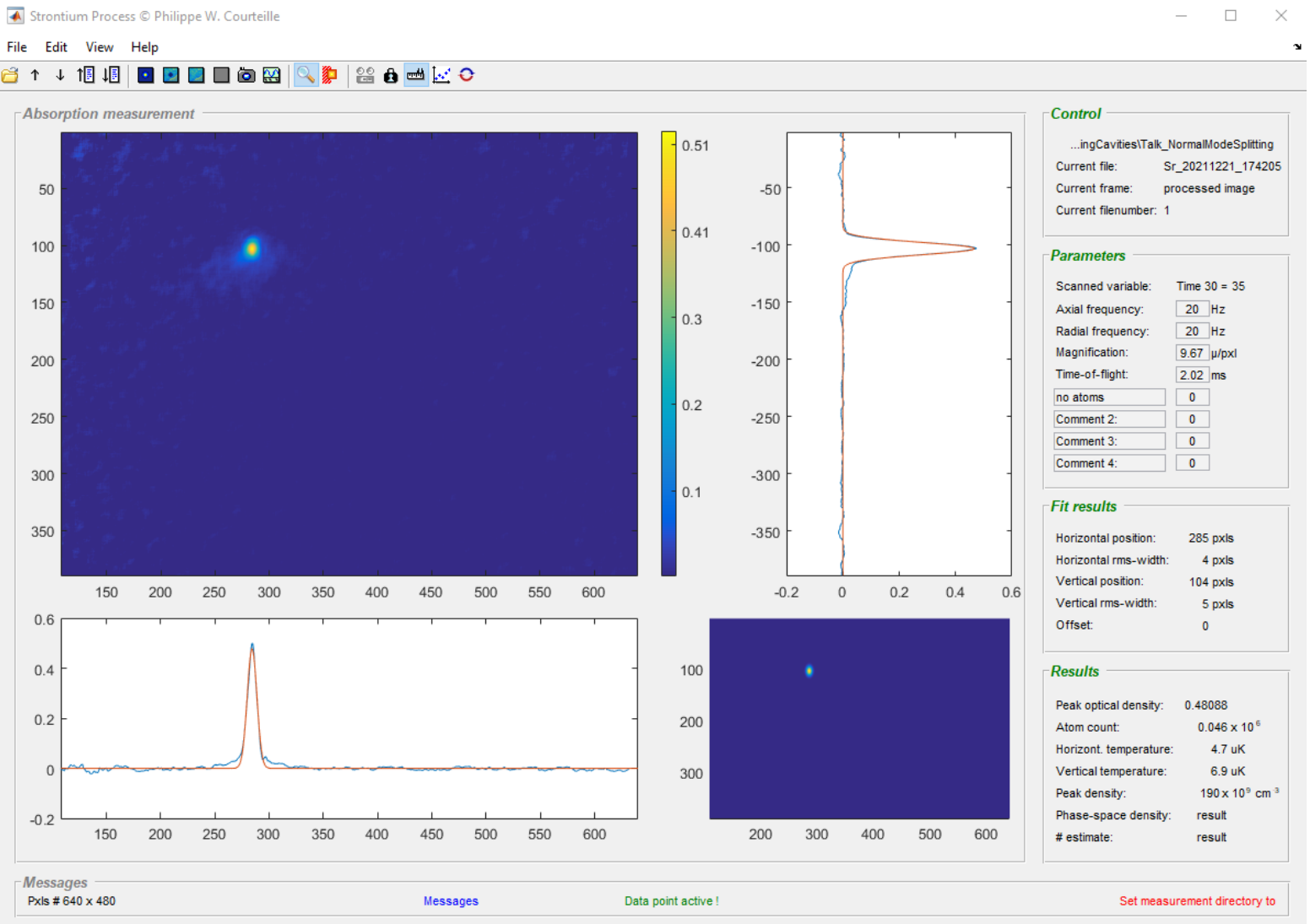
Experimental procedure & state of the art

cooling atoms in the red MOT



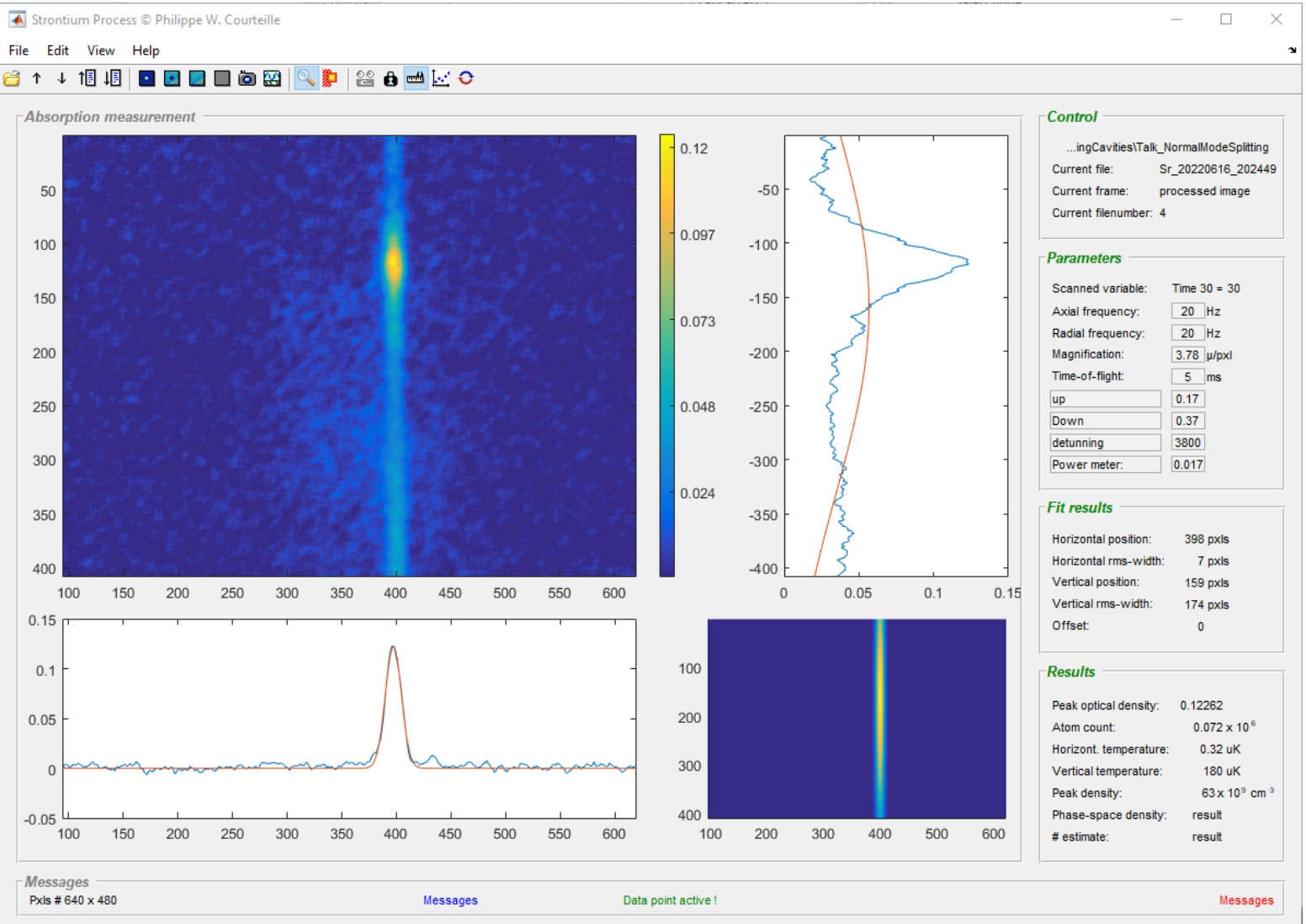
Experimental procedure & state of the art

