Imaging Detectors and UV Technology

Udo Schühle

IMPRS lecture on 27. October 2010

Brand new Book in our Library

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IMPRS Oct. 2010

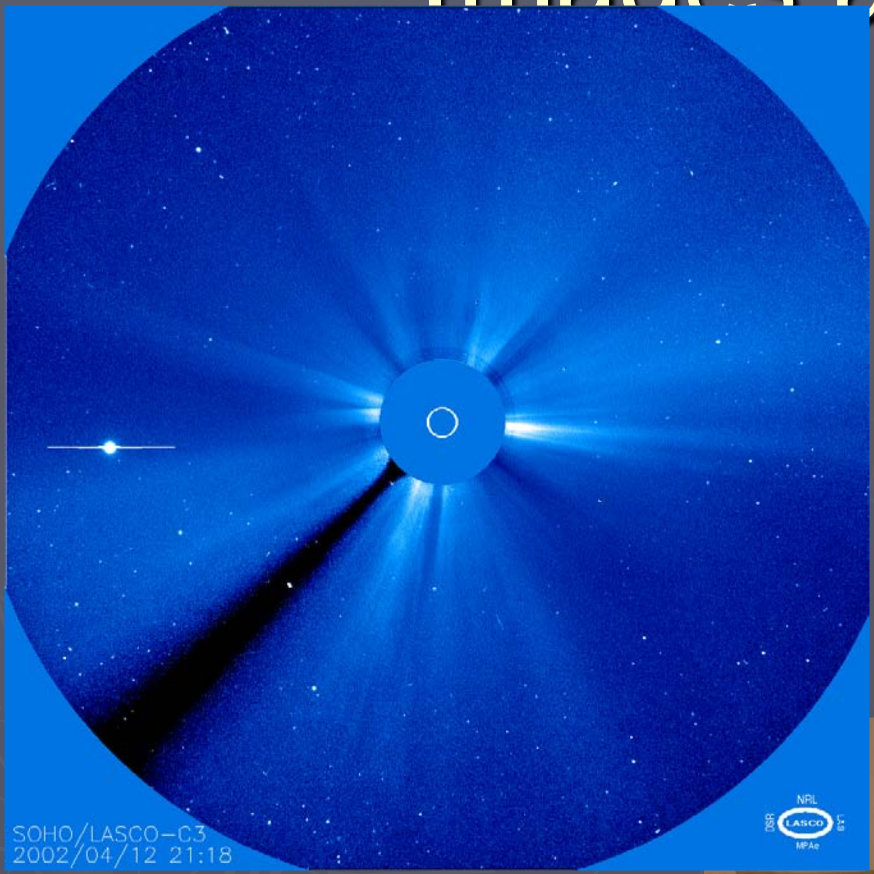
Outline

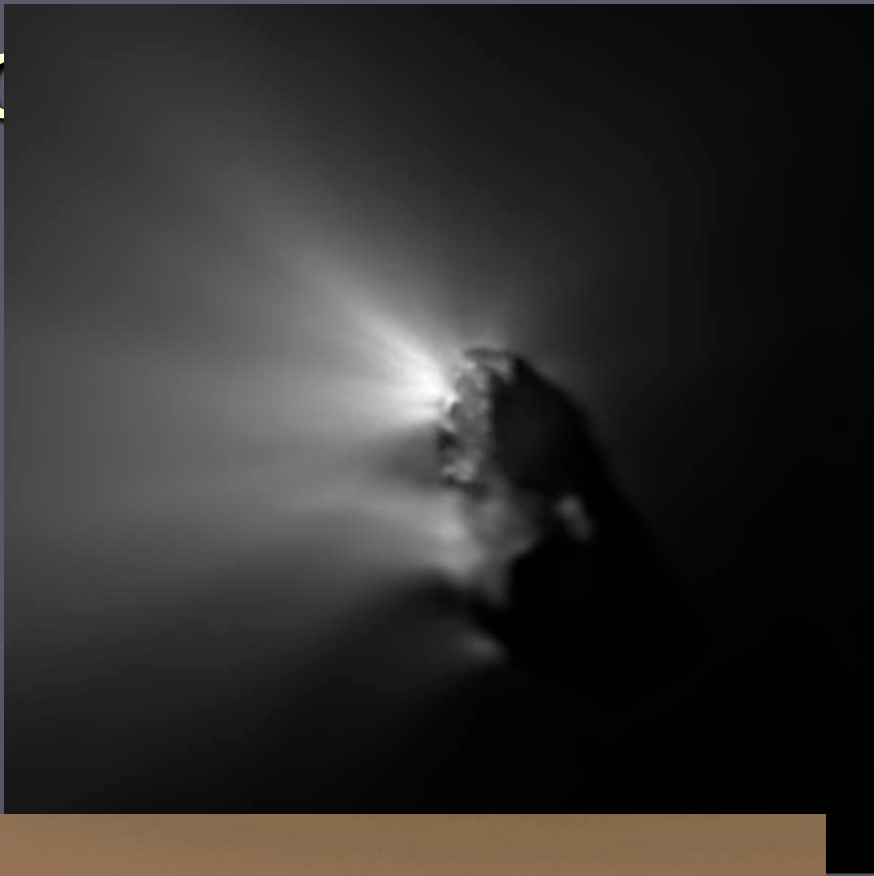
Imaging Detectors:

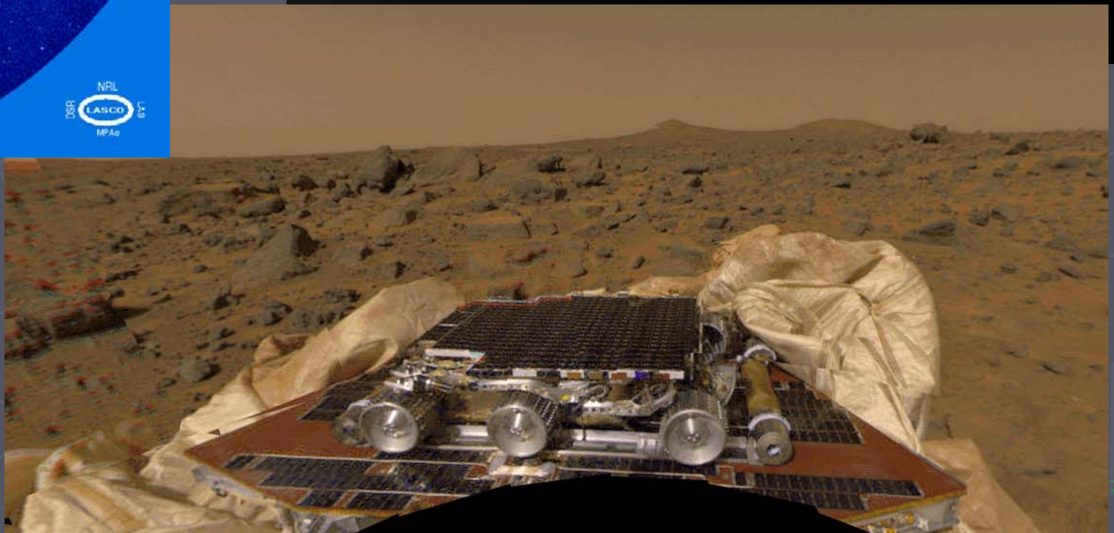
- digital cameras: general remarks, terminology
- sensor arrays: materials
- general performance characteristics
- CCDs vs CMOS-APS sensors
- UV detectors for solar observations
  - hybrid sensors with wide bandgap materials
  - microchannel plate detectors
    - analog read-out MCP detectors
    - Intensified APS detectors

UV Technology developments

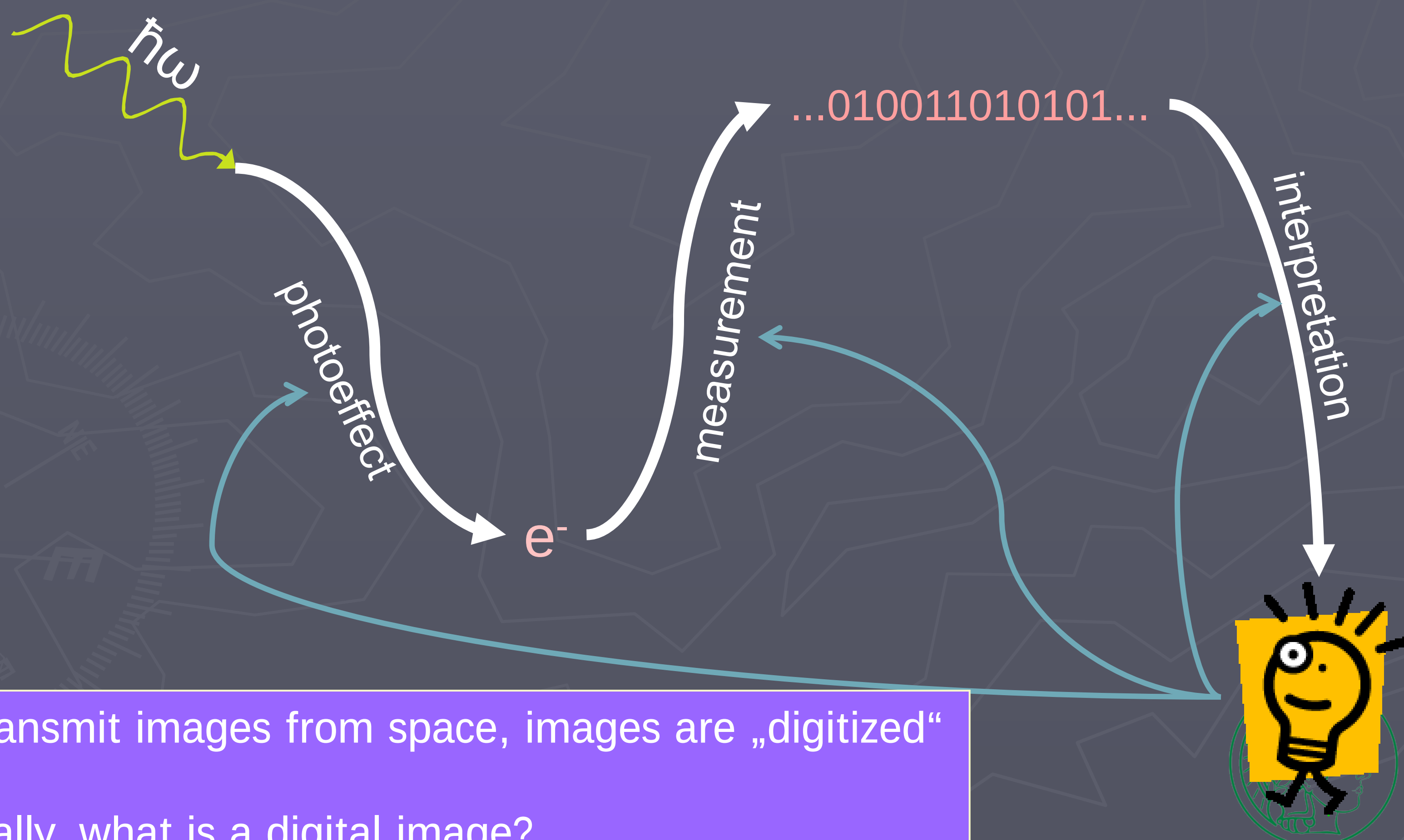
Images an







From photon to knowledge



To transmit images from space, images are „digitized“

Actually, what is a digital image?

Terminology

lens

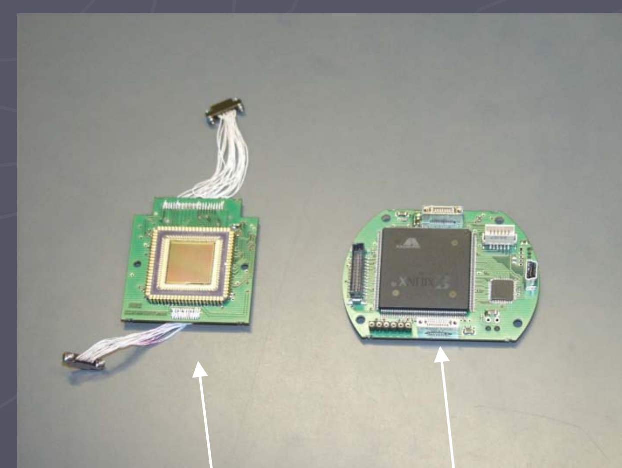
digital camera

sensor

camera or detector ?

