Quantum Measurement of Motion in the Negative Mass Reference Frame

Presented by:

OSA Quantum Computing
and Communication
Technical Group

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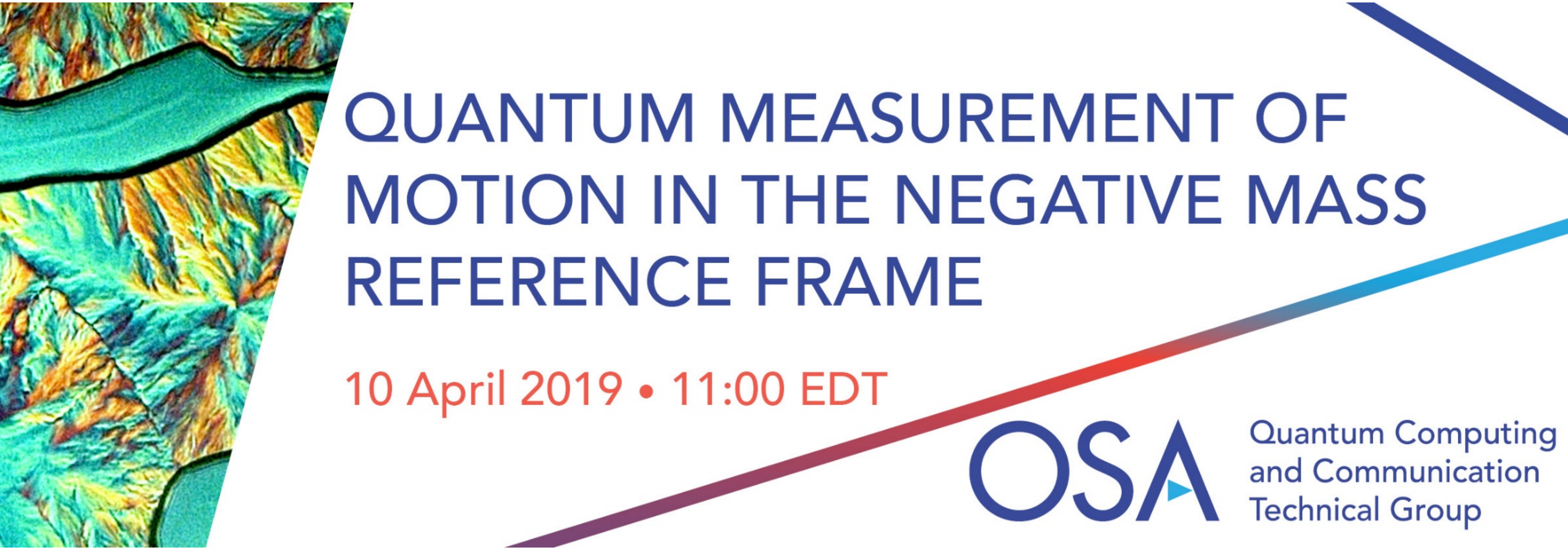

QUANTUM MEASUREMENT OF MOTION IN THE NEGATIVE MASS REFERENCE FRAME

10 April 2019 • 11:00 EDT

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OSA Quantum Computing and Communication Technical Group

Technical Group at a Glance

Focus

- Theoretical and experimental aspects of quantum computing
- Quantum communication systems - Cryptography
- Generation, detection and applications of non-classical light
- Quantum measurement and quantum control

Mission

- To maximize the exchange of information and the creation of networking opportunities for our community
- Webinars, technical events (workshops, tutorials, poster sessions), outreach activities
- Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.

Find us here

- Website: www.osa.org/OC
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OSA

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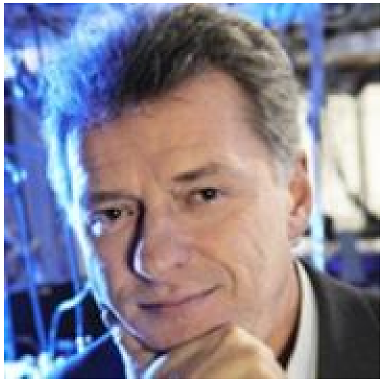
Today’s Webinar

OSA Quantum Computing and Communication Technical Group



Quantum Measurement of Motion in the Negative Mass Reference Frame

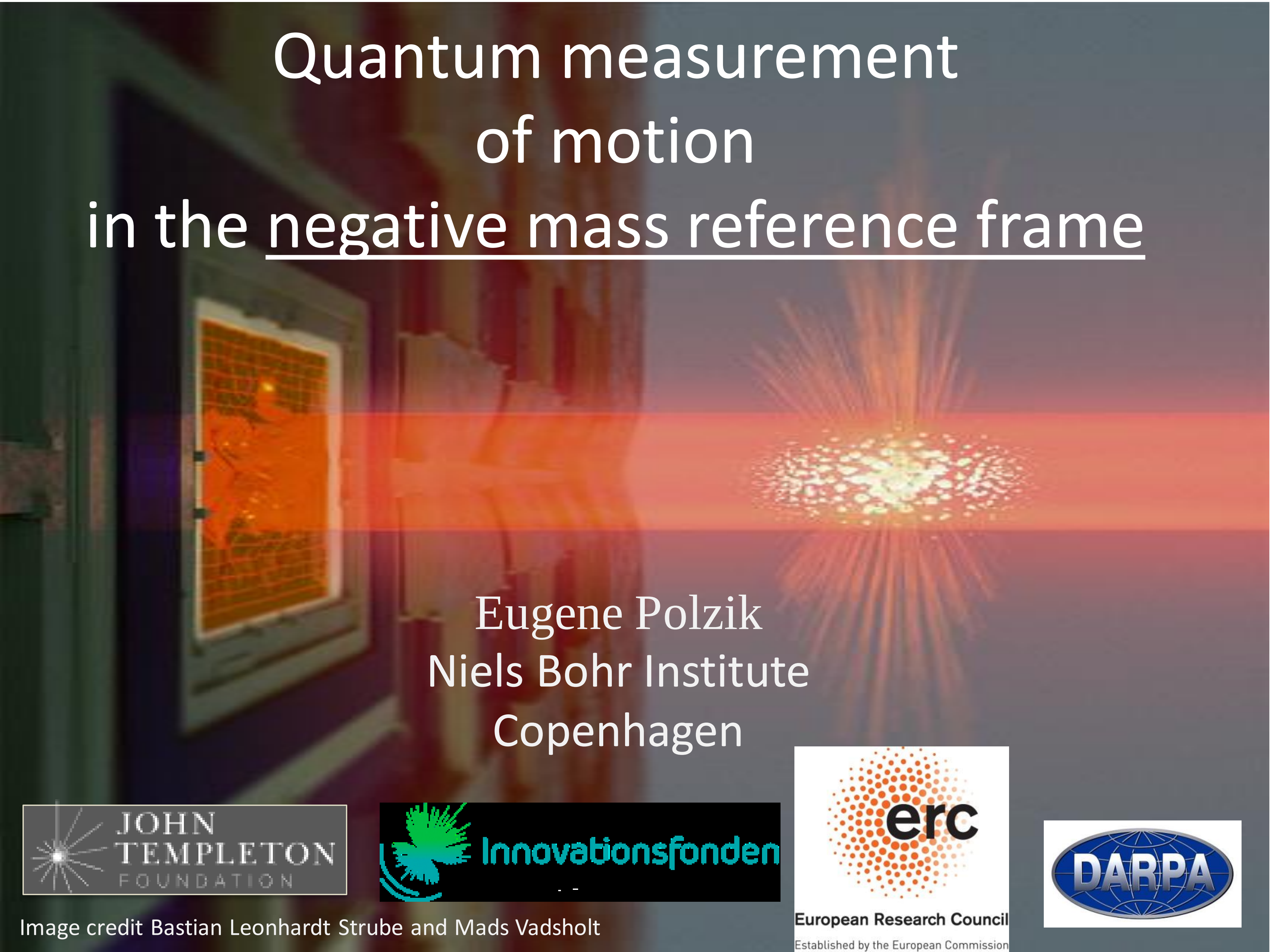
Prof. Eugene Polzik

Professor of Physics
The Niels Bohr Institute
University of Copenhagen, Denmark

Speaker’s Short Bio:

Director of the Danish National Research Foundation Center for Quantum Optics (QUANTOP). Member of the Royal Danish Academy of Science. Fellow of the American Physical Society and The Optical Society. Recipient of several awards, including the Gordon Moore Distinguished Scholar award, the Scientific American Research Leadership Award and the Danish Association of Academics award.

Quantum measurement of motion in the negative mass reference frame



Eugene Polzik
Niels Bohr Institute
Copenhagen

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

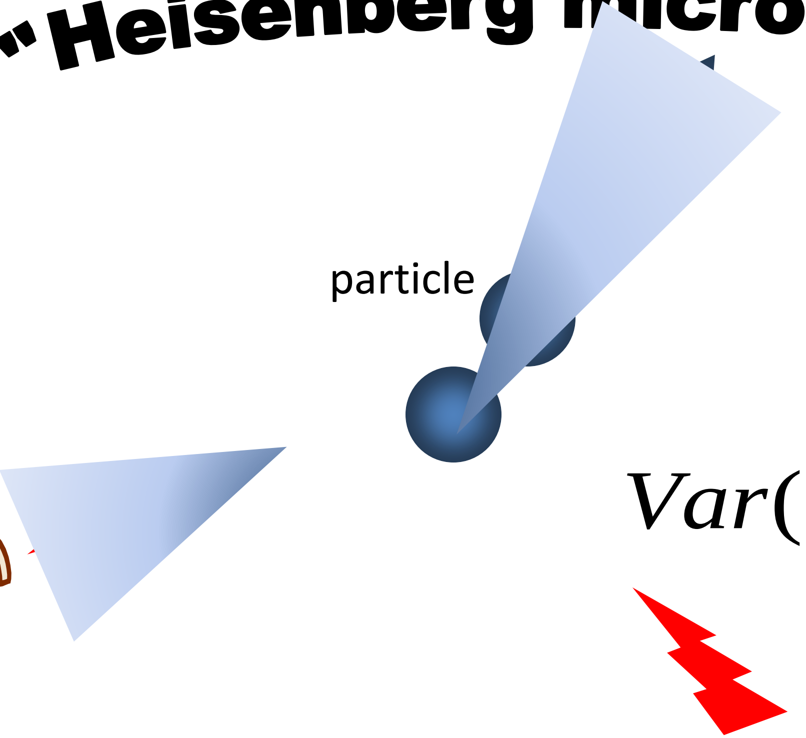
Image credit Bastian Leonhardt Strube and Mads Vadsholt

Standard quantum limit of displacement measurement

"Heisenberg microscope"

W. Heisenberg

N. Bohr



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

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

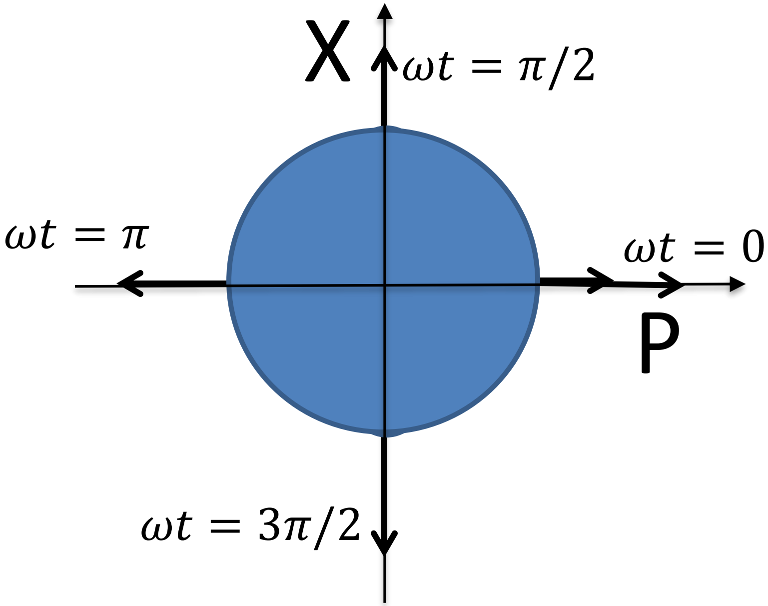
$$X(t)=X+\frac{Pt}{m},\quad \Delta X\Delta P\geqslant\frac{\hbar}{2}\Rightarrow$$

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

Quantum limits for an oscillator

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

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



The more you measure – the more you disturb!

