MANITOU

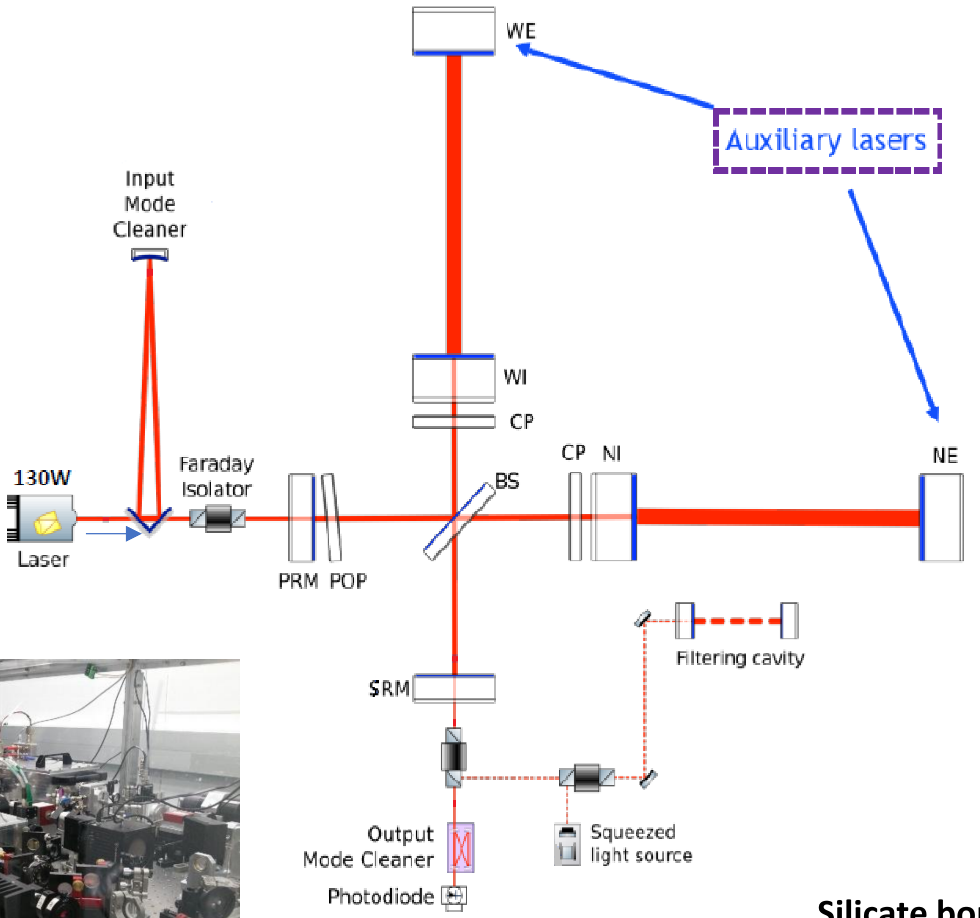
summer school

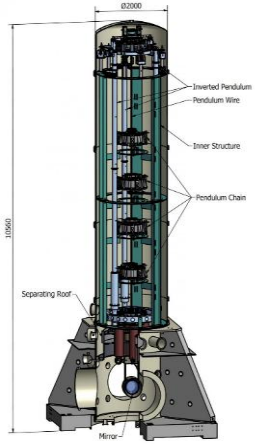
Ground based GW detectors

Walid Chaibi

French-Italian-(Dutch) ground based Gravitational wave detector

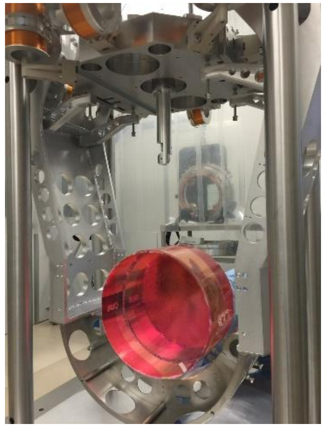
Cascina-Pisa-Italy

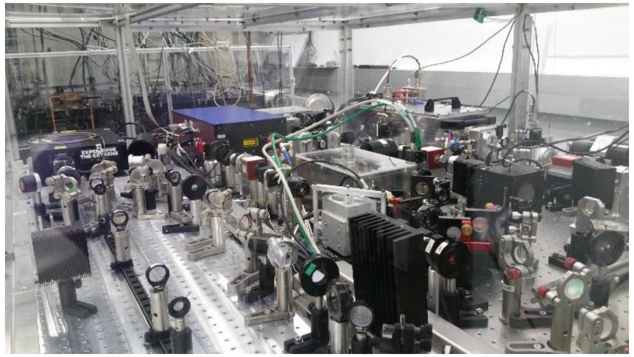




Super-attenuator

Monolithic suspension



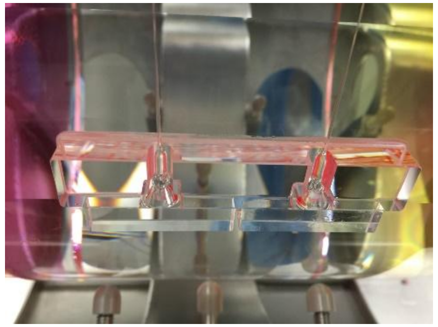


High power laser

- O4 : 45W
- O5 : 80-150W
- Post-O5 : 450W
- E-T : 700W

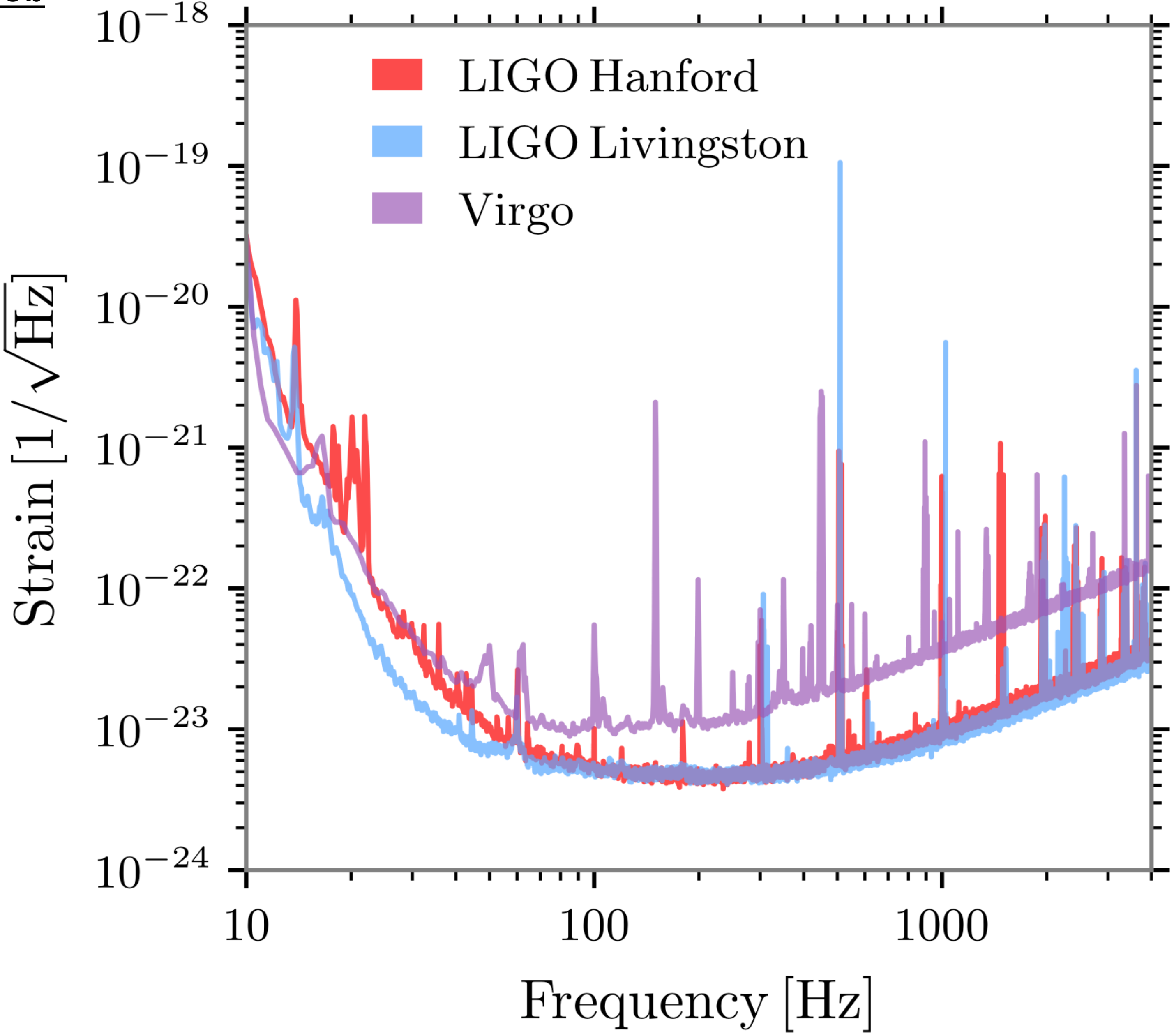
Squeezed light source

Silicate bonding



Sensitivity curves

Observing run: O3b



Outline

Optical detection principle : interferometry

Sensitivity enhancement : The Fabry Perot cavity

Stable recycling cavities

Towards low frequency : Atom interferometry

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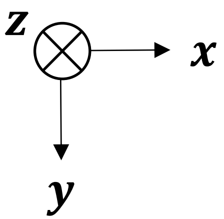
GW, plane wave



