The Maia Detector System: A New Way to do Scanning Probe Fluorescence Imaging

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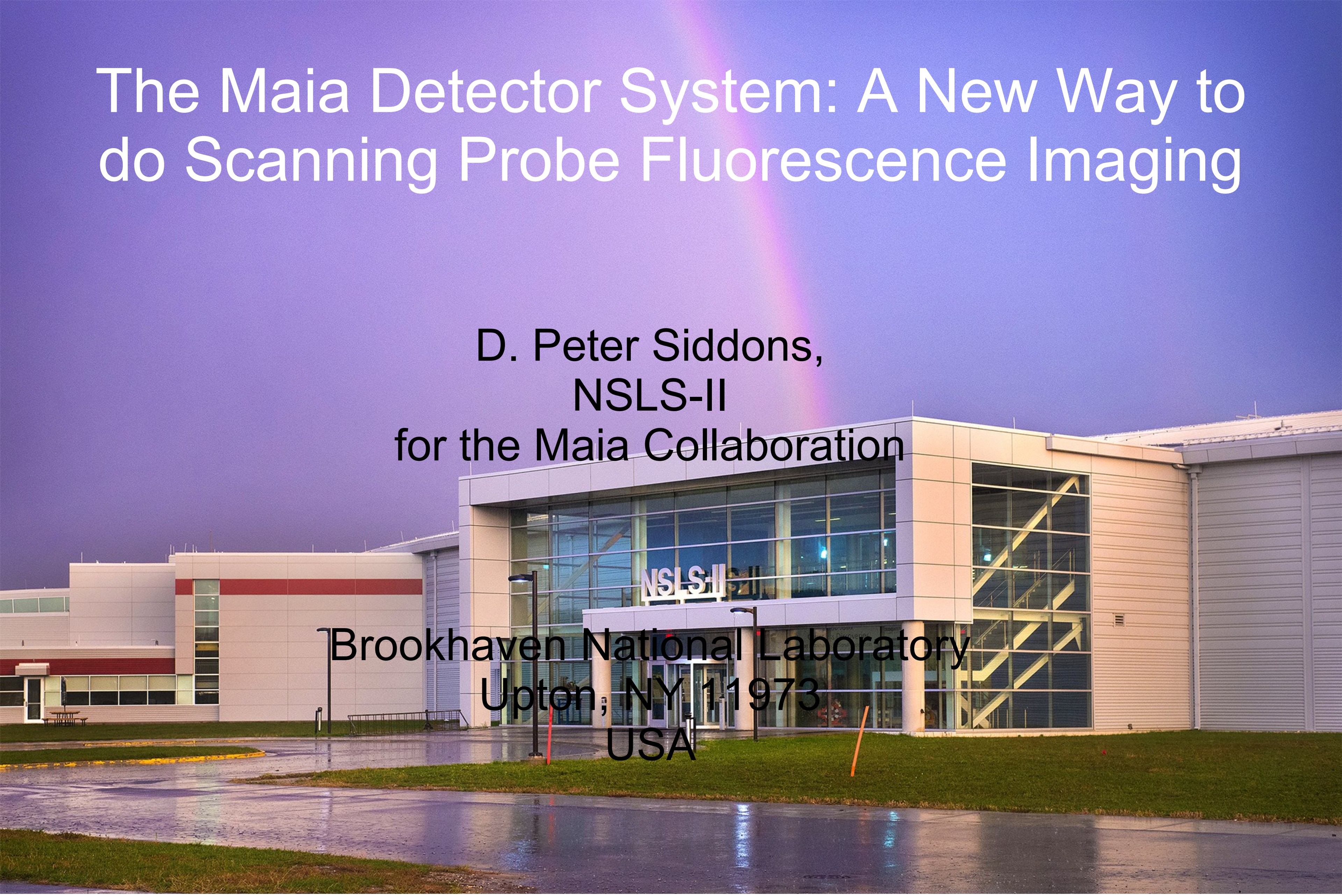
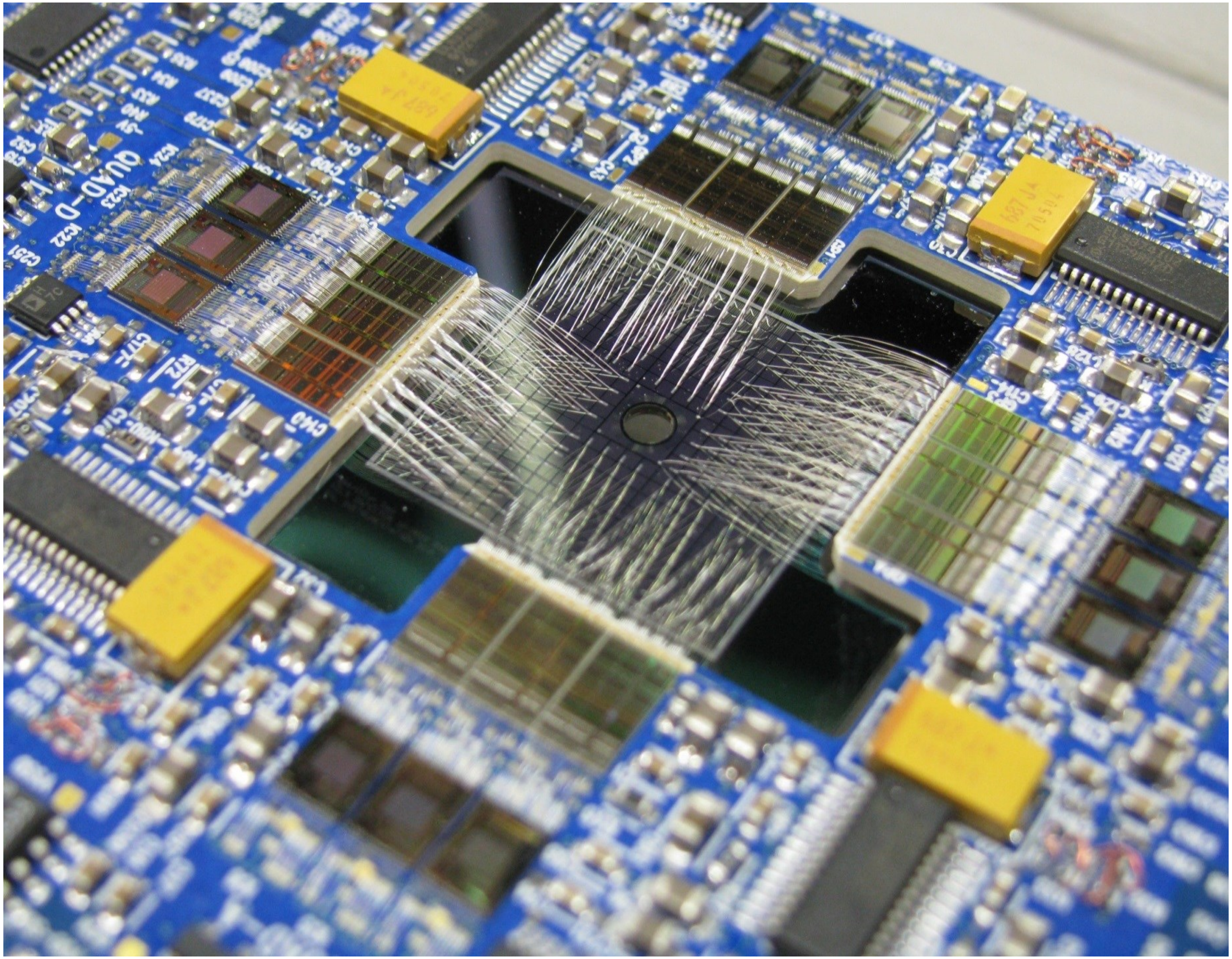


IFDEPS 2018, Annecy, France

What’s new?

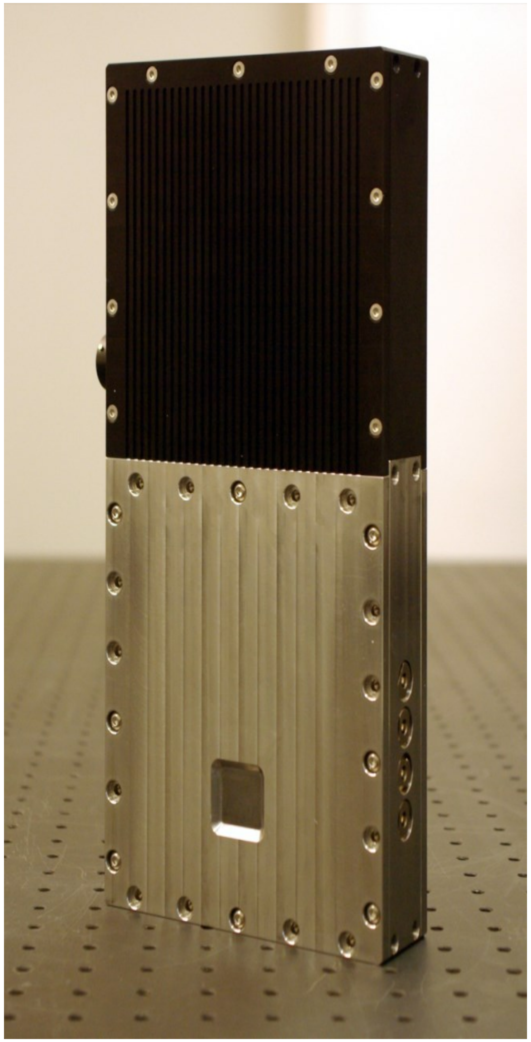
- When we started the Maia project, fly-scanning was not common. First demonstration in 2005 (not yet Maia!)
- New acquisition model; “Event-based”, photon-by-photon, with embedded scan information
- New fitting method: “Dynamic Analysis” from Chris Ryan, again, photon-by-photon.
- Very large detector array: 384 independent detectors with independent readout chains.
- ASIC-based high density readout
- FPGA-based fast, on-the-fly computation of elemental maps.
- R&D100 Award in 2011.

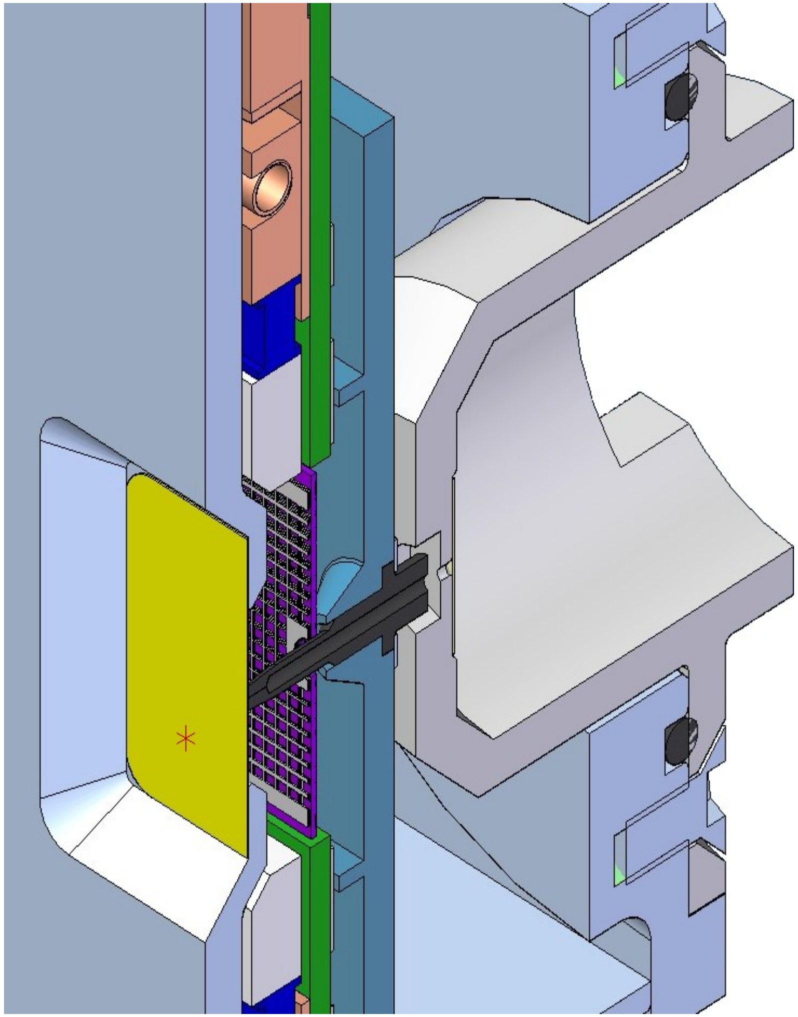
Maia Sensor + ASICs



Siddons et al., Journal of Physics:Conference series 499 (2014) 012001

Photo and cross-section

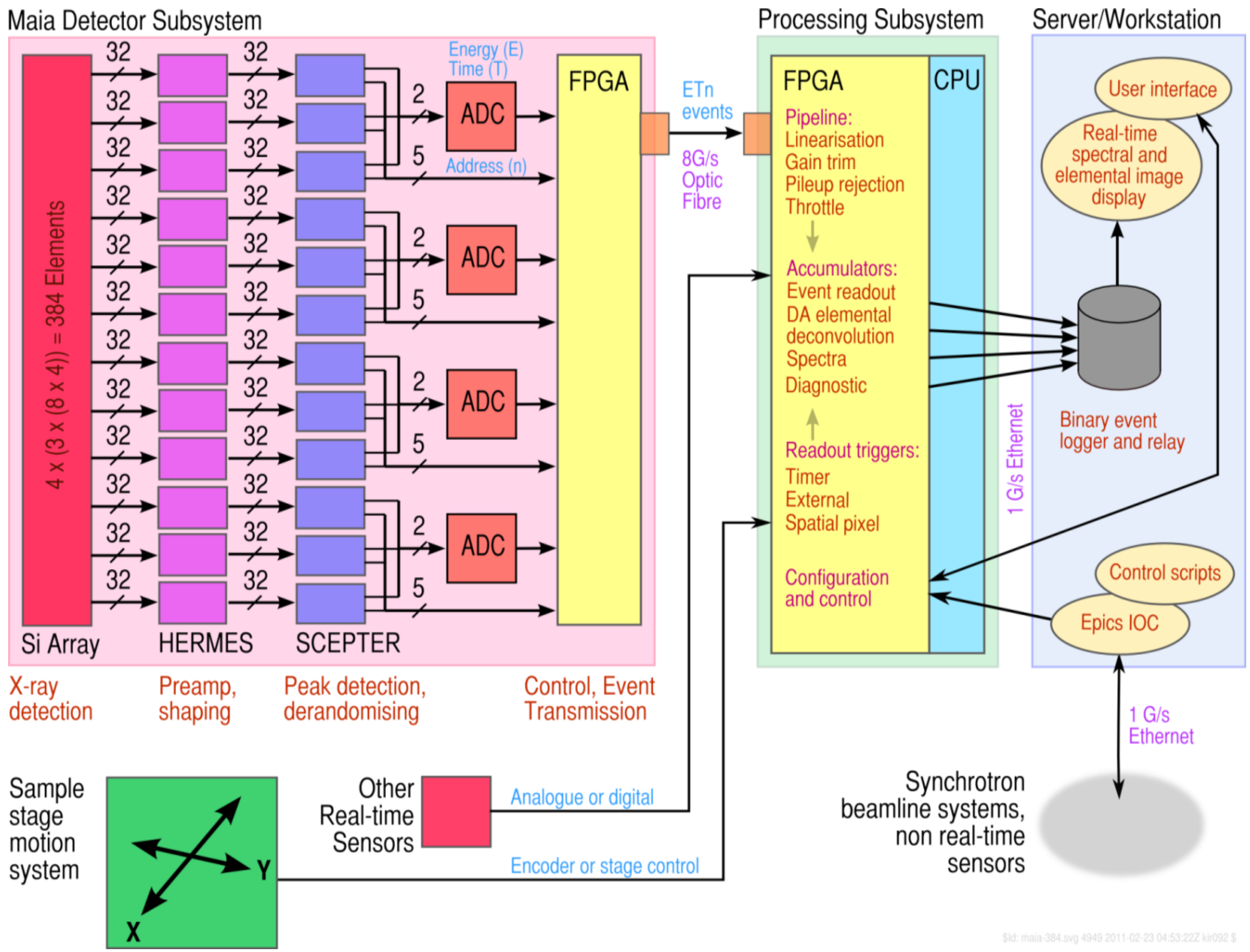




Kirkham et al., AIP Conference series 1234 (2010) 240-243

Block diagram of Maia processing chain

- HYMOD controls stage and reads detector
- Each photon tagged with energy, XY position and pileup status
- Initial coarse scan generates 'average' spectrum which makes DA matrix
- DA technique then presents elemental map as acquisition proceeds.



