

Displacement sensor based on a maser reference

C. Bragard^{1,2}, A.S. Bogomolov¹, A. Altman¹, A. Goodwin-Jones¹ and C. Lauzin¹

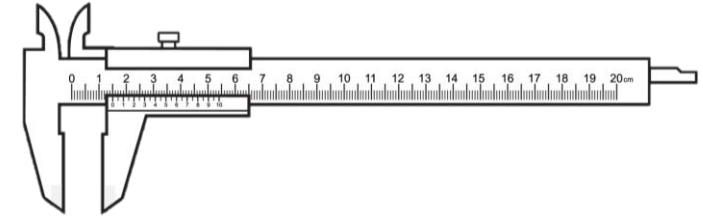
¹Université Catholique de Louvain, Louvain-La-Neuve, 1348, Belgium

²Université de Namur, Namur, 5000, Belgium

Belgian-Dutch Gravitational Wave meeting 2026

Interest of displacement sensing

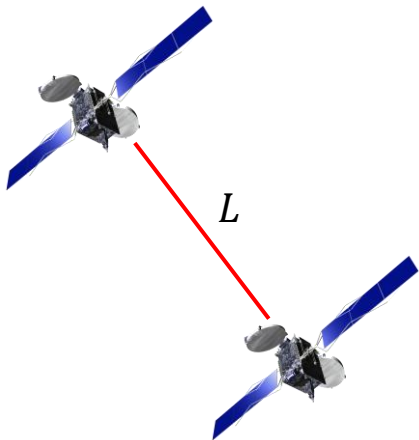
Displacement sensors measure a distance variation ΔL



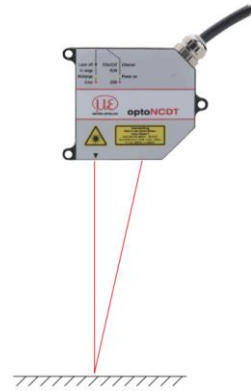
Interest of displacement sensing

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Satellites

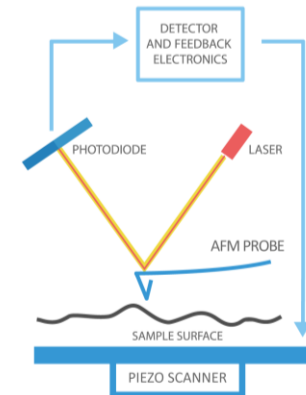


Industry



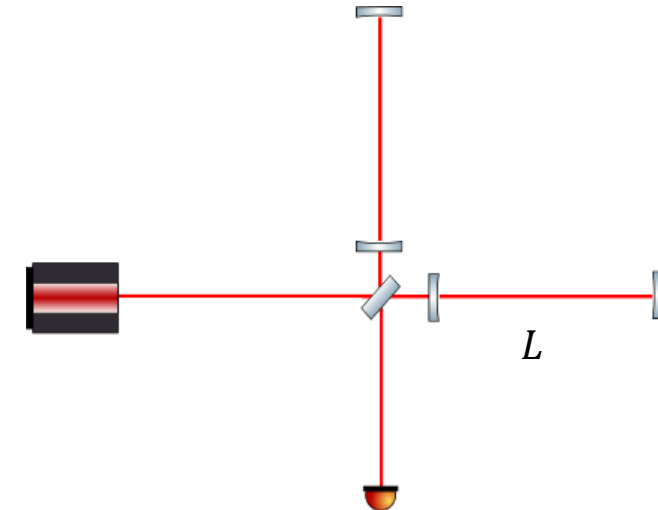
Micro-Epsilon, *optoNCDT – Laser displacement sensors*, product catalog, accessed 2026.

Precision microscopy



<https://www.nanoandmore.com/what-is-atomic-force-microscopy>

Fundamental physics

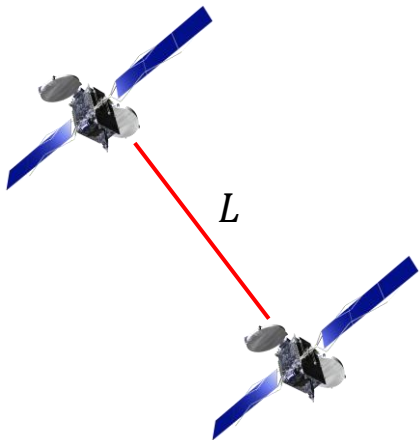


$$\Delta L = c \Delta \tau$$

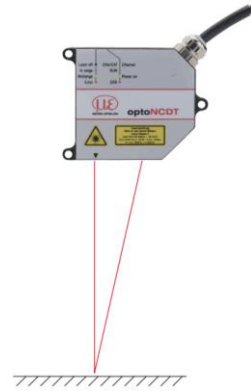
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Satellites

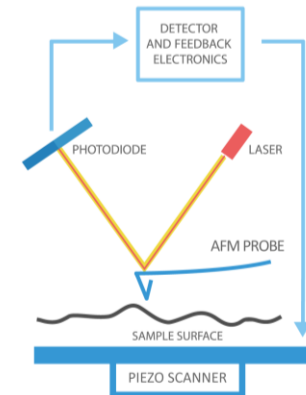


Industry



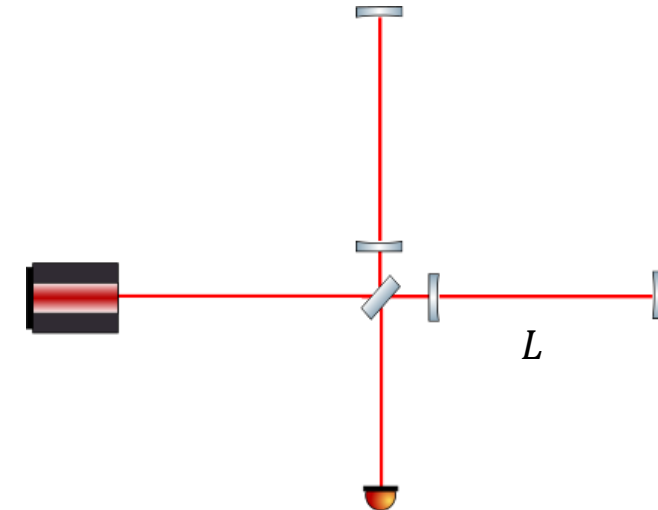
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Precision microscopy



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Fundamental physics



$$\Delta L = \boxed{c} \Delta \tau$$

constant

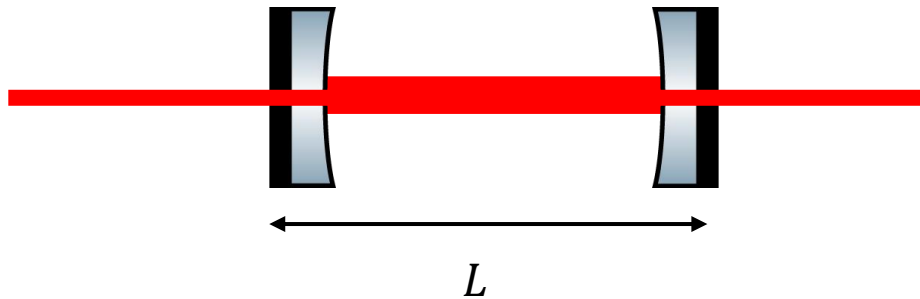


Time
1 ns
=
Length
30 cm

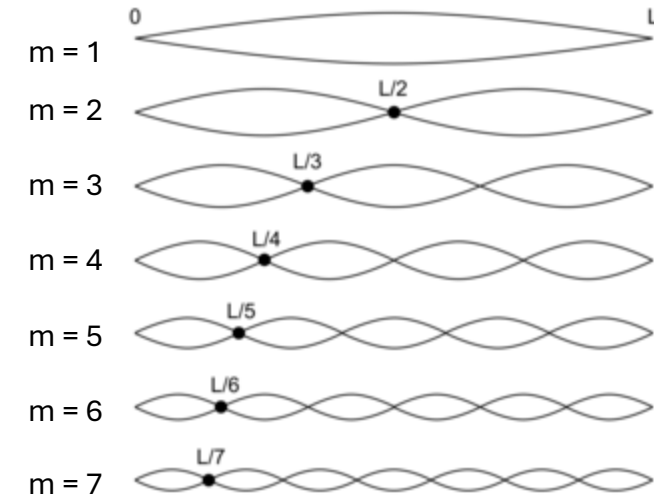
$$\frac{\Delta \tau}{\tau} = \frac{\Delta \nu}{\nu}$$

Interferometry to probe distance variation

Fabry-Perot interferometer

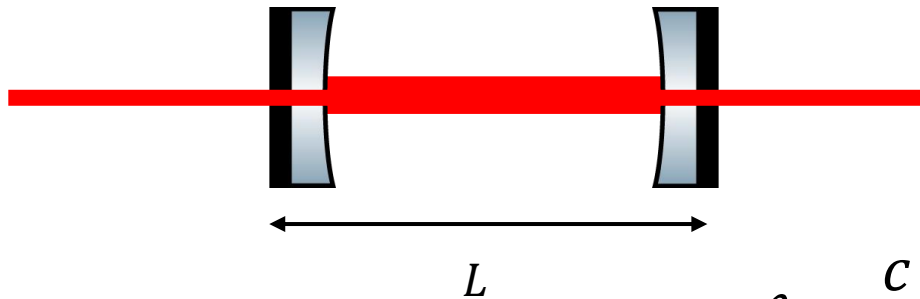


$$L = \frac{m\lambda}{2}, \quad m \in \mathbb{Z}$$



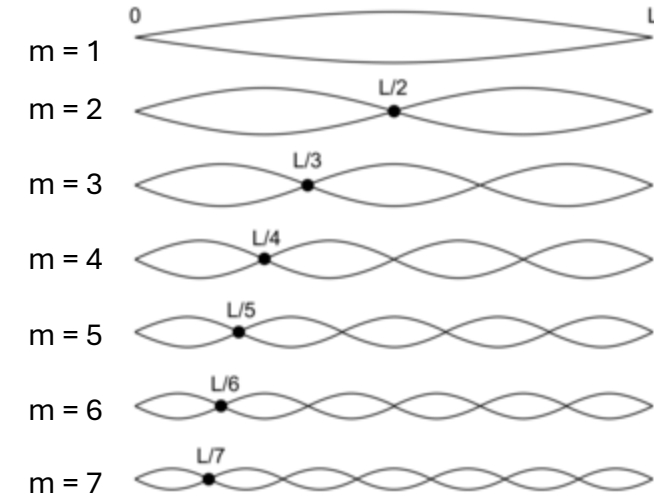
Interferometry to probe distance variation

Fabry-Perot interferometer



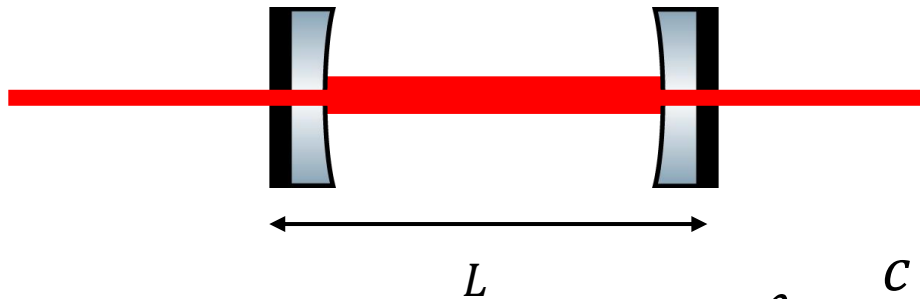
$$\lambda = \frac{c}{\nu}$$

$$L = \frac{m\lambda}{2}, \quad m \in \mathbb{Z}$$
$$\Rightarrow \nu_m = m \frac{c}{2L}$$



Interferometry to probe distance variation

Fabry-Perot interferometer



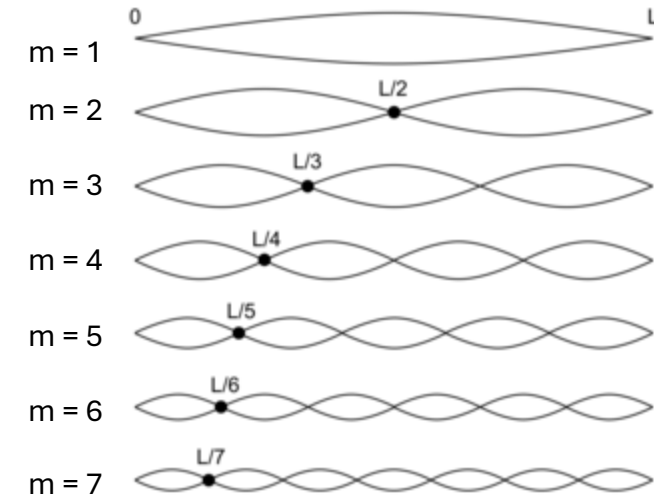
$$L = \frac{m\lambda}{2}, \quad m \in \mathbb{Z}$$

$$\lambda = \frac{c}{\nu} \Rightarrow \nu_m = m \frac{c}{2L}$$

$$\Rightarrow \Delta \nu_m = -m \frac{c}{2L^2} \Delta L$$

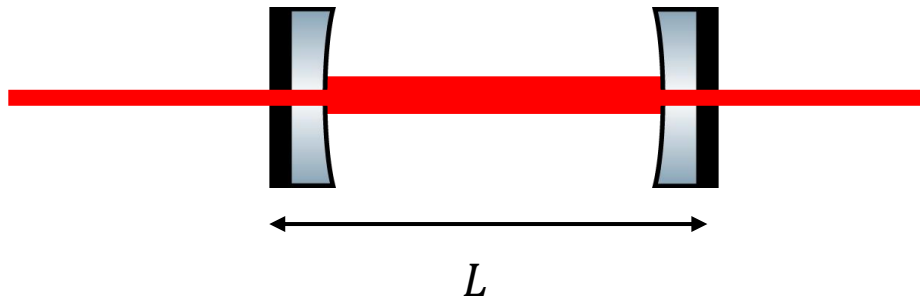
Therefore :

