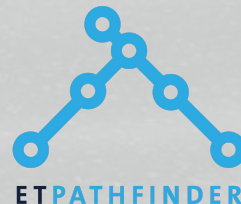


Output Mode Cleaner for ETpathfinder

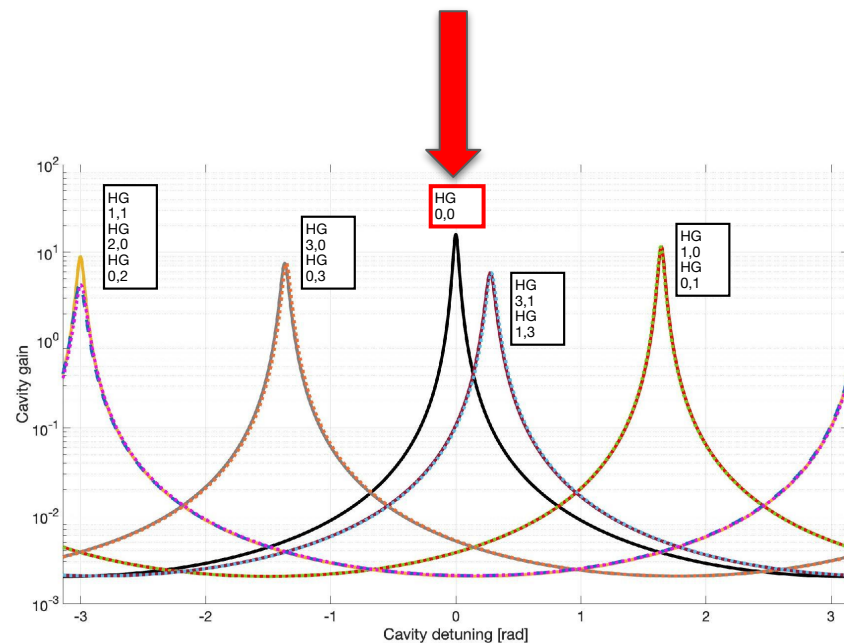
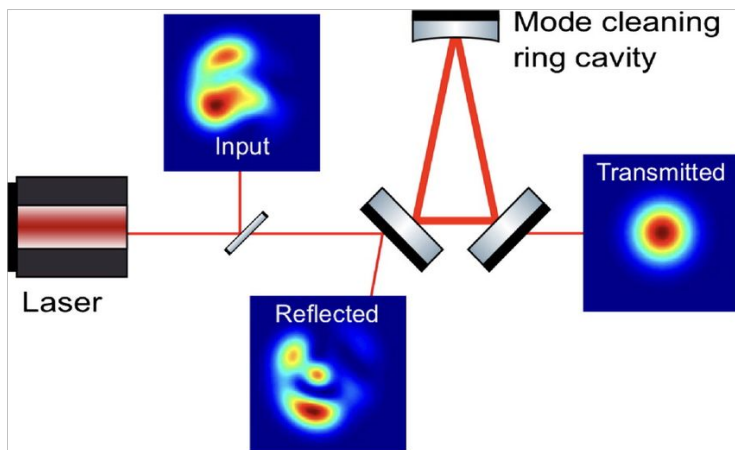
F. De Marco, D. Pascucci, O. Marchand

Belgian-Dutch Gravitational Wave Meeting - Louvain-la-Neuve, 7-9 October 2026



Mode cleaner cavity

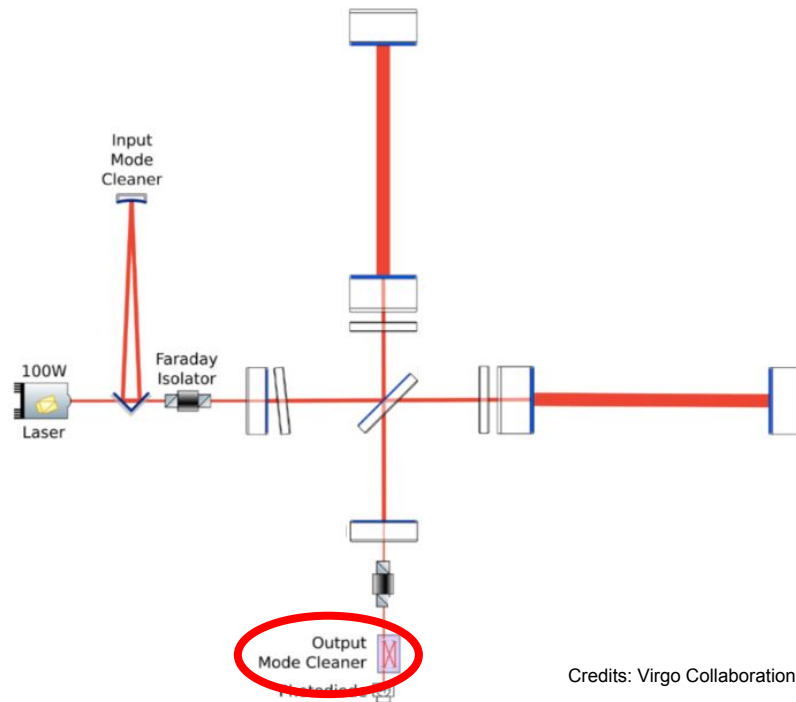
- A mode cleaner is an optical cavity that allows to select a preferred mode for the light beam and removes any other unwanted modes
- Its resonance frequency is tuned on a selected mode, which will then be enhanced while the others are reduced



