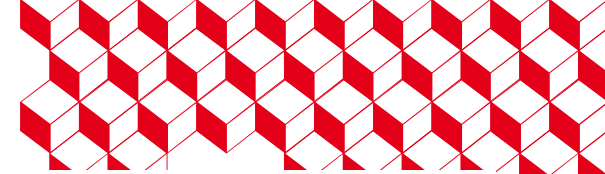
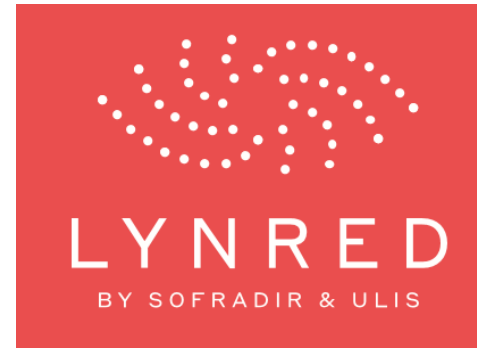




leti irfu



III-V lab

MON PHOTONICS

MCT and APD IR detector developments at CEA-LETI for astronomy and environmental monitoring

T. Le Goff^a, O. Gravrand^a, N. Baier^a, E. De Borniol^a, E. Rodriguez^a, M. Soria^a, O. Boulade^b, T. Pichon^b, C. Ketchazo^b

^a CEA LETI, Grenoble, France

^b CEA IRFU, Grenoble, France

Email : titouan.legoff@cea.fr



Co-funded by the European Union



Agenda

1. II VI process line at LETI

2. IR APD at LETI

3. Cooled IR imaging history

4. Characterization means

**5. Detectors for astronomy
developments**

From ALFA SWIR to VLWIR Earth observation

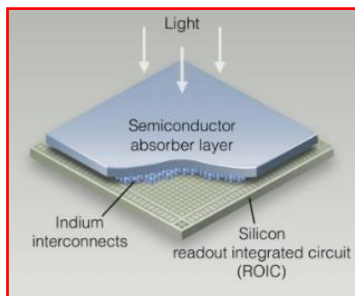
6. Conclusion



At LETI we master the full MCT R&T and integration

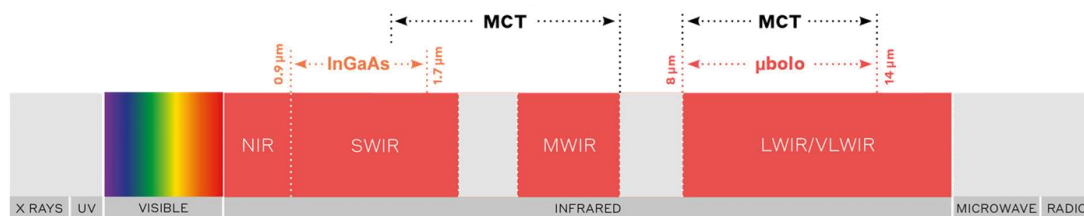
What do we do:

Developing technologies for high performance **cooled IR imagers** and **APD**.



For what ?

Defense
 Earth observation
 Science and astronomy
 Telecom FSO, LIDAR, quantum optics



Diode process

Absorbing layer growth

Substrate growth

Interconnection process

Si ROIC design

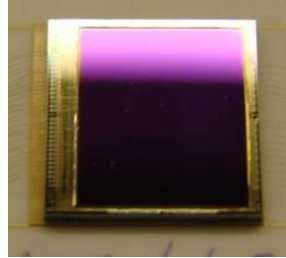
Packaging

EO charact / Simul / process design

IR eAPD history at LETI



- [3D] DeBorriol et al., Optical Engineering 51, 1305 (2012)
- [LLCD] I. Zayer et al., 13th ICSOS (2014)
- [RAPID] M. Hillen, et al., AA 08544 (2016)
- [LIDAR] A. Dumas et. al., Appl. Opt. **56**, 7577 (2017)
- [DS FSO] J. Rothman et. al. *CEAS Space J.* **9**, 507 (2017)



Fast frame rate for astronomy
2 kfps, 320x256 30 μ m pitch,
sub electron noise

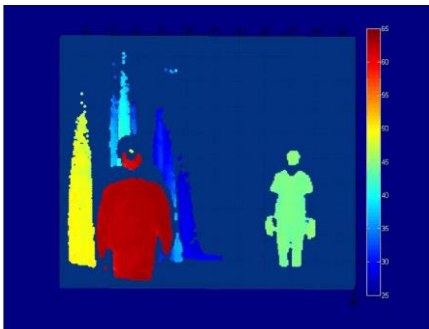
2014: RAPID camera for interferometry at VLTi

2006

First MCT APD @ LETI

2011

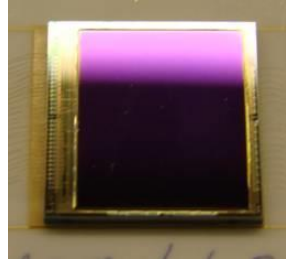
Active imaging FPAs
(LiDAR imagers)
320x256 30 μ m pitch



IR eAPD history at LETI



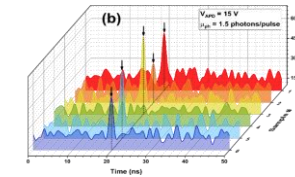
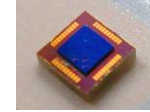
- [3D] DeBorriol et al., Optical Engineering 51, 1305 (2012)
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2014: RAPID camera for interferometry at VLTI

Switch from FPA to single diodes
For high $M \times BW$
Mid 2010's



Photon counting APD
for deep space coms
2022

MONPHOTONICS



2026 : Creation of
Moon Photonics

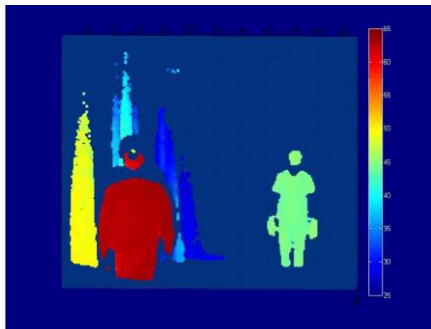
- FSO
- Lidar
- Quantum

2006

First MCT APD @ LETI

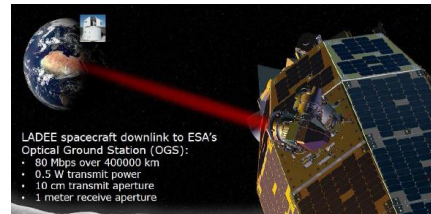
2011

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320x256 30 μ m pitch

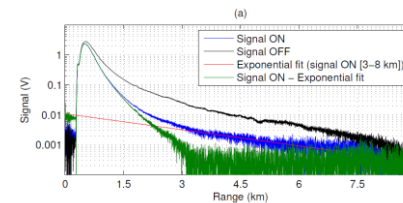


2014

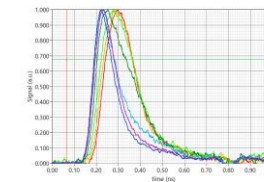
LLCD with Leti APD diode
Earth <-> Moon laser com
@ 80 MHz BW



