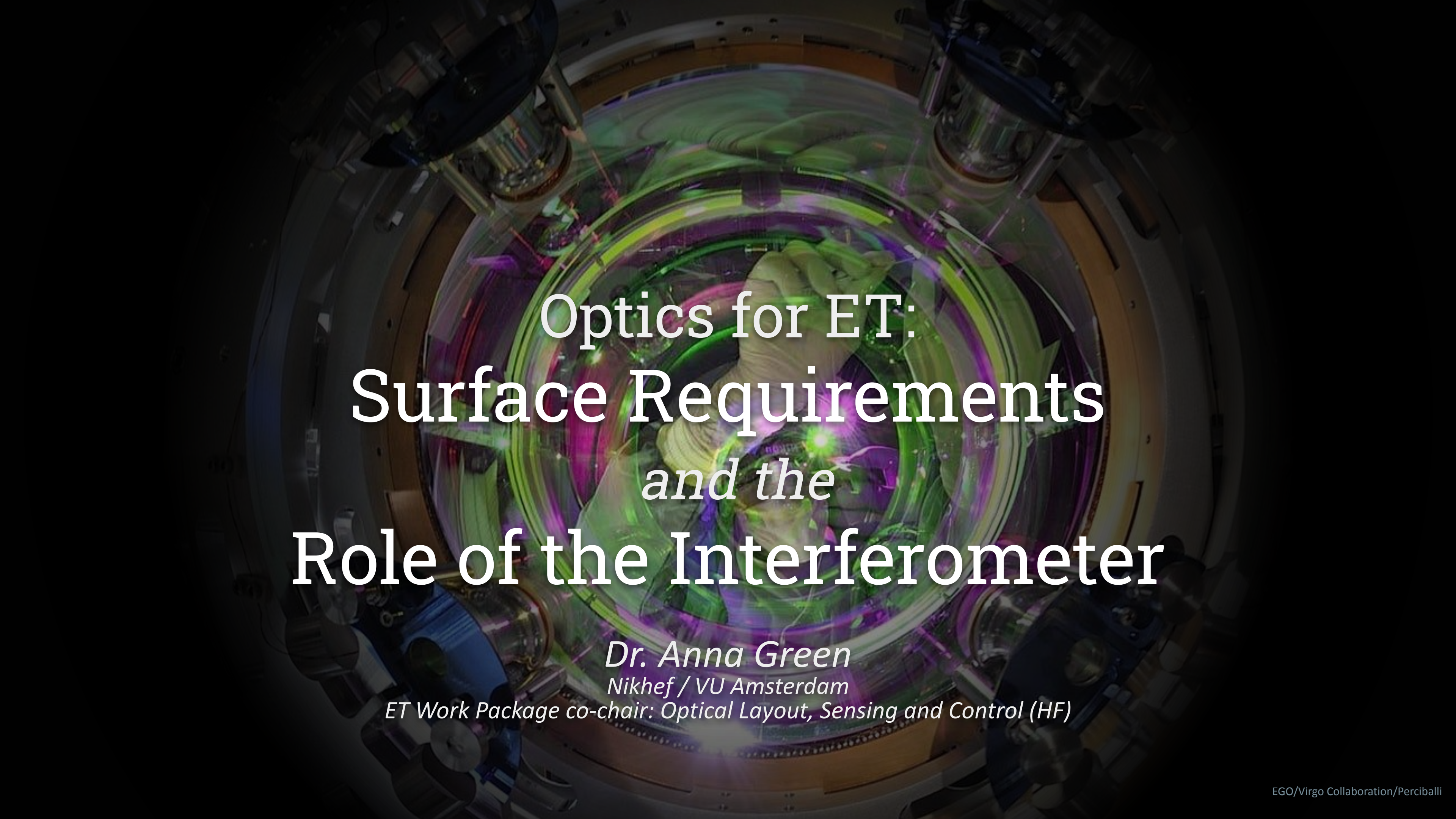

Optics for ET:
Surface Requirements
and the
Role of the Interferometer

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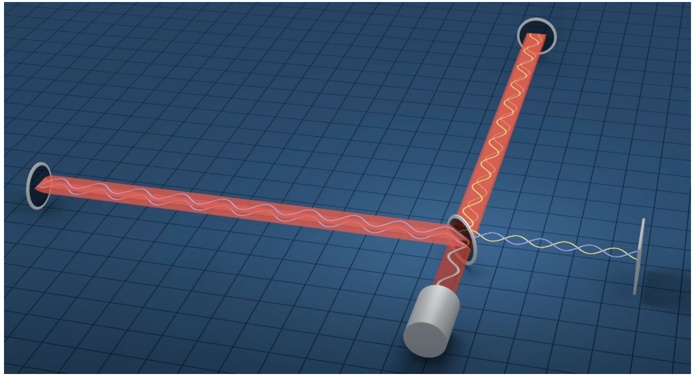
EGO/Virgo Collaboration/Perciballi

The Ultimate Goal

GWs cause a **phase difference** that we measure using **interference**.

→ we need very precise knowledge of the interference pattern:

Anything that affects the phase and amplitudes of the recombining fields can **degrade our ability to distinguish GW signals.**

