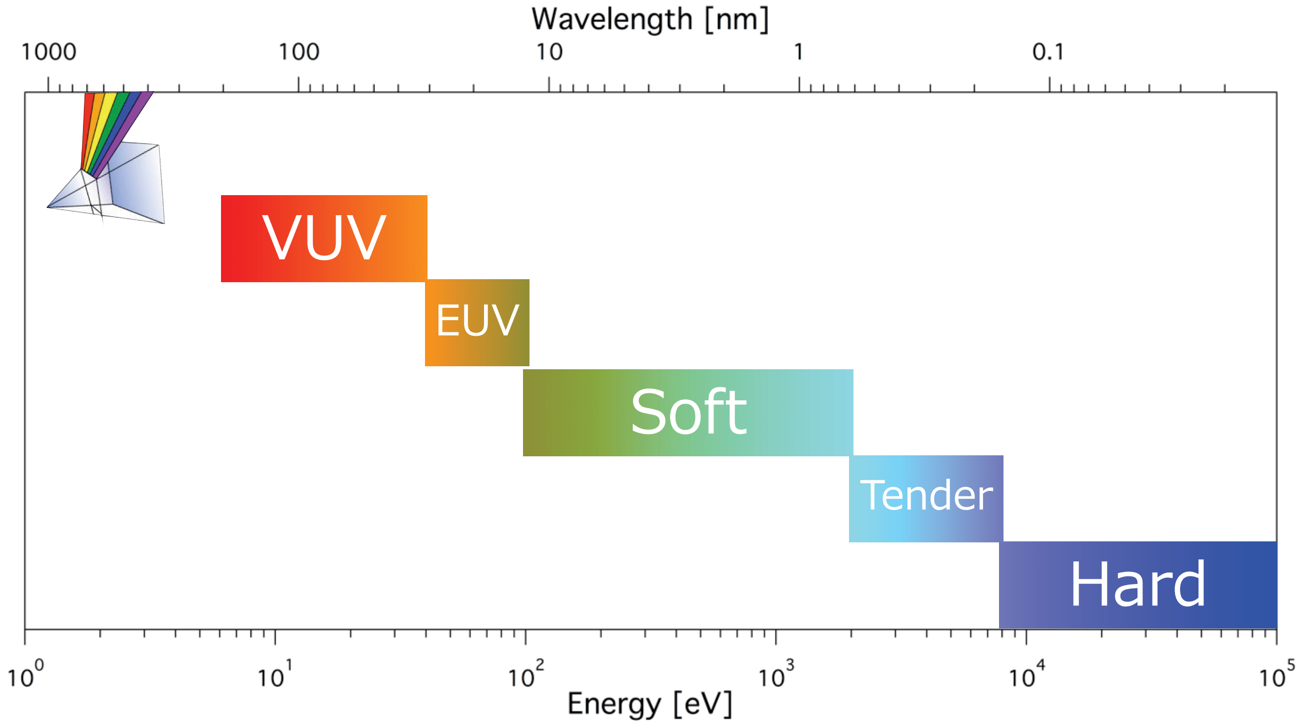
Pixels for Soft X-ray Microscopies



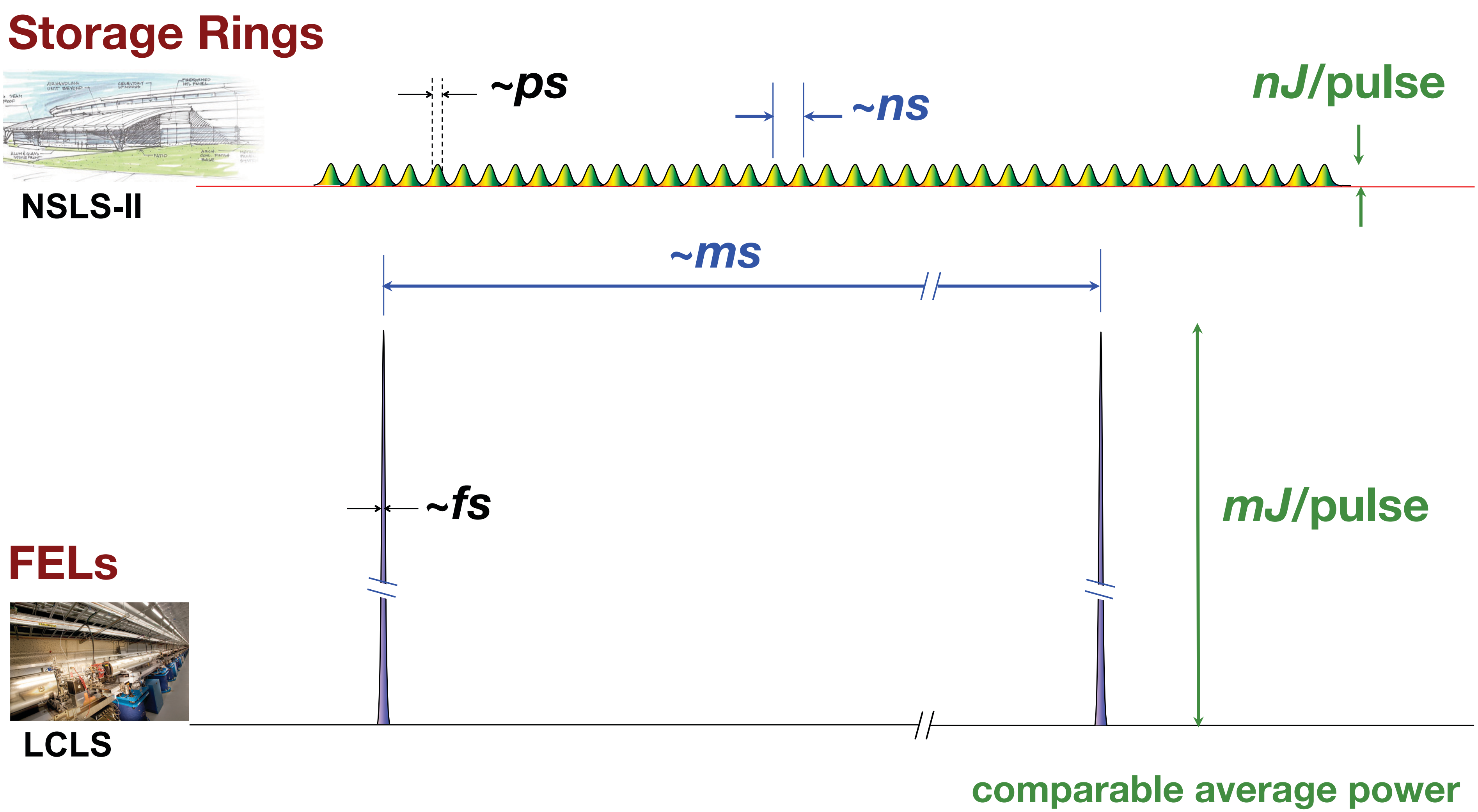
Soft X-rays

- Non-penetrating
- Chemistry
  - Where are the electrons?
  - What are they doing?

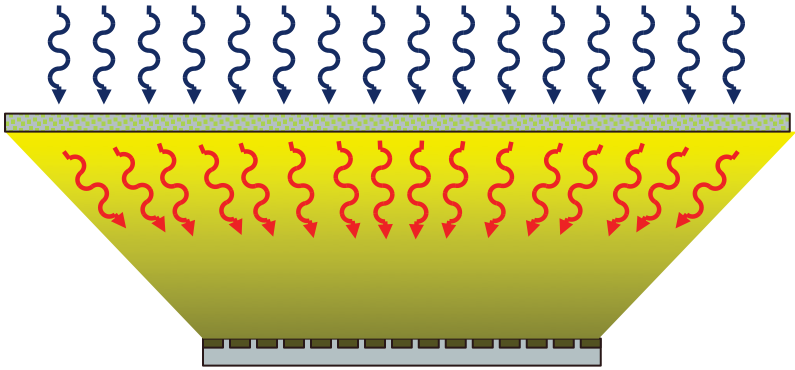
Hard X-rays

- Penetrating
- Structure
  - Where are the atoms?

Sources of (bright) X-rays



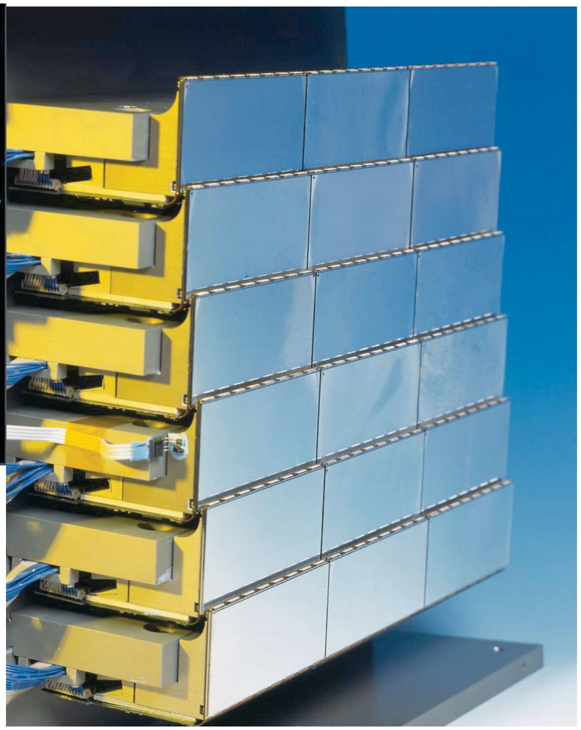
Direct X-ray Detection



phosphor fiber-optically coupled to CCD

This was (is) the ubiquitous X-ray / electron detector

- easy to make large areas
- radiation resistant



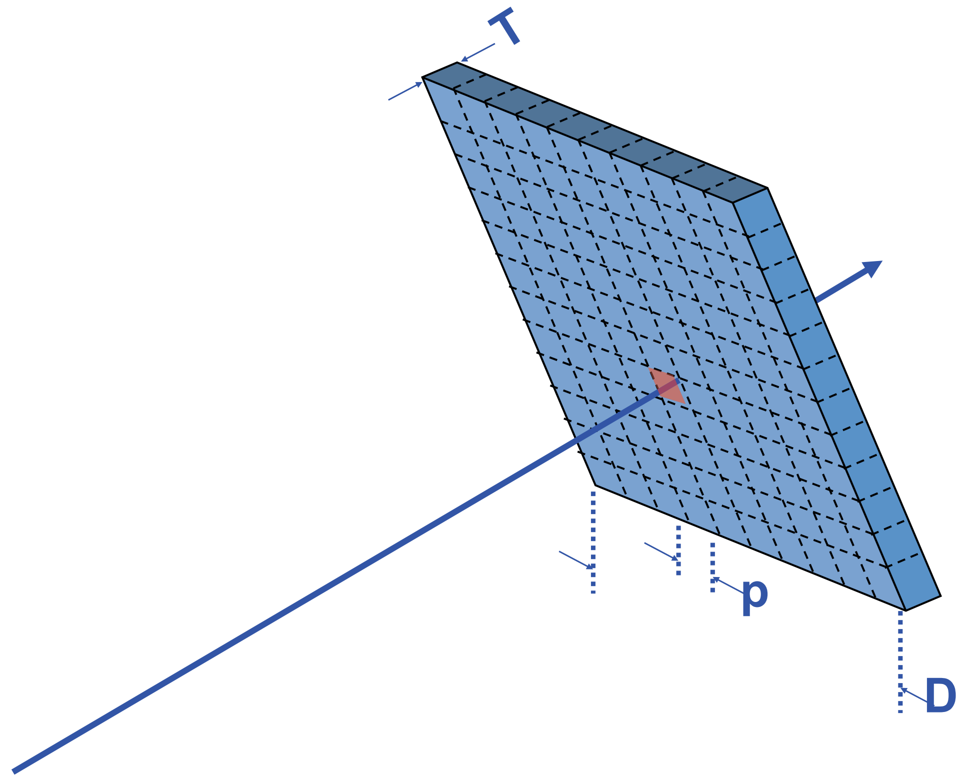
Large impact of *Pilatus* (PSI)

- Hybrid Pixel
- Leverage LHC
- typ. 12 keV X-ray ↔ >3,000 e−
- Count individual X-rays
  - (not so simple, but ...)

Detector Requirements

- Geometric:
  - 2D (pixilated) detector
    - N x N pixels
      - Pitch **p** δx (Size)
      - Dimension **D** = N x p
    - Thickness **T**$(E_\gamma)_{MAX}$ ε (Efficiency)
- Electric:
  - Frame rate 1/Δt δT (Speed) δt (Time)
  - Noise*
  - Full-scale per pixel **Q_{MAX}** Q (Intensity)
  - SR: Counting detector **N(x,y)**
  - SR: Single photon detector **(x,y,t)** - *better* **(x,y,E,t)** δE (Resolution)
  - FEL: all photons arrive at the same time → integrating detector **Q(x,y)**

*Need gain for SXR counting pixel

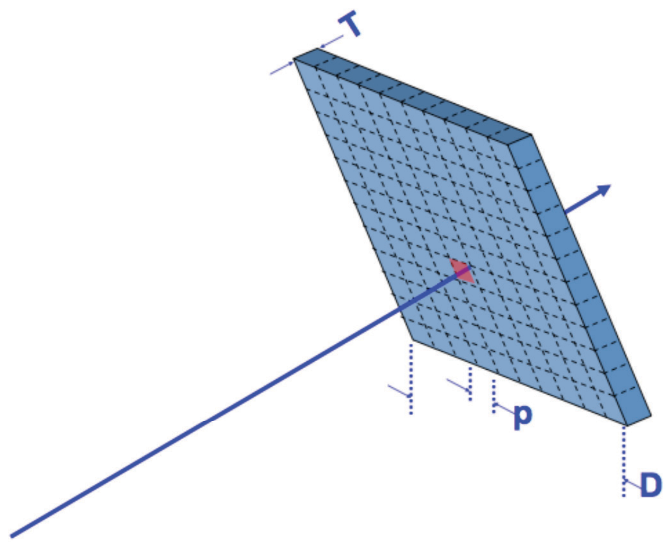


Problem Statement

Meet these requirements

Detector Requirements

- Geometric:
  - 2D (pixilated) detector
    - N x N pixels
      - Pitch **p**
      - Dimension **D** = N x p
    - Thickness $\mathbf{T}(E_\gamma)_{MAX}$

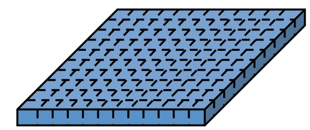


- Electric:
  - Frame rate 1/Δt
  - Noise
  - Full-scale per pixel $\mathbf{Q_{MAX}}$
  - FEL: all photons arrive at the same time → integrating detector

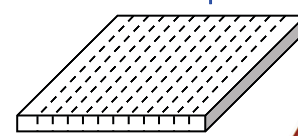
- and cheap
- and easy to use
- and developed quickly

