iLocater

Finding Earth-like planets among the noise

Achieving precision radial velocity measurements with single-mode fibres

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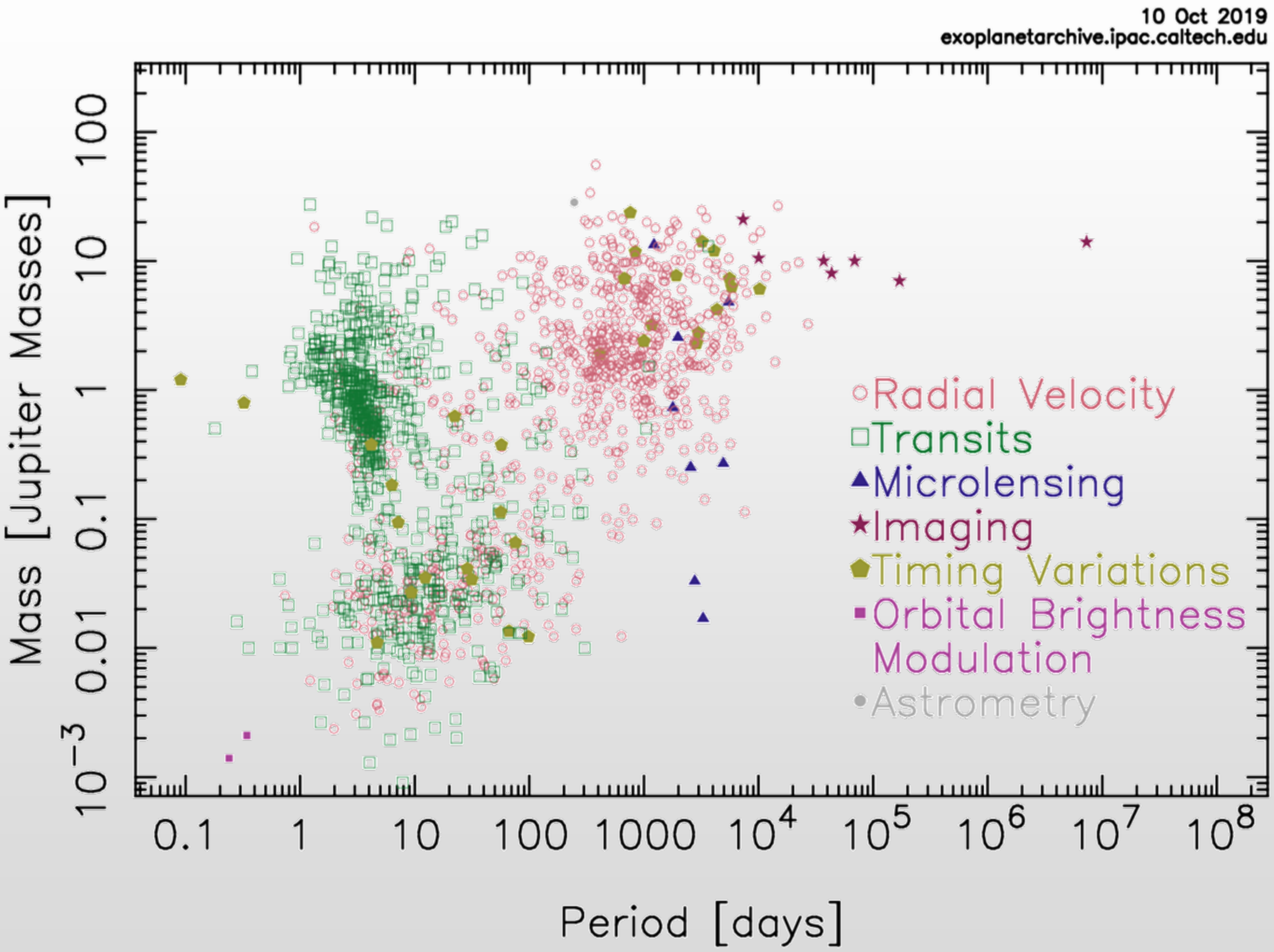
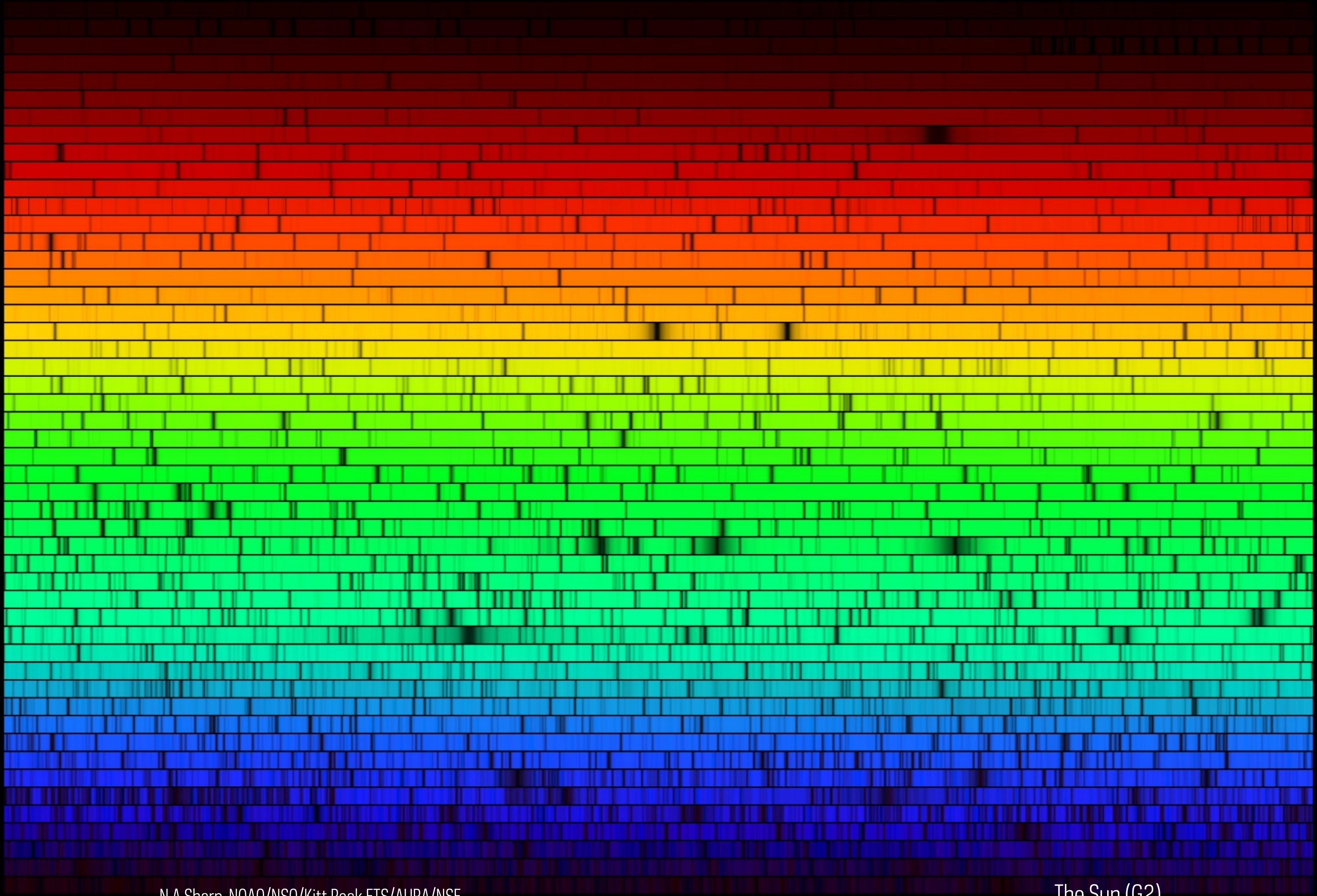
Exoplanets to date





N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

The Sun (G2)

$$\frac{v}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda_{rest}}$$

$$K = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_p \sin i}{{m_s}^{2/3}} \frac{1}{\sqrt{1-\epsilon^2}}$$

