State of the art Adaptive Optics wavefront sensor cameras at First Light Imaging

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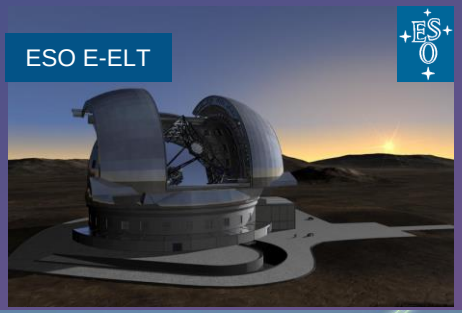
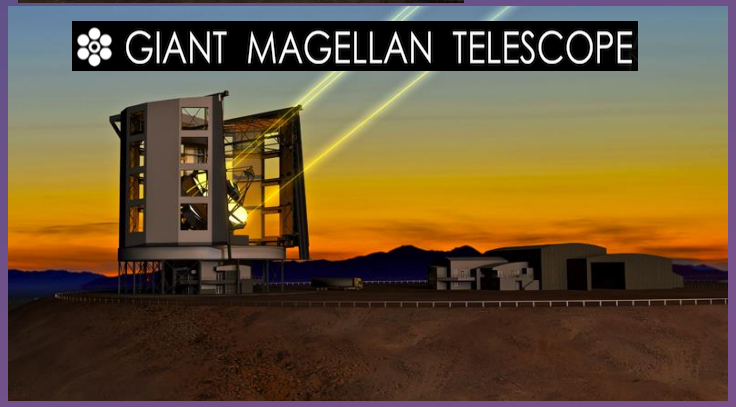
First Light Imaging: our origins

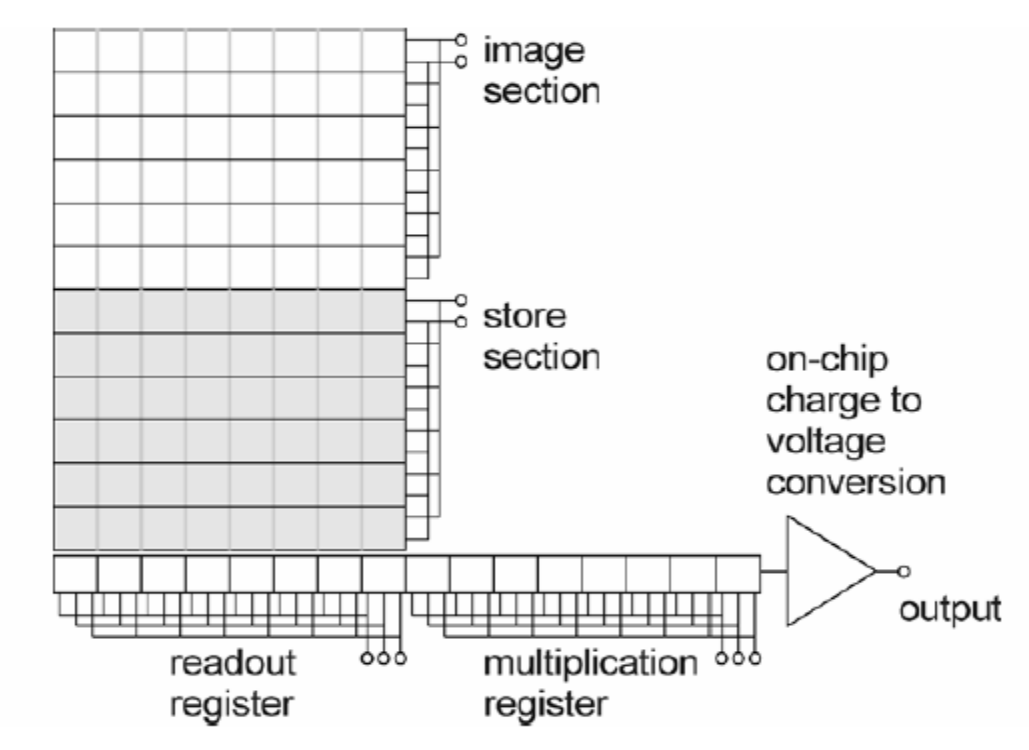
- FLI came from the sharpest French instrumentation labs in Astronomy.
- The FLI R&D and production is still linked to those labs and universities.
- FLI team is also involved in academic world-size projects.

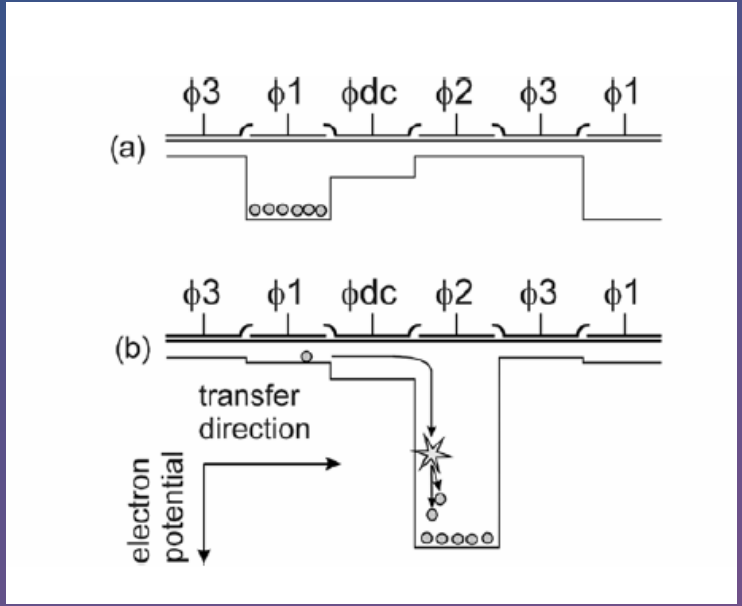




CCD220 EMCCD and OCAM2 visible wavefront sensing

EMCCD: Electron Multiplying CCD



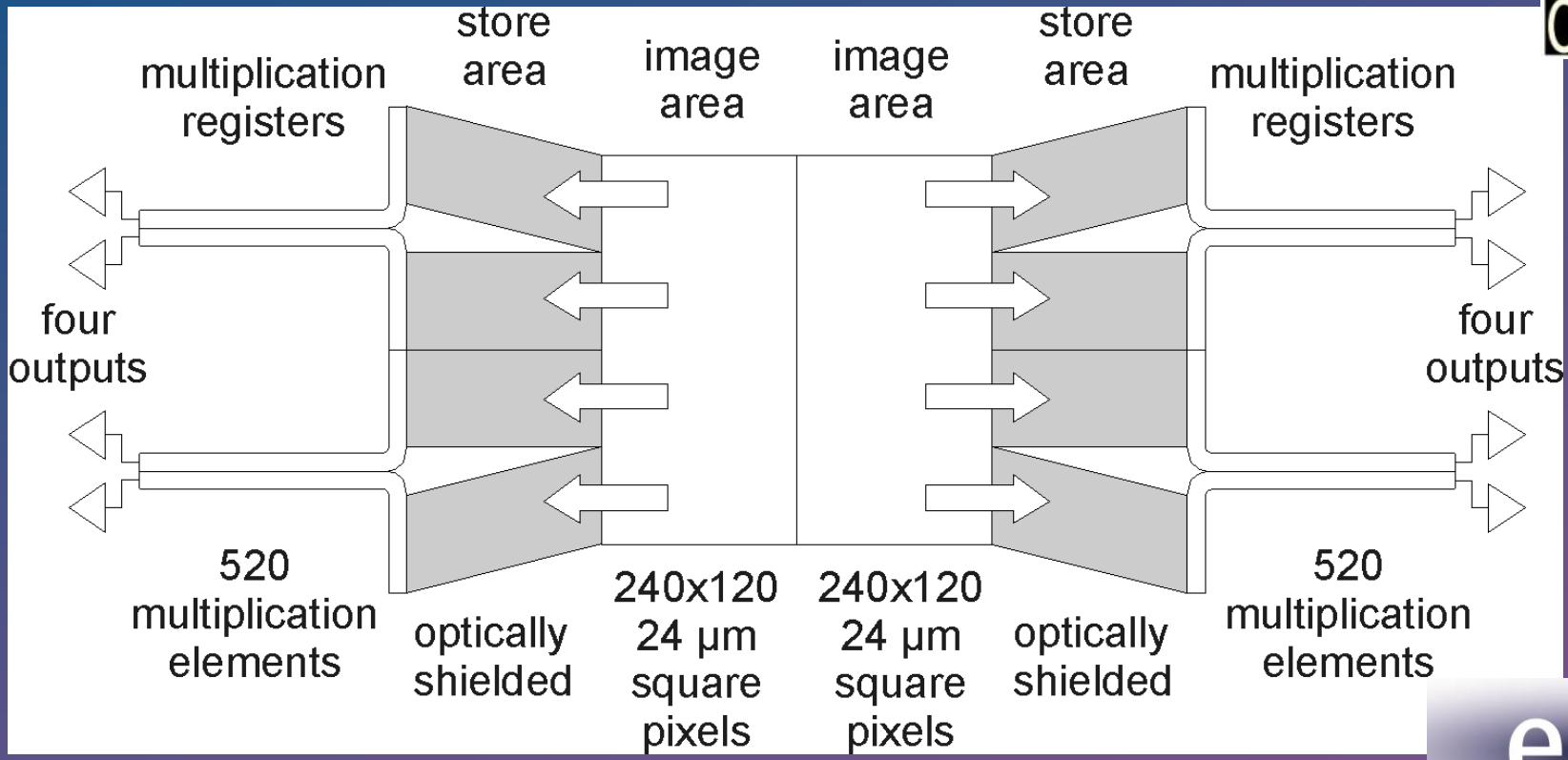


$$\sigma_{\text{eff}} = \sqrt{\left(F \cdot (S + S_{\text{dark}}) + \frac{\sigma^2_{\text{readout}}}{M^2} \right)}$$

