Macroscopic Quantum Mechanics with GW detectors:
What the mad theoreticians can turn the working machine into and how the normal experimentalist can bear it

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Outline

1. What is Macroscopic Quantum Mechanics? Bird's-eye view on MQM experiments
    - A bit of history
    - All MQM projects
    - Why GW detectors?

2. MQM with GW detectors: Hedgehog's-eye view on MQM experiment
    - State preparation stage
        - Conditional state preparation
        - State preparation with feedback control
    - State free evolution and verification
    - Quantum entanglement and EPR
    - Quantum state swaping
    - Alternative Q-theories testing: Penrose's gravity decoherence

3. "Copenhagen interpretation" of MQM experiment

4. Conclusion

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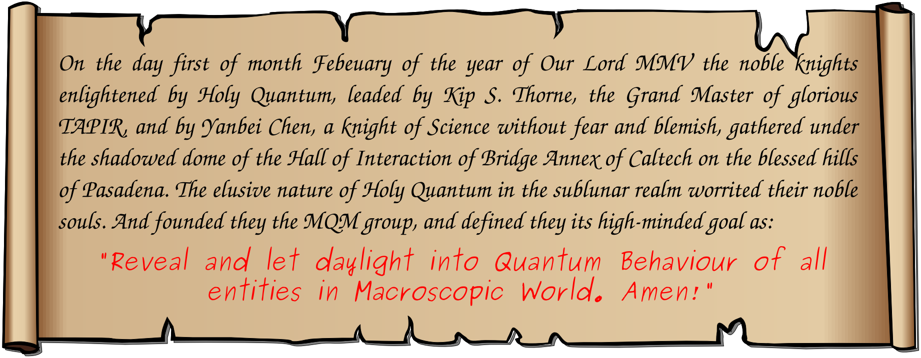
How it started?

The first mentioning of MQM group in historical records...



On the day first of month Febeuary of the year of Our Lord MMV the noble knights enlightened by Holy Quantum, leaded by Kip S. Thorne, the Grand Master of glorious TAPIR, and by Yanbei Chen, a knight of Science without fear and blemish, gathered under the shadowed dome of the Hall of Interaction of Bridge Annex of Caltech on the blessed hills of Pasadena. The elusive nature of Holy Quantum in the sublunar realm worrited their noble souls. And founded they the MQM group, and defined they its high-minded goal as:

"Reveal and let daylight into Quantum Behaviour of all entities in Macroscopic World. Amen!"

How it started?

MQM goals

Prepare, manipulate and observe quantum state of macroscopic test masses, thereby testing quantum mechanics in macroscopic world, using interferometric gravitational wave detectors

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PREREQUISITES FOR MQM PROJECT SUCCESS

1. Optical rigidity provides low-noise restoring forces, and shifts quantum mechanical signatures of test masses from the pendulum frequency of $\sim 1\,\mathrm{Hz}$ into the observation band of $100\,\mathrm{Hz}$ or even kHz;
2. SQL limited optical sensitivity at the observation band guarantees our ability to observe test-mass motion down to the quantum scale;
3. Availability of low-noise control systems developed for gravitational-wave detectors allows us to manipulate state of test masses at the quantum scale;
4. Sub-SQL classical noise at the observation band allows the test-mass quantum state to survive long enough to be observed.

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All MQM projects

What do people wait from MQM experiments and what had been being done till now?

1. Prepare macroscopic oscillator in a state as close to ground state as possible (code word: COOLING)

   Easier to count those, who're not doing this

2. See the back-action noise of the measurement
   (code words: OBSERVATION OF RADIATION PRESSURE)

   B12 experiment (AEI), J.G.E. Harris et al (Yale), K.C Schwab et al (Cornell), T.J. Kippenberg et al (MPQ)

3. See entanglement between macroscopic bodies
   (code words: MACROSCOPIC ENTANGLEMENT, SEEING EPR)

   MQM group: H. Müller-Ebhardt et al (2007), Y. Chen et al (in preparation)

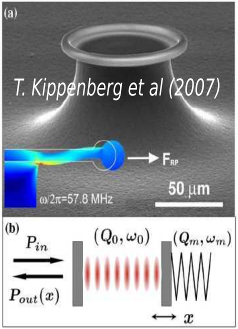
4. Test alternative quantum theories
   (code words: MACROREALISM (GRW-Theory), GRAVITY DECOHERENCE)

   MQM group, D. Bouwmeester et al (UCSB)

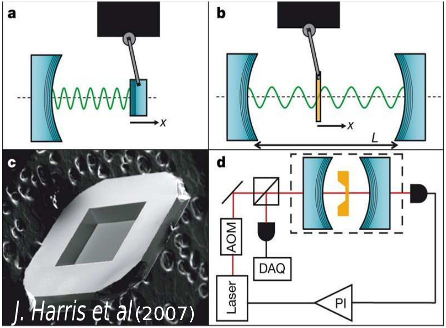
5. See non-Gaussian states and nonlinear quantum effects
   (code words: QUANTUM JUMPS, SCHROEDINGER CAT STATES, MACROSCOPIC INTERFERENCE)

   MQM group, J.G.E. Harris et al (Yale), K.C Schwab et al (Cornell)

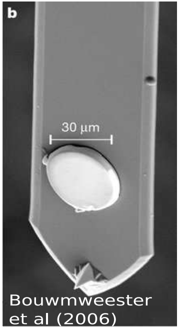
All MQM projects



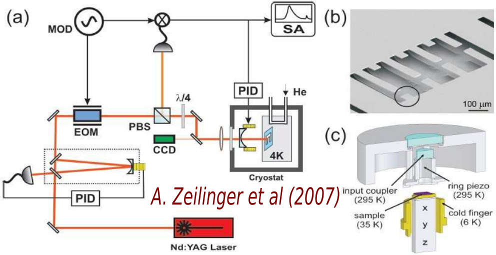
T. Kippenberg et al (2007)



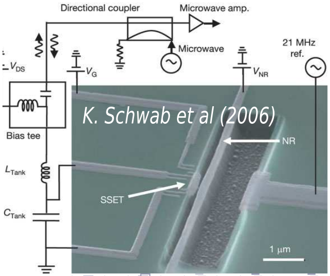
J. Harris et al (2007)



Bouwmweester et al (2006)

