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
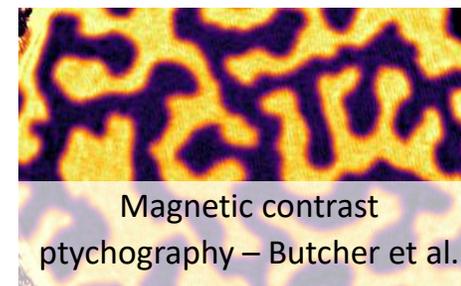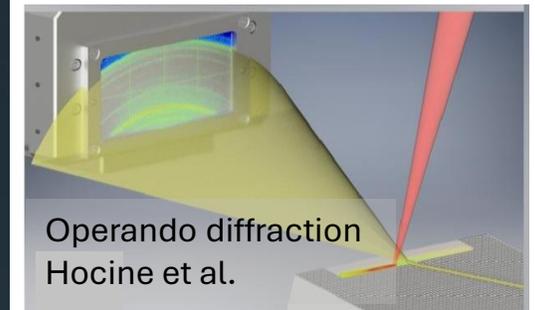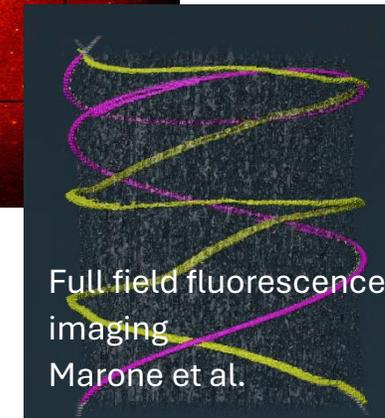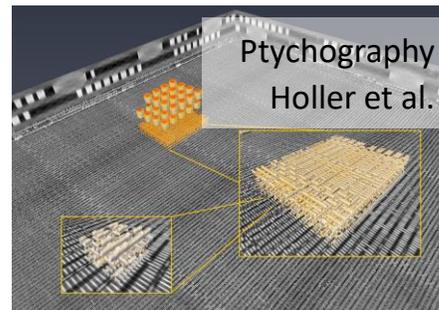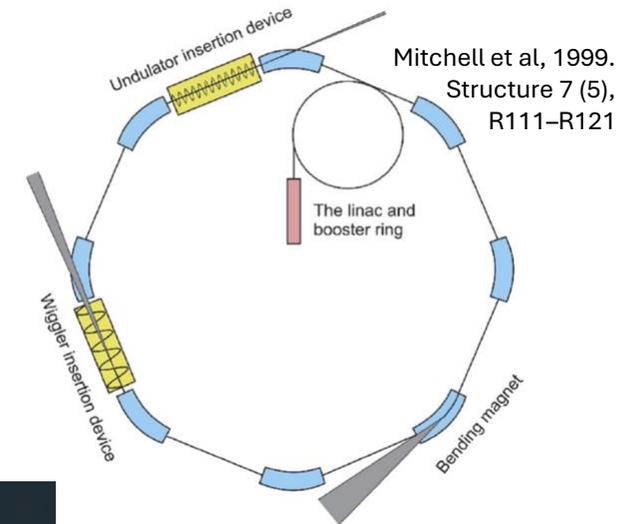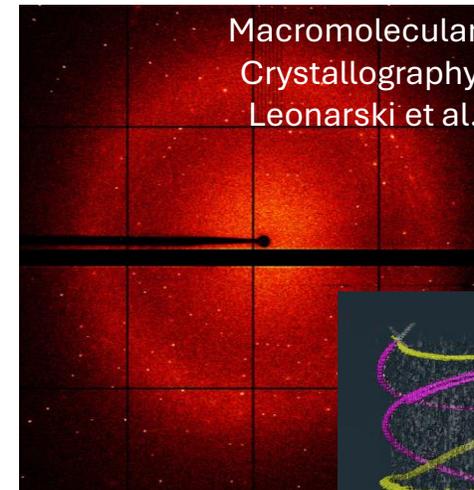
Center for Photon Science, Paul Scherrer Institute (Switzerland)

IWORID20205, Bratislava (SK)
Monday 7th July 2025

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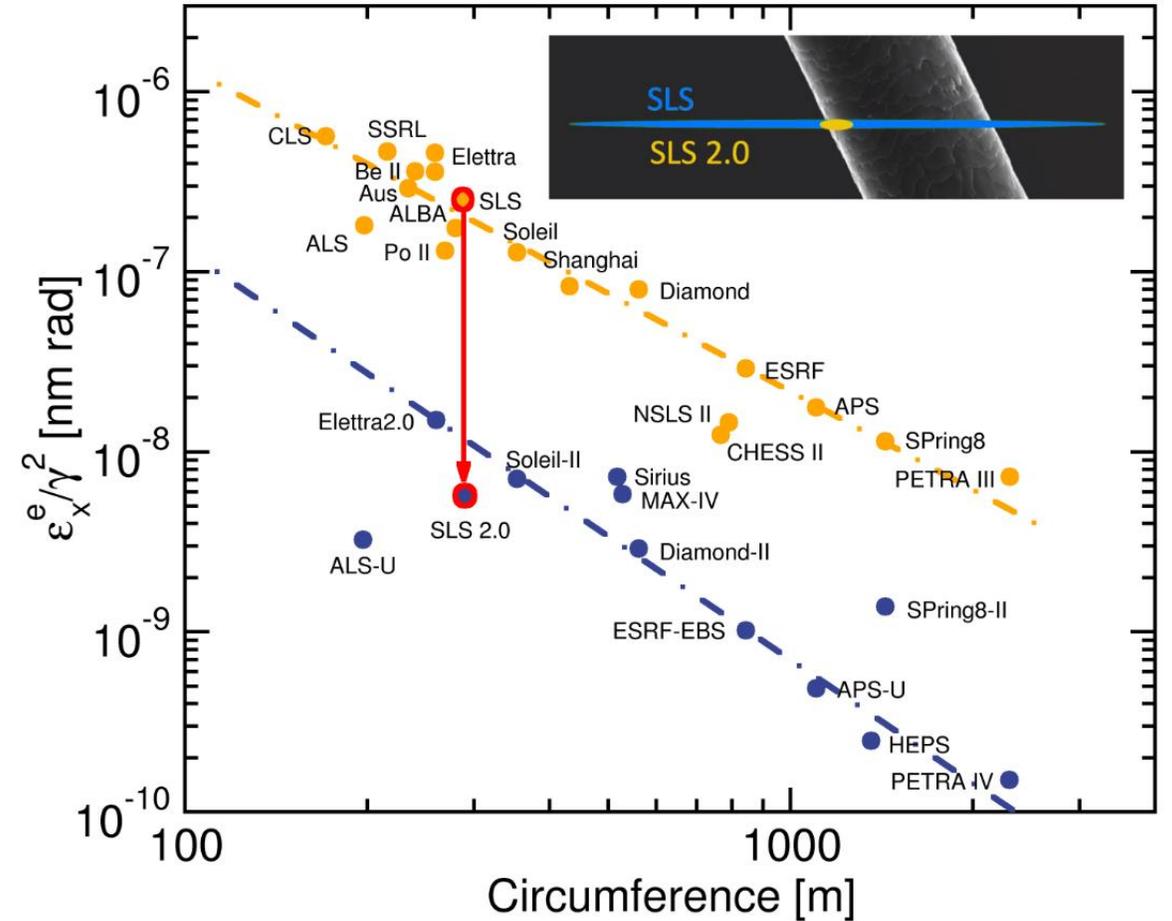
- Synchrotrons are electron accelerators used to generate X-rays
- High X-ray flux
  - Energy selection through monochromator
    - EUV (<100 eV) to hard X-rays (>100keV)
  - High intensity on the detector
  - Photon-starved applications possible
  - High speed
- Coherence
- Polarization
- Pulsed time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

Mitchell et al, 1999. Structure 7 (5), R111–R121

Macromolecular Crystallography Leonarski et al.

Full field fluorescence imaging Marone et al.

Operando diffraction Hocine et al.

Ptychography Holler et al.

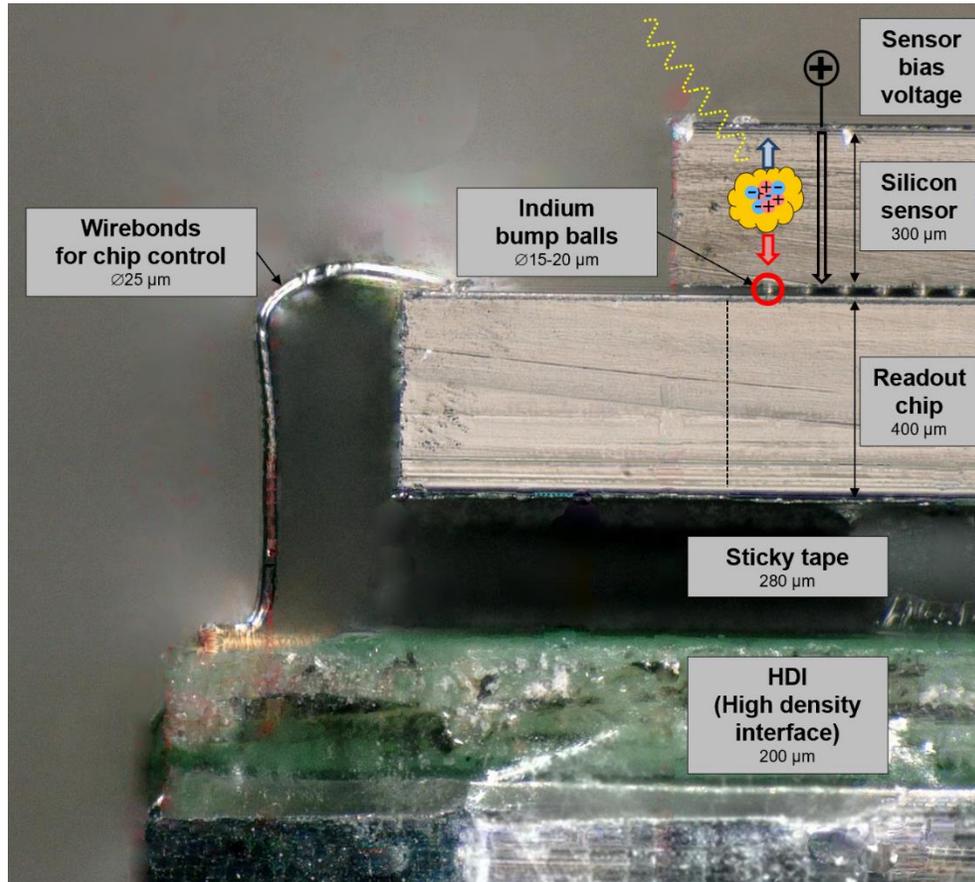Magnetic contrast ptychography – Butcher et al.

