Friedrich-Alexander-Universität
Erlangen-Nürnberg

FRANCI 2026
20 July 2026
JMU Würzburg

EINSTEIN TELESCOPE

Erlangen Centre for Astroparticle Physics

FAU

Fibre-based Phase Camera for the Einstein Telescope

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20-07-2026

FAU Erlangen-Nürnberg
Erlangen Centre for Astroparticle Physics (ECAP)

Presentation Outline

01

The Einstein Telescope

A next-generation gravitational wave observatory.

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The Fibre-Based Phase Camera Concept

How a 56-pixel array measures the spatial phase and amplitude of the laser wavefront, validated in a **Measurement Campaign.**

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The Fibre-Based Phase Camera Concept

How a 56-pixel array measures the spatial phase and amplitude of the laser wavefront, validated in a **Measurement Campaign.**

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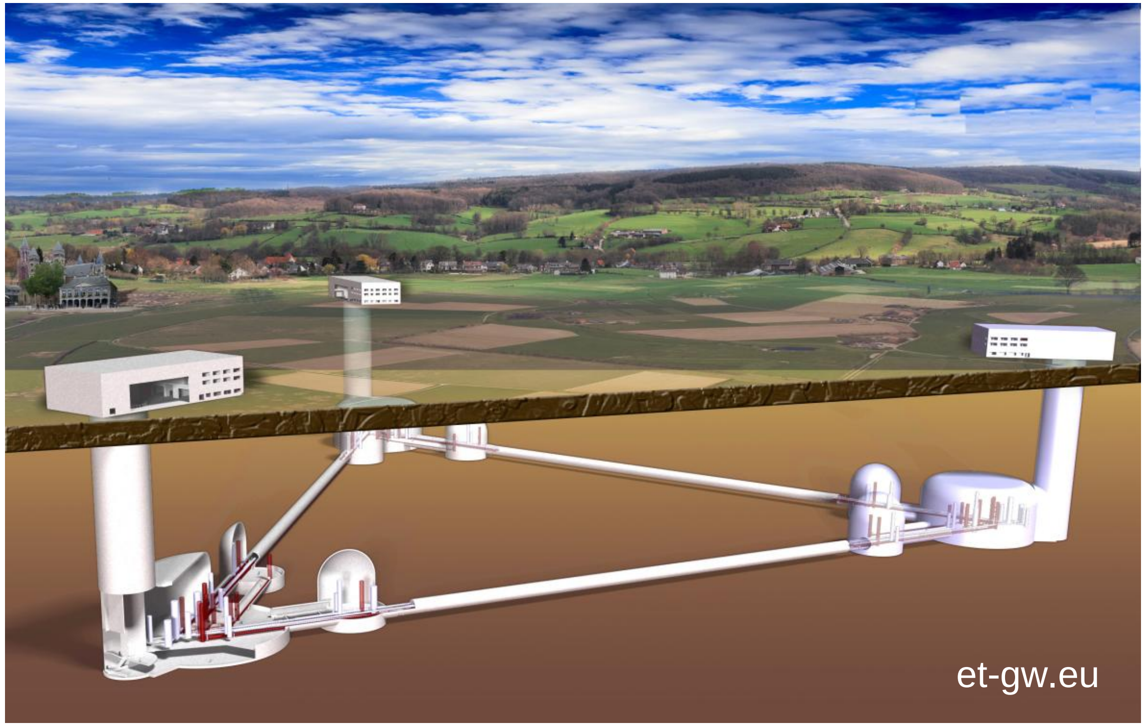
Interpreting Phase Camera Images

Using Machine Learning for Mode Decomposition and comparing it with classical benchmarks.

What is the Einstein Telescope (ET)?

Proposed third generation gravitational wave observatory.

Proposed Locations: *Euregio Meuse-Rhine* (border region of Netherlands, Belgium & Germany), *Sardinia* (Italy), and *Lusatia* (Saxony, Germany)



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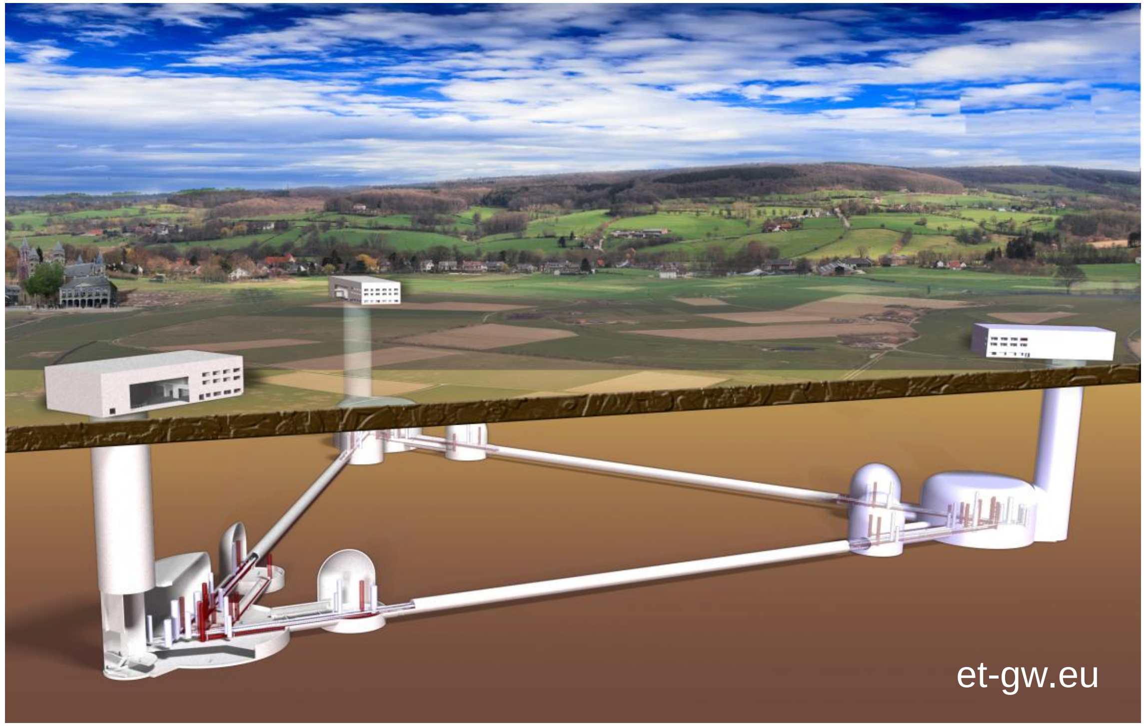
Xylophone design:

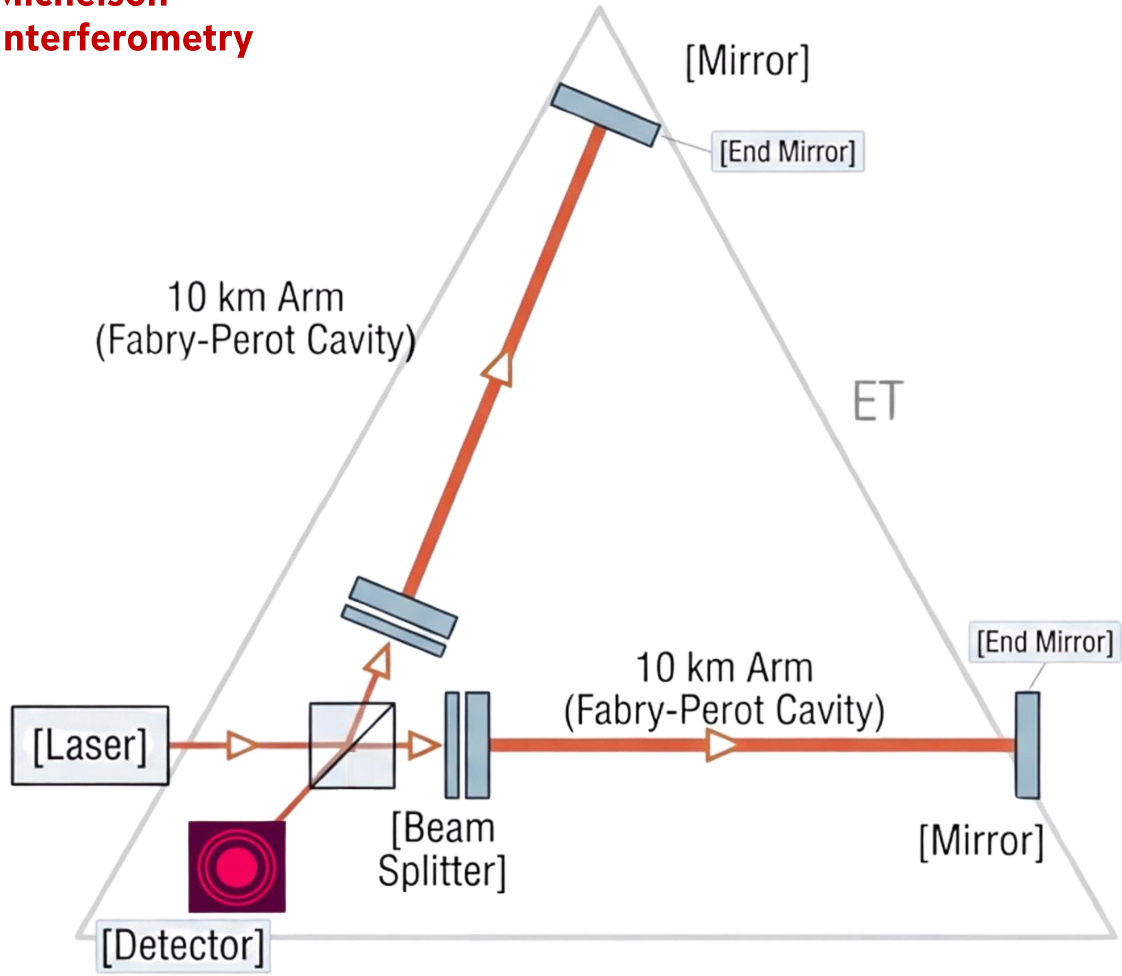
- **High-frequency interferometer :** 1064 nm wavelength, fused-silica optics to reduce photon shot noise

- **Low-frequency interferometer :** 1550 nm wavelength, silicon optics for reduced thermal noise



What is the Einstein Telescope (ET)?

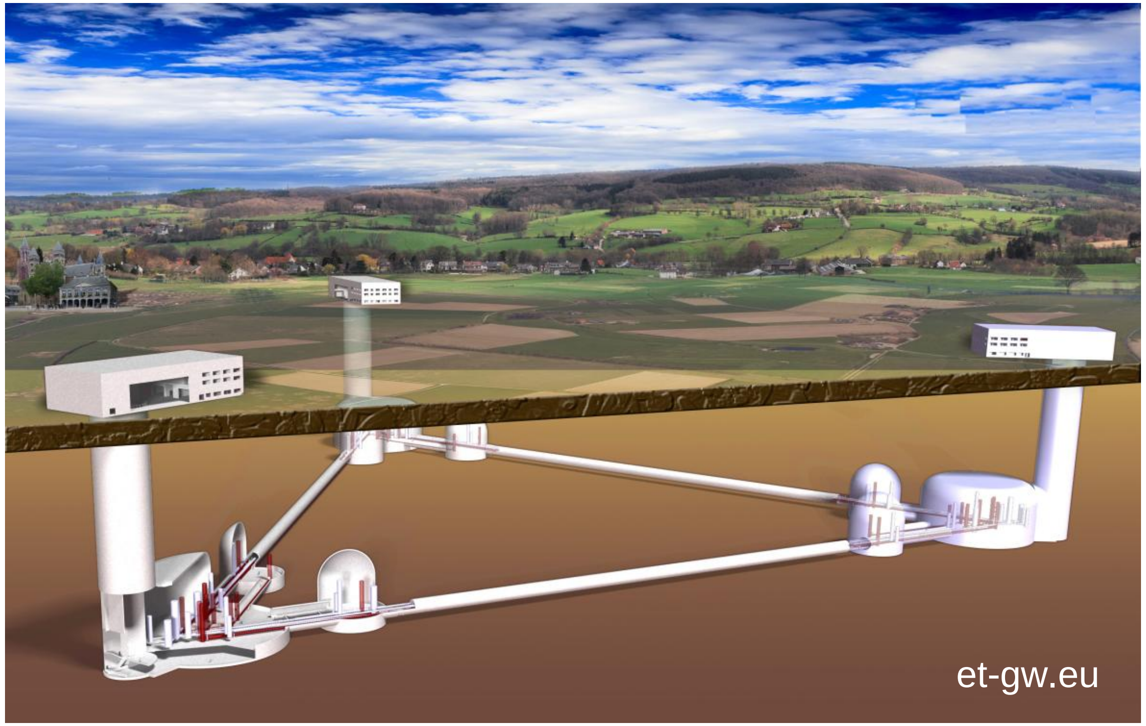
Michelson Interferometry



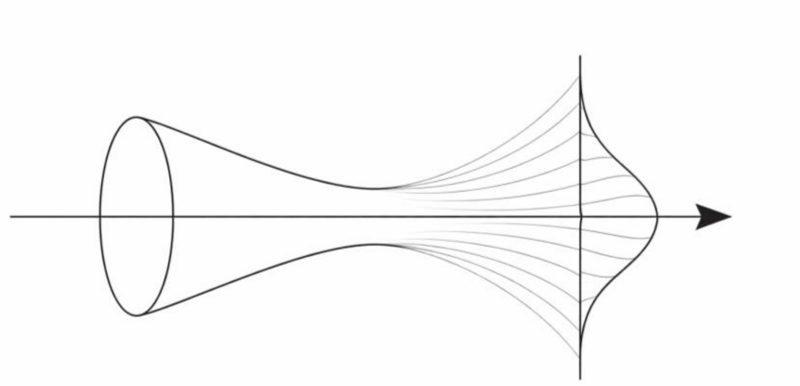
→ A laser is split into two arms

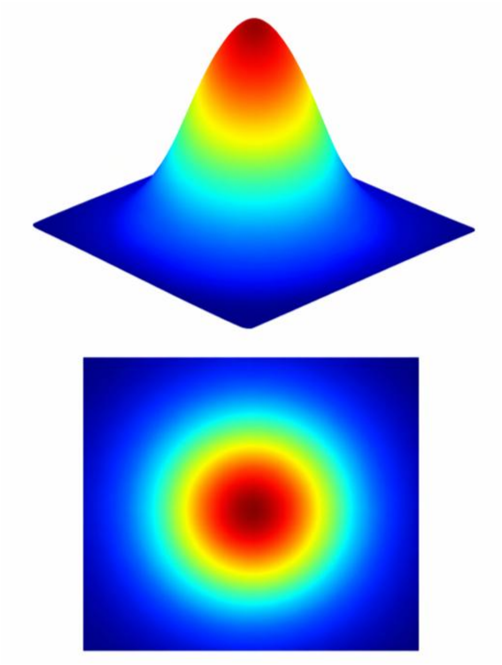
→ Passing gravitational waves stretch space in one direction and squeeze it in the other

→ This slightly alters the travel distance of the light, changing the interference pattern at the detector.

