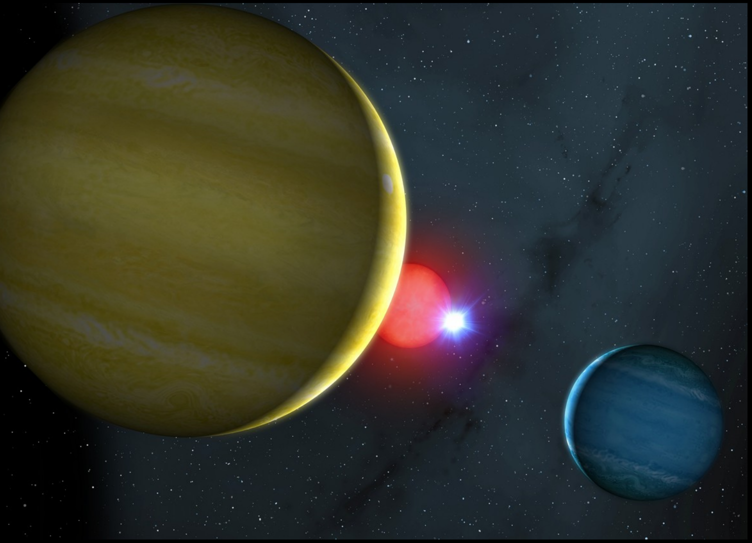


## HIGH TIME-RESOLUTION ASTROPHYSICS

# OPTICAL INSTRUMENTATION

Vik Dhillon (Sheffield/IAC)

# OVERVIEW

**Lecture 1: ULTRACAM**

- High time-resolution astrophysics (HTRA) - what is it and why study it?
- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

**Lecture 2: ULTRASPEC**

- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
- Instrumentation for high-speed photometry II: ULTRASPEC on the TNT

**Lecture 3: HiPERCAM**

- How can we improve ULTRACAM and what would this enable us to do?
- Eliminating atmospheric scintillation noise: Conjugate-plane photometry
- Instrumentation for high-speed photometry III: HiPERCAM

**Lecture 4: Data Reduction**

- Demonstration of photometric data reduction using the ULTRACAM pipeline

# OVERVIEW

**Lecture 1: ULTRACAM**

- High time-resolution astrophysics (HTRA) - what is it and why study it?
- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

**Lecture 2: ULTRASPEC**

- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
- Instrumentation for high-speed photometry II: ULTRASPEC on the TNT

**Lecture 3: HiPERCAM**

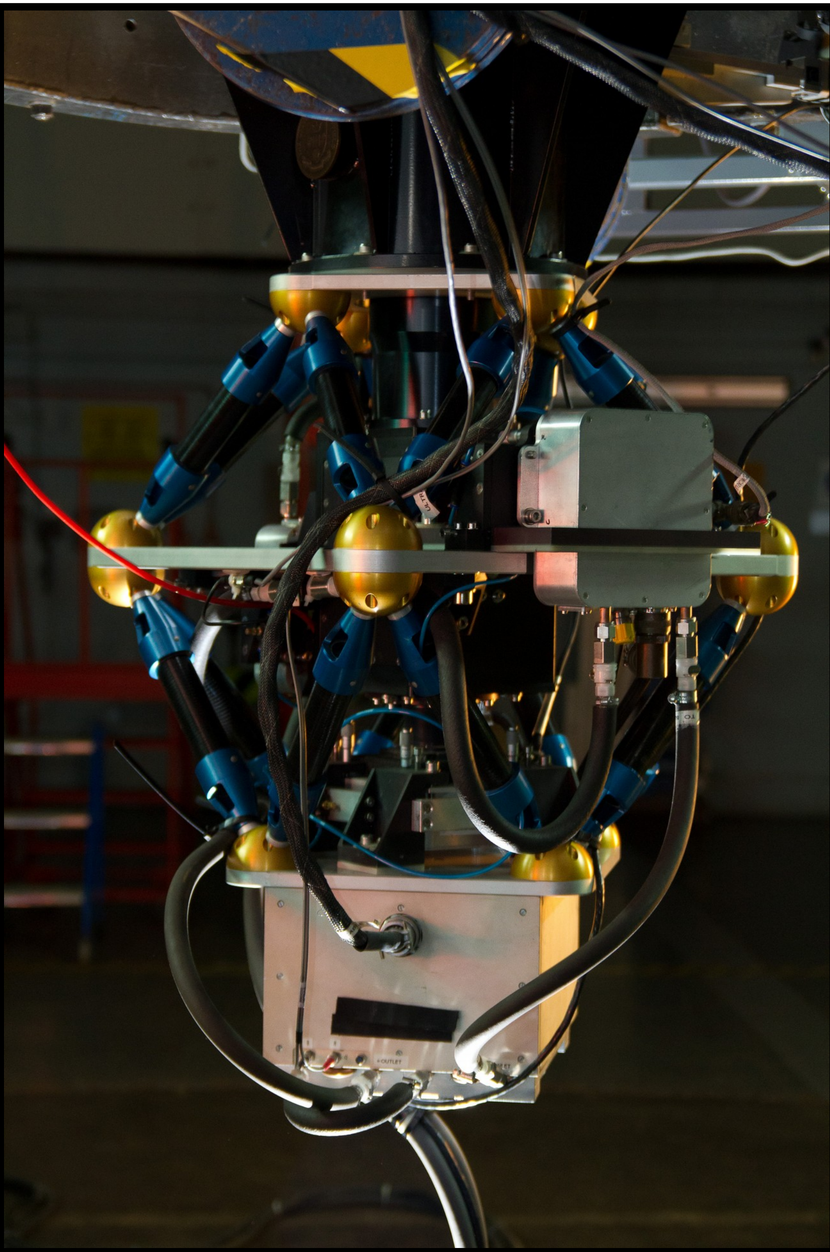
- How can we improve ULTRACAM and what would this enable us to do?
- Eliminating atmospheric scintillation noise: Conjugate-plane photometry
- Instrumentation for high-speed photometry III: HiPERCAM

**Lecture 4: Data Reduction**

- Demonstration of photometric data reduction using the ULTRACAM pipeline

# PROBLEMS WITH ULTRACAM

- Only 3 arms
- Not fast enough
- Not large enough field of view
- Limited by scintillation noise
- Can’t do long exposures
- Not sensitive enough in the red
- Suffers from fringing
- Suffers from pickup noise



# OVERVIEW

**Lecture 1: ULTRACAM**

- High time-resolution astrophysics (HTRA) - what is it and why study it?
- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

**Lecture 2: ULTRASPEC**

- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
- Instrumentation for high-speed photometry II: ULTRASPEC on the TNT

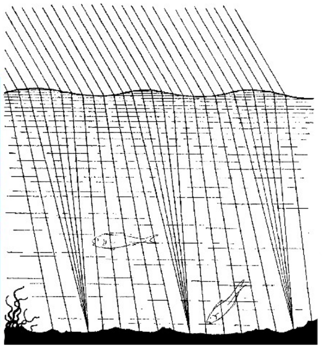
**Lecture 3: HiPERCAM**

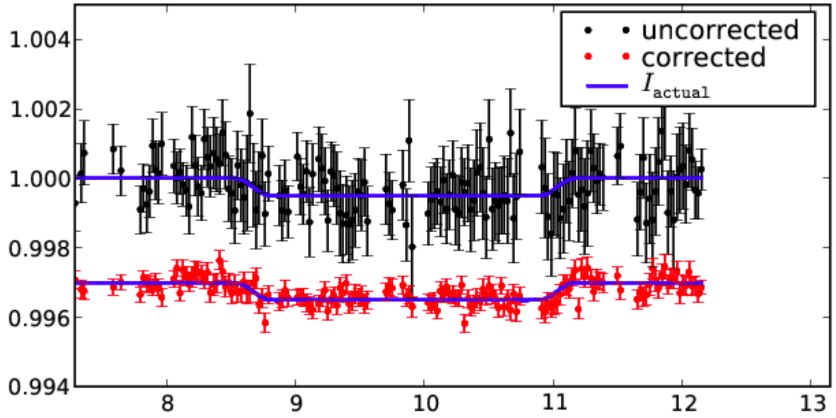
- How can we improve ULTRACAM and what would this enable us to do?
- Eliminating atmospheric scintillation noise: Conjugate-plane photometry
- Instrumentation for high-speed photometry III: HiPERCAM