2016 : APD for CO₂
Atmospheric Lidar



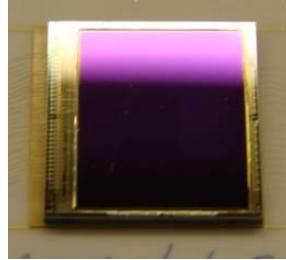
2023 : 1st gen
HOT APDs for FSO
@ 2.5 Gbps



IR eAPD history at LETI



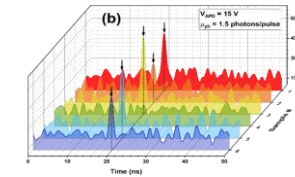
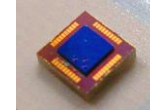
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- [LIDAR] A. Dumas et. al., Appl. Opt. **56**, 7577 (2017)
- [DS FSO] J. Rothman et. al. CEAS Space J. **9**, 507 (2017)



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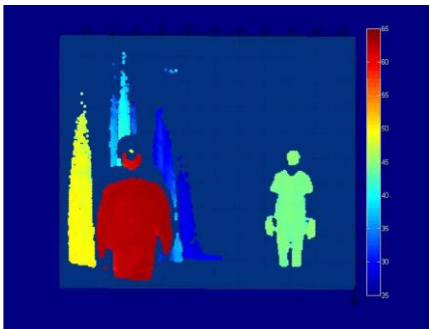
- FSO
- Lidar
- Quantum

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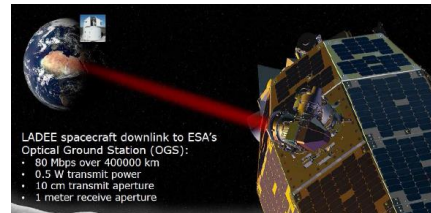
2011

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(LiDAR imagers)
320x256 30 μ m pitch

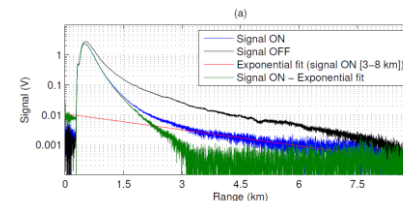


2014

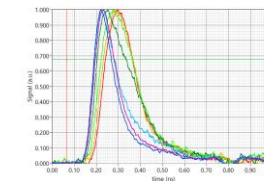
LLCD with Leti APD diode
Earth <-> Moon laser com
@ 80 MHz BW



2016 : APD for CO₂
Atmospheric Lidar



2023 : 1st gen
HOT APDs for FSO
@ 2.5 Gbps



1380*640 pixels
LYNRED
< 10 el. noise (goal)

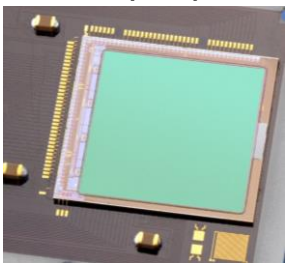
Back to imaging with
COBRA CTIA ROIC MPx6



Brief cooled IR imaging history @ LETI



2004
1k² 15μm pitch

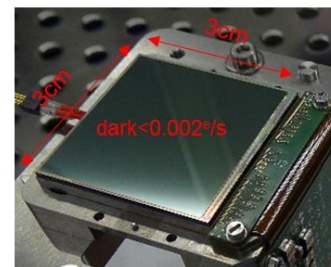


P/N FPAs
MW-LW-VLW
2008

Low flux P/N
NIR LFSA
TV p15
2012



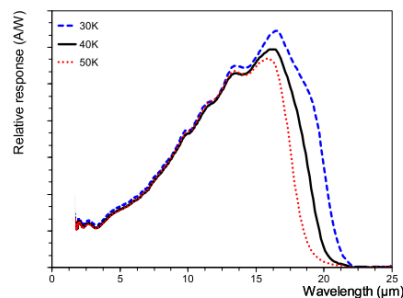
ALFA NIR
(2k)² p15
2021



- [MPX] Catelein et al. (2004) SPIE, 5251
- [VLWIR] Gravrand, et al (2007) JEM, 36(8), 981–987
- [APD] Perrais, . (2009) JEM 36(8), 963
- [P/N] Mollard, et al. (2008). SPIE, 6940.
- [NIRLFSA] Gravrand et al. (2012) JEM 41(10), 2686
- [ALFA] Gravrand et al. (2022) SPIE, 1210706
- [HOT] Gravrand et al. JEM to be published 2026



Brief cooled IR imaging history @ LETI

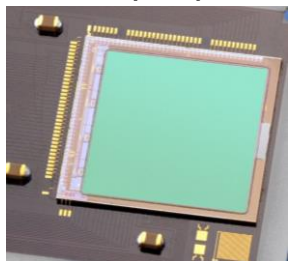


VLWIR FPA n/p
20μm co
2006

MTG selection
2010

VLWIR P/N
2026

2004
1k² 15μm pitch

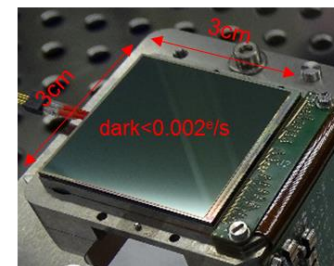


P/N FPAs
MW-LW-VLW
2008

Low flux P/N
NIR LFSA
TV p15
2012



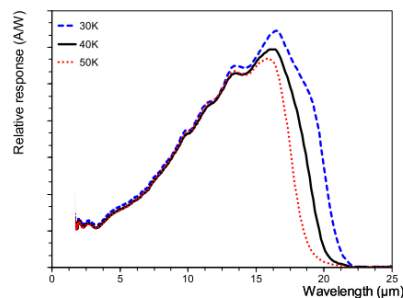
ALFA NIR
(2k)² p15
2021



[MPX] Catelein et al. (2004) SPIE, 5251
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Brief cooled IR imaging history @ LETI



