

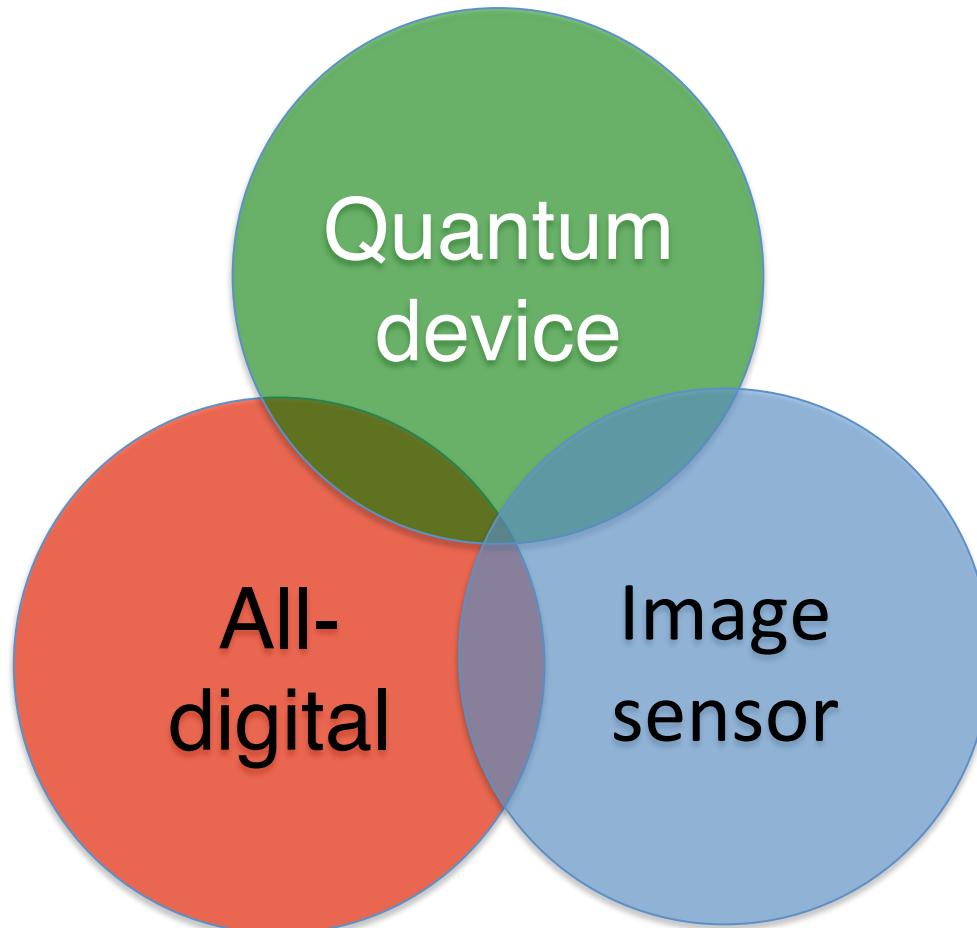
From SPADs to Quantum Computing

Edoardo Charbon



Les Diablerets, Switzerland

Single-Photon Avalanche Diodes (SPADs) Are:



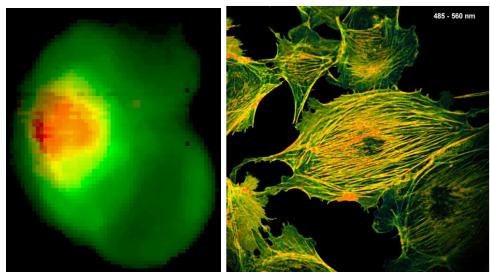
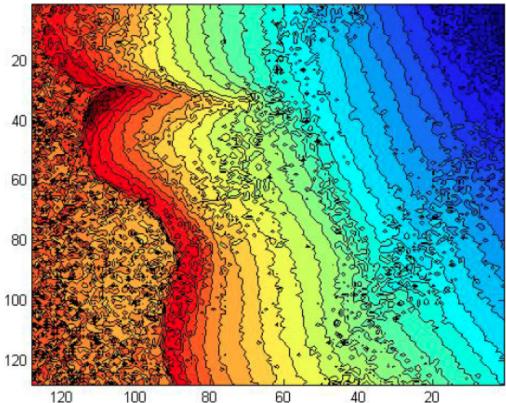
The Goals of this Talk

- To convince you that SPADs are quantum devices and that they can be used for quantum applications
- Modularity is an important ingredient to large photonic systems and even the technology of a cellphone camera will do
- To demonstrate that one can actually make a product (and money) out of SPADs

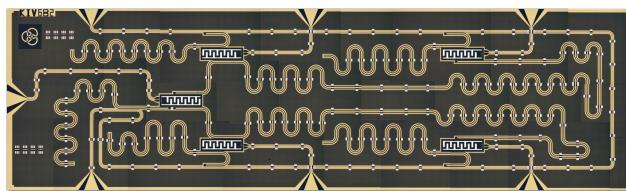
Some SPAD Applications



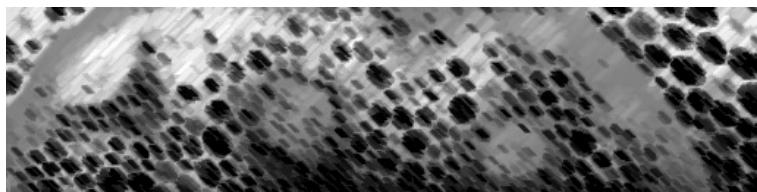
Near Infrared Imaging (NIRI)



Fluorescence Lifetime Imaging Microscopy (FLIM)



Quantum Computing QRNG

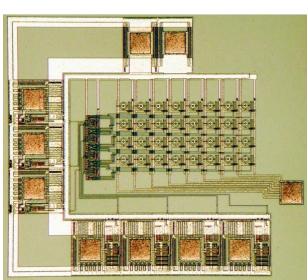


Super-resolution (GSDIM)

Time-of-Flight Positron Emission Tomography (TOF PET)



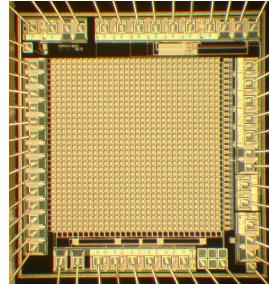
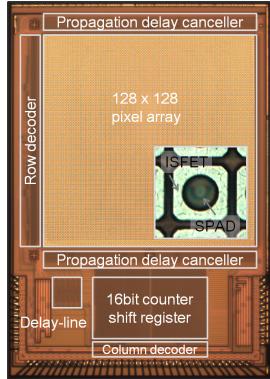
SPAD Image Sensors Targeted to Apps



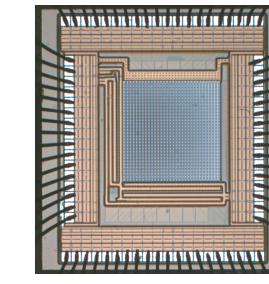
ISSCC 2004



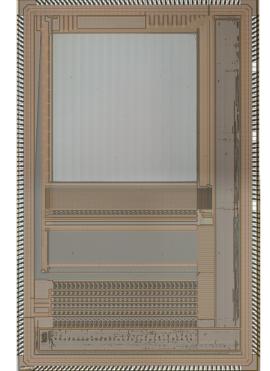
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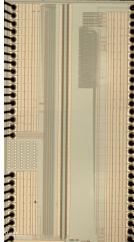
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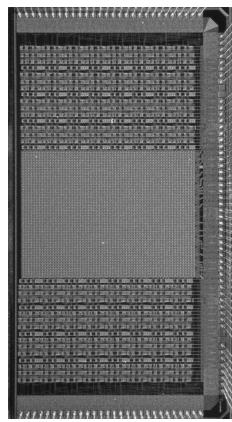
ISSCC 2009



