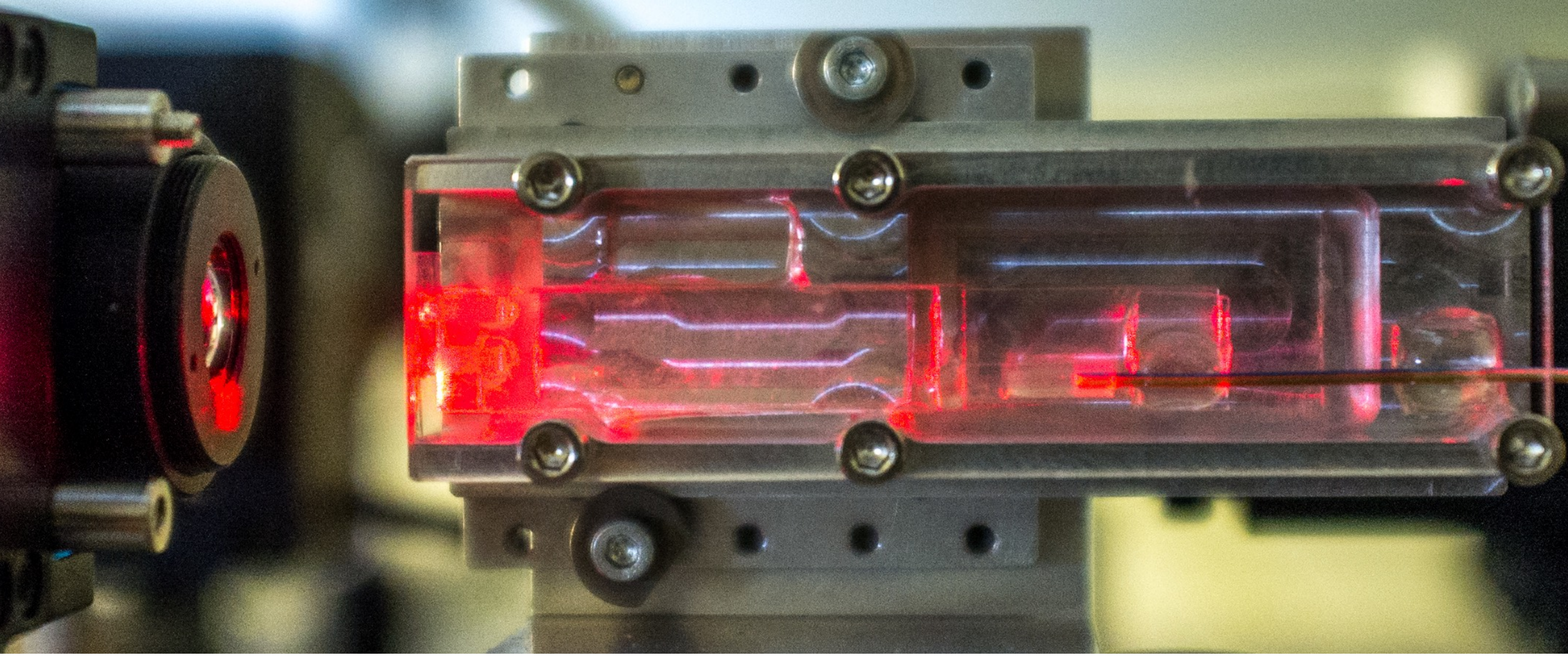

DRAGONFLY / GLINT

Nulling interferometry with direct-write integrated optics

THE UNIVERSITY OF SYDNEY

MACQUARIE University

AAO

University of Sydney

Barnaby Norris

Tiphaine Lagadec

Peter Tuthill

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Simon Gross

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Mick Withford

Australian Astronomical Observatory

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Jon Lawrence

and collaborators:

Nem Jovanovic (*Caltech*)

Julien Lozi (*Subaru Telescope*)

Olivier Guyon (*Subaru Telescope*)

Nick Cvetojevic (*Observatoire de Paris*)

Sylvestre Lacour (*Observatoire de Paris*)

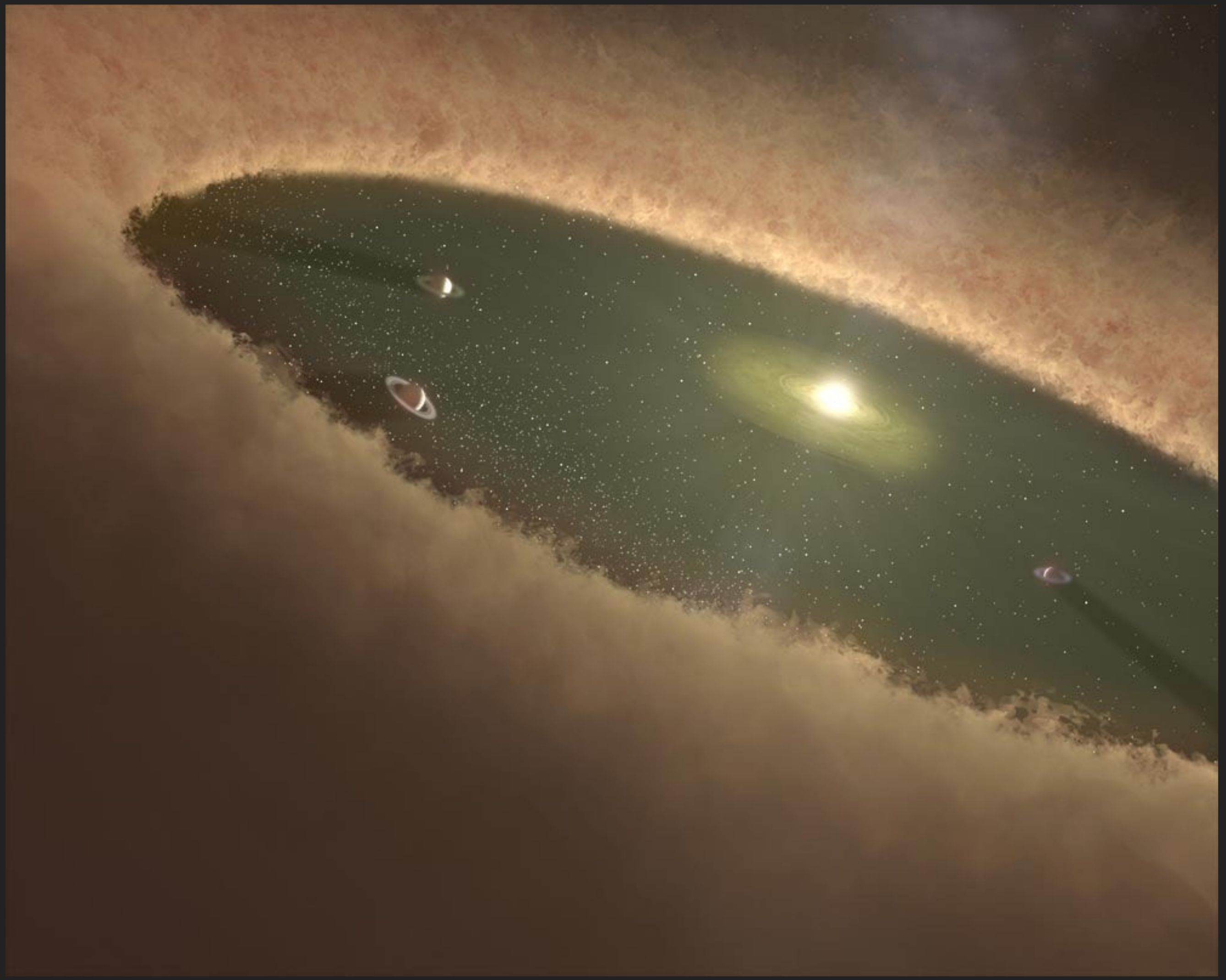
Takayuki Kotani (*NAOJ*)

OVERVIEW

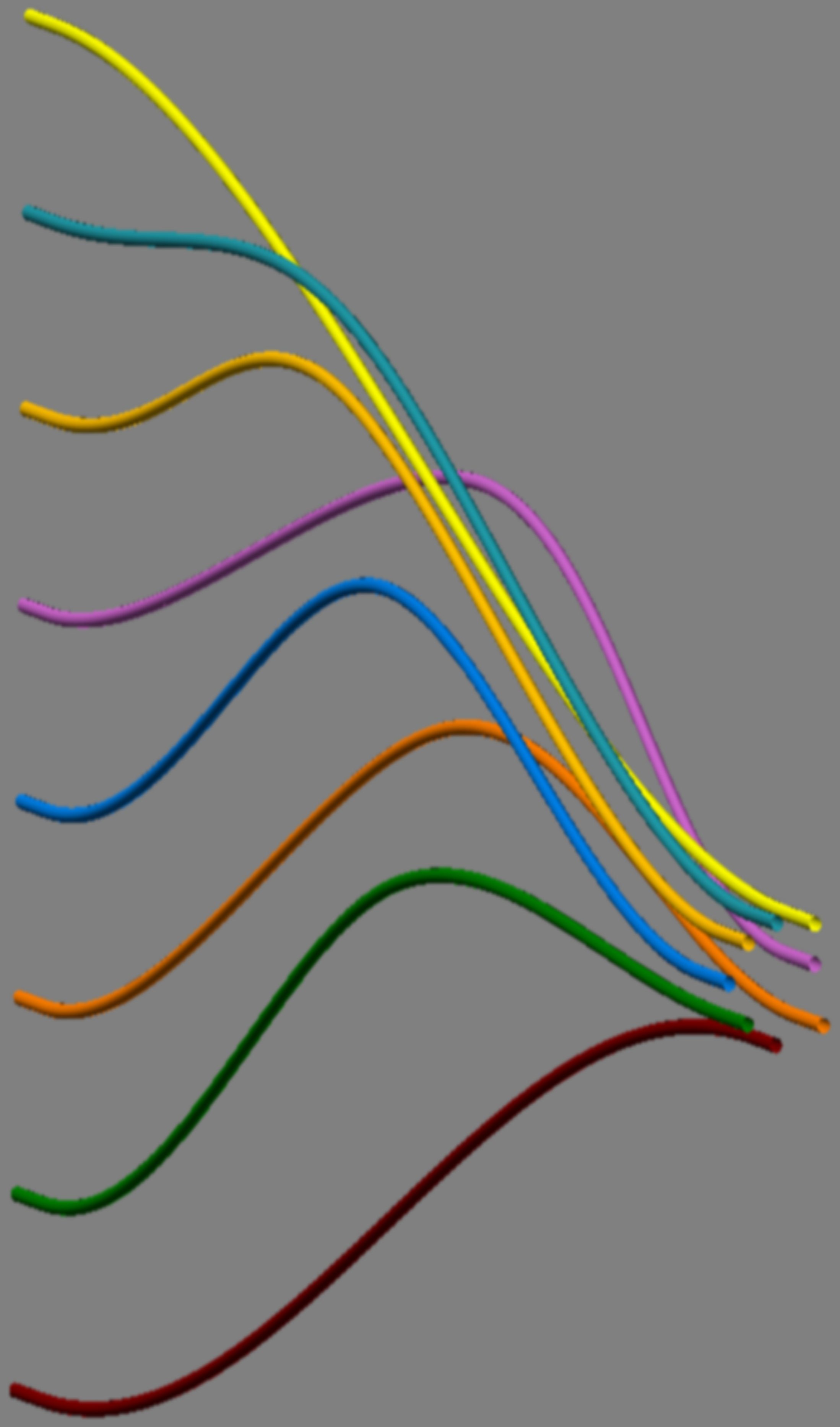
- The ‘classic’ Dragonfly Project
  - Integrated photonic pupil remapping using ULI
  - Hybrid 3D-2D architecture, closure phases and visibilities
- GLINT integrated nuller
  - ULI integrated pupil remapper and nulling interferometer
- To the MIR

KEY SCIENCE GOAL: UNDERSTANDING PLANET FORMATION

- Protoplanetary disks - map image dust, gaps, density perturbations, …
- Direct imaging of hot, young exoplanets
- Exozodi studies
- Stellar astrophysics



http://www.jpl.nasa.gov/news/news.php?feature=927

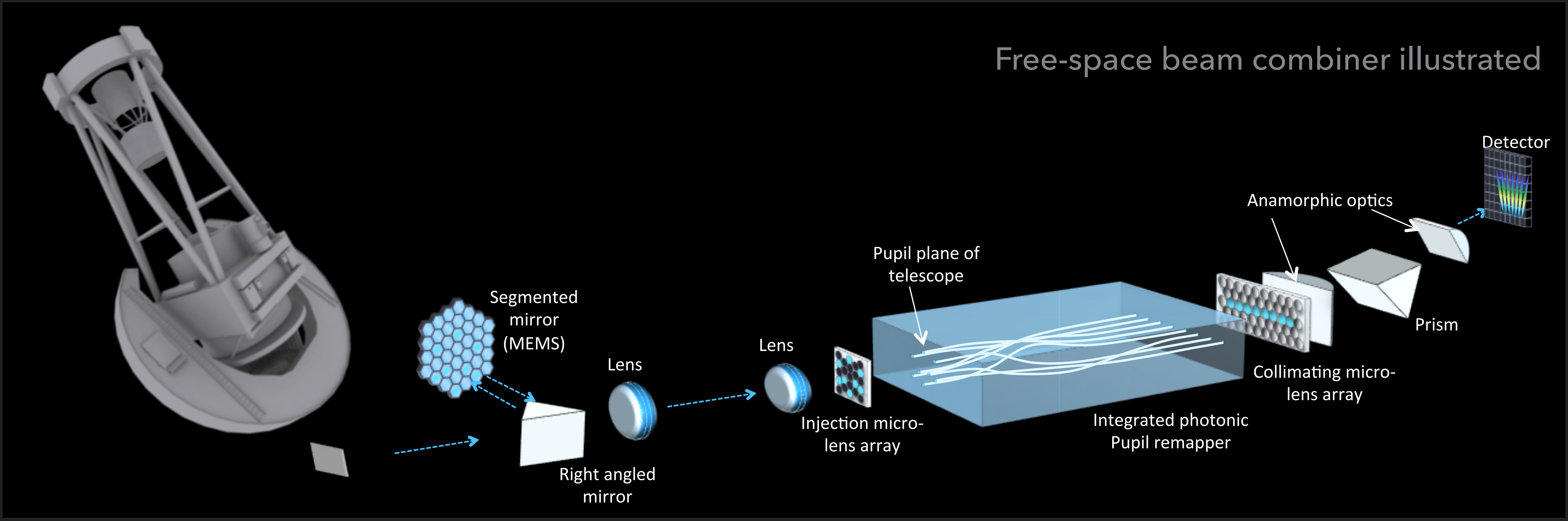


PART 1 – PUPIL REMAPPING INTERFEROMETRY

Efficiently re-map 2D telescope pupil to linear SM waveguide array, while maintaining coherence

'CLASSIC' DRAGONFLY: PHOTONIC PUPIL REMAPPER

compare to Non Redundant Masking (aka Sparse Aperture Masking)

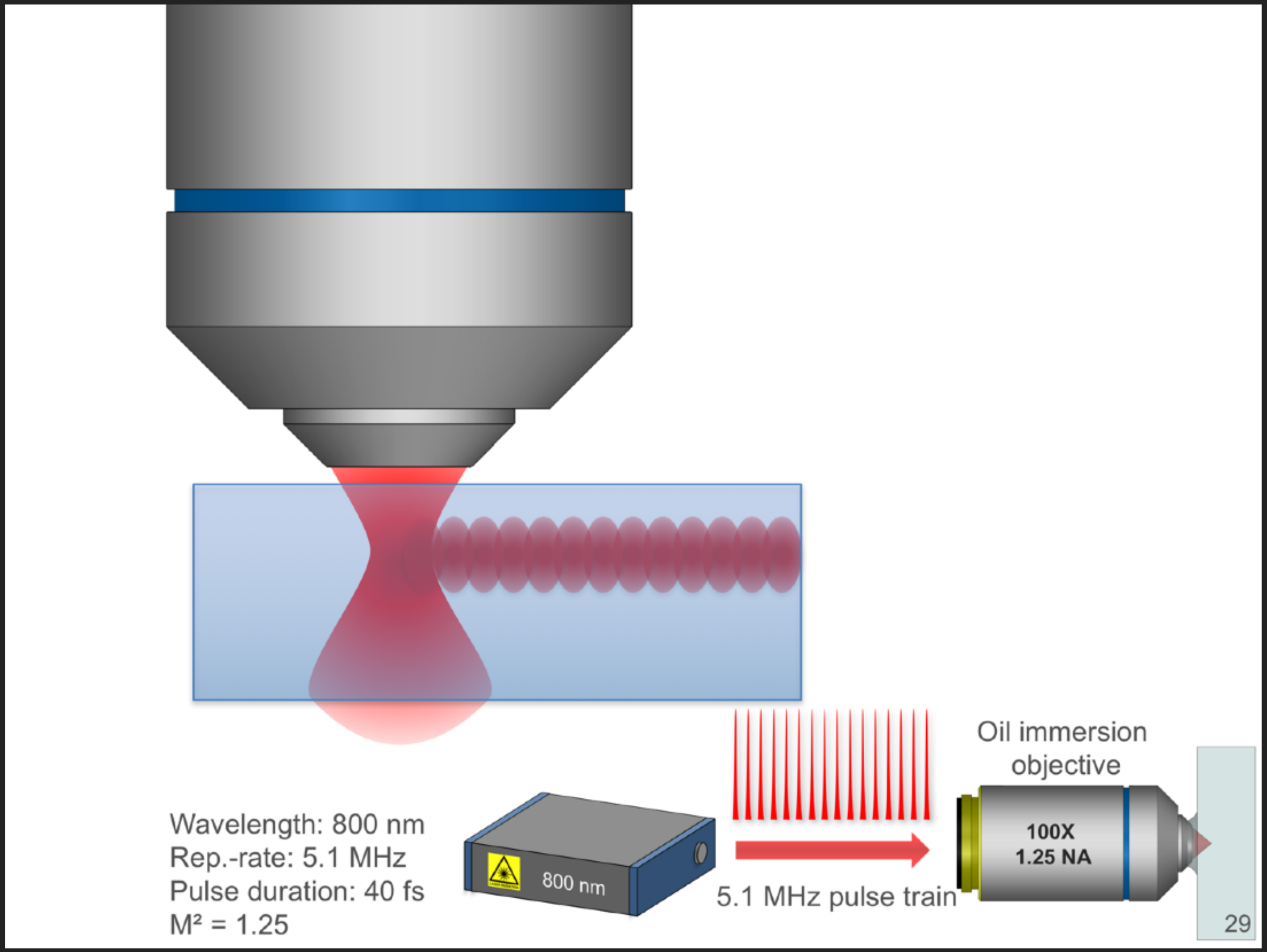


Photonic pupil remapper (NIR) - Remaps arbitrary 2D pattern into 1D

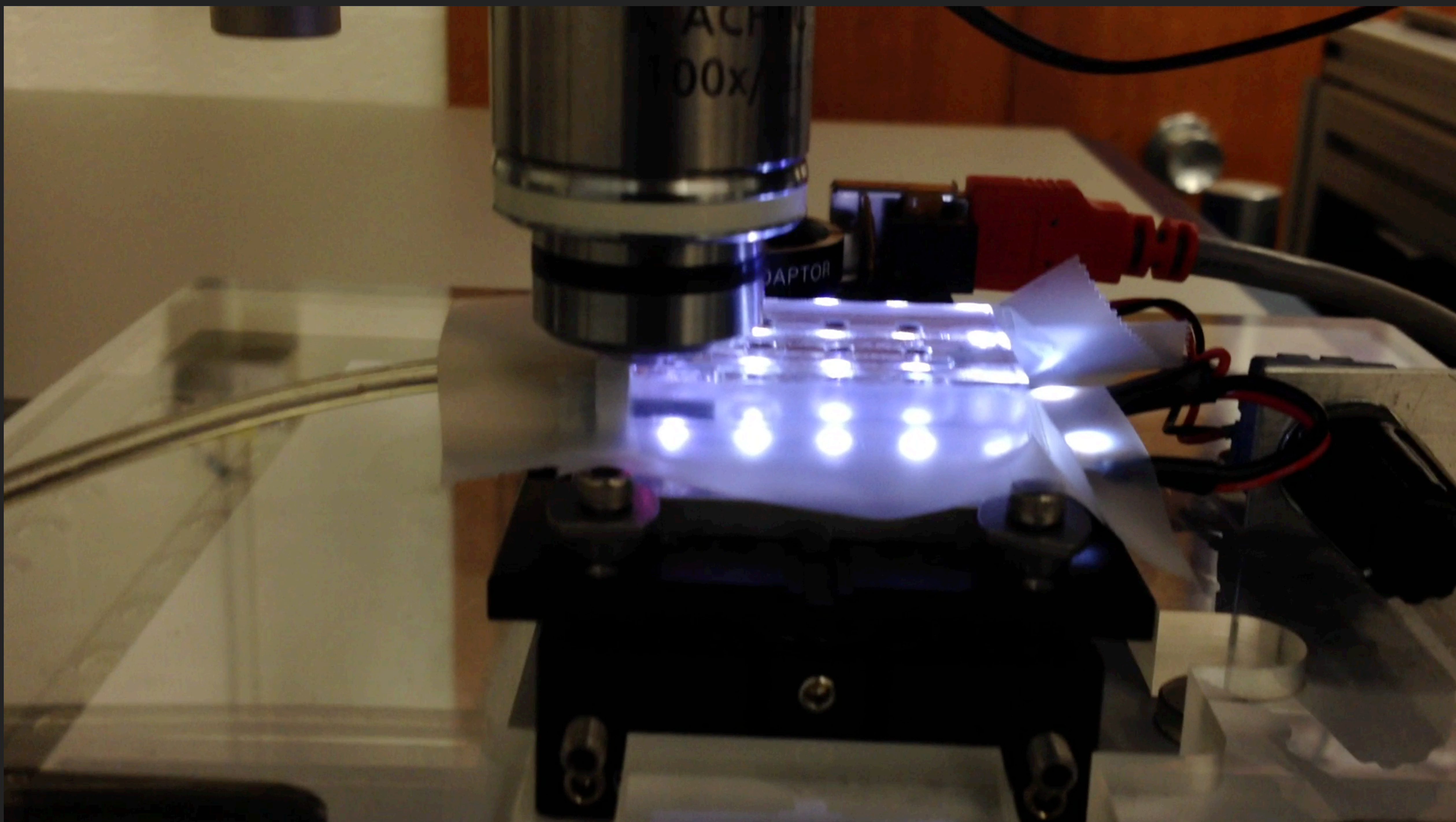
- Redundant (full pupil coverage) → non-redundant
- 1D → can be spectrally dispersed
- <u>Single-mode waveguides</u> → flat phase across "sub-aperture"

THE PHOTONIC PUPIL REMAPPER

- Waveguides directly written into glass using tightly focused femtosecond laser - 'direct write' (aka 'ultrafast laser inscription')
- Chemical structure modified, positive change in index
- Translating glass allows waveguides to be written in 3 dimensions
- Must be path-length matched to <1 micron. **Photonic chip provides necessary stability**