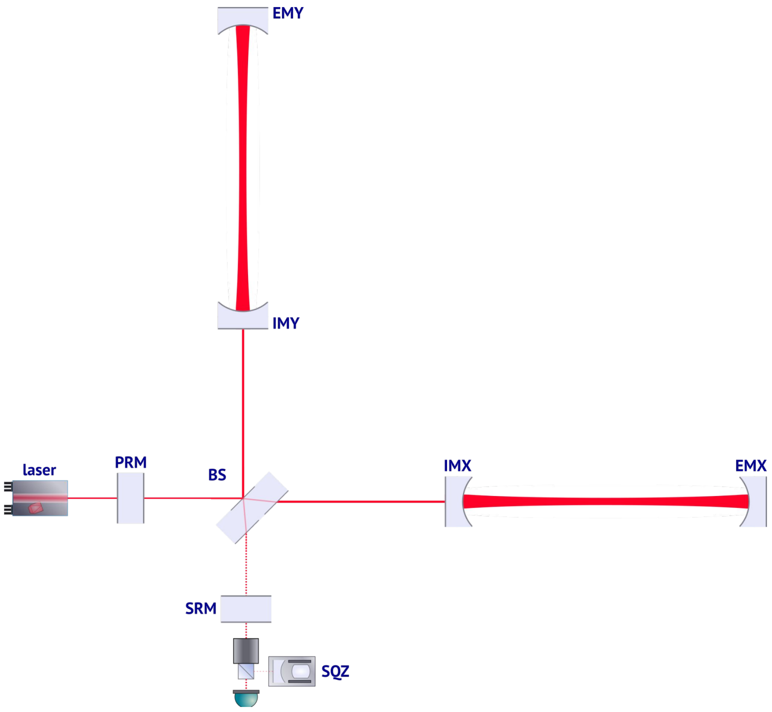


Most Precise Ruler Ever Constructed
Animation by T. Pyle, Caltech/MIT/LIGO Lab

Improving ET’s Sensitivity

- High **power**
  - larger signal; reduces shot noise
- Injecting **squeezed light**
  - reduce quantum noise (including shot noise)
- Resonant **cavities**
  - increased circulating power
  - modified frequency response
  - strict conditions on beam shape
  - requires careful control to maintain resonance

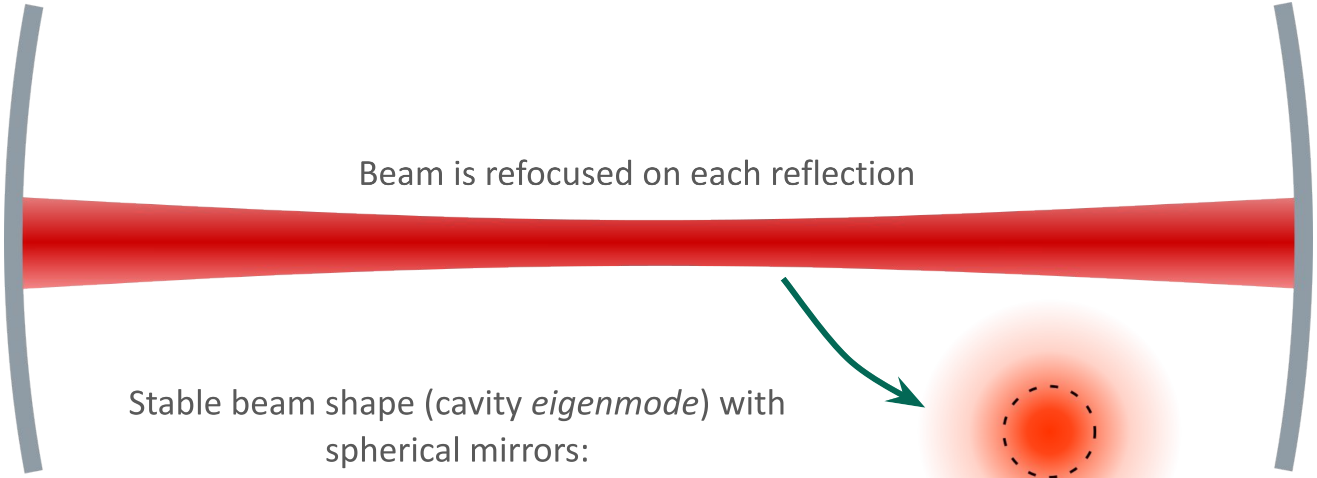
(...and many more)



