Output Mode Cleaners: implementation and design

Daniela Pascucci

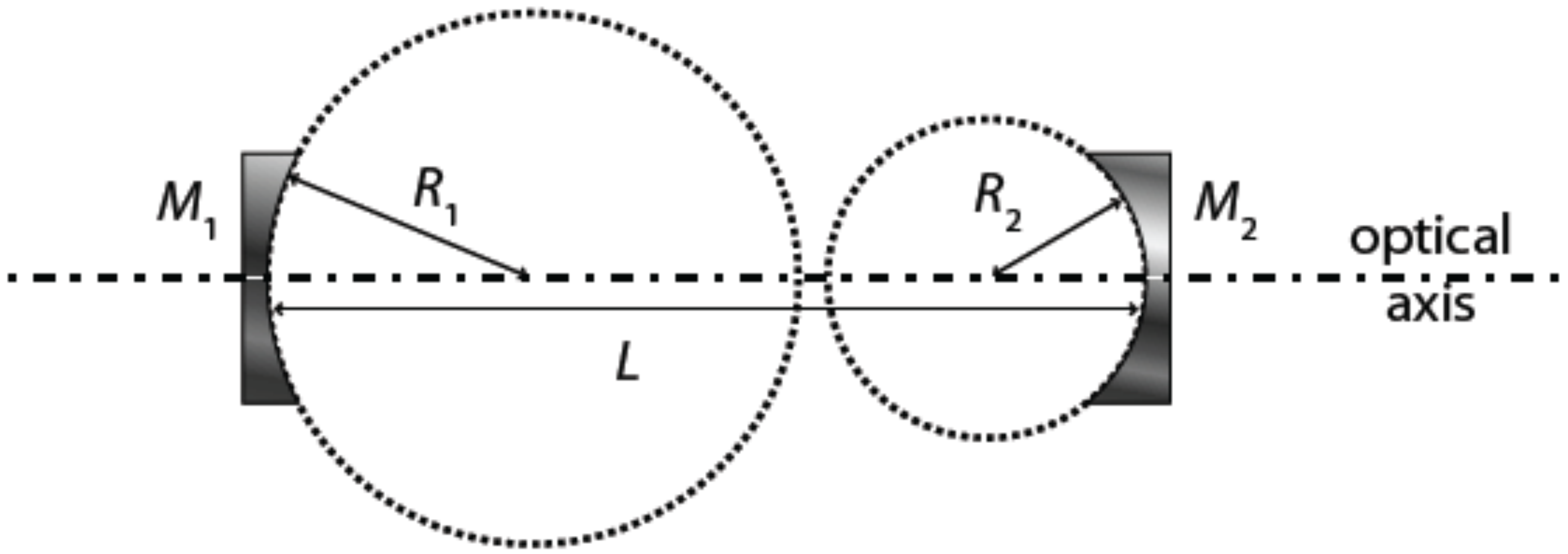
Workshop: Essential Technologies for the EinsteinTelescope - 27/11/2023

Outline

- Optical cavities
- Output Mode Cleaner
- Development of 2µm OMC for ETpf: work plan
  - Optical simulations
  - Assembly and characterisation
  - Installation and commissioning

Optical cavities: stability

An optical resonator (or resonant optical cavity) is an arrangement of optical components which allows a beam of light to circulate in a closed path.



$$g_1 = 1 - \frac{L}{R_1} \qquad g_2 = 1 - \frac{L}{R_2}$$

Stability criterion

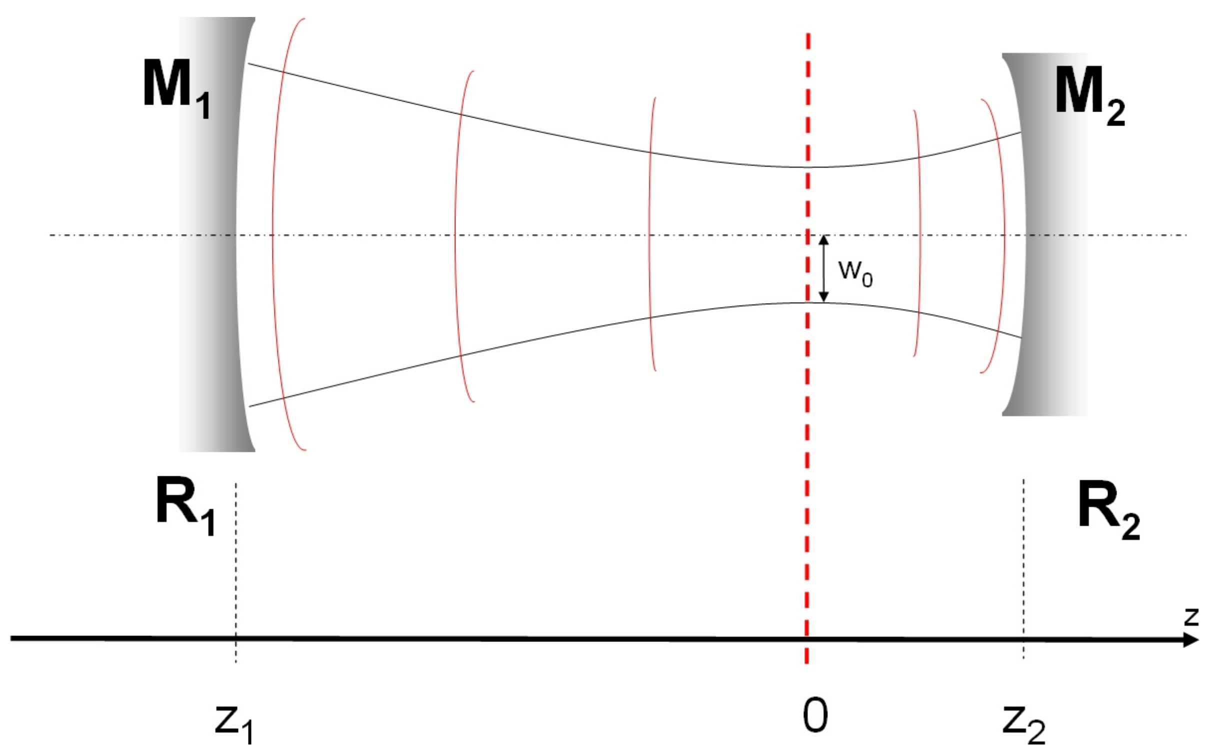
$$0 \leq g_1 g_2 \leq 1$$

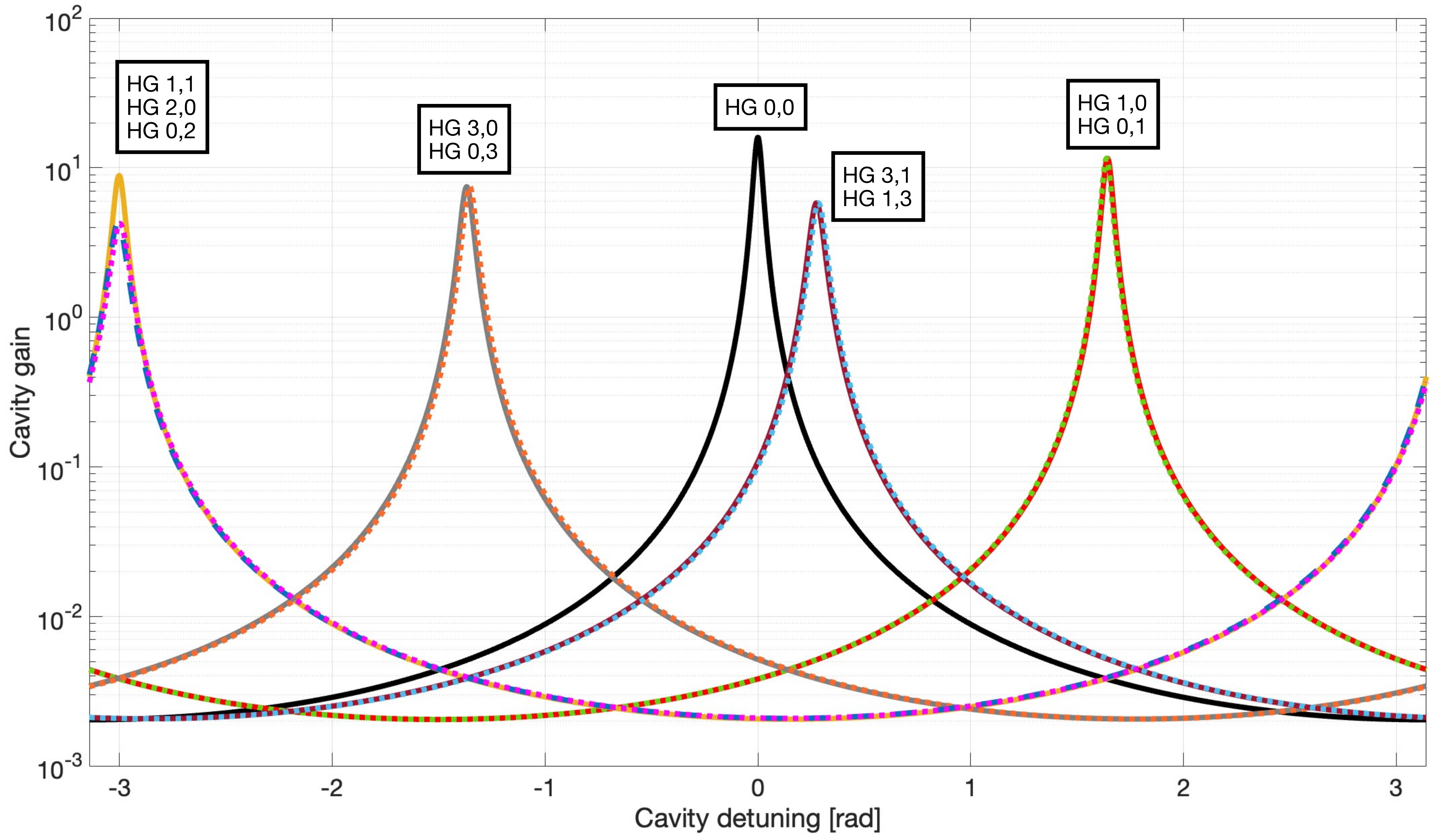
In a stable cavity:

- a ray is periodically re-focussed, it is trapped and does not escape the cavity;
- there are low losses;
- after a large number of reflections, a paraxial ray continues to remain close to the optic axis.

