An optical readout configuration for advanced massive GW detectors

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Optical readout of displacement

- Standard detection technique in interferometers
- Proposed in the 80's for bar detectors[1]
- Recently applied to a room temperature detector[2]

[1] J.-P. Richard, J. Appl. Phys. **64**, 2202 (1988)
[2] L. Conti *et al*., J. Appl. Phys. **93**, 3589 (2003)

Room temperature Weber bar with optical readout

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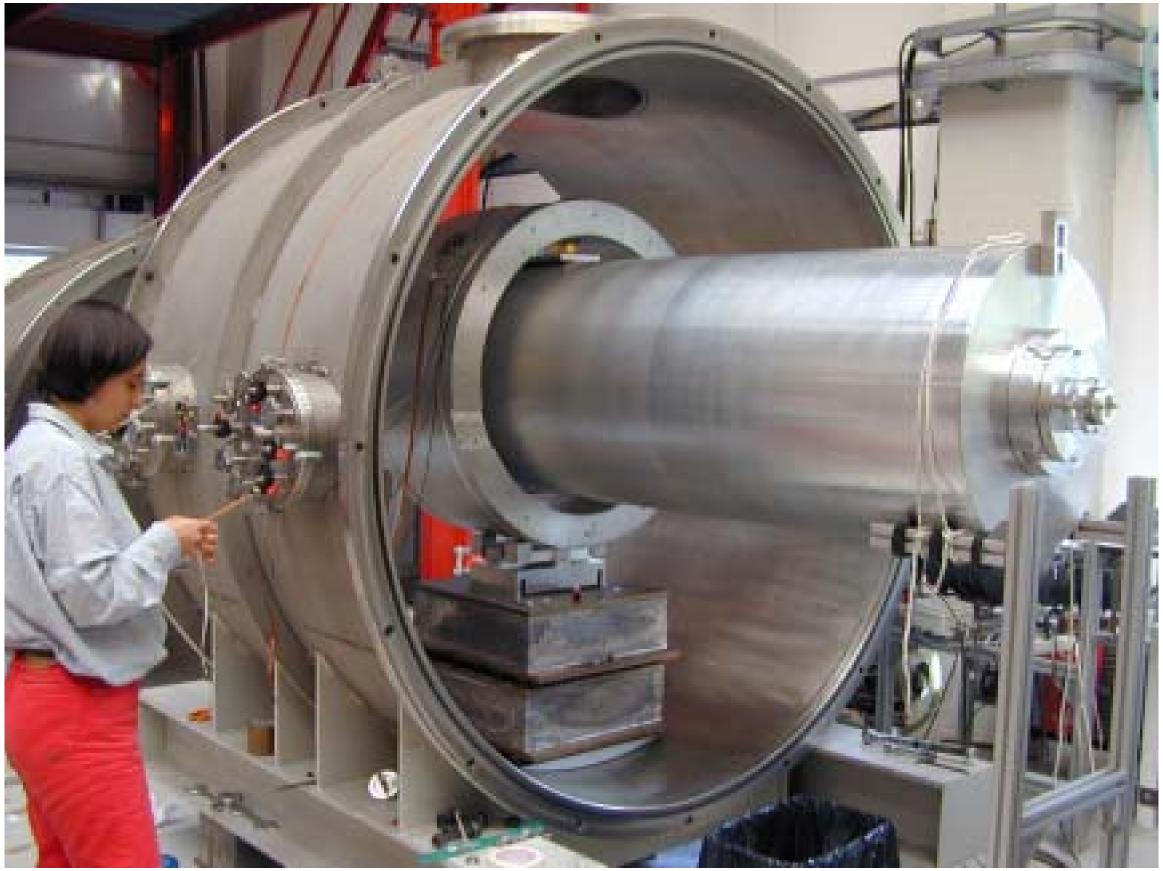

