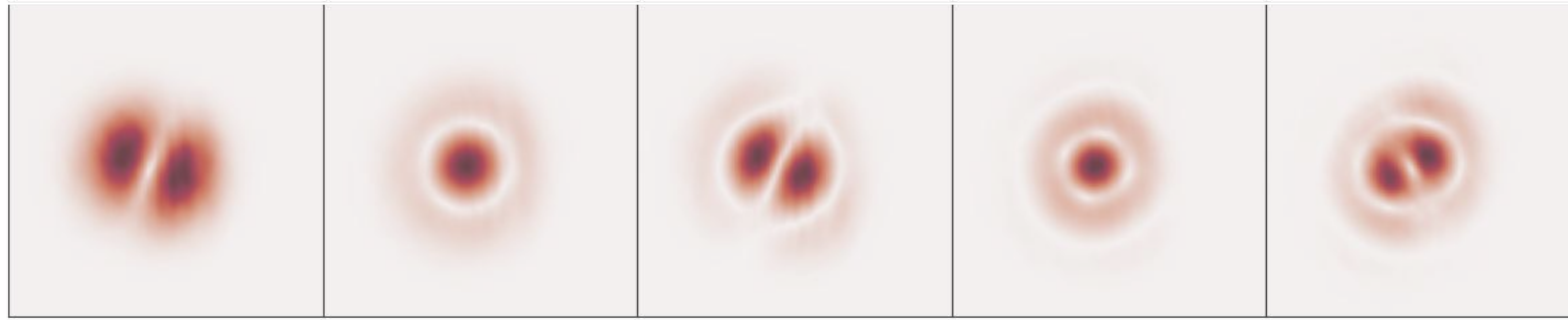


Continuous tracking of the eigenmodes of a locked cavity

Inferring mirror aberrations during a thermal transient

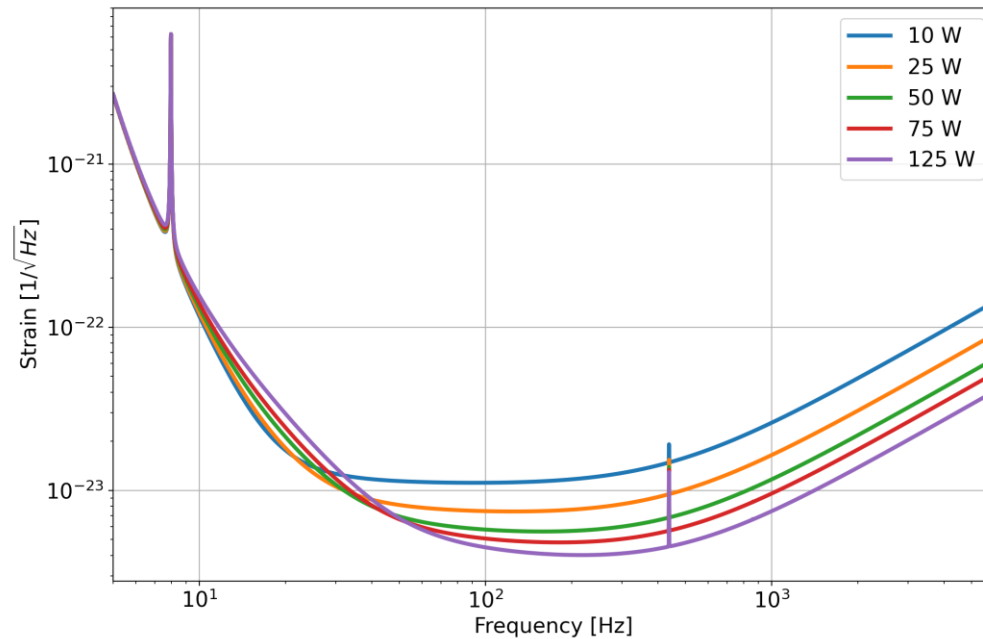


Ricardo Cabrita,

Cheyenne Gruber, Charlotte Bragard, Jue Zhang, Swapnil Dhage, Justin Janquart,
Clement Lauzin, Giacomo Bruno, Aaron Goodwin-Jones

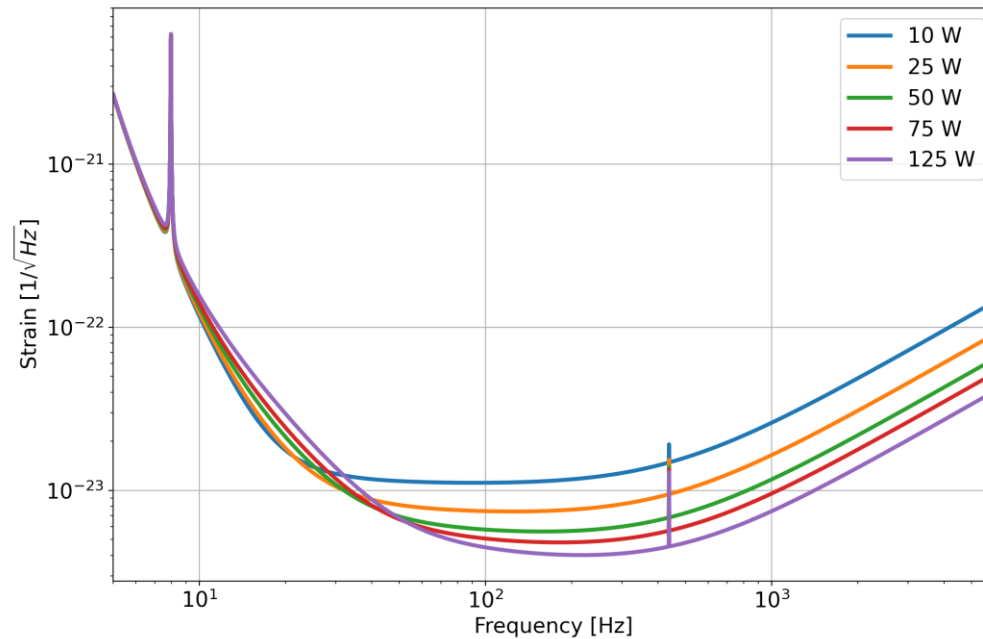
XIV Belgian-Dutch Gravitational-wave meeting, 8th October 2026

Increasing power in GW detectors

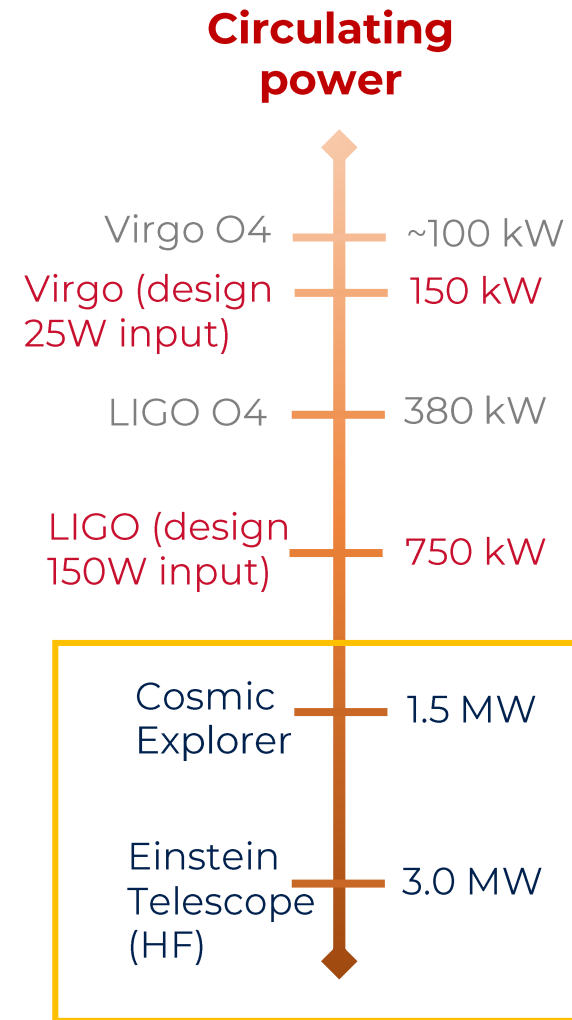


Produced with GWINC with the Virgo design parameters

Increasing power in GW detectors



Produced with GWINC with the Virgo design parameters



The challenge(s) of high-power operation



Km-long optical cavities storing hundreds of kW

- **Angular instabilities** caused by the radiation pressure force.
- Thermally excited higher-order modes overlap with the mirror mechanical modes giving origin **to parametric instabilities**.
- Photons absorbed in the mirror substrate and coatings lead to thermal deformations that:
 - Shift the cavity eigenmodes leading to optical loss
 - Squeezed light degradation
 - Interferometer locking issues