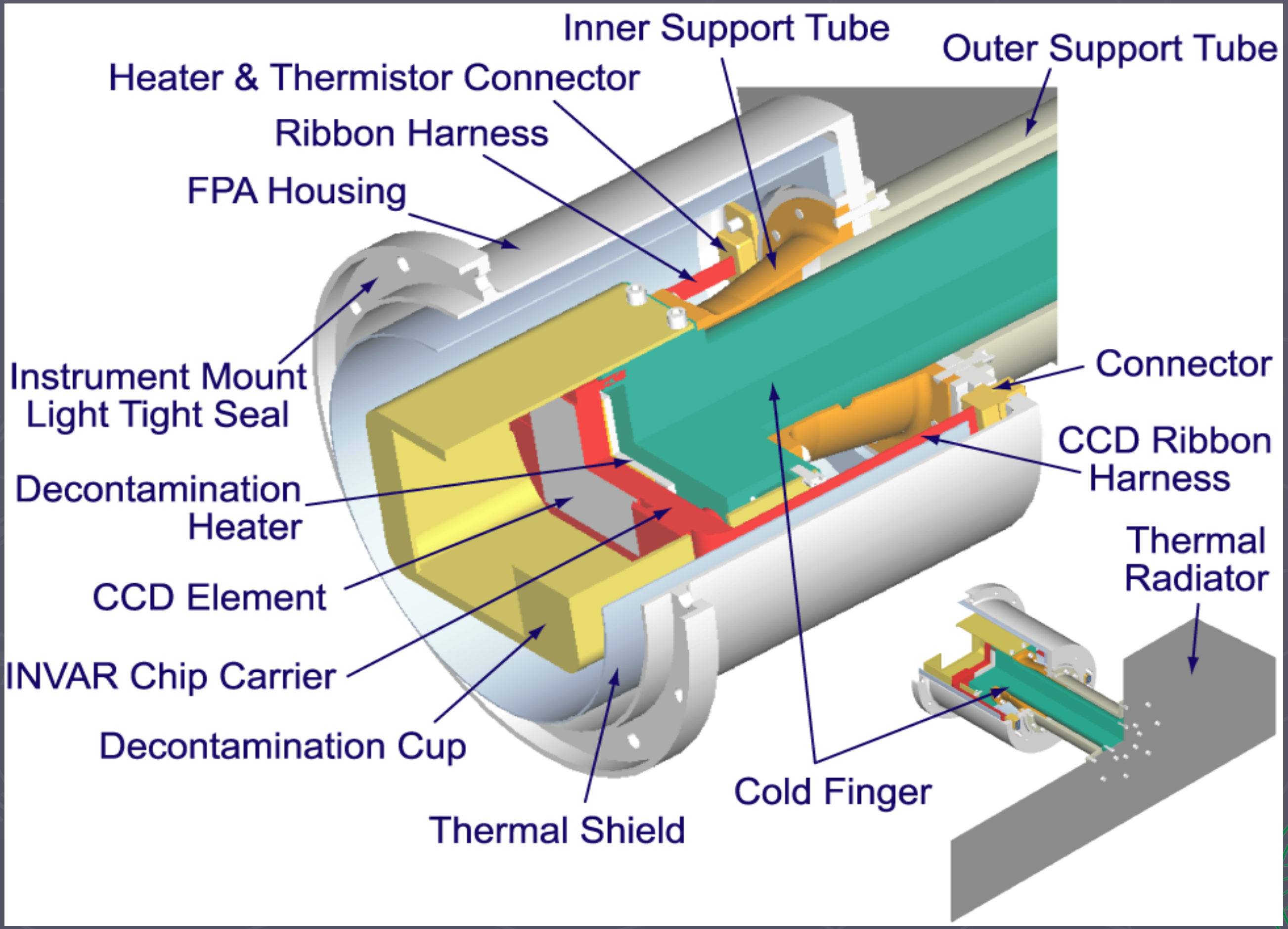
housing

„detector“ or
„focal plane unit“ or
„focal plane assembly“ (FPA)



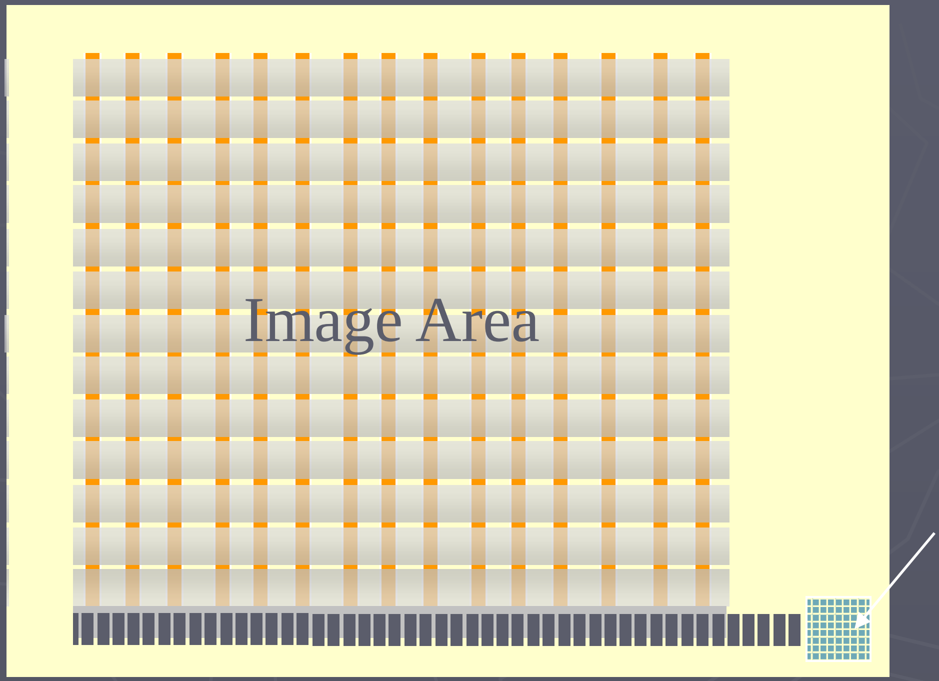
sensor board & FEE board

Focal plane assembly for space instrumentation



semiconductor array sensors

array of pixels



On-chip amplifier
at end of the serial
register.
Transfer to electronic
readout system
for digitization.

To form a digital image, the charge collected by each pixel is associated with a pixel address by which it can be identified: px(x,y,value)

remark

Note that the pixel size of a sensor array is of the order of 10 to 20 um.

If you design an optical system (a telescope), the image scale must be such that the resolution element corresponds with the pixel size
and the field of view corresponds with the array size.

The parameter to adjust is the Focal Length.

Photodetector materials

Material	E_{gap}(eV)	λ [nm]	band
Si	1,12	1100	Visible
GaAs	1,42	875	Visible
Ge	0,66	1800	NIR
InGaAs	0,73-0,47	1700-2600	NIR
InAs	0,36	3400	NIR
InSn	0,17	5700	IR
HgCd	0,7-0,1	1700-12500	NIR-FIR

Other detector materials

- PtSi (3-5 um)
- HgCdTe (3-5 or 8-10 um)
- CdZnTe
- GaN (360 nm)
- AlGaN (360 to 260 nm)
- C (diamond) (220 nm)

infrared materials

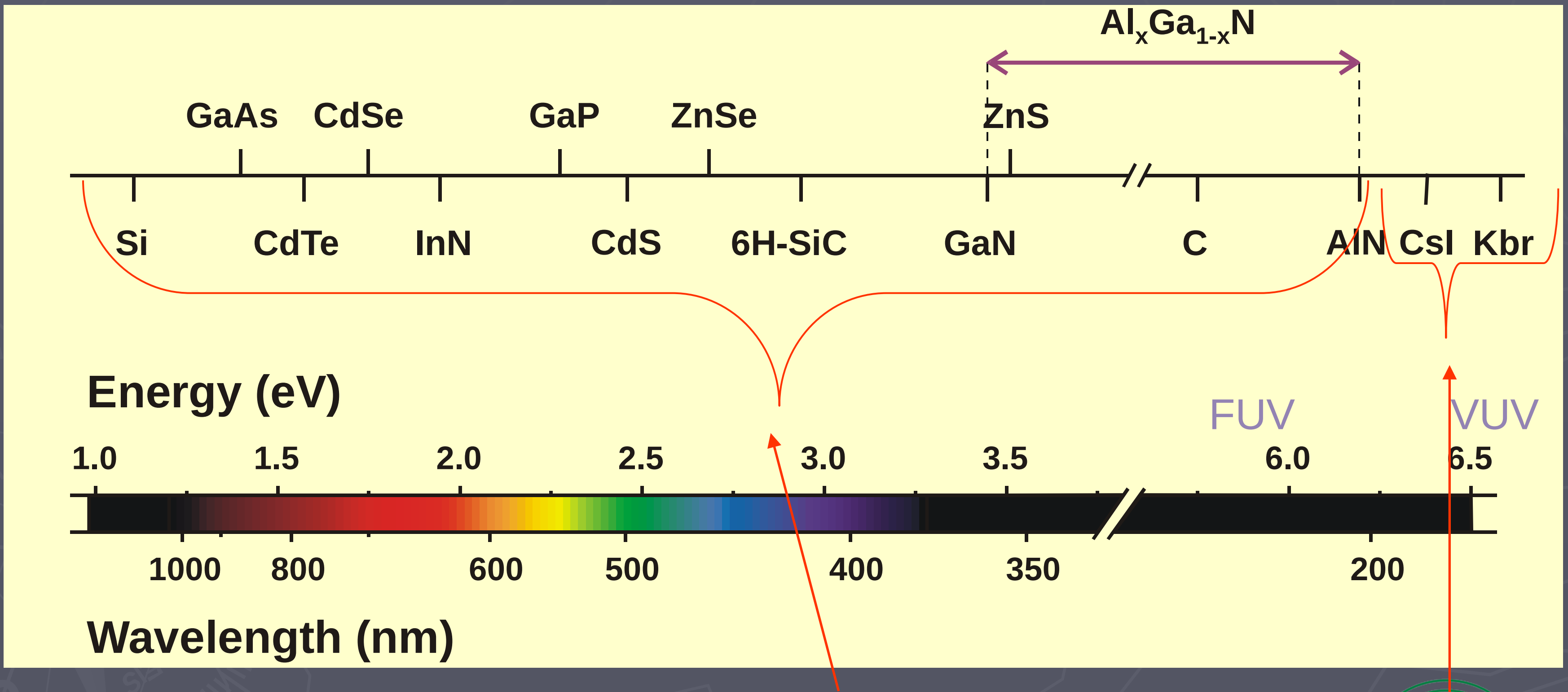
X-ray materials

ultraviolet materials

„wide band gap“ materials

Photodetector materials

band gap energy of materials:



charge creation and photo-conduction

photo-emission in vacuum

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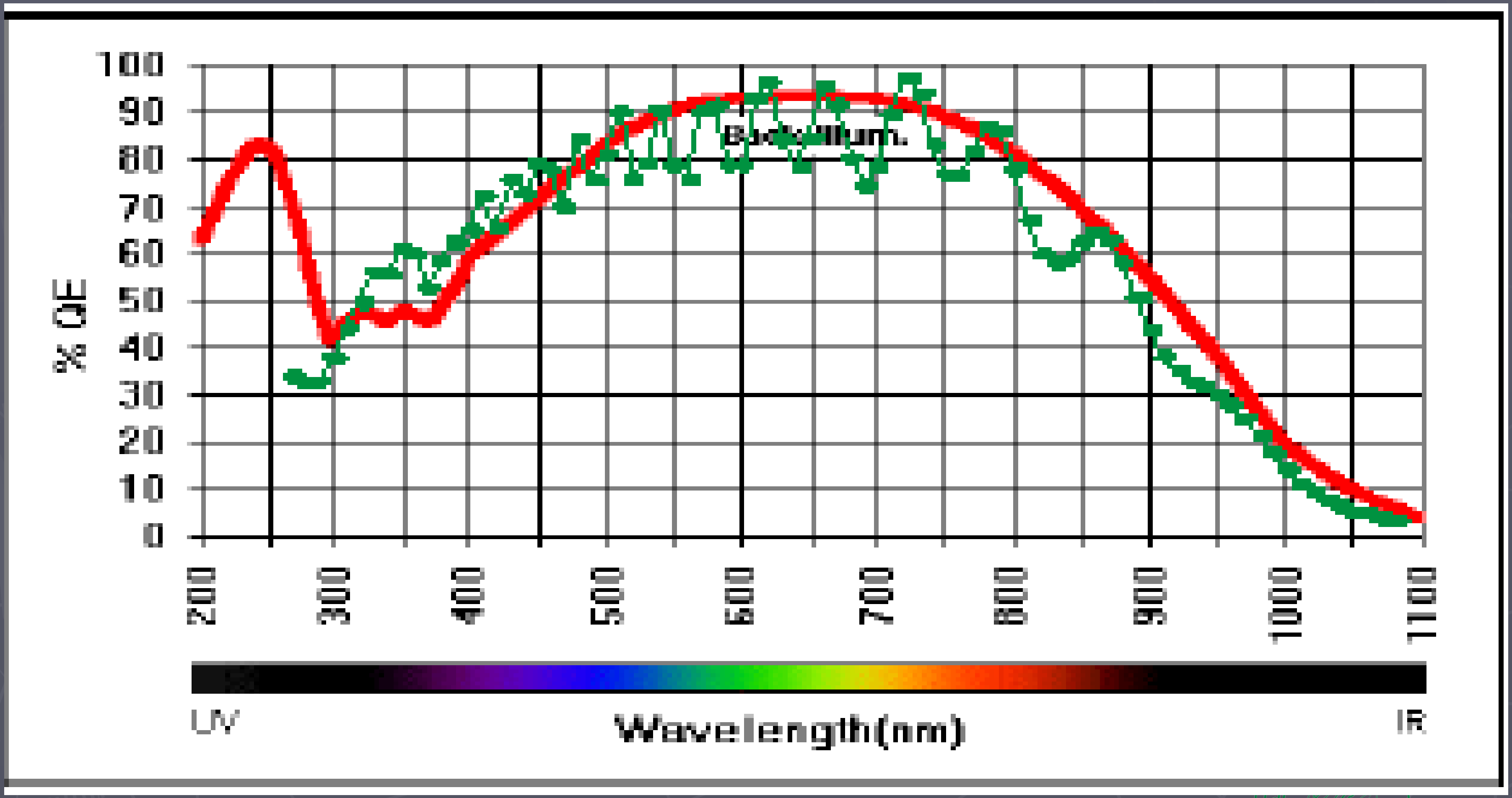
QE = quantum efficiency



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Types of sensor arrays

Si-based sensors:

- charge coupled devices (CCDs)
- CMOS – APS active pixel sensors
    - expanding the sensitivity range to the UV
    - thinned backside illumination
    - deep depletion