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



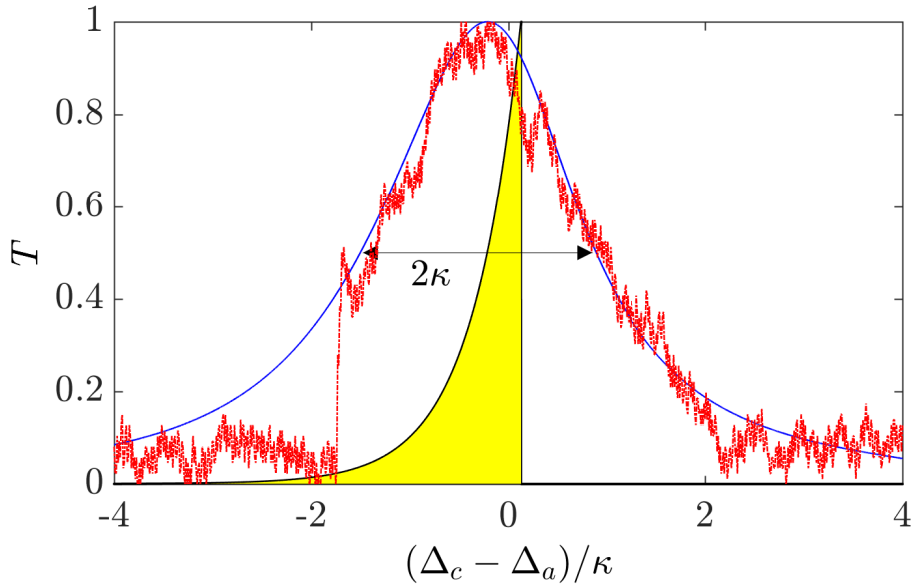
Experimental procedure & state of the art

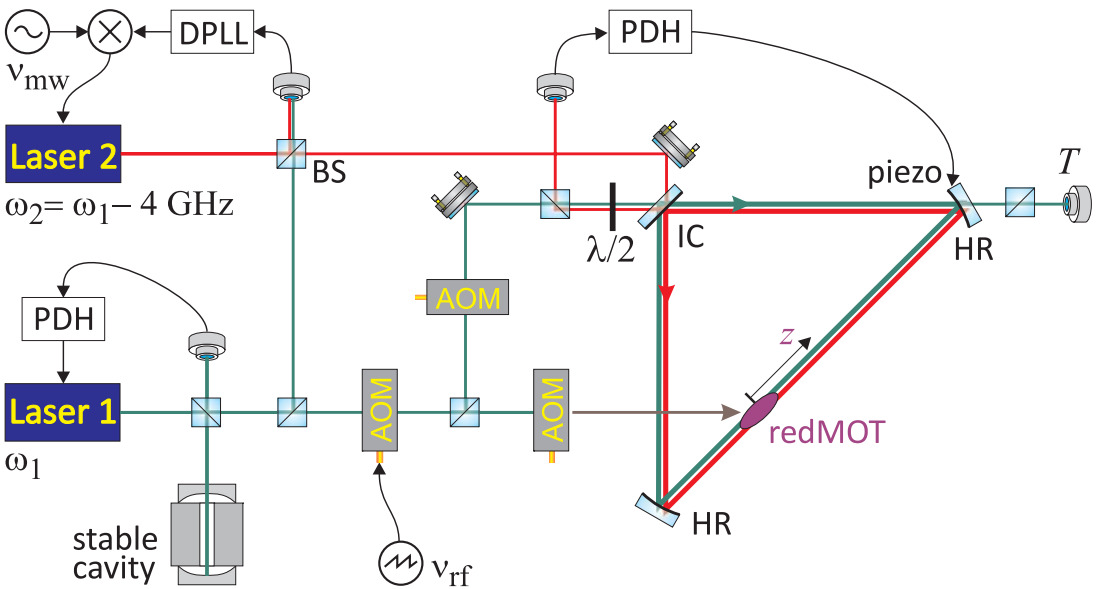
transferring atoms to the ring cavity mode via magnetic field ramp



Normal mode splitting

scanning laser frequency which pumps the cavity





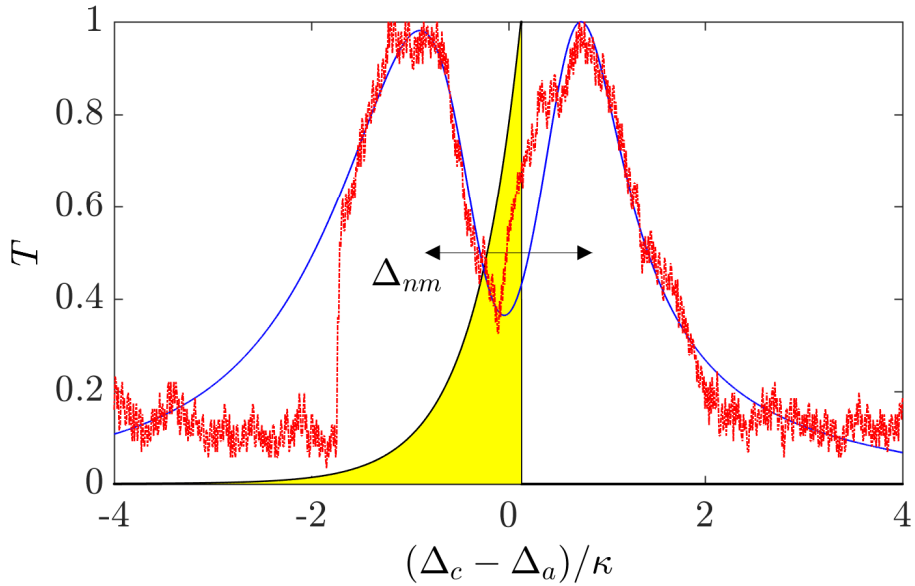
[Rivero, Beli, Armijo, da Silva, Kessler, Shiozaki, Teixeira, Courteille, Appl. Phys. B **128**, 44 (2022)]