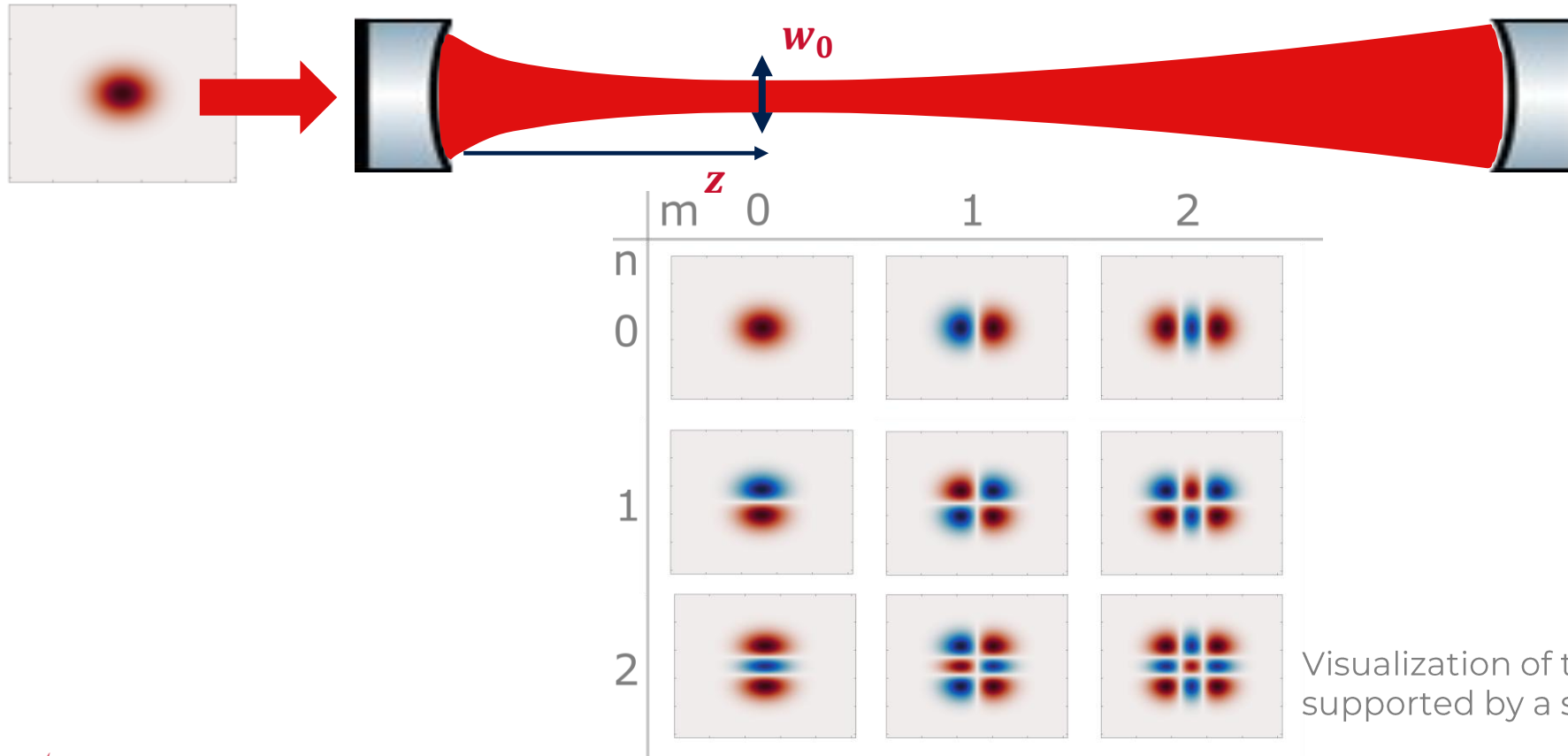
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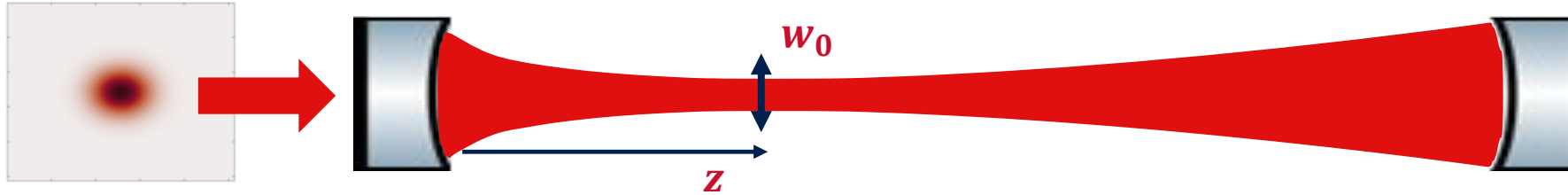
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Cavity eigenmode(s)



Visualization of the **Hermite-Gauss** basis supported by a spherical cavity.

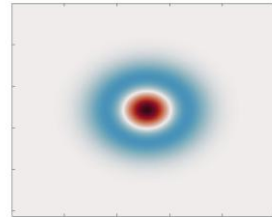
Excitation of higher-order modes (HOM)



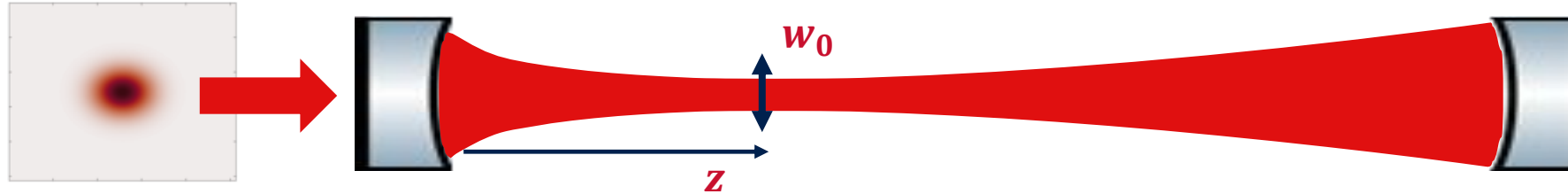
Mode mismatch

$$k_{0,2} \sim \frac{1}{2\sqrt{2}} \left(i \frac{\Delta z}{z_R} + \frac{\Delta z_R}{z_R} \right)$$

$$\text{with } z_R = \frac{\pi w_0^2}{\lambda}$$



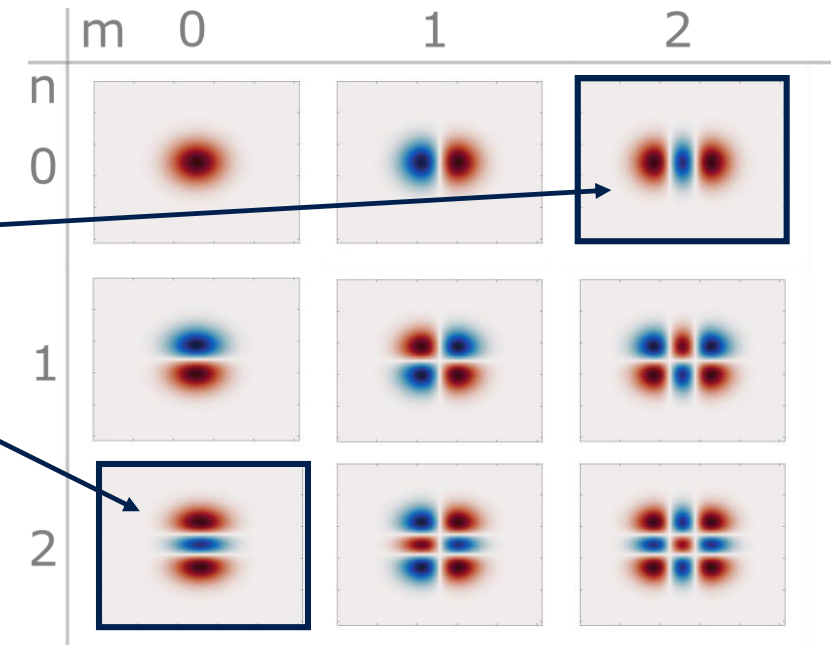
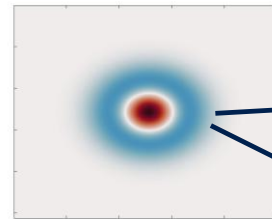
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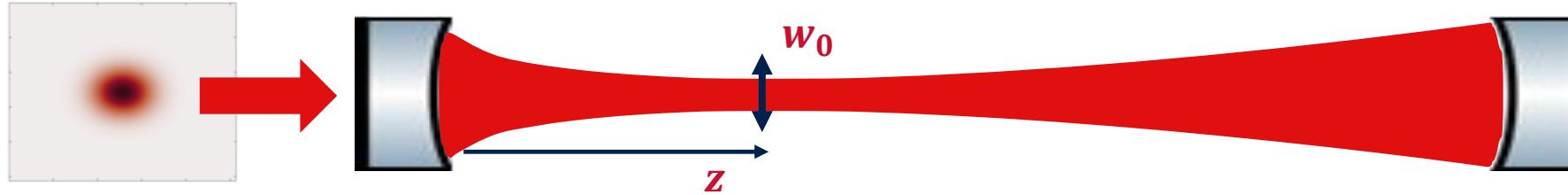
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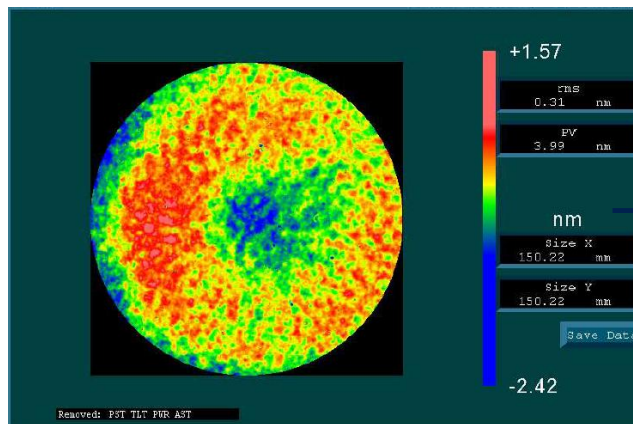
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Excitation of higher-order modes (HOM)