Optical cavities: resonances

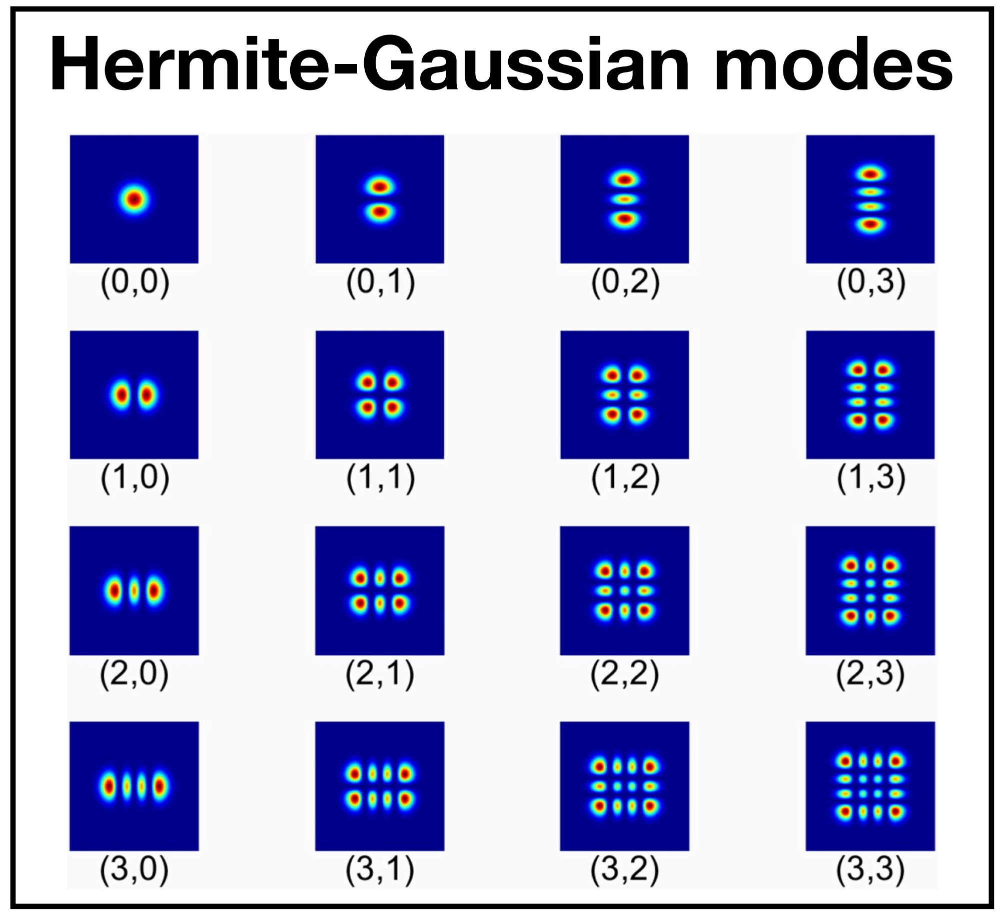
Resonant mode -> $RoC_{mode} = RoC_{mirror}$





To fully resonate an incoming laser beam in a cavity, two resonance conditions need to be fulfilled:

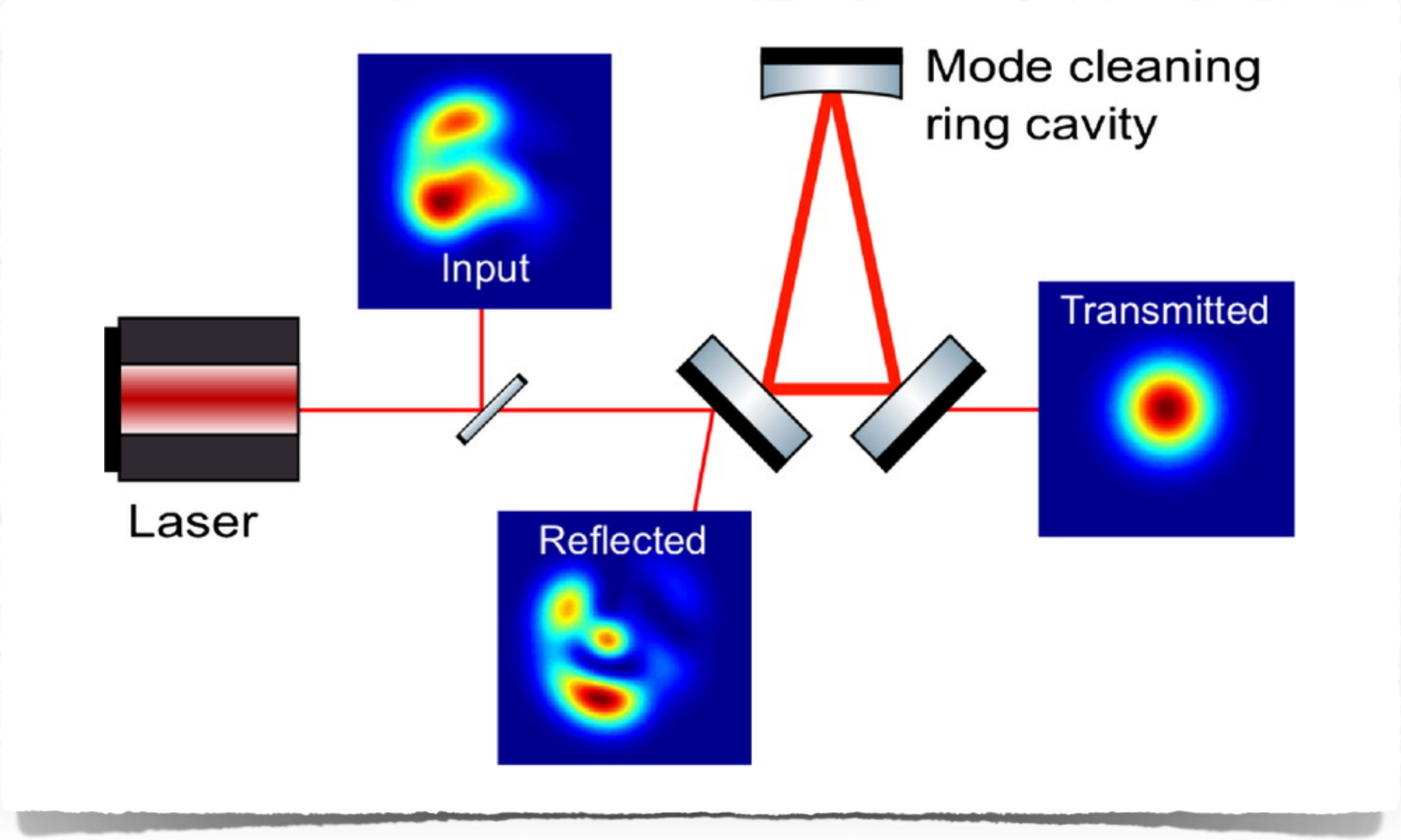
- The Gaussian beam parameter after a full round trip equals the Gaussian beam parameter of the laser beam entering the cavity. ↛ **mode mismatch**
- The cavity round trip length must be a multiple of the wavelength of the incoming light. ↛ **detuning**



Mode Cleaner Cavity

A mode cleaner is an optical device that allows to select a preferred mode for the light beam and removes any other unwanted modes.

It is basically an optical cavity with resonance frequency equal to the one of the selected mode, which will then be enhanced while the others are reduced.



Output Mode Cleaner

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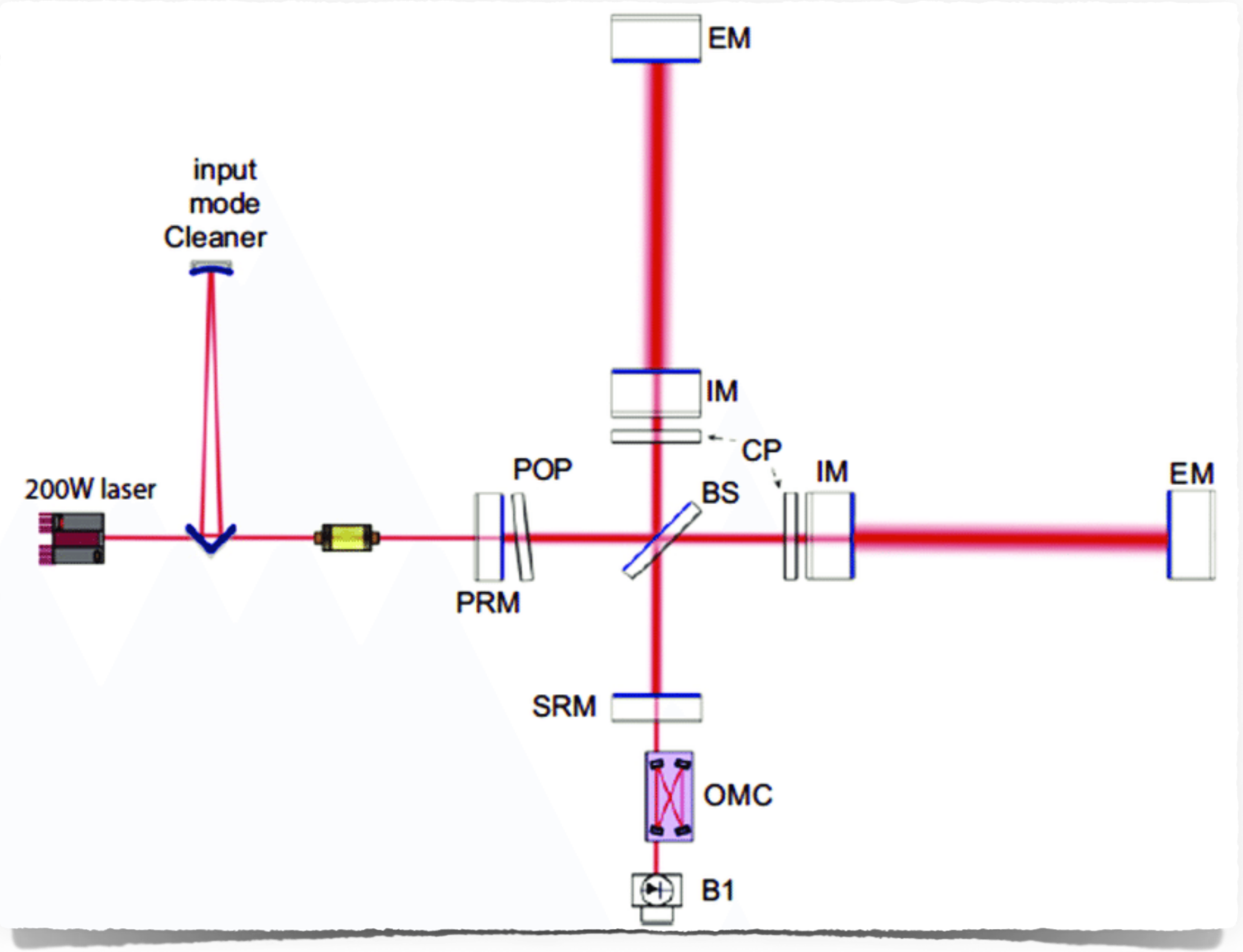
The output mode cleaner is placed between the output of the interferometer and the photodetector.

