

Investigating mirror surface parameters for Einstein Telescope

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GOALS:

- **Testing surface reproduction tools**
- **Testing our own surface reproduction algorithm**
- **Provide mirror surface parameters for Einstein Telescope (ET)**

OVERVIEW:

- Gravitational Waves context
- Optics background
- Testing surface reproduction tools
- Summary

A. Einstein wrote the
General Relativity Theory



Gravitational Waves sources:

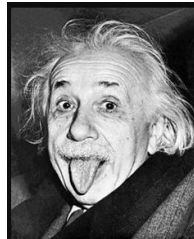
- Binary mergers
- Stochastic background
- Burst (GRB)
- Pulsar



Detectors:

- Advanced LIGO (AdLIGO)
- Advaced Virgo (AdVirgo)
- GEO600
- KAGRA
- LIGO India

3rd generation:
Einstein Telescope



How do we detect GW signals?

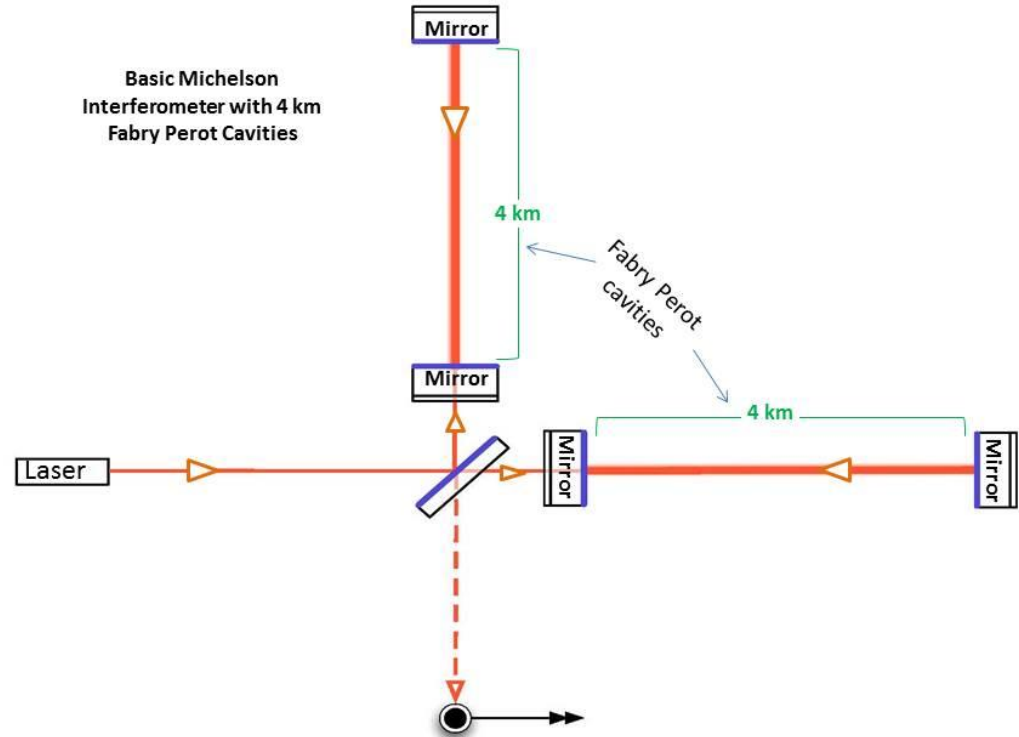
- **Interferometer** = **interference** effect.
- Gravitational waves change arm lengths, causing interference.

