Trieste Junior Quantum Days 2019

Optomechanical systems as noise spectrometers

(in collaboration with Dan Goldwater, Angelo Bassi, Peter Barker)

Sandro Donadi

FIAS Frankfurt Institute for Advanced Studies

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WHAT I WILL DISCUSS:

I will present a protocol which allows to measure the spectrum of bosonic baths and classical noises using optomechanical devices.

AND WHERE IT CAN BE USEFUL

In general: open quantum systems i.e. systems where the interaction with the external environment plays a relevant role.

- Probing a specific source of noise using a system which interaction with the noise can be tuned (e.g. electric noise in a trap);
- Models predicting gravitational decoherence;
- Collapse models;
- …

THE MODEL

$$\hat{H} \quad = \hat{H}_{\mathcal{S}} + \hat{H}_{\mathcal{B}} + \hat{H}_{\mathcal{I}}$$

$$\hat{H}_{\mathcal{S}} = \omega_m(\hat{a}^\dagger \hat{a} + \frac{1}{2}) \qquad \hat{H}_{\mathcal{B}} = \sum_\alpha \omega_\alpha (b_\alpha^\dagger b_\alpha + \frac{1}{2})$$

$$\hat{H}_{\mathcal{I}} = -\hat{q}\sum_\alpha g_\alpha \hat{q}_\alpha \qquad \hat{B} = \sum_\alpha g_\alpha \hat{q}_\alpha \qquad C(t,s) = \mathrm{Tr}[\hat{B}(t)\hat{B}(s)\rho_B]$$

↓

THE EXACT MASTER EQUATION

B. L. Hu, J. P. Paz, and Y. Zhang, Phys. Rev. D **45**, 2843 (1992),
L. Ferialdi, Physical Review A **95**, 052109 (2017).

$$\frac{d}{dt}\rho_t = -i[\hat{H}_S - \Xi(t)q^2, \rho_t] + \Gamma(t)[\hat{q},[\hat{q},\rho_t]]$$

$$+\Theta(t)[\hat{q},[\hat{p},\rho_t]] + i\Upsilon(t)[\hat{q},\{\hat{p},\rho_t\}]$$

THE MODEL

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$$\hat{H}_{\mathcal{S}} = \omega_m(\hat{a}^\dagger \hat{a} + \frac{1}{2}) \qquad \hat{H}_{\mathcal{B}} = \sum_\alpha \omega_\alpha (b_\alpha^\dagger b_\alpha + \frac{1}{2})$$

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THE APPROXIMATE MASTER EQUATION

$$\frac{d}{dt}\rho_t = -i[\hat{H}_S, \rho_t] + \Gamma(t)[\hat{q}, [\hat{q}, \rho_t]] + \Theta(t)[\hat{q}, [\hat{p}, \rho_t]]$$

$$\Gamma(t) = -\int_0^t ds\, C(t,s) \cos[\omega_m(t-s)] \qquad \Theta(t) = \int_0^t ds\, C(t,s) \frac{\sin[\omega_m(t-s)]}{m\omega_m}$$

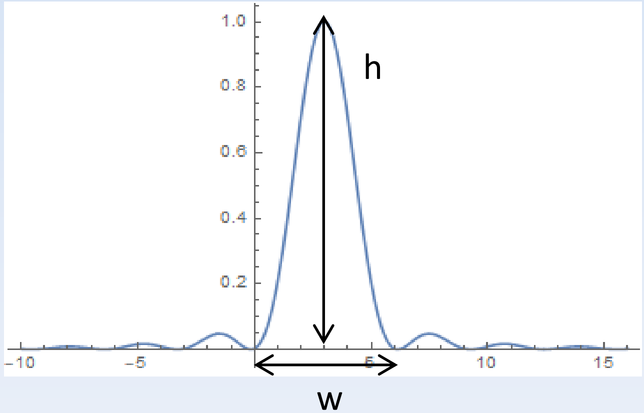
- Weak coupling limit
- Neglect dissipative effects (high temperature bath)

AVERAGED OCCUPATION NUMBER

$$\langle \hat{n} \rangle_t = \langle \hat{n} \rangle_0 + \frac{1}{2\pi m \omega_m} \int_{-\infty}^{\infty} d\nu \, \tilde{C}(\nu) \frac{\sin^2[(\omega_m - \nu)t/2]}{(\omega_m - \nu)^2}$$

$$h = t^2/4$$
$$w = 4\pi/t$$

with: $C(s,t) = C(|s-t|)$



Acts as a filter which is more and more sharp for large times!