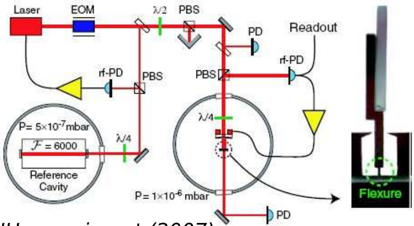


A. Zeilinger et al (2007)

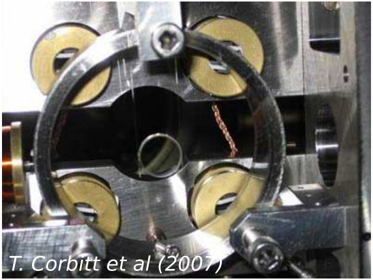


K. Schwab et al (2006)

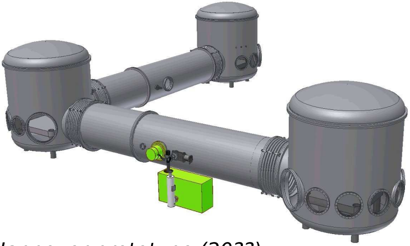
All MQM projects



ANU experiment (2007)



T. Corbitt et al (2007)



Hannover prototype (20??)

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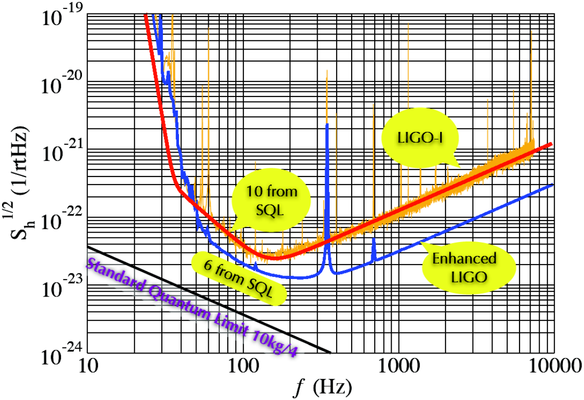
How classic are GW detectors?



- Initial LIGO already operates at $10\times$ SQL level, and enchanced LIGO should start operate at $6\times$ SQL level this year;
- Advanced LIGO should have classical noise budget BELOW the SQL $\Longrightarrow$ MQM becomes feasible!

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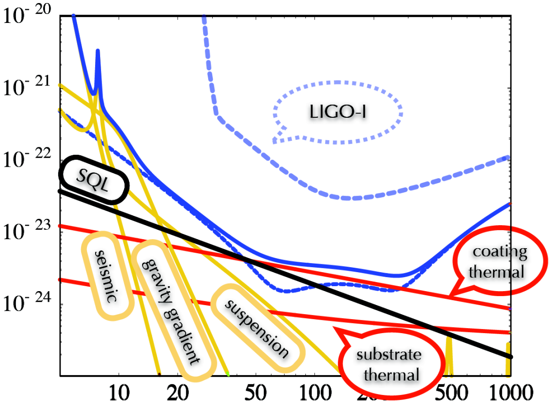

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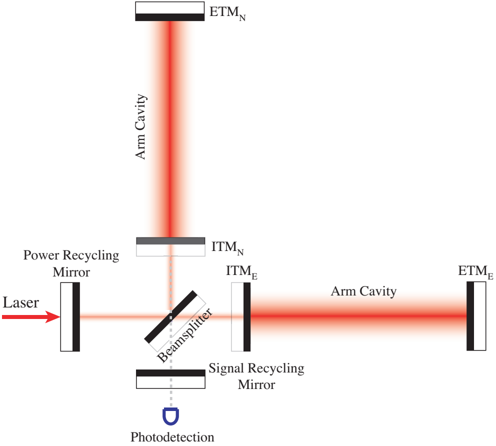
Our playground

Our Great Plan: Get and observe mirrors of AdvLIGO in quantum state!

Our playground

Theoretical approach to horserace results prediction:

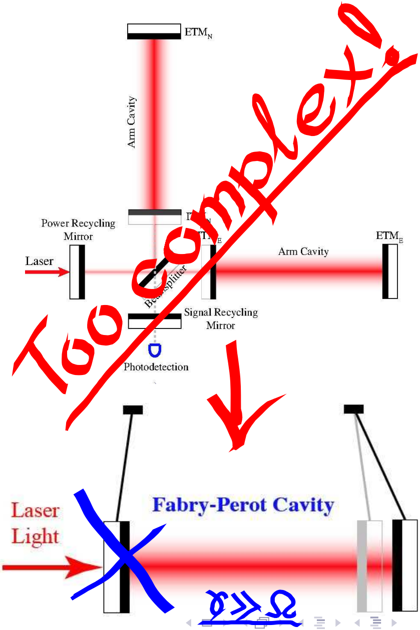
"Let's adopt the model of spherically symmetric horse with viscous friction. Hm-m. This should be analytically solvable ..."



Our playground

Let us simplify everything a bit

- Dual recycled FP-Michelson $\Longrightarrow$ single Fabry-Perot
- Assume bandwidth much bigger than signal frequencies: $\gamma \gg \Omega$



Our playground

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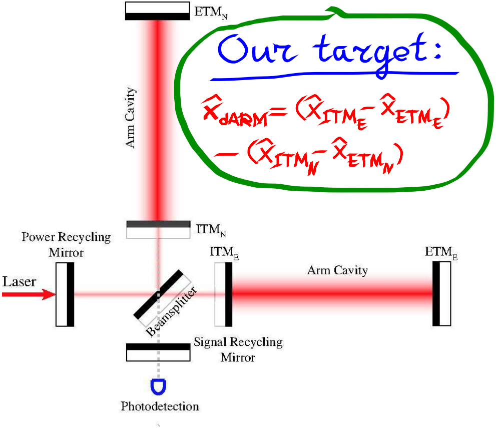
Our “test particle” is the differential mechanical mode, AKA dARM, though for advanced tasks, as mirrors entanglement, we’ll also use common mode as the second independent “particle”.



Our target:

$$\hat{x}_{dARM} = (\hat{x}_{ITM_E} - \hat{x}_{ETM_E}) - (\hat{x}_{ITM_N} - \hat{x}_{ETM_N})$$

What and how is measured?