M: mean gain
F: excess noise factor

For Si EMCCD:
F = 2 but $\sigma_{\text{readout}}/M \sim 0$

The e2v CCD220 EMCCD



- 240 x 240 pixels with 24 µm pitch
- 8 EMCCD outputs split frame transfer => 110 Mpixels/s
- Nominal frame rate: 1500 frames/sec
- Peltier cooled @ - 45 °C
- Very challenging to use properly

OCAM2 by First Light
www.firstlight.fr

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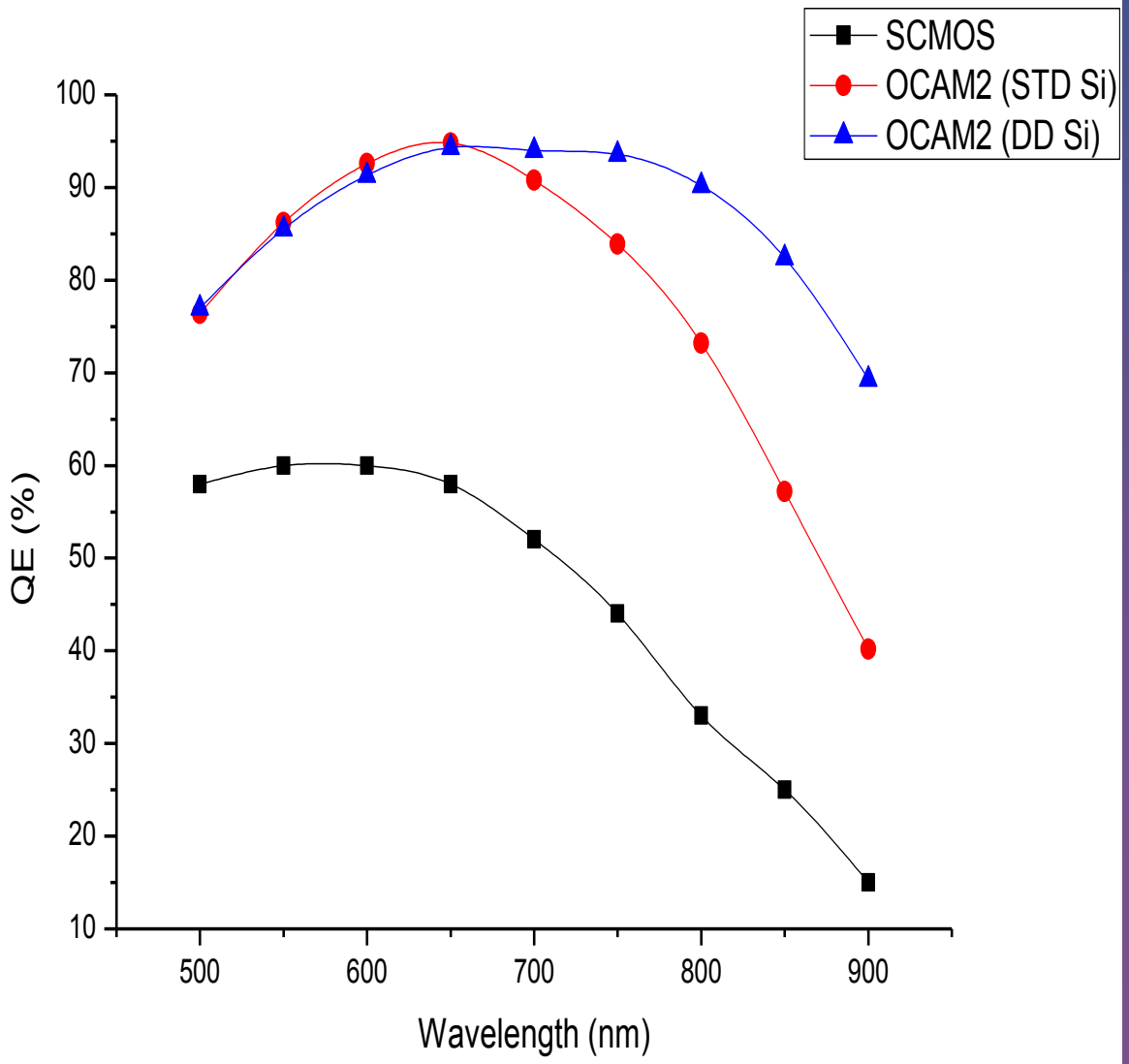
OCAM2 QE (standard and DD)