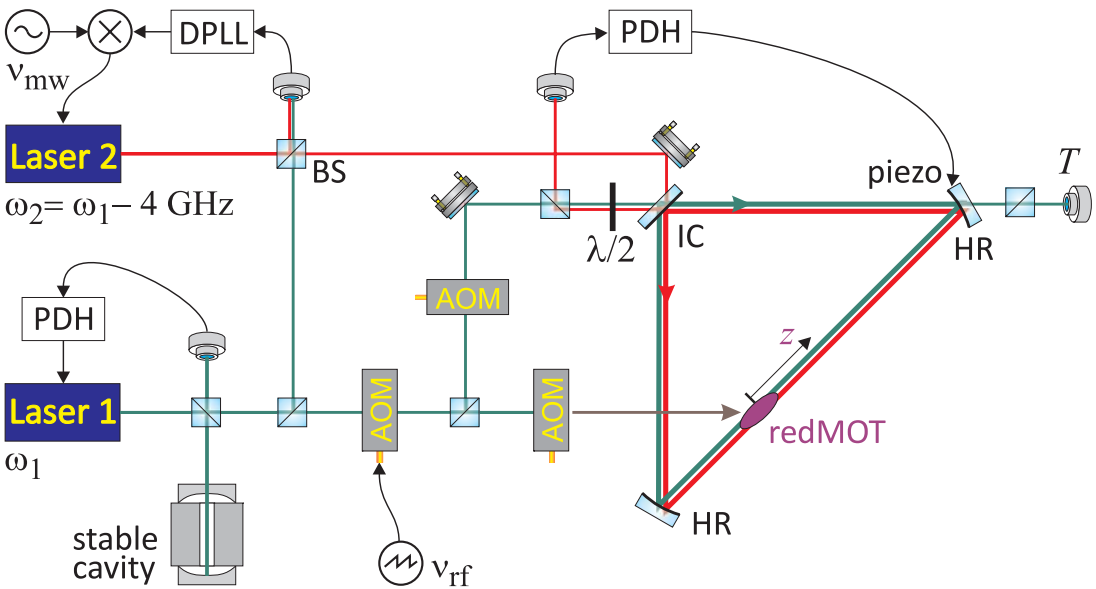
[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

Normal mode splitting

scanning laser frequency which pumps the cavity

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

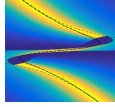




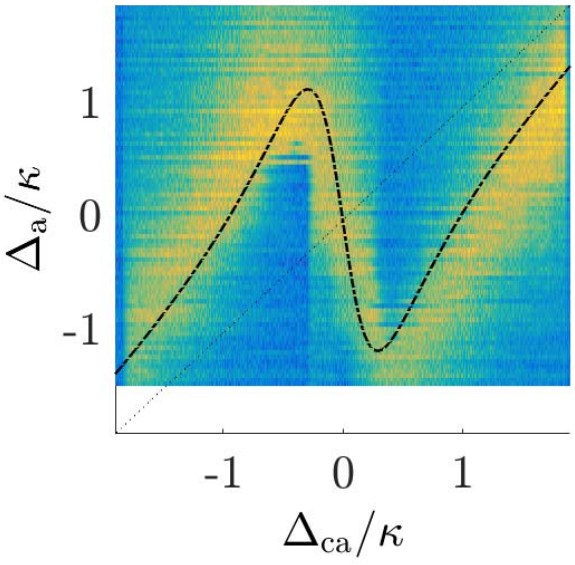
[Rivero, Beli, Armijo, da Silva, Kessler, Shiozaki, Teixeira, Courteille, Appl. Phys. B **128**, 44 (2022)]

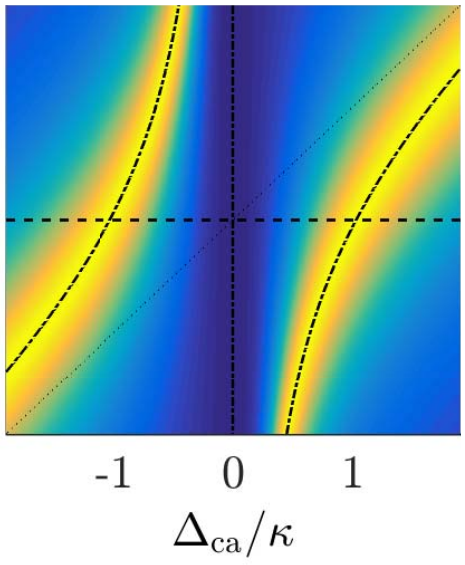
[Rivero, de França, Pessoa, Teixeira, Slama, Courteille, New J. Phys. **25**, 093053 (2023)]

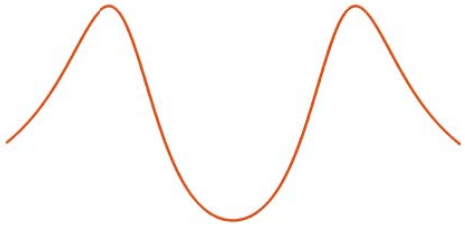
Normal mode splitting $\equiv$ 1D photonic band gap



avoided crossing $+$ instable feature





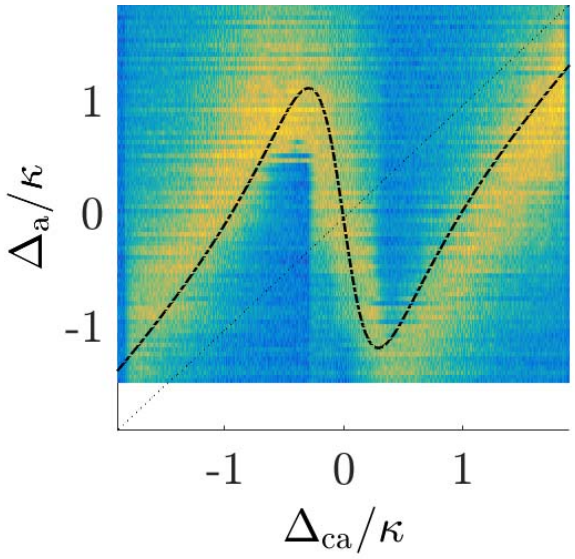


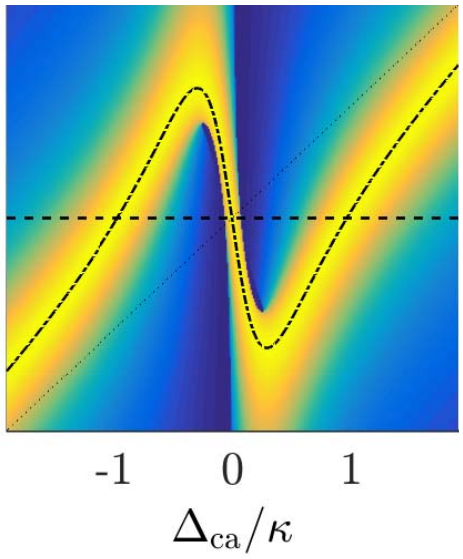
$$\Delta_{ca} \equiv \Delta_a - \Delta_c$$