Room temperature Weber bar with optical readout

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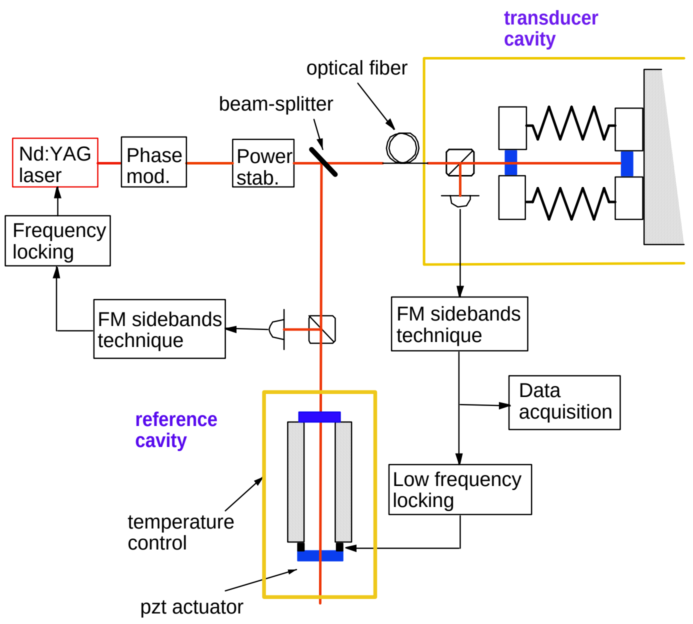

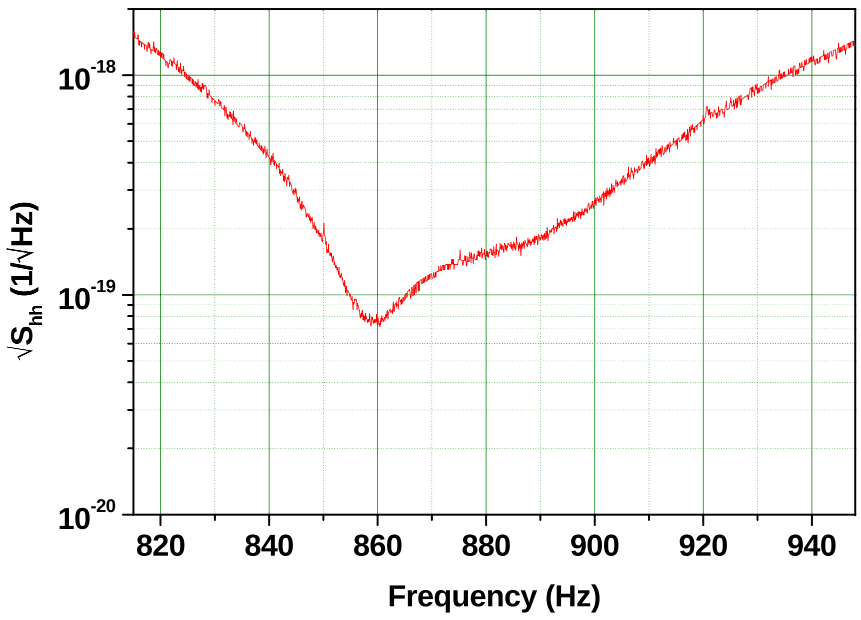

Room temperature Weber bar with optical readout

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Work in progress:

- Cleaner vacuum system
- New mechanical suspension
- Higher Finesse transducer cavity
- Cooling (at least 77K)

Brownian noise and radiation pressure (back-action) are the usual sensitivity limiting sources in a few-modes model, together with the displacement detection sensitivity (displacement noise)

In a real, massive system: several modes, with their thermal noise and back-action.

→ **Small interrogation region means large fluctuations**

One must average over high order modes:

→ **needs large interrogation region**

We must consider ‘local’ effects:

- **Thermal noise**
  - phototermal
  - thermodynamic
  - Brownian

  Depends on material parameters

  At cryo-T:
  - best material is sapphire
  - predominant Brownian

- **Radiation pressure**

Brownian noise:

$$S_{\mathrm{Br}}(\omega) = \frac{4\,k_{\mathrm{B}}T}{\omega}\,\mathrm{Im}\,[\chi(\omega)]$$