$$\frac{\Delta \tau}{\tau} = \frac{\Delta \nu}{\nu} \propto \frac{\Delta L}{L}$$



Interferometry to probe distance variation

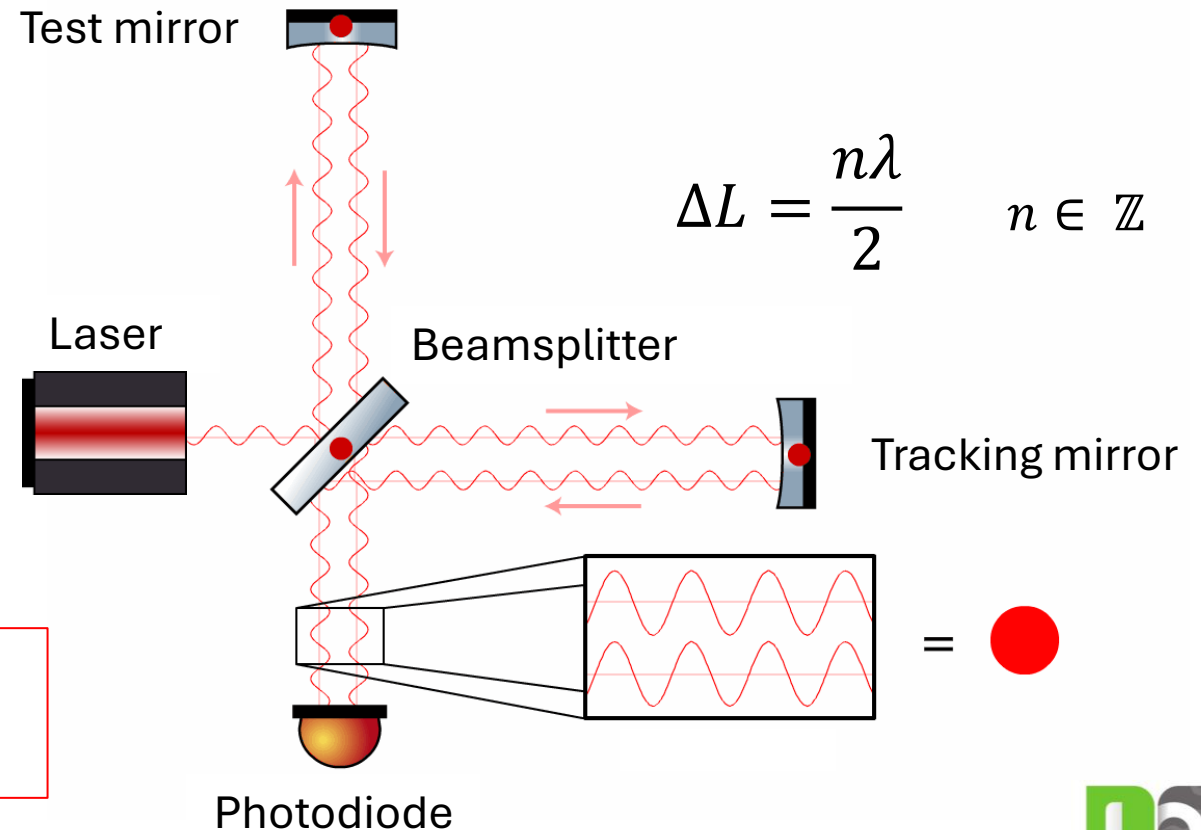
Fabry-Perot interferometer



$$L = \frac{m\lambda}{2}, \quad m \in \mathbb{Z}$$

$$\frac{\Delta\nu}{\nu} \propto \frac{\Delta L}{L}$$

Michelson interferometer



State-of-the-art interferometric displacement sensor

574

M. B. GRAY *ET AL.*

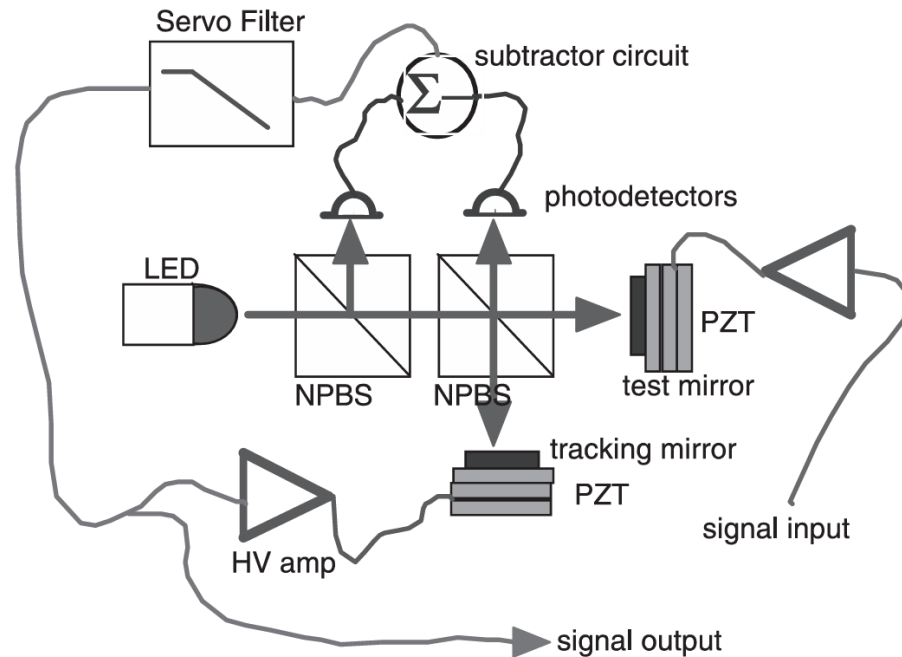
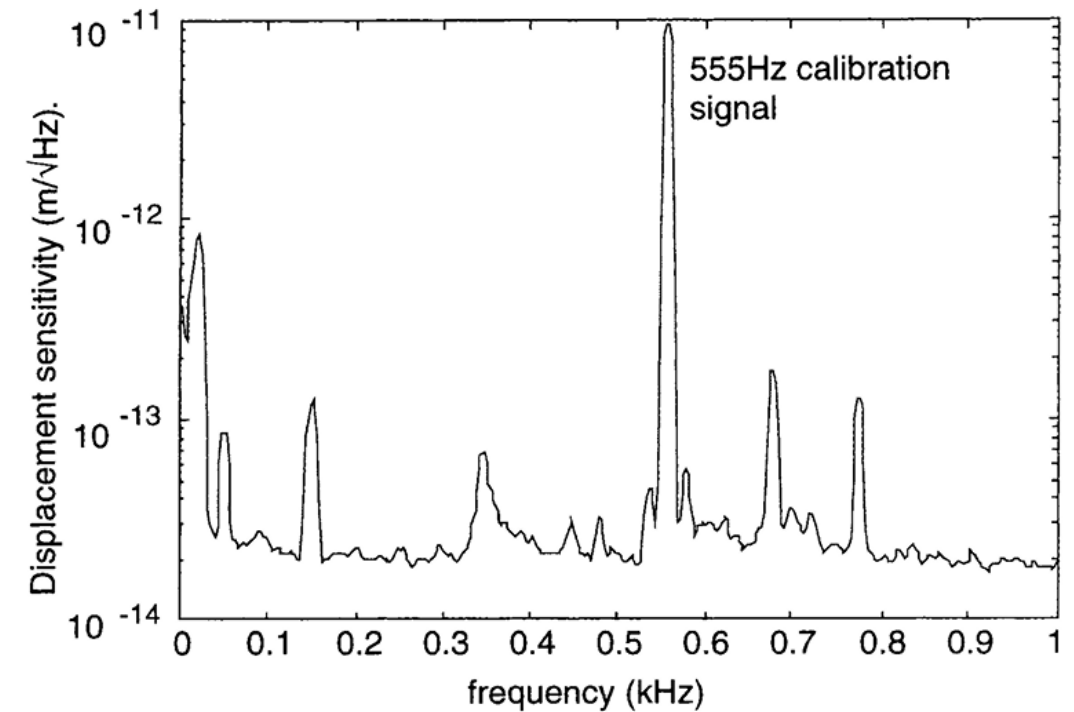
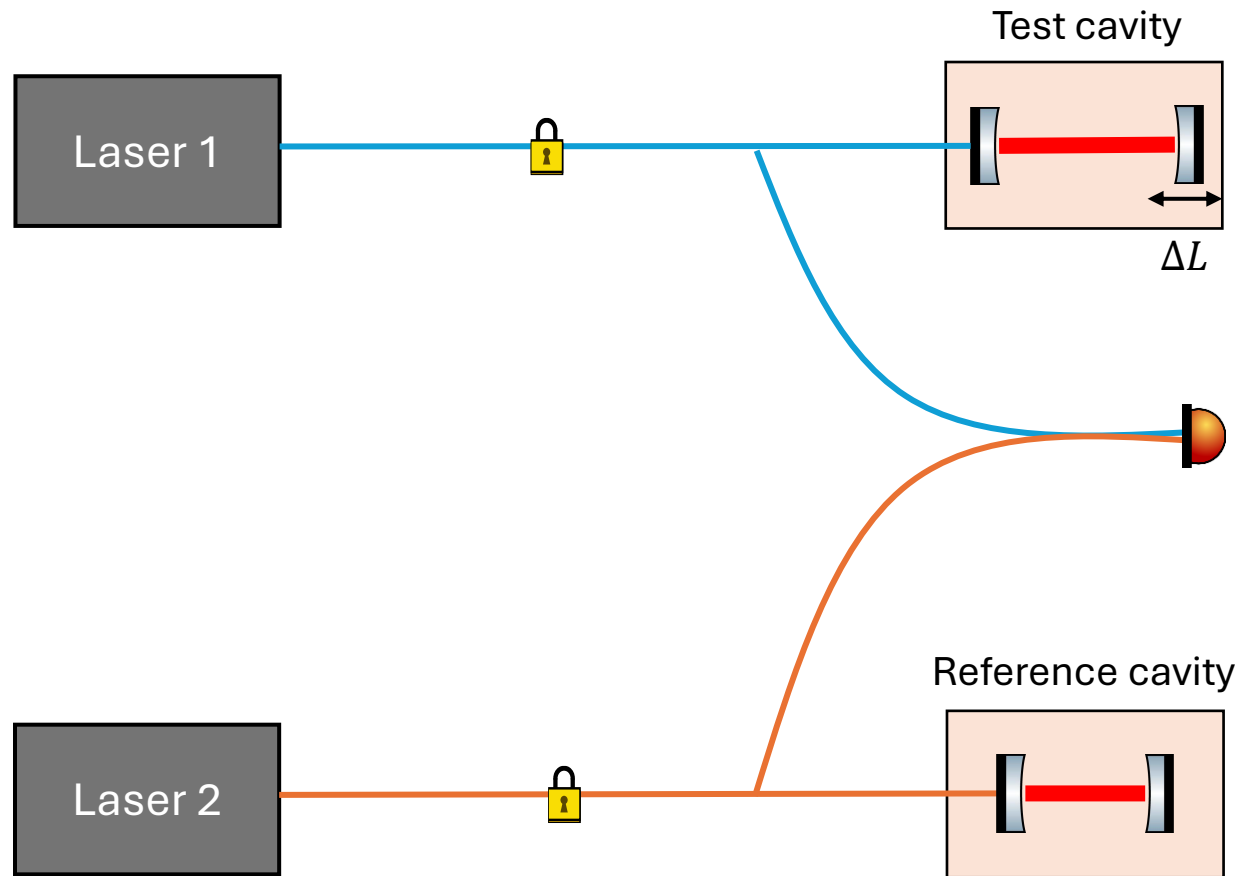


Fig. 1. Schematic representation of the interferometric sensor.

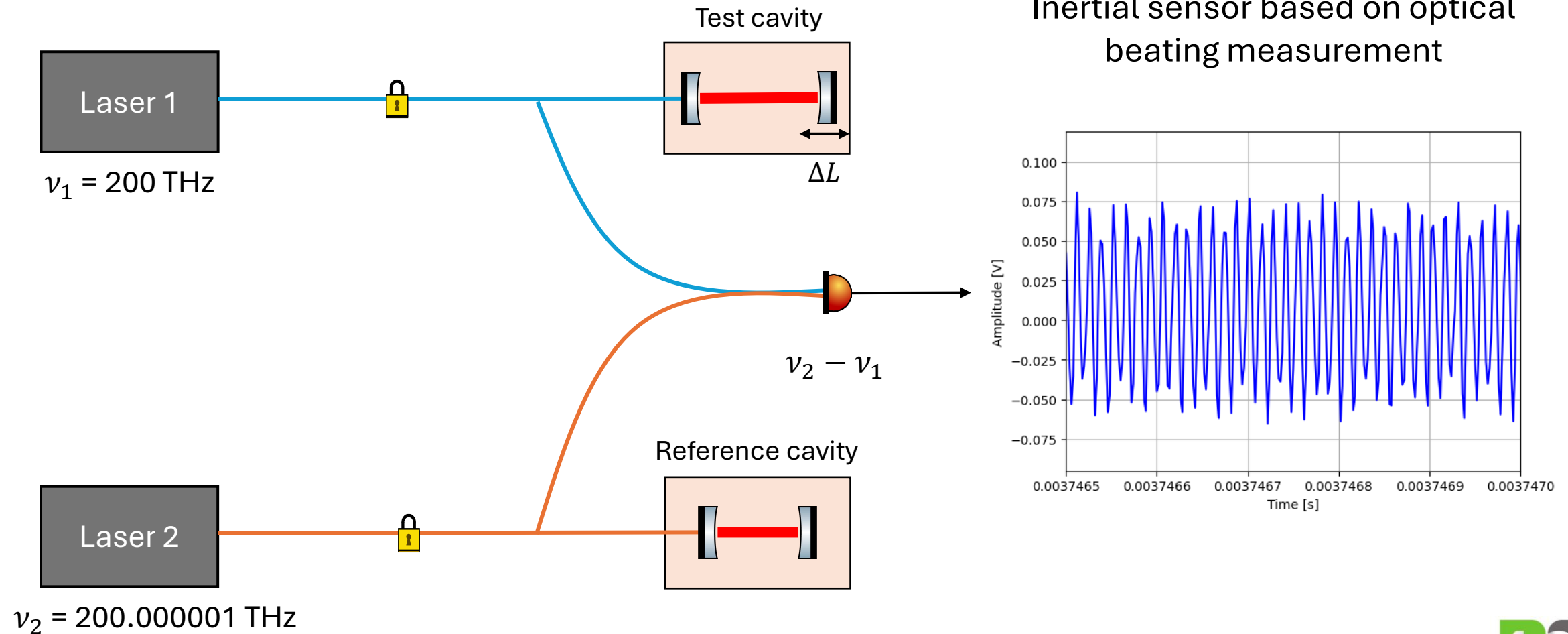
$\Rightarrow 20 \text{ fm}/\sqrt{\text{Hz}}$ sensitivity



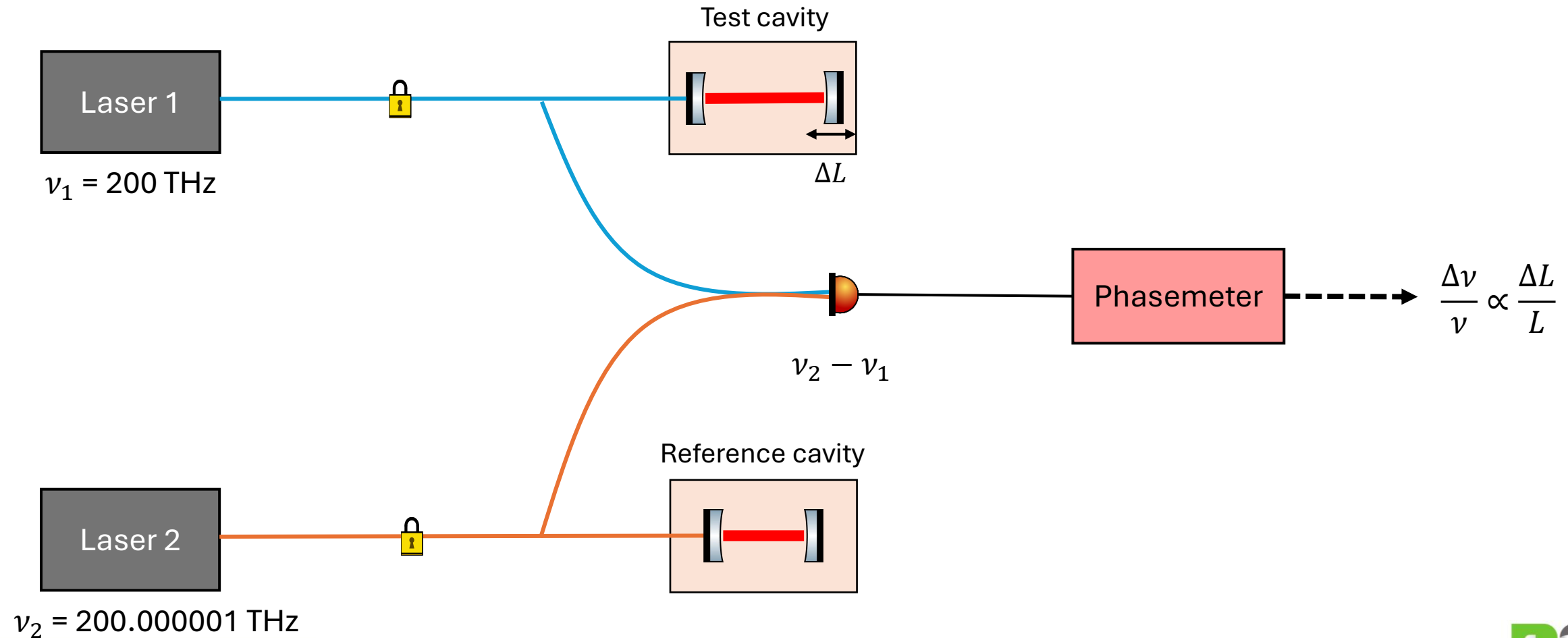
Sensor recently developed by the community : Heterodyne cavity tracking