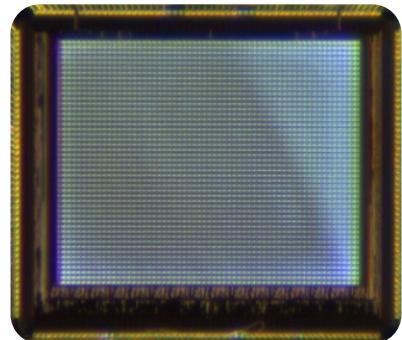
ISSCC 2008



SPIE 2006



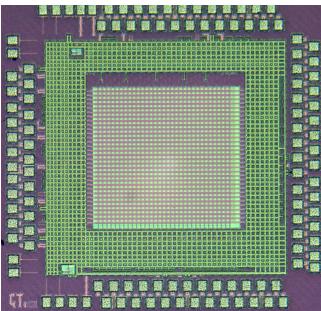
ESSCIRC 2007



ESSCIRC 2009



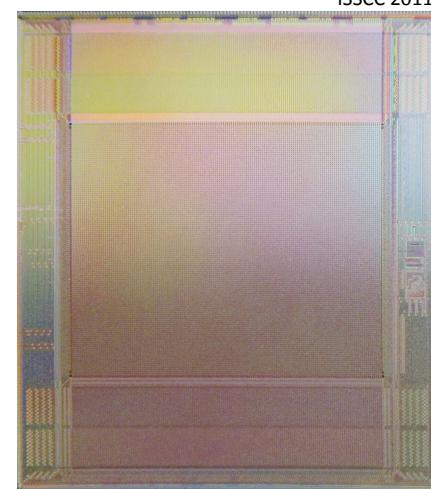
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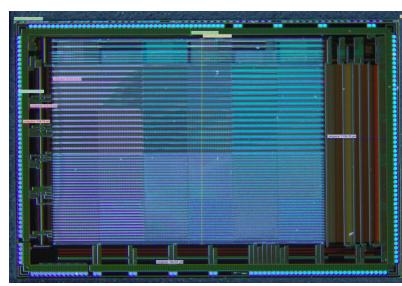
IEDM 2013



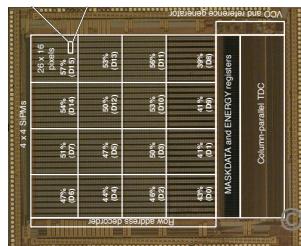
ISSCC2015



ISSCC 2011



ESSCIRC 2011

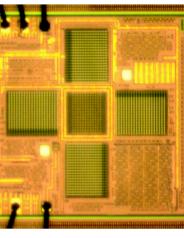
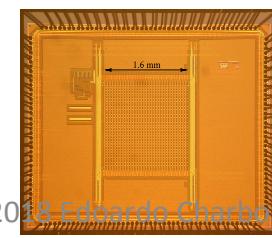


NSS 2012

4x4 SPADs		25x16 SPADs								VDD regulation per group							
51%	(D7)	5%	(D14)	13%	(D9)	53%	(D13)	5%	(D10)	5%	(D11)	5%	(D12)	5%	(D15)	5%	(D16)
47%	(D6)	47%	(D8)	53%	(D12)	53%	(D14)	41%	(D11)	41%	(D13)	49%	(D10)	49%	(D15)	49%	(D16)
4%	(D4)	4%	(D2)	50%	(D3)	50%	(D5)	50%	(D1)	50%	(D2)	50%	(D4)	50%	(D6)	50%	(D8)
46%	(D23)	46%	(D22)	50%	(D21)	50%	(D20)	50%	(D19)	50%	(D18)	50%	(D17)	50%	(D16)	50%	(D15)
49%	(D1)	49%	(D0)	41%	(D1)	41%	(D0)	41%	(D0)	41%	(D0)	41%	(D0)	41%	(D0)	41%	(D0)

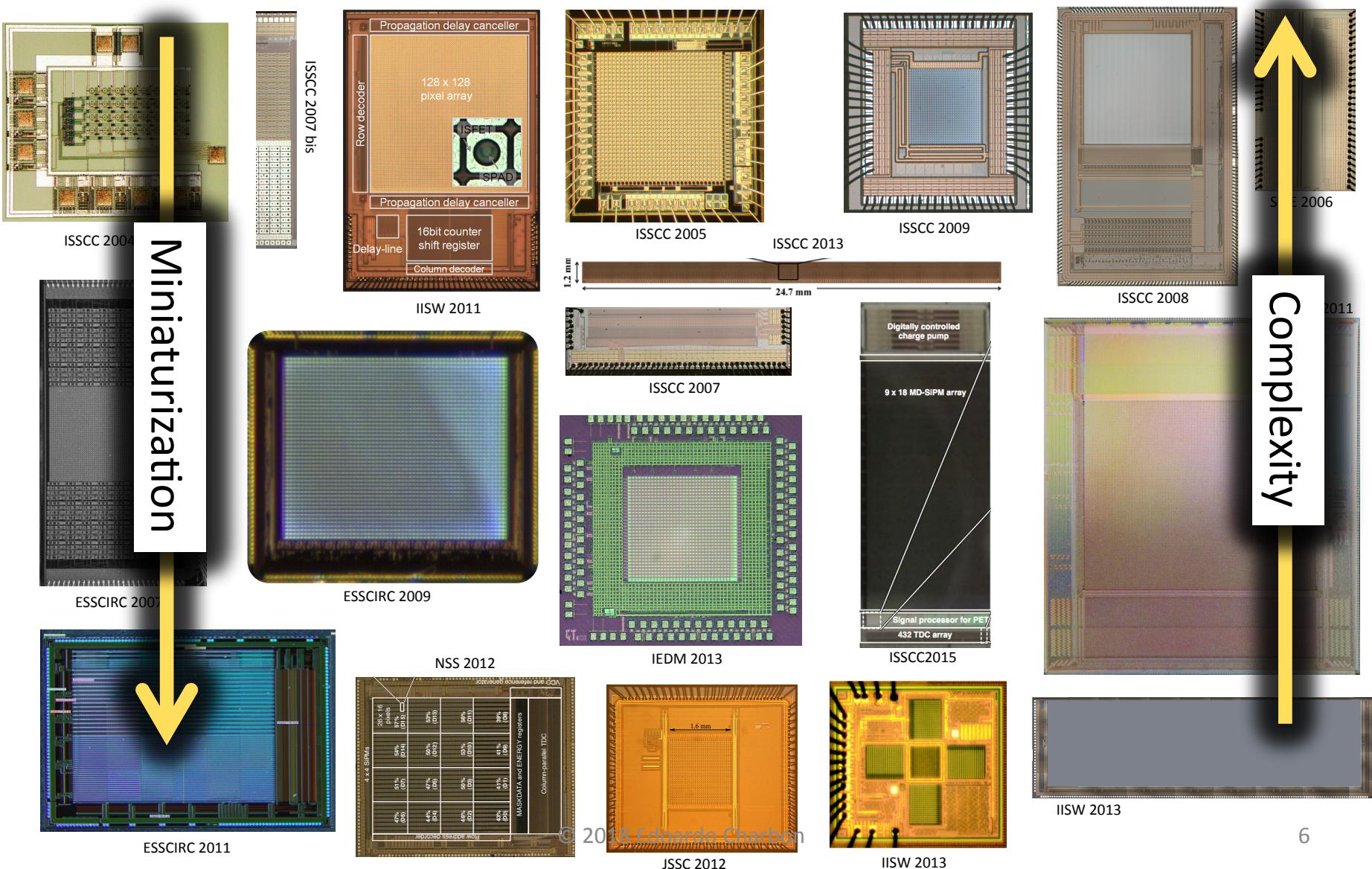
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JSSC 2012



