MARVEL:
MERCATOR ARRAY FOR RADIAL VELOCITIES

UNRAVELLING THE NATURE OF EXOPLANETS

Gert Raskin

11 Sept. 2023

Observing techniques, instrumentation and science for metre-class telescopes III

MACQUARIE University SYDNEY·AUSTRALIA | universität wien | Stockholm University | CSIC | fwo | Science & Technology Facilities Council UK Astronomy Technology Centre | UCL | WARWICK THE UNIVERSITY OF WARWICK | ZAH | KU LEUVEN

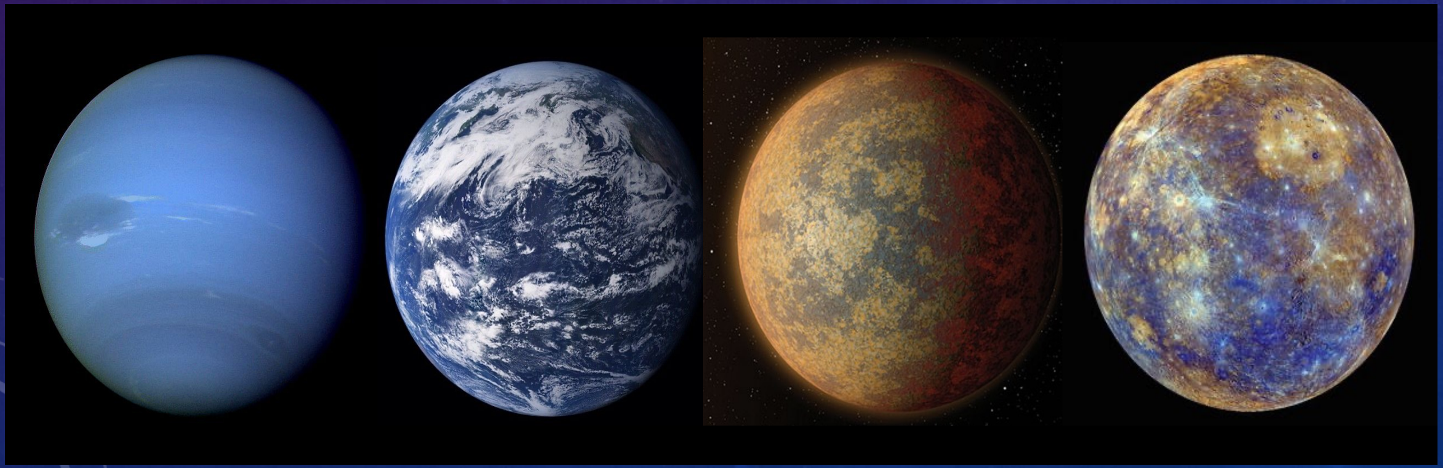
MARVEL PROJECT CONTEXT

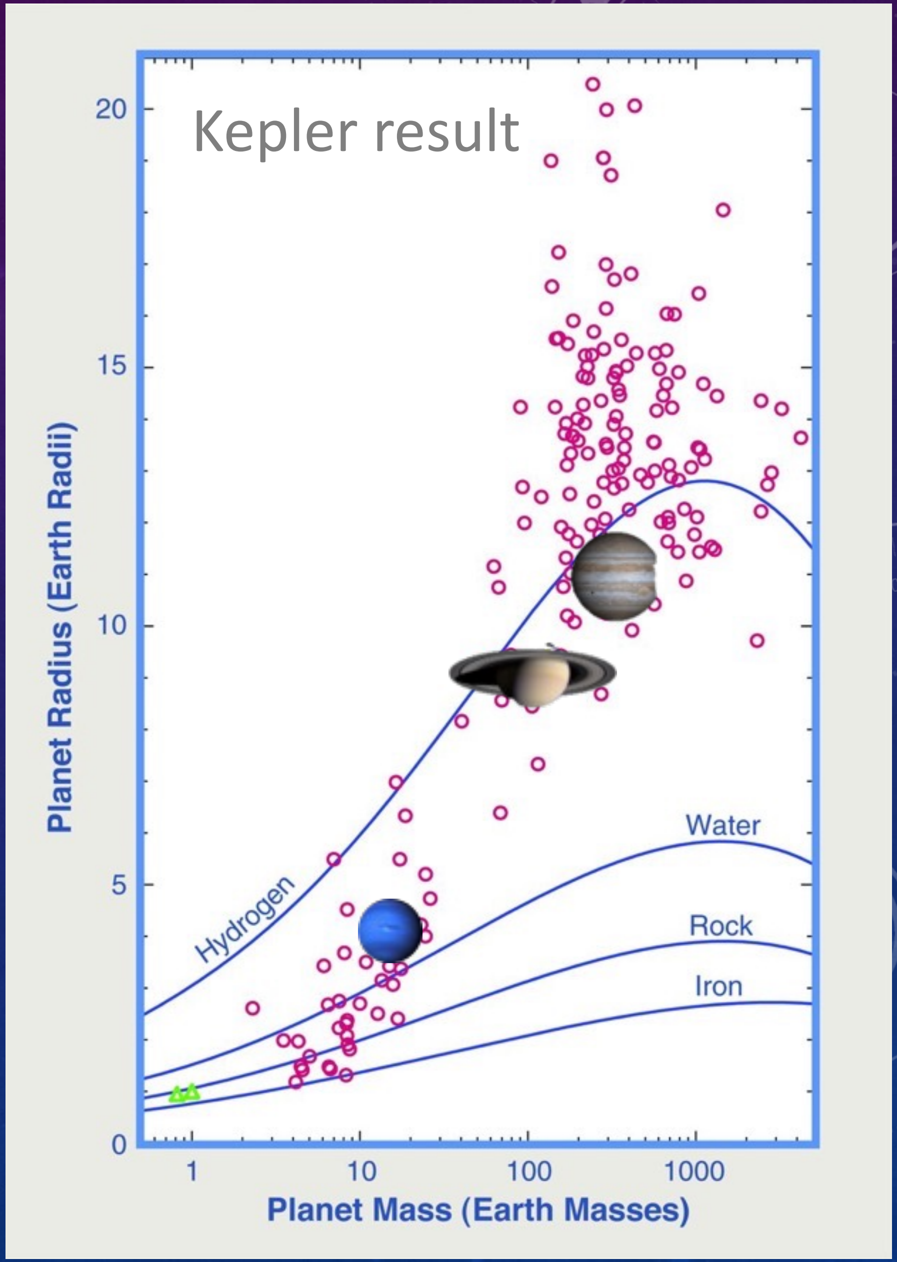
- Harvesting on the KU Leuven involvement in ESA's exoplanet space missions: PLATO & ARIEL
- Need for high-precision high-resolution spectroscopy capability
  - PLATO: ~ 4000 candidates requiring multi-epoch PRV follow up
    MARVEL will be largely dedicated to these observations
  - ARIEL: transit spectroscopy requires HR spectroscopy for characterisation of stellar activity
- Fresh boost for the 1.2-m Mercator Telescope Observatory (La Palma, Spain)

PLATO WILL MEASURE PLANET SIZES

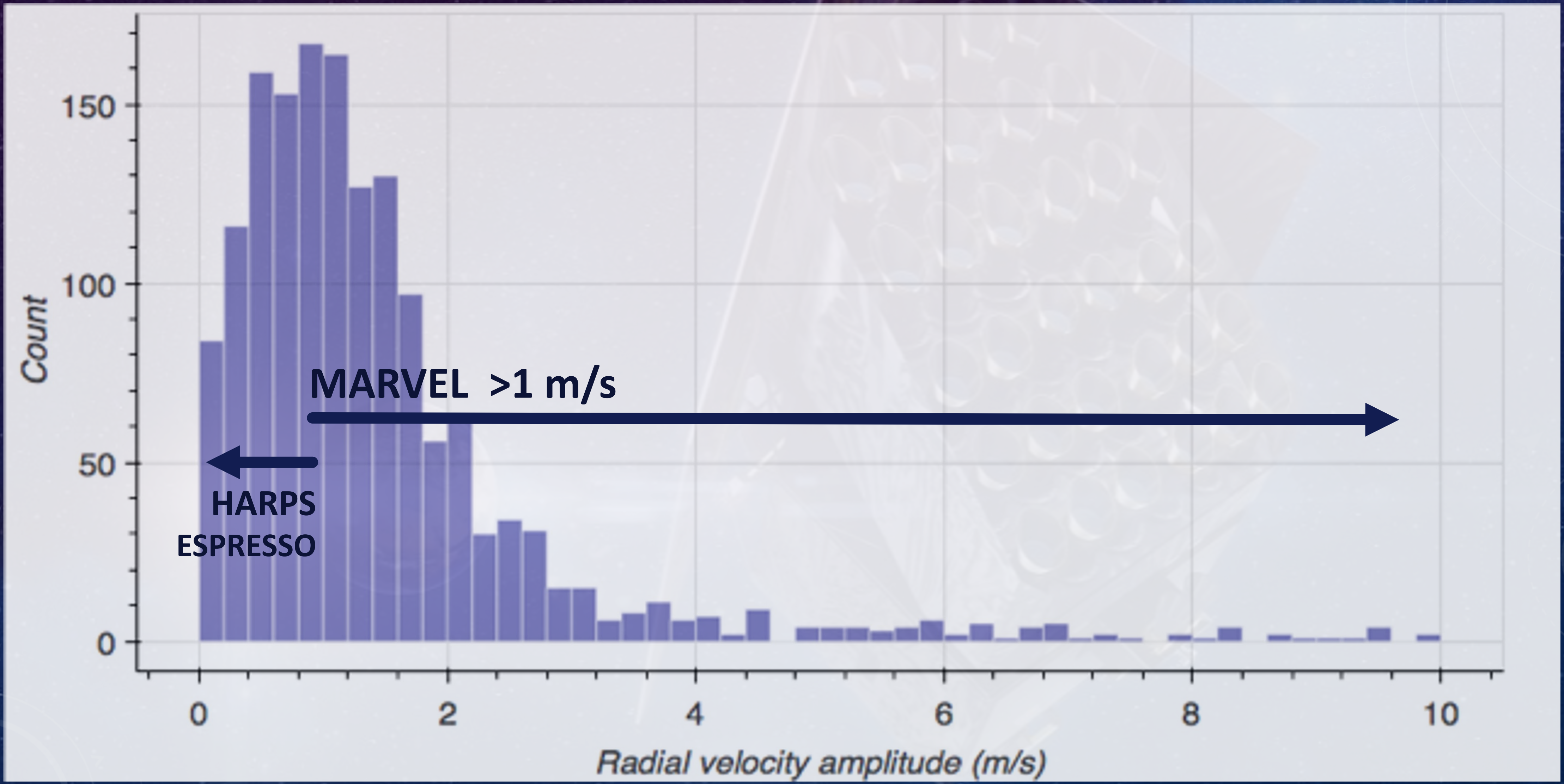
MARVEL WILL WEIGH THEM

- What are PLATO exoplanets made of?
- Light curve dips give radius of the planet
- We need to measure planet mass to know its density





