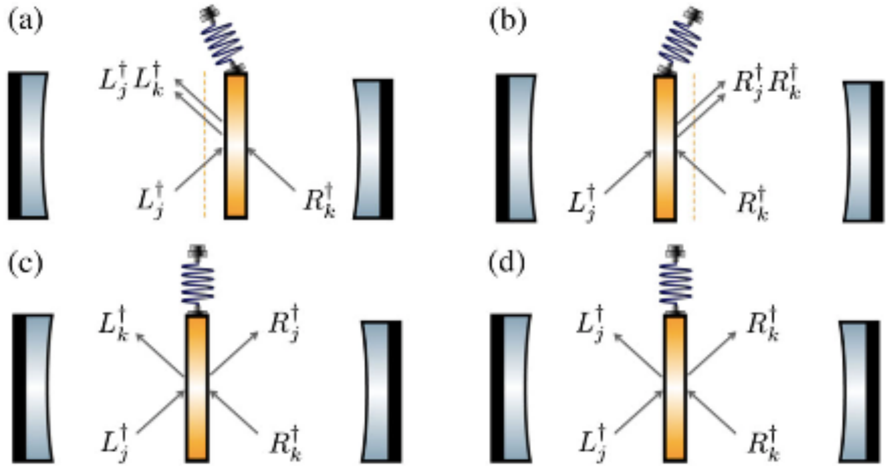
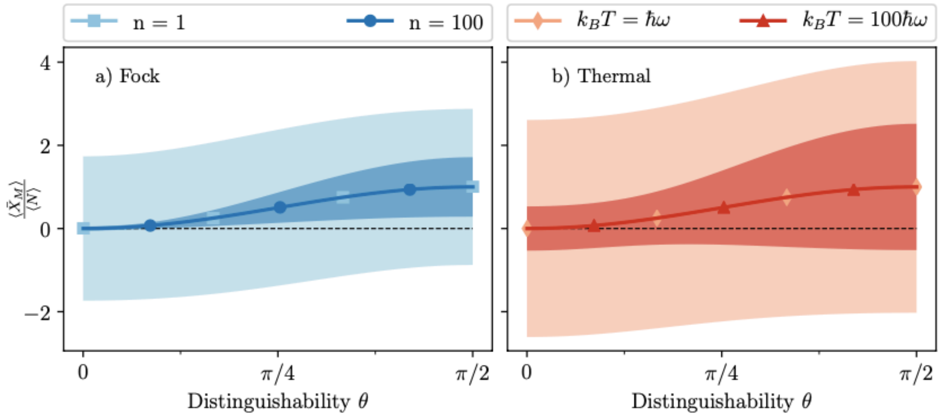




[1] Enhanced Energy Transfer to an Optomechanical Piston from Indistinguishable Photons,
Holmes, Anders, Mintert, PRL124, 210601 (2020)

[2] Gibbs mixing of partially distinguishable photons with a polarising beamsplitter membrane,
Holmes, Mintert, Anders, arxiv 2006.00613v1 (2020)

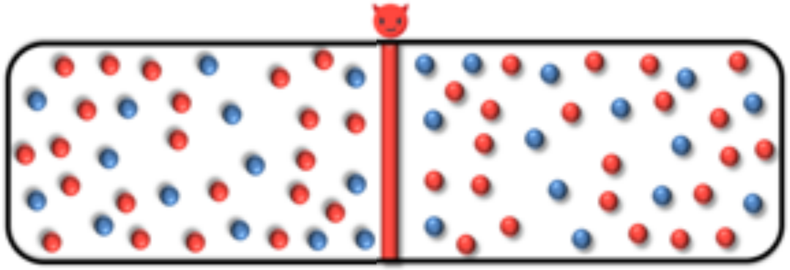
Thermodynamic signatures of distinguishability in an optomechanical setting

Janet Anders
University of Exeter (part-time)
& University of Potsdam (part-time)

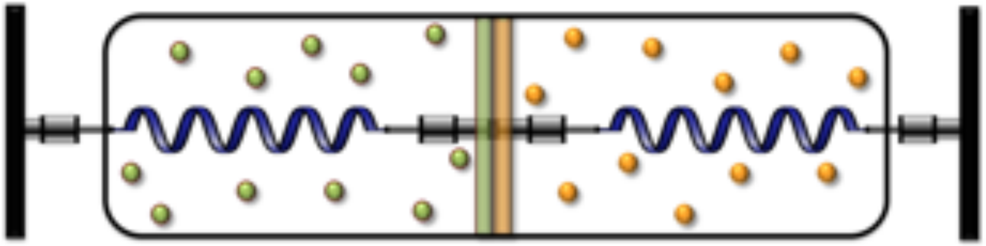
joint work with:
Zoe Holmes (LosAlamos)
Florian Mintert (Imperial C)

Workshop Quantum Thermodynamics of Non-Equilibrium Systems (QTDNEQ20)
(virtually in) **Donostia-San Sebastian, 15 Oct 2020**

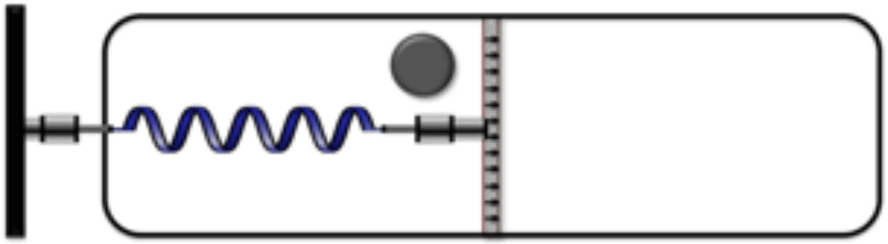
Thermodynamic thought experiments



Maxwell's demon

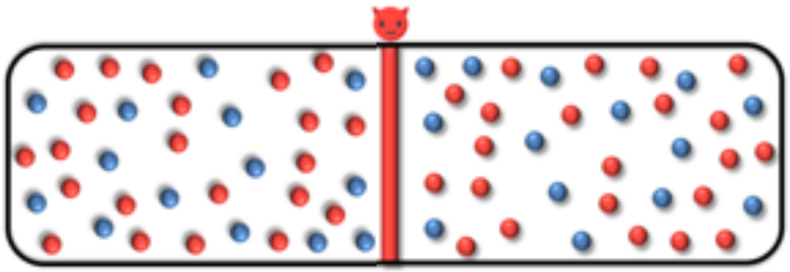


Gibbs mixing

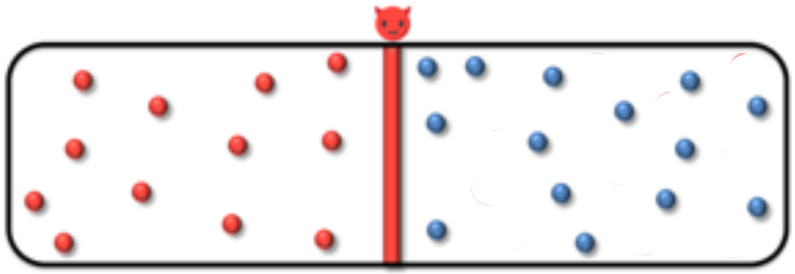


Feynman's ratchet

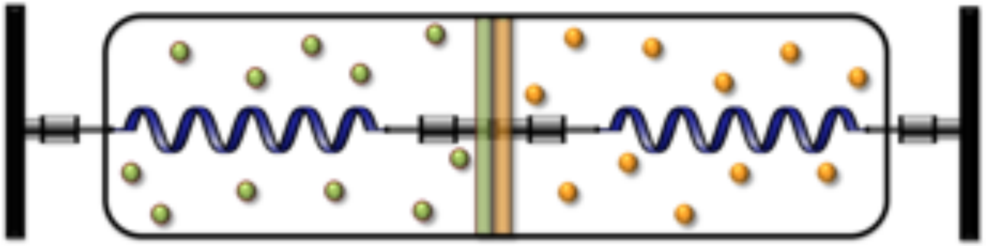
Thermodynamic thought experiments



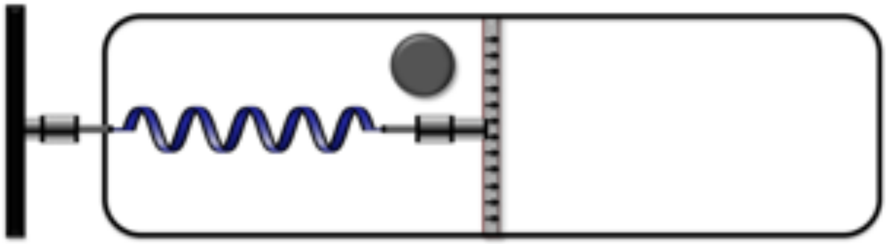
Maxwell's demon



Fast (high E) and slow (low E) particles are separated, from which work may later be extracted.



Gibbs mixing

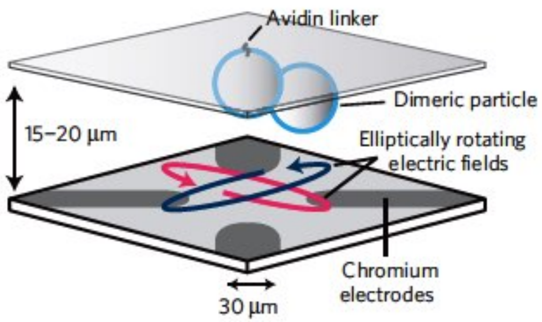


Feynman's ratchet

Many recent experiments:

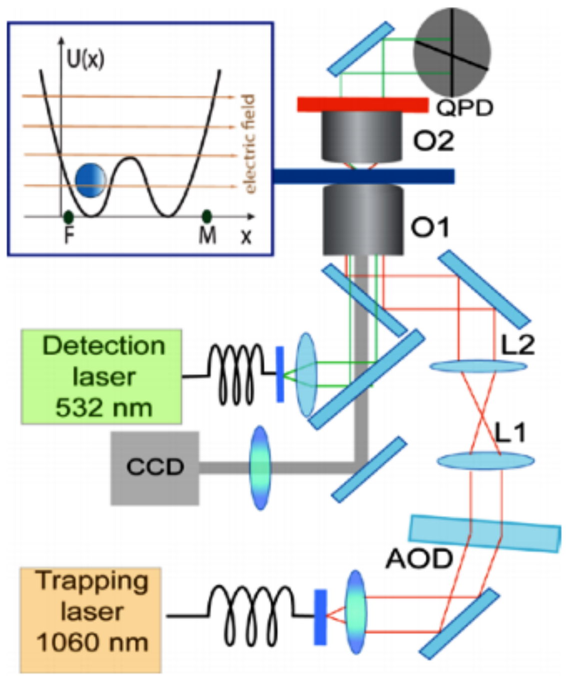
Maxwell Demons

classical demons



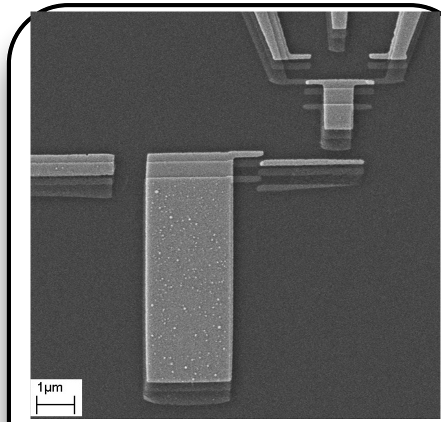
colloidal particle in electrical potential