(+) polarization

(x) polarization

Space time metric in the TT gauge

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Minkowski

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

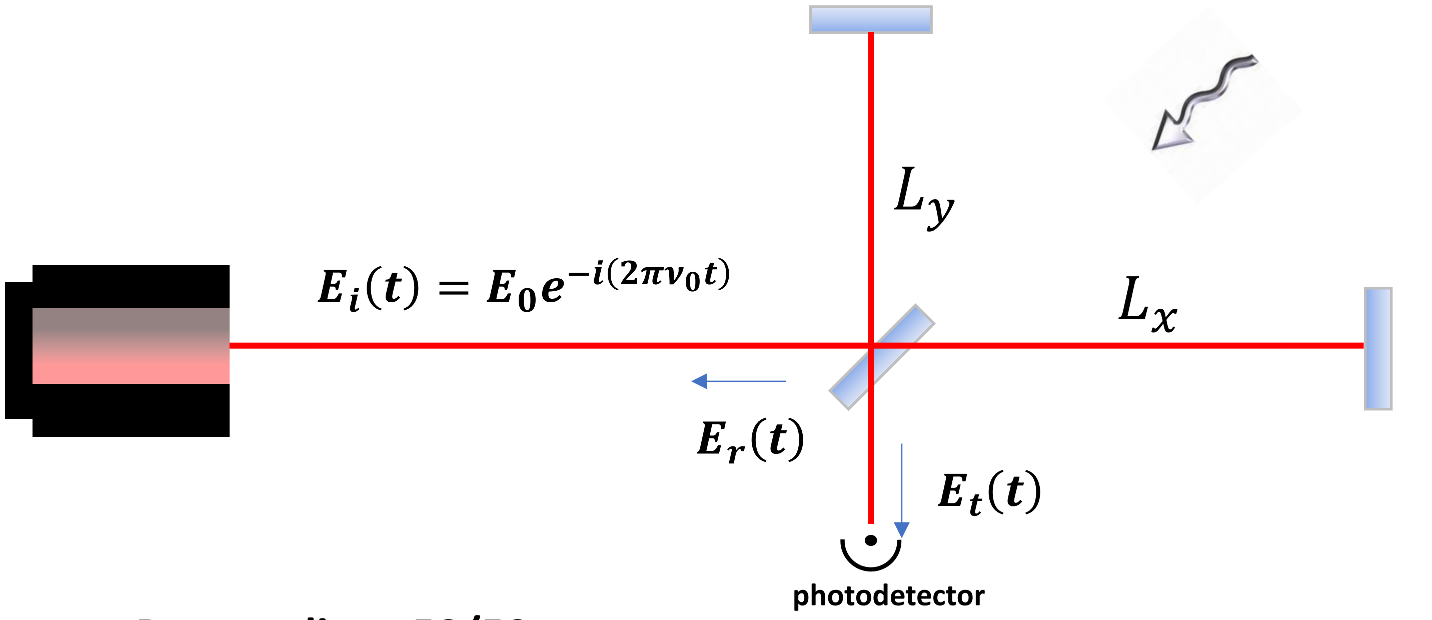
GW

Light follows the geodesic

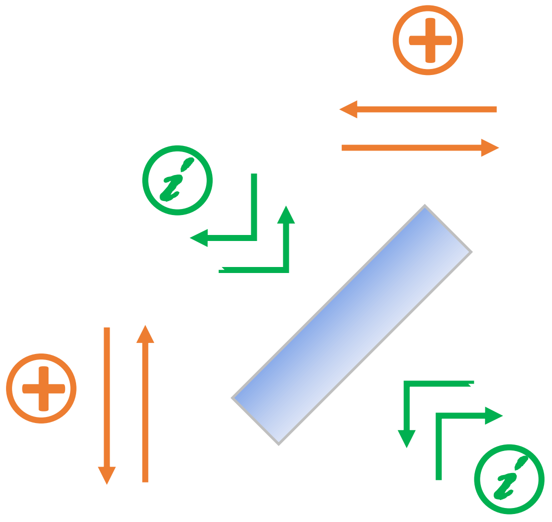
$$g_{\mu\nu} dx^\mu dx^\nu = 0$$

$$dx^\mu = (cdt, dx, dy, dz)$$

Michelson interferometer



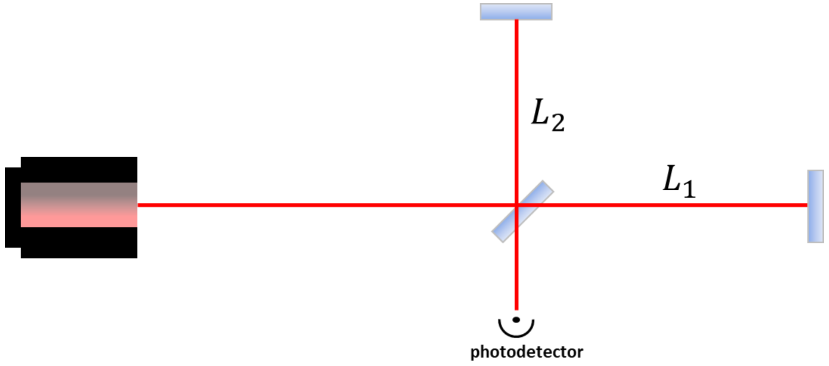
Beam splitter 50/50



$$E_t(t) = -\frac{1}{2} E_0 e^{-i2\pi\nu_0 t}\left(e^{i\phi_x} + e^{i\phi_y}\right)$$

$$E_r(t) = \frac{i}{2} E_0 e^{-i2\pi\nu_0 t}\left(e^{i\phi_x} - e^{i\phi_y}\right)$$

Michelson interferometer : Dark fringe



$$P_t(t) \propto |E_t(t)|^2 = P_0 \times \cos^2\left(\Delta\phi + \phi_h \cos\left(\Omega\left(t - \frac{\bar{L}}{c}\right)\right)\right)$$

Signal $\propto \frac{Lh(t)}{\lambda}$: increase the arm length of the interferometer

Dark fringe $\Delta L \simeq 0, P_t \propto \left(\frac{L \times h}{\lambda}\right)^2$: need an offset $\Delta\phi$

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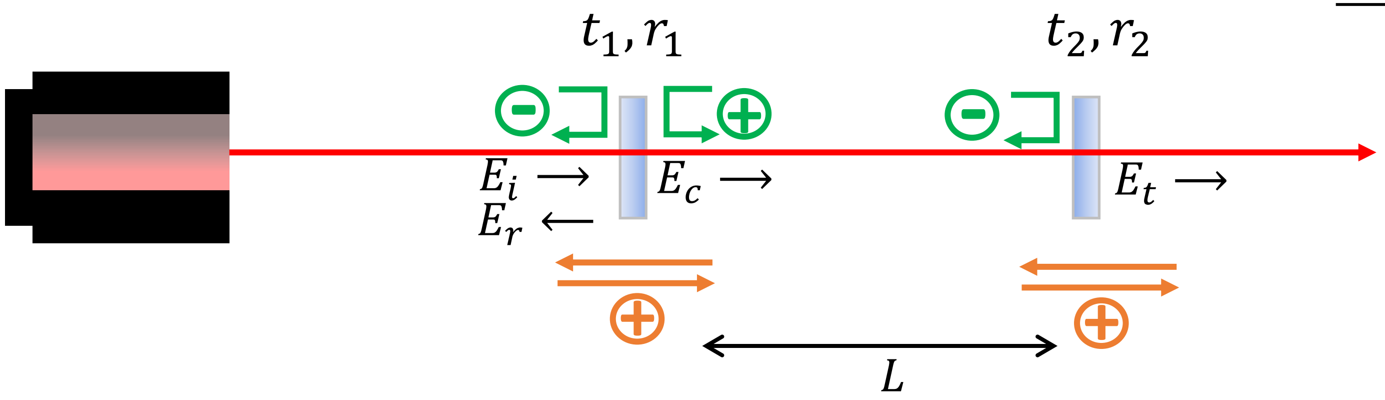
Towards low frequency : Atom interferometry

Enhancement of the interferometer sensitivity: Optical Cavities

2 mirrors cavity



Perfect mirrors : energy conservation

$$t_1^2 + r_1^2 = 1$$
$$t_2^2 + r_2^2 = 1$$

Cavity equation

$$\begin{cases} E_c(t) = t_1\ E_i(t) - r_2 r_1\ E_c\left(t - \frac{2L}{c}\right) \\ E_t(t) = t_2 E_c\left(t - \frac{L}{c}\right) \\ E_r(t) = -r_1\ E_i(t) - r_2 t_1 E_c\left(t - \frac{L}{c}\right) \\ E_{(i,r,c,t)}(t) = E_{(i,c,r,t)0}(t) e^{-i2\pi\nu_0 t} \end{cases}$$

Steady state

$E_{(i,c,r,t)0}(\not{t})$

$$\begin{cases} E_{c0} = t_1\ E_{i0} - r_2 r_1 e^{i\frac{4\pi\nu_0 L}{c}}\ E_{c0} \\ E_{t0} = t_2 e^{i\frac{2\pi\nu_0 L}{c}} E_{c0} \\ E_{r0} = -r_1\ E_{i0} - r_2 t_1 E_{c0} e^{i\frac{4\pi\nu_0 L}{c}} \end{cases}$$

Intracavity wave

$\phi = \frac{4\pi\nu_0 L}{c}$: Round trip propagation phase

$$E_{c0} = \frac{t_1}{1+r_2 r_1 e^{i\phi}} E_{i0} = \Sigma(\phi)\ E_{i0}$$

$\Sigma(\phi)$: Enhancement factor

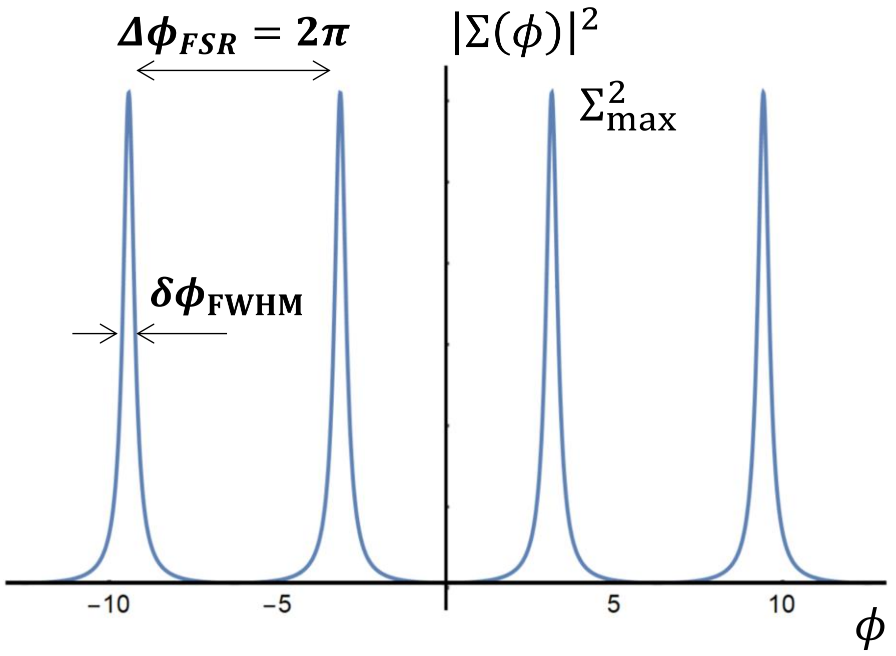
$$|\Sigma(\phi)|^2 = \frac{\Sigma^2_{\max}}{1 + \frac{4F^2}{\pi^2}\cos^2\left(\frac{\phi}{2}\right)}$$

$$\Sigma^2_{\max} = \frac{t_1^2}{(1 - r_2 r_1)^2} \simeq_{r_1=r_2} \frac{1}{t_1^2} \gg 1$$

$$F = \frac{\pi\sqrt{r_1 r_2}}{1-r_2 r_1} \simeq_{r_1=r_2} \frac{\pi}{t_1^2} \gg 1, F = 10 \to 10^6$$

$$\Delta\phi_{FSR} = 2\pi\ ;\ \Delta\nu_{FSR} = \frac{c}{2L}\ ;\Delta L_{FSR} = \frac{\lambda}{2}$$

$$\delta\phi_{\mathrm{FWHM}} = \frac{2\pi}{F}\ ;\delta\nu_{\mathrm{FWHM}} = \frac{\Delta\nu_{FSR}}{F}\ ;\delta L_{\mathrm{FWHM}} = \frac{\lambda}{2F}$$