Mirror surfaces are not perfect

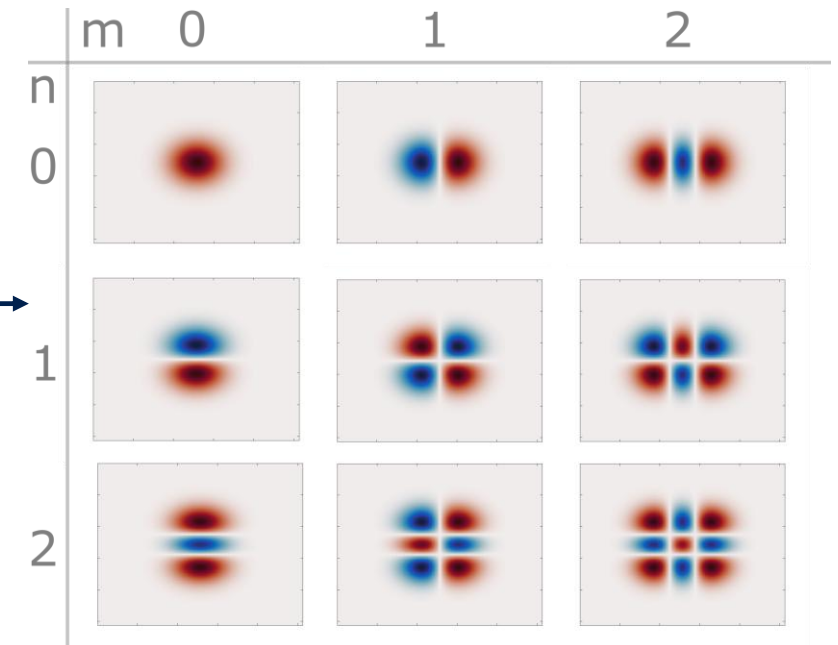


VIR-0543A-14, data taken at Laboratoire des Matériaux Avancés, Villeurbanne, France



Wallonie

$$\begin{pmatrix} k_{0',0} & \dots & k_{0',j} & \dots & k_{0',N} \\ \dots & \dots & \dots & \dots & \dots \\ k_{i',0'} & \dots & k_{i',j'} & \dots & k_{i',N} \\ \dots & \dots & \dots & \dots & \dots \\ k_{N',0} & \dots & k_{N',j} & \dots & k_{N',N} \end{pmatrix}$$



Thermal deformations

The timescales for the thermal deformations are > 1 hour at 100 kW.

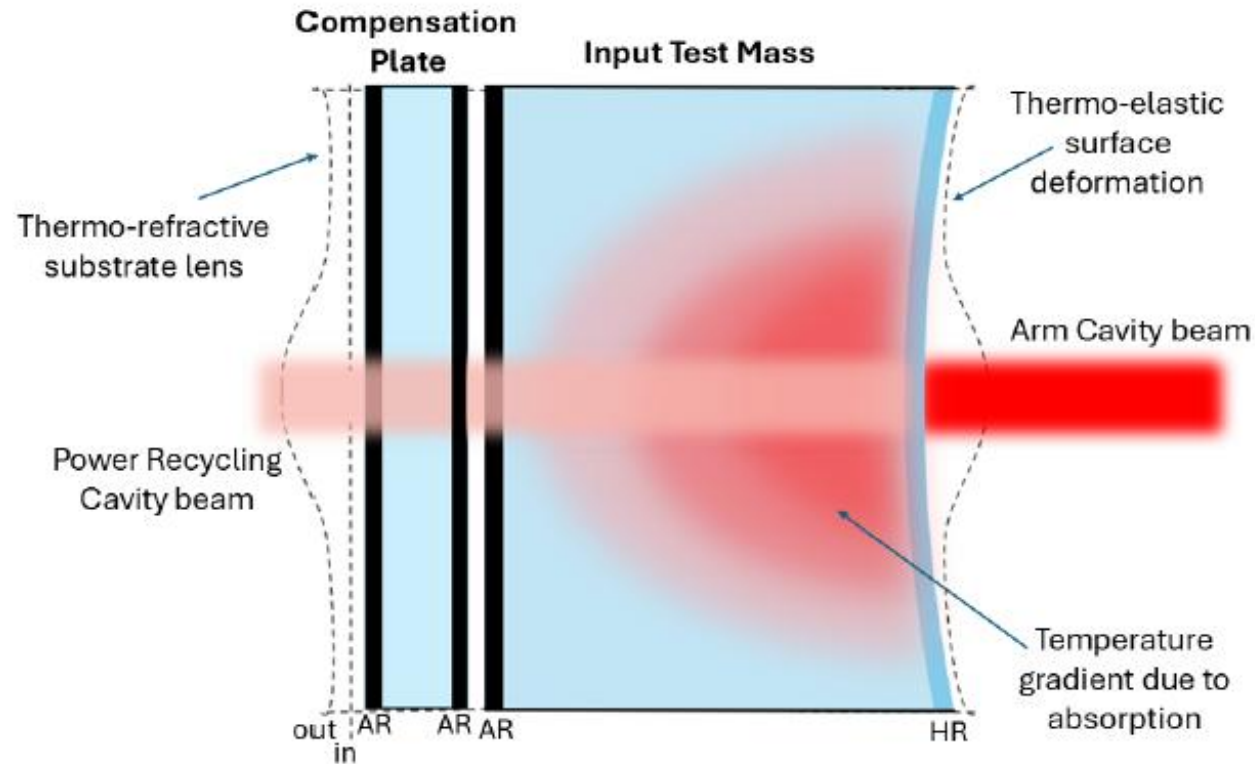
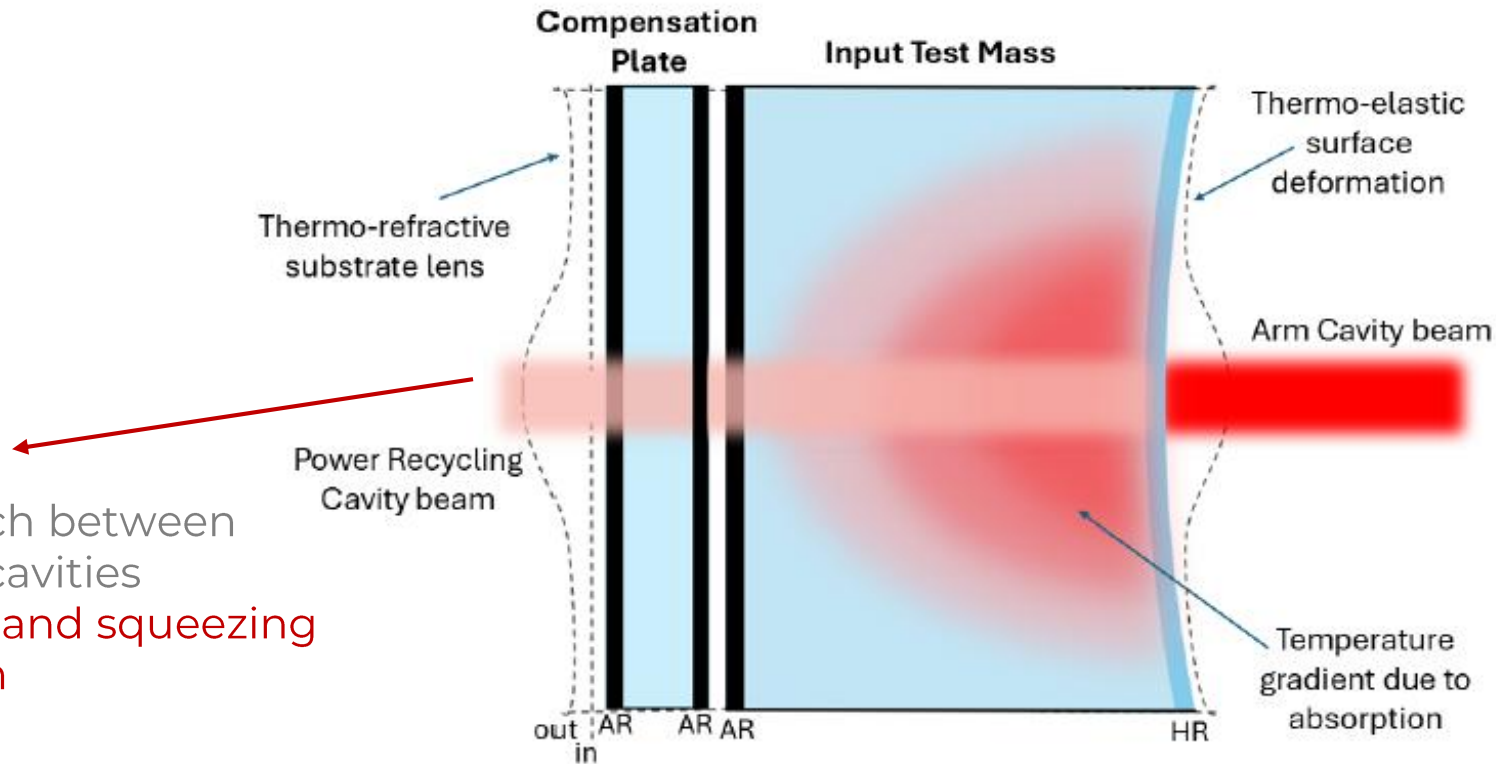