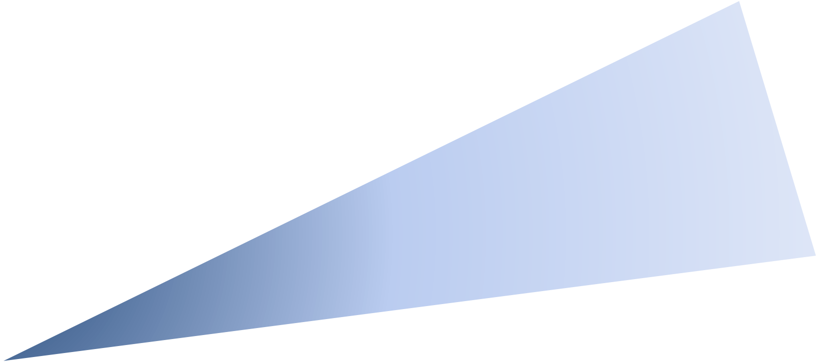
The optimal measurement strength/duration allows to reach the Standard Quantum Limit (SQL) for position measurement:

$$Var(X_{lab}) = \frac{\hbar}{m\Omega}$$

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

Trajectories without quantum uncertainties

in negative mass reference frame



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

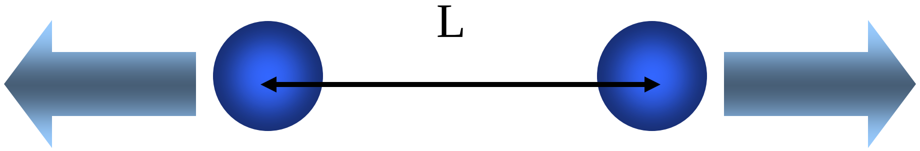
E.S. Polzik, K. Hammerer. Ann. der Physik 527, A15 (2015).
W. Wasilewski et al. **PRL**, 104, 133601 (2010).
K. Hammerer et al. **PRL**102, 020501 (2009).

Einstein-Podolsky-Rosen (EPR) entanglement 1935

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

2 particles entangled
in position/momentum

$$\left[\hat{X}_1-\hat{X}_2,\hat{P}_1+\hat{P}_2\right]=0$$



$\hat{X}_1,\hat{P}_1$ $\hat{X}_2,\hat{P}_2$

$$\hat{X}_1-\hat{X}_2=L \qquad \hat{P}_1+\hat{P}_2=0$$

Simon (2000); *Duan, Giedke, Cirac, Zoller* (2000)

Necessary and sufficient condition for entanglement

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

3 steps to noiseless quantum trajectories

1. Define trajectory relative to a quantum reference

2. Reference system has an effective negative mass

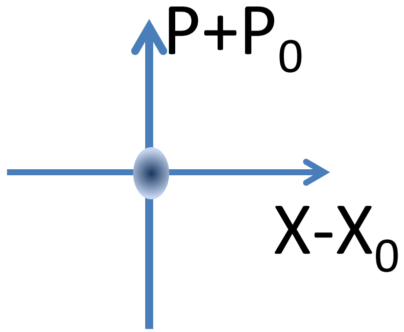
3. Entangled state of the reference and
the probed systems is generated

“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 with negative mass



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

$$P + P_0 \to 0$$

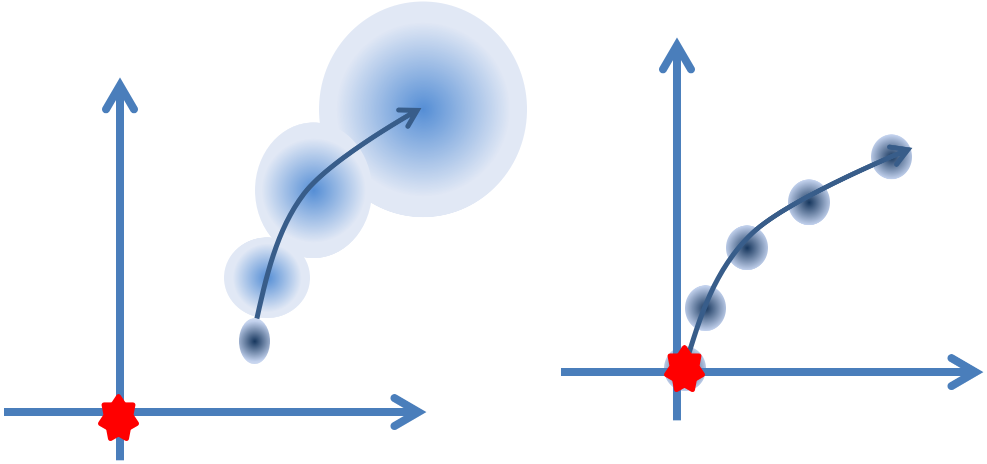
Probe system entangled with origin system

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

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

$m = \enclose{circle}{-} m_0 = 1$

Not good enough



Oscillators: negative mass=negative frequency

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

For a reference oscillator with a negative frequency:

$$X(t) - X_0(t) =$$
$$[X(0) - X_0(0)\,]\cos(\omega t) + [P(0)\ +\ P_0(0)]\sin(\omega t)$$

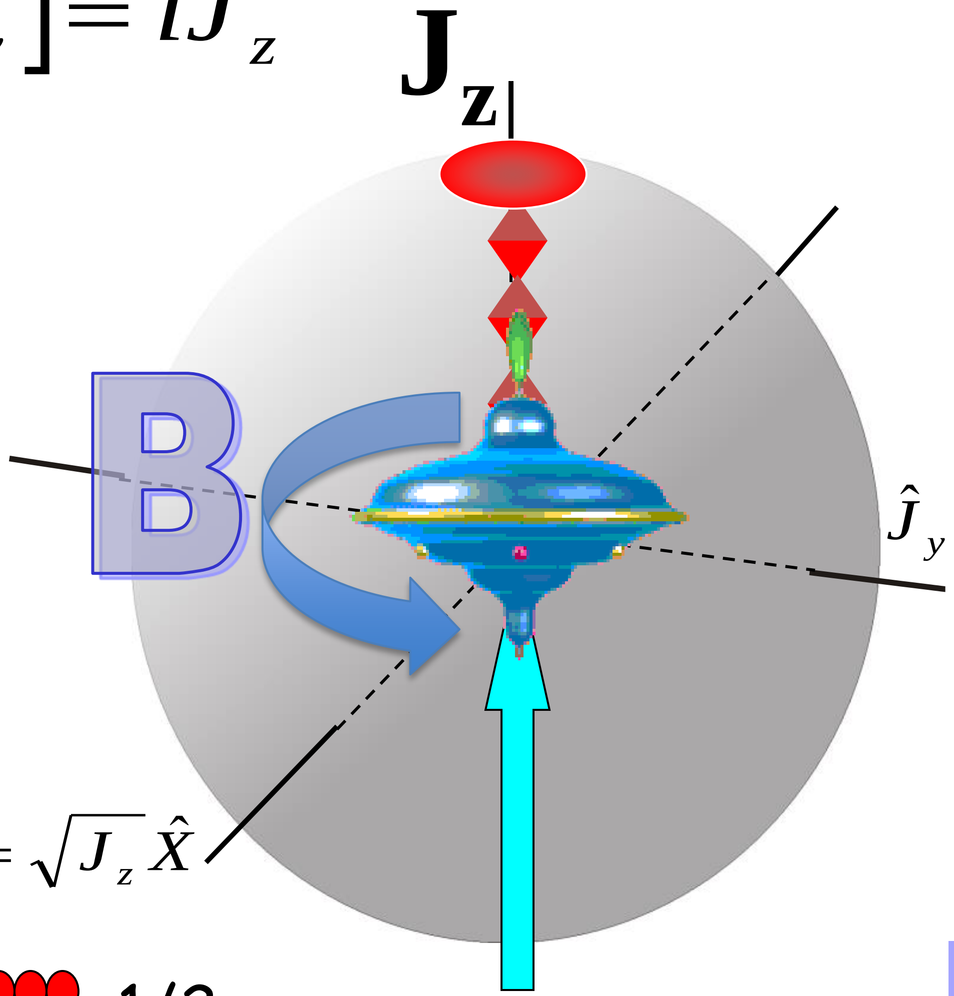
Q: how to implement a negative mass oscillator?

spin in magnetic field

Spin ensemble in magnetic field as harmonic oscillator

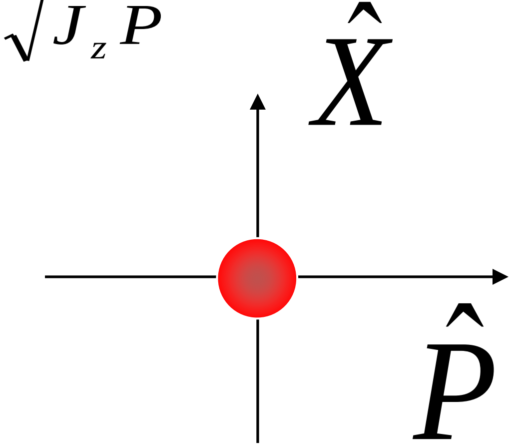
$$\left[\hat{J}_x, \hat{J}_y\right] = iJ_z$$

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



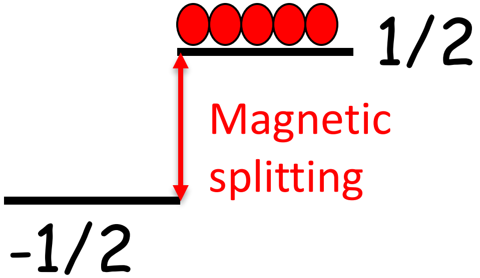
$$\hat{J}_y = \sqrt{J_z}\,\hat{P}$$

$$\hat{J}_x = \sqrt{J_z}\,\hat{X}$$



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

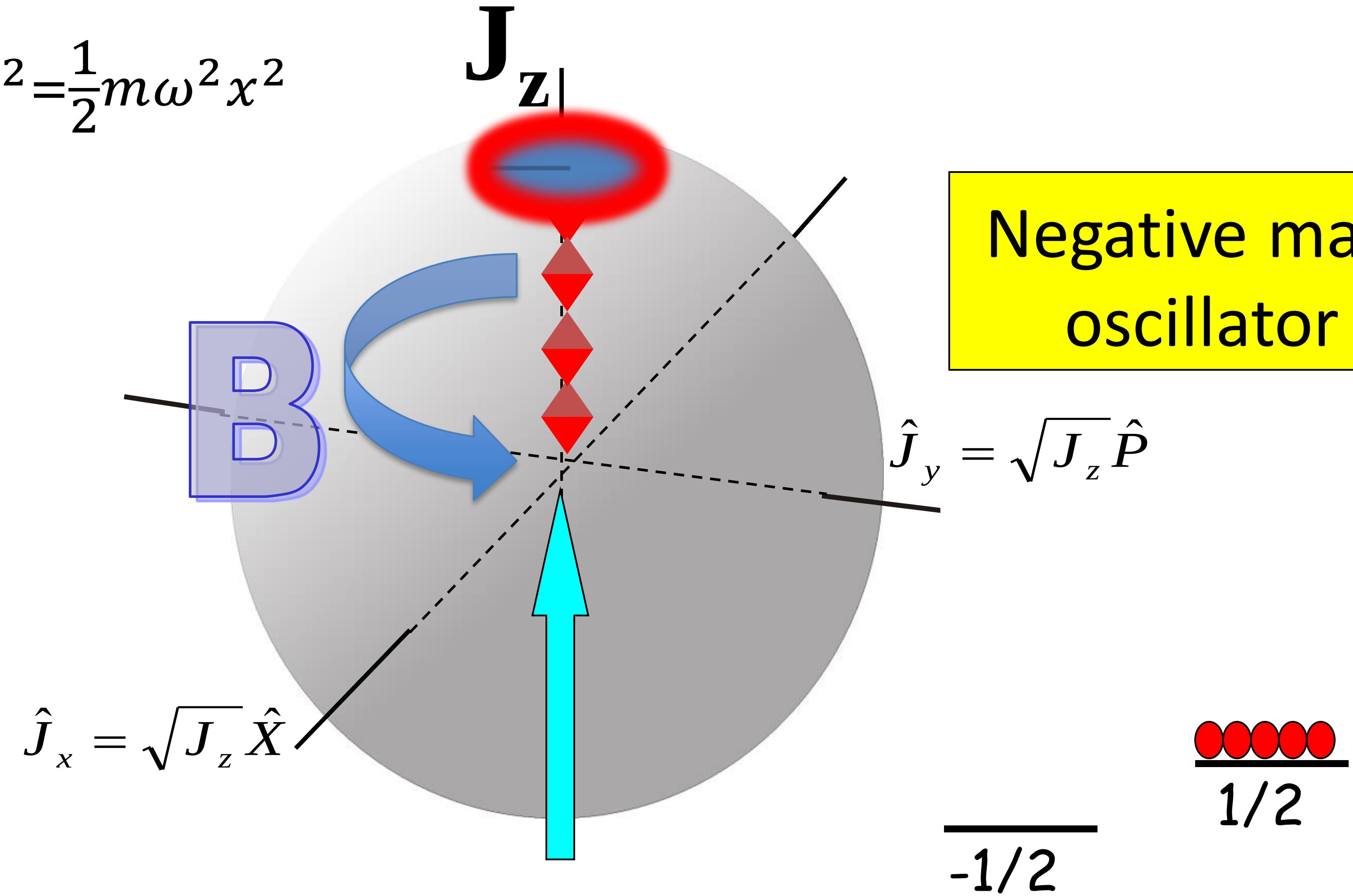
Holstein-Primakoff



Spin ensemble = negative mass harmonic oscillator

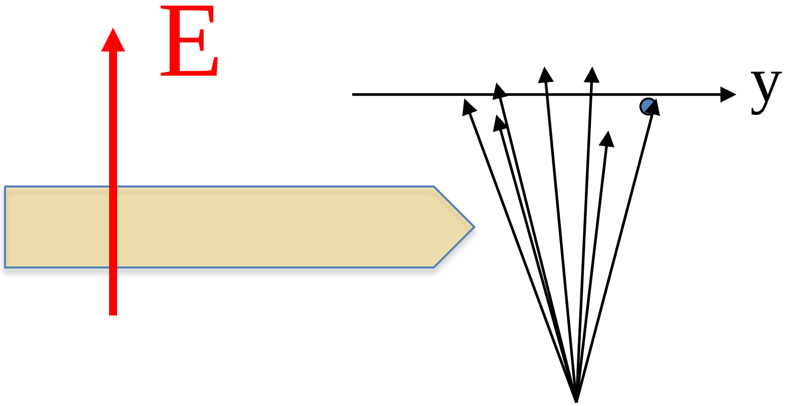
$$\frac{1}{2}kx^2=\frac{1}{2}m\omega^2x^2$$