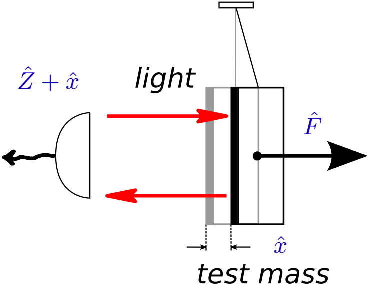
Simplified model of measurement

$$\hat{y} = \hat{Z} + \hat{x} = \hat{Z} + [R_{xx}\hat{F} + \hat{x}_{cm}]$$

$$R_{xx} = -\frac{1}{M(\Omega^2 - \omega_p^2 + 2i\gamma_p\Omega)}$$

$$\hat{Z} = \hat{Z}_Q + Z_{cl}, \quad \hat{F} = \hat{F}_Q + F_{cl},$$

Linear measurement $\Longleftrightarrow$ Gaussian noises & state



- $\hat{Z}$, "sensing" noise: quantum shot noise, internal thermal noise etc.
- $\hat{F}$, force noise: quantum radiation pressure noise, suspension thermal noise etc.

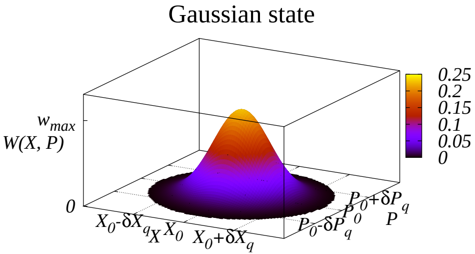
What and how is measured?

Gaussian state $\Longleftrightarrow$ Covariance matrix

Test mass Wigner function:

$$W(x,\,p)=\frac{1}{2\pi\sqrt{det\mathbb{V}}}\exp\left[-\frac{1}{2}\boldsymbol{\xi}^{T}\mathbb{V}^{-1}\boldsymbol{\xi}\right]$$

where $\mathbb{V}$ is covariance matrix and $\boldsymbol{\xi}=\{x-\bar{x},\,p-\bar{p}\}^{T}$



What and how is measured?

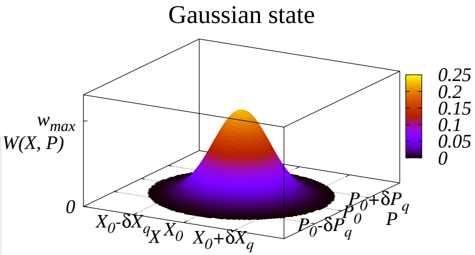
Gaussian state $\Longleftrightarrow$ Covariance matrix

Covariance matrix of the test mass:

$$\mathbb{V} = \begin{bmatrix} \langle \delta\hat{x}^2 \rangle & \langle \delta\hat{x}\delta\hat{p} \rangle_{\rm sym} \\ \langle \delta\hat{p}\delta\hat{x} \rangle_{\rm sym} & \langle \delta\hat{p}^2 \rangle \end{bmatrix}$$

State purity: $U = \frac{2}{\hbar}\sqrt{\det \mathbb{V}}$

- Pure quantum state
  $\Longrightarrow \det \mathbb{V} = \hbar^2/4,\ U = 1$
- Classical mixed state
  $\Longrightarrow \det \mathbb{V} \gg \hbar^2/4,\ U \gg 1$



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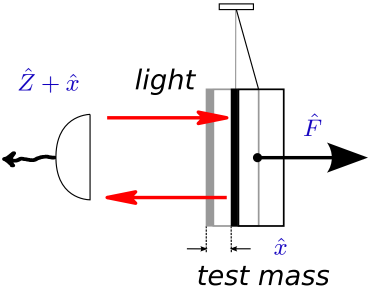

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1. **Measurement process & Heisenberg principle:**

$$S_{ZZ}S_{FF} - S_{ZF}^2 = \frac{\hbar^2}{4}U^2 \geqslant \frac{\hbar^2}{4}$$

2. **Standard Quantum Limit:**

$$S_{yy} = S_{ZZ} + 2\Re(R_{xx})S_{ZF} + |R_{xx}|^2 S_{FF}$$

$$S_{ZF} \Rightarrow 0\,, S_{yy} = S_{ZZ} + |R_{xx}|^2 S_{FF} \geqslant 2\sqrt{|R_{xx}|^2 S_{ZZ} S_{FF}} \geqslant \hbar |R_{xx}|$$

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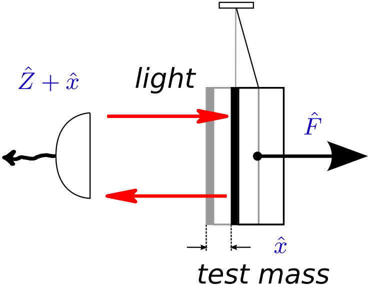

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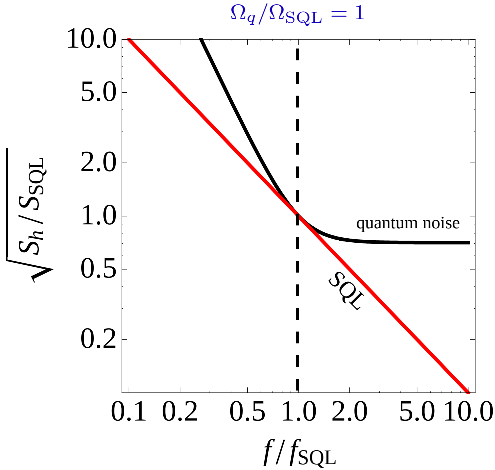
1. **Measurement process & Heisenberg principle:**

$$S_{ZZ}S_{FF} - S_{ZF}^2 = \frac{\hbar^2}{4}U^2 \geqslant \frac{\hbar^2}{4}$$

3. Generally, SQL can be beaten if

$$\frac{S_{ZF}}{\sqrt{S_{ZZ}S_{FF}}} \longrightarrow 1\,, \quad \frac{S_{ZZ}}{S_{FF}} \longrightarrow 1$$

Further simplification: Markovian noises model



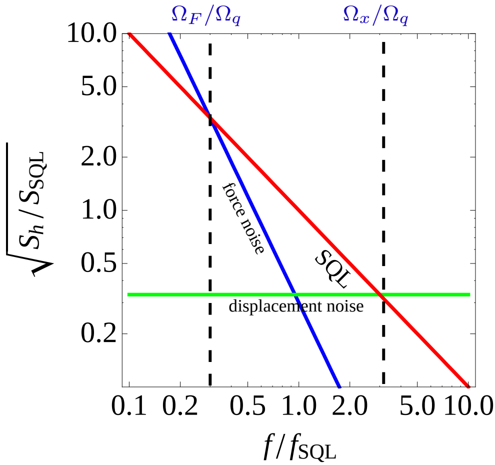
Quantum noise

Shot and radiation pressure noises $\Longrightarrow$ white:

$$
\begin{aligned}
S_x^q &= \frac{\hbar}{m\Omega_q^2} = const \\
S_F^q &= \hbar m \Omega_q^2 = const \\
S_{\rm GW}^q(\Omega) &= S_x^q + \frac{S_F^q}{m^2\Omega^4} \\
&= \frac{\hbar}{m\Omega^2}\left[\frac{\Omega^2}{\Omega_q^2} + \frac{\Omega_q^2}{\Omega^2}\right]
\end{aligned}
$$