Radiation pressure effect:

$$S_{\mathrm{rp}}(\omega) = |\chi(\omega)|^2 \left(\frac{2}{c}\right)^2 S_{\mathrm{cav}}$$

intracavity radiation noise spectral power:

$$S_{\mathrm{cav}} = 2\,h\nu \left(\frac{F}{\pi}\right)^2 P_{\mathrm{in}}$$

Gaussian spot on a half-infinite mirror:

$$\mathrm{Im}\left[\chi(\omega)\right] \simeq \phi\,|\chi(\omega)|$$

$$|\chi^{\mathrm{single}}| = \frac{1}{\pi^{1/2}\,w}\,\frac{1-\sigma^2}{Y}$$

Single-spot noise:

$$S_{\mathrm{Br}}^{\mathrm{single}}(\omega) = \frac{4\,k_{\mathrm{B}}T}{\pi^{1/2}}\,\frac{\phi}{\omega}\,\frac{1}{w}\,\frac{1-\sigma^2}{Y}$$

$$S_{\mathrm{rp}}^{\mathrm{single}} = \left(\frac{2(1-\sigma^2)F}{\pi^{3/2}c\,Y\,\boxed{w}}\right)^2 2\,h\nu\,P_{\mathrm{in}}$$

Main figures

Sapphire (1 K):

Young modulus	$Y = 4 \cdot 10^{11}$ Pa
Poisson coefficient	$\sigma = 0.25$
Loss angle	$\phi = 3 \cdot 10^{9}$

Cavity Finesse: $F = 10^{6}$

Displacement sensitivity

with 1 W:	$7 \cdot 10^{-45}$ m^2/Hz
with 10 W:	$7 \cdot 10^{-46}$ m^2/Hz

Target (Ex.: dual sphere *)

- Best stiffness: for laser power = 7 W
- Thermal noise negligible for $Q/T > 2\cdot10^{8}$

$$S_{xx} = 10^{-45}\ \mathrm{m^2/Hz}$$

... but

With a waist of $\underline{w = 1\ \mathrm{mm}}$:

$$S_{Br} = 5\cdot10^{-44}\ \mathrm{m^2/Hz}$$

$$S_{rp} = 8\cdot10^{-41}\ \mathrm{m^2/Hz}$$

→ We need a waist of **$w > 20$ cm !!!!**

* M. Cerdonio *et al*., Phys. Rev. Lett. **87**, 031101 (2001)

Possible solutions?

Concave – Convex cavity :

$(-R_2) = R_1 + r$
Stable if $d > r$

Plano-concave Cavity:

$$W^2 \cong \frac{\lambda}{\pi}\sqrt{Rd}$$

If $(d - r) << d << R_1, R_2$:

$$W^2 \cong \frac{\lambda R}{\pi}\sqrt{\frac{d}{d-r}}$$

Ex. : $R = 10$ m
$r = 10$ mm
$d - r = 0.1$ mm
$\lambda = 1.064\ \mu$m

→ **W = 5.8 mm**

Delay line : **Low equivalent Finesse**

Folded Fabry-Perot (FFP)

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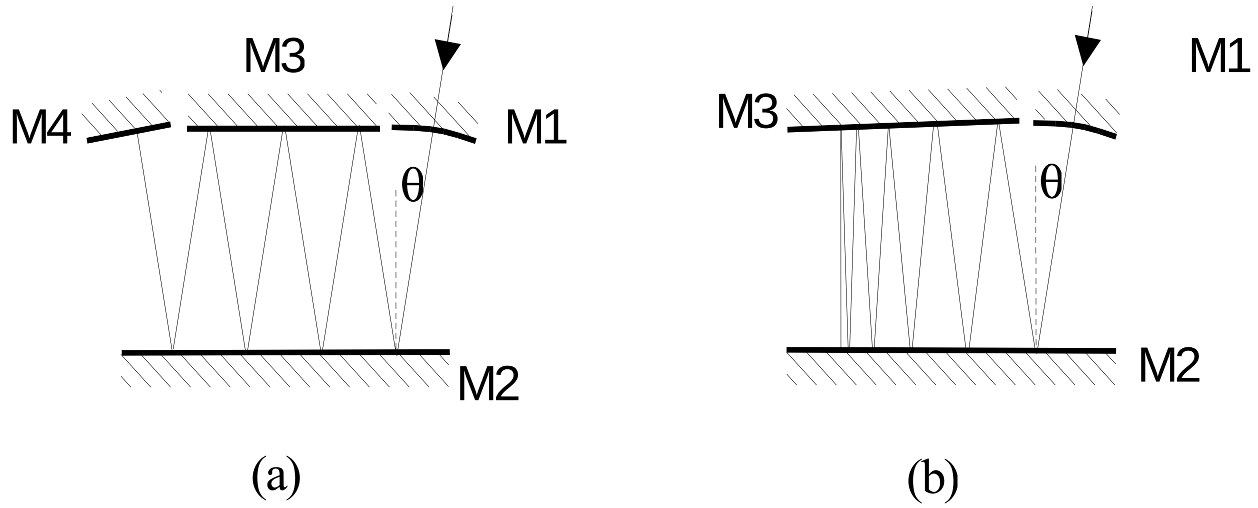