The output beam is almost purely Gaussian (zero-order mode), and it exhibits improved pointing stability

Output Mode Cleaner (OMC) in GW detectors

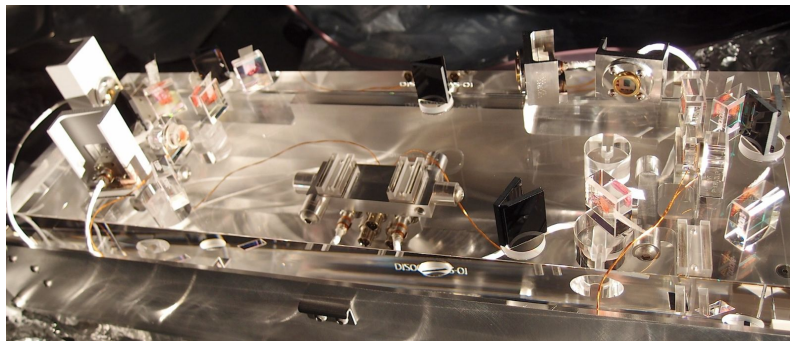
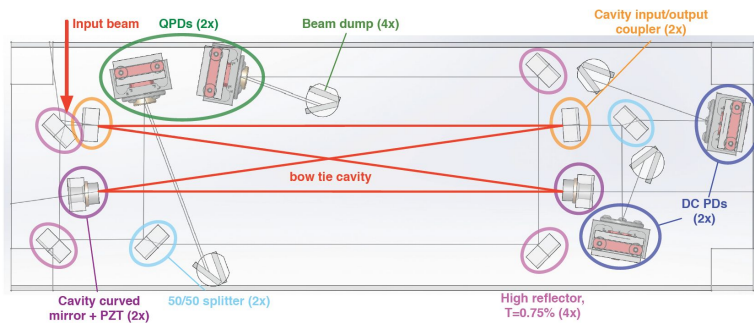
- The Output Mode Cleaner is placed between the output of the interferometer and the detection photodiode
- Its purpose is to “clean” the output signal from unwanted light, such as:
 - Higher-Order Modes (HOM) generated in the interferometer by thermal effects, mirrors imperfections, etc.
 - Radio-Frequency (RF) sidebands used to control the interferometer
- Only the Gaussian beam carrying the GW signal is sent to the detection photodiode



Credits: Virgo Collaboration

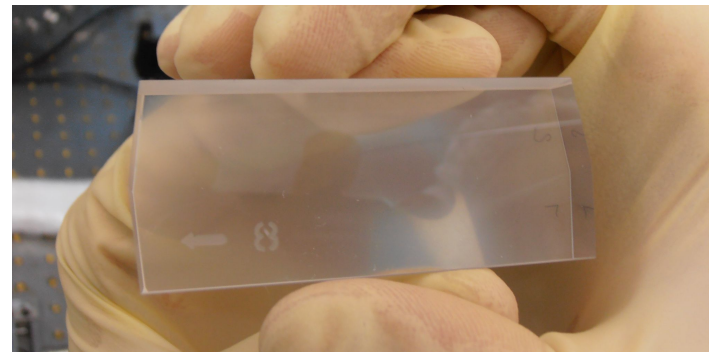
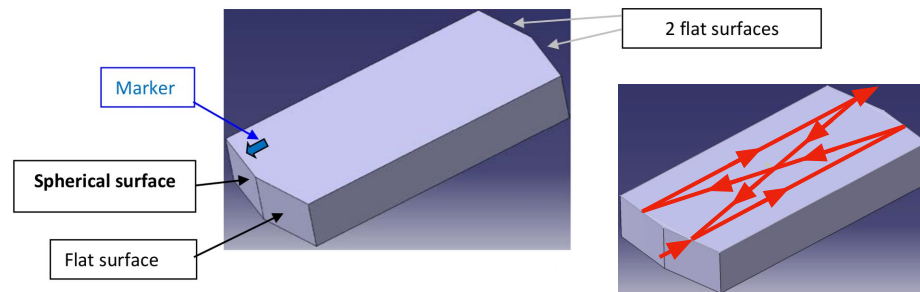
OMC in current detectors