Toyabe et al. (Tokyo) Nature Phys 2010



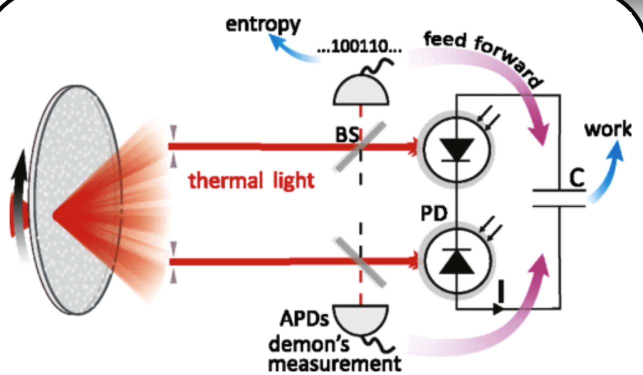
optically trapped colloidal particle

Roldan et al. (Barcelona), Nature Physics 2014



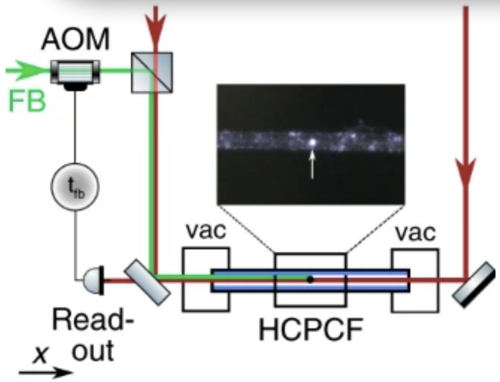
single electron box

Koski et al. (Helsinki), PNAS 2014



photons

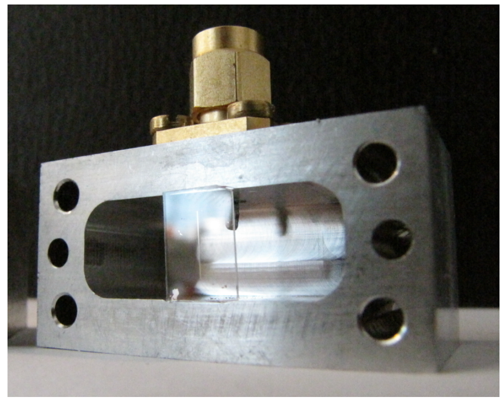
Vidrighin et al. (Oxford), PRL 2015



optically levitated microparticle

Debiossac et al. (Vienna) Nat Comm 2020

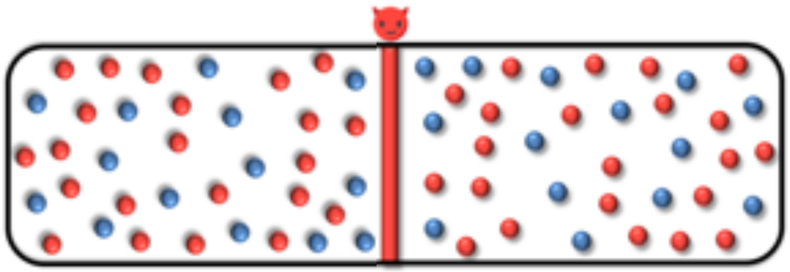
quantum demons



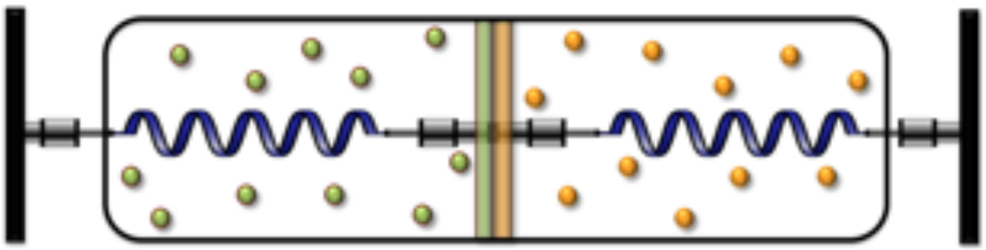
superconducting qubit in cavity

Cottet et al. (Paris) PNAS 2017

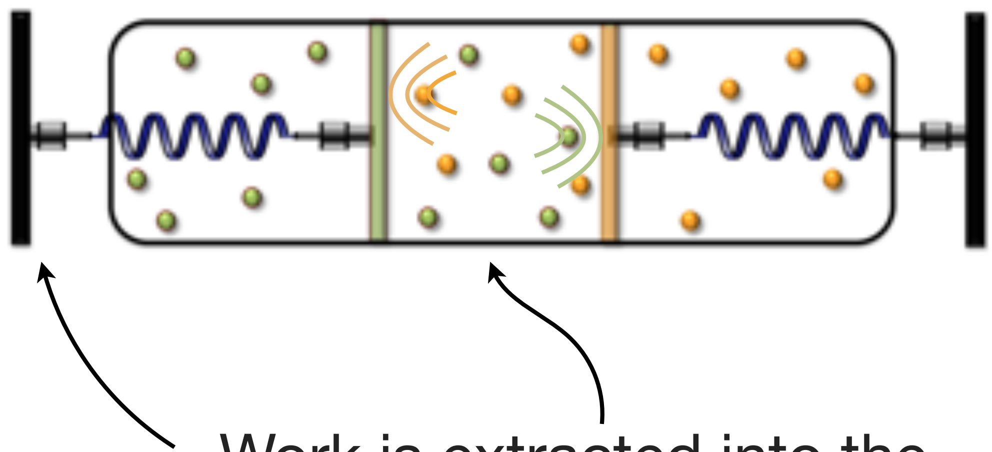
Thermodynamic thought experiments



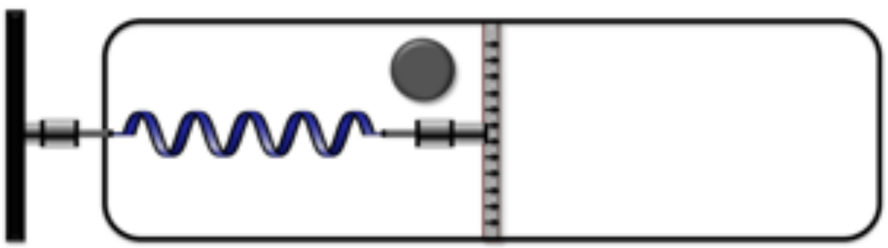
Maxwell's demon



Gibbs mixing

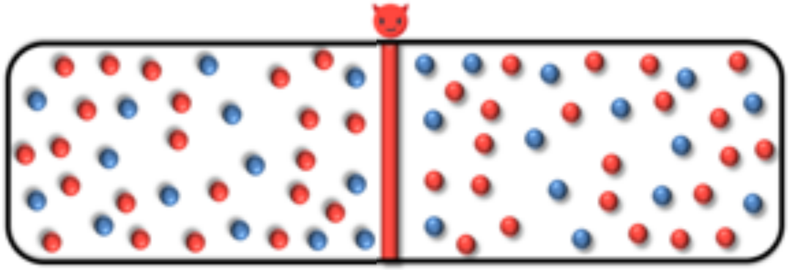


Work is extracted into the piston solely from mixing two gases in space.



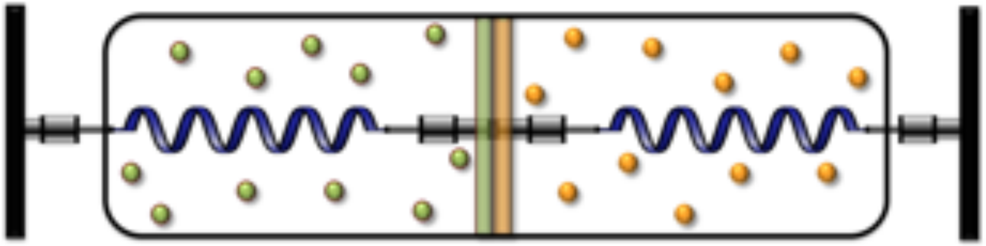
Feynman's ratchet

Thermodynamic thought experiments

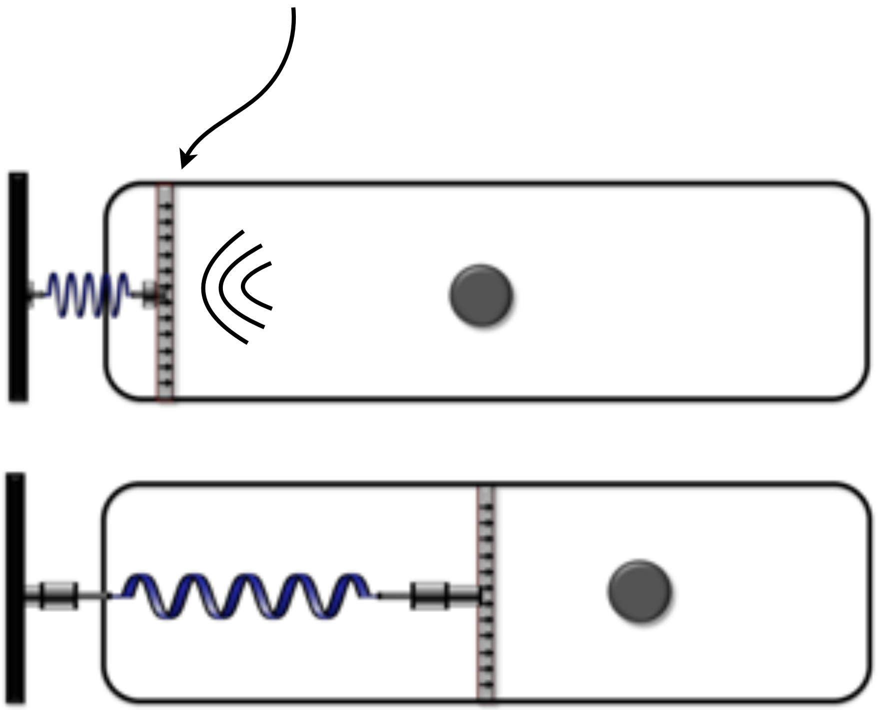


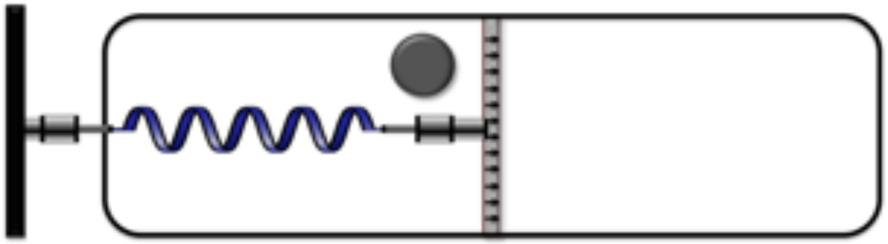
Maxwell's demon

Work is extracted into the piston from one-directional collisions.



Gibbs mixing

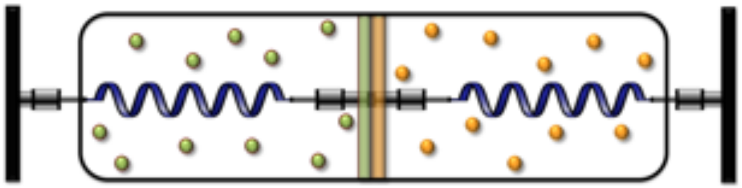


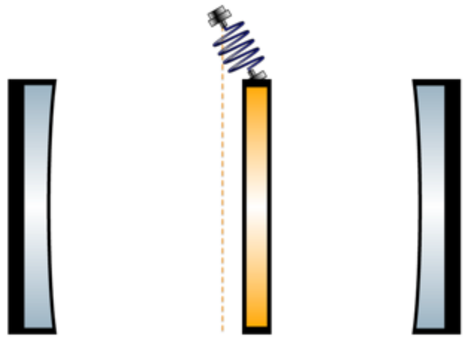


Feynman's ratchet

Key idea: Optomechanic thought exps.

Optomechanical setups enable the conception of **quantum thermodynamics thought experiments** (and possible realisation)





gases → photon gases with variable polarisation

membrane → optical membrane in the middle

beam splitter (BS)
polarisation dependent beam splitter (PBS)

→ **Impact of partial, quantum distinguishability on thermodynamics.**

Outline

Beam splitter (BS) — [1]

- energetic signature of bosonic bunching

Polarisation dependent Beam splitter (PBS) — [2]

- quantum analogue of Gibbs mixing

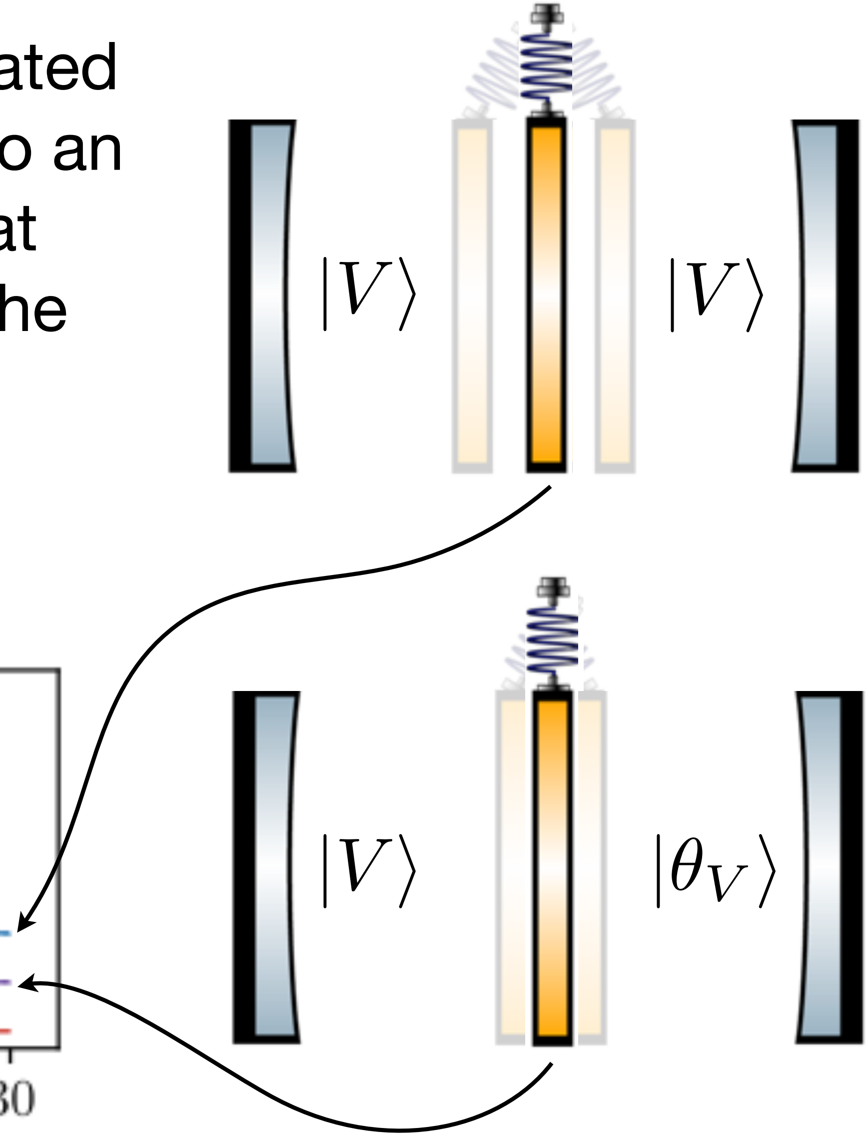
‘Membrane in the middle’ Optomechanics — [1, 2]

[1] Enhanced Energy Transfer to an Optomechanical Piston from Indistinguishable Photons, Holmes, Anders, Mintert, PRL124, 210601 (2020)

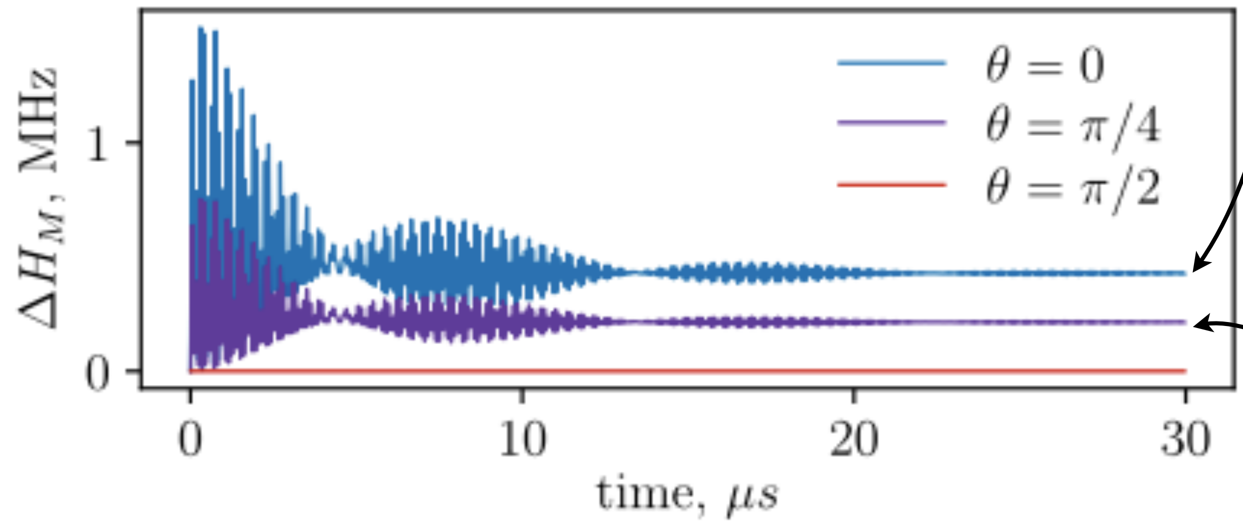
[2] Gibbs mixing of partially distinguishable photons with a polarising beamsplitter membrane, Holmes, Mintert, Anders, arxiv 2006.00613v1 (2020)

Key message [1]

[1] **Two photonic gases** initially separated by a **beam splitter**, dynamically lead to an **energy transfer to the membrane** that depends on the **distinguishability** of the polarisations of the two gases, and scales as N2.

