x-ray diffraction imaging: brilliance limited techniques for the study of electronic devices and functional nanostructures

Tobias Schülli and Colleagues from ESRF Experiments Division

Brilliance hungry methods and their potential progress with new sources

How "nano" and how fast do we need to get ?

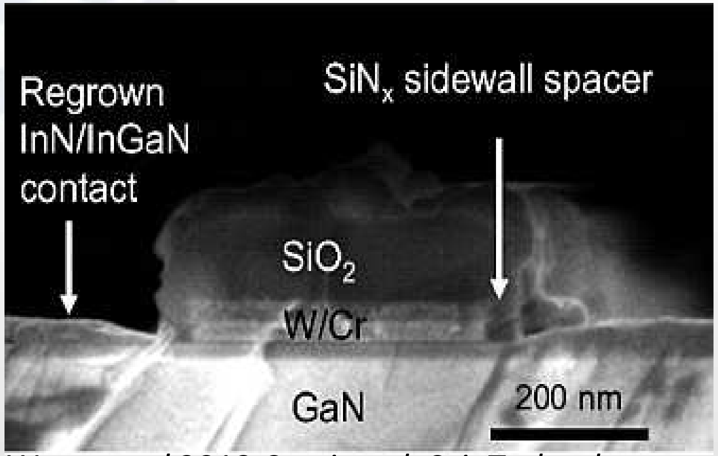
Challenges 2018

High power/nano-electronics:

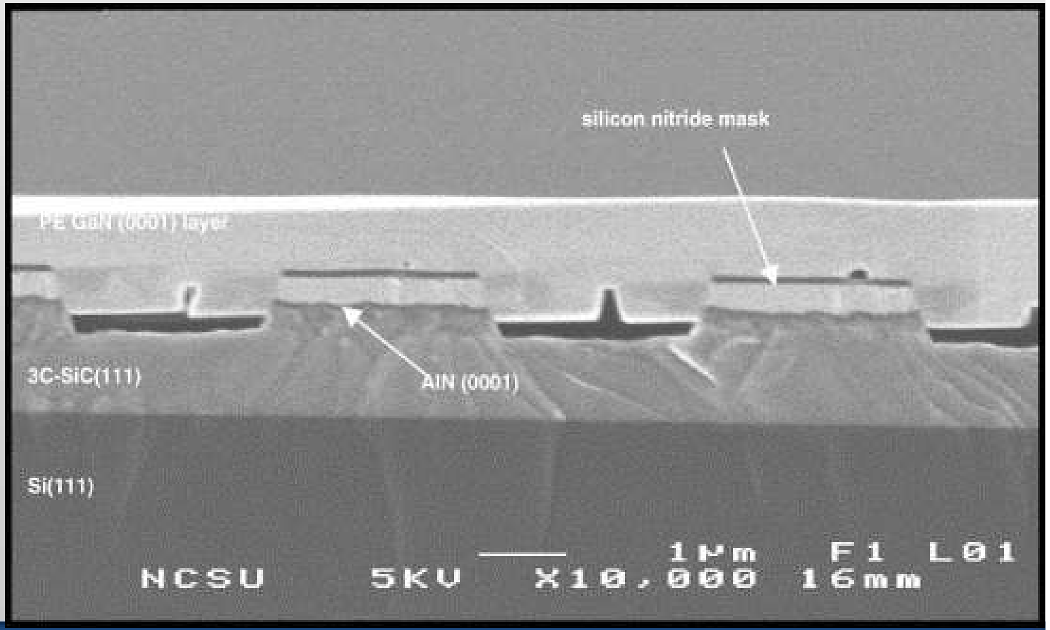
Increased multi Material complexity ! ("More than Moore")

High performance alternatives to Si (SiC, GaN, AlN,..) have difficulties to achieve full performance (defects)