PLATO RADIAL VELOCITY AMPLITUDES

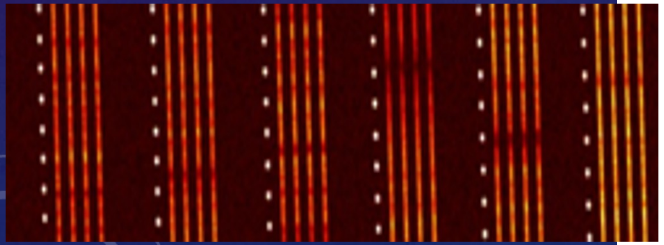


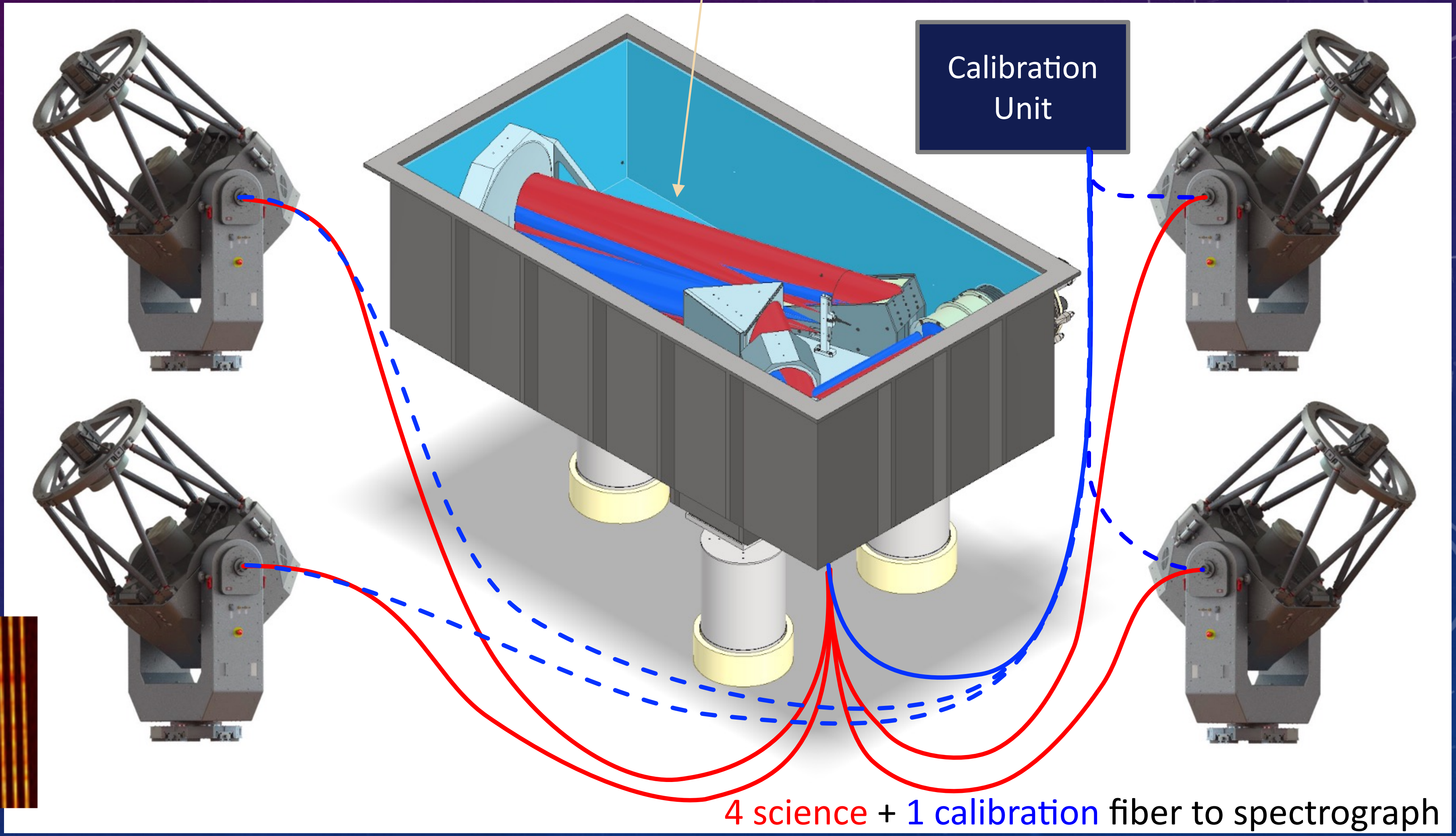
MARVEL CONCEPT

Four 80-cm COTS Telescopes:

4 x AZ800 (*f*/10)
ASA (Austria)

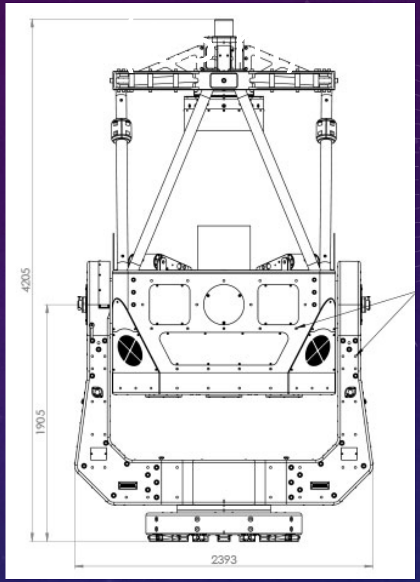
Single HR spectrograph
Records 4 science + 1 cal.
Spectrum per exposure





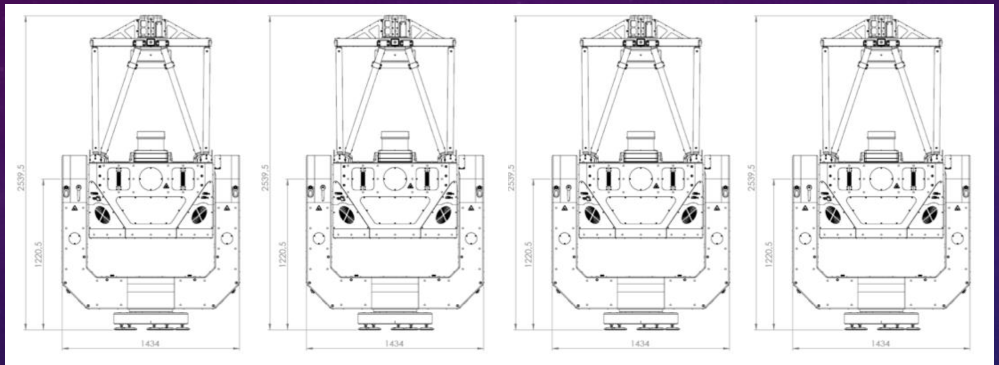
WHY FOUR 80-CM TELESCOPES?

1 x AZ1500



4 x AZ800

1. Telescope cost:



4 x 250 k€ = **1 M€** < **1.5 M€**

A = 4 x 0.5 m^2 = **2 m^2** > A = **1.77 m^2**

2. Spectrograph cost:

   Conservation of étendue: spectrograph beam diameter scales with telescope aperture

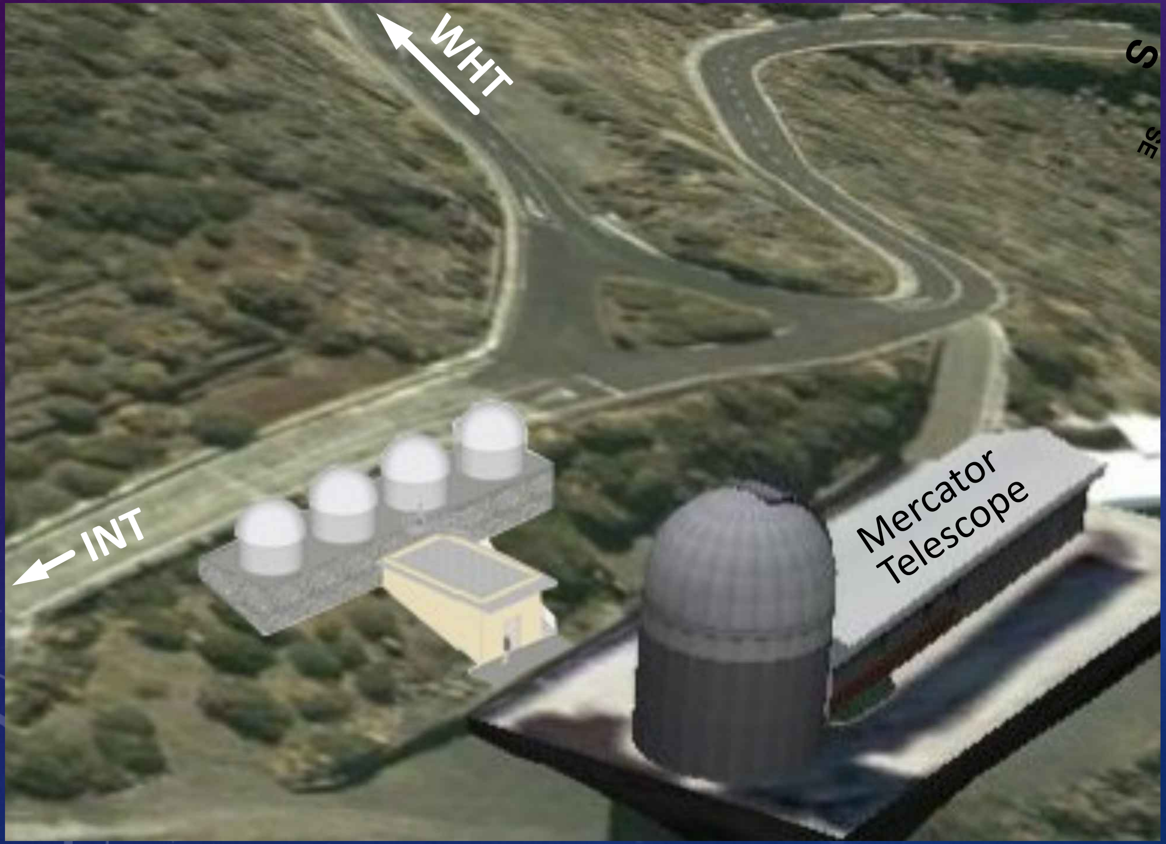
   Telescope diameter 0.8m ↗ 1.6m ⇒ Echelle grating, cross-disperser & camera dimensions: **x2**

3. Added flexibility & reliability of 4 telescopes vs. 1 telescope

4. Why not?
   - 4 (+1) interlaced spectra ⇒ Stronger cross-dispersion ⇒ Larger prism
   - Extra read-noise? Precision RVs ⇒ High SNR – Photon noise limited
   - Larger detector

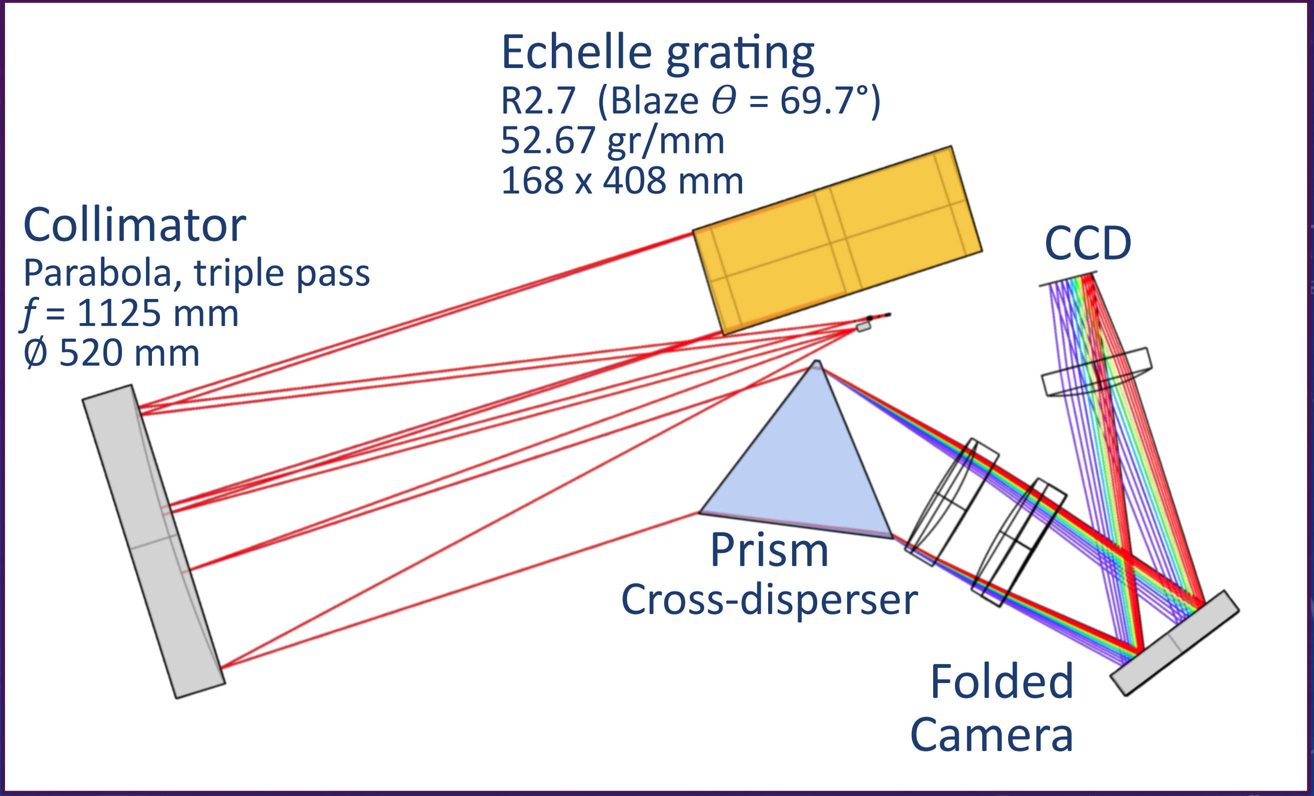
SITE AND BUILDING

- Roque De Los Muchachos Observatory, La Palma (Canary Islands), altitude: 2333m
- Four 4-m Domes on concrete platform + Adjacent spectrograph building