VLWIR FPA n/p
20μm co
2006

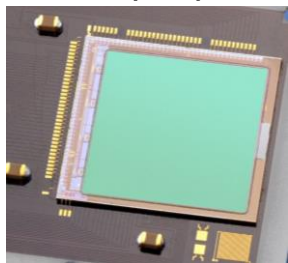
MTG selection
2010

1st P/N NG FPA
TV p15 LW
2020



VLWIR P/N
2026

2004
1k² 15μm pitch

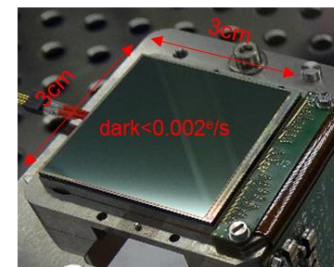


P/N FPAs
MW-LW-VLW
2008

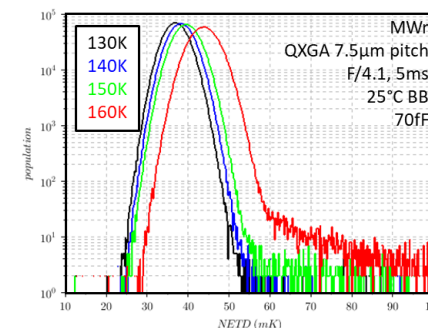
Low flux P/N
NIR LFSA
TV p15
2012



ALFA NIR
(2k)² p15
2021



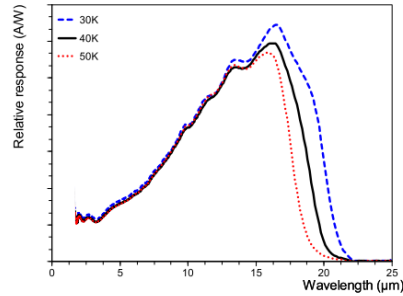
NG 3Mpx p7.5
MWr HOT 150K
2025



[MPX] Catelein et Al. (2004) SPIE, 5251
[VLWIR] Gravrand, et al (2007) JEM, 36(8), 981–987
[APD] Perrais,. (2009) JEM 36(8), 963
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Brief cooled IR imaging history @ LETI



VLWIR FPA n/p
20μm co
2006

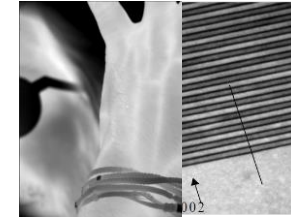


MTG selection
2010



IGn InAsSb
MWb = 4.1μm co
TV p15 150K
2018

1st NG FPA
TV p15 LW
2020

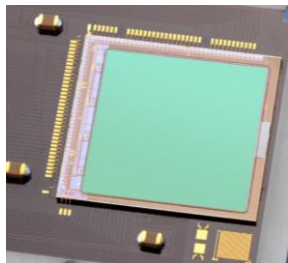


T2SL p15/7.5
MWr = 5μm co
HOT 130K
2025



VLWIR P/N
2026

2004
1k² 15μm pitch

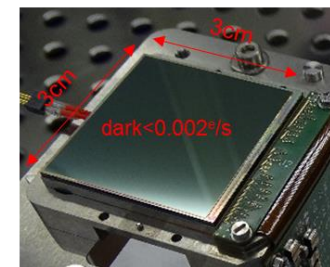


P/N FPAs
MW-LW-VLW
2008

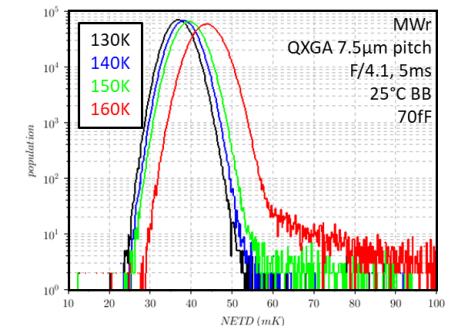
Low flux P/N
NIR LFSA
TV p15
2012



ALFA NIR
(2k)² p15
2021



NG 3Mpx p7.5
MWr HOT 150K
2025



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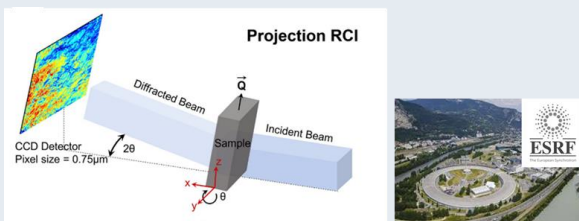
Characterization means supporting technological developments

Material properties

TOF-SIMS

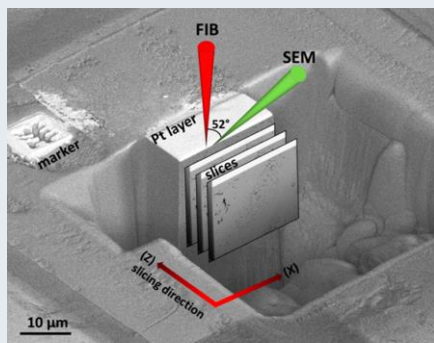
Carrier mobility & lifetime ...

Xray diffraction & Synchrotron microscopy & imaging for substrate quality or dislocation quantification

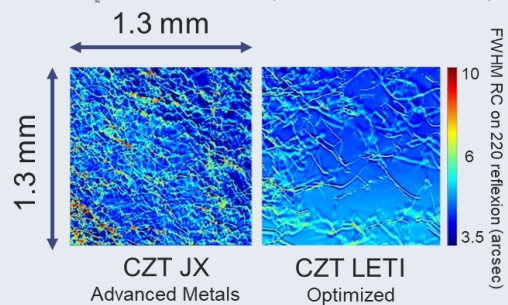


[C. Yildirim et al., J. Electron. Mater., 2020]

TEM/FIB/ FIB-SEM Tomography for implantation induced defect observation



[Liu, Y. & al. 2016 . Minerals 2016, 6, 104]



[T. Journot et al., J. Appl. Crystallogr., 2023]

EO on test diodes and Full hybridized array

All types of ROIC : SFD, DI, CTIA, APD...