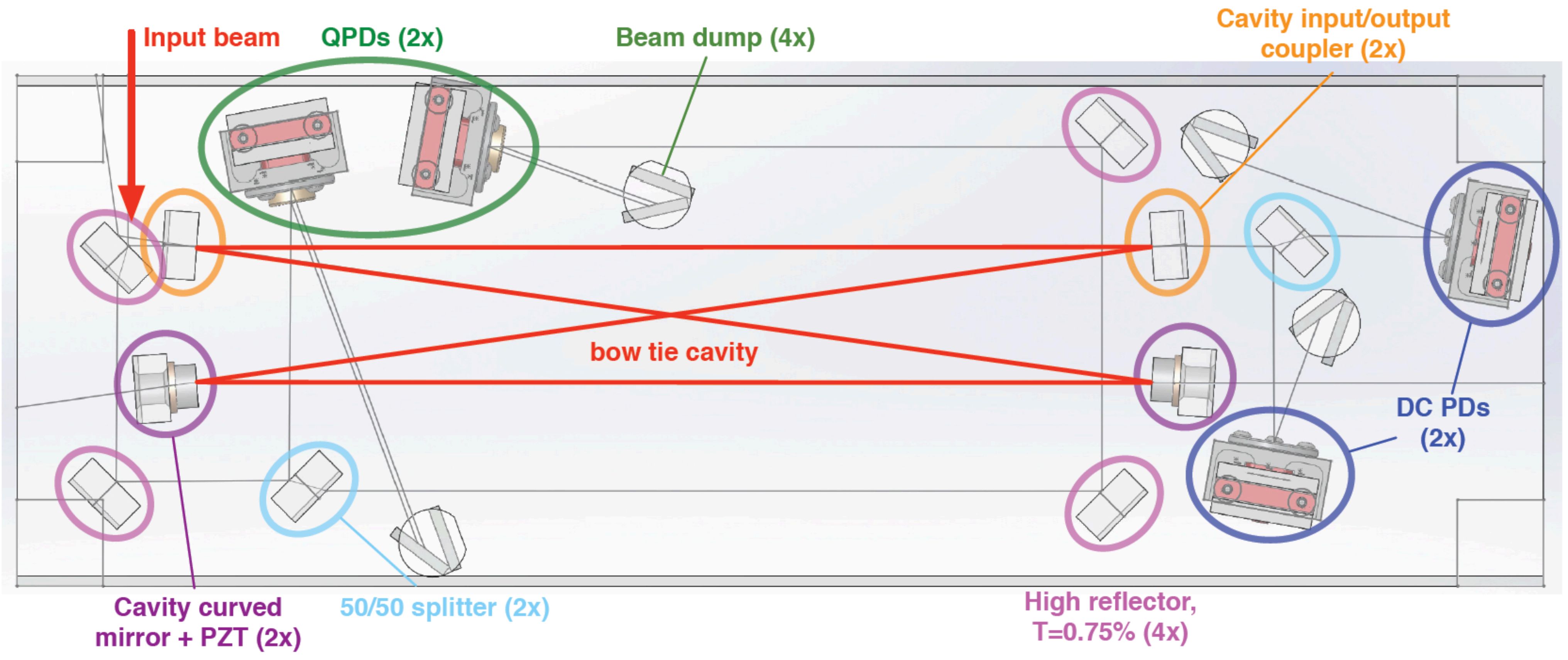
Its main purpose is to “clean” the output signal from “junk” light, such as:

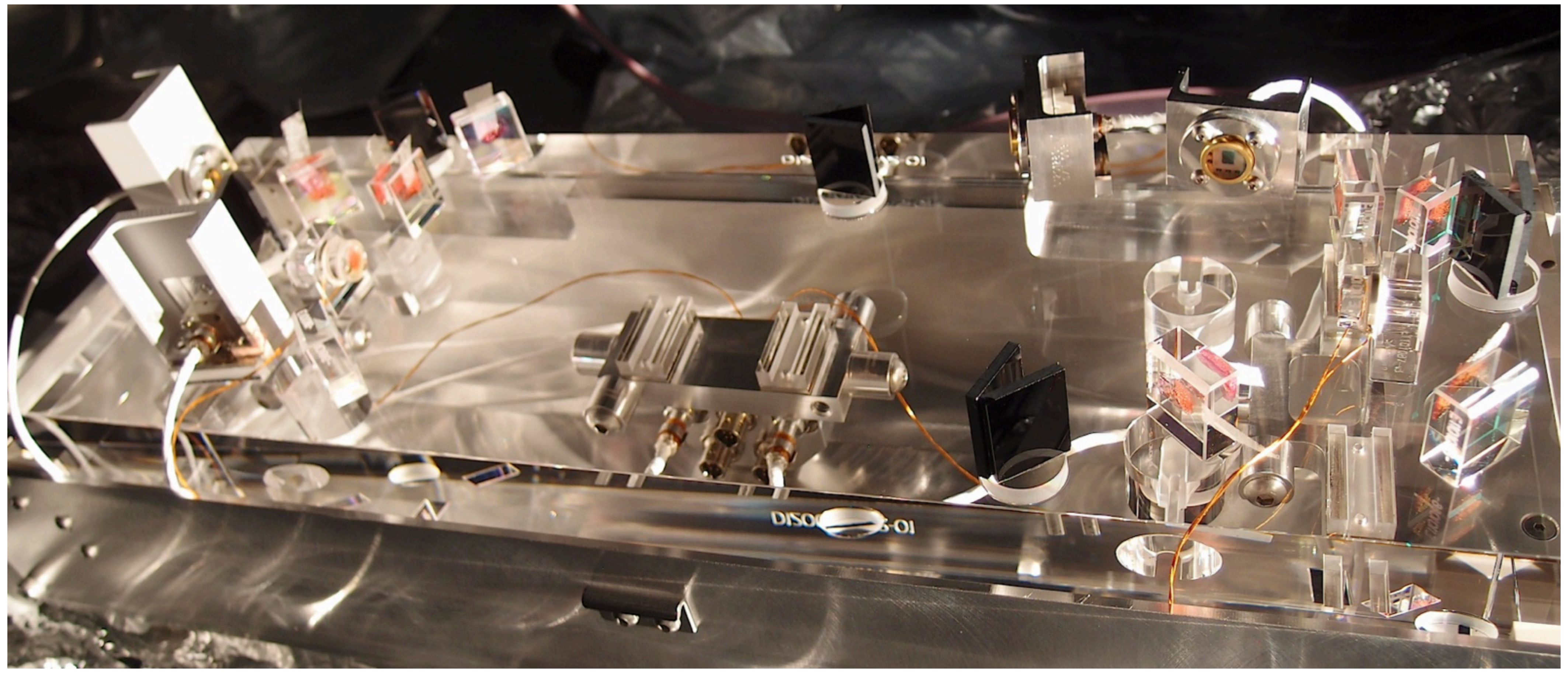
- **HOM** generated in the interferometer by thermal effects, mirrors imperfections, etc.;
- **Sidebands** used to control the interferometer.