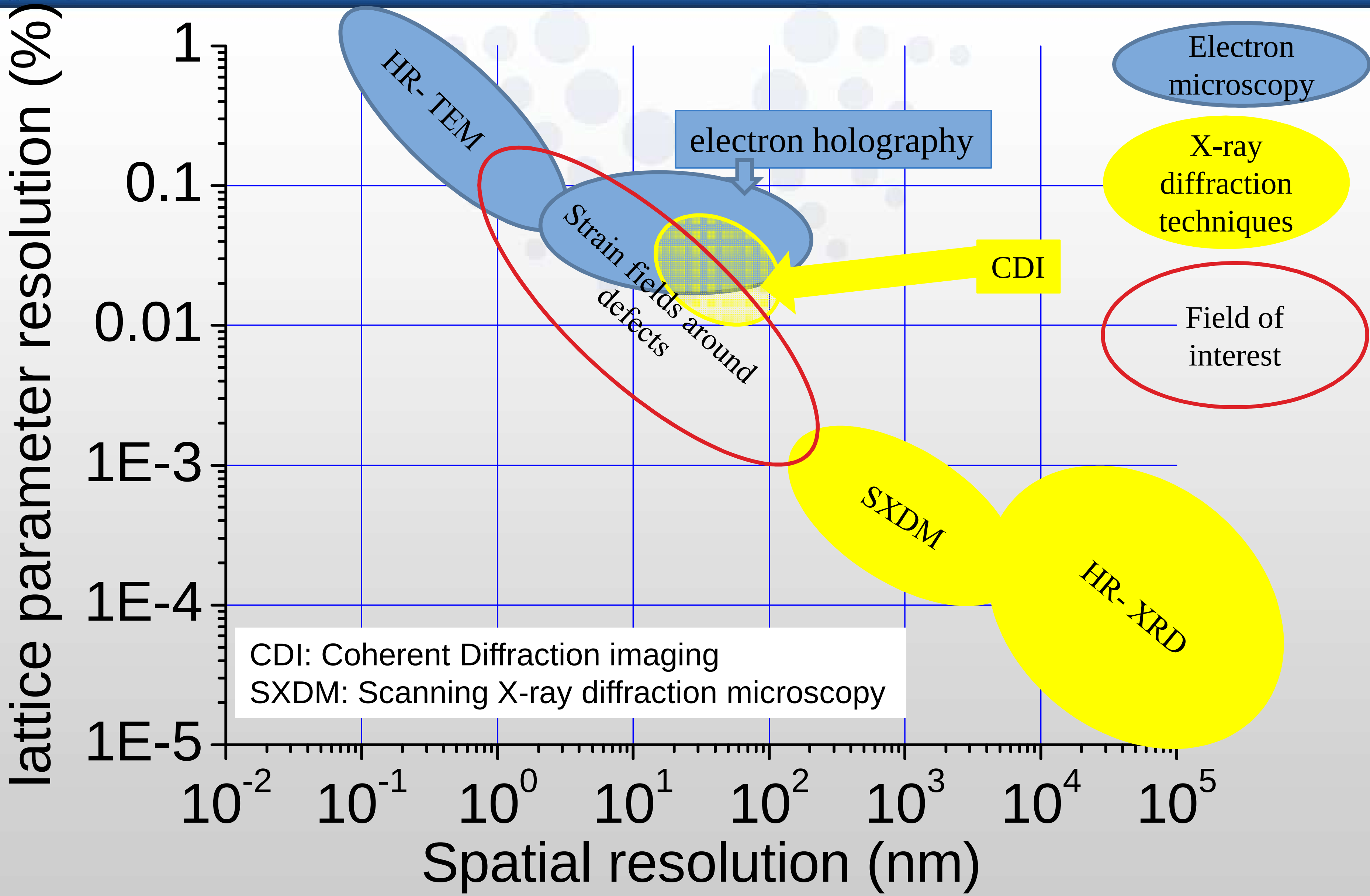
Defects and strain are critical
Typical system sizes: sub 100 nm
Lattice strain values: 0.01-0.001%



Wong *et al* 2013 *Semicond. Sci. Technol.*



Diffraction imaging of strain fields today (2013)