Dark current & ROIC glow

Blinking pixels (RTS)

Low frequency stability (RFPN)

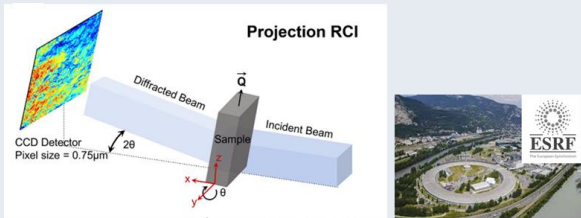
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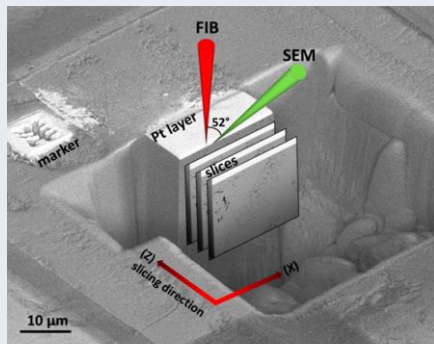
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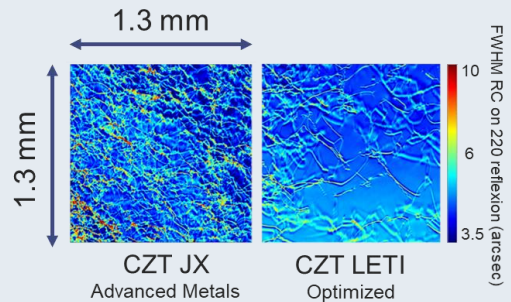


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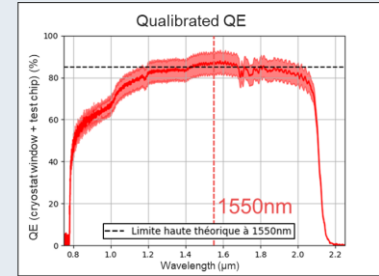
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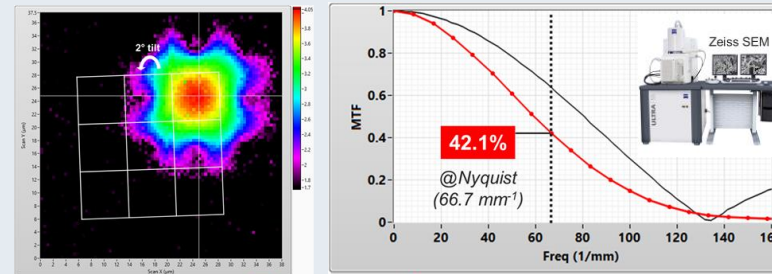
Dark current & ROIC glow

Blinking pixels (RTS)

Low frequency stability (RFPN)



Test chip and FPA pixel PSF with EBIC



Pixel PSF

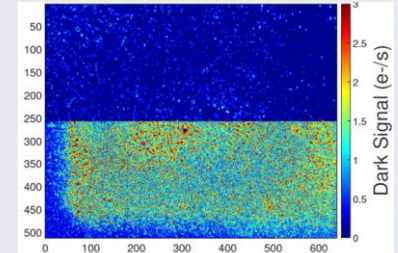
FFT

Pixel MTF

N. Baier & al, Scientific Detector Workshop, 2025

Irradiation induced defect and tolerance on FPA

Before Irradiation



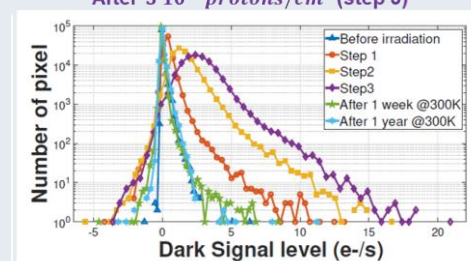
After 5 10¹¹ protons/cm² (step 3)

Persistence on SWIR Source Follower for astronomy

Reference dark

Illumination

Persistence emission



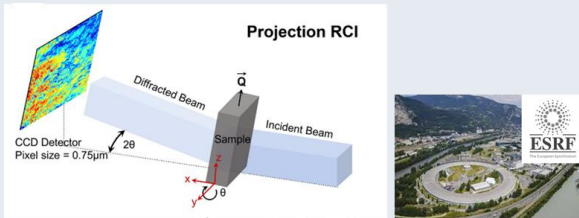
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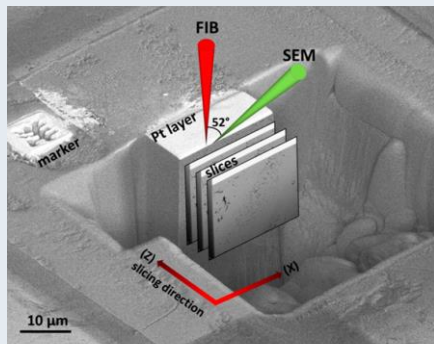
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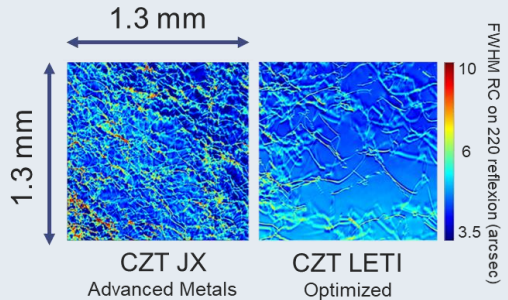


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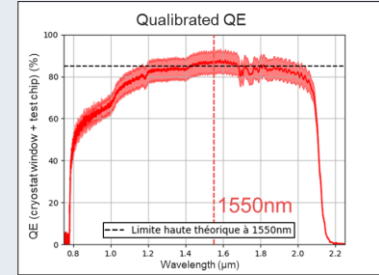
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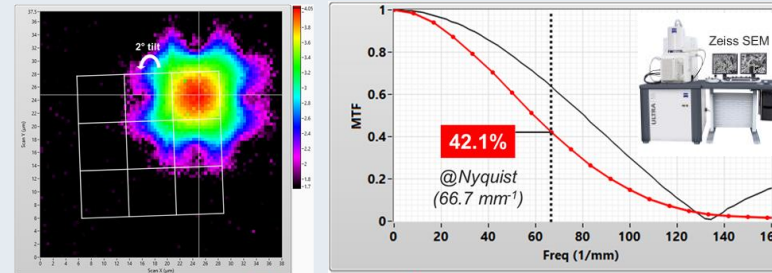
Dark current & ROIC glow

Blinking pixels (RTS)

Low frequency stability (RFPN)



Test chip and FPA pixel PSF with EBIC



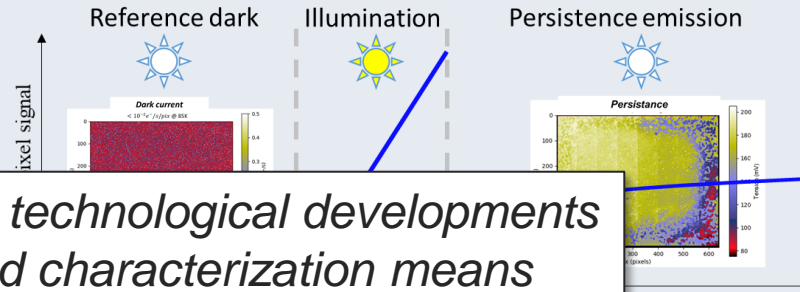
Pixel PSF

FFT

Pixel MTF

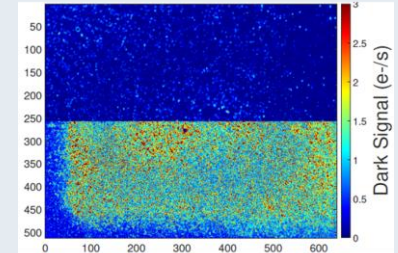
N. Baier & al, Scientific Detector Workshop, 2025

