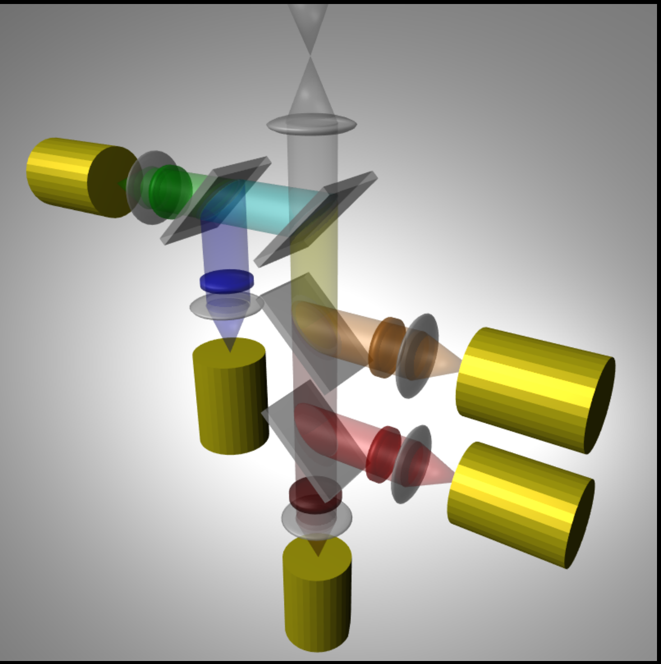


HiPERCAM

A high-speed quintuple-beam CCD camera for the study of rapid variability in the Universe

Vik Dhillon

University of Sheffield/Instituto de Astrofisica de Canarias

With thanks to:

Simon Dixon, Trevor Gamble, Paul Kerry, Stuart Littlefair, Steven Parsons – University of Sheffield

Naidu Bezawada, Martin Black, Xiaofeng Gao, David Henry, David Lunney - UKATC

Tom Marsh – University of Warwick

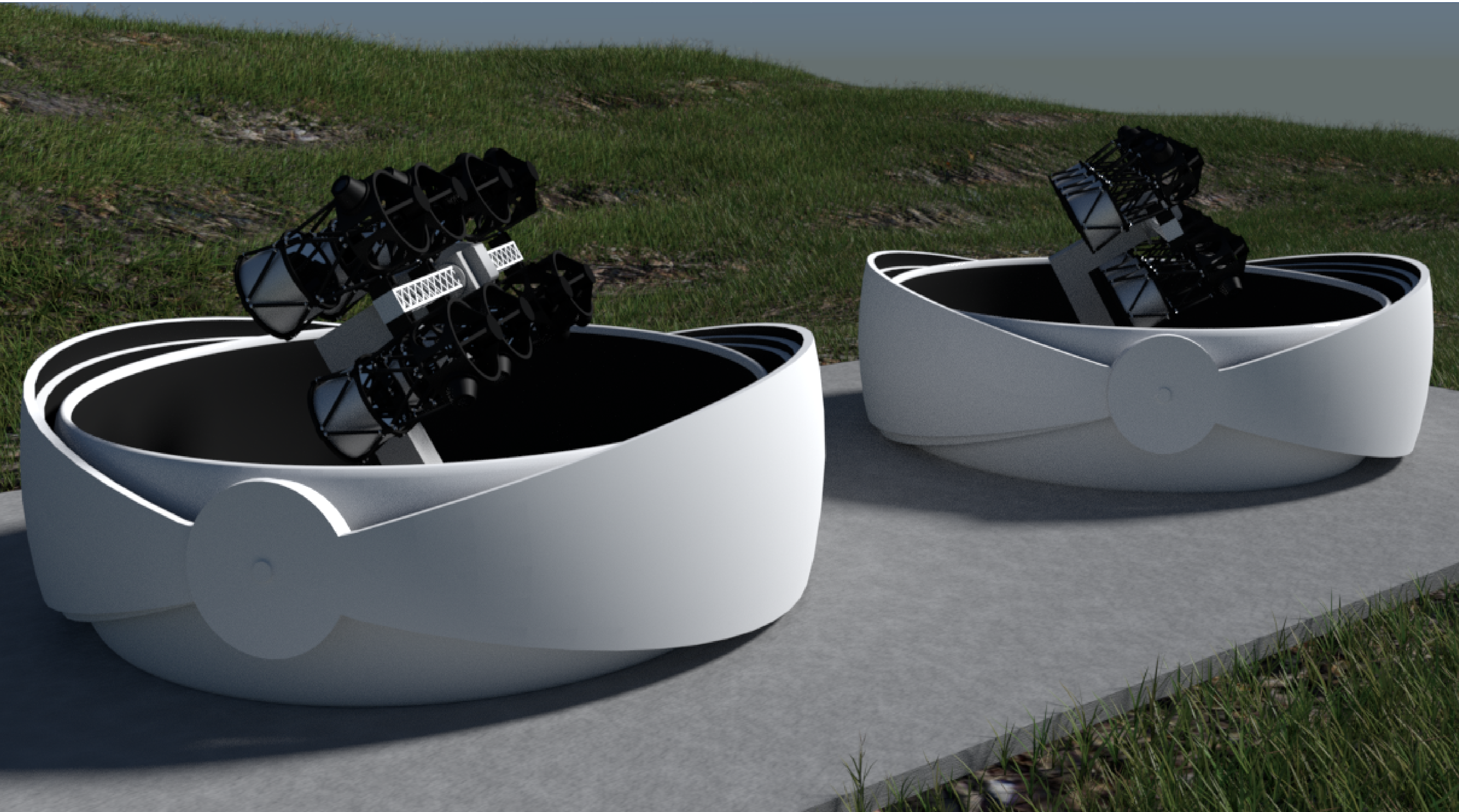
Tim Morris, James Osborn, Richard Wilson – University of Durham

PT5M

La Palma

GOTO

GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER



OVERVIEW

- Scientific Motivation
- ULTRACAM
- HiPERCAM

WHY OBSERVE AT HIGH SPEED?

Defining high speed as timescales of tens of seconds and below, and generalising somewhat,

.....it enables the study of compact objects.

DYNAMICAL TIMESCALE

In the absence of any pressure, the time taken for a test particle released at the surface of a star to fall to the centre:

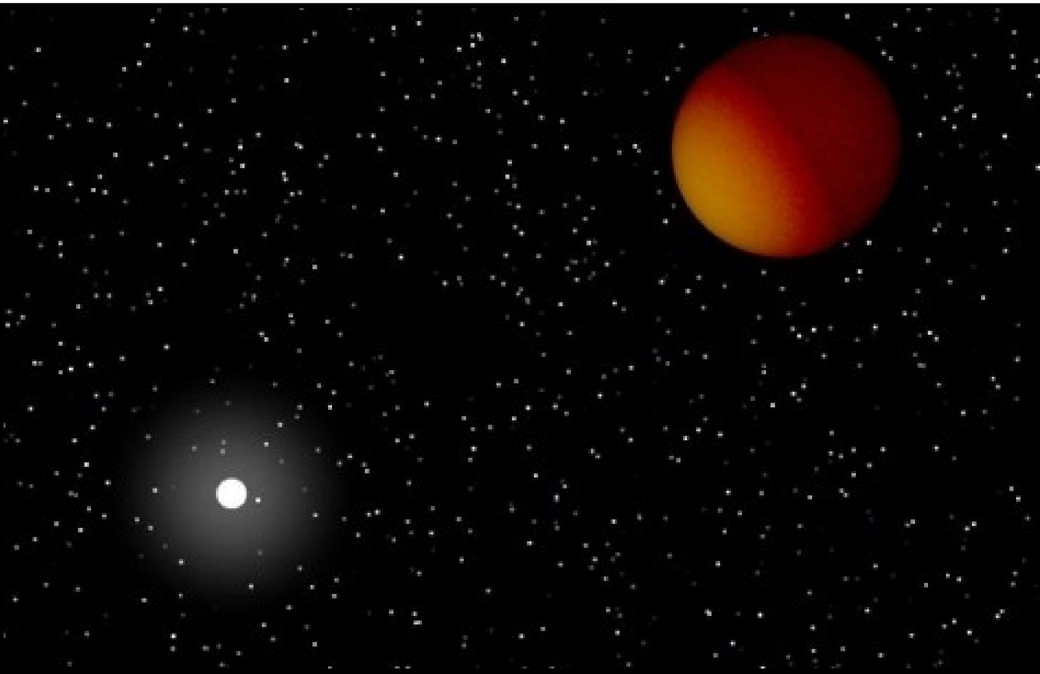
$$t_{dyn} \sim \sqrt{\frac{R^3}{GM}}$$

- For the Sun, M = 2x10^{30} kg, R = 7x10^5 km ⇒ **t_{dyn} ~ 2000 s**
- For white dwarfs, M ~ 1 M_{Sun}, R ~ 0.01 R_{Sun} ⇒ **t_{dyn} ~ 2 s**
- For neutron stars and black holes, M ~ 3 $M_{Sun,}$ R ~ 10^{-5} R_{Sun} ⇒ **t_{dyn} ~ 0.1 ms**

WHY OBSERVE AT HIGH SPEED?

A great deal of information on the nature, origin and evolution of compact objects is encoded in their brightness variations, e.g. their:

- Outbursts
- Eruptions
- Explosions
- Eclipses
- Transits
- Occultations
- Pulsations
- Oscillations
- Flickers
- Flares



WHY STUDY COMPACT OBJECTS?

- White dwarfs, neutron stars and black holes are the dead remnants of stars, providing a fossil record of stellar evolution.
- White dwarfs, neutron stars and black holes are extreme cosmic environments, allowing us to tests theories of fundamental physics.
- White dwarfs, neutron stars and black holes in binaries, provide us with some of the most exotic and scientifically valuable inhabitants of our Universe.
- The study of Solar System objects and extrasolar planets also benefit from high-speed observations.

ULTRACAM

- ULTRACAM is a high-speed (0.05-300 Hz), triple-beam optical CCD camera with a 5’x5’ field of view.
- It was built in 2002 by a consortium from the Universities of Sheffield, Warwick and the UKATC, Edinburgh.
- ULTRACAM is a visitor instrument which mounts on the 4.2m WHT, 8.2m VLT and 3.5m NTT.

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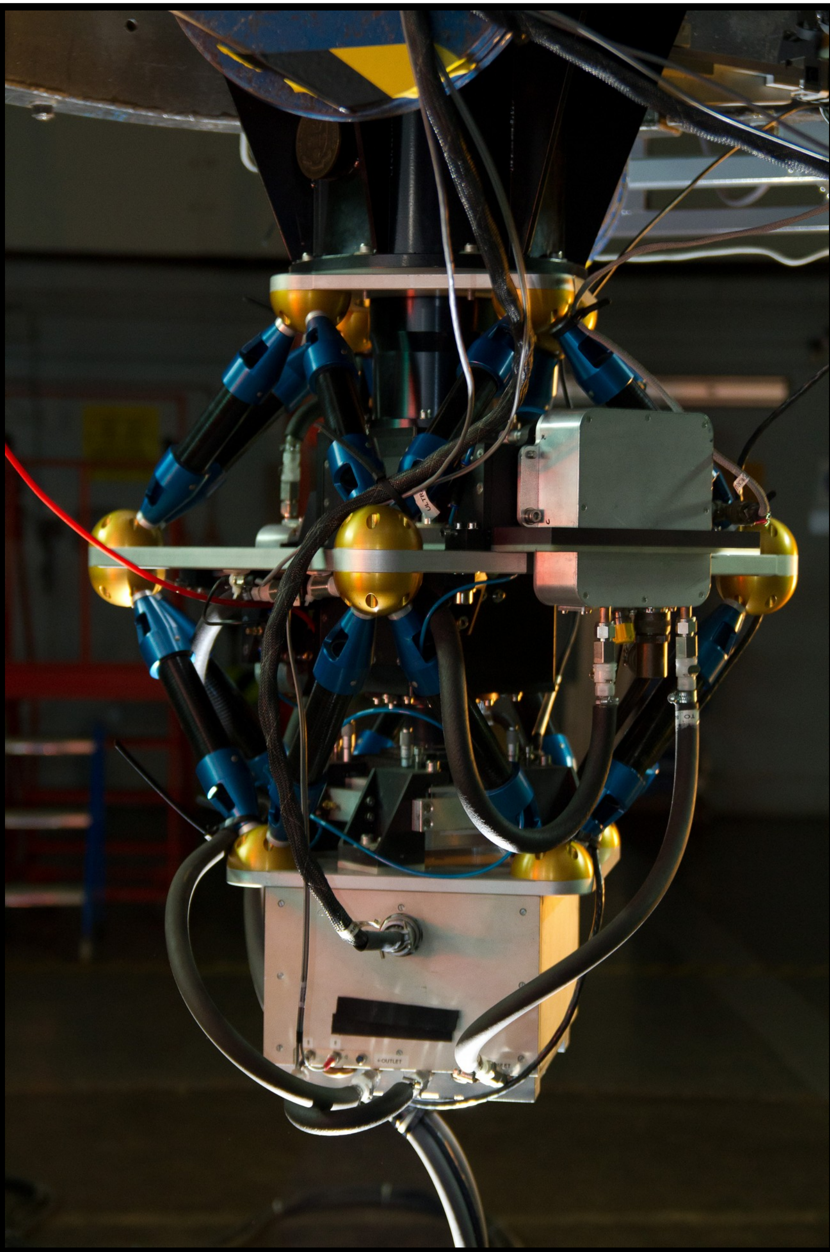

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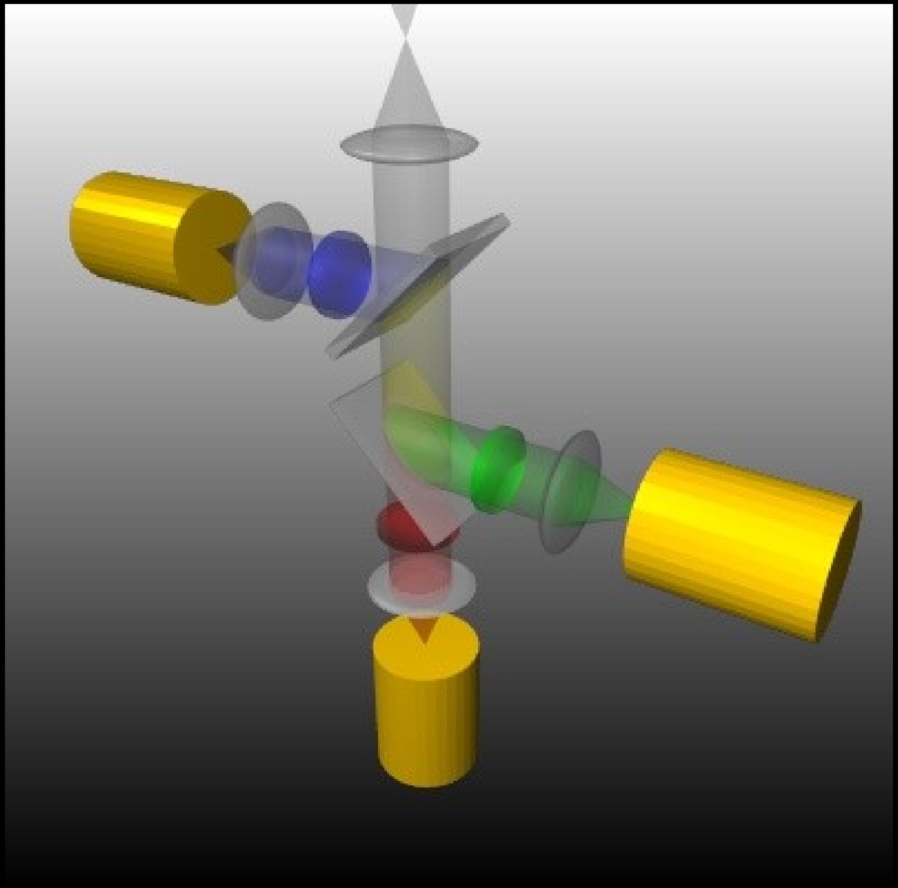
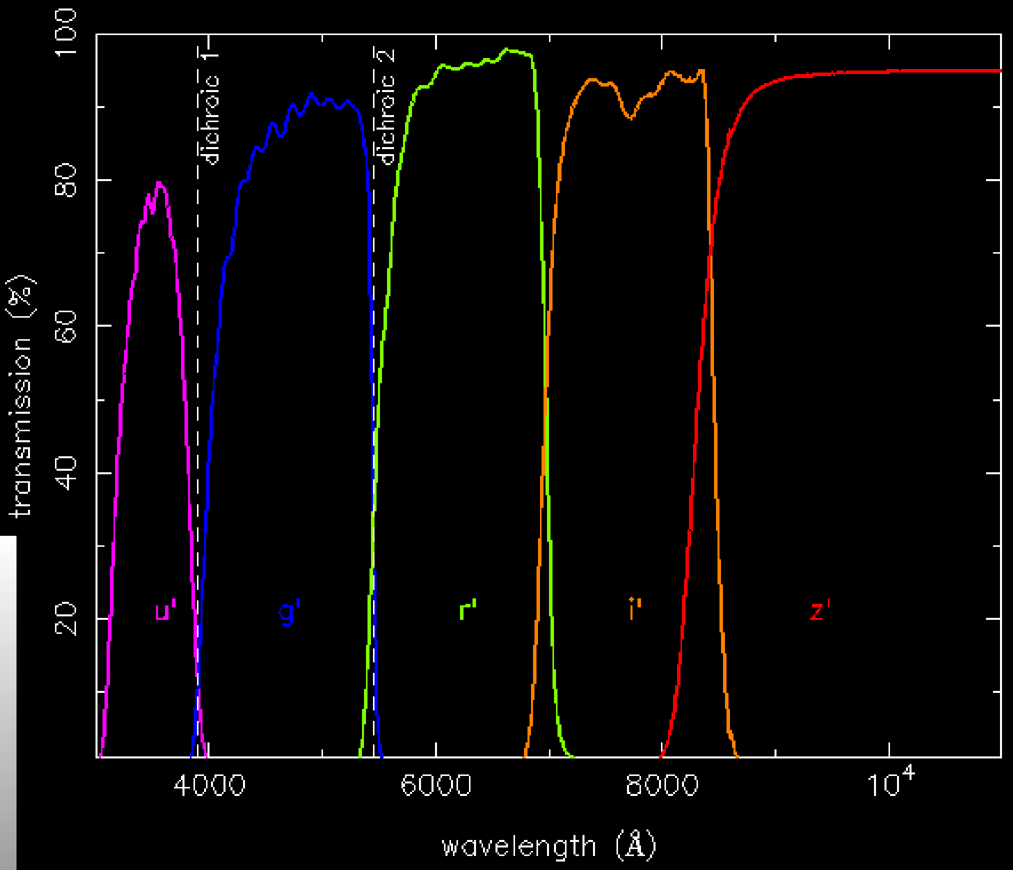
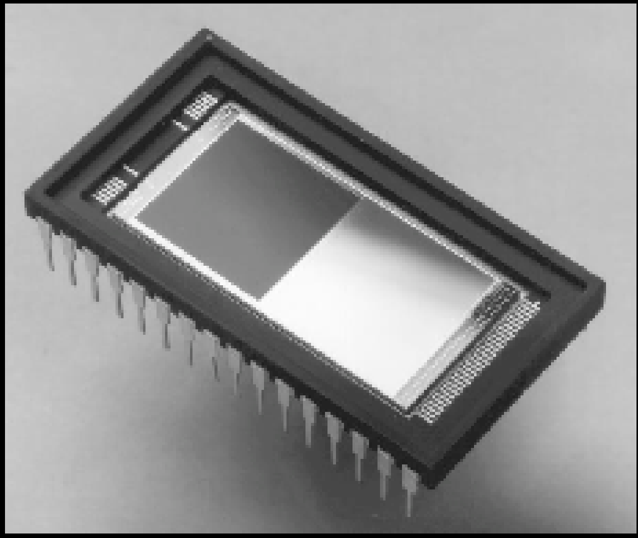
ULTRACAM Mounted on Visitor Focus of MELIPAL

