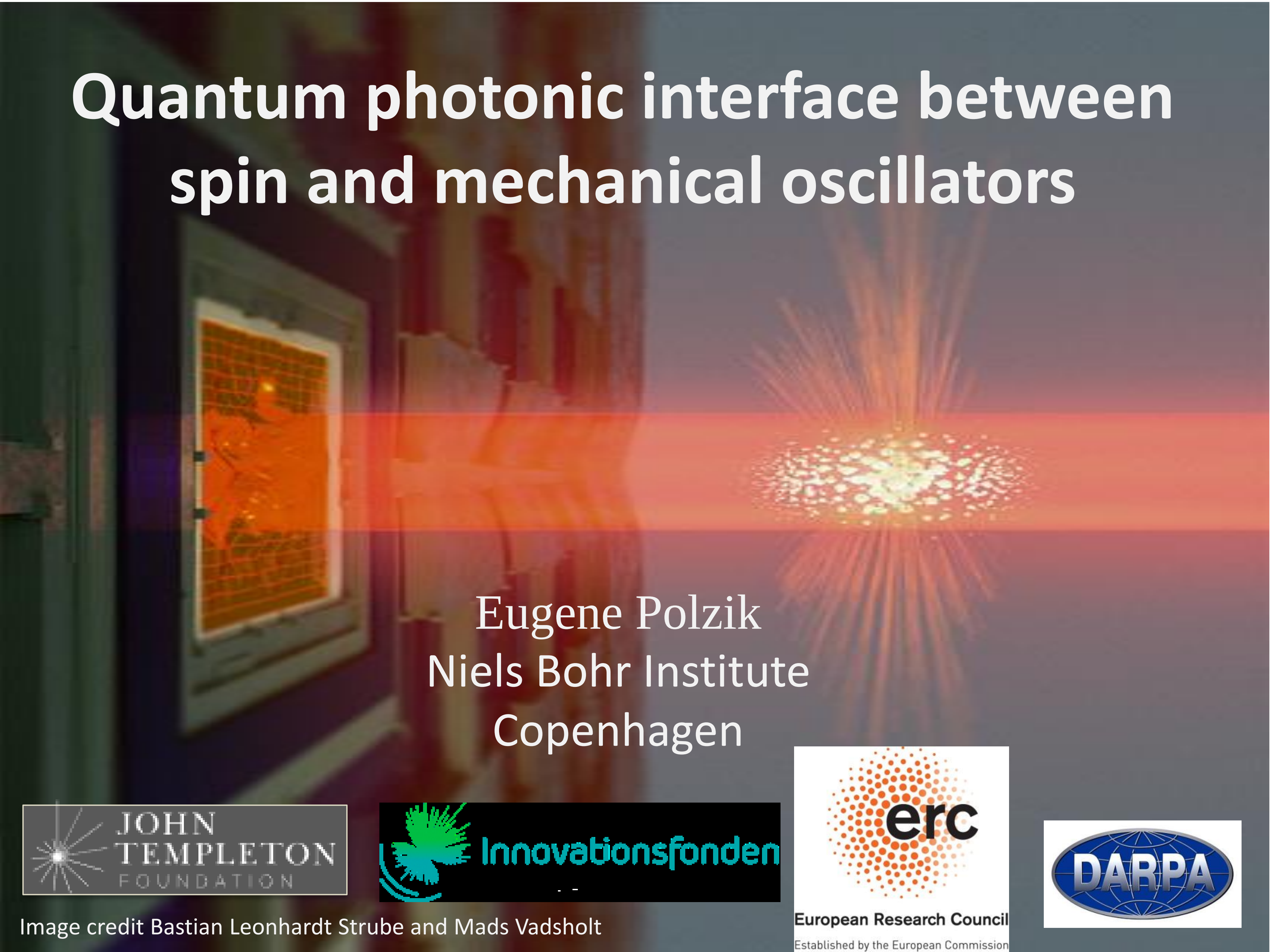


Quantum photonic interface between spin and mechanical oscillators

Eugene Polzik
Niels Bohr Institute
Copenhagen

JOHN TEMPLETON FOUNDATION
Innovationsfonden
erc European Research Council
Established by the European Commission
DARPA

Image credit Bastian Leonhardt Strube and Mads Vadsholt

Room temperature long-lived macro-spin

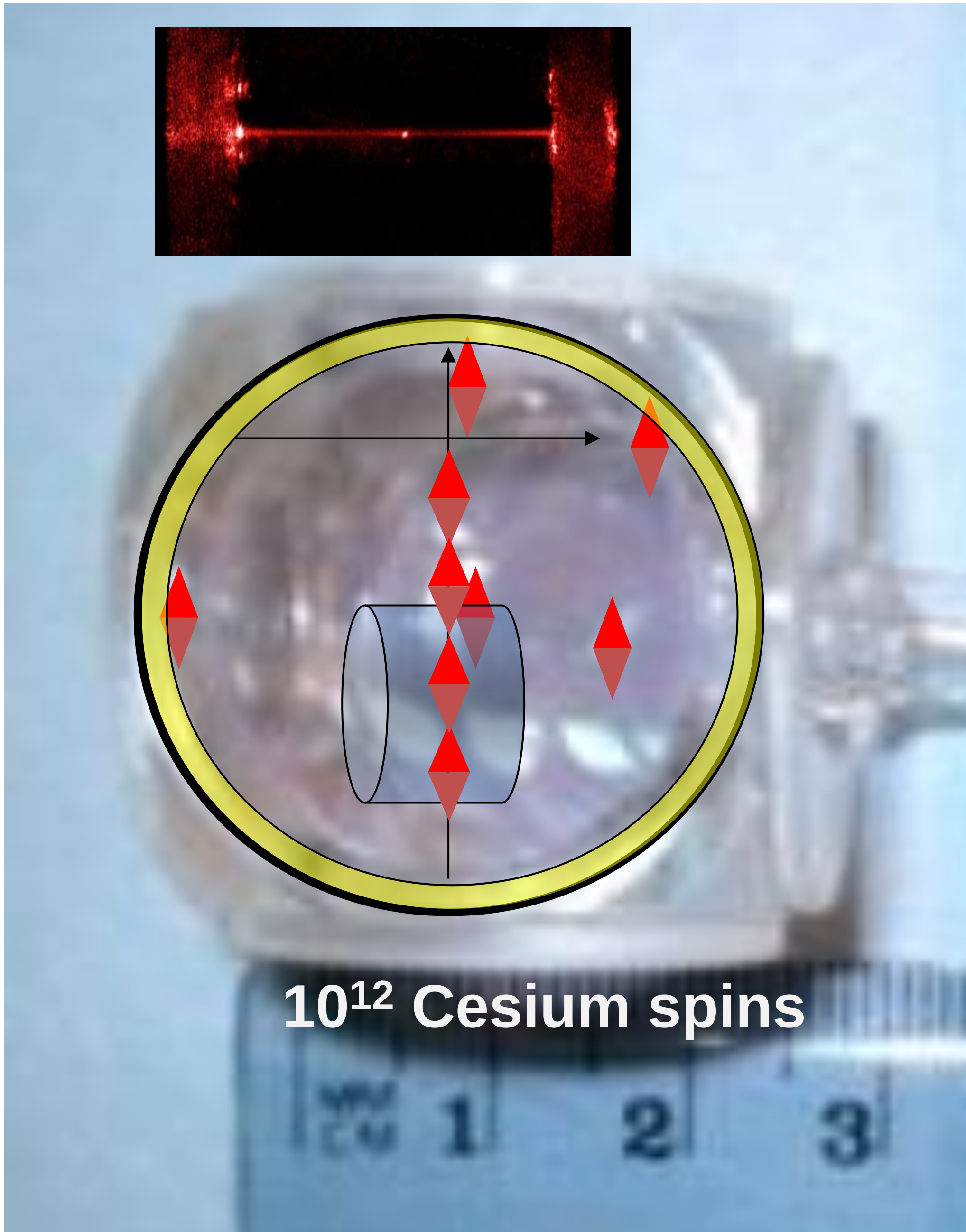
NoiseTemperature < 300 nanoK

$N_{thermal}$ < 0.03

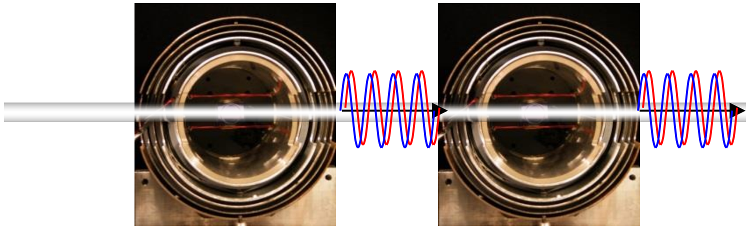
Frequency $10^2 – 10^7$ Hz

T_2 0.01 – 10 sec

Alkane wall coating protects spin quantum state for > 10^4 wall collisions


10^{12} Cesium spins

Forever entangled 2011

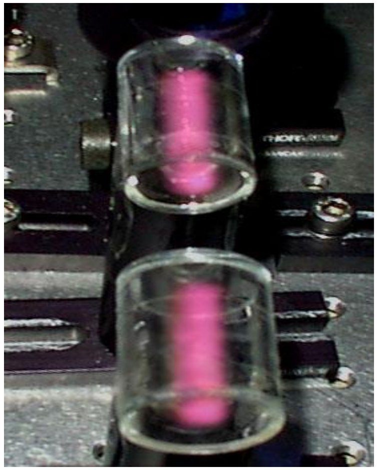


10^{12} atoms at RT 10^{12} atoms at RT

Teleported 2013 and more

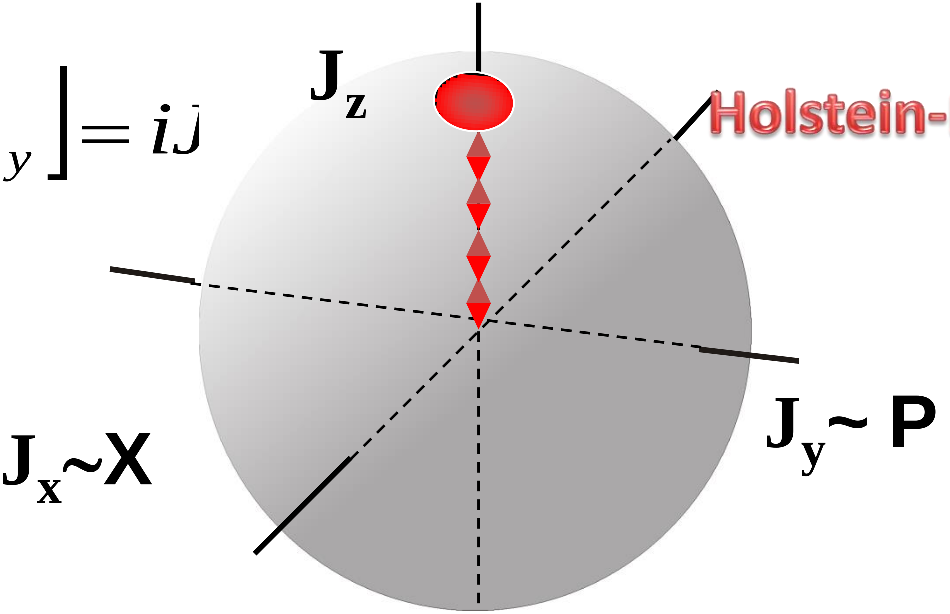
Entangled 2001

Atoms-mechanics interface2017



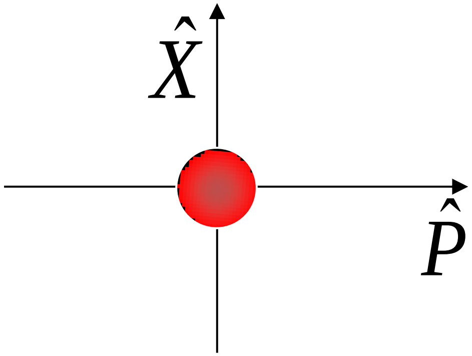
Continuous quantum variables

$$\left[\hat{J}_x, \hat{J}_y\right] = iJ$$



Holstein-Primakoff

$$\left[\hat{X}, \hat{P}\right] = i$$



B. Julsgard, A. Kozhekin and ESP, ***Nature***, **413**, 400 **(2001)**

H. Krauter, C. Muschik, K. Jensen, W. Wasilewski, J. Pedersen, I. Cirac, and ESP. ***PRL*** 107, 080503 **(2011)**

H.Krauter, D.Salart, C.Muschik, J. M. Petersen, T. Fernholz, and ESP. ***Nature Physics***, July **(2013)**

