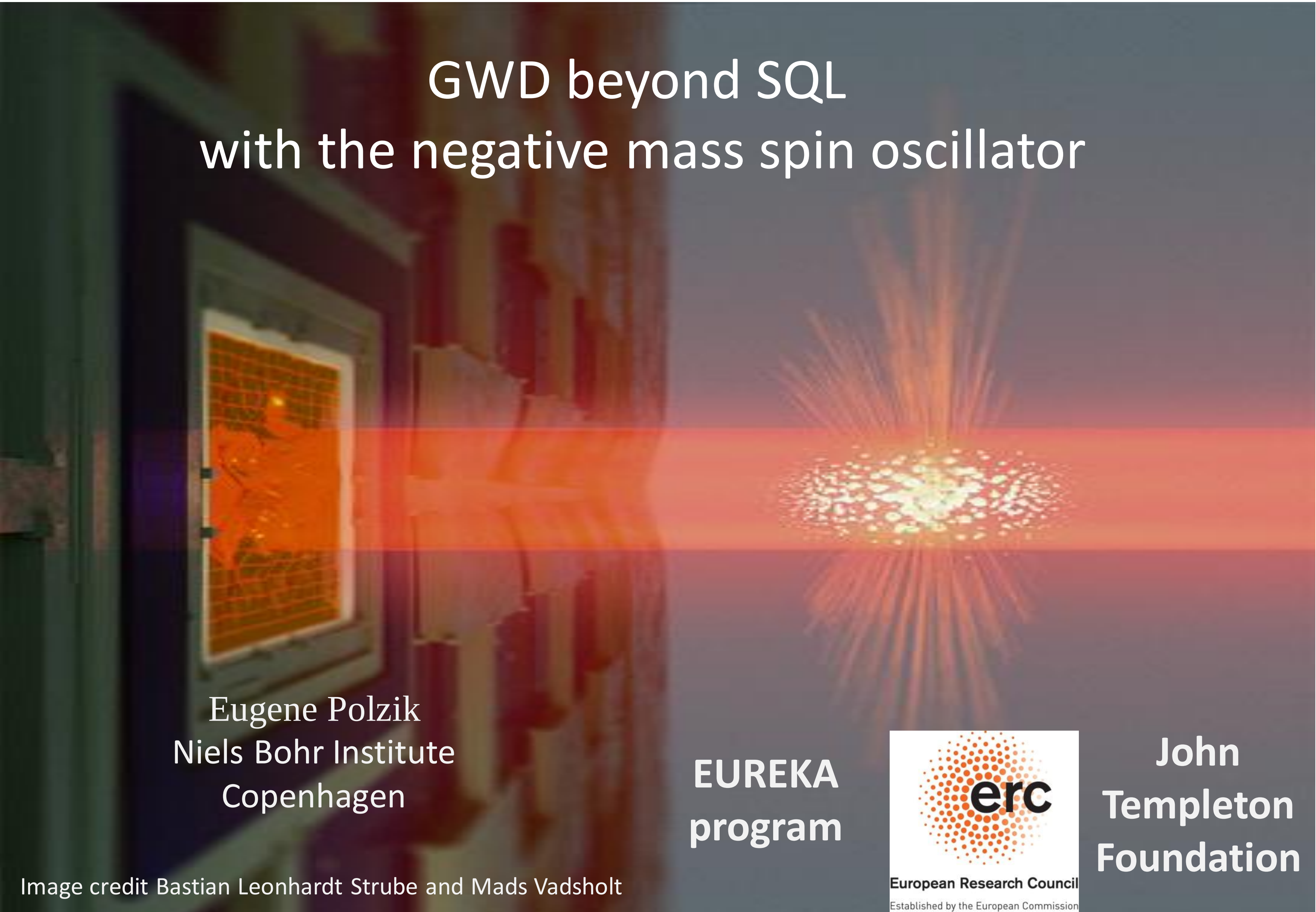
GWD beyond SQL with the negative mass spin oscillator



Eugene Polzik
Niels Bohr Institute
Copenhagen

EUREKA program

European Research Council
Established by the European Commission

John Templeton Foundation

Image credit Bastian Leonhardt Strube and Mads Vadsholt

X, P – noncommuting variables

Standard Quantum Limit
for motion of a free mass

$$X(t) = X + \frac{Pt}{m}, \quad \Delta X \Delta P \geqslant \frac{\hbar}{2} \Rightarrow$$

$$[\Delta X(t)]^2 \geqslant (\Delta X)^2 + \frac{\hbar^2 t^2}{4m^2(\Delta X)^2} \geqslant \frac{\hbar t}{m} \quad \text{(SQL)}$$

Motion in reference frame with negative mass

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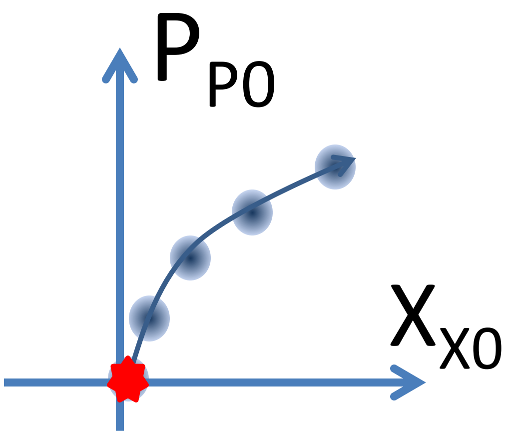
$P+P_0$, $X-X_0$ – commuting variables can be measured precisely

↓

Beyond SQL

$$X(t)_{X0} = X(0)_{X0} + \left(\dot{X} - \dot{X}_0\right)t$$
$$= X(0)_{X0} + (P + P_0)\,t\,/m =$$
$$= X(0)_{X0} + \text{ classical dynamics}$$

$$m_0 = -m$$



Spin ensemble = negative mass harmonic oscillator

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

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

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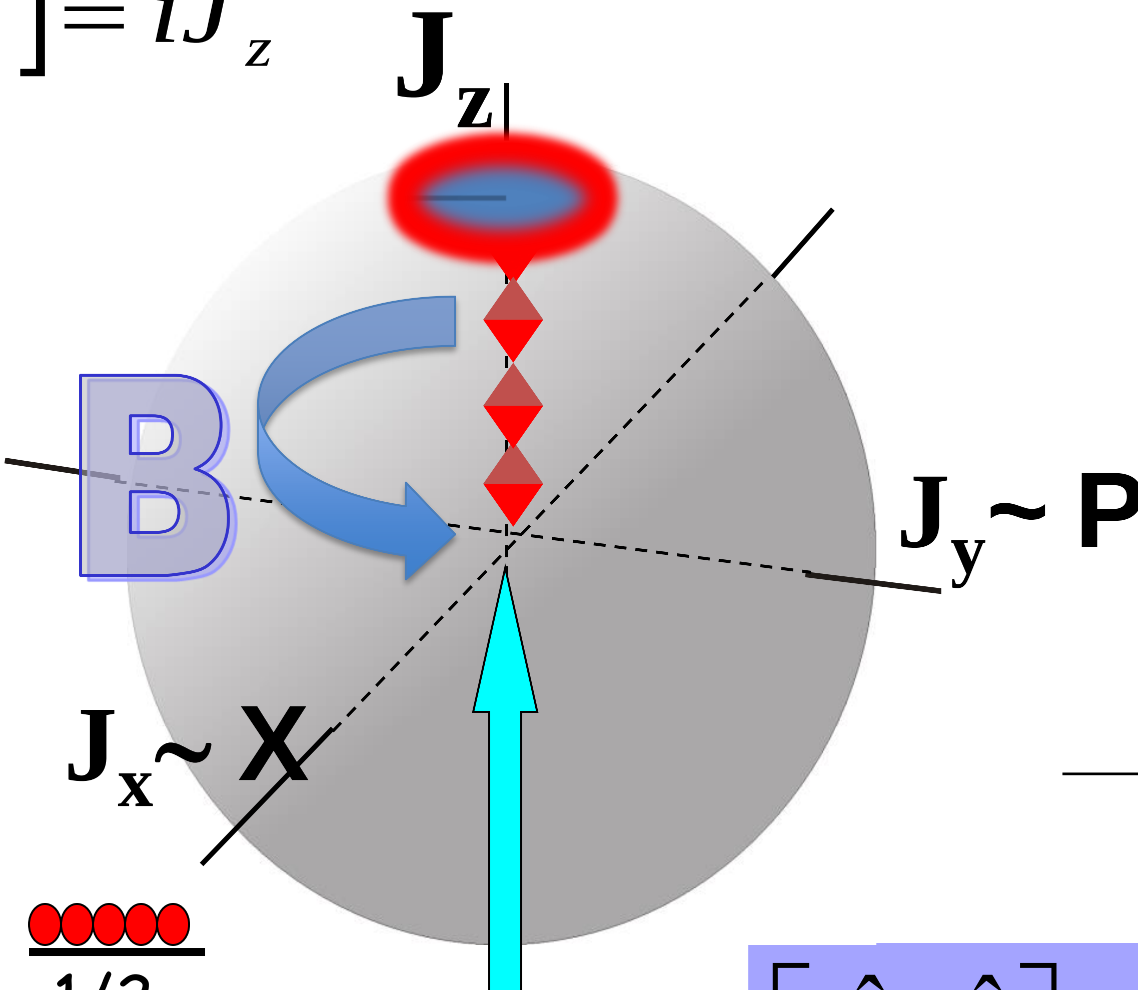
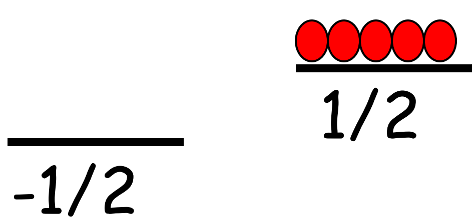
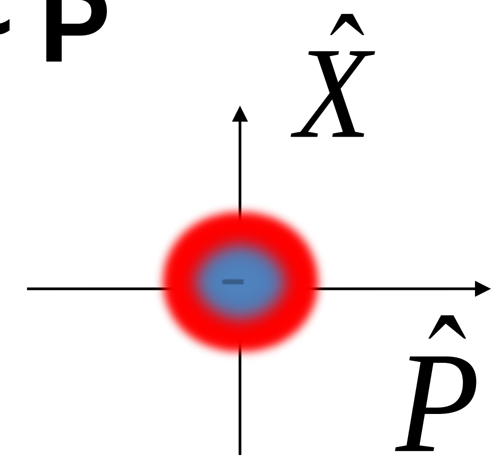




