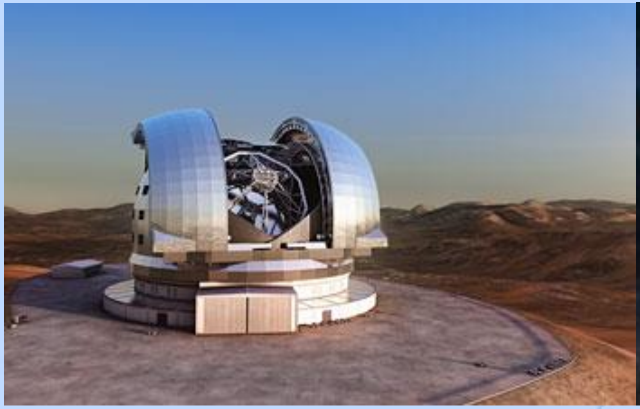


ESO
European Organisation for Astronomical Research in the Southern Hemisphere

High speed CMOS photon detectors and cameras

Mark Downing, Paola Amico, Martin Brinkmann, Mark Casali, Ralf Conzelmann, Christoph Geimer, Enrico Marchetti, Ignacio Molina-Conde, Leander Mehrgan, Javier Reyes, Matthias Seidel, Joerg Stegmeier, Mirko Todorovic

European Southern Observatory ESO (http://www.eso.org)



Outline

ESO
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- Adaptive Optics Wavefront Sensing
- Camera Program
- CCD220
- LVSM CMOS Imager
- Visible Camera Design
- Summary

Adaptive Optics (AO)
- removing the twinkle of the stars

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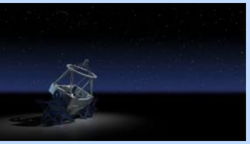
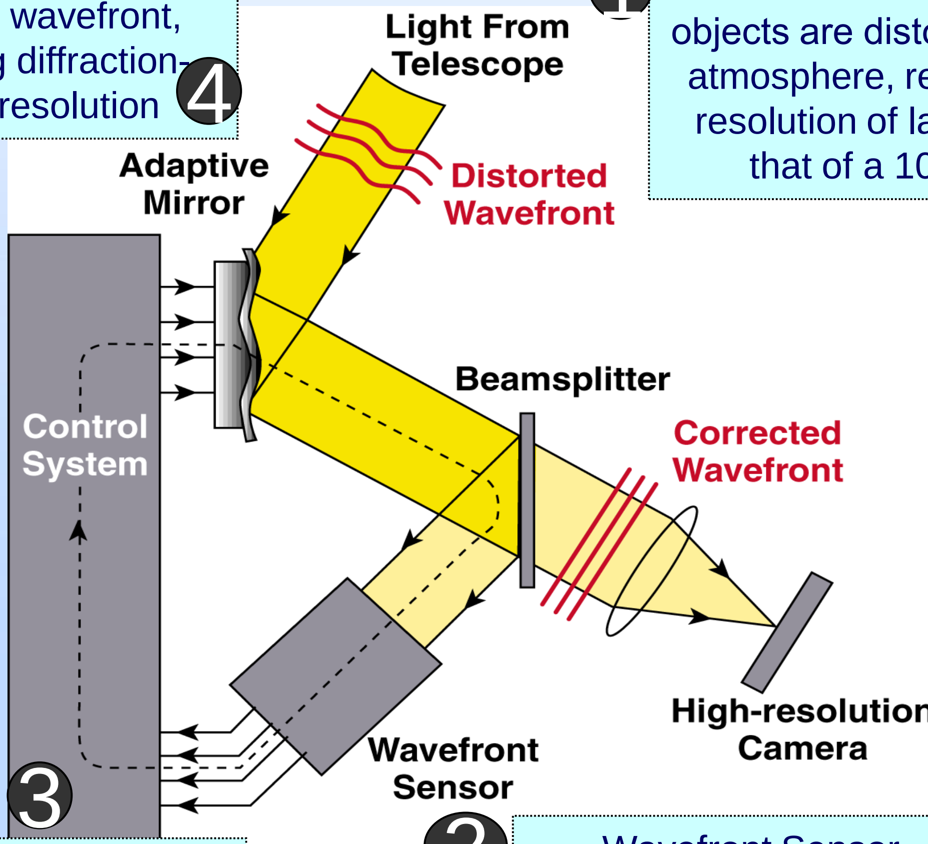
4 Deformable mirror compensates the distorted wavefront, achieving diffraction-limited resolution

1 Wavefronts from astronomical objects are distorted by the Earth's atmosphere, reducing the spatial resolution of large telescopes to that of a 10 cm telescope





2 Wavefront Sensor measures deviation of wavefront from a flat (undistorted) wave

3 Control System computes commands for the deformable mirror(s)

AOF GLAO

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Science User Portal Intranet (en)

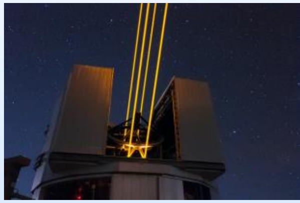
eso1724 — Organisation Release

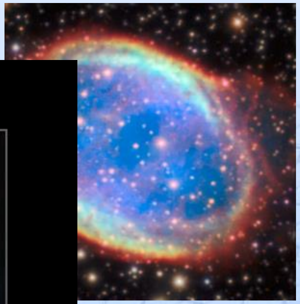
Cutting-edge Adaptive Optics Facility Sees First Light

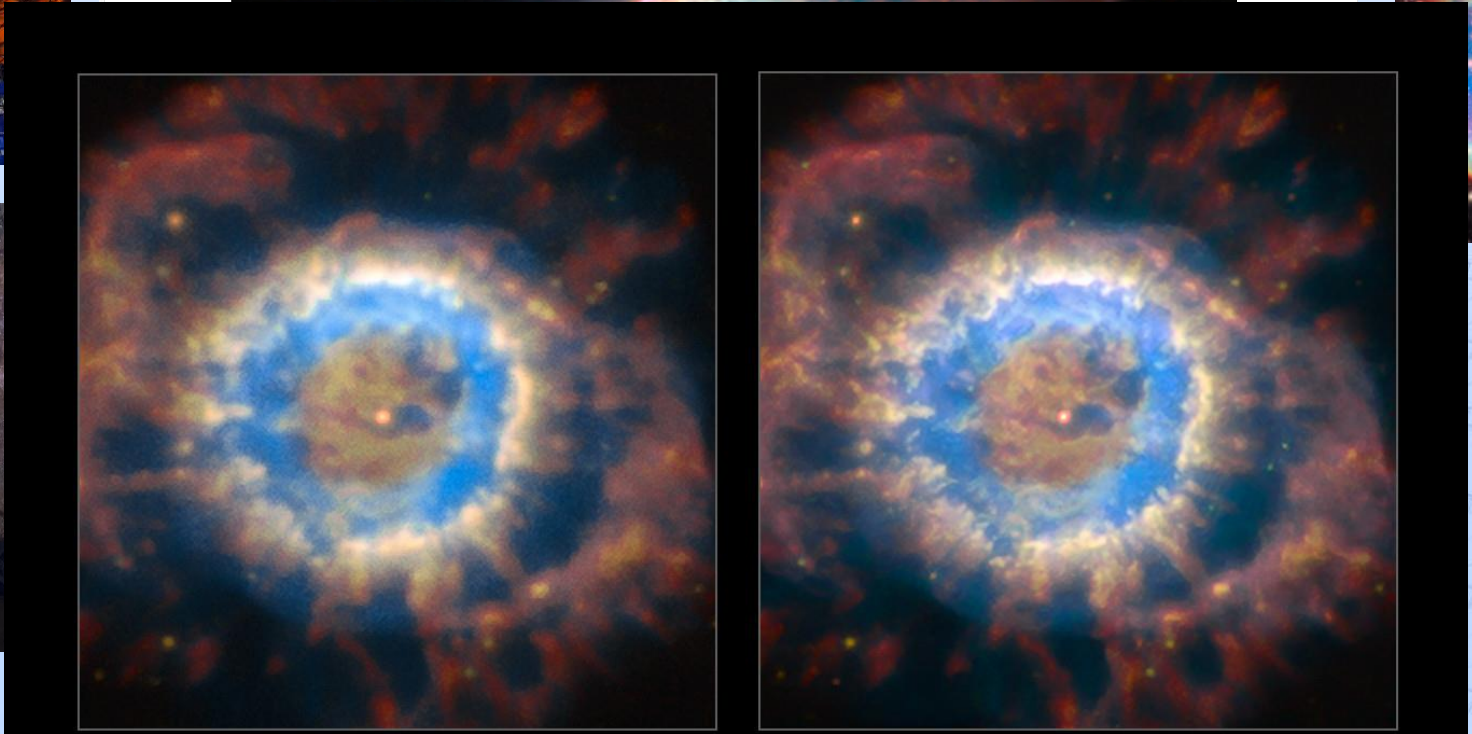
Spectacular improvement in the sharpness of MUSE images