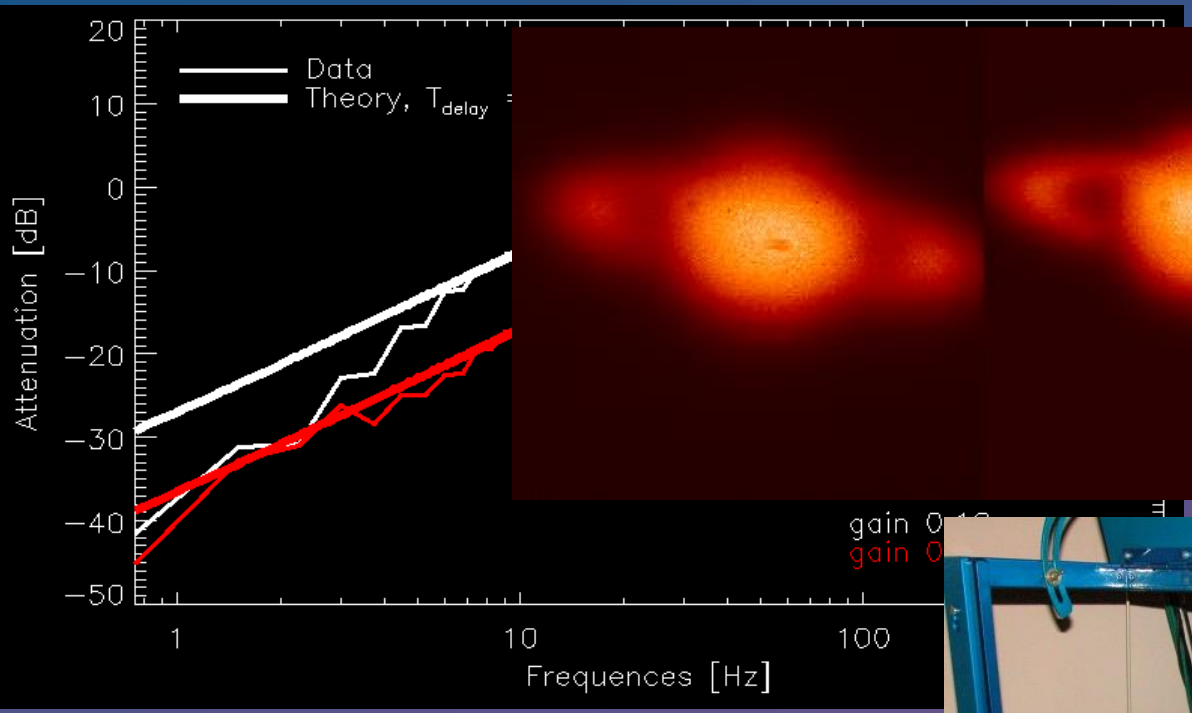


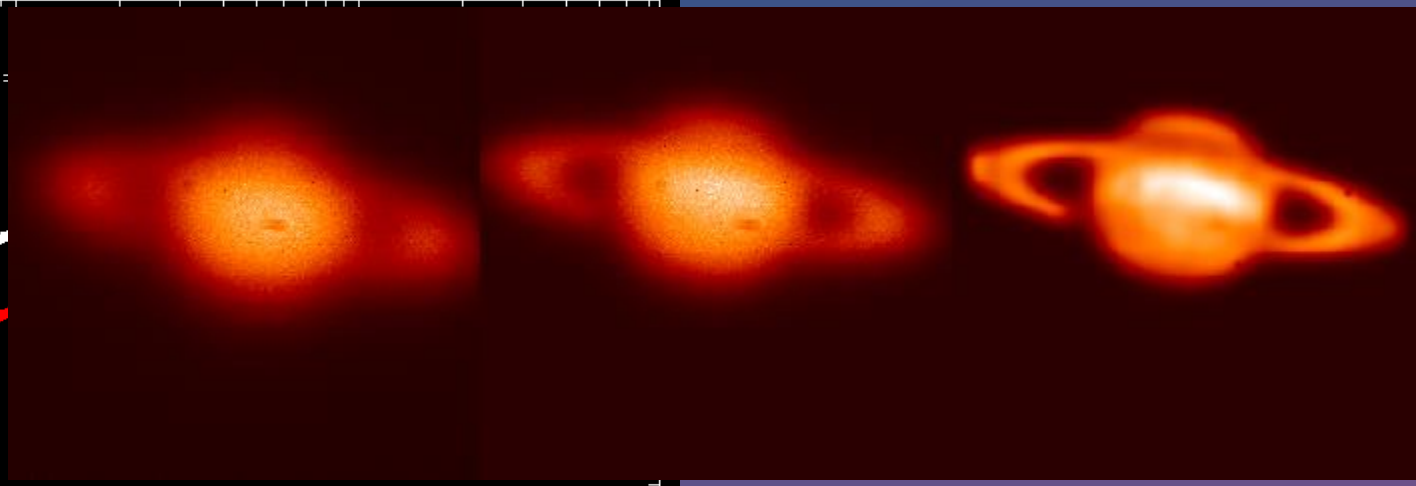
Centroiding with 5 photons…

Shack hartmann centroiding possible only with a few photons @ 1500 FPS

Central peak is only 5 photons/frame amplitude (mean value)
1503 FPS
Gain x 800
~ 0.2 e noise

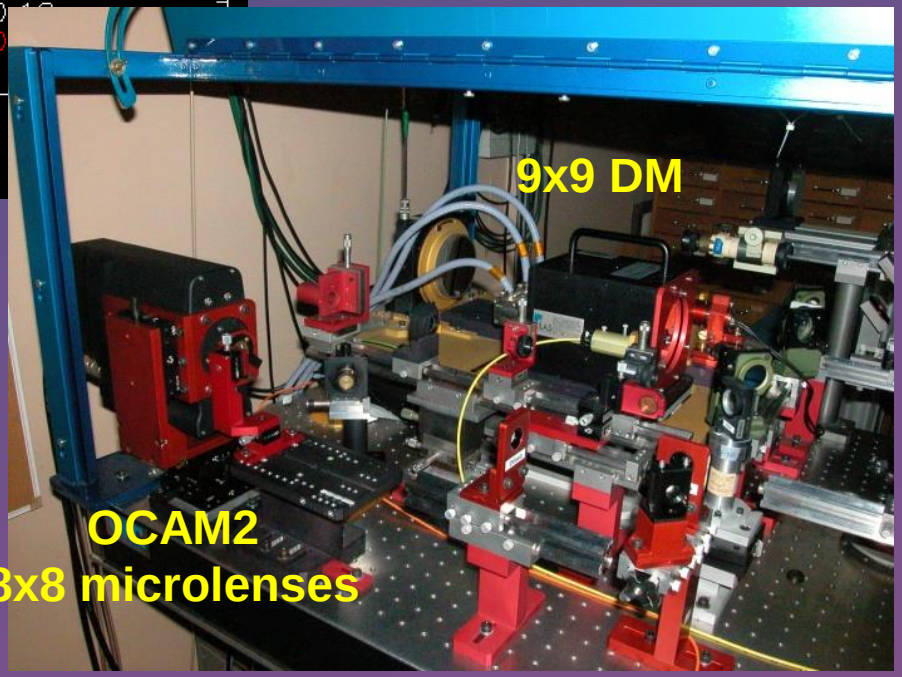
OCAM2 closed loop on the sky - ONERA





Rejection transfer function of the AO loop system. Sampling frequency is 1503 Hz.
Shakti RTC

Courtesy of T. Fusco & al., SPIE Amsterdam 2012 [8447-68]



OCAM2 observation run on CHARA interferometer (Mount Wilson CA)

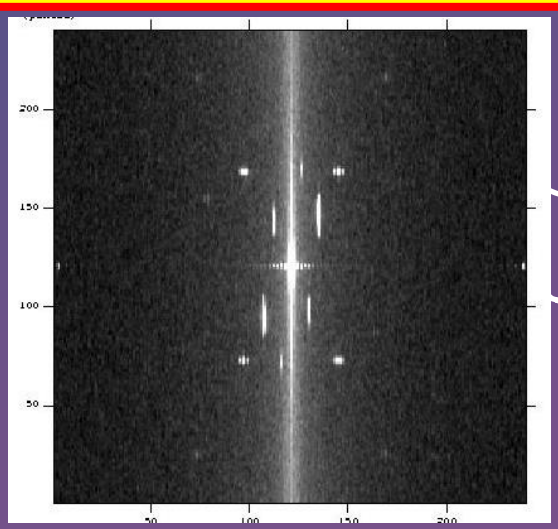
Telescopes (6 x 1m)

Delay lines

Beam recombinator focus

Gain x1000 0.13 e noise

HD58923 FFT
3T observation
Dispersed granges vis λ
Photon counting mode
(threshold: 5 σ)



OCAM^2

Results courtesy of
D. Mourard/P. Berio
Obs. Côte d'Azur F

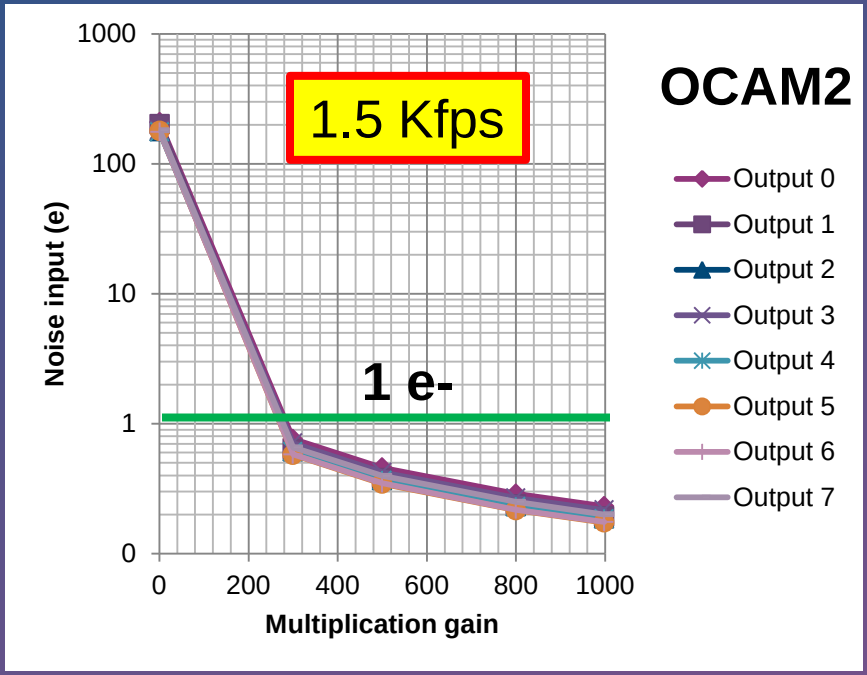
The OCAM^{2K} First Light product

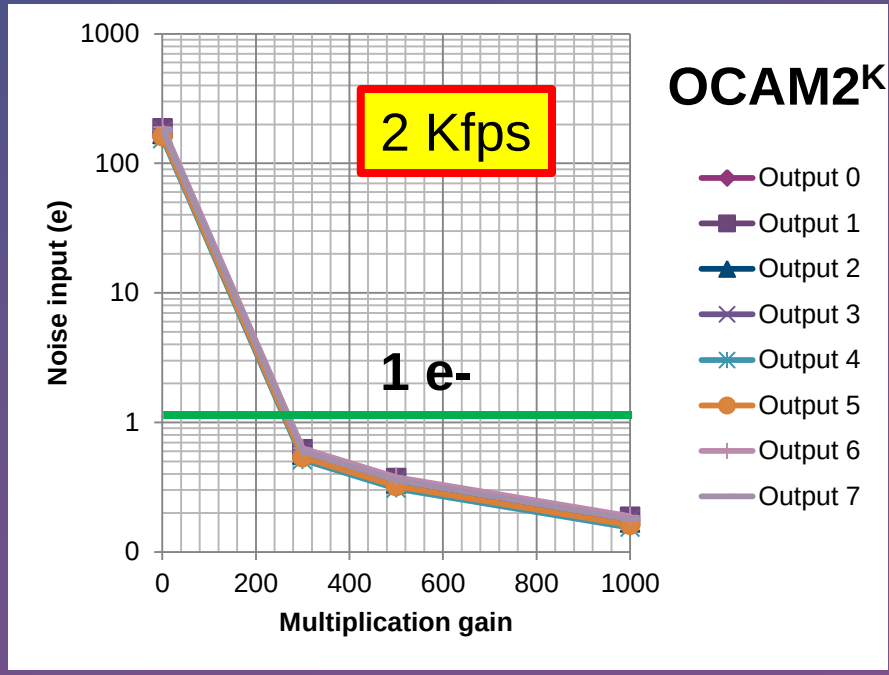
- Development carried by First Light Imaging with internal ressources
- Goal : increase the OCAM2 camera speed to more than 2000 FPS.