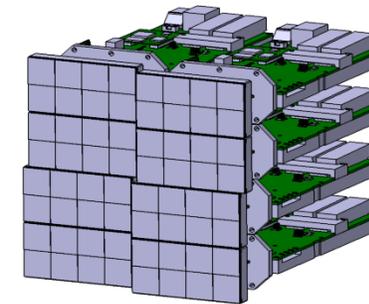# SLS 2.0 – a 4th generation synchrotron

- 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
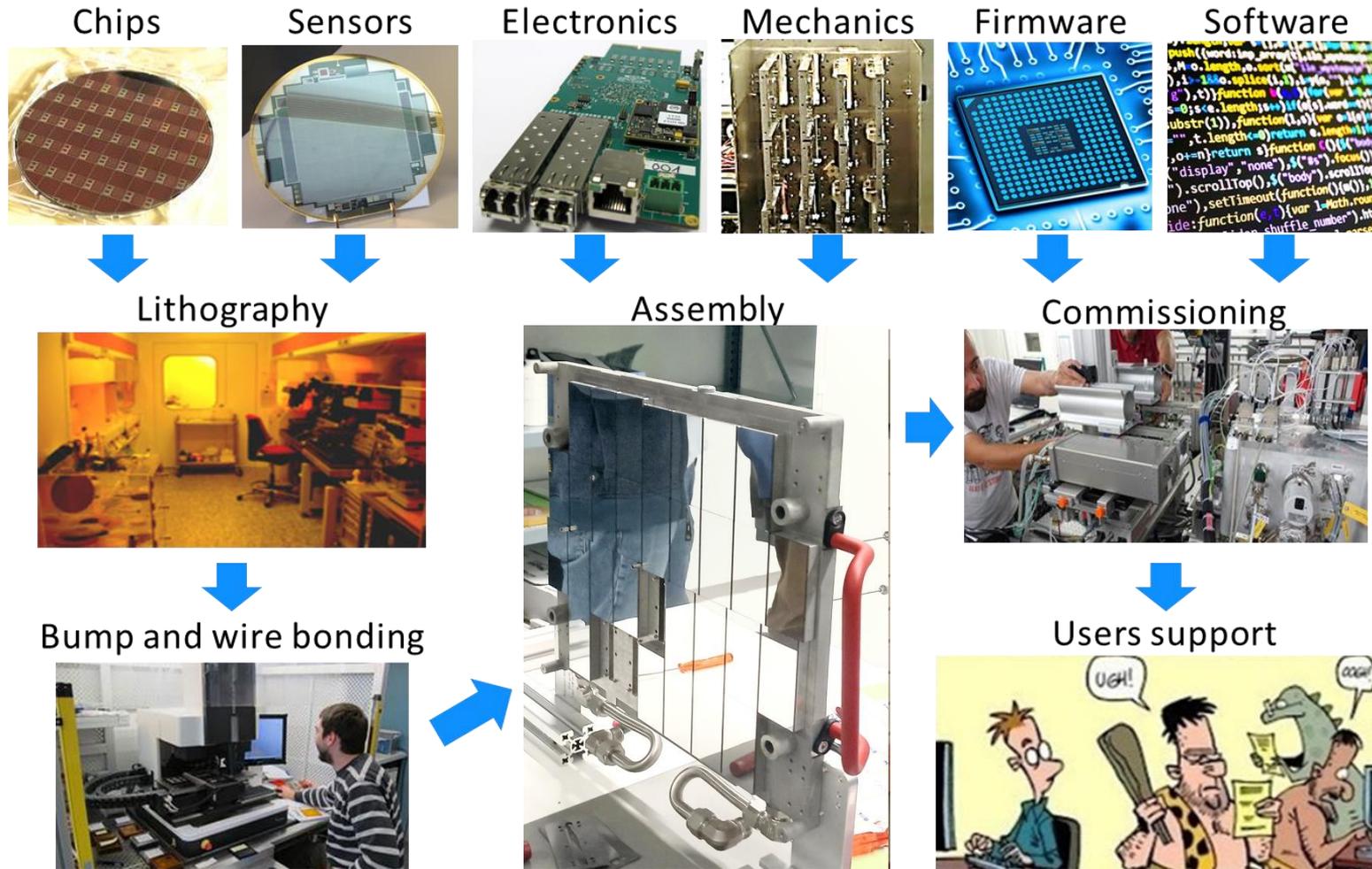
Hybrid detectors
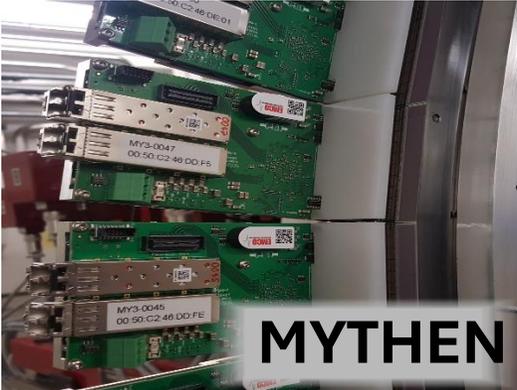

- Semiconductor sensor
  - Direct conversion
- Versatile CMOS readout chip
  - Fast readout
  - Radiation hardness
- Bump bonding
  - Minimum pixel pitch ~ 20 µm
  - Noise due to input capacitance
- Large area by tiling

Everything in-house

Chips   Sensors   Electronics   Mechanics   Firmware   Software

Lithography   Assembly   Commissioning

Bump and wire bonding   Users support

PSI Detector portfolio

	Microstrip 1D	Pixel 2D	
	25/50 µm pitch	75 µm pitch	25 µm pitch
Single photon counting	MYTHEN	EIGER	
Charge integrating	GOTTHARD	JUNGFRAU	MÖNCH 0.3

Readout modes

Photon counting

- ✓ Noiseless, very large dynamic range
- ✓ Stable operation, well established calibration
- ✓ Fluorescence suppression
- ✓ Frame rate scales with counter depth
- ✗ Pile-up ≳1MHz/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
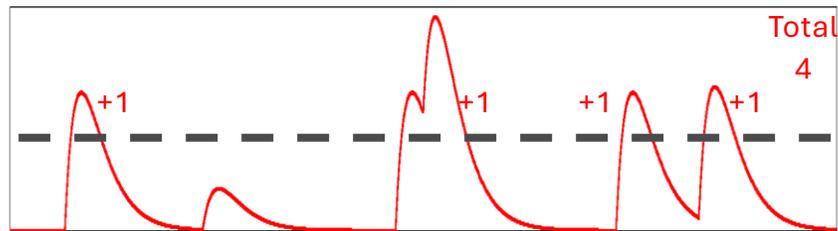
State of the art

Photon counting

- ✓ Noiseless, very large dynamic range
- ✓ Stable operation, well established calibration
- ✓ Fluorescence suppression
- ✓ Frame rate scales with counter depth
- ✗ Pile-up $\gtrsim$1MHz/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**

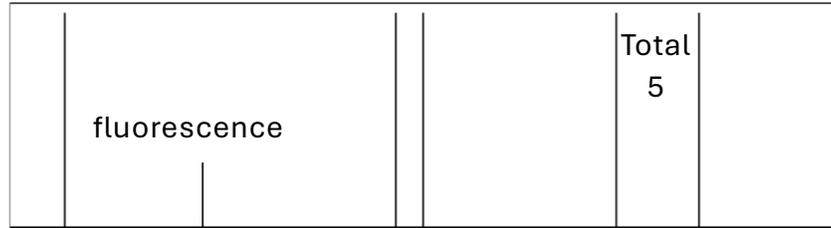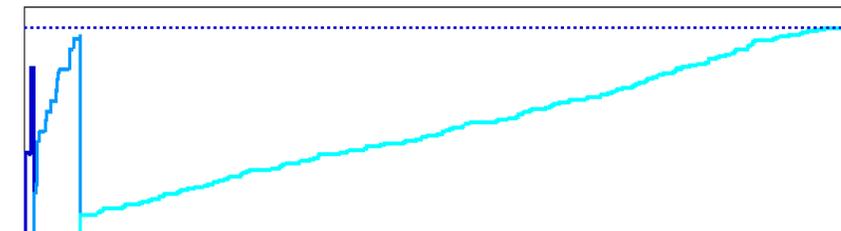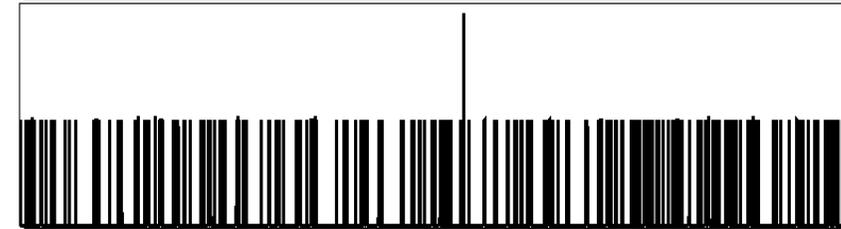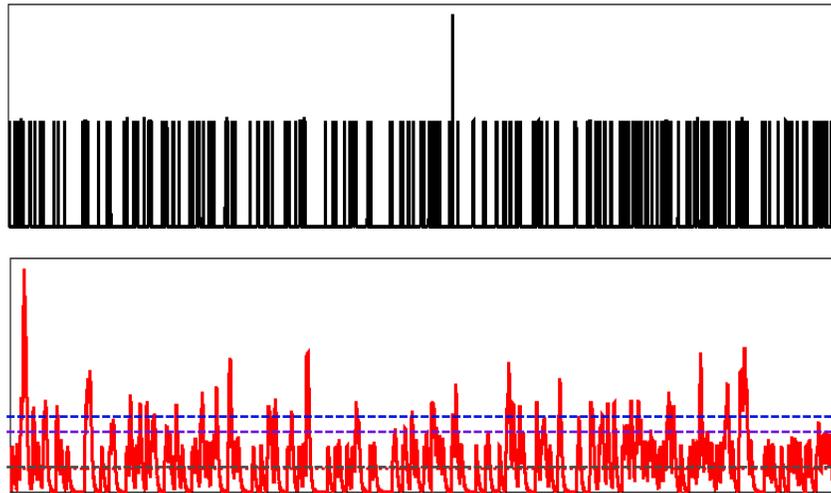# Upgraded light sources: many more photons!

