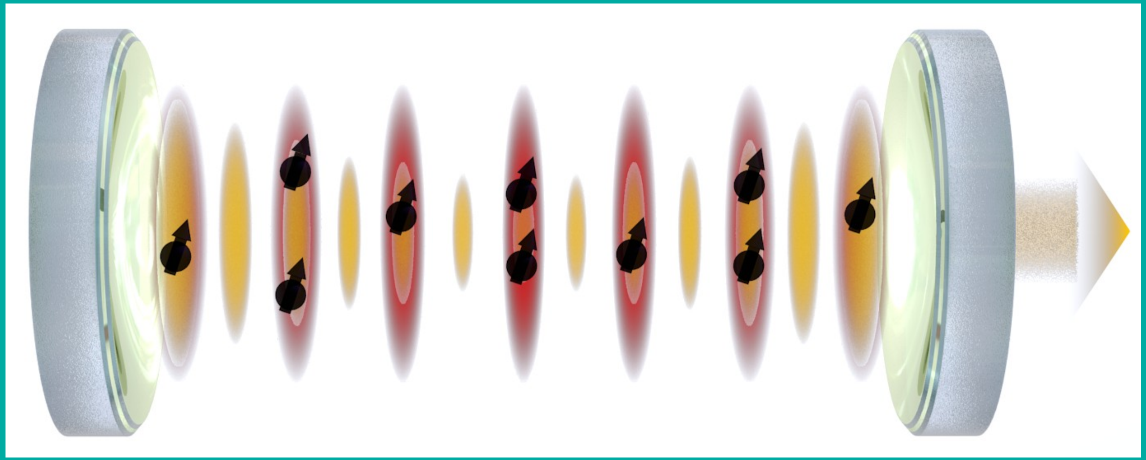
femto-st SCIENCES & TECHNOLOGIES

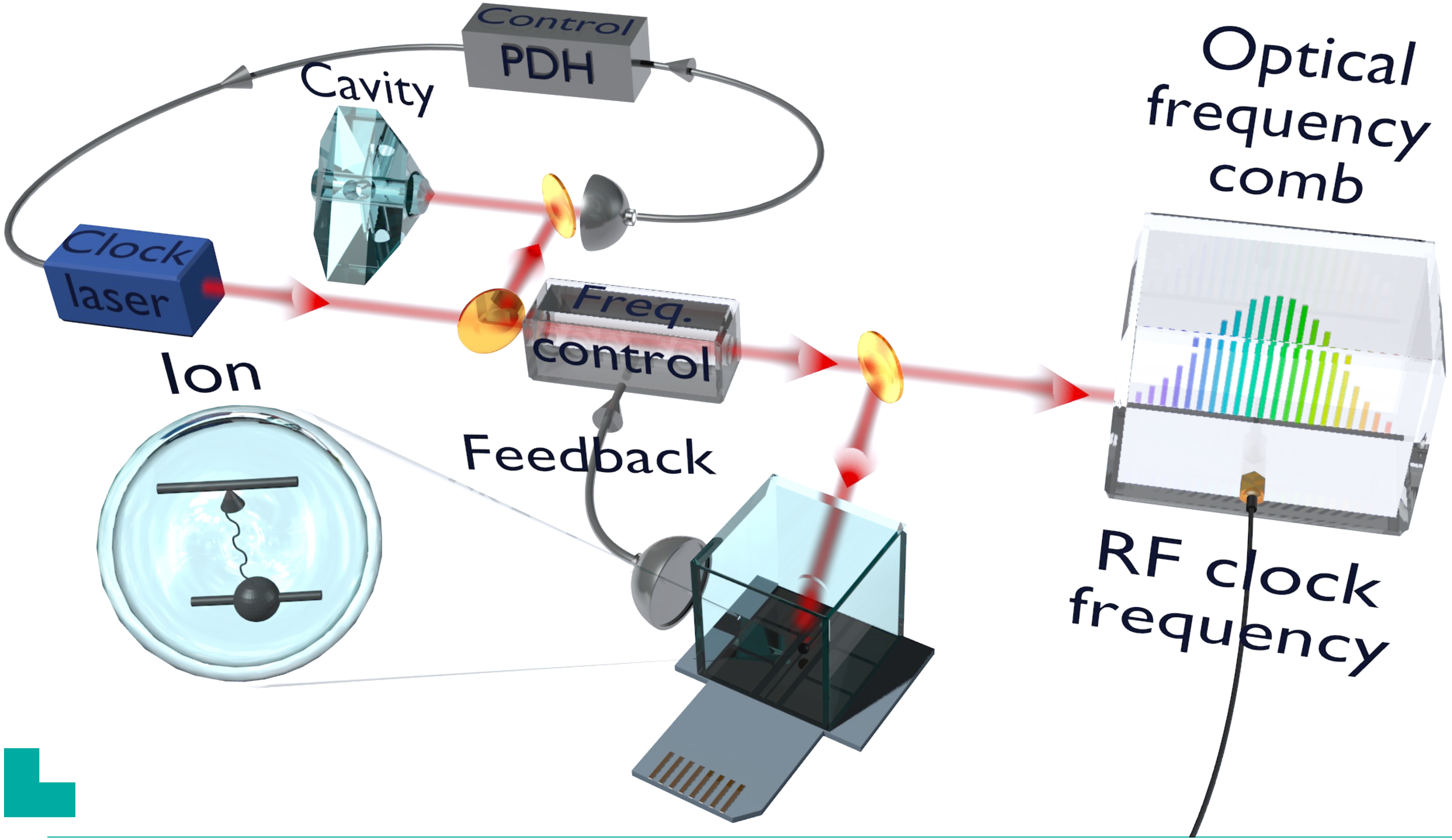
TOWARDS A SUPERRADIANT LASER AS A NEXT GENERATION OPTICAL FREQUENCY REFERENCE



Marion DELEHAYE

Oscillator IMP cnrs UBFC UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ FIRST TF UNIVERSITÉ DE FRANCHE-COMTÉ SUPMICROTECH ENSMM anr utbm EIPHI-BFC

PASSIVE OPTICAL CLOCKS



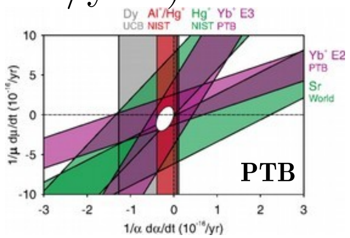
Accuracy ~ 10^{-18}
Stability ~ 10^{-16} @ 1s

doi: 10.1038/nature12941 (2014)

NEED OF BETTER FREQUENCY REFERENCES

- sensitive to potential variations of fundamental constants ($\lesssim 10^{-16}$/year)

doi : 10.1103/PhysRevLett.113.210802



- sensitive to heights → relativistic geodesy

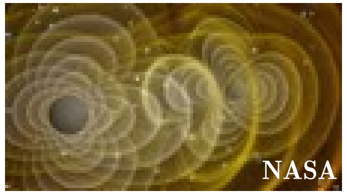
doi : 10.1038/ncomms12443

gravitational redshift : 10^{-16}/m ⇒ 10^{-18} : measurement of the geoid within a cm
→ monitor geophysical/plate subduction processes

doi: 10.1093/gji/ggv246 (2015), 10.1007/s00190-021-01548-y (2021)

- probably sensitive to dark matter ($\sim 10^{-19}$)