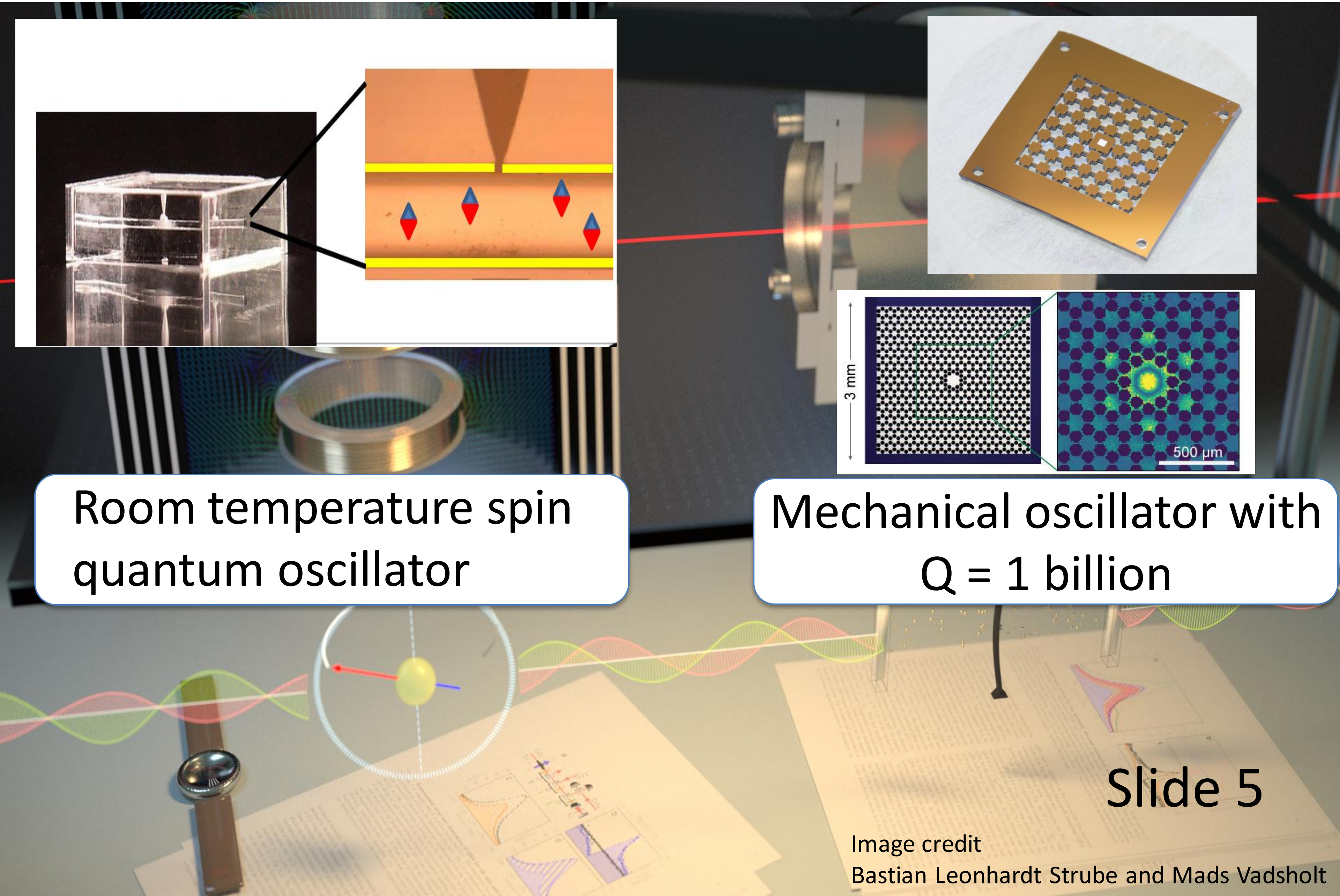


$$\left[\hat{X}, \hat{P}\right] = i$$

Negative mass oscillator

Holstein-Primakoff

Experimental demonstration for SPIN and Nano-MECHANICS



Room temperature spin quantum oscillator

Mechanical oscillator with Q = 1 billion

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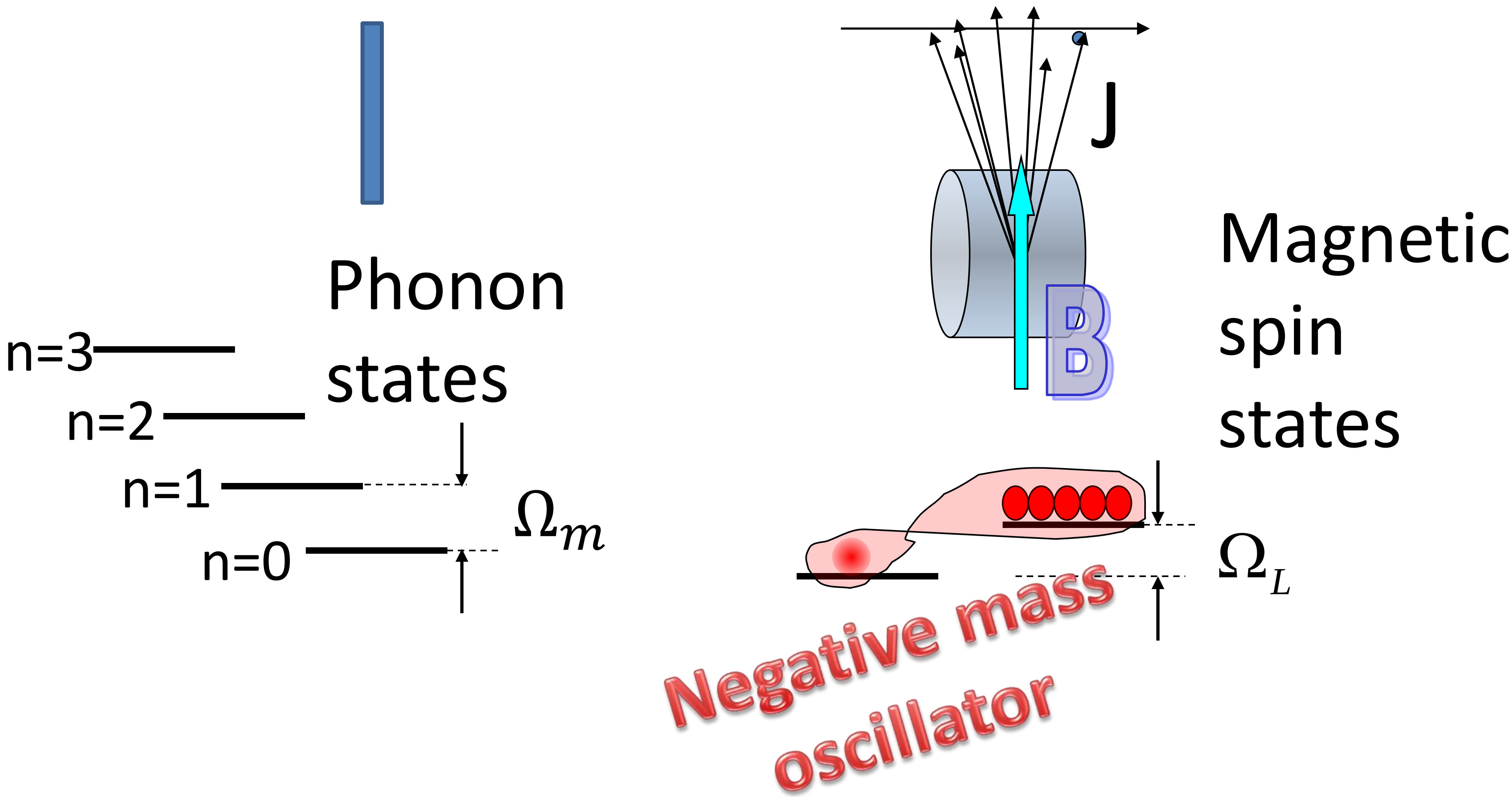
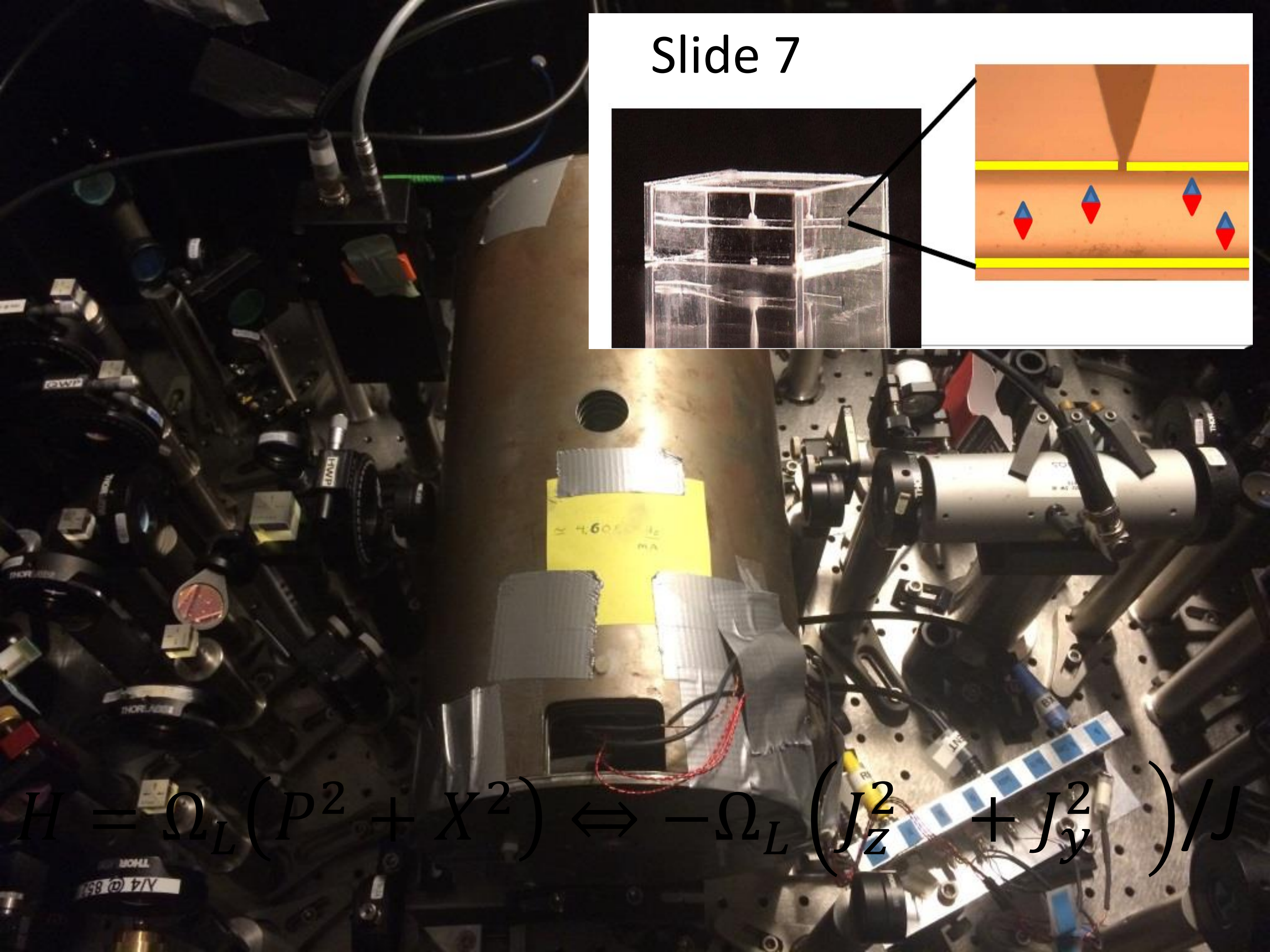
Image credit
Bastian Leonhardt Strube and Mads Vadsholt

LETTER doi:10.1038/nature22980

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]