Measurement timescale: $\tau_q \sim 1/\Omega_q$
Thermal decoherence timescale: $\tau_F \sim 1/\Omega_F$

Further simplification: Markovian noises model



Classical noise

Classical suspension and mirror internal $\Longrightarrow$ white:

$$S_x^{\rm th} = \frac{2\hbar}{m\Omega_x^2} = const\,,$$

$$S_F^{\rm th} = 2\hbar m\Omega_F^2 = const\,,$$

$$S_{\rm GW}^{\rm th}(\Omega) = S_x^{\rm th} + \frac{S_F^{\rm force}}{m^2\Omega^4}\,.$$

Measurement timescale: $\tau_q \sim 1/\Omega_q$
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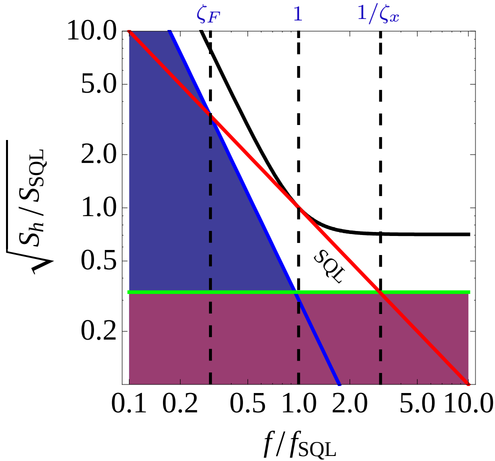

Total noise

Spectral density of the total noise will be then:

$$S^{\rm tot}_{\rm GW}(\Omega) = S^{q}_{\rm GW}(\Omega) + S^{\rm th}_{\rm GW}(\Omega) =$$

$$= S^q_x(1+2\zeta_x^2) + \frac{S^q_F(1+2\zeta_F^2)}{m^2\Omega^4},$$

where

$$\zeta_x = \frac{\Omega_q}{\Omega_x} \quad \text{and} \quad \zeta_F = \frac{\Omega_F}{\Omega_q}.$$

Measurement timescale: $\tau_q \sim 1/\Omega_q$
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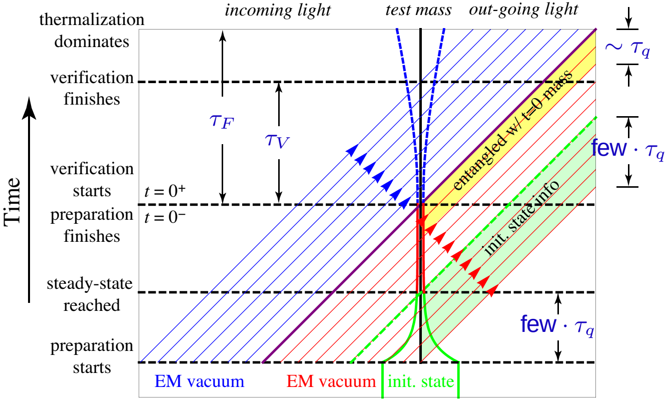
Tree stages of MQM experiment

1. STATE PREPARATION: Measuring output light of the interferometer, collapse test particle into some noisy thermal state



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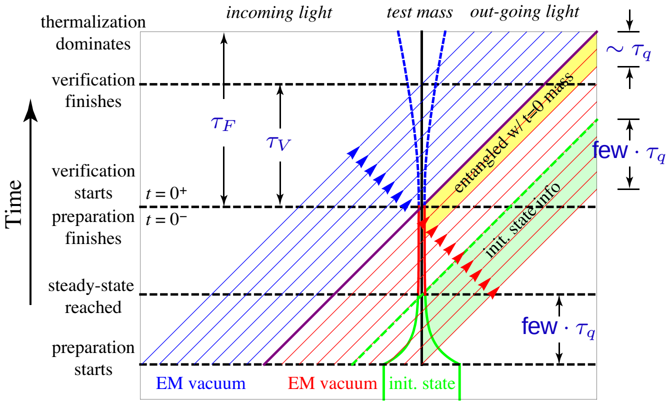
2. FREE EVOLUTION (optional): Let prepared state evolve for short time

   May serve as a buffer for transients, allows to observe quantum state evolution



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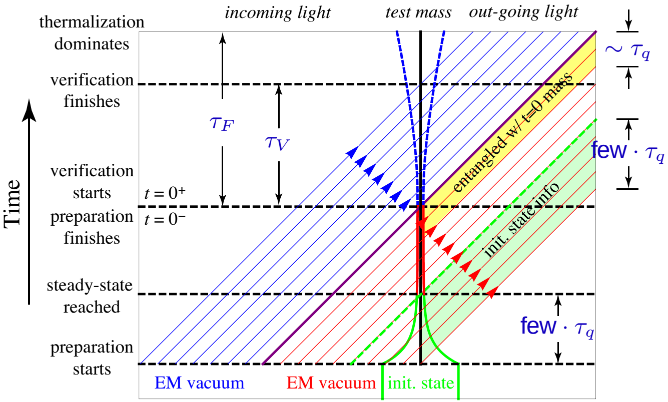
1. STATE PREPARATION: Measuring output light of the interferometer, collapse test particle into some noisy thermal state
2. FREE EVOLUTION (optional): Let prepared state evolve for short time

   May serve as a buffer for transients, allows to observe quantum state evolution
3. STATE VERIFICATION: Measure the prepared state with independent light



