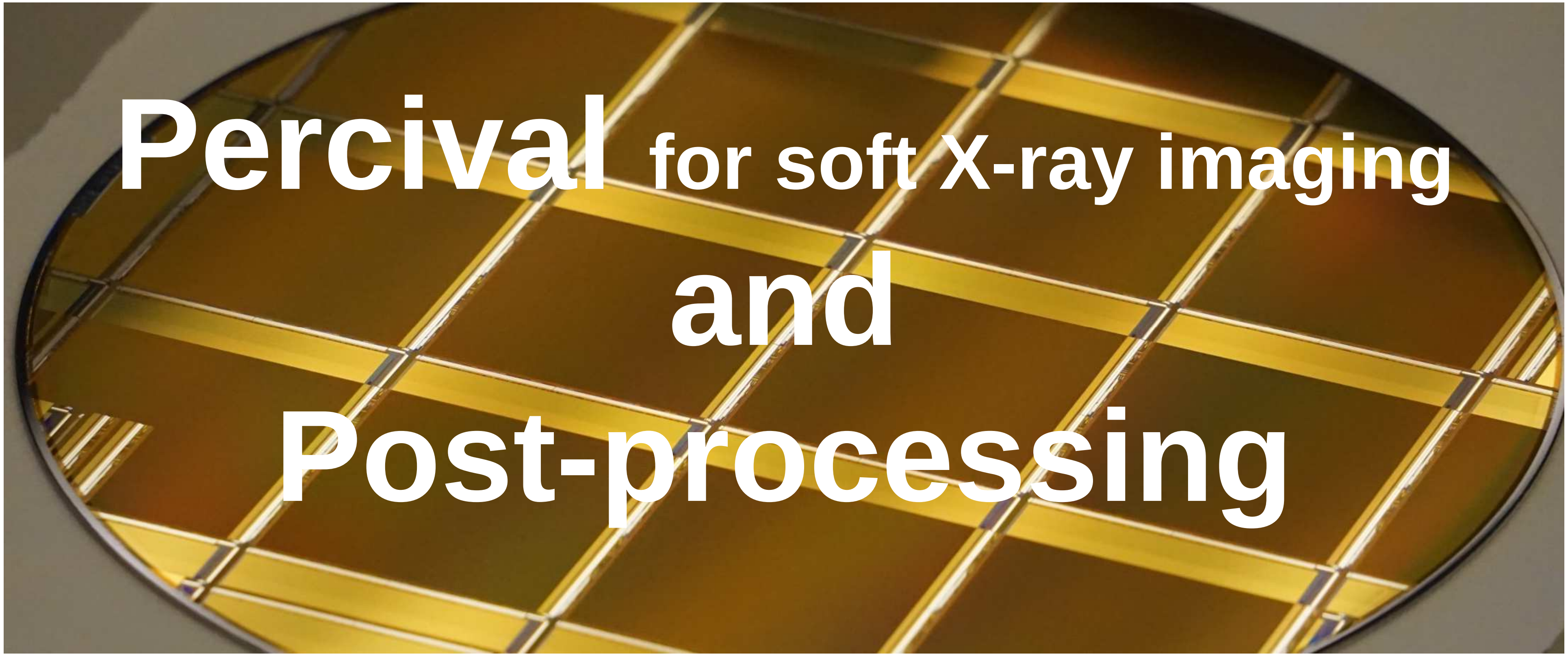


Percival for soft X-ray imaging and Post-processing

Cornelia Wunderer
DESY – Photon Science Detectors
MT Meeting Berlin, 12-14 June 2018

CFEL SCIENCE

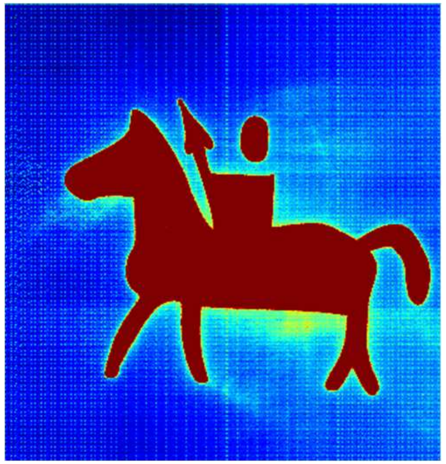
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

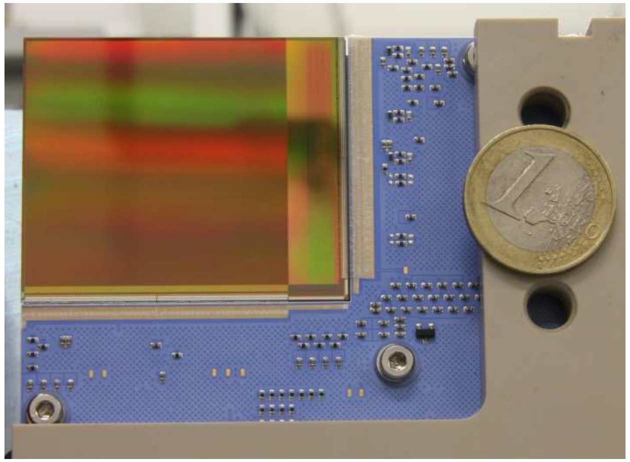
PAL

DESY.

Percival

Pixellated Energy-Resolving CMOS Imager, Versatile And Large





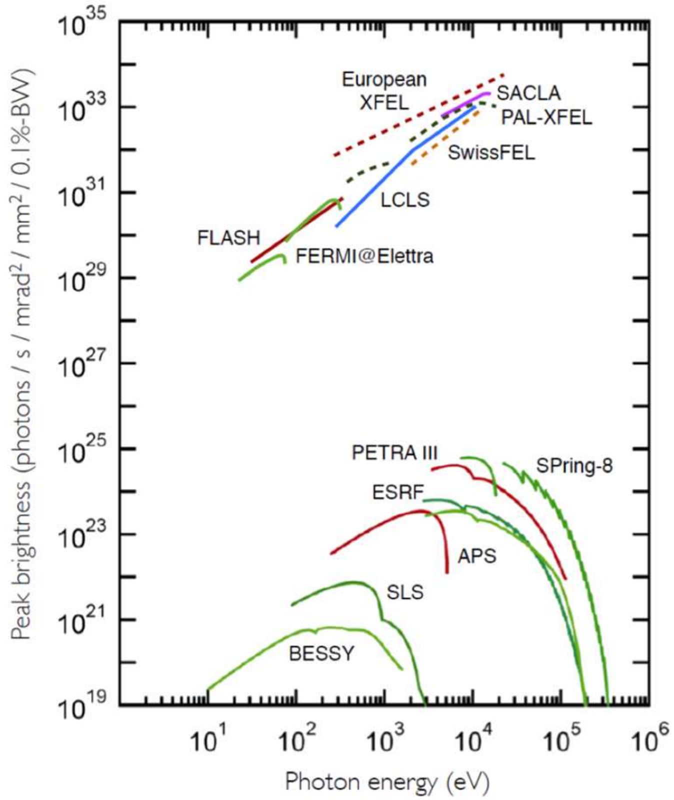
Unprecedented combination:

- 1408×1484 pixels
- 300 Hz frame rate
- below 15 e^- noise
- sensitive to single photons
- handle $5 \cdot 10^4$ ph/pix/frame