Implementation

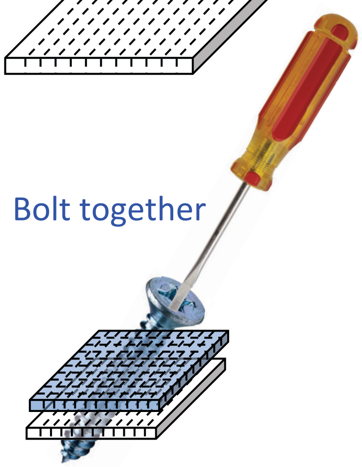
Identify suitable sensor



Design suitable readout and data acquisition

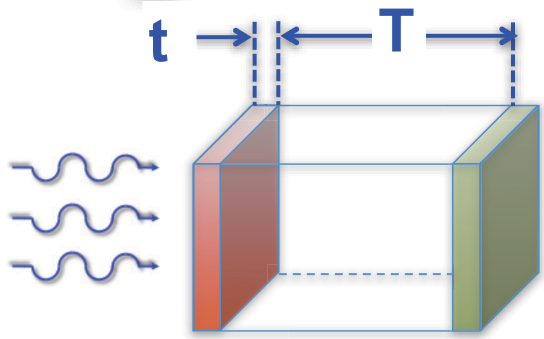


Bolt together

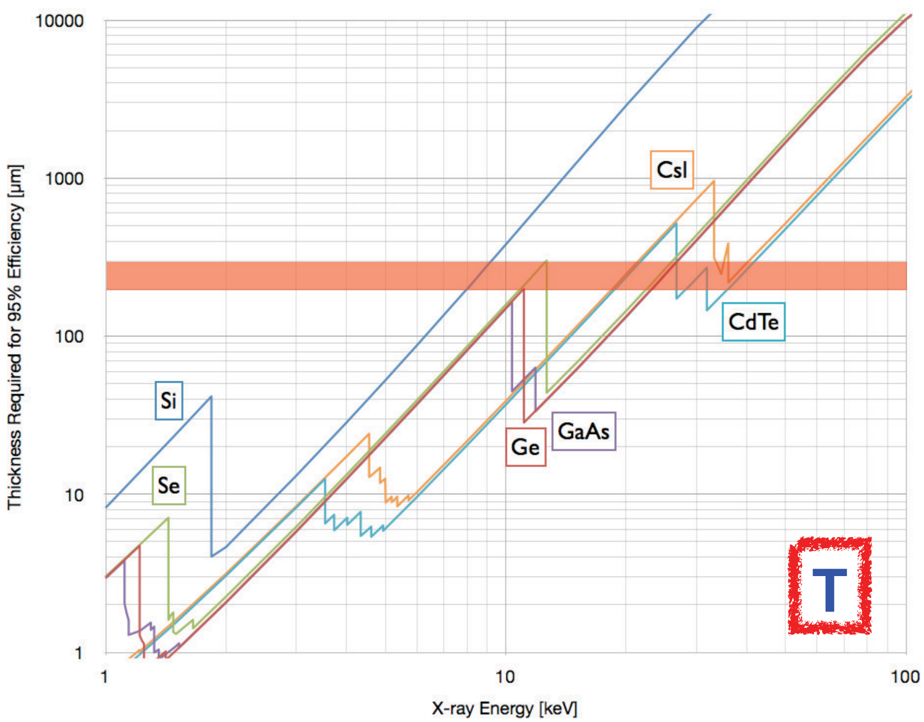


Sensor Challenges

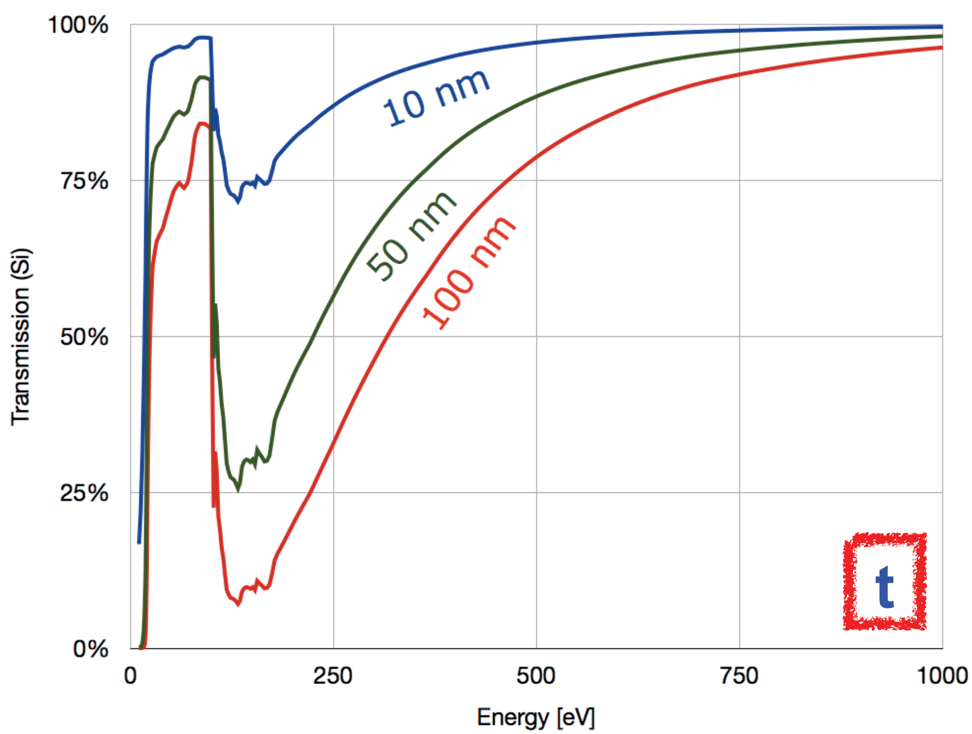
Efficiency



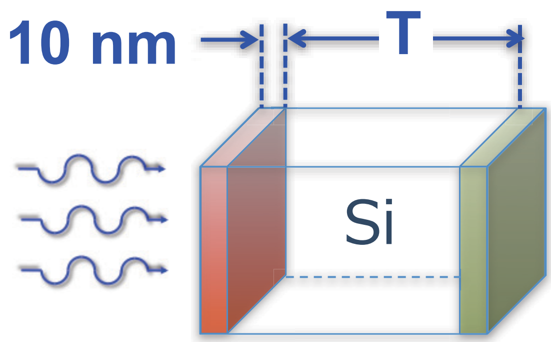
Hard X-rays

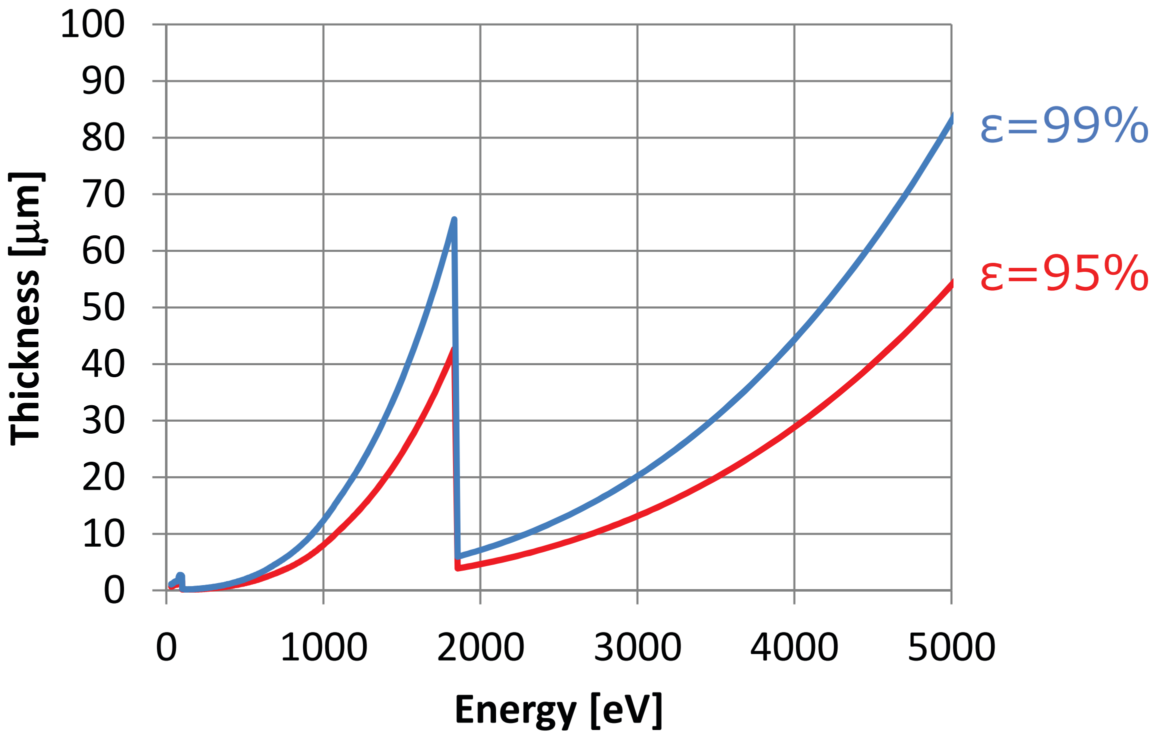


Soft X-rays



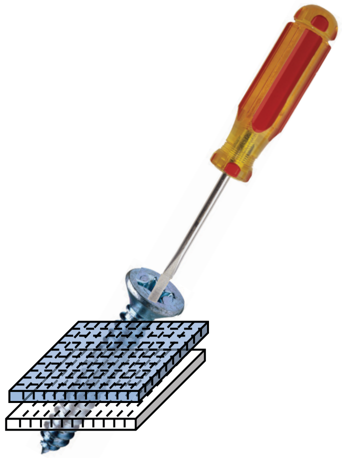
Ideal for Soft X-rays



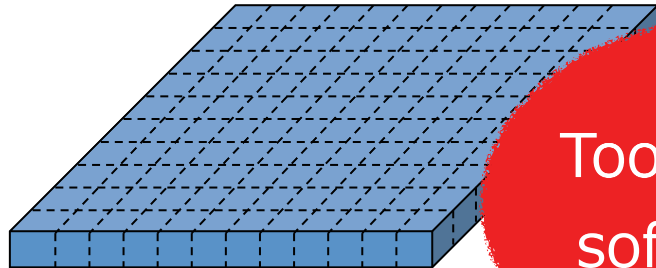


- Silicon
- 50 - 100 µm thick
- 10 nm contact
- High resistivity substrate
  - Full depletion
  - Minimize diffusion
  - Maximize spatial resolution
  - Maximize charge (energy) resolution

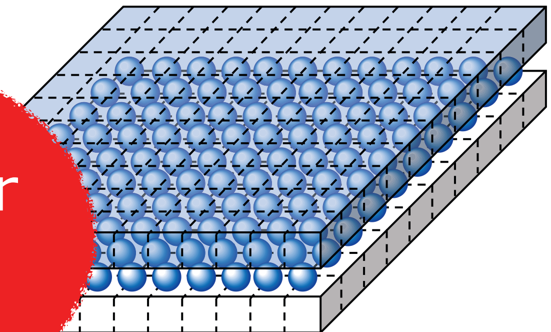
Interconnect



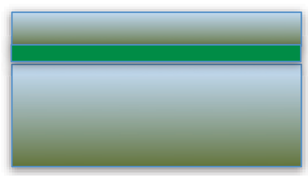
Monolithic

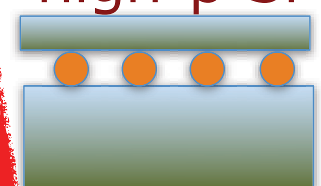


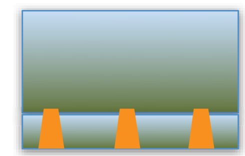
Hybrid



Too high for soft X-rays





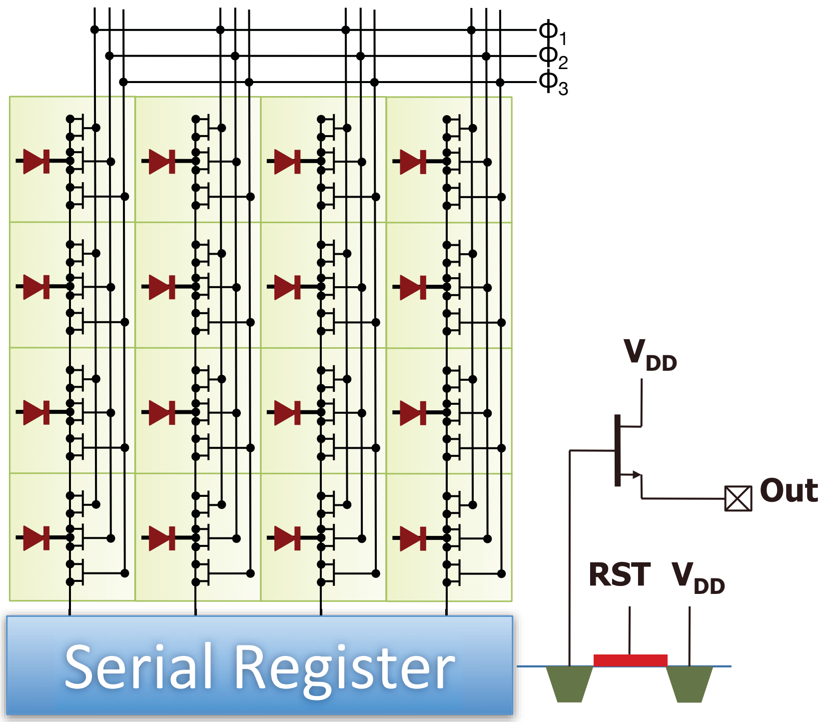


	CCD on thick, high-ρ Si	CMOS, SOI on thick, high-ρ Si	Hybrid on thick, high-ρ Si	3D
Pixel Size	≤10 – <50 µm	≤5 – <20 µm	50 – 100 µm	
Area	$10^2 - 10^3$ µm²	$10^1 - 10^3$ µm²	$10^3 - 10^4$ µm²	
/ pixel	0	$10^0 - 10^2$	$10^2 - 10^3$	
ENC	$10^0 - 10^1$ e⁻	10^1 e⁻	10^2 e⁻	

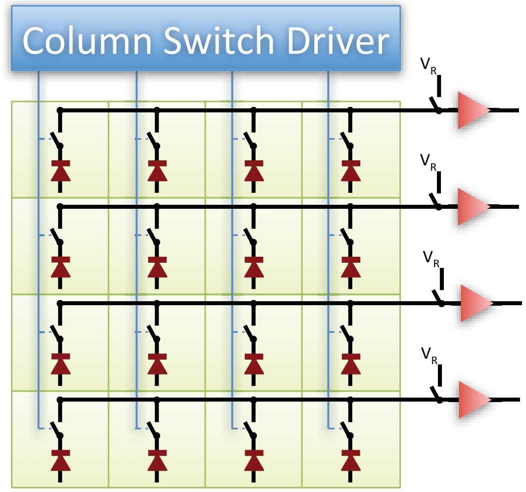
Different detailed mechanisms, but lower noise with monolithic pixels

Monolithic Approaches on thick, high-resistivity silicon

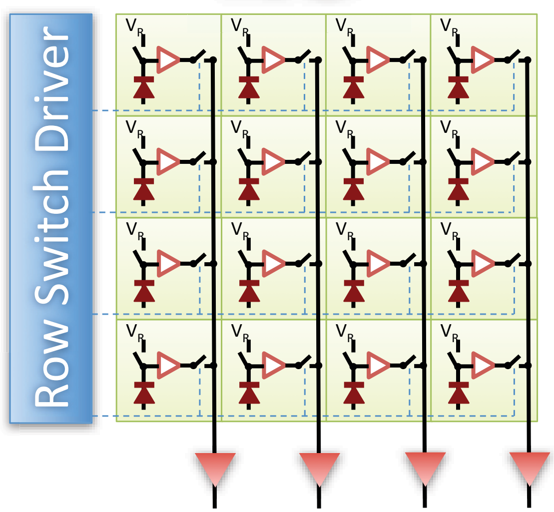
CCD



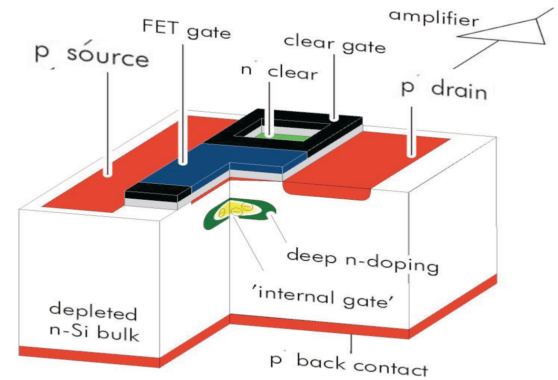
PPS

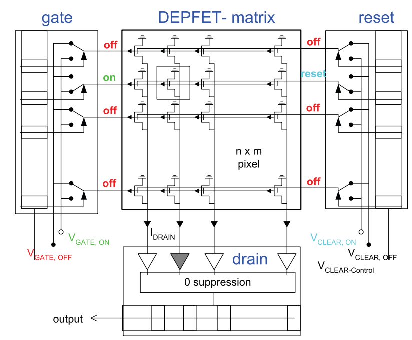


APS



DEPFET





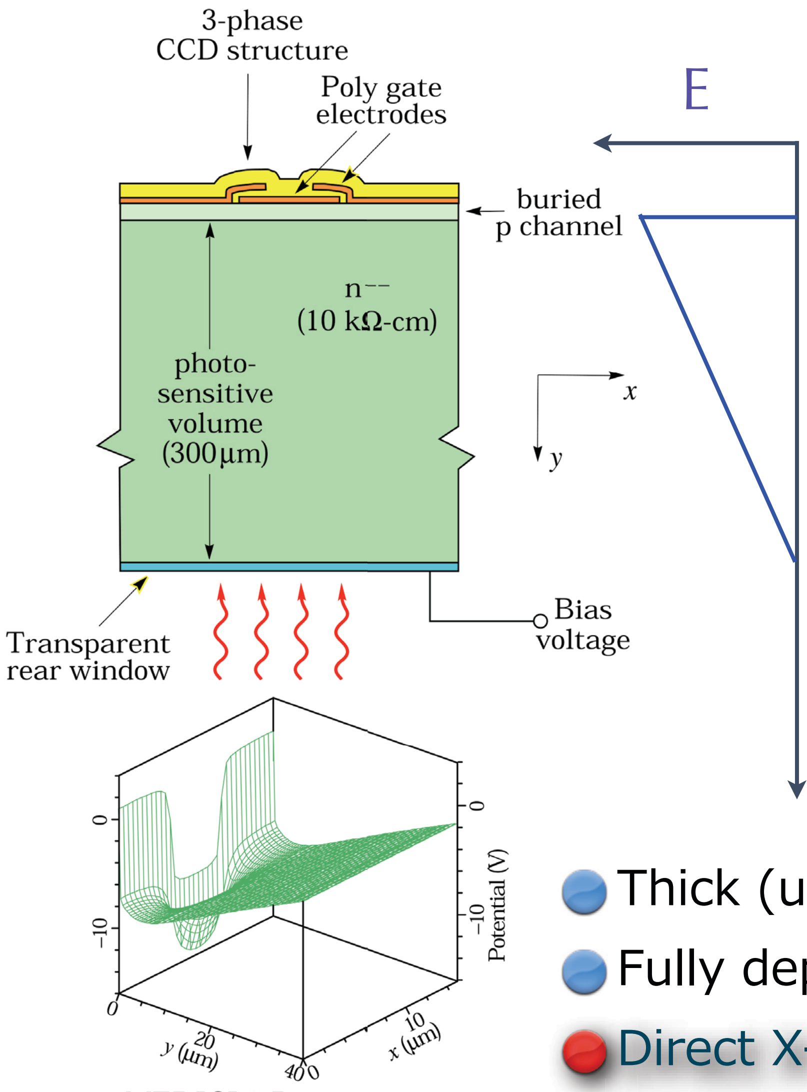
3D

Physics: MMIX

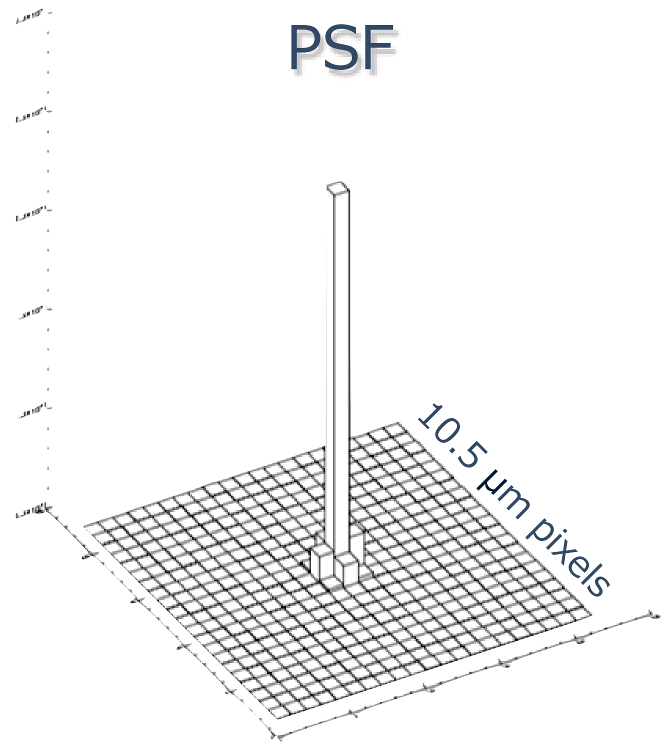
CMOS (?)