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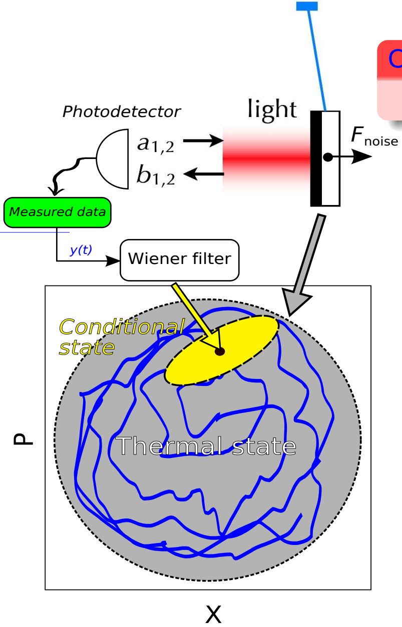
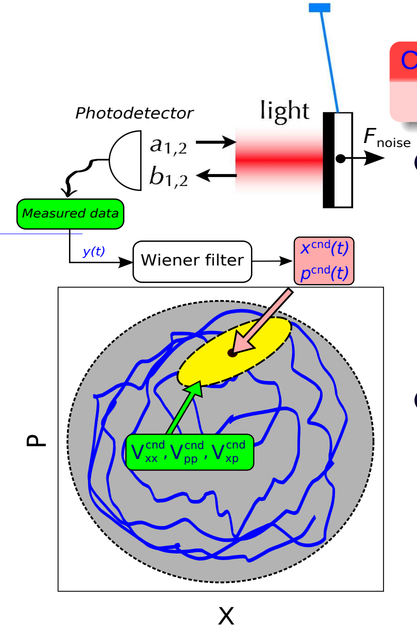
Conditional state preparation



Conditioning:

Noise budget $\Longrightarrow$ optimal Wiener filter for data

Conditional state preparation



Conditioning:

Noise budget $\Longrightarrow$ optimal Wiener filter for data

1. Filtering measured data $y(t') : t' < t$ gives conditional mean displacement $x^{\rm cnd}(t)$ and momentum $p^{\rm cnd}(t)$:

$$x^{\rm cnd}(t) = \int_{-\infty}^{t} dt'\, K_x(t-t')y(t')$$

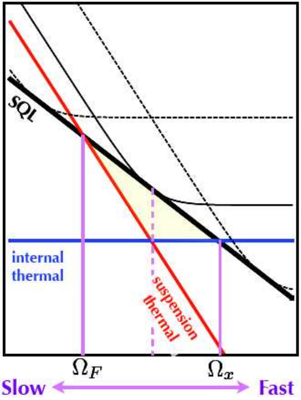
$$p^{\rm cnd}(t) = \int_{-\infty}^{t} dt'\, K_p(t-t')y(t')$$

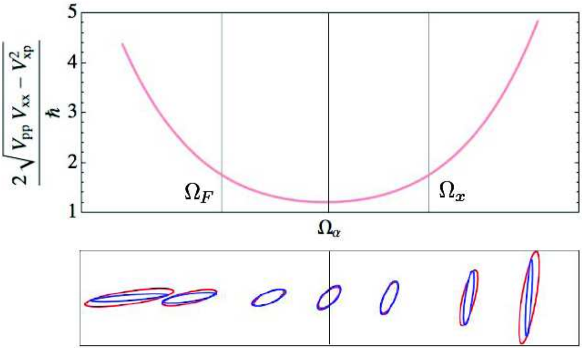
2. Both $(K_x,\, K_p)$ and $\{V^{\rm cnd}_{xx},\, V^{\rm cnd}_{xp},\, V^{\rm cnd}_{pp}\}$ are NOT RANDOM and derived from noise budget via Wiener-Hopf equations:

$$\langle [\hat{x}(t) - x^{\rm cnd}(t)] | y(t') \rangle = 0\,, \quad t' < t$$

$$\langle [\hat{p}(t) - p^{\rm cnd}(t)] | y(t') \rangle = 0\,, \quad t' < t$$

Conditional state preparation





Slow measurement,
p better than *x*

Fast measurement,
x better than *p*

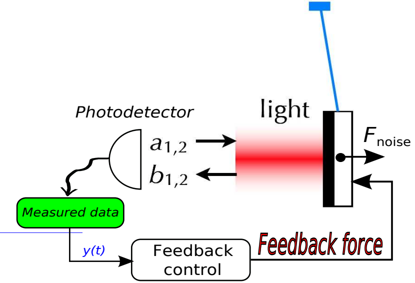
1. Conditional state purity is EQUAL to measurement uncertainty

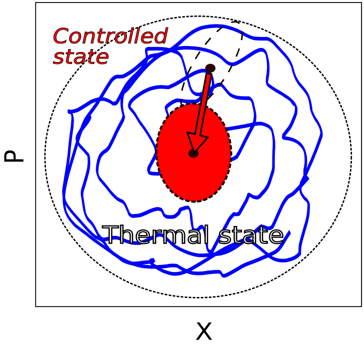
$$U^{\rm cnd}\equiv\frac{\sqrt{V_{xx}^{\rm cnd}V_{pp}^{\rm cnd}-(V_{xp}^{\rm cnd})^2}}{\hbar/2}=\frac{\sqrt{S_{ZZ}S_{FF}-S_{ZF}^2}}{\hbar/2}\equiv U^{\rm meas}$$

2. Thermal decoherence makes once prepared conditional state uncertainty to grow as:

$$U^{\rm cnd}(t>0)=U^{\rm cnd}(0)[1+\sqrt{2}(\Omega_q t)+(\Omega_q t)^2+\sqrt{2}(\Omega_q t)^3/3+(\Omega_q t)^4/12]$$

Preparation using feedback conrol





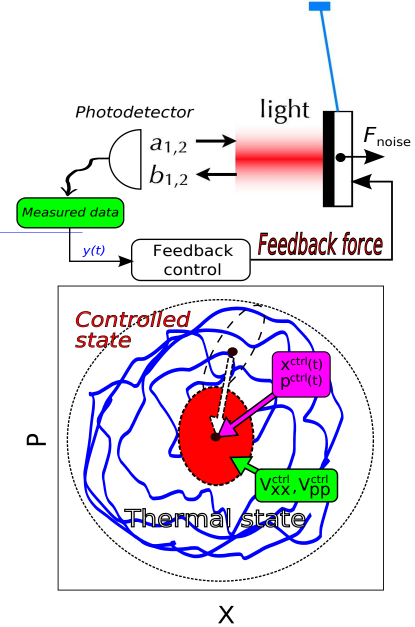
- Can one suppress conditional $x^{\rm cnd}(t)$ and $p^{\rm cnd}(t)$ and thus prepare oscillator in the state with purity equal to conditional state purity?