Persistence on SWIR Source Follower for astronomy

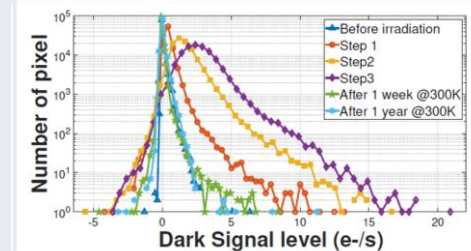


Irradiation induced defect and tolerance on FPA

Before Irradiation



After 5 10¹¹ protons/cm² (step 3)

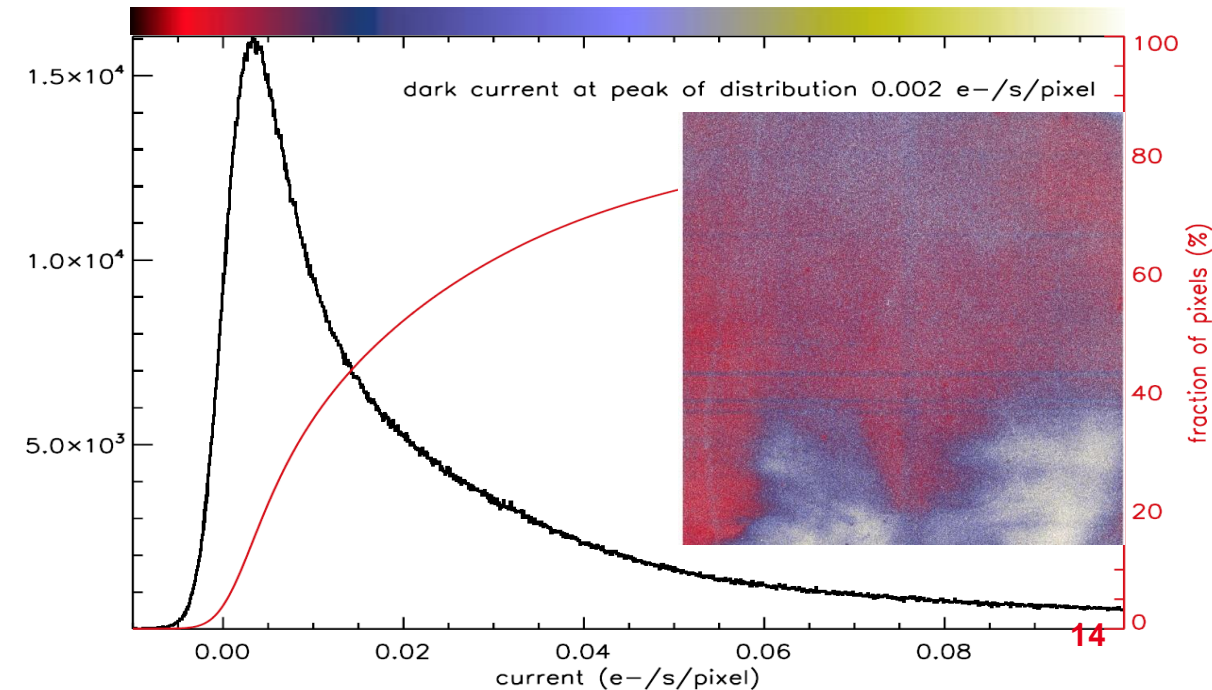
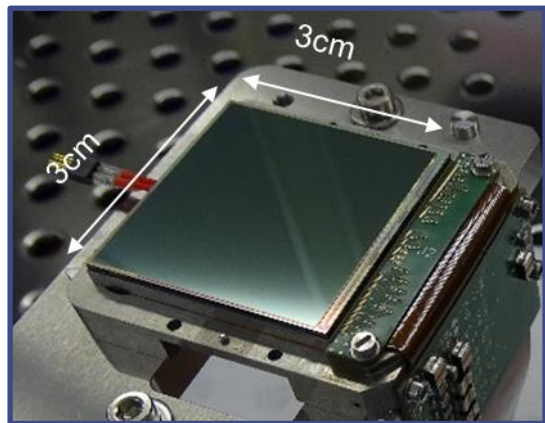
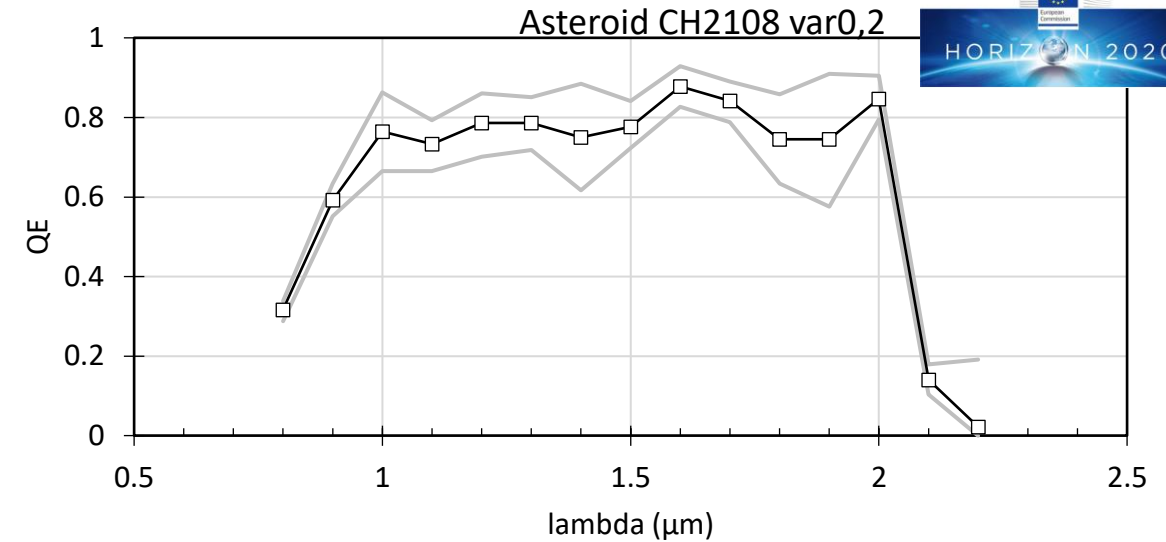