2 August 2017

IC 4406 -> Retina Nebula



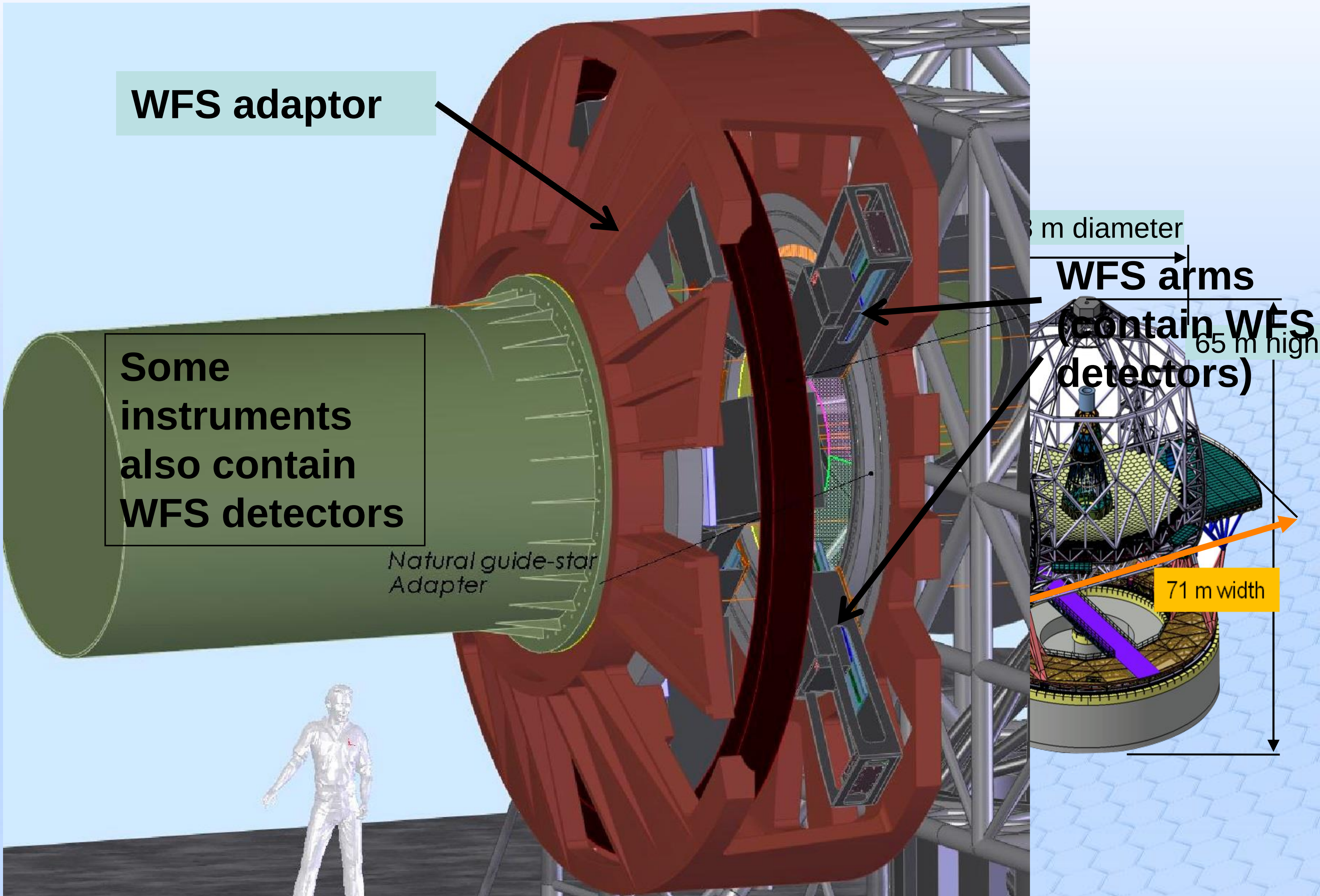




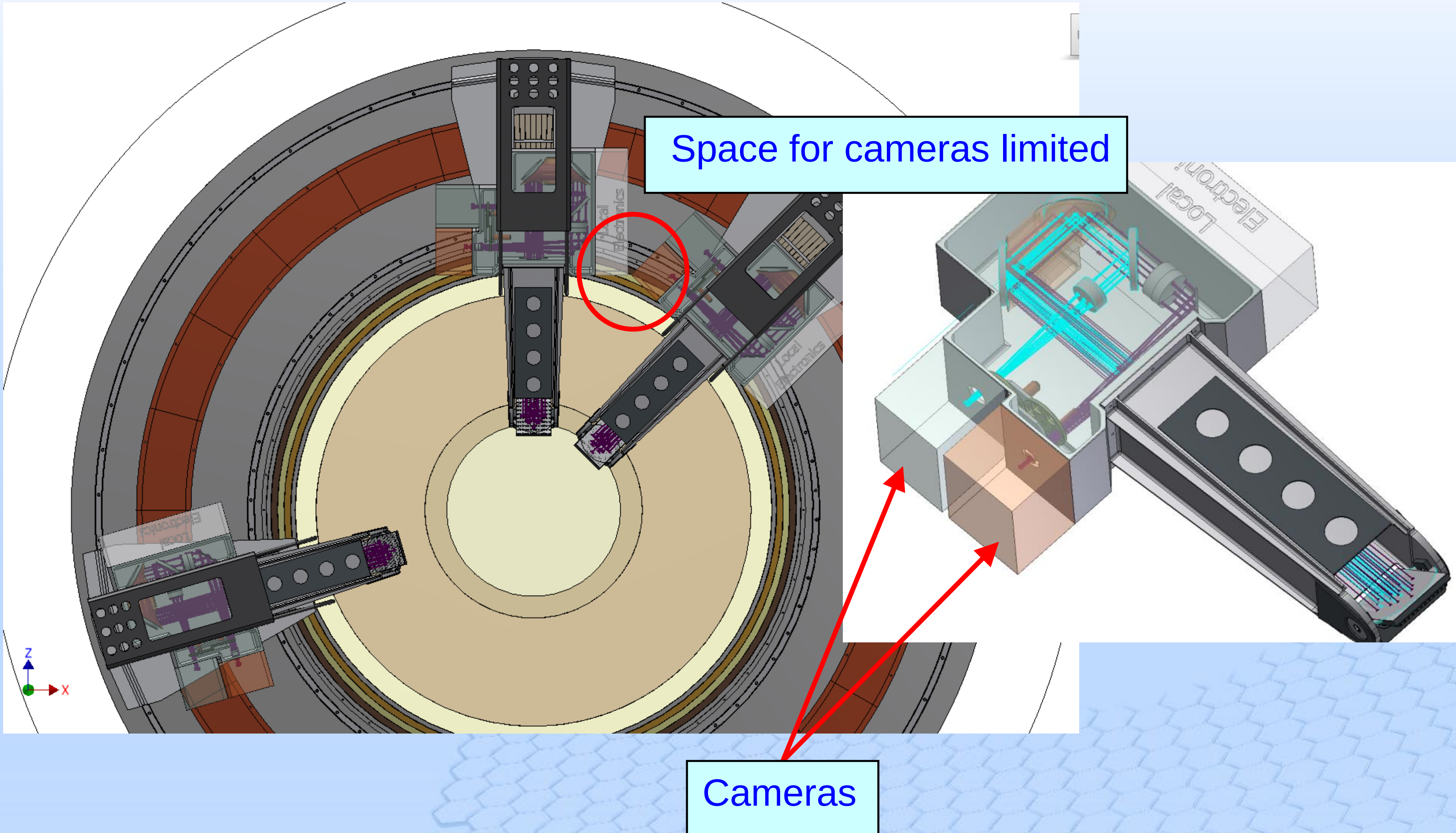
planetary nebula NGC 6563

* http://www.eso.org/public/news/eso1724/

Location of Wavefront sensors on the ELT



While the Telescope is large, the volume for cameras are modest



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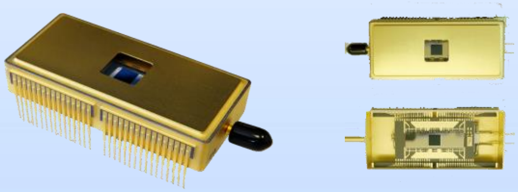
Three WFS Cameras under development

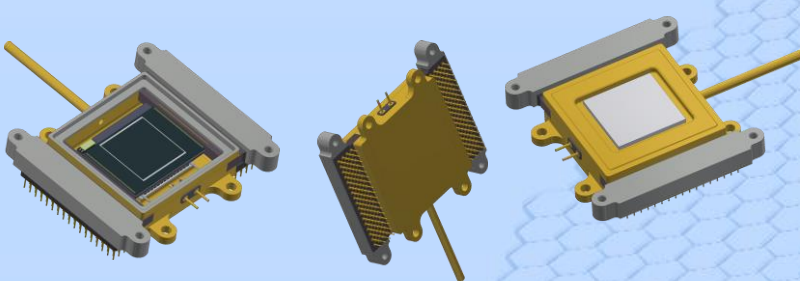
All share requirements of high speed (700-1000fps), low noise/dark current, high QE, large 24µm pixel

1) Extremely low noise (0.1e-) small format (240x240) → CCD220

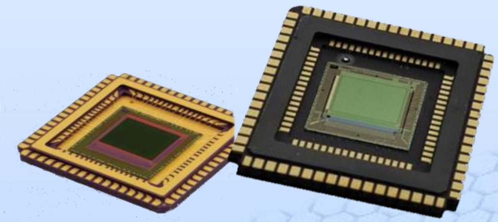


TELEDYNE e2V Everywhereyoulook™

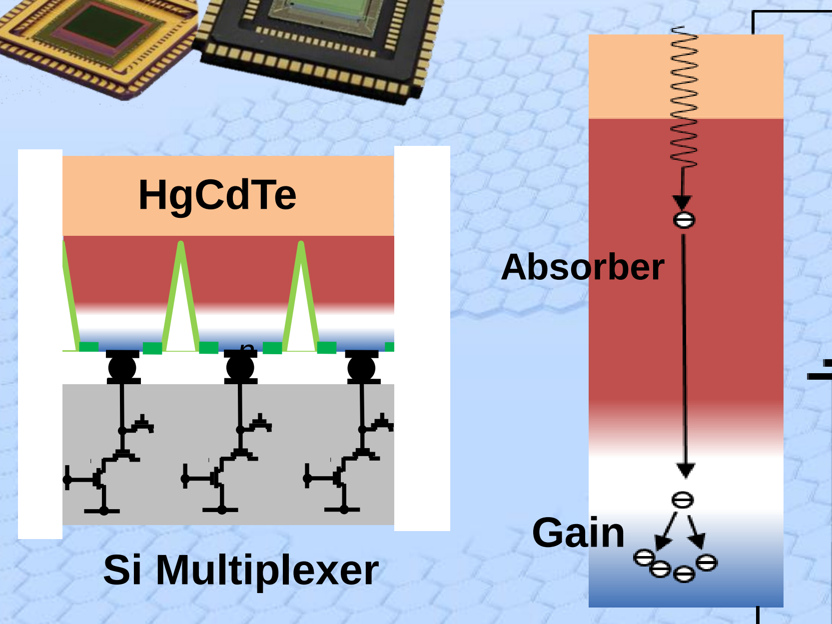
2) Large format (>800x800) modest noise (3e-) → LVSM



3) Low noise (1e-) small format (320x256) → SAPHIRA



LEONARDO LAND & NAVAL DEFENCE ELECTRONICS



Visible

NIR

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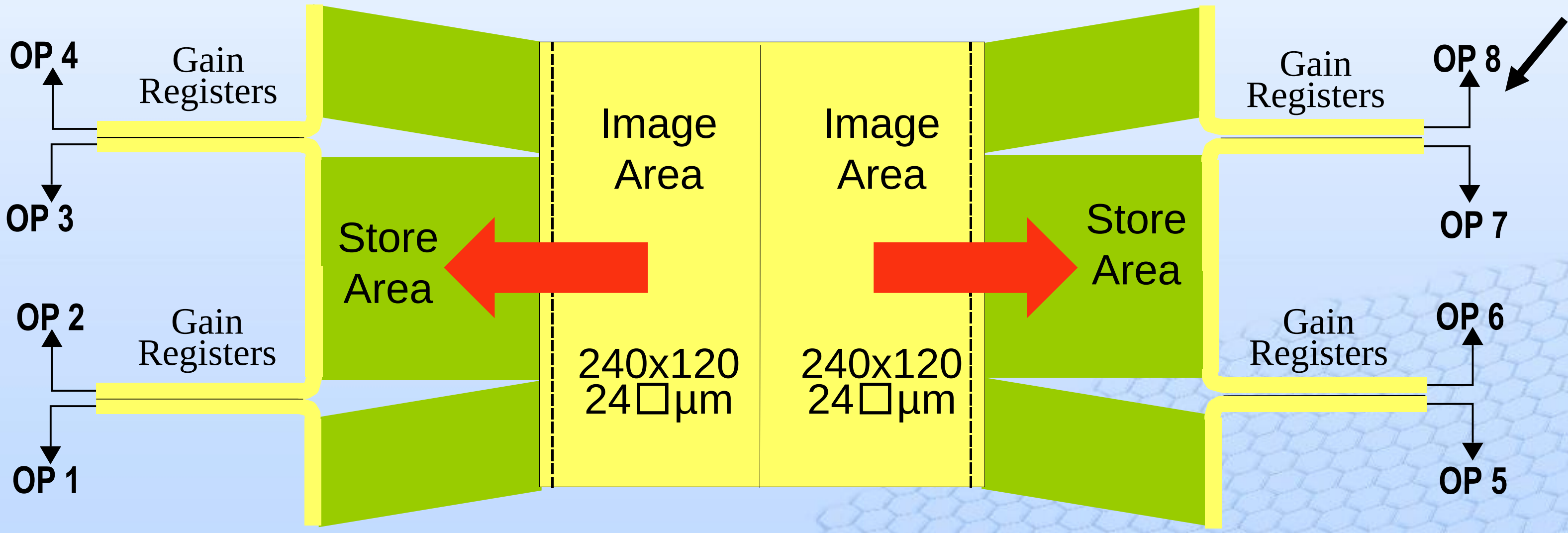
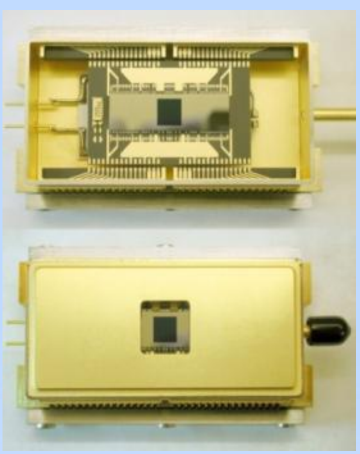
Existing Teledyne-e2v CCD220-DD





e2v CCD220:

- → Tried and proved
- → 240x240 24 µm pixels
- → 8 L3Vision Electron Multiplication outputs
- → < 0.1 e- RoN at > 1,000 fps
- → Integral Peltier package to cool to -40ºC

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Large Visible AO WFS Detector needed to sample the spot elongation

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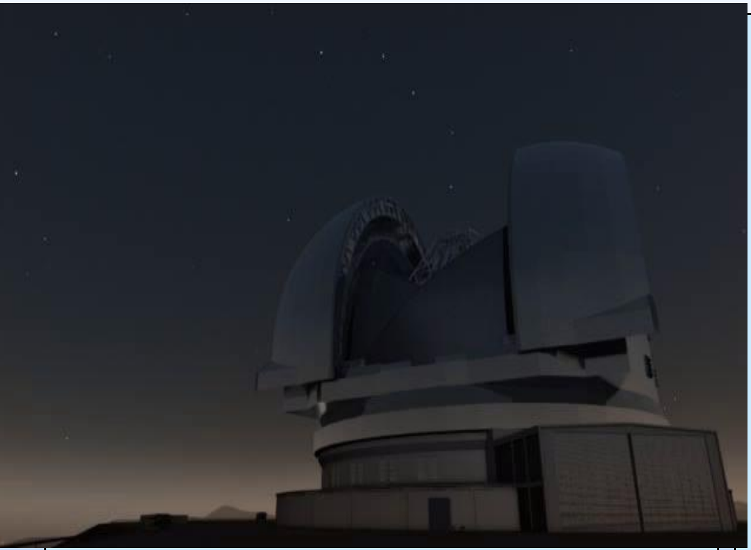
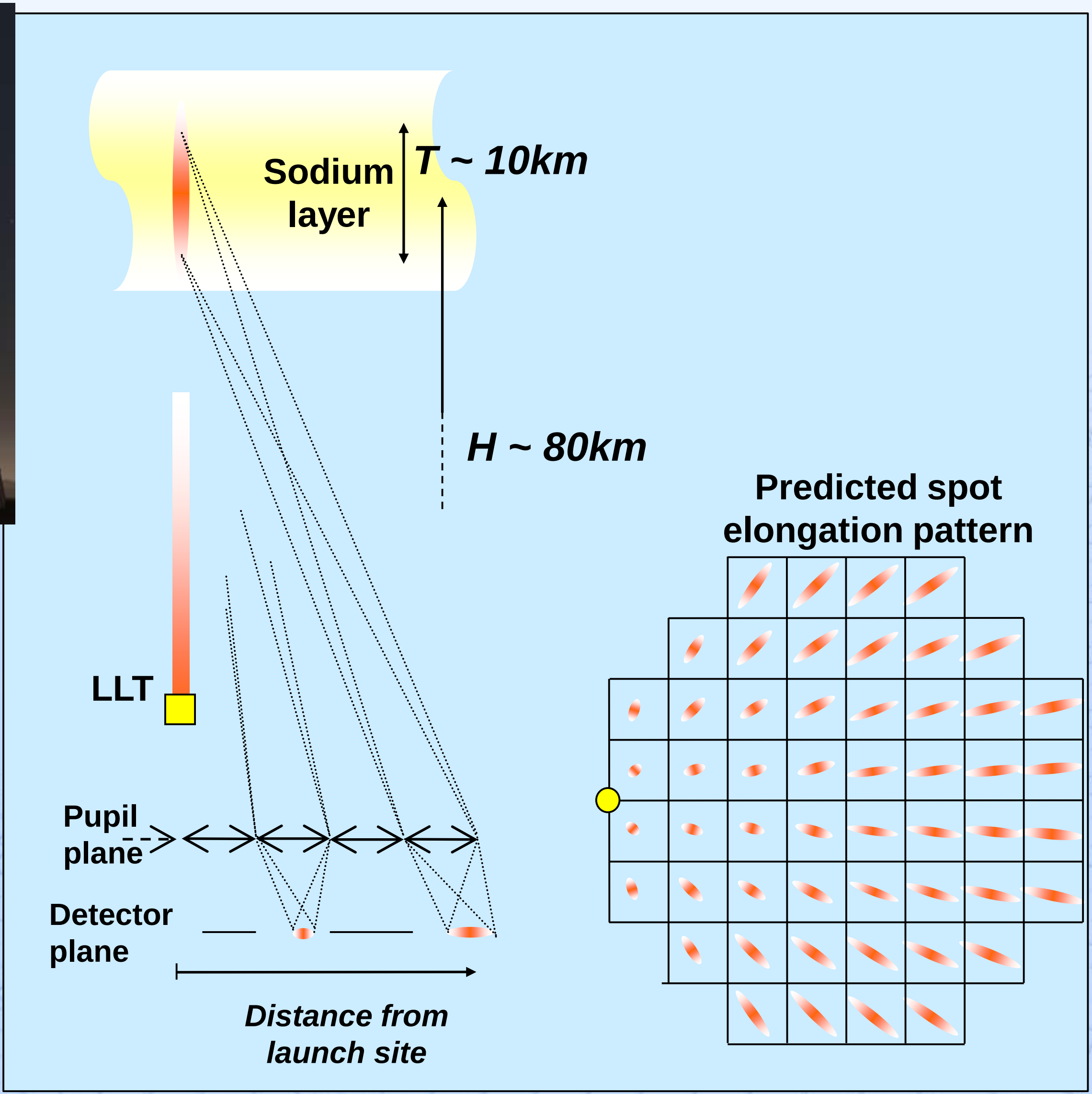


Sodium Laser Guide Stars

- Frame rate ~**<u>1 kframe/sec</u>**

→ require bright "guide stars"

- With natural guide stars only 1% of the sky is accessible
- Sodium layer at 80-90 km altitude can be stimulated by Laser to produce artificial guide stars anywhere on the sky



¼ WFS image

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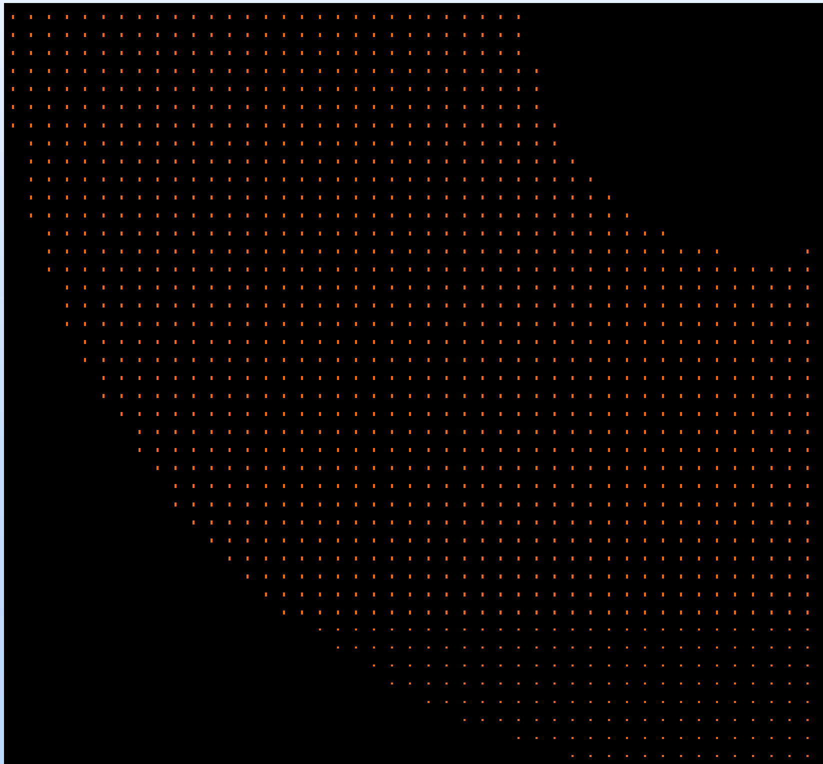


- Would like **80x80** sub-apertures of **25x25** pixels to fully sample the spot elongation → 2kx2k pixels,
- CCD220 not scalable → CMOS Imager

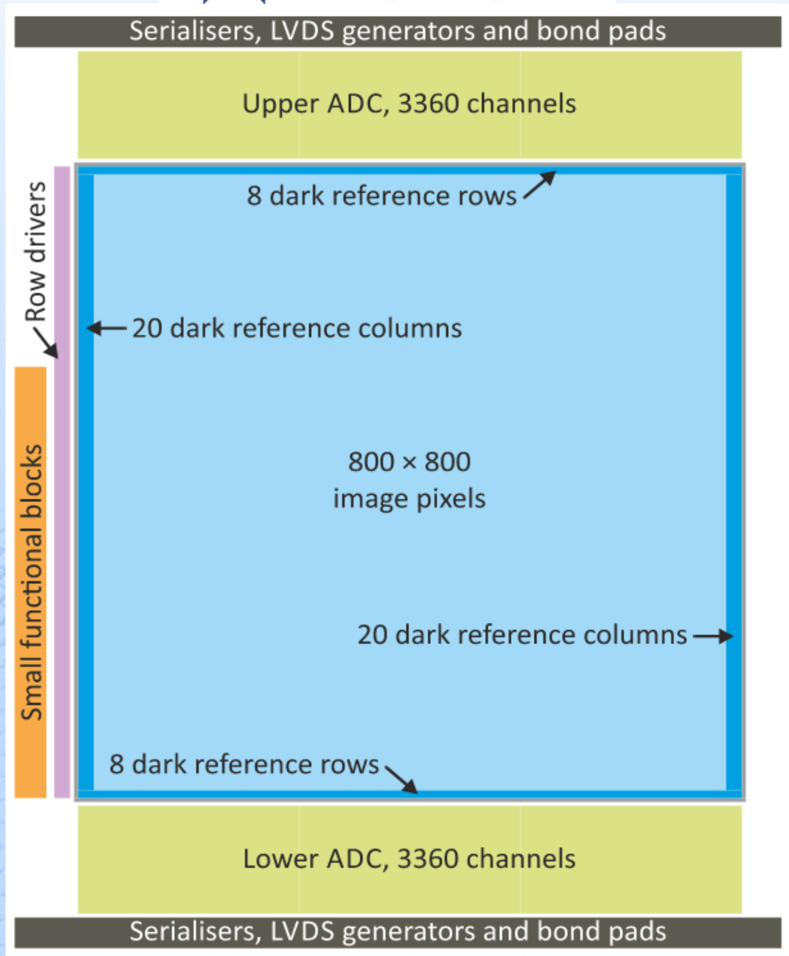
however,

- to ensure devices available on-time for first light instruments, **80x80** sub-apertures of **10x10** pixels → 800x800 pixel Large Visible Sensor Module, LVSM, being developed as first step
- Studies underway to develops techniques of how to handle truncation of spot elongation or use pixels more efficiently