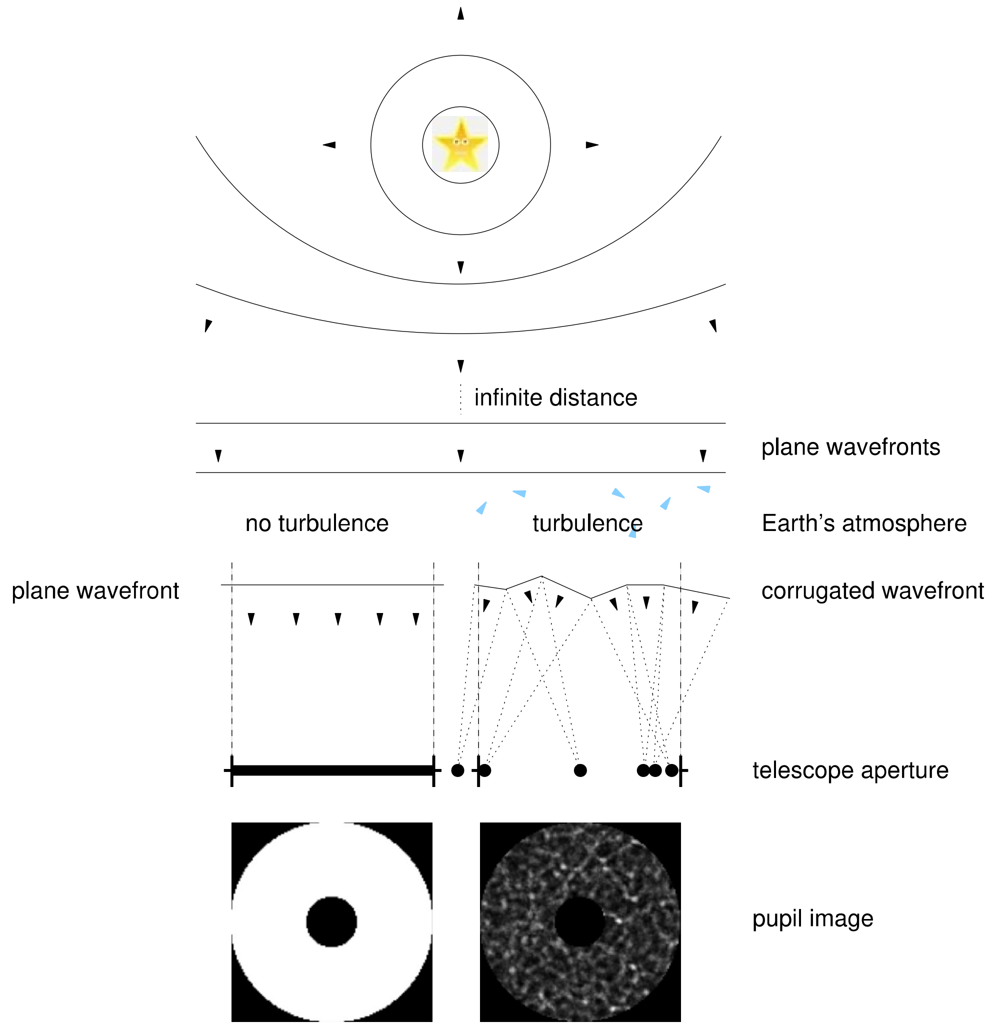
**Lecture 4: Data Reduction**

- Demonstration of photometric data reduction using the ULTRACAM pipeline

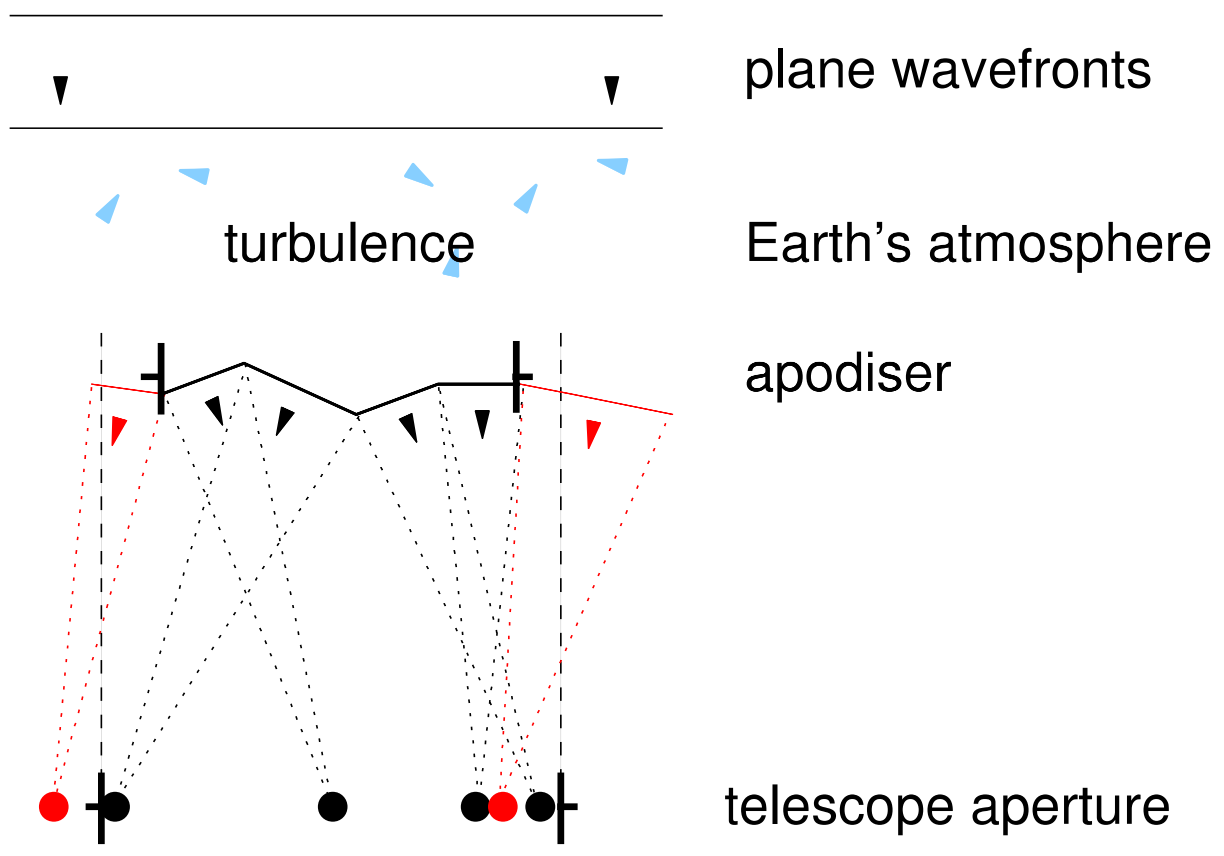
# SCINTILLATION CORRECTION



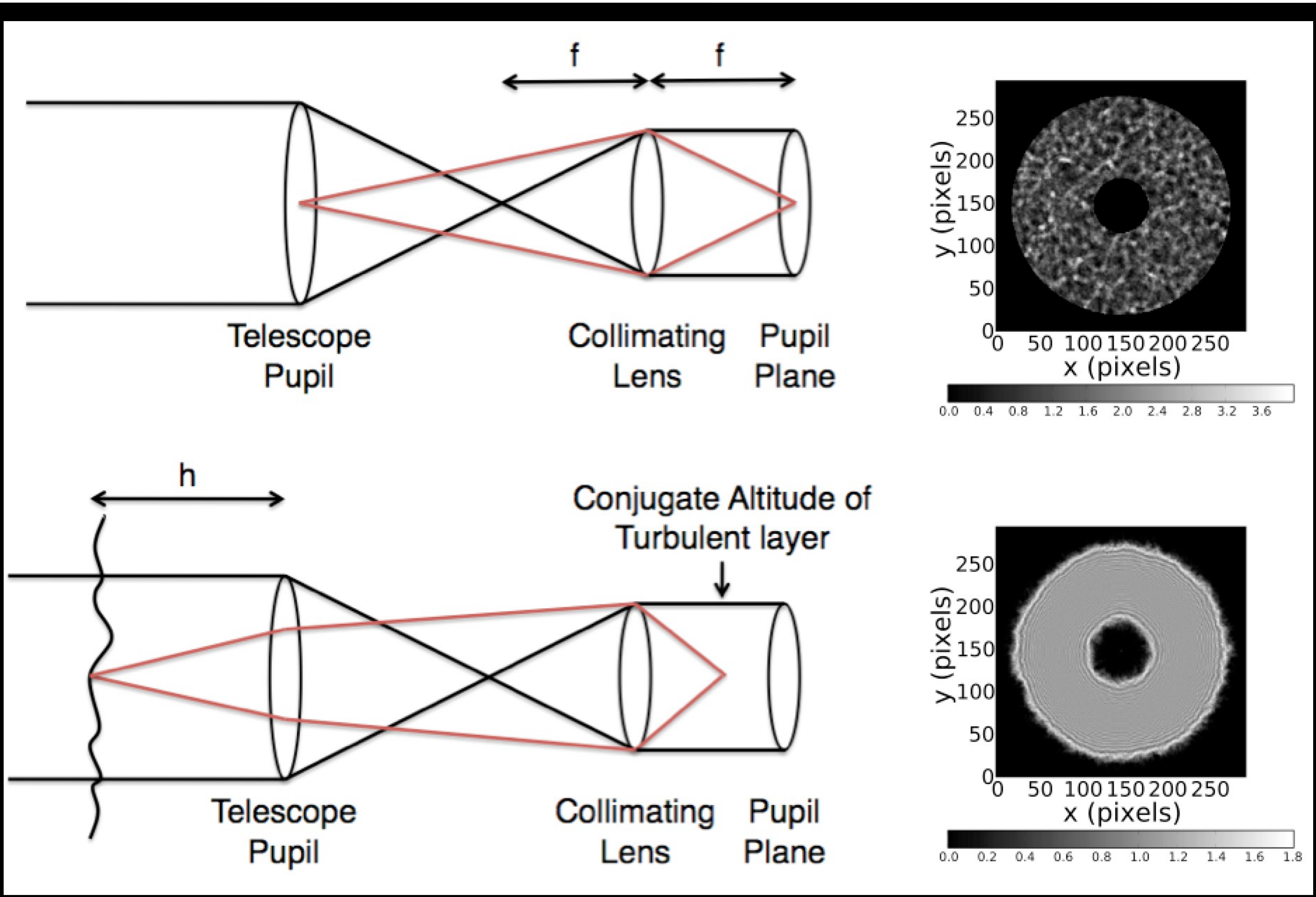




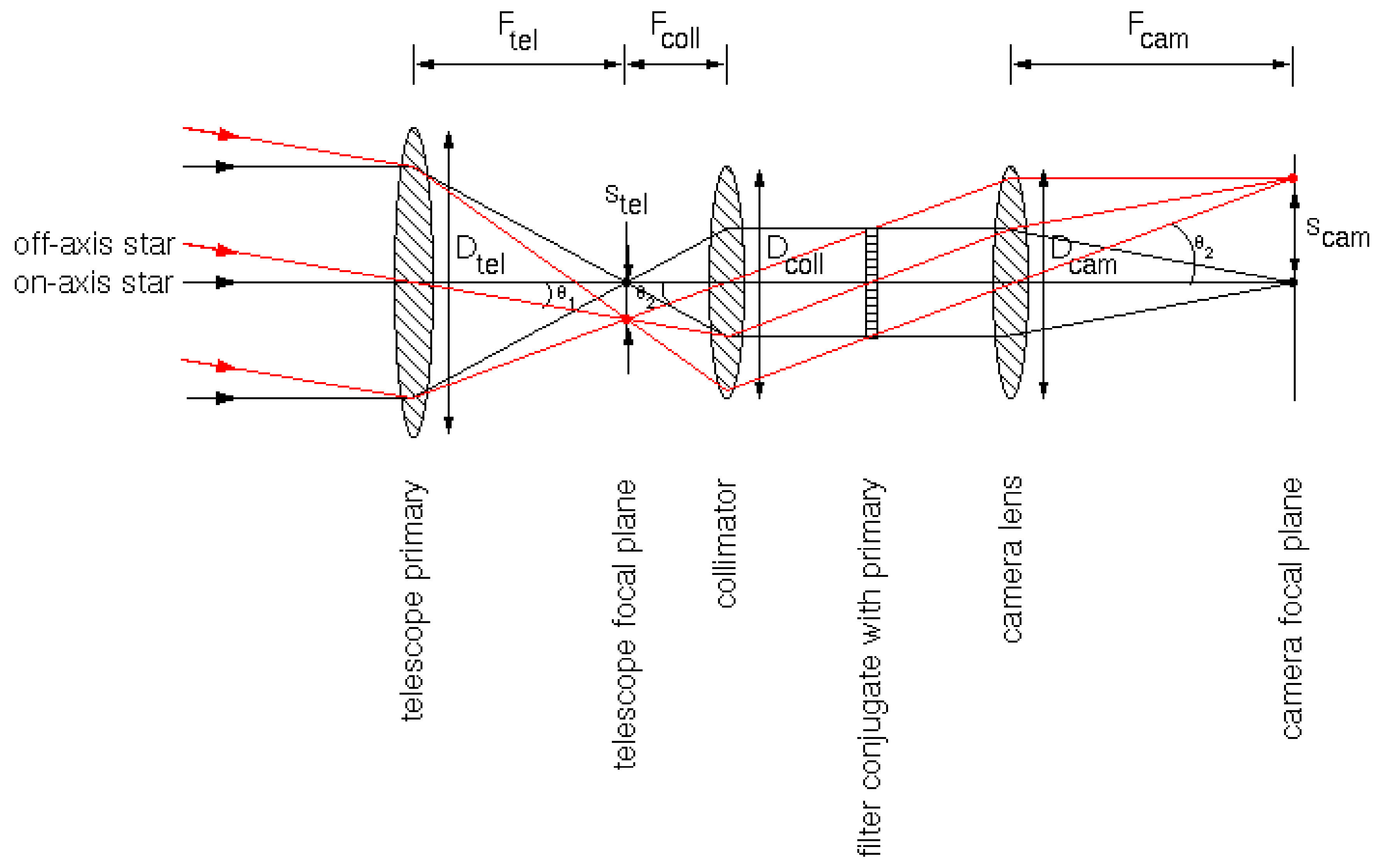
# SCINTILLATION CORRECTION



# SCINTILLATION CORRECTION

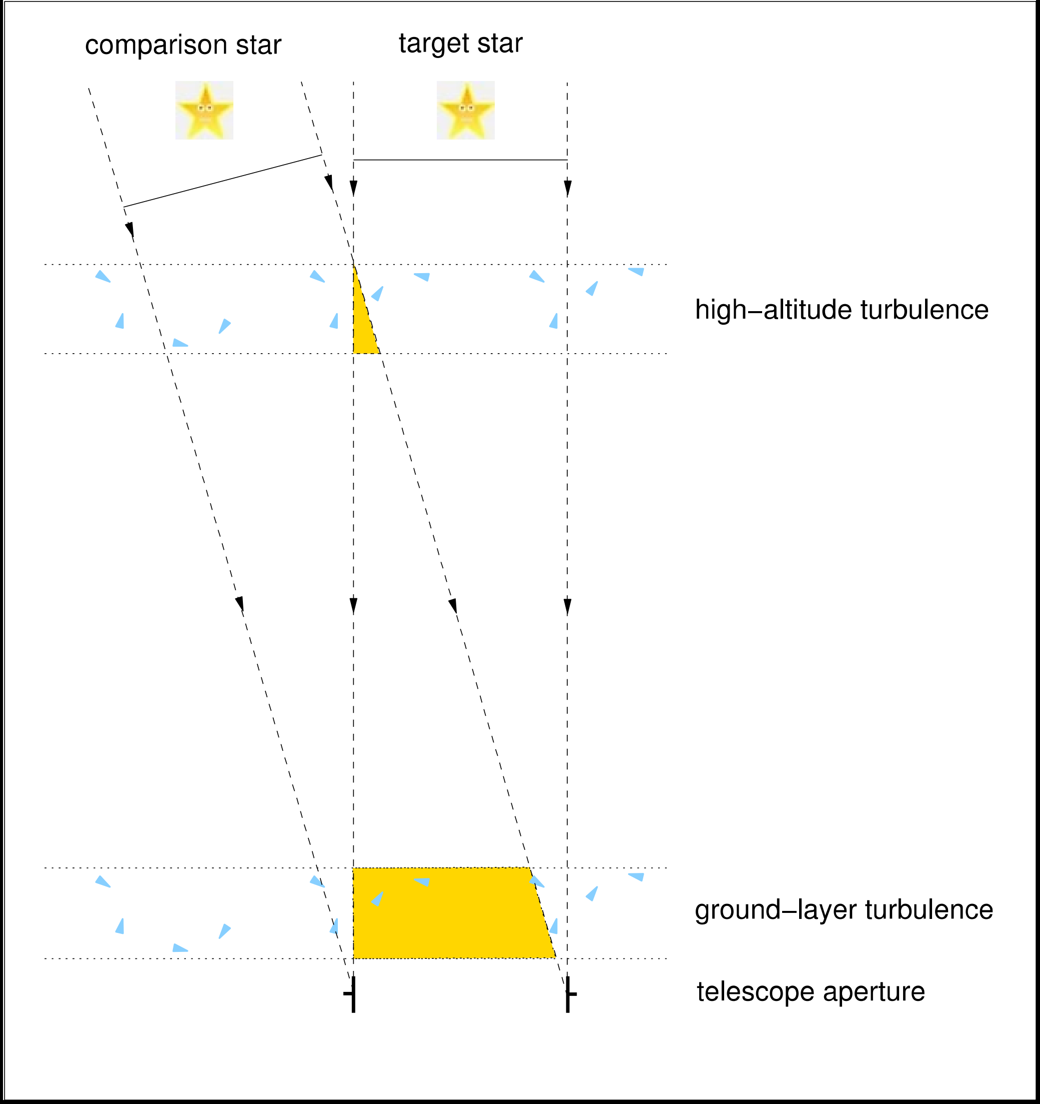


# OPTICS



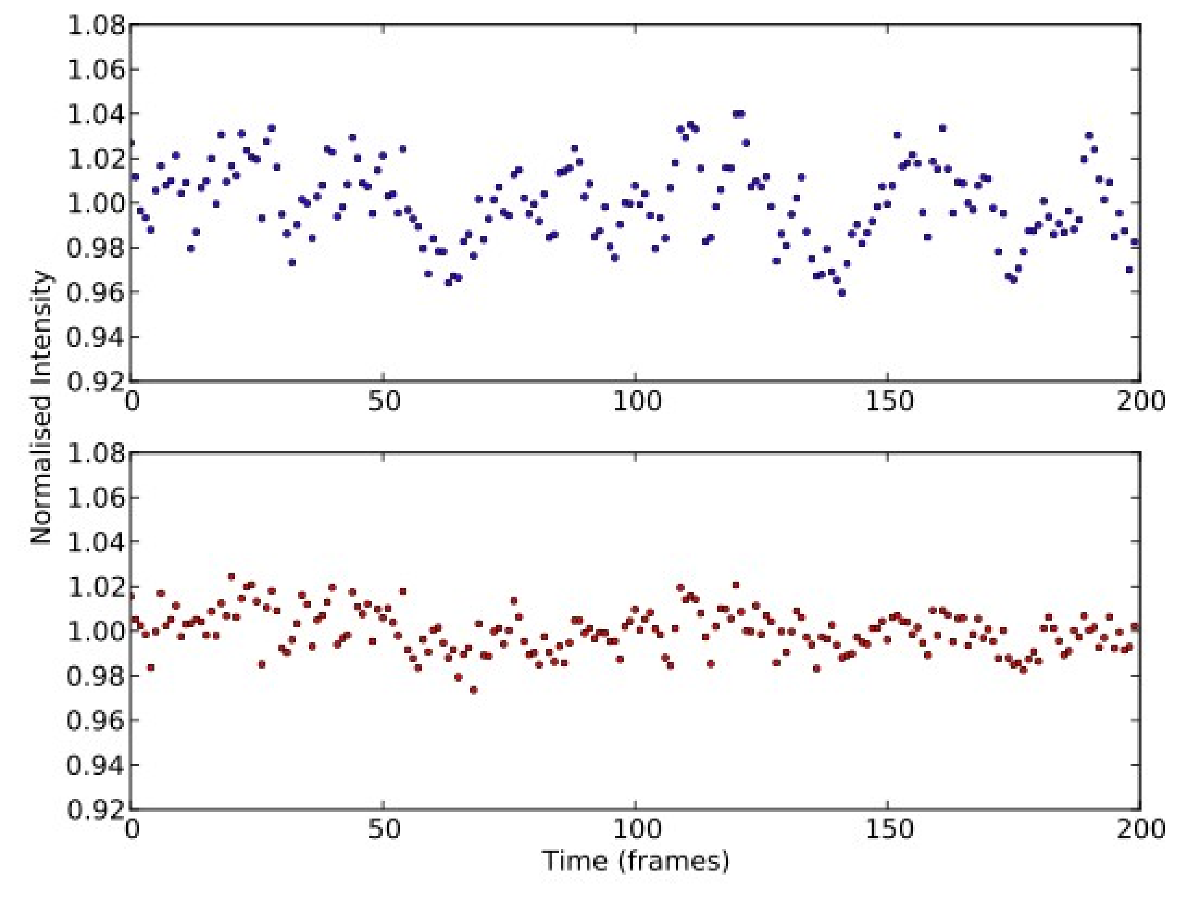
$F_{tel}$
$F_{coll}$
$F_{cam}$
$s_{tel}$
$s_{cam}$
$D_{tel}$
$D_{coll}$
$D_{cam}$
$\theta_1$
$\theta_2$
$\theta_2$
off-axis star
on-axis star
telescope primary
telescope focal plane
collimator
filter conjugate with primary
camera lens
camera focal plane

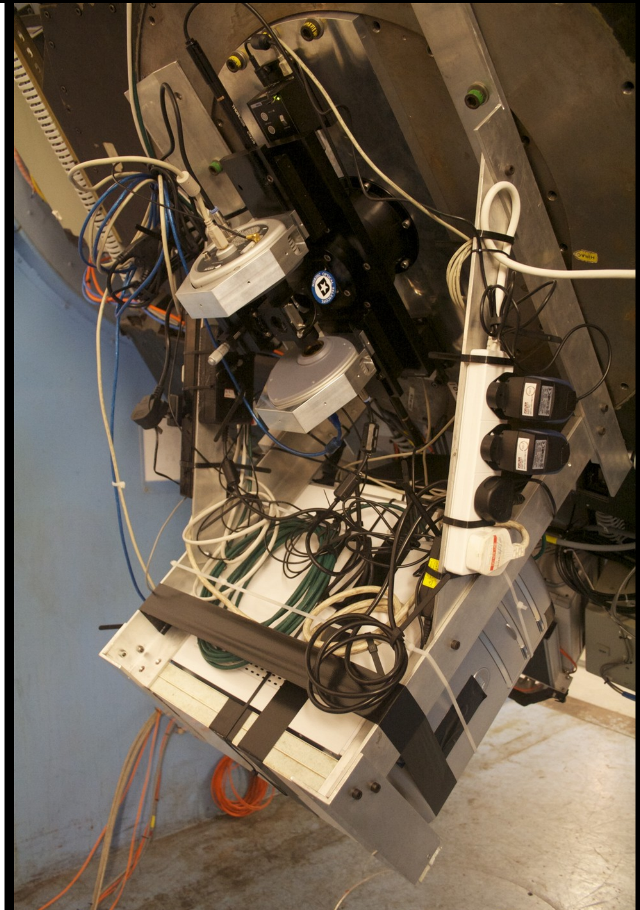
# SCINTILLATION CORRECTION



# CONJUGATE PLANE PHOTOMETRY

Prototype conjugate-plane photometer on the 2.5m NOT on La Palma demonstrated that the technique works.





# CONJUGATE PLANE PHOTOMETRY

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000)    Printed 12 June 2015    (MN LaTeX style file v2.2)

## Atmospheric Scintillation in Astronomical Photometry

J. Osborn[1]*, D. Föhring[1], V. S. Dhillon[2] and R. W. Wilson[1]
[1] *Department of Physics, Centre for Advanced Instrumentation, University of Durham, South Road, Durham DH1 3LE, UK*
[2] *Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK*

12 June 2015

**ABSTRACT**

Scintillation noise due to the Earth's turbulent atmosphere can be a dominant noise source in high-precision astronomical photometry when observing bright targets from the ground. Here we describe the phenomenon of scintillation from its physical origins to its effect on photometry. We show that Young's (1967) scintillation-noise approximation used by many astronomers tends to underestimate the median scintillation noise at several major observatories around the world. We show that using median atmospheric optical turbulence profiles, which are now available for most sites, provides a better estimate of the expected scintillation noise and that real-time turbulence profiles can be used to precisely characterise the scintillation noise component of contemporaneous photometric measurements. This will enable a better understanding and calibration of photometric noise sources and the effectiveness of scintillation correction techniques. We also provide new equations for calculating scintillation noise, including for extremely large telescopes where the scintillation noise will actually be lower than previously thought. These equations highlight the fact that scintillation noise and shot noise have the same dependence on exposure time and so if an observation is scintillation limited, it will be scintillation limited for all exposure times. The ratio of scintillation noise to shot noise is also only weakly dependent on telescope diameter and so a bigger telescope may not yield a reduction in fractional scintillation noise.

