PRISMA, APS-U- R&D BEAMLINE, PTYCHOGRAPHY, VELOCIPROBE…

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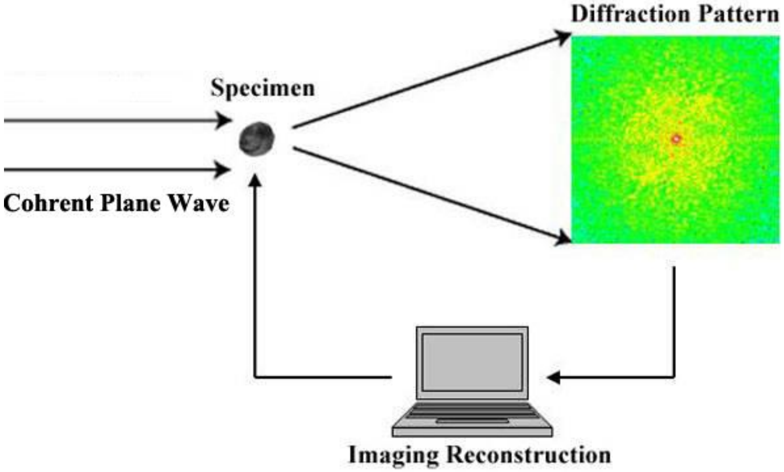
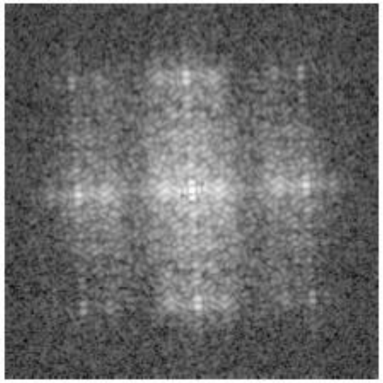
COHERENT DIFFRACTIVE IMAGING

***Lensless* method**

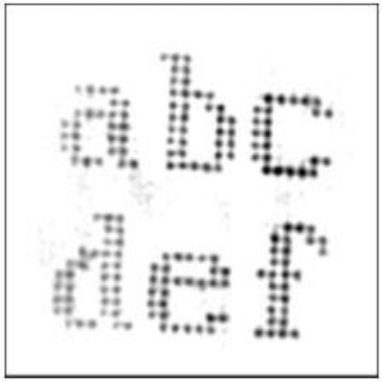
Resolution ~ λ / angular size   limited only by wavelength and signal

- Two-step process: record coherent diffraction pattern, recover object structure numerically (iterative phase retrieval)
- Sensitive to phase as well as absorption of the specimen
- Get 3D by tomographic methods; no depth of field limit
- But: must assume some information to recover phase, e.g. known object extent or illumination profile





Diffraction pattern



Reconstruction

J. Miao, Nature 400, 342 (1999)

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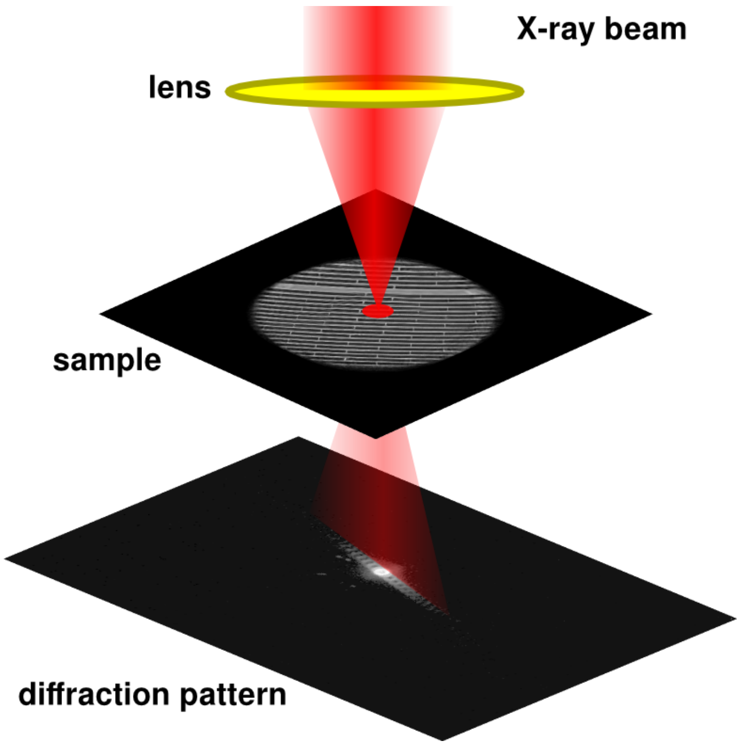
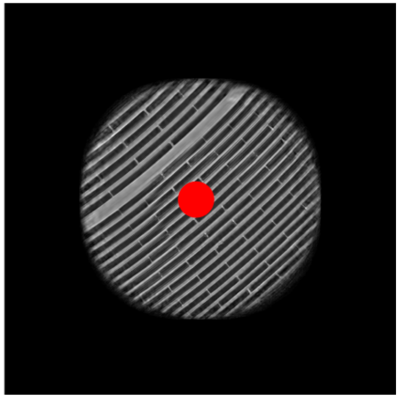
WHAT IS PTYCHOGRAPHY?





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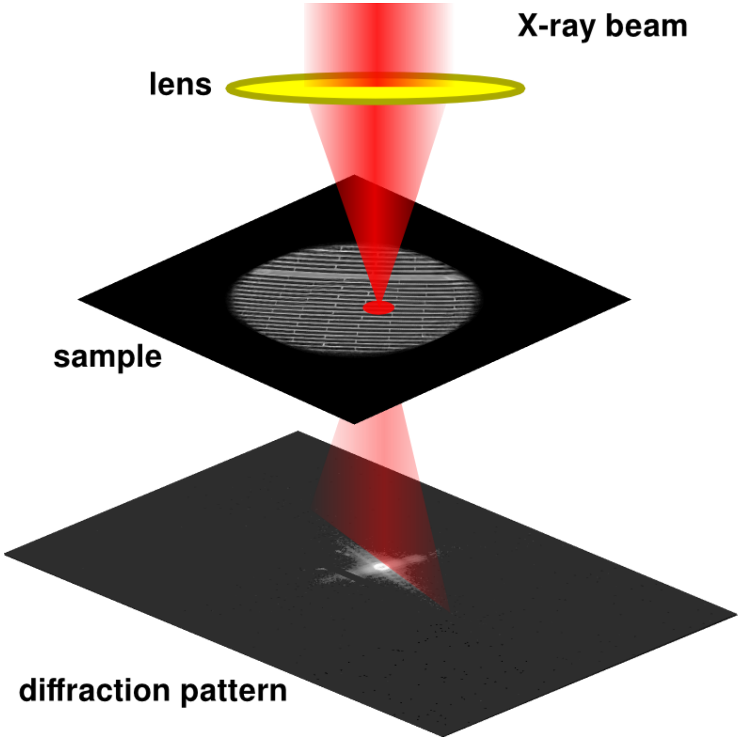

