Wavefront sensors for 3rd generation GW detectors

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on behalf of
the LISA Quadrant Photo-Receiver Working Group
and the Virgo Phase Camera Group

GWADW, 17-21 May 2021

Outline

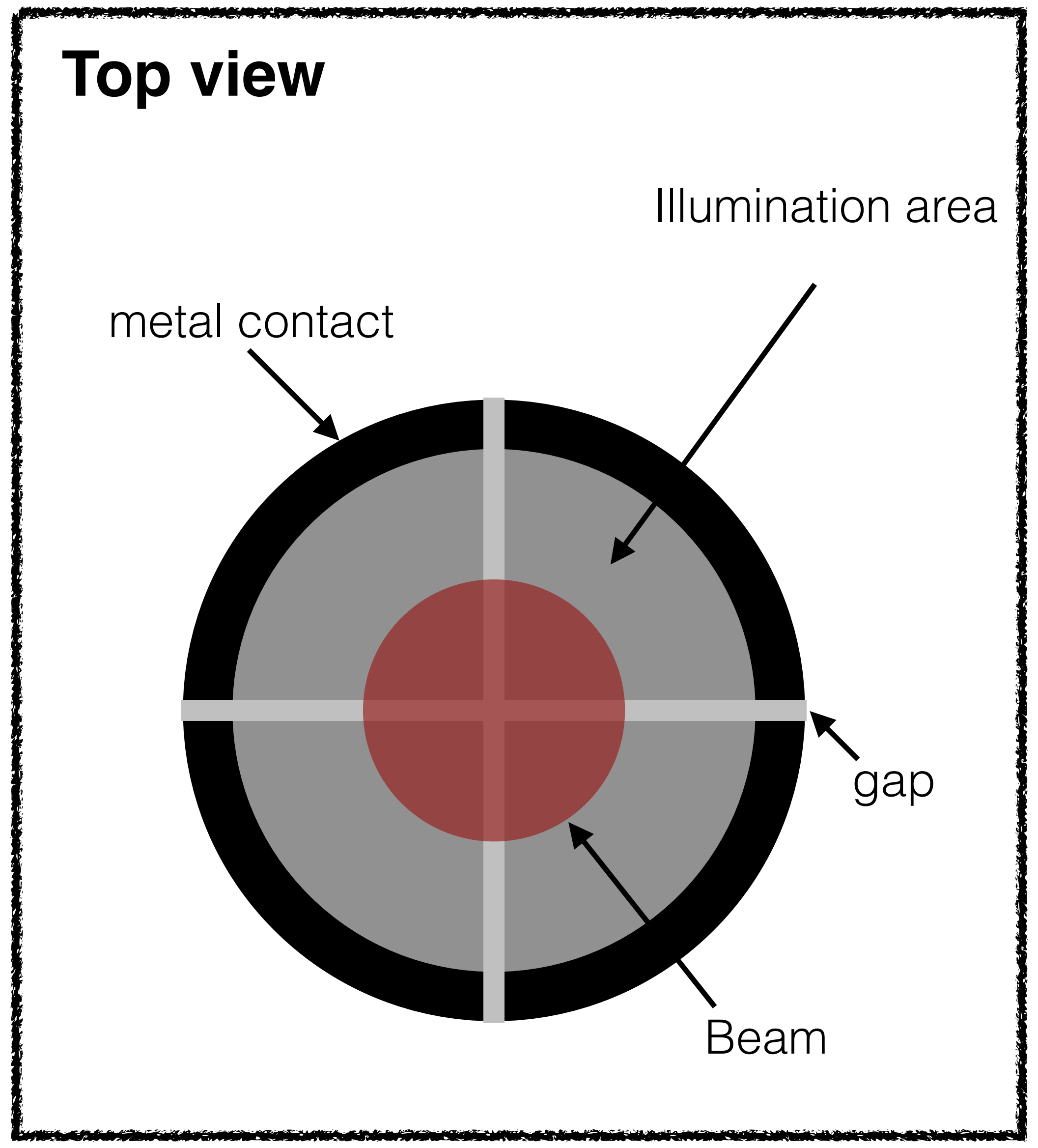
- Introduction to wavefront sensors
- LISA Quadrant Photodiode: development and characterisation
- Virgo Phase Camera: status and challenges
- Future of wavefront sensors

Wavefront sensors

Wavefront sensors are optical devices able to measure the features of the beam wavefront (shape, aberration, etc.) in order to verify deviations from an ideal reference beam.

Quadrant photodiodes provide the position of the beam

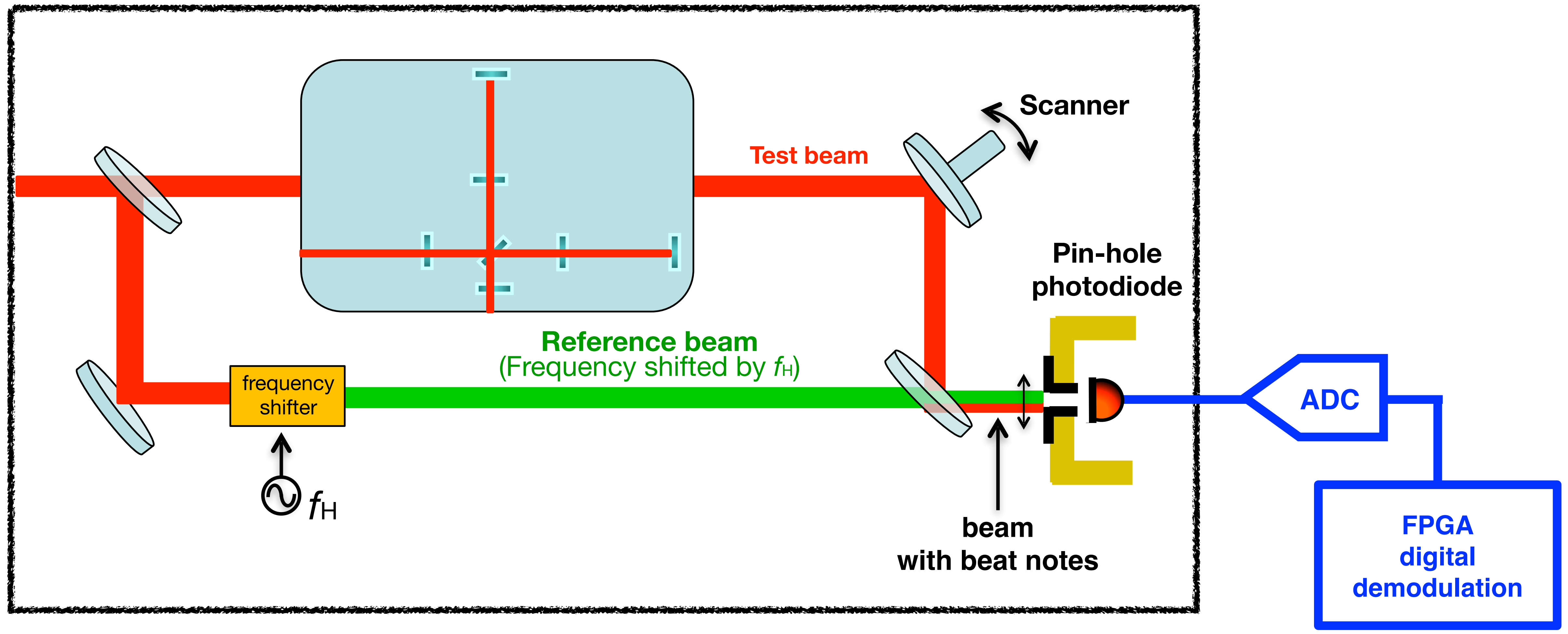
used for the alignment



Phase cameras provide phase and amplitude images

aid commissioning

provide input to correct thermal effect

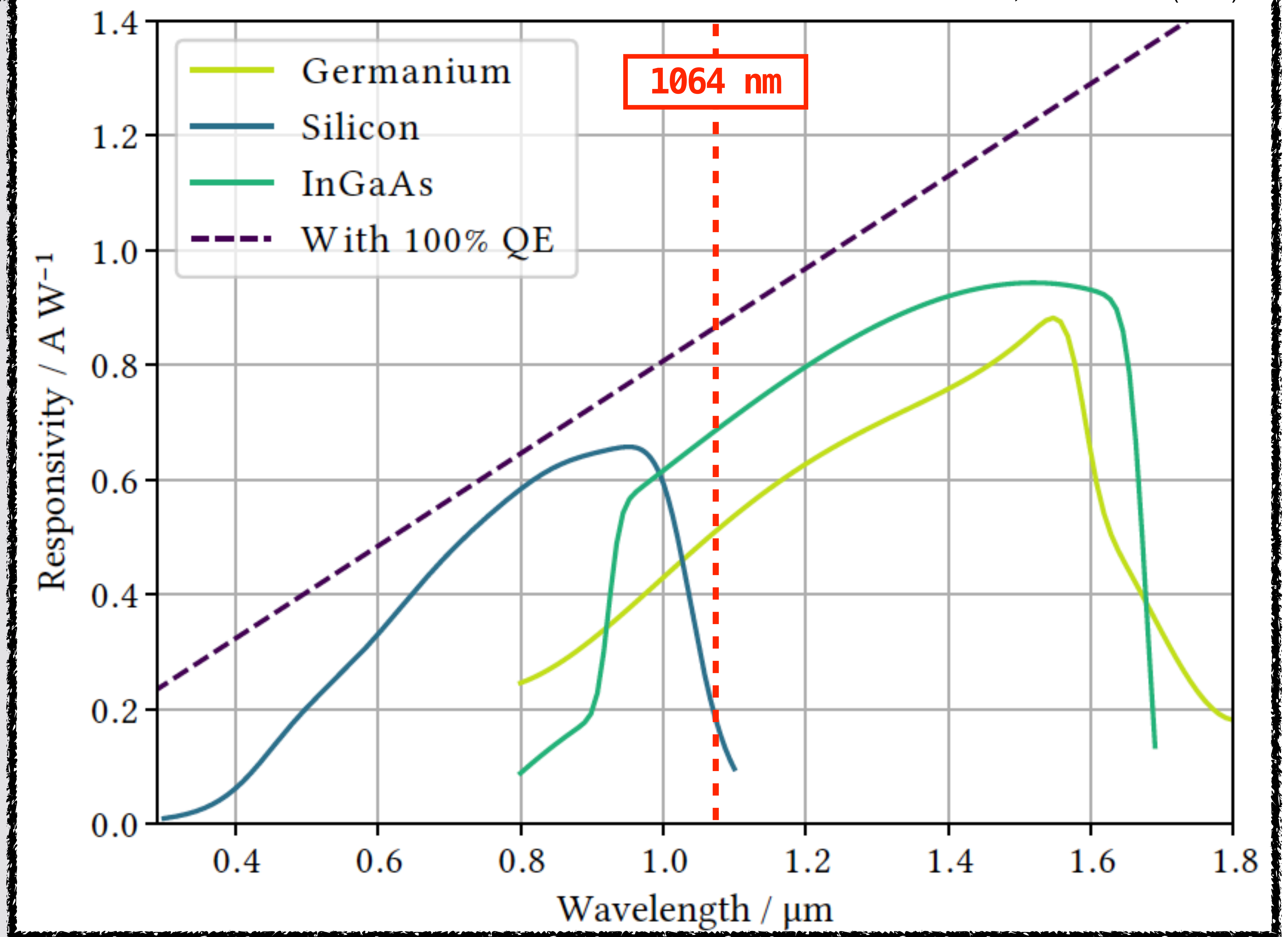


LISA Quadrant Photodiode

Requirements

- **Diameter: 2.0 mm (goal)**
  - Large is better to simplify alignment, but it would imply large capacitance
- **Gaps: 10 – 20 μm**
  - Large gap will waste light and increase TTL coupling noise
- **Current noise: < 2 pA/$\sqrt{Hz}$**
  - It requires low capacitance
- **Bandwidth: 2 … 25 (30) MHz**
  - It will depend from the Doppler shifts from the relative motion of the spacecraft
- **Responsivity: > 0.7 A/W (@1064 nm)**
  - To avoid wasting photons which would reduce SN ratio ➡ InGaAs
- **Radiation hardness, mechanical and thermal stability, lifetime …**

credits: G.F. Barranco, Ph.D. Thesis (2017)



Low-noise large-area PD

low noise requires low capacitance

$$C = \frac{\epsilon\, A}{d}$$

~~Absolute permittivity of the material~~ (ϵ)

~~Detector area~~ (A)

Capacitance (C)

Width of depletion region (d)

Low capacitance

- Reduce ϵ ⇒ change material ⇒ all semiconductors have close values of ϵ (the change would be insignificant)
- Reduce A ⇒ large area needed for alignment issue
- Increase d ⇒ requires higher voltage to deplete (on spacecrafts we have max. 24 V) ⇒ **reduce doping**

Reduce doping: how low?

