

**PSI** Center for  
Photon Science

# Detector Developments for the Swiss Light Source Upgrade

A. Bergamaschi, M. Brückner, M. Carulla, R. Dinapoli, S. Ebner, K. Ferjaoui, E. Fröjdh, V. Gautam, D. Greiffenberg, S. Hasanaj, A. Haugdal, J. Heymes, V. Hinger, V. Kedych, T. King, S. Li, C. Lopez-Cuenca, A. Mazzoleni, D. Mezza, K. Moustakas, A. Mozzanica, J. Mulvey, M. Müller, K.A. Paton, C. Posada Soto, C. Ruder, B. Schmitt, P. Sieberer, S. Silletta, D. Thattil, X. Xie, J. Zhang



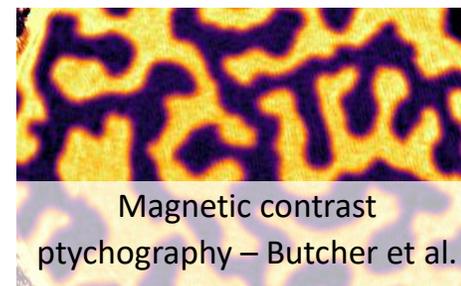
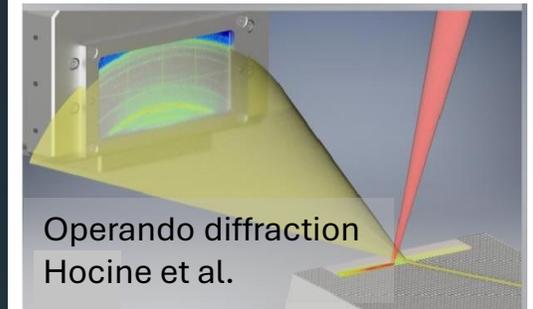
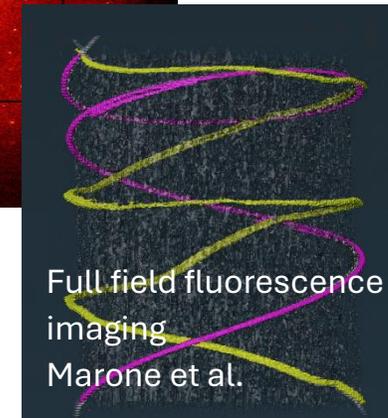
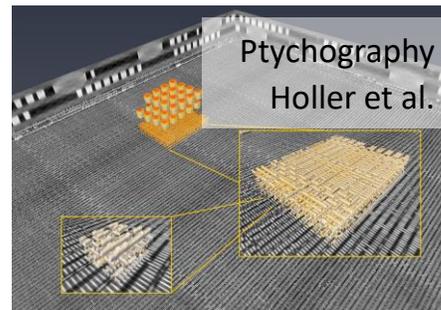
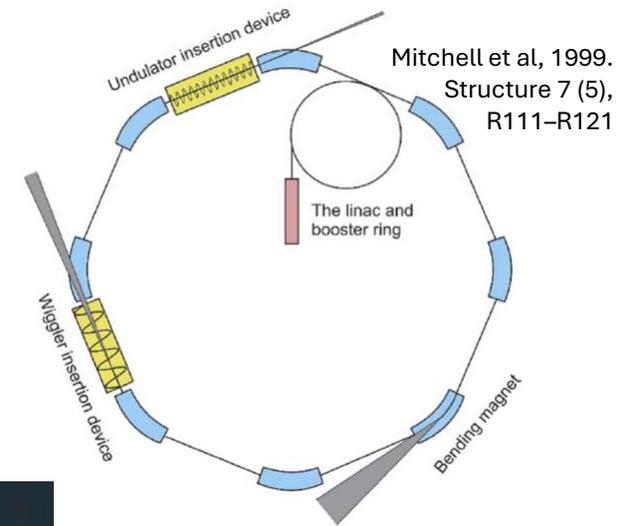
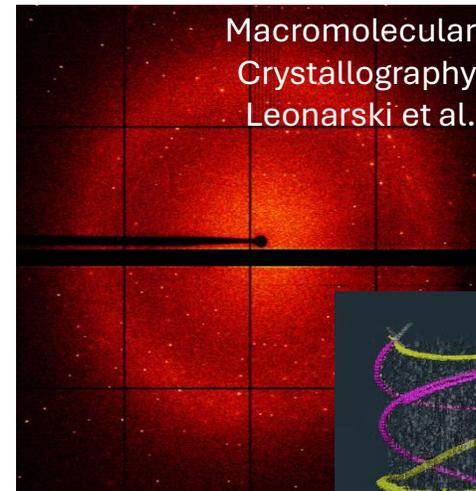
**Center for Photon Science, Paul Scherrer Institute (Switzerland)**

IWORID20205, Bratislava (SK)

Monday 7<sup>th</sup> July 2025

# Synchrotron applications

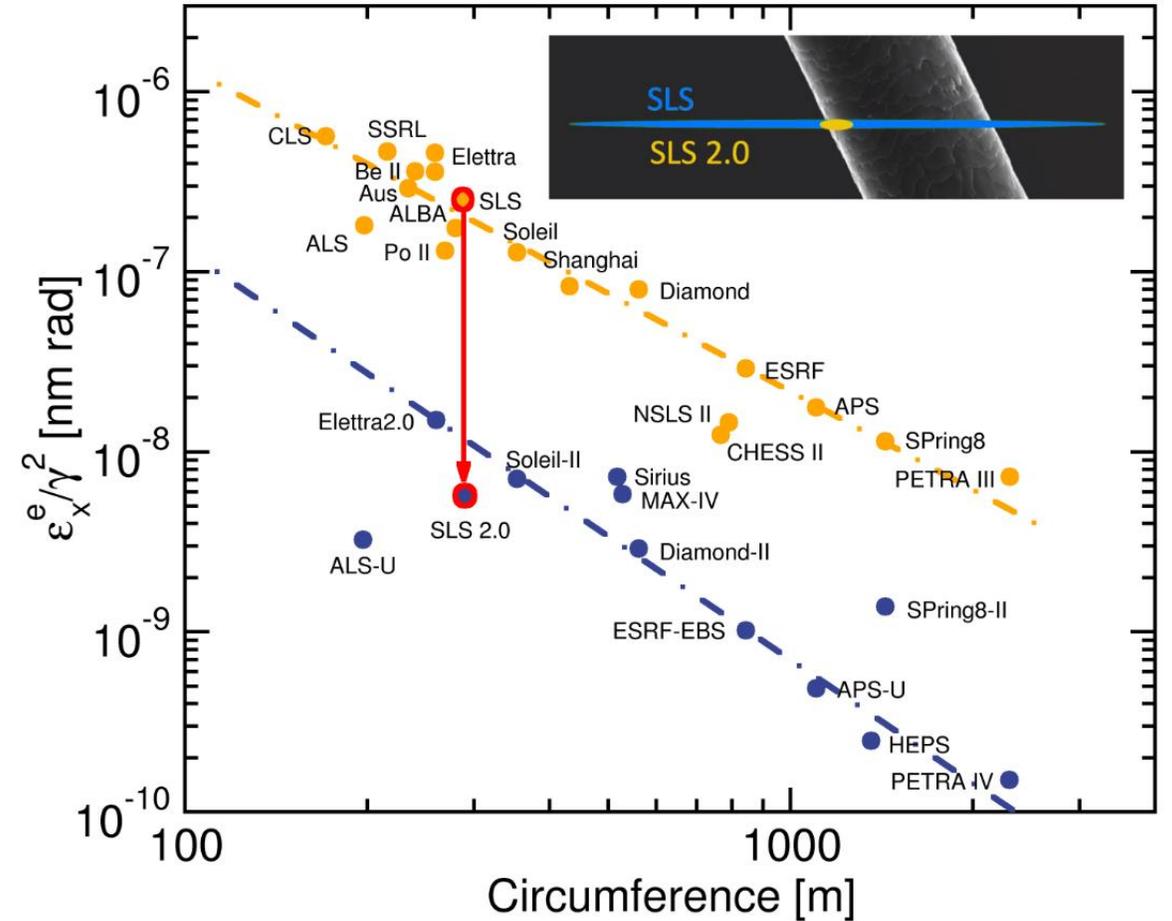
- Synchrotrons are electron accelerators used to generate X-rays
- High X-ray flux
  - Energy selection through monochromator
    - EUV (<100 eV) to hard X-rays (>100keV)
  - High intensity on the detector
  - Photon-starved applications possible
  - High speed
- Coherence
- Polarization
- Pulsed time structure

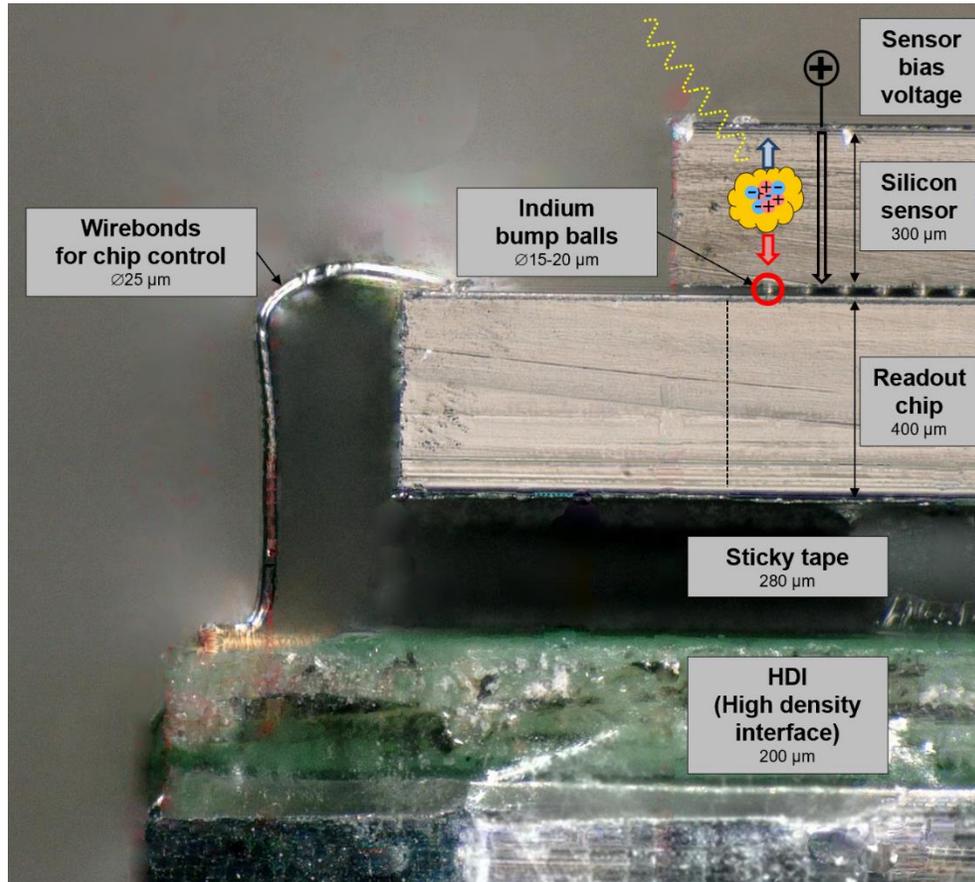


# SLS 2.0 – a 4<sup>th</sup> generation synchrotron

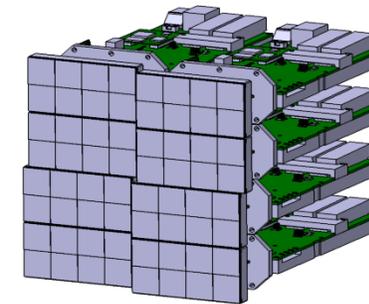


- Improved emittance, increased brightness
  - Higher coherence
  - More photons hitting the sample
- First photons to the beamlines now
- Pilot users at some beamlines Q3/2025
- User operation Q3/2026

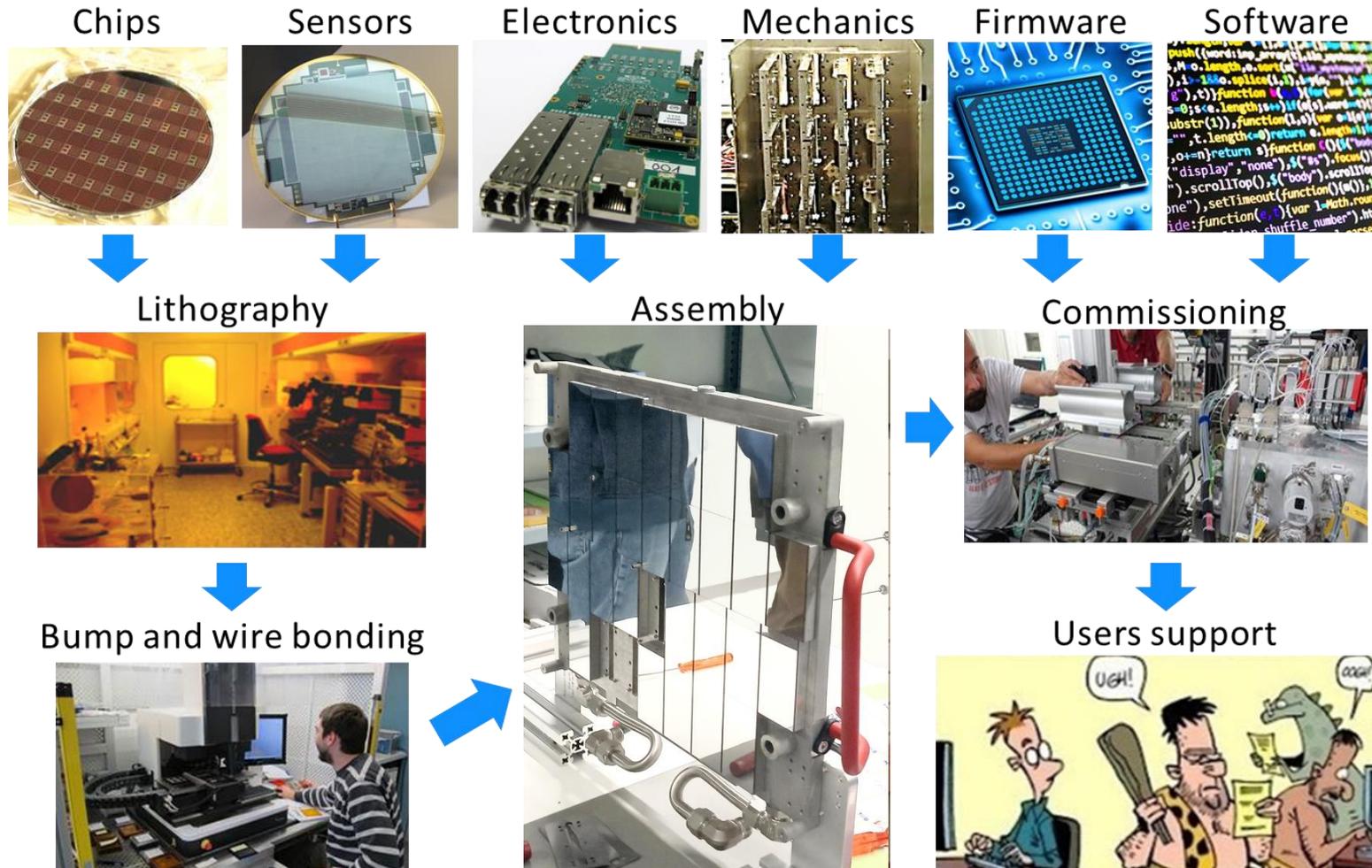


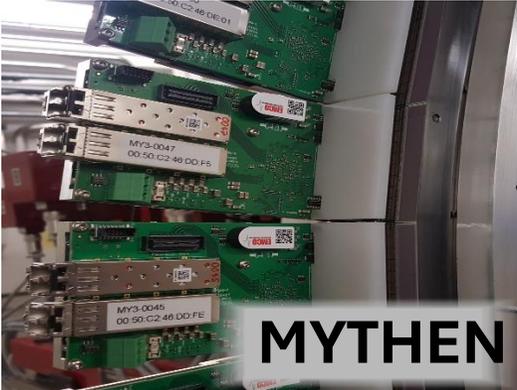


- Semiconductor sensor
  - Direct conversion
- Versatile CMOS readout chip
  - Fast readout
  - Radiation hardness
- Bump bonding
  - Minimum pixel pitch  $\sim 20 \mu\text{m}$
  - Noise due to input capacitance
- Large area by tiling