ESO PR Photo 19a/05 (9 June 2005)





transmission (%)
wavelength (Å)
100
80
60
40
20
4000
6000
8000
10^4
dichroic 1
dichroic 2
u'
g'
r'
i'
z'



SCIENCE WITH ULTRACAM

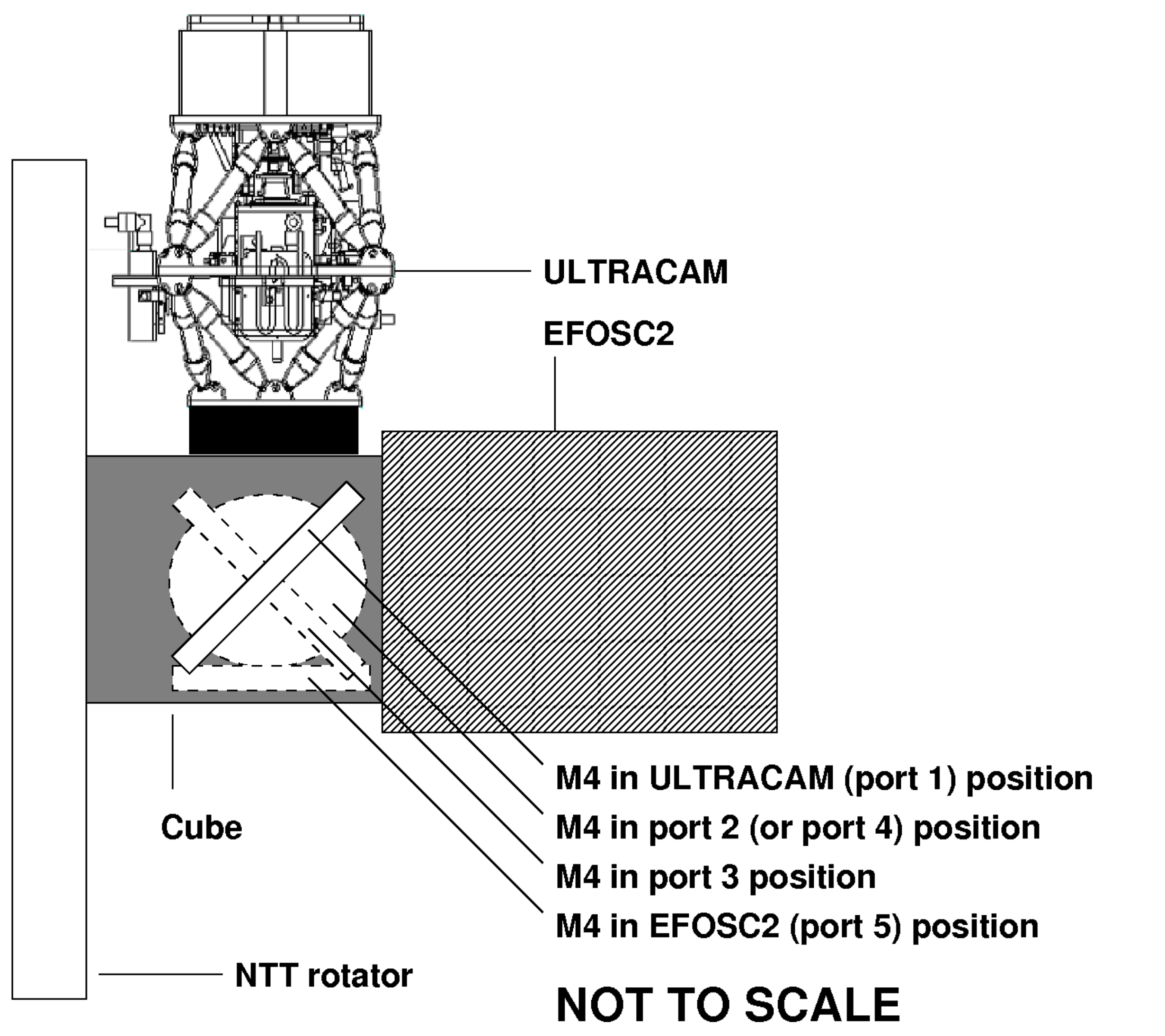
515 nights of time
WHT: 283
NTT: 192
VLT: 40

>100 refereed papers
3 Nature papers
2 Science papers

accreting white dwarfs/cataclysmic variables	19%
black-hole/neutron star X-ray binaries	13%
extrasolar planet transits and eclipses	11%
asteroseismology/sdB stars	11%
eclipsing, detached white-dwarf/red-dwarf binaries	10%
Isolated/non-acccreting white dwarfs	10%
pulsars	6%
flare stars	5%
ultra-compact binaries/double degenerates	5%
occultations by Titan, Pluto, Uranus, Kuiper Belt Objects	4%
isolated brown dwarfs	2%
GRBs	2%
miscellaneous objects (AGN, contact binaries, etc)	2%

ULTRACAM ON NTT: 2017-2022+

- ULTRACAM now located at the 3.5m NTT at La Silla, Chile.
- “Cube” will enable permanent mounting.
- Available to anyone in the ESO community (in return we get guaranteed time).



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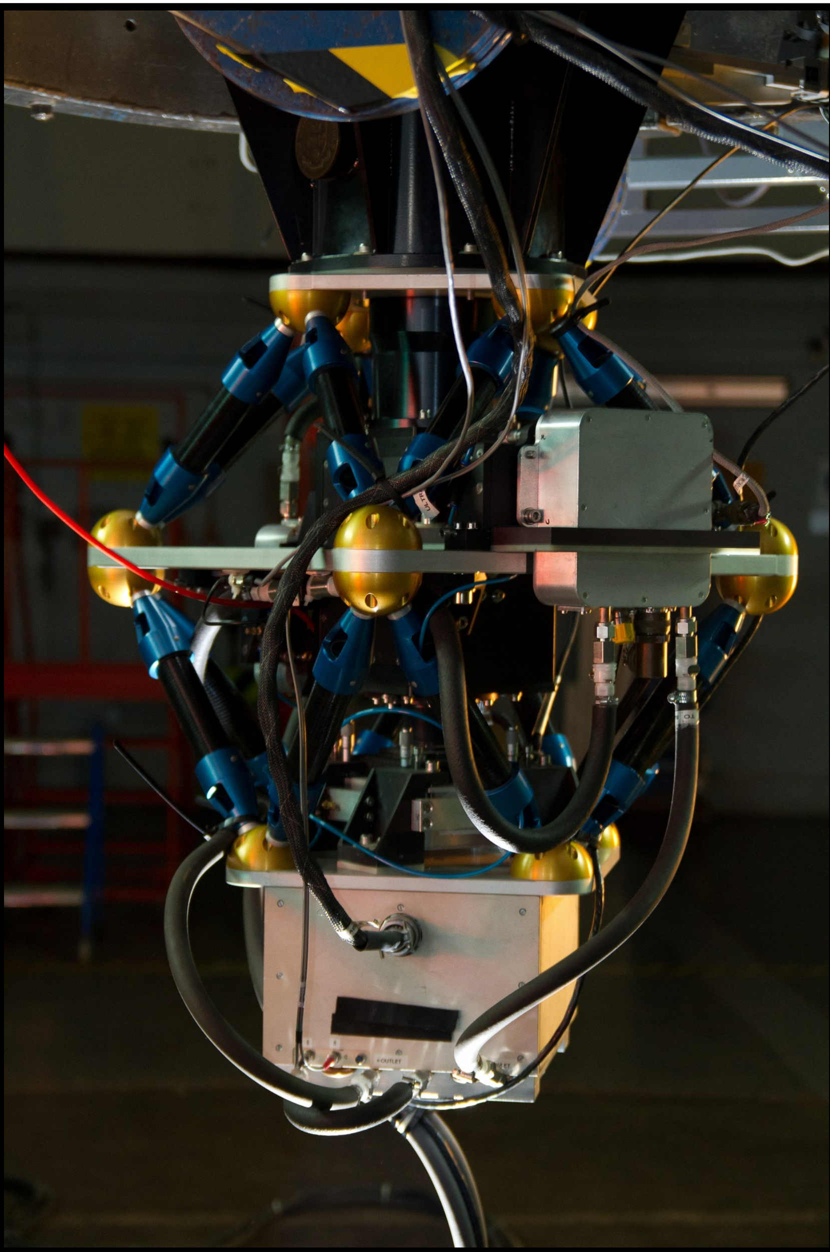
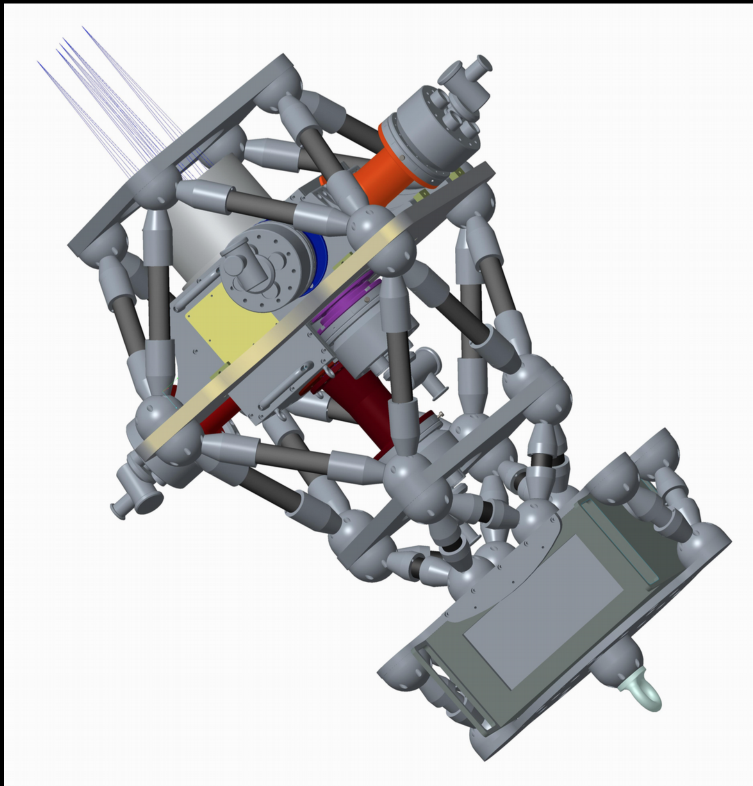
PROBLEMS WITH ULTRACAM

- 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
- Only in one hemisphere



HiPERCAM

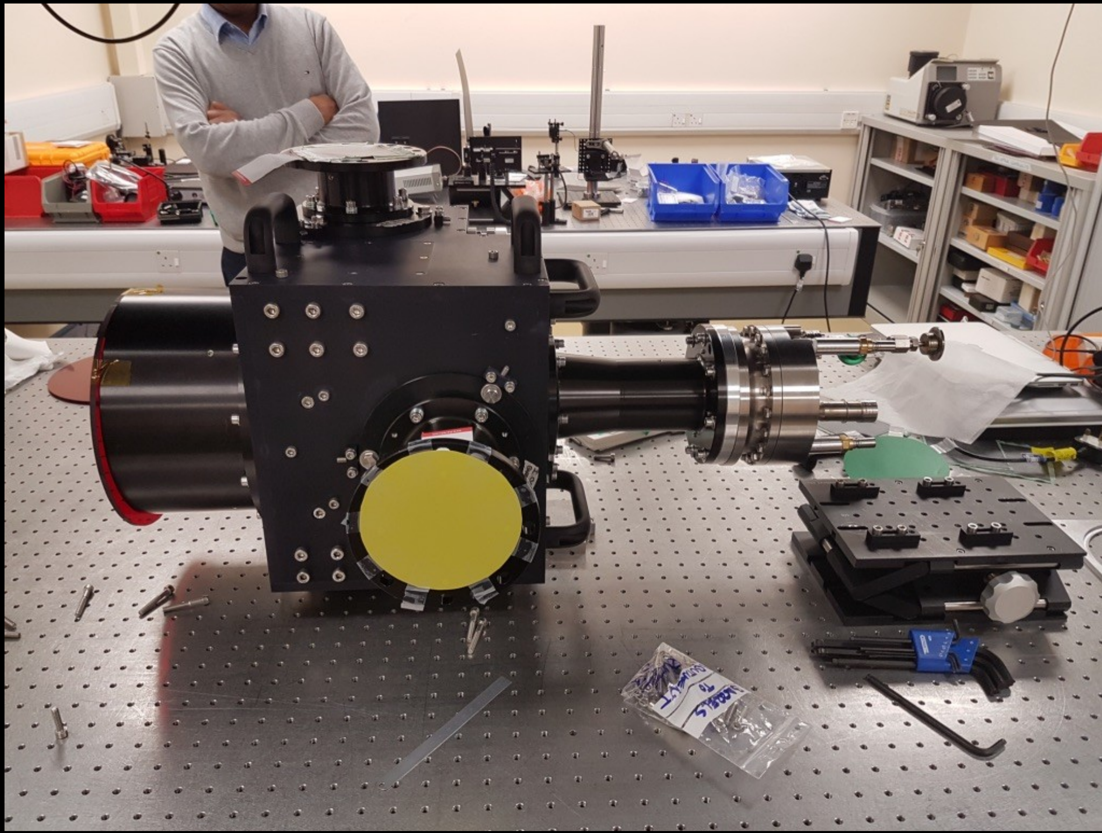
- High PERformance CAMera.
- Funded by ERC Advanced Grant for 3.5M€ awarded to Dhillon in 2014.
- Collaboration between Sheffield/IAC, Warwick, Durham and UKATC.
- Visitor instrument, to be commissioned on the 4.2m WHT and 10.4m GTC on La Palma in 2017.
- Provides an “order-of-magnitude” improvement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



OPTICS

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

- Double the field of view of ULTRACAM.
- Brighter comparison stars for differential photometry



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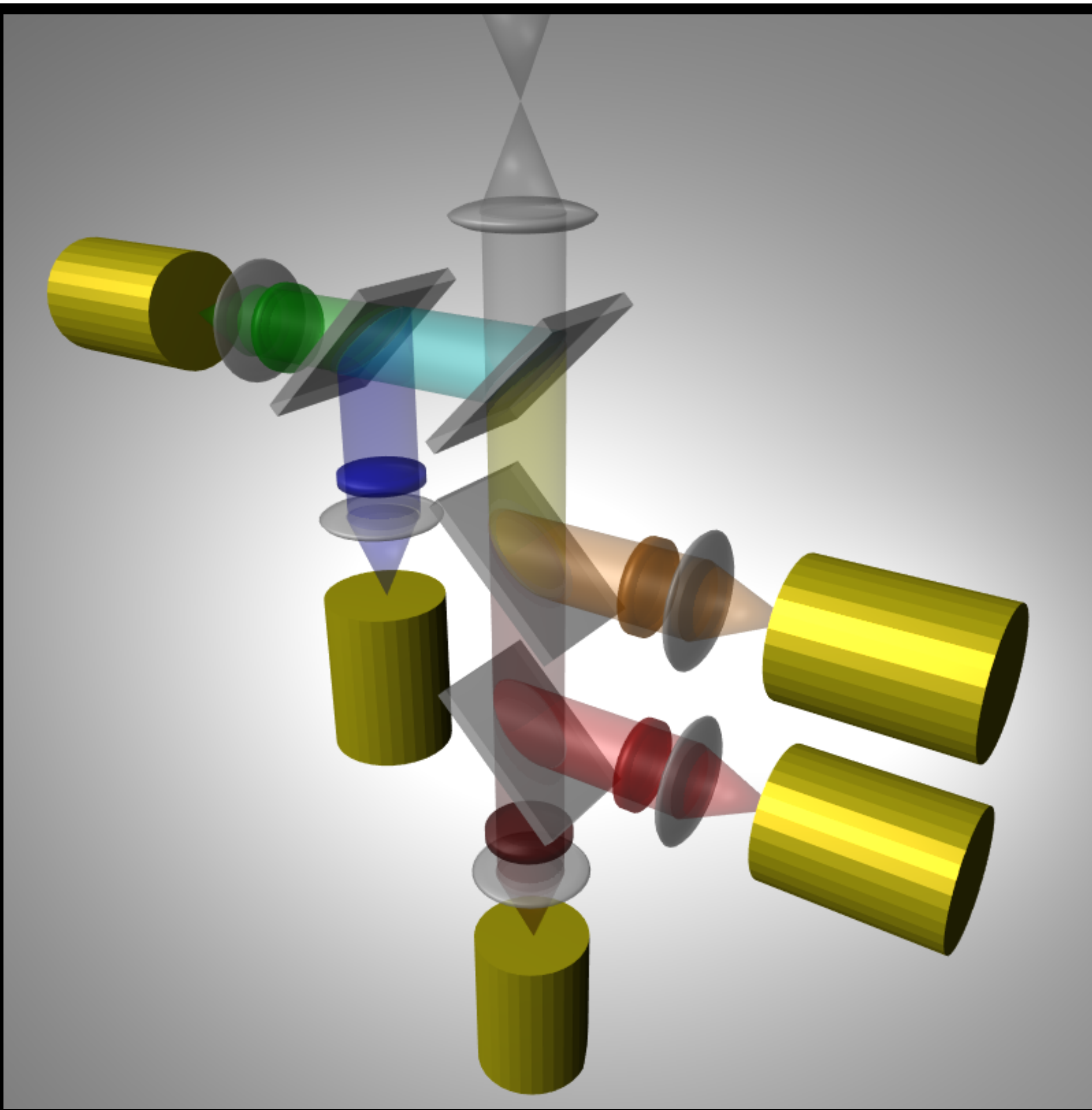