**Key words:** planets and satellites: detection – atmospheric effects – instrumentation: photometers – methods: observational – site testing – techniques: photometric

### 1 INTRODUCTION

High-precision photometry is key to several branches of astronomical research, including (but not limited to) the study of extrasolar planets, astroseismology and the detection of small Kuiper-belt objects within our Solar System. The difficulty with such observations is that, although the targets are bright, the variations one needs to detect are often small (typically ∼0.01% to ∼0.1%). This is within the capabilities of modern detectors. However, when the light from the star passes through the Earth's atmosphere, regions of turbulence cause intensity fluctuations (seen as twinkling by the naked eye) called scintillation. This scintillation, which induces photometric variations in the range of ∼0.1% to 1.0%, limits the detection capabilities of ground based telescopes (e.g. Brown & Gilliland 1994; Heasley et al. 1996; Ryan & Sandler 1998).

Knowing the level of scintillation noise is important because it will enable performance assessment, calibration and optimisation of photometric instrumentation. It will also help to explain and constrain model fits to photometric data (for example, extrasolar planet transit/eclipse light curves; Föhring 2014), and to help develop scintillation correction concepts such as Conjugate-Plane Photometry (Osborn et al. 2011), Tomographic wavefront reconstruction (Osborn 2015) and active deformable mirror techniques (Viotto et al. 2012). It would also enable passive techniques such as 'lucky photometry' where only data taken during photometric conditions (i.e. in times of low scintillation noise) are used in the reduction process.

Young proposed an equation which can be used to estimate the scintillation noise for an observation given the telescope's altitude and diameter, and the observation's exposure time and airmass. This equation is regularly used by many astronomers (for example Southworth et al. 2009) to estimate the scintillation noise in their measurements. Recent work by Kornilov et al. (2012) showed that this equation tends to underestimate the median scintillation noise by a mean factor of 1.5.