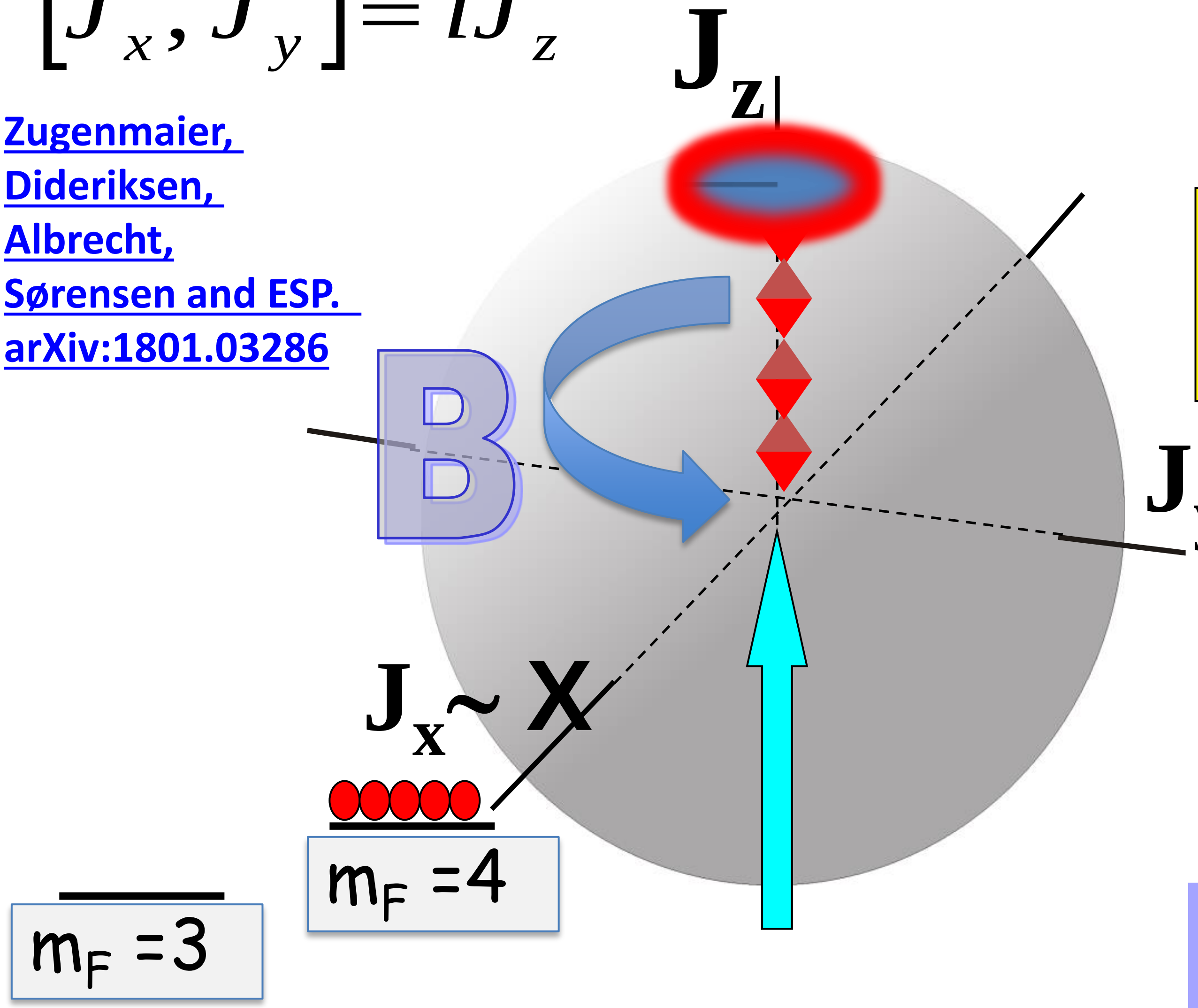
C. Møller et al. ***Nature***, 547, 191 **(2017)**

Spin ensemble = inverted (m<0) harmonic oscillator

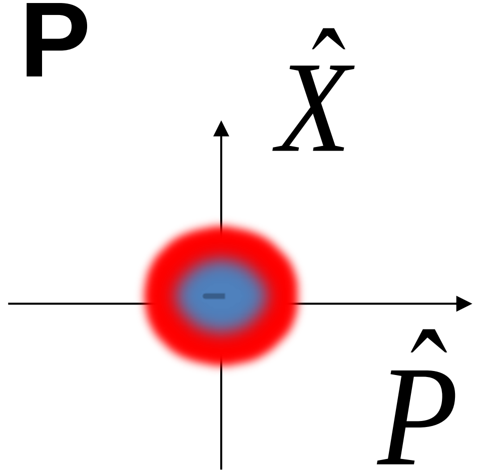
$$\left[\hat{J}_x, \hat{J}_y\right] = iJ_z$$

$$J = \sum_{i=1}^{N} j_i$$

Zugenmaier, Dideriksen, Albrecht, Sørensen and ESP. arXiv:1801.03286



Negative mass oscillator

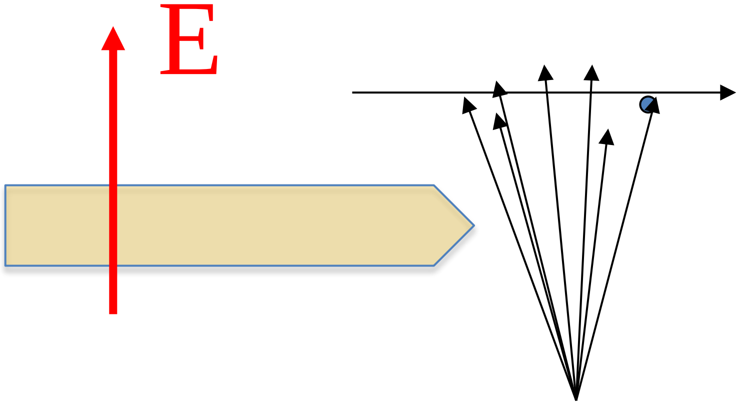


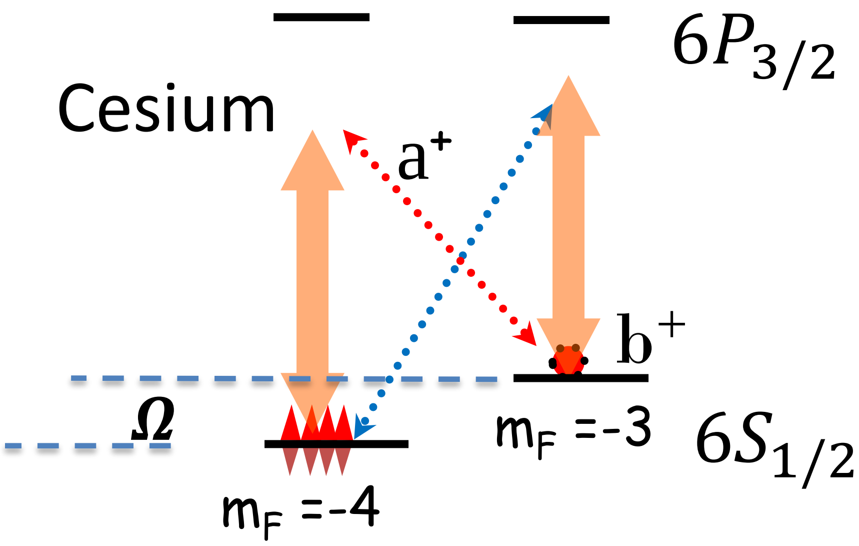
$$\left[\hat{X}, \hat{P}\right] = i$$

Holstein-Primakoff

$$\left|-\frac{1}{2},\frac{1}{2},\frac{1}{2}\ldots\right\rangle + \left|\frac{1}{2},-\frac{1}{2},\frac{1}{2}\ldots\right\rangle + \left|\frac{1}{2},\frac{1}{2},-\frac{1}{2}\ldots\right\rangle + \ldots$$

Quantum opto-spintronics



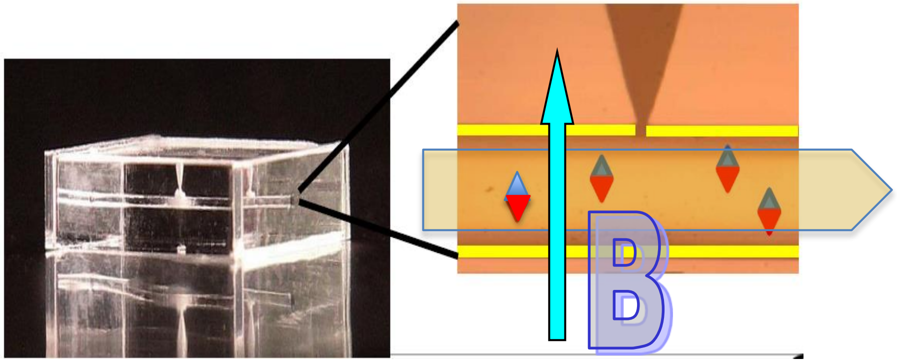


$$H = \chi_{Par}\hat{a}^\dagger\hat{b}^\dagger + \chi_{BS}\hat{a}^\dagger\hat{b} + h.c. = gX_SX_L,$$

$$g = \chi_{Par} = \chi_{BS}$$

photon

Polariton=collective spin



$$\boxed{\hat{P}^S_{L,\mathrm{out}} = \hat{P}^S_{L,\mathrm{in}} - \sqrt{\Gamma_S}\hat{X}_S}$$

Spin readout rate ~ photon flux and optical depth

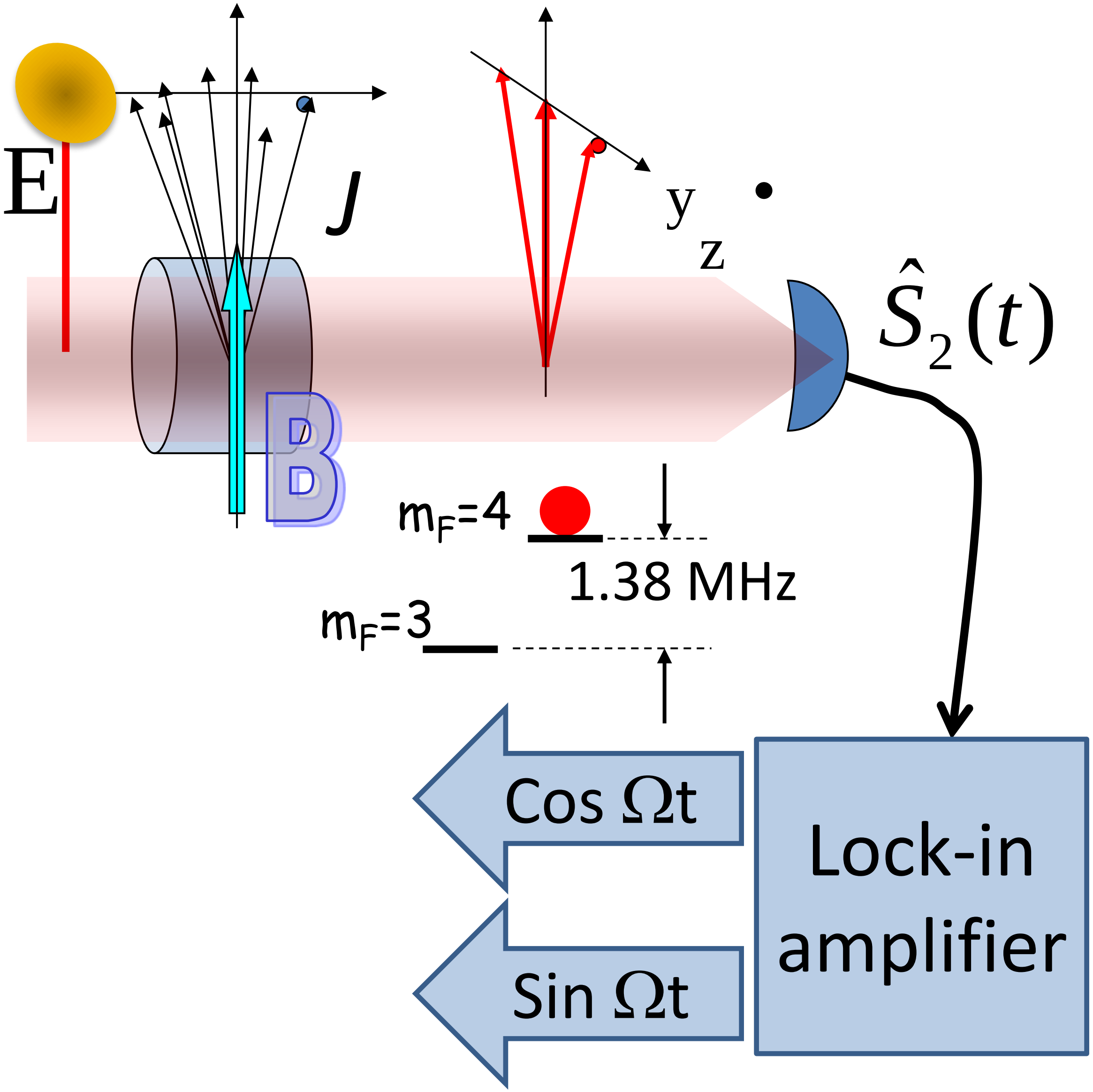
Spin coherence > 3 msec at RT

High quality anti-relaxation coating material for alkali atom vapor cells

M. V. Balabas[1,2,*], K. Jensen[1], W. Wasilewski[1], H. Krauter[1], L. S. Madsen[1],
J. H. Müller[1], T. Fernholz[1], and E. S. Polzik[1]