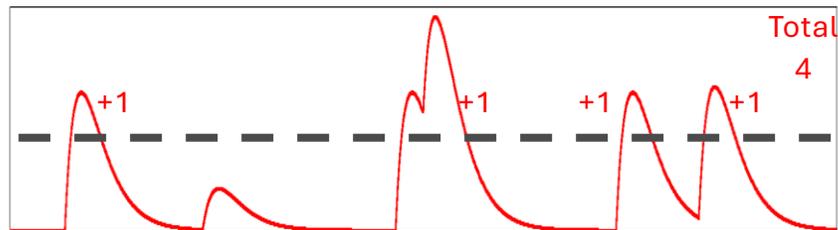
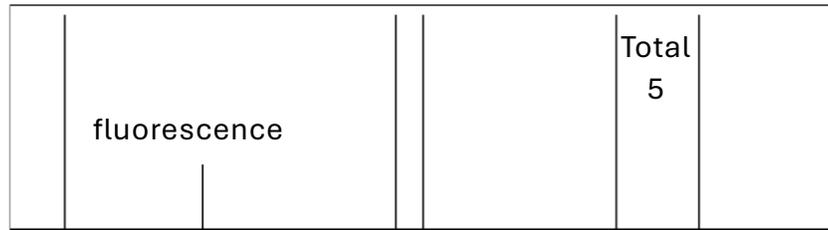


# Everything in-house



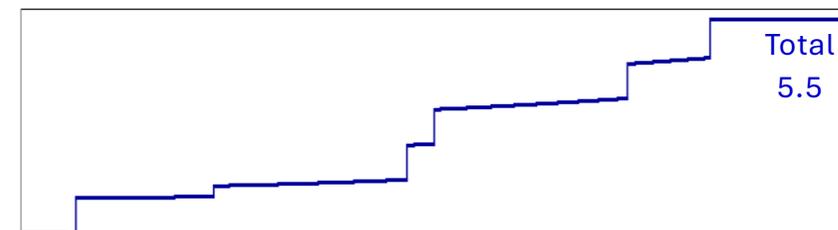
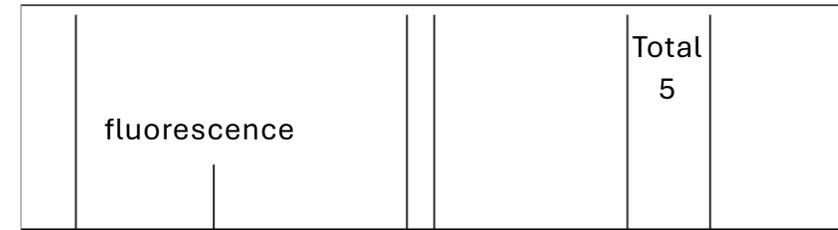
	Microstrip 1D	Pixel 2D	
Single photon counting	25/50 $\mu\text{m}$ pitch  <b>MYTHEN</b>	75 $\mu\text{m}$ pitch  <b>EIGER</b>	25 $\mu\text{m}$ pitch
Charge integrating	 <b>GOTTHARD</b>	 <b>JUNGFRAU</b>	 <b>MÖNCH 0.3</b>

## Photon counting



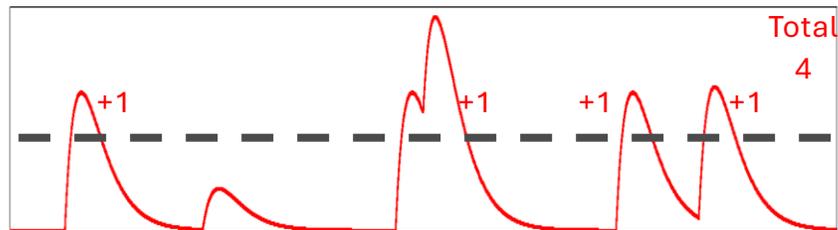
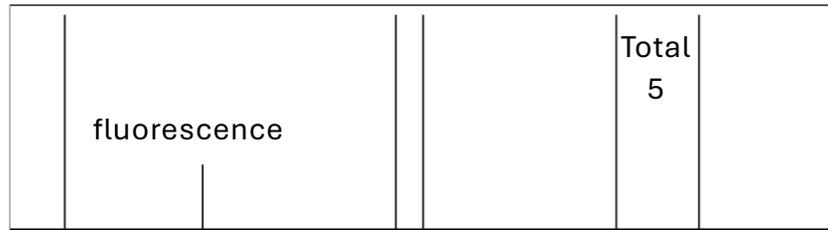
- ✓ Noiseless, very large dynamic range
- ✓ Stable operation, well established calibration
- ✓ Fluorescence suppression
- ✓ Frame rate scales with counter depth
- ✗ Pile-up  $\gtrsim 1\text{MHz/pixel}$
- ✗ Soft X-ray detection prevented by noise

## Charge integrating



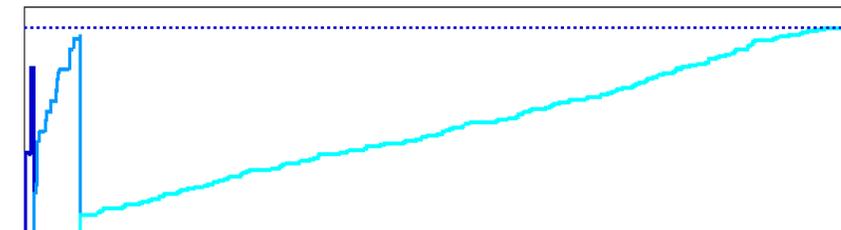
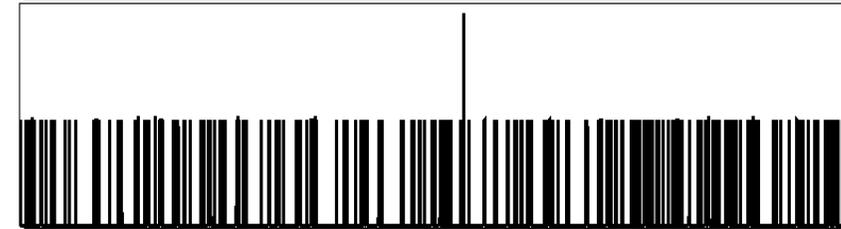
- ✓ Compromise between noise and dynamic range
- ✓ Works also at pulsed sources
- ✓ Detection of multiple soft X-rays
- ✗ Saturation for long integration times

## Photon counting



- ✓ Noiseless, very large dynamic range
- ✓ Stable operation, well established calibration
- ✓ Fluorescence suppression
- ✓ Frame rate scales with counter depth
- ✗ Pile-up  $\gtrsim 1\text{MHz/pixel}$
- ✗ Soft X-ray detection prevented by noise

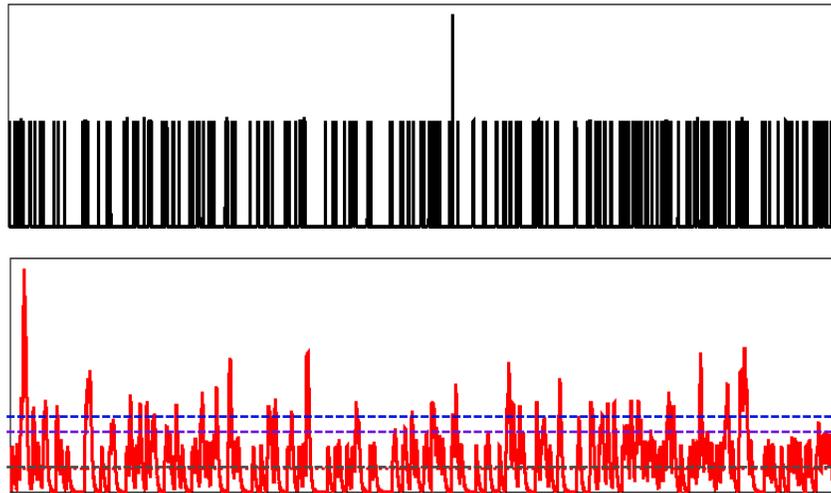
## Charge integrating with adaptive gain



- ✓ **Single photon resolution for hard/tender X-rays**
- ✓ Detection of multiple soft X-rays
- ✓ **Dynamic range up to  $10^4$  photons/pixel/s**
- ✗ Saturations for long integration times
- ✗ **Challenging calibration and cumbersome data processing**

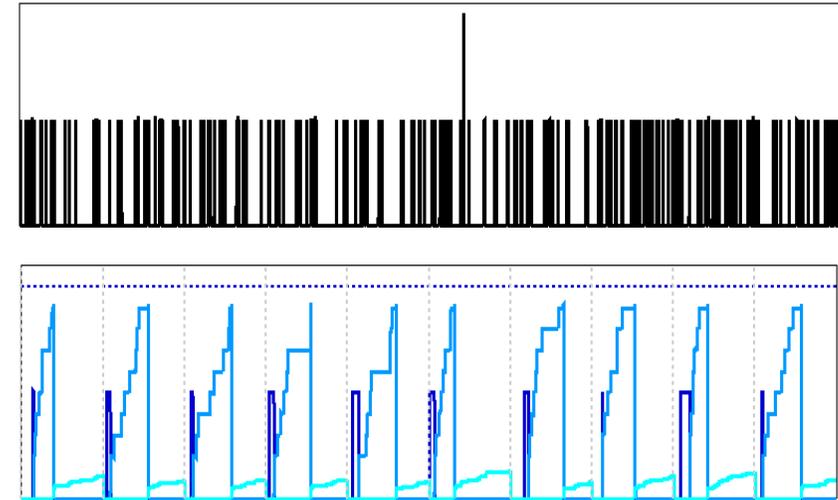
# Upgraded light sources: many more photons!

Photon counting



- ✓ Noiseless, very large dynamic range
- ✓ Stable operation, well established calibration
- ✓ Fluorescence suppression
- ✓ Frame rate scales with counter depth
- ✓ **Faster shaping, pile-up tracking**
- ✗ Pile-up  $\gtrsim 1\text{MHz/pixel}$
- ✗ Soft X-ray detection prevented by noise

Charge integrating with adaptive gain



- ✓ Single photon resolution for hard/tender X-rays
- ✓ Detection of multiple soft X-ray
- ✓ Works also at pulsed sources
- ✓ Dynamic range up to  $\sim 10^4$  photons/pixel/s
- ✓ **Supported flux scales with frame rate**
- ✗ Saturations for long integration times
- ✗ **Challenging calibration and cumbersome data processing needs high throughput!**

**Microstrip  
1D**

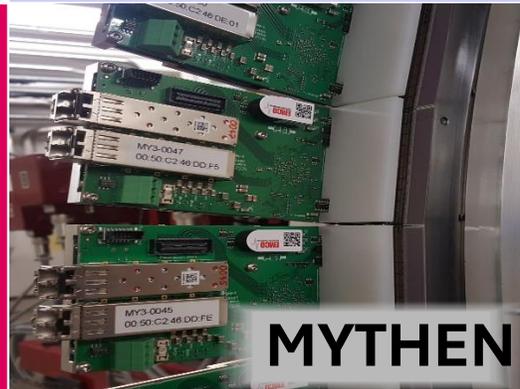
**Pixel  
2D**

25/50  $\mu\text{m}$  pitch

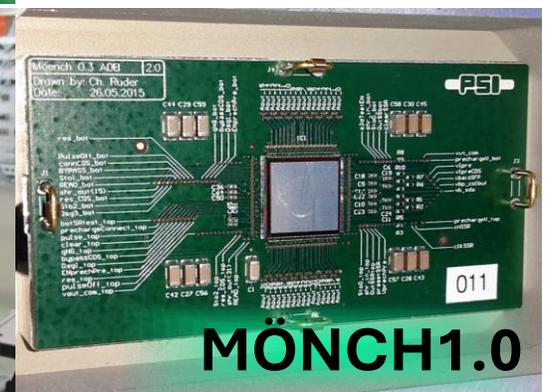
75  $\mu\text{m}$  pitch

25  $\mu\text{m}$  pitch

**Single photon  
counting**



**Charge  
integrating**

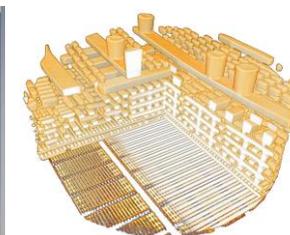
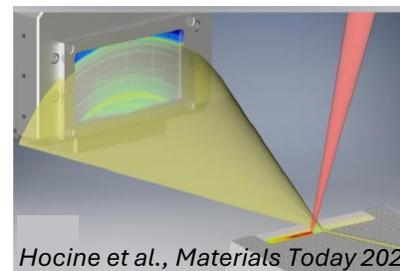


# MATTERHORN: the next peak for single photon counting

	EIGER	MATTERHORN
Pixel size	75 x 75 $\mu\text{m}^2$	
Module size	4 x 8 $\text{cm}^2$	
Thresholds	1	4
Min Threshold	$\sim 3$ keV	$\sim 1.5$ keV
Counter depth	12 bit	4 x 16 bit
Max. Frame rate (8 bit)	10 kHz (burst)	<b>20 kHz (continuous)</b>
Count rate (90% efficiency)	0.35 Mcounts/pixel/s	<b>20 Mcounts/pixel/s</b>
Gating	$\sim \mu\text{s}$	<b><math>\sim 20</math> ns</b>