OMC in current detectors

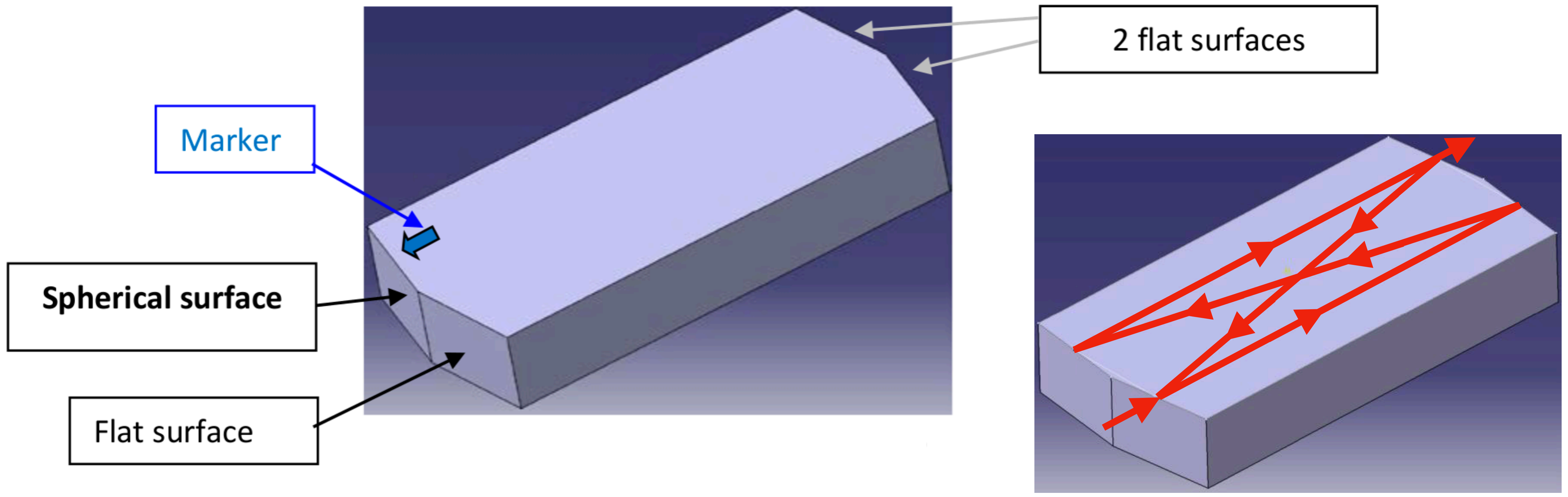
AdLIGO

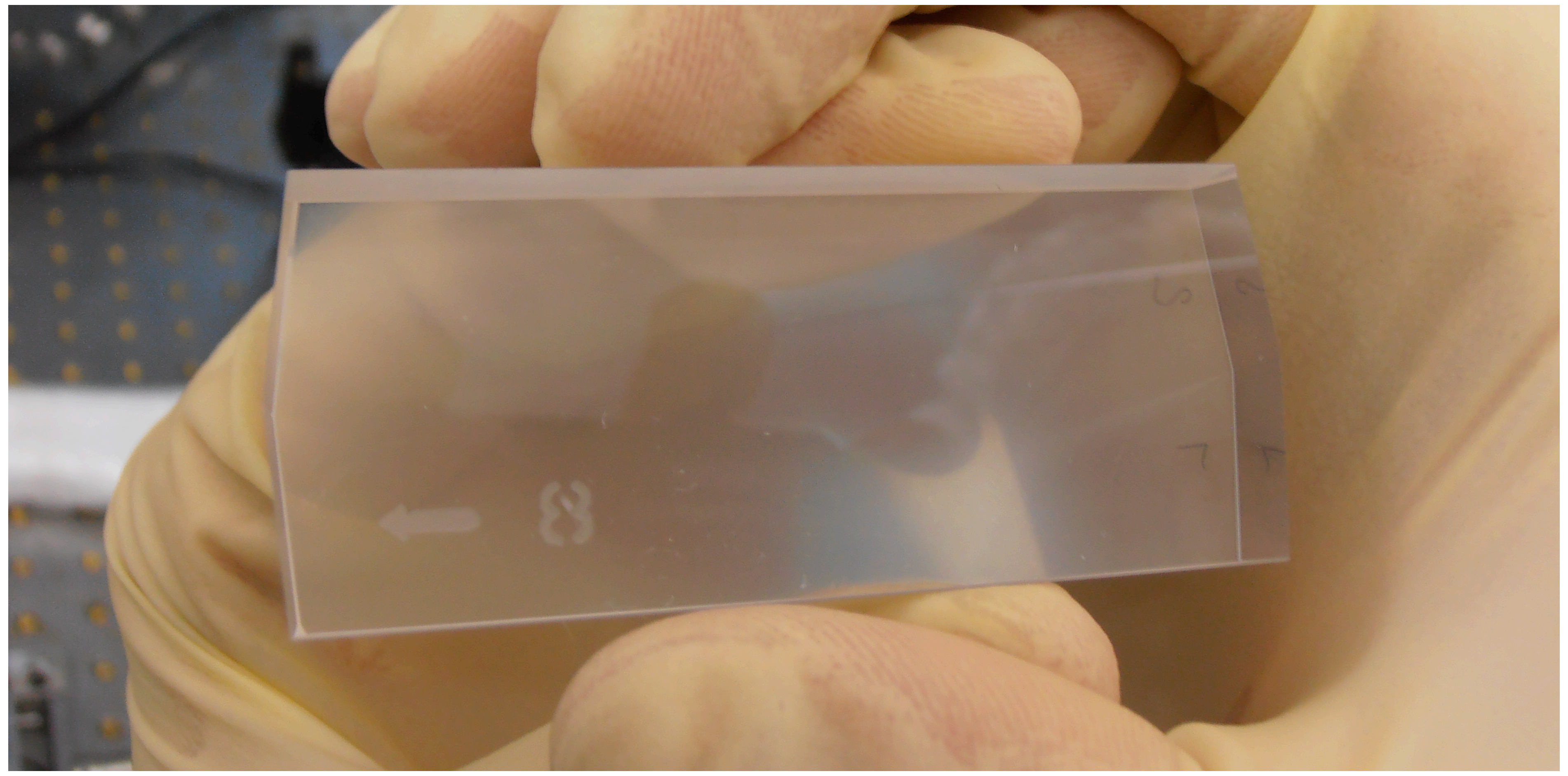




Images credit: https://dcc.ligo.org/public/0108/G1301001/001/KArai_OMC_LVC_2013_9.pdf

AdVirgo





Images credit: VIR-0093A-14, VIR-0635A-22

Why a 4 mirrors cavity?

- It can be made **compact** in the direction of the beam.
- The equal distribution of mass on either side of the optical axis **simplifies the seismic isolation**.
- Of the four mirrors of the cavity:
  - two are used as **input and output mirrors**,
  - one is mounted on a PZT for **length control**,
  - one can be partially transparent and be used as a pickup to **monitor** the beam circulating in the OMC.
- Using an even number of mirrors keep the **resonance degeneracy** between the transverse electromagnetic modes of the same orders.

[source: M. Prijatelj et al. The output mode cleaner of GEO 600, Class. Quantum Grav. **29** 055009 (2012)]

OMC for ETpathfinder (2μm)

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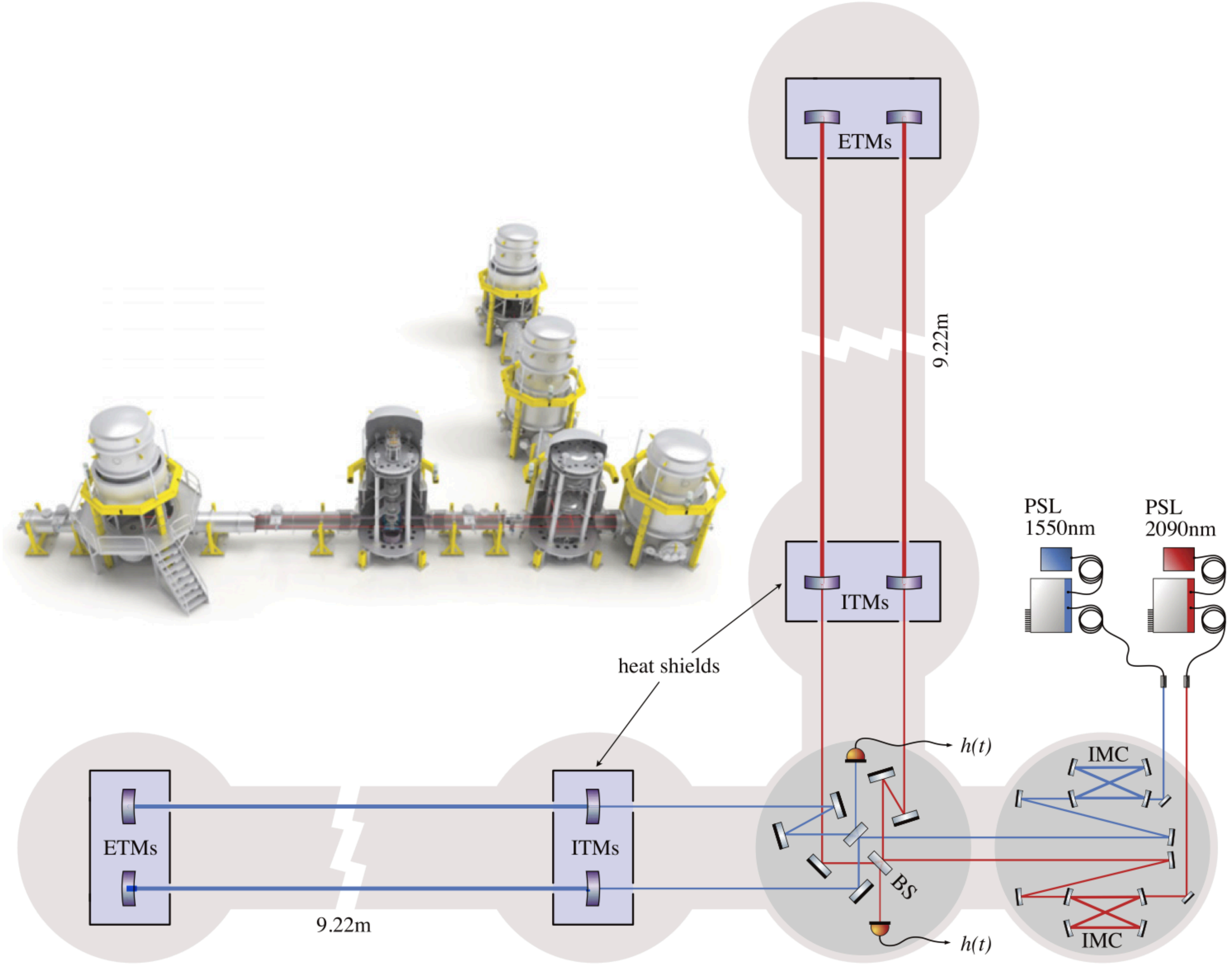
ETpathfinder is an R&D facility, located in Maastricht, with the aim to test new techniques and give important inputs for the design and the construction of 3rd generation GW detectors, like ET.

The proposed laser wavelengths for next generation GW detectors are 1550nm and 2μm. While for the first most of the technologies have already been tested and developed, that is not true for 2μm.

In agreement with ETpathfinder project leader, Ghent University is taking charge of the development of the OMC for 2μm wavelengths that will be installed in ETpathfinder.

The design will be based on the LIGO model.