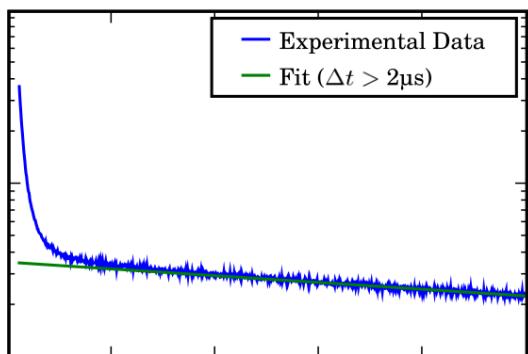
IISW 2013

SPAD Image Sensors Targeted to Apps

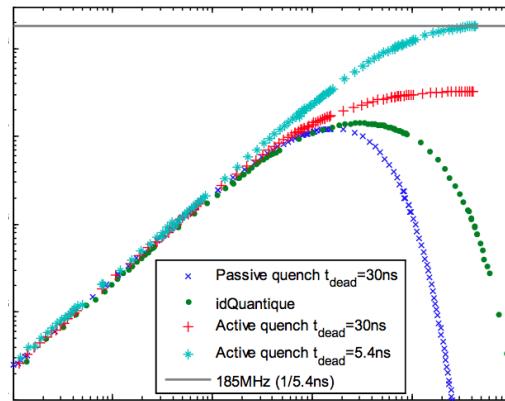


SPAD Non-idealities

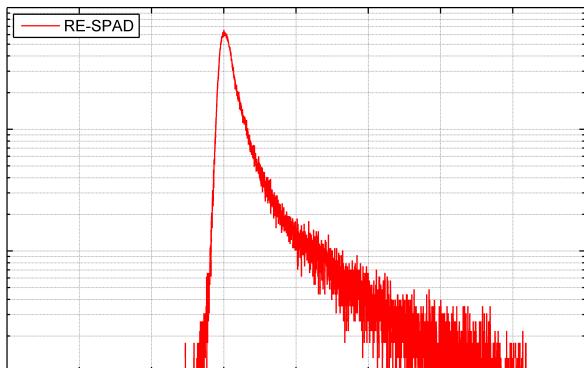
Afterpulsing



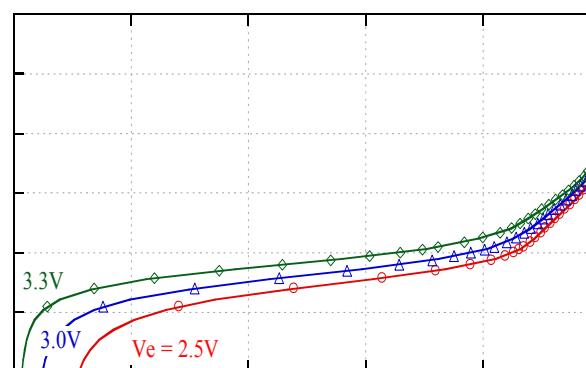
Dynamic Range



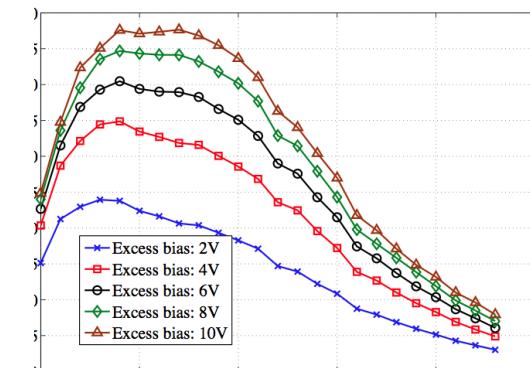
Jitter



DCR

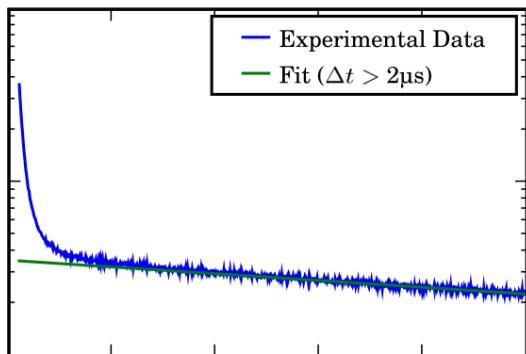


PDP/PDE

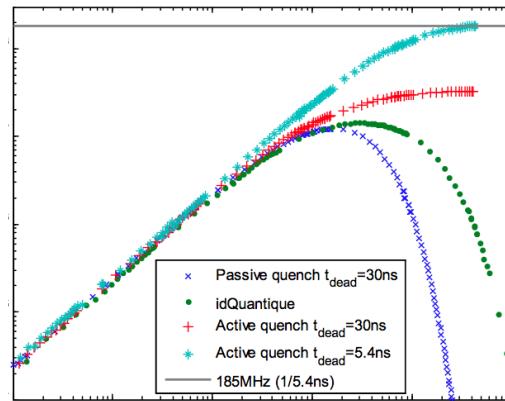


SPAD Image Sensor Non-idealities