Optical coupling to oscillating spin

$$J_z^{\,lab} = J_z^{\,rot} \cos\Omega t - J_y^{\,rot} \sin \Omega t$$

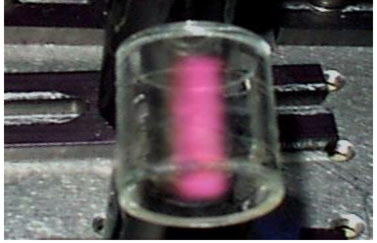


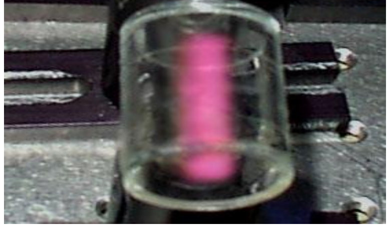
Cos Ωt

Sin Ωt

Lock-in amplifier

EPR entanglement of two atomic spins





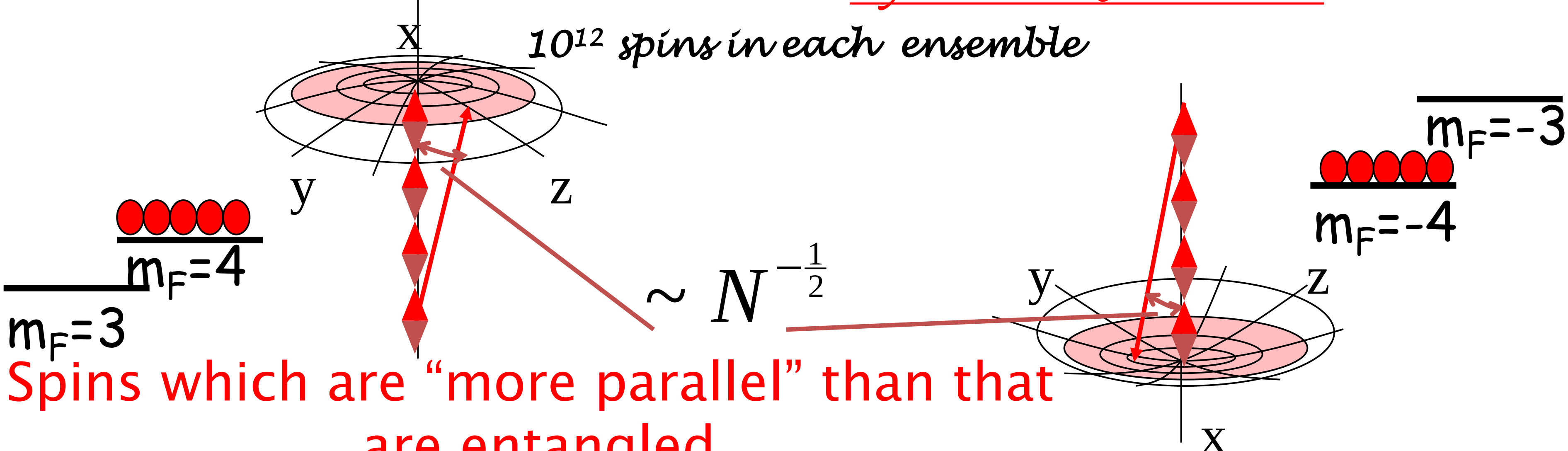
B. Julsgaard, A. Kozhekin, EP, ***Nature***, **413**, 400 (2001)

$$Var(X - X_0) + Var(P + P_0) < 2$$

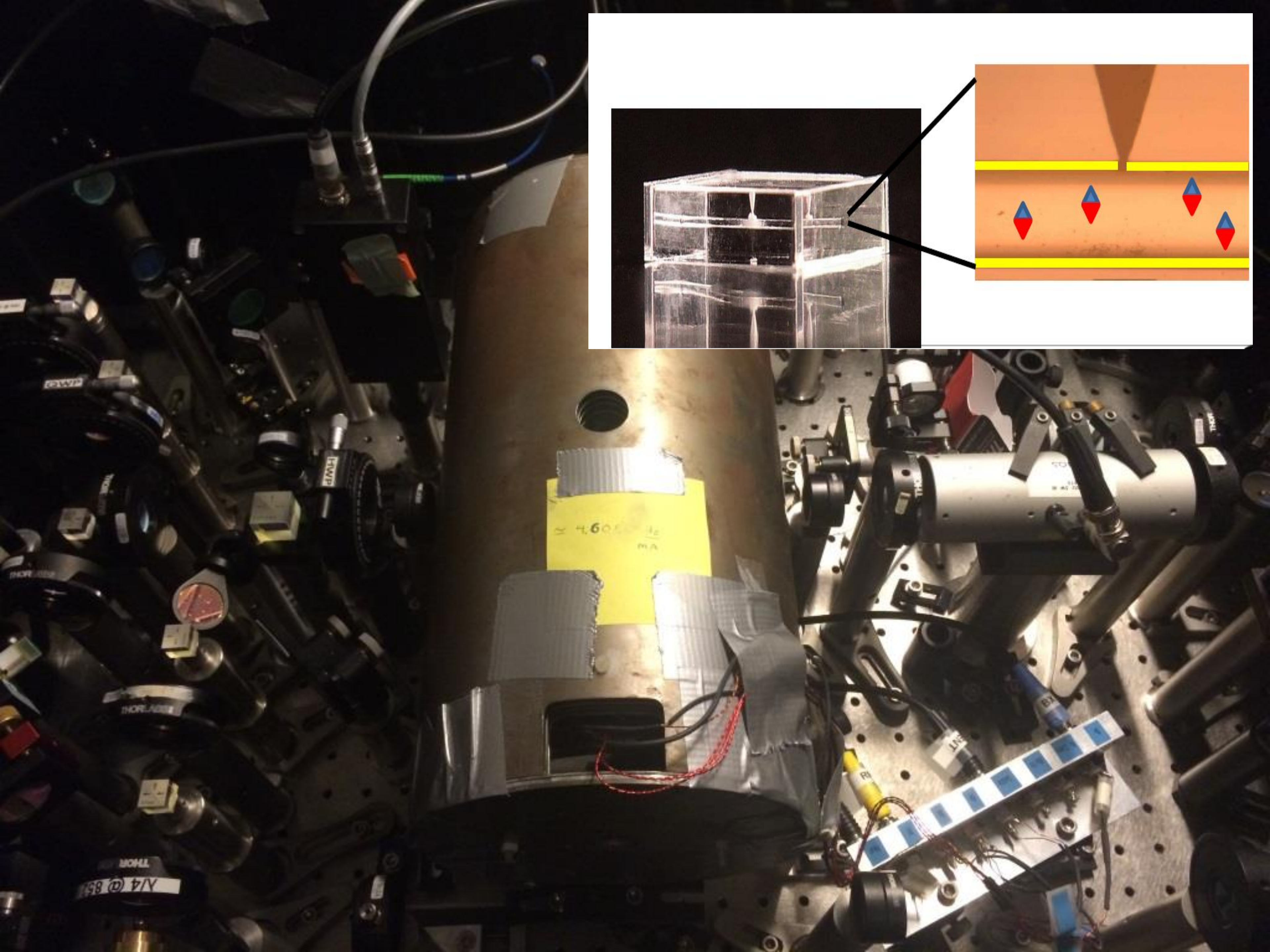
$$Var\left(\hat{J}_{z1} + \hat{J}_{z2}\right)/2J_x + Var\left(\hat{J}_{y1} + \hat{J}_{y2}\right)/2J_x < \boxed{2}$$

Can be created by a measurement

10^{12} spins in each ensemble



Spins which are “more parallel” than that are entangled

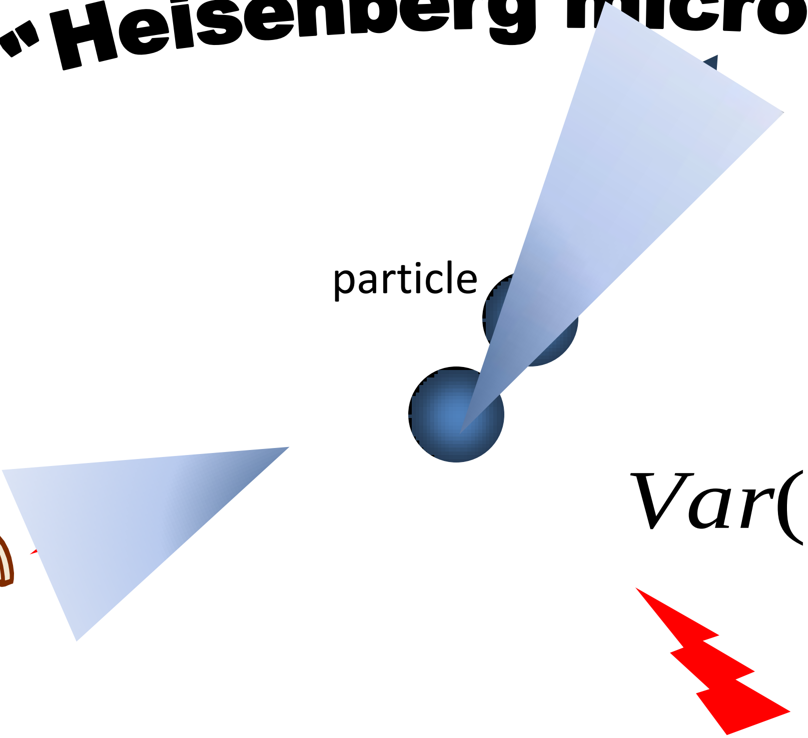

QWP
HWP
THORLABS
λ/4 @ 85

Standard quantum limit of displacement measurement

"Heisenberg microscope"

W. Heisenberg

N. Bohr



$$Var(X)Var(P) \geq 1/4$$

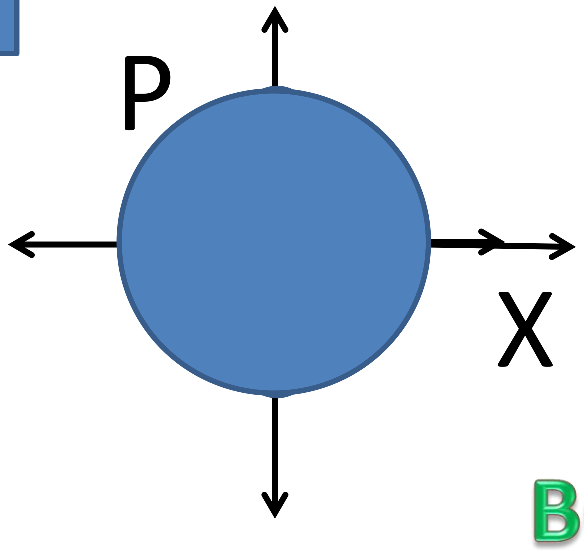
THE UNCERTAINTY PRINCIPLE

$$\left[\hat{X},\hat{P}\right]=i$$

Quantum limits for detection of motion

$$Var(X)Var(P) \geq 1/4$$

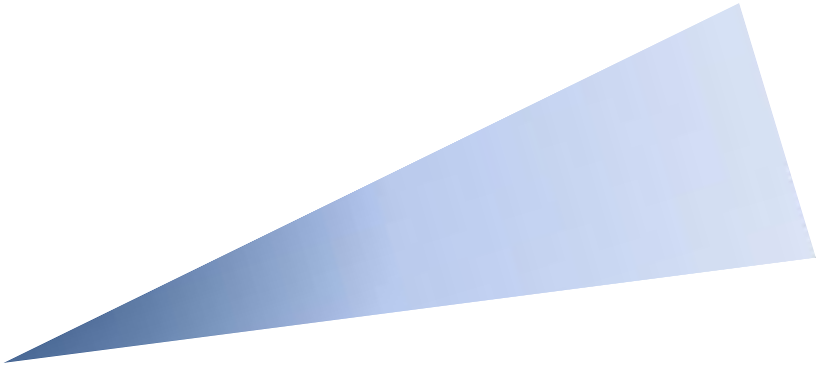
$$X_{Lab}(t) = \mathrm{X}\sin(\omega t) + \mathrm{P}\cos(\omega t)$$



And yet, arbitrary small perturbations in BOTH position and momentum can be measured simultaneously

Trajectories without quantum uncertainties

in negative mass reference frame



E.S. Polzik, K. Hammerer. Ann. der Physik 527, A15 (2015).