- choice of materials
- sensor architecture
- hybrid devices

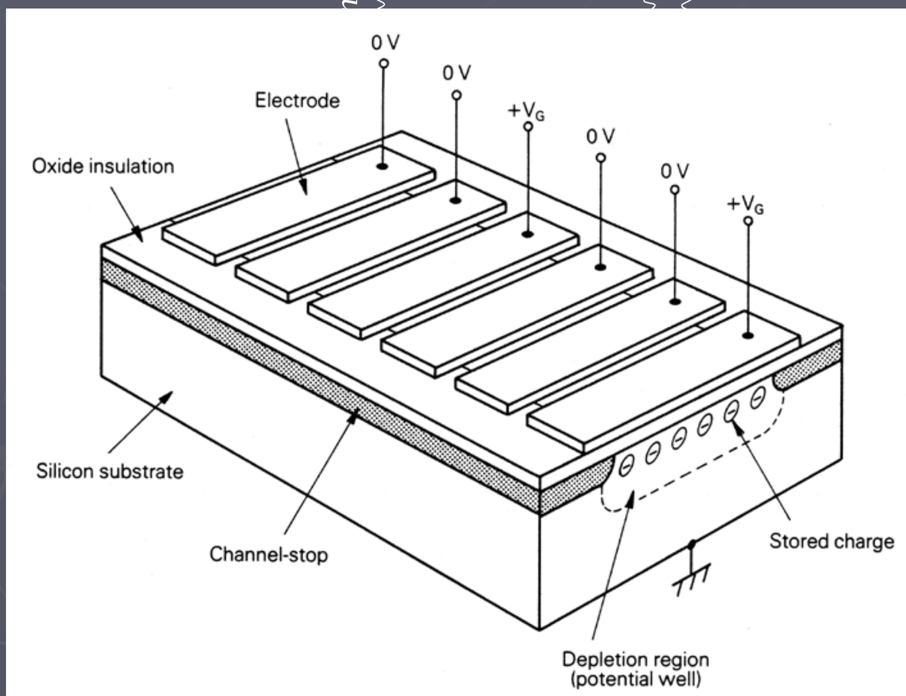
→

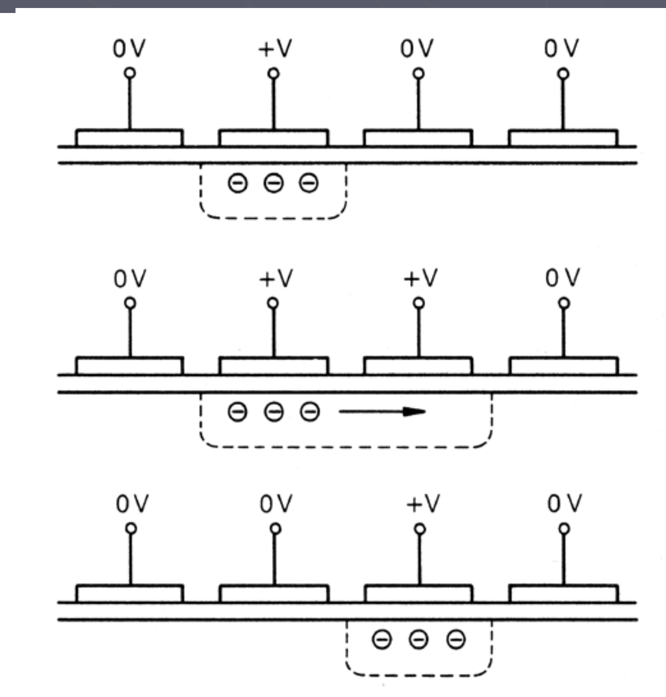
CCDs

diode arrays

CMOS active pixel arrays (APS)

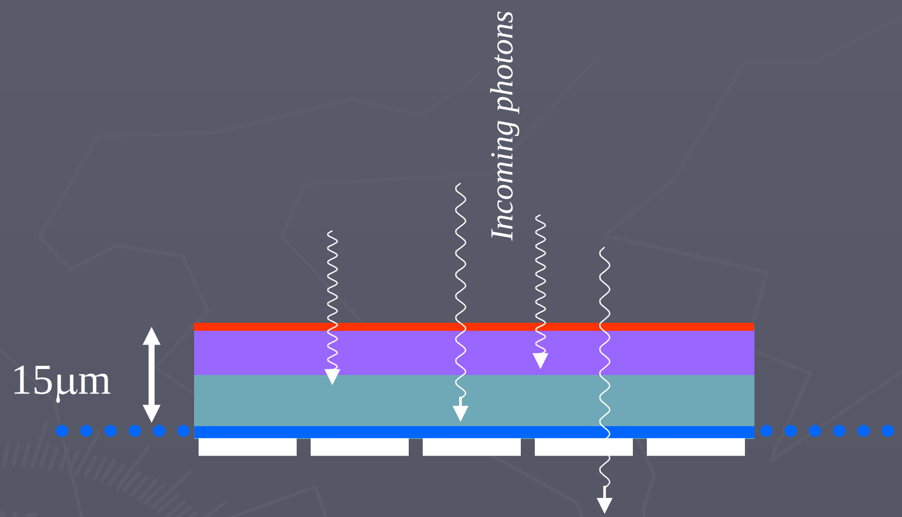
Front-side Illuminated CCD





find more info about CCDs at http://www.ing.iac.es/%7Esmt/CCD_Primer/CCD_Primer.htm

Thinned Back-side Illuminated CCD

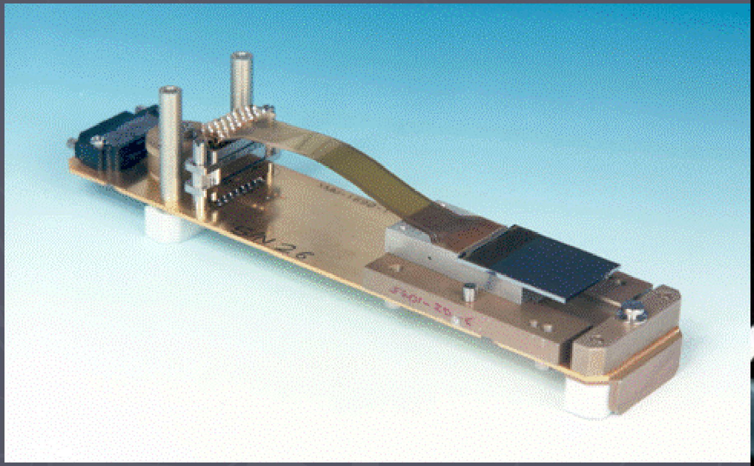


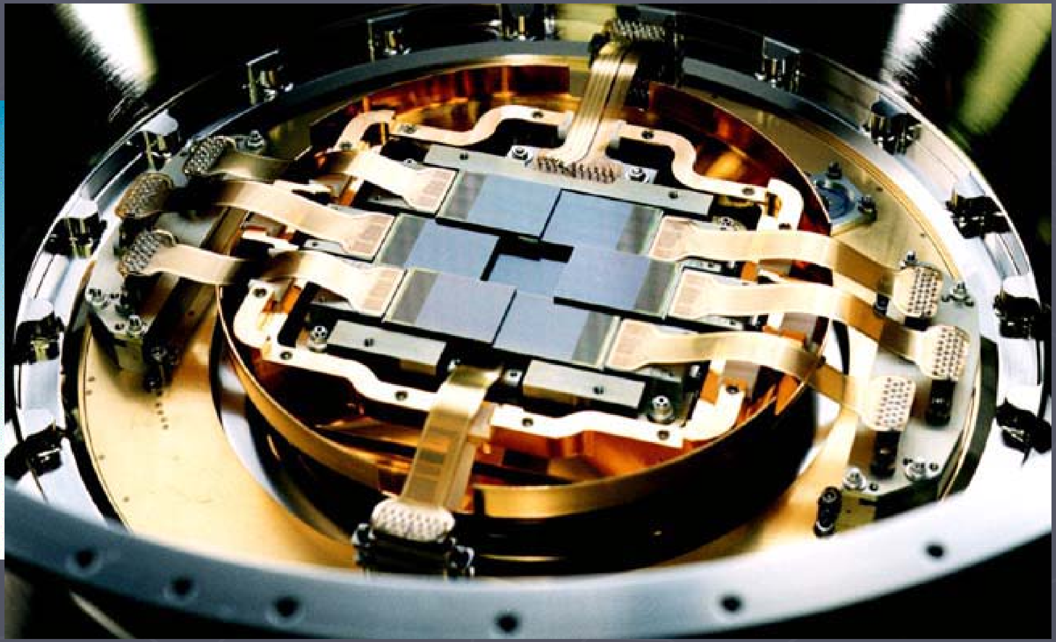
The silicon is chemically etched and polished down to a thickness of about 15microns. Light enters from the rear and so the electrodes do not obstruct the photons. The QE can approach 100% .

These are very expensive to produce since the thinning is a non-standard process that reduces the chip yield. These thinned CCDs become transparent to near infra-red light and the red response is poor. Response can be boosted by the application of an anti-reflective coating on the thinned rear-side.

Almost all astronomical CCDs are Thinned Backside Illuminated.

an X-ray CCD focal plane unit





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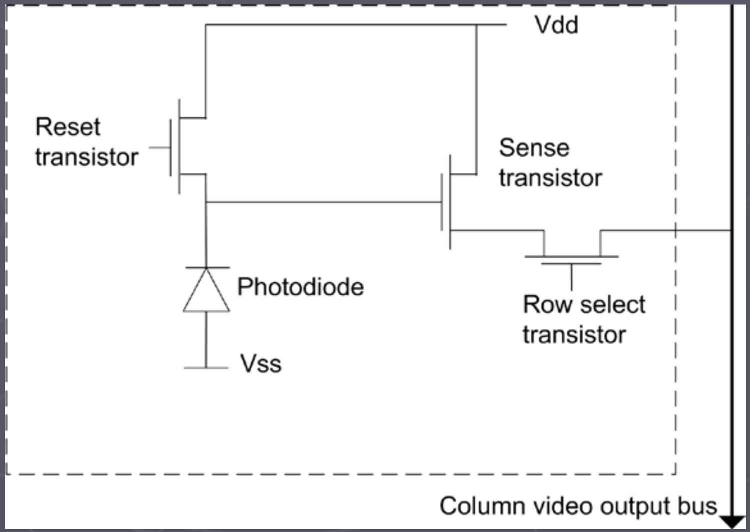
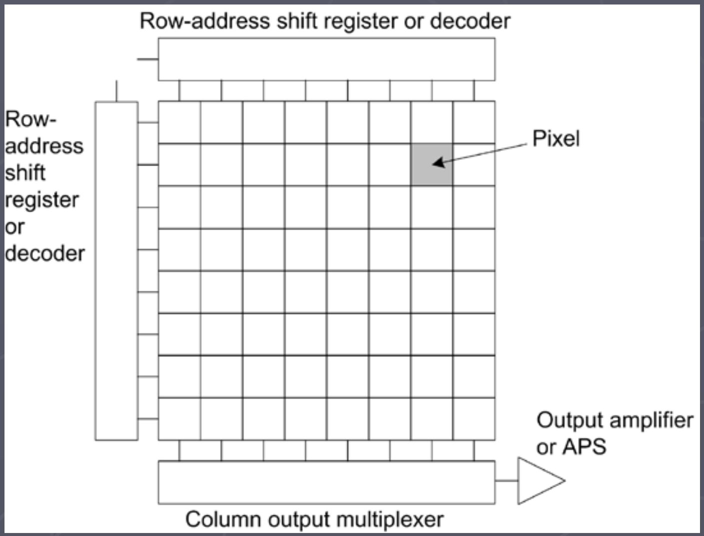
Active pixel sensor CMOS-APS

functional principle





one pixel

pixel array

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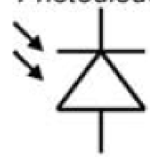
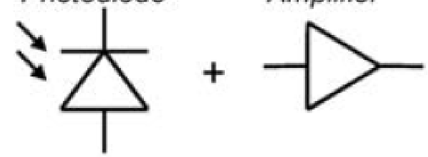
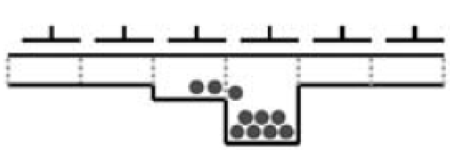
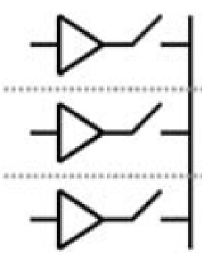
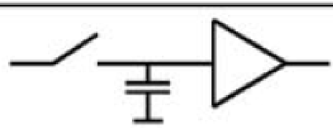
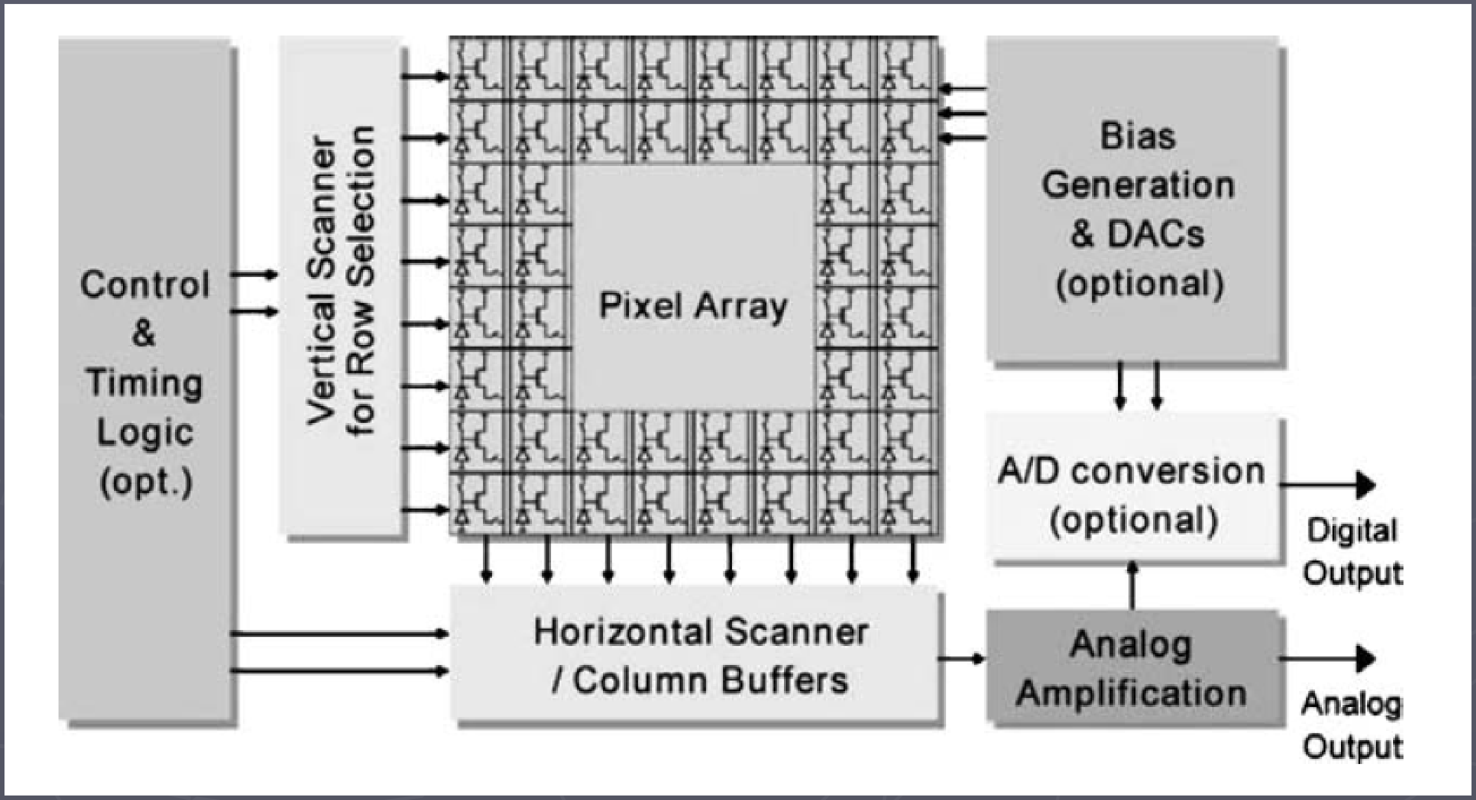
CCD versus CMOS sensors

