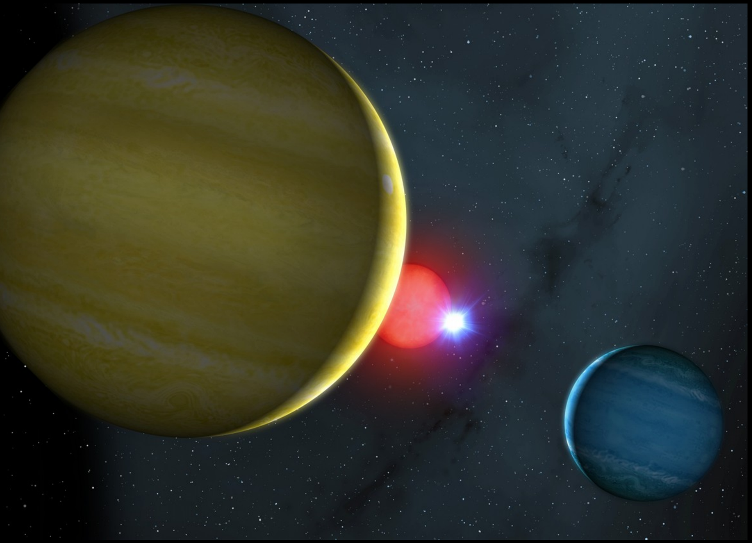

HIGH TIME-RESOLUTION ASTROPHYSICS

OPTICAL INSTRUMENTATION

Vik Dhillon (Sheffield/IAC)

OVERVIEW

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- 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

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- An introduction to EMCCDs
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- Demonstration of photometric data reduction using the ULTRACAM pipeline

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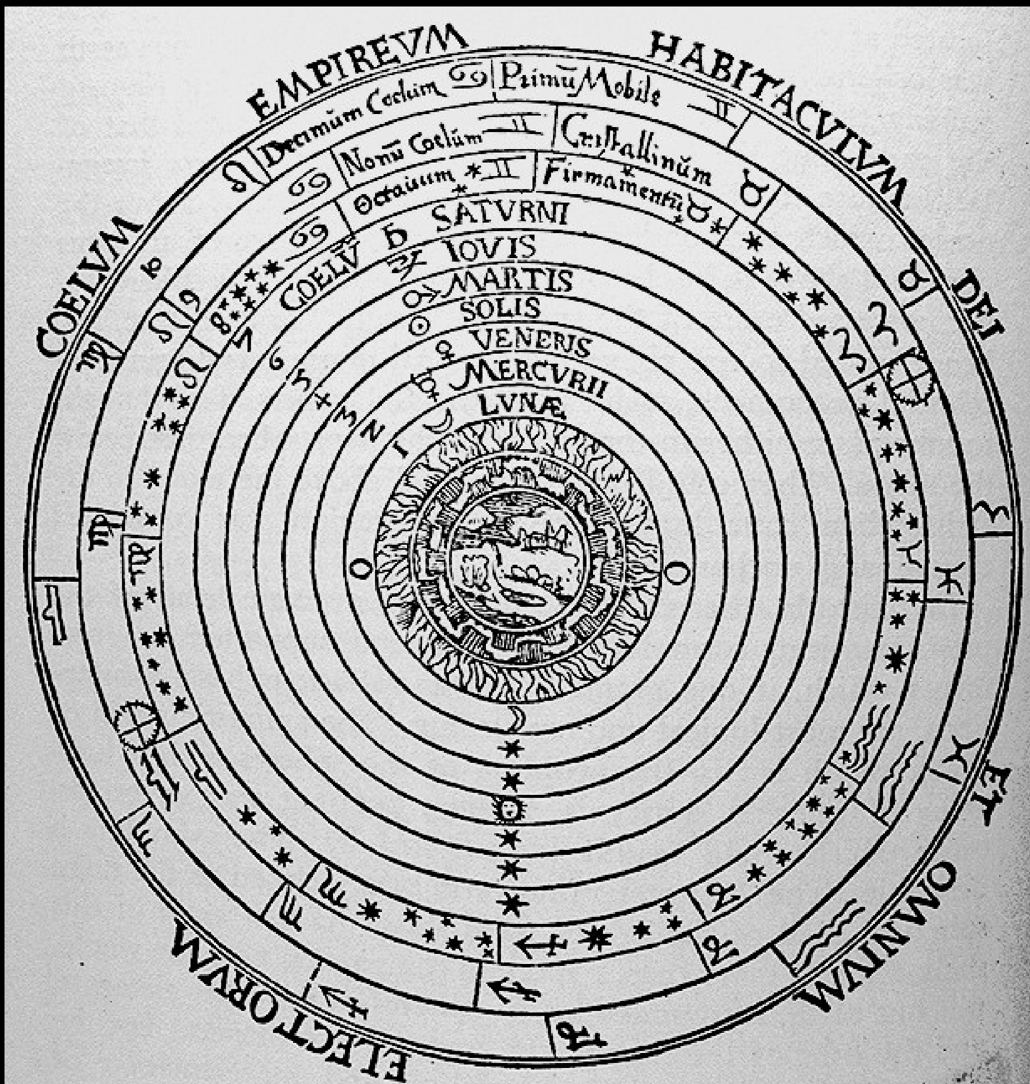
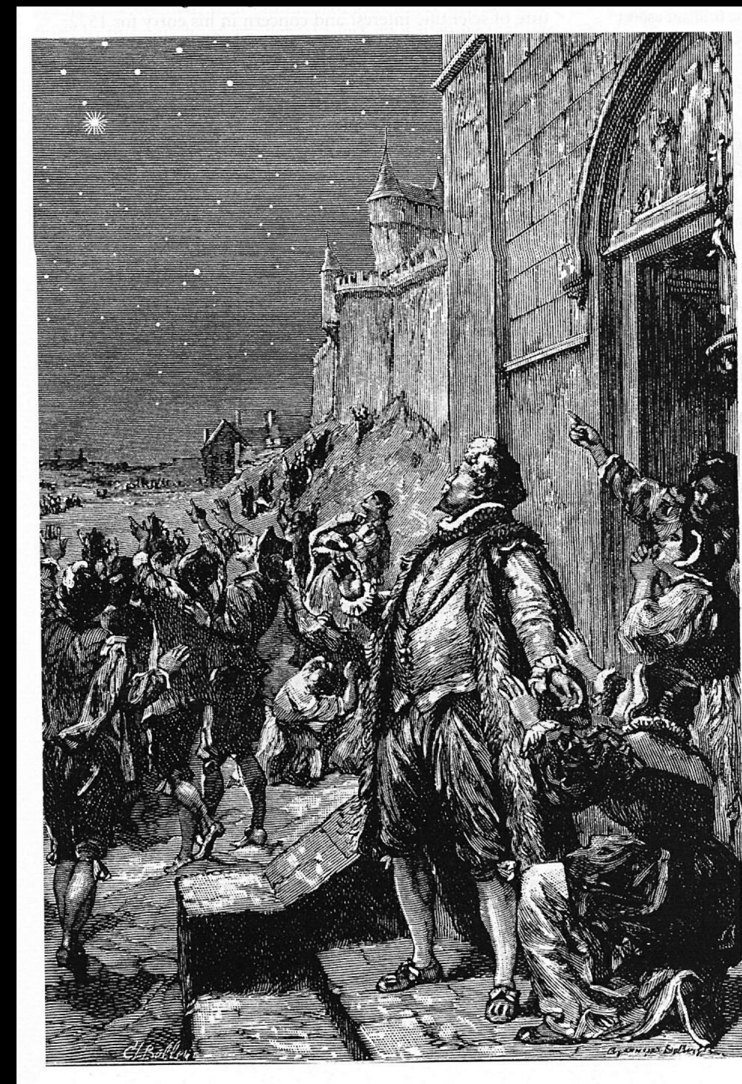
THE EVER-CHANGING SKY

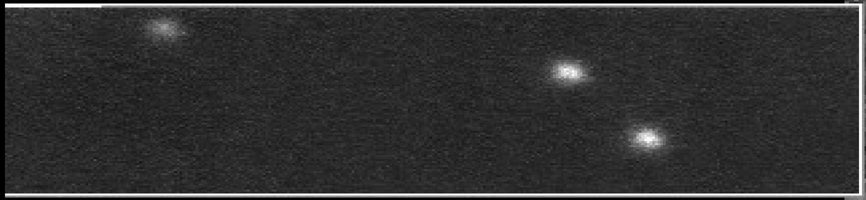
- The Ancient Greeks believed celestial objects were perfect and unchanging.

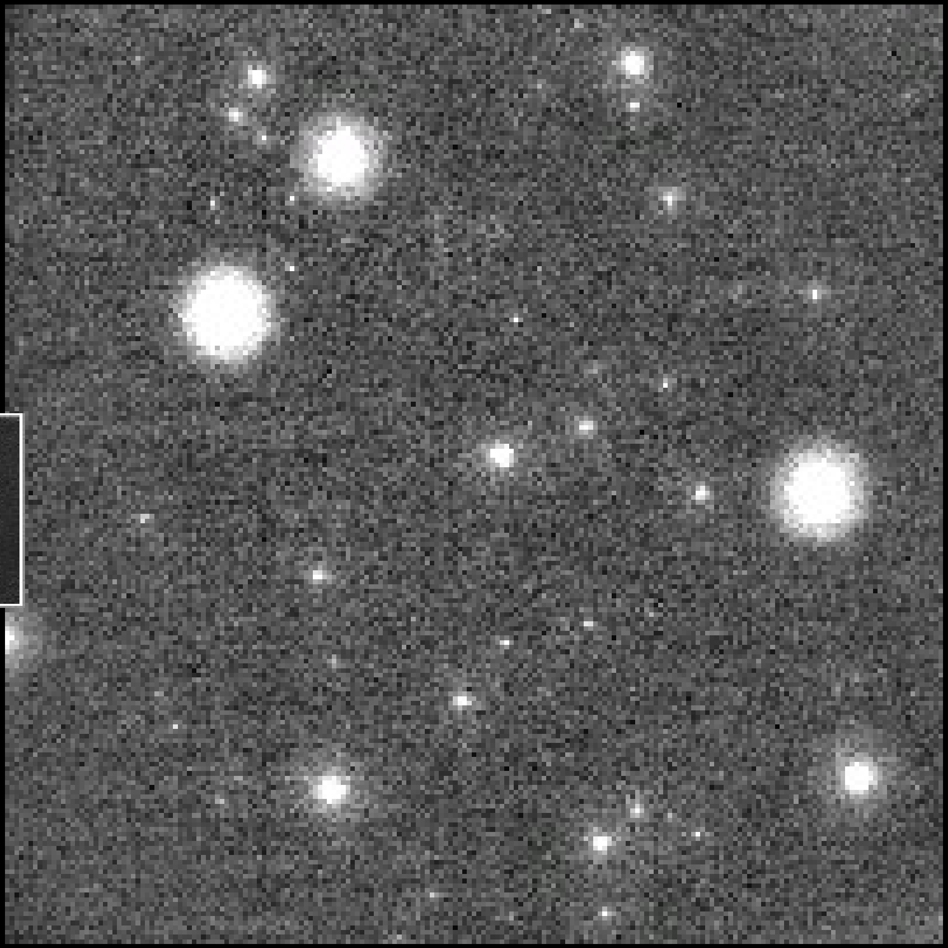




THE EVER-CHANGING SKY

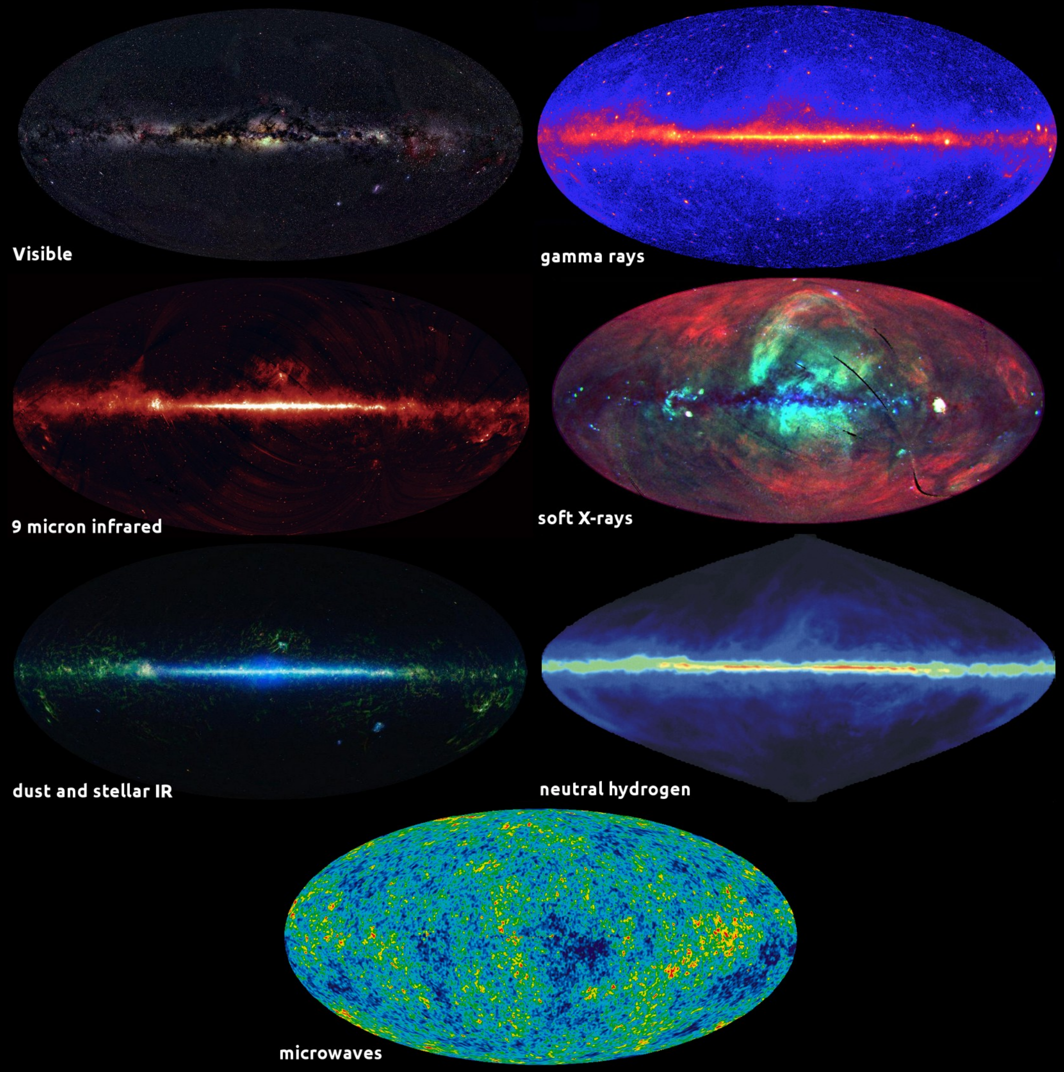
- We now know that all objects in the Universe vary in brightness on timescales ranging from milliseconds to billions of years.





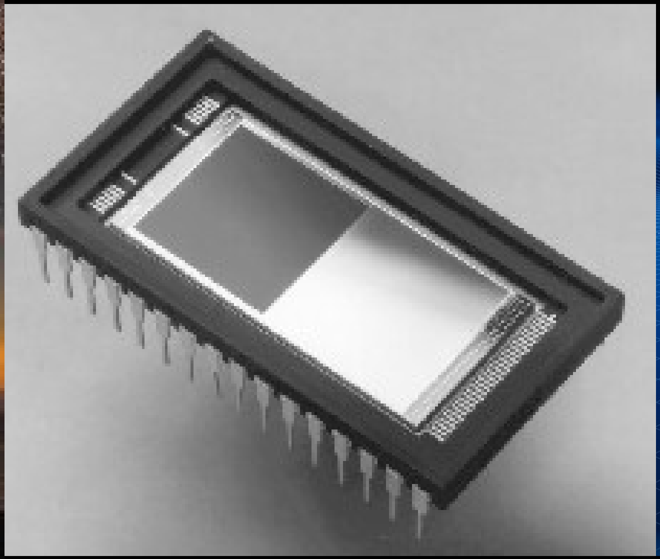
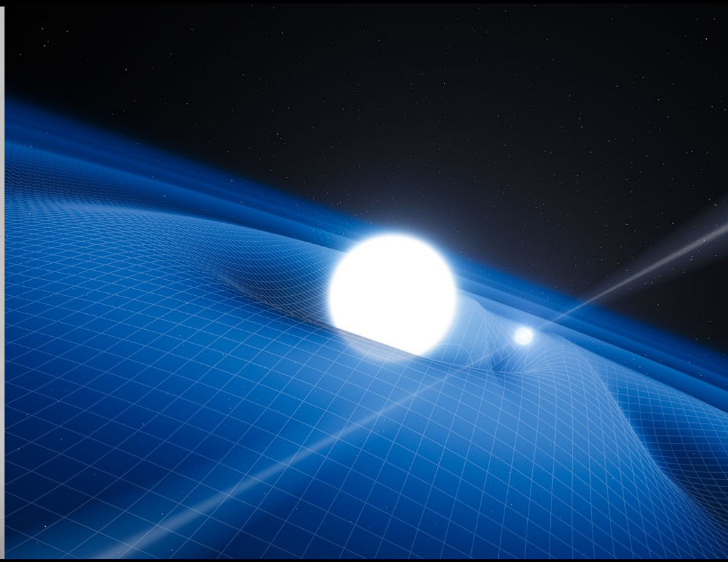
THE EVER-CHANGING SKY

- Although astronomy has made great strides in recent decades, the study of the most rapidly varying phenomena has been largely ignored (at least in the optical!)