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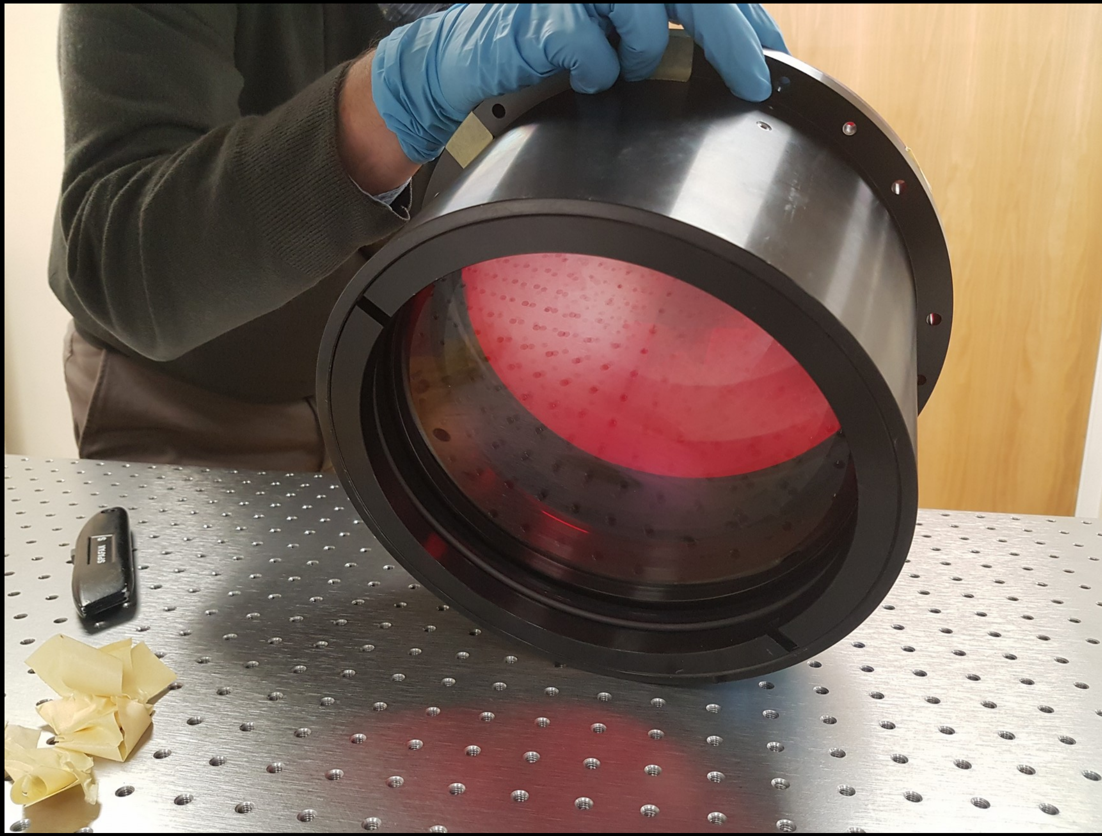
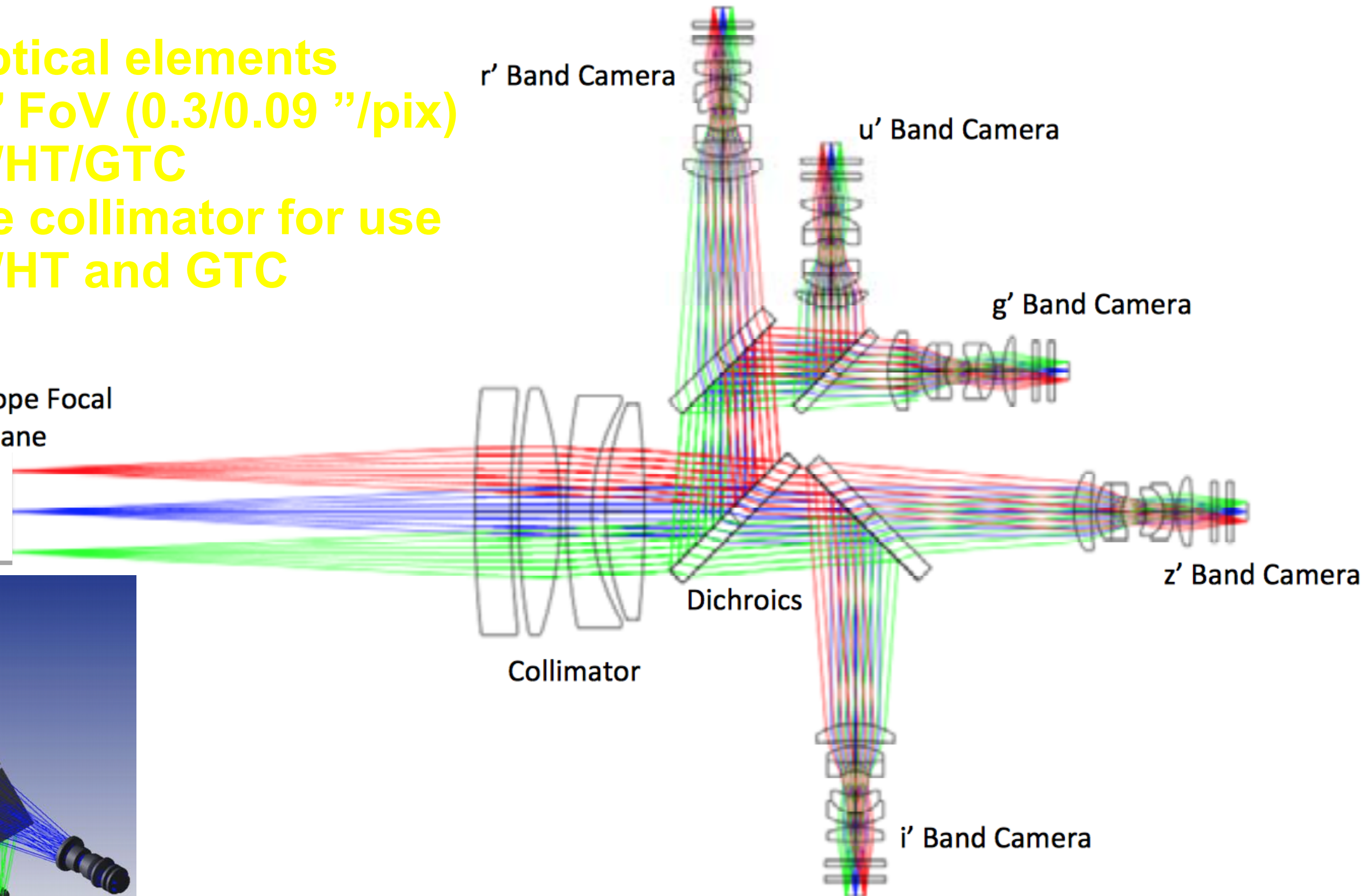
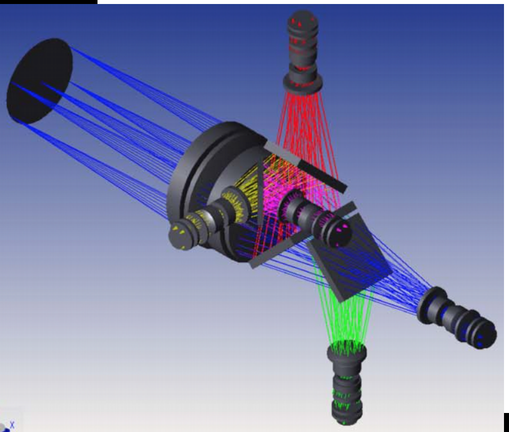


OPTICS

- 48 optical elements
- 10'/3' FoV (0.3/0.09 "/pix) on WHT/GTC
- Same collimator for use on WHT and GTC





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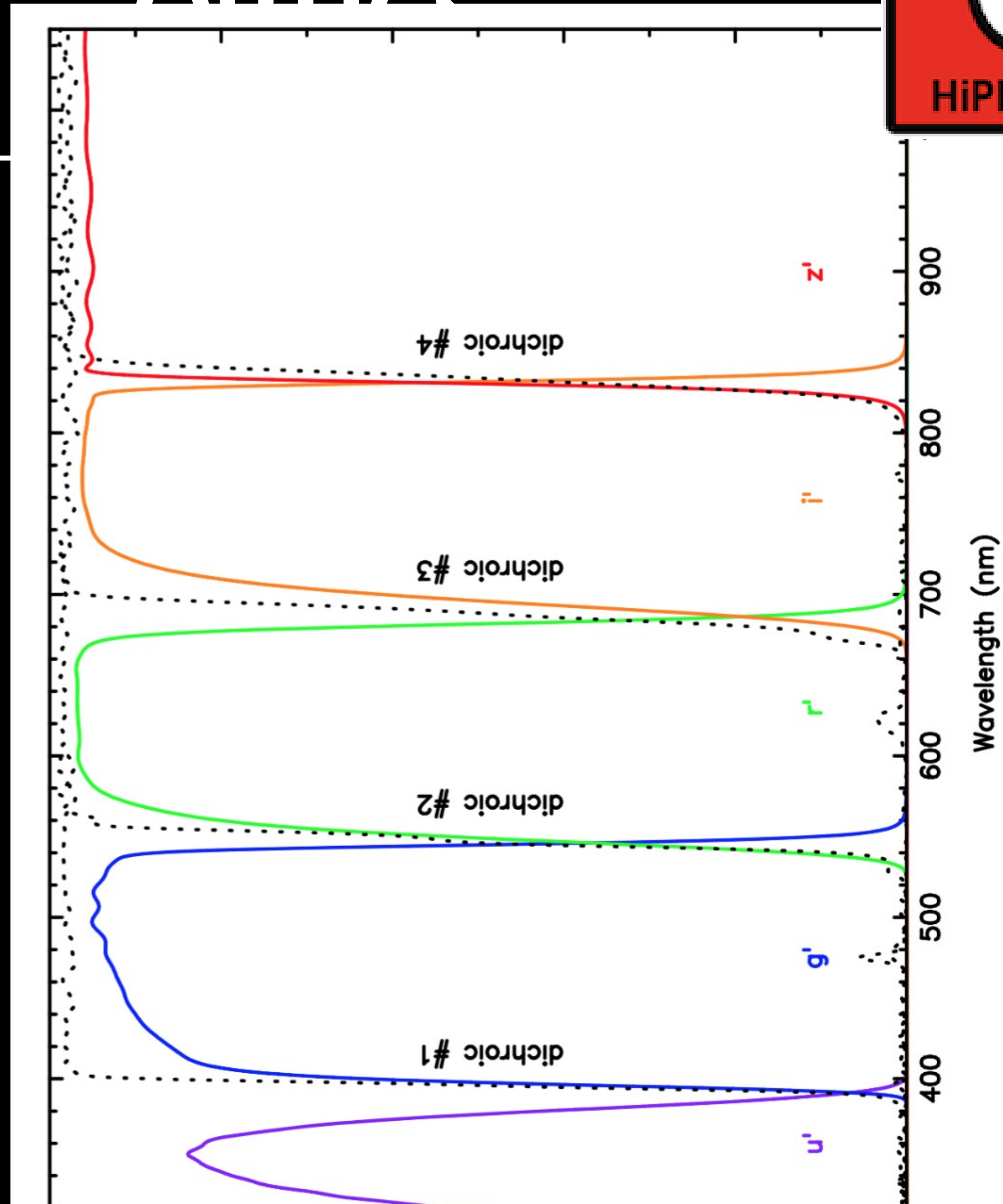
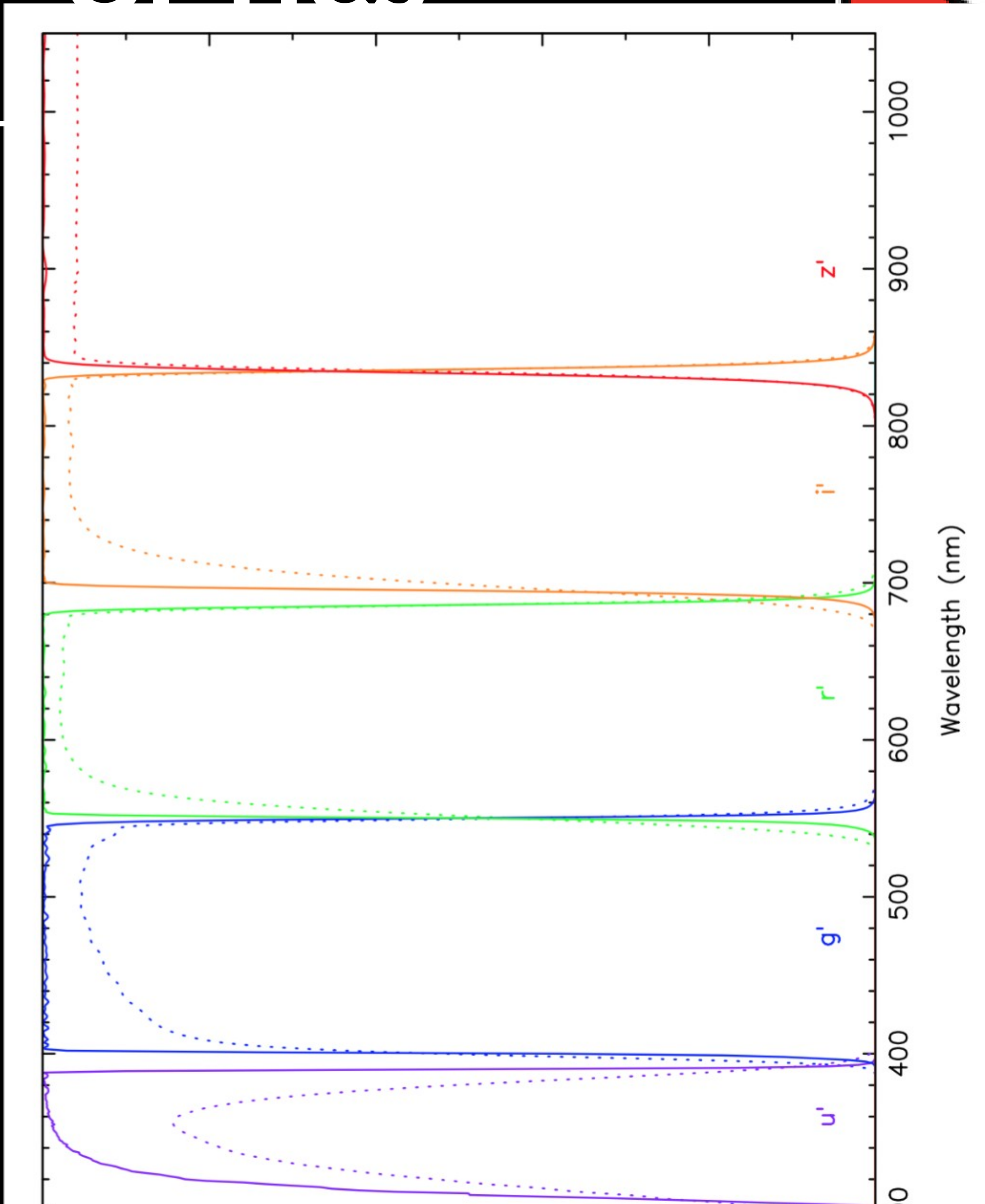


- High-performance dichroic beamsplitters and lens AR coatings.

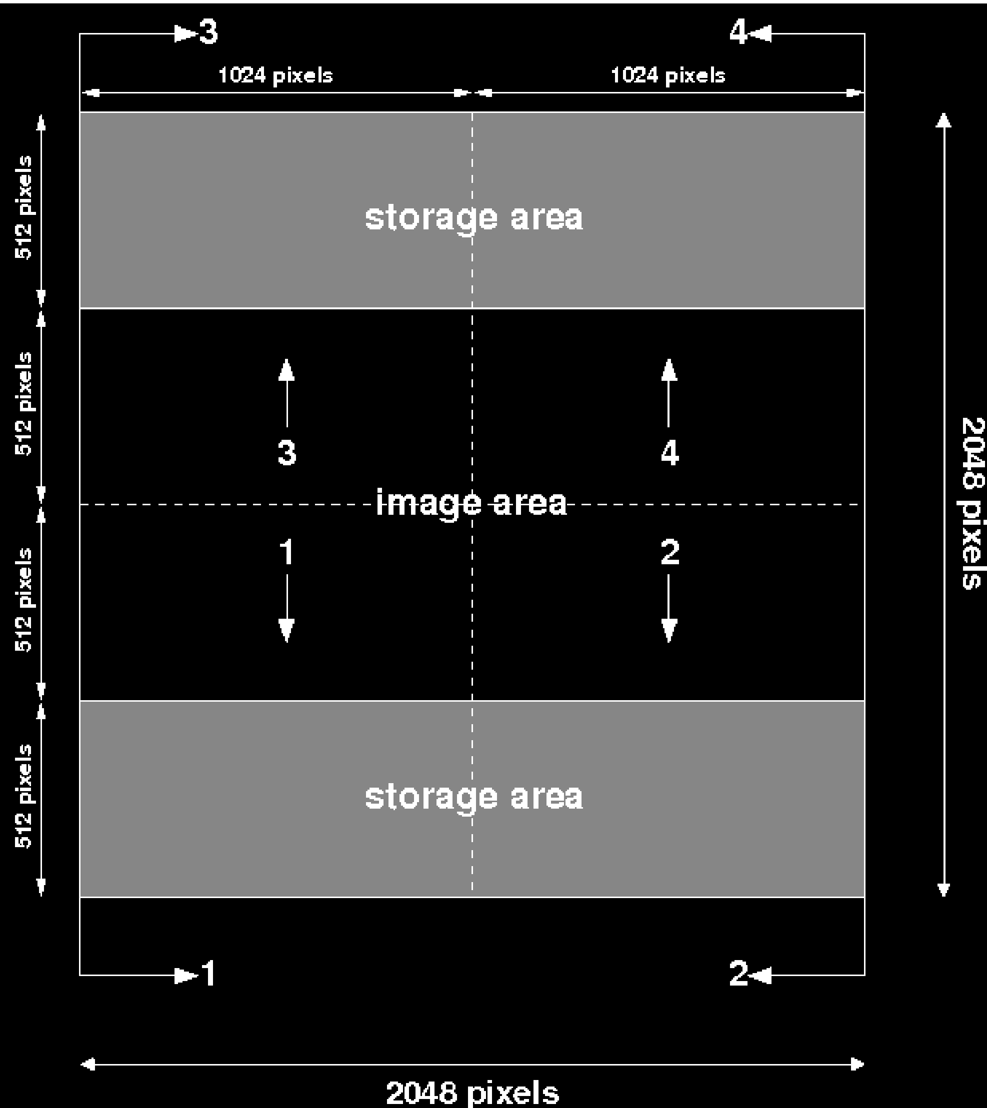
OPTICS

- “Super-SDSS” filters with enhanced throughput.



HIPERCAM CCDs

- 6x custom e2v back-thinned CCD231-42 grade 1 devices
- Split frame-transfer with 4 outputs, 2048x1024 image area, 15µm pixels
- NIMO: 8 e^-/pix/hr dark current at 173 K
- 3.0 e^- RNO at 200 kHz pixel rate
- 2 phase devices, 10µs row time, 0.1µs/pix serial clocking, split serial clocking, 100 ke^- full well
    - 1600 Hz with 4x8” windows
- Dummy outputs for noise rejection
- Fringe suppression
- Optimised AR coating and Si type for each CCD