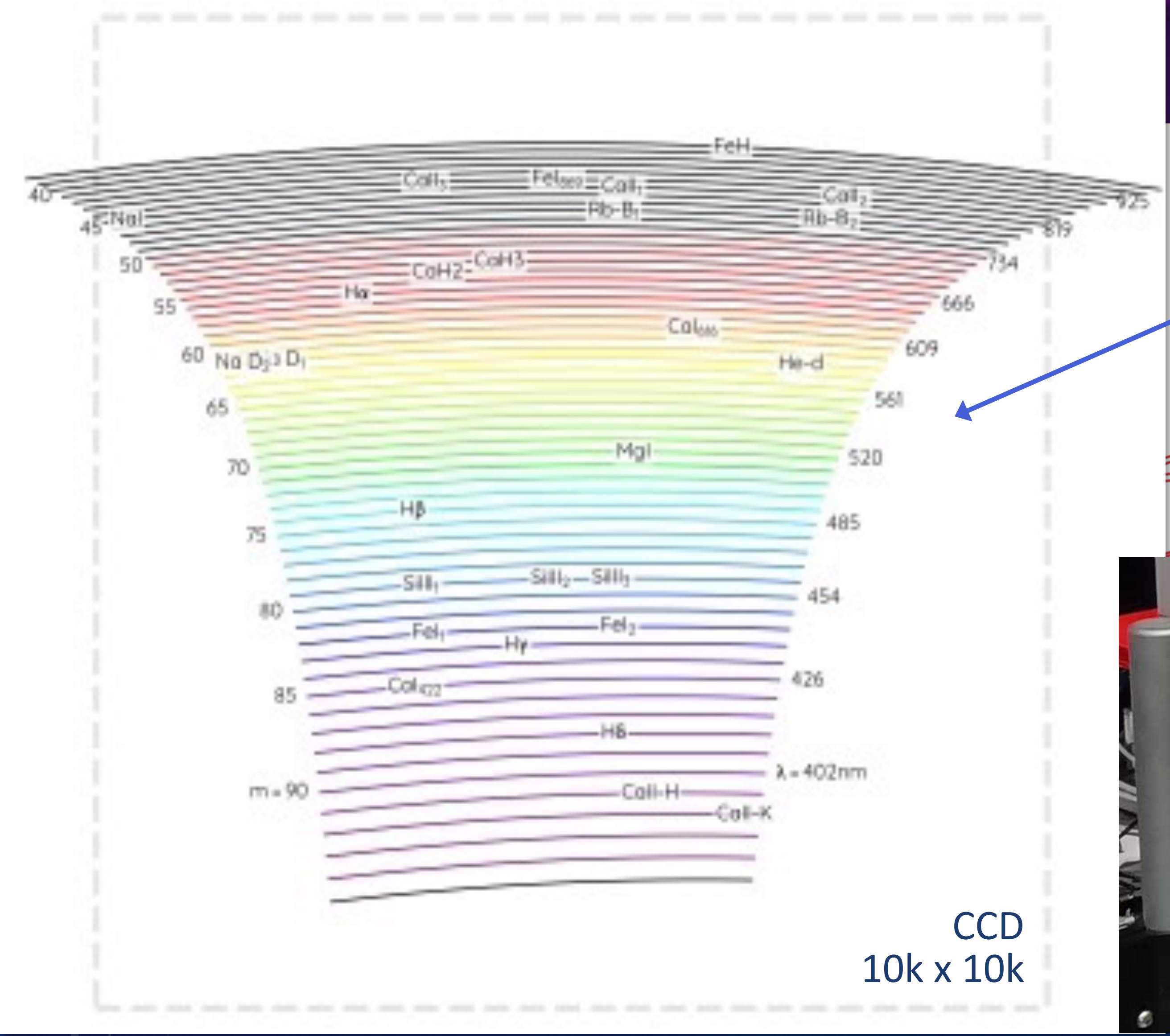


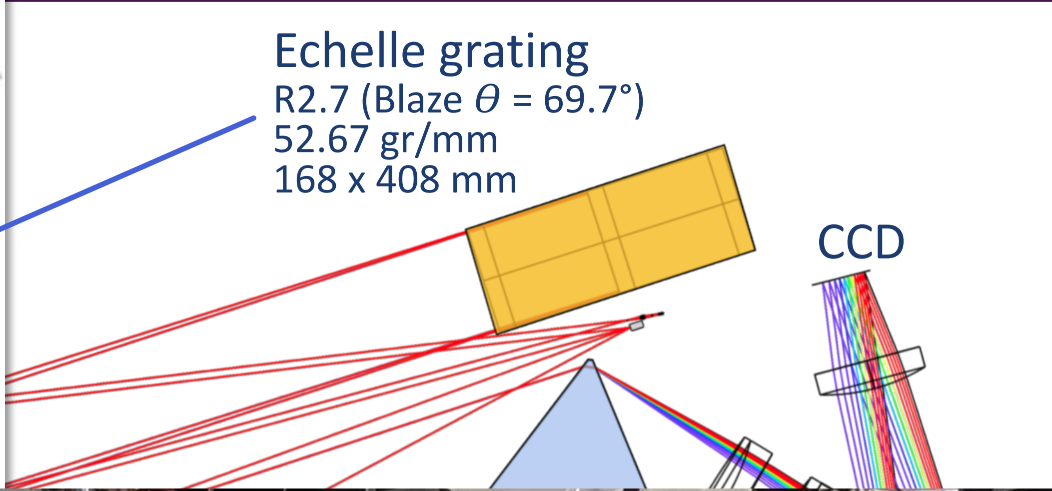
SPECTROGRAPH OPTICAL DESIGN

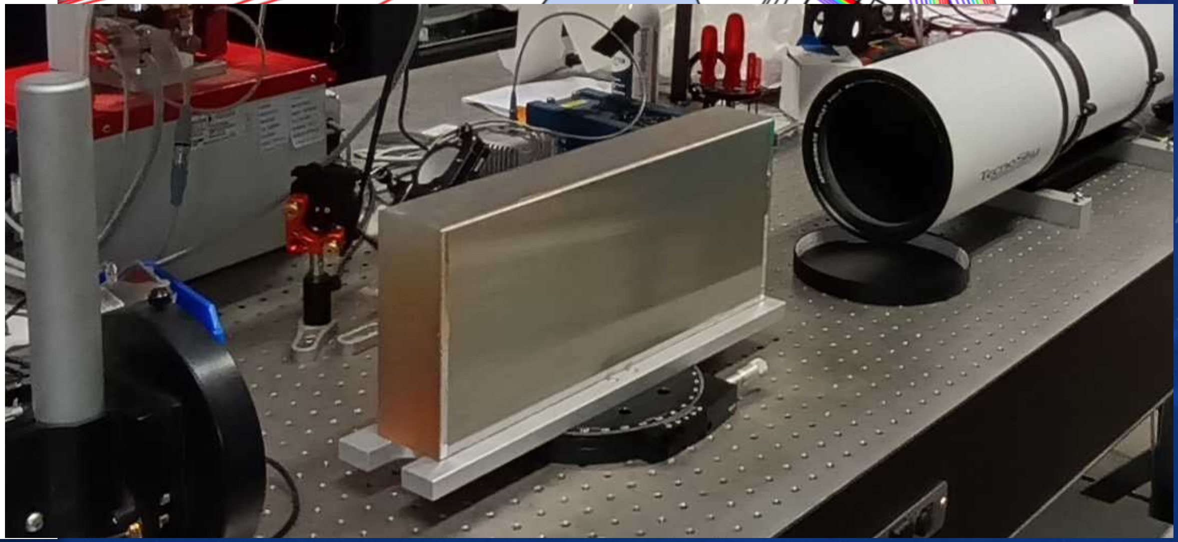
- Design heritage from NEID (Schwab+2016) and HERMES (Raskin+2011)
- Single-arm prism-cross-dispersed echelle spectrograph
- White-pupil layout
- Spectral range: 380 nm – 950 nm
- High-resolution: R = 90 000
- Ultra-high resolution: R = 150 000
- 10k x 10k STA1600 CCD detector



SPECTROGRAPH OPTICAL DESIGN

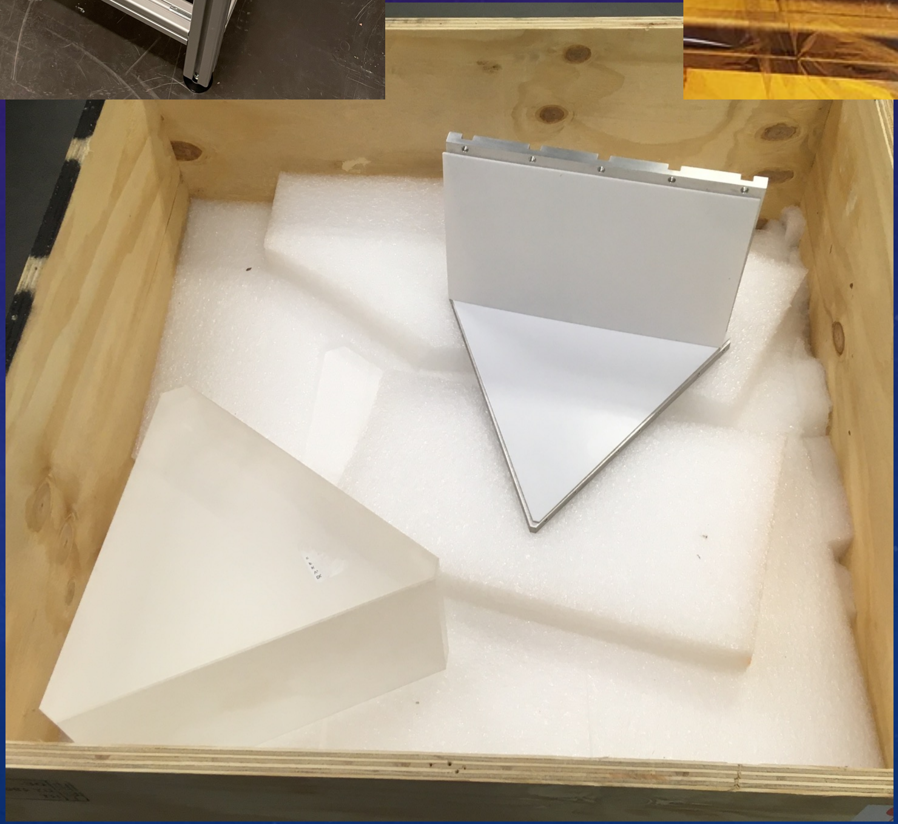






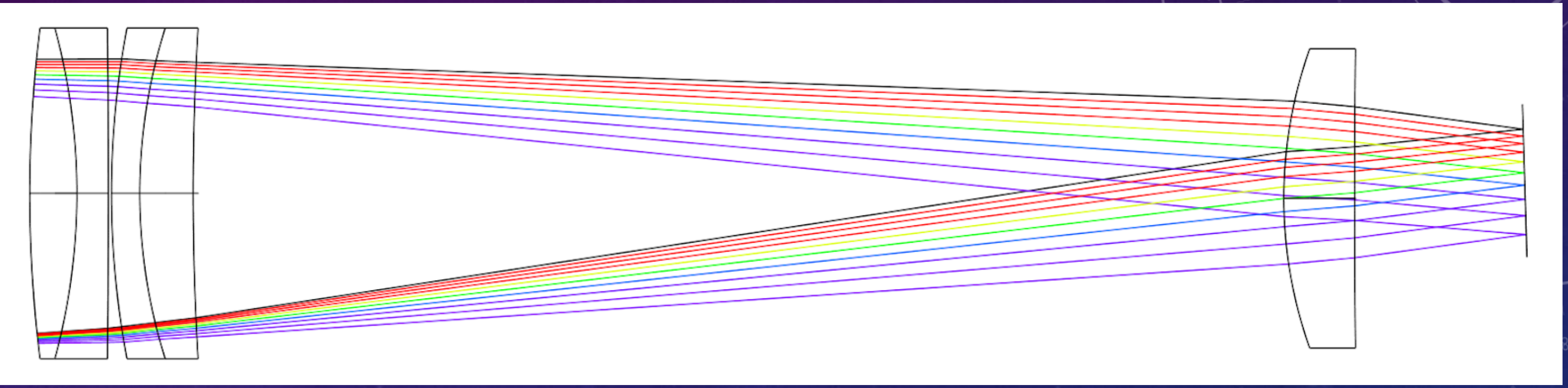
CROSS-DISPERSER

- 5 Interlaced spectra spectra
  ⇒ Strong cross dispersion
- Wide spectral range ⇒ No grating!
- Prism:
  - High throughput
  - High dispersion glass:
    Schott F2 (n_d = 1.62, V_d = 36.4)
    Good UV transmission (390nm)
  - 310 x 220 mm, ~40 kg
  - Apex angle: 60°
  - Polishing: Rik Ter Horst, Nova (NL)