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 ≳1MHz/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 ~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!**

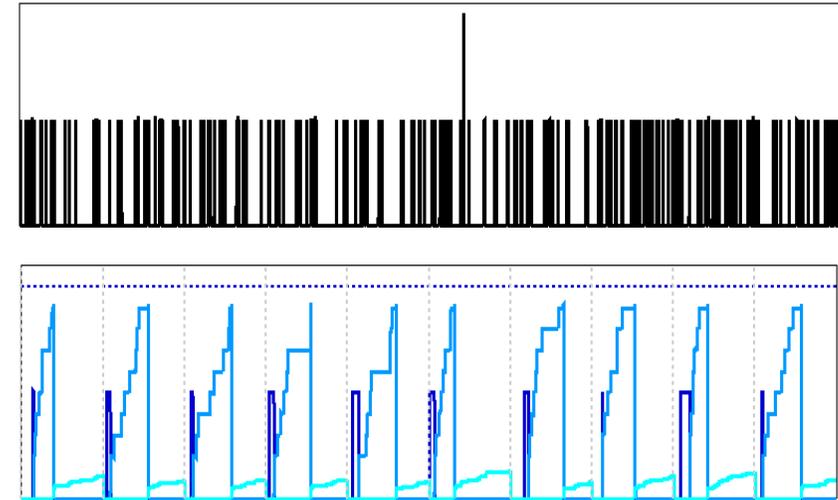# PSI Detector portfolio
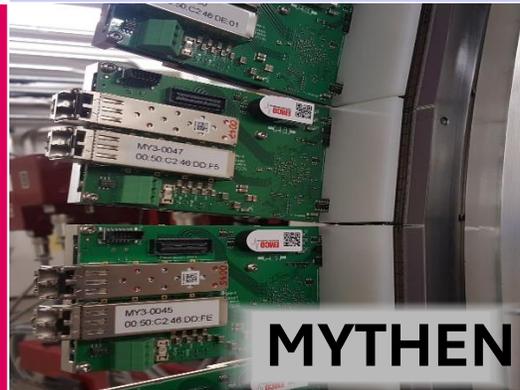
PSI

	Microstrip 1D	Pixel 2D	
	25/50 μm pitch	75 μm pitch	25 μm pitch
Single photon counting	MYTHEN	MATTERHORN	
Charge integrating	GOTTHARD	JUNGFRAU2	MÖNCH1.0

MATTERHORN: the next peak for single photon counting

	EIGER	MATTERHORN
Pixel size	75 x 75 µm^2	
Module size	4 x 8 cm^2	
Thresholds	1	**4**
Min Threshold	~ 3 keV	~ 1.5 keV
Counter depth	12 bit	4 x 16 bit
Max. Frame rate (8 bit)	10 kHz (burst)	**20 kHz (continuous)**
Count rate (90% efficiency)	0.35 Mcounts/pixel/s	**20 Mcounts/pixel/s**
Gating	~ µs	**~ 20 ns**

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

Hocine et al., Materials Today 2020

Aidukas et at., Nature 632, 81–88 (2024).

MATTERHORN prototypes

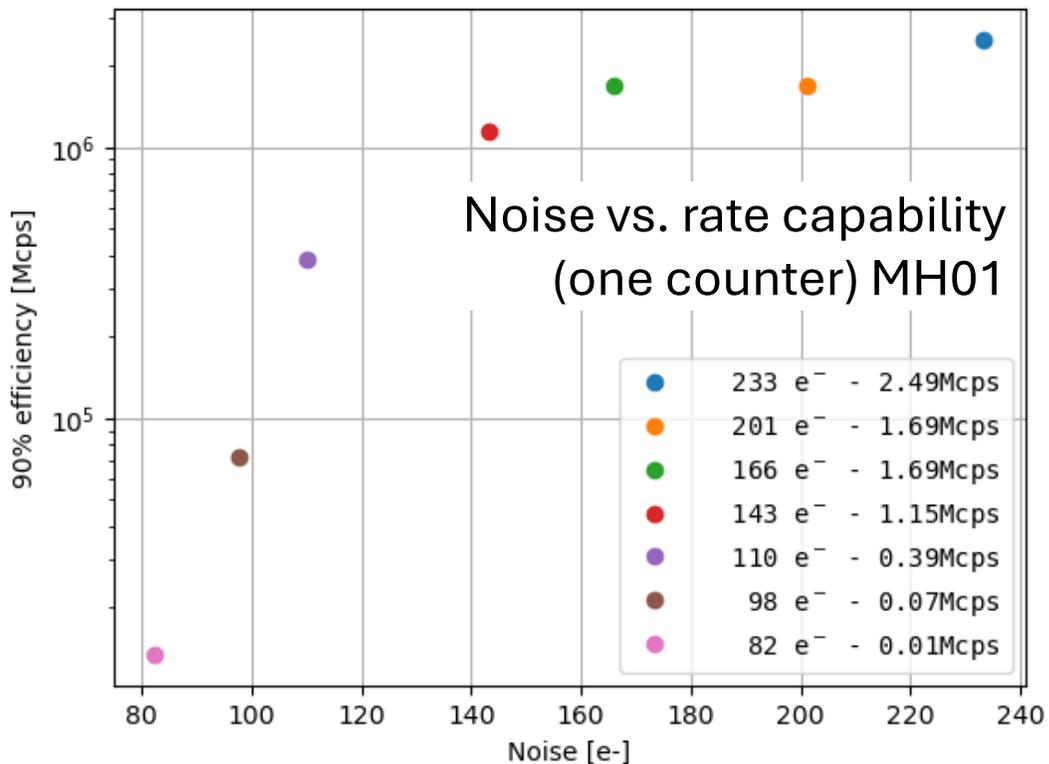| Preliminary prototype results (MH01-MH02)	
Pixels	48 x 48
Min threshold	< 2keV
Noise	80 e- ENC rms
Threshold dispersion	33 eV rms

Noise vs. rate capability (one counter) MH01

Legend:
- 233 e$^-$ - 2.49Mcps
- 201 e$^-$ - 1.69Mcps
- 166 e$^-$ - 1.69Mcps
- 143 e$^-$ - 1.15Mcps
- 110 e$^-$ - 0.39Mcps
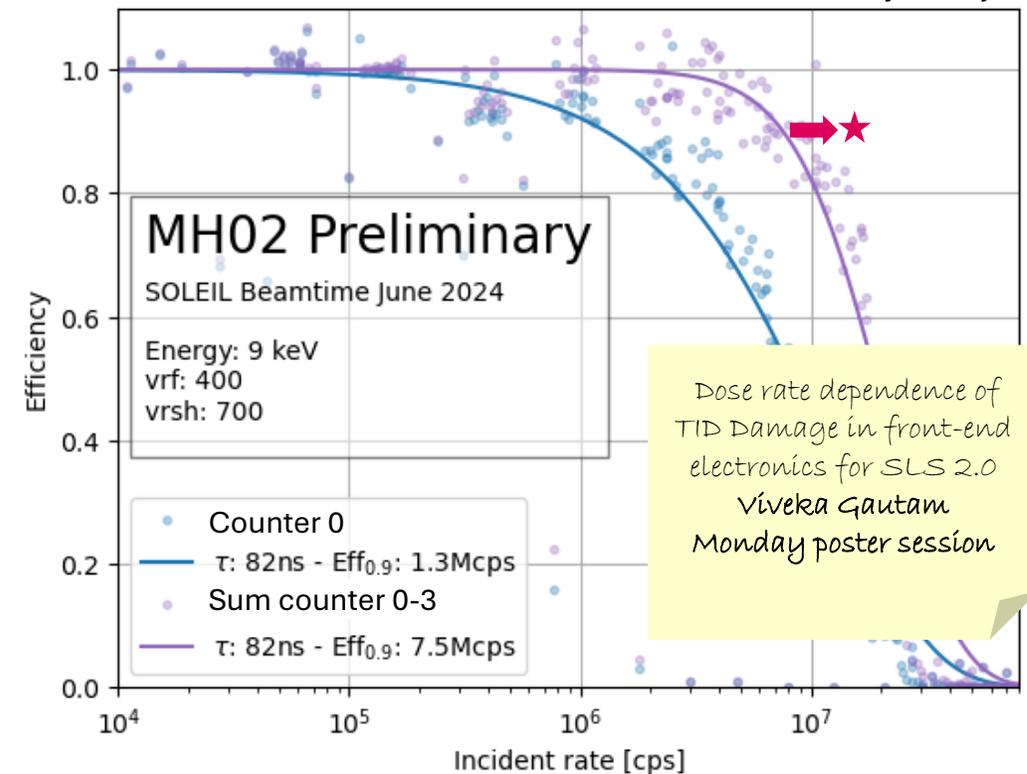- 98 e$^-$ - 0.07Mcps
- 82 e$^-$ - 0.01Mcps

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

MH02 Preliminary

SOLEIL Beamtime June 2024

Energy: 9 keV
vrf: 400
vrsh: 700

- Counter 0
- τ: 82ns - Eff$_{0.9}$: 1.3Mcps
- Sum counter 0-3
- τ: 82ns - Eff$_{0.9}$: 7.5Mcps

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

025

JUNGFRAU2: faster, even higher intensities

PSI

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

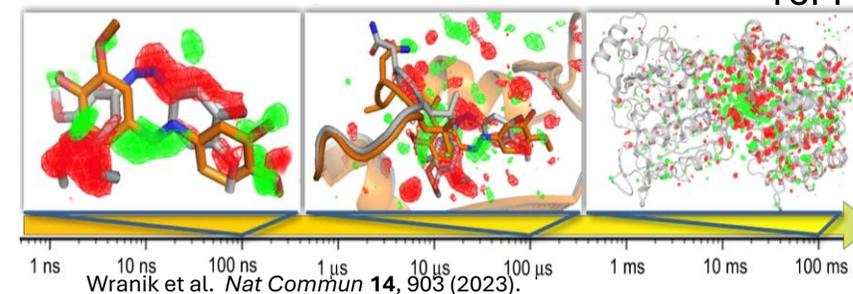***** with single photon resolution, standard silicon

A 1M charge integrating hybrid pixel detector for electron diffraction
Khalil Ferjaoui
Monday 15:00