LVSM
Custom Development by Teledyne-e2v

CMOS Imager with Highly integrated readout

- 800x800 continuous array of 24µm pixels
- 700fps at < 3e- read noise
- Backside illuminate for high QE: > 90% at 589nm
- All analog processing on-chip:
  - correlated double sampling (CDS),
  - programmable gain of x1/2/4/8 settable on the fly,
  - 9/10 bit single slope ADCs,
  - for total effective 12 bit data conversion
- 4 rows top + bottom processed in parallel to slow the read out per pixel and beat down the noise
  - 14us/row = 12µs to sample the analog + 2µs ADC
- 24 line at 256Mbit/sec LVDS serial interface to outside world
  - simple easy digital interface to FPGA



Photodiode Design

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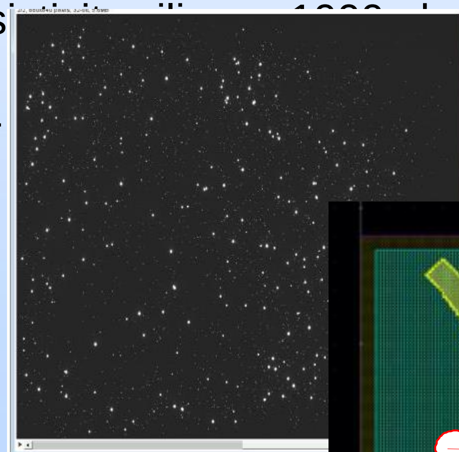
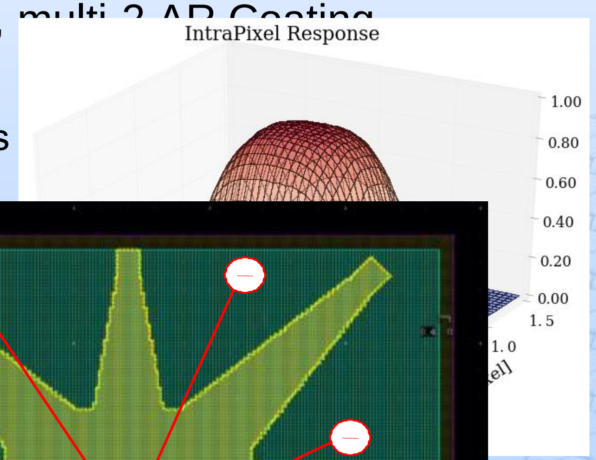
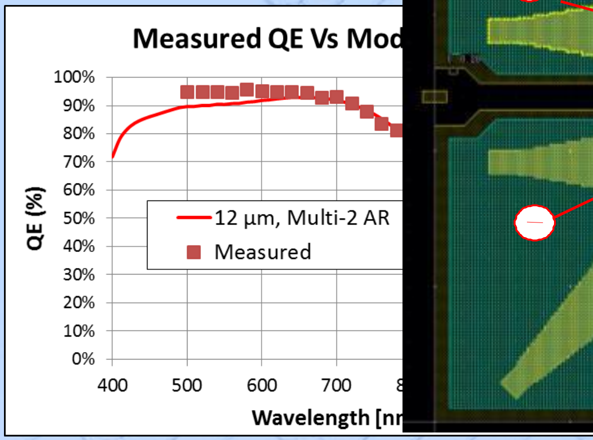
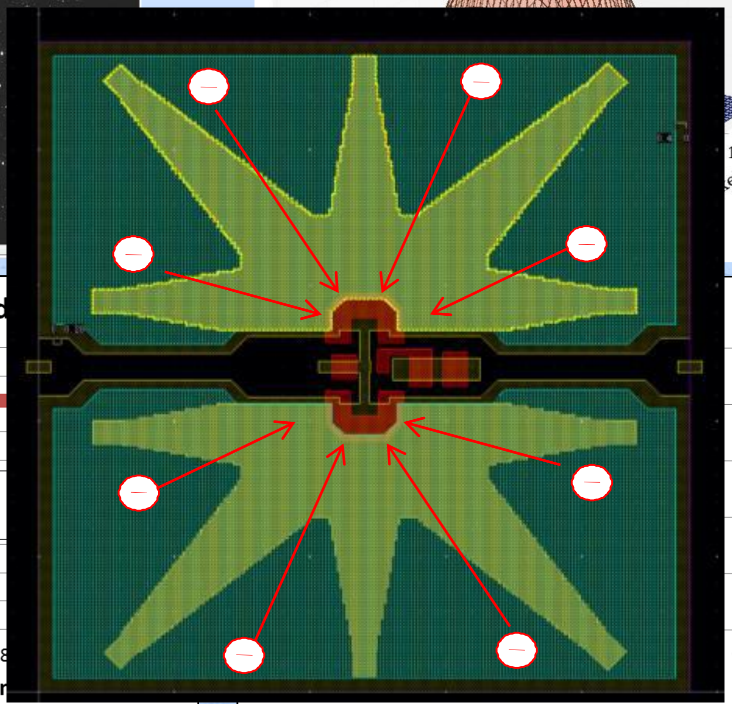
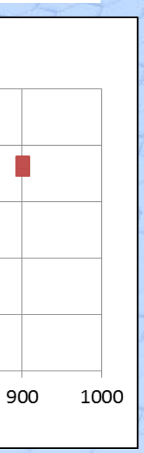
- No white spots - uniform intrapixel response– high QE – good PSF – low image lag
- Photodiode - double-N implant:
  1. a large square implant to guarantee uniform response and good PSF
  2. a tapered finger implant, that provides a potential gradient towards the TG, to improve image lag
- At least 50% area of reflective metal to give high QE in the "red"
- Back-illuminated, high res … n-cm, multi-2 AR Coating
- 12 µm thick:
  - best trade between PSF … evious







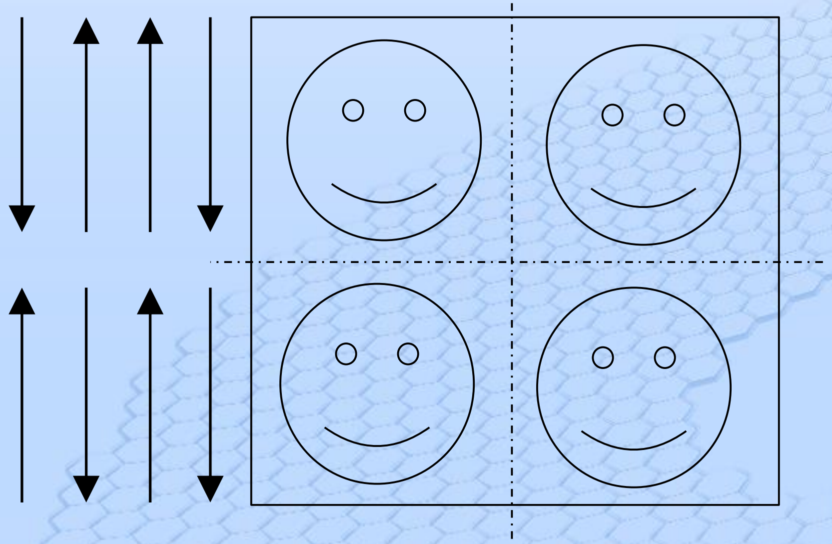


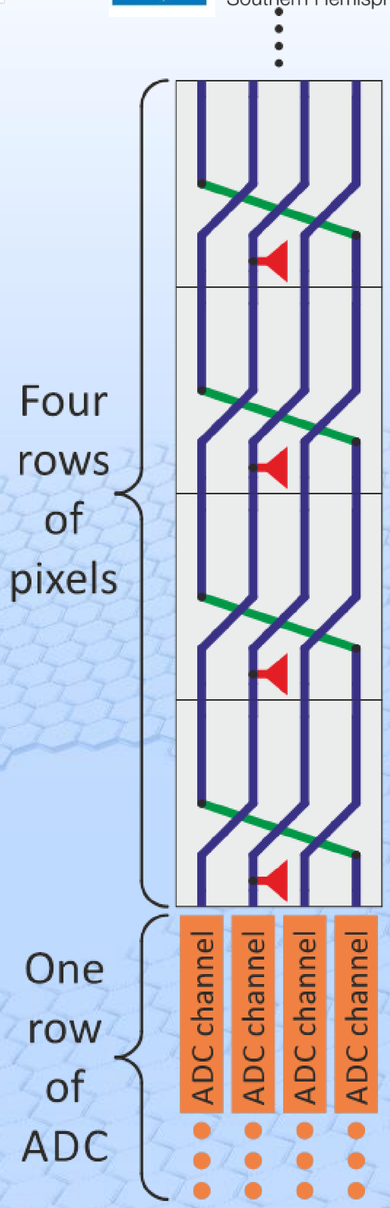


Highly Parallelized Readout

- At top and bottom, in the shadow of each pixel column, is a single row of four readout channels (each 4µm wide) for total of (4x840) 3360 channels across the device.
  - Clean/simple layout with good separation and no capacitive cross-coupling between analog and digital signals
  - Good synchronicity and low latency within a 10x10 pixel sub-aperture (< 2% of exposure time)