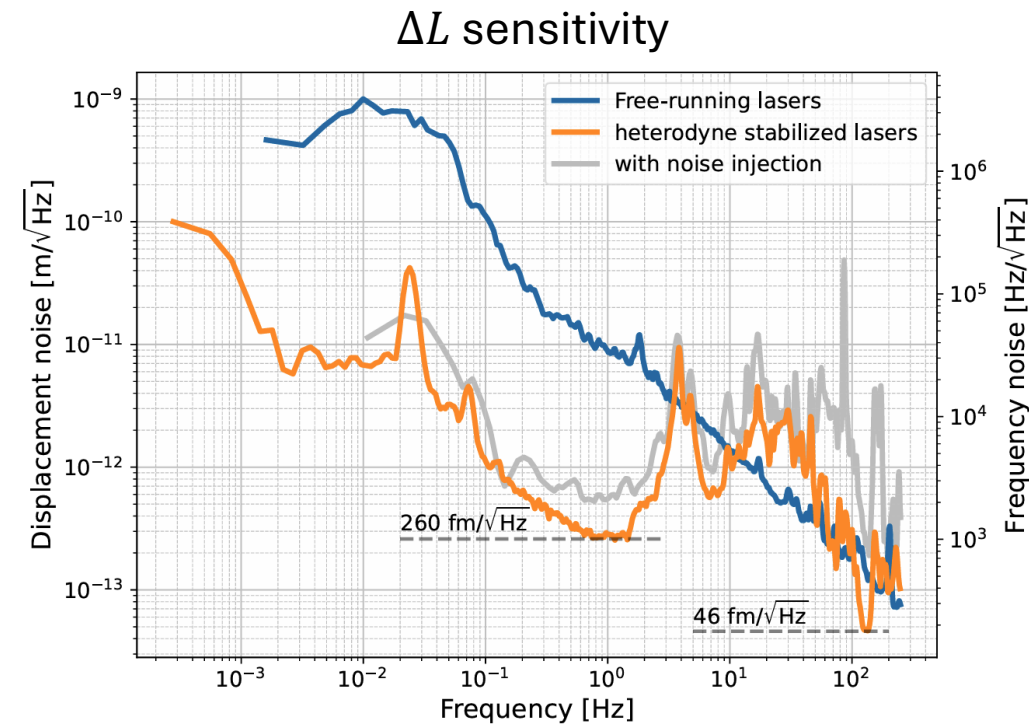
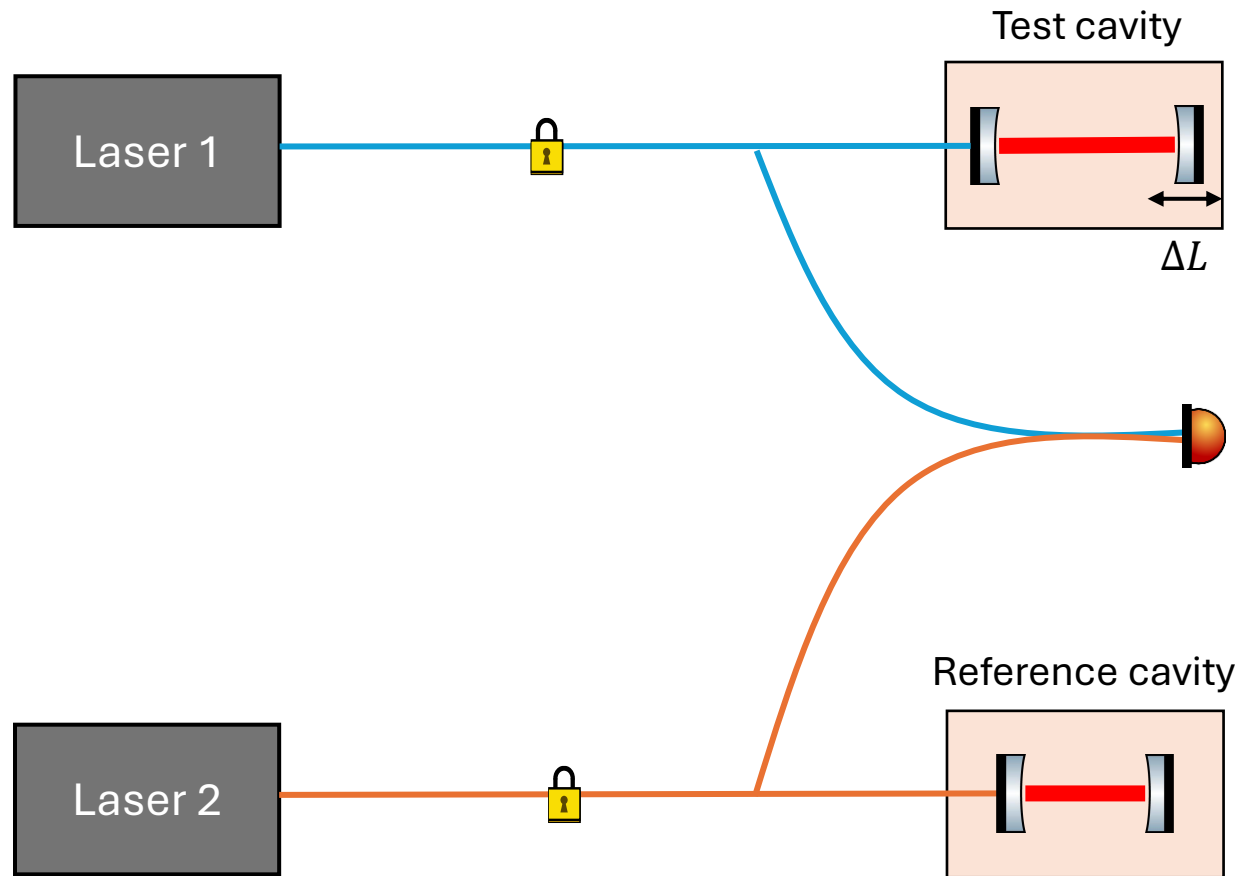
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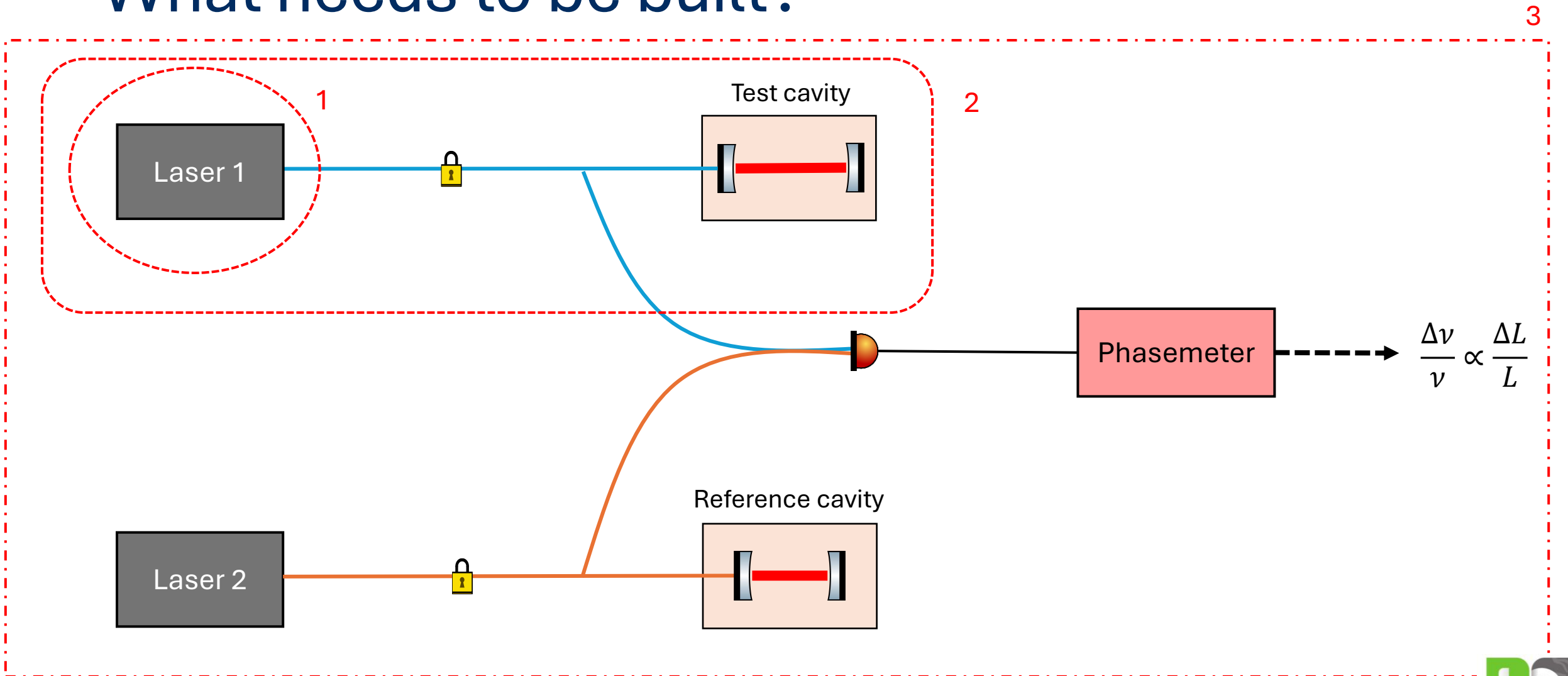


Sensor recently developed by the community : Heterodyne cavity tracking



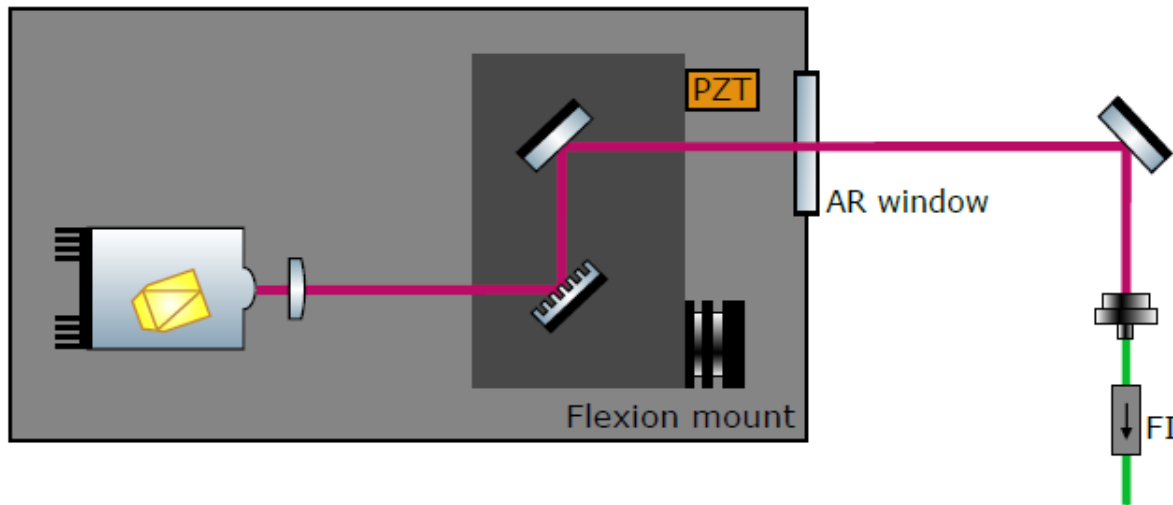
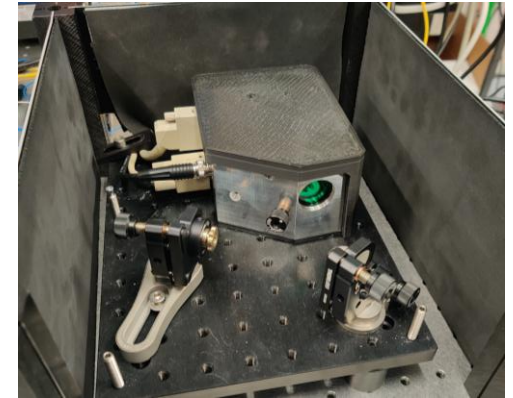
$\Rightarrow 5 \cdot 10^{-12}$ sensitivity at 1 Hz
 $\Rightarrow 9 \cdot 10^{-13}$ sensitivity at 130 Hz

What needs to be built?



Laser source

Home-built External Cavity Diode Laser (ECDL)

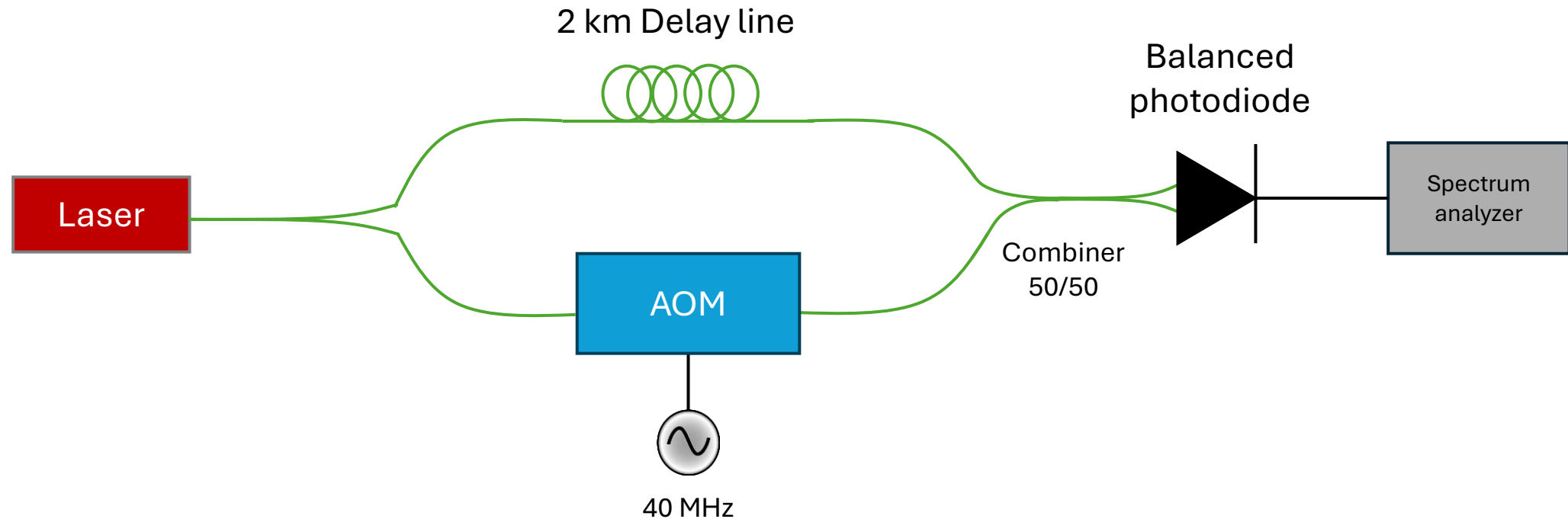


- Tunable
- Narrow linewidth ?

Dr A.S. Bogomolov's design

Laser source characterisation

Short Delay Self-Heterodyne interferometry



Laser source characterisation

Short Delay Self-Heterodyne interferometry

$$S(f) = \frac{P_0^2}{4\pi} \frac{\Delta f}{\Delta f^2 + (f - f_1)^2} \left(1 - \exp(-2\pi\tau\Delta f) \left[\cos(2\pi\tau(f - f_1)) + \Delta f \frac{\sin(2\pi\tau(f - f_1))}{f - f_1} \right] \right) + \frac{\pi P_0^2}{2} \exp(-2\pi\tau\Delta f) \delta(f - f_1)$$

Laser source characterisation

Short Delay Self-Heterodyne interferometry

$$S(f) = \boxed{\frac{P_0^2}{4\pi} \frac{\Delta f}{\Delta f^2 + (f - f_1)^2}} \left(1 - \exp(-2\pi\tau\Delta f) \left[\cos(2\pi\tau(f - f_1)) + \Delta f \frac{\sin(2\pi\tau(f - f_1))}{f - f_1} \right] \right) + \frac{\pi P_0^2}{2} \exp(-2\pi\tau\Delta f) \delta(f - f_1)$$