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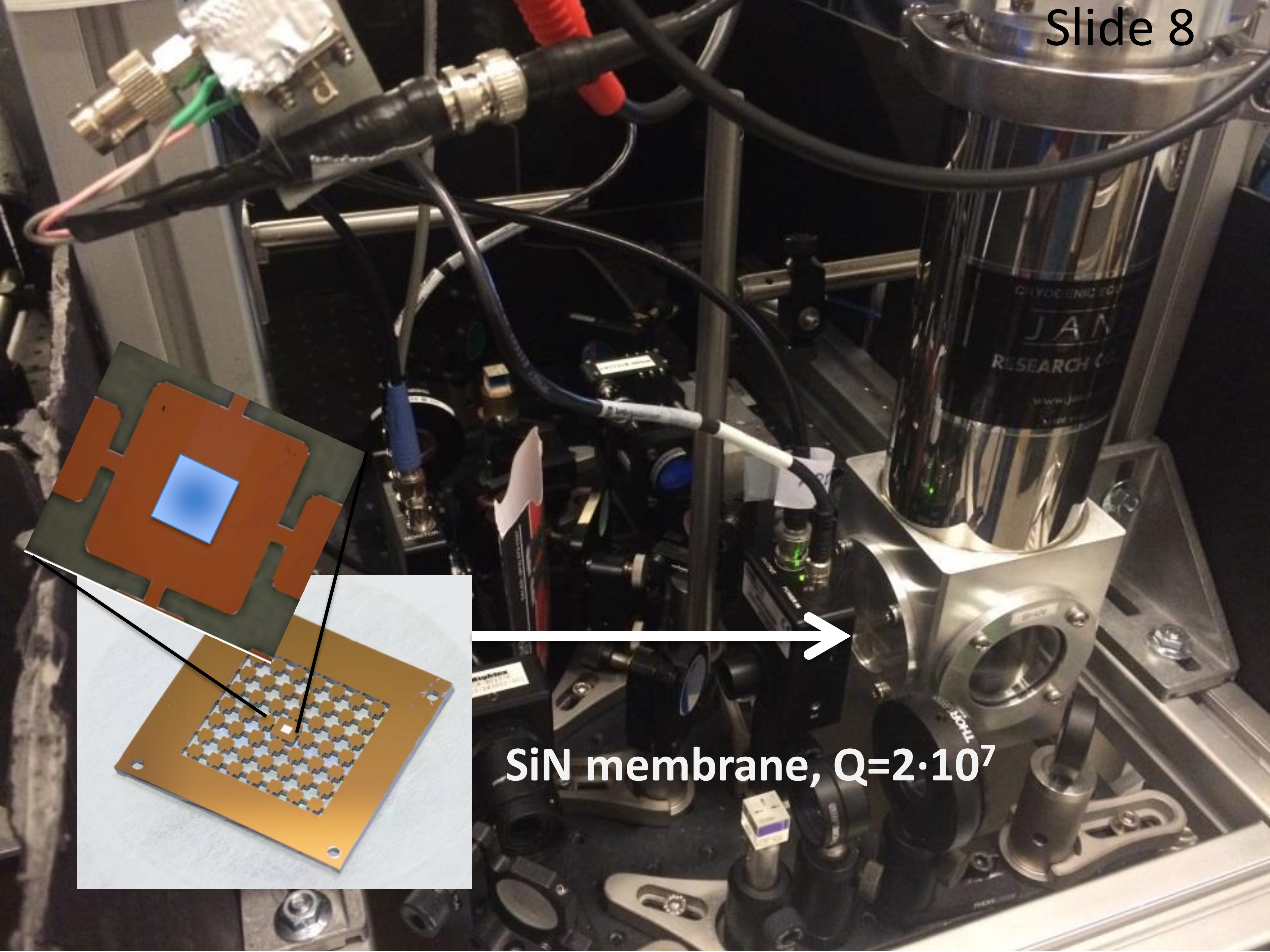
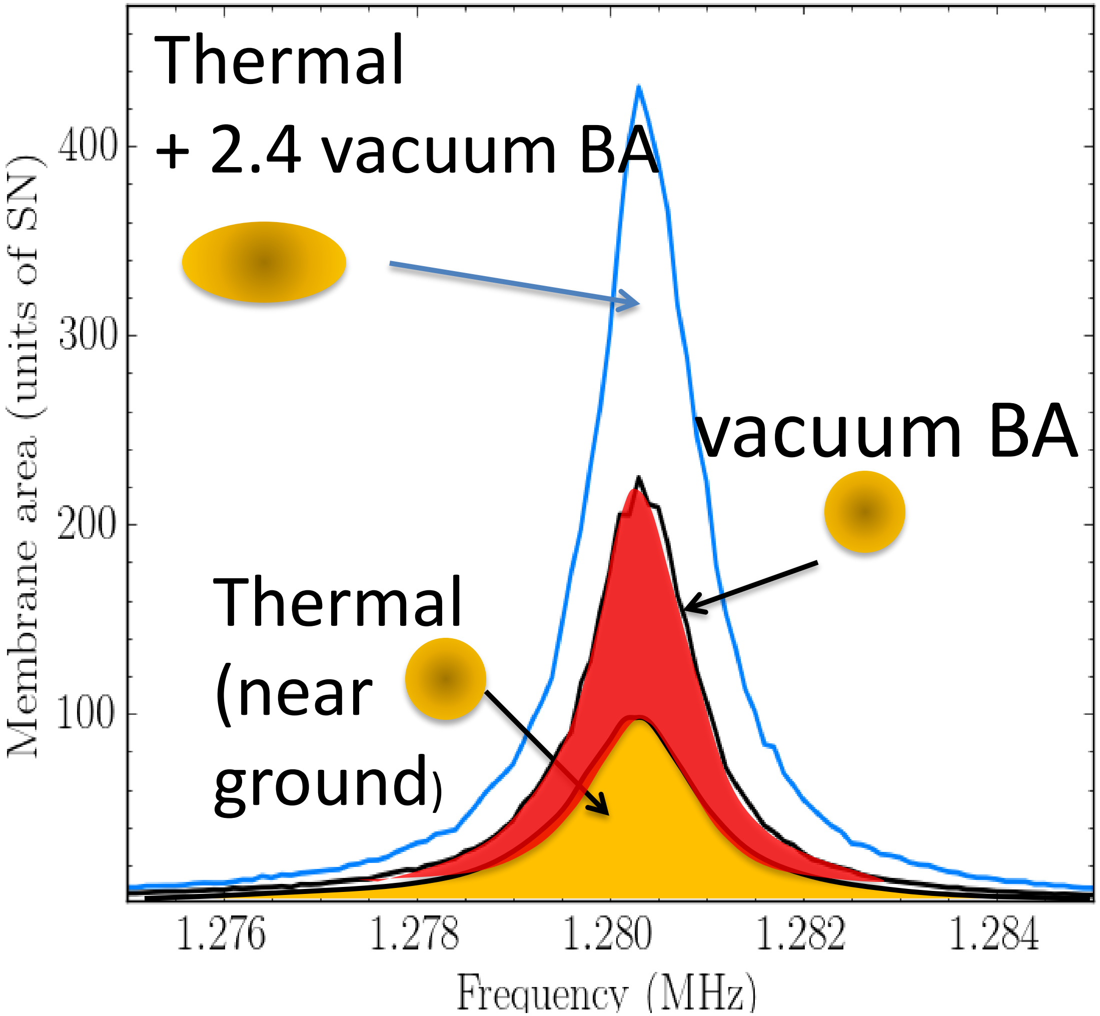
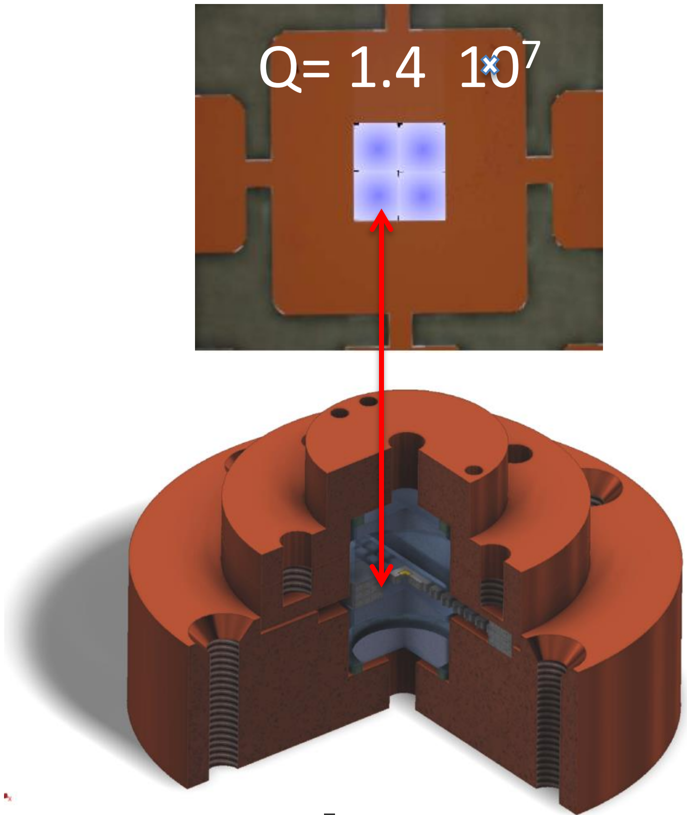
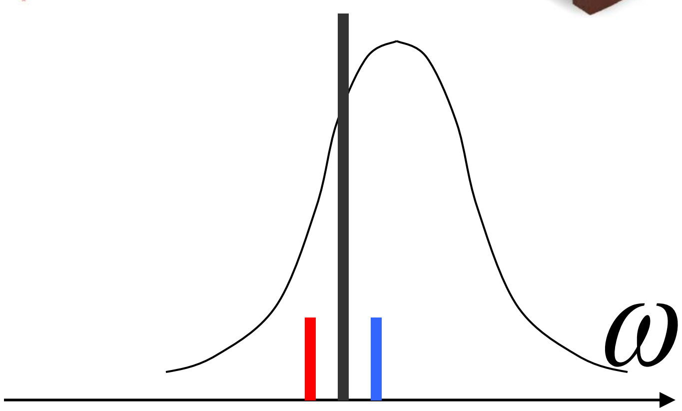
$$H = \Omega_L\left(P^2 + X^2\right) \Leftrightarrow -\Omega_L\left(J_z^2 + J_y^2\right)/J$$