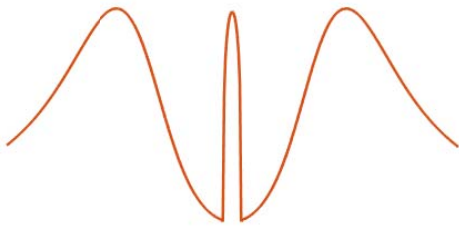
$$\Delta_c = \frac{N g^2 \Delta_a}{\Delta_a^2 + \Gamma^2/4}$$

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

avoided crossing $+$ instable feature







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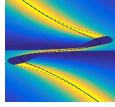

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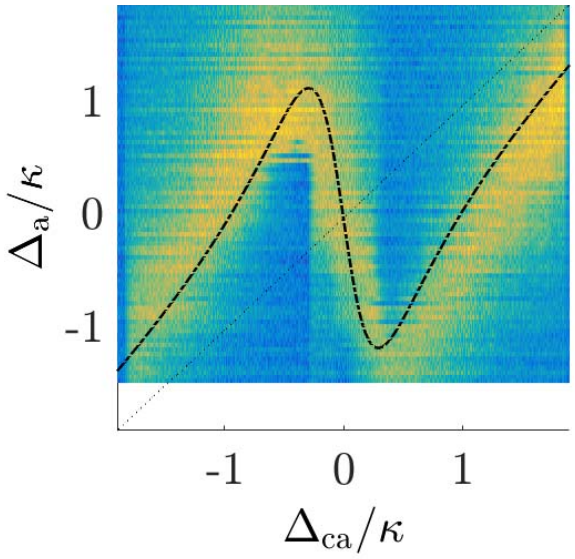

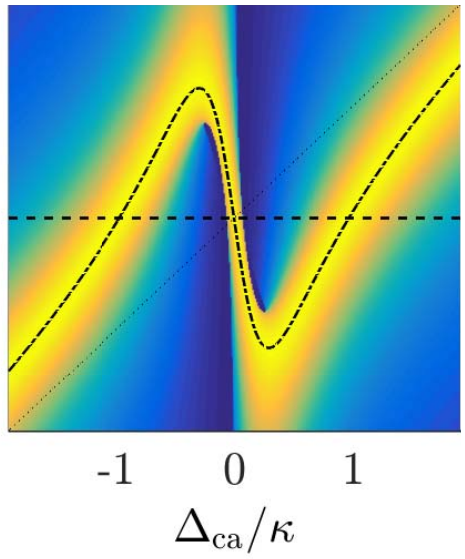

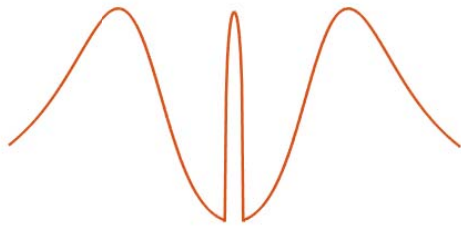

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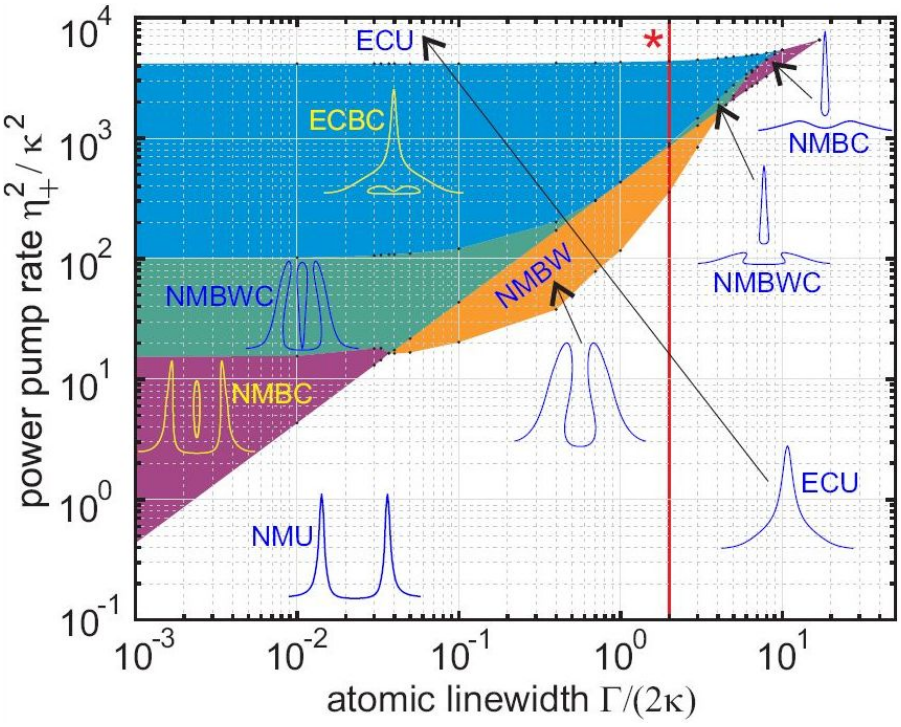
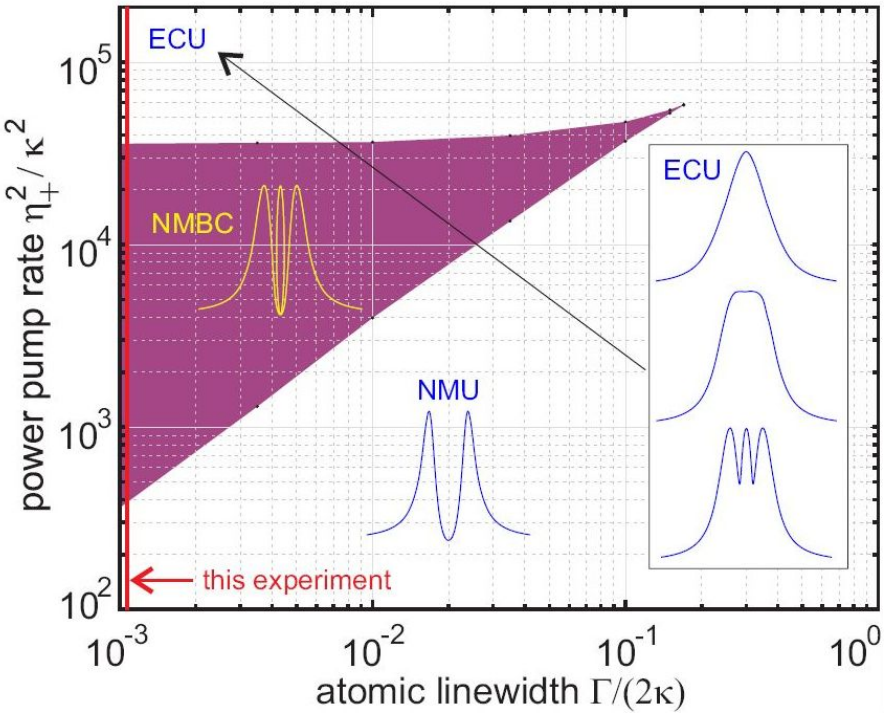
$$\Delta_c = \frac{N g^2 \Delta_a}{\Delta_a^2 + \Gamma^2/4 + \Omega_\eta^2/4}$$