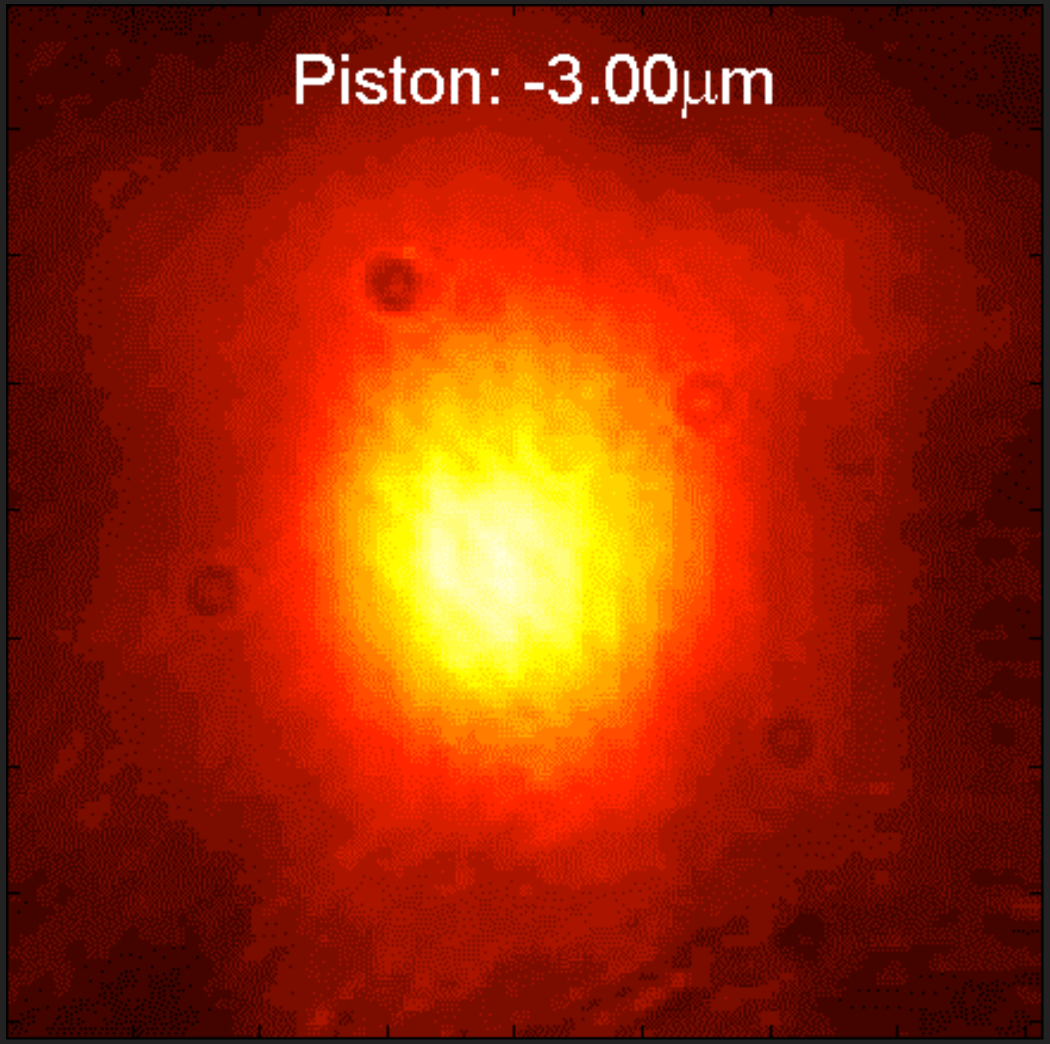


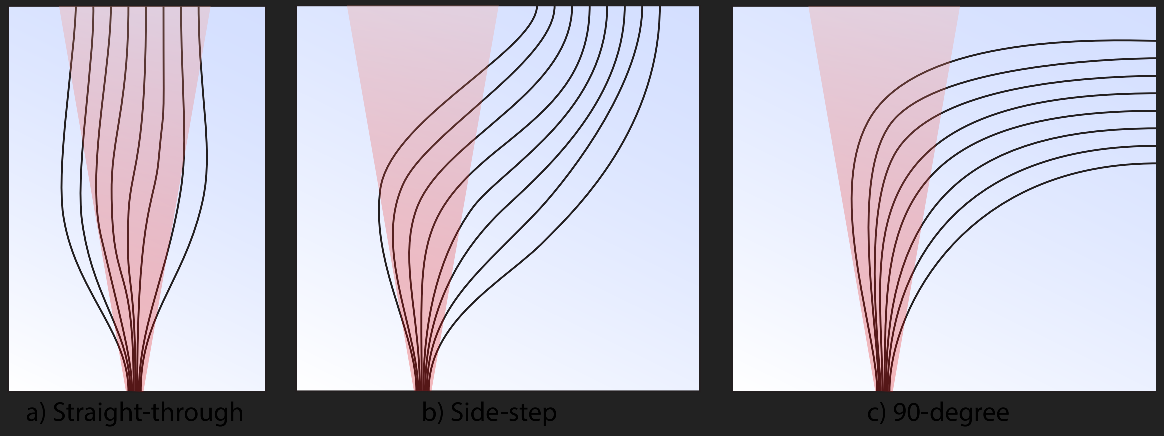
THE PHOTONIC PUPIL REMAPPER



IMPACT OF STRAY LIGHT

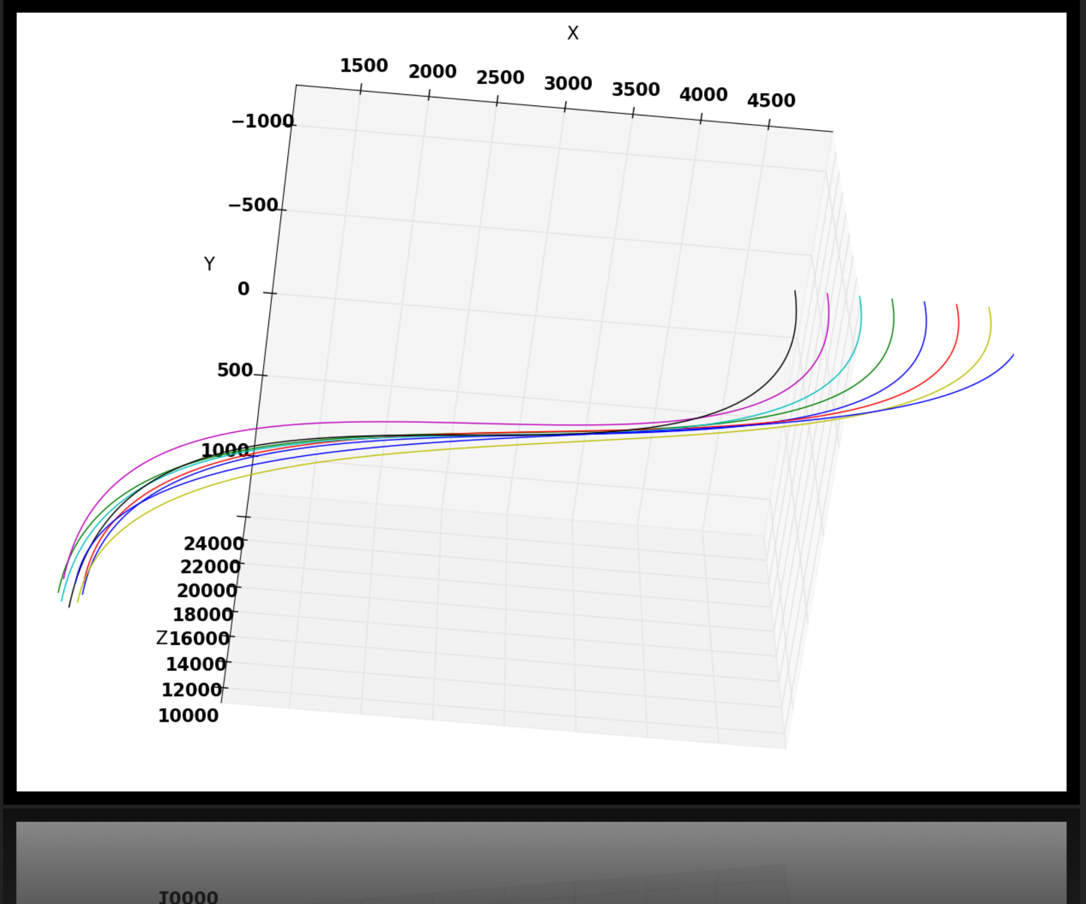
- Un-coupled light propagates through bulk and interferes at output face - reduce CP precision (at least in free-space beam combination)





WAVEGUIDE DESIGN

- Arbitrary 3D geometry, but strict design requirements:
  - Path-length matched (<< micron)
  - Bend radii limit ~ 25 mm
  - Min proximity ~30 um

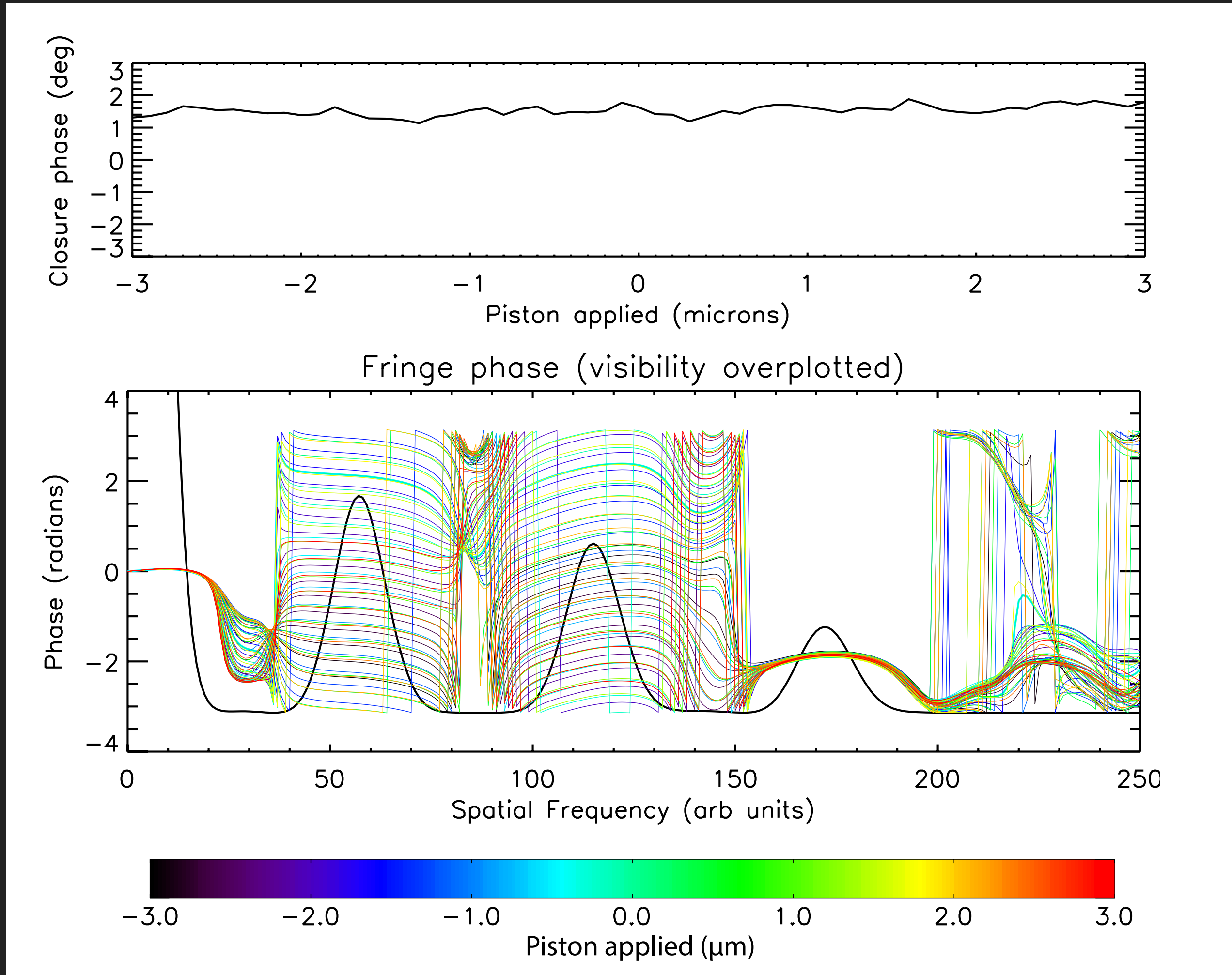


- Waveguide optimisation code
  - Parameterise each waveguide as set of 3D cubic Bezier curves
  - Cost function derived from length matching, ROC, write depth, proximity (exp. weighted), …
  - Deploy global and local optimisers
  - -> Produce G-code for writing stages

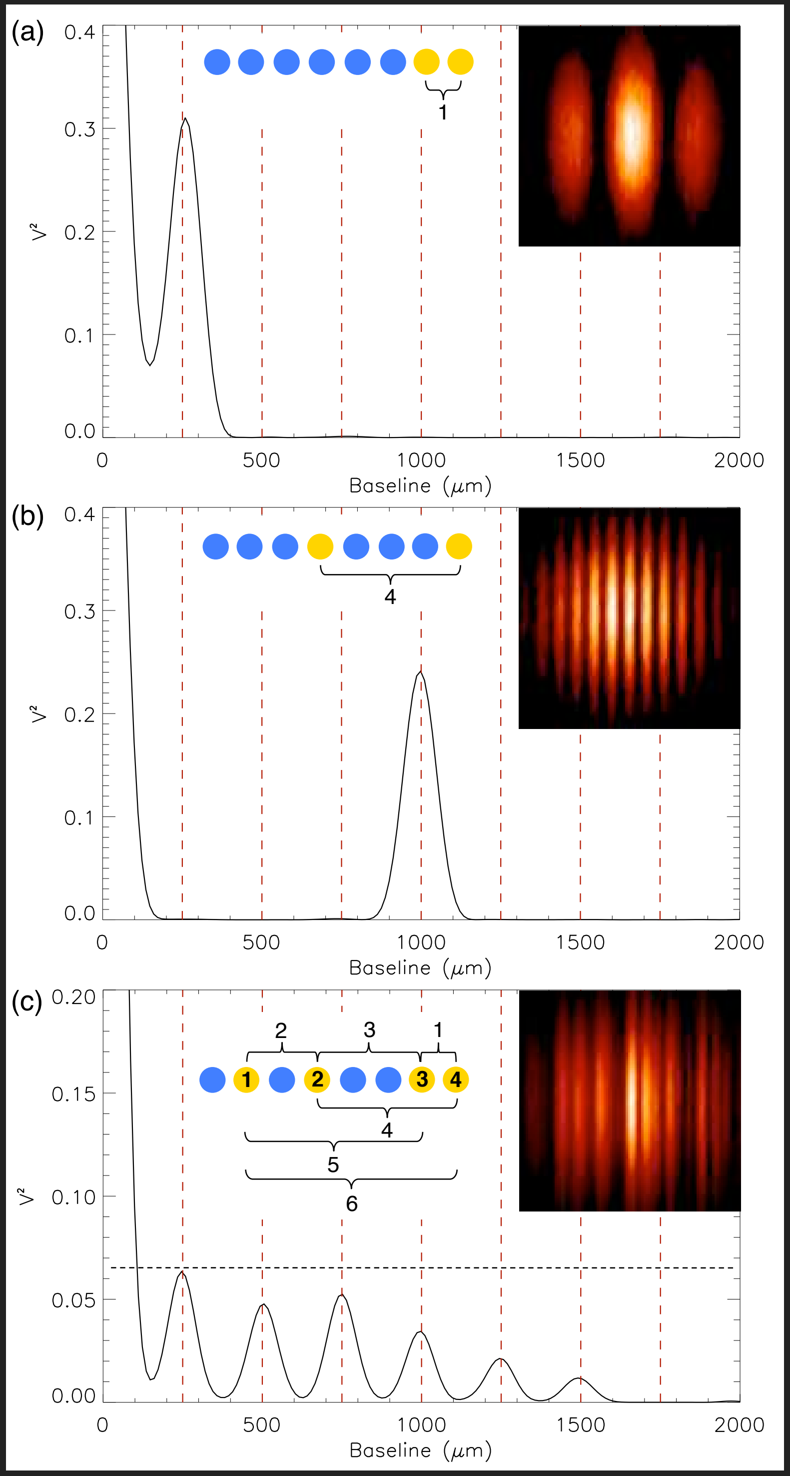
(Lagadec et al. 2017 in prep.)

FREE-SPACE BEAM COMBINATION

- Map pupil to linear non-redundant output
  - Simple, easy spectral dispersion, effective
  - But limited to ~< 9 wgs, no separate photometry

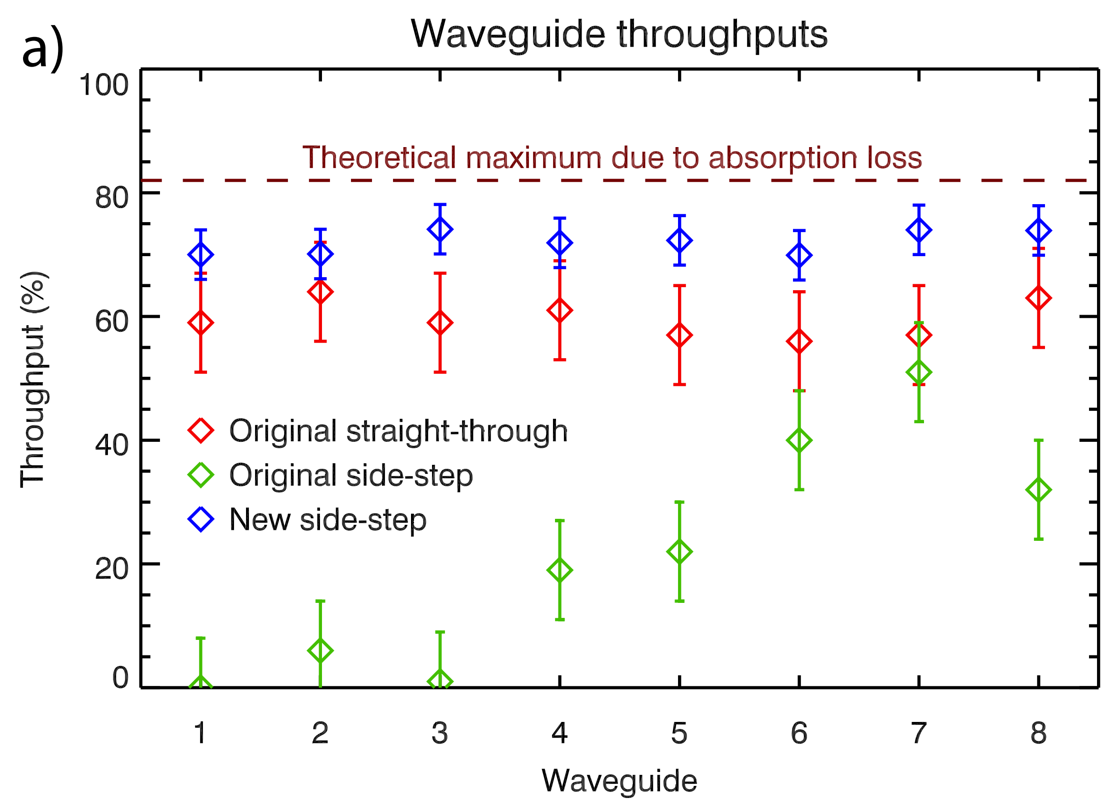


$\sigma_{CP} = 0.22°$



FREE-SPACE VERSION - PERFORMANCE

- Residual stress -> high bend-loss
  - Address with thermal annealing



Throughputs for side-step design previously shown

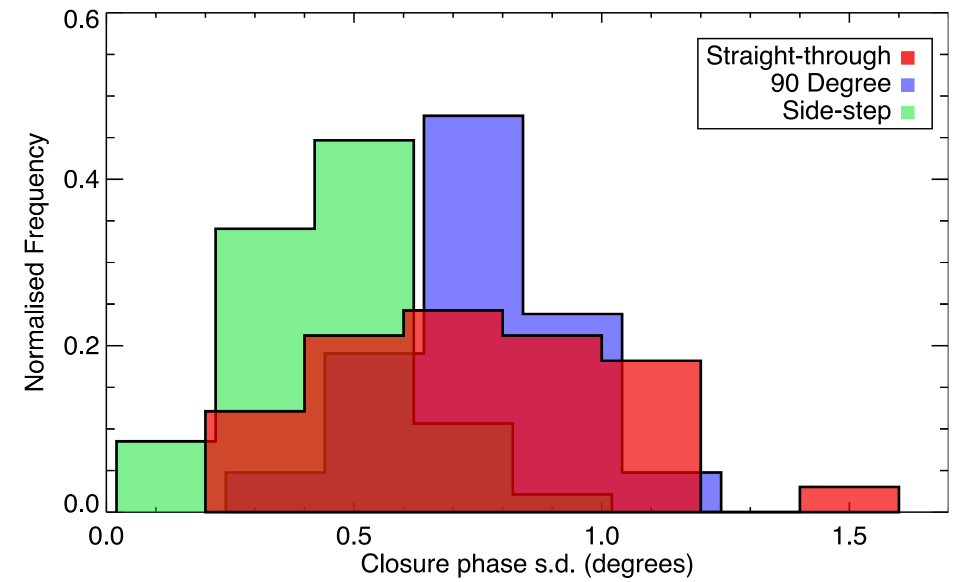
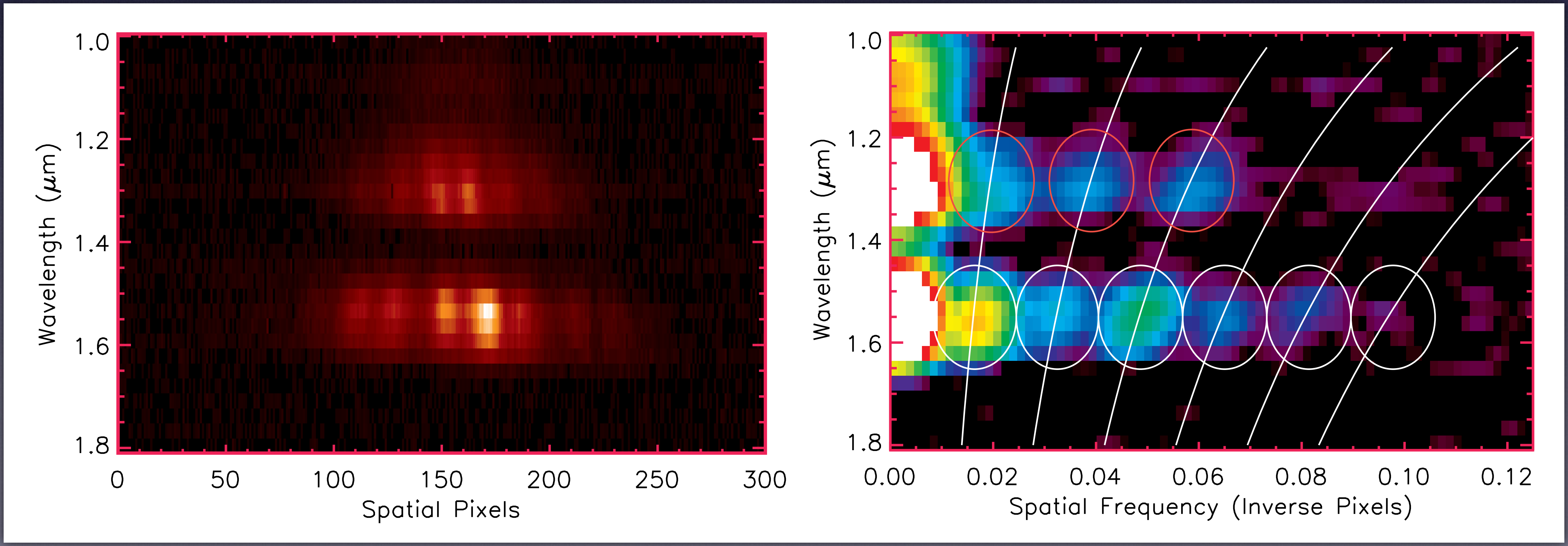


Fig. 10. A histogram showing the distribution of σ_{CP} when the pupil-remapper and microlens-array are subjected to repeated realignments. The frequencies have been normalized such that the integral of each histogram is unity.

On-sky Performance

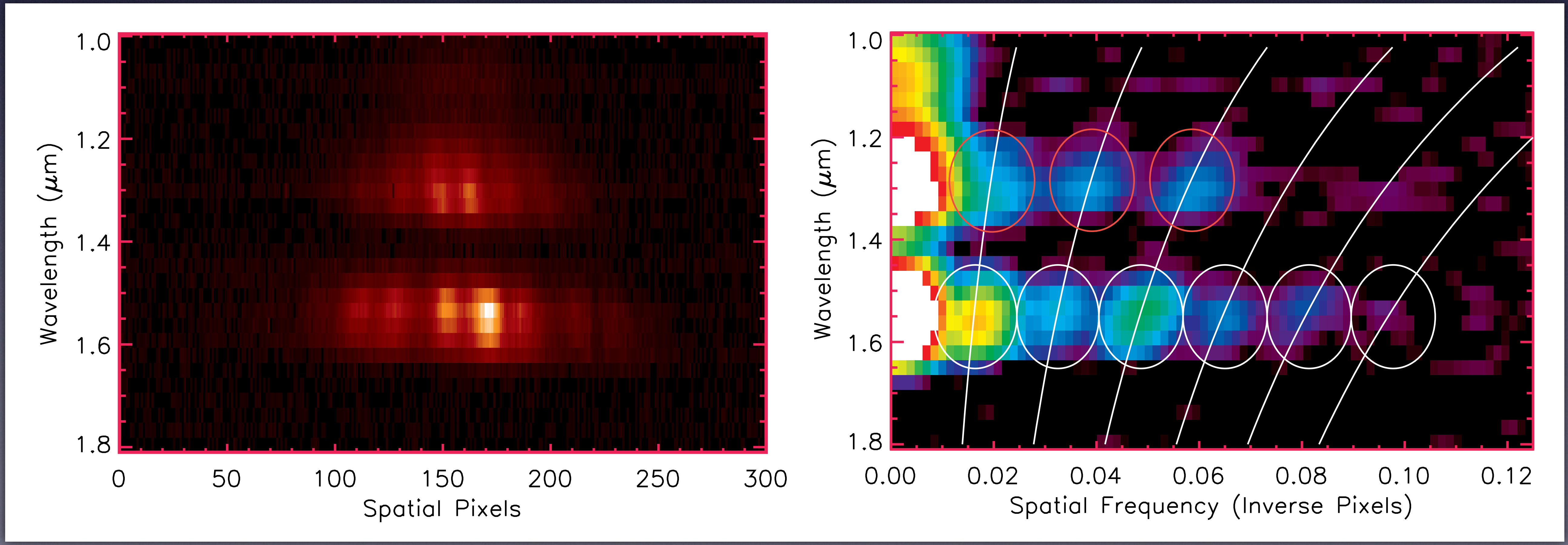
- 20th-21st May 2011 at AAT - r_0 1.8 arcsec, t_0 30ms at H
- r_0 2.5x greater than projected sub-aperture - large WF error across sub-ap, - poor coupling
- t_{int} (200ms) >> t_0 - low system visibility



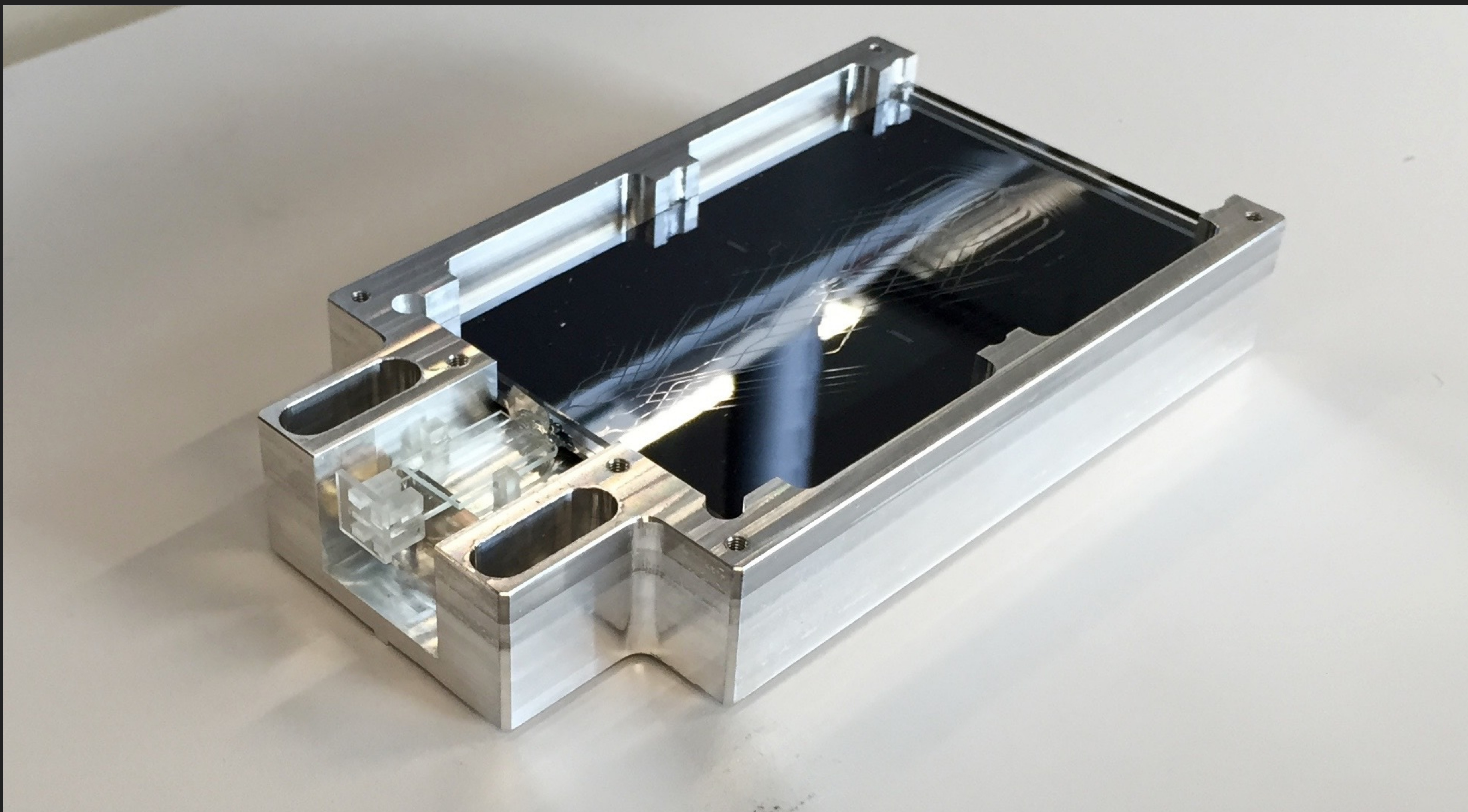
On-sky Performance

	On-sky measured	Ideal prediction (numerical model)
System visibility	0.36	0.39
Closure phase	0° ± 5° (SEM)	0° ± 4° (SEM)