W. Wasilewski et al. **PRL**, 104, 133601 (2010).

K. Hammerer et al. **PRL**102, 020501 (2009).

See also:
Tsai and Caves, PRL 2010
M. Ozawa

3 steps to noiseless quantum trajectories

1. Define trajectory relative to a quantum reference

2. Reference system has an effective negative mass

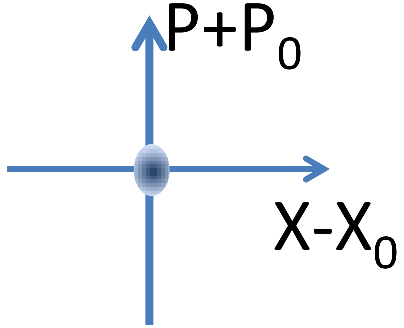
3. Entangled state of the reference and the probed systems is generated

“Experimental long-lived entanglement of two macroscopic objects”.
B. Julsgaard, A. Kozhekin and ESP. **Nature**, 413, 400 (**2001**)

“Establishing Einstein-Podolsky-Rosen channels between nanomechanics and atomic ensembles”. K. Hammerer, M. Aspelmeyer, ESP, P. Zoller. **PRL** 102, 020501 (**2009**).

“Trajectories without quantum uncertainties”. K. Hammerer and ESP, **Annalen der Physik . (2015)**

Trajectory in a quantum reference frame



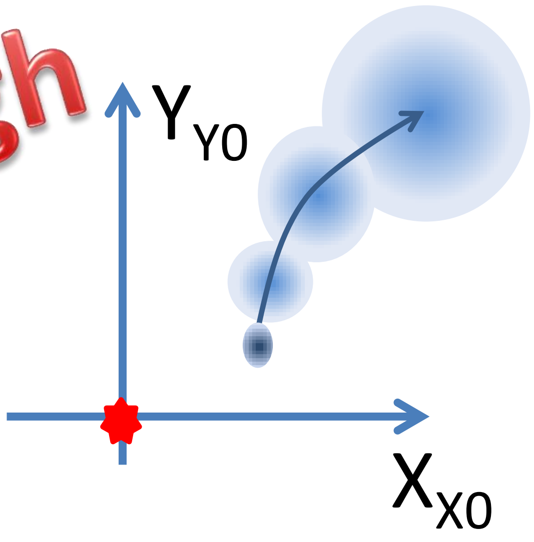
$$X - X_0 = X_{X0} \to 0$$
$$P + P_0 \to 0$$

Probe system entangled with origin system

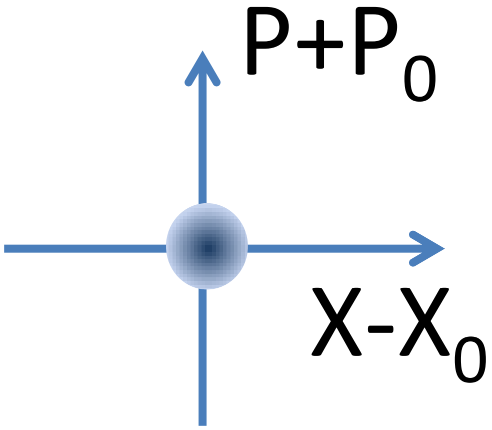
$$
\begin{aligned}
X(dt)_{X0} &= X(0)_{X0} + \left(\dot{X} - \dot{X}_0\right)dt \\
&= X(0)_{X0} + (P - P_0)dt
\end{aligned}
$$

$m = m_0 = 1$

Not good enough



Trajectory in reference frame with negative mass



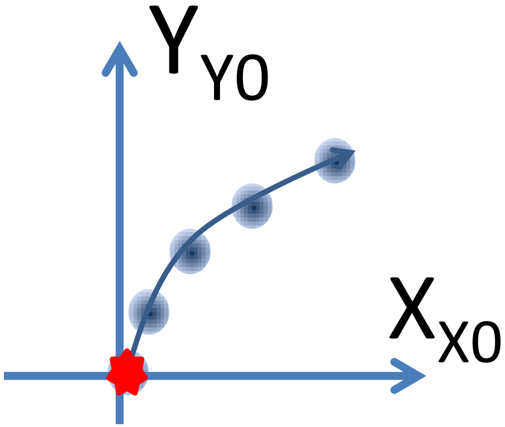
EPR state relative to a negative mass origin

$$X(t)_{X0} = X(0)_{X0} + \left(\dot{X} - \dot{X}_0\right)dt$$

$$= X(0)_{X0} + (P + P_0)\,dt =$$

$$= X(0)_{X0} + \text{ classical dynamics}$$

$m = - m_0 = 1$



Oscillator: mass, spring constant, frequency<0

$$X(t) = X(0)\cos(\omega t) + P(0)\sin(\omega t)\,/m$$

Oscillator in negative mass ($m = - m_0$) reference oscillator frame:

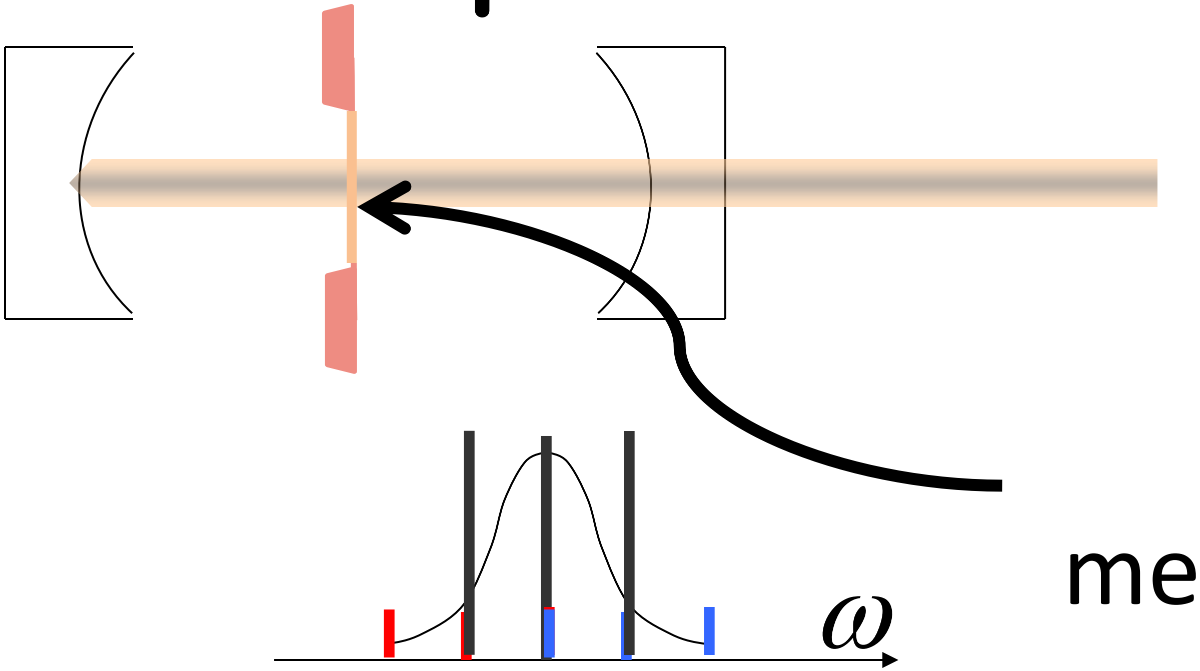
$$X(t) - X_0(t) =$$
$$[X(0) - X_0(0)]\cos(\omega t) + [P(0) + P_0(0)]\sin(\omega t)/\omega \mathrm{m}$$

$$Var[X(t) - X_0(t)] < 1$$

<u>EPR:</u>

$$Var(X - X_0) + Var(P + P_0) < 2$$

Quantum Optomechanics




Yeghishe Tsaturyan

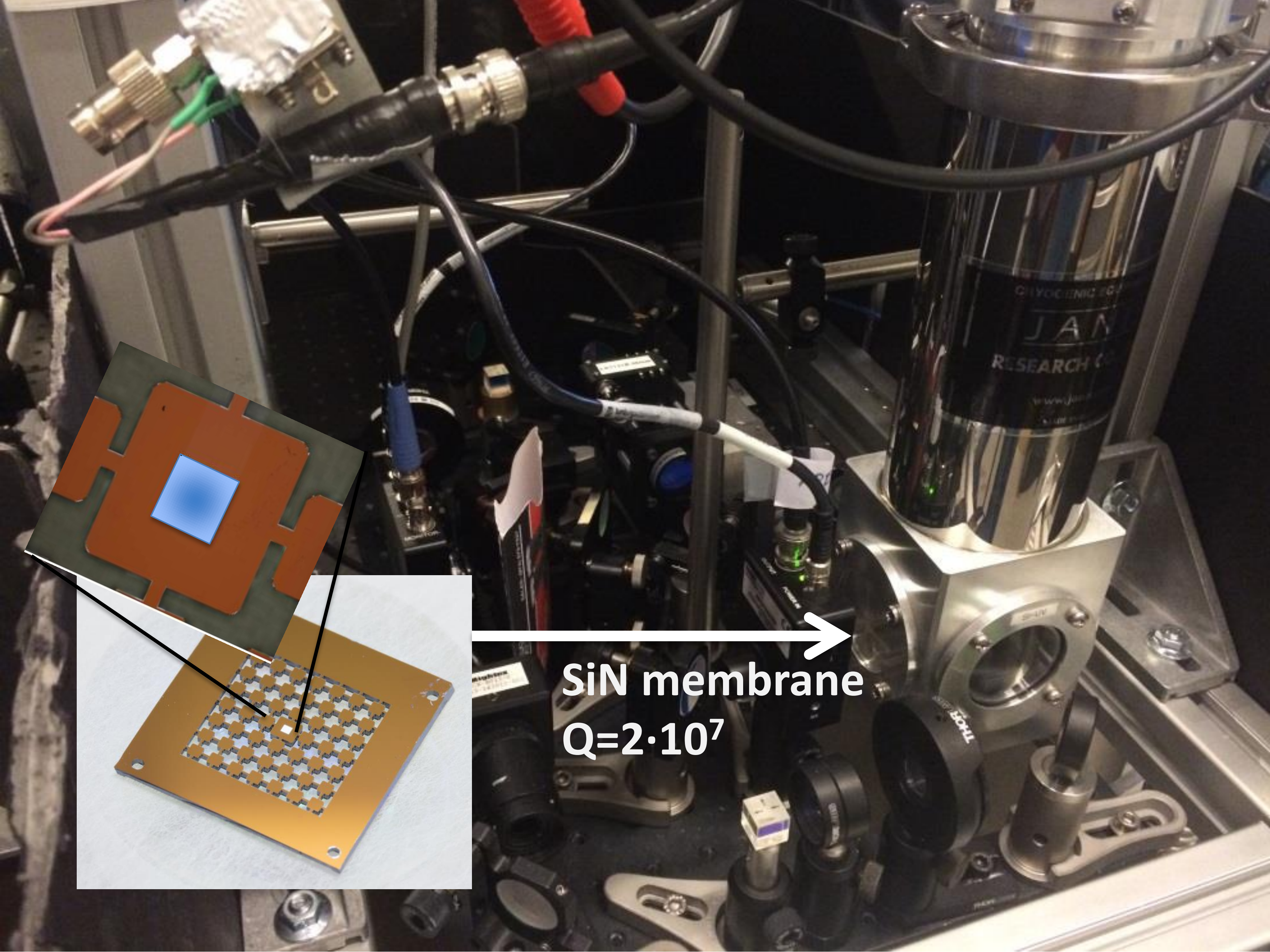
$$H = \chi_{Par}\hat{a}^{\dagger}\hat{b}^{\dagger} + \chi_{BS}\hat{a}^{\dagger}\hat{b} + h.c.$$