PROTOCOL FOR DETERMINING THE SPECTRUM

1) Set the oscillator at the desired spectrum frequency to be explored;
2) Cool down the oscillator;
3) Wait some time *t*;
4) Measure the averaged occupation number at time *t*.

FROM THE THEORY…TO POSSIBLE EXPERIMENTAL SETUPS

- Range of ω; $100 < \omega < 10^6$ Hz — V. Jain, et al. *Phys. Rev. Lett.* ***116*(24)**, 243601 (2016).
- Preparations as close as possible to the ground state; $n_0 < 100$ (for $T = 10^{-4}$ K, $\omega = 10^6$ Hz)
- Low noise environment; $\Delta g=10^4/\omega$, $\Delta bb=10^{-2}/\omega$ (Te = 4 K, Ti = 400 K, P = 10^{-9} Pa, R = 50 nm)
- Precise measurement of $\langle n(t) \rangle$;
- The ability to increase or decrease the coupling to the bath of interest; e.g. electric field noise
- The duration of the experiment. t=10s → accuracy of order 1 Hz

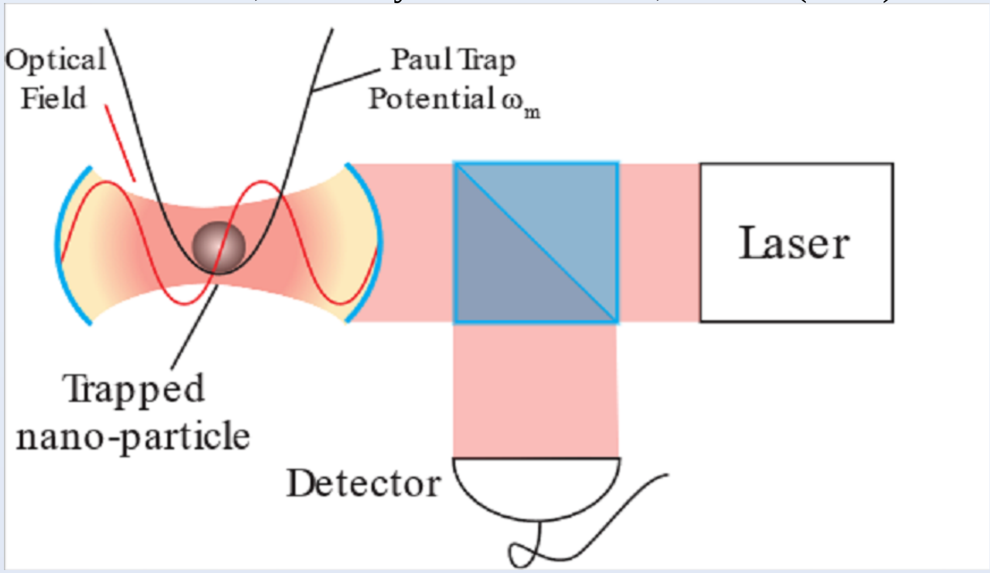
IN PARTICULAR WE CONSIDERED

A `hybrid' type trap, composed of a quadrupole electric field trap working in conjunction with an optical trap.

