



# High QE, Thinned Backside-Illuminated, 3e- RoN, Fast 700fps, 1760x1760 Pixels Wave-Front Sensor Imager with Highly Parallel Readout

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# Outline

- ESO and European Extremely Large Telescope E-ELT
- Wavefront Sensing and Adaptive Optics
- Specifications of the E-ELT WFS
- Results of the Technology Demonstrator, the TVP
- WFS Architecture and Design
- The massive parallel data problem
  - Solution - balanced clock tree of 88 LVDS channels



# Who is ESO?

- European Organization
  - 15 member states: Germany, France, Italy, Switzerland, Netherlands, Belgium, Portugal, Denmark, Sweden, UK, Finland, Spain, and Czech Republic, Austria, Brazil
- Goal – to provide astronomers with state-of-the-art observational facilities



Garching bei München



Chajnantor

La Silla

Paranal

Santiago

Operates 3 sites in Chile

Two optical observatories

Paranal (2600m)

La Silla (2400m)

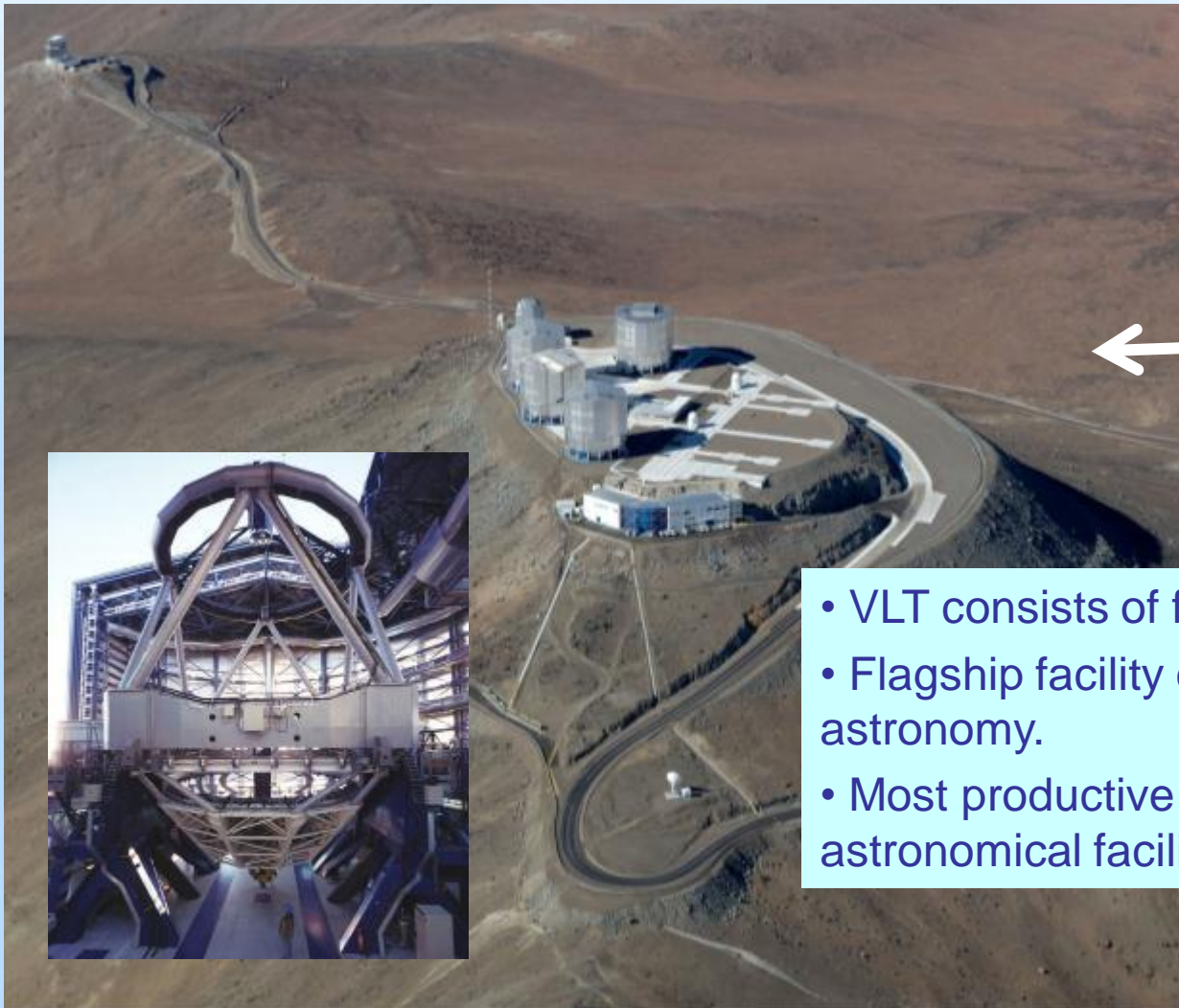
One submillimeter

Chajnantor (5000m)



# Paranal

→ Very Large Telescope



- VLT consists of four 8.2 m Telescopes
- Flagship facility of European ground-based astronomy.
- Most productive individual ground-based astronomical facility.