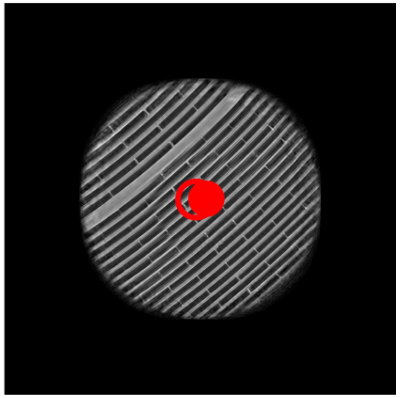

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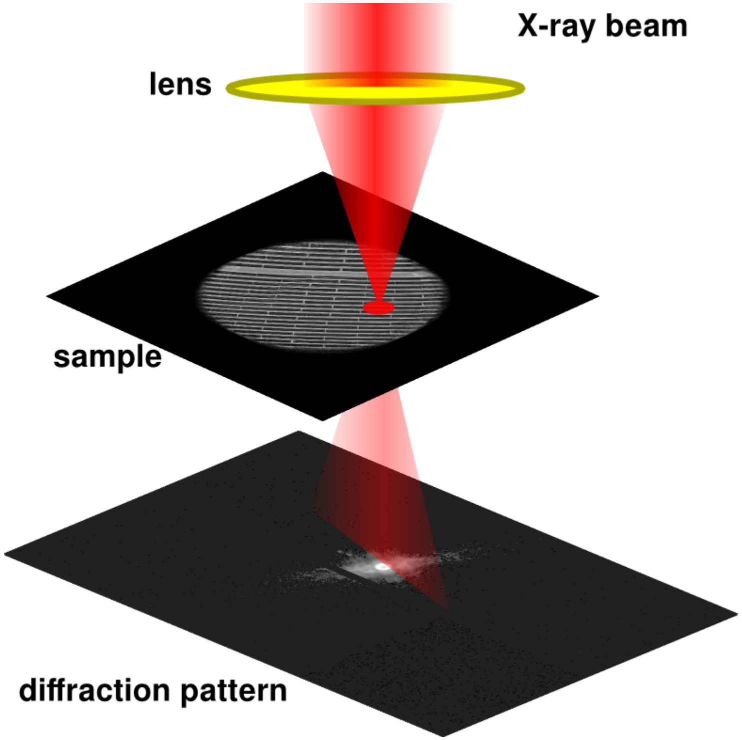
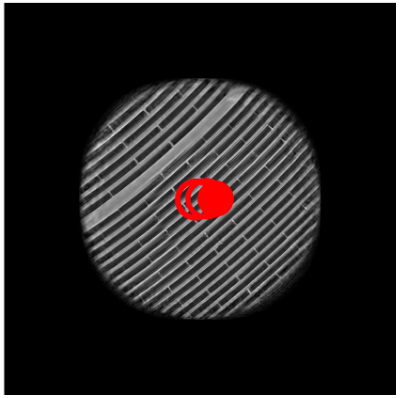
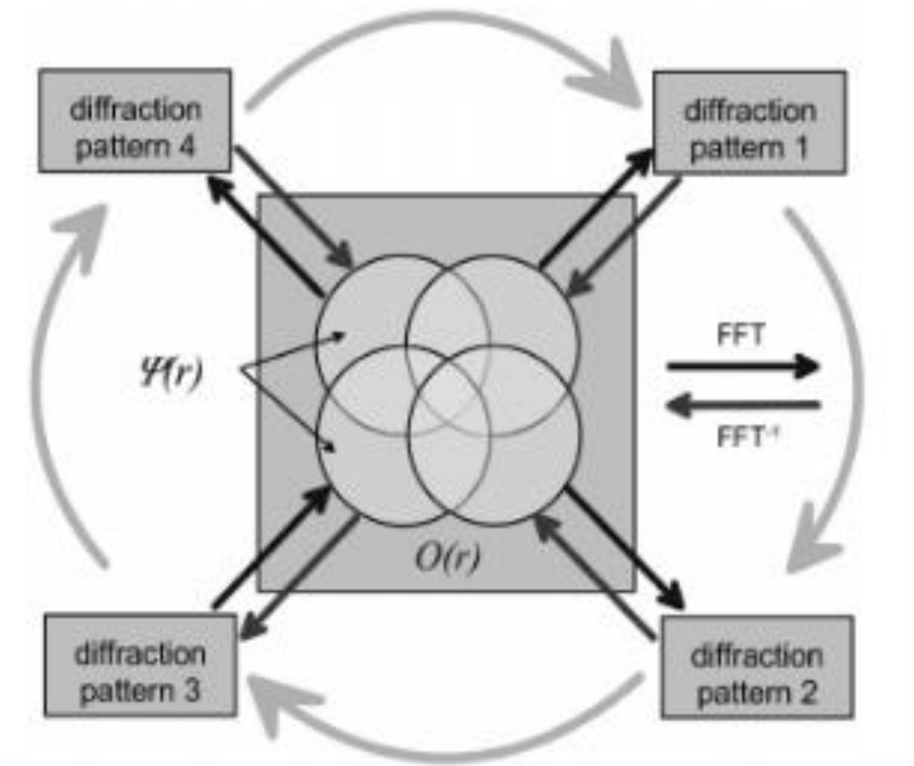
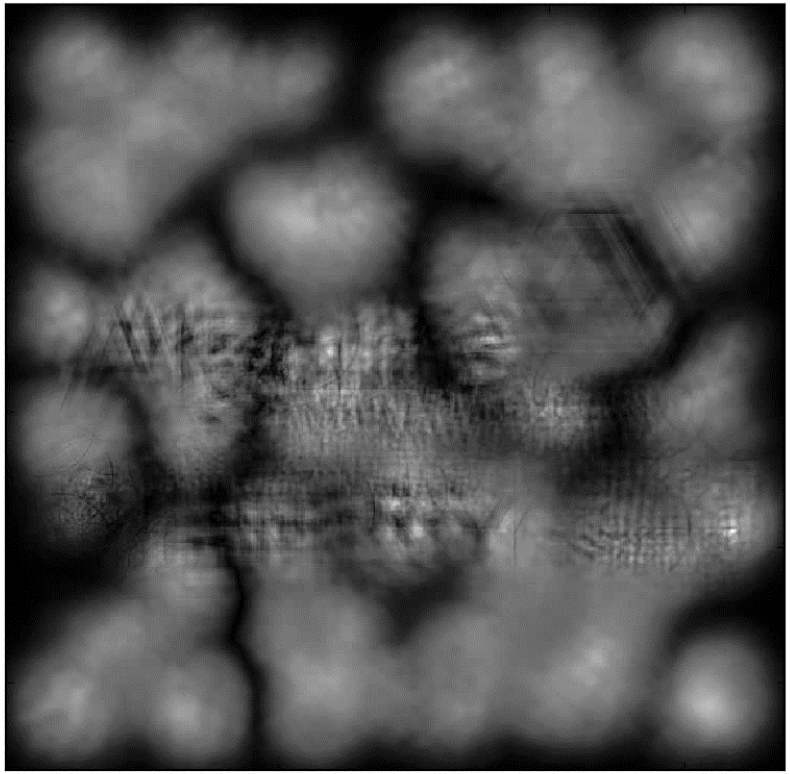
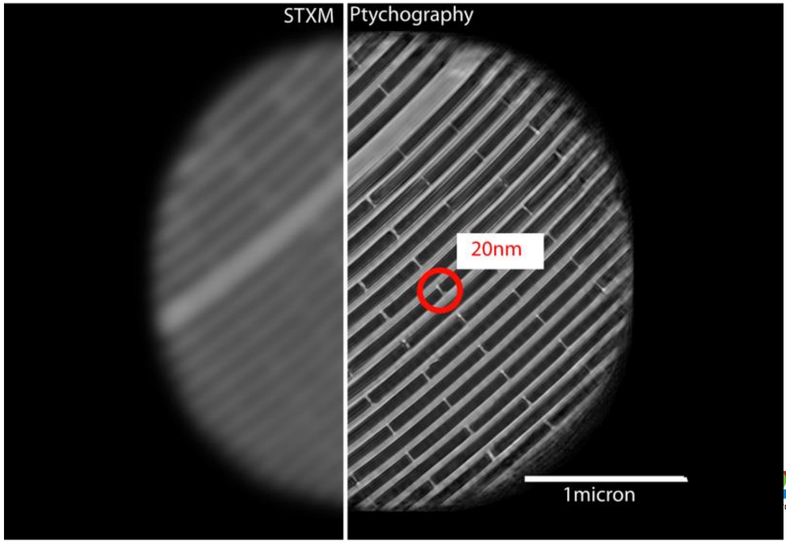