Lorentzian

Laser source characterisation

Short Delay Self-Heterodyne interferometry

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Lorentzian

Interference between
the two arms

Laser source characterisation

Short Delay Self-Heterodyne interferometry

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Lorentzian

Interference between
the two arms

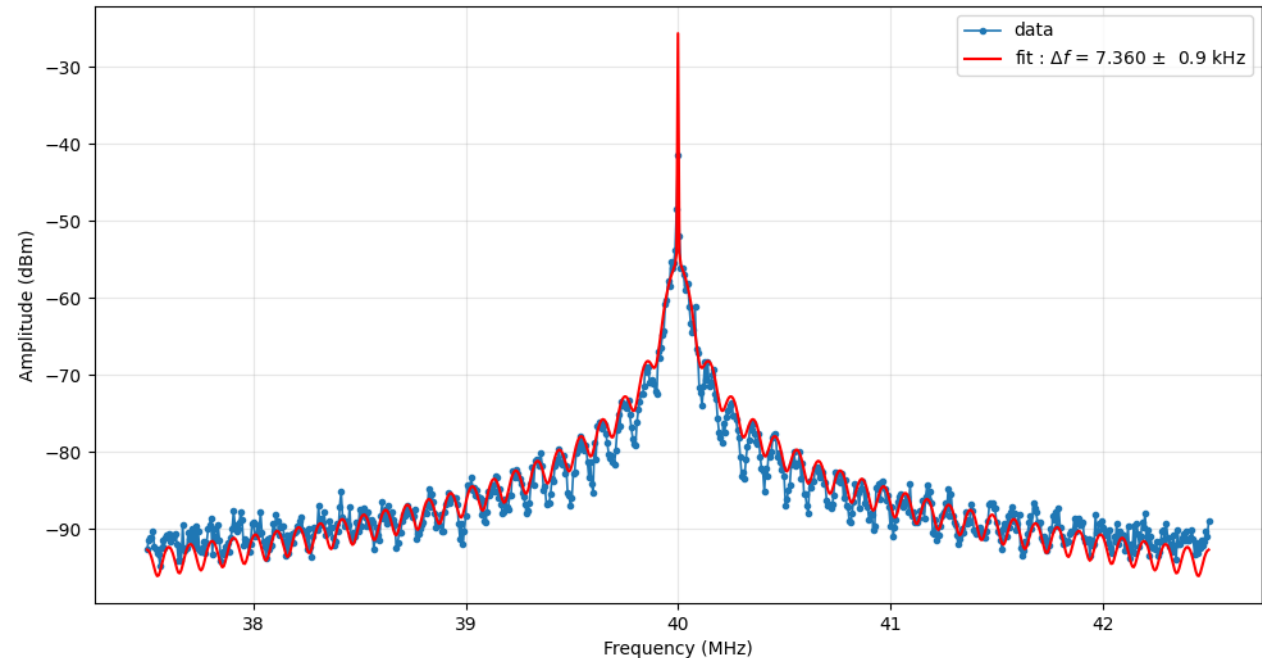
AOM carrier frequency

Laser source characterisation

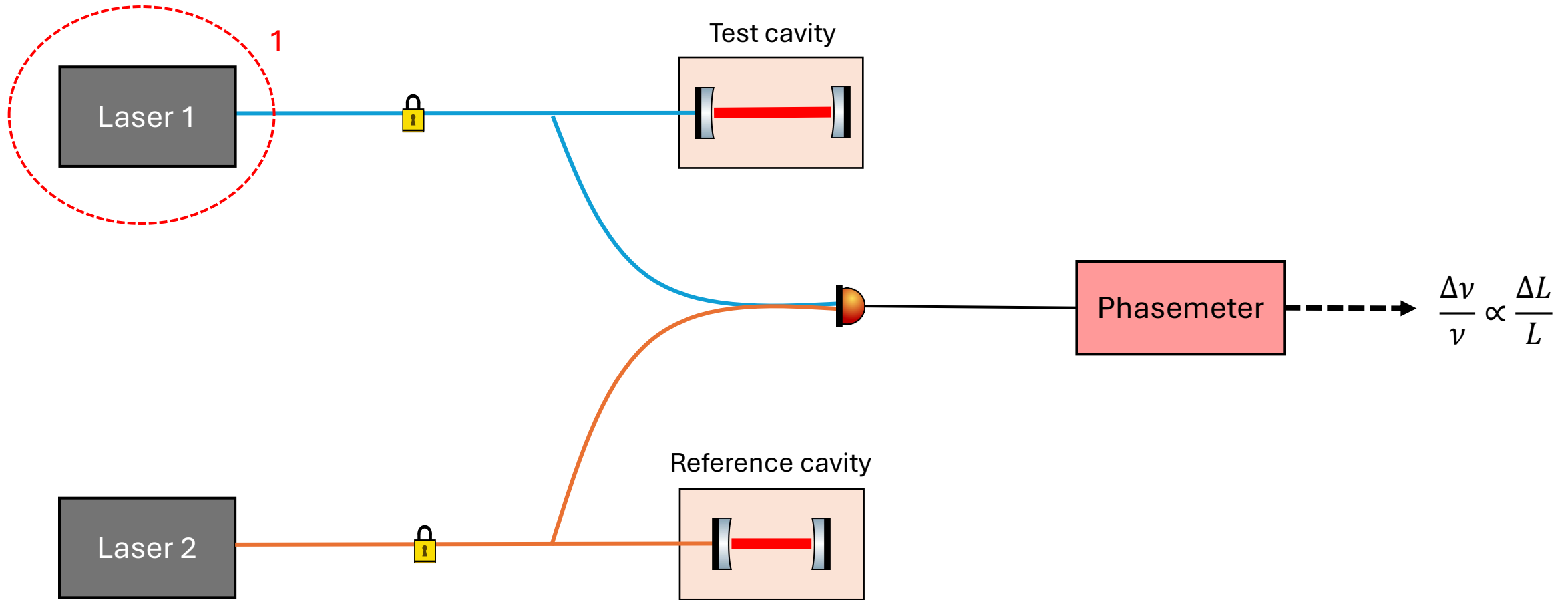
Short Delay Self-Heterodyne interferometry

$$S(f) = \frac{P_0^2}{4\pi} \frac{\Delta f}{\Delta f^2 + (f - f_1)^2} \left(1 - \exp(-2\pi\tau\Delta f) \left[\cos(2\pi\tau(f - f_1)) + \Delta f \frac{\sin(2\pi\tau(f - f_1))}{f - f_1} \right] \right) + \frac{\pi P_0^2}{2} \exp(-2\pi\tau\Delta f) \delta(f - f_1)$$

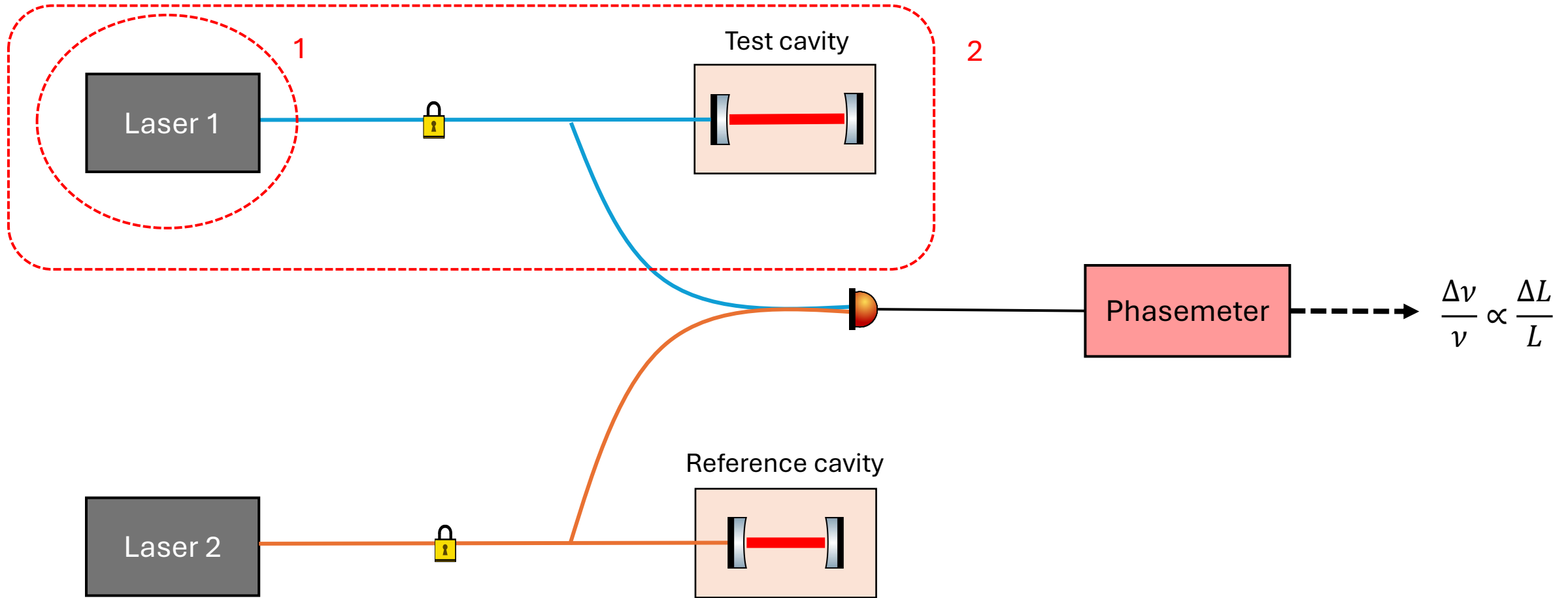
Measured linewidth of
 7.4 ± 0.9 kHz



What needs to be built?

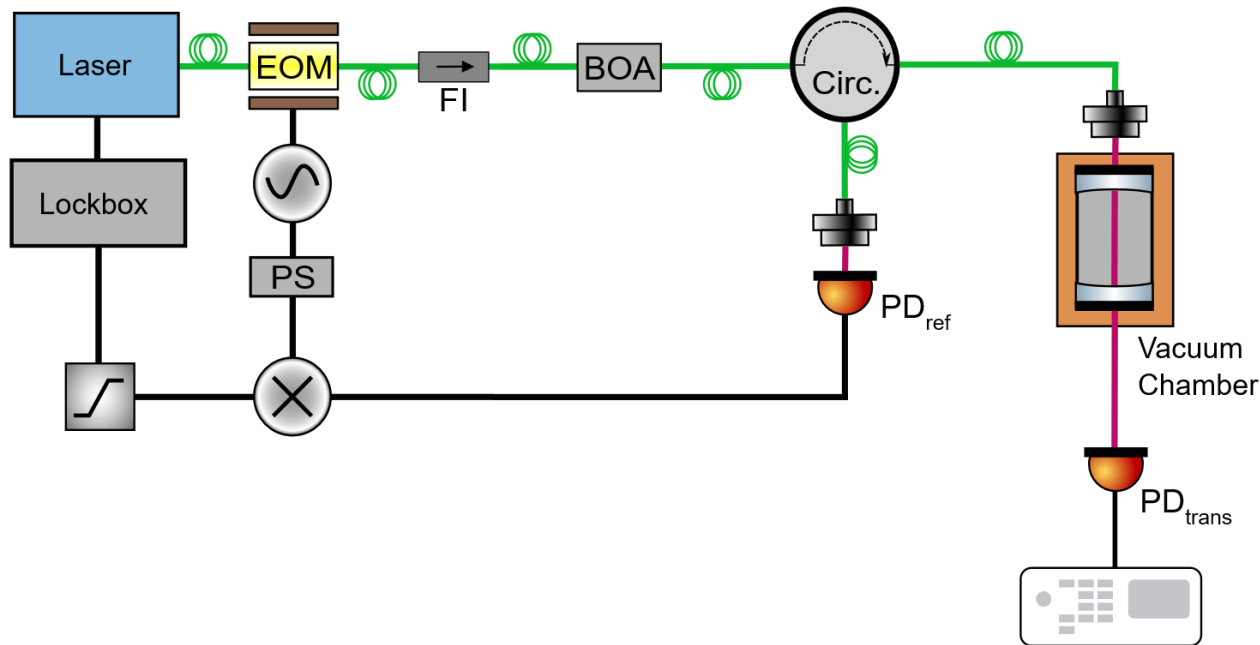


What needs to be built?



Locking to test cavity

 = Pound-Drever-Hall (PDH) lock



Coherence transfer between the cavity and the laser

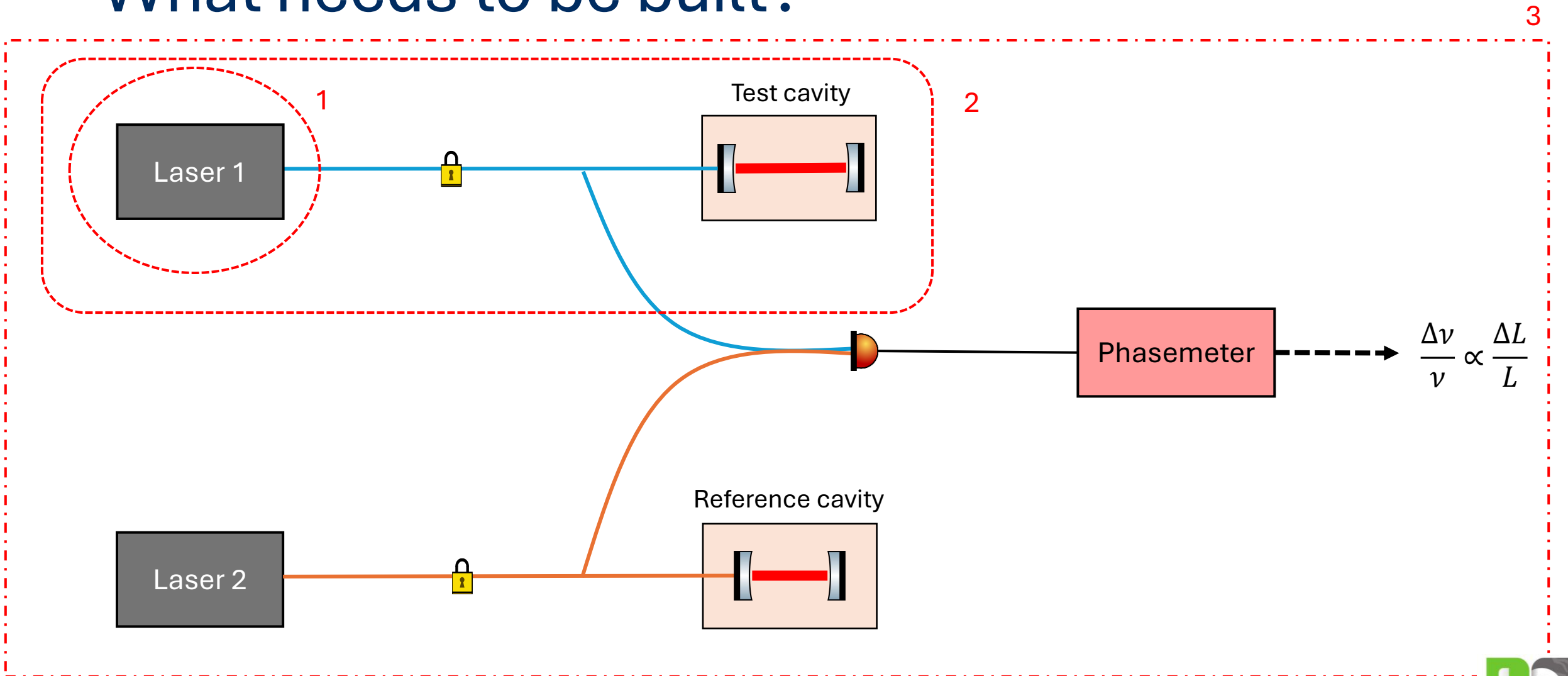
⇒ The laser follows the cavity :

$$\Delta\nu_{laser} = \Delta\nu_{cavity}.$$

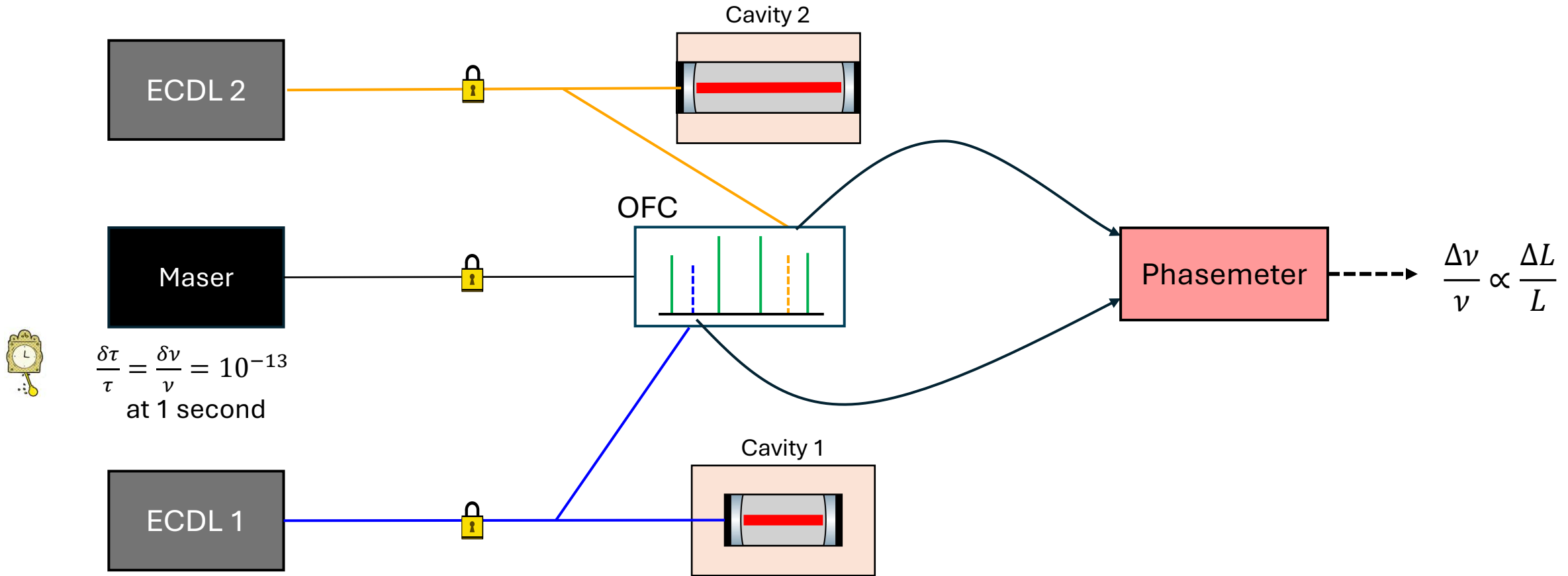
And we know that :

$$\frac{\Delta\nu}{\nu} \propto \frac{\Delta L}{L}$$

What needs to be built?