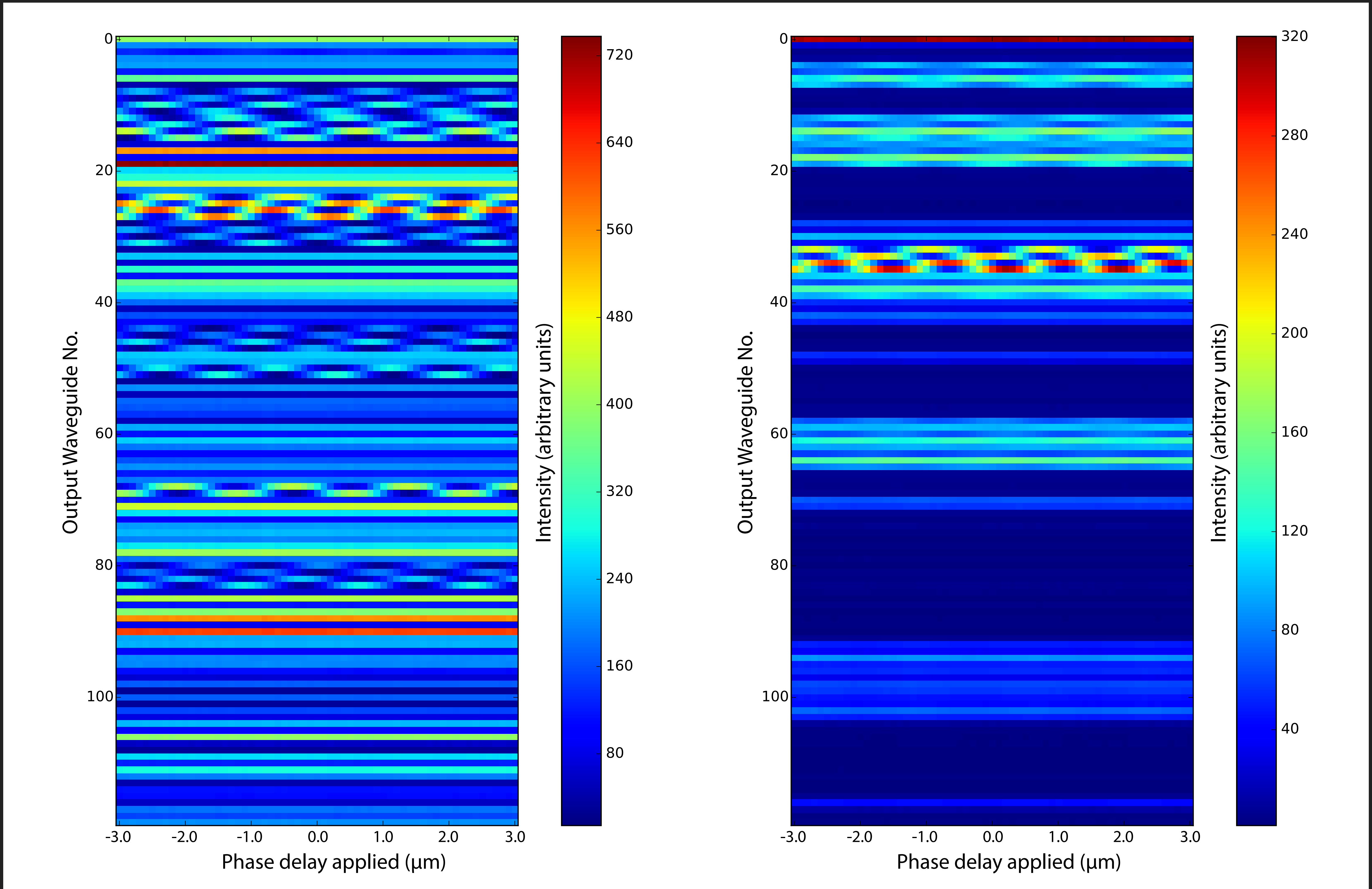
On-sky results consistent with lab when seeing taken into account.



HYBRID BEAM COMBINATION

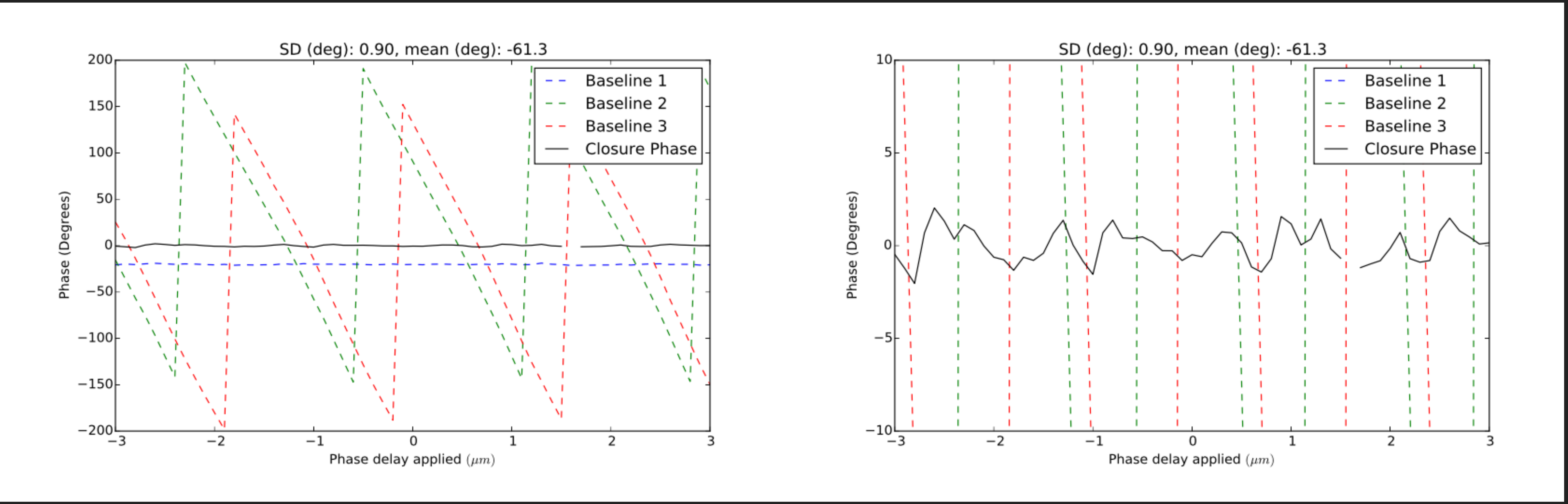


BEAM COMBINATION - ANALYSIS



BEAM COMBINATION - ANALYSIS

- **Instantaneous** (not temporally modulated) measurement
  - Originally limitation of slow detector, works well
- Test worst-case CP precision by postponing through >2π rad
  - CP standard deviation < 1 degree



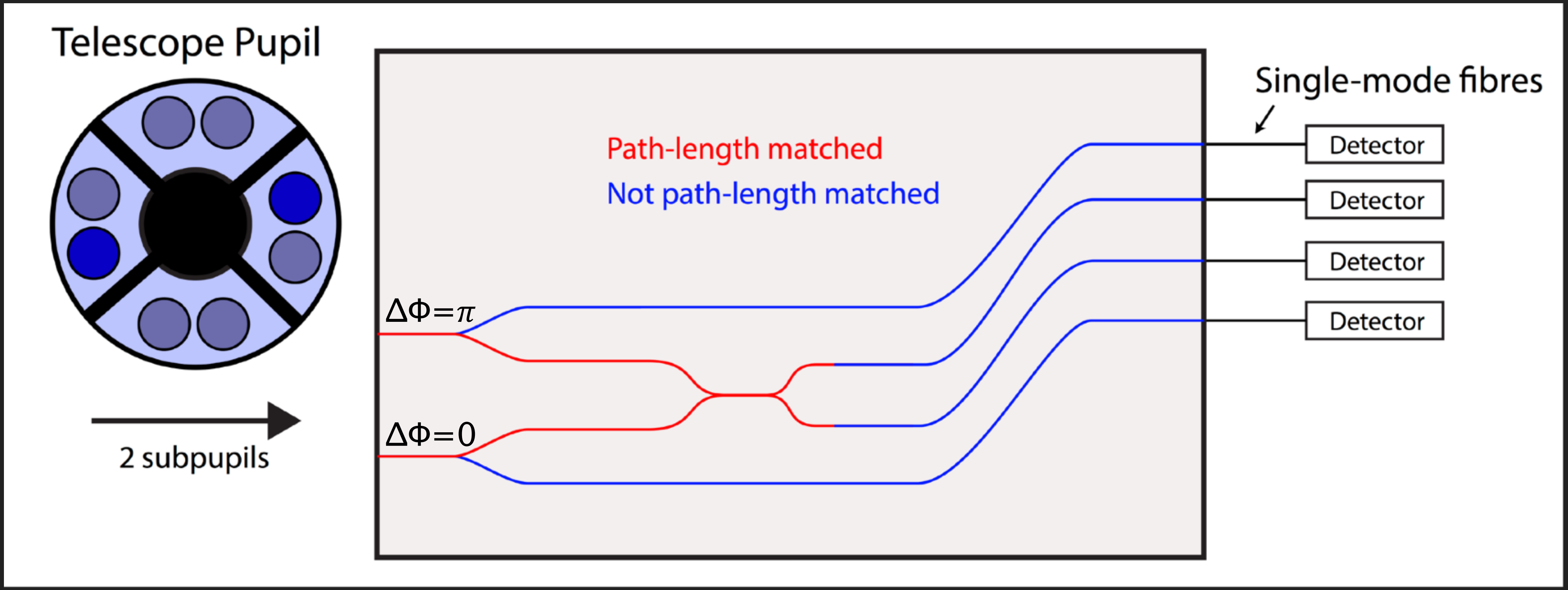
Guided Light Interferometric Nulling Technology

PART 2 – NIR INTEGRATED NULLING

Beat photon-noise while exploiting integrated ULI beam-combiners

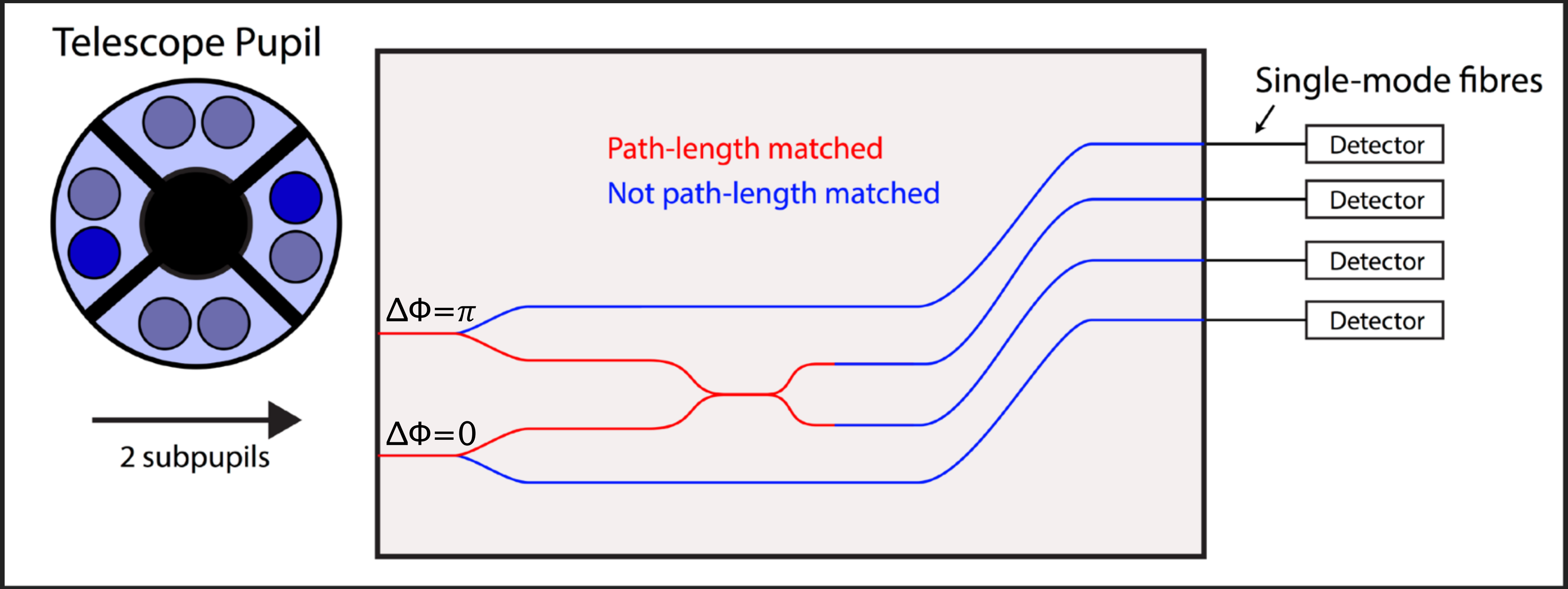
GLINT NULLER

- Uses a 3D photonic chip (ULI) to destructively interfere starlight, revealing signal of high contrast structure
  - Telescope pupil imaged onto chip
  - Remapping + interference via evanescent couplers in chip
  - 10s of outputs, encoding time domain signal as pupil rotates

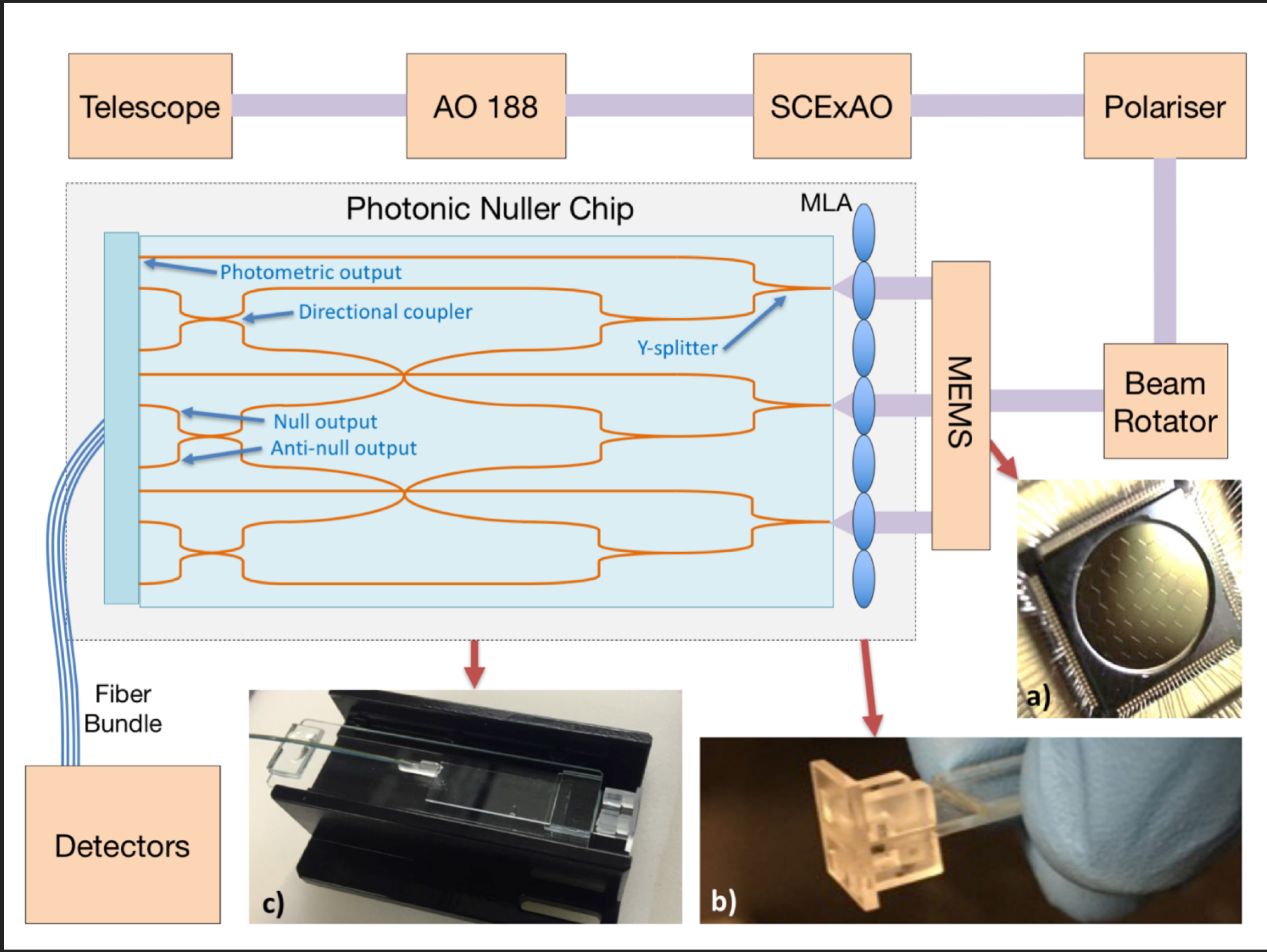


GLINT NULLER

- Advantages of integrated photonic approach
  - Pupil-Remapped and nulling interferometer in one device
  - Truly simultaneous photometry (not chopper) and I^+ measurement -> Better null-depth estimate
  - Ideal for multiple, cascaded beam combination - e.g. closure-phase nulling
  - Intrinsically stable



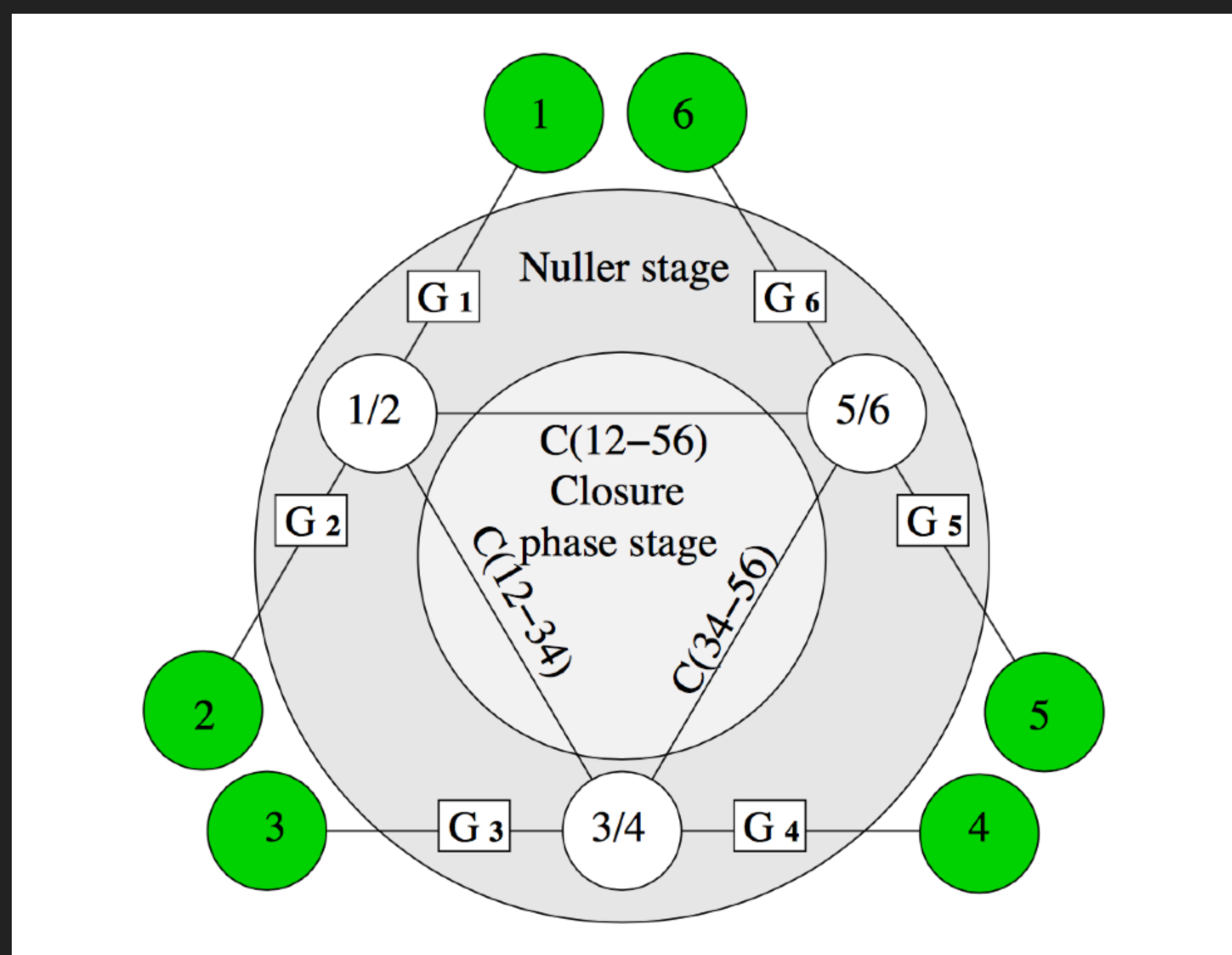
GLINT NULLER – 3 WG AND 4 WG CHIPS IN PROCESS



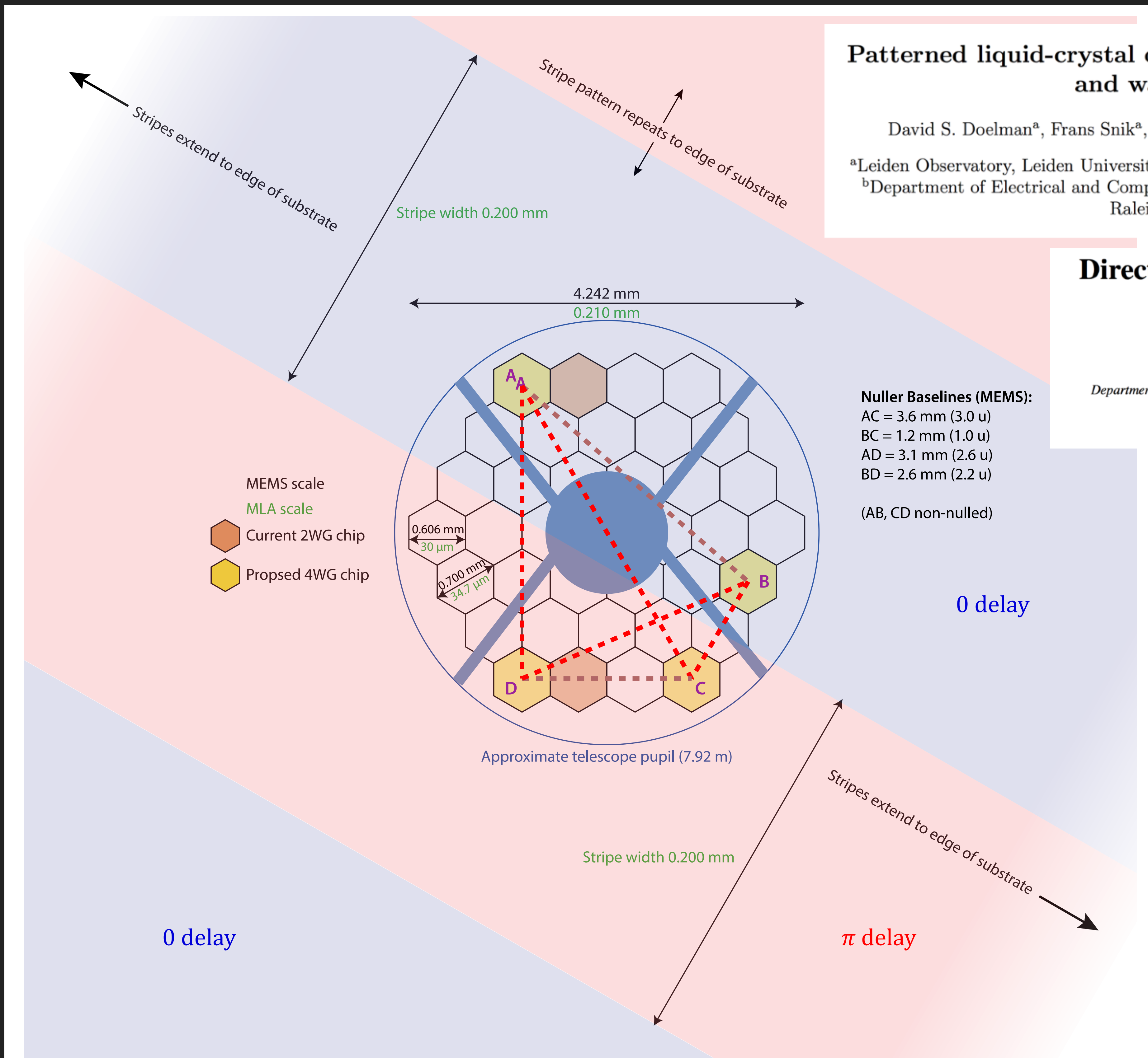
GLINT NULLER – TOWARDS CP NULLING

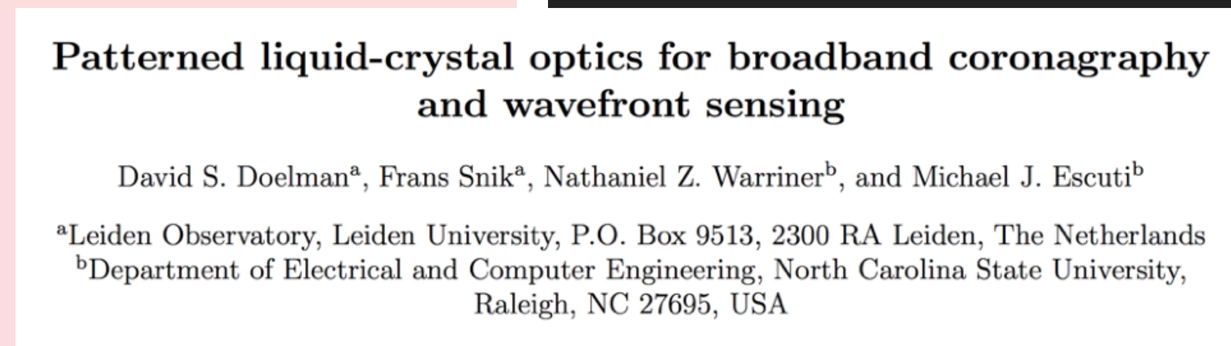
A new interferometer architecture combining nulling with phase closure measurements

S. Lacour,[1] P. Tuthill,[2] J. D. Monnier,[3] T. Kotani,[4] L. Gauchet[1] and P. Labeye[5]
[1] *LESIA/Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, 5 place Jules Janssen, 92195 Meudon, France*
[2] *Sydney Institute for Astronomy, School of Physics, The Univeristy of Sydney, N.S.W. 2006, Australia*
[3] *Department of Astronomy, University of Michigan, 941 Dennison Building, Ann Arbor, MI 48109, USA*
[4] *National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[5] *CEA-LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*



PART 2 - INTEGRATED NULLING (GLINT)

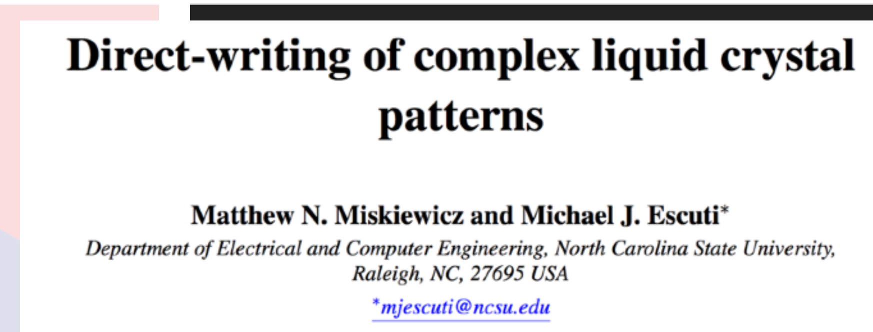




Patterned liquid-crystal optics for broadband coronagraphy and wavefront sensing

David S. Doelman[a], Frans Snik[a], Nathaniel Z. Warriner[b], and Michael J. Escuti[b]

[a]Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[b]Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695, USA



Direct-writing of complex liquid crystal patterns

Matthew N. Miskiewicz and Michael J. Escuti*

Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC, 27695 USA

*mjescuti@ncsu.edu

GLINT NULLER – SPECTROGRAPHIC BACK END

- Prototype back-end built and tested in lab (Enrico Biancalani)
- ~40 fibers in v-groove diffraction limited
- Low R - 5 nm spectral channels

- Awaiting delivery of C-RED 2!
- Plan for on sky Q1 2018

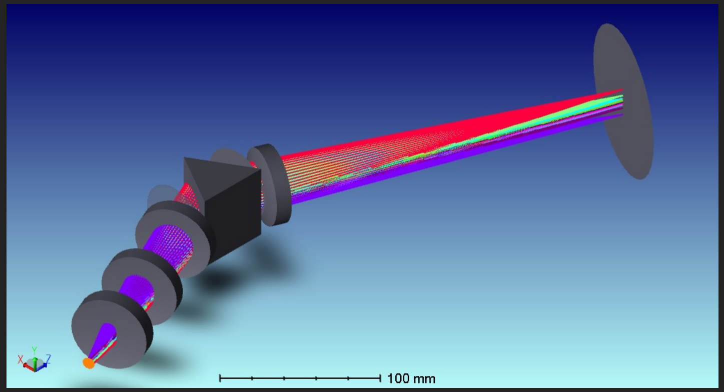


Fig. 4 – .

