On-sky performance verification of near infrared e-APD technology for wavefront sensing and demonstration of e-APD pixel performance to improve the sensitivity of large science focal planes

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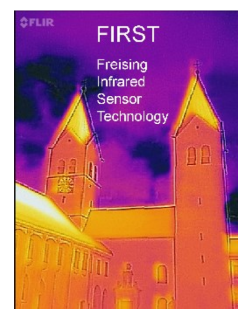
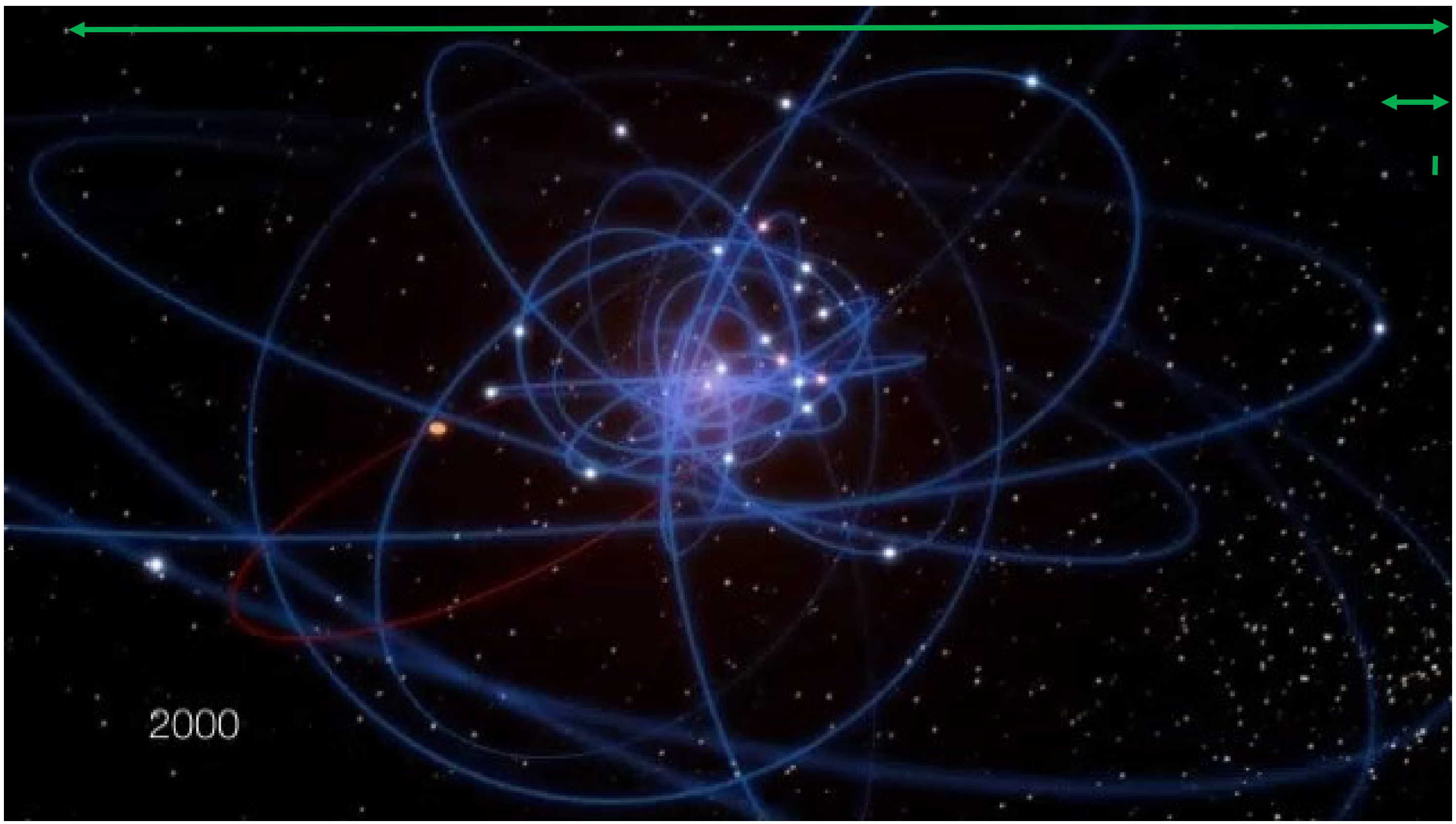
(former SELEX)



GRAVITY: observe black hole in Galactic Center

- stars orbiting the black hole used to probe theory of general relativity
- Galactic Center Event in 2018: distance of S2 to black hole: 17 light hours
  speed: 2.5% the speed of light
- measure general relativistic periastron shift with high precision



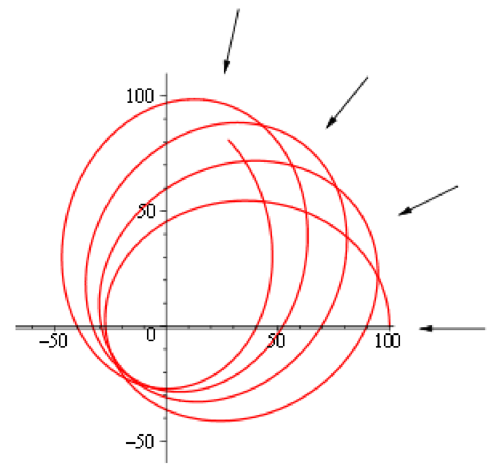
1 arcsec

50 mas λ/8m

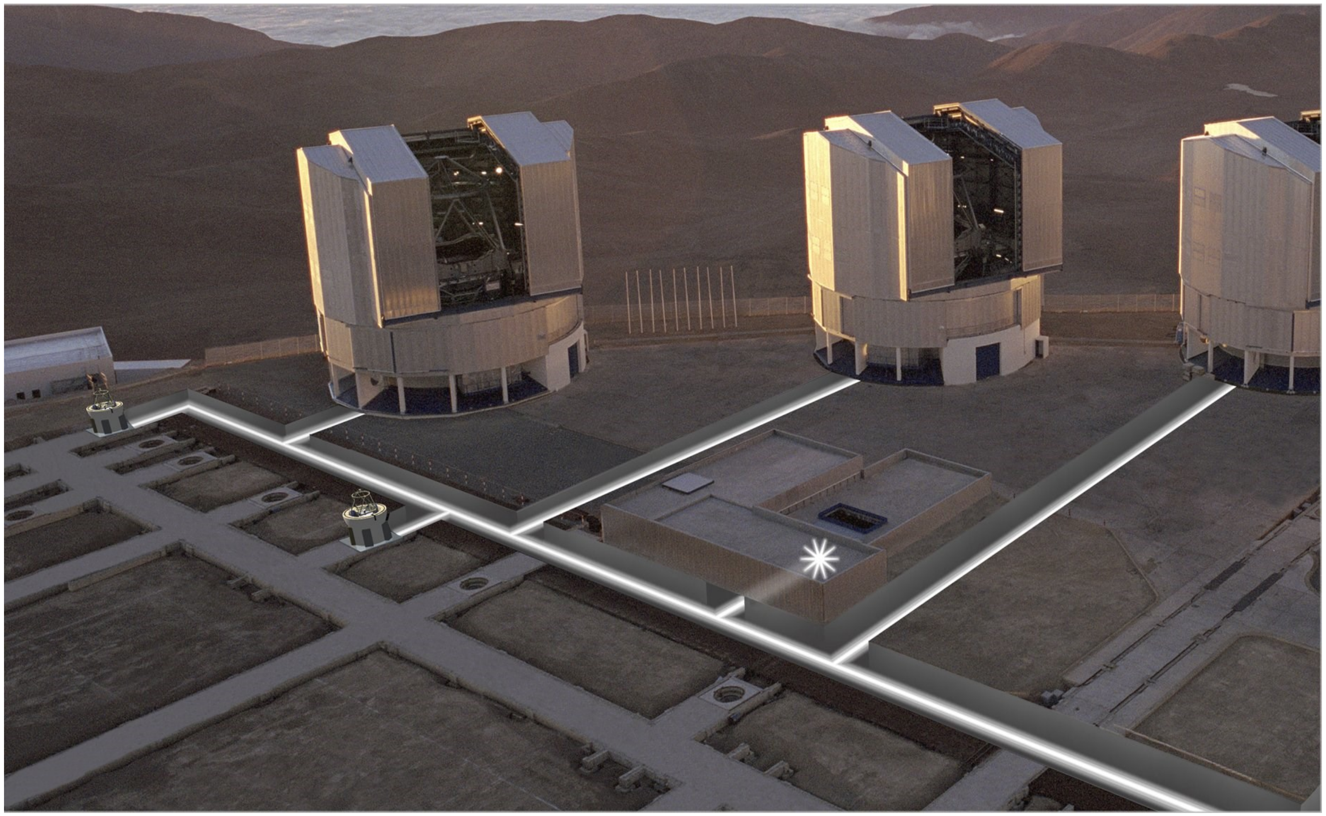
3.4 mas λ/120m

astrometric precision:

goal 10μarcsec



VLTI: VLT Interferometer



- VLTI instrument GRAVITY:
  - phase referenced imaging coherently combining light of four 8m telescopes with baseline of 120 m
  - high precision narrow angle astrometry : 10 µas
    OPD 10nm
- the spatial resolution of the VLTI (120 m baseline) will outperform the ELT (39m)

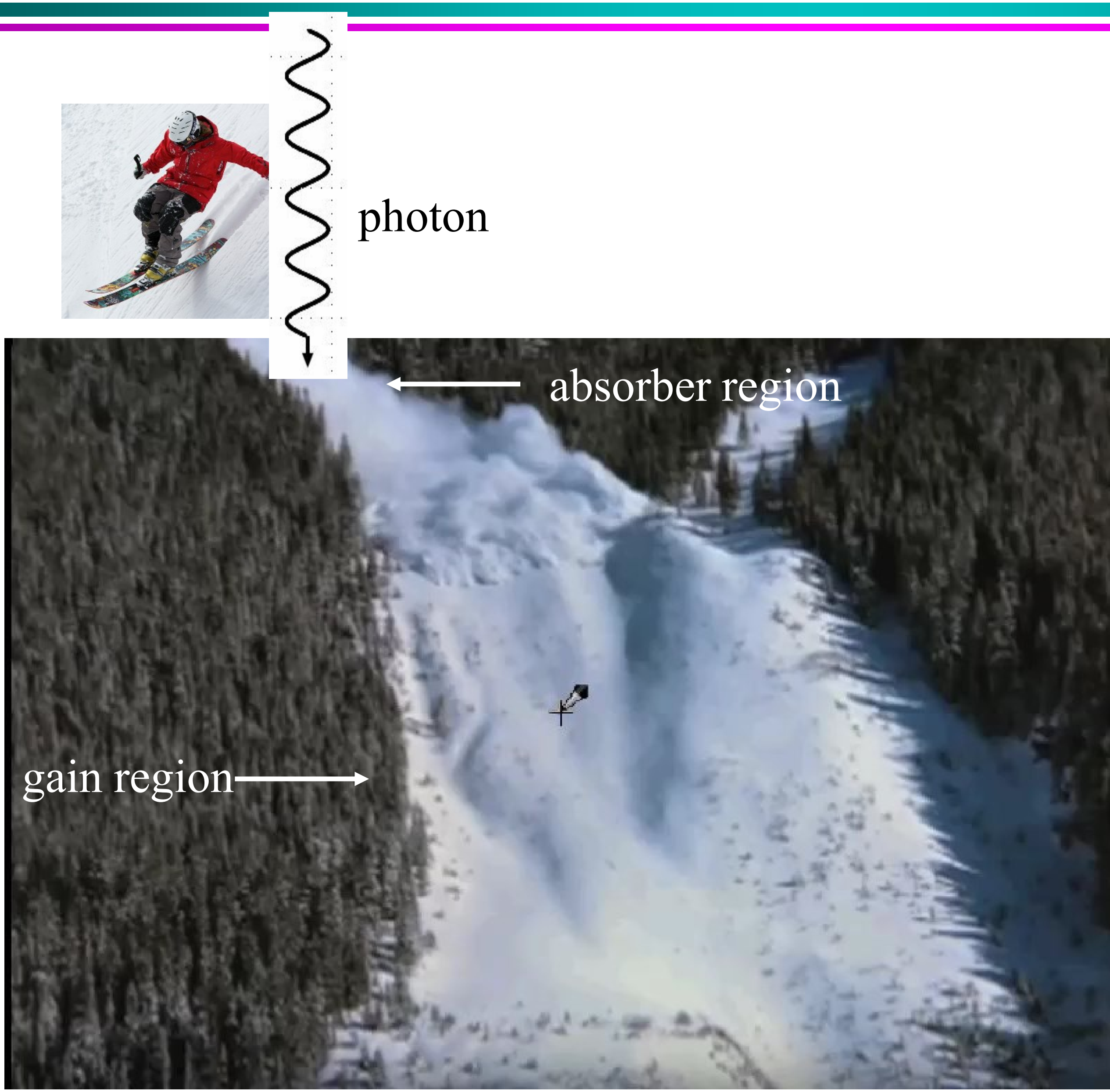
detectors for GRAVITY

- needed: four high speed low noise near infrared wavefront sensors (one for each telescope)
  one fringe tracker for beam combiner instrument
- sensor: the sensor should have:
  cutoff wavelength λ_c=2.5 µm ($Hg_{1-x}Cd_xTe$)
  frame rate ~ 1KHz
  readout noise << 3erms

how to achieve noise of <<3 erms at 5 MHz ?

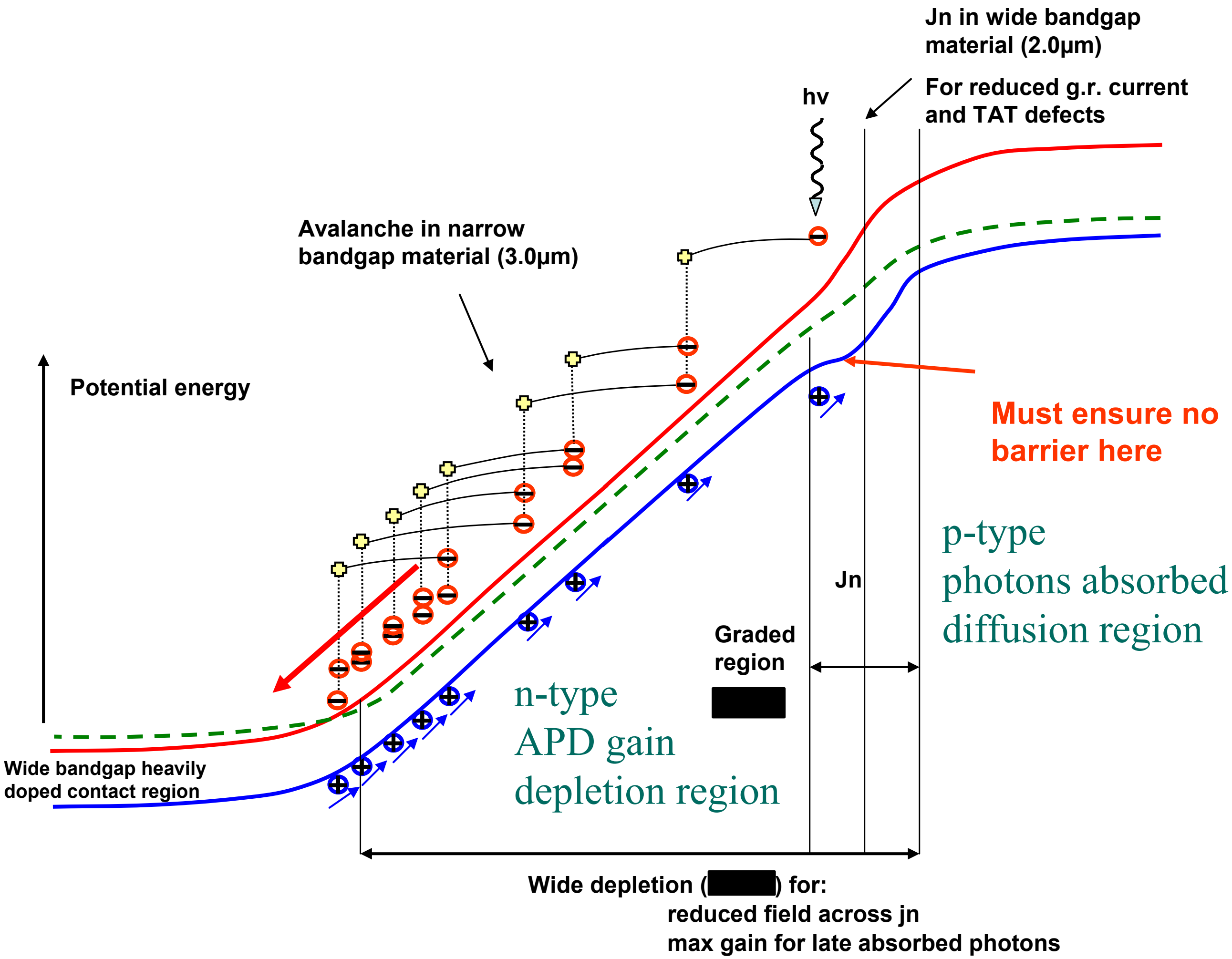
- noise of CMOS sensors (PICNIC,H2RG) scaled to speed of 5 MHz: RON ~ 70 erms
- APD: Avalanche Photo Diode:
- HgCdTe is a direct seminconductor :
  noiseless amplification inside infrared pixel
- $m_e << m_h$: rapid energy loss of holes due to phonon scattering
- pure electron multiplication

electron Avalanche PhotoDiode : eAPD



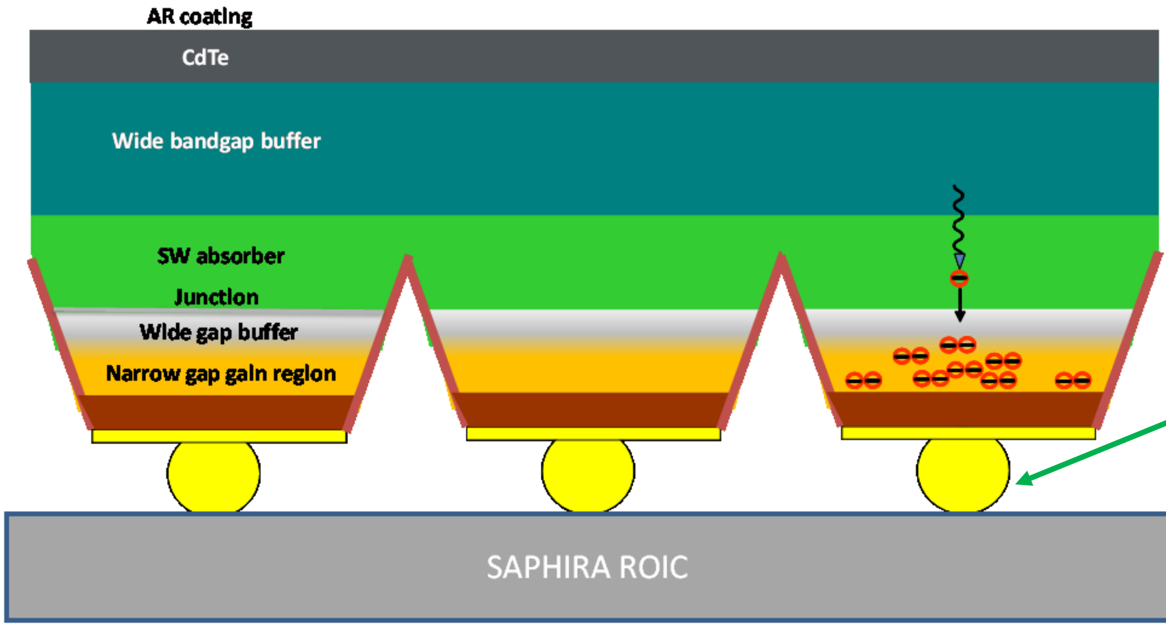
- absorbed photon creates free electron
- electron accelerated in electric field
- by impact ionization an avalanche of electrons is created
- it is easier to detect an avalanche of electrons than a single electron