AdLIGO



Images credit:
https://dcc.ligo.org/public/0108/G1301001/001/KArar_OMC_LVC_2013_9.pdf

AdVirgo



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

Why a 4-mirror (bow-tie) cavity?

Pros:

- It can be made compact in the direction of the beam
- Off-axis reflection to minimize back-scattered light
- The symmetric distribution of mass on either side of the optical axis simplifies the seismic isolation
- Using an even number of mirrors keeps the resonance degeneracy between TEM modes of the same order
- The 4 available mirrors can be used as follows:
 - 2 as input and output mirrors (flat)
 - 1 is mounted on a PZT for length control (curved, HR)
 - 1 can be used as a pickup to monitor the beam circulating in the OMC with a camera (curved, HR)

Cons:

- Higher optical losses (more surfaces), to be kept in mind while designing the cavity

Design and requirements

Requirements

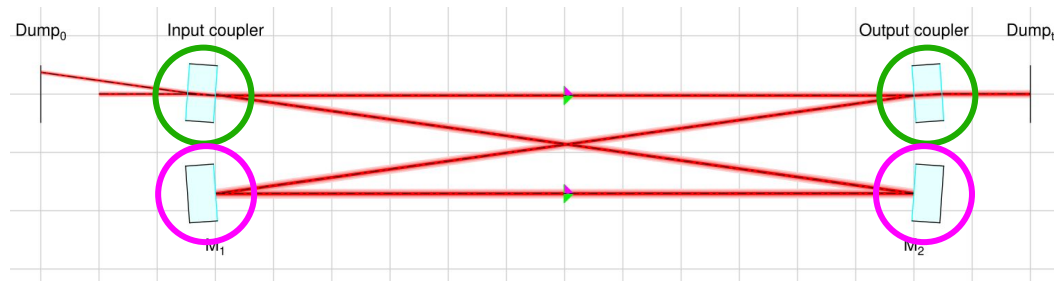
- Optical stability (g-factor)
- High HOM suppression factor (>20 dB)
- Low stray light
- Negligible astigmatism
- Compactness
- Easy to install and align



Parameters (geometrical and optical)

- Round trip length and mirror spacings
- Mirrors' radius of curvature
- Angle of incidence
- Finesse
- TEM spacing
- Optical loss
- Mechanical resonances

Optical design



1. Basic assumptions

- **I/O couplers** identical and flat
- The **other two mirrors** are identical, curved and HR-coated

2. Define safe regions for optical stability in the L_{rt} - RoC space

3. Find the (L_{rt}, RoC) couple minimizing the HOMs + RF sidebands transmission (assuming a given HOM distribution in input!)

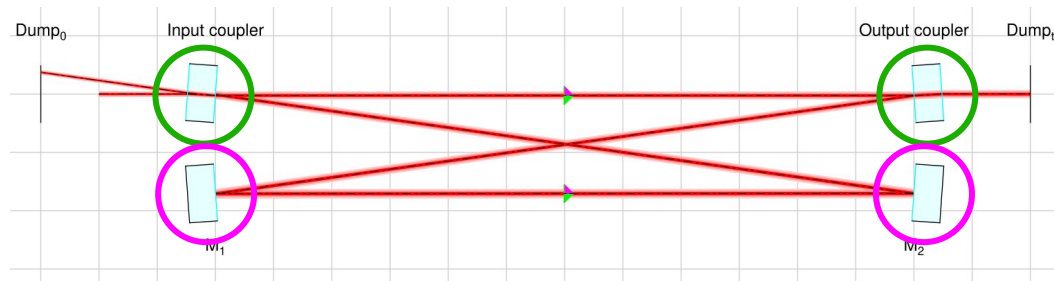
4. Find the angle of incidence

- Lower bound: back-reflected stray light and geometrical constraints
- Upper bound: astigmatism

5. Cavity finesse

- Lower bound: HOM suppression factor
- Upper bound: round-trip optical losses and dither locking

Optical design



1. Basic assumptions

- I/O couplers identical and flat
- The other two mirrors are identical, curved and HR-coated