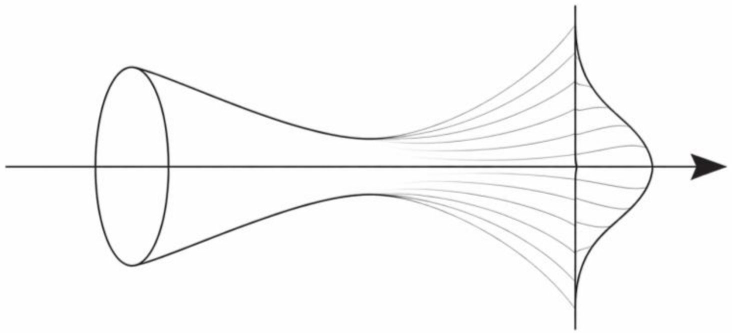


Analyzing the Beam:
Gaussian vs. Higher-Order Modes

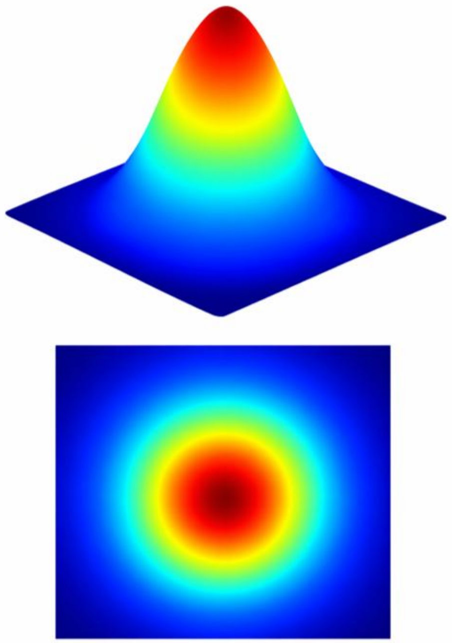




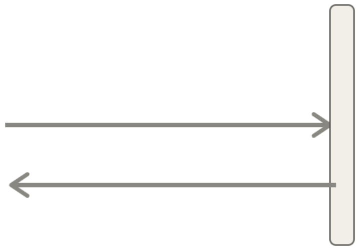
Analyzing the Beam: Gaussian vs. Higher-Order Modes



A simple example: How mirror defects distort a reflected laser beam

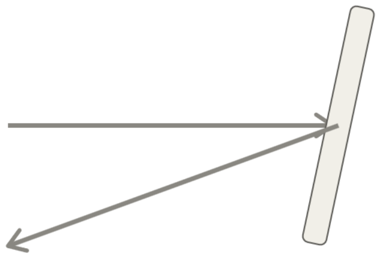


Correct setup



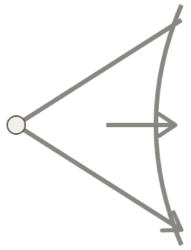
Beam returns unchanged

Tilted mirror



Reflected axis bends

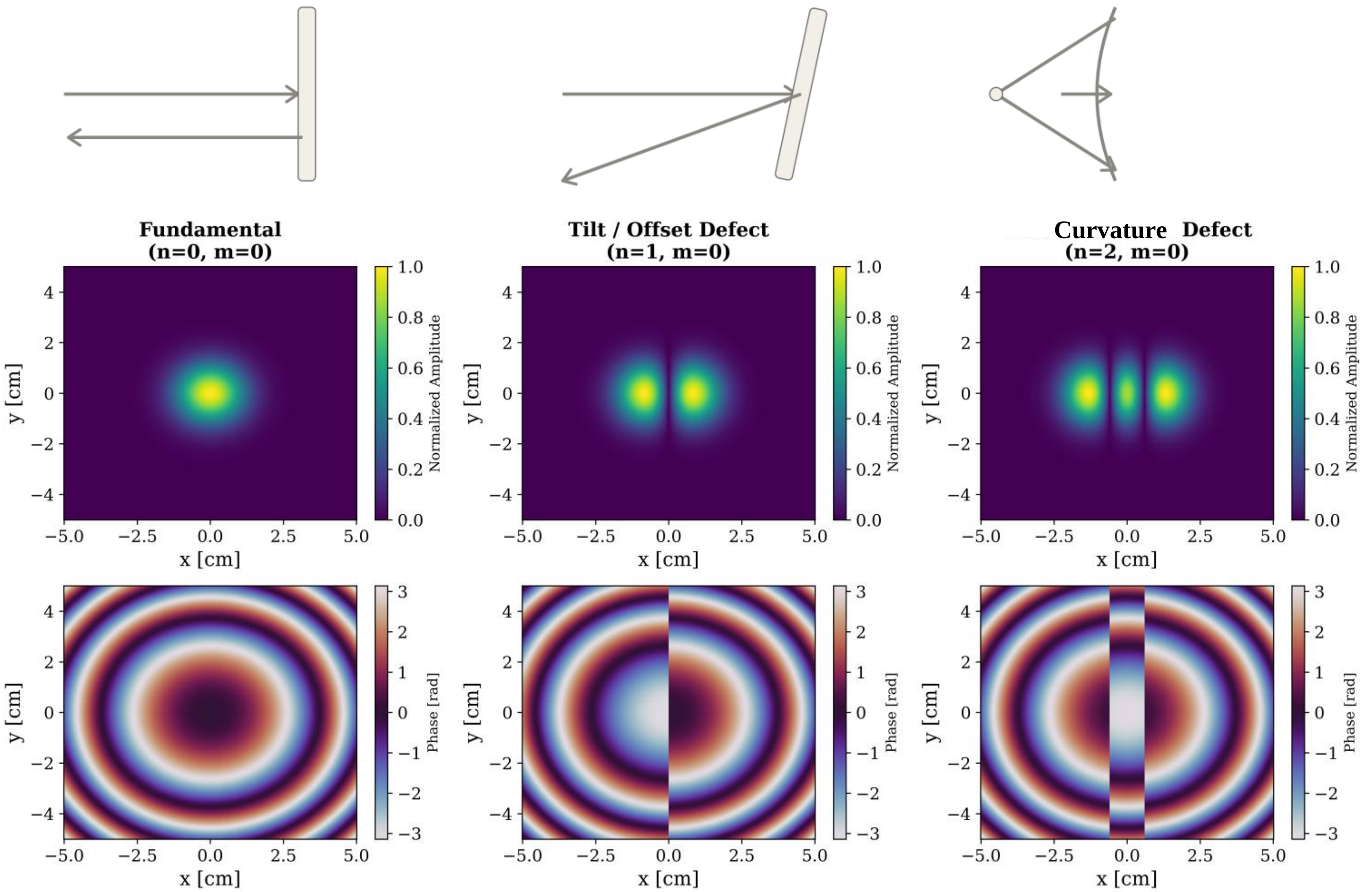
Wrong curvature



Focus lands at wrong distance

Analyzing the Beam:
Gaussian vs. Higher-Order Modes

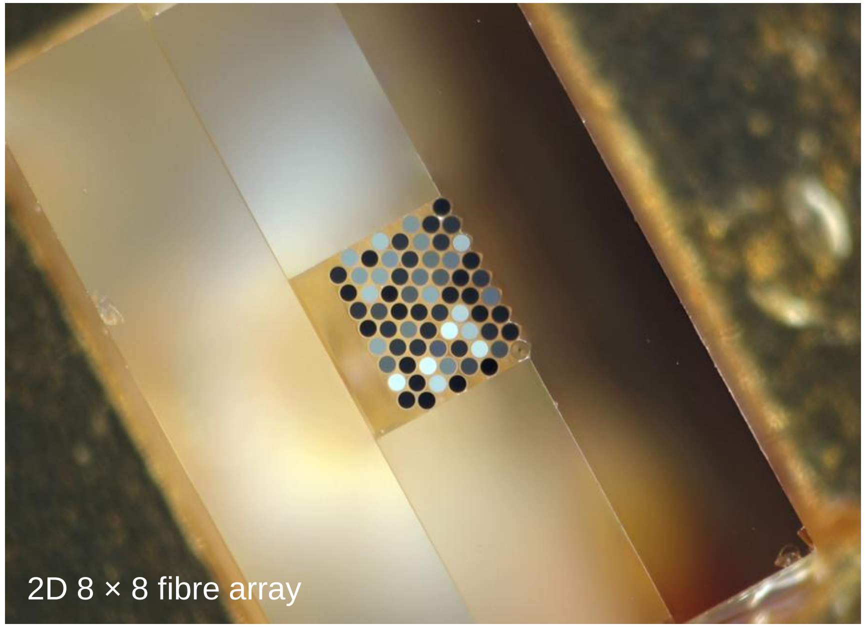
Correct setup | Tilted mirror | Wrong curvature



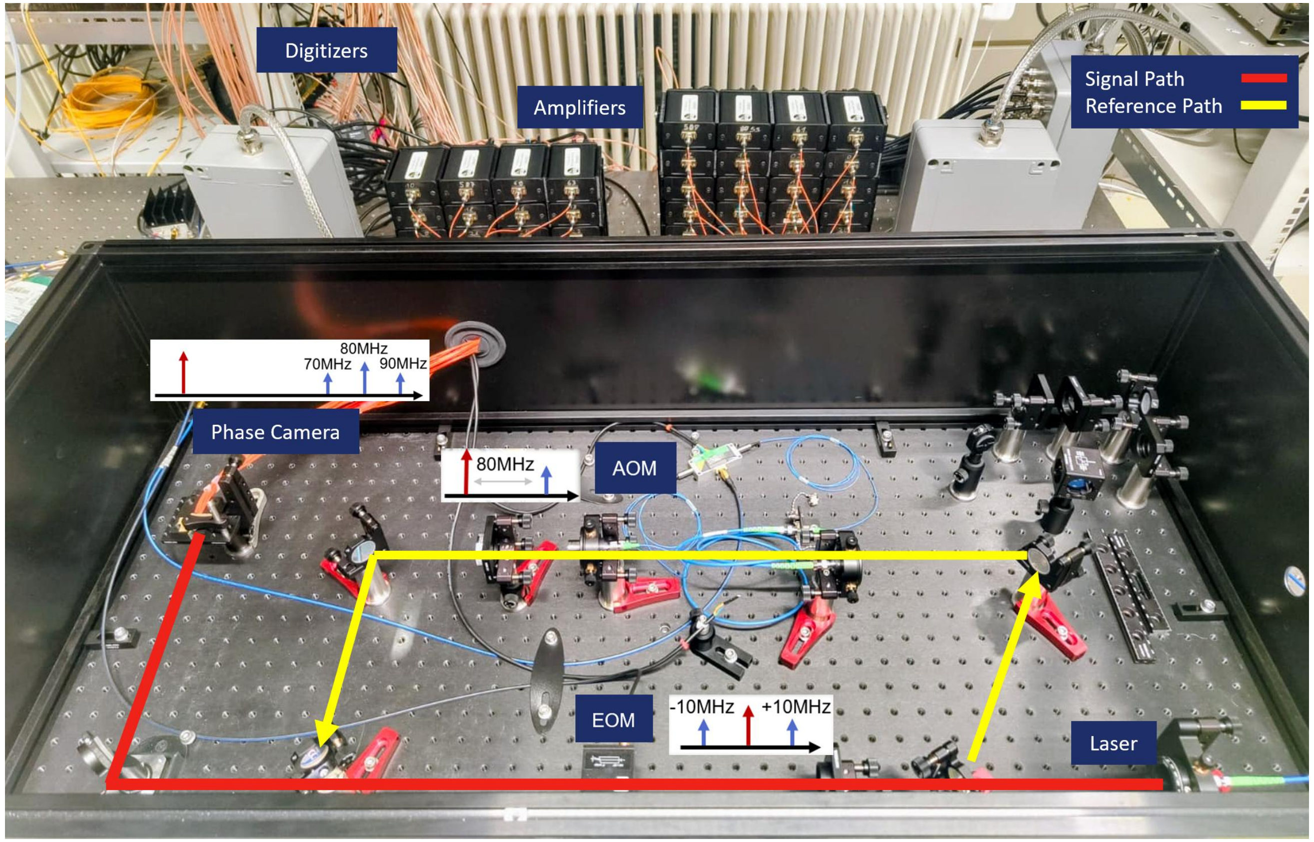
The Phase Camera Concept

- Measures the **spatial phase** and **amplitude** of the laser wavefront.
- Acts as a diagnostic tool to map exactly how and where the beam is misaligned or deformed.

Fibre Based Approach: Each fiber is read out by an individual photodiode, ensuring per-pixel isolation and preventing electrical cross-talk.



Dr. Benjamin Schwab, Einstein Telescope and CTAO, 2026

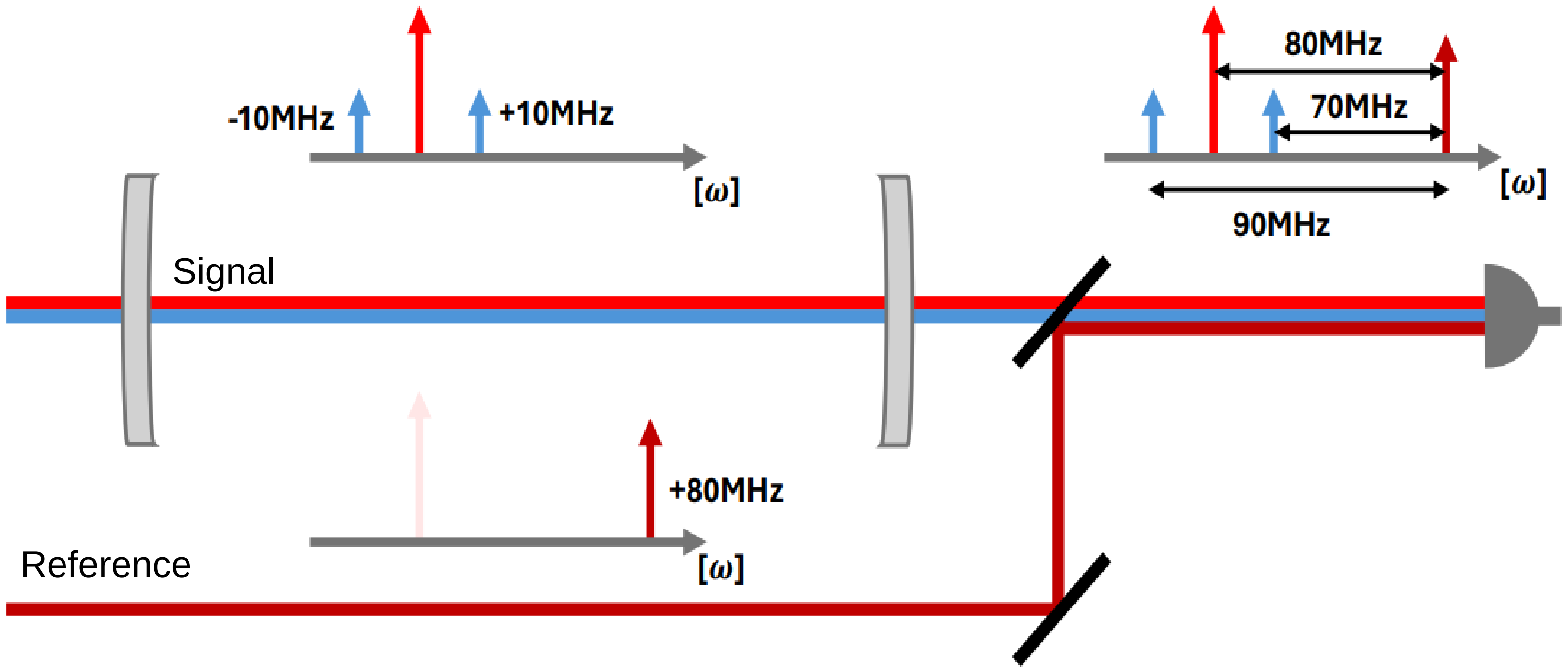


ECAP Lab Setup of Phase Camera

The Phase Camera Concept

- **The Challenge:** Standard detectors only measure intensity!