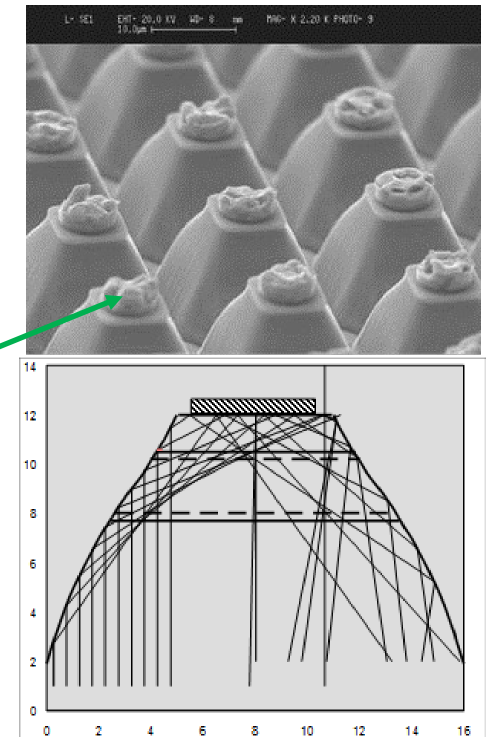
band diagram of MOVPE heterojunction



- heterojunction
  wide bandgap absorber
  narrow bandgap gain region
  to maximize APD gain
- photons absorbed in p-type and amplified in n-type region
  n-on-p diodes
- danger area at junction:
  crystallographic defects cause excessive dark current
  at high electric field due to trap assisted tunneling

MOVPE heterostructure eAPD array





- **solid state engineering**
- growth process: metal organic vapour phase epitaxy MOVPE on GaAs substrate
- mesa structure, excellent QE due to cone effect and low crosstalk (< 1E-4)
- wide bandgap buffer layer : λ_c=1.3 µm, absorber layer λ_c=2.5 µm, narrow bandgap gain region : for high APD gain $\propto \exp(\alpha\ \lambda_c)$: λ_c=3.5 µm
- sensitive in H and K band

design of custom specific ROIC SAPHIRA

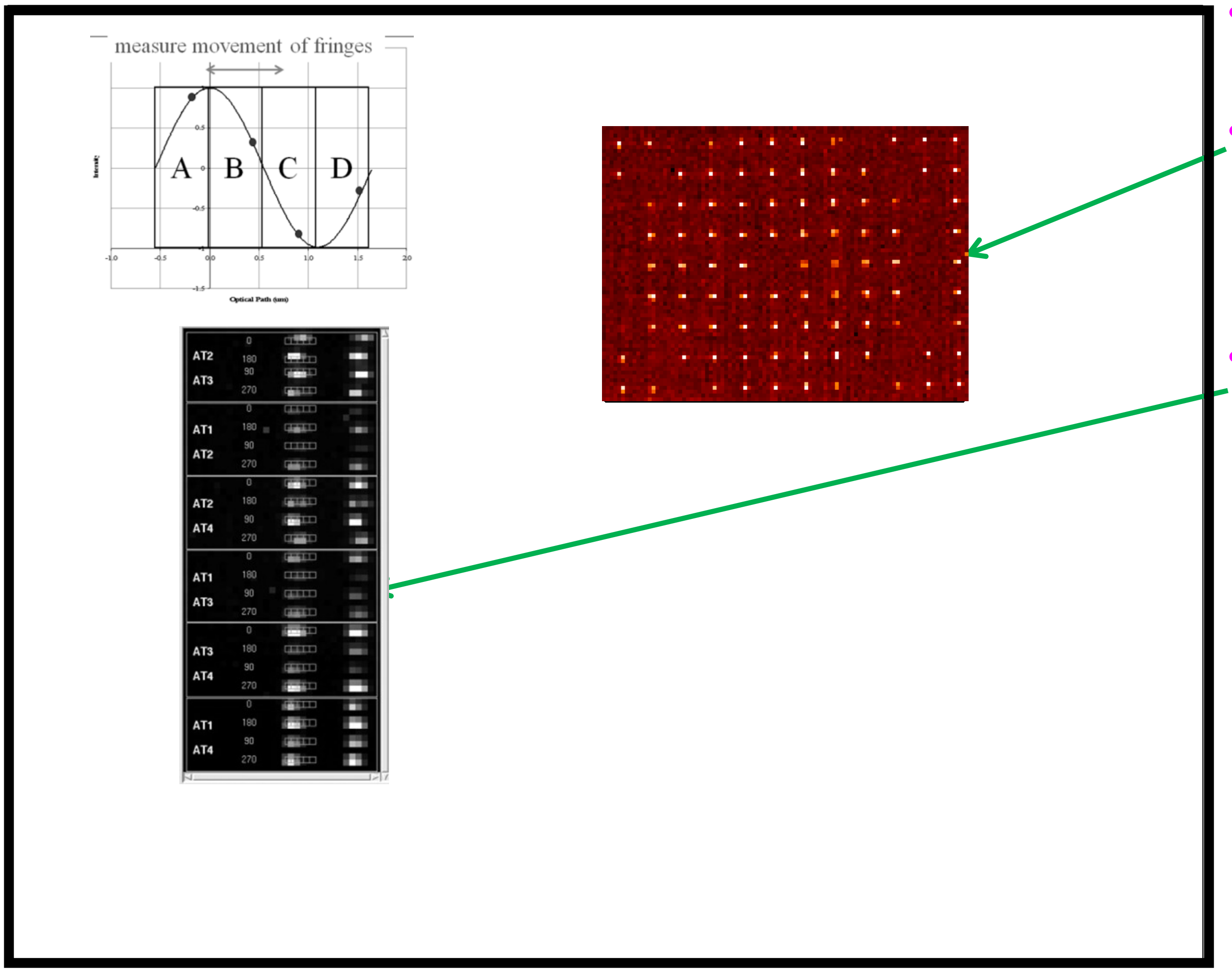
- design a new low noise ROIC needed which is specialized for AO and FT
  Selex **A**valanche **PH**otodiode **I**nfra**R**ed **A**rray **SAPHIRA**

- key features:

- format: 320 x 256 NIR HgCdTe Diode Array
- 32 parallel video outputs corresponding to 32 adjacent pixels in a row
  sub-frame with multiplex advantage
- full frame readout in less than 500µs with 5MHz clock
- SFD in unit cell
- nondestructive readout
- selectable reset for each window to get different integration times for each window (star separator)

SAPHIRA window topology for GRAVITY

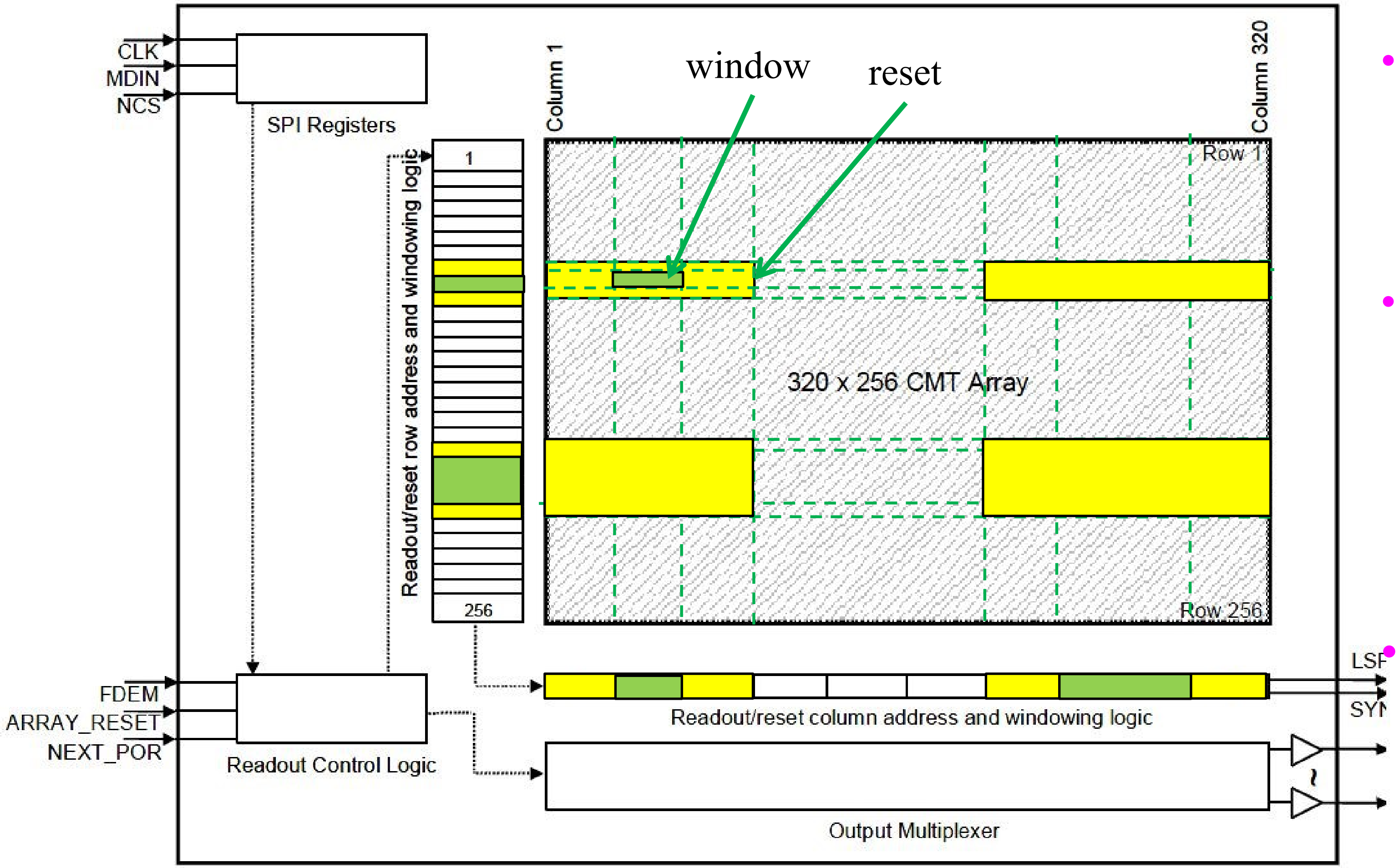
full frame (320x256)



- full array 320x256 pixel
  frame time **512 µs**
- Wavefront sensor:
  96x72 pixels needed
  3x72 conversion strobes
  frame time: **43 µs**
- fringe tracker:
  6 baselines for 4 telescopes
  ABCD algorithm 4 spectra
  2 polarizations:
  48 spectra to be read
  with 24 windows each
  having 32x1 pixel
  separation 5 rows
  24 conversion strobes
  frame time: **4.8 µs**

SAPHIRA window topology

- reset region lager than window region because of edge effects



- Programmable windows and reset regions with download of bit stream
- Wavefront sensor:

  96 x72 pixels needed

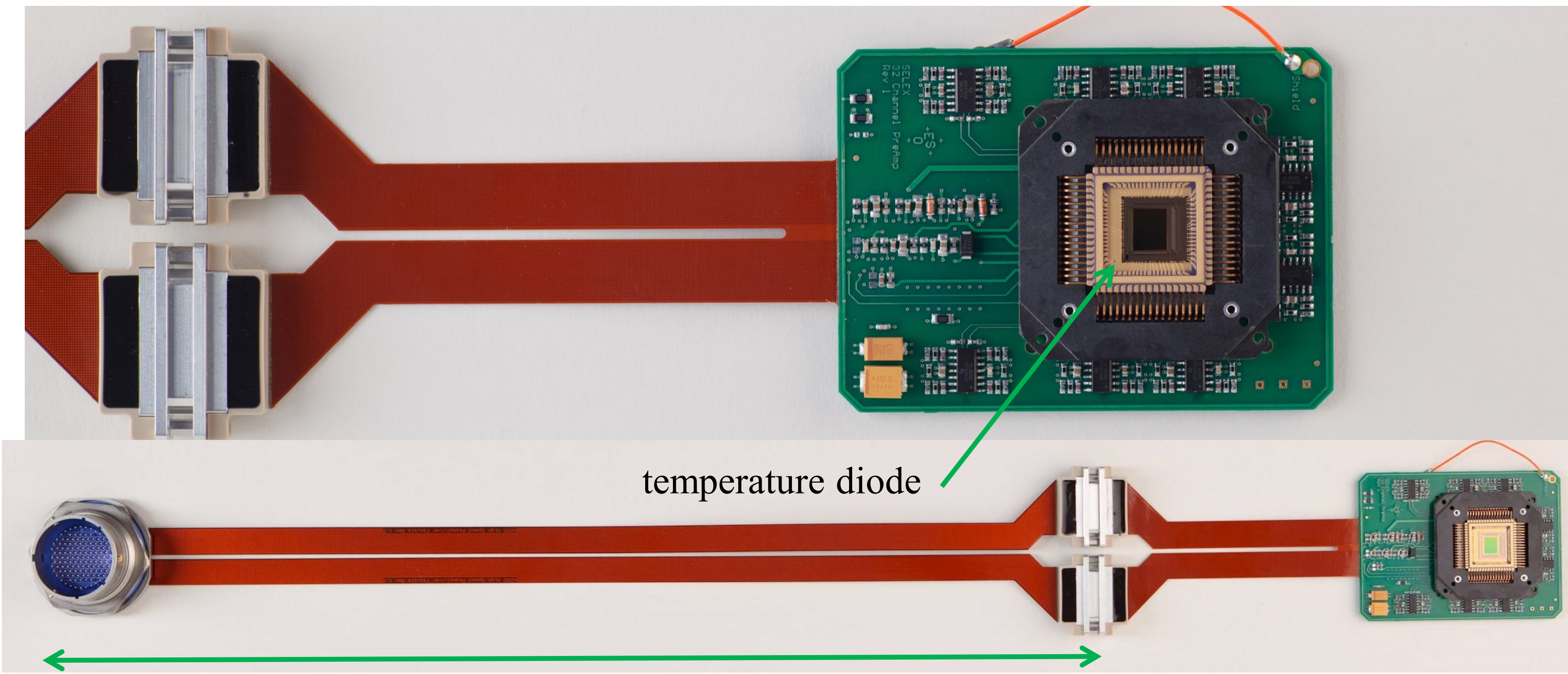
  Fowler-12 possible for DIT=1ms
- fringe tracker:

  48 spectra to be read with 24 x 32x1 pixel windows

  Fowler-90 possible for DIT of 1 ms
- readout noise reduced by Fowler sampling

SAPHIRA readout electronics

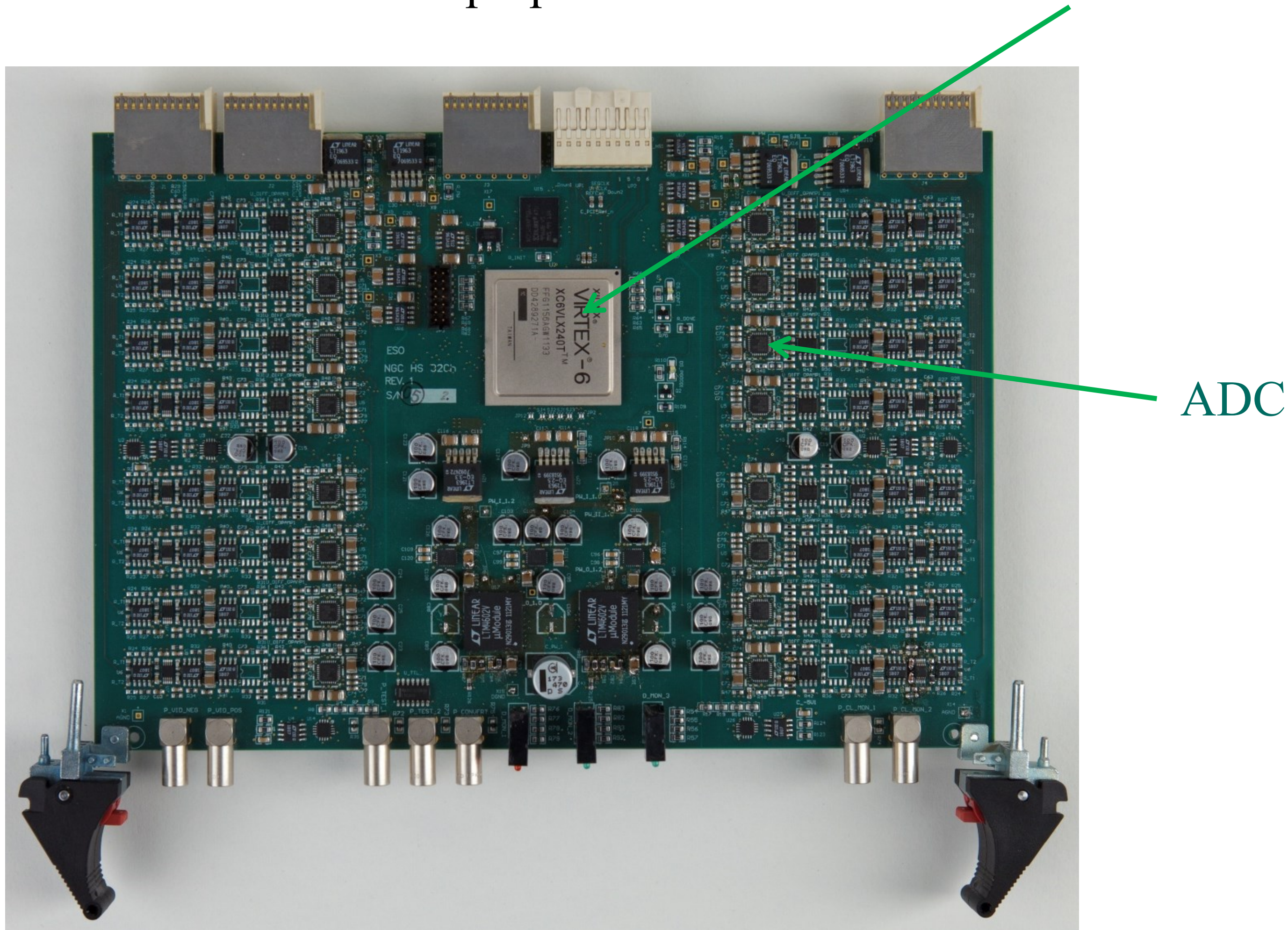
- 32 channel 5 MHz cryogenic preamplifier board is compatible with PICNIC board
- 68-pin LCC package compatible with PICNIC socket
- 50 cm flexboard is compatible with Hawaii-2RG flexboard and 128 pin hermetic connector
- 150 cm external cable to NGC DFE



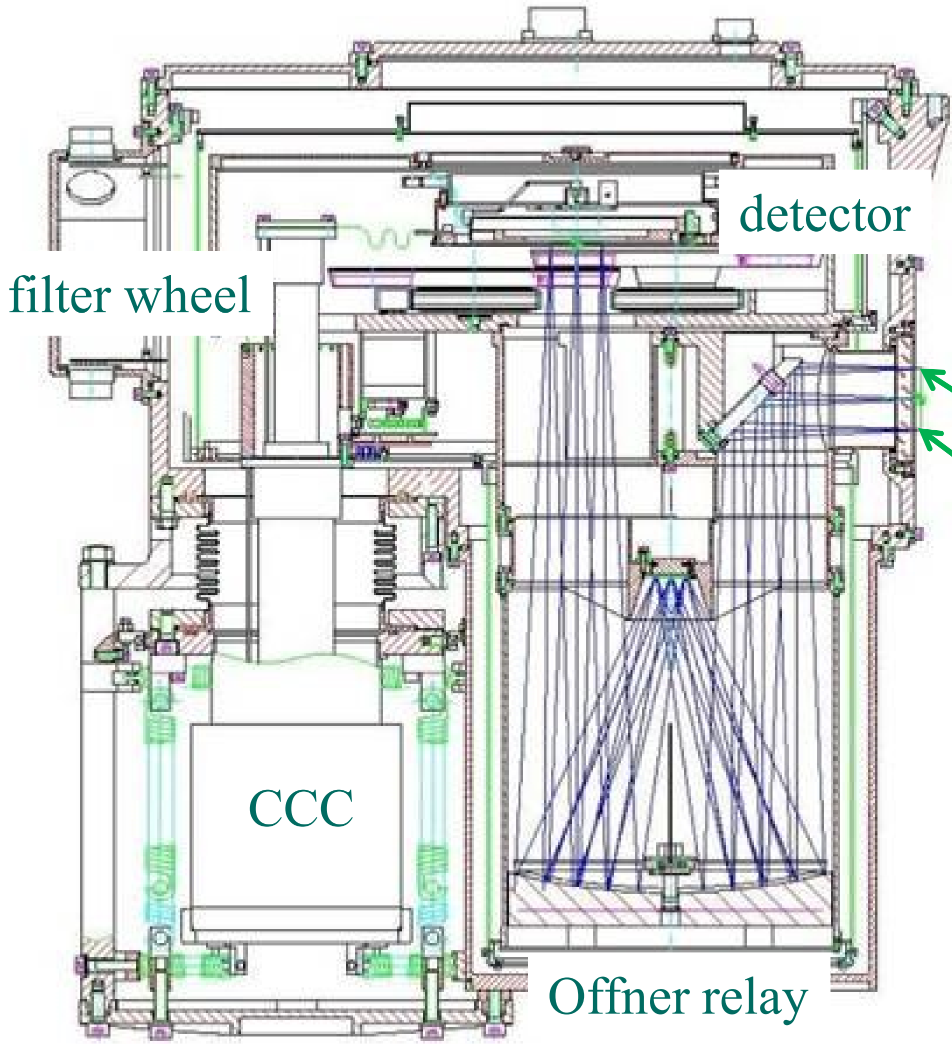
50 cm flex board + 150 cm external cable

SAPHIRA readout electronics

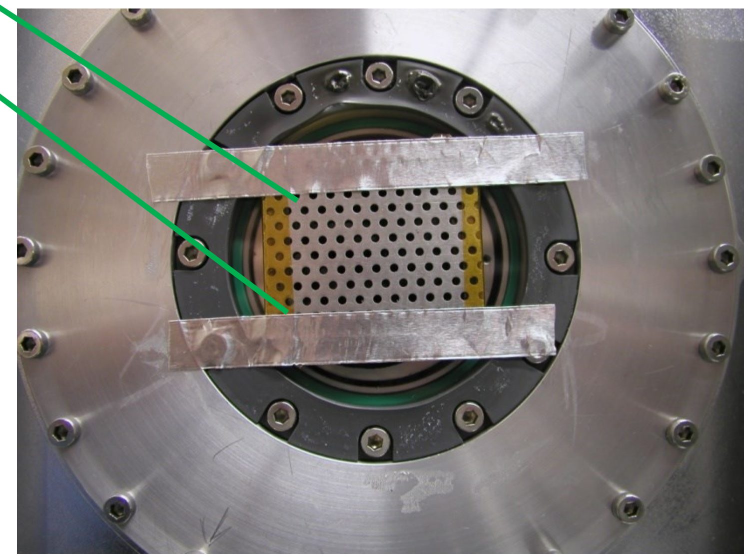
- standard 2-slot NGC system: front-end basic board (sequencer, clock &bias)
- new 32-channel 10 MHz ADC board & preprocessor in FPGA



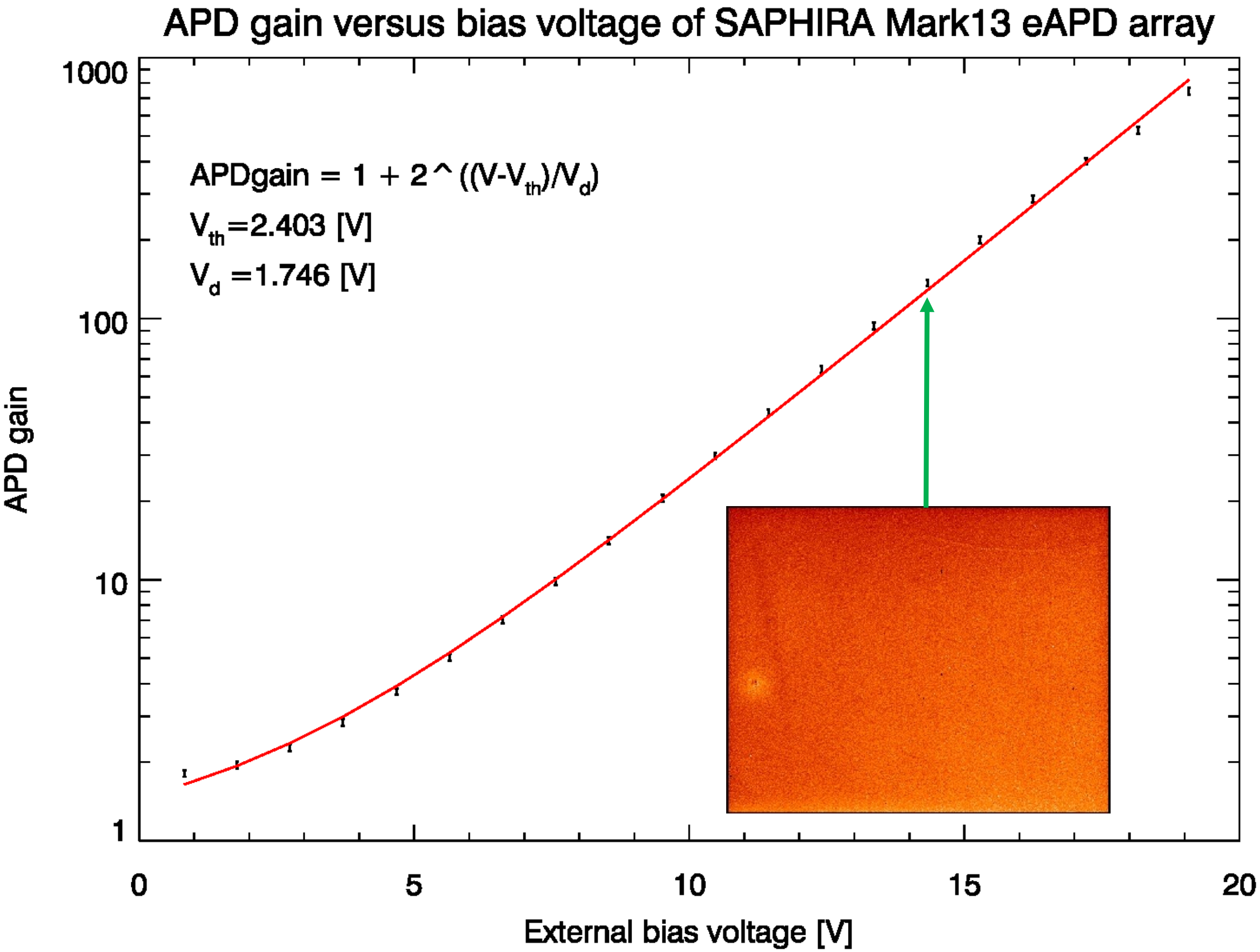
IRATEC test camera



- Offner relay f/11
- clod filter wheel with bandpass filters: J,H,K
- test pattern with grid of holes in image plane illuminated by extended blackbody

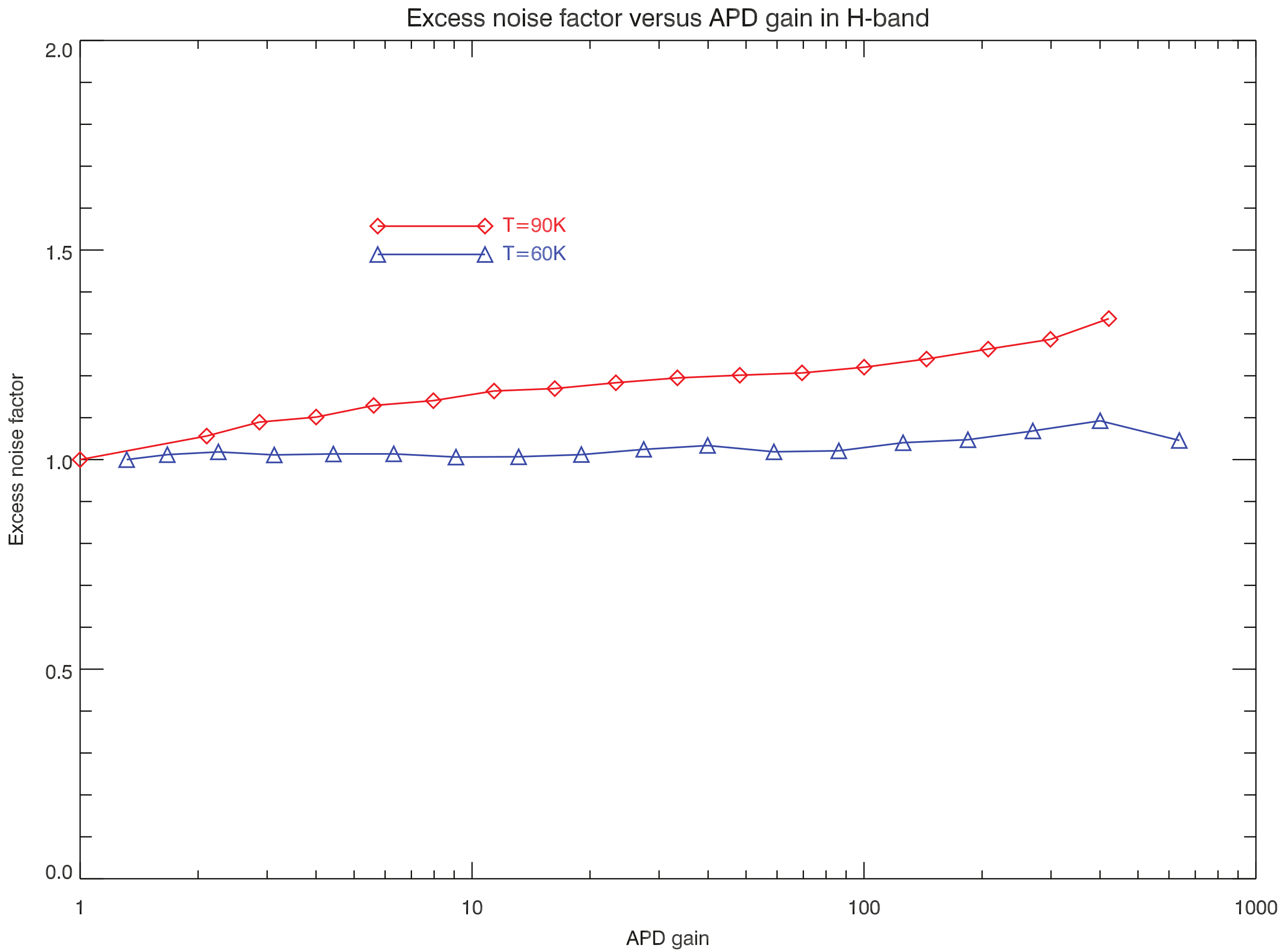


APD gain of Mark13



- measure signal versus photon flux and determine slopes for different bias voltages
- fit 3 free parameters:
  scaling parameter f
  APD gain = f * slope
  threshold Voltage V_{th}
  double gain Voltage V_d
- still well behaved with **excellent cosmetic quality at APD gain > 100**