$$= gX_M X_L \qquad g = \chi_{Par} = \chi_{BS}$$

phoTon

phoNon


Albert Schliesser

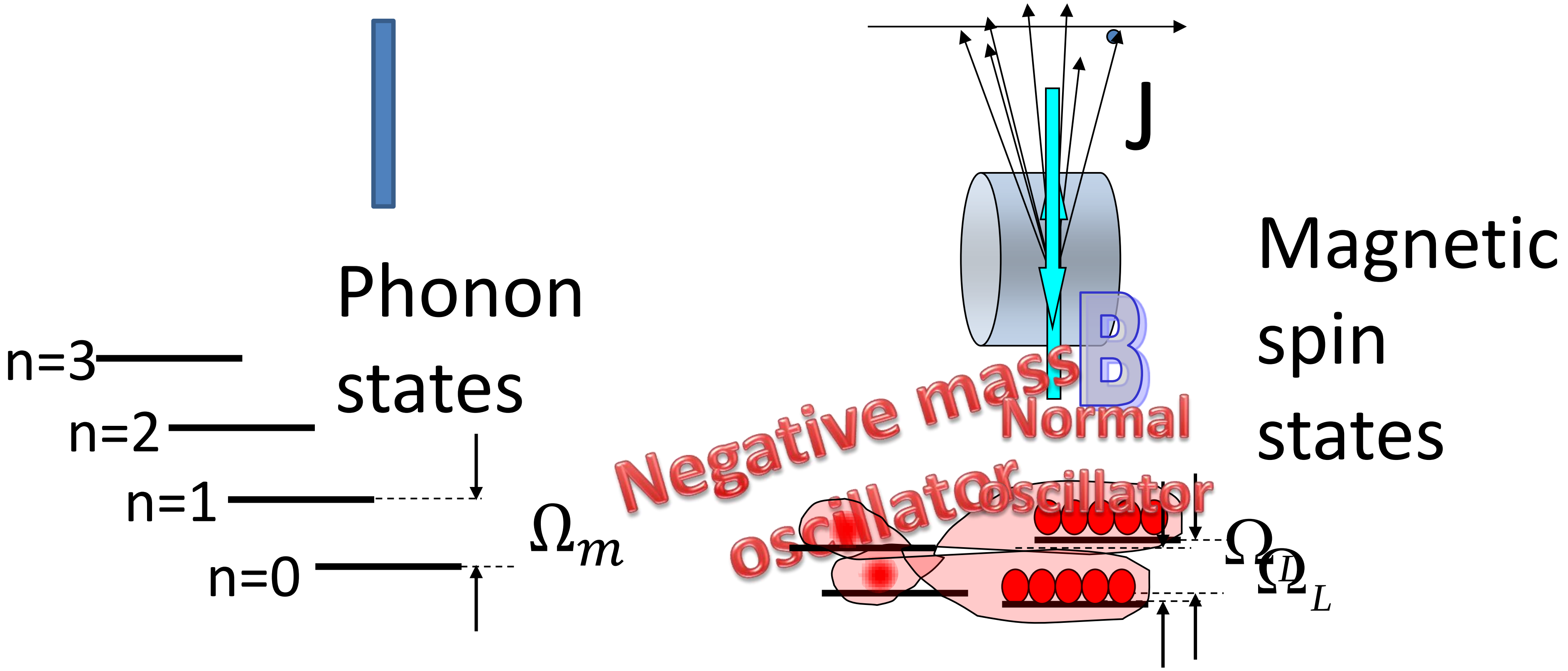


SiN membrane

$Q=2\cdot10^7$

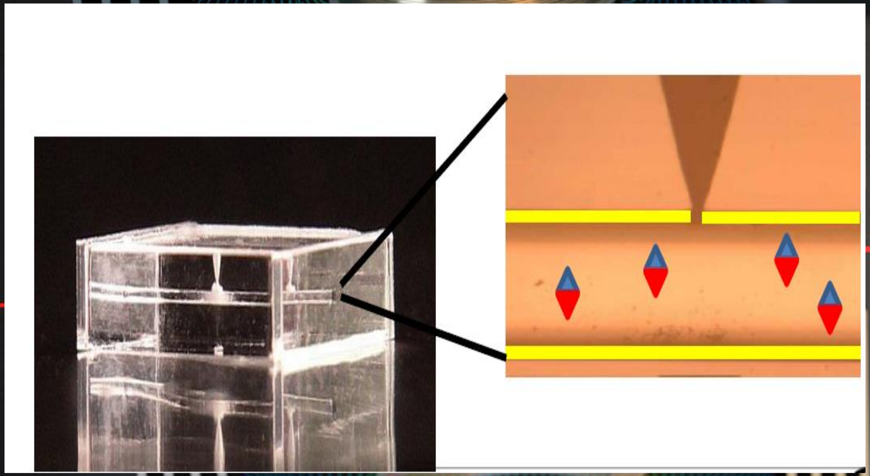
Quantum back-action-evading measurement of motion in a negative mass reference frame

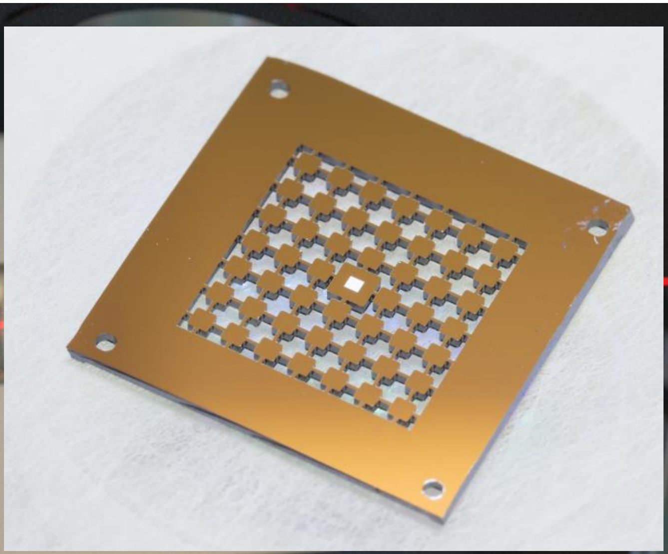
Christoffer B. Møller[1*], Rodrigo A. Thomas[1*], Georgios Vasilakis[1,2], Emil Zeuthen[1,3], Yeghishe Tsaturyan[1], Mikhail Balabas[1,4], Kasper Jensen[1], Albert Schliesser[1], Klemens Hammerer[3] & Eugene S. Polzik[1]



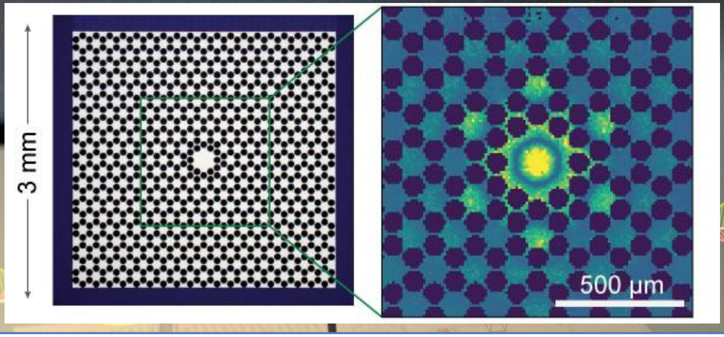
LETTER doi:10.1038/nature22980

Distributed HYBRID quantum system of SPIN and MECHANICS at (nearly) room temperature





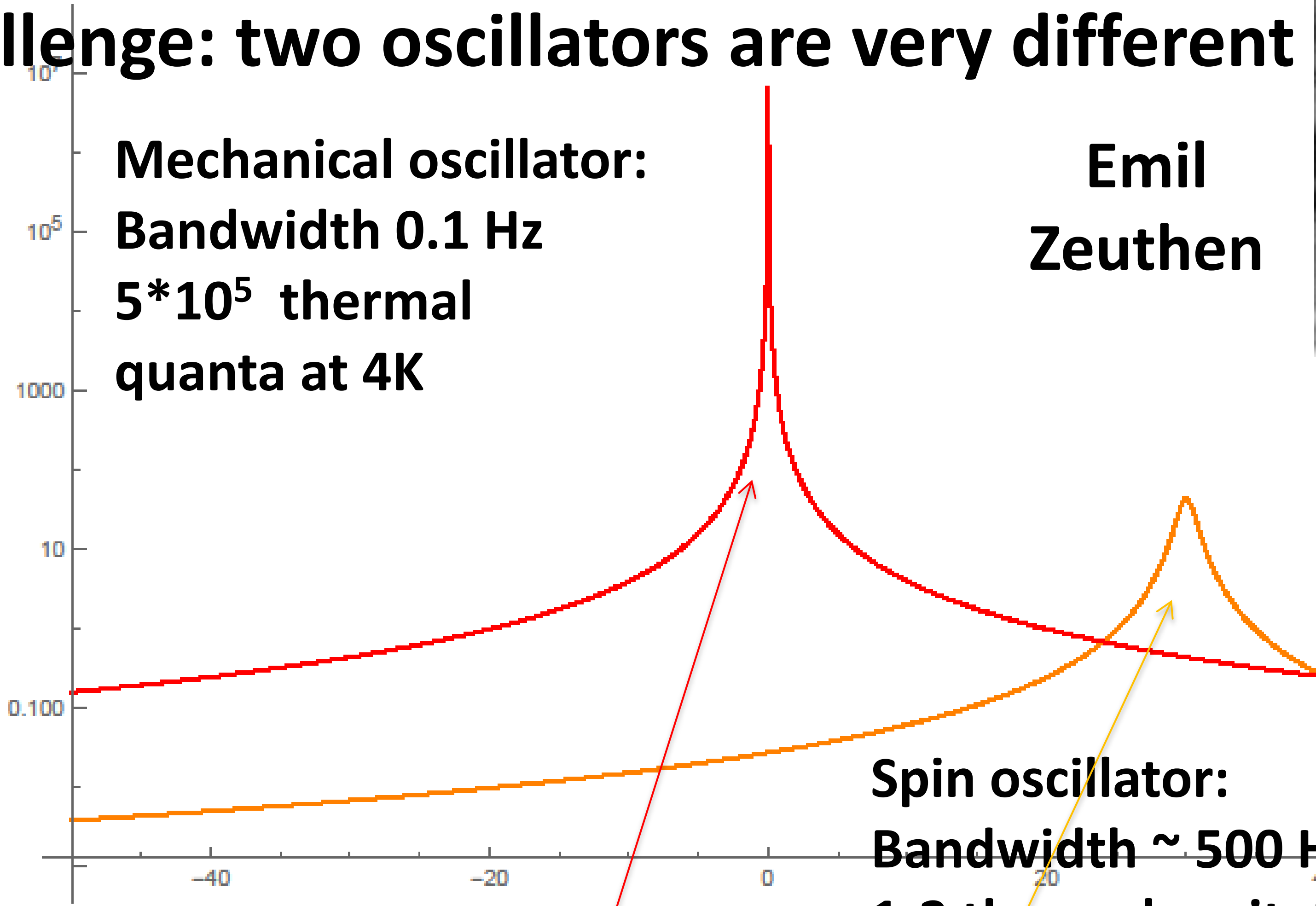
Room temperature spin quantum oscillator



Mechanical oscillator with Q = 1 billion

Image credit
Bastian Leonhardt Strube and Mads Vadsholt

Challenge: two oscillators are very different



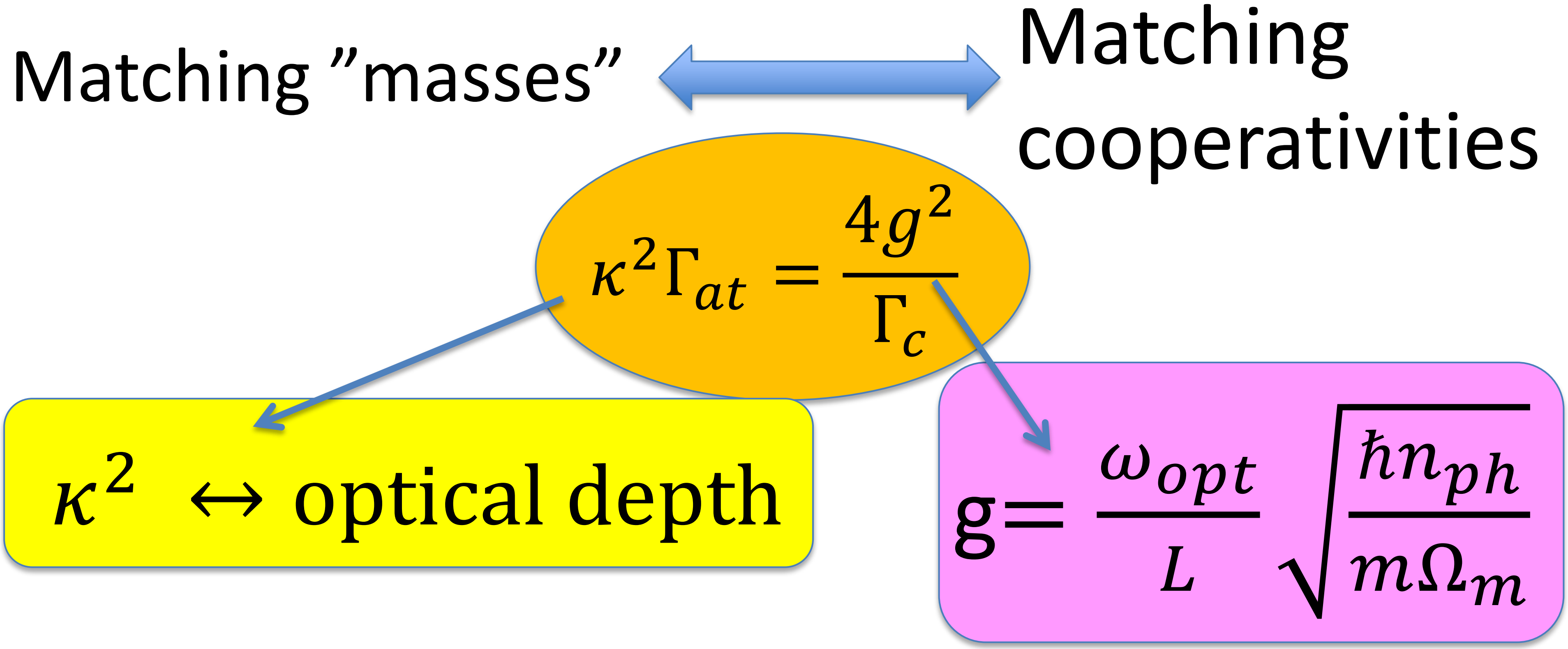
Mechanical oscillator:
Bandwidth 0.1 Hz
$5*10^5$ thermal
quanta at 4K