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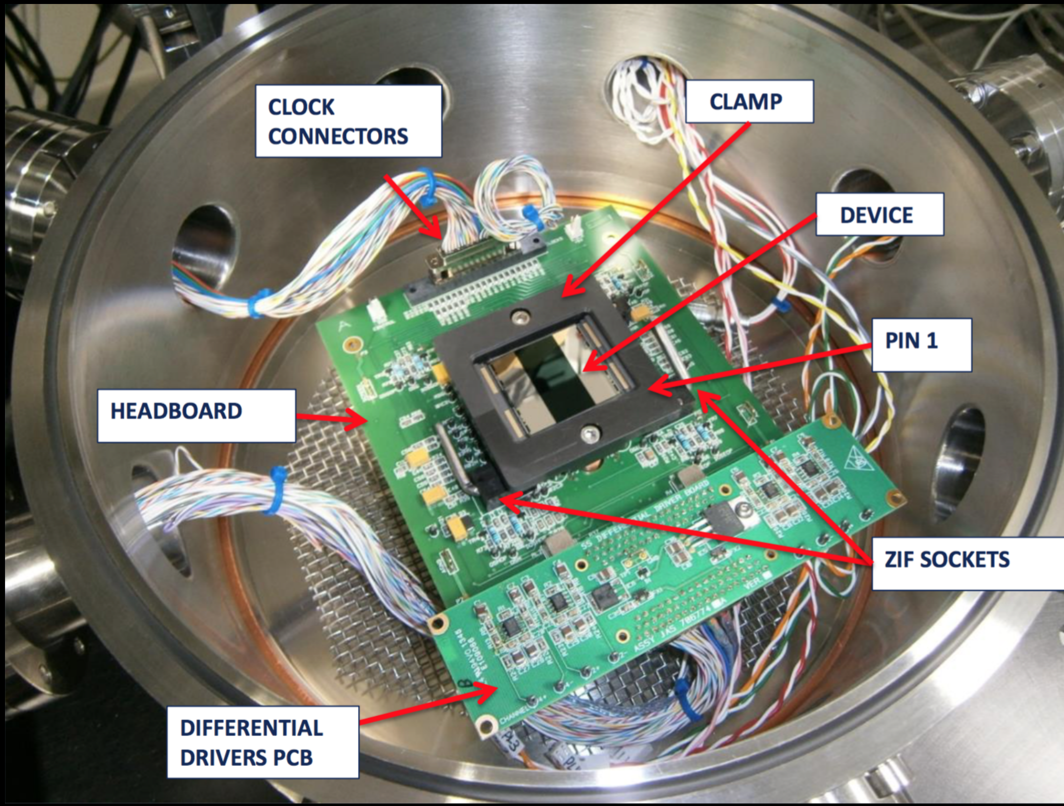
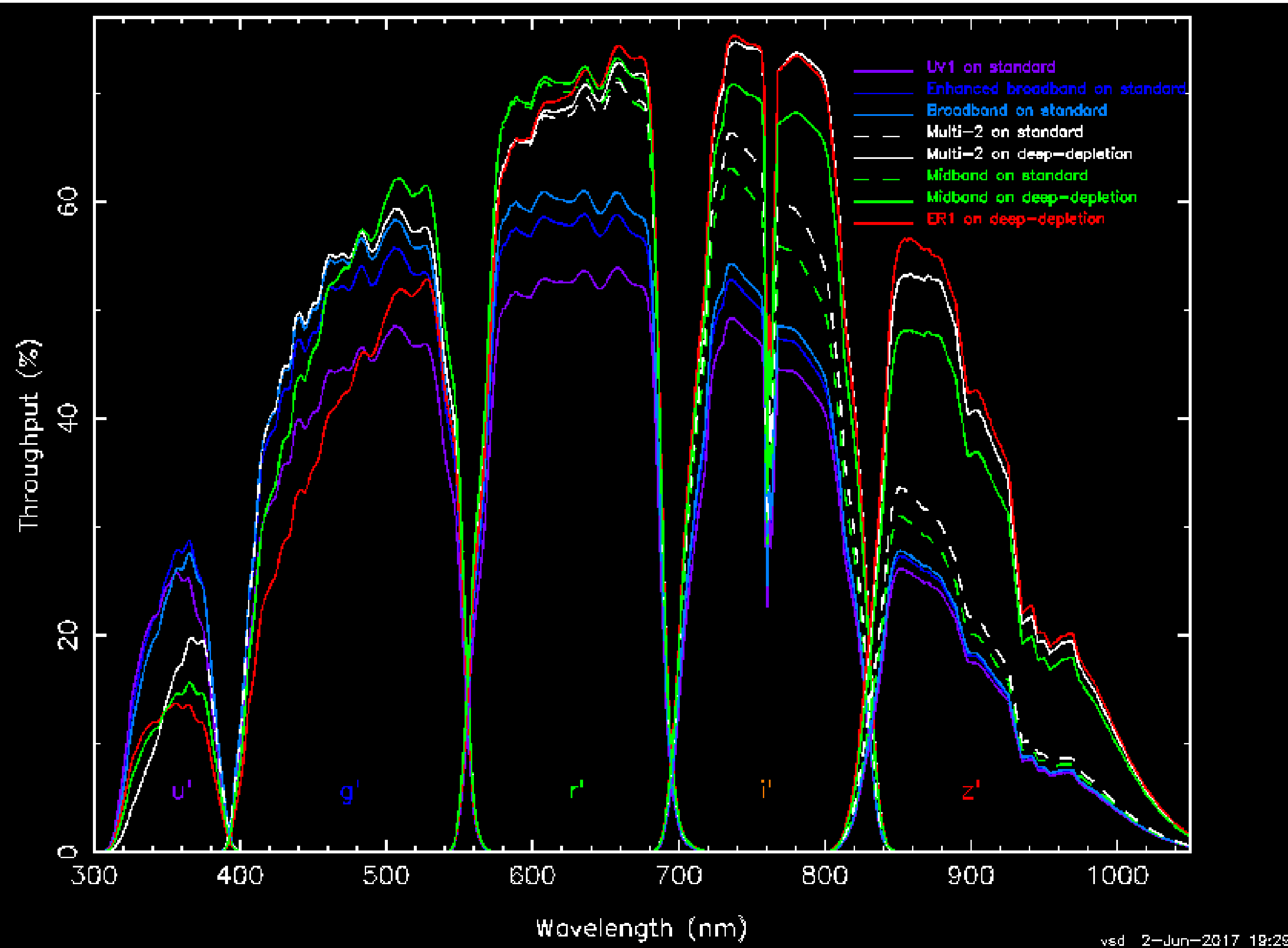
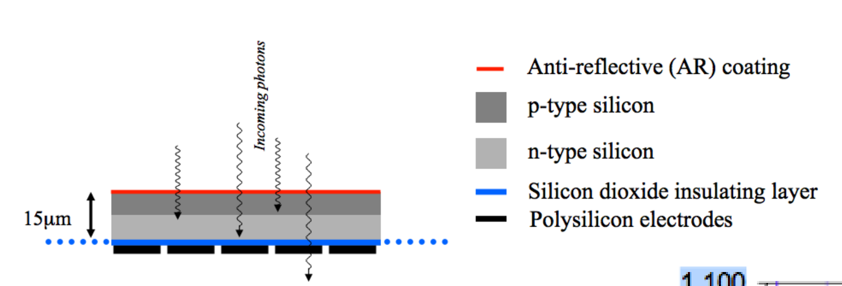
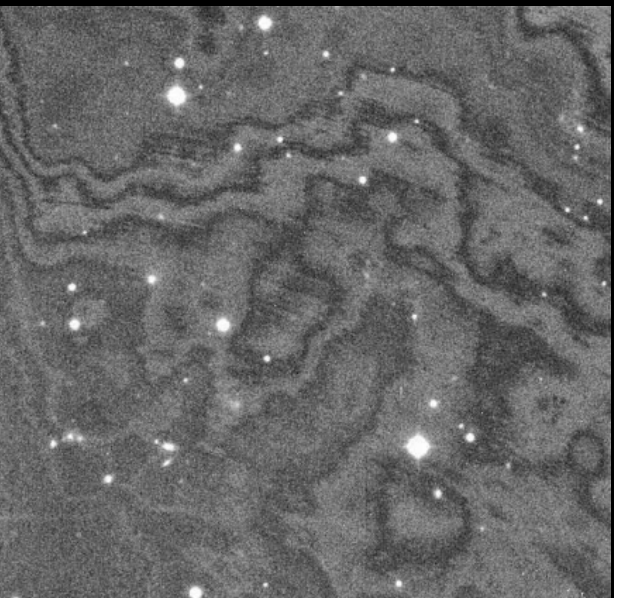


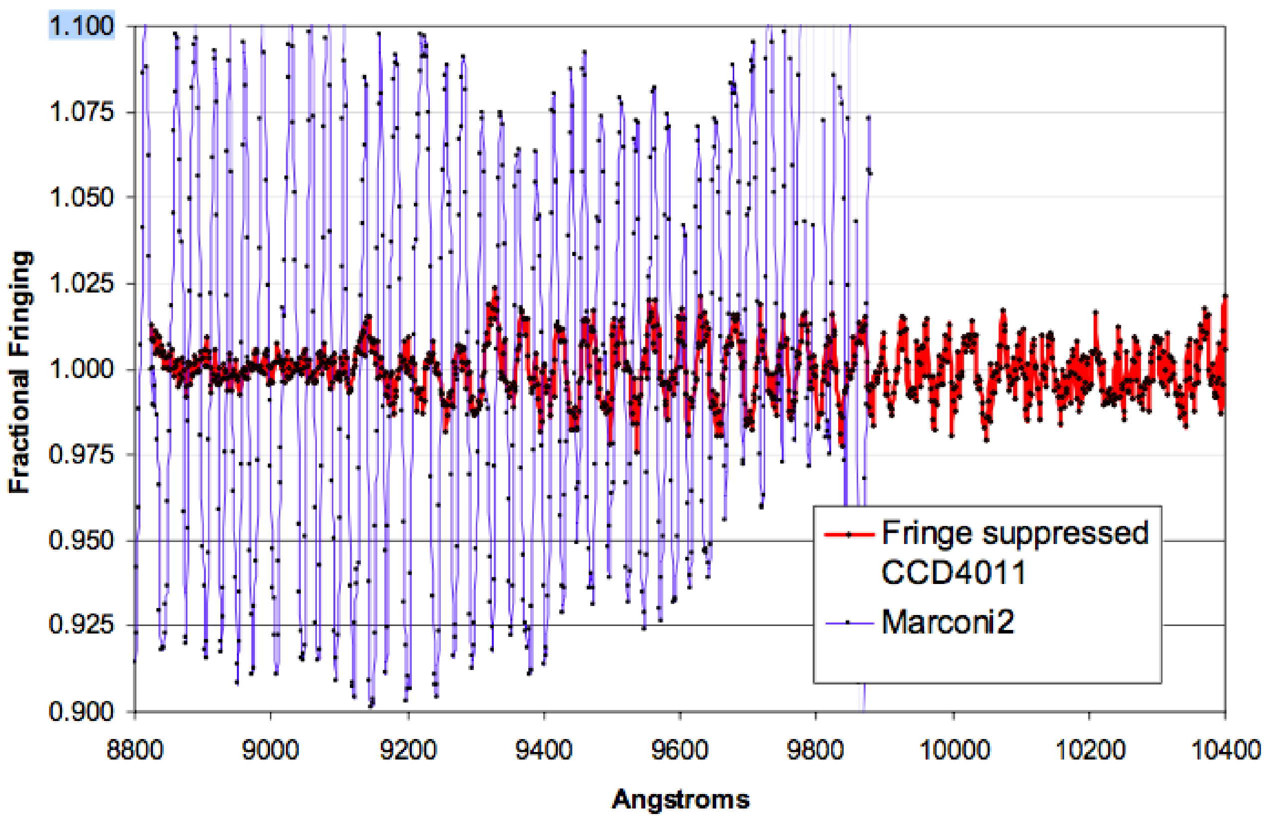
AR COATINGS AND Si TYPE



FRINGE SUPPRESSION

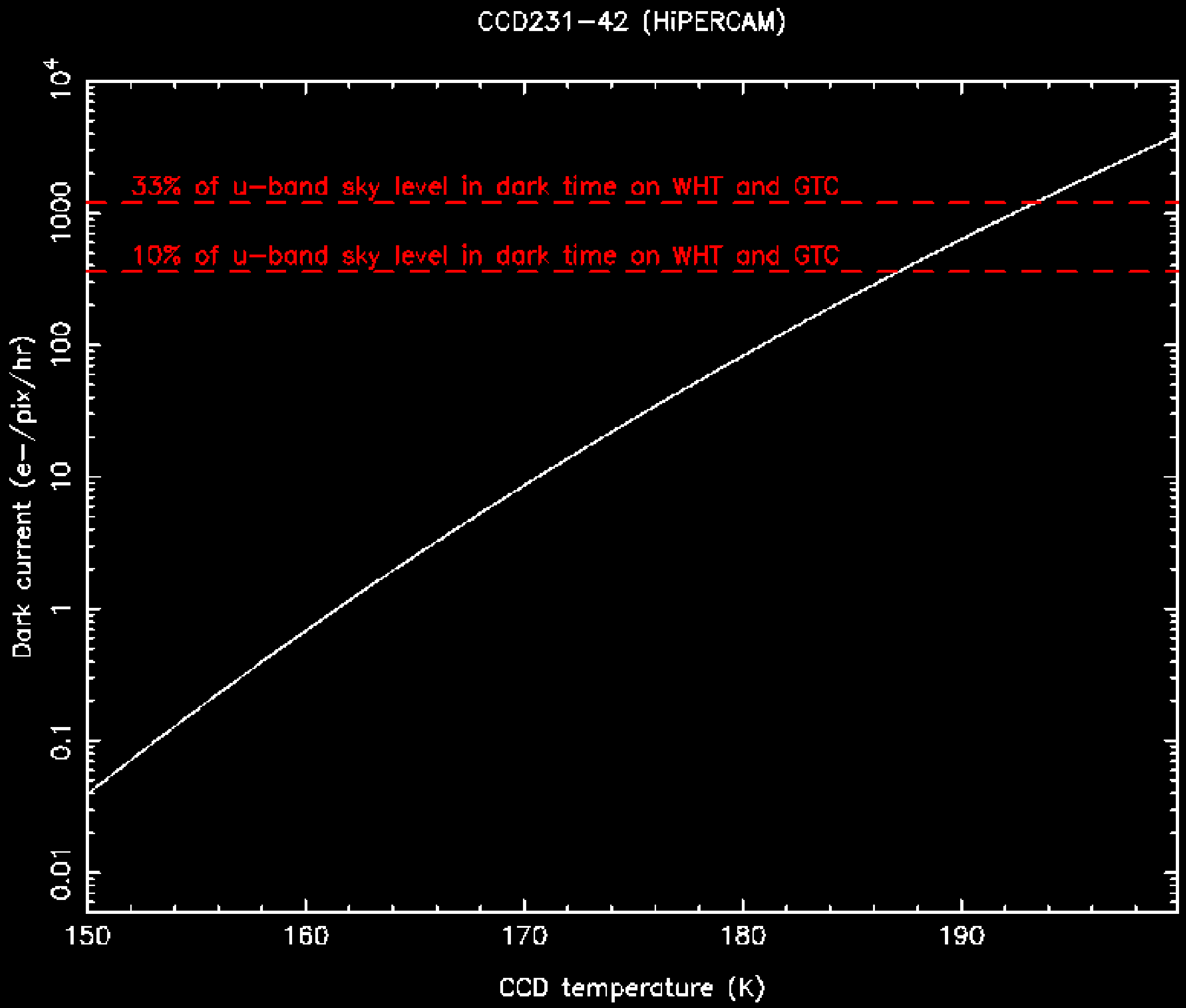






CCDs: HOW COLD?

- There is little point in cooling a CCD below the temperature at which the dark current becomes an insignificant noise source compared to the sky.
- With the HIPERCAM CCDs, this requires cooling to <187K.



CCDs: HOW TO COOL?

We rejected a number of different cooling options:

- Liquid nitrogen cooling:
  - Impractical to fill 5 cryostats once or twice a day.
  - Instrument would be large and heavy.
  - Continuous flow or automatic filling systems problematic as HIPERCAM is a Visitor Instrument.

CCDs: HOW TO COOL?

We rejected a number of different cooling options:

- Joule-Thomson coolers (e.g. CryoTiger):
  - Impractical to house up to 5 compressors.
  - Difficult to deal with up to 10 stainless-steel braided hoses in a cable wrap.

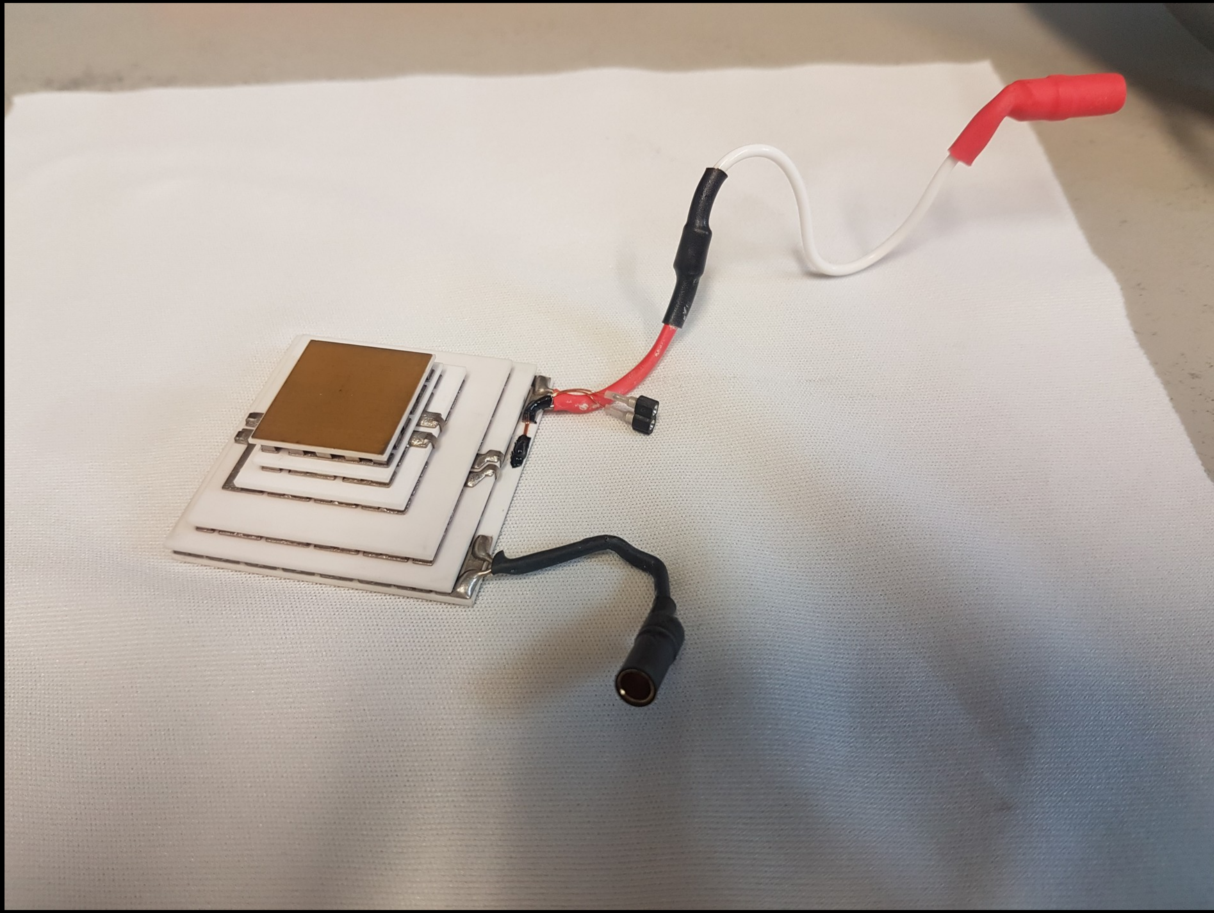
CCDs: HOW TO COOL?

We rejected a number of different cooling options:

- Stirling coolers:
    - Difficult to guarantee no vibrations induced in telescope, without using complex, bulky anti-vibration mounts.

TEC CCD HEADS

- CCDs to be cooled to below 180K with two 5-stage thermo-electric (peltier) coolers.
- Advantages: convenience, cost, no vibrations, low mass/size CCD heads.