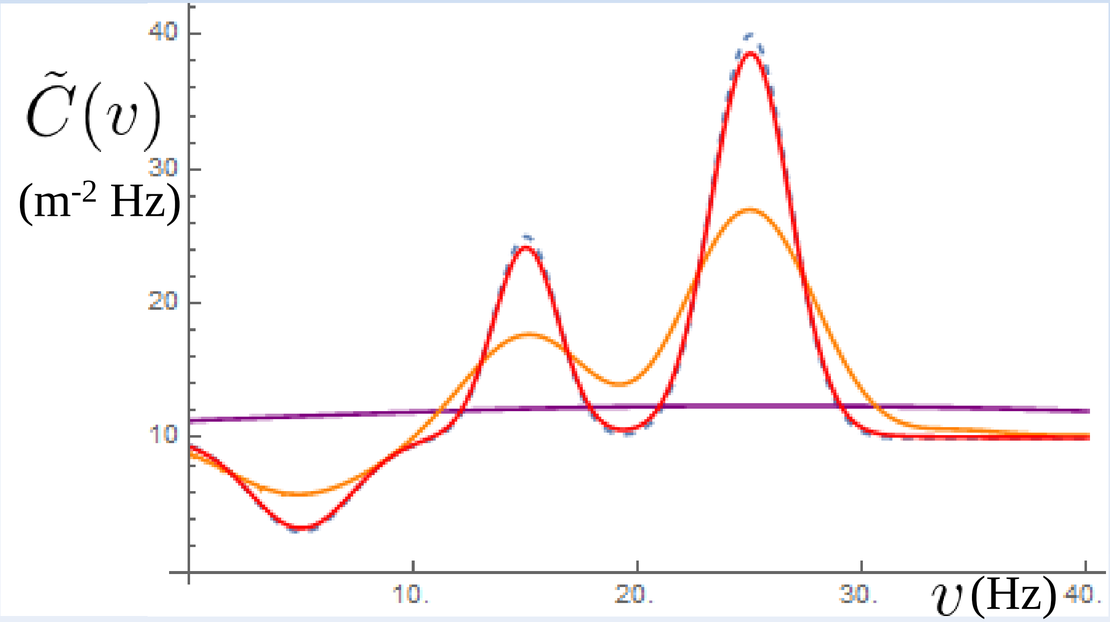
Optical trap: useful for cooling and doing precise measurements;

Paul trap: useful to trap the system with low noise.

J. Millen, et al. Phys. Rev. Lett. **114**, 123602 (2015).



EXAMPLE 1



$$\tilde{C}(v) = 10 - 7e^{-\frac{1}{10}(v-5)^2} + 15e^{-\frac{1}{4}(v-15)^2} + 30e^{-\frac{1}{6}(v-25)^2}$$