SOI

LBNL CCD



MEDICI 2-D simulation



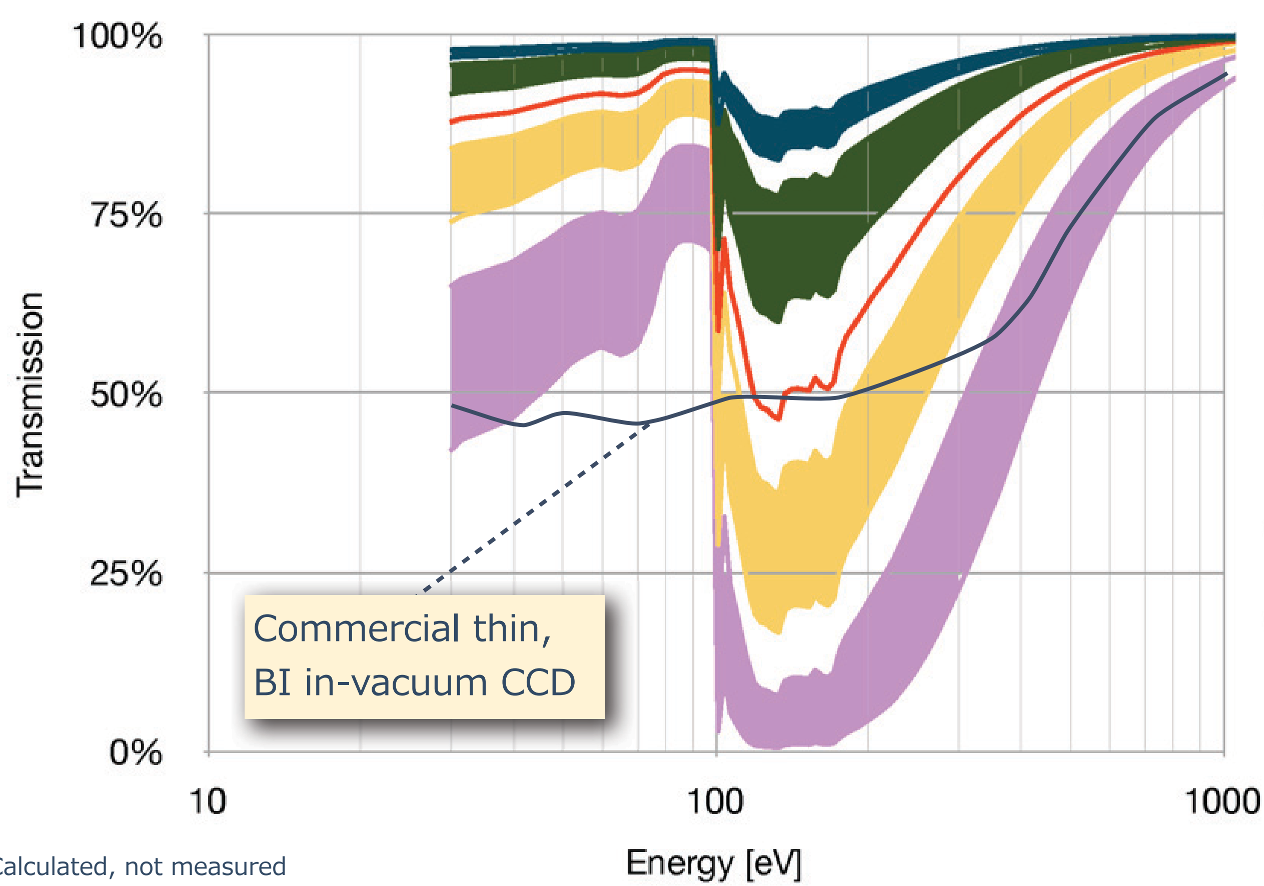
At V_{SUB} = 115 V,
$\sigma_D = 3.7 \pm 0.2$ μm

- Thick (up to 650 μm) high-resistivity Si
- Fully depleted
- Direct X-ray detection

- n-type (p-channel) for enhanced radiation resistance

Thin Contact Development

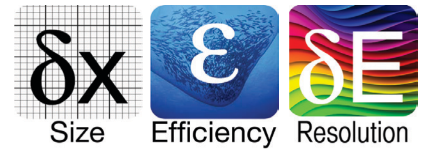
Process	Window thickness	Status
Low energy implantation + 500 C annealing	1,000-2,000 Å	Standard process for 800 eV+ devices
Low energy implantation + laser annealing	400-700 Å	Works, but low yield
a-Si contact deposition by sputtering	300 Å	Works, but high leakage
In-situ doped poly (ISDP)	100-250 Å	Recent progress - 100 Å demonstrated
Molecular Beam Epitaxy	50-75 Å	R&D (MBE system being assembled now)



- Low temperature process desired
  - Apply after all other process steps complete
- robust, simple, fast
- ultimate performance
  - R&D

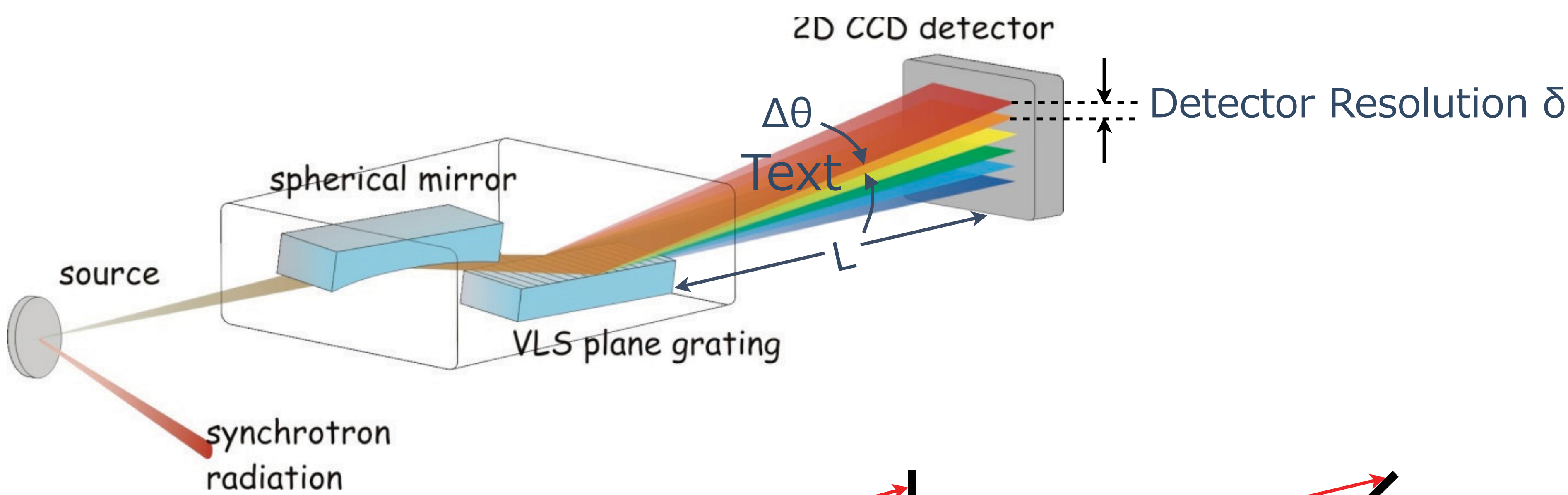
Calculated, not measured

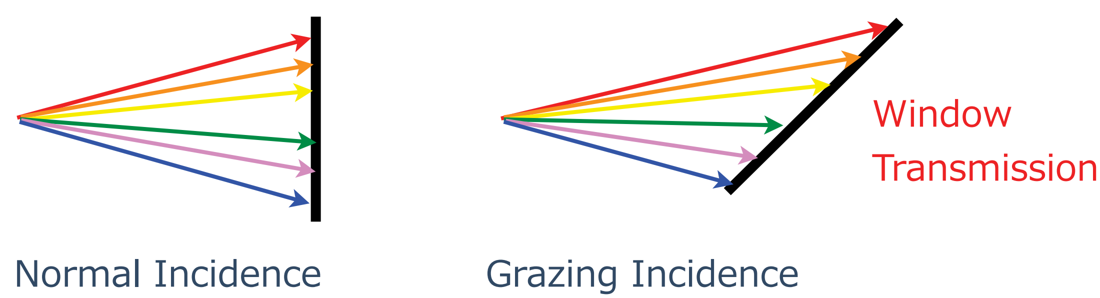
Spectroscopy (with Grating)



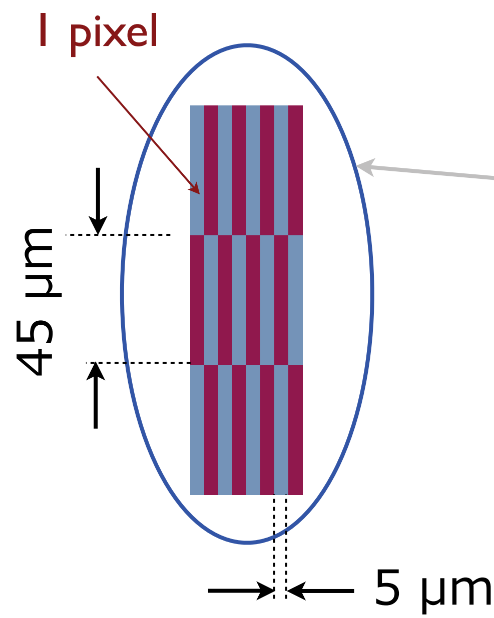
Example

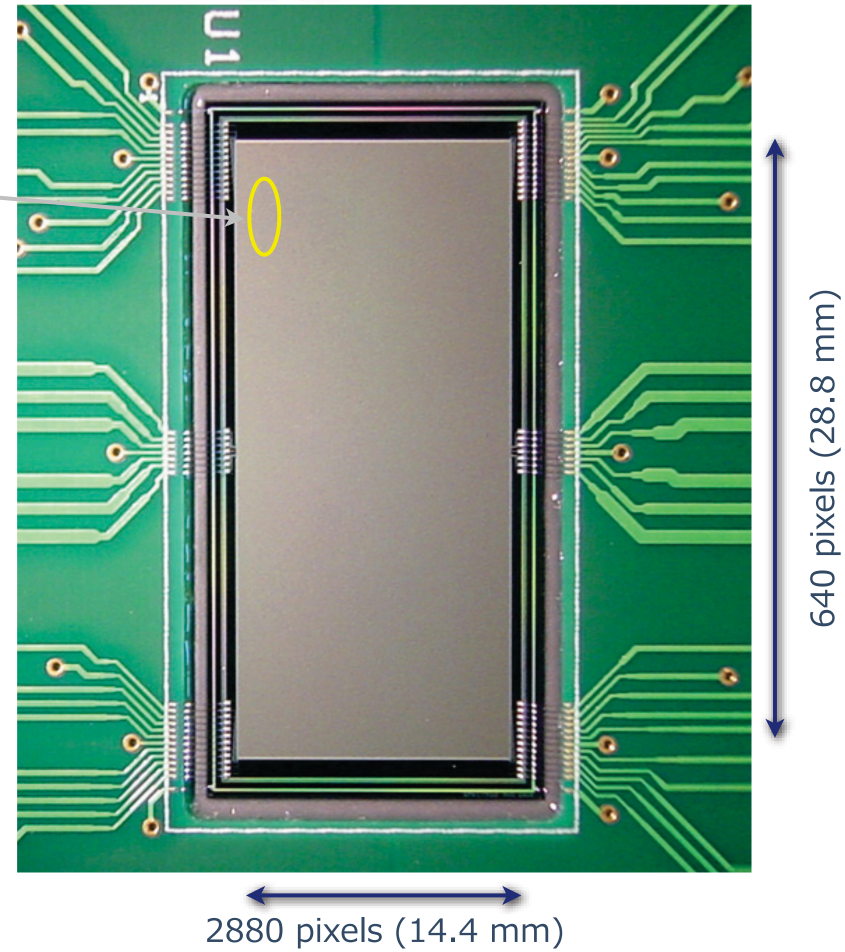
- For a given resolution, $\Delta\theta = \delta/L$
  - Smaller δ allows shorter beamline (L)
  - Today δ~15 μm (can always do better with single photons)





Fine-pitch CCD for Spectroscopy

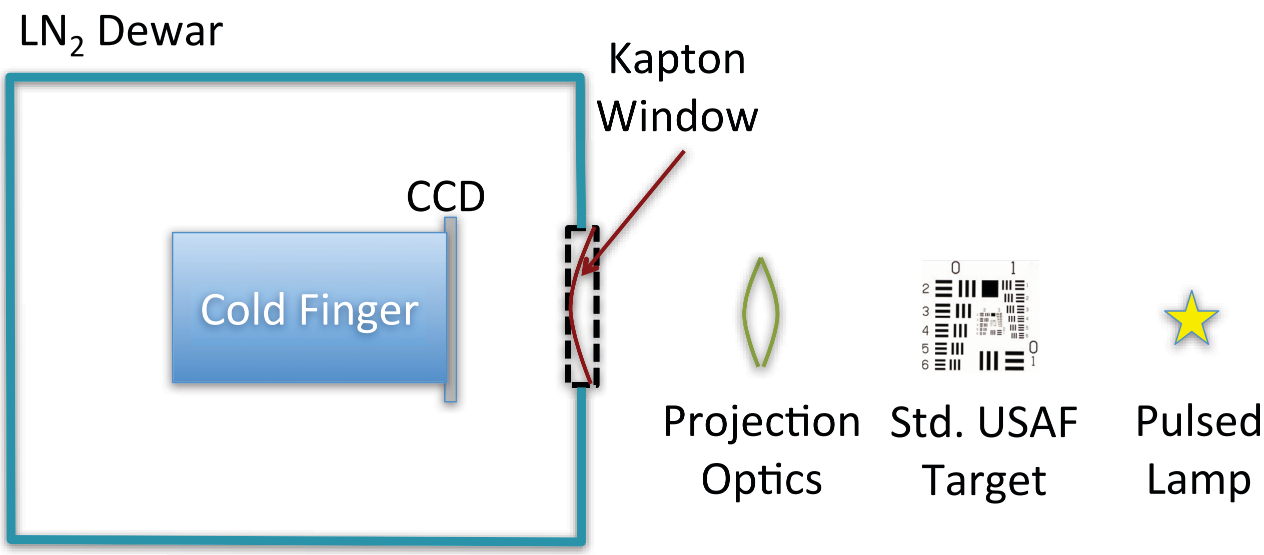




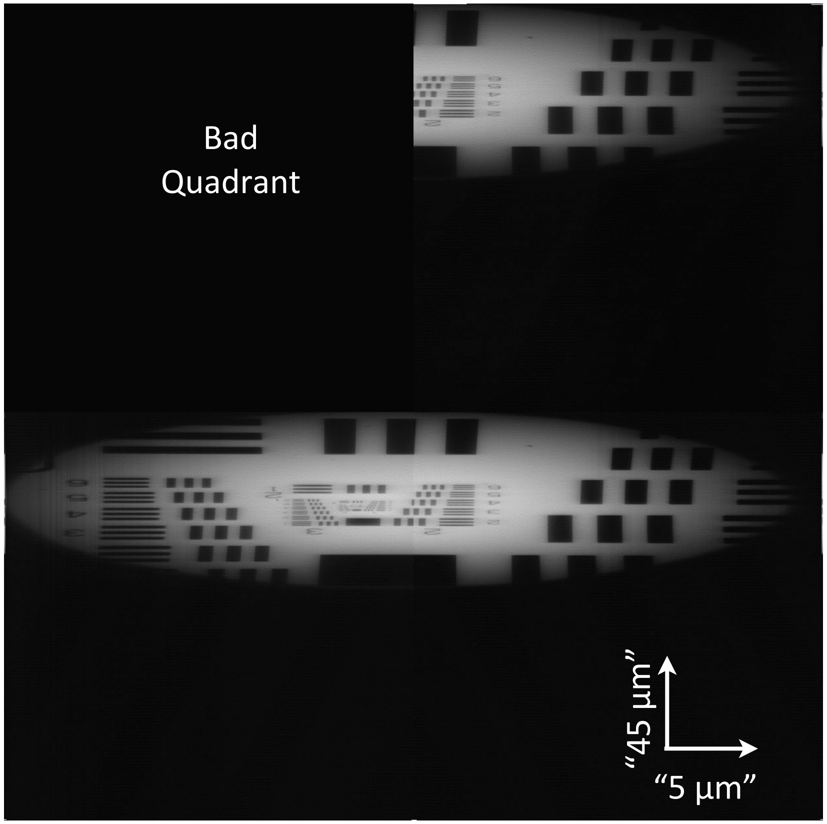
- "Conventional" 4-port CCD
  - 2880 x 640 = 1.8 x 10^6 pixels
  - 4 ports → 4.6 x 10^5 pixels / port
  - ~5 (10) second readout at 100 (50) kHz
- "Interdigitated" gate structure