THE EVER-CHANGING SKY

- The advent of big telescopes and new detector technologies has now made it possible to study astrophysics on the fastest timescales (milliseconds to seconds).
- Why bother? Because, 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 = $2\text{x}10^{30}$ kg, R = $7\text{x}10^{5}$ km **t_{dyn} ~ 2000 s**
- For white dwarfs, $M \sim 1\ M_{Sun}$, $R \sim 0.01\ R_{Sun}$ **t_{dyn} ~ 2 s**
- For neutron stars and black holes, $M \sim 3\ M_{Sun}$, $R \sim 10^{-5}\ R_{Sun}$ **t_{dyn} ~ 0.1 ms**

WHY BOTHER?

- 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 to the limits of their predictive powers.
- 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 other small celestial bodies, such as Solar System objects and extrasolar planets, also benefits from high-speed observations, as shall be revealed later.

DEFINITION OF "HTRA"

- Our working definition of high time-resolution astrophysics (HTRA) *in the optical* is a technological one.
- It is based on the typical CCD frame rates achievable with common-user instrumentation on the world's largest telescopes:
  - Non-HTRA: Frame rates of greater than one per minute.
  - HTRA: Frame rates of less than one per minute.
- **Hence HTRA nearly always requires specialist instrumentation.**

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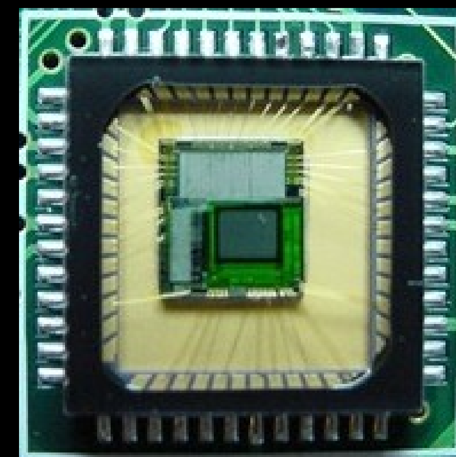
THE DETECTION OF LIGHT

- Nowadays, you won’t find photographic plates, APDs or photomultiplier tubes at the largest telescopes in the world. You won’t even find CMOS detectors, such as used in your mobile phones or most digital cameras.



SINGLE PIXEL vs MULTI-PIXEL DETECTORS

- Strictly speaking, it is not necessary to know the spatial distribution of the photons in order to make a photometric measurement - all that matters is the total number of photons received from the source.

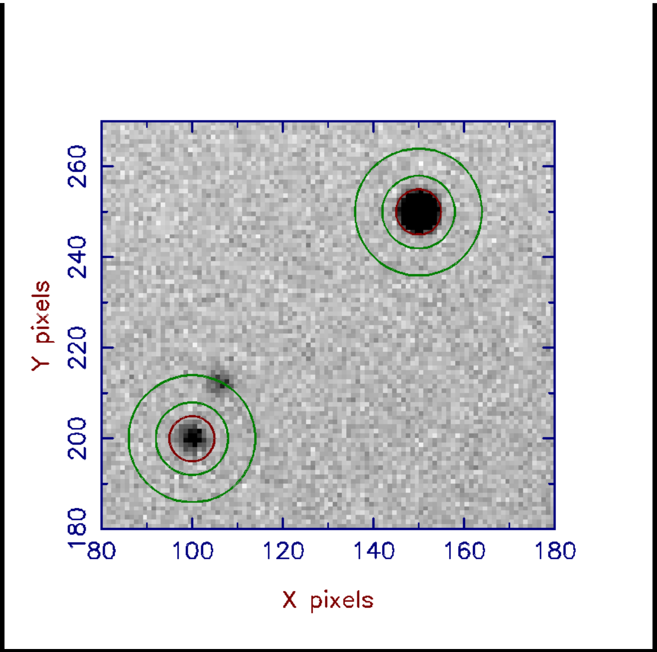
- So, it is possible to perform photometry with a single-pixel detector, such as a photomultiplier tube or an avalanche photodiode (APD).

SINGLE PIXEL vs MULTI-PIXEL DETECTORS

<u>SINGLE-PIXEL DETECTORS ARE FAST, BUT:</u>

- The pixel must be larger than the seeing disc and typical guiding errors of the source. So extra sky is collected, degrading the SNR.
- Photometry of extended sources and crowded fields is impossible.
- Only one star at a time can be recorded, so they cannot be used in non-photometric conditions.
- Simultaneous measurement of the sky brightness is difficult.

SINGLE PIXEL vs MULTI-PIXEL DETECTORS

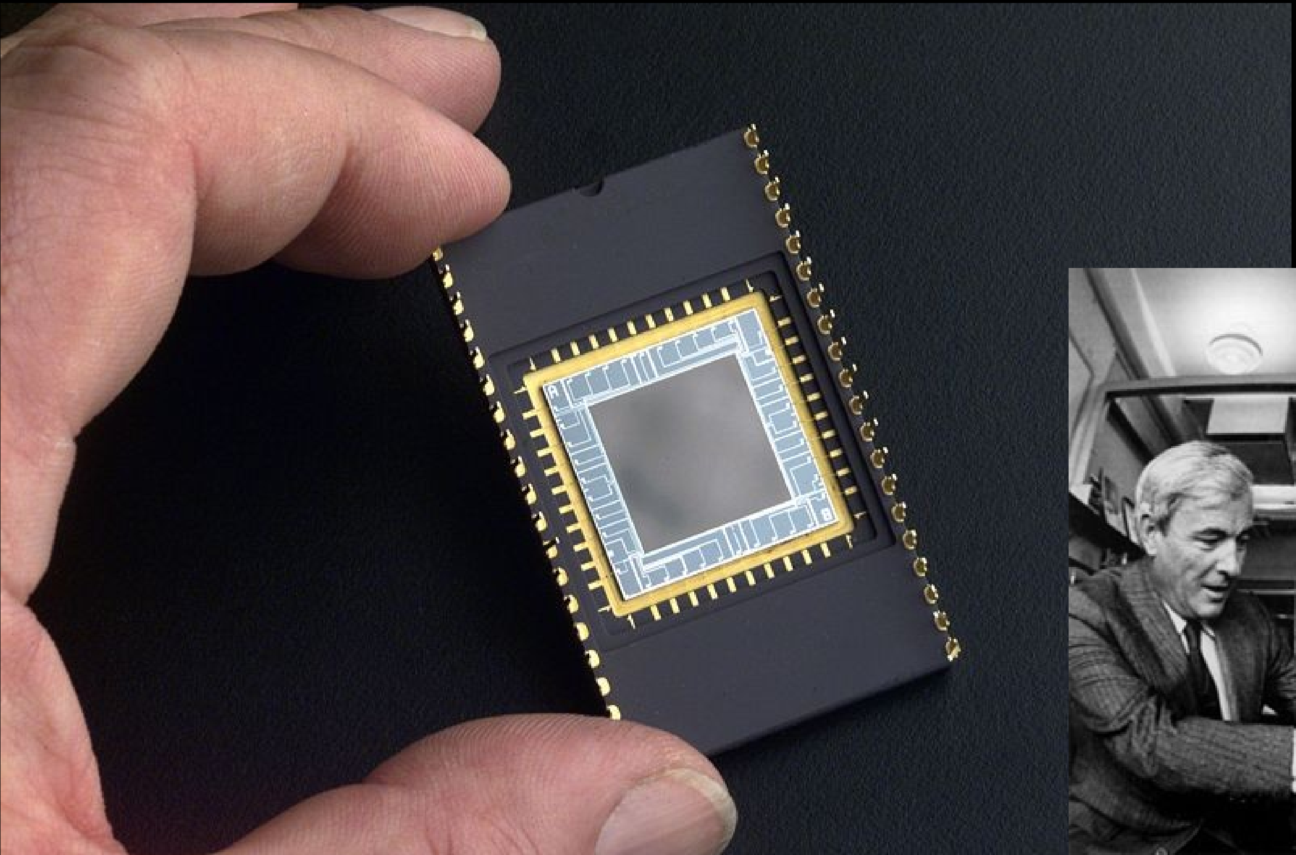


<u>MULTI-PIXEL DETECTORS ARE PREFERRED BECAUSE:</u>

- The same instrument can provide imaging *and* photometry.
- Software apertures that are adjustable during data reduction can be used, maximising SNR.
- Photometry of crowded fields and extended sources is possible.
- Simultaneous measurement of comparison stars is possible, allowing transparency variations to be corrected.
- Simultaneous measurement of the nearby sky is straightforward.

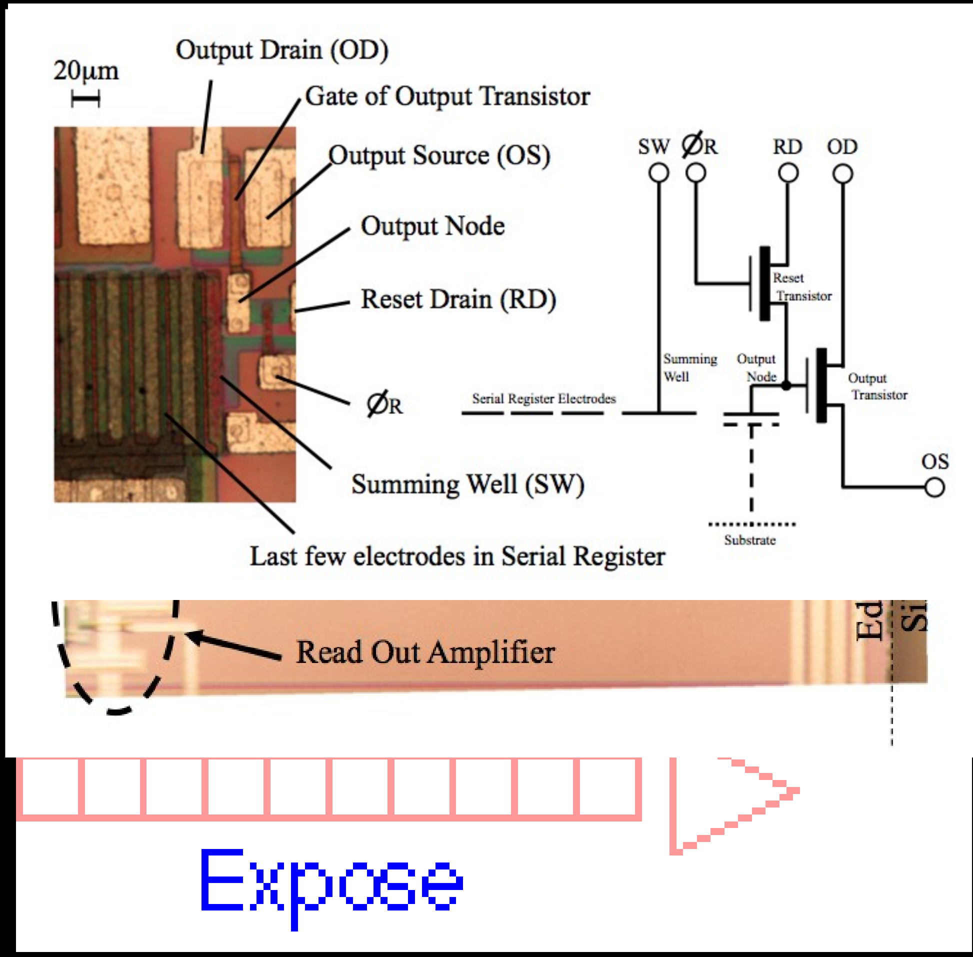
THE DETECTION OF LIGHT

- The detector of choice is the Charge-Coupled Device (CCD), for which Willard Boyle and George Smith were awarded a Nobel Prize in 2009.
- The problem is, although almost perfect detectors in almost every other respect, CCDs are slow to read out – up to minutes between frames.



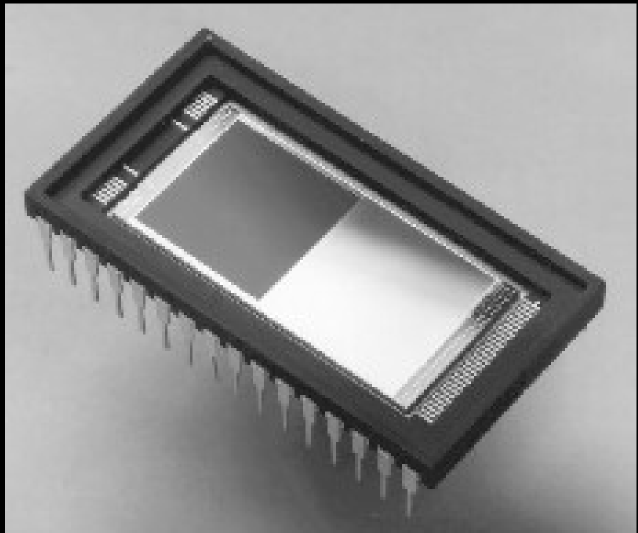
THE DETECTION OF LIGHT

- Photons hit the silicon and create electrons (known as *photoelectrons*)
- On completion of the exposure, the electrons are "clocked out", counted, and then digitised.
- Only when all of the electrons have been "read out" can the next exposure begin.



FRAME-TRANSFER CCDs

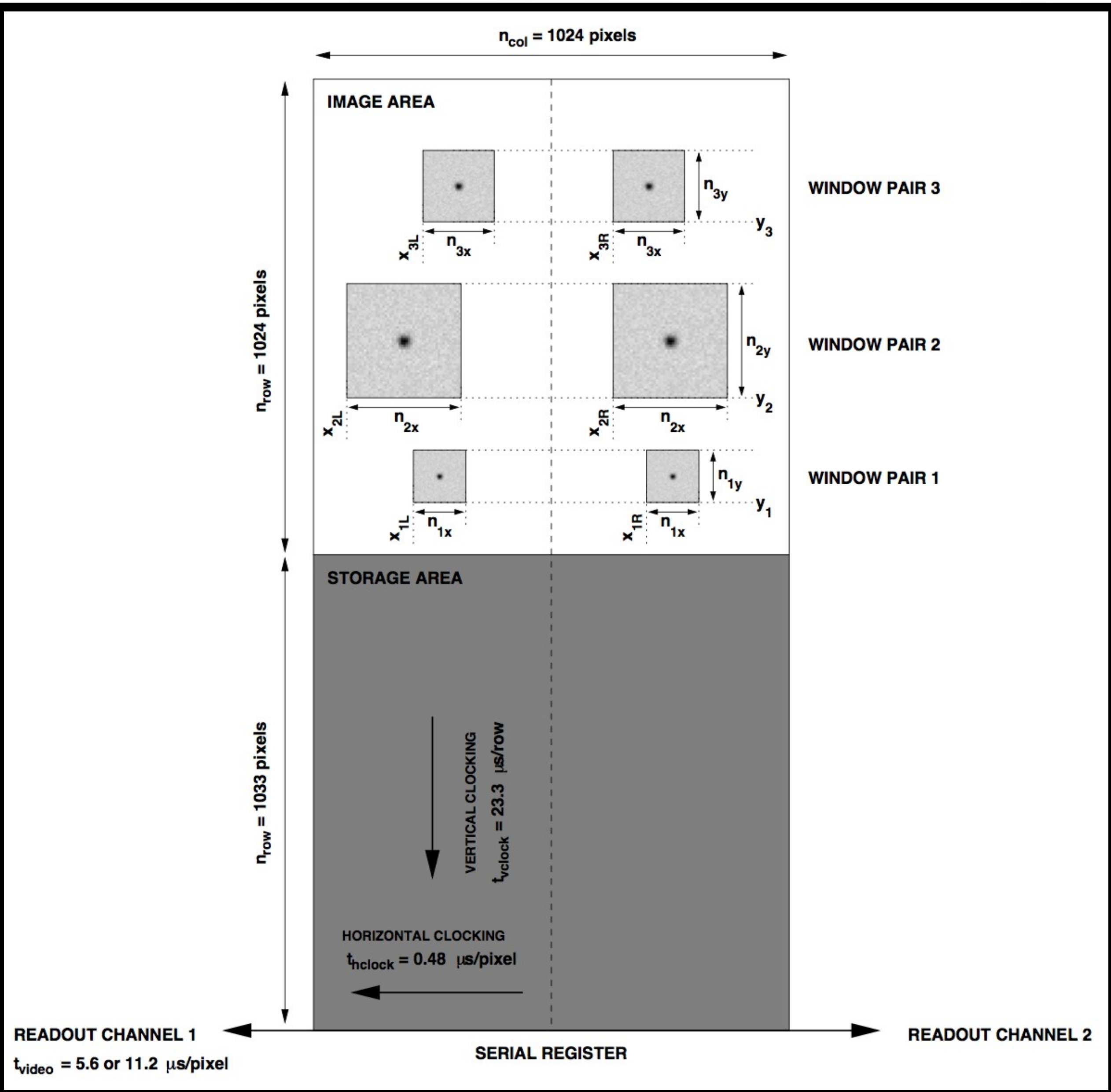
- Speeding up the clocking and readout of CCDs results in unacceptably poor charge transfer and high detector noise.
- So how can we read out CCDs faster? One solution is to use a frame-transfer architecture.
- Frame-transfer CCD demo…….



