

What can be done without sapphire mirrors?

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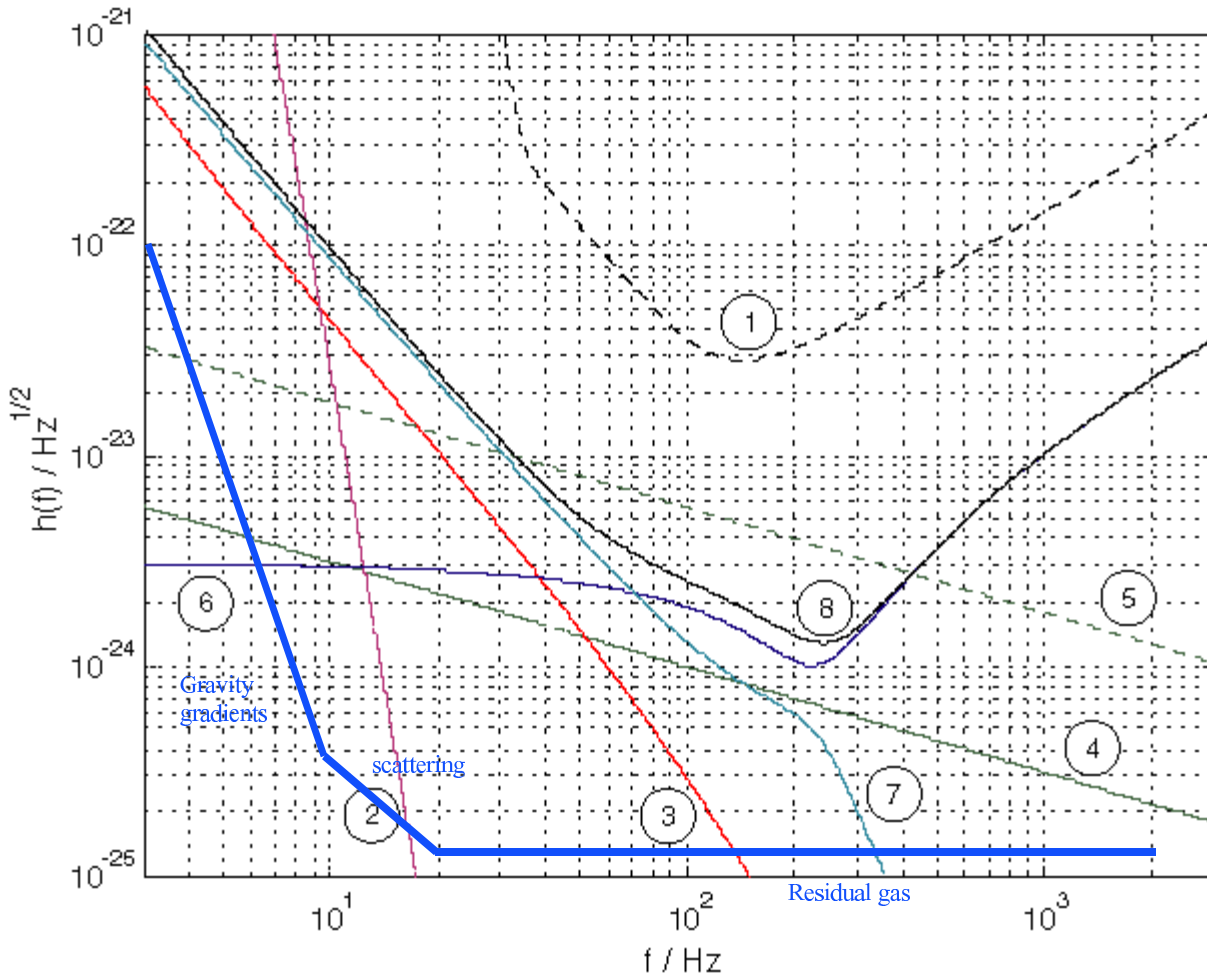
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from: *LSC Overview* by R. Weiss, Oct. 25, 1999.