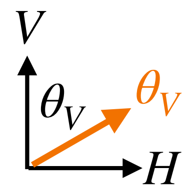


$$\Delta H_M(t) = \langle H_M(t)\rangle - \langle H_M(0)\rangle$$



$$\langle H_M(t)\rangle = \left\langle \frac{m\omega_M^2 X_M(t)^2}{2} + \frac{m\dot{X}_M(t)^2}{2} \right\rangle$$

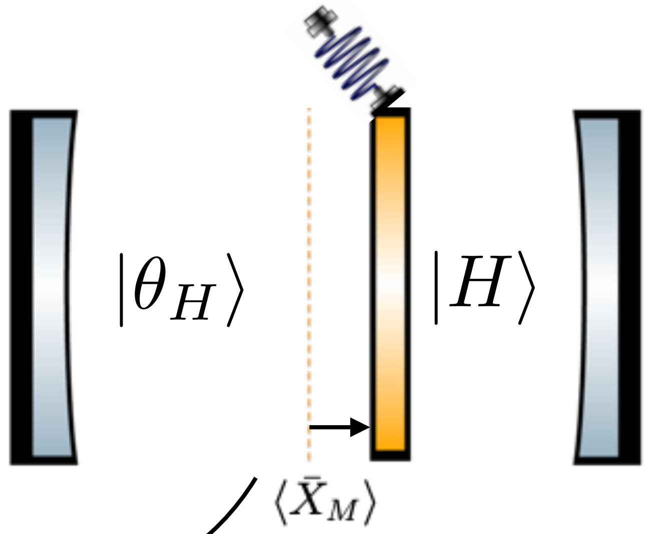
in [1]:
θ_V is the angle against V



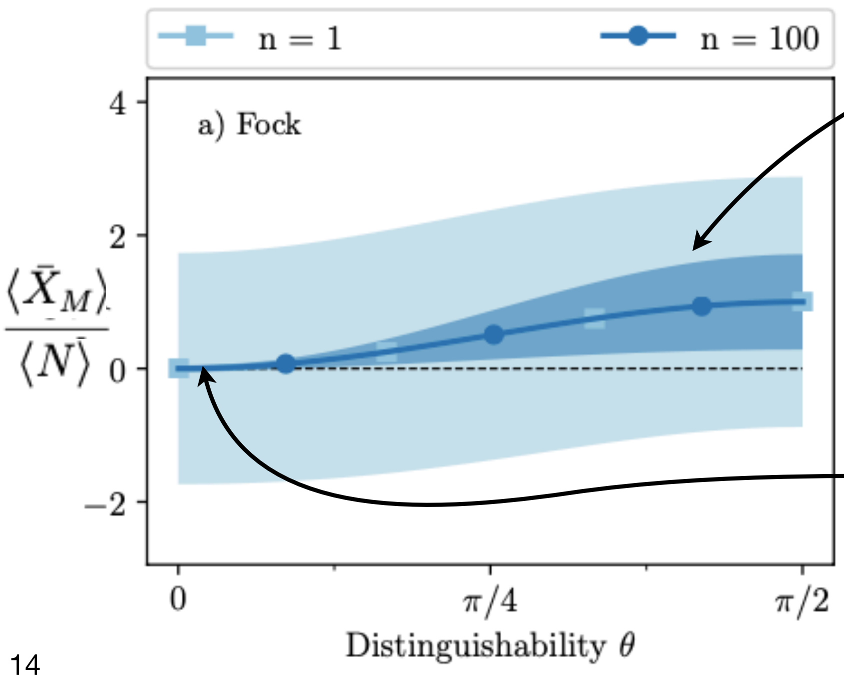
Key message [2]

[2] **Two photonic gases** initially separated by a **polarisation dependent beam splitter***, dynamically lead to a **displacement (work) of the membrane** that depends on the **distinguishability** of the polarisations of the two gases.

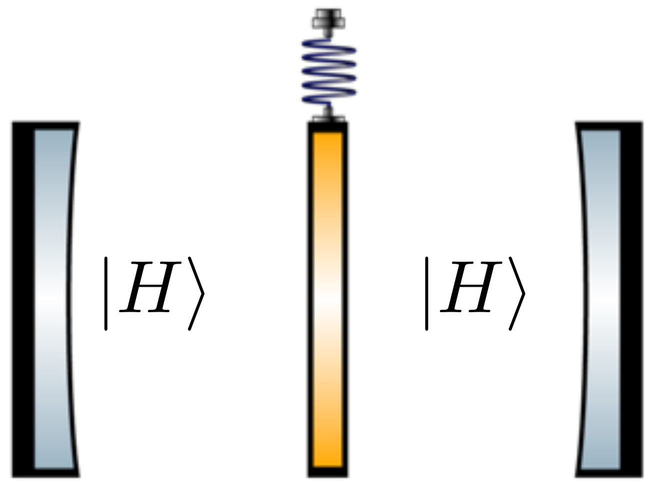
*mirror for V, BS for H



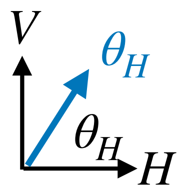
$$\langle \bar{X}_M \rangle := \mathrm{Tr}\left[\frac{1}{\tau}\int_0^\tau dt X_M(t)\ \rho\right]$$



$$W_M^{\text{mix}} := \frac{1}{2} m\omega_M^2 \langle \bar{X}_M \rangle^2$$



in [2]:
θ_H is the angle against H



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Modes & Hamiltonian

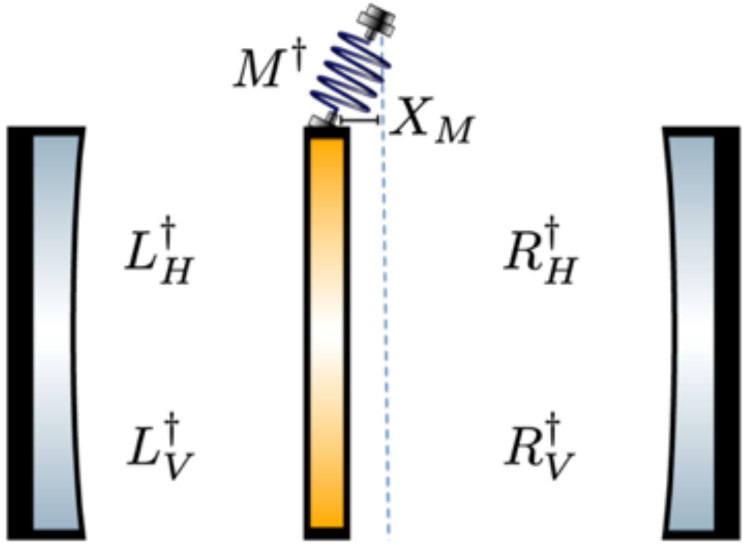
multi-mode: five creation operators

$$L_H^\dagger \quad L_V^\dagger \quad R_H^\dagger \quad R_V^\dagger \quad M^\dagger$$

photon number operators L/R

$$N_L = L_H^\dagger L_H + L_V^\dagger L_V$$

$$N_R = R_H^\dagger R_H + R_V^\dagger R_V$$



Modes & Hamiltonian

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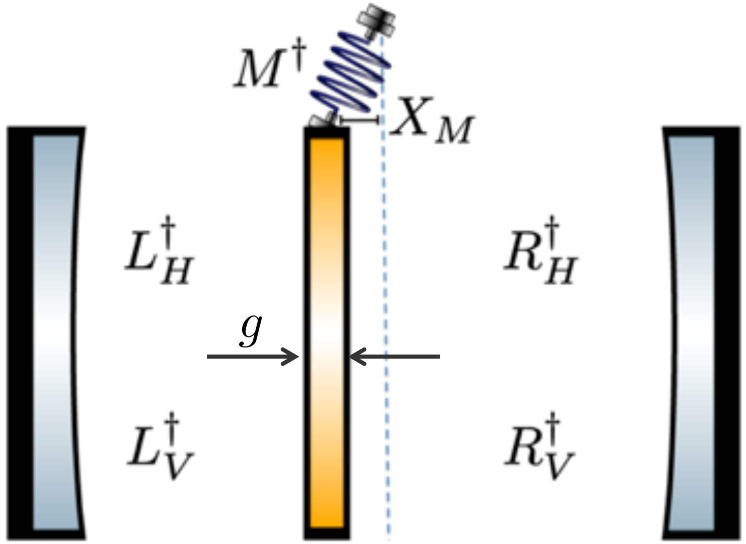


photon number operators L/R

$$N_L = L_H^\dagger L_H + L_V^\dagger L_V$$

$$N_R = R_H^\dagger R_H + R_V^\dagger R_V$$

photon gas Hamiltonian

$$H_C = \omega(N_L + N_R)$$

membrane Hamiltonian

$$H_M = \omega_M M^\dagger M$$

membrane position operator

$$X_M = x_{\text{zpf}}(M + M^\dagger)$$

beam splitter interaction

$$H_{\text{BS}} = \sum_{p=H,V} \frac{\lambda}{2}(R_p^\dagger L_p + L_p^\dagger R_p)$$

transmit photon on R with p
to L with same p + vice versa

photon-membrane interaction

$$H_I = -g(N_L - N_R)X_M$$

(radiation pressure)

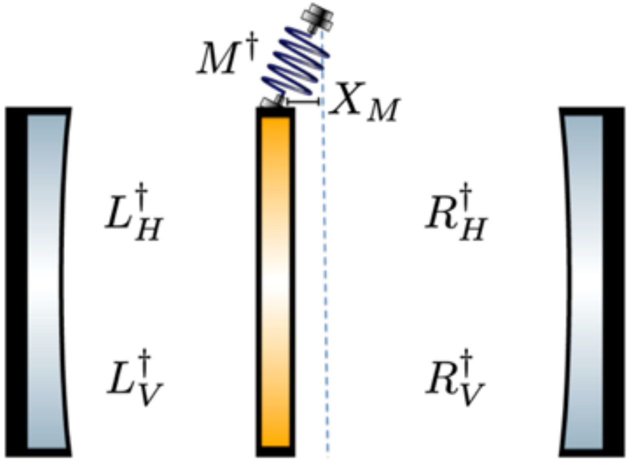
Initial state

Initial product state:

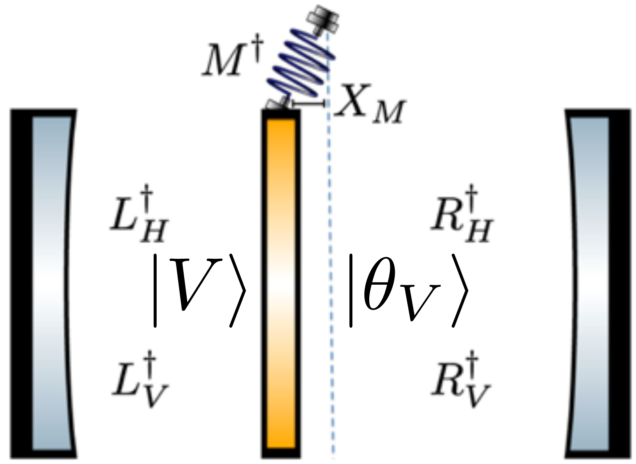
$$\rho_L \otimes \rho_R \otimes \sigma_M$$

Initial photon gases:

L: one photon polarised: $|V\rangle = L_V^\dagger |0\rangle$



Initial state



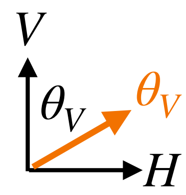
Initial product state:

$$\rho_L \otimes \rho_R \otimes \sigma_M$$

Initial photon gases:

L: one photon polarised: $|V\rangle = L_V^\dagger \, |0\rangle$

R: one photon polarised: $|\theta_V\rangle = (\cos\theta \ R_V^\dagger + \sin\theta \ R_H^\dagger)|0\rangle$



perfectly distinguishable (orthogonal) $\theta = \pi/2$

partially distinguishable $0 < \theta < \pi/2$

perfectly indistinguishable (same) $\theta = 0$

many photons:

set: same number distribution on both sides

=> same number average and variance

$$\langle N(0)\rangle = \mathrm{tr}_L[N_L(0)\rho_L] = \mathrm{tr}_R[N_R(0)\rho_R]$$

$\delta N(0)$ ...

Initial membrane state:

set: zero avg displacement and momentum

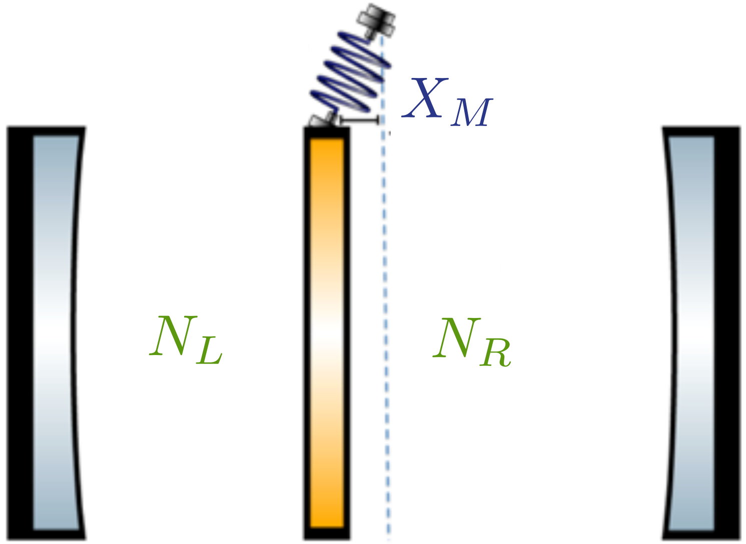
$$\mathrm{tr}_M[X_M(0)\sigma_M] = 0$$

=> eg thermal state

Dynamics (Heisenberg pic)

total Hamiltonian for 5 modes:

$$H = H_C + H_M + H_{BS} + H_I$$



membrane:

$$\frac{d^2 X_M}{dt^2} + \omega_M^2 X_M = \frac{g}{m}(N_L - N_R)$$

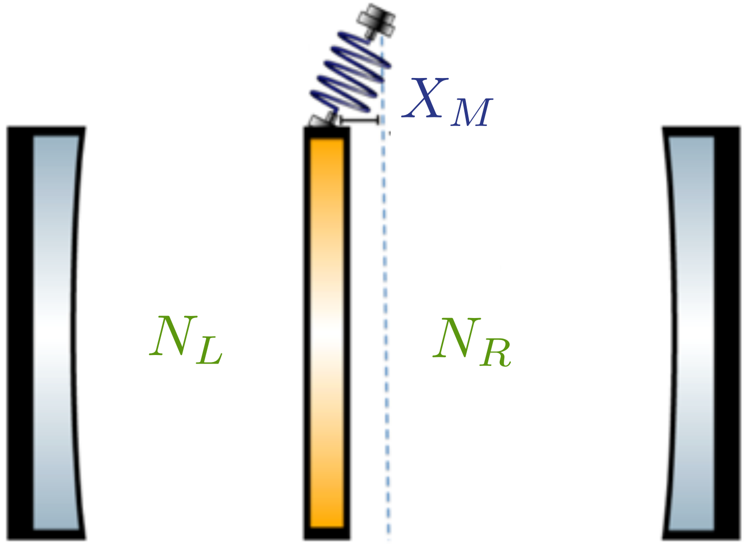
harmonic osci

driven by oscillations
of photons

Dynamics (Heisenberg pic)

total Hamiltonian for 5 modes:

$$H = H_C + H_M + H_{BS} + H_I$$



membrane:

$$\frac{d^2 X_M}{dt^2} + \omega_M^2 X_M = \frac{g}{m}\left(N_L - N_R\right)$$

harmonic osci

driven by oscillations of photons

photons:

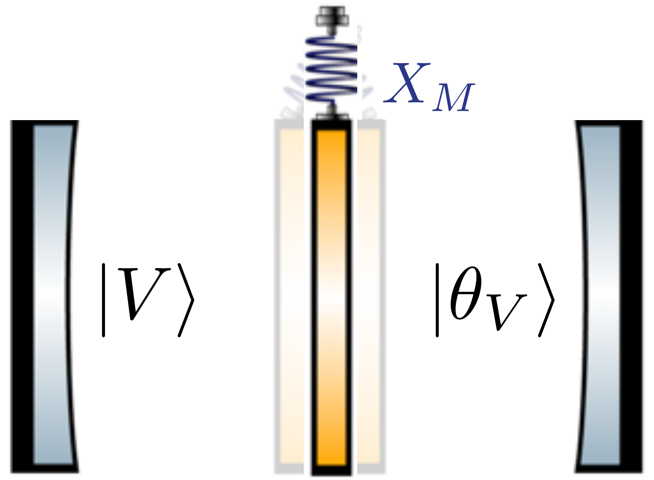
$$\frac{d^2 \Delta N_p}{dt^2} = -\lambda^2 \Delta N_p - 2g\lambda X_M \left(L_p^\dagger R_p + L_p R_p^\dagger\right)$$

solve coupled dynamics perturbatively in g

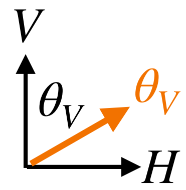
Dynamics (Heisenberg pic)

$$\Delta H_M(t) = \langle H_M(t)\rangle - \langle H_M(0)\rangle$$

$$\langle H_M(t)\rangle = \left\langle \frac{m\omega_M^2 X_M(t)^2}{2} + \frac{m\dot{X}_M(t)^2}{2} \right\rangle$$



θ_V = angle against V



Average change in energy of the membrane

Positive functions depending on parameters of setup

$$\Delta H_M(t) = u(t)\,\delta N(0) + v(t)\left(\langle N(0)\rangle + \langle N(0)\rangle^2 \cos^2(\theta)\right)$$

Initial fluctuations in photon number

Average number of photons per gas

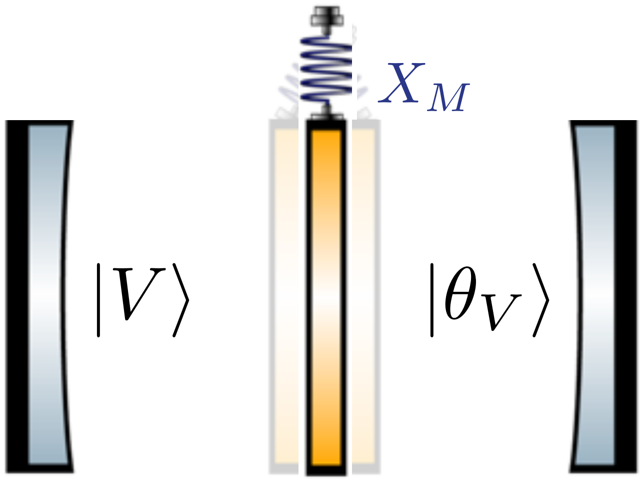
Distinguishability

Dynamics (Heisenberg pic)

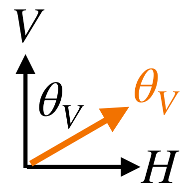
UNIVERSITY OF EXETER

Universität Potsdam

Quadratically enhanced energy transfer for indistinguishable (same pol.) photons.



θ_V = angle against V



Average change in energy of the membrane

Positive functions depending on parameters of setup

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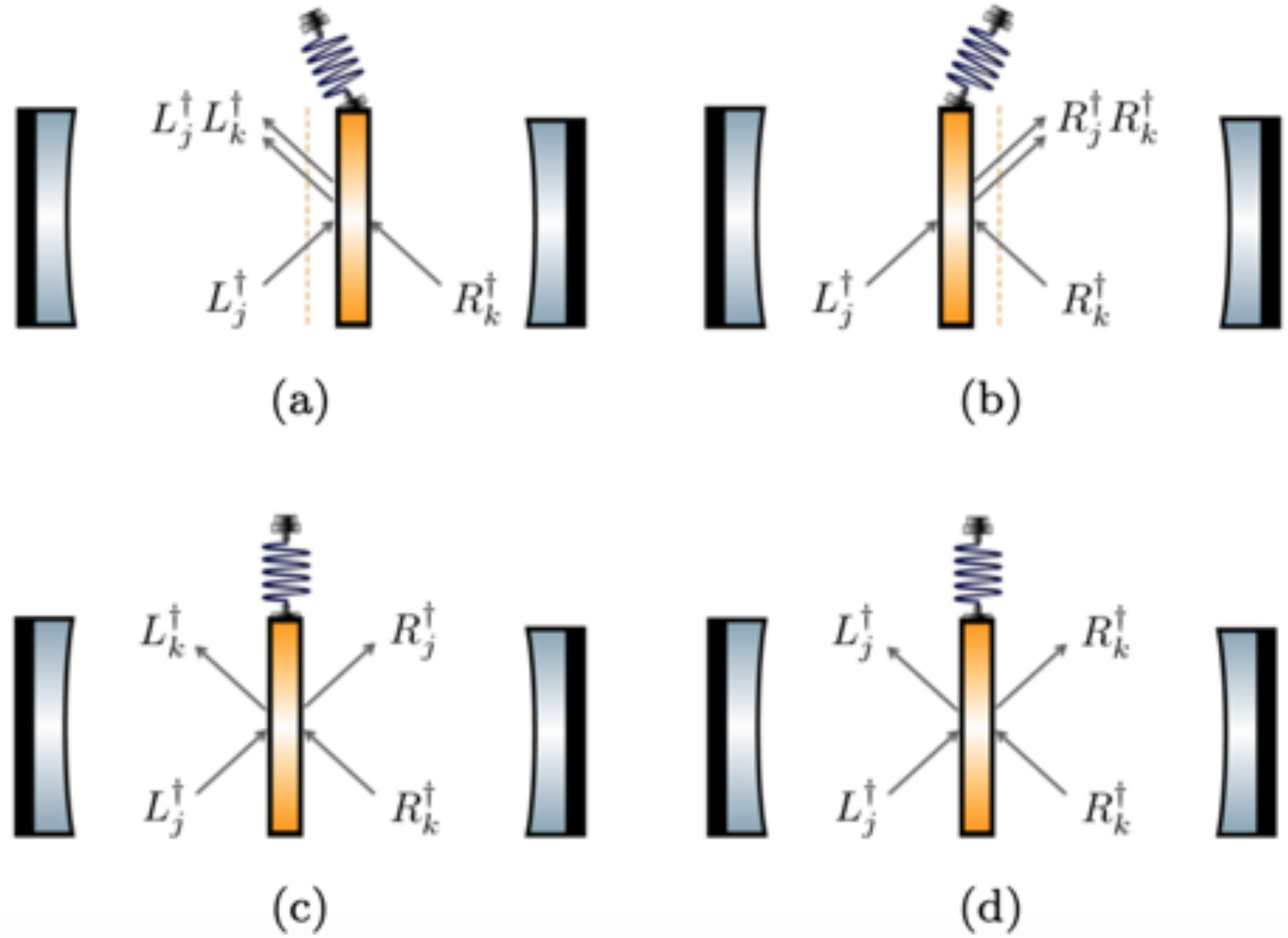
Initial fluctuations in photon number

Average number of photons per gas

Distinguishability

The back-action of the HOM effect



CK Hong, ZY Ou and L Mandel, PRL **59**, 2044 (1987)

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Recent revival in interest

Quantum Szilard Engine with Attractively Interacting Bosons

J. Bengtsson, M. Nilsson Tengstrand, A. Wacker, P. Samuelsson, M. Ueda, H. Linke, and S. M. Reimann
Phys. Rev. Lett. **120**, 100601 – Published 9 March 2018

QTDNEQ

Bosons outperform fermions: The thermodynamic advantage of symmetry

Nathan M. Myers and Sebastian Deffner QTD
Phys. Rev. E **101**, 012110 – Published 8 January 2020

Quantum Statistical Enhancement of the Collective Performance of Multiple Bosonic Engines

QTD Gentaro Watanabe, B. Prasanna Venkatesh, Peter Talkner, Myung-Joong Hwang, and Adolfo del Campo QTDNEQ
Phys. Rev. Lett. **124**, 210603 – Published 27 May 2020

QTD

arXiv.org > quant-ph > arXiv:2006.12482

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Quantum Physics

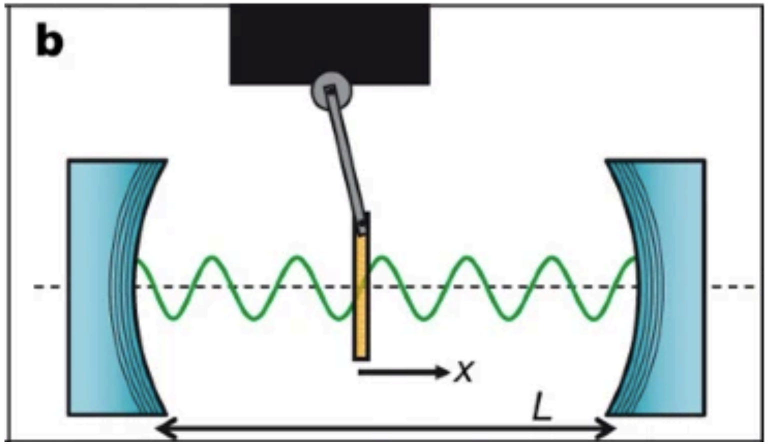
[Submitted on 22 Jun 2020]

Extracting work from mixing indistinguishable systems: A quantum Gibbs "paradox"

Benjamin Yadin, Benjamin Morris, Gerardo Adesso

Quarantine

Membrane in the middle optomechanics



Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane

J. D. Thompson, B. M. Zwickl, A. M. Jayich, Florian Marquardt, S. M. Girvin & J. G. E. Harris

Nature **452**, 72–75(2008) | Cite this article

Membrane in the middle optomechanics

Cooling and squeezing via quadratic optomechanical coupling

A. Nunnenkamp, K. Børkje, J. G. E. Harris, and S. M. Girvin
Phys. Rev. A **82**, 021806(R) – Published 31 August 2010

Observability of radiation-pressure shot noise in optomechanical systems

K. Børkje, A. Nunnenkamp, B. M. Zwickl, C. Yang, J. G. E. Harris, and S. M. Girvin
Phys. Rev. A **82**, 013818 – Published 15 July 2010

Integrated Optomechanical Arrays of Two High Reflectivity SiN Membranes

Claus Gärtner, João P. Moura, Wouter Haaxman, Richard A. Norte, and Simon Gröblacher*

Macroscopic Tunneling of a Membrane in an Optomechanical Double-Well Potential

L. F. Buchmann, L. Zhang, A. Chiruvelli, and P. Meystre
Phys. Rev. Lett. **108**, 210403 – Published 23 May 2012

Tunable linear and quadratic optomechanical coupling for a tilted membrane within an optical cavity: theory and experiment

M Karuza[1,2,3], M Galassi[1,2], C Biancofiore[1,2], C Molinelli[1,2], R Natali[1,2], P Tombesi[1,2], G Di Giuseppe[1,2] and D Vitali[1,2]
Published 20 December 2012 • 2013 IOP Publishing Ltd
Journal of Optics, Volume 15, Number 2

From membrane-in-the-middle to mirror-in-the-middle with a high-reflectivity sub-wavelength grating

Corey Stambaugh, Haitan Xu, Utku Kemiktarak, Jacob Taylor, John Lawall

First published:02 October 2014 | https://doi.org/10.1002/andp.201400142 | Citations: 16

Demonstration of suppressed phonon tunneling losses in phononic bandgap shielded membrane resonators for high-*Q* optomechanics

Yeghishe Tsaturyan, Andreas Barg, Anders Simonsen, Luis Guillermo Villanueva, Silvan Schmid, Albert Schliesser, and Eugene S. Polzik

Dynamics and entanglement of a membrane-in-the-middle optomechanical system in the extremely-large-amplitude regime

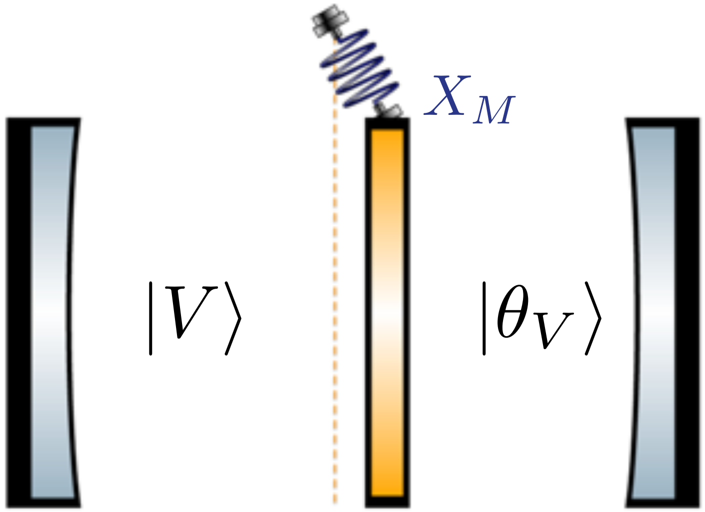
Ming Gao, FuChuan Lei, ChunGuang Du & GuiLu Long

Science China Physics, Mechanics & Astronomy **59**, Article number: 610301 (2016) | Ci

Controllable two-membrane-in-the-middle cavity optomechanical system

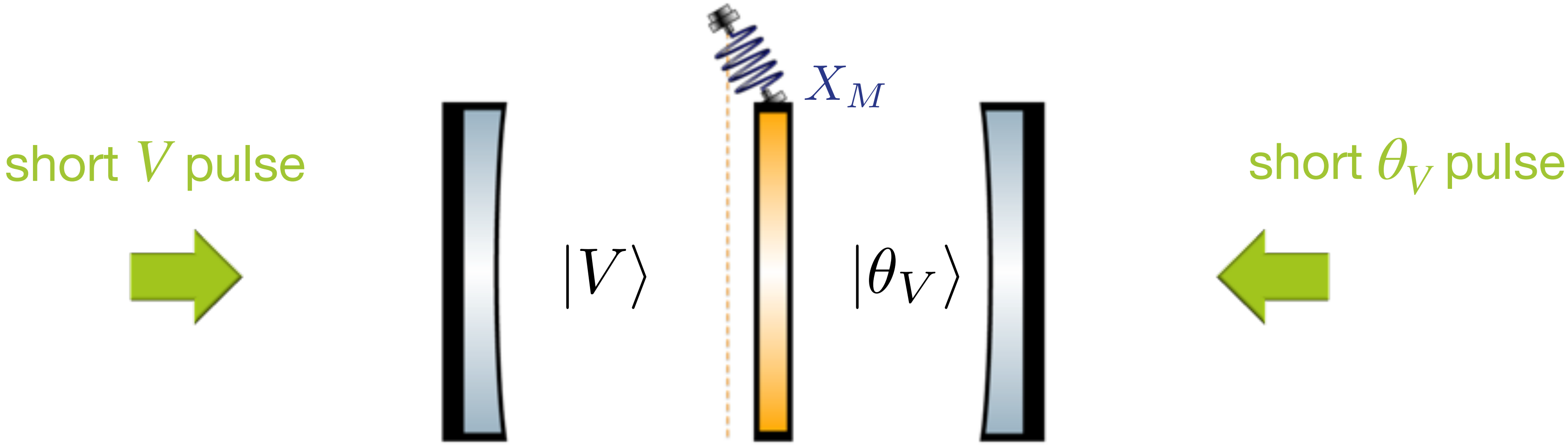
Xinrui Wei, Jiteng Sheng, Cheng Yang, Yuelong Wu, and Haibin Wu
Phys. Rev. A **99**, 023851 – Published 26 February 2019

Experimentally realisable?