Direct phase measurement: Light oscillates far too fast for any electronics to follow directly.



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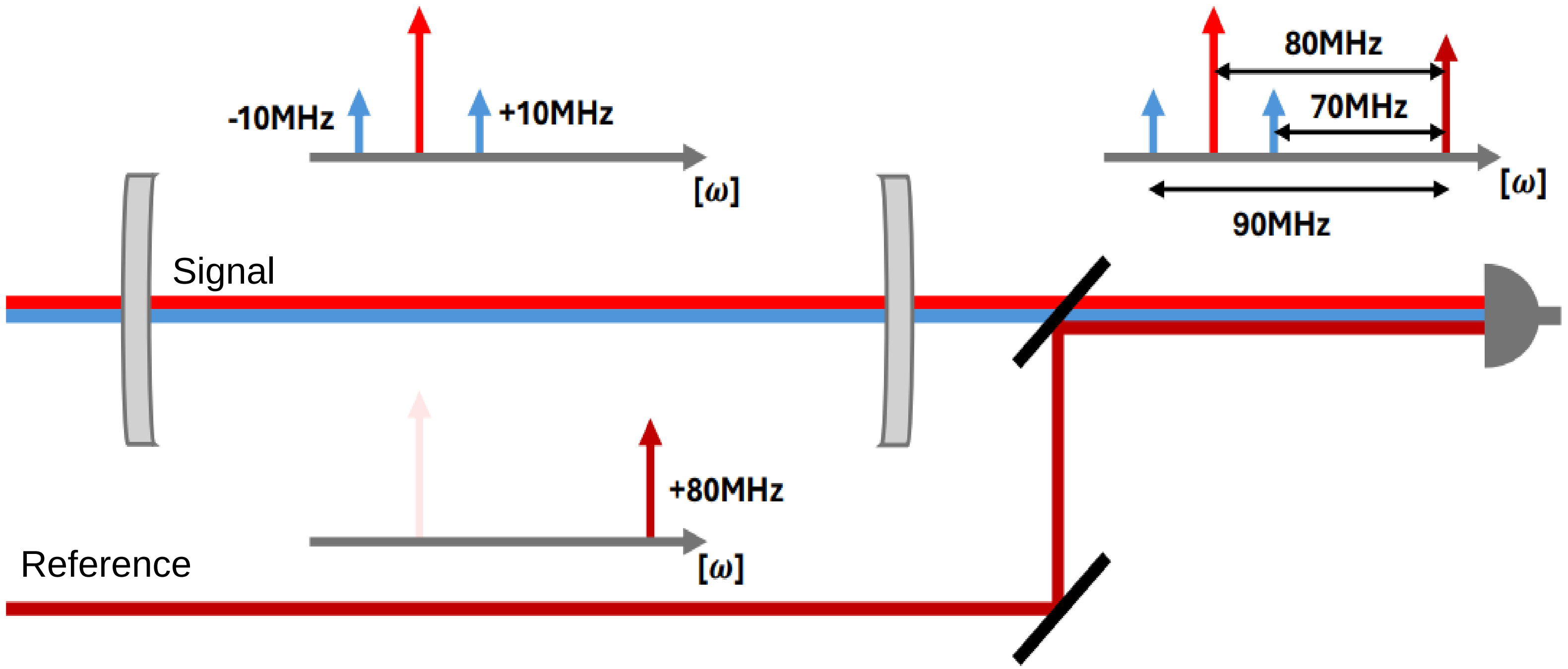

- **(Heterodyne Detection):** Overlapping sidebands with a slightly detuned reference beam (e.g., shifted by 80 MHz) , we successfully transfer the phase information into measurable intensity.

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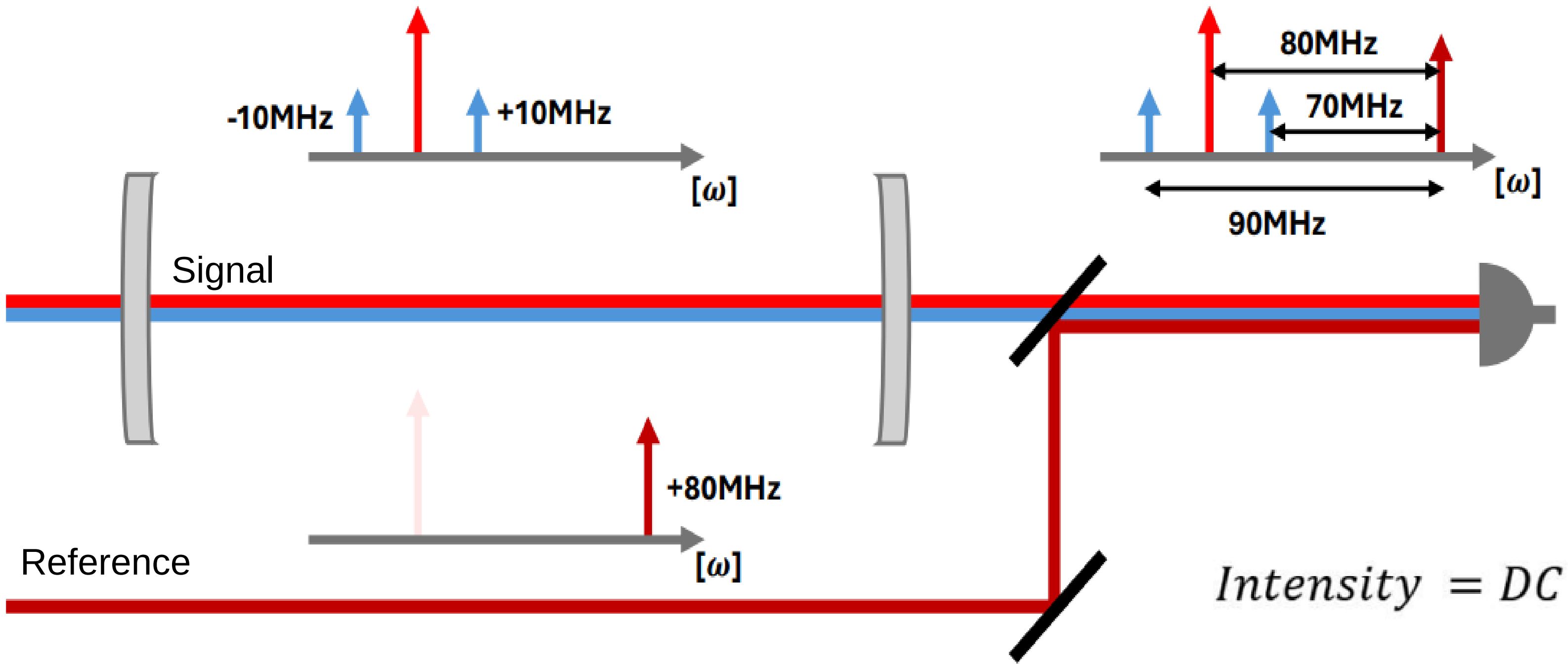

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detuned beat frequency

$$Intensity = DC + 2E_{1550}E_{ref}\cos(\omega_{80MHz}t + \Delta\varphi)$$

Spatial phase difference between the beams.

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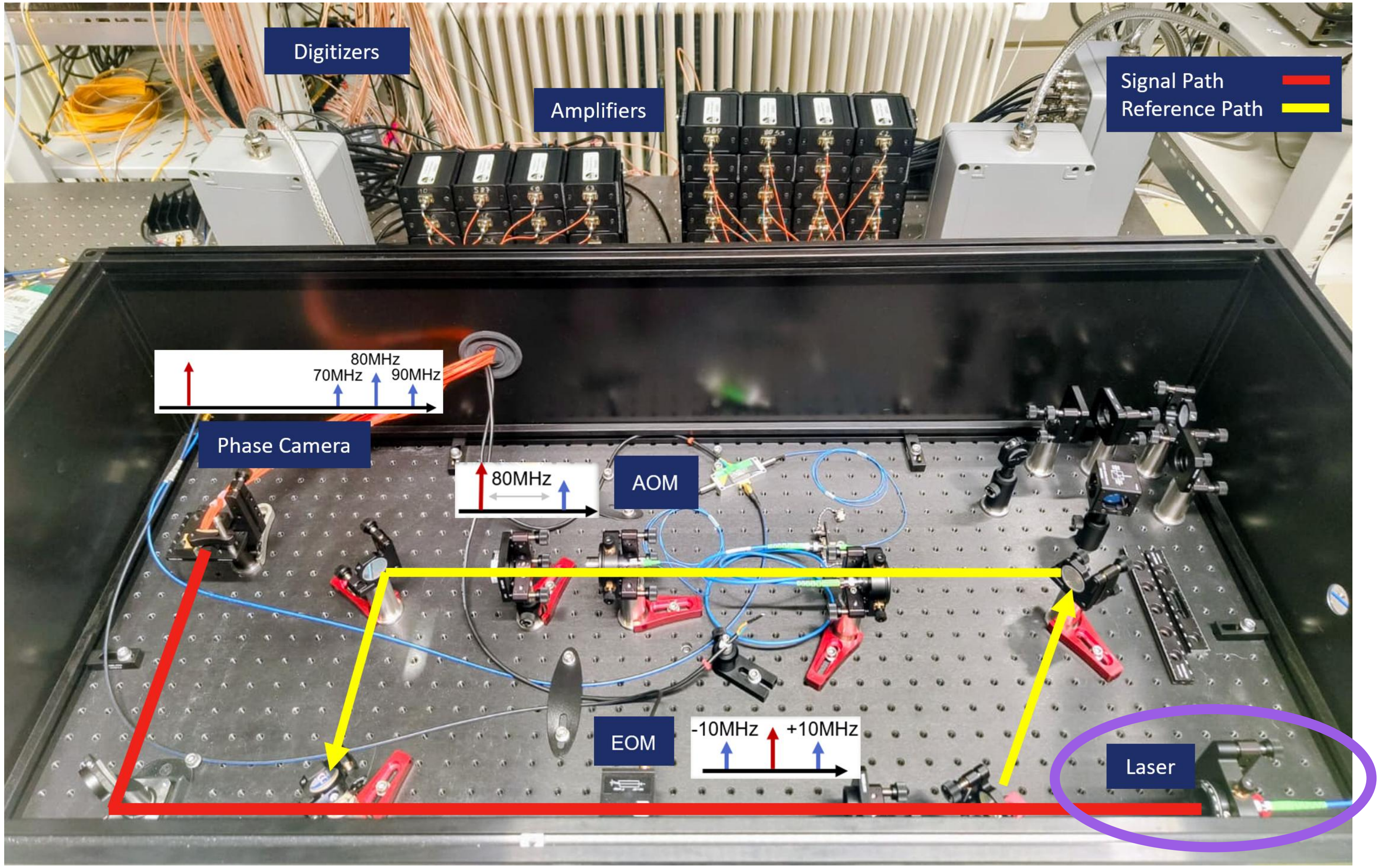
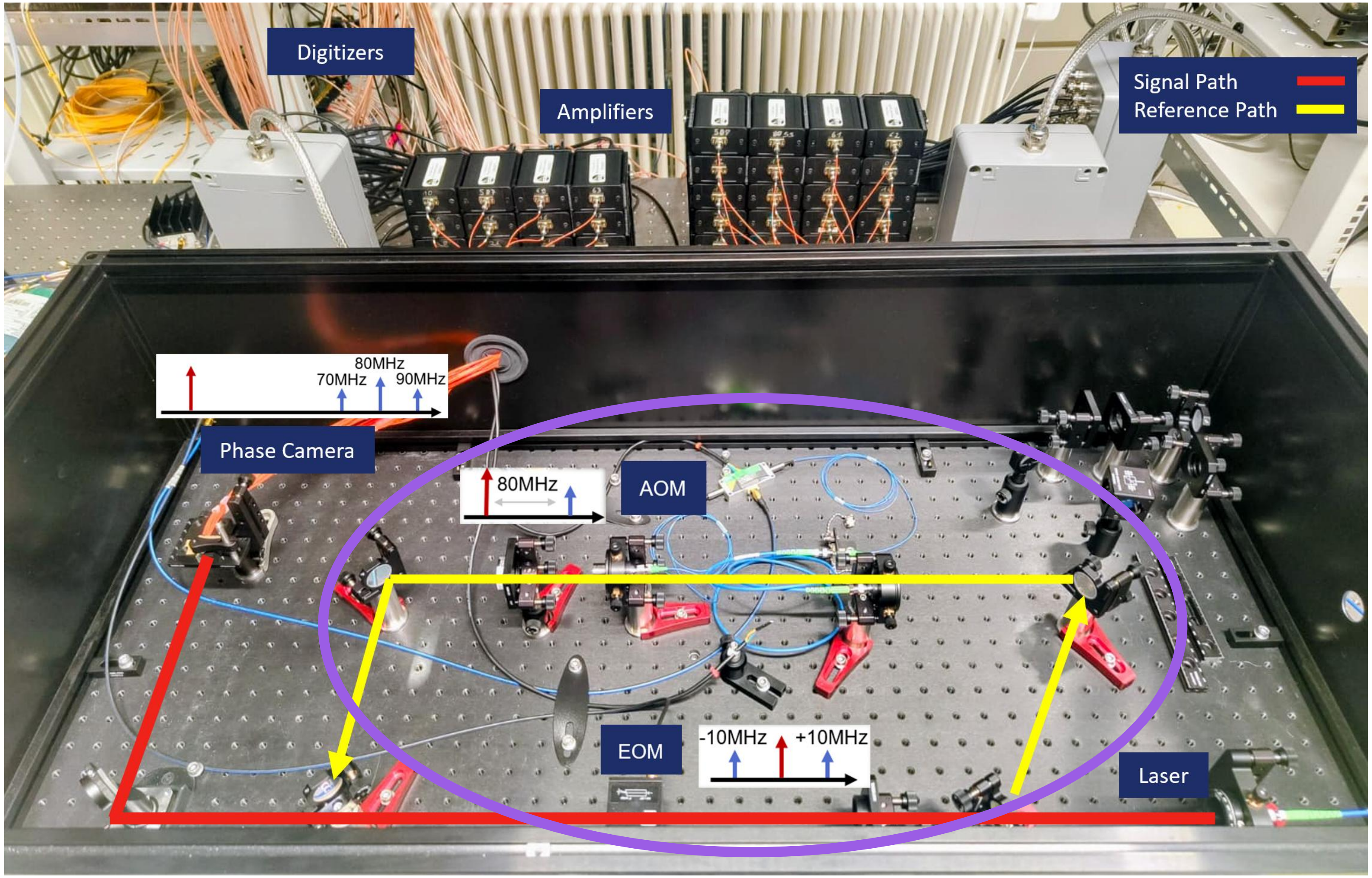
The Phase Camera Concept