Resonance condition

$$\boldsymbol{\phi = \pi + 2l\pi}$$

Arm Cavity reflectivity

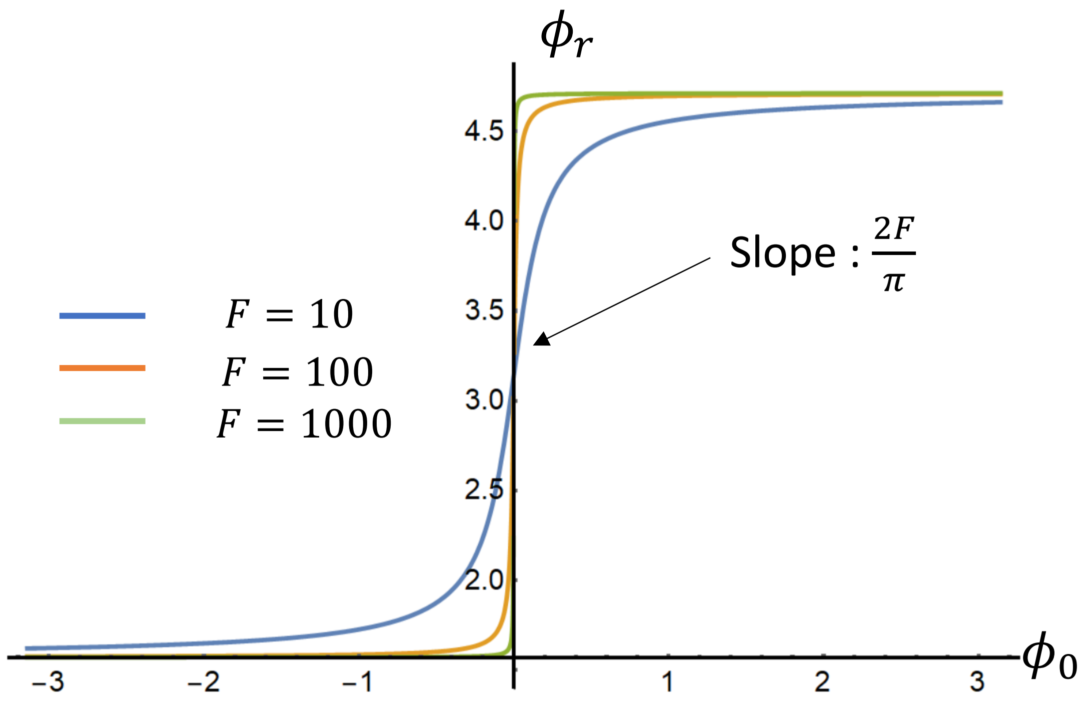
$\varrho(\phi_0) = \frac{E_r}{E_i}$ Specific configuration : $r_2 = 1$; $t_2 = 0$ ⟹ $\tau = \frac{E_t}{E_i}$; $|\varrho(\phi_0)|^2 = 1$

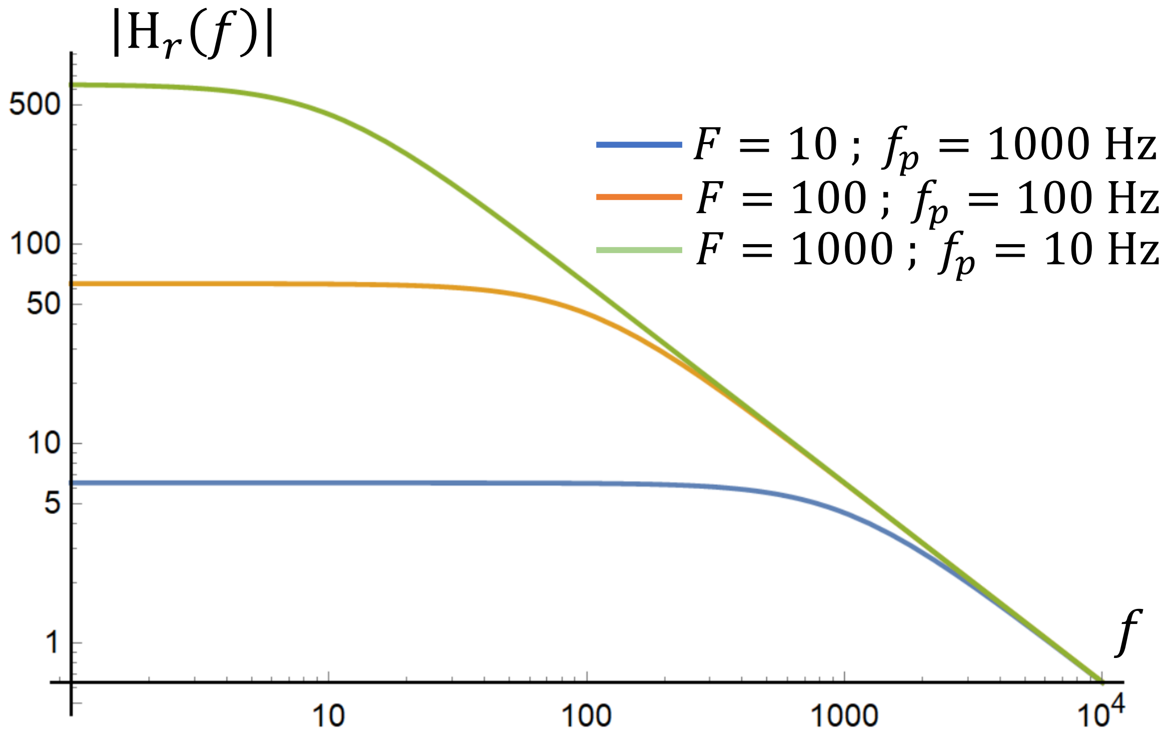
ϕ_0 → Phase without cavity

$$\phi_r = \mathrm{Arg}\big(\varrho(\phi_0)\big) = \pi + \tan^{-1}\left(\frac{2F}{\pi}\phi_0\right)$$

$$H_r(f) = \frac{\phi_r}{\phi_0}(f) \simeq \frac{2F/\pi}{1+i\frac{f}{f_p}} \; ; \; f_p = \frac{\delta\nu_{FWHM}}{2}\text{: cavity pole}$$

1st order filter





Outline

Optical detection principle : interferometry

Sensitivity enhancement : The Fabry Perot cavity

Stable recycling cavities

Towards low frequency : Atom interferometry

Gaussian beams : solution of the paraxial equation

Fundamental mode

Propagation phase — Gouy phase

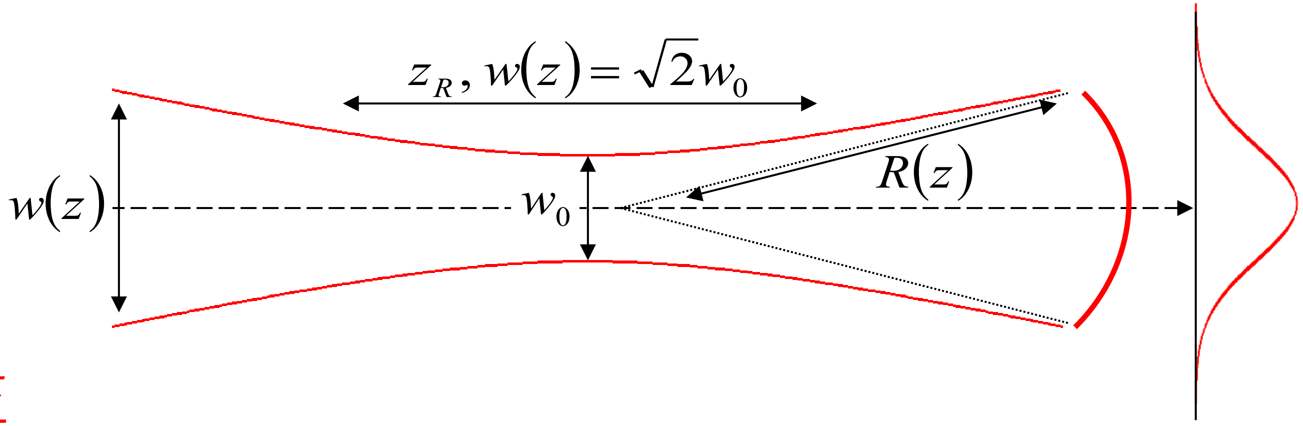
$$E(x,y,z,t) = E_0 \underbrace{\frac{1}{w(z)}}_{\text{Beam radius}} \times e^{i\left(\frac{2\pi}{\lambda}z + \psi_G(z)\right)} \times \underbrace{e^{-i\frac{2\pi}{\lambda}\frac{x^2+y^2}{2R(z)}}}_{\text{Spherical wave front}} \times \underbrace{e^{-\frac{x^2+y^2}{w^2(z)}}}_{\text{Gaussian profile}}$$

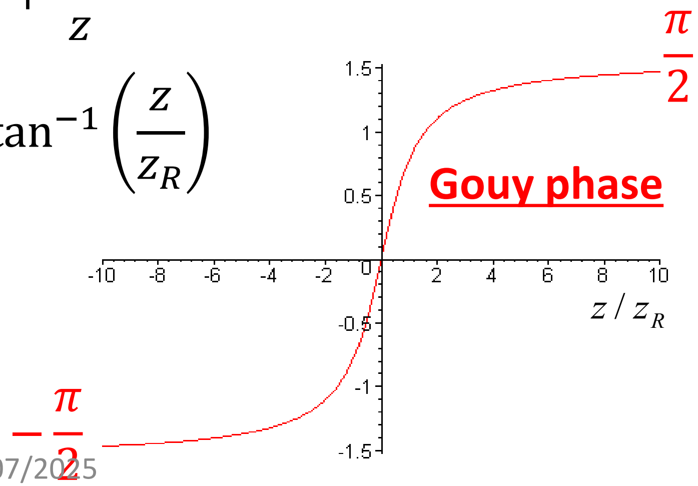
$z_R = \frac{\pi w_0^2}{\lambda}$: Rayleigh range

$$w(z) = w_0\sqrt{1+\frac{z^2}{z_R^2}}$$

$$R(z) = z + \frac{z_R^2}{z}$$

$$\psi_G(z) = \tan^{-1}\left(\frac{z}{z_R}\right)$$





Resonance condition

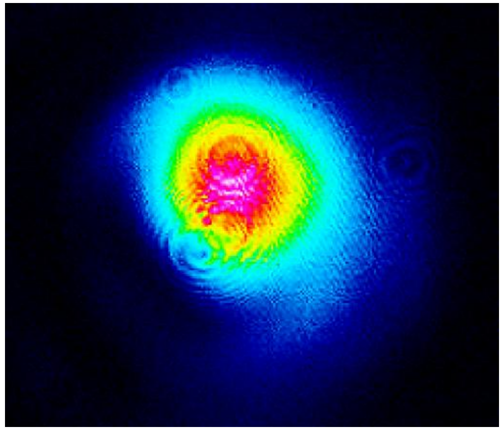
$$\mathbf{2\phi_{res} + 2\,\Delta\psi_G = \pi + 2l\pi}$$