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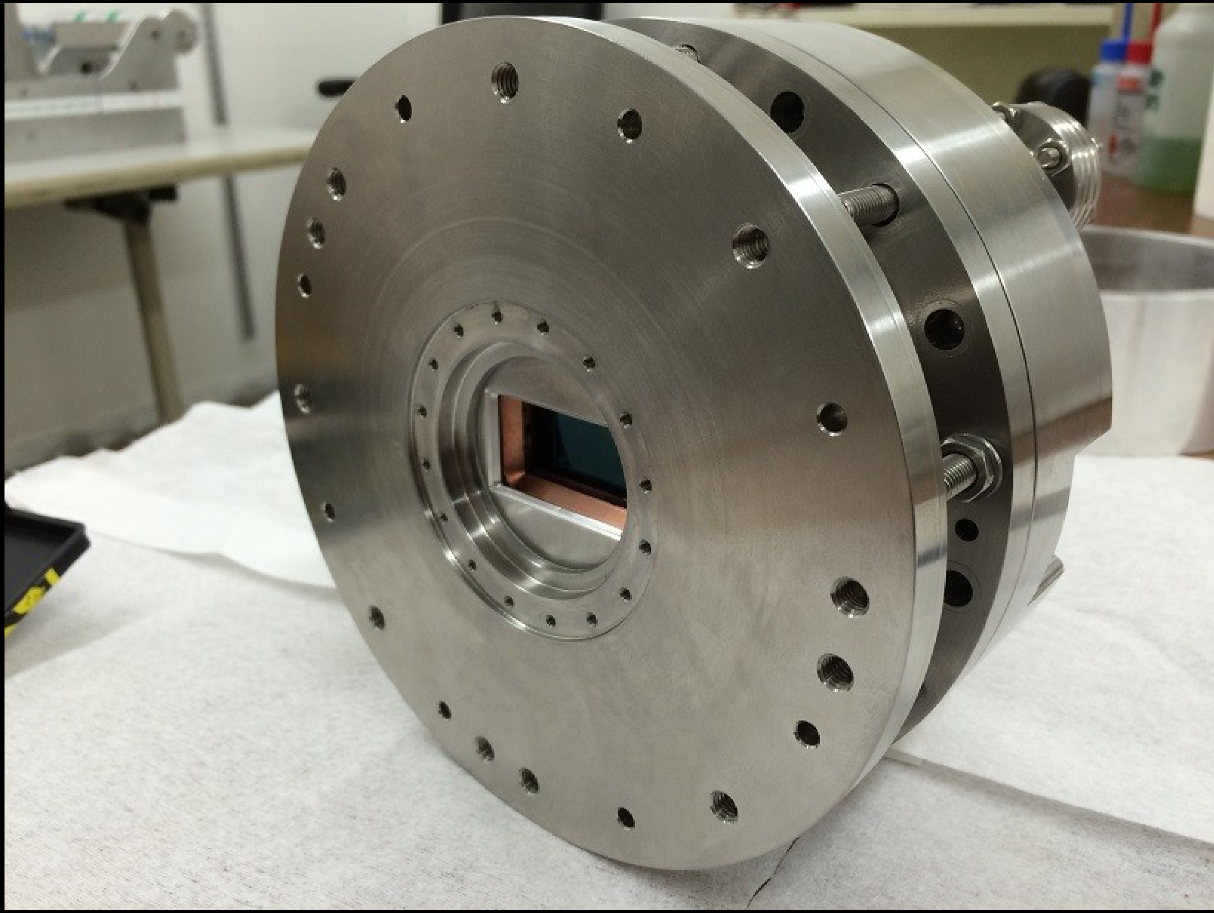

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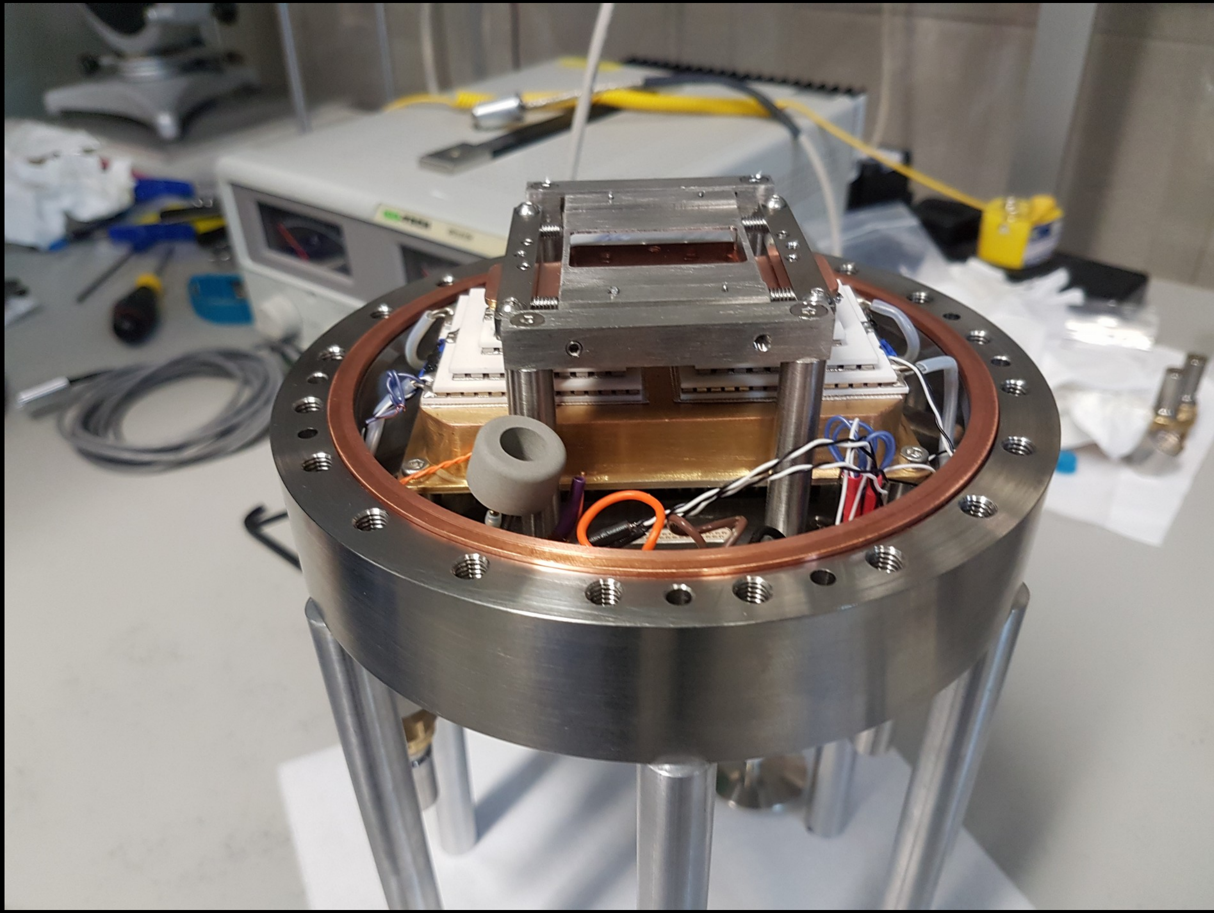
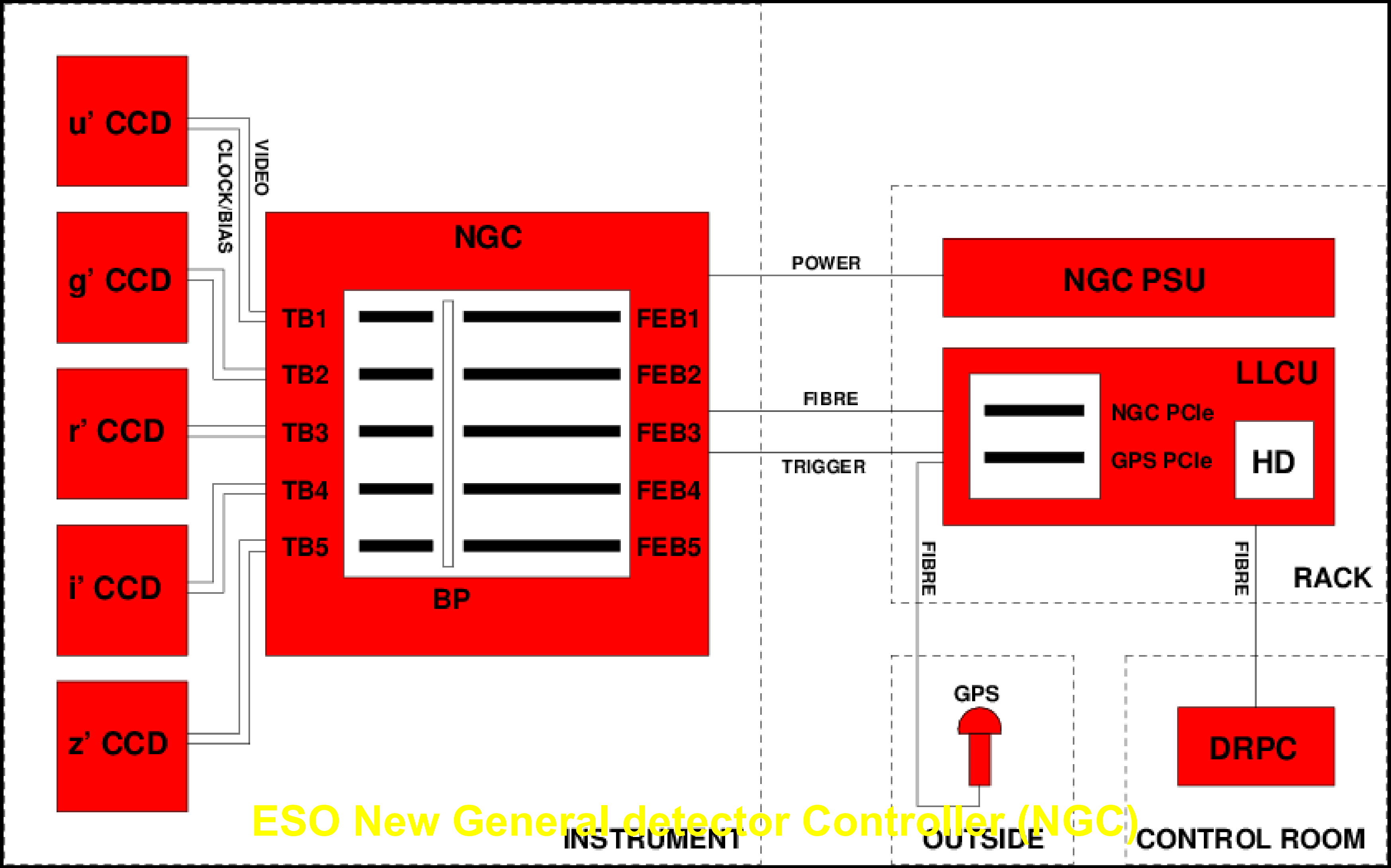
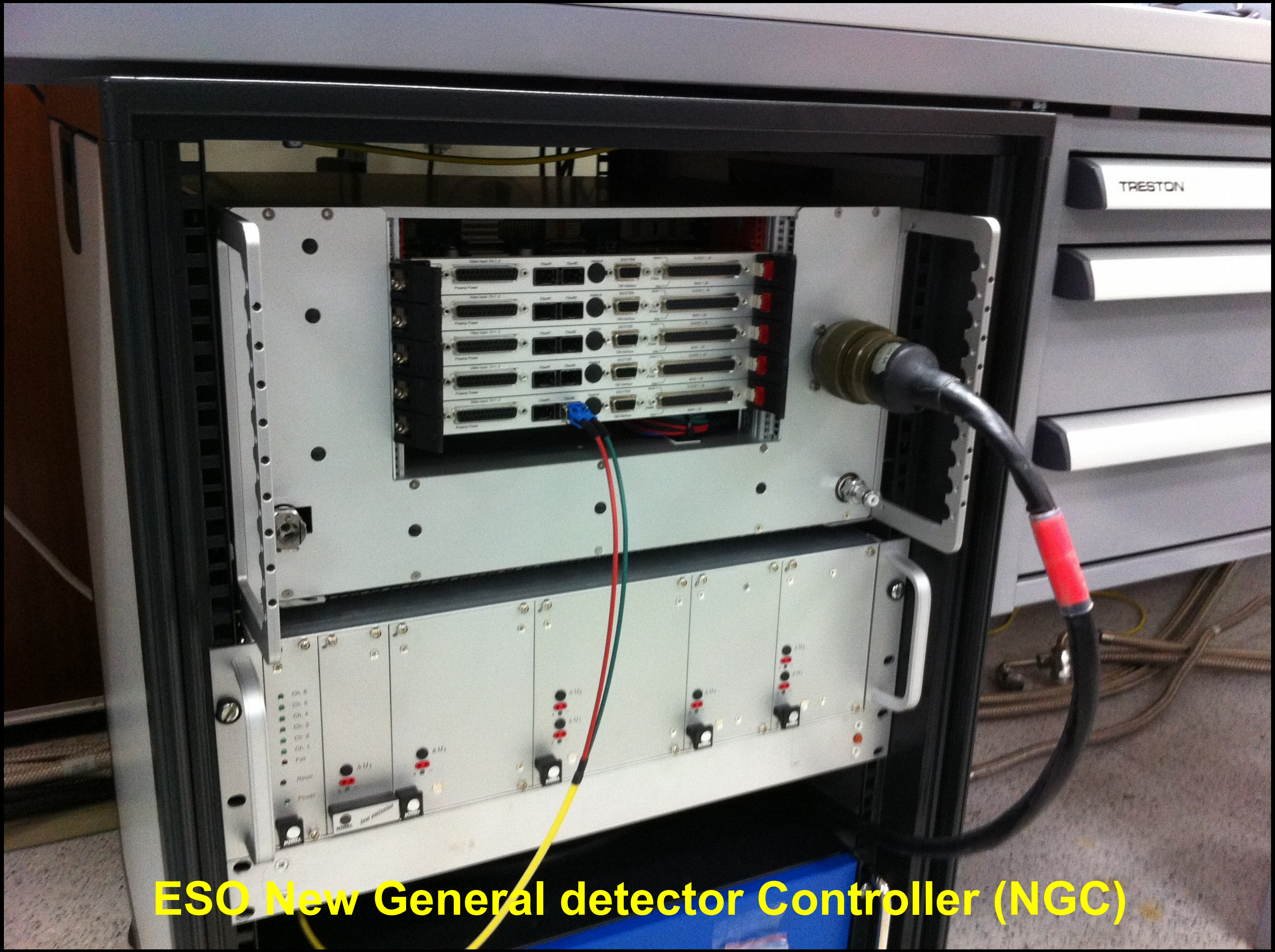


DATA ACQUISITION SYSTEM



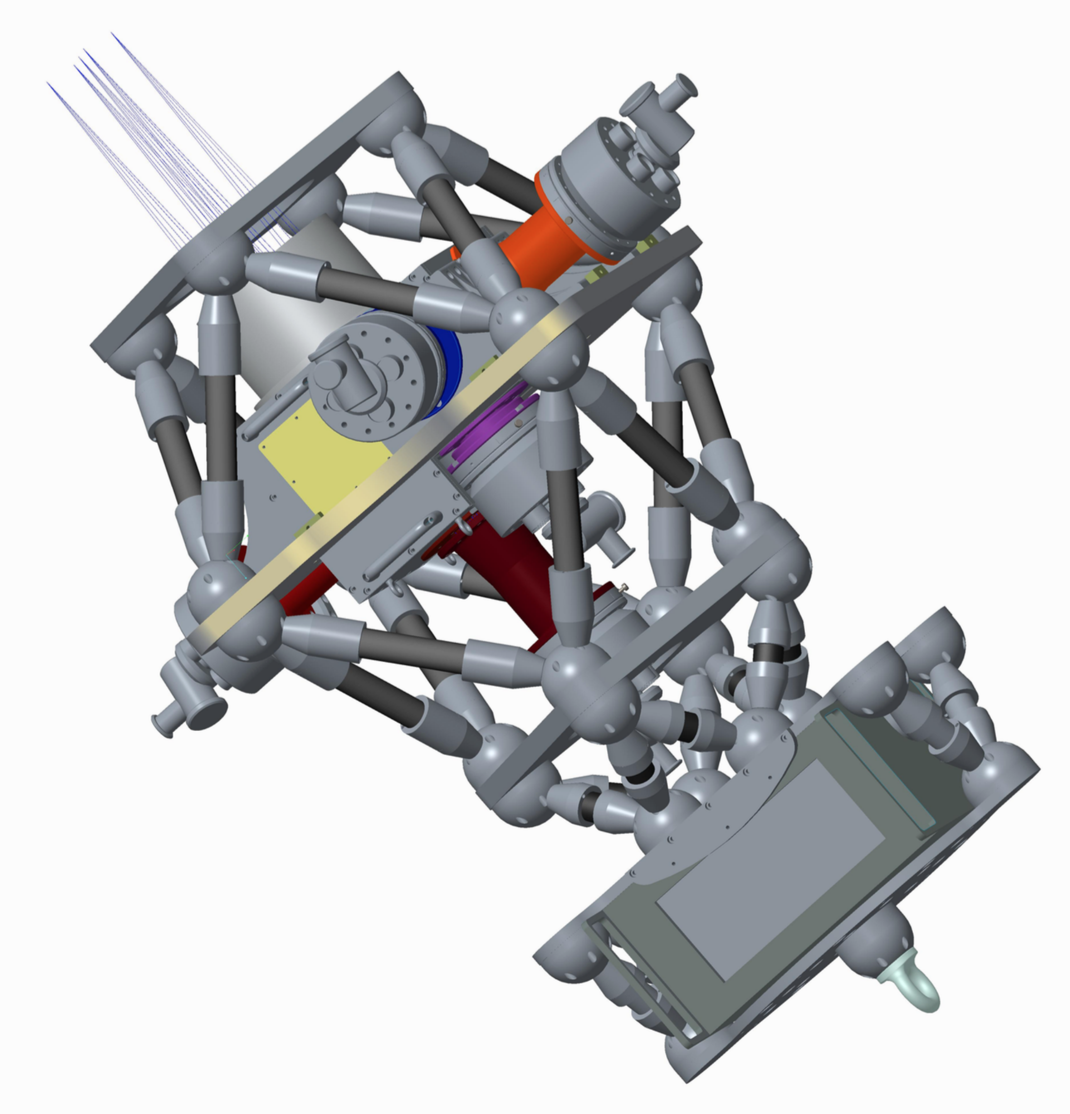
ESO New General detector Controller (NGC)

DATA ACQUISITION SYSTEM

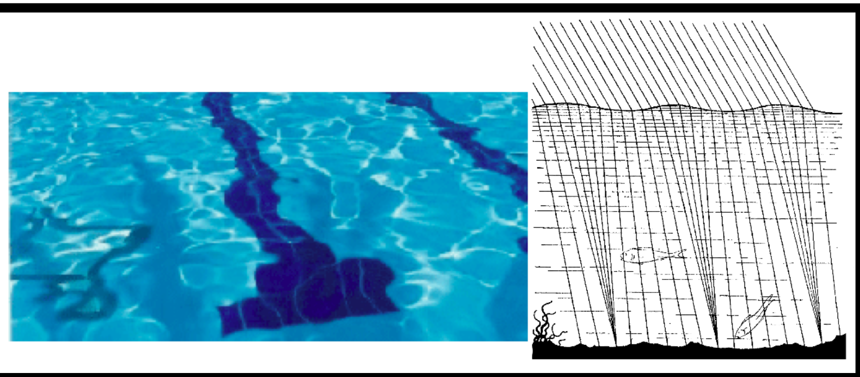


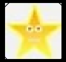
ESO New General detector Controller (NGC)

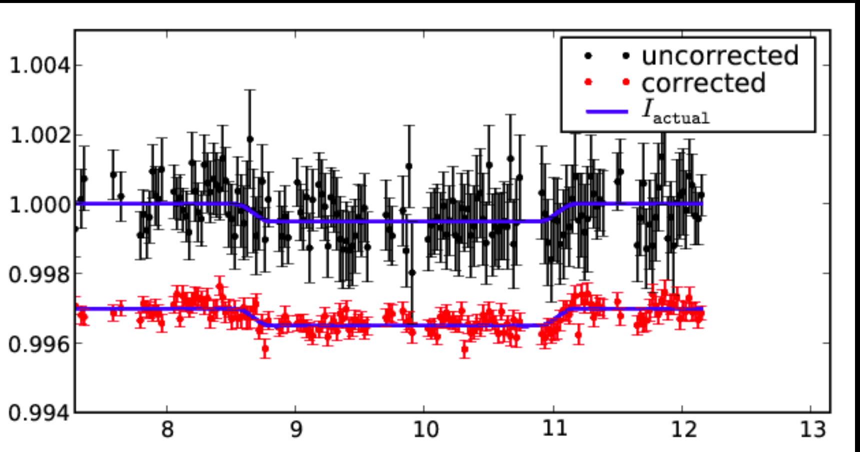
MECHANICAL STRUCTURE

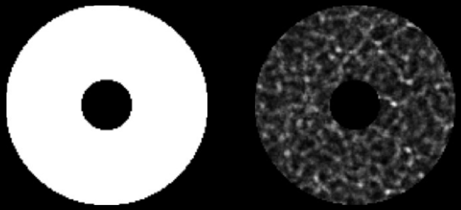


SCINTILLATION CORRECTION









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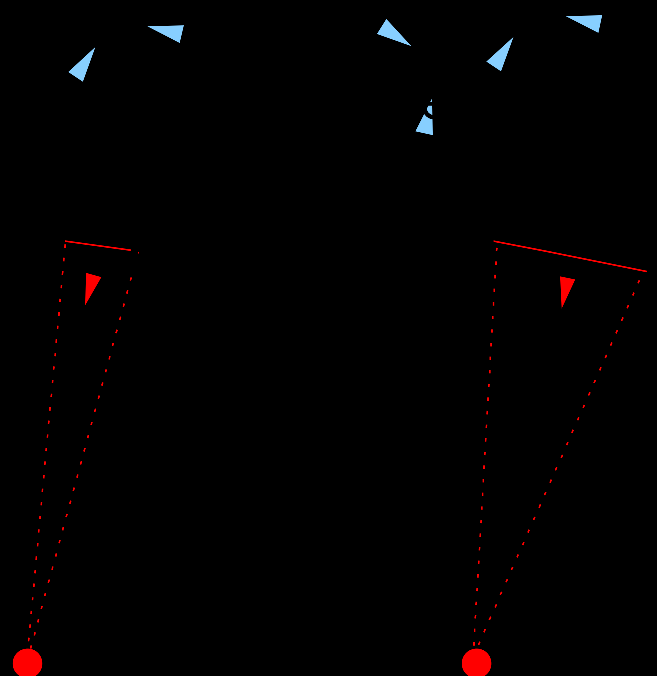