Doping

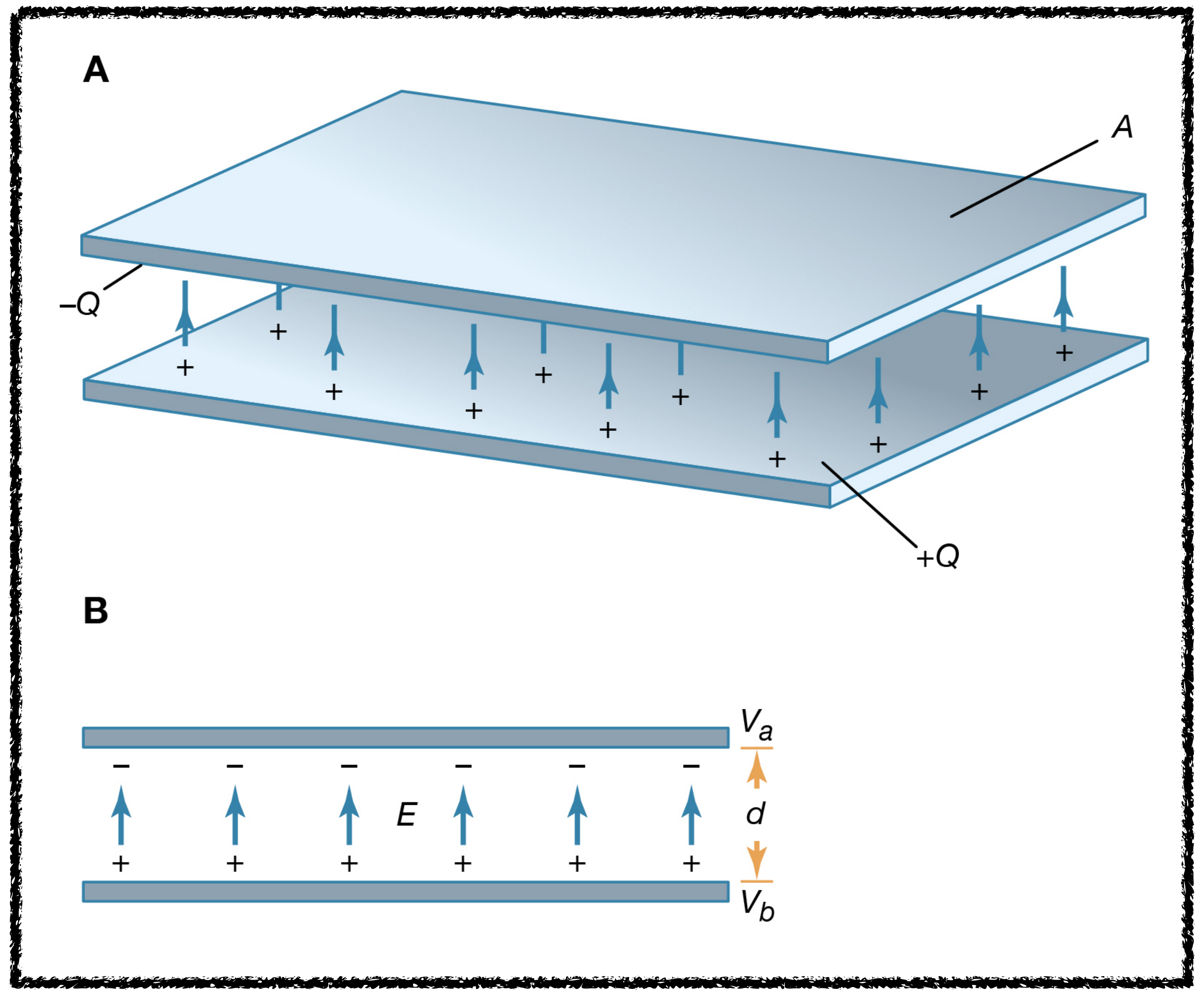
Elementary charge

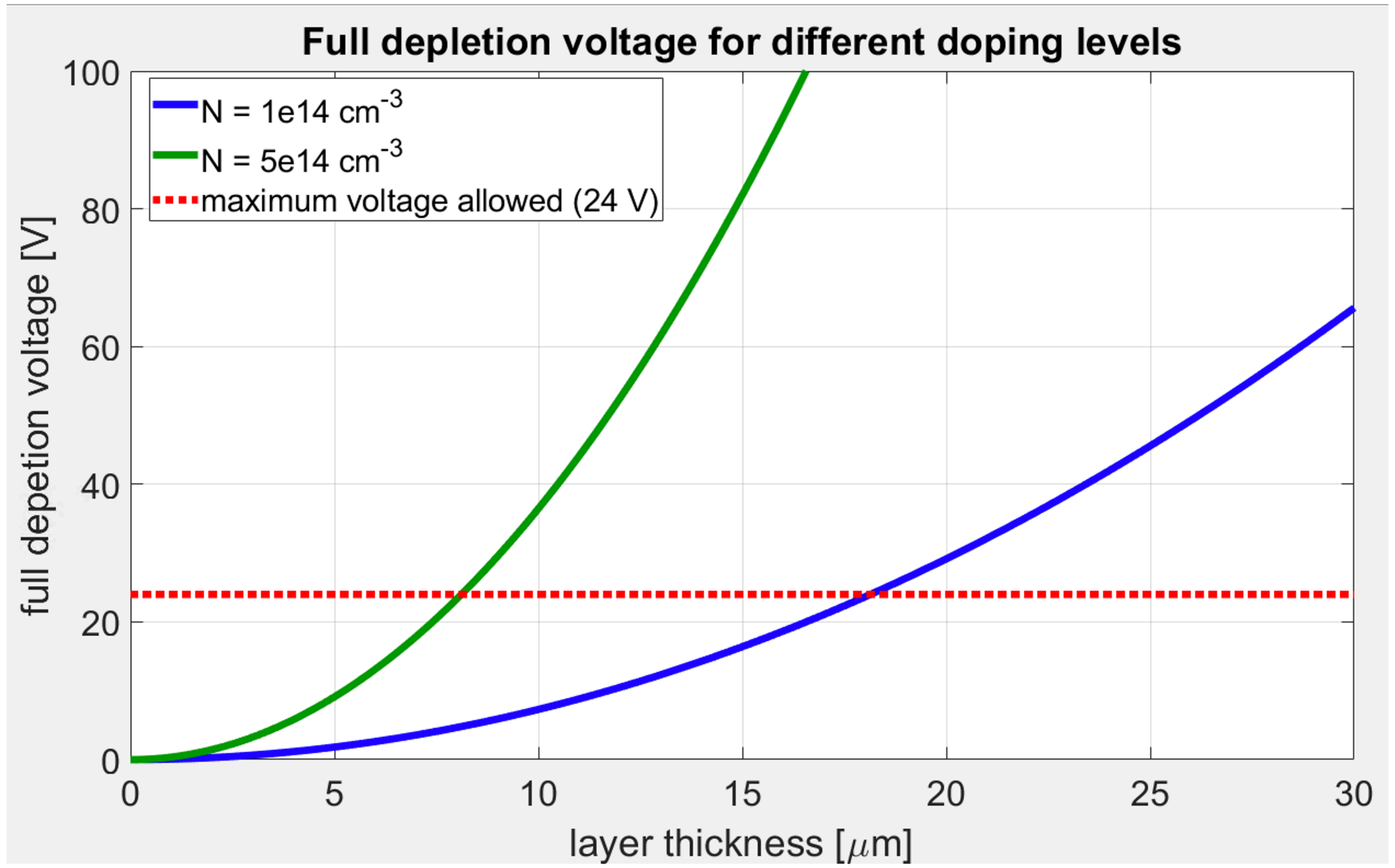
Width of depletion region

Full depletion voltage

$$V = \frac{q\,N\,d^2}{2\,\epsilon}$$

Absolute permittivity of the material





Our target value is

N ≤ 1x10^{14} cm^{-3}

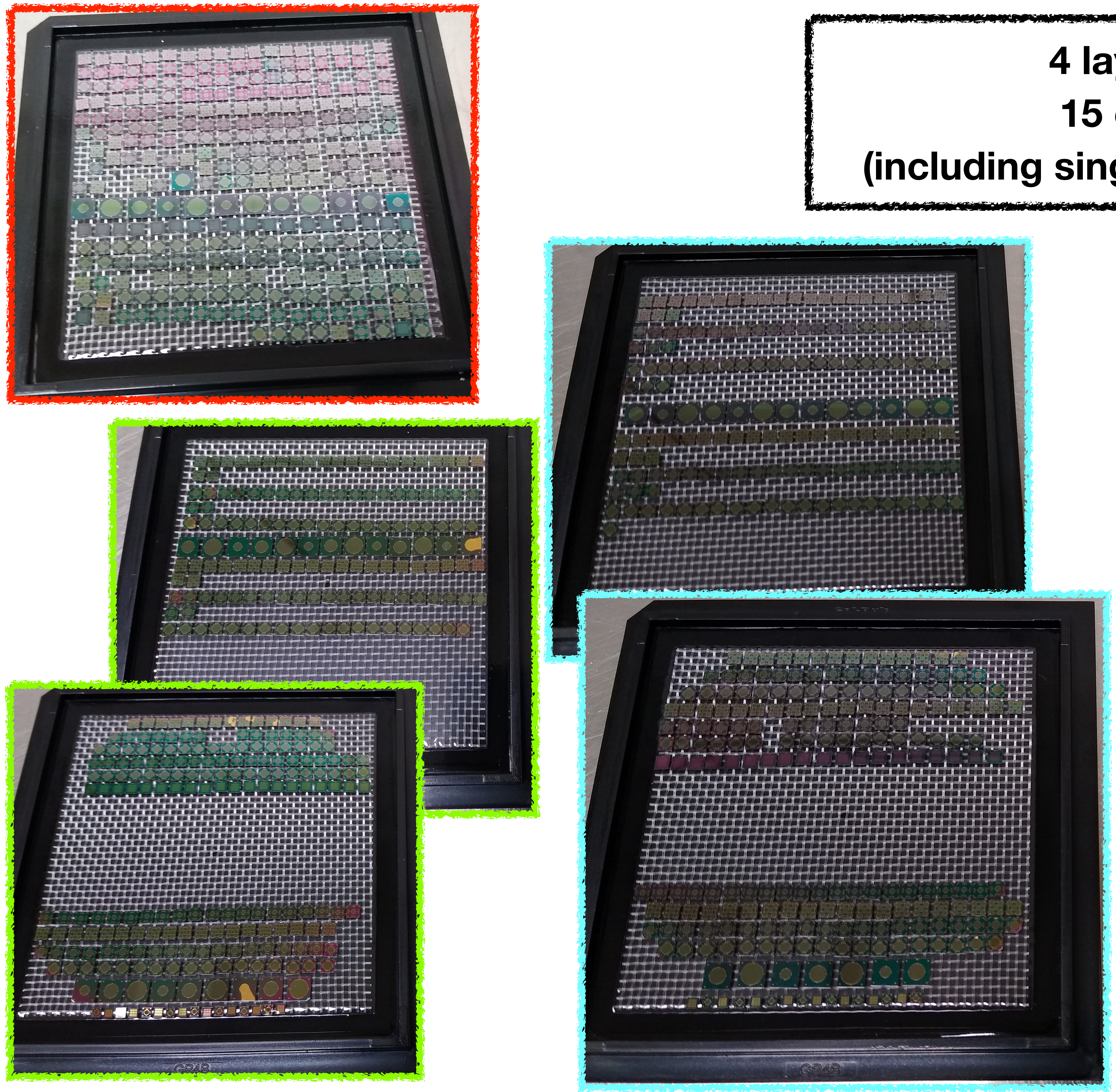
Sensitivity limit of typical doping concentration measurements techniques

~ 1x10^{14} cm^{-3}

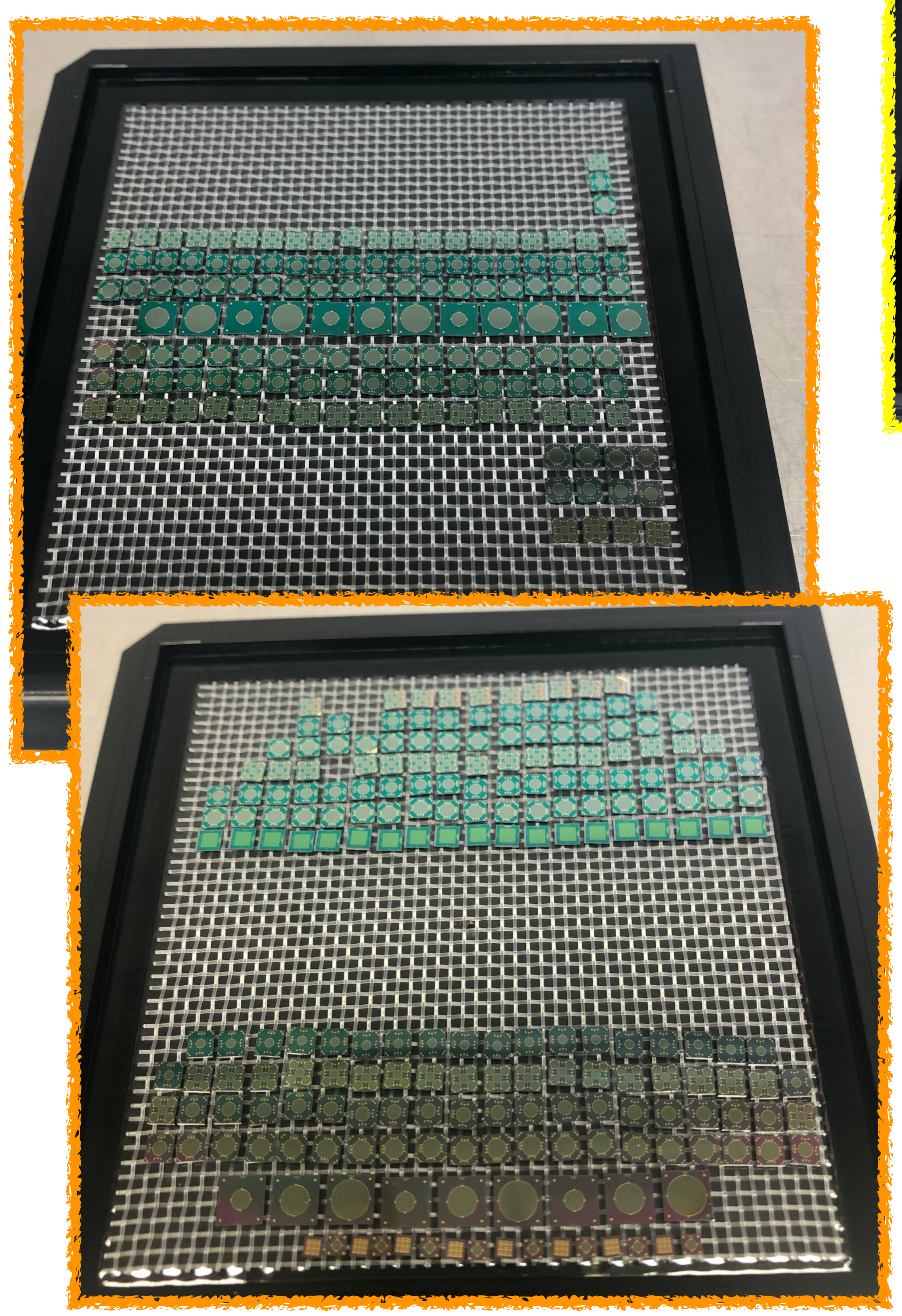
Number of InGaAs atoms per volume

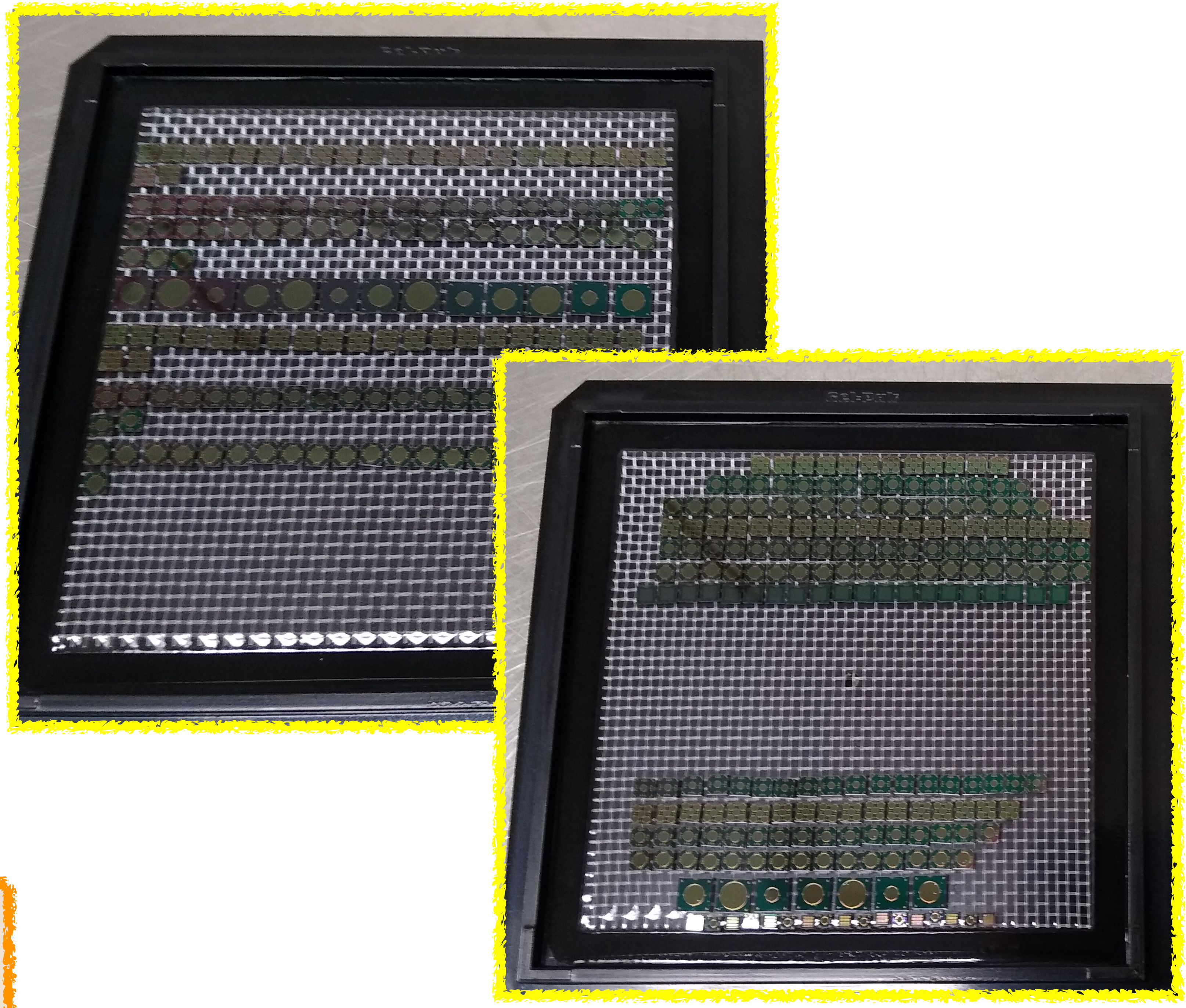
~ 4x10^{22} cm^{-3}

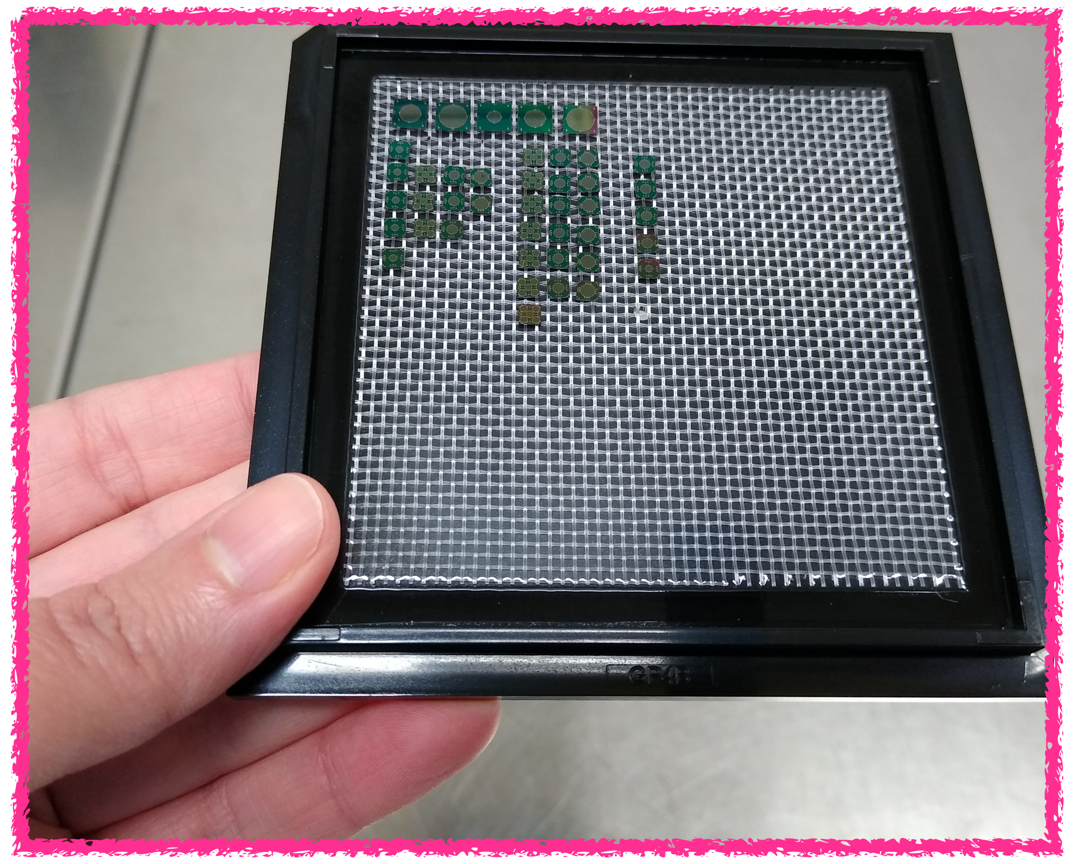
First run ready



4 layers structures
15 configurations
(including single element photodiodes)