Pulsed protocol

A short pulse ($\tau \ll 1/\lambda$) generates coherent state $|\alpha\rangle$ in cavity



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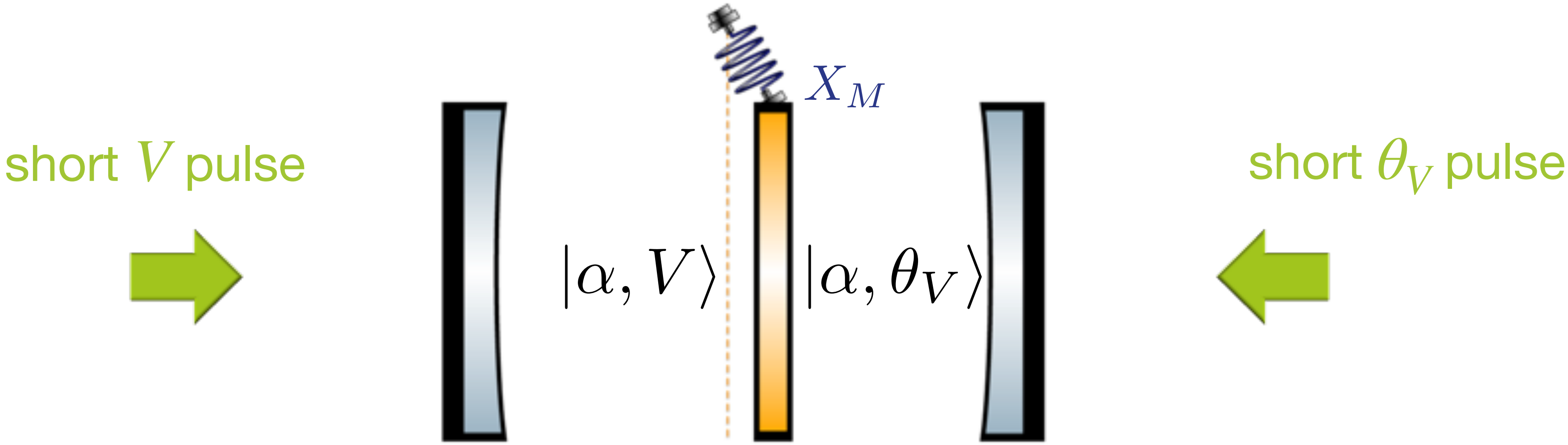

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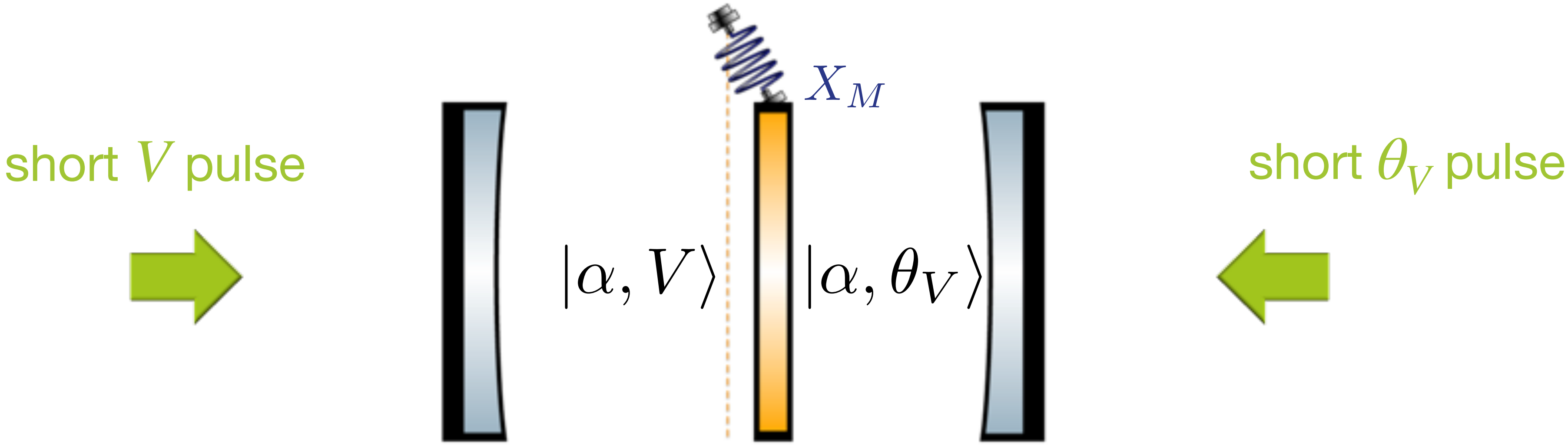


$$\Delta H_M(t) = u(t)\, \underbrace{\delta N(0)}_{|\alpha|^2} + v(t)\left(\underbrace{\langle N(0)\rangle + \langle N(0)\rangle^2}_{|\alpha|^2} \cos^2(\theta)\right)$$

$$\Delta H_M(t) = u(t)\,|\alpha|^2 + v(t)\left(|\alpha|^2 + |\alpha|^4 \cos^2(\theta)\right)$$

Pulsed protocol

Tunable linear and quadratic optomechanical coupling for a tilted membrane within an optical cavity: theory and experiment

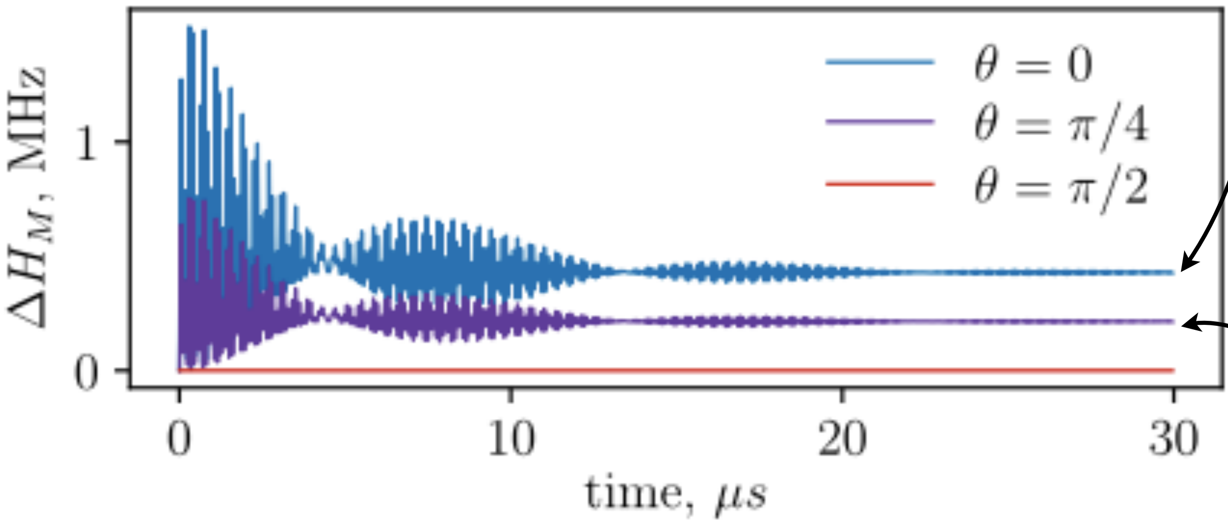
M Karuza[1,2,3], M Galassi[1,2], C Biancofiore[1,2], C Molinelli[1,2], R Natali[1,2], P Tombesi[1,2], G Di Giuseppe[1,2] and D Vitali[1,2]

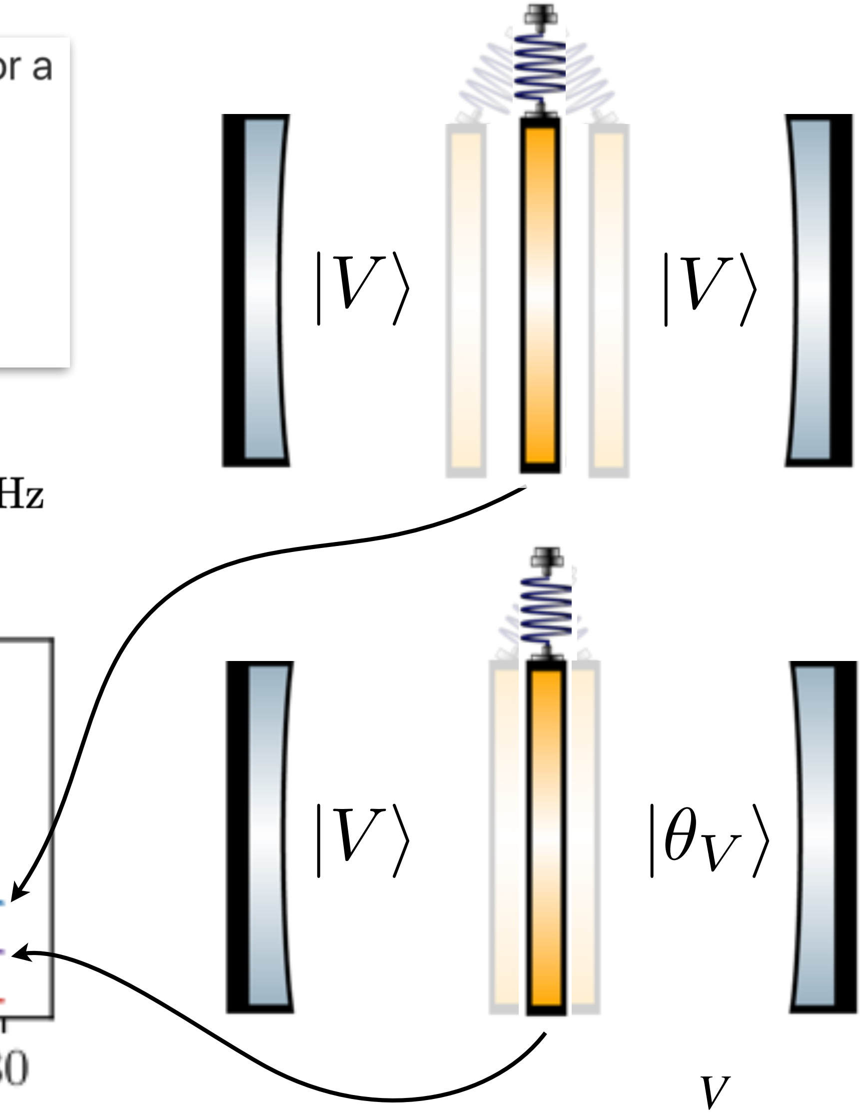
Published 20 December 2012 • 2013 IOP Publishing Ltd

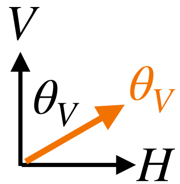
Journal of Optics, Volume 15, Number 2

$|\alpha|^2 = 6\times10^6$, $\omega_M = 350\text{kHz}$, $\omega = 20\text{THz}$, $\lambda = 34\text{GHz}$

$\kappa = 85\text{kHz}$, $\kappa_M = 1\text{Hz}$, $m = 45\text{ng}$ and $gx_{\text{zpf}} = 3.3\text{kHz}$







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Outline

Beam splitter (BS) — [1]

- energetic signature of bosonic bunching

Polarisation dependent Beam splitter (PBS) — [2]

- quantum analogue of Gibbs mixing

'Membrane in the middle' Optomechanics — [1, 2]

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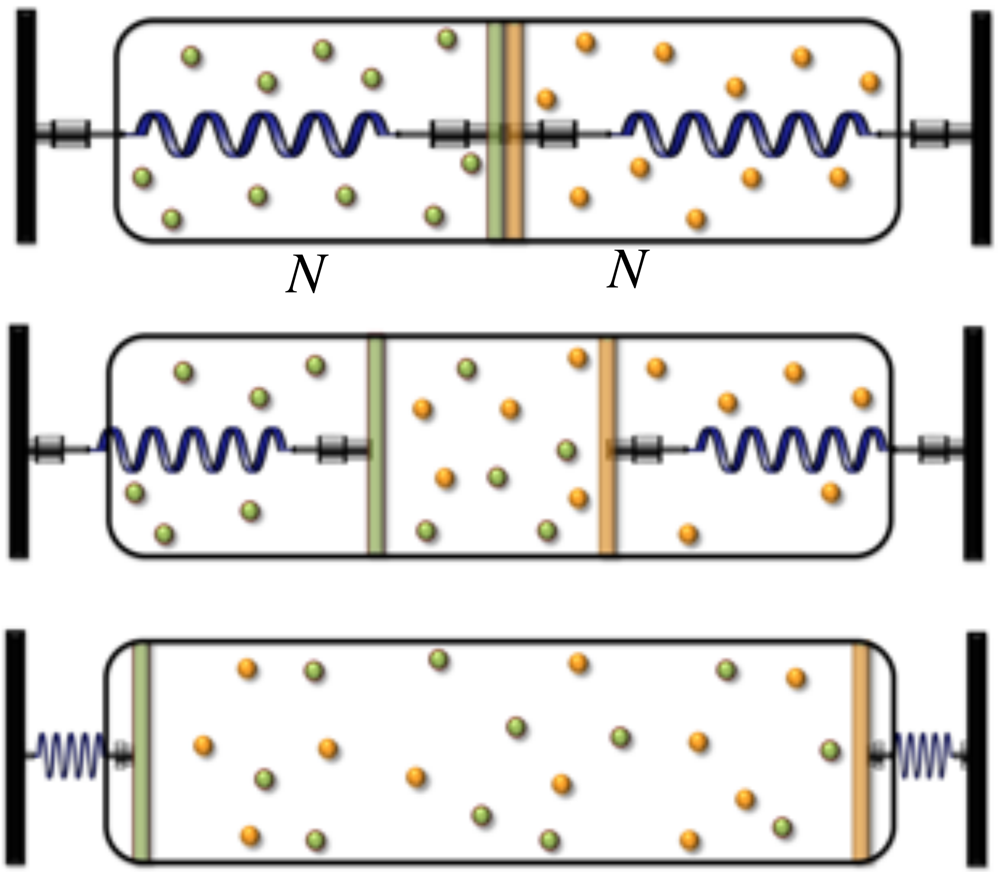
[2] Gibbs mixing of partially distinguishable photons with a polarising beamsplitter membrane, Holmes, Mintert, Anders, arxiv 2006.00613v1 (2020)