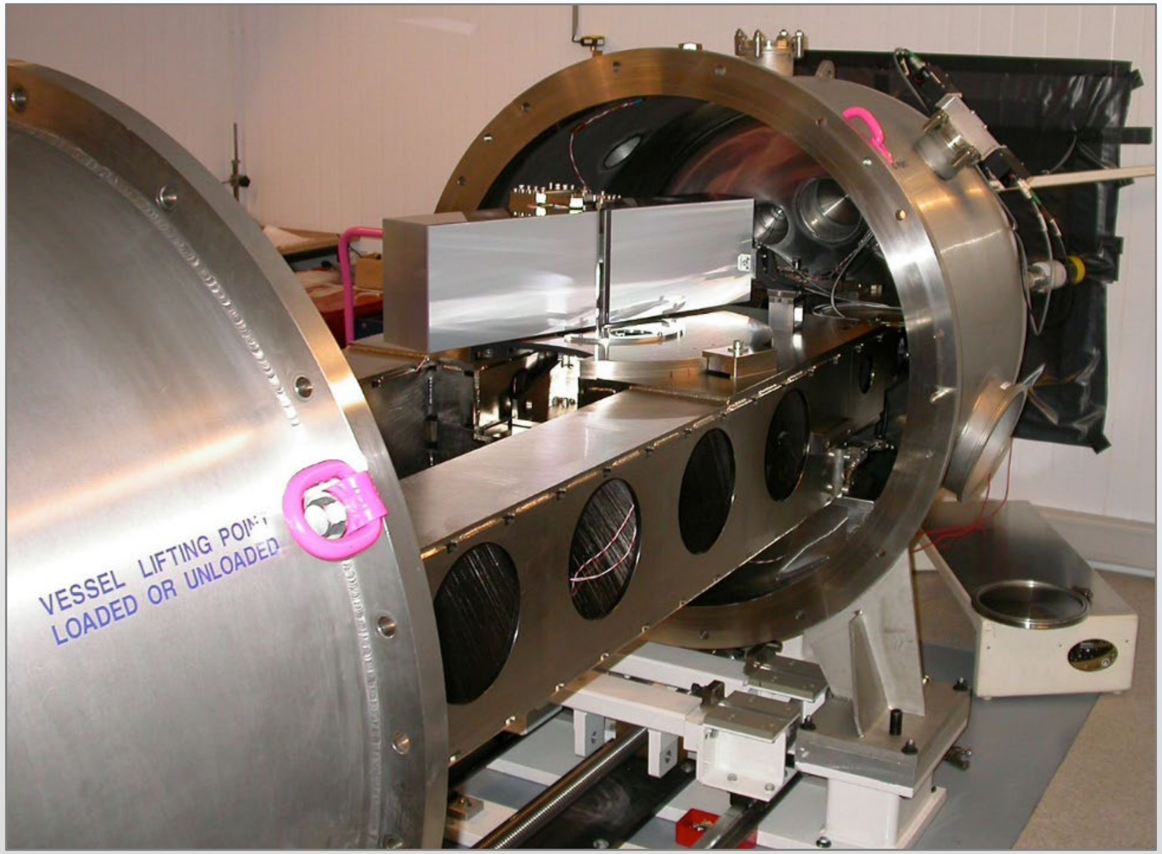
$K_{Jupiter} \approx 10m/s$

$\Delta\lambda_{Jupiter} \approx 30fm$

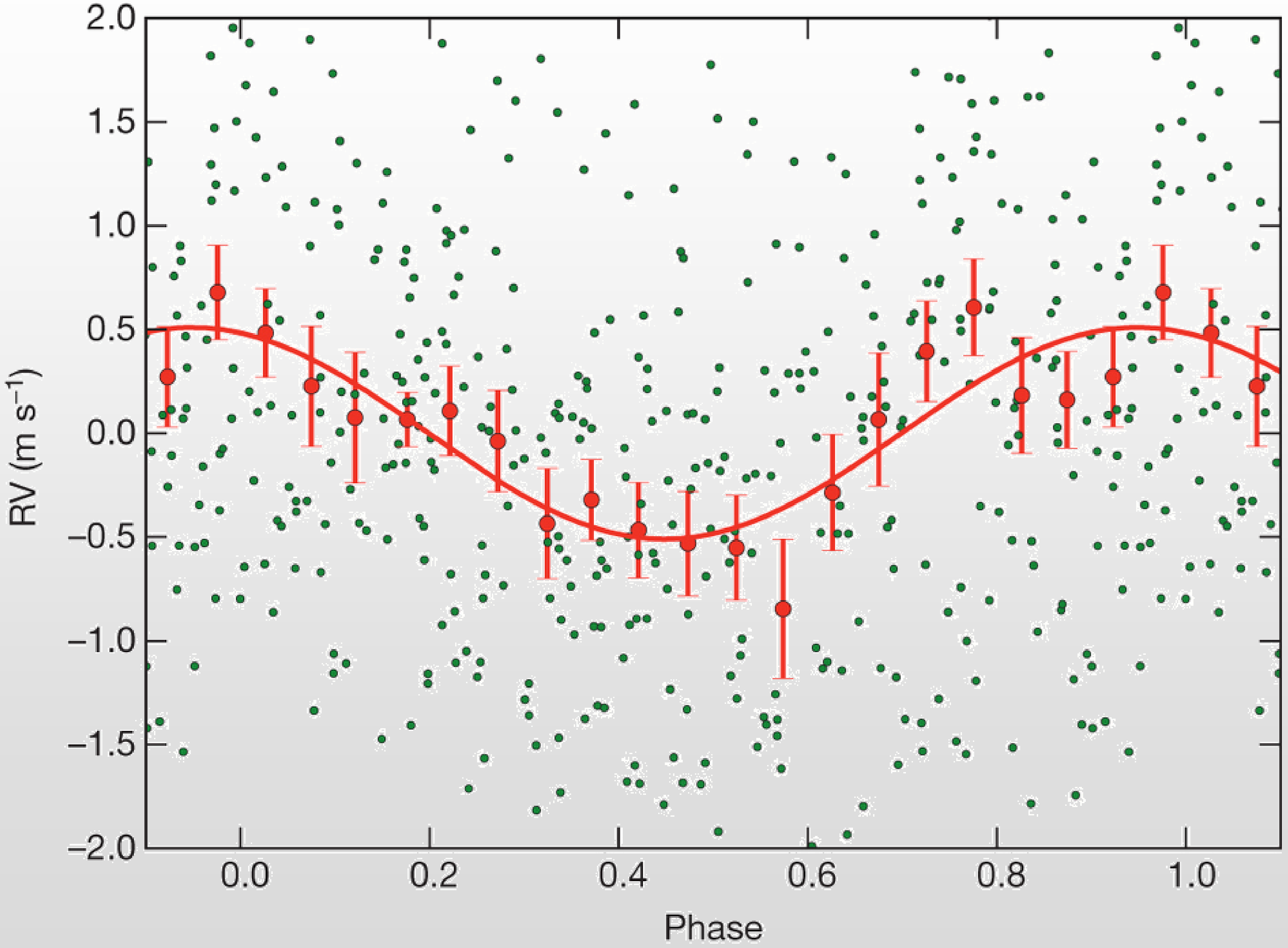
$K_{Earth} \approx 10cm/s$

$\Delta\lambda_{Earth} \approx 0.33fm$

Current Generation Precision RV - HARPS

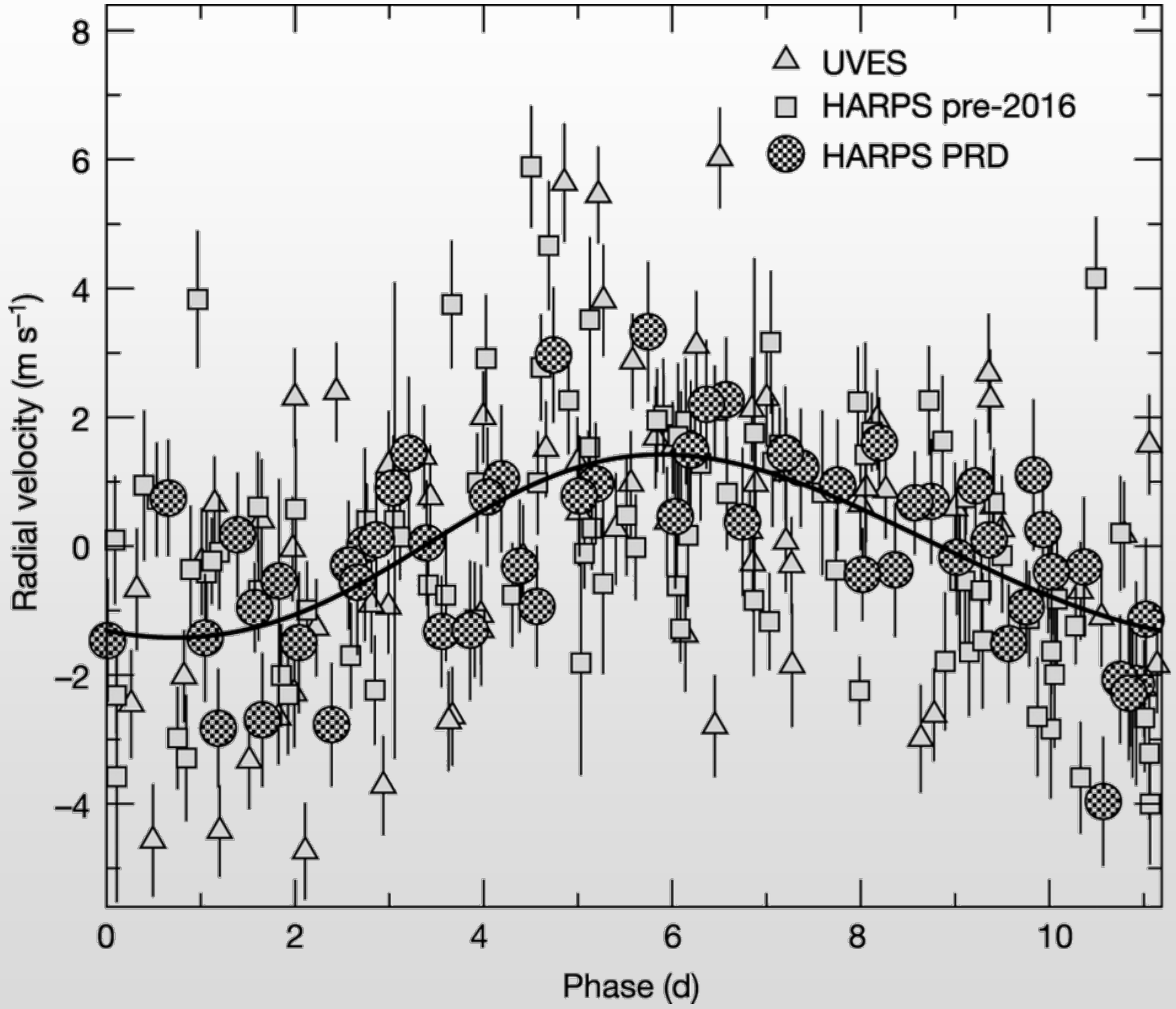


Current Generation Precision RV - HARPS



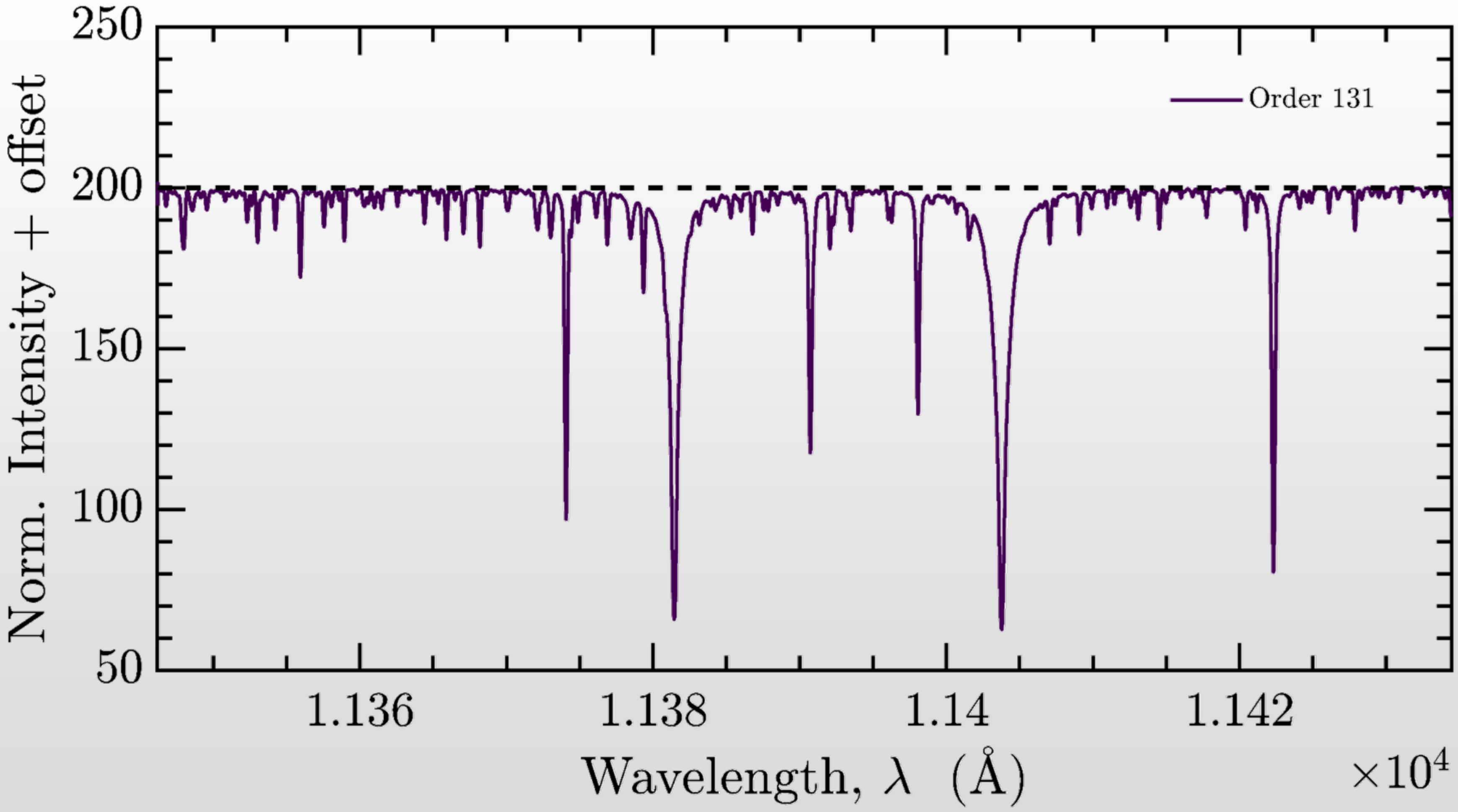
Dumusque et al. 2012
Hatzes 2013

Current Generation Precision RV - HARPS



Anglada-Escudé,et al. 2016

Radial Velocity Measurements



Radial Velocity – Instrument Precision

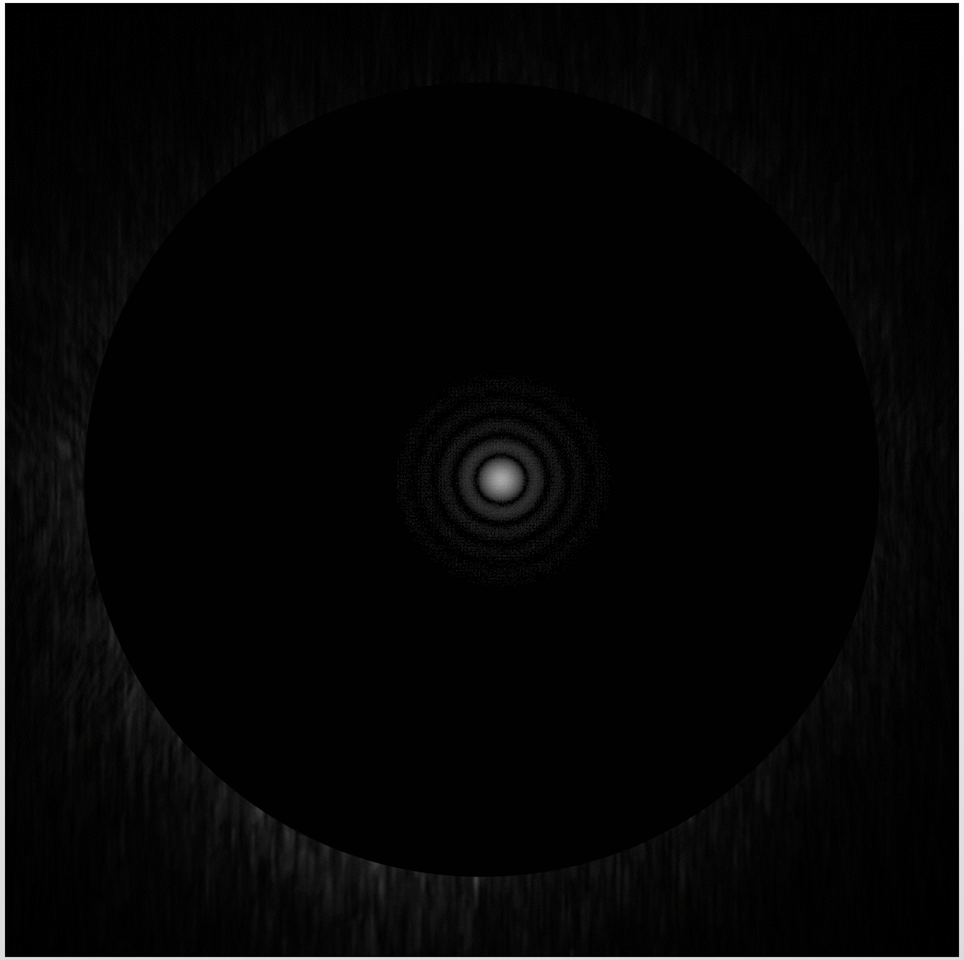
Barycentric Correction

Photon Noise

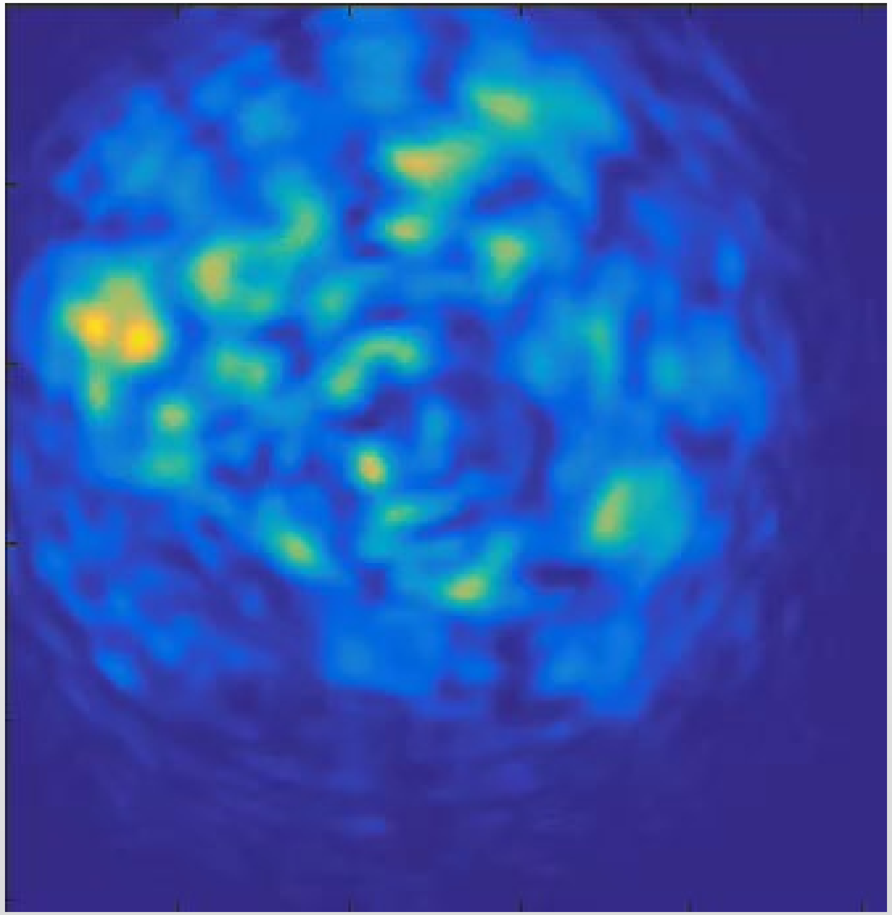
Tellurics

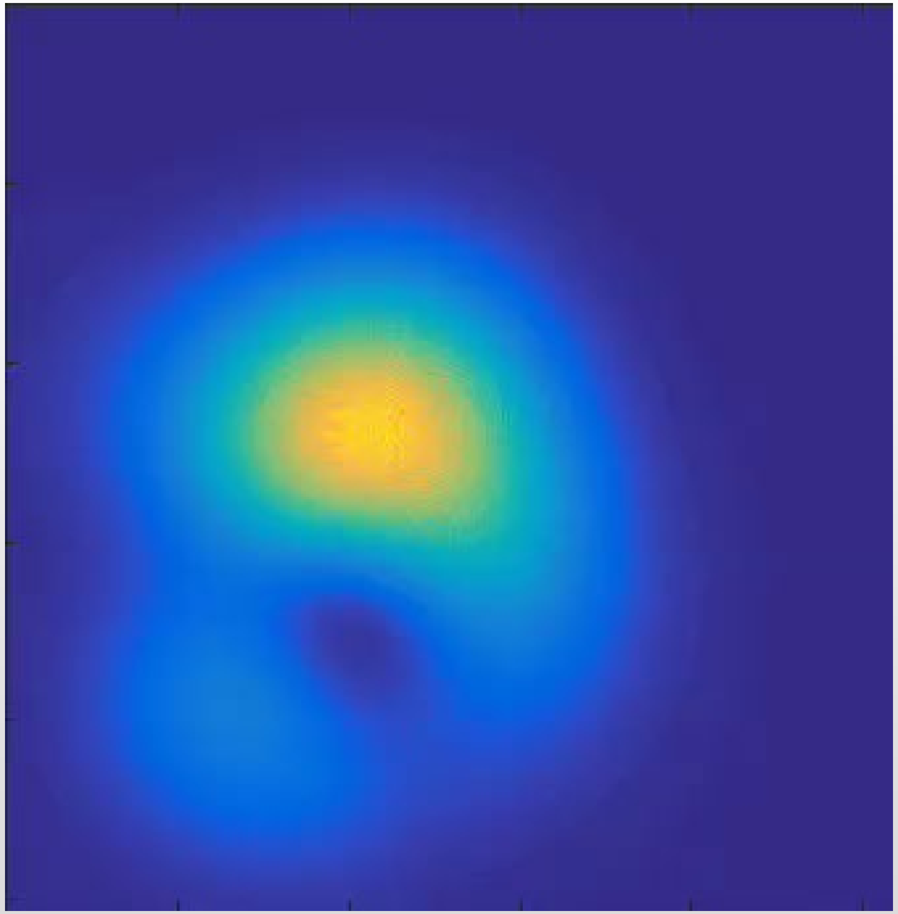
Polarization Effects

Spectrograph Illumination

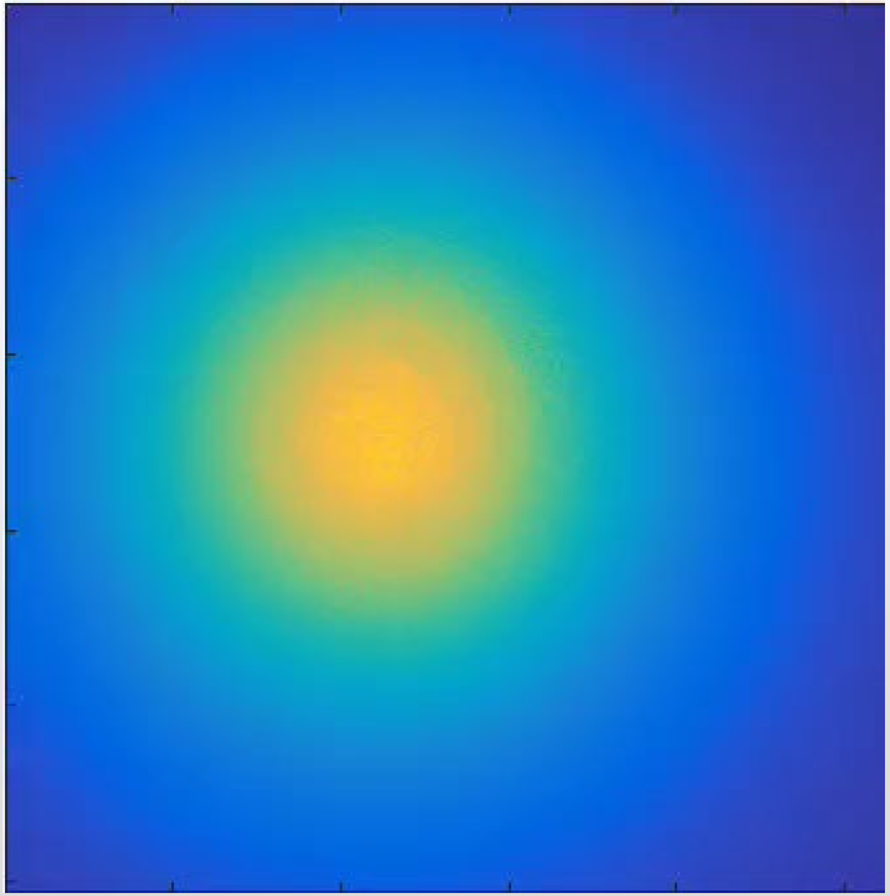


Single-Mode vs Multi-Mode





Single-Mode vs Multi-Mode



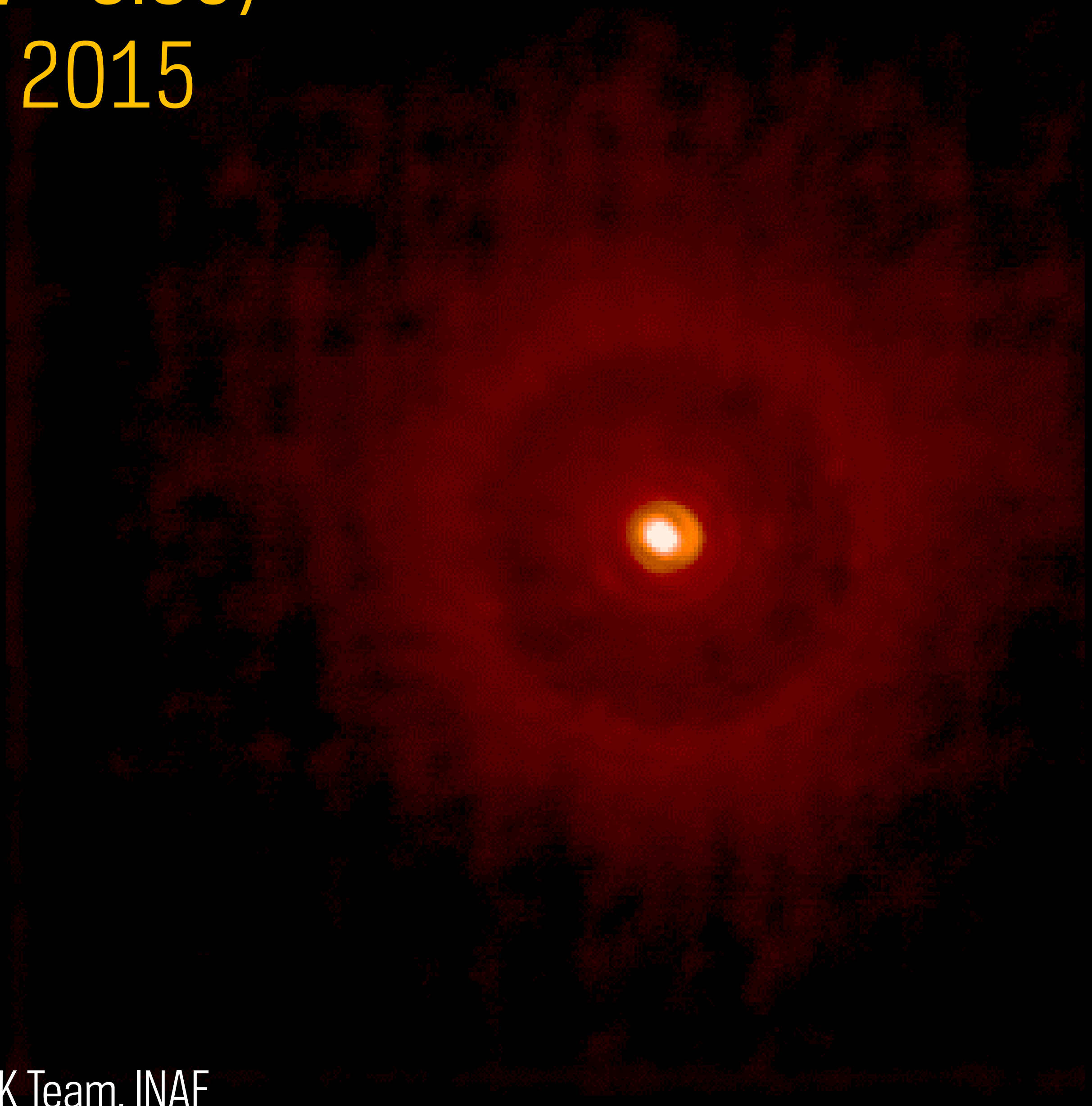
The benefits of Single-Mode Fibres

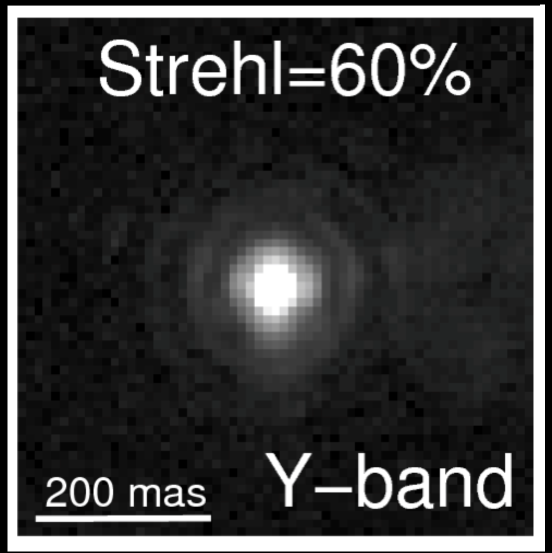
- Mitigates the effects of modal noise
- Diffraction-limited input to spectrograph
  - Reduces overall spectrograph size/envelope
  - Easier to stabilize
  - Use of more intrinsically stable materials
  - Makes spectrograph decoupled from specifics of telescope feeding it
- Diffraction-limited input on the sky
  - Reduces the effect of sky contamination
  - Reduces the effect of contamination from other close sources