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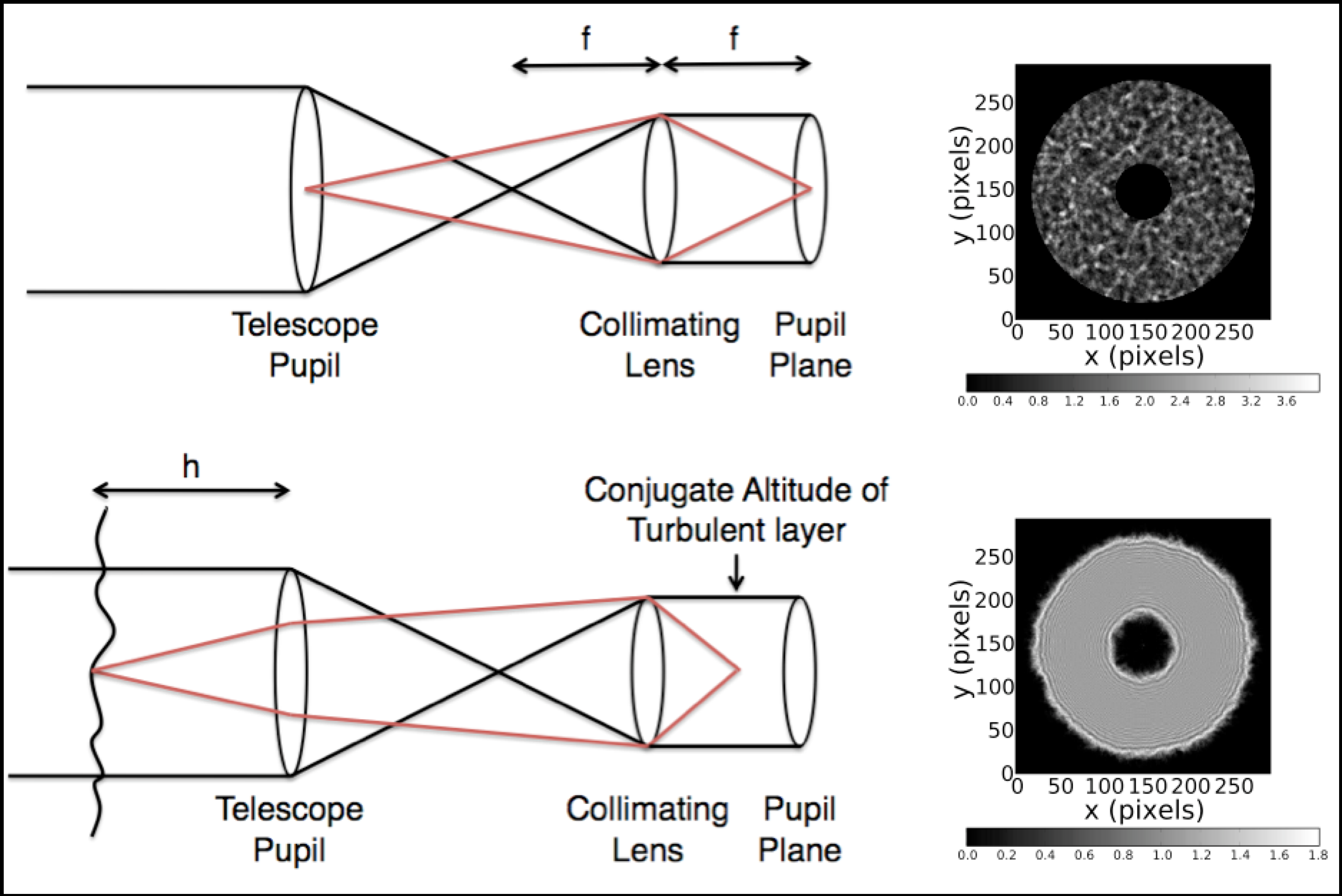

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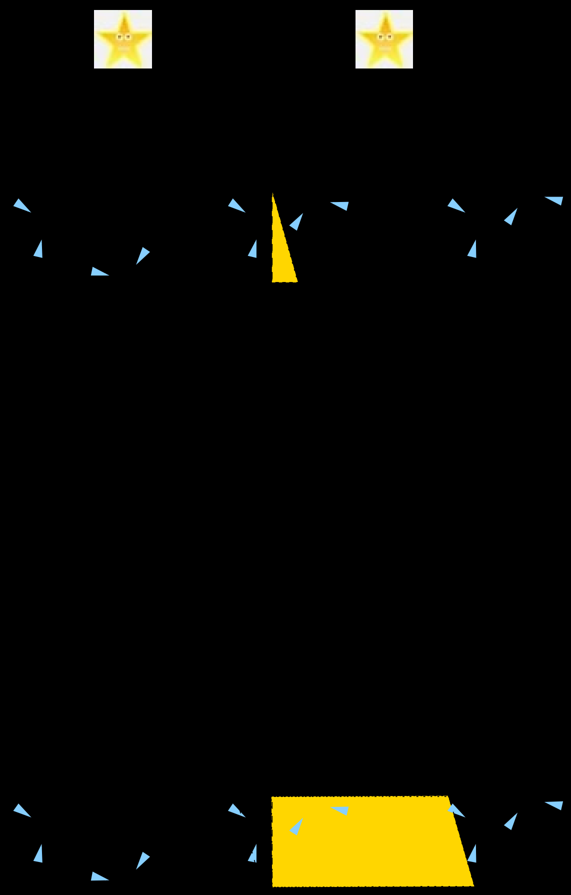
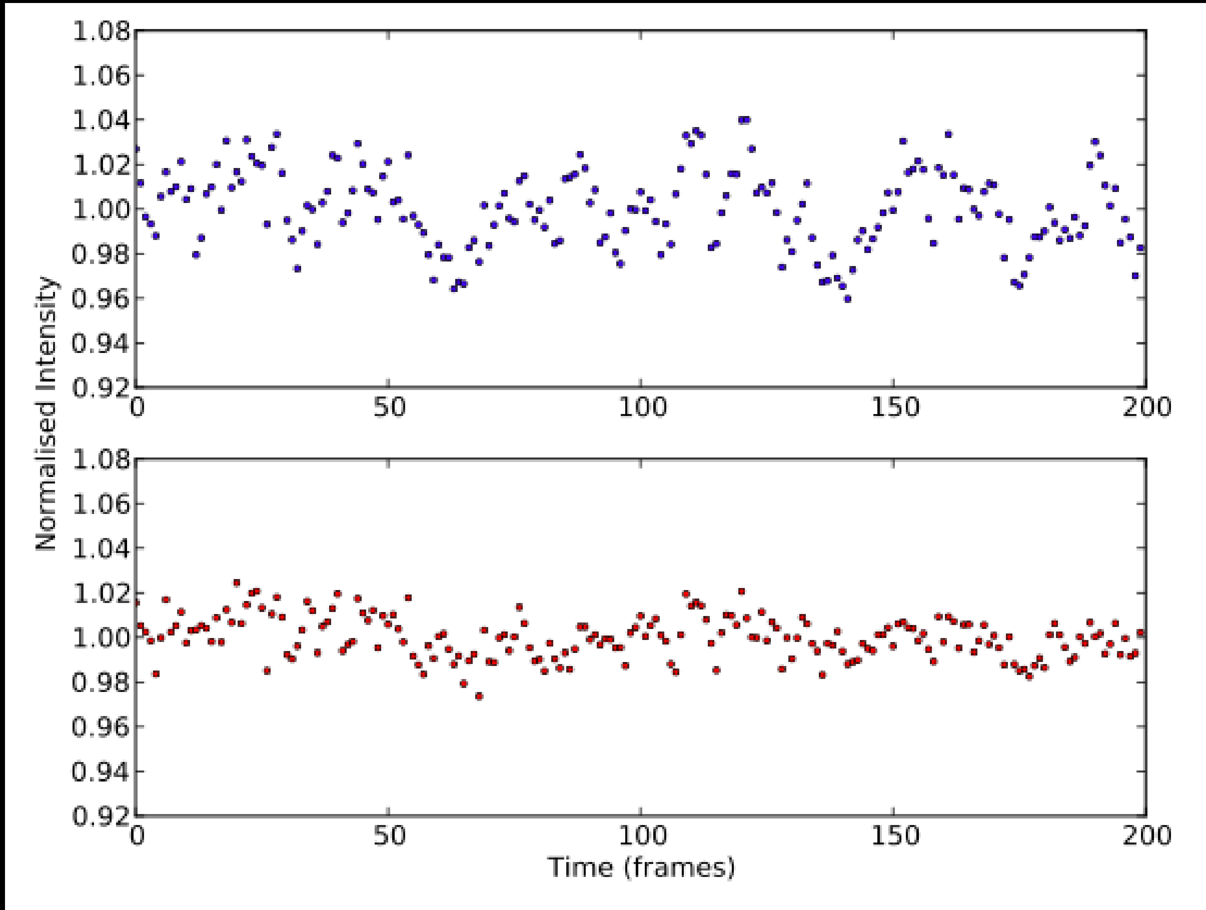
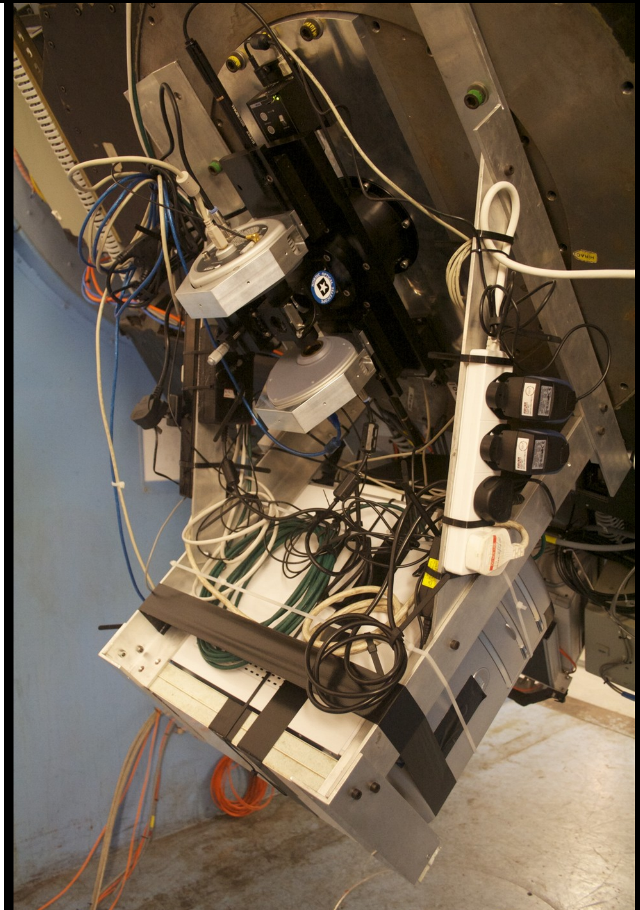


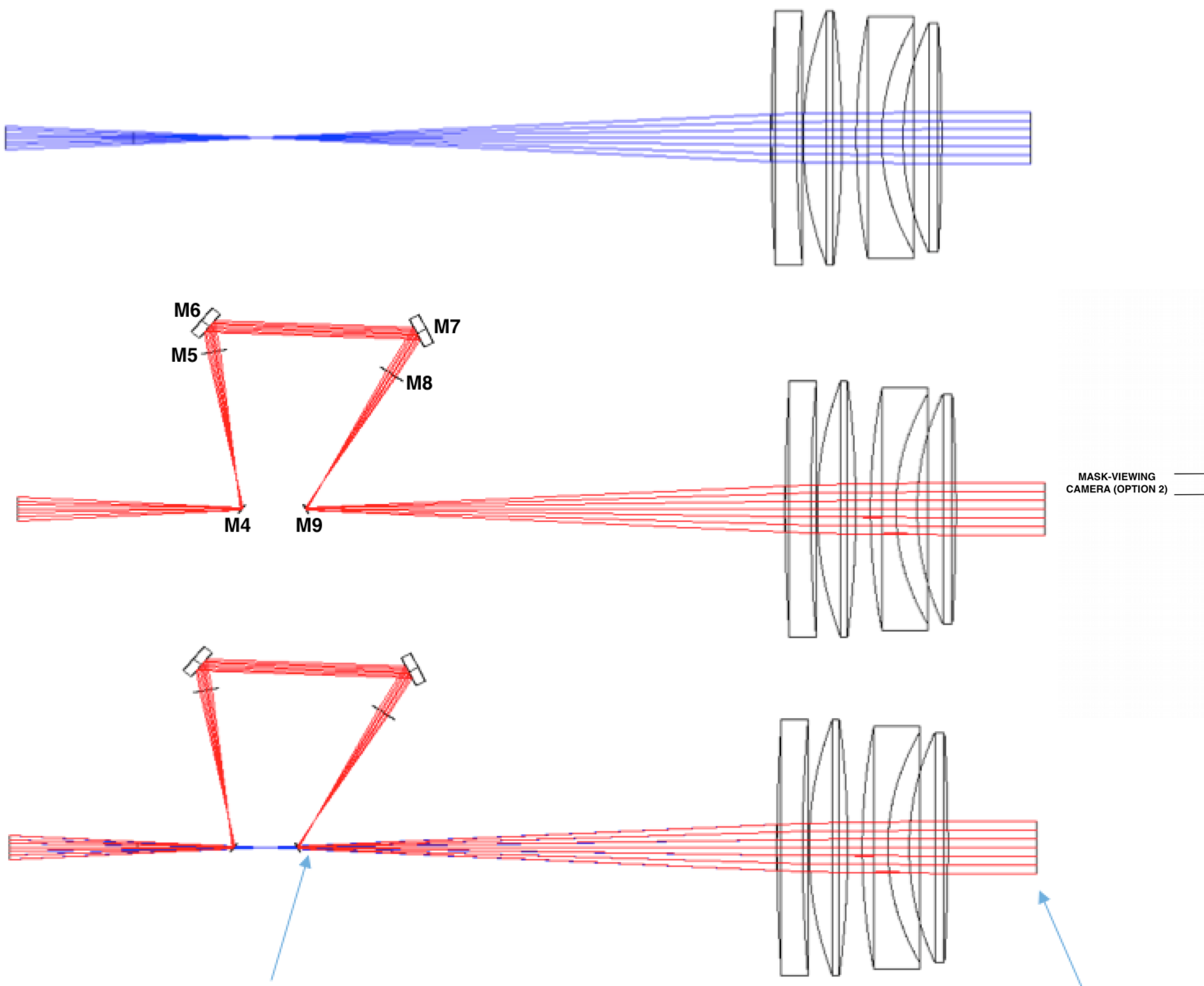
CONJUGATE PLANE PHOTOMETRY

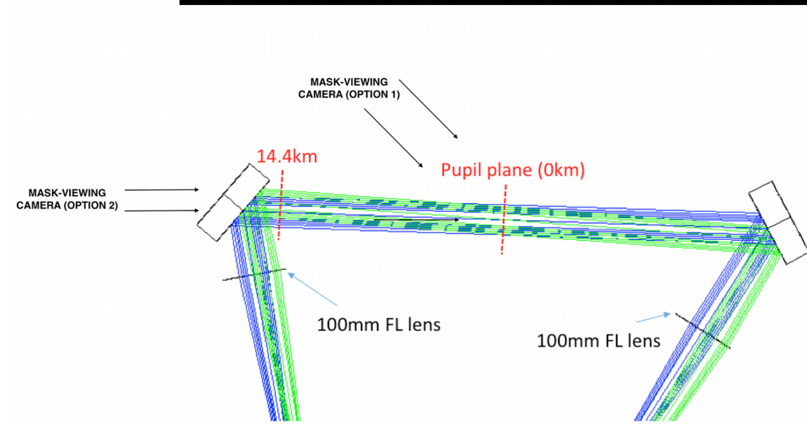
Prototype conjugate-plane photometer on the 2.5m NOT on La Palma demonstrated that the technique works.





CPP IN HIPERCAM

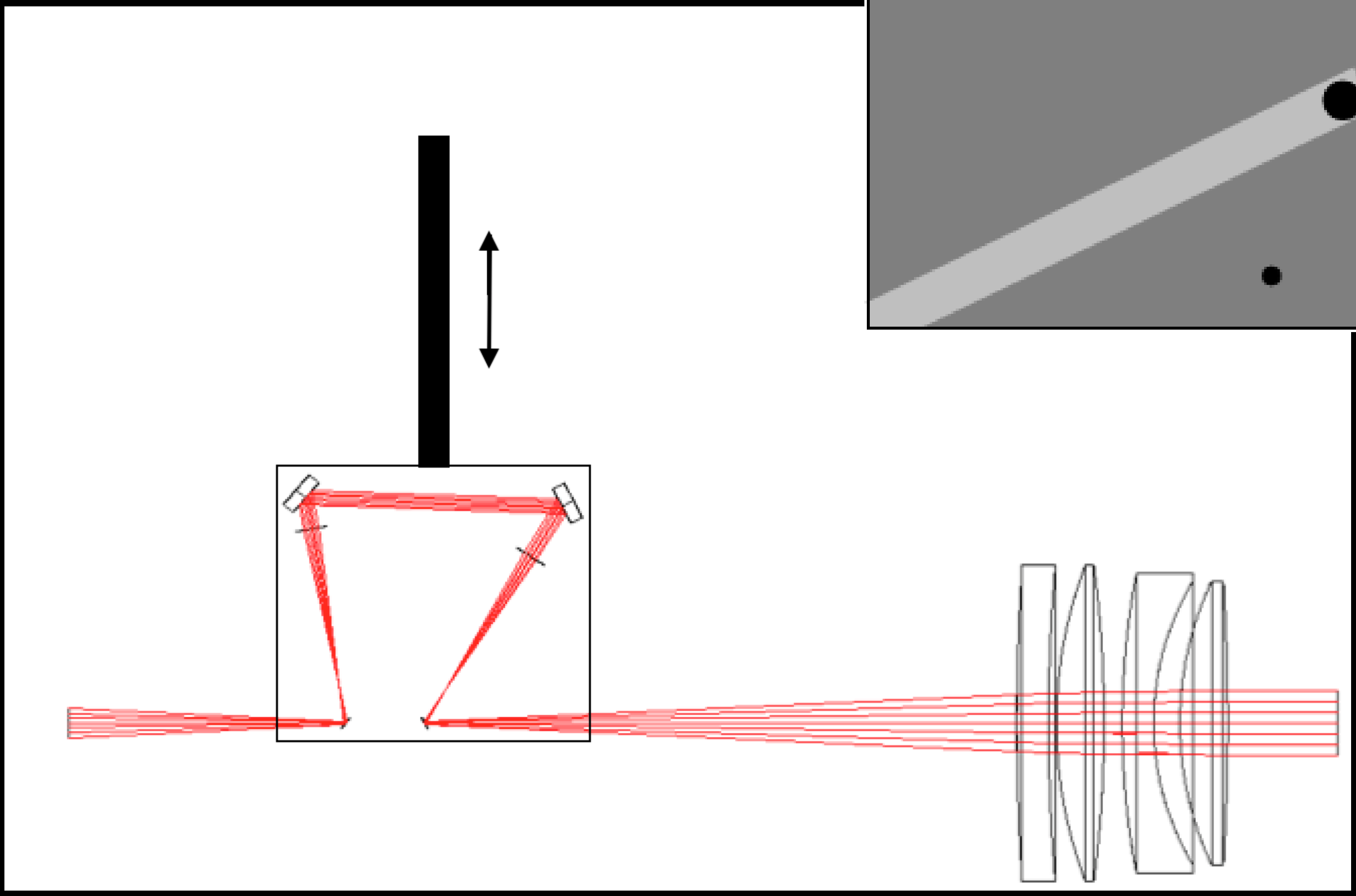


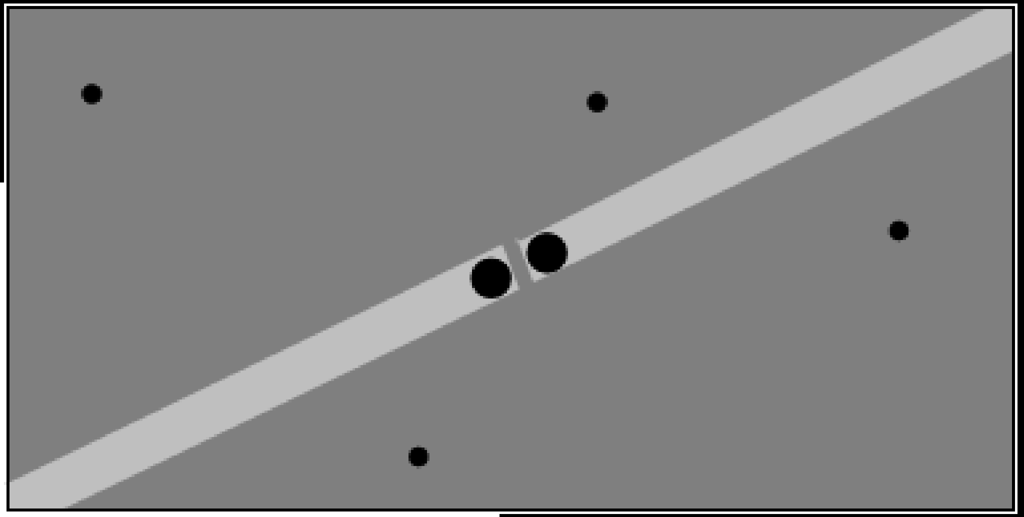


Beams overlap – f-ratio matched

Collimated beams overlap

CPP IN HIPERCAM





SCINTILLATION CORRECTION

Space-quality photometry from the ground? For more information:

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **411,** 1223–1230 (2011) doi:10.1111/j.1365-2966.2010.17759.x

Conjugate-plane photometry: reducing scintillation in ground-based photometry

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ABSTRACT

High-precision fast photometry from ground-based observatories is a challenge due to intensity fluctuations (scintillation) produced by the Earth's atmosphere. Here we describe a method to reduce the effects of scintillation by a combination of pupil reconjugation and calibration using a comparison star. Because scintillation is produced by high-altitude turbulence, the range of angles over which the scintillation is [illegible] small [illegible] a comparison star [illegible] impossible. We propose [illegible] pupil to high dominant layer of turbulence, then apodizing it before calibration with a comparison star. We find by simulation that given a simple atmosphere with a single high-altitude turbulent layer and a strong surface layer, a reduction in the intensity variance by a factor of ∼30 is possible. Given a more realistic atmosphere as measured by Scintillation Detection and Ranging (SCIDAR) at San Pedro Mártir, we find that on a night with a strong high-altitude layer we can expect the median variance to be reduced by a factor of ∼11. By reducing the scintillation noise we will be able to detect much smaller changes in brightness. If we assume a 2-m telescope and an exposure time of 30 s, a reduction in the scintillation noise from 0.78 to 0.21 mmag is possible, which will enable the routine detection of, for example, the secondary transits of extrasolar planets from the ground.

Key words: atmospheric effects – techniques: photometric.

1 INTRODUCTION

High-precision fast photometry is key to several branches of research including (but not limited to) the study of extrasolar planet transits (e.g. Charbonneau et al. 2000), stellar seismology (Christensen-Dalsgaard et al. 2006) and the detection of small Kuiper belt objects (e.g. Schlichting et al. 2009). The difficulty with such observations is that, although the targets are often bright, the variation one wishes to detect is often very small (typically millimagnitudes or less) and hence the signal-to-noise ratio is not limited by the detector or sky but by intensity fluctuations (scintillation) produced by the Earth's atmosphere. For this reason fast photometers are generally put in space (e.g. *CoRoT*, *Kepler* and *PLATO*).

Extrasolar planetary transits can be detected from the ground. However, the measurement of the secondary eclipse (i.e. where the planet goes behind the star) is a challenge. Such observations are crucial, as only the secondary eclipse can give information on the planetary atmosphere, including the temperature and albedo (Knutson et al. 2007). Secondary eclipses were detected for the first time from space in 2005 using *Spitzer* at 3 μm (Charbonneau et al. 2005). There has been a great deal of effort to detect secondary eclipses from the ground, but for years no detections were made (in large part due to scintillation noise). Finally, in 2009, the first ground-based detections were made, but these relied on near-IR measurements and had to target the most bloated, closest (to their host star) exoplanets to maximize the eclipse signal (Sing & López-Morales 2009). Since then a few other exoplanets have had secondary eclipses detected from the ground in this way. As noted by Deming & Seager (2009), secondary eclipses recorded in visible light in addition to IR measurements are crucial if we are to understand the relative contribution of thermal emission and reflected light, and the planetary albedo.

Time averaging the intensity will reduce the scintillation noise by an amount proportional to the square root of the exposure time (Dravins et al. 1998), but this will often result in saturating the CCD which then requires defocusing the telescope to distribute the image of the star over more pixels. Defocusing has certain

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Osborn et al. 2011, MNRAS, 411, 1223

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Atmospheric scintillation in astronomical photometry

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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 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 characterize the scintillation-noise component of contemporaneous photometric measurements. This will enable a better understanding and calibration of photometric noise sources and [illegible] scintillation correction techniques. We also [illegible] 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: atmospheric effects – instrumentation: photometers – methods: observational – site testing – techniques: photometric – planets and satellites: detection.

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 per cent to ∼0.1 per cent). 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 ∼0.1–1.0 per cent, 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 optimization 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 scintillation. We show that using the theoretical scintillation noise calculated from the median optical turbulence profile for a particular site is a better estimate of the median scintillation noise. However, we also show that the measured scintillation noise has large variability due to changes in

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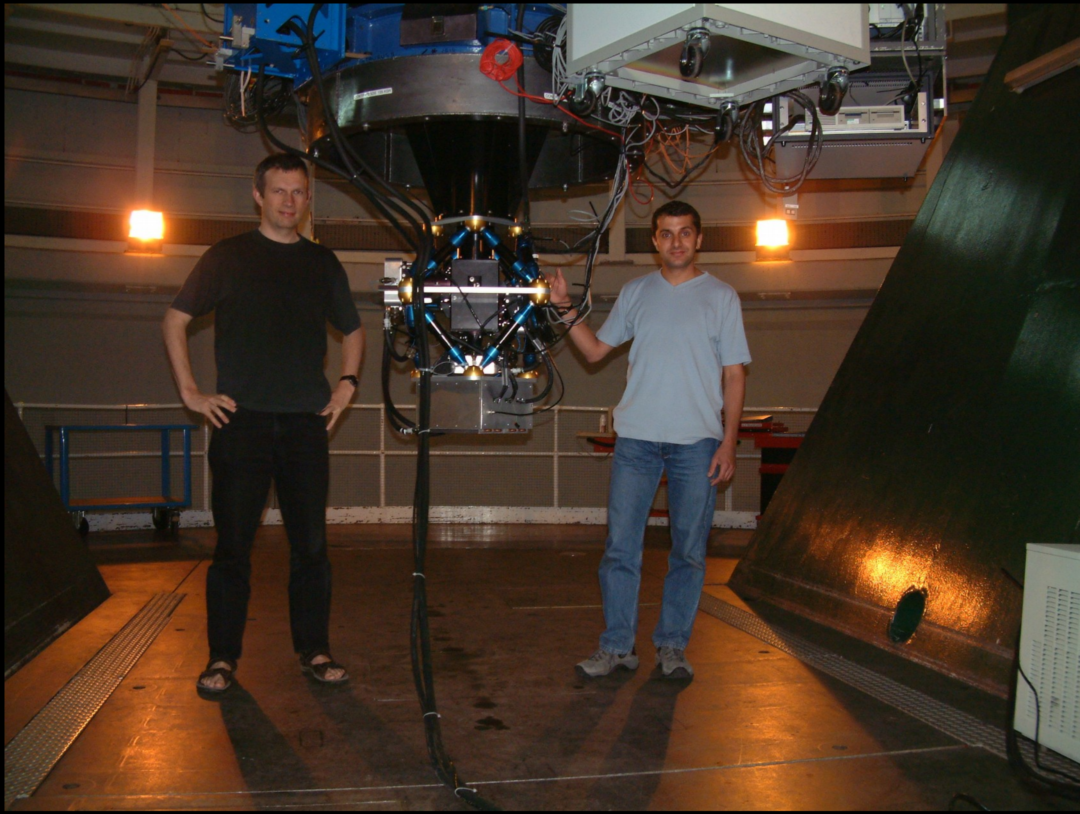
Osborn et al. 2015, MNRAS, 452, 1707

HiPERCAM: IMPACT ON ING

HiPERCAM should have a minimal additional impact on ING operations compared to ULTRACAM:

- HiPERCAM mounts at Cassegrain using similar custom-made collar.
- Same electronics rack as ULTRACAM.
- Similar water chiller to ULTRACAM.
- Same GPS cable and antenna location as ULTRACAM.
- Same private ethernet link to control room.
- Same instrument control/data-reduction PC location in control room.



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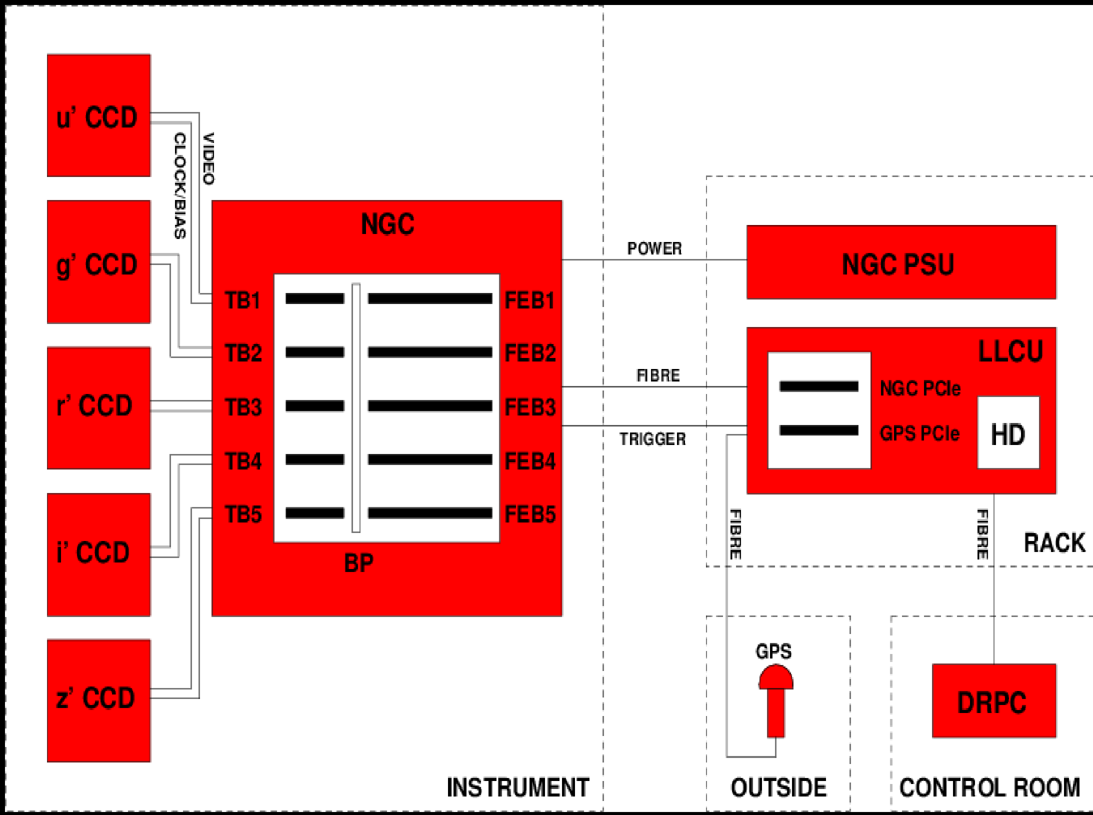
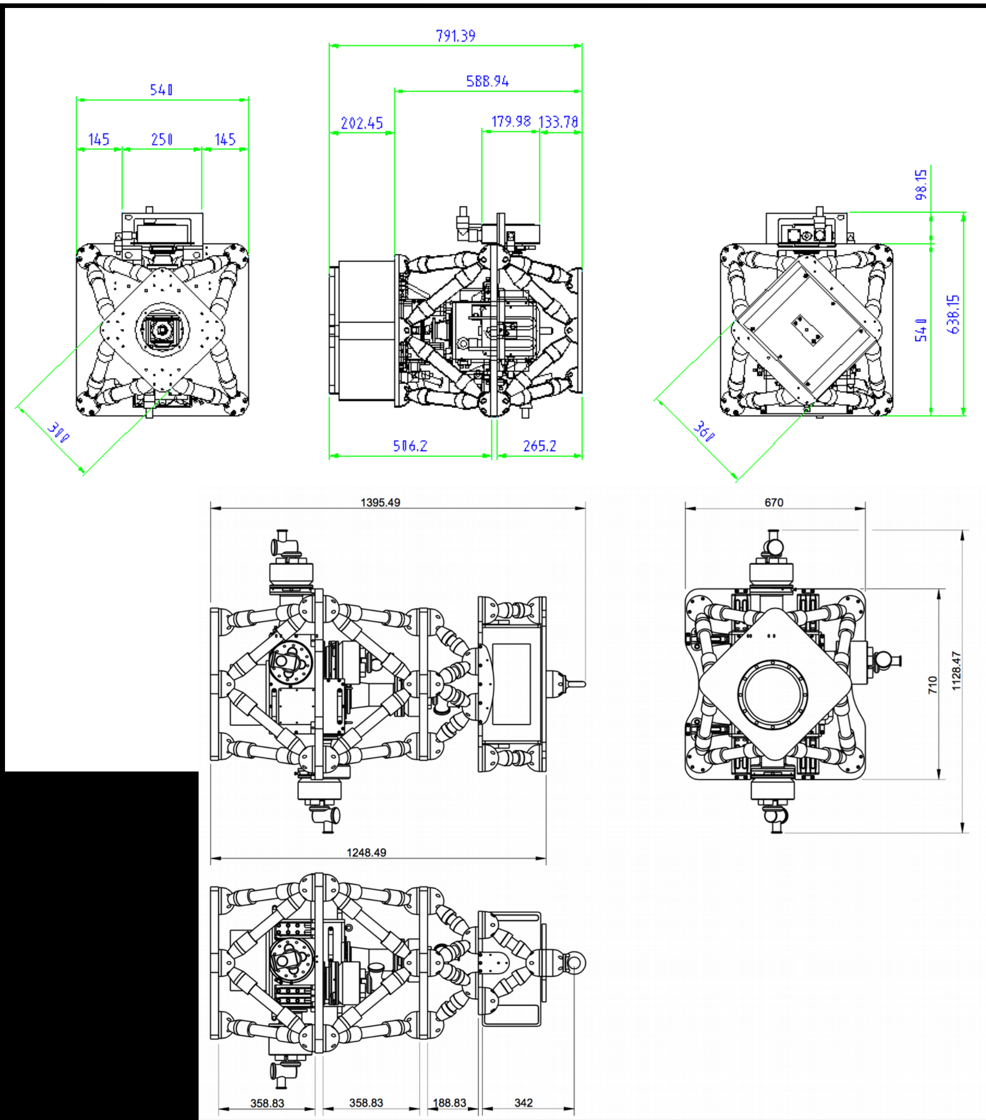


HiPERCAM: IMPACT ON ING

HiPERCAM should have a minimal additional impact on ING operations compared to ULTRACAM:

- Mass of HiPERCAM: 200 kg
- Mass of ULTRACAM: 85 kg
- Length of HiPERCAM: 1.4m
- Length of ULTRACAM: 0.8m

HiPERCAM has a handling trolley to enable easy transportation, use of crane, and attachment to A&G box.



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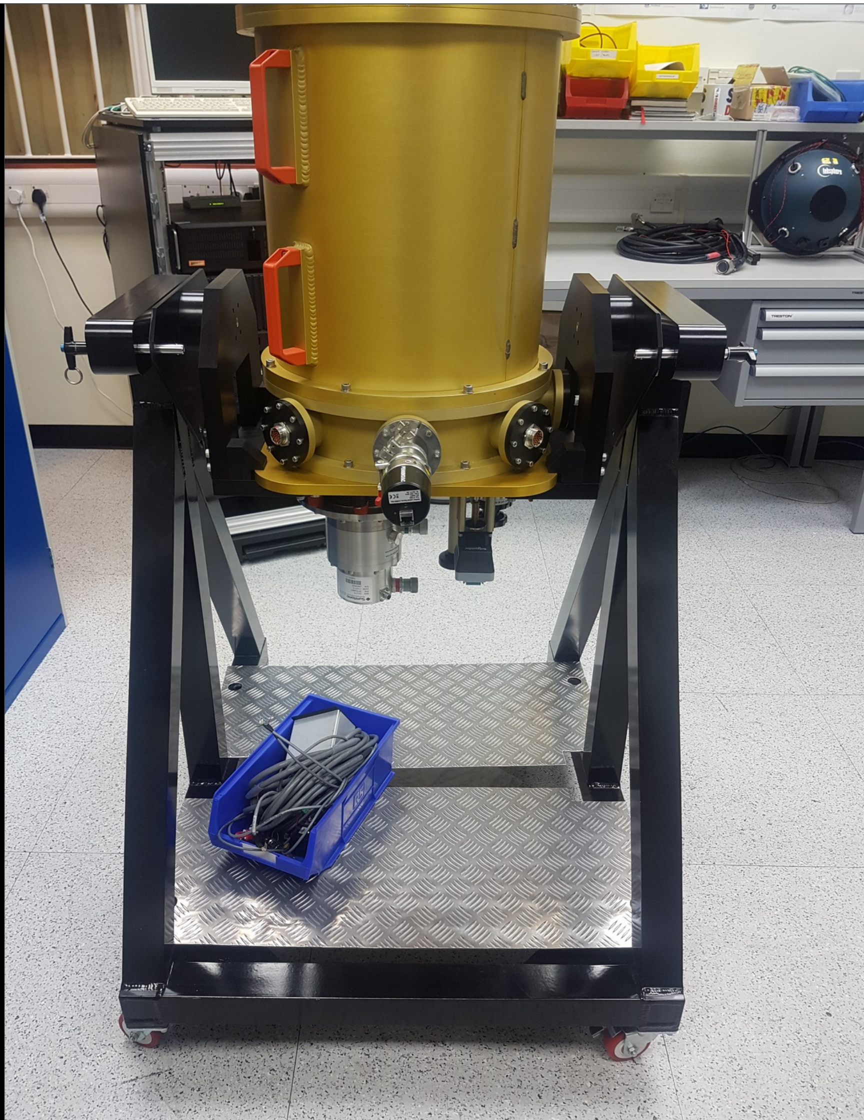
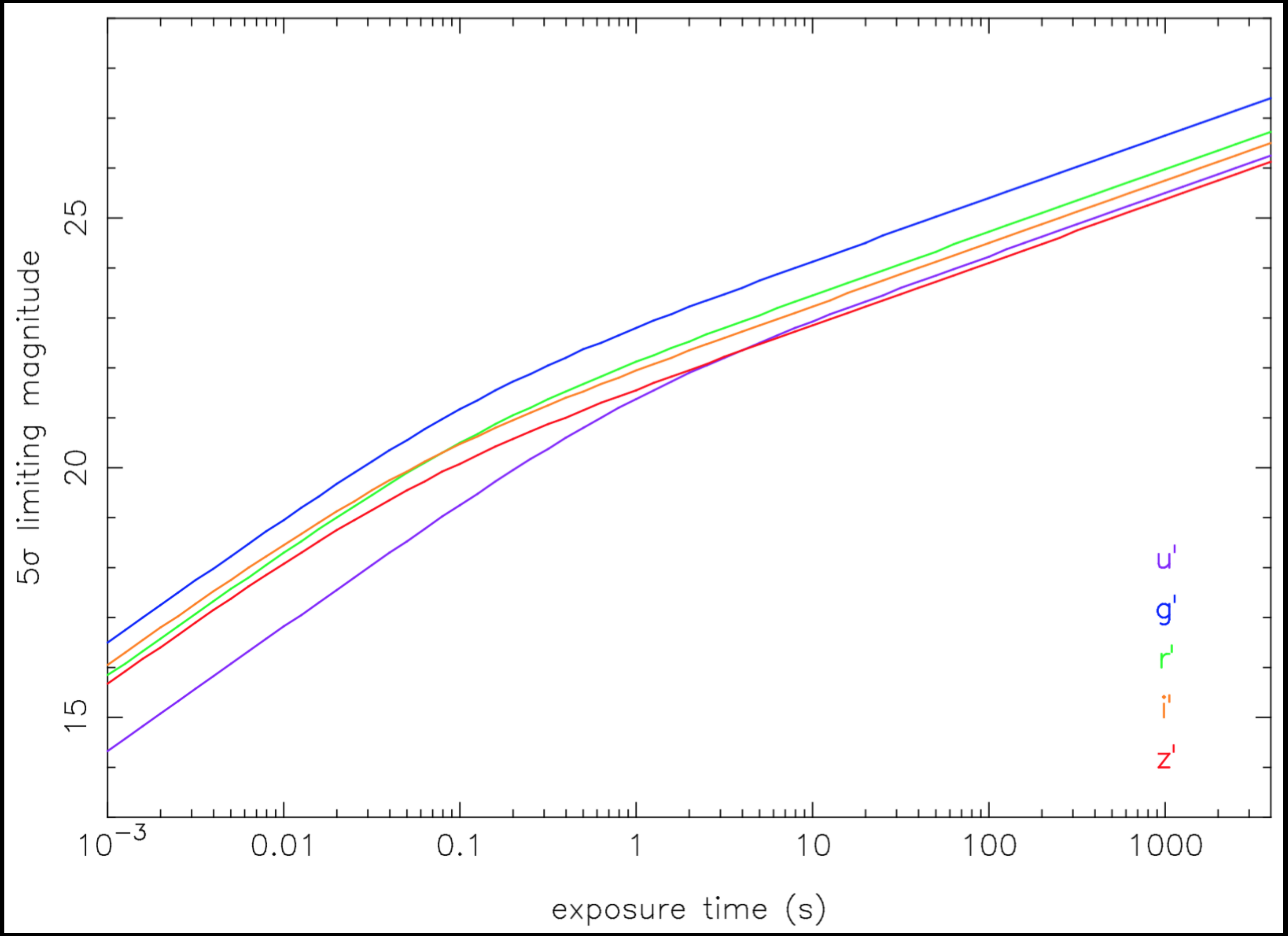