BINNING AND WINDOWING

As well as using a frame-transfer architecture, CCDs can be further speeded up as follows:

- Use of multiple outputs.
- On-chip binning.
- Windowing.
- Use of high-speed data acquisition systems.
- Reducing the clocking time.
- Reducing the time taken to measure the charge in each pixel.



ULTRACAM Demo.

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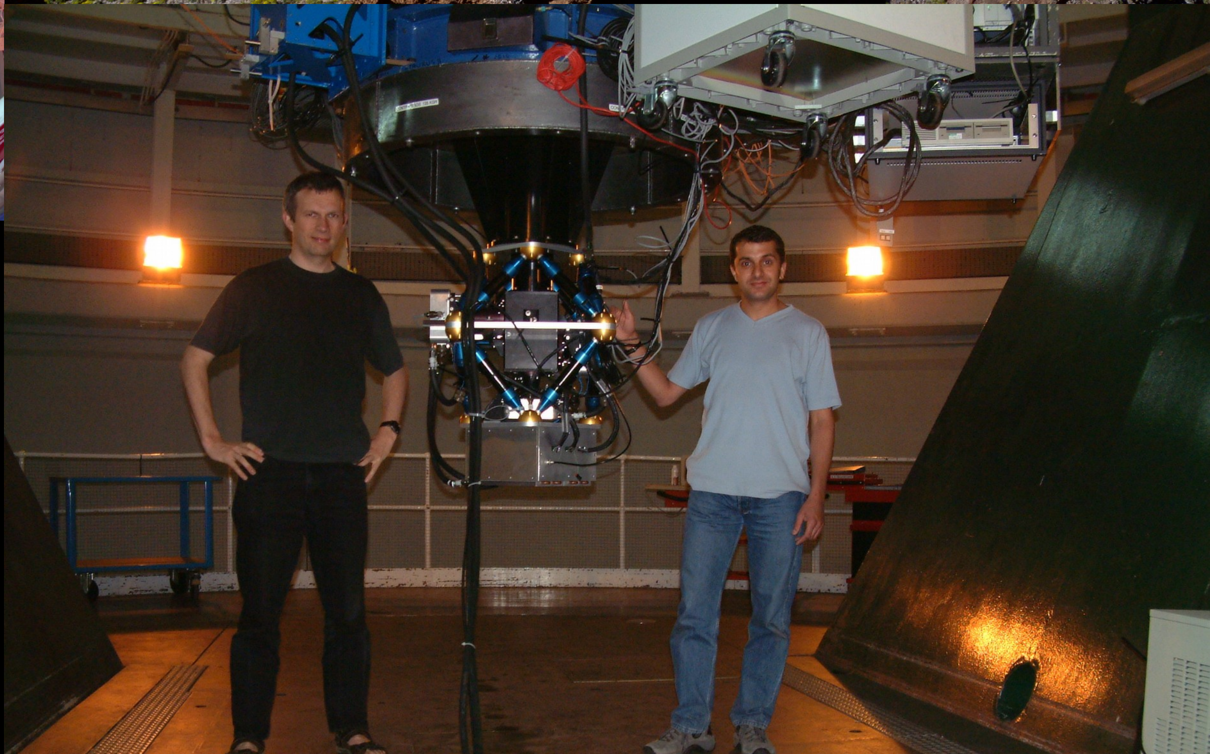
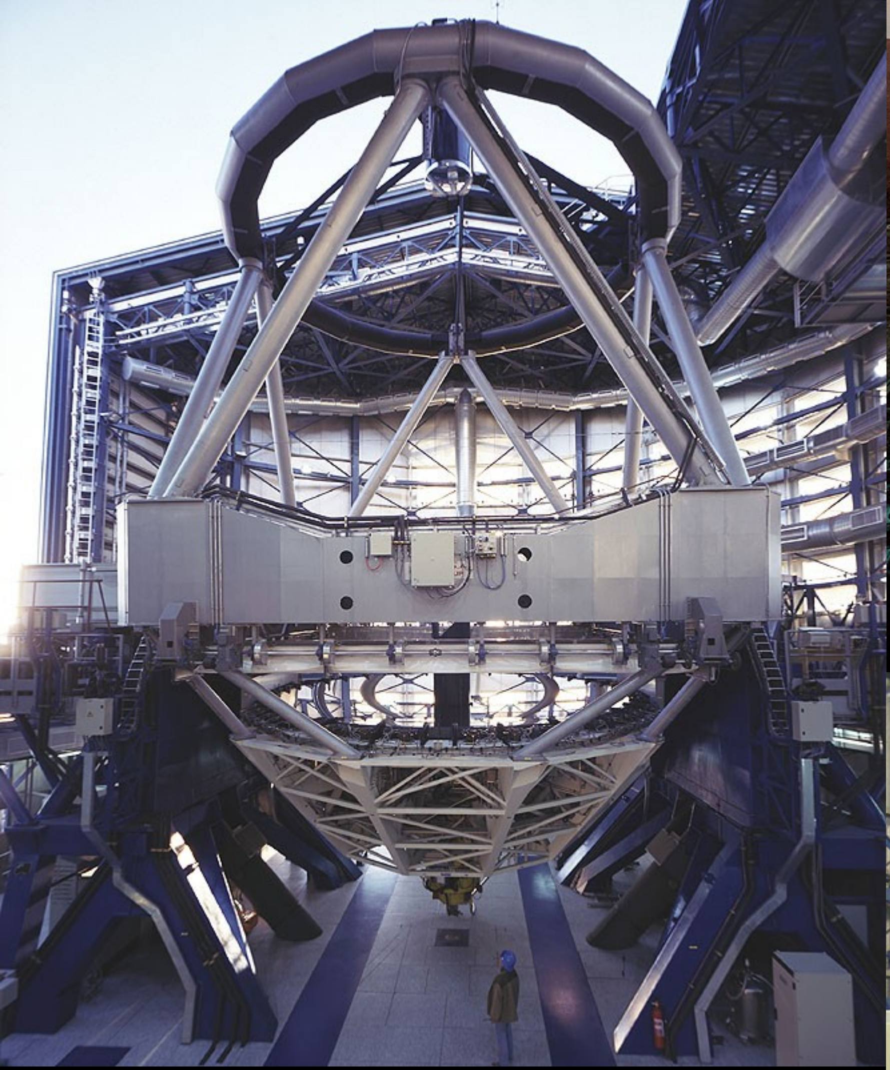
ULTRACAM

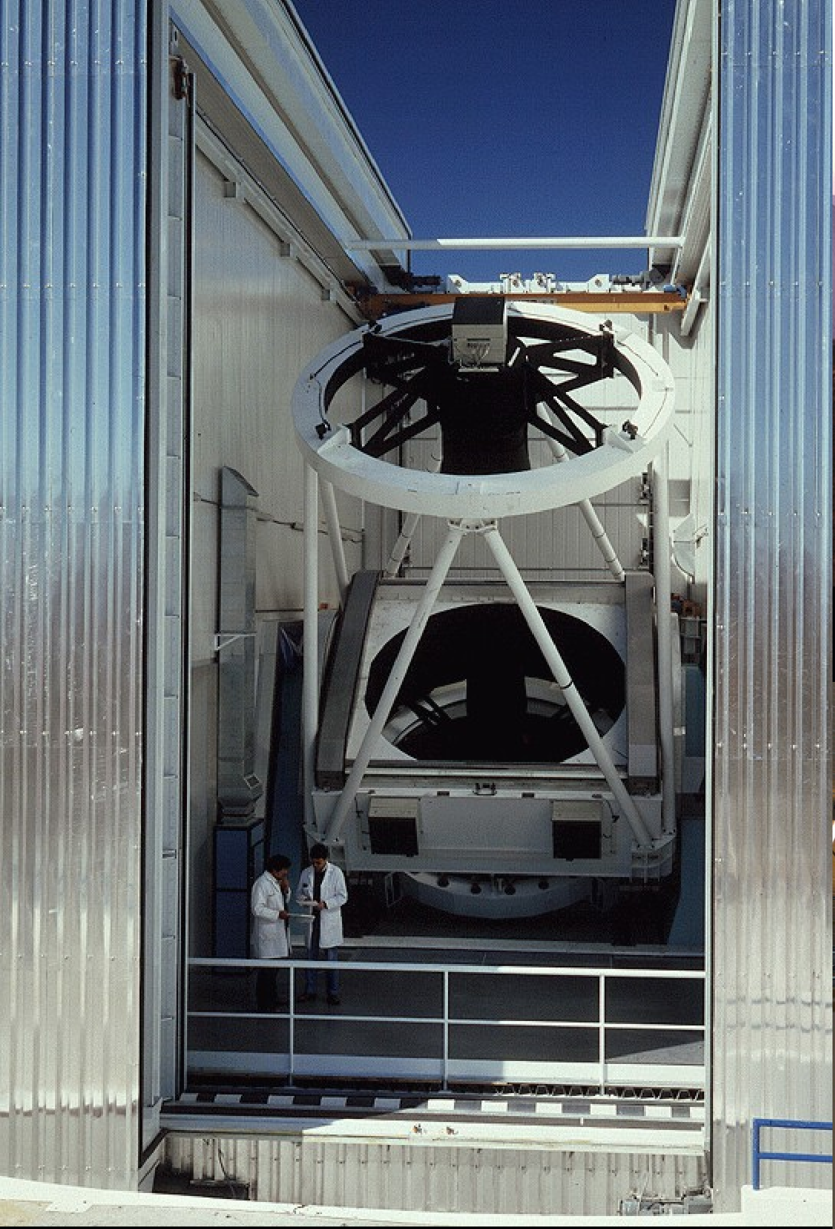
- ULTRACAM is a high-speed (0.05-300 Hz), triple-beam optical CCD camera with a 5’x5’ field of view.
- It was built by a consortium from the Universities of Sheffield, Warwick and the UKATC, Edinburgh.
- ULTRACAM is a private instrument which mounts on the 4.2m WHT, 8.2m VLT and 3.5m NTT.