Work plan

1. Simulations will be done in order to define the **design** and the **requirements** of the OMC. **[in progress]**

2. The **characterisation** will be done through tests on the single components, both optical and electronics.

3. After the characterisation of the single components there will be the **assembly** of the full device.

4. After the assembly, the **characterisation** to check the performance of the full device will be done..

5. Last part of the project will be the **installation** and **commissioning** of the OMC in ETpathfinder.

Design and requirements

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Requirements/constraints

- SB attenuation factor
- HOM attenuation factor
- Space on the bench
- Astigmatism
- Topology: symmetrical bowtie
- Scattering
- Misalignment

→

Specifications

- Finesse
- g-factor
- Round trip length (detuning)
- Resonances (mode mismatch)
- Loss
- Angles
- Backscattering
- Mechanical resonances

Softwares

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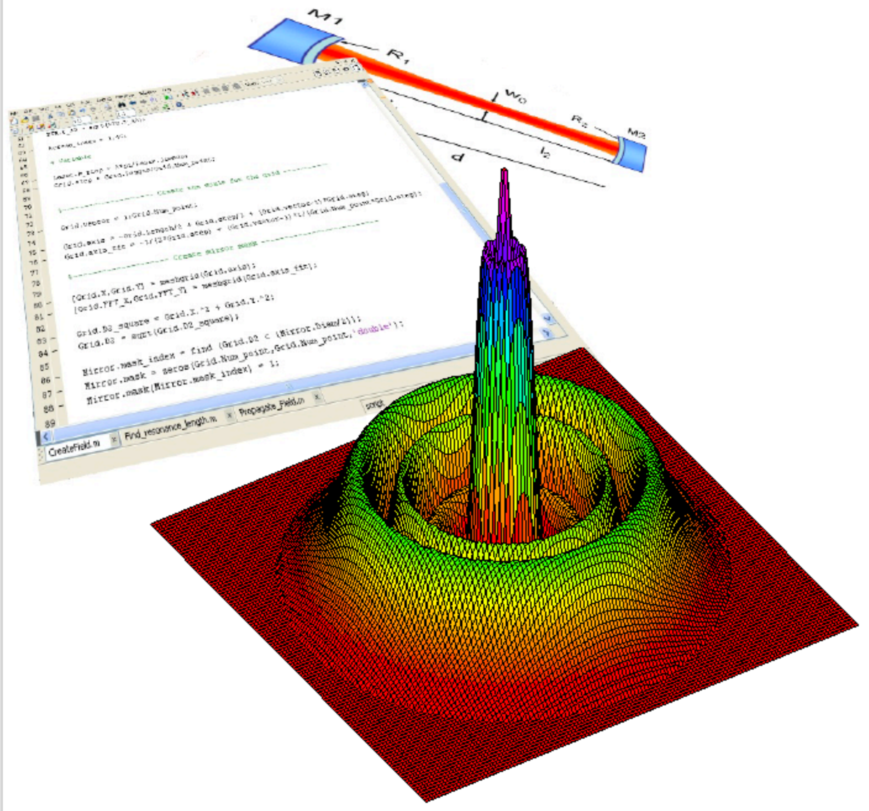
➡ **OSCAR** *is an optical FFT code used to calculate the steady state optical field circulating in Fabry-Perot cavities. The code can integrate non-spherical mirrors and any arbitrary input fields. Typical applications for OSCAR have been: calculation of thermal lensing effect and calculation of diffraction loss and cavity eigenmodes for arbitrary beam shapes* [1].

➡ **Finesse** *is an interferometer simulation program. It calculates light amplitudes in a user-specified interferometer configuration and can generate output signals for various photo detector types. All calculations are done in the frequency domain* [2].

OSCAR

A Matlab-based optical FFT code



Finesse 2

(Frequency domain INterfErometer Simulation SoftwarE)

[1] https://www.mathworks.com/matlabcentral/fileexchange/20607-oscar

[2] http://www.gwoptics.org/finesse/

Simulations: OSCAR (I)

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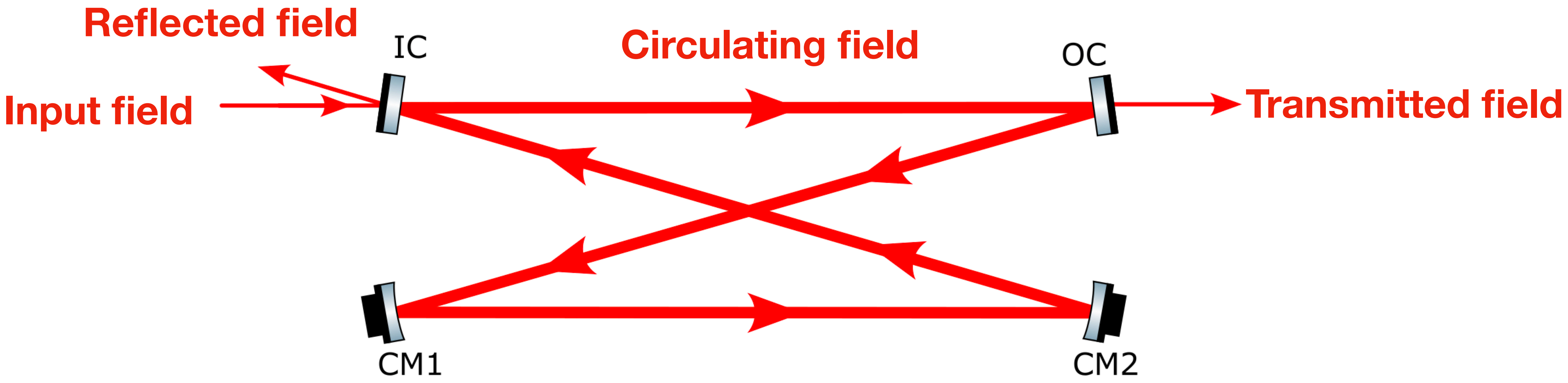
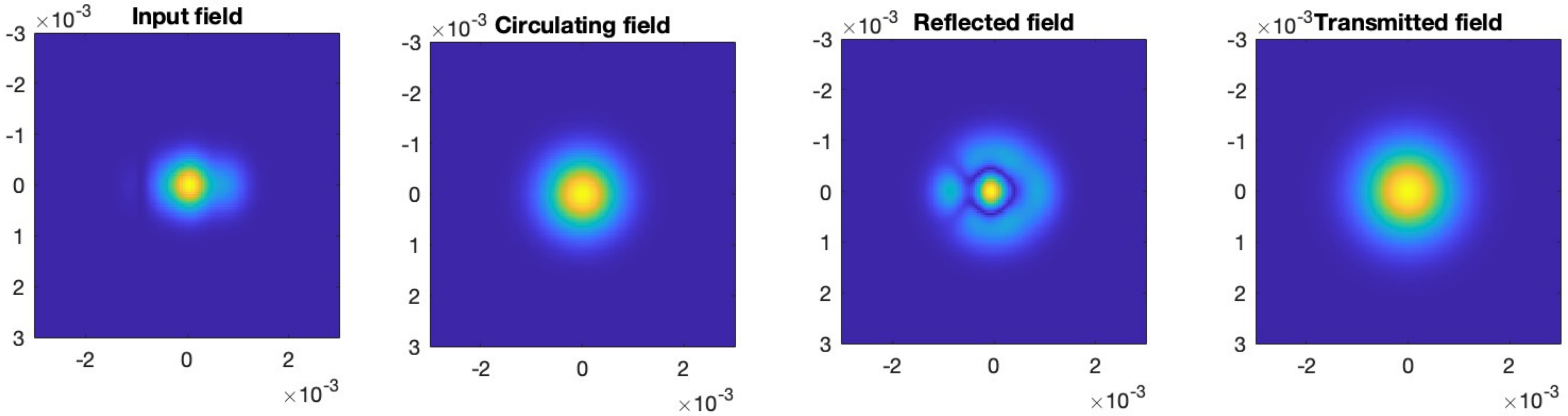
Example of an input beam not purely gaussian

```
E_input = E_Field(G1, 'w0',5e-4, 'P',1.0, 'Wavelength',2090E-9, 'mode','HG 0 0') +…
          E_Field(G1, 'w0',5e-4, 'P',0.01, 'Wavelength',2090E-9, 'mode','HG 1 0') +…
          E_Field(G1, 'w0',5e-4, 'P',0.01, 'Wavelength',2090E-9, 'mode','HG 2 0') +…
          E_Field(G1, 'w0',5e-4, 'P',0.01, 'Wavelength',2090E-9, 'mode','HG 3 0') +…
          E_Field(G1, 'w0',5e-4, 'P',0.01, 'Wavelength',2090E-9, 'mode','HG 4 0') +…
          E_Field(G1, 'w0',5e-4, 'P',0.01, 'Wavelength',2090E-9, 'mode','HG 5 0')
```

→ 1 W (HG 0 0)

→ 0.05 W (HG 1 0 to HG 5 0)