Full size ASIC submitted last week

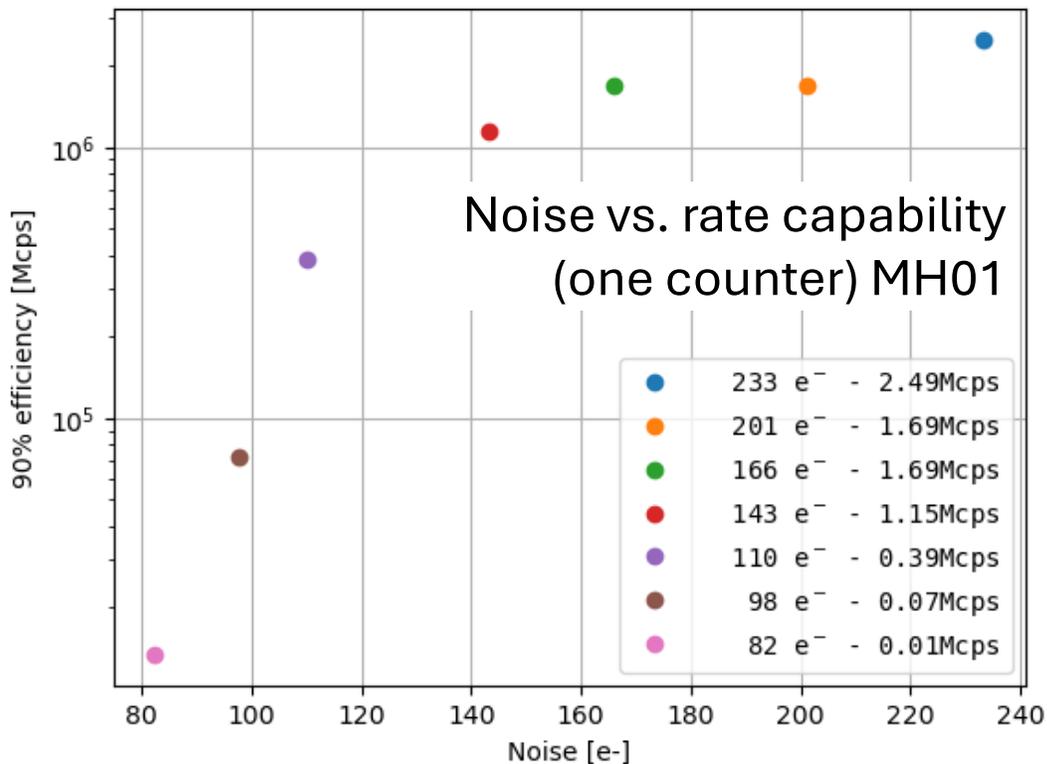
- Dual polarity analog chain
- 4 independent comparators and gatable counters
  - Pile-up tracking
  - Pump-multiprobe measurements
- Synthesized digital periphery
- On-chip PLL
- 4 x 3.125 GHz serializers / chip
- 100 Gb/s link / module



# MATTERHORN prototypes



Preliminary prototype results (MH01-MH02)	
<b>Pixels</b>	48 x 48
<b>Min threshold</b>	< 2keV
<b>Noise</b>	80 e- ENC rms
<b>Threshold dispersion</b>	33 eV rms

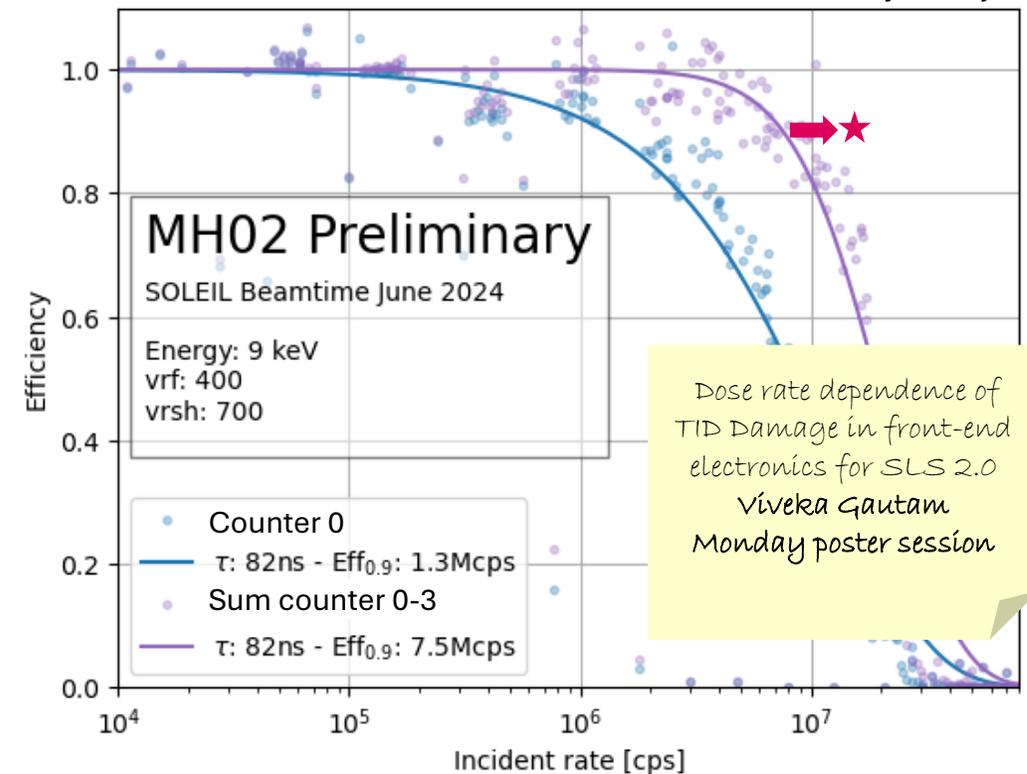


## Count rate capability with 90% efficiency

- 2.5 MHz (1 counter)
- >7.5 MHz (3 counters)

Below expectation, due to low comparator current used

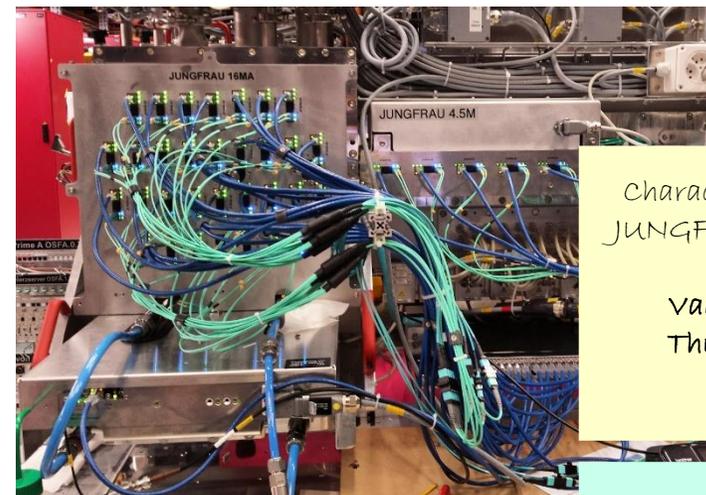
Courtesy E. Frojdh



# JUNGFRAU2: faster, even higher intensities

	JUNGFRAU	JUNGFRAU2
Pixel size	75x75 $\mu\text{m}^2$	
Module size	4x8 $\text{cm}^2$	
Dynamic range (12 keV)	$10^4$	
Min Energy*	~ 800 eV	~ 600 eV
Max Frame rate	2.2 kHz	<b>10 kHz</b>
Max count rate (12 keV)	22 Mcounts/pixel/s	<b>100 Mcounts/pixel/s</b>
Storage cells (burst mode)	16	<b>16-64 Rebin-able</b>

\* with single photon resolution, standard silicon

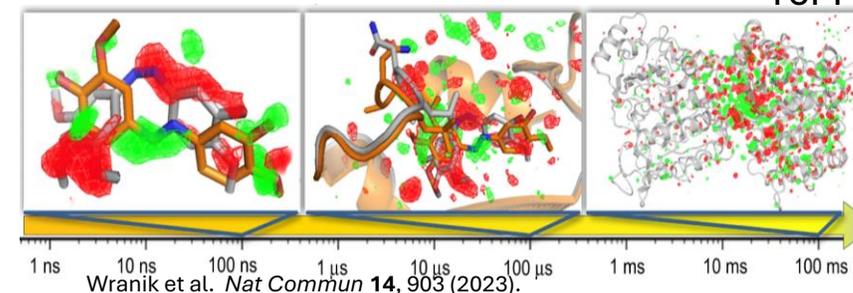


Characterization of the JUNGFRAU 1.2 readout ASIC  
Vadym Kedych  
Thursday 11:00

A 1M charge integrating hybrid pixel detector for electron diffraction  
Khalil Ferjaoui  
Wednesday 15:10

At Synchrotrons full duty cycle

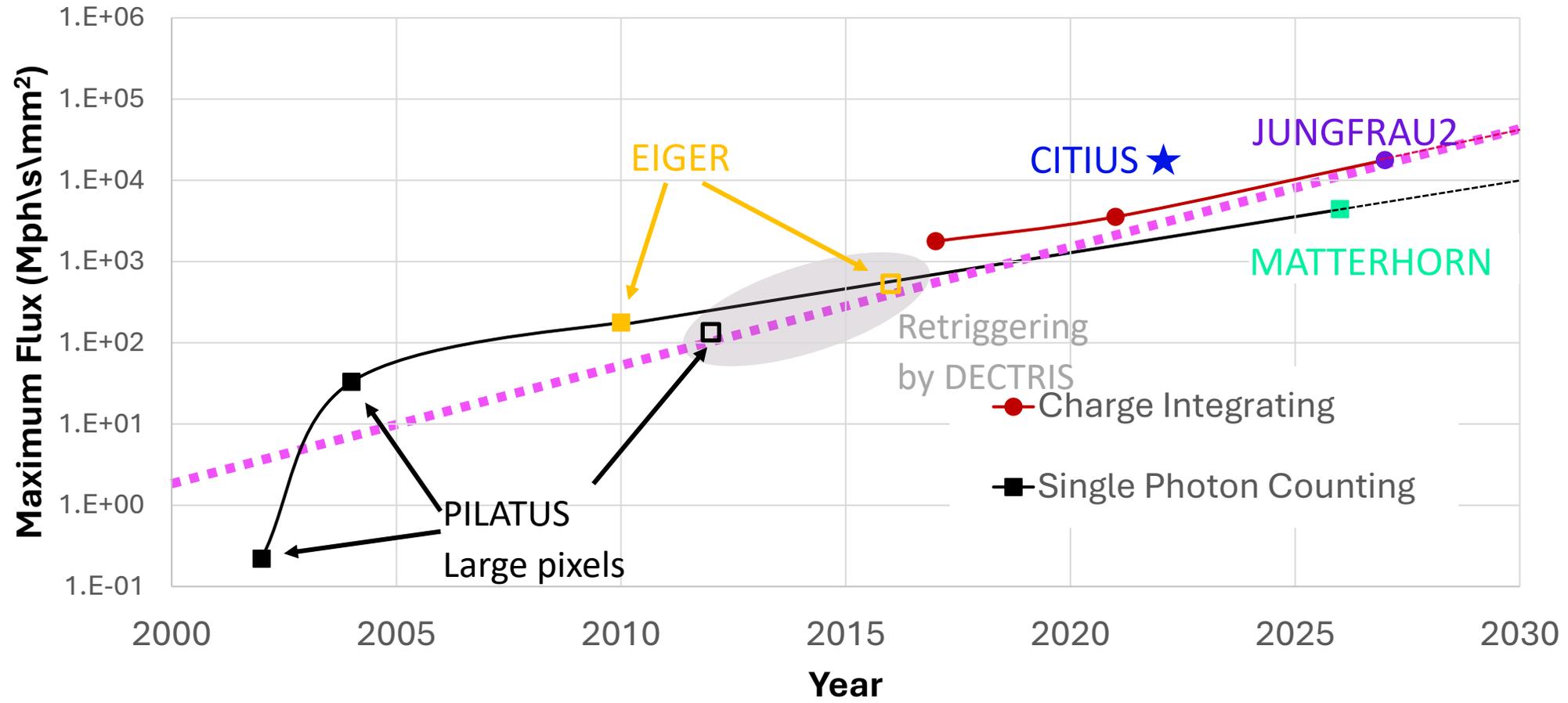
- 2 GB/s/module →
- 190 TB/day/module →
- 5.3 PB/day for a 16M detector →



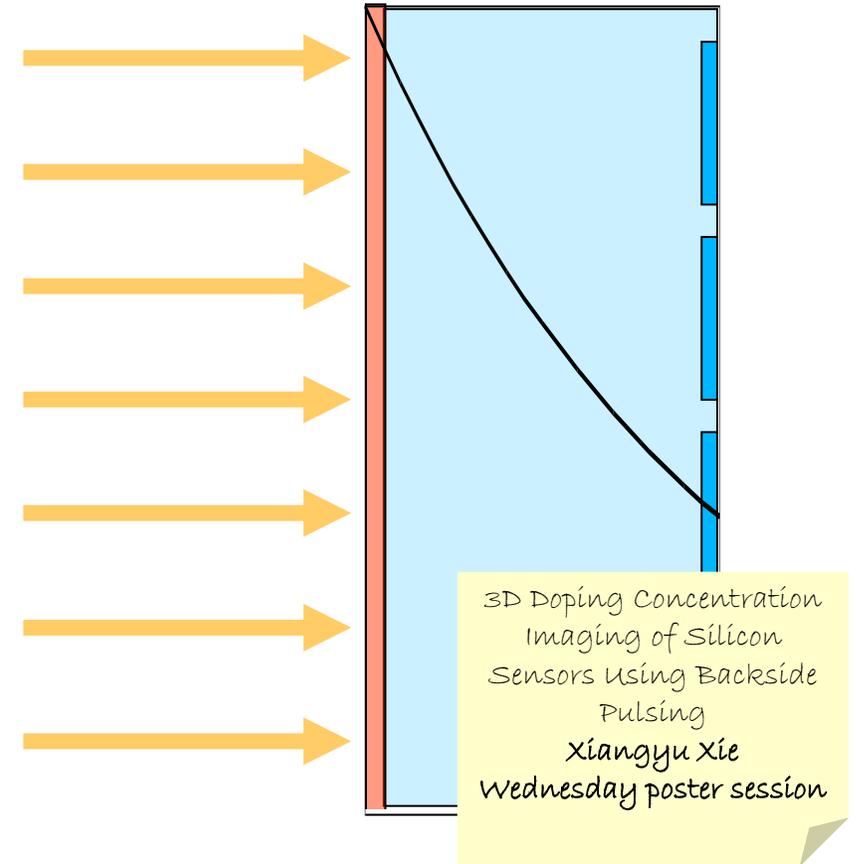
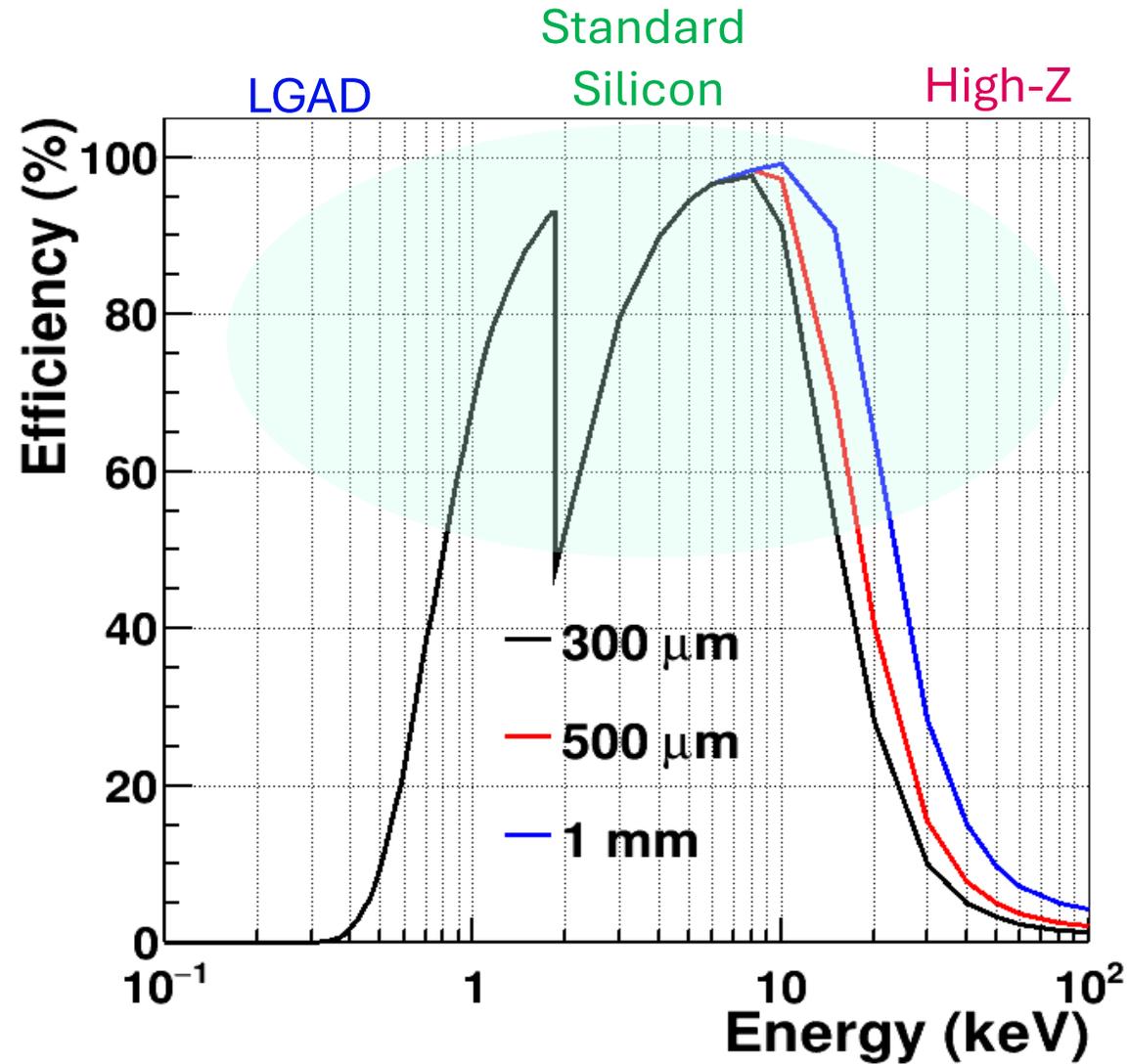
# Maximum detectable intensities