As well as presenting new results on scintillation, we hope this paper will serve as a useful guide for astronomers to understand, estimate the size of, and correct for scintilla-

---

* E-mail:james.osborn@durham.ac.uk (JO)

Space-quality photometry from the ground?:

***Conjugate-plane photometry: reducing scintillation in ground-based photometry***
Osborn et al, 2011, MNRAS, 411, 1223

# OVERVIEW

**Lecture 1: ULTRACAM**

- High time-resolution astrophysics (HTRA) - what is it and why study it?
- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

**Lecture 2: ULTRASPEC**

- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
- Instrumentation for high-speed photometry II: ULTRASPEC on the TNT

**Lecture 3: HiPERCAM**

- How can we improve ULTRACAM and what would this enable us to do?
- Eliminating atmospheric scintillation noise: Conjugate-plane photometry
- Instrumentation for high-speed photometry III: HiPERCAM

**Lecture 4: Data Reduction**

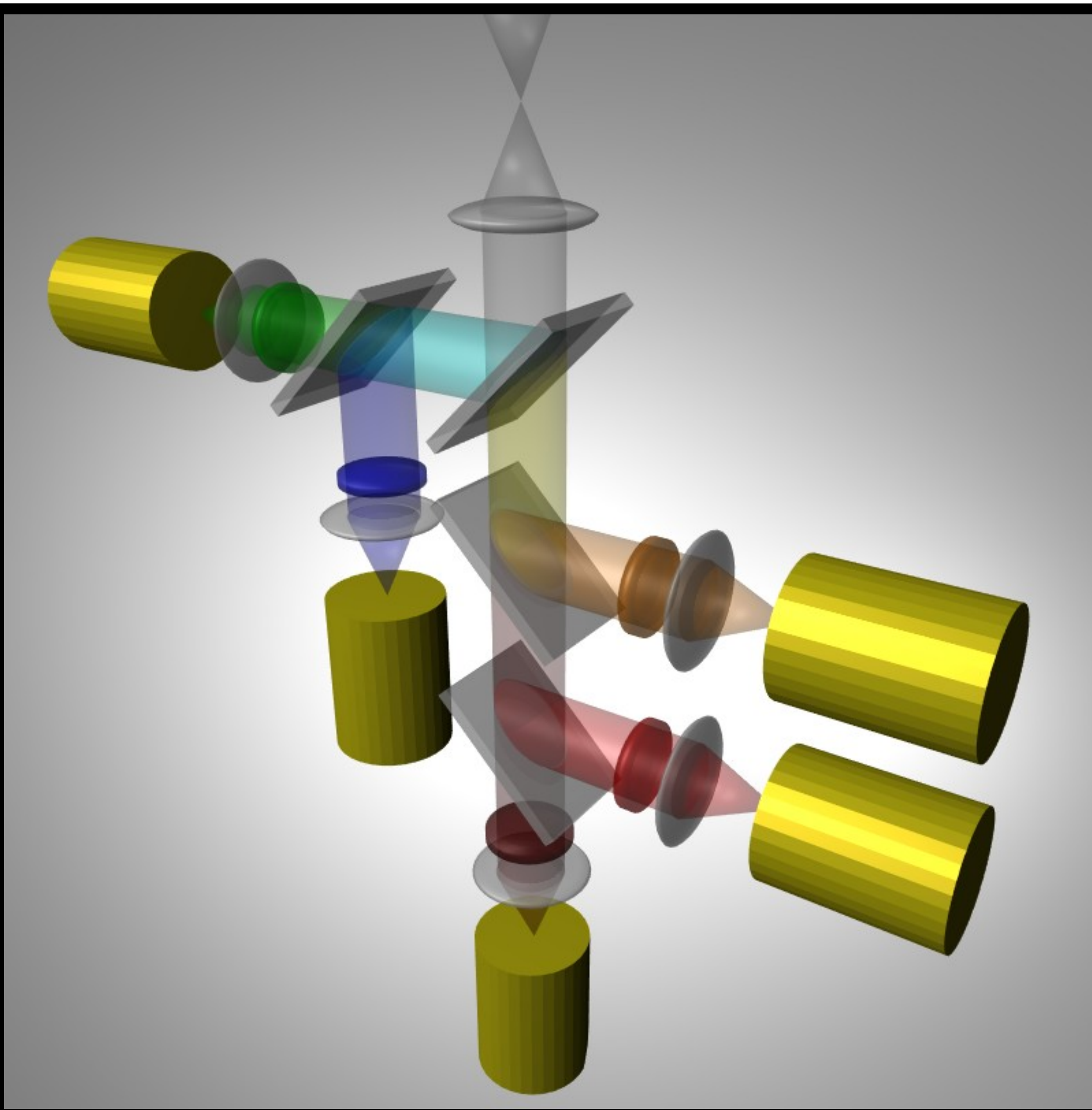
- Demonstration of photometric data reduction using the ULTRACAM pipeline

# HiPERCAM

- High PERformance CAMera.
- Funded by ERC Advanced Grant for 3.5M€, started Jan 2014.
- Collaboration between Sheffield, Warwick, Durham and UKATC.
- Visitor instrument, to be commissioned on the 4.2m WHT and 10.4m GTC in 2017.
- Provides an “order-of-magnitude” improvement in performance over ULTRACAM.

# OPTICS

- 5 arms covering *u'g'r'I'z'*.
- Single-shot optical SED with no wasted light.

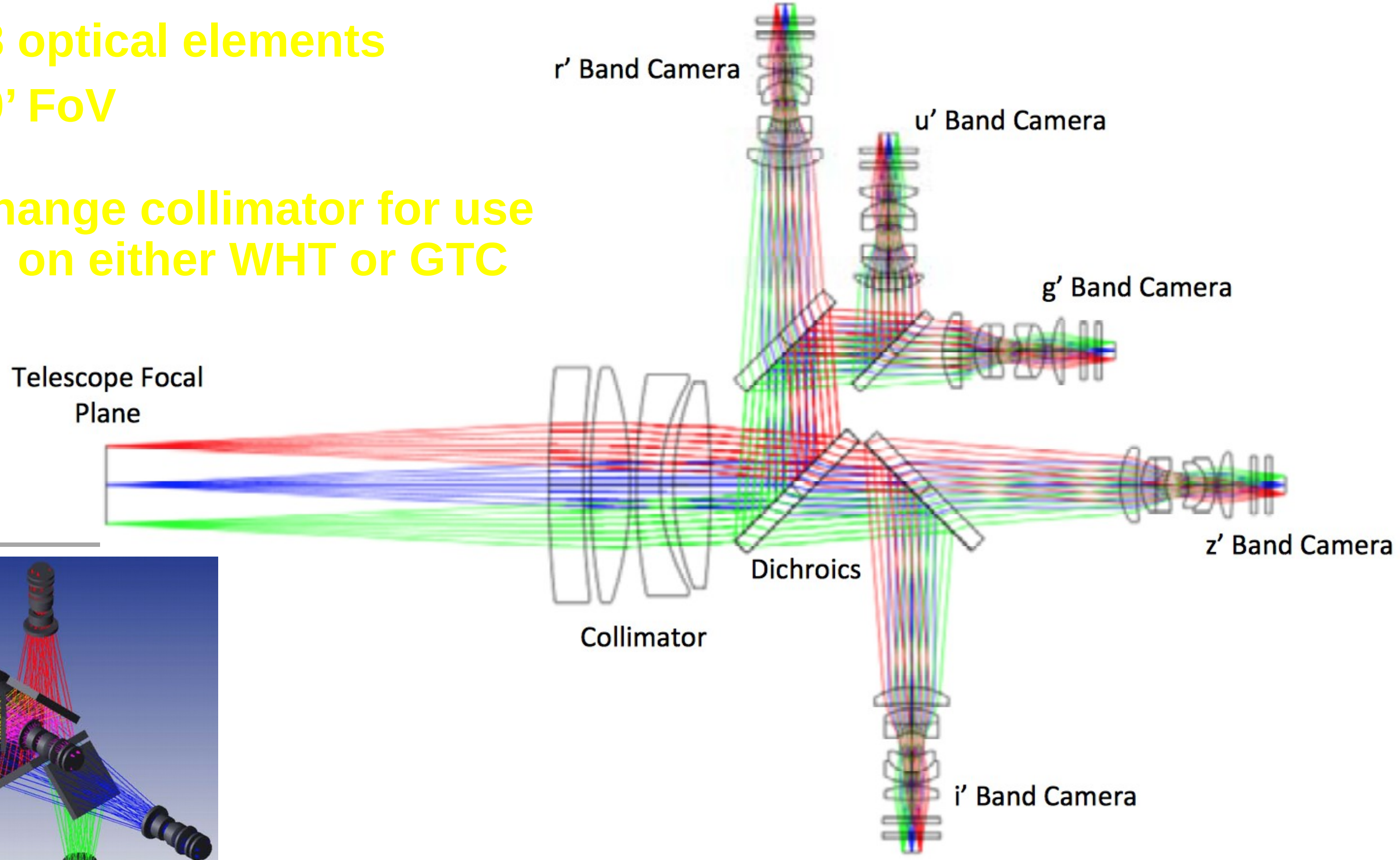


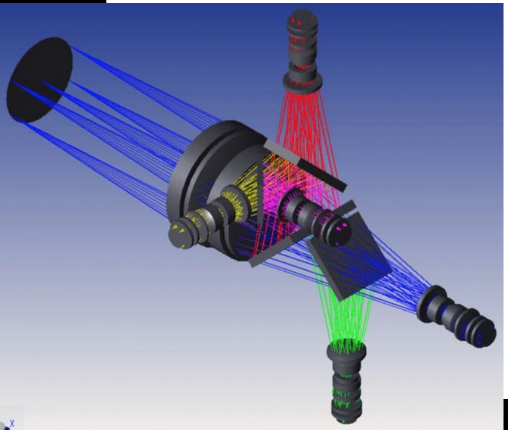
# OPTICS

48 optical elements

10’ FoV

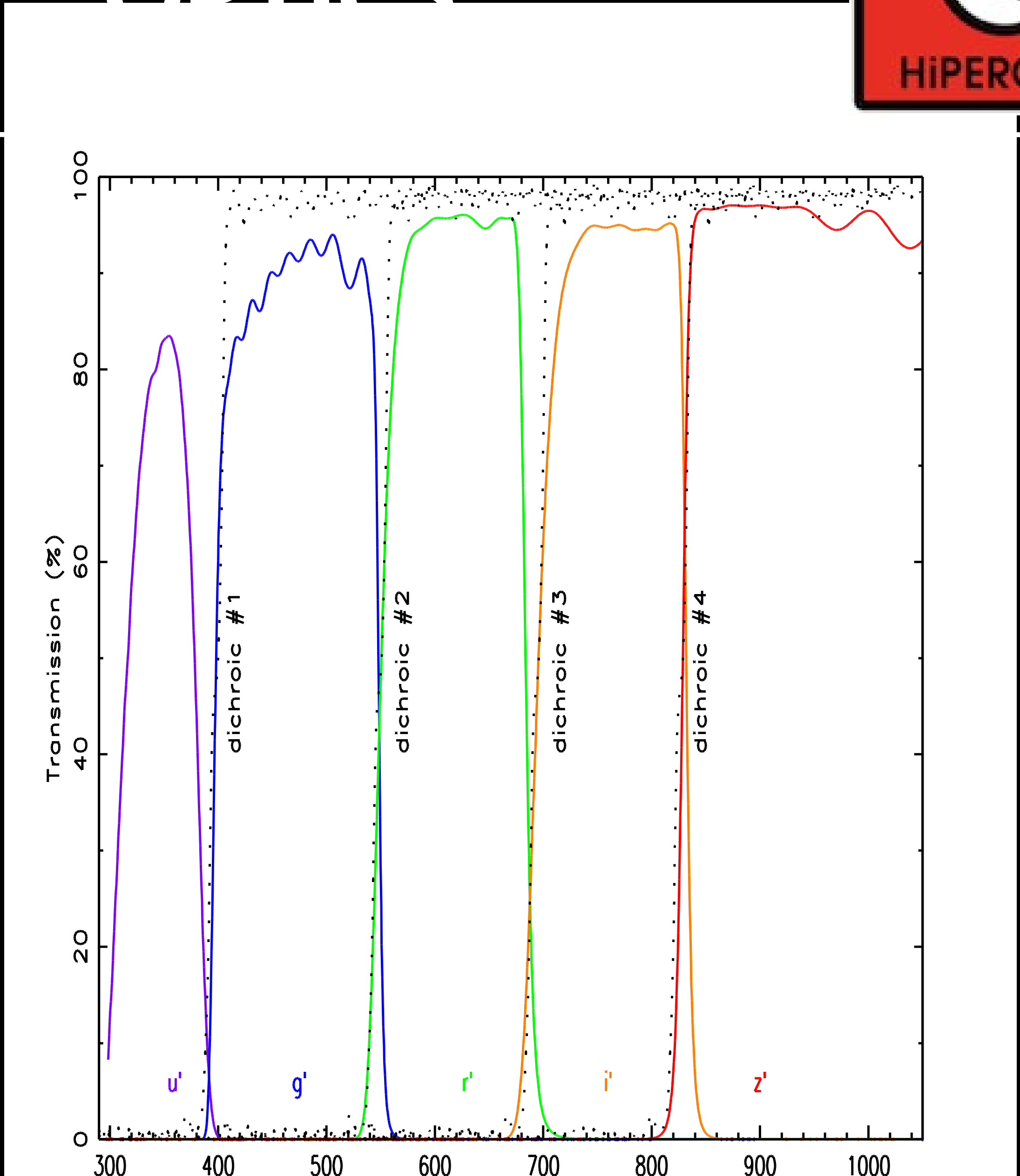
Change collimator for use on either WHT or GTC