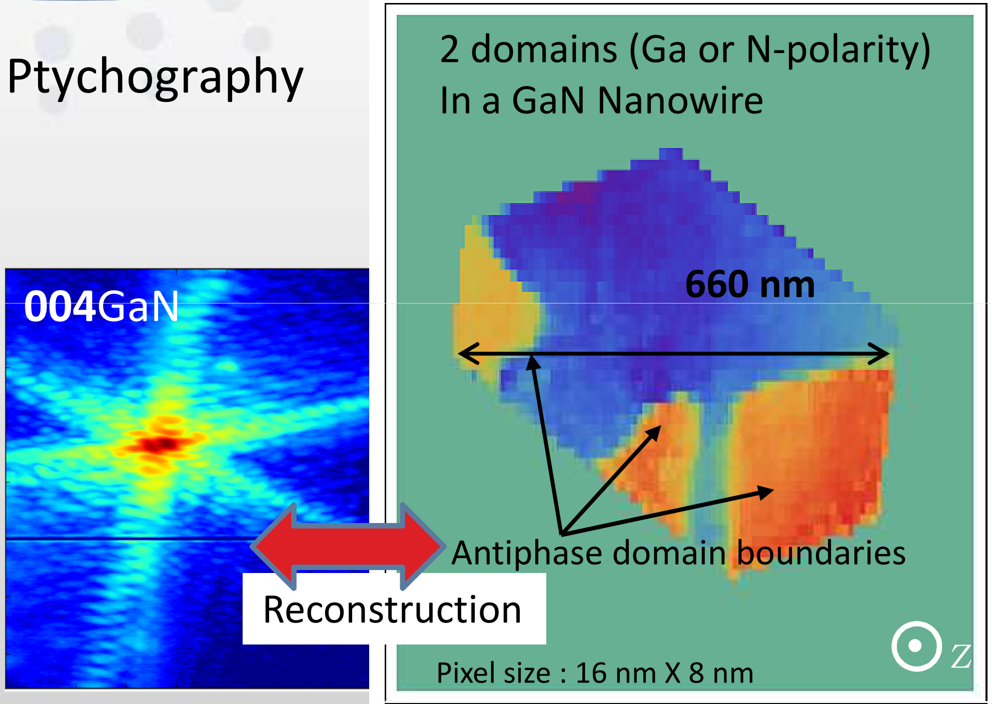


Methods

Methods which today are mainly Brilliance (*B*) limited:

1) Coherent Diffraction Imaging (**CDI**)/ Ptychography

Example today**: Typical exposure times for 10 nm voxel** for CDI ~ 1 hour (Z=20-30)
Ptychography: same procedure for 20-100 positions ->20-50 h



Coll. IM2NP, CEA-Grenoble, SIMaP

Resolution ~$\sqrt{B}$ (supposed that optics can follow)

Speed ~ *B*

2) Fast Scanning X-ray Diffraction Microscopy (SXDM)

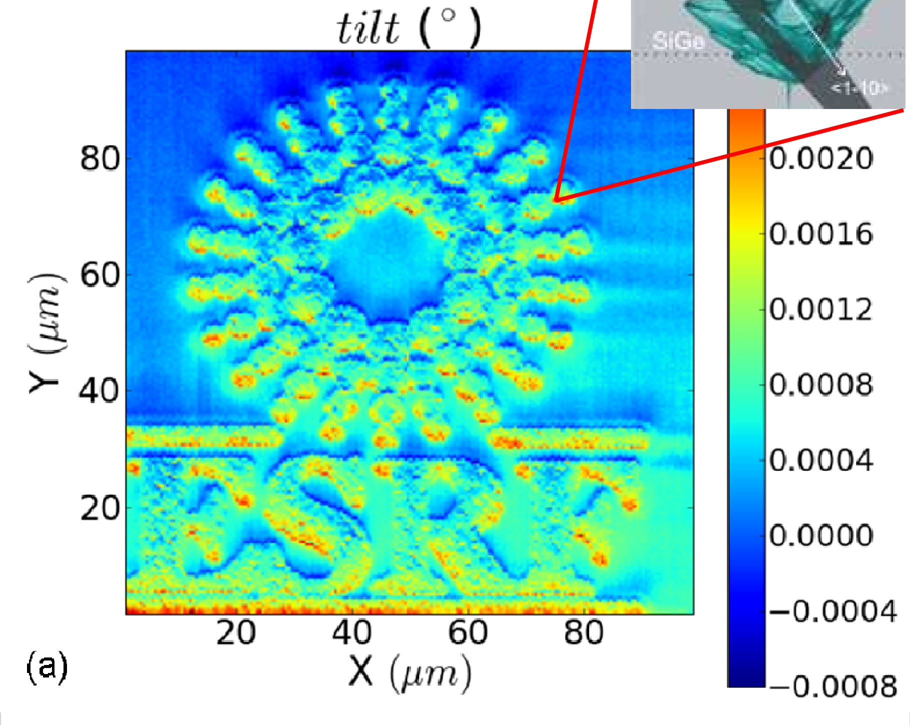
Resolution in space and time today in SXDM

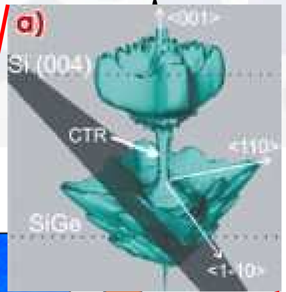
Methods: SXDM

SXDM: device like structures and industrial samples.