# Our Next Challenge → European Extremely Large Telescope (E-ELT)

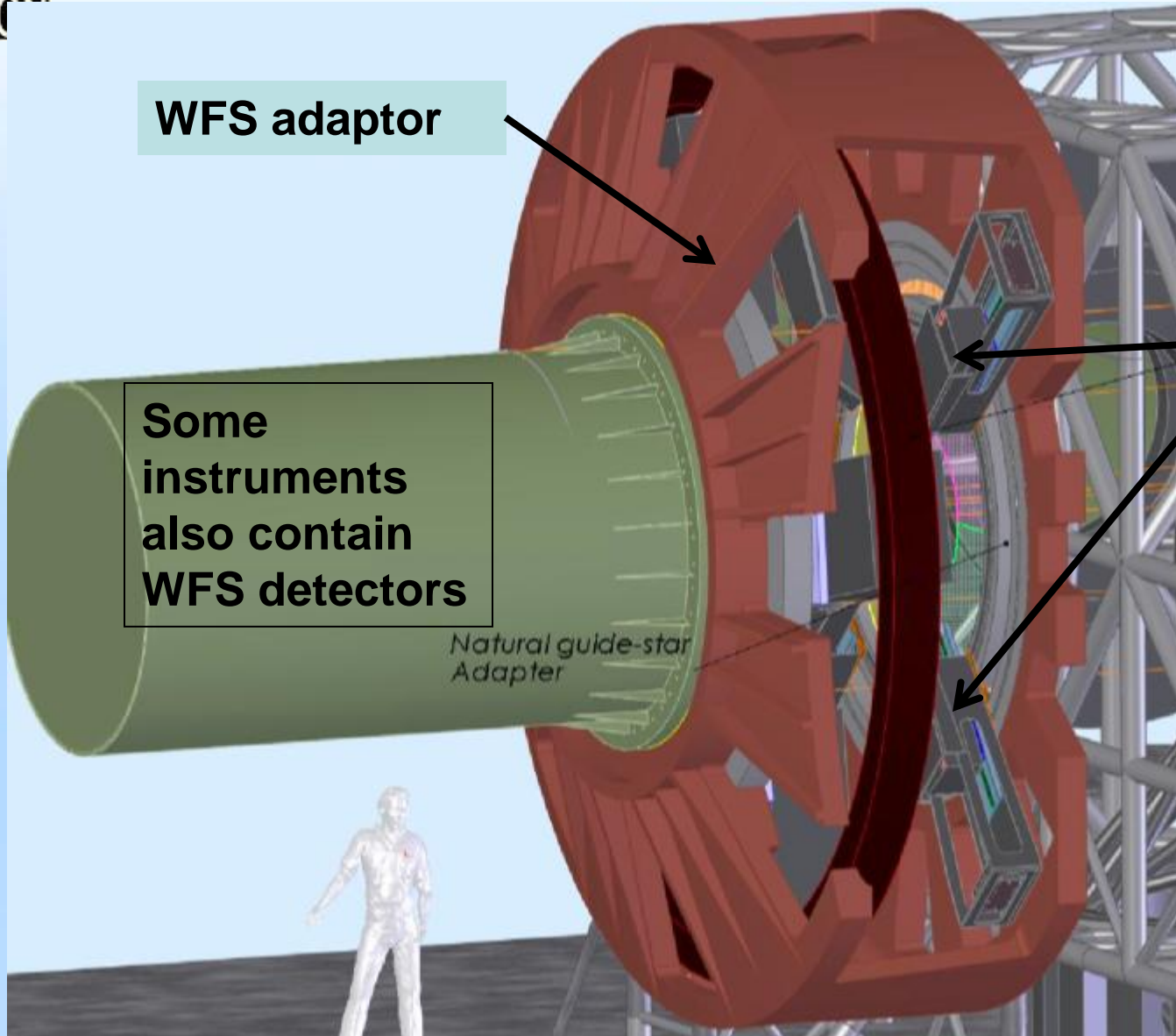


- E-ELT - a 39.5 m diameter, fully Adaptive Optics telescope.
- The E-ELT will be the **largest** optical/near-infrared telescope in the world (its mirror diameter will be almost half the length of a football field).
- Construction planned to begin next year; design complete and accepted





# Wavefront sensors



**WFS adaptor**

**Some instruments also contain WFS detectors**

*Natural guide-star Adapter*

**WFS arms (contain WFS detectors)**



# Adaptive Optics (AO)

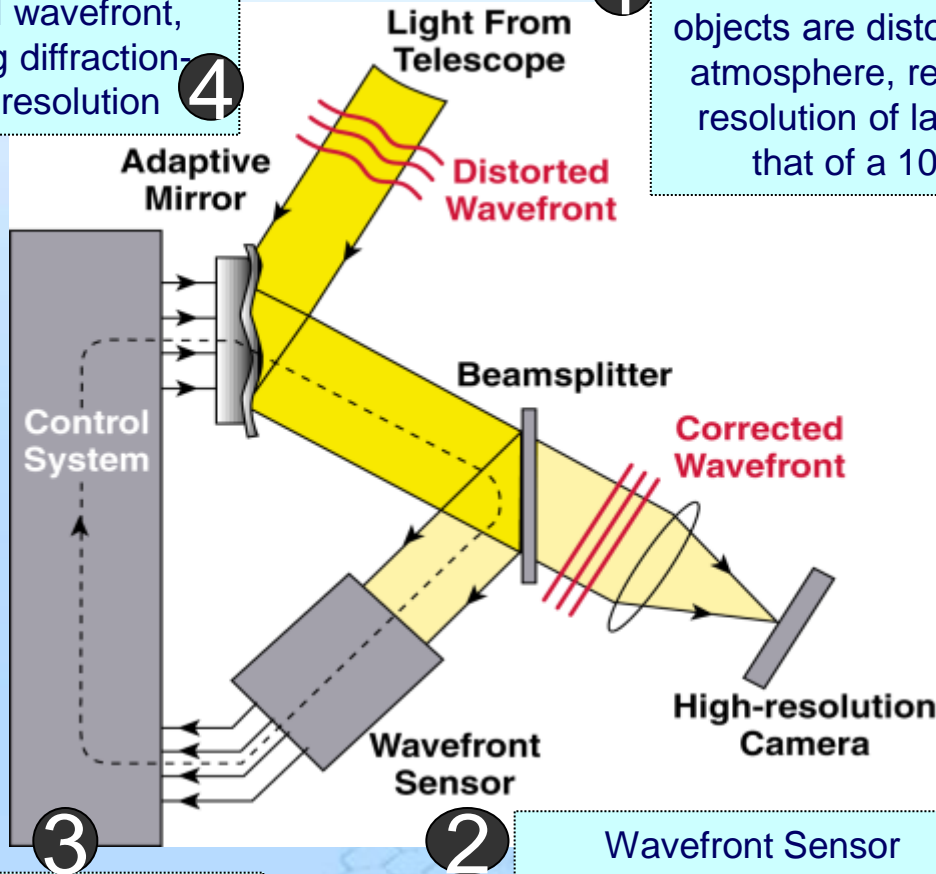
- removing the twinkle of the stars

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

4

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



3

Control System  
computes  
commands for the  
deformable mirror(s)