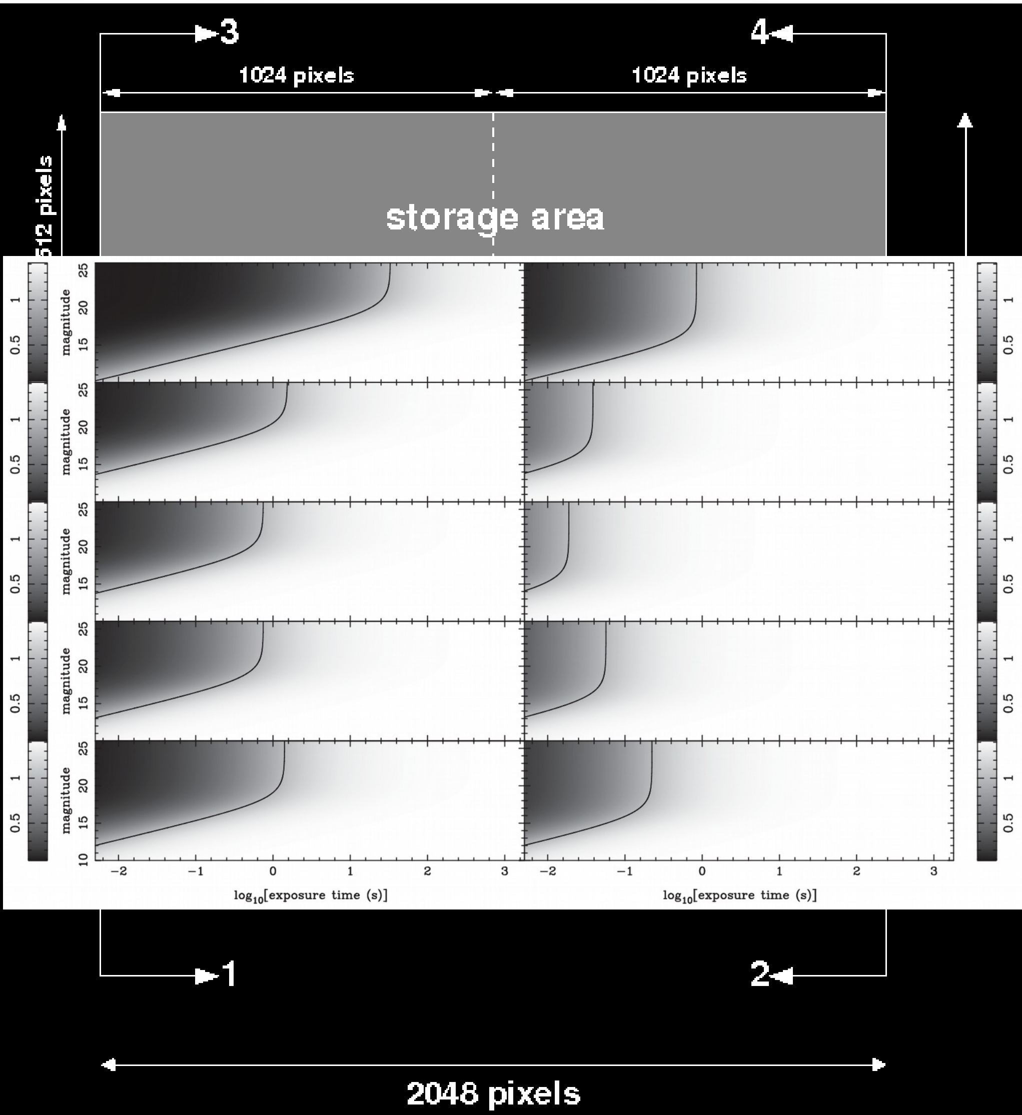
# OPTICS

- High-performance dichroic beamsplitters.

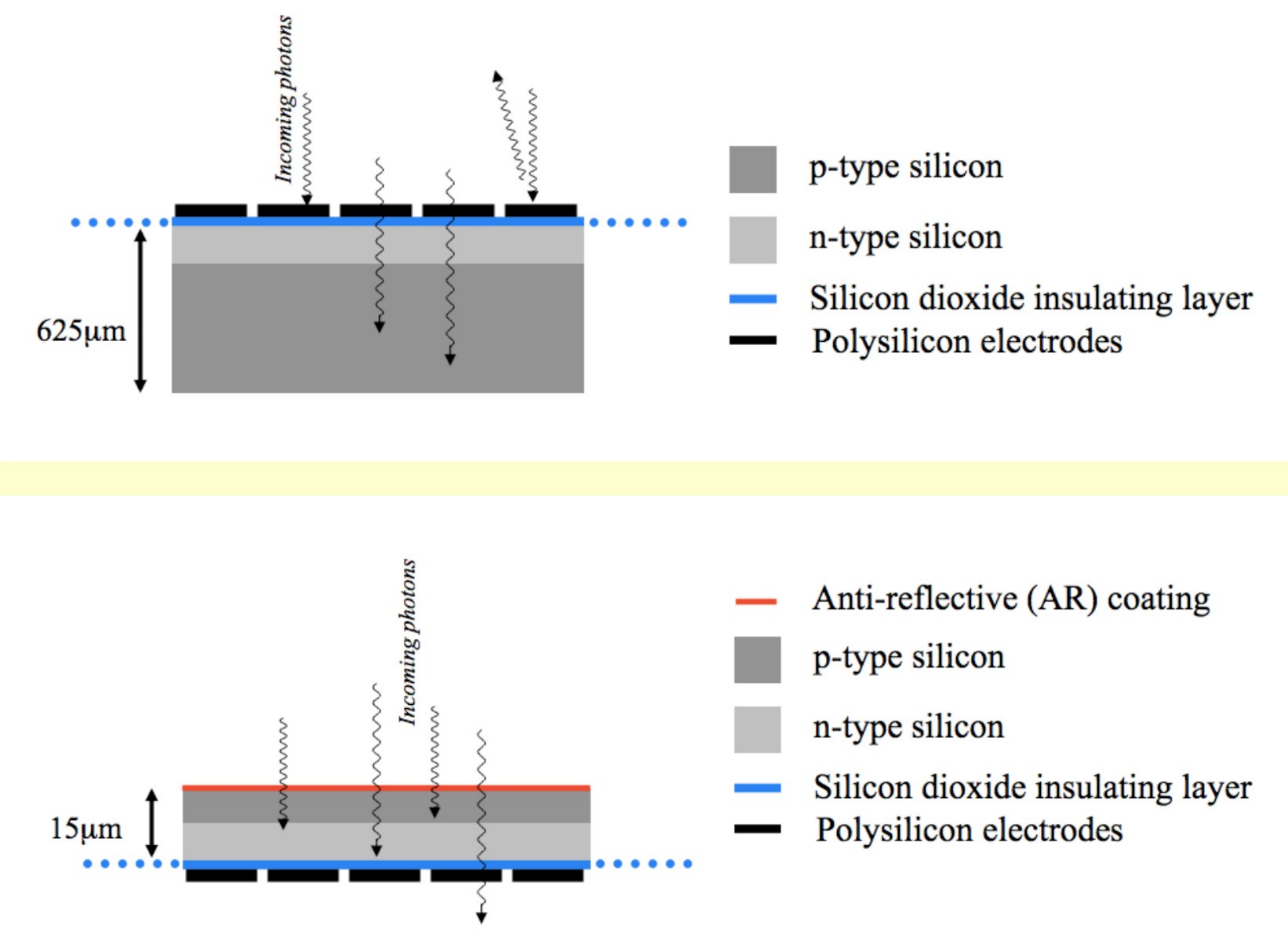


# CCDs & CONTROLLER

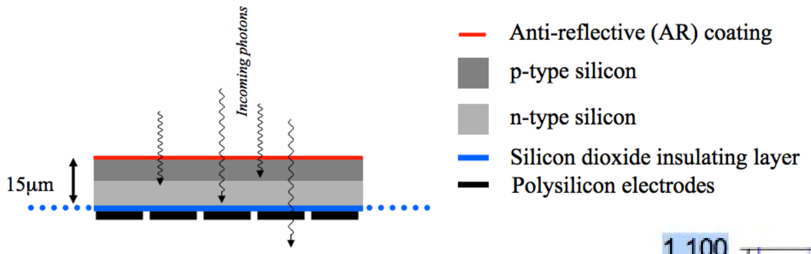
- Big chips are not necessarily better, as they are slower.
- Lots of outputs are not necessarily better, as we study point sources.
- Too many compromises had to be made to use EMCCDs, for negligible benefit.
- 6 custom versions of CCD231-42 ordered from e2v.
- In conjunction with an ESO NGC CCD controller, we can easily break the kHz frame-rate barrier.