LIGO II Noise Contributions



- | | |
|-------------------------------------|--|
| 1 LIGO I total | 5 Internal thermal noise - fused silica (fallback) |
| 2 Filtered seismic noise | 6 Shot noise |
| 3 Suspension thermal noise | 7 Radiation pressure noise |
| 4 Internal thermal noise - sapphire | 8 LIGO II total |

————— Facility limits

Problem :

- LIGO II sensitivity is projected based on the thermal noise of sapphire mirrors.
- Their availability is, however, uncertain.

Assumption :

- silicon mirrors are available.
- sensitivity to gravitational waves is limited mainly by thermal motion of the mirrors.

Simple possibilities

- When b -folded cavity is made only by SiO₂ mirrors :

$$\text{gain} \approx \sqrt{b}.$$

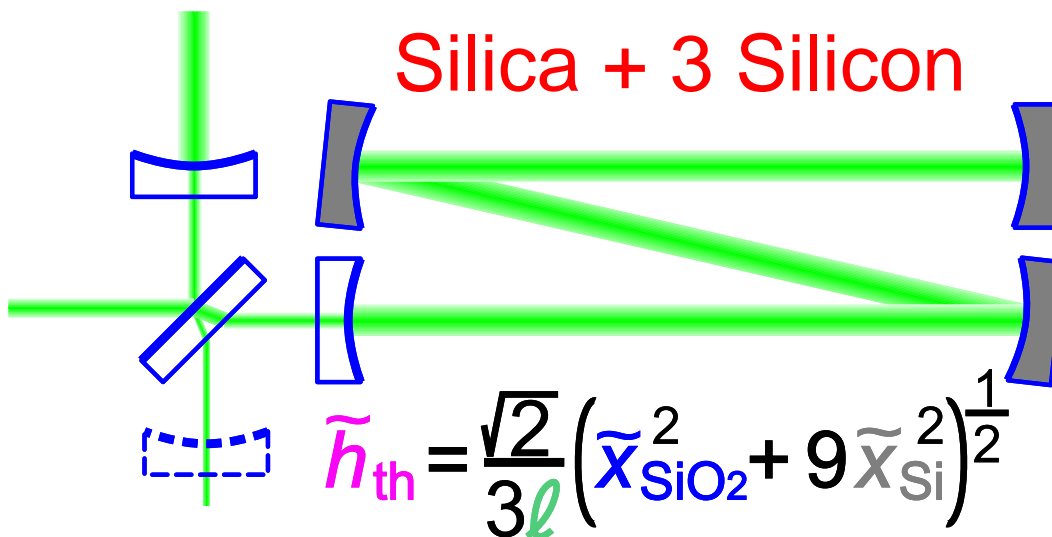
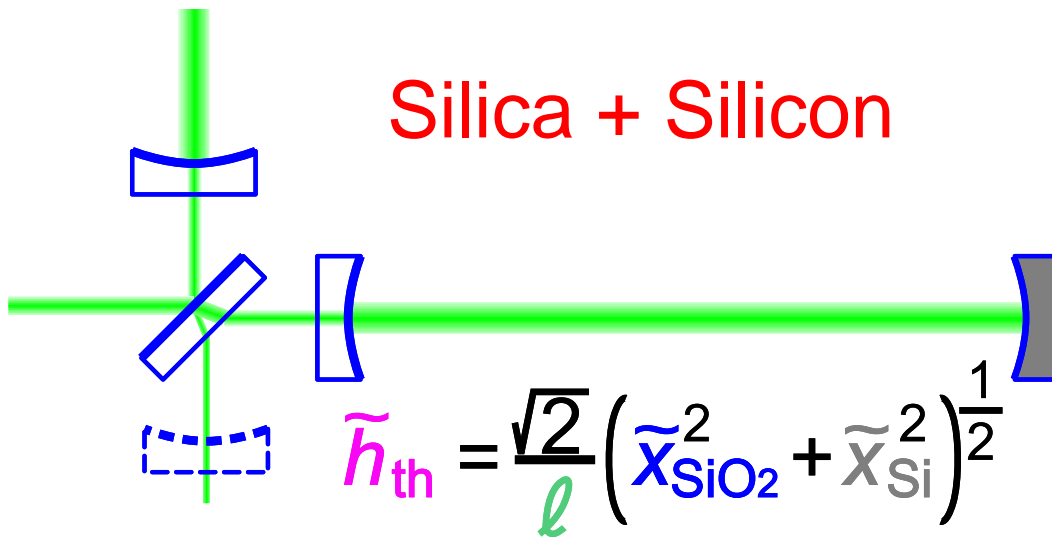
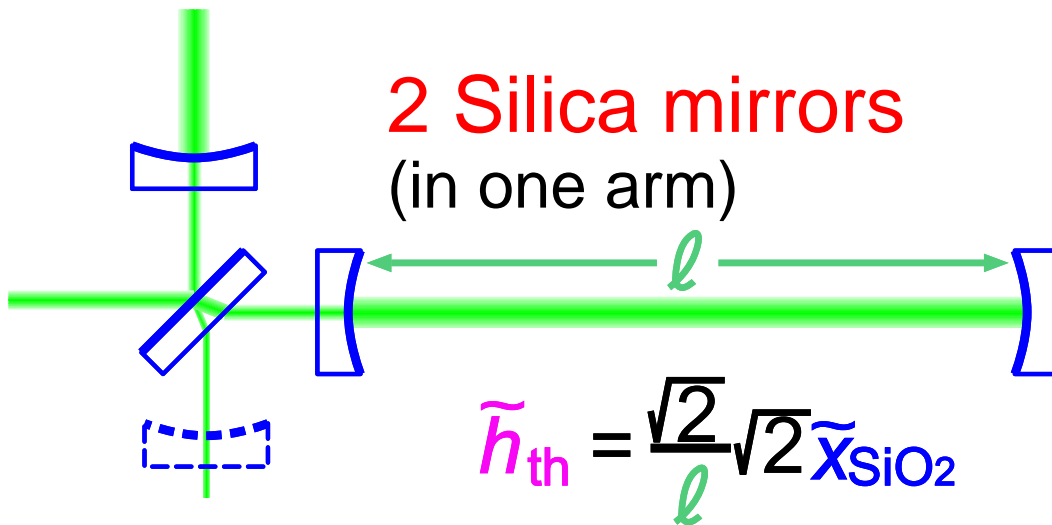
- × However, b is limited to a small number by the tube diameter.