Read out direction compatible for both Shack Hartmann and pyramid WFS





Video Chain – single slope ADC

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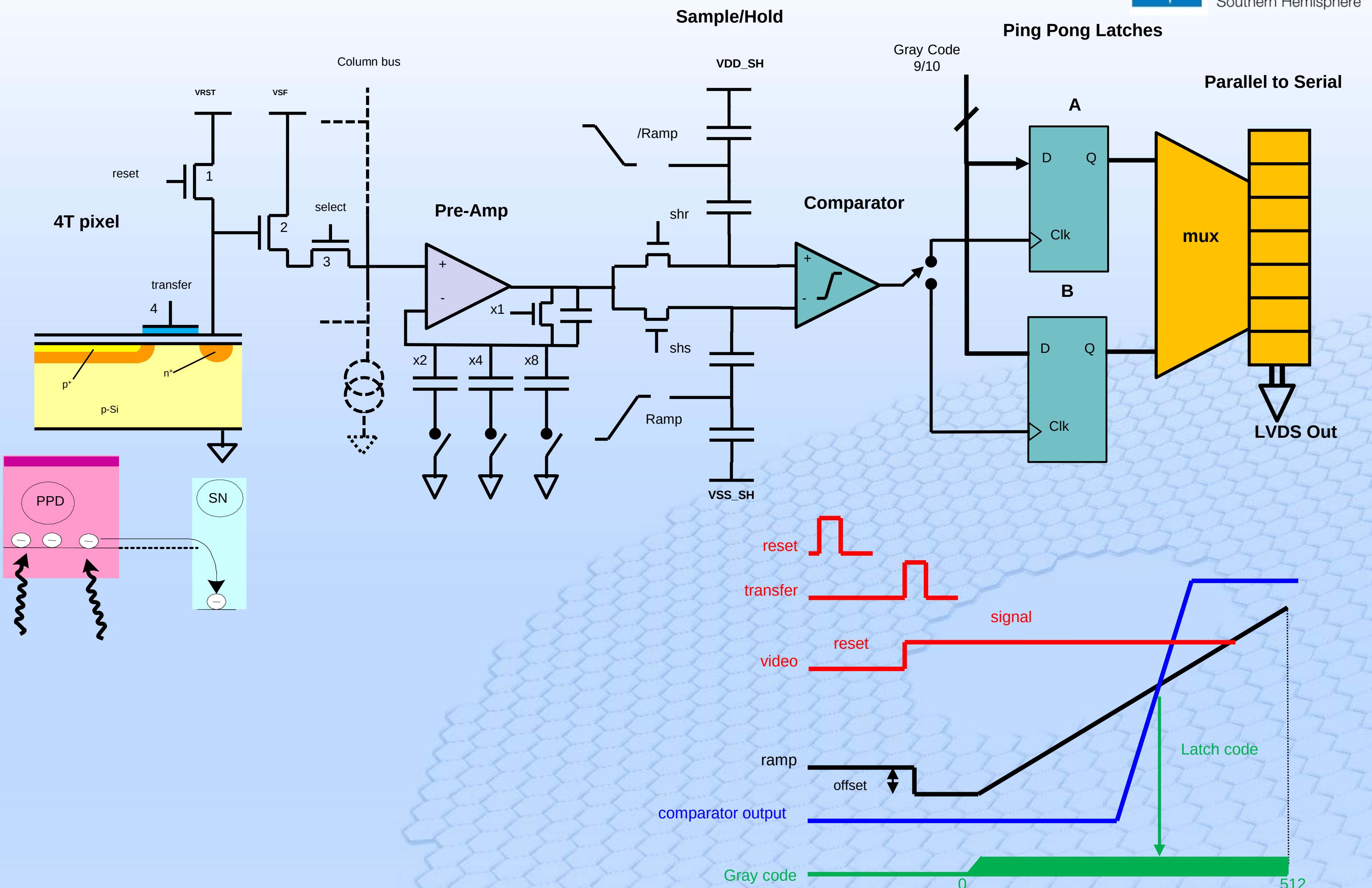
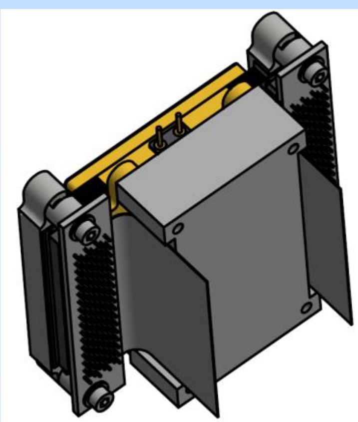
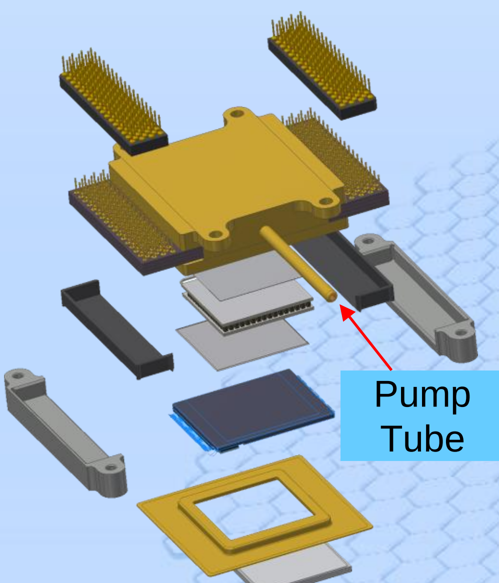


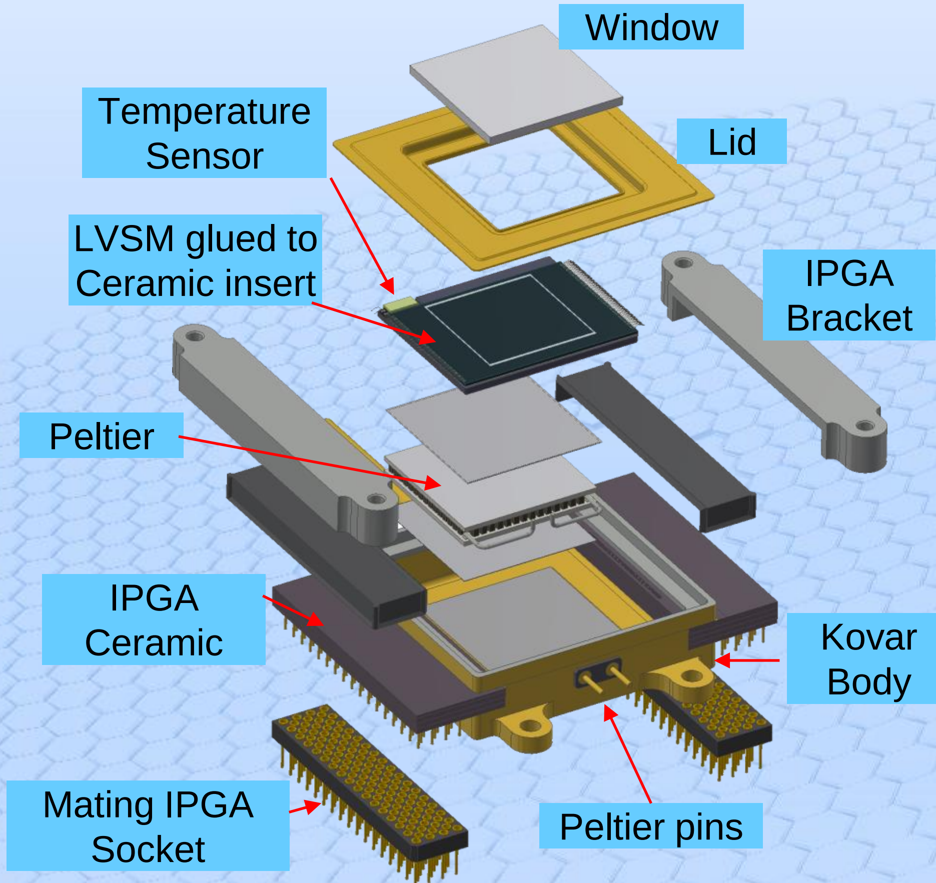
LVSM package - developed with ease of use in mind

- LVSM comes in a integral Peltier package to cool to < -10ºC
- Flat metal base with holes for firmly bolting to heat exchanger
- Kovar body filled with low thermal conductive Krypton gas
- Temperature sensor mounted on chip ceramic carrier
- IPGA array for electrical connections
- Mating socket soldered to flex circuit

TELEDYNE e2V Everywhereyoulook™







LVSM Required Performance

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Pixel full well Q_{FW}	> 4000 e-
Linearity to full well	< 5%
Read noise including ADC	< 3.0 e^{-}_{RMS}
Image lag	< 2 %
Dark Current	< 5 e-/pixel/s ; < read noise at 1fps
QE	> 90% at 589nm; optimized for LGS Sodium Laser → BackSide Illumination (BSI)
Point Spread Function	< 0.8 pixel FWHM
Cosmetics	< 0.1% bad pixels

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Heritage: AONGC - 20 deployed in VLT SPHERE, AO Facility (MUSE & HAWK-I), and ERIS

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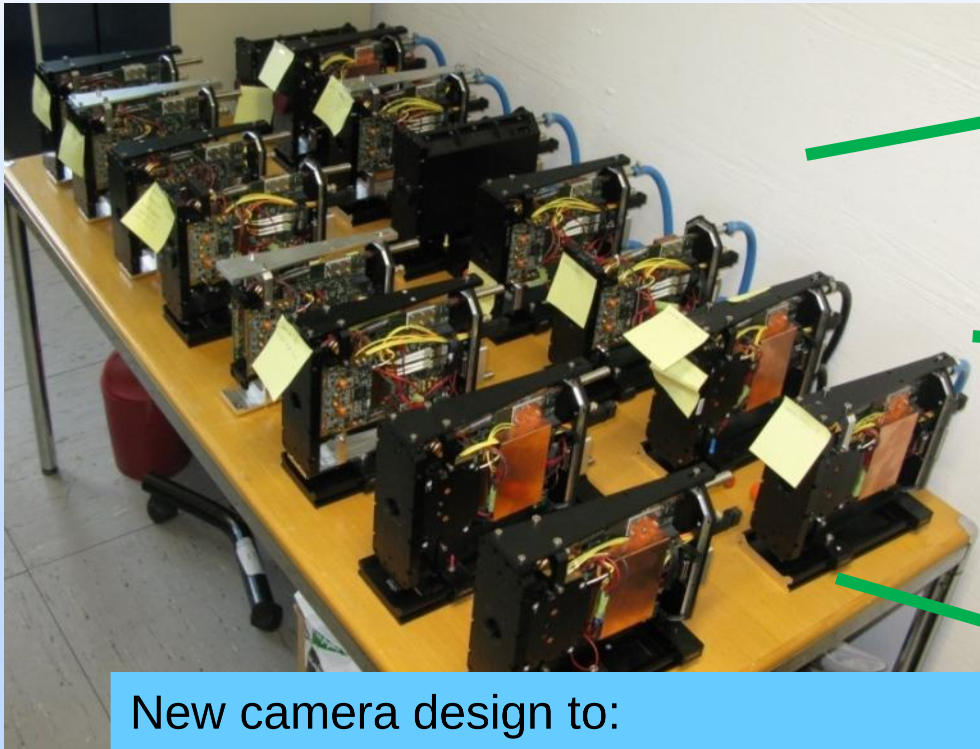
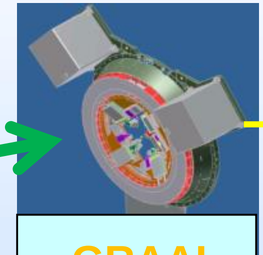
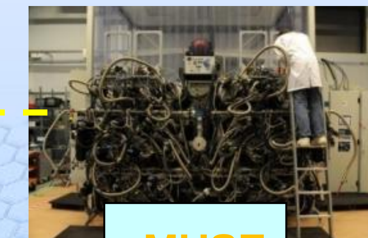




GRAAL

HAWK-I

GALACI



MUSE

ERIS

New camera design to:

- support new detector: LVSM
- add ELT interfaces - 10GbE for data and control and 1GbE for Precision Time Protocol, PTP
- solve obsolescence – AONGC design > 10 years old
- build on previous experience and take on board lessons learnt

Two visible cameras
→ single camera design

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- Approach is a single camera design with customisable front-ends to support the different type of detectors:
  - CCD220-DD for optical Truth/High Order NGS/Telescope Guiding: 1,000fps, ultra low noise (< 1e-), 240x240 of 24µm pixels
  - LVSM CMOS imager for Shack-Hartmann LGS/Telescope WFS: 700fps, low noise (3e-), 800x800 of 24µm pixels
- Depending on the Detector installed, the camera will have a specific name:
  - CCD220-DD → **ALICE** (smALl vIsible CamEra)
  - LVSM → **LISA** (Large vISble cAmera)
- Cameras will be fully integrated with minimal external support equipment
  - only an external 24VDC supply