Image from Cifaldi, M., Taranto, C., et. al (2025). Adaptive Optics for Aberration Control in Einstein Telescope. *Galaxies*, 13(2), 18.

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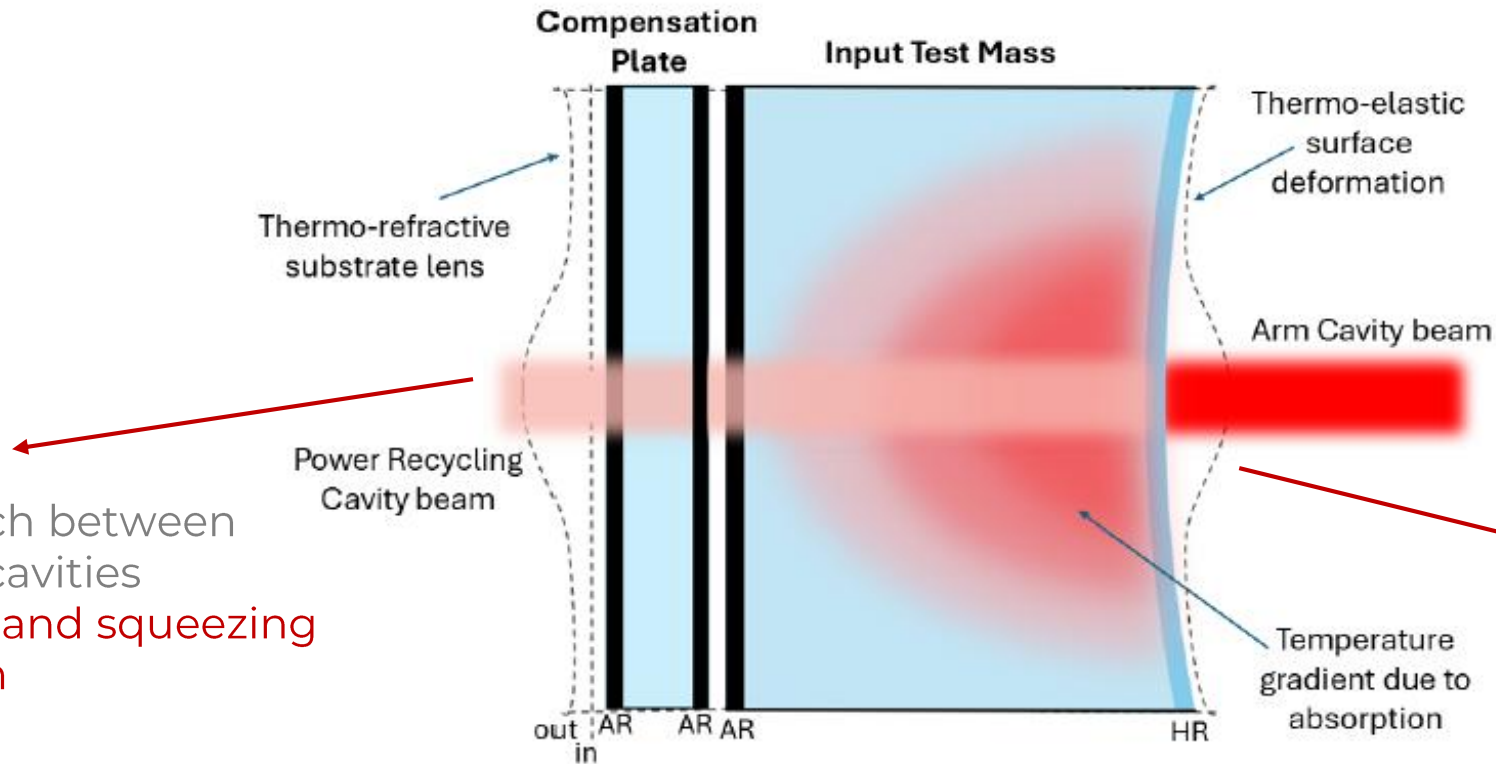
Mode mismatch between PRC and arm cavities

- Optical loss and squeezing degradation

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Mode mismatch between PRC and arm cavities

- Optical loss and squeezing degradation

Mode mismatch and shift of the cavity eigenmodes

- Optical loss control issues

Image from Cifaldi, M., Taranto, C., et. al (2025). Adaptive Optics for Aberration Control in Einstein Telescope. *Galaxies*, 13(2), 18.