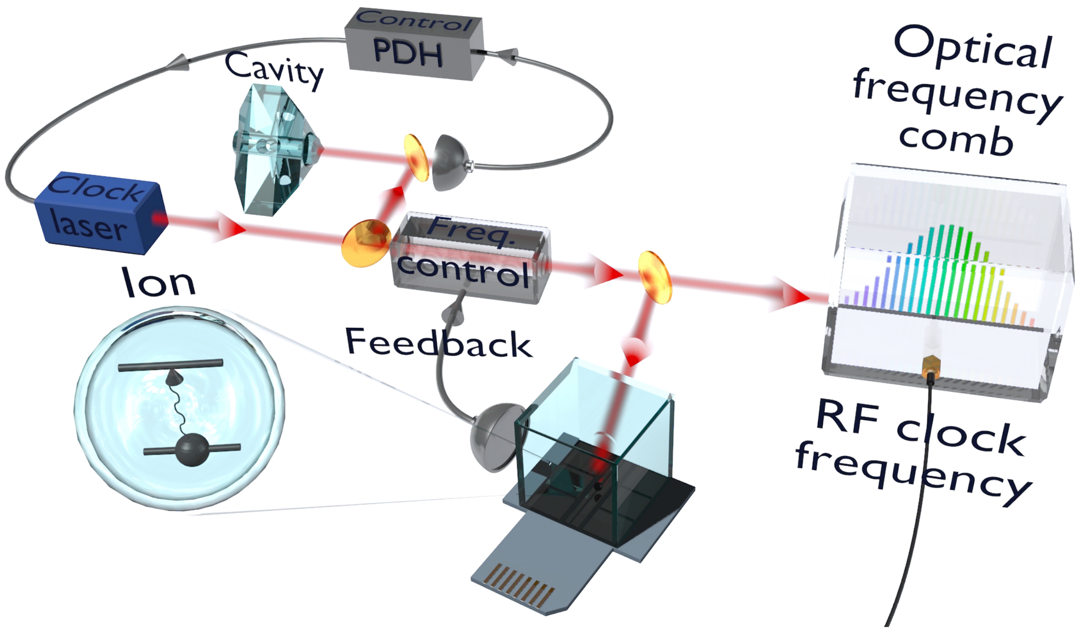
doi : 10.1088/1742-6596/723/1/012043



- (soon) sensitive to gravitationnal waves ($\sim 10^{-20}\ \tau^{-1/2}$), on a different bandwidth than current detectors

doi : 10.1103/PhysRevD.94.124043

PASSIVE OPTICAL CLOCKS: LIMITATIONS



Quantum Projection Noise (QPN)

$$\sigma_{\text{QPN}}(\tau) = \frac{0.264}{\nu_c T_p}\sqrt{\frac{T_c}{N\tau}}$$

(Rabi interrogation)

$\sigma_{\text{QPN}} \sim 10^{-17}\ \tau^{-1/2}$ (N ~ 5000)

Mitigation possible by **squeezing**

Accuracy ~ 10^{-18}
Stability ~ 10^{-16} @ 1s

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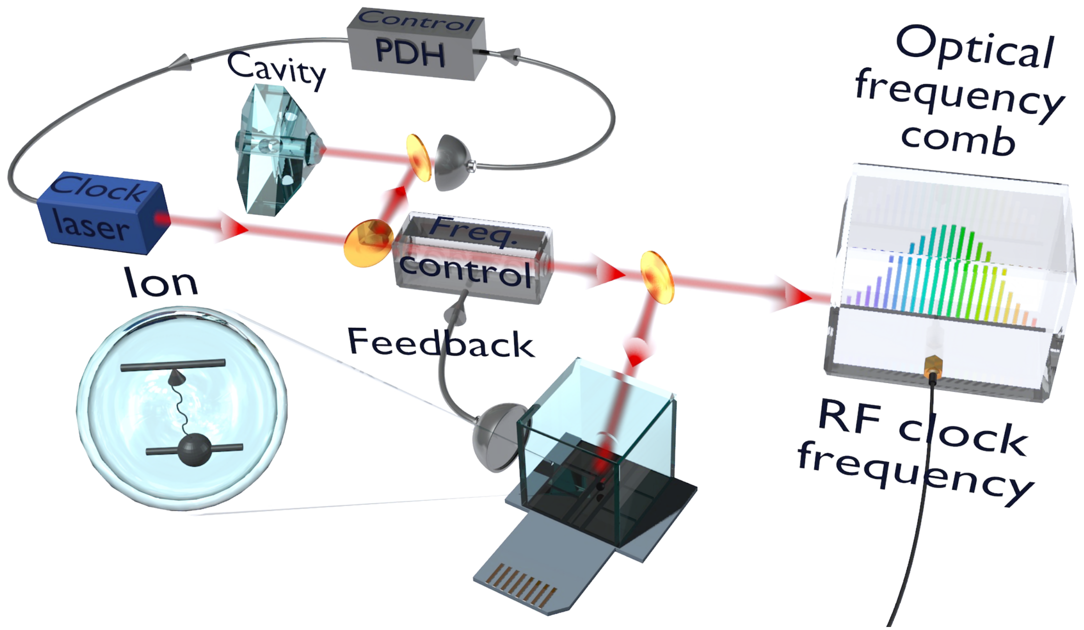

Accuracy $<10^{-18}$
Stability $\sim 10^{-16}$ @ 1s

doi: 10.1038/nature12941 (2014)

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$$\sigma_{\mathrm{QPN}}(\tau) = \frac{0.264}{\nu_c T_p}\sqrt{\frac{T_c}{N\tau}}$$

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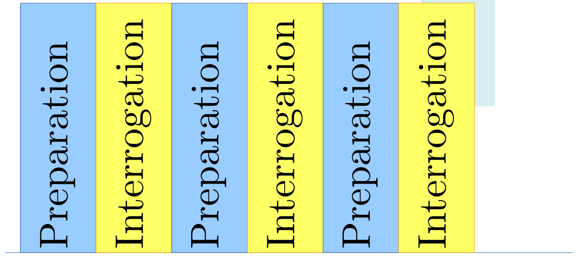
Mitigation possible by **squeezing**

Dick effect

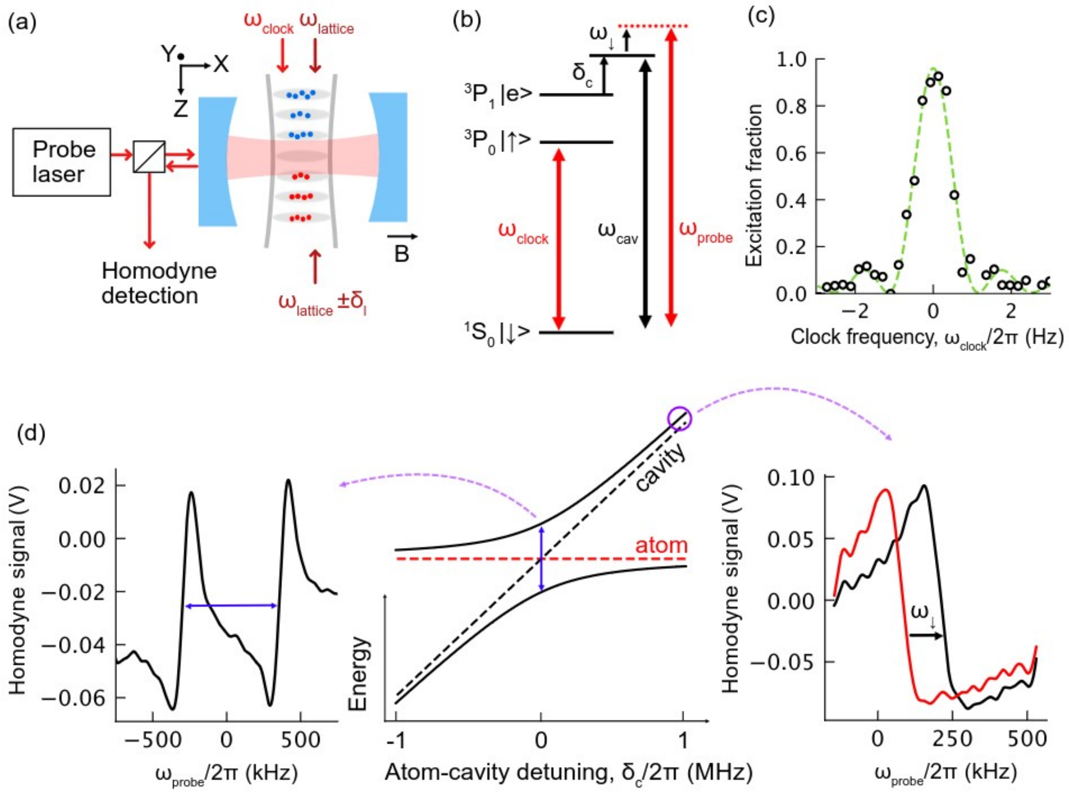
doi: 10.1109/58.710548 (1998)