FROM DIFFRACTION PATTERN TO IMAGE: PHASE RETRIEVAL

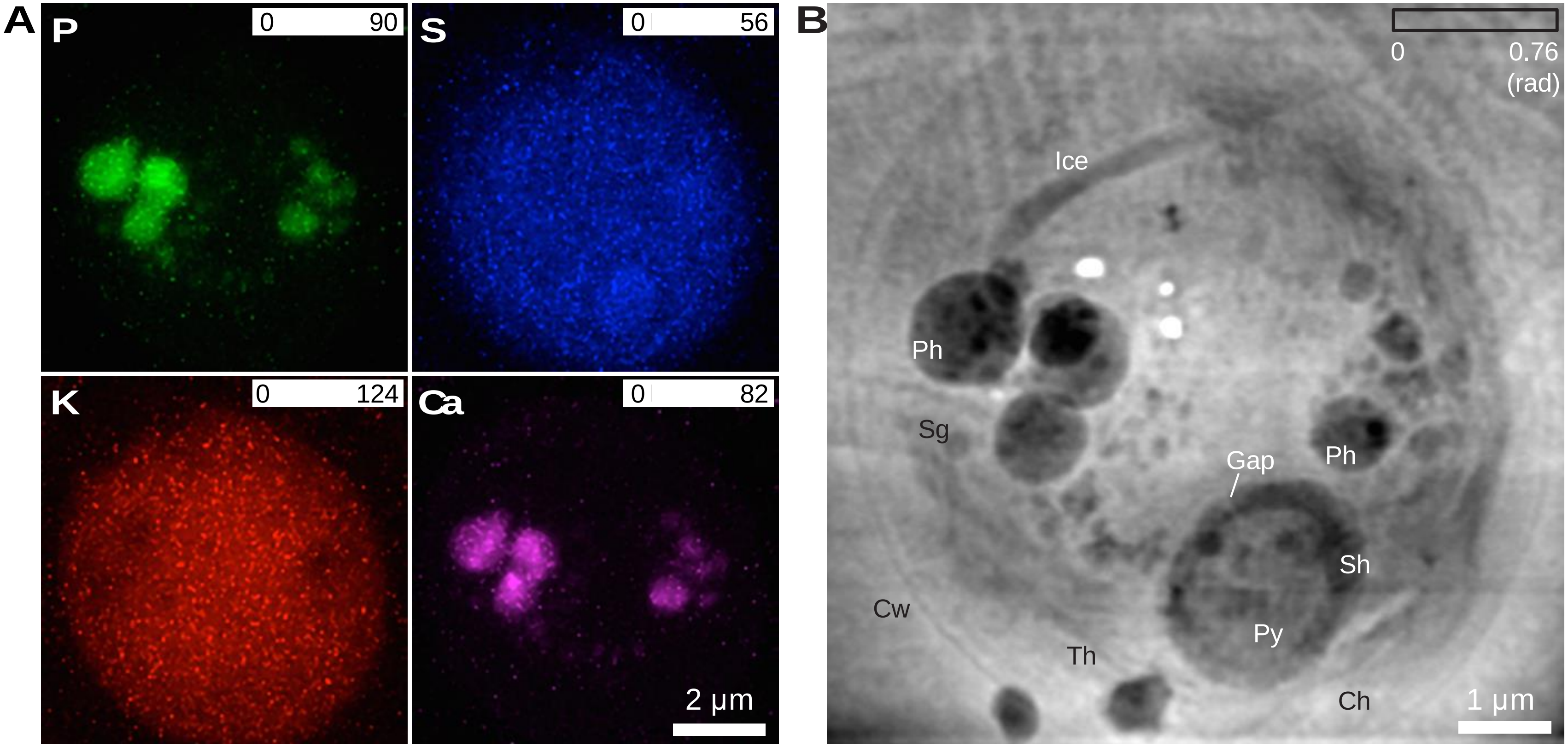






- Iterate between real & reciprocal space
- Reconstruct sample, beam (composed of coherent modes)

CRYO-PTYCHOGRAPHY & XRF OF CHLAMYDOMONAS REINHARDTII



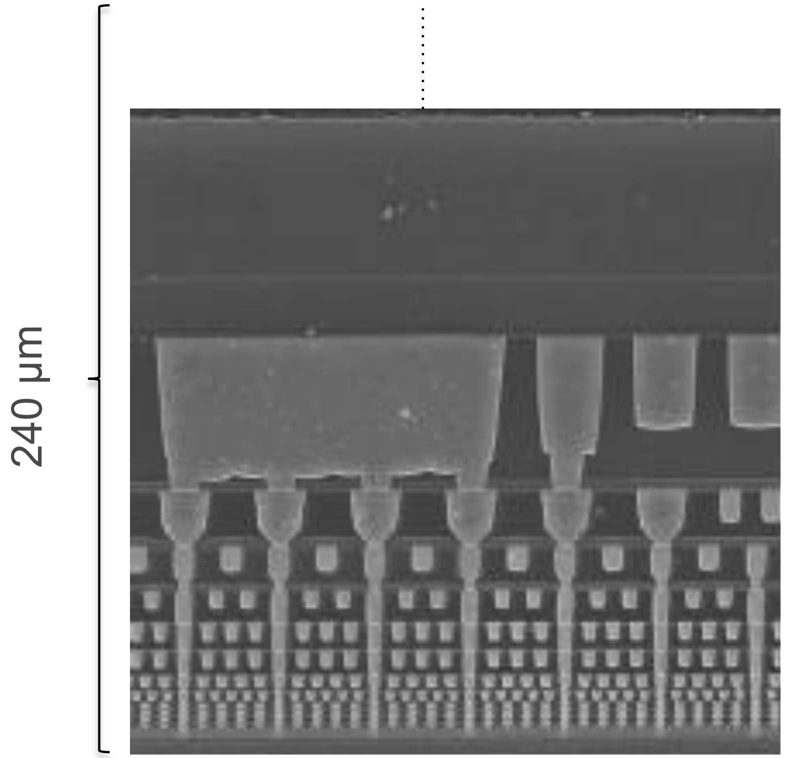
Junjing Deng et al., PNAS 2015

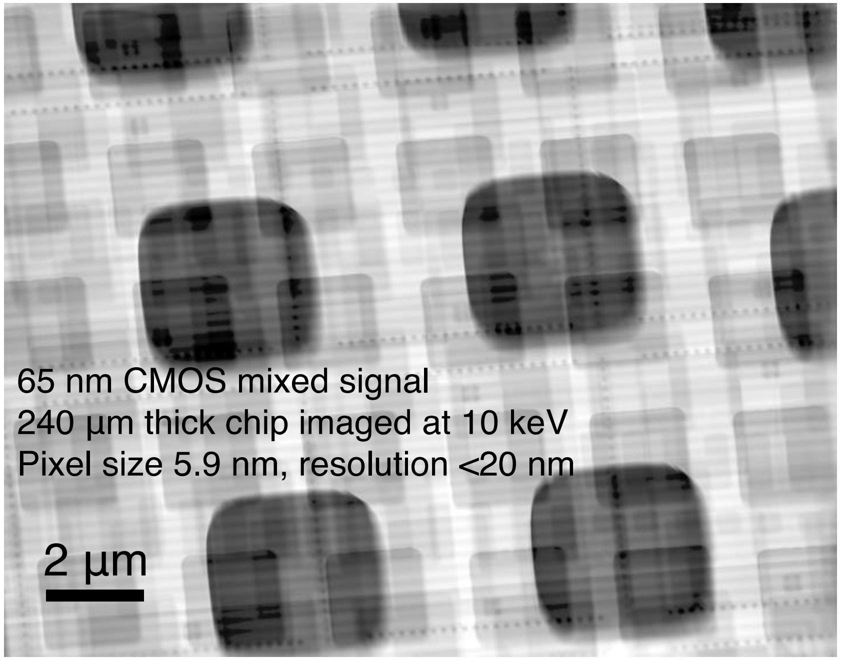
- 5.2keV, 70nm ZP, 167x151 Cartesian grid
- 0.5s exposure, 6.5h measurement
- white spots beam damage (not careful)
- ~20 nm resolution

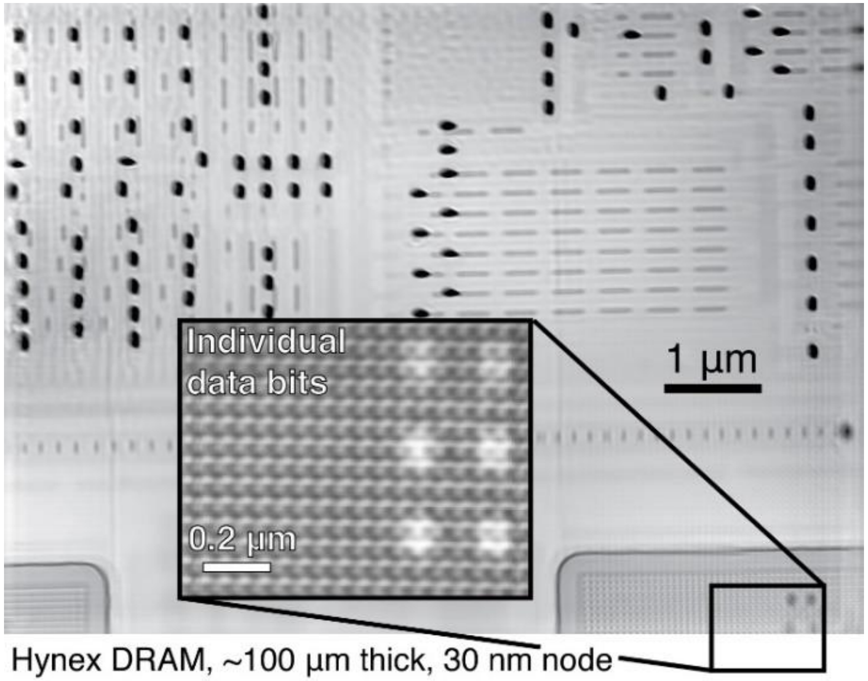
=> Beautiful structural visualization, strong contrast

TXM: Hummel et al, PLOS One, 2012

Chip structures







Hynex DRAM, ~100 µm thick, 30 nm node

Ptychographic images of a non-production CMOS IC fabricated in 65-nm technology. Deng *et al*, Phys Rev B, 2017

The
IARPA RAVEN Program

(Rapid Analysis of Various Emerging Nanoelectronics)

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Ptychography-based Rapid Imaging of Nano-structures with Multi-layer Assemblies (PRISMA)

RAVEN/RAVEN: Goals/Metrics

Metric	Phase-1 per BAA		Phase 2	Phase 3
IC Area	1 cm^2	1 mm^2	1 cm^2	1 cm^2
Duration/Goal	24 months – Develop Test Bench Tool	24 months – Develop Test Bench Tool	24 months – Develop Alpha Prototype	12 months – Develop Beta Prototype
Time	80 days to acquire images and reconstruct all circuit layers with >90% accuracy	80 days to acquire images and reconstruct all circuit layers with >90% accuracy	40 days to acquire images and reconstruct all circuit layers with 100% accuracy	25 days to acquire images and reconstruct all circuit layers with 100% accuracy
Lateral Resolution	20 nm	20 nm	≤ 10 nm	≤ 10 nm
Vertical Resolution	20 nm	20 nm	≤ 10 nm	≤ 10 nm
Metal Layers	≤ 13	≤ 13	≤ 13	≤ 13
Reproducibility	-	-	95%	100%
Test Articles	Bare die ≥ 14 nm feature size	Bare die ≥ 14 nm feature size	Bare die, 10 nm feature size	Bare die, 10 nm feature size
IC Thickness	≥ 50 µm	≥ 50 µm	50 - 200 µm	≥ 50 - 200 µm

Both resolution and timing are very challenging goals/metrics. To meet them, it requires special imaging equipment (monochromator, microscope, detector, etc.), a powerful x-ray source with substantial photon flux, and powerful advanced computing resources.