Camera size ~ 98x183x266 mm^3

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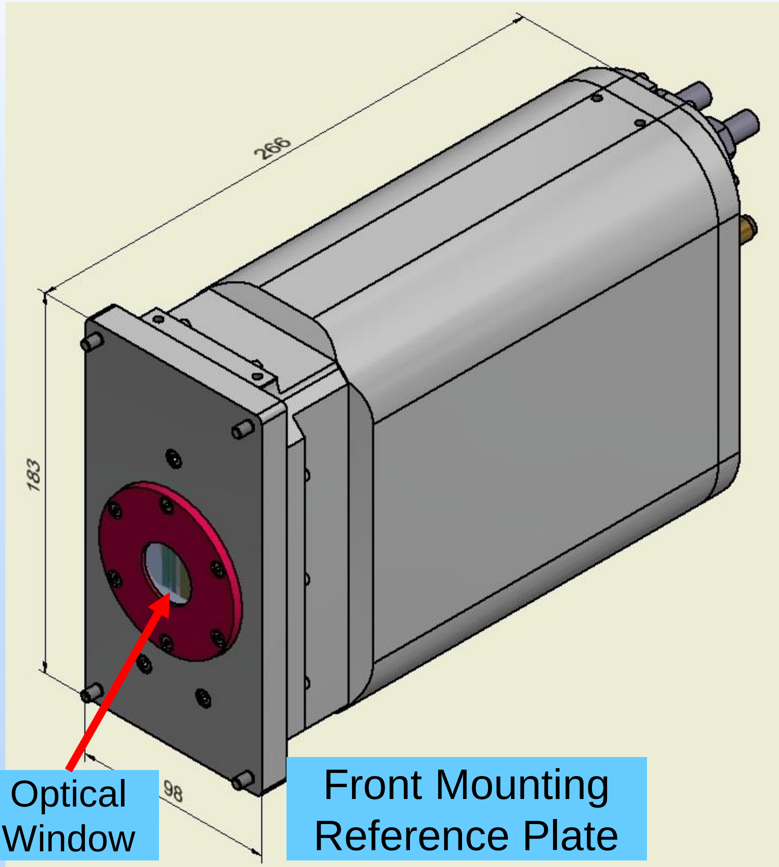
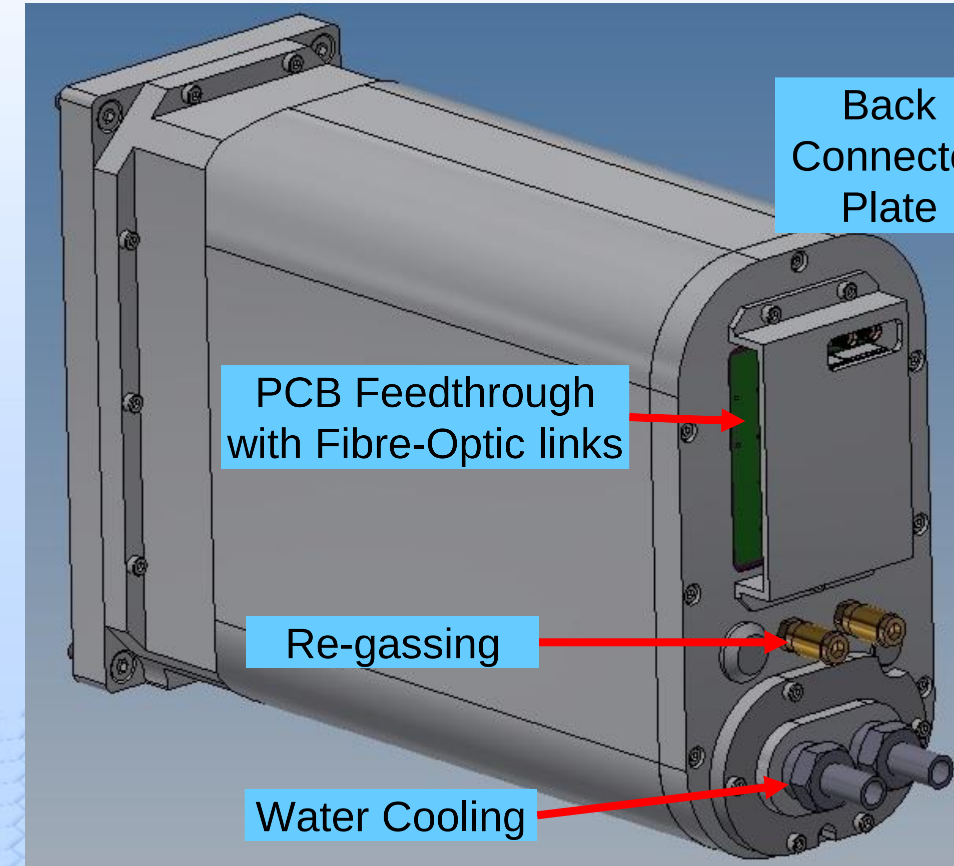
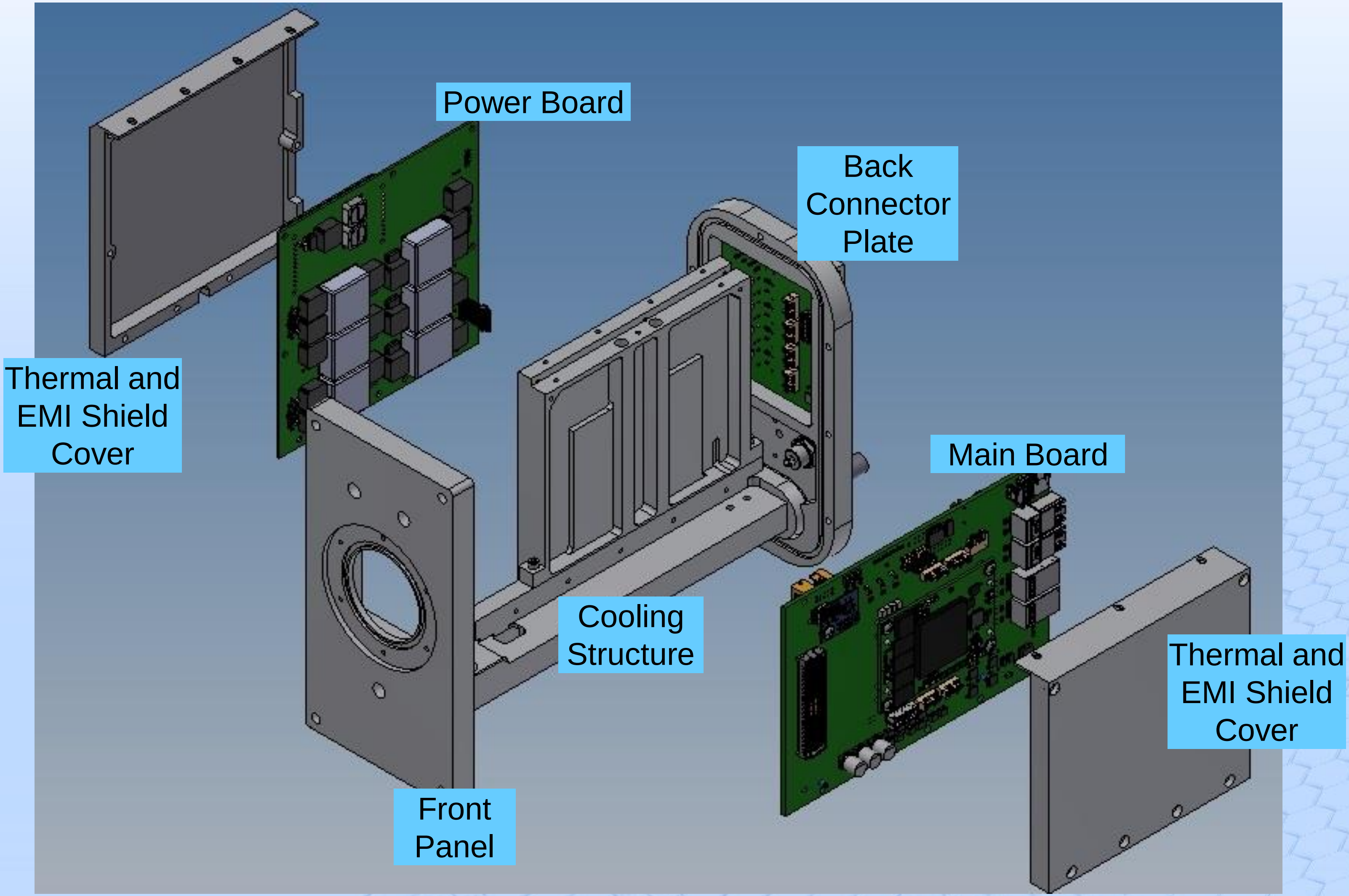




- Externals of cameras are identical except the opening of the optical window
- Front Plate – reference for all alignment of optics and mechanics
- Housing sealed to stop ingress of dust and moisture (condensation).
- Water Cooled → conductive cooling → housing external surface < 1.5ºC

Cameras are built around a Common Backbone



Power Board designed for high efficiency using Switch-Mode Power Supplies

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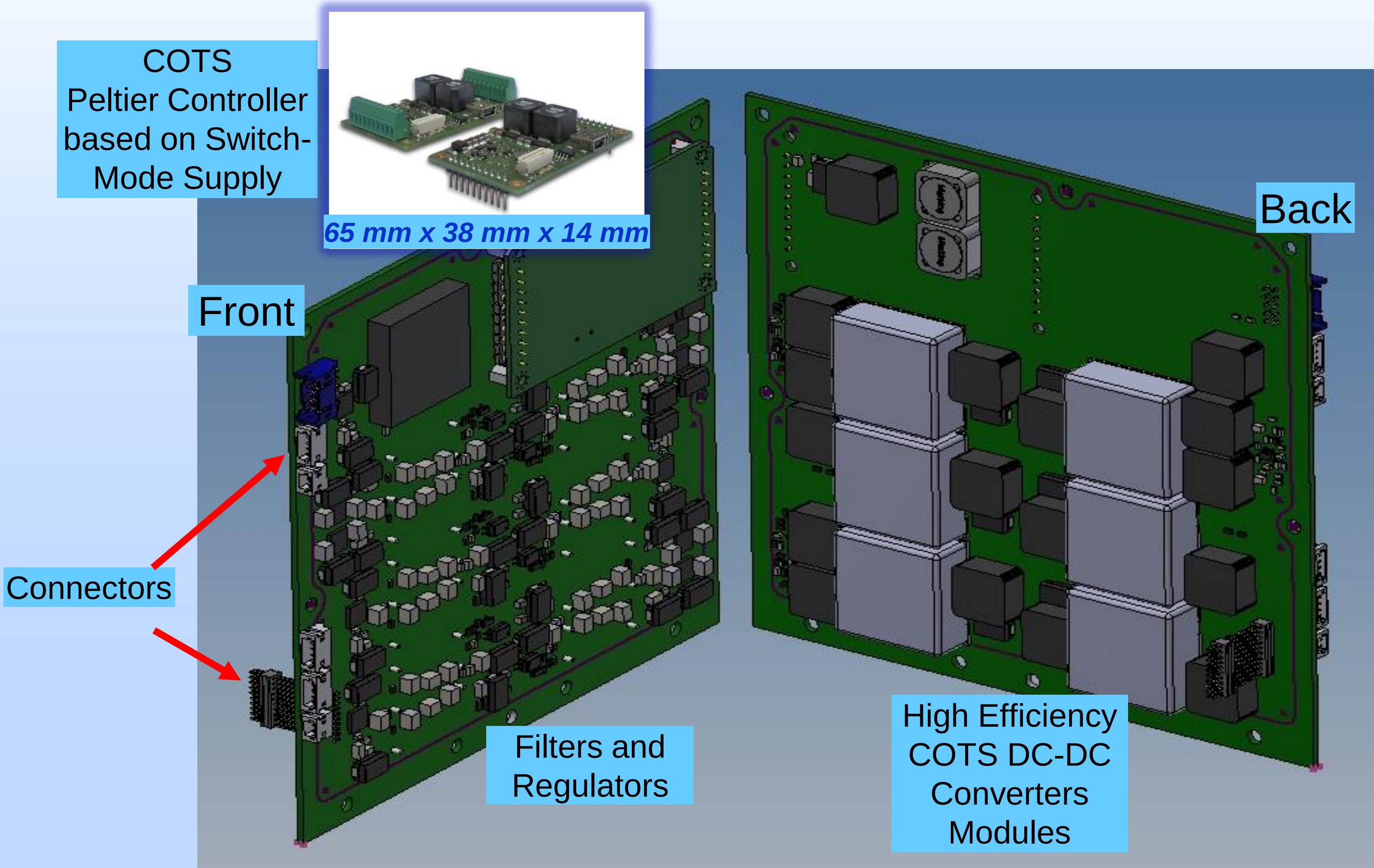