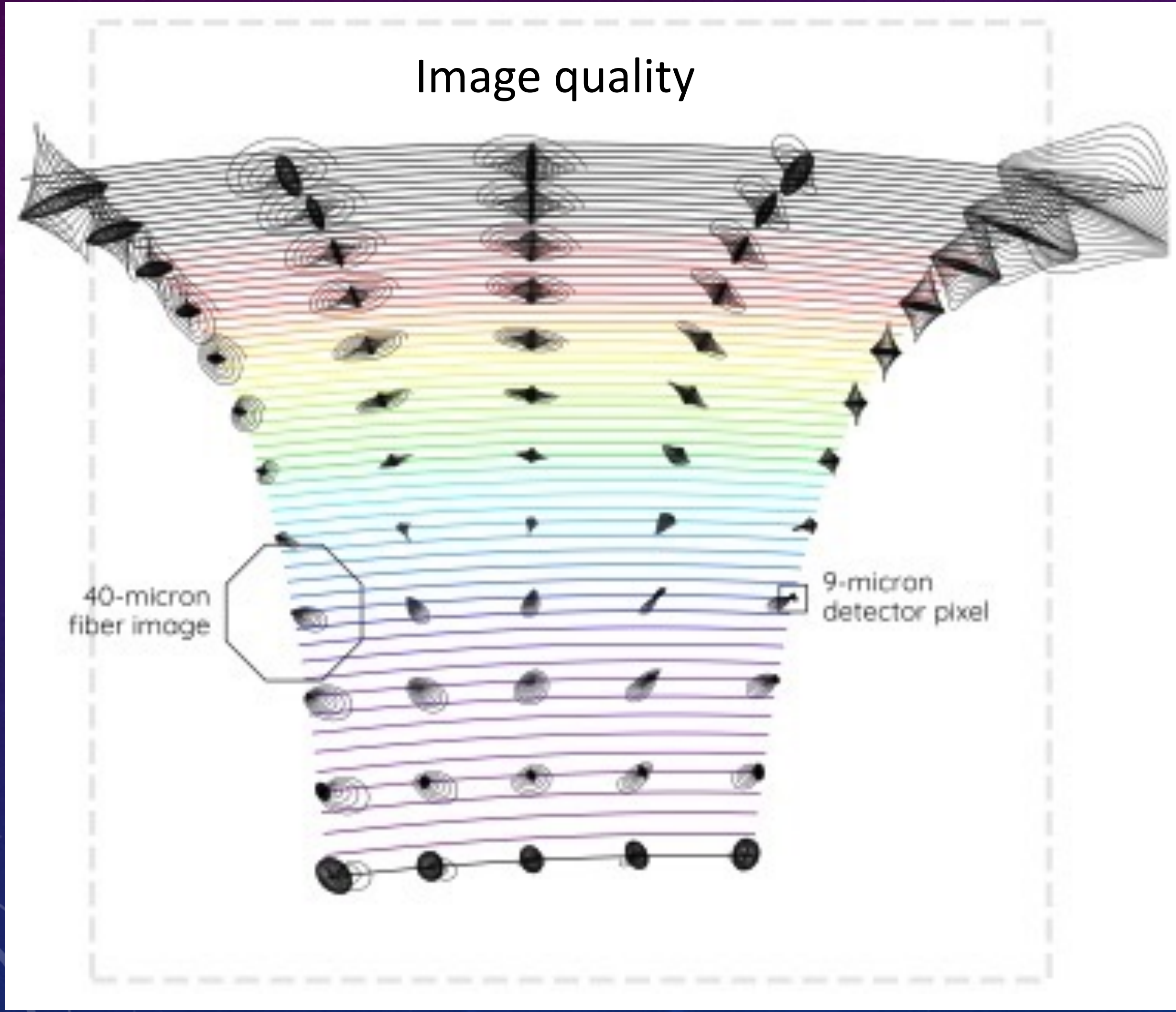
REFRACTIVE CAMERA

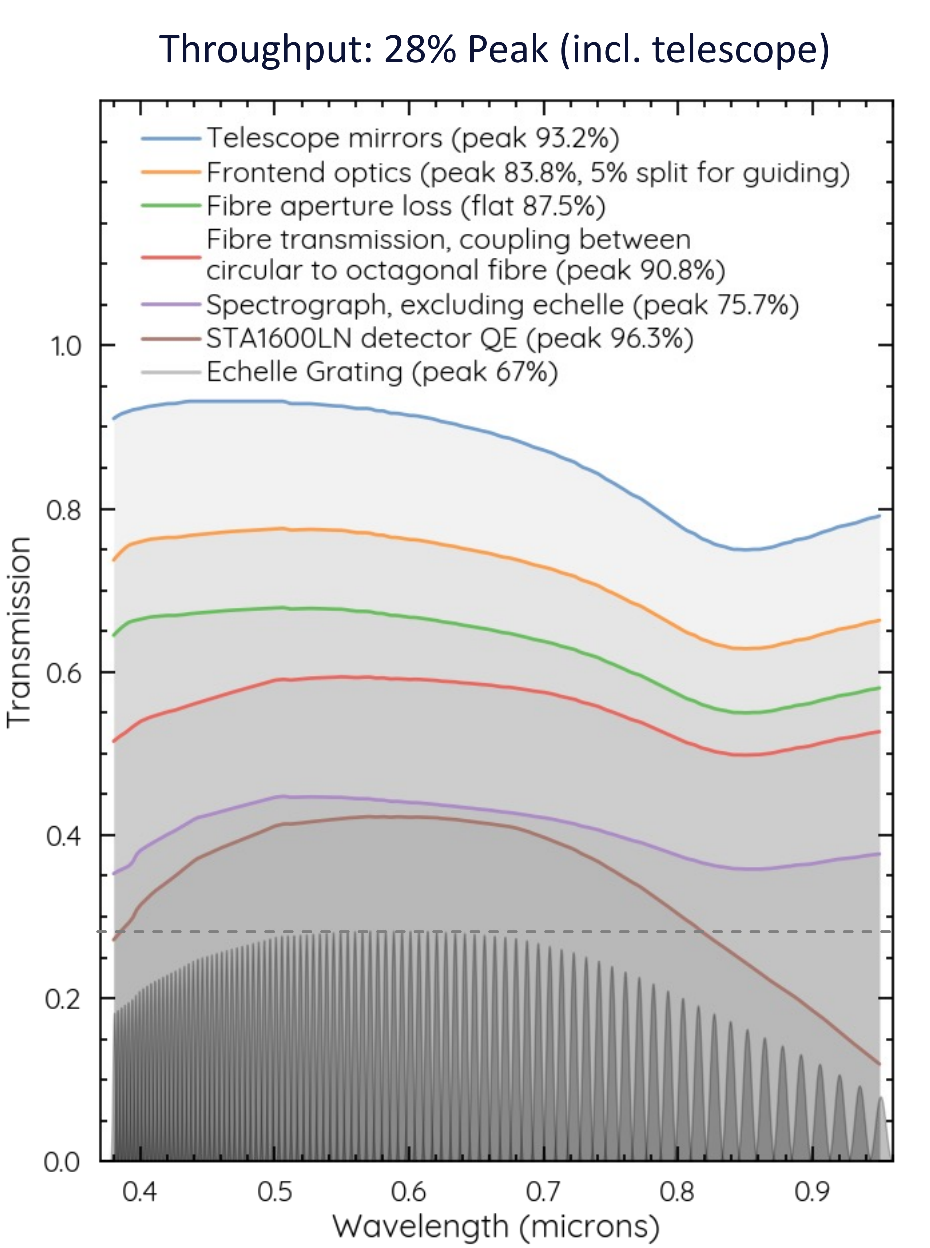
- *f* = 730mm, *f*/4.5
- Only 5 lenses!
  - Only spherical surfaces
  - High-transmission lithography glass
    2 Doublets:
        S-FPL51/PBM2Y
        BSL7Y/S-FPL51
    1 Field flattener (SiO2), cryostat vacuum window



- Tilted focal plane to correct cylindrical field curvature from white-pupil relay
- Optimised for precision RV:
  - Near-telecentric in dispersion direction
  - Defocus spectral shift is symmetric around blaze peak
  - Aberrations with minimal asymmetry

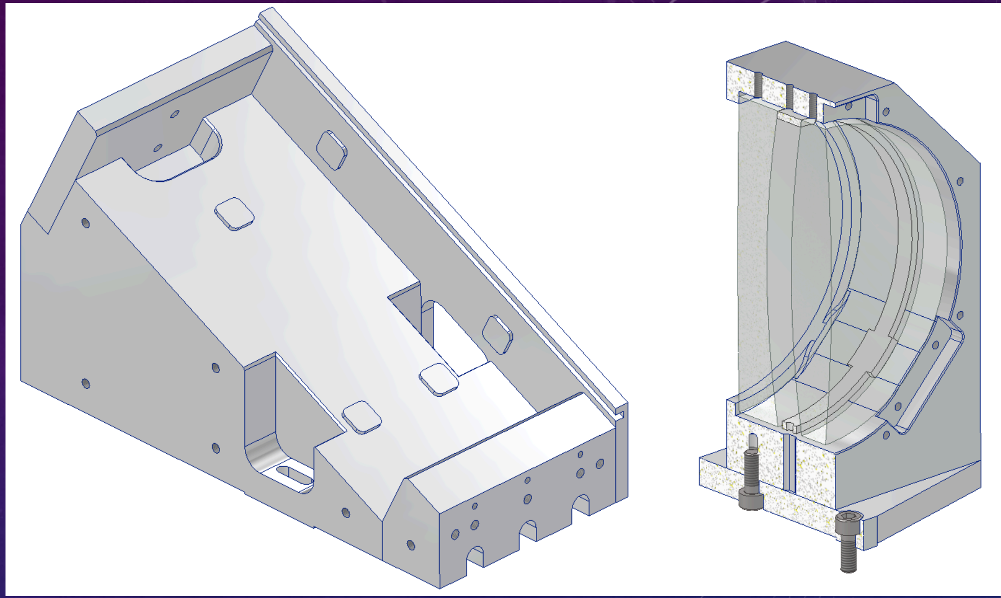
MARVEL OPTICAL PERFORMANCE

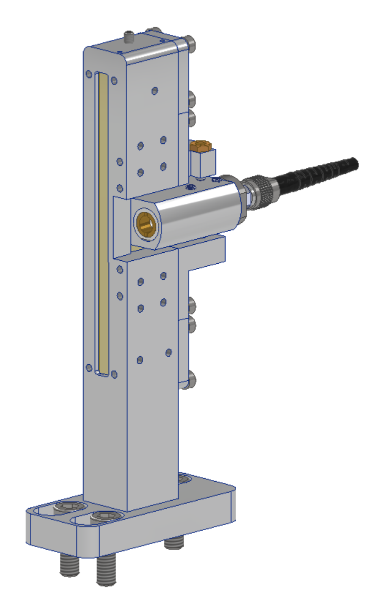


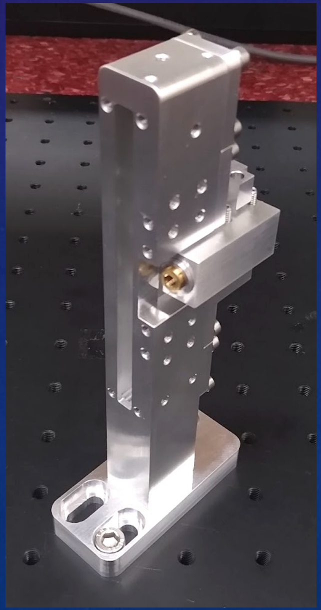


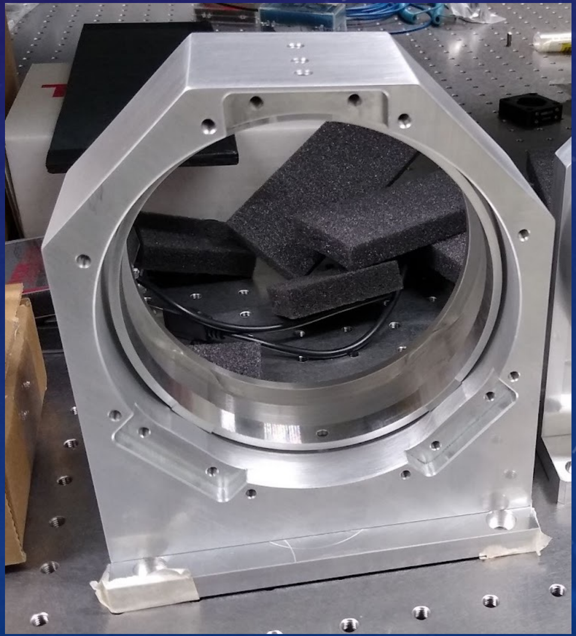
SPECTROGRAPH OPTOMECHANICS

- Kinematically constrained optics mounting
- Monolithic mounts wherever possible
- Minimal fine-adjustment (zero on large optics)
- Long-term stability, simple alignment
- Bench & optomechanics all Aluminium:
  - High thermal conductivity
  - Minimise thermal gradients