- High overclocking of the CCD 220
- 18.6 Mpixel rate : unprecedented L3CCD readout speed

OCAM readout noise

- Measured noise : no noise degradation, made possible with upgraded analogic design electronics





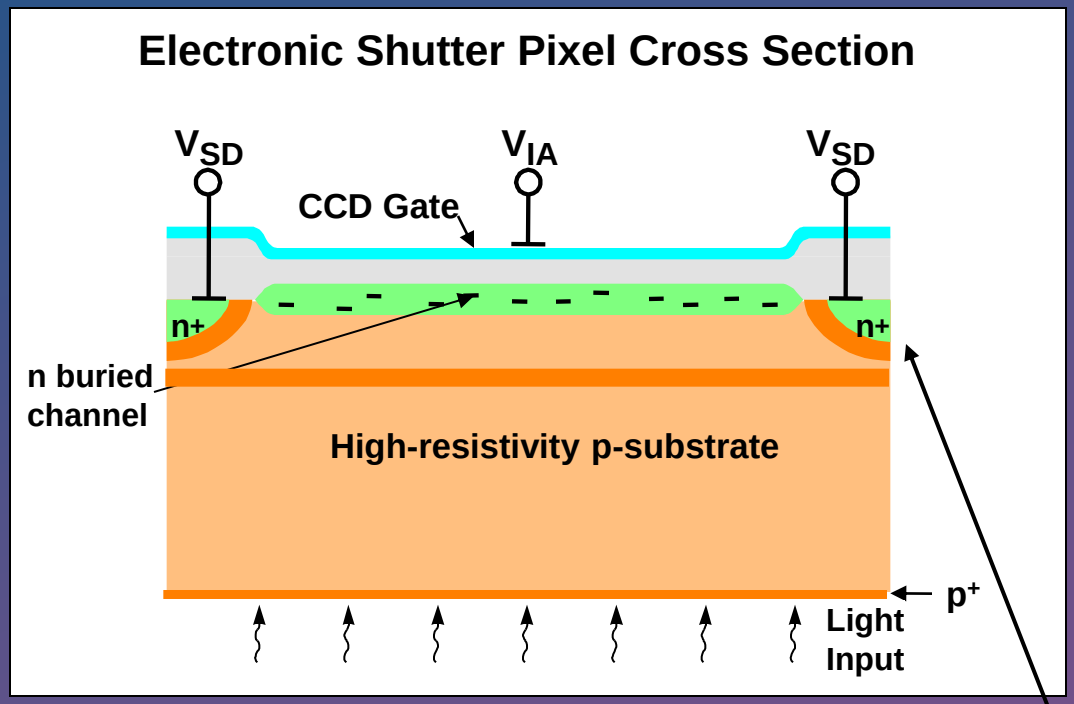
OCAM2 and OCAM2K noise

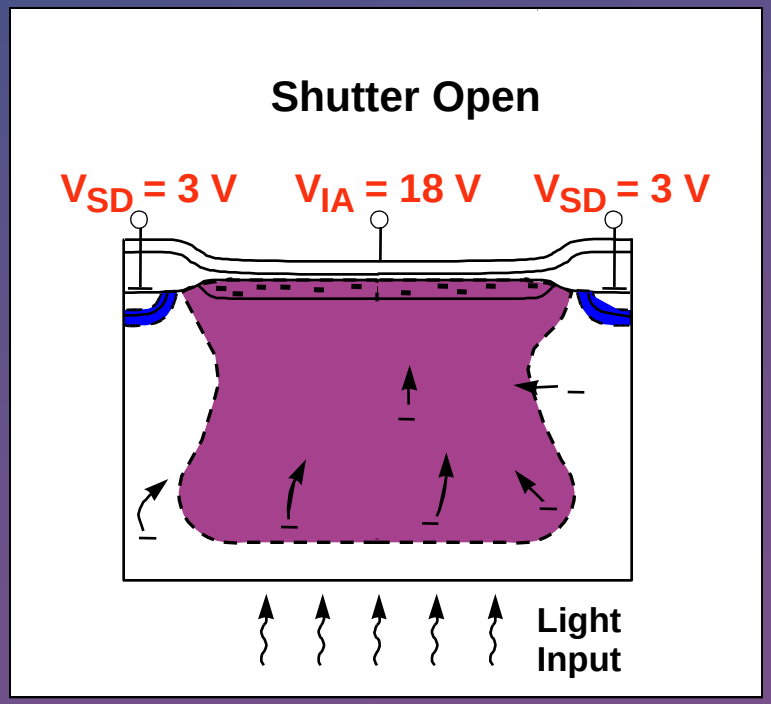
OCAM^2 vs OCAM^{2K}

Test measurement	OCAM^2	OCAM^{2K}	Unit
Nominal speed (full frame)	1503	2067	FPS
Mean readout noise (full frame, full speed)	0.13	0.13	e-
Pure Latency	60	43	µs
Dark signal at 1503 fps	0.0023	0.002	e-/pix/ frame
Detector operating temperature	- 45	-45	°C
Peak Quantum Efficiency at 650 nm	94	94	%
Linearity at gain x1000 from 10 to 150 ke	<3	<3	%
Image area Full Well Capacity at gain x1, 1503 fps	300	300	ke$^-$
Parallel CTE at gain x1, 1503 fps	0.9999	0.9999	N/A
Serial CTE at gain x1, 1503 fps	0.9999	0.9999	N/A