$$\hat y = \hat Z + \hat x\,,$$

$$\hat x = R_{xx}[\hat F + C]\,,$$

$$C = -K^{\rm ctrl} y$$

Preparation using feedback conrol



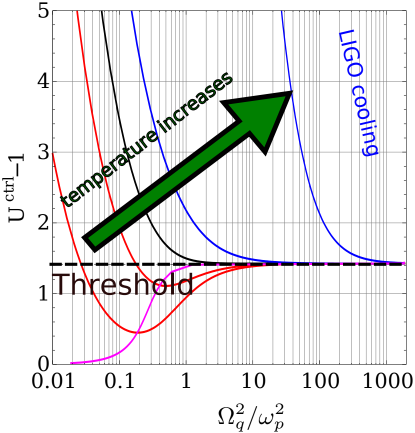
- Can one suppress conditional $x^{\rm cnd}(t)$ and $p^{\rm cnd}(t)$ and thus prepare oscillator in the state with purity equal to conditional state purity?
- The answer, in general, is NO, unless $V_{xp}^{\rm cnd} = 0$, as otherwise the state ceases to be steady:

$$U^{\rm ctrl} = \frac{2}{\hbar}\sqrt{V_{xx}^{\rm ctrl}V_{pp}^{\rm ctrl}} \geqslant \frac{2}{\hbar}\left[\sqrt{V_{xx}^{\rm cnd}V_{pp}^{\rm cnd}} + V_{xp}^{\rm cnd}\right] \geqslant U^{\rm cnd} \qquad (1)$$

- But $\{K_x,\ K_p\}$ can be used to calculate optimal controller:

$$K^{\rm ctrl} = \frac{C_1 + iC_2\Omega}{C_3 + iC_4\Omega}$$

Properties of controlled state



Phase transition

(Conventional phase quadrature readout)

Critical temperature:

$$\theta_{\mathrm{cr}} \equiv \frac{2k_B T_{\mathrm{cr}}}{\hbar\omega_p Q_p} = \frac{1}{\sqrt{2}}$$

- Initial temperature too HIGH:

$$\theta \geqslant \frac{1}{\sqrt{2}} \Rightarrow U^{\mathrm{ctrl}} \geqslant 1+\sqrt{2}$$

- Initial temperature LOW:

$$\theta < \frac{1}{\sqrt{2}} \Rightarrow U^{\mathrm{ctrl}} \to 1$$

if optical power is optimal $\Omega_q \to \Omega_q^{\mathrm{opt}}(\theta)$

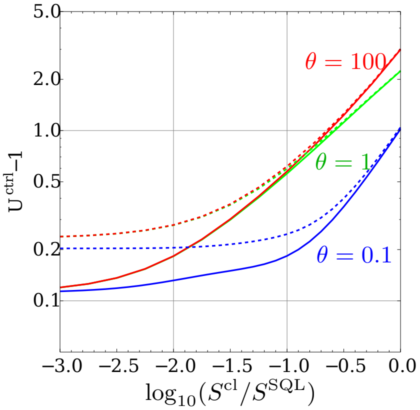
Conventional GW detectors (LIGO) have too high initial temperature

$$\theta \sim 10^6 \gg 1/\sqrt{2}, \Longrightarrow U^{\mathrm{ctrl}}_{\mathrm{LIGO}} \gg 1+\sqrt{2}$$

Properties of controlled state

Arbitrary quadrature readout & squeezing

Reading out different quadratures and use of input squeezing lead to almost pure state provided that classical noise is much lower than SQL



- Classical noise below the SQL $\Longrightarrow$

$$U^{\text{ctrl}} \to 1$$

- Squeezing makes difference only if classical noise is already small enough (compare solid (10 dB squeezing) and dashed (w/o squeezing) curves)

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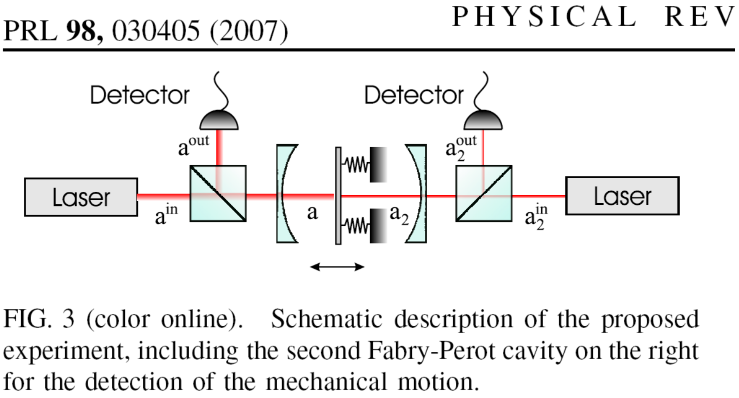
Free evolution & verification

- How real is prepared conditional state? Or how pure is controlled state?
- ***By definition*** measured data $y(t)$ contains no information about V_{xx}^{cnd}, V_{pp}^{cnd} and V_{xp}^{cnd}

Independent verification is necessary!

Moreover, for state tomography different intervals of free evolution might be required.

Free evolution & verification



PRL **98,** 030405 (2007) PHYSICAL REV

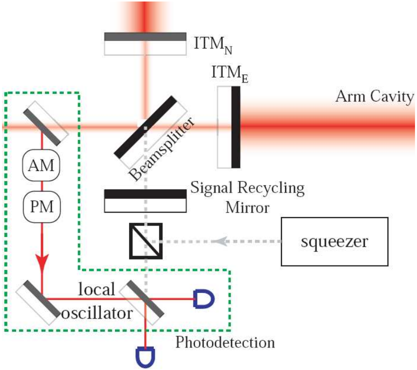
FIG. 3 (color online). Schematic description of the proposed experiment, including the second Fabry-Perot cavity on the right for the detection of the mechanical motion.