L = arm length

$h(t)$ = gravitational wave

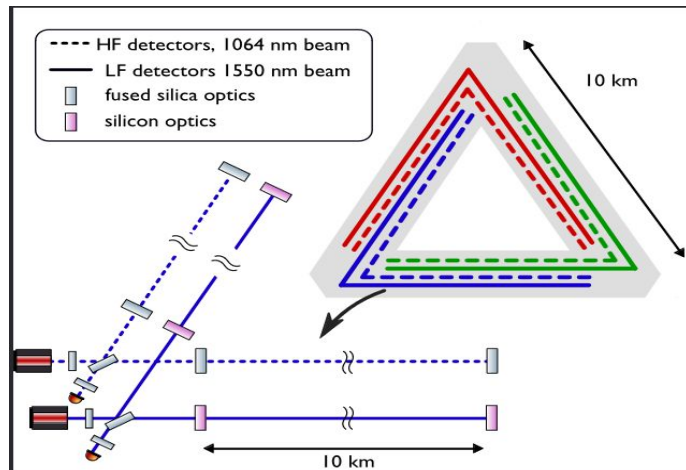
$$h(t) = \frac{\Delta L}{L}$$

$$\phi = \frac{2\pi \Delta L}{\lambda}$$

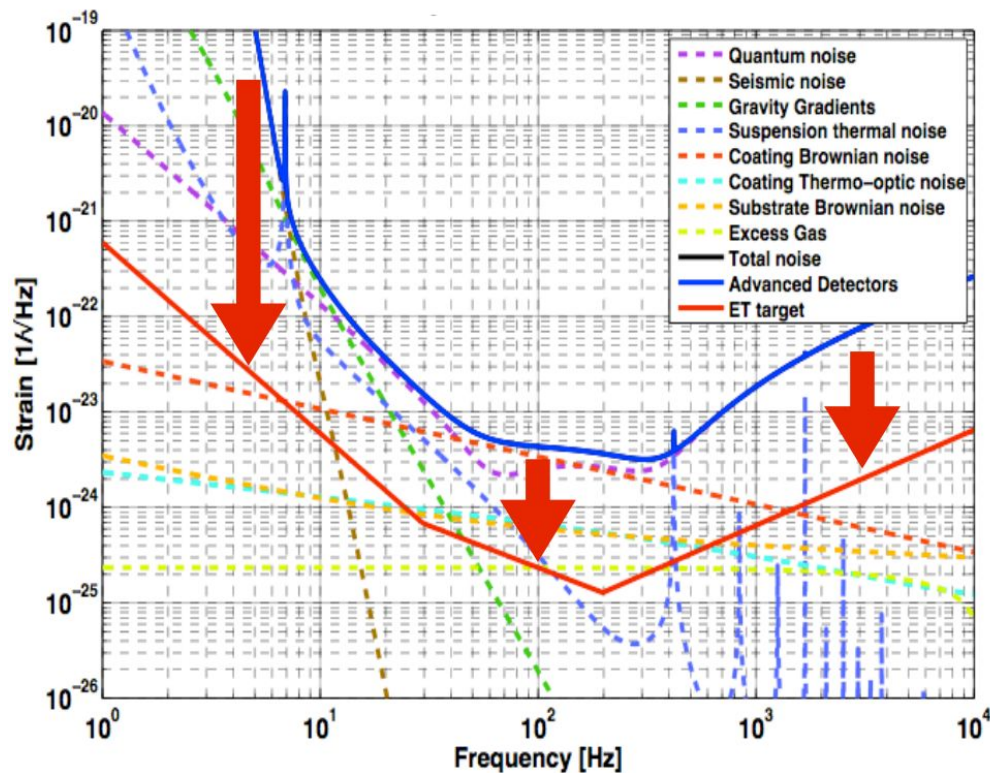


Einstein Telescope: 3rd generation interferometer

- Triangular shape = 3 interferometers in 1.