- When end mirror is replaced by Si mirrors :

$$\text{gain} \approx \sqrt{2}.$$

⇒ not very much improvement.

Further improvement?



Hybrid folded cavity

b -folded cavity composed of

SiO₂-coupling mirror

Si-reflector $\times b$

thermal-noise limited sensitivity

$$\tilde{h}_{\text{th}} = \frac{\sqrt{2}}{b\ell} \left[(\tilde{x}_{\text{SiO}_2})^2 + (4b - 3)(\tilde{x}_{\text{Si}})^2 \right]^{\frac{1}{2}}$$

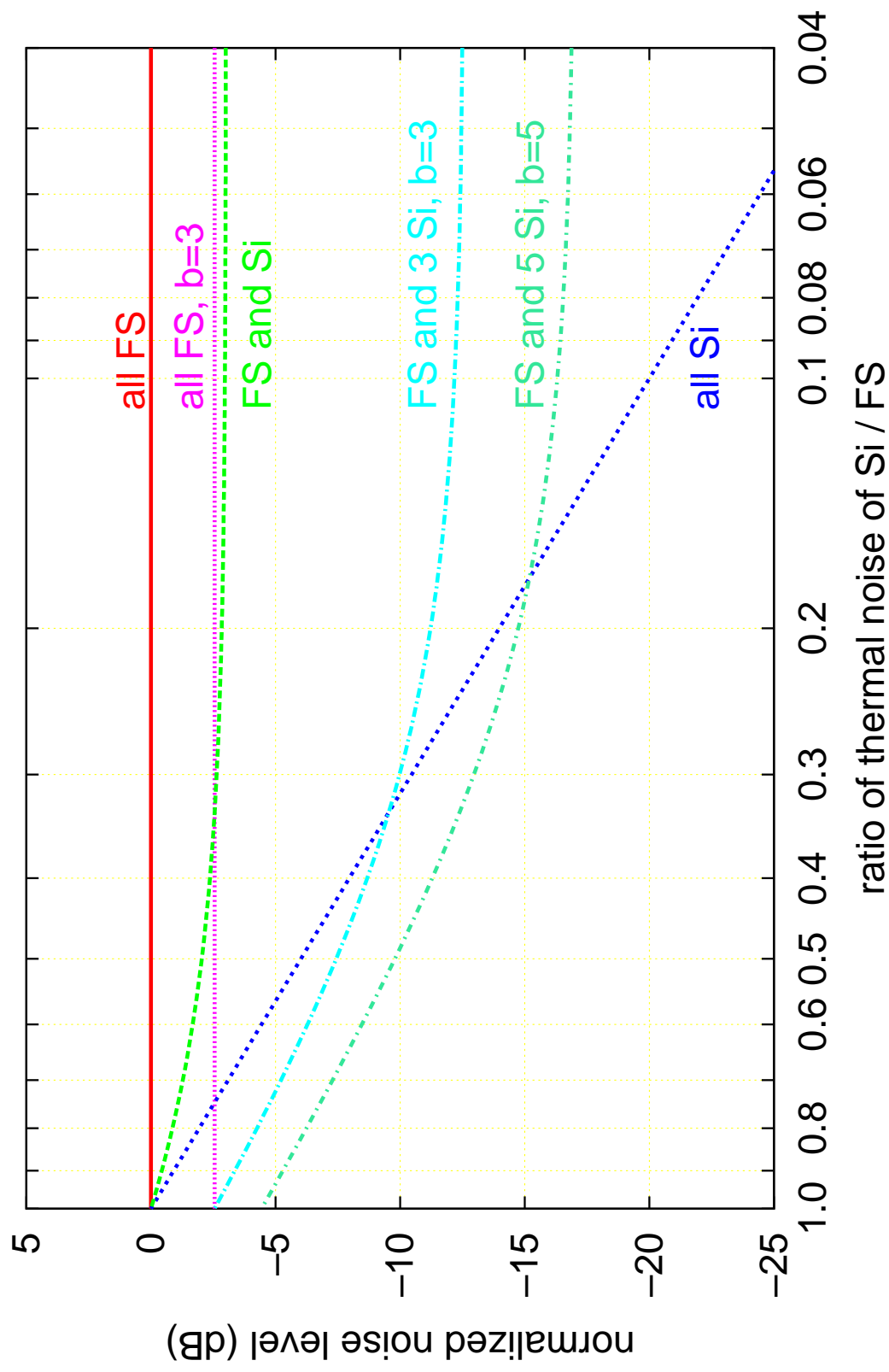
ℓ : arm length of the interferometer

$\sqrt{2}$: two arms of an interferometer

$$(4b - 3) = 2^2(b - 1) + 1 :$$

$(b - 1)$ mirrors have two reflections in a round trip that must be added linearly.

improvement by using silicon mirrors



Silicon mirrors :

- higher Q than SiO₂ mirrors
- bigger substrate available
(used only in reflection)

If silicon mirrors are low noise enough, hybrid folded cavities provide an improvement of $\approx b$ (limited by SiO₂ mirror thermal motion).

Maybe sufficient for realizing
LIGO II sensitivity.

Further improvement?

Thermal motion canceler

Measuring thermal motion independent of the main (GW) detector, and subtract it from the main detector output.