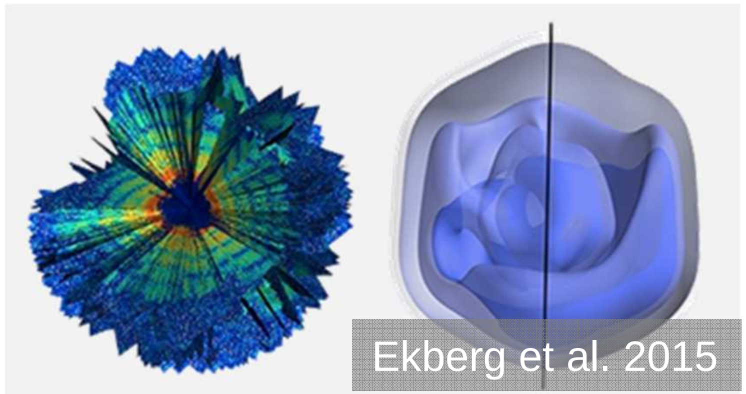
Science Motivation

Watching biomolecules in action … and more

- Making optimal use of the brilliance of today’s photon sources requires
  - Single-shot imagers with suitable frame rates
  - Very large dynamic range
    - single-photon discrimination to
    - 10^4 photons/pixel/frame and more
  - Millions of pixels with little/no dead area



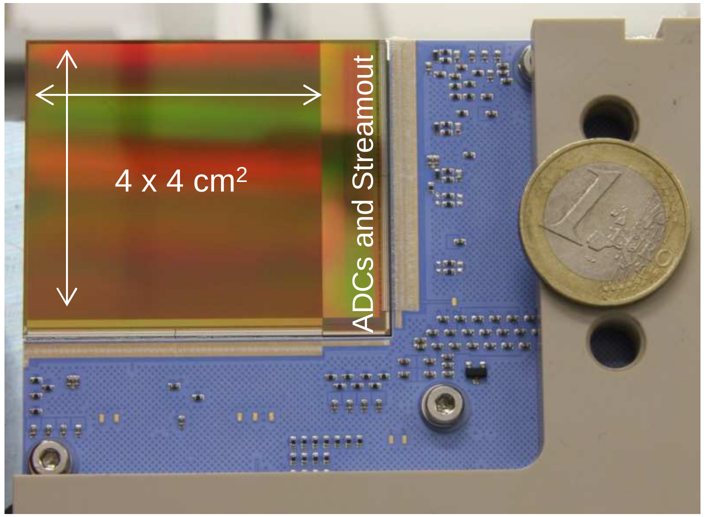
- In the soft X-ray regime
  - Scientific interest e.g. biosystems, weakly scattering samples
  - Particular challenge: small signal requires very low noise
  - Particular challenge: sensor surface

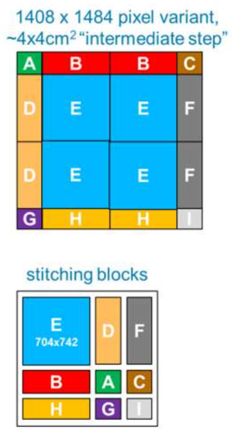

Ekberg et al. 2015

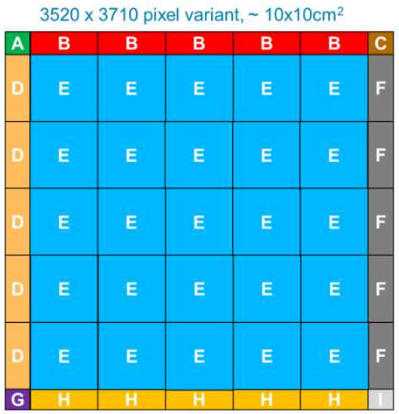
Percival P2M Sensor

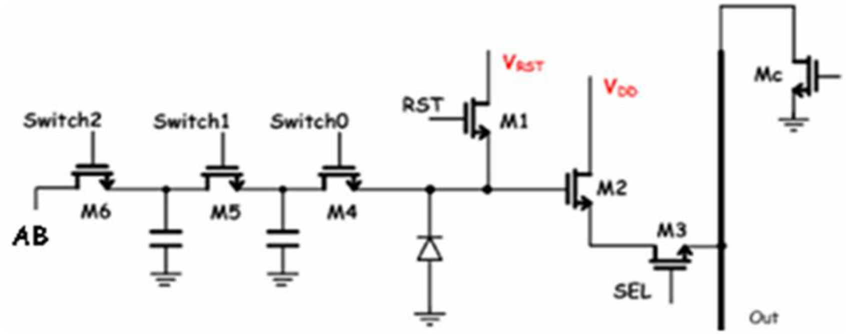
Designed by partner Rutherford Appleton Lab / STFC

- CMOS imager (180nm technology)
- On-chip digitization (11520 ADCs)
- 3 auto-adjusting gain levels
  (per pixel, per frame, overflow)
- 1408 × 1484 pixels, 27µm × 27µm
- ~ 4 × 4cm^2 continuous imaging area
  (stitched sensor)









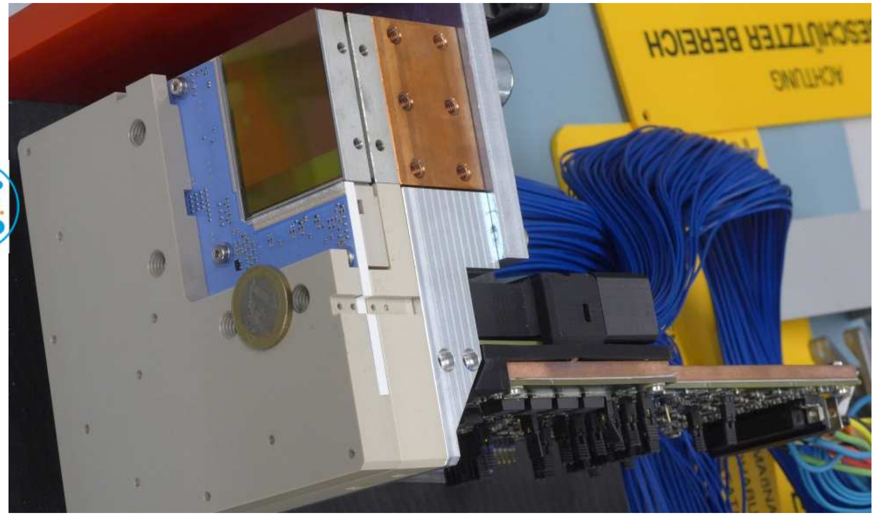
Multi-Gain Pixel Design

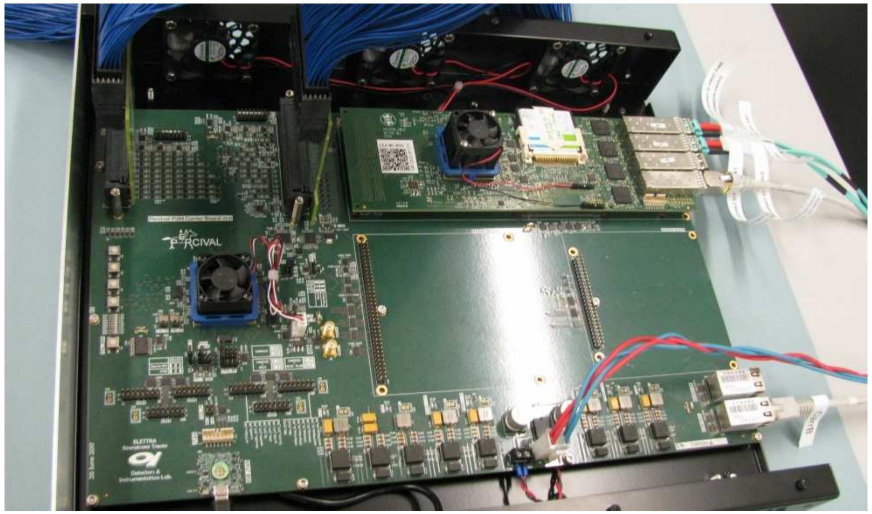
Percival P2M System

Currently undergoing benchtop tests in front-illuminated configuration

- In-vacuum detector head
  - sensor
  - Includes sensor biasing board
  - Several hundred LVDS control & data lines, are (re)distributed here
  - Sensor will be cooled to ~ -30°C
  - 2-side buttable
  - movable