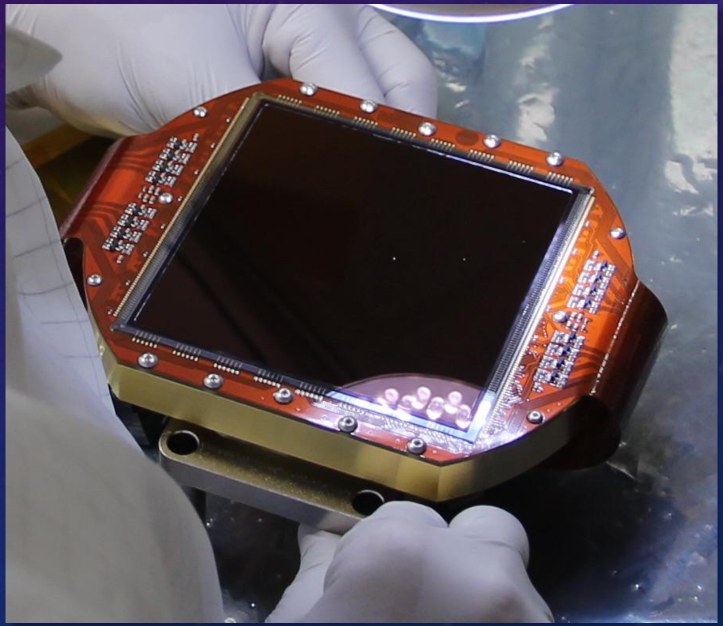


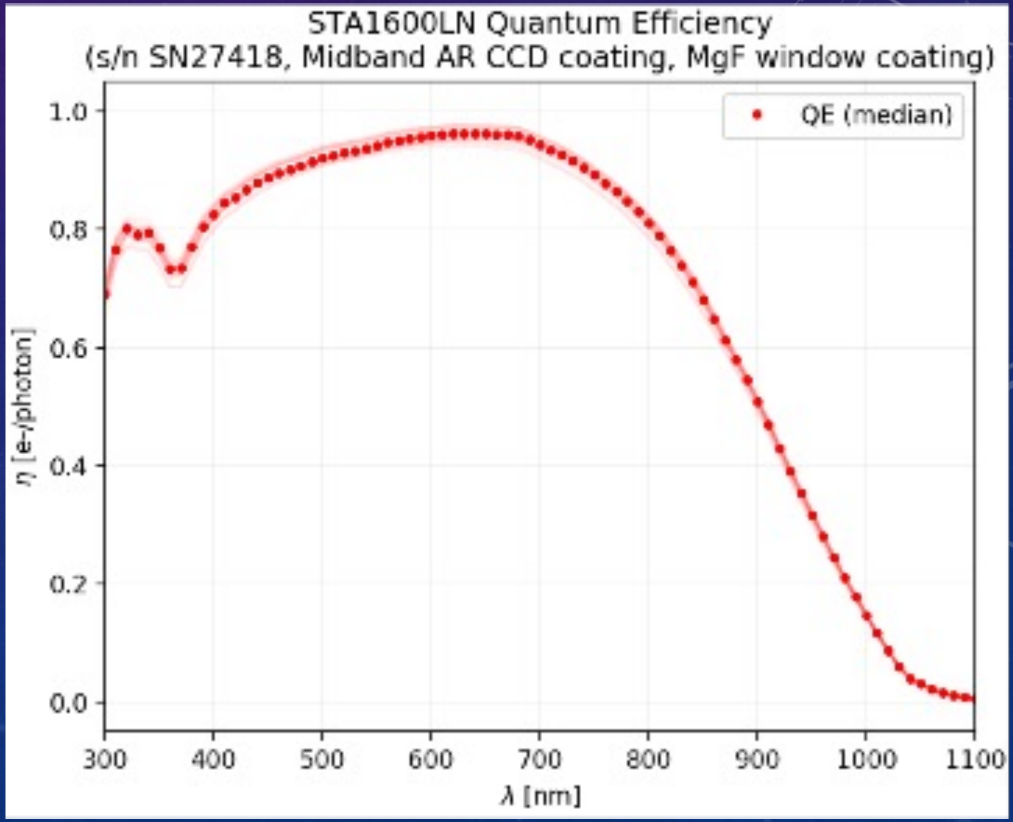




DETECTOR SYSTEM

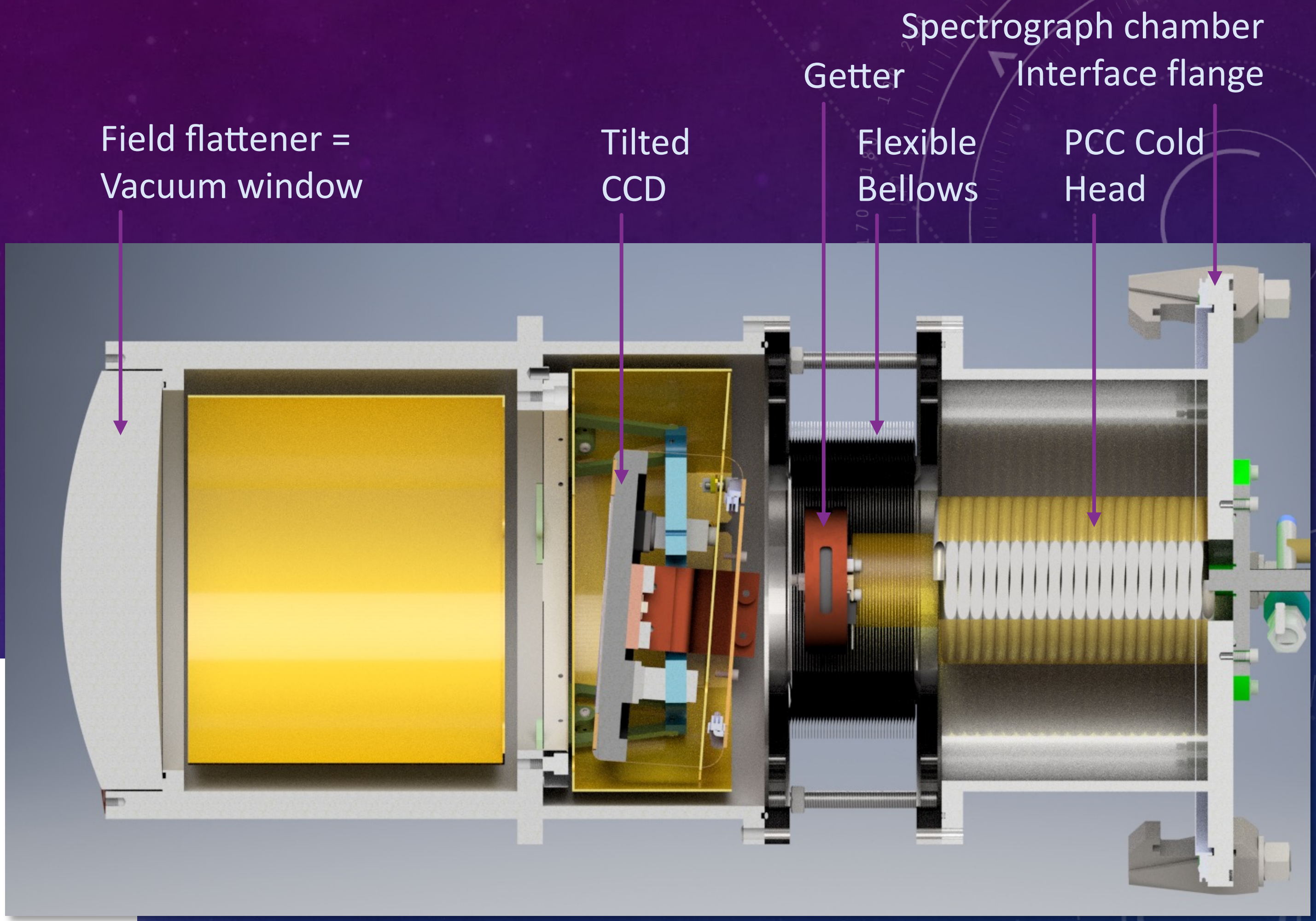
- CCD: STA1600LNC 10k x 10k, 9-µm pixels (95 x 95 mm)
  - HR-mode: 5 pix. / 2.5 pix. (2x2 binning) sampling
  - UHR-mode: 3 pixel sampling
- Extremely stable temperature control
  - Charge shuffling clocking to maintain constant thermal load during integration

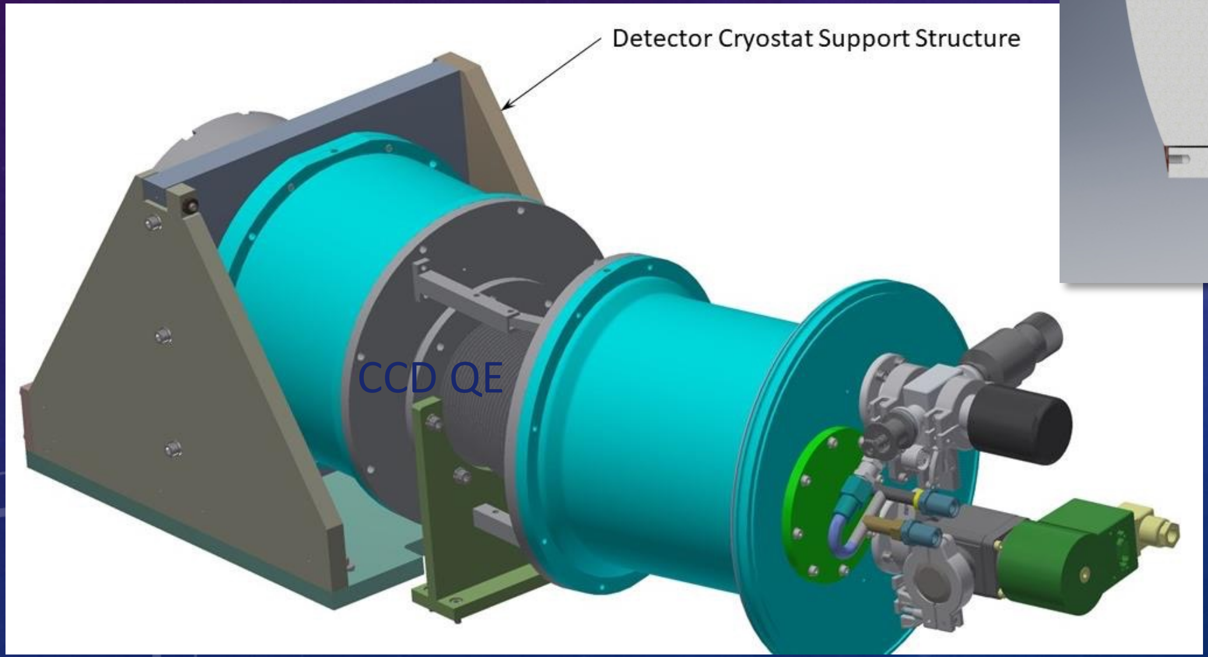




DETECTOR SYSTEM CRYOSTAT

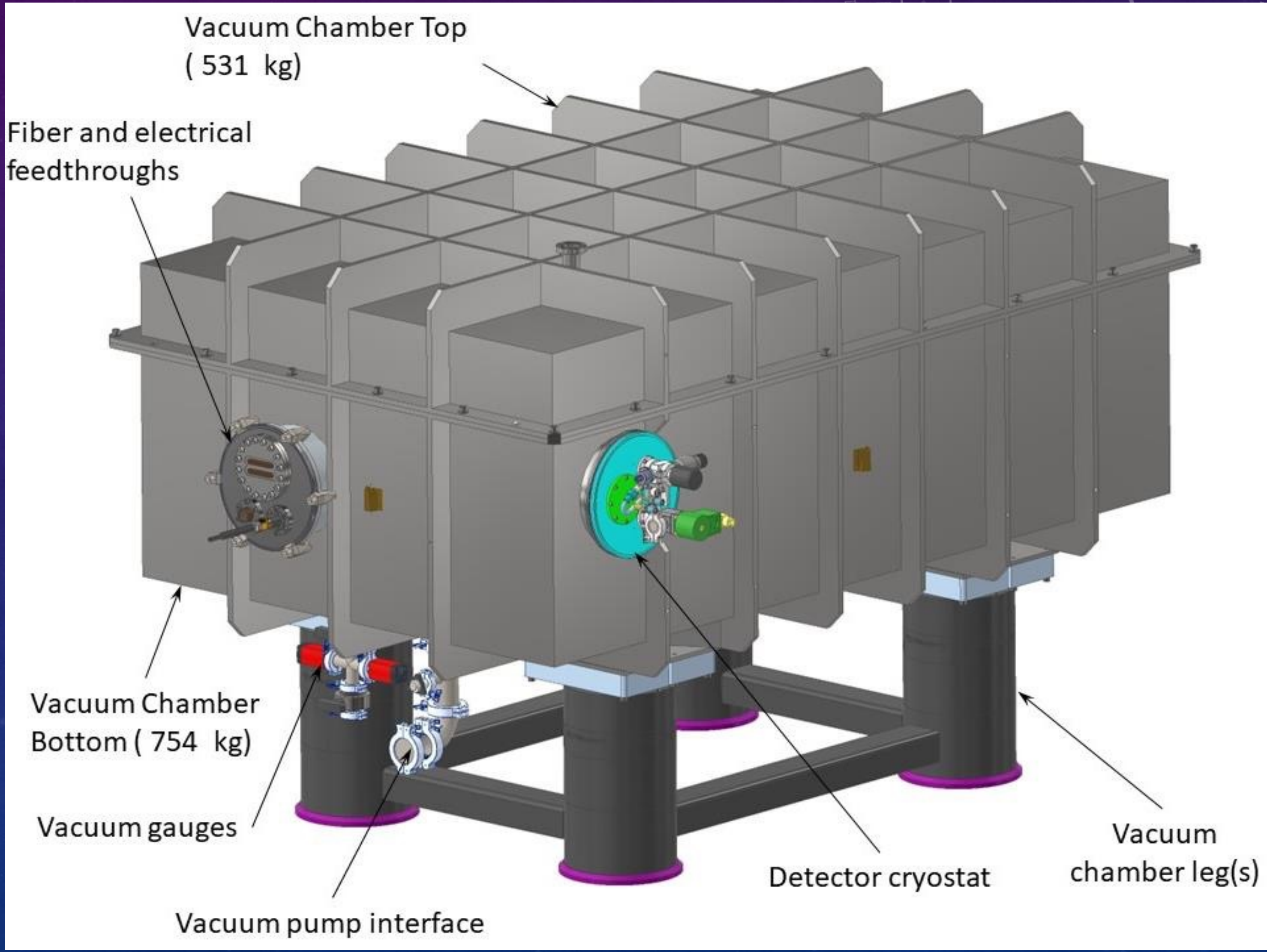
- Vacuum isolated from Spectrograph chamber
- Flexible bellows between front and Rear part
- CryoTiger cooling (Edwards PCC)