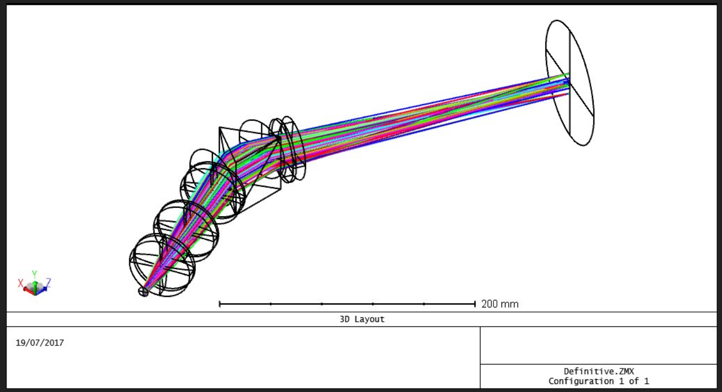


Fig. 8 – .

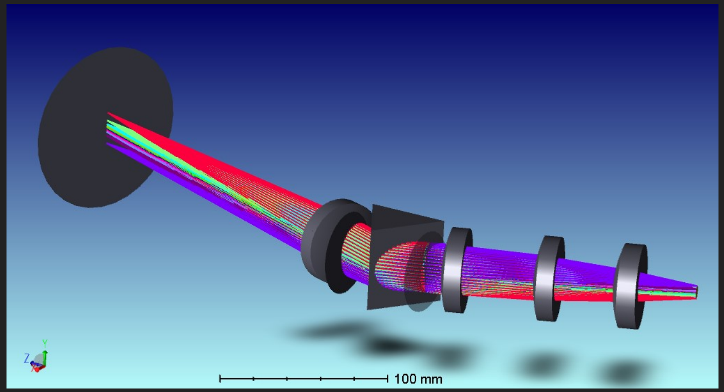


Fig. 5 – .

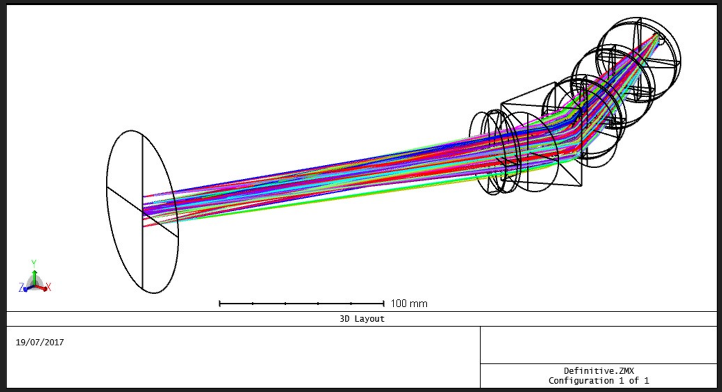
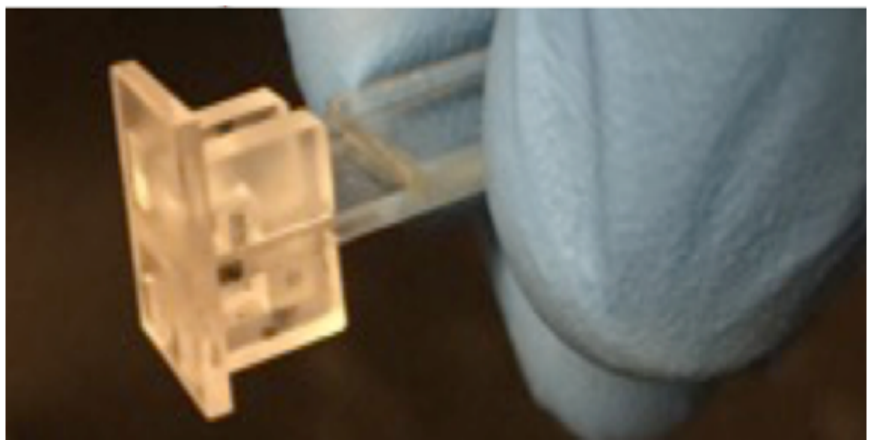


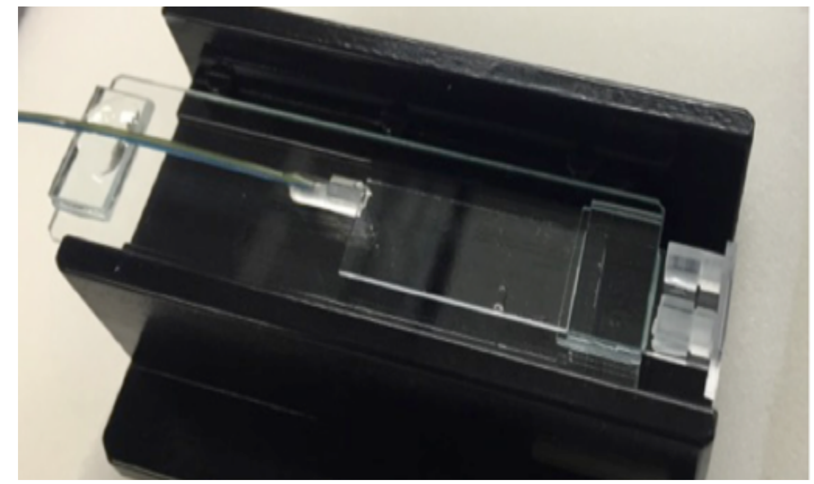
Fig. 9 – .