SiN membrane, Q=2·10^7

Mechanical oscillator. Cooling + Q back action

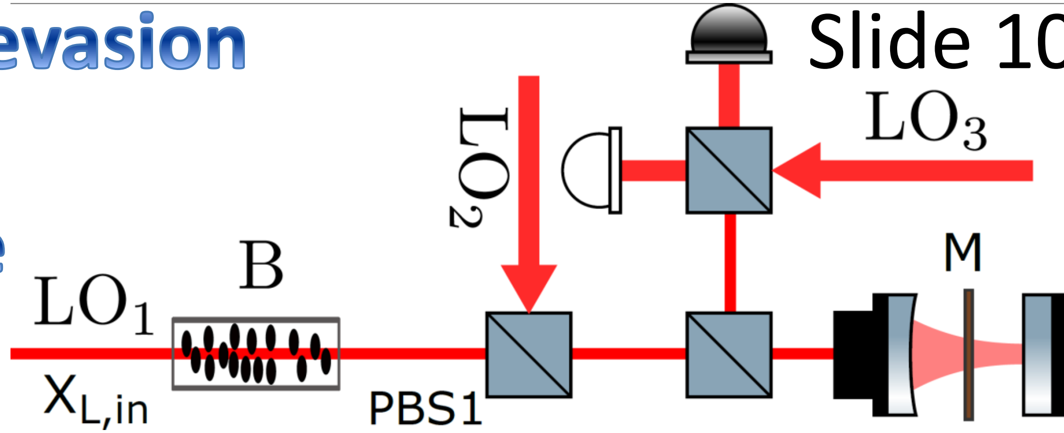




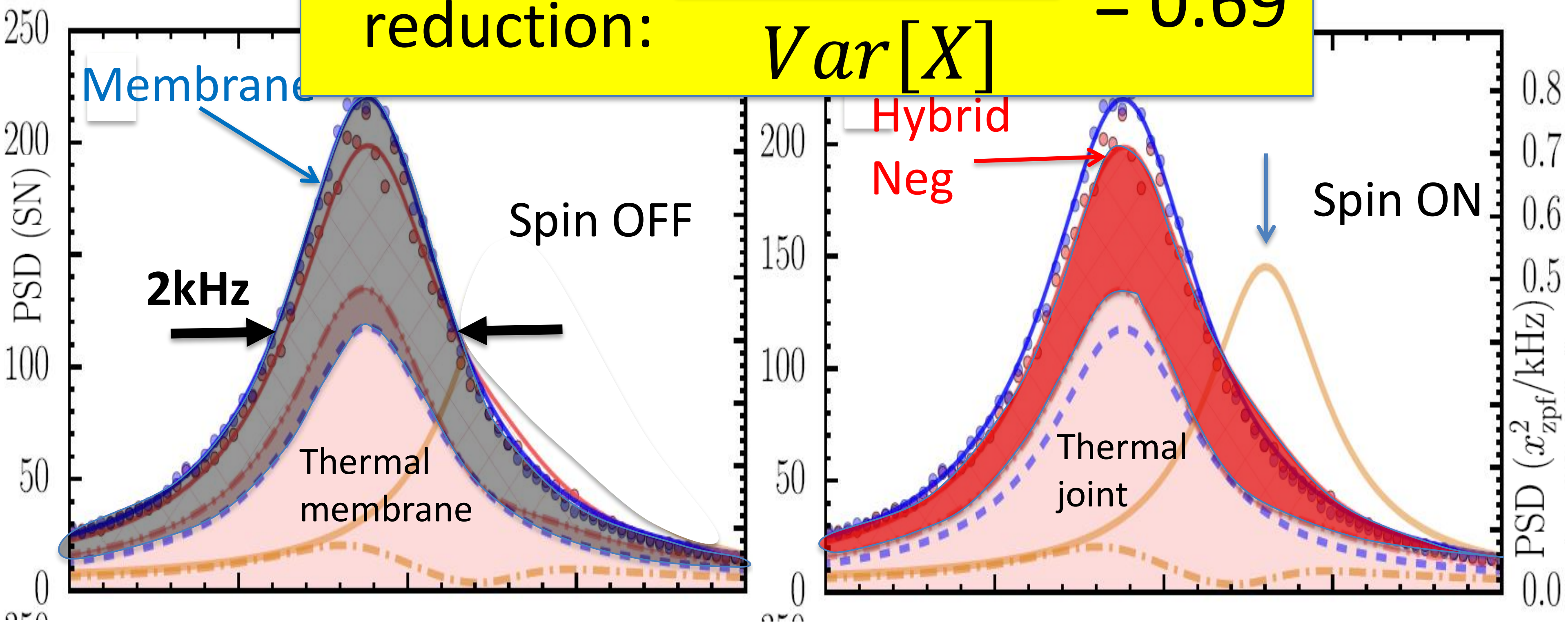


See also: Regal group, Science 2013; Stamper-Kurn group, Nat. Phys. 2016

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

