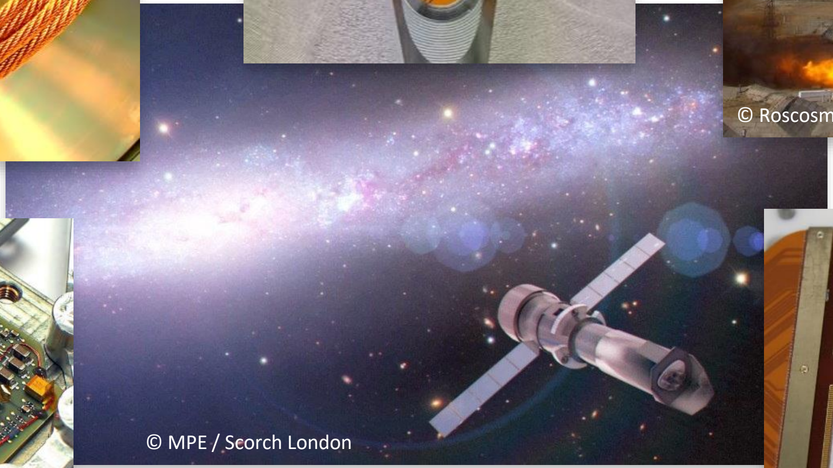
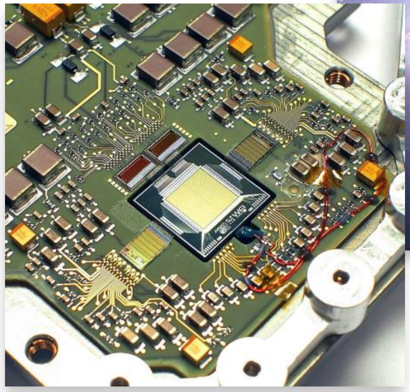
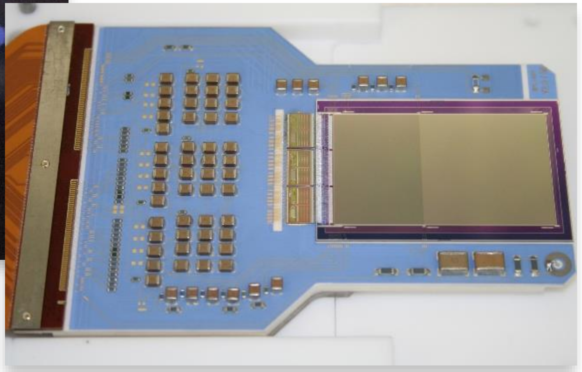
MAX-PLANCK-GESELLSCHAFT

© Roscosmos



© MPE / Scorch London





Silicon Detectors for Future X-Ray Astrophysics

Johannes Müller-Seidlitz
on behalf of the MPE High Energy Group

Outline

- High Energy Group @ MPE
- Projects in Preparation
  - eXTP - enhanced X-ray Timing and Polarimetry mission
  - EP - Einstein Probe
  - Athena – Advanced Telescope for High ENergy Astrophysics
- Requirements for Future Sensors for X-Ray Astrophysics

High Energy Group @ MPE

Investigation of the X-ray and gamma-ray universe

- Extremely hot baryonic matter (millions of degrees)
- Highly energetic non-thermal emission

Main research topics of the HEG

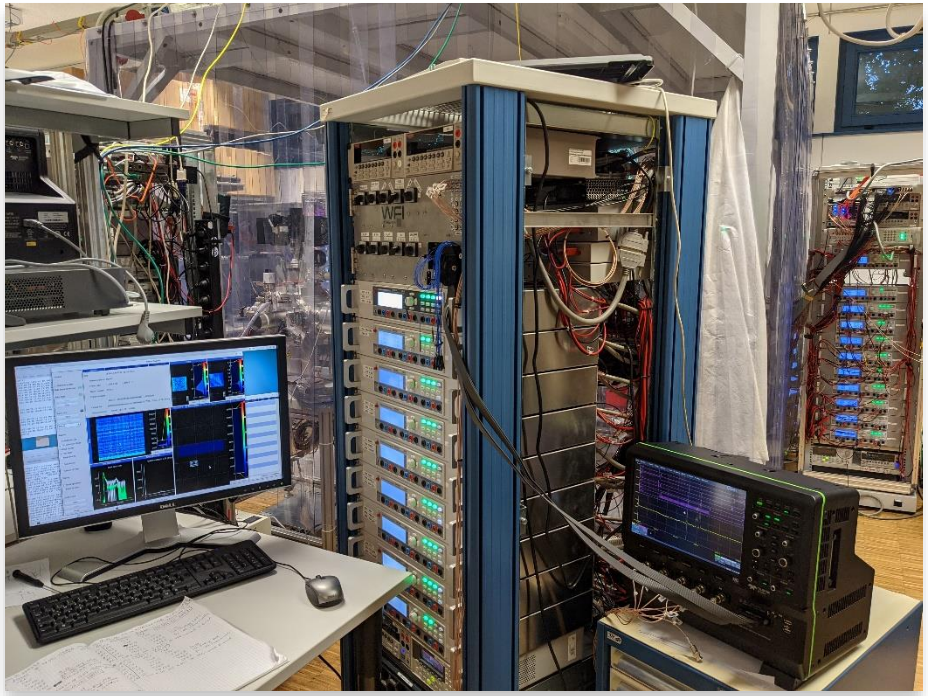
- Compact Objects and Extreme Astrophysics
- Supermassive Black Hole Evolution
- Large Scale Structure

Observation from above the atmosphere

- Early instruments on balloons and sounding rockets
- Contemporary projects are space based

HEG Detector Development @ MPE

- Dedicated detector development team in the HEG @ MPE
- Several laboratories on the Max Planck campus in Garching
- X-ray test facility with 130 m vacuum tube in Neuried