HIP 48455 (V=3.85)
February 13, 2015

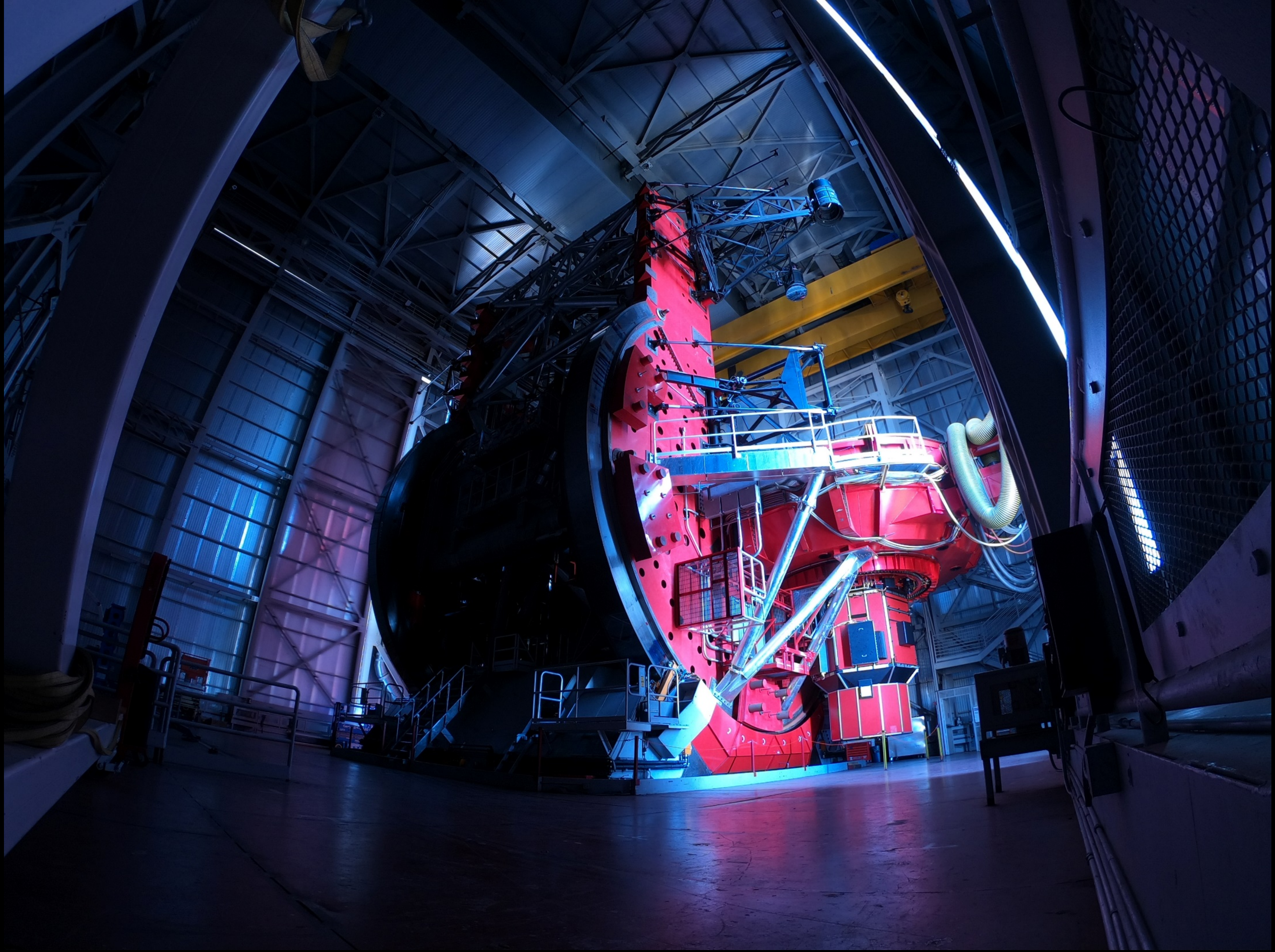
Raw FWHM=34 mas
λ=630 nm (6% bandpass)
f=990 Hz, 300 modes
Seeing=0.8″

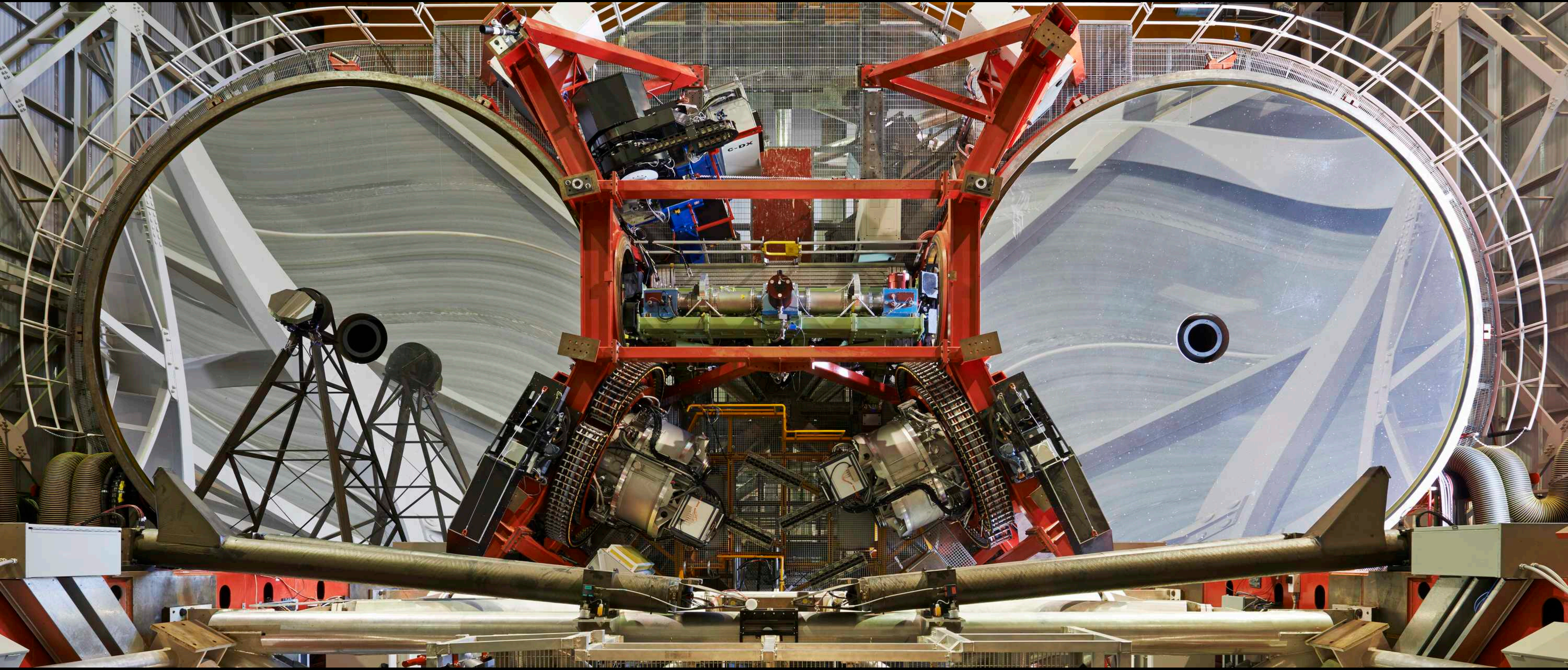
Strehl ratio: >30%





Data Courtesy of SHARK Team, INAF





iLocater

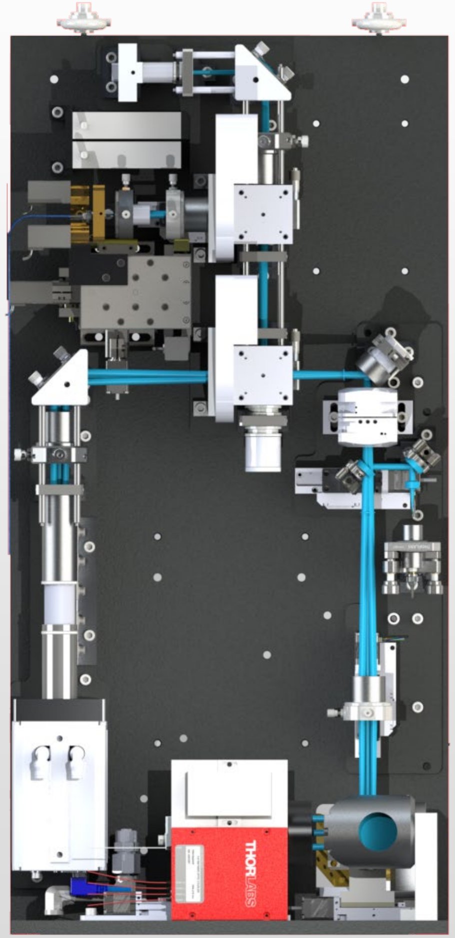
UNIVERSITY OF NOTRE DAME

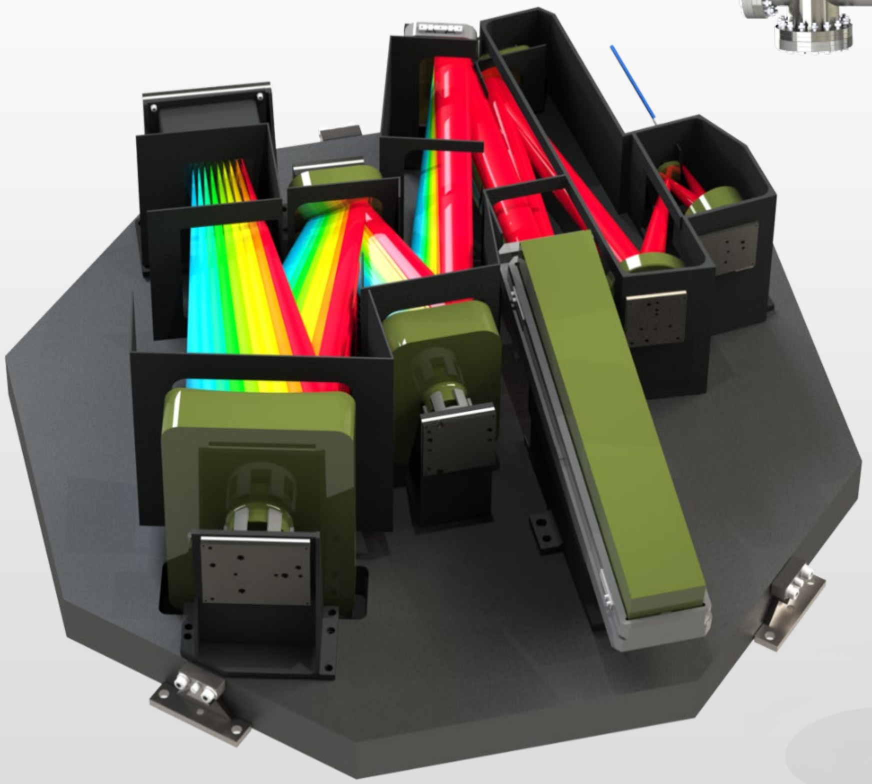
The iLocater Instrument

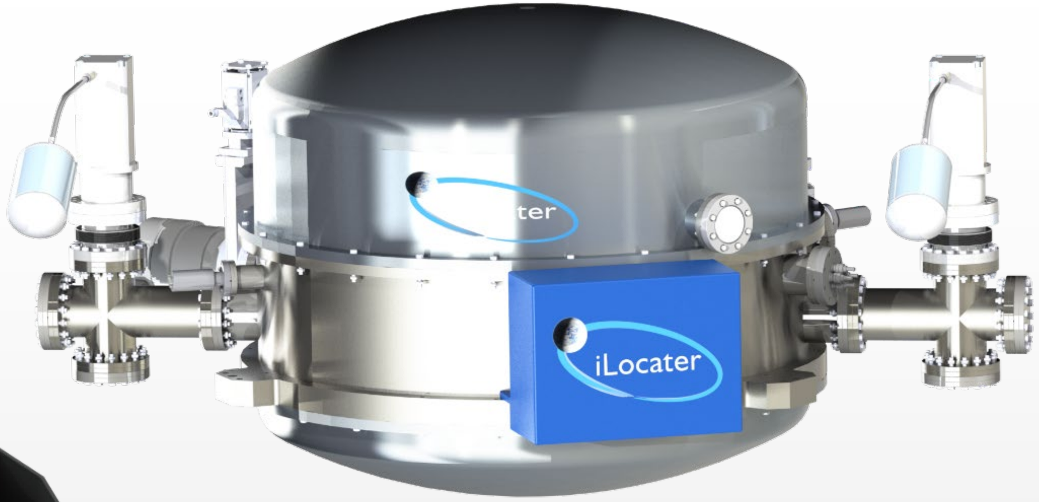
- Designed for use on the Large Binocular Telescope
- Operates in the Y- and J-bands (0.97-1.27μm)

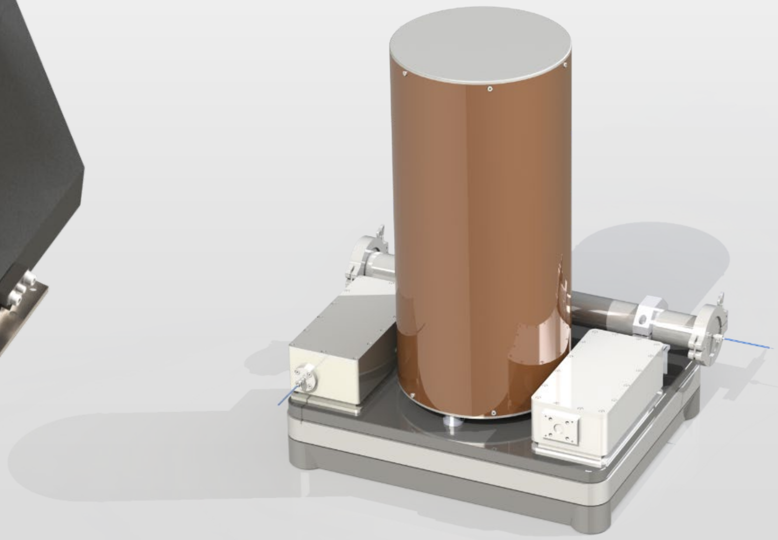
- Four major components:

The iLocater Instrument







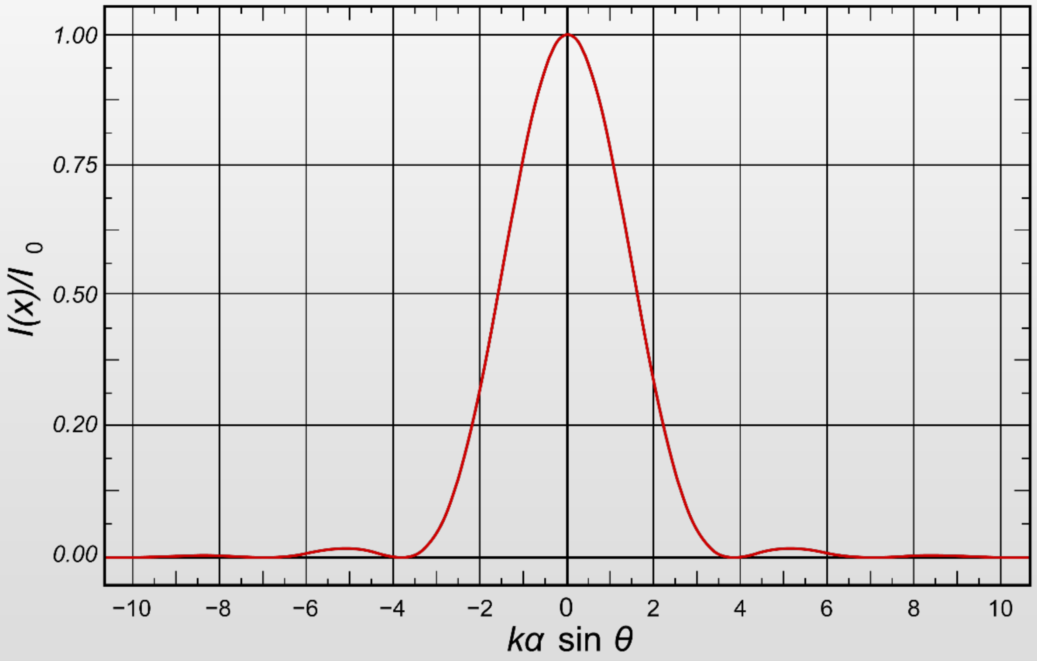


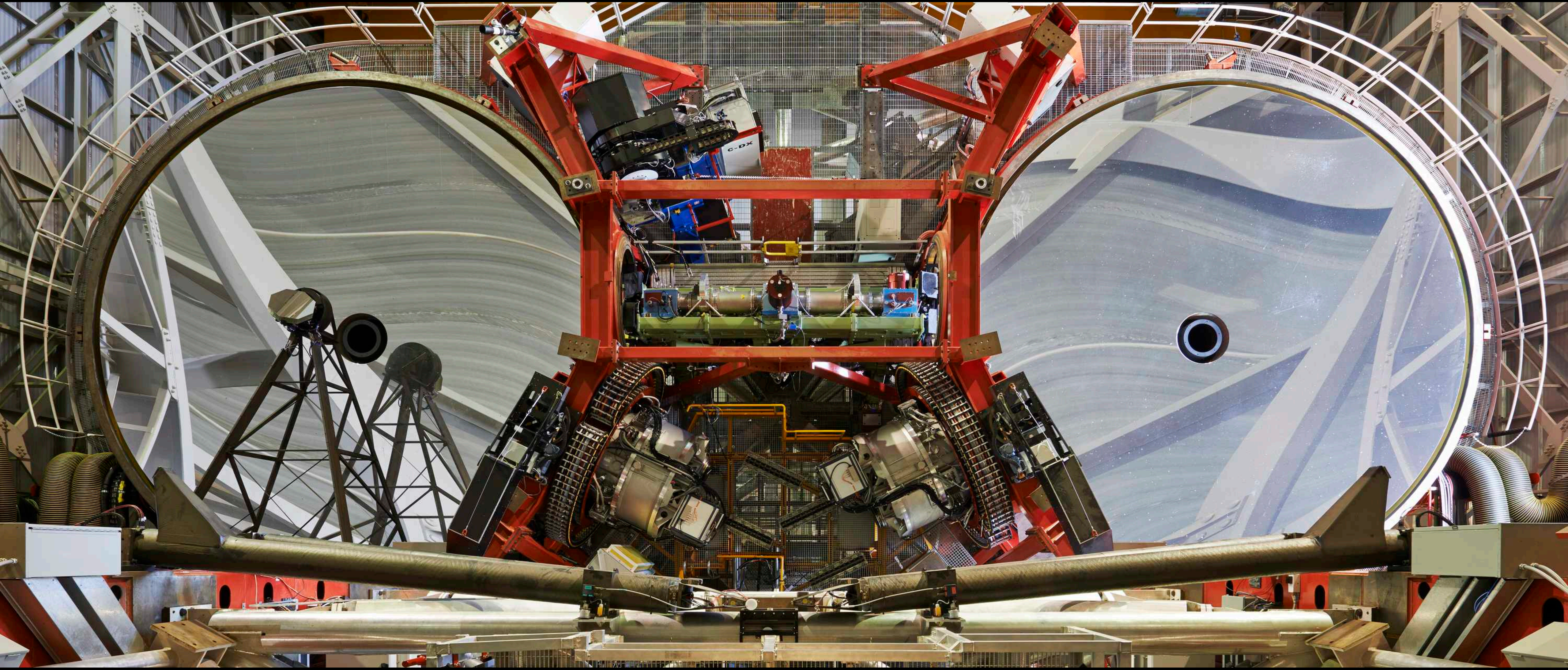
Acquisition Camera

How do you get light into a single-mode fibre?

