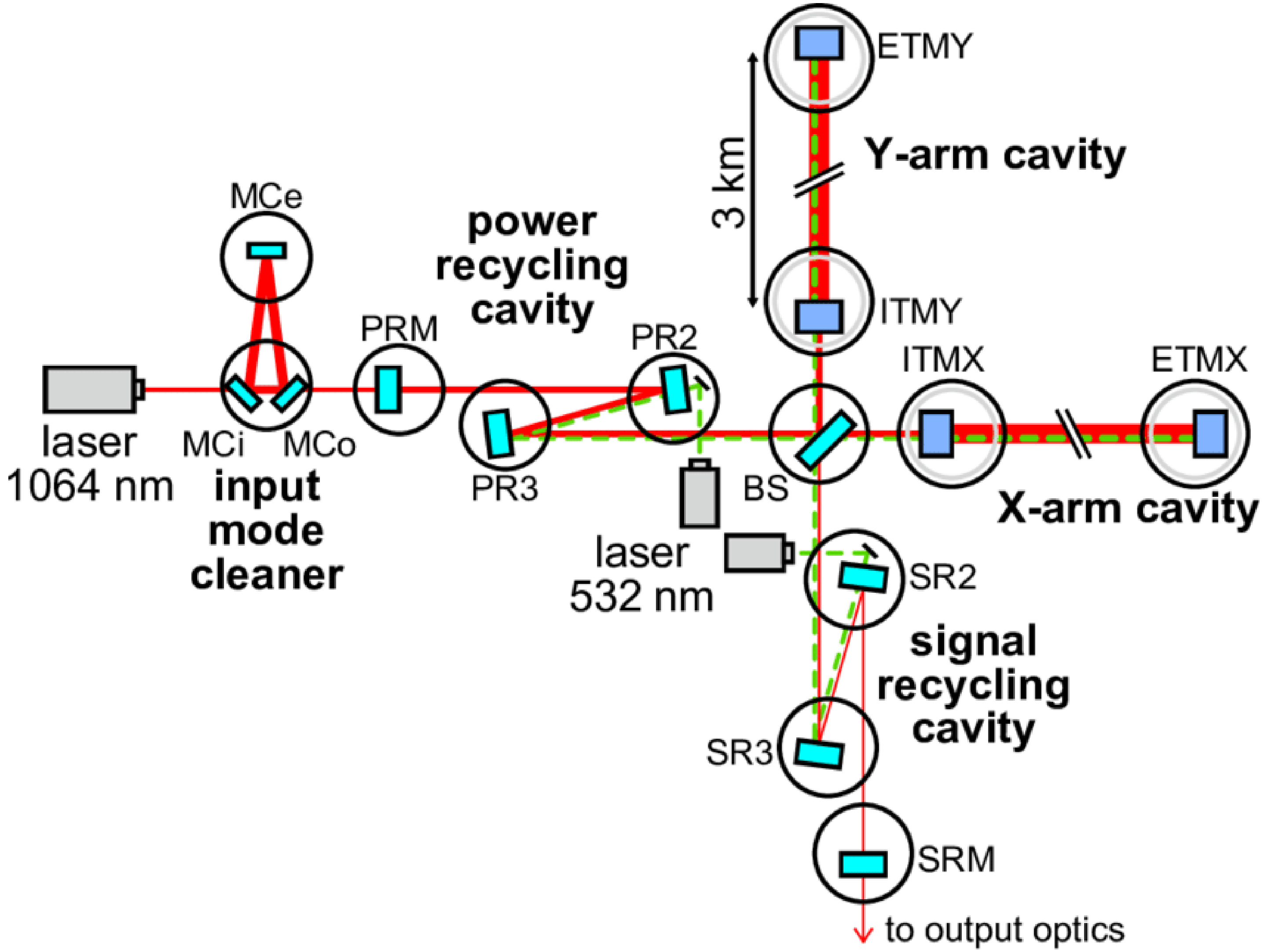
# Optical Absorption and Birefringence correlation in KAGRA Sapphire Test Masses

M. Leonardi on behalf of KAGRA MIR subsystem

# Introduction to KAGRA's mirrors




**Sapphire mirrors:**

- Two input test masses (ITMX and ITMY)
- Two end test masses (ETMX and ETMY)

**Fused silica mirrors:**

- One beam splitter (BS)
- Three input mode cleaner mirrors (MCi, MCo, MCe)
- Three power recycling cavity mirrors (PRM, PR2, PR3)
- Three signal recycling cavity mirrors (SRM, SR2, SR3)
- Two input mode matching telescope mirrors (IMMT1, IMMT2)
- Two output mode matching telescope mirrors (OMMT1, OMMT2)
- …

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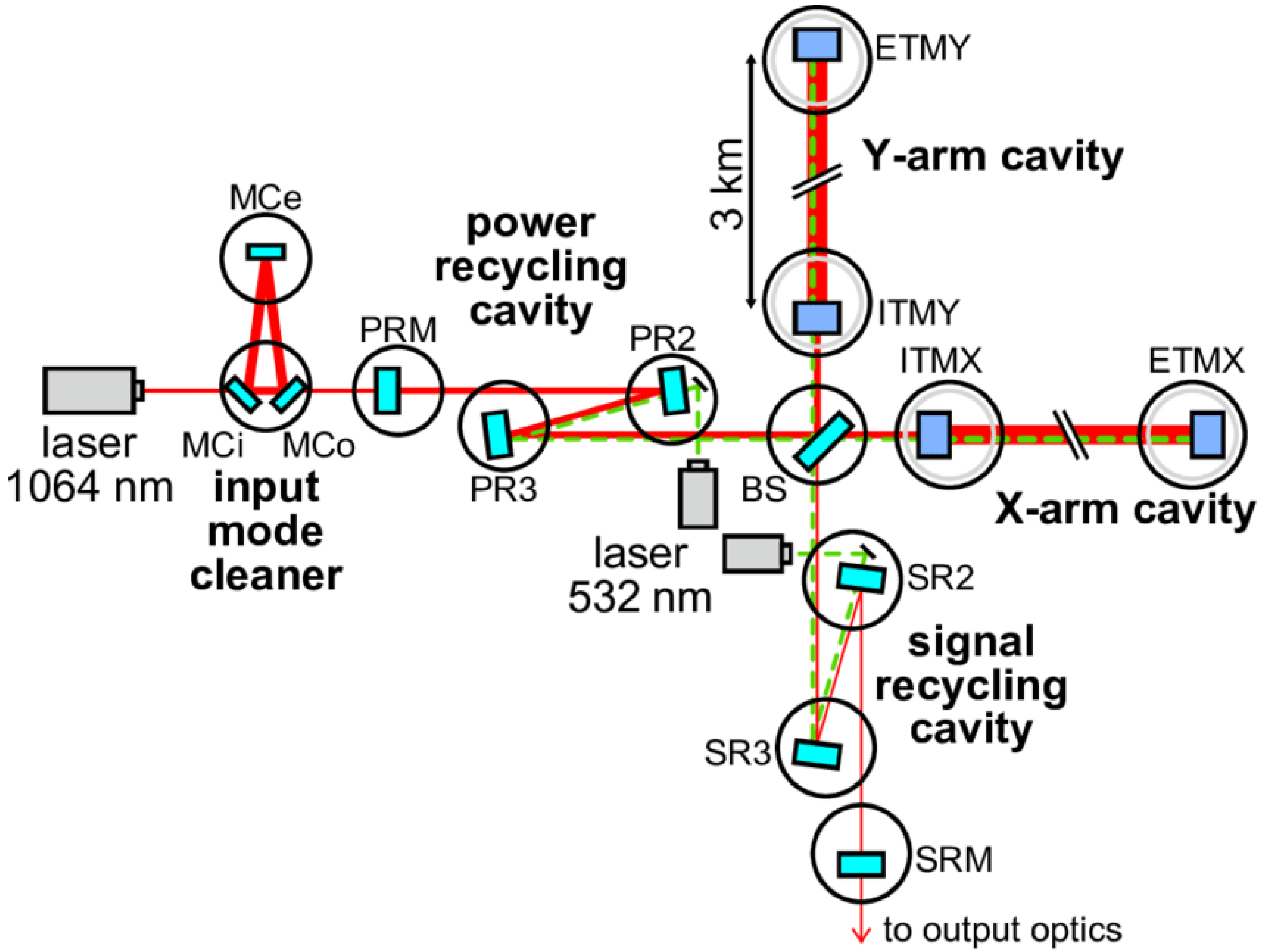