- Carrier board hosts
  - FPGA running finite state machine
  - Mezzanine board (also AGIPD, Lambda) streaming out 20 Gbit/s data
  - Interface to slow control, facility information, trigger

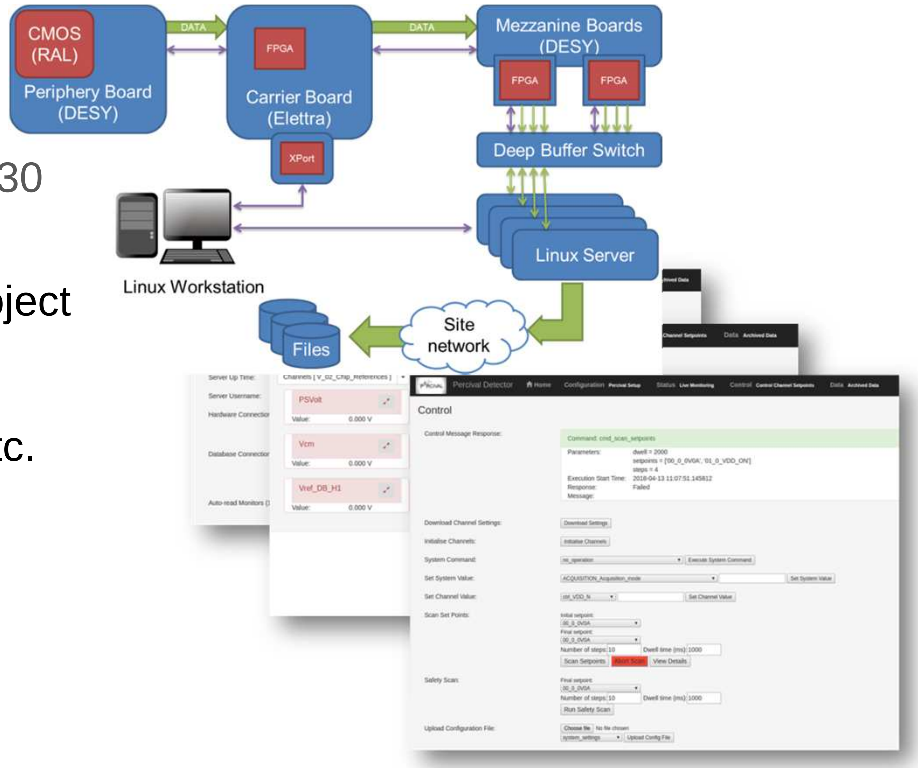




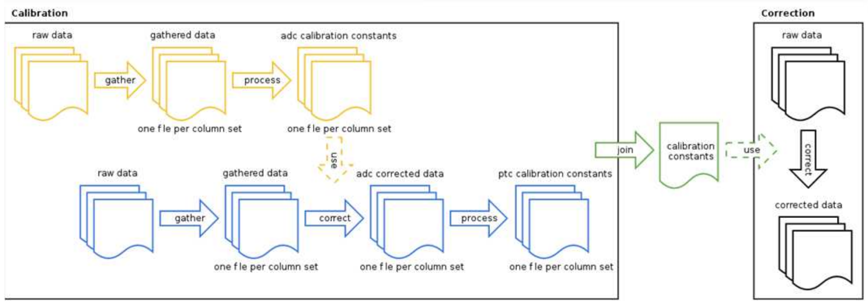
Percival P2M System

Currently undergoing benchtop tests in front-illuminated configuration

- Control & DAQ
  - 20 Gbit/s from one sensor
    (reading full images: 300 Hz, 2M pixels, 30 bit/pixel incl. CDS)
  - Virtual hdf5 developed in part for this project
  - Python interface & Odin GUI interface
  - API for link to Tango, DOOCs, EPICS, etc.



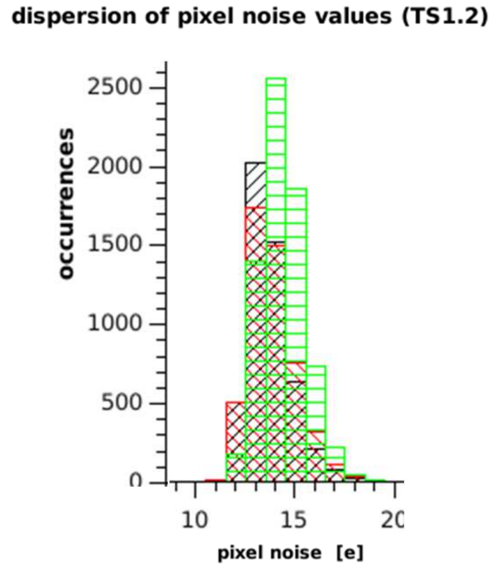
- Software Framework for Characterization
  - Data validation
  - Calibration constants
  - Sensor characterization



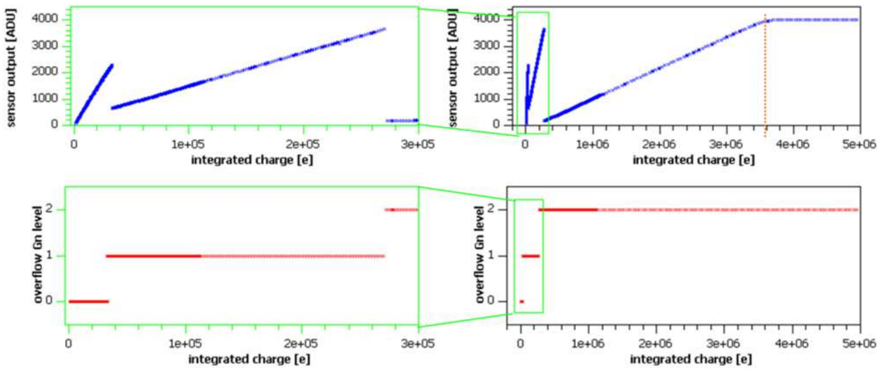
- Testing

Prototype Performance

- Noise on average below 15e- rms for prototype sensors from different wafers & locations
- Multiple samples of signal & reset levels promise further reduction (prelim tests indicate ~10e- rms achievable)



- Automatic gain adjustment works
- 3 gains accessible via overflow switch architecture
- Dynamic range to 3.5 Me- i.e. 50k photons at 250eV