High order modes

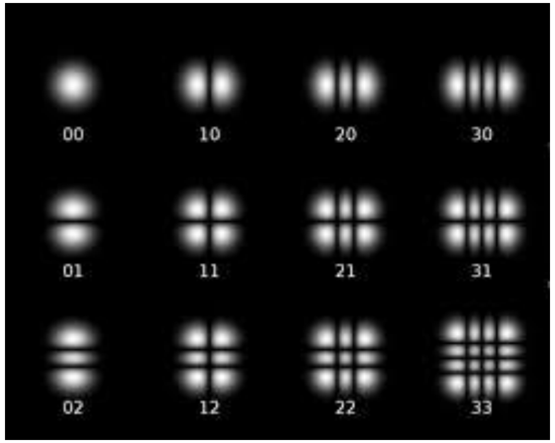
Gaussian mode : fundamental mode of a set of high order modes ; example : Hermite-Gauss modes

$$E_{n,m}(x,y,z,t) = E_{n,m,0}\,\frac{1}{w(z)} \times e^{i\left(\frac{2\pi}{\lambda}z+(n+m+1)\psi_G(z)\right)} \times H_m\left(\frac{\sqrt{2}x}{w(2)}\right) H_n\left(\frac{\sqrt{2}y}{w(2)}\right) e^{-i\,\frac{2\pi}{\lambda}\,\frac{x^2+y^2}{2R(z)}} \times e^{-\frac{x^2+y^2}{w^2(z)}}$$

H_j: Hermite polynomial of order j



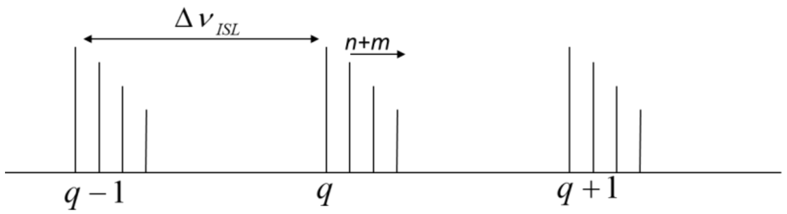
decomposition



Resonance condition

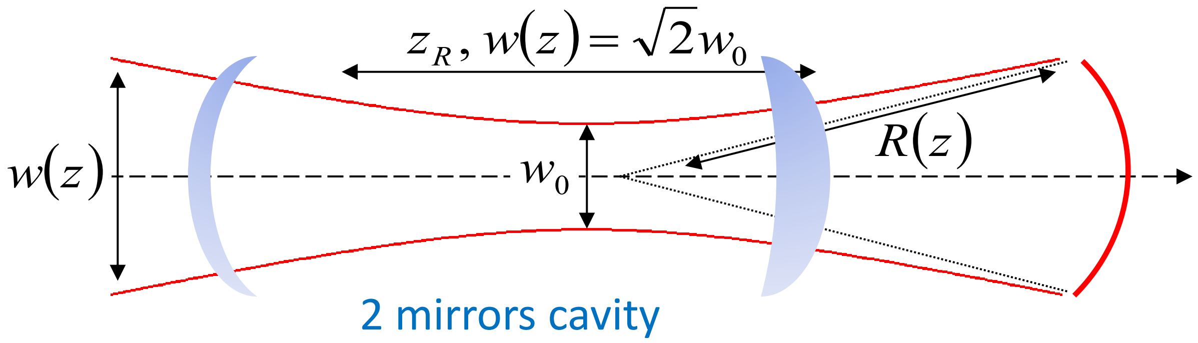
$$\boldsymbol{\phi_{n,m,res} + 2(m+n+1)\,\Delta\psi_G = \pi + 2l\pi}$$

depends on the mode order

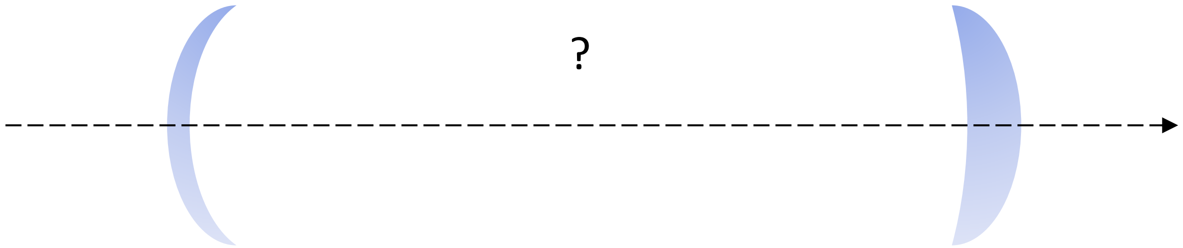


Optical cavity

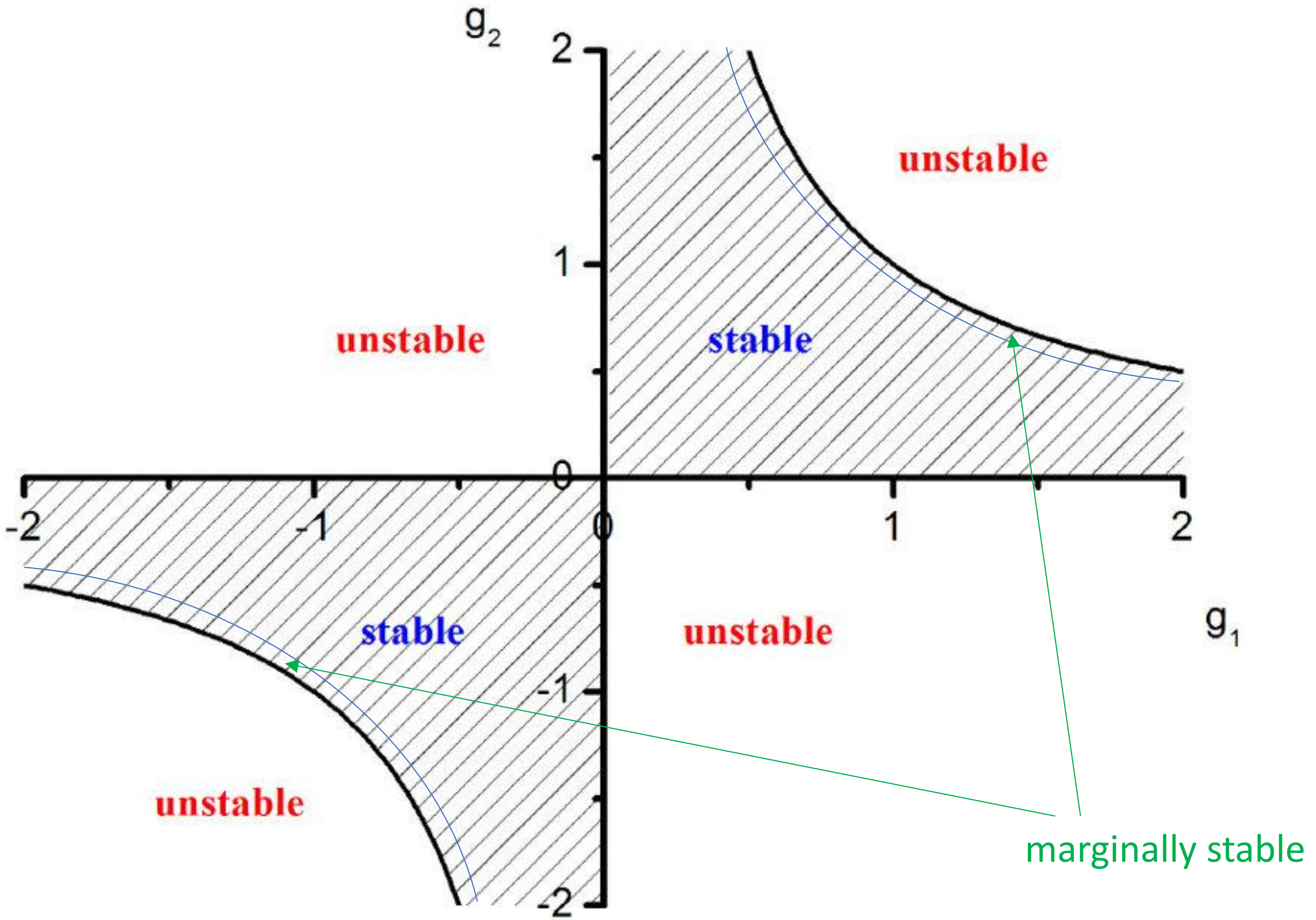
Spherical wavefront ➡ Spherical mirrors



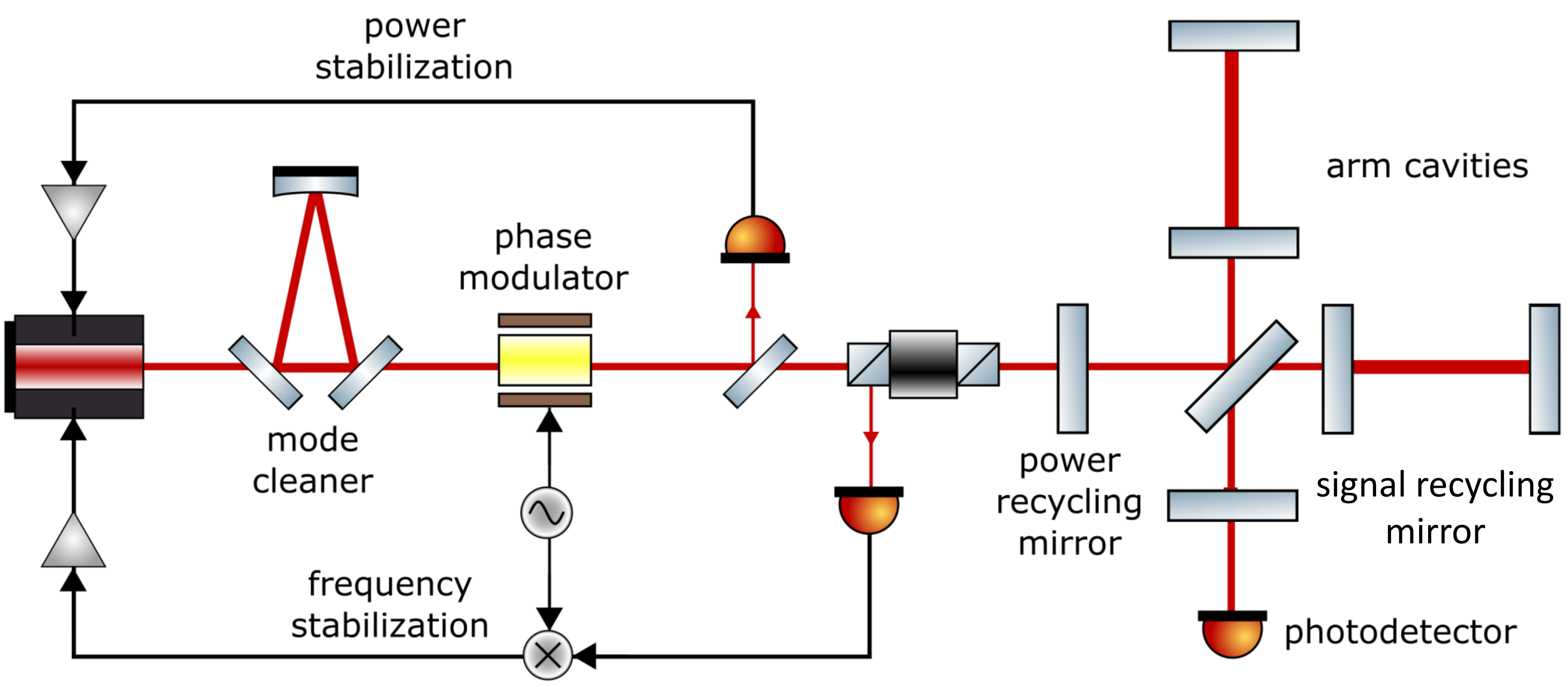
We set two mirrors ➡ Which Gaussian beam can fit inside the cavity (mode of the cavity)? Is there a solution? Unicity?