GLINT NULLER

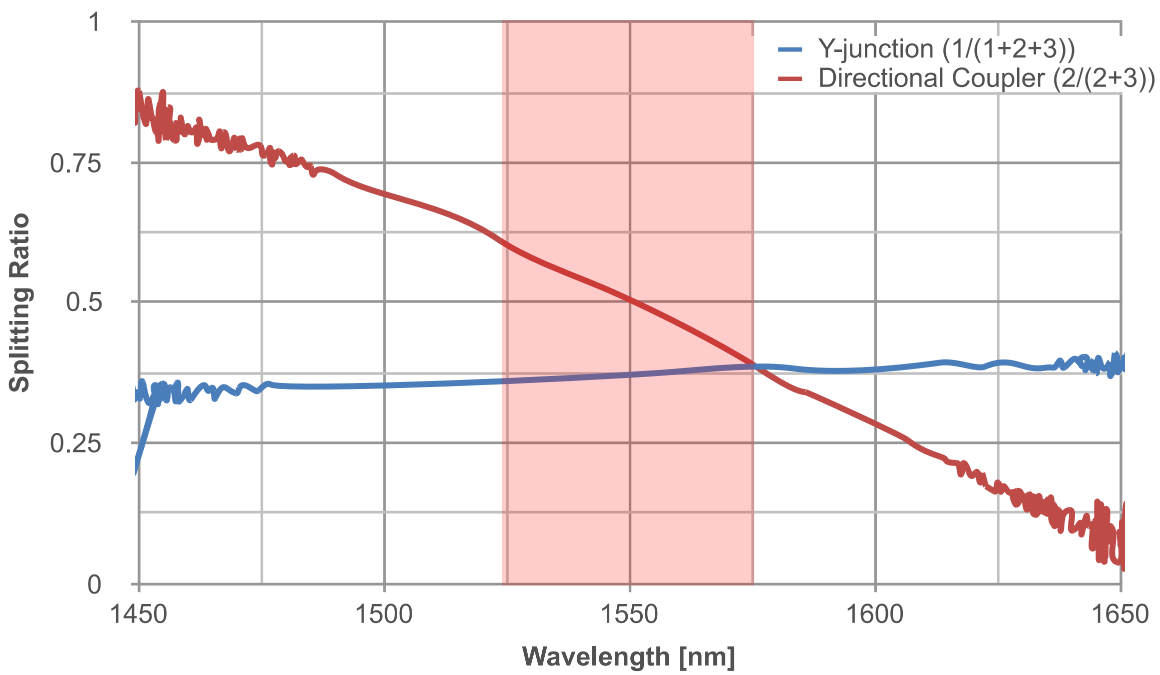
Microlens array



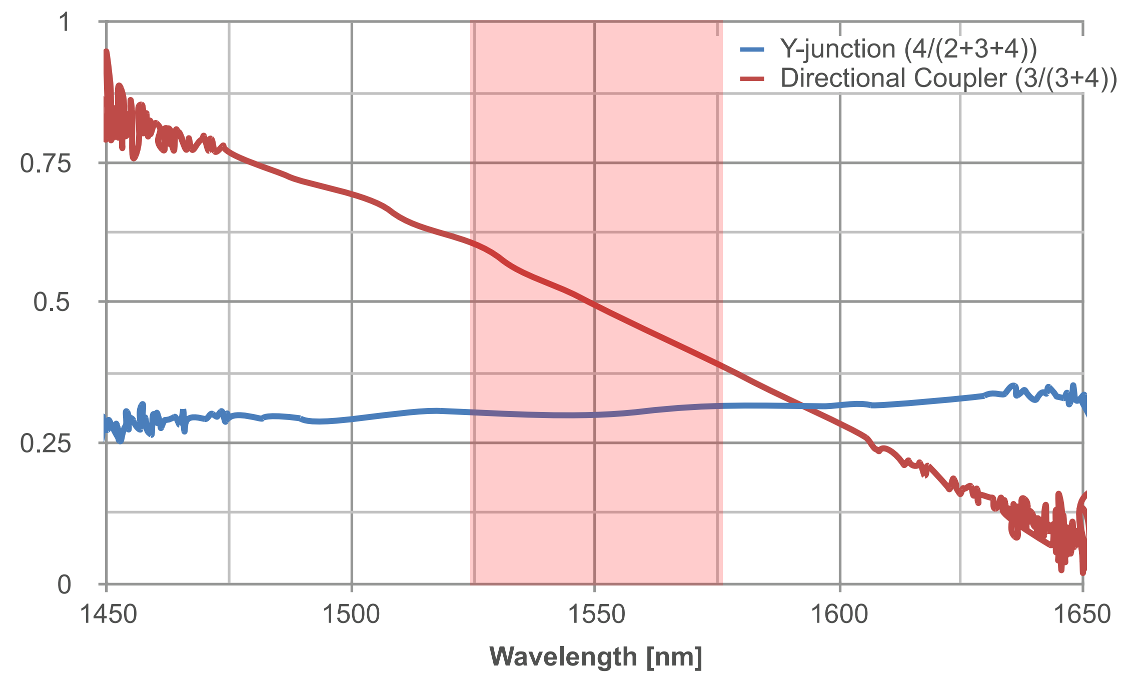
Fully packaged chip



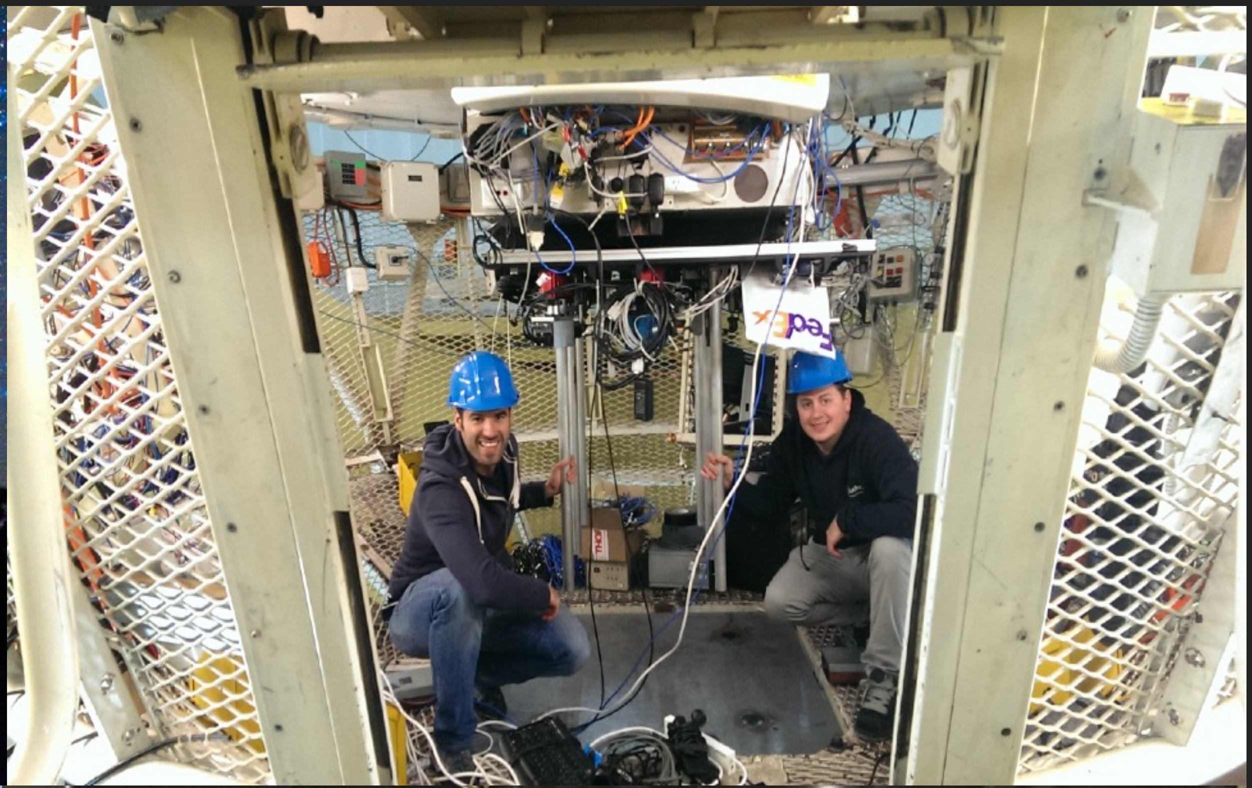
1st Branch



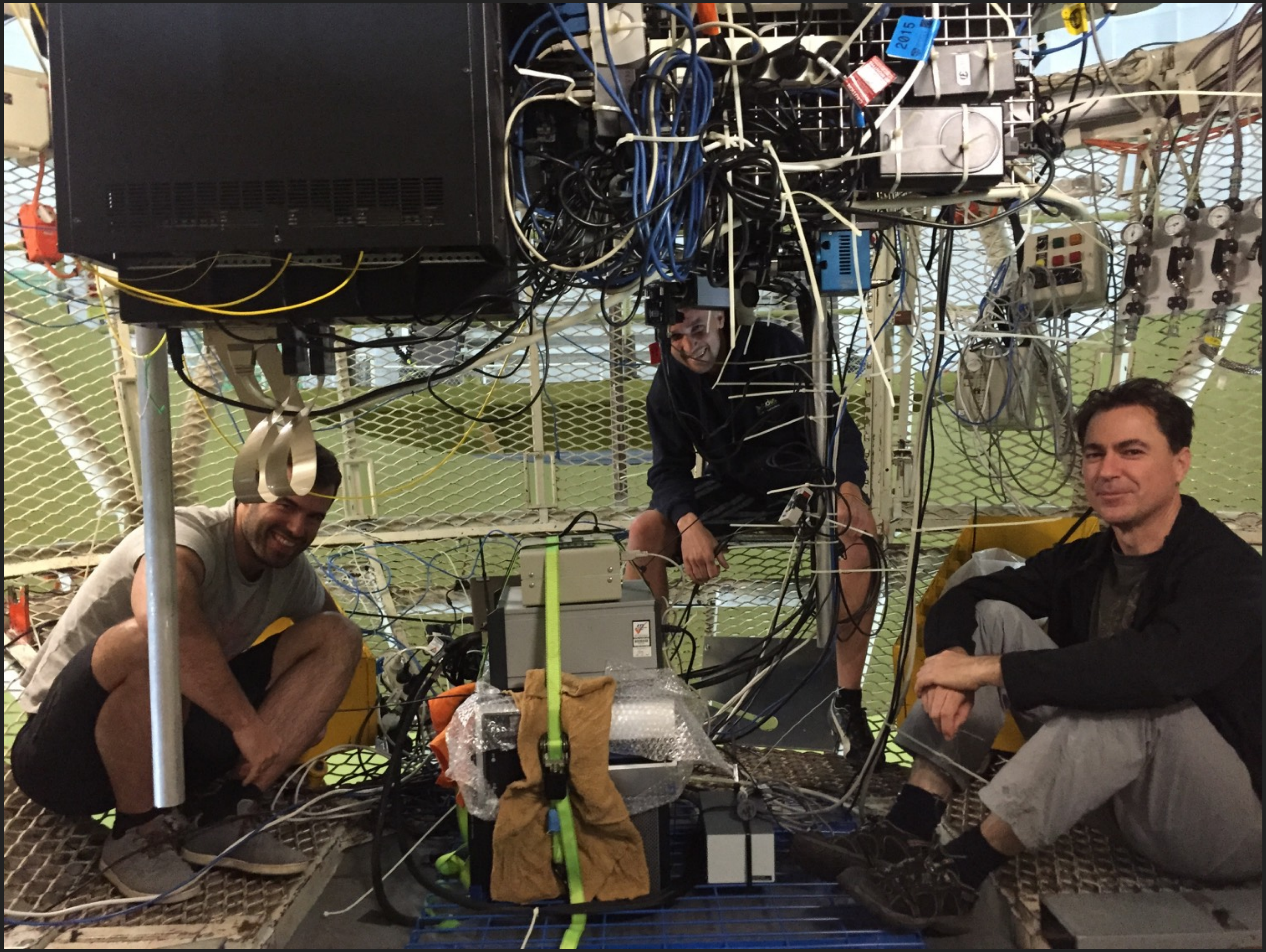
2nd Branch

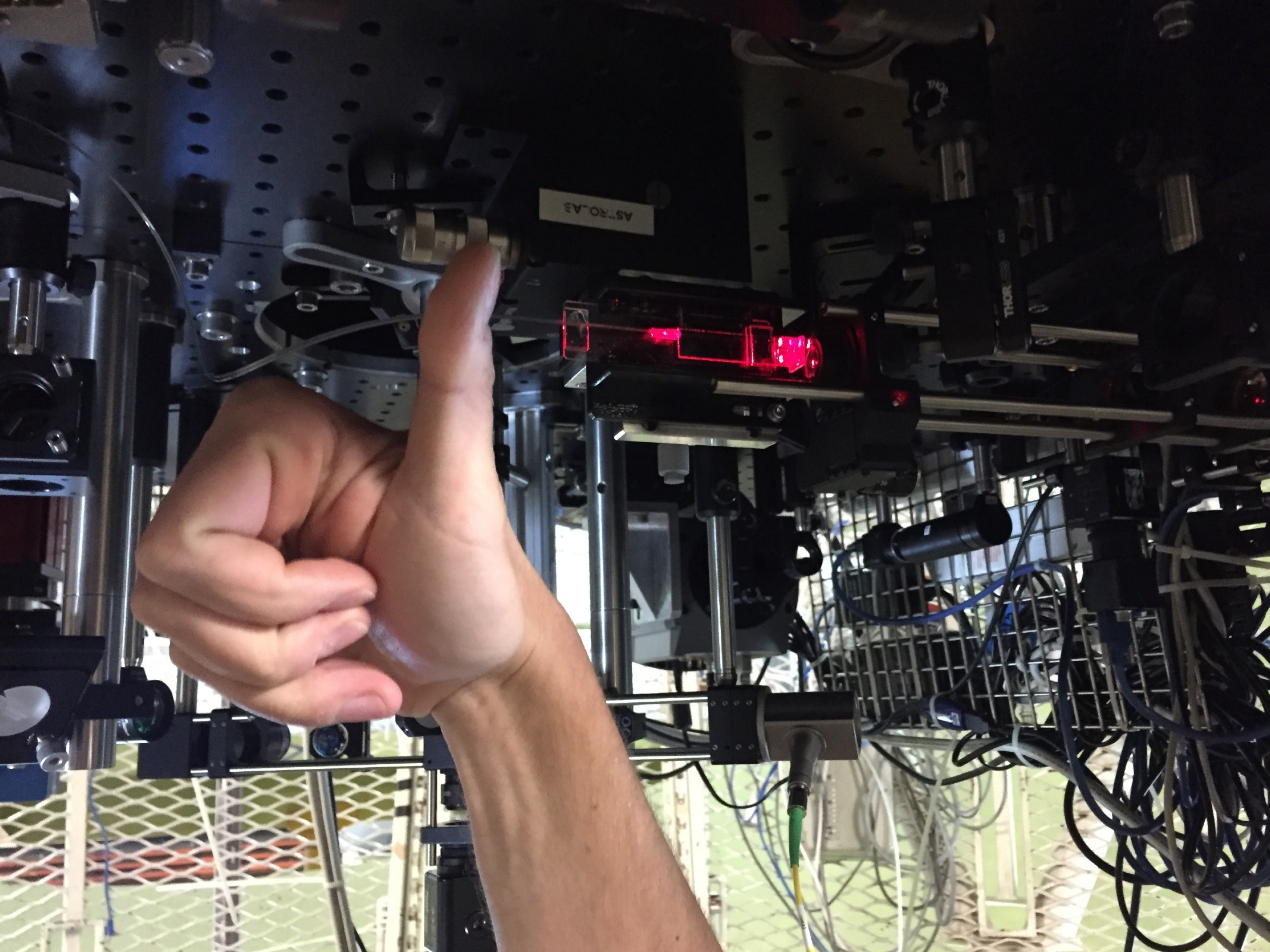


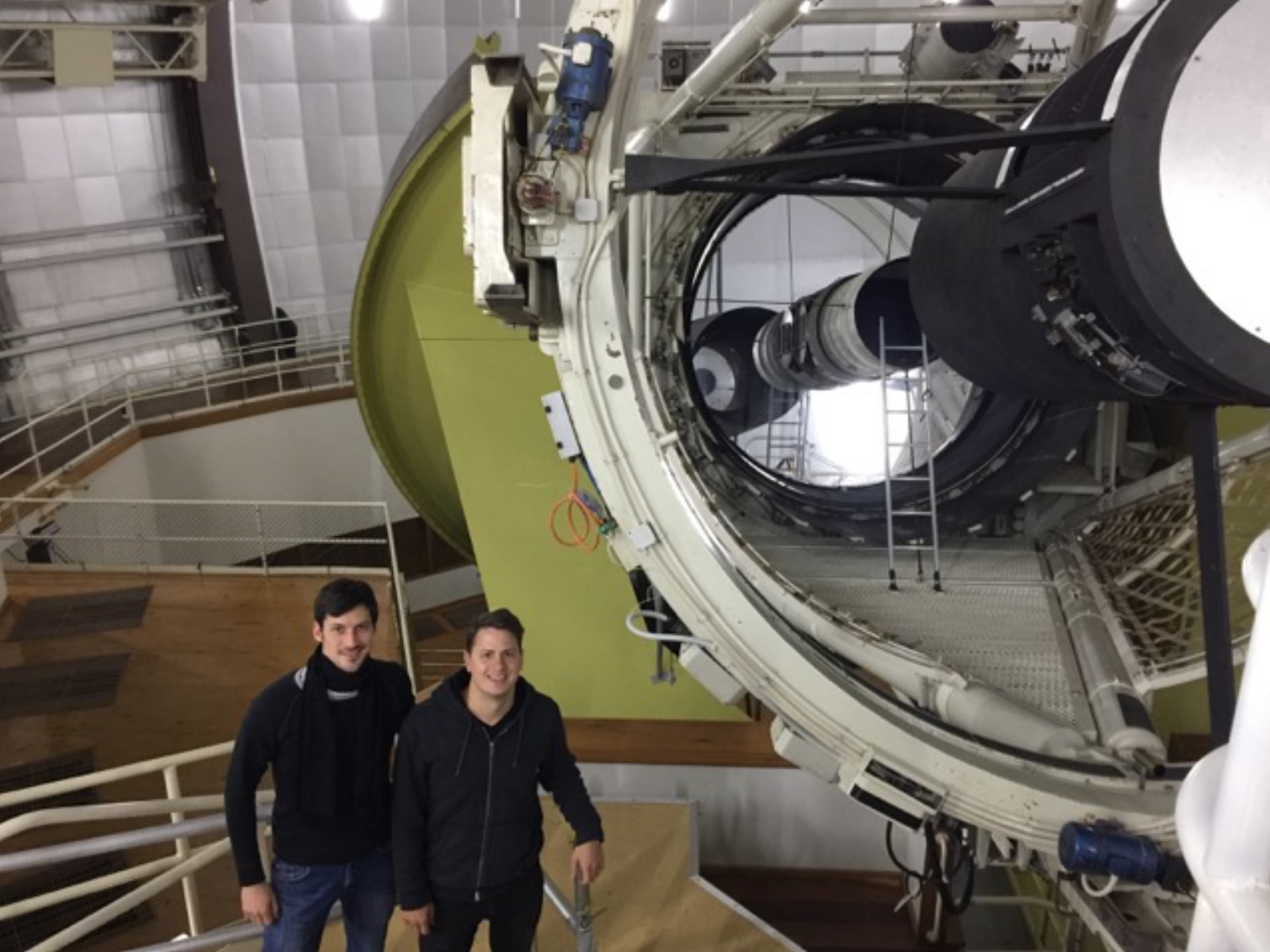
ON-SKY TESTING

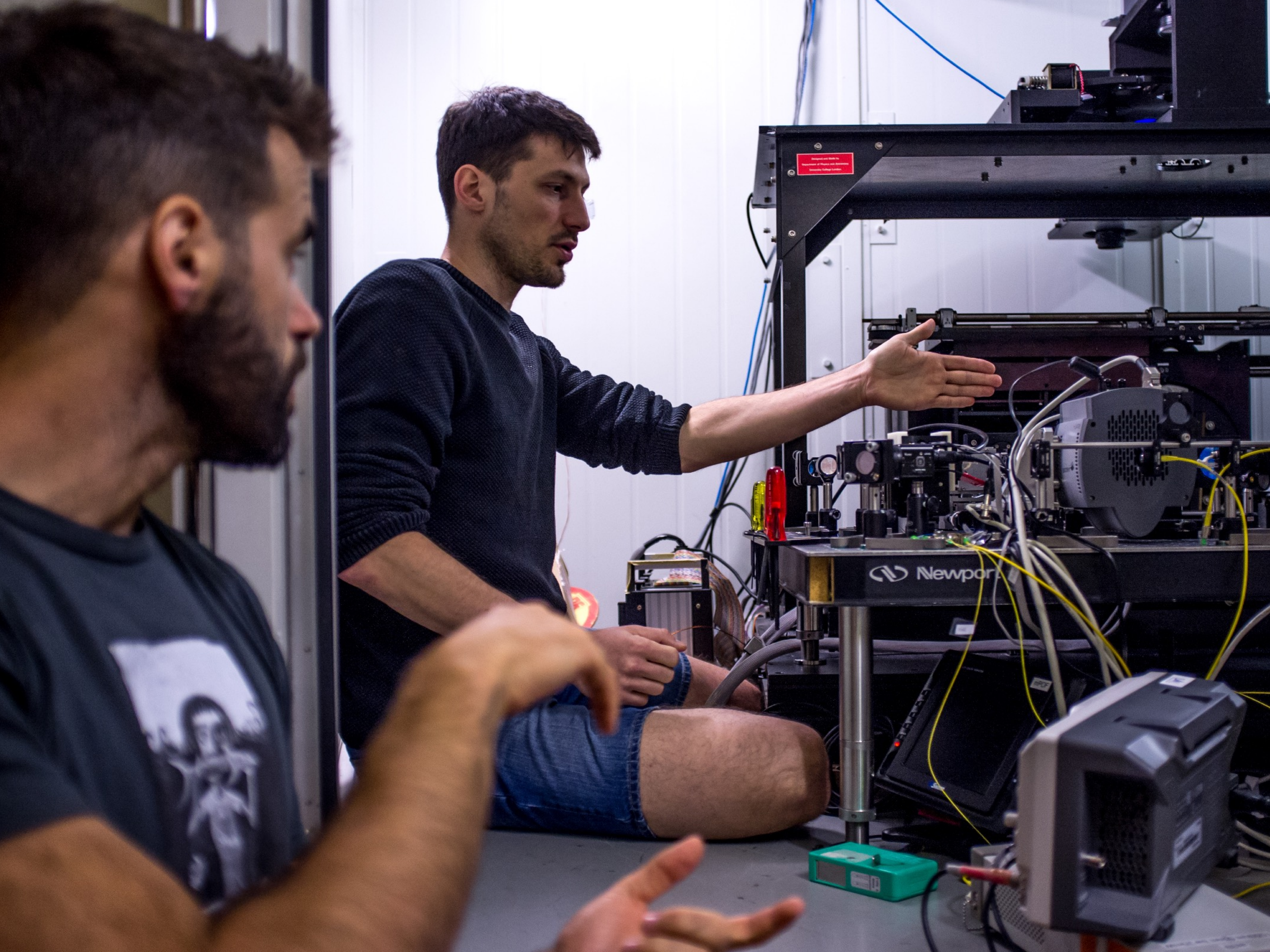


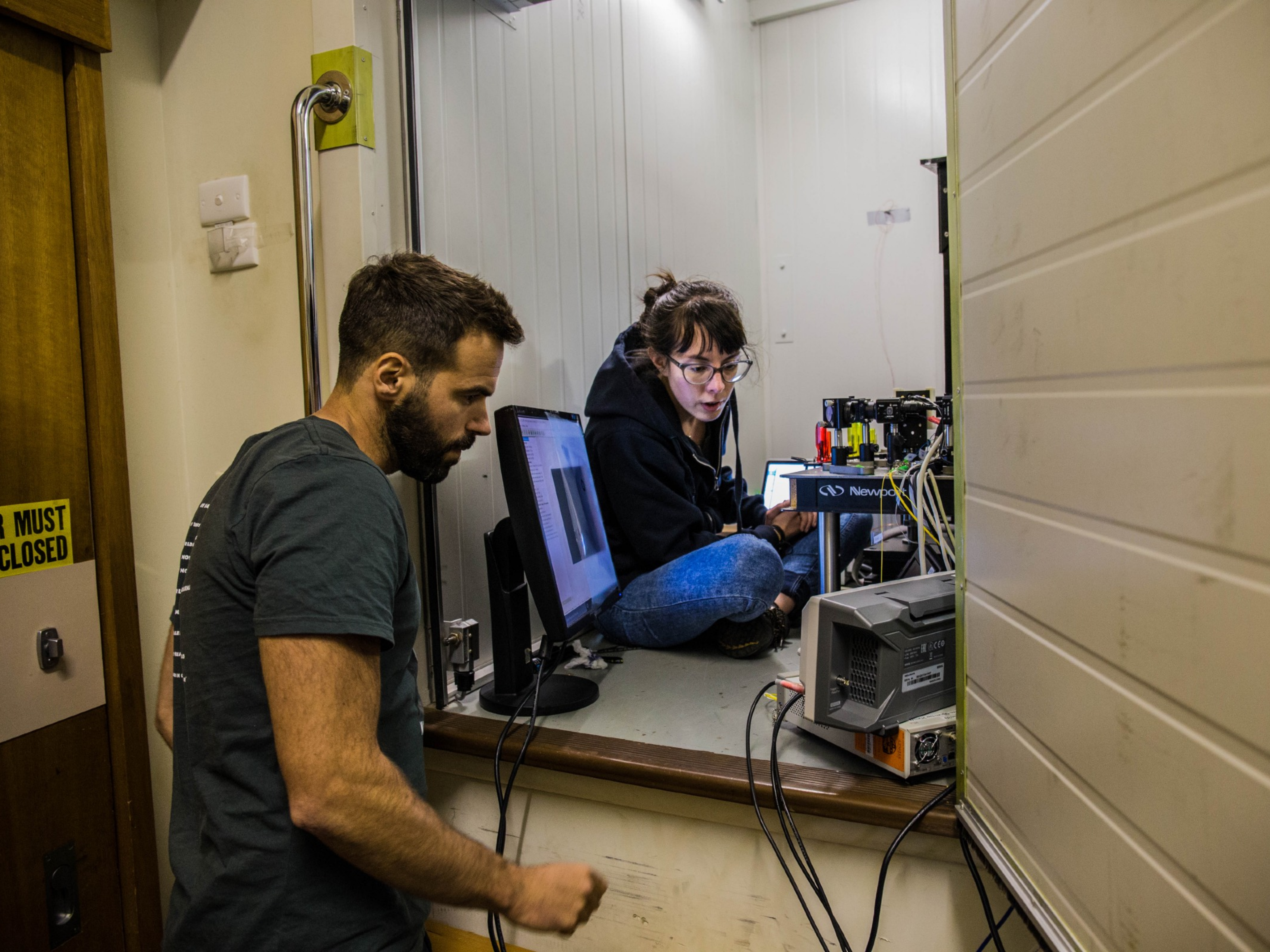
TESTING AT AAT







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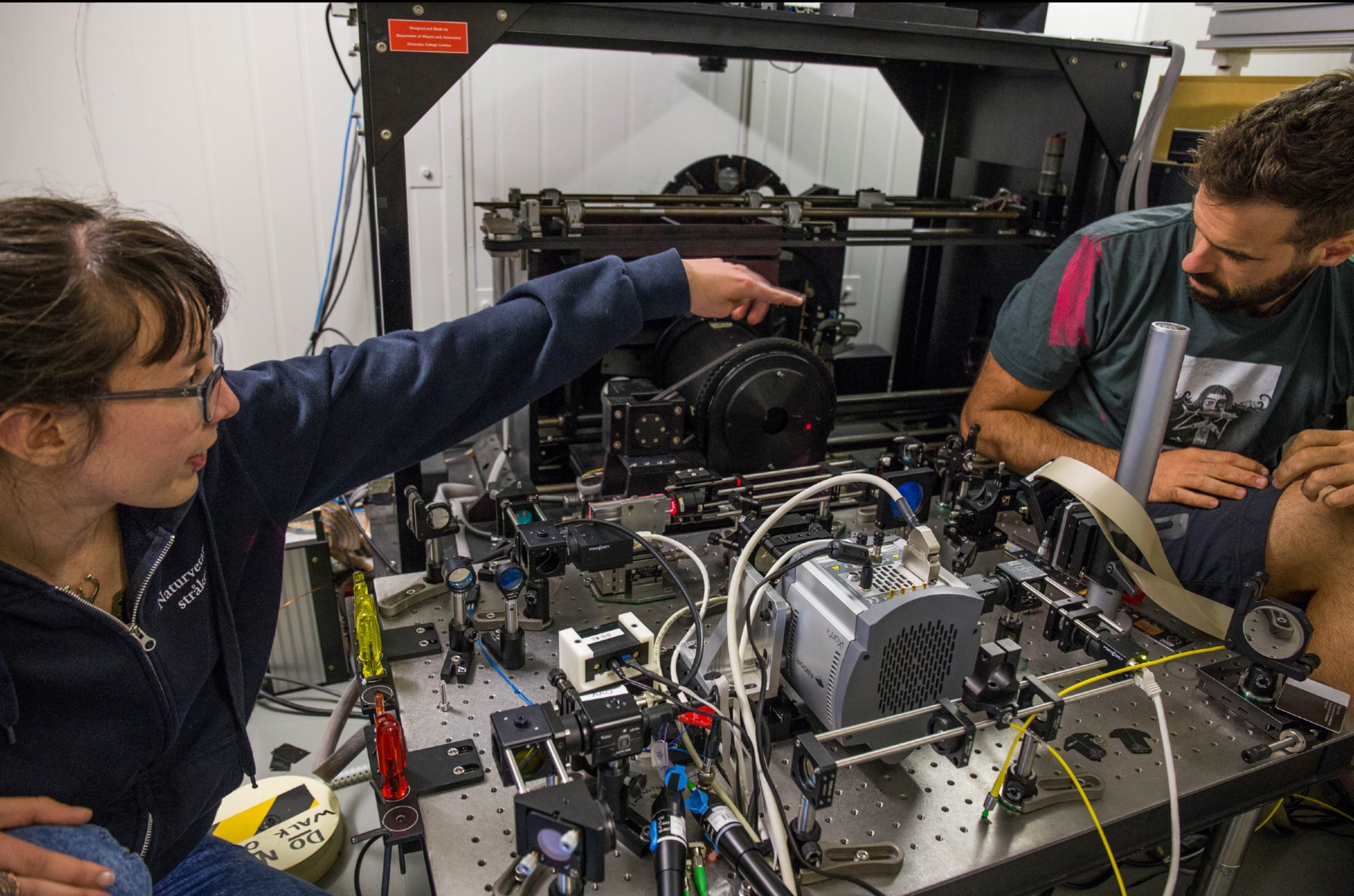
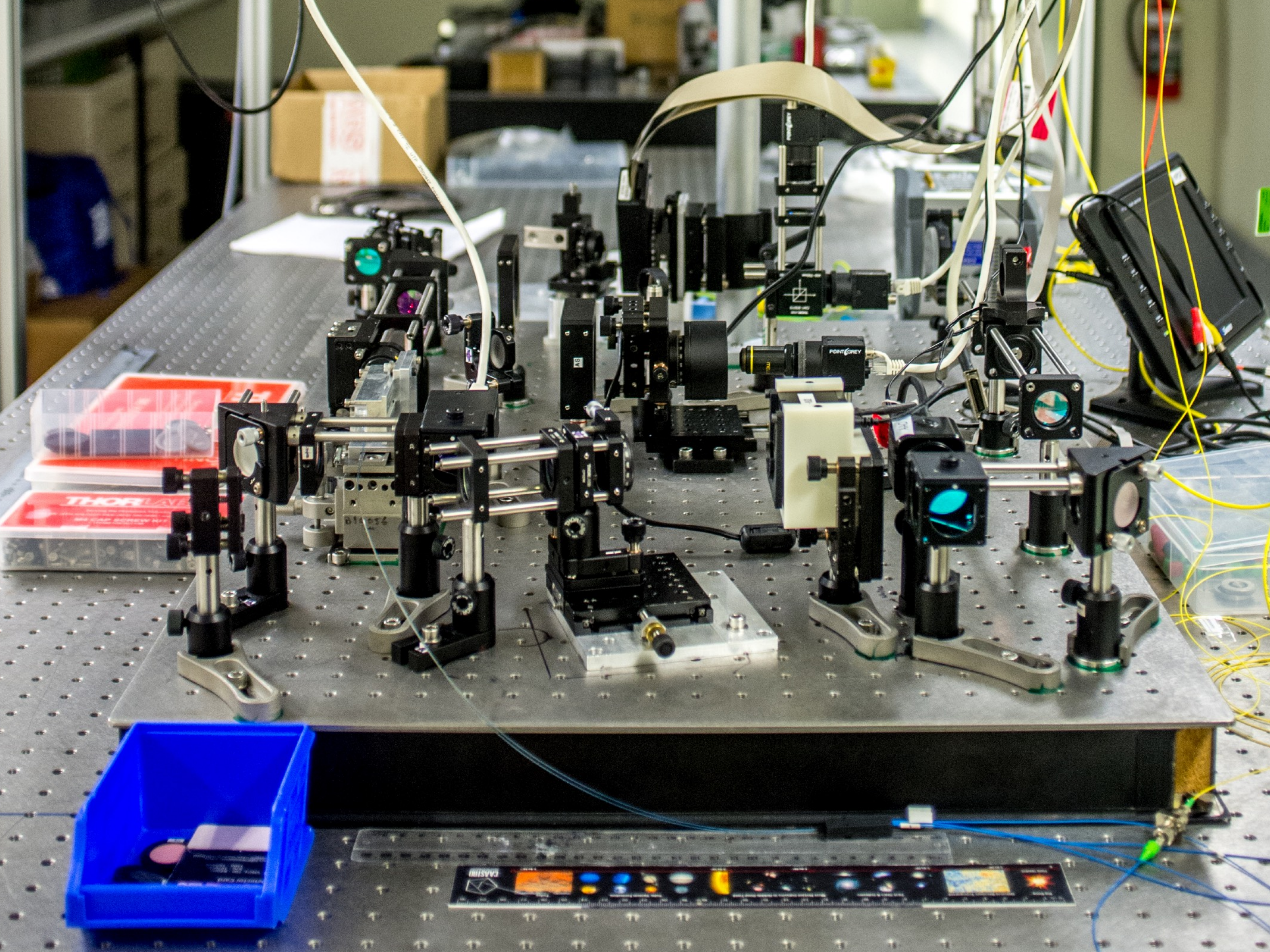
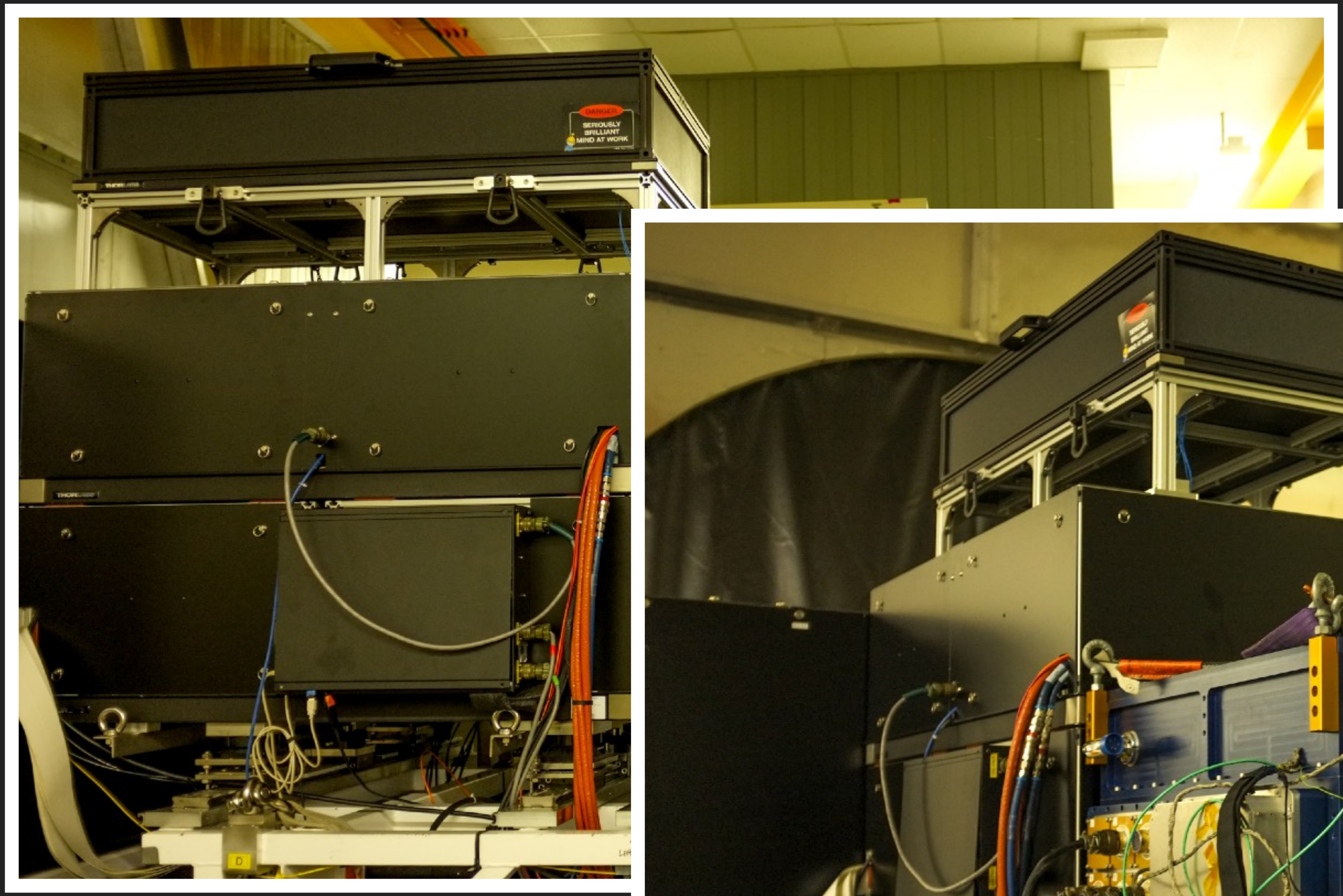
CLOSED
Newport

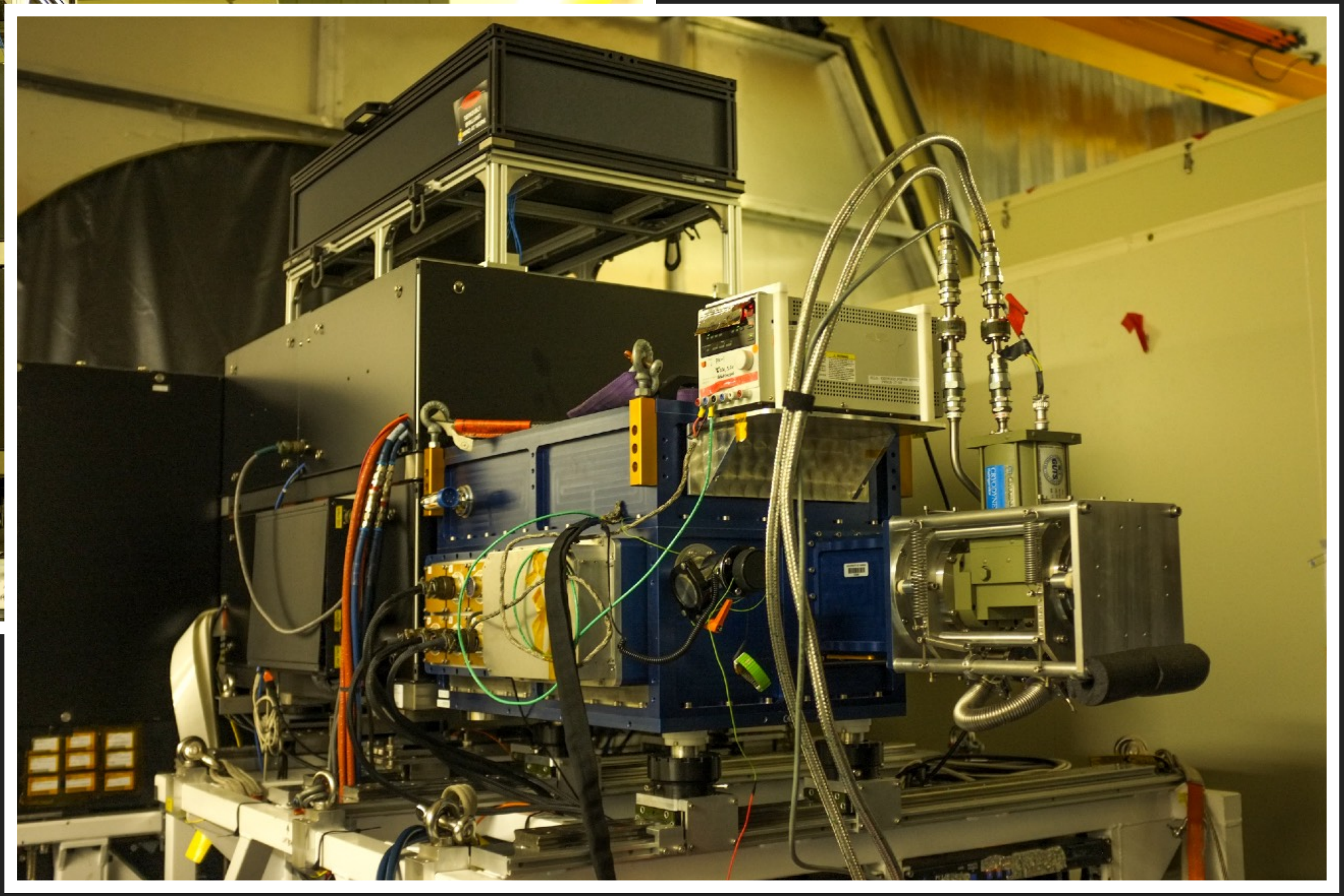

Designed and Made by
Department of Physics and Astronomy
University College London