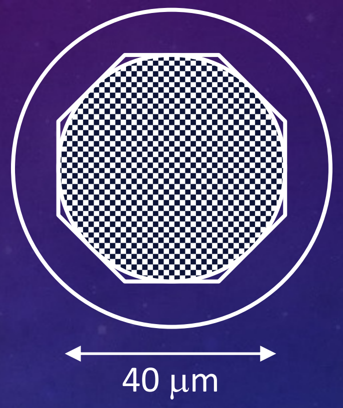
SPECTROGRAPH VACUUM CHAMBER

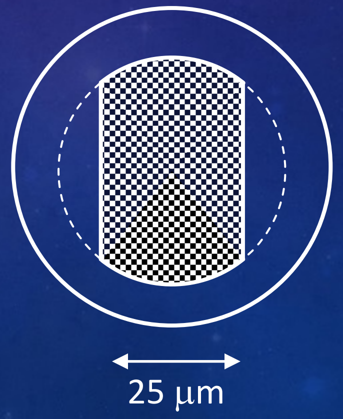
- Stainless steel vacuum tank
- Spectrograph bench enclosed by Temperature-controlled radiation Shield (based on NEID design), Temperature stability < 1 mK
- Installed in temperature-controlled Room
- Support legs with passive vibration Isolation

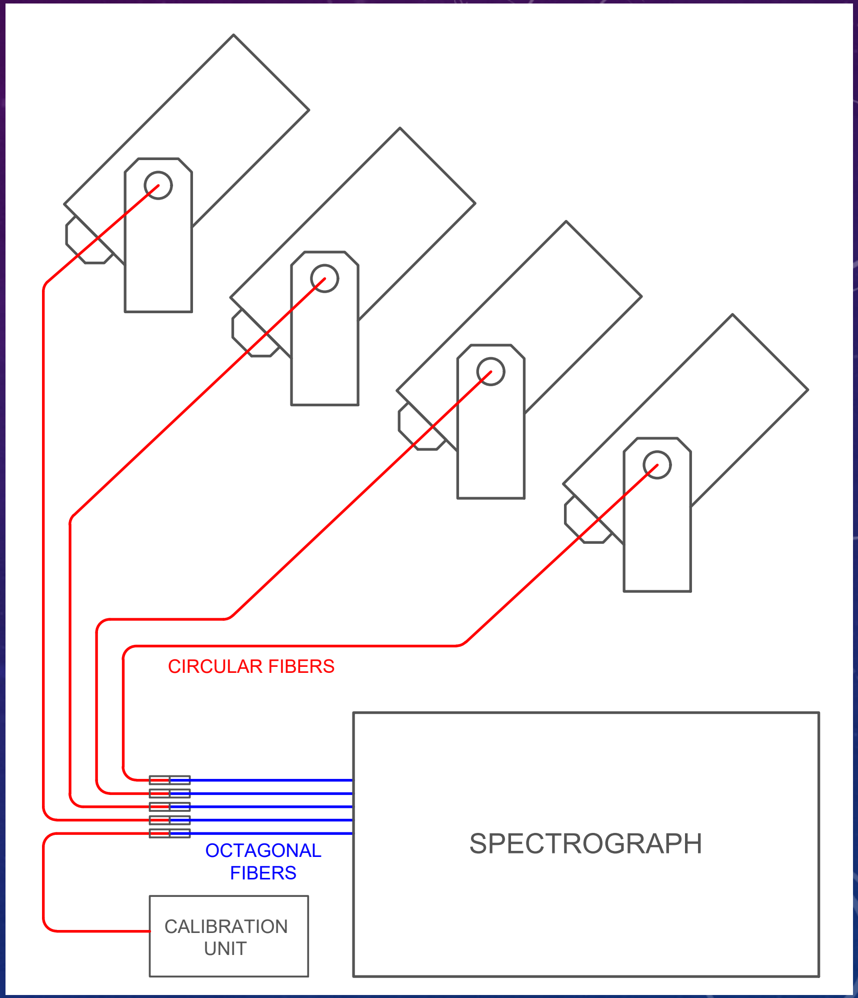


OPTICAL FIBER LINK

- Sky aperture: 2.3 arcsec
- High-resolution fiber:
  Ø40μm Circular fiber from telescope
  Butt–coupled with
  40μm Octagonal fiber to spectrograph
- Coupling efficiency:
  - Circular To Octagonal: > 97%
  - FRD (F/4.3 ⇒ F/3.85): > 94%
  - Total: > 90%
- Ultra-high-resolution fiber:
  "Stadium" shaped fiber 25 x 40 μm
  Aperture: 1.4 x 2.3 arcsec

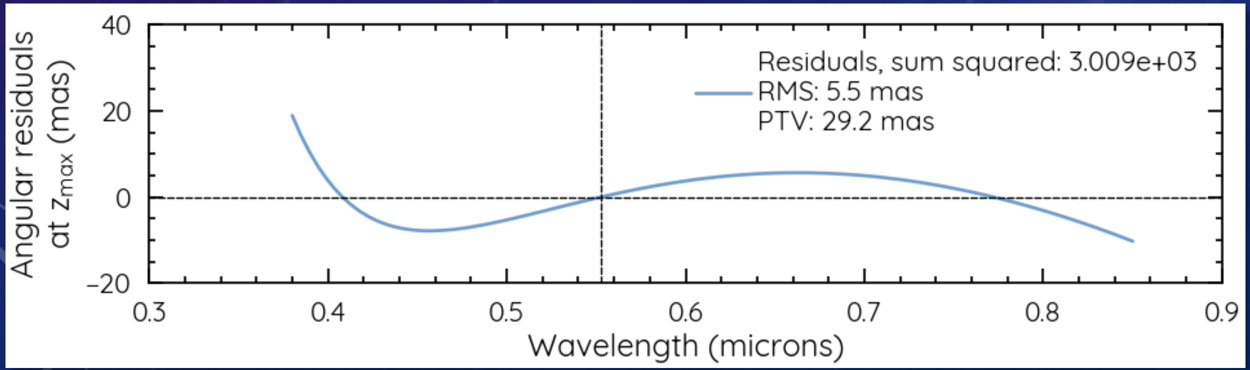


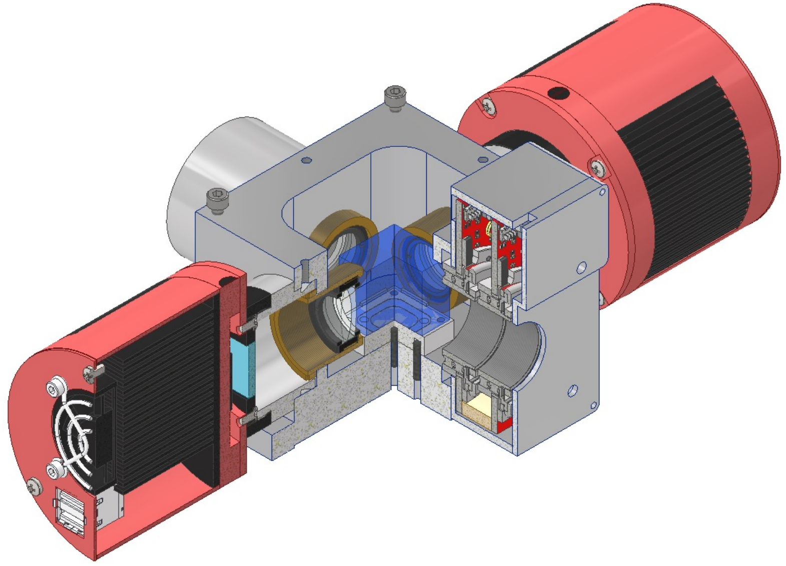


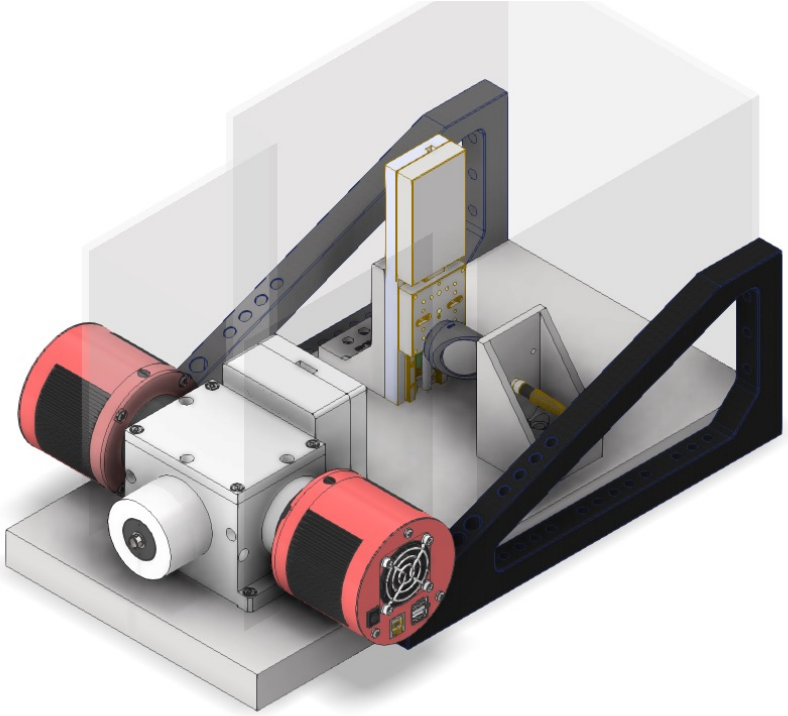


ACQUISITION AND GUIDING UNITS

- Injection of telescope beam (and calibration light) in fiber
- Front ends is built around custom cube beam splitter: picks off ~3% of light for guiding
- 2 CMOS cameras to see star and fiber
- Piezo Tip/Tilt mirror for fast guiding, dithering of target image across fiber face during expsure
- Atmospheric Dispersion Corrector
  - 2 identical counter-rotating compound prisms
  - PtV residuals < 30 mas