	CCD Approach	CMOS Approach
Pixel	*Photodiode*  Charge generation and charge integration	*Photodiode* + *Amplifier*  Charge generation, charge integration and charge-to-voltage conversion
Array Readout	 Charge transfer from pixel to pixel	 Multiplexing of pixel voltages: Successively connect amplifiers to common bus
Sensor Output	 Output amplifier performs charge-to-voltage conversion	Various options possible: - no further circuitry (analog out) - add. amplifiers (analog output) - A/D conversion (digital output)

generic architecture of a CMOS sensor

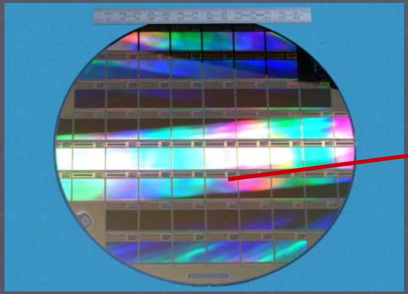


- ✓ flexibility of read-out scheme (pixels can be adressed individually)
- ✓ no shutter is needed

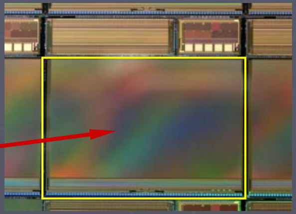
CMOS APS development

4k x 3k Pixel Sensor Development for ESA's Solar Orbiter

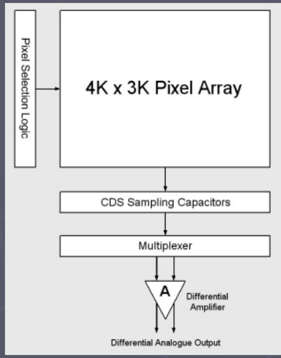
- 5 μm pixel size.
- 12 bit dynamic range.
- 4-transistor CDS pixel for low noise.
- 0.25 μm CMOS process.
- EUV sensitivity by back-thinning or front-etch.



8-inch Wafer 0.25 μm CMOS

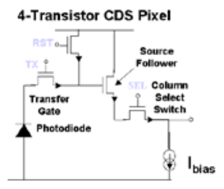


4kx3k pixel sensor die

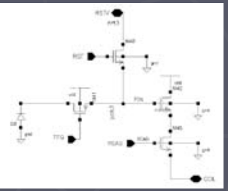


Architecture

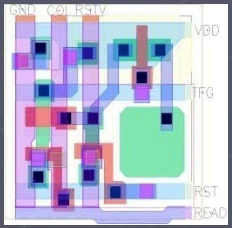
Pixel Circuit

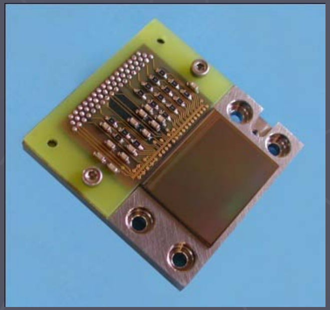


CAD Simulation

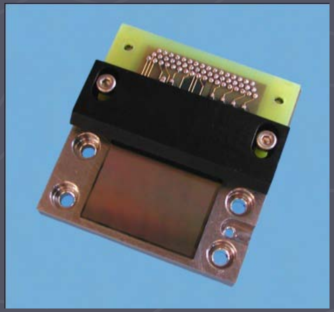


CAD Layout





Sensor mounted on an invar block and wire-bonded to a PCB



Bond-wire protection-cover fitted

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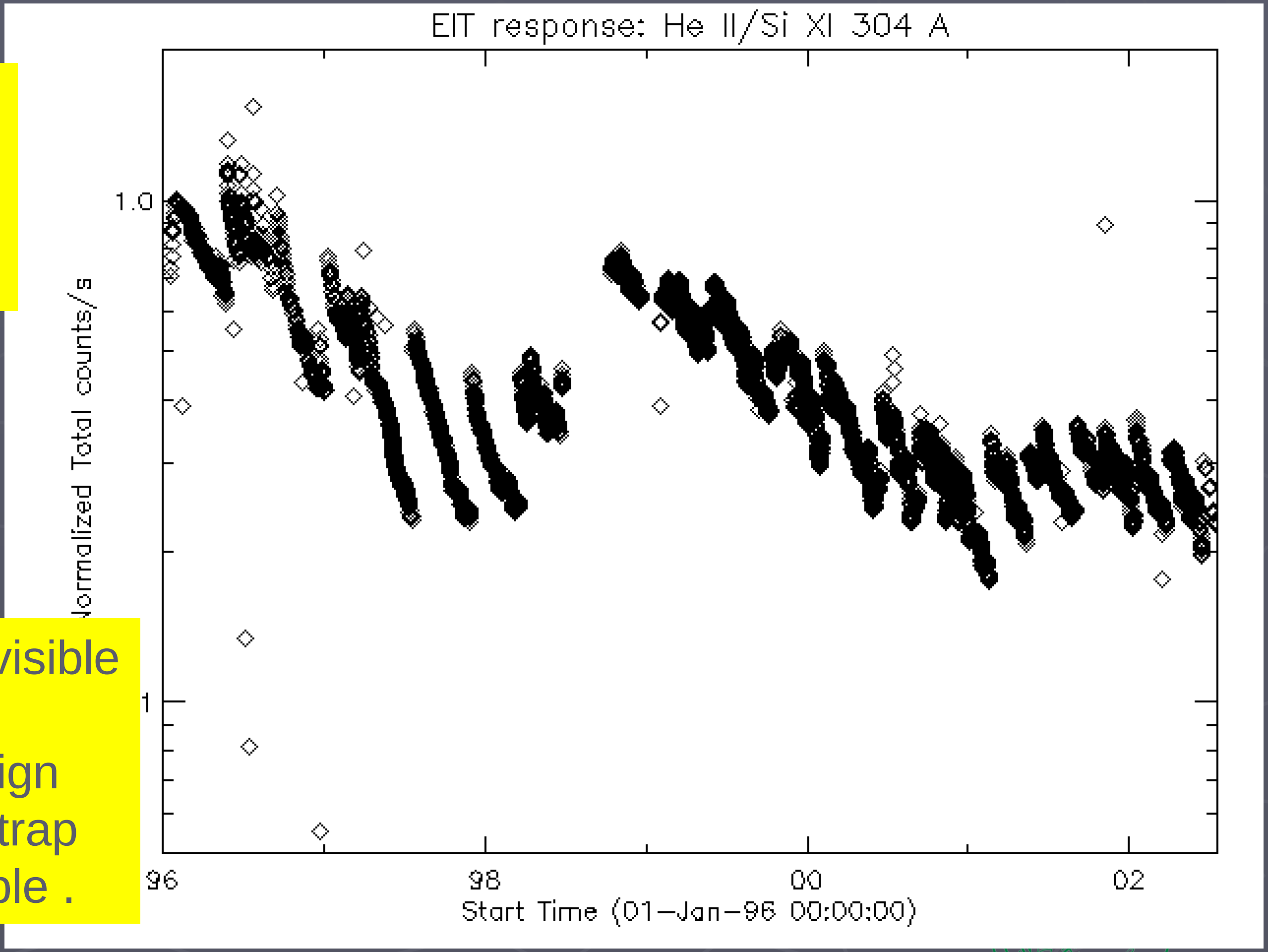
Drawbacks of current Si-based sensors

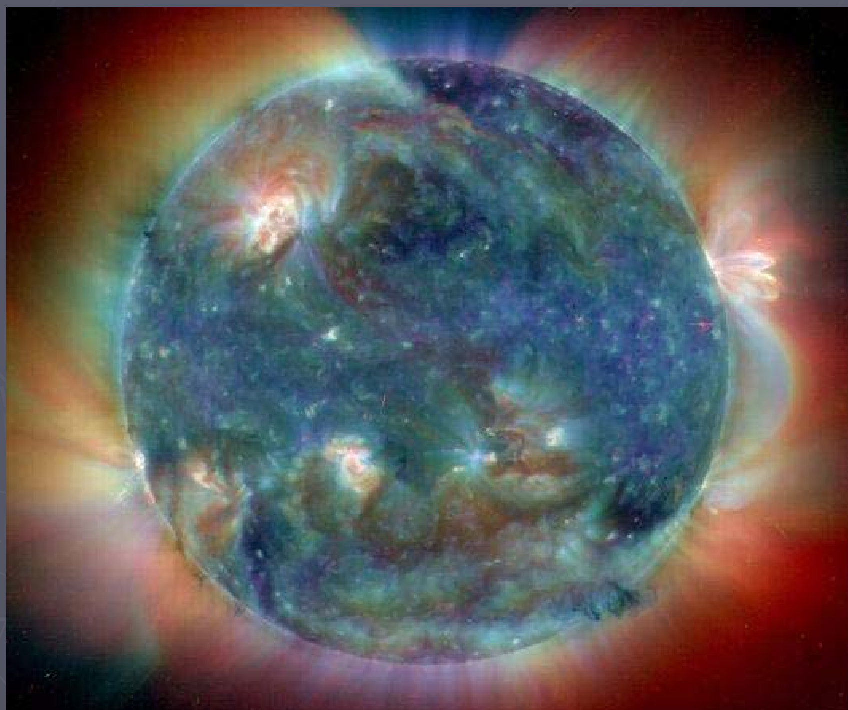
the EUV-teleskope
EIT on SOHO:

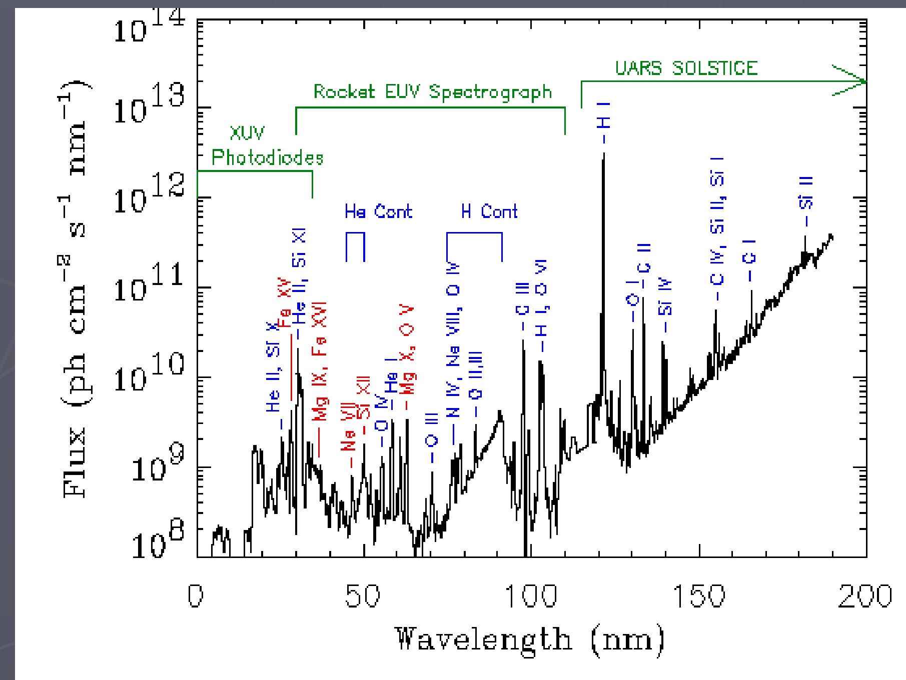
back-thinned CCD sensor



• need filters to suppress visible
• need cooling.
• complicates thermal design
• results in contamination trap
==> Efficiency very unstable .