An Ideal Beam in an Ideal Cavity

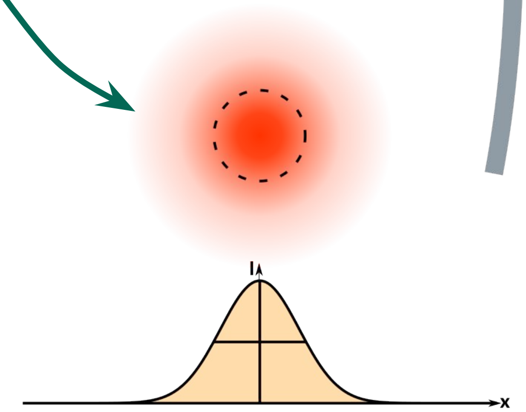
Resonance condition depends on phase:

cavity is selective for both **wavelength**/frequency ($n\lambda = L_{round\ trip}$), and **beam shape**



Beam is refocused on each reflection

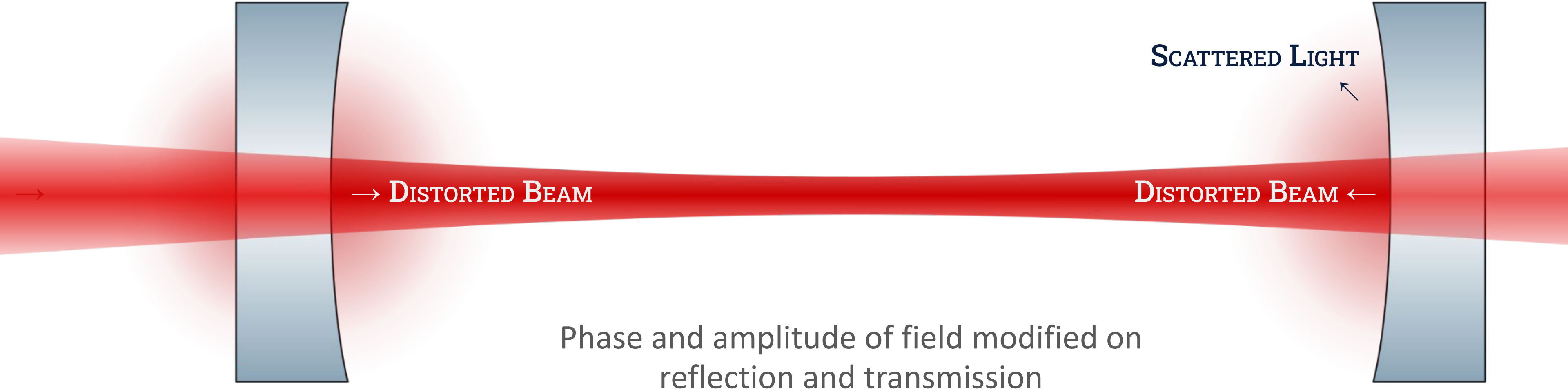
Stable beam shape (cavity *eigenmode*) with spherical mirrors:
Gaussian beam