- COTS components are used wherever possible and practical
  - saves substantial development effort and validation time

Low Noise of Power Board fully validated on previous generation of camera

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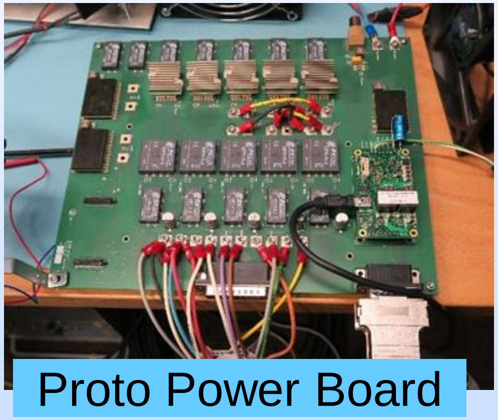

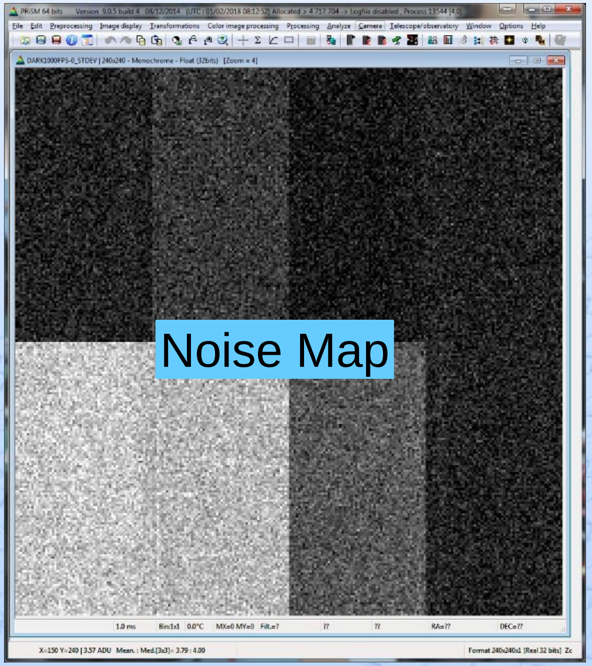

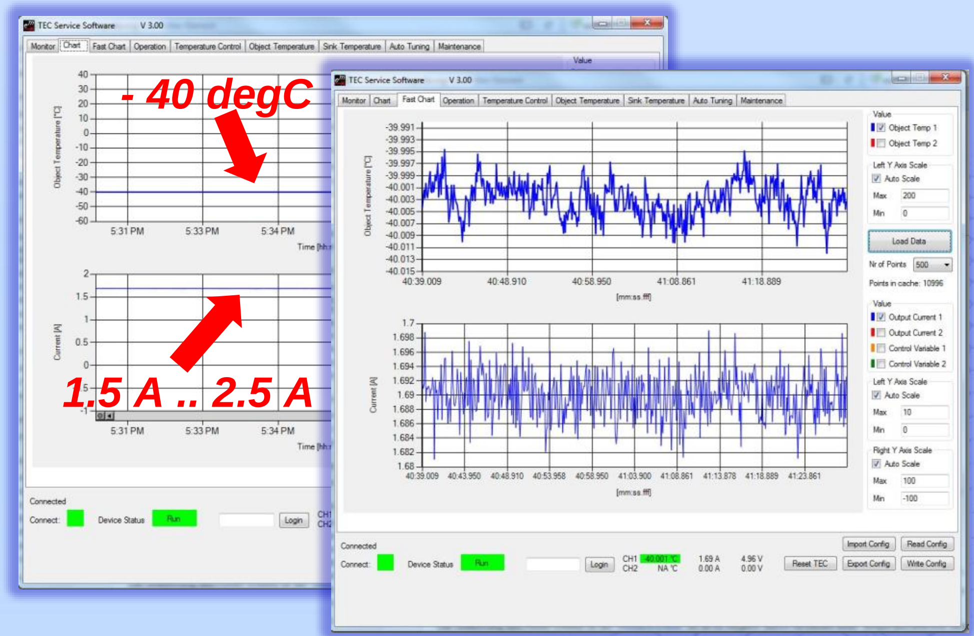

- Detector temperature cooled and stabilized to high stability of ±10mK
- No structure or appreciable increase in the very low noise of AONGC

Main Board based on COTS FPGA Module

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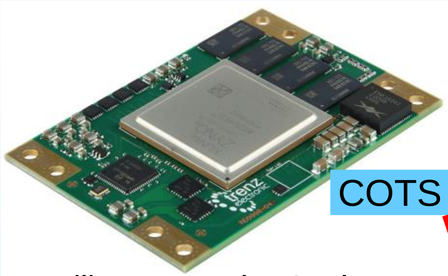
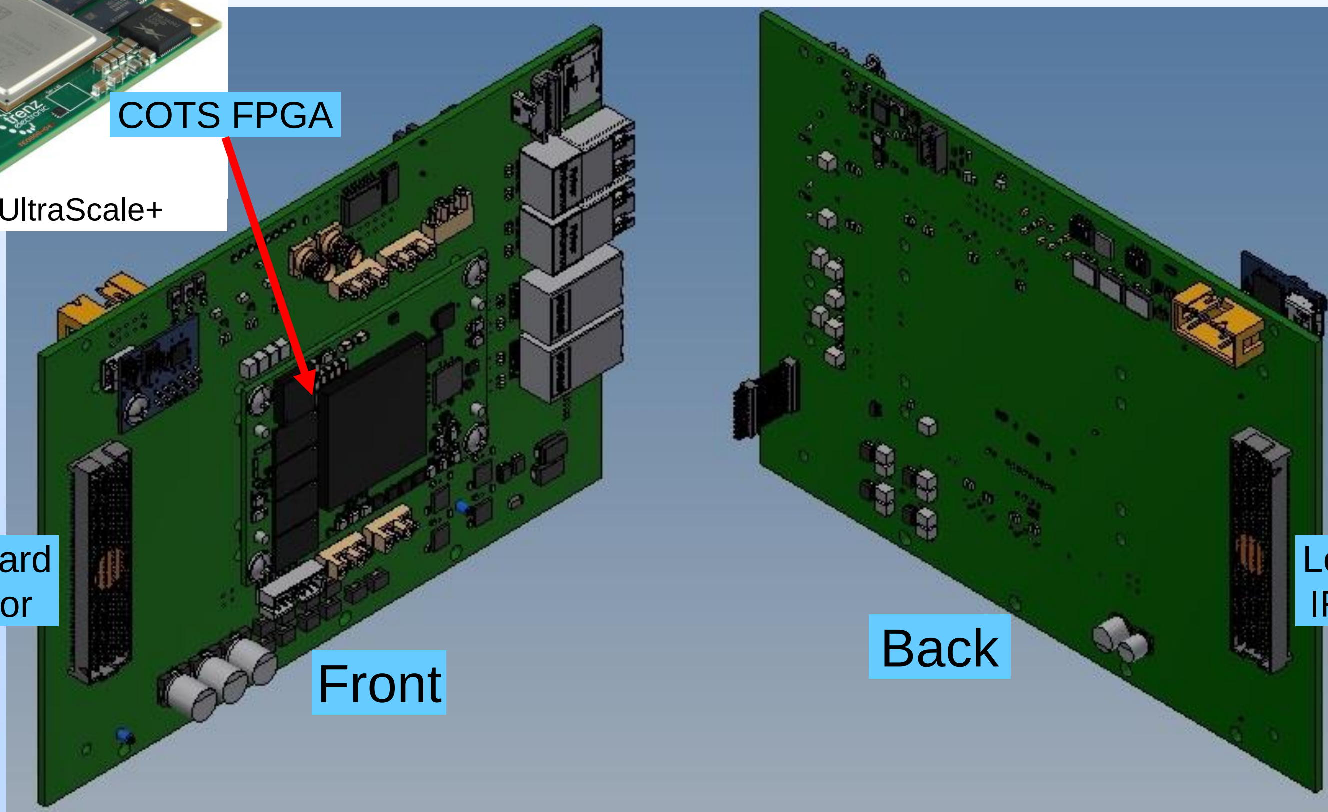


Xilinx Zynq UltraScale+



Controls the read out of the Detector and handles all external communication:

- 10GbE optical fibre links to the NGC control computer and RTC (UDP)
- 1GbE optical fibre link of the Precision Time Protocol (the ELT time reference standard) for synchronizing, scheduling, and time stamping frames.