adiabatic elimination only near $\Delta_a = 0$

Phase diagram





'good-cavity' limit: $\Gamma = 2\kappa$

$g_N = 12\kappa$

'bad-cavity' limit: $\Gamma = 0.0022\kappa$

$g_N = 1.2\kappa$

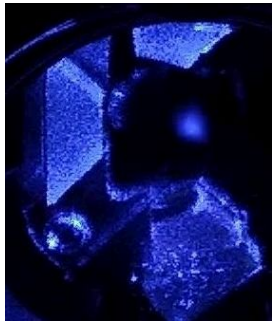
[Lambrecht, Courty, Giacobino, Opt. Commun. **115**, 199 (1995)]

[Gothe, Valenzuela, Cristiani, Eschner, PRA **99**, 013849 (2019)]

[Gripp, Mielke, Orozco, PRA **56**, 3262 (1997)]

[Rivero, de Franca, Pessoa, Teixeira, Slama, Courteille, arXiv2305.07133]

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)]

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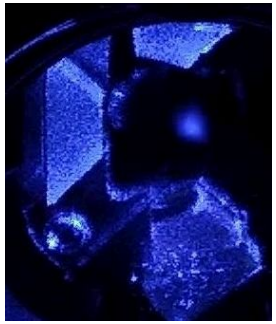

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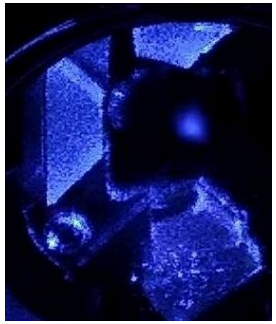

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non-linearity + quantumness $\Longrightarrow$ implementation of new ideas on squeezing or superradiant lasing?

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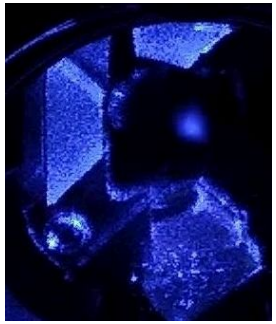

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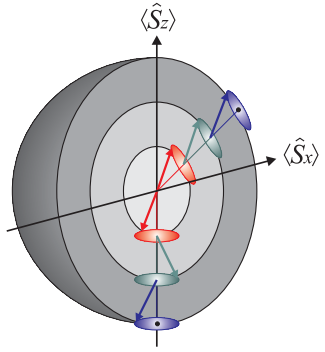
To do:

implement spin-squeezing sequences in Ramsey interferometry



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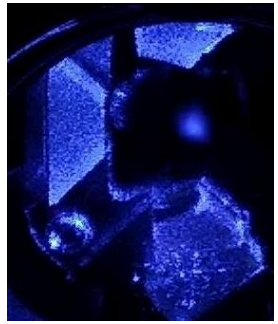

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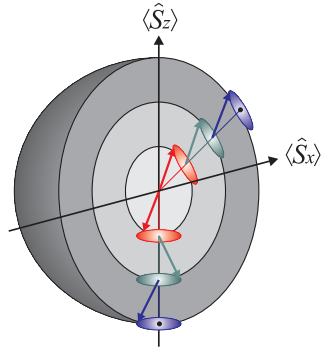
To do:

implement spin-squeezing sequences in Ramsey interferometry

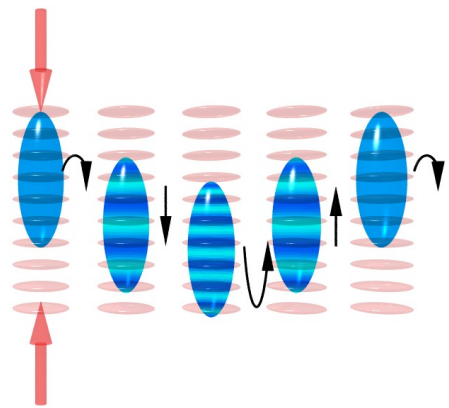
generate inversion $> 50\%$ (e.g. via optical pumping) for light amplification



[Meiser et al., PRL **102**, 163601 (2009)]
[Debnath, Zhang, Mølmer, PRA **98**, 063837 (2018)]