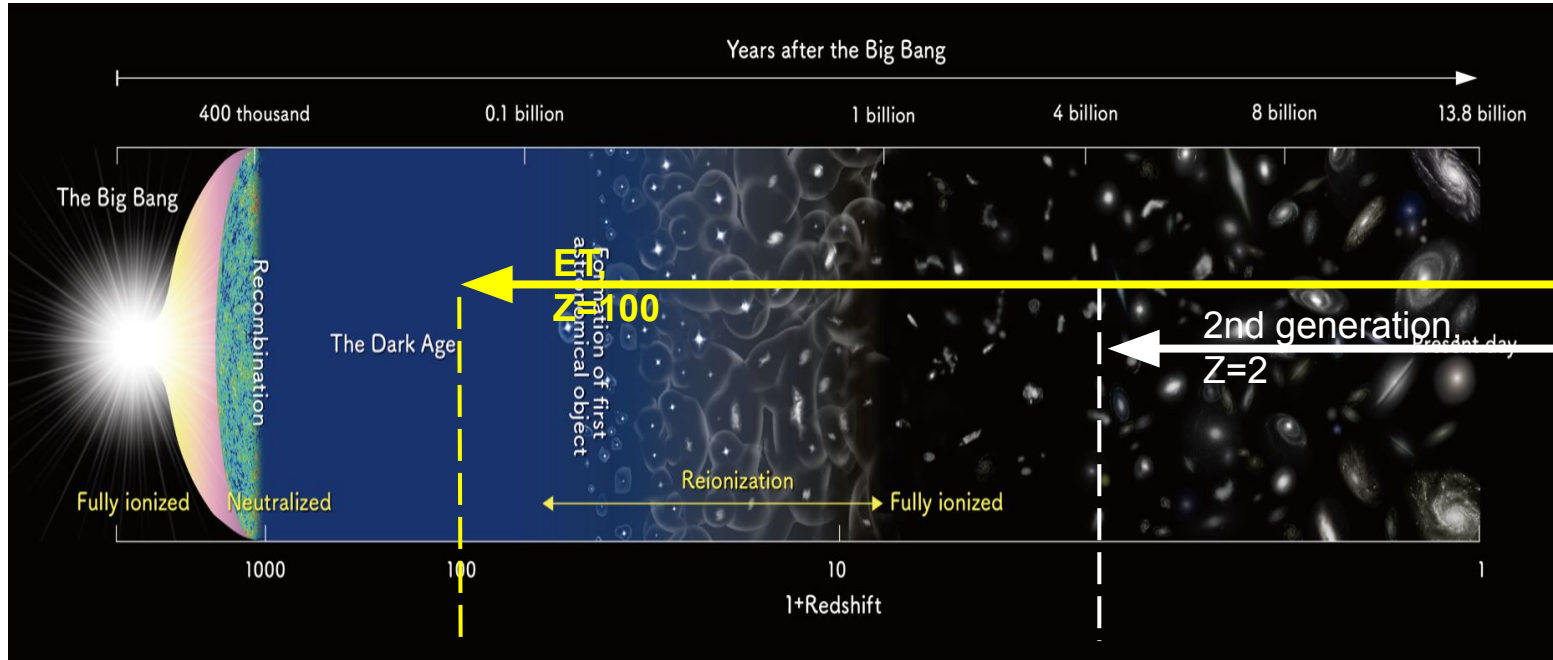
- 10x times better sensitivity (at least) vs 2nd generation.
- GW data for astronomy and fundamental physics for the next 50 years.
- Cryogenic for thermal noise.
- Underground for brownian noise (>200m).



“How you’ll do it?..... Without ever sparing effort to go back.”(GATTACA).

Einstein Telescope: how far can you see?

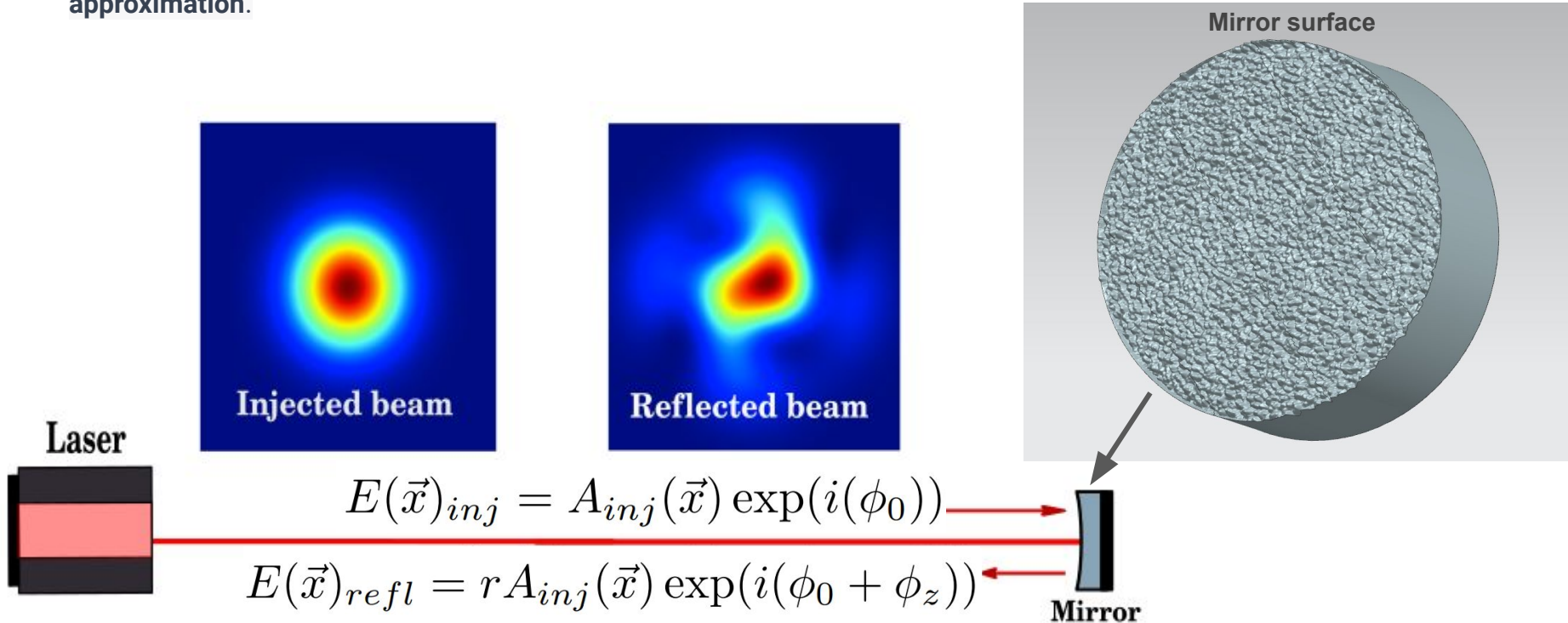
Aims to observe gravitational waves originating from the Big Bang.