10x10x0.1mm3 => 10PB @ 1 byte greyscale

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Early Data on 22 nm Technology

Sockel LGA 1150, 3MB Cache, 22nm, 53Watt, inkl. GMA HD Grafikkern (350/1100 MHz GPU), Intel HD, inkl. Cooler

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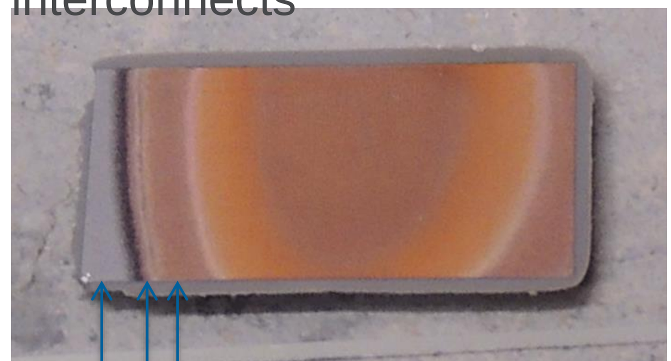
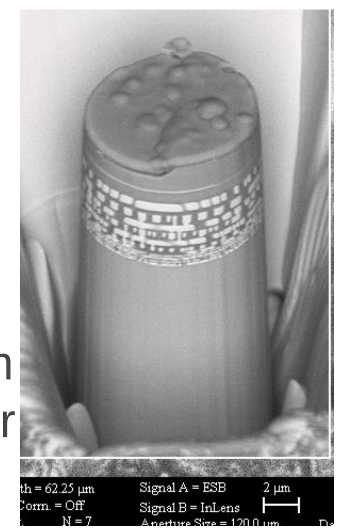
Inhomogeneous polishing trying to remove copper layer and interconnects



Copper & interconnects

Active layer

Silicon



~10 µm cylinder

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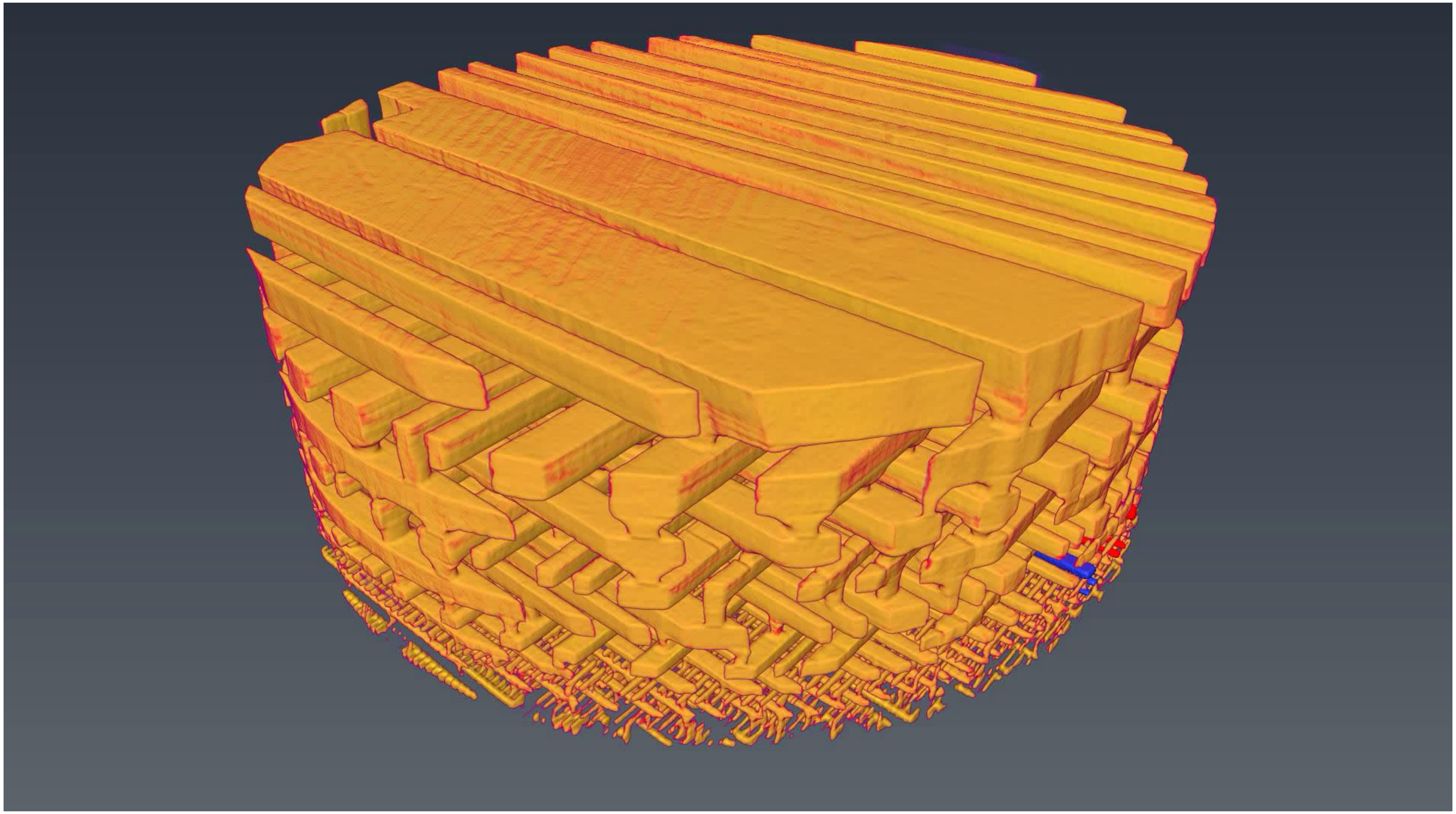
Early Data on 22 nm Technology