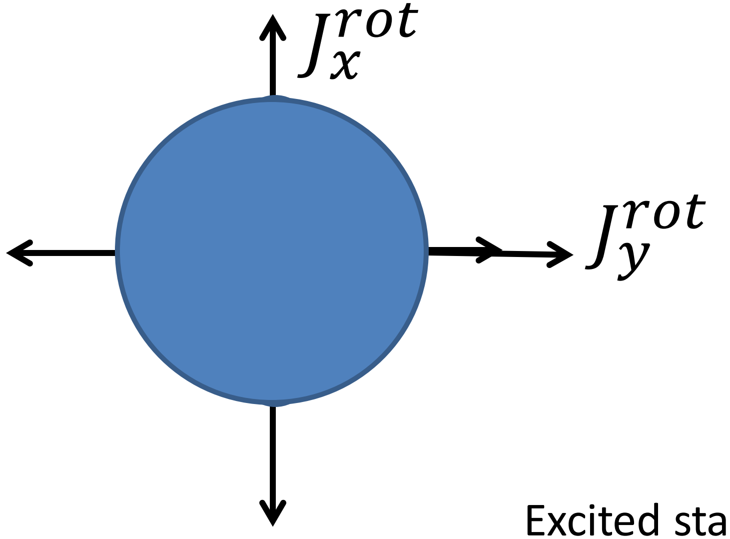
Negative mass oscillator



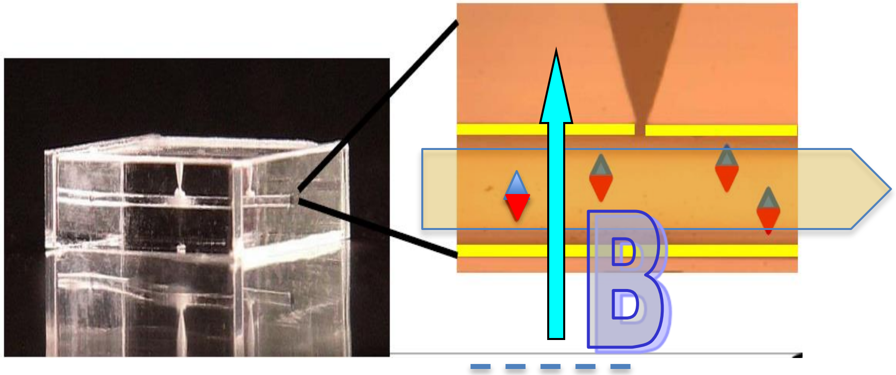
$$\left|-\frac{1}{2},\frac{1}{2},\frac{1}{2}\ldots\right\rangle+\left|\frac{1}{2},-\frac{1}{2},\frac{1}{2}\ldots\right\rangle+\left|\frac{1}{2},\frac{1}{2},-\frac{1}{2}\ldots\right\rangle+\ldots$$

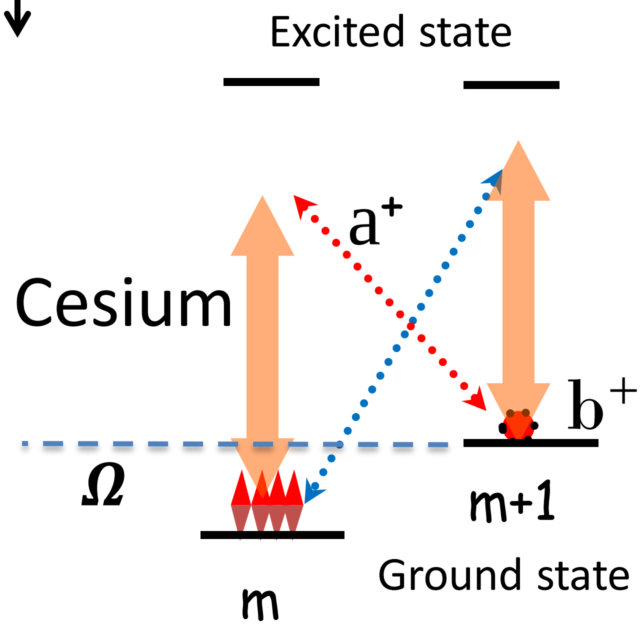
Quantum opto-spintronics





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

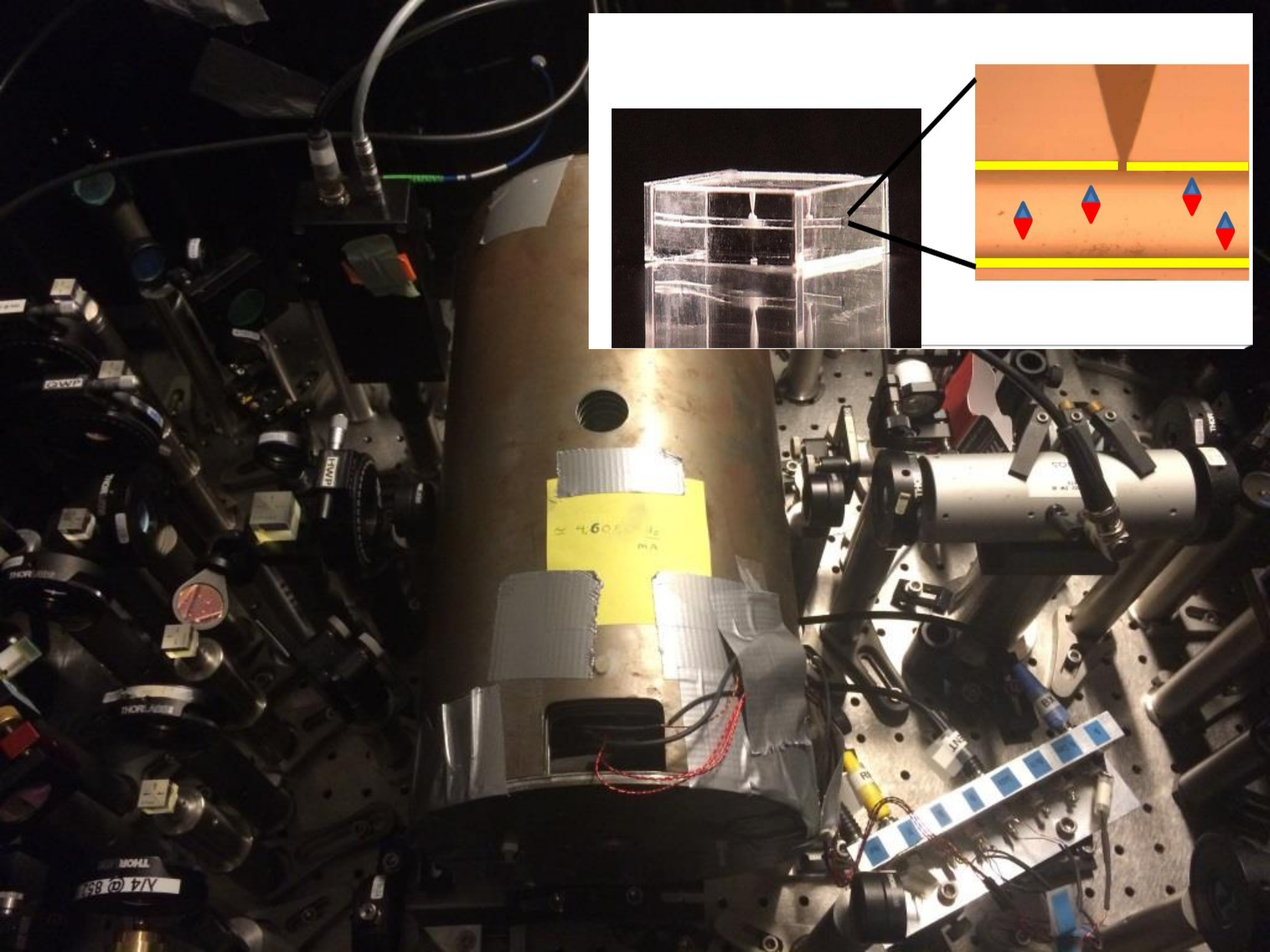




$$H = \chi_{Par}\hat{a}^{\dagger}\hat{b}^{\dagger} + \chi_{BS}\hat{a}^{\dagger}\hat{b} + h.c. = gX_S X_L,$$