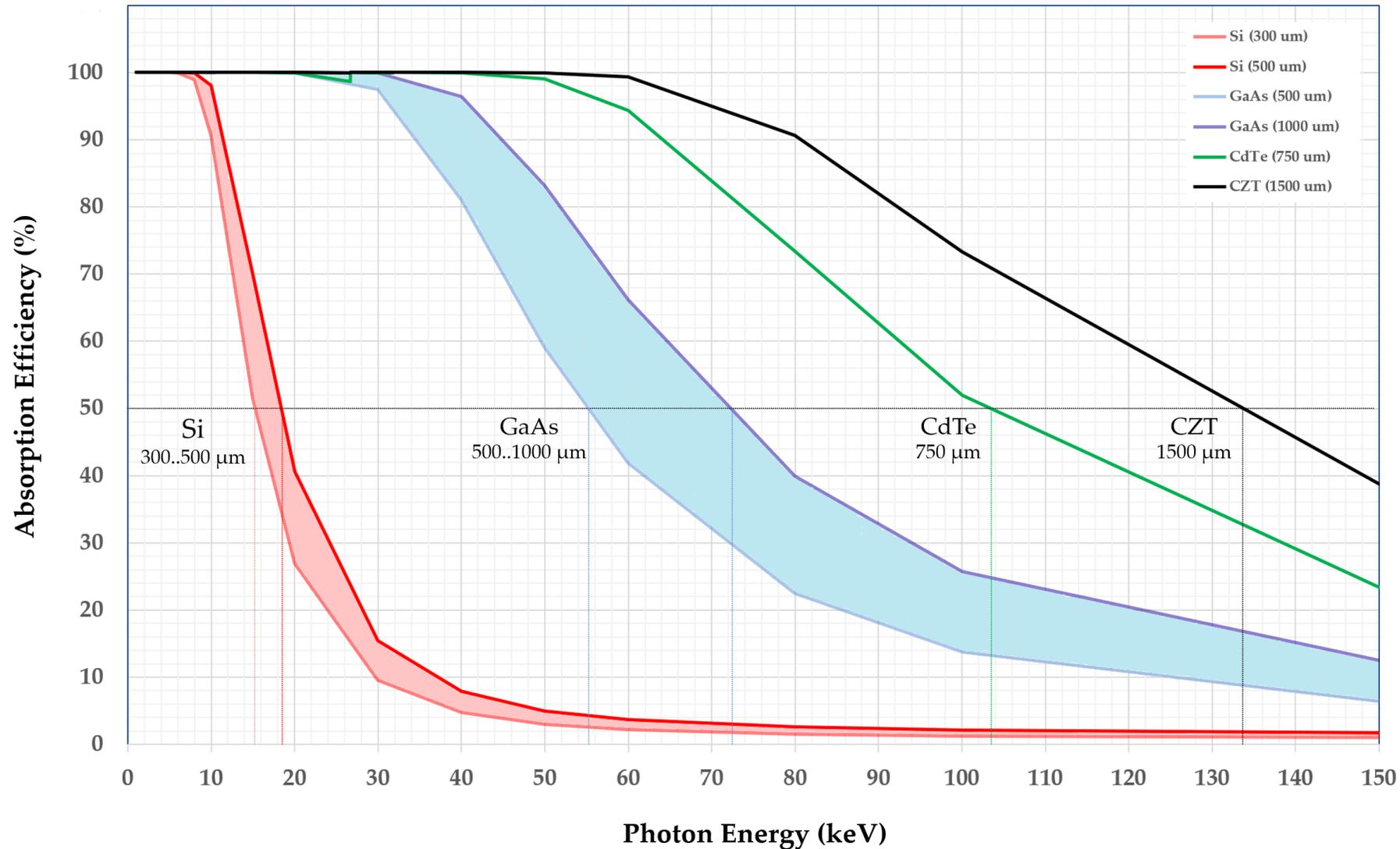
Faster than Moore!  $\approx 2^{t/1.55y}$



# Silicon quantum efficiency



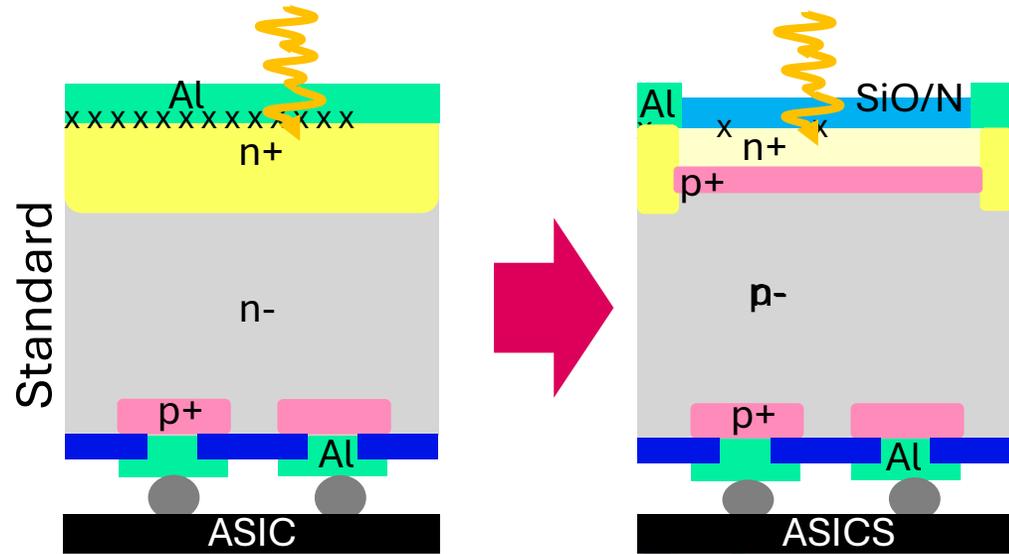
# High-Z sensors for hard X-rays



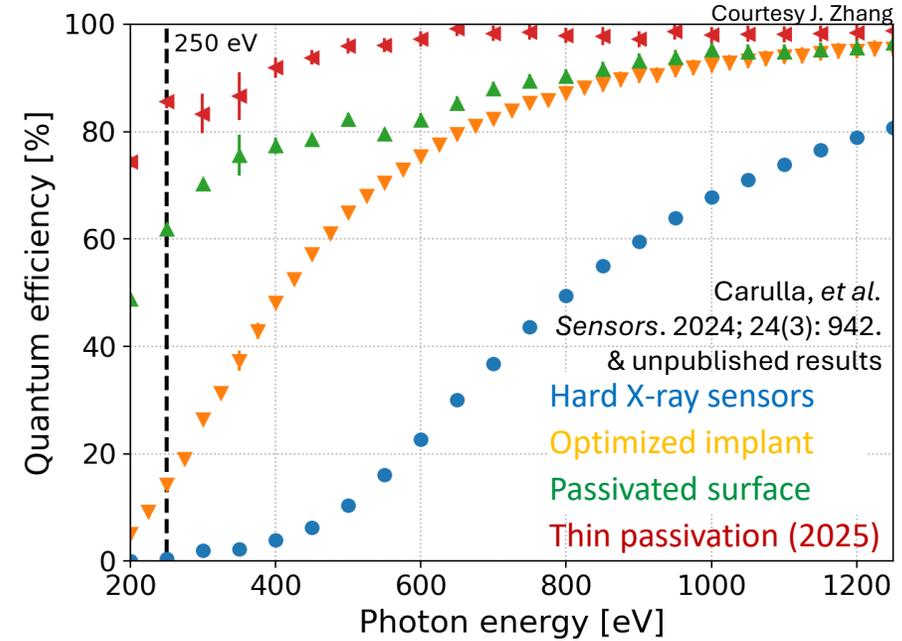
*CZT as a Material for  
Detecting Hard X-rays at  
Synchrotrons and FELs  
Jonathan Mulvey  
Tuesday 9:50*

*Enhancing the  
Performance of High-Z  
Sensors for Photon  
Science Applications  
Kirsty Paton  
Tuesday 10:10*

# Soft X-rays detection



Zhang, et al. JINST 2022; 17(11): C11011.



Courtesy J. Zhang

Carulla, et al. Sensors. 2024; 24(3): 942. & unpublished results

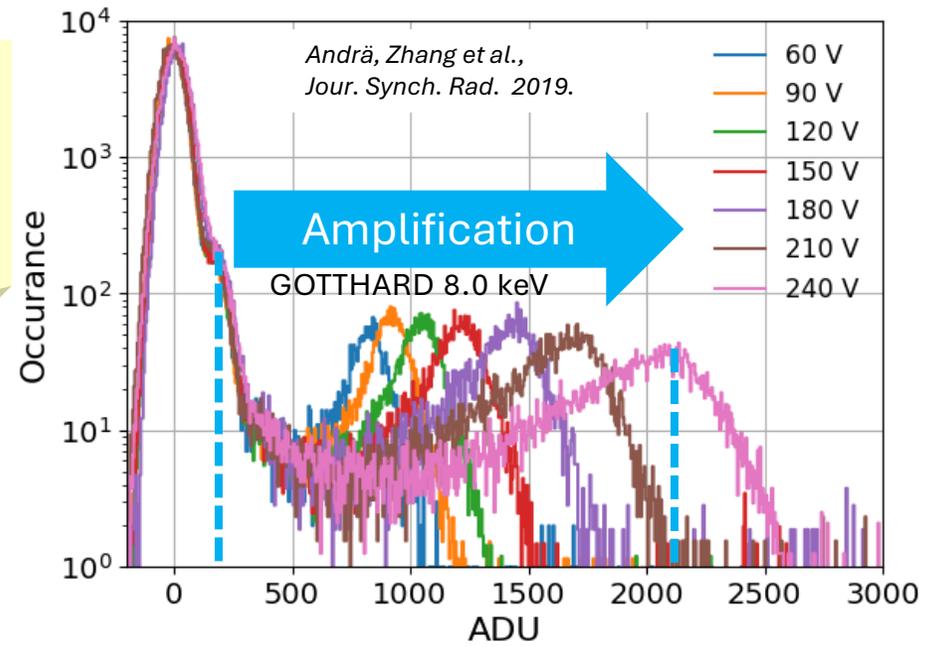
## Shallow absorption of soft X-rays

- Thin entrance window technology with improved dop and thin passivation

## Charge per photon comparable to electronic noise

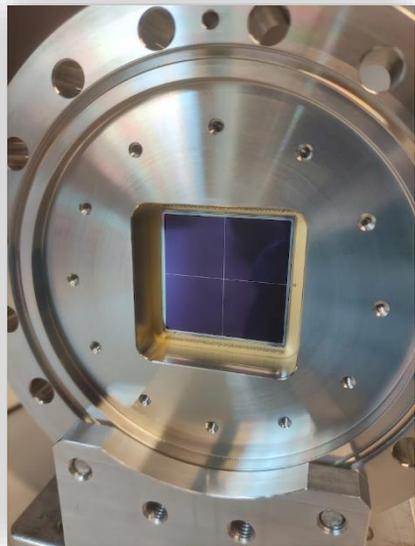
- Exploit internal multiplication of LGADs to increase SNR

Characterisation of inverse LGADs in the soft X-ray energy range  
 Shuqi Li  
 Tuesday 11:00

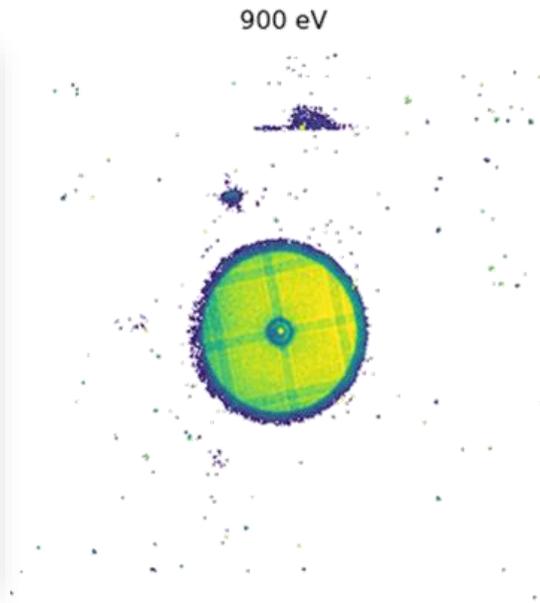


Andrä, Zhang et al., Jour. Synch. Rad. 2019.