Optical Test

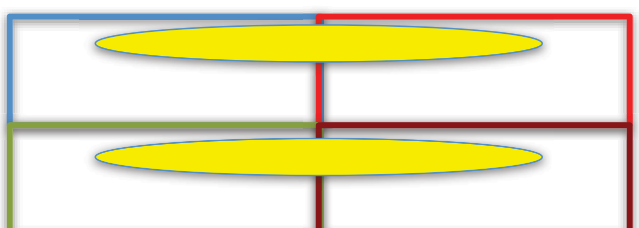
- 5 µm pitch necessitated unconventional gate structure
  - Does it work?
- First look – project USAF target (as best as possible) onto CCD



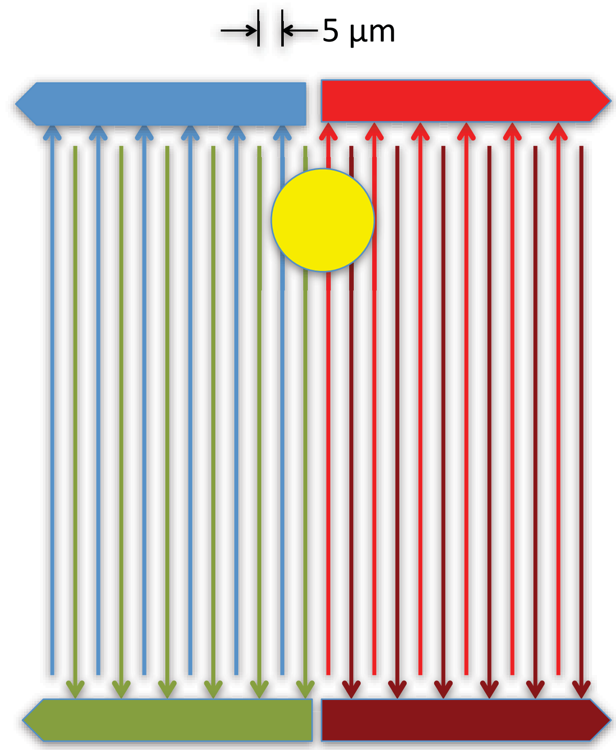
1st Light (03.13)



Mapping onto 4-port readout
(represented by square pixels)

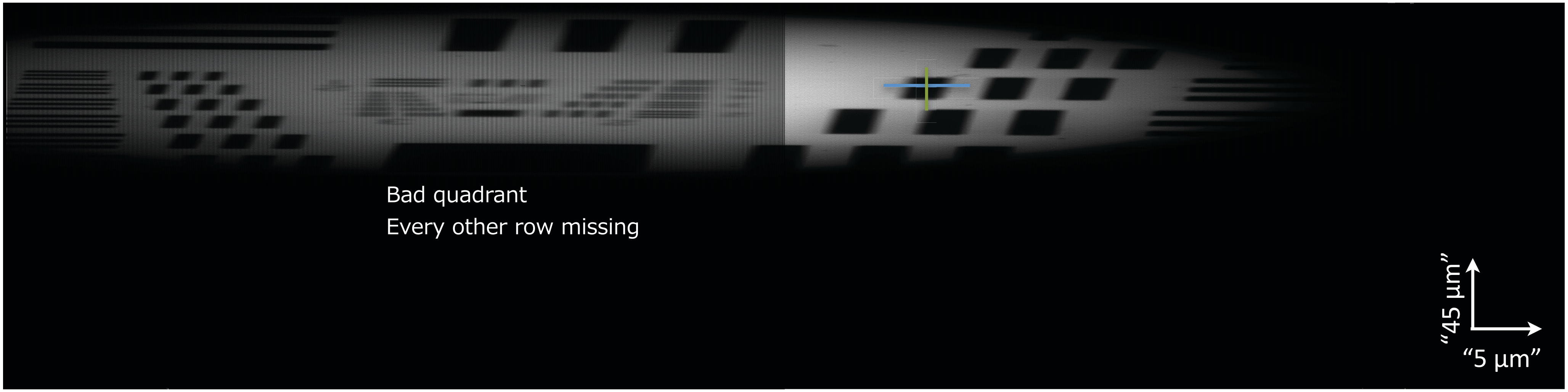


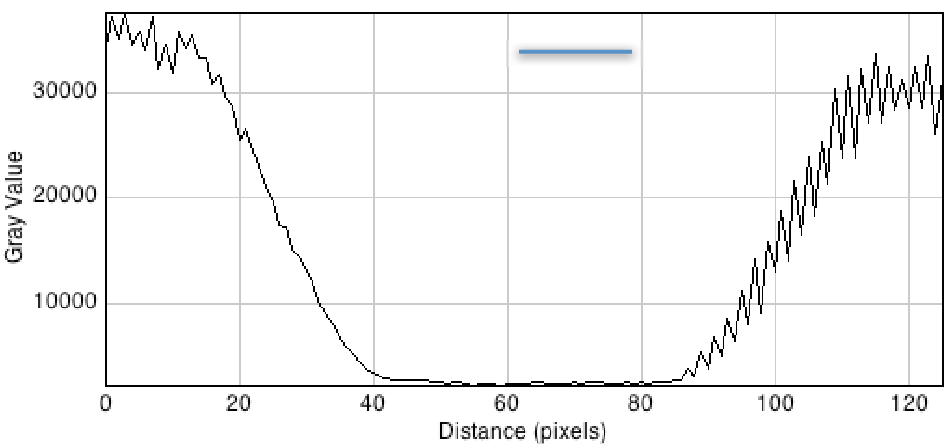
- USAF target
  - Hand-focused onto CCD
- Behavior correct
  - Validates that unorthodox clocking scheme works (the only real question)
- One bad quadrant (wire bond)

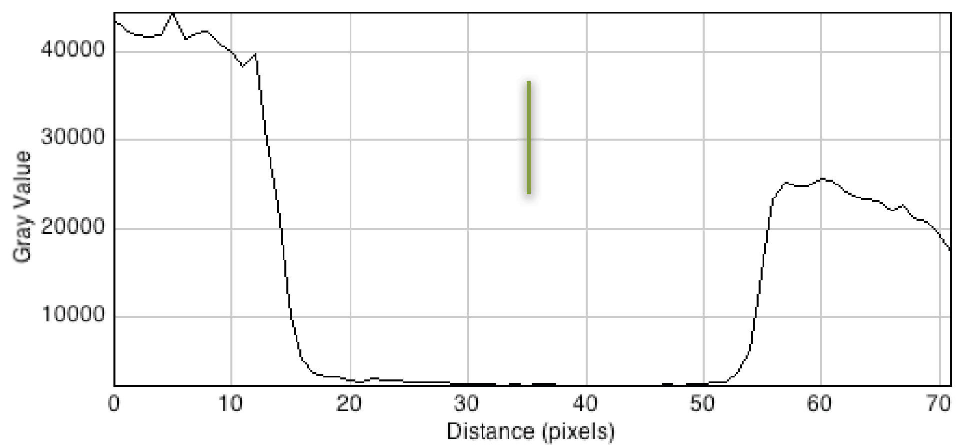


As Expected

Descramble





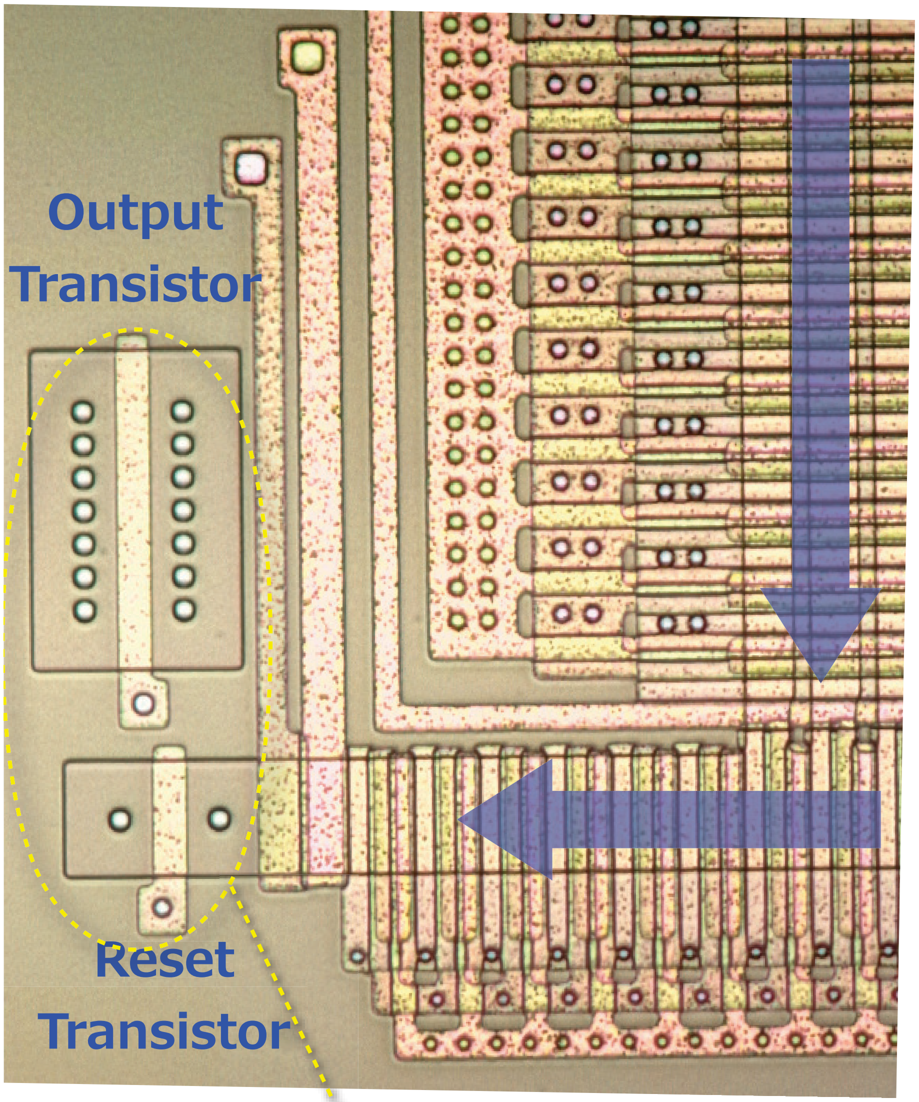


- Next: characterize at ALS BL 5.3.1

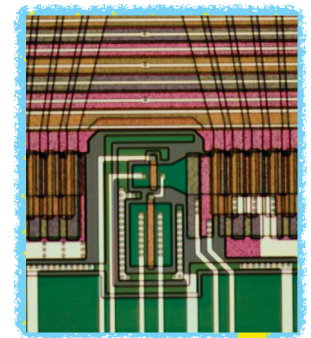
(almost) Column-Parallel CCD

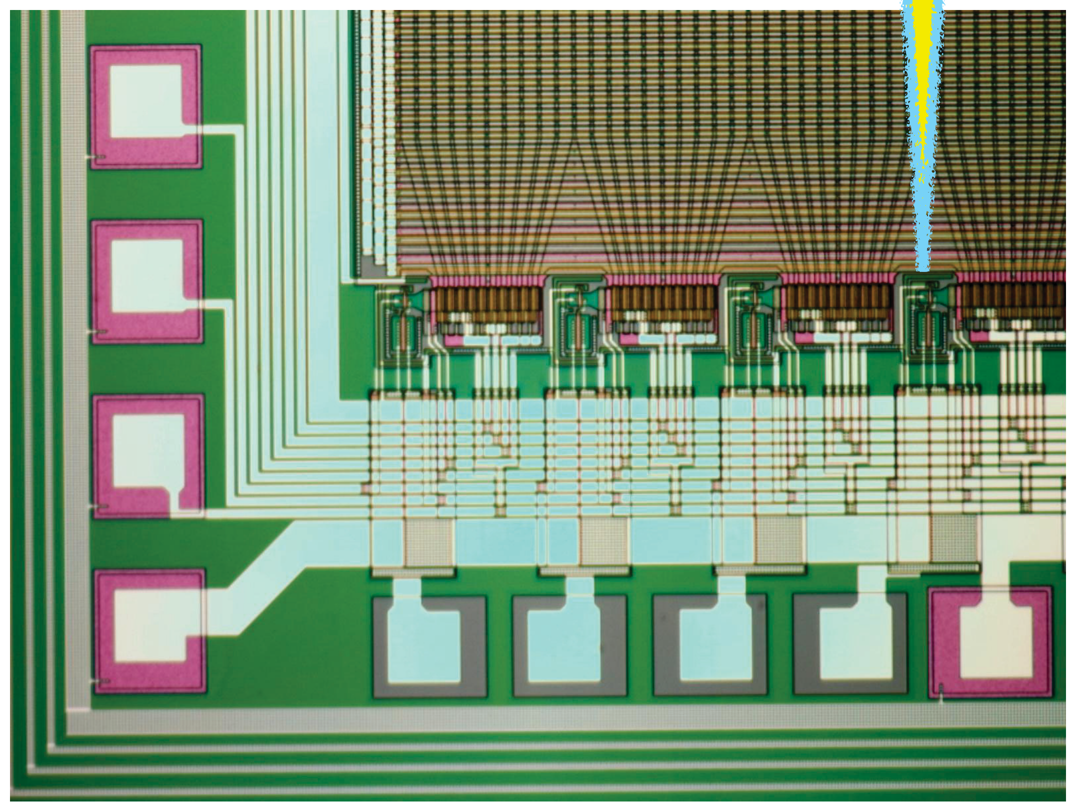
Speed

Conventional CCD



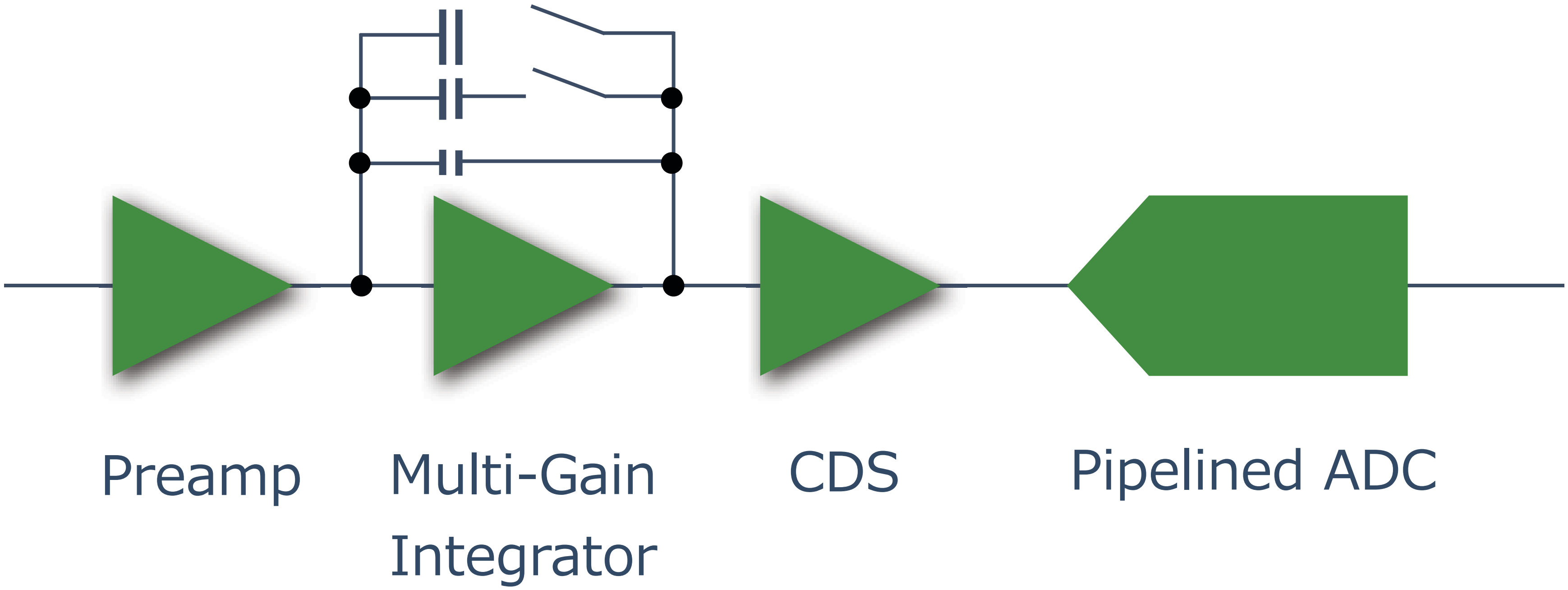
Speed up CCDs from O(10^{-1}) Hz to O(10^{2}) Hz per megapixel

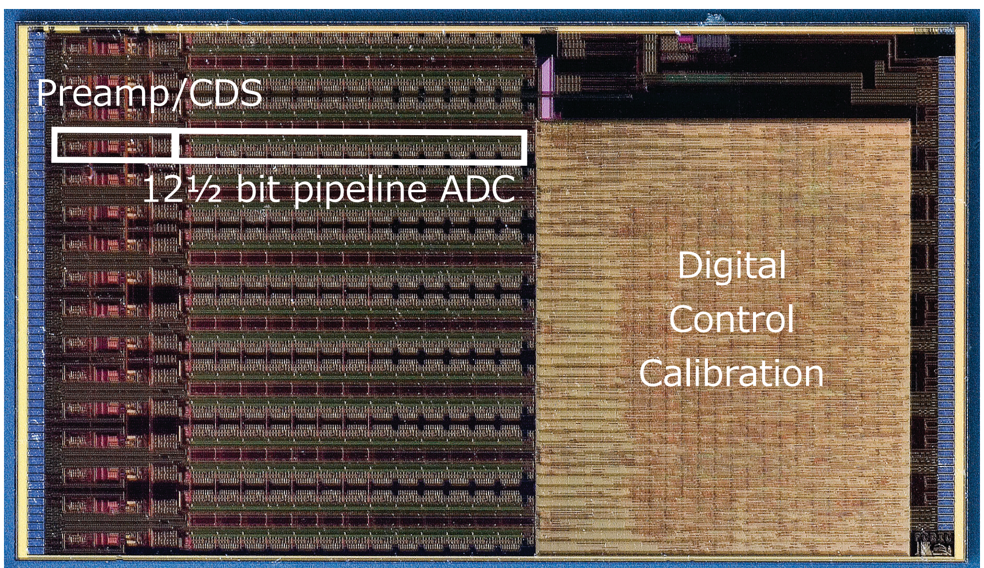




Where to put these transistors?