Weak light verification:

- Applies only to verification of steady state
- Requires very precise knowledge of 2^{nd} laser shot noise

D. Vitali et al, (2007)

Free evolution & verification



Back-action evasion (BAE) verification

- Time-domain amplitude (AM) and phase (PM) modulation of output light allows to eliminate back-action from the final result of measurement
- Makes possible verification of time-dependent non-Gaussian states
- Gives sub-SQL sensitivity for efficient state tomography

$$Y_{out} = \int_{\tau_{f.e.}}^{\infty} dt\, [g_1(t) b_1^{\rm out}(t) + g_2(t) b_2^{\rm out}(t)]$$

$$b_1^{out} = a_1^{in},\ b_2^{out} = a_2^{in} + \alpha[x_{sign} + R_{xx}(a_1^{in} + \ldots)]$$

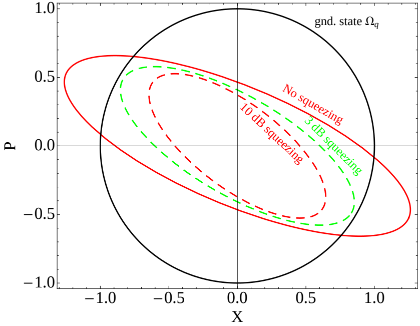
"Variation measurement", S. Vyatchanin & E. Zubova (1996)

Free evolution & verification

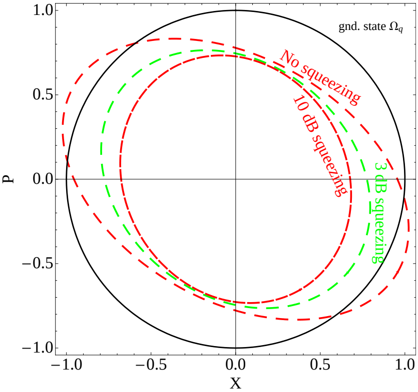
Verification uncertainty ellipse

provides effective “pixel” size for prepared state reconstruction/tomography

Markovian noise



Non-Markovian noise



Y. Chen et al, (in preparation)

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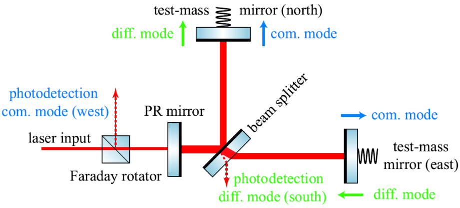
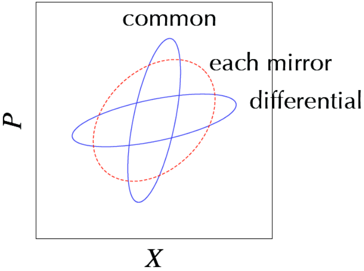
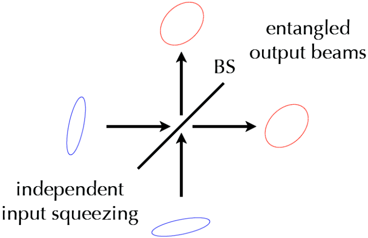
Macroscopic entanglement





- Measure both common and differential motion of the end mirrors
- If they are both in pure Gaussian state then individual motions of the mirrors will be entangled
- In presence of large enough classical noise entanglement may be destroyed, leaving only classical correlations

$$\Psi(x_n - x_e) \otimes \Psi(x_n + x_e) \neq \Psi(x_n) \otimes \Psi(x_n)$$



H. Müller-Ebhardt et al. (2008)

Macroscopic entanglement

Entanglement survives if classical noises are well below SQL!

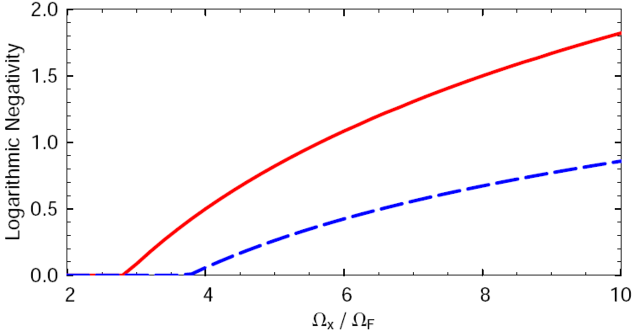


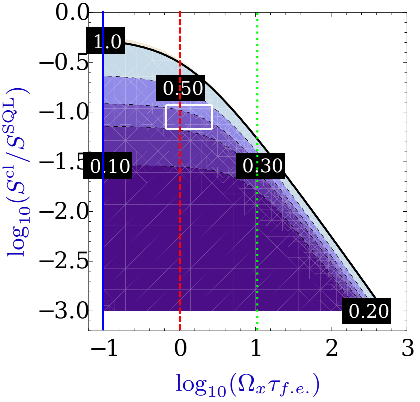
FIG. 4: Logarithmic negativity versus Ω_x/Ω_F, maximized with respect to $\Omega_\alpha^{\rm c}$ and $\Omega_\alpha^{\rm d}$ using phase quadrature detection (dashed line) as well as additionally maximized with respect to $\phi^{\rm c}$ and $\phi^{\rm d}$ (solid line). No laser noise.

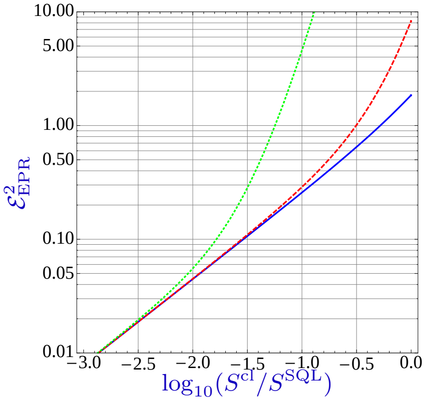
H. Müller-Ebhardt et al, (2008)

Experimental test of EPR-paradox

Provided that two mirrors are entangled, one can test EPR-paradox by measuring:

$$\frac{\hbar}{2}\mathcal{E}_{\rm EPR} \equiv \langle\Delta(x_n - x_e)/2\rangle\langle\Delta(p_n + p_e)\rangle < \hbar/2$$





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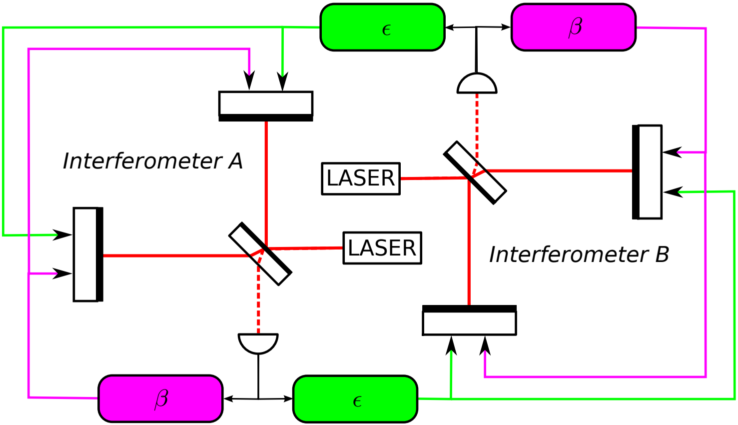
Mechanical quantum swaping (Very sketchy)