Table-top experiment

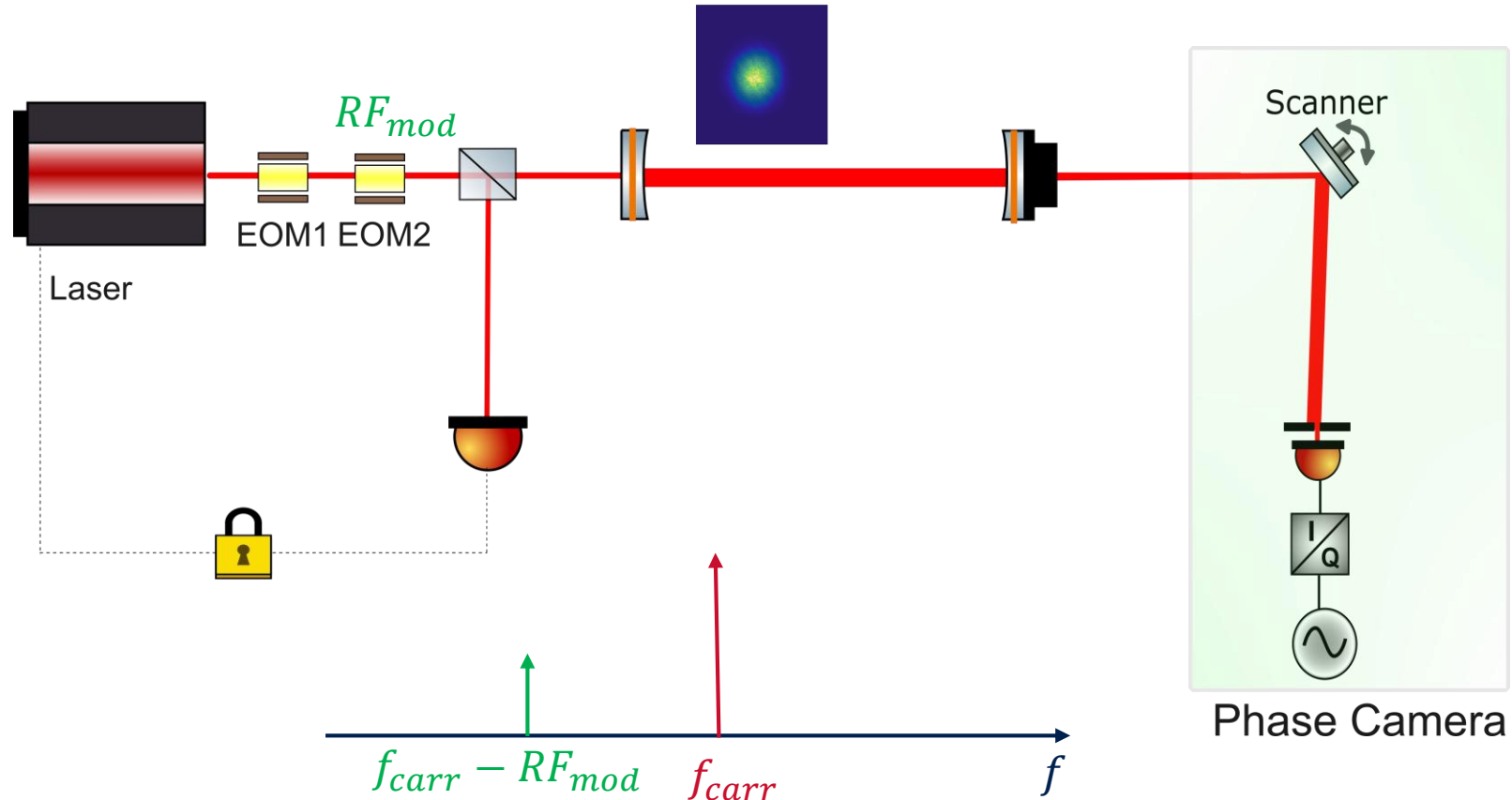


Table-top experiment

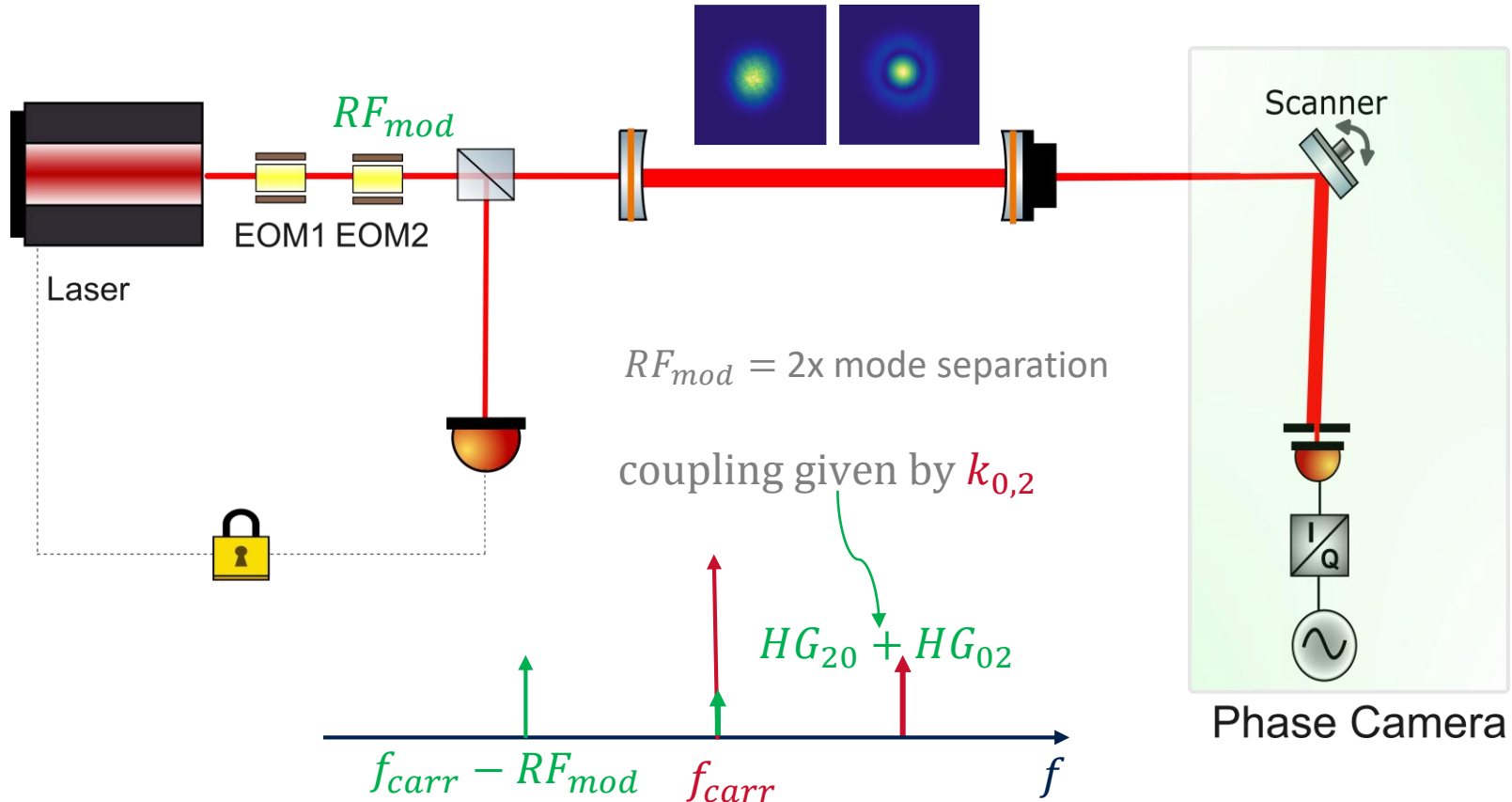


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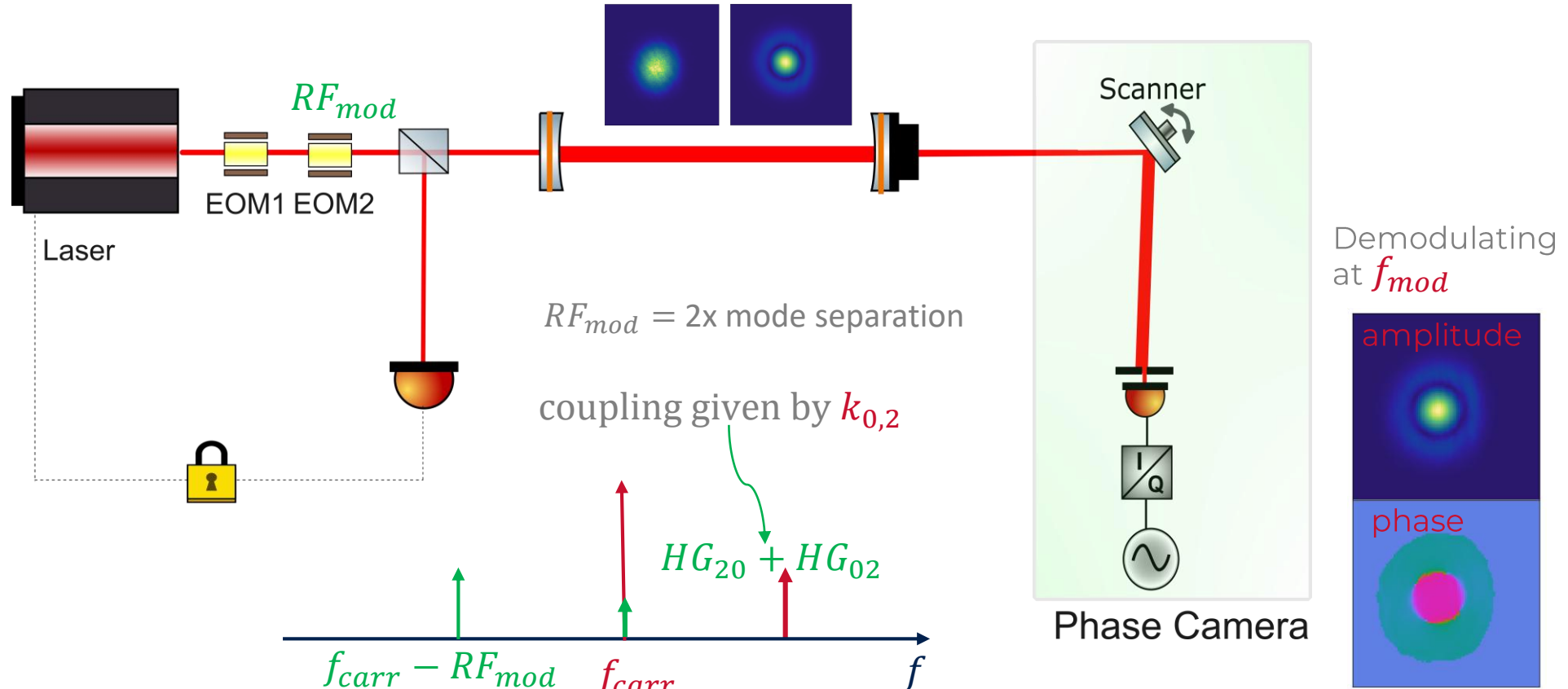
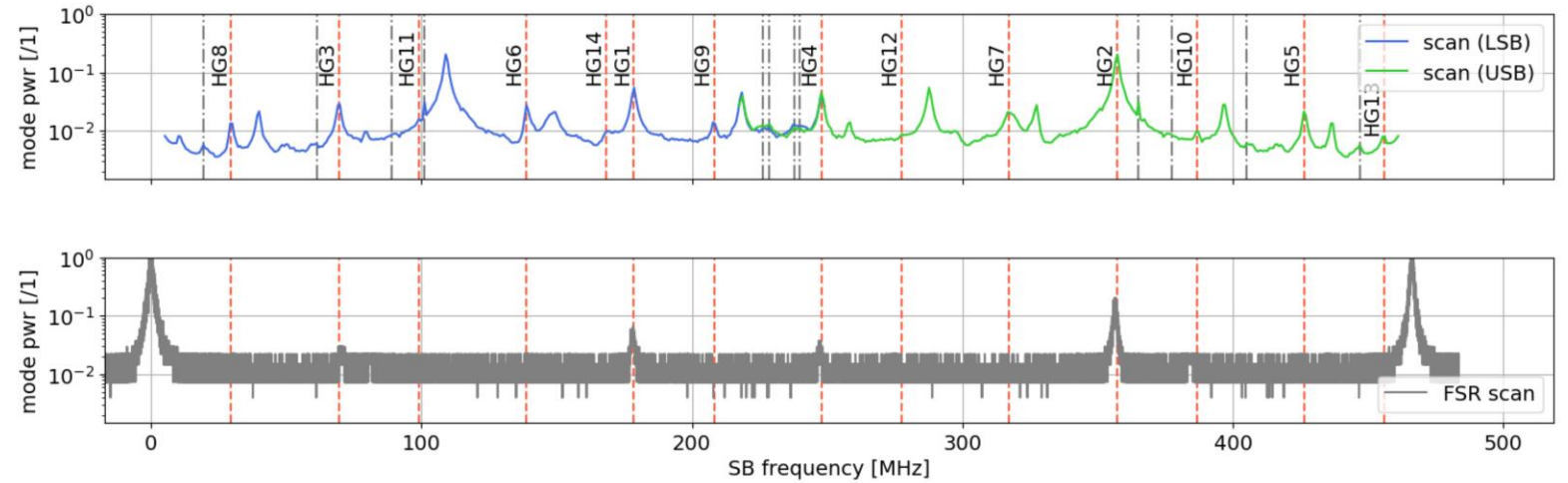
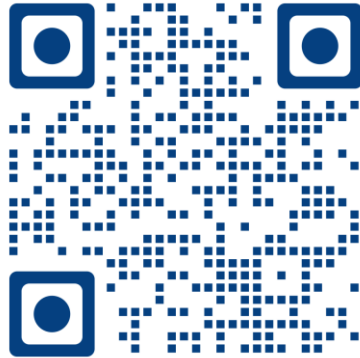