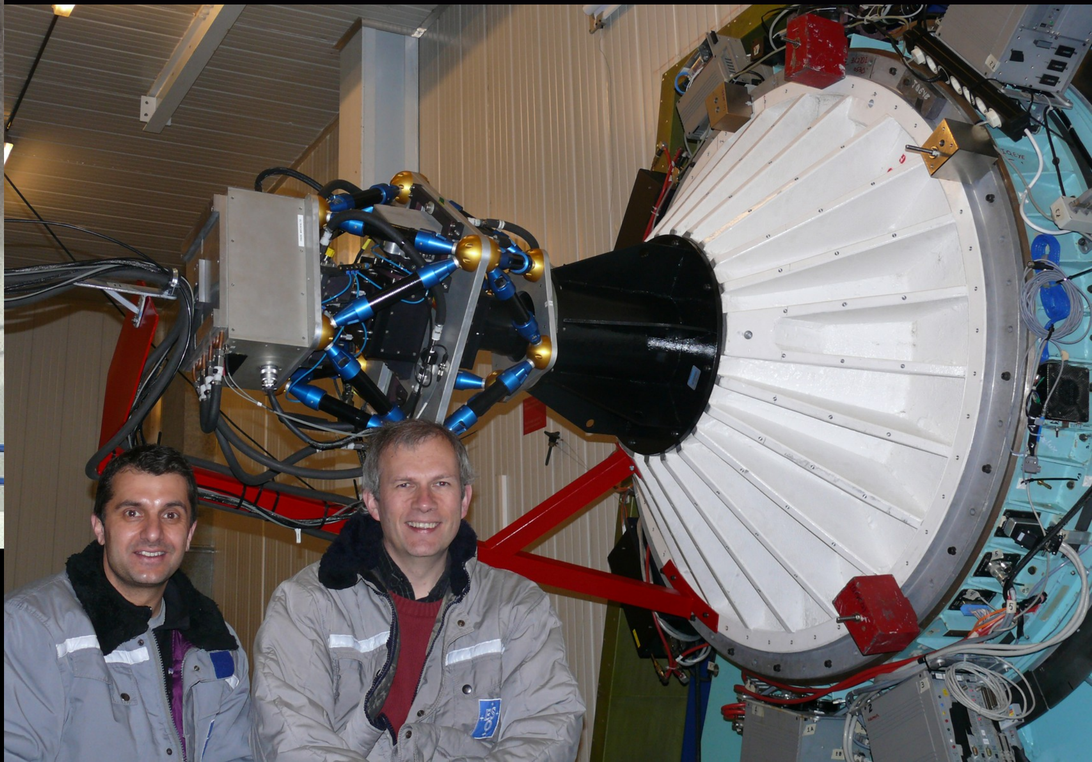


4.2m WHT
La Palma



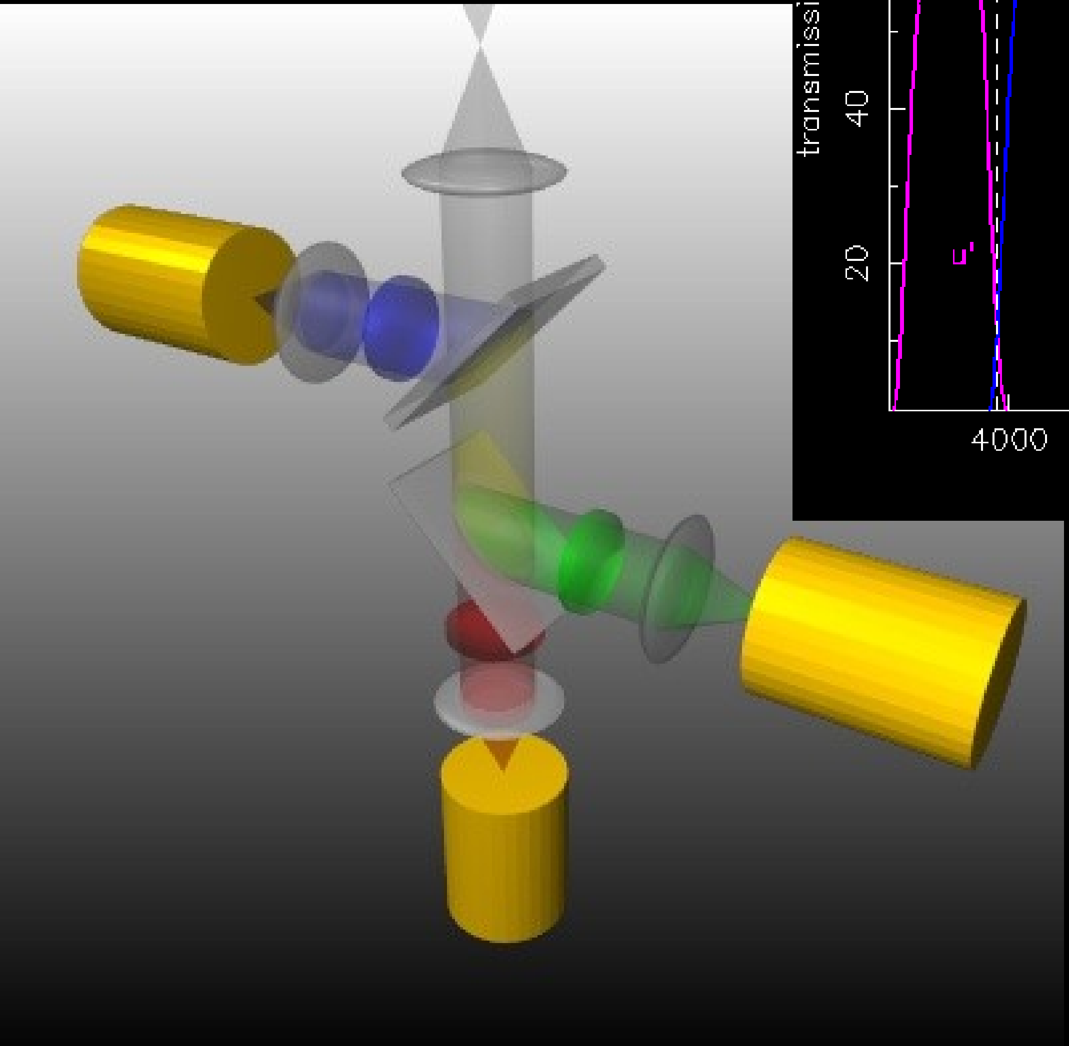
8.2m VLT
Chile

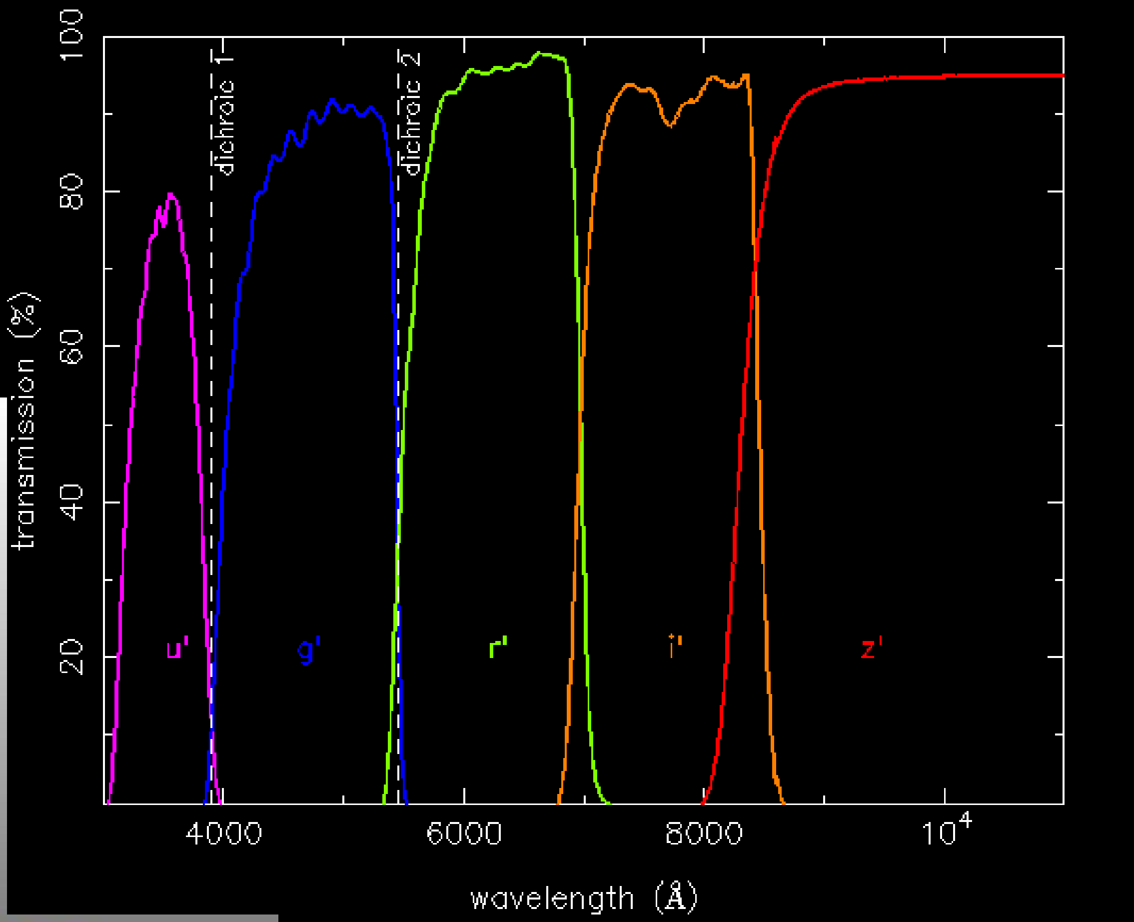




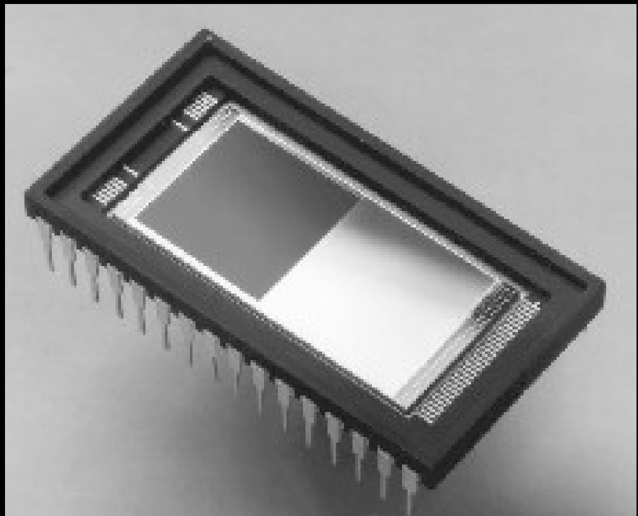
3.5m NTT

Chile

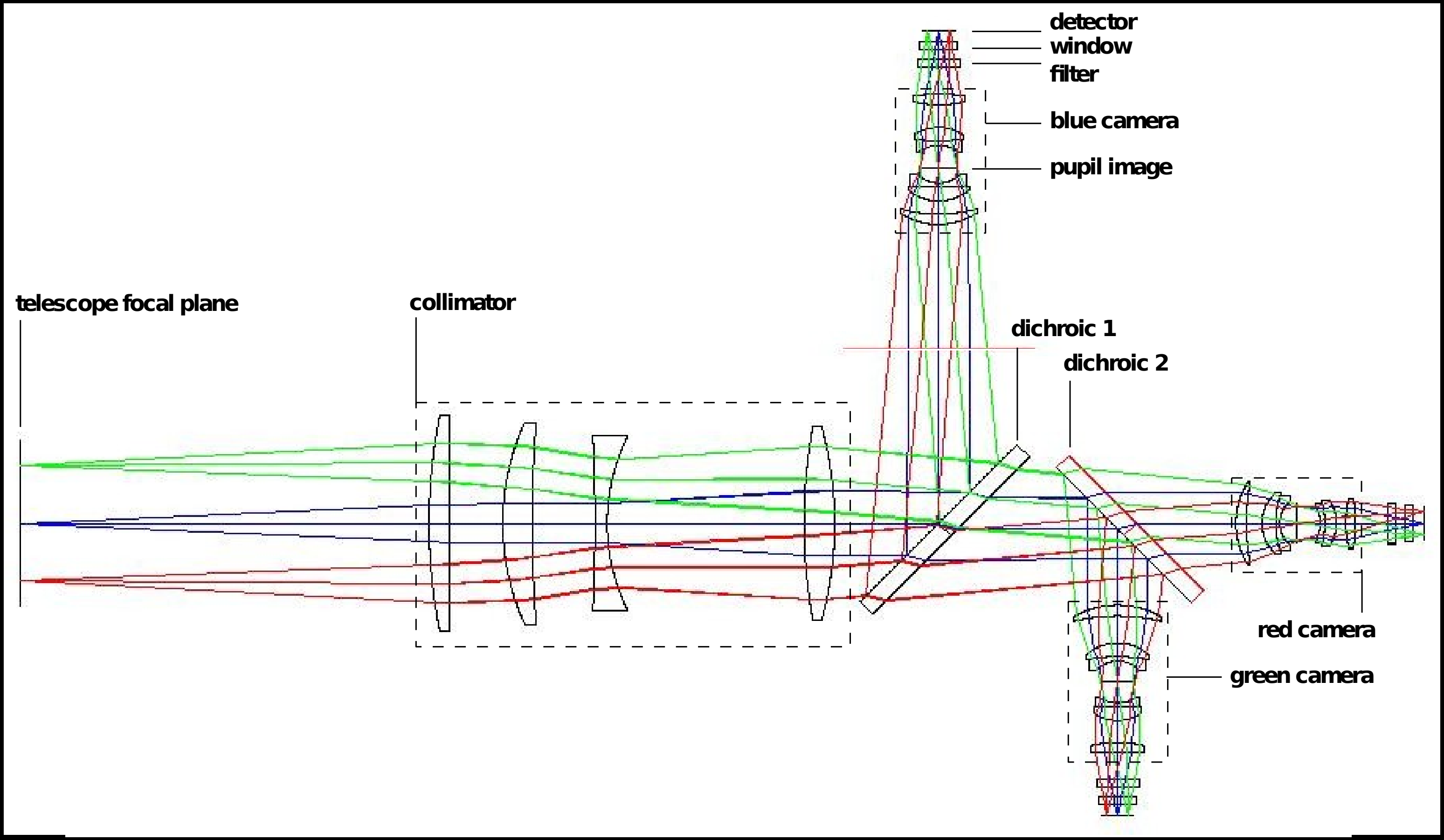




transmission (%)
wavelength (Å)
dichroic 1
dichroic 2
u'
g'
r'
i'
z'
20
40
60
80
100
4000
6000
8000
10^4



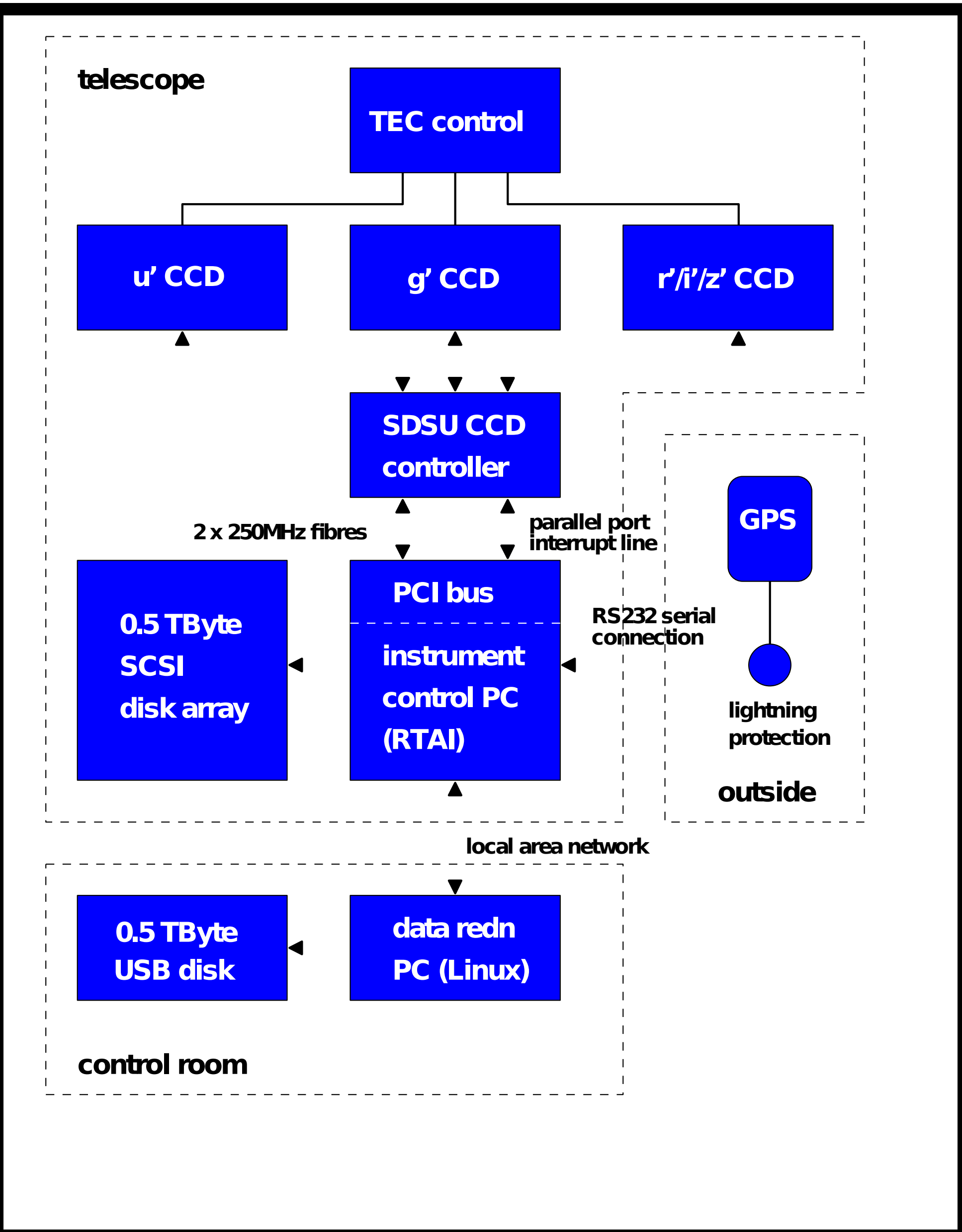
OPTICS



- ULTRACAM is a re-imager – the native WHT platescale of 4.51”/mm is demagnified to the CCD platescale of 0.3”/pixel (where 1 pixel = 13μm).

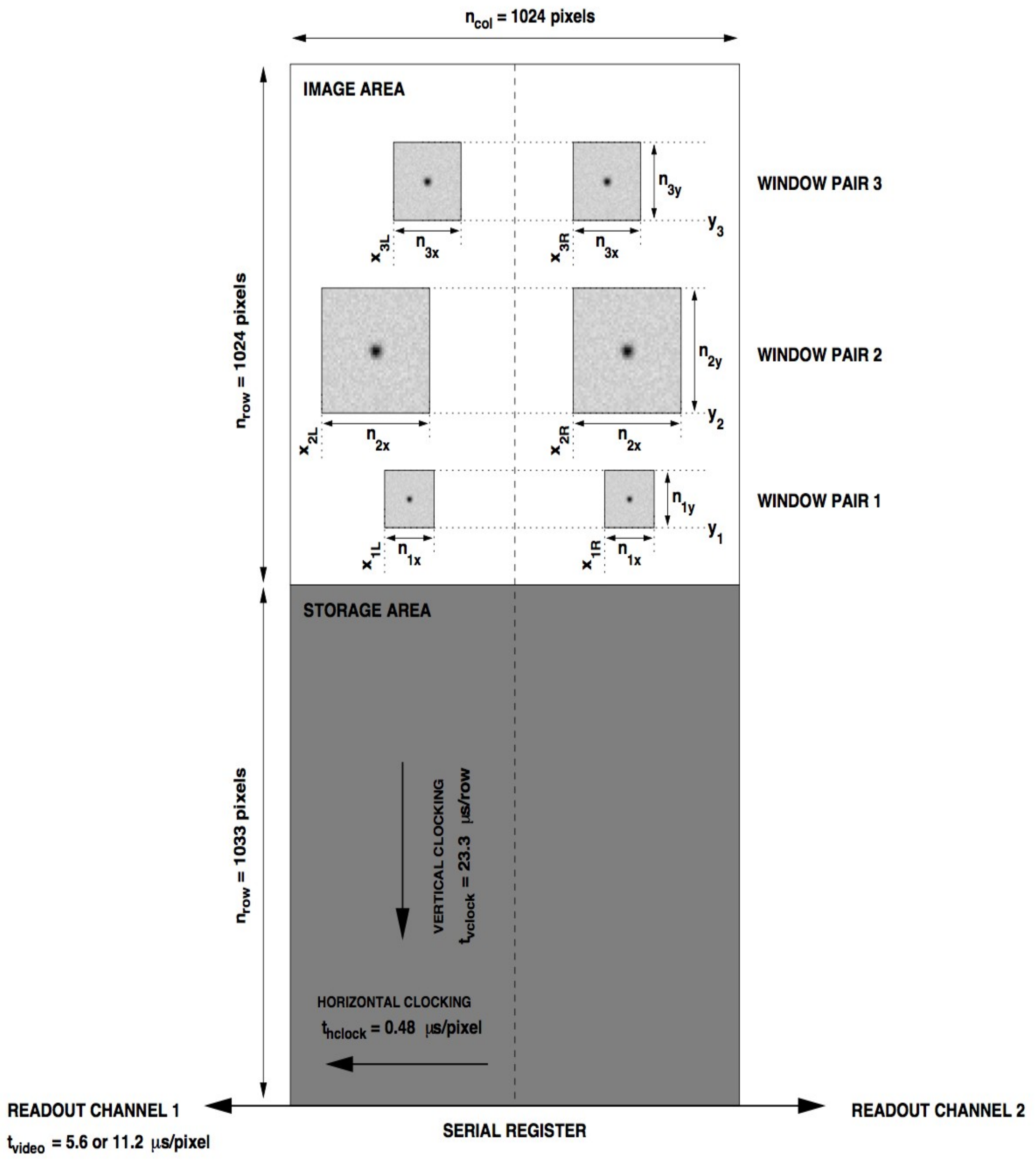
Magnification, $M = s_{cam}/s_{coll} = F_{cam}\theta_2 / F_{coll}\theta_2 = F_{cam}/F_{coll} \approx 5$.