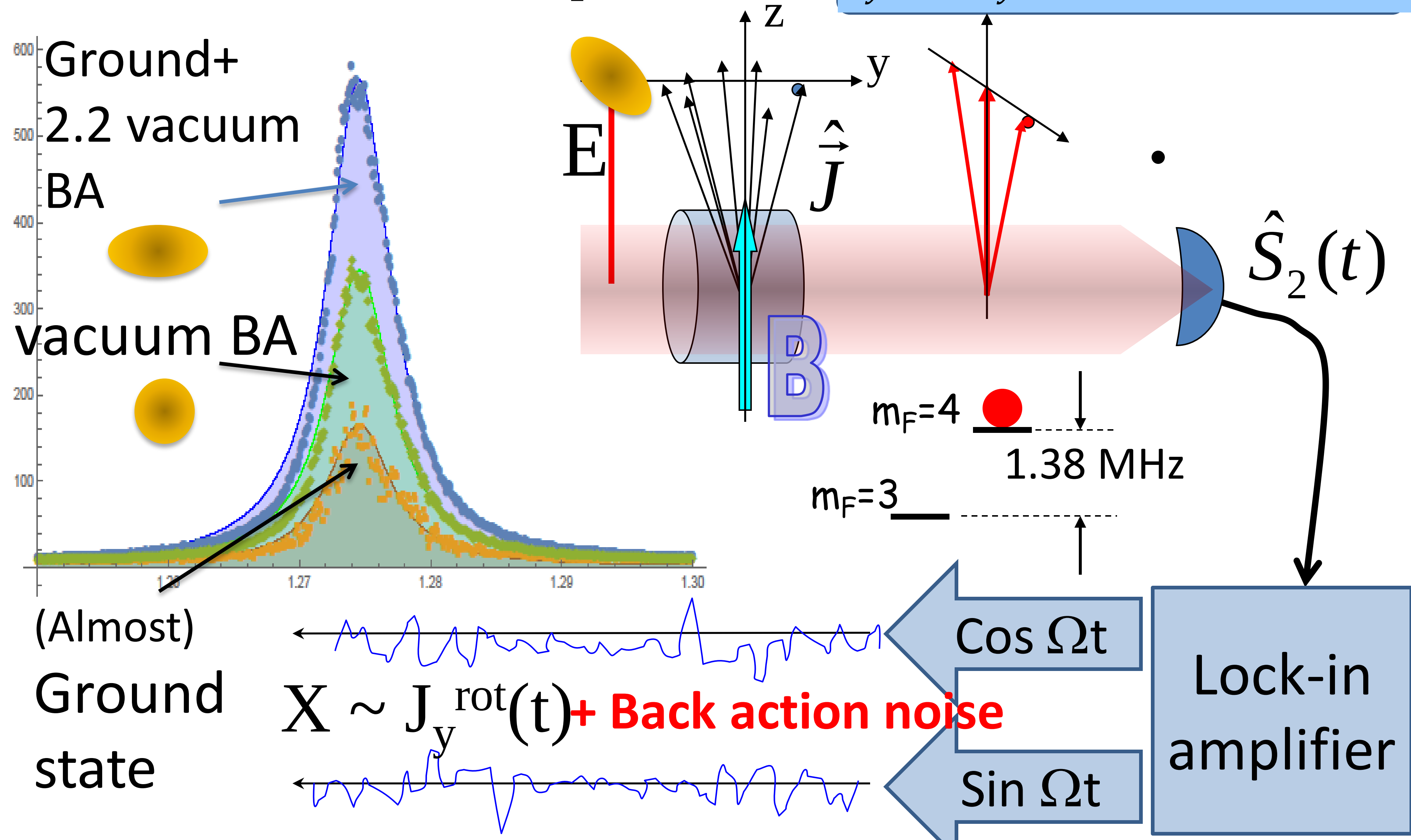
photon

Polariton=collective spin


QWP
HWP
THORLABS
λ/4 @ 85

Quantum back action onto spin oscillator

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



Ground+
2.2 vacuum
BA

vacuum BA

(Almost)
Ground
state

m_F=4

1.38 MHz

m_F=3

Cos Ωt

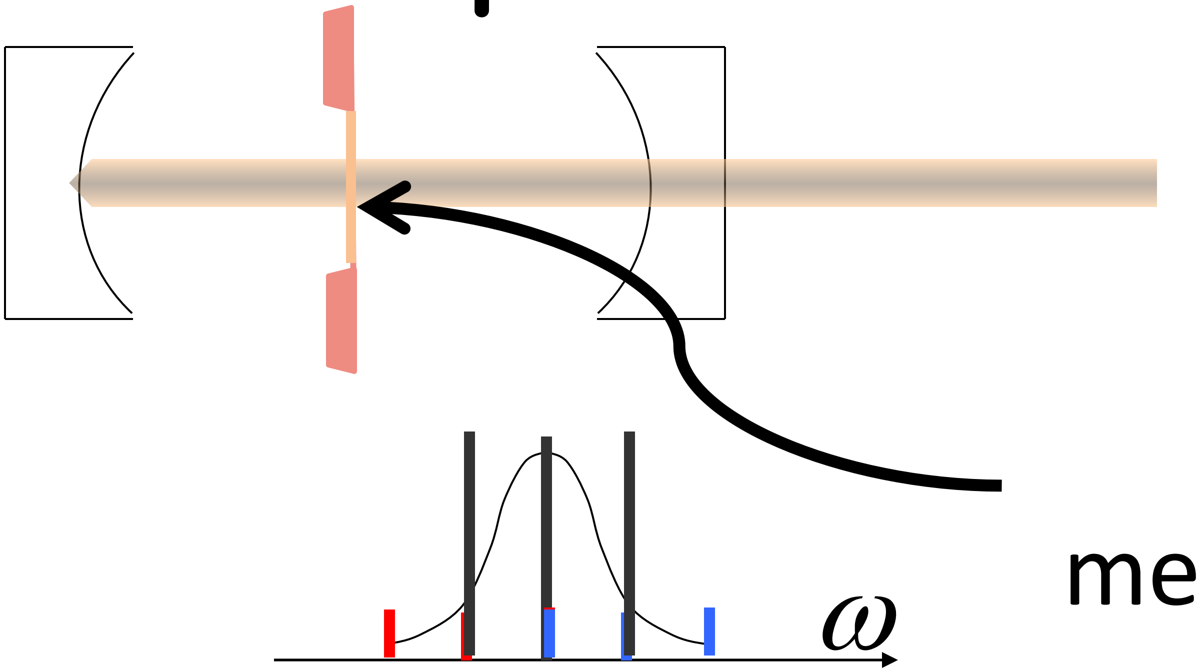
Sin Ωt

Lock-in amplifier

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

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

Quantum Optomechanics



membrane

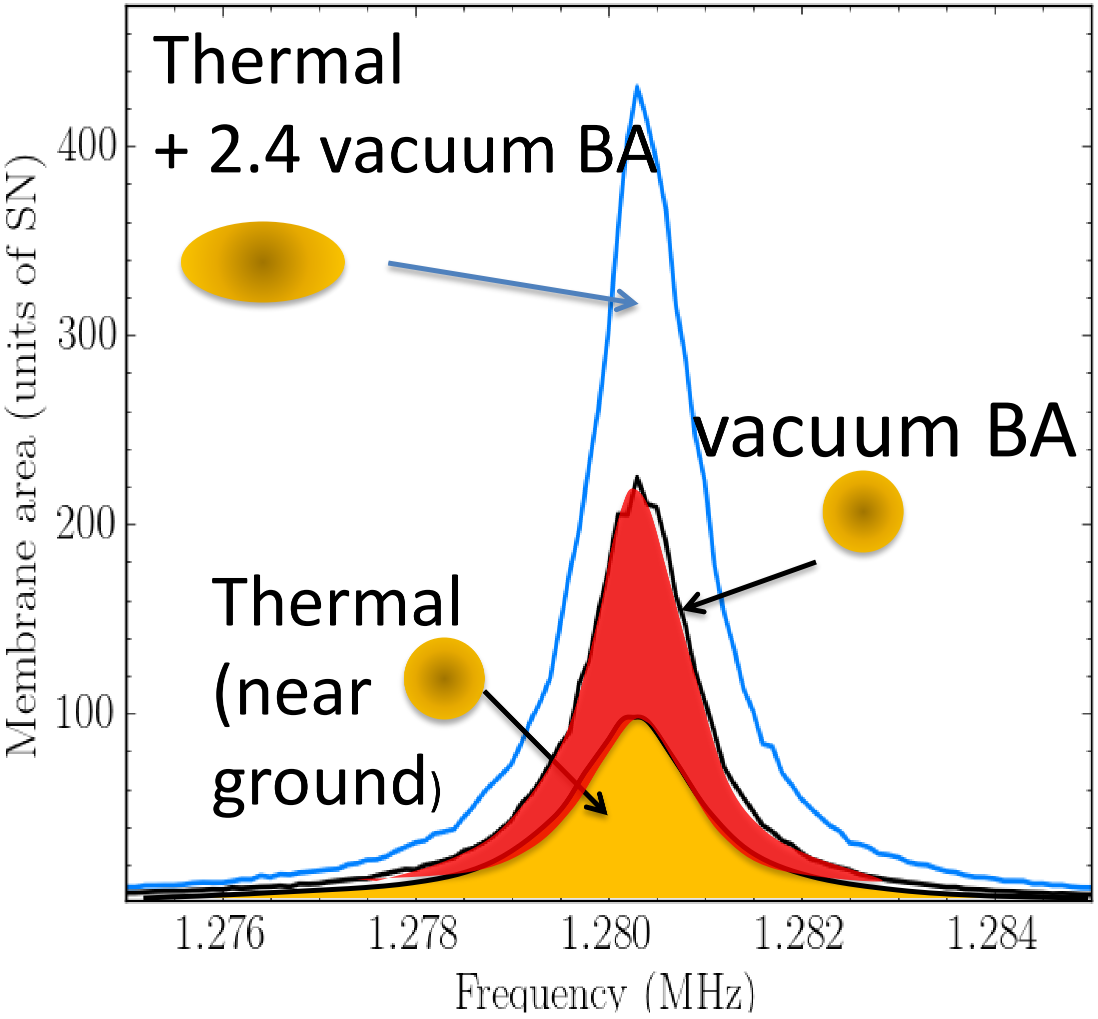
$$H = \chi_{Par}\hat{a}^{\dagger}\hat{b}^{\dagger} + \chi_{BS}\hat{a}^{\dagger}\hat{b} + h.c.$$

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

phoTon

phoNon

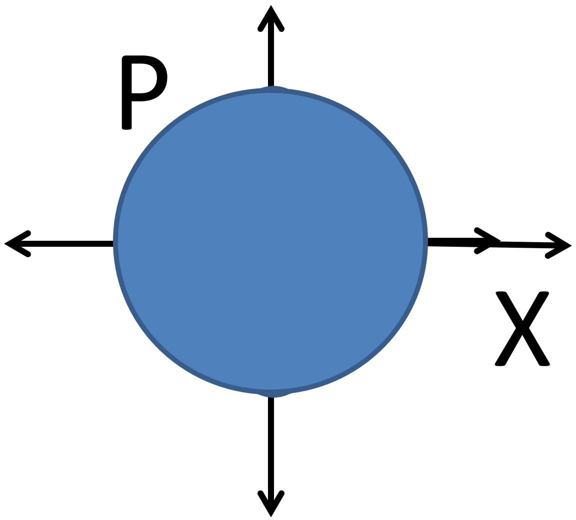
Mechanical oscillator. Cooling + Q back action

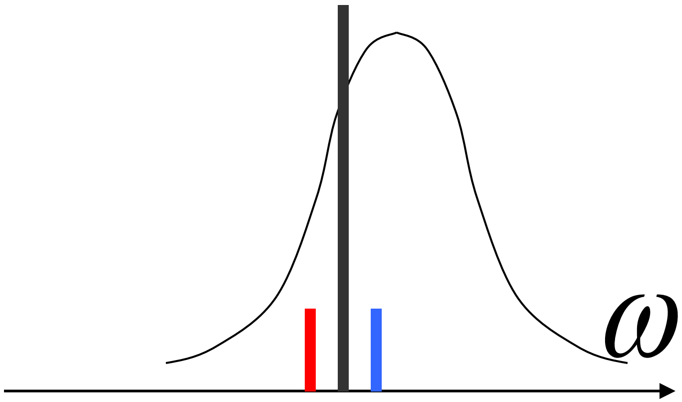


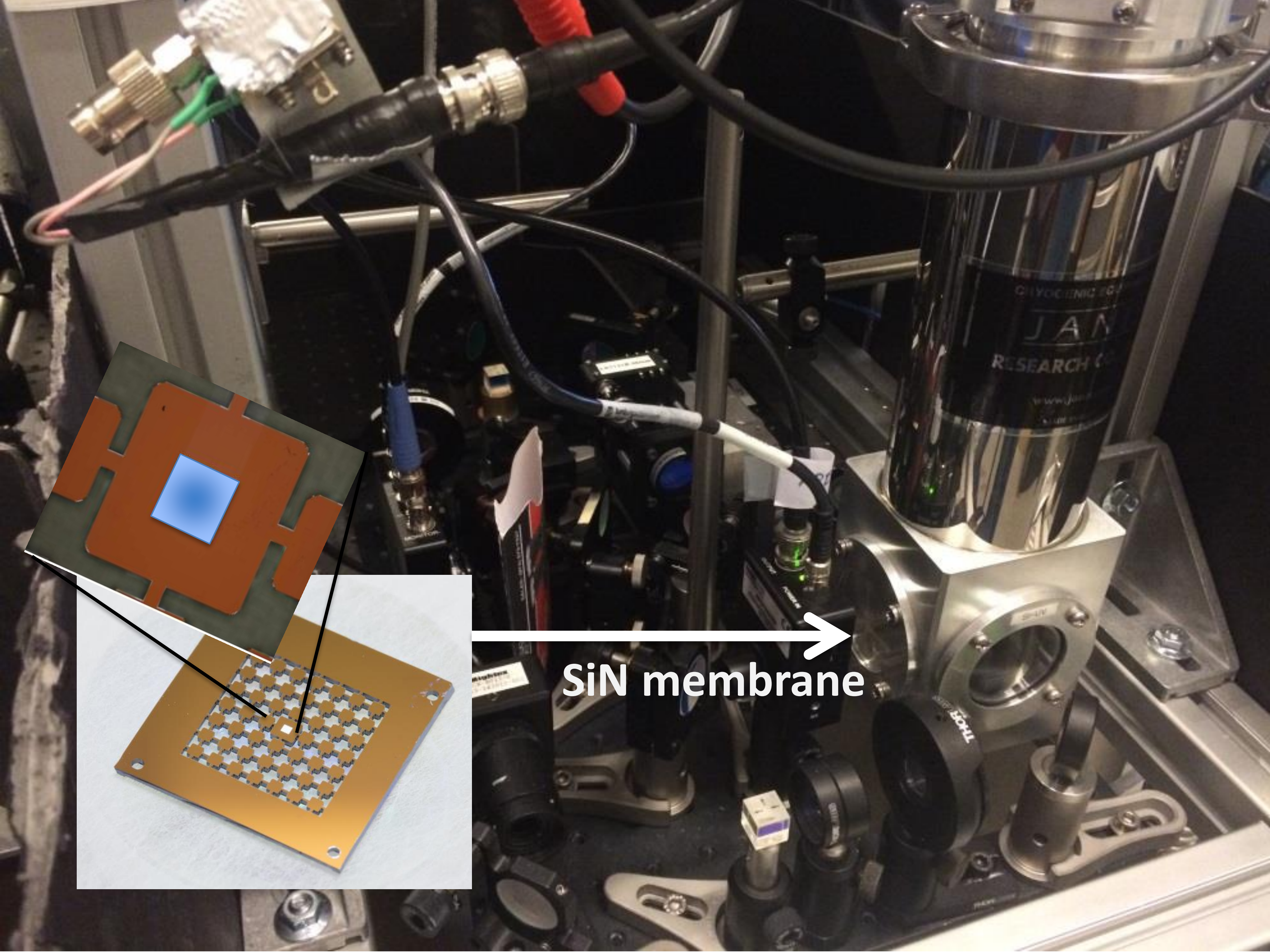
Thermal
+ 2.4 vacuum BA

vacuum BA

Thermal
(near
ground)