2

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

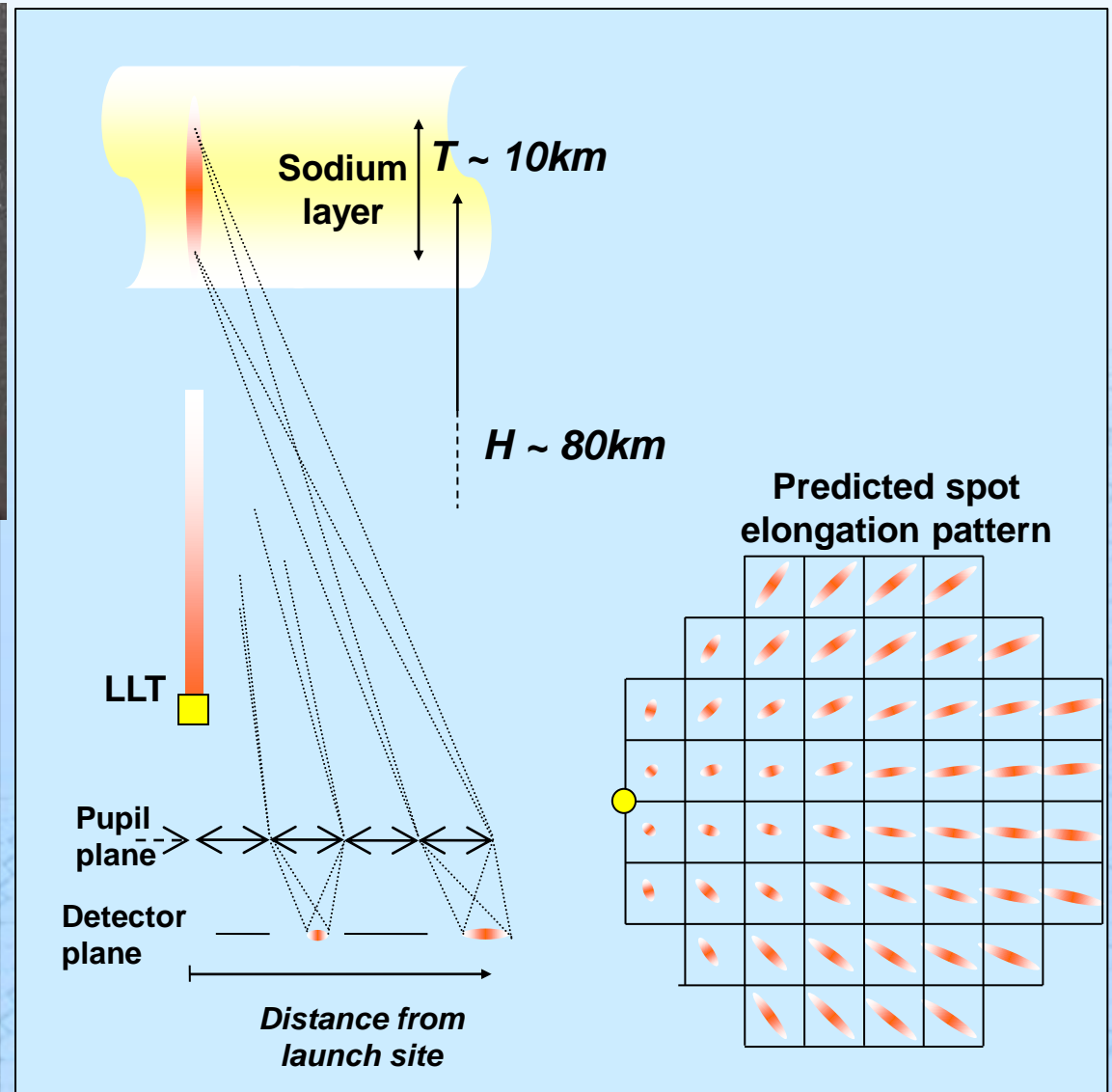


# Large Visible AO WFS Detector needed to sample the spot elongation



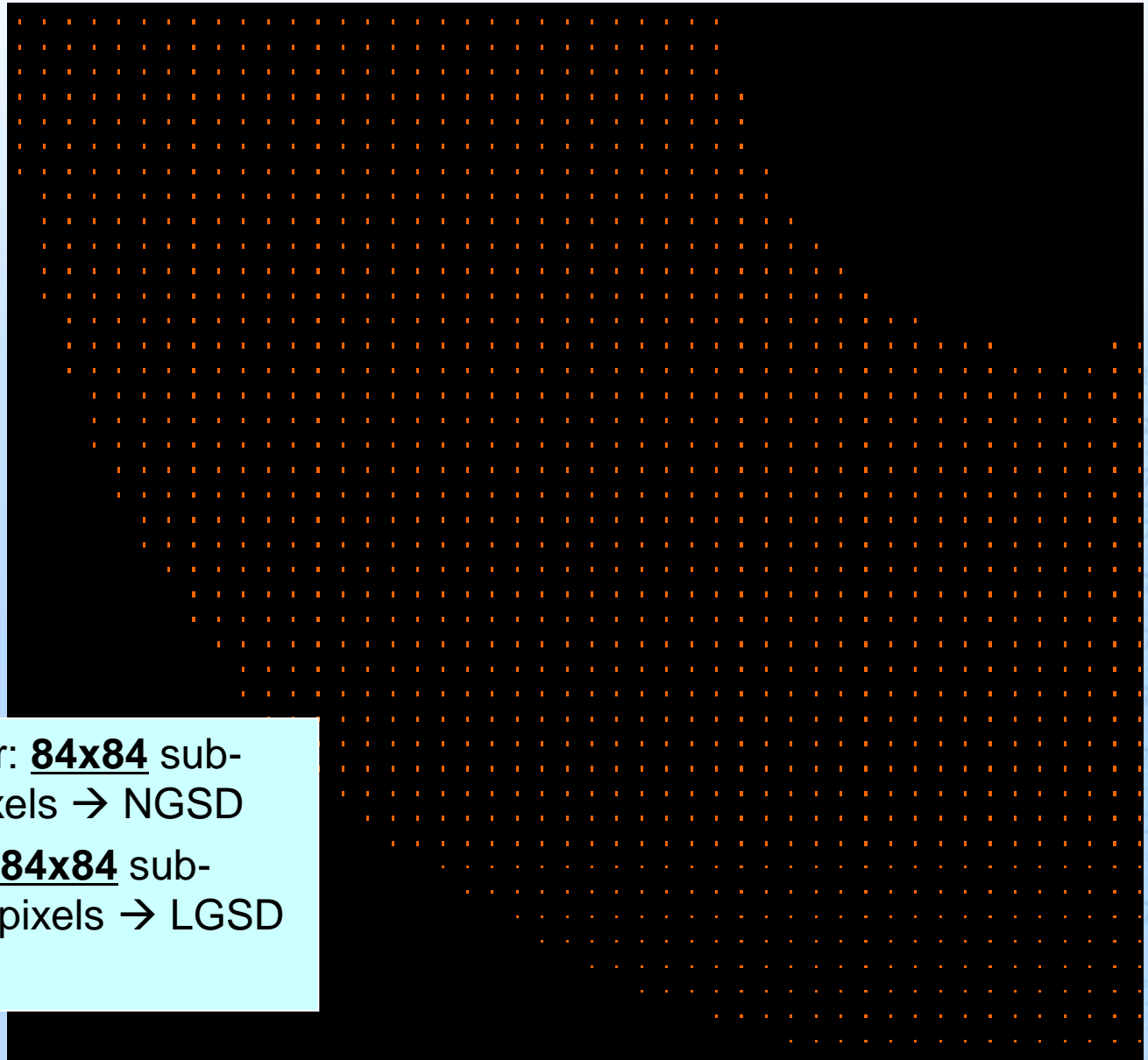
## Sodium Laser Guide Stars

- Frame rate  $\sim 1$  kframe/sec  
→ 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