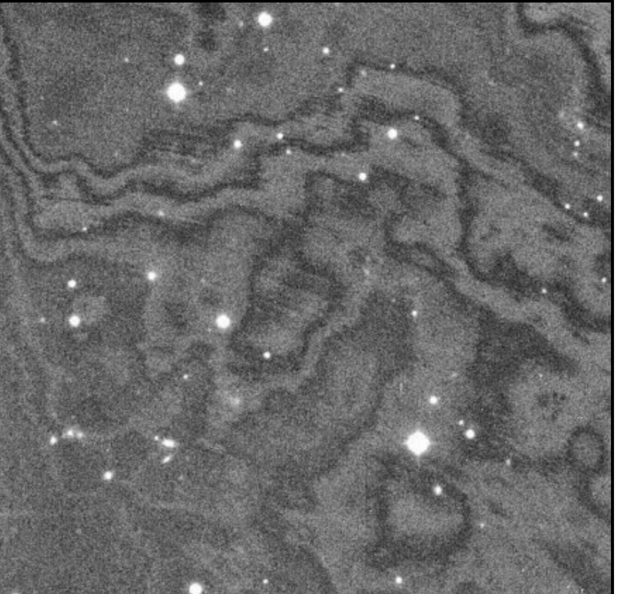


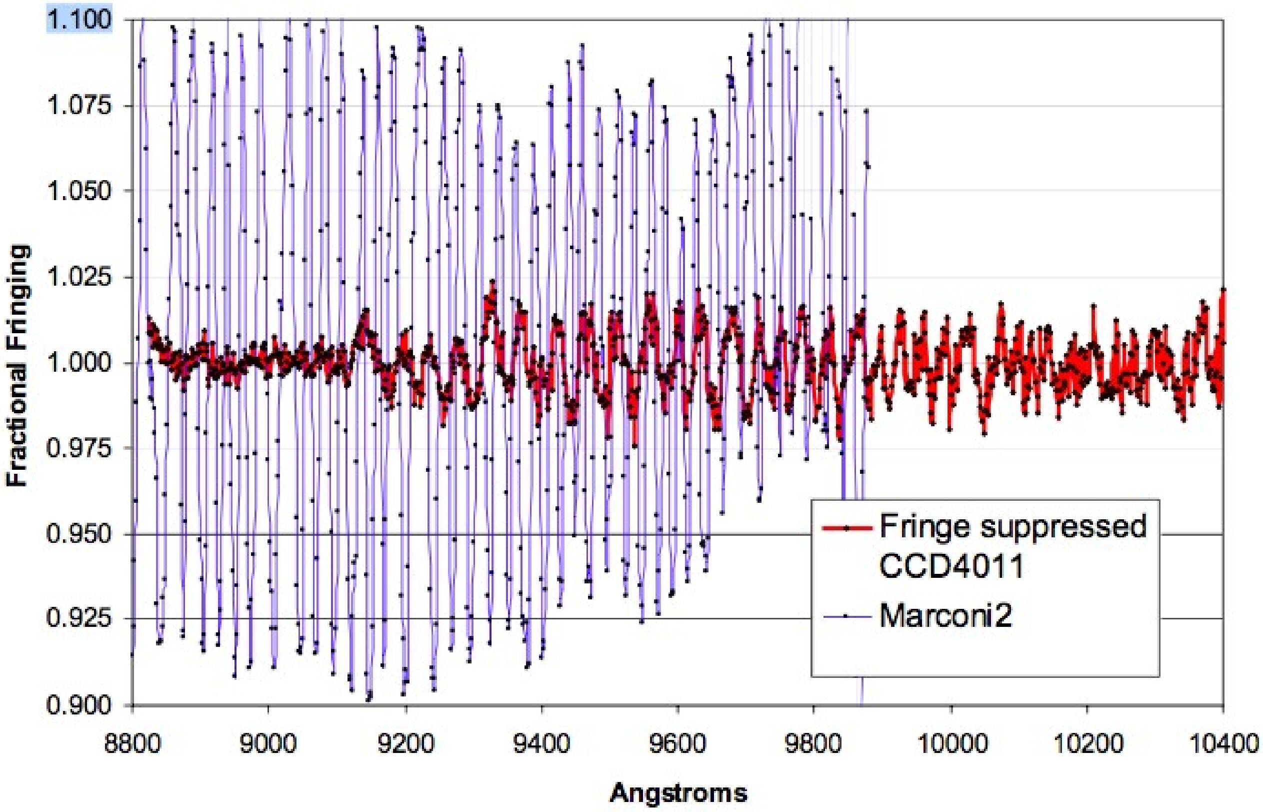
# DEEP DEPLETION CCDs



# FRINGE SUPPRESSION

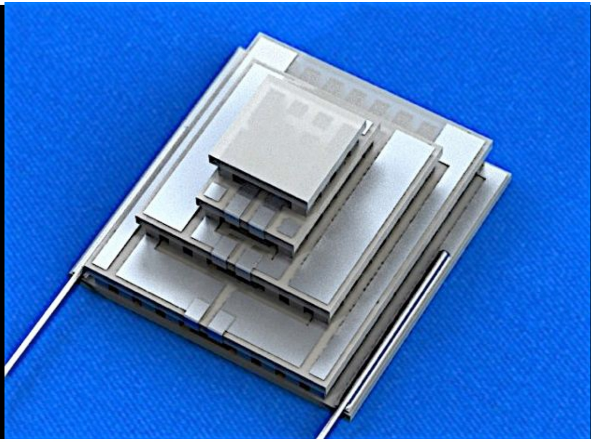


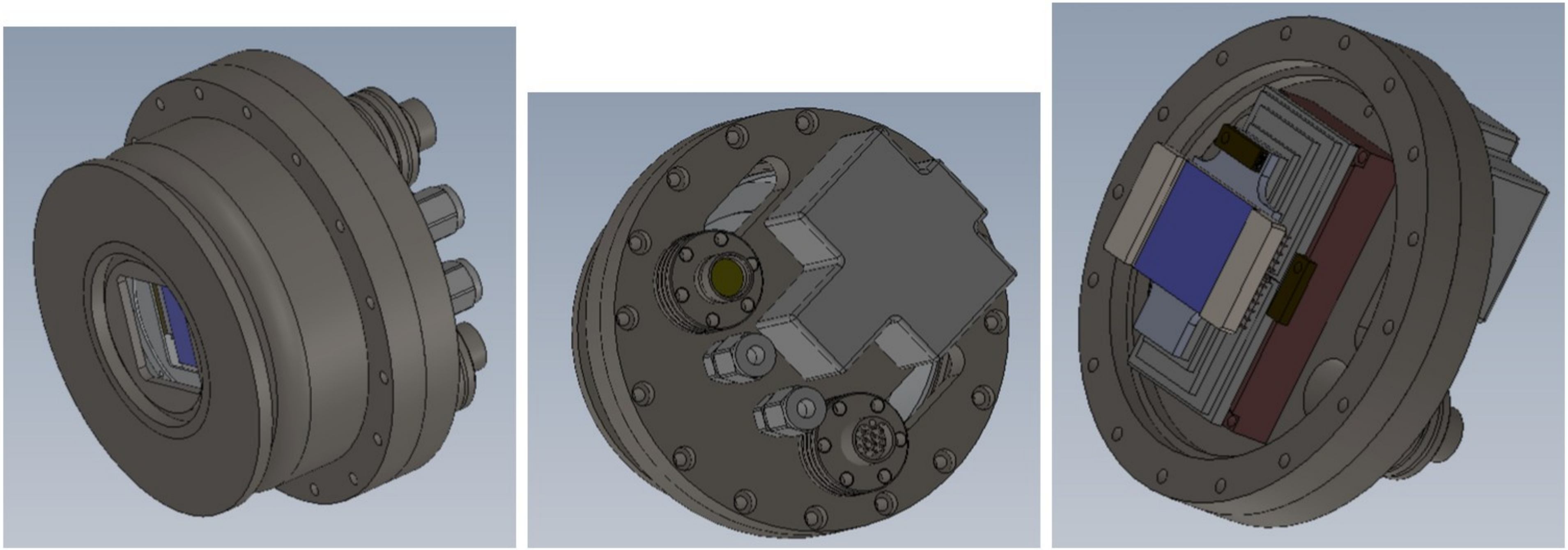




# CCD HEADS

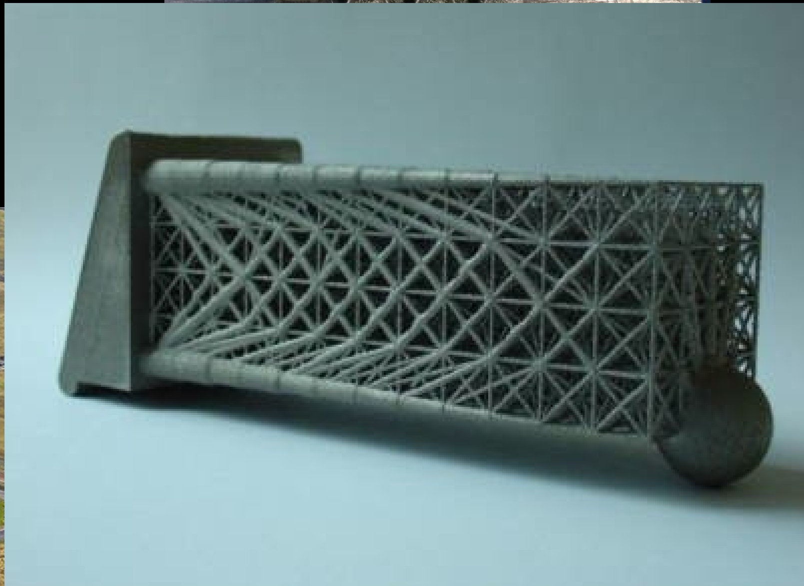
- CCDs to be cooled to 180K with two 6-stage peltier coolers.
- Advantages: convenience, cost, no vibrations, low mass/size CCD heads.