- Lab-System developed in house
- Flexible usage for different projects

eXTP: Mission

enhanced X-ray Timing and Polarimetry mission

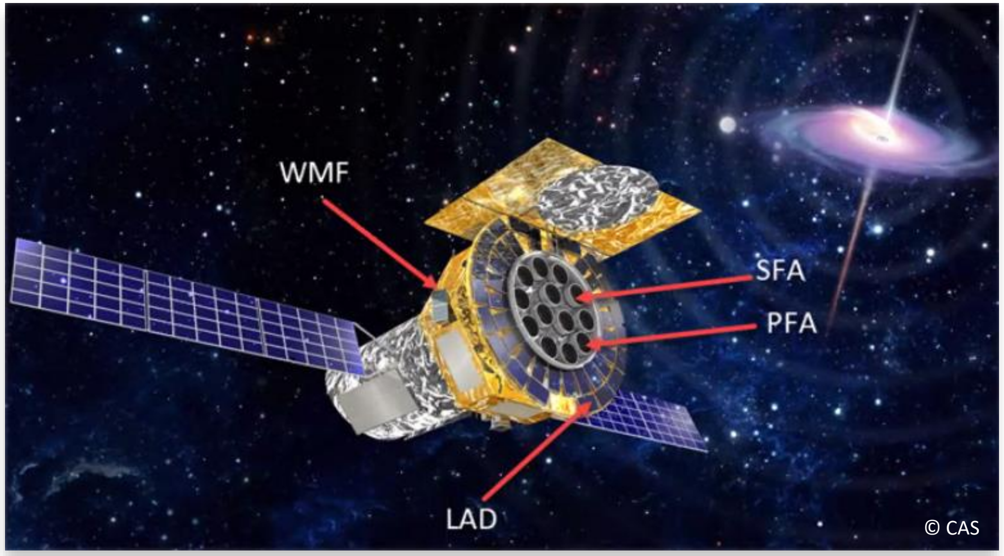
Mission of the Chinese Academy of Sciences (CAS)

Key science goals – astrophysics of bright sources / extreme physics

- Dense Matter: (exotic) states of matter at supranuclear densities
- Strong Gravity: Properties of space-time under extreme gravity
- Strong Magnetism: Behavior of light in ultra-strong magnetic fields

Mission overview:

- 5 to 8 years mission duration
- Launch mass: ~5200 kg
- Orbit at 550 km
- Launch date: ~2027

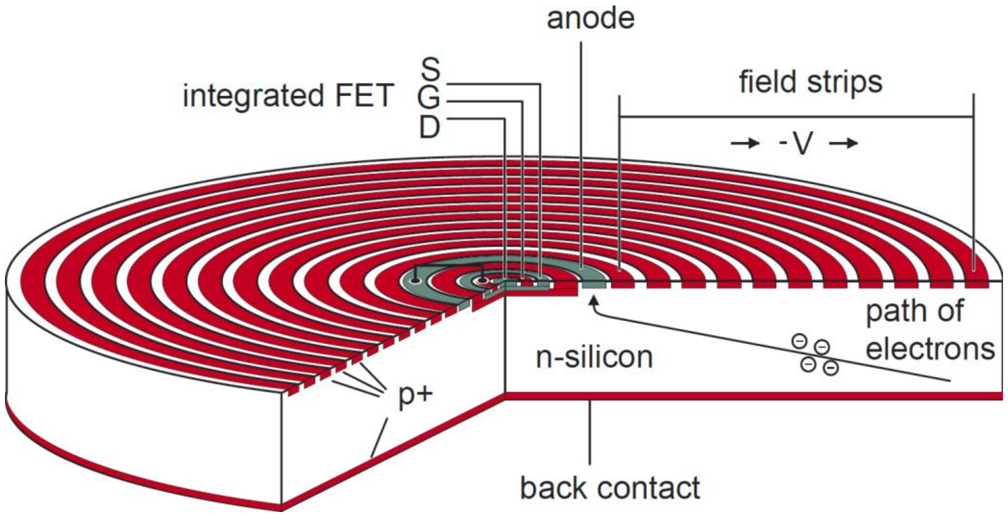


eXTP: SFA

- MPE contributing to SFA – Spectroscopy Focusing Array
- 9 telescopes with Wolter I optics
- Each equipped with a 19-cell SDD from HLL
  - Cell in the center for the object of interest
  - Surrounding cells to track the X-ray background
  - Three 8-channel ASICs with pile-up rejection

Requirements:

- 0.5 – 10 keV
- 180 eV @ 6 keV
- 10 µs resolution
- 2 µs accuracy



- ASIC test successful
  - Shaping and pile-up rejection is working
- SDD is currently in commissioning

Einstein Probe: Mission

Small mission of the Chinese Academy of Sciences (CAS) together with ESA and MPE

Science objectives:

- High energy transients
- Monitoring of variable objects

Mission overview:

- 3 to 5 years mission duration
- Launch mass: ~1050 kg
- Orbit at 600 km
- Launch date: End of 2022

Two instruments

- WXT: Wide-field X-ray Telescope (60° x 60° Field-of-View featuring Lobster optics)
- FXT: Follow-up X-ray Telescope

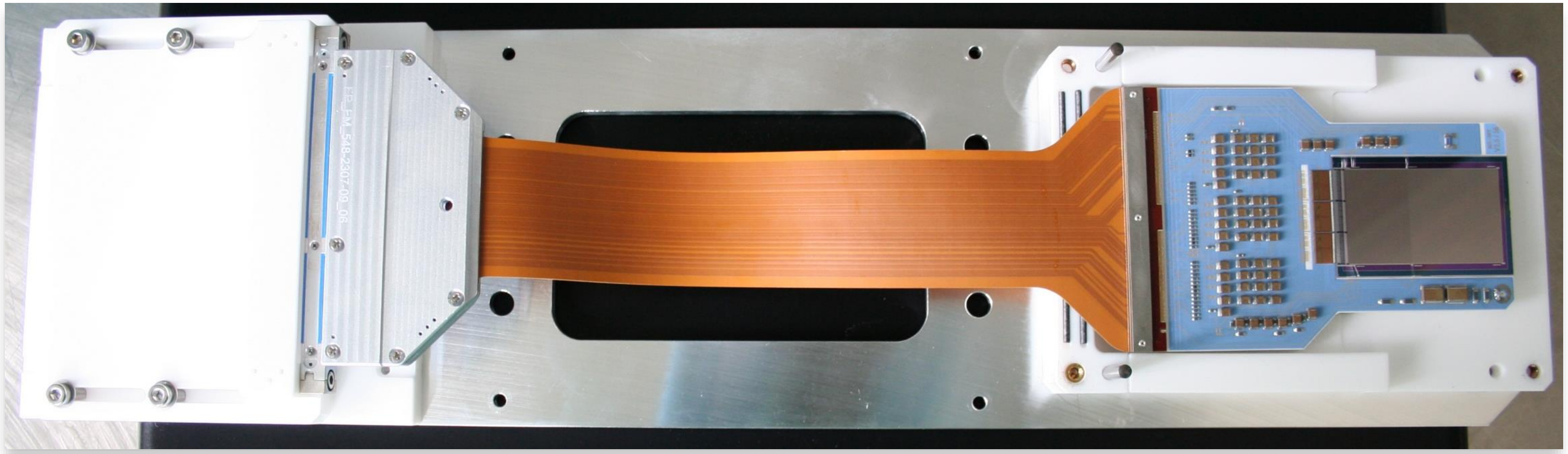
Einstein Probe: FXT

pnCCDs (eRosita) from HLL, electronics from MPE

Qualification at MPE

Status:

- Engineering Module: shipped to China in Oct. ’20
- Qualification Module: shipped in Jan. ’21
- First Flight Module: shipped in Aug. ‘21
- Second Flight Module: under test, shipment planned for end of ‘21



Requirements:

- 0.3 – 10 keV
- 120 eV @ 1.25 keV
- ≥ 20 Hz Frame Rate

FM1 performance (T = -90°C):

- CTI: 31.14e-6
- 152 eV @ 6 keV
- Noise: 2.6 e^- RMS

Athena: Mission

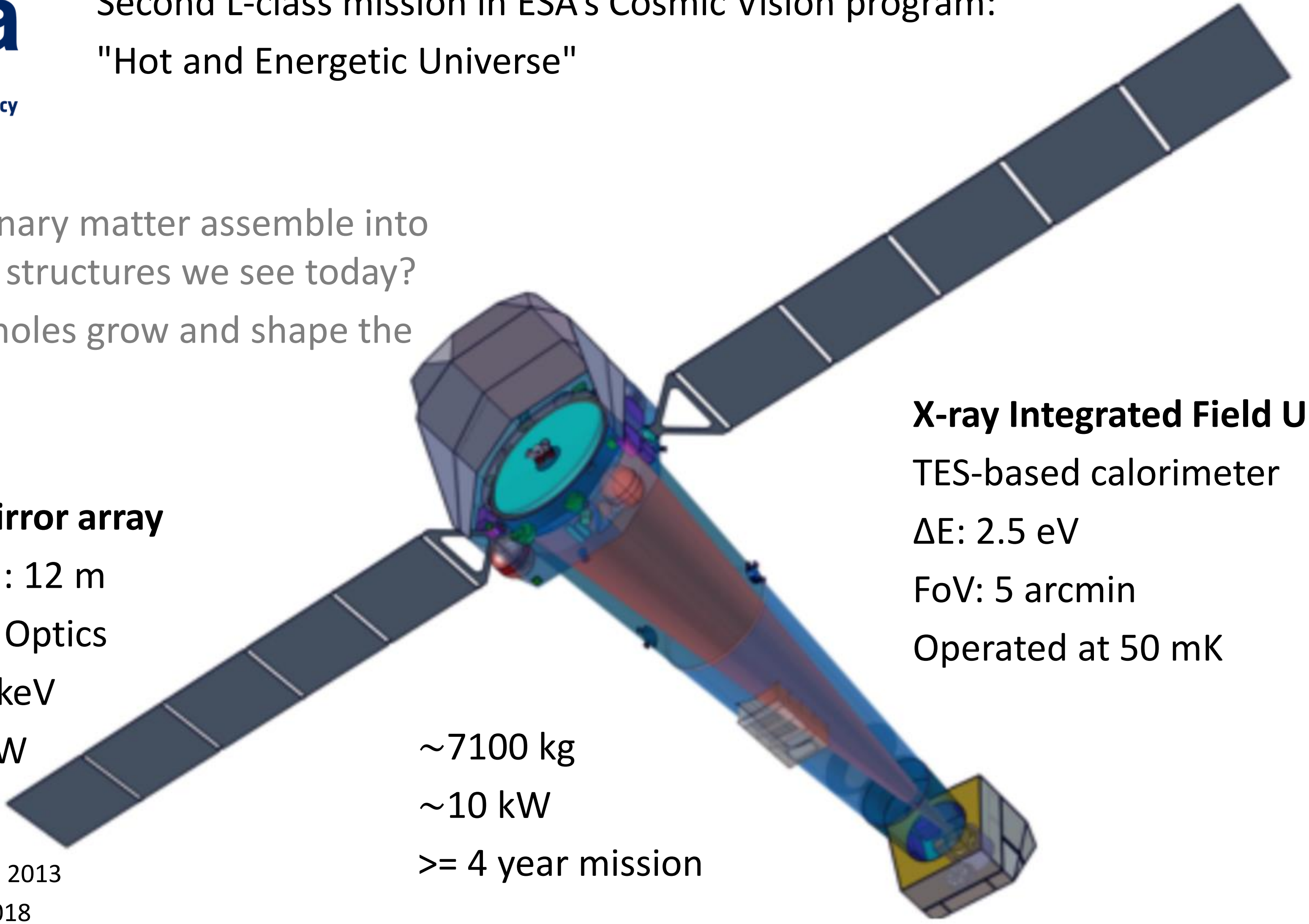
European Space Agency

Second L-class mission in ESA's Cosmic Vision program:
"Hot and Energetic Universe"

Launch:
~2034
Ariane 64
L1 orbit?

How does ordinary matter assemble into the large-scale structures we see today?

How do black holes grow and shape the universe?