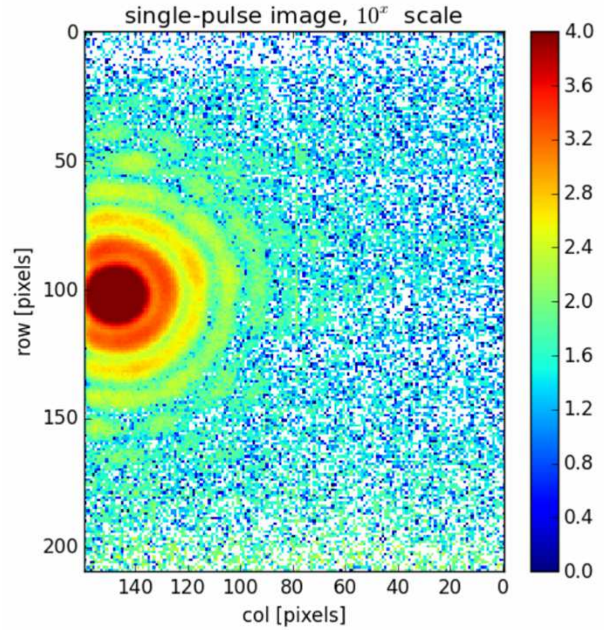
Prototype Performance

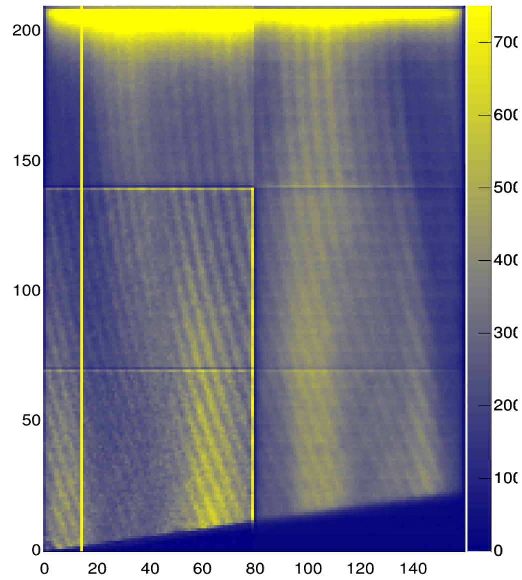
backside-illuminated (BSI)

- Imaging at 92 eV, single-shot at FLASH

  left: Airy ring pattern

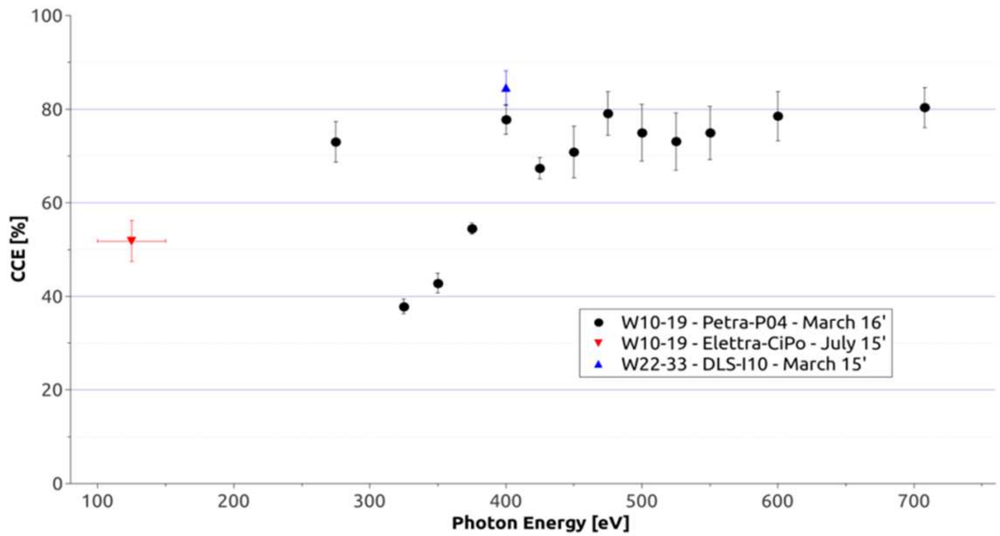
  right: fine diffraction rings from liquid sample





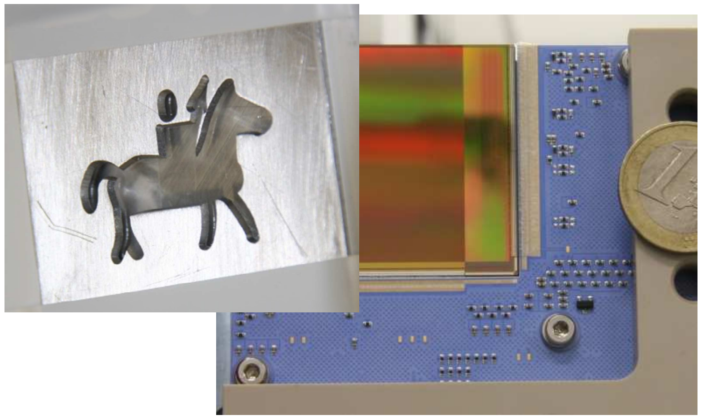
- Airy rings match expectation

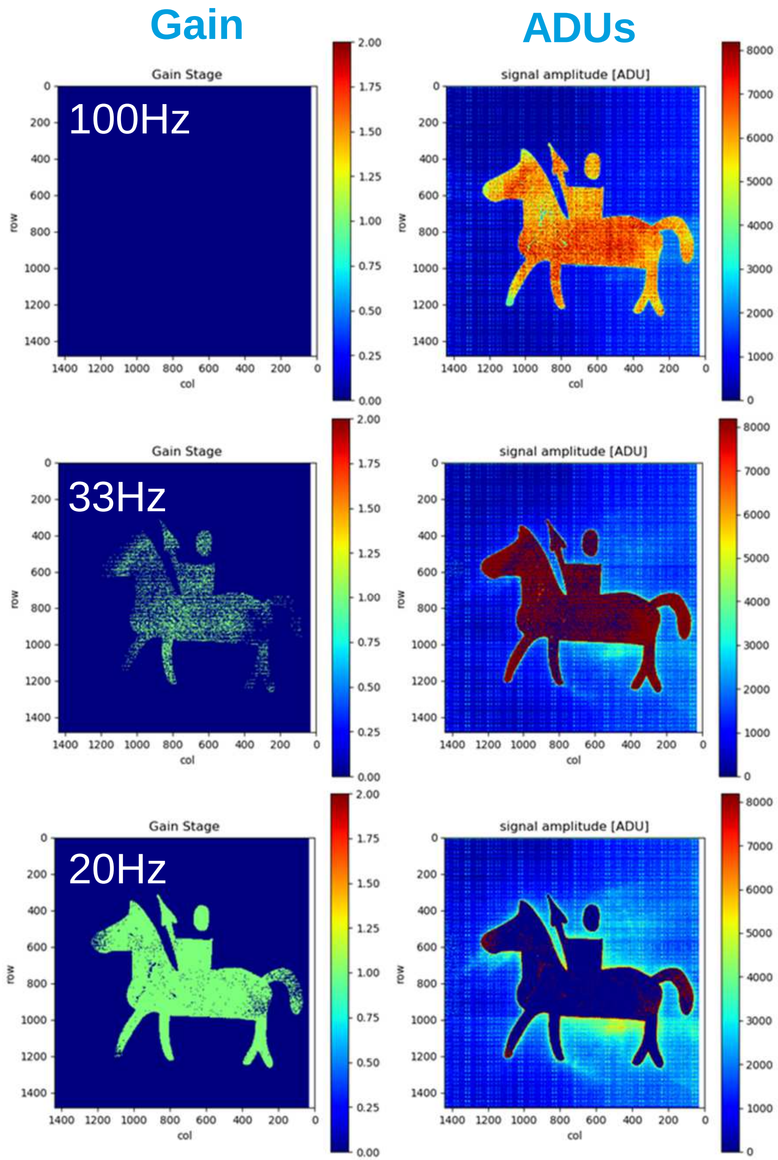
- Charge Collection Efficiency (lower limit to Quantum Efficiency) measured at ~70% above 400 eV