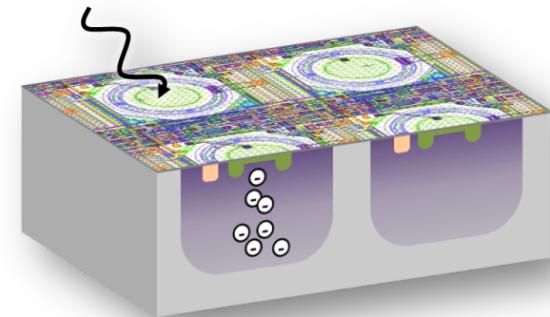
Afterpulsing
non-uniformity



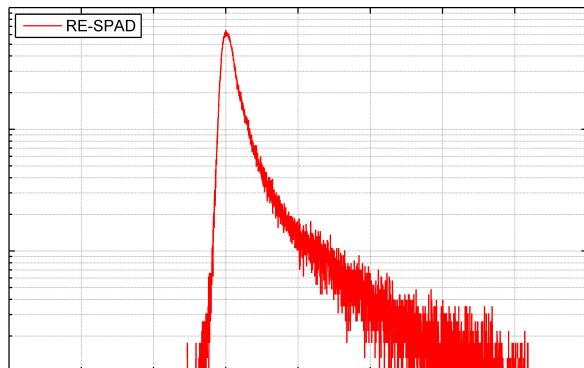
Dynamic Range
non-uniformity



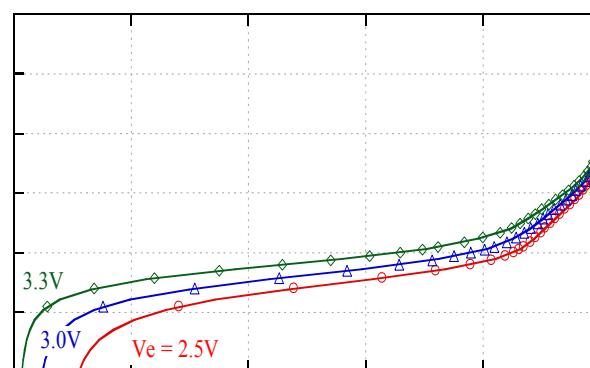
Crosstalk



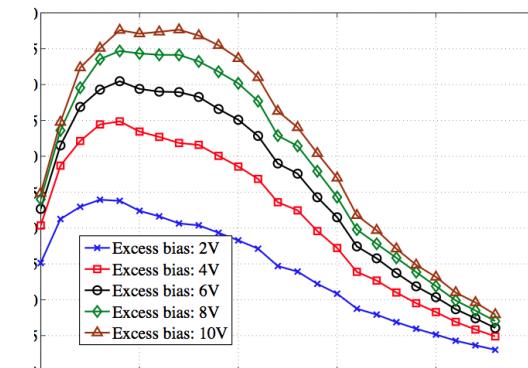
Jitter
non-uniformity



DCR
non-uniformity

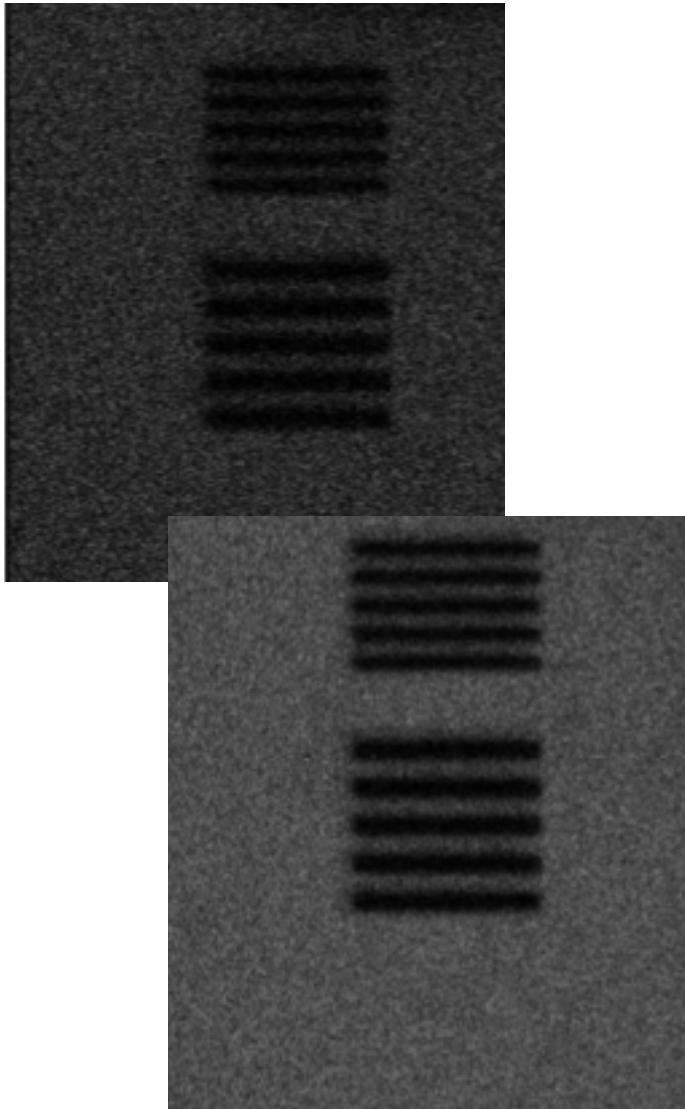


PDP/PDE
non-uniformity

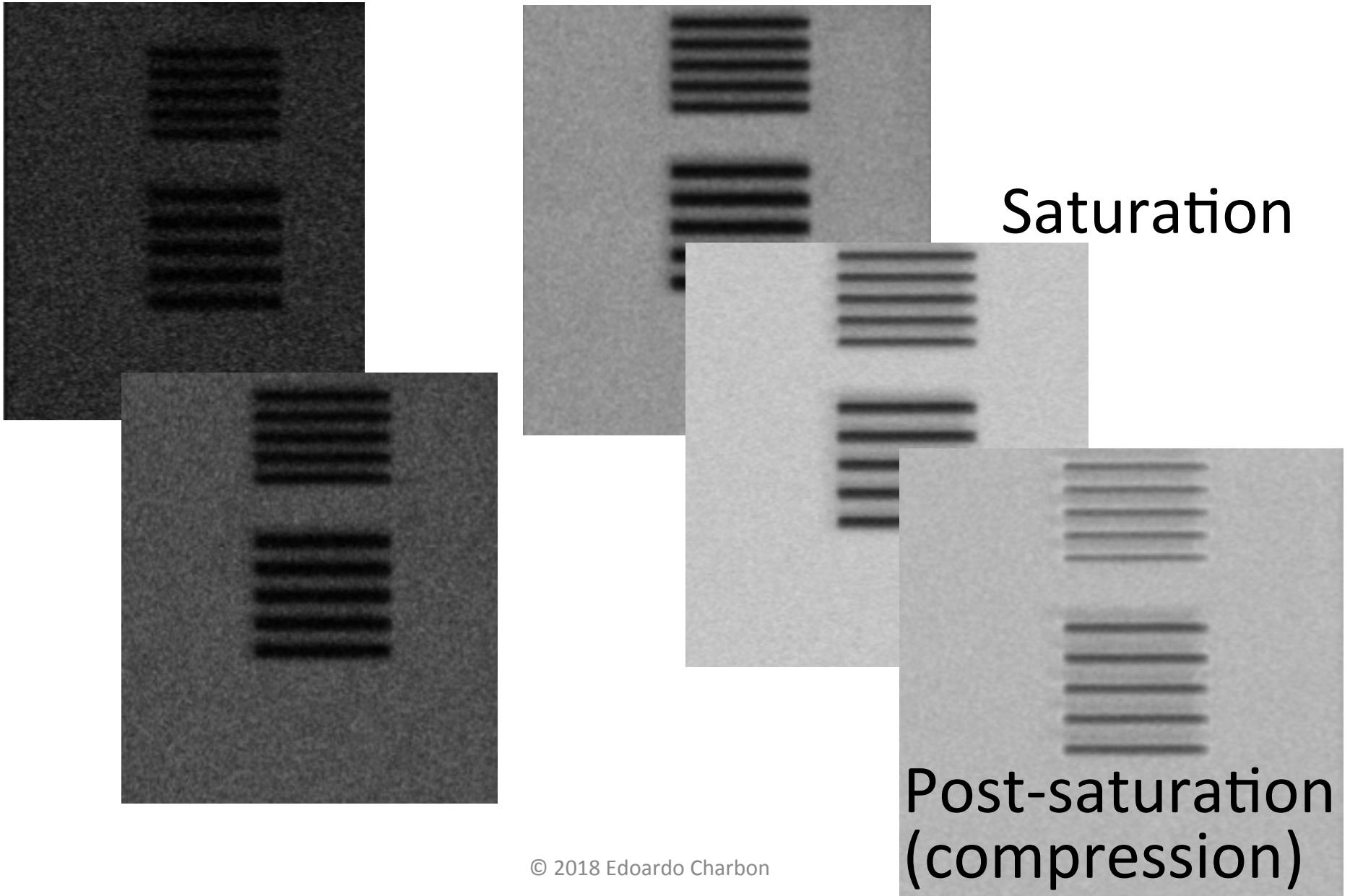


How to Deal with Non-uniformity?