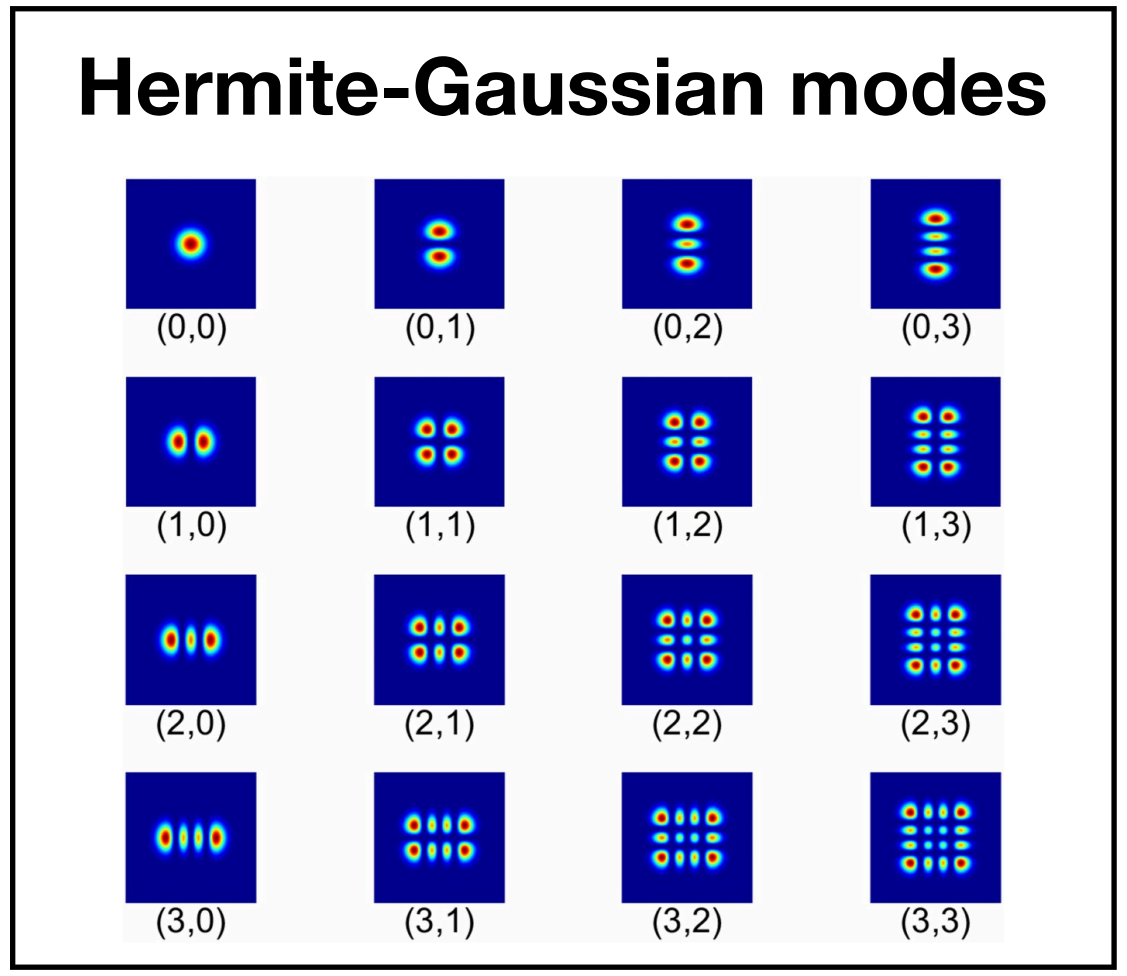


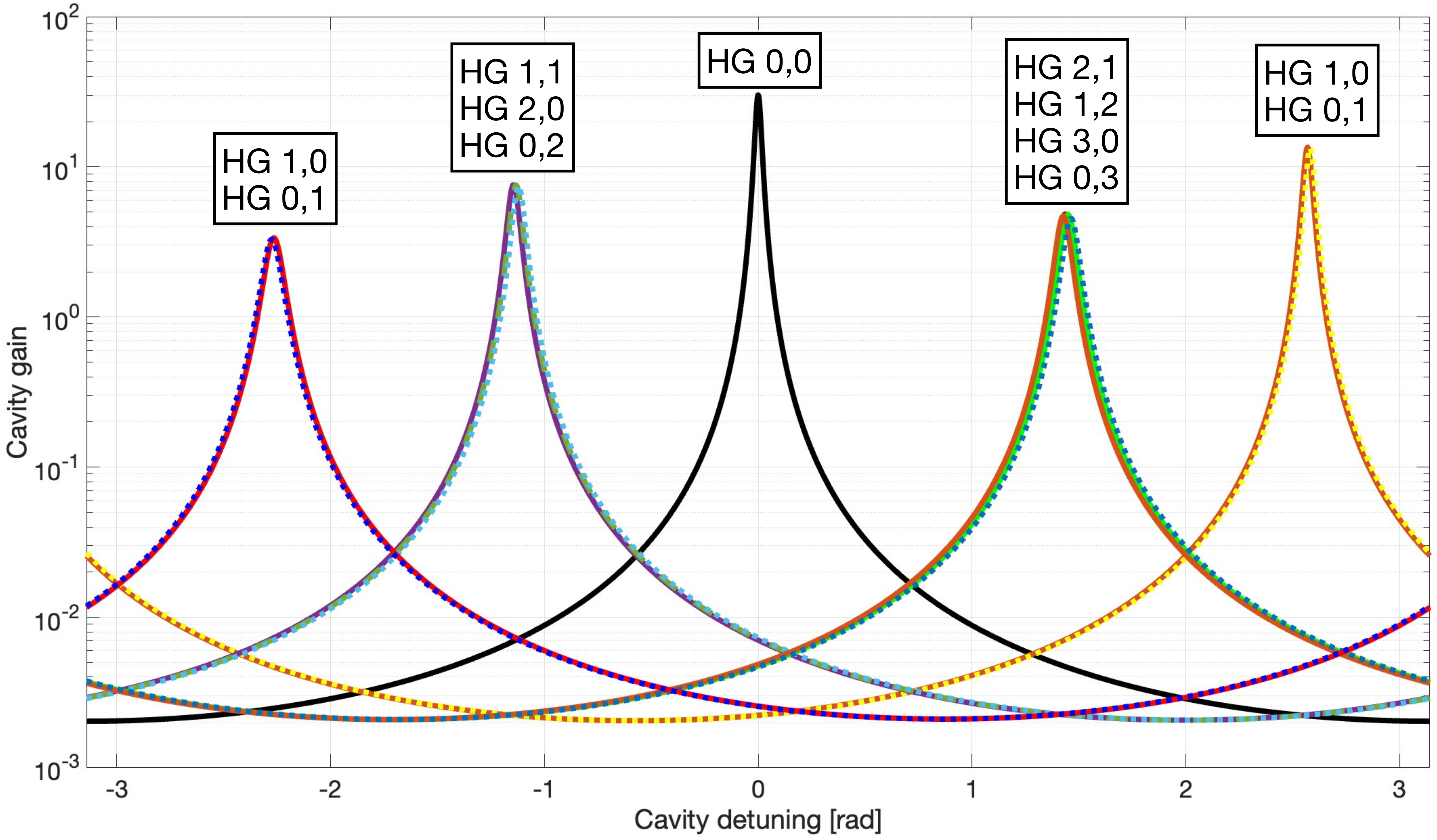

```
You have created a ring cavity with 4 mirrors
Found the phase for resonance in cavity OMC
 Power in the input beam 1.05 [W]
 Circulating power 114.202 [W]
 Total transmitted power 0.924942 [W]
 Reflected power 0.124966 [W]

----------------- For the surface 1  -----------------
RofC fitted (m): -5.54202e+98
Center of the map, horizontal (mm): 0
Center of the map, vertical (mm): 0
Tilt horizontal (nrad): 0
Tilt vertical (nrad): 0
Flatness RMS (nm): 5.32032e-96,

----------------- For the surface 2  -----------------
RofC fitted (m): -5.54202e+98
Center of the map, horizontal (mm): 0
Center of the map, vertical (mm): 0
Tilt horizontal (nrad): 0
Tilt vertical (nrad): 0
Flatness RMS (nm): 5.32032e-96,

----------------- For the surface 3  -----------------
RofC fitted (m): 2.49999
Center of the map, horizontal (mm): -3.32633e-08
Center of the map, vertical (mm): -6.03896e-08
Tilt horizontal (nrad): 0.0132952
Tilt vertical (nrad): 0.0241452
Flatness RMS (nm): 1.85079,

----------------- For the surface 4  -----------------
RofC fitted (m): 2.49999
Center of the map, horizontal (mm): -3.32633e-08
Center of the map, vertical (mm): -6.03896e-08
Tilt horizontal (nrad): 0.0132952
Tilt vertical (nrad): 0.0241452
Flatness RMS (nm): 1.85079,

  Beam radius on the first mirror: 0.000720981
  Beam radius on mirror 2 [m]: 0.000720981
  Beam radius on mirror 3 [m]: 0.000882337
  Beam radius on mirror 4 [m]: 0.000882337
  Cavity finesse: 388.705
  Cavity gain: 123.464
  Mode matched input beam parameters:
  Beam radius [m]: 0.000721039    Wavefront curvature [m]: -3.05752
```

Simulations: OSCAR (II)

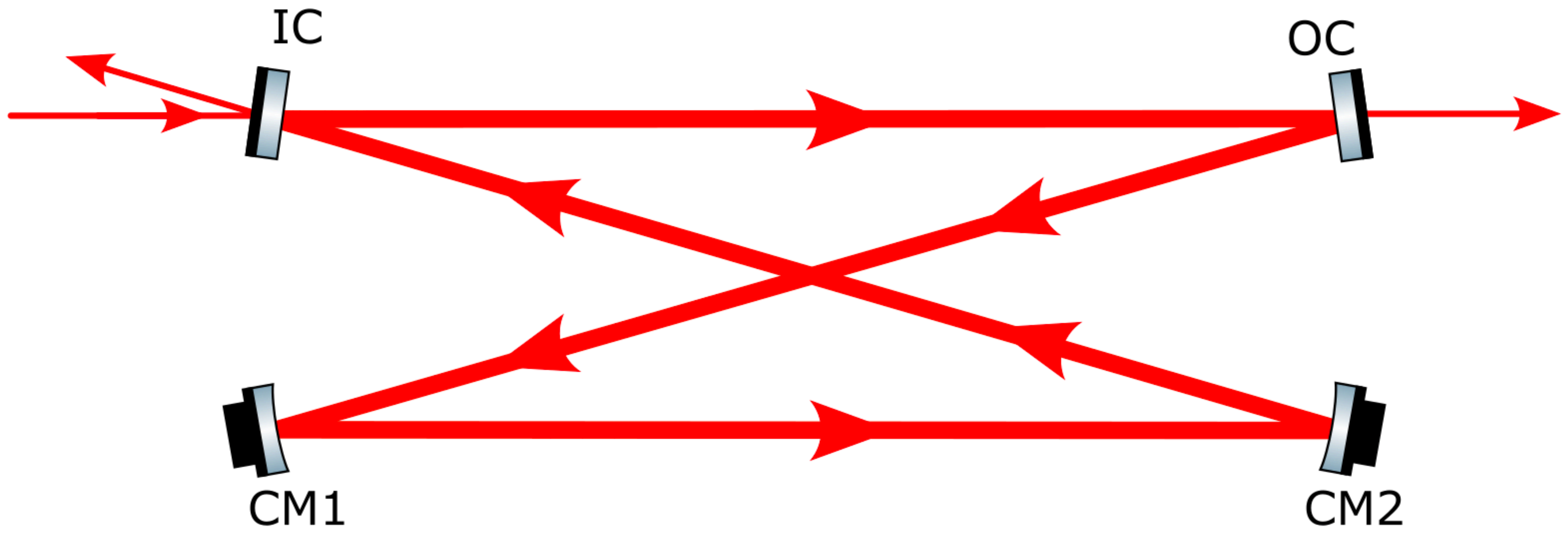
Simulations for a OMC similar to LIGO model, but with 2090 nm wavelength.