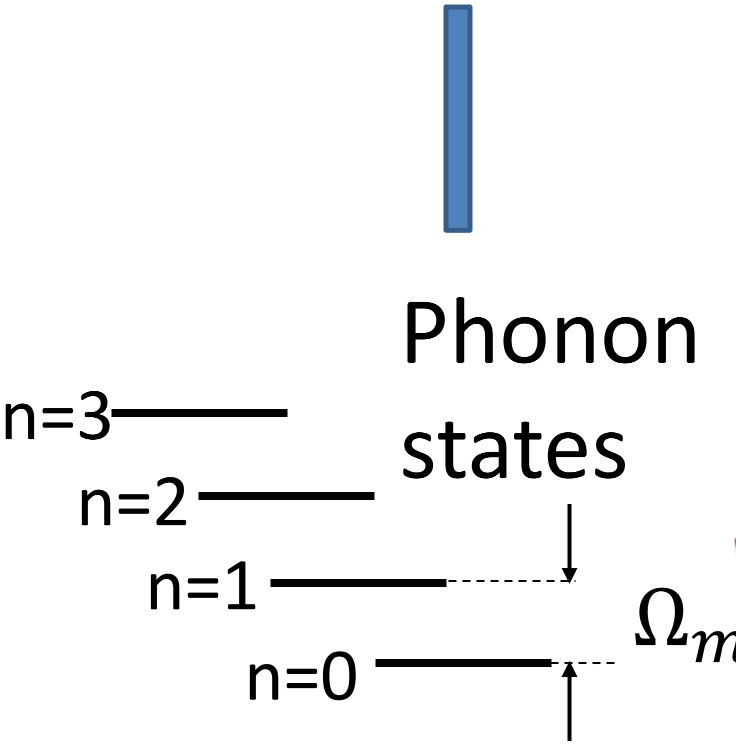




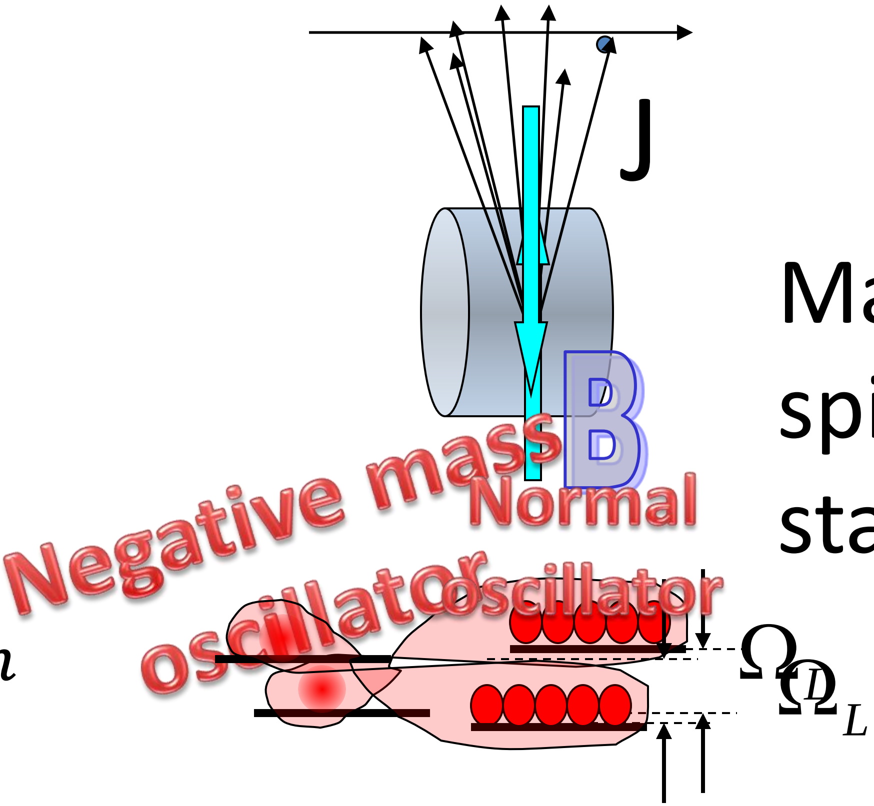
SiN membrane

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

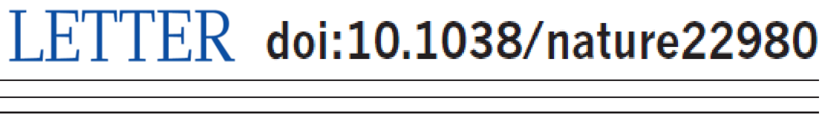
Christoffer B. Møller[1]*, Rodrigo A. Thomas[1]*, Georgios Vasilakis[1,2], Emil Zeuthen[1,3], Yeghishe Tsaturyan[1], Mikhail Balabas[1,4], Kasper Jensen[1], Albert Schliesser[1], Klemens Hammerer[3] & Eugene S. Polzik[1]



Phonon states



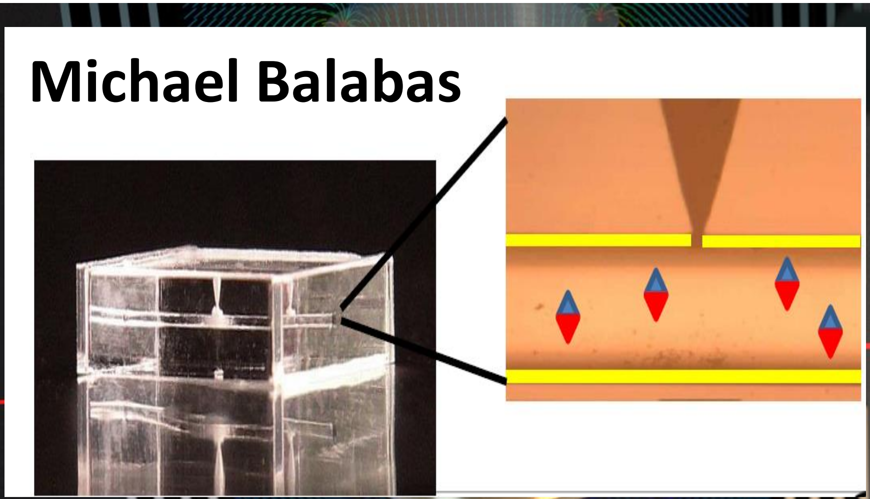
Magnetic spin states



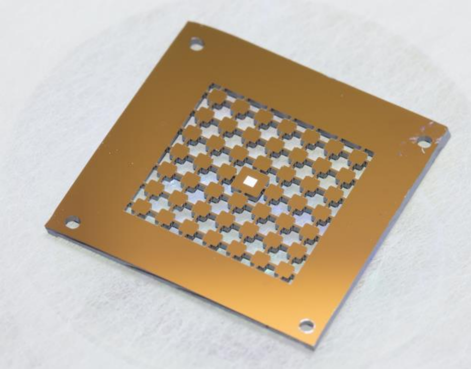
LETTER doi:10.1038/nature22980

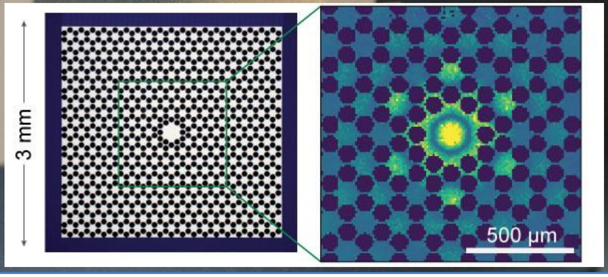
Treutlein group: Coupling atomic and mirror motion. PRL 2018

Distributed HYBRID quantum system of SPIN and MECHANICS



Room temperature spin quantum oscillator

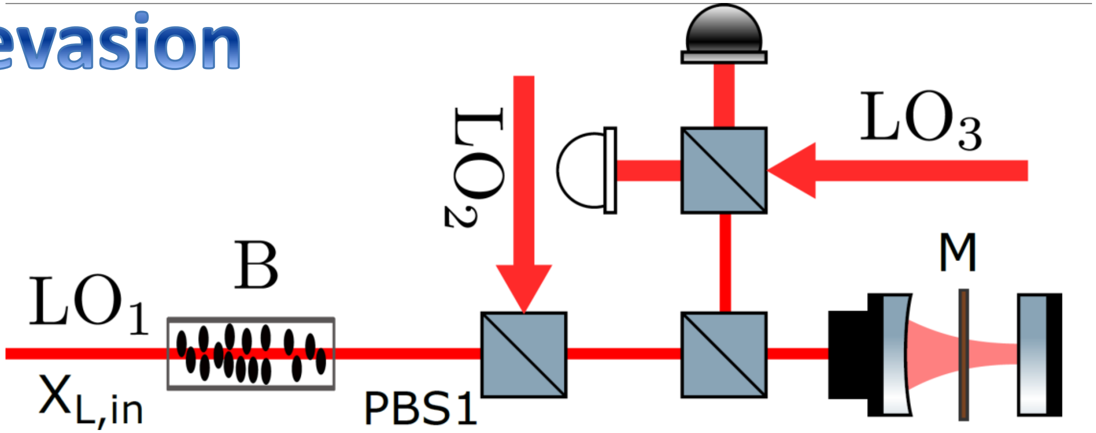




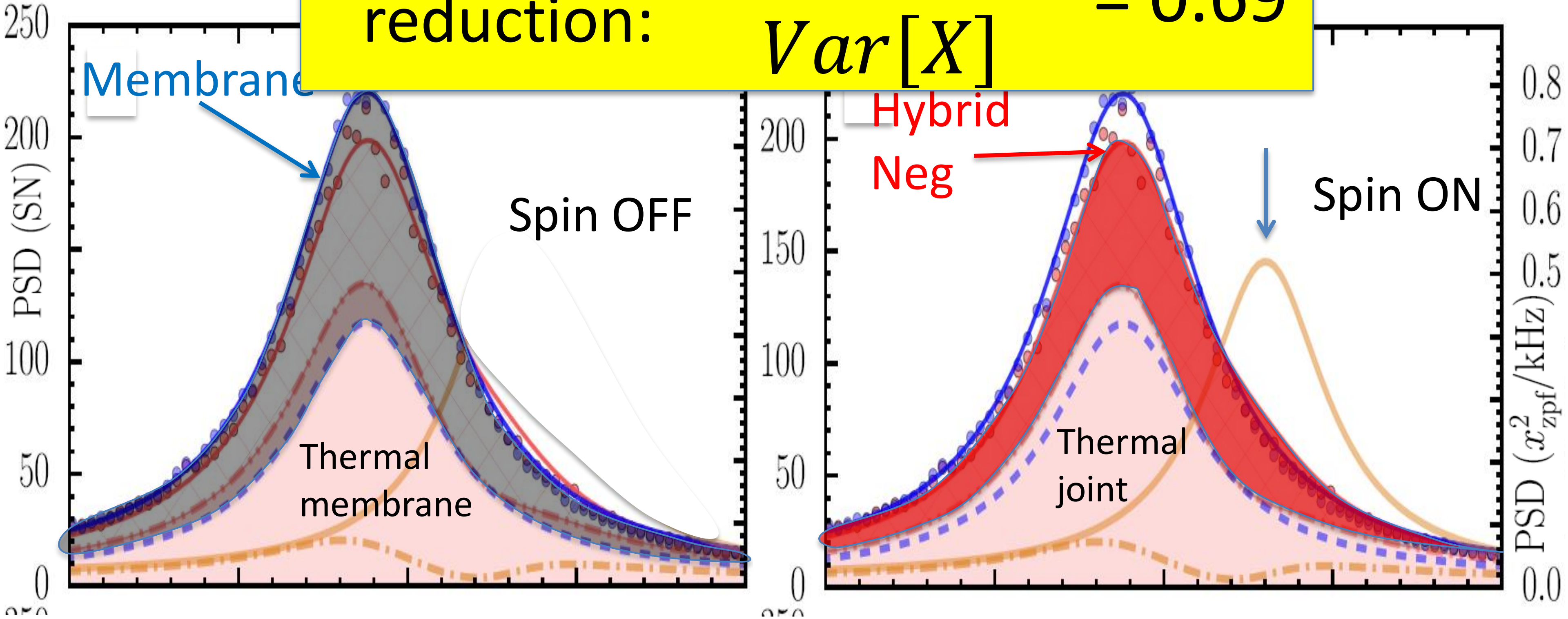
Mechanical oscillator with $Q = 10^7 - 10^9$

Image credit
Bastian Leonhardt Strube and Mads Vadsholt

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

PRL **116,** 061102 (2016)