ECAP Lab Setup of Phase Camera

The Phase Camera Concept



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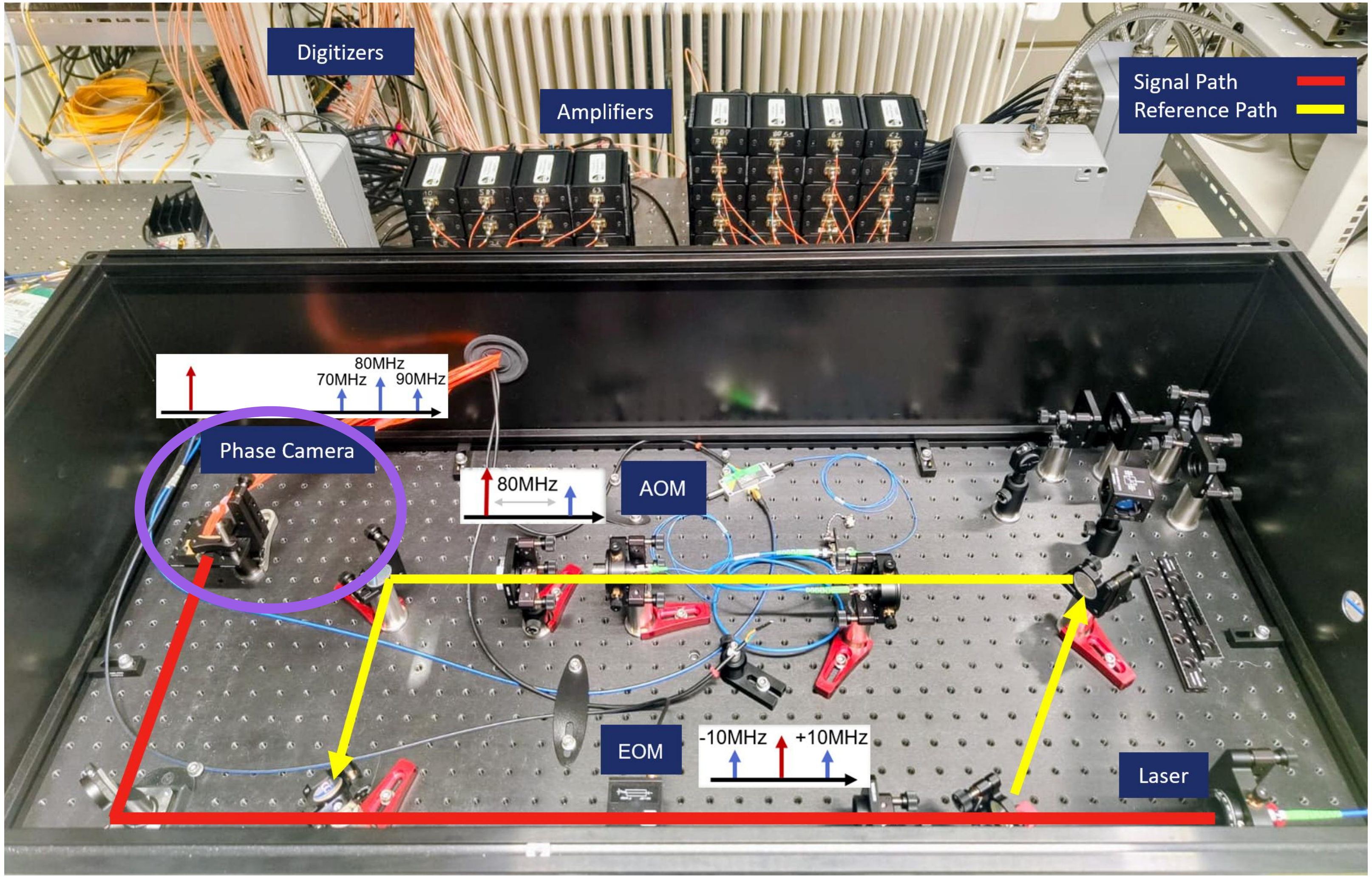

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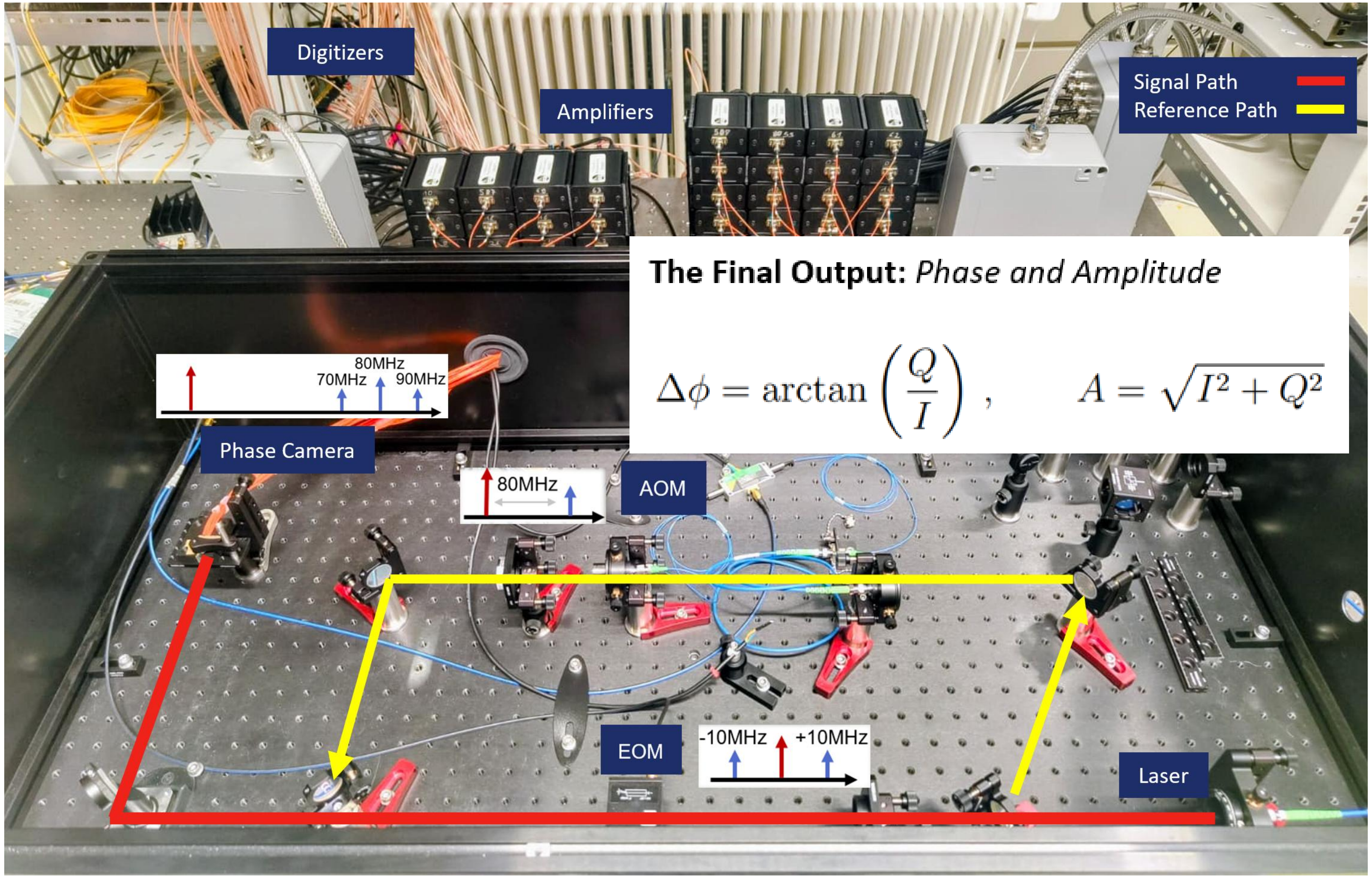

ECAP Lab Setup of Phase Camera

Measurement Campaign

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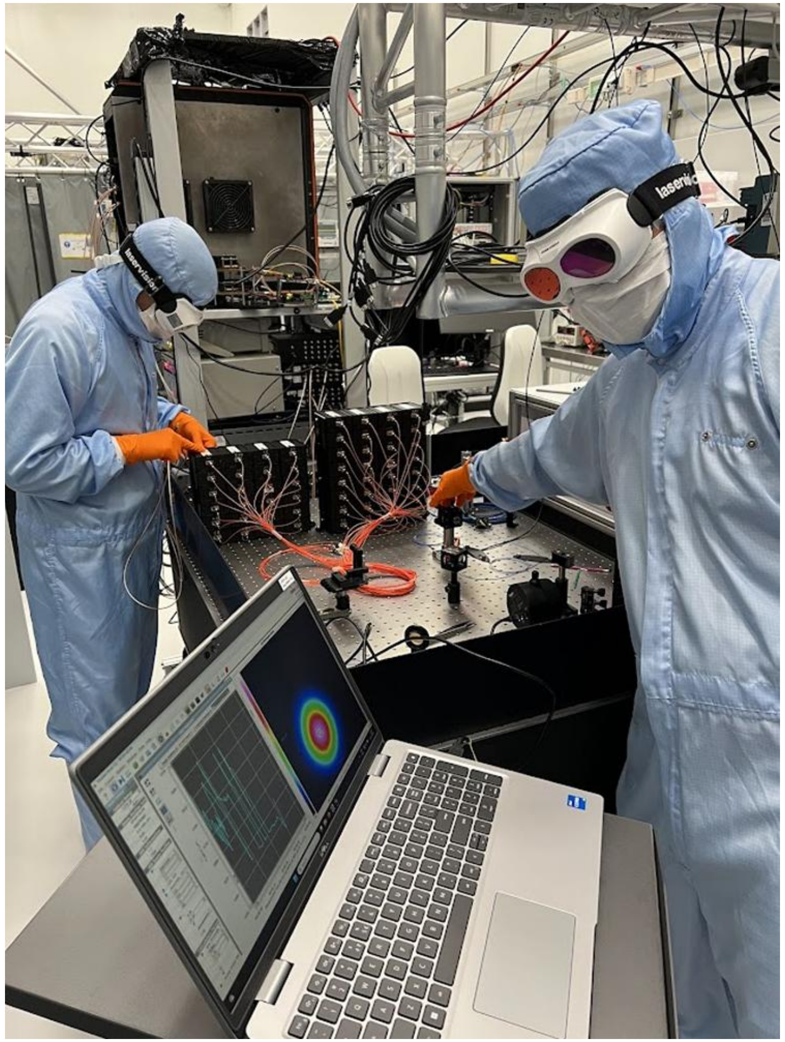
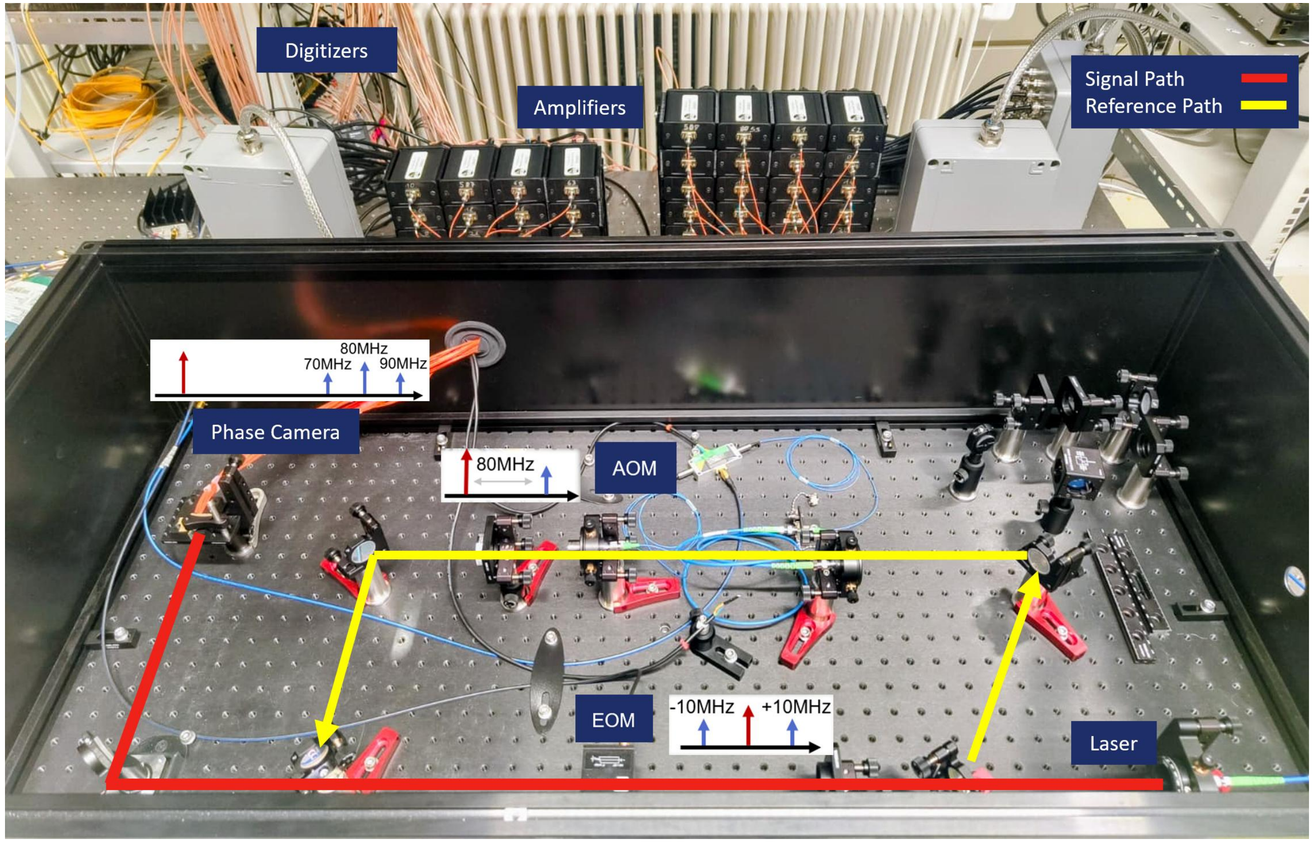
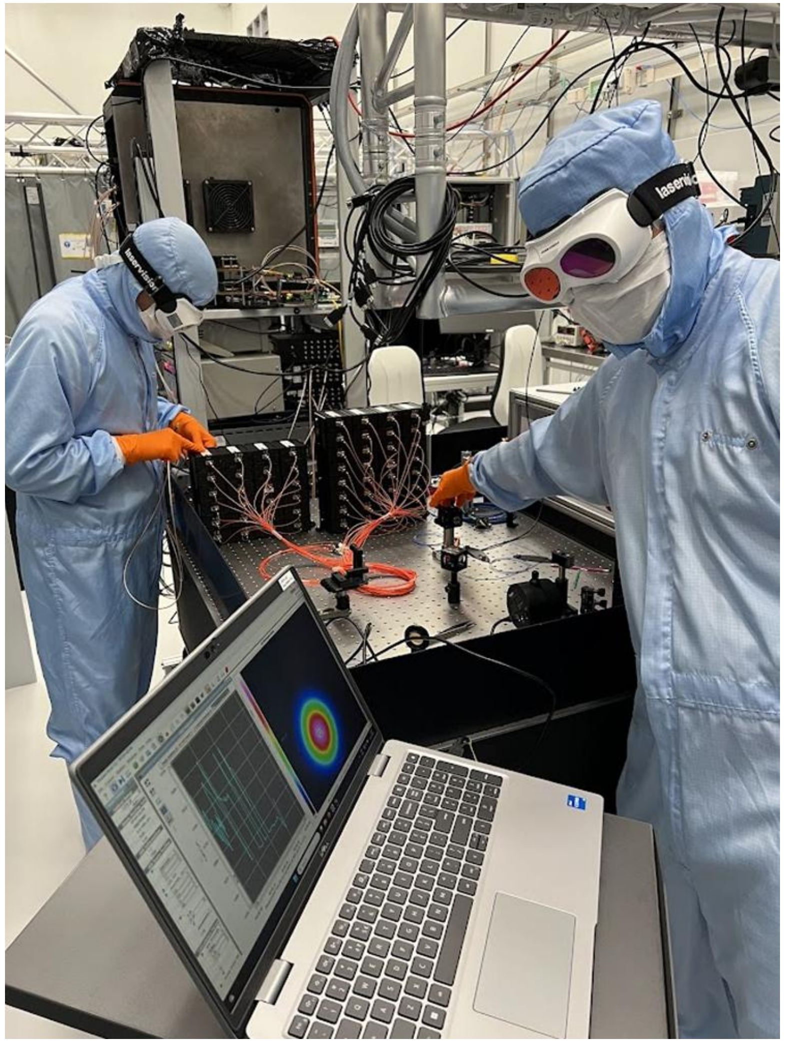
Test facility at Maastricht, Netherlands. The measurement campaign was held from (20.07.2025 to 01.08.2025). Picture Credit: Stefan Hild