F. Marin, L. Conti, M. De Rosa: **“A folded Fabry-Perot cavity for optical sensing in gravitational wave detectors”**, Phys. Lett. A **309**, 15 (2003)

Folded Fabry-Perot (FFP)

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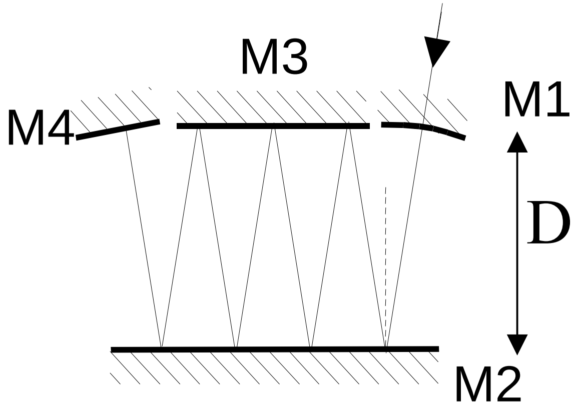

Signal: $\propto$ N

Brownian noise: $\propto \sqrt{N}$

Radiation pressure: $\propto N \cdot F$ (constant)

Displacement noise: $\propto 1/F \propto N$

Linewidth ($\rightarrow$ bandwidth): $\propto 1/(N \cdot F)$ (constant)

For non-correlated spot fluctuations

Brownian noise effect:

$$\frac{S_\nu}{\nu^2} = \frac{S_{\rm Br}^{2L}}{(2L)^2} = \boxed{\frac{S_{\rm Br}^{\rm single}}{2\,D^2}}\frac{1}{N}$$

Radiation pressure effect:

$$\frac{S_\nu}{\nu^2} = \frac{S_{\rm rp}^{2L}}{(2L)^2} = \boxed{\frac{S_{\rm rp}^{\rm single}}{4D^2}}\boxed{\frac{1}{N^2}}$$

Taking into account correlations

$$\chi_N = \chi^{\rm single} \left\{ N + 2 \sum_{n=2}^{N} \sum_{q=1}^{n-1} \exp\left(-\frac{|\mathbf{r}_n - \mathbf{r}_q|^2}{2w^2}\right) I_0\left(\frac{|\mathbf{r}_n - \mathbf{r}_q|^2}{2w^2}\right) \right\}$$

N Nakagawa *et al*., Phys. Rev. D **65**, 082002 (2002)

Brownian noise effect:

$$S_{\rm Br}^{\rm FFP}(\omega) = \frac{4\,k_{\rm B}T}{\omega}\,\phi\,(4\chi_N + 4\chi_{N'} + 2\chi^{\rm single})$$

Radiation pressure effect:

$$S_{\rm rp}^{\rm FFP} = \left(\frac{2}{c}\right)^2 S_{\rm cav}\,\left|2\chi_N + 2\chi_{N'} + 2\chi^{\rm single}\right|^2$$