Classical Gibbs mixing (of homogenous gases)

distinguishable = different

(membranes can be found that act differently on the two gases)

held at T



N N

$2N$

$$W_{dist} = 2N\ k_B T\ \ \ln 2$$

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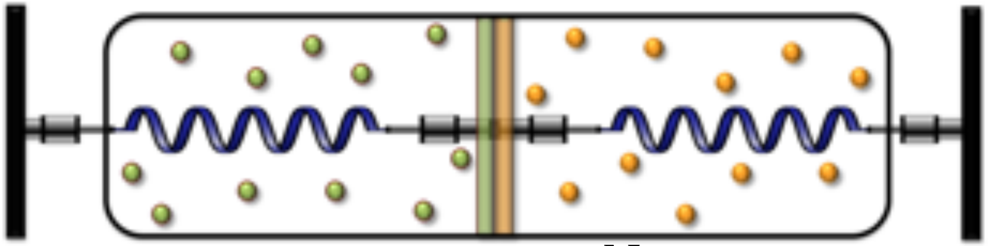

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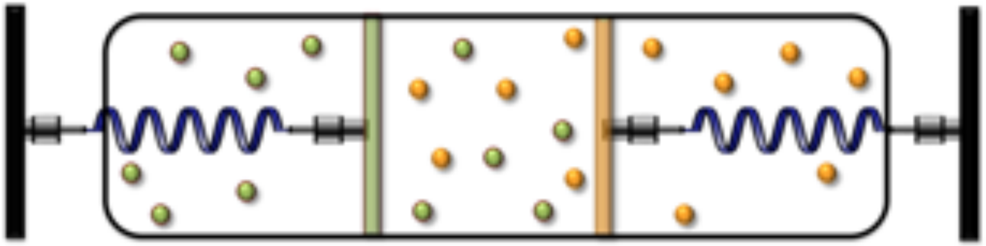

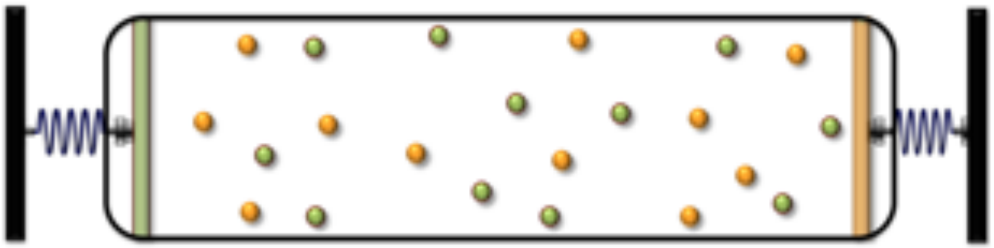

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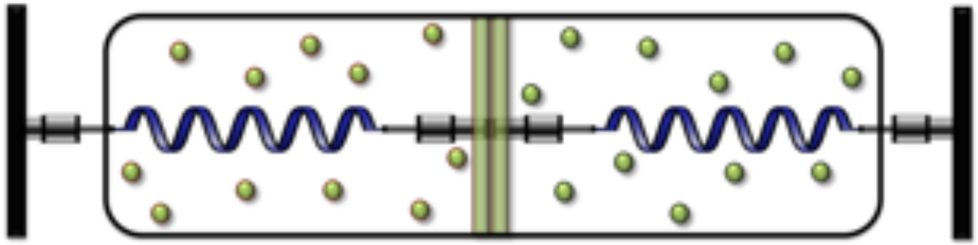

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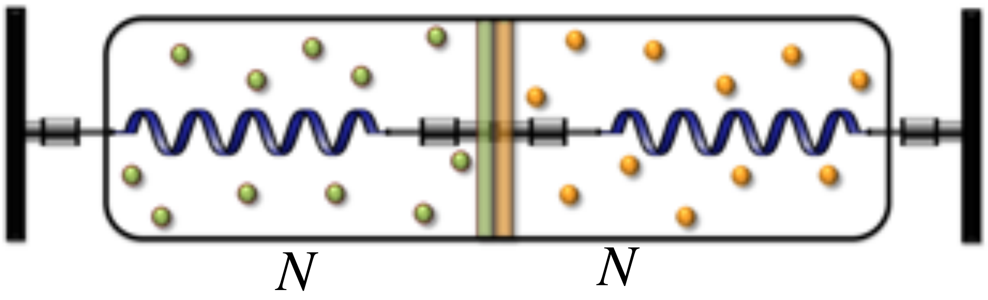

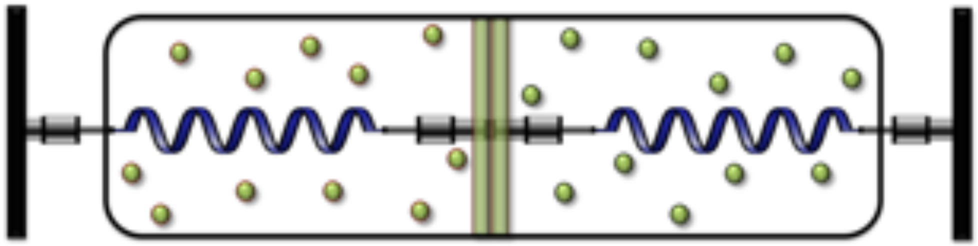

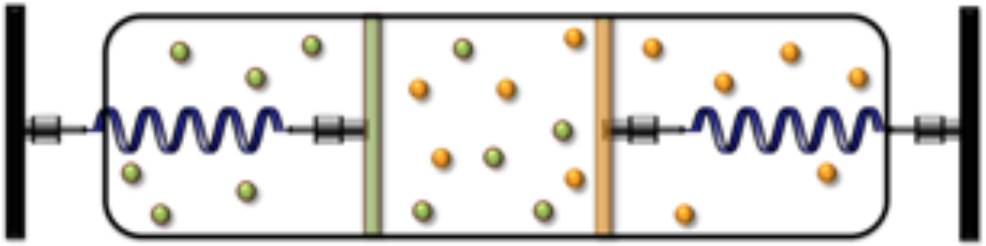

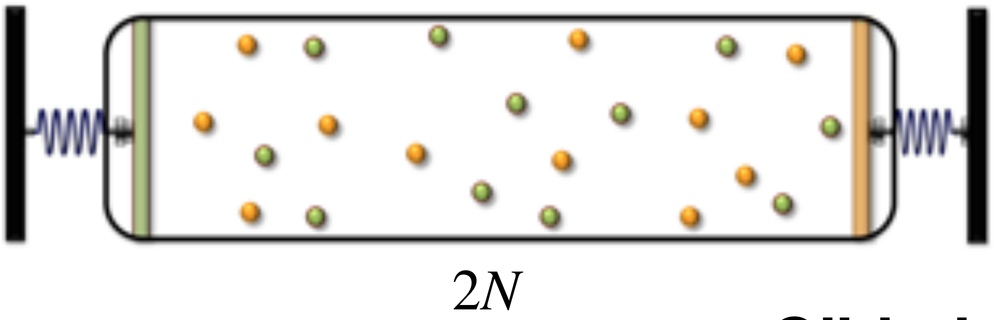

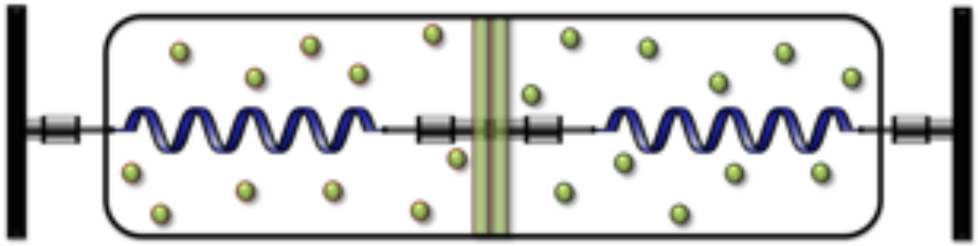

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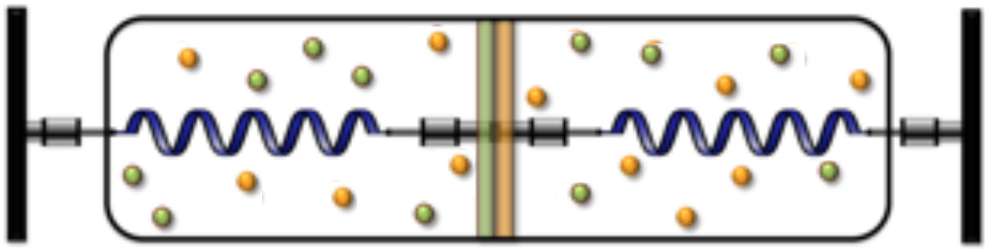
Gibbs' paradox:

discontinuous jump

$$W_{indist} = 0$$

Classical Gibbs mixing (of homogenous gases)

Note: if instead one considers **inhomogeneous** gases,
i.e. two gases **each** consisting of particles of different type,



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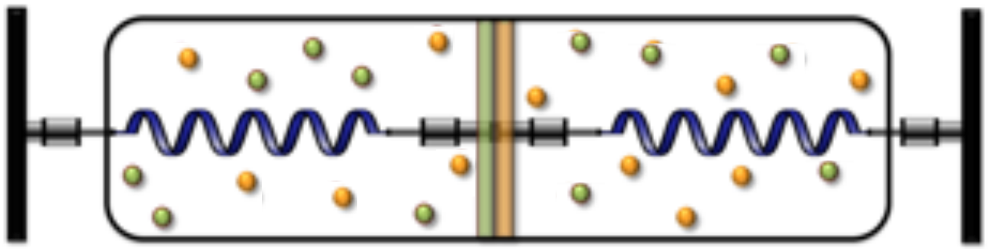

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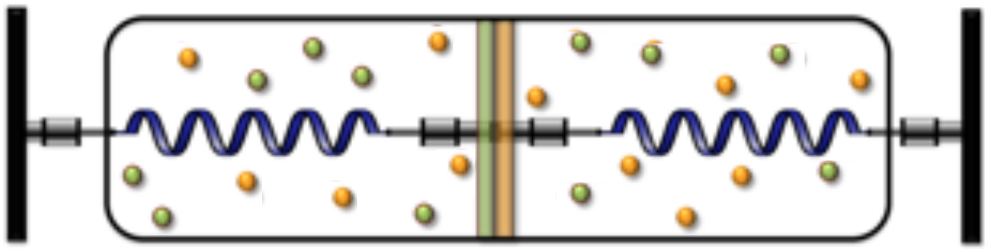

Hence, we will only consider mixing of two **homogenous** gases

$$W_{dist} = 2N\ k_B T\ \ln 2$$

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Quantum Gibbs mixing (of homogenous gases)

It is known that **in the quantum regime** …

✓ gas particles can be distinguished by their internal state

✓ distinguishability of gases varies continuously

✓ extractable work varies continuously

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✓ information theoretic approaches based on
entropy changes and ergotropy

✗ how to do quantum Gibbs mixing conceivably physically???
time-dynamics?

Quantum Gibbs mixing (of homogenous gases)

UNIVERSITY OF EXETER

Universität Potsdam

Recent paper on quantum Gibbs mixing

B. Yadin, B. Morris, G. Adesso,
arxiv (2020)

watch: Ben Yadin's Quarantine Thermo talk

Youtube — QuSys Group TCD — 17 July 2020

✓ analyses work extraction depending on whether observer knows particles are distinguishable or not

counterintuitive conclusion: *ignorance is a bliss*

arXiv.org > quant-ph > arXiv:2006.12482

Search...

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Quantum Physics

[Submitted on 22 Jun 2020]

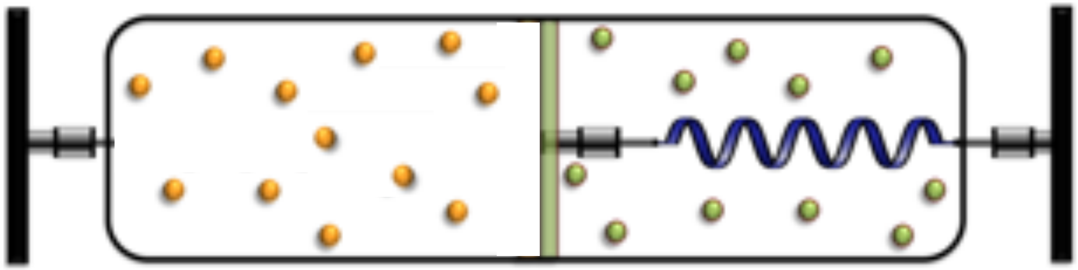
Extracting work from mixing indistinguishable systems: A quantum Gibbs "paradox"

Benjamin Yadin, Benjamin Morris, Gerardo Adesso

Classical Gibbs mixing (of homogenous gases)

simpler version: 1 membrane

(confining yellow only)



green membrane always reflects yellow particles

green membrane always transmits green particles

Classical Gibbs mixing (of homogenous gases)

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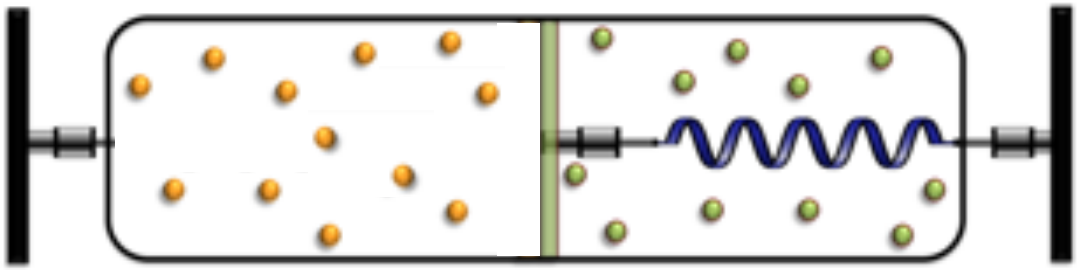

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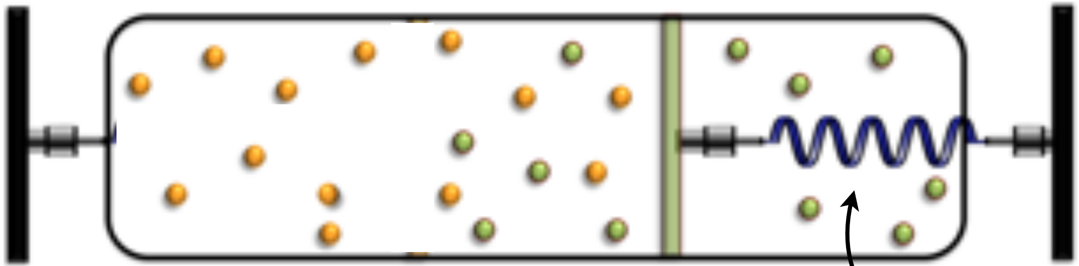

mixing

$W_{dist} > 0$

work extracted

Polarisation dependent **B**eam **S**plitter

simpler version: 1 membrane

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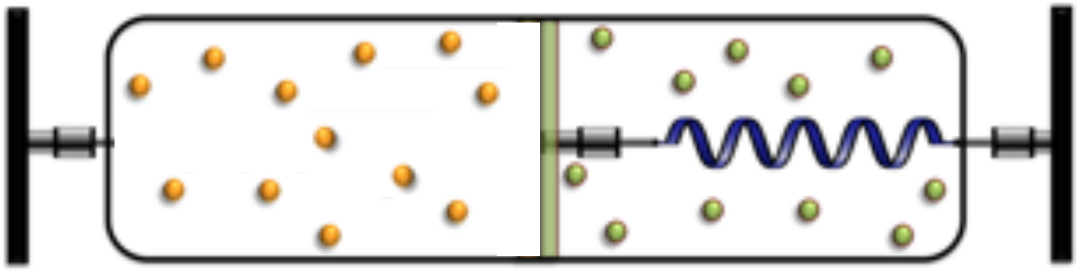