Kirkham et al., AIP Conference series 1234 (2010) 240-243

Spectral deconvolution →
Dynamic Analysis method

PIXE/SXRF spectra are linear combinations of pure element spectral signatures.

Deconvolution cast as a matrix transformation:

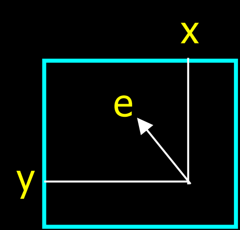
$$C \;=\; Q^{-1}\,\Gamma\,\mathbf{S}$$

- C: Concentration vector
- Γ: Transform matrix
- **S**: Spectrum vector

PIXE/SXRF Imaging:

X-ray event: Energy 'e'

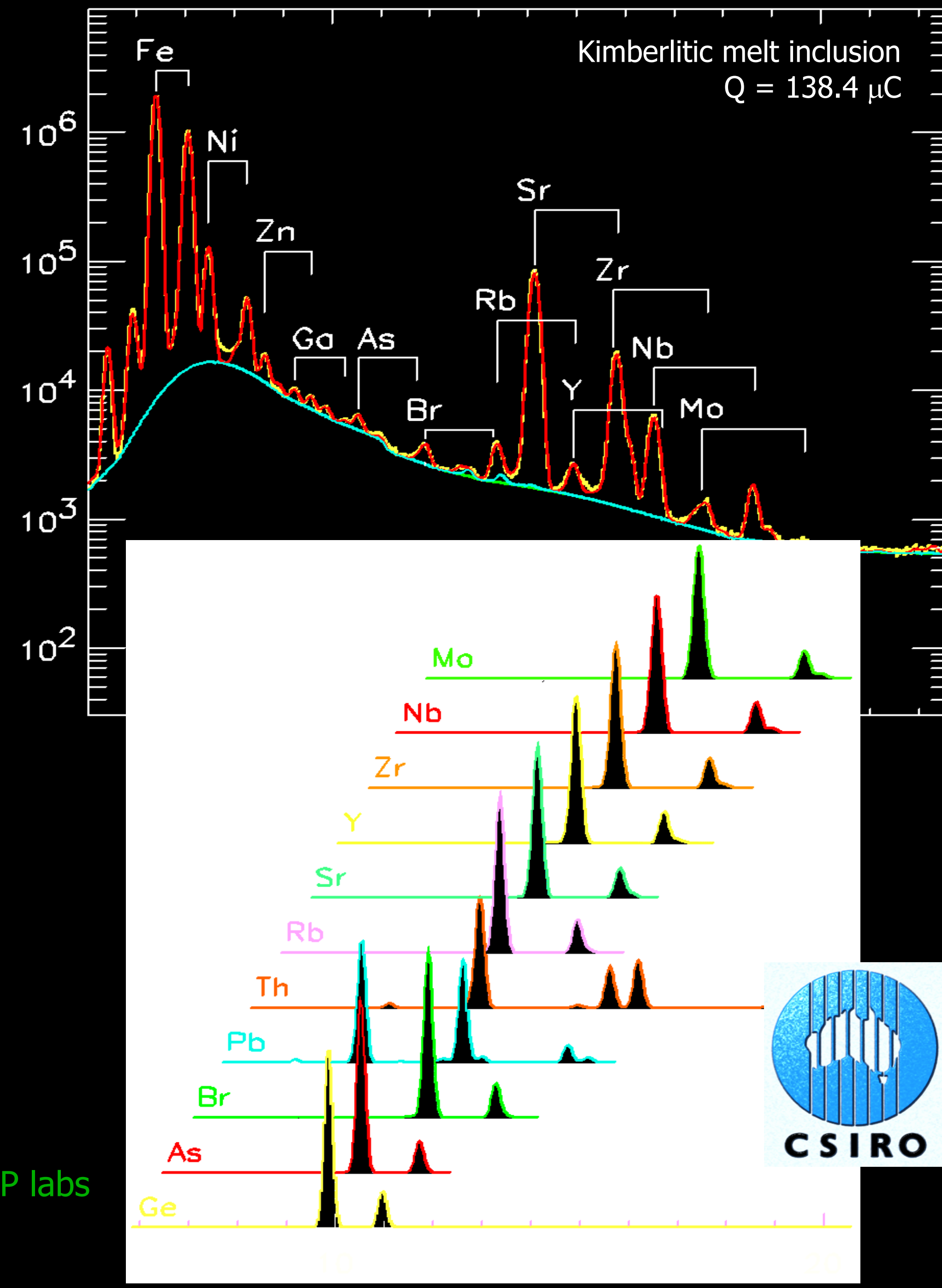
Position 'x,y'



The elements of the Γ matrix for column 'e' are the increments to make to all images at 'x,y'.

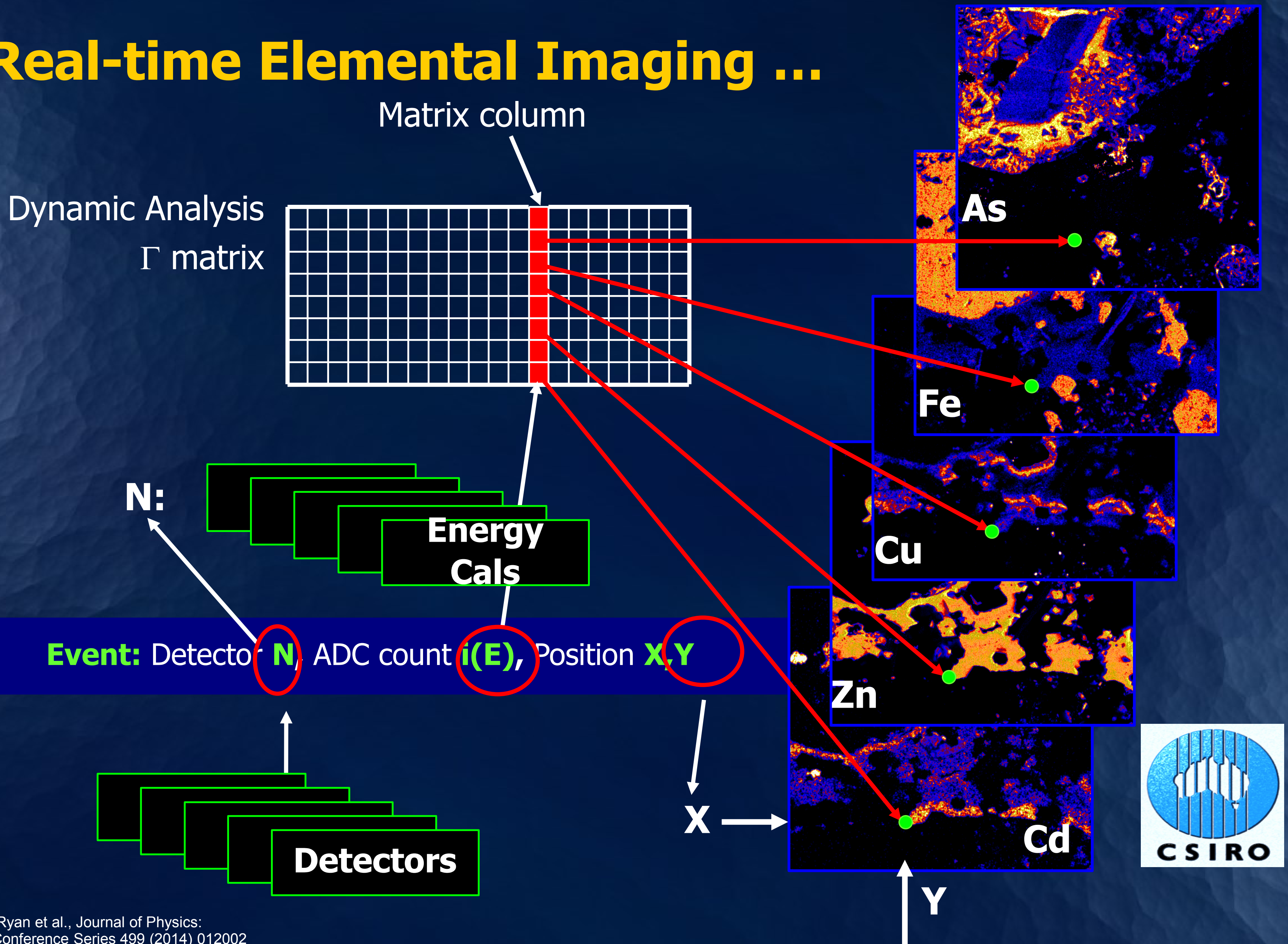
GeoPIXE software

Now at APS, NSLS, CLS, 19 NMP labs



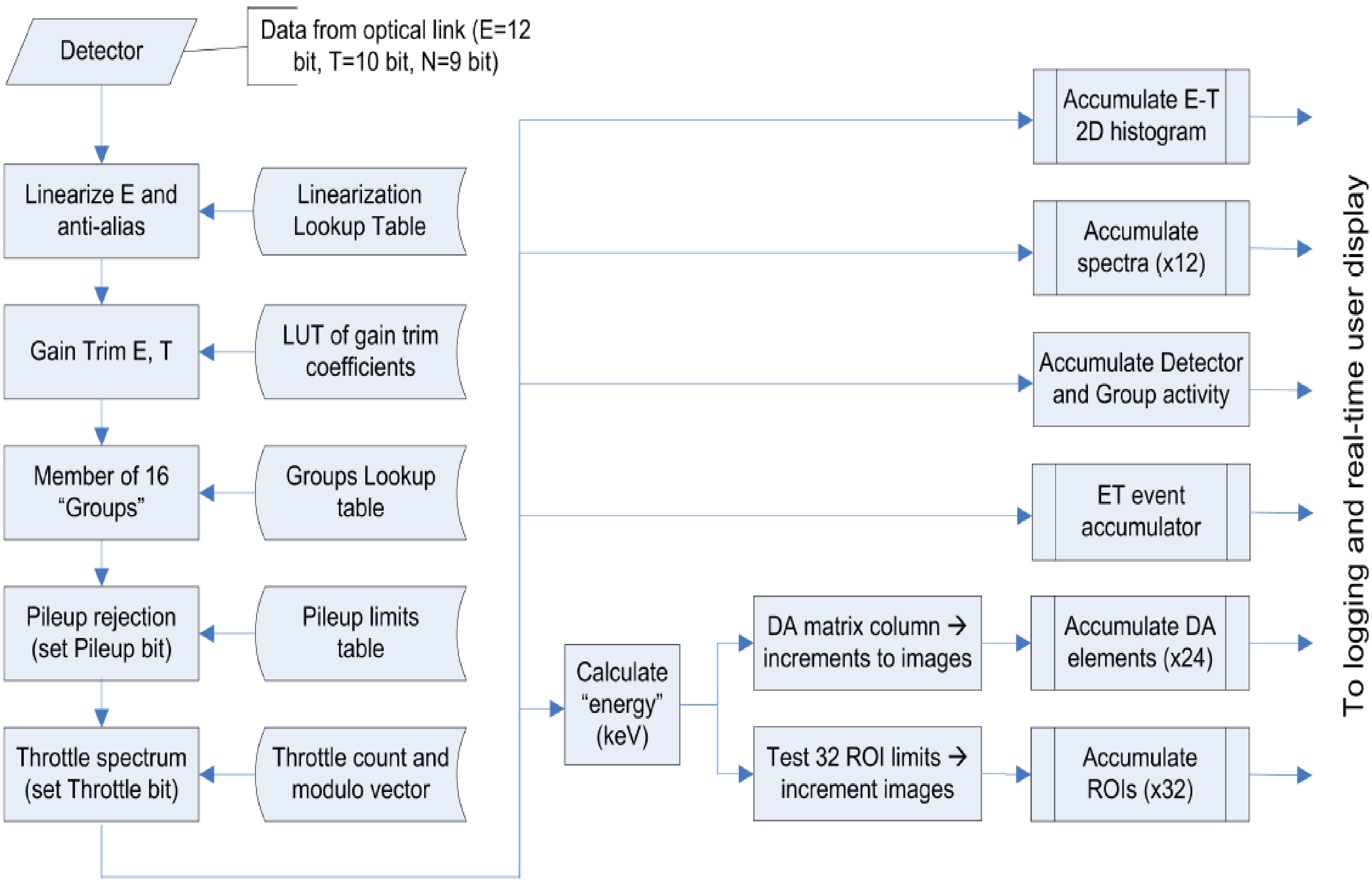
Ryan, Int. J. Imaging Systems and Technology 11 (2000) 219-230

Real-time Elemental Imaging …



Ryan et al., Journal of Physics: Conference Series 499 (2014) 012002

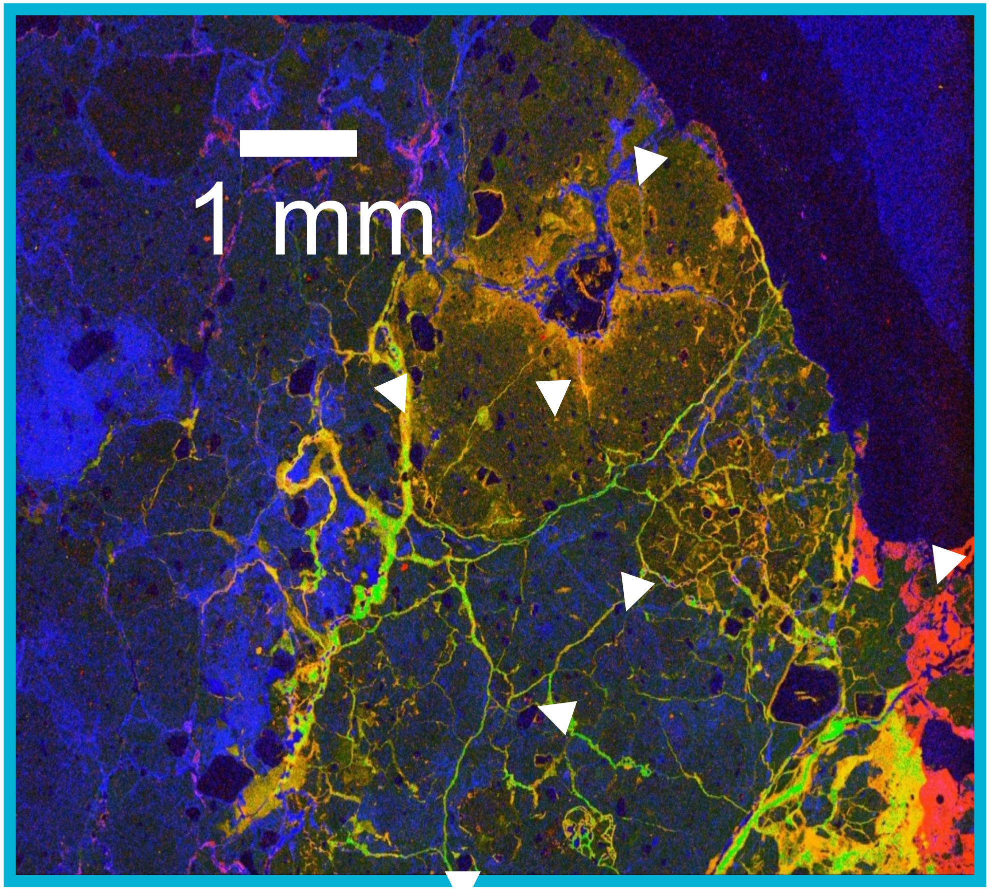
Maia data flow



Ryan et al., Journal of Physics: Conference Series 499 (2014) 012002

Extremely inhomogeneous samples

- 9600 x 8000 pixels
- 0.6 ms/pixel
- 1.25 um pixels
- Arrows point to micron-scale gold particles