Proposal: F. Khalili and E.S.P. ***Quantum back action evading detection of gravitational waves in a negative mass reference frame.*** Phys. Rev. Lett. July 2018

Advanced proposal in preparation.

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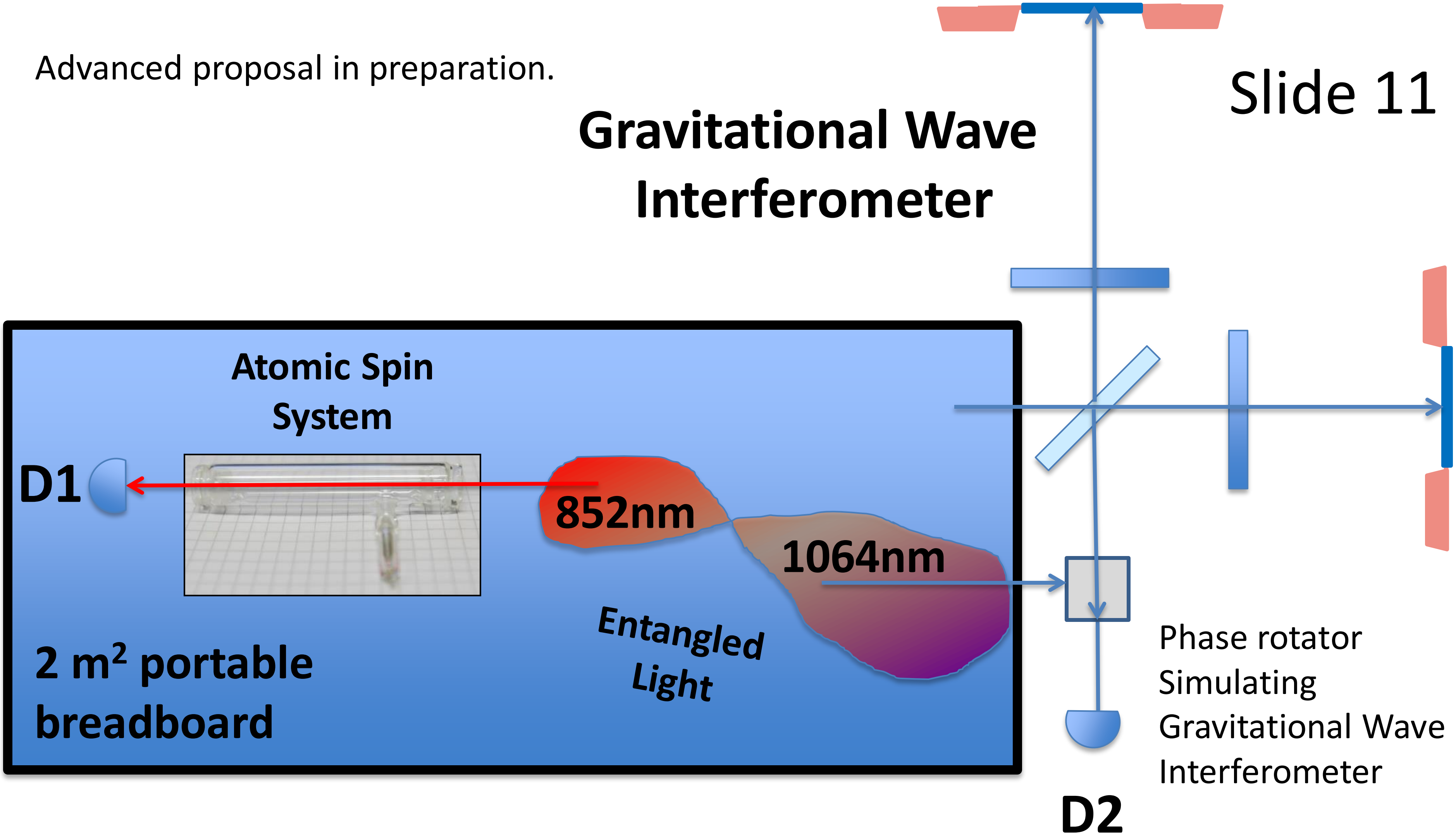
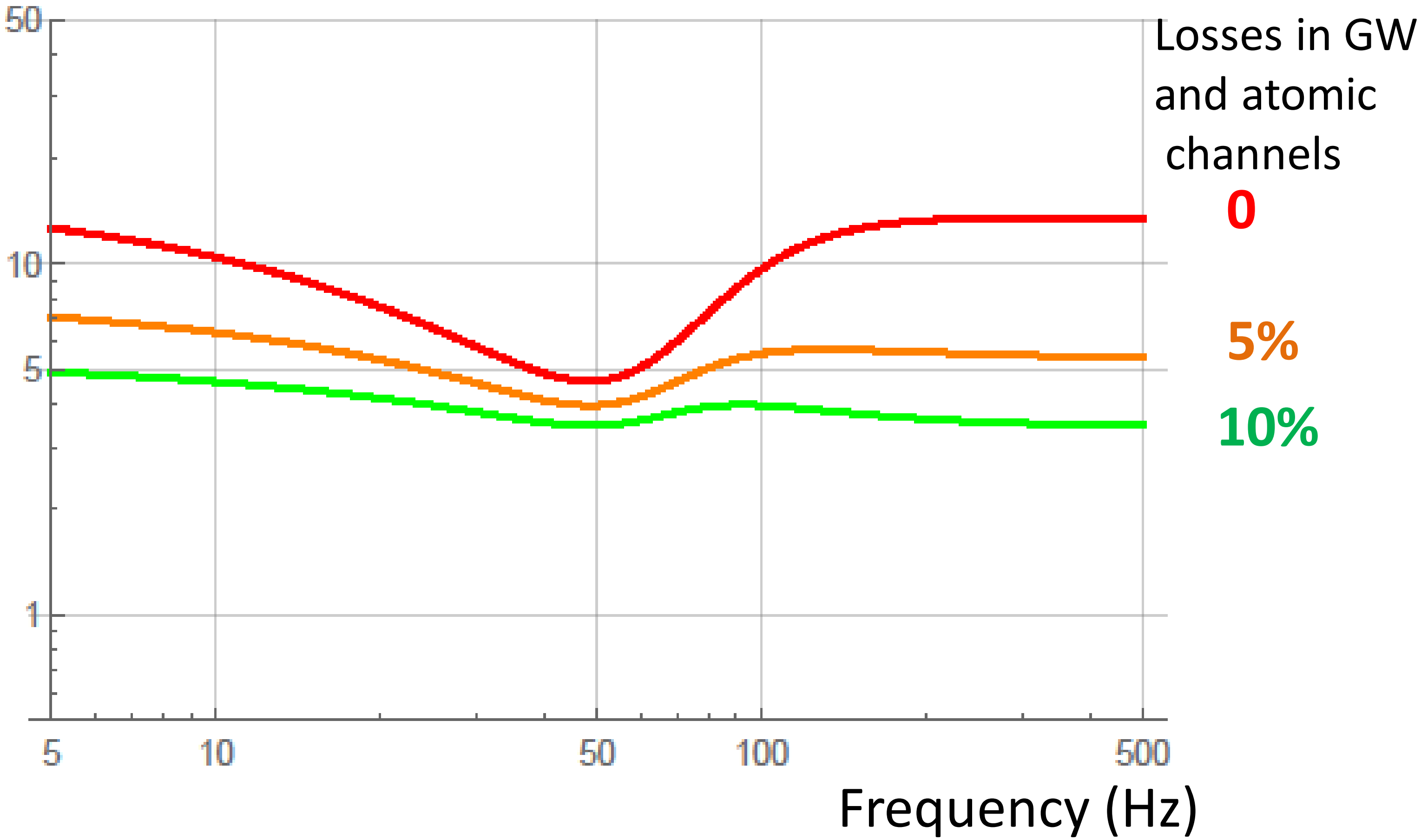