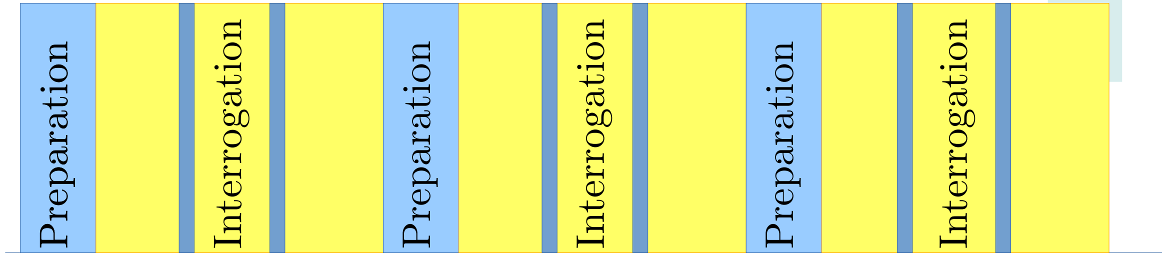
$$\sigma^2_{\mathrm{Dick}}(\tau) = \frac{1}{\tau}\sum_{n=1}^{\infty}\left|\frac{G(n/T_c)}{G(0)}\right|^2 S_y(n/T_c)$$

$\sigma_{\mathrm{Dick}} \sim 10^{-16}\ \tau^{-1/2}$ (typ.)

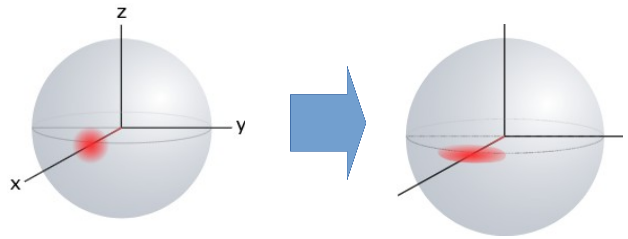
(→ cf spin squeezing obtained by QND measurements)