No performances degradation with OCAM ^{2K}

Electronic Shutter

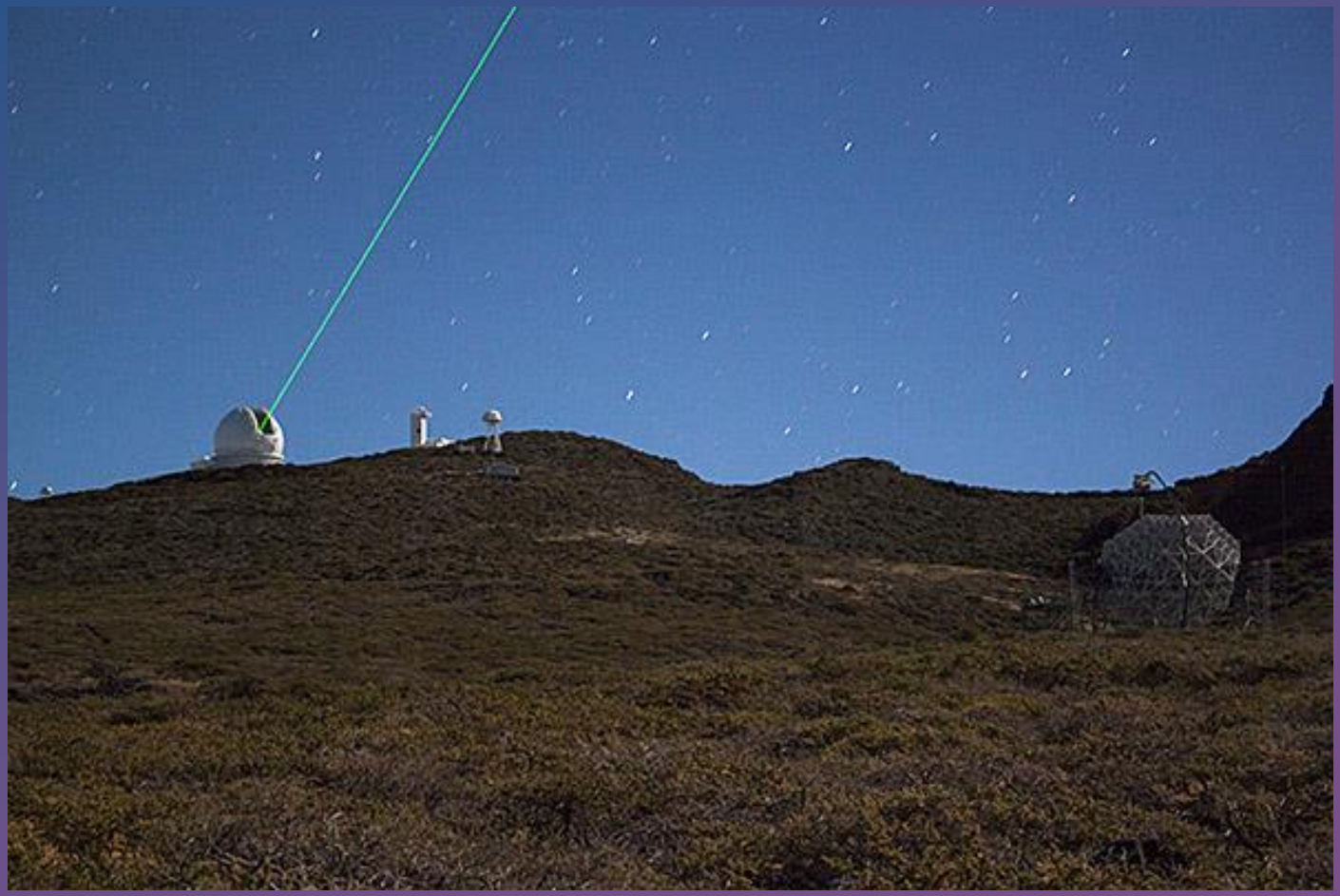




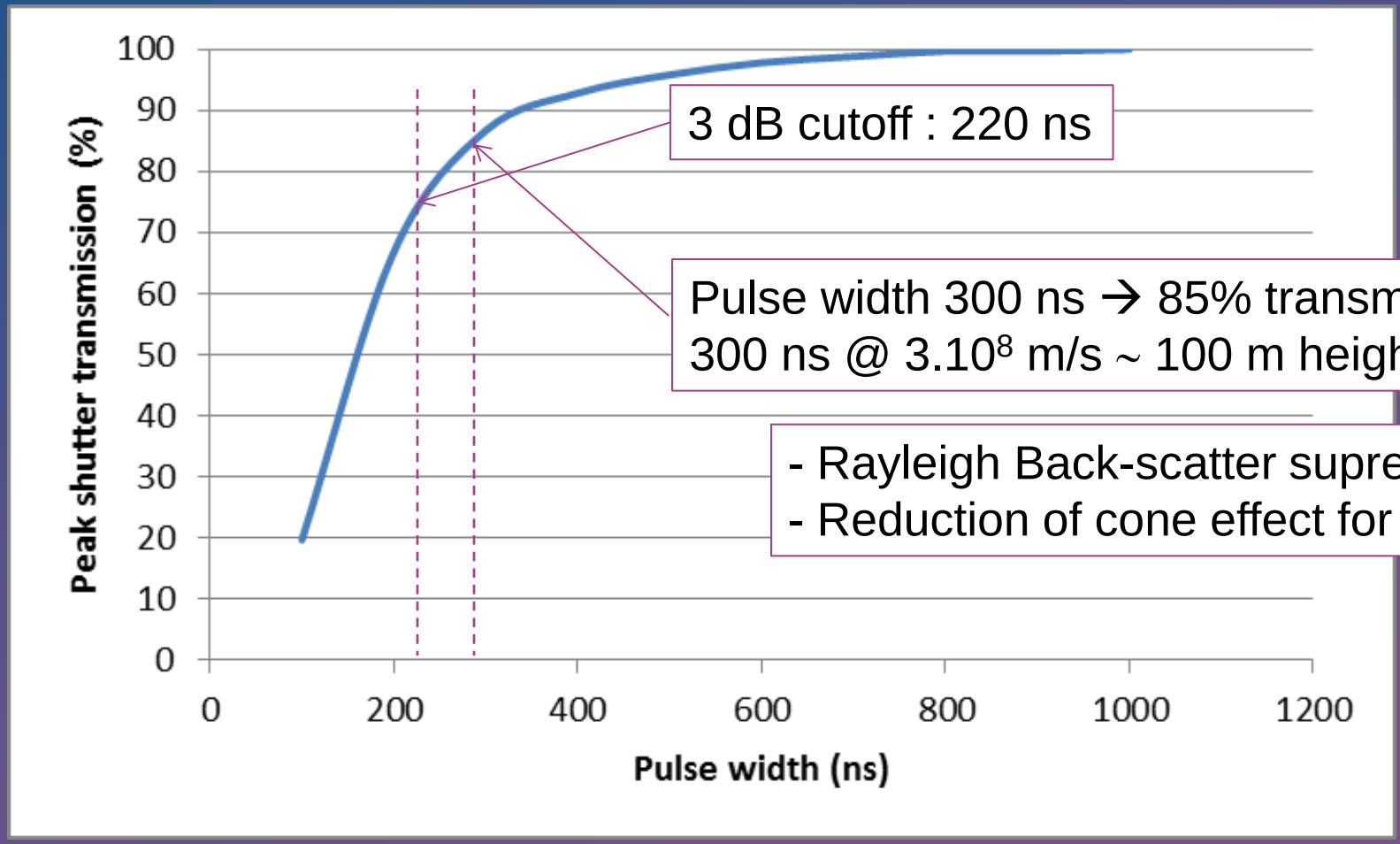
Add Inter-column drain/gate

OCAM^{2S}

Extinction ratio optimized for green lasers (Nd:YAG + LiB_3O_5 crystal = 532nm)



Good transmission of 300 nm pulse: 100 m pulse height detection possible



IR APD arrays developments at FLI for IR wavefront sensing/interferometry

320x255 IR APD

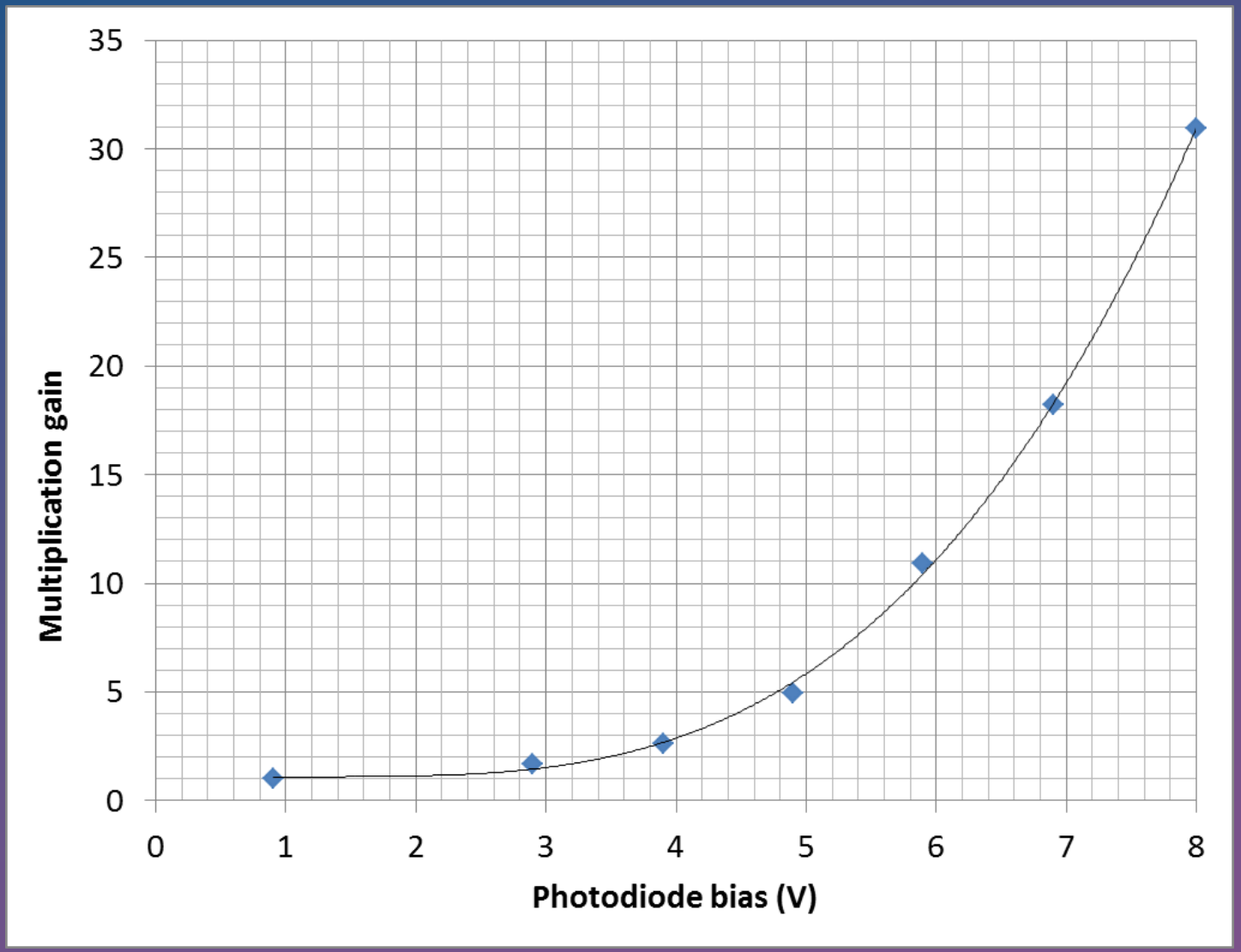
- Detector specification:
  - SOFRADIR 320 x 255 pixels APD array, 8 outputs of 32 columns, 30 µm pitch
  - Pixel architecture : CTIA amplifier, integrated CDS
  - Wavelength: 0.4 – 3 µm
  - Full frame readout: 1600 Hz min, up to 2 kHz, pixel frequency 20 MHz
  - Windows: one rectangular window of any number of lines, each line read in 2.7 µs
  - System Noise: <2 e at 1600 Hz frame rate (with gain nx10)
  - Dark: 100 e/s/pixel
  - Full well: 37 000 e (with gain x1)
  - Operability: ~ 99.5%
  - Power consumption: 210 mW (→ cryocoolers)
- Devices available by 2014.