SPOILER: NO GOOD MIRRORS NO DETECTION!

The effect of imperfect mirrors

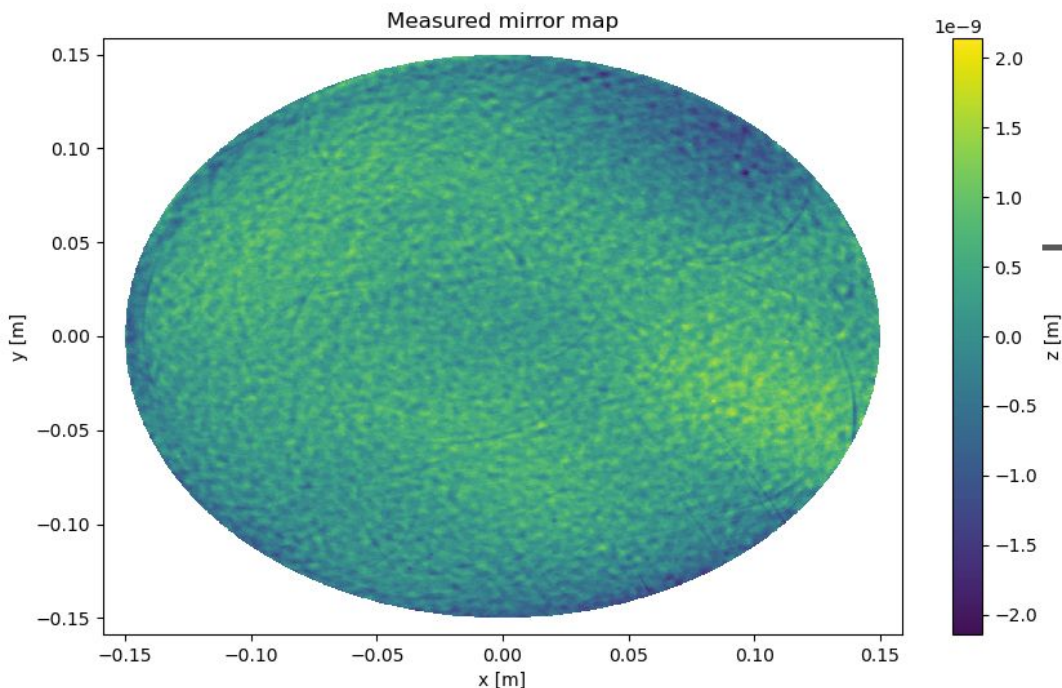
- "Imperfect **optical surfaces** deform the reflected beam"
- Gravitational wave detectors are designed with a **Gaussian beam** shape as the sole resonant mode, assuming the **paraxial approximation**.