doi: 10.48550/arXiv.2211.08621



Squeezing



Up to 2 dB below QPN demonstrated

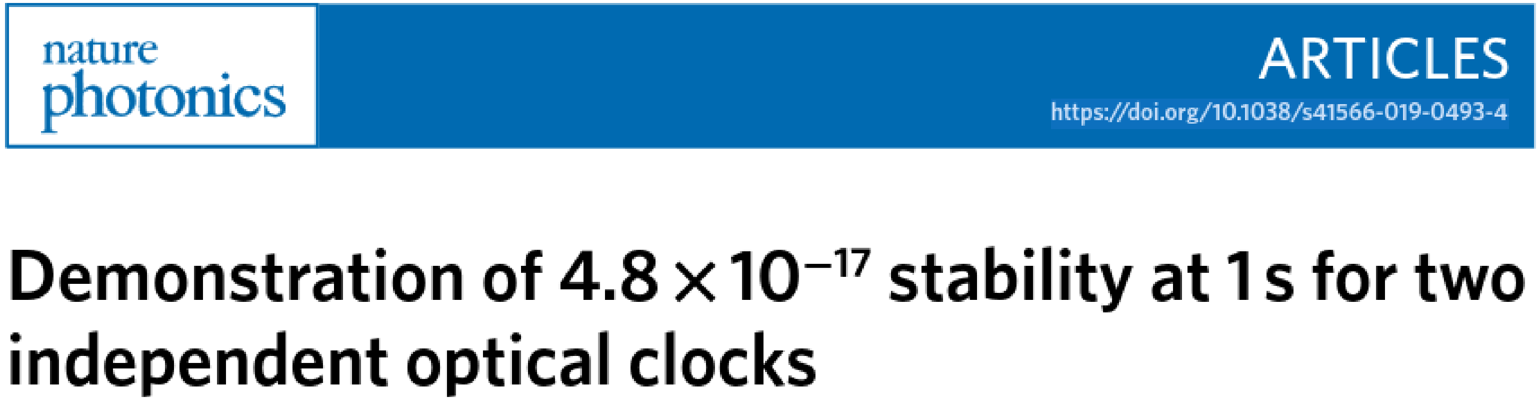
doi: 10.48550/arXiv.2211.08621

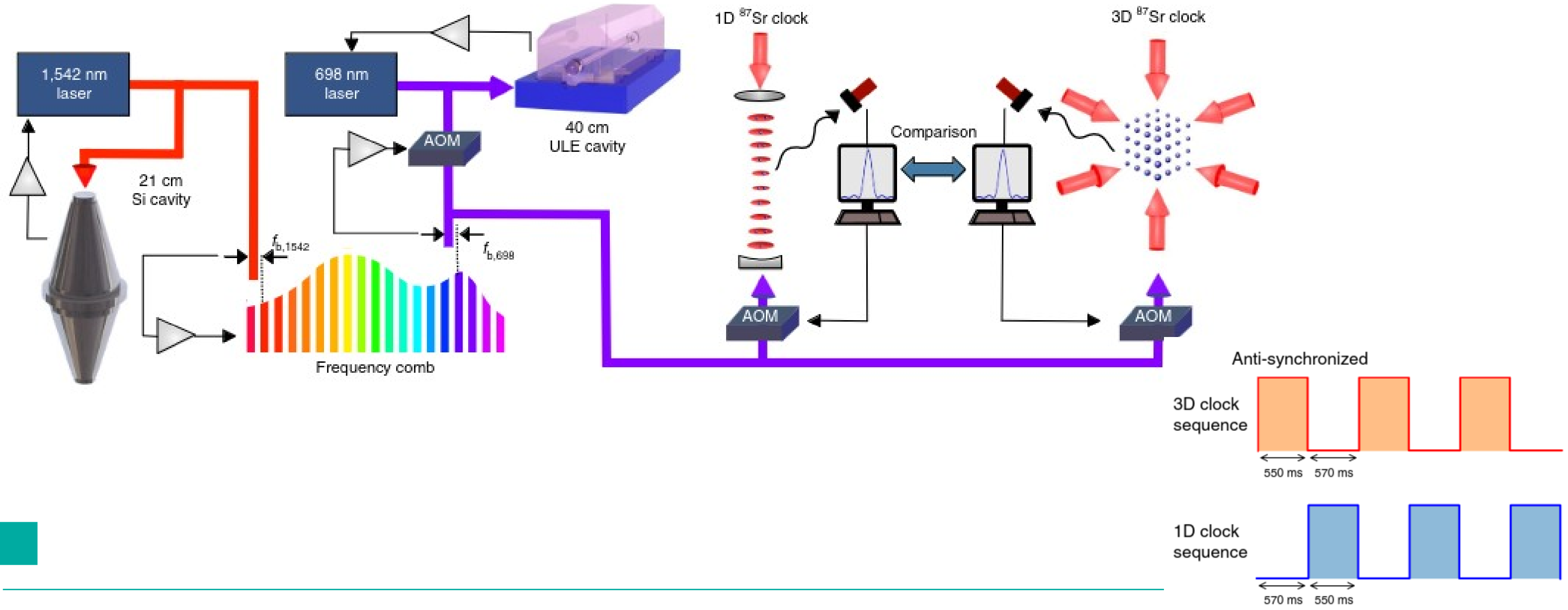
Now at $1\times10^{-15}\ \tau^{-1/2}$

Still aliasing local oscillator frequency noise

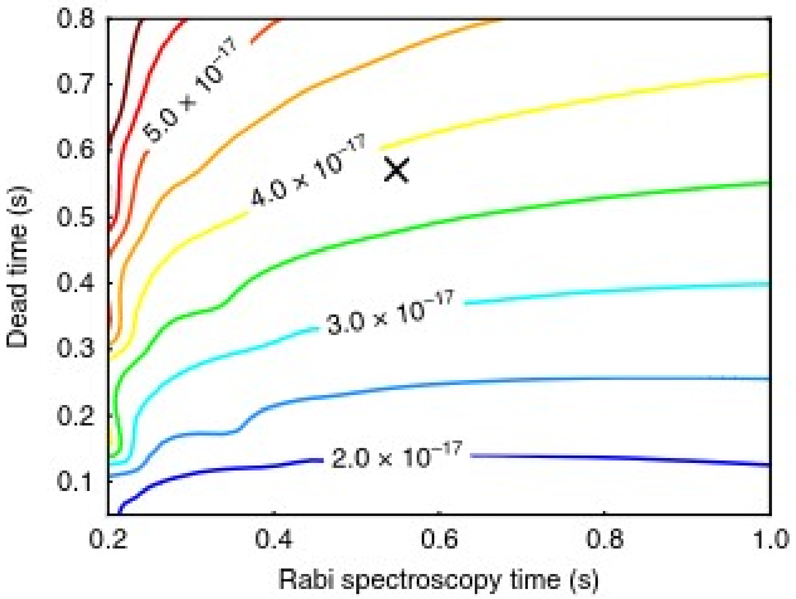
ZERO DEAD-TIME MEASUREMENTS

NIST (2019):





For a cavity with $\sigma_y = 6{,}5\times10^{-17}$



https://doi.org/10.1038/s41566-019-0493-4

HOW TO BUILD BETTER LOCAL OSCILLATORS ?

NIST

Now limited by thermal Brownian noise:

→ increase length → L = 48 cm

$\sigma_y \geq 8 \times 10^{-17}$ (doi: 10.1364/OL.40.002112)

$S_x(f) = S_x^{spacer}(f) + 2\ S_x^{substrate}(f) + 2\ S_x^{coat}(f) \quad \propto T$,

dominated by $S_x^{coat}(f)$ for silicon spacer

→ use crystalline coatings (doi: 10.1038/nphoton.2013.174)

$S_x^{coat}(f) \rightarrow S_x^{coat}(f)\ /10$

→ reduce T → put cavities in cryostats

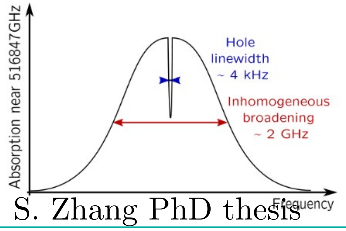
(4 K, 16-18 K, 124 K reported, prospects for 100 mK)

$\sigma_y \geq 3{,}5 \times 10^{-17}$ (21 cm, 124 K, crystalline coatings)

But: - no 50 cm long cavity in a cryostat...

- cryostat = hardly compatible with (future) transportability

Spectral Hole Burning = promising, but still a cryostat



S. Zhang PhD thesis

THE IDEA OF AN ULTRA-STABLE SUPERRADIANT LASER

PRL **102**, 163601 (2009) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2009

Prospects for a Millihertz-Linewidth Laser

D. Meiser, Jun Ye, D. R. Carlson, and M. J. Holland
JILA, National Institute of Standards and Technology, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA
(Received 20 January 2009; published 20 April 2009)

→based on superradiance

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PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

R. H. Dicke
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

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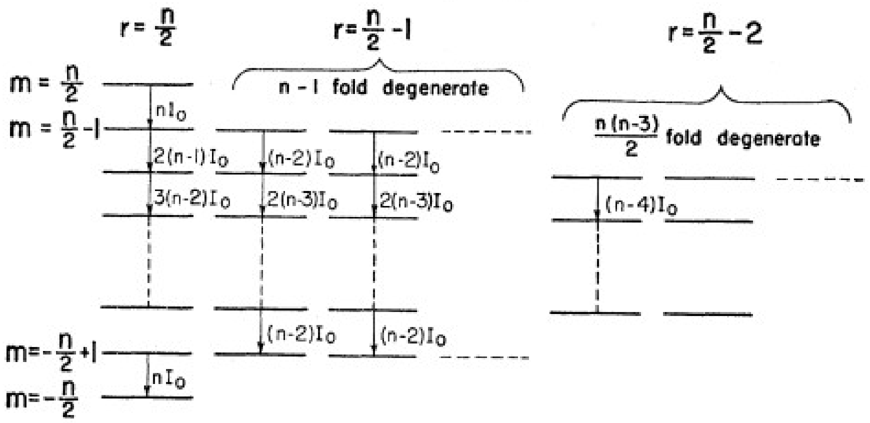

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PHYSICS REPORTS (Review Section of Physics Letters) 93, No. 5 (1982) 301–396. North-Holland Publishing Company

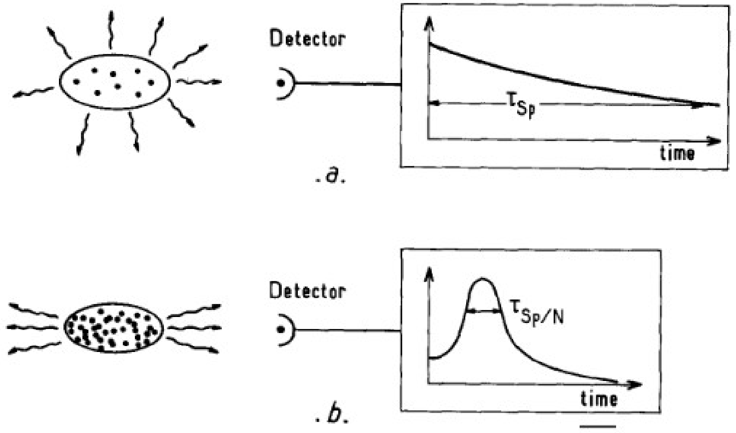
SUPERRADIANCE: AN ESSAY ON THE THEORY OF COLLECTIVE SPONTANEOUS EMISSION

M. GROSS and S. HAROCHE
Laboratoire de Physique de l'Ecole Normale Supérieure, Paris, France

Received September 1982

$d \gg \lambda$

$d \ll \lambda$



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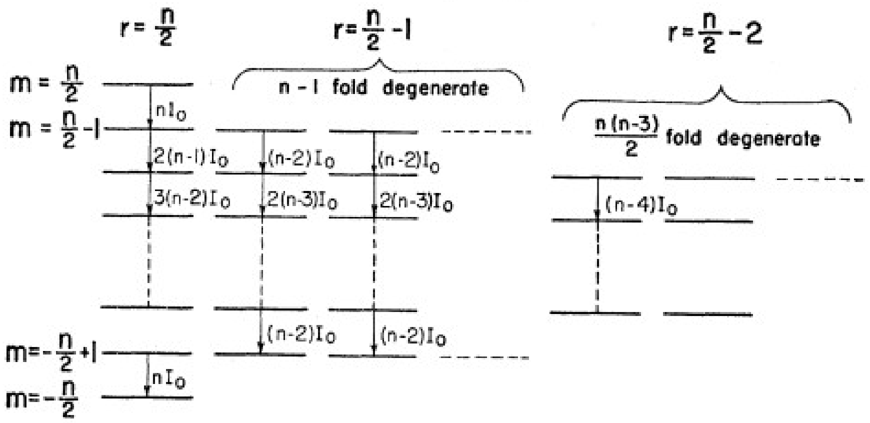