No change is GWD core optics required

Expected improvement in sensitivity (variance) for aLIGO (ET – similar)



ET parameters taken from ET-0106C-10.pdf

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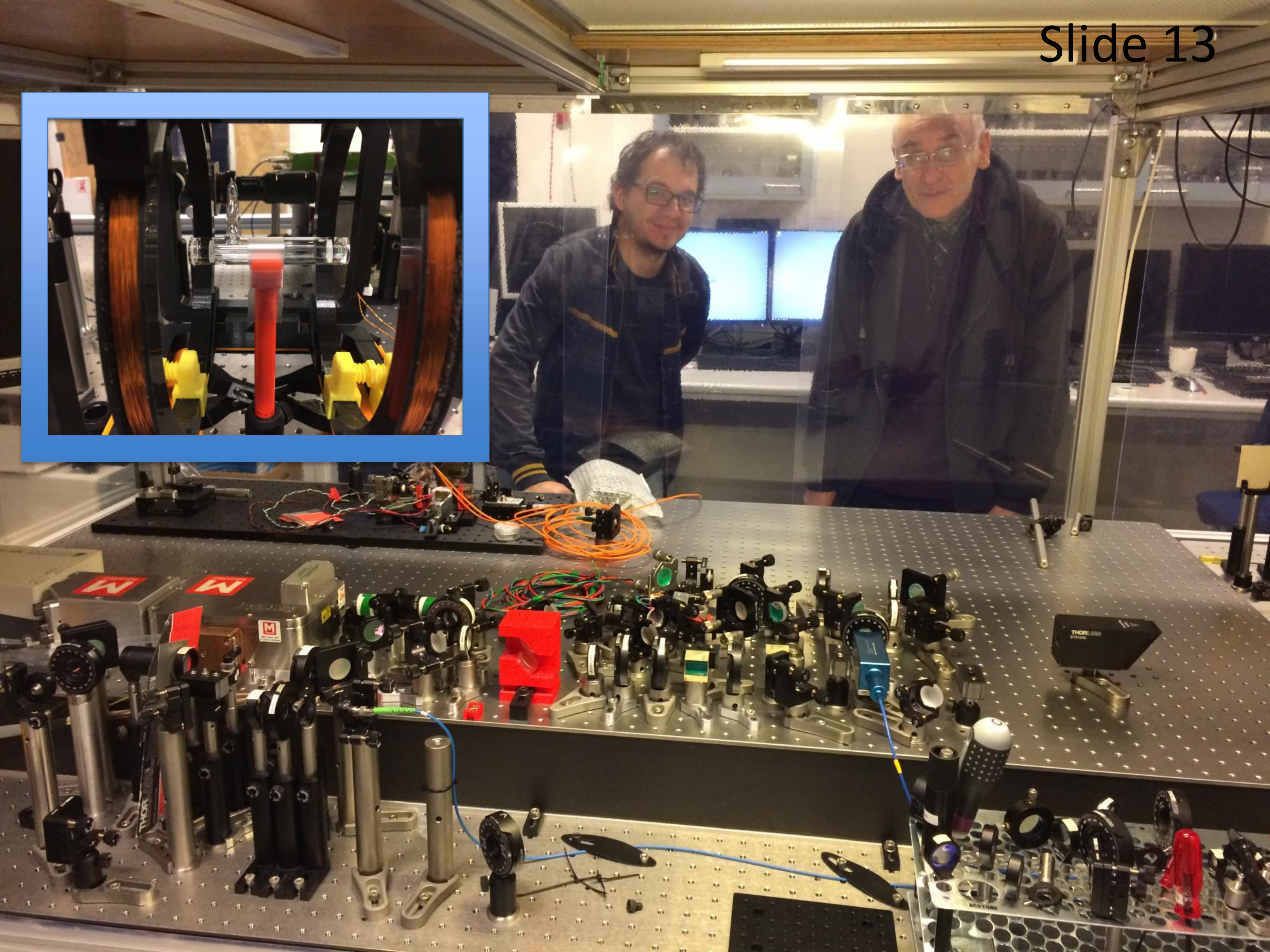
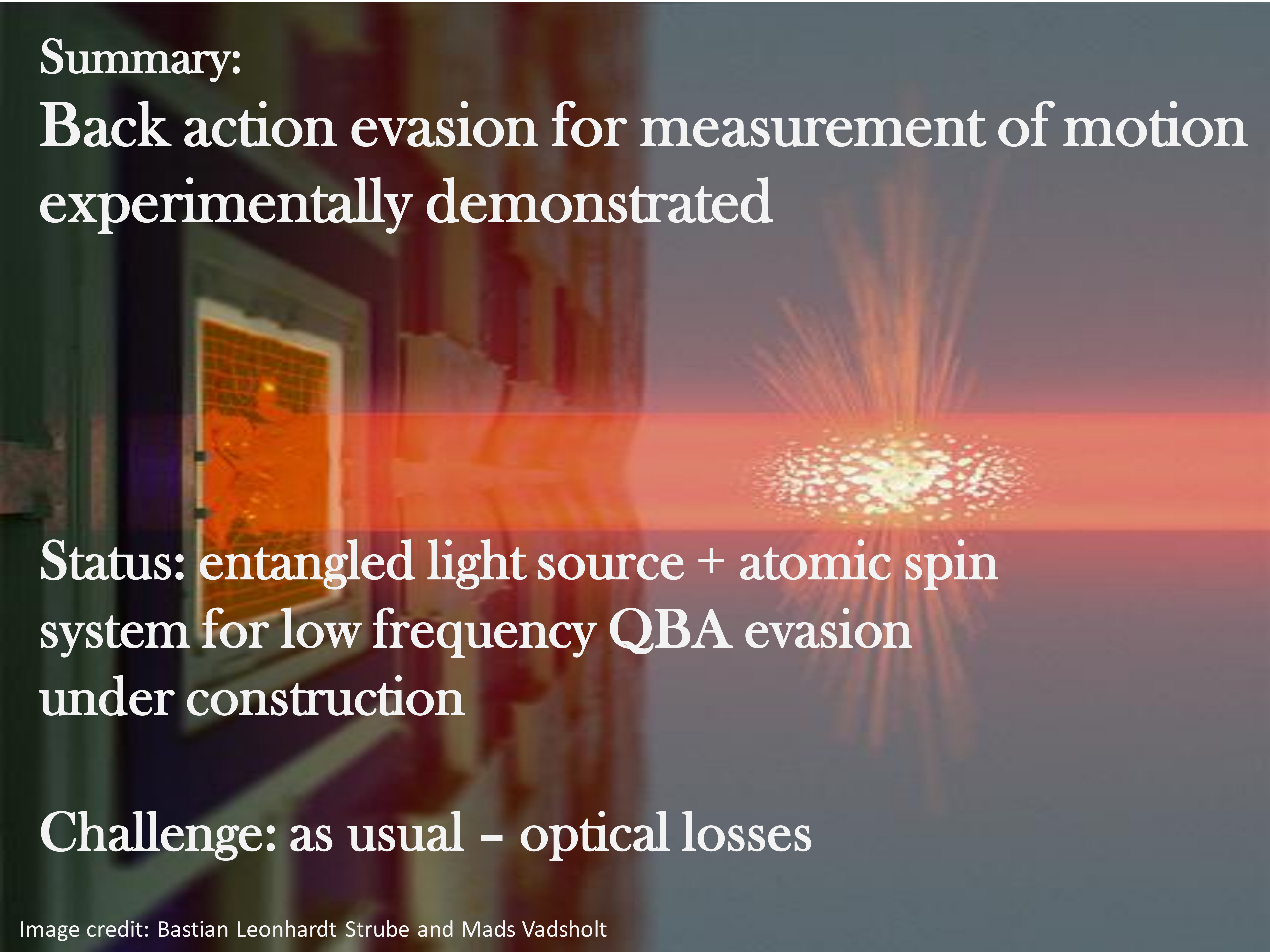