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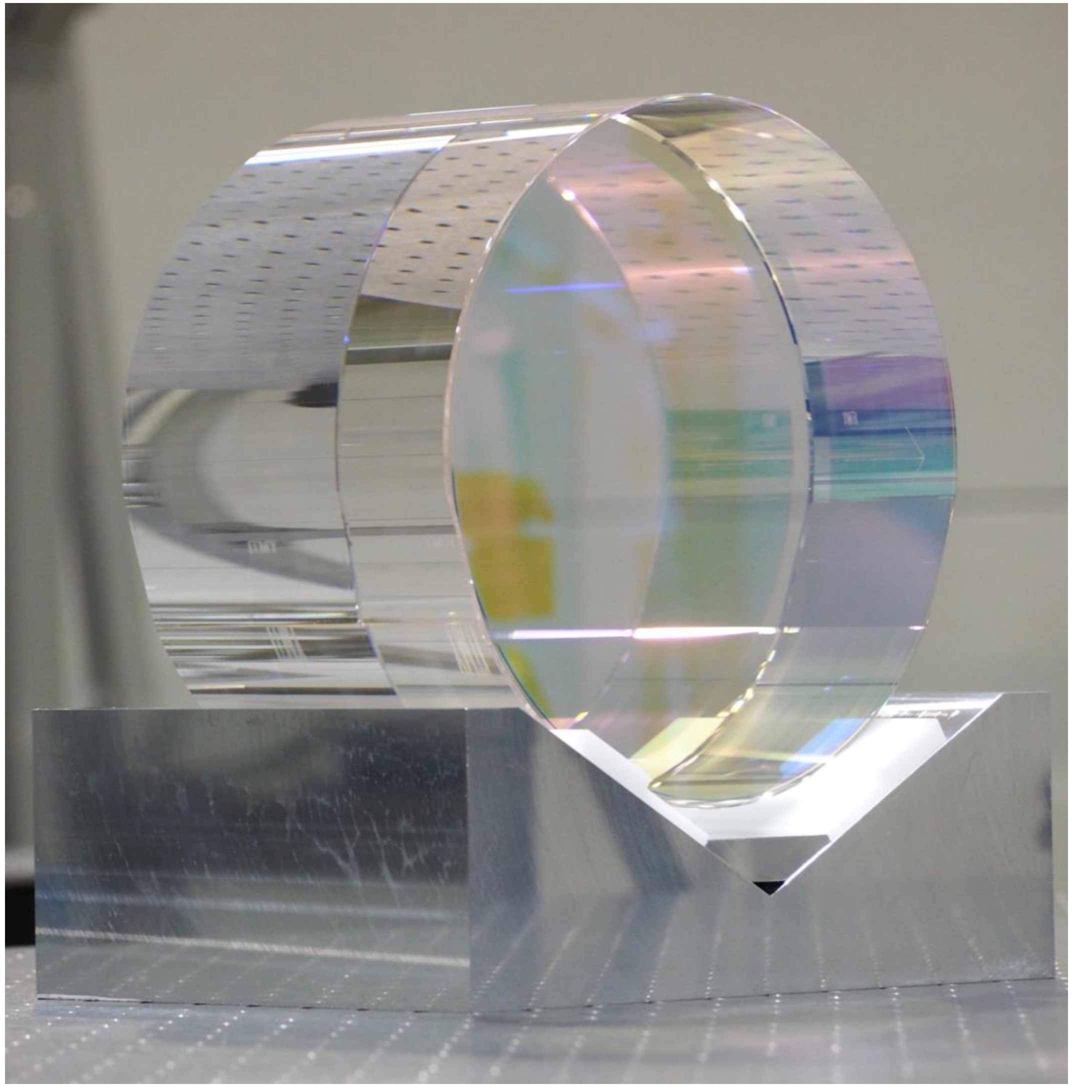
# Introduction to “sapphire”

**KAGRA mirrors:** Aluminum oxide (corundum)



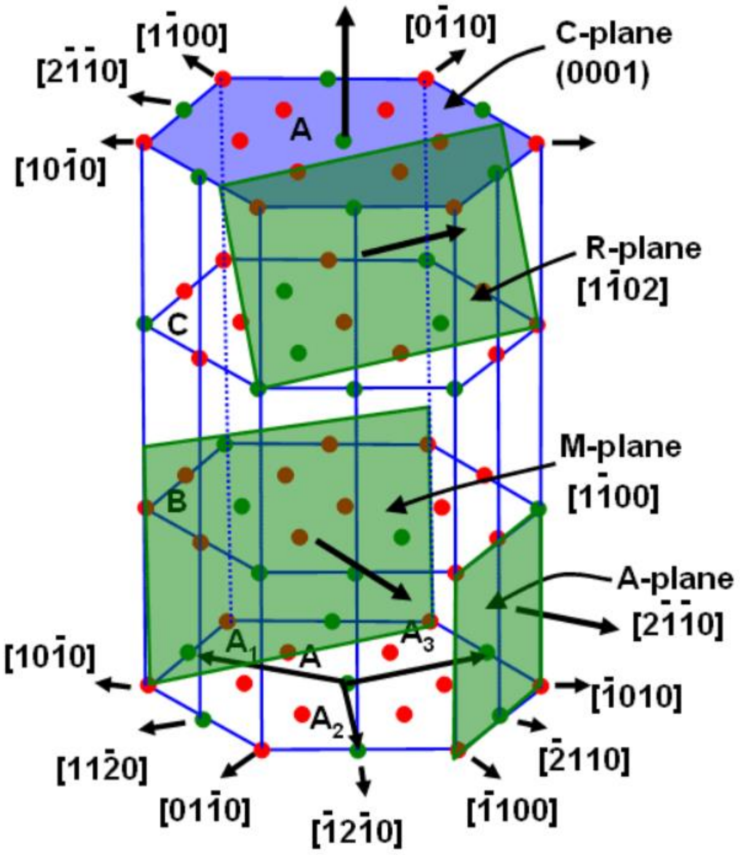
**Pro:**
- Very high thermal conductivity at cryogenic temperature
- Transparent at 1064nm
- High density
- Good industrial manufacture techniques
- …

**Cons:**
- Second hardest material in the world
- Birefringent material (in a-axis)
- …

# Recap on sapphire known problems

Sapphire substrate:

- Absorption:
  <u>*well known problem from design phases*</u>
- Birefringence:
  <u>**partially unexpected problem**</u>



# Recap on sapphire known problems

Sapphire substrate:

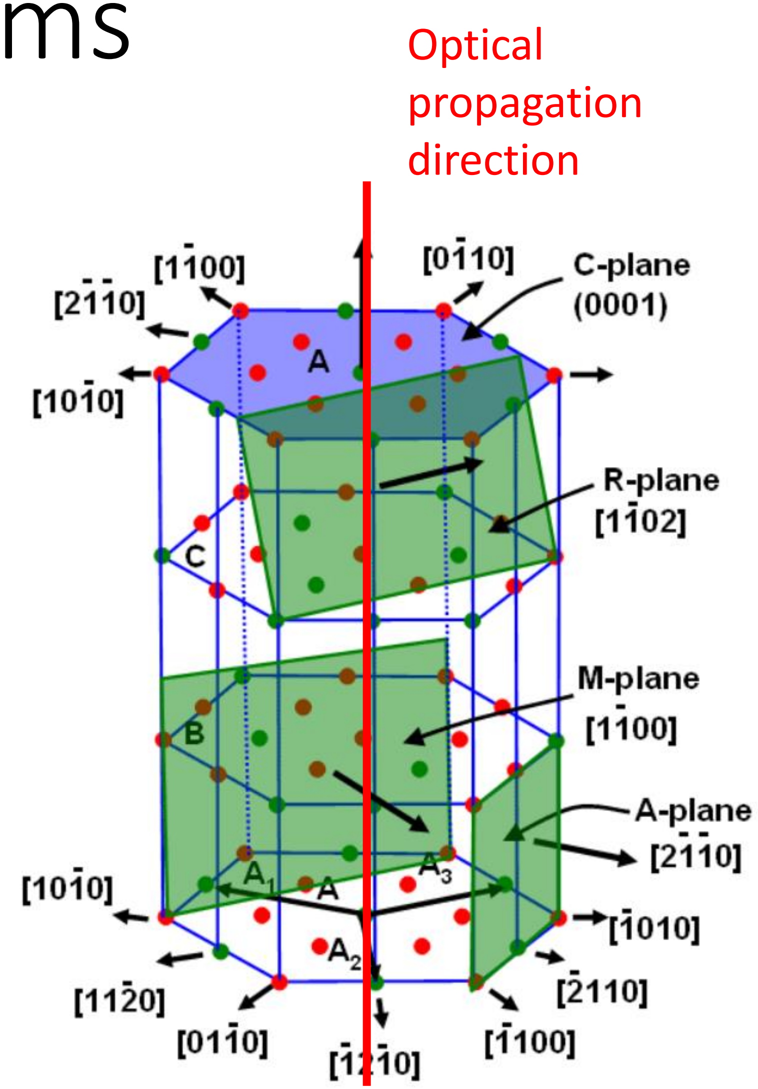
- Absorption:

  *well known problem from design phases*

- Birefringence:

  **partially unexpected problem**

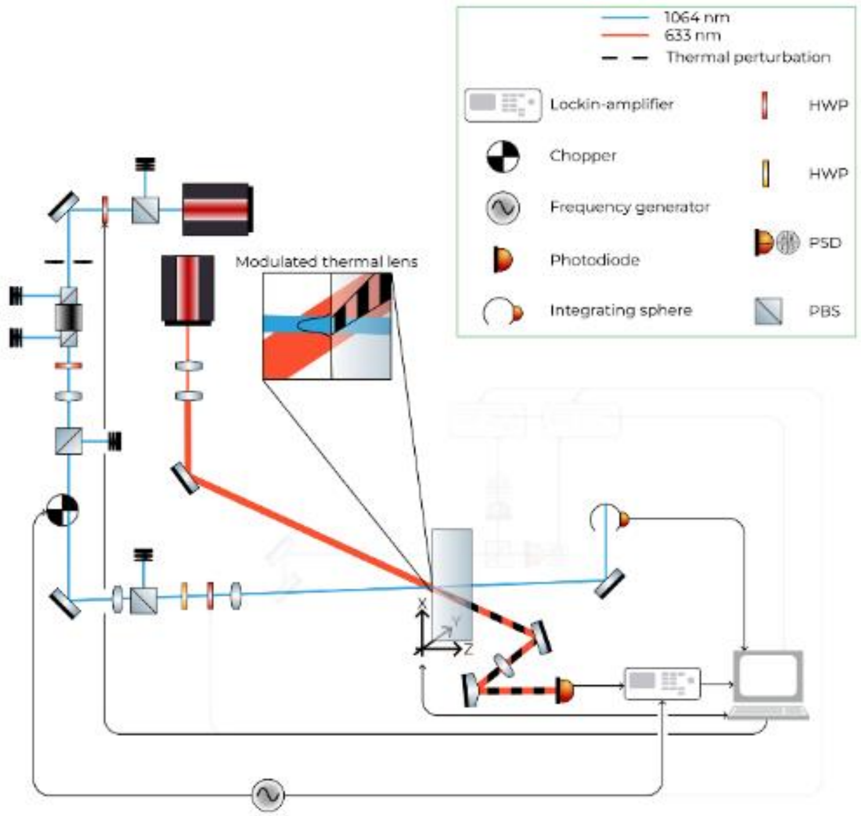
  (Strict requirement were placed on c-axis orientation)



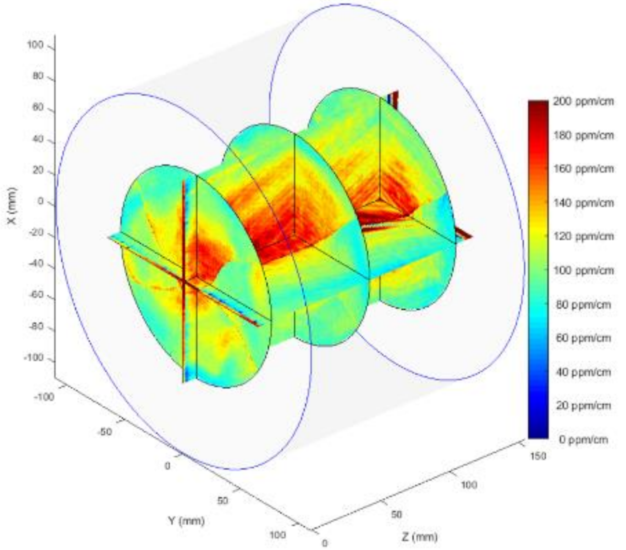
# Absorption measurement

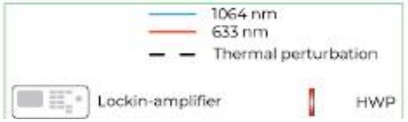
## Photo-thermal Common path Interferometry (PCI):

- Intensity modulated pump laser generates a modulated thermal lens that distorts part of the probe beam
- Absorption proportional to probe beam signal at modulation frequency
- Absorption measurement at 1064nm with sub-ppm resolution
- 3D spatial resolution
- Samples from 0.5 inch to 22cm diameter (up to KAGRA test-mass size)
- Cross-calibrated with CalTech, LMA and SPTS