80 K operation
Vis to IR

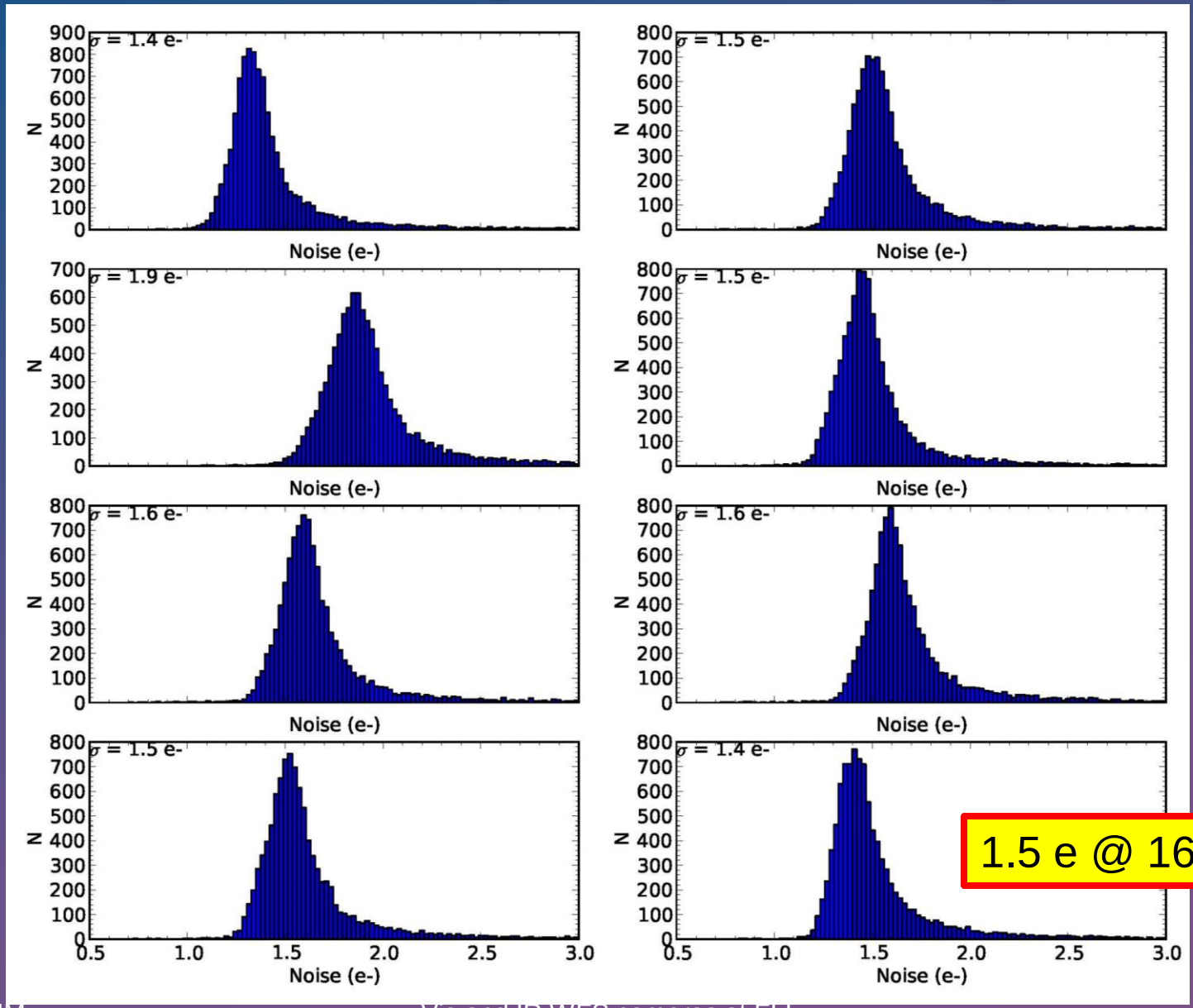
RAPID 1600 fps operation

1600 fps record in the infrared
Just bias image substraction, no image processing…