2. Define safe regions for optical stability in the L_{rt} - RoC space

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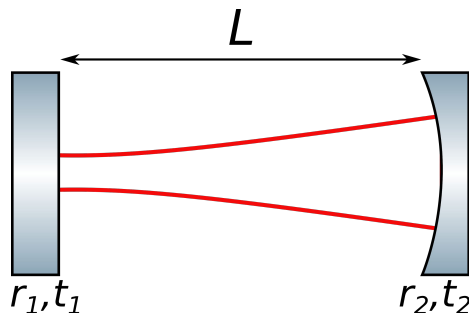
5. Cavity finesse

- Lower bound: HOM suppression factor
- Upper bound: round-trip optical losses and dither locking

Optical stability

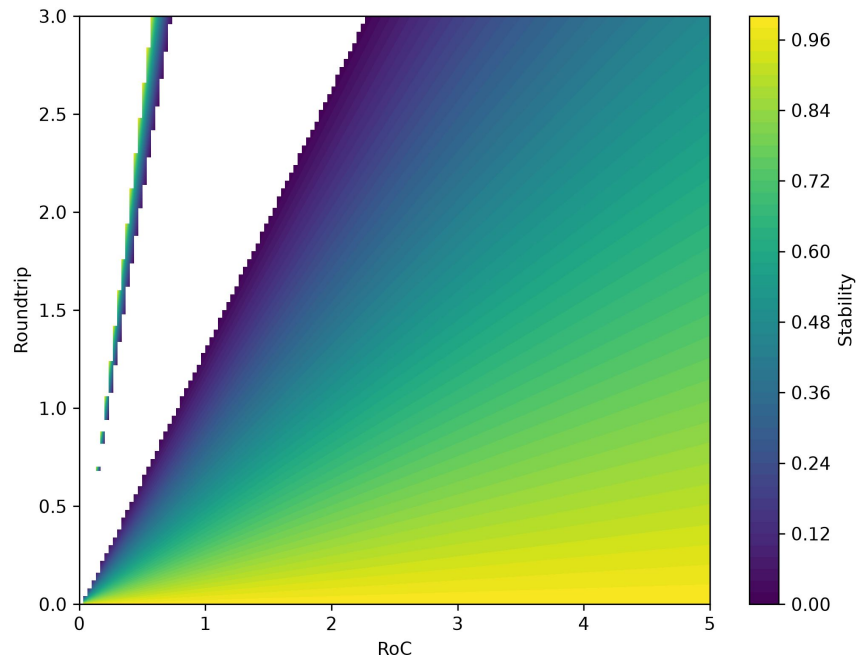
- Stability condition for a simplified plano-concave cavity model

$$0 < 1 - \frac{L_{rt}}{R} < 1$$



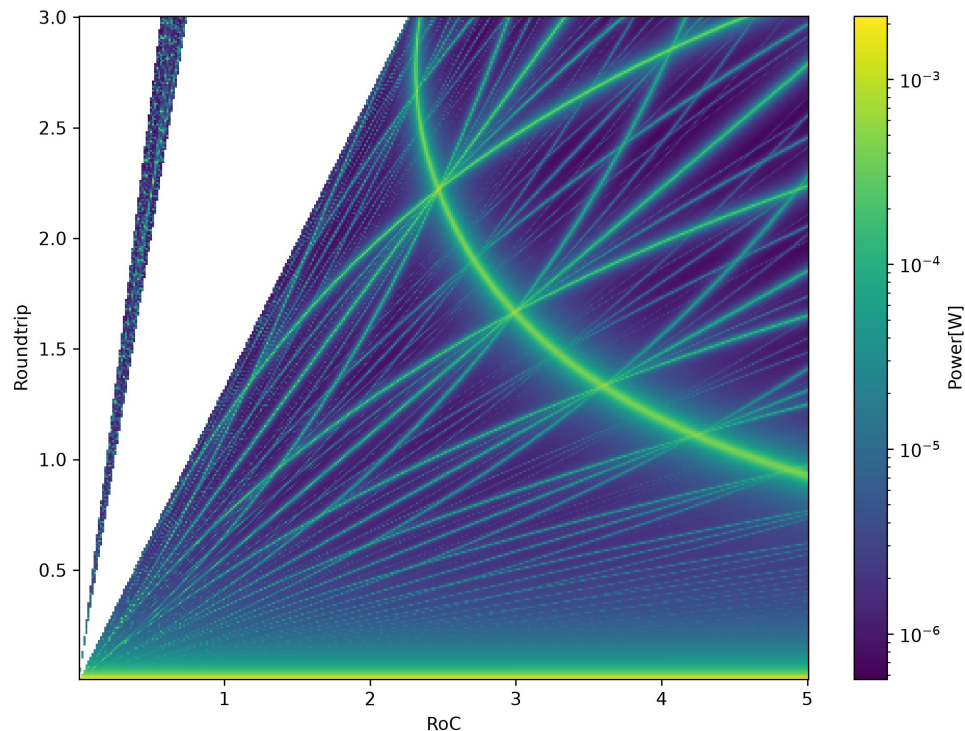
- We will keep the round-trip length <1.5 m for space constraints on the suspended optical bench