Mirror Maps and Virtual Mirror Maps

Measured mirrors surfaces = Mirror Maps

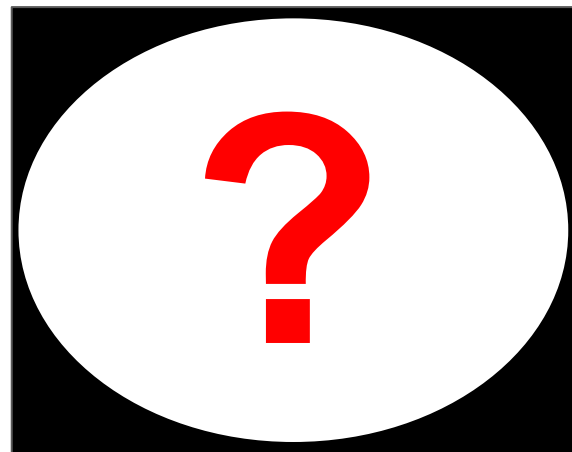
2D array of mirror property (phase, distortion, reflectivity).



Predict ET mirrors performance

=

Virtual Mirror Maps

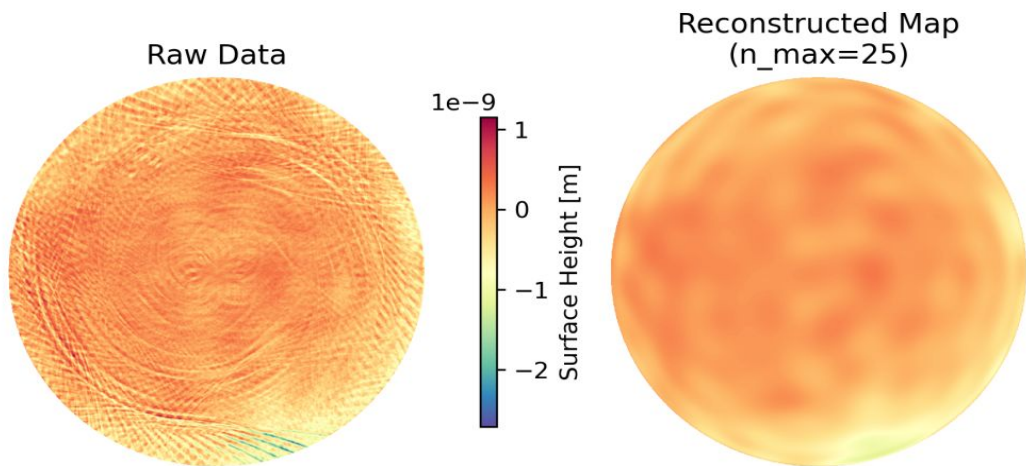
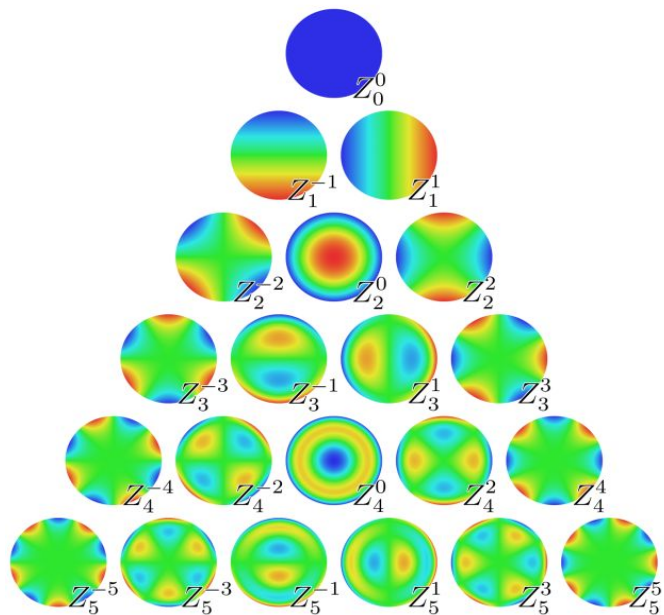


- Base: AdLIGO, AdVirgo mirror maps.
- Tools: Zernike, FFT
- Our algorithm: tools + randomness to make unique maps.

Surface reproduction with Zernike basis

- Zernike polynomials represent many distortion types
- Defined on a unit disc.
- Its orthogonality simplifies the analysis of complex wavefronts.