Matter wave Bloch oscillations

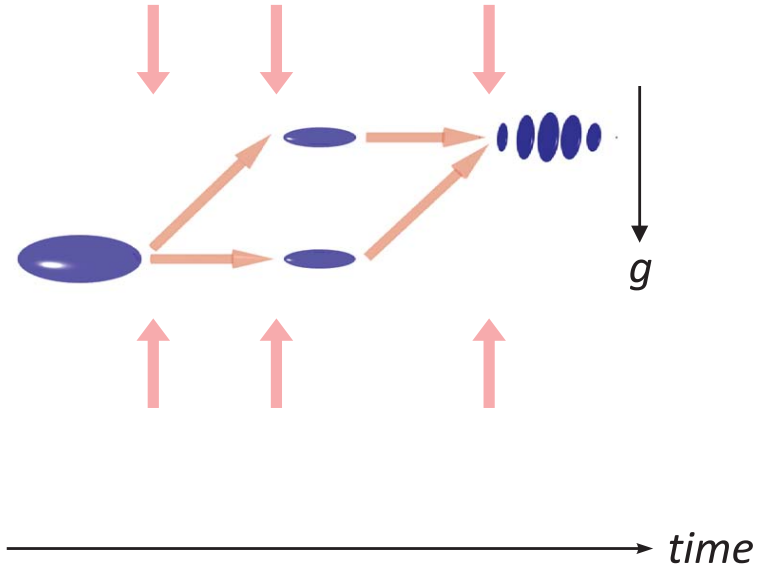
for inertial sensing



Gravimetry with Bose-Einstein condensates

differential phase shift of de Broglie waves

$\longrightarrow$ matter wave interferometers



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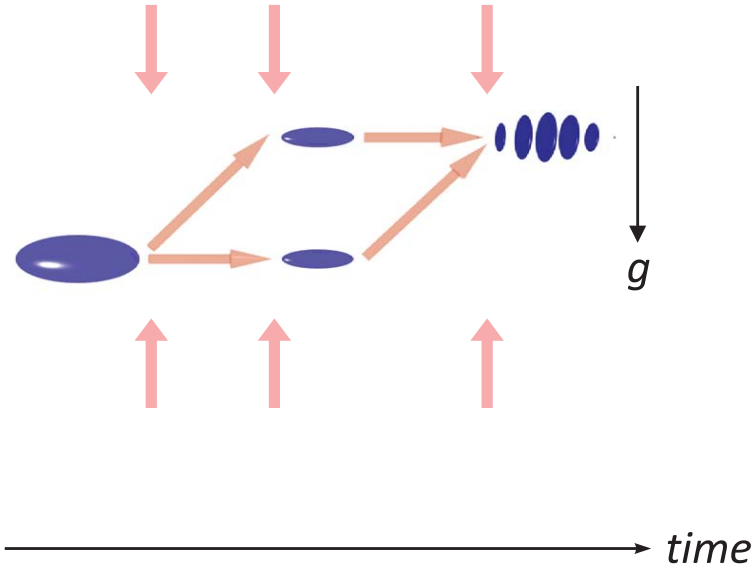
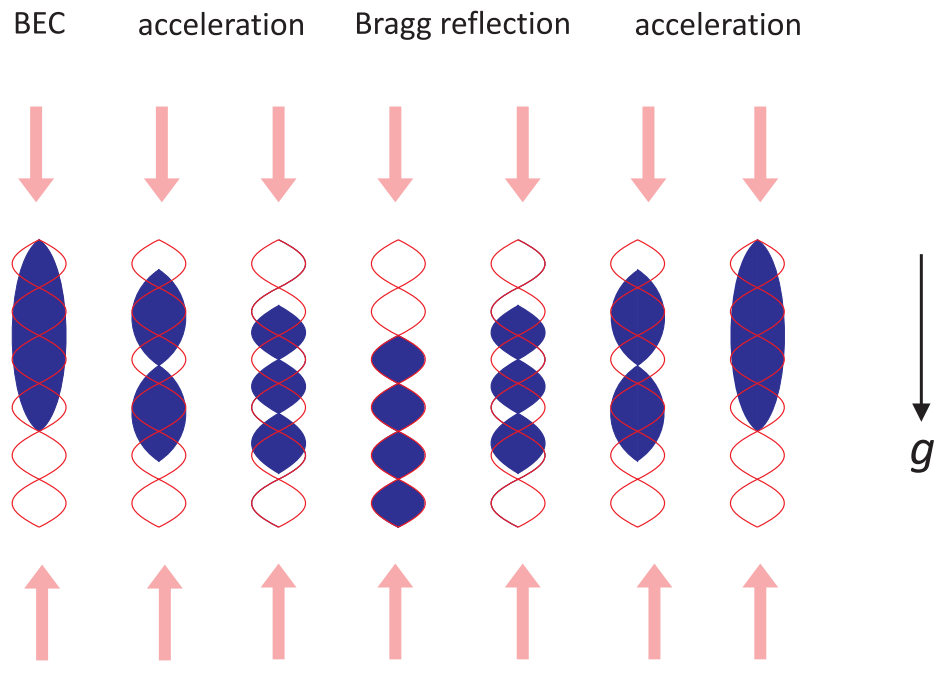


matter wave Bloch oscillations in a periodic potential

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



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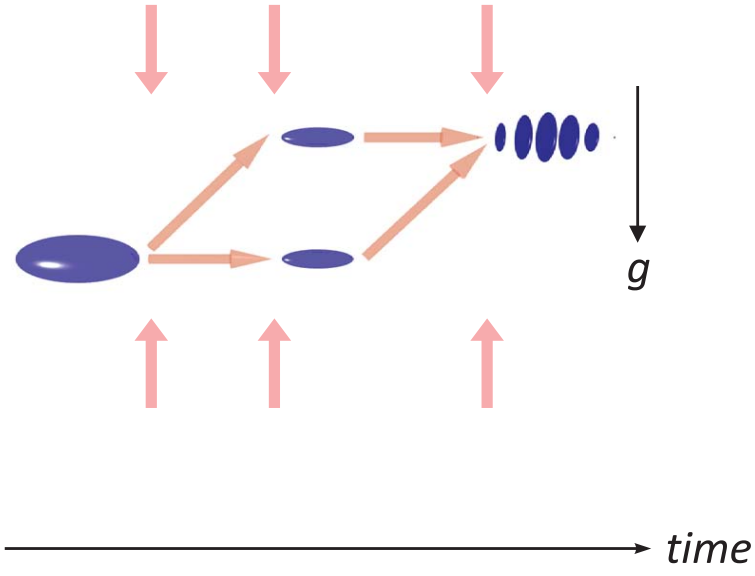
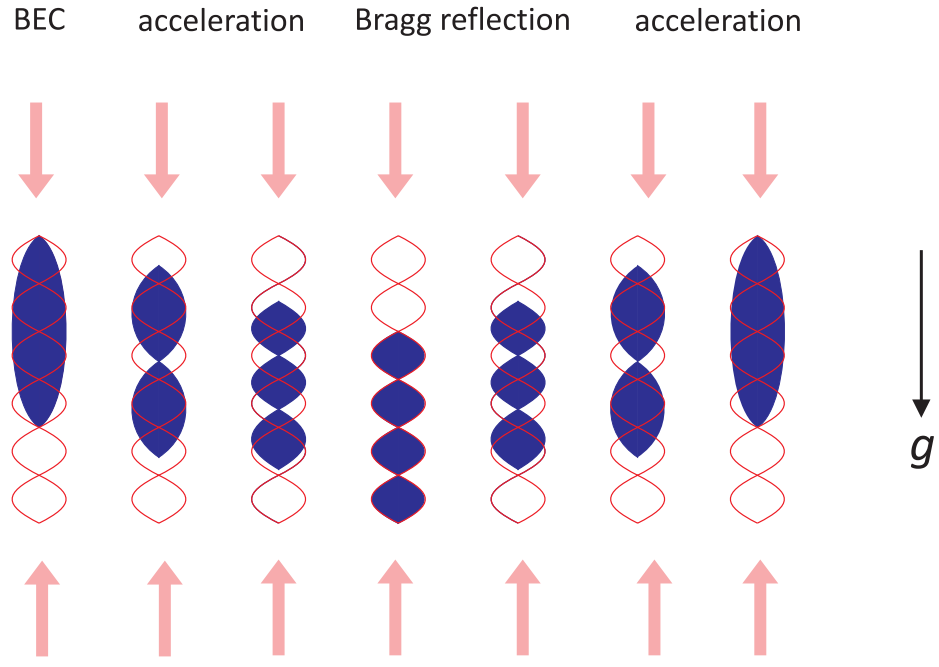


matter wave Bloch oscillations in a periodic potential

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

$\longrightarrow$ measure gravity g



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

Brazilian gravimeter

República Federativa do Brasil
Ministério da Indústria, Comércio Exterior
e Serviços
Instituto Nacional da Propriedade Industrial