UV detectors for solar observations



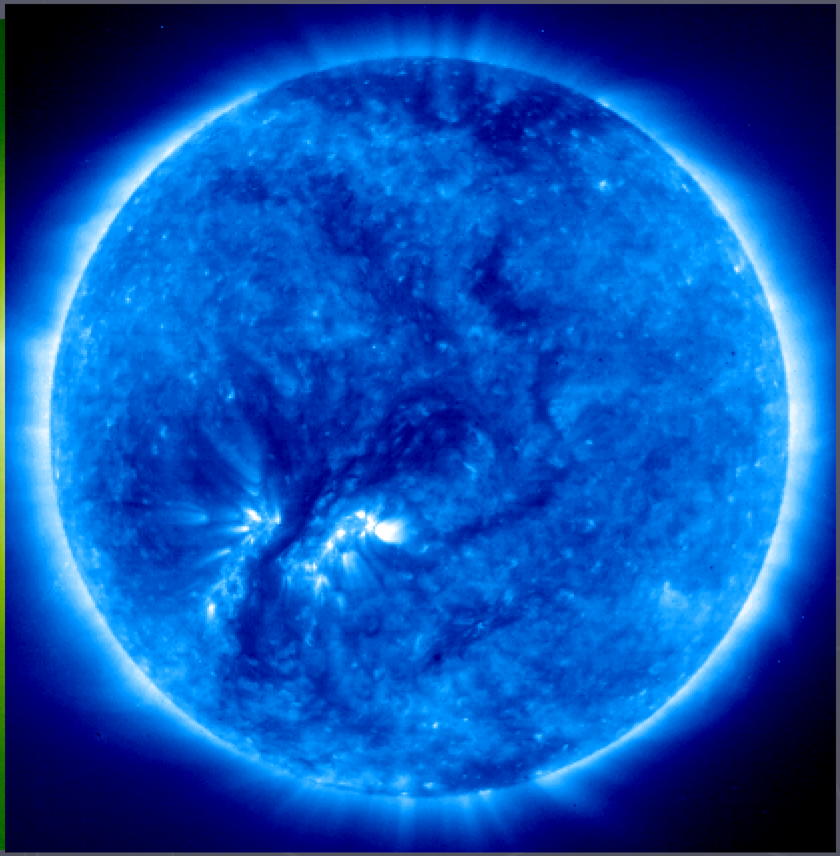


TRACE-image of the Sun in the EUV

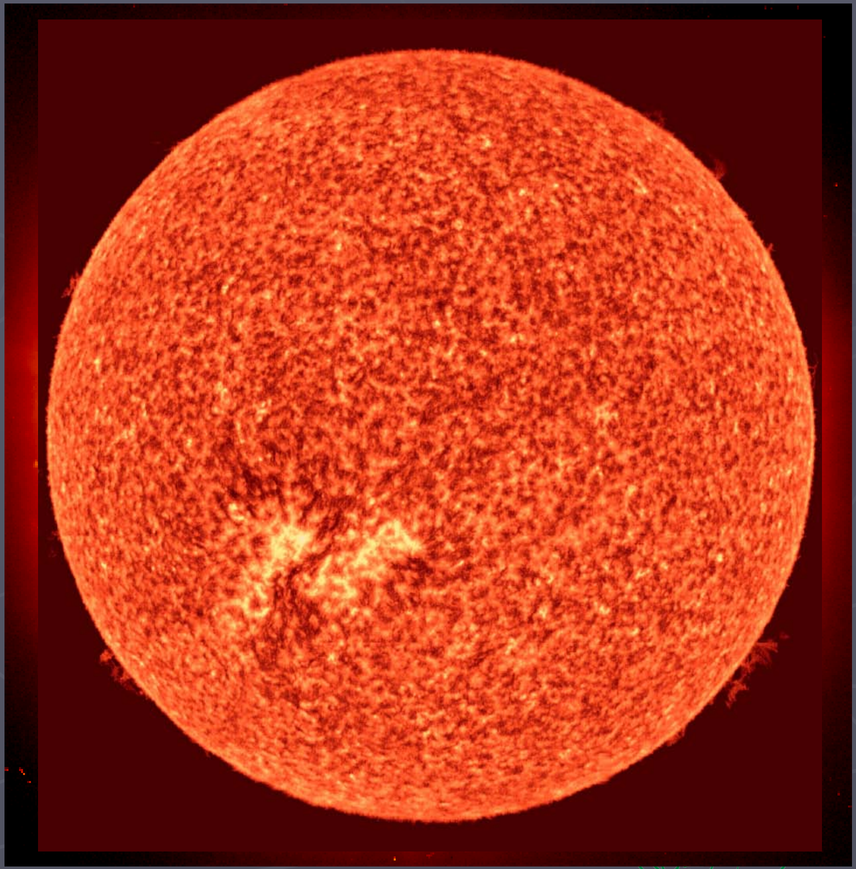
Emission spectra of the Sun in the VUV

The Sun on 24 September 1996

Fe IX/X 17.2 nm
(SOHO/EIT)



H I Lyman-ε
(SOHO/SUMER)



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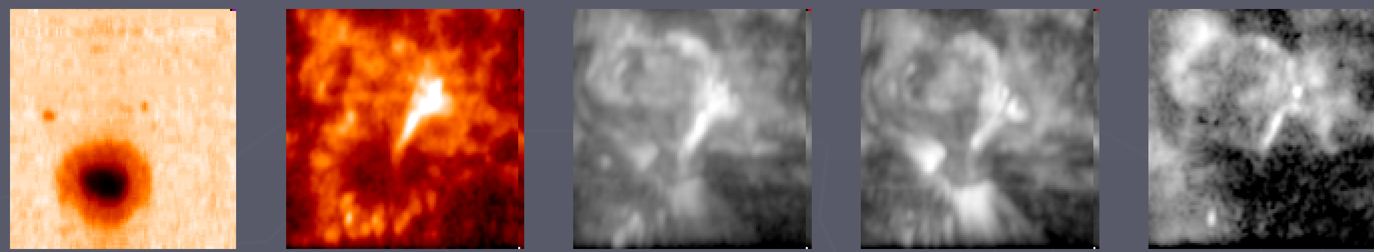
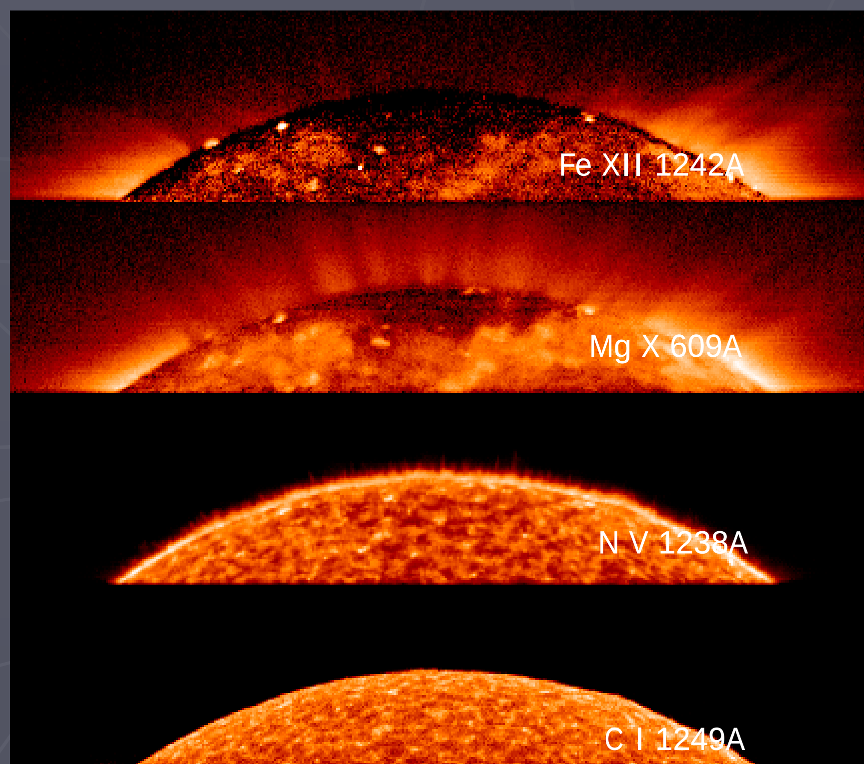
VUV spectrograph SUMER on SOHO

raster scan of sunspot:



vis 6330A | cont. ~1250A | N V 1238A | O V 629A | Fe XII 1242A

raster scan of polar region:



- no background noise
- no cosmic ray spikes

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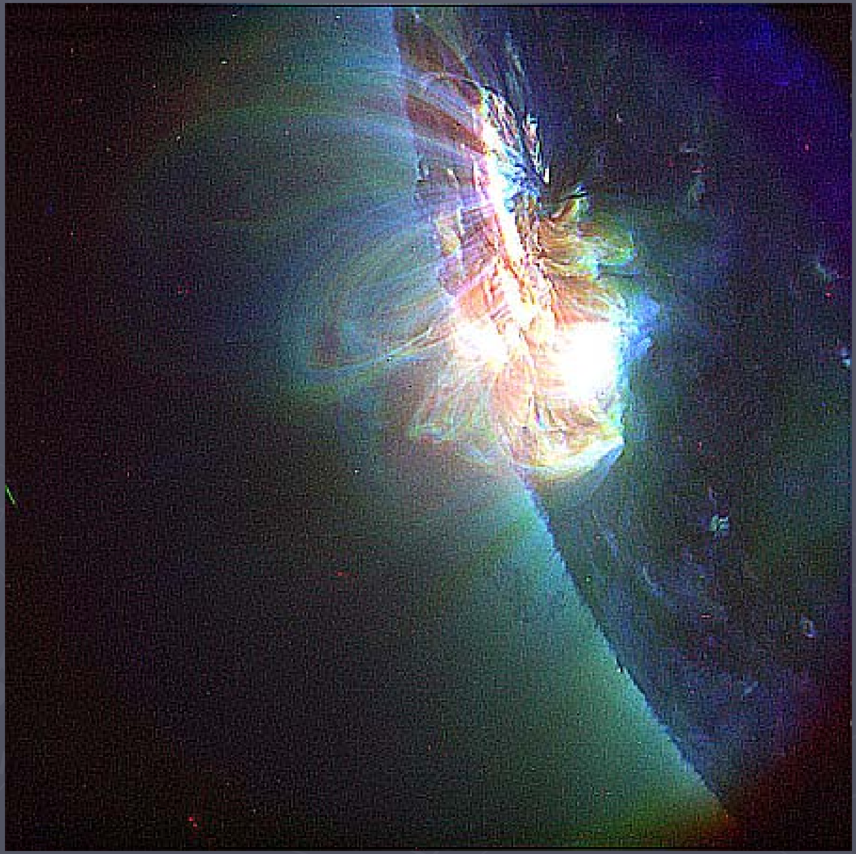
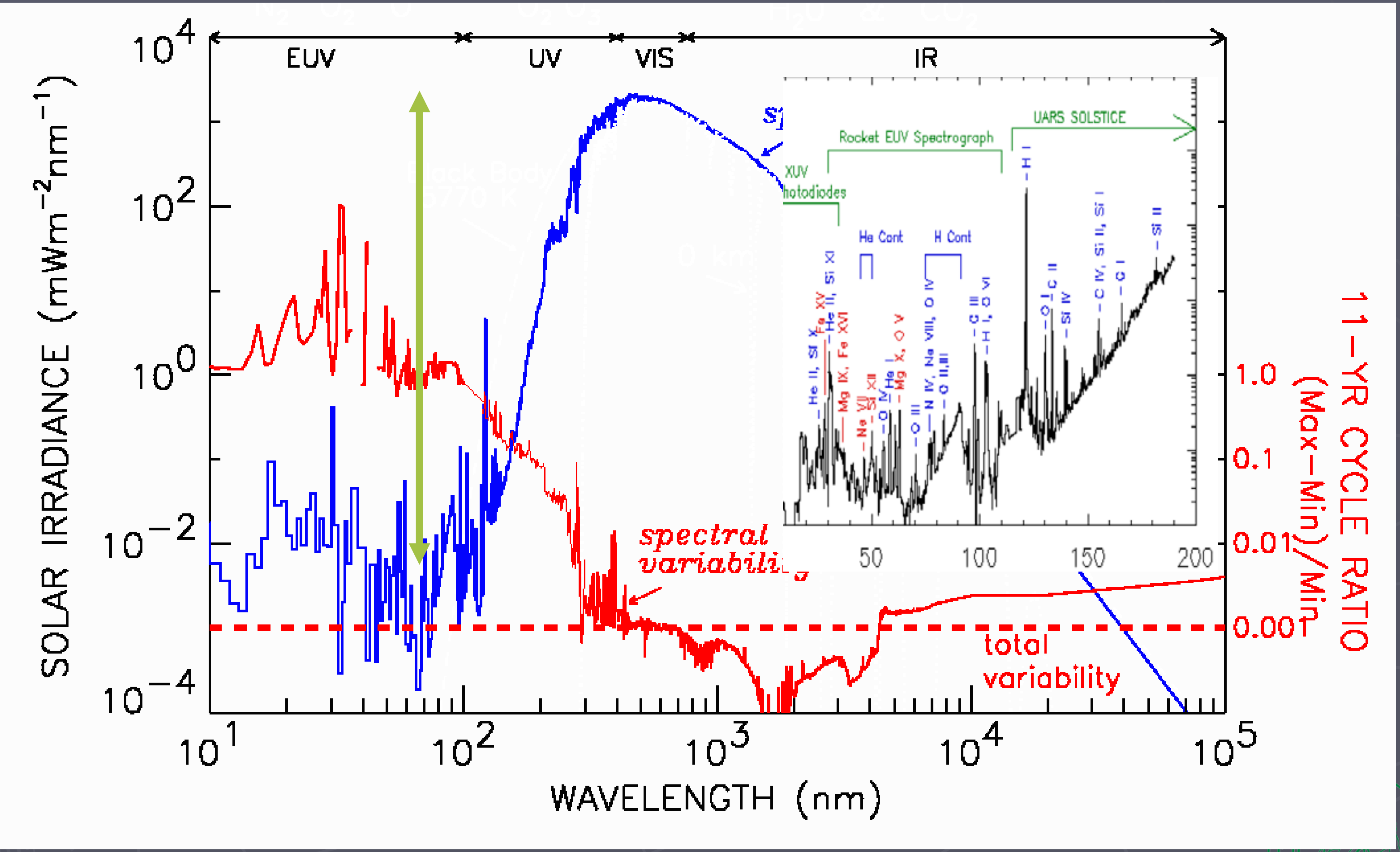
higher resolution and radiation hardness

0.5 Arcsec
~ 350 km at Sun



Solar spectral irradiance (and variability)



5.5 magnitudes!