# Single photon counting below 1 keV



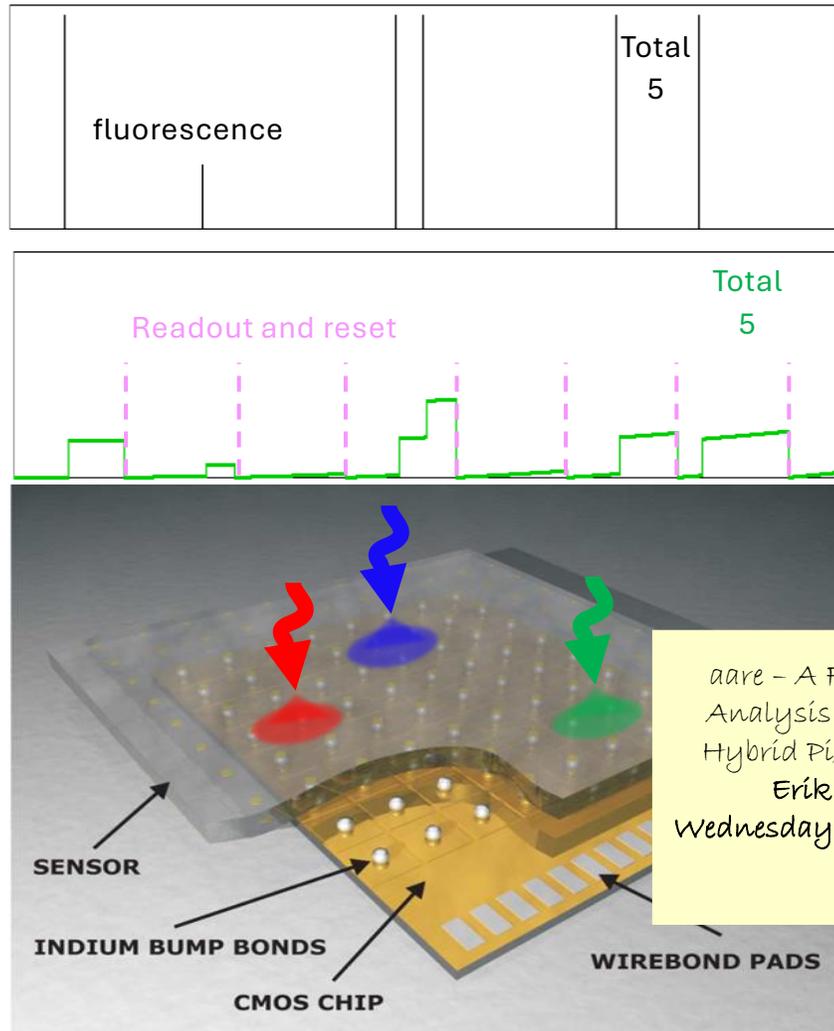
4 × 4 cm<sup>2</sup> iLGAD



- Largest LGAD ever!
- Single photon resolution down to ~500 eV
- Effective noise reduction
- Cooling required
- Scientific papers at the Fe L-edge (700eV) and O K-edge (530 eV)

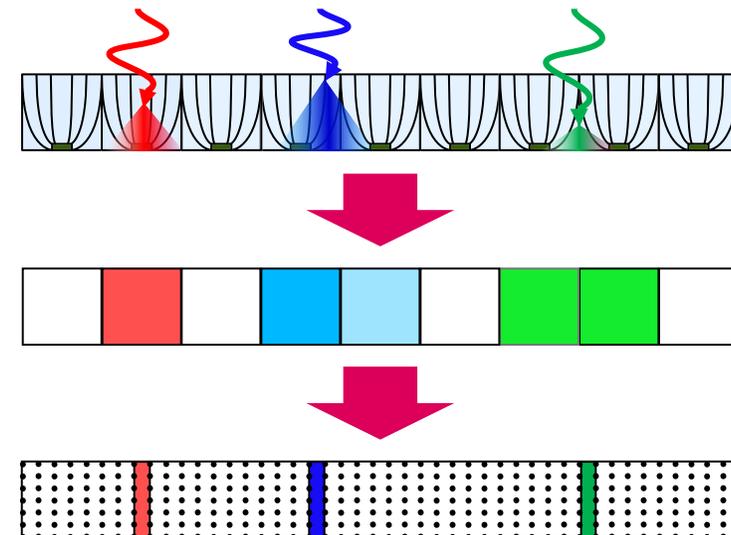
Image of a FZP acquired using EIGER  
SIM beamline SLS  
F. Baruffaldi et al., under review.

# More X-rays for photon-starved applications



aave - A Flexible Data Analysis Library for Hybrid Pixel Detectors  
Erik Fröjdh  
Wednesday poster session

- With fast frame rates and low fluxes
  - Energy resolution  $\lesssim$  keV
  - Super-resolution  $\sim \mu\text{m}$
- Developments to sustain higher fluxes
  - Faster frame rates
  - Machine learning to handle pile-up

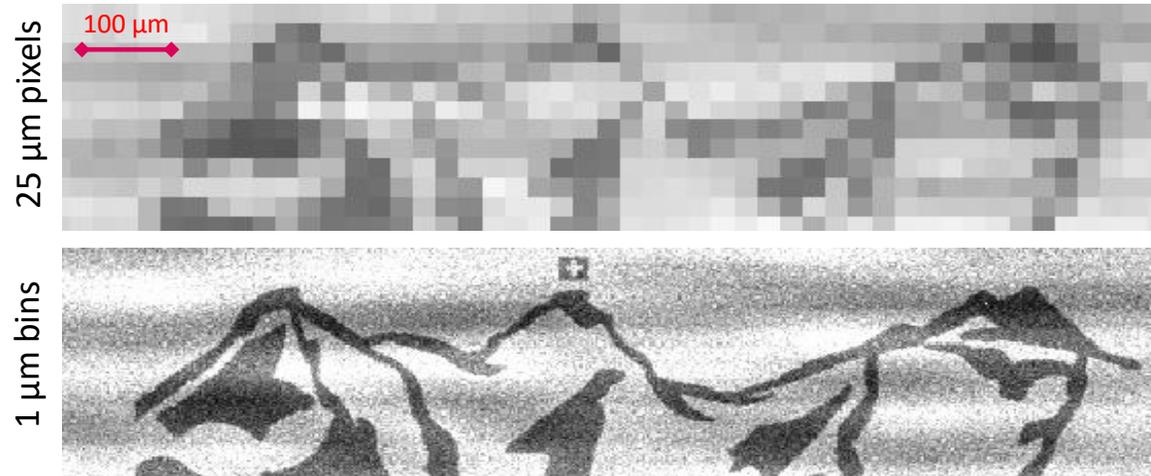


# Super-resolution

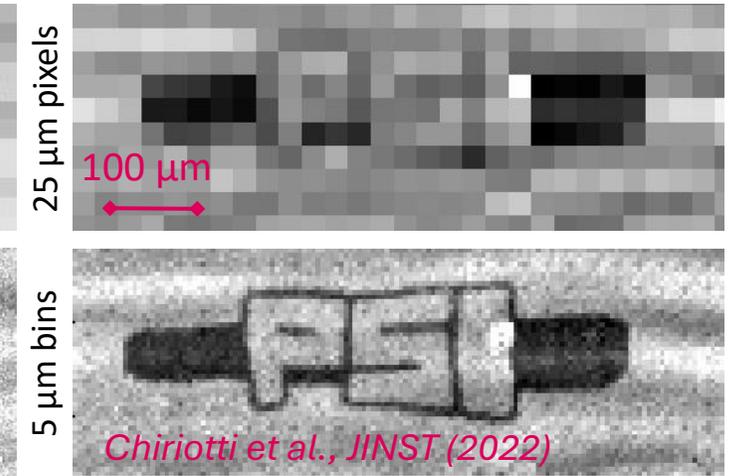
LGAD sensor @ 500eV



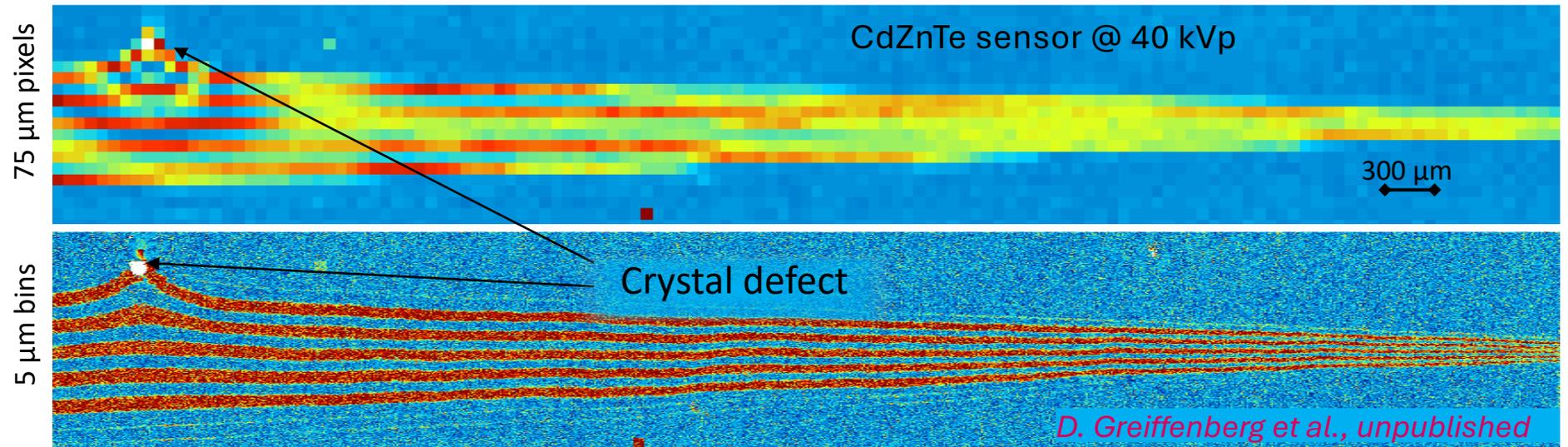
Silicon sensor @ 10keV



GaAs sensor @ 10keV

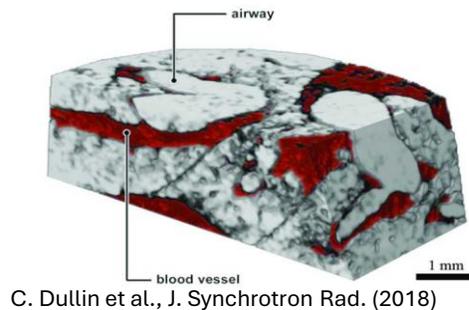


CdZnTe sensor @ 40 kVp



# MÖNCH: high spatial and energy resolution

- Targeting low noise
  - Hyperspectral imaging with super-resolution
  - RIXS combined with LGADs
- Scalability is challenging
  - 800 kpixel on a single chip
  - 1.6 Mpixel module, non negligible gap
- Huge data throughput
  - ~ kHz frame rate, compromise with ROI
  - On-the-fly data reduction is mandatory!

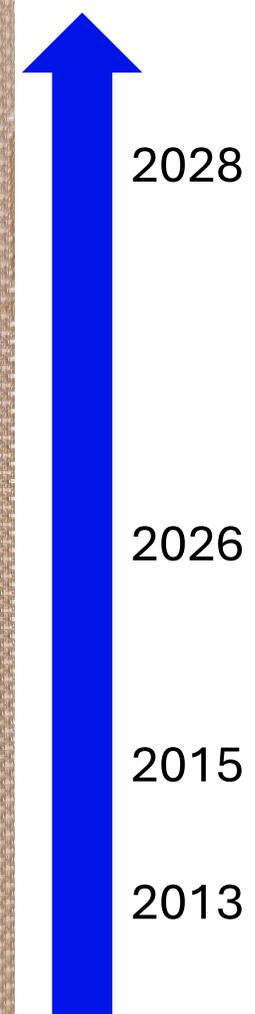


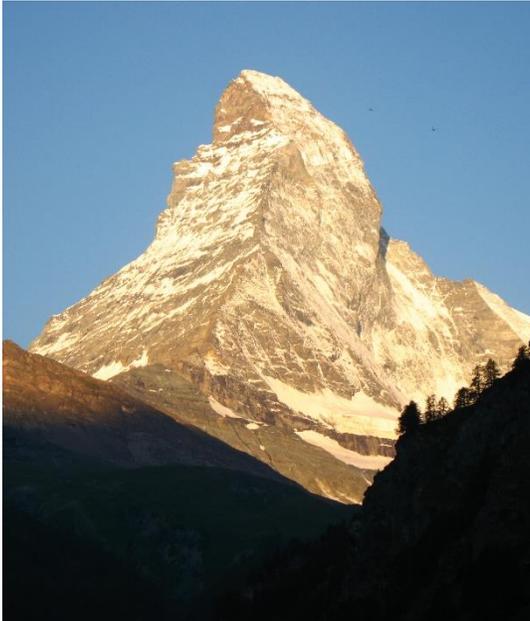
MÖNCH1.0  
modules  
2.56 x 3.84 cm<sup>2</sup>

MÖNCH1.0  
2.56 x 1.92 cm<sup>2</sup>

MÖNCH big  
prototype  
1 x 1 cm<sup>2</sup>

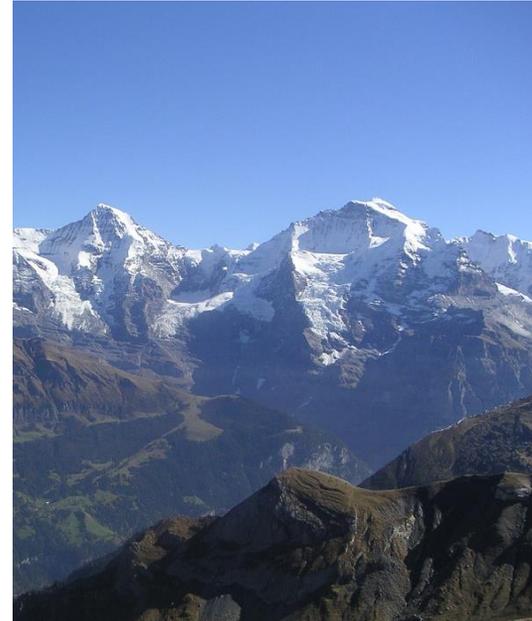
MÖNCH  
prototype  
0.4 x 0.4 cm<sup>2</sup>