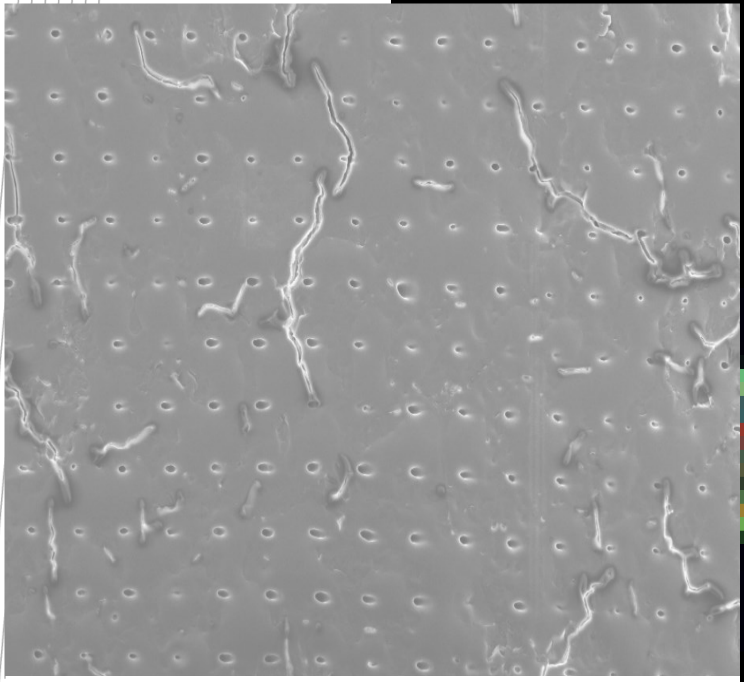


Rob Hough, James Cleverley, CSIRO, private communication

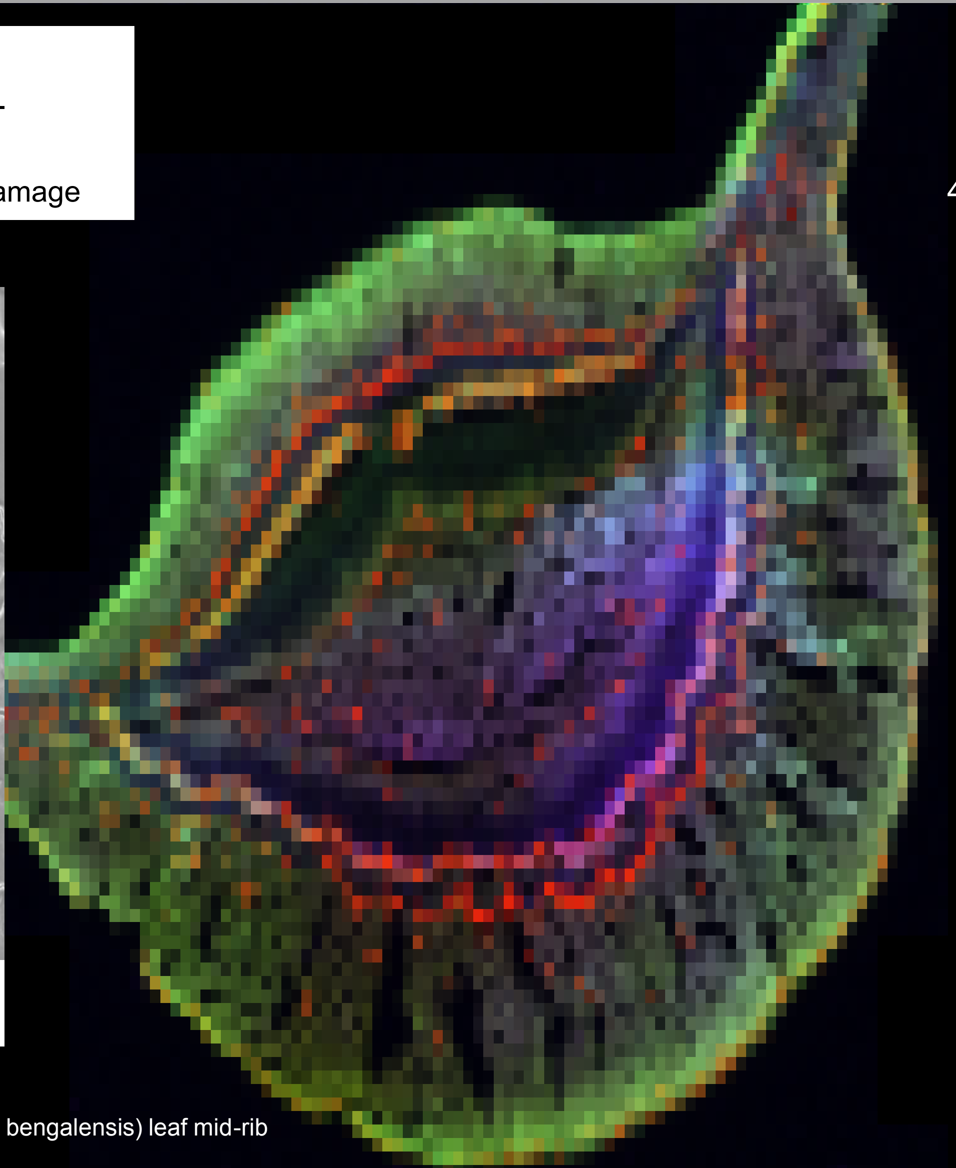
Ryan et al., AIP Conference Proc. 1221 (2010) 9

Why high definition imaging?
Minimize damage

- **Avoid step-scans and long pixel dwell**
  - ✓ Long dwells → few pixels → under-sampling
  - ✓ Concentrated dose → increased damage



SEM of wheat sample post-SXRF showing grid of damage holes (2 μm beam, 15 μm steps for 0.5 sec)

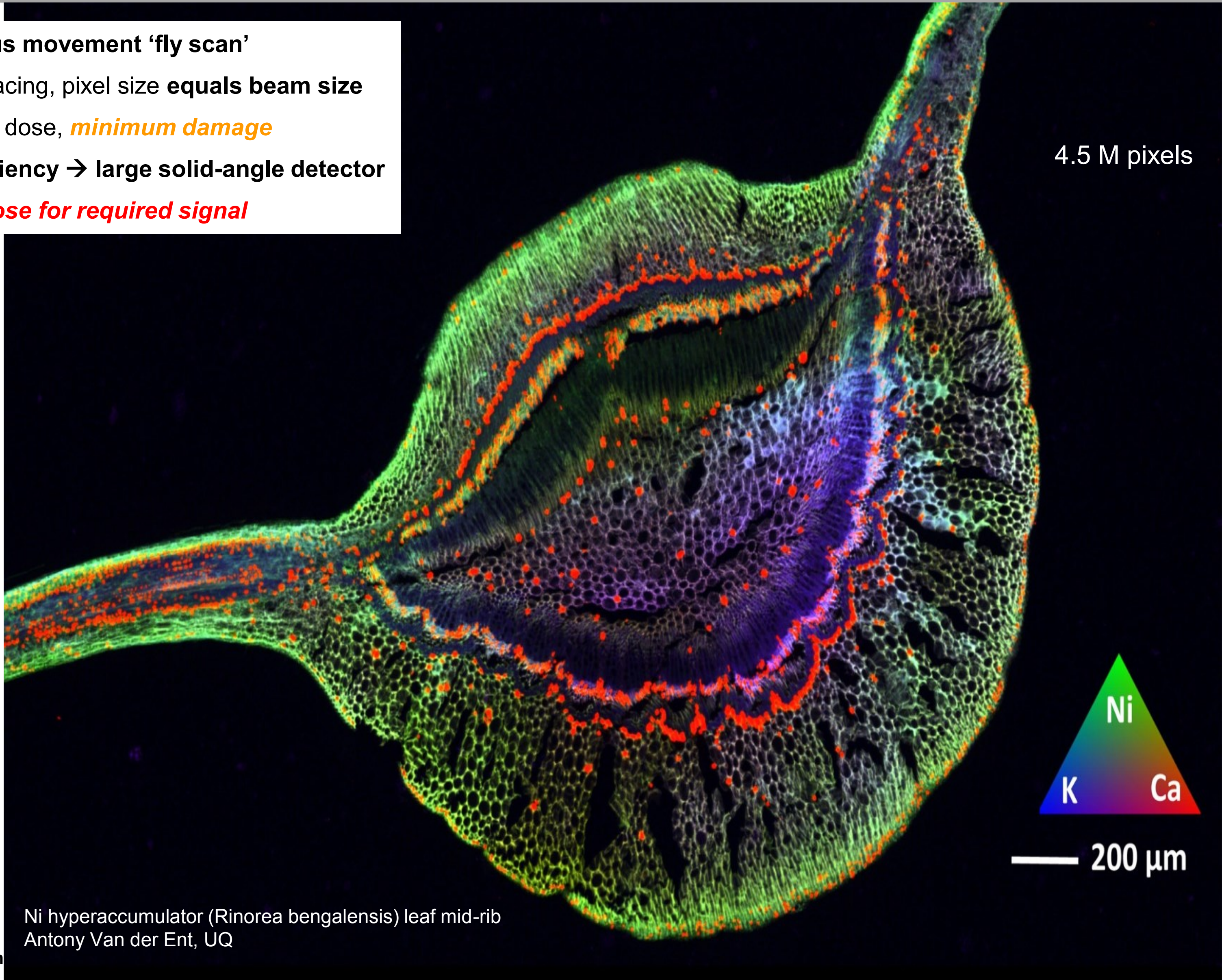


40k pixels

Ni hyperaccumulator (Rinorea bengalensis) leaf mid-rib
Antony Van der Ent, UQ

Why high definition imaging?
Minimize damage

- **Use continuous movement ‘fly scan’**
  - ✓ Line spacing, pixel size **equals beam size**
  - ✓ Uniform dose, ***minimum damage***
- **Maximize efficiency → large solid-angle detector**
  - ✓ ***Less dose for required signal***



Ni hyperaccumulator (Rinorea bengalensis) leaf mid-rib
Antony Van der Ent, UQ

Maia 384

3D data-sets:

XANES imaging

Dynamic Analysis method - XANES

SXRF Spectrum - linear combination of element spectra.

... cast as a matrix transformation:

$$C \quad = \quad Q^{-1}\,\Gamma(E_b)\,\mathbf{S}$$

Concentration vector

Transform matrix

Spectrum vector

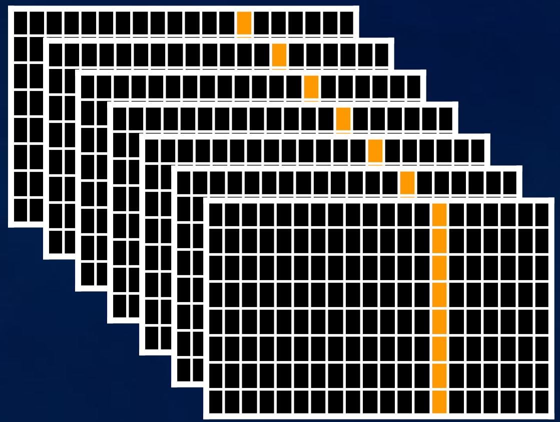
XANES Imaging:

X-ray event: Energy 'e'
Position 'x,y'
Beam energy 'E_b'

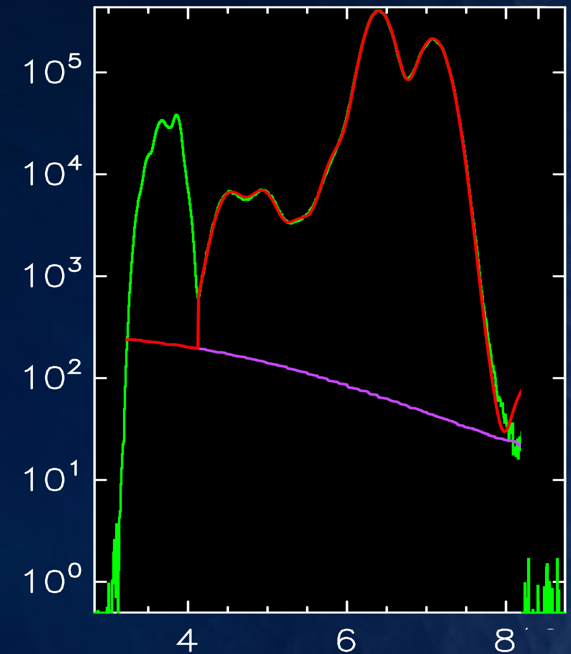
'E_b' selects matrix Γ in stack →

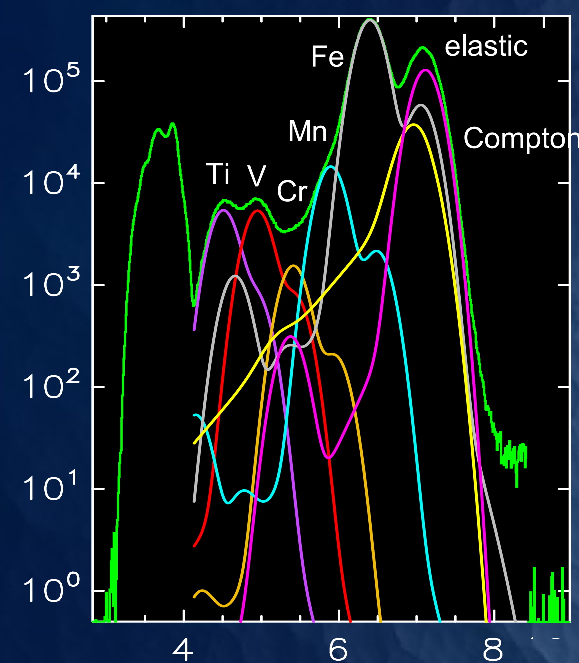
'e' selects column of matrix $\Gamma(E_b)$ → the increments to images at 'x,y'

Γ Matrix stack



one for each beam energy 'E_b'



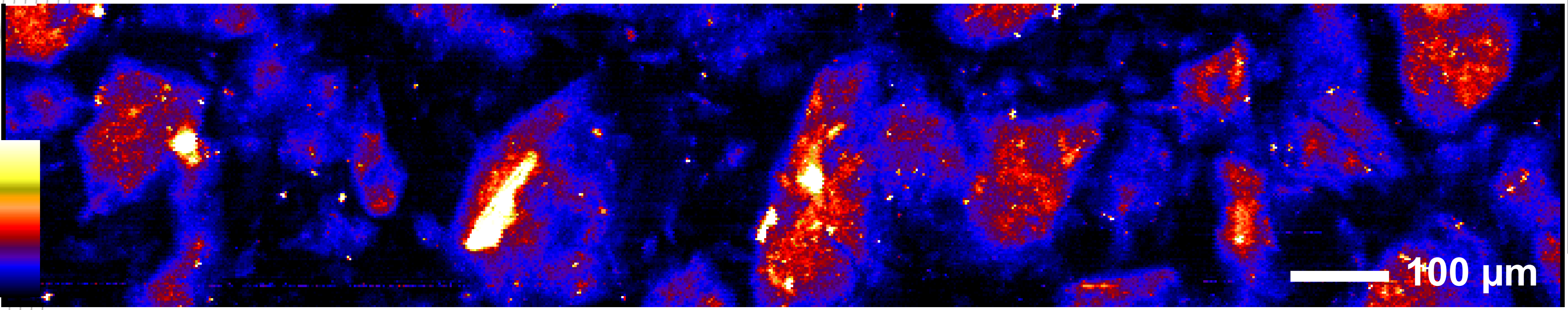


Metal speciation in biosolids
Contaminant time bomb?