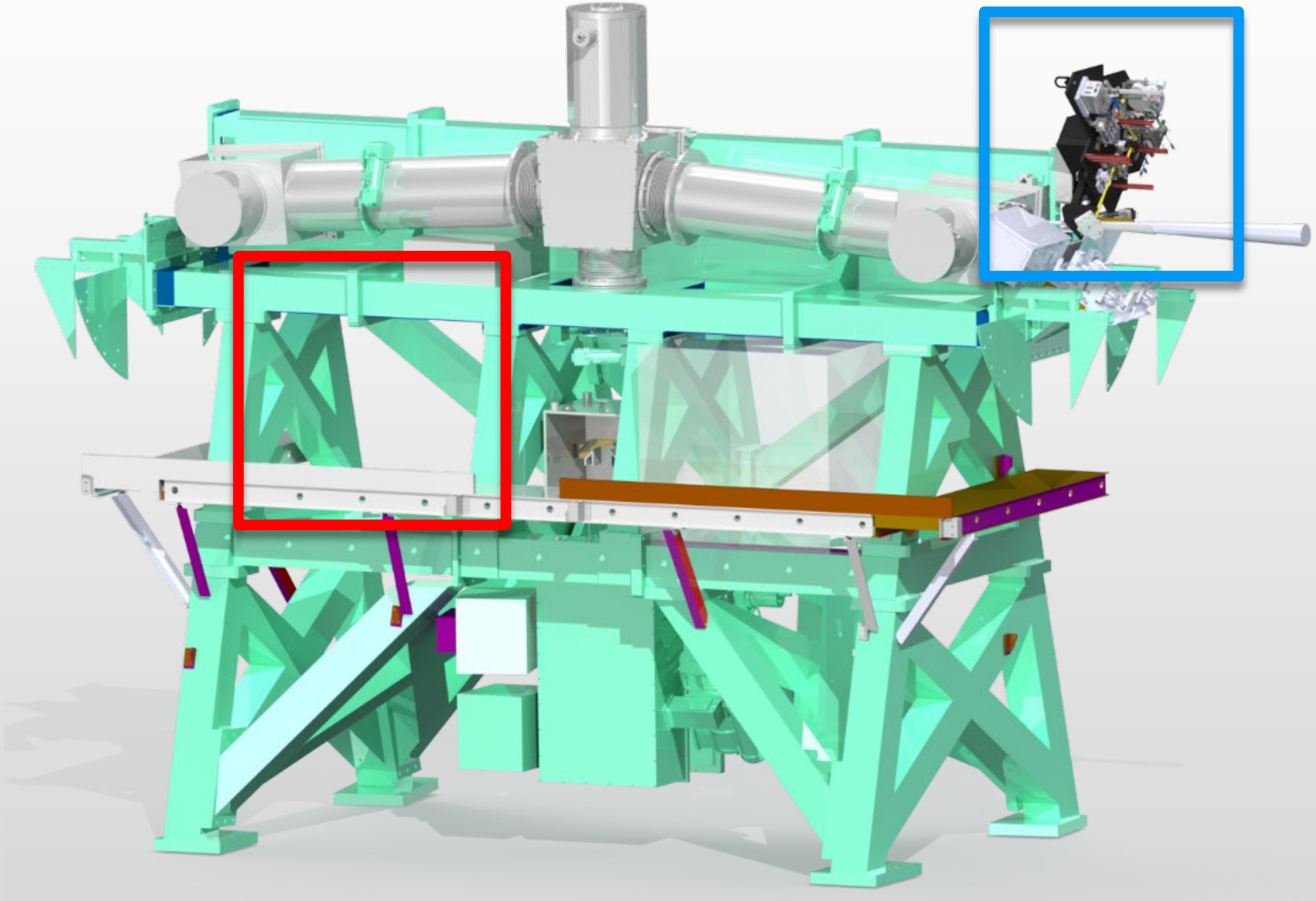
- To efficiently couple light into a single-mode fibre – you're trying to match the incident beam to the spatial mode of the fibre as closely as possible.

- To do that, you need to:
  - Scale so the $1/e^2$ diameter of Airy disk PSF matches the mode field diameter of your fibre.
  - Don't exceed the NA of the fibre
  - Have a 'flat' wavefront
  - Have very good atmospheric dispersion correction
  - Have a stable beam

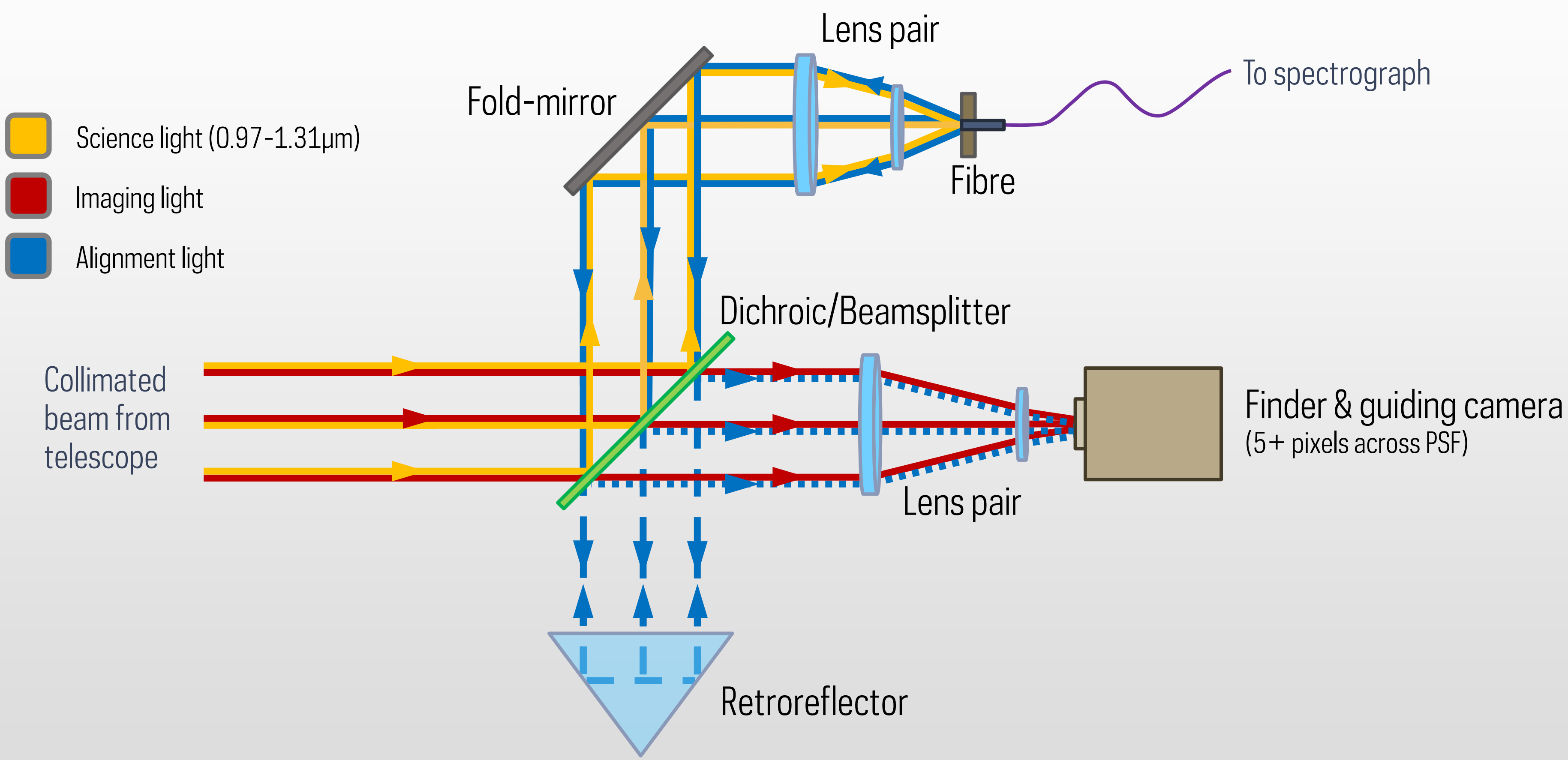


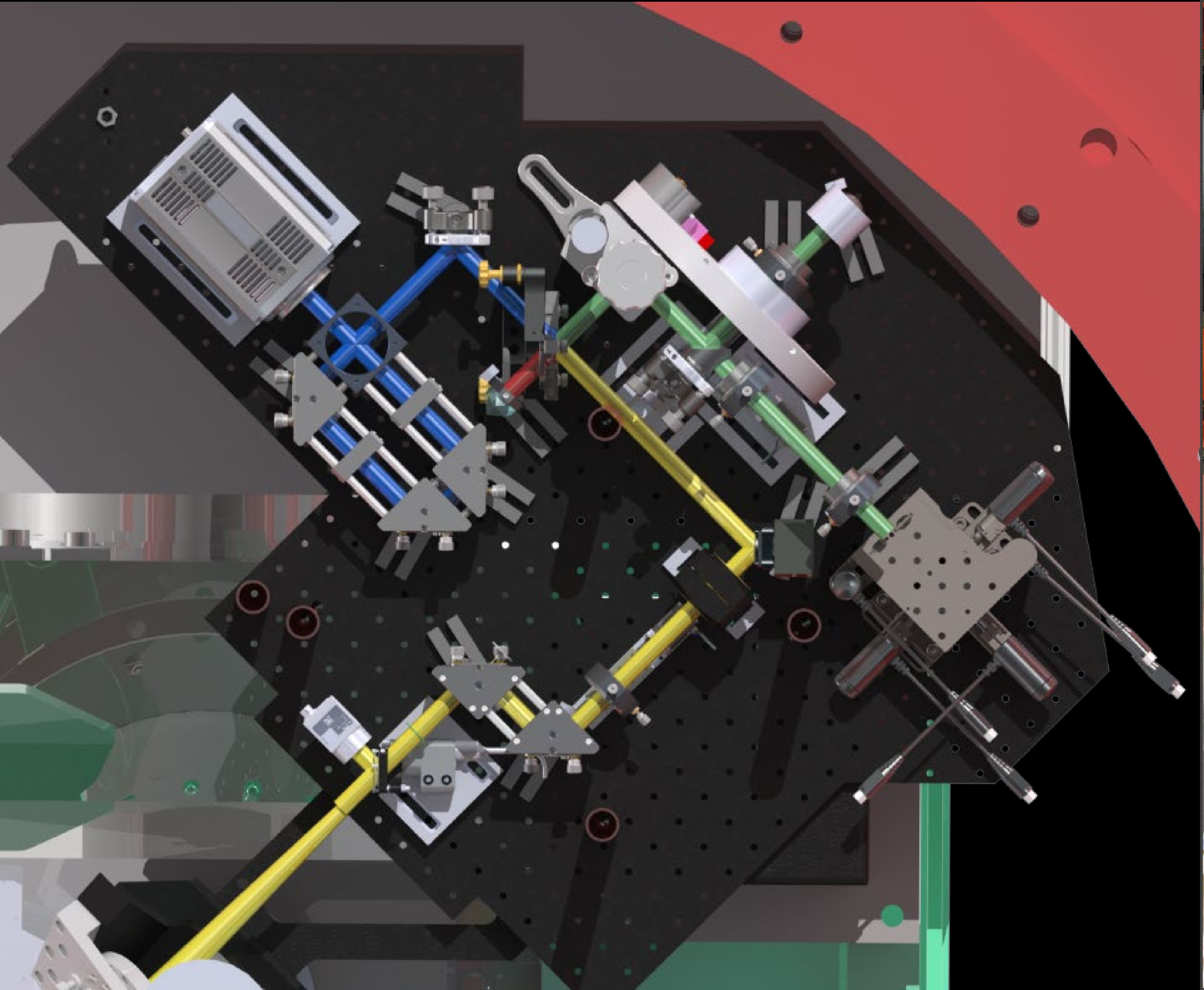


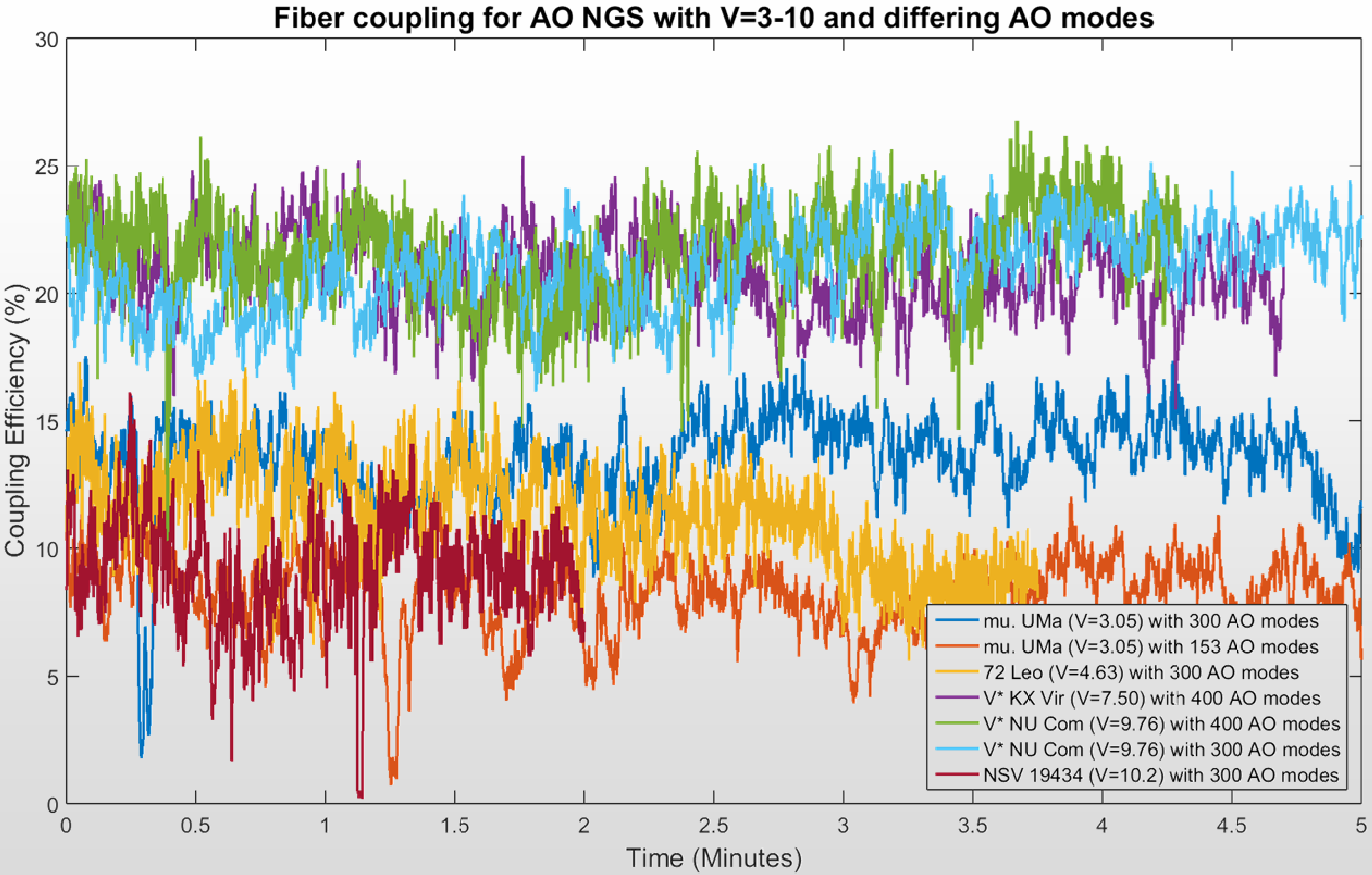
iLocater & LBTI



Single-Mode Fibre Coupling

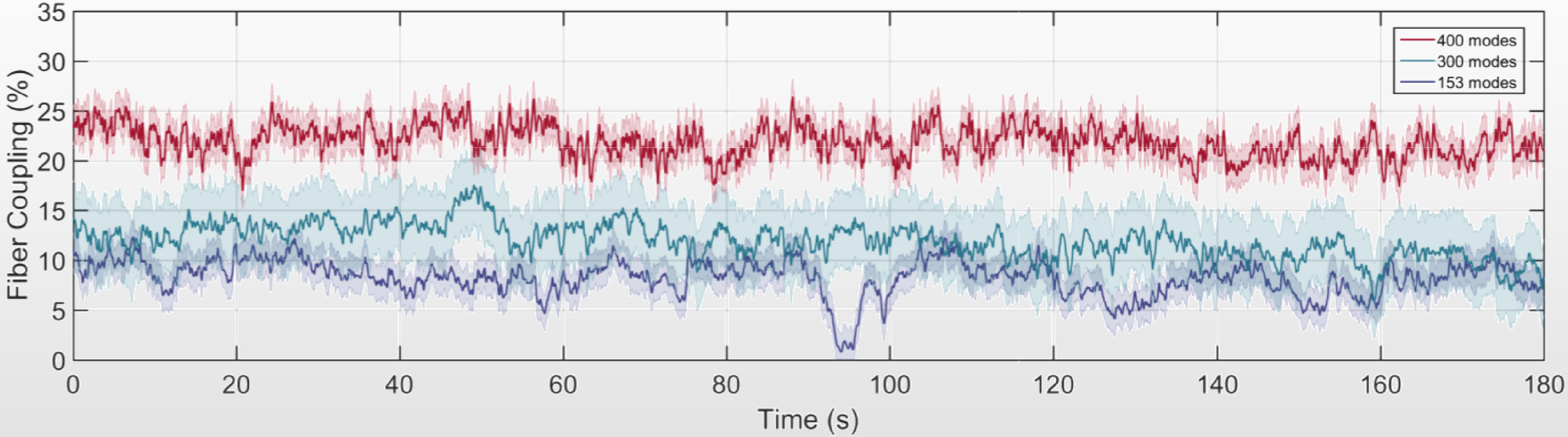





Fiber coupling for AO NGS with V=3-10 and differing AO modes
Coupling Efficiency (%)
Time (Minutes)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
mu. UMa (V=3.05) with 300 AO modes
mu. UMa (V=3.05) with 153 AO modes
72 Leo (V=4.63) with 300 AO modes
V* KX Vir (V=7.50) with 400 AO modes
V* NU Com (V=9.76) with 400 AO modes
V* NU Com (V=9.76) with 300 AO modes
NSV 19434 (V=10.2) with 300 AO modes