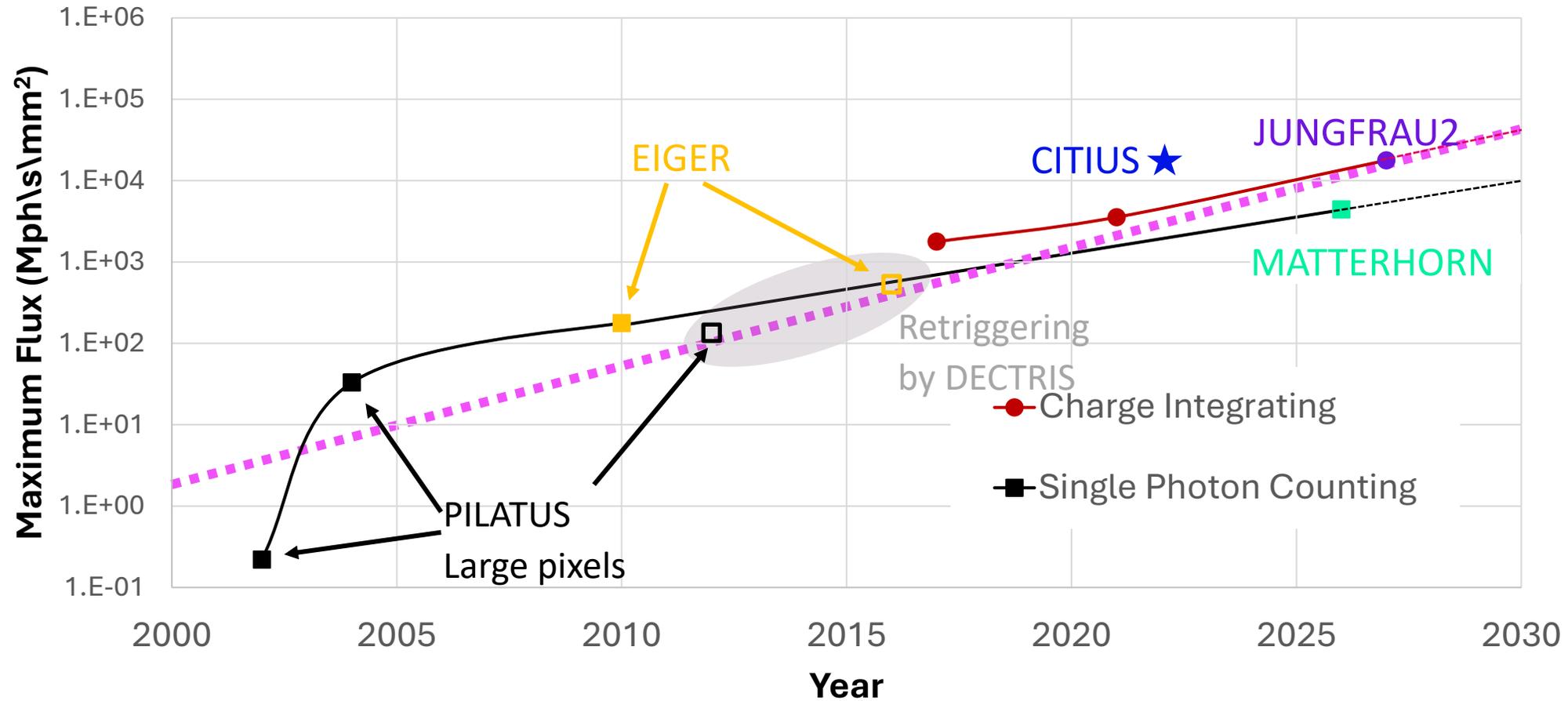*Characterization of the JUNGFRAU 1.2 readout ASIC*
Vadym Kedych
Thursday 11:00

At Synchrotrons full duty cycle 2 kHz ➡ 10 kHz

- 2 GB/s/module ➡ 10 GB/s/module
- 190 TB/day/module ➡ 1 PB/day/module
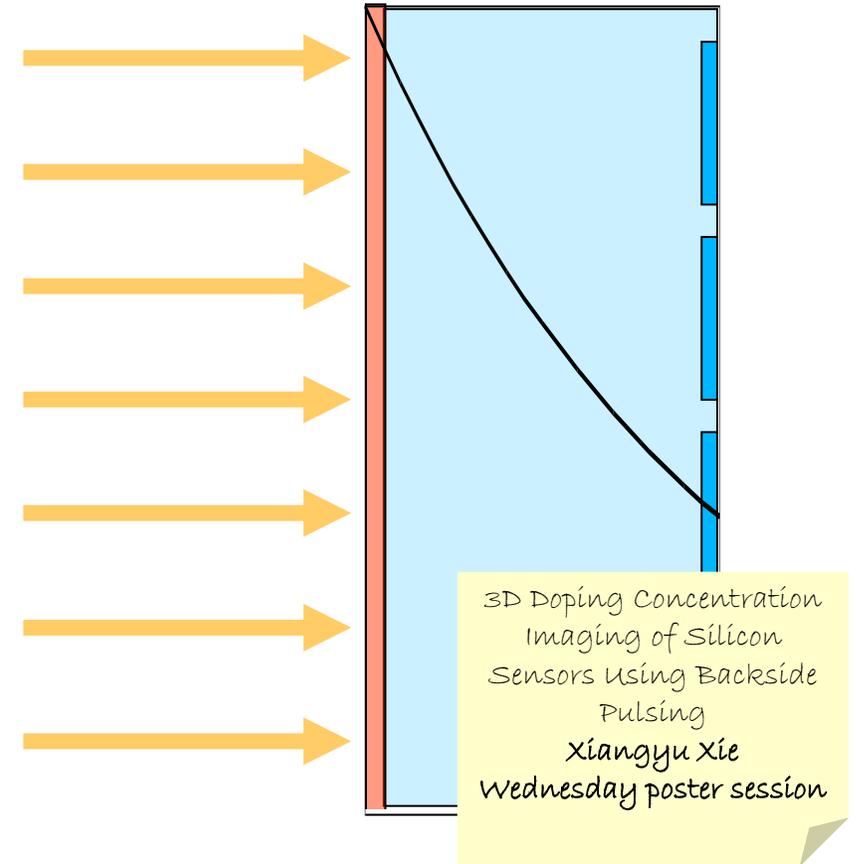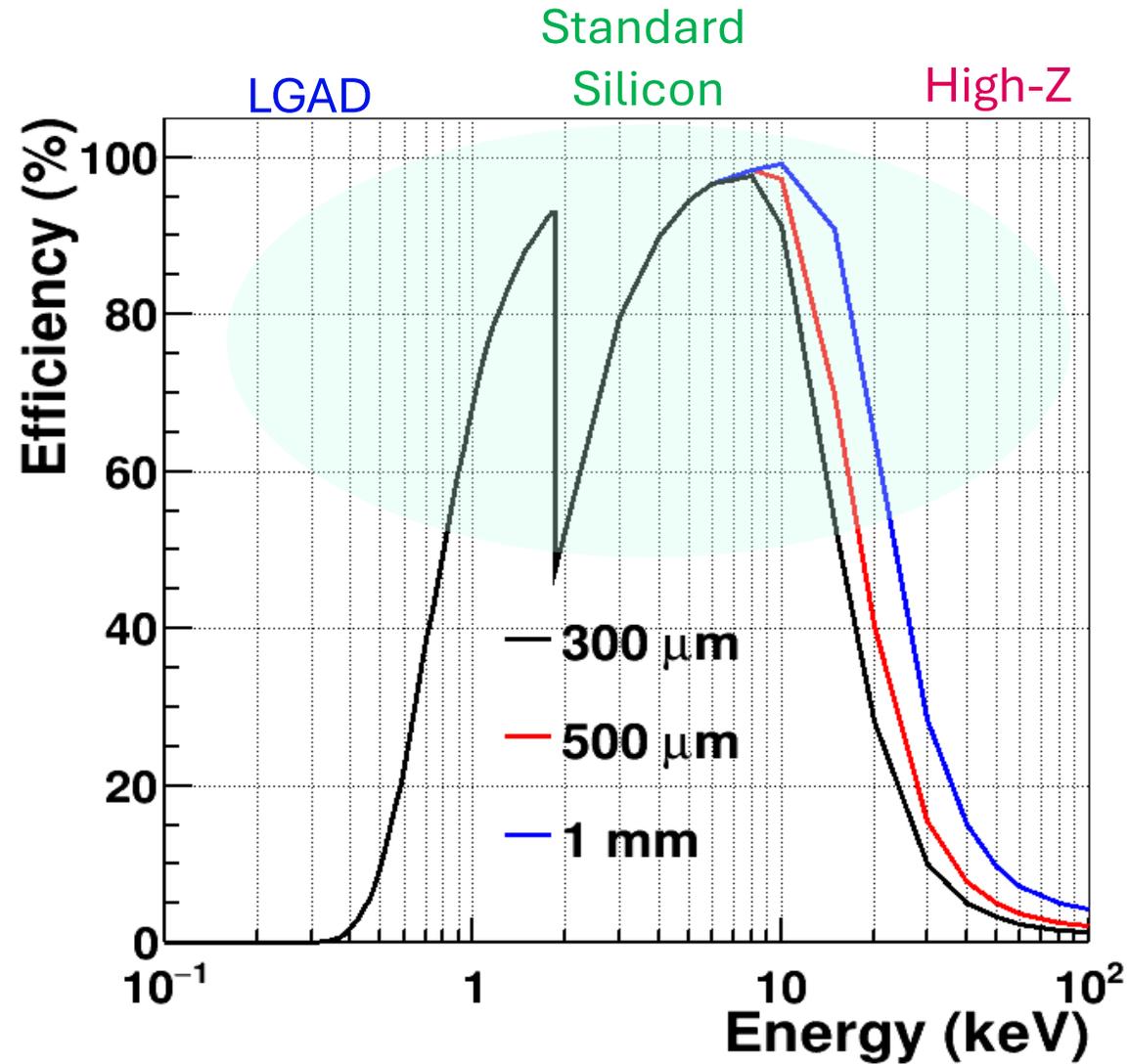- 5.3 PB/day for a 16M detector ➡ 25 PB/day for a 16M detector

Wranik et al. *Nat Commun* **14**, 903 (2023).

Maximum detectable intensities

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

★ Hatsui, PIXEL 2022, full duty cycle, burst mode 17.4 kHz

Silicon quantum efficiency

15

High-Z sensors for hard X-rays

Soft X-rays detection

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

Courtesy J. Zhang

250 eV

Carulla, *et al.*
Sensors. 2024; 24(3): 942.
& unpublished results
Hard X-ray sensors
Optimized implant
Passivated surface
Thin passivation (2025)

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

Shallow absorption of soft X-rays

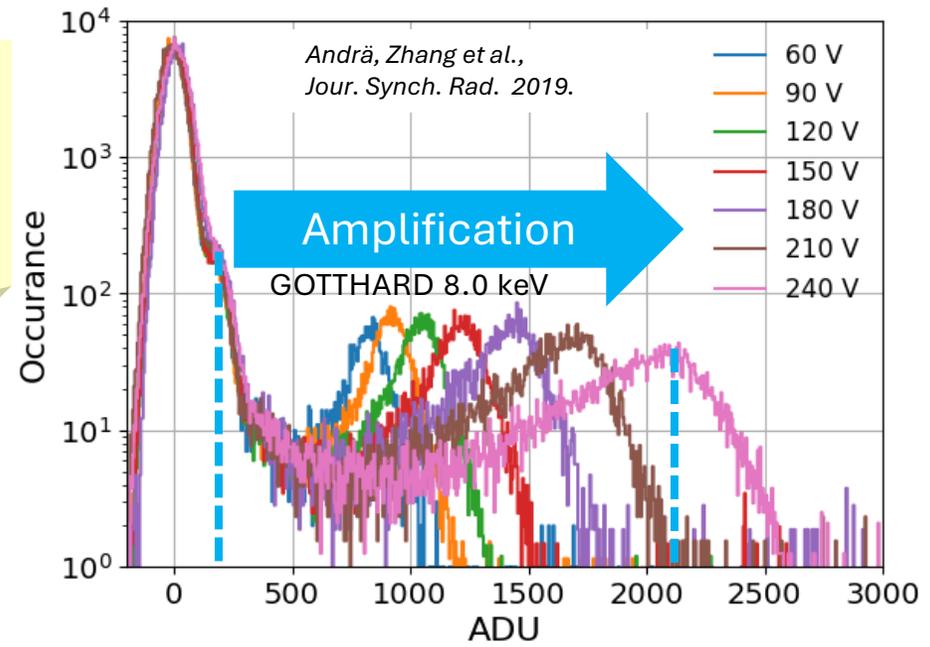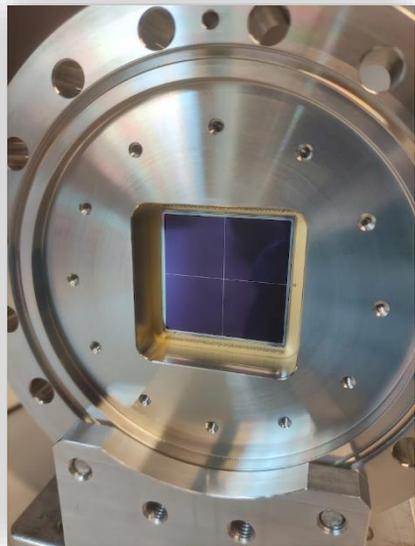- Thin entrance window technology with improved do[ping]
  and thin passivation

Charge per photon comparable to electronic noise

- Exploit internal multiplication of LGADs to increase SNR

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

60 V
90 V
120 V
150 V
180 V
210 V
240 V

Amplification

GOTTHARD 8.0 keV

Single photon counting below 1 keV

900 eV

4 × 4 cm² 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.