(21) BR 102015007944-3 A2

(22) Data do Depósito: 09/04/2015

(43) Data da Publicação: 07/11/2017

(54) Título: DISPOSITIVO E MÉTODO PARA MEDIDA DA ACELERAÇÃO GRAVITACIONAL

(51) Int. Cl.: G01V 7/00

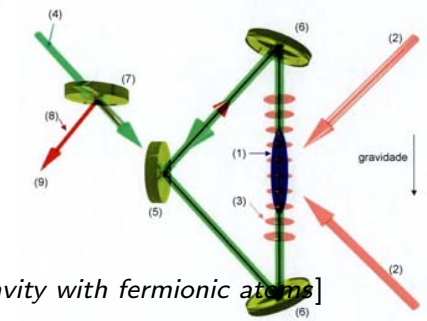
(52) CPC: G01V 7/00

(73) Titular(es): UNIVERSIDADE DE SÃO PAULO - USP

(72) Inventor(es): PHILIPPE WILHELM COURTEILLE; ROMAIN PIERRE MARCEL BACHELARD

(74) Procurador(es): MARIA APARECIDA DE SOUZA

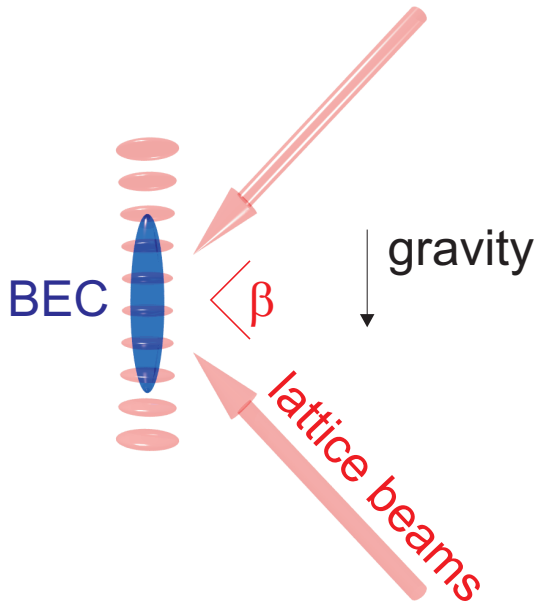
(57) Resumo: DISPOSITIVO E MÉTODO PARA MEDIDA DA ACELERAÇÃO GRAVITACIONAL. A presente invenção refere-se a dispositivo e método, em especial a um gravímetro baseado em interferometria atômica, no qual os átomos são resfriados até uma temperatura em que formam uma onda de matéria coerente e depois são transferidos dentro de uma onda estacionária vertical de luz quase-ressonante com uma transição atômica. Os átomos são colocados dentro de uma cavidade óptica anular (23) bombeada em uma direção por um feixe laser (18) e executam oscilações de Bloch, cuja frequência é estritamente proporcional à aceleração gravitacional. O método compreende as etapas de: a) Preparar um feixe de átomos frios; b) Capturar este feixe atômico por uma armadilha magneto-óptica operada numa transição atômica larga e resfriá-lo para temperaturas em torno de 5 mK; c) Resfriar os átomos ainda mais por uma armadilha magneto-óptica operada numa transição atômica fina para temperaturas em torno de 300 nK; d) Transferir a onda de matéria para onda estacionária de luz; e) Incitar os átomos a executar oscilações de Bloch devido à aceleração gravitacional; f) Injetar um las(...)



[Inguscio et al., WO 2005 076042A1 (2005), *Apparatus and method for the measurement of the acceleration of gravity with fermionic atoms*]

[Courteille et al., BR 10 2015 007944-3 (2015), *Device and method for gravitational acceleration measurement*]

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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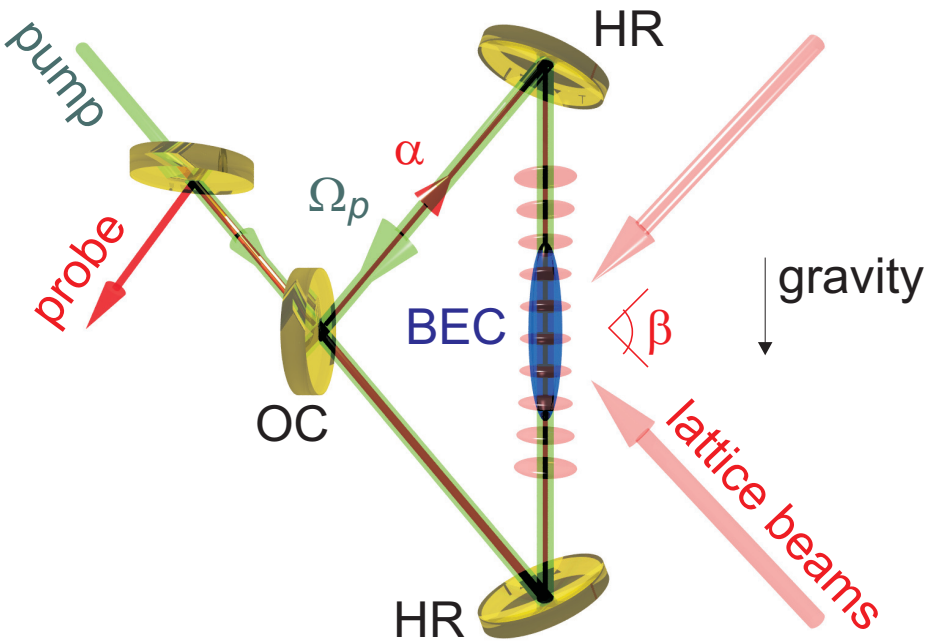