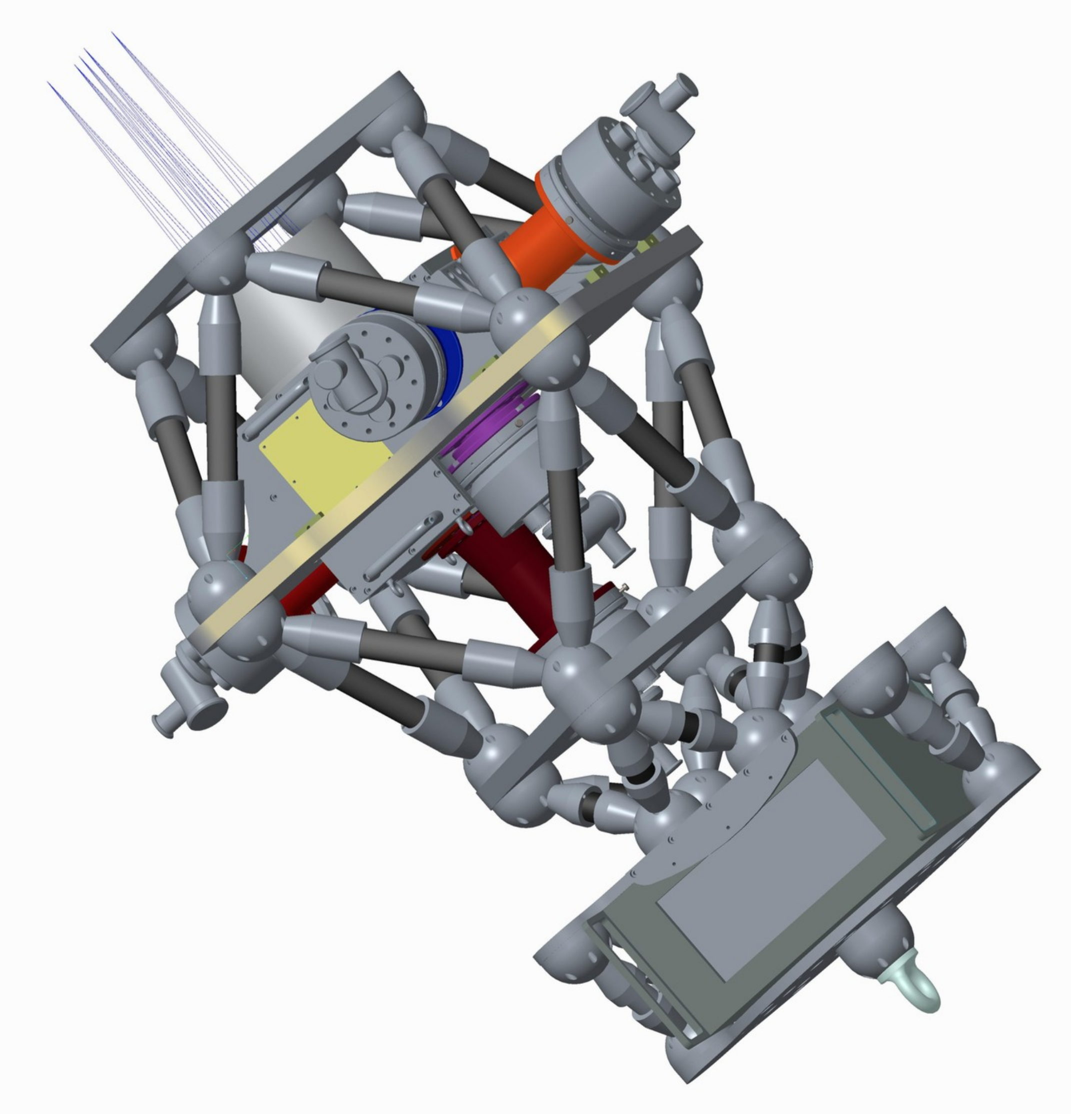


# MECHANICAL STRUCTURE

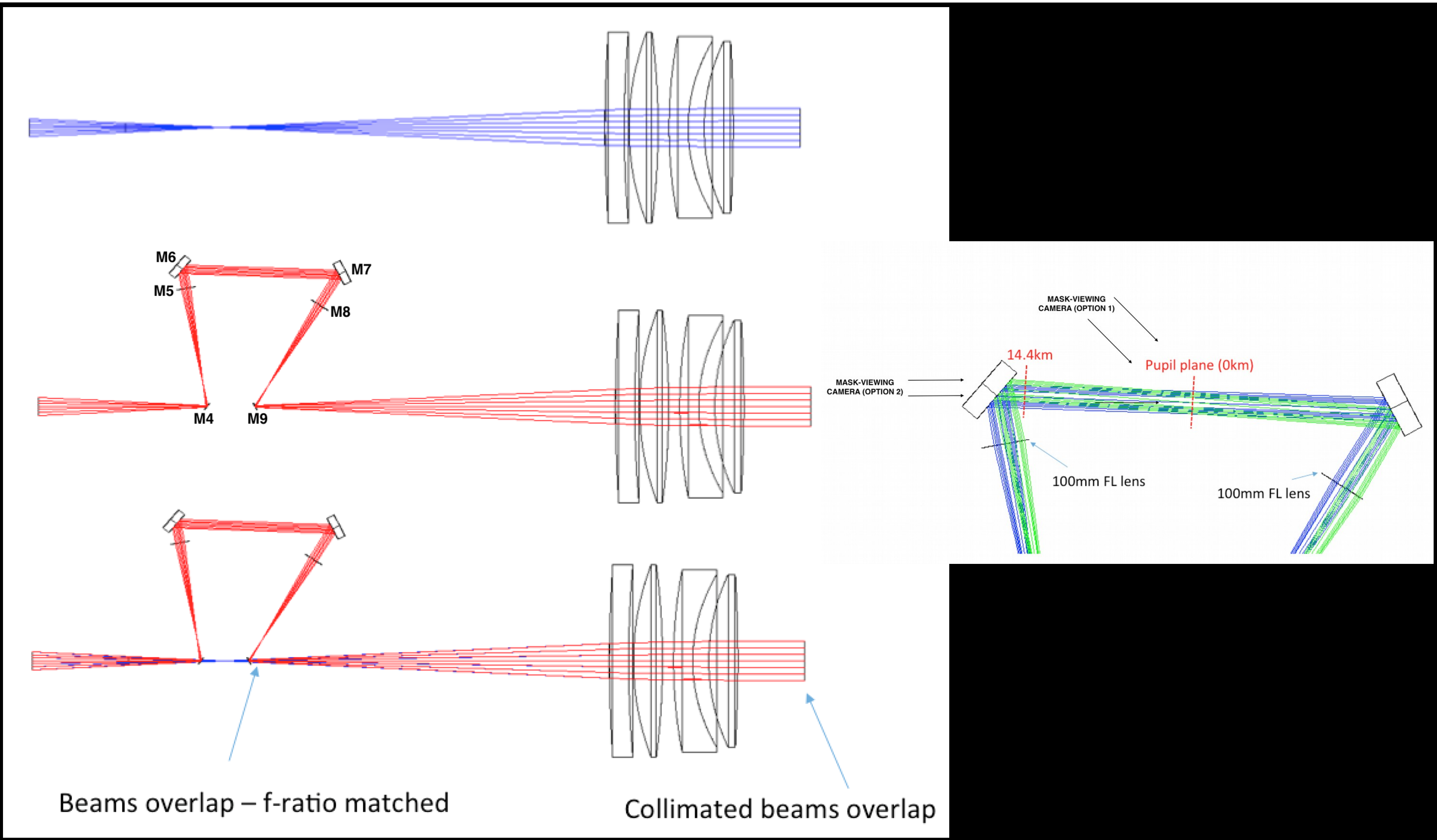
- HiPERCAM will be made using additive manufacturing techniques (i.e. 3D printing).
- Exploiting Sheffield’s world-leading Advanced Manufacturing Research Centre, a £100M+ collaboration between the University, Boeing and Rolls Royce.
- Components will be manufactured from invar using laser sintering, providing a stiff, lightweight, temperature invariant structure.



# MECHANICAL STRUCTURE



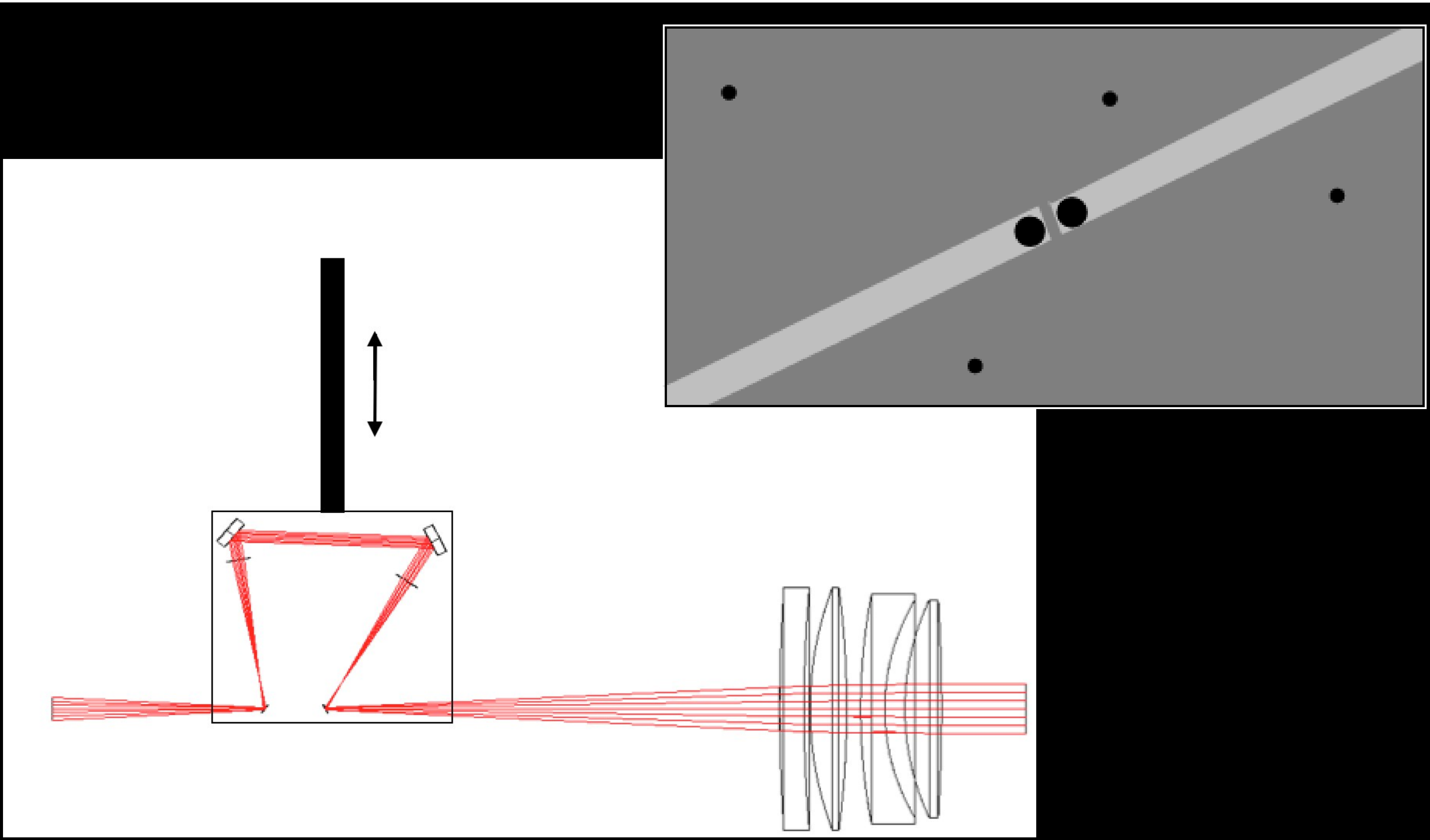
# CPP IN HiPERCAM



Beams overlap – f-ratio matched

Collimated beams overlap

# CPP IN HiPERCAM



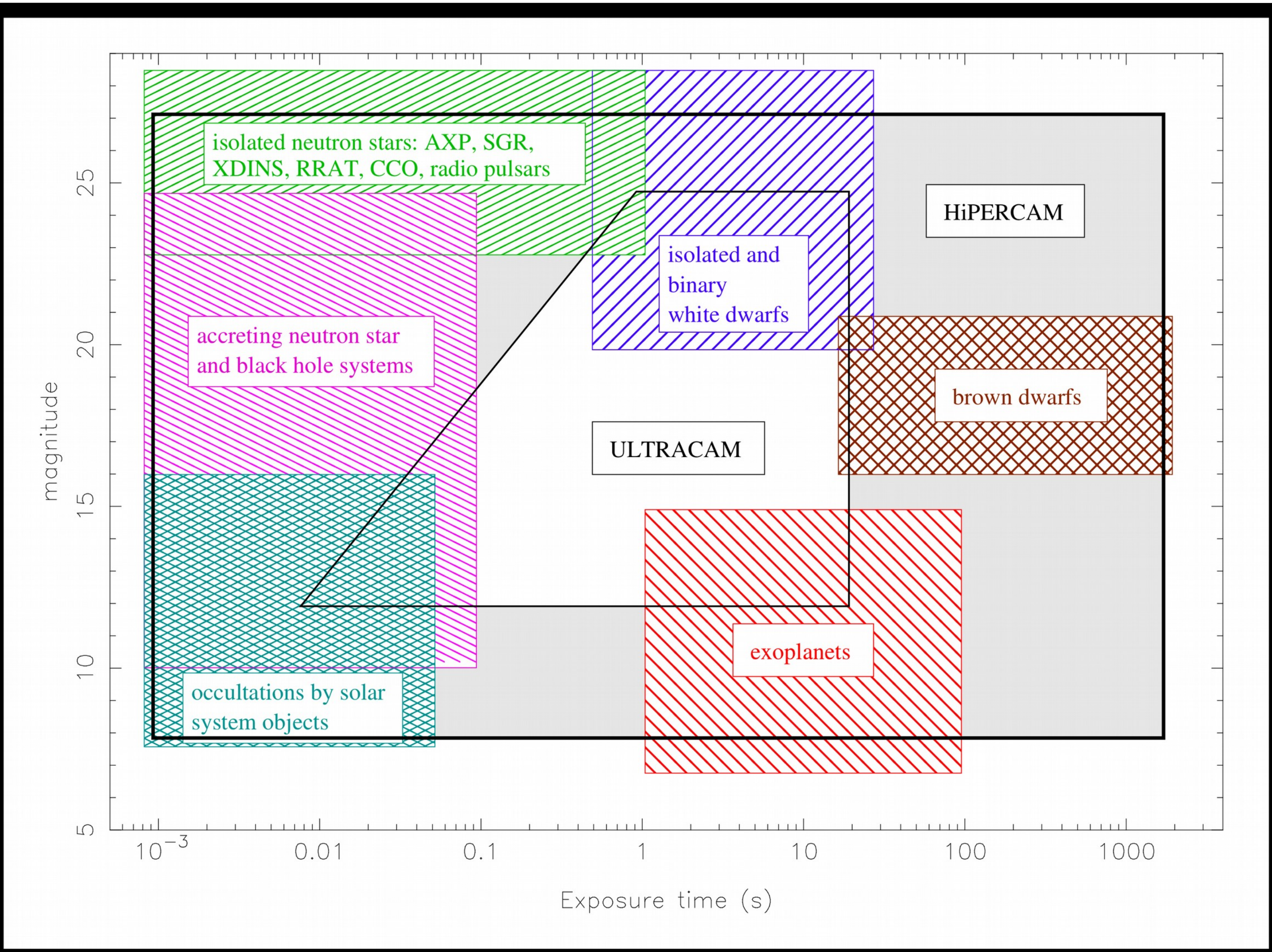
# ULTRACAM vs HiPERCAM

| | **ULTRACAM** | **HiPERCAM** |
|---|---|---|
| Number of simultaneous colours | 3 (*u’g’r’*, *u’g’I’* or *u’g’z’*) | 5 (*u’g’r’I’z’*) |
| Readout noise | 3.5e- @100 kHz | 2.5e- @200 kHz |
| Dark current | 360 e-/pix/hr | 1 e-/pix/hr |
| Longest exposure time | 20 s | 1800 s |
| Highest frame rate | 300 Hz | 1500 Hz |
| Field of view on 4m telescope | 5’ (at 0.3”/pixel) | 10’ (at 0.3”/pixel) |
| Probability of R=11 comparison | 50% | 94% |
| Scintillation correction | No | Yes |
| Deep depletion | No | Yes |
| QE at 700/800/900/1000 nm (%) | 84% / 61% / 29% / 5% | 92% / 87% / 58% / 13% |
| Fringe suppression | No | Yes |
| Fringe amplitude at 900 nm | >10% | <1% |
| Dummy CCD outputs? | No | Yes |

# HiPERCAM ON THE GTC

- And we hope to mount HiPERCAM on the largest telescope in the world, the 10.4m GTC on La Palma.