Lombi, Donner, Etschmann *et al*., U. South Australia

PUTTING
WASTE
TO WORK

What is the speciation of Cu?



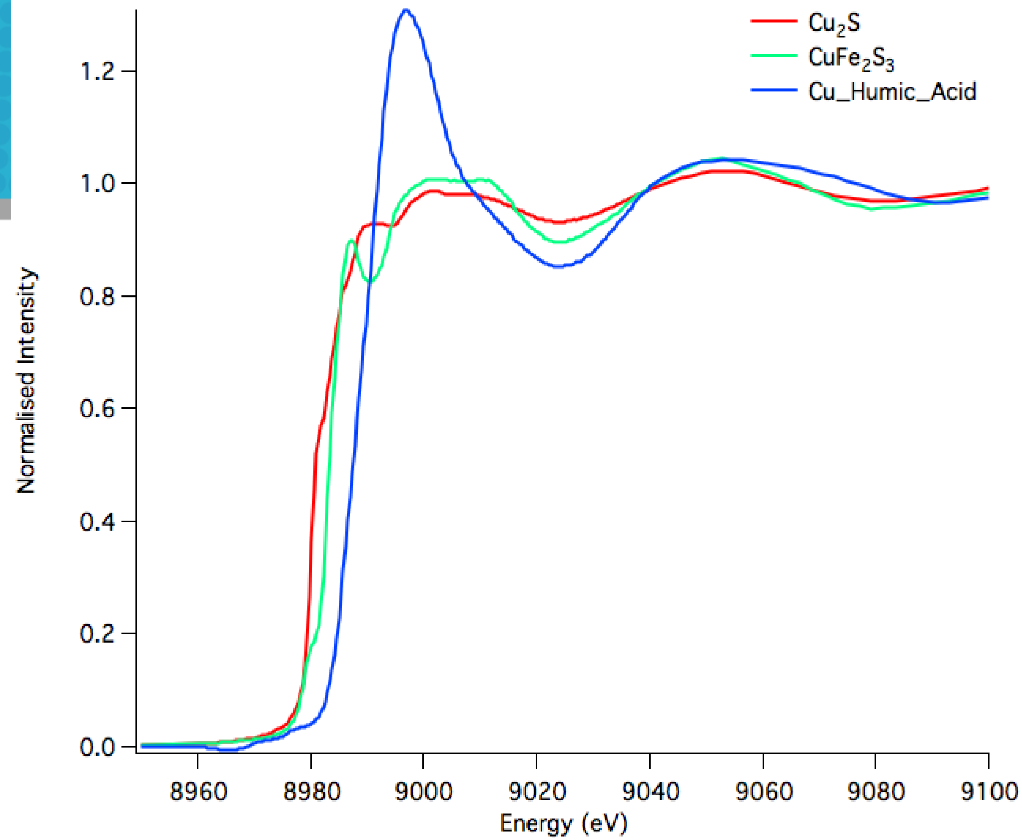
Cu elemental map

Etschmann et al., Environmental Chemistry 11, 341-350

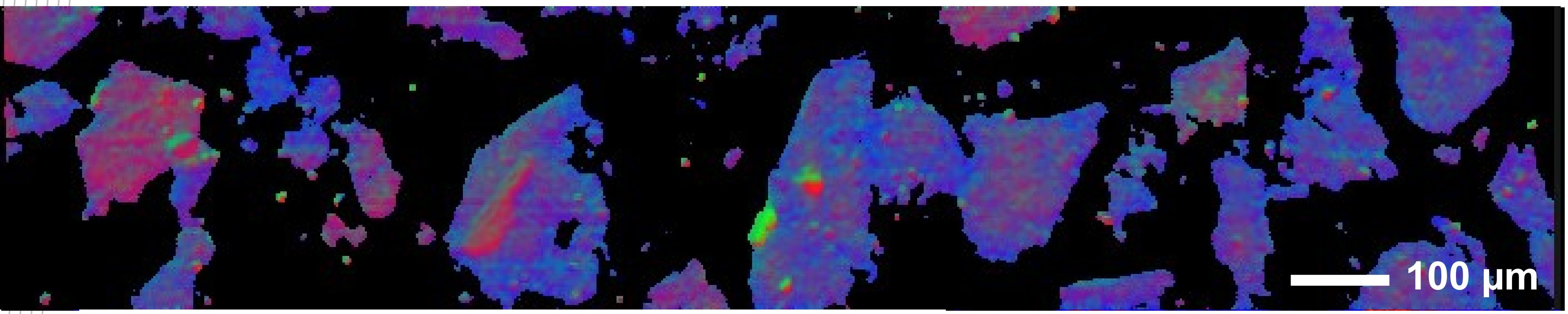
Metal speciation in biosolids

Lombi, Donner, Etschmann *et al.*

- **XANES imaging**
  - 1.6 x 0.27 mm (800 x 136 pixels)
  - 1.9 ms/pixel
  - 80 energies across Cu K edge
- **Component fitting**
  - from bulk XAS and PCA analysis
  - PCA analysis indicated 3 significant components



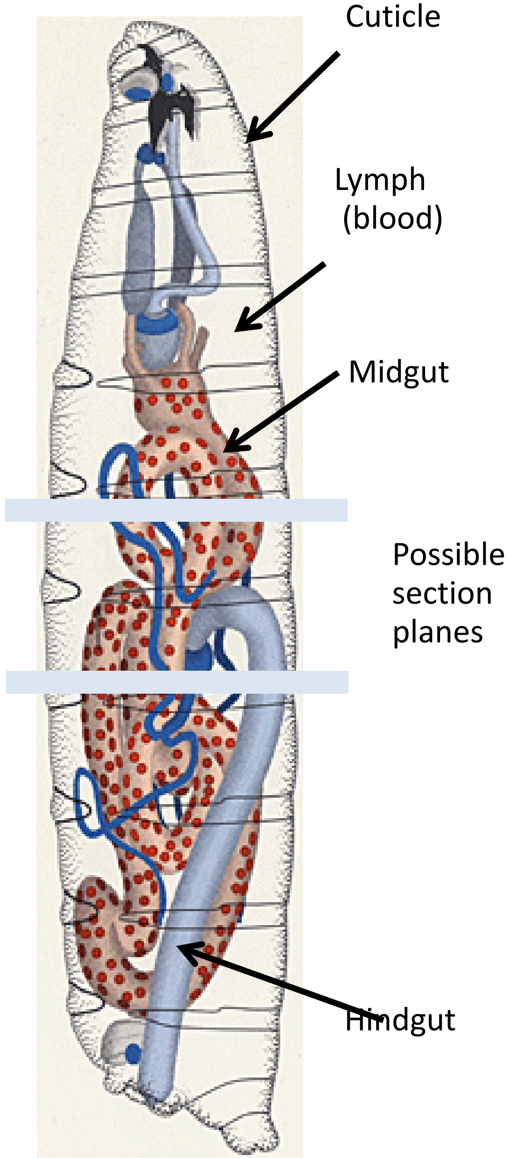
XANES imaging: Cu speciation map



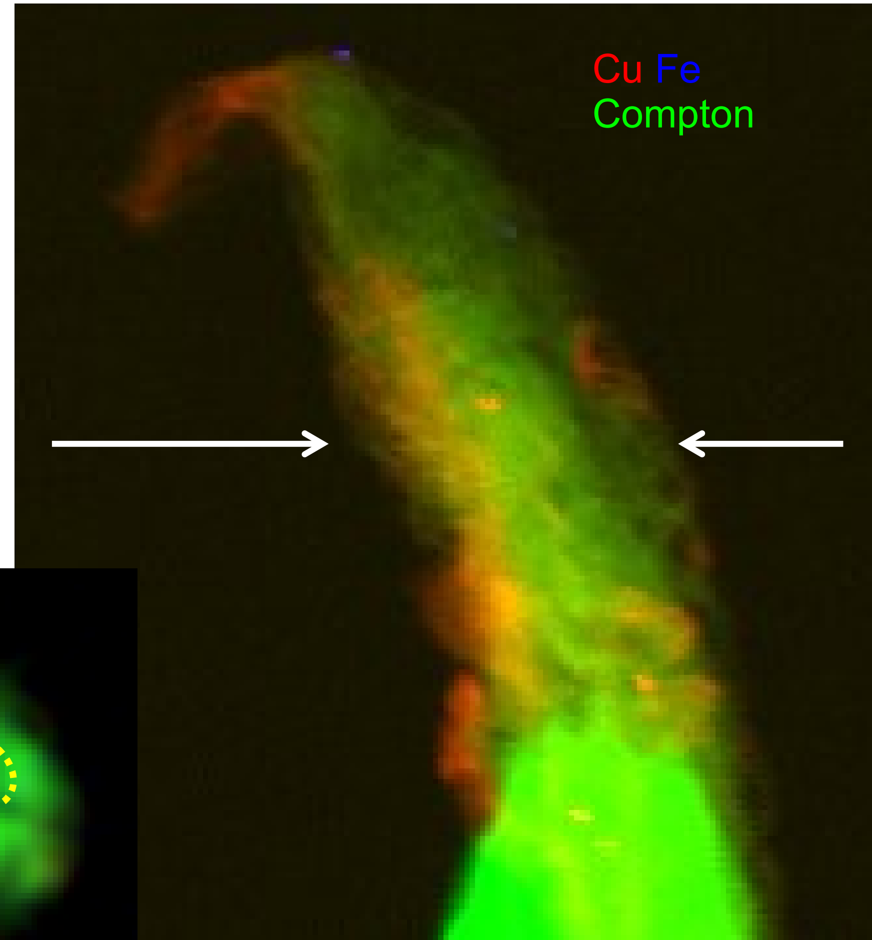
Red=Cu_2S, **Green**=$CuFe_2S_3$, **Blue**=Cu-HA

Etschmann et al., Environmental Chemistry 11, 341-350

Cu oxidation state mapping in Drosophila (Cu efflux transporter ATP7 knockout)

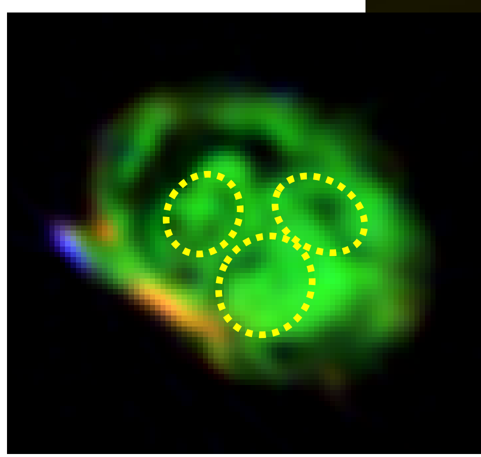


2D XFM



0.4 x 0.55 mm; 200 x 275 pixels, 16 minutes

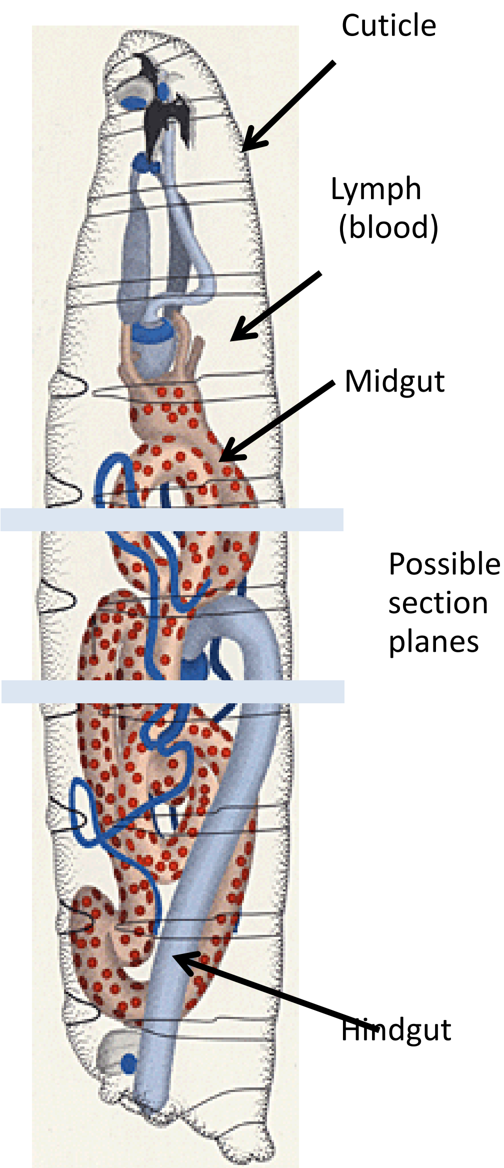
2D Fluor. Tomography section



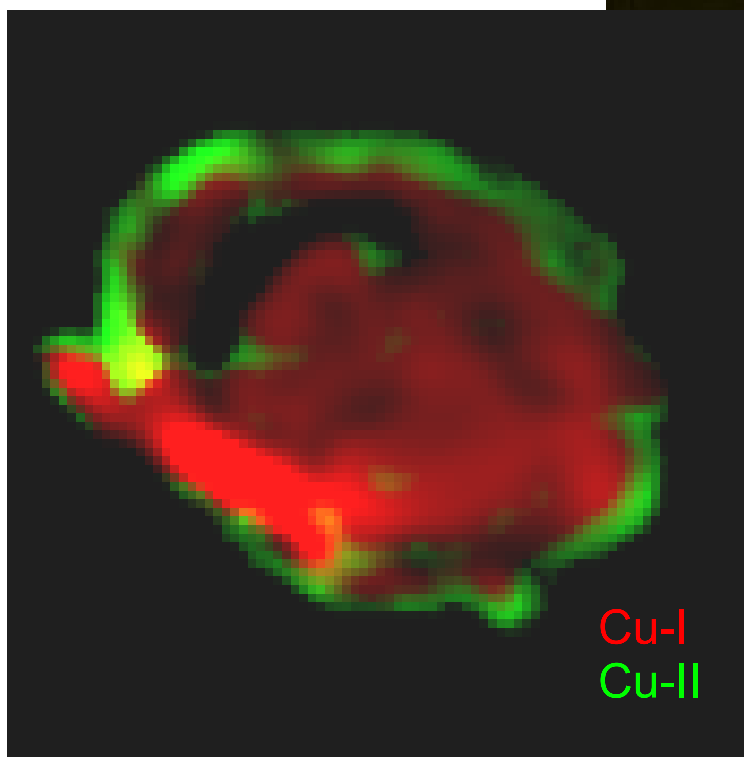
0.3 mm x 360°, 400 angles; 150 x 400 pixel sinogram, 18 minutes