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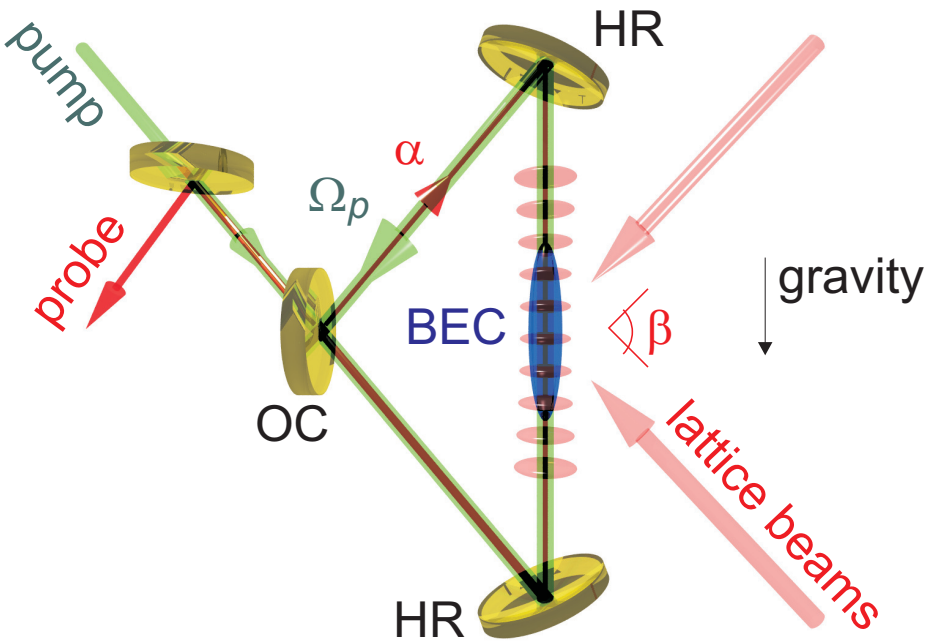
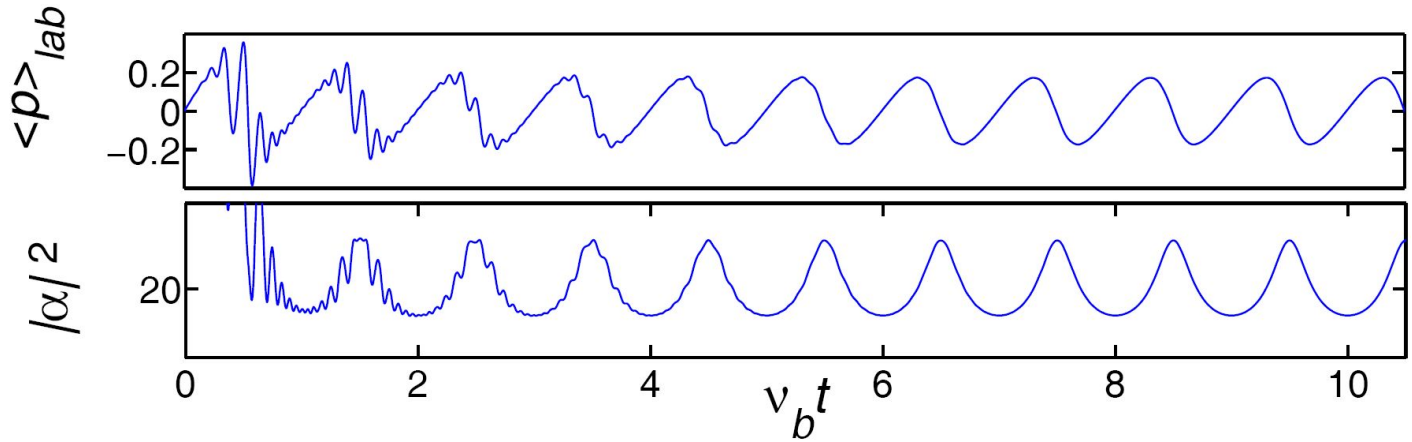


$N = 8 \cdot 10^4$

$\kappa = 160\omega_r$

$U_0 = 0.04\omega_r$

$W_0 = 80U_0$



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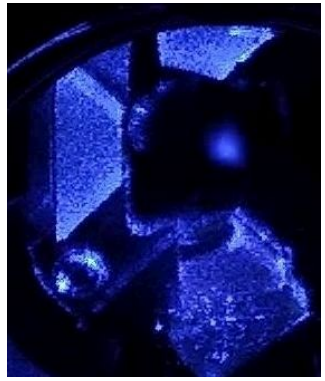
Quintessence

Done:

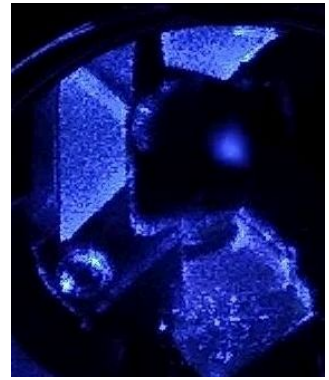
- 200000 atoms cooled down to single-photon recoil limit



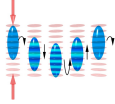
Quintessence

Done:

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



Quintessence



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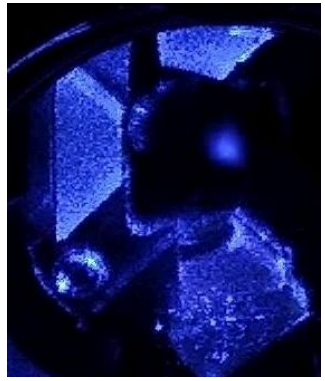
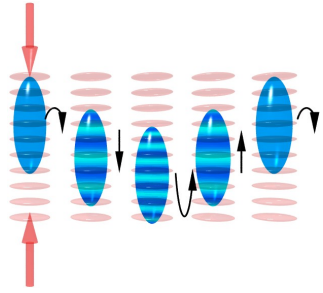
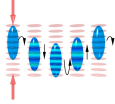


To do:

search for signatures of Bloch oscillations in light modes



Quintessence



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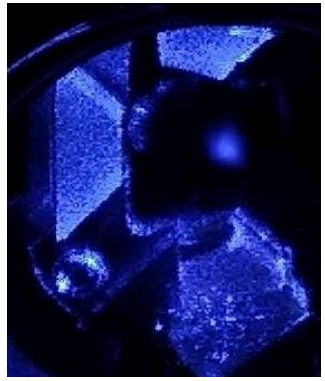
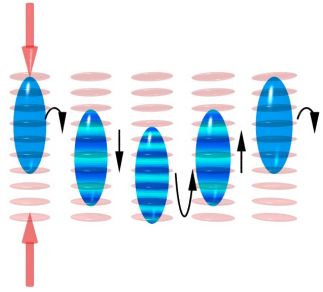


To do:

search for signatures of Bloch oscillations in light modes

continuous monitoring of gravity



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CONCLUSION