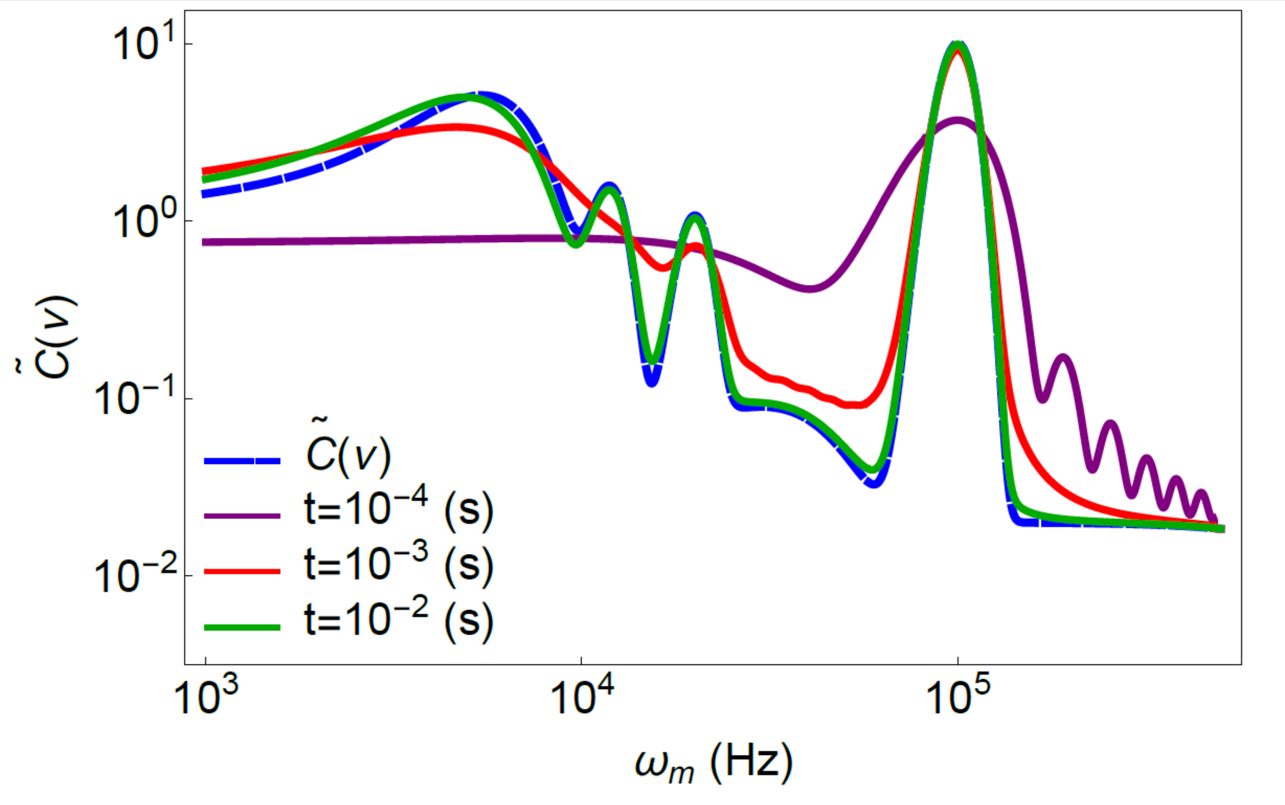
Noise spectrum

Spectrum reconstruction with t = 0.1 s (accuracy ≈ 100 Hz)

Spectrum reconstruction with t = 1 s (accuracy ≈ 10 Hz)

Spectrum reconstruction with t = 10 s (accuracy ≈ 1 Hz)

EXAMPLE 2



The oscillation in the purple line tells us that the accuracy we are using is too low:

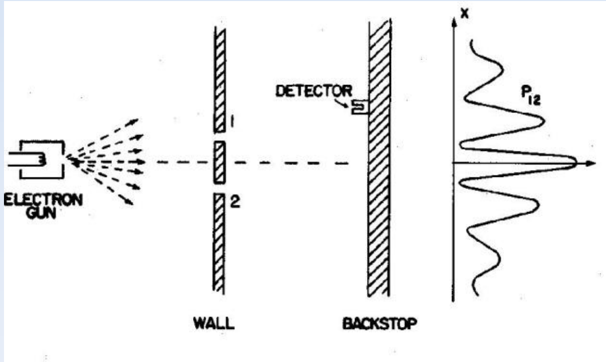
⟶ very relevant for knowing if the accuracy we are using is enough for reconstructing the spectrum.

THE MEASUREMENT PROBLEM AND COLLAPSE MODELS

The Schrödinger equation:

- Linear
- Deterministic

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = H |\Psi(t)\rangle$$



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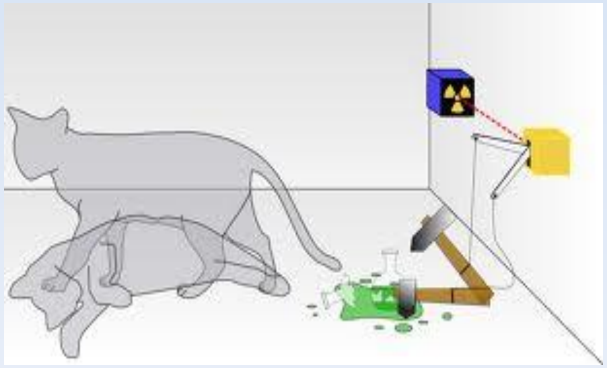


KO

The wave packet reduction postulate:

- Non Linear
- Stochastic

$$\frac{|a_1\rangle + |a_2\rangle}{\sqrt{2}} \xrightarrow{\text{measurement}} \begin{cases} \xrightarrow{\text{half times}} |a_1\rangle \\ \xrightarrow{\text{half times}} |a_2\rangle \end{cases}$$

There are two different laws for the evolution of the state vectors but it is not clear when to use which one.