Table-top experiment results

- Scan the modulation frequency of the EOM – inject different HOMs.
- At each step, demodulate phase camera data at same frequency.
- We obtain a spectrum of the cavity.



Link to paper



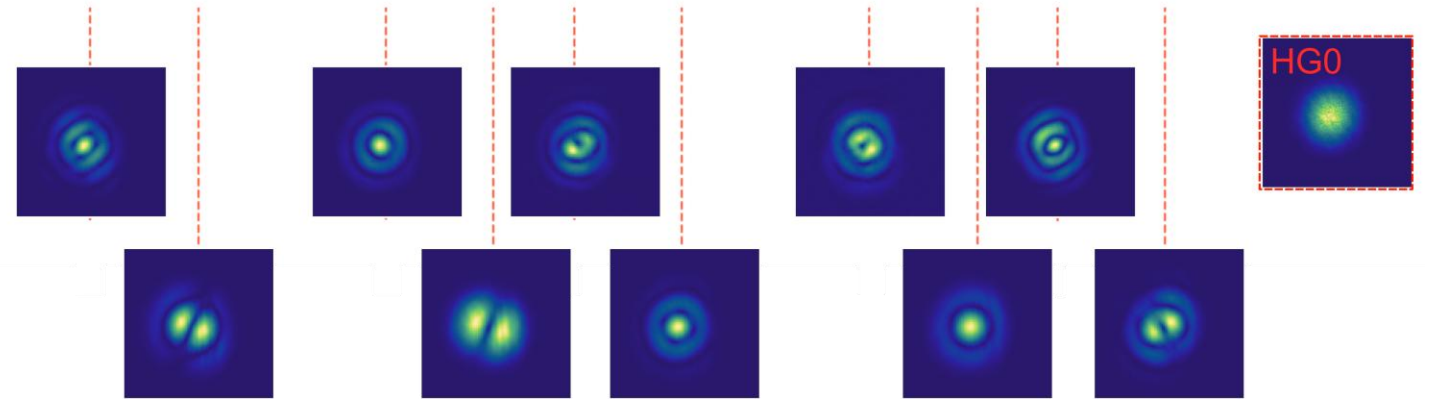
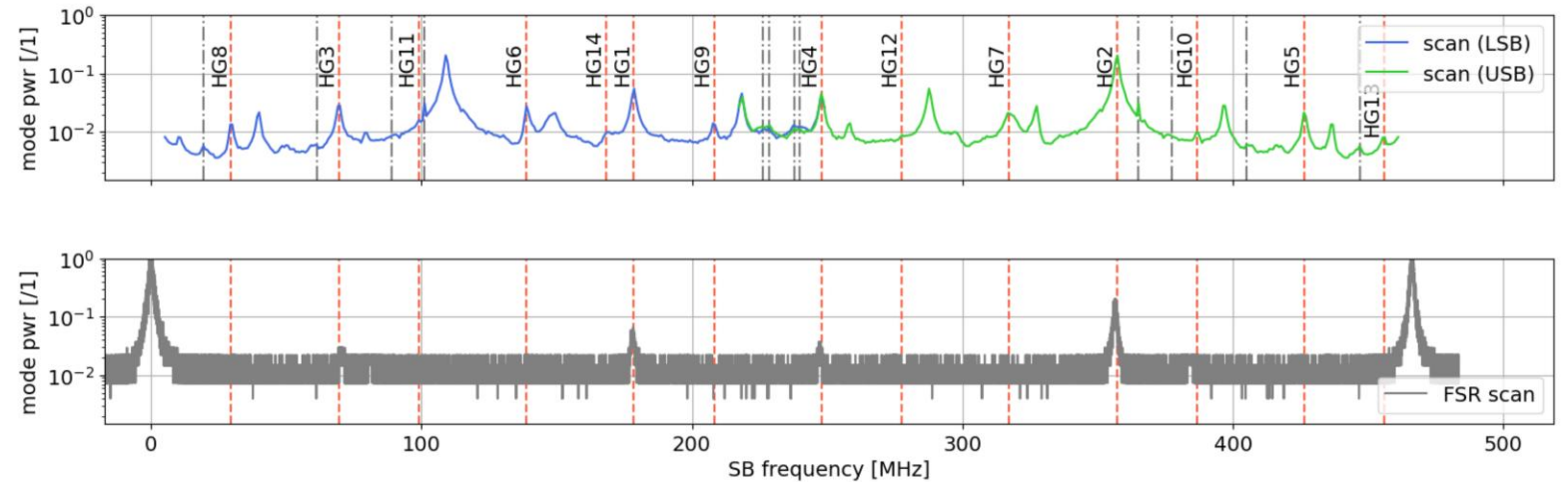
R. Cabrita, A. Goodwin-Jones, et. al, "Resonant enhanced detection of the higher-order modes of a locked cavity," Opt. Express 33, 30209-30220 (2025)

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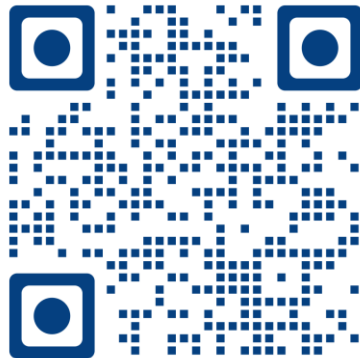
Or

- Pick a frequency, and image the beam.