Stability diagram

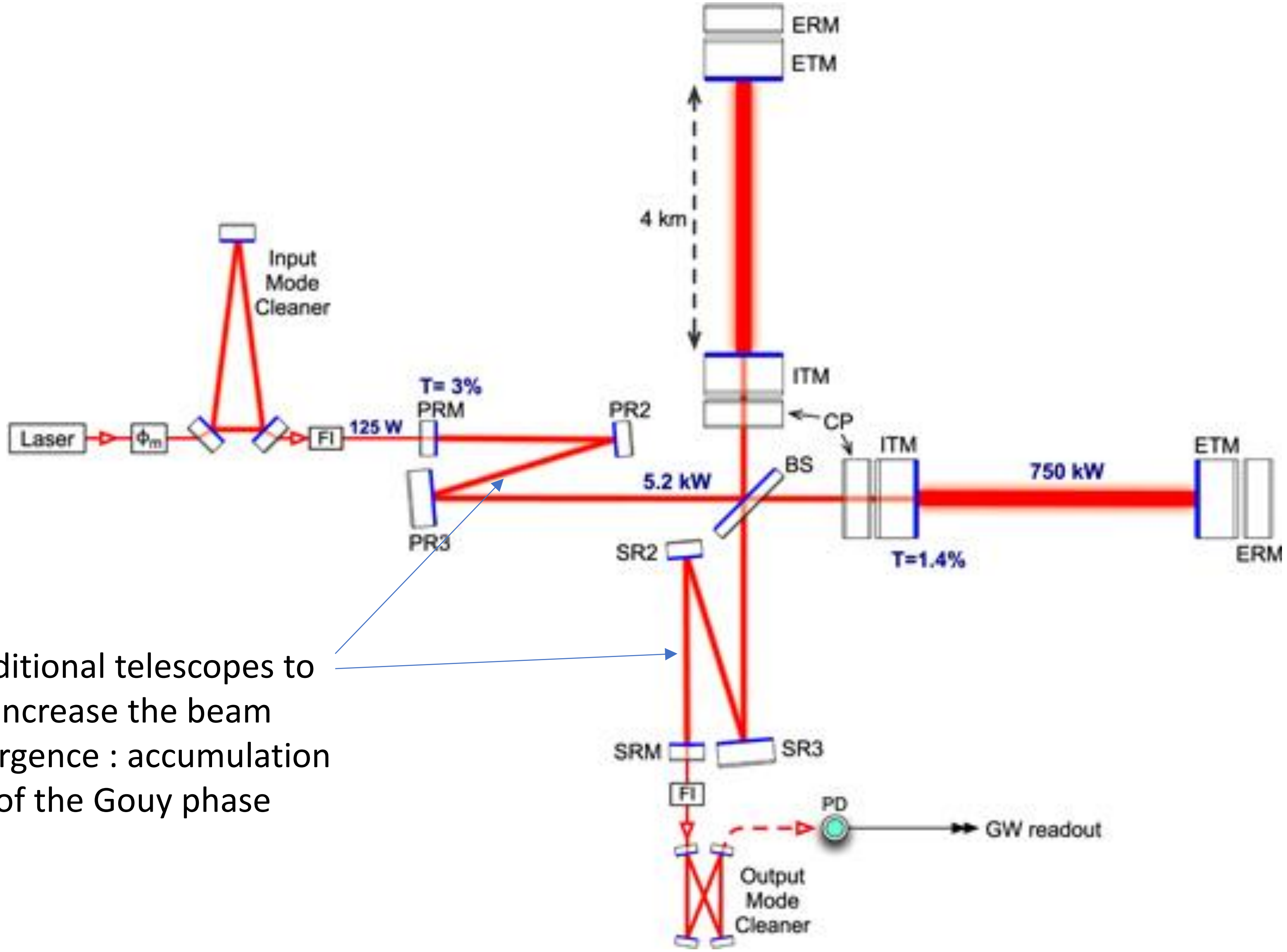


Marginally stable recycling cavities



$P_0 = 25\ \mathrm{W}\,; G = 50\,; P_{PD} = 1\ \mathrm{mW}\,; F = 400\,;\ h = 2\ \times 10^{-23}\mathrm{Hz}^{-1/2}@100\mathrm{Hz}$

stable recycling cavities : LIGO



Additional telescopes to increase the beam divergence : accumulation of the Gouy phase

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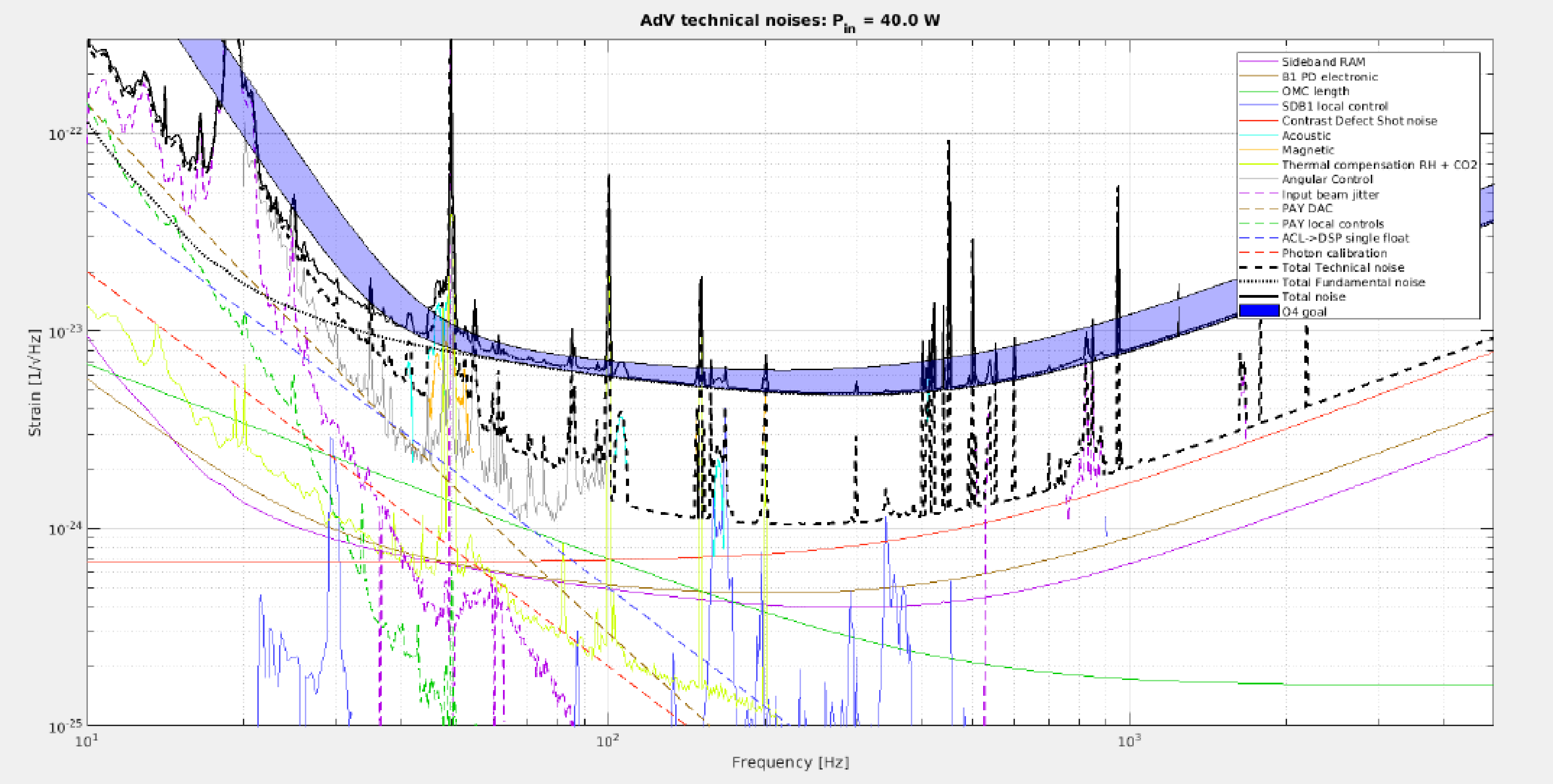
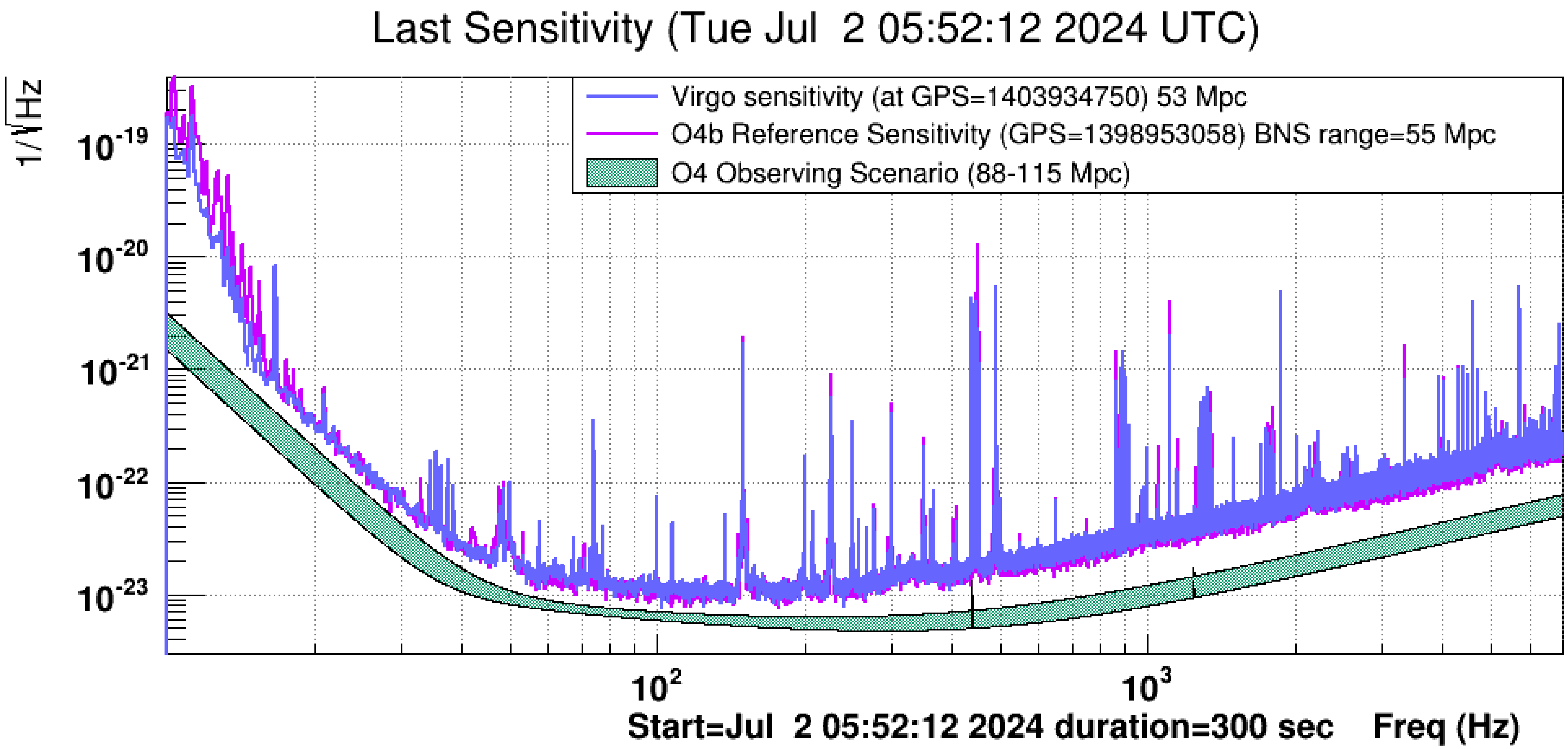
A lot of noise