Afterpulsing, Dynamic Range NU

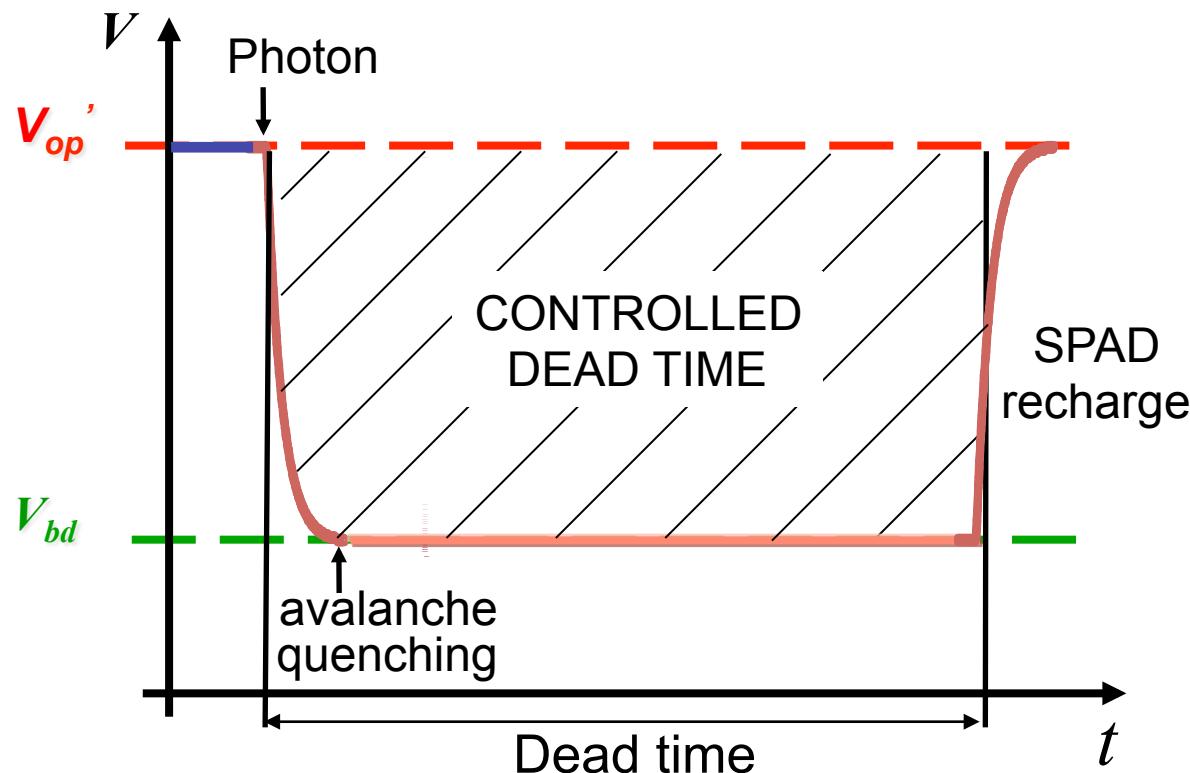


Afterpulsing, Dynamic Range NU

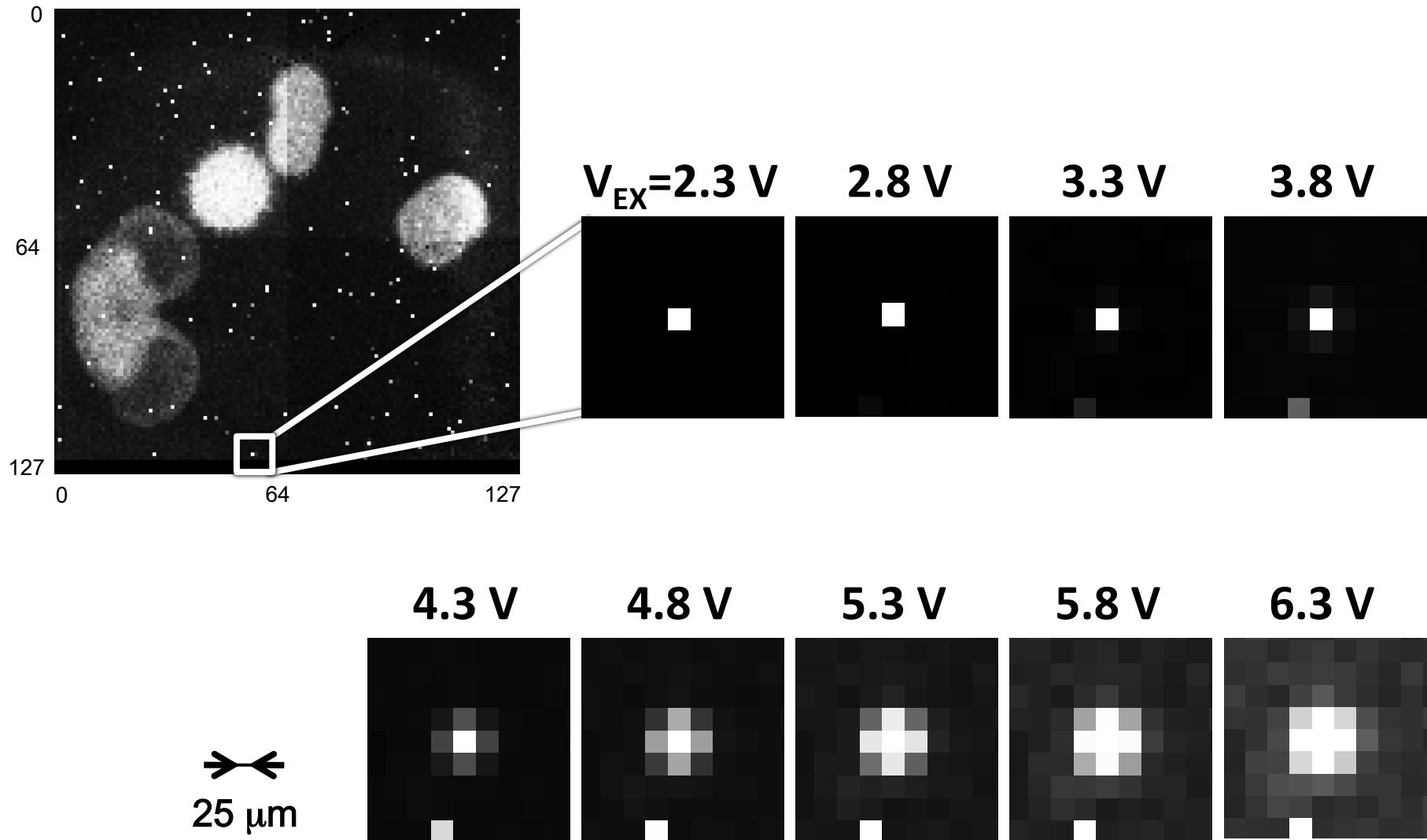


Solution

- Accelerate quenching (and minimize quenching current) with active quenching
- Control dead time with active recharge