ECAP Lab Setup of Phase Camera

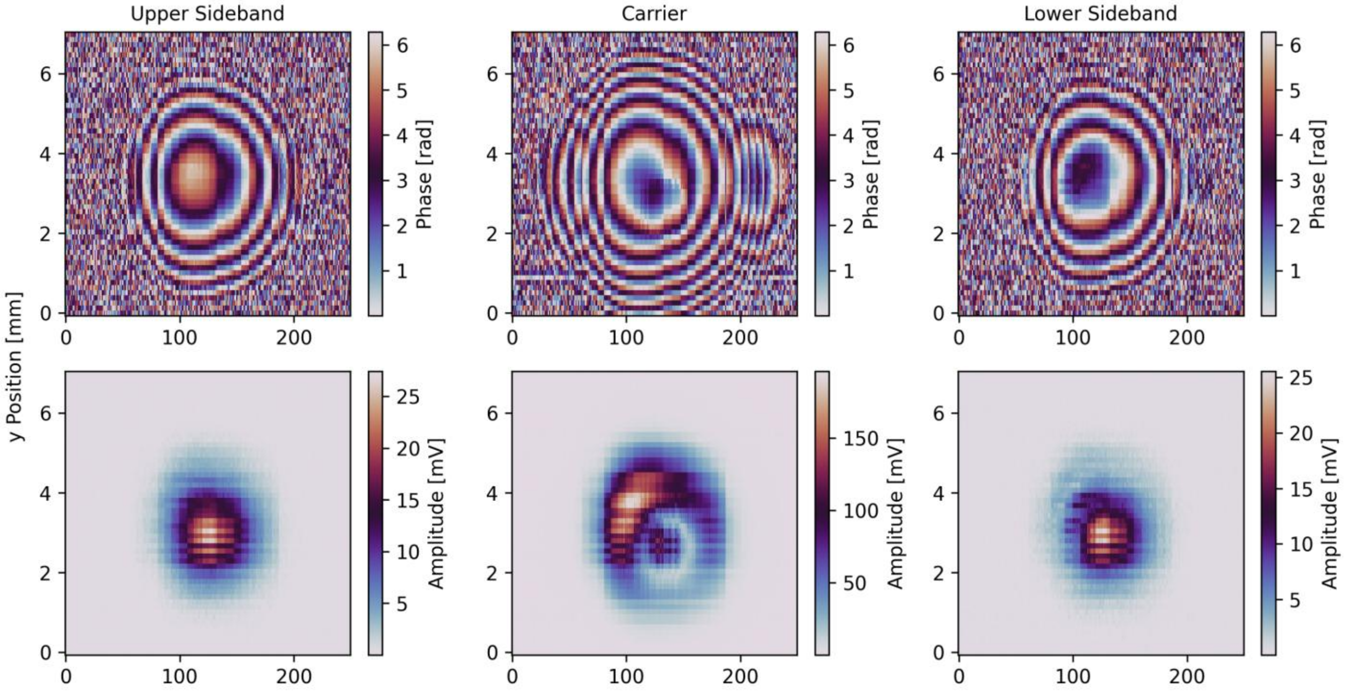
Measurement Campaign - Results



Dr. Benjamin Schwab, Einstein Telescope and CTAO, 2026

Test facility at Maastricht, Netherlands. The measurement campaign was held from (20.07.2025 to 01.08.2025). Picture Credit: Stefan Hild

- Validated a 56-pixel fibre-based phase camera's operation in a realistic environment.
- Successfully mapped **Higher-Order Modes (HOM)** caused by cavity misalignment by Scanning the 1D array horizontally.



What's Next?

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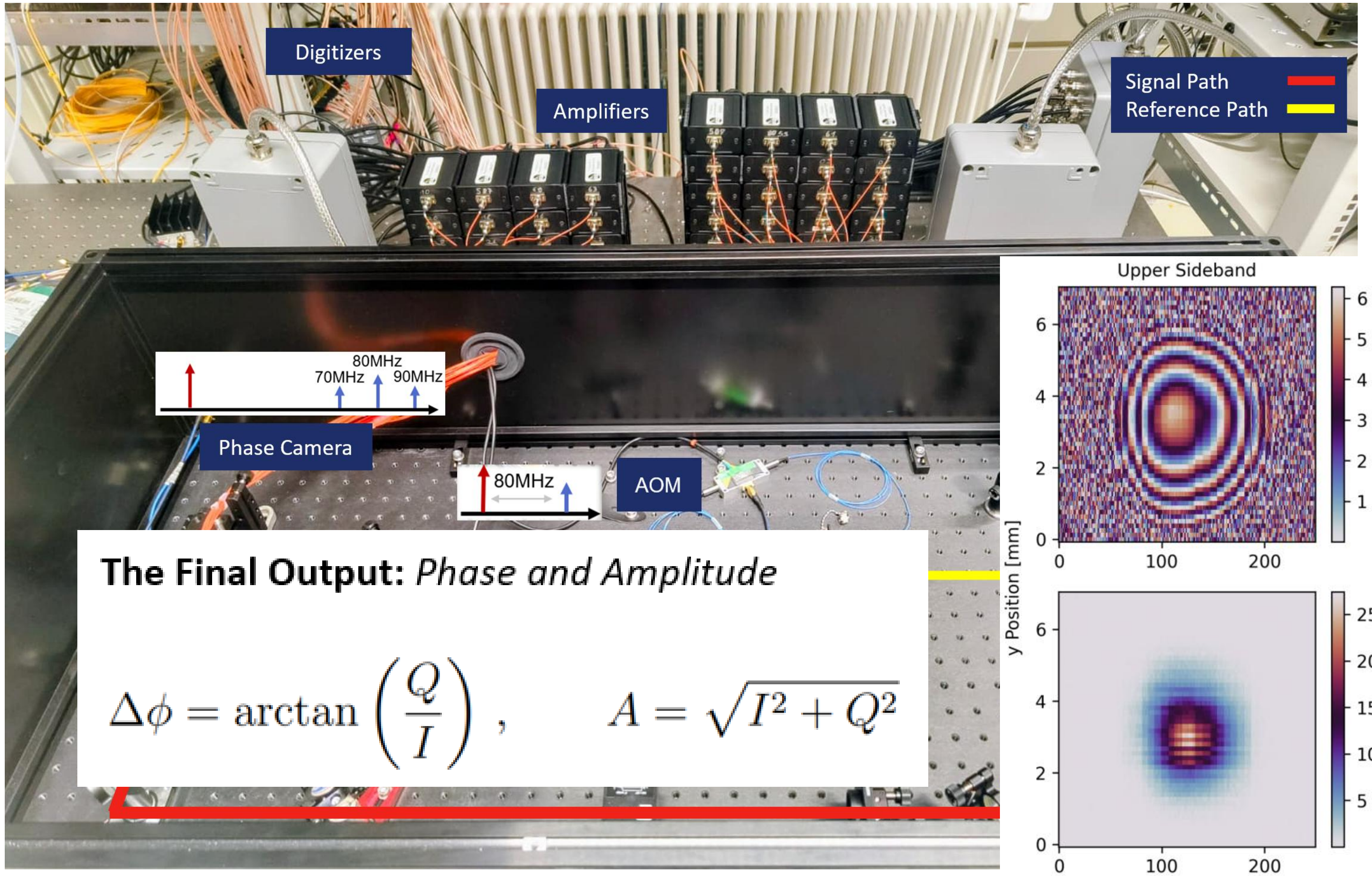
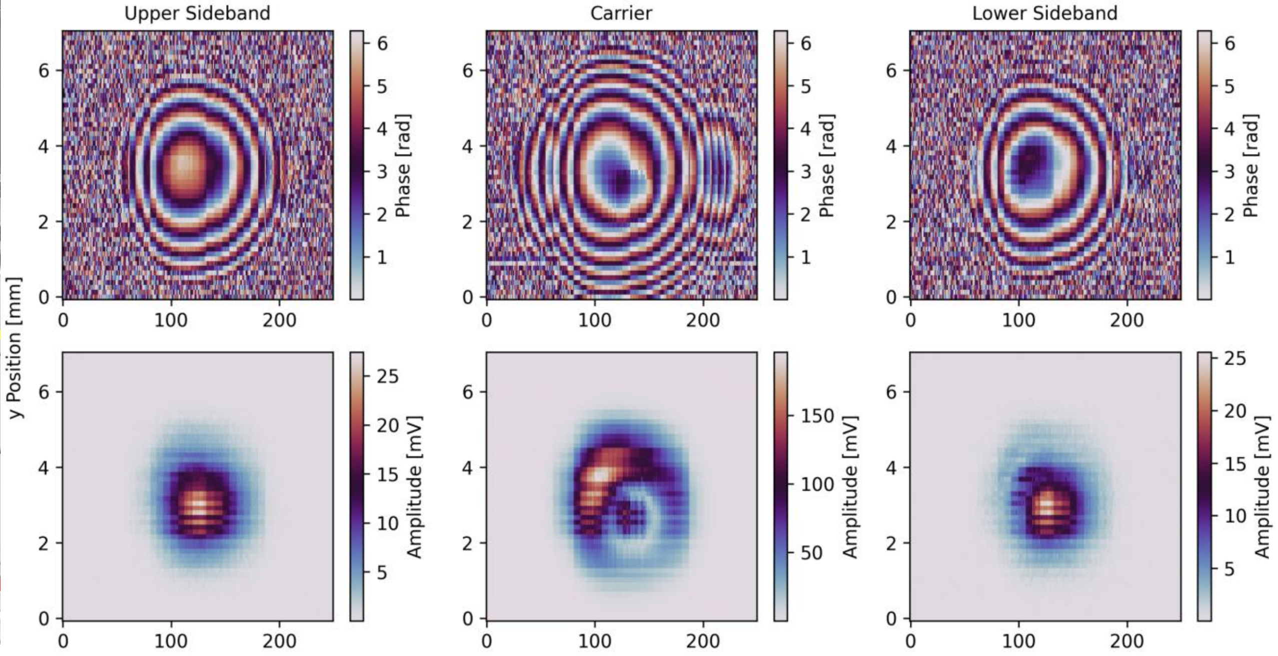


The Final Output: *Phase and Amplitude*

$$\Delta\phi = \arctan\left(\frac{Q}{I}\right), \qquad A = \sqrt{I^2 + Q^2}$$



ECAP Lab Setup of Phase Camera

- Our Camera Works!
- How to interpret it's images?

Mode Decomposition in Brief!