Martin de Jonge, XFM, AS

Cu oxidation state mapping in Drosophila (Cu efflux transporter ATP7 knockout)

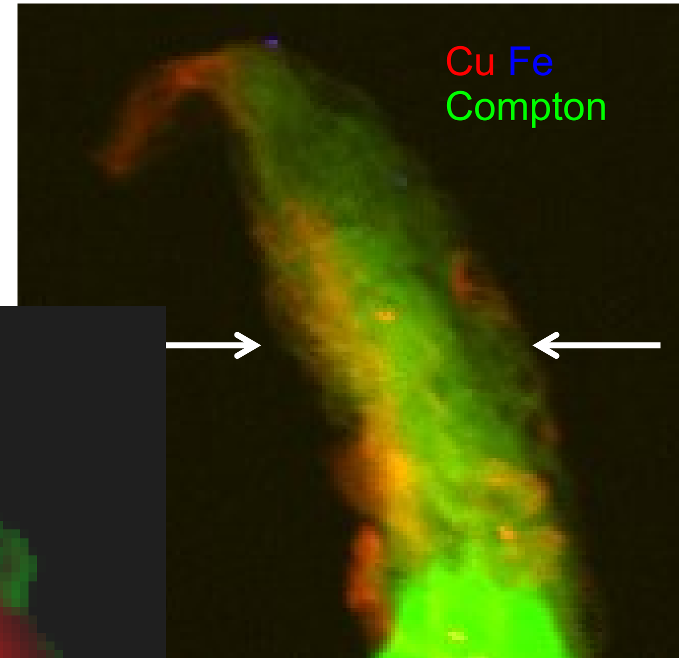


XANES Tomography section



0.3 mm x 180°, 100 angles; 150 x 100 pixel sinogram, 4.7 minutes per energy x 80 energies

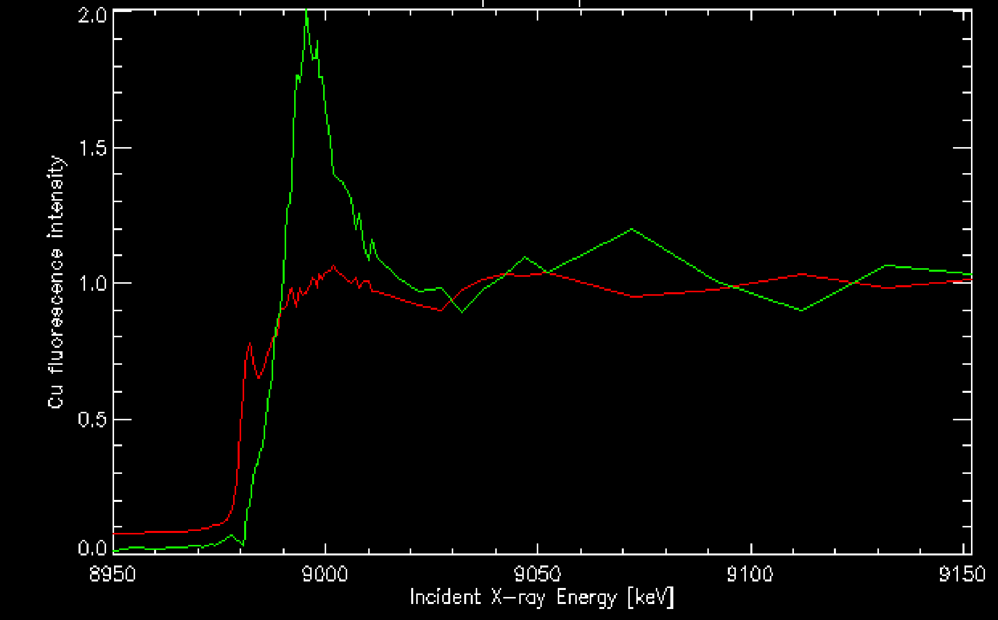
2D XFM



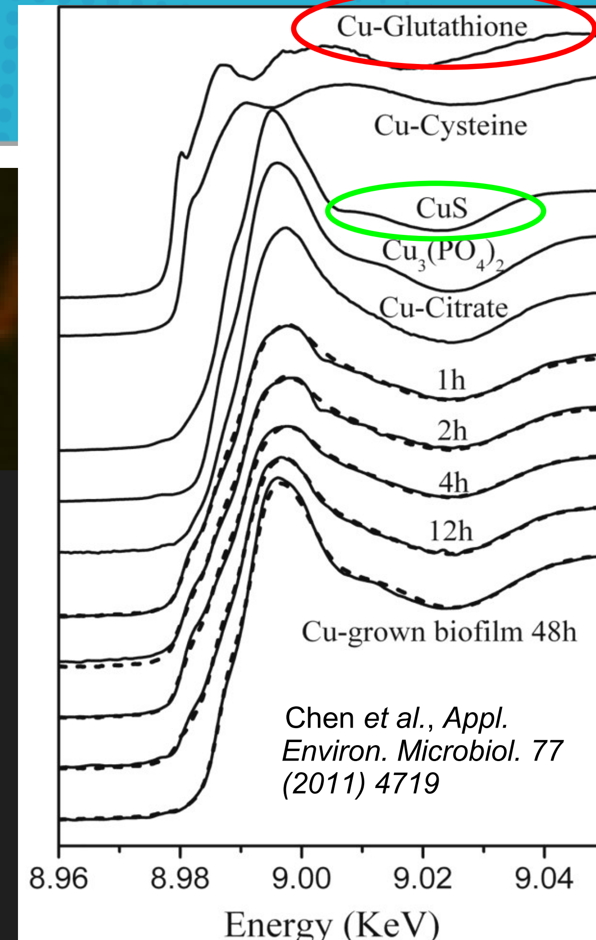
0.4 x 0.55 mm; 200 x 275 pixels, 16 minutes

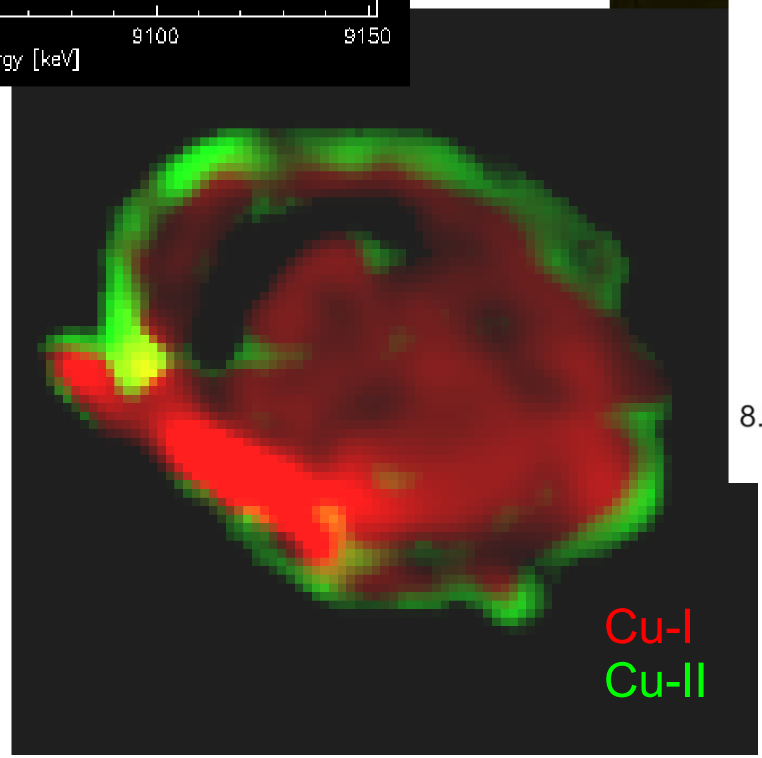
Cu speciation maintained in Drosophila…
de Jonge *et al.*, in prep.

sophila
out)



2D XFM



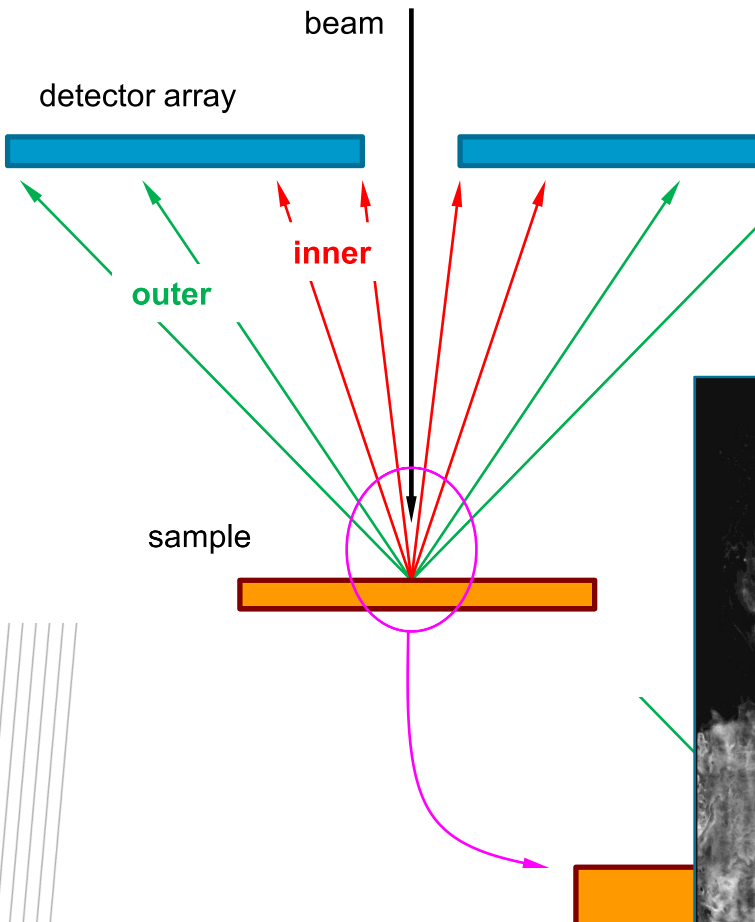


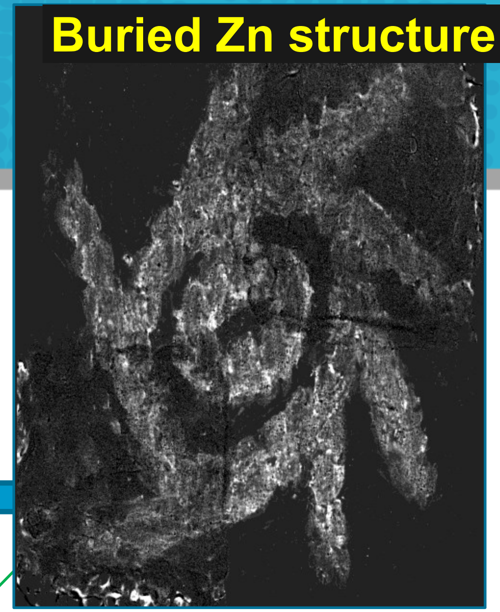
0.3 mm x 180°, 100 angles; 150 x 100 pixel sinogram, 4.7 minutes per energy x 80 energies

Cu speciation maintained in Drosophila…
de Jonge *et al.*, in prep.

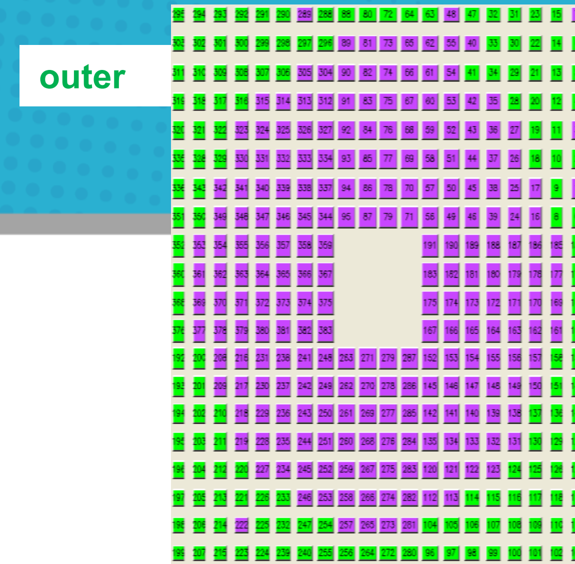
Maia Depth Sensitivity

Depth contrast

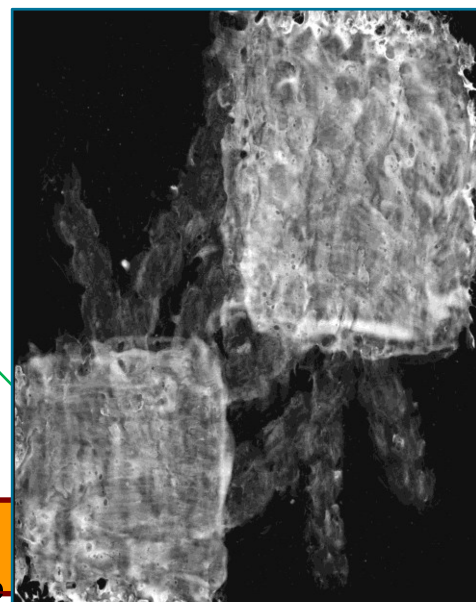




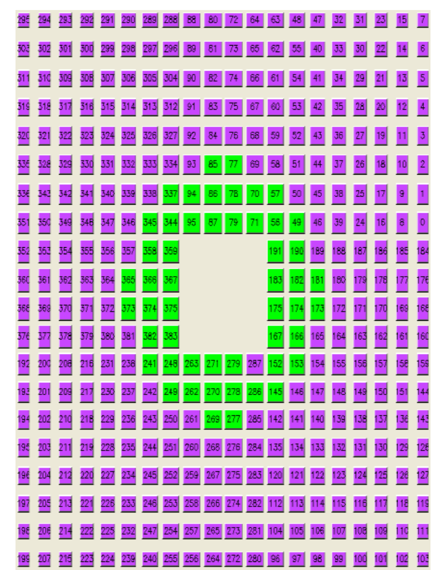
Zn map ("inner" minus "outer" scaled)