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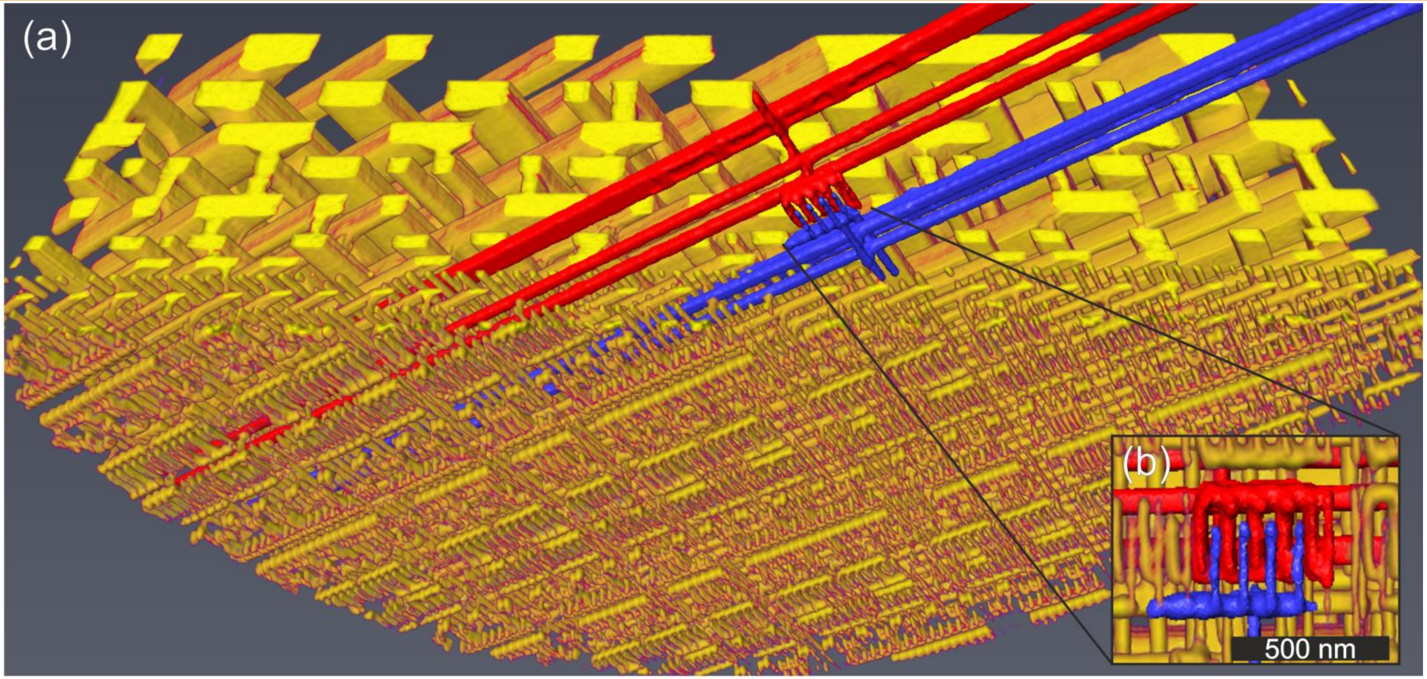
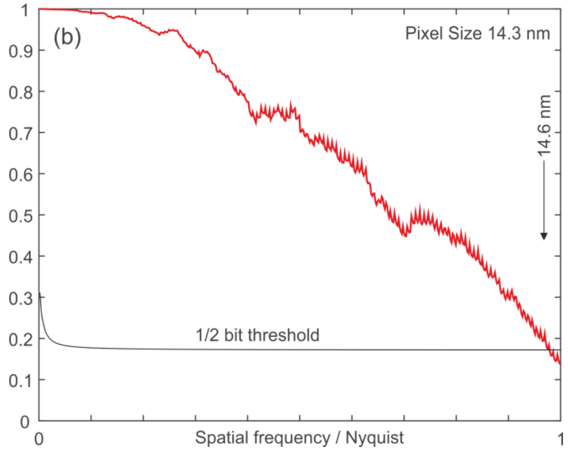
Early Data on 22 nm Technology





3D resolution 14.6 nm

DOI:10.1038/nature21698

Normal incidence tomography, limited to small sample volumes.

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PRISMA Program - Overview

TEAM DESCRPTION

Performers:

- USC's Information Sciences Institute (ISI) and Dep. of Electrical Engineering – Prime
- Northwestern University's EE Dept. - Sub
- Stanford University's EE Dept. - Sub
- Paul Scherrer Institute (PSI) - Sub

Collaborators:

- Intel Corporation
- Argonne's Advanced Photon Source (APS) [1]

APPROACH

- Non-destructive X-ray IC imaging of 1 cm^2 bare die up to 50 μm thick.
- Coherent Diffraction Imaging (Ptychography) X-ray and novel HPC algorithms.
- Use of IC collateral/available information to tune the imaging process parameters, and expedite the image acquisition process.
- Construction of a CDI-tailored microscope, detector, and high-efficiency FZPs.

EXPECTED RESULTS

- PHASE-1:
  - 2D and 3D X-ray imaging of 1 mm^2 bare IC die.
  - Establishment/completion of a RAVEN-centric X-ray endstation at ANL's APS.
  - Imaging algorithms and HPC infrastructure.
- PHASE-2 & 3:
  - 2D and 3D imaging of 1 cm^2 bare IC die up to 50 μm thick.
  - Full engagement of integrated X-ray endstation at ANL's APS for experiments.

SCHEDULE AND STATUS

- IC specimens for initial experiments currently available (Intel-provided).
- Initial X-ray endstation and companion instrumentation currently available.
- Initial experiments: June, 2017 (starting).
- Completion of RAVEN-centric X-ray endstation 24 months ACA (end of Phase-1).
- Integration of PSI-provided instrumentation at ANL's APS: 32 months ACA.
- Phase-2 & -3 experiments: Starting 36 mos. ACA

1. Argonne APS collaboration/involvement in PRISMA is "GFE" per BAA's instructions

PRISMA@APS

- Prisma will access APS through either CDT or PUP
- Early access (2017 & 2018) on existing instrumentation (Velociprobe - up to 30% of available time)
  - Early experiments and data
  - Develop / prototype analysis pipeline
- Build new beamline with APS/APS-U/Prisma resources
  - Prisma will be installed at sector 28 of APS
    - Assembling package for procurement of hutches at Sector 28
    - Expect award by 6/30/2017
- Prisma @ S28 Online 2019
  - 30% beamtime dedicated to Prisma
  - Planning to optimize for high stability, high flux
  - H-DMM planned

THE VELOCIPROBE

Early Access: Velociprobe

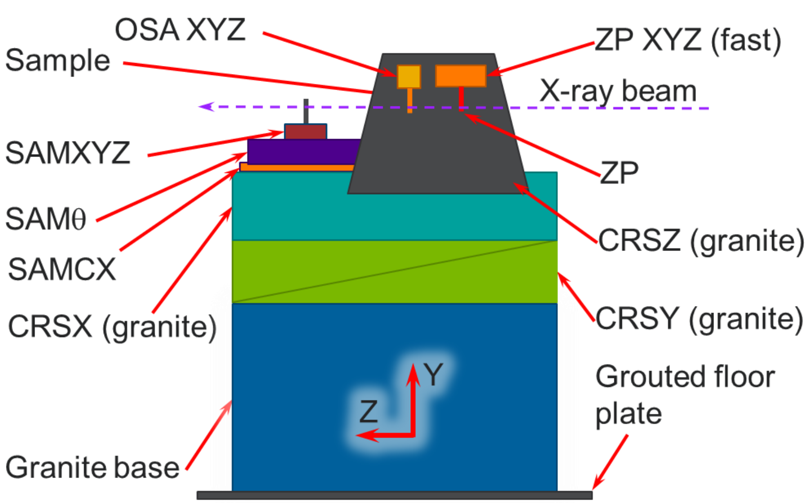
Goal:

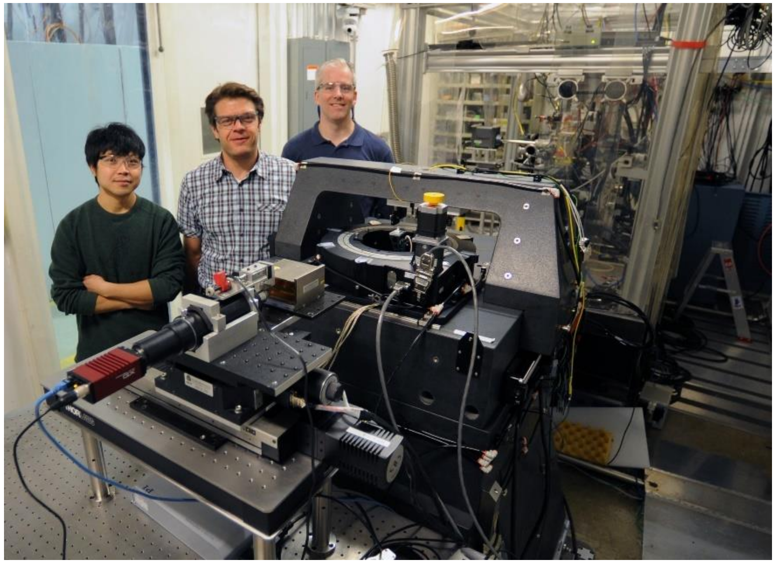
- To push speed limit for scanning, while retaining high stability and position control
- Ptychography: 10 nm and below
- Fluorescence: 50 nm and below

Note: focus on 2D images,
but tomography capable (not laminography)

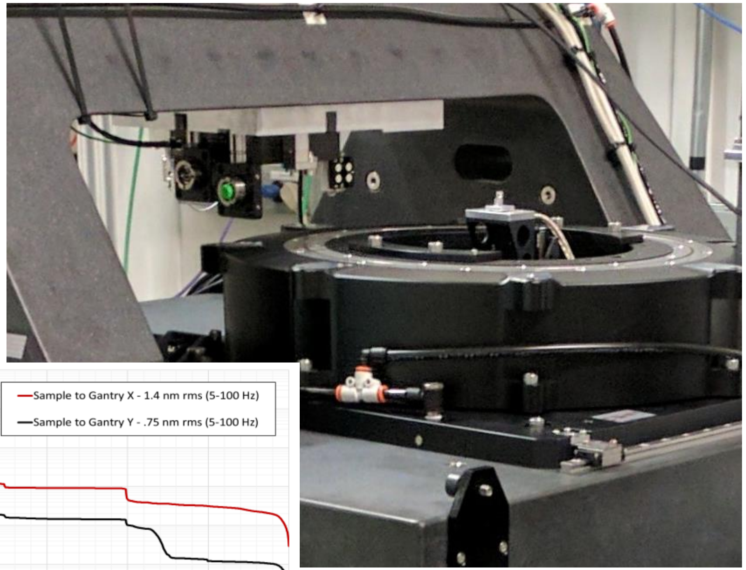
Concept:

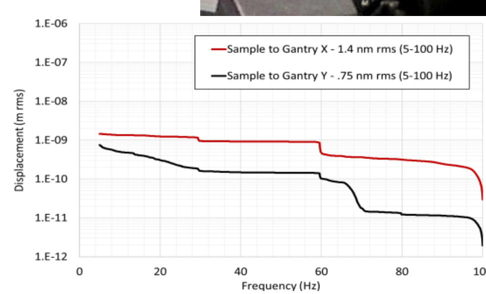
- Ultra-stable granite coarse stages
- Fast scanning of zone plate
- Low-noise, high-bandwidth, interferometer-encoded control



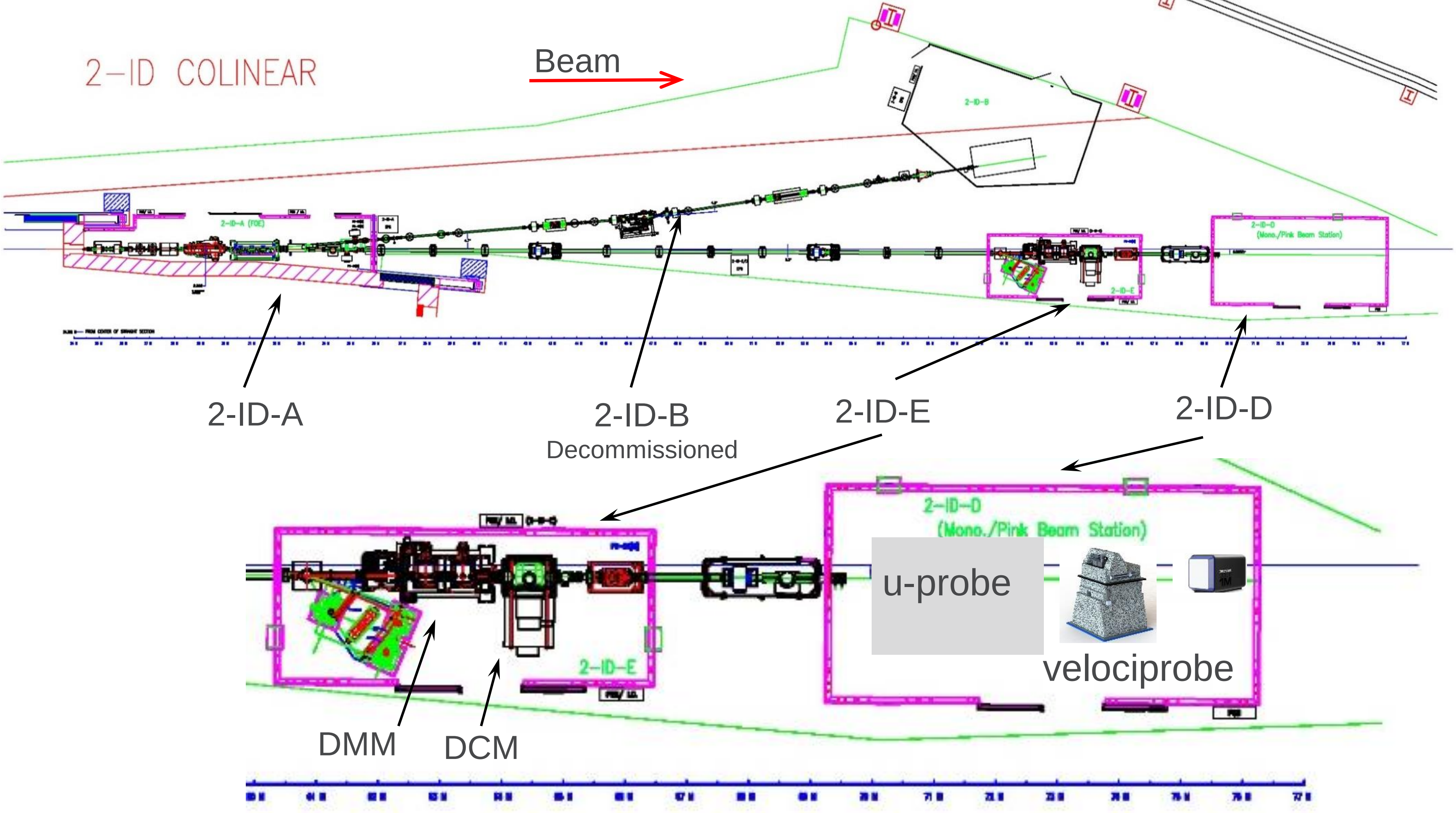


L to R: Junjing Deng, Curt Preissner, and Chris Roehrig, also Shane Sullivan, Zhonghou Cai, Barry Lai, Joerg Maser, David Vine, Stefan Vogt , …





VELOCIPROBE INSTALLED AT 2-ID-D



- 2-ID-D and 2-ID-E operate in parallel
- 2-ID-D :
  - Microfluorescence: 100-200 nm beam
  - New velociprobe instrument
- 2-ID-E: Microfluorescence: 300 nm beam

- Shared beam defining slits
- 2x 3.3cm Undulator (collinear)
- Mirror (Si, Rh, Pt stripes)
- For 2-ID-D: DCM & DMM

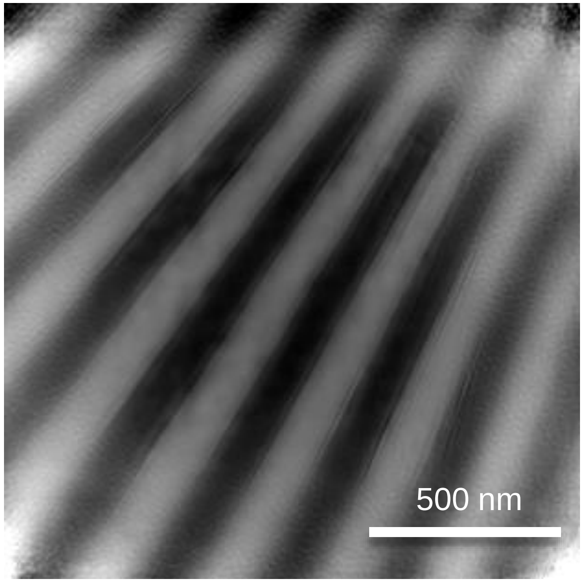
First experiments

Optics
- Zone plate: 180 um diameter, 50 nm outmost width
- Beam stop: 65 um
- OSA: 30 um

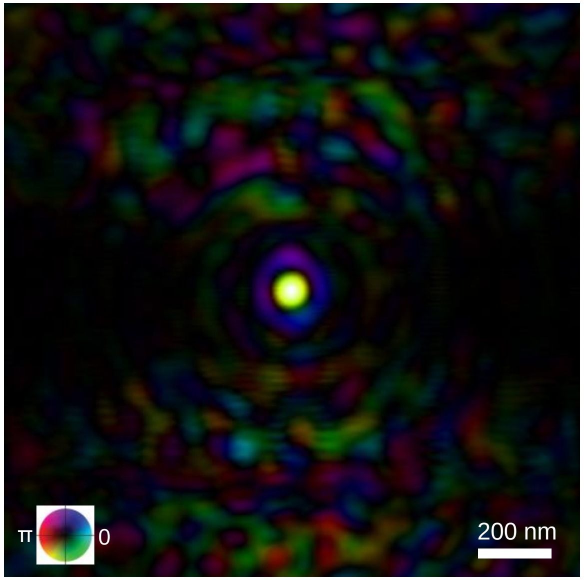
Scans
- 40 nm step size
- 50 ms /point
- 8 keV x-rays

Reconstruction
- Ptychographic image: 12.5 nm resolution
- Focused beam: 58 nm FWHM

Test pattern



Phase of reconstructed object



Ge particles
- Highly promising anode materials for lithium-ion batteries.
- Particle size: 500 nm – 5 um

Reconstruction:
19.2 nm resolution

VELOCIPROBE TIMELINE:

- Installed in January 2017
- Initial commissioning 2017-1 cycle (Feb-Apr)
- 2017-2 (Jun-Aug): continue commissioning + friendly 1st users
  - Prisma 3-6 days as required

Tentative plan 2017-2:

May 31st – June 5th	: commissioning
June 13th – June 19th	: commissioning
July 8th – July 14th	: Prisma
July 25th – July 31st	: tbd
August 9th – 22nd	: tbd

- 2017-3 (Oct-Dec): open to GU
  - Prisma 3-6 days as required
- 2018-1: GU, Prisma 3-6 days as required
- 2018-2: GU, Prisma 3-4 weeks as required
- 2018-3: GU, Prisma 4-5 weeks as required
  - ‘end’ of prisma CDT at 2-ID
- 2019-1: sector 2 down for canting (change from original plan)
- 2019-2: sector 2 commissioning (LN2 mono, HDCM, …), friendly users
- 2019-3: GU operations