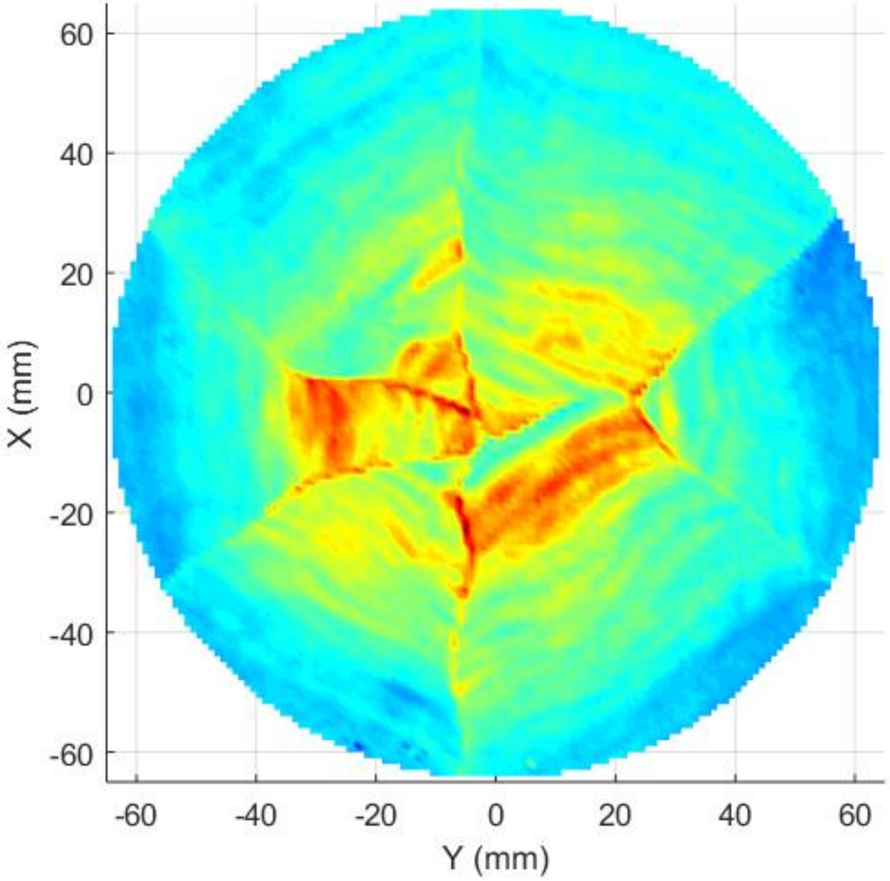


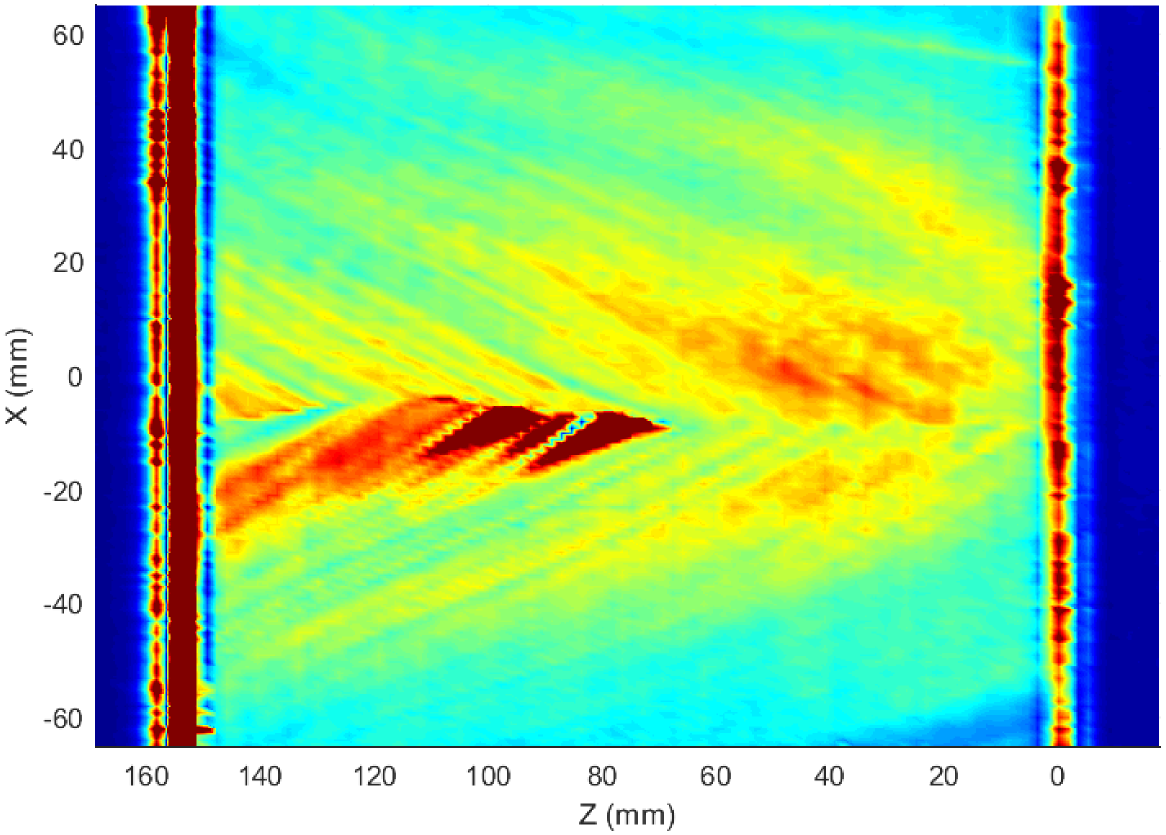

Manuel Marchio PhD thesis






# Absorption measurer



# Dislocation and optical absorption

Structural defects as preferential sites for the inclusion of absorbing centers

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**scientific** reports

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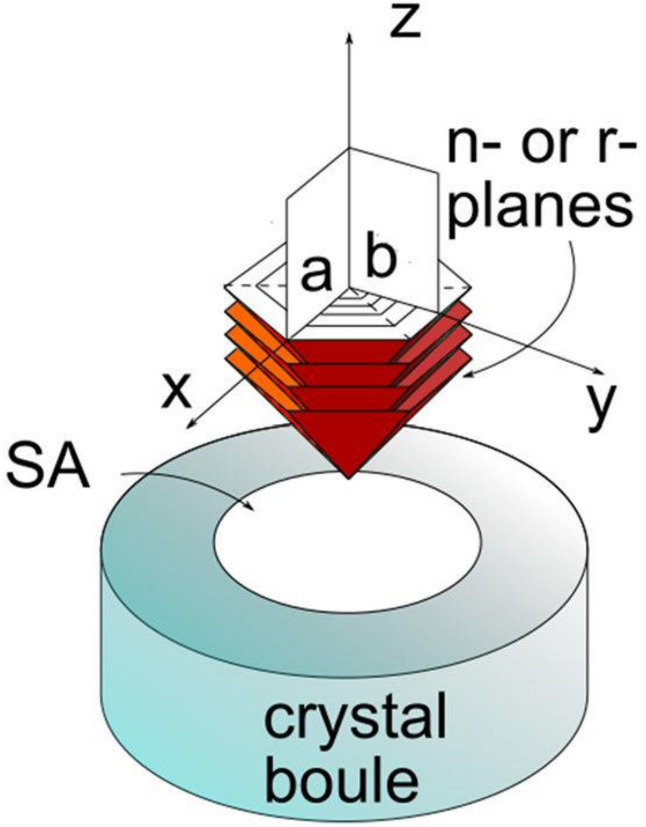
OPEN

## 3D characterization of low optical absorption structures in large crystalline sapphire substrates for gravitational wave detectors

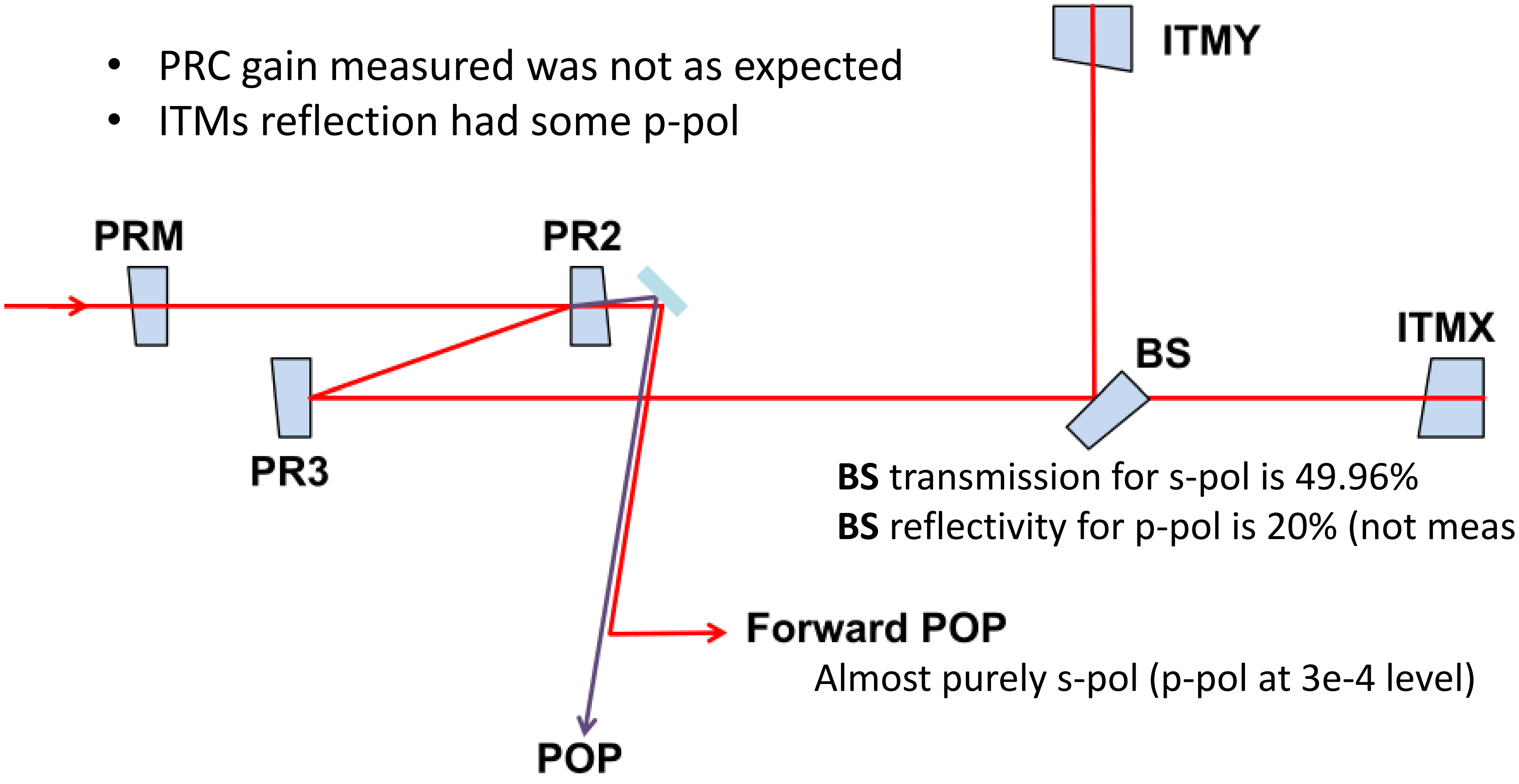
Manuel Marchiò[1,2], Matteo Leonardi[2], Marco Bazzan[3] & Raffaele Flaminio[2,4]




https://doi.org/10.1038/s41598-020-80313-1

# Discovery of birefringence in KAGRA

- PRC gain measured was not as expected
- ITMs reflection had some p-pol




**BS** transmission for s-pol is 49.96%
**BS** reflectivity for p-pol is 20% (not measured)

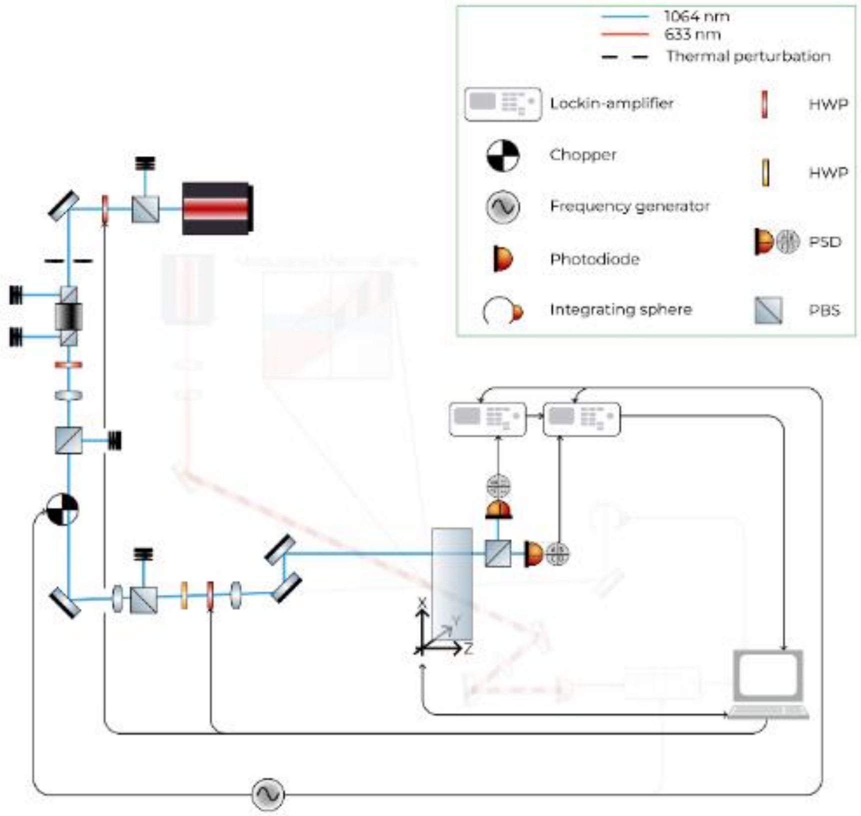
Forward POP: Almost purely s-pol (p-pol at 3e-4 level)

POP:
6.1 % p-pol from ITMX single bounce
10.8 % p-pol from ITMY single bounce

A portion of input light in s-pol is converted to p-pol.