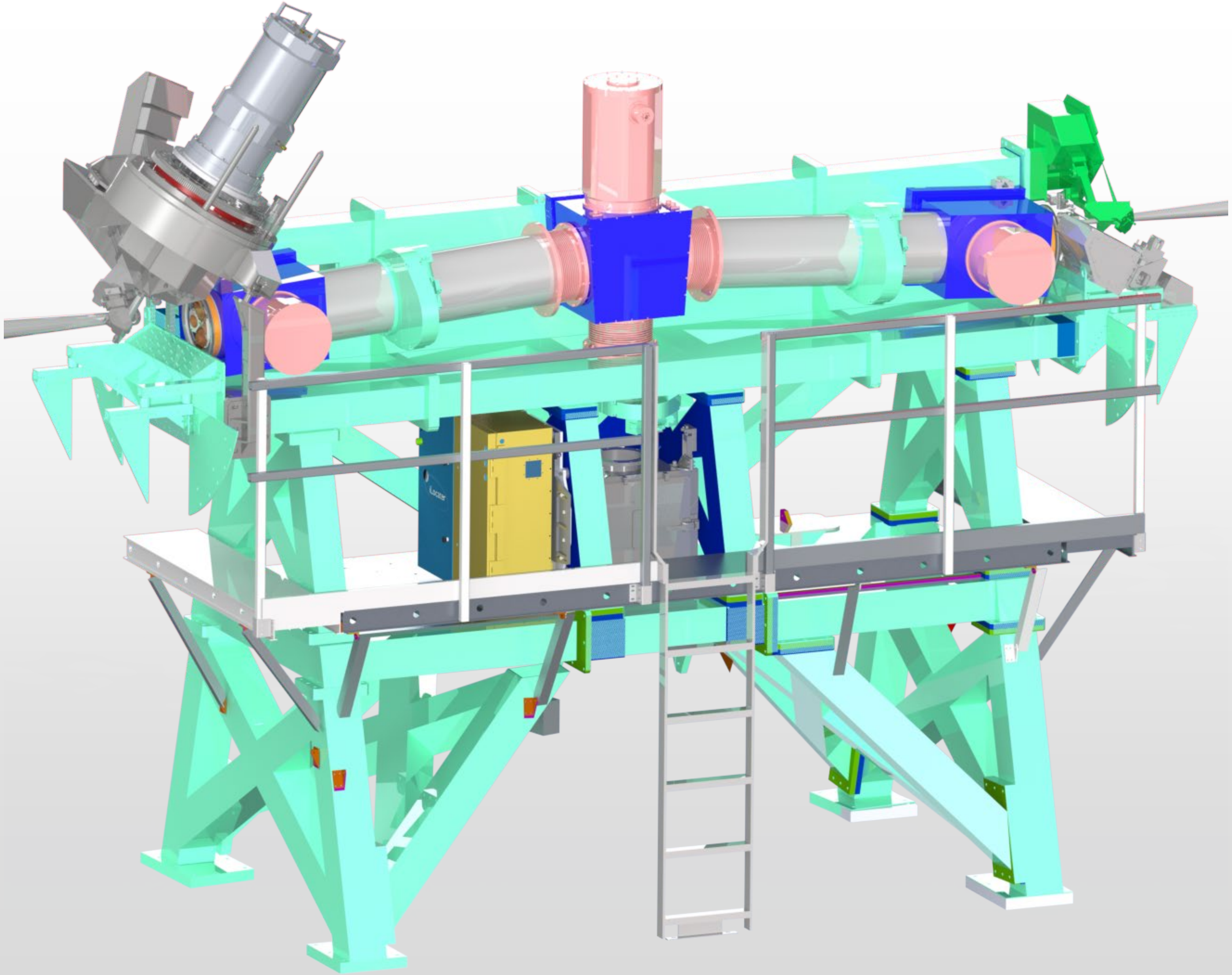
Single-Mode Fibre Coupling Efficiency

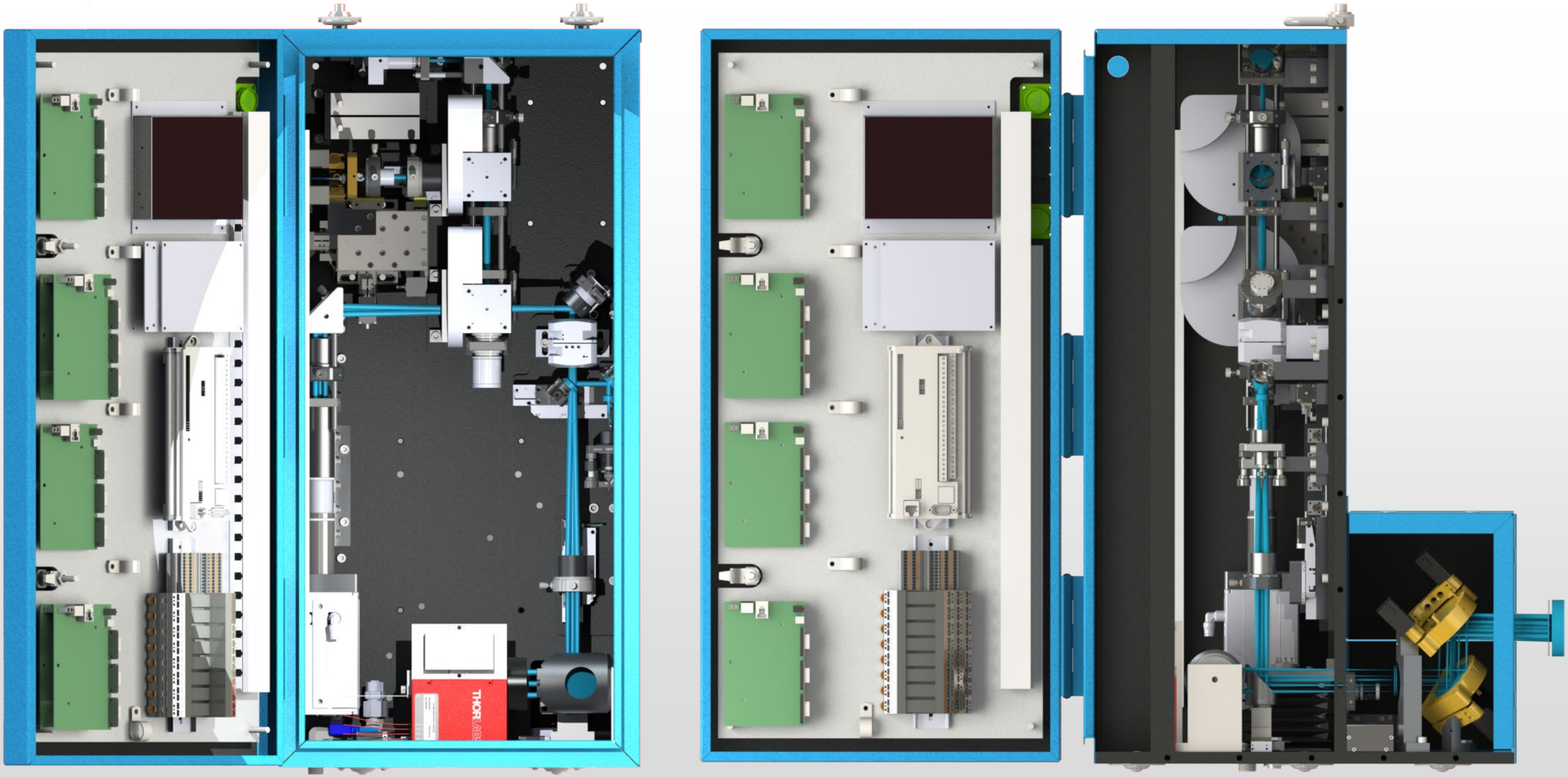
Bechter et al. 2019, PASP

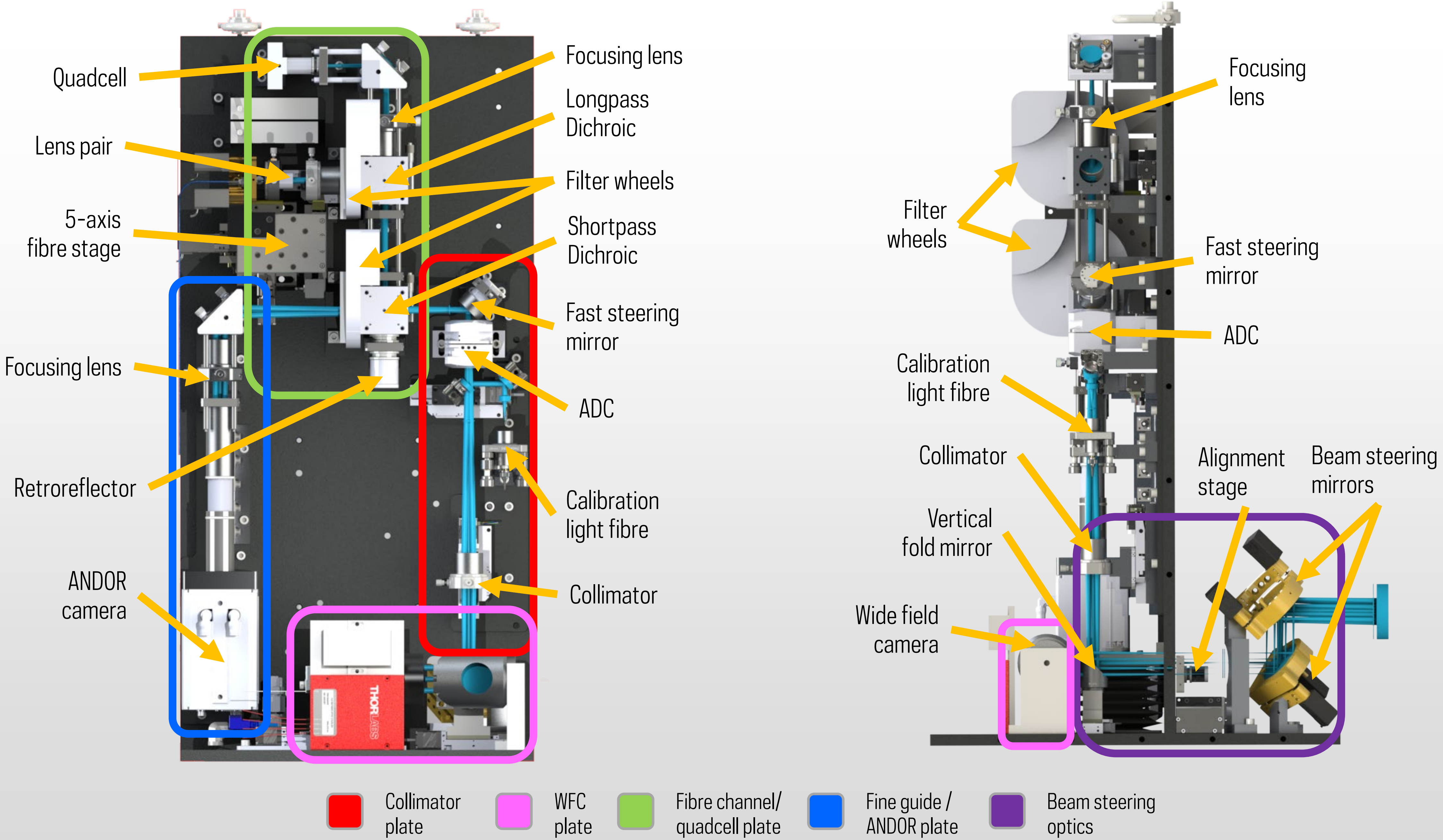


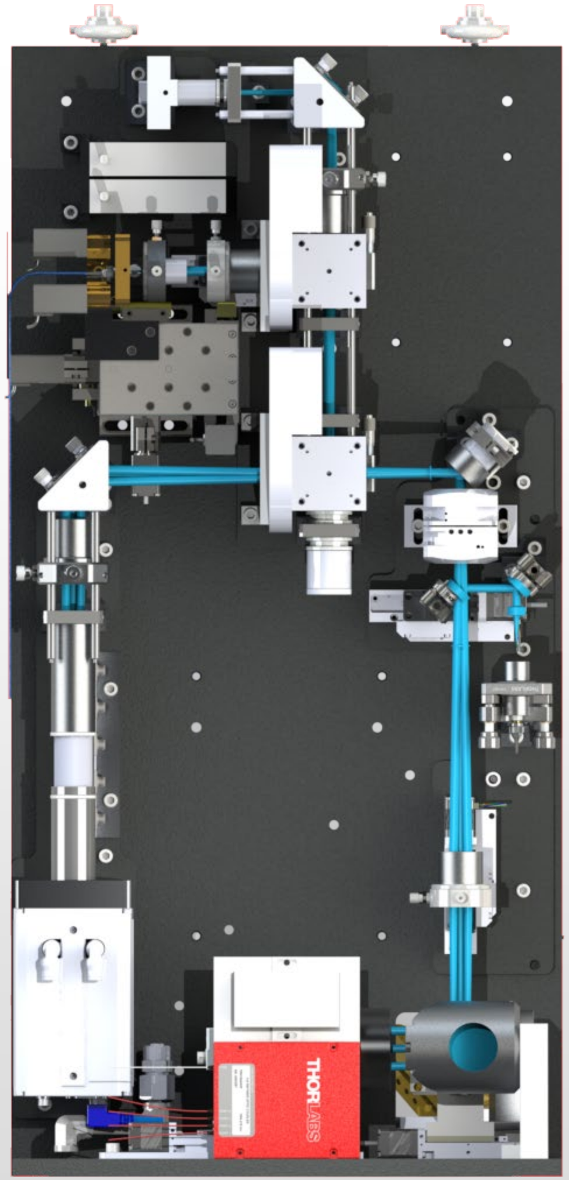
What is the limiting factor?

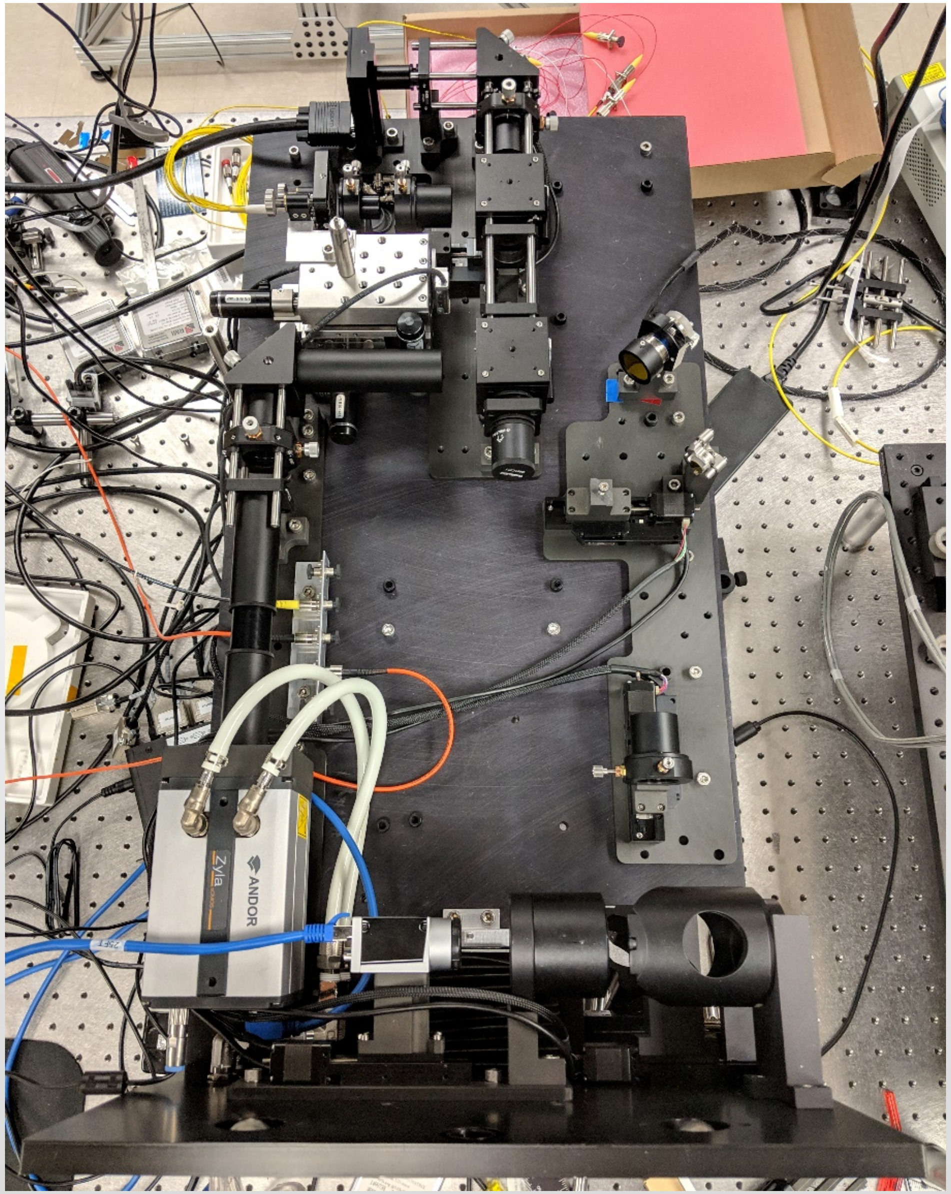
- Strong visual correlation with AO performance
- What are the additional effects?