DATA ACQUISITION SYSTEM



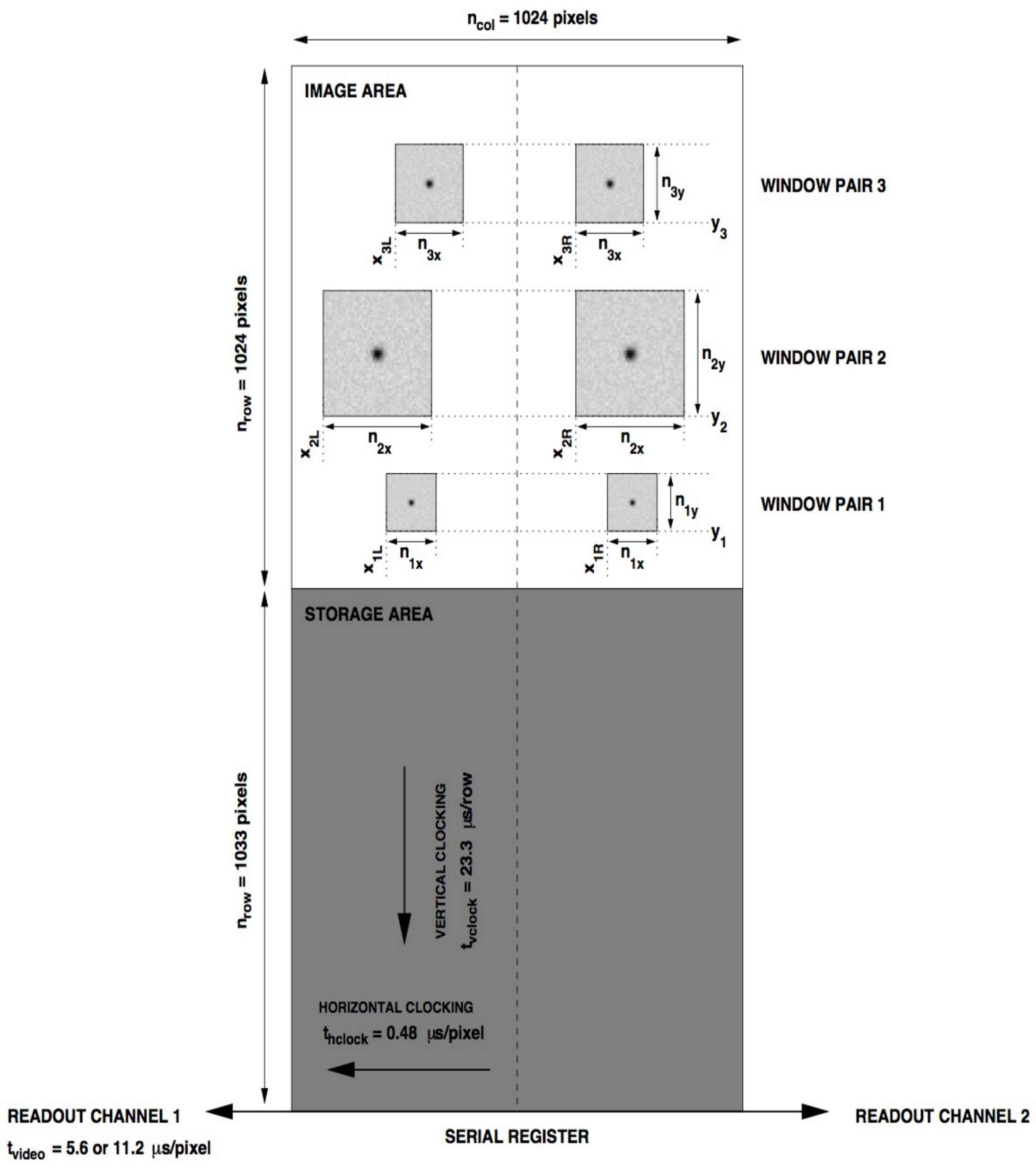
EXPOSURE TIMES

- Setting an exposure time with a frame-transfer CCD is more complex than with a normal CCD.
- ULTRACAM can shift the image area into the storage area only when there is room in the storage area to do so.
- Hence the fastest exposure time is given by the time it takes to empty the storage area, which depends on the number of pixels being read out, their location, and the digitisation speed.
- Reading out the whole storage area takes ~5 s (0.2 Hz), so this is the full-frame readout time.
- Reading out only 1 pixel takes 25 ms (40 Hz) - the vertical clocking time. This sets the maximum frame rate in this mode, but the exposure time is essentially 0 ms.



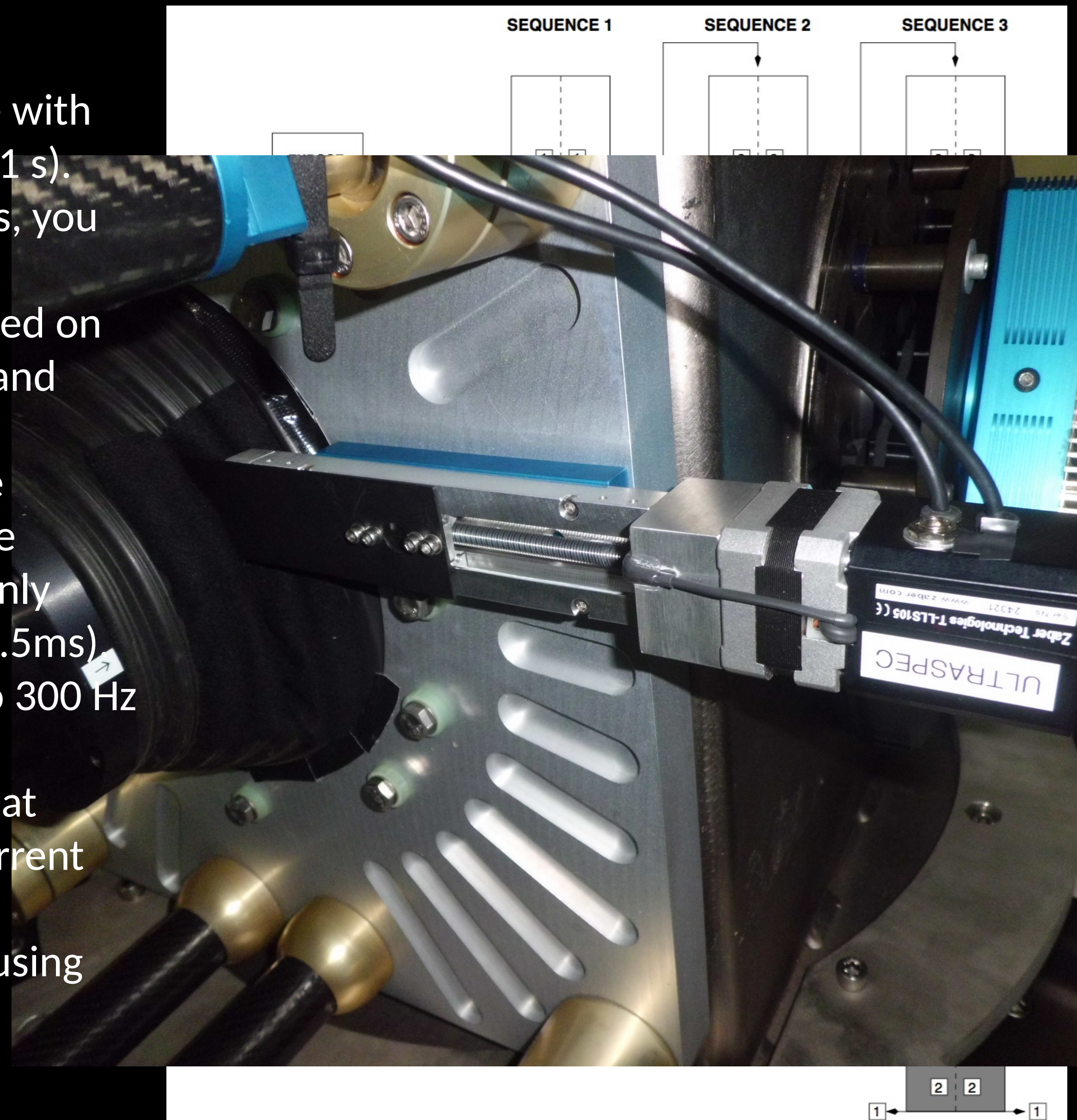
EXPOSURE DELAY & CLEAR MODE

- To obtain an arbitrarily long exposure time, it is possible to add an exposure delay, which allows photons to accumulate for the required amount of time in the image area.
- What if you need full frame images but also need a shorter exposure time than 5 s? (e.g. for a flat field or standard star.)
- The solution is to use clear mode - the data in the image area is dumped prior to exposing for the requested amount of time.
- The disadvantage is that clear mode is very inefficient – only a small fraction of the time is spent exposing, just like a normal CCD.



DRIFT MODE

- The maximum useful frame rate with two small windows is ~10 Hz (0.1 s).
- If you want to go faster than this, you must use drift mode.
- Two small windows are positioned on the border between the image and storage areas.
- Instead of vertically clocking the windows the entire height of the storage area (25 ms), they are only clocked just over the border (~0.5ms).
- In this case, frame rates of up to 300 Hz can be obtained.
- Disadvantage of drift mode is that pixels accumulate more dark current and sky.
- The latter can be minimized by using the focal-plane mask.



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SCIENCE WITH ULTRACAM

443 nights of time
WHT: 283
NTT: 120
VLT: 40

~100 refereed papers
2 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%
sdB stars/asteroseismology	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%

WHITE DWARFS WITH ULTRACAM

- Cataclysmic Variables (CVs)

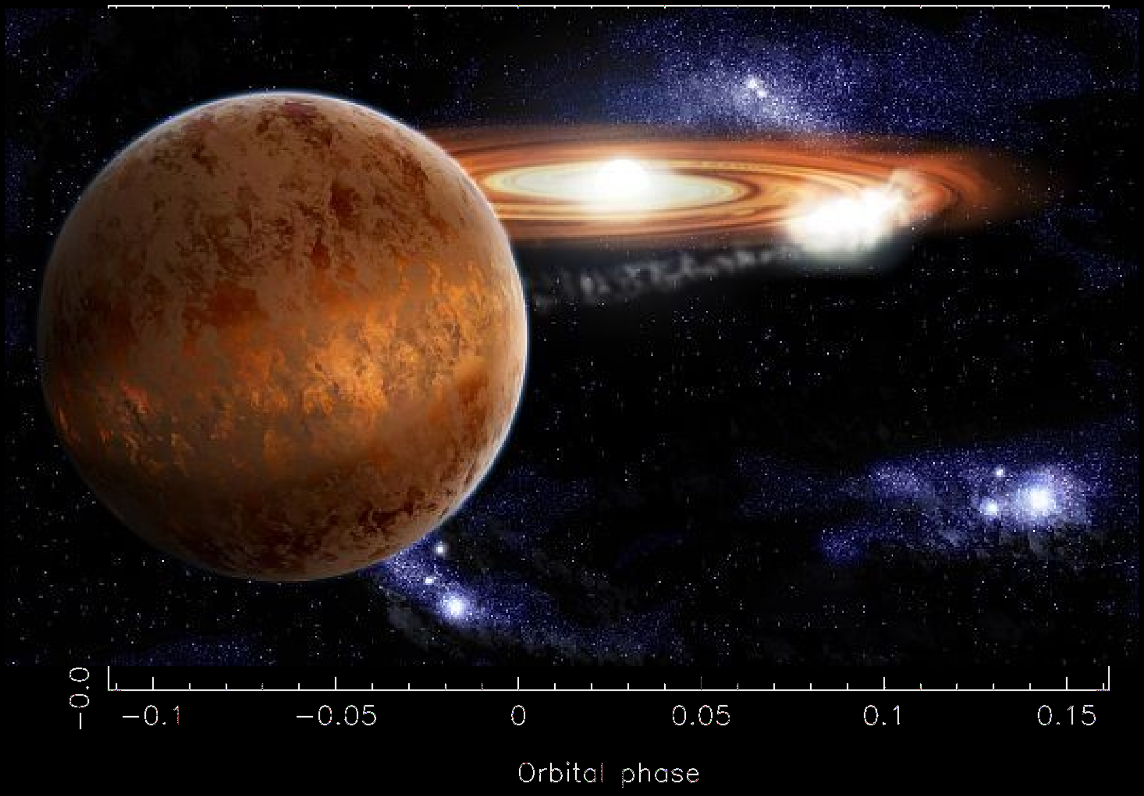
  SDSS 1035+0551

  Littlefair et al. 2006, Science, 314, 1578

- Detached white-dwarf/red-dwarf binaries (PCEBs/pre-CVs)

  NN Ser

  Marsh et al, 2014, MNRAS, 437, 475



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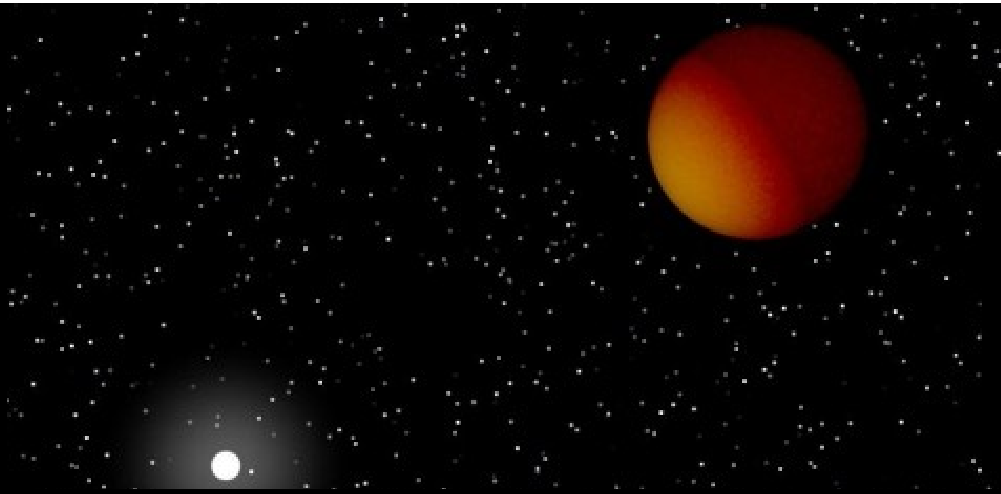