RAPID Gain – 3.3 µm photodiodes – 75 K

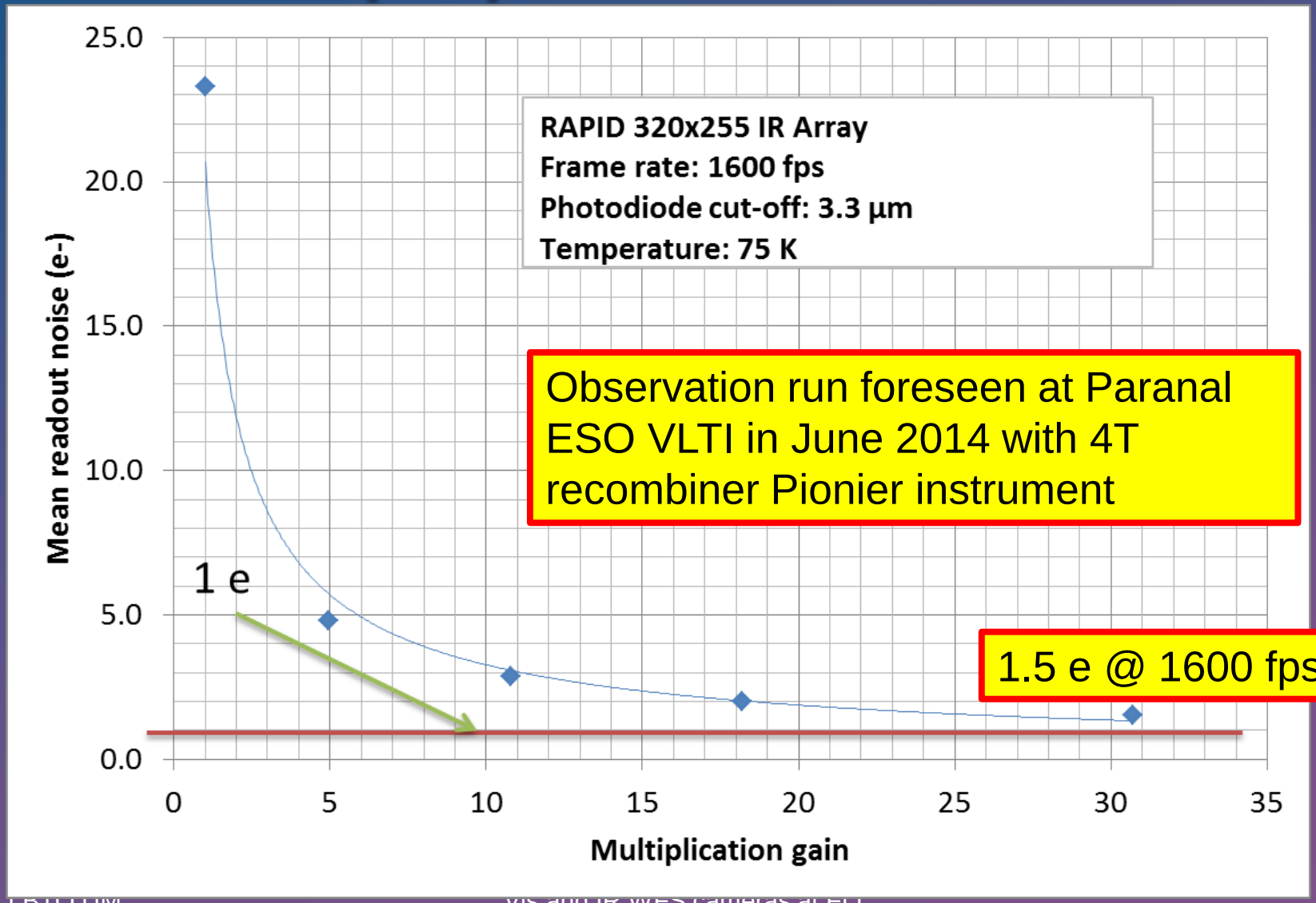


RAPID Noise histograms in dark @ 1600 fps

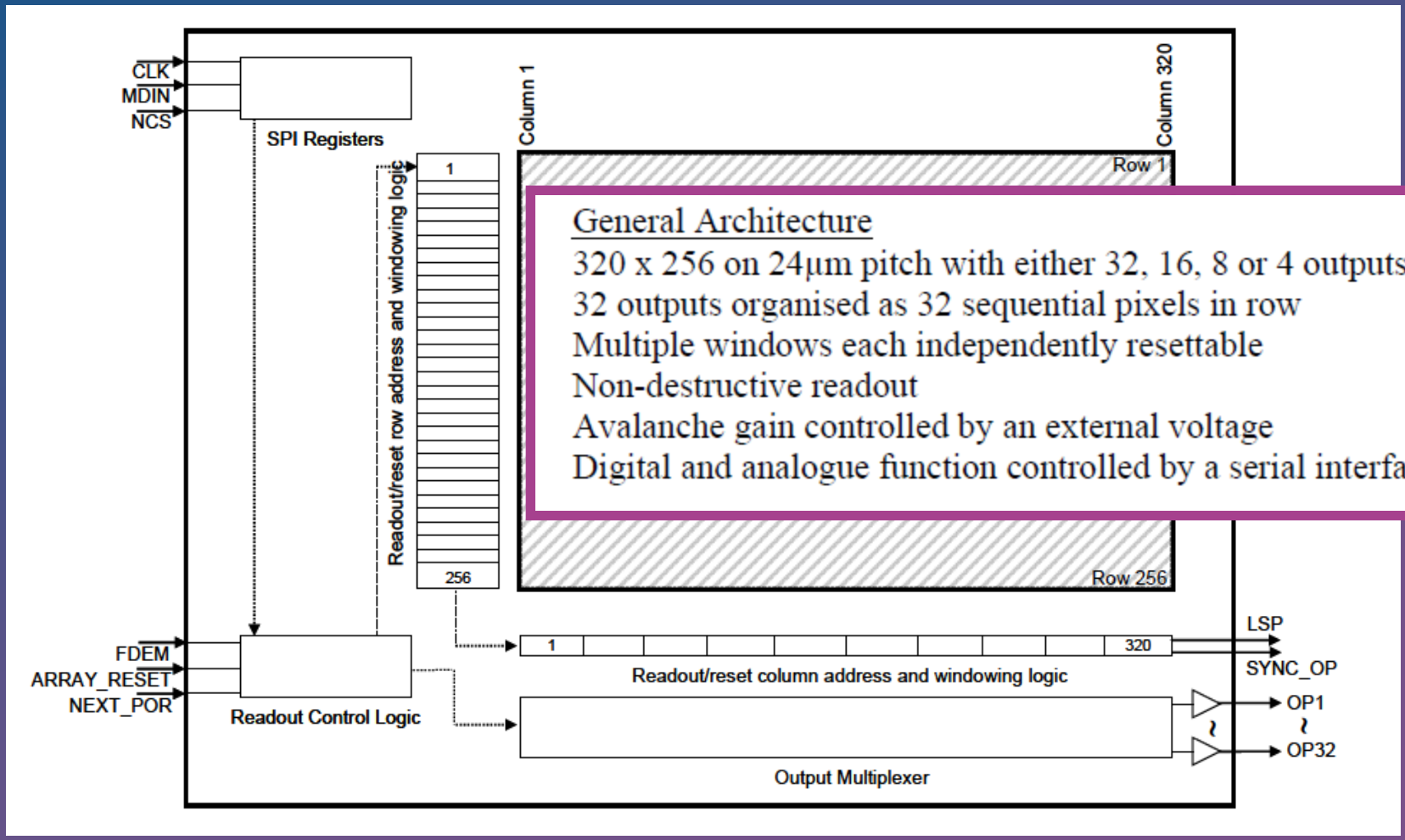


1.5 e @ 1600 fps

RAPID Noise 1600 fps
3.3 µm photodiodes – 75 K



Selex SAPHIRA IR APD



A 880X800 700 HZ CMOS DEVICE FOR NATURAL/LASER GUIDE STAR WAVEFRONT SENSING ON ELTs

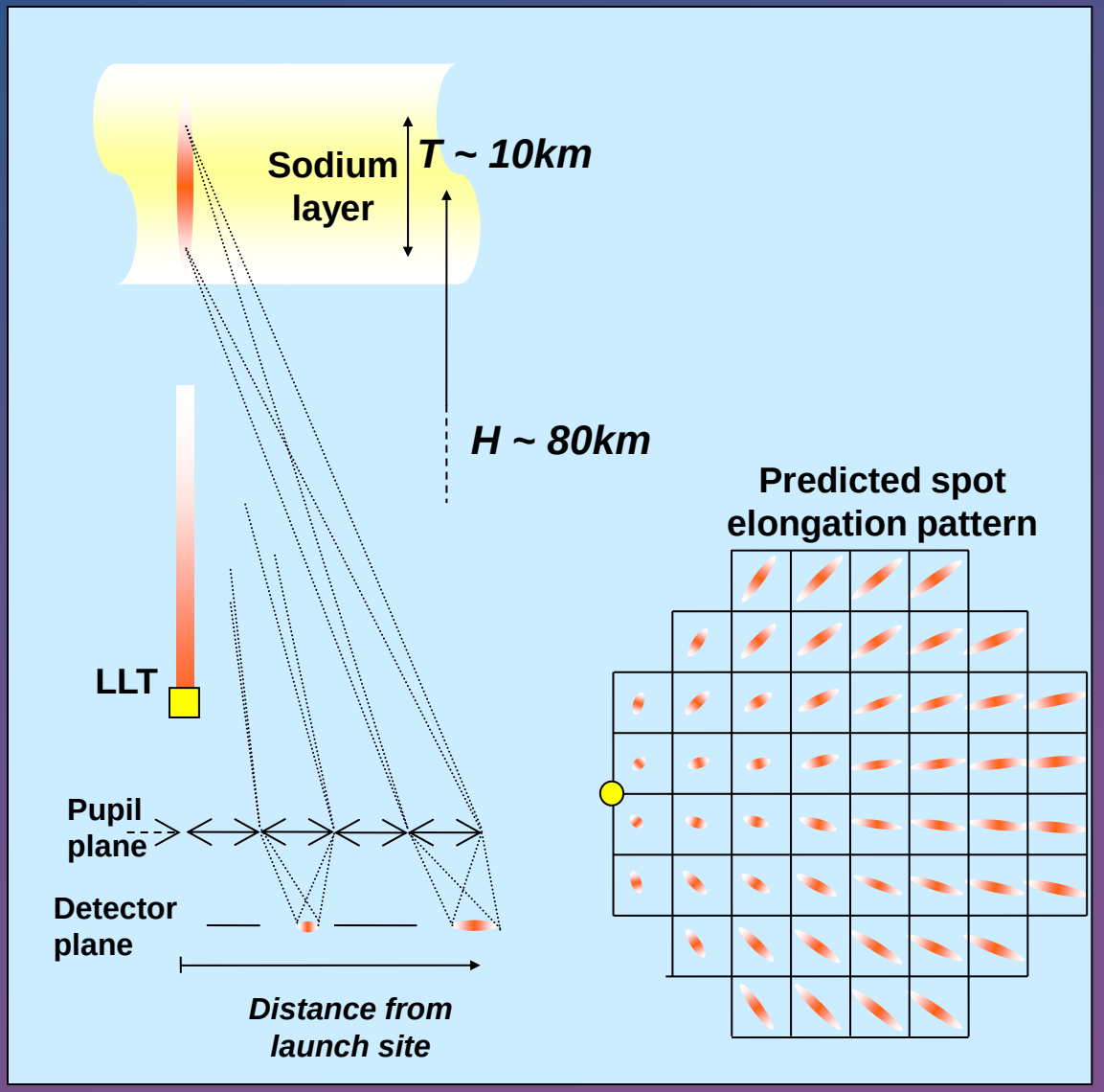
Large Visible AO WFS Detector needed to sample the spot elongation of LGS on ELT