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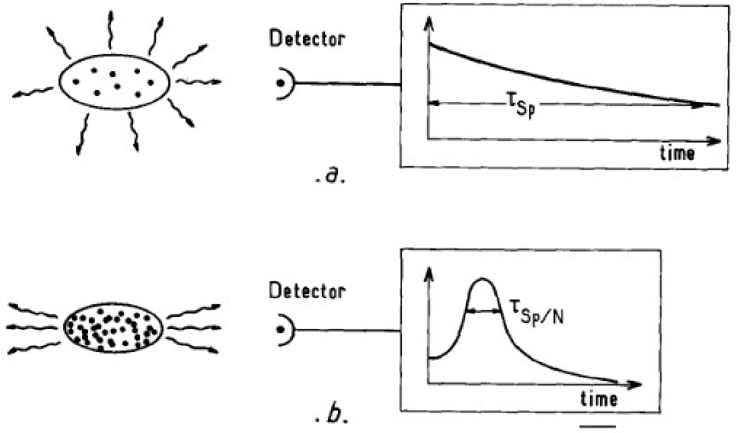

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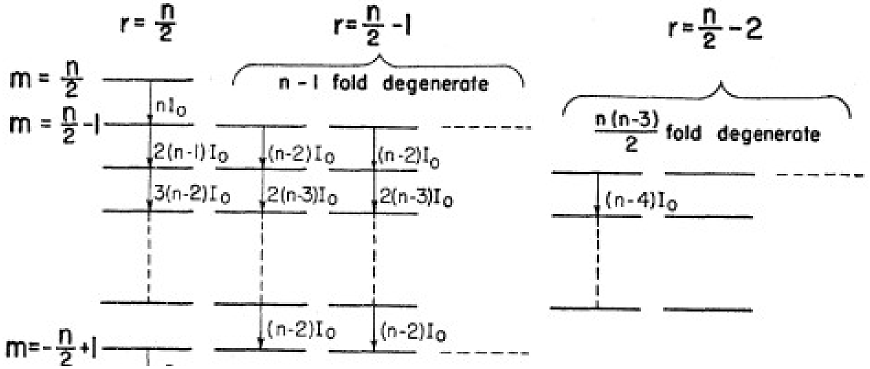

VOLUME 71, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1993

Superradiant Laser

Fritz Haake and Mikhail I. Kolobov*
Fachbereich Physik Universität-Gesamthochschule Essen 4300 Essen, Germany

Claude Fabre, Elisabeth Giacobino, and Serge Reynaud
Laboratoire de Spectroscopie Hertzienne de l'École Normale Supérieure, Universite Pierre et Marie Curie, 4 place Jussieu 75252 Paris, Cedex 05, France
(Received 11 March 1993)

→ Bad-cavity regime

THE IDEA OF AN ULTRA-STABLE SUPERRADIANT LASER

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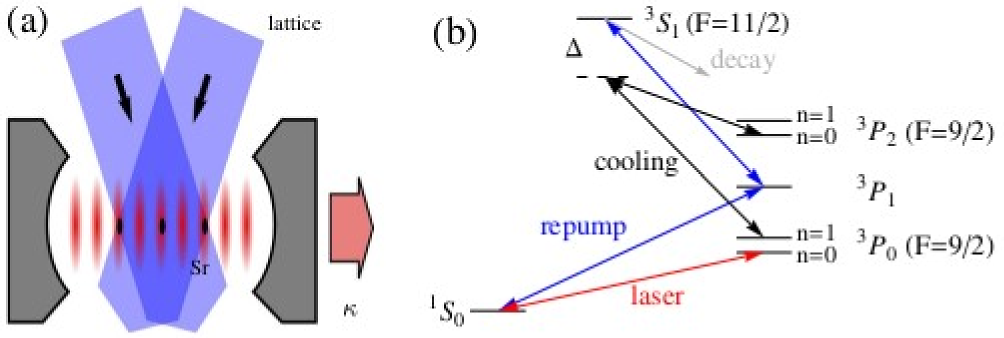
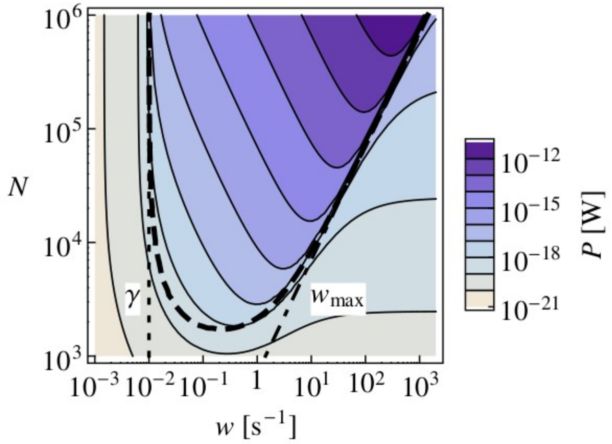
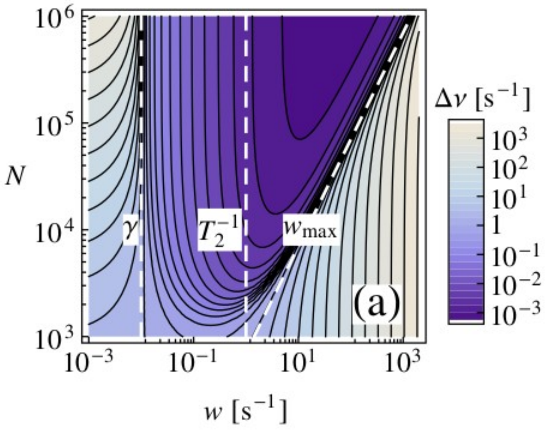