# $\frac{1}{4}$ WFS image

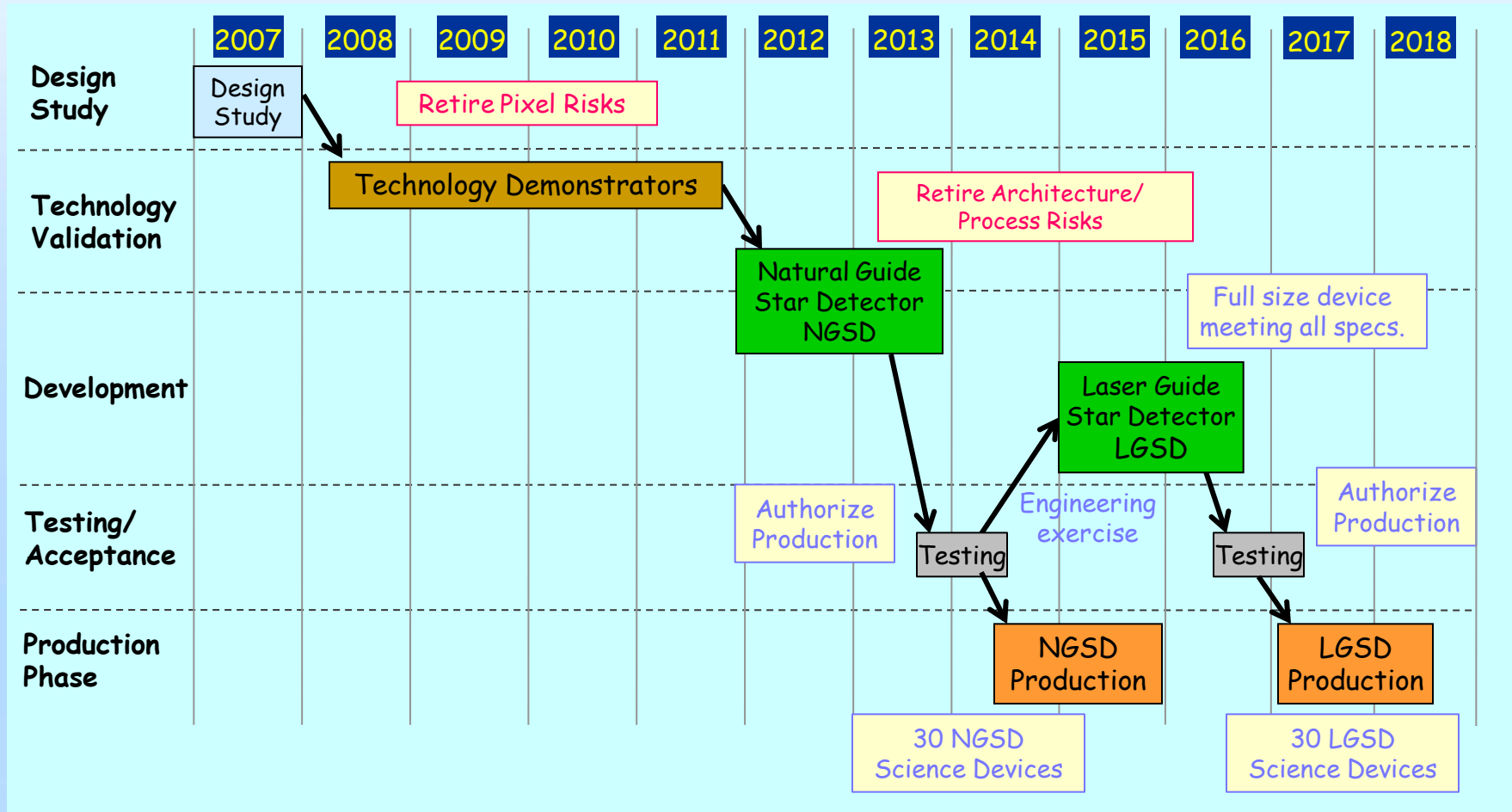


- Natural Guide Star: **84x84** sub-apertures of **8x8** pixels  $\rightarrow$  NGSD
- Laser Guide Star: **84x84** sub-apertures of **20x20** pixels  $\rightarrow$  LGSD



# ELT WFS DETECTOR

Multi-phase plan to progressively retire risk





# Specifications of the ELT WFS

## Physical characteristics

Pixel array (includes dark reference pixels)	Stitched design for two versions: “Natural Guide Star Detector” NGSD - 880x840 pixels then “Laser Guide Star Detector” LGSD - 1760x1760 pixels
Technology	Thinned backside illuminated CMOS 0.18 $\mu$ m
Pixel pitch	24 $\mu$ m
Pixel topology	4T pinned photodiode pixel
Array architecture	<u>84x84</u> time coherent “sub arrays” of <u>20x20</u> pixels - LGSD image area size of 4x4cm
Shutter	Rolling shutter in chunks of 20 rows → synchronous detection within a sub-array.



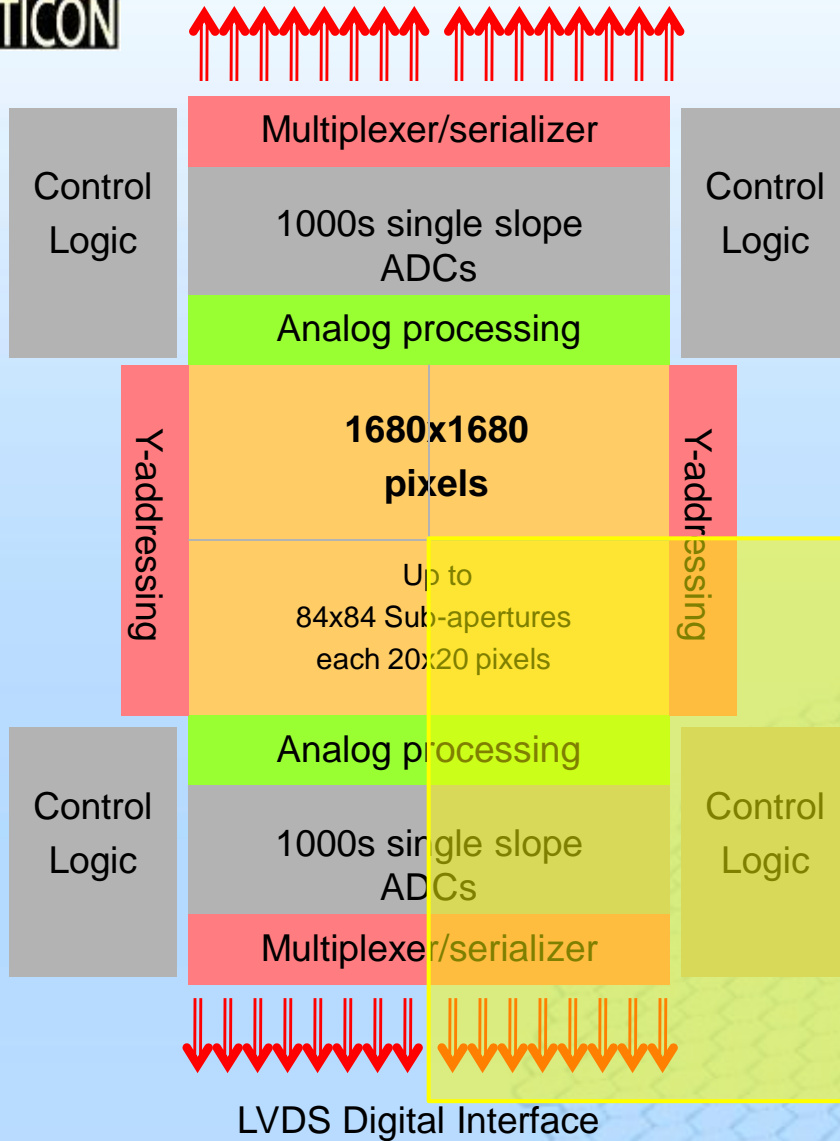
# Specifications of the ELT WFS Performance

Responsivity	100 to 160 $\mu\text{V}/\text{electron}$
Pixel full well $Q_{\text{FW}}$	4000 $e^-$
Read noise including ADC	$< 3.0 e^-_{\text{RMS}}$
QE	QE above 90% over the visible range → BackSide Illumination (BSI)
Image lag	$< 0.1 \%$
MTF	ideal and symmetric in X and Y by design



# Block Diagram of Full Size Device

LVDS Digital Interface



## Highly integrated

- All analog processing on-chip:
  - correlated double sampling (CDS),
  - programmable gain,
  - ADCs
- Many rows processed in parallel to slow the read out per pixel and beat down the noise.
  - trade study showed 20-40 to be the optimum number
- Fast digital serial interface to outside world
  - power consumption similar to high speed drivers to transport the analog signal off chip
  - better guarantee of achieving and maintaining low noise performance