Characteristic 'waist' size and position, spherically curved wavefronts

More realistically…

Finite-sized, thick optics: substrate + HR, AR coatings



Phase and amplitude of field modified on reflection and transmission

→ 2 broad regimes typically considered

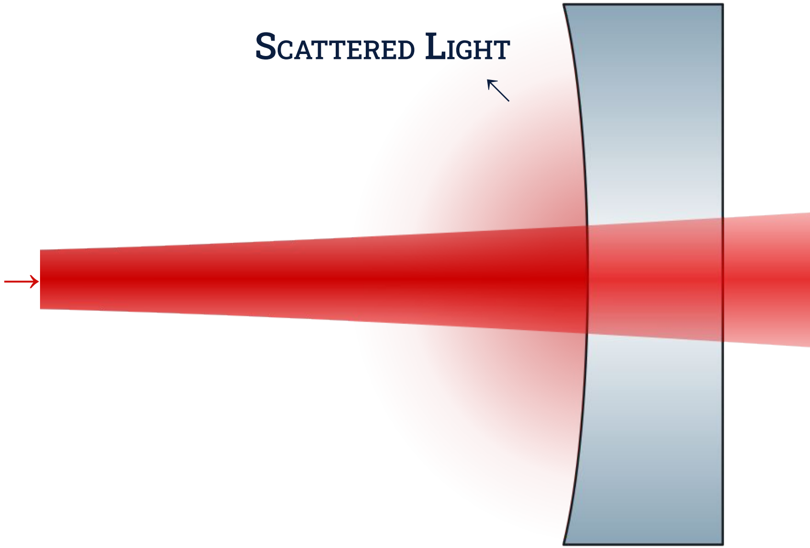
Scattered Light

Wide-angle scatter: light **leaves the cavity**

Origin: surface **micro-roughness**

Consequences:

- **loss** (diffraction loss)
  - Reduced circulating power; smaller GW signal
- environmental **noise**
  - Light exits cavity, reflects off another surface (e.g. vacuum tube), re-enters cavity
  - Surface moves due to ground motion, can look like a GW signal



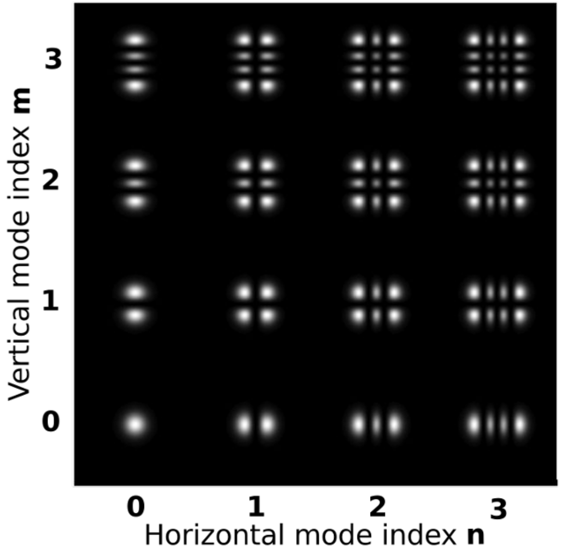
Beam Distortions

Lower spatial frequency defects **distort** the beam but the light still propagates through the cavity

The distorted optical field can be described as a sum of **higher order** Gaussian modes *e.g. Hermite-Gauss modes*⟶

Different beam shapes accumulate phase at different rates on propagation *(Gouy phase)*

⟶ affects resonance in cavity:
some distortions are **amplified** (x300 for LIGO/Virgo arms), others are **suppressed**