g-factor of the bow-tie cavity model

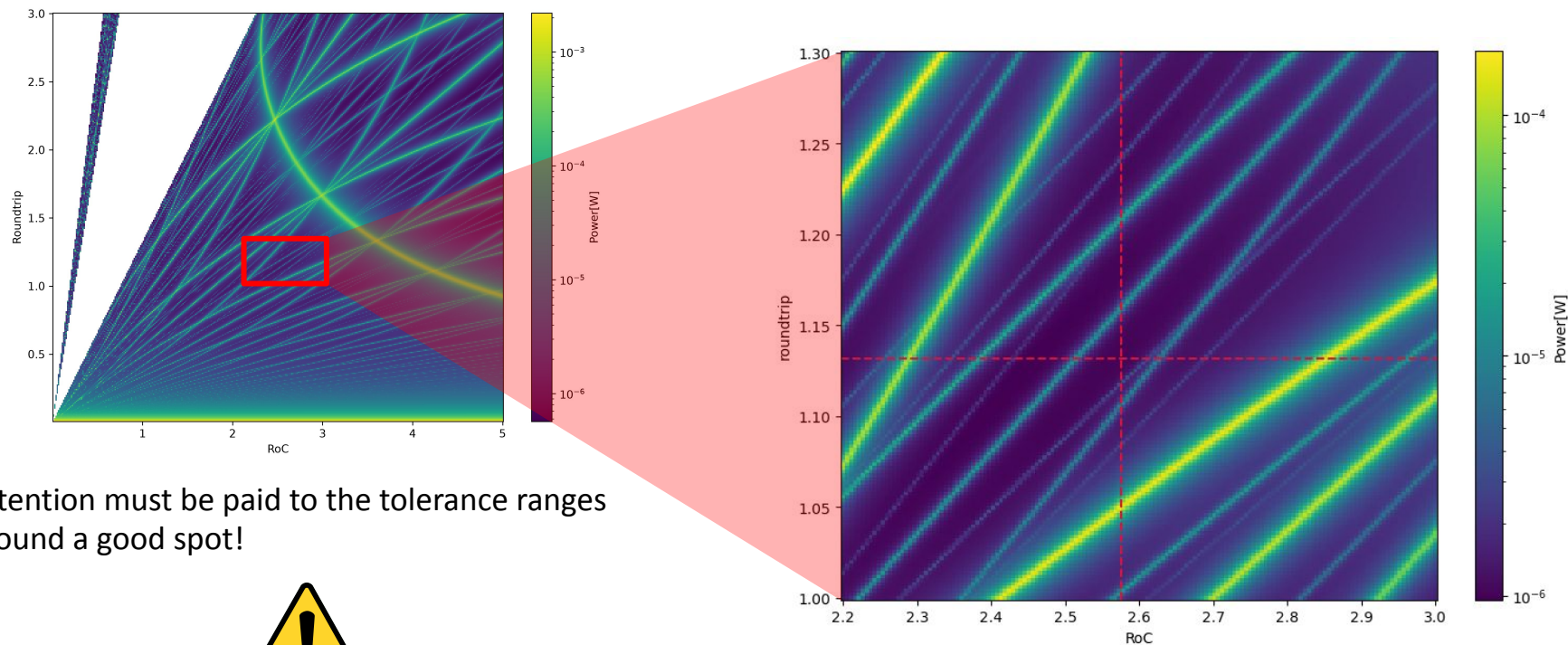


HOM and RF sidebands rejection

- The most important outcome from the OMC is reflecting out the HOM and RF sidebands
- To have a blueprint simulation, we took the aLIGO OMC as reference model
 - RF sidebands: 9 MHz, 45 MHz (ETpf will have only one control sideband at 12.3 MHz)
 - Input HOM content: empirical power-law model for orders ≥ 2 , normalized to 1 W
- LIGO reports
 - [T1000276-v5](#) (2013)
 - [G1201111-v2](#) (2013)
 - [G1802004-v1](#) (2018)