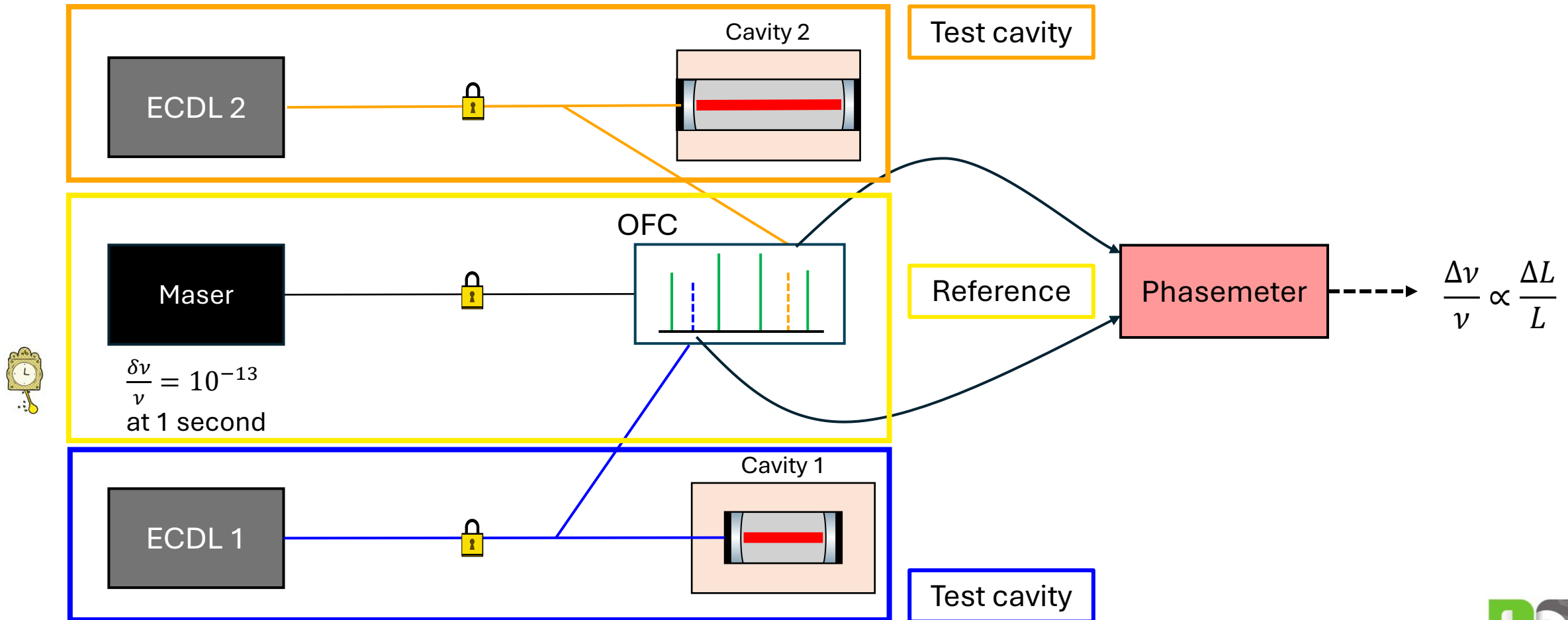


Heterodyne cavity tracking: our approach

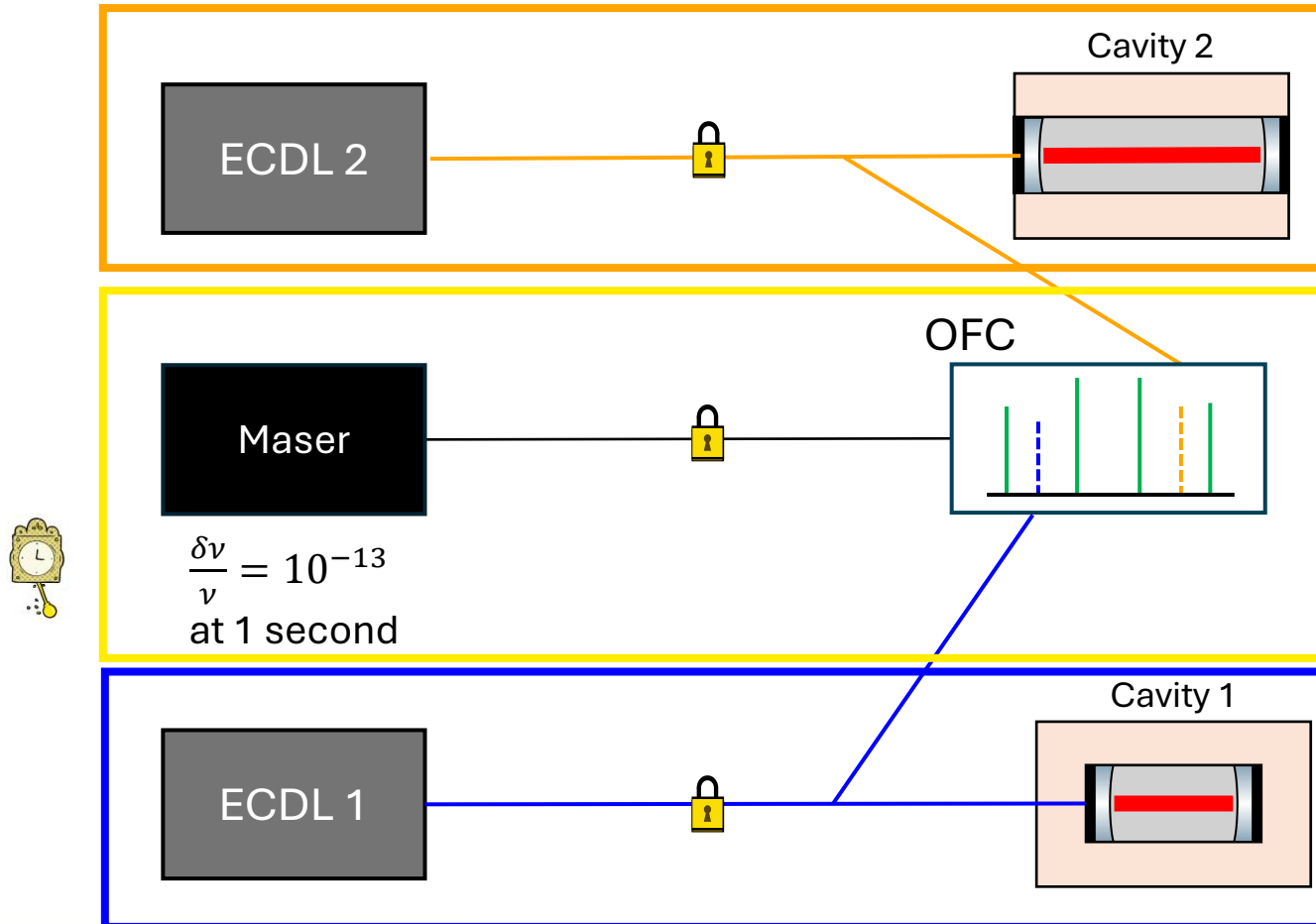


OFC = Optical Frequency Comb: $\nu_n = \nu_0 + n\nu_{rep}$

Heterodyne cavity tracking: our approach



Heterodyne cavity tracking: our approach



Two advantages:

Use of the most sensitive clocks

Reference

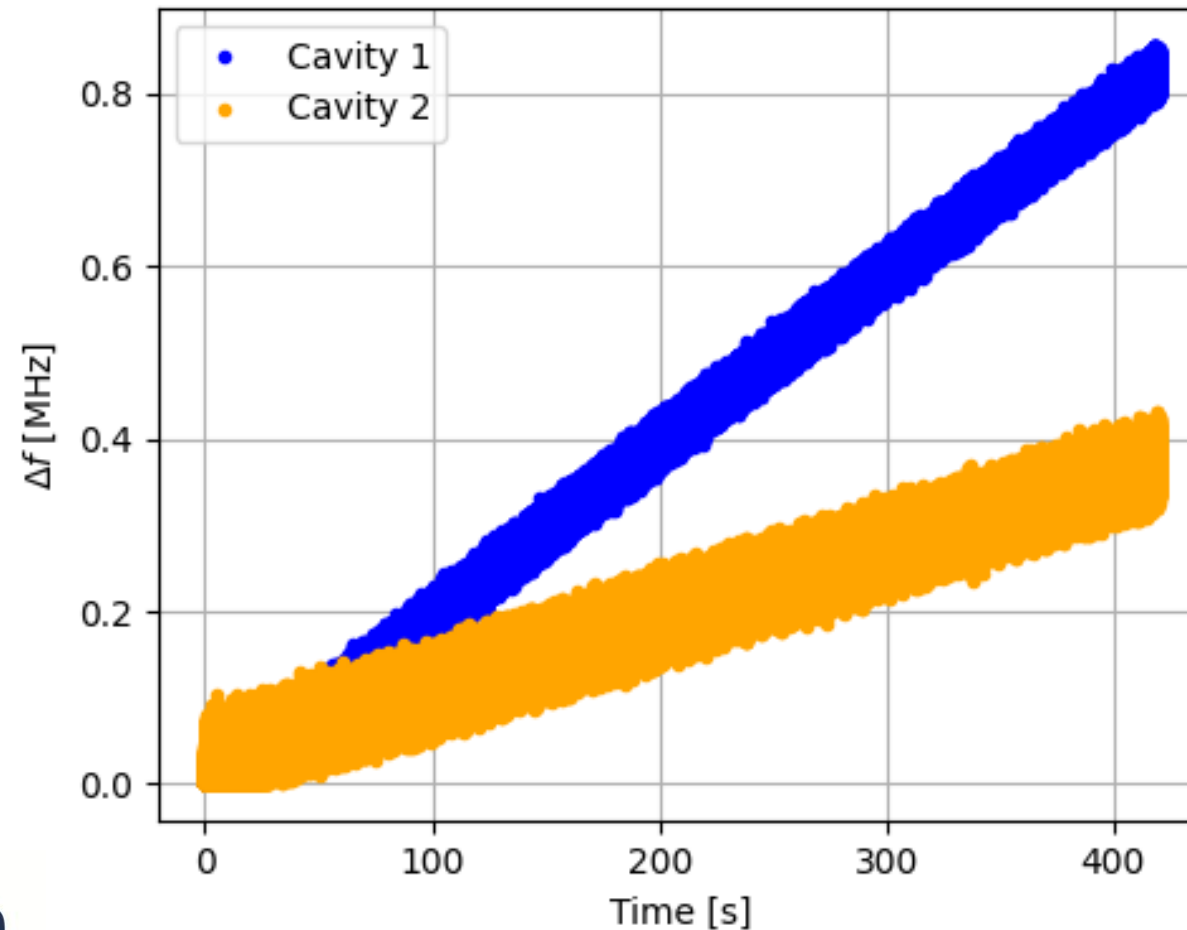
Knowledge of which cavity is moving

Test cavity

Test cavity

Heterodyne cavity tracking: our results

Evolution of the beating frequency variations over time



Cavity 1 ≈ 2 kHz/s

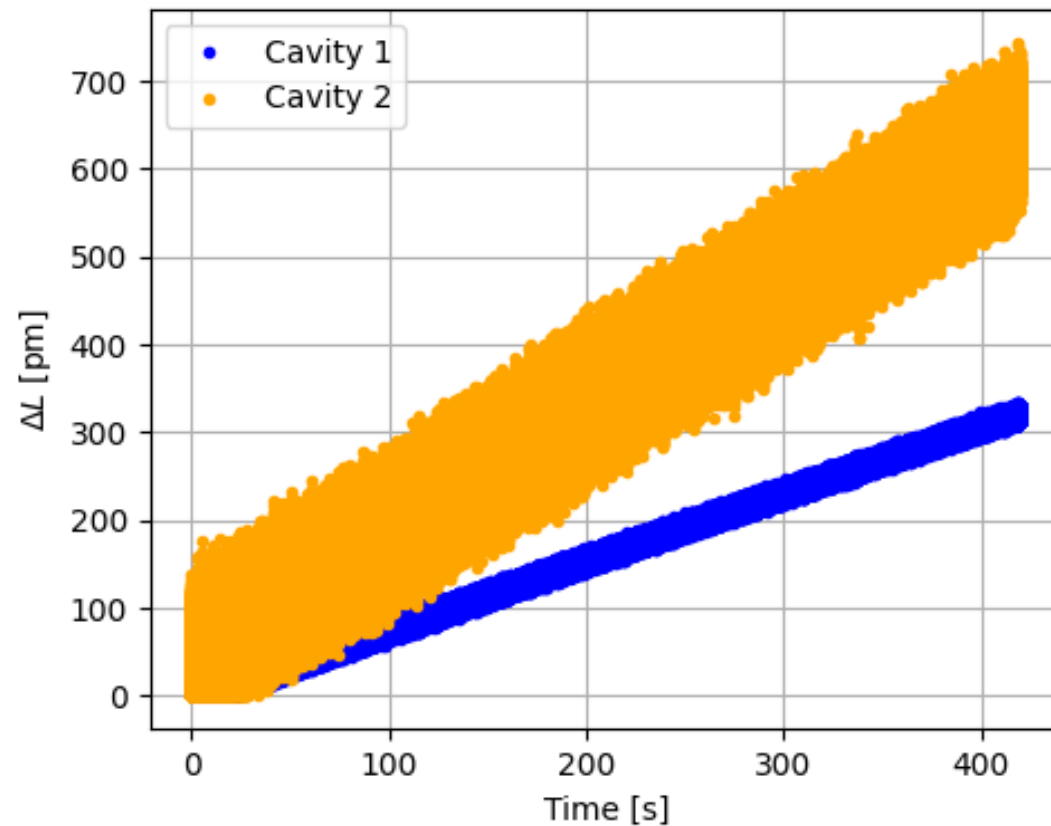
Cavity 2 ≈ 1 kHz/s

$$L_{cavity1} = 7.5 \text{ cm}$$

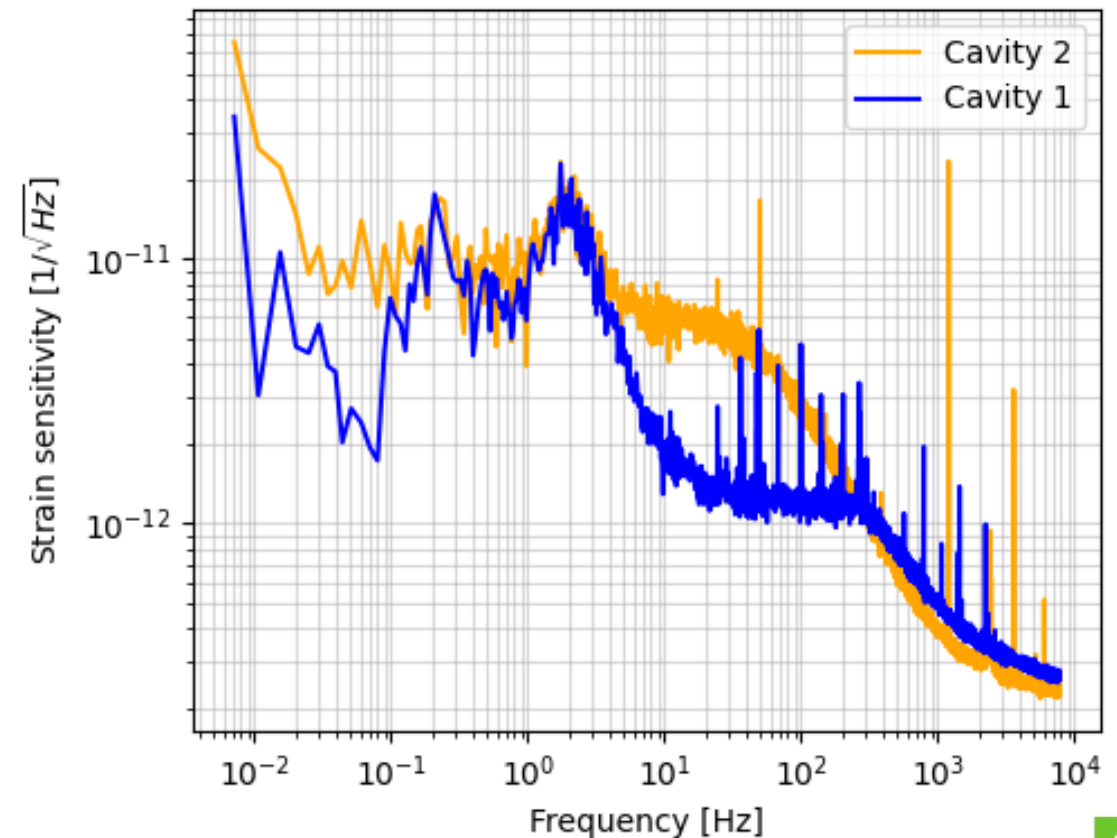
$$L_{cavity2} = 37.1 \text{ cm}$$

Heterodyne cavity tracking: our results

Evolution of the cavity length variations over time

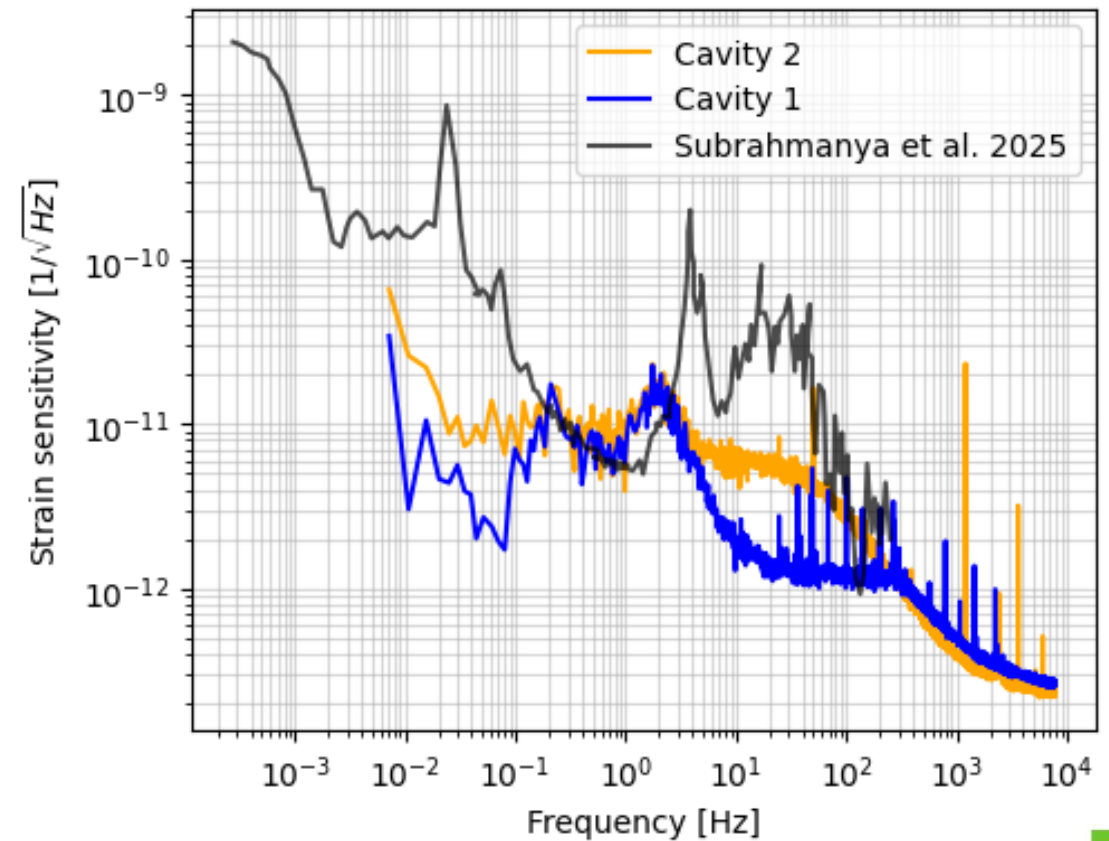


$\Delta L/L$ sensitivity of both cavities



Heterodyne cavity tracking: comparison

$\Delta L/L$ sensitivity comparison



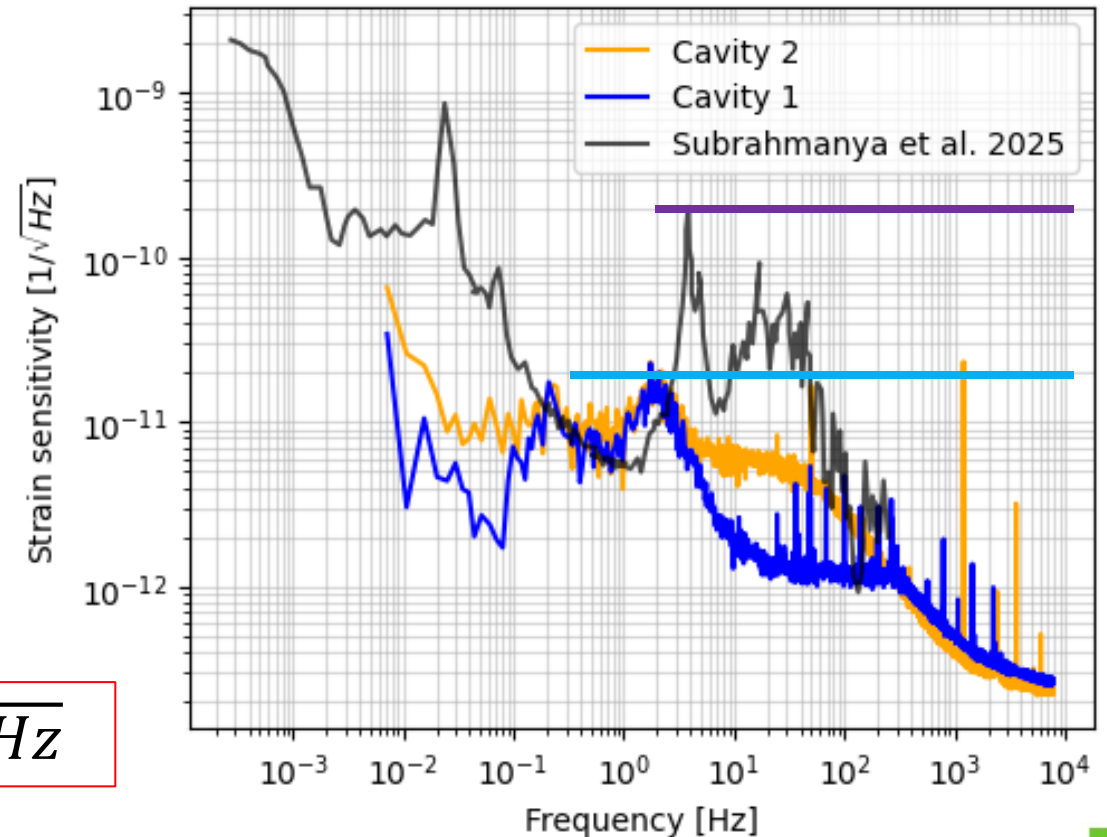
Heterodyne cavity tracking: comparison

Between 200 mHz and 10 kHz, they reach sensitivities **below** $2 \times 10^{-10} / \sqrt{\text{Hz}}$

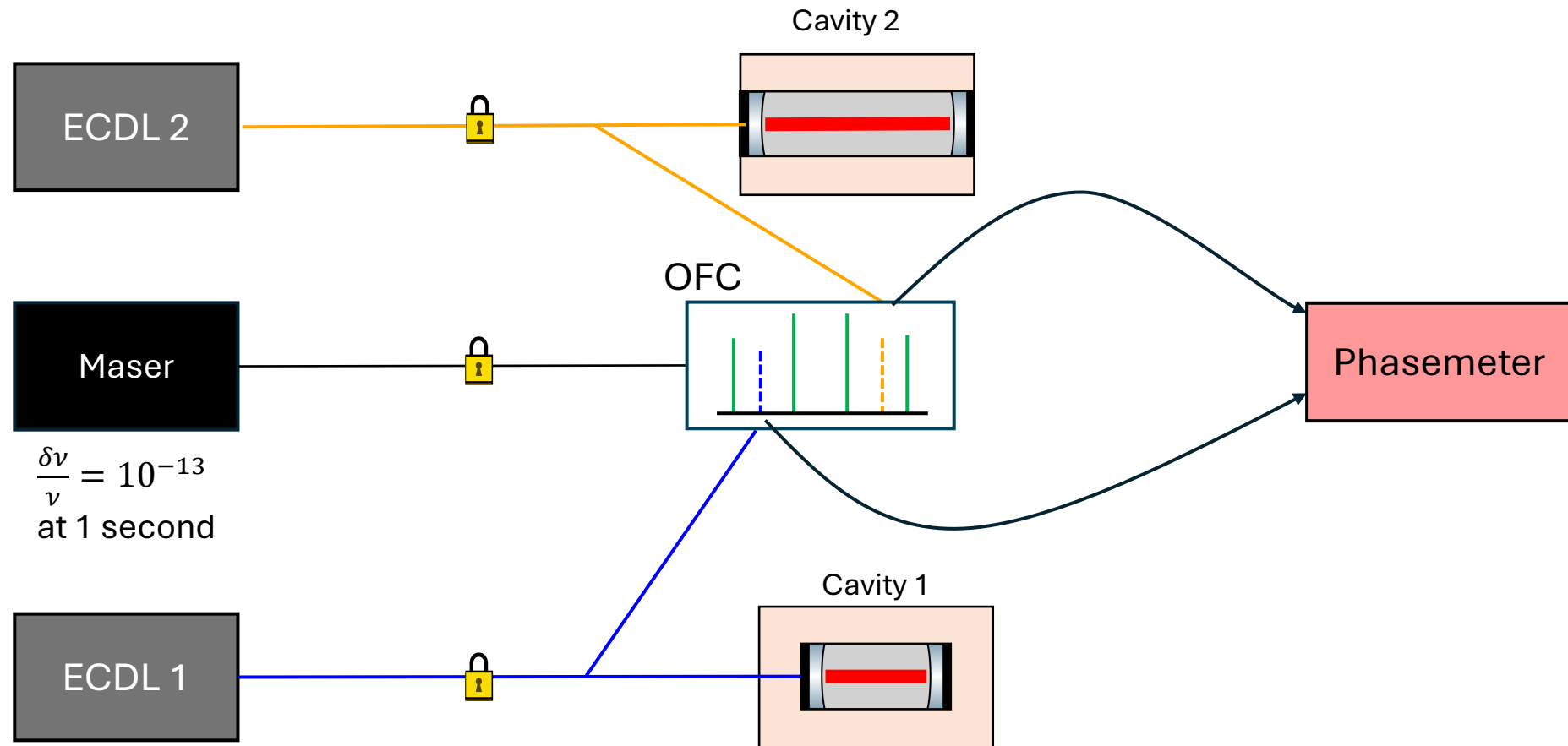
Between 200 mHz and 10 kHz, we reach sensitivities **below** $2 \times 10^{-11} / \sqrt{\text{Hz}}$

$\Rightarrow$ At 100 Hz, we have a sensitivity of $75 \text{ fm}/\sqrt{\text{Hz}}$