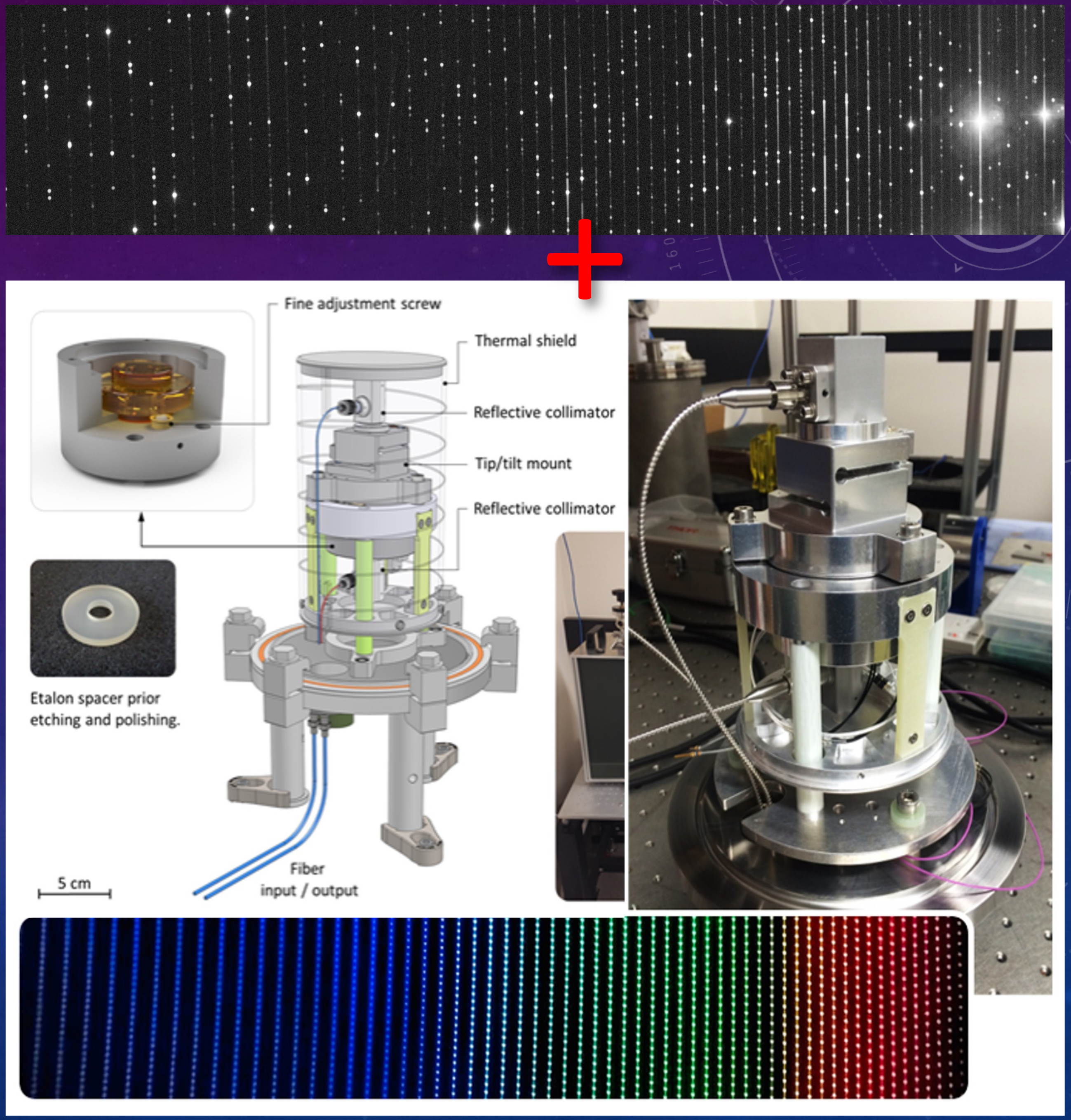






WAVELENGTH CALIBRATION

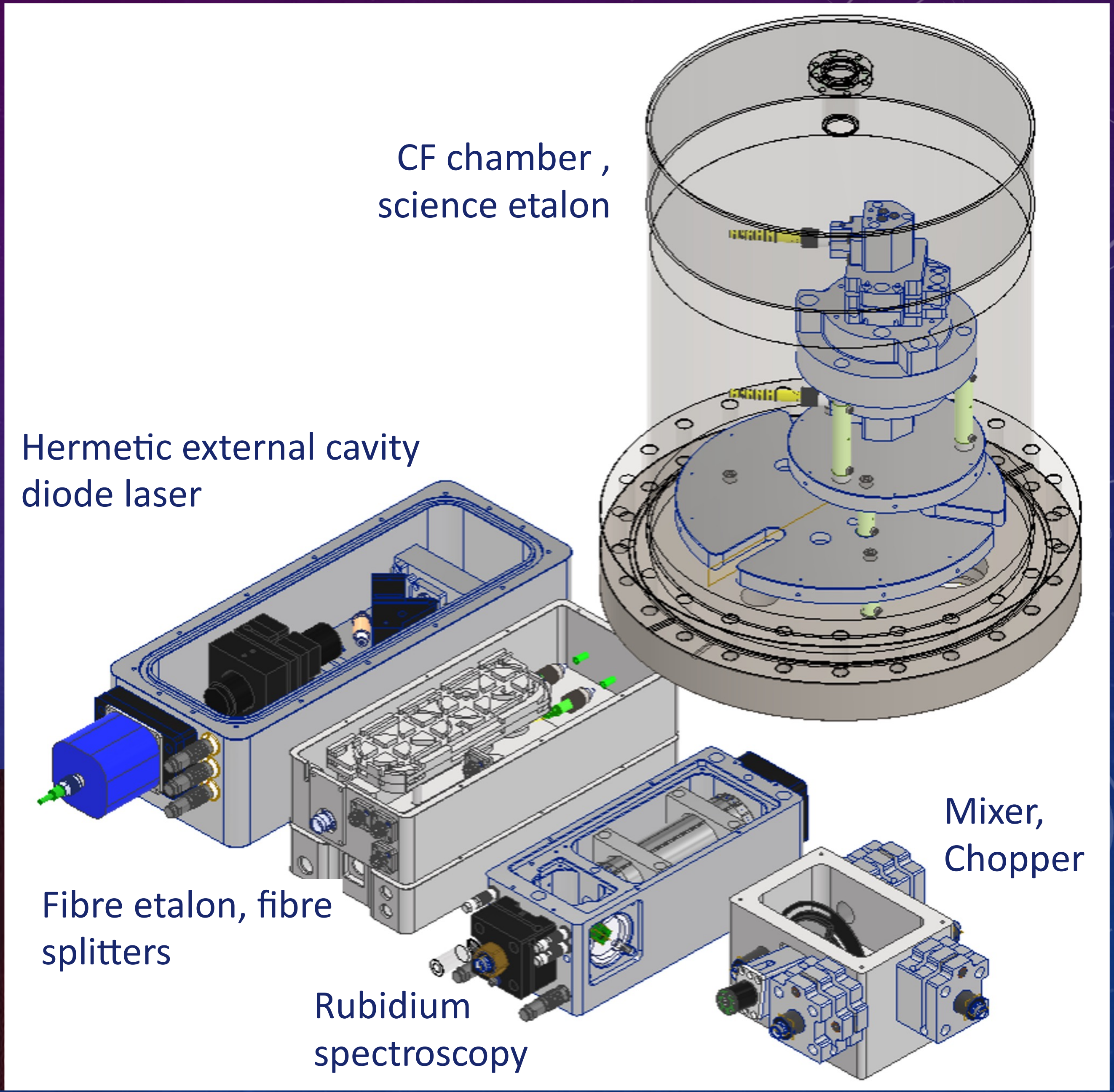
- Nightly absolute wavelength reference from Thorium-Argon lamp
- Simultaneous reference with each science exposure from white-light illuminated Fabry-Pérot etalon



ETALON SYSTEM

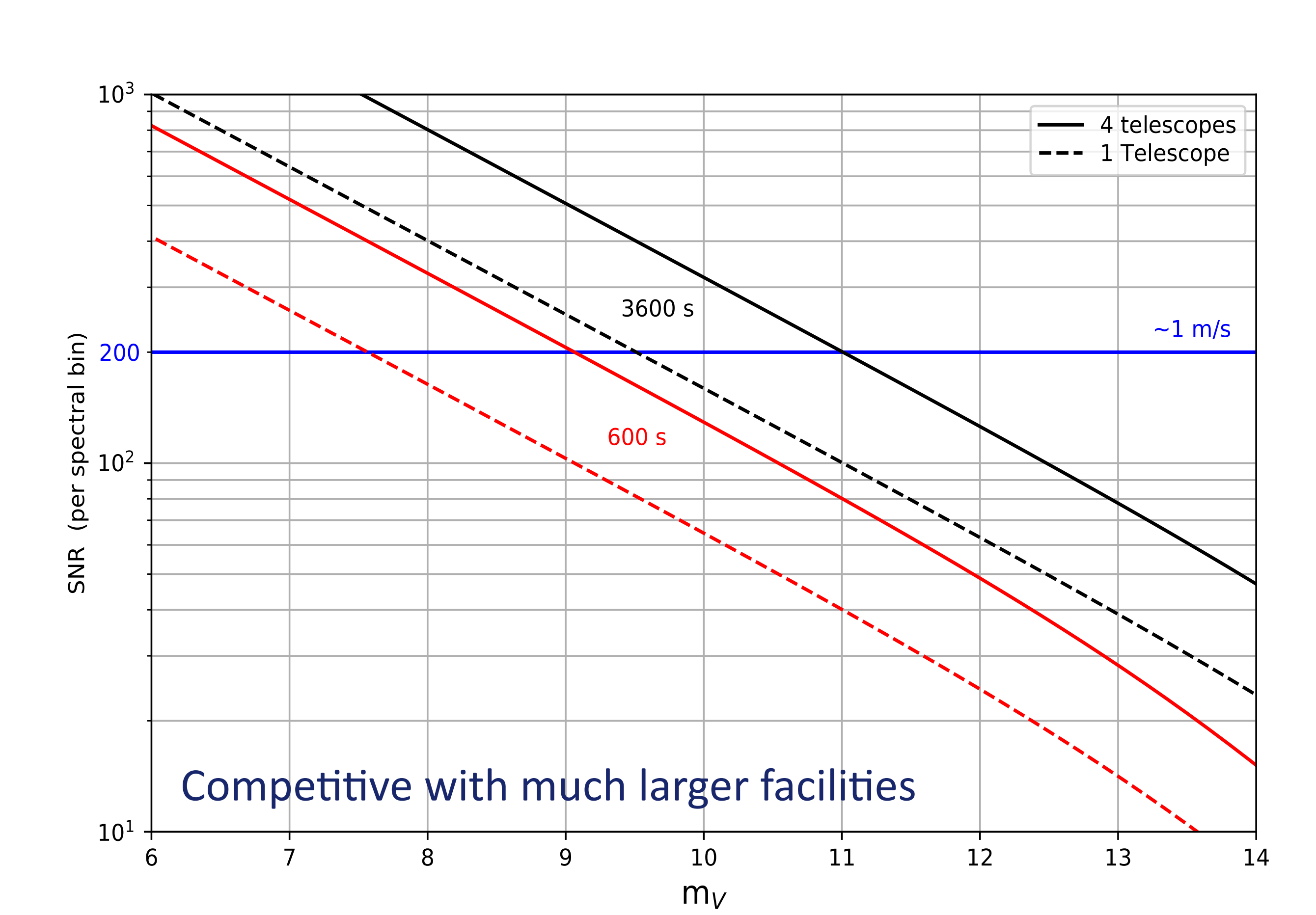
- Fabry-Pérot etalon is held under vacuum, Temperature stable to **<100 uK**
- Scanning laser probes single etalon peak and Rubidium hyperfine lines @780nm
- Etalon is **optically passive**, laser tracking system only monitors behaviour

Real spectrum

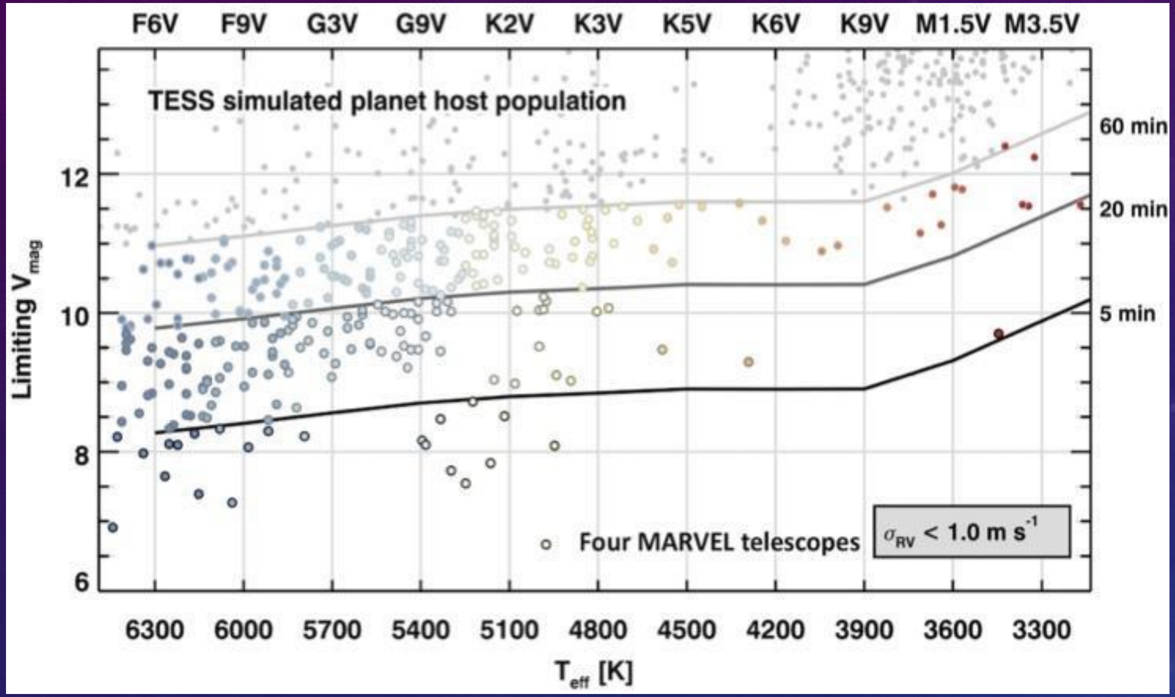


DESIGN TARGETS & GOALS

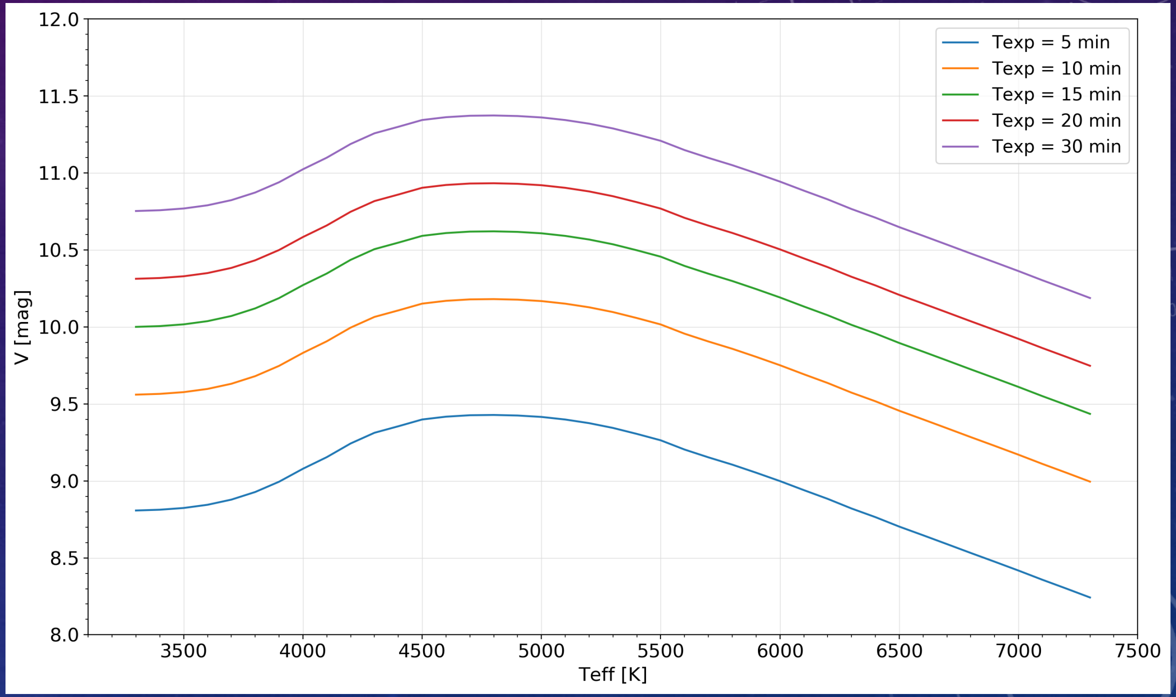
- Maximise optical throughput where possible (coatings, materials, # elements, ...) to compensate for small telescope aperture(s)
- RV precision: < 1 m/s
- Limiting magnitudes for 1 hour exposures, SNR=200:
  - m_V = 11 (4× telescopes)
  - m_V = 9.5 (1× telescope)
- Instrumental temperature Stability: < 1mK