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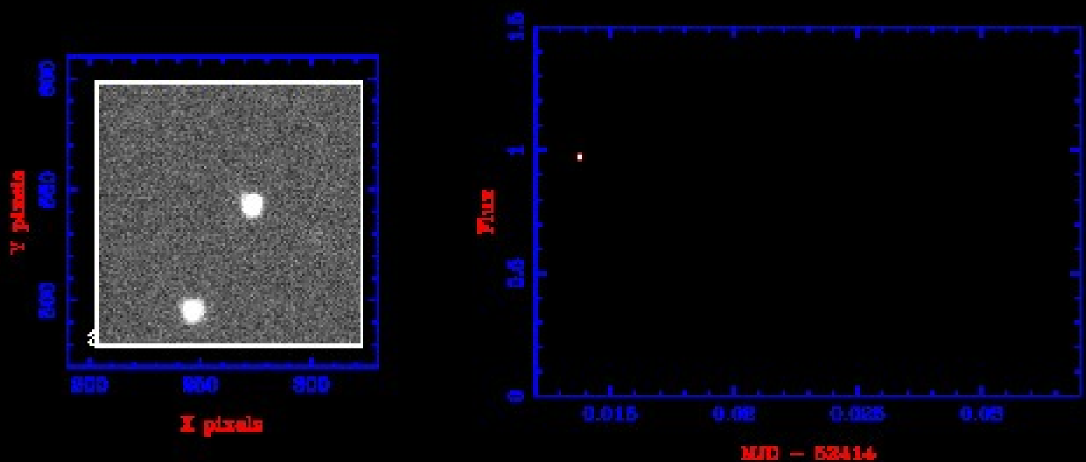
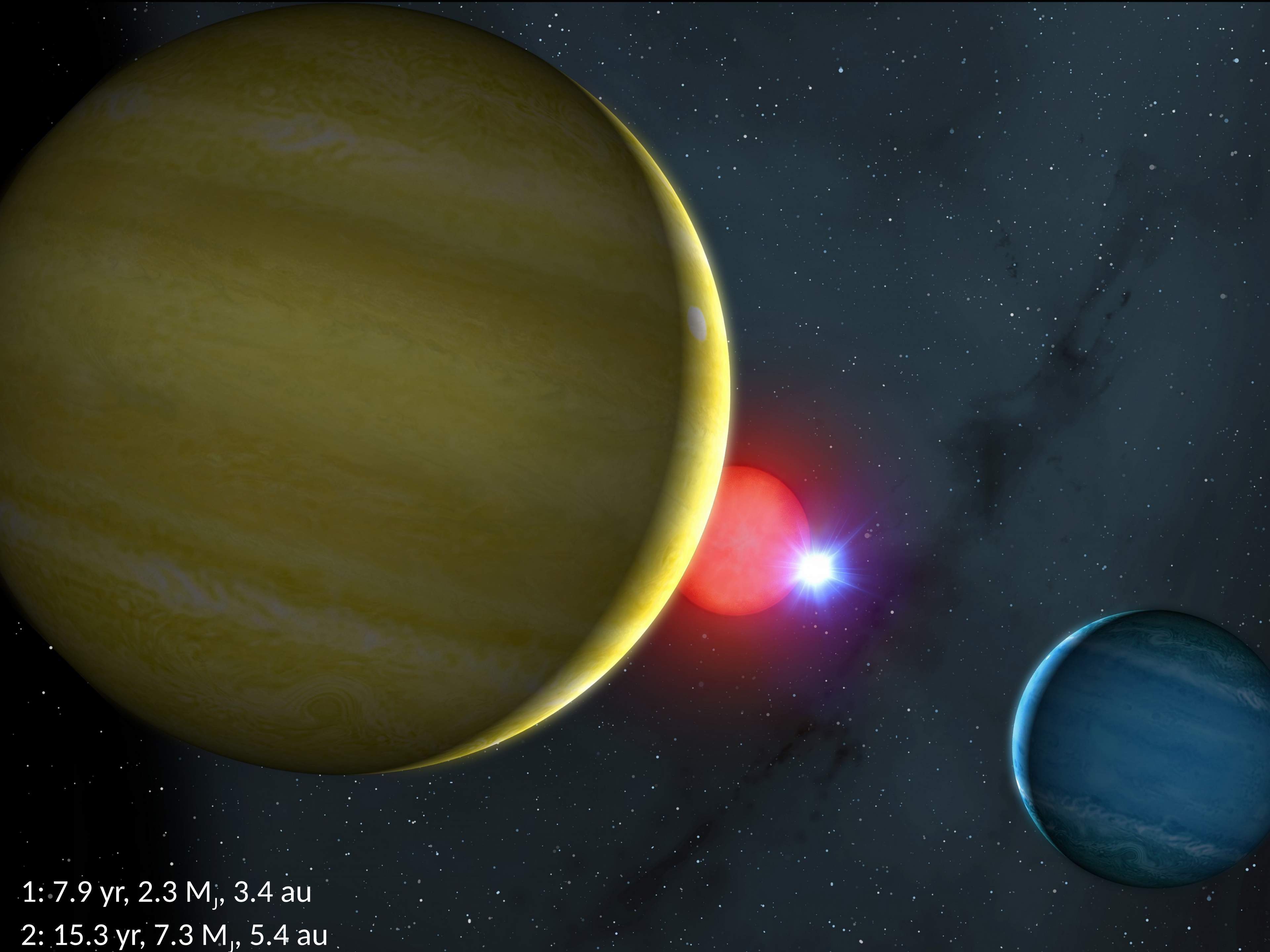



1: 7.9 yr, 2.3 M_J, 3.4 au
2: 15.3 yr, 7.3 M_J, 5.4 au

NEUTRON STARS WITH ULTRACAM

- **Anomalous X-ray pulsars (AXPs)**

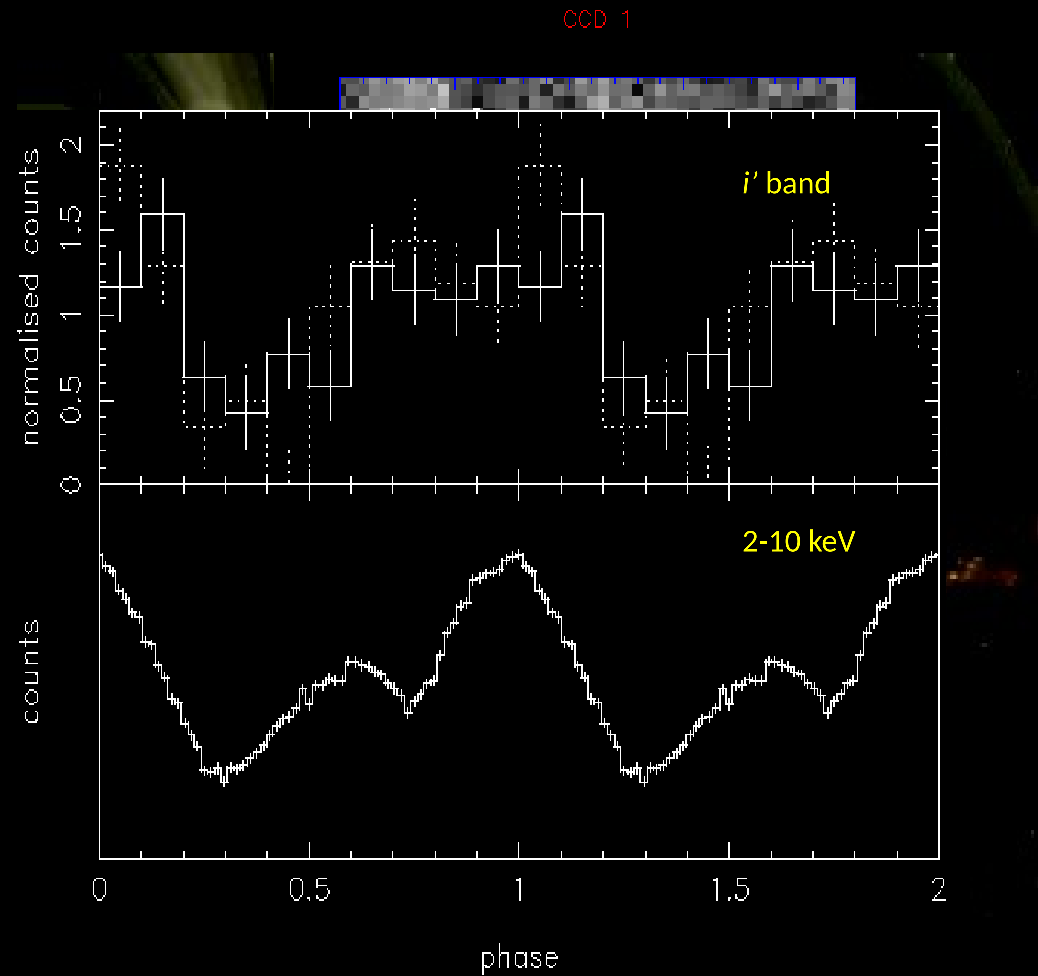
  AXP 4U0142+61
  Dhillon et al, 2005, MNRAS, 363, 609

- Soft Gamma Repeaters (SGRs)

  SGR 0501+4516
  Dhillon et al, 2011, MNRAS, 416, L16

- Binary Millisecond Pulsars (MSPs)

  PSR J2215+5135
  Breton et al, 2014, MNRAS, in prep



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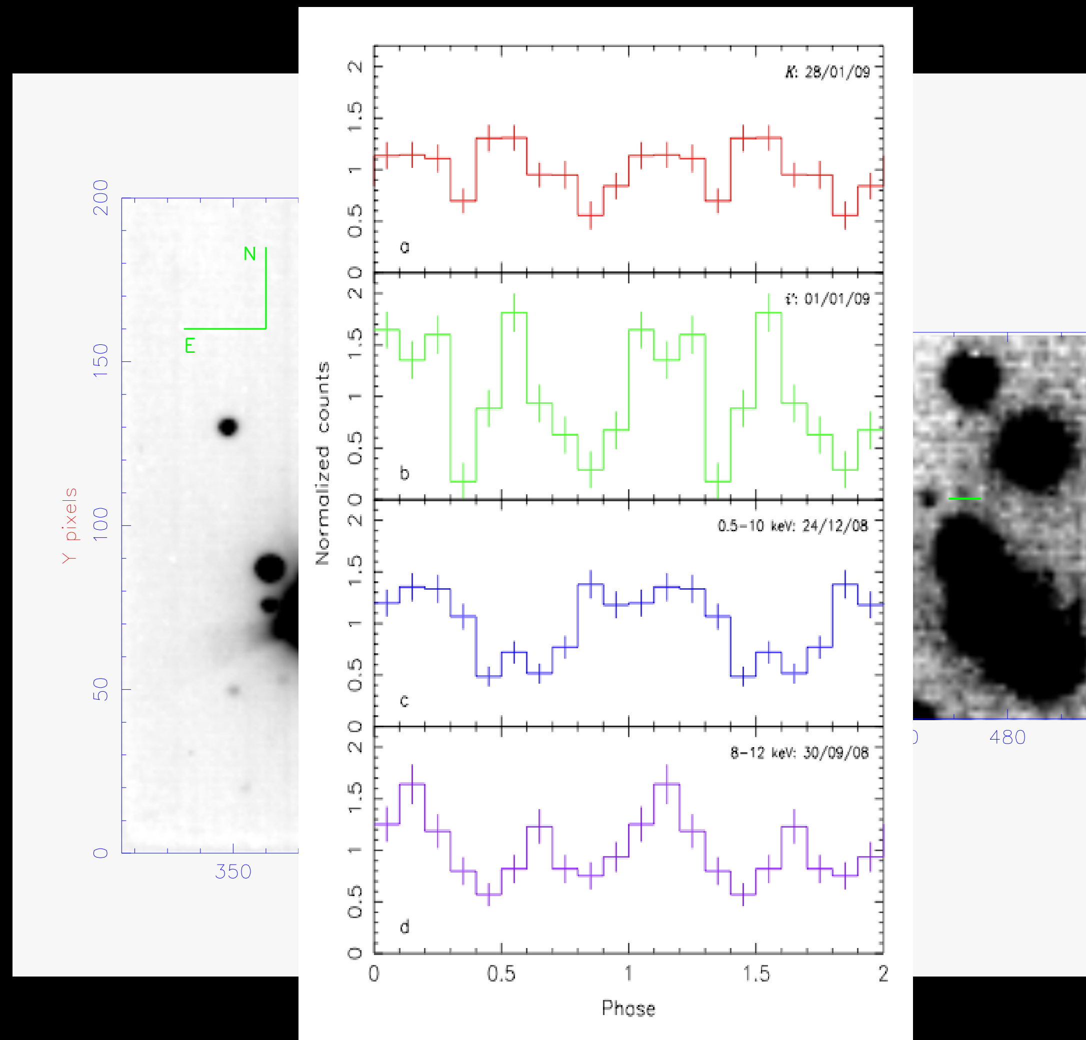

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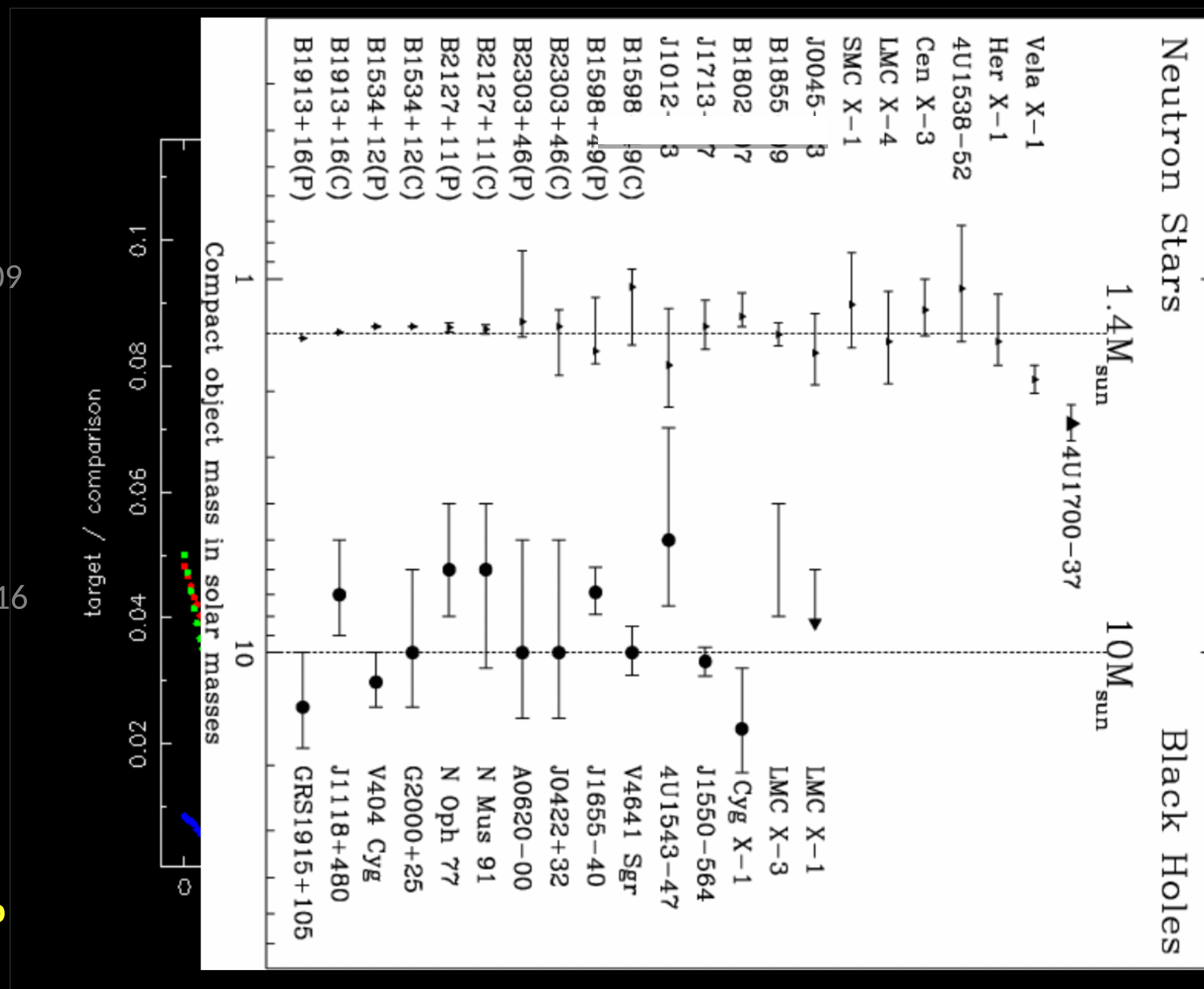
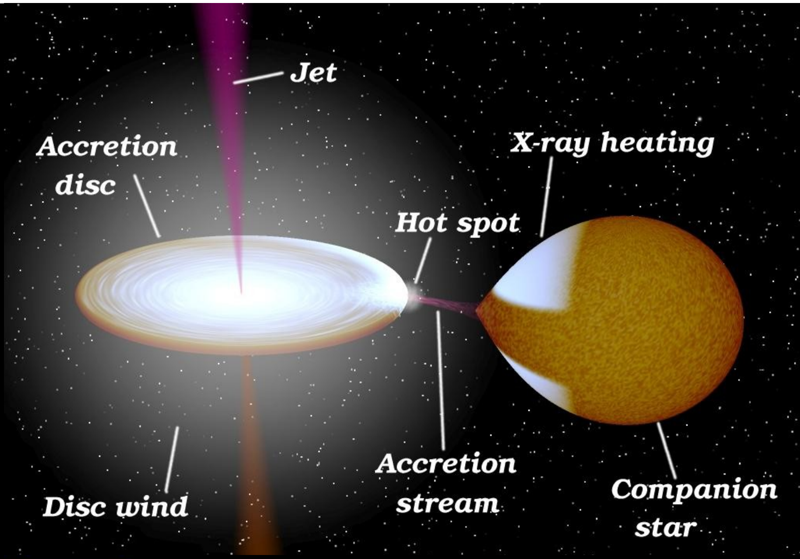
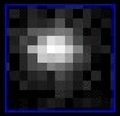


BLACK HOLES WITH ULTRACAM



- GX339-4: X-Ray Binary (XRB)