POINTGREY

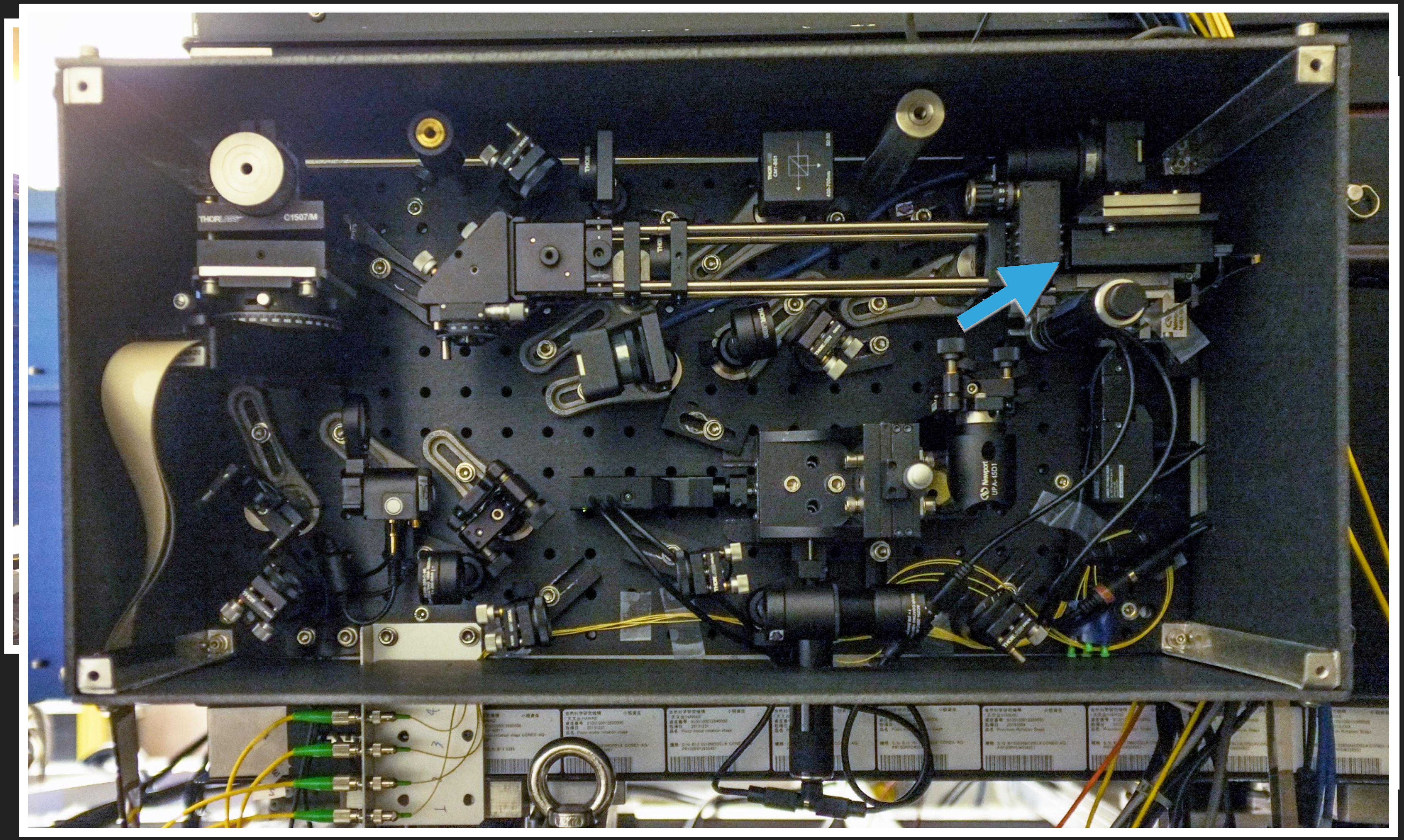
GLINT @ SUBARU – SCEXAO

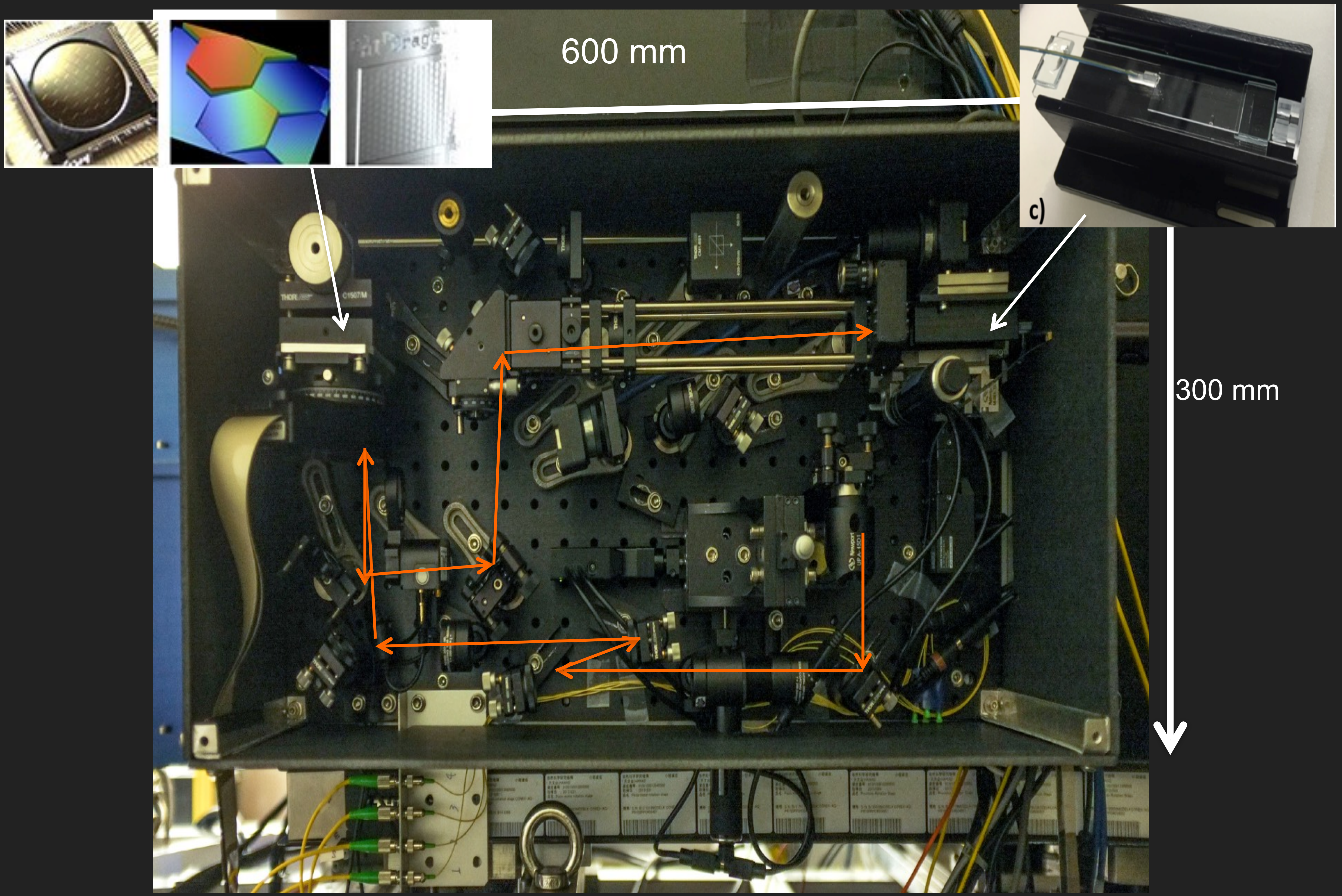
GLINT @ SUBARU - SCEXAO





GLINT @ SUBARU




600 mm
c)
300 mm

RESULTS

- Results use NSC method - will let Denis describe details
  - Essentially, fit model of null depth PDF histogram (or KDF)
    - Some parameters known from data (photometry PDFs, dark/bg PDFs, etc)
    - Other parameters fitted - phase variance (mean, sigma), and astro null
- Some other analysis used some small value approximations… we couldn't due to very large phase variance
  - Do full MC model, computationally intensive
  - GPU implantation - ~100x faster than CPU implementation!
  - Fit with nonlinear leastsq (TRR) + basin hopping

Overclocked GTX 1080 Ti

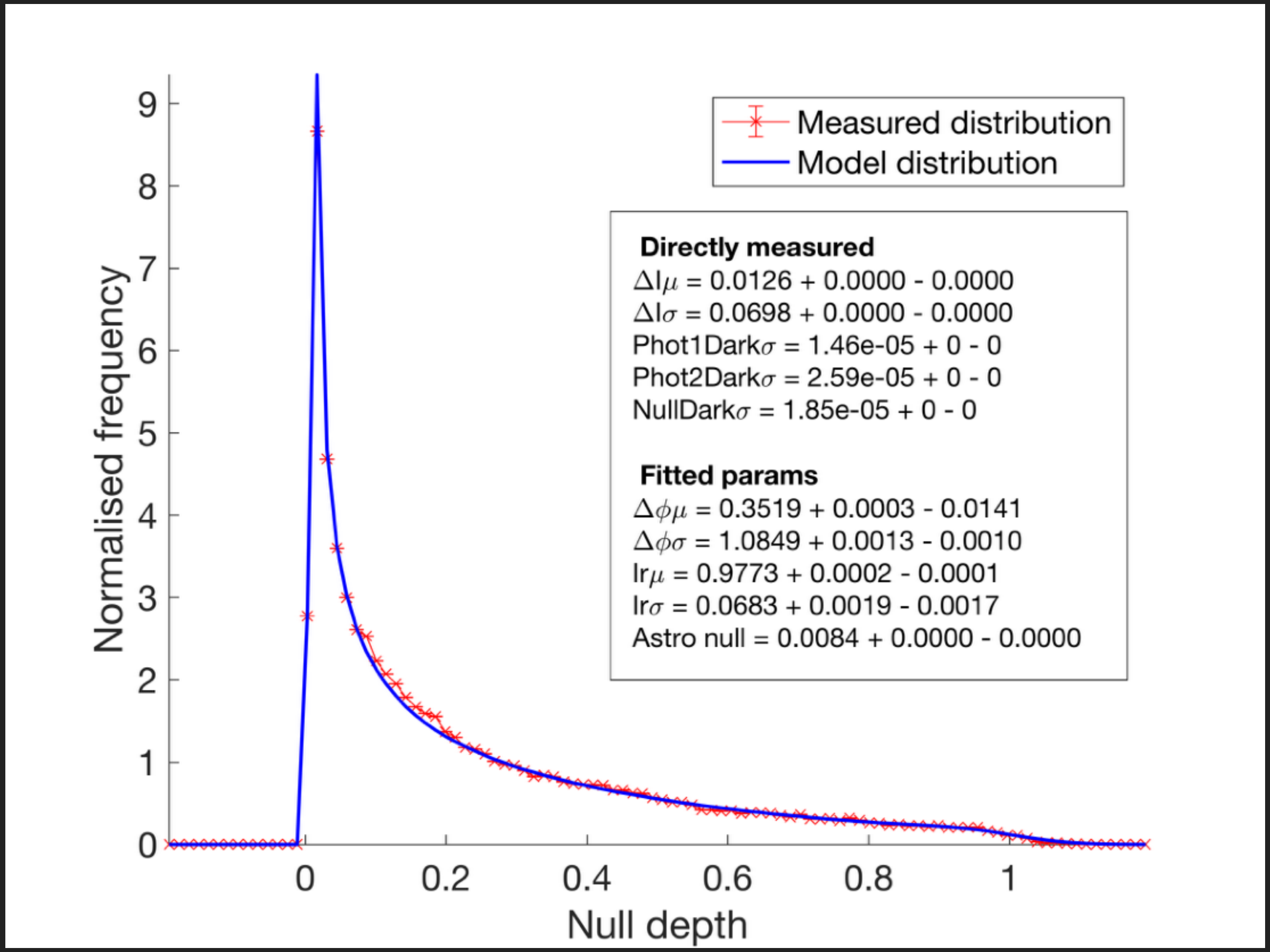
15 TFLOPS (single precision)

~USD 1000!

RESULTS

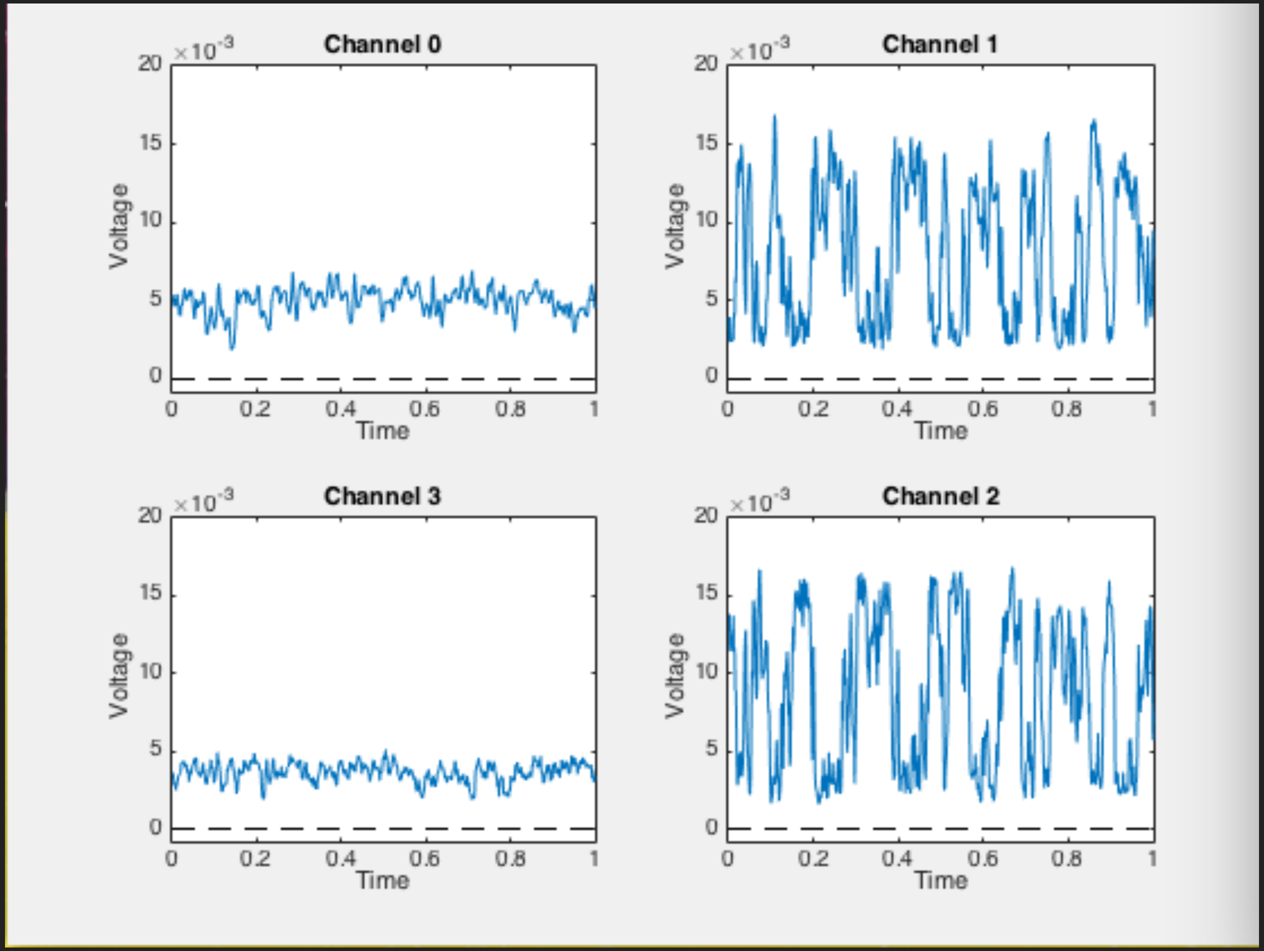
- Allow seeing to move null depth, analyse statistically by fitting model PDF to histogram of data
  - Pioneered by Palomar Fibre Nuller, see Hanot, et al. 2011
  - Very large phase errors -> couldn't use analytical approach, needed Monte Carlo
  - Work in progress - not yet polychromatic & proper polarisation
  - Lab source 'resolved'?

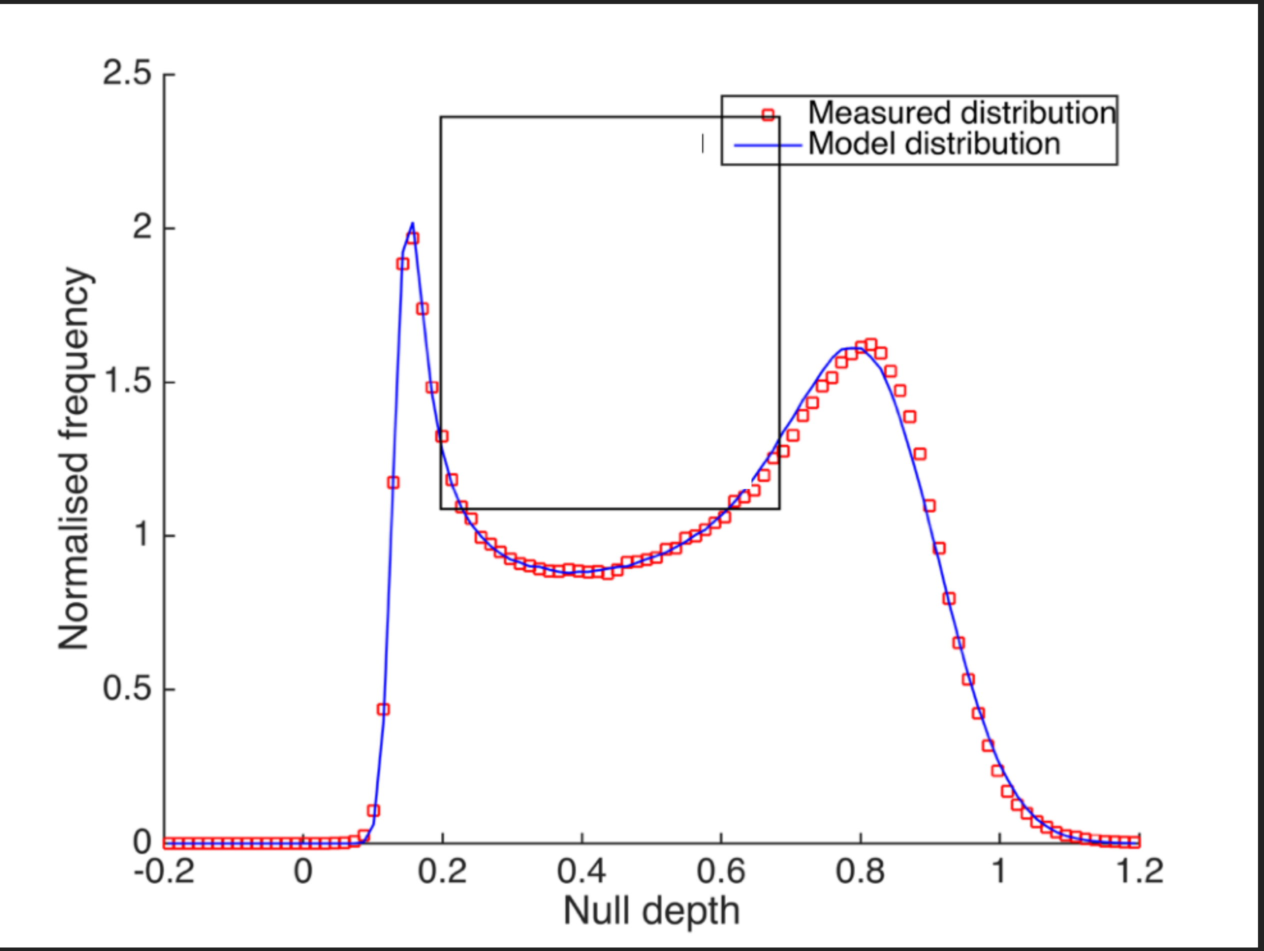
Laboratory measurement in SCExAO, with 200nm RMS wavefront error



RESULTS

- On-sky at Subaru 2016 - large telescope vibrations meant very large phase fluctuation
  - Strongly double-peaked histogram, see e.g. alf Her below





RESULTS

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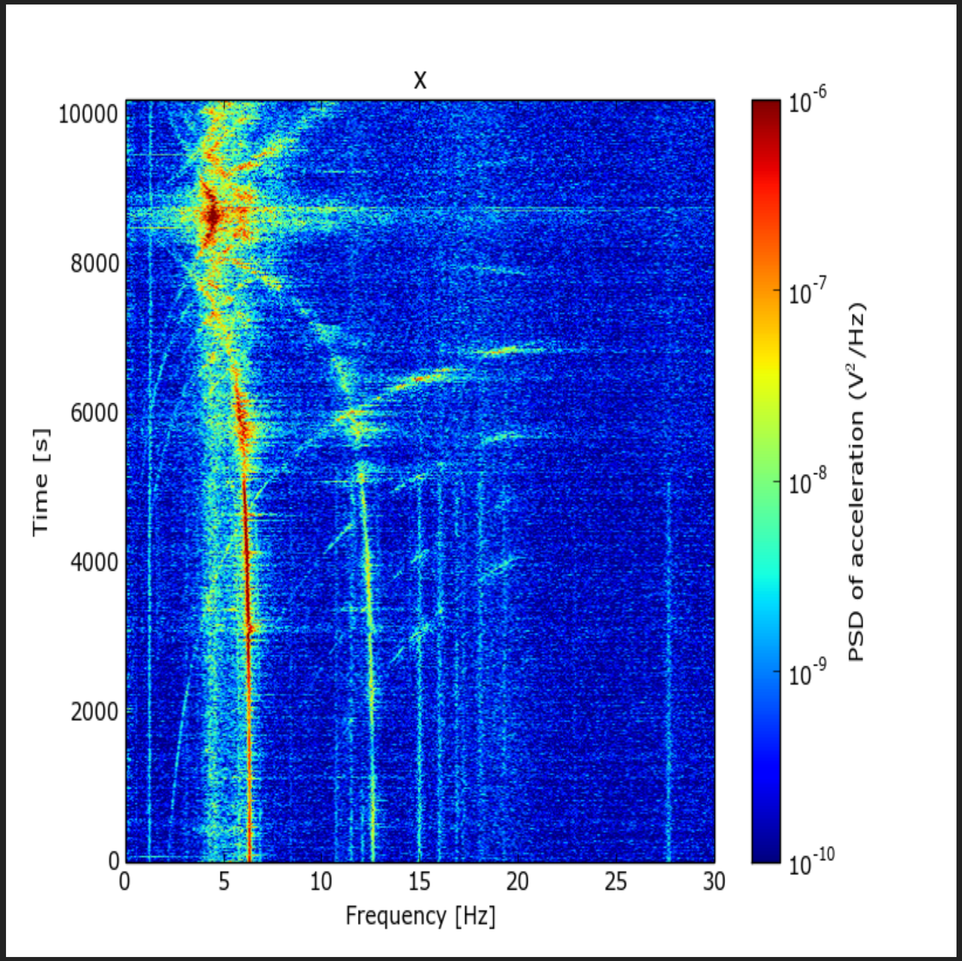
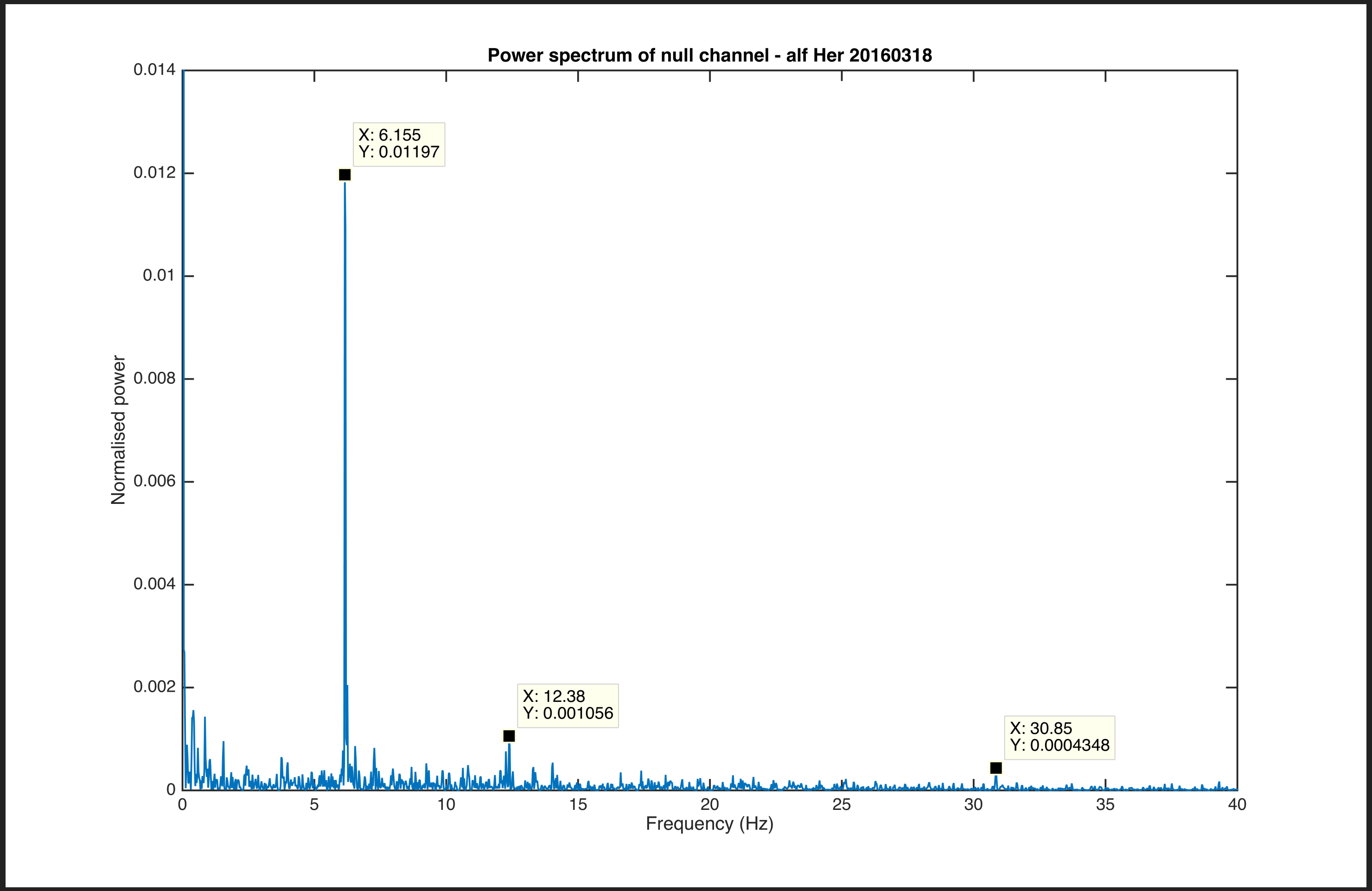