## Natural Guide Star Detector (NGSD)

scaled down demonstrator  
 ~ 1/4 of full size → no stitching

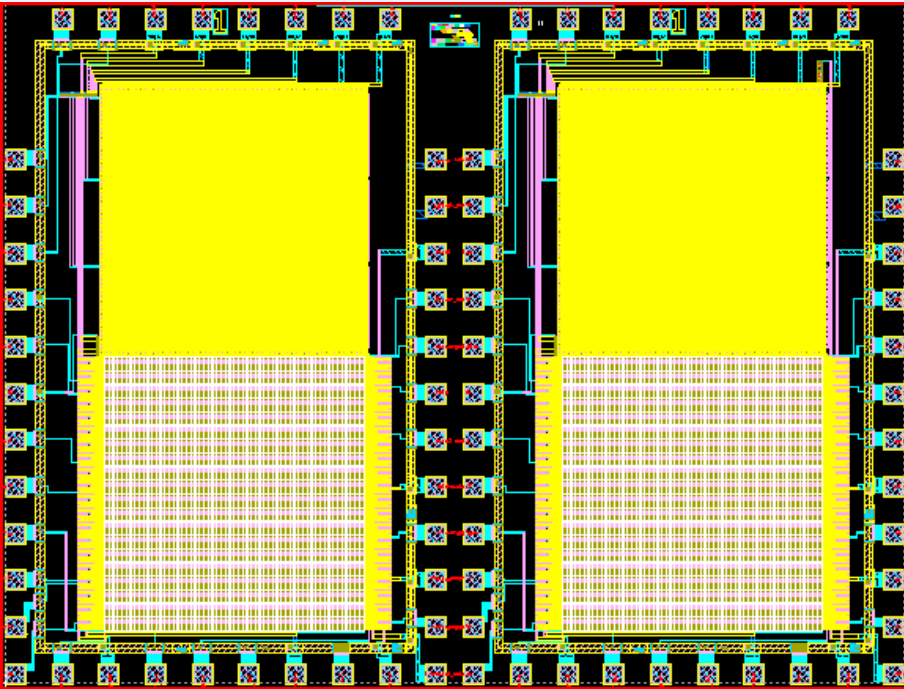


# Specifications of the ELT WFS

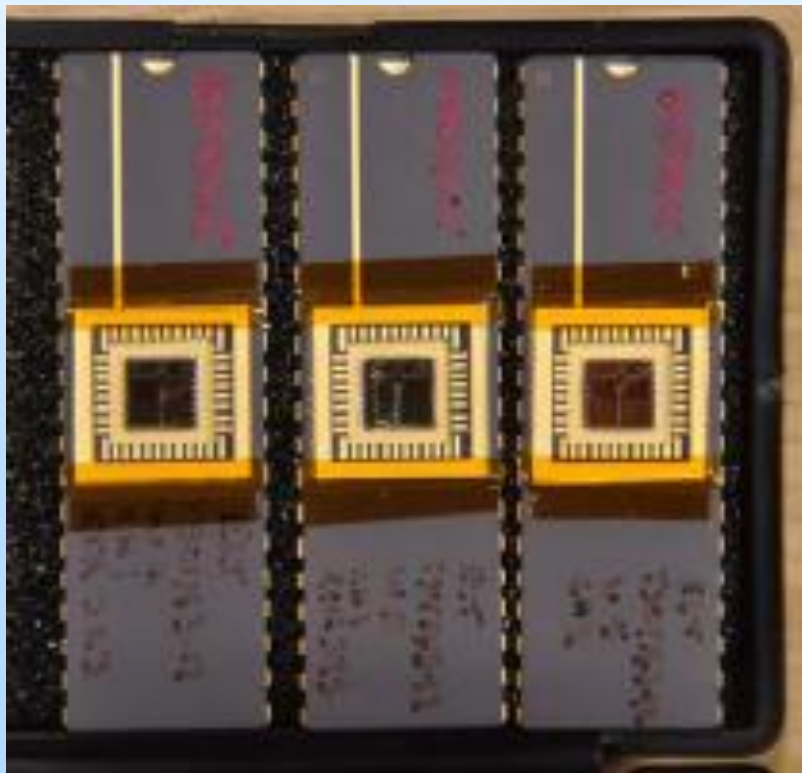
## Read out

Number of rows read in parallel	40 (LGSD) or 20 (NGSD) rows in parallel
Number of ADC's	40x1760 (LGSD) or 20x880 (NGSD)
Number of parallel LVDS channels	22 (NGSD) or 88 (LGSD)
Serial LVDS channel bit rate	210 Mb/s baseline, up to 420 Mb/s (desired)
Frame rate	<u>700 fps</u> up to 1000 fps with degraded performance 2 to 3 Gpixel/s = 20 to 30 Gb/s over 88 parallel LVDS channels
Power dissipation (spec)	Maximum <u>5W</u> , including the 88 LVDS drivers
Actual LVDS driver dissipation per channel	6.0 mW @ at maximum data rate. 4.5 mW in sub-LVDS

# Demonstrated performance on Technology Validator - TVP



- In a nutshell
  - All features of NGSD/LGSD
  - 60x60 pixels,
  - Same pixel and ADC driving
  - 1200 (60x20) column ramp ADCs
  - > 700 frames/sec
- To optimize the pixel:
  - transfer gate and transistor geometries were varied in 12 pixel variants
  - threshold voltage of nmos transistors was varied
  - Implants to improve image lag were varied



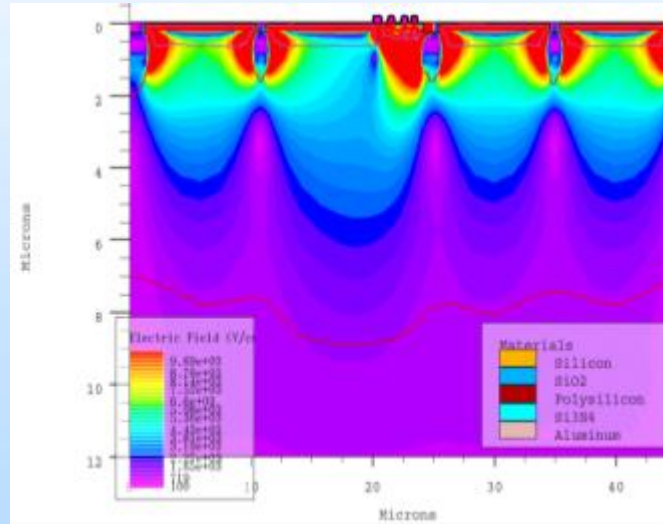
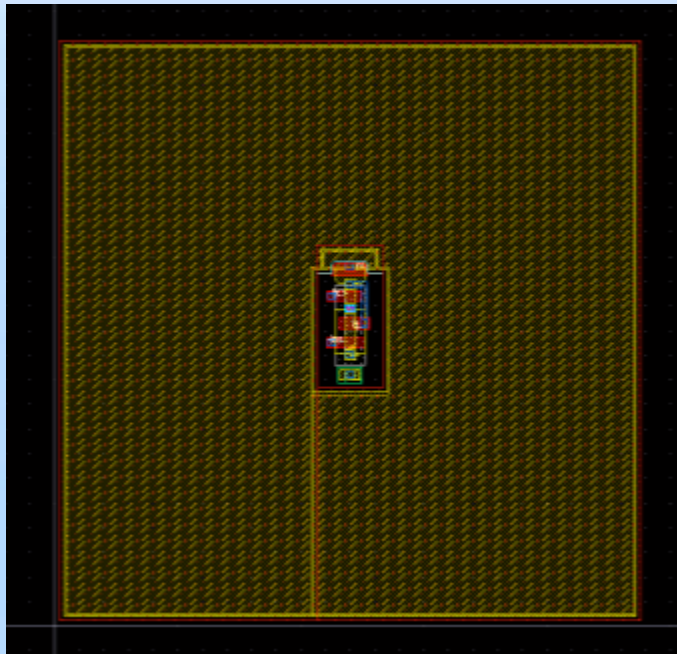
- Key performances have been validated
  - $< 3.0e^{-RMS}$
  - Full well 4000...8000 e-
  - Conversion gains 100...160  $\mu V/e^{-}$
  - Image Lag  $< 0.1 \%$
  - Best pixel and implants found to go forward to next phase, NGSD
- Not tested in TVP:
  - Massive parallelism
  - Array of LVDS IO
  - Back Side Thinning & Back Side Illumination