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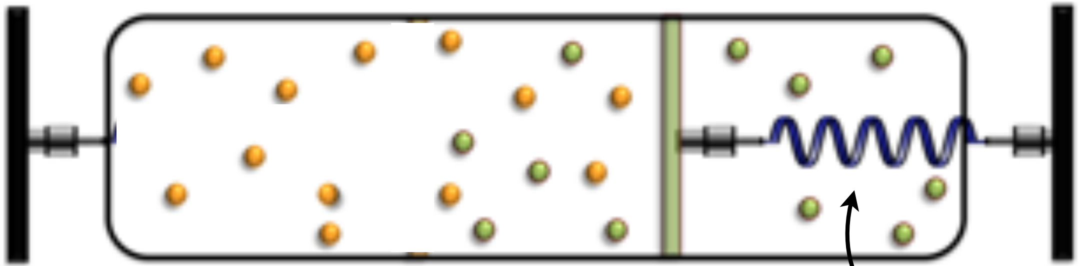

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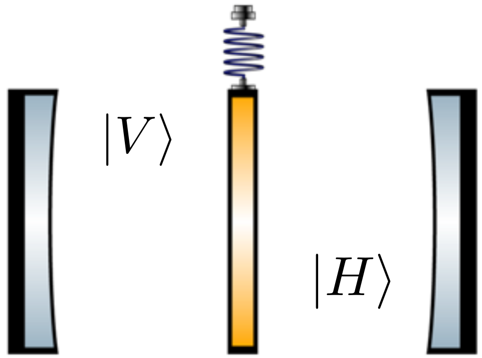

membrane always reflects V

membrane acts as a **BS** on H

$$H_{PBS} = \frac{\lambda_H}{2}(R_H^\dagger L_H + L_H^\dagger R_H)$$

radiation pressure

$$H_I = -(g_H \Delta N_H + g_V \Delta N_V) X_M$$

$$g_V > g_H$$

Polarisation dependent **B**eam **S**plitter

UNIVERSITY OF EXETER

Universität Potsdam

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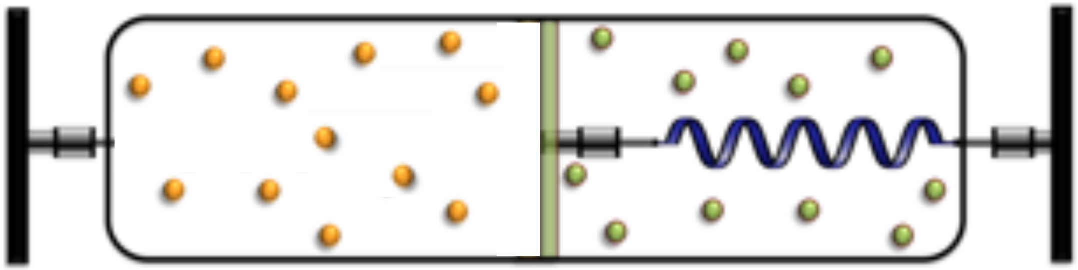

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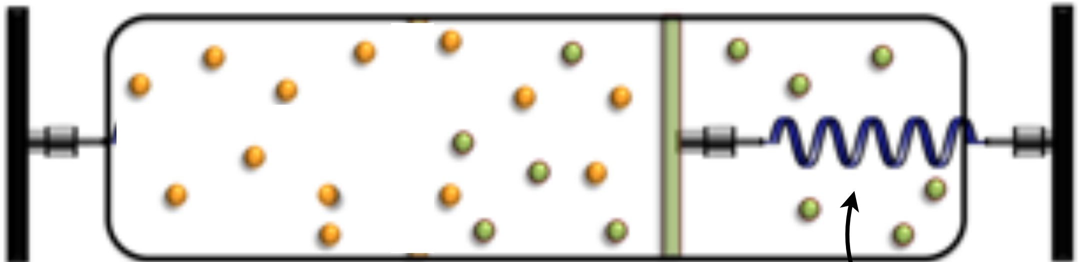

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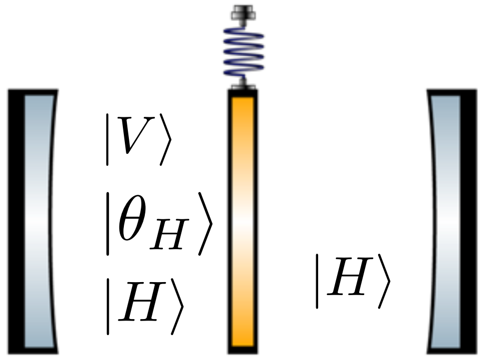

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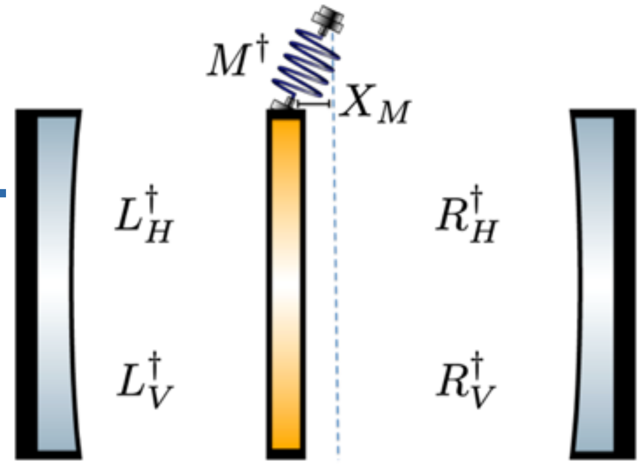
$$g_V > g_H$$

Initial state $\rho_L \otimes \rho_R \otimes \sigma_M$



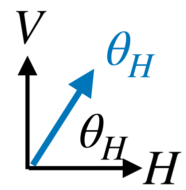
Initial photon gases:

set: same ***number distribution*** on both sides, eg:

Fock states

$$|\psi_{\mathrm{F}}^n\rangle := |\psi_L^n(\theta)\rangle \otimes |\psi_R^n(0)\rangle$$

$$|\psi_C^n(\theta)\rangle \propto \left(\cos(\theta)\, C_H^\dagger + \sin(\theta)\, C_V^\dagger\right)^n |0\rangle \quad \text{for} \quad C = R, L$$



thermal states

$$\rho^T := \gamma_L^T(\theta) \otimes \gamma_R^T(0)$$

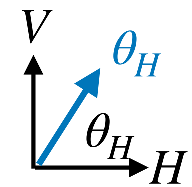
$$\gamma_C^T(\theta) \propto \sum_{n=0}^{\infty} e^{-n\hbar\omega/k_B T} |\psi_C^n(\theta)\rangle \langle\psi_C^n(\theta)| \quad \text{for} \quad C = R, L,$$

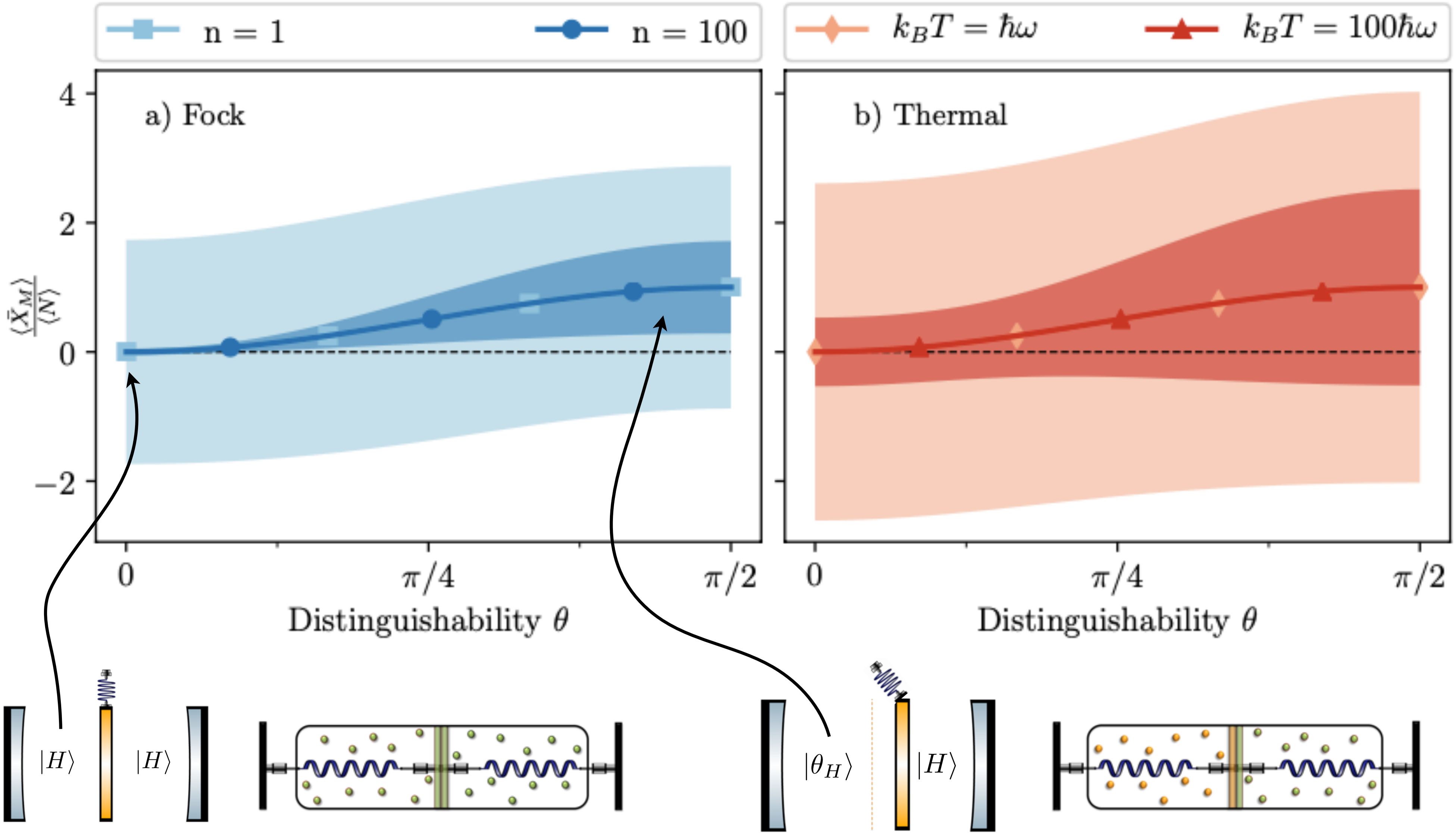
Initial membrane state:

$$\gamma_M^T \propto \exp\left(-\frac{\hbar\omega_M M^\dagger M}{k_B T}\right)$$

Displacement of membrane

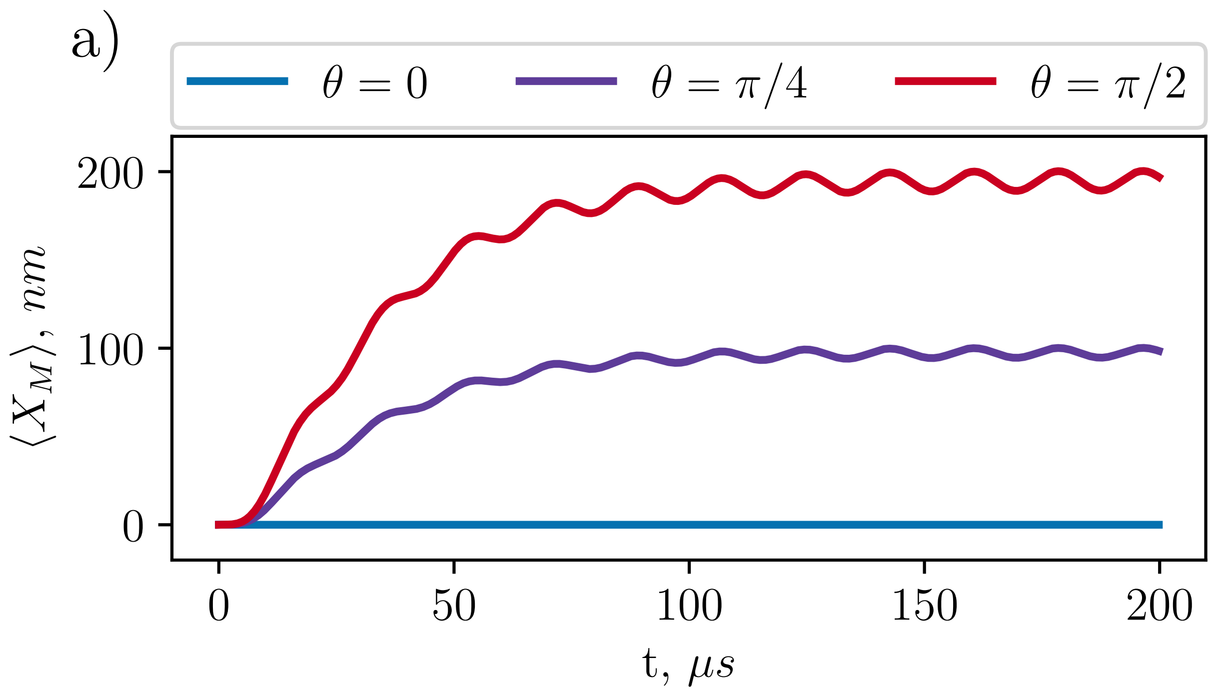
$$\langle \bar{X}_M \rangle \propto \langle N(0) \rangle \ \sin^2 \theta \qquad W_M^{\text{mix}} := \frac{1}{2} m \omega_M^2 \langle \bar{X}_M \rangle^2$$





Displacement of membrane

Similar effect observed for laser driven variations and **experimentally** more realistic parameters



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Membrane in the middle optomechanics

1) temperature gradients/heat flow/thermalisation

photons @T_c,
membrane @ T_h

photons @T_c and T_h,
membrane @ T_m

Membrane in the middle optomechanics

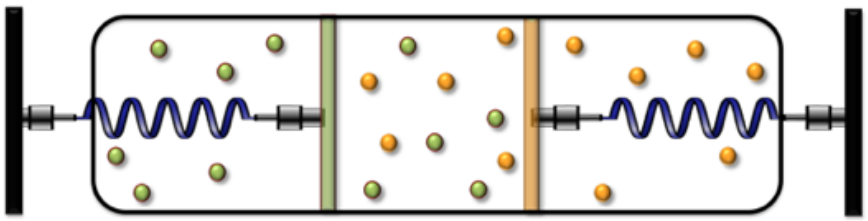
1) temperature gradients/heat flow/thermalisation