P2M Operation

- First light
- Visible light, room temperature
- 100Hz frame rate
  (streamout speed of full acquisition system still ramping up)
- Automatic gain switching works



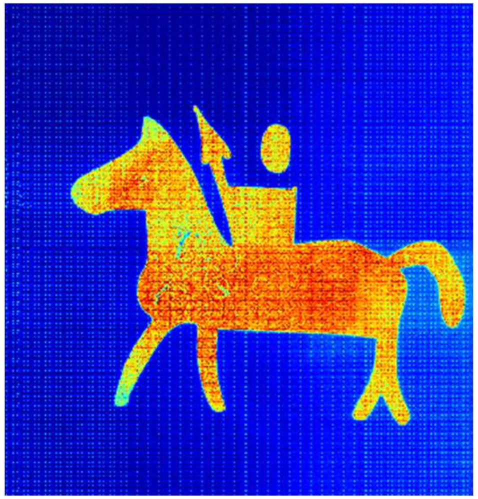


Percival Project Status & Outlook

P2M FSI undergoing benchtop testing

- P2M system operates, saw first light
- P2M sensor demonstrates auto gain switching in response to illumination
- Detailed characterization (including bias tweaking etc) ongoing
- Chip functionality at 300Hz frame rate demonstrated, full readout & system ramping up to this

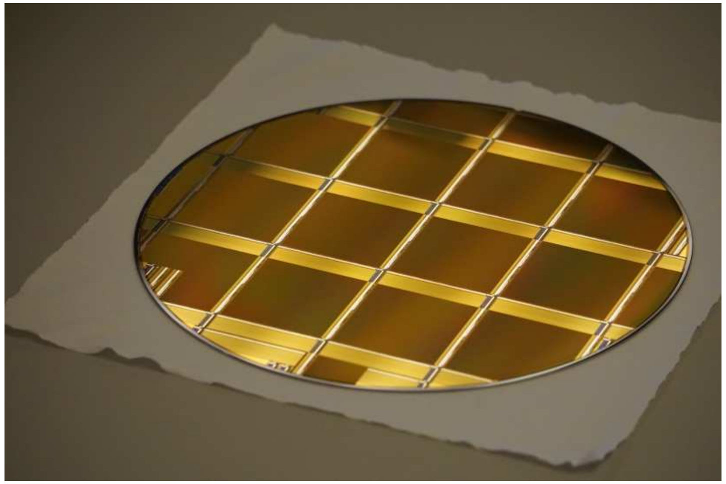
- P2M backthinned sensor in hand, awaiting wirebonding
- Expect first X-ray tests in fall 2018
- First delta-doped P2M BSI ~ Xmas 2018

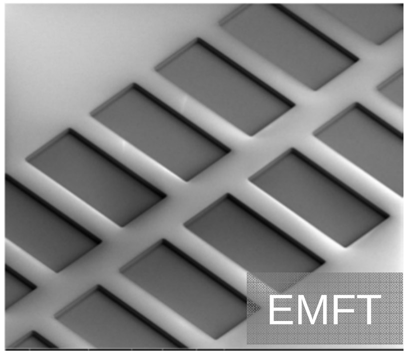


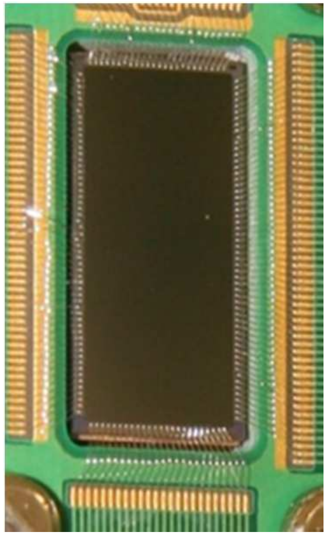
P2M
backthinned & pads exposed
by Fraunhofer EMFT Munich

Post-Processing

Making Sensors and CMOS Imagers optimally suited for Science



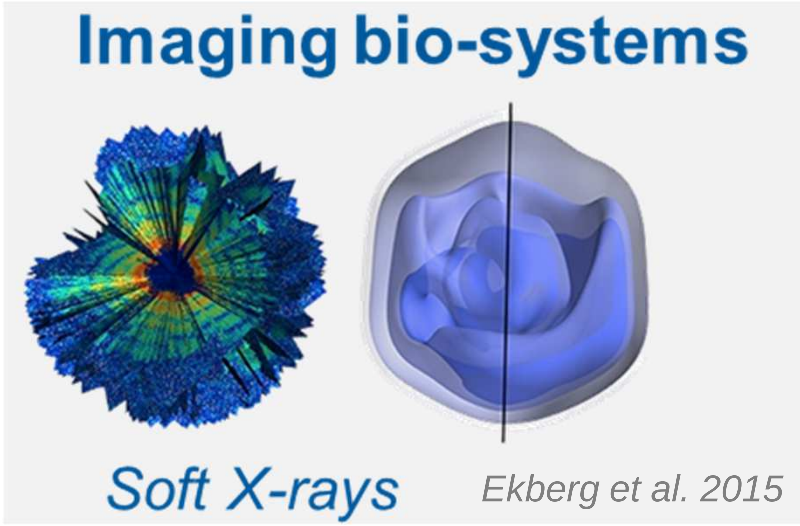




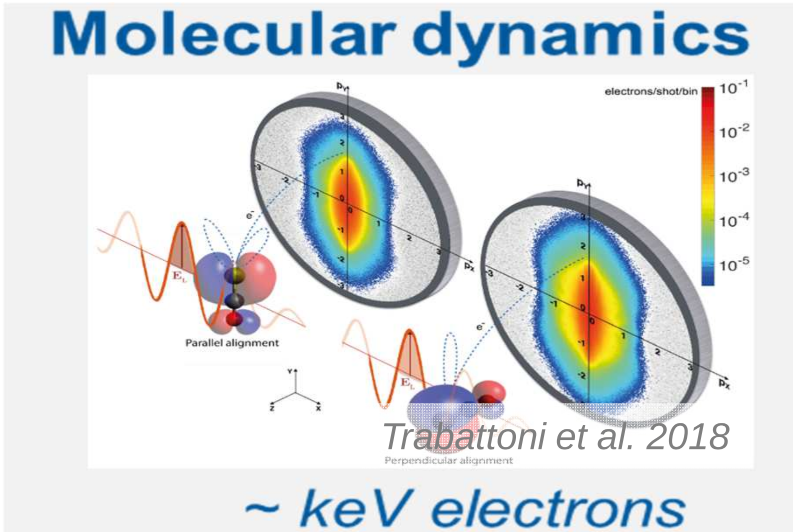
Post-Processing is necessary

Science challenges – two examples

- Water window offers unique view of biological systems:
  Between Carbon and Oxygen edges, water is transparent but carbon absorbs
- 282 eV to 533 eV photons