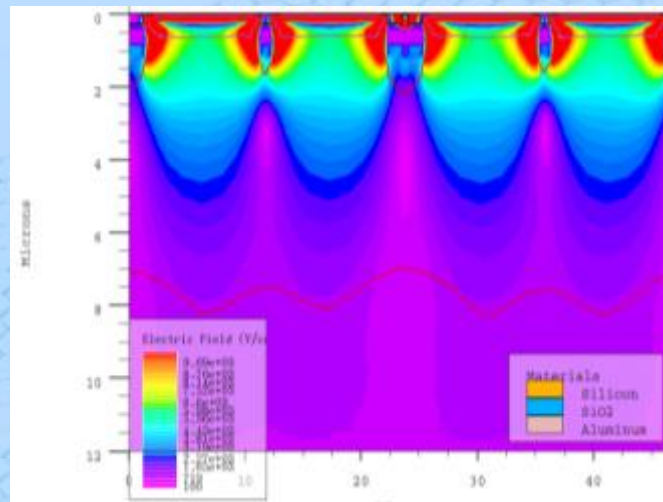
Process, Pixel Architecture and Radiation Hardness			
14h15	JERRAM Paul	e2v technologies	Optimisation of performance of Backthinned CMOS devices



# Pixel designed for best centroiding performances, TCAD simulations



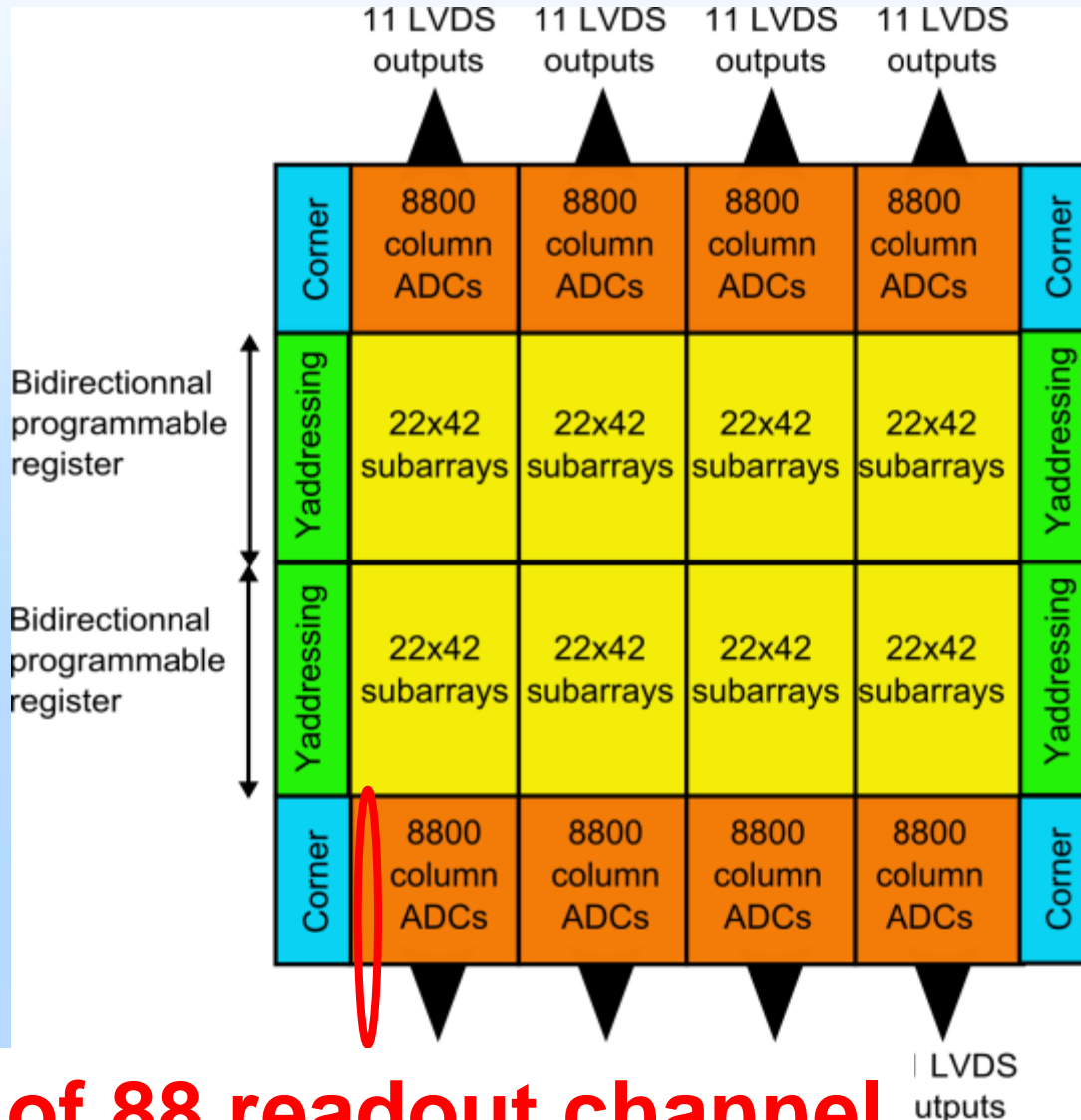
Y / center



X



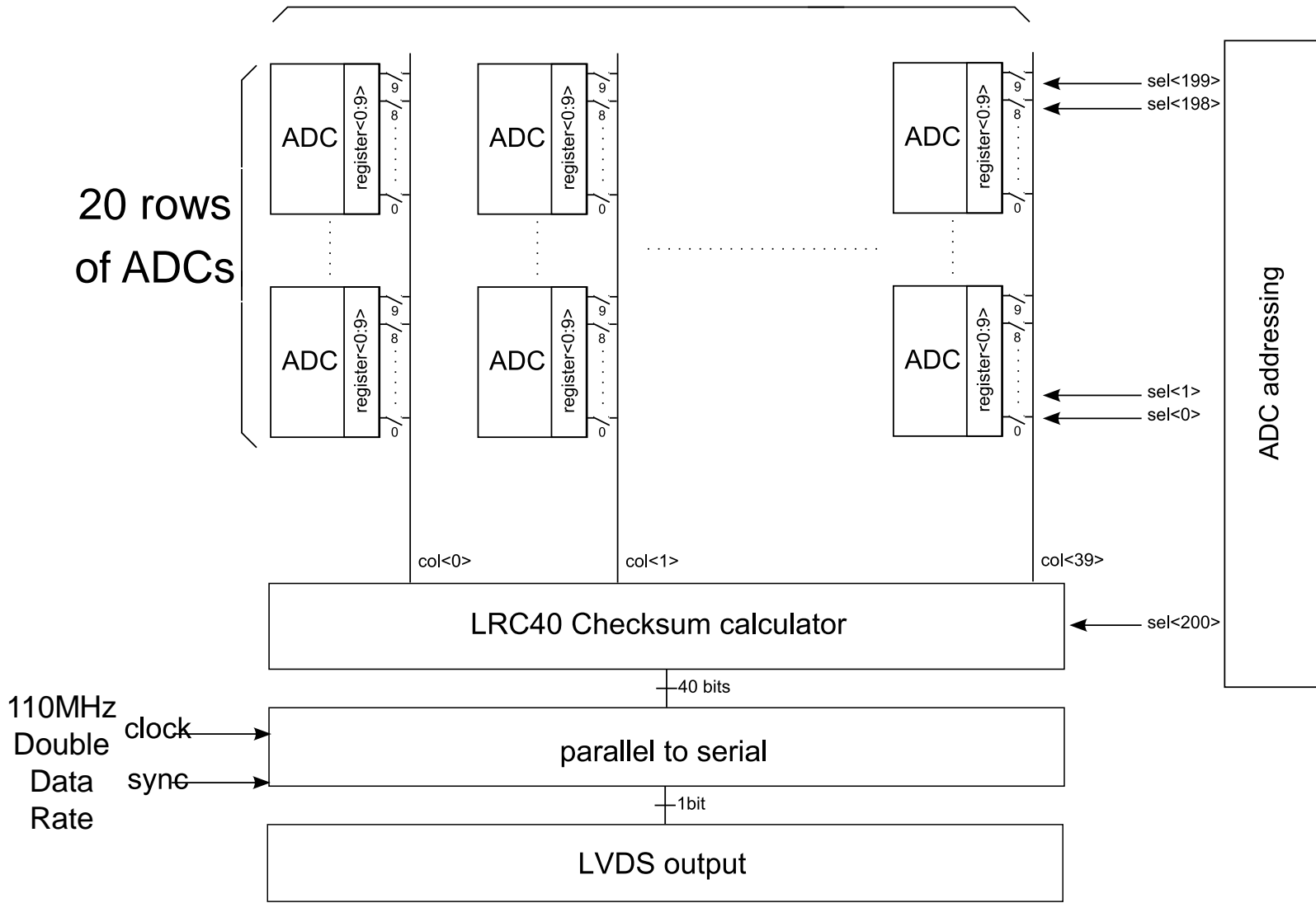
# LGSD/NGSD Stitching Plan



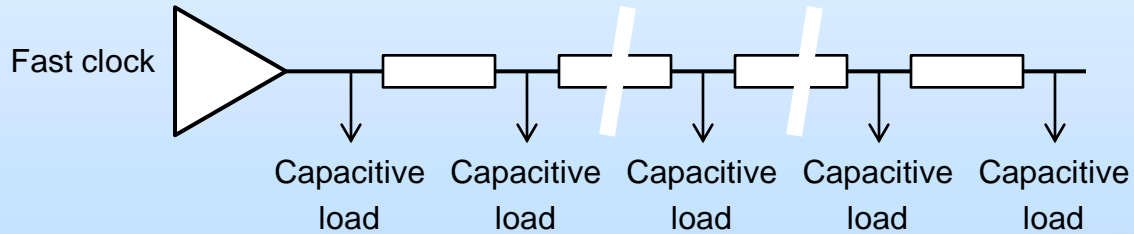


# One readout channel (of 88)

40 Columns of ADCs = 2 sub-arrays

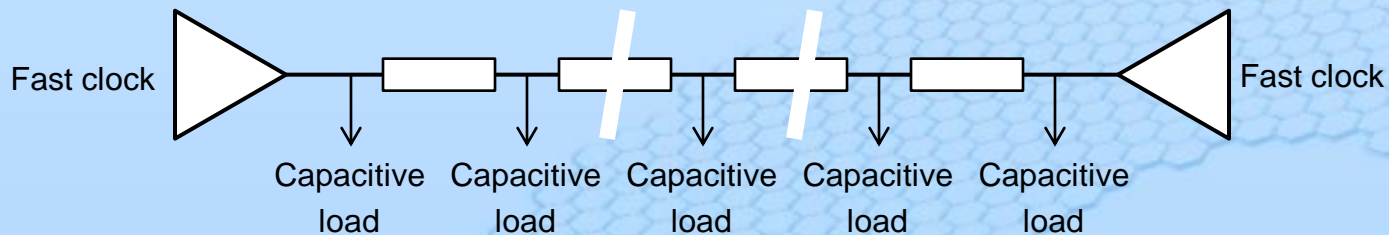