Selecting round-trip length and RoC

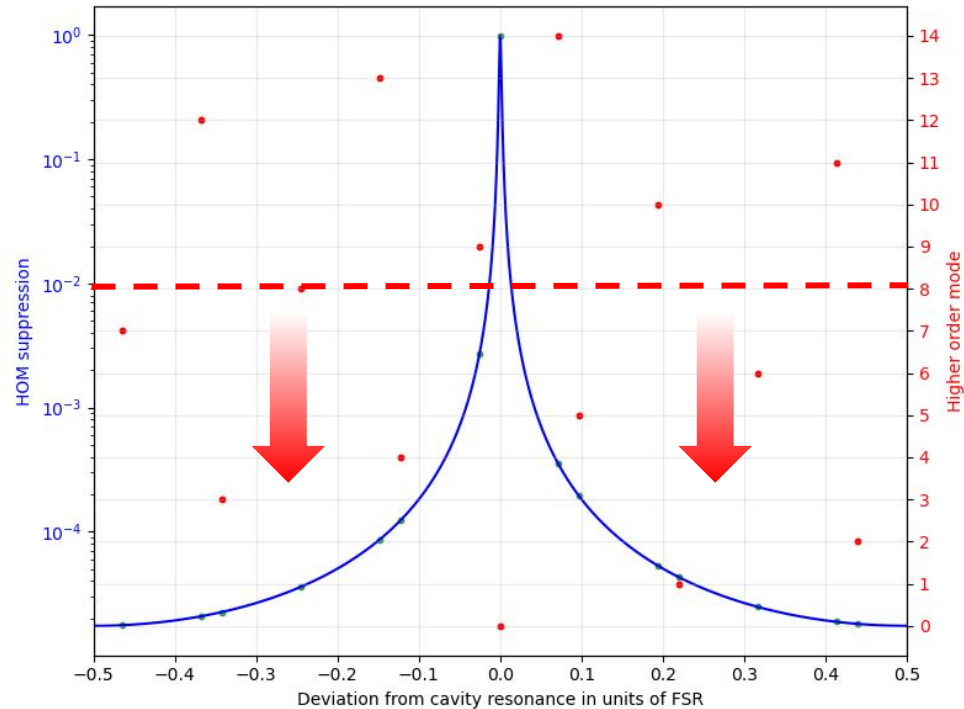


Attention must be paid to the tolerance ranges around a good spot!



Transverse Mode Spacing (TMS)

- TMS is the spectral distance between Gaussian mode and HOM
- HOM repeat periodically at every free-spectral range
- Target HOM suppression: **20 dB** (100 times)



Work plan 2026-27



1. **Simulations** to define the design, complying with given requirements
[in progress, definitive input parameters to be fixed in few weeks]
2. **Characterisation** on the single components, both optical and electronics
3. **Assembly and installation** of the full device to test mechanical holders and base plates
4. **Complete characterization** to check the performance of the full device in terms of HOM suppression and residual optical losses
5. **Installation and commissioning** of the OMC in ETpathfinder @Maastricht