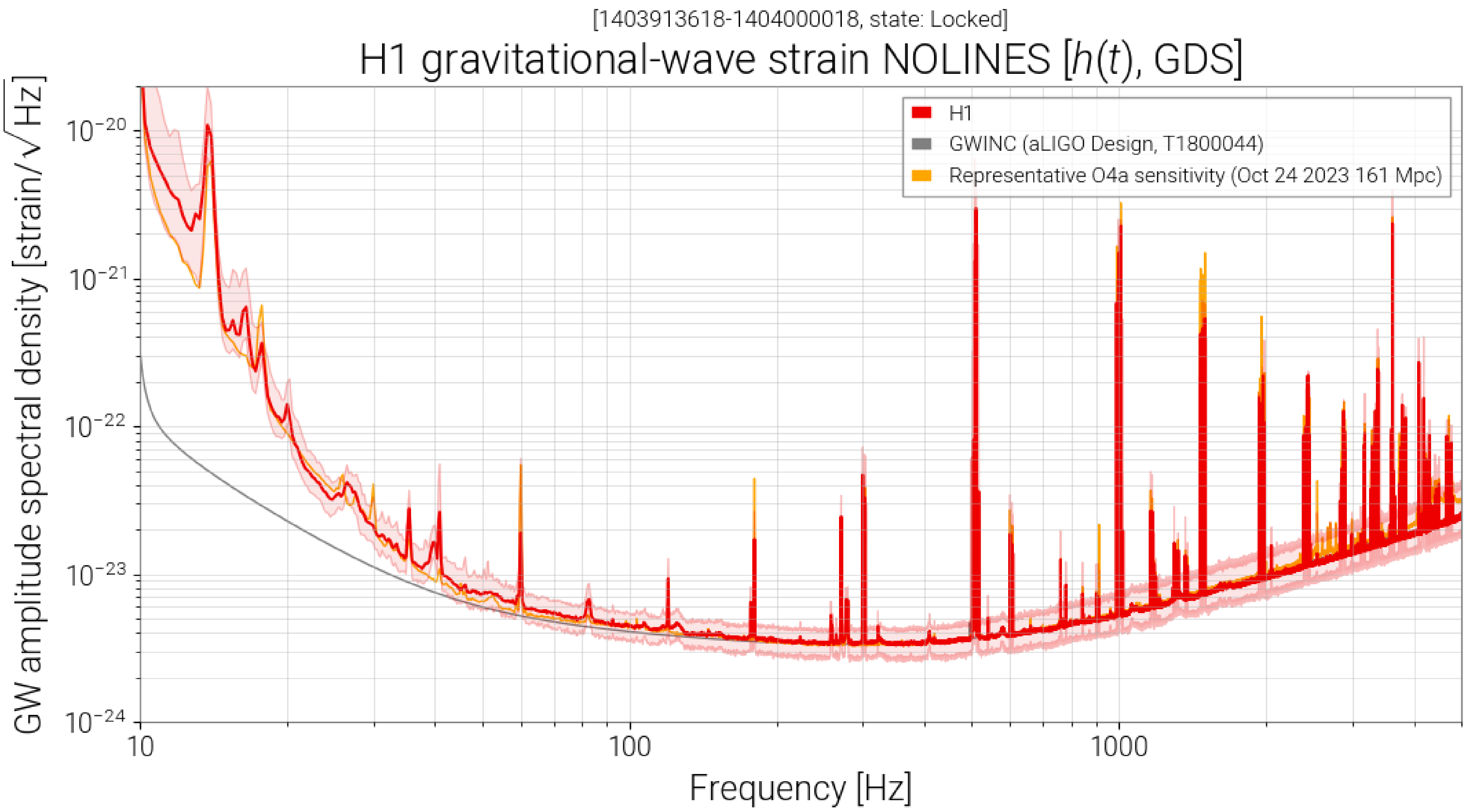
…and a lot of other aspects

Thermal compensation system
Controls
High power laser
Electronics
Vacuum
Parametric instabilities
Newtonian noise
Squeezing, dependent and independent
Calibration
Coatings
Simulations
….and R&D