16-Channel Custom Readout IC





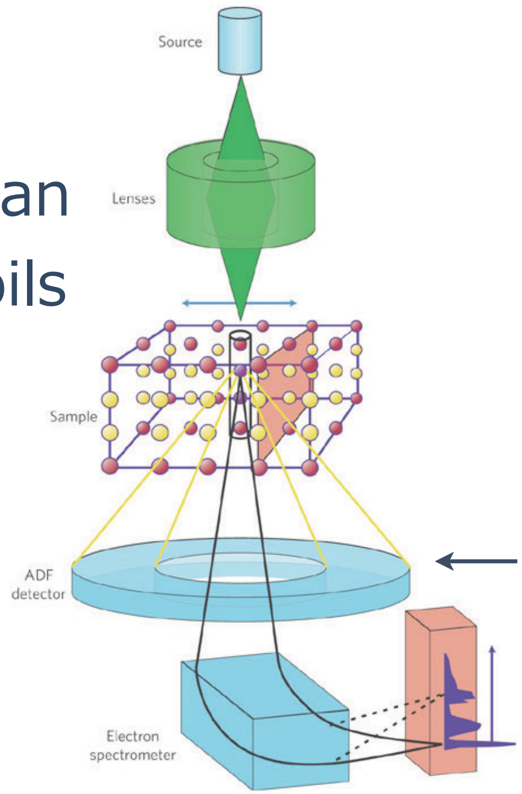
- Gain 8, 2, 1
- 12+1 bit ADC
- Covers 15 bit range
- 300 µm input pad pitch

0.25 µm CMOS - 2006

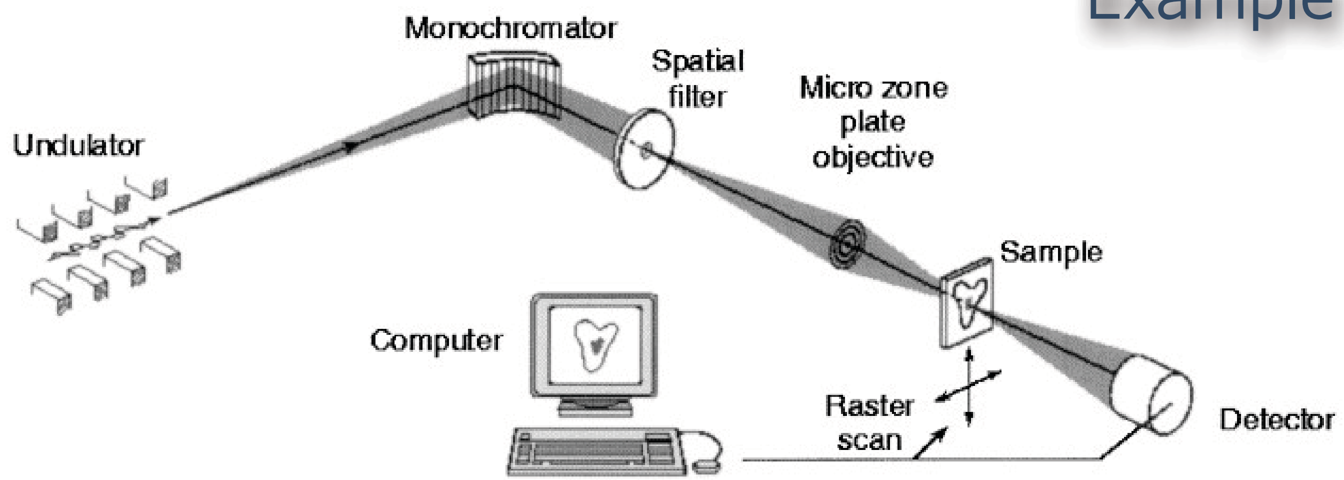
Scanning Microscopies

Example

Scan Coils



Scintillator
- Fast
- Counts only

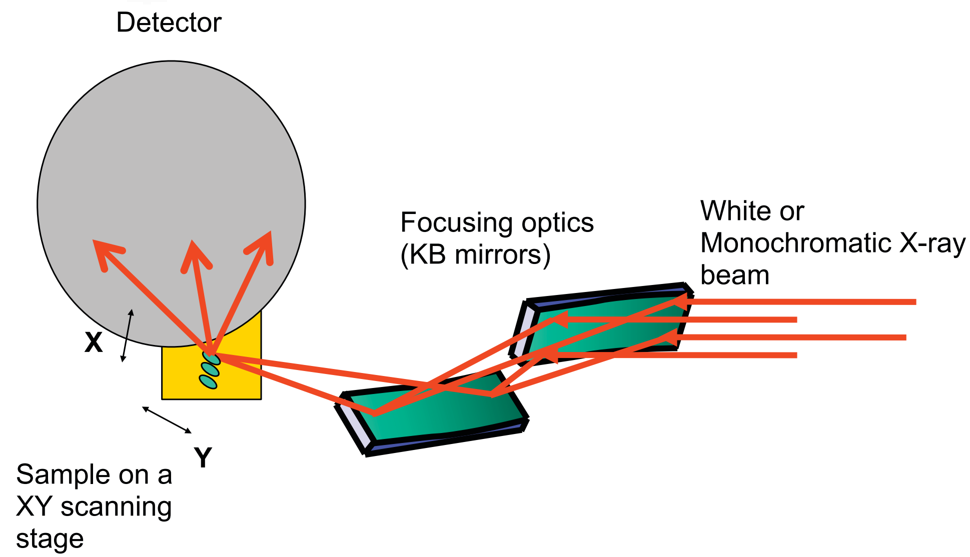


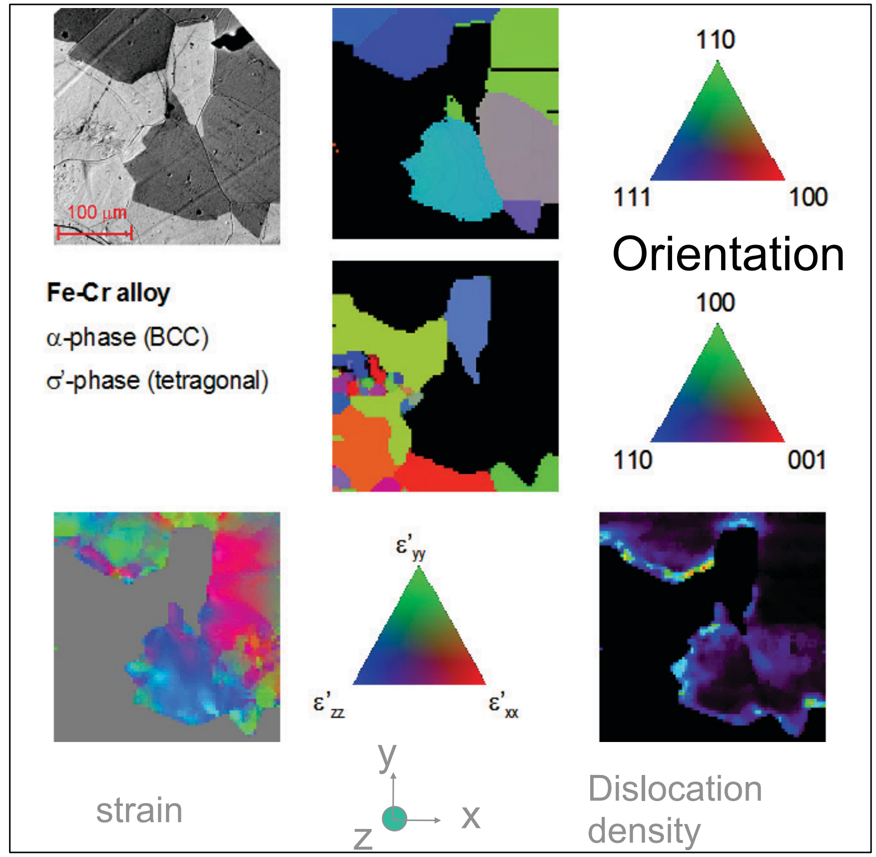
Acquisition Times from Minutes → Seconds

STEM
- Raster scan the electron beam
- Each "dwell" point is a pixel
- Datum is "scattered intensity"

STXM
- Raster scan the sample
- Each "dwell" point is a pixel
- Datum is "scattered intensity"

Polychromatic Laue Microdiffraction





- Conv. CCD: ≳12 hr for a scan
- Scan monochromatic beam (N energies) and use a counting detector
- Fast energy-resolving detector

Fatigue cracking of a High-Pressure turbine blade of a Boing 737 engine (Courtesy: ATSB)

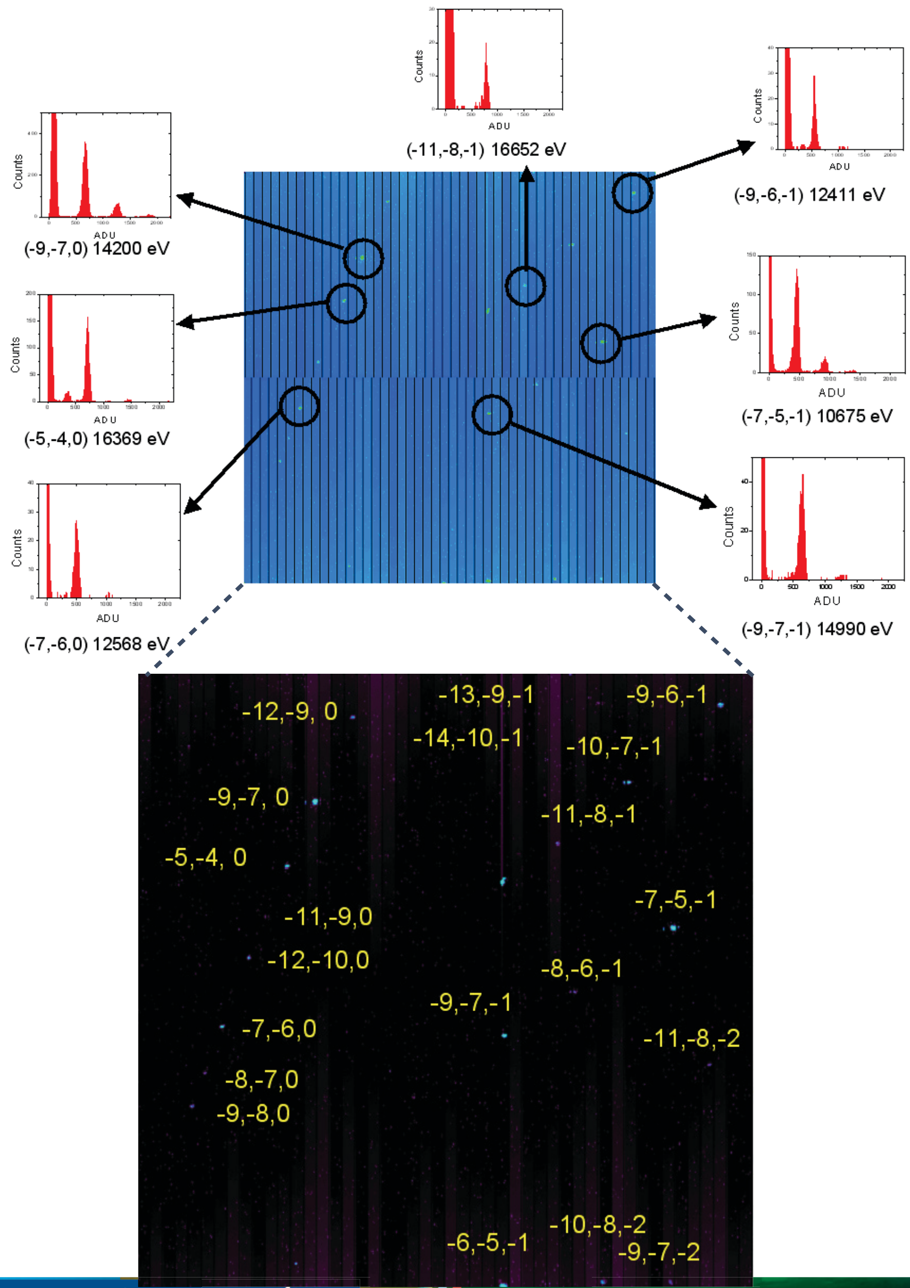
-phase mapping

-grain orientation mapping

-strain mapping

-dislocation density mapping

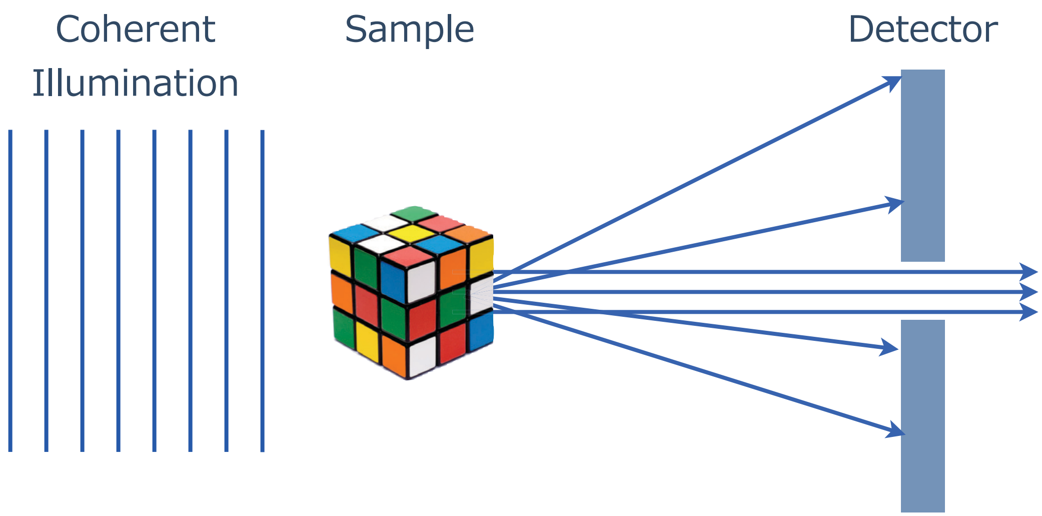
Developing Fast Energy-Resolved Laue Microdiffraction



- Proof-of-Principle on ALS BL 12.3.2
- CCD is analog ➜ energy resolving
- Acquire data rapidly enough to record ~individual photons, and reconstruct spectra
  - Measure the energy of each reflection
- Alternative to monochromator scan
- Do all N energies at once
- Needs very large solid angle