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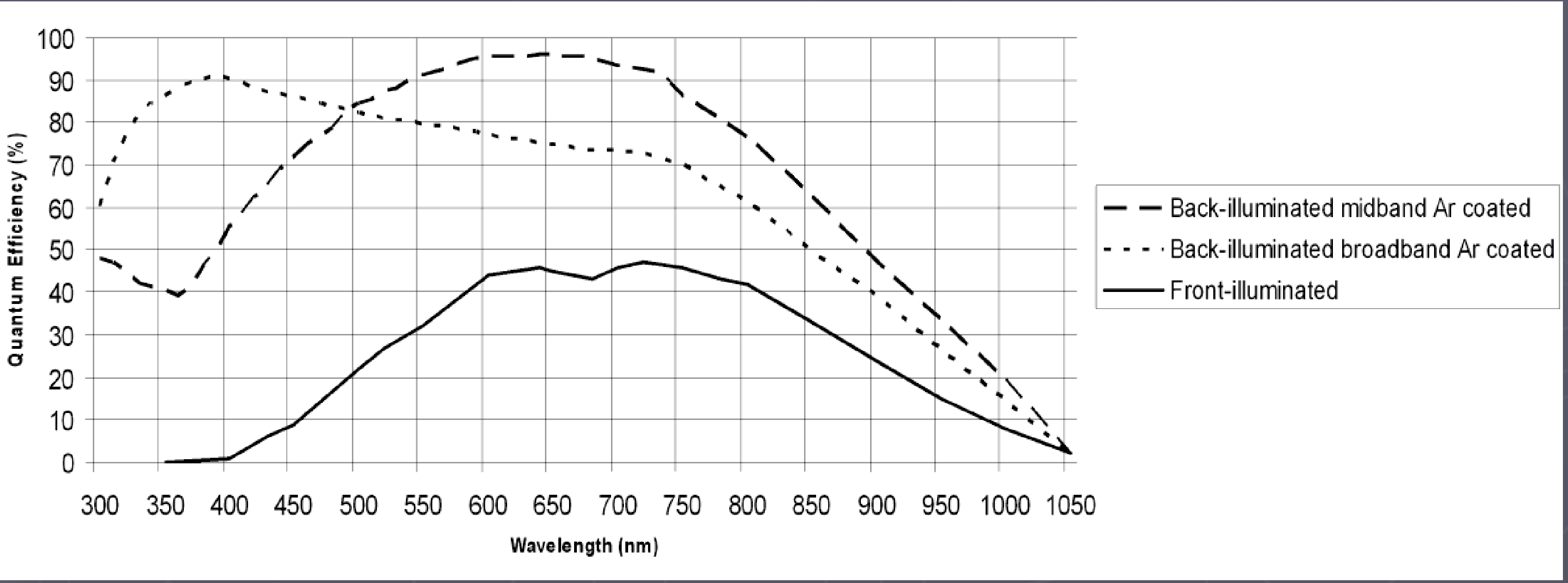
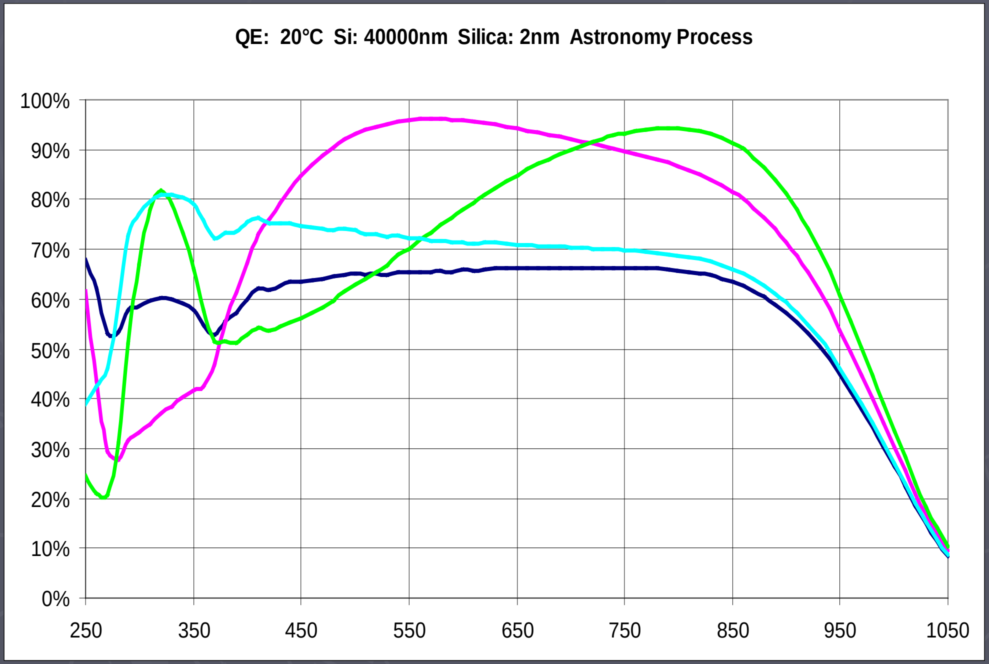
quantum efficiency of Si CCD



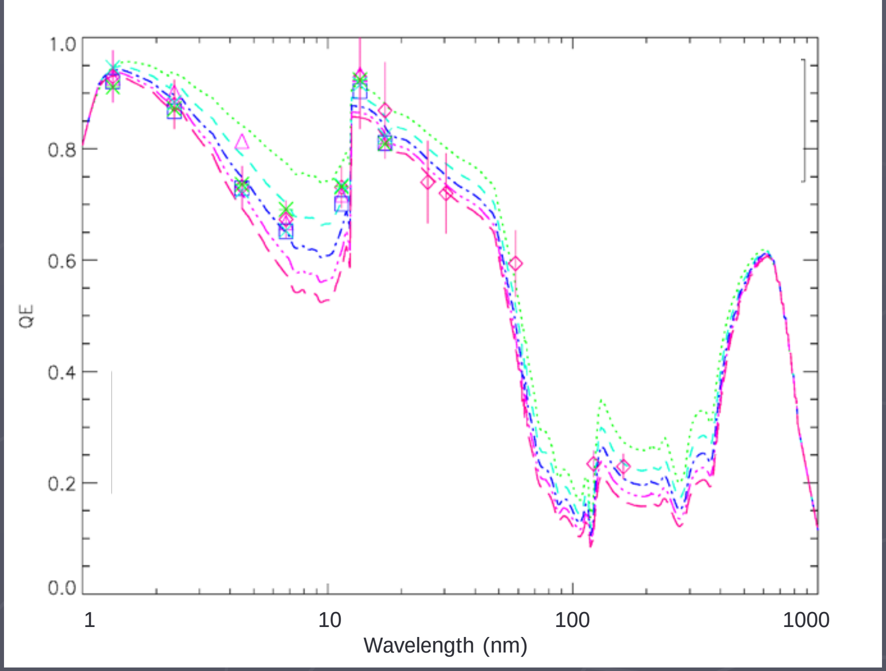
increased QE by back-side thinning

Backside thinning of CCDs and APSs

UV to NIR



VUV to soft X-ray



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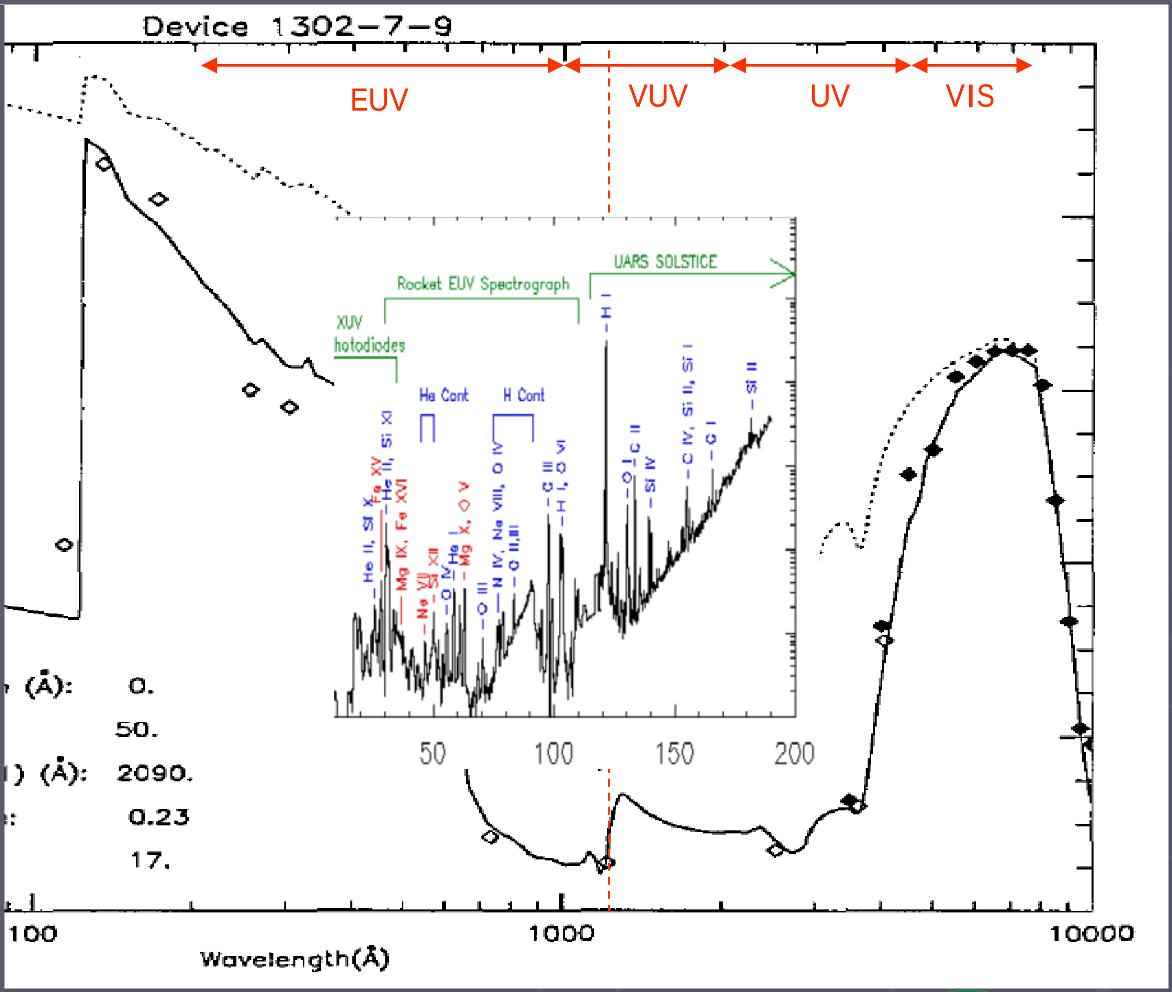
The problem of silicon in the VUV

The efficiency of silicon at 121nm (the hydrogen Lyman-Alpha line) wavelength is minimal.



Measured QE for silicon device. Dotted curve: maximum theoretical QE for 100% CCE; solid curve, best-fit semi-empirical model.

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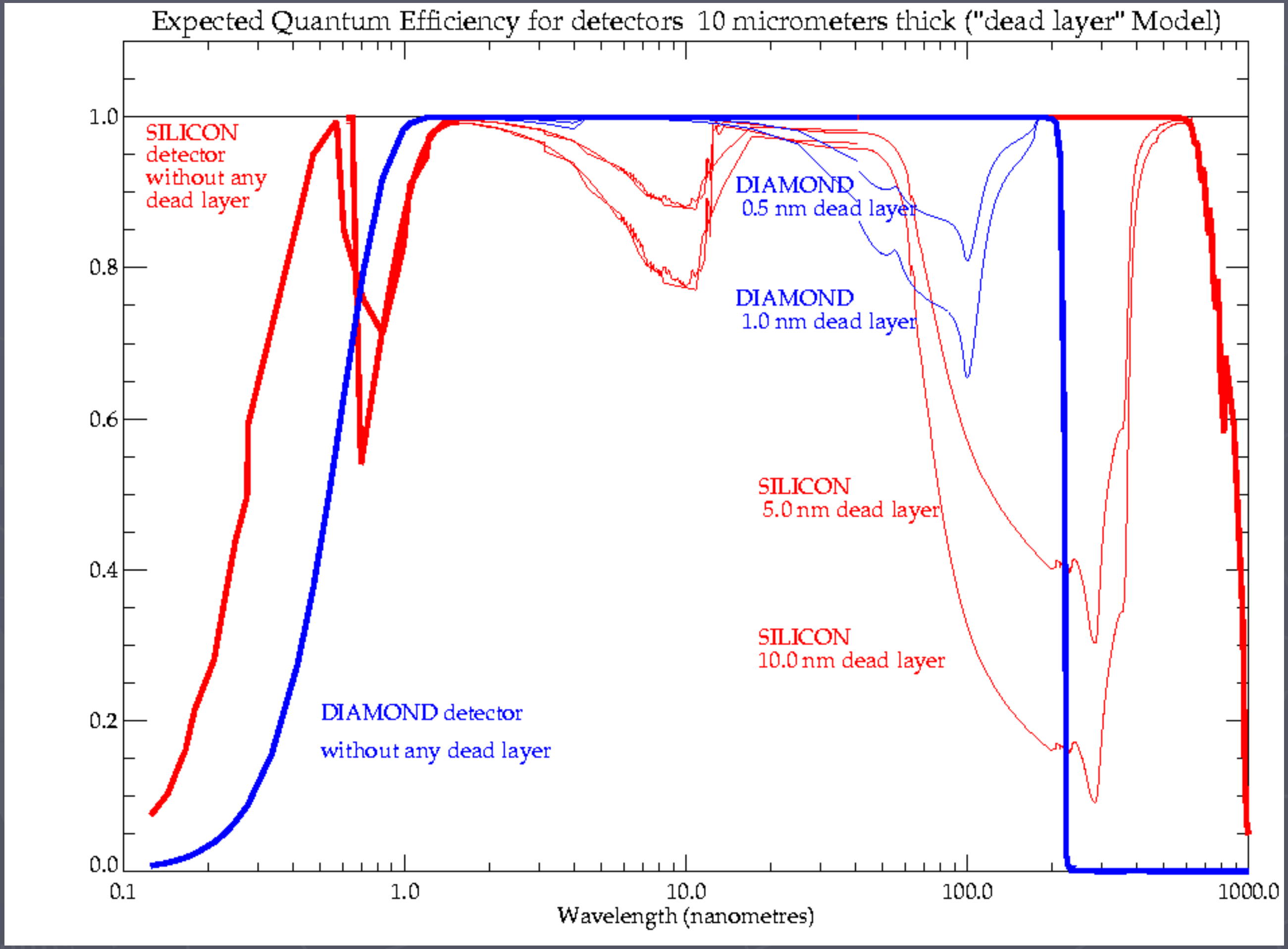
Wide band gab material detectors



Can be selcted to be solar blind

Highly efficient in the VUV and EUV

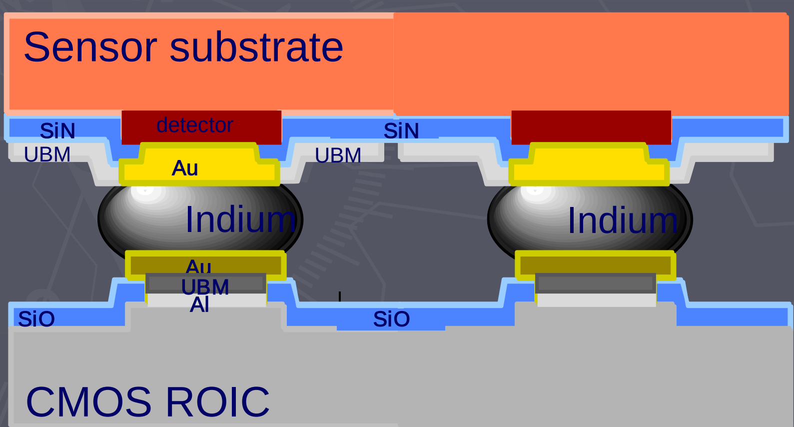
hybrid sensors

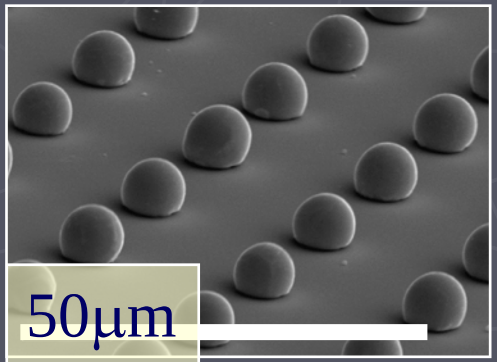
photosensitive substrate
+
silicon read-out circuit
=
hybrid sensor