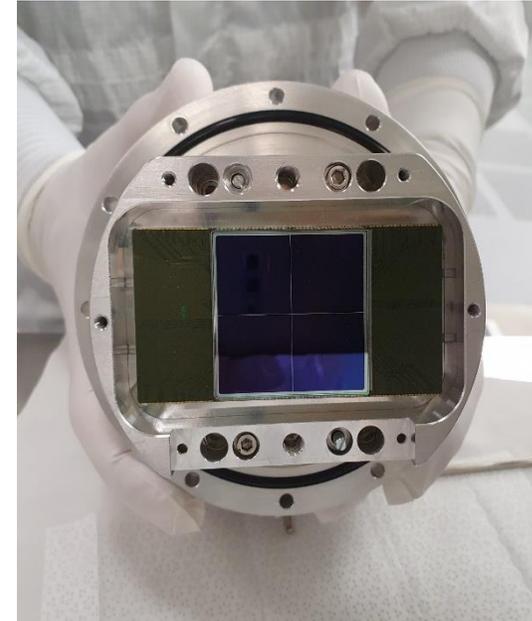
## MATTERHORN single photon counting

- Faster shaping
- Pile-up tracking
- Higher frame rate



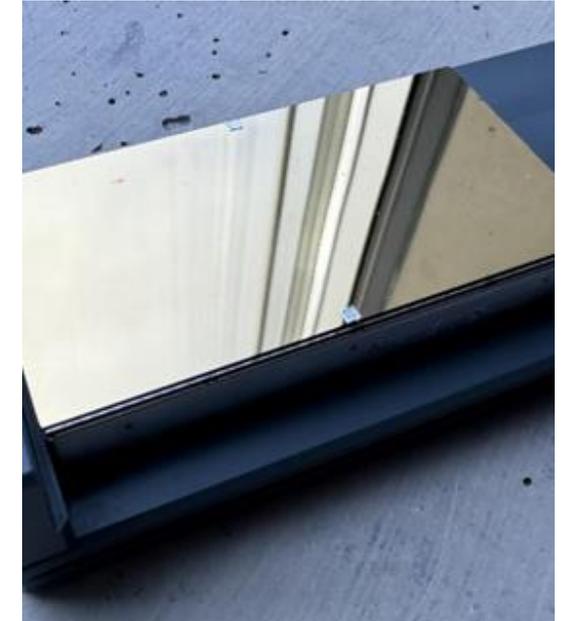
## JUNGFRAU2 and Megapixel MÖNCH

- High frame rate
- High performance data conversion and compression platform



## LGADs for soft X-rays

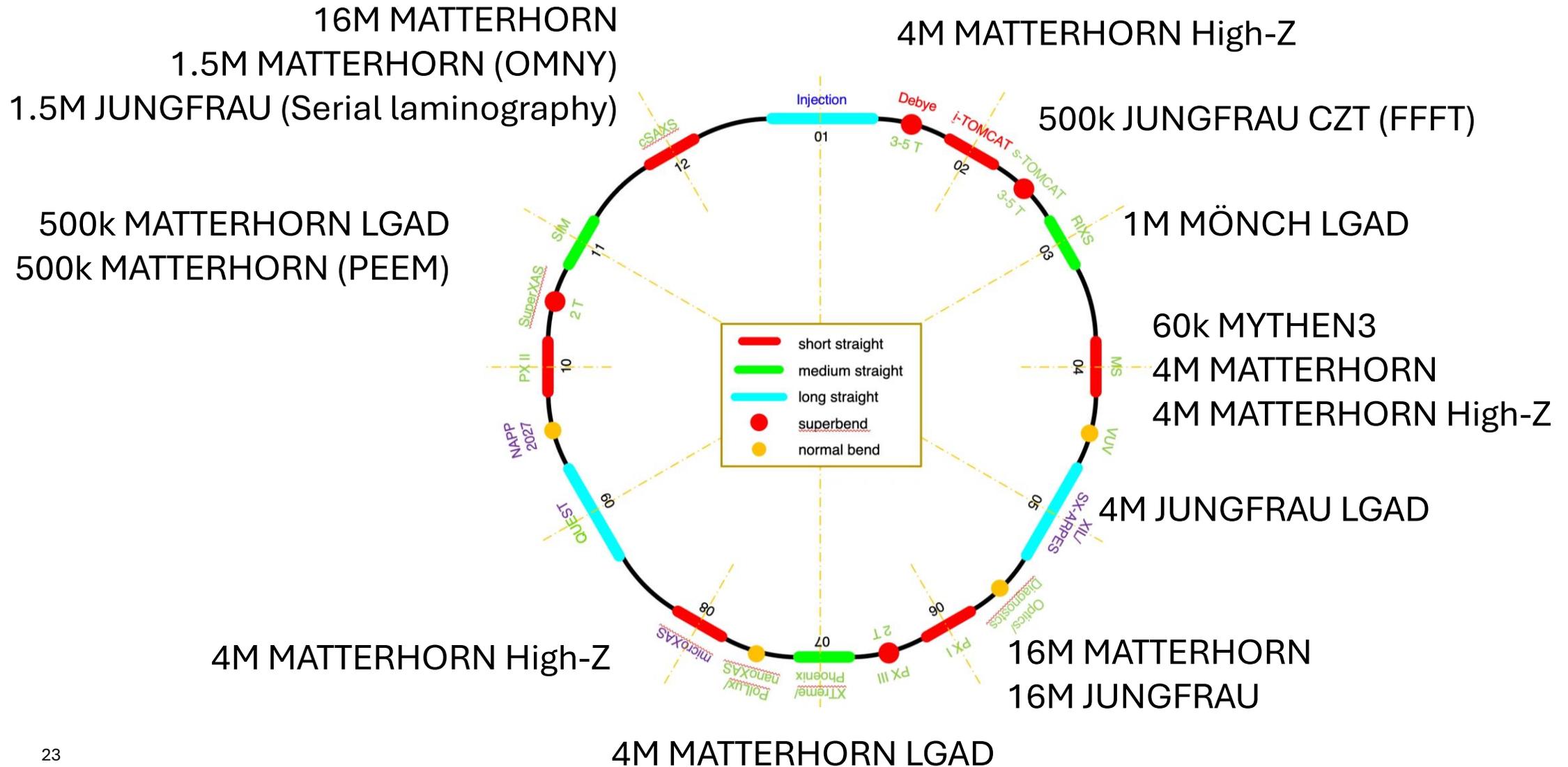
- Soft X-ray single photon counting
- RIXS detector with interpolation

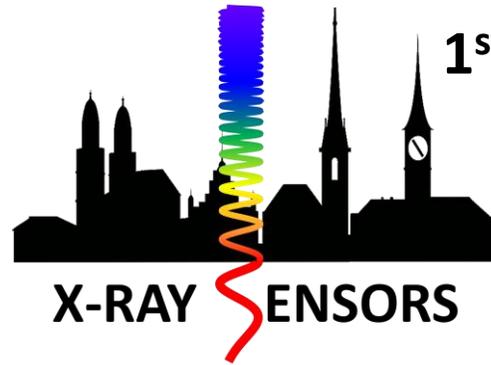


## High-Z sensors for hard X-rays

- Large area single photon counting
- High resolution energy dispersive imaging

# Detector plans for SLS2.0





**1<sup>st</sup> Joint X-ray Sensor Workshop**  
**From Soft to Hard X-rays**  
ETH Zurich (Switzerland)  
12.-16. January 2026



**Bridging Science and Detection**  
**Technology for Soft X-ray Applications**

**Call for abstract is open!**



**High-Z Pixel Array Detectors for Photon**  
**Science**

**Abstract: [hizpad.community@gmail.com](mailto:hizpad.community@gmail.com)**

**Webpage and registration:**  
**<https://indico.psi.ch/e/XRaySensors2026>**

Registration for the two workshops is separate.



# Thank you!



PSI

CZT as a Material for  
Detecting Hard X-rays at  
Synchrotrons and FELs  
Jonathan Mulvey  
Tuesday 9:50

Enhancing the  
Performance of High-Z  
Sensors for Photon  
Science Applications  
Kirsty Paton  
Tuesday 10:10

Characterisation of  
inverse LGADs in the soft  
X-ray energy range  
Shuqi Li  
Tuesday 11:00

A 1M charge integrating  
hybrid pixel detector for  
electron diffraction  
Khalil Ferjaoui  
Wednesday 15:10

Characterization of the  
JUNGFRAU 1.2 readout  
ASIC  
Vadym Kedych  
Thursday 11:00



Dose rate dependence of  
TID Damage in front-end  
electronics for SLS 2.0  
Viveka Gautam  
Monday poster session

High frame rate RIXS  
spectroscopy using a  
JUNGFRAU detector with  
an iLGAD sensor  
Viktoria Hinger  
Wednesday poster session

aare - A Flexible Data  
Analysis Library for  
Hybrid Pixel Detectors  
Erik Fröjdh  
Wednesday poster session

3D Doping Concentration  
Imaging of Silicon  
Sensors Using Backside  
Pulsing  
Xiangyu Xie  
Wednesday poster session

Back: V. Kedych, M. Müller, P. Sieberer, K. Ferjaoui, M. Brückner, E. Fröjdh, J. Heymes, C. Lopez-Cuenca.

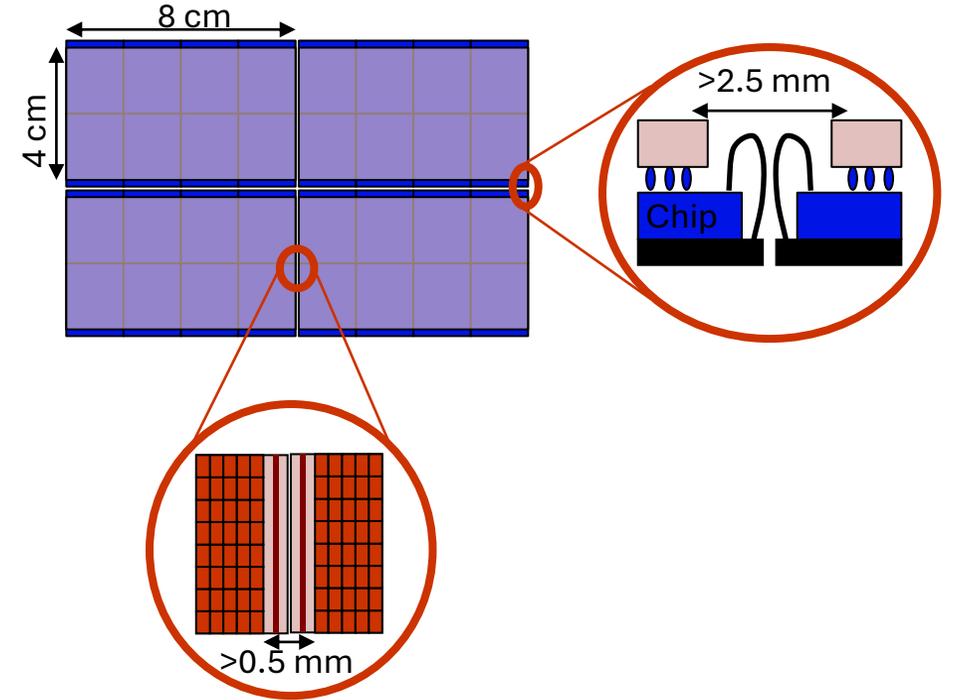
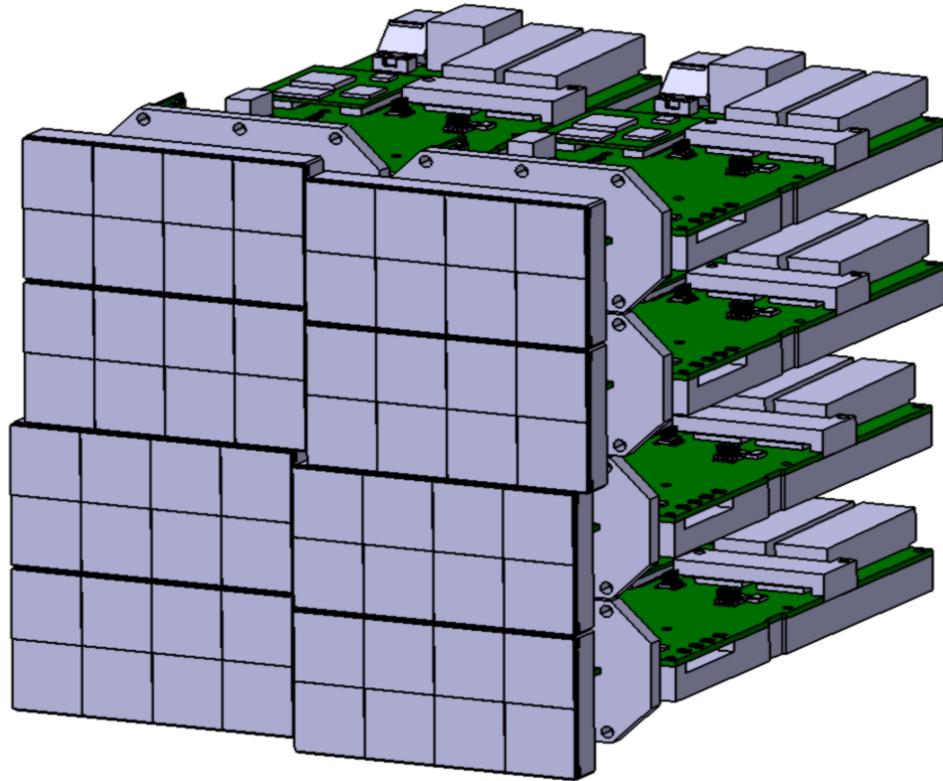
Middle: K. Moustakas, C. Ruder, J. Mulvey, S. Silletta, V. Hinger, A. Mozzanica, M. Carulla, X. Xie,.

Front: R. Dinapoli, A. Bergamaschi, S. Li, D. Thattil, J. Zhang, A. Mazzoleni, V. Gautam, D. Mezza, T. King, B. Schmitt.

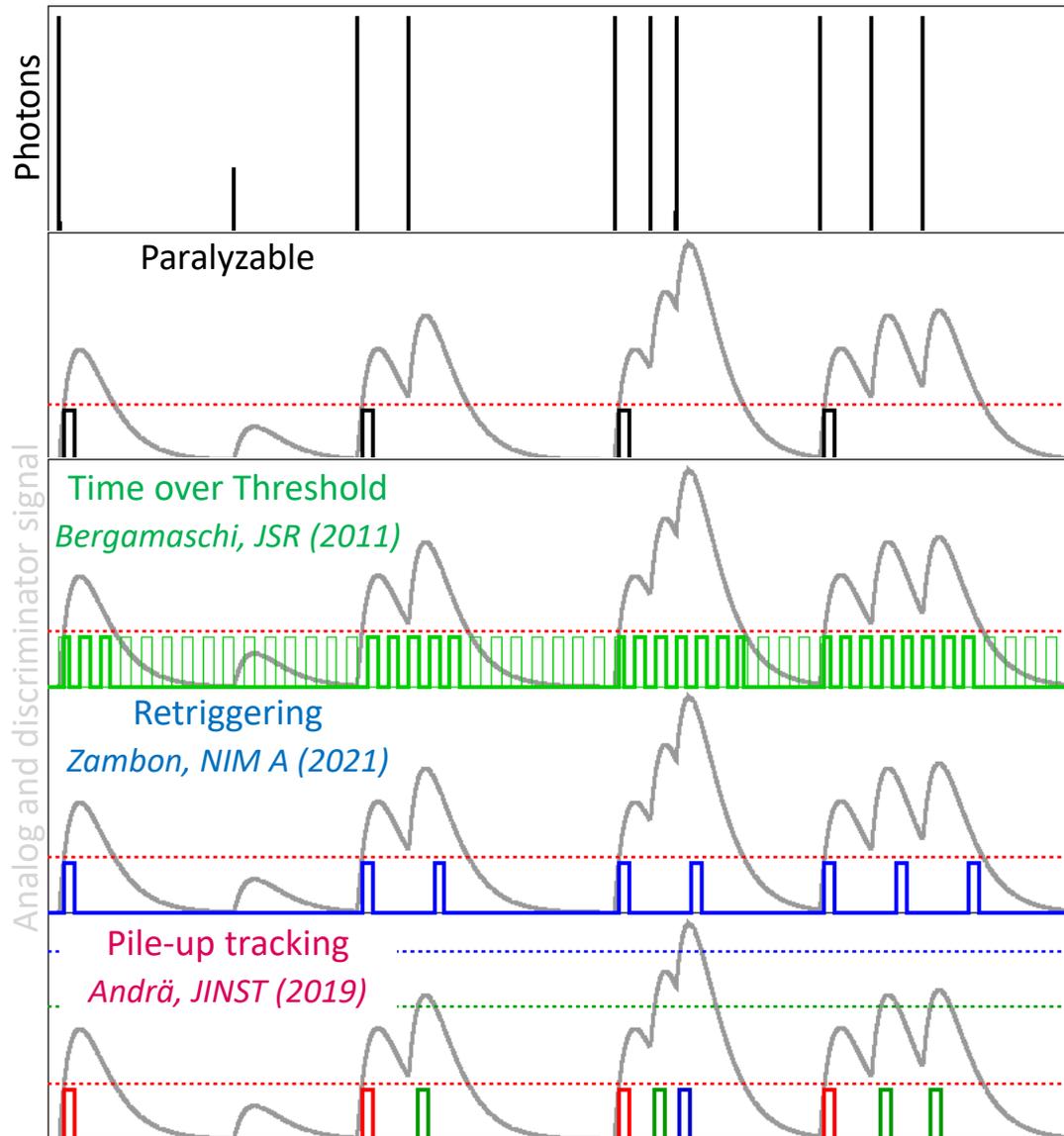
Missing: S. Ebner, D. Greiffenberg, S. Hasanaj, K.A. Paton, C. Posada, A. Haugdal.