THE CONTINUOUS SPONTANEOUS LOCALIZATIONS (CSL) MODEL

G.C. Ghirardi, P. Pearle and A. Rimini, Phys. Rev. A **42**, 78 (1990).

A. Bassi and G.C. Ghirardi, Phys. Rept. **379**, 257 (2003).

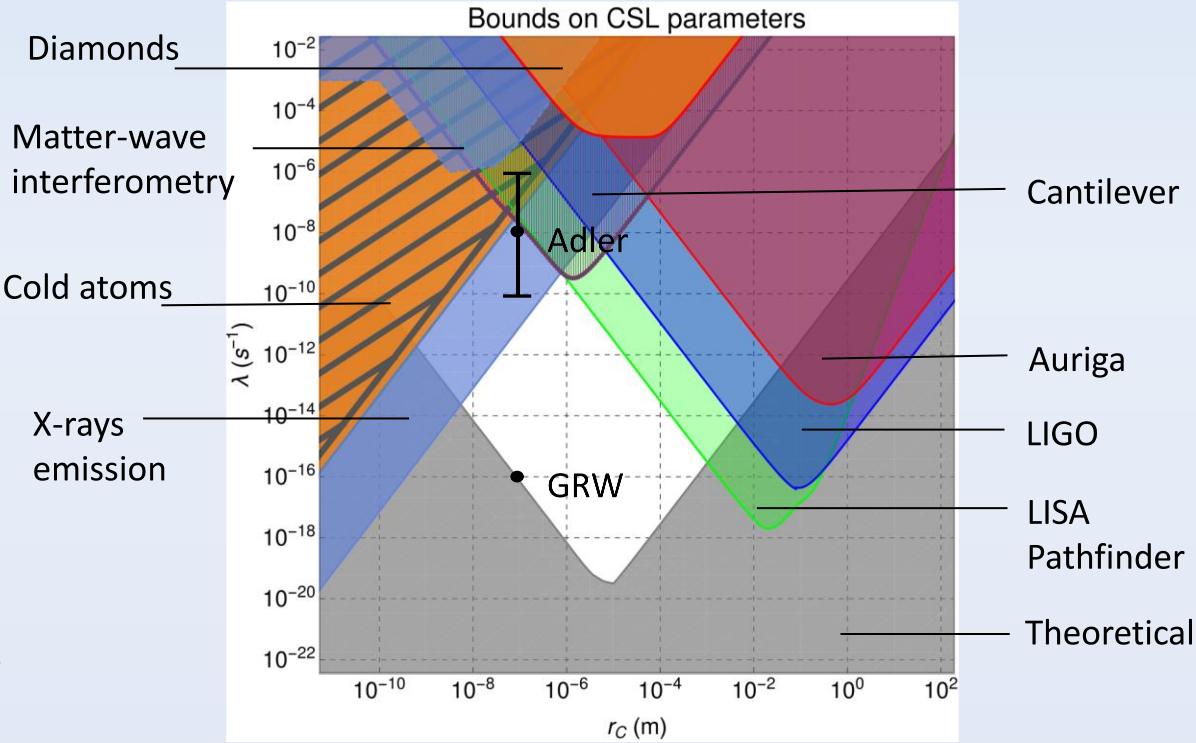
$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H dt + \sqrt{\gamma} \int d\mathbf{z} (M_{\mathbf{z}} - \langle M_{\mathbf{z}} \rangle_t) dW_t(\mathbf{z}) - \frac{\gamma}{2} \int d\mathbf{z} (M_{\mathbf{z}} - \langle M_{\mathbf{z}} \rangle_t)^2 dt \right] |\psi_t\rangle$$

Schroedinger | collapse

$$\gamma = \lambda 8 \pi^{3/2} r_C^3$$

$$\mathbb{E}[dW_t(\mathbf{x}) dW_t(\mathbf{y})] = \delta(\mathbf{x} - \mathbf{y}) dt$$

$$\hat{M}_{\mathbf{z}} = \sum_{j=1}^{N} \frac{m_j}{m_0} \frac{e^{-\frac{(\hat{\mathbf{x}}_j - \mathbf{z})^2}{2 r_c^2}}}{(\sqrt{2\pi} r_c)^3}$$



- Localization in space;
- Amplification mechanism;
- Predictions depends on λ and r_C.