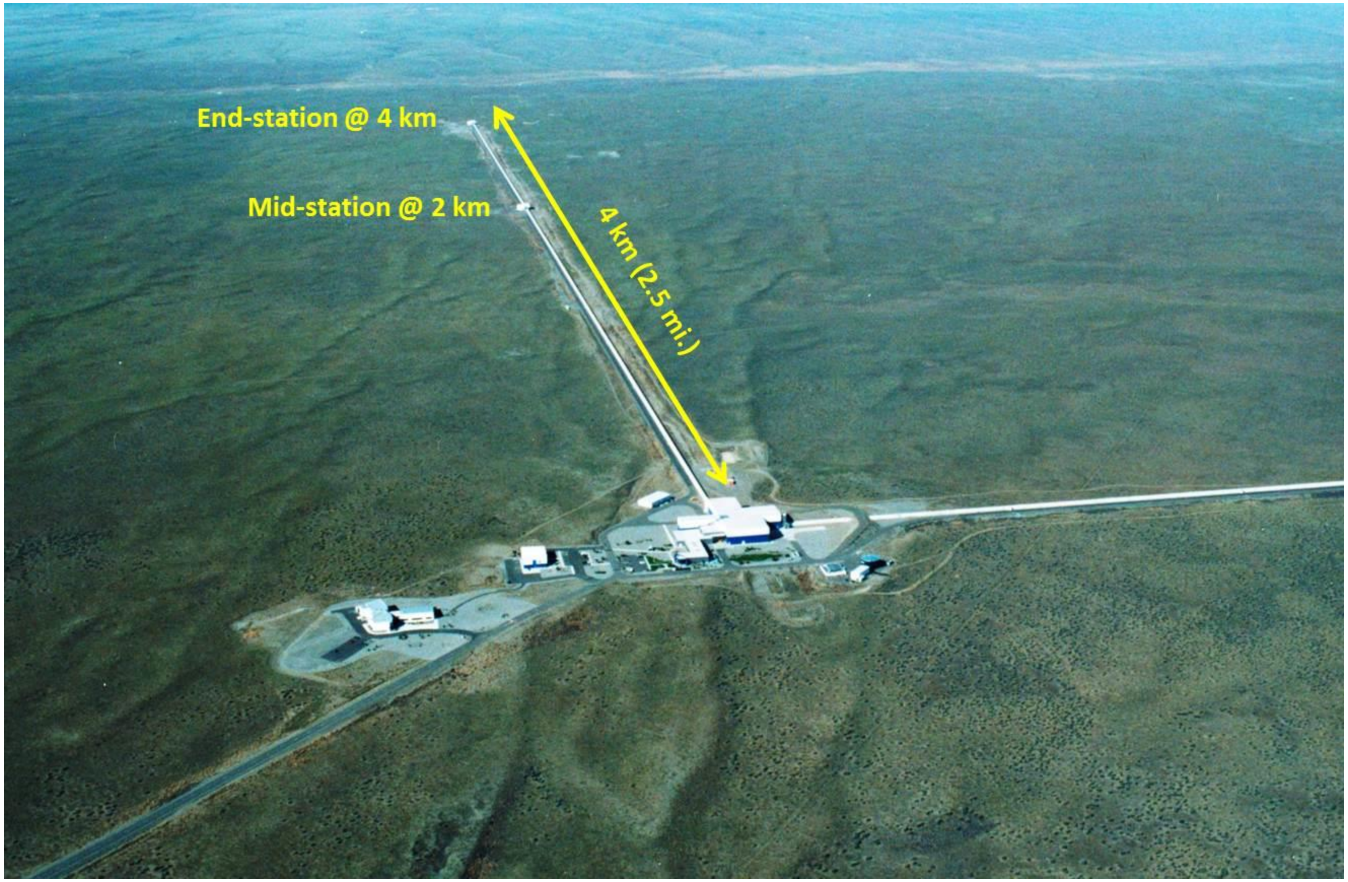
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

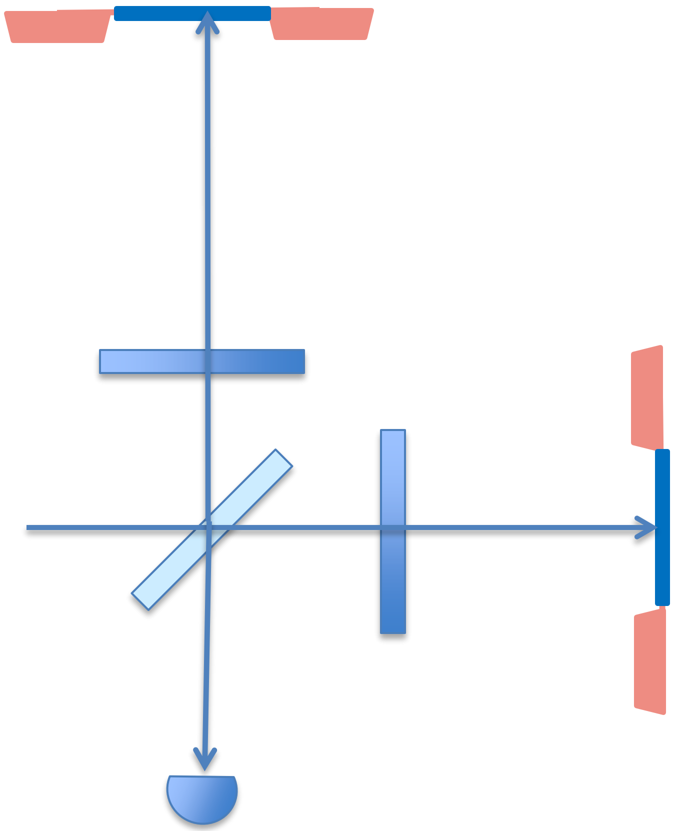
Observation of Gravitational Waves from a Binary Black Hole Merger

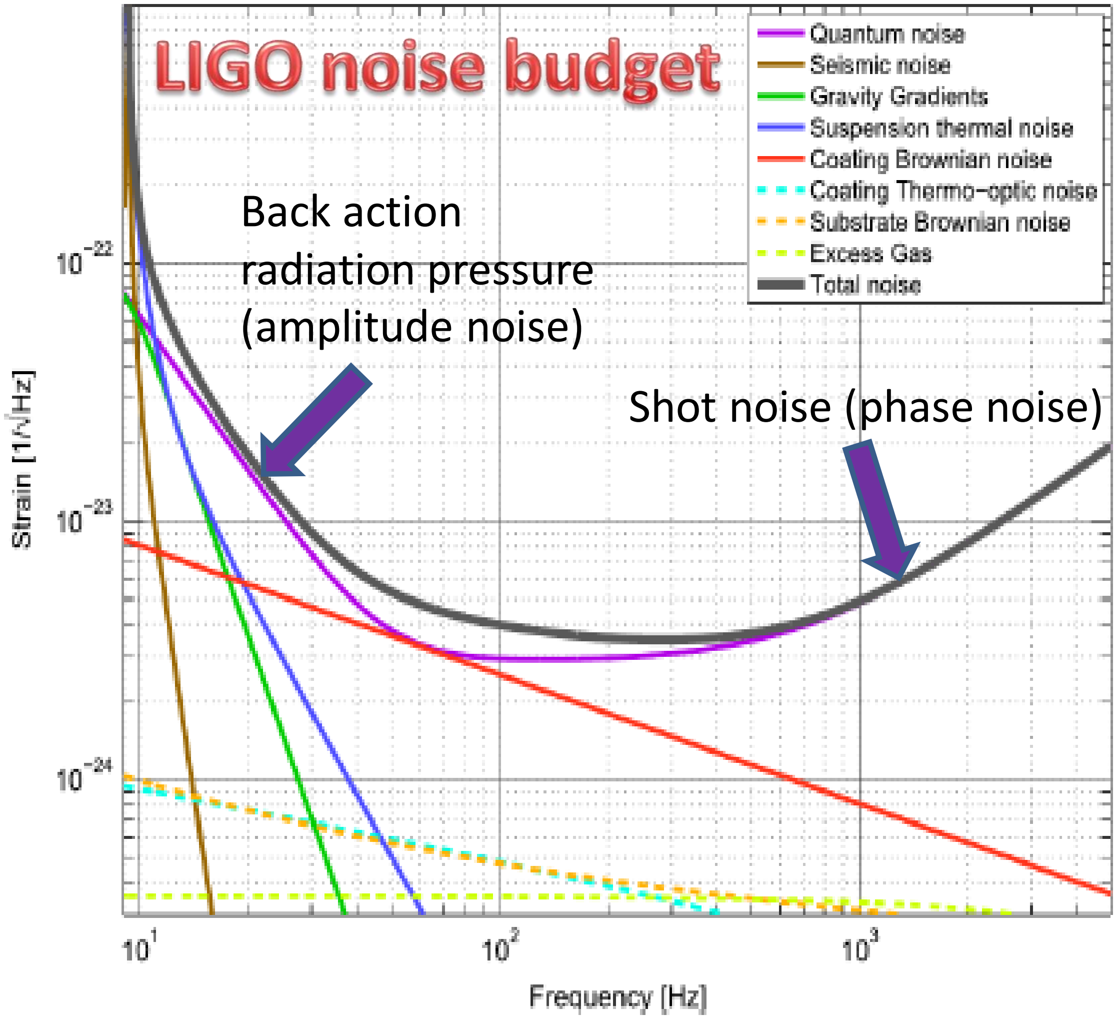
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



GWD BEYOND SQL WITH NEGATIVE MASS SPINS

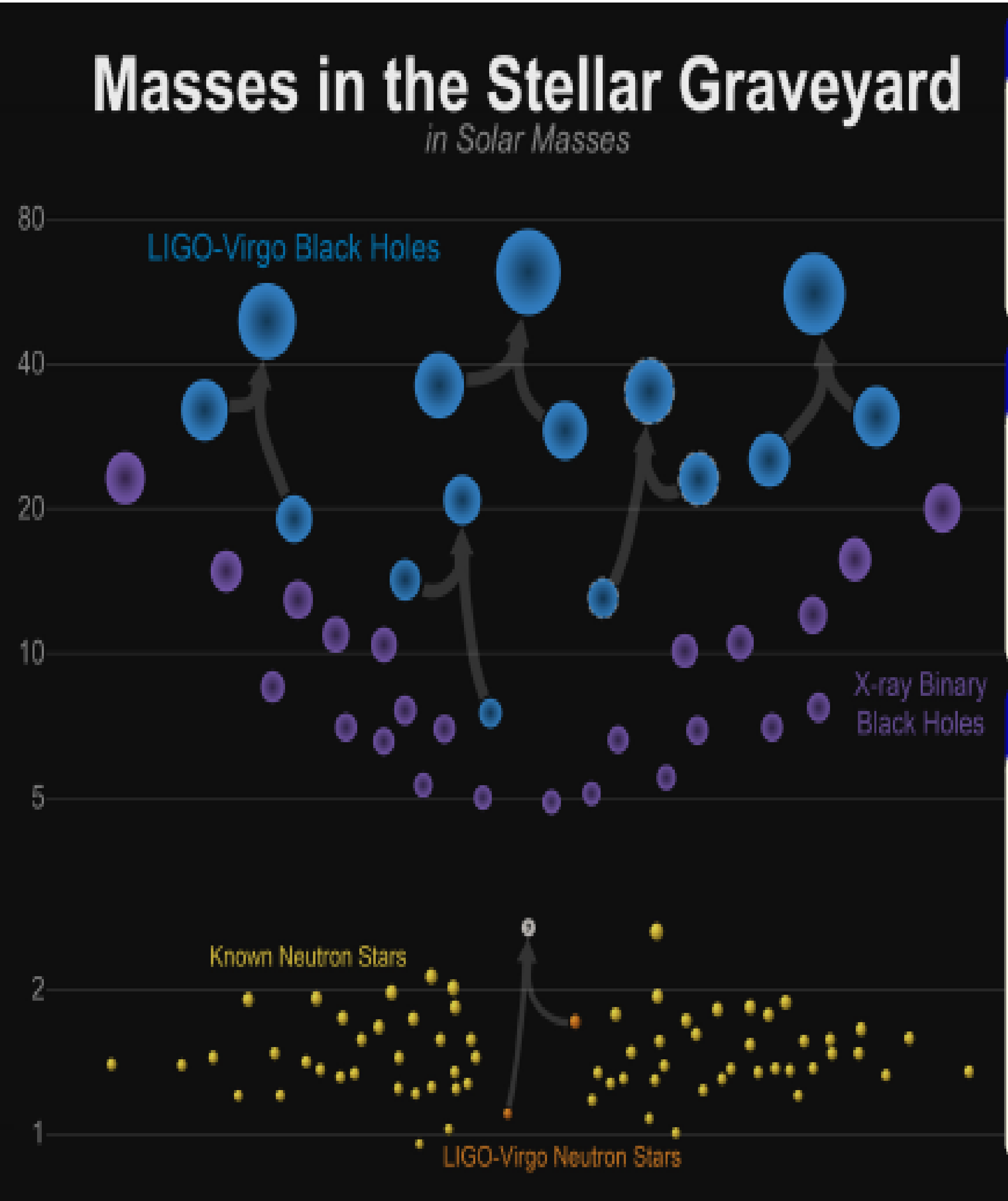




LIGO noise budget

Back action
radiation pressure
(amplitude noise)

Shot noise (phase noise)



2015-2017

- 2 observing runs: ~ 1 year
- 5 BH+BH events
- 1 NS+NS event.