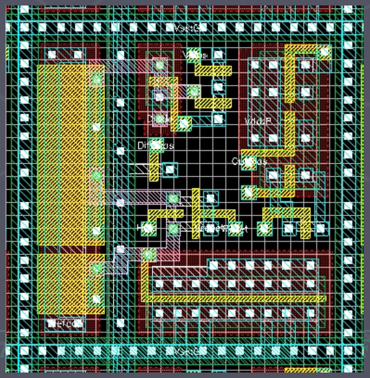
substrate:
array of photosensitive material,
e.g., HgCdTe or AlGaN or CdZnTe
IR UV X-ray

readout circuit array (ROIC):
silicon based integrated circuit (CMOS array)
with individually adressable pixels

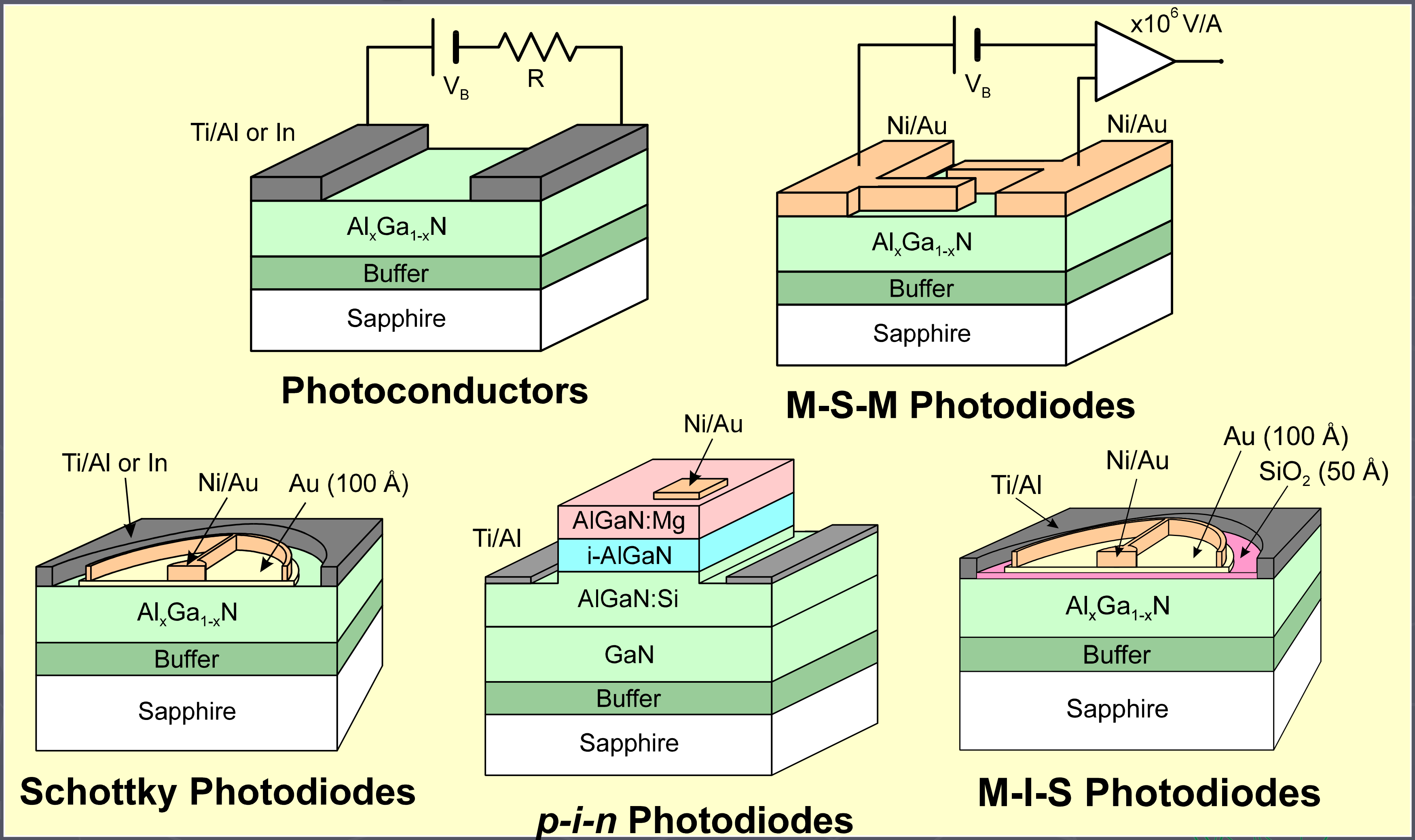
to be mated by „flip-chip technique“
via indium bump contacts





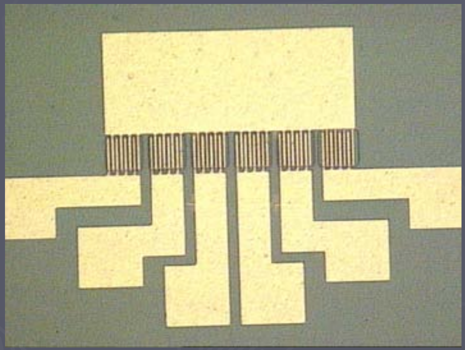


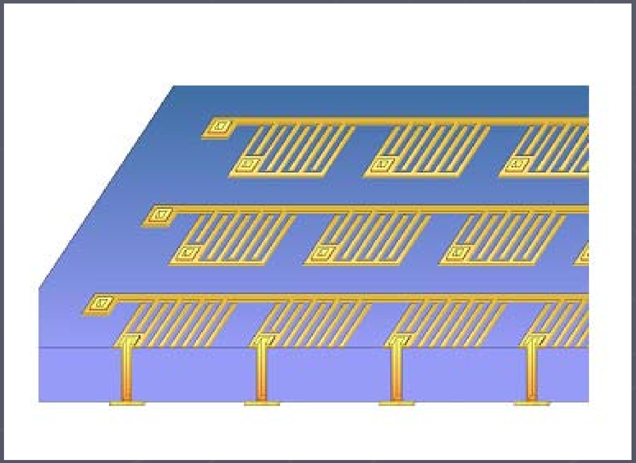
Photodetector types “pixel architecture”

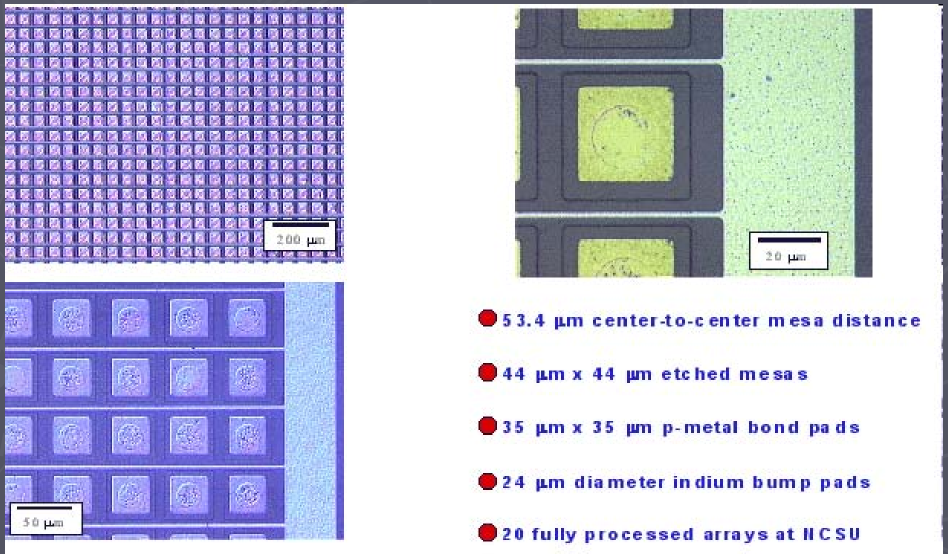


imaging arrays of Wide Band Gap material

build a micro-array of photoconductors

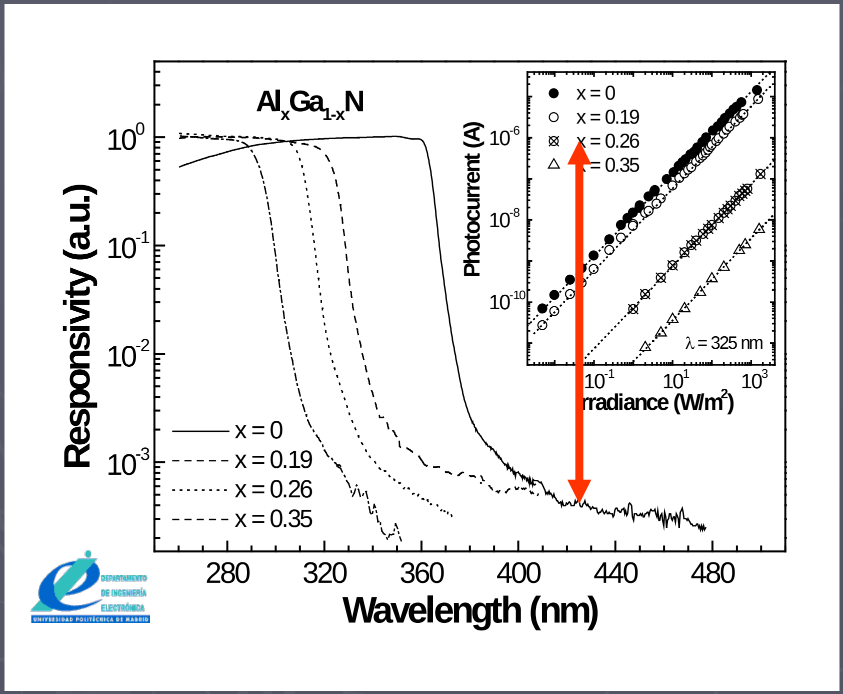






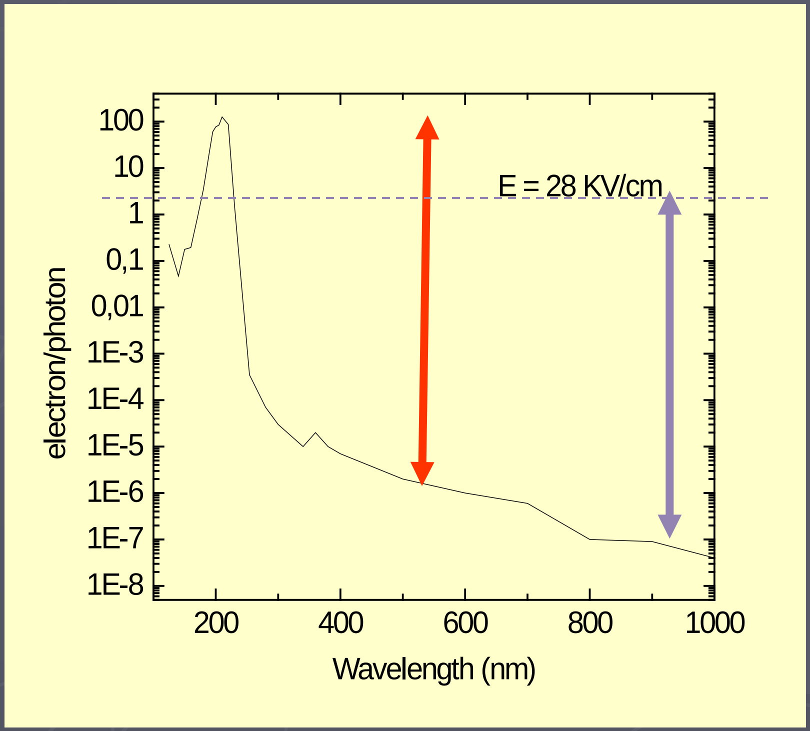
- 53.4 µm center-to-center mesa distance
- 44 µm x 44 µm etched mesas
- 35 µm x 35 µm p-metal bond pads
- 24 µm diameter indium bump pads
- 20 fully processed arrays at NCSU

Solar-blindness of present WBGS detectors



Pau *et al.* 2003.

Nitride



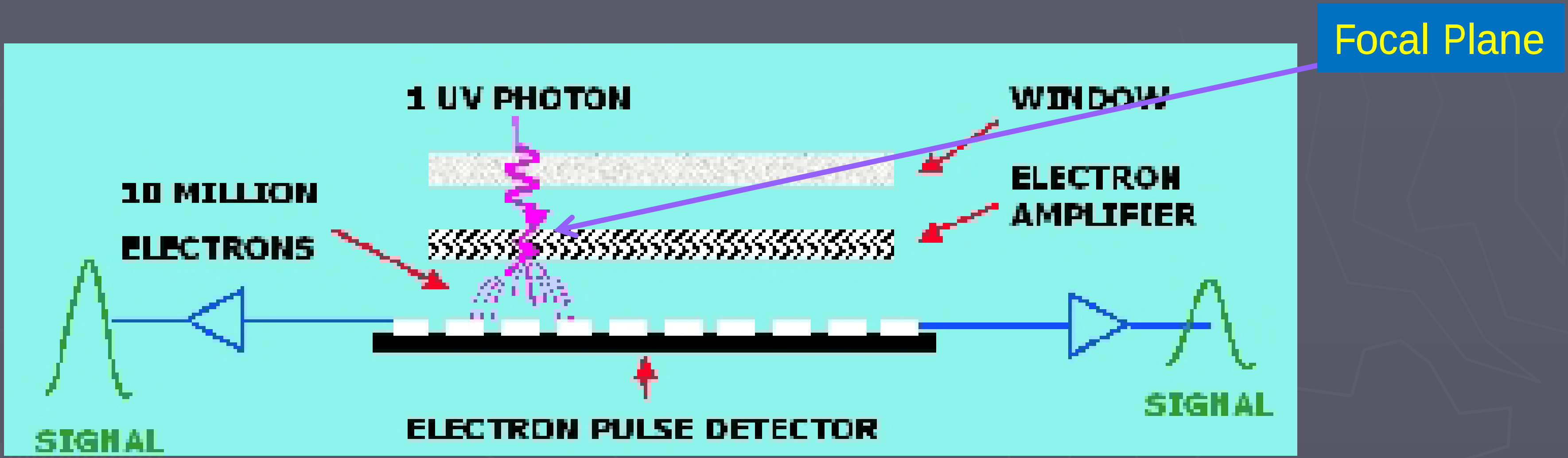
Diamond

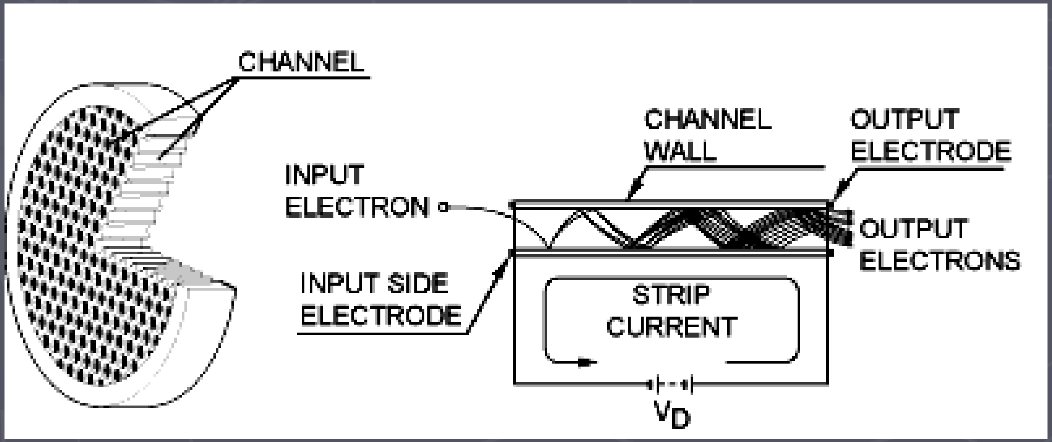
Pace *et al.* 2000.