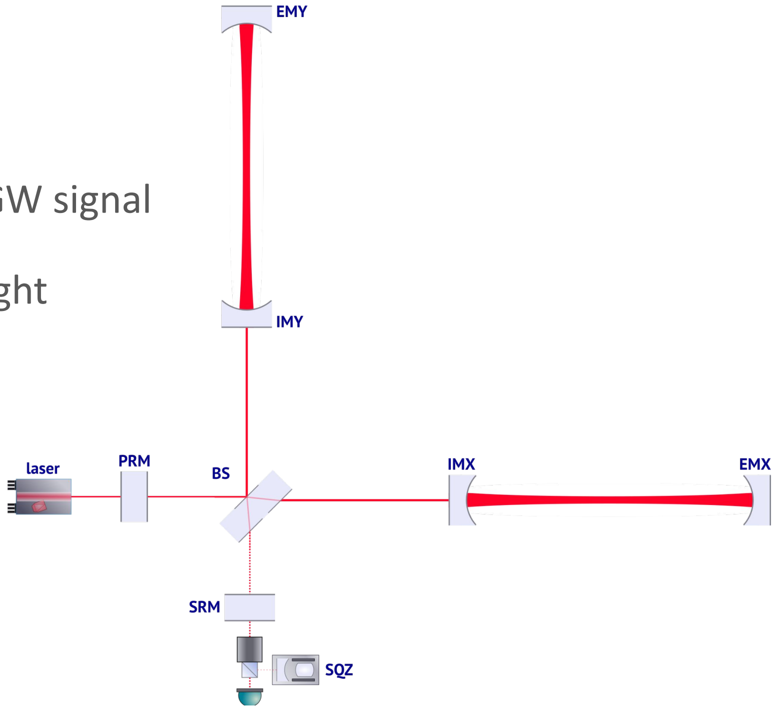


Beam Distortions: Consequences

GW detectors are designed for the Gaussian beam shape

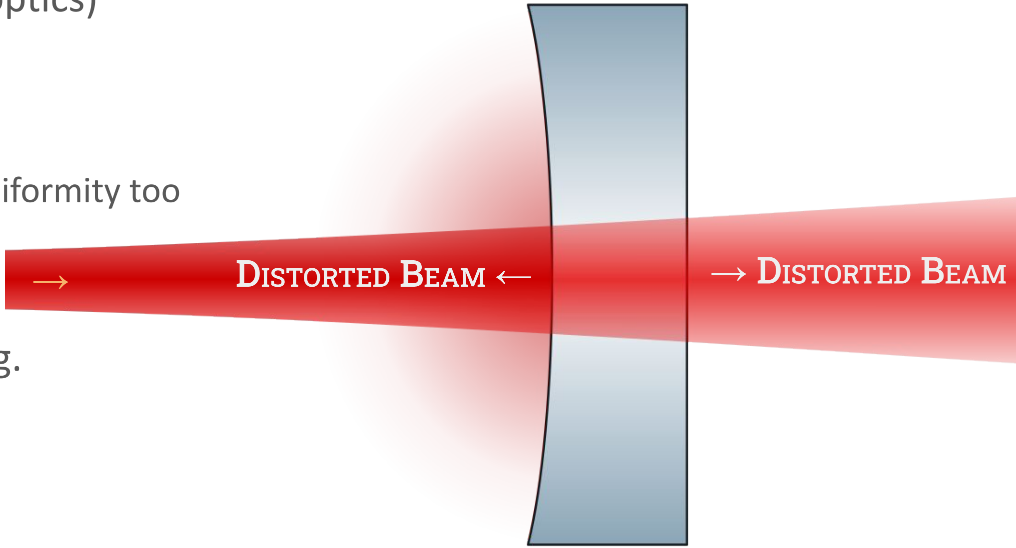
Light not in this shape *does not contribute* to the detected GW signal

- **Loss**: reduced circulating power, degraded squeezed light
- Interference pattern visibility reduces
  - E.g. beam shapes from the arms don't match
- Broader consequences
  - Pollution of controls signals, resonances in other parts of the detector, …



Beam Distortions: Origins

- Substrate homogeneity (for transmitting optics)
- **Surface flatness**
  - Driven by **polishing requirements**
  - Final performance depends on coating uniformity too
- Scratches, point defects,..
- Other more ‘exotic’ & transient effects, e.g.
  - Thermally driven (next call)
    Thermal lenses, point absorbers,..
  - Bulk mechanical resonances
    (determined by overall geometry)
    Parametric instabilities