Requirements :

1. a **reference** that is less noisy than the GW test mass.
2. a **sensor** that has better *displacement* sensitivity than the main (GW) detector.

Possibility of optical measurement

Solutions :

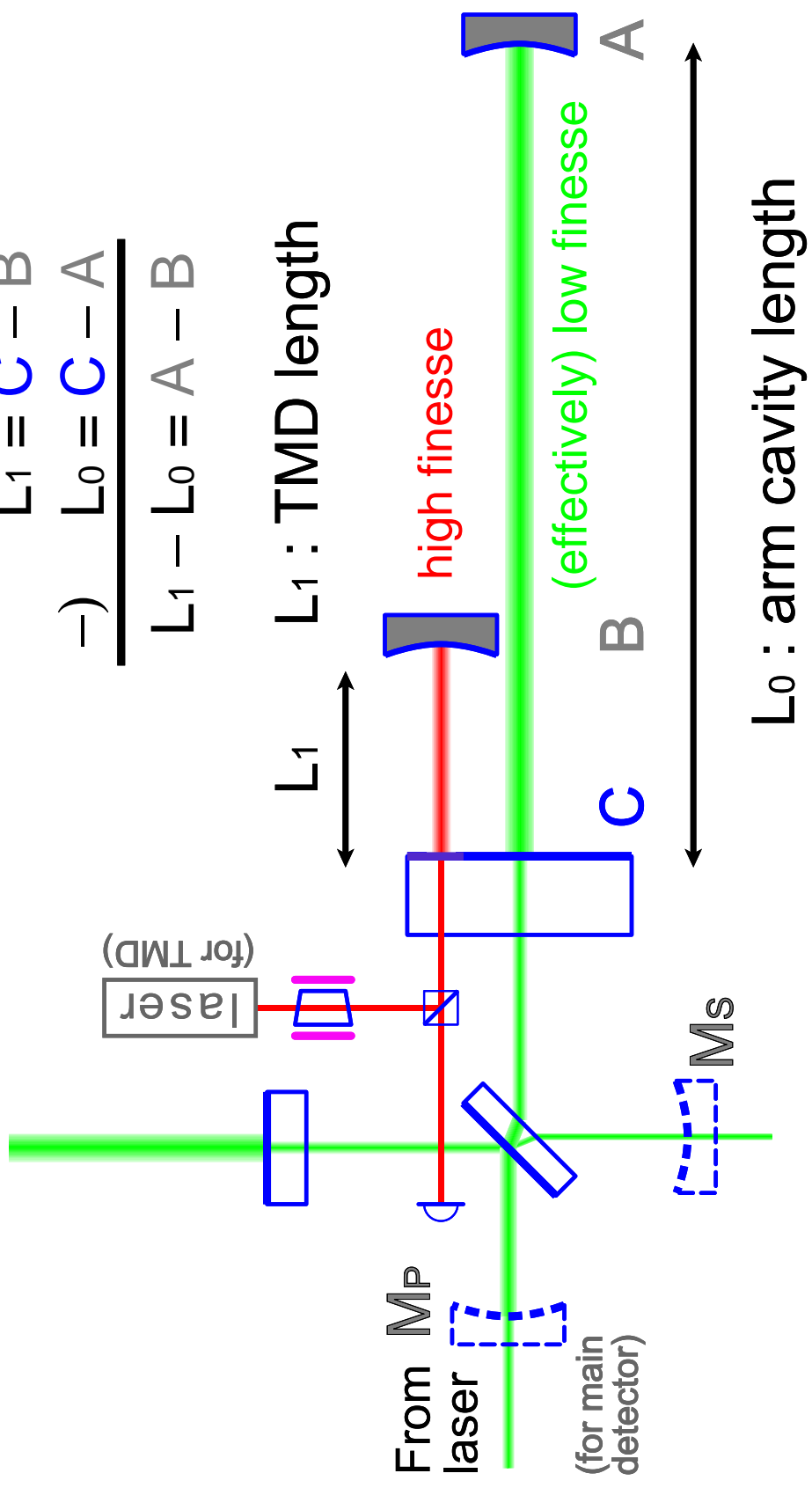
1. a **silicon mirror** can be used as the reference to measure the thermal motion of a SiO_2 mirror.
2. a **high-finesse cavity** can be used as a sensor that has a better *displacement* sensitivity than the main (GW) detector.