More "surface" sensitive

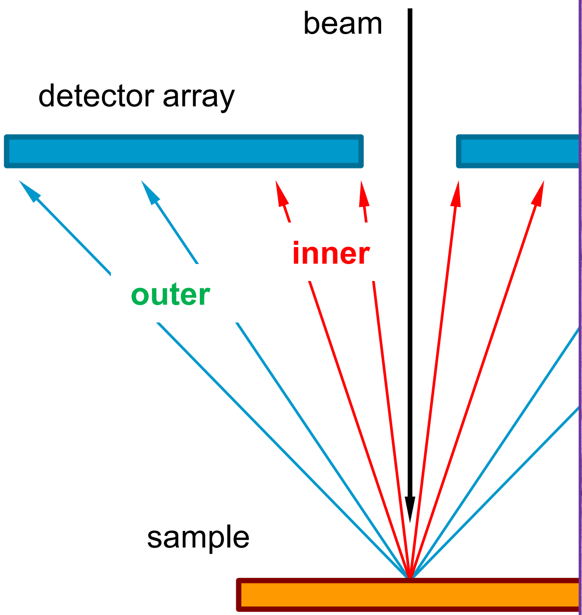

Zn map (all detectors)

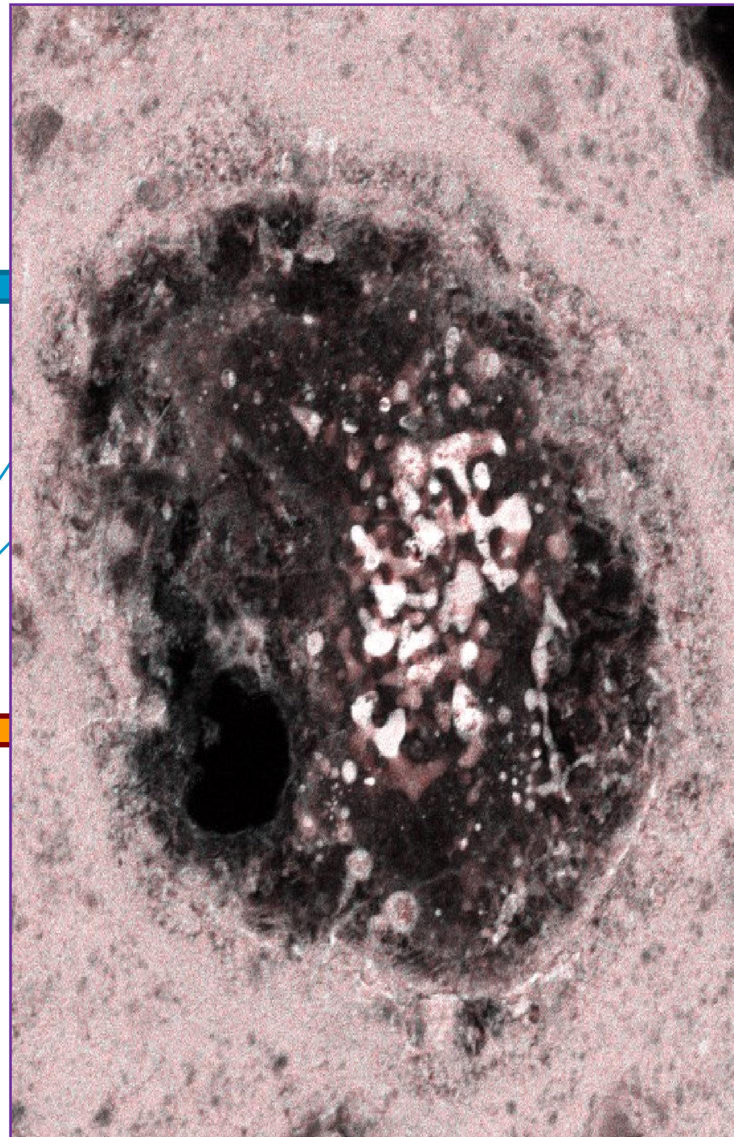
"See" deeper



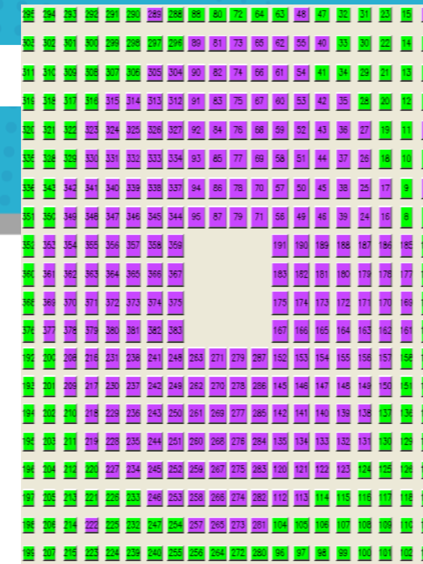
Daryl Howard, XFM beamline

Depth contrast





outer

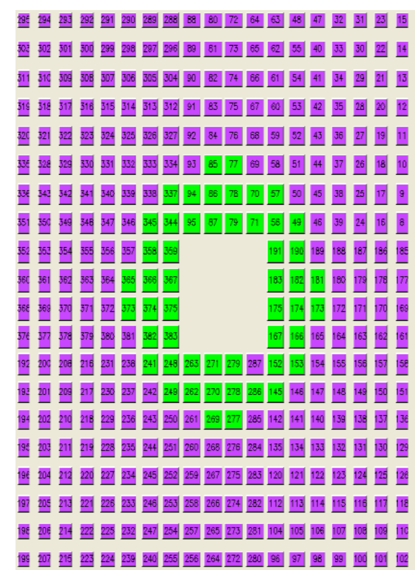


ore "surface" sensitive

Blue + Green

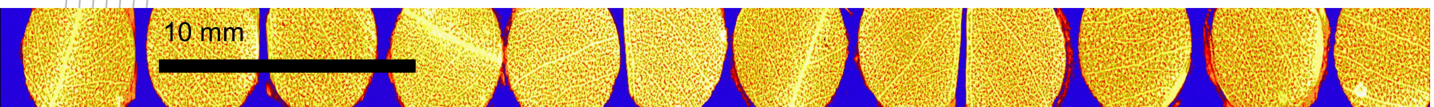
' deeper

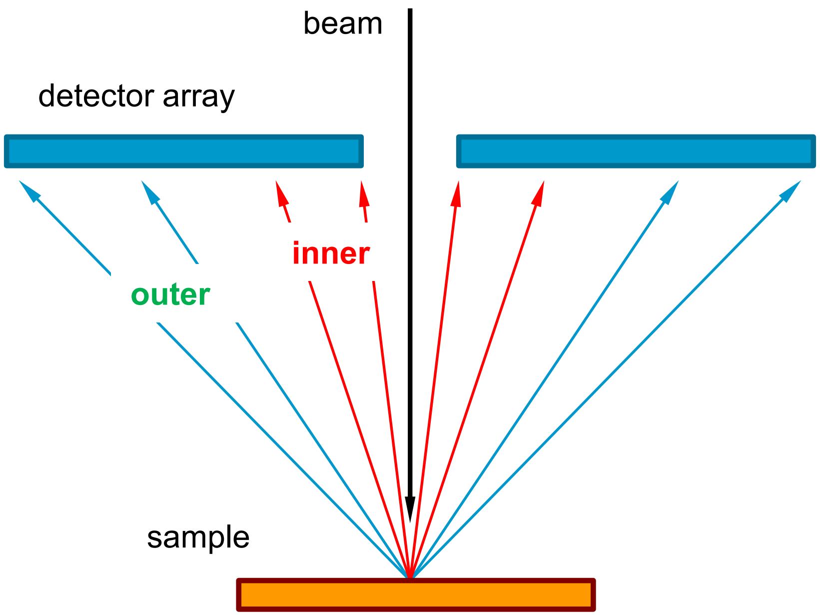
Red

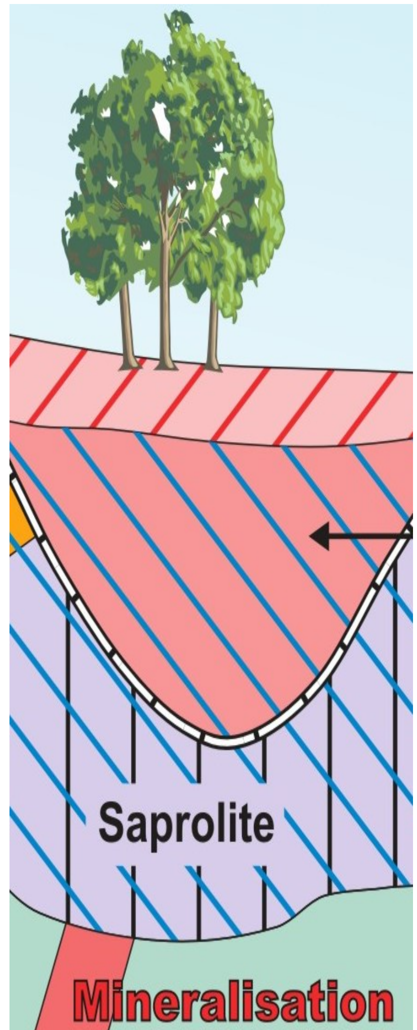


inner

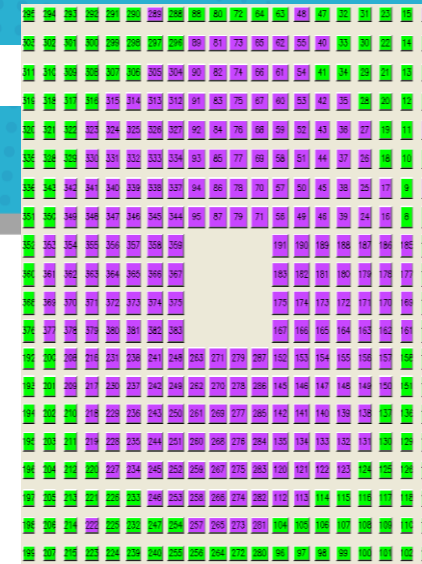
Depth mapping
Gold precipitates in leaves