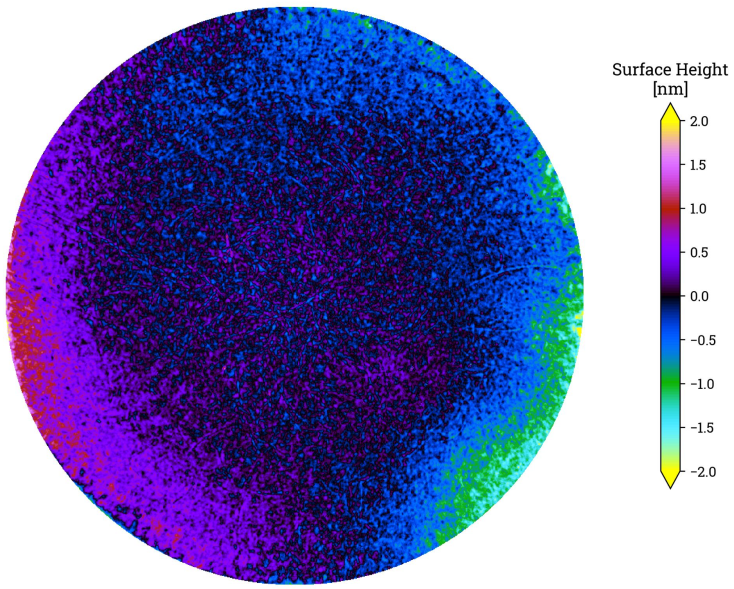
Determining & Assessing Requirements

Surface microroughness + flatness both primarily create **Loss**

→ **'loss budget'**
 = primary driver of mirror surface quality requirements

- Based on overall sensitivity goal + design choices to get there: circulating power, cavity design, ...
  - E.g. LIGO: 75ppm arm cavity round-trip loss goal
    → 37.5ppm per optic, distributed between absorption, microroughness, flatness
- → **RMS < 100pm**, **Flatness < ±2nm** requirements for ET

But the *details matter:*
Maps of wavefront distortion and absorption are essential for validating optics for ET



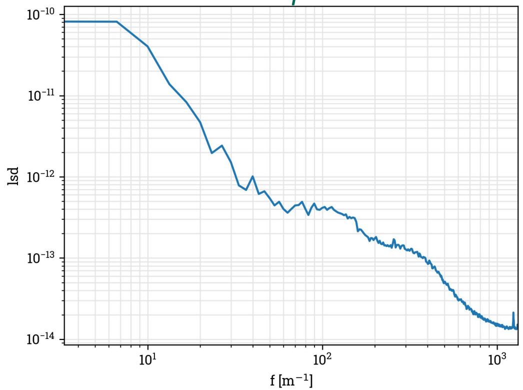
Example phase reflection map of a polished substrate

Validating ET optics

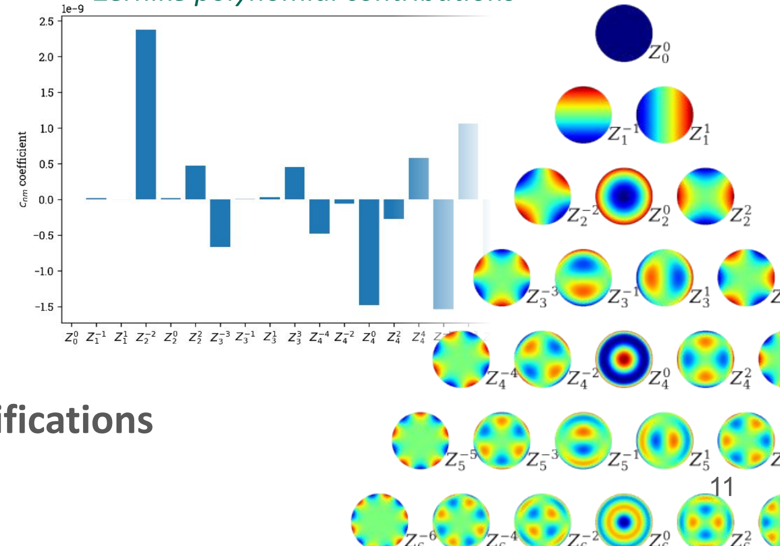
From appropriate surface/substrate maps:

- Power spectra
  - Contributions to beam distortions and scattered light
- Polynomial (Zernike) analysis
  - Impact of particular surface figures on beam distortion
- Optical simulations of ET interferometers
  - Account for resonant effects
  - Consider broader impact: loss, coupled resonances, controls, etc

Power spectrum



Zernike polynomial contributions



→ Active development (with you?): **metrology** & **targeted specifications** for ET mirrors accounting for the interferometer configuration

Thanks for your attention!
Questions?

This publication is part of the project "Smoothing the Optical Bumps in the Road for Future Gravitational-Wave Detectors" with project number VI.Veni.212.047 which is financed by the Dutch Research Council (NWO).