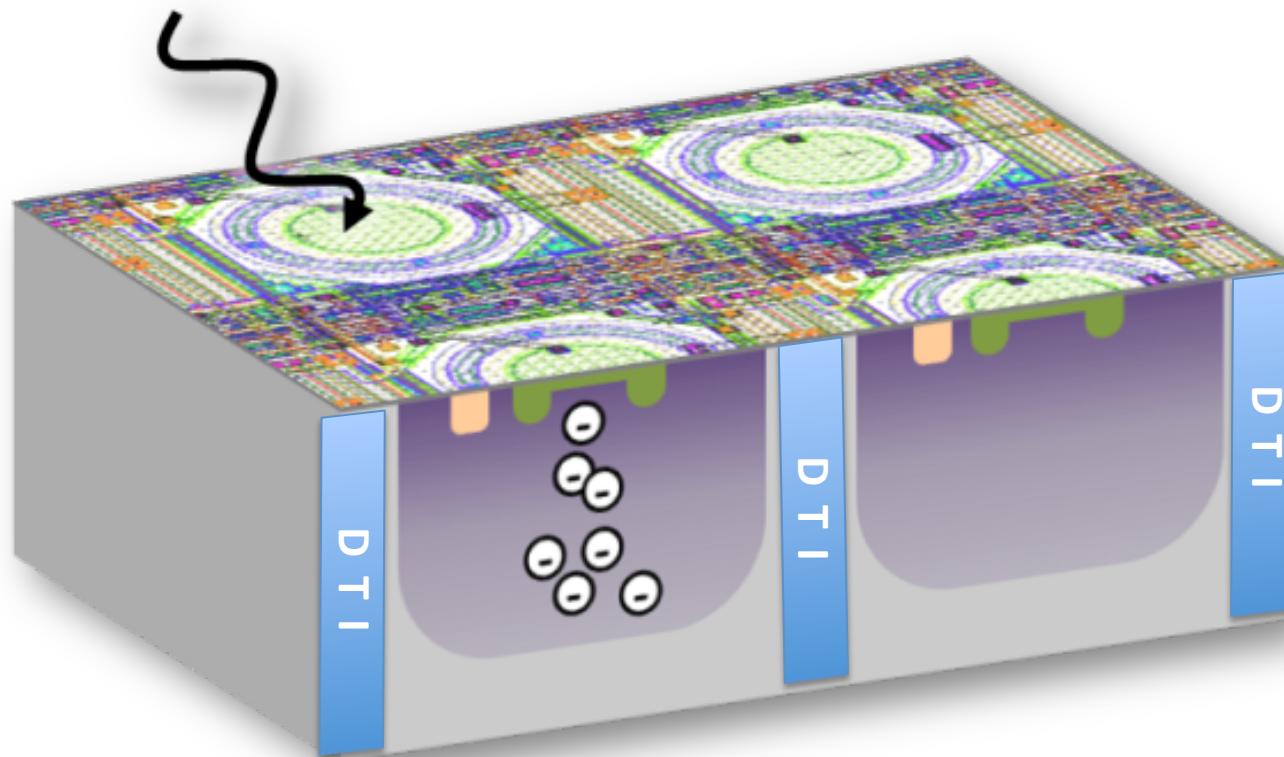


Crosstalk (Evidenced by Hot Pixels)

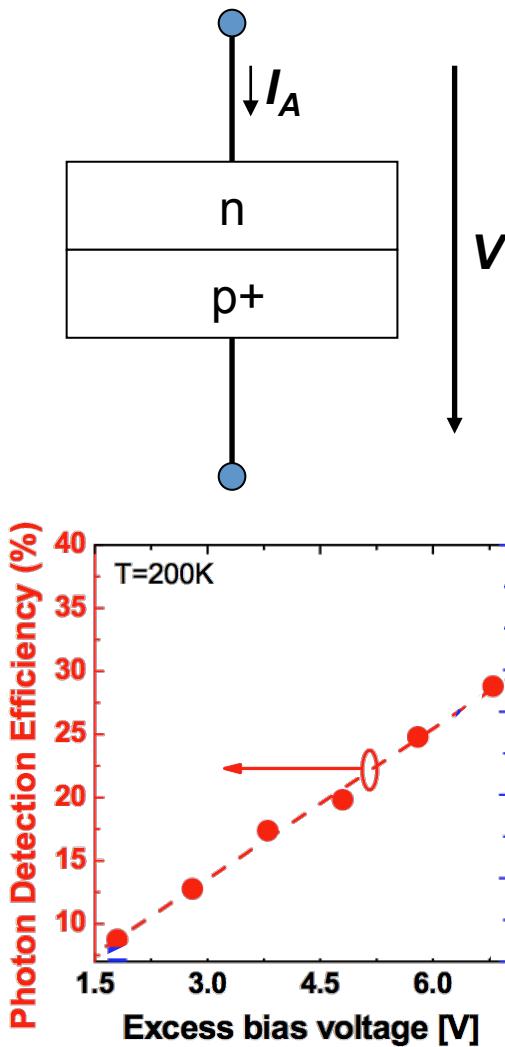


Solution

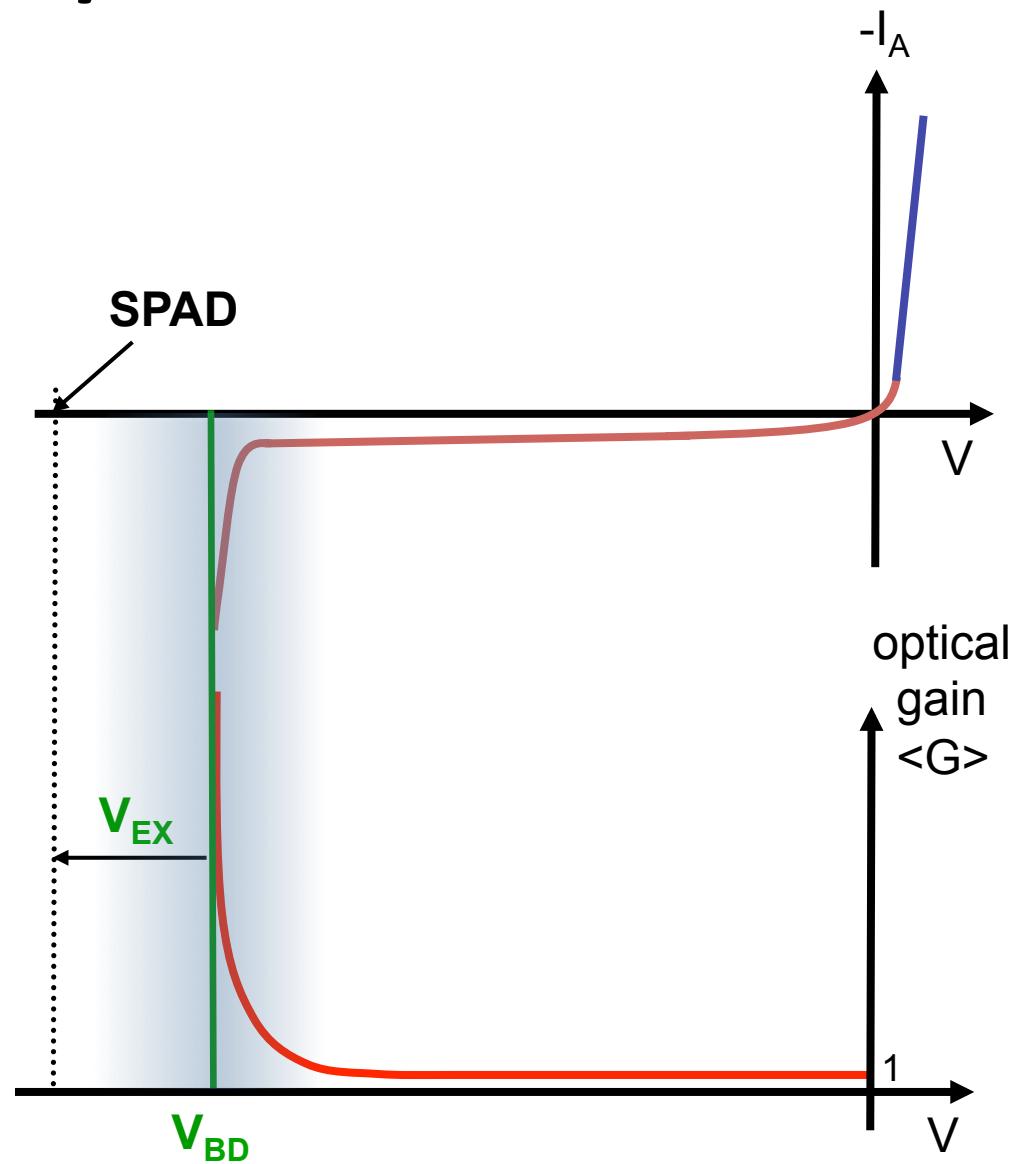
- Accelerate quenching (and minimize photon emission) with active quenching
- Add opaque deep trench isolations