Emil
Zeuthen

Spin oscillator:
Bandwidth ~ 500 Hz
1-2 thermal excitations

$$\hat{P}_{L,\text{out}} = -\hat{P}_{L,\text{in}} - \sqrt{\Gamma_M \gamma_M}\,\chi_M \hat{F}_M + \sqrt{\Gamma_S \gamma_S}\,\chi_S \hat{F}_S + [\Gamma_M \chi_M + \Gamma_S \chi_S]\,\hat{X}^S_{L,\text{in}}$$

Matching quantum back actions for hybrid mechanical – spin system



Matching ”masses” ↔ Matching cooperativities

$$\kappa^2 \Gamma_{at} = \frac{4g^2}{\Gamma_c}$$

$\kappa^2 \leftrightarrow$ optical depth

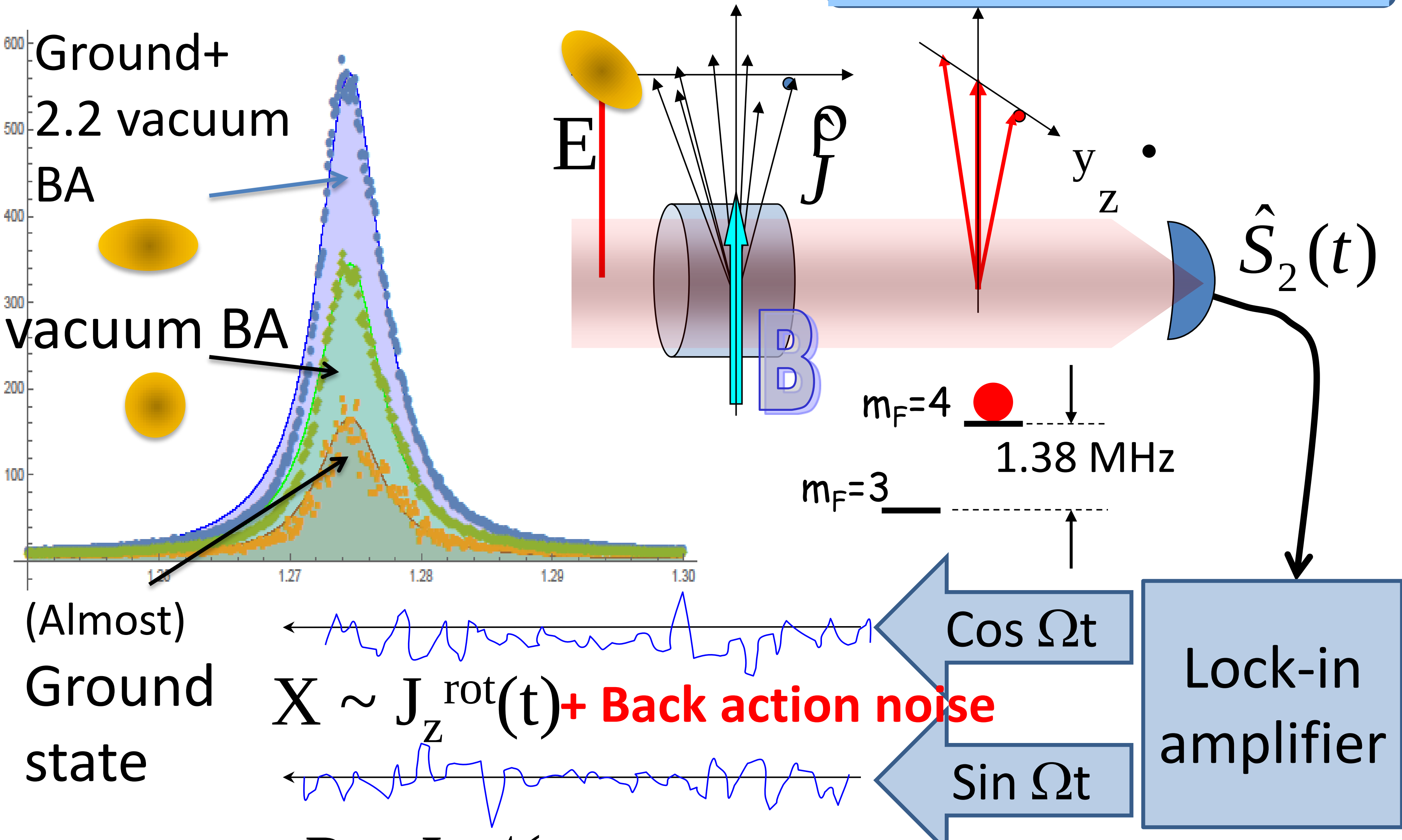
$$g = \frac{\omega_{opt}}{L} \sqrt{\frac{\hbar n_{ph}}{m \Omega_m}}$$

$$H_{spin} = \frac{\kappa}{\tau_p} X_{spin} x_{light}$$

$$H_{mech} = g x_{Mech} x_{light}$$

Quantum back action onto spin oscillator

$$J_z^{lab} = J_z^{rot}\cos\Omega t - J_y^{rot}\sin\Omega t$$



Ground+ 2.2 vacuum BA

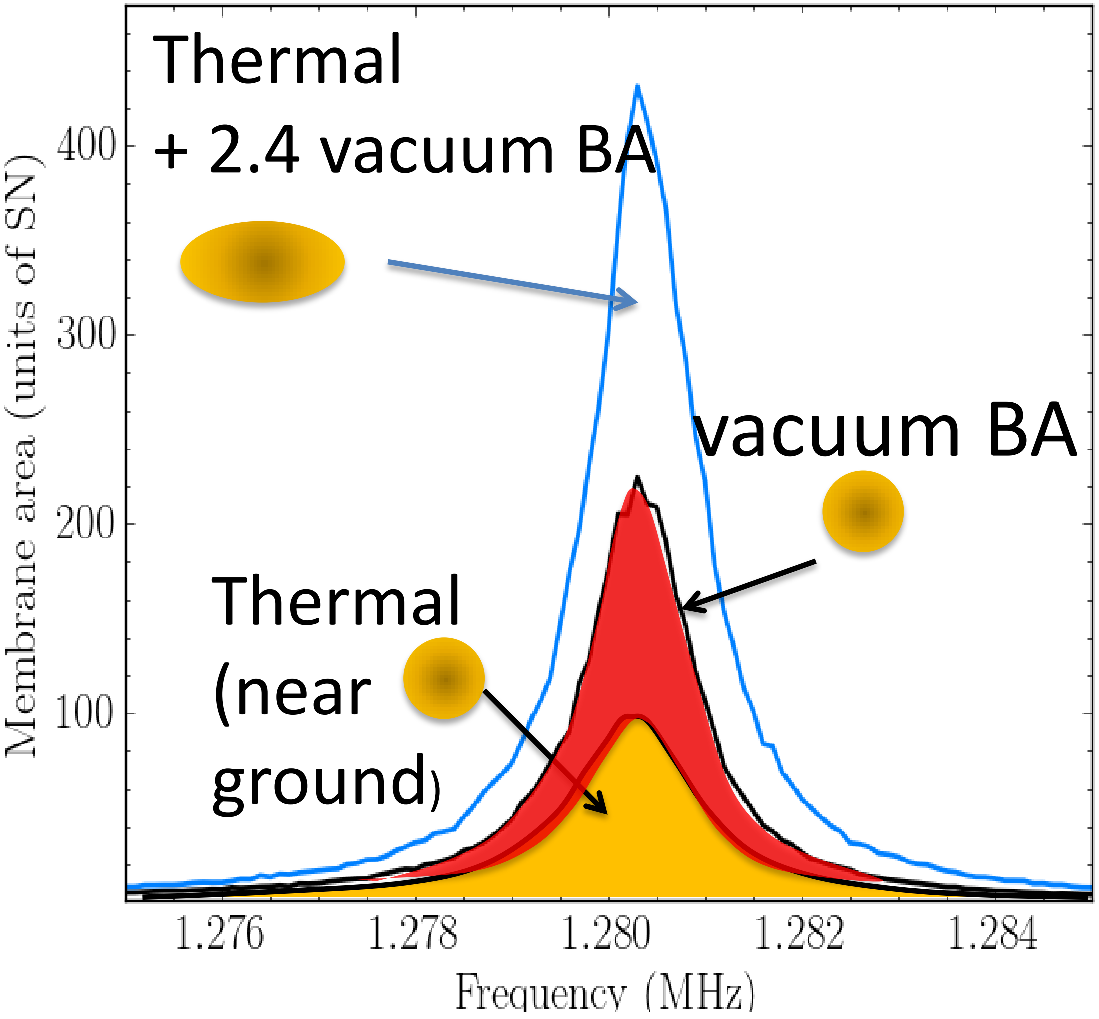
vacuum BA

(Almost) Ground state

$X \sim J_z^{rot}(t)$ **+ Back action noise**

$P \sim J_y^{rot}(t)$ **+ Back action noise**

Mechanical oscillator. Cooling + Q back action

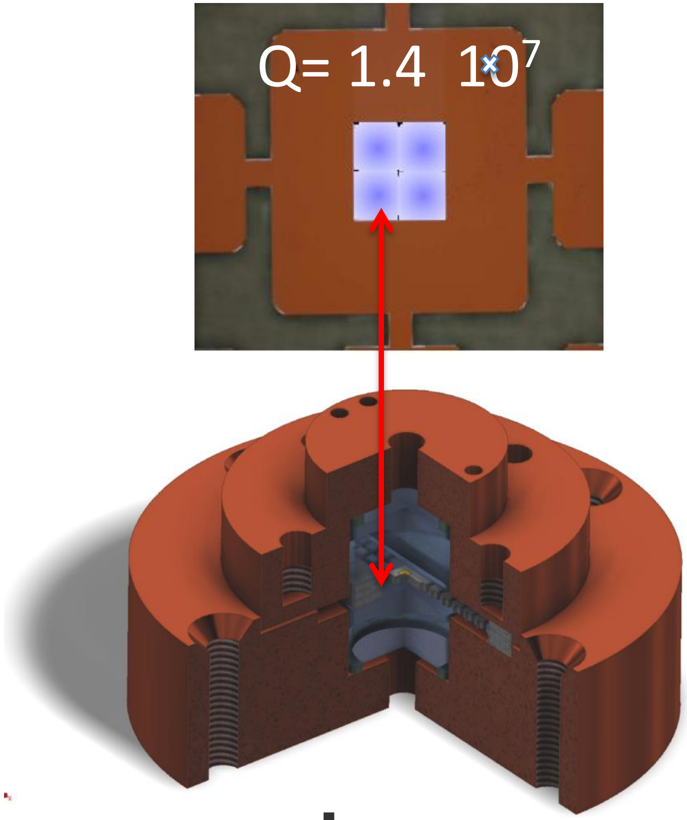


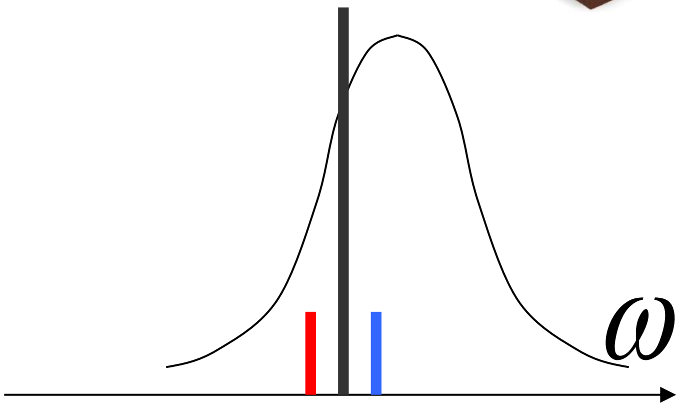
Thermal

+ 2.4 vacuum BA

vacuum BA

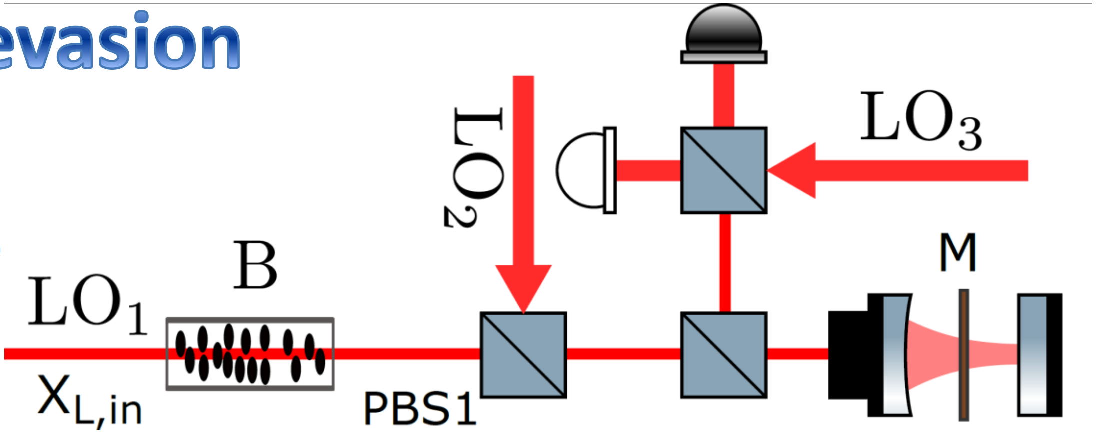
Thermal (near ground)