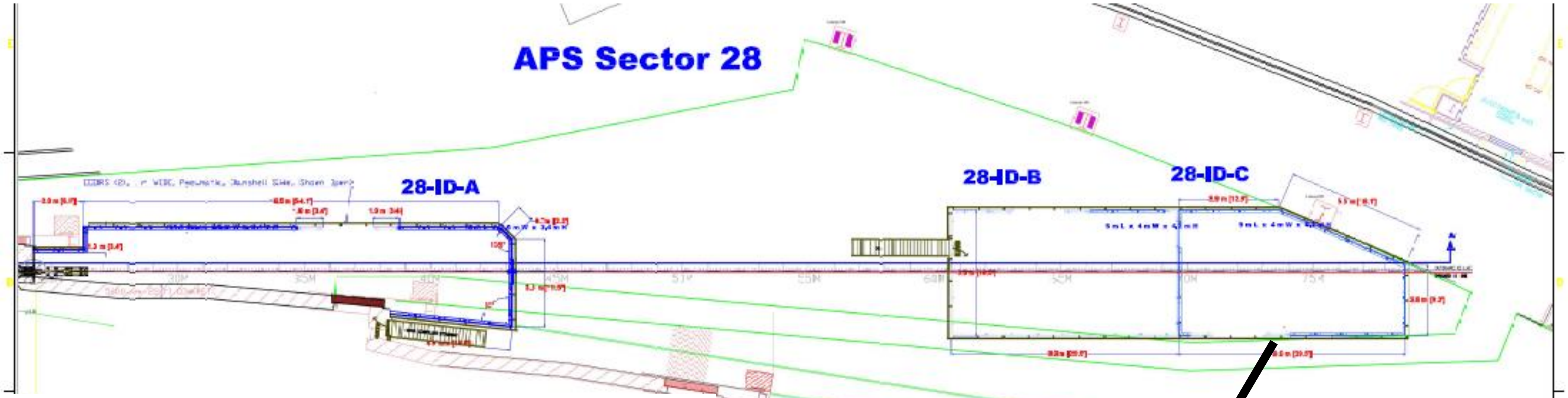
Key points during phase 1

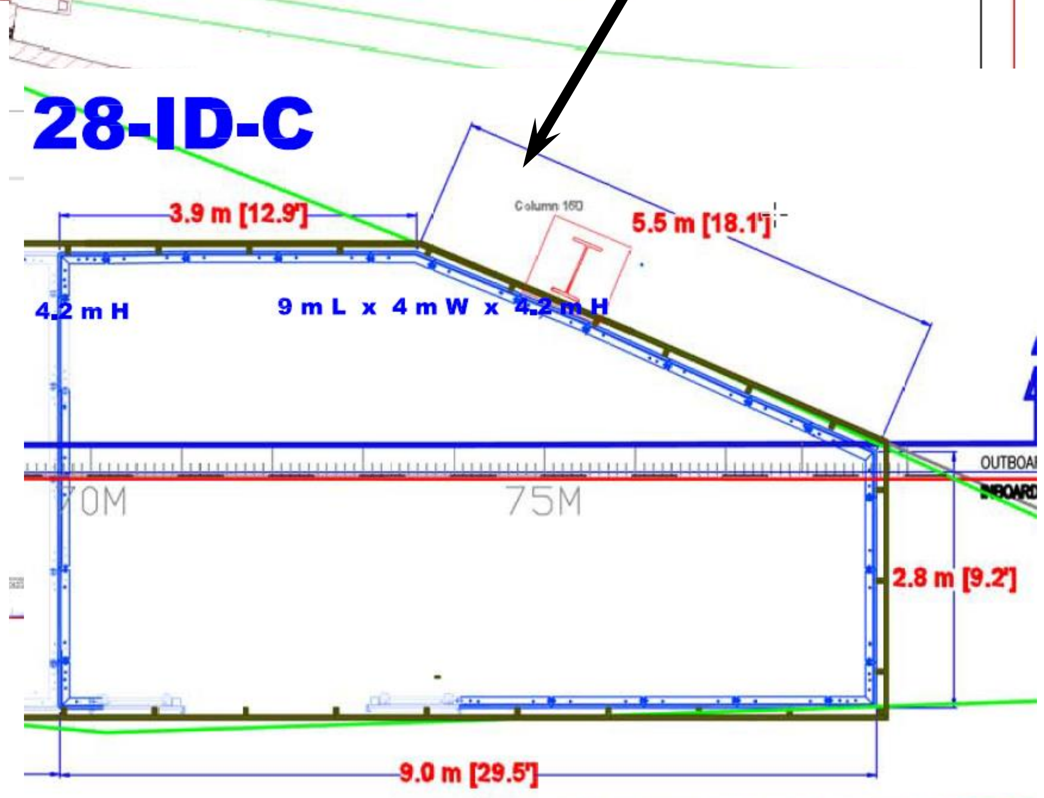
- developing data analysis pipeline, up to 20Gb/s for phase 1, 60Gb/s for phase 2 & 3
- ZPs are chromatic lenses – how well do they work for ptychography with a multilayer monochromator ?
  - Alternatives: capillary optic; narrow bandwidth multilayer
- ZP parameters (size and beam divergence)?
- Tradeoff flux vs degree of spatial coherence ?
- Tradeoff illumination area vs sampling frequency ?
- Acquire data in 'tiles' – what is the ideal tile size (100x100 um^2) for acquisition, processing, etc ?

- Design / develop hutch (S28) for phase 2

PRISMA ENDSTATION @ S28 (APS-U R&D BL)

S28 HUTCH LAYOUT

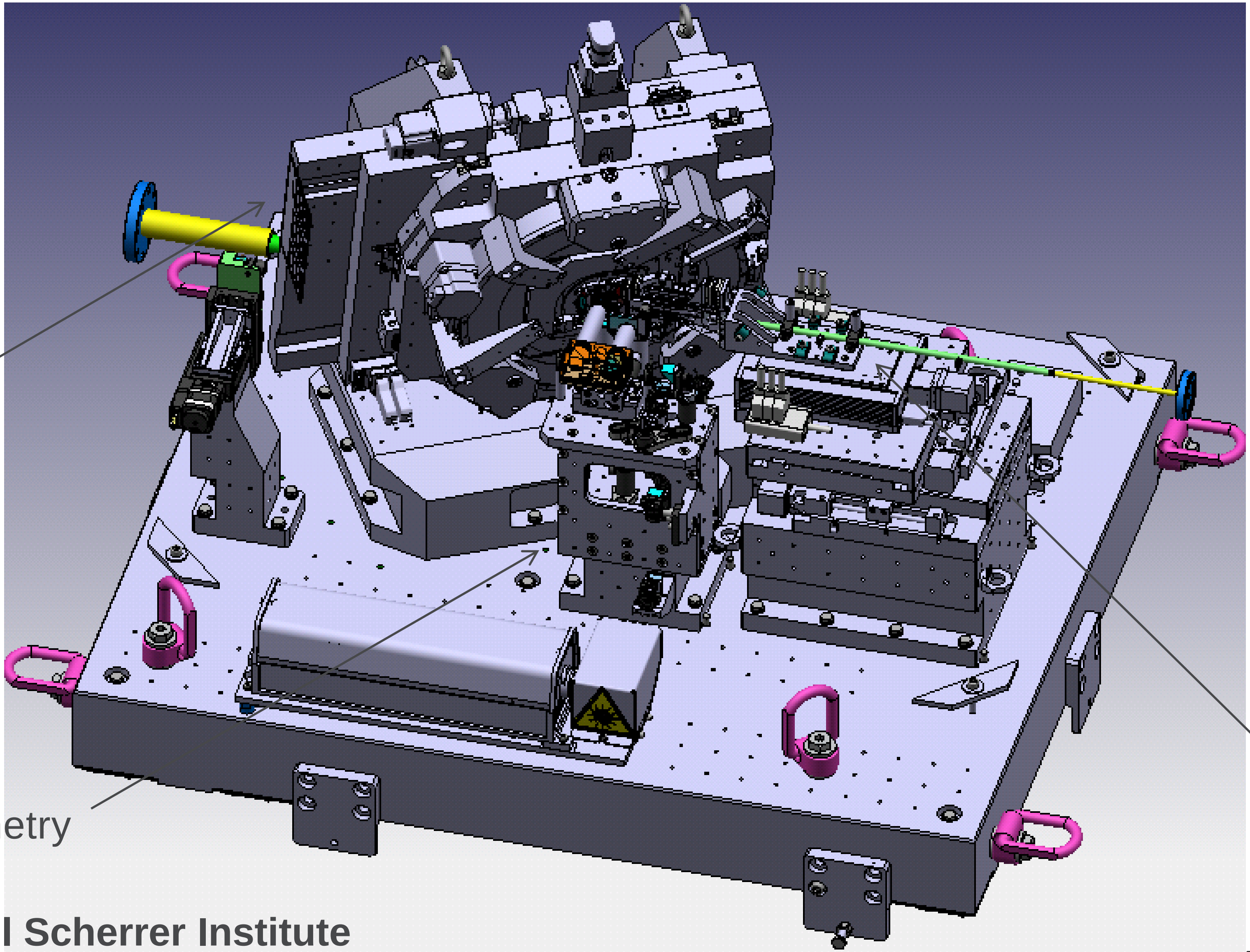




Sector 28 timeline:

- September 2017: award of hutch procurement
- 2017/2018: construction
- Oct 2018: shielding verification of FOE
- Oct-Dec 2018:
  - installation of BL optics (monos, etc)
  - begin commissioning
- Feb-Apr 2019: ready for installation of Prisma endstation instrument

Status of the End Station Instrument



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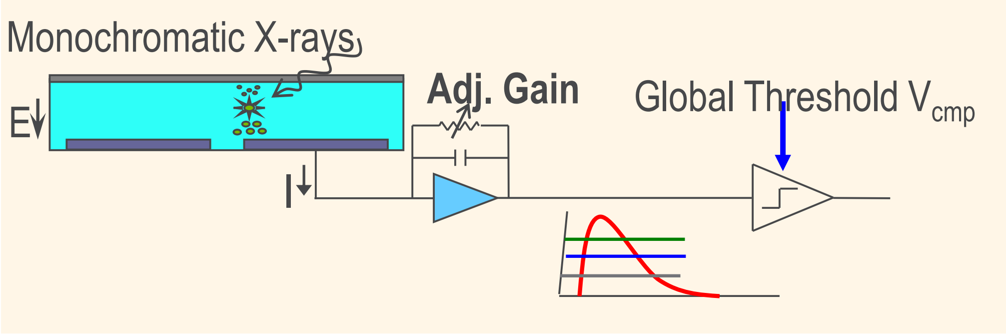
EIGER detector: Characteristics

Single-photon counting with hybrid pixel detectors: No background and no readout noise, high dynamic range.



Key parameters:

Pixel size	75 x 75 um^2
Counter	4/8/12 bit
Chip frame rate	23/12/8 kHz
Dead time between frames	3 us
Min. threshold (high frame rate)	4.5-5 keV
Threshold dispersion (after trimming)	< 50 eV
Noise	350-700 eV RMS

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DATA ACQUISITION CONSIDERATIONS:

- Assume detector operates at 13kHz: 1.1e9 measurements / day, or 2.25e10 measurements in 20 days.
- Distance between measurement spots: 0.66 microns
  (**10.*10000./sqrt**(**2.25e10**) = 0.66)
  this assumes we need 10 projections, each of which is 10x10 mm
- 66% overlap: 2 micron spot size, 50% overlap 1.3 um spot size, 5 nm resolution, 10 keV

Oversample	probe size (um)	pixel	distance (m)
3.5	2.0	1400	4.23
3.8	1.3	1000	3.85
5	2.0	2000	6.05
5.4	1.3	1400	4.23

POTENTIAL APPROACHES

‘easier to implement’:

- Reconstruct local 2D patches, say 50x50 um = 5700 measurements,
  = 8.6 GB in 0.45s
- Throw away data
- Stitch 2D patches into one large 2D projection
- Reconstruct global 3D data set based on ~10 full projections

Better quality reconstruction ?

- Reconstruct local 3D volumes, local tomography based on ptychography, eg, 50x50umx10 projections= 57000 measurements,
  86GB in 4.5s.
- Throw away data
- Stitch 3D patches into final 3D dataset.

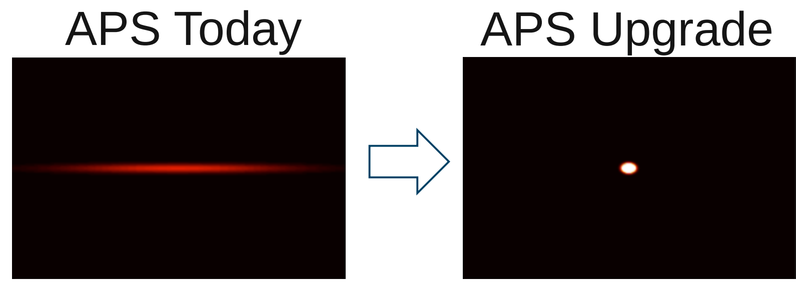
REASONING

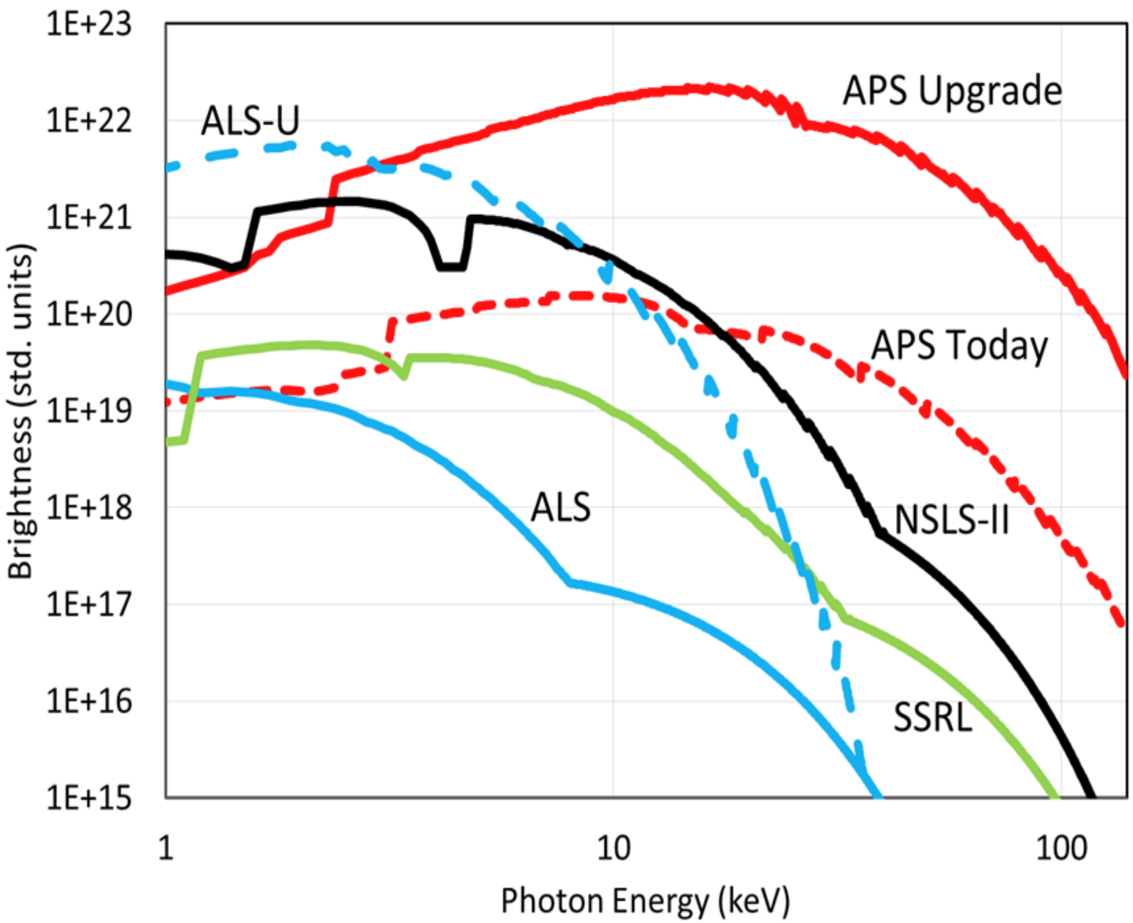
- $2.1M in equipment money
  - Includes hutch to be used for CHEX later
- 2 FTEs starting in year 2,3
- Helps us push technology and methods that will be directly relevant for APS-U
  - Consistent, fast data handling
  - Data analysis
  - Lensless imaging

no commitment after 5 years

APS MBA UPGRADE

Brightness vs. x-ray energy





- Brightness increases of 100x and more compared to what we have today
- Micro/nanoprobes directly brightness driven

⇒ possible to get nearly 100% of APS flux into a 0.3x0.25 um spot !!!

⇒ 5nm and below for elemental mapping and with CDI/Ptychography

This upgrade will revolutionize scanning probe microscopies…

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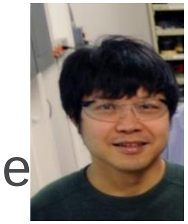
ACKNOWLEDGEMENTS



- **J. Deng**, **C. Roehrig** et al, Microscopy group, Argonne

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- Piero Pienetta, SLAC
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Thanks!