Mutual feed-back channels turn mechanical modes of A and B into system of 2 coupled oscillators with eigenfrequencies:

$$\Omega_- = \sqrt{\omega_p^2 + \Omega_q(\beta - \epsilon)}, \quad \Omega_+ = \sqrt{\omega_p^2 + \Omega_q(\beta + \epsilon)}$$

Mechanical quantum swaping (Very sketchy)

Mechanical state of two coupled oscillators is swaped after sloshing time T:

$$\Omega_- T = \pi j \,, \text{ and } \Omega_+ T = \pi k$$

where $j = 1, 2, \ldots$ and $k = j + 1, j + 3, \ldots$;

- Thermal noises introduce additional error to the swapped states:

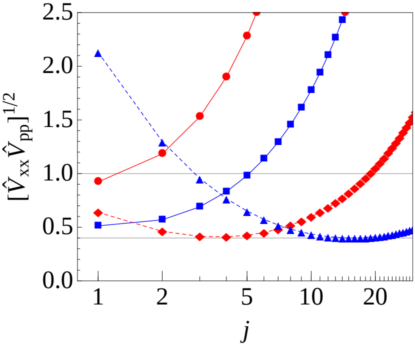
$$\sigma_{swap} = \frac{2}{\hbar} \sqrt{V^{add}_{xx} V^{add}_{pp}}$$

- Fixing j, k, Ω_q and ω_p there exists optimal sloshing time T:

$$T_{\rm opt} = \pi \left[\frac{(j^4 + k^4) N_x}{N_F \Omega_q^4 + N_x \omega_p^4} \right]^{1/4}$$

where

$$N_x = e^{-2q} + 2\zeta_x^2 \,, \quad N_F = e^{-2q} + 2\zeta_F^2 .$$



Teleportation error as function of j, for ω_p/Ω_q =0, 1, 2 and 4. Horizontal grid lines: vacuum level (1), and the minimum error when $\omega_p/\Omega_q \gg 1$.

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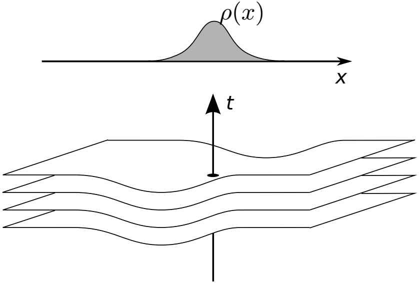
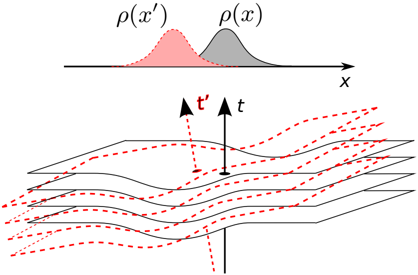
Gravity decoherence?

- **Penrose:** Quantum superposition of massive particle leads to ambiguity in defining space-time.
- **Penrose:** Only one “version” of space-time can exist $\Longrightarrow$ gravitationally induced collapse of wave function





Gravity decoherence?

- In multiple particle case: Entanglement state must reduce to classical superposition

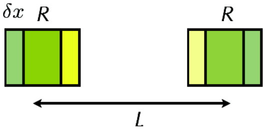
$$\tau_G = \frac{\hbar}{E_G}$$

$$E_G^A = \int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y} \frac{[\rho(\mathbf{x}) - \rho'(\mathbf{x})][\rho(\mathbf{y}) - \rho'(\mathbf{y})]}{|\mathbf{x} - \mathbf{y}|}$$

self gravitational energy
due to difference in distribution
Penrose, 1996

$$E_G^B = \int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y} \frac{\rho(\mathbf{x})\rho'(\mathbf{y})}{|\mathbf{x} - \mathbf{y}|}$$

mutual attraction energy
between different components
Diosi 1989, based on earlier idea of Penrose



$$E_A \sim \frac{G(M\delta x/R)^2}{R} \sim \frac{GM^2\delta x^2}{R^3}$$

$$E_B \sim \frac{GM^2\delta x}{L^2} \sim E_A \left(\frac{R}{L}\right)^2 \left(\frac{R}{\delta x}\right)^2$$

much shorter decoherence time!!!

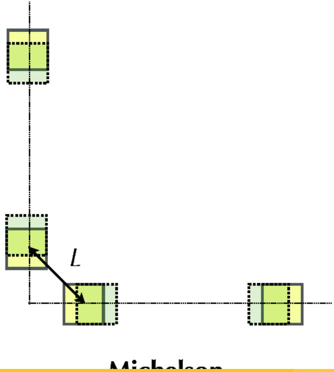
Gravity decoherence?

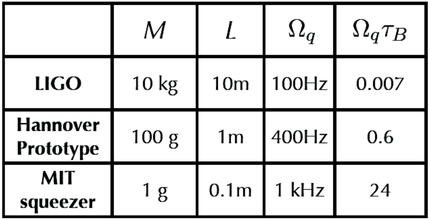
ORDER OF MAGNITUDE ESTIMATES

- In the two scenarious, assuming uncertainty in x comparable to one for ground state of oscillator with frequency Ω_q

$$\Omega_q \tau_A \sim \frac{\Omega_q^2}{G\rho_0} \quad \text{where } \sqrt{G\rho_0} < 2 \times 10^{-4}\ \text{Hz}$$

$$\Omega_q \tau_B \sim \frac{\hbar^{1/2} L^2 \Omega_q^{3/2}}{G M^{3/2}}$$





	M	L	Ω_q	$\Omega_q \tau_B$
LIGO	10 kg	10m	100Hz	0.007
Hannover Prototype	100 g	1m	400Hz	0.6
MIT squeezer	1 g	0.1m	1 kHz	24

Pure quantum state: perfectly regular and coherent

Slightly thermalized state

Highly thermalized state

The daily grind of experimentalist: Keep noises behind the line!

Conclusion

1. Observation of quantum phenomena in macroscpic world seams to be feasible in GW detectors within several years from now

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5. To test utterly quantum phenomena, such as macroscopic tunneling, quantum jumps or interference non-Gaussian non-linear experiments should be elaborated.
6. Our fight is good, thus we'll win!

THANK YOU

FOR YOUR ATTENTION!!!