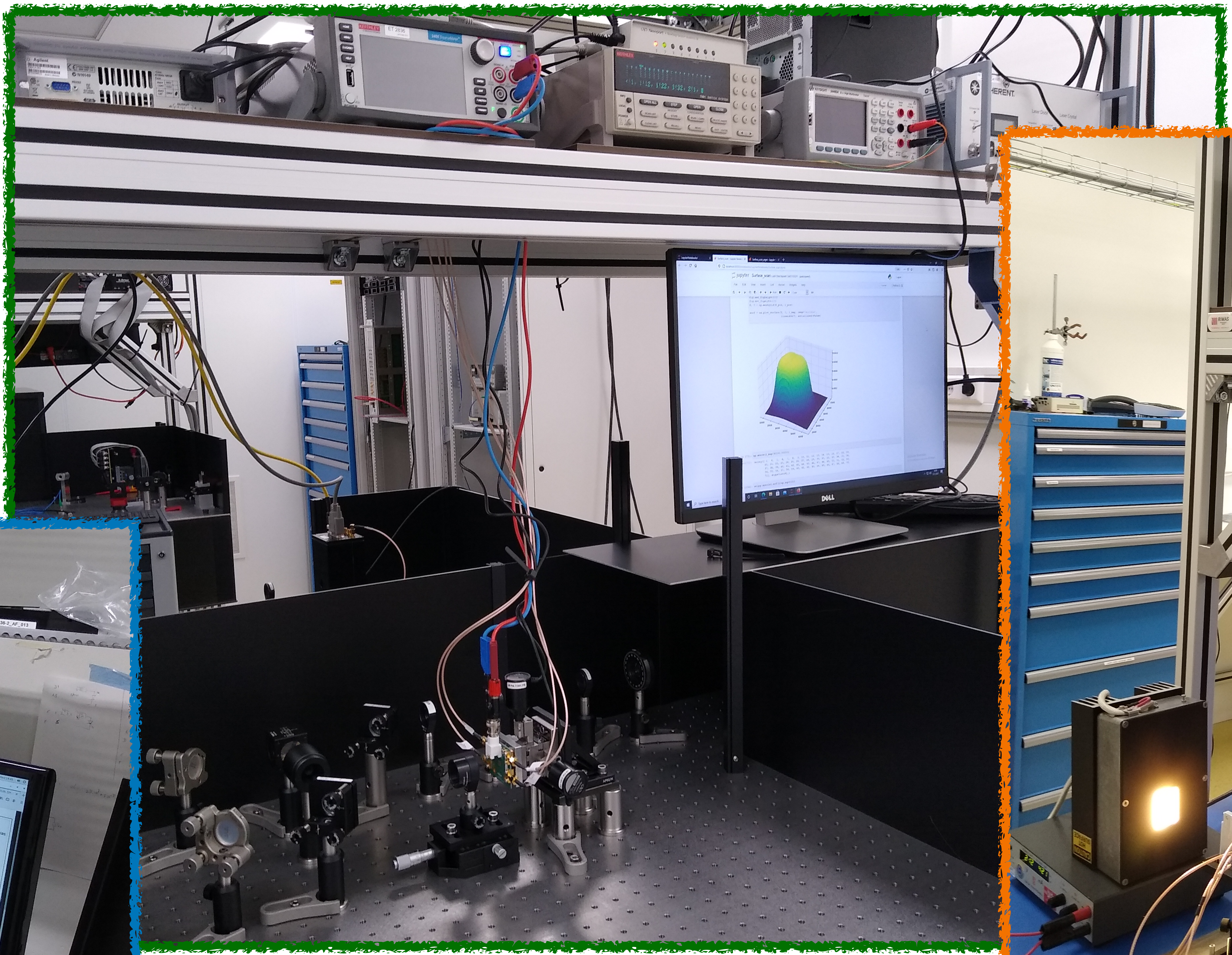


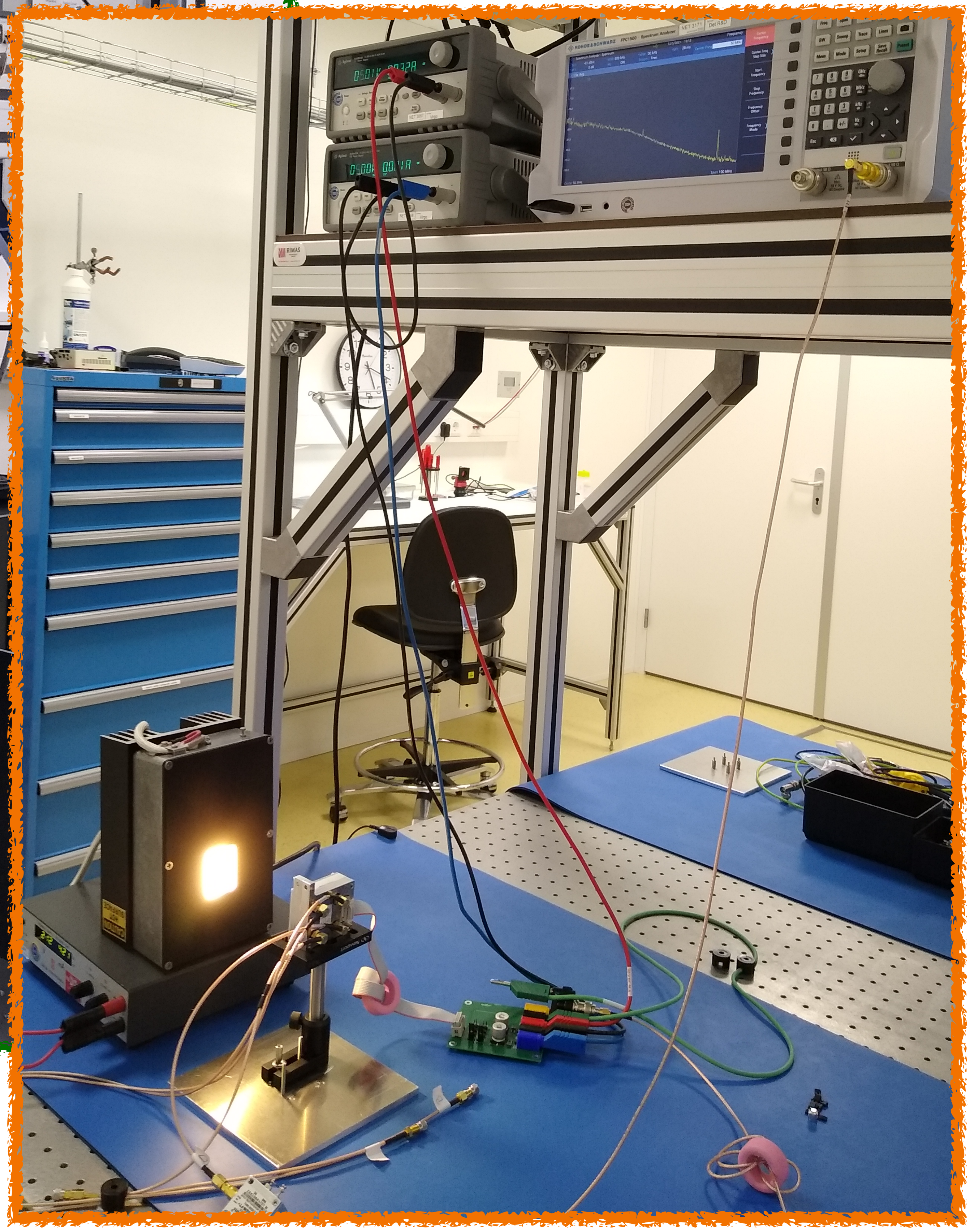




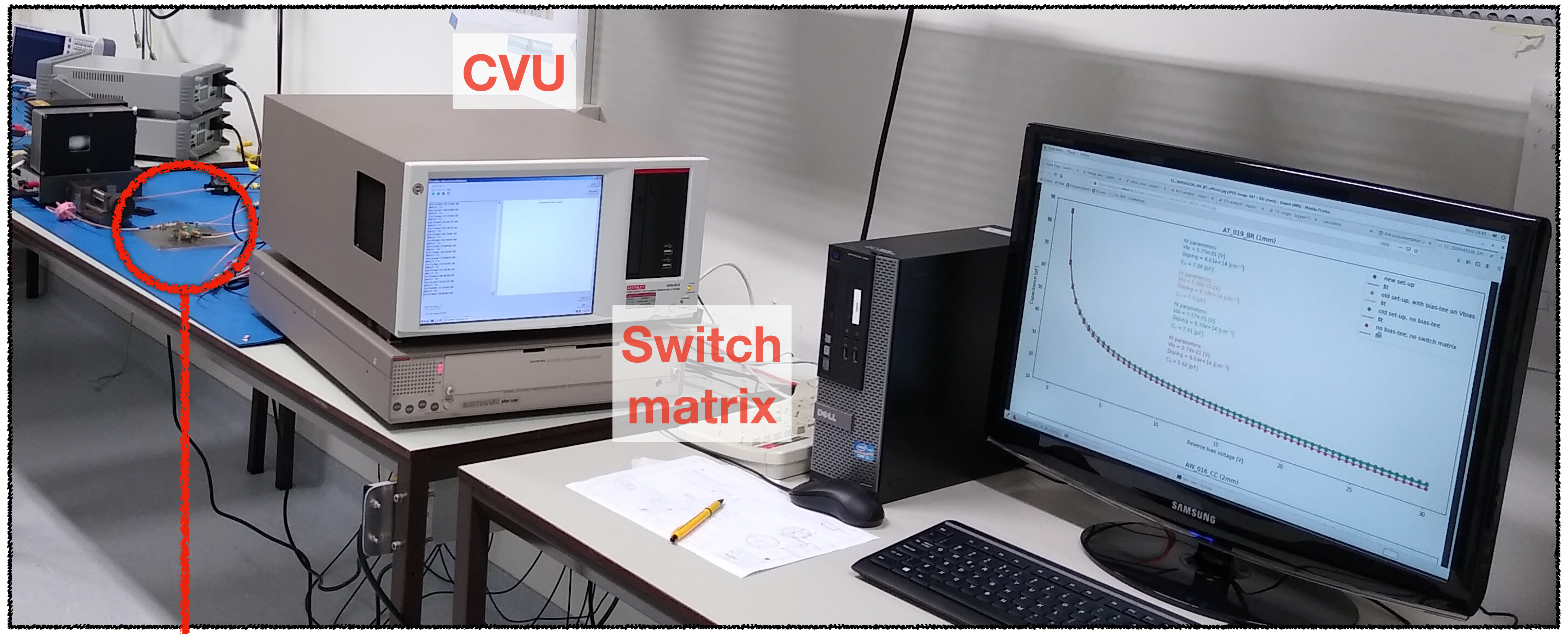
Characterisation tests in progress

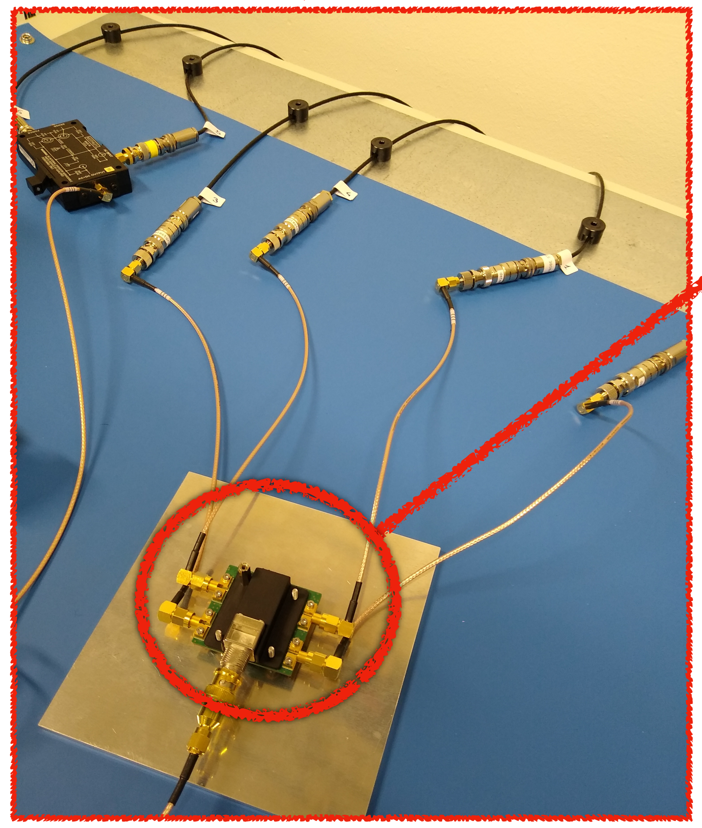
- ☑ Capacitance/doping
- ☑ Photocurrent
- ☑ Bandwidth
- ☑ Surface uniformity
- ☑ Quantum efficiency