Customisable FE for Detector specific support

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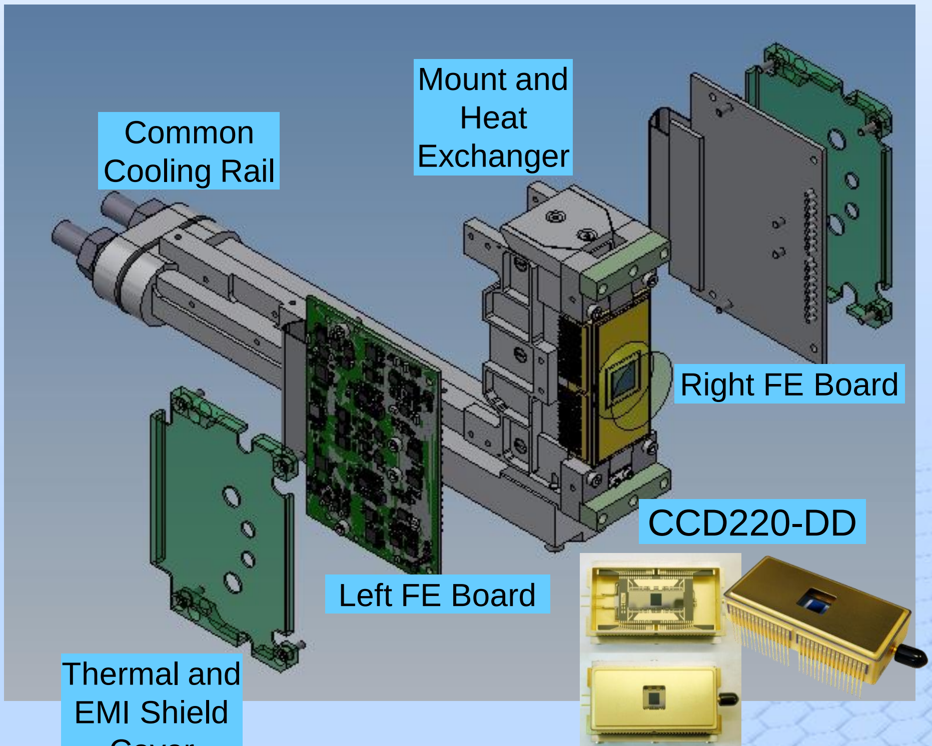
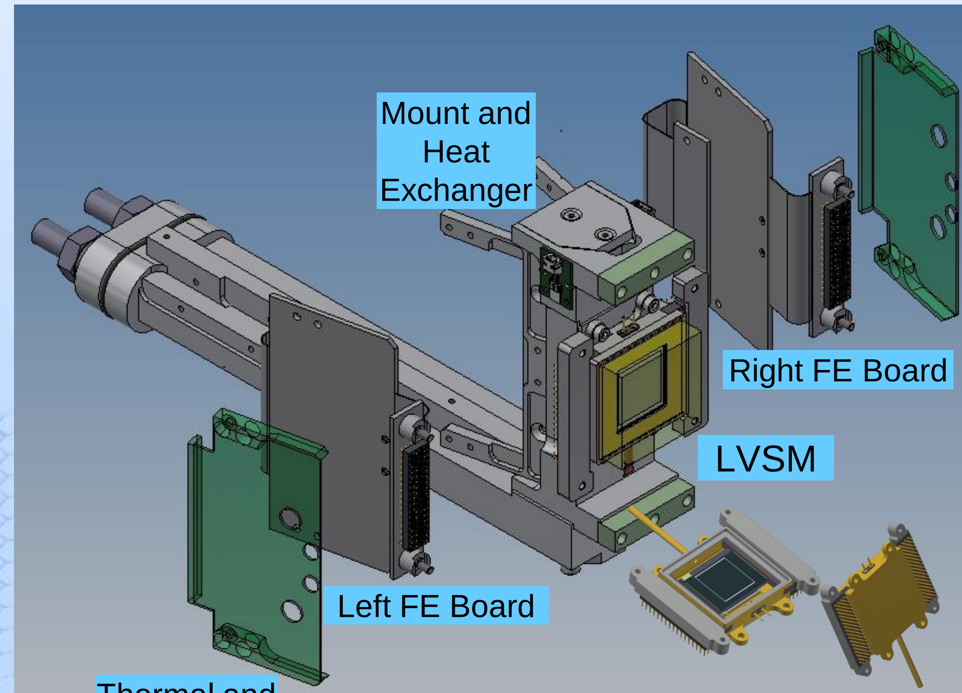
ALICE



LISA



Summary

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- ESO has a very active Detector and Camera technology development program to meet current and future needs of wave-front sensing
- The new CMOS Imager, LVSM, has passed its FDR milestone and is in manufacture with first Electrical Grade devices available later this year for camera testing
- Cameras are at an advanced stage of design, and, manufacturing of the first revision is under way with integration and test of the first cameras scheduled later this year
- High confidence of success from using all lesson's learnt from previous developments and prototypes.
- The development phase of the cameras is expected to take another 18 months followed by out sourcing of production to have cameras available in time for ELT Telescope and Instrument AIV

Future CMOS Imager

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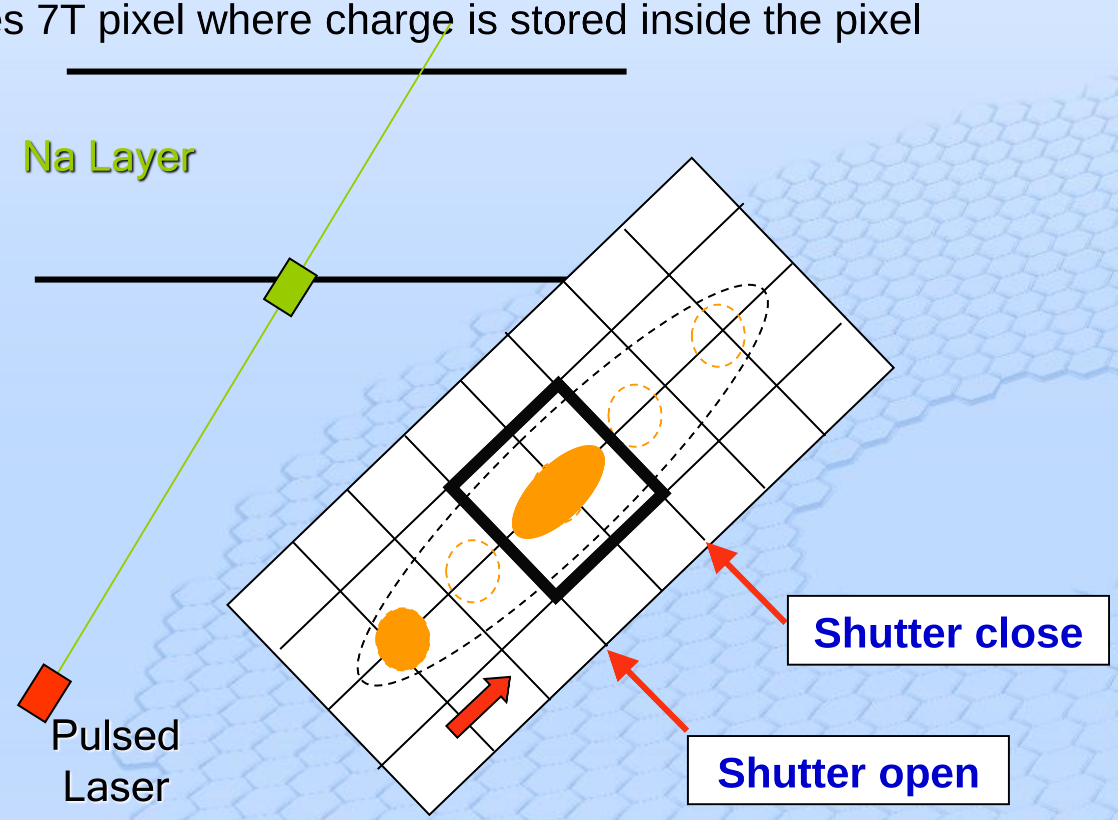
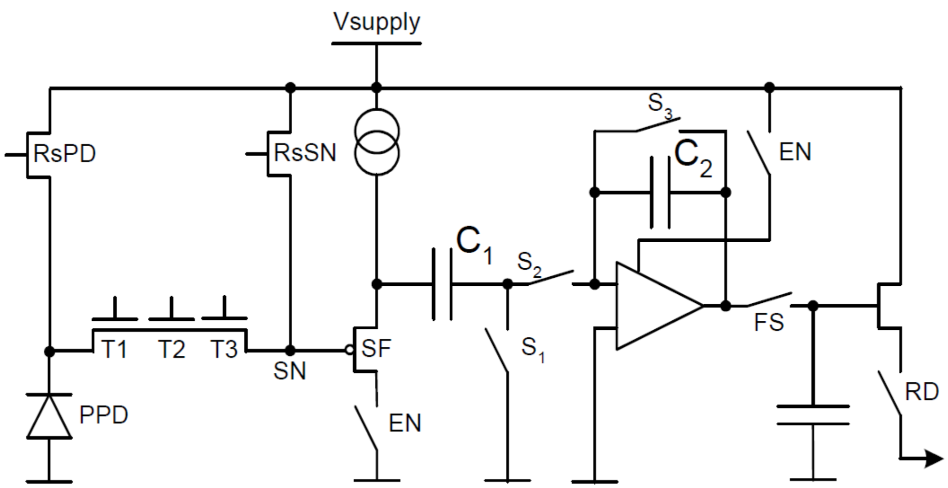
- Larger
  - LVSM at 700fps – 2k x 2k
  - SAPHIRA – 512x512
- Handle Pulsed Laser:
  - Shutter opens for 2-3us
  - Requires 7T pixel where charge is stored inside the pixel



7T pixel



PPD	**- Pinned Photodiode**
T1 – T3	**- Transfer Gates (Pixel Level CCD)**
SN	**- Sense Node**
SF	**- Source Follower**
FS	**- Frame Sample**
RD	**- Read**
Rs	**- Reset**
EN	**- Enable**
LP	**- Laser Pulse**
Q_{LP_x}	**- Photo generated charge from LP number x**
M	**- number of laser pulses per frame**
C_{SN}	**- Sense node capacitance**

$$V_{out} = \frac{C_1}{C_2} \cdot V_{LP_\Sigma}$$

$$V_{LP_\Sigma} = \frac{Q_{LP_1} + Q_{LP_2} + \ldots + Q_{LP_n}}{C_{SN}}$$

- Gates T1 – T3 are clocked
- Pixel provides
  - Charge Domain Accumulation
  - Correlated Double Sampling readout (offset and kTC noise corrected)
  - Voltage amplification
  - Snapshot shutter functionality

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END

Pulsed laser: track spot on CCD

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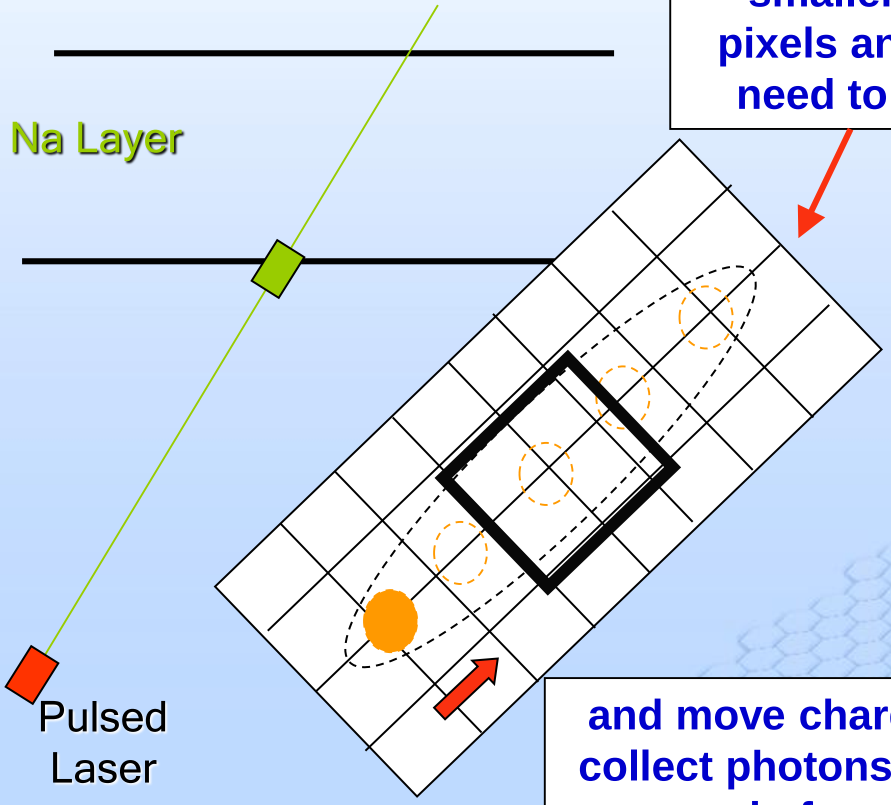

Spot contained in much smaller number of pixels and only these need to be read out

and move charge back and forth to collect photons from several pulses before reading out.