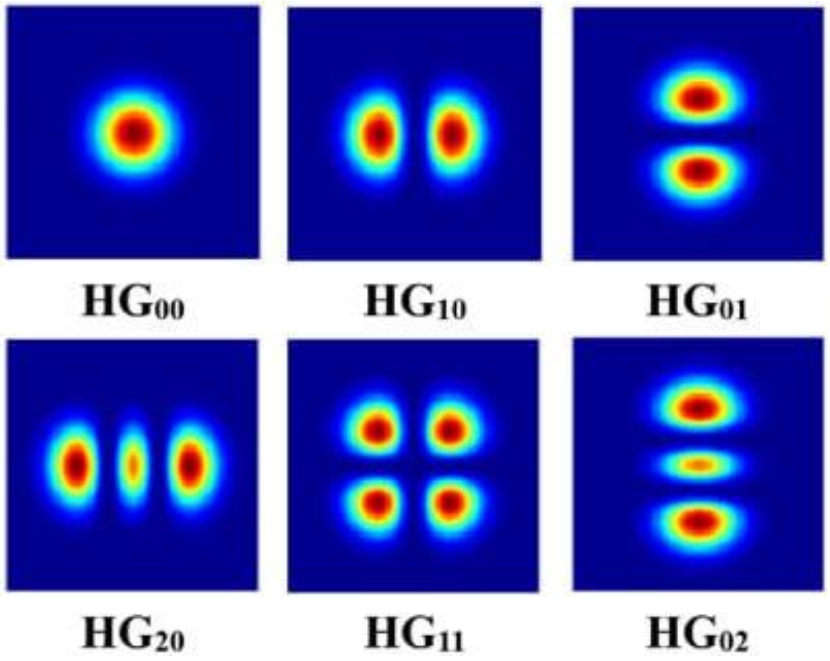
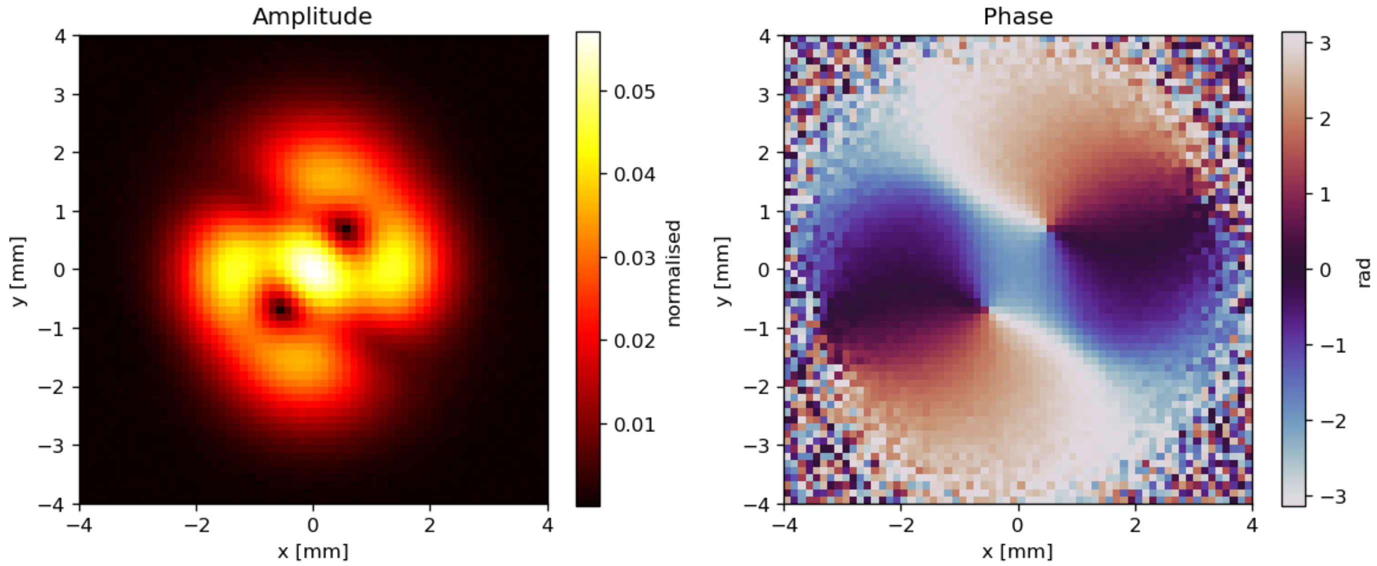


Image: An et al., 2020, *Applied Optics*



What is Mode Decomposition (MD) ?

When multiple modes propagate simultaneously they interfere and superpose into a ***complex pattern*** at the fibre output. MD is the inverse process of mathematically disentangling that mixture to recover the amplitude and phase contribution of each individual mode.

Our Approach

CNN Architecture: Dr. Jonas Glombitza

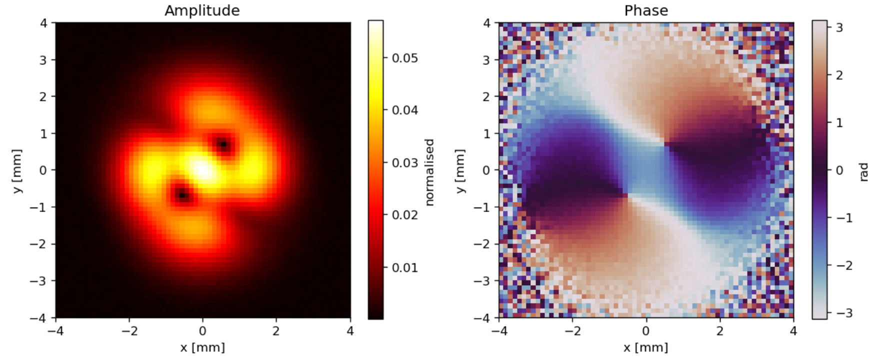
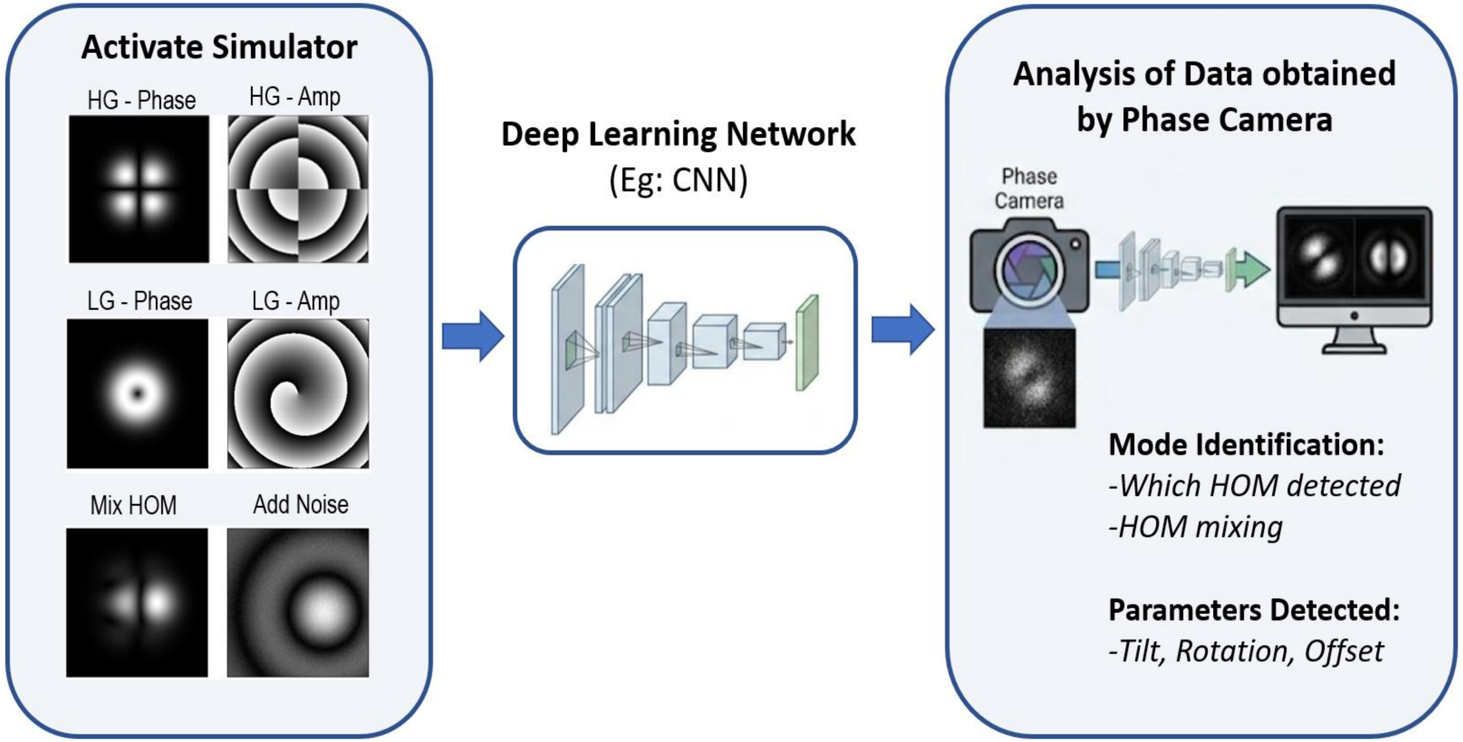


Image Recognition – Machine Learning



Our Approach

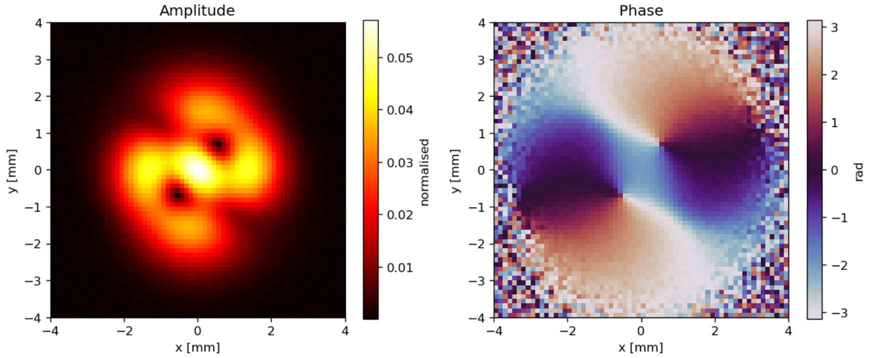


Image Recognition – Machine Learning

Benchmark – Classical Methods

1. Overlap Integral: Phase & Amp
2. SPGD: Intensity Only

$$c_{nm} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U(x,y,z_0) HG^*_{nm}(x,y,\tilde{q})\,dx\,dy.$$

arXiv:2104.08458

Overlap Integral: Uses orthonormality of modes but is prone to misalignment of the laser beam.

$$J = \left| \frac{\iint \Delta I_{re}(r,\varphi)\Delta I_{me}(r,\varphi) r dr d\varphi}{\sqrt{\iint \Delta I_{re}^2(r,\varphi) r dr d\varphi \iint \Delta I_{me}^2(r,\varphi) r dr d\varphi}} \right|$$

https://doi.org/10.1364/OE.23.004620

Stochastic Parallel Gradient Descent Algorithm: An iterative, intensity based mode decomposition method that optimizes a merit (cost) function through random perturbations to converge on the best-fit solution.