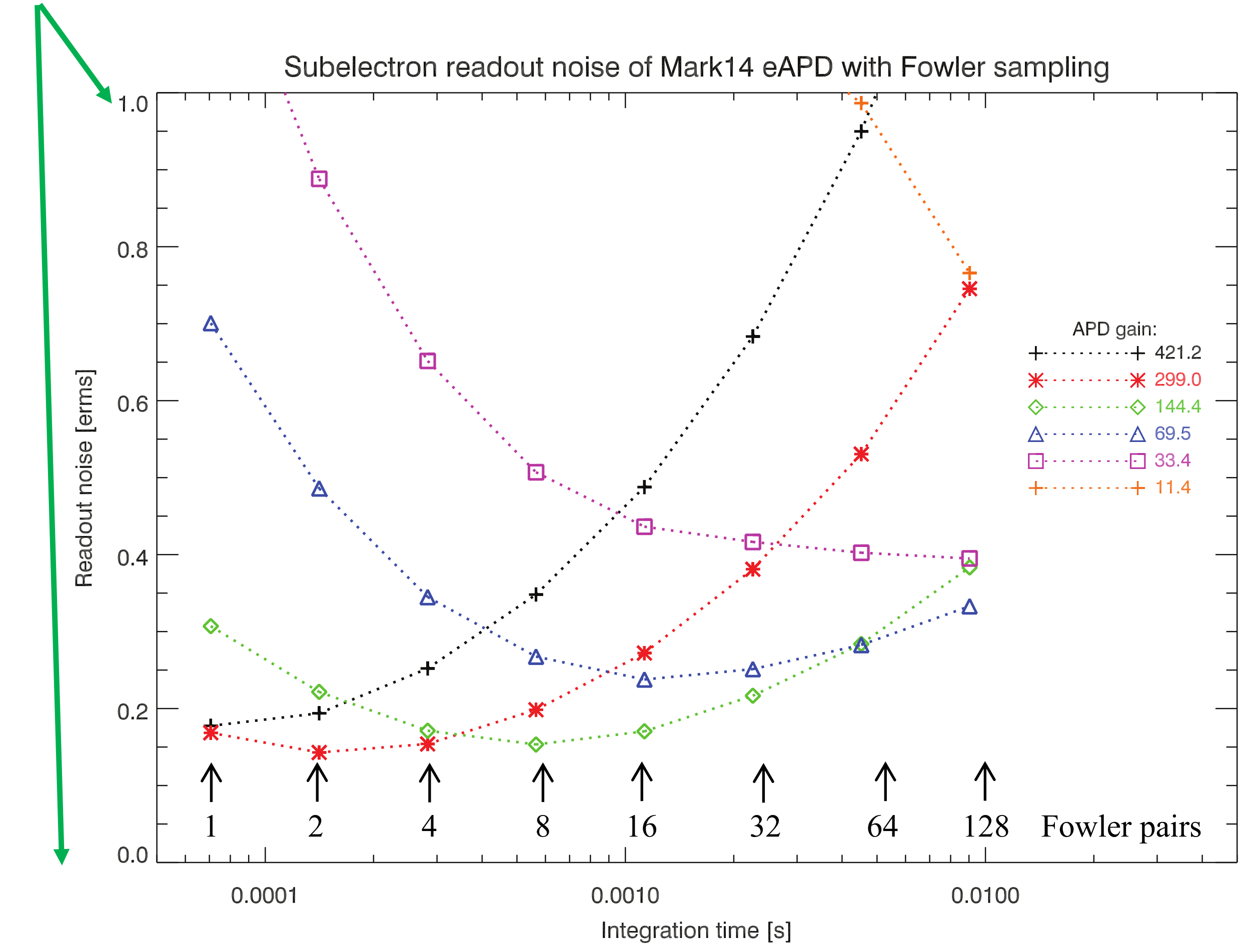
excess noise versus APD gain



- noise figure 1.3 at APD gain of 421 at T=90K noise increase by factor of 1.14
- noise figure 1 at APD gain of 637 at T=90K

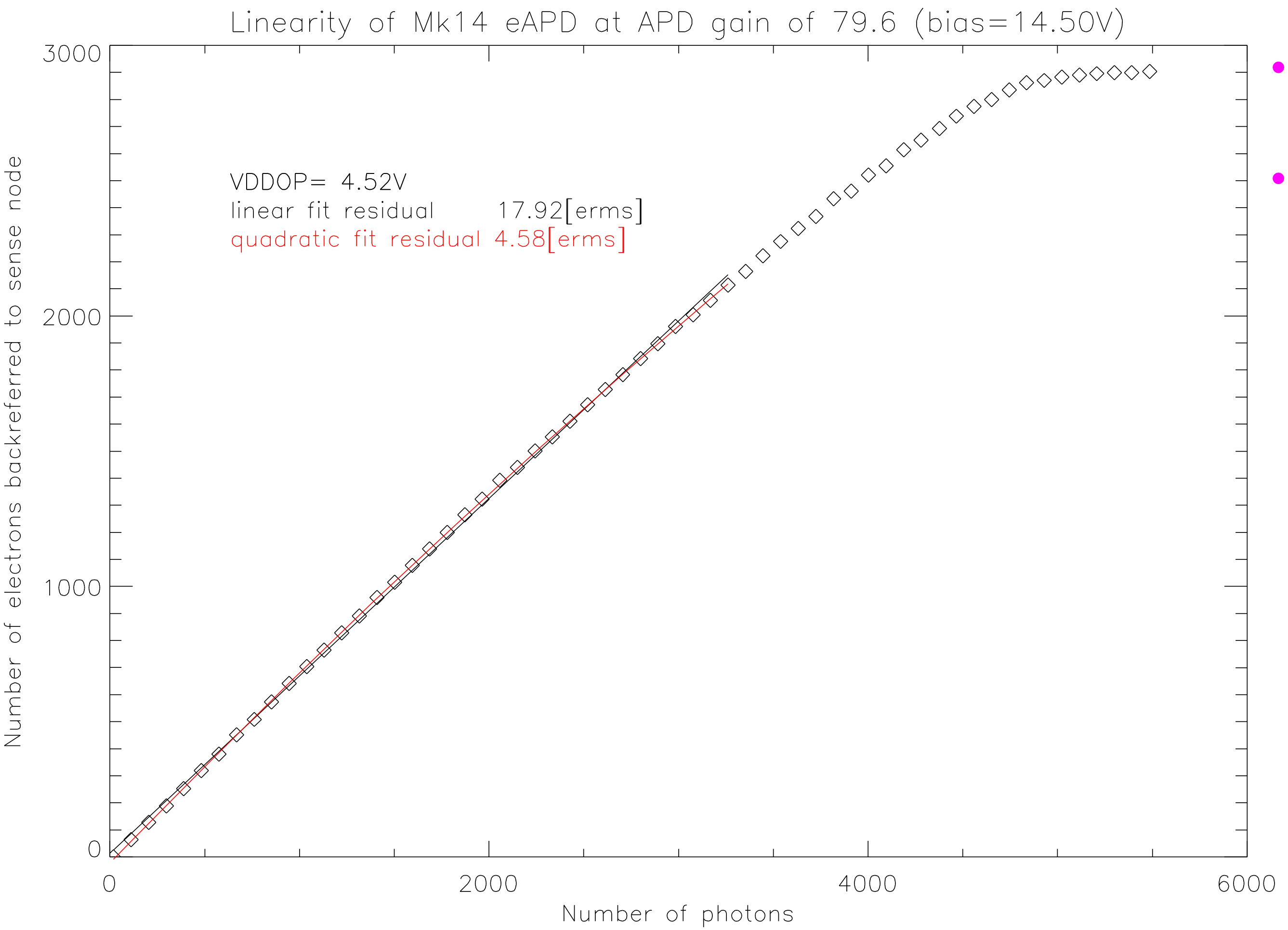
subelectron noise with Fowler sampling for window

all subelectron



- windowed readout 96x72 pixel
- GRAVITY has 9x9 subapertures with 8x8 pixels (72x72 pixels needed)
- frame time for window 70 µs
- temperature 90K
- at APD gain of 299 and DIT=140 µs with Fowler-2 the readout noise is **0.14 electrons rms**
- for long integration times and high APD gain readout noise is dominated by detector dark current

linearity of eAPD with APD gain



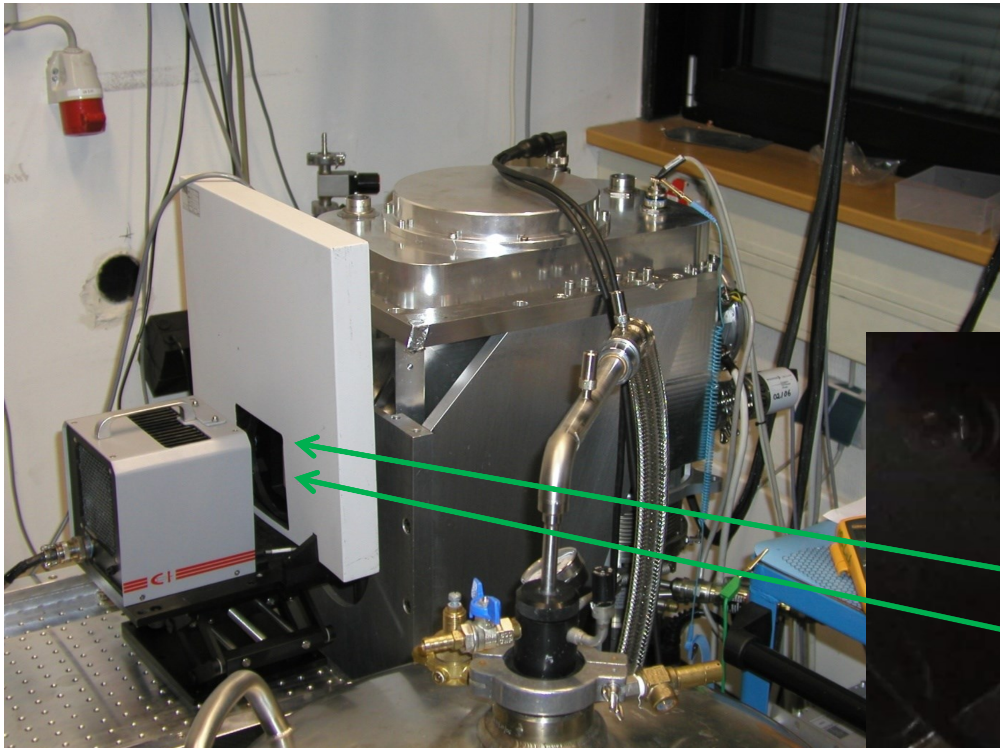
- APD gain changes during integration due to voltage decrease
- can be calibrated

  residuals at APD gain of 79.6:

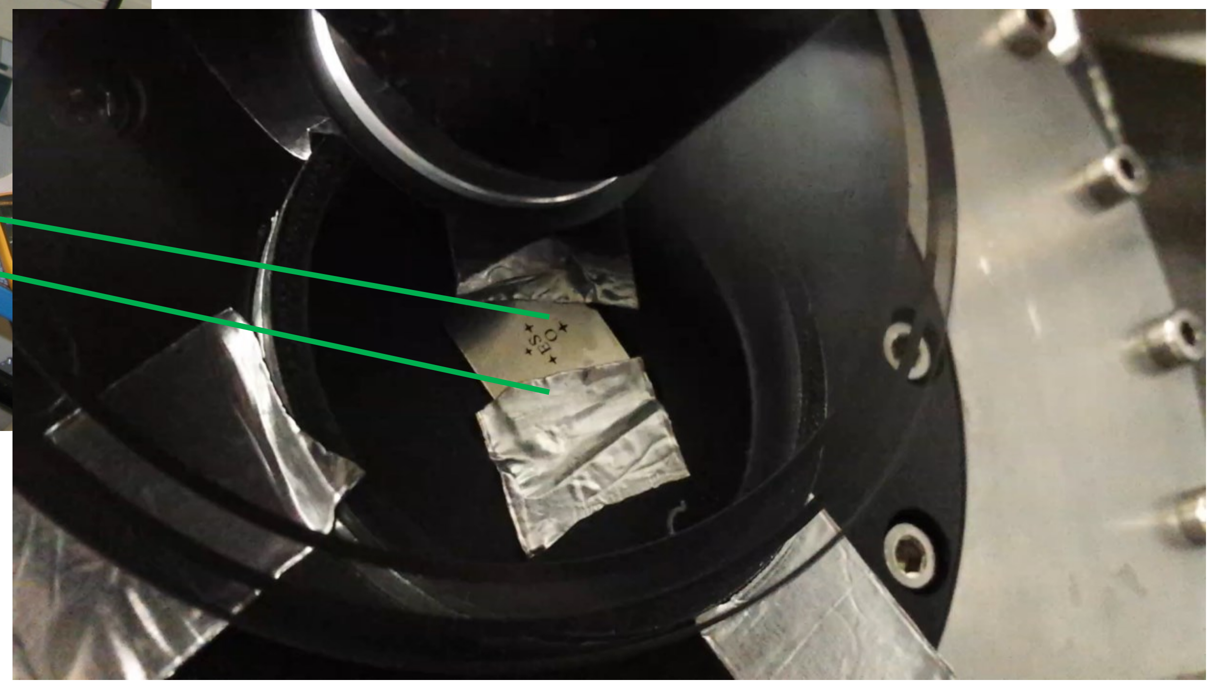
  linear fit: 17.92 erms

  quadratic fit: 4.58erms

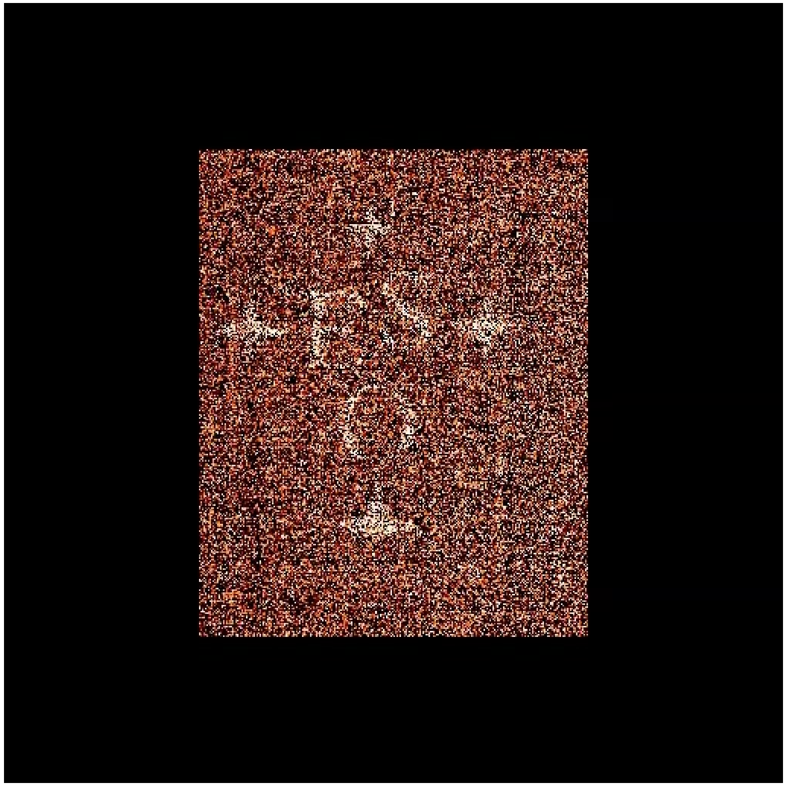
NIR HgCdTe eAPD: calibrated test pattern



- Offner relay f/11
- clod filter wheel with bandpass filters: J,H,K
- test pattern with ESO logo in image plane illuminated by extended blackbody



subelectron sensitivity



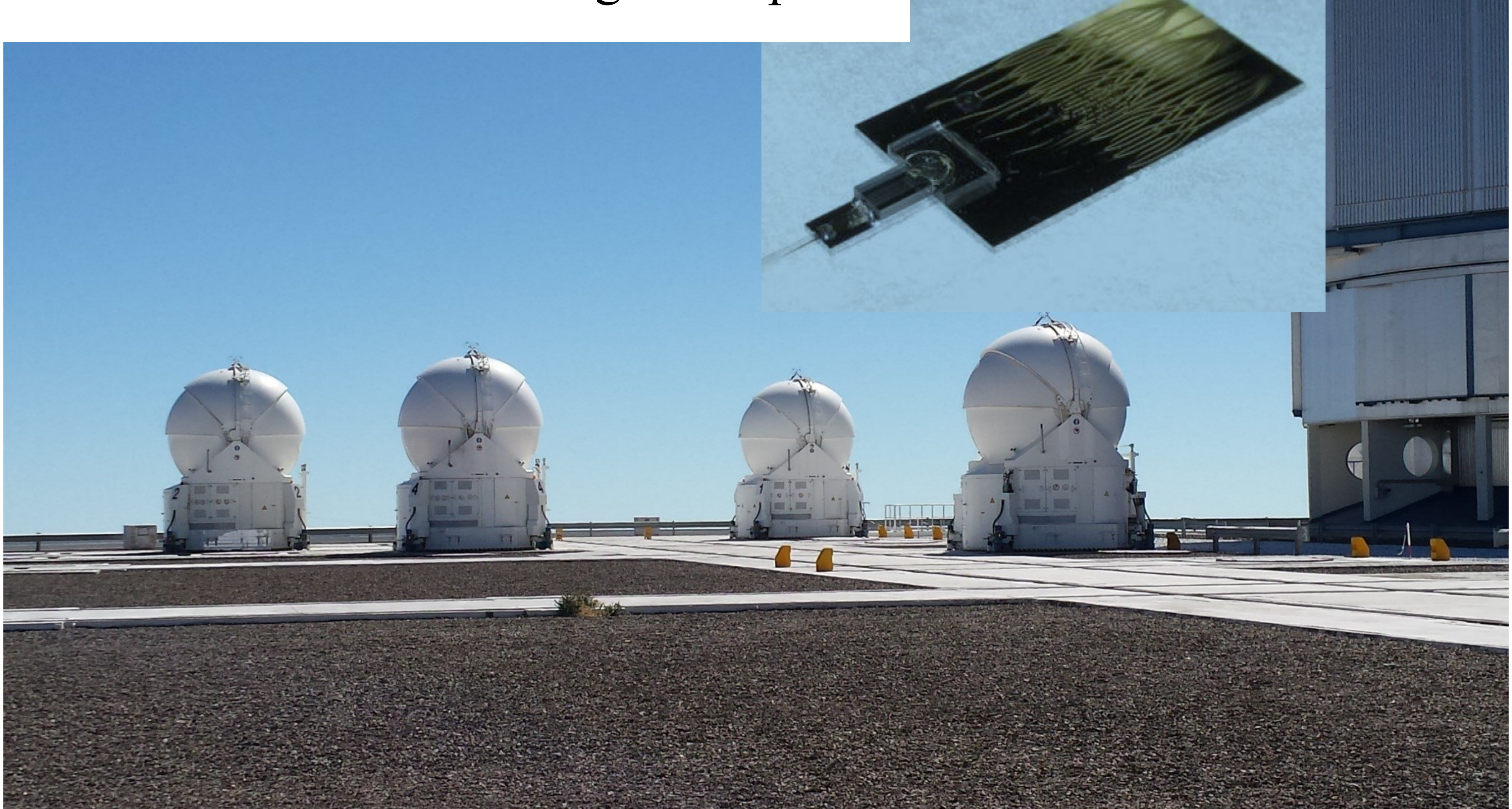
- filter H-band
- single double correlated clamp
- chop frequency 10 Hz
- blackbody temperature : on 70C
  off 20C
- optics: Offner relay f/11
- fluence
  1 electrons / pixel / integration time
  for integration time of 1.4 msec