$\Delta L/L$ sensitivity comparison

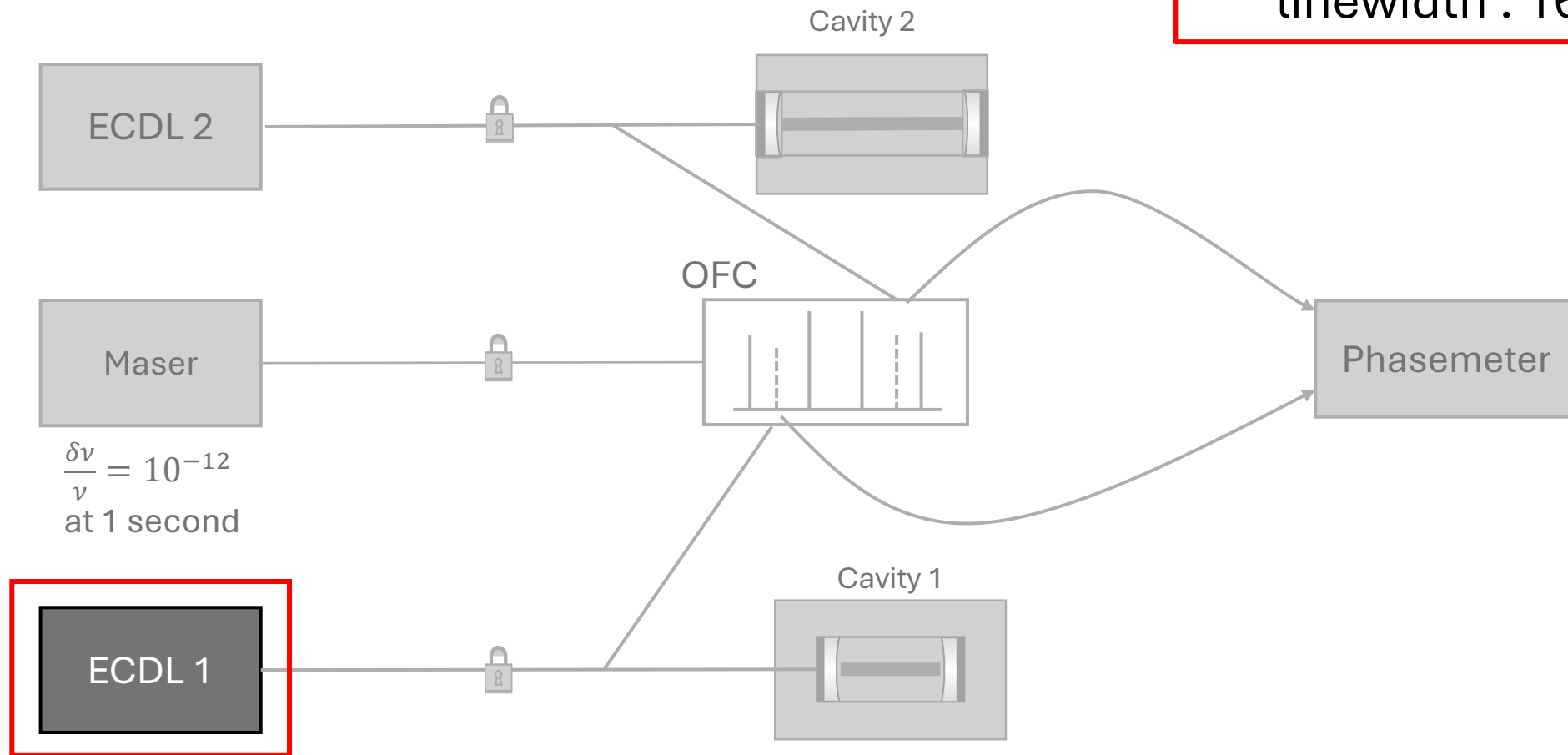


Perspectives

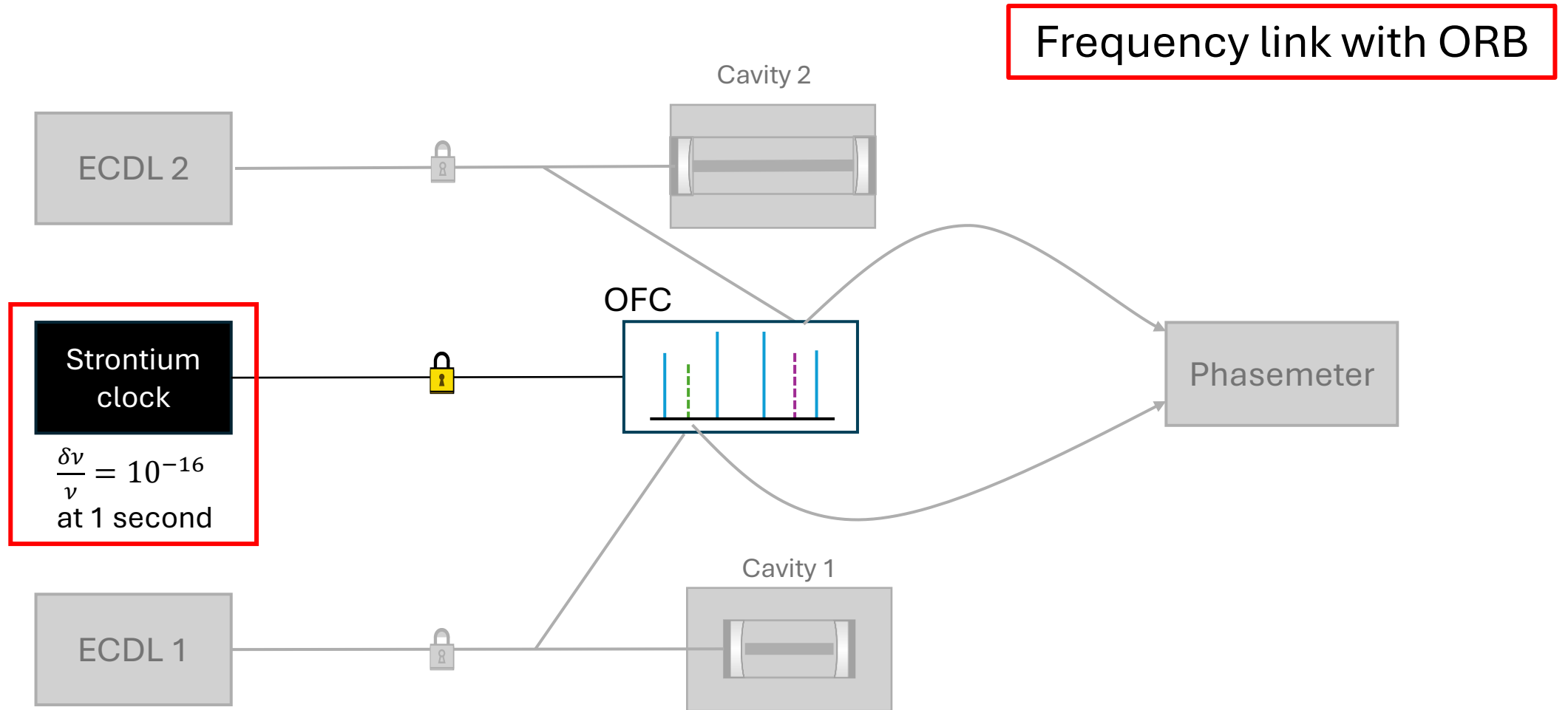


Perspectives

Stable laser with narrow
linewidth : 160 Hz

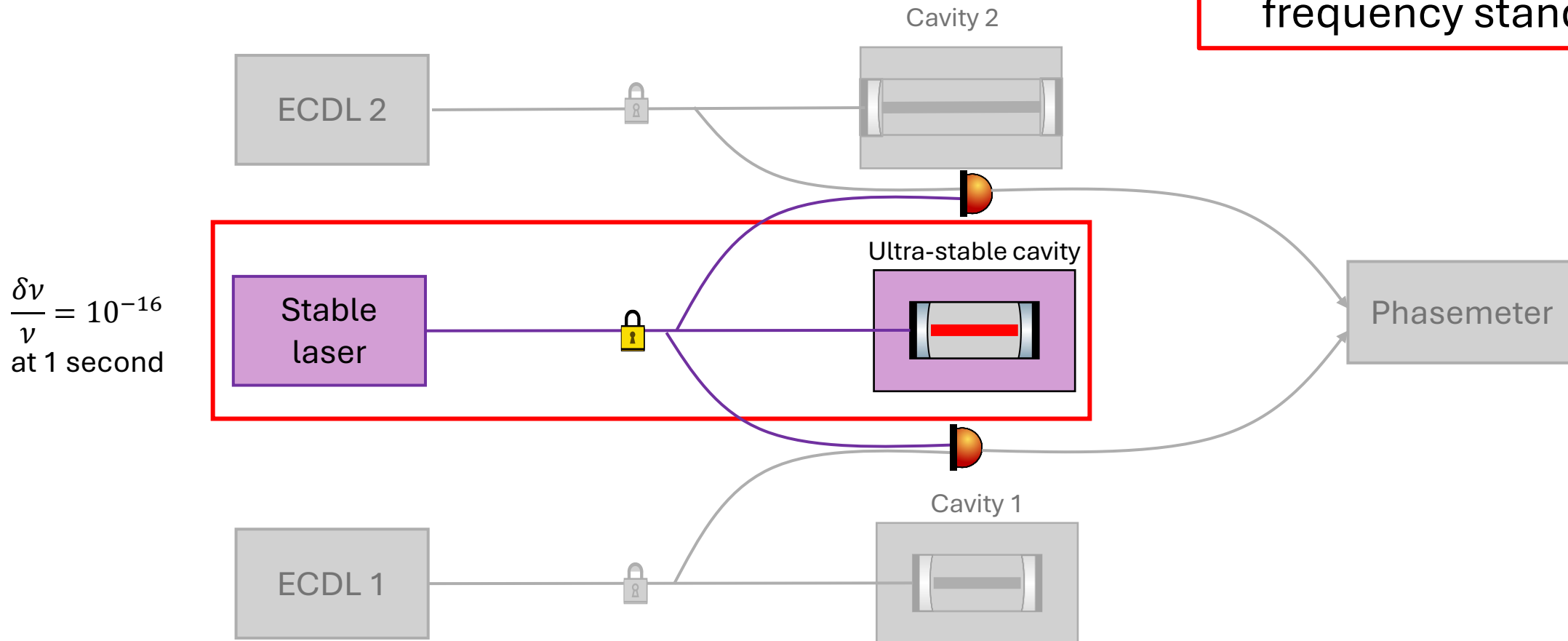


Perspectives



Perspectives

Development of other
frequency standards



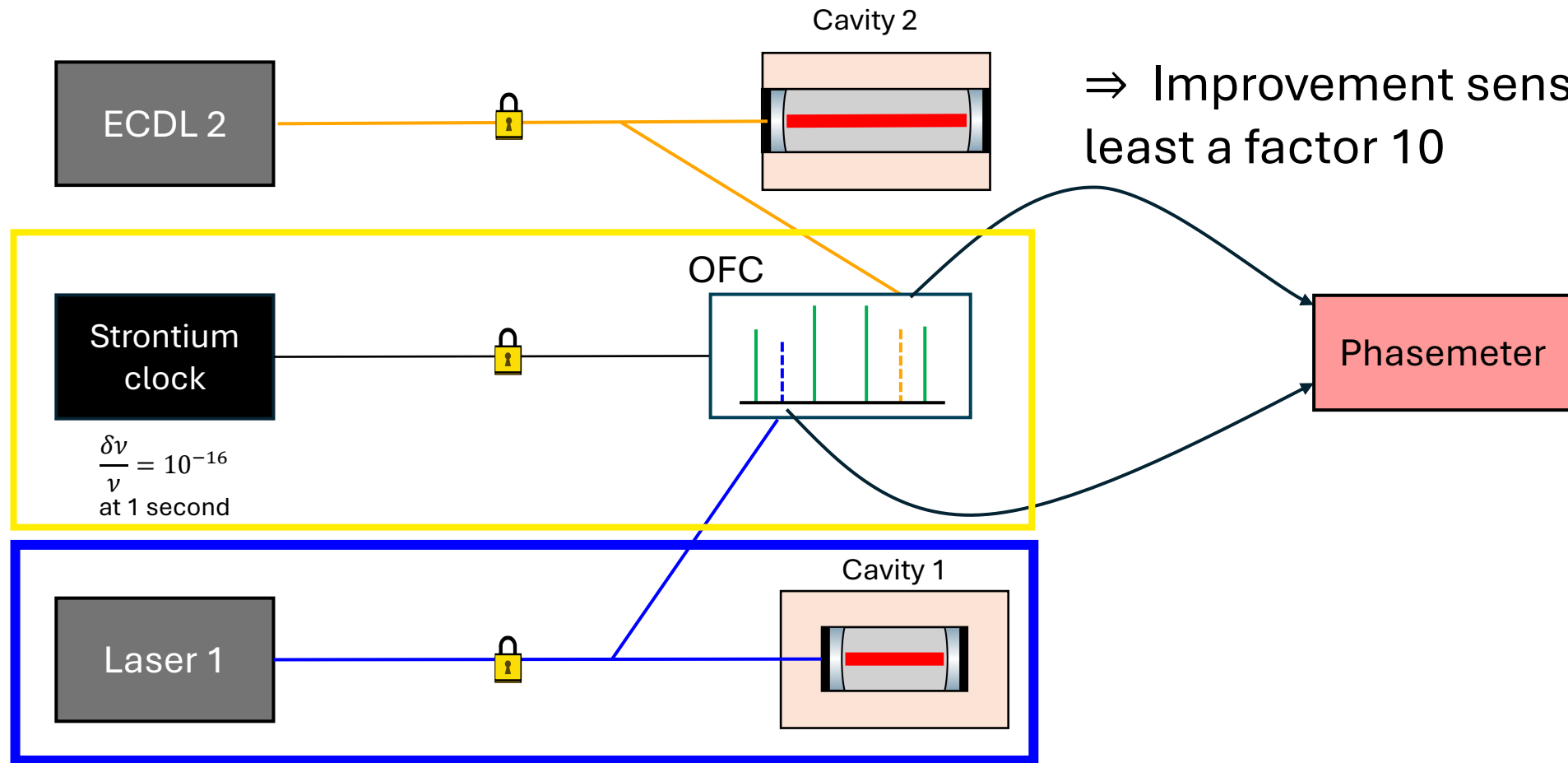
Perspectives

Increased sensitivity for :

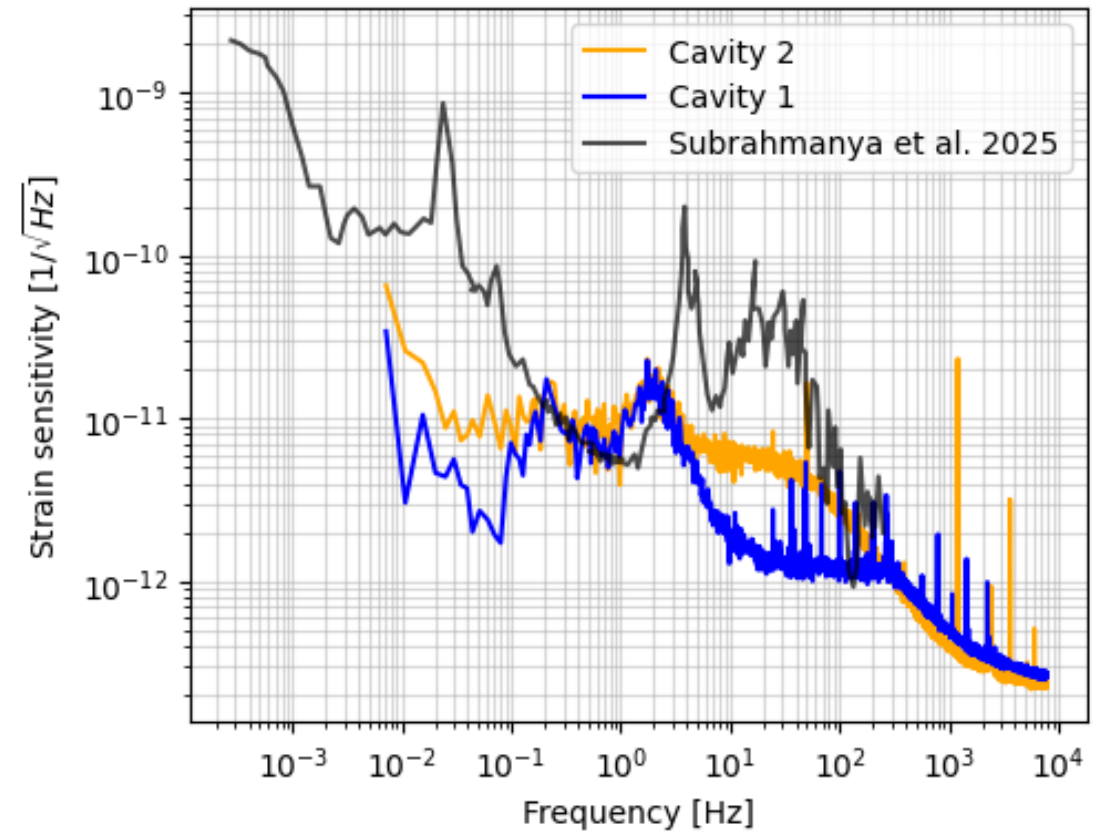
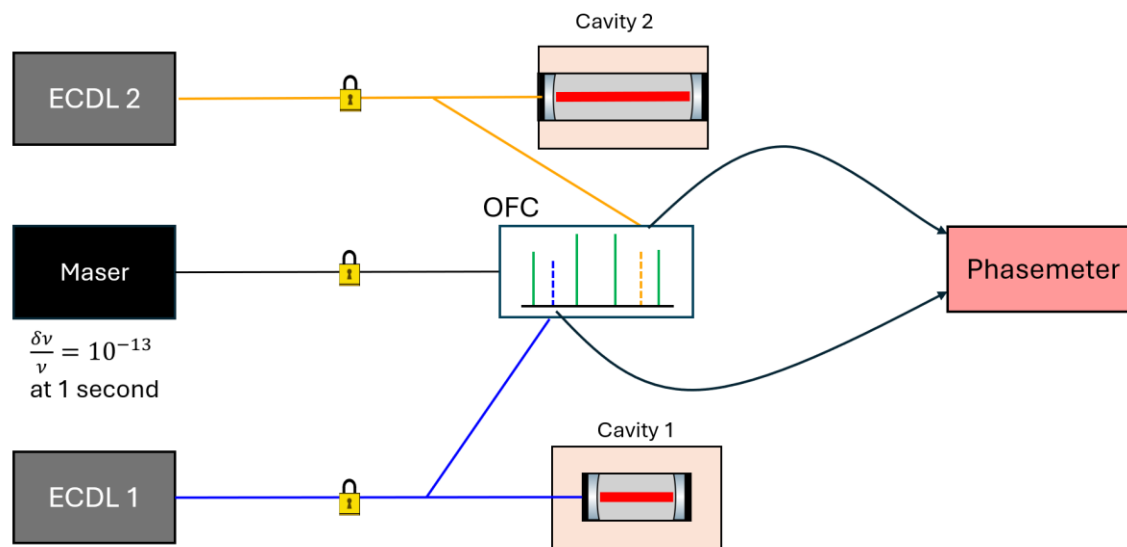
Reference clock