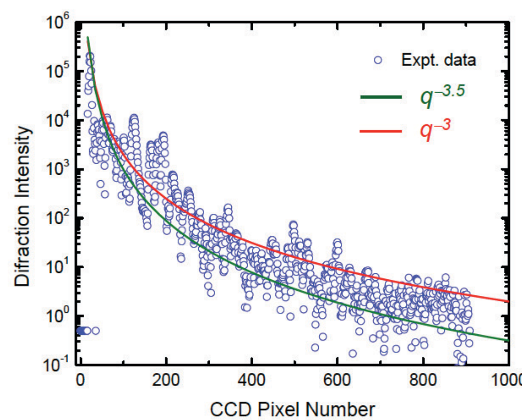
Coherent (lensless) Imaging

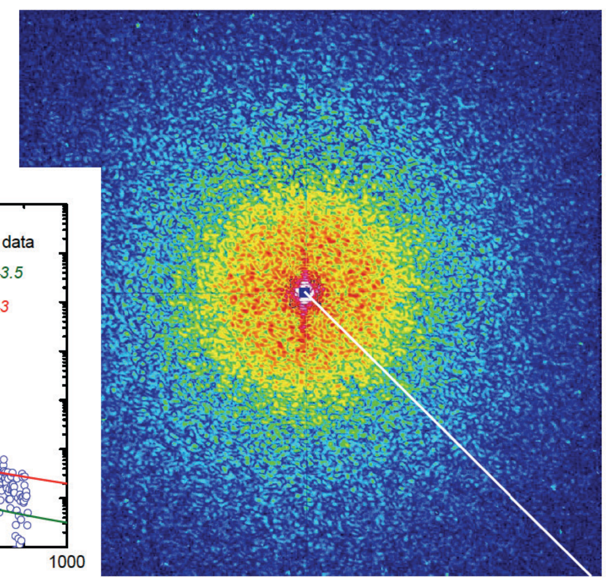
δT Speed · δx Size · Q Intensity



Crystallography for non-crystalline objects

- Dynamic range
  - Intensity I ~ $1/\sin^4(\theta)$
- Noise
  - Single photon
- Size
  - Resolution d ~ $\lambda/\sin(\theta)$
  - Small objects ➜ large angles / detectors

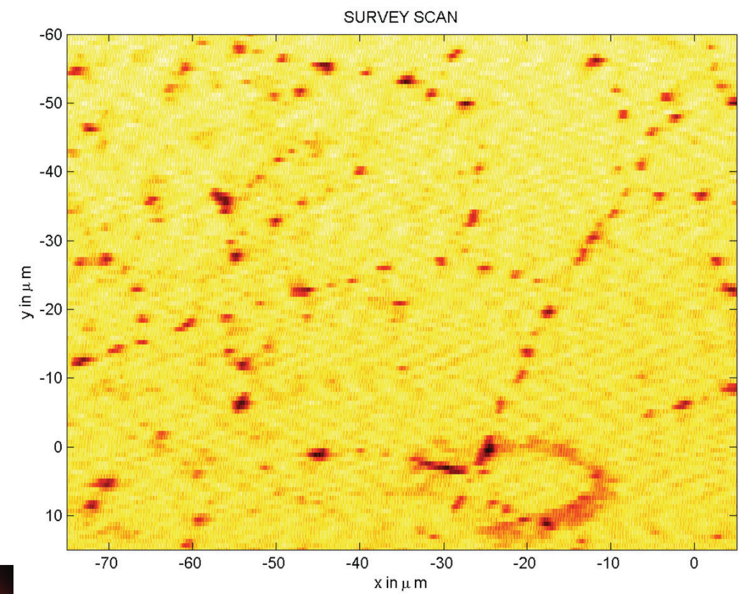


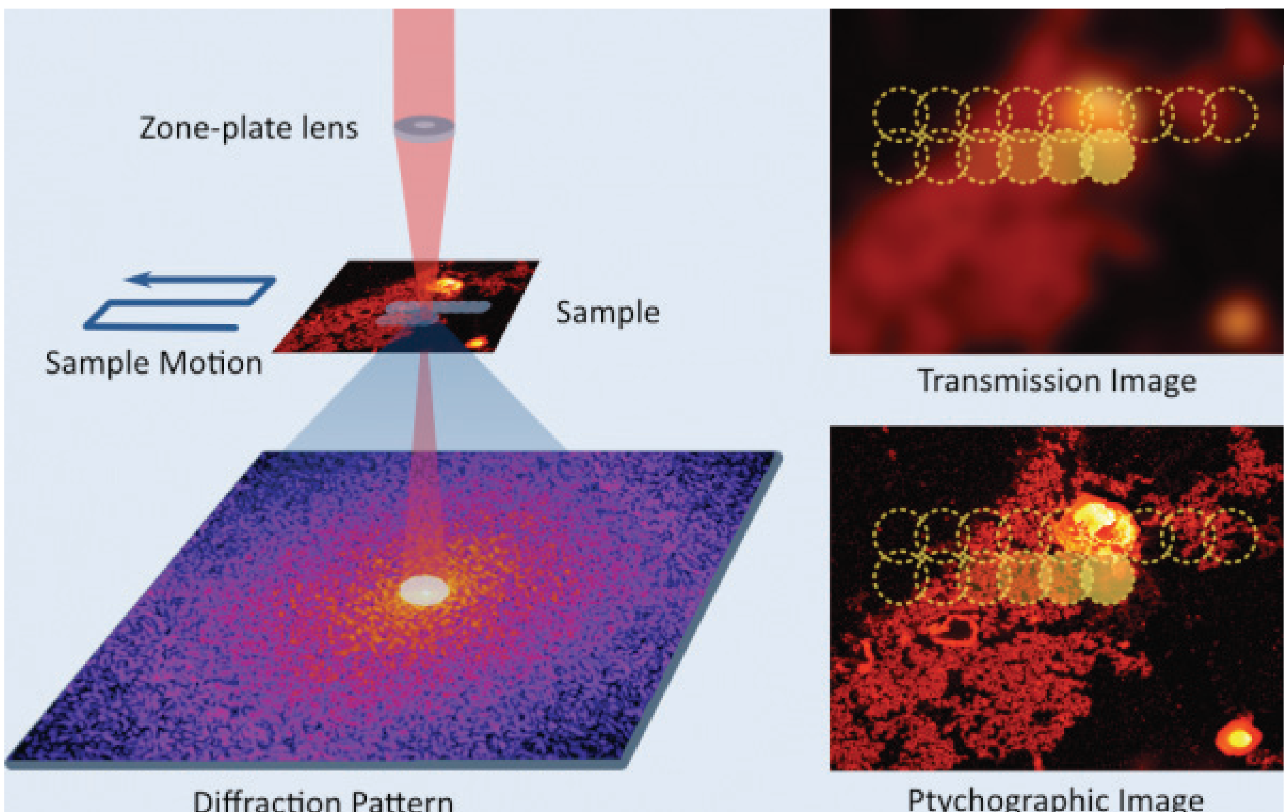


Au nanofoam Shen et al. APS

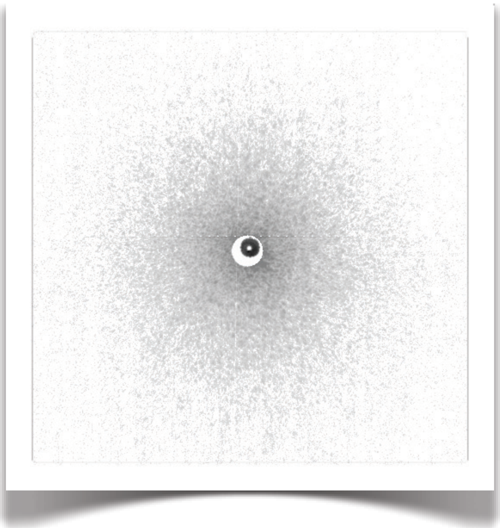
Ptychography

- Scanning microscopy
  - But record diffraction pattern at each point
- Hard X-rays → Pilatus@SLS
- Soft X-rays → FastCCD@ALS

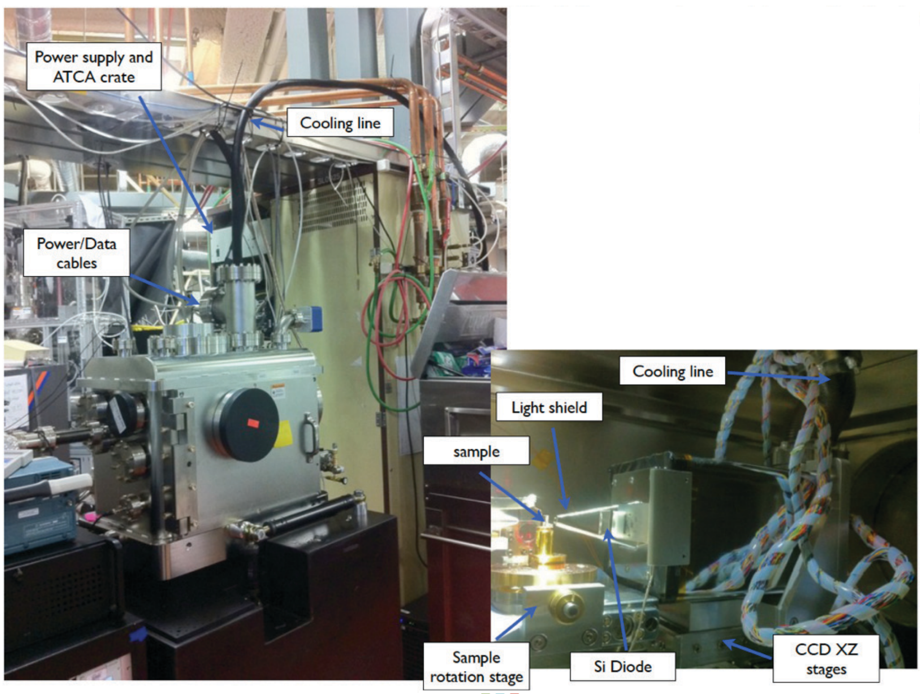


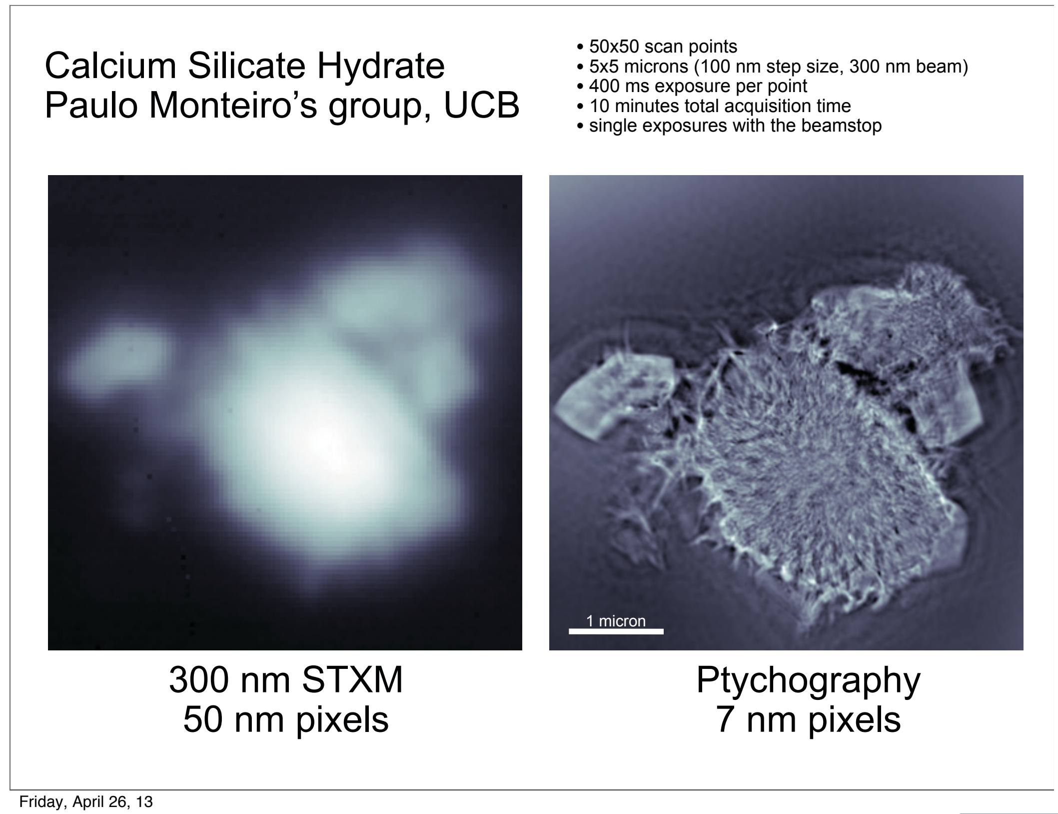


ALS Nanosurveyor



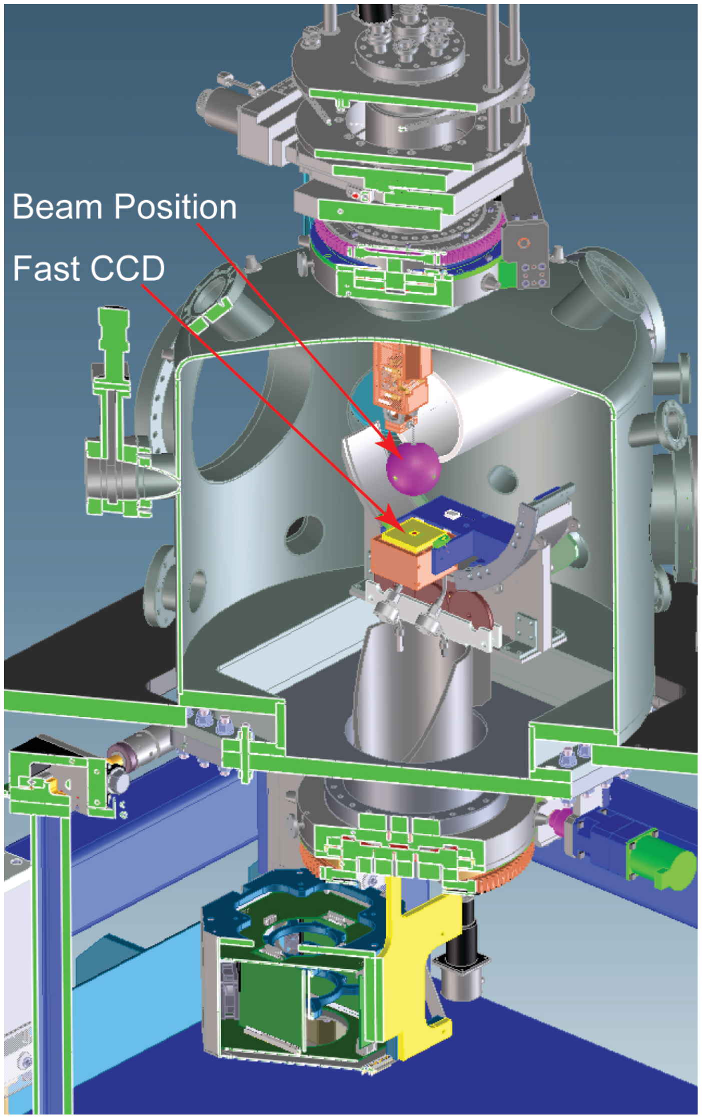
- Concrete - energy and GHG intensive
  - 5% of manmade GHG
- Water + cement → CaO-SiO_2-H_2O
- Goal is understanding composition and formation of C-S-H