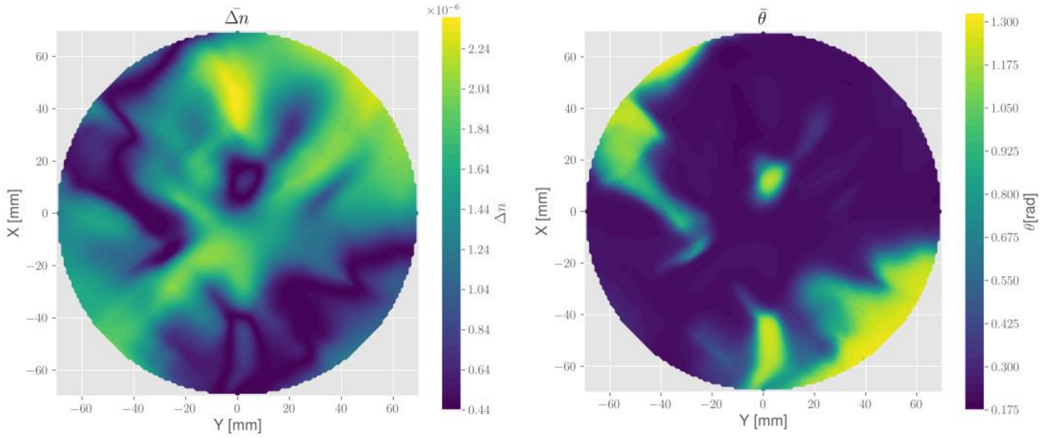
P-pol image observed in 2019

# Birefringence measurement



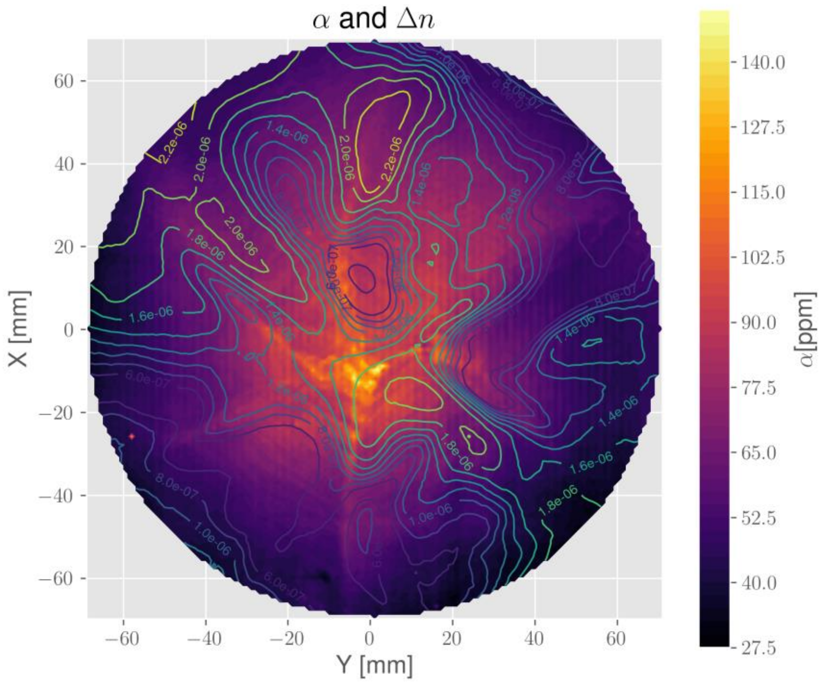

## Linear polarimetry:

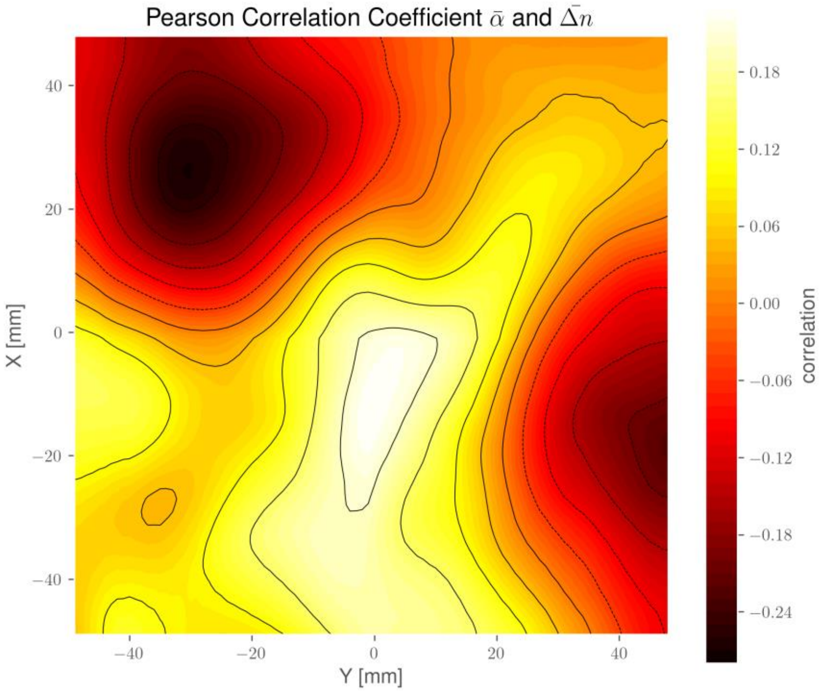
- Inject linear polarized light with various polarization angle and measure the transmitted s and p polarization
- Combining several measurements allow to reconstruct the sample birefringence
- Need at least two measurements to extract birefringence information (i.e. polarization rotation ($\theta$) and polarization retardation ($\Delta n$))
- Birefringence measurement at 1064nm with $2.10^{-9}$ resolution in $\Delta n$ for KAGRA size sample
- 2D spatial resolution (integrated along Z direction)



# Birefringence and absorption spatial correlation

$\Delta n_{RMS}$ is within original specs



# Birefringence and absorption spatial correlation

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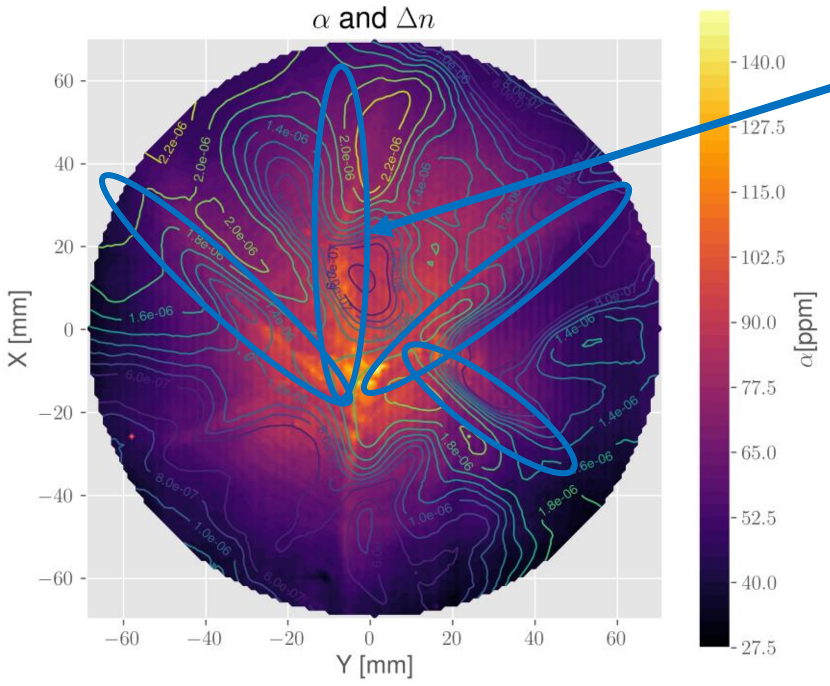
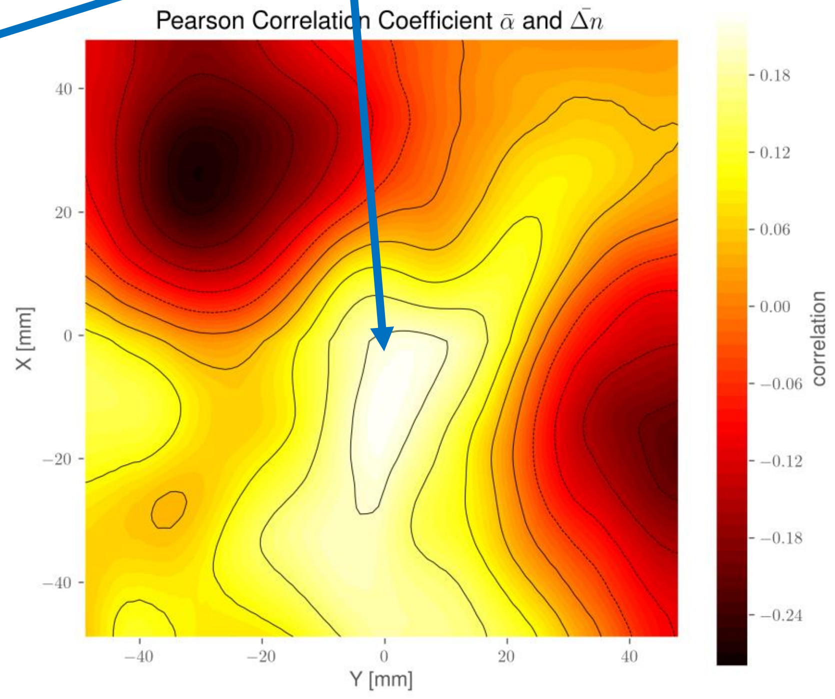
Correlation between absorption and internal stress leading to birefringence