Summary:

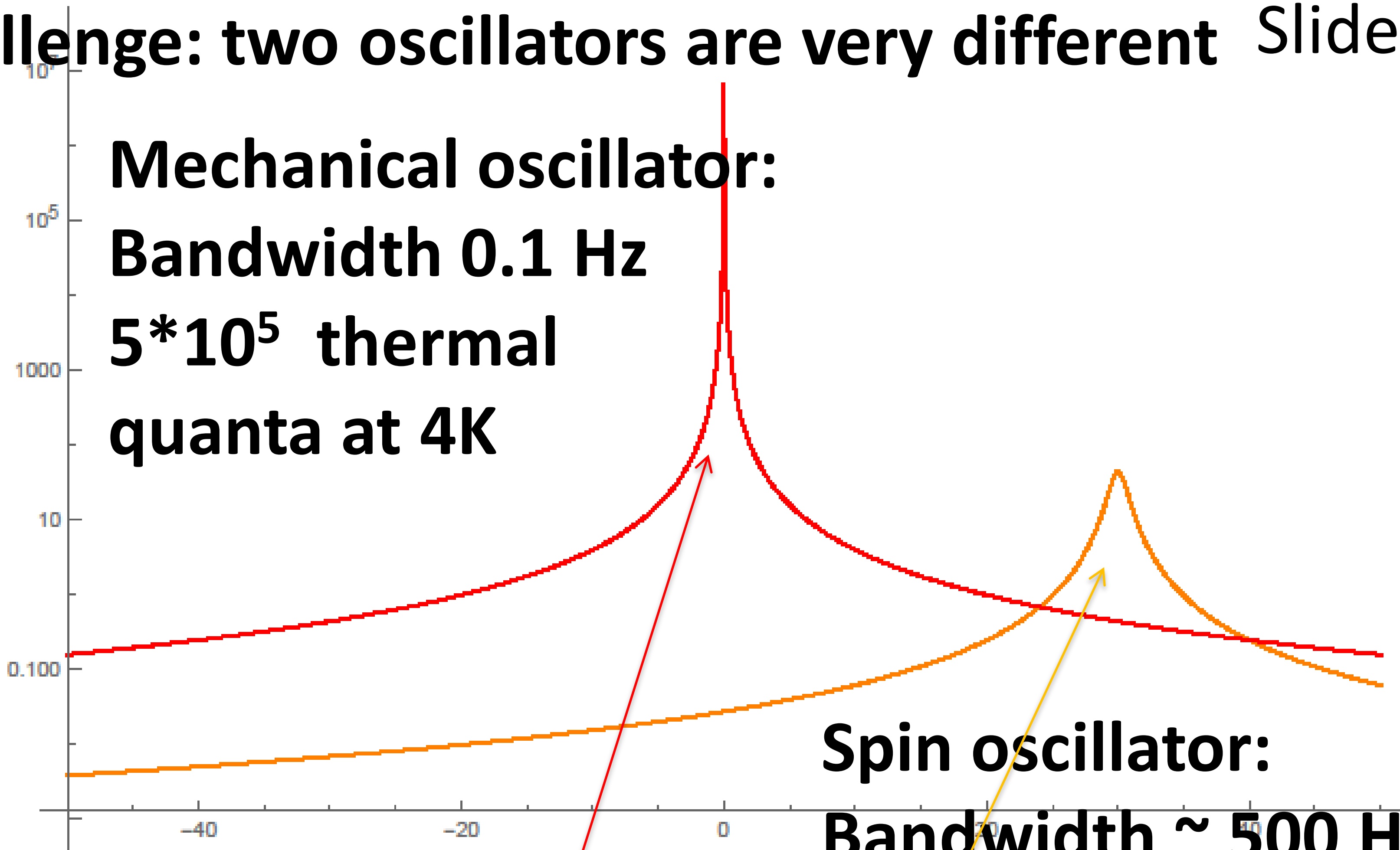
Back action evasion for measurement of motion experimentally demonstrated

Status: entangled light source + atomic spin system for low frequency QBA evasion under construction

Challenge: as usual – optical losses

Image credit: Bastian Leonhardt Strube and Mads Vadsholt

Challenge: two oscillators are very different



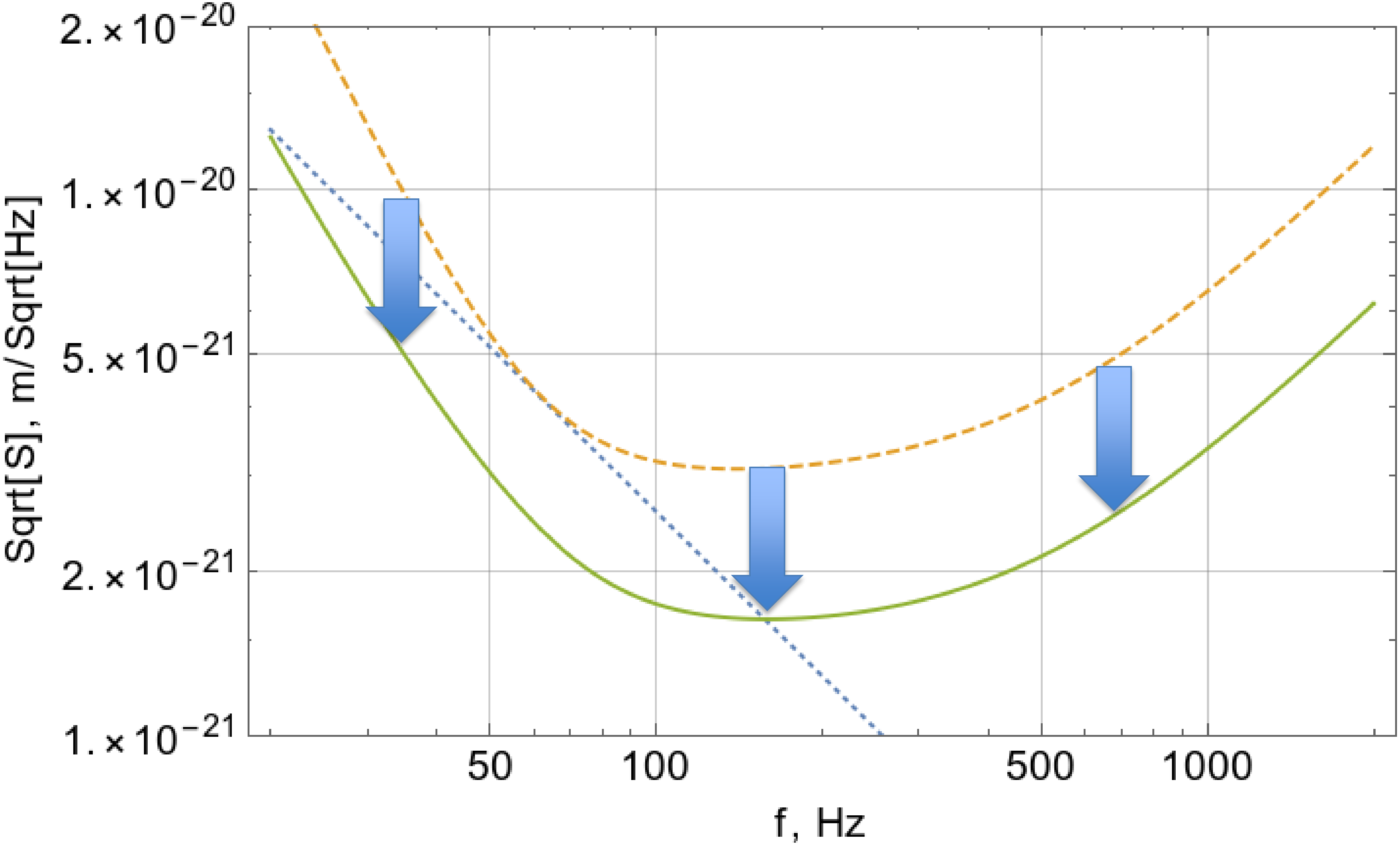
Mechanical oscillator:
Bandwidth 0.1 Hz
$5*10^5$ thermal quanta at 4K