# OBSERVATIONAL PARAMETER SPACE



# HiPERCAM SCIENCE QUESTIONS

- What are the progenitors of Type Ia Supernovae?
- What are the properties of exoplanet atmospheres?
- What is the equation of state of the degenerate matter found in white dwarfs and neutron stars?
- What is the nature of the flow of matter close to the event horizon of black holes?
- What gravitational wave signals are likely to be detected by the next generation of space and ground-based detectors?
- What are the properties of Kuiper Belt Objects?

The End.

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 12 June 2015 (MN LaTeX style file v2.2)

# Atmospheric Scintillation in Astronomical Photometry

J. Osborn[1]*, D. Föhring[1], V. S. Dhillon[2] and R. W. Wilson[1]
[1] *Department of Physics, Centre for Advanced Instrumentation, University of Durham, South Road, Durham DH1 3LE, UK*
[2] *Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK*

12 June 2015

**ABSTRACT**
Scintillation noise due to the Earth's turbulent atmosphere can be a dominant noise source in high-precision astronomical photometry when observing bright targets from the ground. Here we describe the phenomenon of scintillation from its physical origins to its effect on photometry. We show that Young's (1967) scintillation-noise approximation used by many astronomers tends to underestimate the median scintillation noise at several major observatories around the world. We show that using median atmospheric optical turbulence profiles, which are now available for most sites, provides a better estimate of the expected scintillation noise and that real-time turbulence profiles can be used to precisely characterise the scintillation noise component of contemporaneous photometric measurements. This will enable a better understanding and calibration of photometric noise sources and the effectiveness of scintillation correction techniques. We also provide new equations for calculating scintillation noise, including for extremely large telescopes where the scintillation noise will actually be lower than previously thought. These equations highlight the fact that scintillation noise and shot noise have the same dependence on exposure time and so if an observation is scintillation limited, it will be scintillation limited for all exposure times. The ratio of scintillation noise to shot noise is also only weakly dependent on telescope diameter and so a bigger telescope may not yield a reduction in fractional scintillation noise.

**Key words:** planets and satellites: detection – atmospheric effects – instrumentation: photometers – methods: observational – site testing – techniques: photometric

## 1 INTRODUCTION

High-precision photometry is key to several branches of astronomical research, including (but not limited to) the study of extrasolar planets, astroseismology and the detection of small Kuiper-belt objects within our Solar System. The difficulty with such observations is that, although the targets are bright, the variations one needs to detect are often small (typically ~0.01% to ~0.1%). This is within the capabilities of modern detectors. However, when the light from the star passes through the Earth's atmosphere, regions of turbulence cause intensity fluctuations (seen as twinkling by the naked eye) called scintillation. This scintillation, which induces photometric variations in the range of ~0.1% to 1.0%, limits the detection capabilities of ground based telescopes (e.g. Brown & Gilliland 1994; Heasley et al. 1996; Ryan & Sandler 1998).

Knowing the level of scintillation noise is important because it will enable performance assessment, calibration and optimisation of photometric instrumentation. It will also help to explain and constrain model fits to photometric data (for example, extrasolar planet transit/eclipse light curves; Föhring 2014), and to help develop scintillation correction concepts such as Conjugate-Plane Photometry (Osborn et al. 2011), Tomographic wavefront reconstruction (Osborn 2015) and active deformable mirror techniques (Viotto et al. 2012). It would also enable passive techniques such as 'lucky photometry' where only data taken during photometric conditions (i.e. in times of low scintillation noise) are used in the reduction process.

Young proposed an equation which can be used to estimate the scintillation noise for an observation given the telescope's altitude and diameter, and the observation's exposure time and airmass. This equation is regularly used by many astronomers (for example Southworth et al. 2009) to estimate the scintillation noise in their measurements. Recent work by Kornilov et al. (2012) showed that this equation tends to underestimate the median scintillation noise by a mean factor of 1.5.

As well as presenting new results on scintillation, we hope this paper will serve as a useful guide for astronomers to understand, estimate the size of, and correct for scintilla-

---

* E-mail:james.osborn@durham.ac.uk (JO)

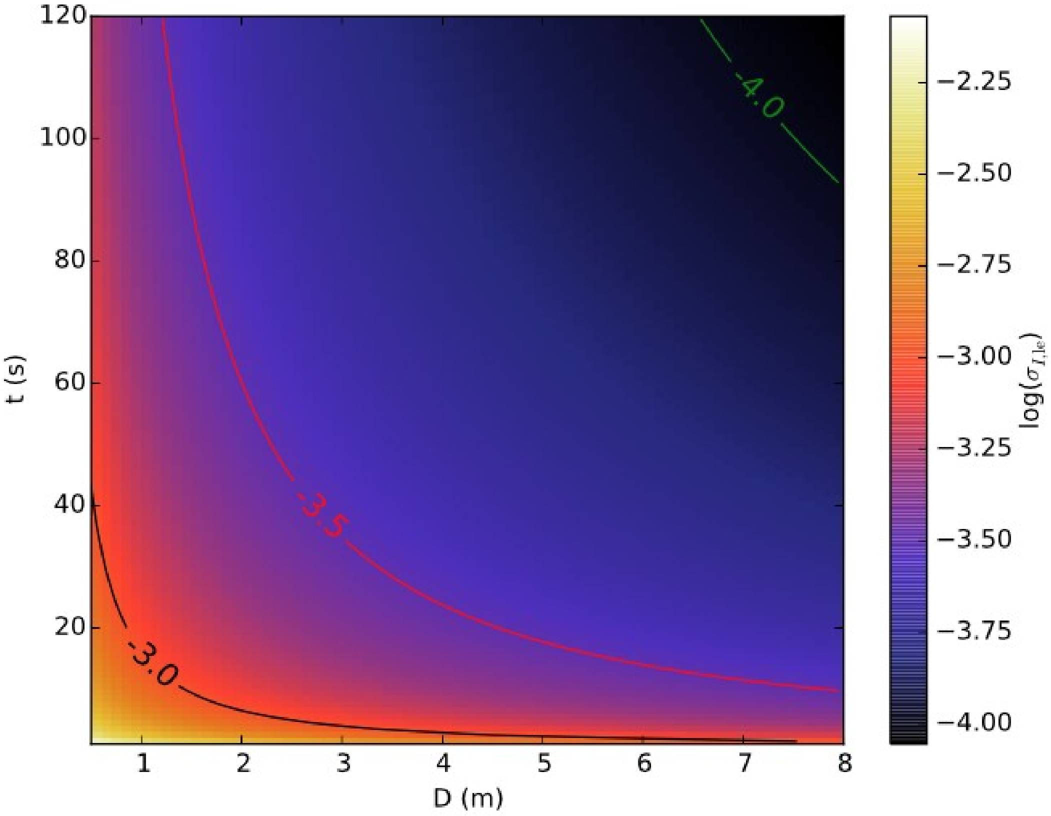


**Figure 9.** Theoretical long exposure scintillation noise as a function of exposure time and telescope diameter. The scintillation noise was calculated for median atmospheric conditions on La Palma and varies between 1% for small telescopes and short exposure times, and 0.01% for larger telescopes and longer exposure times.

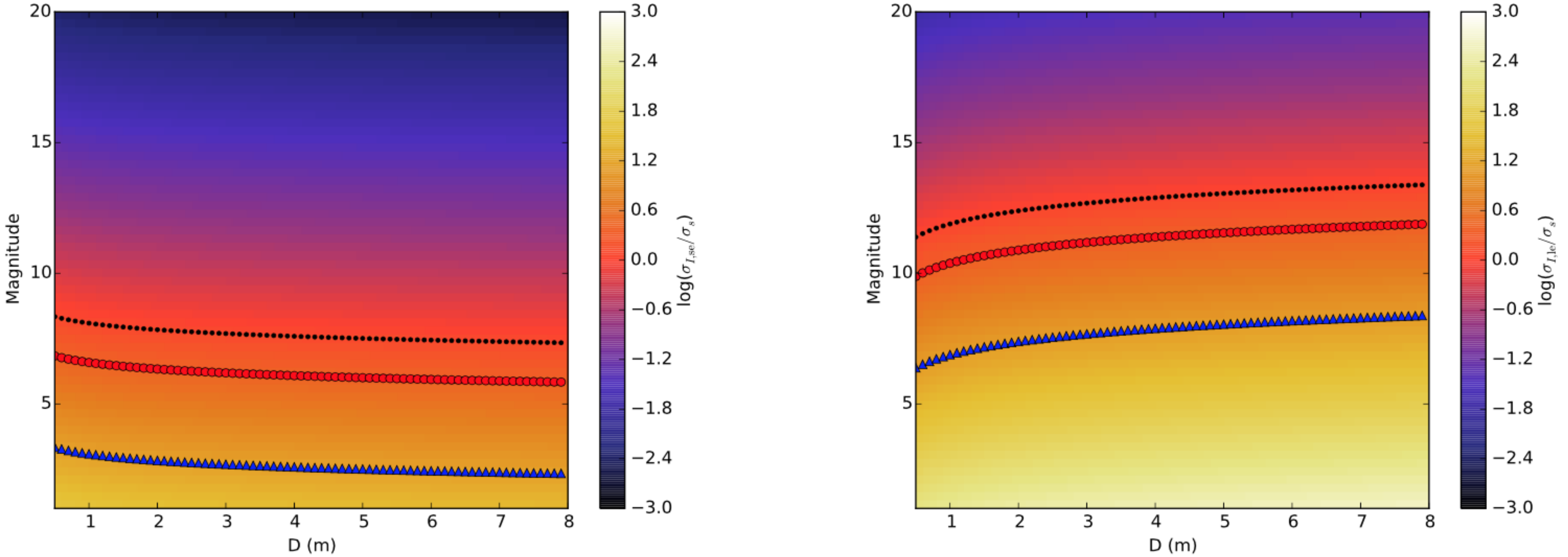


**Figure 11.** Theoretical parameter space plots for the ratio of the scintillation to shot noise in the short exposure regime (left) and the long exposure regime (right), for varying telescope diameter and target stellar magnitude ($V$-band). The short exposure time is set to 2 ms. The long exposure time is irrelevant as both noise sources have the same exposure time dependence, making the ratio independent of exposure time. The black dotted line shows where the scintillation noise equals the shot noise. For any telescope diameter / target magnitude combinations below this line, the scintillation noise is greater than the shot noise and vice versa. The red line composed of circles indicates a ratio of 2, i.e. when the scintillation noise is twice the shot noise. The blue line composed of triangles indicates the point where the scintillation noise is an order of magnitude larger than the shot noise.