Results show the first 12 HOM with higher amplitude as a function of the detuning.

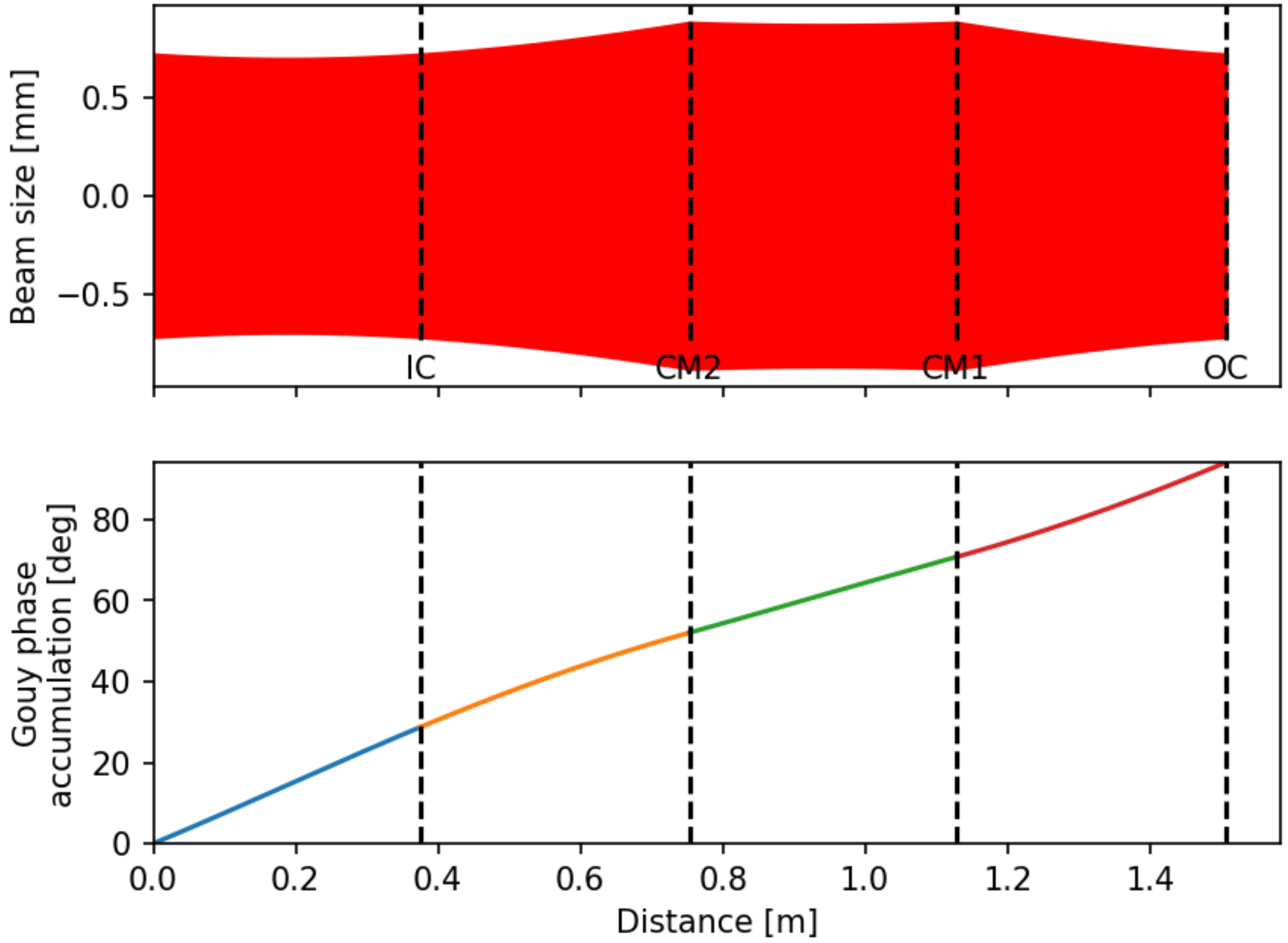




Simulations: Finesse



	z	w0	zr	w	RoC	Acc. Gouy	q
OC.p1.o	0 m	697.78 um	731.88 mm	720.3 um	−3.045 m	0°	−0.187 + 0.732j
IC.p3.i	374.9 mm	697.78 um	731.88 mm	720.3 um	3.045 m	28.732°	0.187 + 0.732j
IC.p4.o	374.9 mm	697.78 um	731.88 mm	720.3 um	3.045 m	28.732°	0.187 + 0.732j
CM2.p2.i	753.5 mm	697.78 um	731.88 mm	882.13 um	1.5123 m	52.085°	0.566 + 0.732j
CM2.p1.o	753.5 mm	870.41 um	1.1388 m	882.13 um	−7.1061 m	52.085°	−0.187 + 1.139j
CM1.p2.i	1.1284 m	870.41 um	1.1388 m	882.13 um	7.1061 m	70.779°	0.187 + 1.139j
CM1.p1.o	1.1284 m	697.78 um	731.88 mm	882.13 um	−1.5123 m	70.779°	−0.566 + 0.732j
OC.p2.i	1.507 m	697.78 um	731.88 mm	720.3 um	−3.045 m	94.133°	−0.187 + 0.732j



Characterisation

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Single components characterisation

- Mirrors: reflection, transmission, scattering, radius of curvature, centre of curvature, …
- Photodiode: response, dark noise, …
- Piezo: length noise, …
- …

Characterisation of the integrated OMC

- Alignment
- Backscattering
- Loss
- Cavity length
- …

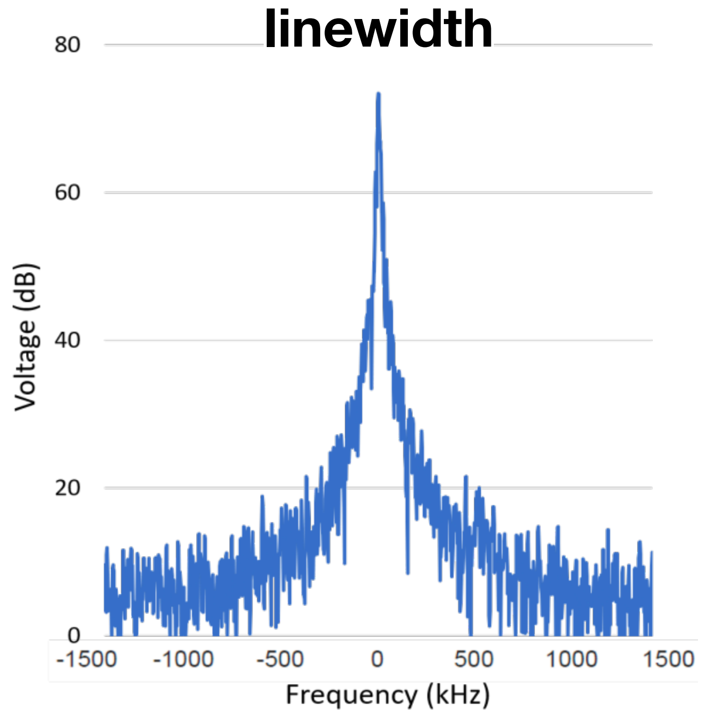
Optical lab

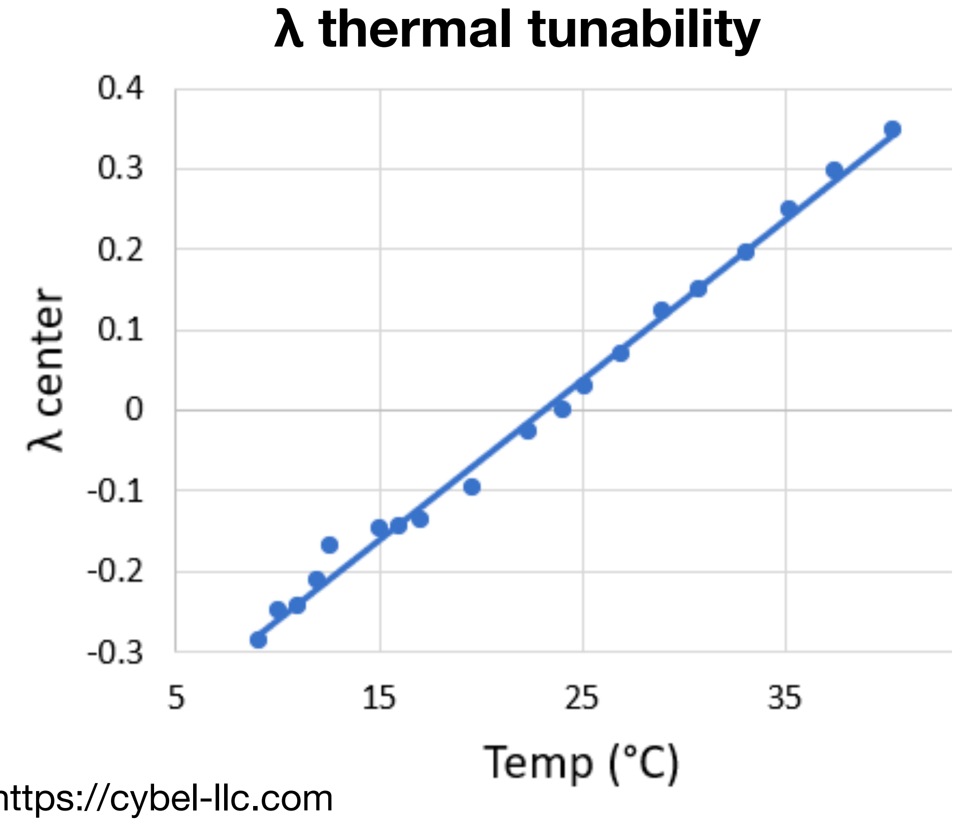
Lab for optical characterisation at 2µm wavelength.