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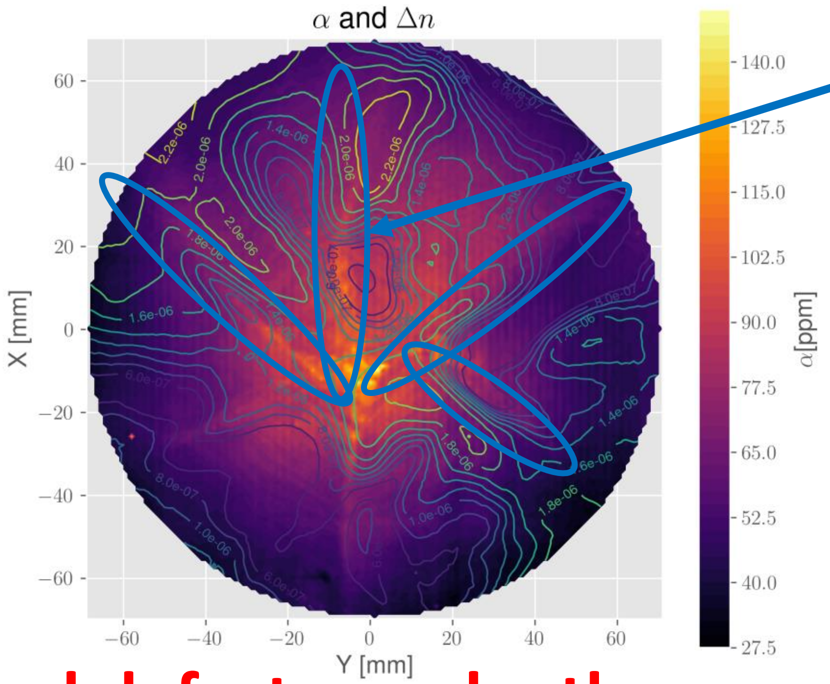
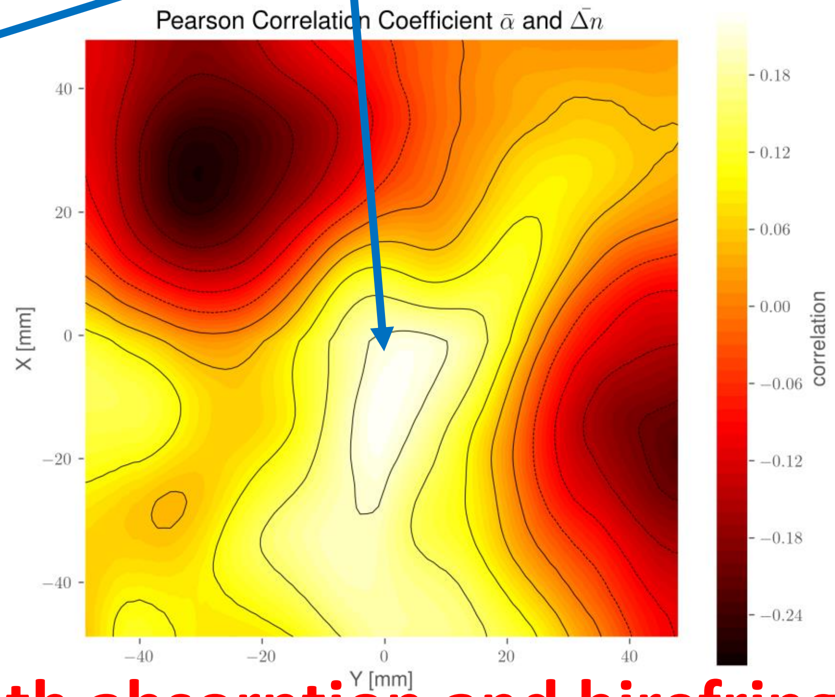


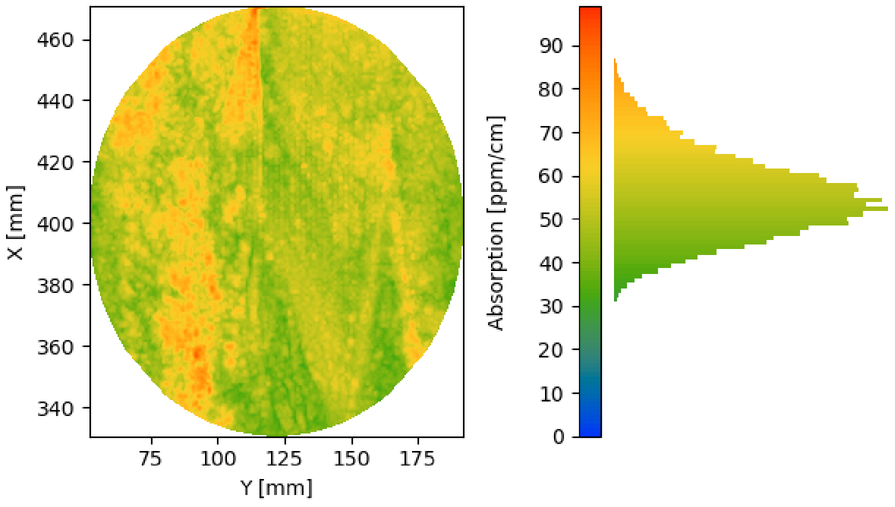




**Structural defects can be the cause of both absorption and birefringence***

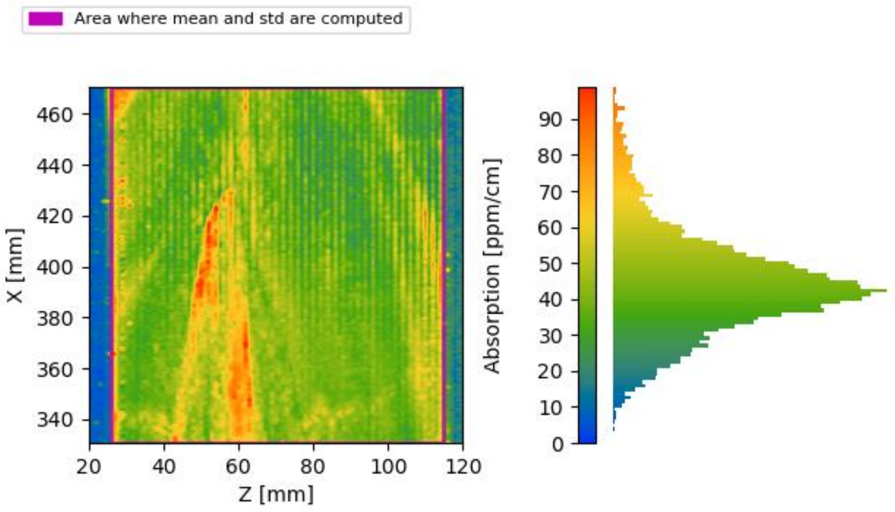
*Paper submitted to Scientific Reports.