Correlation effect

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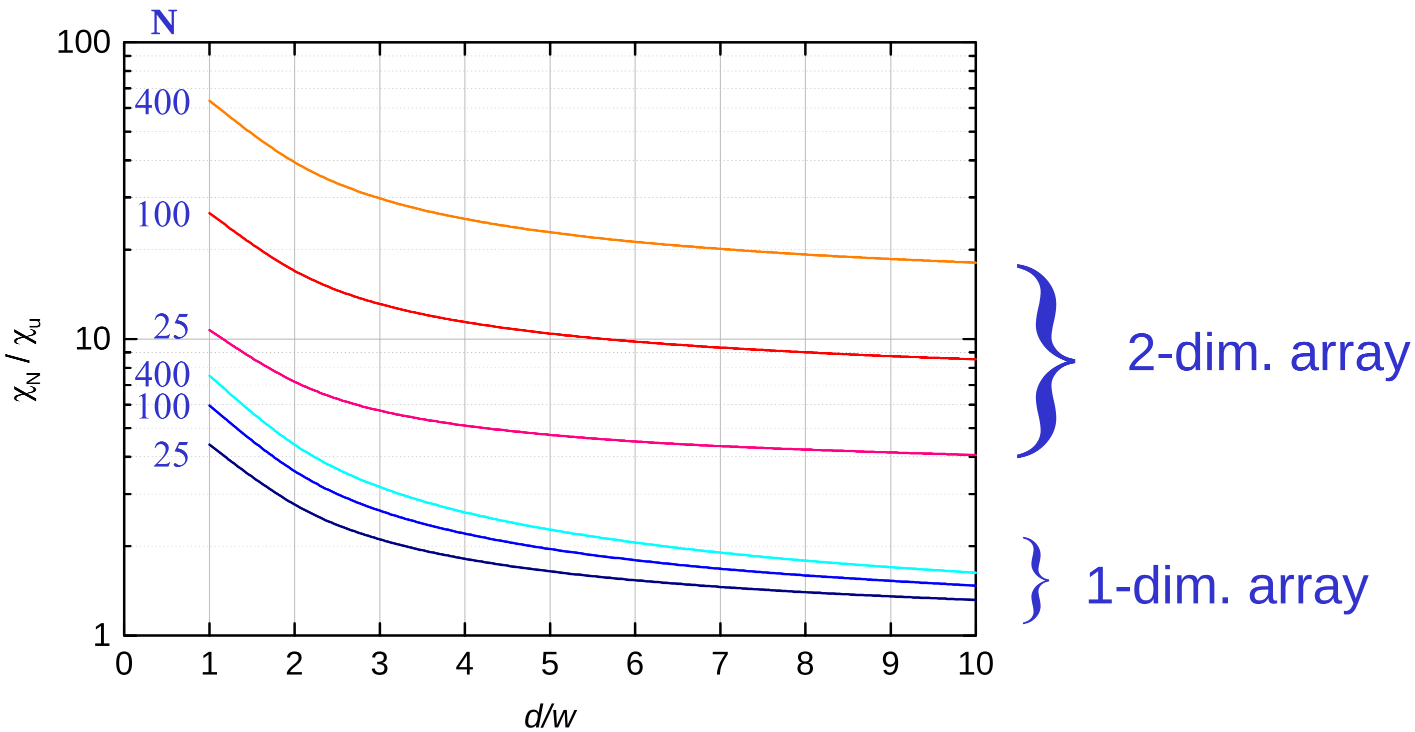
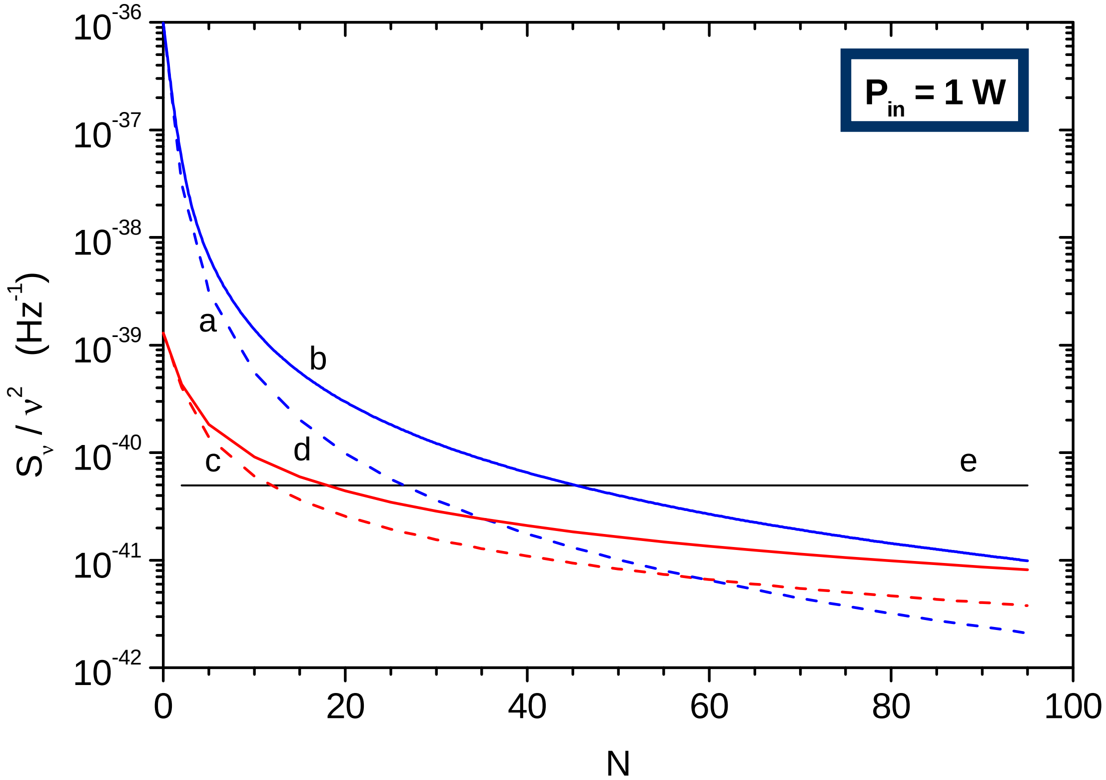