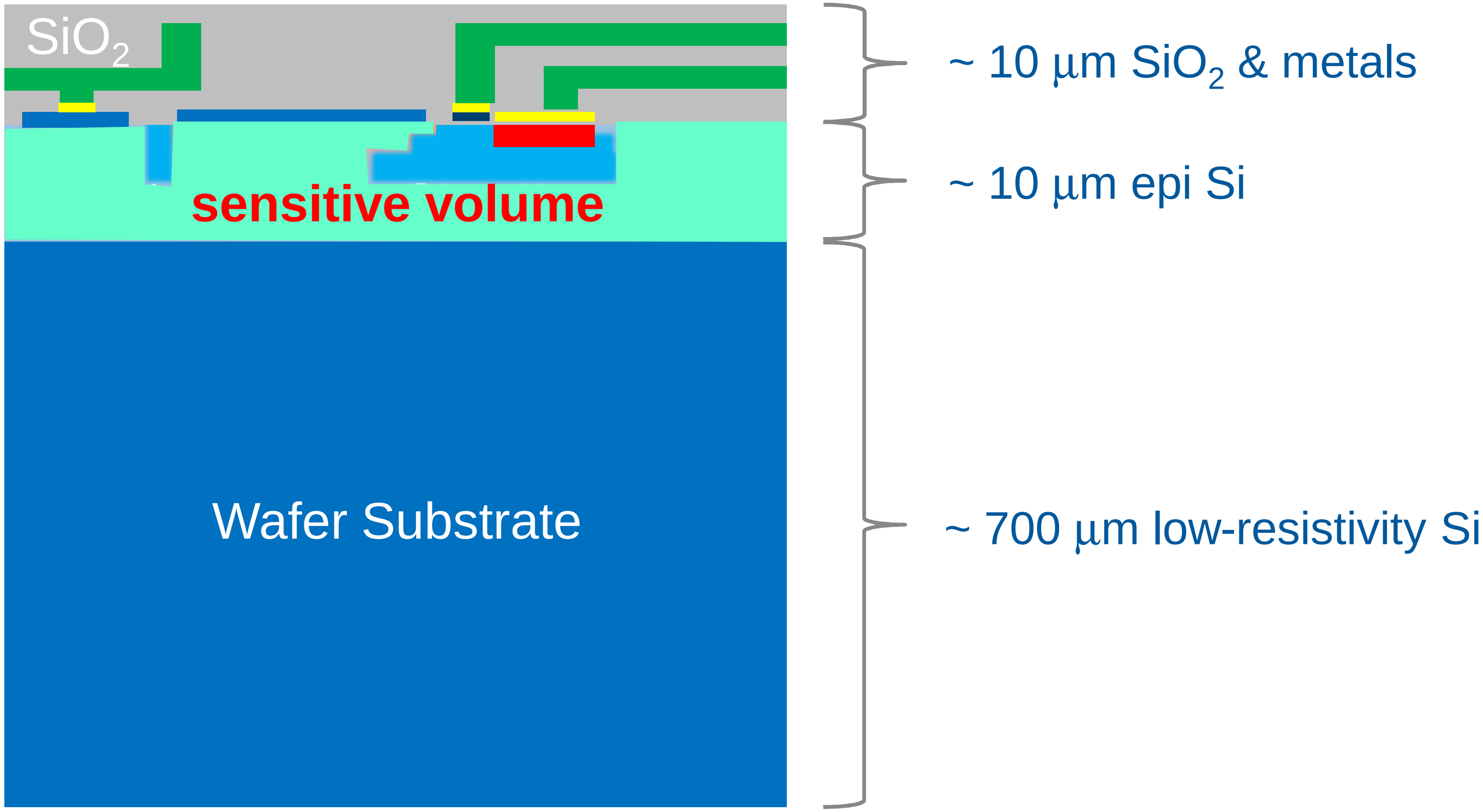


- Laser-Induced Electron Diffraction:
  re-scattered electrons can give simultaneous access to sub-100pm-spatial and sub-fs temporal resolution
- Sweet spot for these measurements is around 500 eV electron energy
  (plus few keV acceleration from optics)