X-ray Integrated Field Unit
TES-based calorimeter
ΔE: 2.5 eV
FoV: 5 arcmin
Operated at 50 mK

Movable mirror array
Focal length: 12 m
Silicon Pore Optics
1.4 m² @ 1 keV
5 arcsec HEW

Wide Field Imager
DEPFET-based Si sensor
ΔE: 130 eV @ 6 keV
FoV: 40 arcmin
High count rate capability

~7100 kg
~10 kW
>= 4 year mission

Willingale et al., 2013
Bavdaz et al., 2018

Athena: WFI

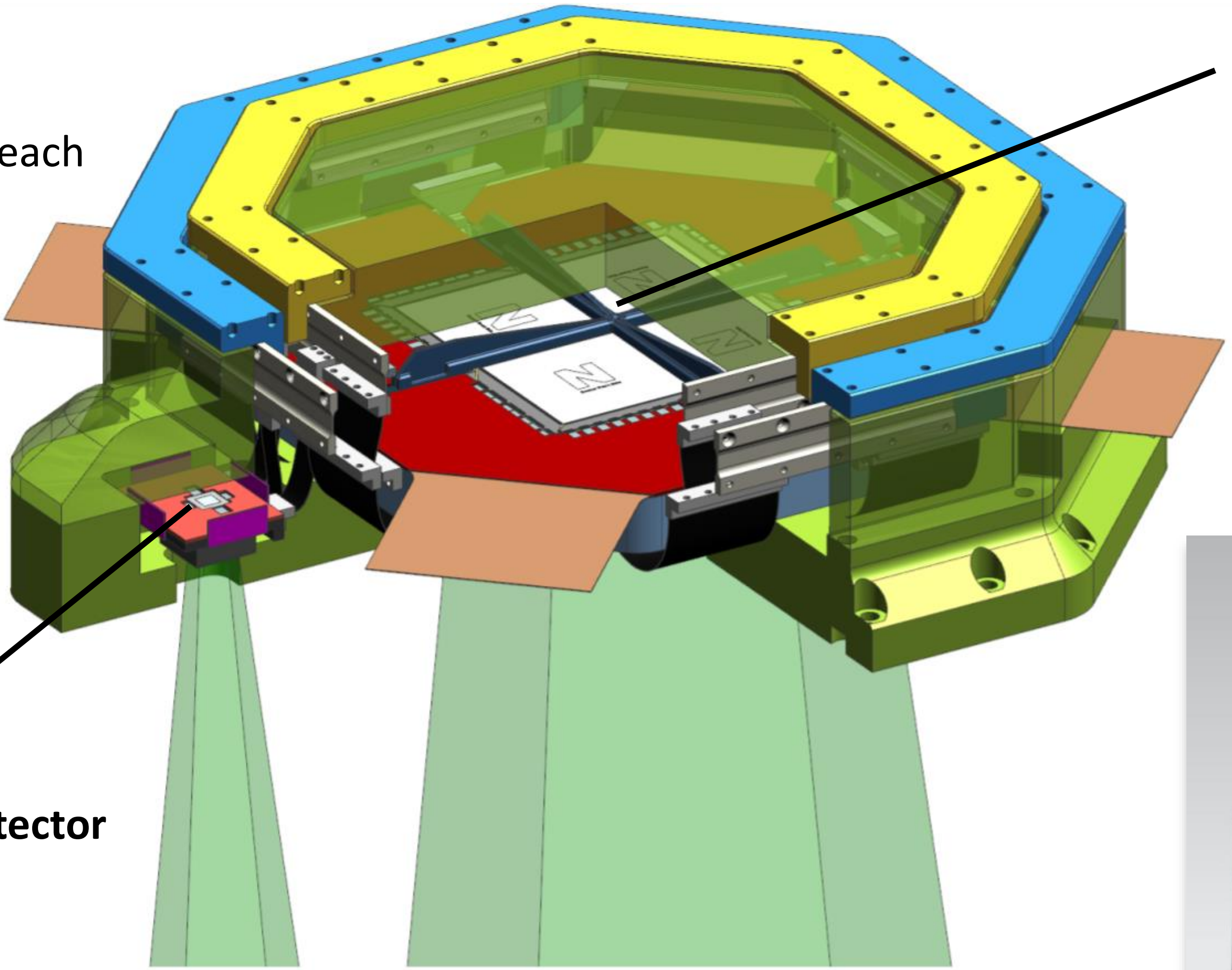
DEPFET pixels

130 µm x 130 µm each

Readout:

row-wise

column-parallel



Large Detector Array

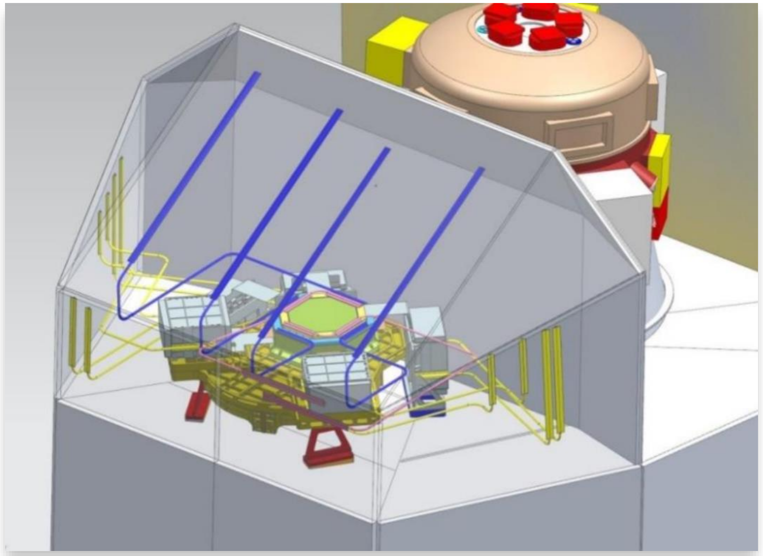
4 times 512 x 512 pixels

40 arcmin field of view in total

5 ms / frame (goal: 1.3 ms / frame)