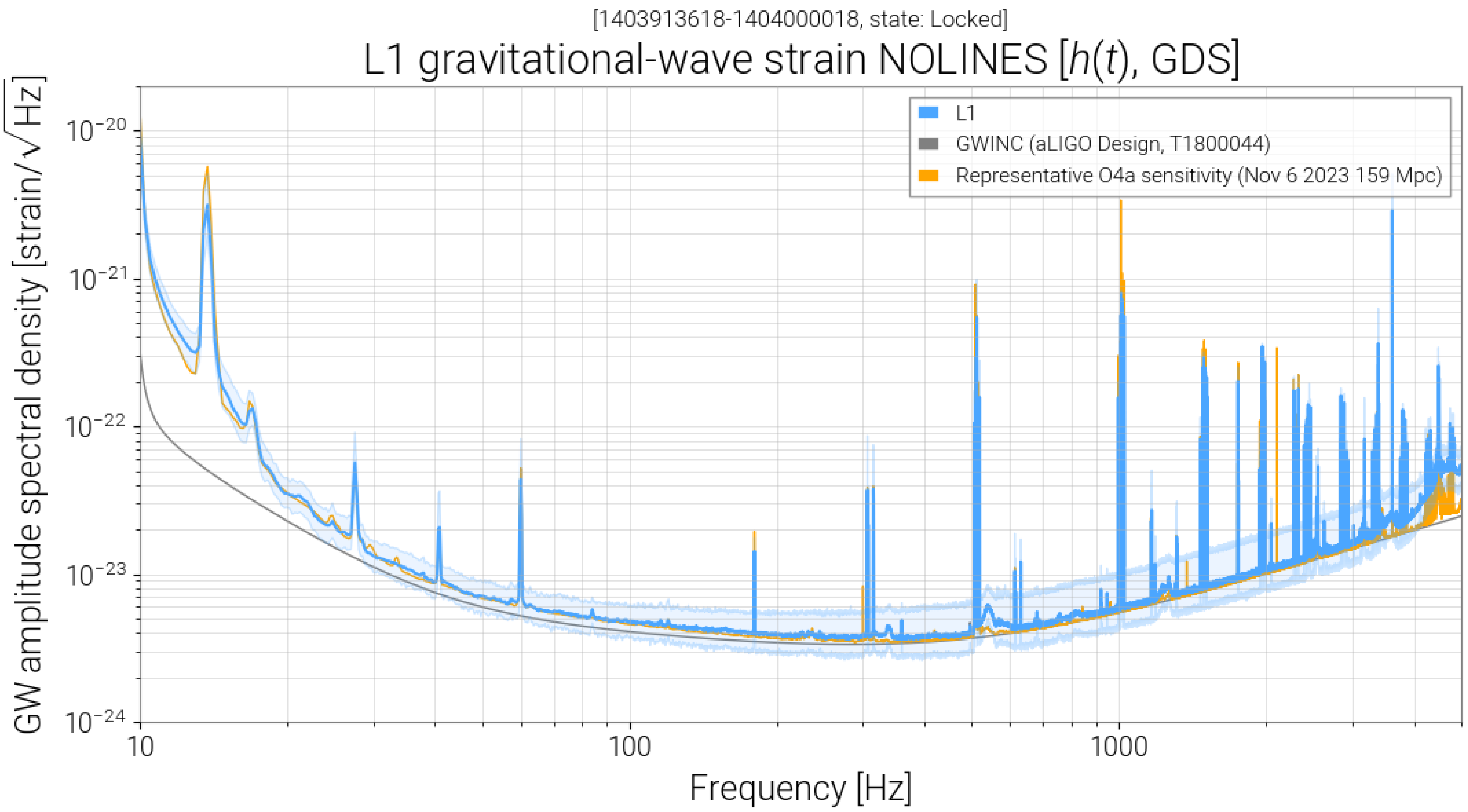
VIRGO sensitivity



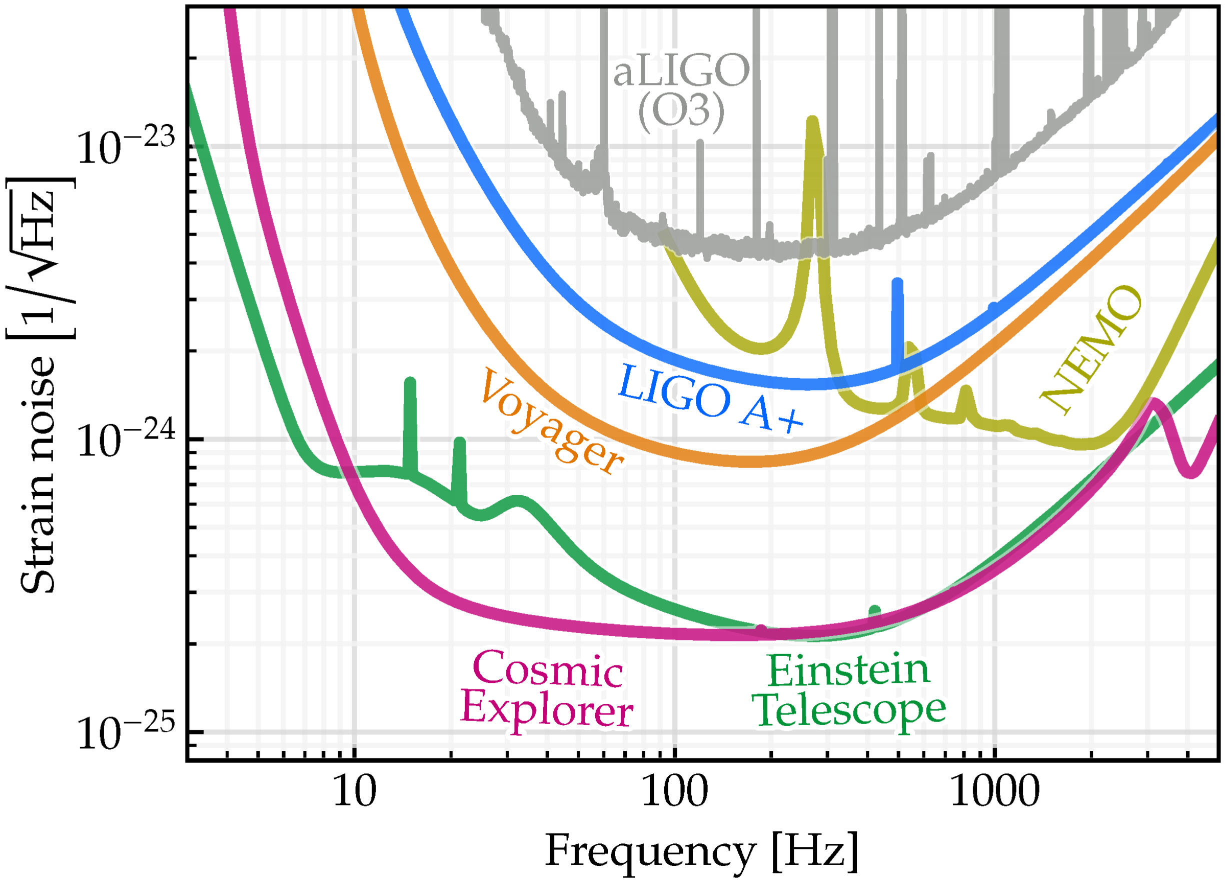
LIGO Hanford sensitivity

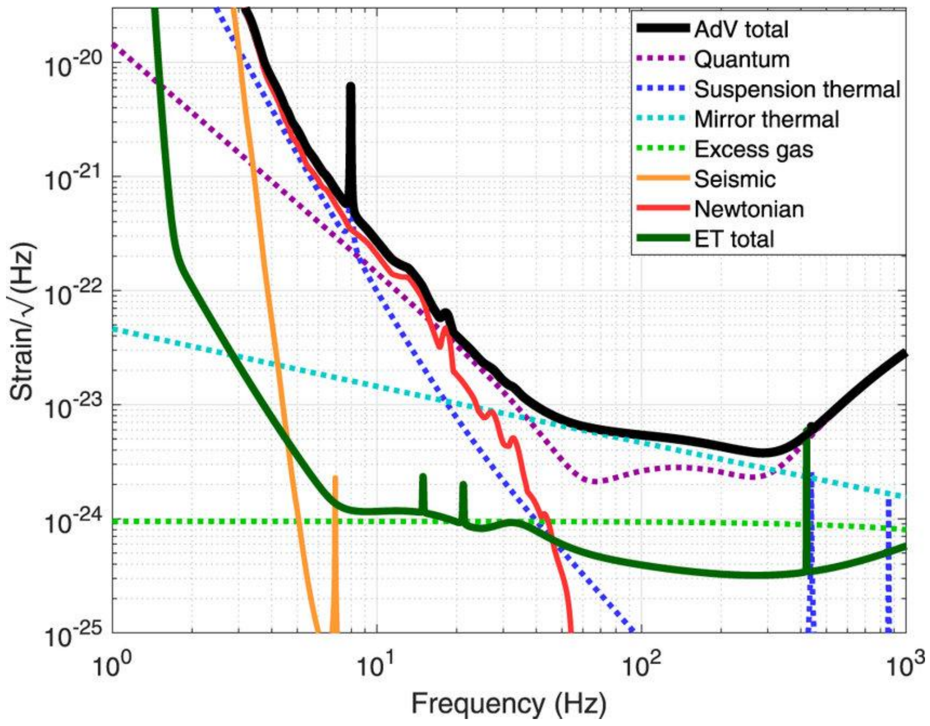


LIGO Livingston sensitivity



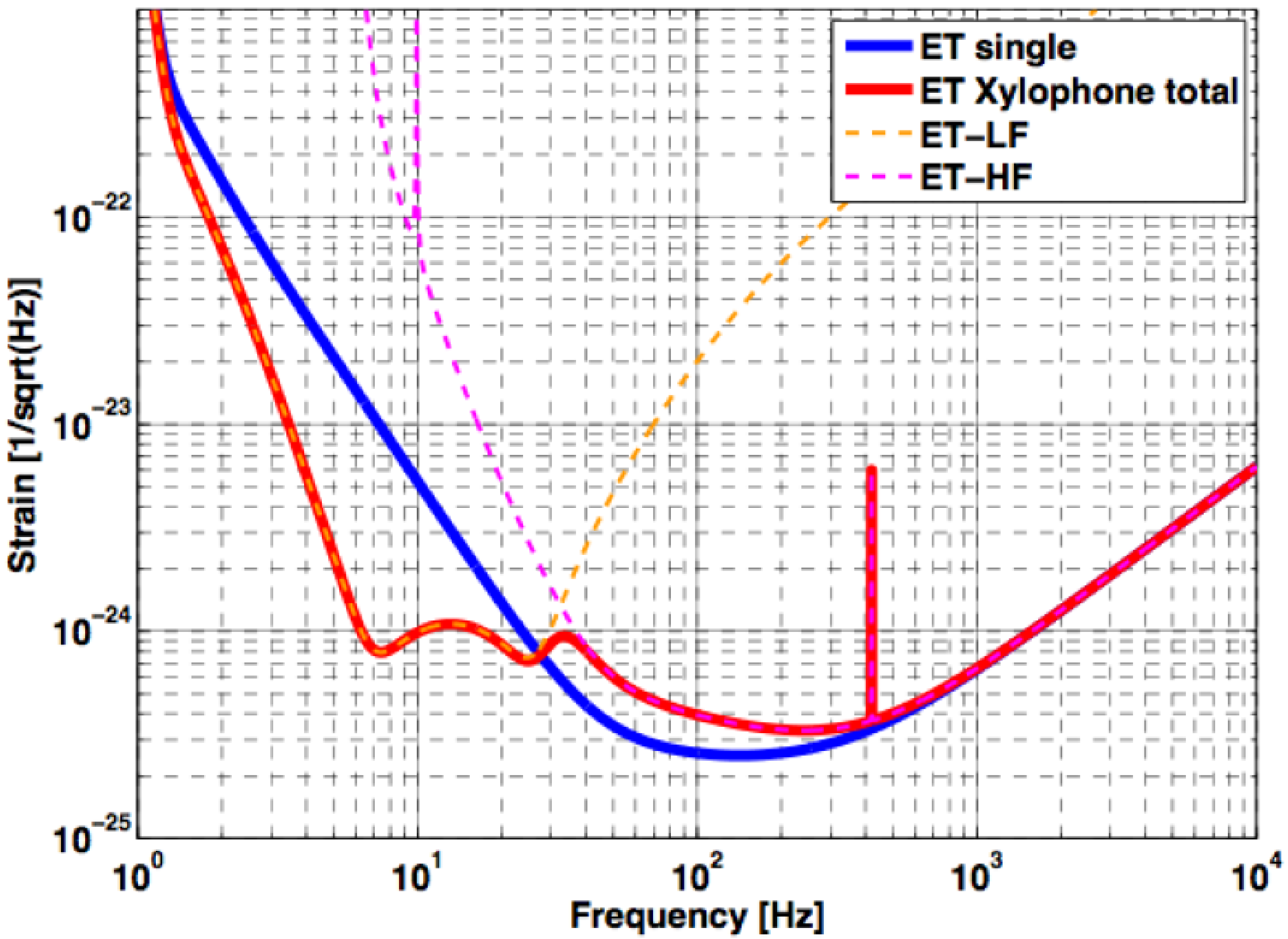
Third generation detectors





➡ Towards low frequency : technological issues

Third generation detectors : The Einstein Telescope



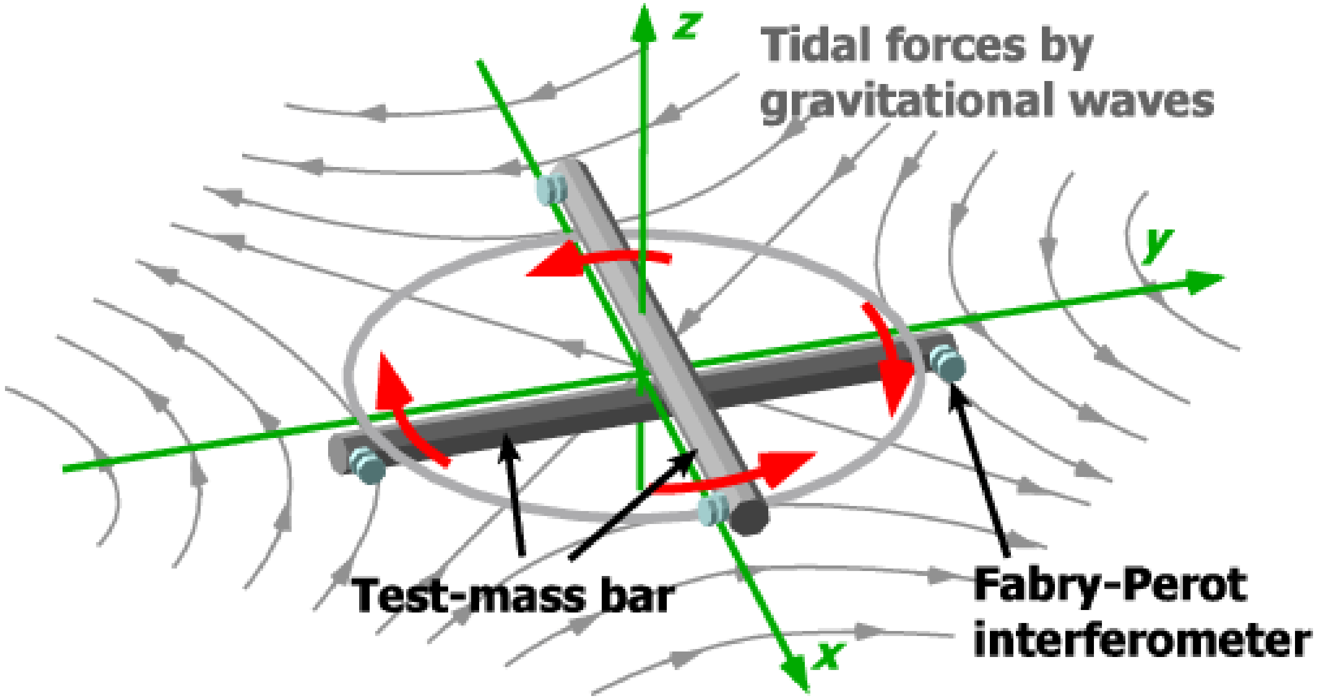
ET-HF :