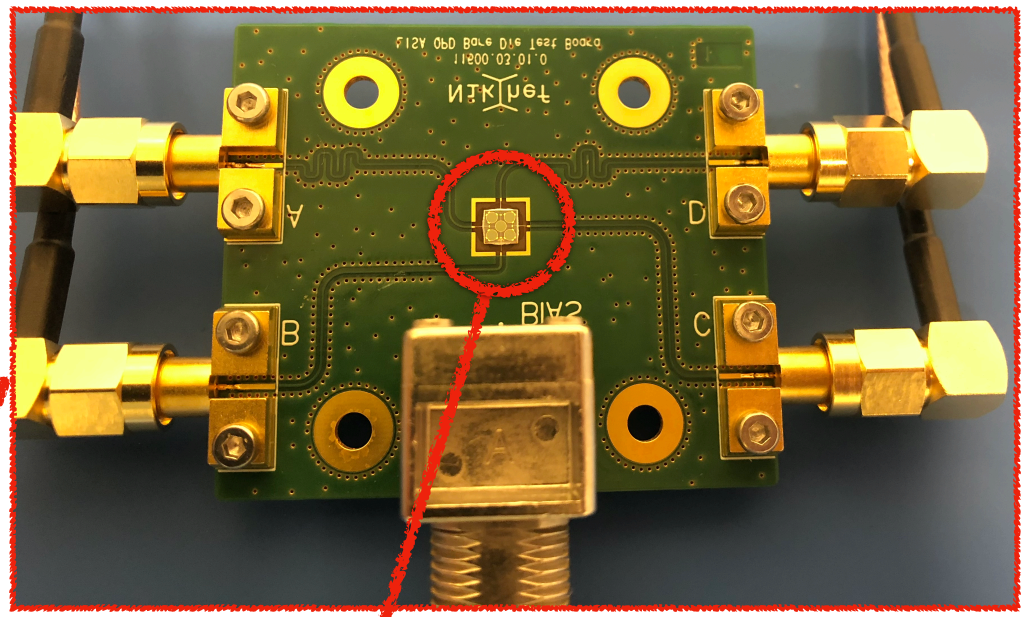


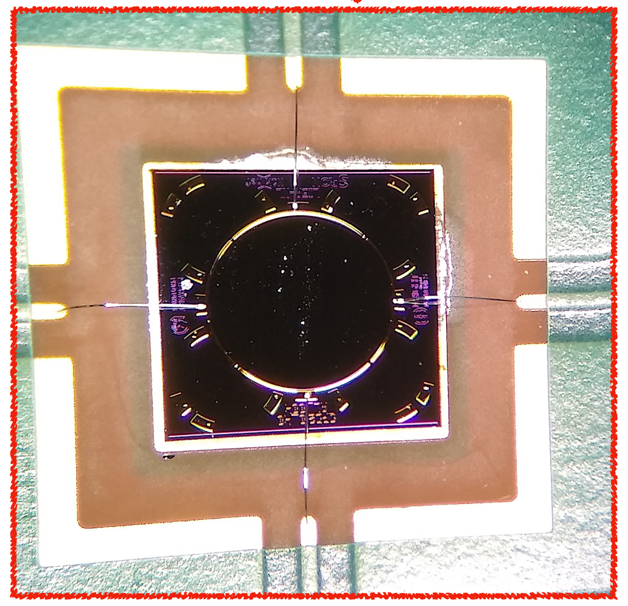


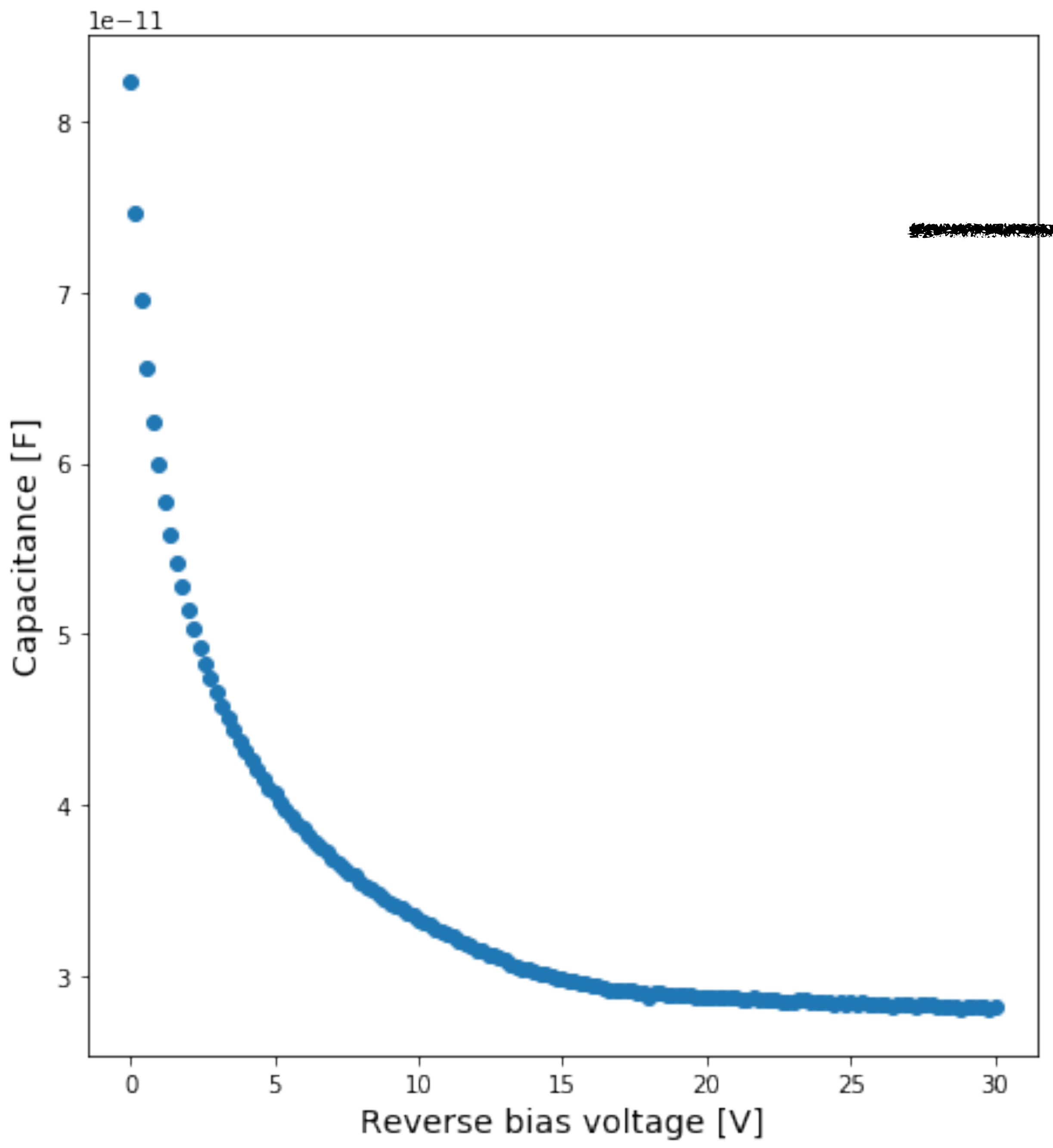
Capacitance/doping

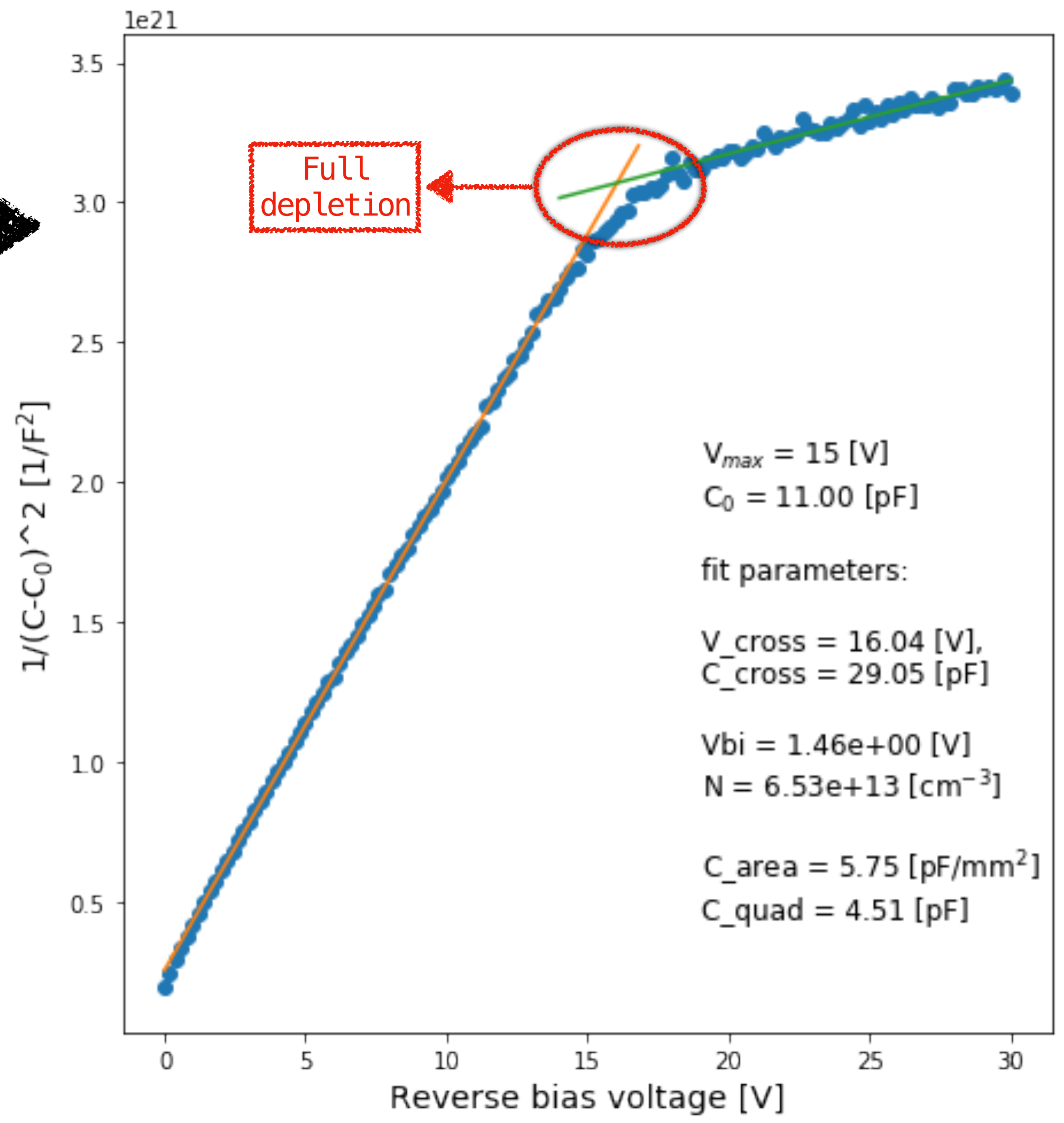












$$C = \sqrt{\frac{qN\epsilon A^2}{2(V+V_{bi})}} + C_o$$

Elementary charge

Doping

Absolute permittivity of the material

Detector area

Capacitance

Additional capacitance

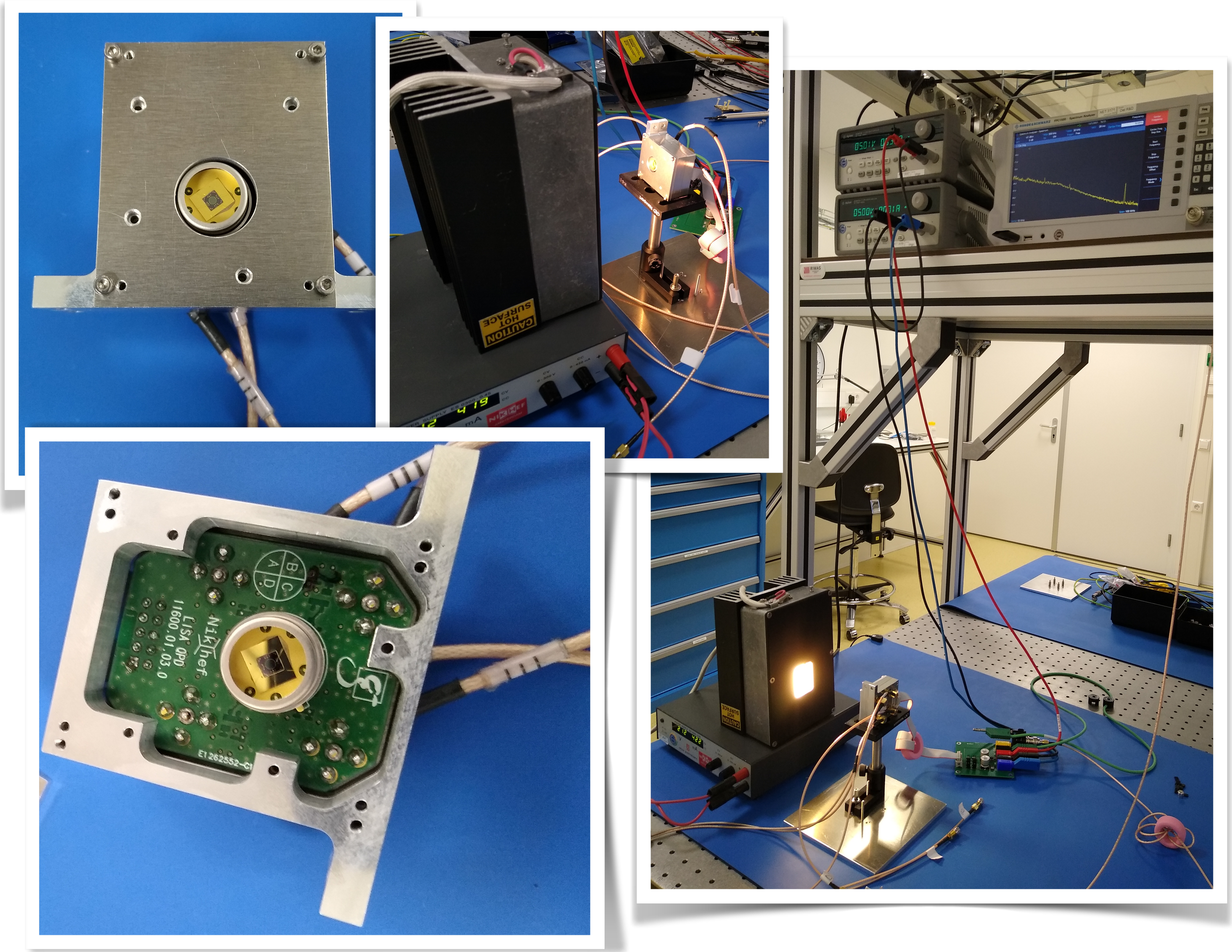
Applied voltage

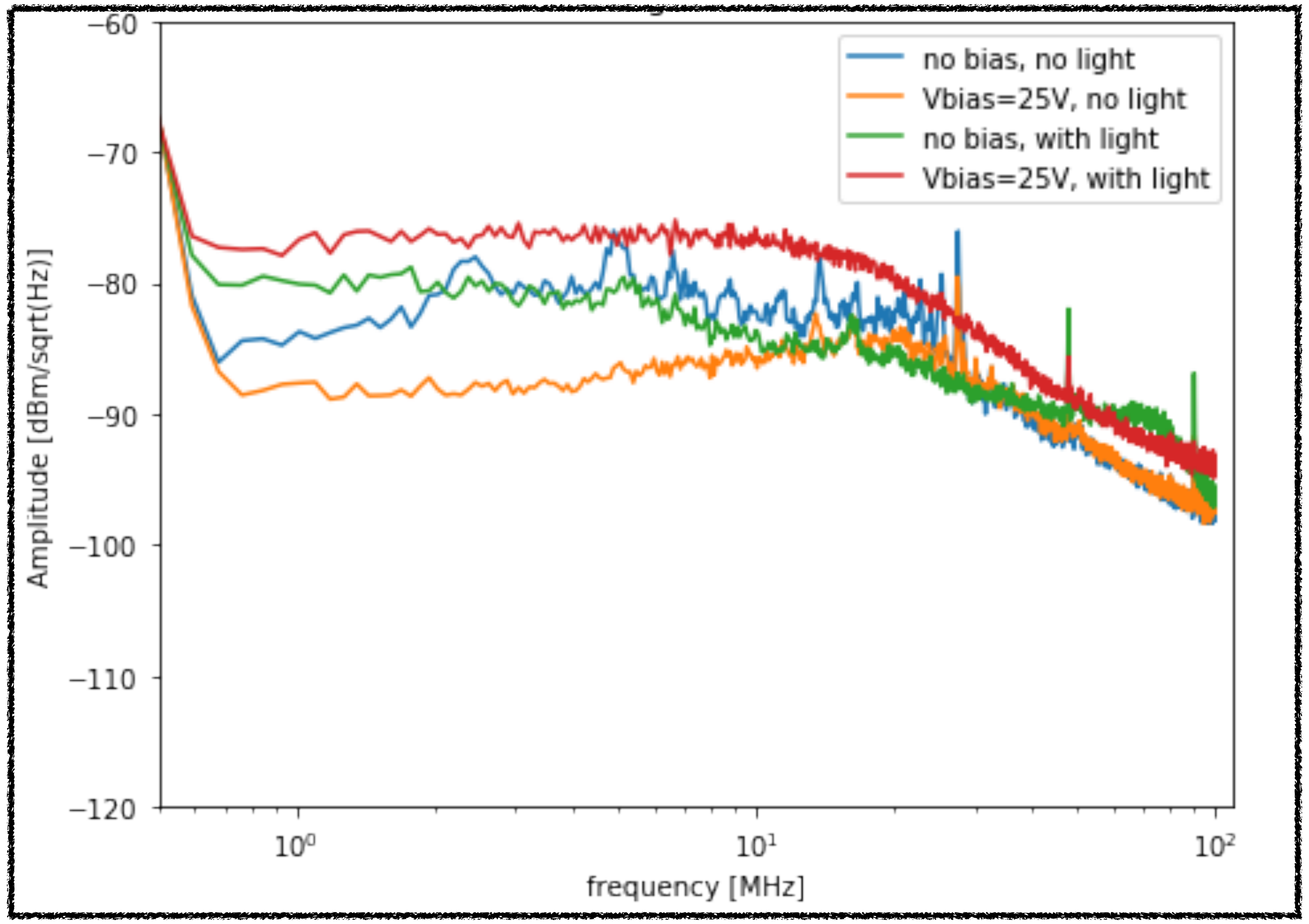
Built-in voltage

To do:

- Optimise the fit
- Error analysis
- Determine specific capacitance contributions