Inhomogeneous broadening $\rightarrow T_2$





$$N_{th} = 2/(C\,\gamma\,T_2)$$

$$P_{max} = \hbar\,\omega_a\,N^2\,C\,\gamma/8$$

$$\Delta\nu_{min} = C\,\gamma$$

Assuming white frequency noise,
$\sigma_{min} \sim 10^{-18}\,\tau^{-1/2}$

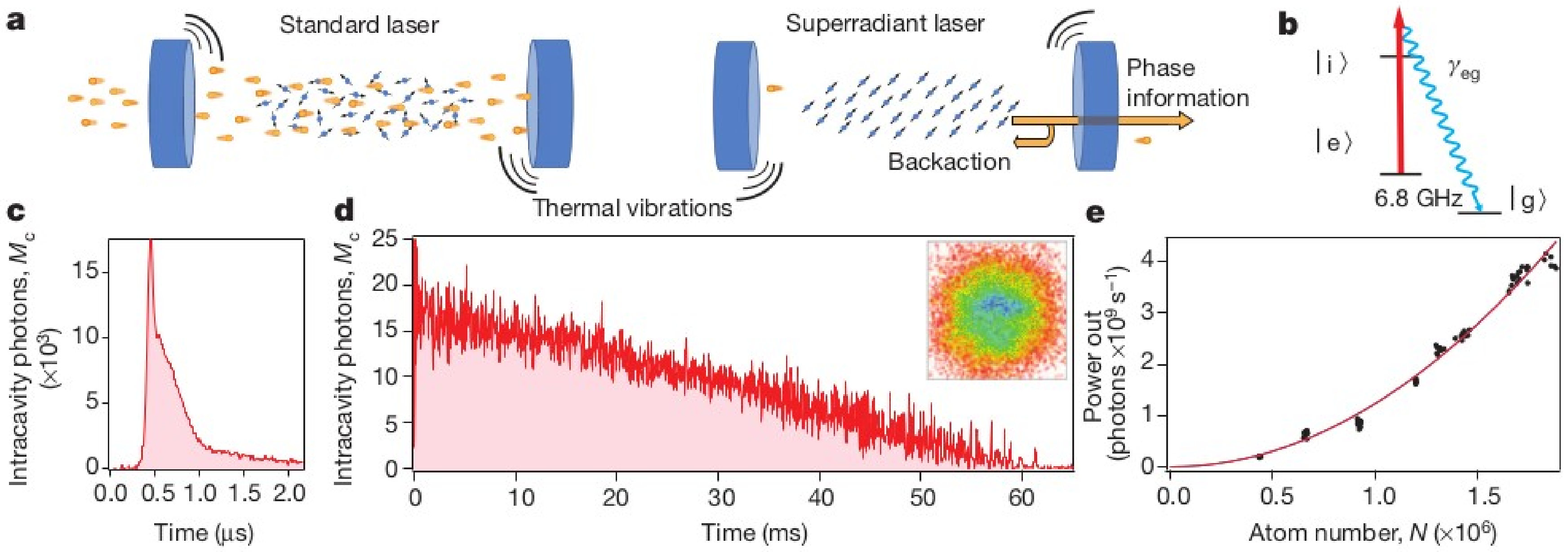
LETTER (2012)

doi:10.1038/nature10920

A steady-state superradiant laser with less than one intracavity photon

Justin G. Bohnet[1], Zilong Chen[1], Joshua M. Weiner[1], Dominic Meiser[1]†, Murray J. Holland[1] & James K. Thompson[1]

Dressed state of ^{87}Rb



No repumping

Repumping

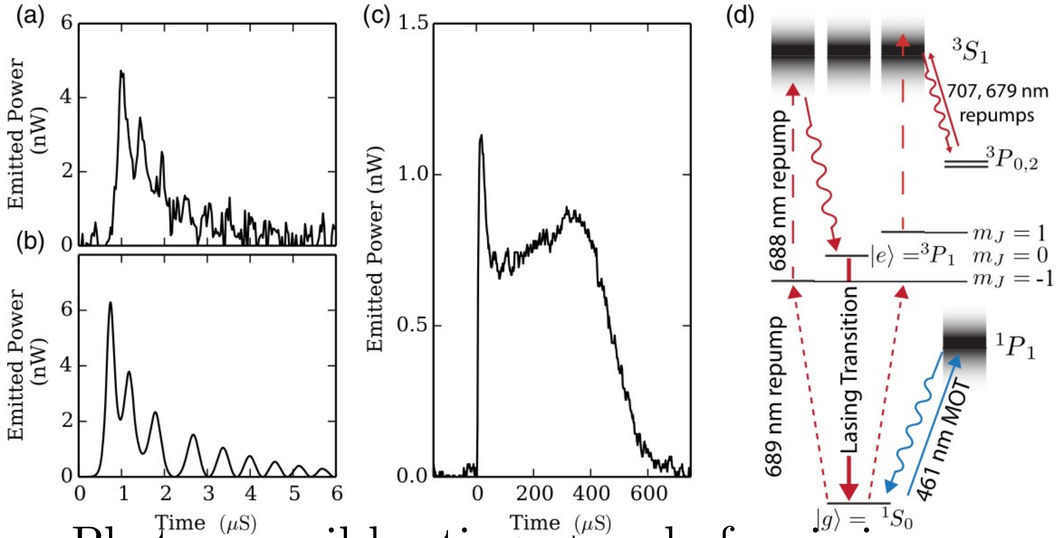
DIRECTLY ON AN OPTICAL TRANSITION?

PHYSICAL REVIEW X **6,** 011025 (2016)

Cold-Strontium Laser in the Superradiant Crossover Regime

Matthew A. Norcia* and James K. Thompson
JILA, NIST, and University of Colorado, 440 UCB, Boulder, Colorado 80309, USA
(Received 23 October 2015; revised manuscript received 11 January 2016; published 9 March 2016)

^{88}Sr on $^1S_0 \rightarrow {}^3P_1$ transition (8 kHz)



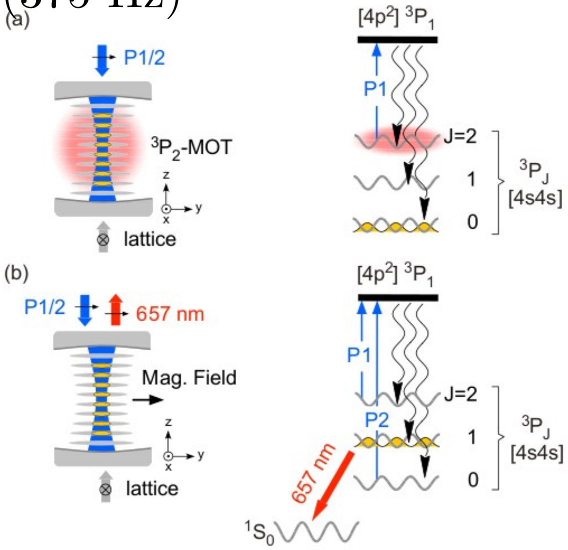
Photon recoil heating → end of emission

PHYSICAL REVIEW LETTERS

Pulse Delay Time Statistics in a Superradiant Laser with Calcium Atoms

Torben Laske, Hannes Winter, and Andreas Hemmerich
Phys. Rev. Lett. **123**, 103601 – Published 3 September 2019

^{40}Ca on $^1S_0 \rightarrow {}^3P_1$ transition (375 Hz)



CAN WE DO FREQUENCY MEASUREMENTS?