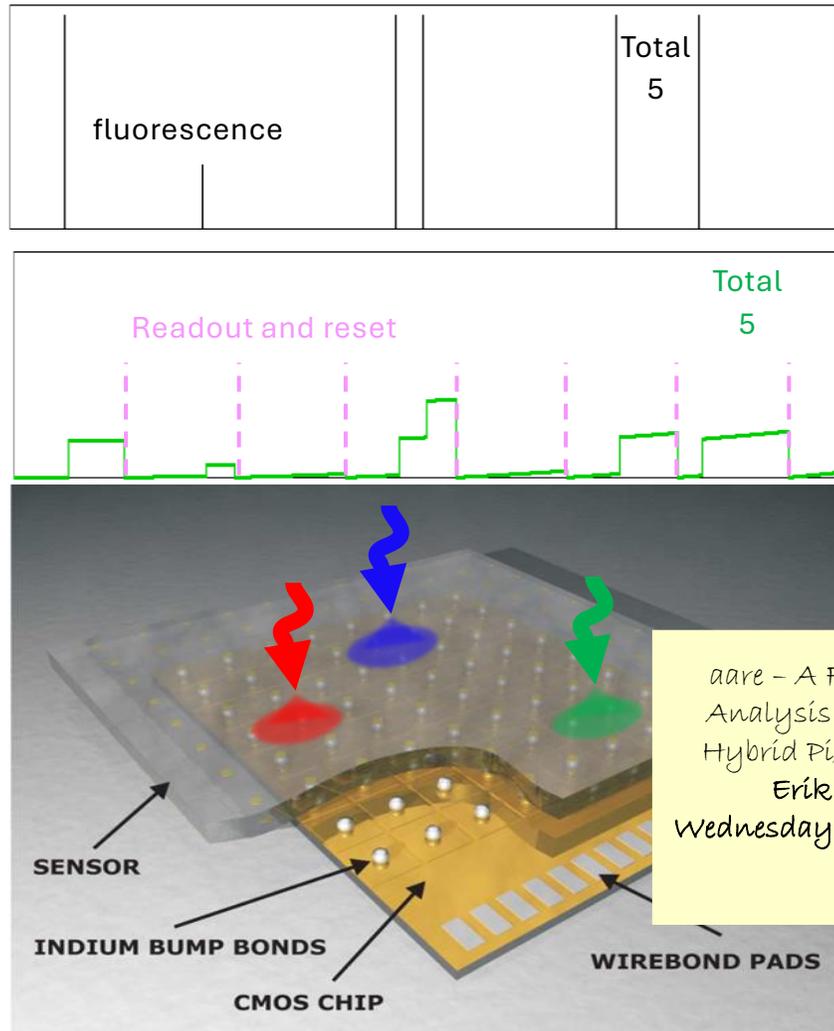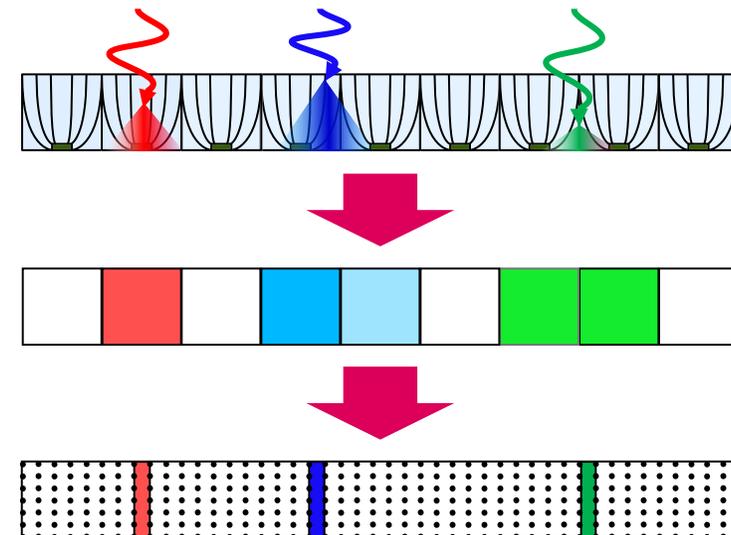# More X-rays for photon-starved applications

fluorescence

Total 5

Readout and reset

Total 5

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

SENSOR

INDIUM BUMP BONDS

CMOS CHIP

WIREBOND PADS

- With fast frame rates and low fluxes
  - Energy resolution $\lesssim$ keV
  - Super-resolution ~µm
- Developments to sustain higher fluxes
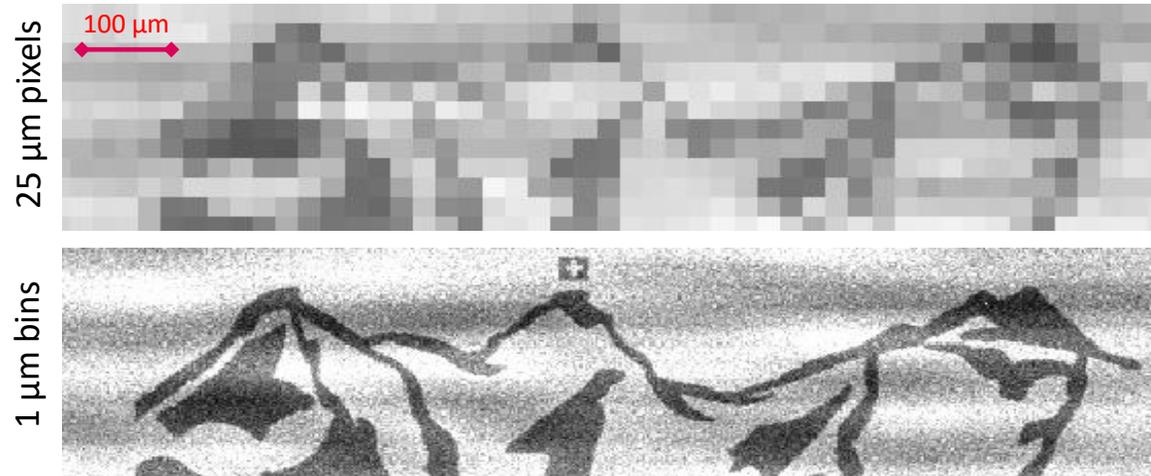 - Faster frame rates
  - Machine learning to handle pile-up

PSI

LGAD sensor @ 500eV

Silicon sensor @ 10keV

GaAs sensor @ 10keV

25 μm pixels

100 μm

25 μm pixels

100 μm

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

25 μm pixels

1 μm bins

5 μm bins

Chiriotti et al., JINST (2022)

2.5 μm bins

75 μm pixels

CdZnTe sensor @ 40 kVp

300 μm

5 μm bins

Crystal defect

J. Zhang et al., unpublished

D. Greiffenberg et al., unpublished

MÖNCH: high spatial and energy resolution
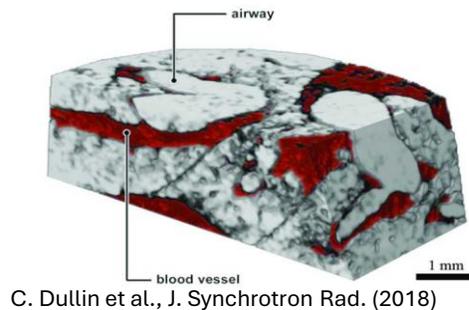

- Targeting low noise
  - Hyperspectral imaging with super-resolution
  - RIXS combined with LGADs
- Scalability is challenging
  - 800 kpixel on a single chip
  - 1.6 Mpixel module, non negligible gap
- Huge data throughput
  - ~ kHz frame rate, compromise with ROI
  - On-the-fly data reduction is mandatory!
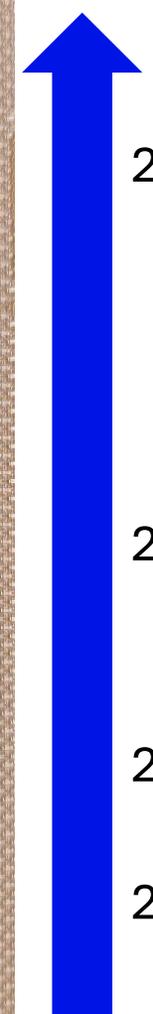
MÖNCH1.0 modules
2.56 x 3.84 cm^2

MÖNCH1.0
2.56 x 1.92 cm^2

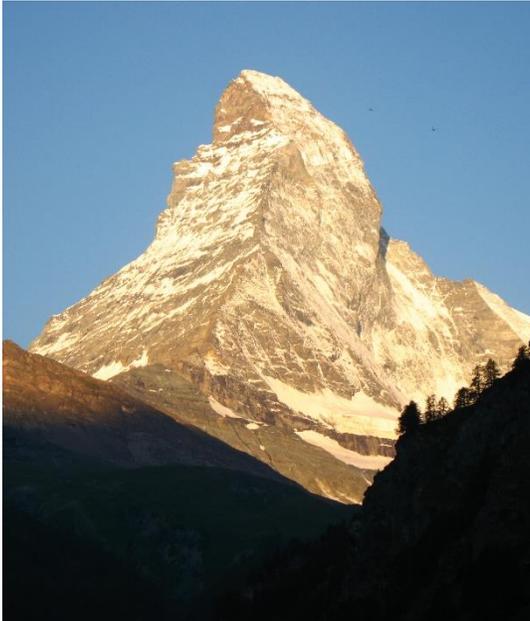MÖNCH big prototype
1 x 1 cm^2

MÖNCH prototype
0.4 x 0.4 cm^2

2028

2026

2015

2013

C. Dullin et al., J. Synchrotron Rad. (2018)

Full field fluorescence imaging
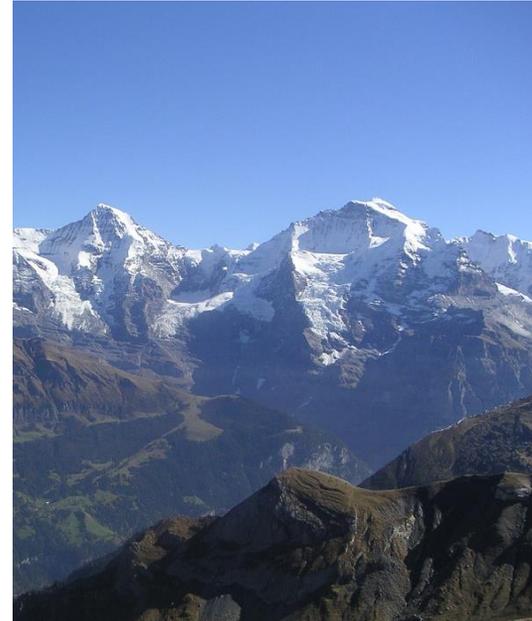Marone et al.