- readout mode:
  Fowler 2
- bias voltage 14.4V

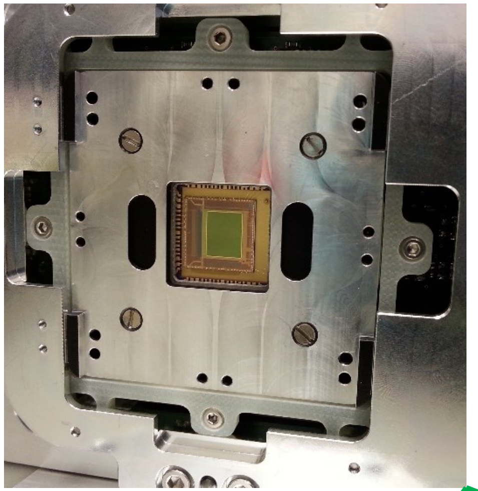
- on sky verification with GRAVITY

GRAVITY on Paranal

- combine light of four movable 1.8 m auxiliary telescopes or four 8 meter UT telescopes in beam combiner instrument
- beam combination with integrated optics



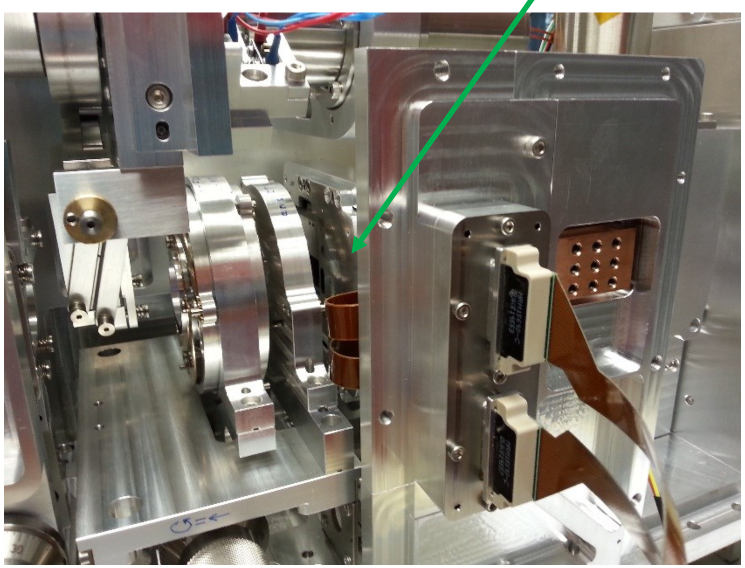
SAPHIRA deployed in GRAVITY

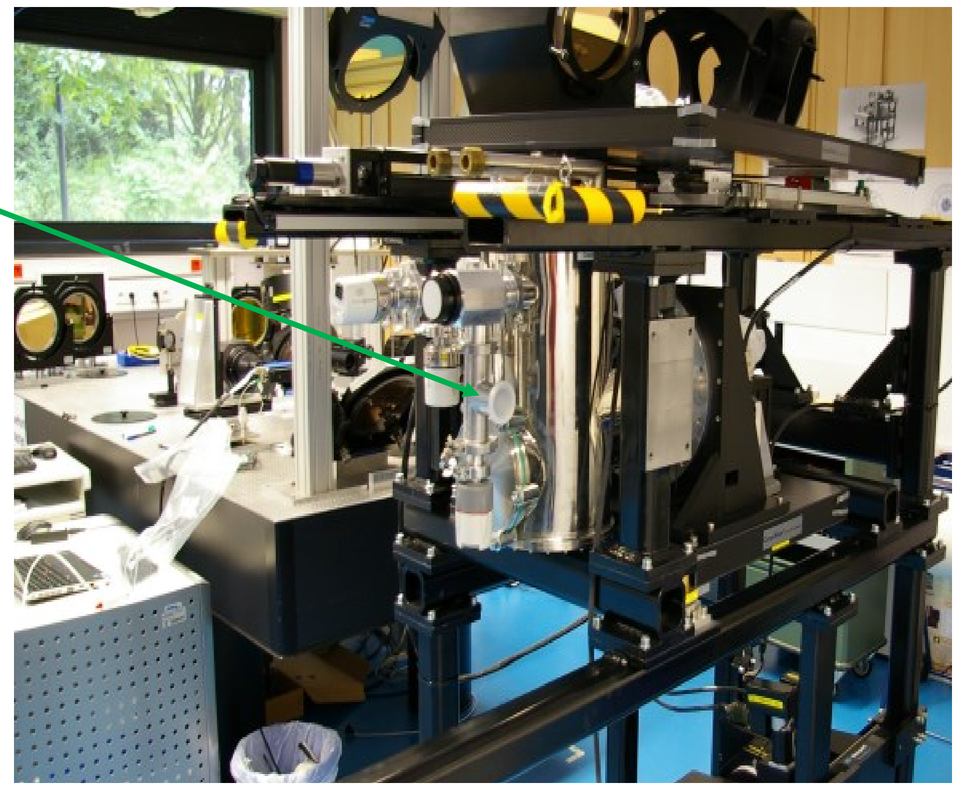


- SAPHIRA in:

- 4 devices in Coude Infrared Adaptive optics systems CIAO with bimorph mirror

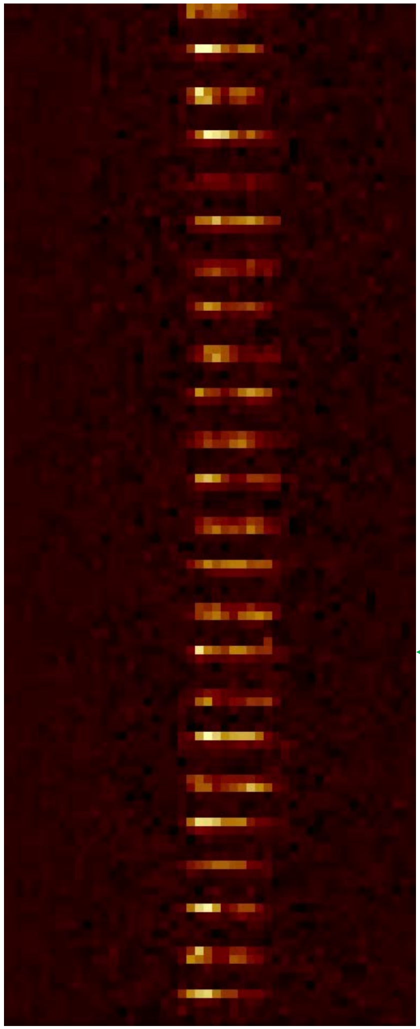
- 1 device in fringe tracker of beam combiner instrument





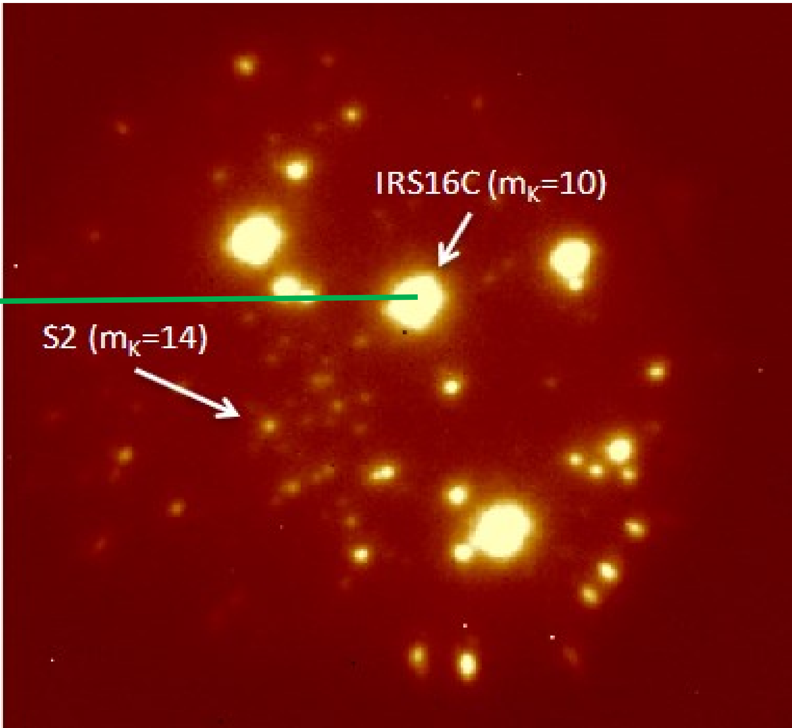
performance of fringe tracker in GRAVITY

SAPHIRA performance in fringe tracker:

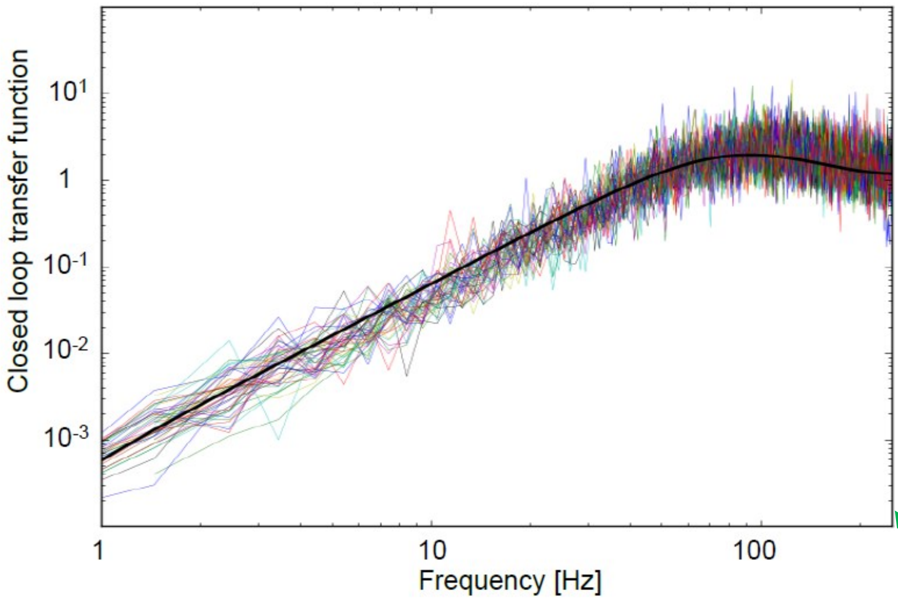


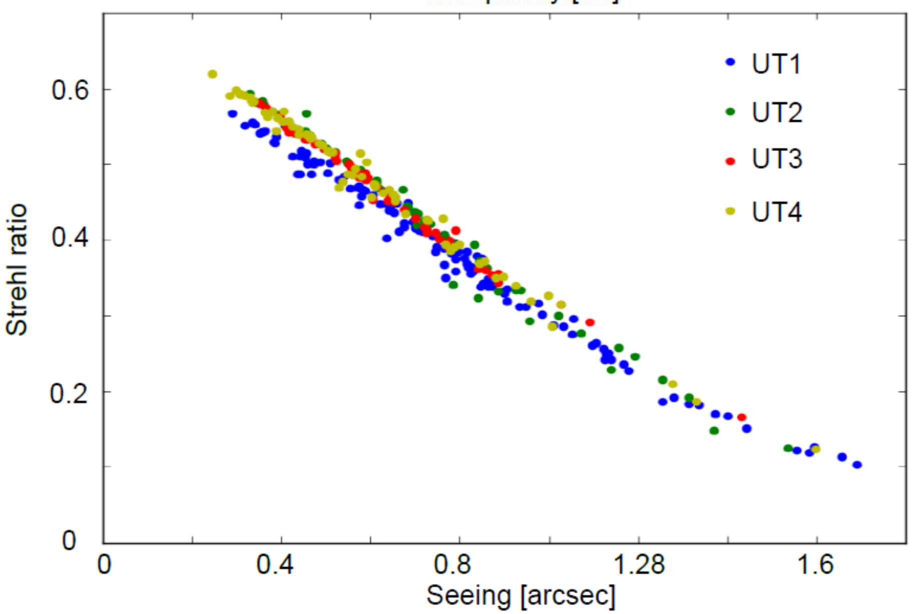
- fringe tracking sensitivity
  m_K= 10
- science fringes obtained on S2
  m_K= 14
- limiting magnitude for phase referenced imaging
  m_K~17

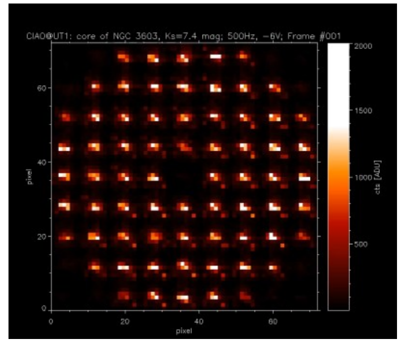
- **record in sensitivity**
- movement of S2 can be seen on a daily basis new

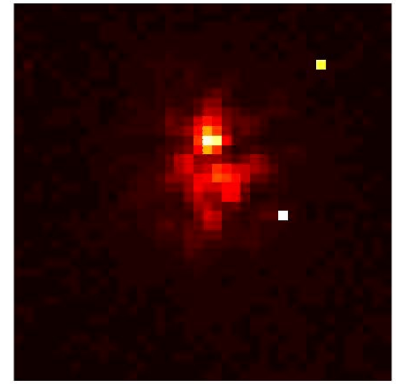


Performance of wavefront sensor in CIAO



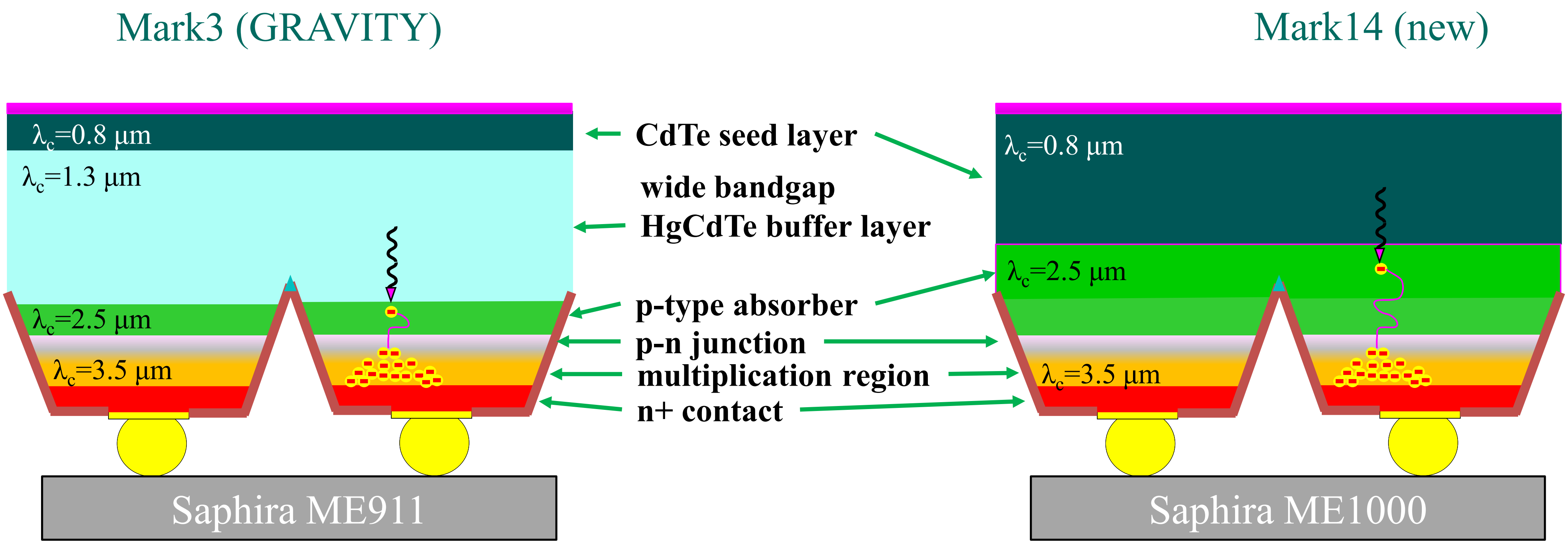






- Coude Infrared Adaptive Optics with bimorph mirrors
- 9x9 subapertures with a FOV of 2'' sampled by 4x4 pixels and separated by 8 pixels
- closed loop rejection transfer function for Zernike modes up to order 44
- Strehl ratios as a function of seeing measured on a mK=6.5 mag star, **SR=60%**
- CIAO works on guide stars up to **mK=11**