CSL MASTER EQUATION

$$\frac{d\rho\left(t\right)}{dt}=-\frac{i}{\hbar}\left[\hat{H},\rho\left(t\right)\right]-4\lambda\pi^{\frac{3}{2}}r_{c}^{3}\int d\mathbf{z}\left[\hat{M}_{\mathbf{z}},\left[\hat{M}_{\mathbf{z}},\rho\left(t\right)\right]\right]$$

THE NON-WHITE CSL MASTER EQUATION

S. L. Adler and A. Bassi J. Phys. A: Math. Theor. **40**, 15083-98 (2007).

$$\frac{d\rho\left(t\right)}{dt}=-i\left[\hat{H},\rho\left(t\right)\right]-8\lambda\pi^{\frac{3}{2}}r_{c}^{3}\int d\mathbf{z}\int_{0}^{t}ds\,C(t,s)\left[\hat{M}_{\mathbf{z}},\left[\hat{M}_{\mathbf{z}}\left(s-t\right),\rho\left(t\right)\right]\right]$$

Under the assumption $\langle\hat{\mathrm{x}}\left(t\right)^{2}\rangle\ll r_{C}^{2}$ and considering only the motion along one axes:

$$\frac{d\rho\left(t\right)}{dt}=-i\left[\hat{H},\rho\left(t\right)\right]-\eta_{z}\int_{0}^{t}ds\,C\left(t,s\right)\left[\hat{q},\left[\hat{q}\left(s-t\right),\rho\left(t\right)\right]\right]$$

with (for a sphere)

$$\eta_{z}=\frac{M^{2}}{m_{0}^{2}}3\lambda\frac{r_{C}^{2}}{R^{6}}\left[R^{2}-2r_{c}^{2}+e^{-\frac{R^{2}}{r_{c}^{2}}}\left(R^{2}+2r_{c}^{2}\right)\right]$$

THE NON-WHITE CSL MASTER EQUATION

S. L. Adler and A. Bassi J. Phys. A: Math. Theor. **40**, 15083-98 (2007).

For an harmonic oscillator: $\hat{q}(t) = \cos(\omega t)\,\hat{q} + \frac{\sin(\omega t)}{m\omega}\hat{p}$

THE APPROXIMATED NON-WHITE CSL MASTER EQUATION

$$\frac{d\rho(t)}{dt} = -i\left[\hat{H}, \rho(t)\right] - \eta_z \Gamma(t)\left[\hat{q}, \left[\hat{q}, \rho(t)\right]\right] - \eta_z \Theta(t)\left[\hat{q}, \left[\hat{p}, \rho(t)\right]\right]$$

AVERAGED OCCUPATION NUMBER

$$\langle\hat{n}\rangle_t = \langle\hat{n}\rangle_0 + \frac{\eta_z}{2\pi m\omega_m}\int_{-\infty}^{+\infty} d\nu\,\tilde{C}(\nu)\frac{\sin^2[(\omega_m-\nu)t/2]}{(\omega_m-\nu)^2}$$

The protocol introduced before can be used!

CONCLUSIONS

- We showed how optomechanical systems can be used as spectrometers.
- The basic idea is that the oscillator goes resonant with the noise spectrum at its frequency, so by changing that we can probe the noise (similar to a radio).
- Can be relevant for testing non-white CSL.

arXiv: 1901.10445v2

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COLLABORATORS FOR THIS WORK

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ANGELO BASSI
(TRIESTE UNIVERSITY)

PETER BARKER
(UNIVERSITY COLLEGE LONDON)

THE GROUP AT FIAS (FRANKFURT)

SABINE HOSSENFELDER

TOBIAS MISTELE

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THANKS