Advanced LIGO design goal

- $\times 2.5 \div 3$ in sensitivity
- $\sim 10^2$ BH+BH events/year
- $\gtrsim 10$ NS+NS events/year

Still not enough for:

- Supernovae
- Pulsars
- Cosmic strings
- Background radiation
- …

GWD end mirrors

suspended 40 kg ”free” masses: oscillation frequency < 1Hz with $Q = 10^8$

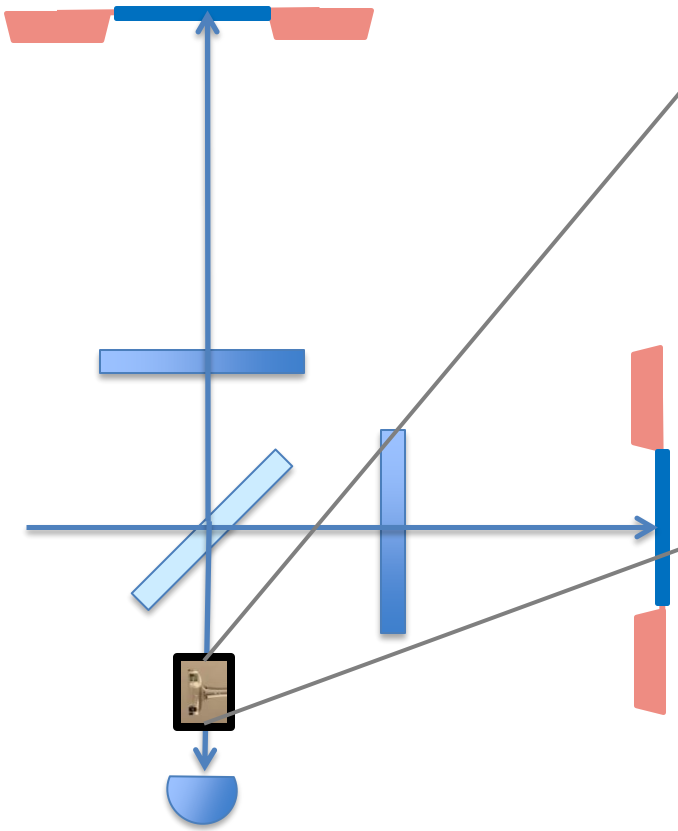
Standard Quantum Limit for measurement of motion of a free mass

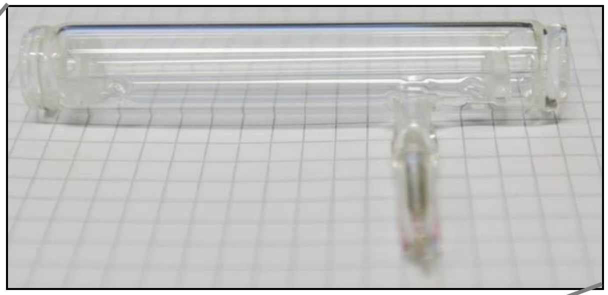
$$X(t) = X + \frac{Pt}{m}, \quad \Delta X \Delta P \geqslant \frac{\hbar}{2} \Rightarrow$$

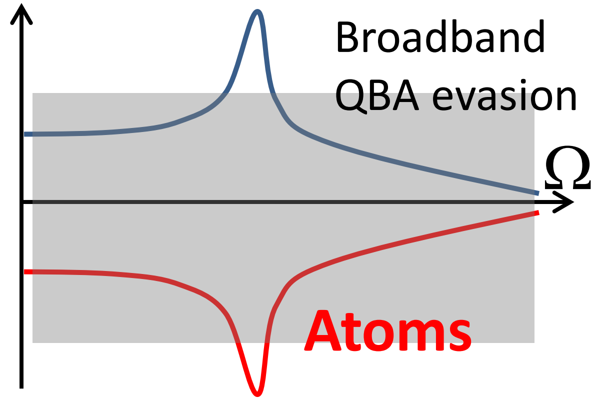
$$[\Delta X(t)]^2 \geqslant (\Delta X)^2 + \frac{\hbar^2 t^2}{4m^2(\Delta X)^2} \geqslant \frac{\hbar t}{m} \quad \text{(SQL)}$$

Other proposals for beyond SQL Gravitational Wave Interferometry:
H.J. Kimble et al, PRD65, 022002 (2001). Squeezed light with phase rotated by GWI
Y.Ma et al, Nature Physics 13, 776 (2017). Entangled light injected into GWI

GWD BEYOND SQL WITH NEGATIVE MASS SPINS





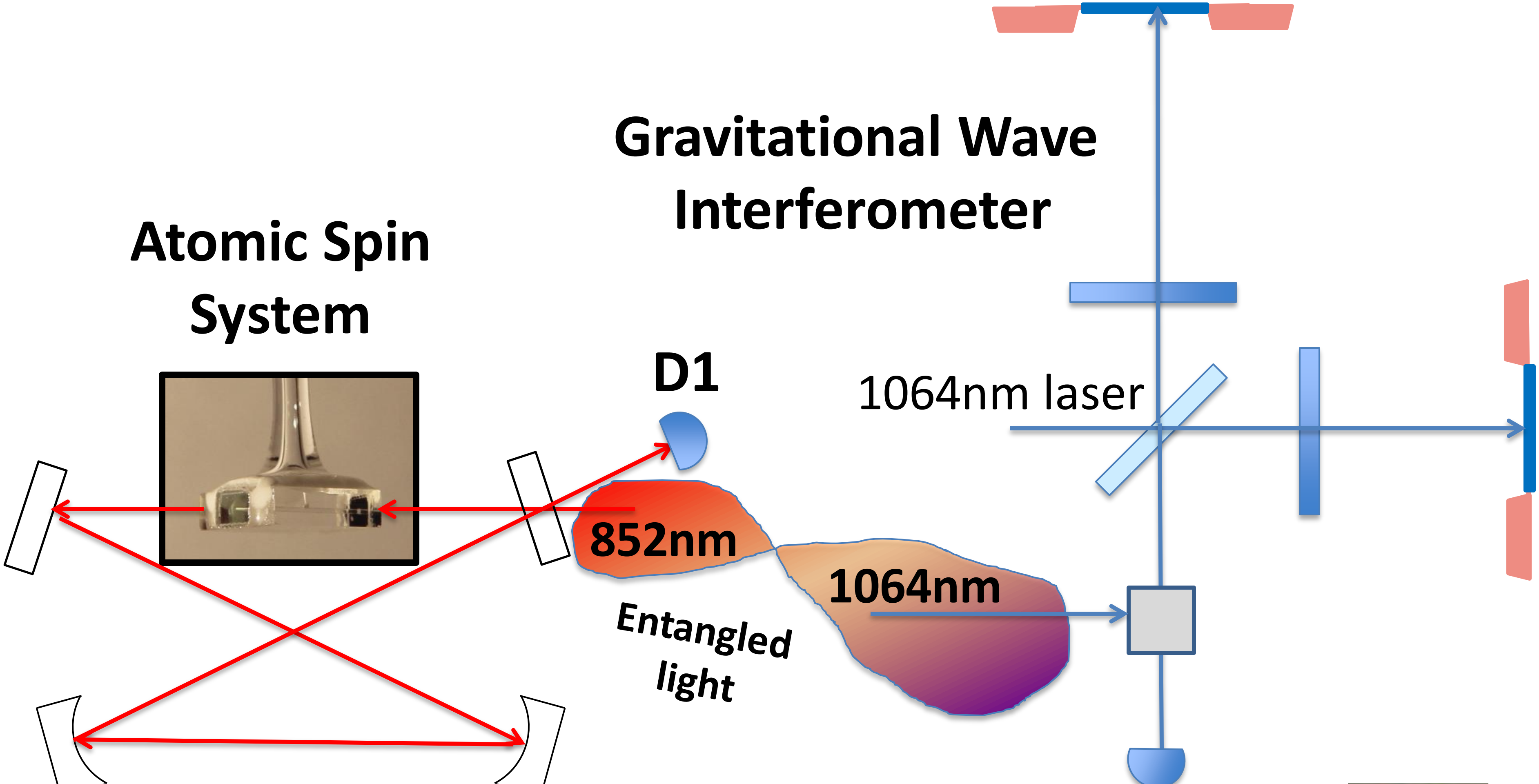


Free mass + negative mass

$$X_-(t) = X(t) - X_0(t) = X - X_0 + \frac{Pt}{m} - \frac{P_0 t}{-m} = X_- + \frac{P_+ t}{m}$$

$$[\hat{X}_-, \hat{P}_+] = 0 \Rightarrow \Delta X_- \Delta P_+ \geqslant 0 \Rightarrow [\Delta X_-(t)]^2 \geqslant 0 \quad \text{(EPR)}$$