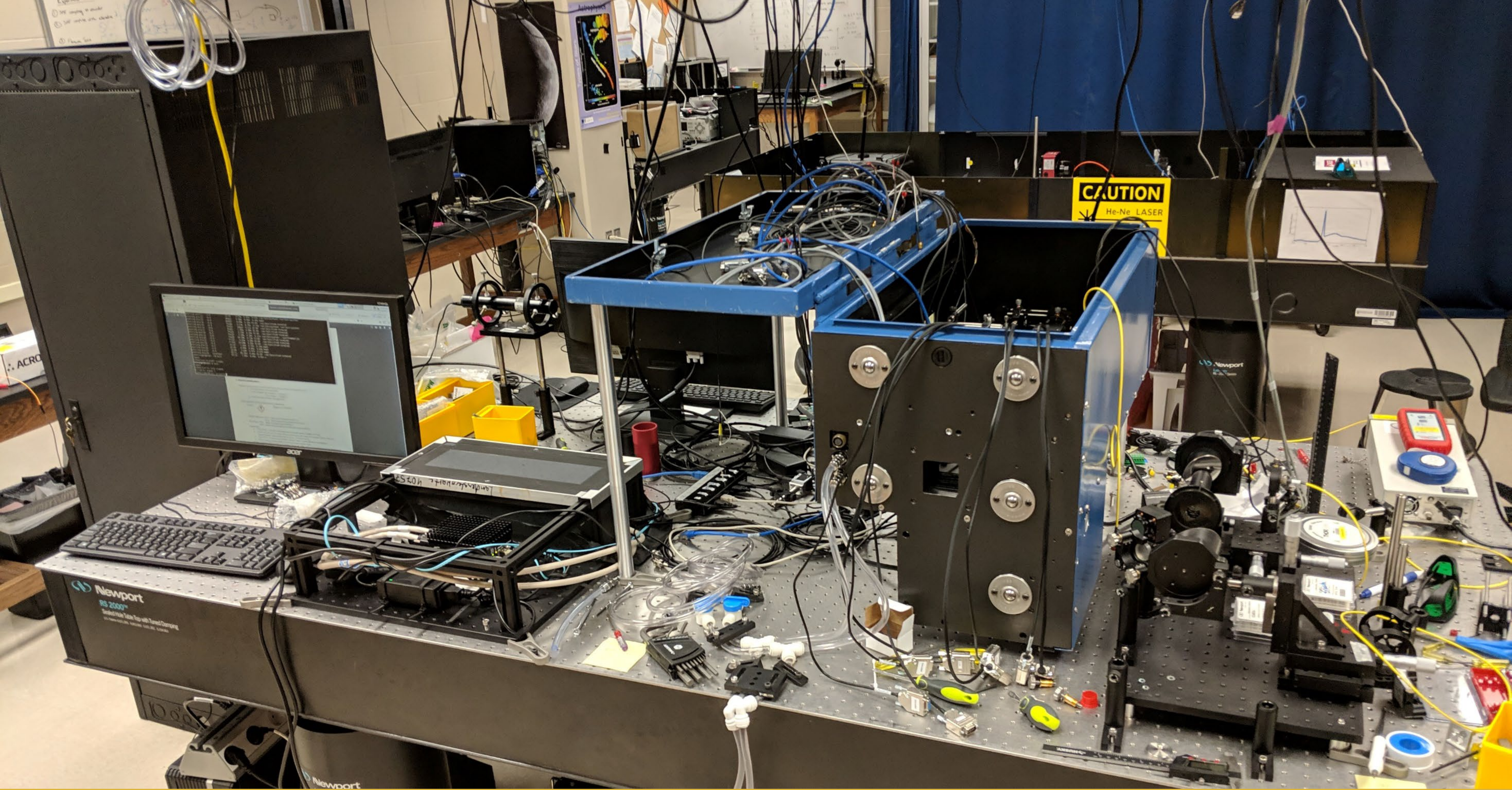



THORLABS

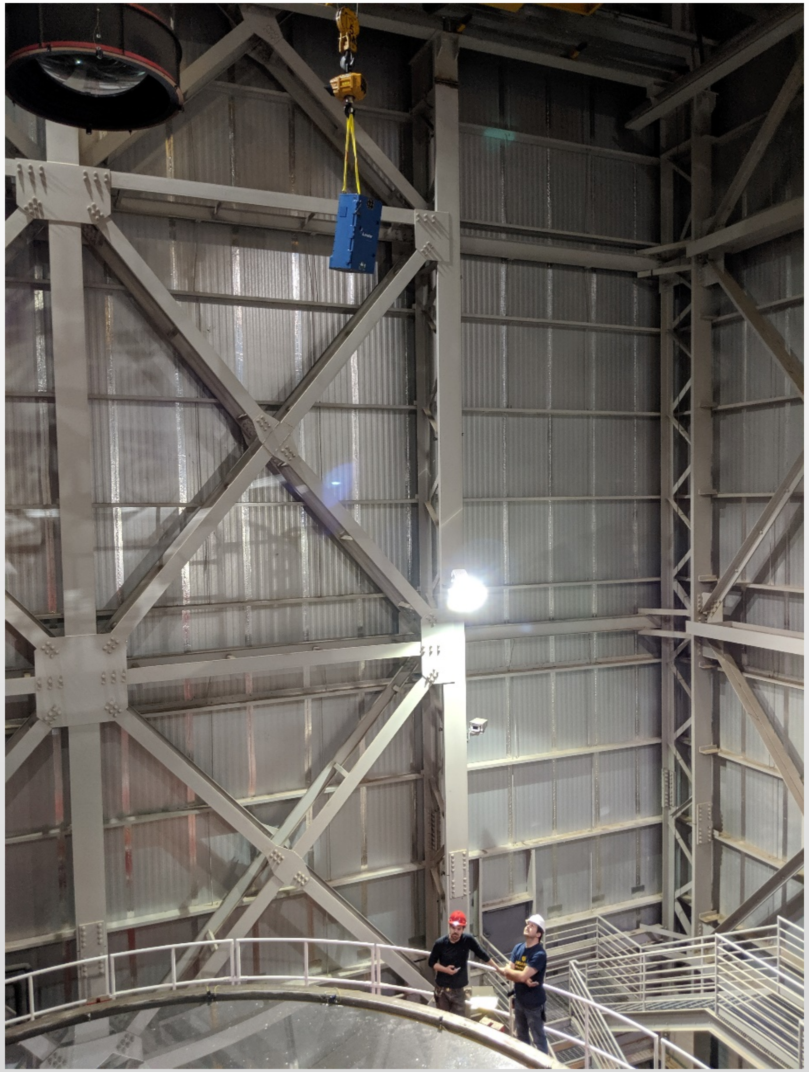

Quadcell
Lens pair
5-axis fibre stage
Focusing lens
Retroreflector
ANDOR camera
Focusing lens
Longpass Dichroic
Filter wheels
Shortpass Dichroic
Fast steering mirror
ADC
Calibration light fibre
Collimator
THORLABS
Focusing lens
Filter wheels
Fast steering mirror
ADC
Calibration light fibre
Collimator
Alignment stage
Beam steering mirrors
Vertical fold mirror
Wide field camera
Collimator plate
WFC plate
Fibre channel/ quadcell plate
Fine guide / ANDOR plate
Beam steering optics


THORLABS

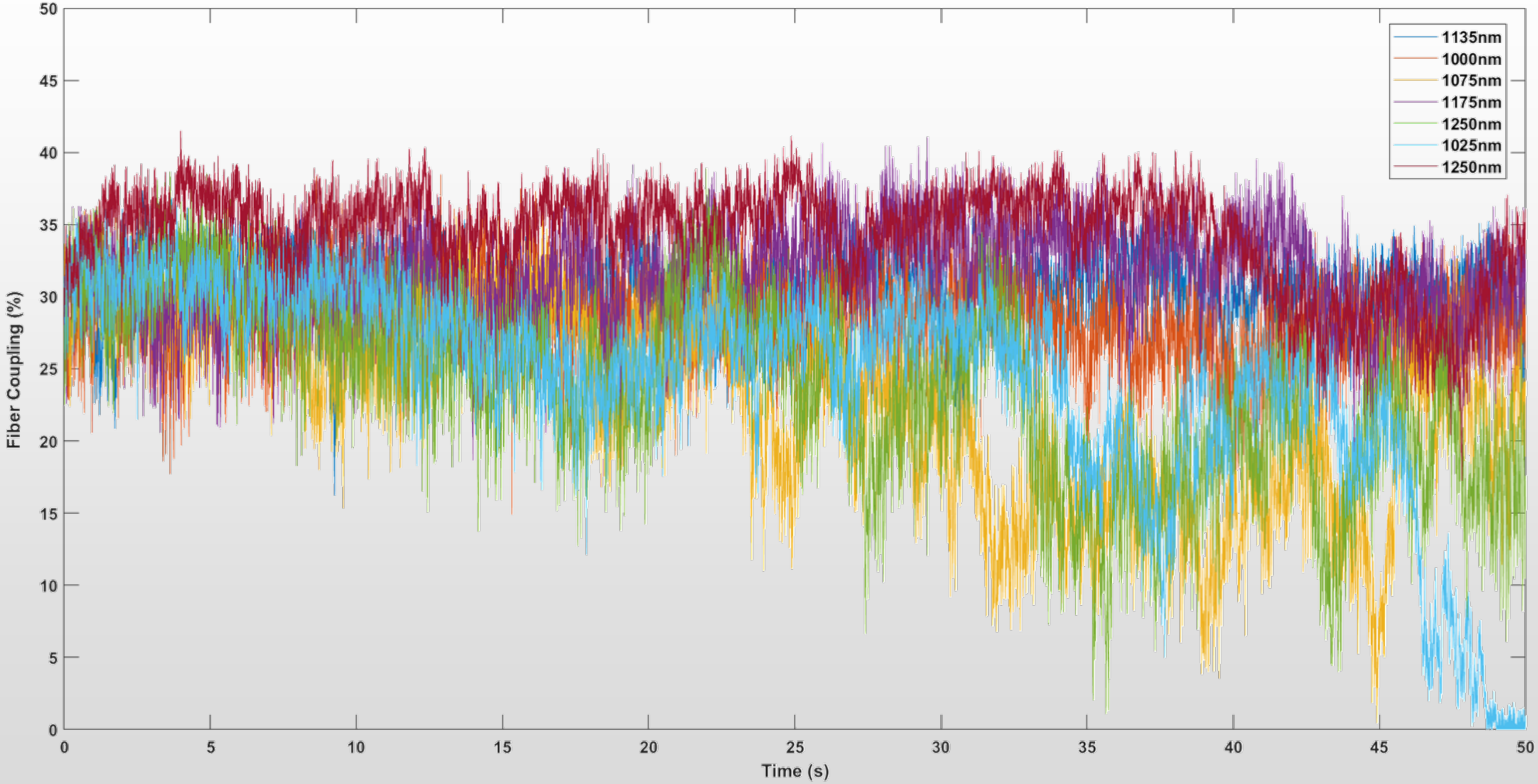

ANDOR
Zyla


CAUTION
He-Ne LASER
Newport
RS 2000
acer

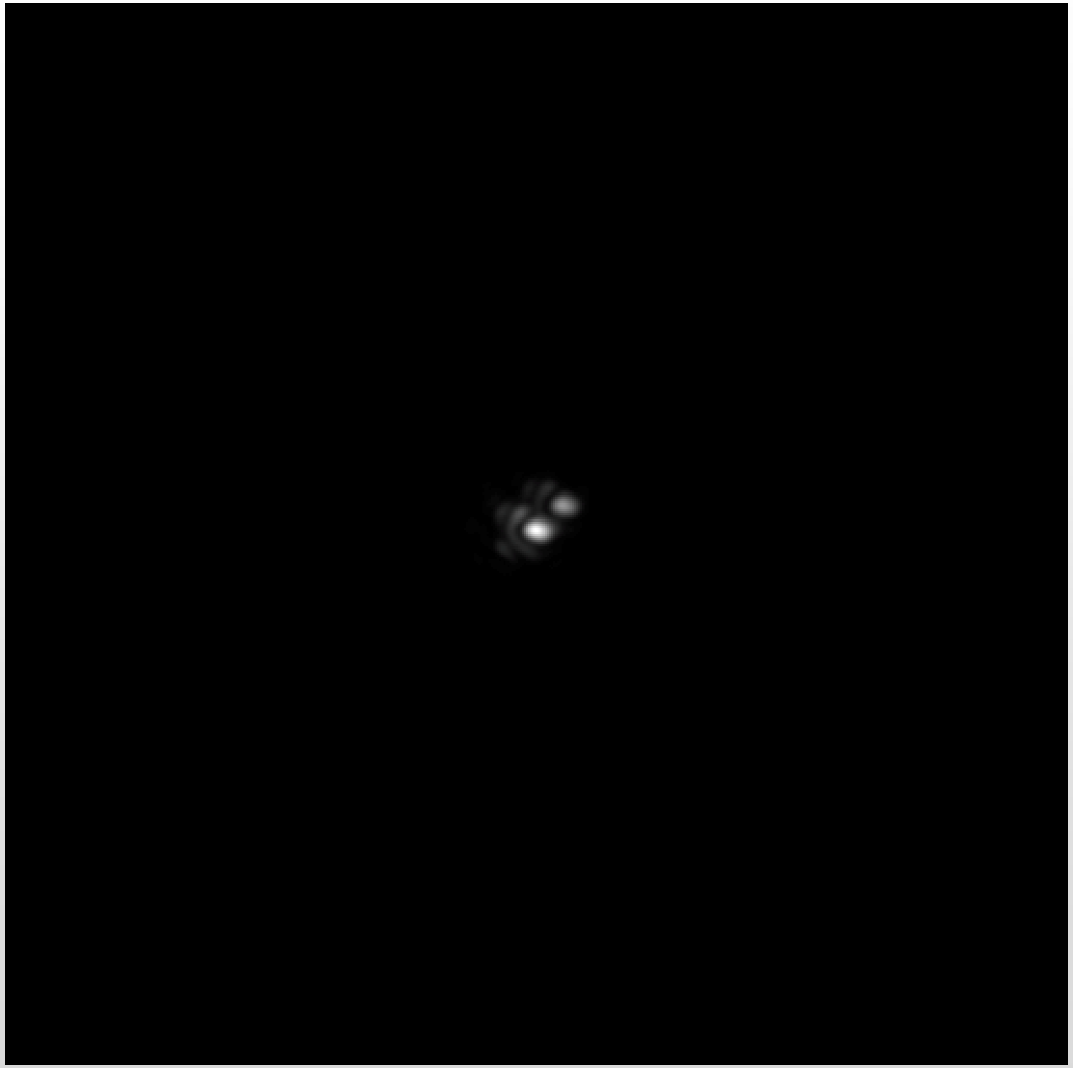
LBT Install/Commissioning – June/July 2019



Fibre coupling on HR5553 (K type), $R_{mag}=5.5$



Unresolved Binary?



Spectrograph Design

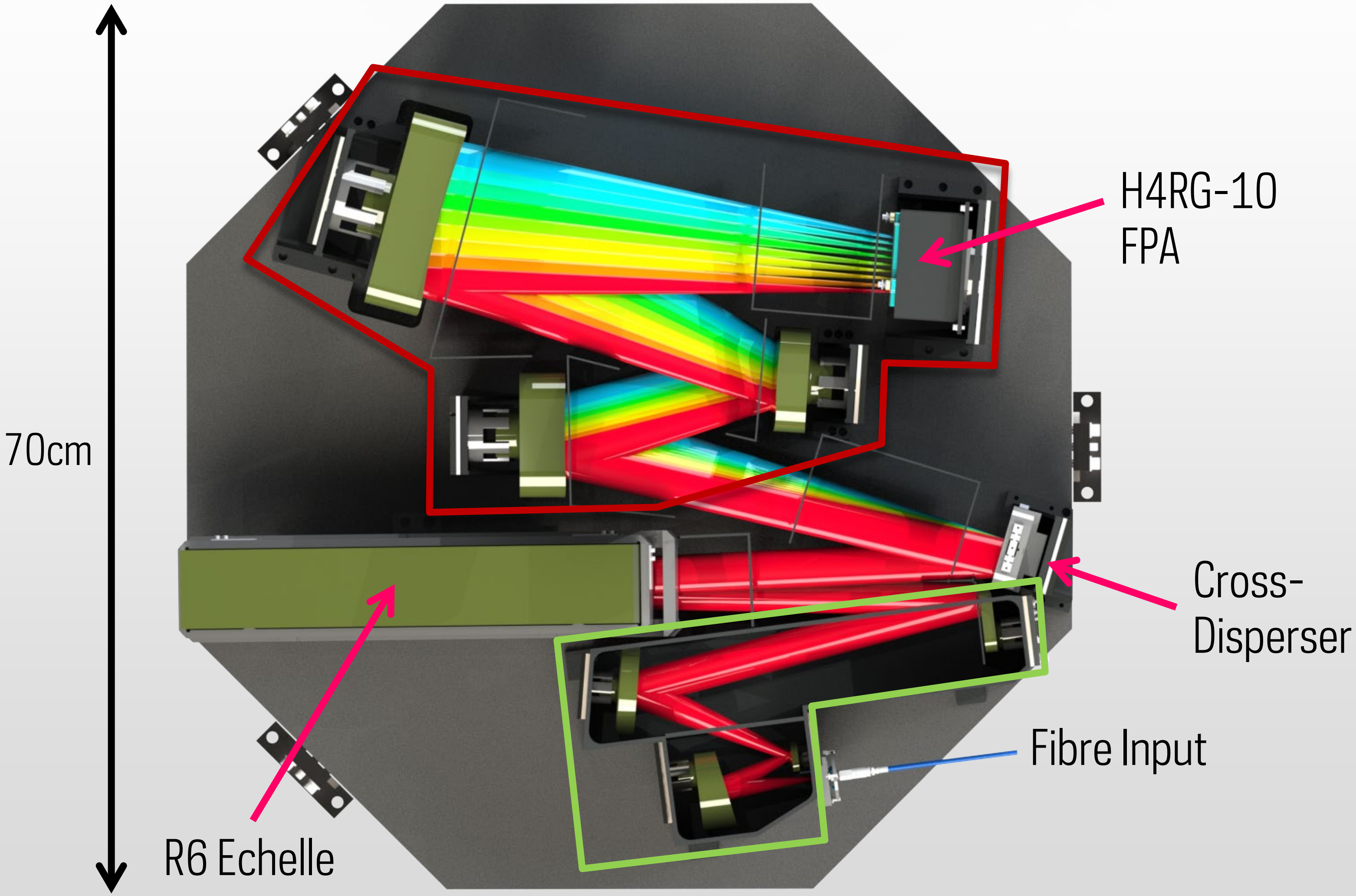
Single-mode fibre fed spectrograph = Gaussian beam spectrograph

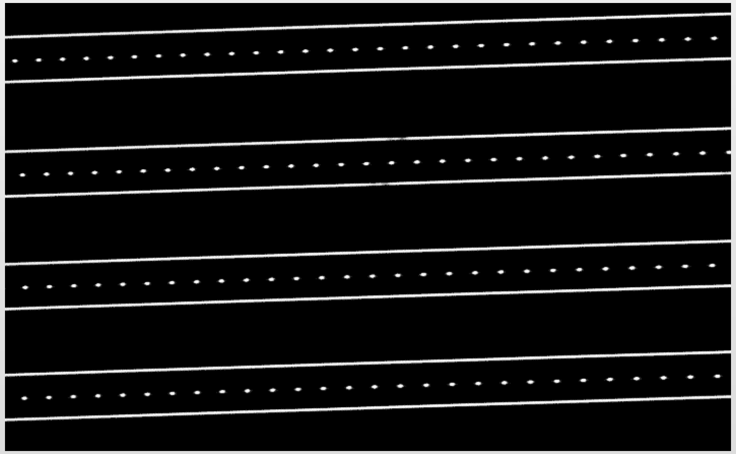
- Single-mode fibres are small
  - Output a spatially stable Gaussian beam profile
    - Two polarization modes
  - Fibres are small enough to be considered a point source rather than an extended source (slit/multi-mode fibre)
    - Working in 'diffraction-limited' system if you want to maintain PSF profile
  - Spectrograph design completely decoupled from telescope

- It is important to maintain optical quality through the entire system
  - Aberrations broaden instrument profile ⇒ degradation in effective optical resolution
  - All surfaces have to be high-quality to achieve this
  - All surfaces have to be 'oversized' to accommodate Gaussian beam profile

iLocater spectrograph design has been built from the ground up to ensure this performance.