R. Cabrita, A. Goodwin-Jones, et. al, "Resonant enhanced detection of the higher-order modes of a locked cavity," Opt. Express 33, 30209-30220 (2025)

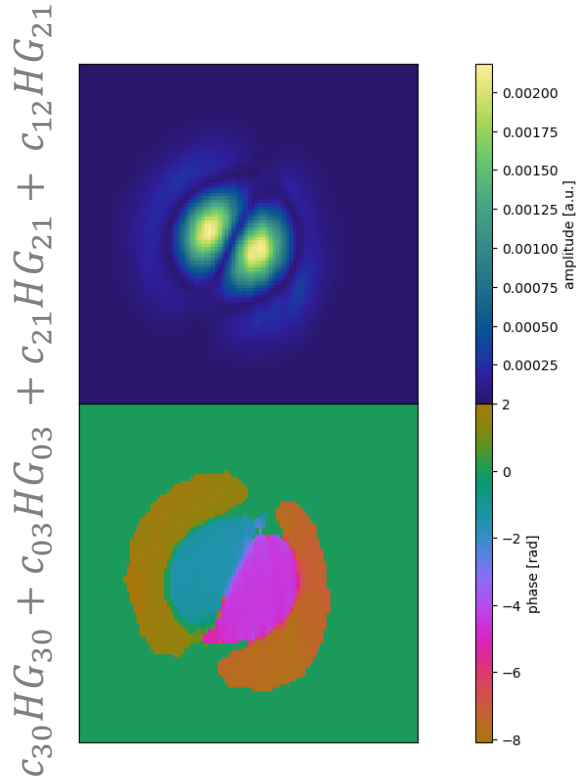
Link to paper



Modal amplitude analysis

- Cavity is degenerate for same order modes, so we measure

$$A(x, y) = \sum_{n+m=3} U_{nm}(x, y) U_{00}(x, y)$$



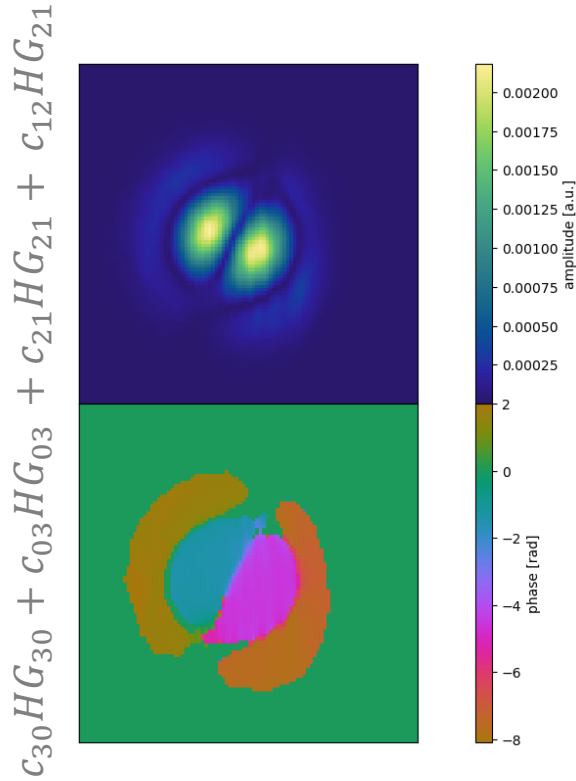
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$$c_{nm} = \iint A(x, y) H G_{nm}(x, y) \underline{U_{00}(x, y)}$$



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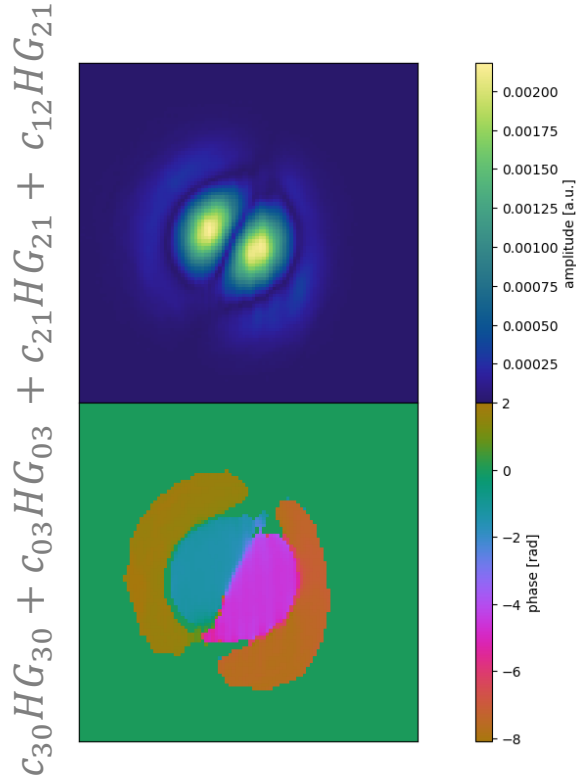
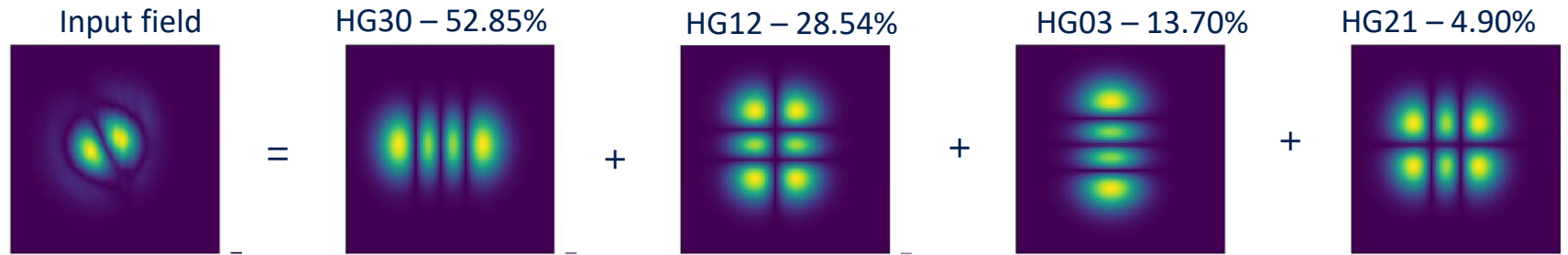
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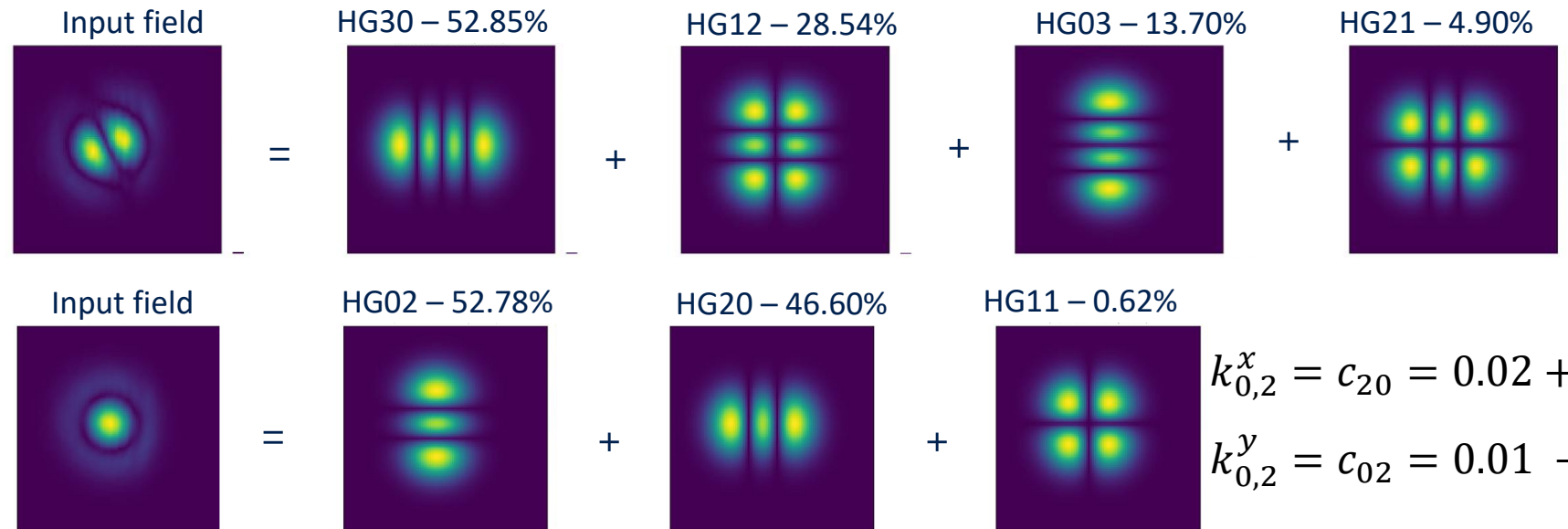
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$$k_{0,2}^x = c_{20} = 0.02 + 0.06i$$

$$k_{0,2}^y = c_{02} = 0.01 - 0.003i$$

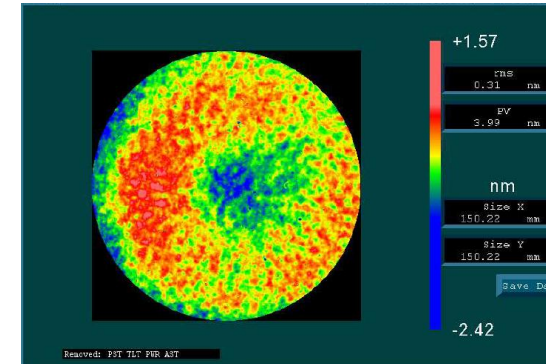
Mirror aberrations and HOM couplings

What about the small deformations in the cavity mirrors ?