Objective: guiding technological developments through high-end characterization means

ALFA = Astronomical Large Focal Plane Array

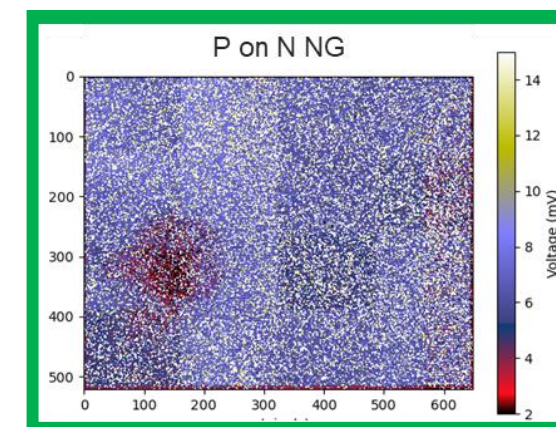
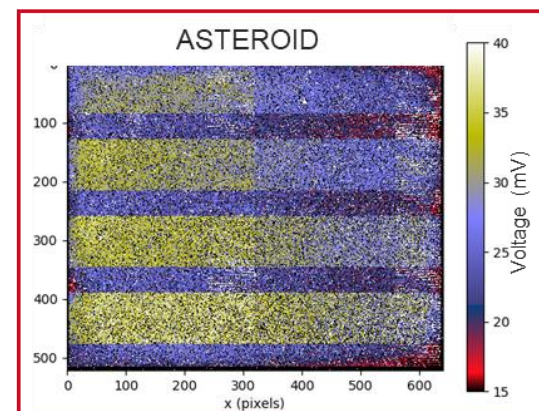
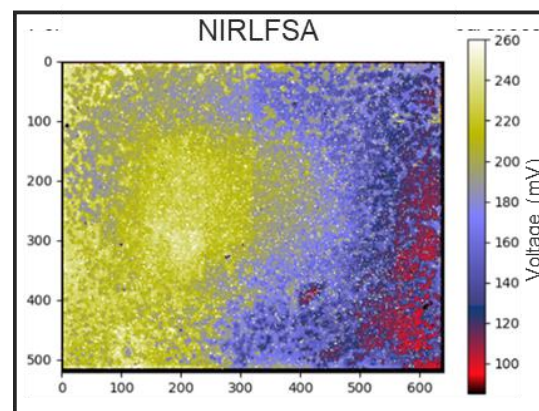
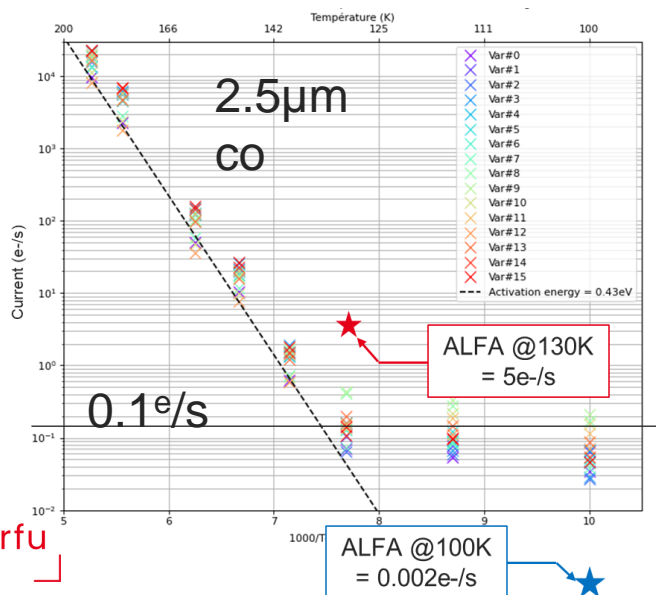
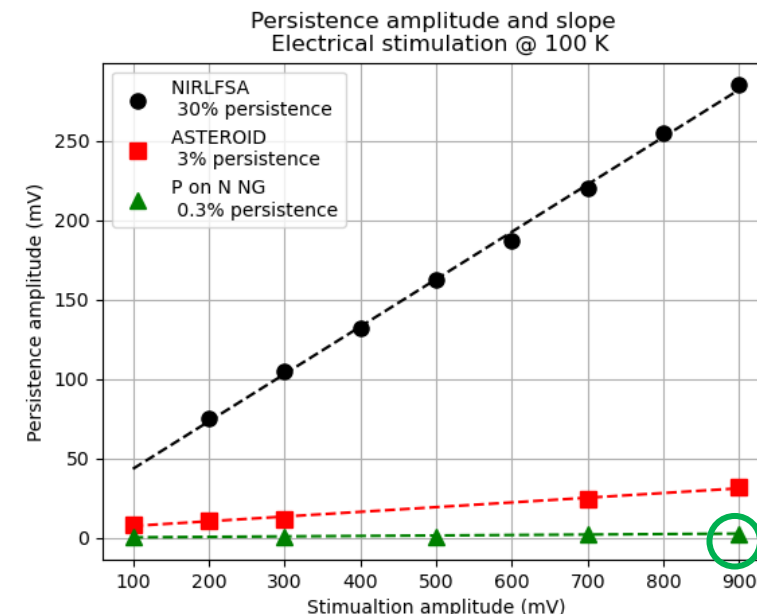
SWIR : $\lambda_c = 2.1 \mu\text{m}$

- ❑ ESA prog for NIR low flux $(2\text{k})^2$ $15\mu\text{m}$ pitch
- ❑ CdHgTe LIR – ROIC+Packaging Lynred
- ❑ Dark $\sim 2 \times 10^{-3}$ e/s/px @ 100K
- ❑ IPC < 3% / Low persistence
- ❑ Installed in Colobri telescope in Mexico (IR ground follow-up for the SVOM mission)



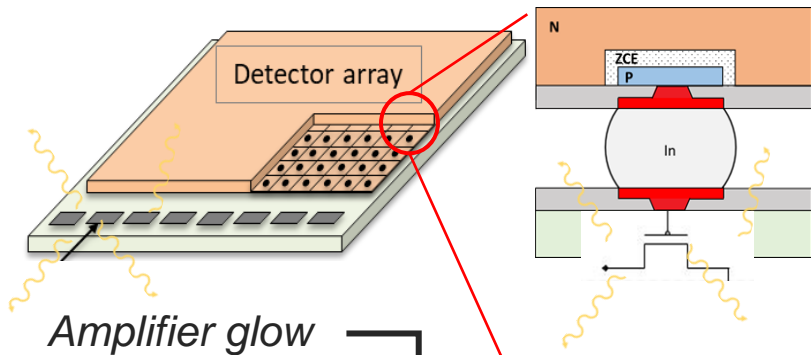
Lastest SWIR process : **NG** for low persistence

- 1st batch on structures for very low flux Astro applications
 - 15 μ m 640x512 pixels SFD ROIC (pre ALFA study ROIC)
 - **Stability in MW translates into low persistence in SW SFD?**
- Very low dark current demonstrated on first trial!
 - < 0.1 e^- /s limited by ROIC glow
- Very low persistence levels (close to measurement limit!)