optional window mode

Thermal connections



High Count Rate Detector

64 x 64 pixel

80 µs / frame

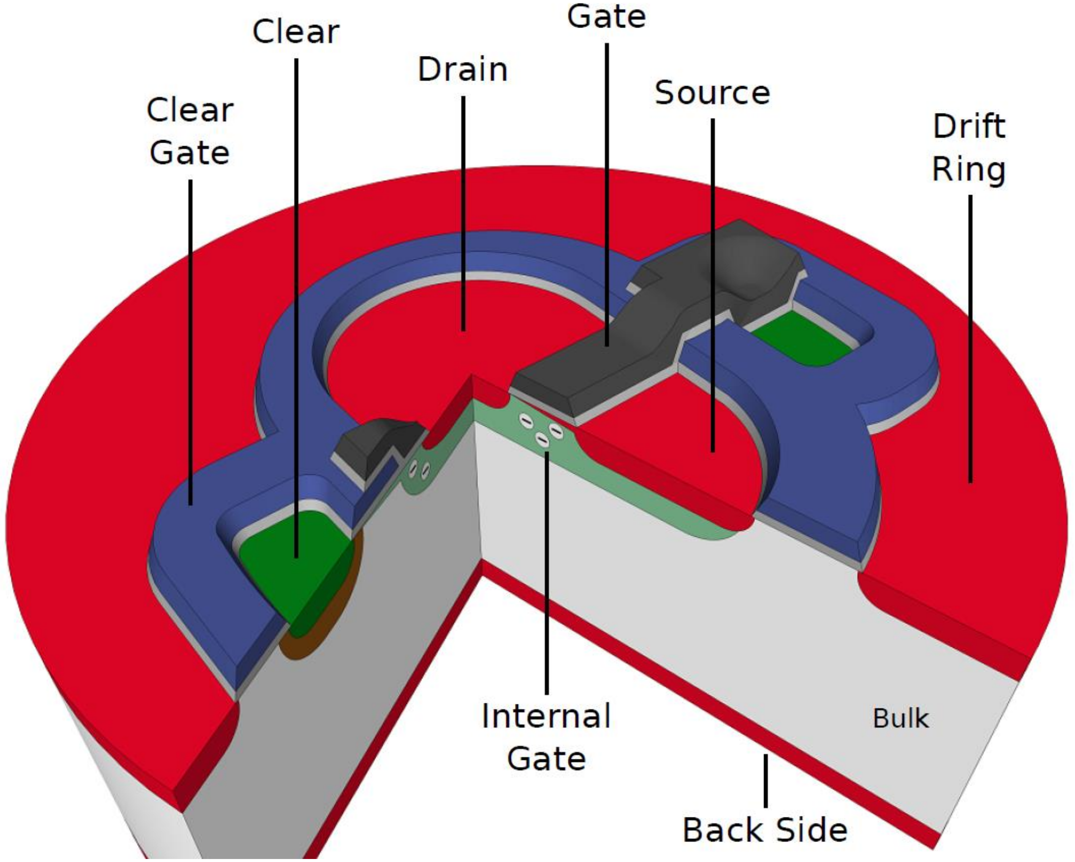
<1% pile-up, >80% throughput @ 1 Crab

↓ Mirror

Athena WFI: Sensor Concept

DEPFET

DEpleted P-channel Field Effect Transistor



- back side illuminated
- 450 µm wafer thickness
- fully depleted, high resistivity (~5 kΩ·cm)
- sideward drift enabled by ring-like structures on the front side

- MOS transistor
- hole current
- electrons from sensitive volume collected in "internal gate"
- mirror charges change conductivity in transistor channel
  - proportional to number of collected electrons

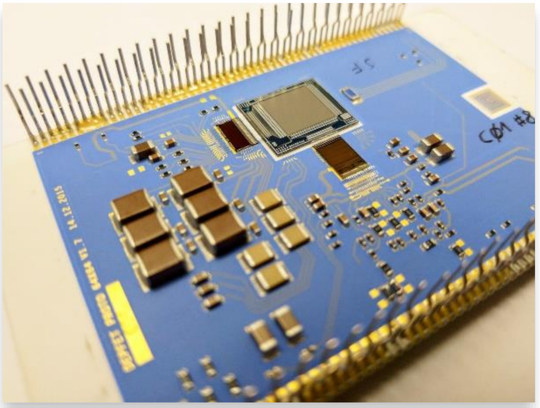
Athena WFI: Prototyping Phase

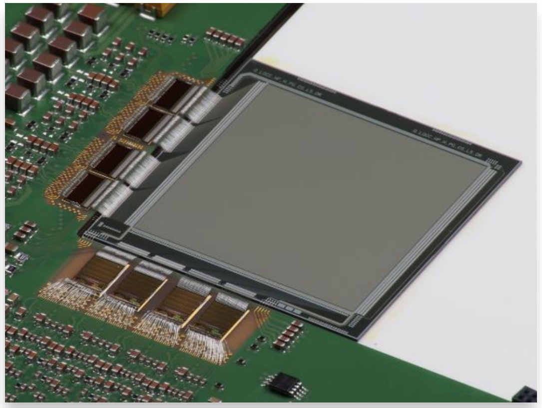
Prototype DEPFETs (64 x 64 pixels):

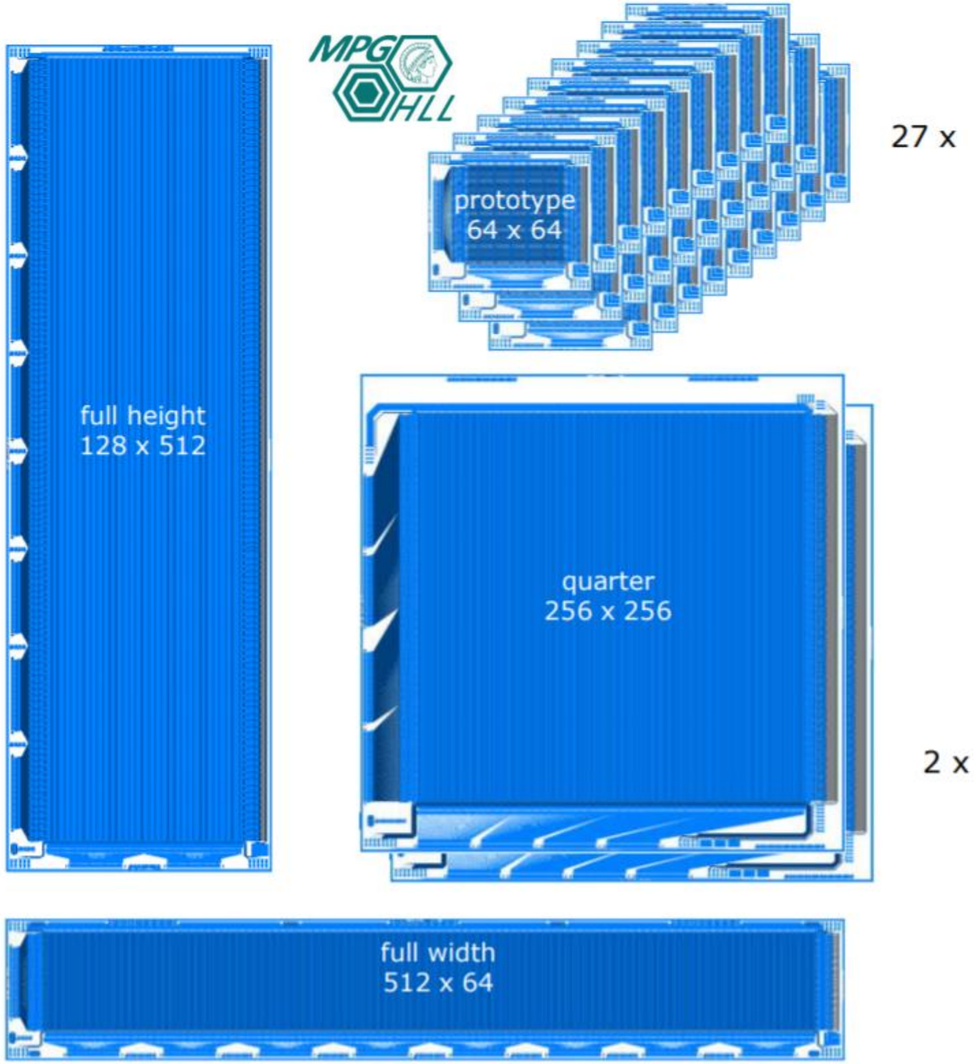
- 17 different DEPFET design variations
- 7 different fabrication technology options
- 2 different readout modes