Our Approach

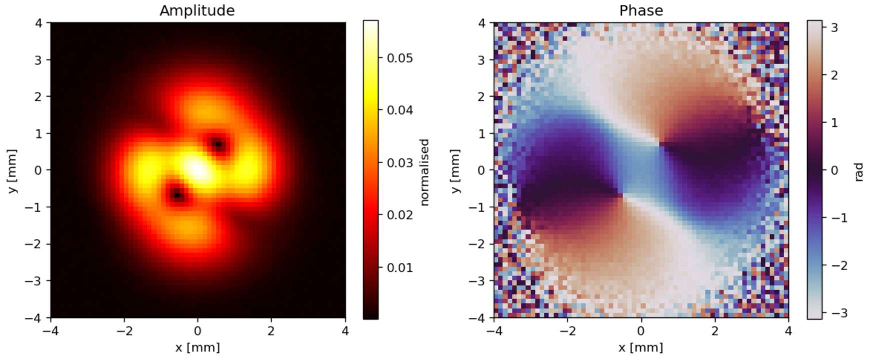


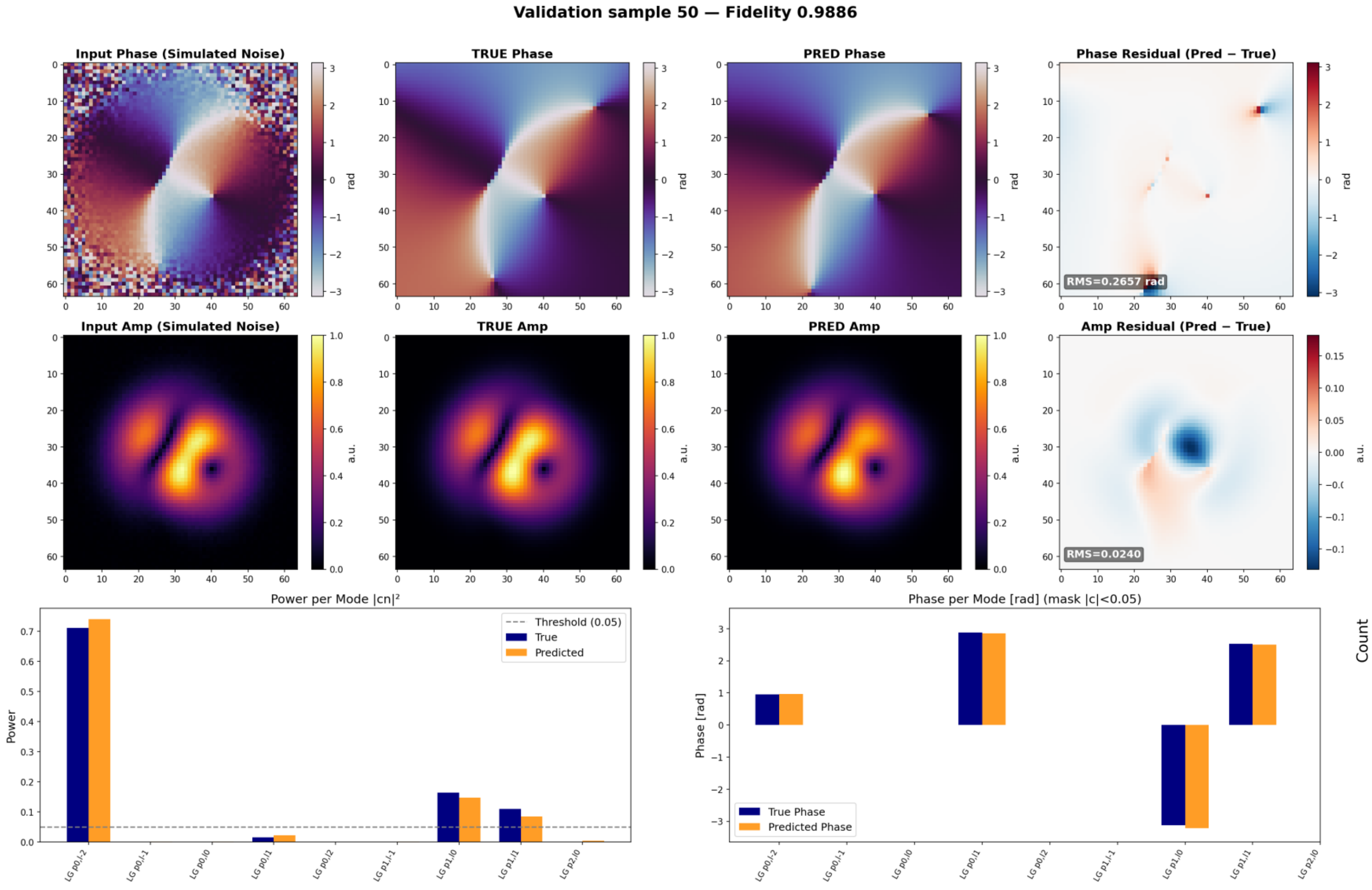
Image Recognition – Machine Learning

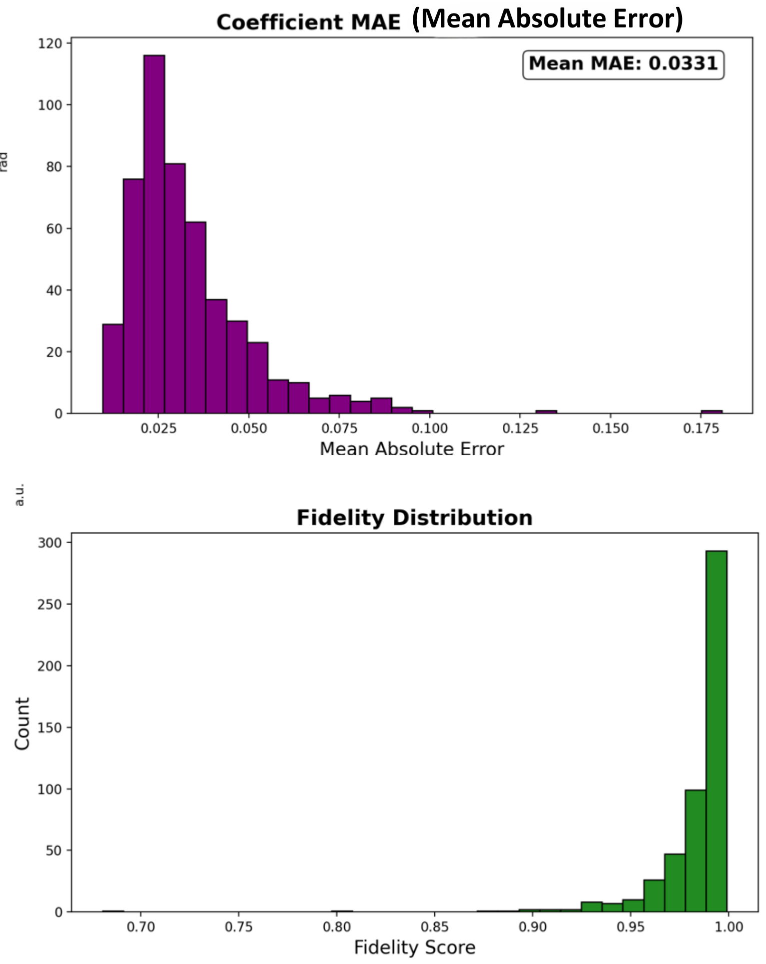
Benchmark – Classical Methods

1. Overlap Integral: Phase & Amp
2. SPGD: Intensity Only

Test both methods with Simulations and Real Data

ML Results – 50,000 images as input





Conclusion

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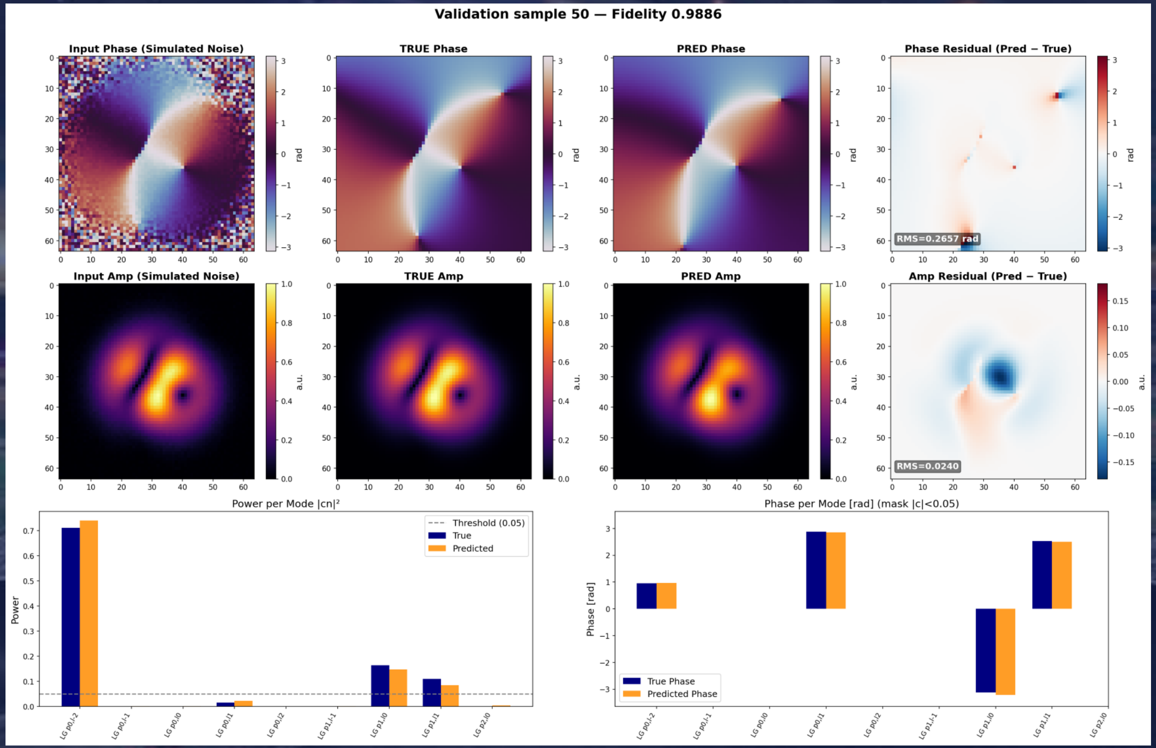
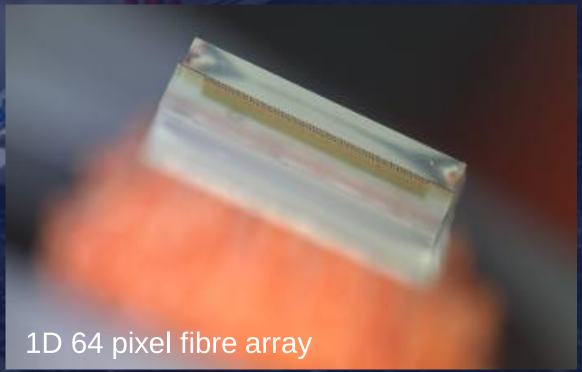
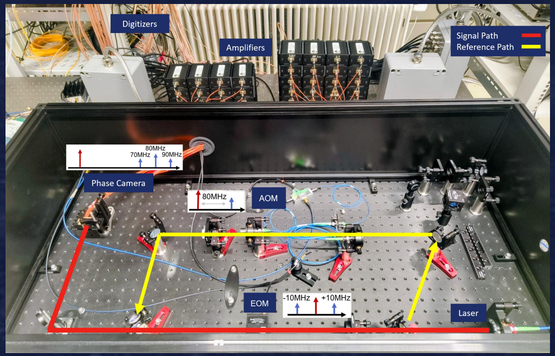
- Proof-of-concept:56-pixel Fibre-based Phase Camera
- Using ML to identify Higher Order Modes and compare it with classical Benchmarks
- Upgrading to a 1024-pixel for higher spatial resolution.



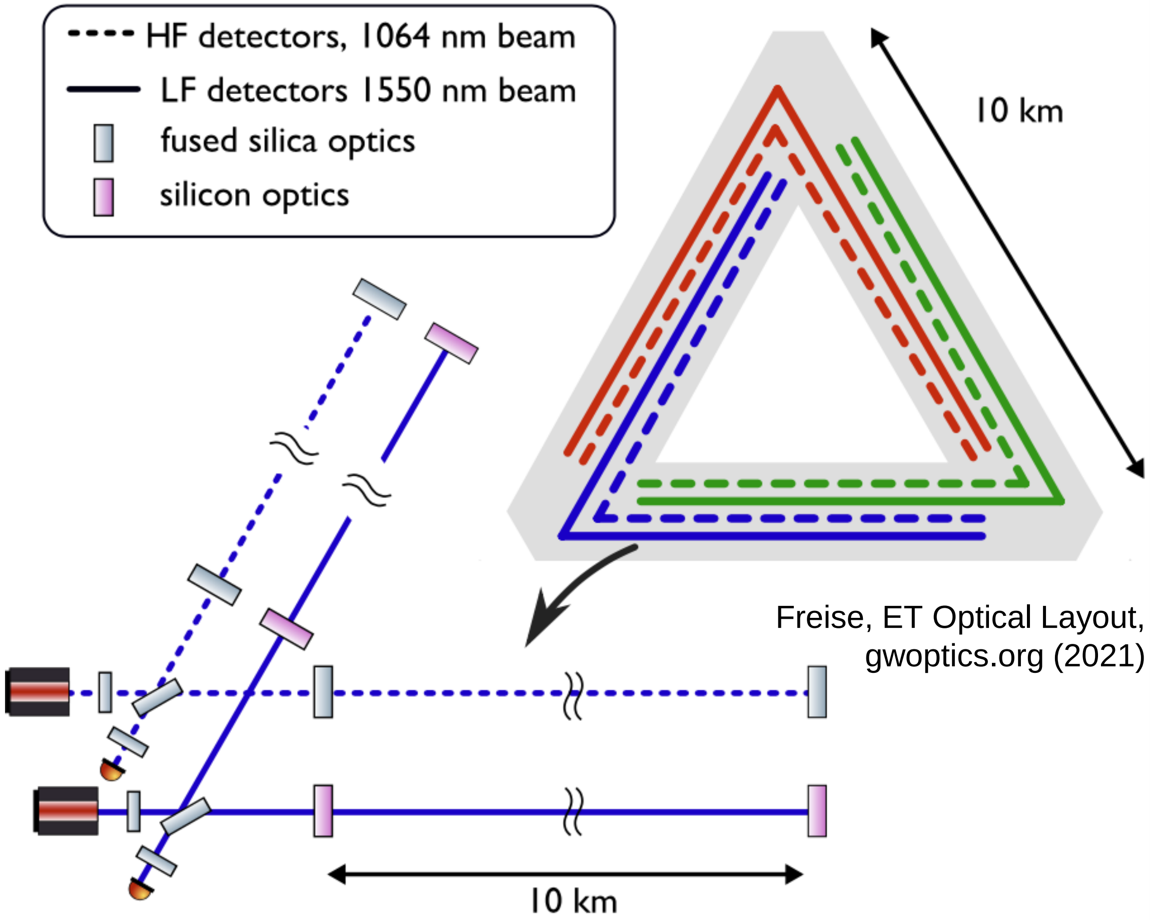
Thank You for your attention!


1D 64 pixel fibre array



Back-Up

Einstein Telescope (ET)



Freise, ET Optical Layout, gwoptics.org (2021)

Xylophone design:

•**High-frequency need :** Catching fast, quiet ripples requires a **massive, high-power laser** to reduce shot noise.

•**Low-frequency need :** Catching slow, heavy ripples requires **freezing the mirrors (10–20 K)** so internal heat vibrations don't mask the signal.

The Conflict: Blasting a multi-megawatt laser onto a freezing mirror heats it up, destroying the delicate cryogenic freeze.

Solution: Two specialized detectors running side-by-side.

Einstein Telescope (ET)

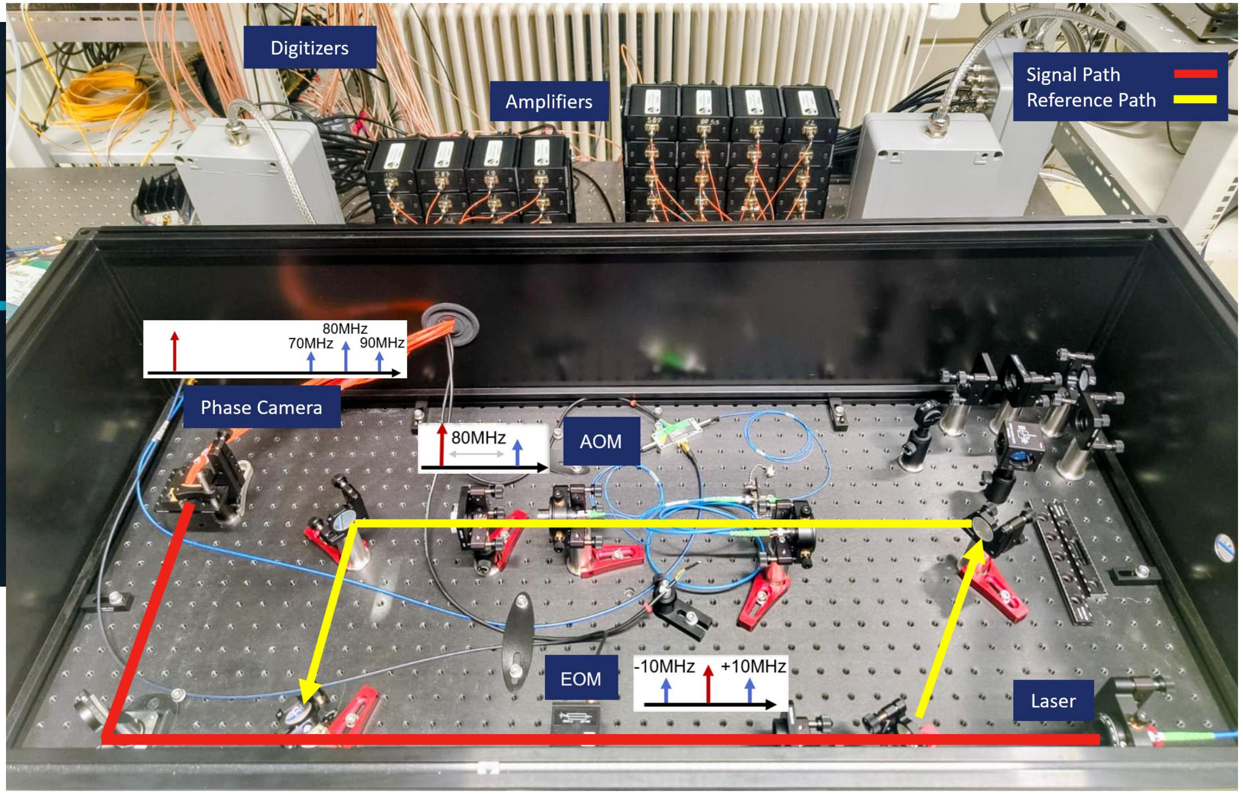
Feature	High-Frequency Specialist (ET-HF)	Low-Frequency Specialist (ET-LF)
Target band	**30 Hz – several kHz**	**3 – 30 Hz**
Environment	**Room temperature (~290 K)**	**Cryogenic (10 – 20 K)**
Circulating laser power	**3 MW**	**18 kW**
Mirror substrate	**Fused silica**	**Crystalline silicon**
Wavelength	**1064 nm**	**1550 nm**
Why this wavelength?	1064 nm is the standard wavelength for GW detectors; fused silica is highly transparent at this wavelength, letting 3 MW of circulating power pass with minimal absorption heating.	Fused silica becomes mechanically lossy when cooled, so ET-LF uses crystalline silicon instead. Silicon is opaque at 1064 nm, so the laser wavelength shifts to 1550 nm, where silicon is transparent.