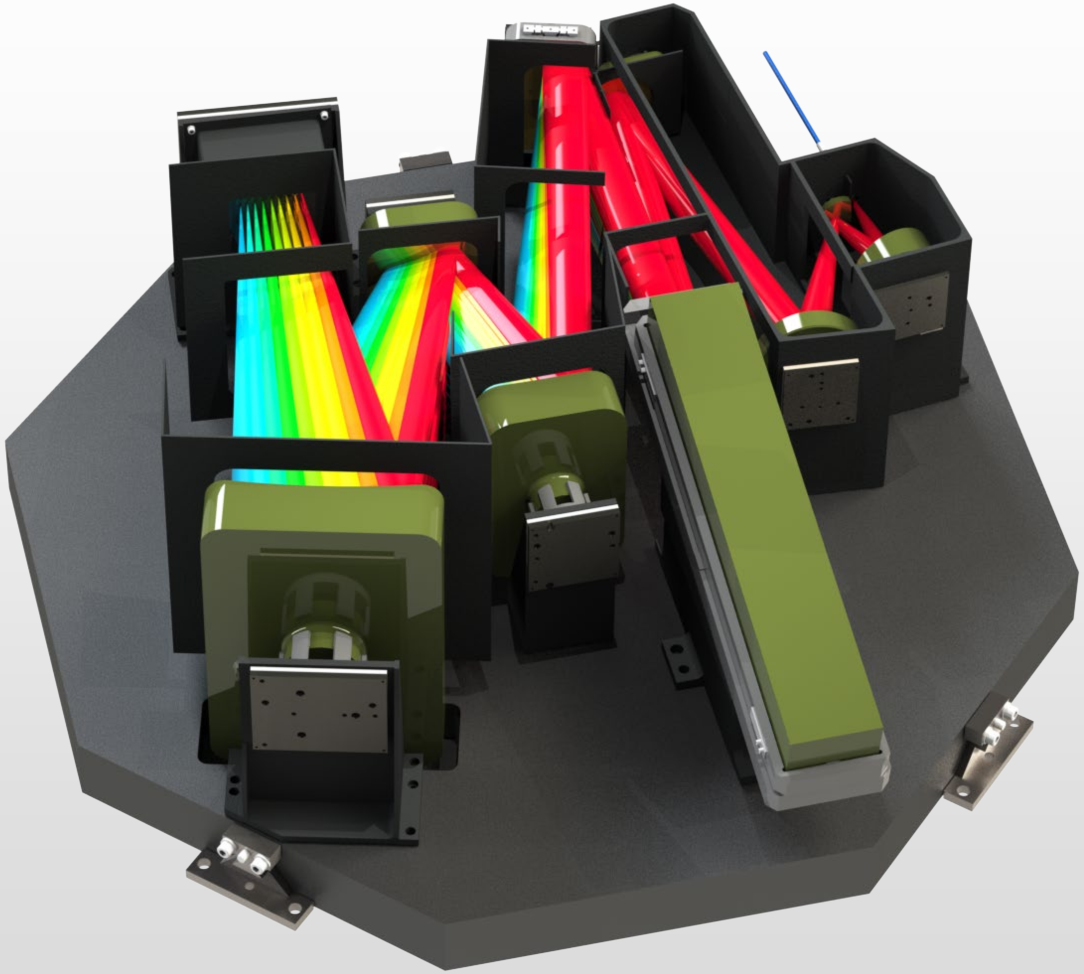
Spectrograph optical design

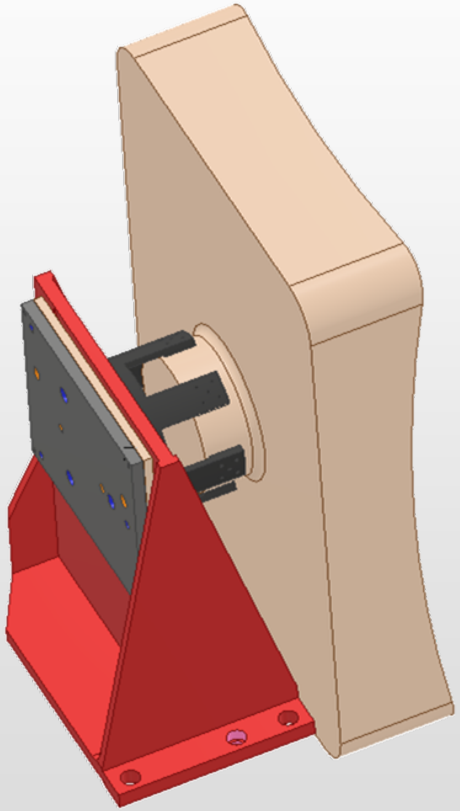


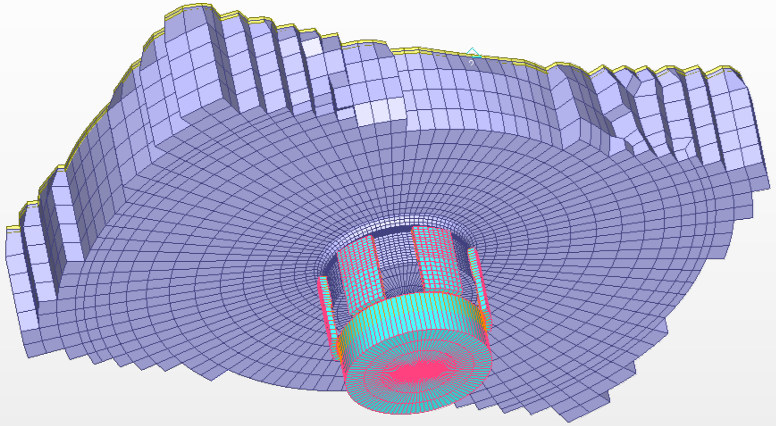


Bandpass: Y- and J-bands: 0.97-1.27μm
Orders: 117-152

Spectrograph optical design – optomechanics



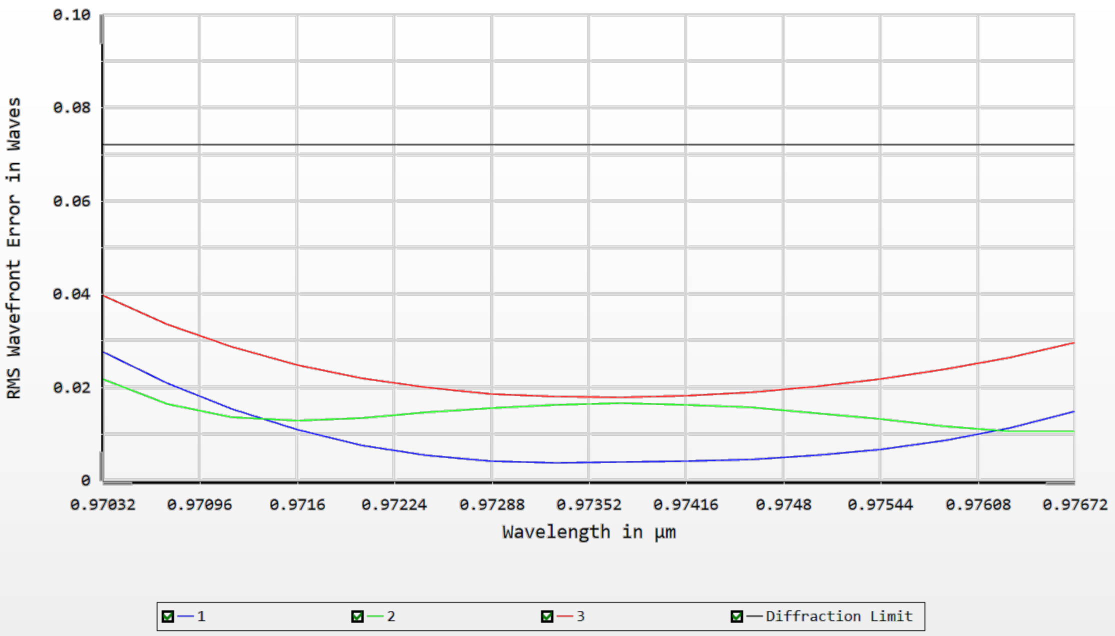


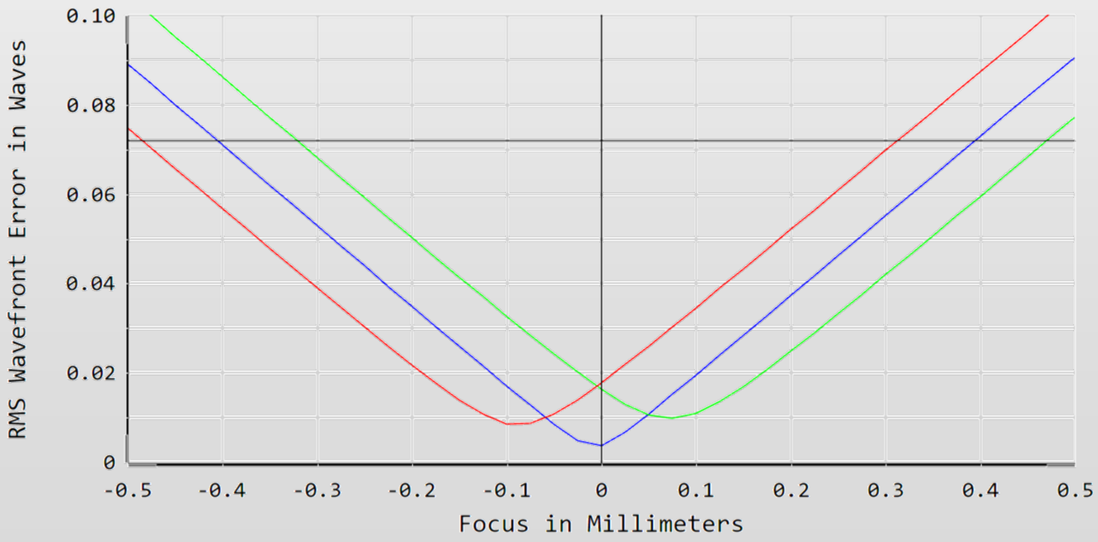


Error Term	Zernike	Residual RMS (waves @ 632.8nm)
Raw		0.01319
Piston	-6.93E-03	0.01176
Tip	1.03E-05	0.01176
Tilt	-2.58E-02	0.00137
Focus	-1.74E-03	0.00096
Astig1	-1.20E-06	0.00096
Astig2	-8.66E-04	0.00093
Coma1	5.15E-06	0.00093
Coma2	5.15E-06	0.00093