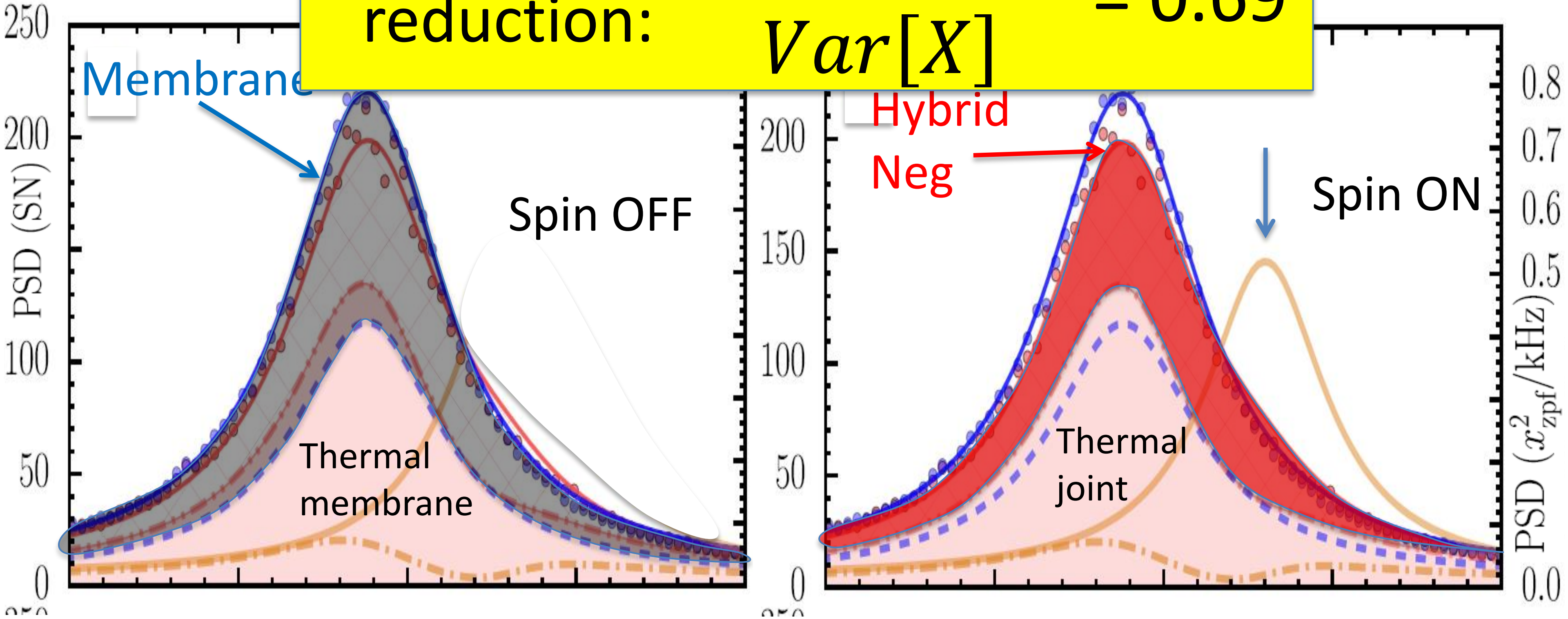


See also: Regal group, Science 2013; Stamper-Kurn group, Nat. Phys. 2016

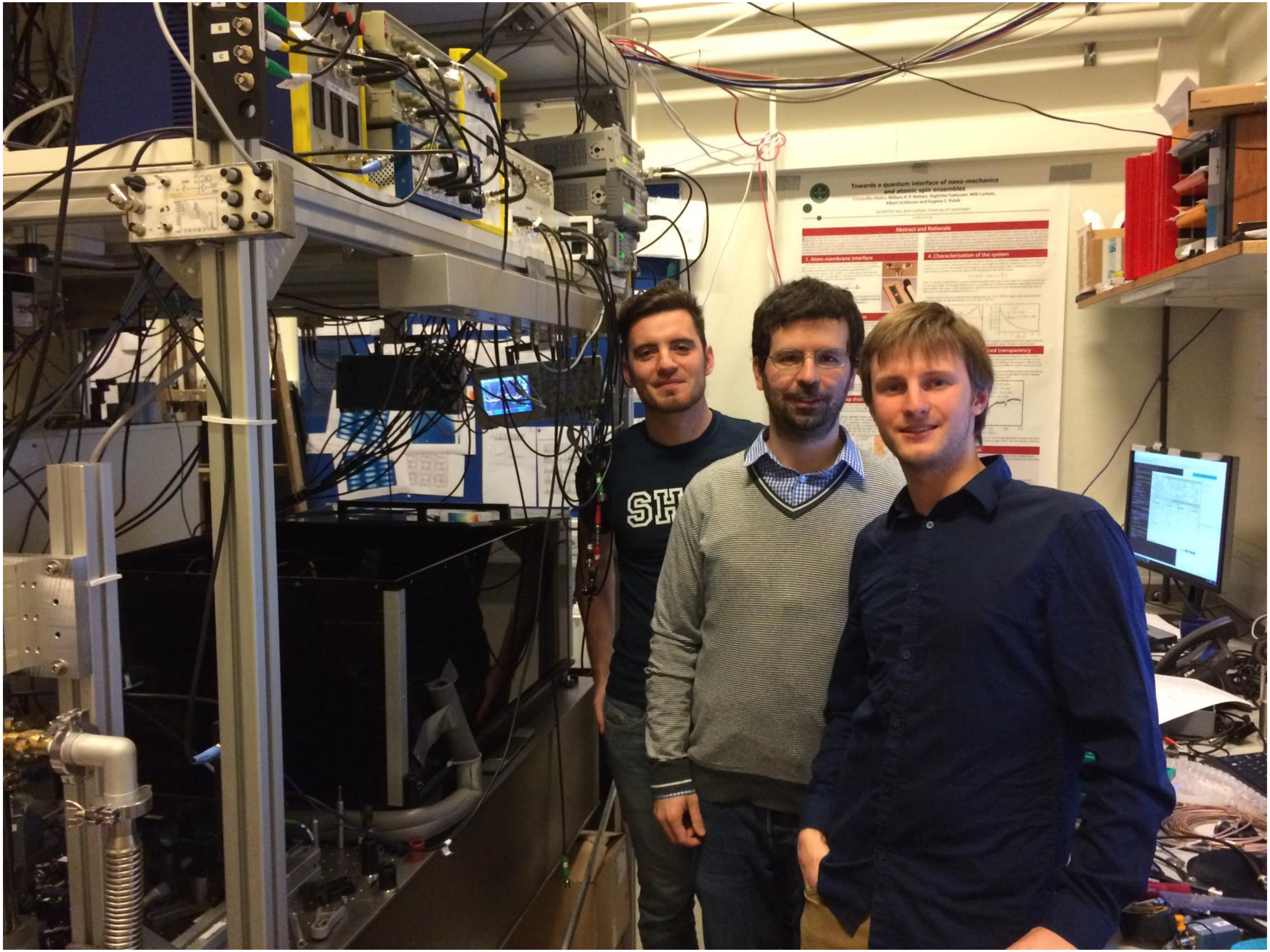
Quantum back action evasion in the spin reference frame



QBA reduction: $\frac{Var[X - X_0]}{Var[X]} = 0.69$



C. B. Møller et al. LETTER doi:10.1038/nature22980



Rodrigo Thomas   Giorgos Vasilakis   Christoffer Møller

PRL **116,** 061102 (2016)

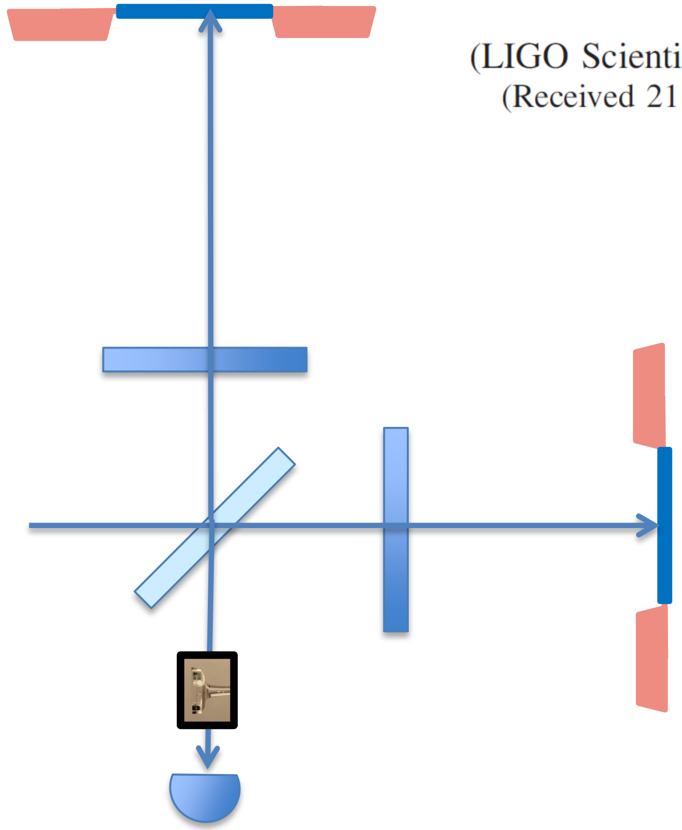
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

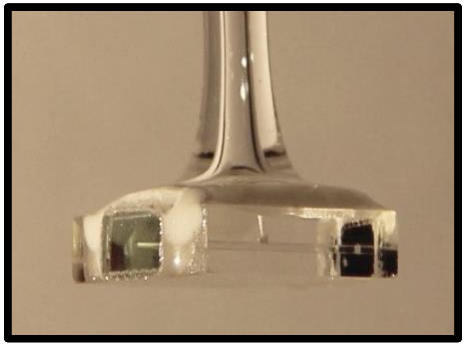
week ending
12 FEBRUARY 2016

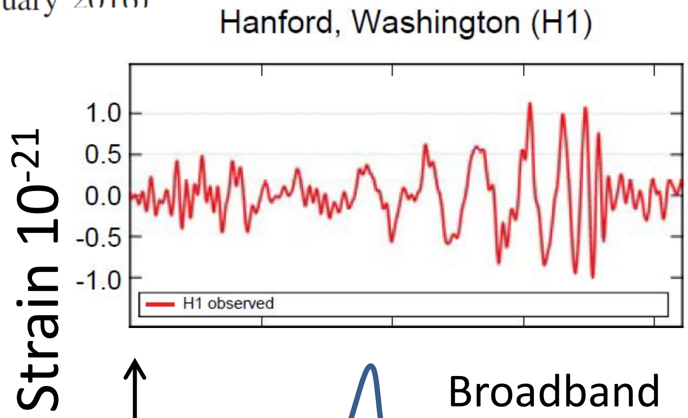
Observation of Gravitational Waves from a Binary Black Hole Merger

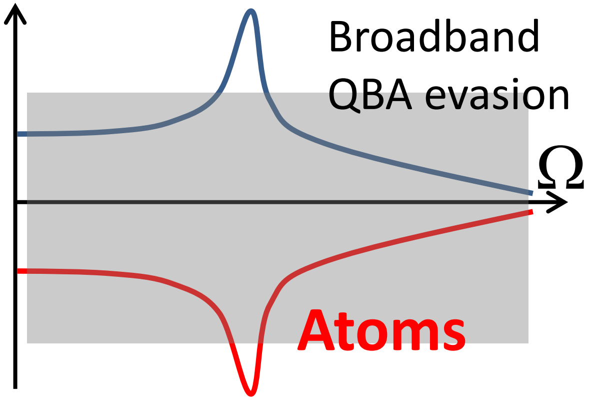
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)