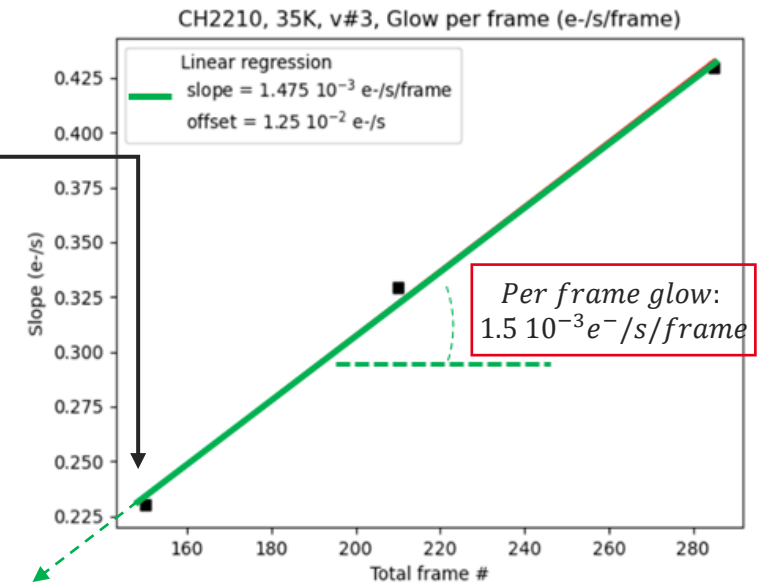
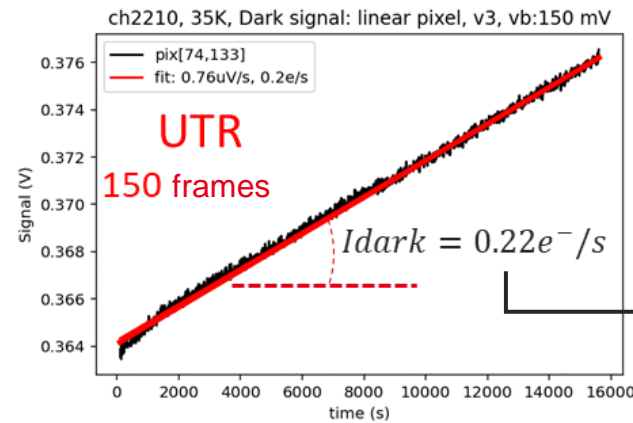
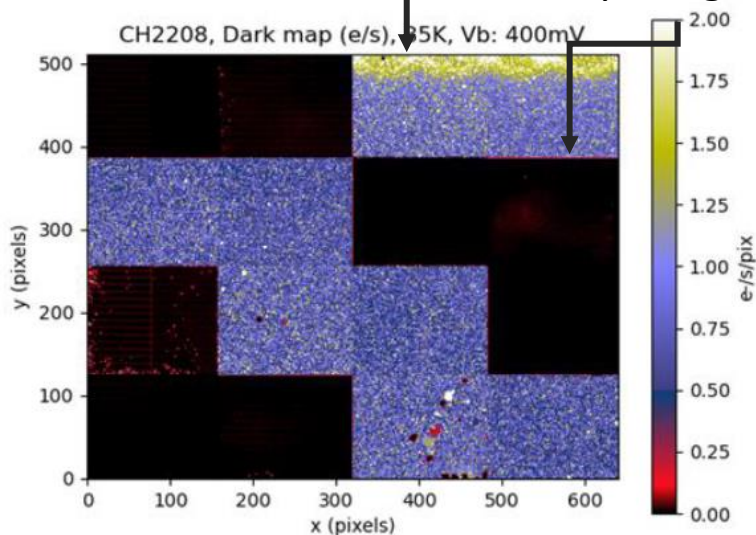
NG for Low flux MCT LW (8 μ m cutoff)

- ❑ ESA contract, IRFU collab
- ❑ Dark LW and Glow estimation, SFD ROIC
 - Same study ROIC as SWIR NG
 - Video output & per frame glow study
- ❑ Dark current compatible for low flux observation
 - $10^{-2} e/s$ dark current at 35K
- ❑ Confirmed with other arrays processed @ Lynred