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

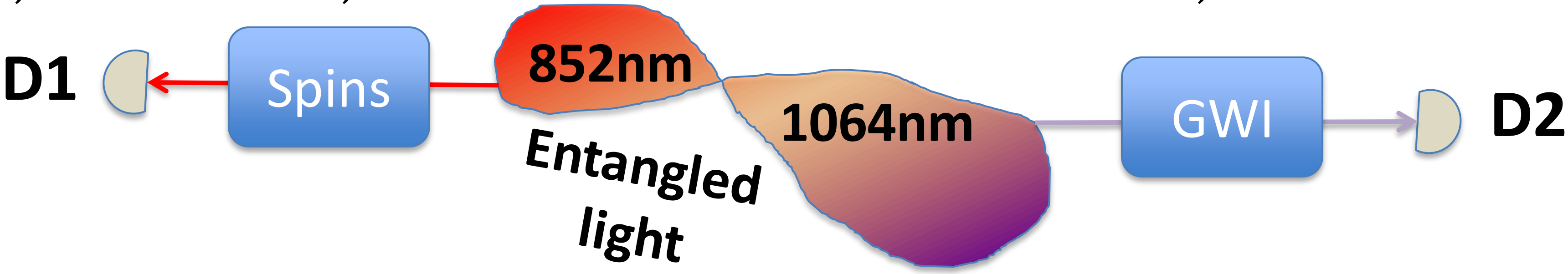


F. Khalili

Probing the hybrid system with EPR entangled light modes

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

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



D1

Spins

852nm

Entangled light

1064nm

GWI

D2

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

$$\Gamma_M \chi_M = -\Gamma_M \chi_M$$

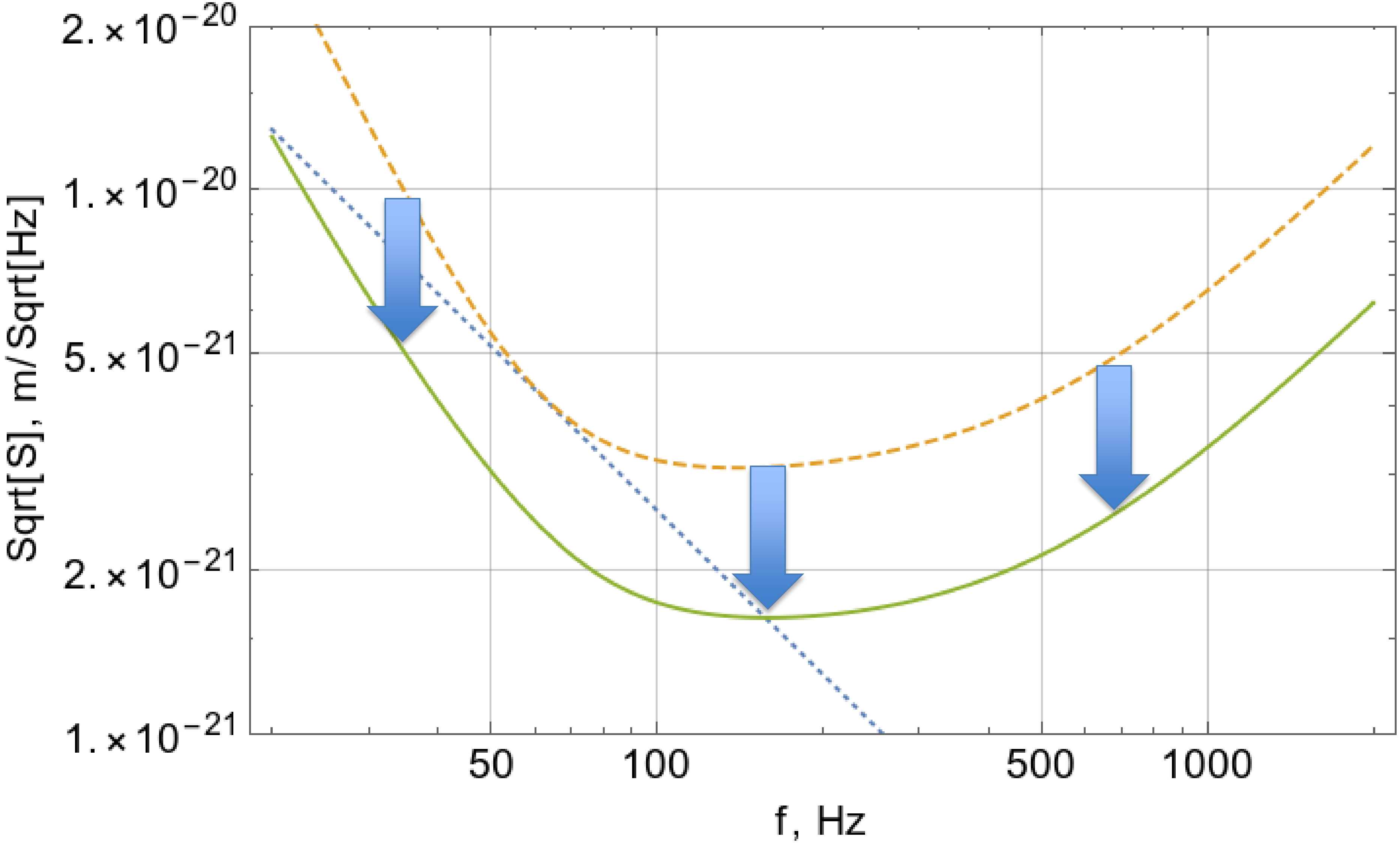
$$(P_{L1,in} - P_{L2,in})^2 = e^{-2r}$$

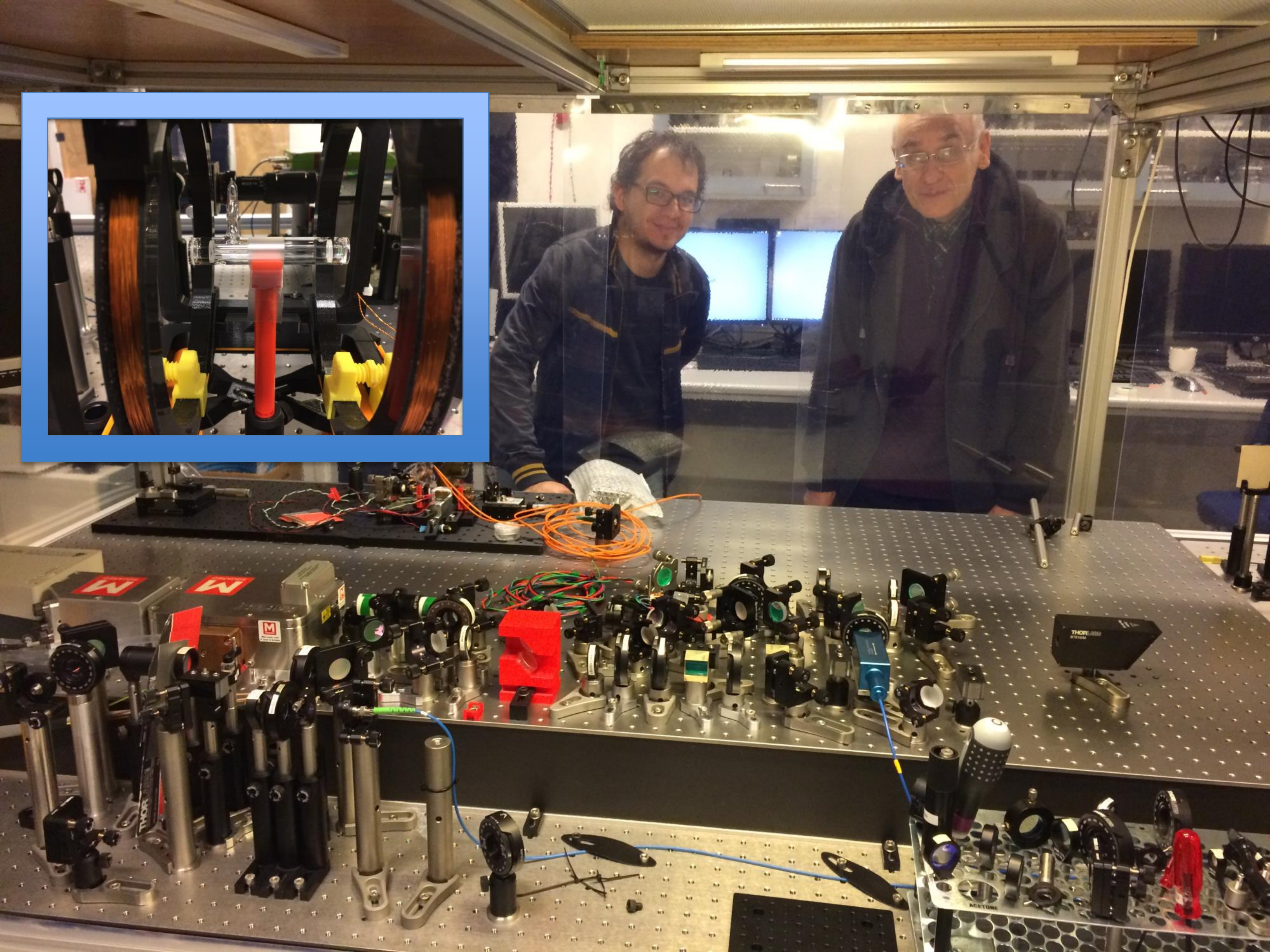
$$(X_{L1,in} + X_{L2,in})^2 = e^{-2r}$$

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

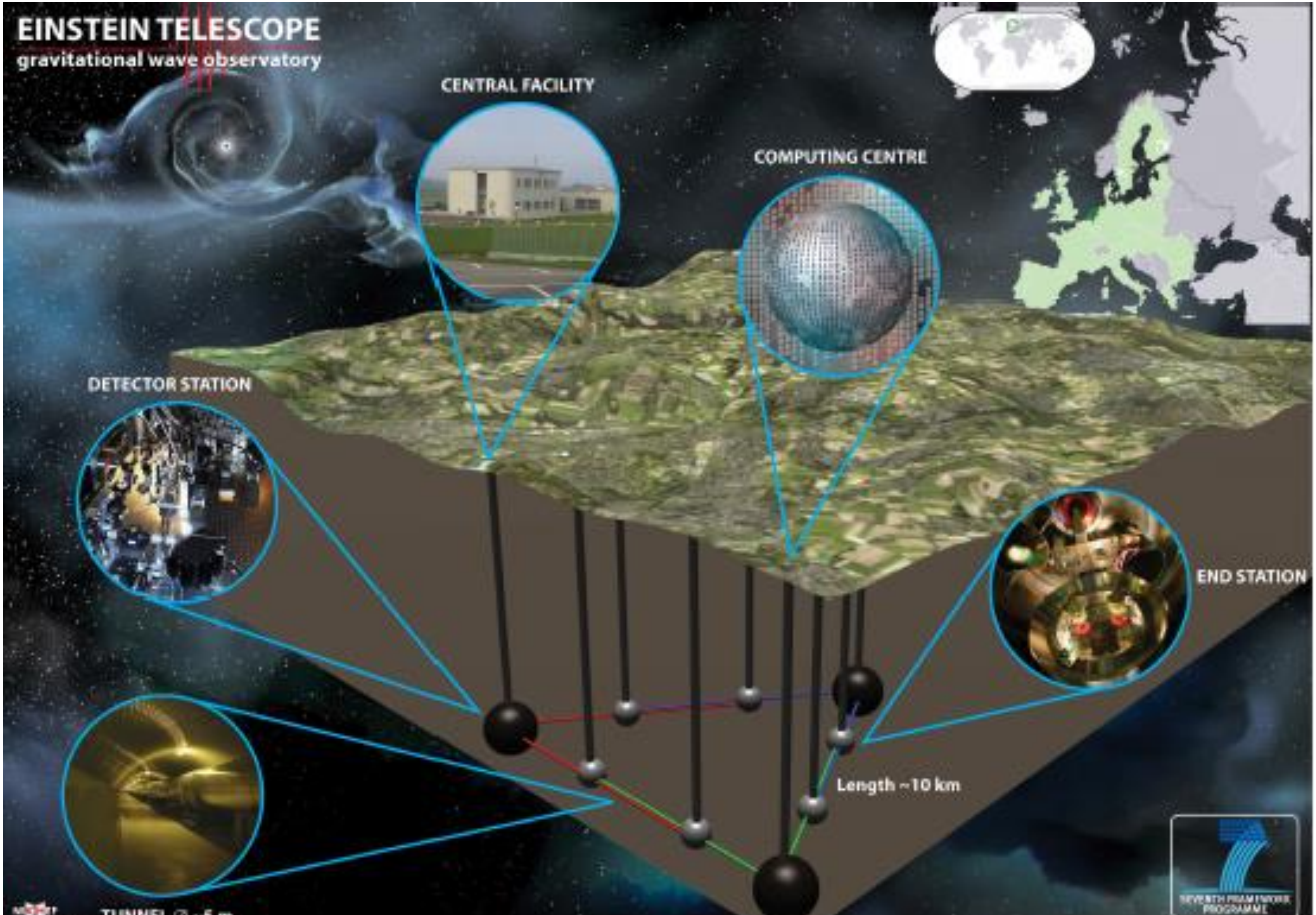
F. Khalili and E.S.P. Phys.Rev.Lett. July 2018

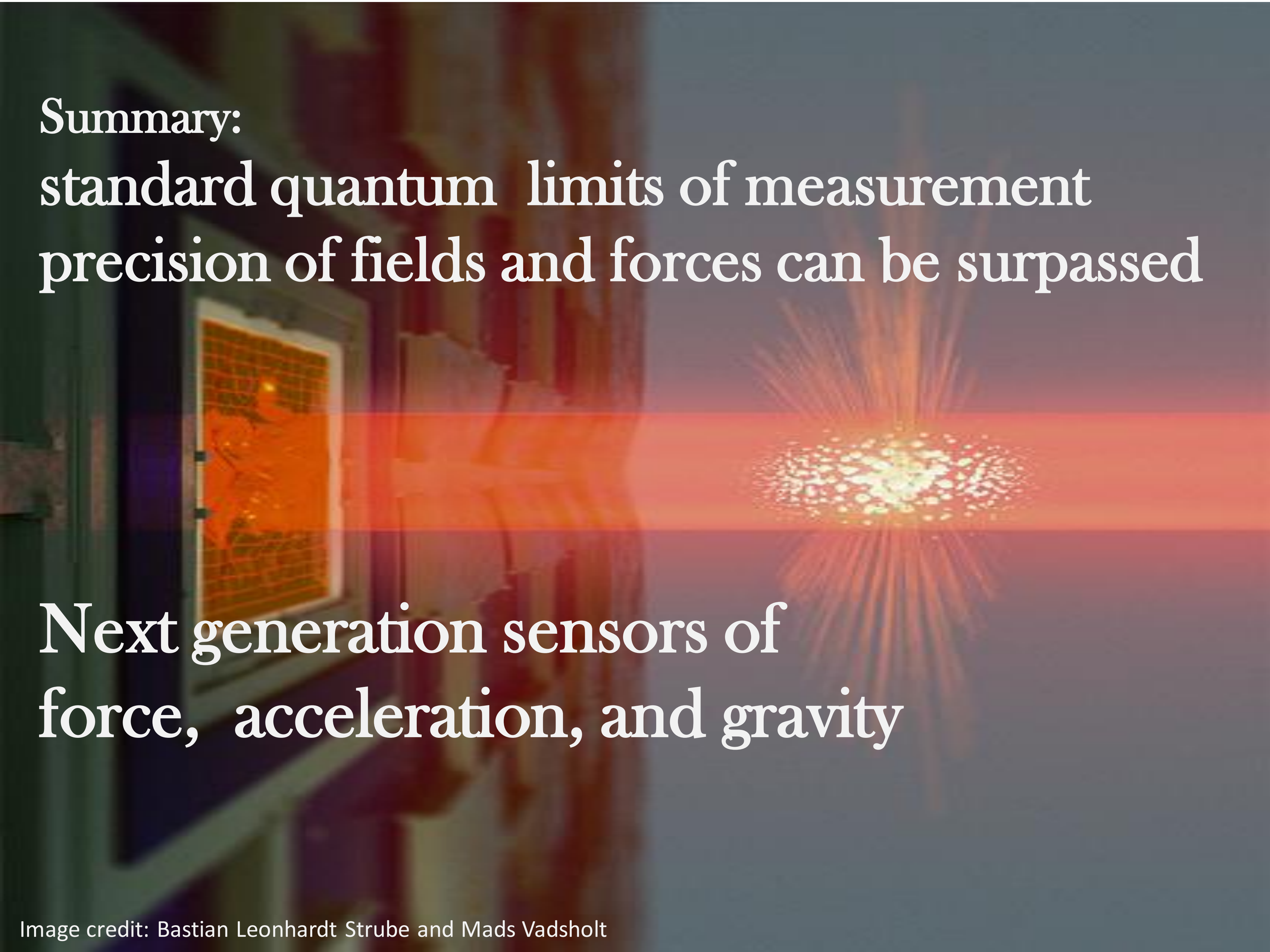
Simulation for LIGO




THORLABS

European Gravitational Wave future





Summary:

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

Next generation sensors of force, acceleration, and gravity

Image credit: Bastian Leonhardt Strube and Mads Vadsholt