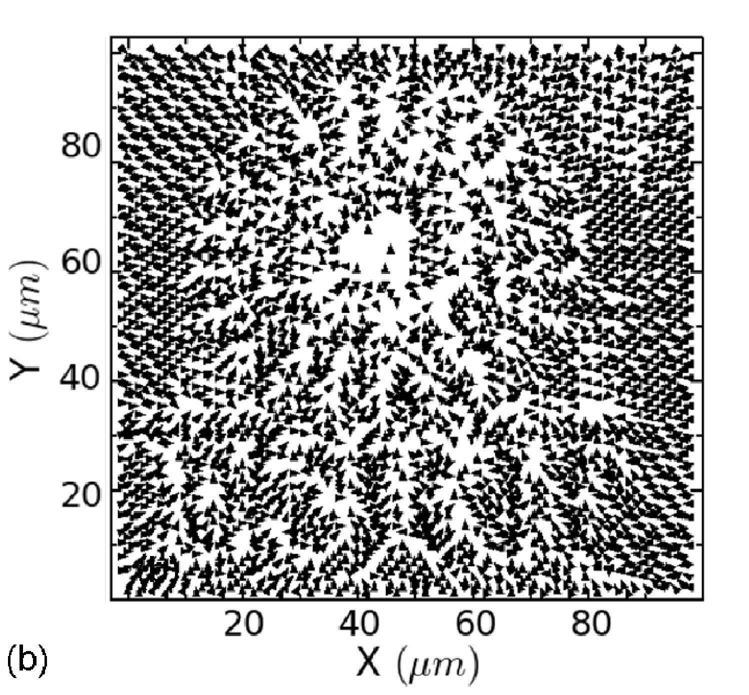
~ **2 hours** (0.5-1 Tbyte). 100x100 μm^2 Spatial resolution: 500 nm.

Example: ESRF logo FIBed into Si/SiGe structure





3D Reciprocal Map in each pixel



SXDM of Tilt magnitude in °

Tilt orientation°

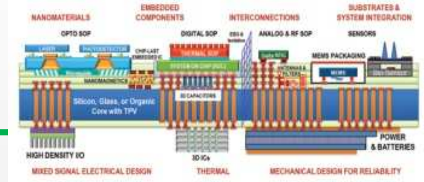
3D reciprocal space diffraction maps on 2D film = 5D

G. Chahine, M.-I. Richard, T. U. Schülli, 2014

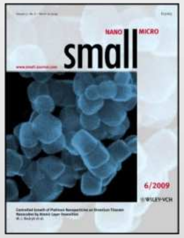
Methods & Challenges

imaging of devices:

“Thick” structures (**100 nm** +), at sub-ms frame rates
5D images within 1 min in SXDM
-> *In situ* growth and ageing of devices under thermal stress



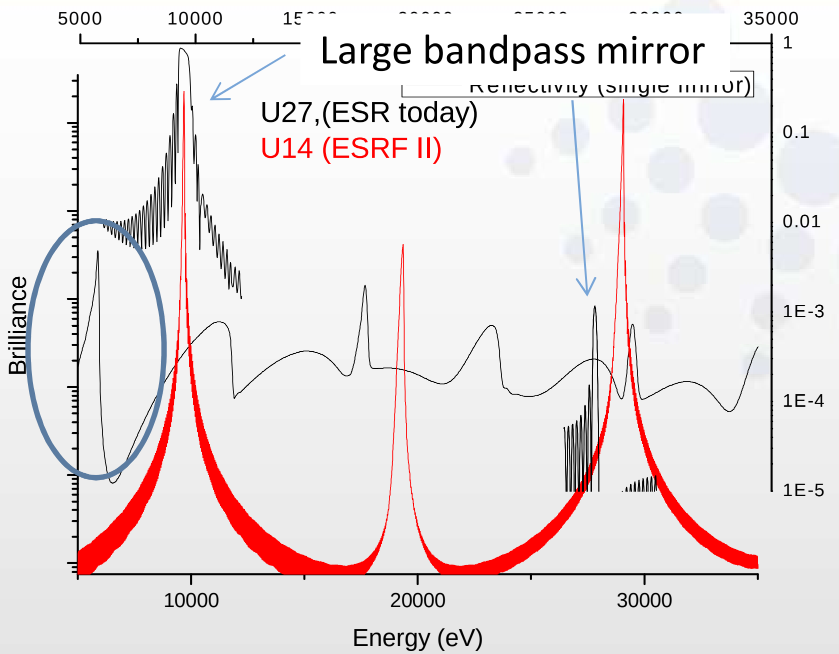
(sub)10 nm layers and functional oxide films (ferroelectrics etc.)
5D images within 1 hour



imaging of catalysis (CDI and SXDM)