Amplifier glow

Per pixel glow

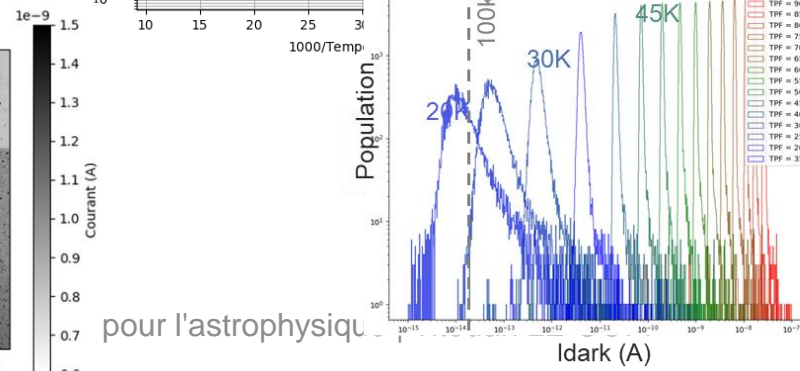
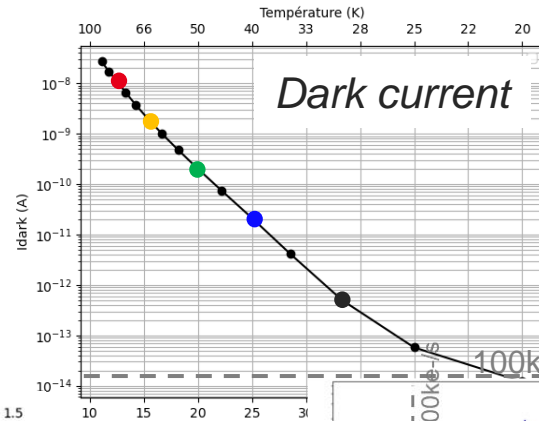
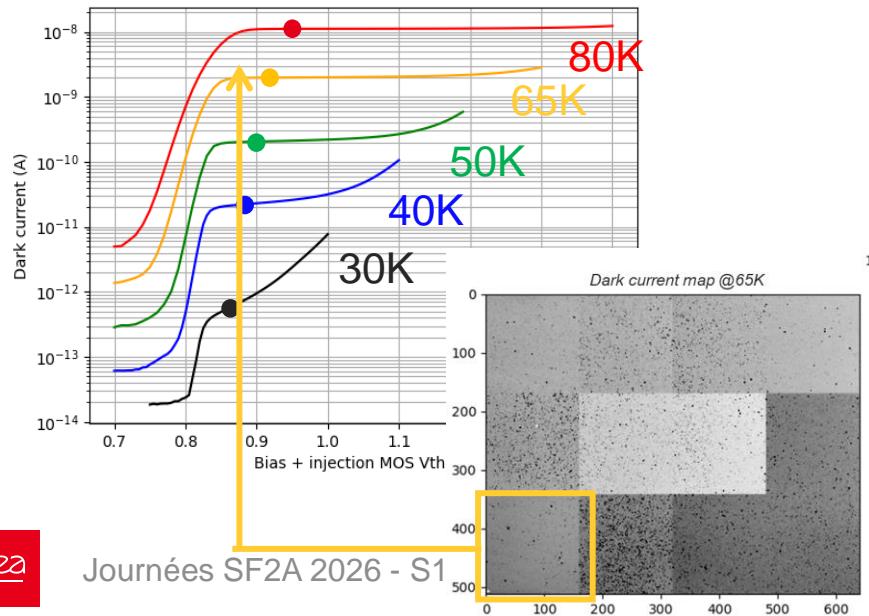
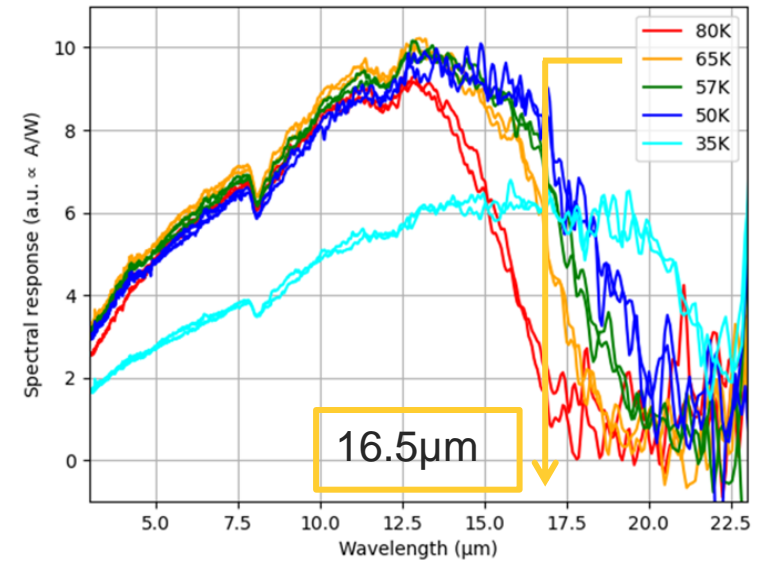


Diode dark current:
 $1.25 \cdot 10^{-2} e^-/s$

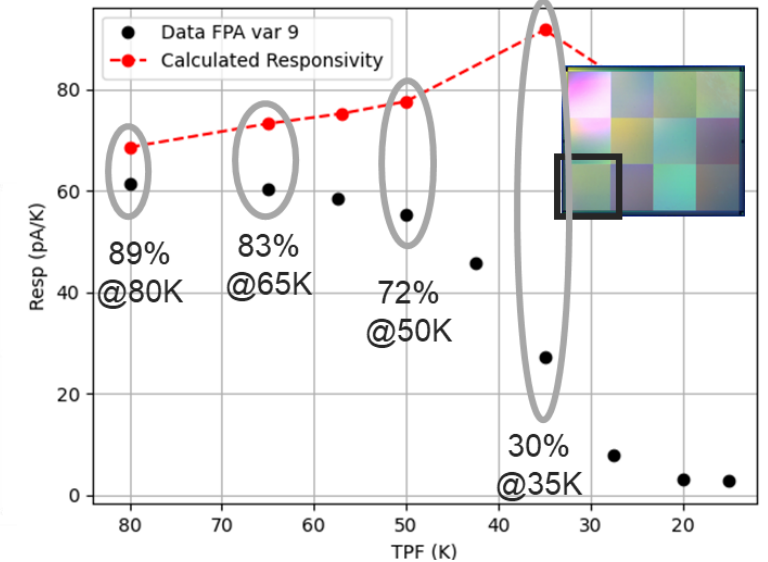
MCT VLWIR NG for space applications (>15μm cutoff)

- ❑ **Small bandgap material :**
 - $\lambda_c = 16.5\mu m \Rightarrow E_g = 75meV @65K !$
- ❑ **Study array :**
 - 15μm pitch 640*520 pix, DI ROIC, 12 diode flavors
 - Large polarization plateau
 - Diffusion limited dark current down to 55K (Rule07)
 - High QE (~80%)
 - Low defectivity

Spectral Response on test chip



Responsivity and estimated QE



Conclusion

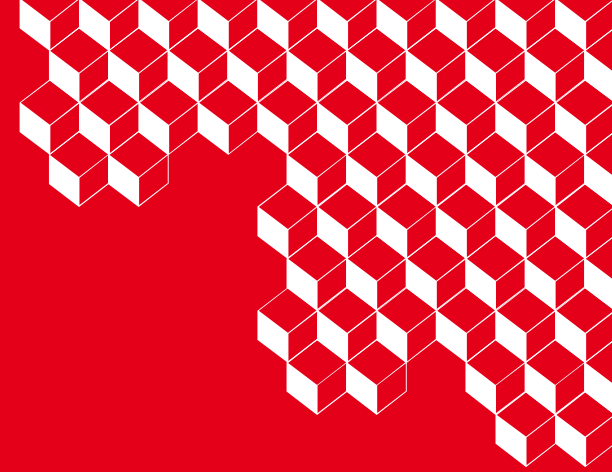
- ❑ **Full process line covered for HgCdTe imagers & APD**

- ❑ **Astronomy and scientific detector realization**
 - ALFA 2K² 15μm SWIR
 - NG for high performance from SWIR -> VLWIR

- ❑ **APD gain remains interesting in photon starved scenarii**
 - Single elements for LIDAR/FSO/Photon counting
 - Moon-Photonics creation
 - Investigation of APD imagers ... to be continued!



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**Thank
you**

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