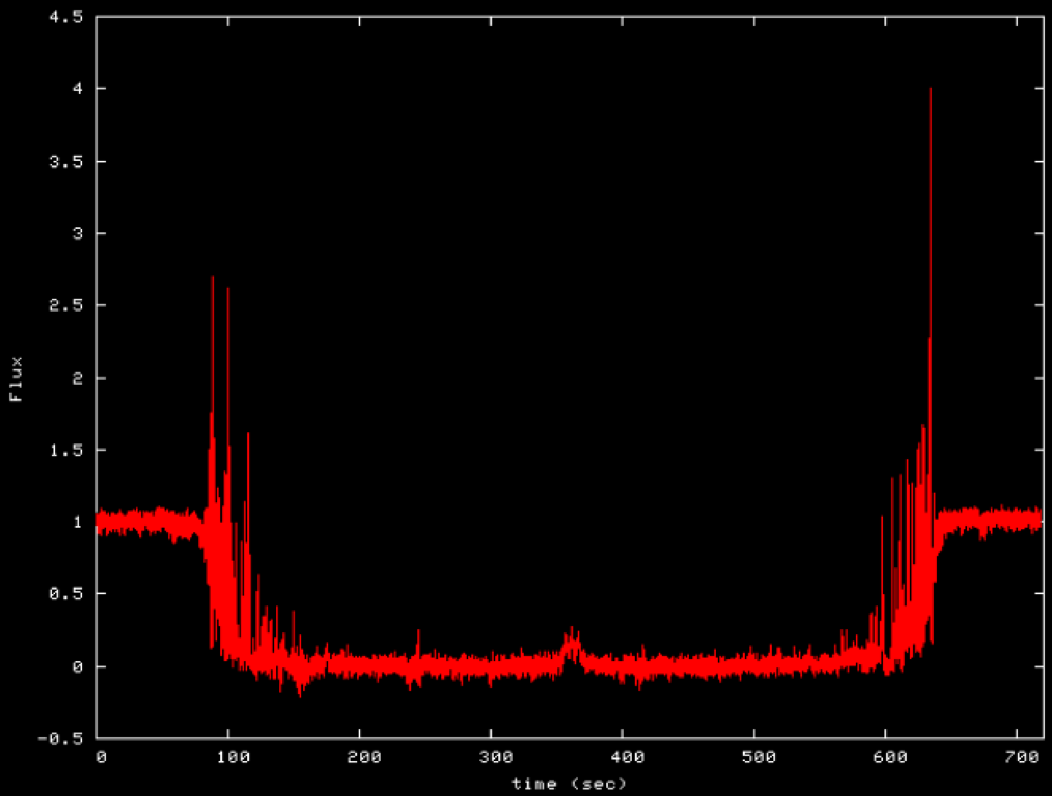
  Gandhi et al, 2008, MNRAS, 390, 29



T=0.00s

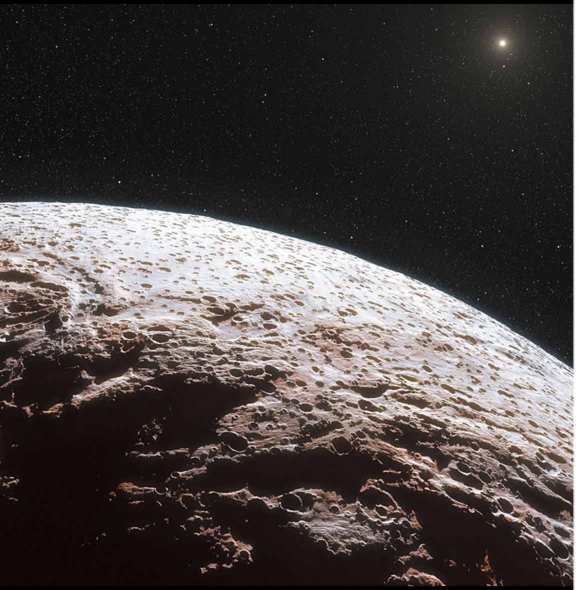
OCCULTATIONS WITH ULTRACAM

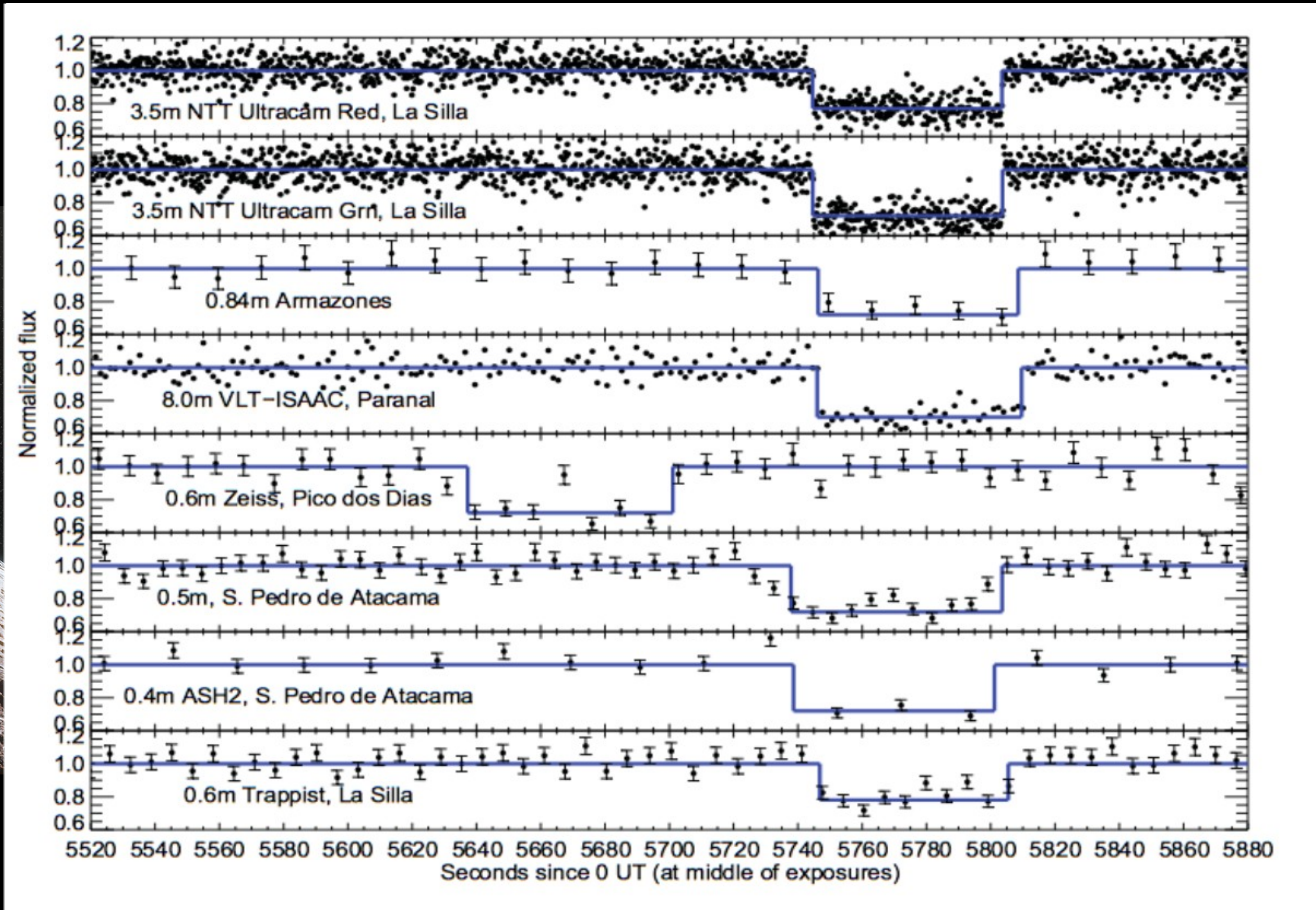
Zalucha et al, 2007, Icarus, 192, 503



OCCULTATIONS WITH ULTRACAM

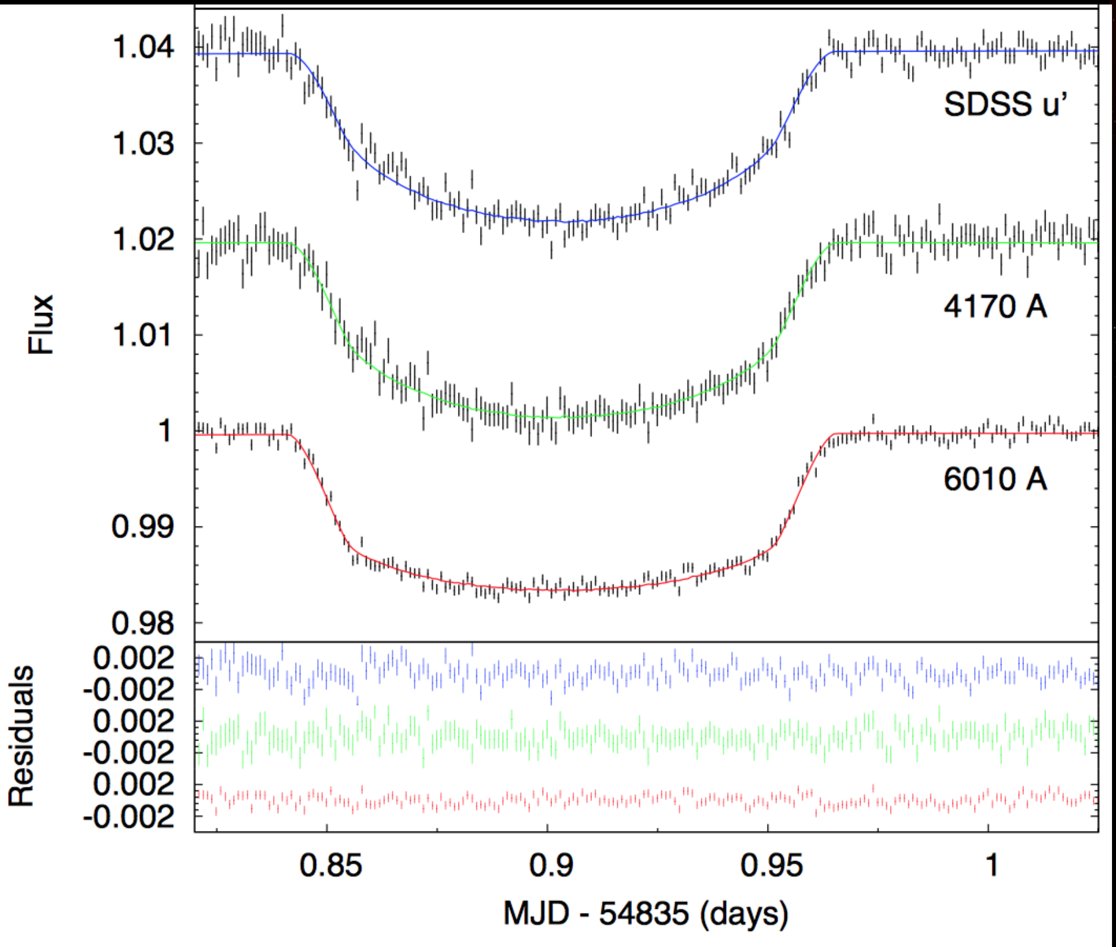
Makemake (TNO @ 52 AU, 1500 km diameter, no atmosphere)
Ortiz et al. 2012, Nature, 491, 566

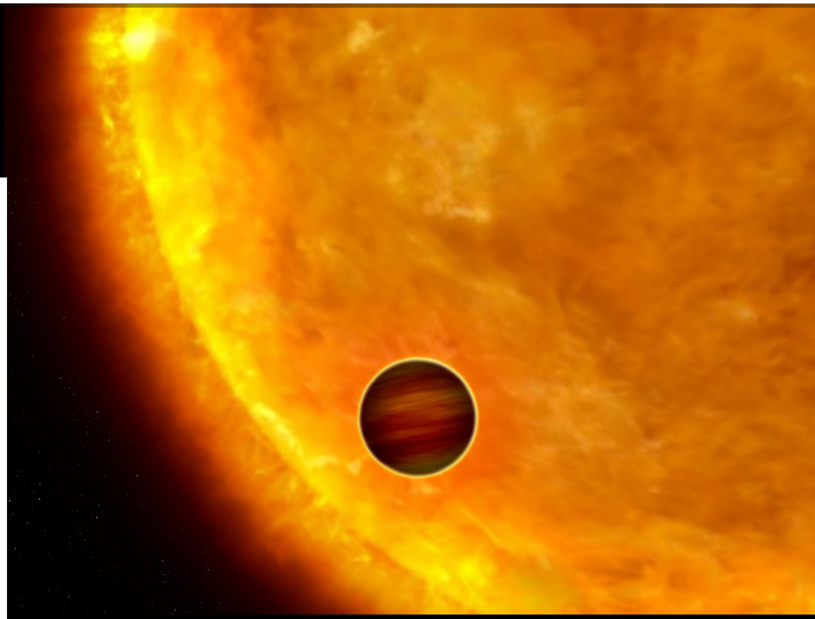




EXOPLANETS WITH ULTRACAM

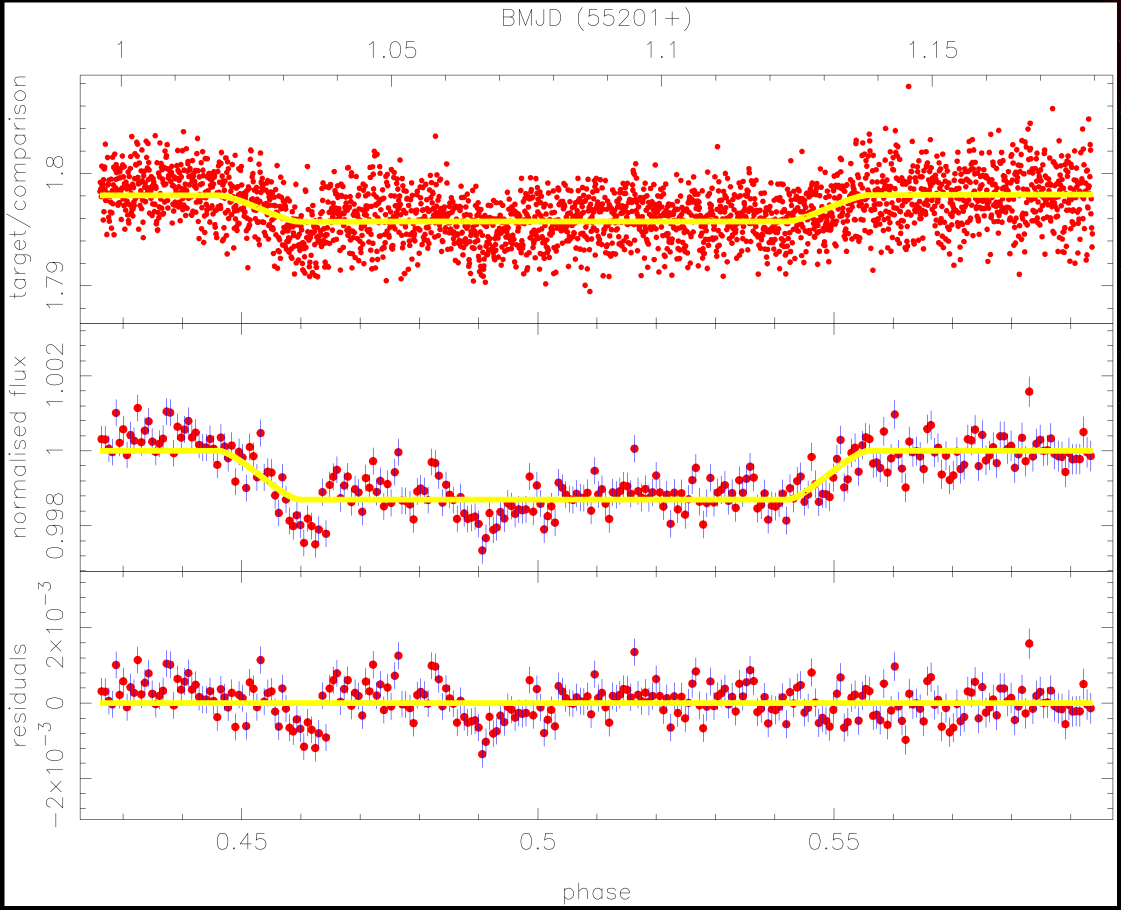
WASP-12b: TRANSIT
Copperwheat et al. 2013, MNRAS, 434, 661