First order couplings from beam mismatches

Coupling Coefficient	Expression	Notes
$k_{n,m,p,q}$	$k_{n,p}k_{m,q}$	2D $\rightarrow$ 1D
$k_{n,n}$	$1 + \frac{i}{4} (2n + 1) \varepsilon_z + \mathcal{O}(\varepsilon^2)$	1+mismatch
$k_{n,n+1}$	$(\varepsilon_\gamma q - \varepsilon_\delta) \sqrt{(n + 1)} + \mathcal{O}(\varepsilon^2)$	misalignment
$k_{n,n+2}$	$-\frac{1}{4} \varepsilon_q^* \sqrt{(n + 1)(n + 2)} + \mathcal{O}(\varepsilon^2)$	mismatch
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Ciobanu, A.A., Brown, D.D, et. al, 2020. Mode matching error signals using radio-frequency beam shape modulation. *Applied Optics*, 59(31), pp.9884-9895.



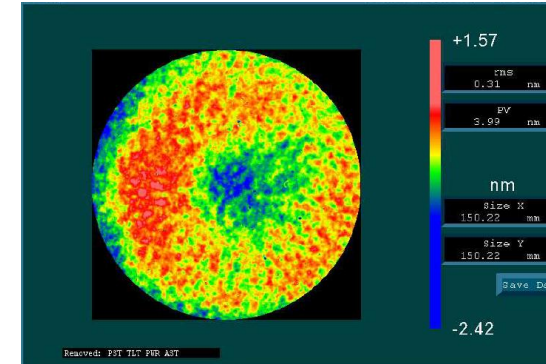
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We can describe the mirror surface z with Zernike polynomials

$$z(\rho, \phi) = \sum_j c_j Z_j$$

An incoming mode (n, m) will couple to a mode (p, l) due to the surface z as

$$k_{nm,pl} = \iint U_{nm} \exp \left(2ik \sum_j c_j Z_j \right) U_{pl}$$

Inferring mirror aberrations - preliminary

$$k_{nm,pl} = \iint U_{nm} \exp\left(2ik \sum_J c_J Z_J\right) U_{pl} \longrightarrow$$

We're interested in the inverse problem:

Obtaining the mirror Zernike description from the modal amplitudes measured by the phase camera

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Generate large dataset with
Finesse + Zernike mirror maps
Introduced in input mirror.



Train a Multilayer Perceptron
(MLP) neural network on the
simulated data

Data generation and training led by
Cheyenne Gruber cheyanne.gruber@lsu.edu,
Publication in prep: LIGO-P2600558



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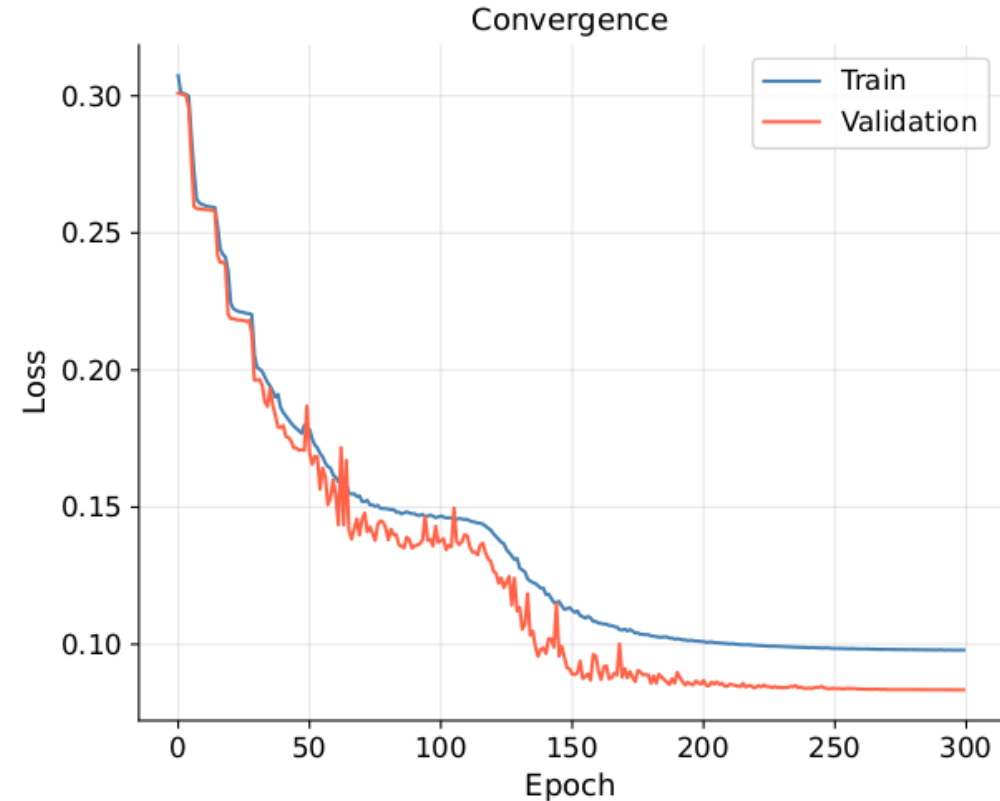
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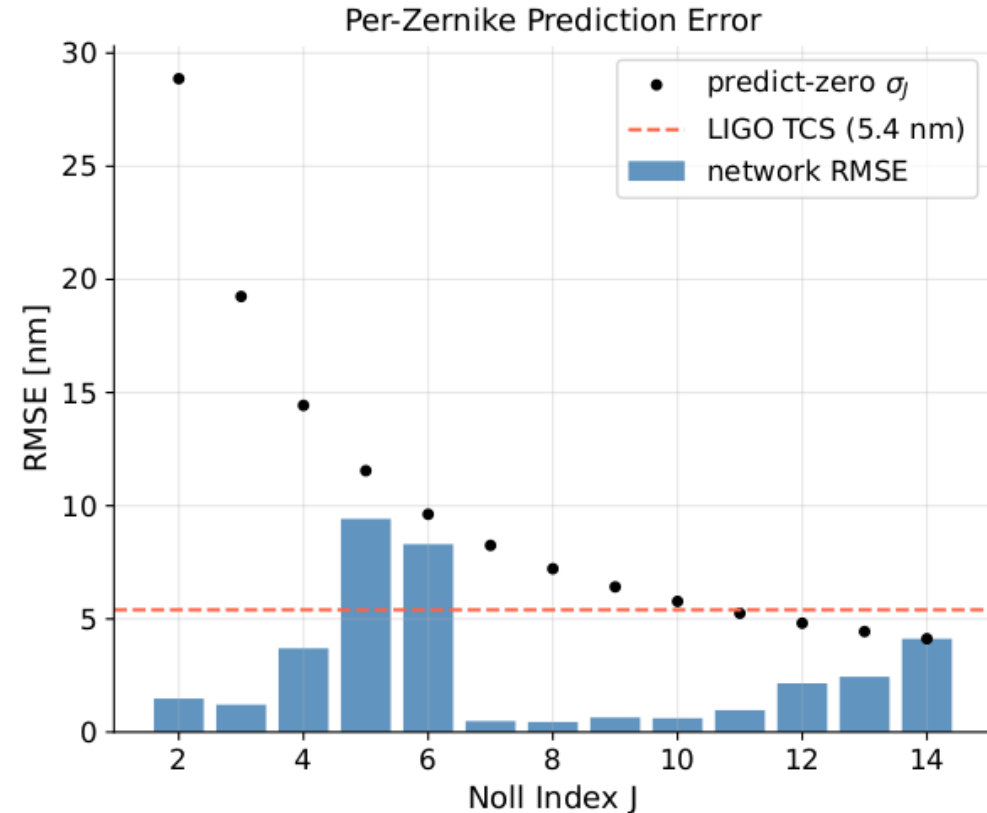
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$$\sigma_J = \frac{100}{J\sqrt{3}} nm$$



Conclusion

We have taken the first steps towards monitoring cavity mirror deformations and cavity HOMs during a thermal transient!

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Guide thermal compensation systems
(future non-axisymmetric corrections)

More realistic interferometer simulations

(Digital twin 🕶️)

Parametric instability suppression via optical feedback

Crucial challenges towards realizing the MW circulating power goal of next-generation detectors