Optical performance

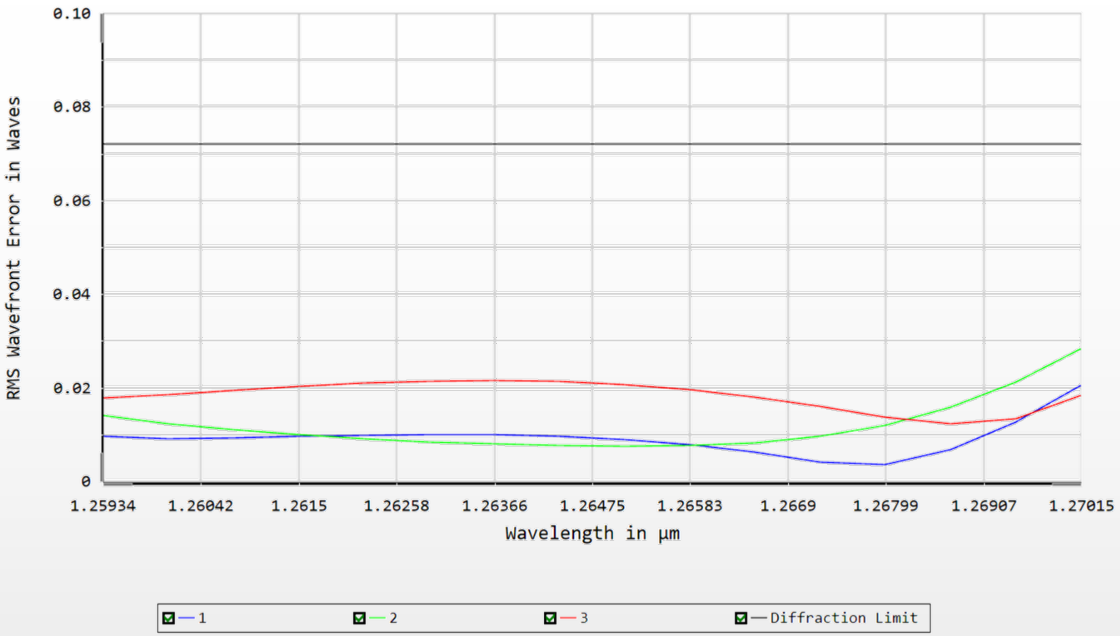
Short wavelengths

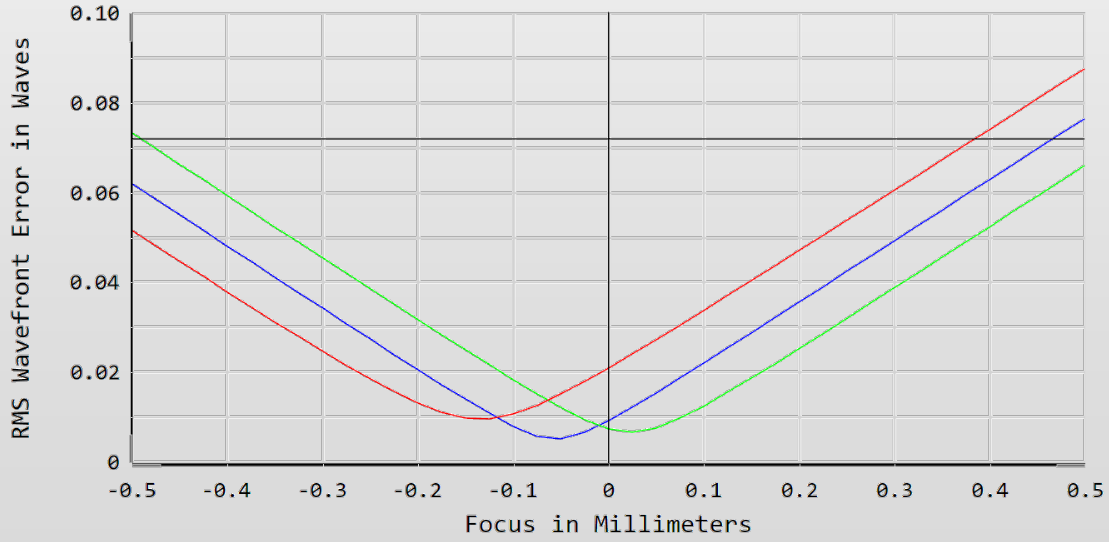




Optical performance

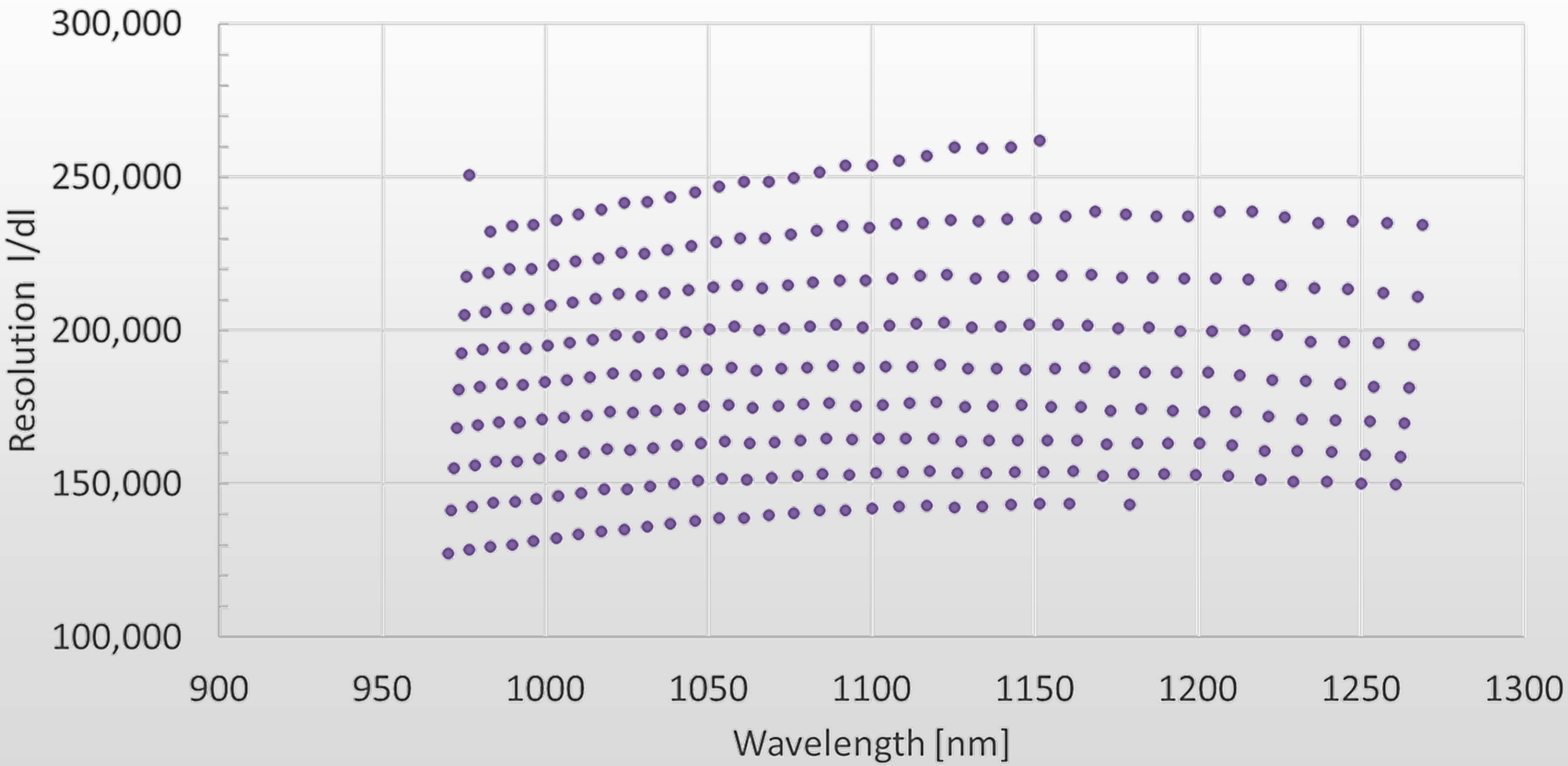
Long wavelengths





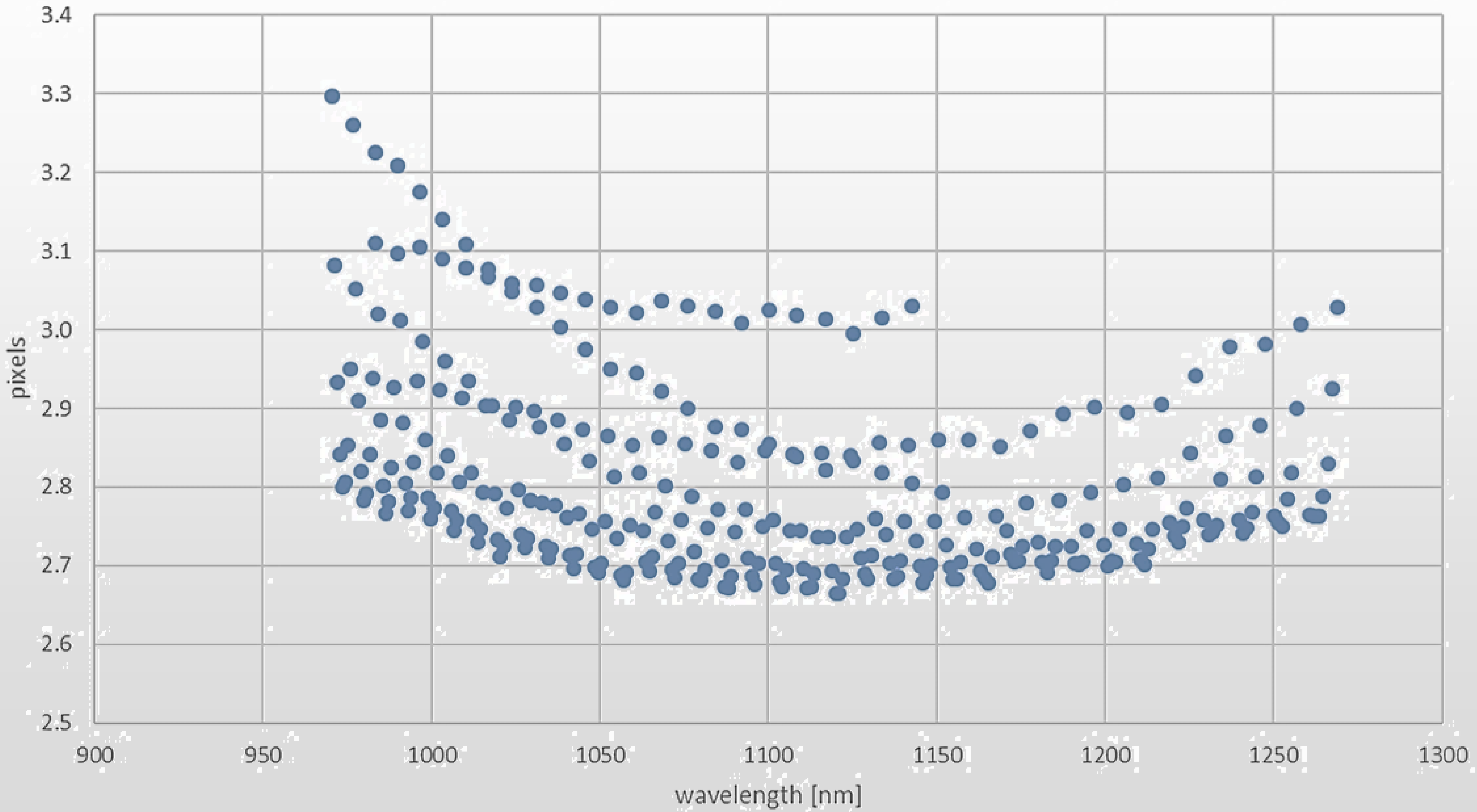
Spectrograph Resolution

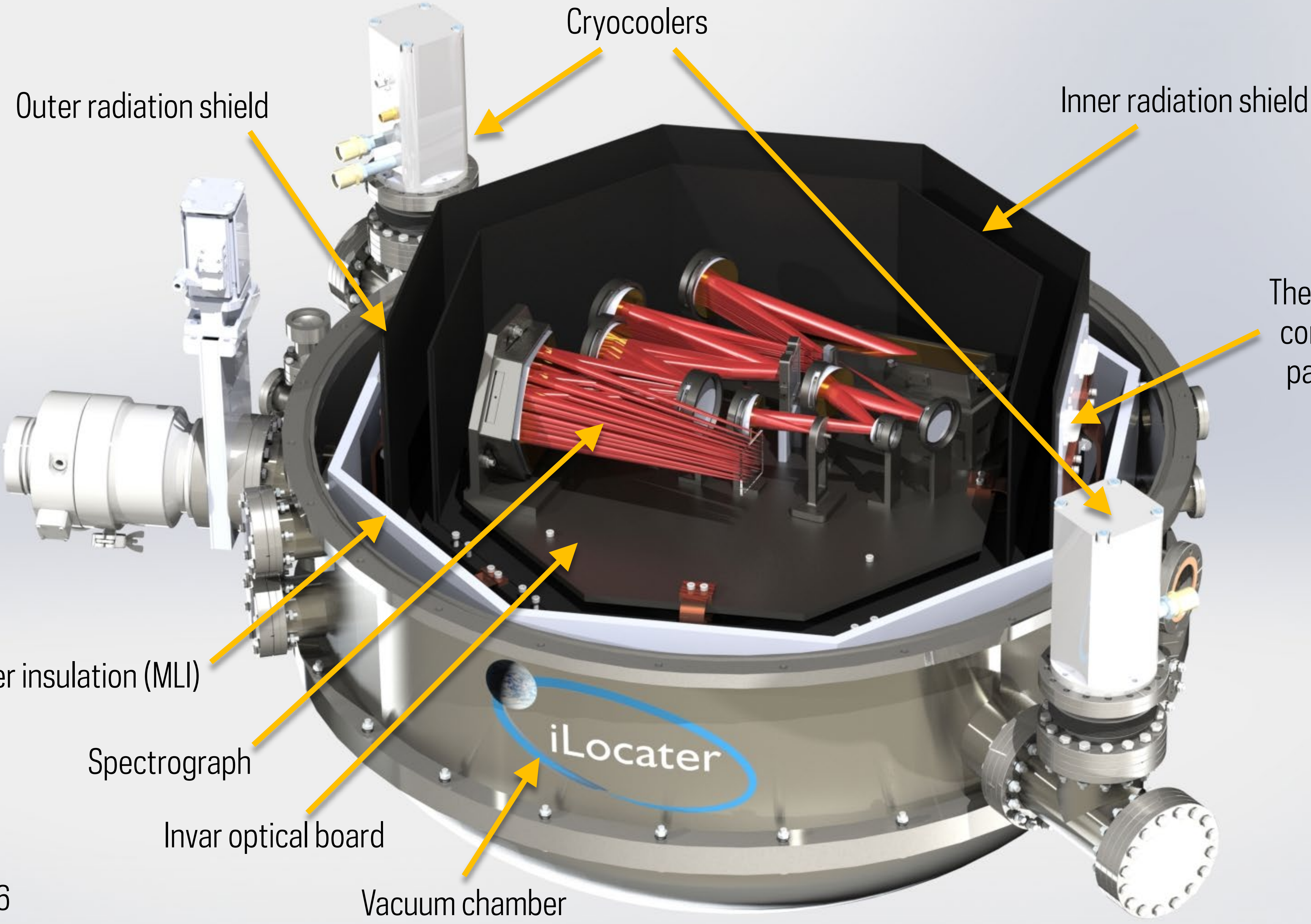
Resolution			
Median:	189,400	Minimum:	131,900
Mean:	193,600	Maximum:	273,600



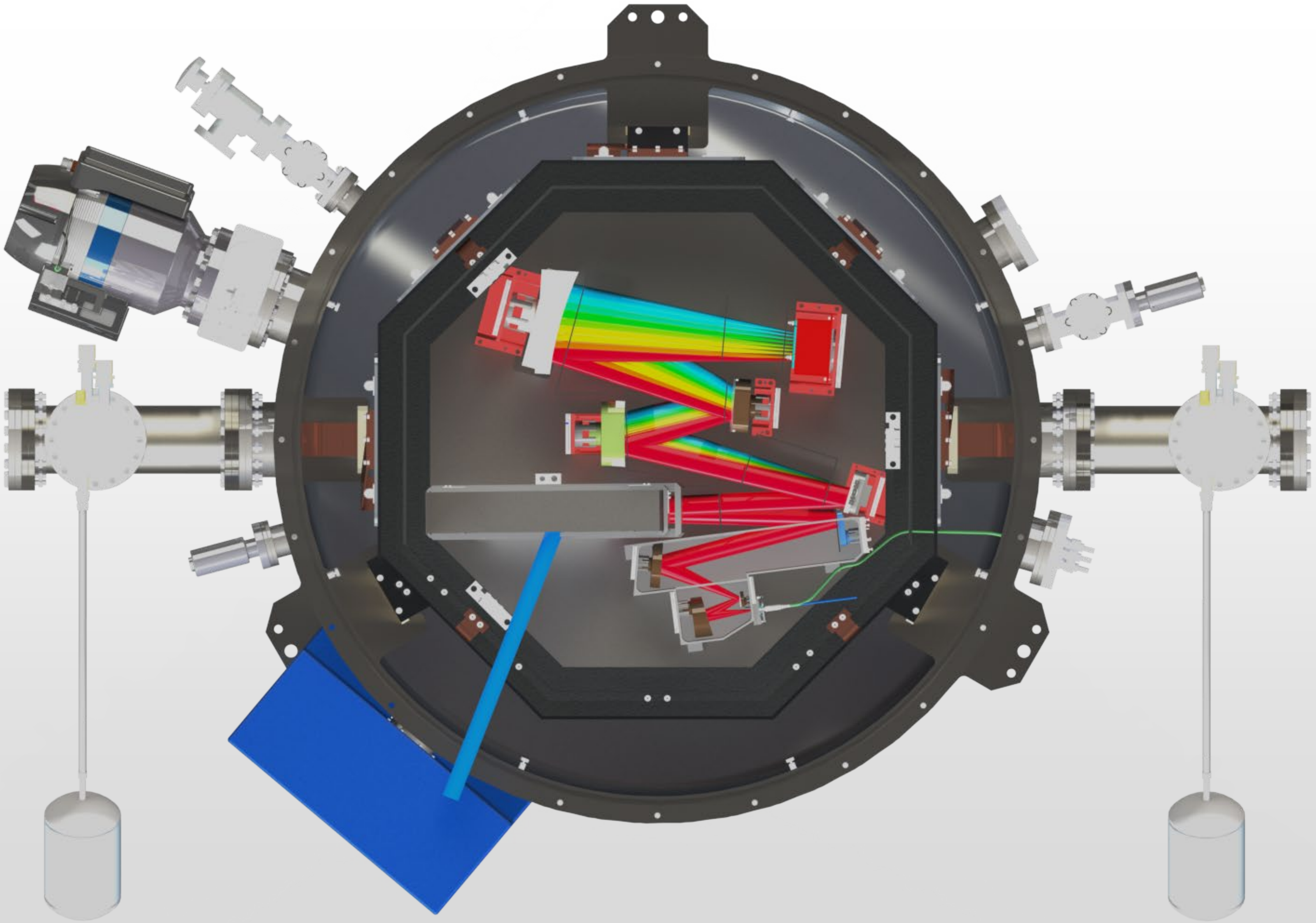
Spectrograph Pixel Sampling

Pixel Sampling/Resolution Element			
Median:	2.69	Minimum:	2.62
Mean:	2.73	Maximum:	3.17

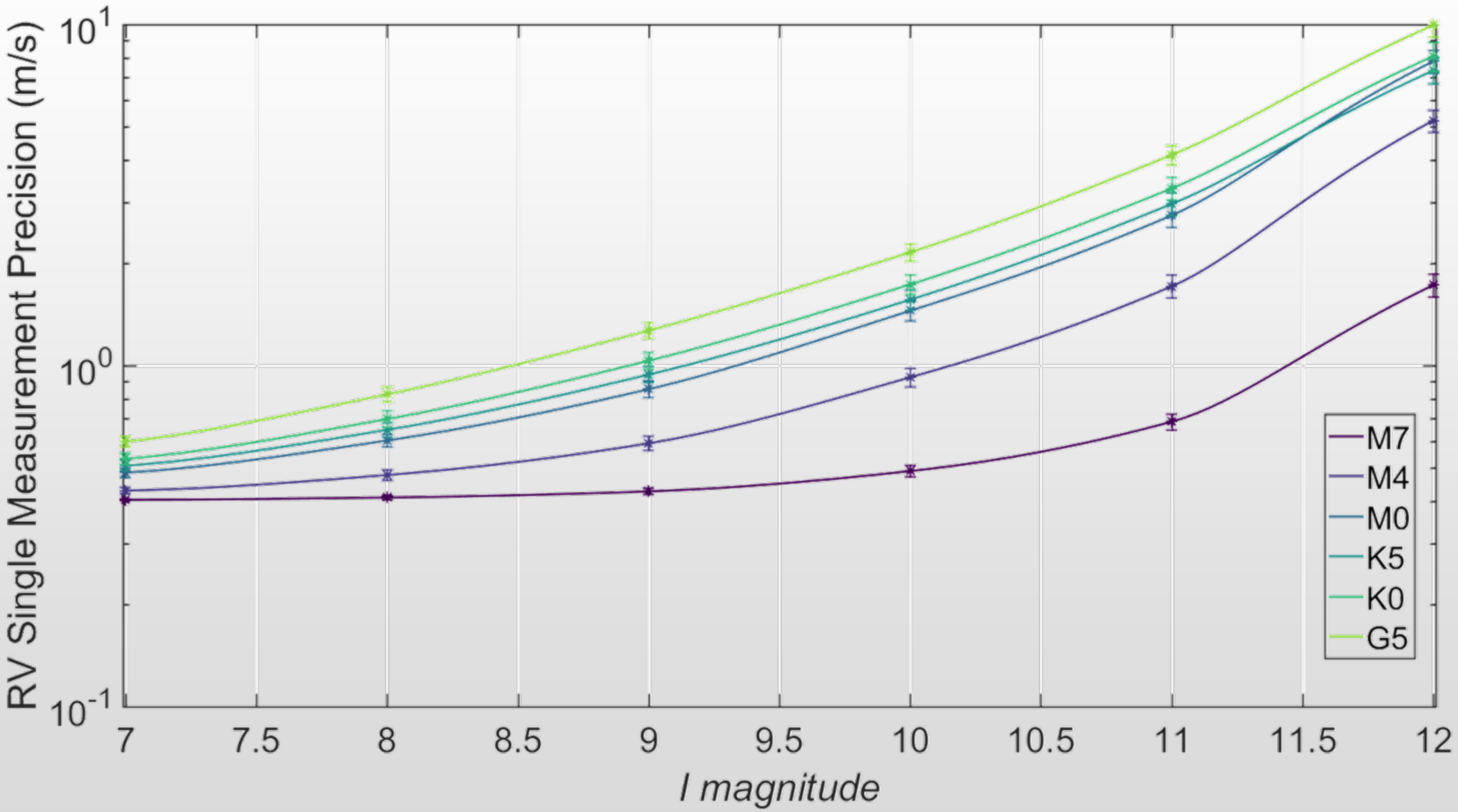




Crass et al., 2016



Single-measurement precision



Selected Science Cases

iLocater Science Case

Designed for studying exoplanets using the radial velocity technique

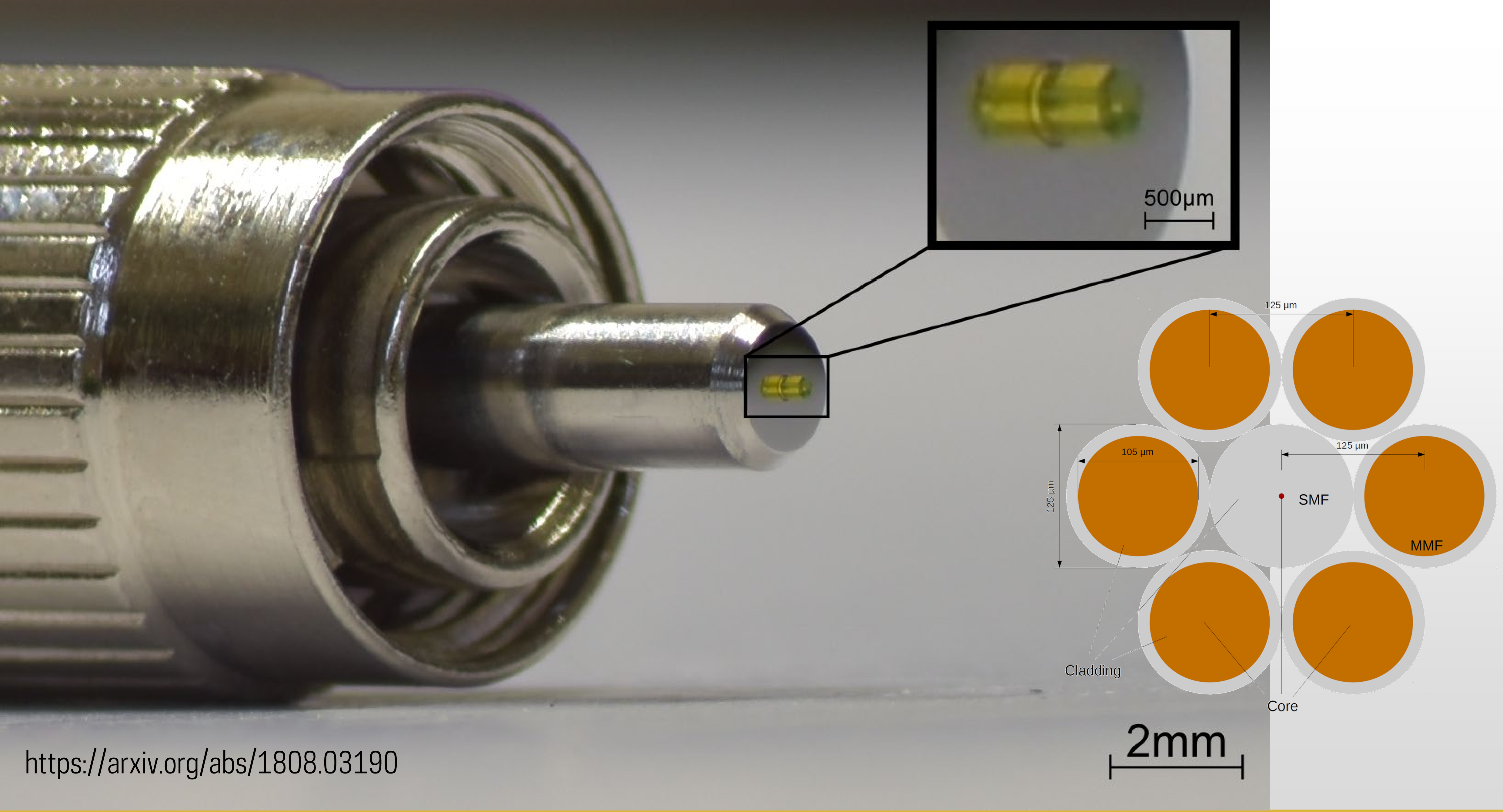
- TESS TOI follow-up
- First Systematic Study of Planets in Binaries
  - Studies of close-binary systems
- Spin-Orbit Measurements of Terrestrial Planets
- M-Dwarf Opportunity
- Transmission Spectroscopy

Instrument is useful for other branches of astrophysics!

Selected Science Programs

- Simultaneous programs with other LBT instruments
  - SHARK high contrast/resolution imaging at NIR/visible
  - PEPSI: R=270,000, λ=0.384-0.913μm
  - iLocater: R=190,000, λ=0.97-1.27μm

Future Plans & Conclusions



https://arxiv.org/abs/1808.03190

Summary

- iLocater is moving rapidly from design to fabrication
- SX fibre injection system installed and tested on-sky
- Spectrograph design – built from the ground up to ensure its suitability for RV science
  - High resolution ⇒ possibility to measure line asymmetries
  - Build currently in progress!

Resolution	
Median: 189,400	Minimum: 131,900
Mean: 193,600	Maximum: 273,600

Pixel Sampling/Resolution Element	
Median: 2.69	Minimum: 2.62
Mean: 2.73	Maximum: 3.17

Bandpass: Y- and J-bands (0.97-1.27μm)