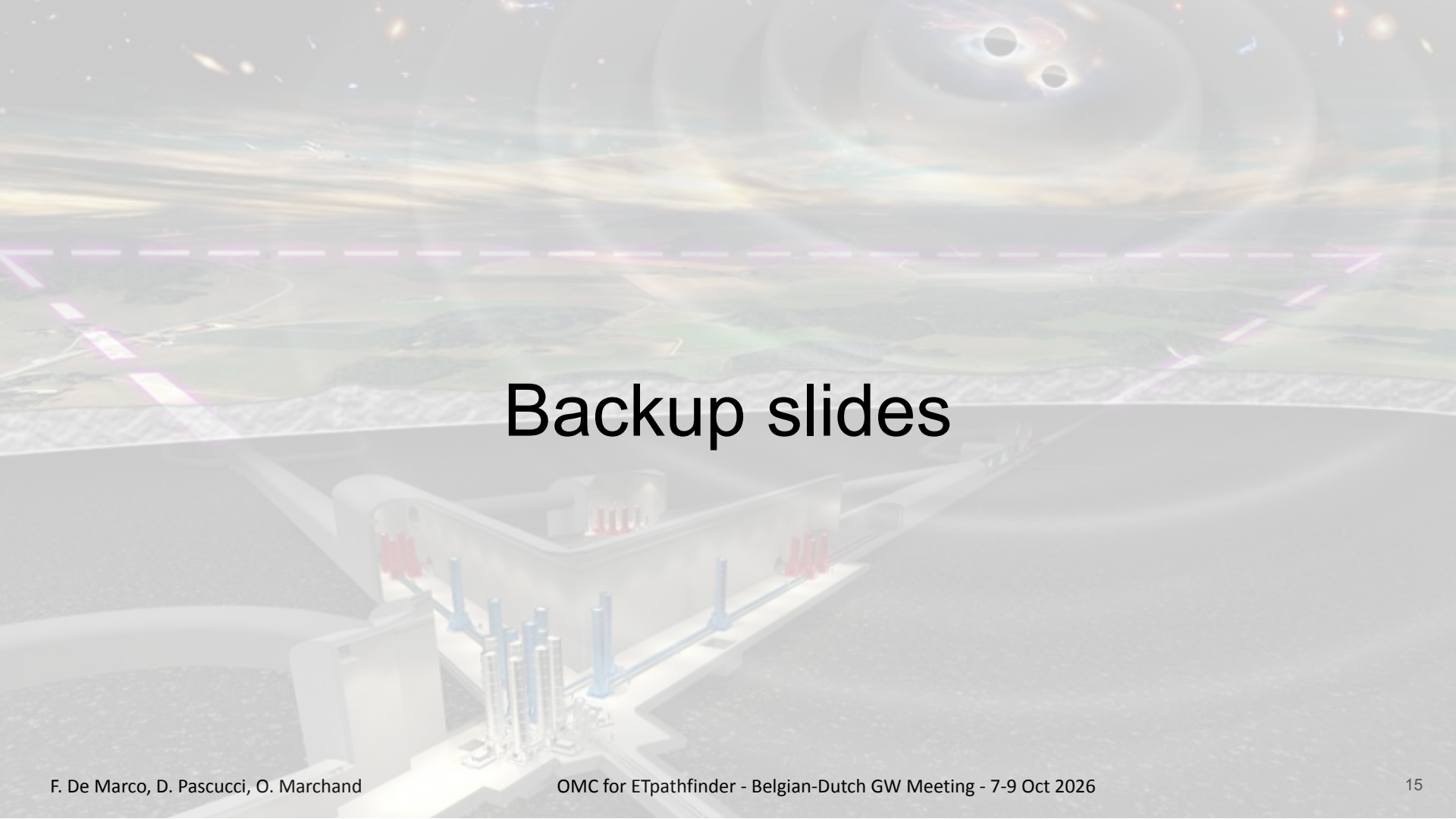
Target timeline for OMC operation in ETpathfinder: **Q1-Q2 2028**



Thank you for your attention!

Questions?





Backup slides

Hermite-Gauss optical modes

This complete set of orthogonal functions describes the propagation of a non-plane paraxial beam:

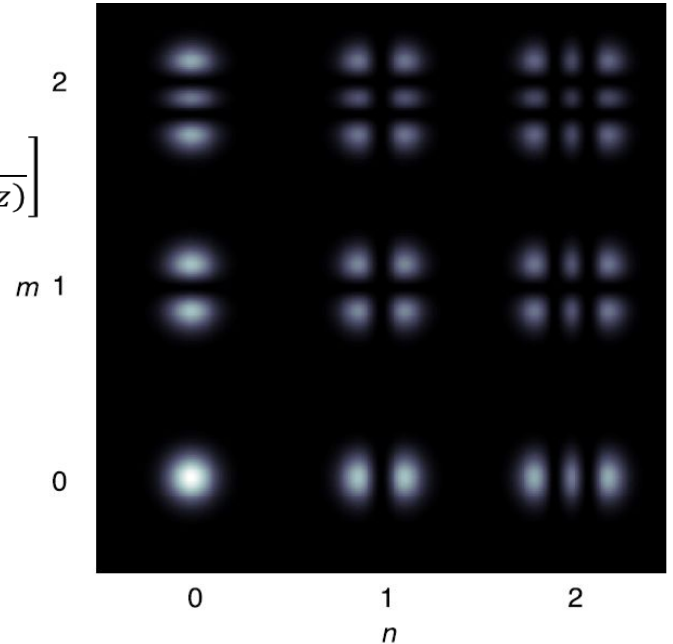
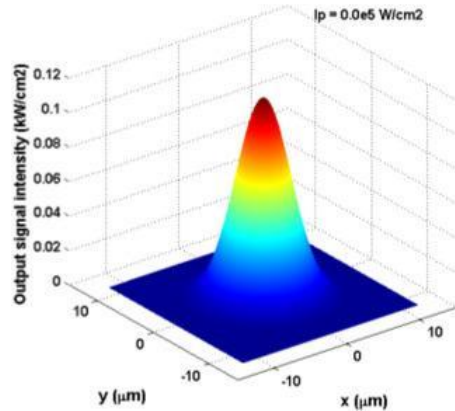
$$E(\mathbf{r}, t) = \sum_{n,m} A_{nm} u_n(x, z) u_m(y, z) e^{i(kz - \omega t)}$$