# New KAGRA ITMs for O5

Using the characterization setup in NAOJ and thanks to the help from KASI, several substrates from old and new crystal manufacturers have been characterized… and we found 2 out of 10! (1 and a half really)




Incident power 7.673 W
at Z = 70.275mm, Mean absorption : (50.1 ± 8.46) ppm/cm

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# New

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KASI, se have
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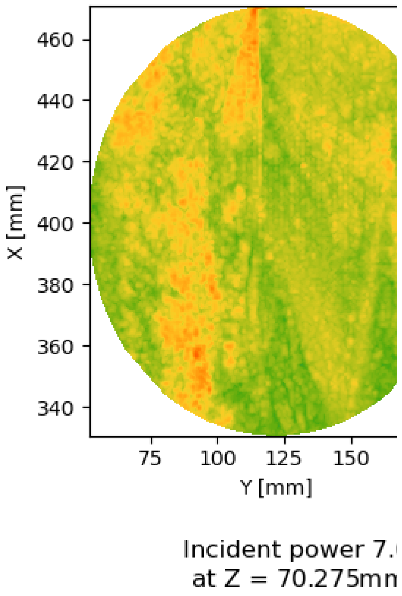


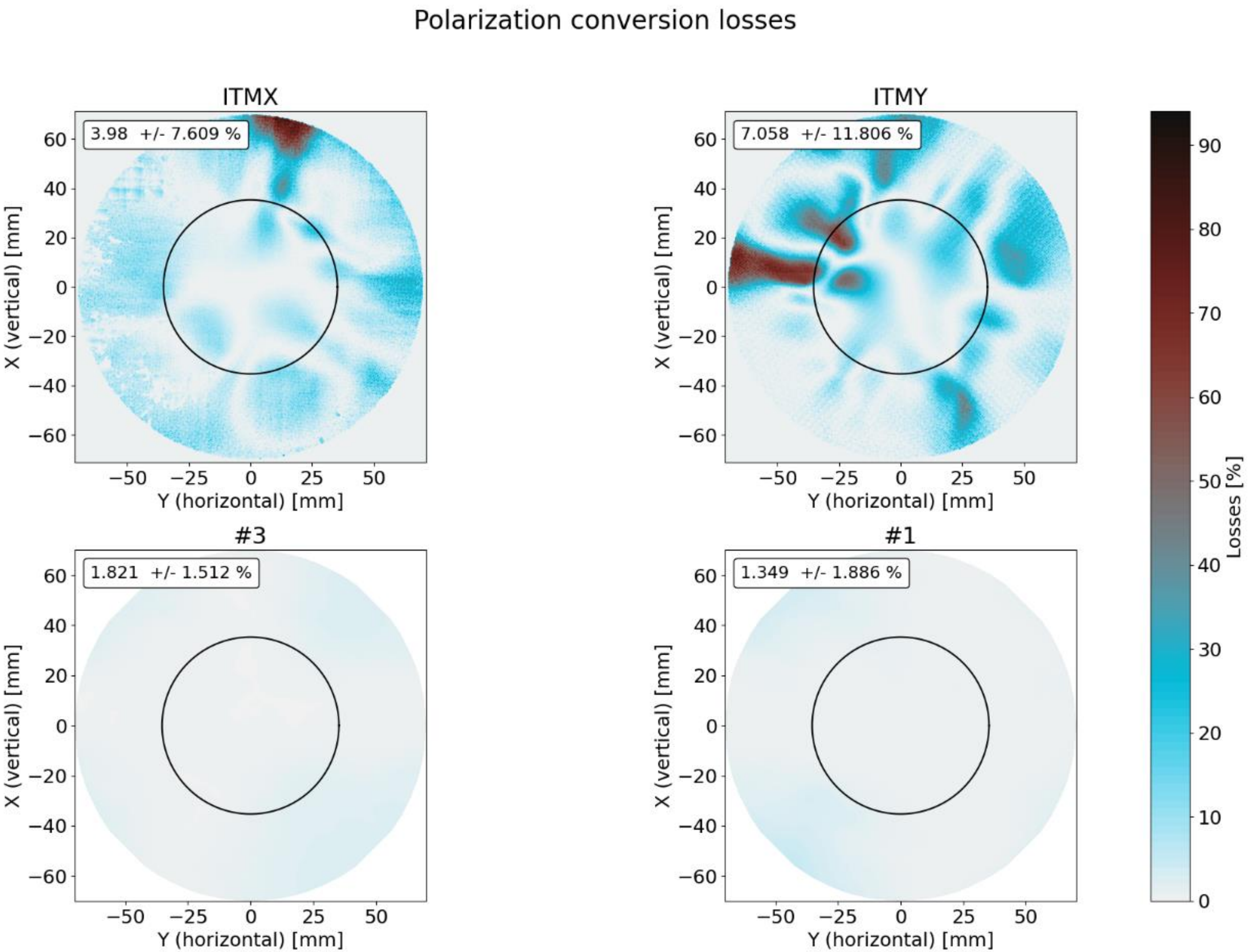

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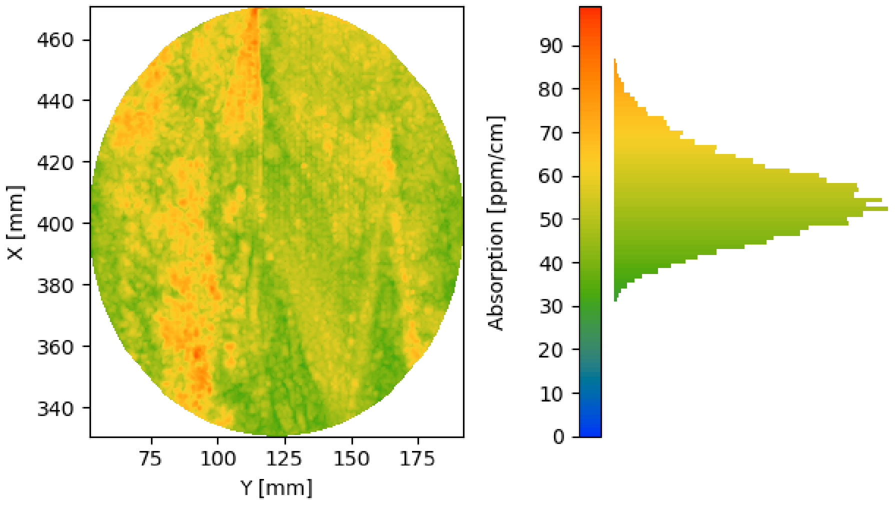


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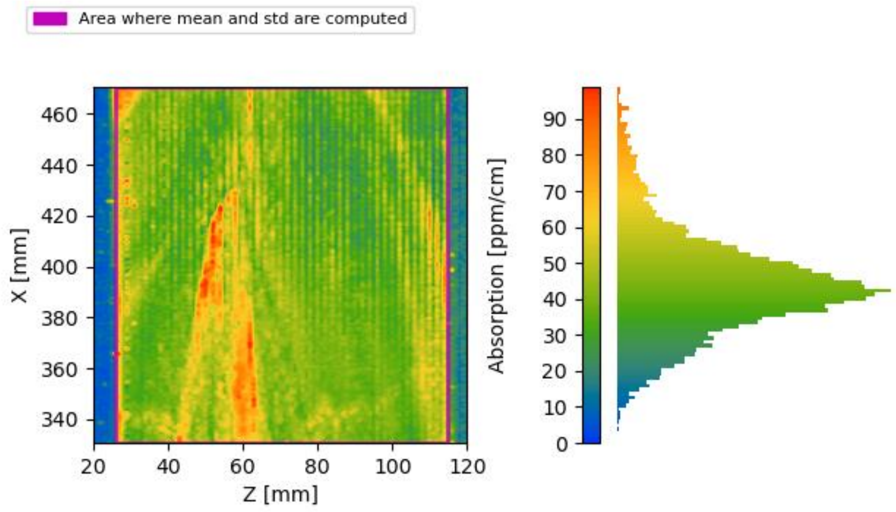



Mean absorption : (40.1 ± 13.49) ppm/cm

Shaping of new ITMs has been finished and prepolishing has started.

# Constructing birefringence from TWE

Slides from SIM meeting presented by Haoyu

$$\theta = -\frac{1}{2}\tan^{-1}\frac{TWE(45) - TWE(135)}{TWE(0) - TWE(90)}$$

$$\alpha_{-} = \frac{2\pi}{\lambda}\cdot\frac{TWE(0) - TWE(90)}{\cos 2\theta}$$

$\theta$ (angle between input polarization direction and e-axis) looks very random due to the inhomogeneity of sapphire substrate.