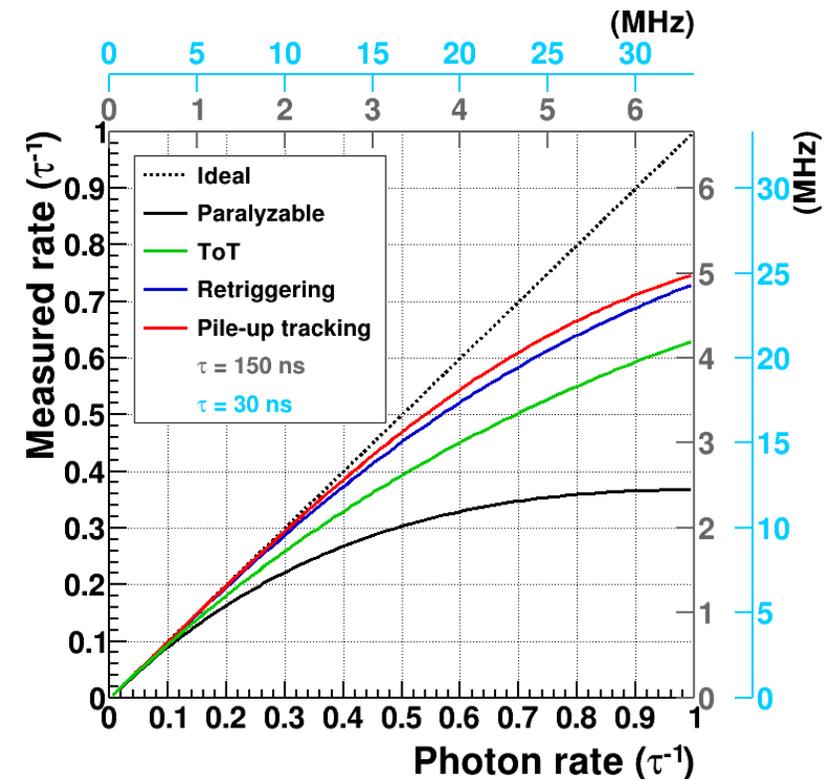
# Large detectors



# New counting modes

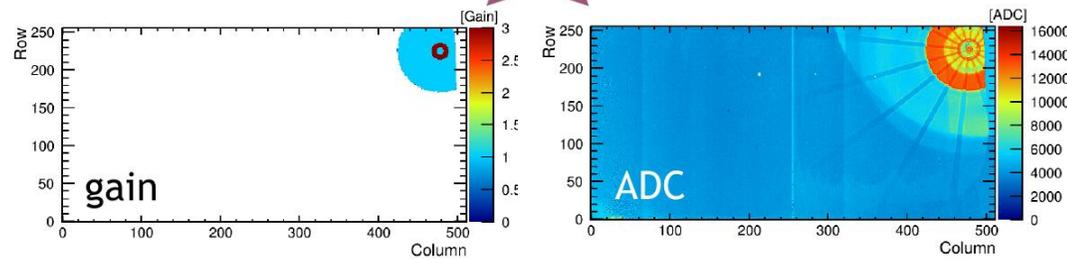
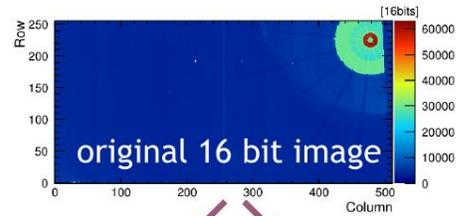


- Reduce shaping time
- Depend on fill pattern
- Challenging calibration

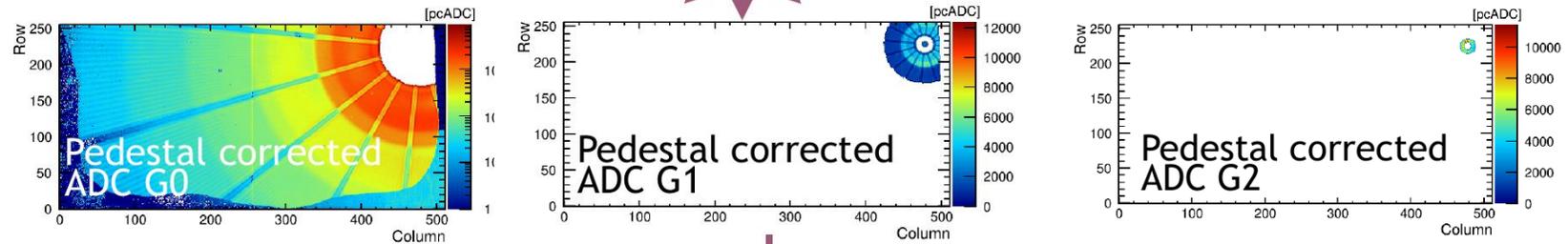


# Calibration into number of photons

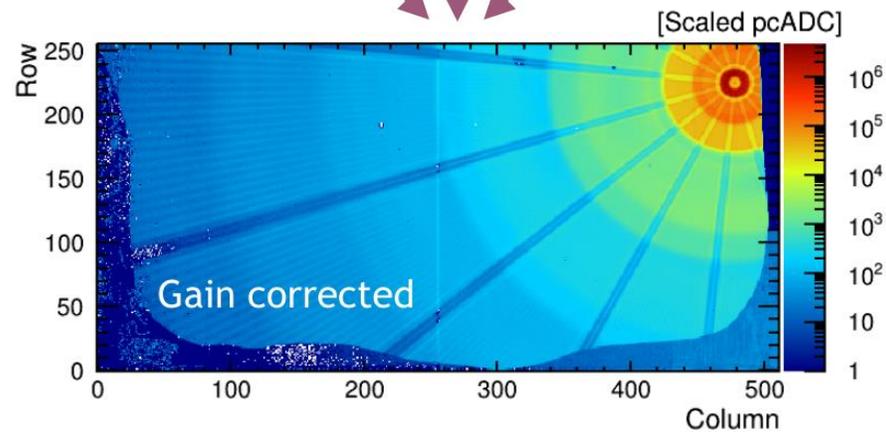
## Bit masking



## Pedestals



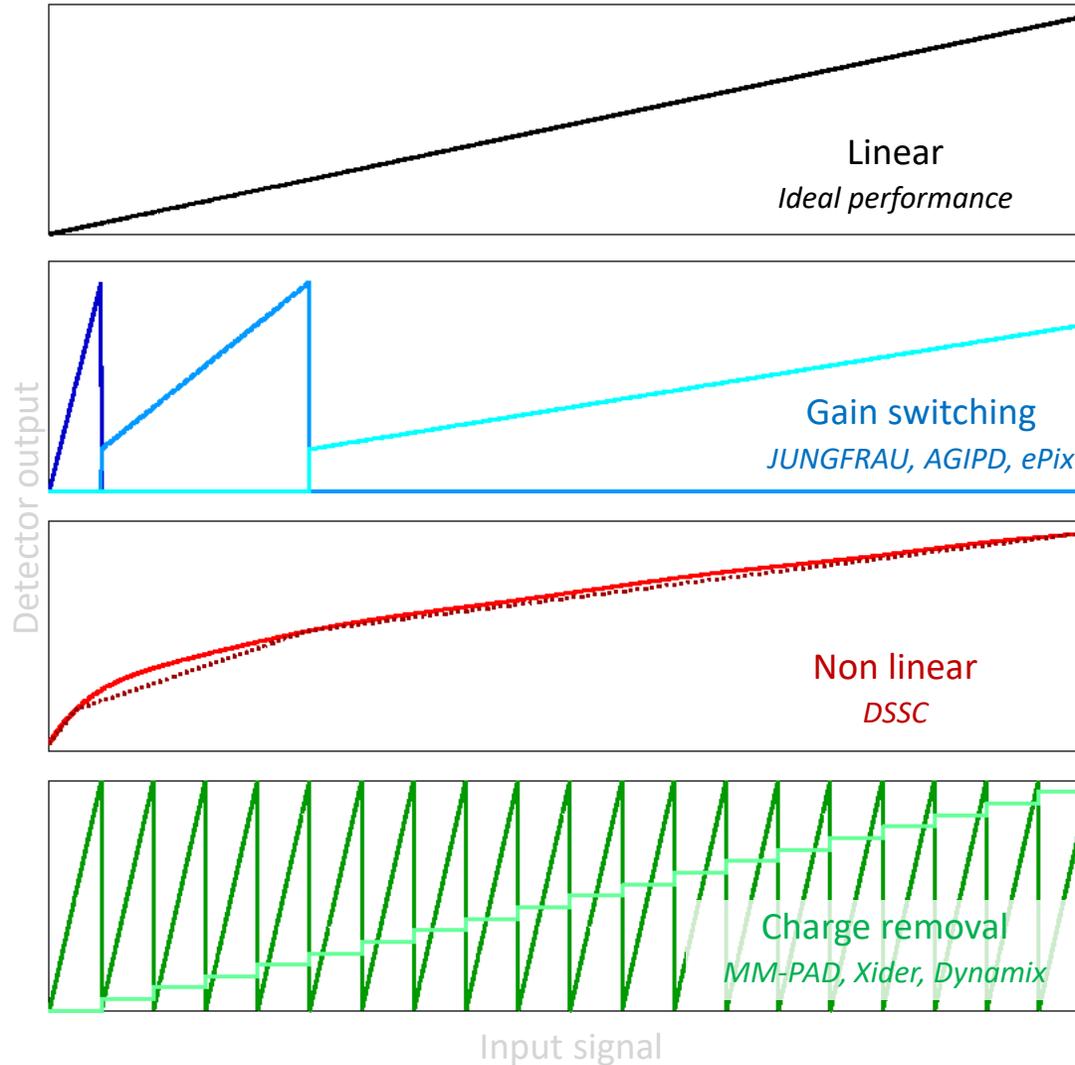
## Gain factors



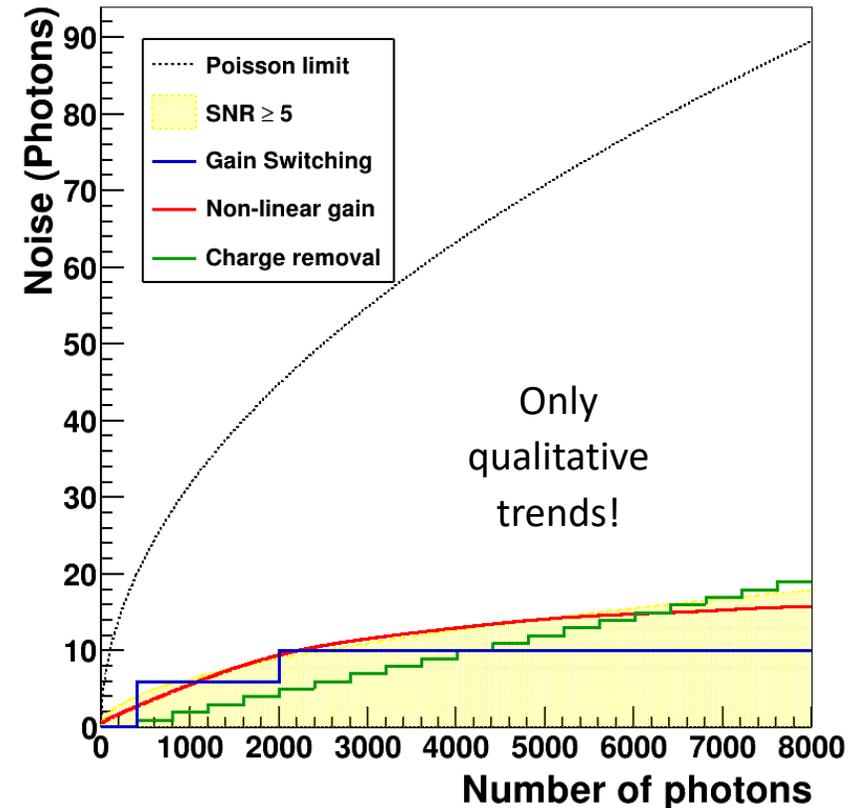
- Fresnel zone plate at XIL beamline, SLS, 92eV
- Etched sensor (no Al), module mounted to flange in high vacuum