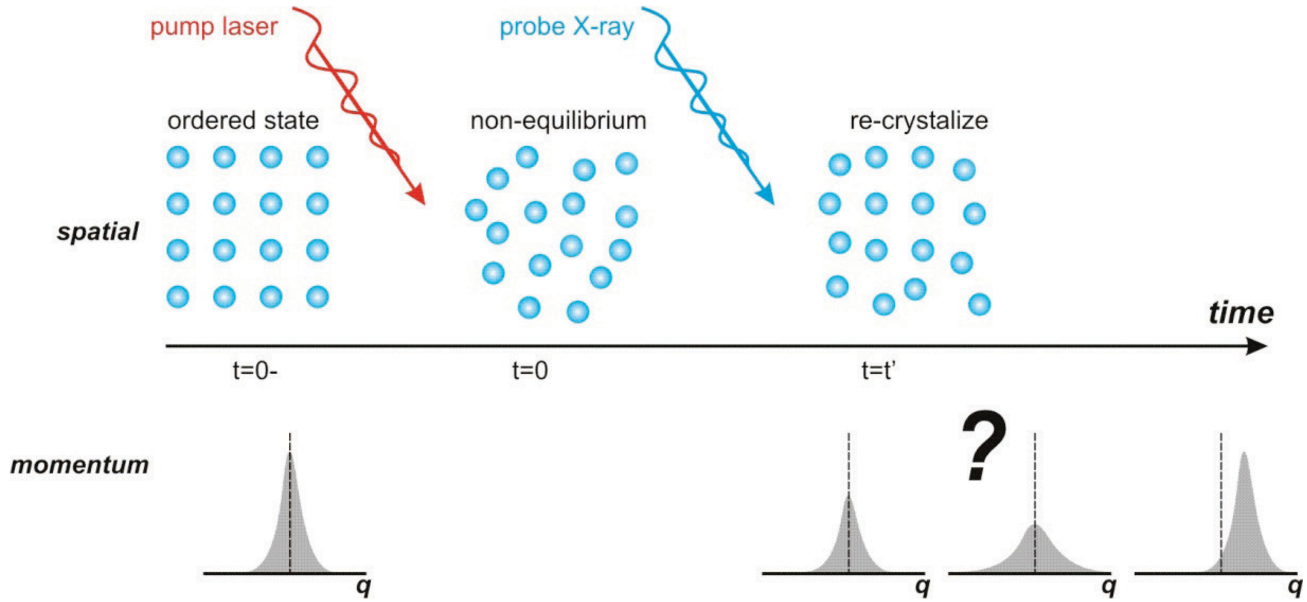


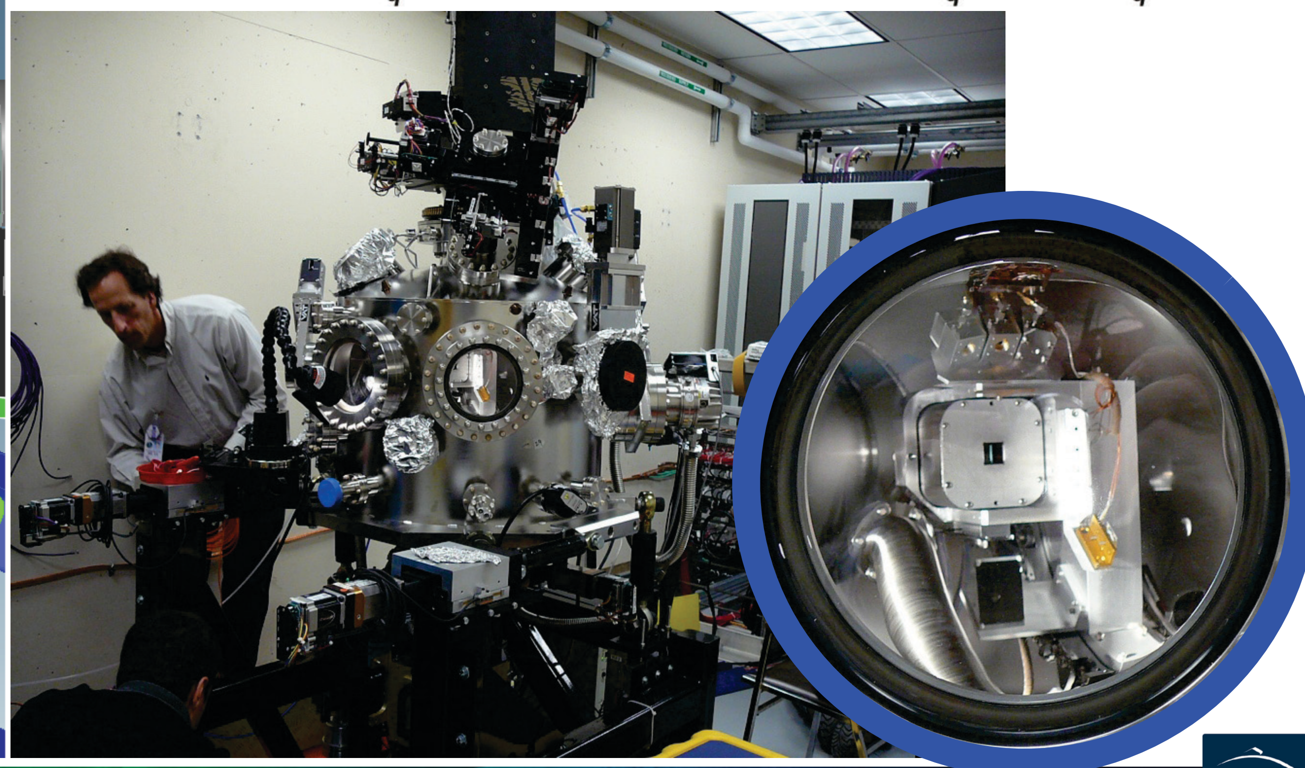


LCLS - RIXS

RSXS Chamber for LCLS Soft X-ray

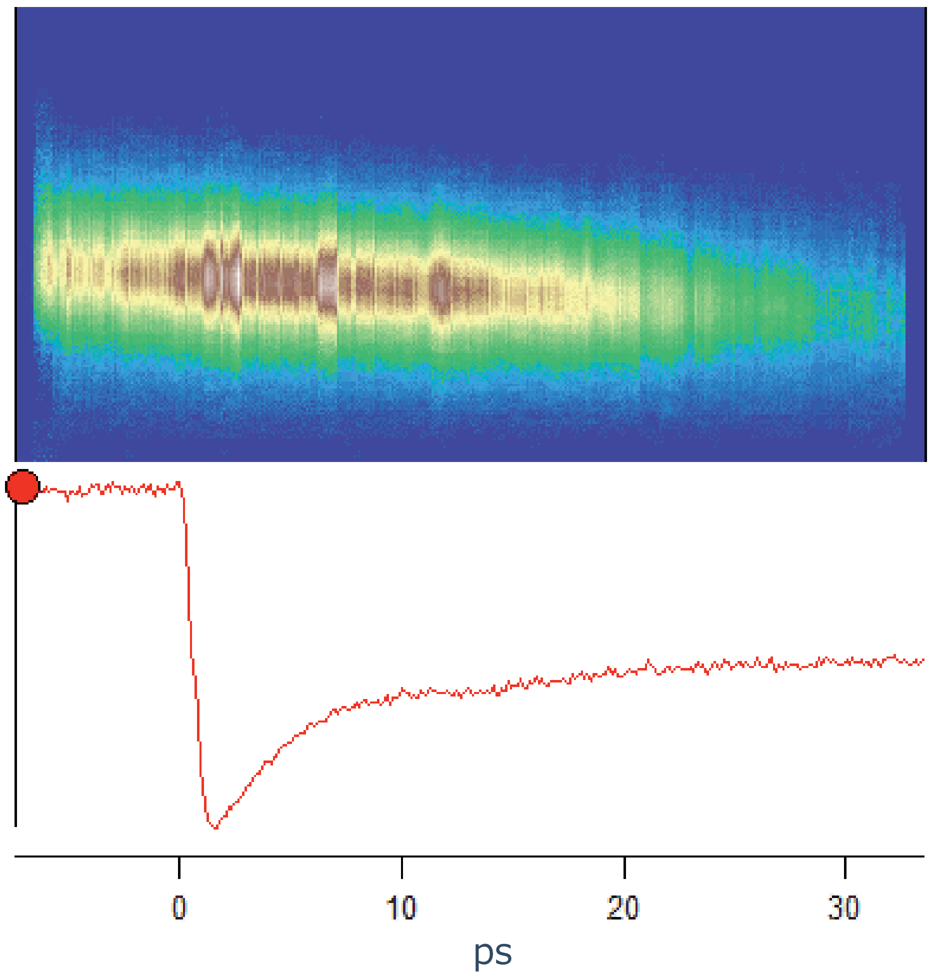


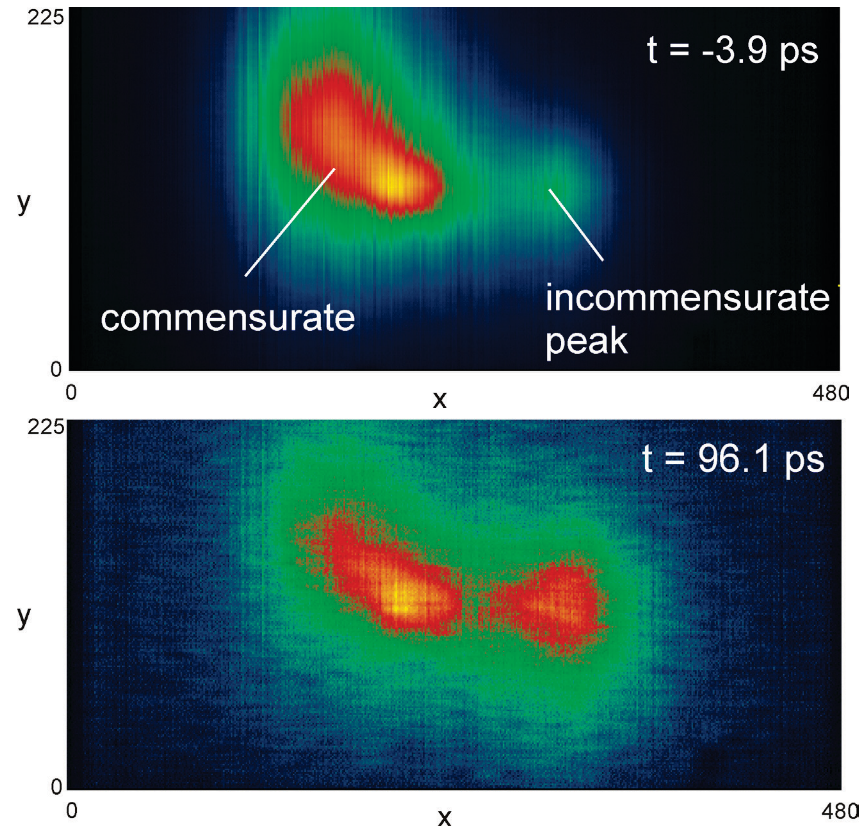




Spin Ordering (SO) – The Movie

Fast melting and slow recovery of spin ordering around 50K
(shot-by-shot readout to correct time jitter and intensity fluctuation)





Aug. 2010 - 28 mJ/cm^2

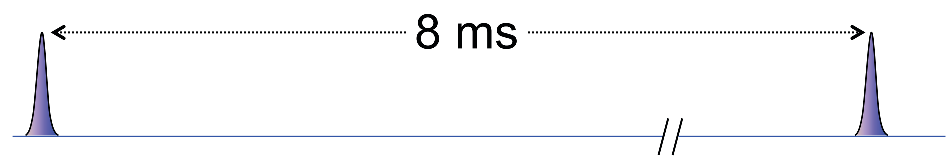
FELs

Intensity Speed

LCLS

pulsed n.c. HXR

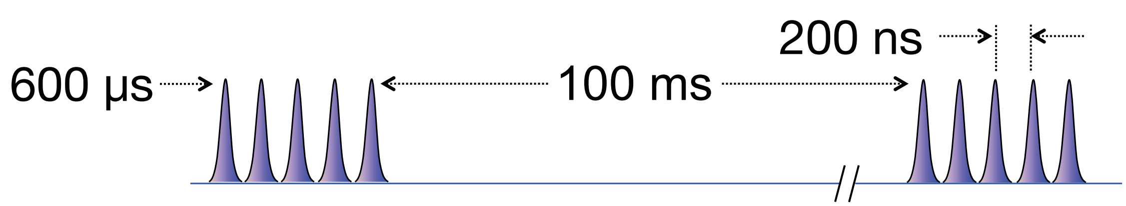
120 Hz



European XFEL

pulsed s.c. HXR
(FLASH - SXR)

5 MHz
x 0.6%

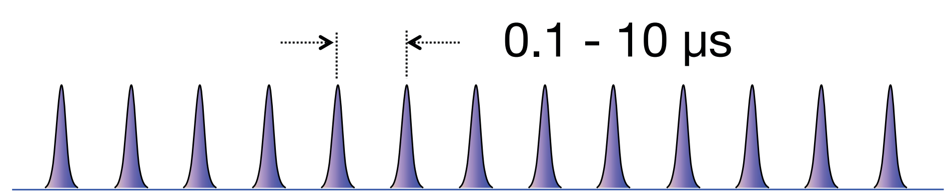


write fast, read slow

NGLS next generation light source

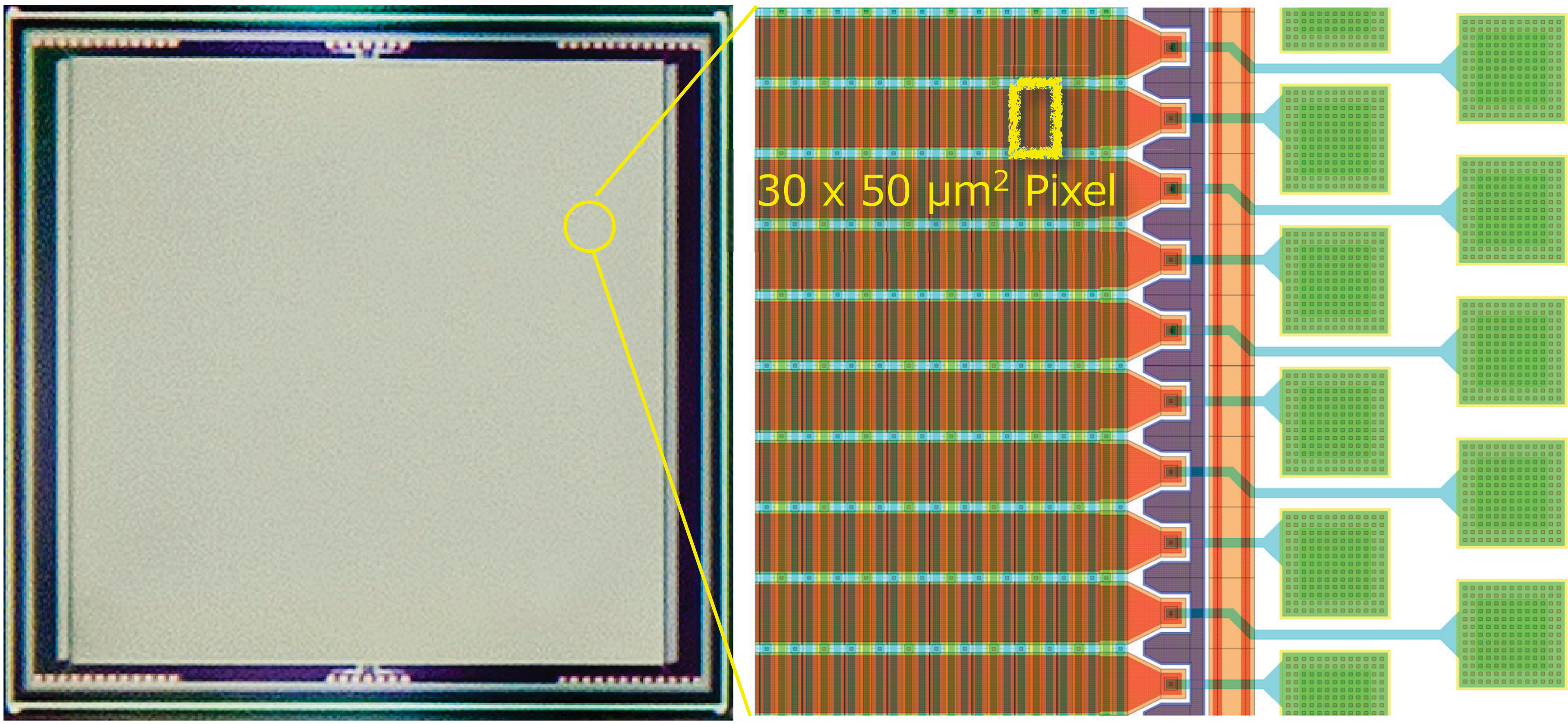
cw s.c. SXR

100+ kHz



continuous data

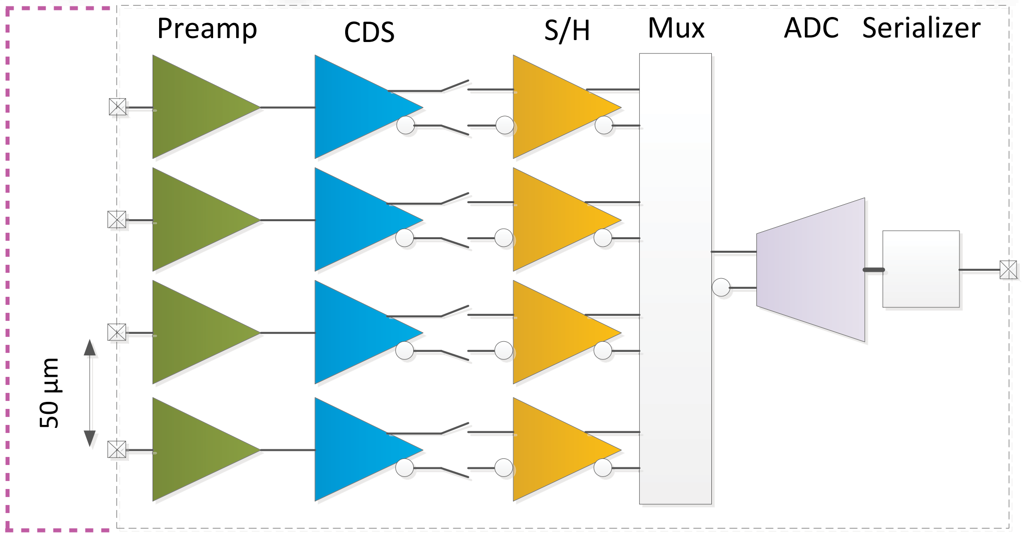
Column-Parallel CCD



- 50 μm pitch for chip-to-chip wire bonding
  - Flip-chip as a next step
- Aim for 10,000 MPix / s
  - Tile 8 x (128 x 1k) to get 100,000 MPix/s

HIPPO High-Speed Image Pre-Processor with Oversampling

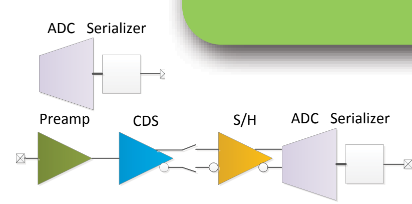
1 4-Channel Cell



Meets spec

Requirement	Value	Units	Comment
Resolution	12	Bits	
Sampling Rate	80	MS/s	
Full Scale	1	Volts	V_{pp}-differential
Noise (ADC)	200	µV-rms	LSB is 250 µV
Noise (Full)	1.4	LSB	
Linearity	10	Bits	Differential
Circuit Pitch	50	µm	match CCD
Serial Output	480	Mb/s	dual data rate