Bandwidth and photocurrent



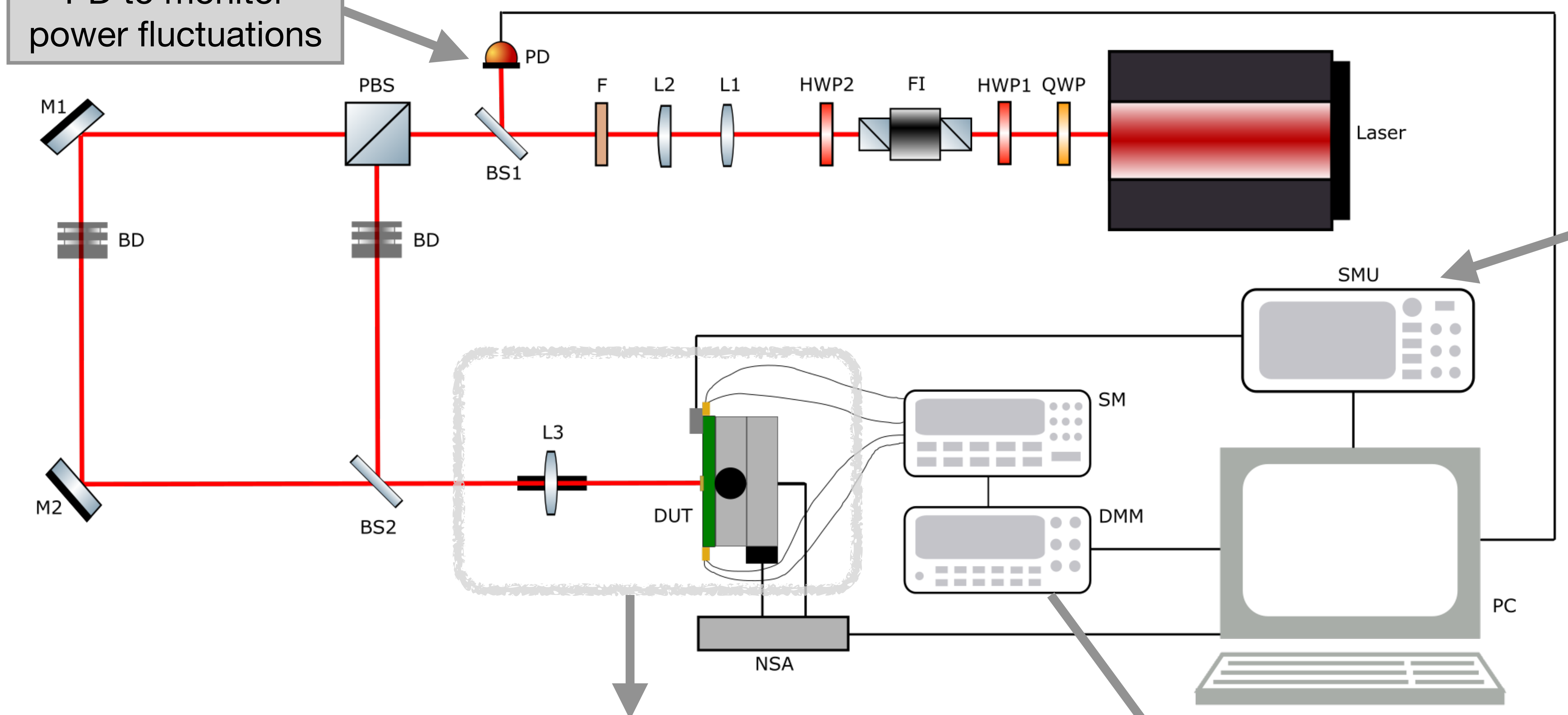


To do:

- Minimise asymmetries between channels
- Optimise the amplifier to reduce electronic noise
- Measure more diodes (from different vendors)

Quantum efficiency and surface uniformity

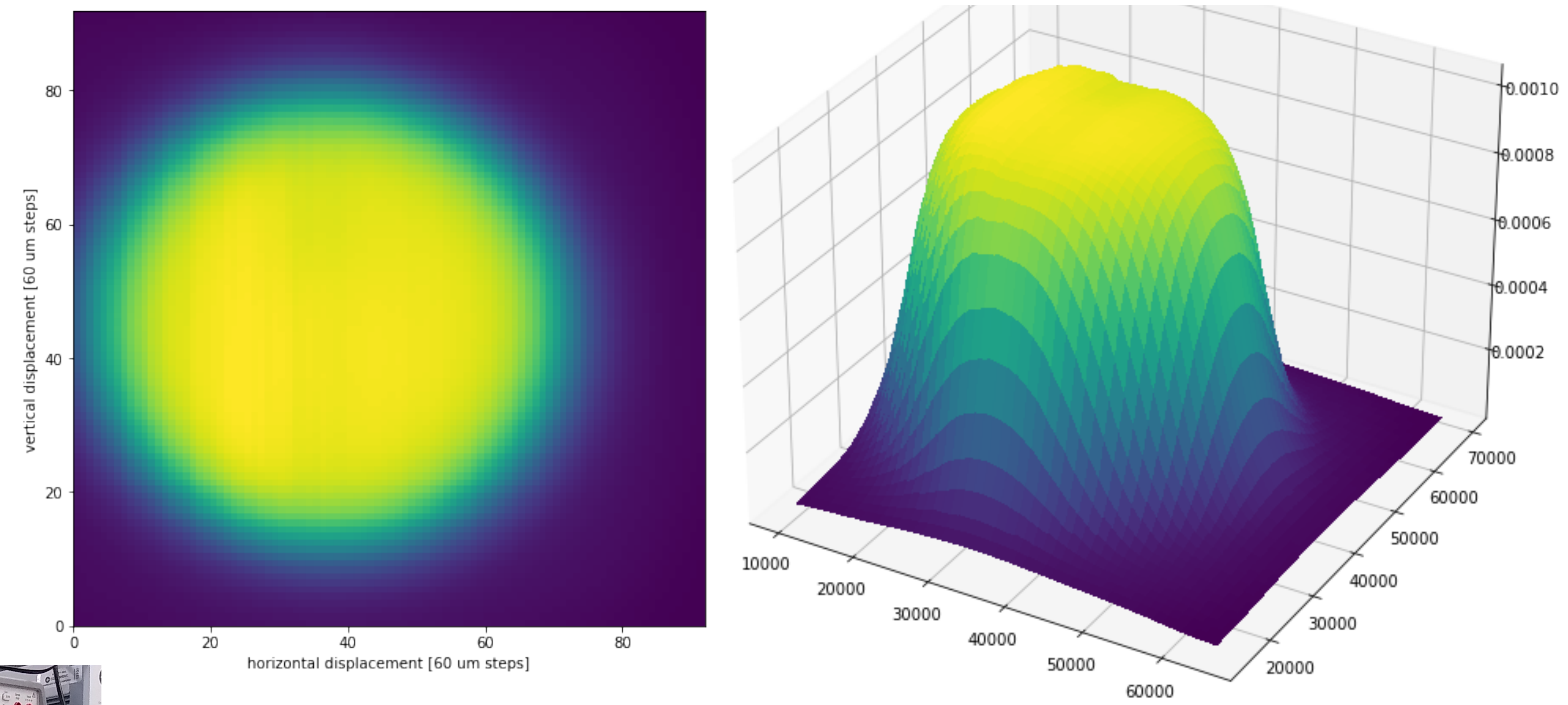
PD to monitor power fluctuations

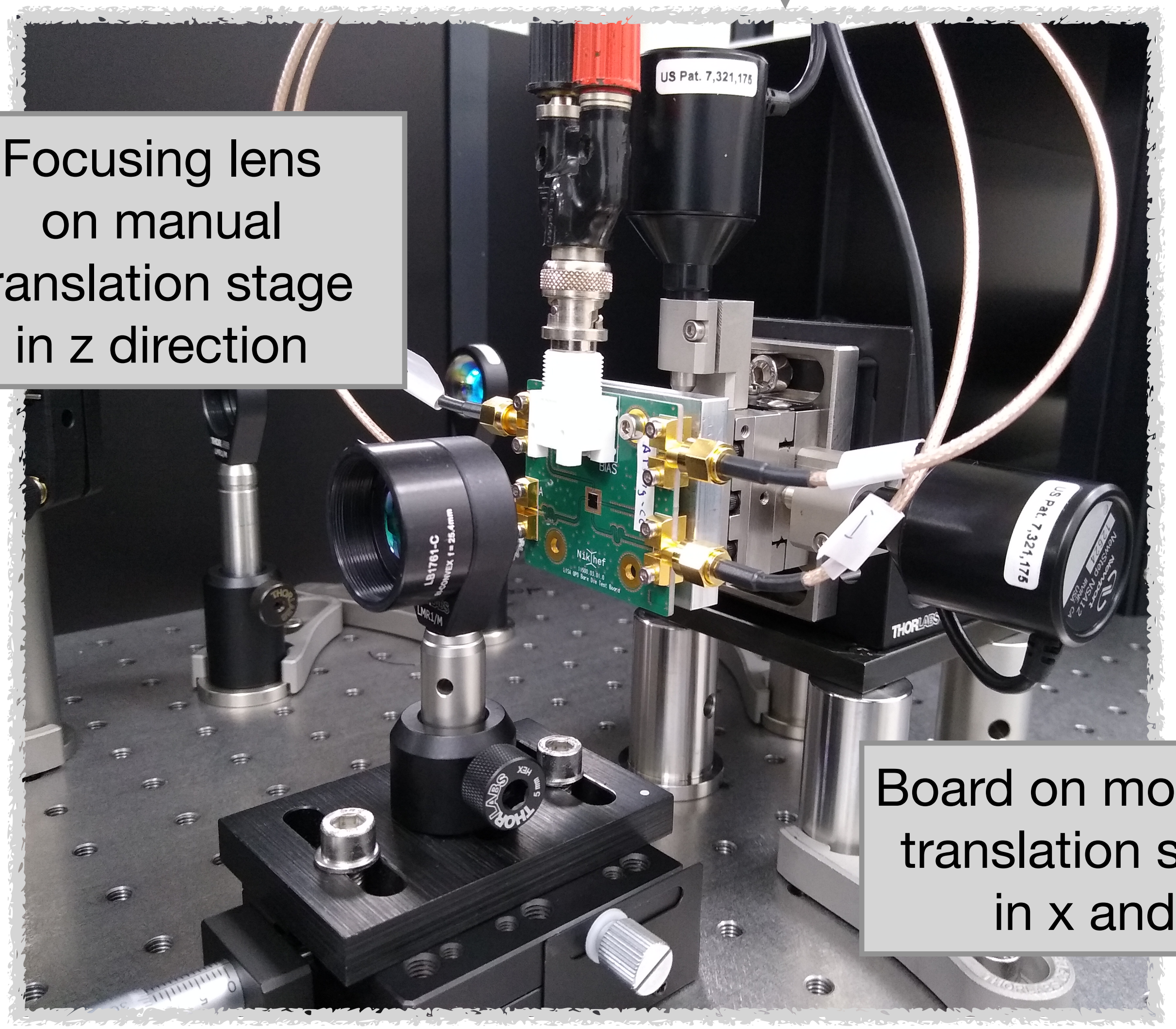


Source Measurement Unit (SMU) to apply bias voltage and read back current

First measurements done to test the set-up

Used a 4mm SEPD and a ~300 µm beam

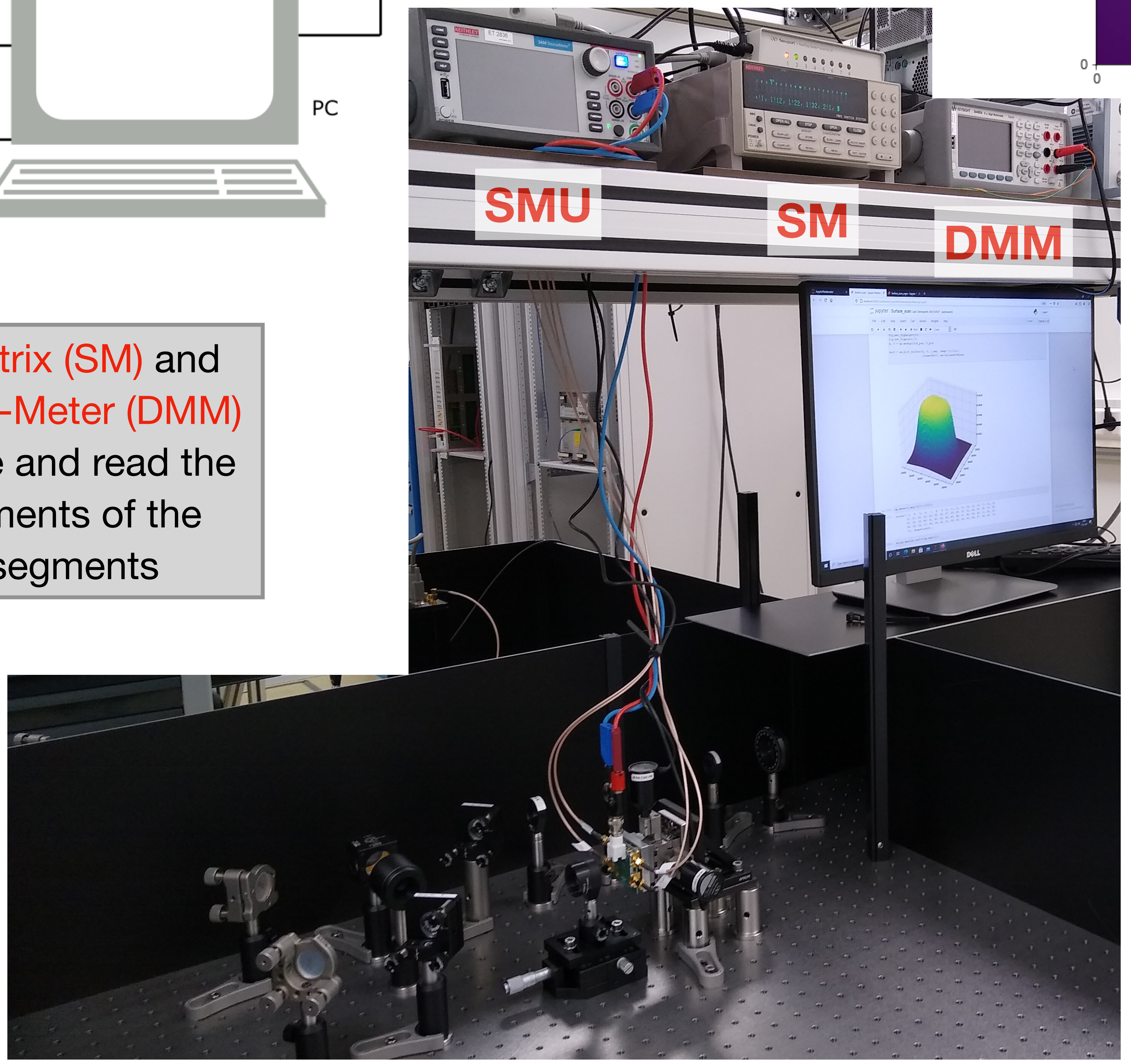




Focusing lens on manual translation stage in z direction

Board on motorised translation stages in x and y

Switch Matrix (SM) and Digital Multi-Meter (DMM) to automise and read the measurements of the single segments

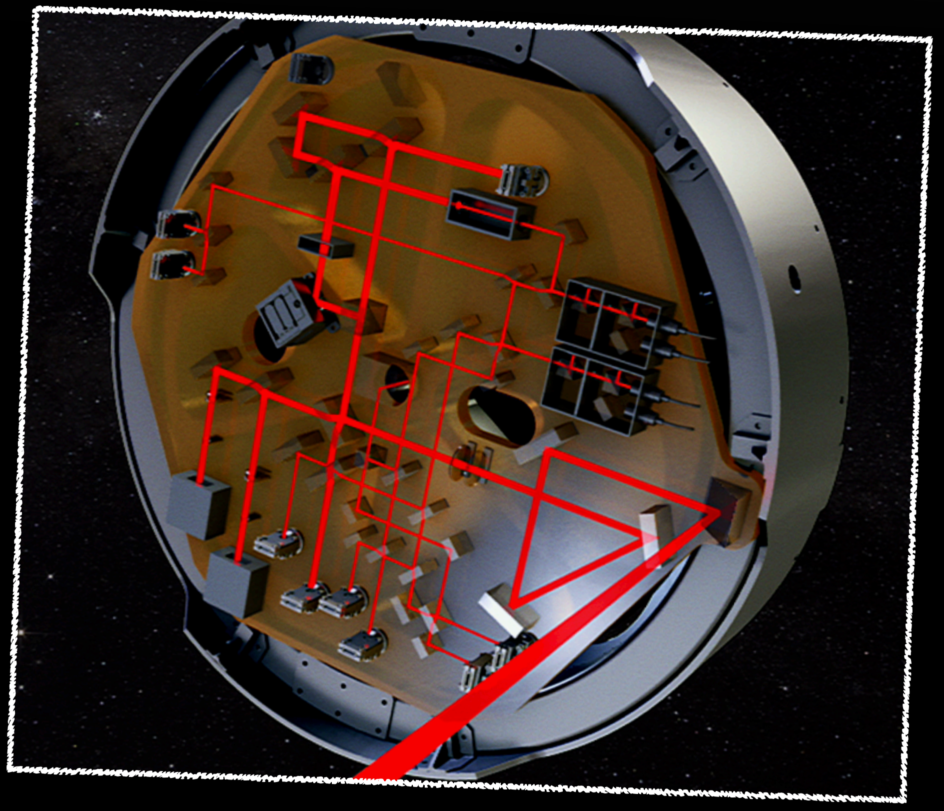


To do:

- Monitor power fluctuations
- Measure QPDs
- Try to evaluate the gap size
- Measure cross-talk

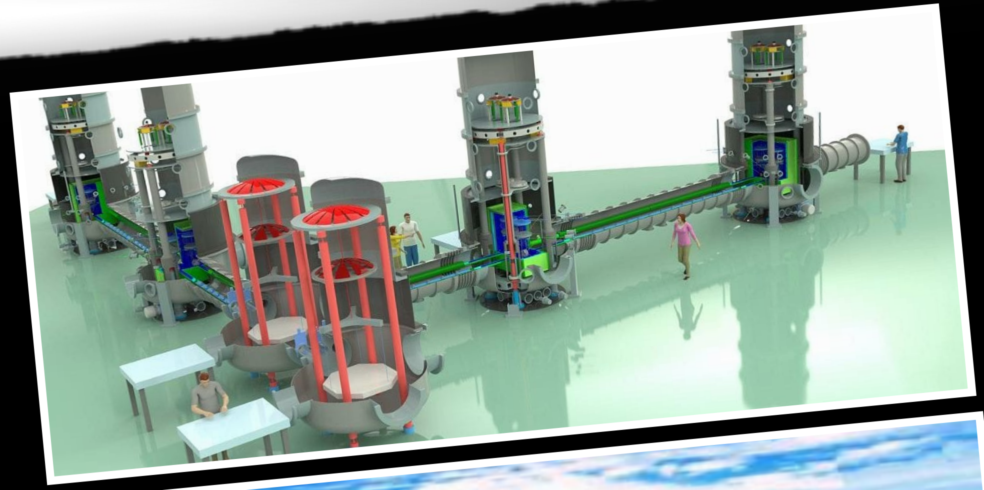
Outlook

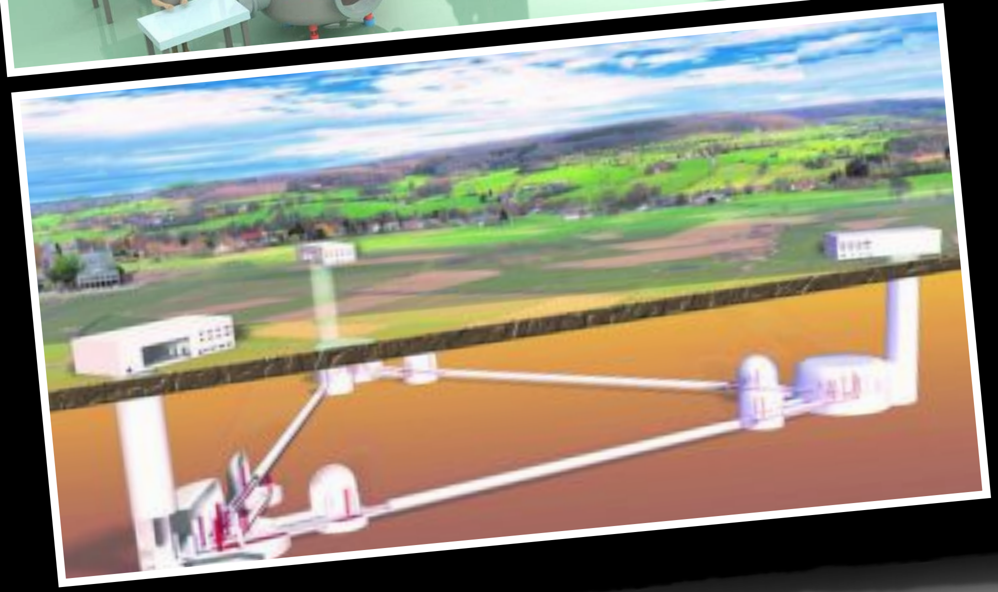
Aiming to build all
72 QPDs
for LISA
(a 5-10 M€ project)



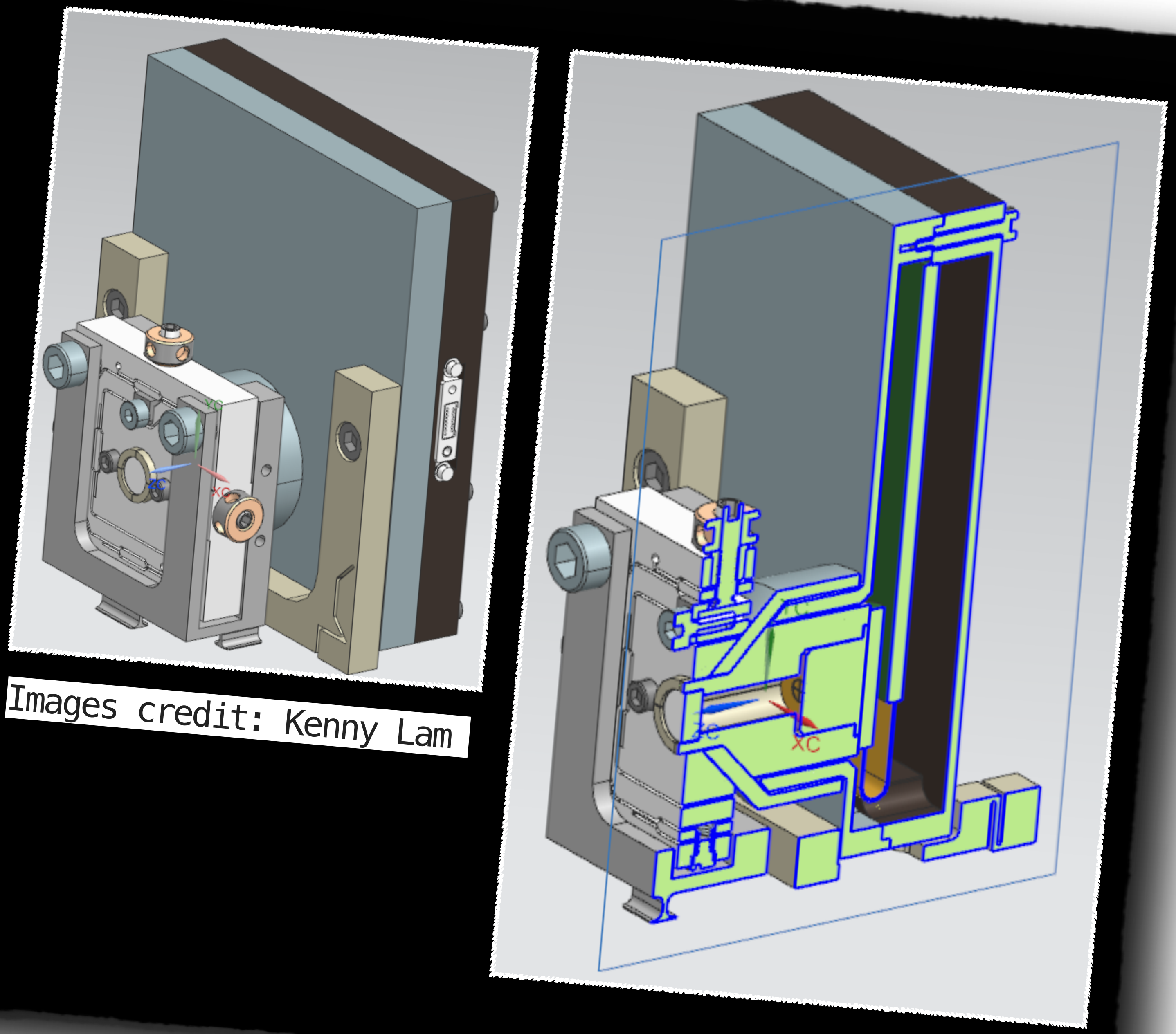
Promising first results.
More tests and analysis needed.

Experience in
InGaAs/InP
photodetectors useful for
future GW detectors.





Housing
design
in progress



Images credit: Kenny Lam

Virgo Phase Camera

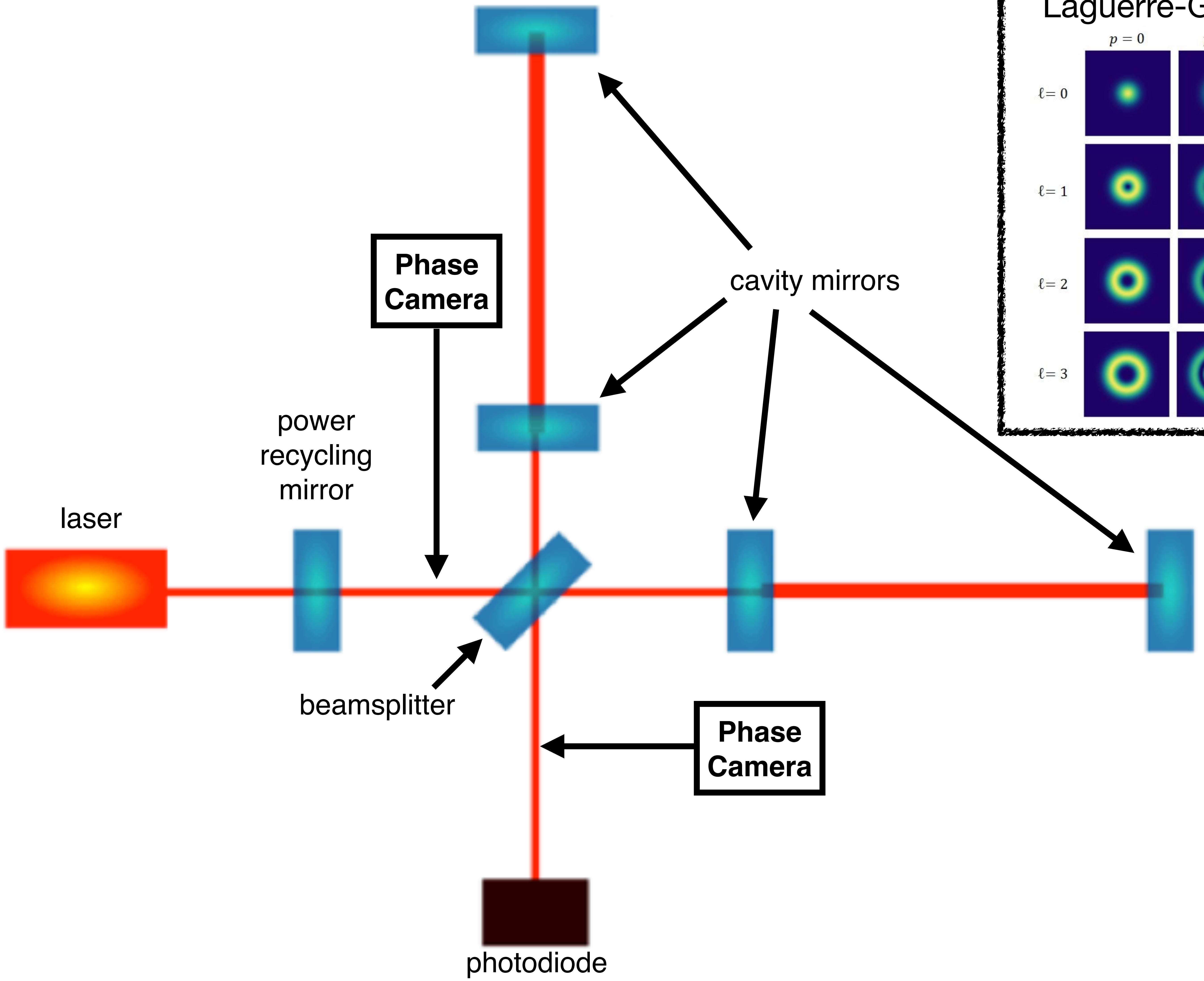
Why a Phase Camera?

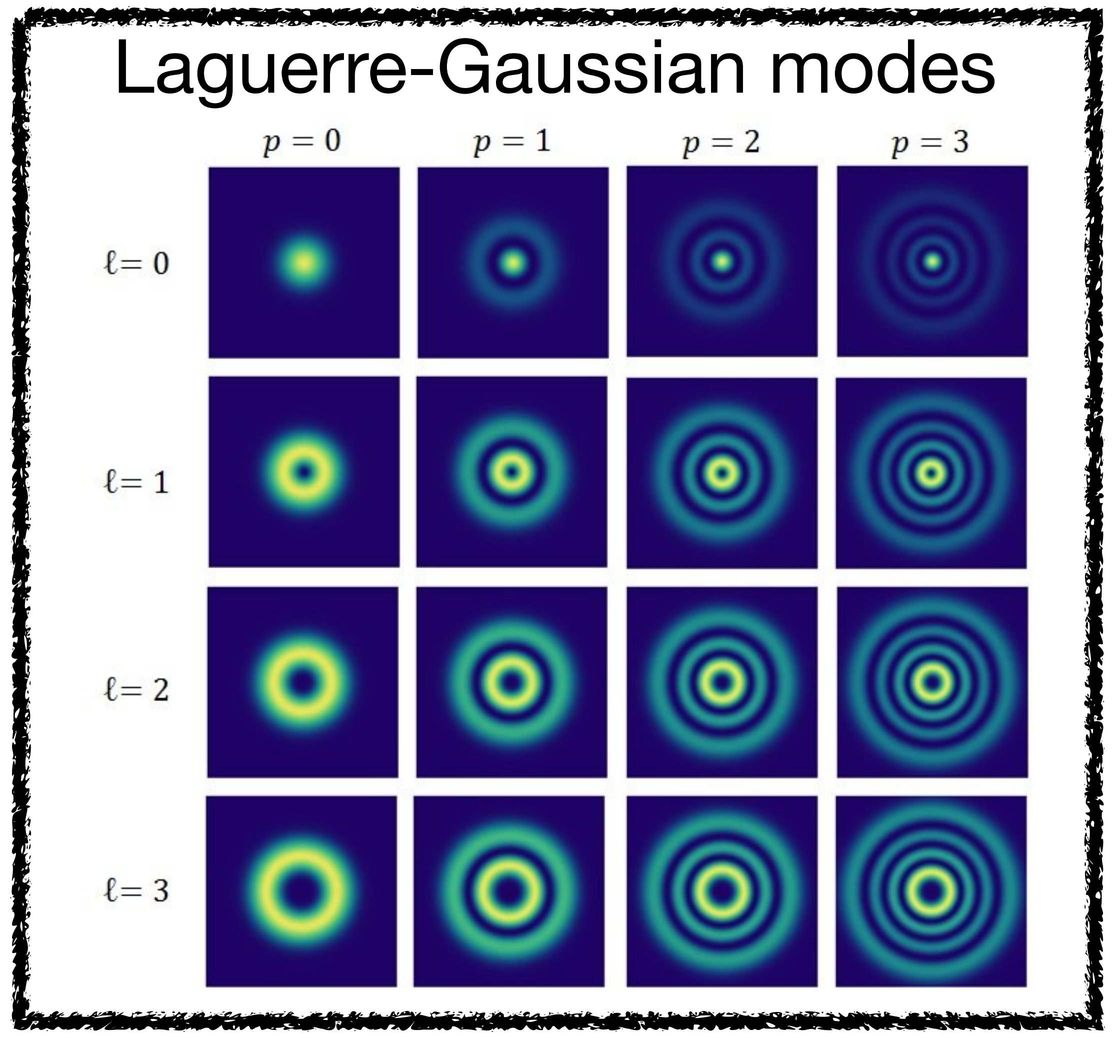
Advanced Virgo has a marginally stable Power Recycling Cavity