Low-Z catalysts: zeolite (Z ~ 12) “ consumption” or poisoning takes few minutes at RT
1 nm resolution in 100 s requires a factor 1000 +

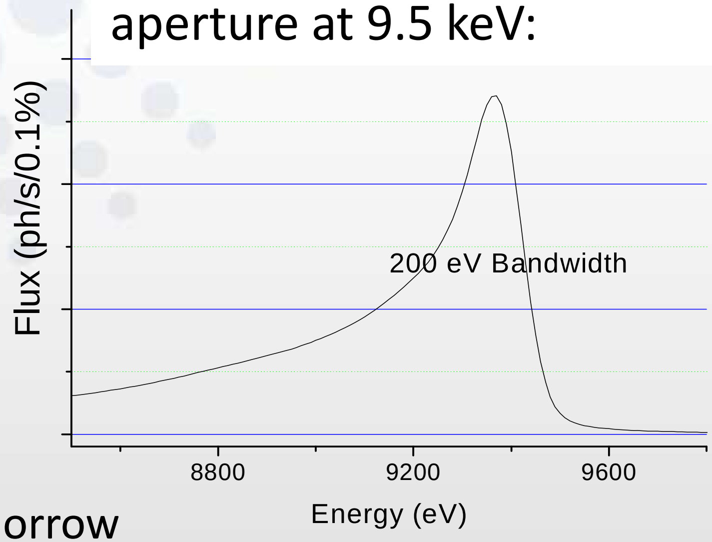
Coherent flux for short coherence lengths (nano particles!):



Large bandpass mirror

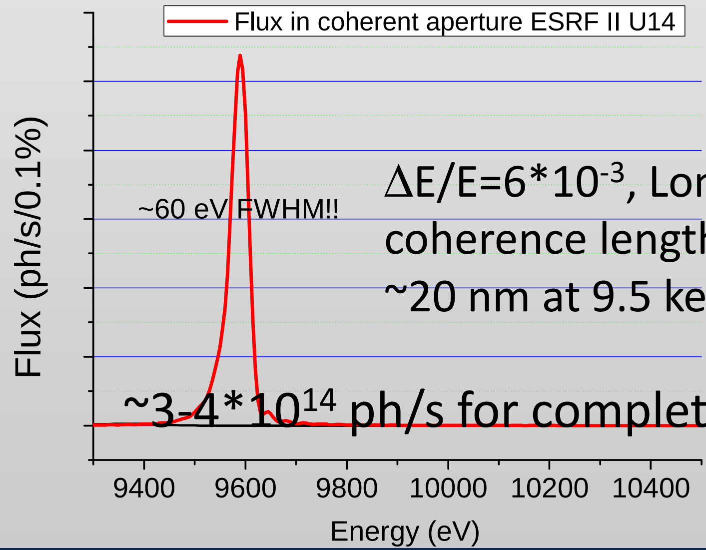
New source

Todays flux inside the coherent aperture at 9.5 keV:



Tomorrow

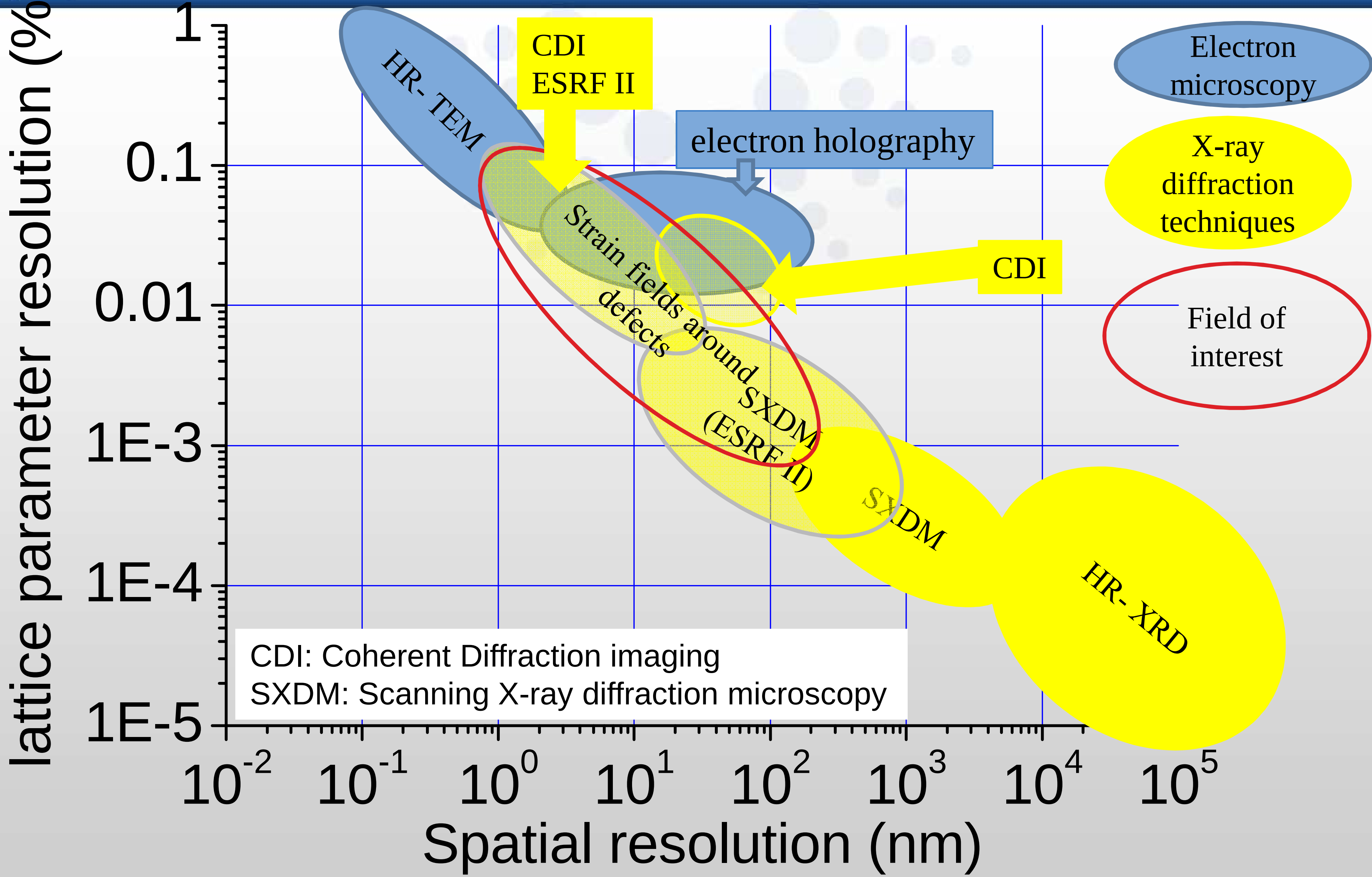
Pink beam (20 nm long. Coh. length) coherent flux * 2000 !!



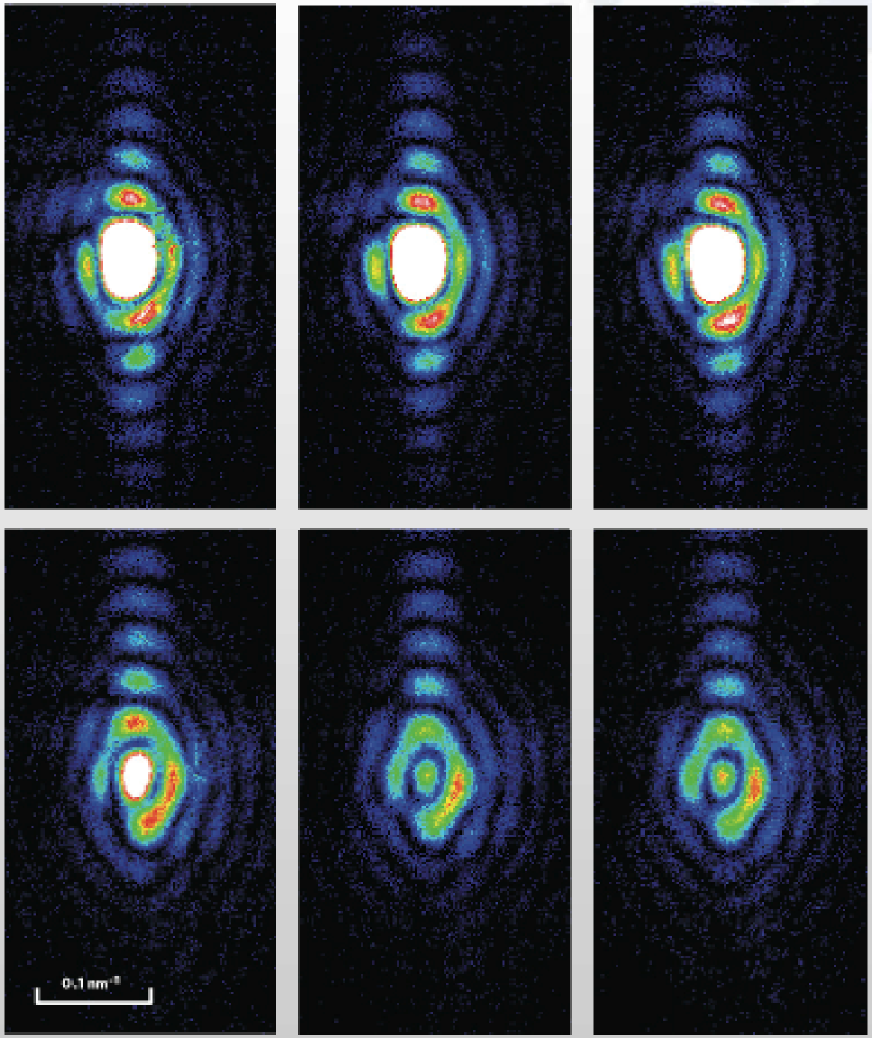
$\Delta E/E=6*10^{-3}$, Long. coherence length ~20 nm at 9.5 keV