Test cavity

⇒ Improvement sensitivity of at least a factor 10



Thank you for your attention

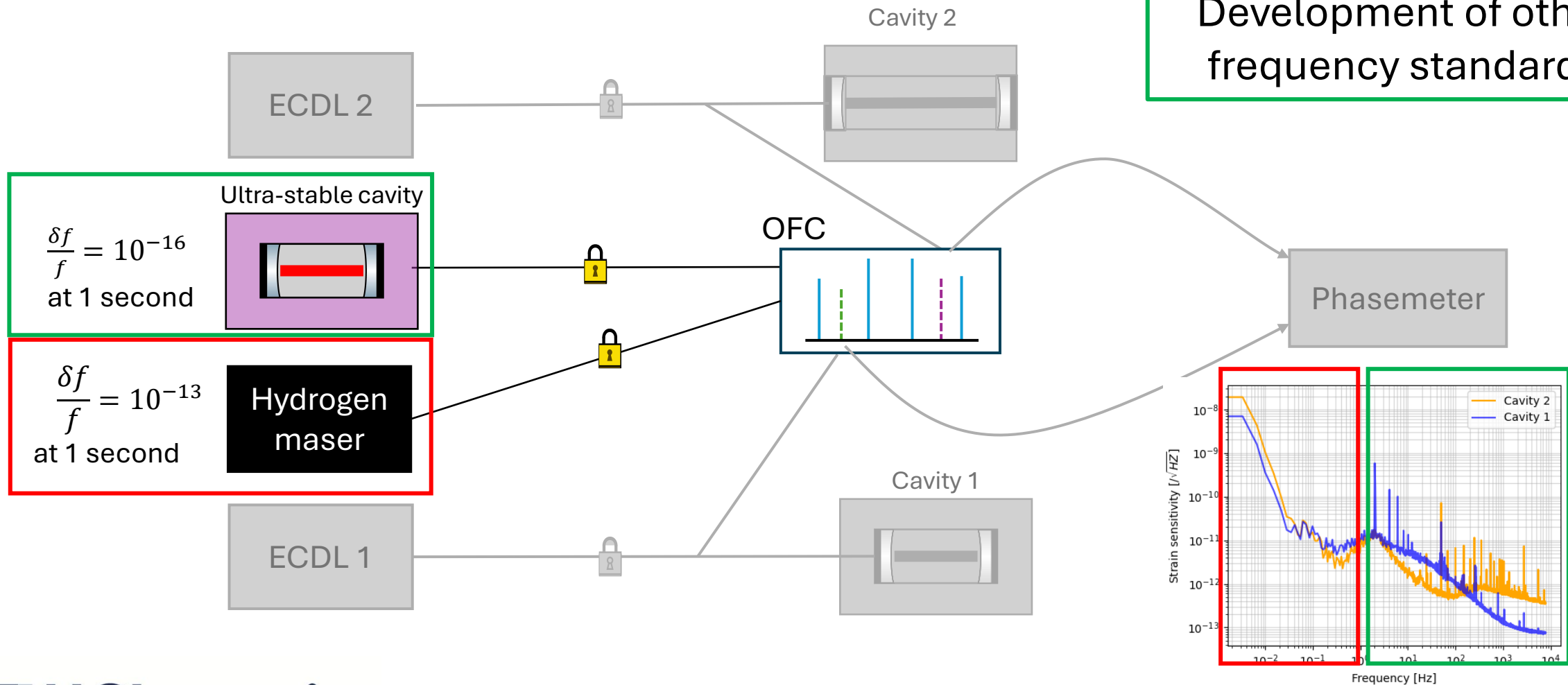


Backups

Perspectives

Frequency link with ORB

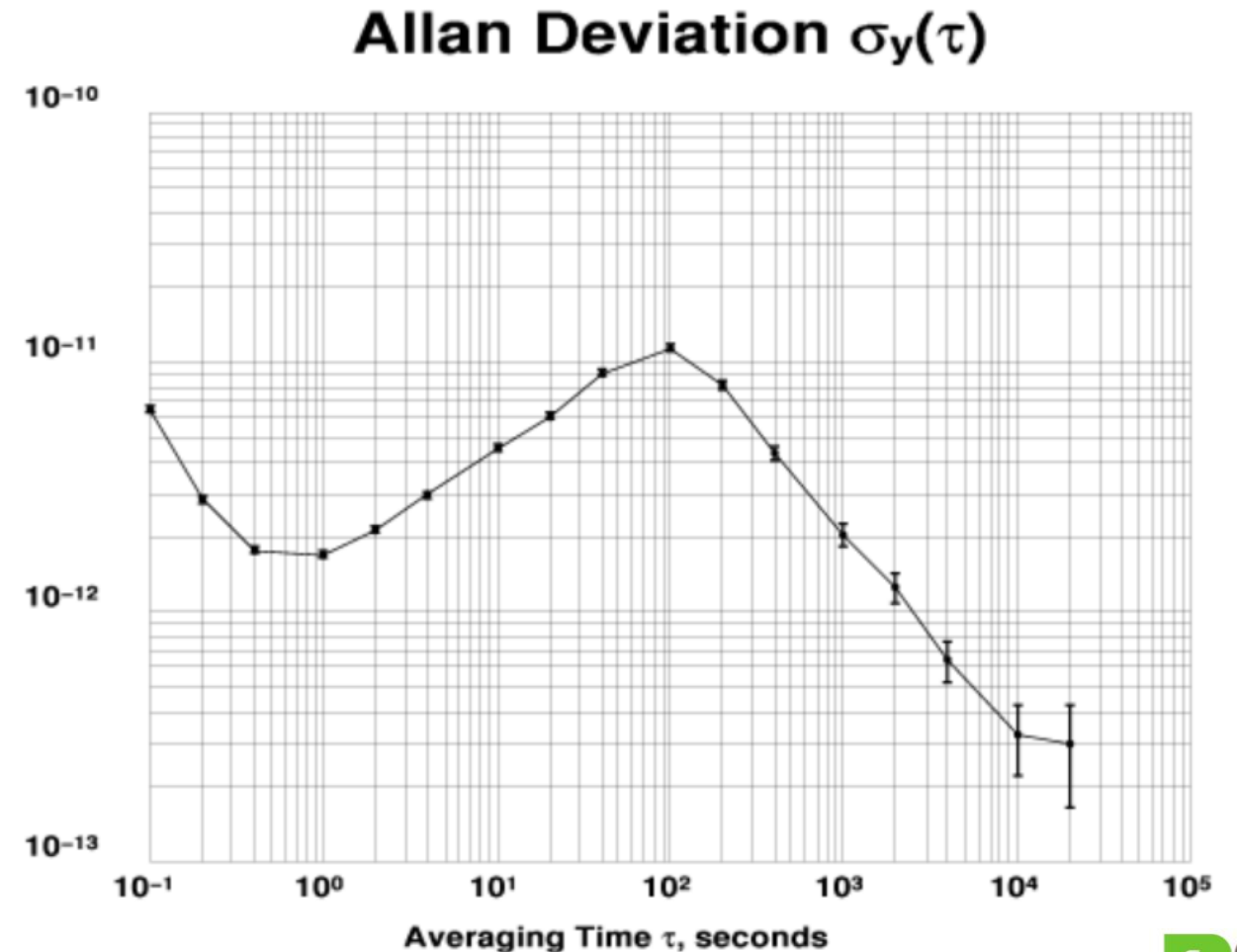
Development of other frequency standards



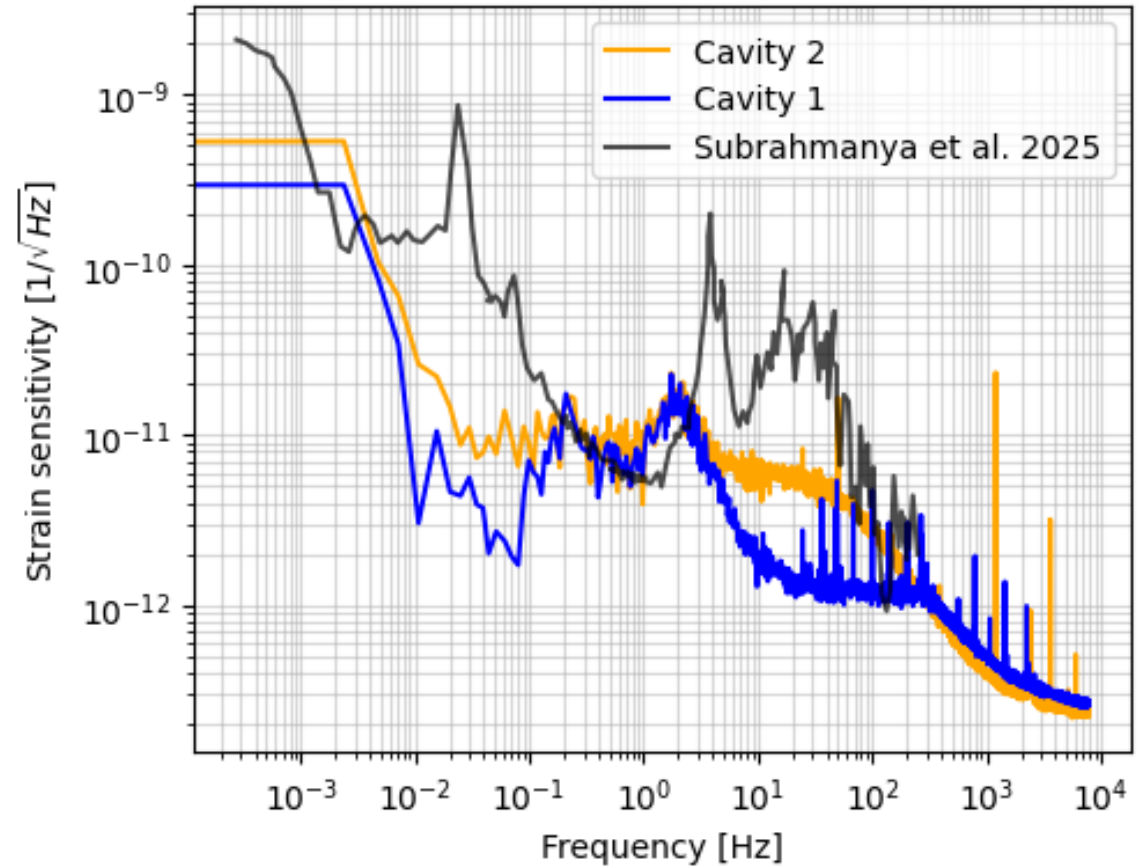
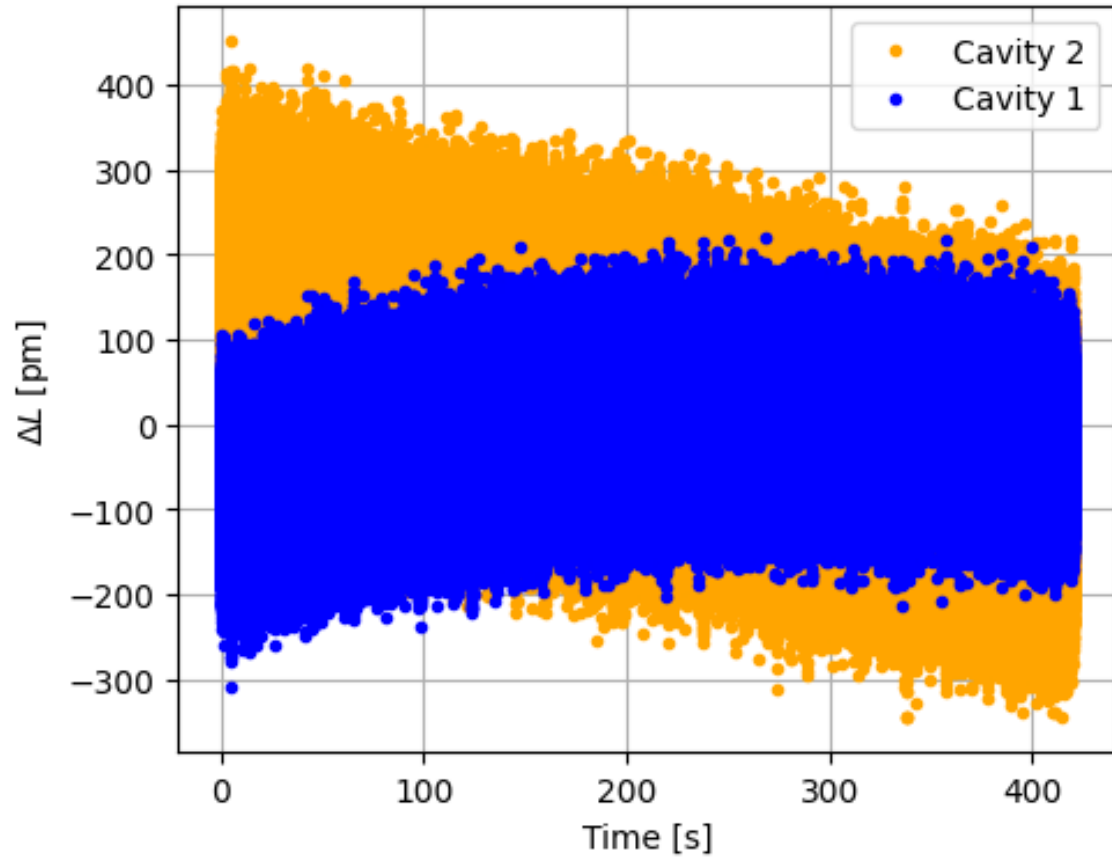
Frequency reference

- GPS-disciplined oscillator

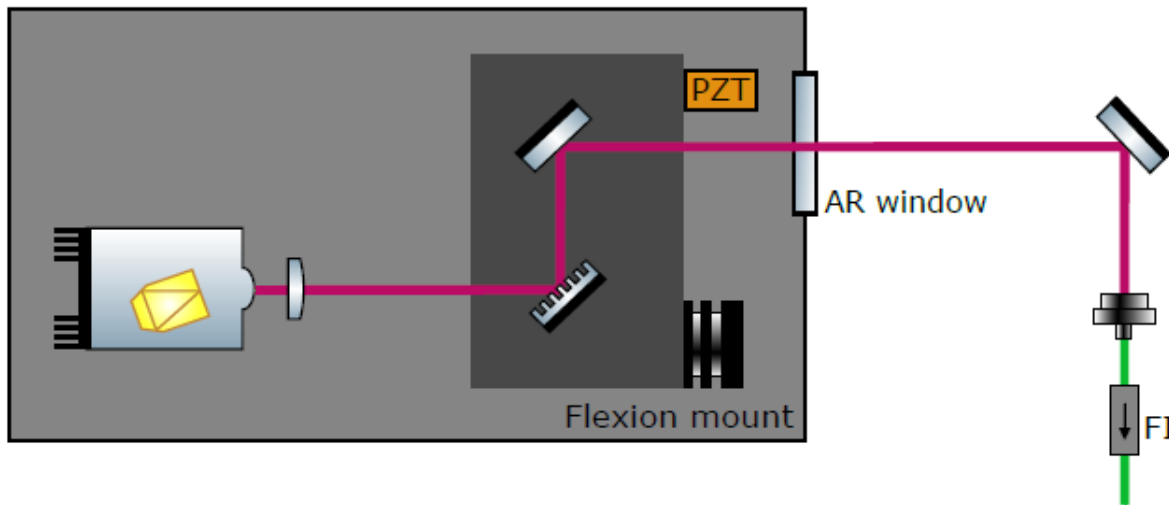
Frequency stability between 10^{-11} and 10^{-13} over 10 000 s



Linear drift removed



ECDL



ECDL center frequency at 193.548 THz
(~1550 nm)

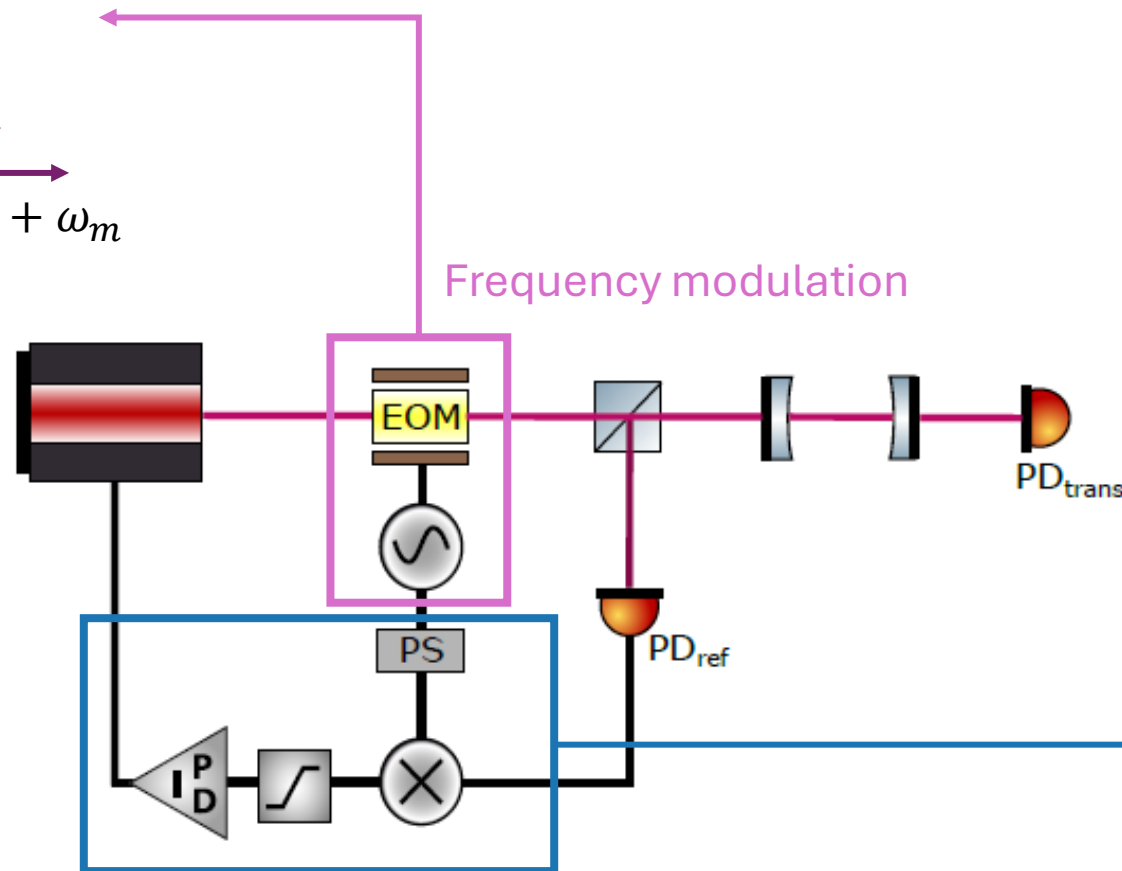
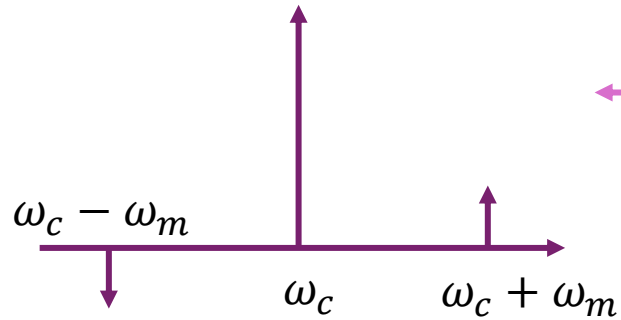
- Laser diode tunability : 1500 to 1630 nm

15 GHz mode hop free tuning range

Dr A.S. Bogomolov's design

Pound-Drever-Hall locking

Generation of sidebands



Frequency modulation

Error signal