⇒ **thermal motion detector**

$$L_1 = C - B$$

$$\text{---) } L_0 = C - A$$

$$L_1 - L_0 = A - B$$



Concept of thermal motion detector

Sensitivity of optical measurement

Shot-noise limited displacement
sensitivity of a cavity :

$$\tilde{x}_{\text{sn}} = \frac{\pi}{4\mathcal{F}} \sqrt{\frac{\hbar c}{\pi} \frac{\lambda}{\eta P_0}} = \frac{\pi}{4\mathcal{F}} \tilde{x}_{\text{sn}0}$$

$$\begin{aligned} \tilde{x}_{\text{sn}0} &= \sqrt{\frac{\hbar c}{\pi} \frac{\lambda}{\eta P_0}} = \frac{\lambda}{2\pi} \sqrt{\frac{2\hbar(2\pi c/\lambda)}{\eta P_0}} \\ &\approx 0.01 \frac{\text{fm}}{\sqrt{\text{Hz}}} \times \left[\frac{\lambda}{1 \mu\text{m}} \right]^{\frac{1}{2}} \left[\frac{\eta P_0}{100 \text{ W}} \right]^{-\frac{1}{2}} \end{aligned}$$

\mathcal{F} : finesse of the cavity

$$\text{GW sensitivity : } \tilde{h}_{\text{sn}} = \frac{1}{L} \tilde{x}_{\text{sn}}$$

The main GW detector :

- long cavity ($L_0 \approx b \times 3 \text{ km}$)
to increase the GW effect
- relatively low finesse
to retain a meaningful bandwidth
- power recycling
to increase the light power

Thermal motion detector :

- short cavity ($L_1 \approx 3 \text{ m}$)
- very high finesse
to achieve high displacement sensitivity

An example

	GWD	TMD
cavity length L	~ 3 km	~ 3 m
light power P	$\sim 100 P_0$	P_0
finesse \mathcal{F}	~ 200	~ 20000
$\tilde{x}_{\text{sn}}/\tilde{x}_{\text{sn}0}$	$\sim 1/2000$	$\sim 1/20000$
bandwidth Δf	125 Hz	1.25 kHz
$\tilde{h}_{\text{sn}}/\tilde{x}_{\text{sn}0}$	1.7×10^{-7}	1.7×10^{-5}

Assumptions :

- minimum loss per reflection ≈ 25 ppm
- both detectors are illuminated by the light power P_0 from the source.
- GWD optimized with power recycling