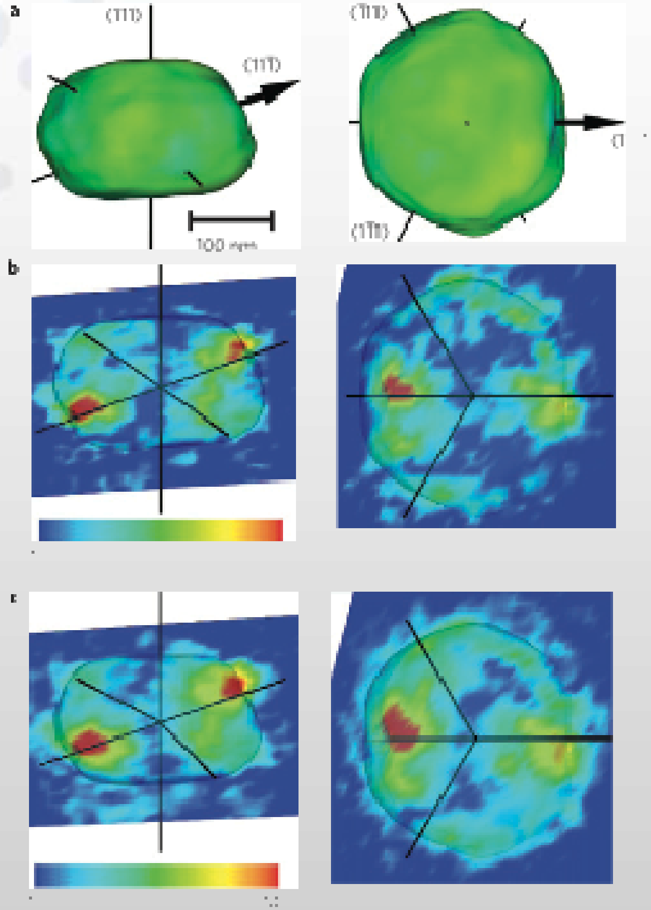
~3-4*10^{14} ph/s for complete line

Diffraction imaging with diffraction limited sources



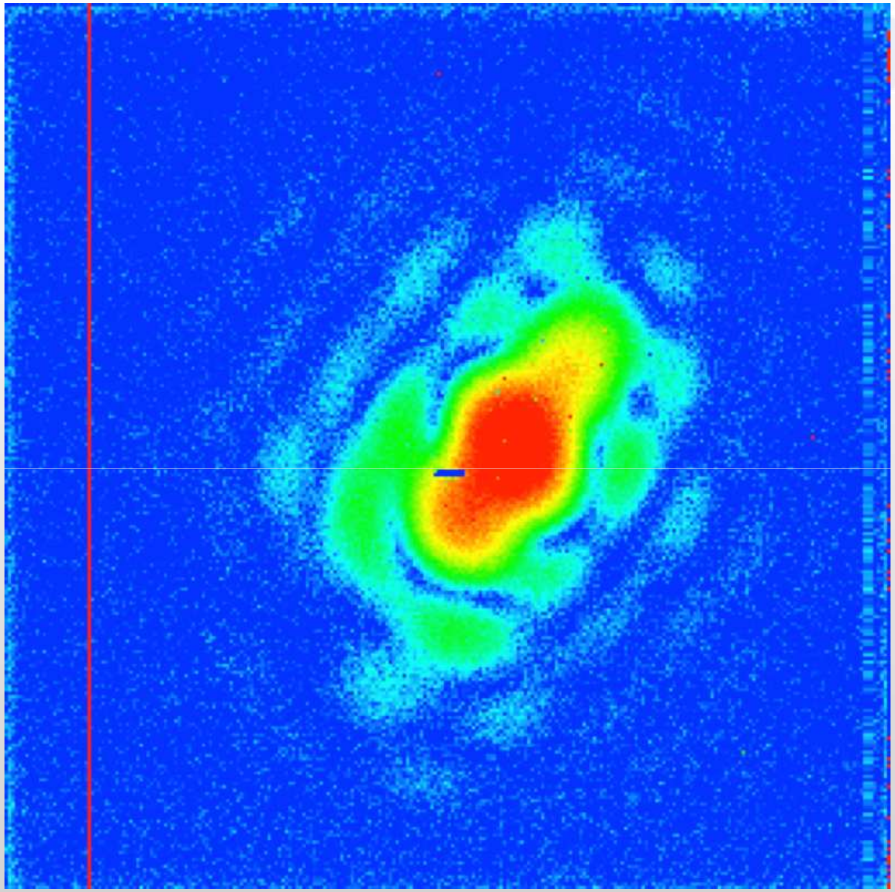
CDI to determine induced stress by thiol adsorption on Gold nano-crystals





M. Watari et al., NMAT 3124 (2011)

Is operando CDI possible?



Today:

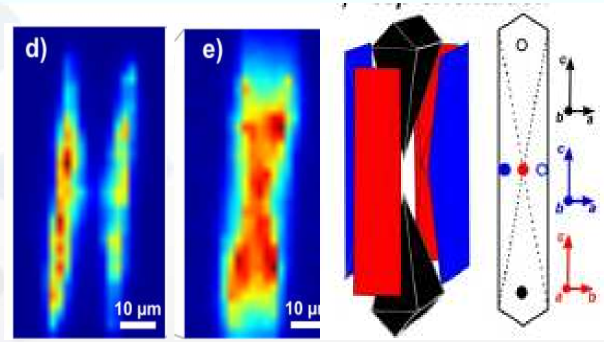
"Satisfactory" quality from Z=30 with 10 nm voxel, 10 s for single coherent frames.

For nanoparticles tomorrow:

1 nm voxel possible at 200 ms frame velocity with "matching longitudinal coherence length"

Tuning coherence length, space and time resolution: From model to real systems