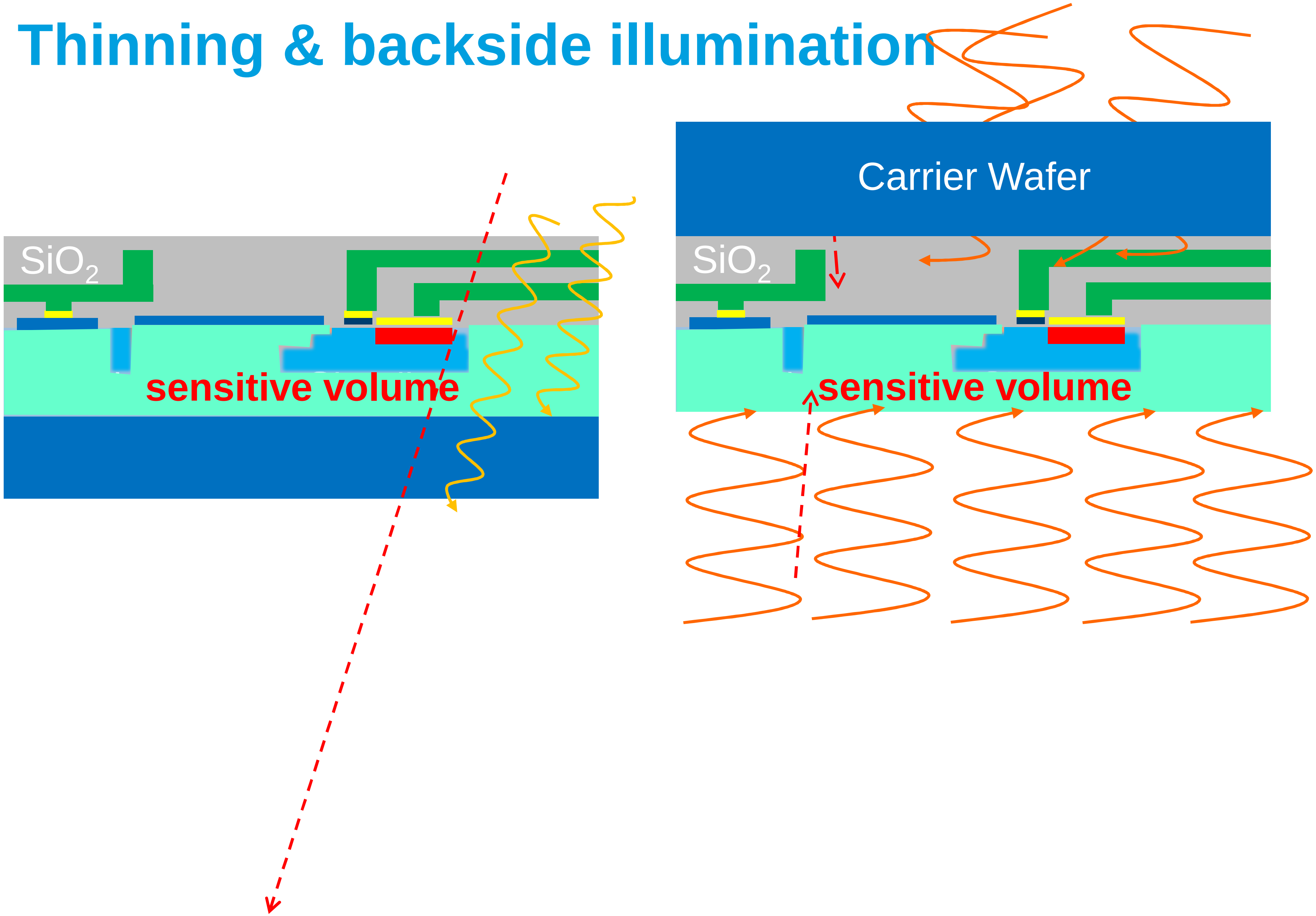


Thinning & backside illumination

CMOS imager one prominent example



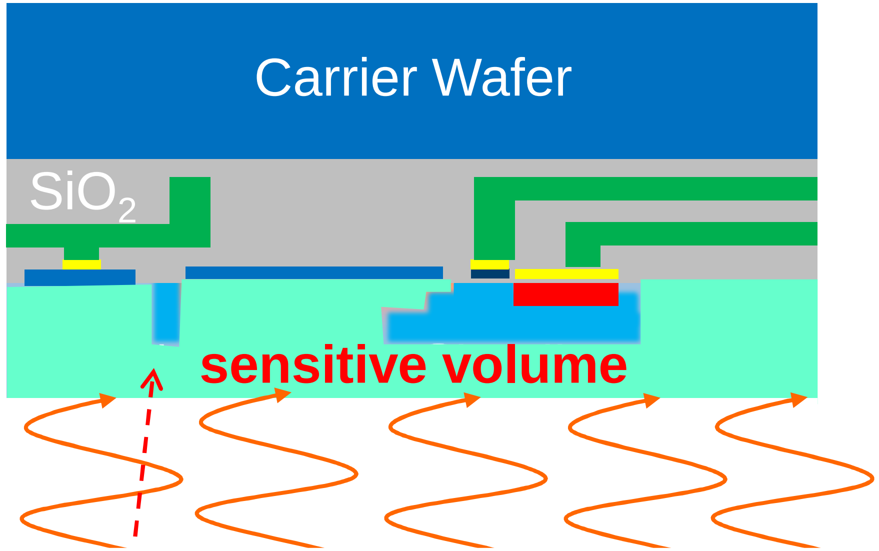
Thinning & backside illumination



Entrance window post-processing

High sensitivity to low-energy radiation requires:

- Absence of passive material
- Absence of traps
- Optimized field geometry at sensor surface

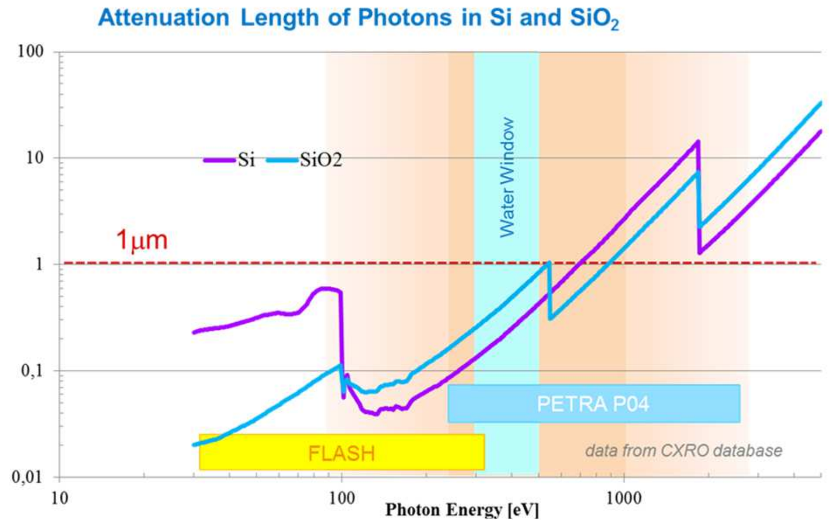


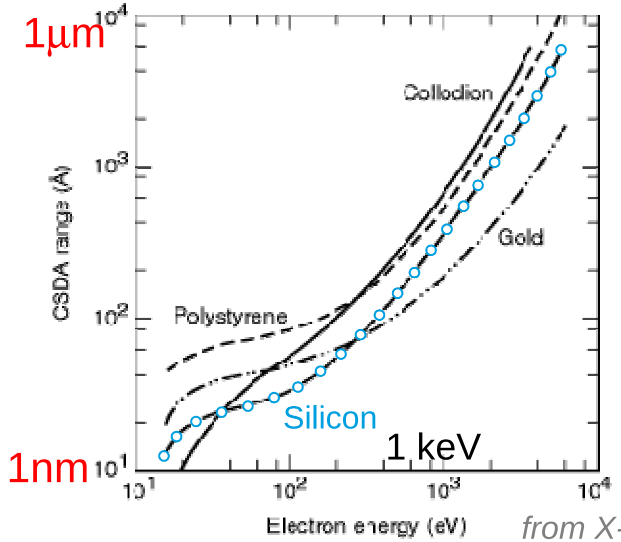
➡ **High-quality backside processing is crucial!**

*… and all processes must be **high-purity** and **low-temperature** in order to not damage the sensor / circuitry*

Post-Processing needs

- Attenuation lengths in Si / SiO_2 at or below 100nm for soft X-rays
- Attenuation lengths for few-keV electrons in Si are on the order of 10s of nm
- Interaction must happen in active Si, and generated charge cloud must reach the circuitry
- Requires:
  - Negligible passive layer
  - Negligible traps
  - Optimized geometry of electric field at surface of sensor





from X-ray Data Booklet

Post-Processing needs

- Attenuation lengths in Si / SiO_2 at or below 100nm for soft X-rays
- Attenuation lengths for few-keV electrons in Si are on the order of 10nm
- Interaction must happen in active Si, and generated charge cloud must reach the circuitry
- Requires:
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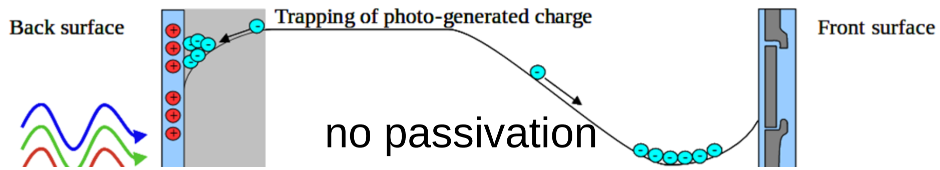
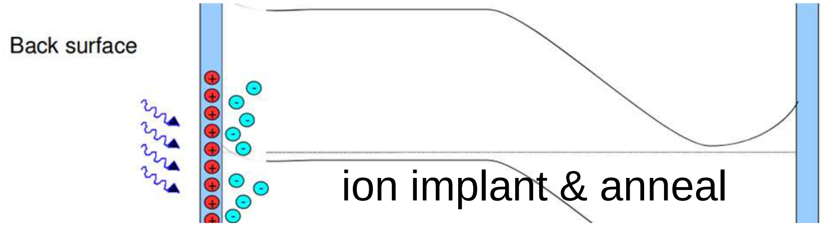
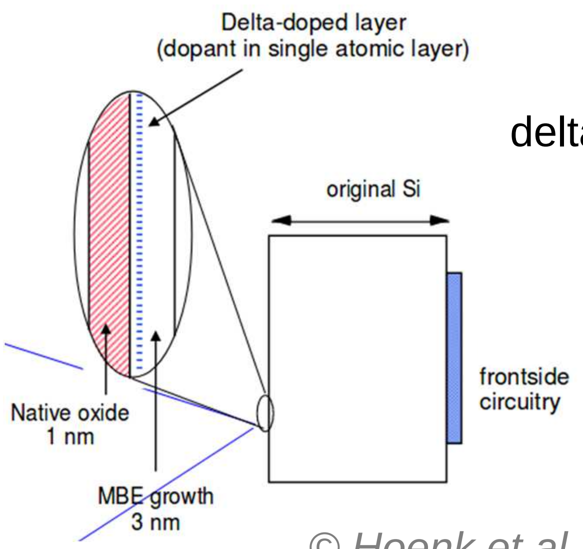
  - Negligible traps
  - Optimized geometry of electric field at surface of sensor