Top-ring accelerometer



Null-depth data power spectrum

RESULTS

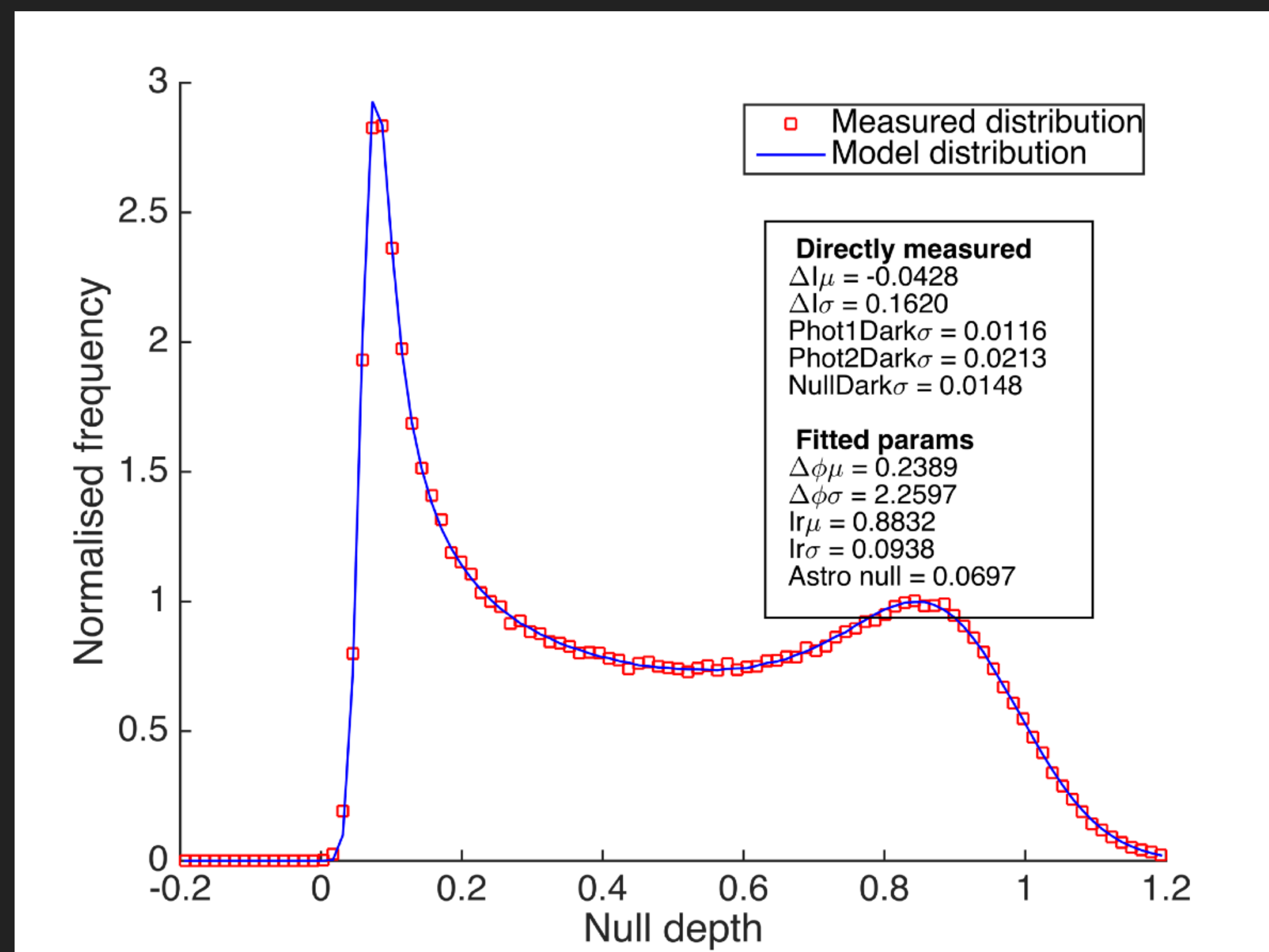
$$N_A = \left(\frac{\pi B \theta_{\mathrm{LD}}}{4\lambda}\right)^2 \left(1 - \frac{7u_\lambda}{15}\right) \left(1 - \frac{u_\lambda}{3}\right)^{-1}$$

Absil 2006, 2011

- Still works!
- Successfully measured stellar diameters from null depth

On-sky measurement (Subaru) of alf Boo. Null measurement gives **UD diameter of 19 mas**, consistent with known value

(Star partially resolved, diffraction limit ~ 40 mas)



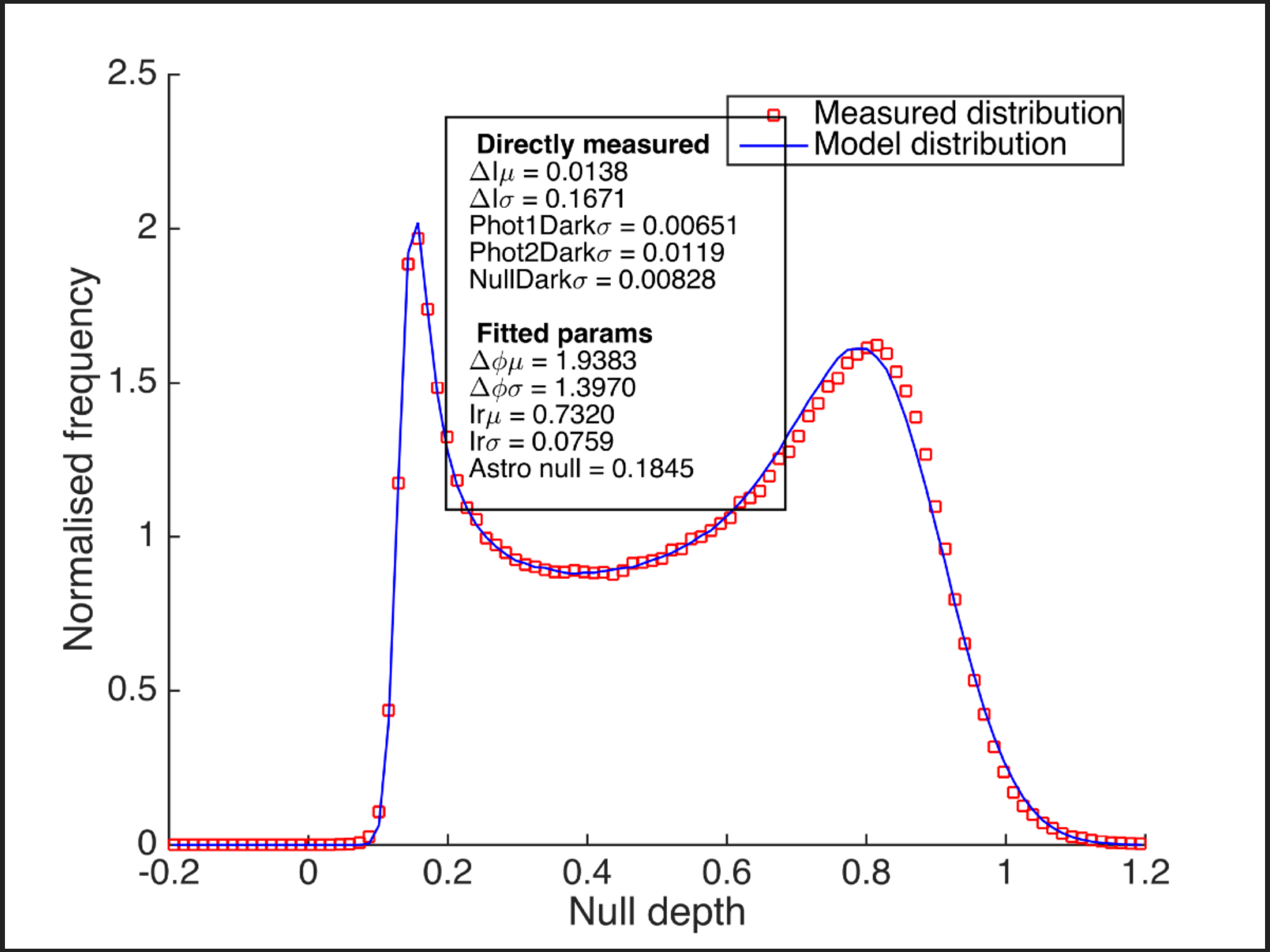
RESULTS

$$N_A = \left(\frac{\pi B \theta_{\rm LD}}{4\lambda}\right)^2 \left(1 - \frac{7u_\lambda}{15}\right)\left(1 - \frac{u_\lambda}{3}\right)^{-1}$$

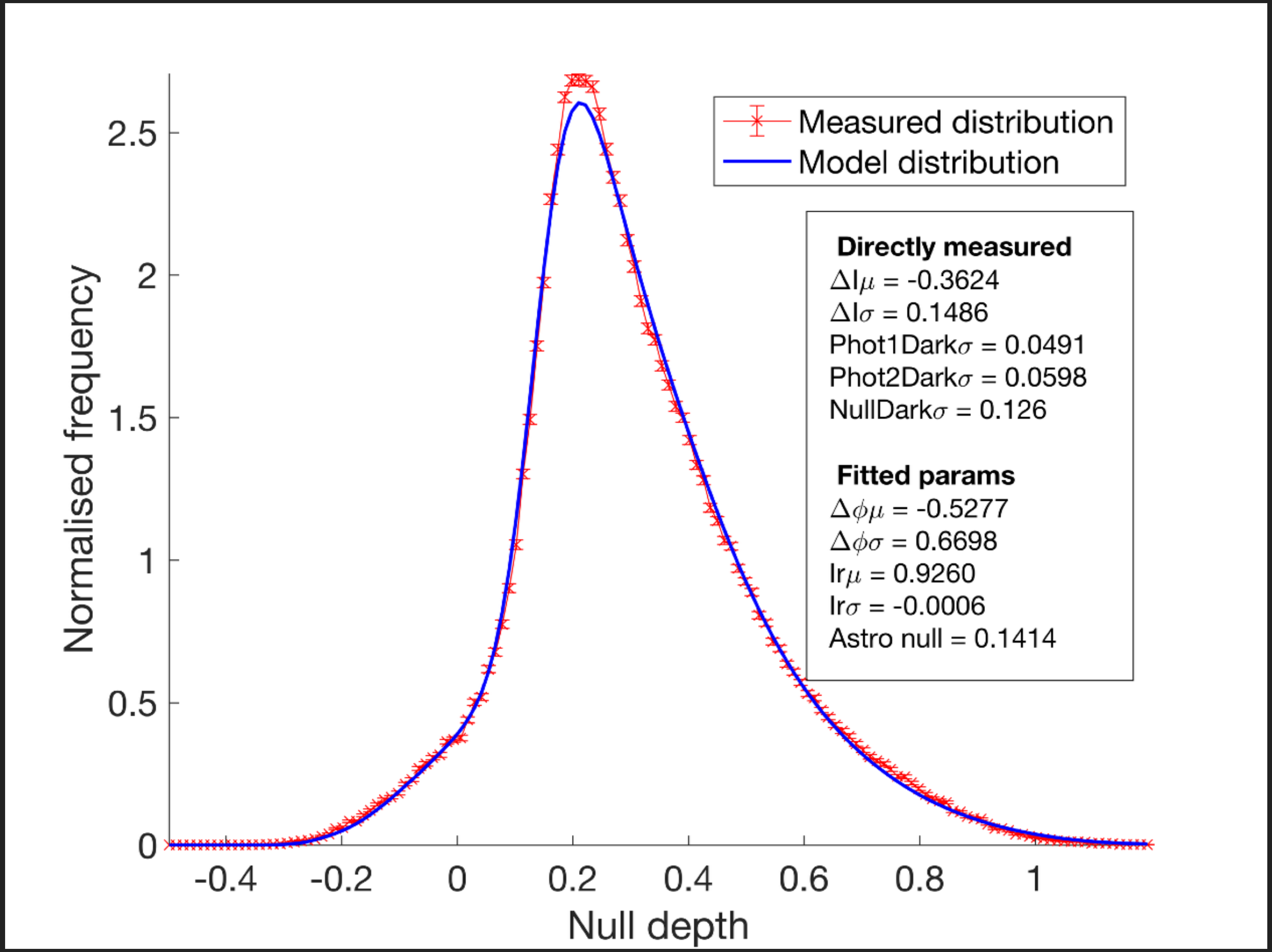
Absil 2006, 2011

- Still works!
- Successfully measured stellar diameters from null depth

On-sky measurement (Subaru) of alf Her. Null measurement gives **UD diameter of 31 mas**, consistent with known value



RECENT RESULTS

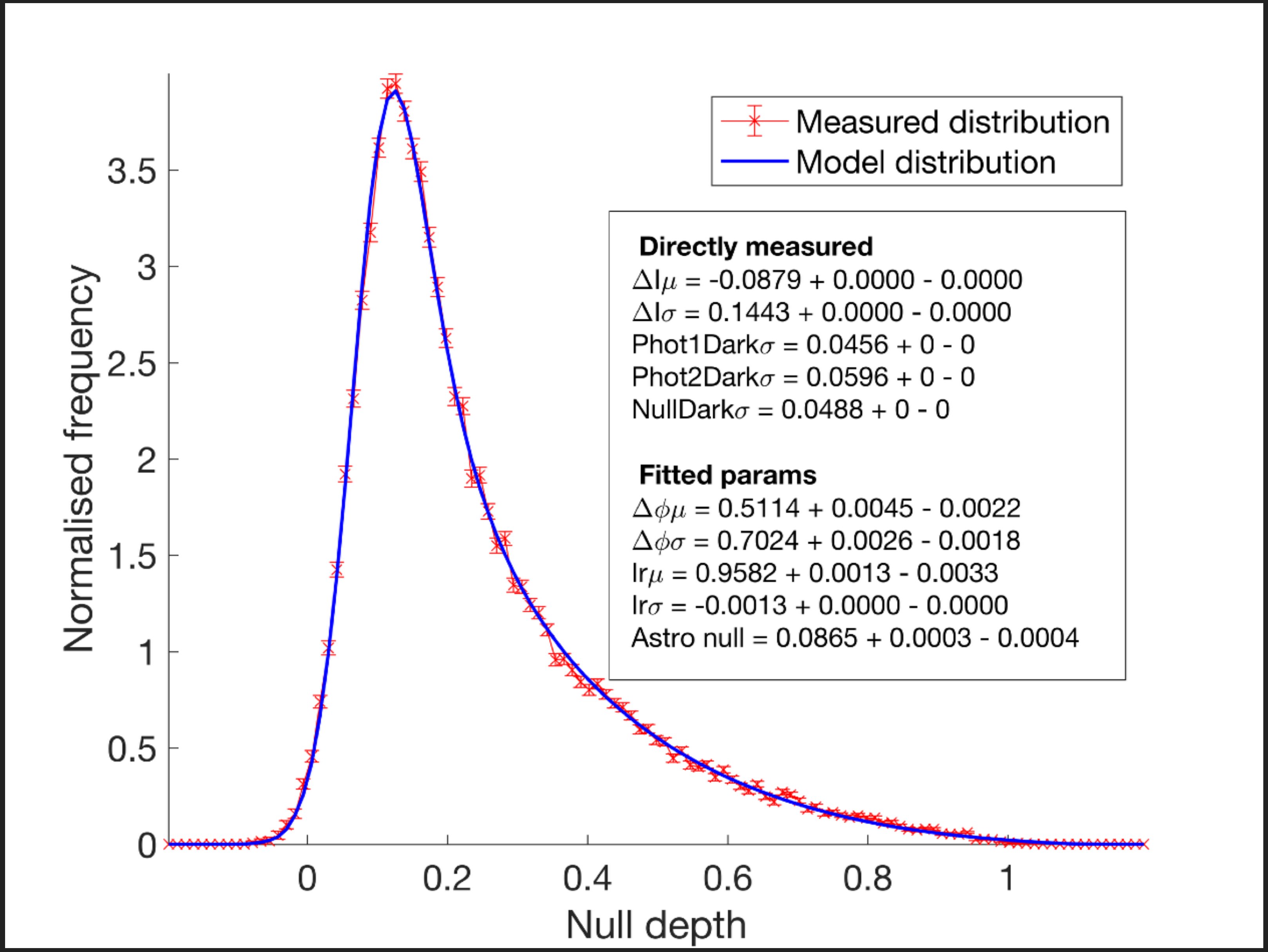


omi Cet - observed at Subaru November 2016.

Measured null = 0.1414

Corresponds to UD = 27.6 mas (Ks known diam 28~36, H?)

RECENT RESULTS

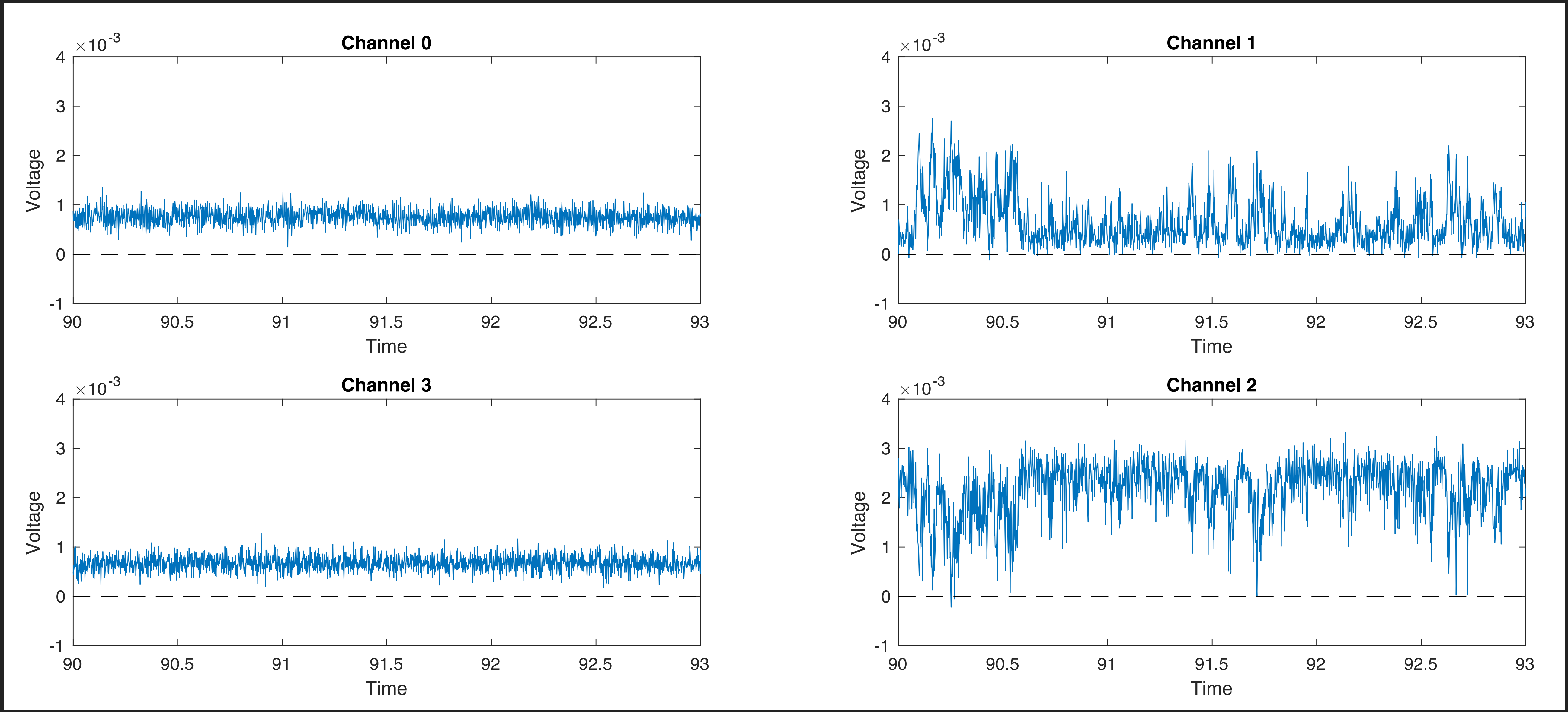


chi Cyg - observed at Subaru June 2017. Better t/t correction in PyWFS evident

Measured null = 0.0865 +- 0.0004

Corresponds to UD = 21.6 mas (literature vals range 20 - 25 mas)

RESULTS



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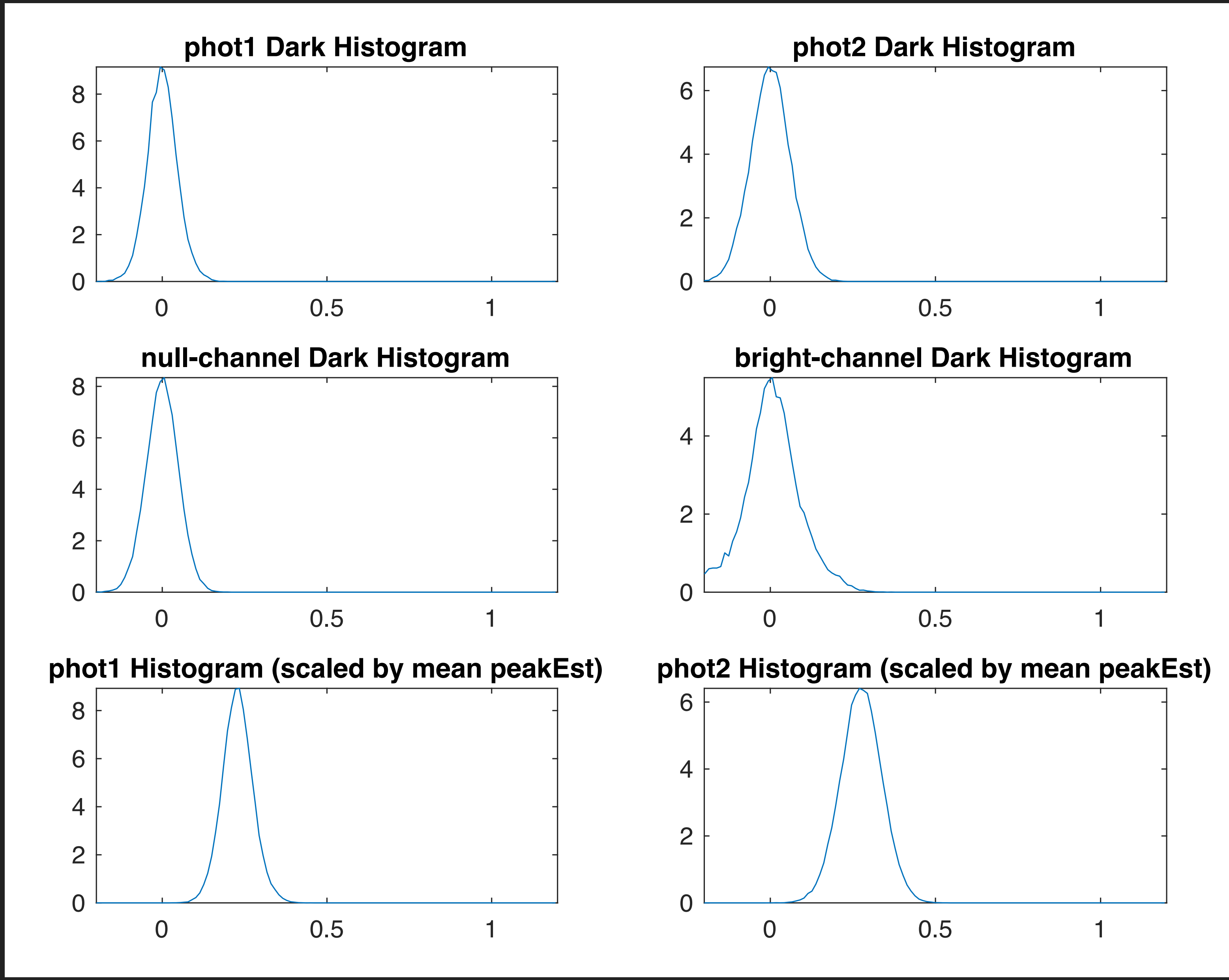
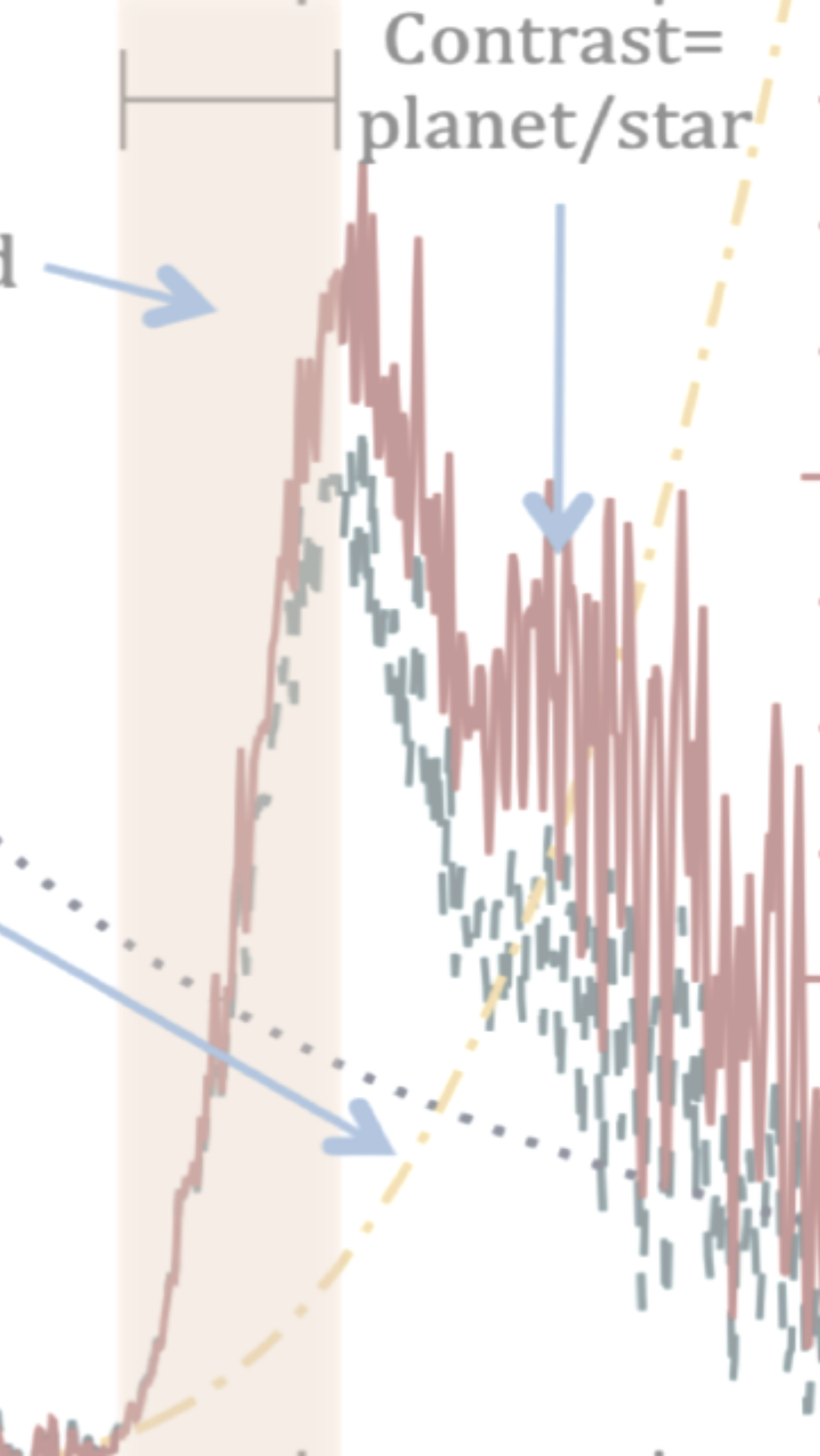
RESULTS



measured PDFS for NSC analysis

CURRENT DEVELOPMENTS AND CHALLENGES

- Proper treatment of chromaticity and polarisation
- Need better detectors!! Currently limited to very bright stars (currently room temp commercial InGaAs photodiodes)
  - Also poses a problem in getting true ‘white-light’ null - hard to see signal in real-time
  - Awaiting C-RED 2 delivery. Also allows spectral dispersion
- Next step - 4 input waveguides
  - 4 nulled baselines, 2 non-nulled
  - How best to use NSC here….?