S. Redford et al.,  
JOURNAL OF  
INSTRUMENTATION 11,  
C11013 (2016).

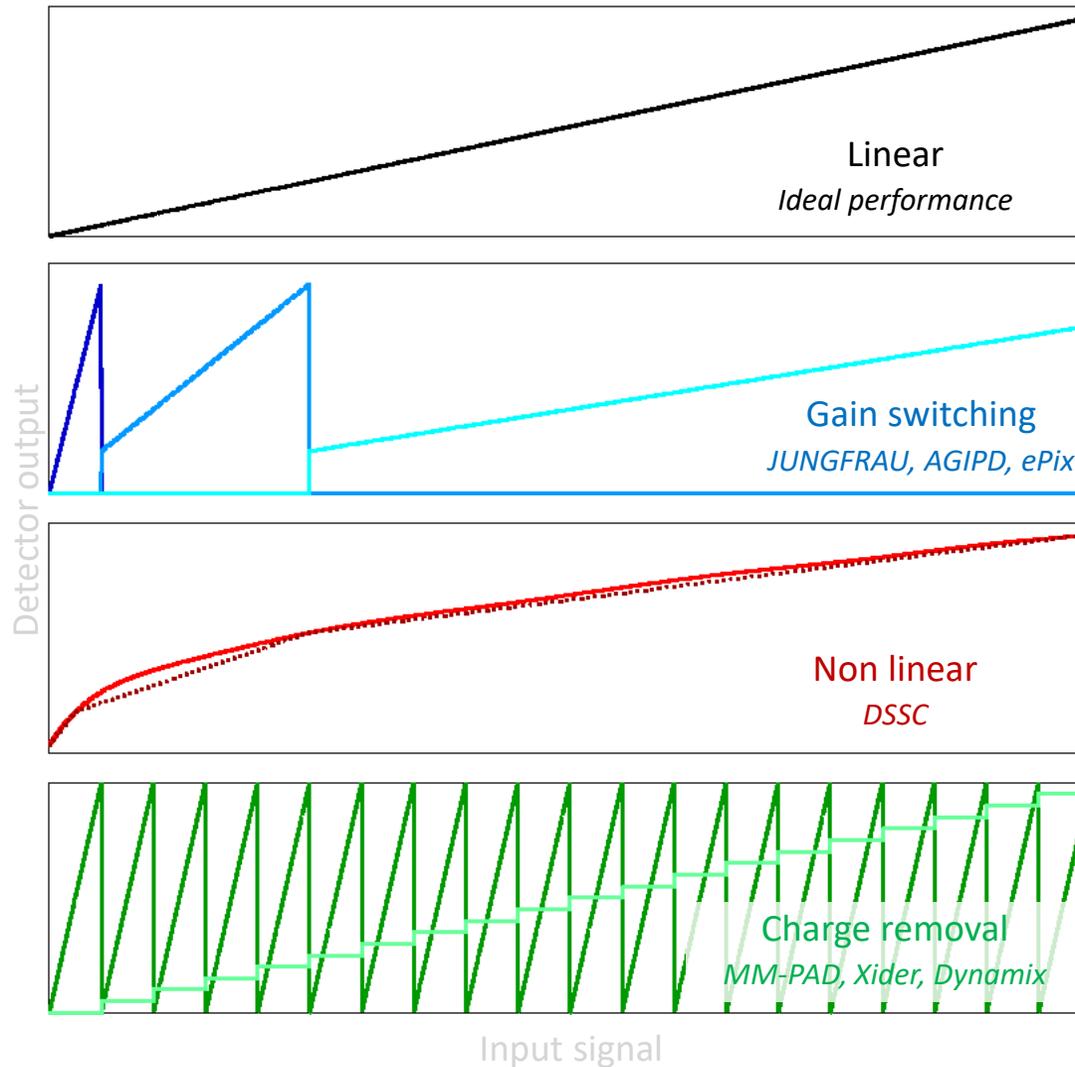
# Adaptive gain methods



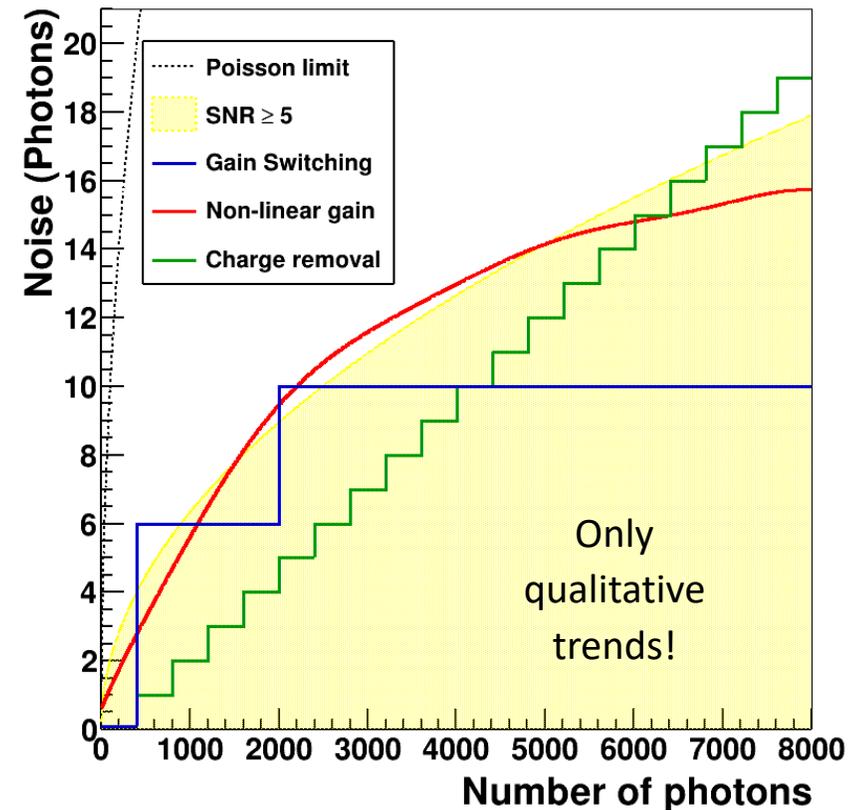
- Noise increases with exposure time
- Fast frame rate extends dynamic range
- Challenging calibration



# Adaptive gain methods

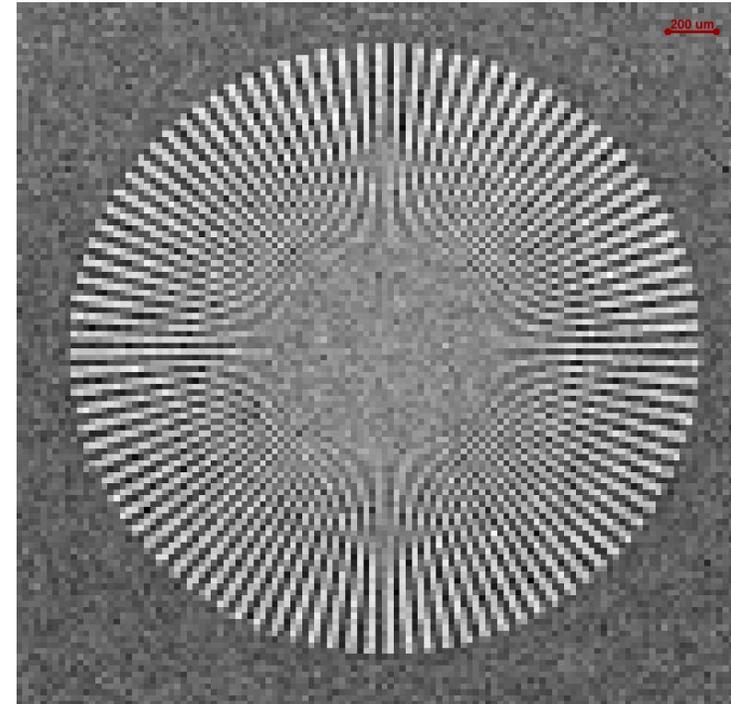
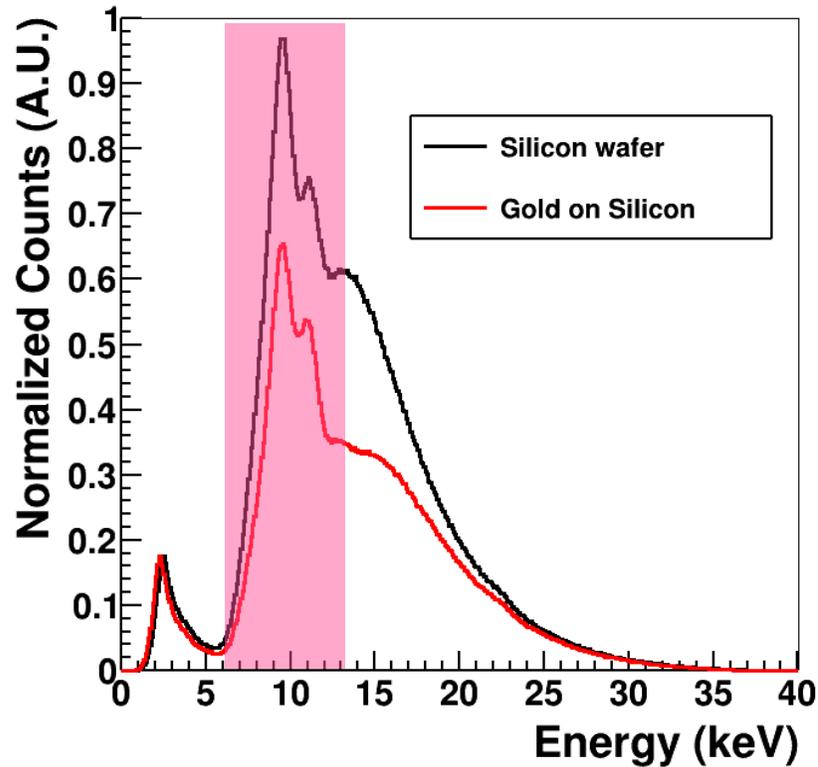


- Noise increases with exposure time
- Fast frame rate extends dynamic range
- Challenging calibration



# Energy resolved imaging at X-ray tubes

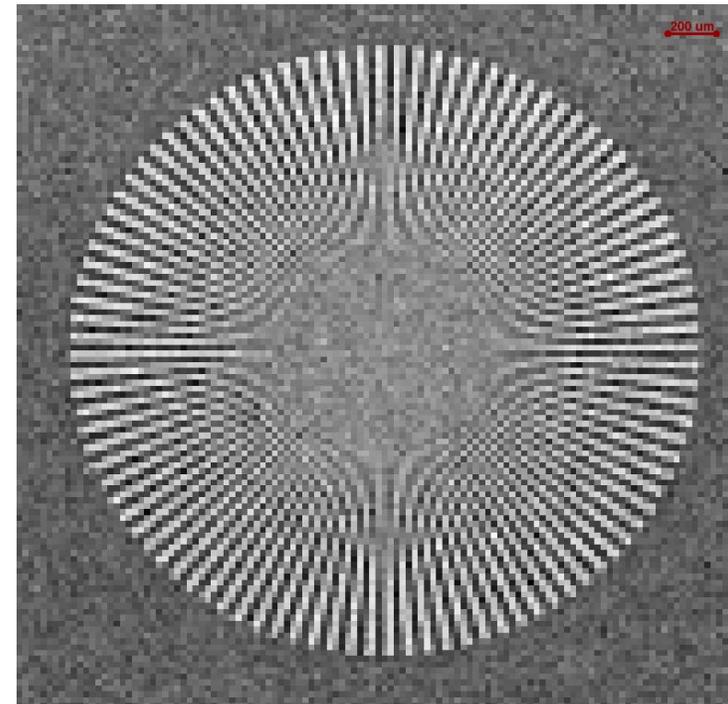
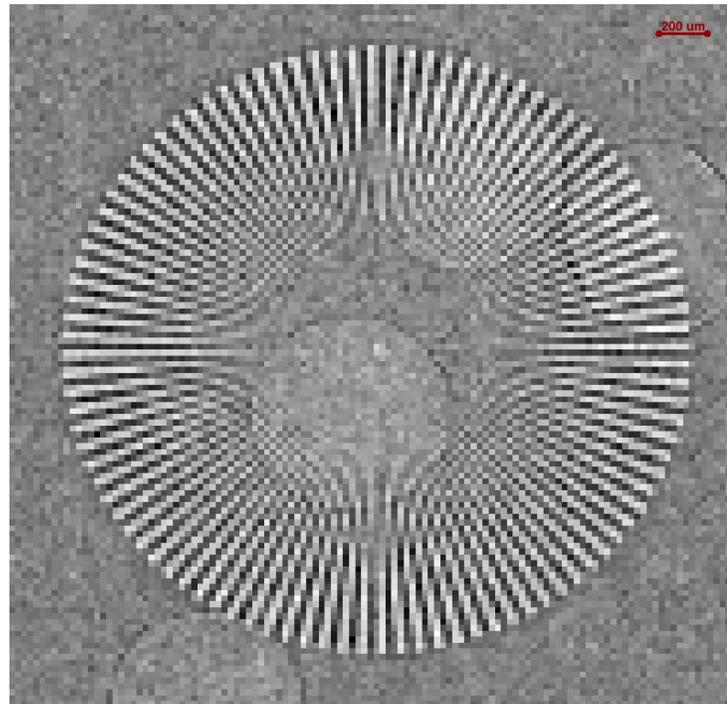
A full spectrum with an energy resolution of about 750 eV FWHM is acquired for each pixel



Siemens Star with spokes 60-0.5  $\mu\text{m}$  gold on silicon with silicon microspheres  
W-anode X-ray tube 40 kV 200  $\mu\text{A}$

# Edge subtraction imaging

Images can be binned in energy  
Below the L-edge gold becomes “transparent” to X-rays

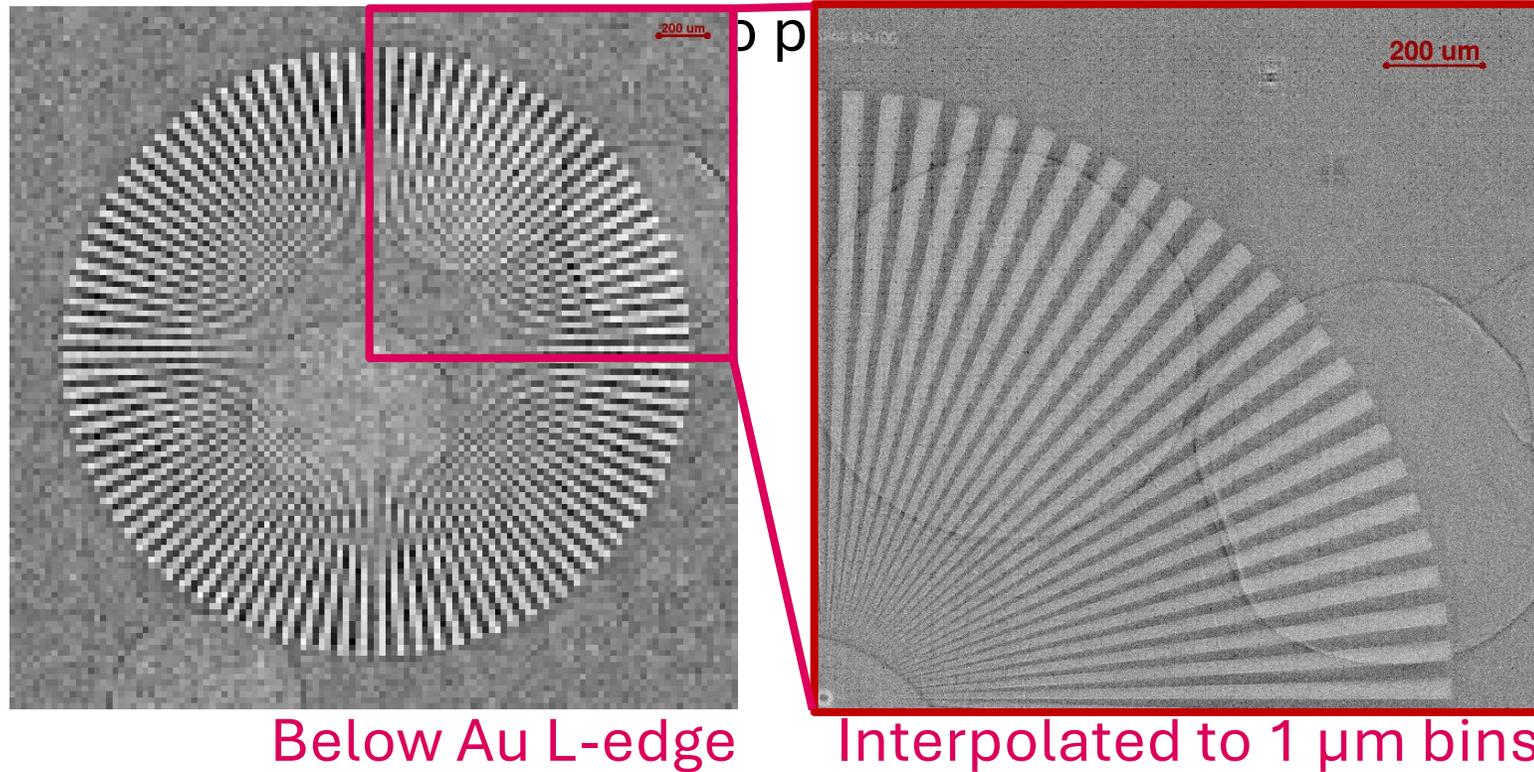


Below Au L-edge

Siemens Star with spokes 60-0.5  $\mu\text{m}$  gold on silicon with silicon microspheres  
W-anode X-ray tube 40 kV 200  $\mu\text{A}$

# High resolution energy resolved imaging

Color imaging works also in combination with interpolation.



Siemens Star with spokes 60-0.5  $\mu\text{m}$  gold on silicon with silicon microspheres  
W-anode X-ray tube 40 kV 200  $\mu\text{A}$