# How to drive 210 MHz over 4cm?



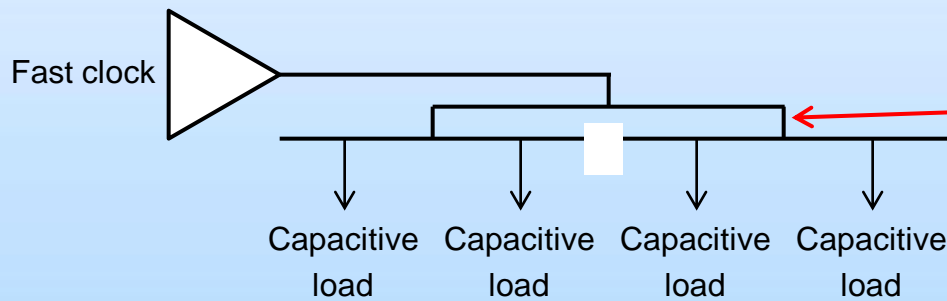
Reference  
case for speed  
and skew

Skew > 2ns

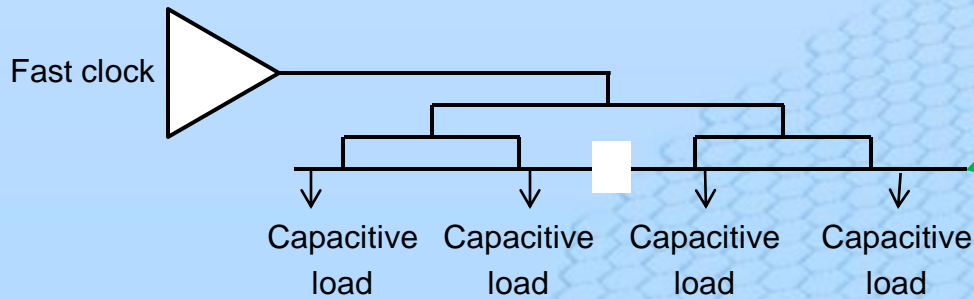


$R/2 \Rightarrow \text{Speed} \sim *4$

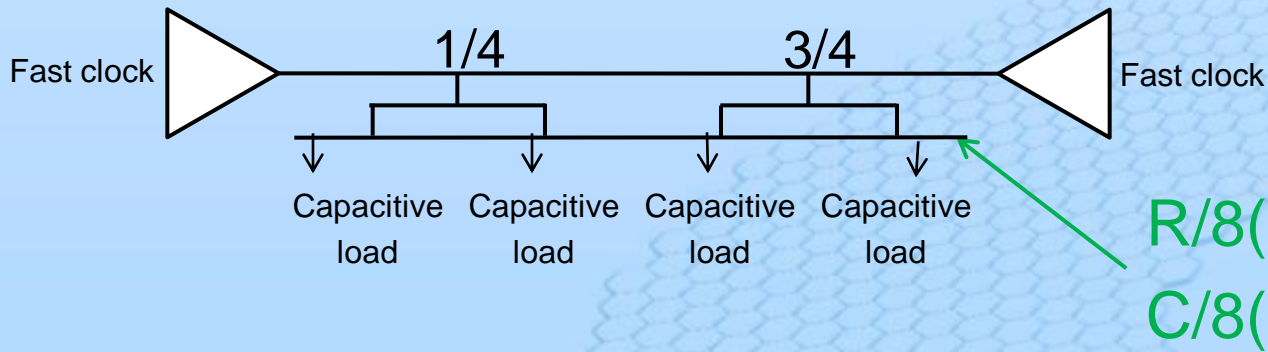
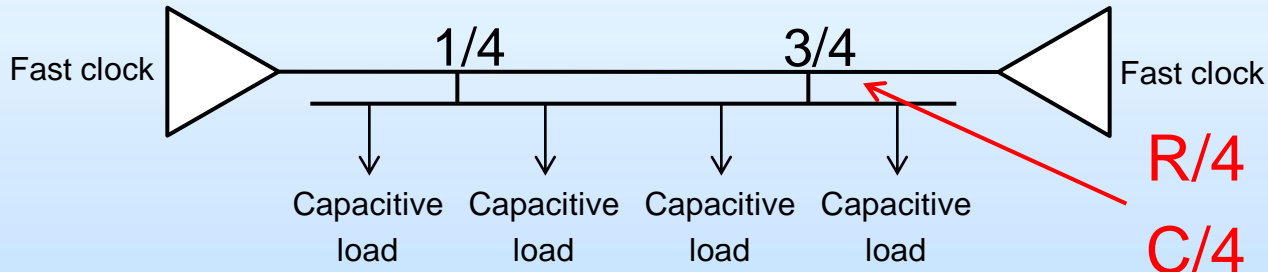
$C/2 \Rightarrow \text{Skew} \sim /4$



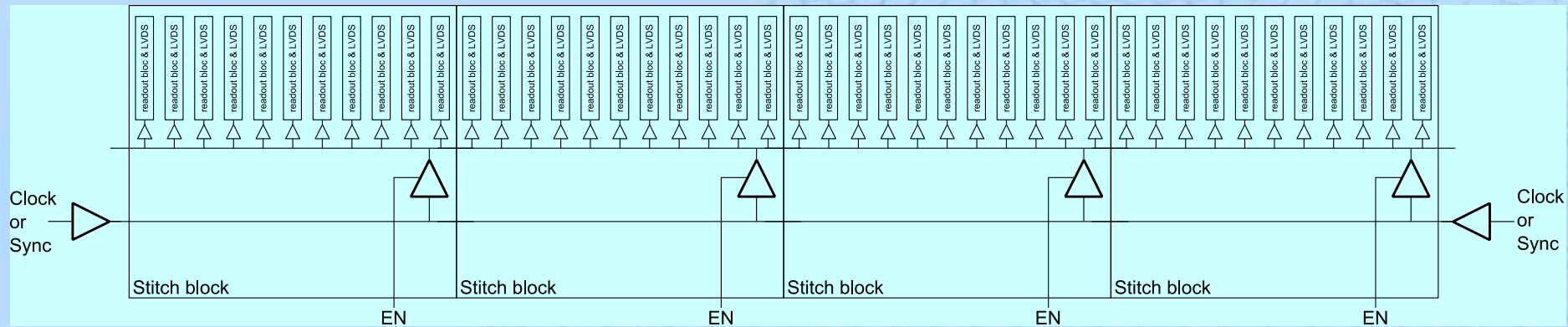
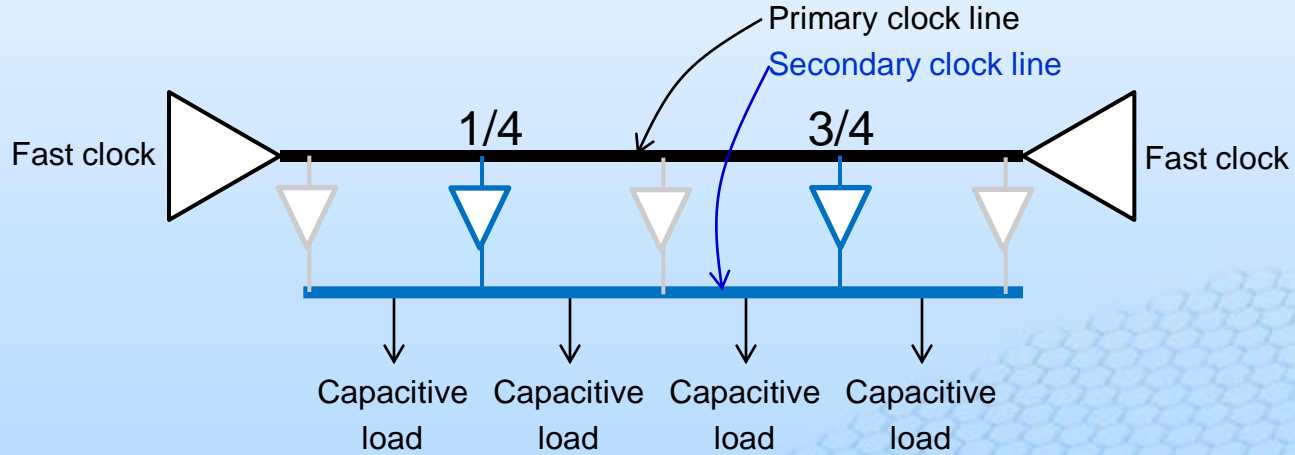
$R/4$   
 $C/4(?)$   $\Rightarrow$  skew  $\sim 1/16$



$R/8(?)$   
 $C/8(?)$   $\Rightarrow$  skew  $\sim 1/64$



# How to implement this when stitching?





# Summary

- Preparation work for our next challenge, the E-ELT, is well under way.
- ESO has formed a good partnership with e2v and Caeleste.
- Multi-phase, progressive risk reduction development plan should guarantee that devices are available on-time that meet specifications.
- Measured results from the TVP have clearly validated the CMOS imager approach.
- The best pixel design that meets the requirements has been found to go forward to the next phase, the NGSD.
- The next phase, the NGSD, starts in January 2012.



# Thank You



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