Fourier ptychography
Wakonig et al.

Summary

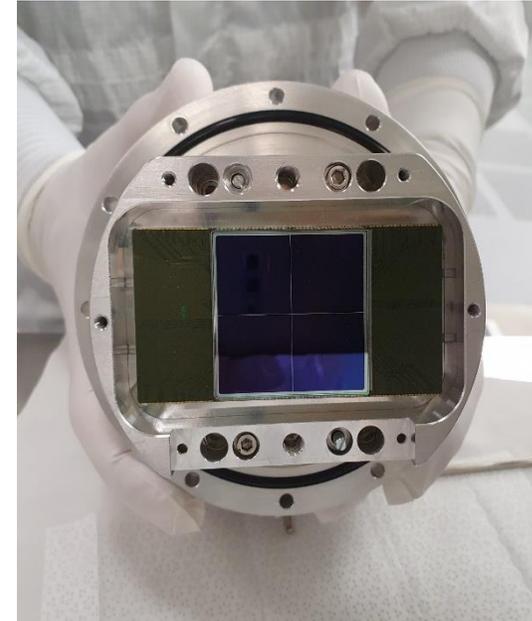MATTERHORN single photon counting
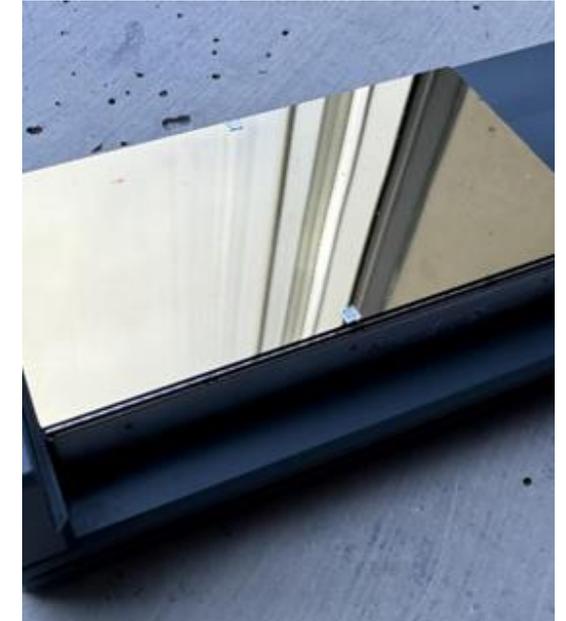
- Faster shaping
- Pile-up tracking
- Higher frame rate

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

16M MATTERHORN
1.5M MATTERHORN (OMNY)
1.5M JUNGFRAU (Serial laminography)

500k MATTERHORN LGAD
500k MATTERHORN (PEEM)

4M MATTERHORN High-Z

500k JUNGFRAU CZT (FFFT)

1M MÖNCH LGAD

60k MYTHEN3
4M MATTERHORN
4M MATTERHORN High-Z

4M JUNGFRAU LGAD

16M MATTERHORN
16M JUNGFRAU

4M MATTERHORN High-Z

4M MATTERHORN LGAD

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

X-RAY SENSORS

SOFT X-RAY DETECTORS
12-14 JANUARY 2026

Bridging Science and Detection Technology for Soft X-ray Applications

Call for abstract is open!

HiZPAD
15-16 JANUARY 2026

High-Z Pixel Array Detectors for Photon Science

Abstract: hizpad.community@gmail.com

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

Registration for the two workshops is separate.

Thank you!

PSI

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

A 1M charge integrating hybrid pixel detector for electron diffraction
Khalil Ferjaoui
Monday 15:00

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

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

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

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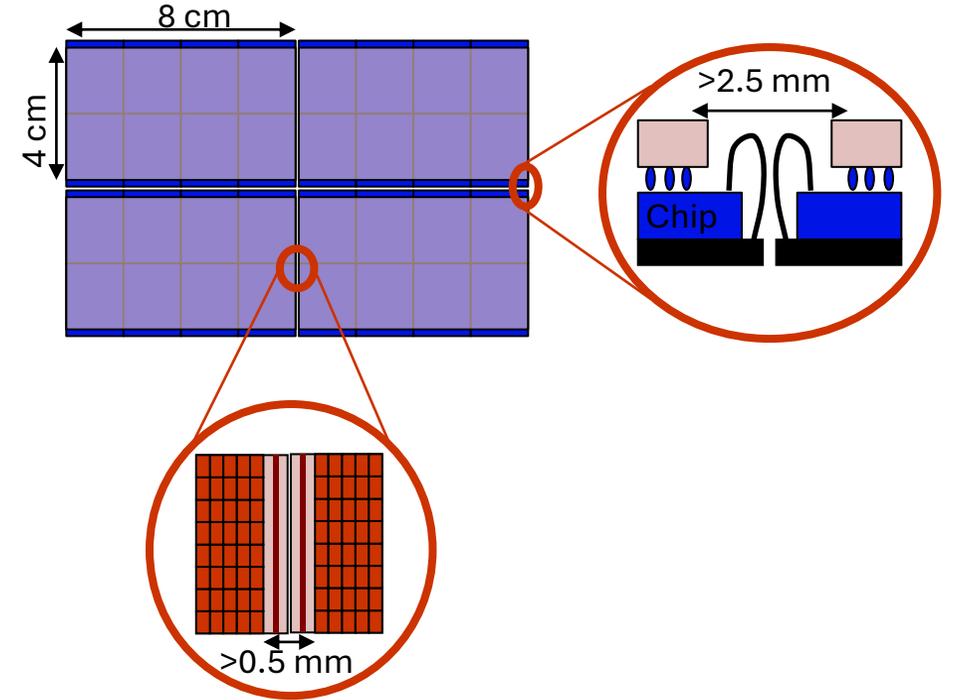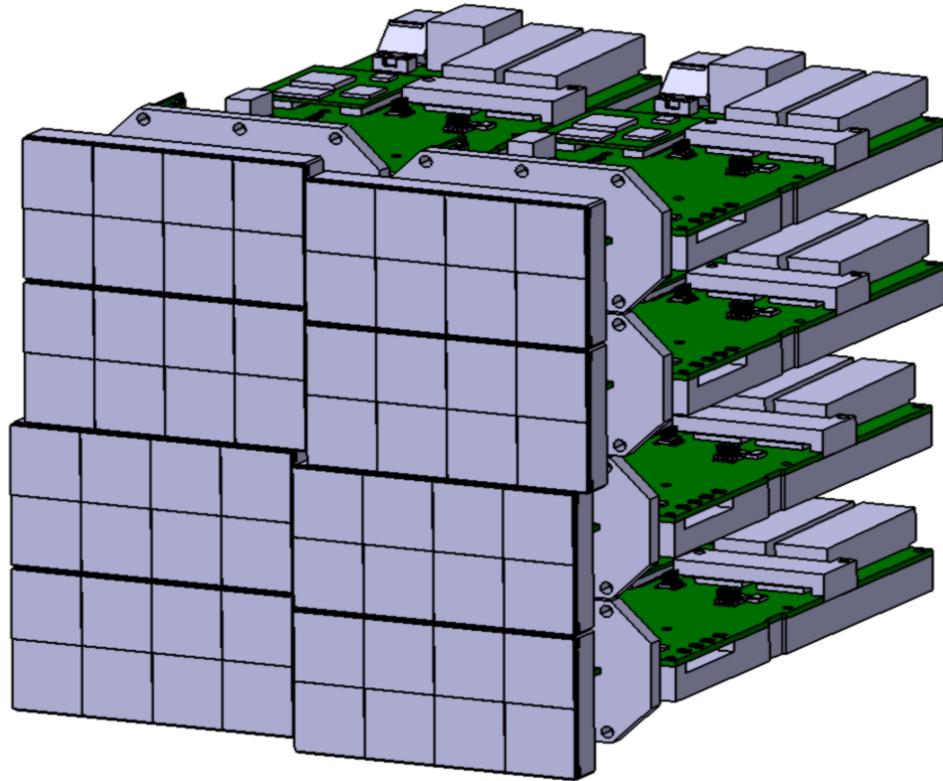Middle: K. Moustakas, C. Ruder, J. Mulvey, S. Silletta, V. Hinger, A. Mozzanica, M. Carulla, X. Xie,.
Front: R. Dinapoli, A. Bergamaschi, S. Li, D. Thattil, J. Zhang, A. Mazzoleni, V. Gautam, D. Mezza, T. King, B. Schmitt.
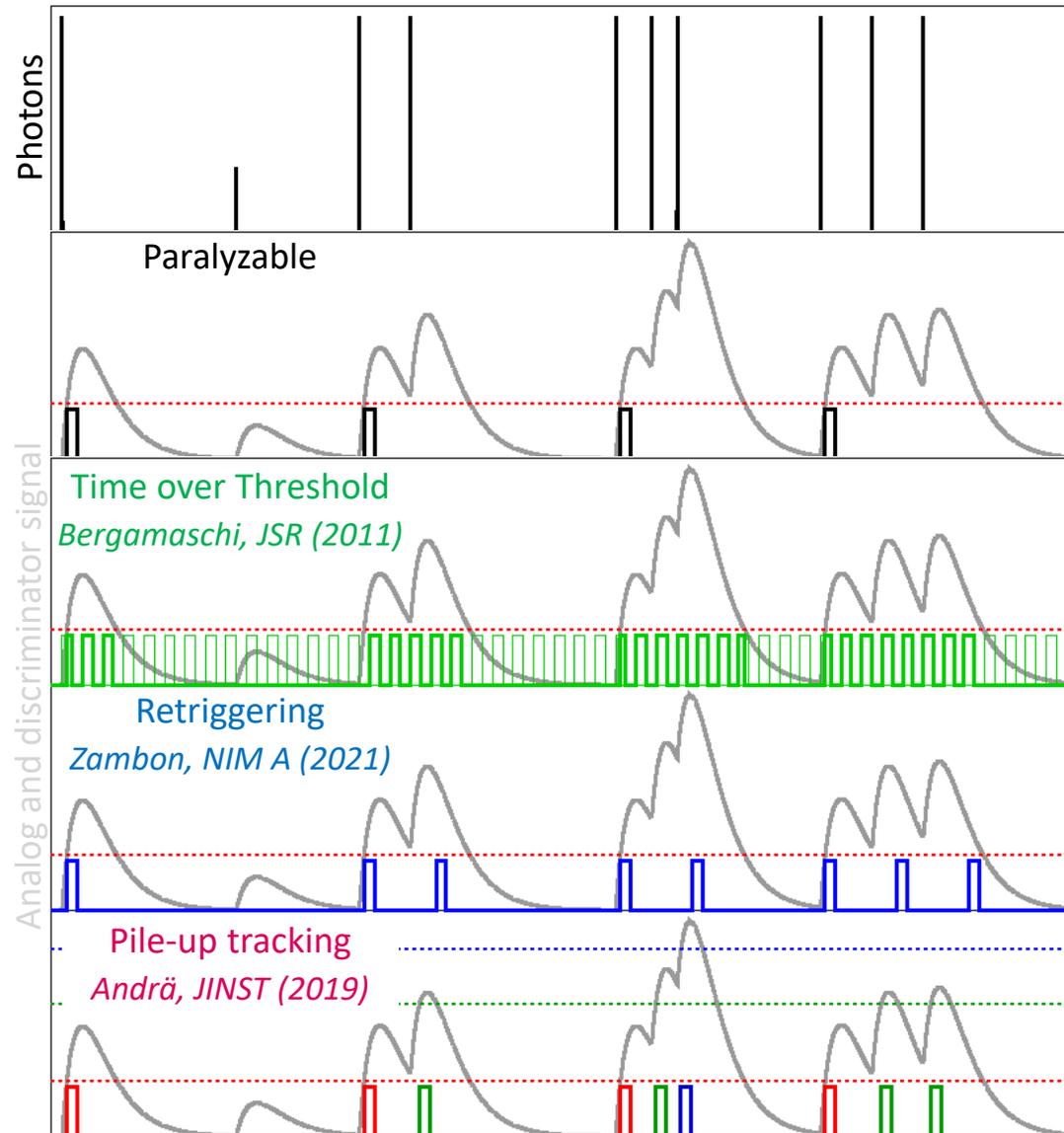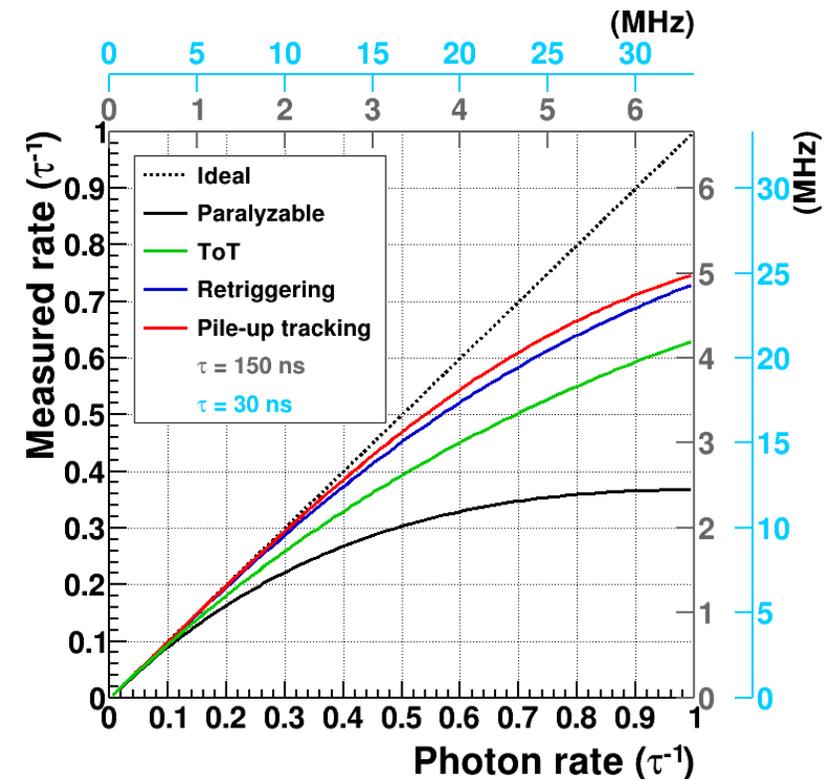Missing: S. Ebner, D. Greiffenberg, S. Hasanaj, K.A. Paton, C. Posada, A. Haugdal.
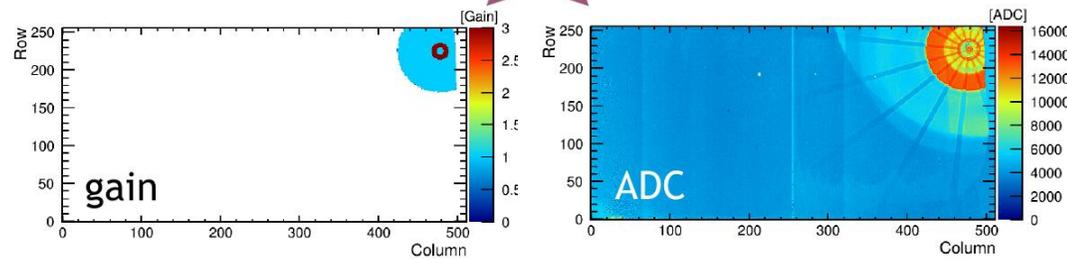
PSI