Larger Arrays:

- test full capacity of a row/column connected to an ASIC
- test homogeneity of a larger number of pixels

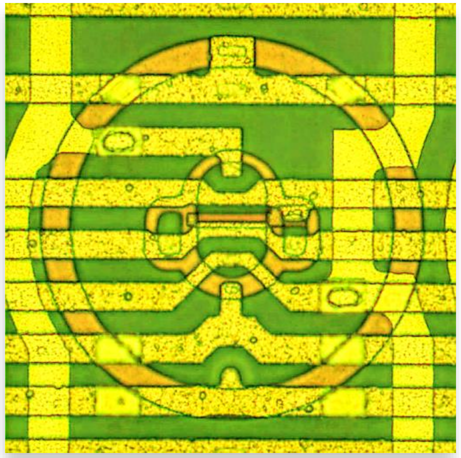




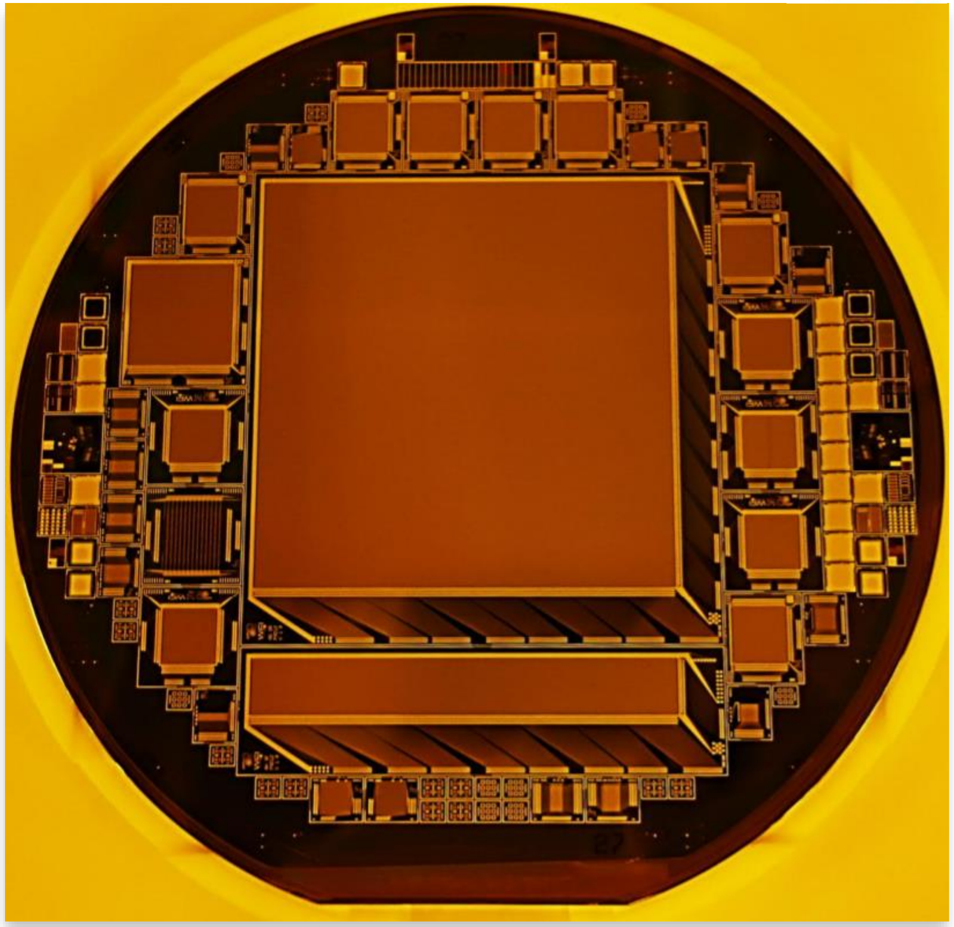


Athena WFI: pre-Flight Production

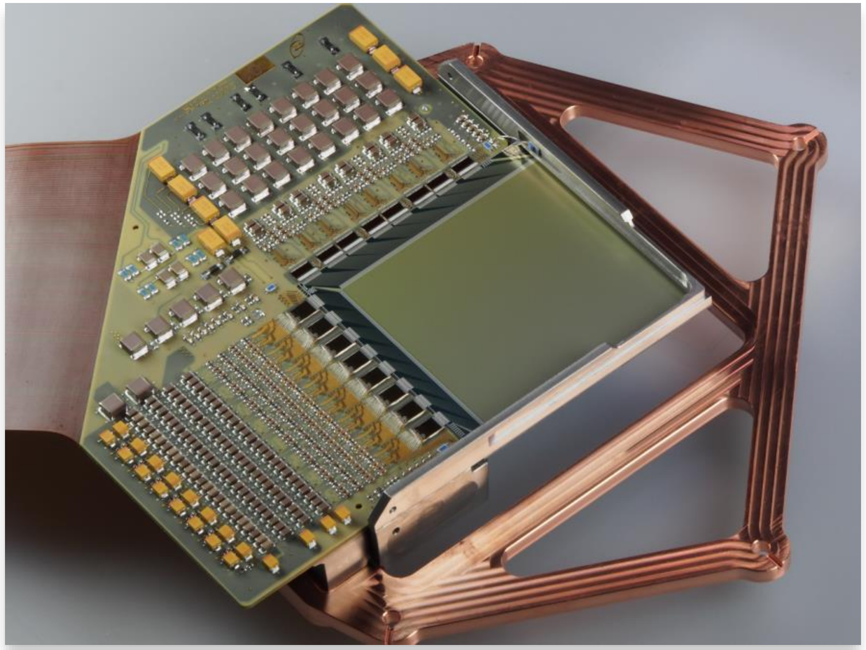
- fabrication of chosen options
  - linear gate DEPFET (20 µm gate width, 5 µm length)
  - thin gate oxide
  - additional implants for less impact ionization and to improve charge transport to the clear contacts
  - drain current readout
- prototype devices for testing / verification
- full size device (512 x 512 pixels)
- full height device in source follower readout mode
- high count rate sensors
- devices are under test