Simulation Pipeline

1 **Spatial Transforms**
Grid size:64 x64

2 **Signal Beam**
LG / HG mode
pure or mixed

3 **Reference Beam**



1

- Defines Camera Geometry
- Adds Astigmatism (Tilt, Offset, Rotation)

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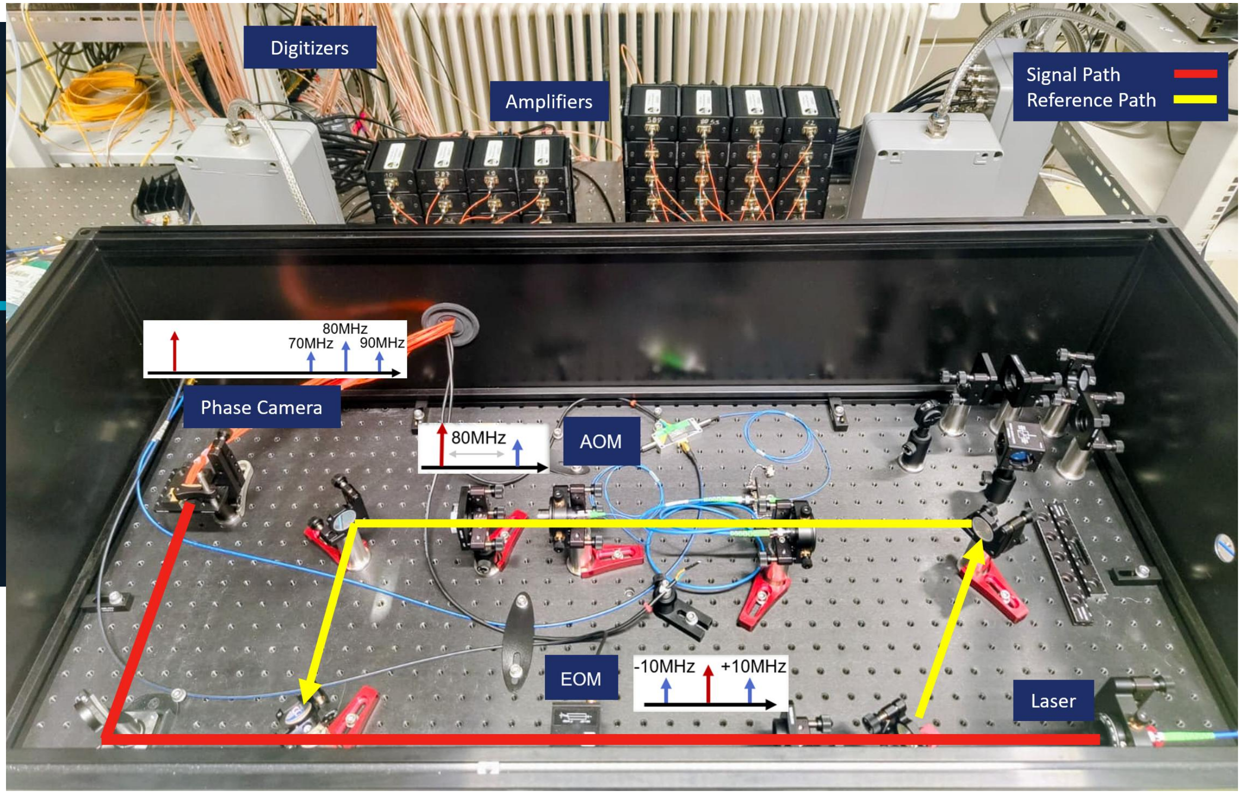

2

- Creates HOM beam up to nm order

$$\mathrm{HG}_{nm}(x,y,z) = \frac{1}{\sqrt{2^{n+m-1}n!m!\pi}}\frac{w_0}{w(z)}H_n\left(\frac{\sqrt{2}x}{w(z)}\right)H_m\left(\frac{\sqrt{2}y}{w(z)}\right)\times \exp\left(-\frac{r^2}{w^2(z)}\right)\exp\left(-ik\frac{r^2}{2R(z)}+i(l+m+1)\psi(z)\right),$$

- Mode content atm random, but could be adjust to observed system

Simulation Pipeline

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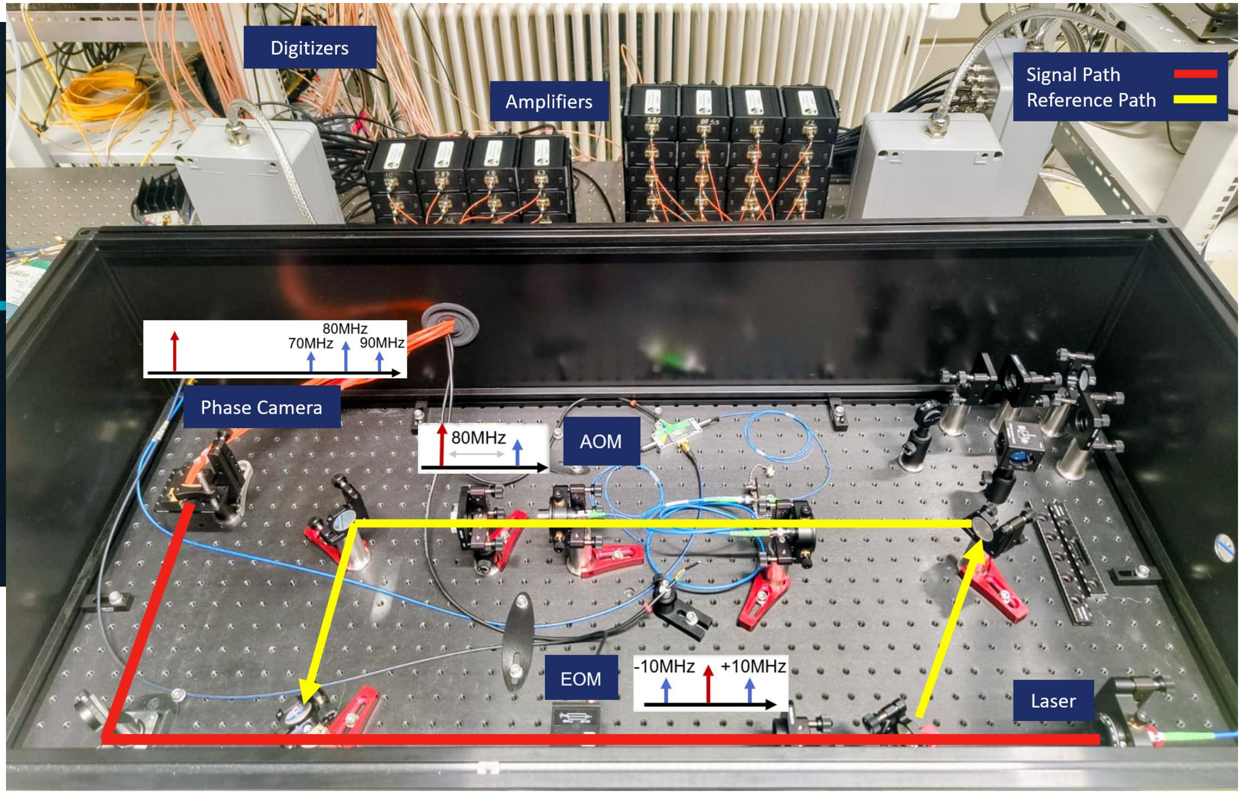
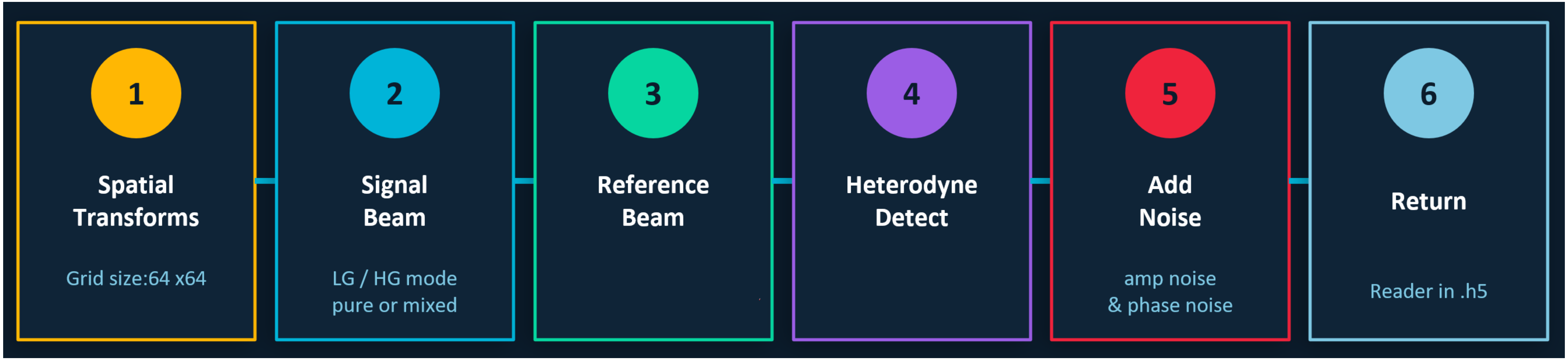


3

- Creates reference beam in the fundamental mode

$$\vec{E}(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{w(z)^2}\right) \exp\left(-i\left(kz + k\frac{r^2}{2R(z)} - \psi(z)\right)\right) \vec{\epsilon}$$

Simulation Pipeline



4

- Mixes both beams
- Calculates amplitude and phase

$$\Delta w(y) = A\exp\left(-\frac{(y-y_{0,\mathrm{sig}})^2}{w_{\mathrm{sig}}^2}\right)\exp\left(-\frac{(y-y_{0,\mathrm{ref}})^2}{w_{\mathrm{ref}}^2}\right) + O$$

$$\Delta\phi(y) = \frac{2\pi}{\lambda}\left[\frac{(y-y_{0,\mathrm{sig}})^2}{2R_{\mathrm{sig}}} - \frac{(y-y_{0,\mathrm{ref}})^2}{2R_{\mathrm{ref}}}\right] + \phi_0$$

Simulation Pipeline

1. **Spatial Transforms** — Grid size:64 x64
2. **Signal Beam** — LG / HG mode pure or mixed
3. **Reference Beam**
4. **Heterodyne Detect**
5. **Add Noise** — amp noise & phase noise
6. **Return** — Reader in .h5

5

6

- Mixes both beams
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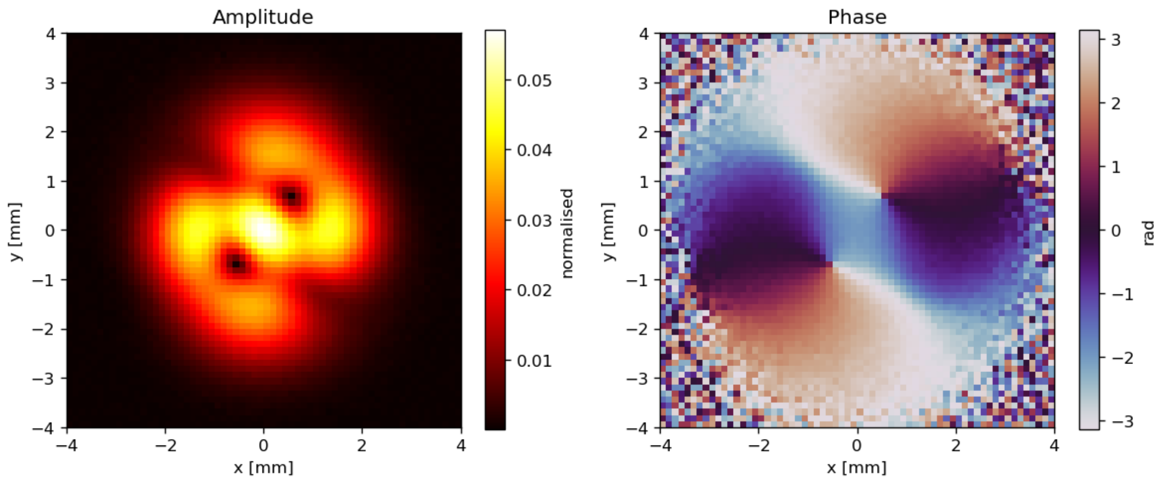


ML for Mode Decomposition

Input: 64×64 phase + amplitude maps (2 channels)

Feature Extraction: Three convolutional blocks (64 → 128 → 256 filters) that learn to recognize rings, lobes, and vortex patterns of the beam

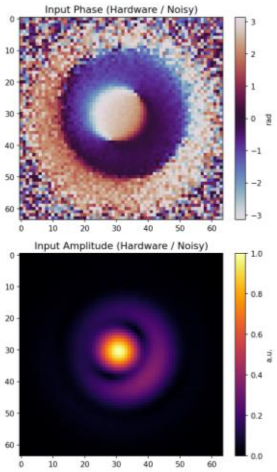
Dense Layers: Squeezes the feature maps into one summary vector, then regresses it to the mixing mode coefficients.

Output Example: ORDER = 4 = 15 modes = 30 output numbers

Fidelity Distribution

$$F = |\langle E\_true \mid E\_pred \rangle|^2 / (\|E\_true\|^2 \cdot \|E\_pred\|^2)$$

Training: 50,000 simulated noisy images



CNN Architecture: Jonas Glombitza

Overlap Integral

A field is just a weighted mix of modes:

$$c_{nm} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U(x, y, z_0) HG_{nm}^*(x, y, \tilde{q}) dx\, dy.$$

arXiv:2104.08458

Orthonormality: modes are "invisible" to each other under this integral

$$\iint HG_{nm} HG_{kl}^* \, dx\, dy \;=\; 1 \;\text{ if }\; (n,m) = (k,l), \quad \text{else } 0$$

Multiply by the conjugate of the mode one wants, then integrate

$$\iint U \cdot HG_{nm}^* \, dx\, dy \;=\; \sum_{k,l} c_{kl} \iint HG_{kl} HG_{nm}^* \, dx\, dy \;=\; c_{nm}$$

Every term in the sum vanishes except the one matching the mode conjugated against

That term alone survives as c_{nm}

SPGD

- SPGD reconstructs the field as a weighted sum of candidate modes ψ_j, iteratively perturbing the amplitude/phase weights (ρ_j, φ_j) at random and keeping changes that reduce a merit (cost) function
- Standard SPGD **uses only measured intensity it never sees the phase directly.**

$$U(x, y) = \sum_{j=1}^{N} \rho_j e^{i\phi_j} \psi_j(x, y)$$

$$D = 1 - \frac{\iint I_{me}(x, y) I_{re}(x, y) dxdy}{\sqrt{\iint I_{me}^2(x, y) dxdy \iint I_{re}^2(x, y) dxdy}}$$

Why intensity-only SPGD is the wrong tool here

- Our phase camera already delivers the complex field (amplitude + phase) via heterodyne detection
- Discarding phase to re-derive it from intensity alone throws away information we already have
- Intensity alone is a non unique target: different complex fields (e.g. conjugate solutions) can produce the same intensity pattern, so the optimizer can converge on the wrong mode mixture