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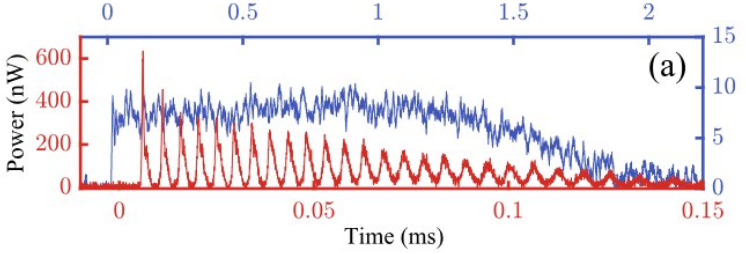
Subnatural Linewidth Superradiant Lasing with Cold ^{88}Sr Atoms

Sofus Laguna Kristensen, Eliot Bohr, Julian Robinson-Tait, Tanya Zelevinsky, Jan W. Thomsen, and Jörg Helge Müller

Phys. Rev. Lett. **130**, 223402 – Published 31 May 2023



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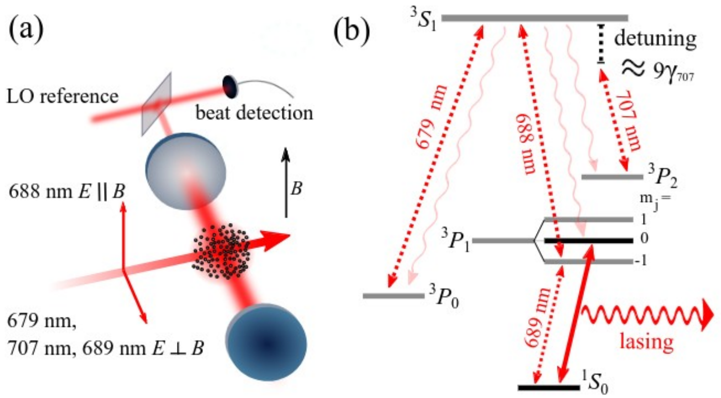
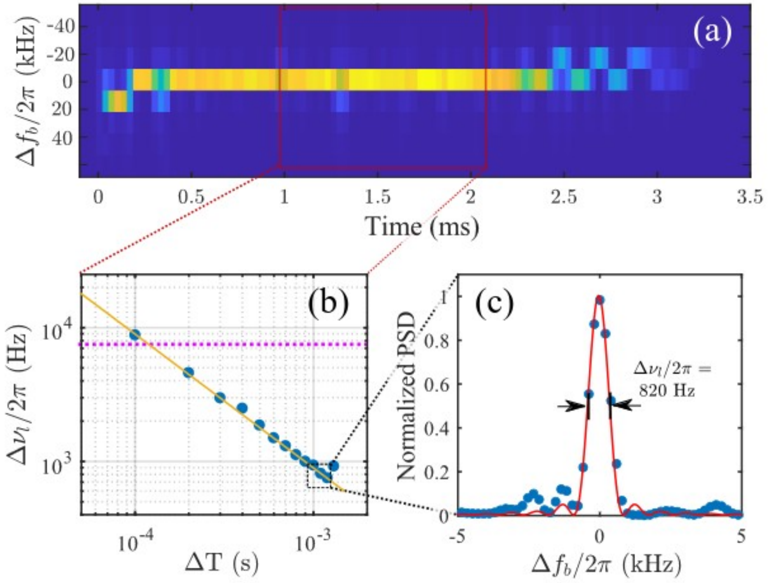




$$\Delta\nu_{\min} = C\,\gamma$$

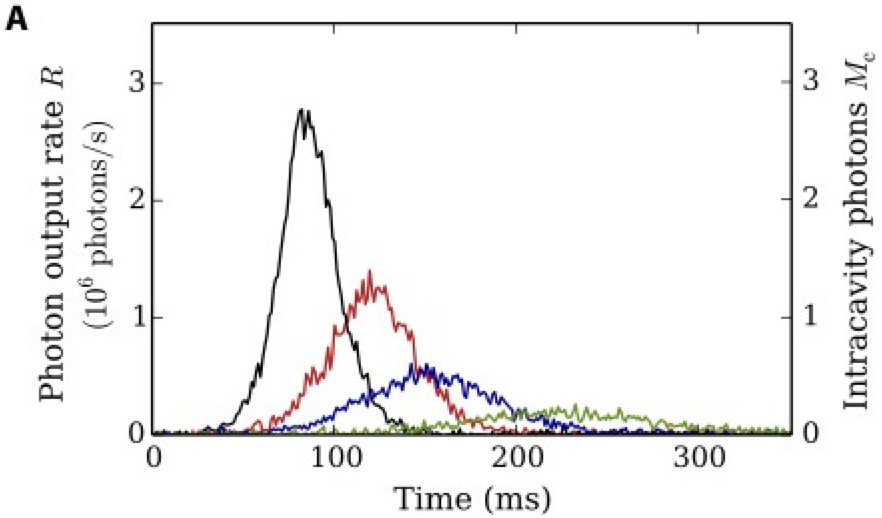
ON A CLOCK TRANSITION?

SCIENCE ADVANCES | RESEARCH ARTICLE (2016)

PHYSICAL SCIENCE

Superradiance on the millihertz linewidth strontium clock transition

Matthew A. Norcia,* Matthew N. Winchester, Julia R. K. Cline, James K. Thompson



^{87}Sr on $^1S_0 \rightarrow {}^3P_0$ transition (1 mHz)

PHYSICAL REVIEW X

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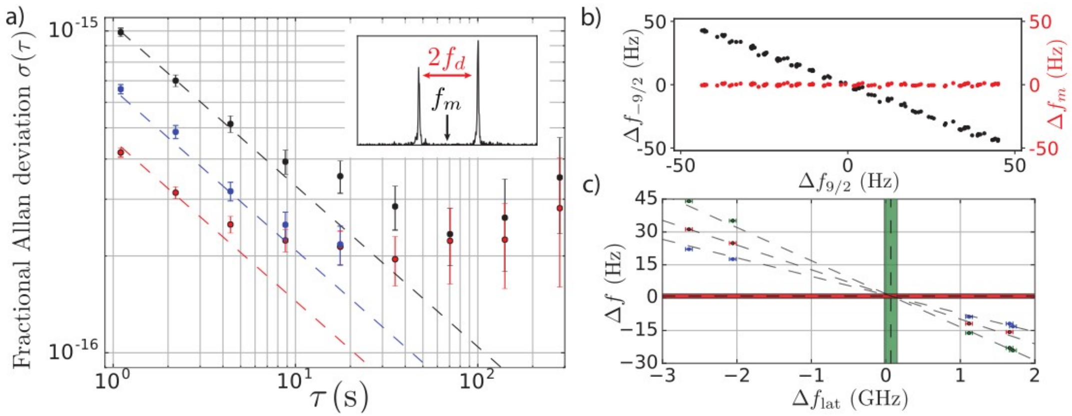
Open Access

Frequency Measurements of Superradiance from the Strontium Clock Transition

Matthew A. Norcia, Julia R. K. Cline, Juan A. Muniz, John M. Robinson, Ross B. Hutson, Akihisa Goban, G. Edward Marti, Jun Ye, and James K. Thompson

Phys. Rev. X **8**, 021036 – Published 9 May 2018



Stability and accuracy measurements Fourier-limited

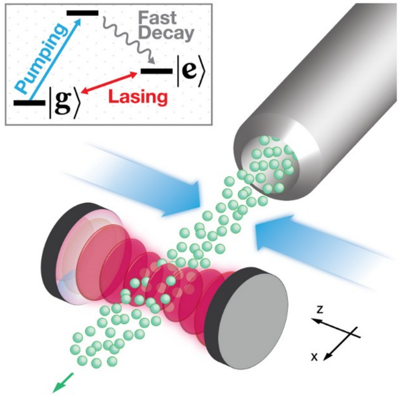
CURRENT CHALLENGE: TRUE CONTINUOUS OPERATION

Quasi-steady state: can be achieved by repumping (JILA) or by seeding atoms from a metastable state (Copenhagen)

BUT: finite lifetime of the atoms

$\rightarrow$ how to bring in new atoms?