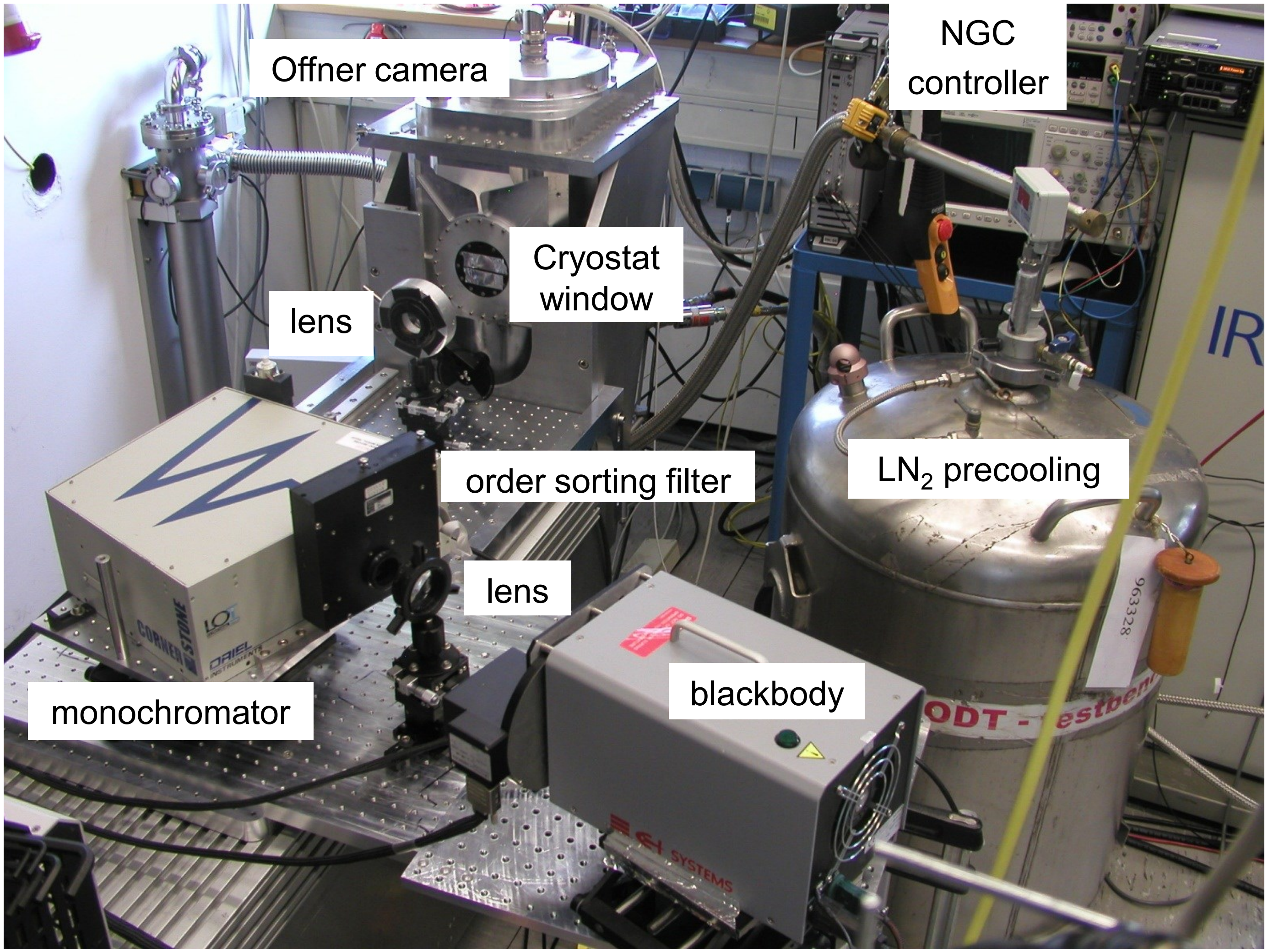
removal of wide bandgap buffer layer



sensitive range: λ=1.3 – 2.5μm
only H and K

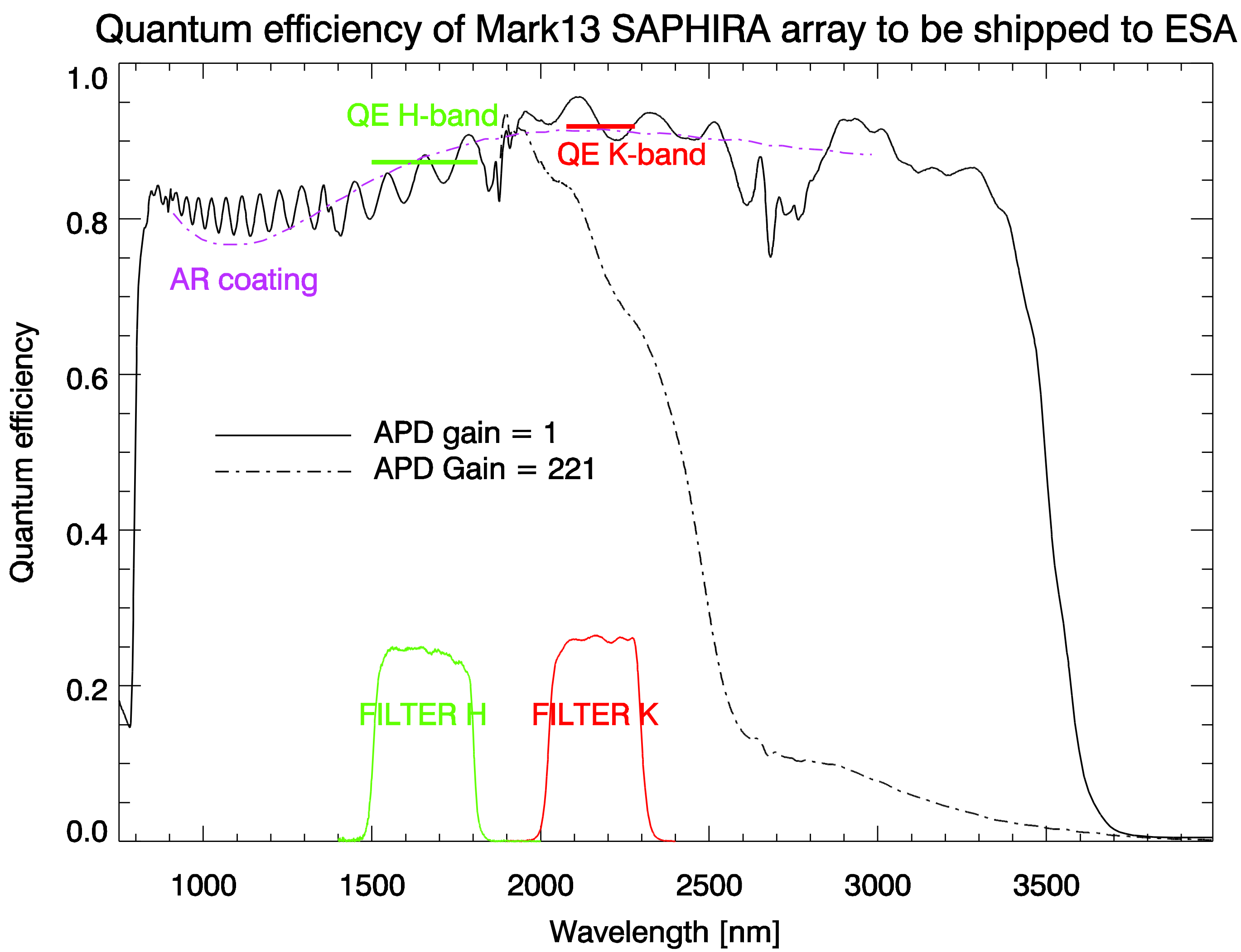
sensitive range: λ=0.8 – 2.5μm
includes Y an J band

experimental setup for spectral QE measurement



- illuminate entrance slit of monochromator with cavity blackbody which can be heated to 1200C
- calibrate efficiency of monochromator with pyroelectric detector
- reimage exit slit of monochromator to plane in front of cryostat window conjugate to the detector

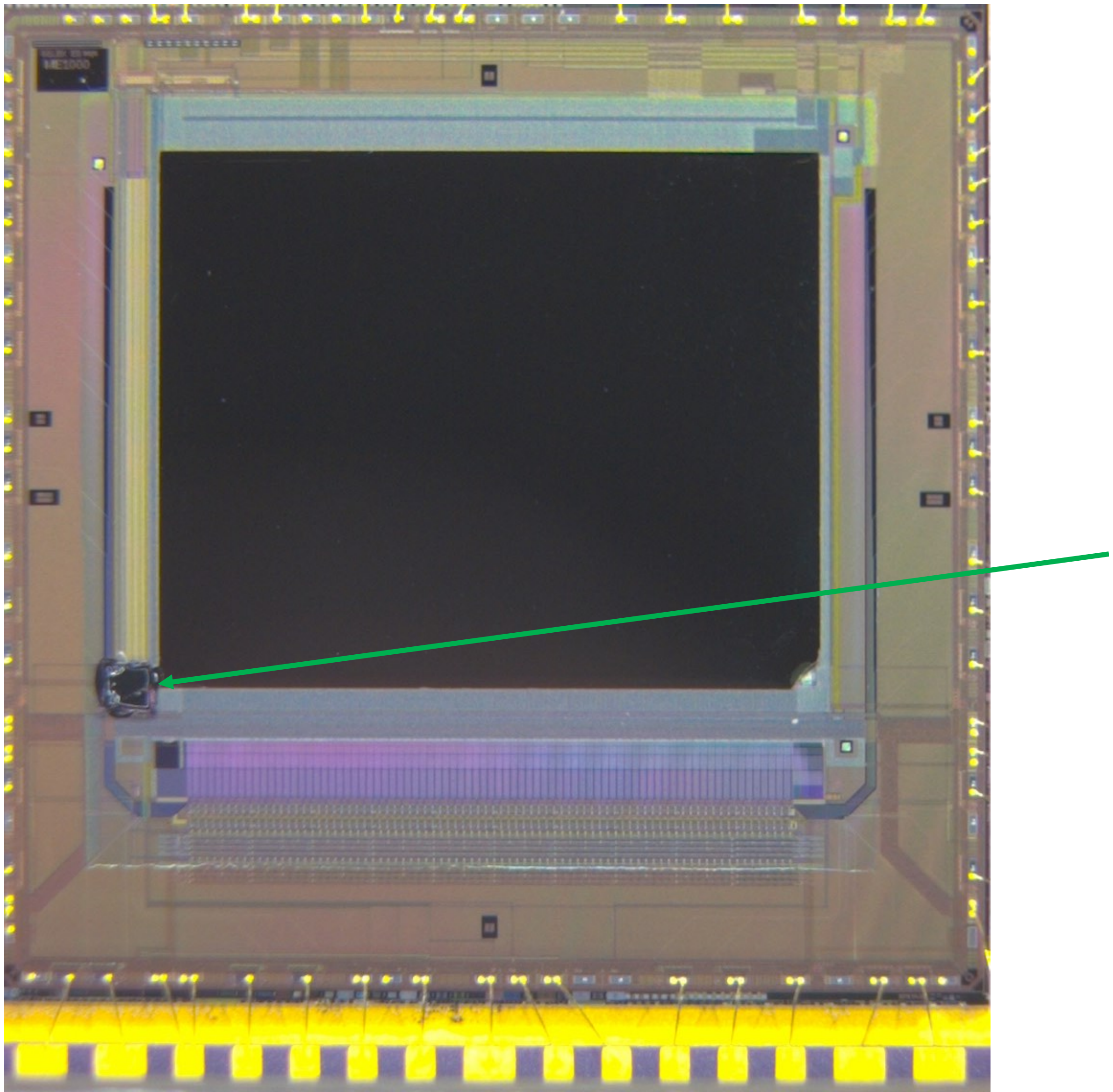
QE versus λ of Mark14 eAPD



- QE defined as Nele/APDgain/Nph
- at APD gain of 1 λ_c=3.5 μm
- at high APD gain λ_c=2.5 μm
- only photons with λ<2.5 μm experience full APD gain
- photons with λ>2.5 μm get only partial APD gain

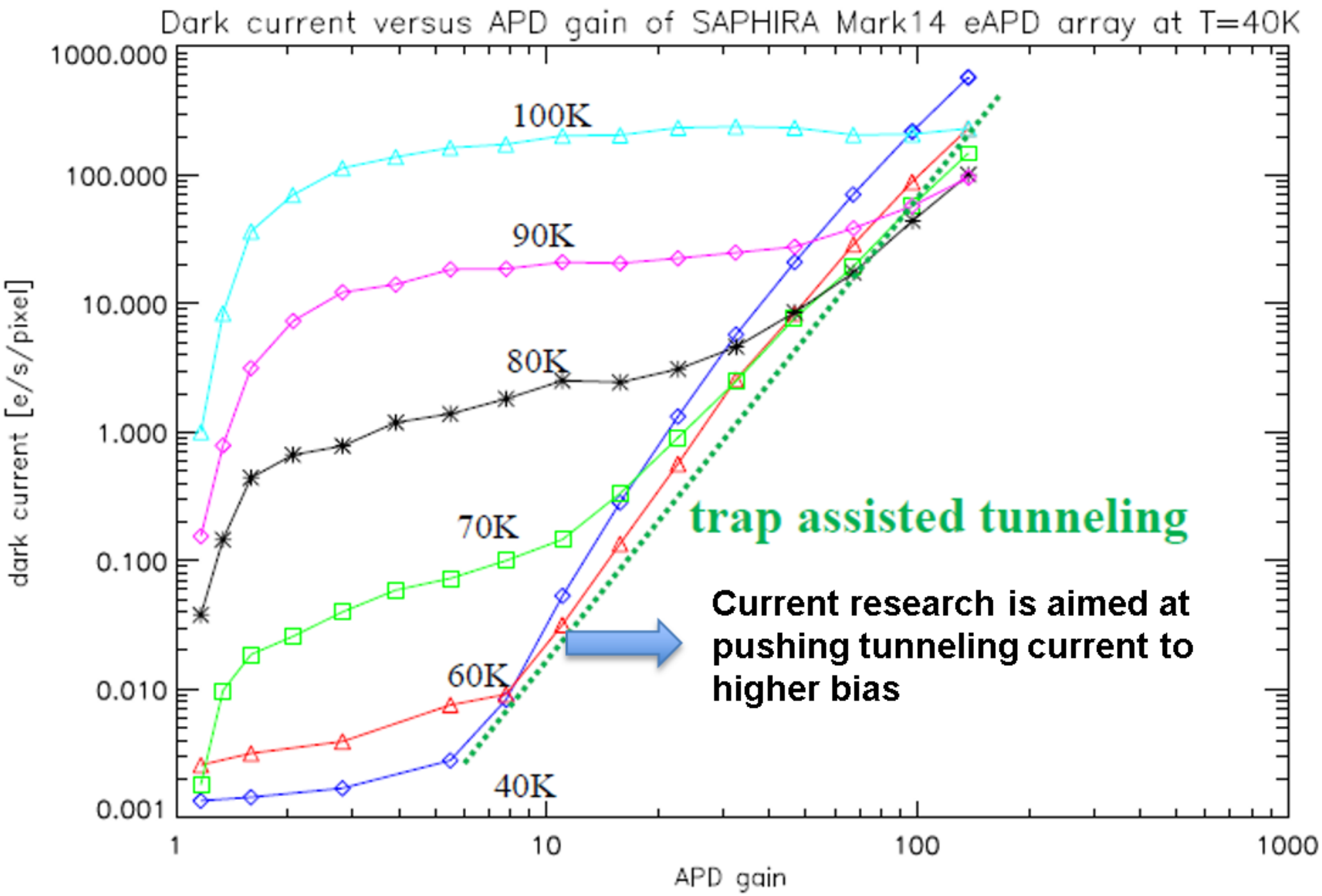
- eAPD technology for large science FPAs ?
  - long (>100 s) exposures
  - improve sensitivity of conventional CMOS IR FPAs ?

glow center taped off



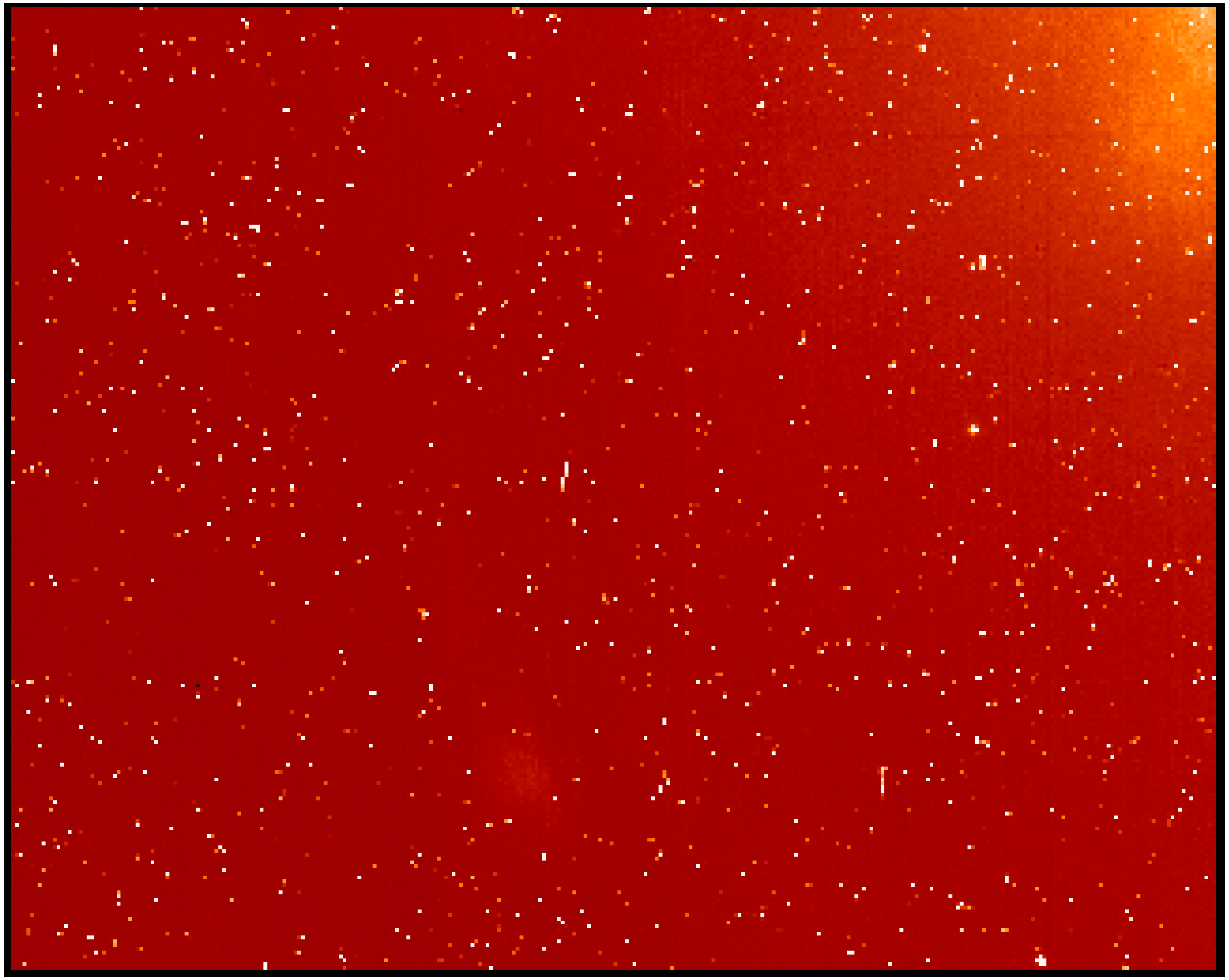
- glow center of ME1000 ROIC dominates dark current: $I_{dark} > 10$ e/s/pixel
- glow center due to floating FET on ME1000
- send Mark14 array back to LEONARDO to tape off glow center
- array returned with masked glow center
- glow center fixed on metal mask of revised ROIC (ME1001)