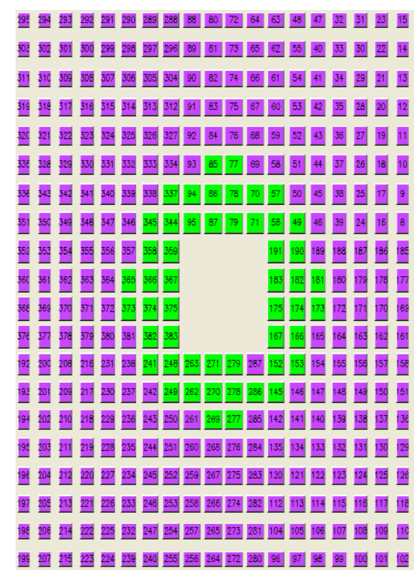




outer

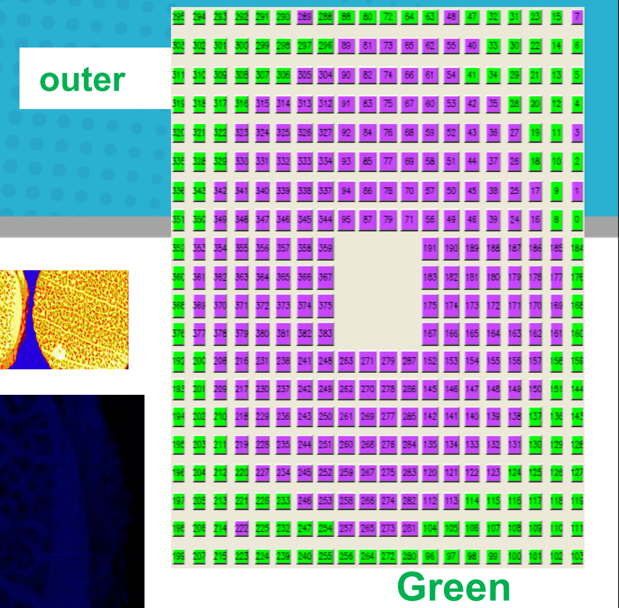


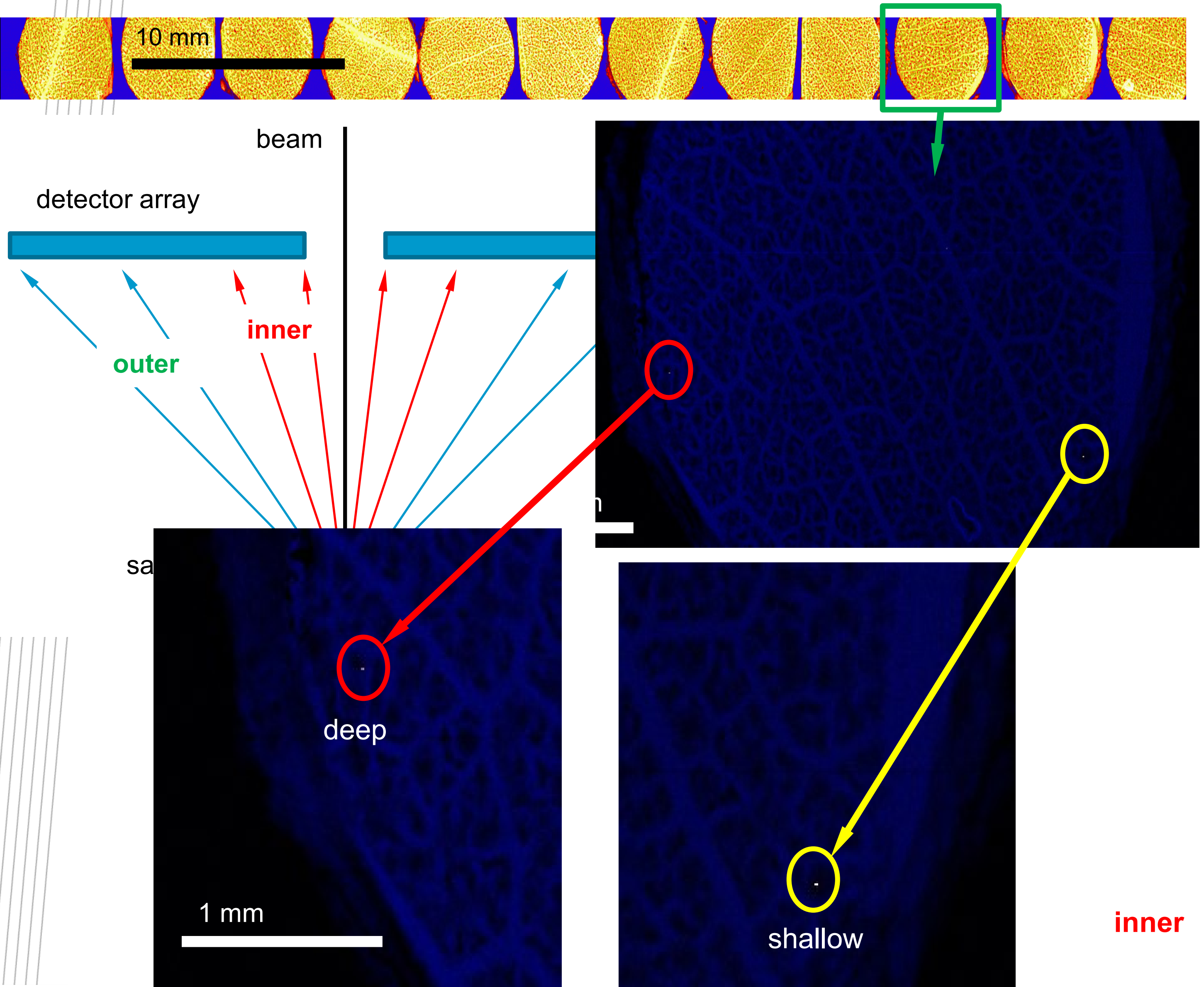
inner

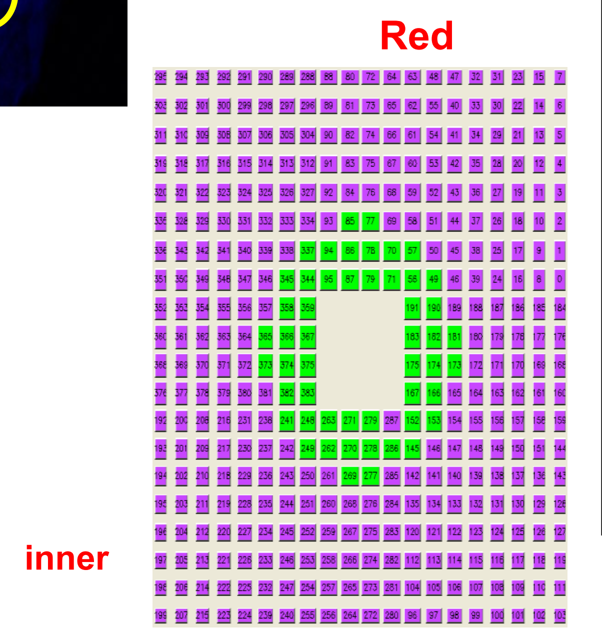


Lintern *et al.,* Nature Communications 4, 2274

Depth mapping
Gold precipitates in leaves

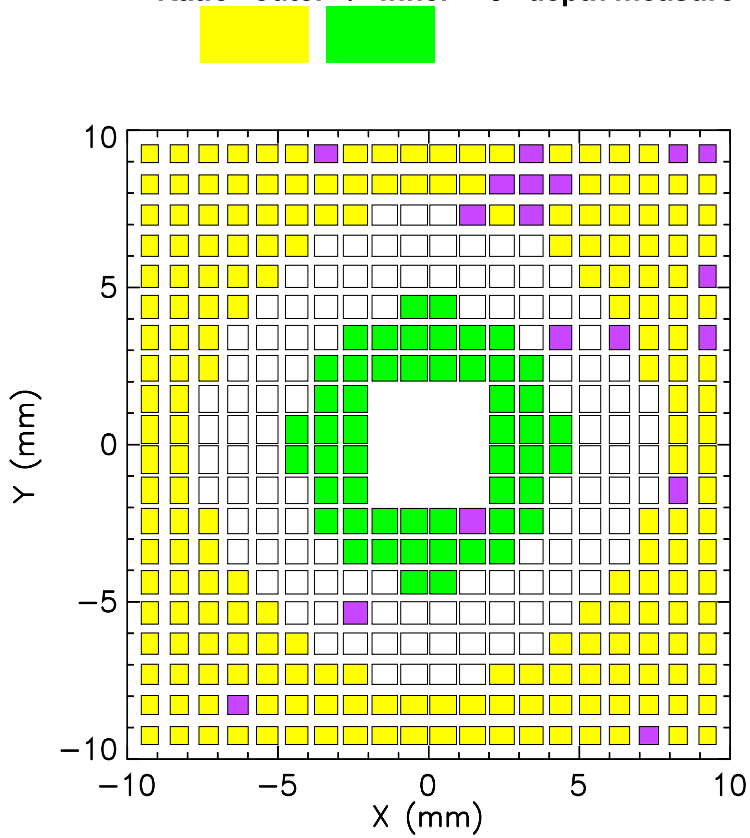


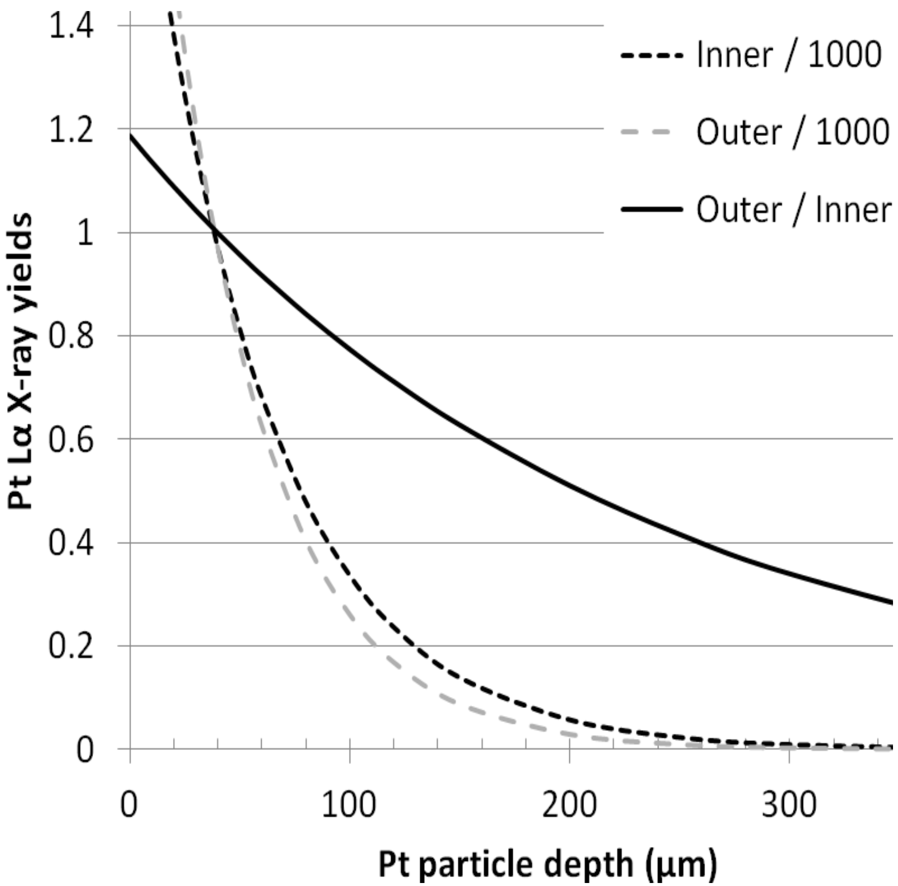




Maia 384 array:
Depth sensitivity and measurement

- **Depth sensitivity using large detector array**
  - ✓ Angles from normal range from 13.9 ° to 52.6°
  - ✓ Outer detectors "see" more self-absorption
  - ✓ Inner detectors "see" deeper particles
  - ✓ **Ratio "outer" / "inner" → depth measure**

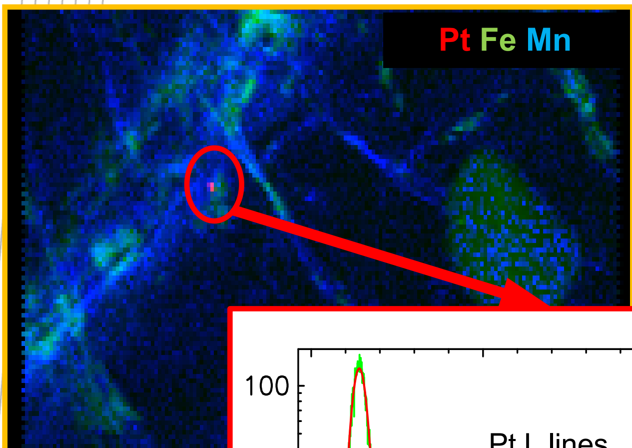


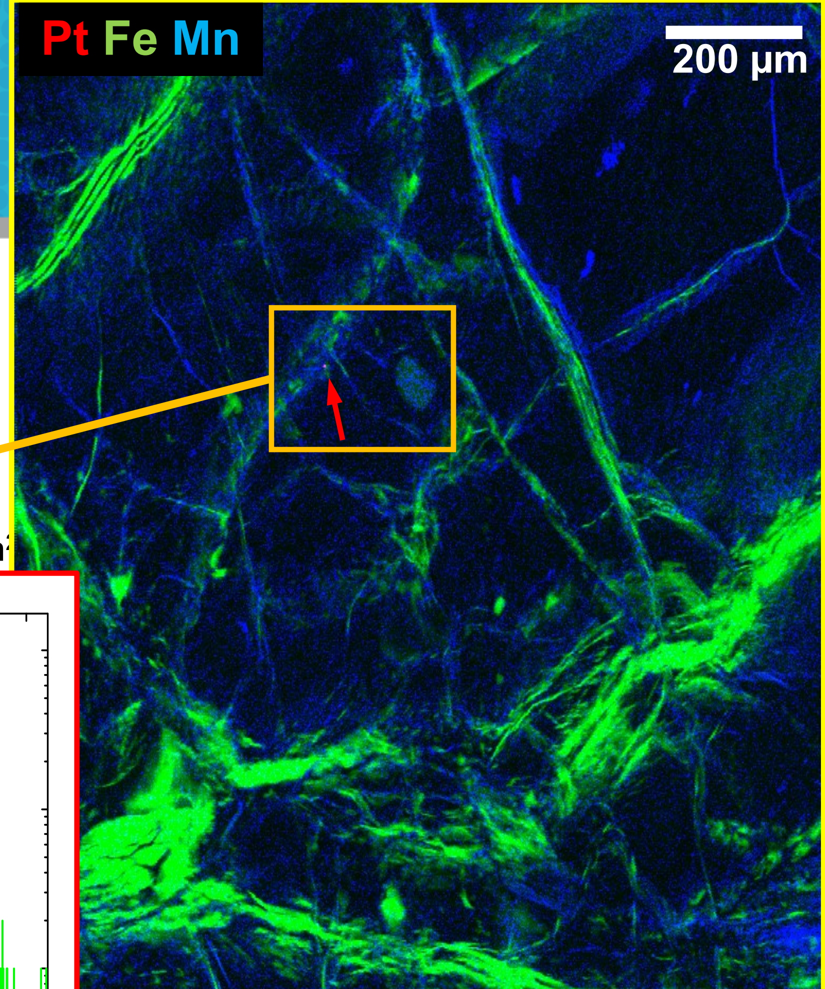


Pt Lα yields, "outer"/"inner" ratio for Pt particle in olivine at 18.5 keV beam energy

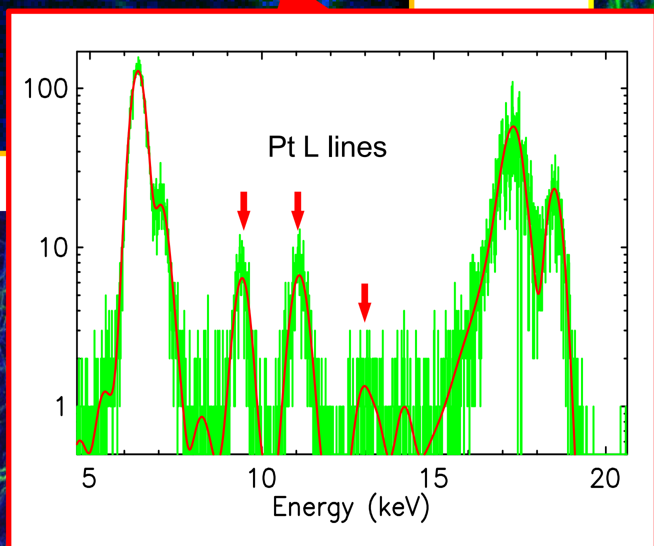
Ryan et al., Proc. SPIE 8851, X-Ray Nanoimaging (2014) 88510Q