Higher Order Modes (HOM) can resonate and complicate the cavity control

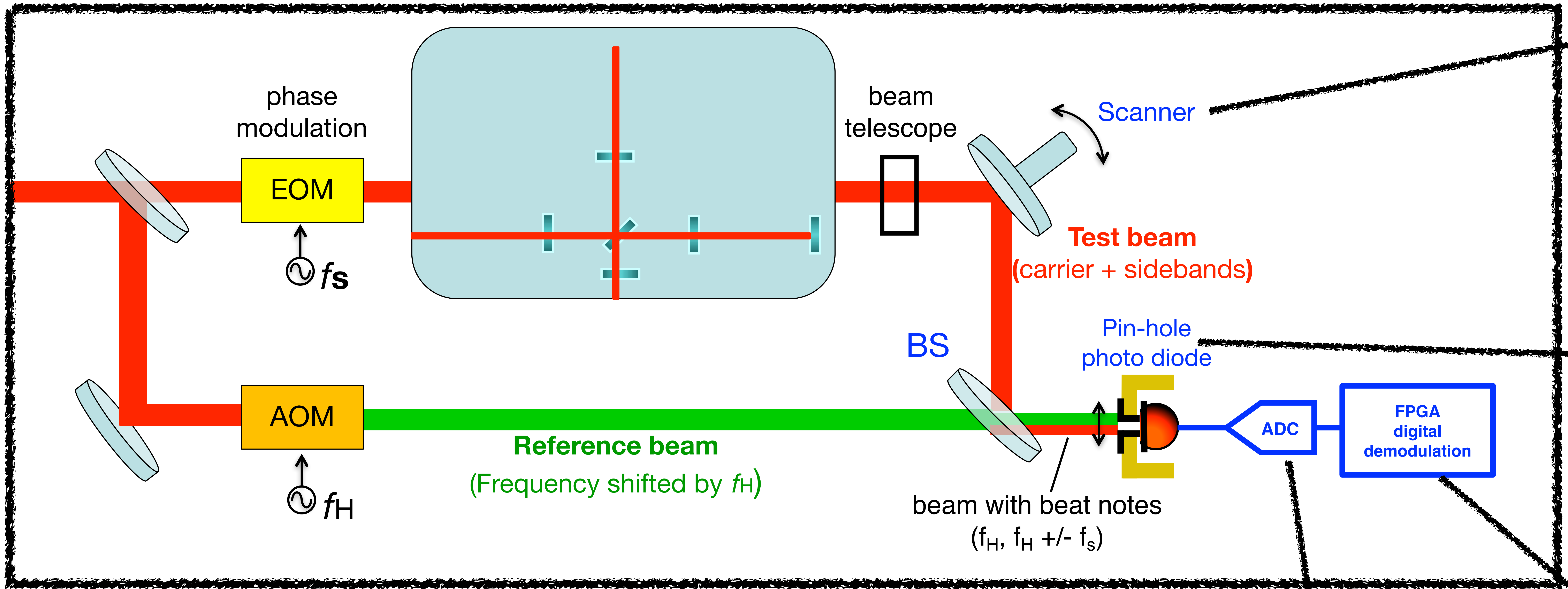
Phase cameras provide phase and amplitude images

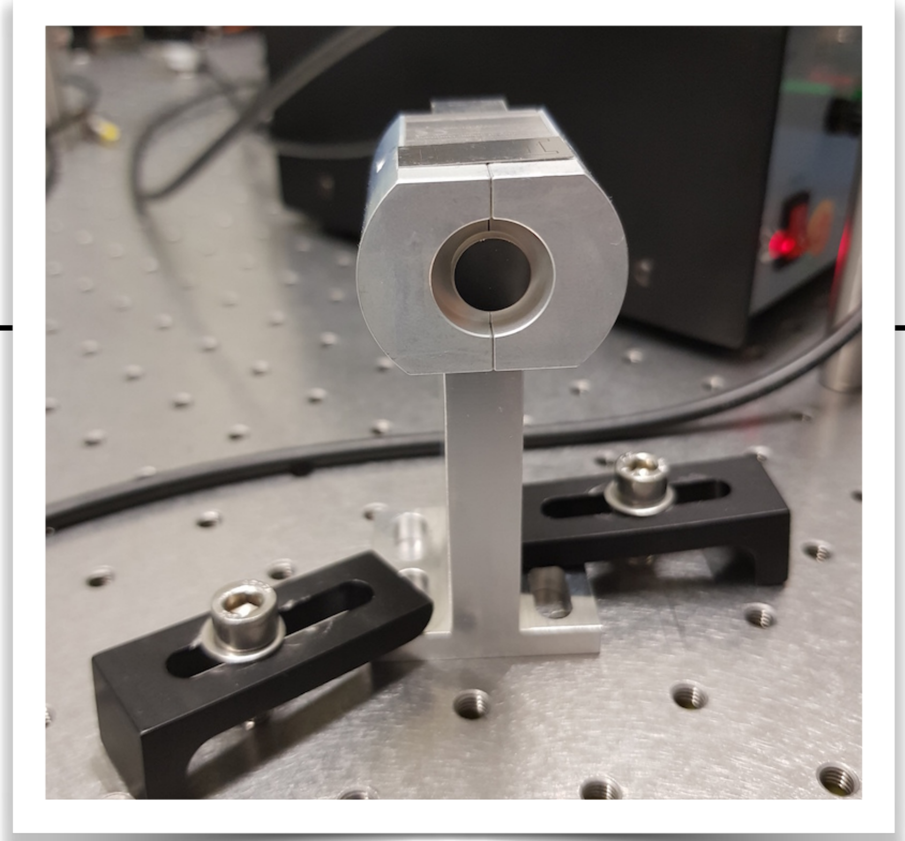
- aid commissioning
- provide input to correct thermal effects

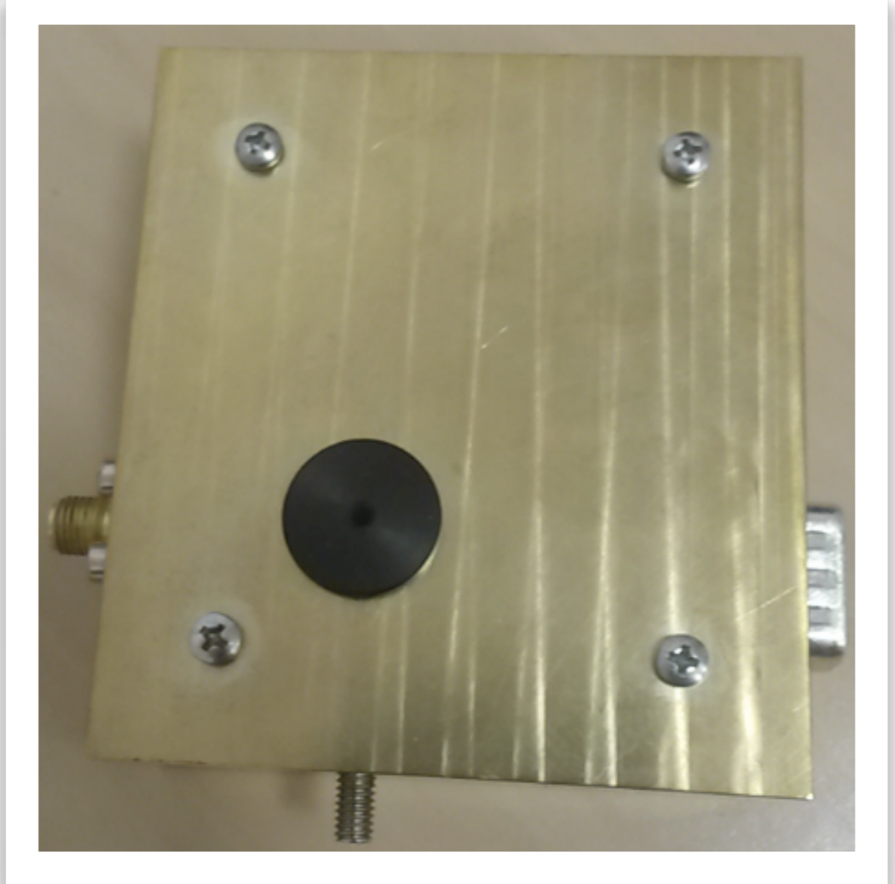


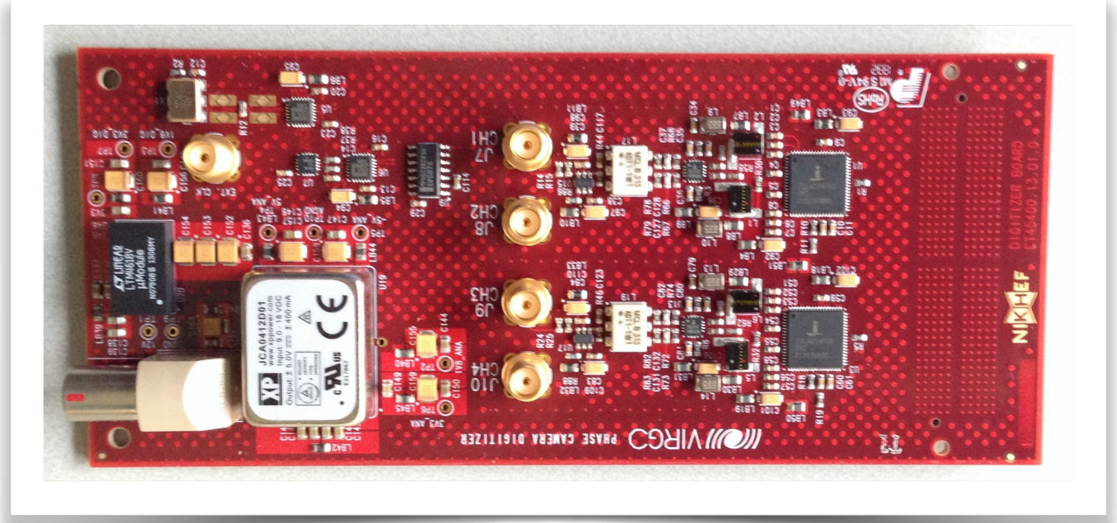


Optical set-up



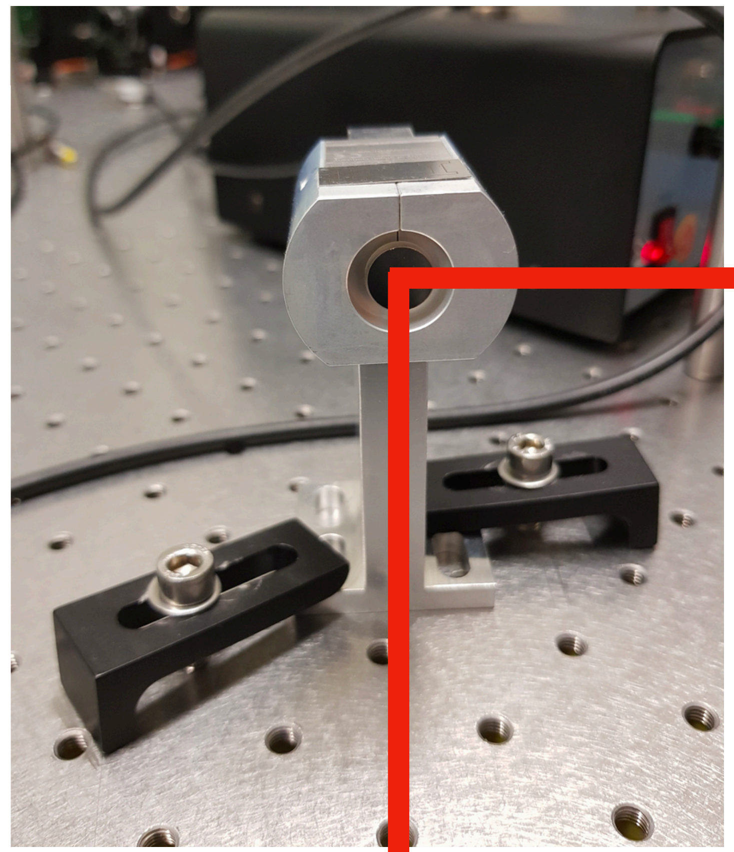


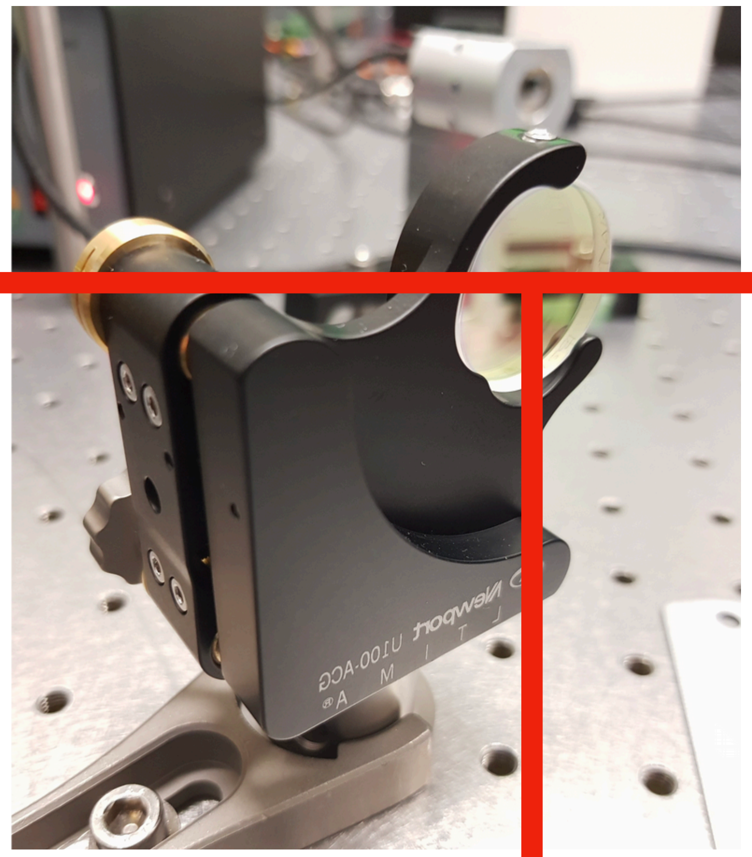


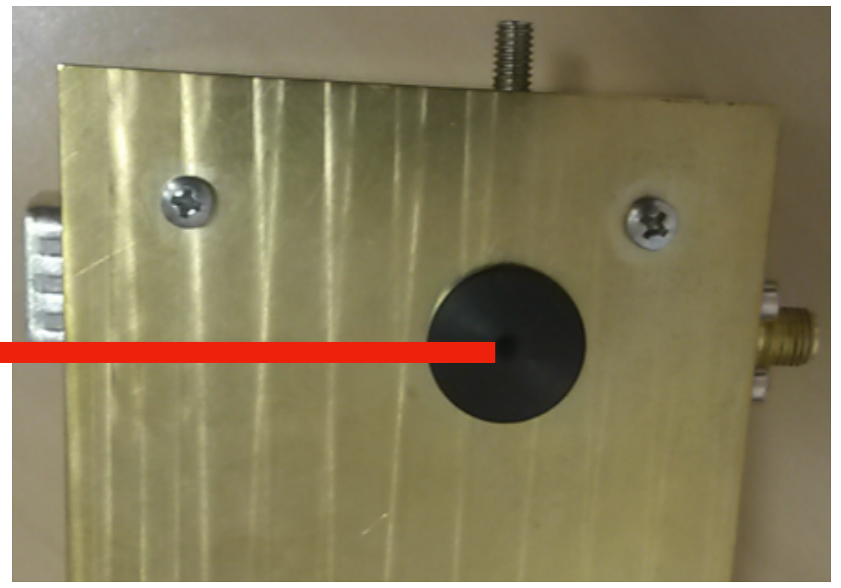


- Upper and lower sidebands (USB/LSB) are at (slightly) different optical frequencies
- Access each sideband separately by mixing it with a 80 MHz frequency shifted beam
- Beat signal with f_H, and f_H +/- f_s

Working principle







$$E_{combined} = \frac{1}{\sqrt{2}} E_{IFO} + \frac{i}{\sqrt{2}} E_{ref}$$

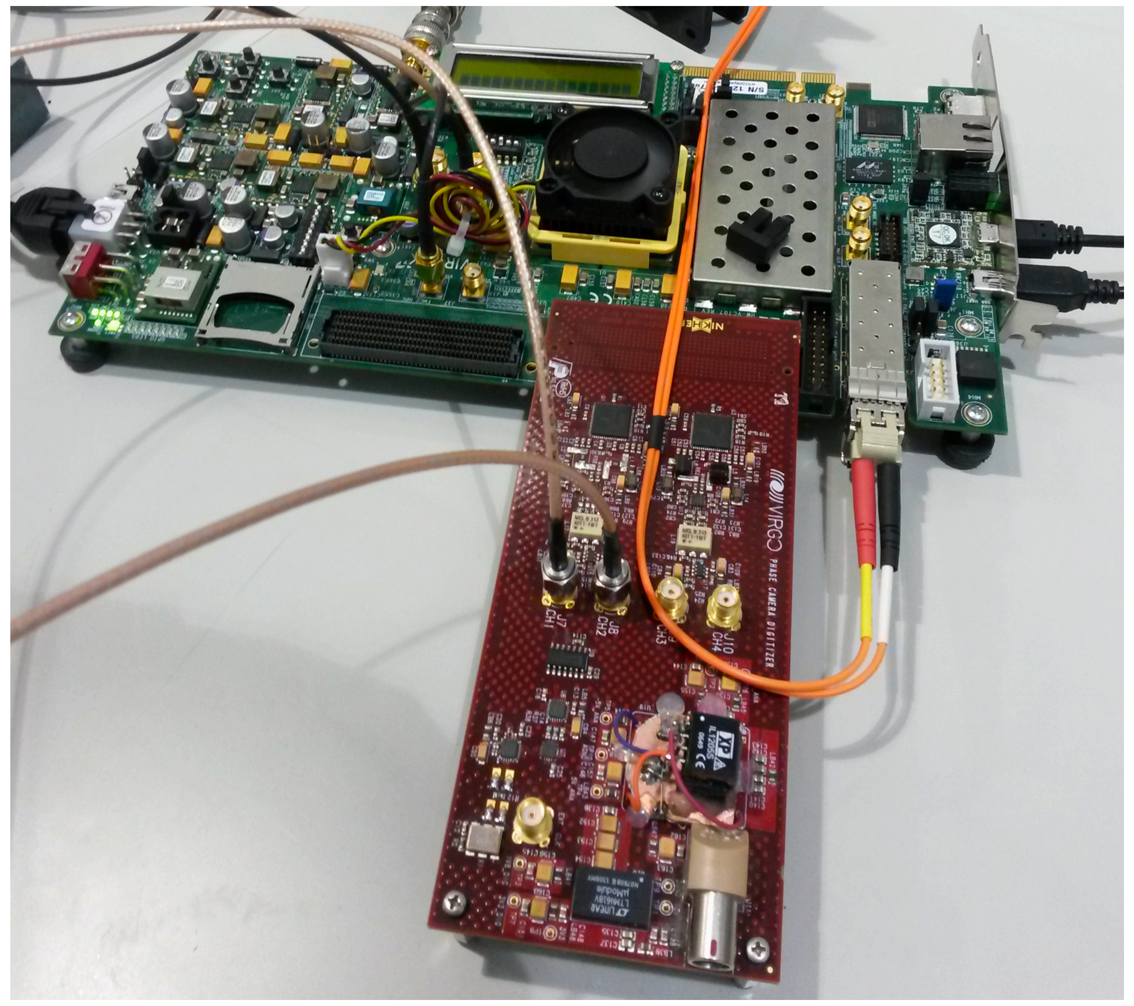
$$E_{IFO} = A\left(\vec{x}\right) e^{i(\omega_c + \omega_s)t + i\phi_s\left(\vec{x}\right)}$$

$$E_{ref} = B\left(\vec{x}\right) e^{i(\omega_c + \omega_h)t + i\phi_h\left(\vec{x}\right)}$$