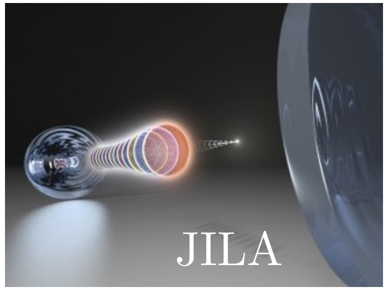
(Thermal) Beam operation



doi: 10.1103/PhysRevLett.125.253602 (2020)

$$N_{\text{th}} = 2/(C\,\gamma\,T_2)$$

Reloading of (cold) atoms
- ring cavity system (JILA)
- cold atomic beam (Amsterdam?)
- refill from MOT (Hamburg)
- sequential reloading (FEMTO-ST)



FEMTO-ST SUPERRADIANT YTTERBIUM LASER

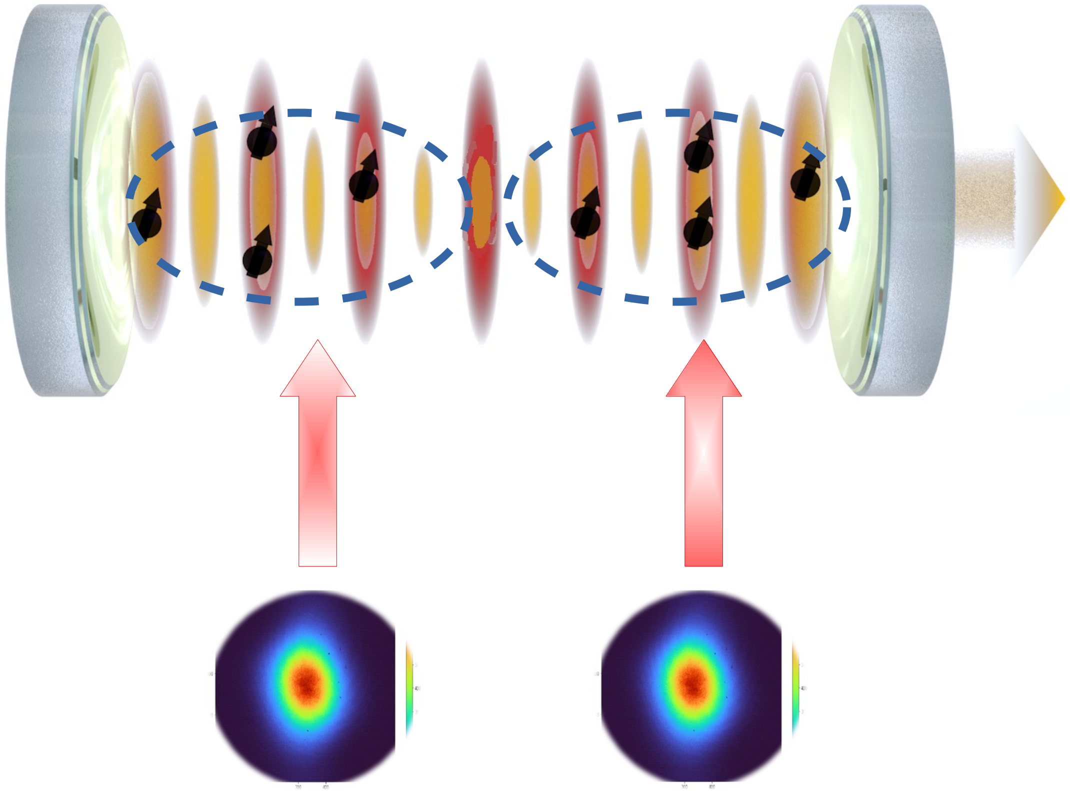
$N_{\mathrm{th}} = 2/(C\,\gamma\,T_2)$

^{171}Yb: 7 mHz wide $^1S_0 \rightarrow {}^3P_0$ transition: threshold atom number 7× smaller than ^{87}Sr

^{171}Yb : I = 1/2 : reduced scattering when repumping wrt ^{87}Sr

But no straightforward reservoir in $^3P_2$ (magic wavelength blue detuned for $^3P_2 \rightarrow {}^3S_1$)

Repumping + sequential reloading



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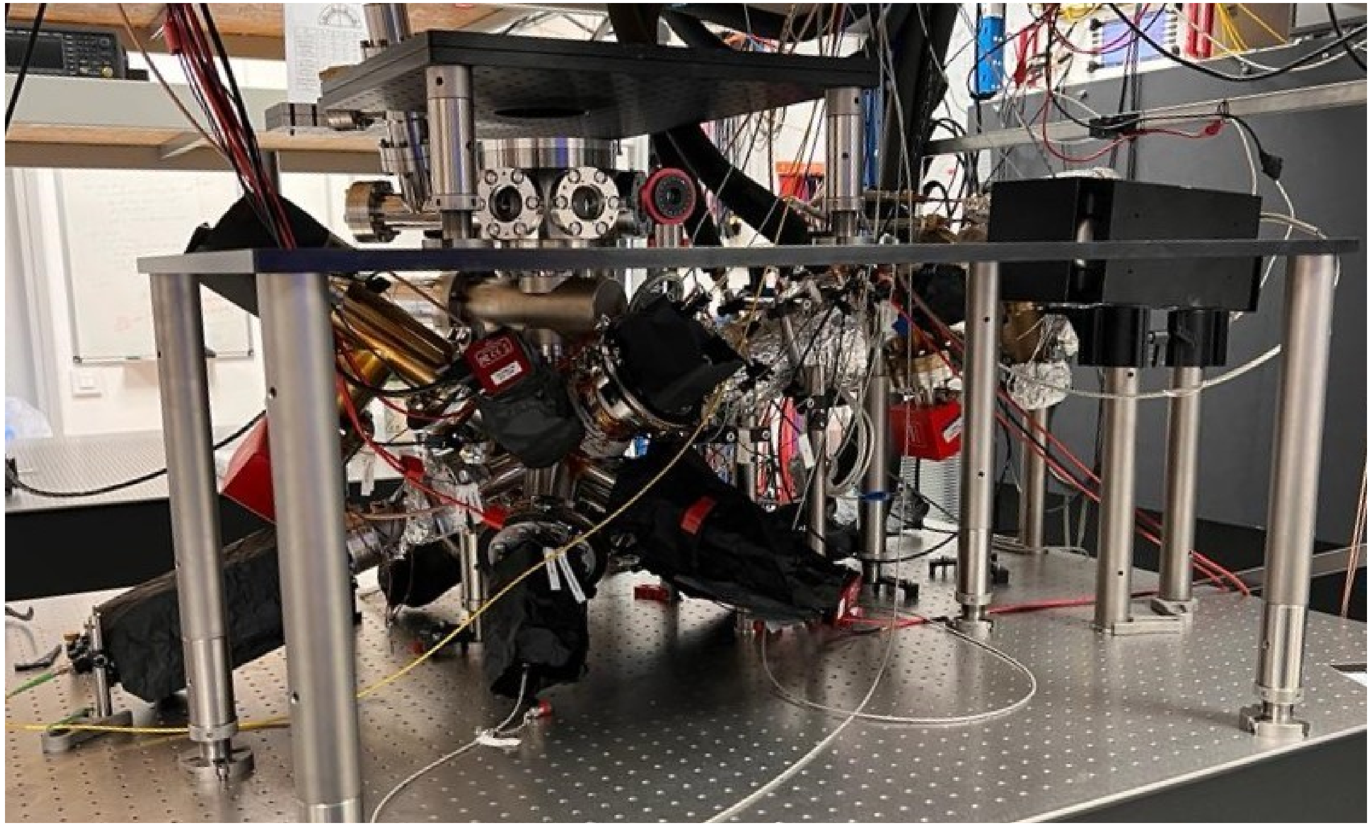

Sebastian Ponciano | Martin Hauden | Martina Matusko | Jana El Badawi

Thank you for your attention!