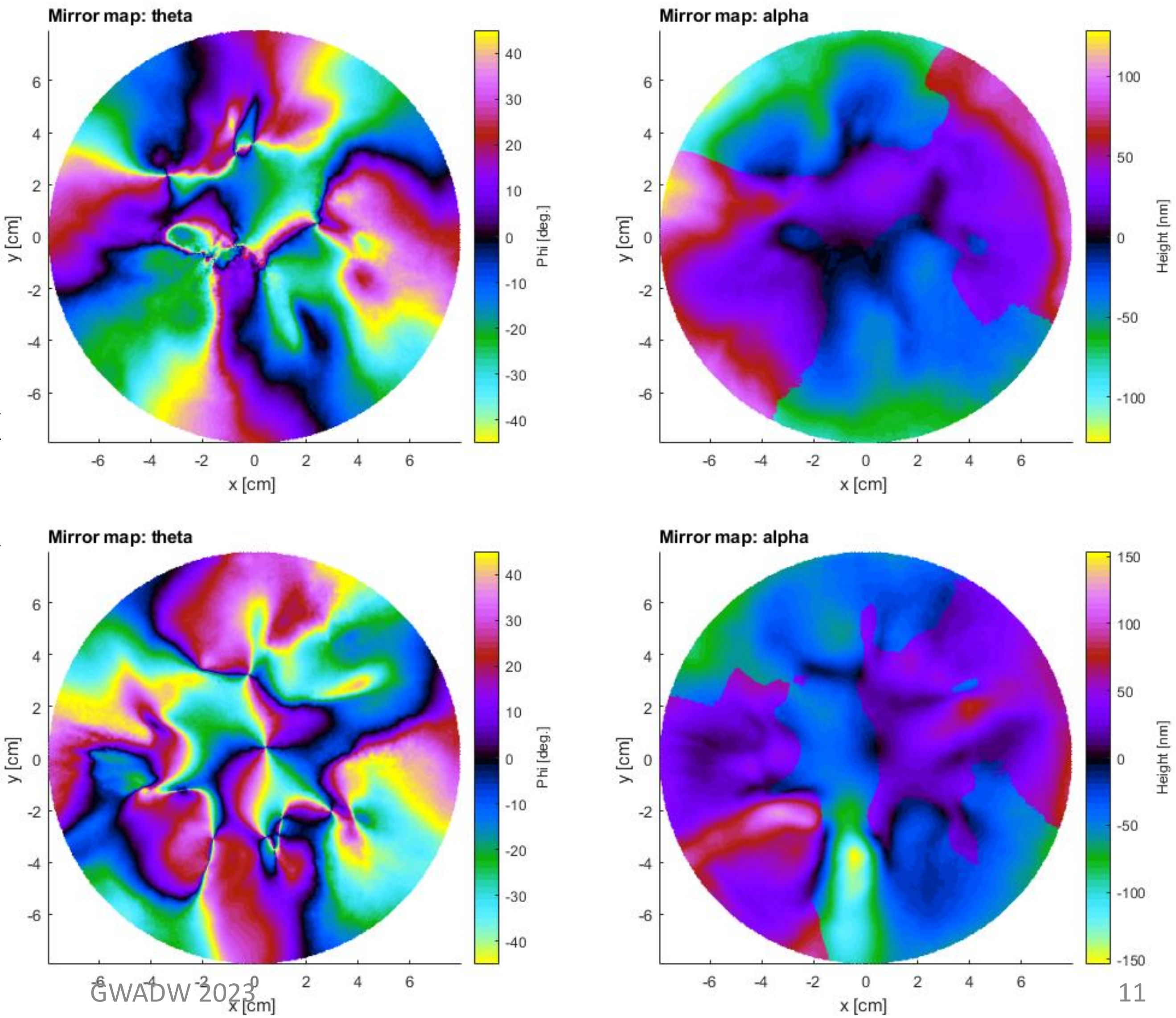
The PV value of $\alpha_{-}$ (one-way differential phase) is around ±150nm.

**There are many sharp features, which is bad.**

$\theta$ $\alpha_{-}$

ITMX

ITMY



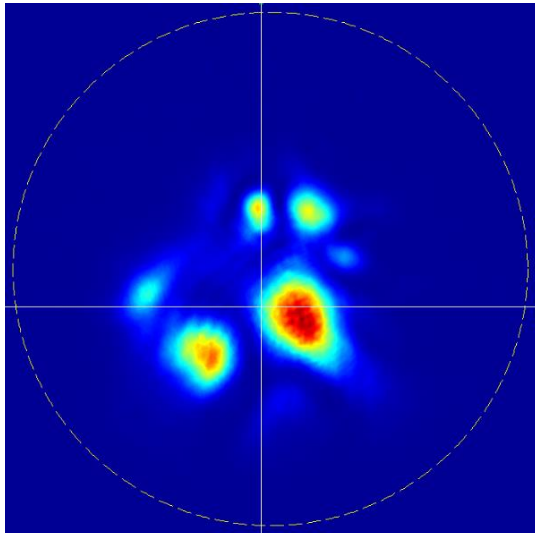
# ITMX single bounce

Slides from SIM meeting presented by Haoyu

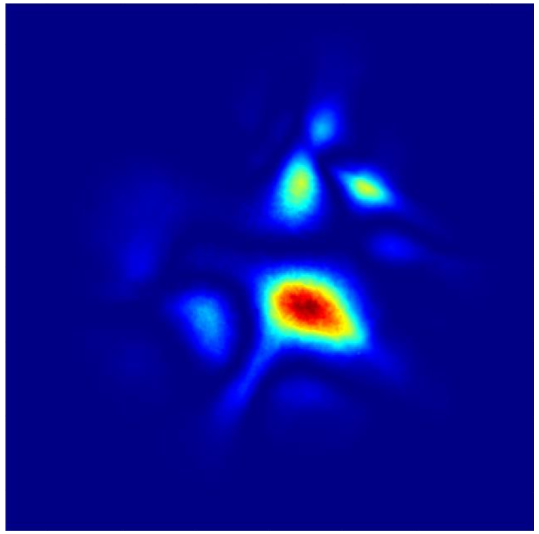
After careful calibrations for the TWE maps

P-pol shape

Measurement



Simulation

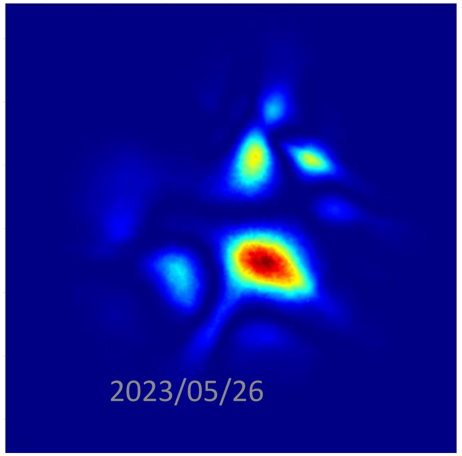


TEM00: <10%
1st mode: ~20%
2nd mode: ~10%
Higher order: >60%

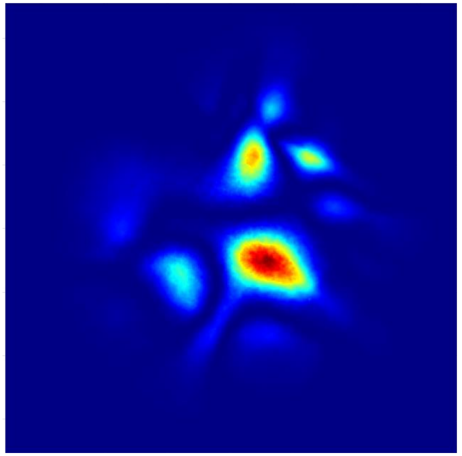
Calibration from rotation error of the 0° TWE map

One last thing, the 0° TWE map may be not measured at 0°.
If there are rotation errors (HR maps indicate the error is around 3°):

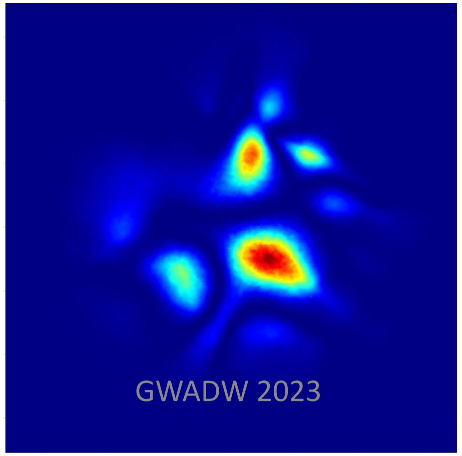
1°



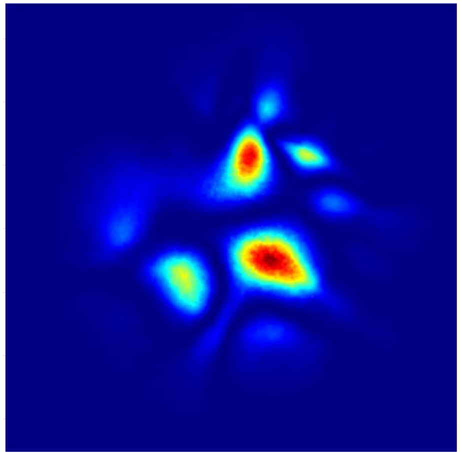
2°



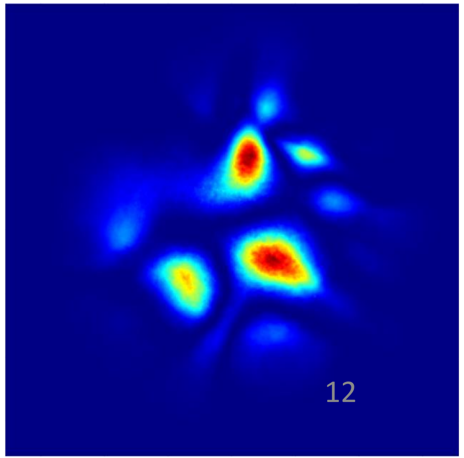
3°



4°



5°



# Summary

**Lessons for future detectors:**

- Testing real size substrates is crucial (but expensive)
  - Improving the testing facilities in speed as well as sensitivity is necessary -> see Marc Eisenmann's poster
- Developing a "birefringence-safe" ASC is preferable -> see Marc Eisenmann's poster

**Status of KAGRA's mirrors:**

- New ITMs have been selected and shaping process was finished
  - New ITMs will also improve the CMRR (due to simultaneous coating process)