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

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

F. Khalili and E.S.P. Phys.Rev.Lett. July 2018

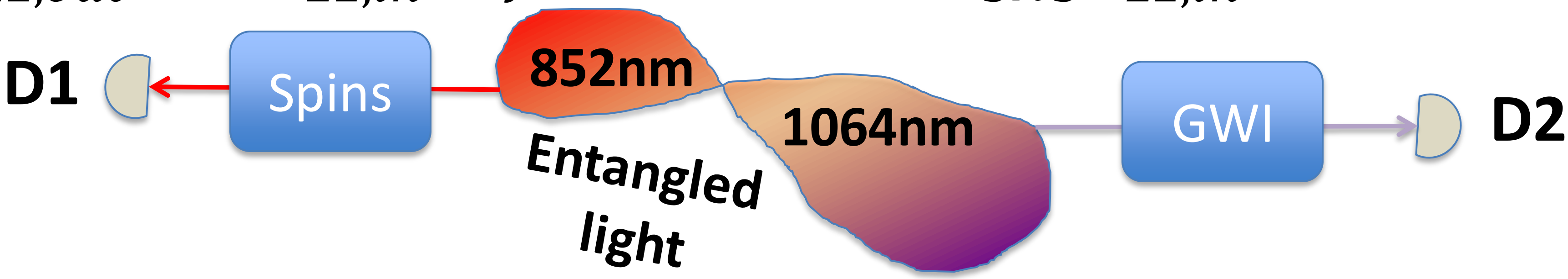
Simulation for LIGO



Probing the hybrid system with EPR entangled light modes

$$P_{L1,out} = -P_{L1,in} + force\ terms + \Gamma_M \chi_M X_{L1,in}$$

$$P_{L2,out} = -P_{L2,in} + force\ terms + \Gamma_S \chi_S X_{L2,in}$$



$$P_{L1,out} - P_{L2,out} = -P_{L1,in} + P_{L2,in} + force\ terms + \Gamma_M \chi_M X_{L1,in} - \Gamma_S \chi_S X_{L2,in}$$

$$\Gamma_S \chi_S = -\Gamma_M \chi_M$$

$$(P_{L1,in} - P_{L2,in})^2 = e^{-2r}$$

$$(X_{L1,in} + X_{L2,in})^2 = e^{-2r}$$

$$P_{L1,out} - P_{L2,out} \Rightarrow force\ terms$$

Measurement beyond SQL

1. Define trajectory relative to a quantum reference

2. Reference system has an effective negative mass

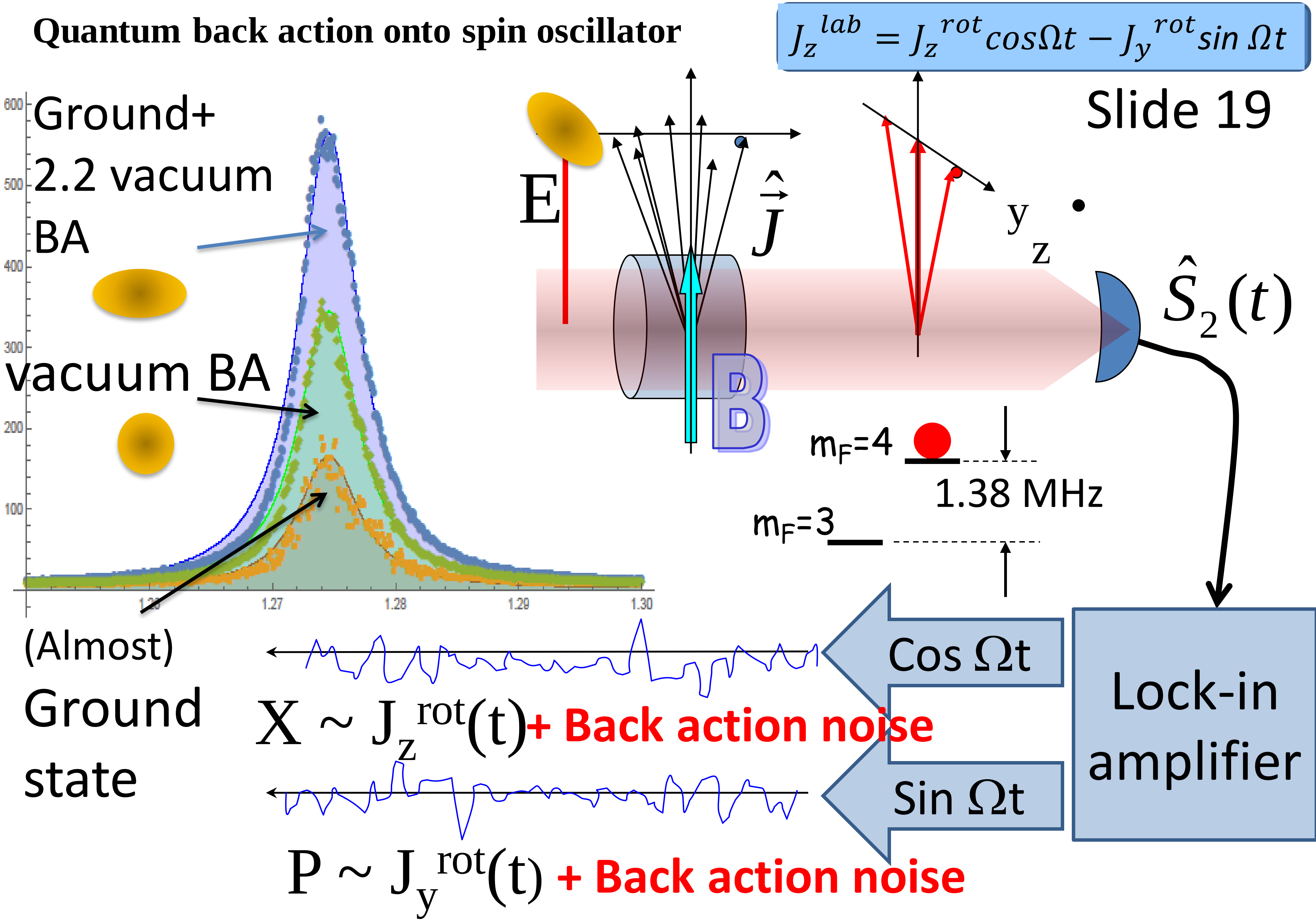
3. Entangled state of the reference and the probed systems is generated

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

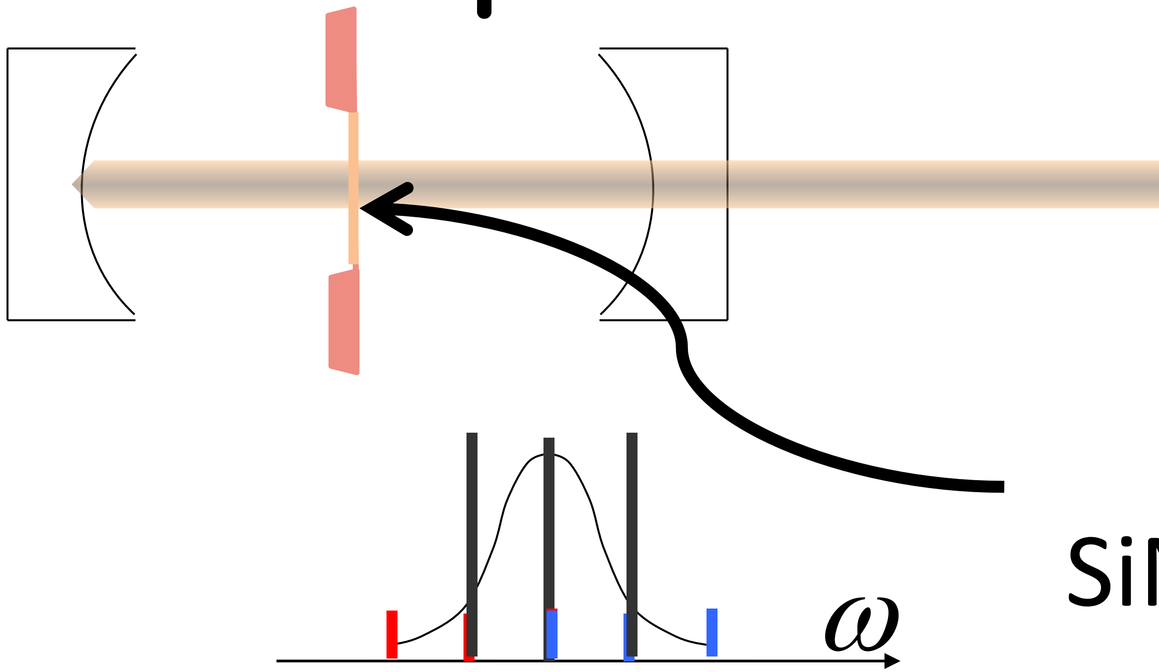
"Establishing Einstein-Podolsky-Rosen channels between nanomechanics and atomic ensembles". K. Hammerer, M. Aspelmeyer, ESP, P. Zoller. **PRL** 102, 020501 (**2009**).

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

Quantum back action onto spin oscillator



Quantum Optomechanics



SiN membrane
high - Q

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

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

phoTon

phoNon