Large detectors

8 cm

4 cm

>2.5 mm

Chip

>0.5 mm

New counting modes

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

Photons

Paralyzable

Time over Threshold
Bergamaschi, JSR (2011)

Analog and discriminator signal

Retriggering
Zambon, NIM A (2021)

Pile-up tracking
Andrä, JINST (2019)

Ideal
Paralyzable
ToT
Retriggering
Pile-up tracking
τ = 150 ns
τ = 30 ns

Measured rate (τ^{-1})

Photon rate (τ^{-1})

(MHz)

Calibration into number of photons

PSI

original 16 bit image

Bit masking

gain

ADC

Pedestals

Pedestal corrected ADC G0

Pedestal corrected ADC G1

Pedestal corrected ADC G2

Gain factors

Gain corrected

S. Redford et al., JOURNAL OF INSTRUMENTATION 11, C11013 (2016).
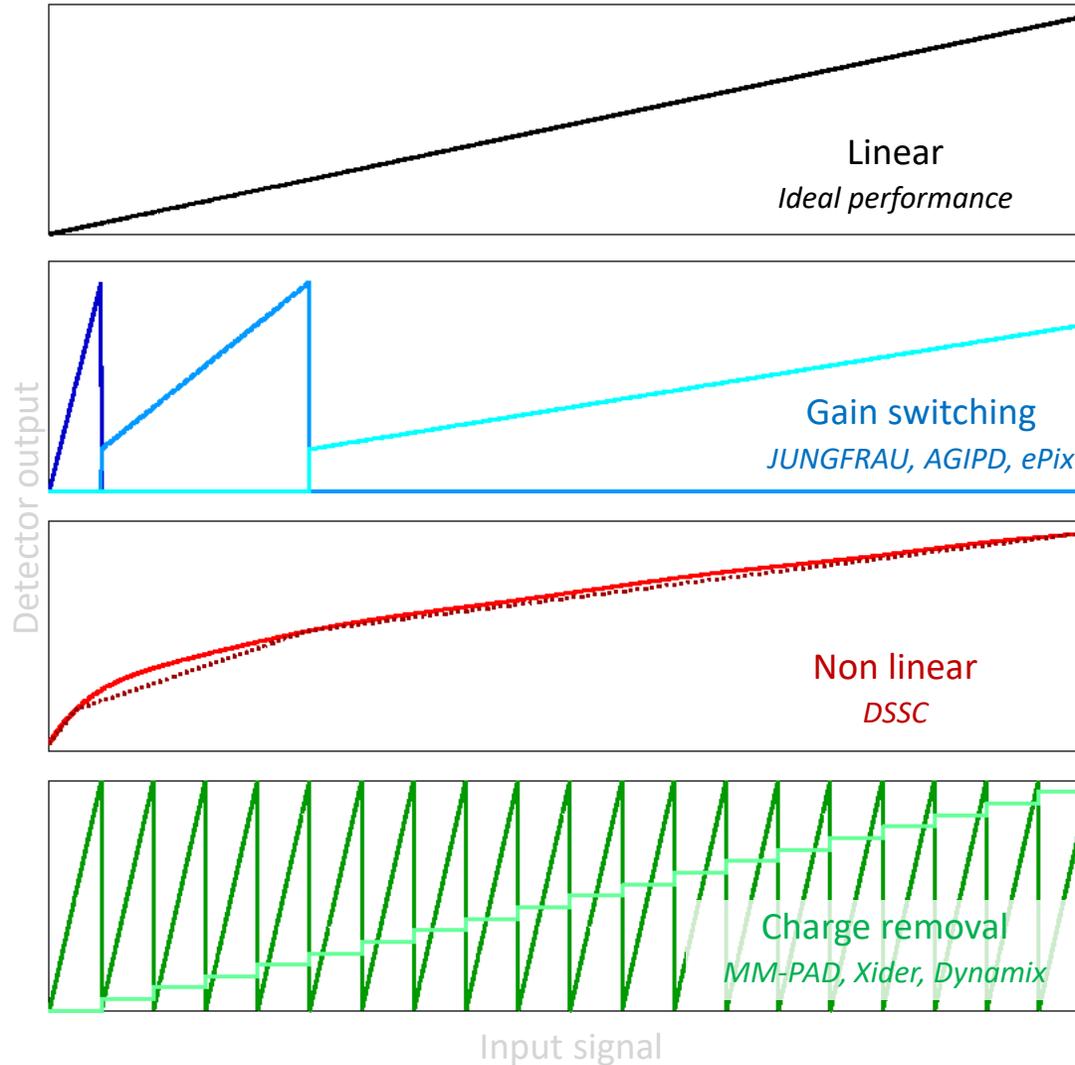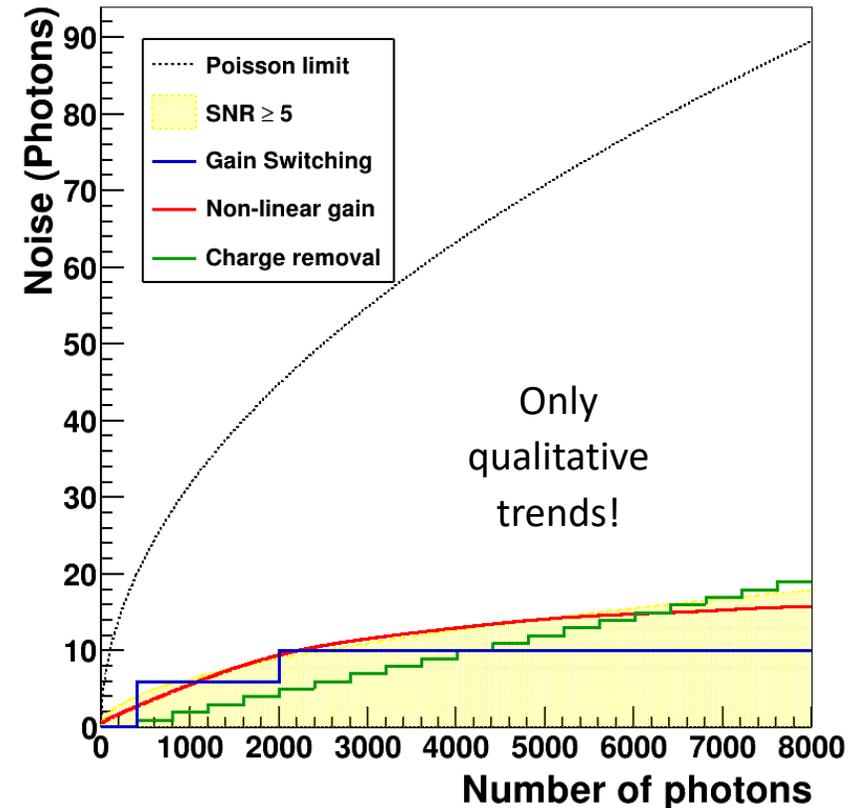
- Fresnel zone plate at XIL beamline, SLS, 92eV
- Etched sensor (no Al), module mounted to flange in high vacuum

29

Adaptive gain methods

Linear
Ideal performance

Gain switching
JUNGFRAU, AGIPD, ePix

Non linear
DSSC

Charge removal
MM-PAD, Xider, Dynamix

Detector output

Input signal

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

Only qualitative trends!