PDP/PDE NU

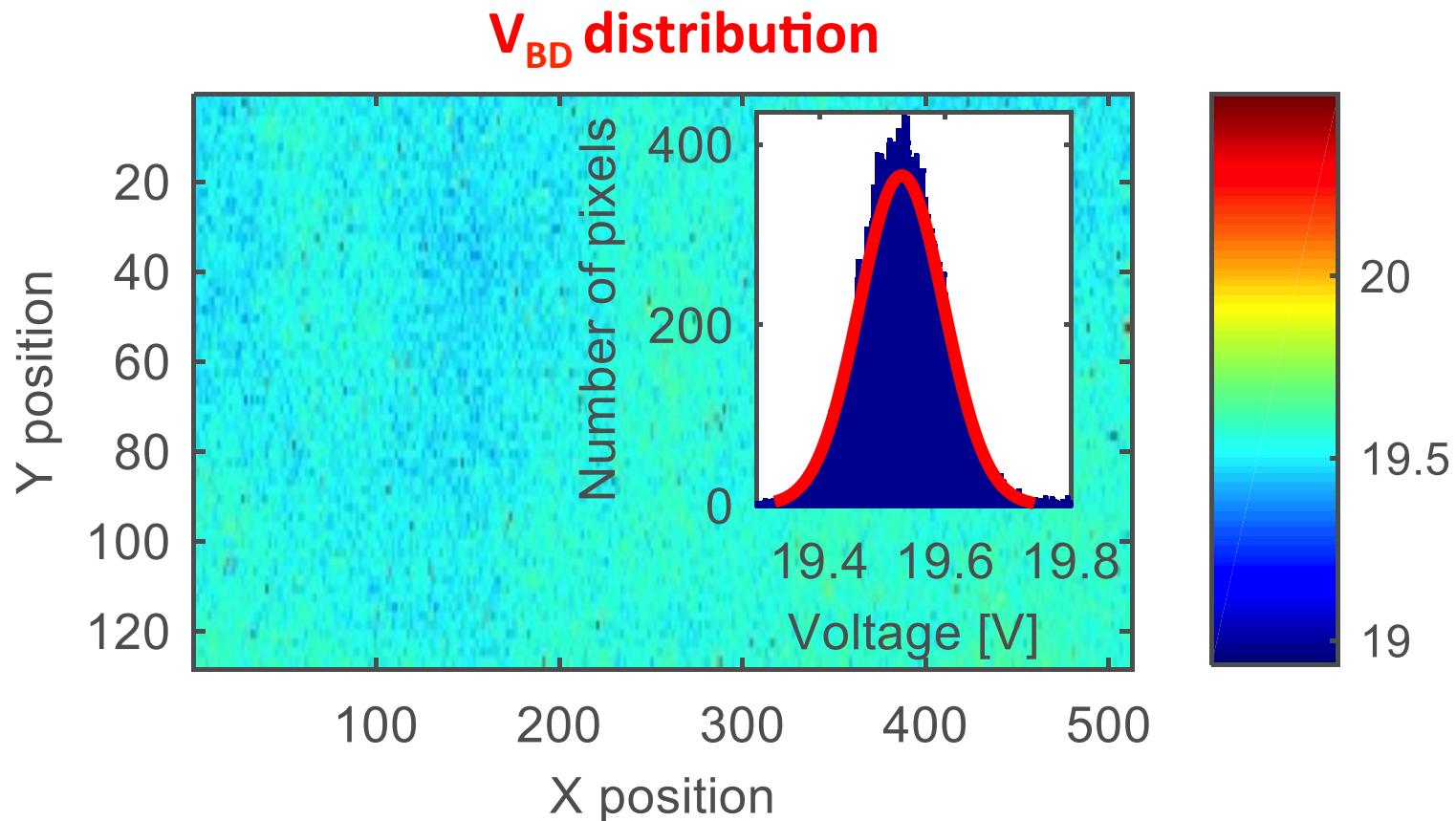


Tosi *et al.*, 2009



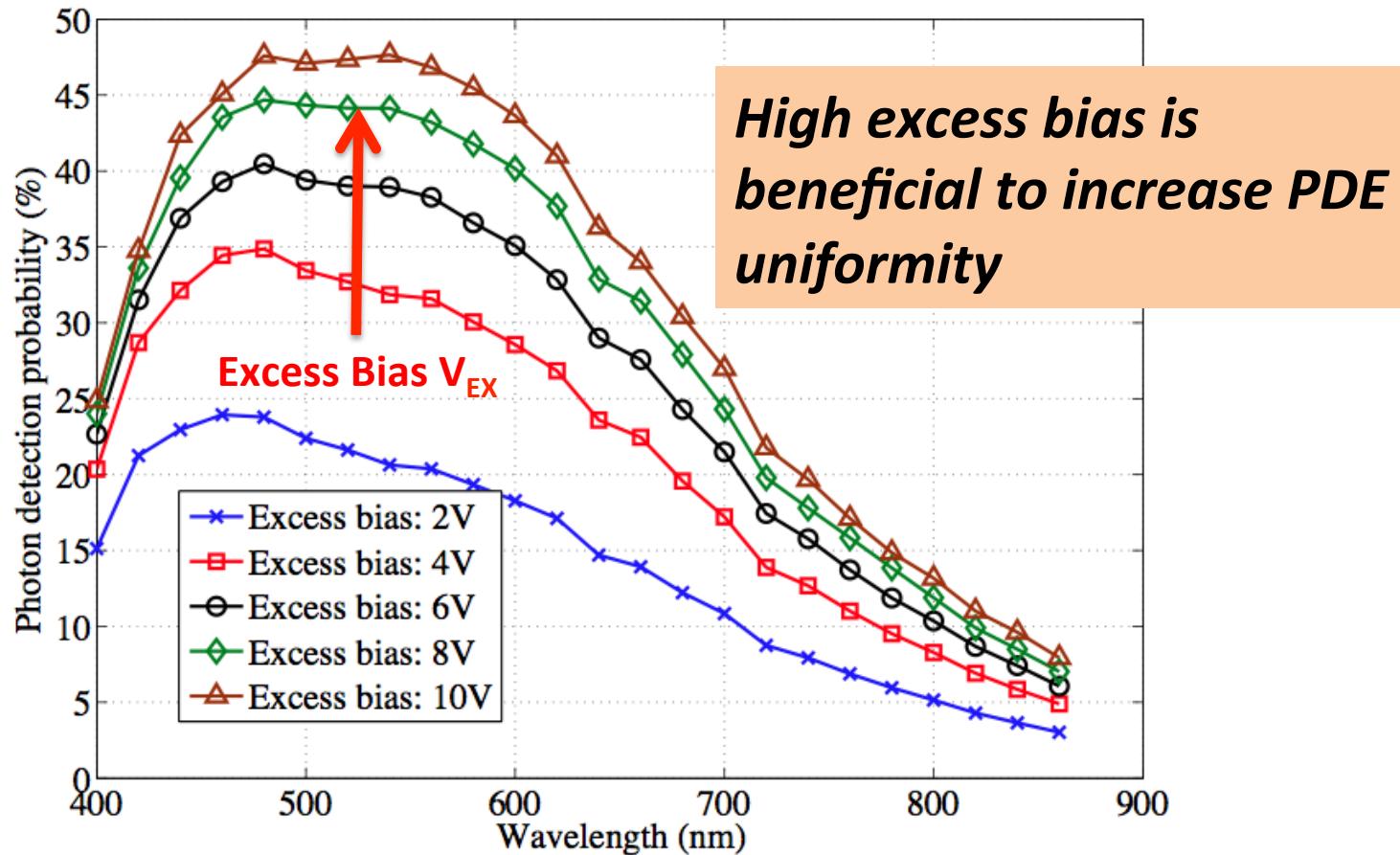
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Breakdown Distribution