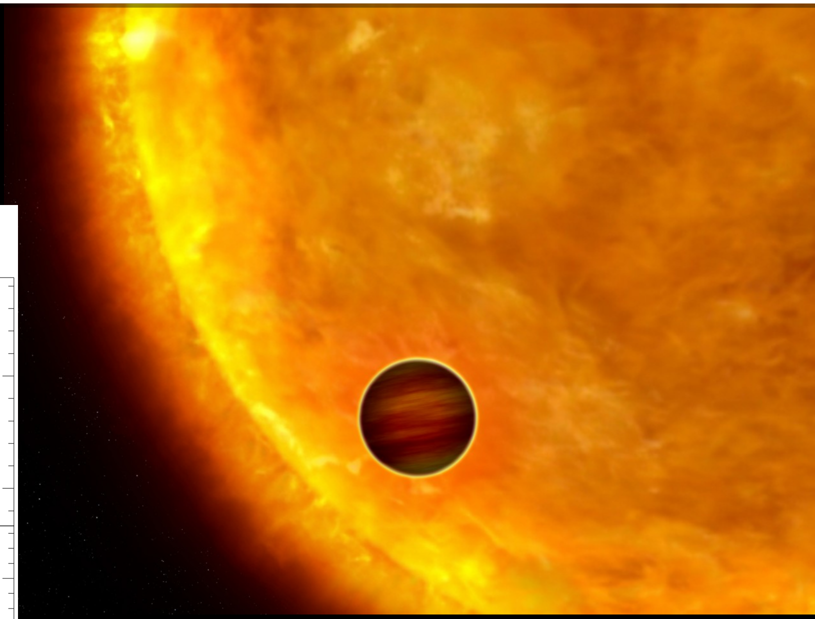




EXOPLANETS WITH ULTRACAM

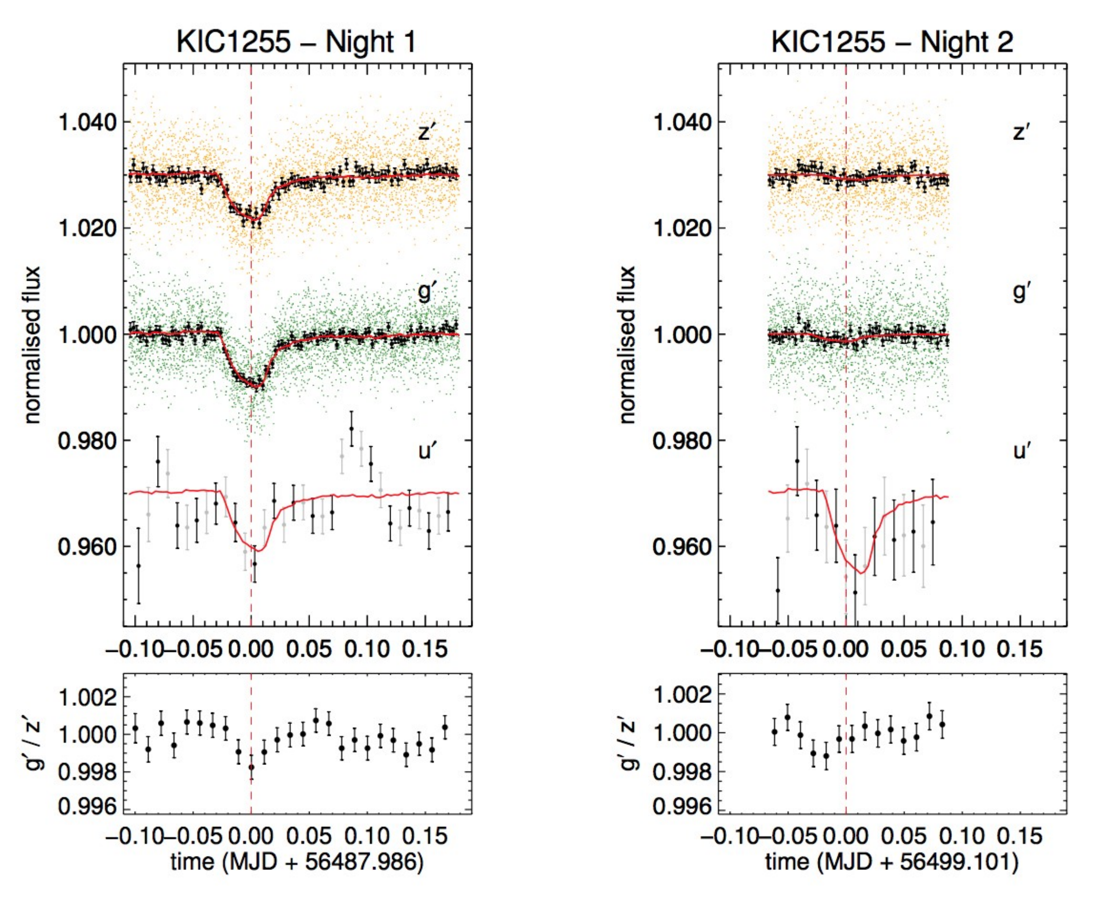
WASP-12b: SECONDARY ECLIPSE
Fohring et al. 2013, MNRAS, 435, 2268





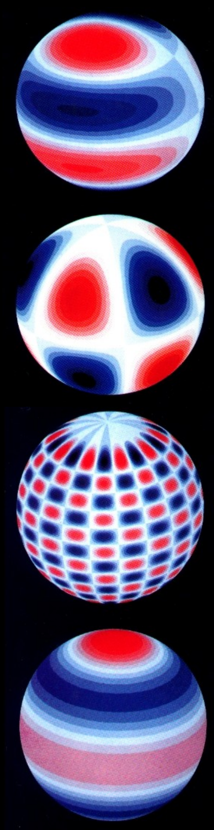
EXOPLANETS WITH ULTRACAM

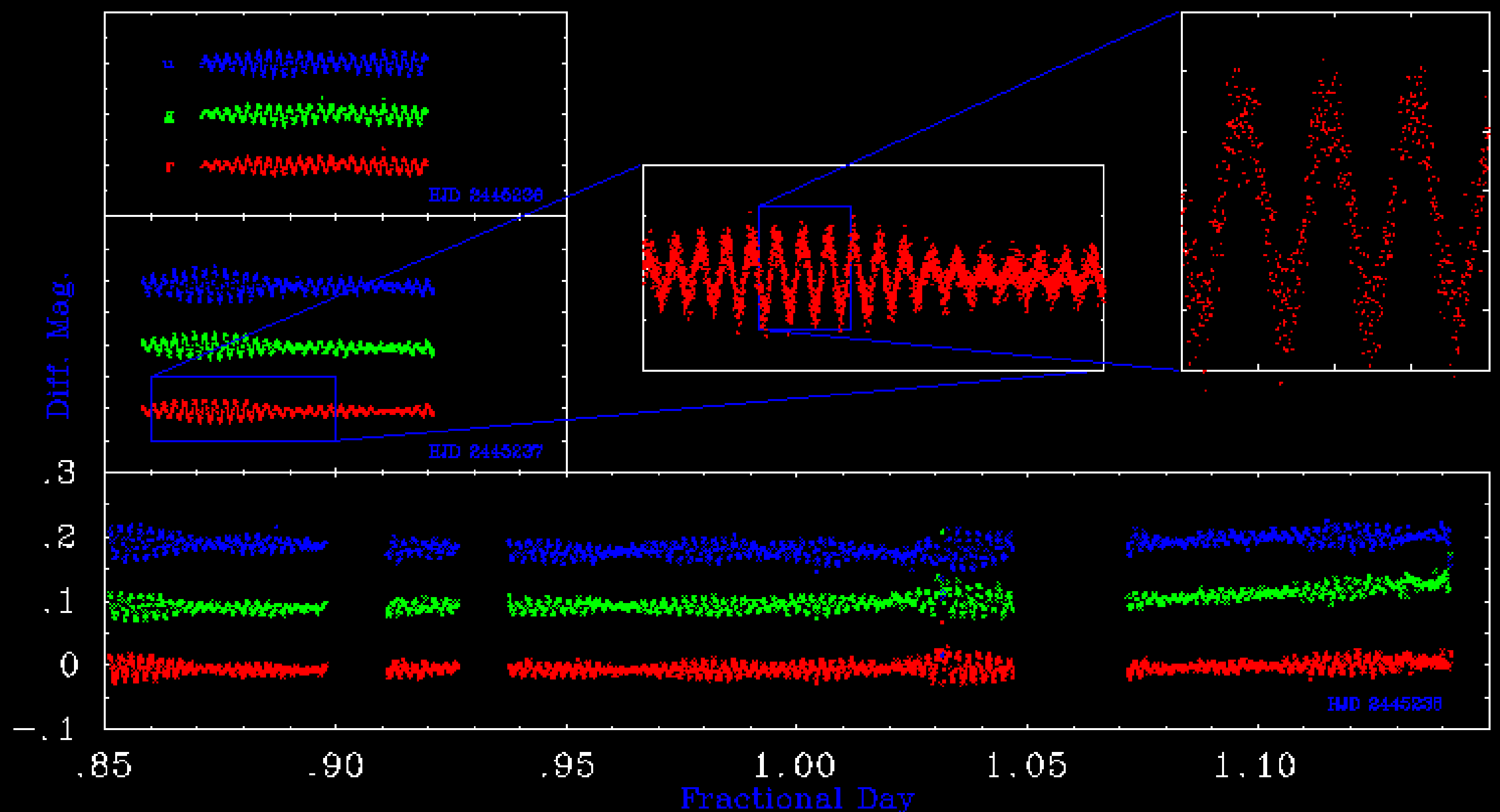
KIC1255754b: VARIABLE TRANSITS
Bochinski et al. 2015, ApJL, 800, L21



ASTEROSEISMOLOGY WITH ULTRACAM

KPD 2109+4401
Jeffery et al. 2004, MNRAS, 352, 699



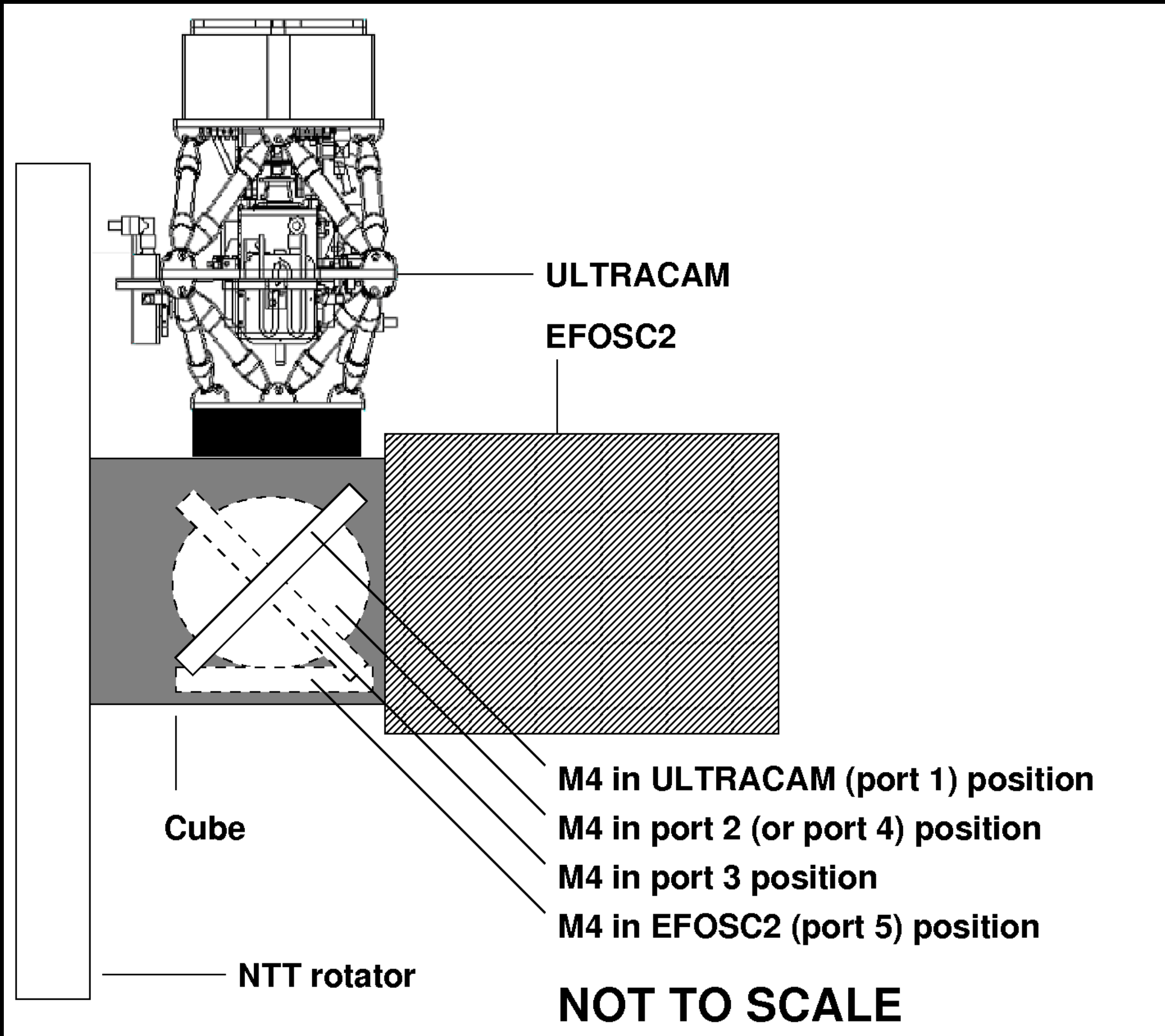


UNIQUE FEATURES OF ULTRACAM

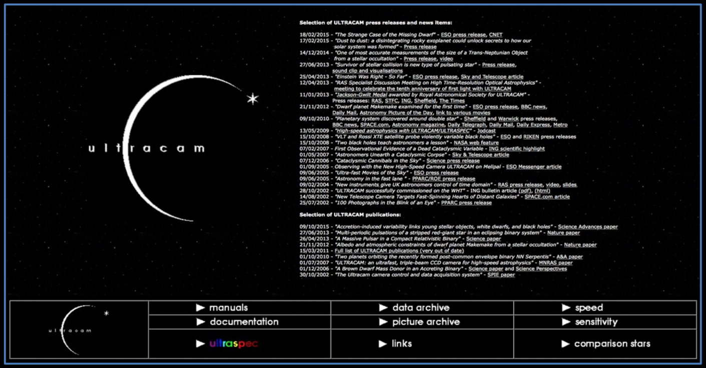
- High-speed imaging
- Three optical bands simultaneously
- Mounted on large telescopes
- Open access policy

ULTRACAM+NTT 2016-2020+

- Top-ranked proposal in recent ESO call for instrumentation for the NTT.
- Permanently mount ULTRACAM on the NTT in 2016-2020+.
- Open time available through ESO OPC.
- GTO provided to instrument team in return for providing cube and support.



FURTHER INFORMATION ON ULTRACAM



ULTRACAM WEB PAGE:
http://www.vikdhillon.staff.shef.ac.uk/ultracam

Mon. Not. R. Astron. Soc. **378,** 825–840 (2007) doi:10.1111/j.1365-2966.2007.11881.x

ULTRACAM: an ultrafast, triple-beam CCD camera for high-speed astrophysics

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ABSTRACT

ULTRACAM is a portable, high-speed imaging photometer designed to study faint astronomical objects at high temporal resolutions. ULTRACAM employs two dichroic beamsplitters and three frame-transfer CCD cameras to provide three-colour optical imaging at frame rates of up to 500 Hz. The instrument has been mounted on both the 4.2-m William Herschel Telescope on La Palma and the 8.2-m Very Large Telescope in Chile, and has been used to study white dwarfs, brown dwarfs, pulsars, black hole/neutron star X-ray binaries, gamma-ray bursts, cataclysmic variables, eclipsing binary stars, extrasolar planets, flare stars, ultracompact binaries, active galactic nuclei, asteroseismology and occultations by Solar System objects (Titan, Pluto and Kuiper Belt objects). In this paper we describe the scientific motivation behind ULTRACAM, present an outline of its design and report on its measured performance.

Key words: instrumentation: detectors – instrumentation: photometers – techniques: photometric.

1 INTRODUCTION

CCDs revolutionized astronomy when they became available in the 1970s. CCDs are linear, stable, robust and low-power devices. They have large formats, small pixels and excellent sensitivity over a wide range of wavelengths and light levels; in fact, they are almost perfect detectors, suffering only from poor time resolution and readout noise compared to the photon-counting detectors that they replaced. These limitations of CCDs are inherent to their architecture, in which the photogenerated electrons must first be extracted (or *clocked*) from the detection site and then digitized.[1]

There are ways in which the readout noise of CCDs can be eliminated – for example, by the use of electron-multiplying devices (Mackay et al. 2001). There are also ways in which CCDs can be made to read out faster. First, the clocking rate can be increased and the digitization time decreased, but only if the CCD is of sufficient quality to allow these adjustments to be made without an unacceptable increase in charge-transfer inefficiency and readout noise. Secondly, the duty cycle of the exposures can be increased; for example, *frame-transfer* CCDs provide a storage area into which photogenerated charge can be clocked. This charge is then digitized whilst the next exposure is taking place and, because digitization generally takes much longer than clocking, the dead time between exposures is significantly reduced. Thirdly, the data acquisition hardware and software can be designed in such a way that the rate at which it is able to archive the data (e.g. to a hard disc) is always greater than the rate at which data are digitized by the CCD – a situation we shall refer to as *detector-limited* operation.

We have employed all three of the techniques described above to harness the greater sensitivity and versatility of CCDs (compared to photon-counting detectors) for high-speed optical photometry. The resulting instrument, known as ULTRACAM (for ULTRAfast CAMera), was commissioned on the 4.2-m William Herschel

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[1] For the purposes of this paper, the word *digitization* shall refer to both the process of determining the charge content of a pixel via correlated double sampling and the subsequent digitization of the charge using an analogue-to-digital converter.

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ULTRACAM JOURNAL PAPER:
Dhillon et al, 2007, MNRAS, 378, 825

The End.