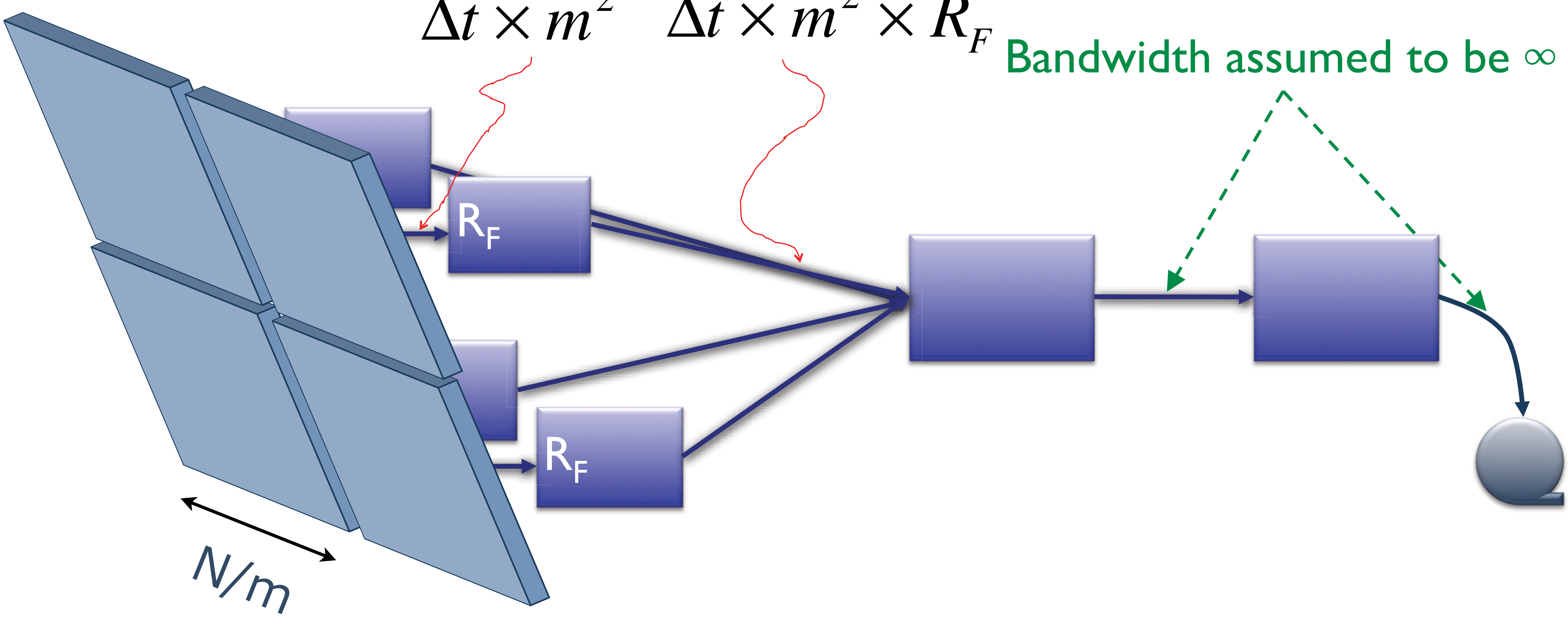
10 MHz
x 4 (40 MHz)
+ CDS (80 MHz)



65 nm CMOS - 2011

Data Challenge - Segmentation

$$\frac{N^2}{\Delta t \times m^2} \qquad \frac{N^2}{\Delta t \times m^2 \times R_F}$$



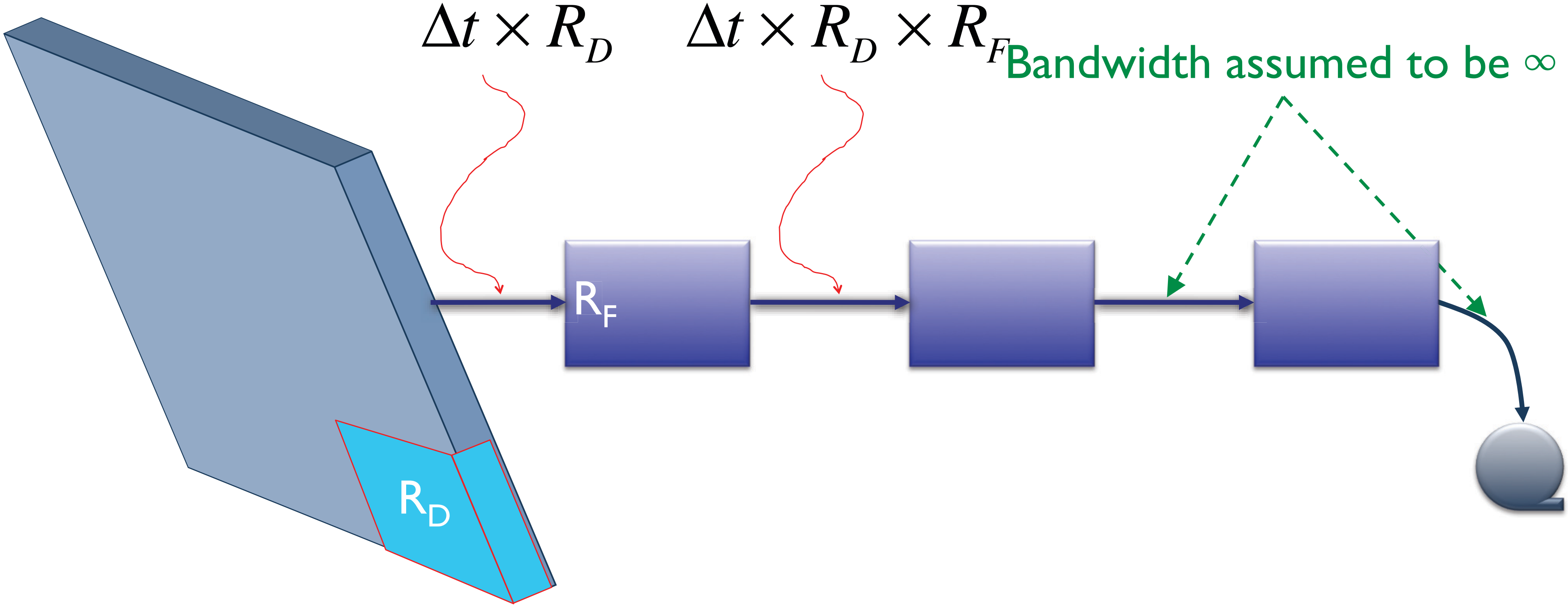
Near Detector Processing (FPGA)

Near Detector Computing (e.g. GPU)

Computing (e.g. HPC)

On-chip reduction

$$\frac{N^2}{\Delta t \times R_D} \qquad \frac{N^2}{\Delta t \times R_D \times R_F}$$



On Detector Processing

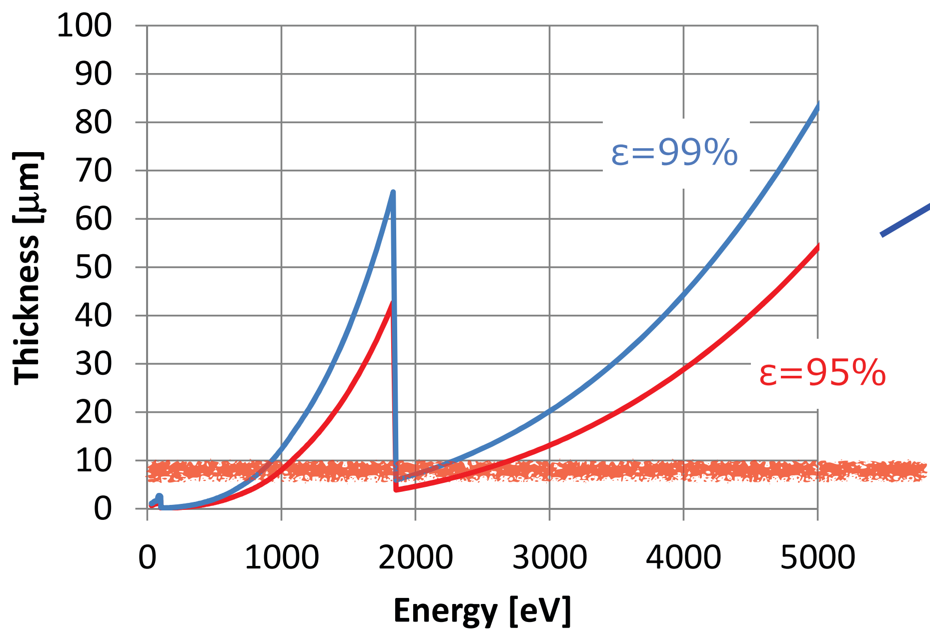
Near Detector Processing (FPGA)

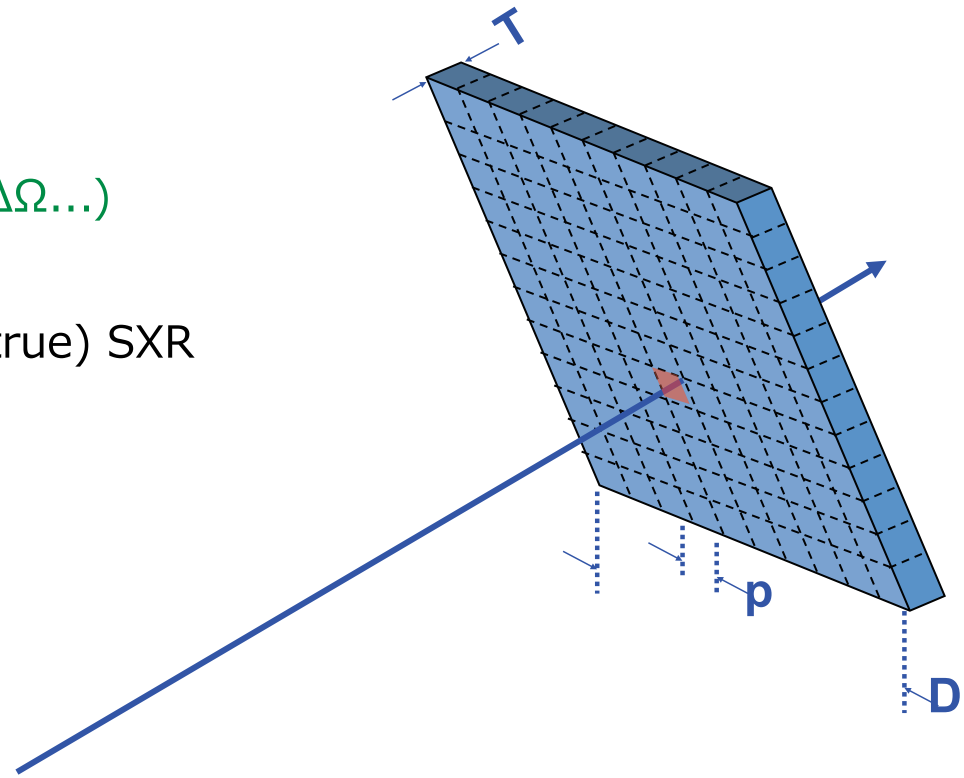
Near Detector Computing (e.g. GPU)

Computing (e.g. HPC)

Monolithic Soft X-ray Detectors - Good For:

- N x N pixels
  - Pitch **p** - 5 to 100 μm
  - Dimension **D** = N x p - 0.1 to 1k (ΔΩ...)
- Thickness **T**$(E_\gamma)_{MAX}$ - 50 - 300 μm Si
- Radiation hardness not an issue for (true) SXR

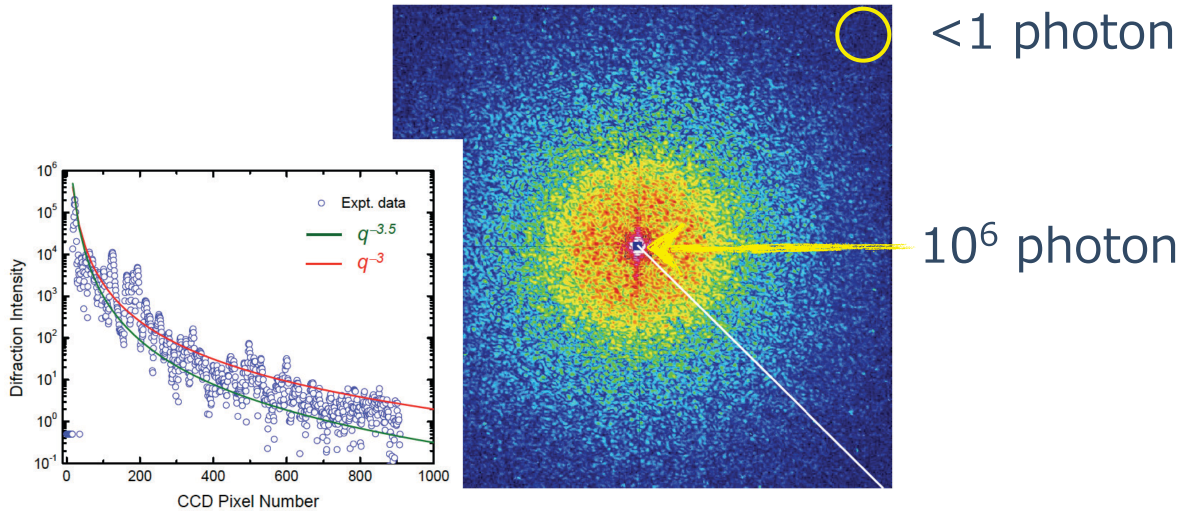




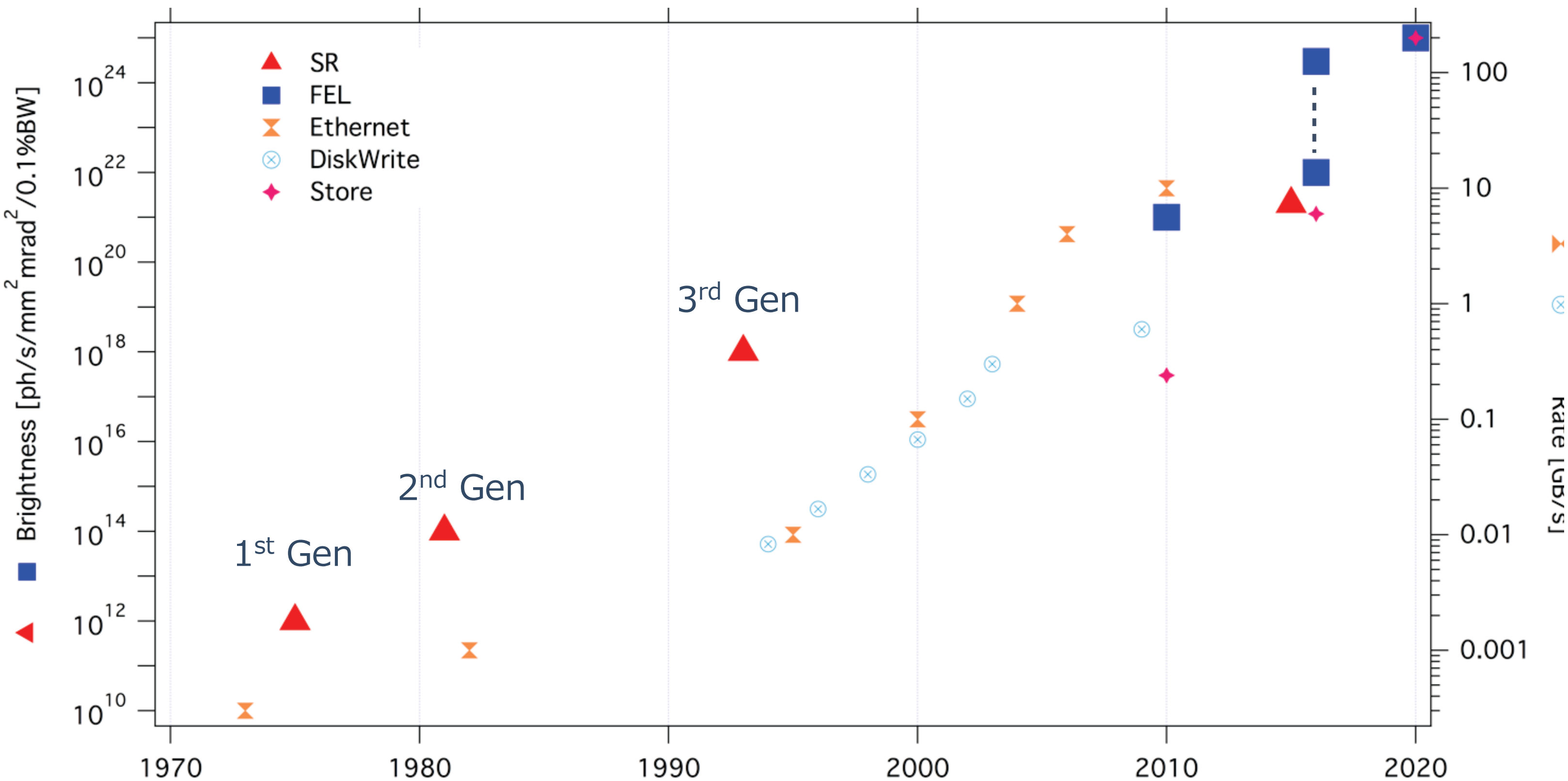
Thicker devices for E > 1 keV
CMOS possible for E < 1 keV

Challenges

	Monolithic Si
Efficiency	~100%
Size	«10 µm
Resolution	Noise
Time	~10 ns
Intensity	R&D!
Speed	R&D!



Data challenges significant!




Thank you!
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