$$u_n(x, z) = \left(\frac{2}{\pi}\right)^{1/4} \left(\frac{e^{i(2n+1)\Psi(z)}}{2^n n! w(z)}\right)^{1/2} H_n\left(\frac{\sqrt{2}x}{w(z)}\right) \exp\left[-i\frac{kx^2}{2R_c(z)} - \frac{x^2}{w^2(z)}\right]$$

Order 0 - Gaussian beam:

- Smooth intensity distribution
- Lowest angular divergence

$$I(r) = \frac{2P}{\pi w^2(z)} e^{-2r^2/w^2}$$



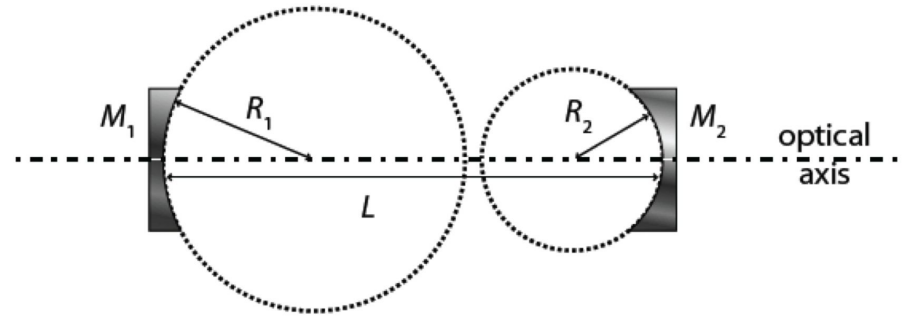
Credits: [Bond, Brown, Freise, Strain - Liv. Rev. Relativ. 19, 1 \(2017\)](#)

Stability in optical cavities

- An optical resonator (or resonant optical cavity) is a configuration of optical components which allows a beam of laser light to circulate in a closed path
- Geometrical parameters
 - Optical path length and spacings between mirrors
 - Radius of Curvature (RoC) of the mirrors
 - Angle Of Incidence (AOI) on each of the mirrors -> if different from 0° it introduces astigmatism
- Spacings and RoCs define the **optical stability condition**:

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

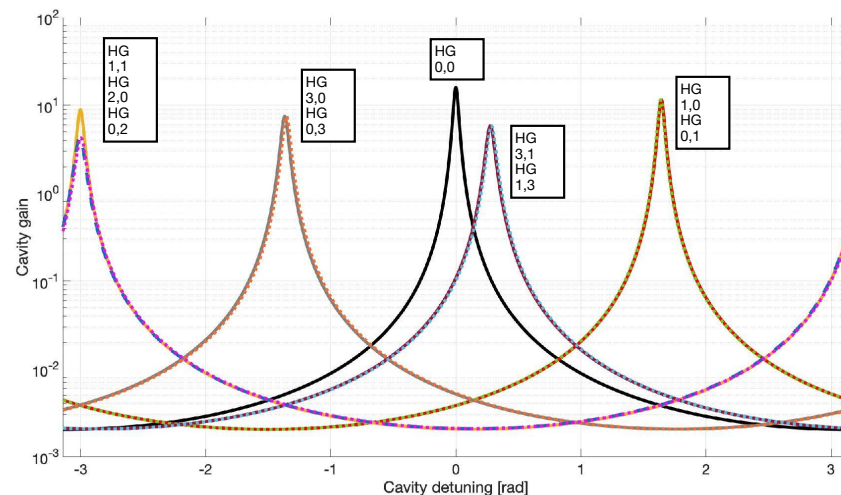
$$g_1 = 1 - \frac{L}{R_1} \quad g_2 = 1 - \frac{L}{R_2}$$



In a stable cavity, the beam is re-focussed at every round trip, and keeps propagating with the same transverse profile

Resonances in optical cavities

- Cavities show resonances when the round-trip length is a multiple of the incoming wavelength (standing wave)
- In principle, a beam is a mixture of transverse modes, (e.g. Hermite-Gauss modes), each resonating at a different cavity length
- Considering also the stability condition, there are 2 requirements to be met
 - The beam transverse shape is steadily the same after each round-trip
 - Cavity length is well tuned on the resonance of *our wanted mode*



Mode-mismatch



Detuning