D = 6 mm
R = - 10 m
d = 4 *w*

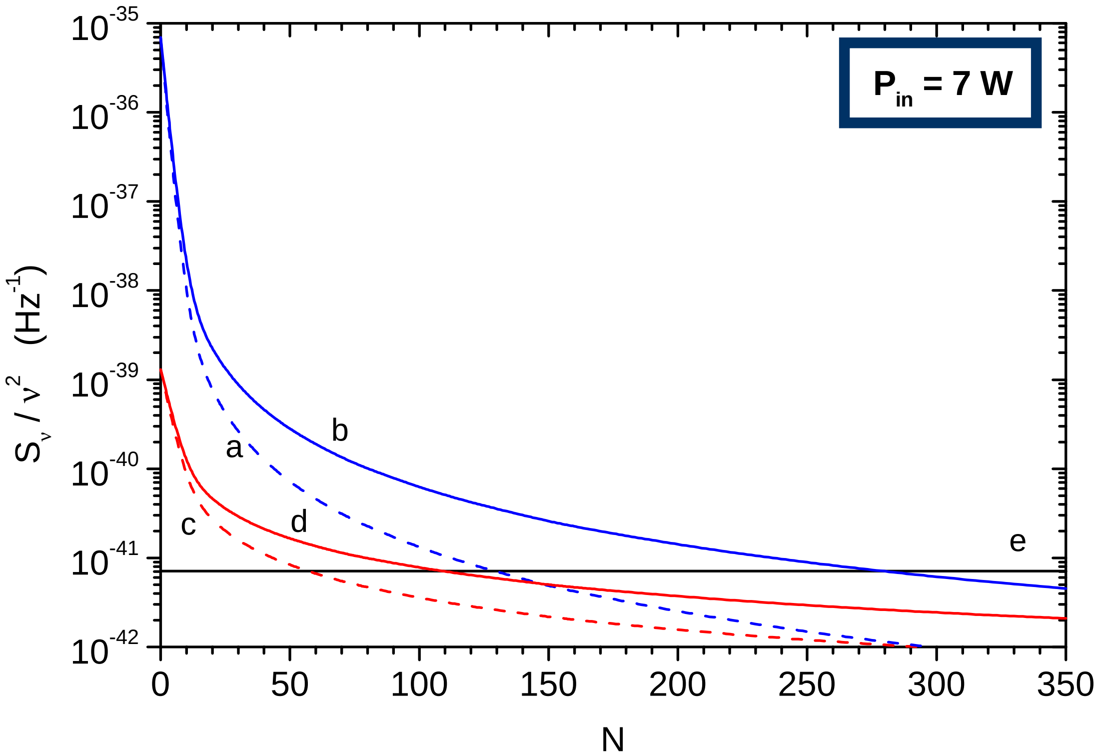
a: radiation pressure effect (no correlations)

b: radiation pressure effect (full)

c: Brownian noise @ 1.3 kHz (no correlations)

d: Brownian noise @ 1.3 kHz (full)

e: Shot-noise limited displacement sensitivity



D = 6 mm
R = - 10 m
d = 4 *w*

Power density:
≈ 10 kW/mm²

a: radiation pressure effect (no correlations)

b: radiation pressure effect (full)

c: Brownian noise @ 1.3 kHz (no correlations)

d: Brownian noise @ 1.3 kHz (full)

e: Shot-noise limited displacement sensitivity

Conclusions

The FFP allows to closely approach with the present technology the quantum-limited sensitivity and best stiffness calculated for the main modes of a high sensitivity, wide bandwidth dual detector