PERFORMANCE SIMULATIONS



Limiting magnitudes for RV uncertainty of 1 m/s

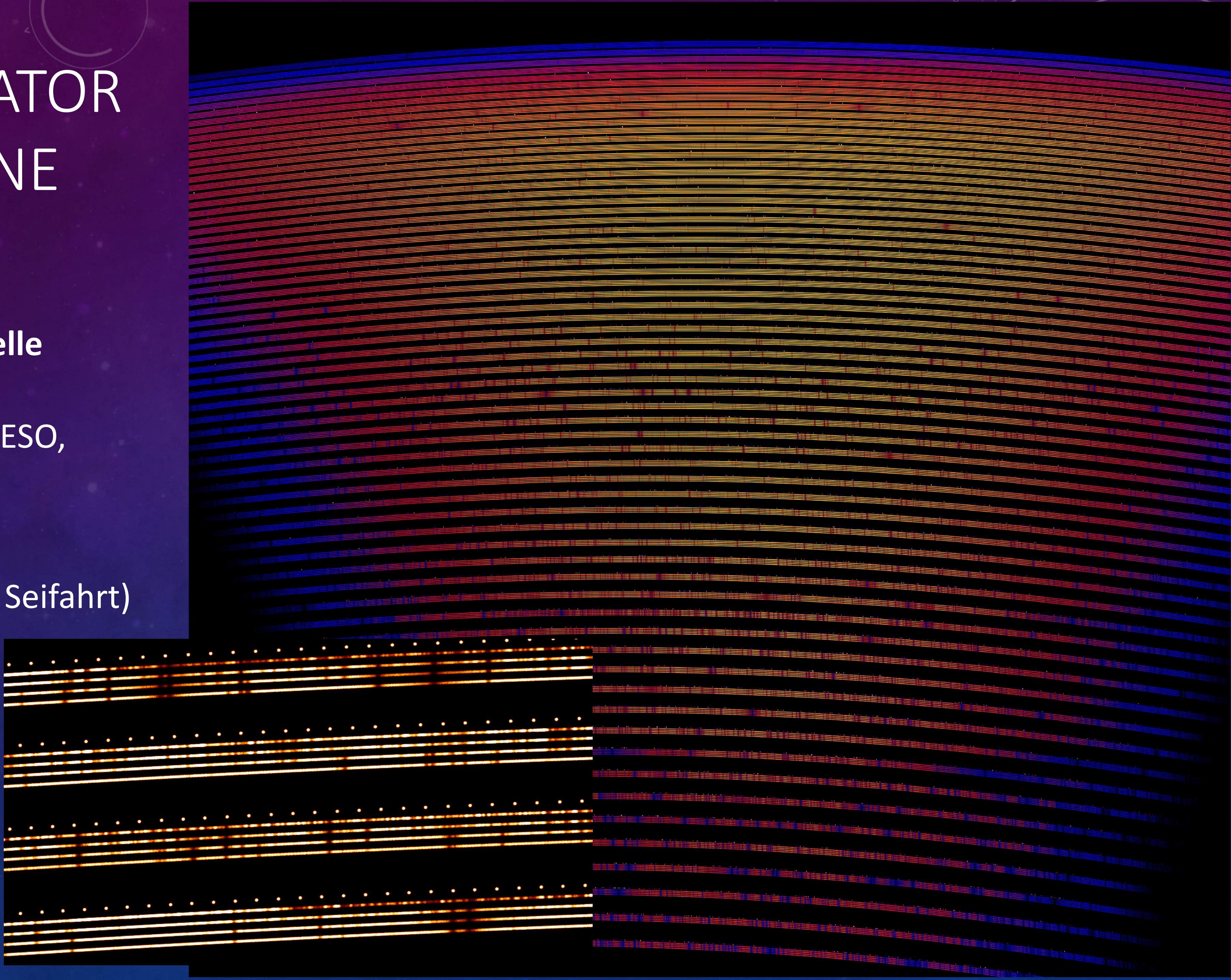


Photon noise limited RV uncertainty of 1 m/s for 15 min. exposure, *v* sin *i* = 2 km/s (4 telescopes)

MARVEL SIMULATOR AND DRS PIPELINE

- MARVEL Simulations
  - Spectrograph: **PyEchelle** (J. Stuermer)
  - Detector: **Pyxel** (ESA/ESO, T. Prod'homme)
- Data reduction pipeline:

  Based on **Maroon-X** (A. Seifahrt) & HERMES



STATUS & SCHEDULE

- Building: construction permit received, contracts signed, pouring concrete starts soon…
- Domes ordered, installation: Q1 2023
- Telescopes ordered, installation: Q2 2024
- Spectrograph optics: procurement on-going, final components expected Q1 2024
- Detector: tests on going at ATC
- System AIV Leuven: Q1-Q2 2024
- Commissioning La Palma: Q3-Q4 2024

MARVEL CONSORTIUM

- KU Leuven (Belgium), PI: Hans Van Winckel
- Macquarie University (Australia)
- Australian Astronomical Optics (AAO) (Australia)
- UK Astronomy Technology Centre (UK)
- ZAH Landessternwarte Heidelberg (Germany)
- Vienna University (Austria)
- ICE, CSIC (Spain)
- AlbaNova University Center (Sweden)
- DTU Space (Denmark)

Thank you!

Questions?

SPECTROGRAPH OPTICAL DESIGN

- Design heritage from NEID (Schwab+2016) and HERMES (Raskin+2011)
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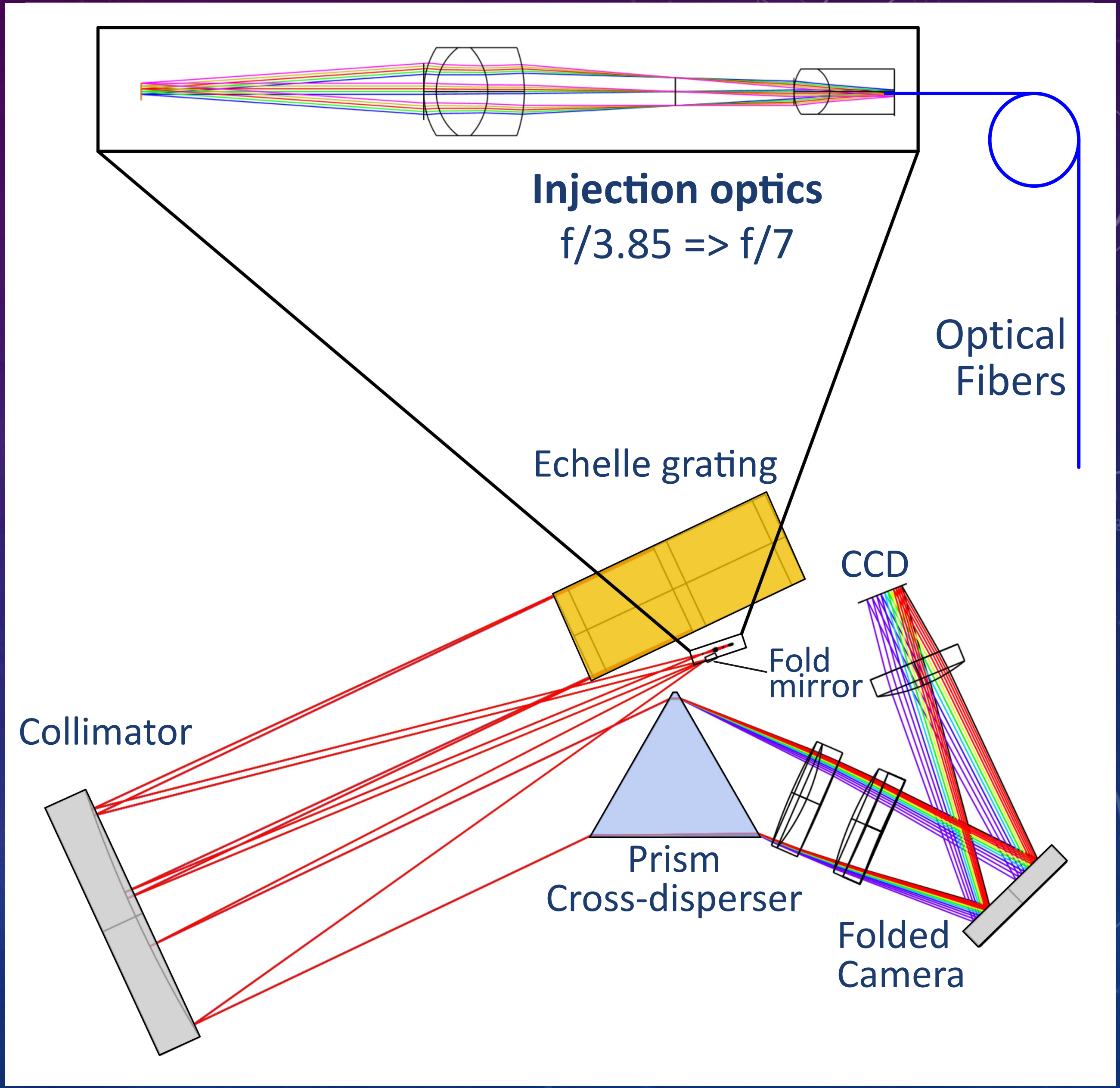
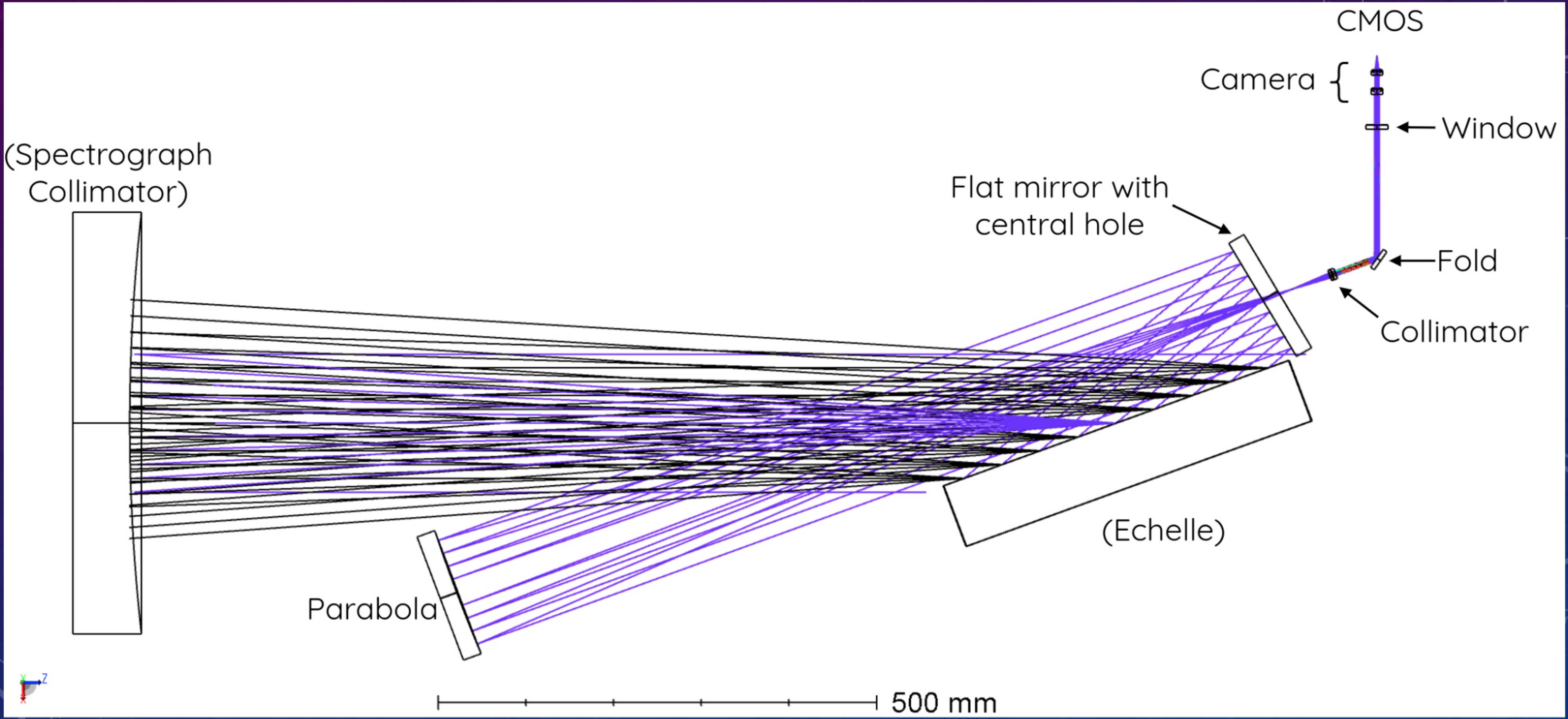


EXPOSURE METER



EXPOSURE METER

- Concept: sample the incident beam by picking up the zeroth-order (non-dispersed) reflection from the Echelle, relay and directly image fibres onto CMOS detector
- We have procured small (25x50mm) replicas of the same grating for measurement of the zeroth-order reflection efficiency