Sodium Laser Guide Stars

- Frame rate ~**1 kframe/sec**

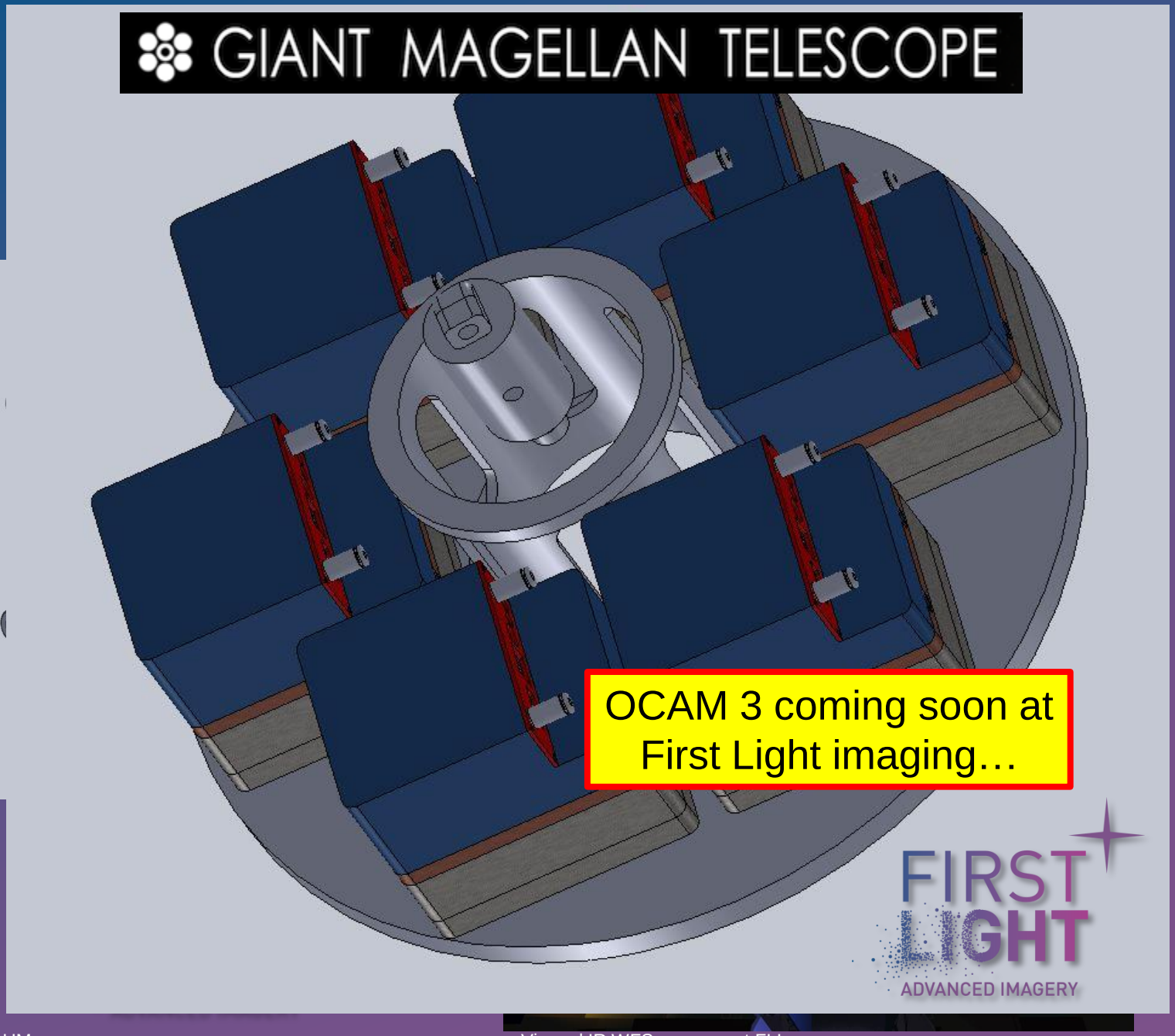
→ require bright "guide stars"

- 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



The e2v CMOS NGSD characteristics

Pixel number (including dark reference pixels)	“Natural Guide Star Detector” NGSD - 880x840 pixels with 840x840 sensitive pixels
Detector technology	Thinned backside illuminated CMOS 0.18µm
Pixel Pitch	24µm
Pixel topology	4T pinned photodiode pixel
Sub-aperture	20x20 pixels
Array architecture	42x42 sub-apertures of 20x20 pixels
Pixel full well	4000 e-
Read noise including ADC	< 3.0 e^-_{RMS}
ADCs configuration	20 x 880 column ADCs, 9 (goal 10) bits
Number of parallel LVDS channels	22
Serial LVDS channel bit rate	210 Mb/s baseline, up to 420 Mb/s (desired)
Frame rate	700 fps up to 1000 fps with degraded performance


GIANT MAGELLAN TELESCOPE
OCAM 3 coming soon at First Light imaging…
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Conclusions

- Joint effort from First Light Imaging and European institutes (ESO, France) for more than 1 decade on low noise fast detectors for AO wavefront sensing
- **OCAM2K is world fastest most sensitive visible WFS camera :**

  0.13 e noise @ 2 K fps with gain x1000
- OCAM2 and OCAM 2K are now mature *First Light Imaging (FLI)* commercial products producing on sky data. OCAM2 with electronic shutter available by SPIE Montreal 2014.
- IR APD at FLI (ICAM?)
  - RAPID:
    - is Fast low noise 320x255 1600 fps vis & infrared array dedicated to AO
    - Amazing noise performance for an IR device (1.6 Kfps 1.5 e at gain x31)
    - Incredible wavelength coverage from visible to IR with flat QE
  - SELEX devices offers also incredible performances and will be also an FLI commercial product.
- Large CMOS devices are now developed with e2v and ESO for NGS + LGS wavefront sensing and ELT: NGSD 880x840 700 fps 3e noise CMOS at FLI in 2015 (OCAM3)

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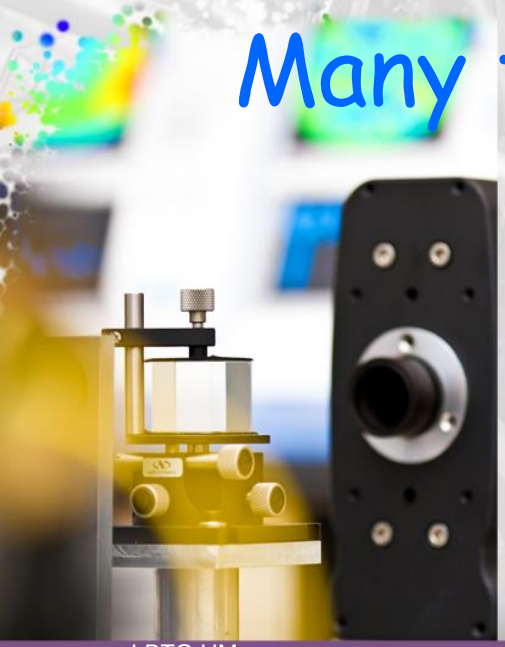
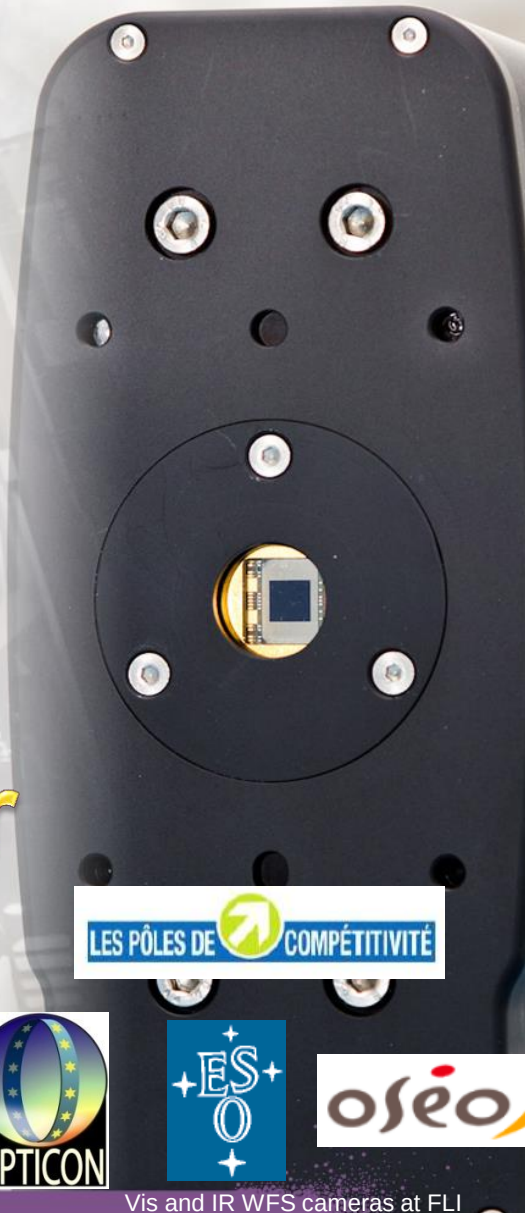


Many thanks for listening

www.firstlight.fr



Acknowledgments

European Commission: FP6 and FP7 Opticon
DGA and FUI OSEO
ESO