- Same wavelength : 1064nm
- High power : 700W
- Squeezing

ET-LF :

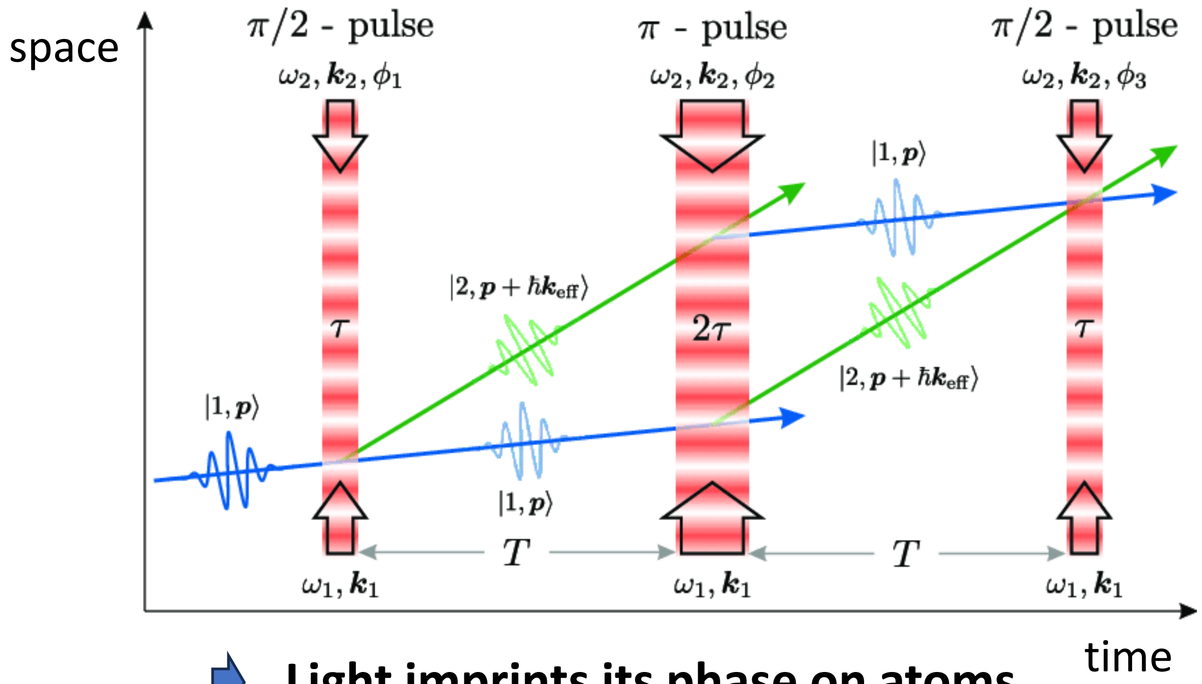
- Low frequency super-attenuators
- Newtonian noise subtraction
- Silicon mirrors @ 10K, low power 1550nm laser
- Squeezing

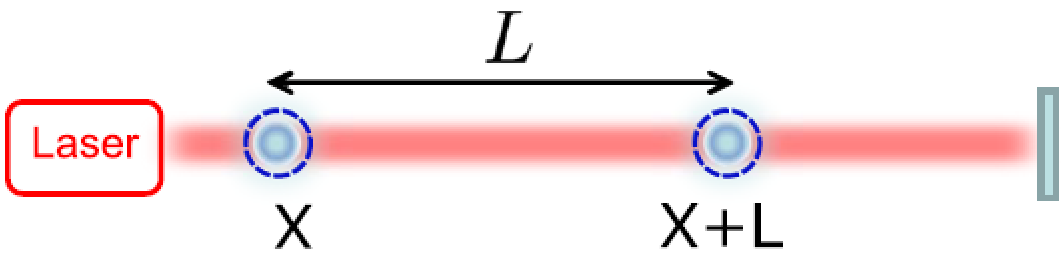
Low frequency detectors : Torsion bars



- Torsion pendulum : very low frequency
- Technically limited by the size of the bars

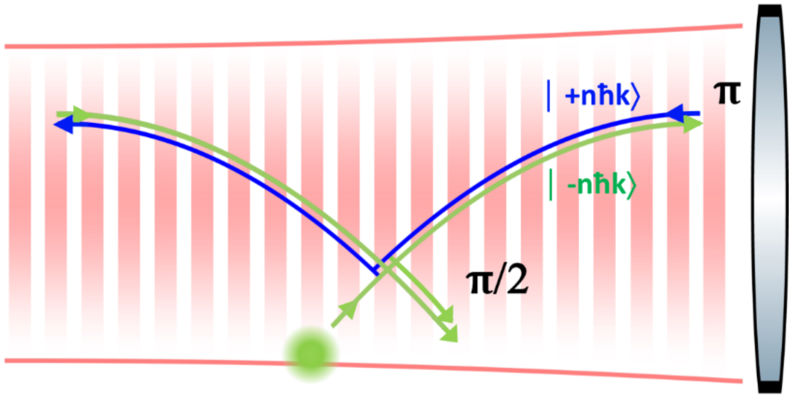
- **Free falling atoms**





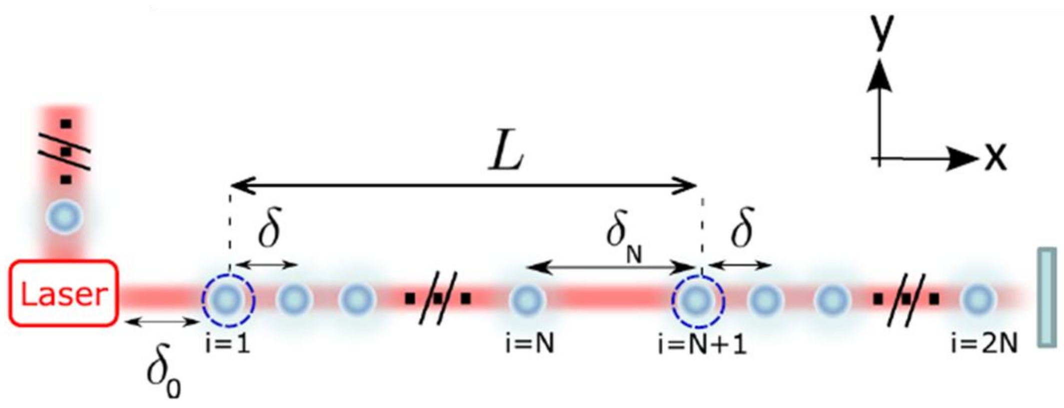
Gradiometer

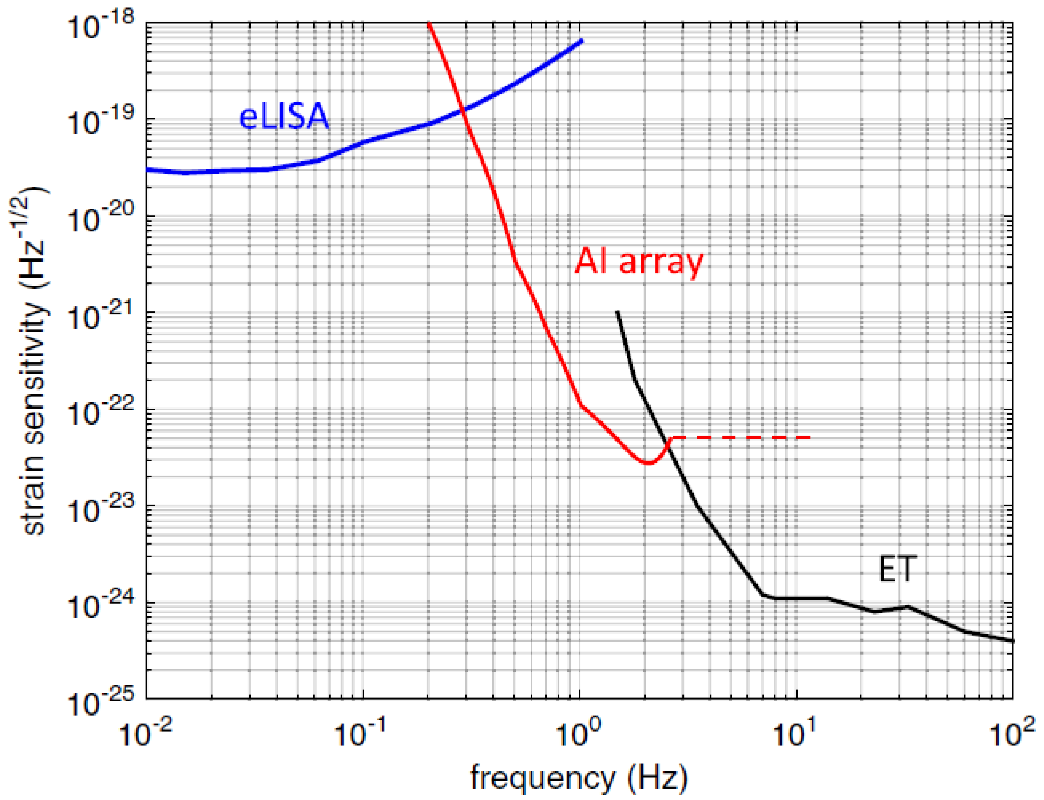
- **Light imprints its phase on atoms**



Bragg configuration

Low frequency detectors : Atom interferometers





➡ **Multi-gradiometer configuration : Cancel out Newtonian noise**

➡ **Fill in the gap 0.1Hz-10Hz**

Multi diffraction, squeezing, but need more atoms…

Thank you!