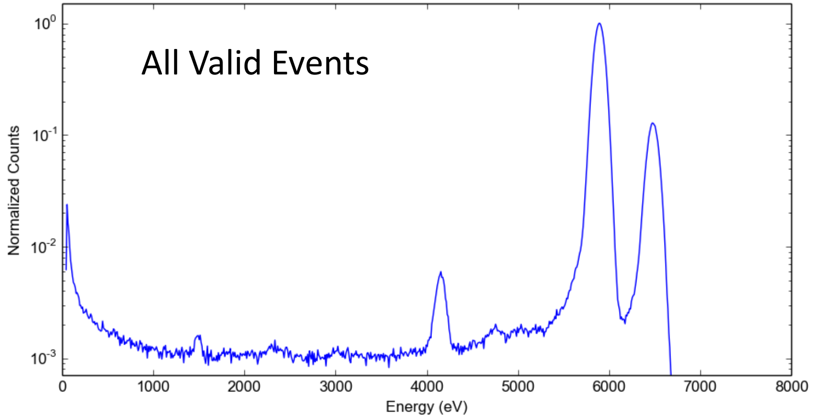
P. Lechner @ HLL



Athena WFI: Status

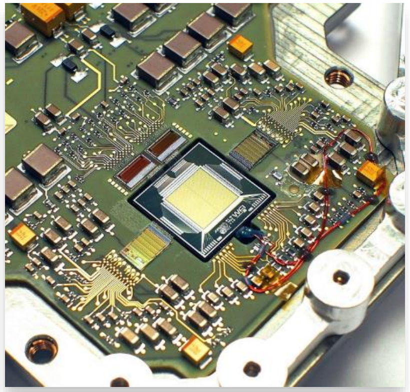


- Prototype DEPFETs (64 x 64 pixels) show excellent performance
- First High Count Rate and Large Detectors mounted

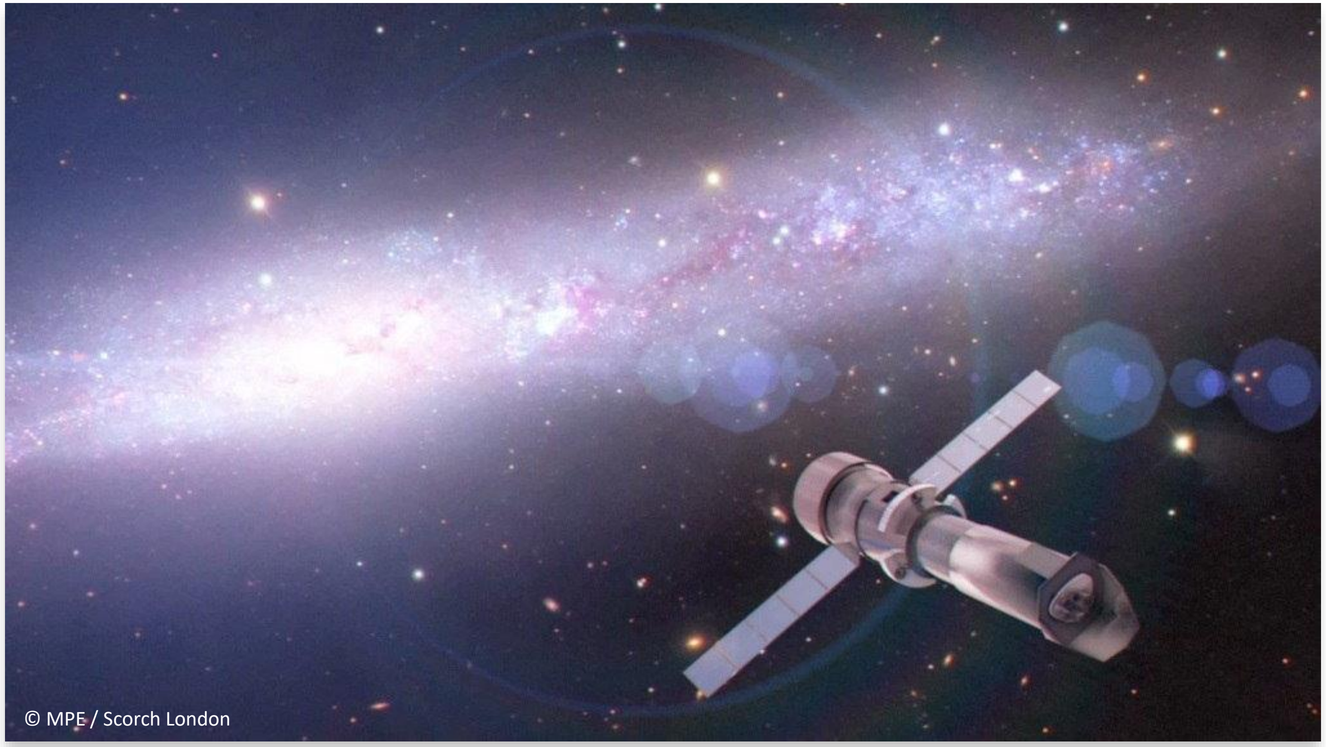


High Count Rate Detector
- 129.4 eV @ 5.9 keV
- Noise: 2.8 e^- ENC
- Time per row: 2.5 µs
- Frame time: 80 µs

Large Detector Quadrant (@ 2 ms)
- In commissioning
- 131 eV @ 5.9 keV
- Noise: 3.2 e^- ENC
- Frame Time:
  - Requirement: 5 ms
  - Goal: 1.28 ms