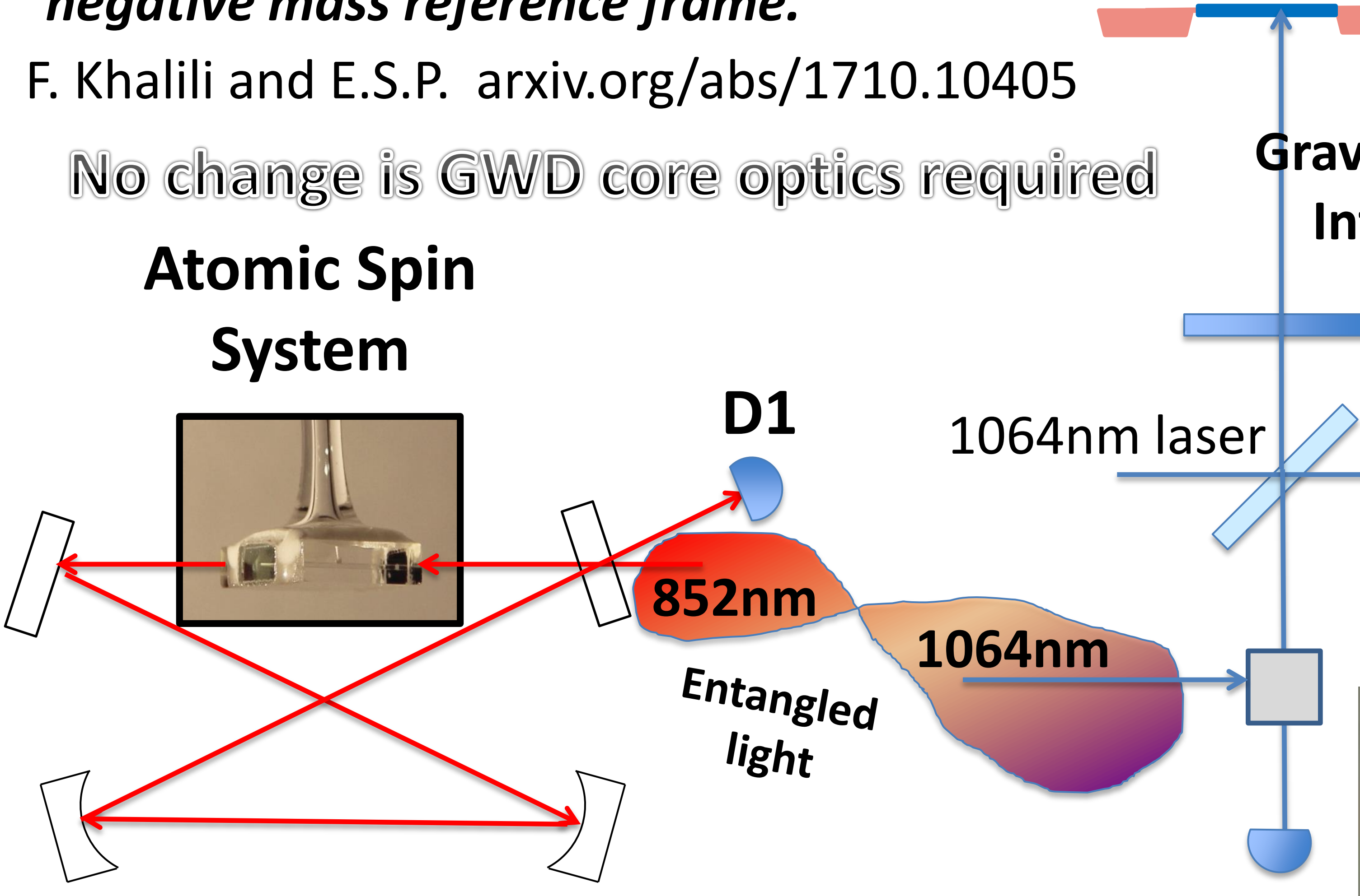
LIGO – LARGE INTERFEROMETER FOR GRAVITATIONAL WAVE OBSERVATION

SOON TO BE LIMITED BY QUANTUM BACK ACTION OF LIGHT

Quantum back action evading detection of gravitational waves in a negative mass reference frame.

F. Khalili and E.S.P. arxiv.org/abs/1710.10405

No change is GWD core optics required



See also:

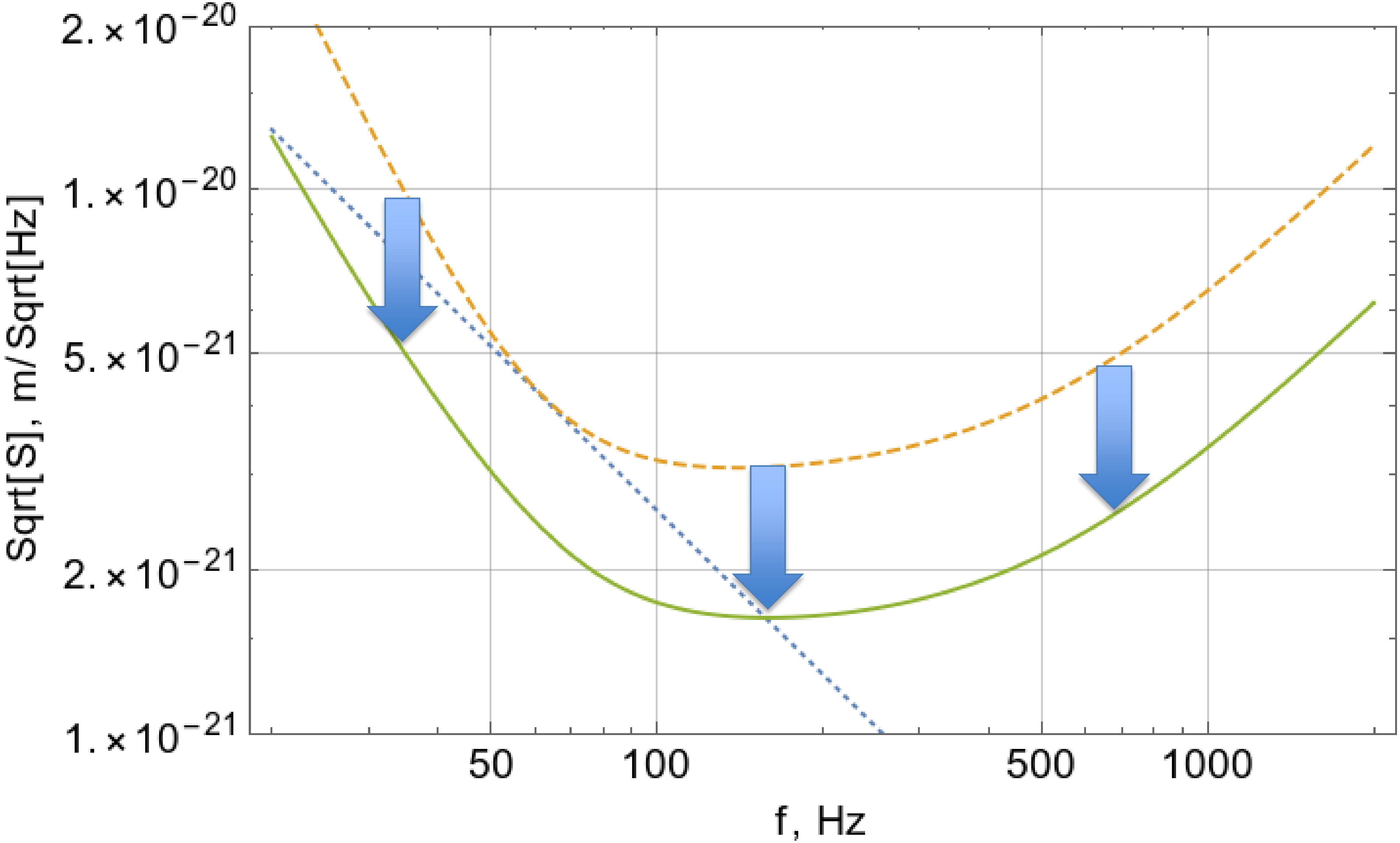
Y. Ma et al. **GWD with EPR light.** Nature Phys. 1, 2017

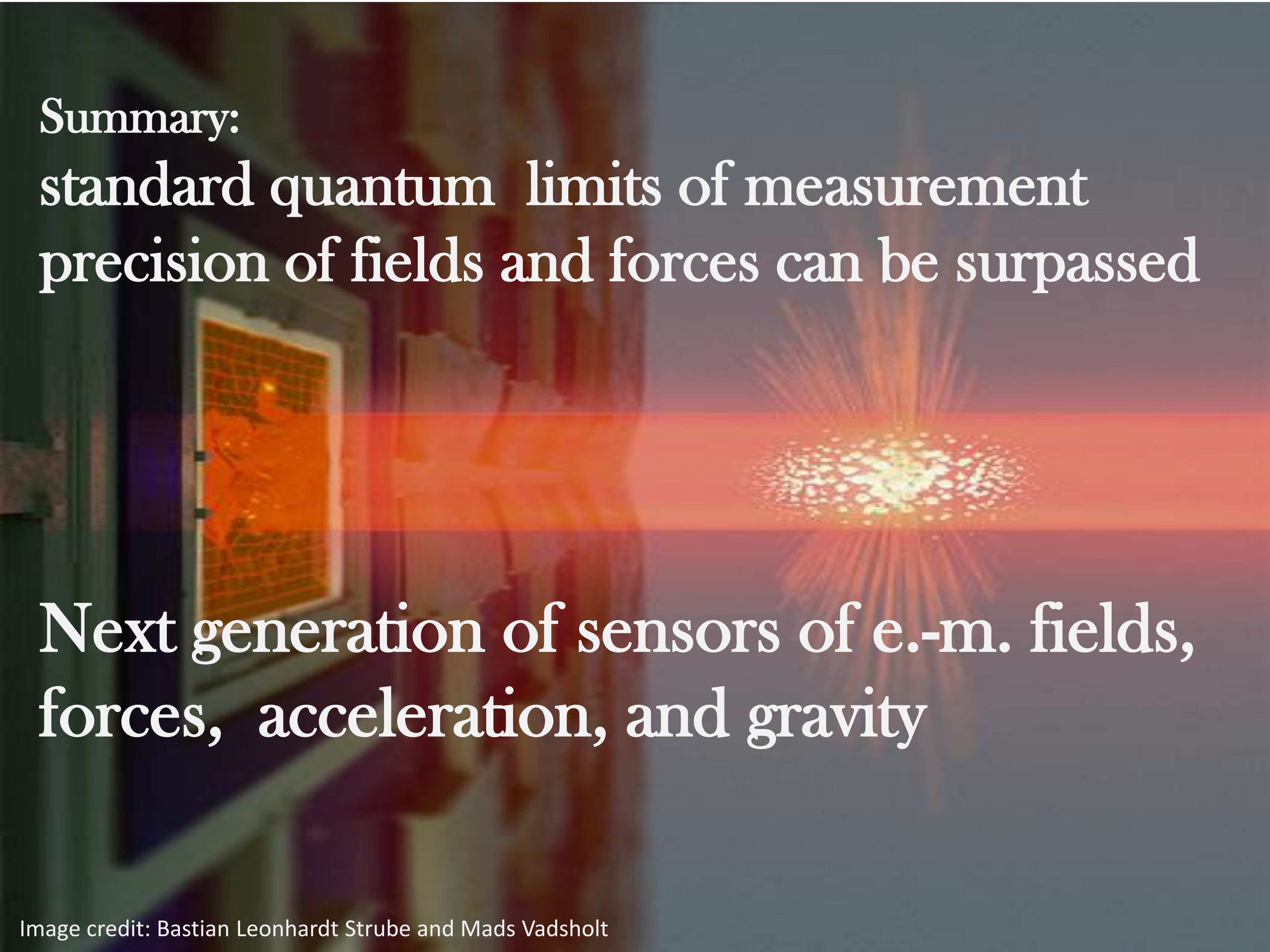
Jaekel and Renaud. **Phase rotation of squeezing**. EuroPhys Lett. 13, 301, 1990

H. Grote et al. ***Squeezed States of Light in GWD***. *PRL 110, 181101 (2013)*

F. Khalili and E.S.P.arxiv.org/abs/1710.10405

Simulation for LIGO





Summary:

standard quantum limits of measurement precision of fields and forces can be surpassed

Next generation of sensors of e.-m. fields, forces, acceleration, and gravity

Image credit: Bastian Leonhardt Strube and Mads Vadsholt