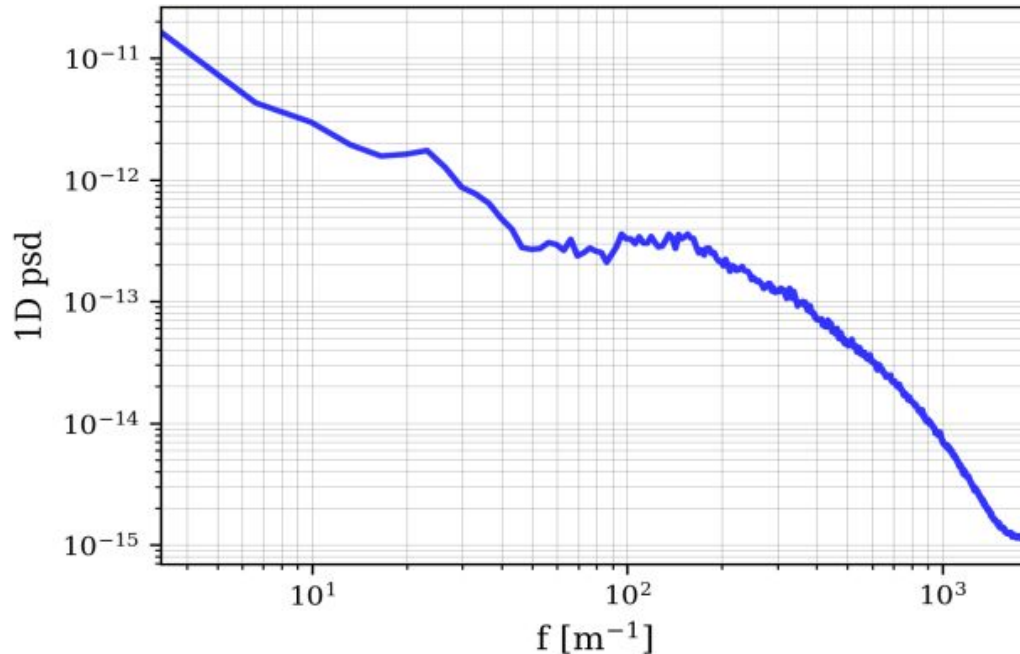
$$Z_n^{+m}(\rho, \phi) = A_n^{+m} \cos(m\phi) R_n^m \text{ even polynomial}$$
$$Z_n^{-m}(\rho, \phi) = A_n^{-m} \sin(m\phi) R_n^m \text{ odd polynomial}$$



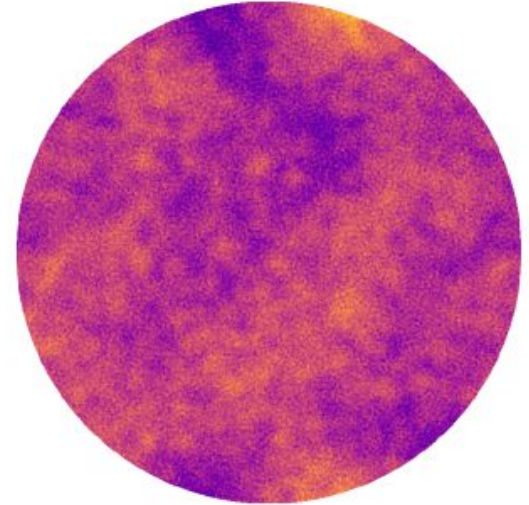
Fast Fourier Transformation and Virtual Mirror Map

Use Fast Fourier Transformation (FFT) to characterize surface roughness at various length scales

Raw data's FFT



Virtual Mirror Map

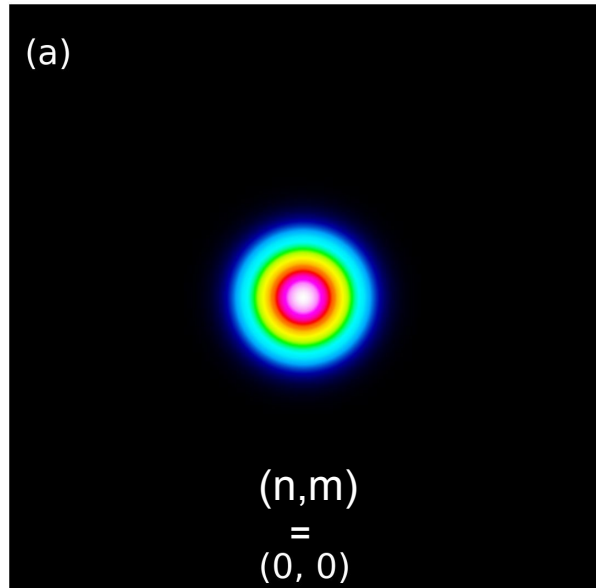


Gaussian beam and Higher Order Modes

Small angle scattering light:

- paraxial approximation.
- Hermite-Gauss basis u_{nm}

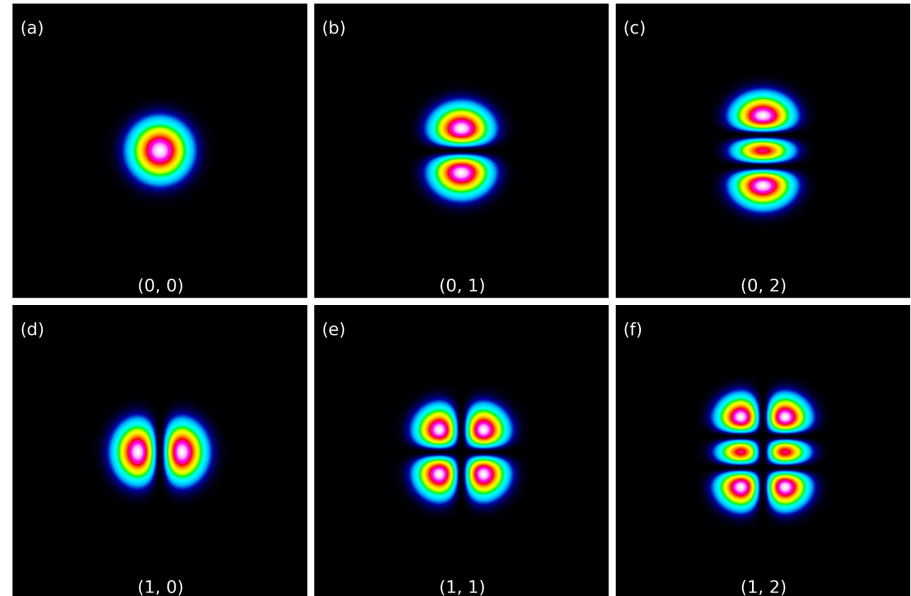
Gaussian beam:



Gaussian beam + imperfect mirror:

- Scattering in **Higher Order Modes** (HOMs).

$$E(\vec{x}, t) = \sum_j \sum_{nm} a_{nmj} u_{nm} \exp(i(w_j t - \vec{k} \cdot \vec{x}))$$