dark current versus temperature and APD gain



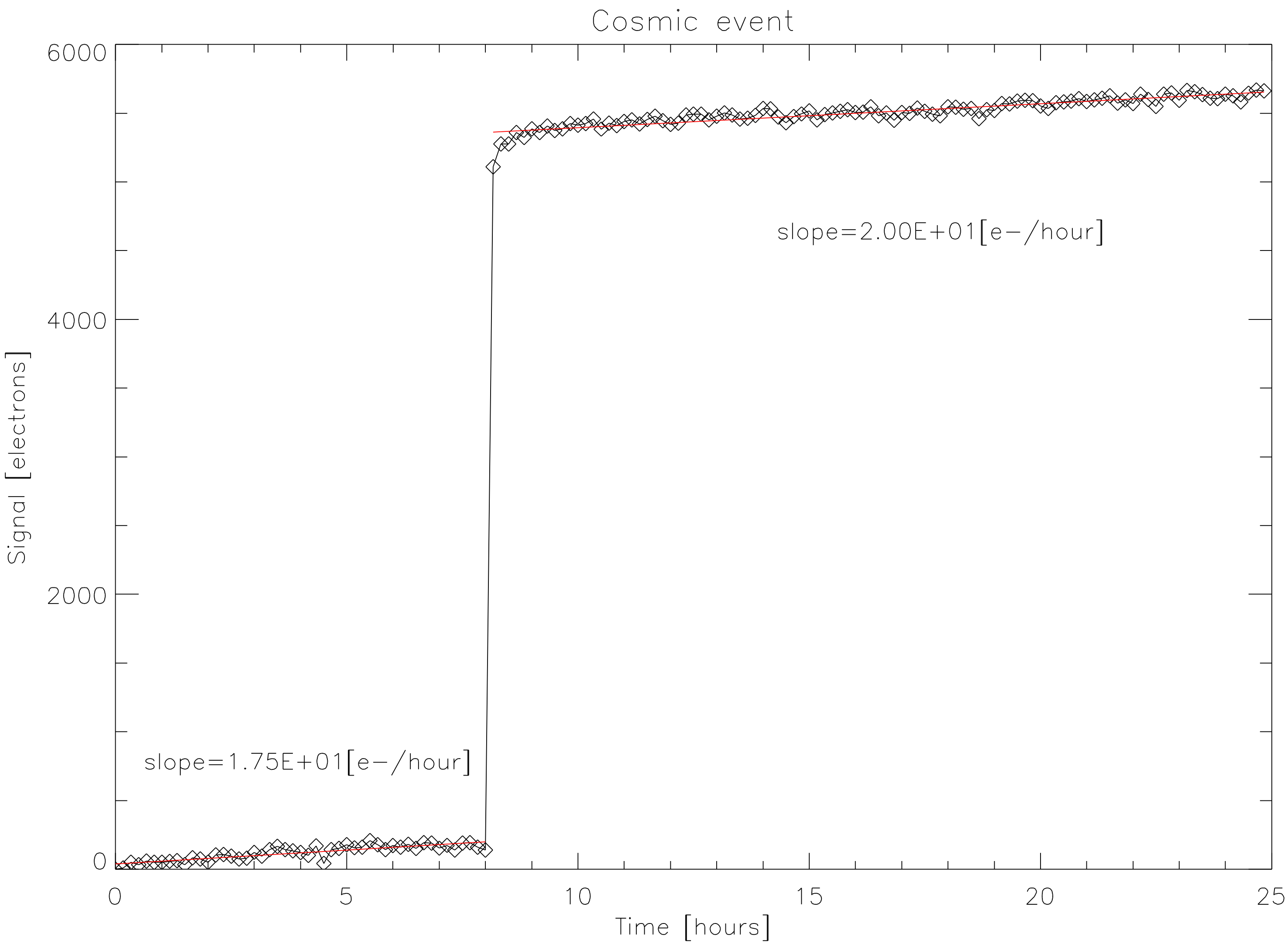
- **reduce voltages** to minimize multiplexer glow:
  reduce rail (VDD) and PRV from **5V to 3.5V**
  preamp rail from 6V to 2.6V
  clocks 0V / 2.5V
- at **T=40K & low APD gain dark current 0.001 e/s/pixel**
- at high APD gain dark current does not depend on temperature
- only process which does not depend on temperature is tunneling (TAT)
- for T<60K dark current 0.01 e/s/pixel
- glow/readout: 4.55E-4 e^-

dark current map with cosmics



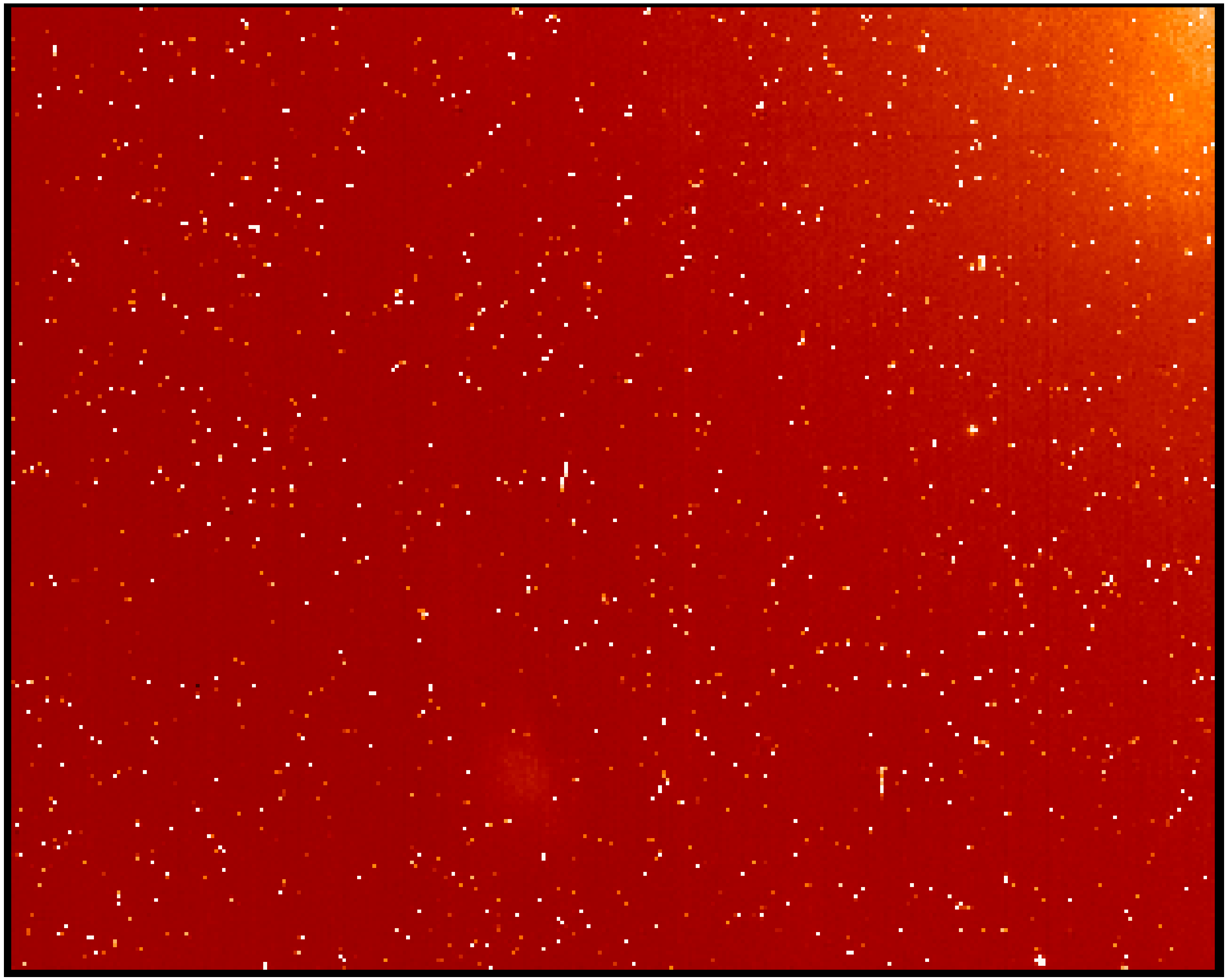
- APD gain = 1
- T=40K
- exposure time: **23.16 hours**
- bias 1.5 V

cosmics



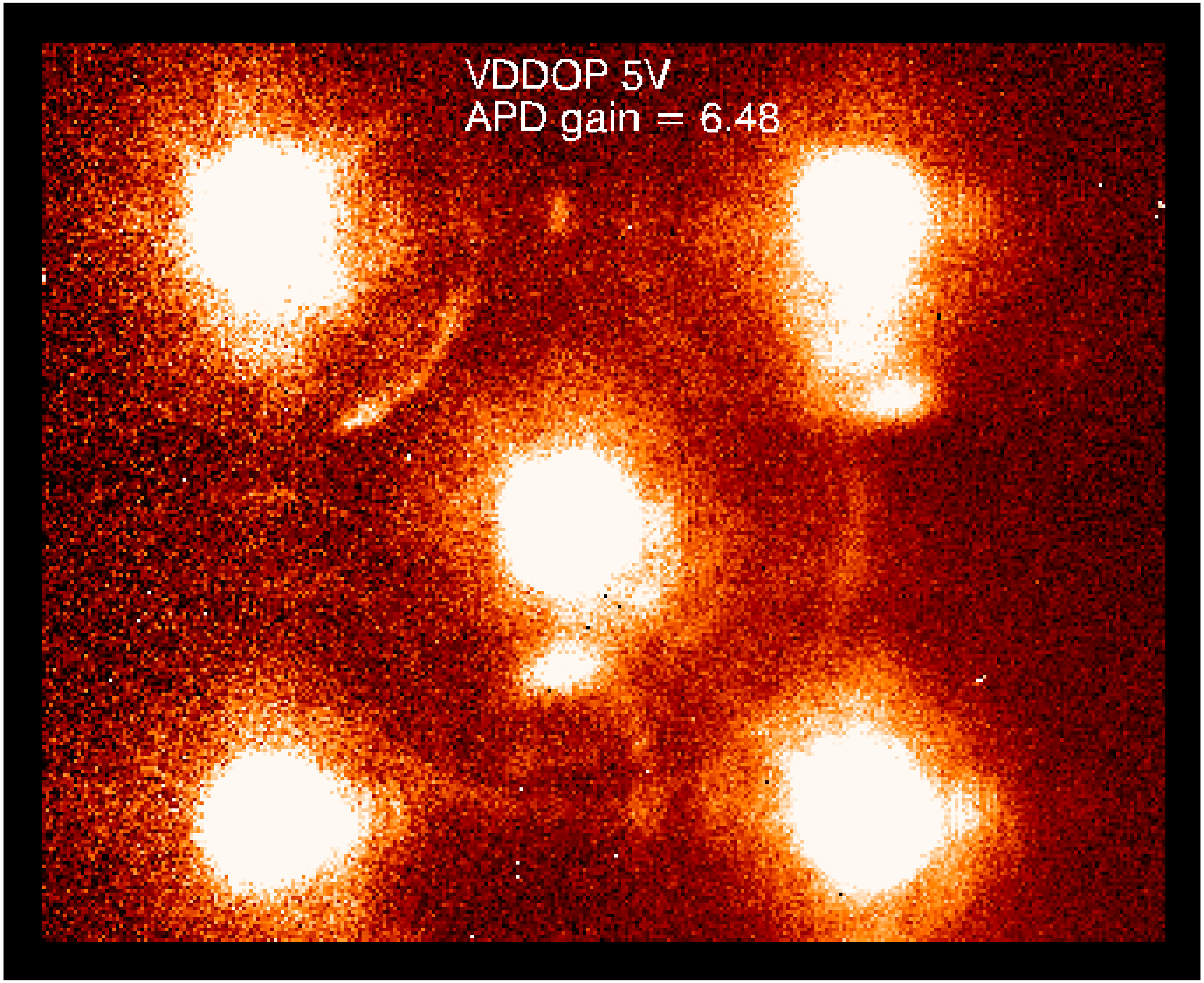
- T=40K
- Exposure time: 23.16 hours
- bias 1.5 V

dark current map without cosmics



- APD gain=1
- T=40K
- exposure time: **23.16 hours**
- bias 1.5 V

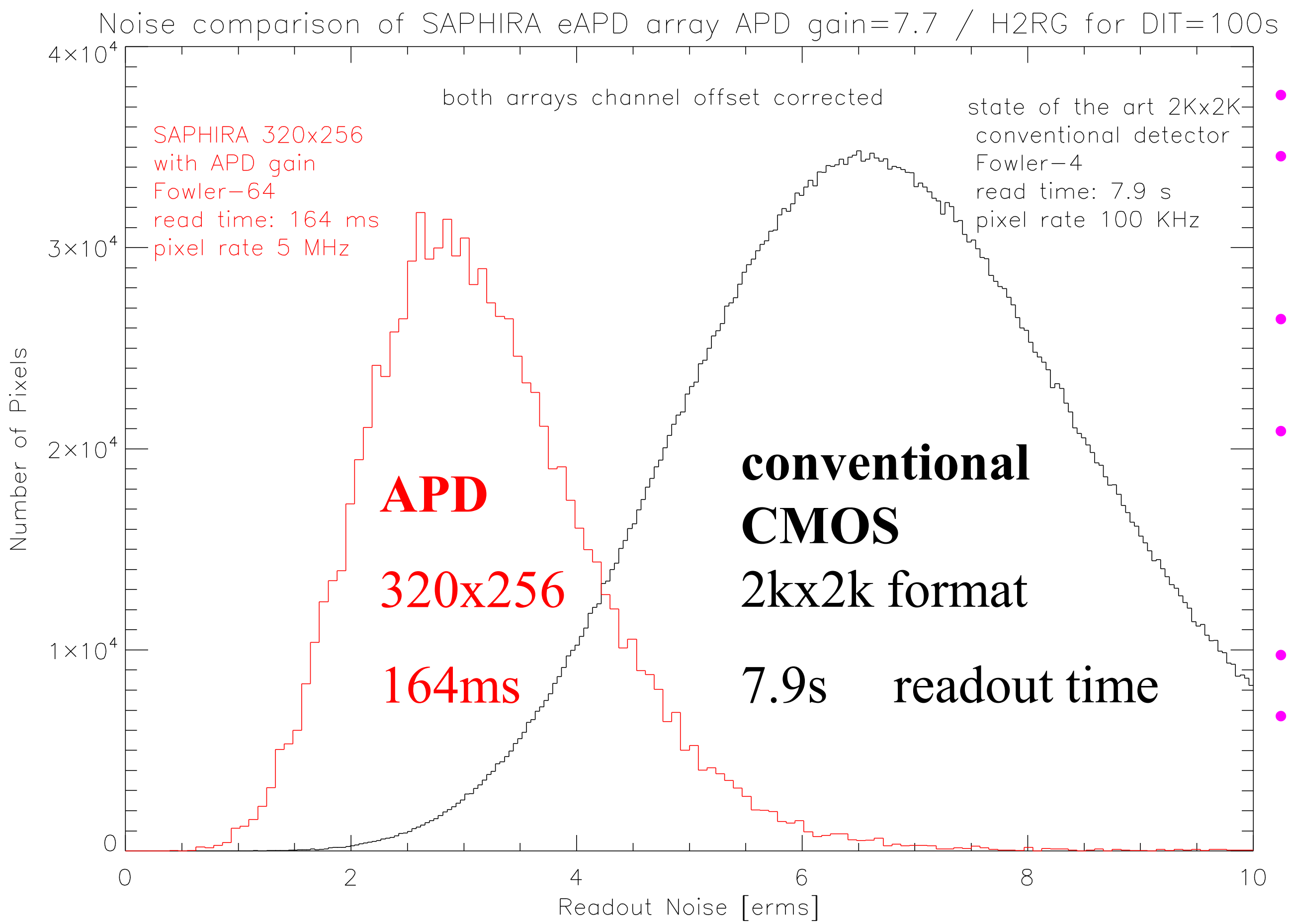
dark current map without cosmics



- reducing rail voltages from 5V to 3.5V also reduces noise for long integrations
- DIT=100 seconds average of 10 frames