A light for Science



Today: Model size 80 micron ZSM-5 Zeolite

Ristanovic. et al, Angew. Chem. 2013

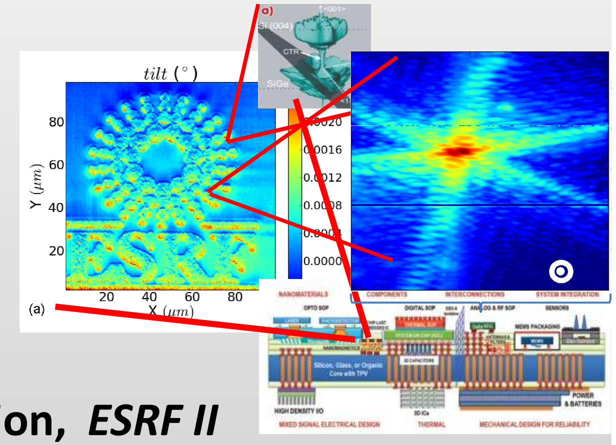
Tomorrow:

Real catalyst (0.5-2 micron)

Today SXDM within 1-2 hours on (not too thin…) films and devices (up to 1TB/hour)

Tomorrow: SXDM & Bragg CDI & Ptychography will merge as techniques (up to 100 TB/hour)

Time resolution: minutes (10^2 s) full 5D or Ptychography down to 10^{-3}..10^{-4} s: single (coherent) scattering frames



Winning 3-4 orders of magnitude in time and space resolution, *ESRF II* will fill the gap between TEM and High resolution XRD potentially under growth and operation conditions