- The optical lab will be located at the Proeftuin Campus of Ghent University.
- A laminar flow enclosure with fan filter unit and air control monitor will be installed to ensure a clean environment. The clean area dimensions will be approximately 2mx3m.
- The lab will be provided with a very stable laser source and devices for optical measurements and characterisation.

The laser

- Model: Cybel ORION-2000
- Type: CW fiber laser
- Wavelength: 2090.0 ± 0.1 nm
- λ thermal tunability: ± 0.4 nm
- Linewidth: 10 kHz
- Output power ≥ 2 mW
- RIN (for f > 10kHz) < -150 dBc/Hz
- Fiber type: PM
- PER > 23 dB
- Integrated output isolator: 25 dB





pictures credit: https://cybel-llc.com

Assembly

All the optical components need to be bonded on the silica breadboard. In order to achieve the maximum possible precision, the work will be done with the help of a mask, which can be produced in the workshop facility available in Ghent University.

LISA optical bench assembly

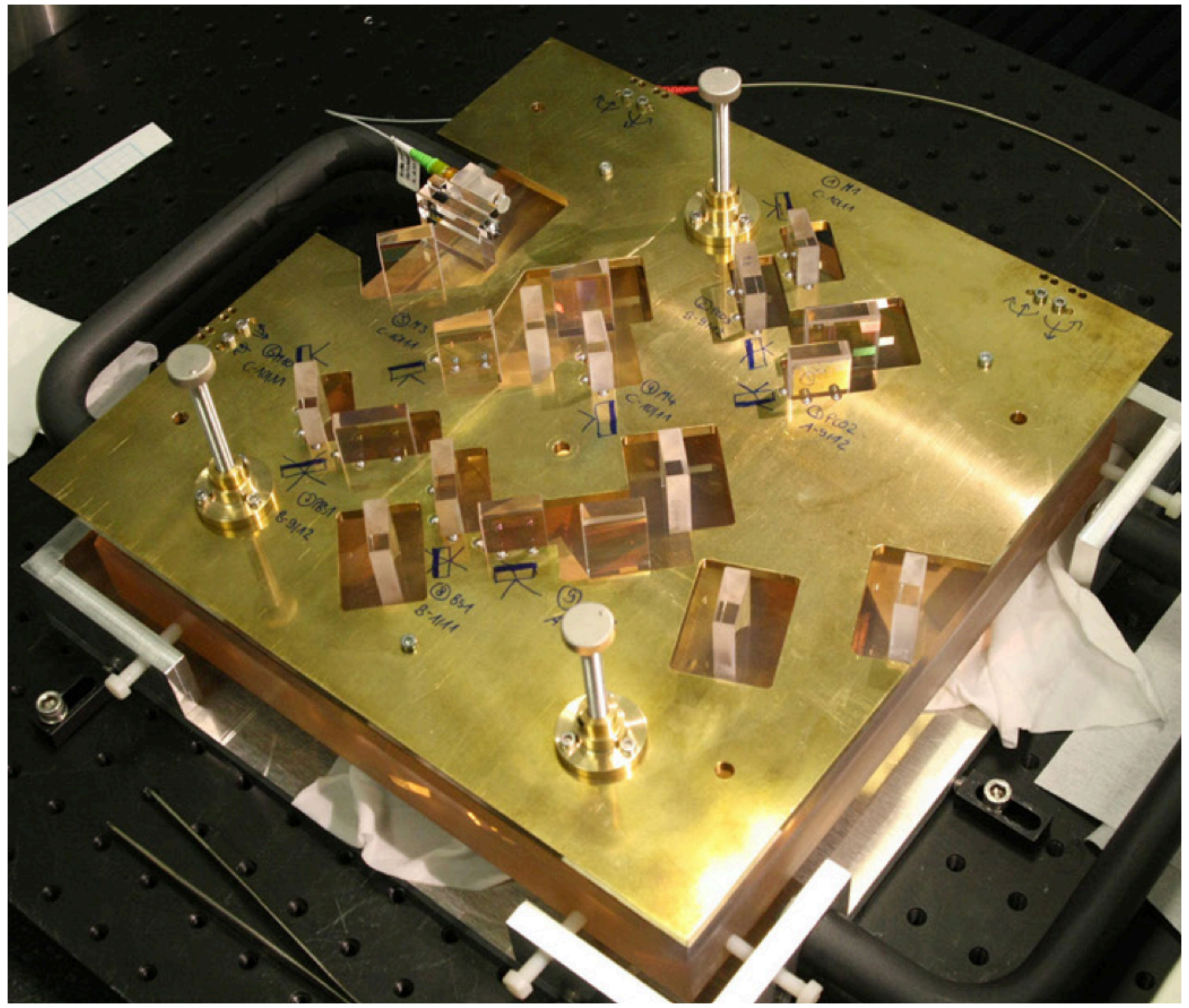


Image credit: https://arxiv.org/pdf/1607.00408.pdf

OMC assembly at LIGO

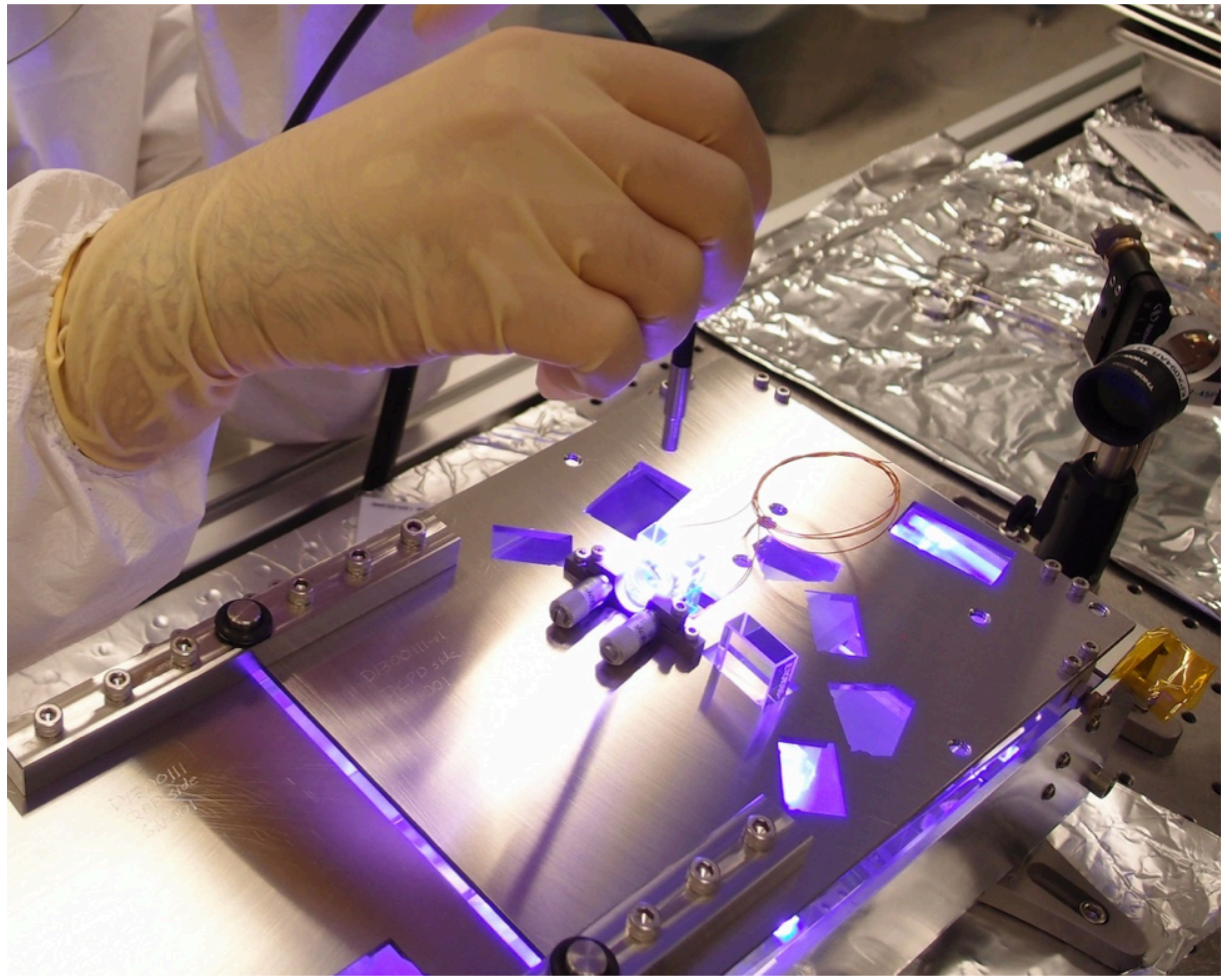


Image credit: https://dcc.ligo.org/public/0108/G1301001/001/KArai_OMC_LVC_2013_9.pdf

Installation and commissioning

Last part of the project will be the installation and commissioning of the OMC in ETpathfinder.

The OMC will be installed on one of the suspended benches located in a vacuum tower. The work will require high precision and caution in order to achieve a perfect alignment and avoid any issue with all the other optics already mounted on the bench.

Finally the commissioning of the device will take place with the purpose of refine the performance and integrate it into the ETpathfinder interferometer.

Conclusions

- The OMC is fundamental to improve the readout signal of a GW detector.
- UGent is taking charge of the development of the OMC for 2 µm wavelengths that will be installed in ETpathfinder.
- Simulations to define the design are in progress using OSCAR and Finesse softwares.
  - Plan to includes mirror maps for more realistic simulations.
  - Other tools are being considered (VirtualLab, RP Resonator).
- After the design is complete the assembly and characterisation will be done at UGent, in collaboration with Nikhef, Maastricht University and VUB.
- Planned to have it ready to be installed in ETpf in ~2025.

Thank you for your attention!