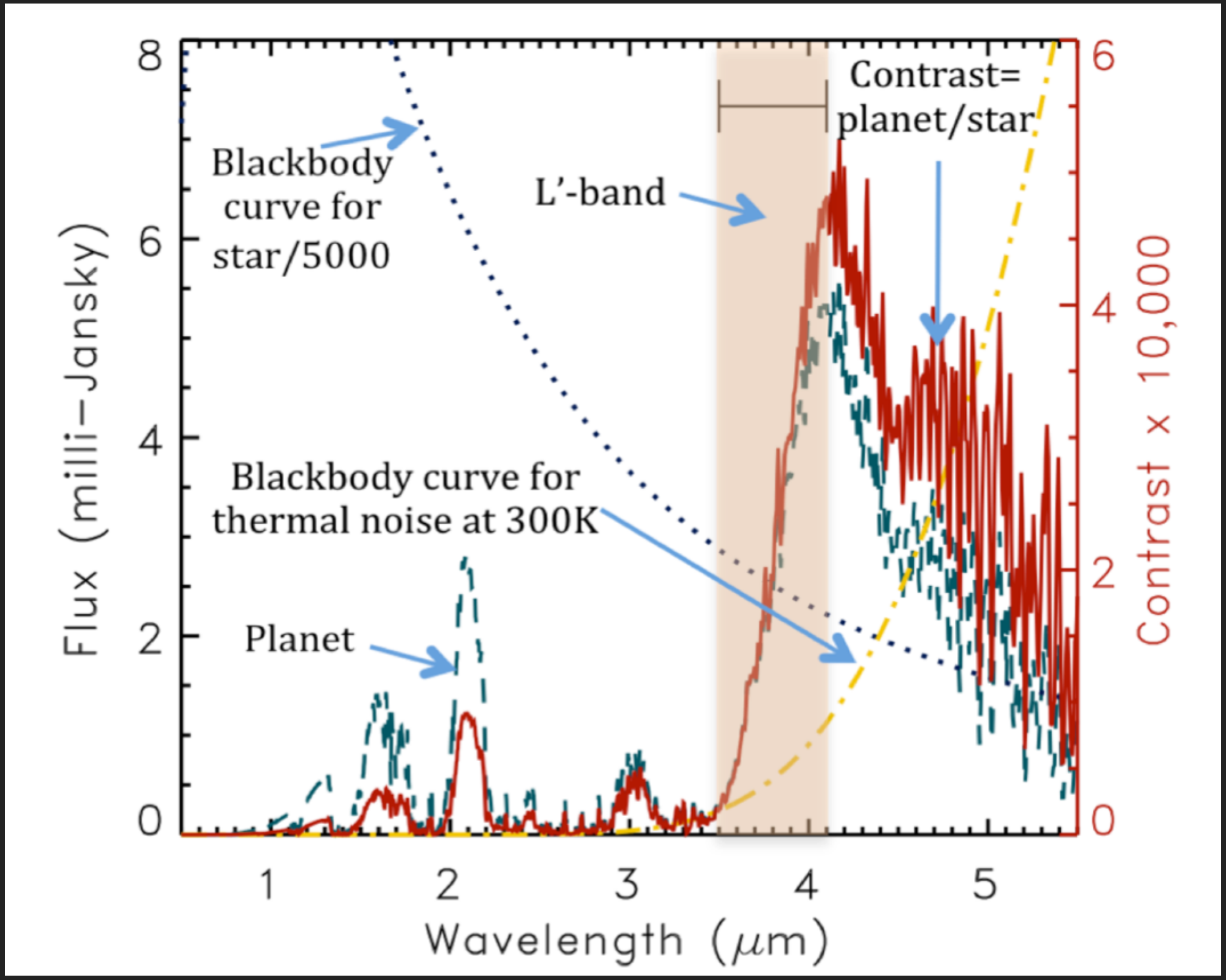


PART 3 – TO THE MID-IR

Current fused-silica good to K band…
… more exotic materials and methods beyond that.

SWEET SPOT WAVELENGTH & MATERIALS

- Existing fused-silica technologies good until ~ K band
- Direct-write in MIR requires new materials and writing techniques

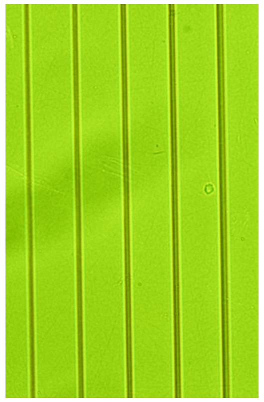


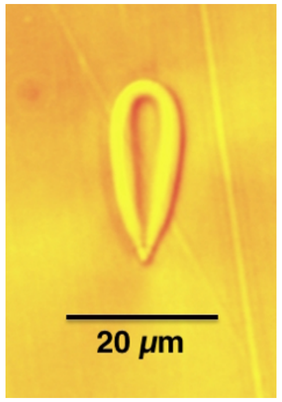
- Tellurides, Chalcogenides, Fluorides
- **Gallium Lanthanum Sulfide (GLS)**
  - High refractive Index
  - High transmission in the IR-Spectrum
  - High photosensitivity
  - Commercially available

Cumulative heating regime

Parameters:

- Pulse energy
- Translation Speed
- Repetition rate
- Writing depth
- NA of focusing objective
- etc.

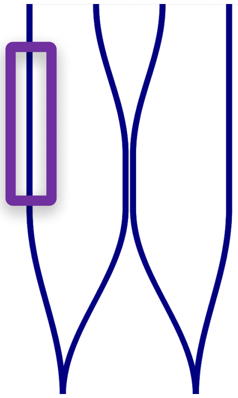




Single scan

0.46 ± 0.09 dB/cm
λ = 3.39 µm

Fairly happy!! But..



- Round mode to avoid coupling losses
- Reduce bending losses

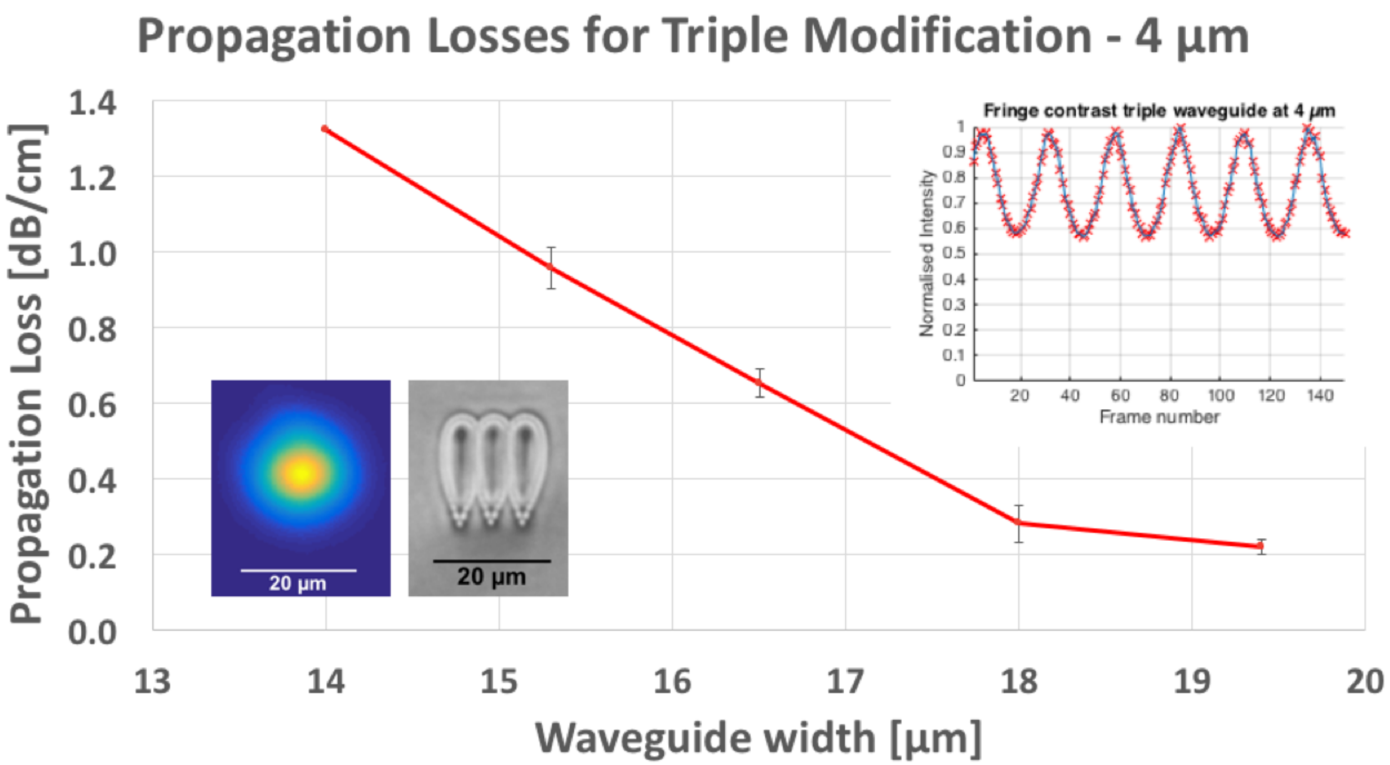
Single scan

0.3 ± 0.07 dB/cm

Triple scan

0.22 ± 0.02 dB/cm

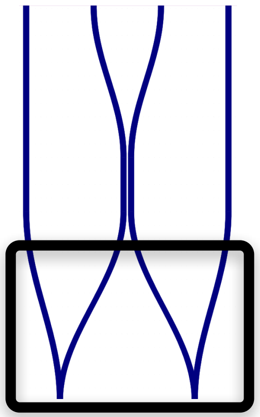
Delta n = 0.012
(RSoft simulation)

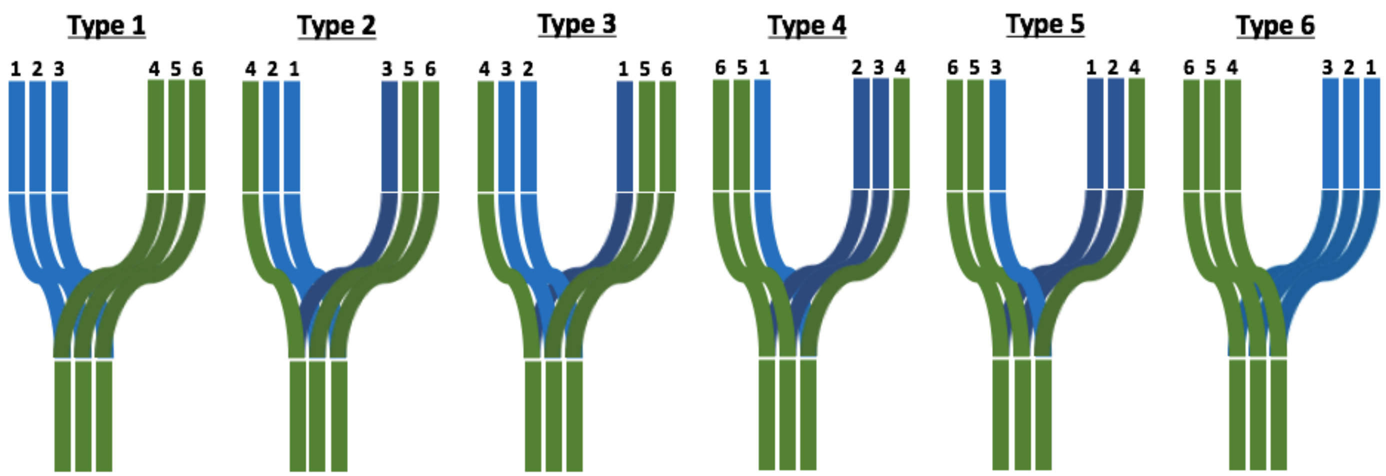


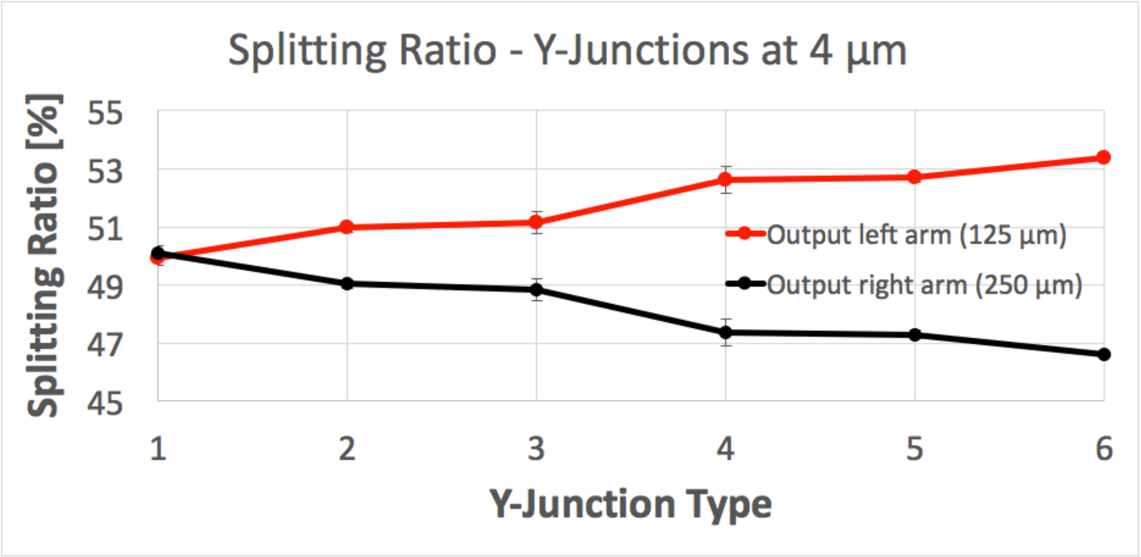
Asymmetric Y-junctions

Waveguide pitch 375 µm (125 + ~250 µm):

- (affordable) micro lens array for injection
- 250 µm pitch for v-groove fiber holder (or camera)

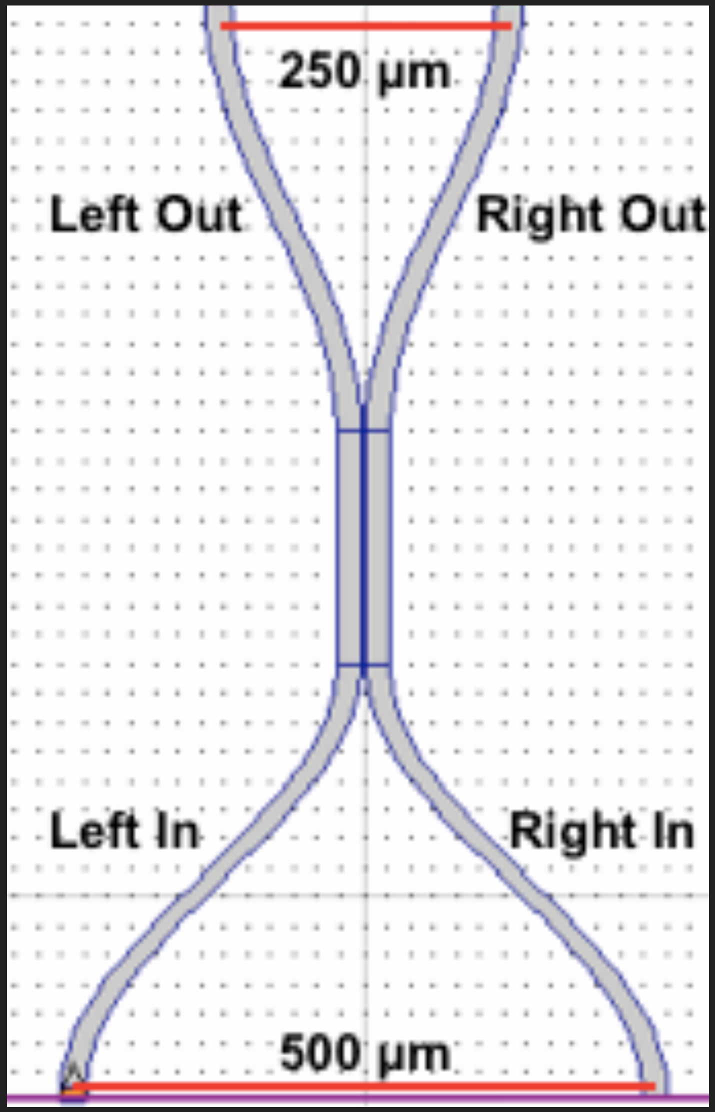


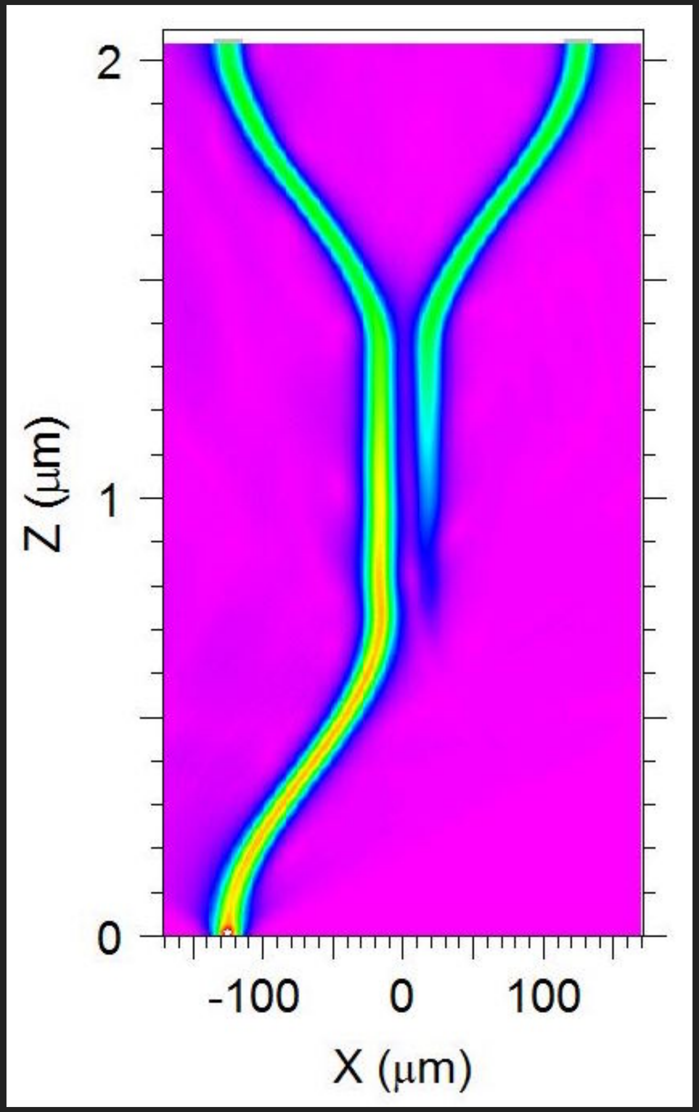


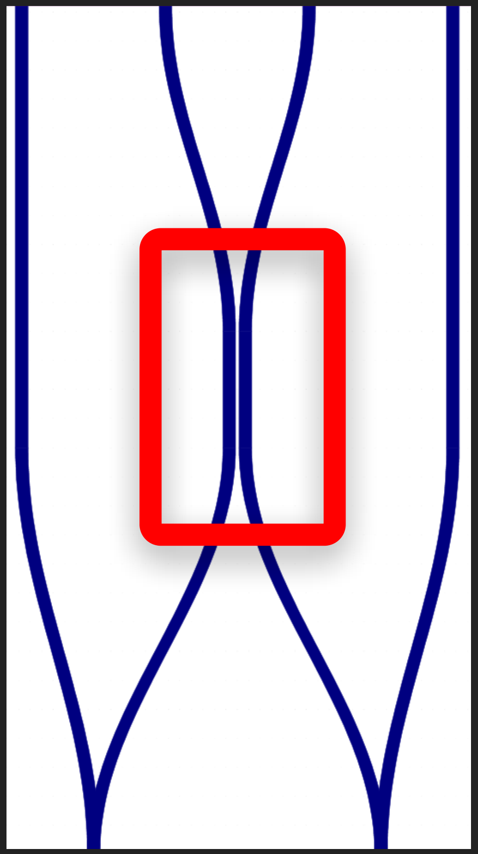


DIRECTIONAL COUPLER

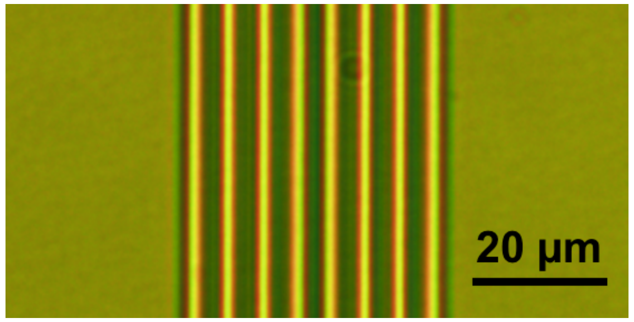
- Key to beam combination

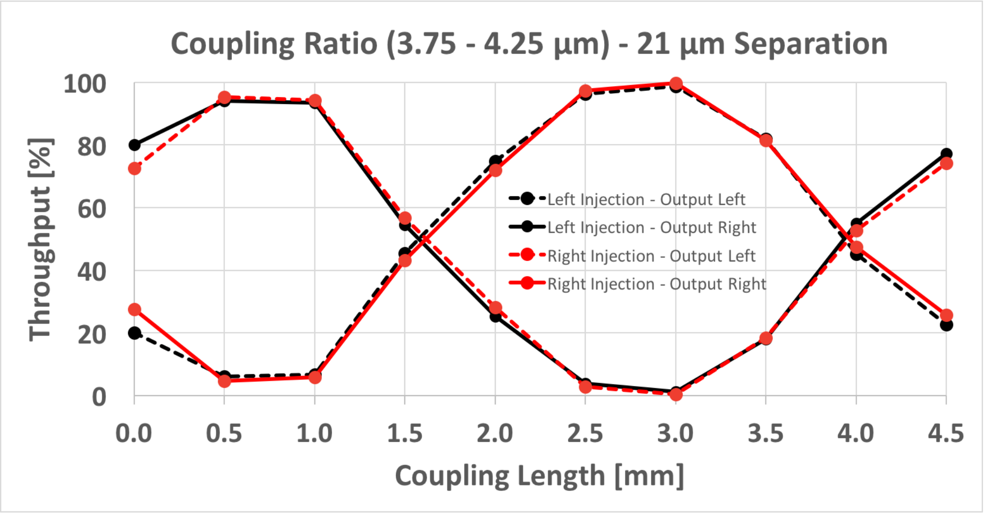


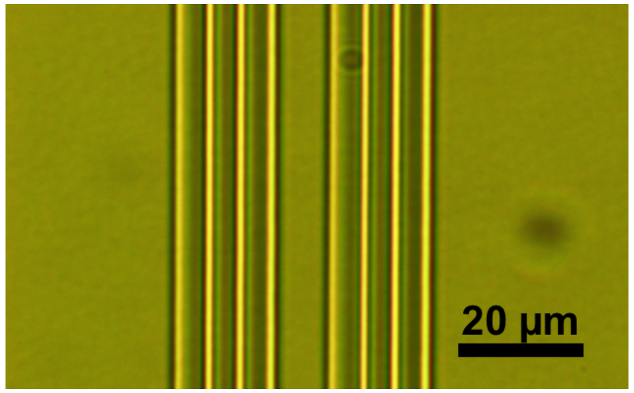


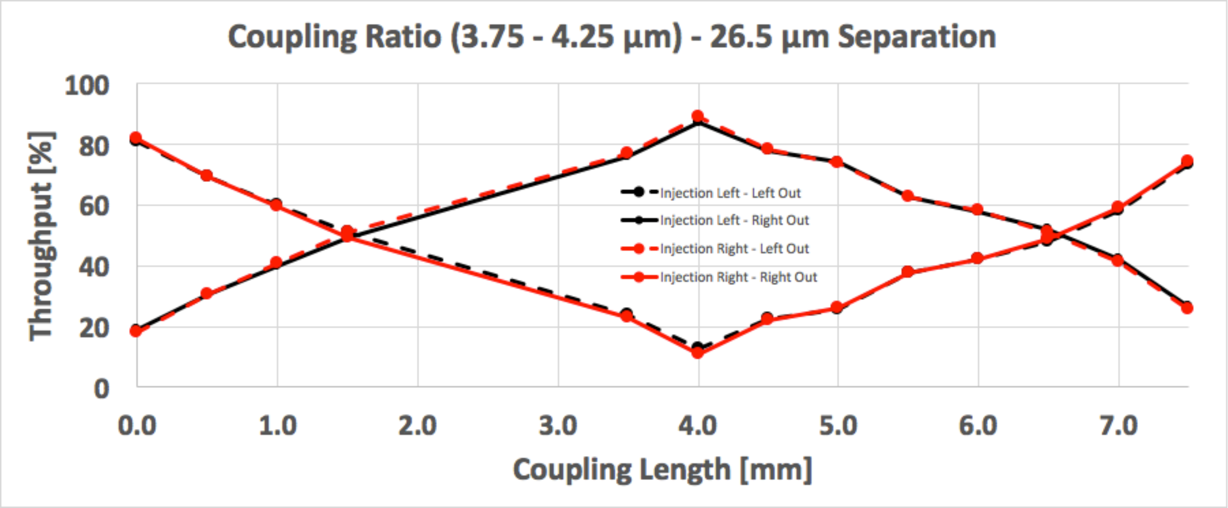


DIRECTIONAL COUPLER









Problem

- Splitting ratio (21 µm seperation): missed the first 50:50
- Coupling starts in the bends

Solution

- Reduce separation or
- Change s-bend style (circular) accepting bending losses

CONCLUSION

- 3D nature of direct-write allows stable (coherent) pupil-remapping
- On-sky demonstration of integrated nulling interferometer in NIR
  - Simultaneous photometry and bright channel
  - NSC analysis
  - Currently dark current limited, high sensitivity spectroscopic back-end Q1 2018
- 4-waveguide version in progress
  - Geometric phase delays?
- Next to the MIR
  - Encouraging results in GLS