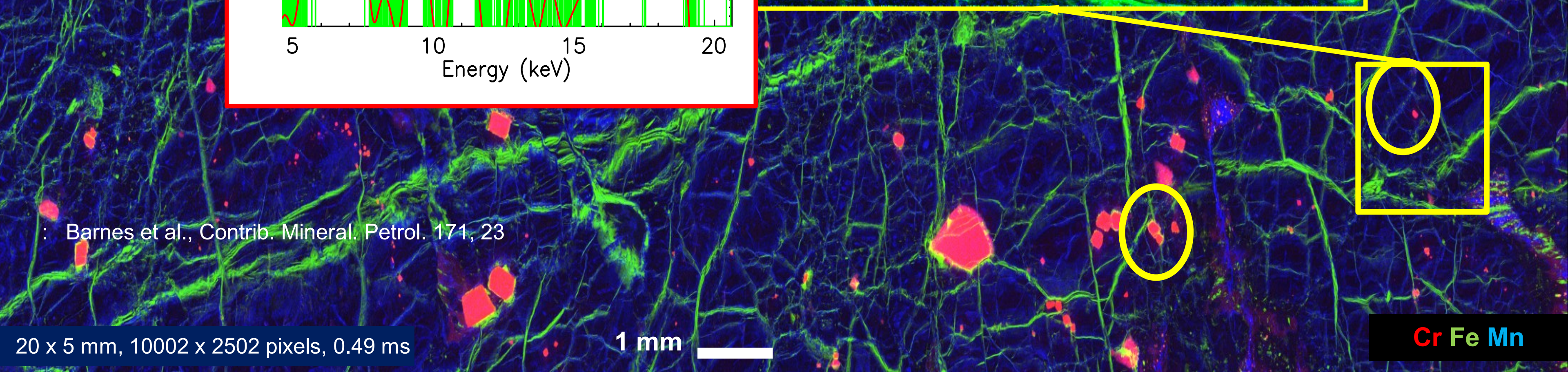
PGM Search:
Depth mapping





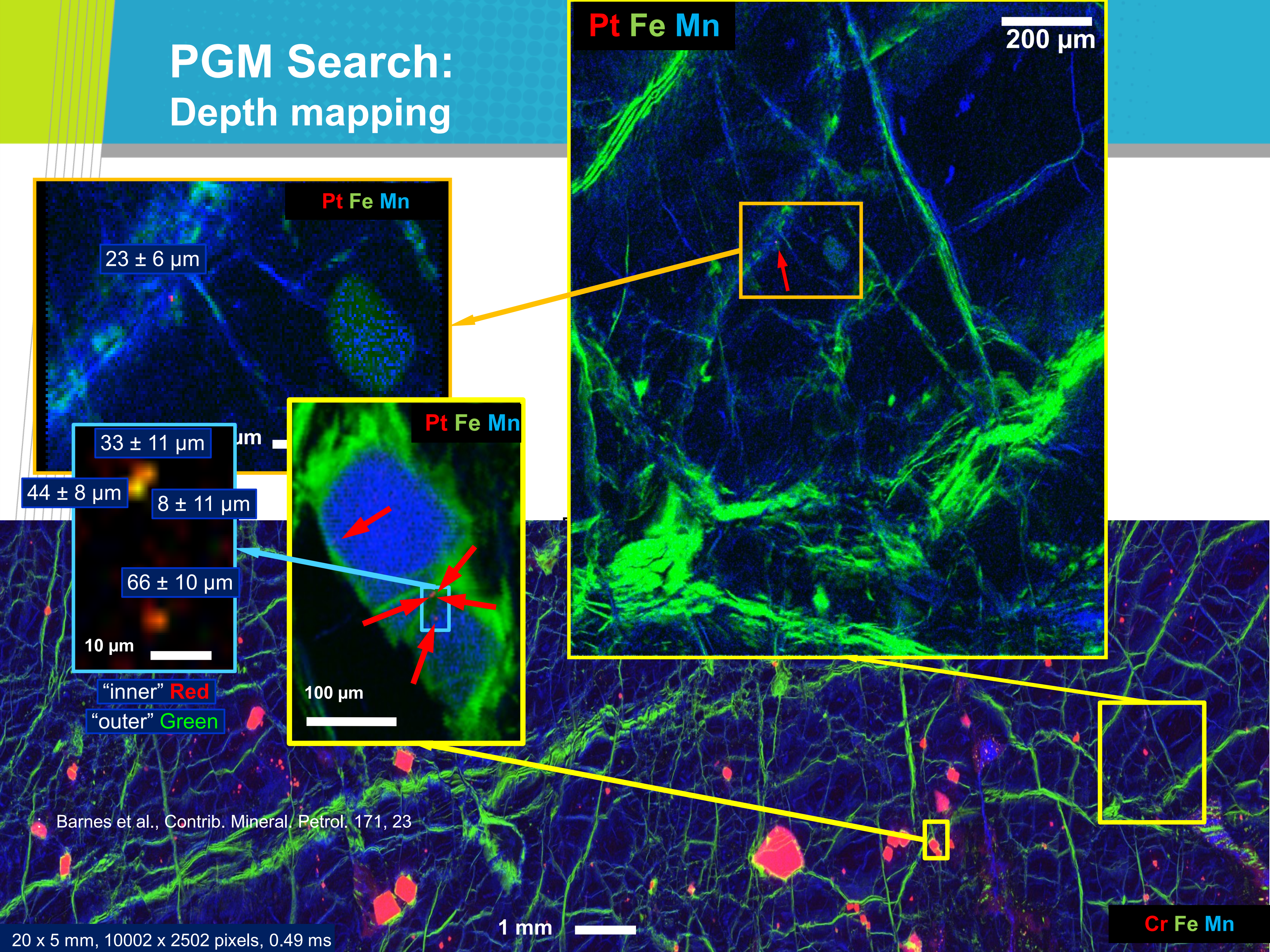
in 100 mm²





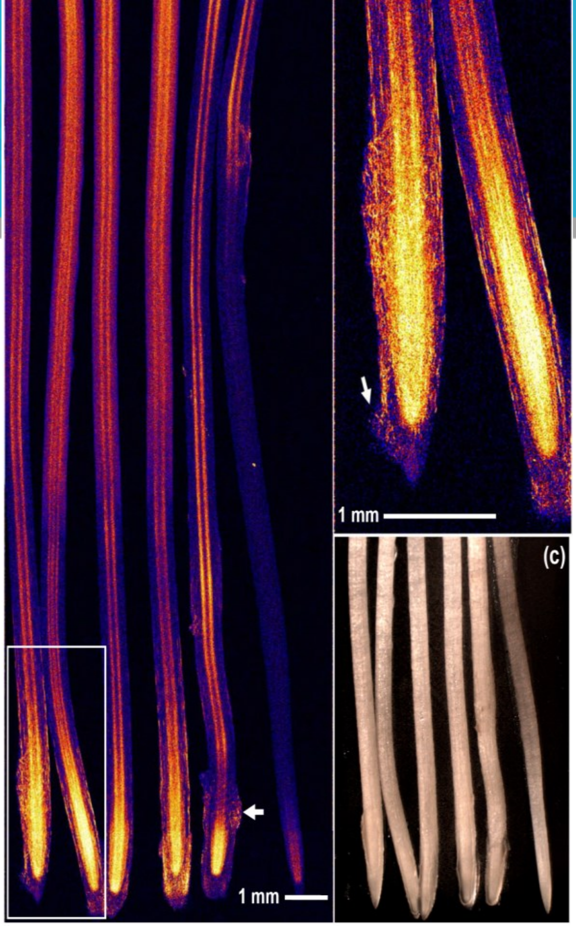
: Barnes et al., Contrib. Mineral. Petrol. 171, 23

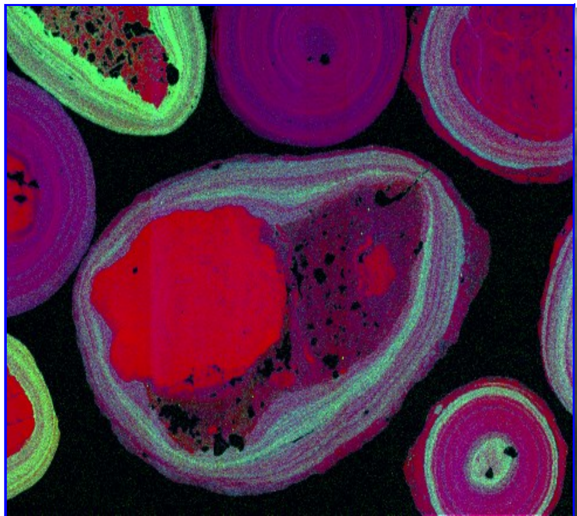
PGM Search:
Depth mapping



Conclusions

- **Maia imaging system**
  - ✓ Large detector array with event-mode acquisition, real-time processing
  - ✓ **Enables high definition XFM with images up to 1G pixels (up to 100M typ.)**
- **Analytical challenge (~10^8 spectra, composition contrasts)**
  - ✓ **DA → MPDA method**: quantitative images despite strong composition contrasts (now part of GeoPIXE s/w)
  - ✓ Still high throughput at **~10^5 pixels per second** processing
- **2D ~10^8 pixels → 3D imaging modes**
  - ✓ XANES imaging (~100 energies)
  - ✓ 3D Fluorescence tomography (~200 angles)
  - ✓ XANES tomography
- **User science: Maia @ XFM (AS), P06 (Petra III, DESY), SRX (NSLS-II), CHESS**
  - ✓ **Large area, high definition 2D and 3D mapping**
  - ✓ High throughput → More samples, less damage
  - ✓ **Greater user "freedom"** (sample regions, balancing fine detail and broader spatial context)



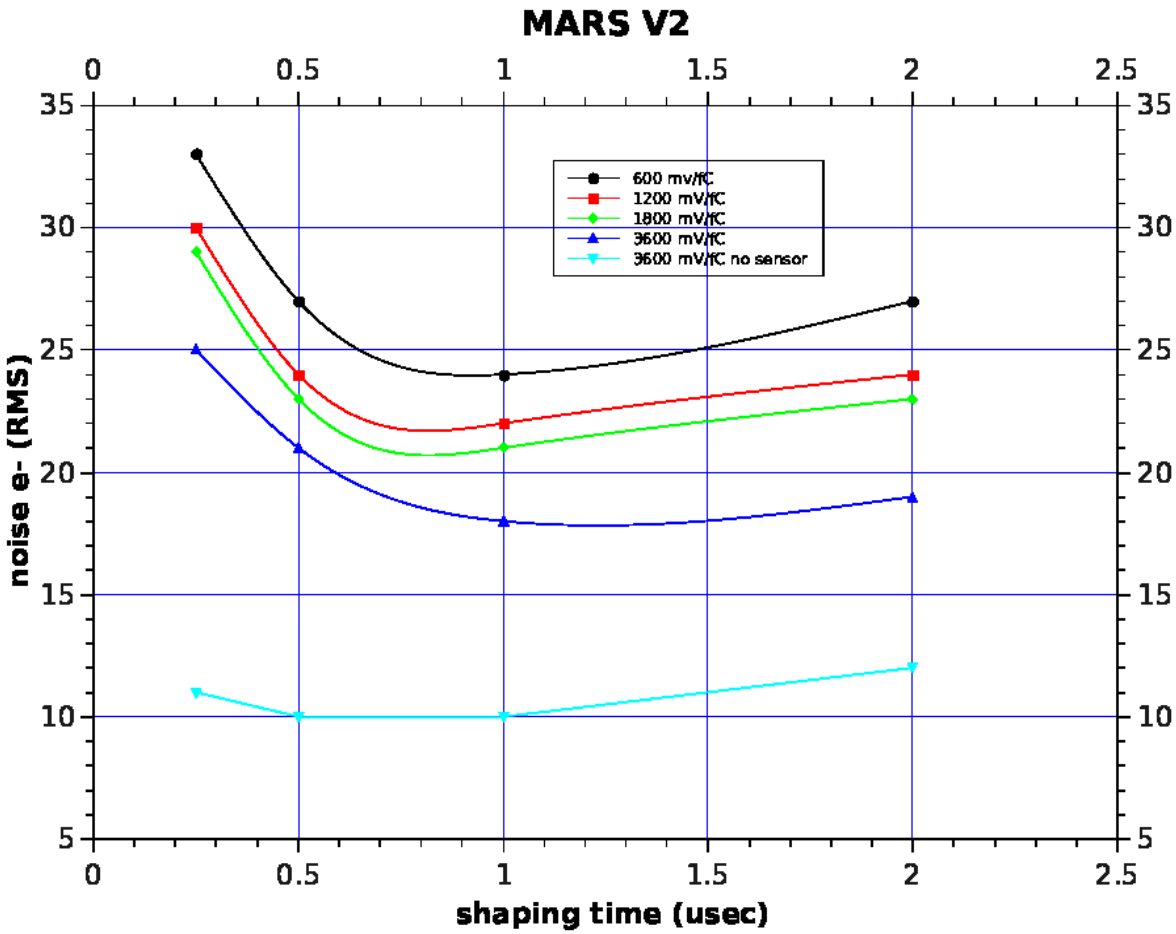


Future developments

- New ASIC (MARS) provides lower noise for low-capacitance sensors plus combining functions of both earlier chips
- New SDD sensor arrays

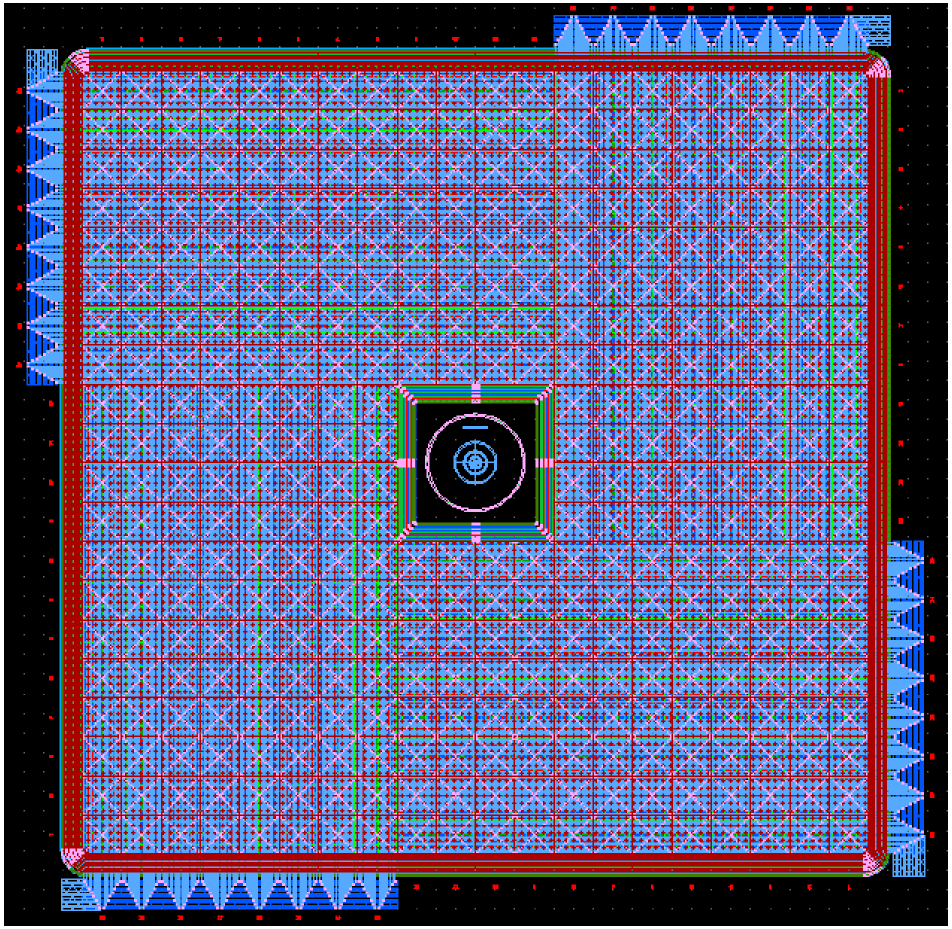
MARS noise performance

- Tested using standard Maia detectors
- MARS is designed for lower-C sensors, so no real improvement over HERMES.
- Lowest curve shows noise with no sensor.



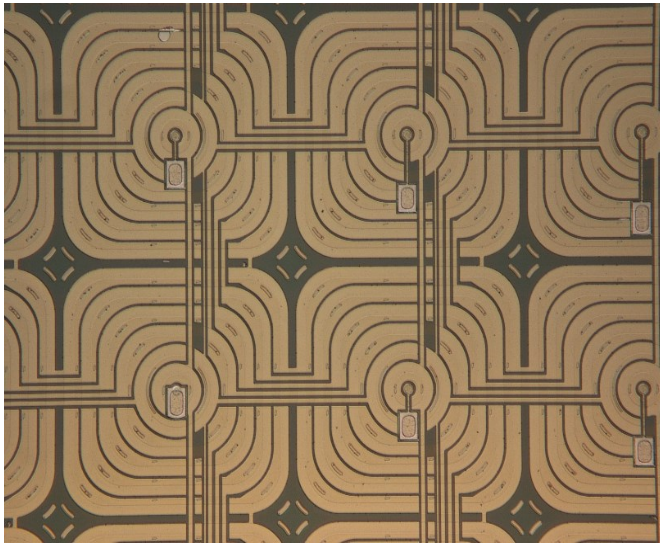
SDD arrays

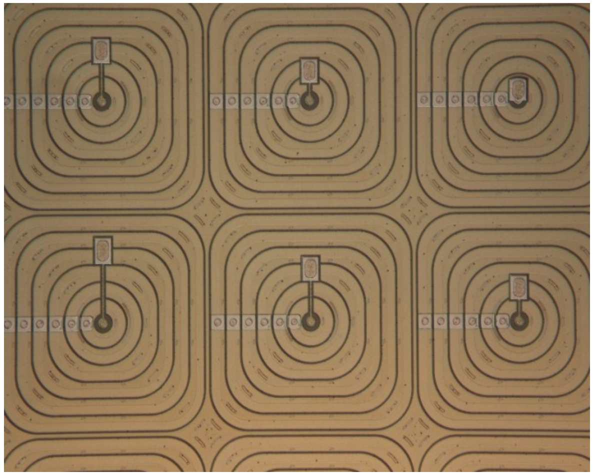
- 20 x 20 array of 1mm devices (to match Maia's layout)

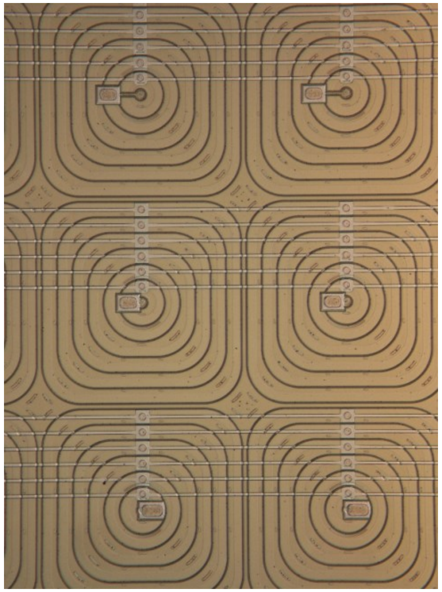


SDD arrays

- 20 x 20 array of 1mm devices (to match Maia's layout)







Summary

- Maia enables “Hi-res” fluorescence imaging, Megapixels rather than kilopixels
- “On-the-fly” scanning minimizes lost time due to motion system
- Higher dimensionality scans (XANES, tomography) become practicable
- Real-time data analysis provides prompt feedback to experimenters

The Maia collaboration

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