Poisson limit
SNR ≥ 5
Gain Switching
Non-linear gain
Charge removal

Noise (Photons)

Number of photons

30

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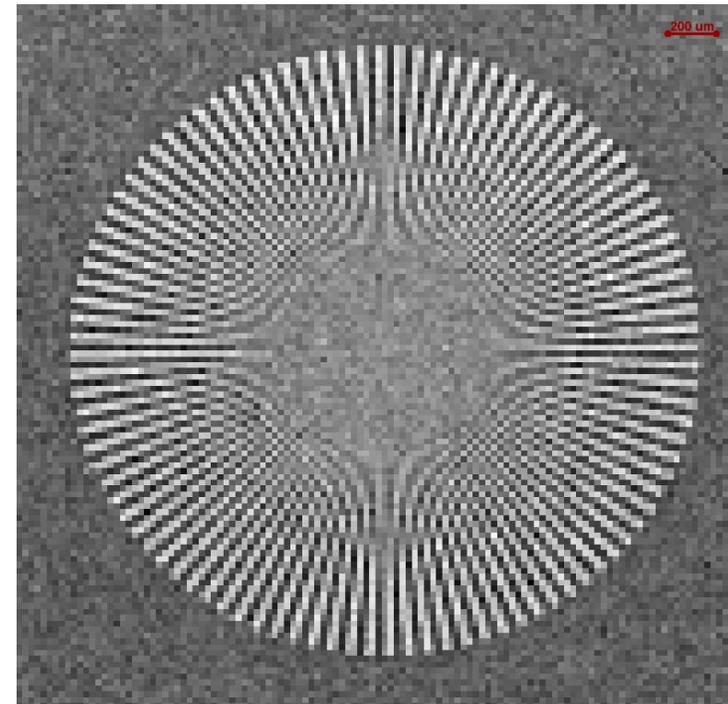*DSSC*

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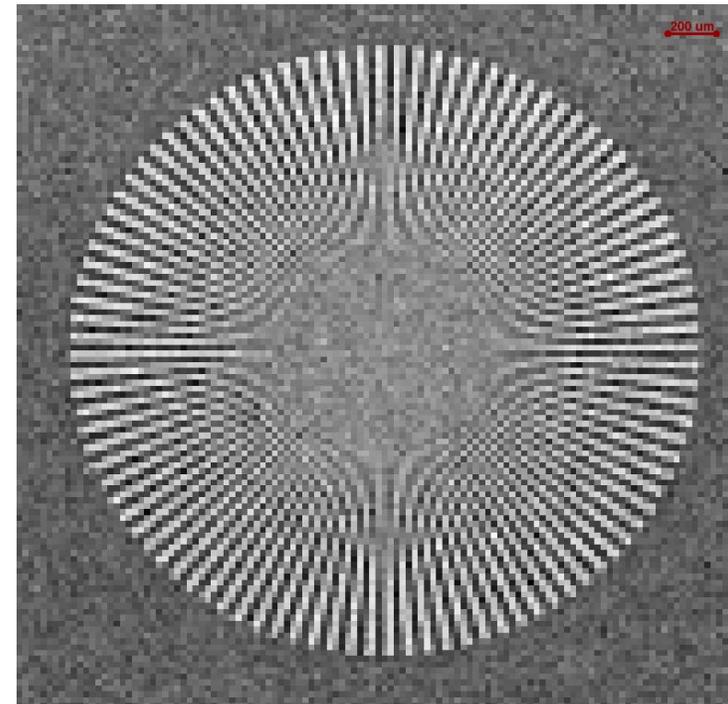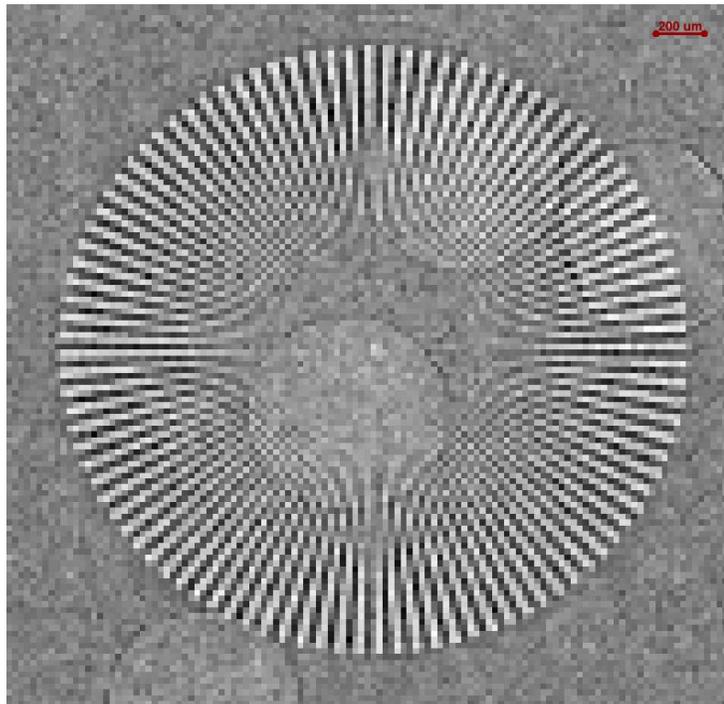
Energy resolved imaging at X-ray tubes

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

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA

Edge subtraction imaging

Images can be binned in energy

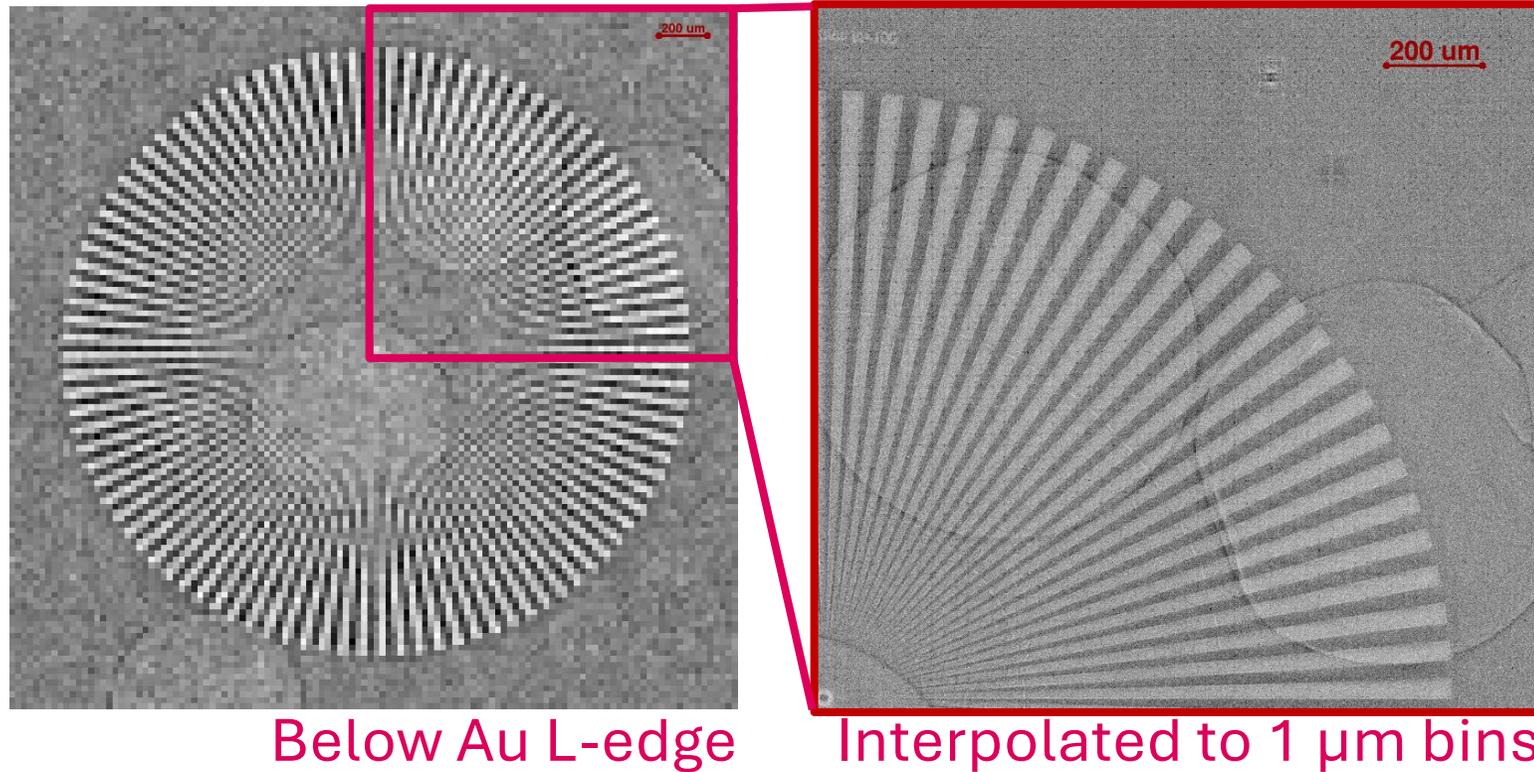Below the L-edge gold becomes "transparent" to X-rays

Below Au L-edge

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres

W-anode X-ray tube 40 kV 200 µA

High resolution energy resolved imaging

Color imaging works also in combination with interpolation.

Below Au L-edge   Interpolated to 1 μm bins

Siemens Star with spokes 60-0.5 μm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 μA