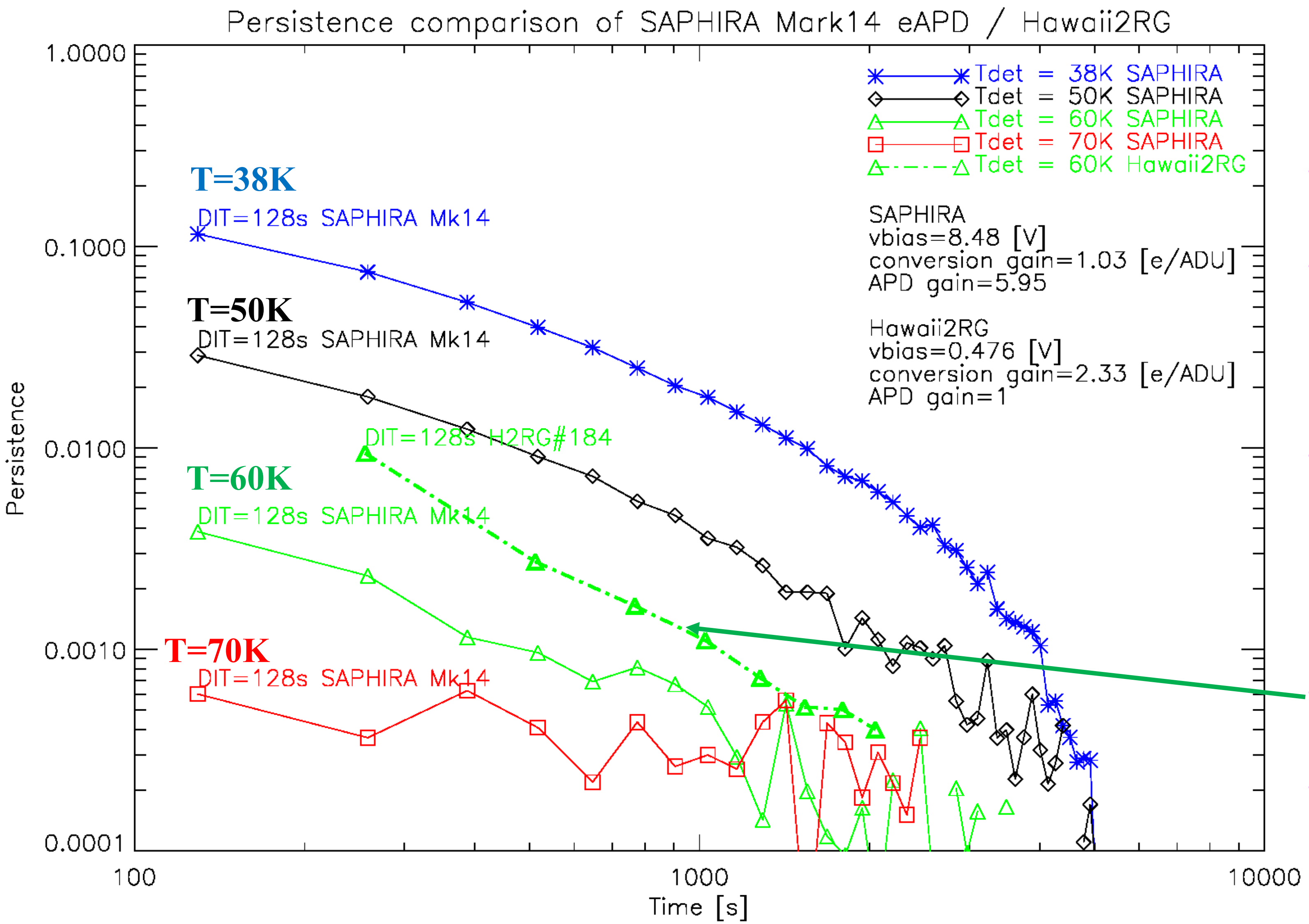
- mask detector with cover which has 5 holes

e-APD for long integration times: 100s



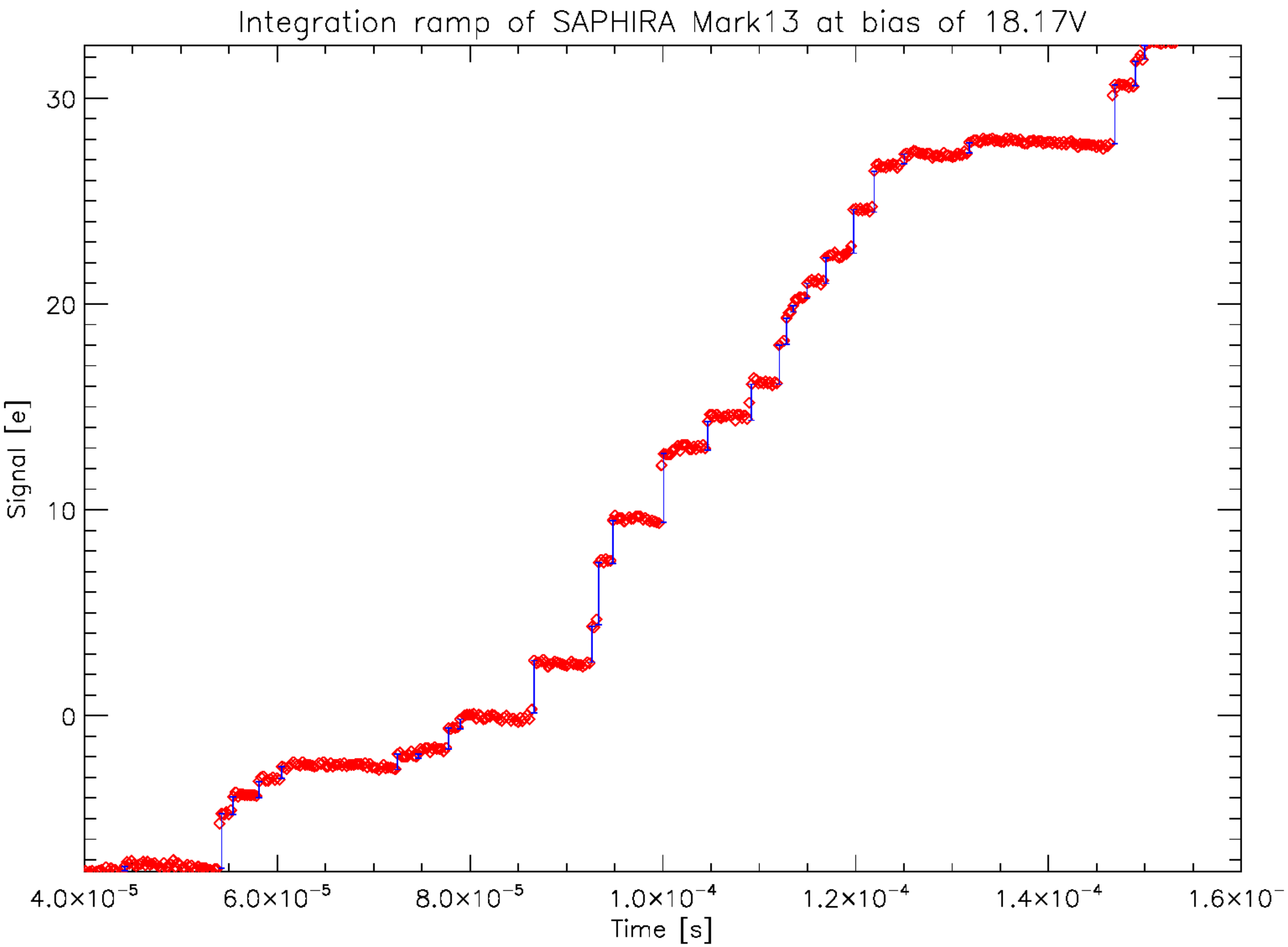
- Mark 14 non-optimized diode structure
- DIT=100s
  dark current at APD gain 7.7
  0.03 electrons/pix/second
- for comparison ratio of array formats equal to ratio of readout times
- comparison of sensitivity of conventional / eAPD arrays for read noise limited case:
  conventional: **6.5 erms**
  SAPHIRA: **2.8 elrms**
- next step: Mark19 wider bandgap
- a factor of 3 higher APD gain without onset of trap assisted tunneling should yield **subelectron readout noise** for long integration times

persistence versus temperature at APD gain=6



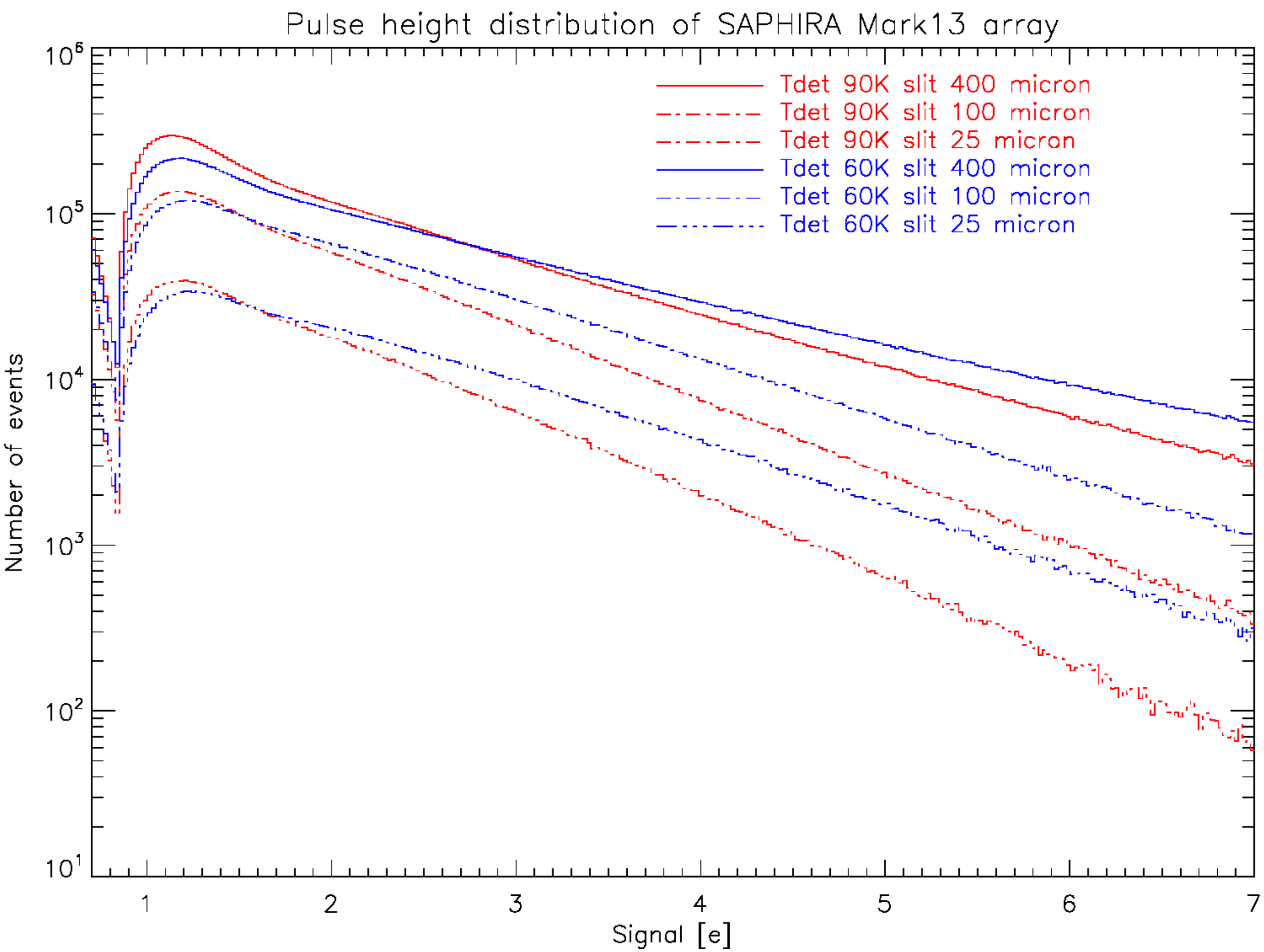
- persistence increases at lower temperatures
- slow response at low temperatures not in gain region but in absorber region
- bandgap variation due to interdiffused multilayer process generates potential wells trapping charge
- Hawaii2RG#184 for comparison
- persistence does not depend on APD gain

photon counting



- integration ramp sampled with time resolution of 200ns
- single photon events clearly seen as steps in integration ramp
- ramps taken at temperatures between T=60K and T=110K at different flux levels and APD gains

pulse height distribution

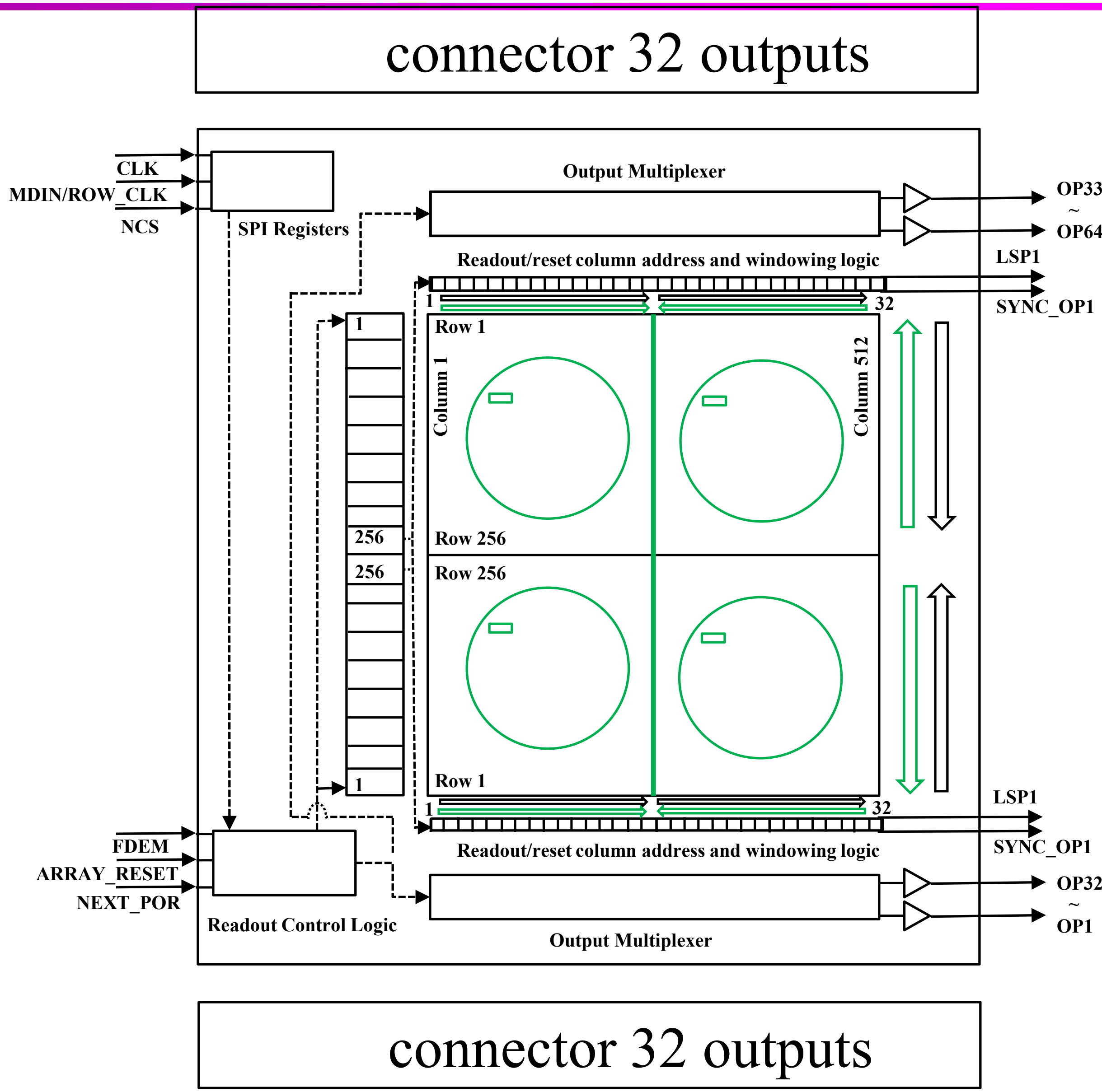


- histogram peak at 1.1 electron (calibration of Mark14 used)
- tail of histogram is exponential
- Tubbs (2003): with g = APD gain >>1

  $P(n)=1/g * \exp(-\alpha n/g)$

  α=1 for EMCCD
  α=1.54 for HgCdTe eAPD
- for high flux histogram becomes Gaussian

readout topology of 512x512 AO SAPHIRA



- format: 512x512
- pixel pitch: 24 µm
- 0.6µm CMOS process
- frame rate:
  1Kframe/s DCS
  2Kframe/s uncorrelated
- minimum ROIC glow
- pixel rate: 8.7 Mpixel/output
- 64 outputs
- 4 quadrants with 16 outputs each
- make direction of vertical and horizontal shift register selectable
- optimized for pyramid WFS:
  concurrent readout of 4x16 subapertures
- processing of pixel data can already start during readout
- may be also IDCA package needed
- status:
  funded by ESO, MPE, NRC Herzberg
  start of contract after FC in November

conclusions

- **near infrared high speed eAPD sensors are mature**: revolution in sensitivity
  - sub-electron readout noise at high APD gain for frame rates of 1KHz
  - superb cosmetic quality at high APD gain, good QE from λ=0.8µm to 2.5µm
  - On-sky performance of SAPHIRA proven: **it works !**
    GRAVITY, Palomar RoboAO, SCExAO, KECK, CHARA,…..
- **eAPD technology promising for large FPA's**
  - low dark current (1E-3e/s/pixel) at T 40K for moderate APD gain
  - for long integration times eAPDs outperform conventional CMOS
- **future**: develop large format SAPHIRA (512x512 pixels)
  optimize diode structures for low dark current at high APD gain
  develop photon counting array for large science FPAs
- **deploy NIR eAPD technology in space**
  (SAPHIRA can be operated with SIDECAR, γ irradiation dose 50krad)


the end
ELT 39m telescope