no passivation



ion implant & anneal



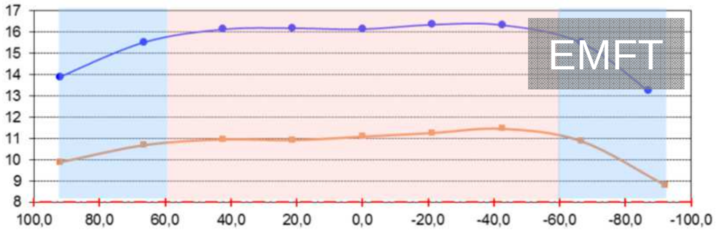
delta doping

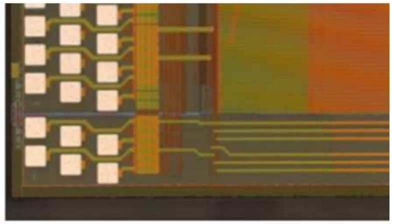
© Hoenk et al, JPL 2010

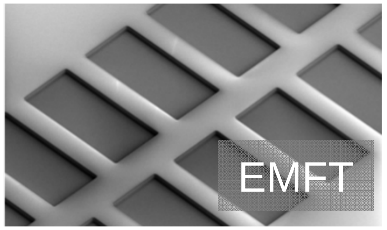
Post-Processing is a challenge

Optimizing the Sensor for the Science

- Expertise on a range of processing steps necessary
  - Bonding to carrier
  - Thinning with um precision
  - Low-temperature passivation (MBE or e.g. implant & anneal)
  - Pad exposure
  - Material growth such as scintillators
- Molecular Beam Epitaxy (MBE) provides thinnest-known dopant layers
- ➢ "delta doping" pioneered by JPL
- Other US national labs have successfully copied the technique





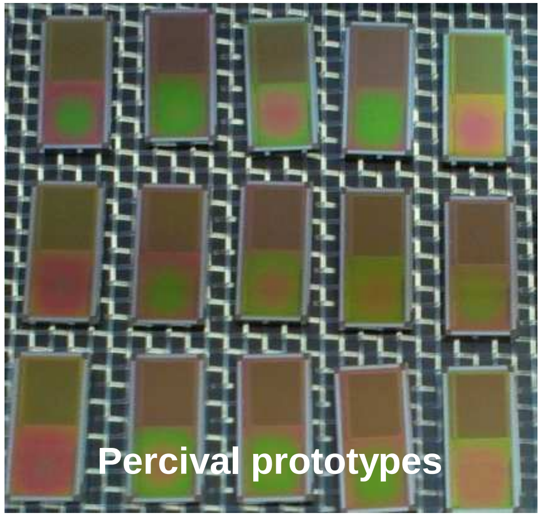


Post-Processing is a challenge

Optimizing the Sensor for the Science

Post-processing of individual chips – as well as full wafers – is crucial:

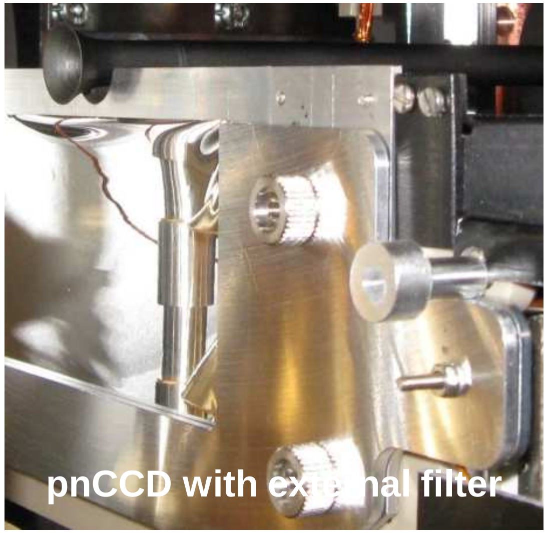
- Testing successive prototypes under realistic application conditions
- Fast turn-around for effective and rapid sensor optimization



Percival prototypes

Vision: Custom sensors post-processed to match specific science experiments

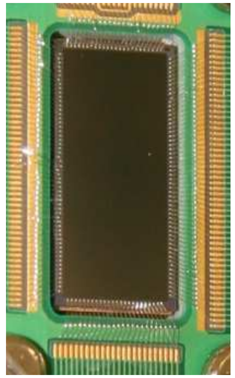
- Sensor thickness
- Delta-doping
- Direct-deposited filters with optimized thickness & material
- Adding & modifying structures



pnCCD with external filter

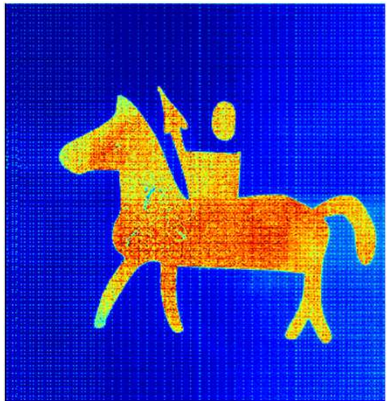
Post-Processing for Percival

- Prototype Sensor post-processed by NASA's JPL "delta-doping"
  - Pioneered the approach to ultra-thin entrance windows (few nm)
  - Bureaucratic difficulties mainly make access difficult & time-consuming
  - TS sensors processed by JPL give nice soft X-ray performance
  - Unfortunately e.g. not possible to BSI-process 2nd generation test devices in reasonable time



- P2M sensor post-processing
  - JPL remains a key partner and will process wafers
  - Exploring alternate routes to "good" post-processing (for some applications 10s of nm are acceptable)
  - EMFT currently a partner in tests (bonding, thinning, pad exposure)
  - Some routes to thicker dopant layers (10s to 100s of nm) exist, not tried yet
  - Easier-to-access (European / German / Helmholtz) MBE-based post-processing capable of processing both wafers and single (prototype) sensors direly needed

Summary and Outlook



- **Percival P2M System running in the laboratory**
- “kinks” to work out in the details
- Currently tests with FSI sensors and visible light ongoing
- First BSI sensor (thicker entrance window) in hand, tests to commence in July 2018

- **Expect first soft X-ray test in Fall 2018**
- Cloverleaf of 4x 2 Mpixel sensors running at 300Hz
- Can be scaled to 13Mpixel sensor => cloverleaf 52Mpixels at 120Hz
- Data rate (single 2PM 20 Gbit/s) a recognized challenge
  IT experts part of team from early stage

- **Postprocessing is a required step for high-performance soft X-ray and low-energy particle detection**
- Industries’ interest lower than that of scientists
- Techniques available at few overseas national laboratories, hard to access (politics & time …)

- **Establishing the required infrastructure and know-how within Helmholtz would form one cornerstone of the coming Distributed Detector Laboratory**

Thank you for your attention!

and

Thanks to Percival collaborators:

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Elettra:
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Dario Giuressi
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Luigi Stebel
Ralf Menk

Diamond:
Alan Greer
Tim Nicholls
Ulrik Pedersen
Nicola Tartoni

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Seungyu Rah

Soleil & DESY:
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Michael E. Hoenk
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