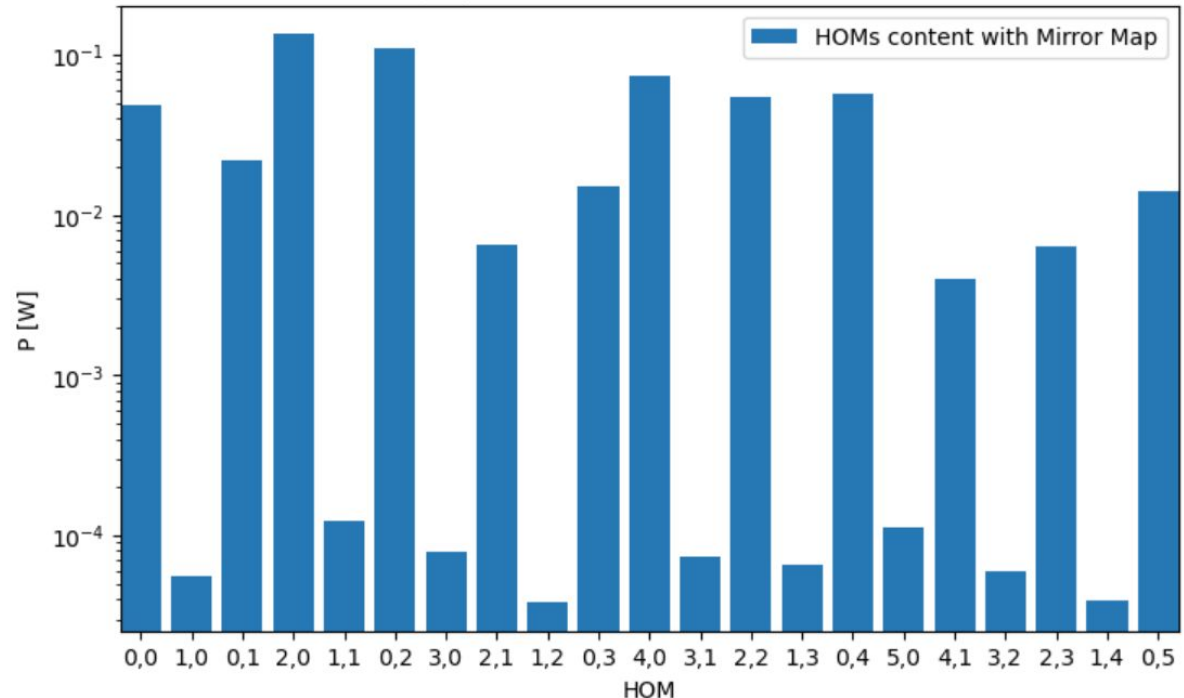


HOMs analysis with Virtual Mirror Maps

- Einstein Telescope model is used to analyze virtual mirror maps impact on higher order modes.

Higher Order modes in ET model:

ET(HF) mirror: reflected Power vs HOMs



Finesse

- Finesse is used to design current and future interferometers in steady-state.
- Virtual Mirror Maps + ET Finesse model = HOMs analysis

Summary

To provide parameter specifications for ET mirrors we need to predict their performances in the interferometer.

- We're testing the accuracy of well-known surface reproduction tools: Zernike basis and Fast Fourier Transformation.
- We are developing our own Virtual Mirror Maps, based on AdLIGO and AdVirgo mirror data.
- We're doing optical simulations with Finesse software to evaluate the Virtual Mirror Maps and, ultimately, provide surface parameter requirements for ET mirrors.

"Curious how this will end? Don't worry, the article is coming!"

Thanks!

Backup slides

ET: Pathfinder is built in Maastricht :-)

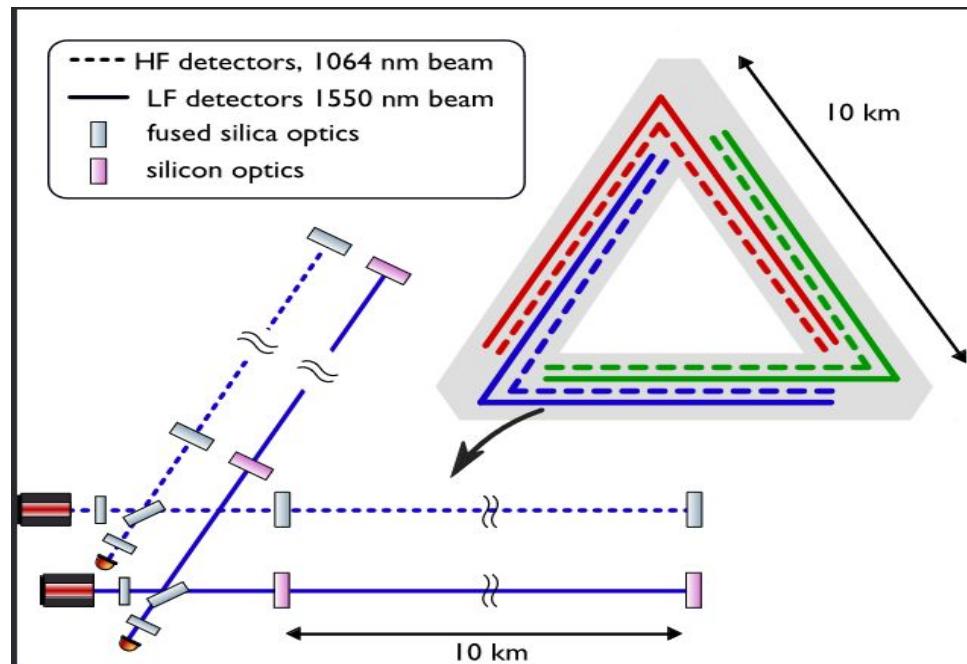
LF:

- 1 to 250 Hz.
 - Optics cooled to 10 K
- vs KAGRA ~20 K.
- Power 18 kW in the arms.

HF:

- 10 Hz to 10 kHz (vs LIGO, Virgo 10-5kHz).
- Room temperature optics.
- Power 3MW in the arms (vs LIGO, Virgo ~200W).

Arms: 10km (vs 4km LIGO, 3km Virgo and KAGRA)



IFO	λ	mode	mirror \varnothing	R_C	w_0	z_0	w	g -factor
ET-HF	1064 nm	TEM_{00}	62 cm	5070 m	1.42 cm	5000 m	12.0 cm	0.95
ET-LF	1550 nm	TEM_{00}	45 cm	5580 m	2.9 cm	5000 m	9.0 cm	0.63