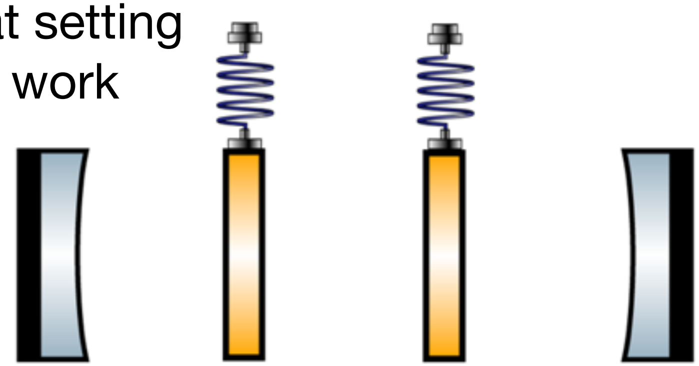
photons @T_c,
membrane @ T_h

photons @T_c and T_h,
membrane @ T_m

2) two membranes

as well as understanding what setting is needed to get optimal/max work





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Membrane in the middle optomechanics

3) higher order optomechanical coupling

$$H_I \propto N X_M^2$$

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Single-photon quadratic optomechanics

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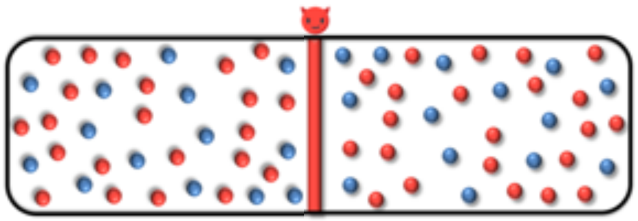
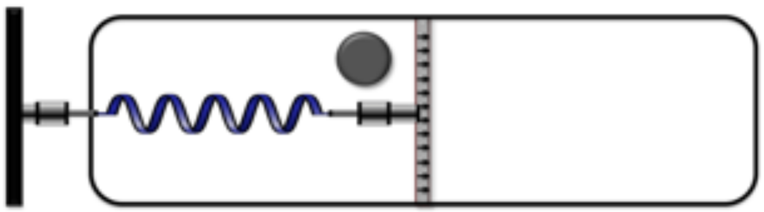
4) new quantum thermodynamics thought experiments



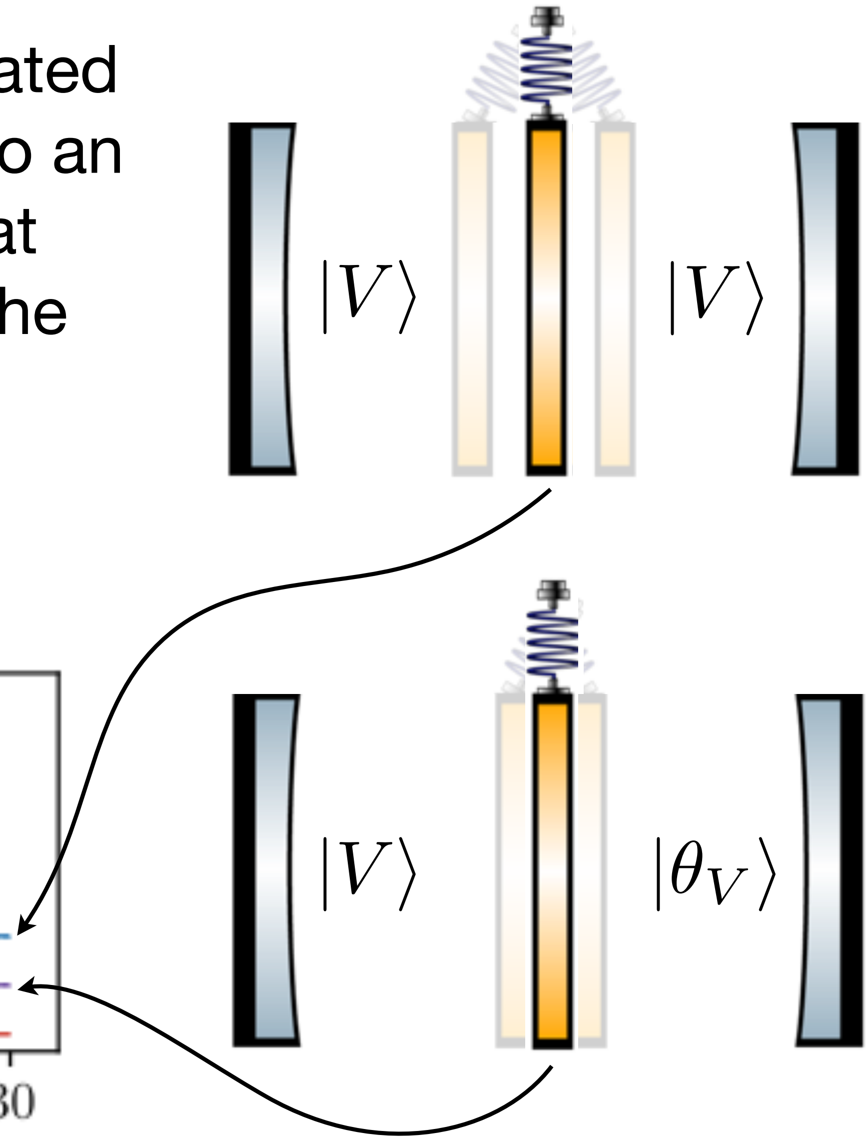


➤ flexible platform for (thought) experiments.

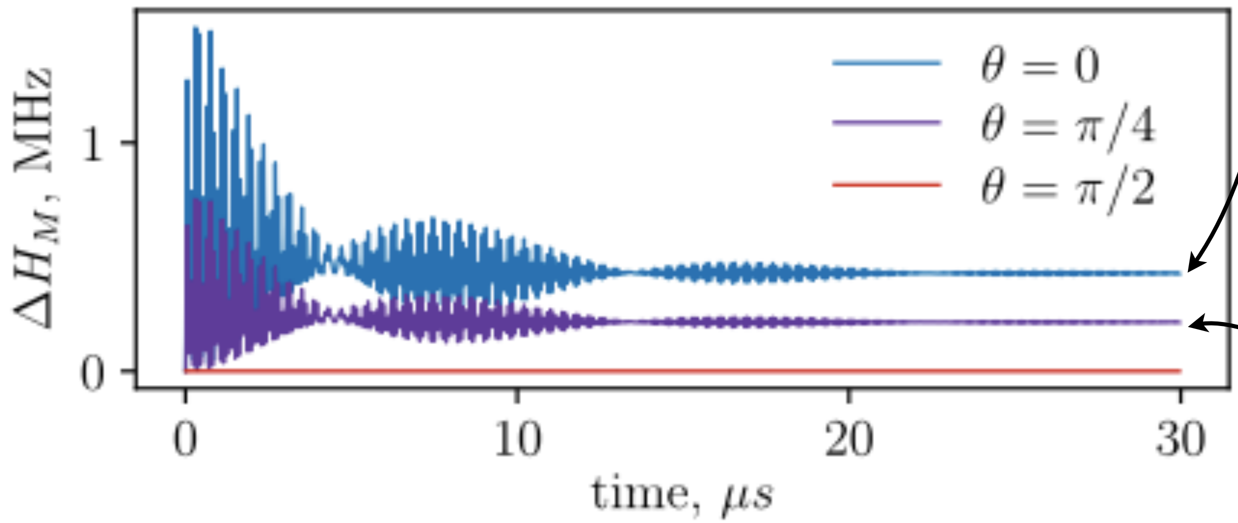
Summary

[1] Enhanced Energy Transfer to an Optomechanical Piston from Indistinguishable Photons, Holmes, Anders, Mintert, PRL124, 210601 (2020)

[1] **Two photonic gases** initially separated by a **beam splitter**, dynamically lead to an **energy transfer to the membrane** that depends on the **distinguishability** of the polarisations of the two gases, and scales as N^2.

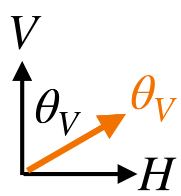


$$\Delta H_M(t) = \langle H_M(t)\rangle - \langle H_M(0)\rangle$$



$$\langle H_M(t)\rangle = \left\langle \frac{m\omega_M^2 X_M(t)^2}{2} + \frac{m\dot{X}_M(t)^2}{2} \right\rangle$$

in [1]:
θ_V is the angle against V

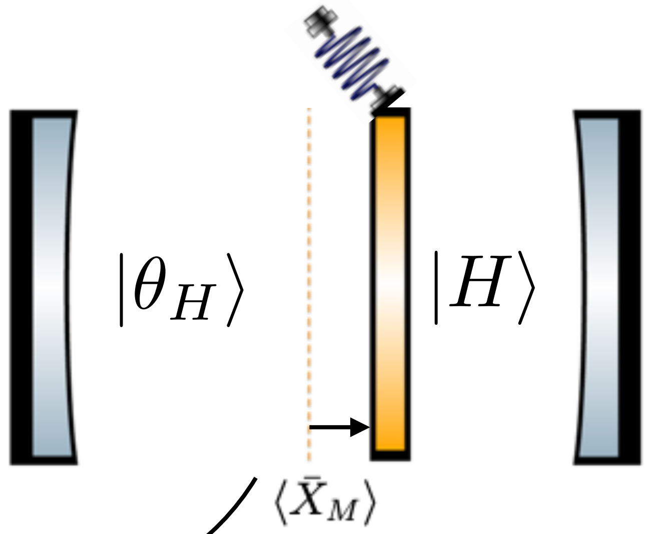


Summary

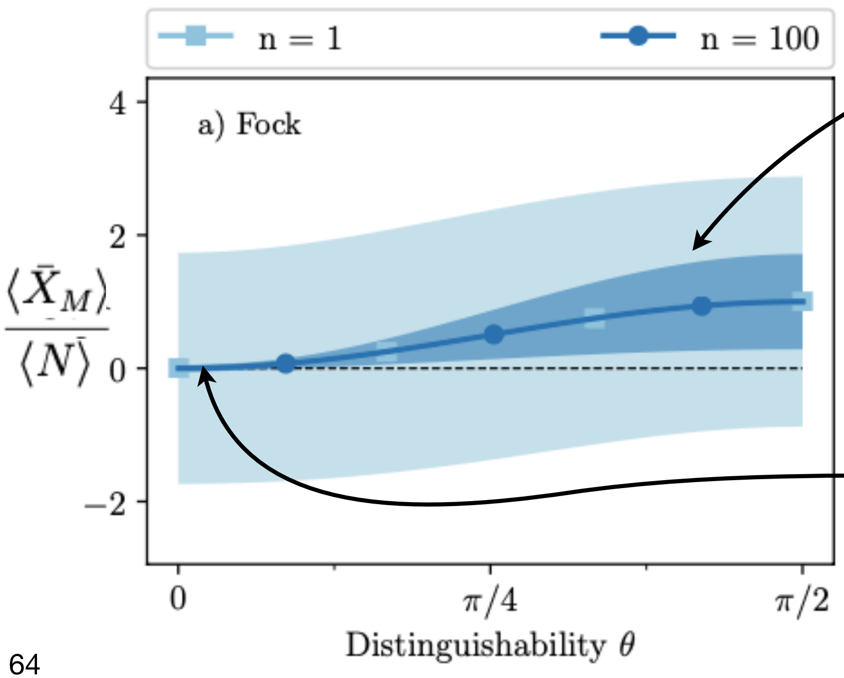
[2] Gibbs mixing of partially distinguishable photons with a polarising beamsplitter membrane, Holmes, Mintert, Anders, arxiv 2006.00613v1 (2020)

[2] **Two photonic gases** initially separated by a **polarisation dependent beam splitter***, dynamically lead to a **displacement (work) of the membrane** that depends on the **distinguishability** of the polarisations of the two gases.

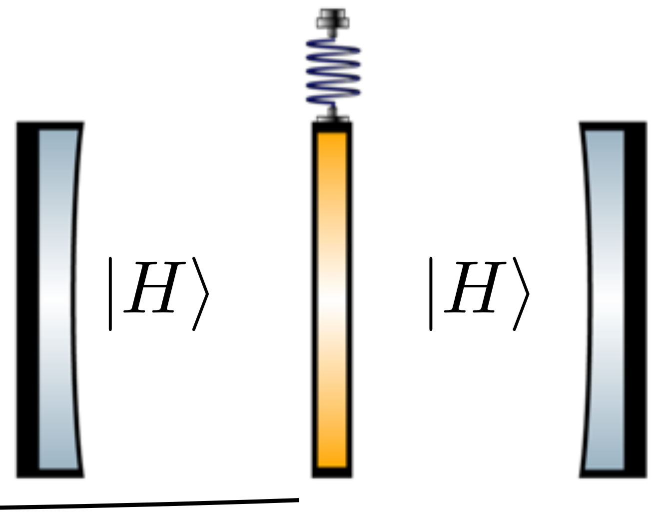
*mirror for V, BS for H



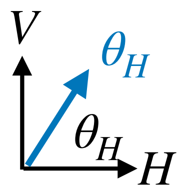
$$\langle \bar{X}_M \rangle := \mathrm{Tr}\left[\frac{1}{\tau}\int_0^\tau dt X_M(t)\ \rho\right]$$



$$W_M^{\text{mix}} := \frac{1}{2} m \omega_M^2 \langle \bar{X}_M \rangle^2$$



in [2]:
θ_H is the angle against H



[1] Enhanced Energy Transfer to an Optomechanical Piston from Indistinguishable Photons,
Holmes, Anders, Mintert, PRL124, 210601 (2020)

[2] Gibbs mixing of partially distinguishable photons with a polarising beamsplitter membrane,
Holmes, Mintert, Anders, arxiv 2006.00613v1 (2020)

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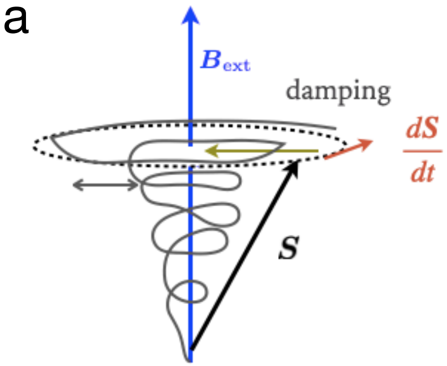
QTD 2020

CONFERENCE ON QUANTUM THERMODYNAMICS

ONLINE, 19-23 OCT 2020

Deriving a generalised Landau-Lifschitz-Gilbert (LLG) equation from a system+bath Hamiltonian



Wed 20:00CEST

http://qtd2020.icfo.eu/

watch: Zoë's Quarantine Thermo talk

Youtube — QuSys Group TCD — 2 June 2020

https://www.youtube.com/watch?v=pb3OwOQ8tQ8

Thank you!