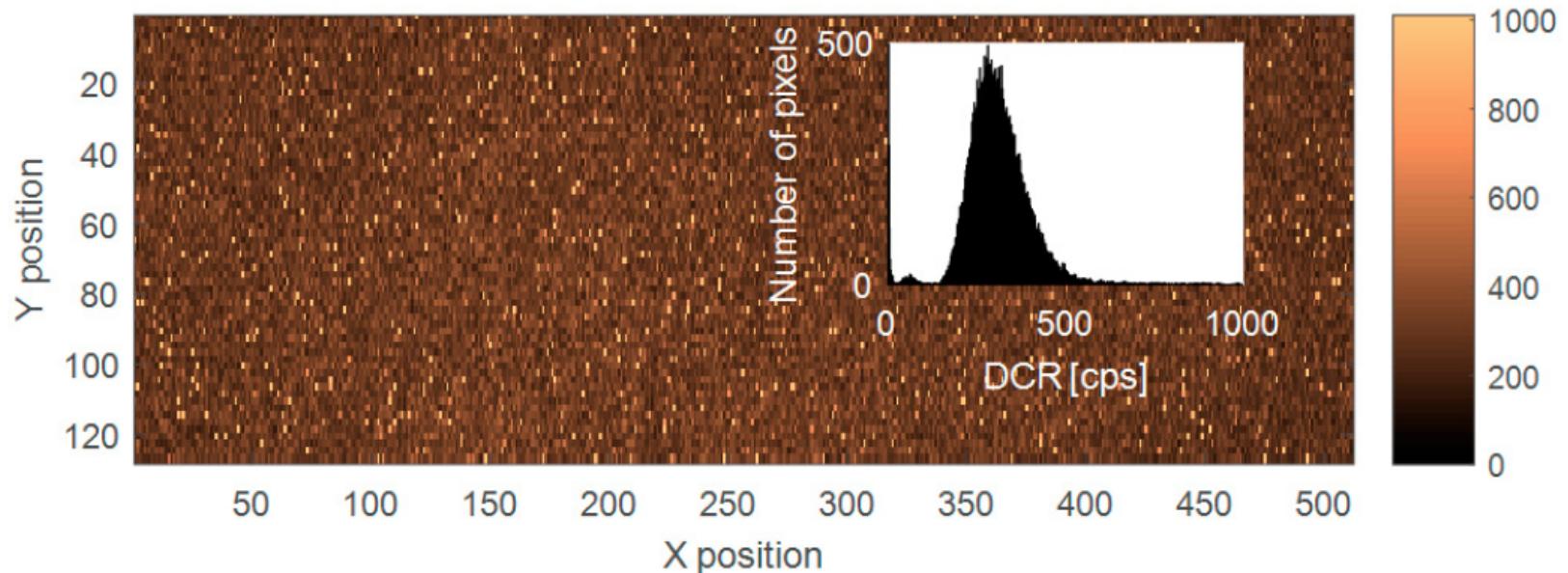
I.M. Antolovic, PhD. Thesis 2017

Solution



C. Veerappan and E. Charbon, JSTQE 2014

Jitter, DCR NU

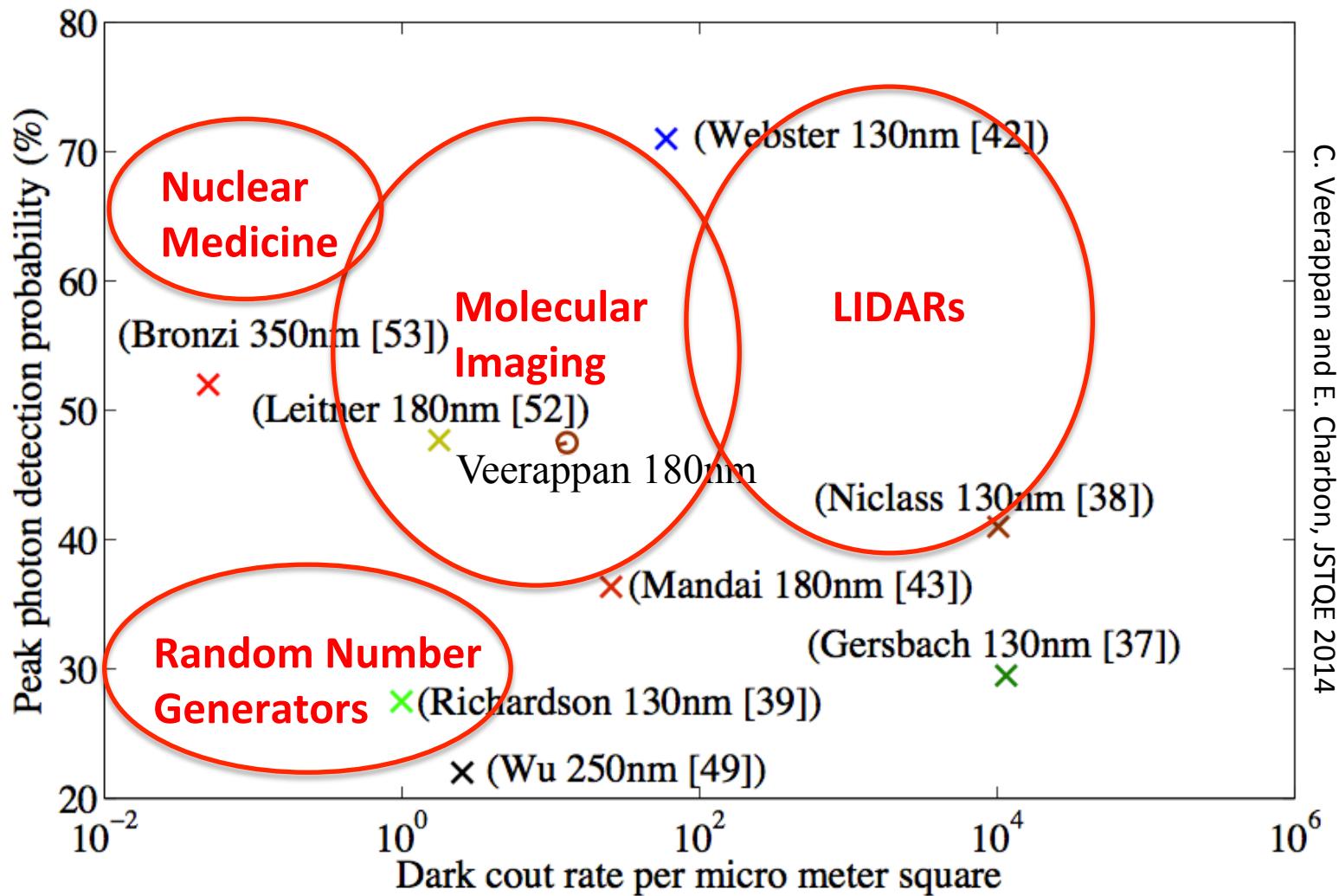


I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

Solution: not much to do, except

- reduce jitter & DCR
- reduce temperature

Sensitivity vs. DCR Issue



C. Veerappan and E. Charbon, JSTQE 2014

Architectures and Quantum Applications