HiPERCAM ON THE GTC

- 2-week commissioning and first science runs have just been confirmed for Jan/Feb 2018 on 10.4m GTC.

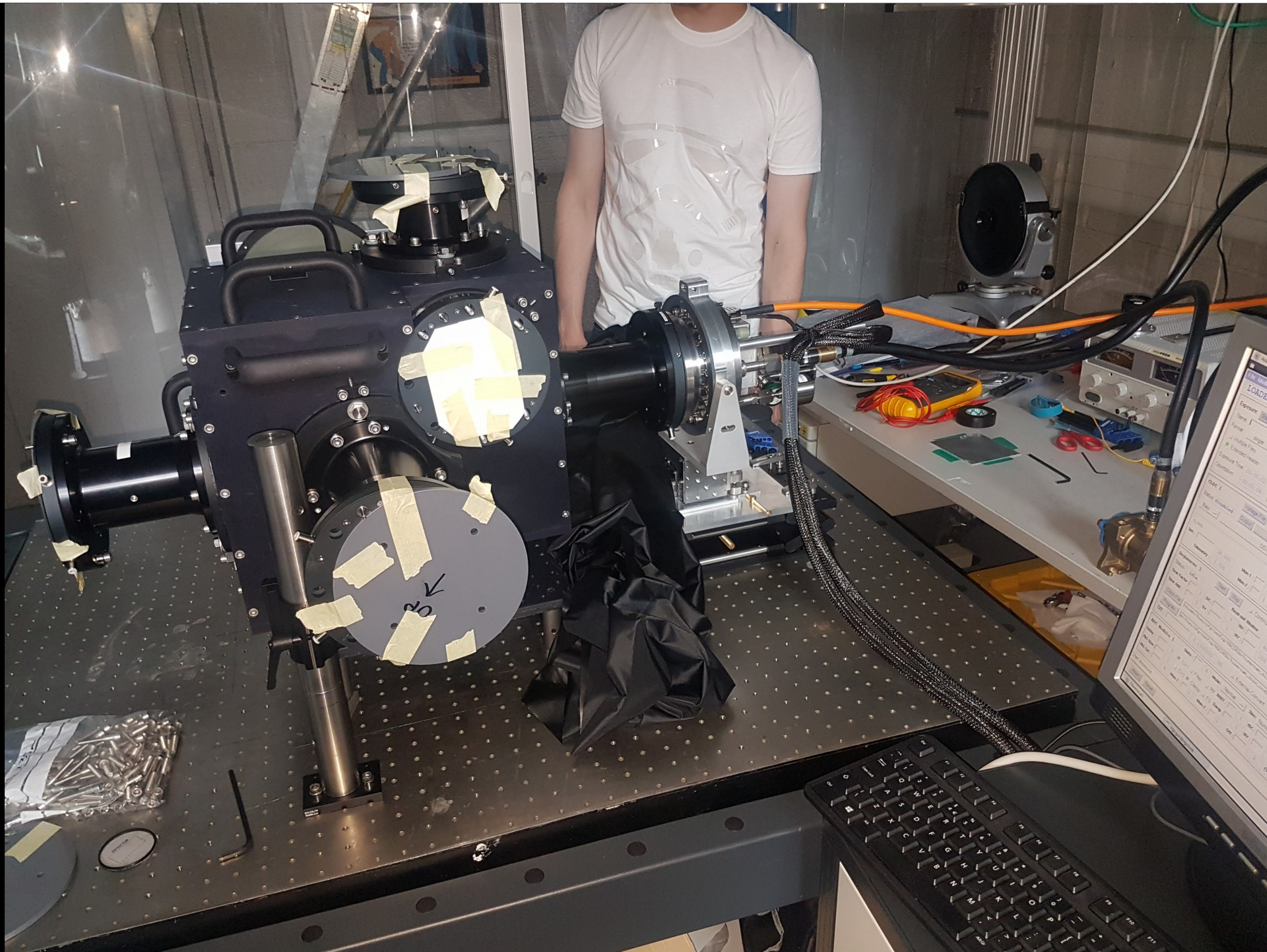
LIMITING MAGS ON GTC



HiPERCAM ON THE GTC

Tariq Shahbaz	D (10.0hrs)	The cause of brown dwarf variability; simultaneous observations with K2
Ignacio Trujillo Cabrera	D (2.65hrs)	A dark object in the Stripe82 survey
Javier Román García	D (7.95hrs)	Ultra-deep imaging of three large ultra-diffuse galaxies
Alberto Rebassa Mansergas	D (13hrs)	The structure of stars at the hydrogen burning limit
Vikram Dhillon	A (6.5hrs)	A search for optical bursts from FRBs with HiPERCAM
Vikram Dhillon	G (11hrs)	Better mass ratio estimates for thousands of accreting binaries.
Tariq Shahbaz	A (7hrs)	The optical pulse time delay in X-ray binary pulsars
Guo Chen	A (3.5hrs)	Does the young sub-Neptune-sized planet have an extended methane atmosphere?
Pablo Rodríguez Gil	G (20hrs)	Watch it live: The tidal disruption of exo-planetesimals at WD 1145+017
Vikram Dhillon	D (21.0hrs)	The maximum mass of neutron stars
Cristina Martinez Lombilla	D (2.86hrs)	Thick disk multi-band properties from ultra-deep imaging of IC610
Tariq Shahbaz	D (6.0hrs)	Probing the inner accretion flow in the quiescent black hole X-ray transients
Pablo Rodríguez Gil	G (14hrs)	Triangulating the dipper: fixed prominence structures in a white dwarf/M-dwarf binary

HiPERCAM: CURRENT STATUS



HiPERCAM: CURRENT STATUS

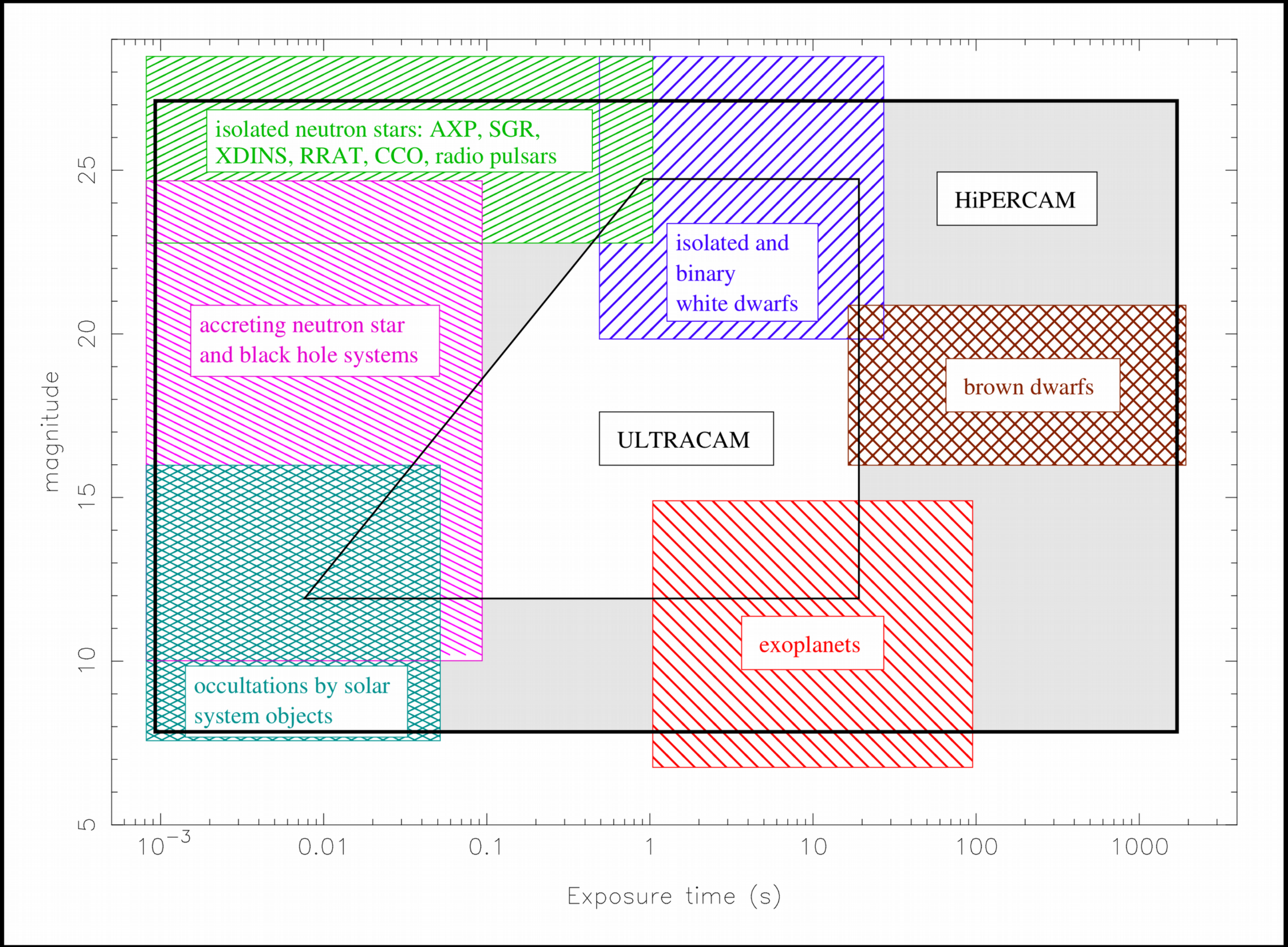
HiPERCAM: FUTURE PLANS

- HiPERCAM commissioning and first science runs on WHT in October 2017.
- HiPERCAM commissioning and first science runs on GTC in Jan/Feb 2018.
- HiPERCAM will then move between these two telescopes each semester, dictated by our science requirements and the availability of the focii.
- If this proves unsuccessful, e.g. due to the pressure of WEAVE and/or new GTC instruments, our backup option is to replace ULTRACAM with HiPERCAM on the NTT, or move it to the new 3.6m Devasthal Optical Telescope in India.

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	3.0e- @200 kHz
Dark current	360 e-/pix/hr	8 e-/pix/hr
Longest exposure time	20 s	1800 s
Highest frame rate	300 Hz	1600 Hz
Field of view WHT	5.1' (at 0.3"/pixel)	10.2' (at 0.3"/pixel)
Field of view VLT/GTC	2.6' (at 0.15"/pixel)	3.9' (at 0.113"/pixel)
Probability of R=11 comparison	52%	95%
Scintillation correction	No	Yes
Deep depletion	No	Yes
QE at 700/800/900/1000 nm (%)	83% / 61% / 29% / 5%	91% / 87% / 58% / 13%
Fringe suppression	No	Yes
Fringe amplitude at 900 nm	>10%	<1%
Dummy CCD outputs?	No	Yes

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?

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Atmospheric Scintillation in Astronomical Photometry

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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

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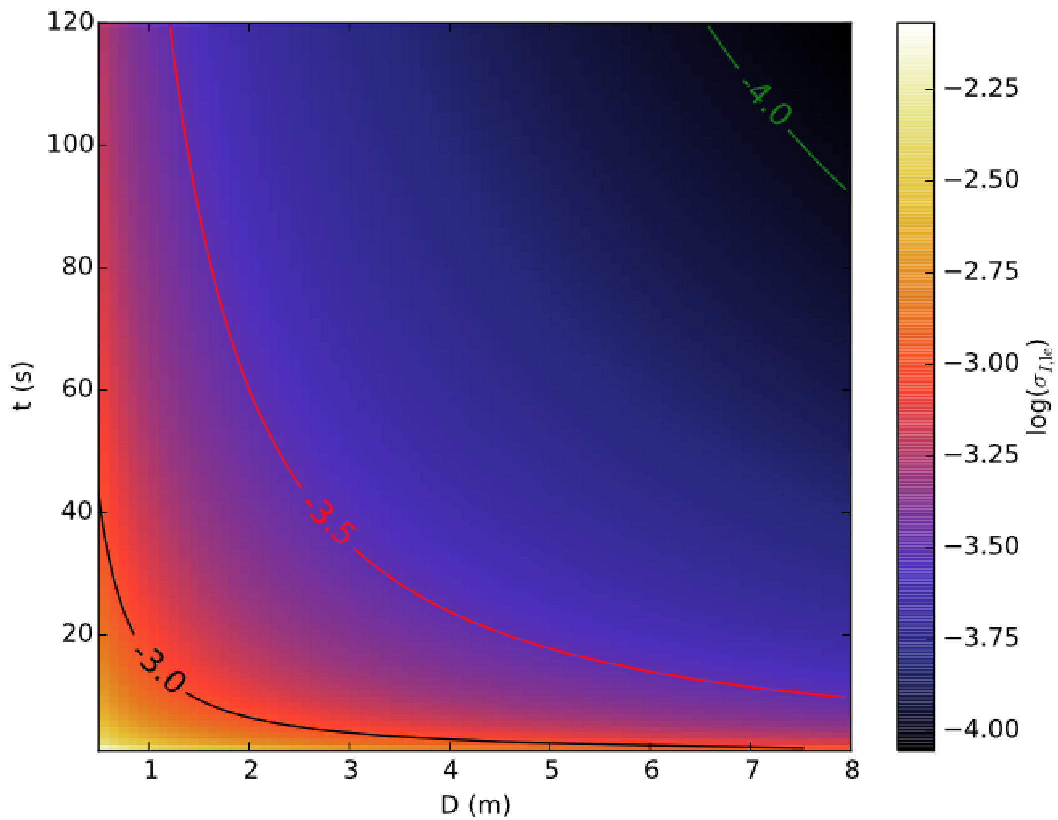

Figure 9. Theoretical long exposure scintillation noise as a function of exposure time and telescope diameter. The scintillation noise was calculated for median atmospheric conditions on La Palma and varies between 1% for small telescopes and short exposure times, and 0.01% for larger telescopes and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

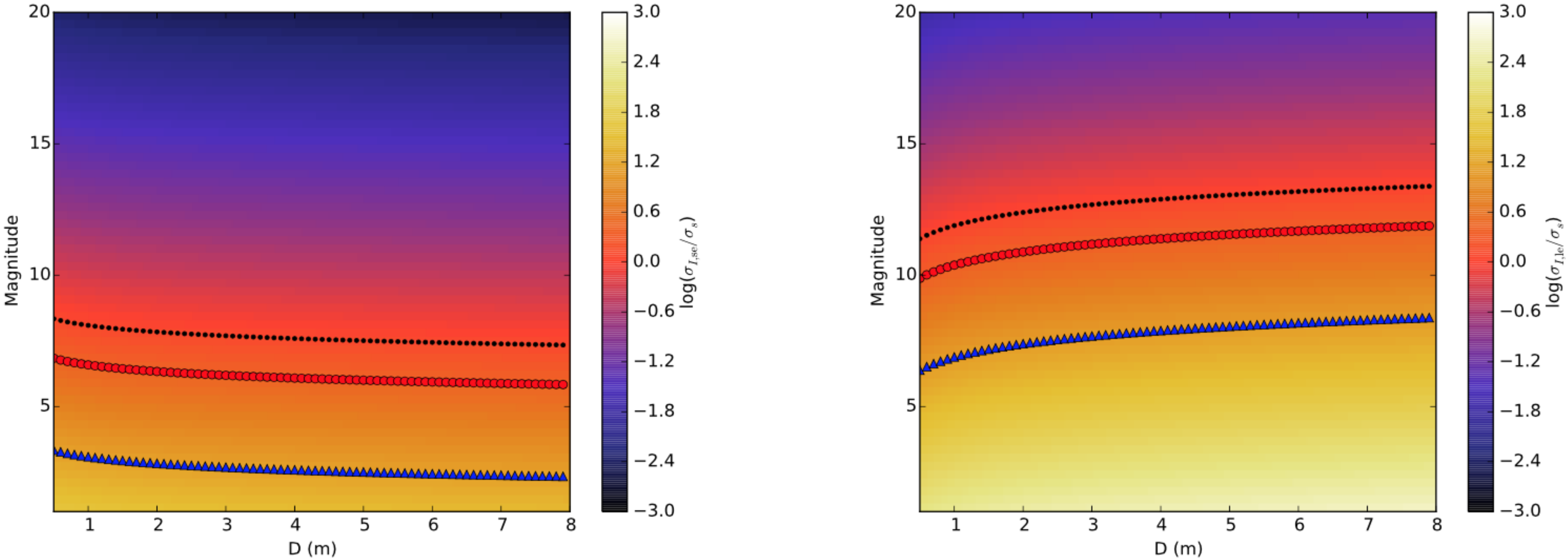

Figure 11. Theoretical parameter space plots for the ratio of the scintillation to shot noise in the short exposure regime (left) and the long exposure regime (right), for varying telescope diameter and target stellar magnitude (V-band). The short exposure time is set to 2 ms. The long exposure time 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.