Implementation of thermal motion detector

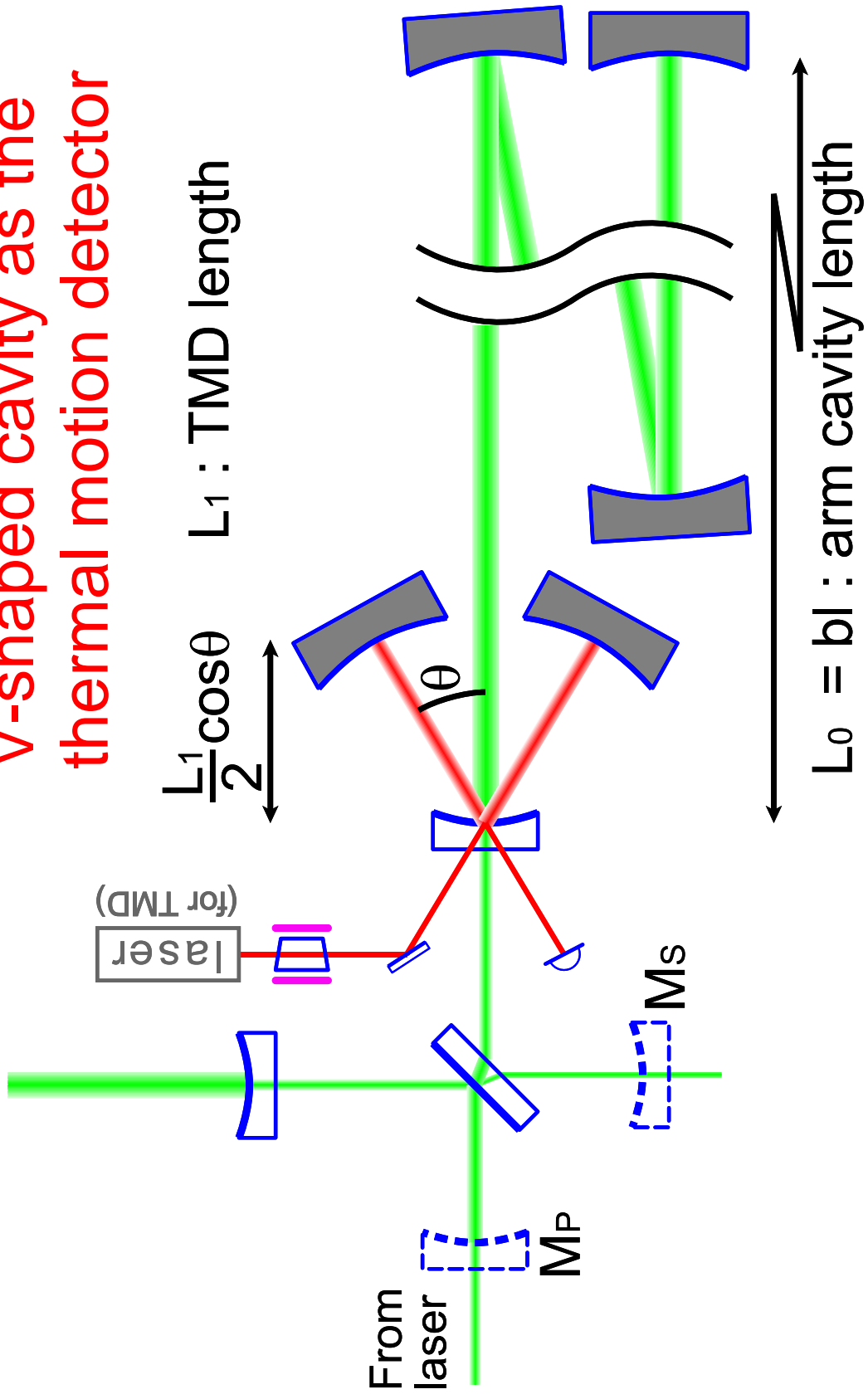
Measuring the same point

⇒ angular separation of two beams

V-shaped cavity : 1 coupling mirror
+ 2 reflectors

- Optical response :
identical to a Fabry-Perot cavity.
- Sensitivity to the coupling mirror motion :
 $2 \cos \theta$ times better than a simple Fabry-Perot cavity.
- Reference noise level :
reference is the average of 2 mirrors
($1/\sqrt{2}$ of single mirror)
- Coupling mirror reflectivity :
lower than a simple Fabry-Perot cavity.

V-shaped cavity as the thermal motion detector



Coupling mirror reflectivity

Problem : How to realize

- low finesse for the main (GW) detector, and
- high finesse for the TMD.

Solution :

- use of different wavelengths and dichroic coating
- angular-dependent reflectivity
- high-finesse arm cavity with resonant sideband extraction

Conclusion

- Provided that silicon mirrors are available, hybrid folded cavity exhibits a considerable improvement on the thermal-noise limited sensitivity.
- In addition, it is possible to cancel the thermal noise of the silica coupling mirror by using thermal motion detector.
- These can be fallback options if sapphire mirrors are not available.