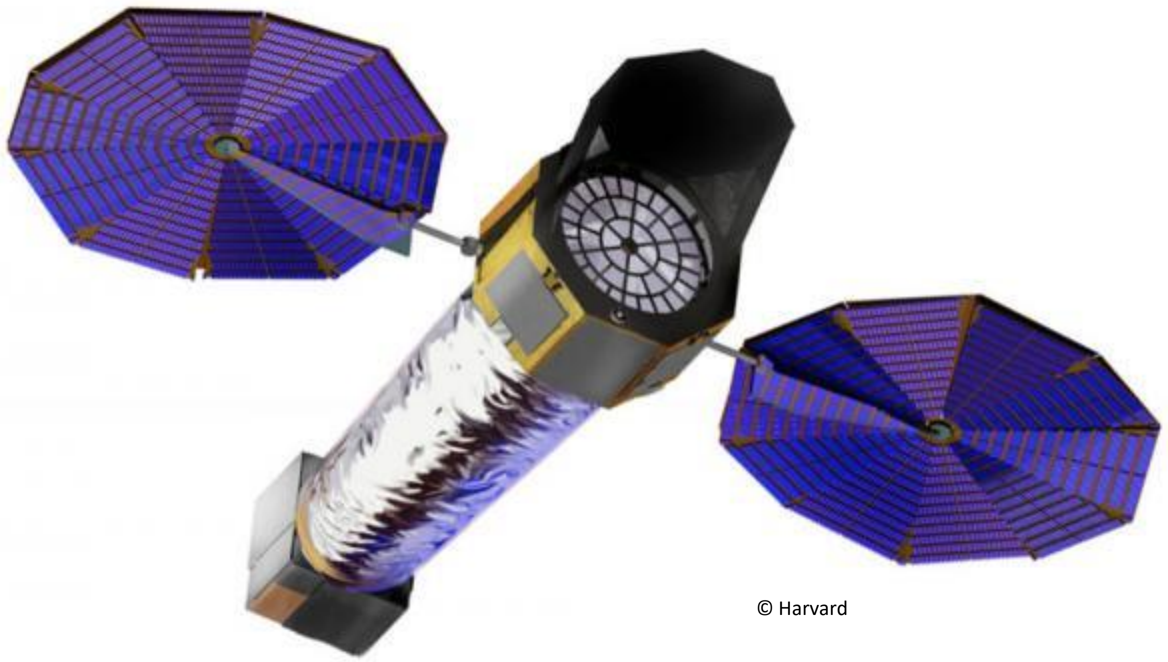
Future Requirements



What’s next?

Spatial Resolution

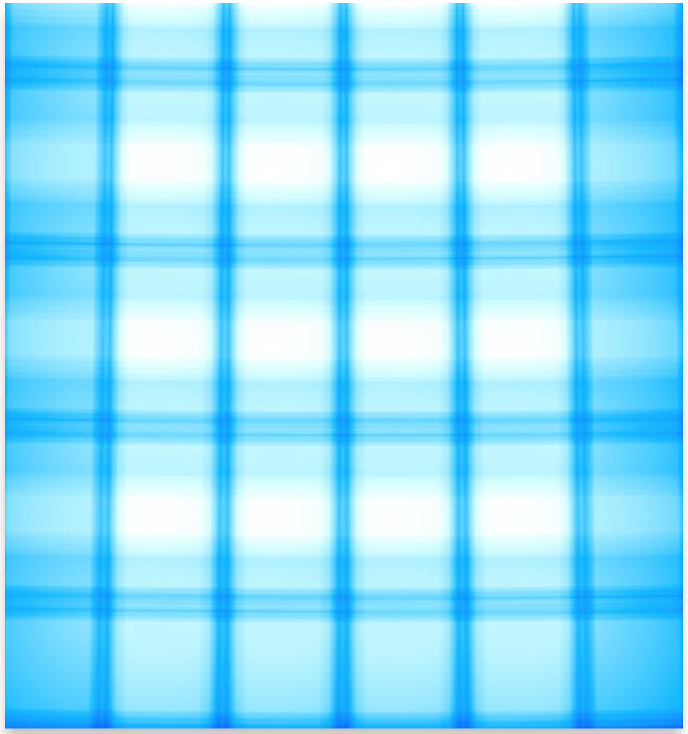
- Smaller pixels for high resolution imaging applications
  - Future X-ray optics will enable a better spatial resolution
  - Lynx (US X-ray mission) targets 0.5“ on-axis PSF (Athena 5“)
  - 10 µm – 20 µm pixels (edge length)



© Harvard

Wide Field Imaging

- Larger matrices for wide-field imaging
  - Observing time is expensive
  - Gaps between sensors require further observations to complete a field
  - Switch to larger wafers?



Exposure Map from Sixte
T. Dauser, Erlangen

Simple Concepts for Small Projects

- “Simpler” spectral-imaging sensors for smaller projects
  - with lower complexity, cost, power consumption, thermal requirements etc.
  - maybe simpler electronics necessary
- ASIC developed at HLL supplied together with the sensor?
- For contributions to small missions like SVOM or EP

Hard X-Ray Sensitivity

- Hard X-ray sensitivity (up to ~30 keV ideally) to observe hard X-ray emission from AGN
  - Not resolvable by contemporary missions
  - QE of 50% @ 30 keV results in 2.3 mm of material in case of silicon

Background Rejection

- Imaging sensors for hard (>2 keV) X-ray imaging with efficient background rejection via anti co-incidence or self anti-co-incidence
  - frame time of about 0.25 ms for an Athena-like mission

Interferometry

- X-ray interferometry:
  - Large area with small pixels to map fringes with high accuracy
  - 30 cm x 30 cm sensor area
  - 10 µm pixel size
  - No gaps (or as small as possible)
  - Good spectral resolution
  - Background reduction is timing driver
    - A few kHz frame time

Summary

Requirements for future X-ray astrophysics

- Small pixels: 10 µm – 20 µm edge length
- Larger sensors for wide-field imaging
- “Simple” sensors concepts, maybe including corresponding ASICs
- Hard X-ray sensitivity (up to 30 keV)
- Fast sensors with about 4 kHz frame rate (any size)
- Large sensors (a few decimeters) with small pixels (10 µm) without gaps but fast readout