Resulting current after the diode (quantities that are scanned over denoted by $\vec{x}$):

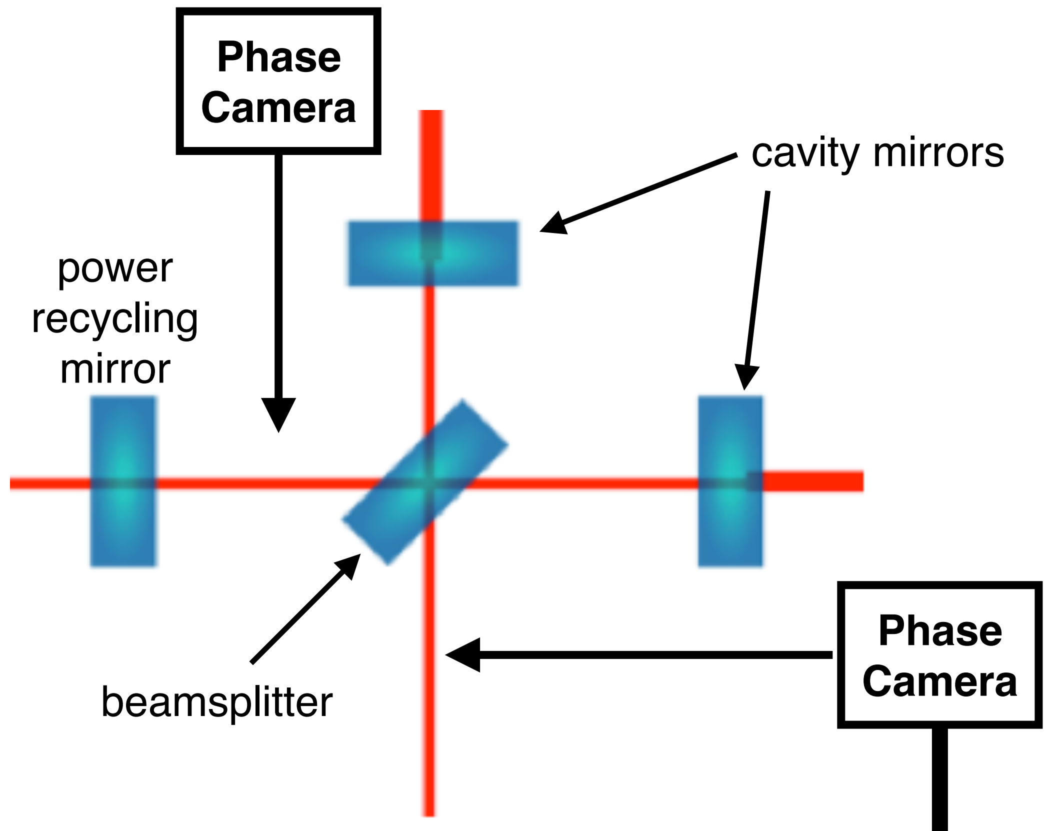
$$I_{diode} = \underbrace{\left|A\right|^2 + \left|B\left(\vec{x}\right)\right|^2}_{\text{DC signal}} + \underbrace{\overbrace{\left|A\right| \left|B\left(\vec{x}\right)\right|}^{\text{amplitude}} \cos\left(\left(\omega_s - \omega_h\right) t + \overbrace{\phi_s\left(\vec{x}\right) - \phi_h}^{\text{phase}}\right)}_{\text{AC signal}}$$

- Demodulation is performed digitally by sampling the AC part of the current with a fast ADC.
- After demodulation we have amplitude and phase for the sidebands.



Power and phase images

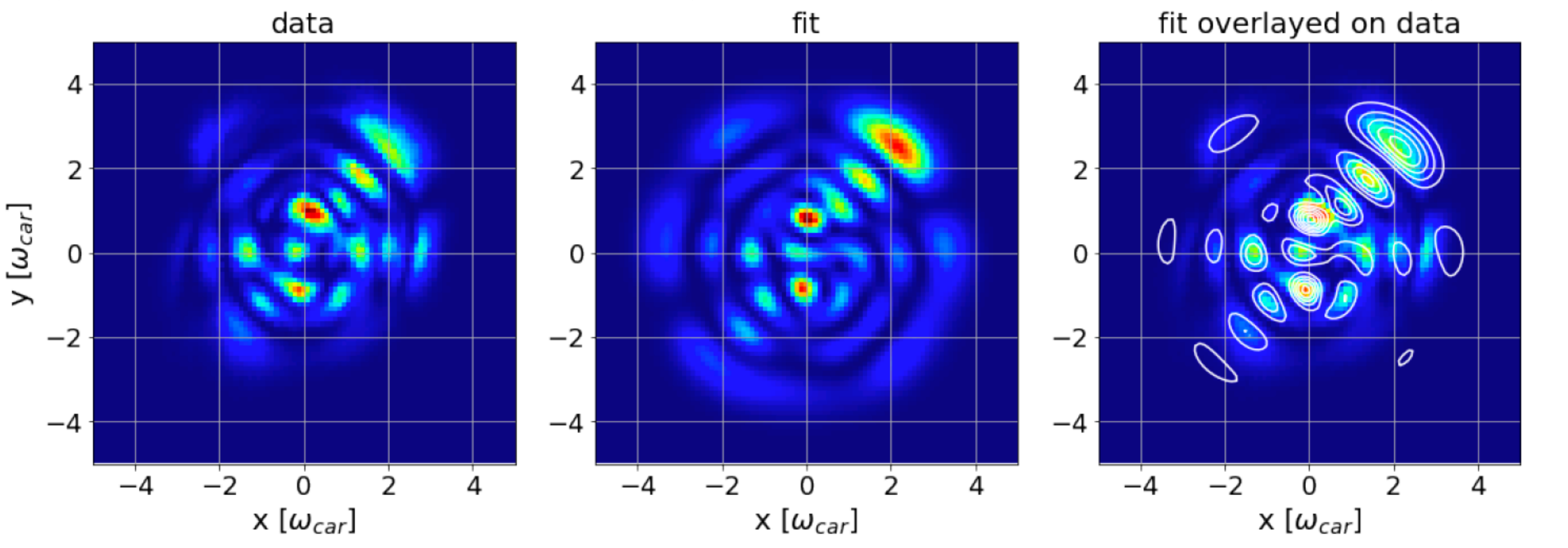
Thermal effects and HOMs



The input power to the interferometer is increased from about 18 W to about 26 W (and will be further increased).

This makes mirrors thermally expand and changes the mode matching.

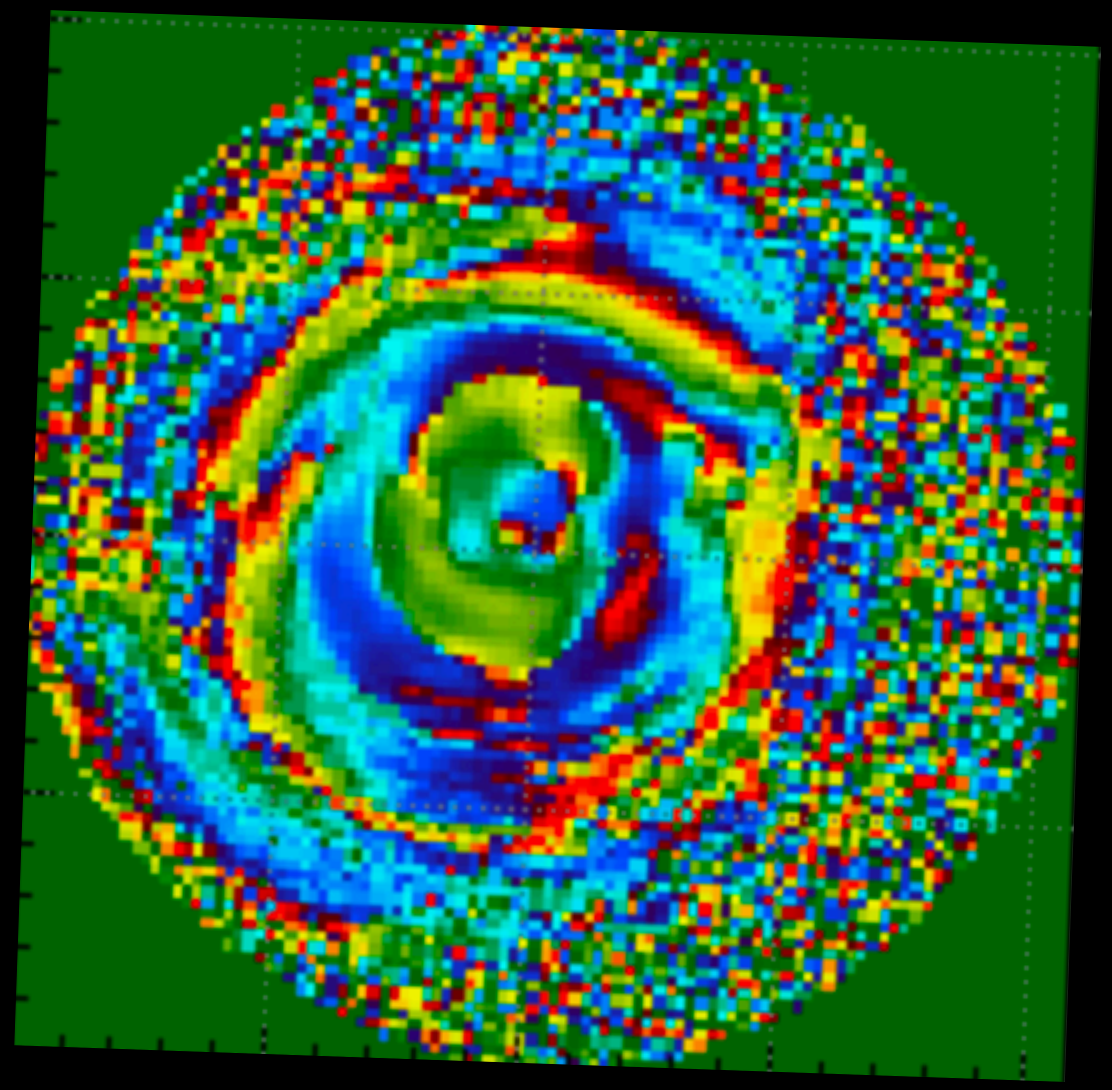
Thermal effects are a source of HOMs.



credits: L. van der Schaaf, Ph.D. Thesis (2020)

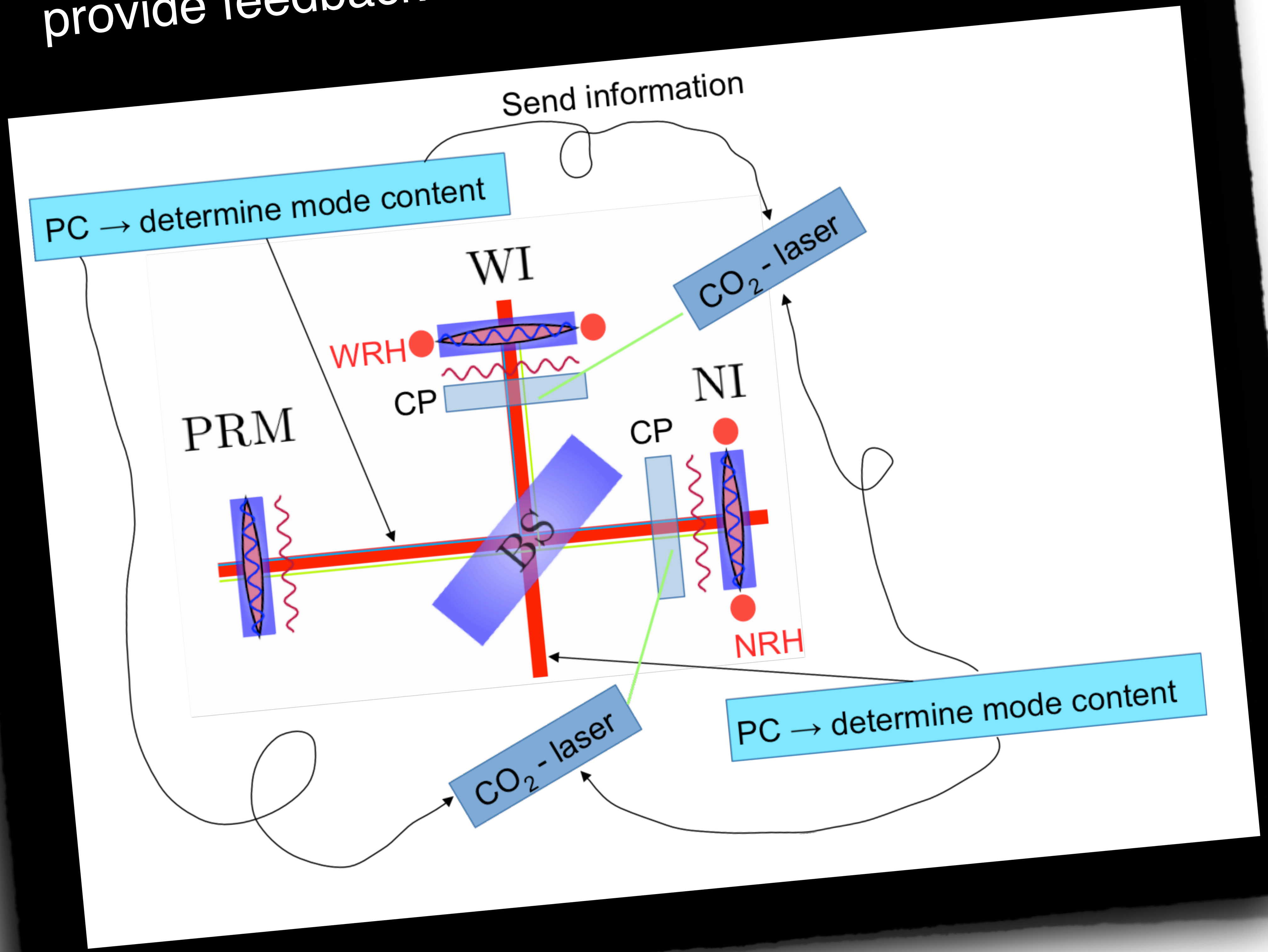
Outlook

Understand the data:
what do the phase
images represent?



Producing 3 phase cameras for LIGO
(in collaboration with the University of Birmingham)

Use the data:
provide feedback to correct the thermal effects



What's next

Future GW detectors will use different laser wavelengths (1.55 μm and 2 μm)

Might require the use of new photodetectors

Quantum dots

Nanometer sized semiconductors in which single electrons and holes can be trapped and manipulated.

- Tuneable band-gap (depends on the size of the nano-crystal).
- High control of light absorbance and emission frequencies.
- High photo-stability.

Extended InGaAs

InGaAs photodiode with a longer cutoff wavelength, obtained increasing the percentage of InAs.

	Standard InGaAs	Extended InGaAs (max.)
InAs	53%	82%
Cutoff wavelength	1.7μm	2.6μm

Thank you!