- ✓ less filters are needed to suppress the visible-NIR continuum
- ✓ negligible dark signal at room temperature
- ✓ no cooling required

Multichannel plate detectors

(photoemission detectors, photon counting detectors)





each MCP operates at
a gain of ~100 electrons

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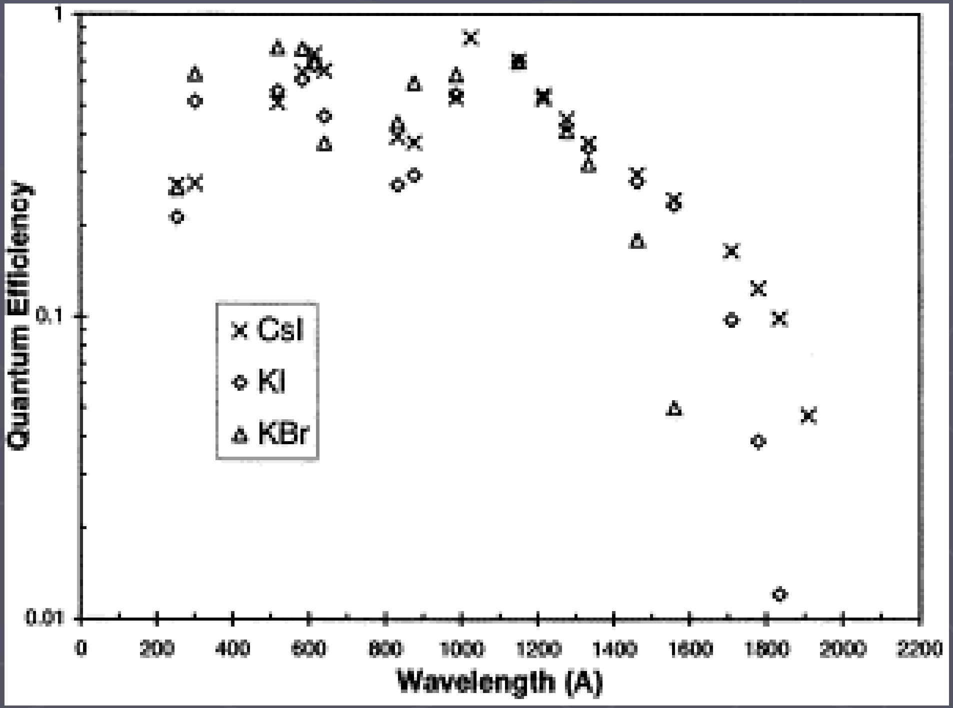
photocathodes on MCPs

• Multichannel plates are „wide band gap“ detectors.
• Photocathode materials with different band gap energies may be applied.
• Alkali halide photocathodes increase the quantum efficiency in selected wavelength ranges: CsI, CsCl, LiF, KCl, KBr, RbI, multi-alkali, etc.



visible blindness

These are also wide band gap materials

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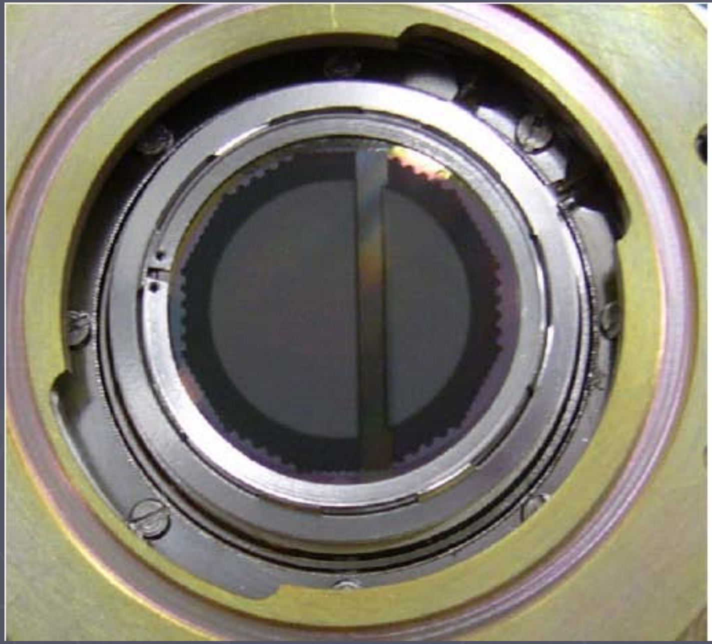
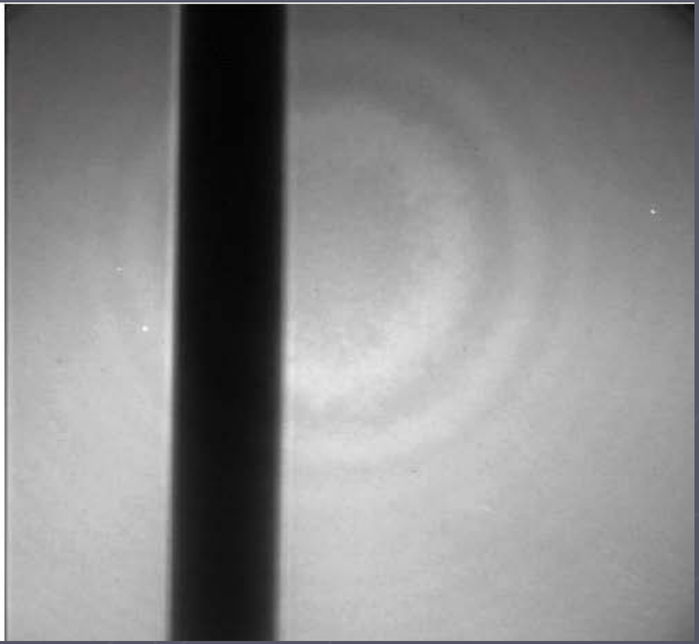
Selective photocathode

Photocathode on front MCP



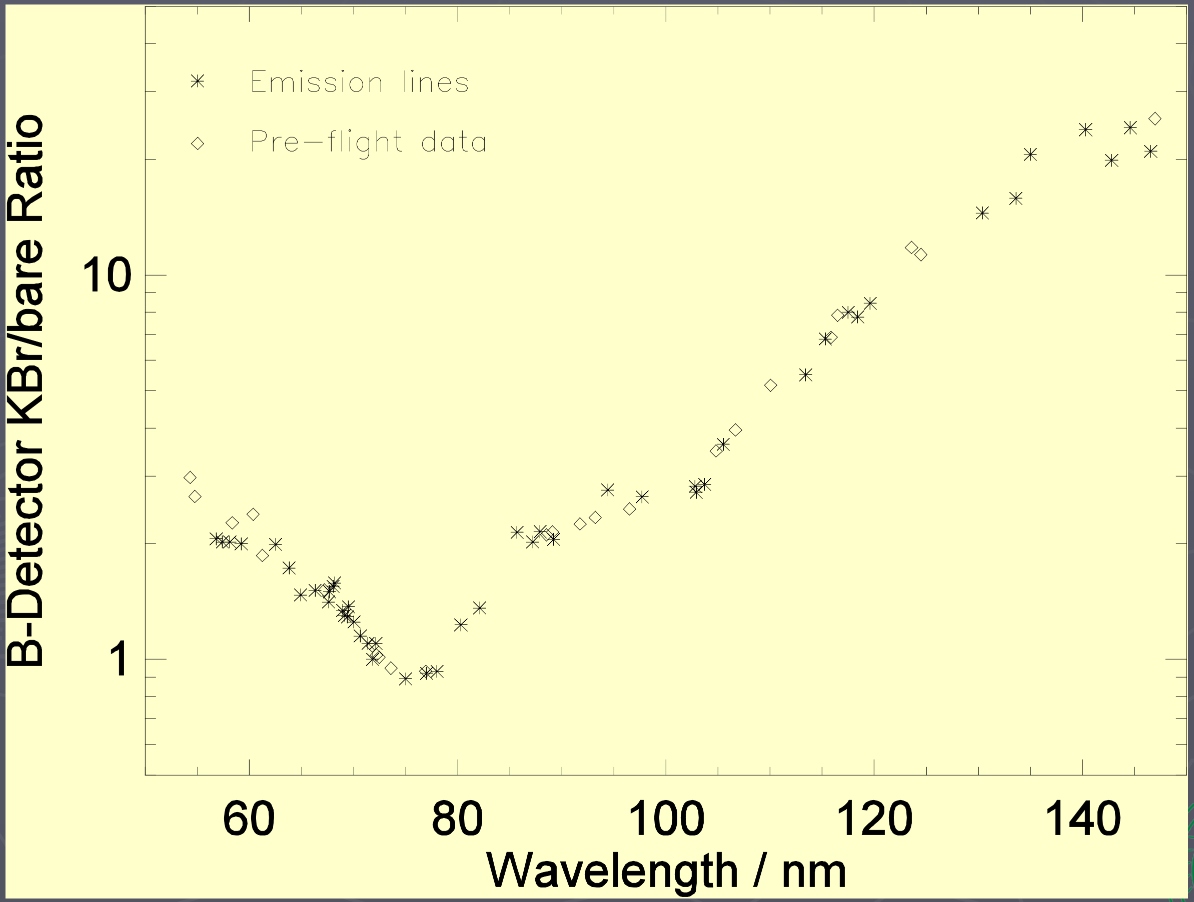
test image at 121.6 nm



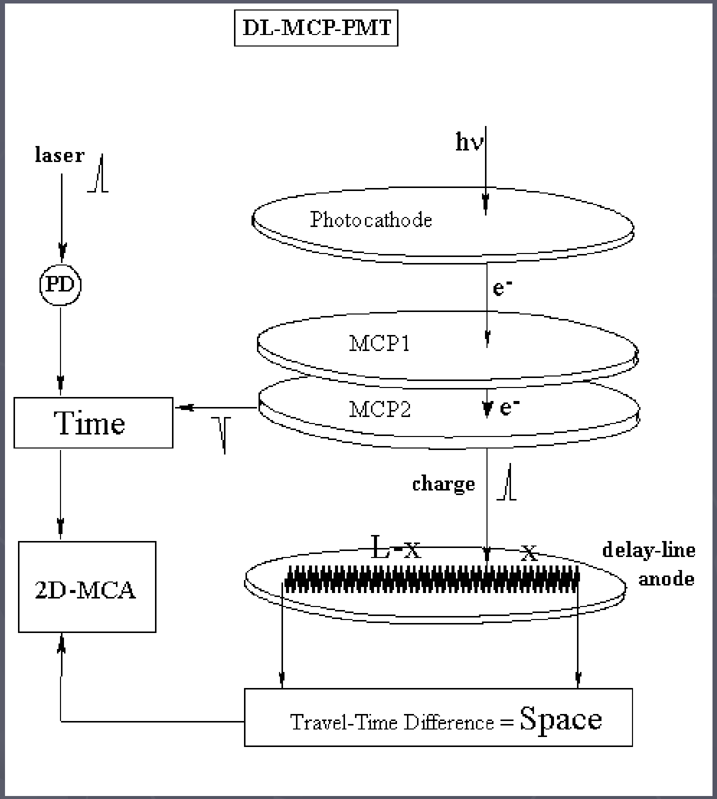
- simple technology:
  deposition by vacuum evaporation even after final assembly!

photocathodes on MCPs

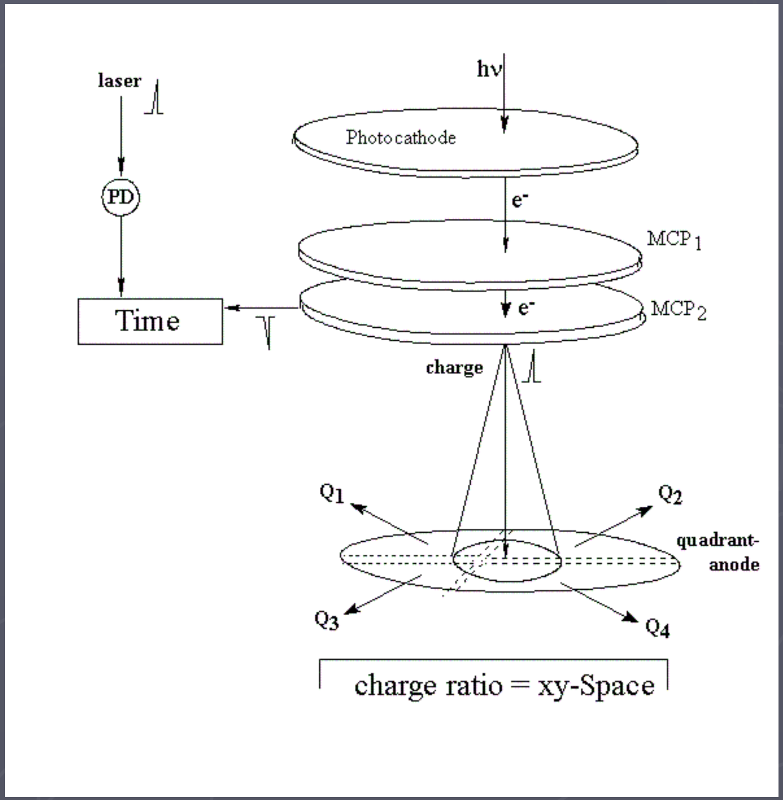
SUMER KBr photocathode



Readout of microchannel plate detectors



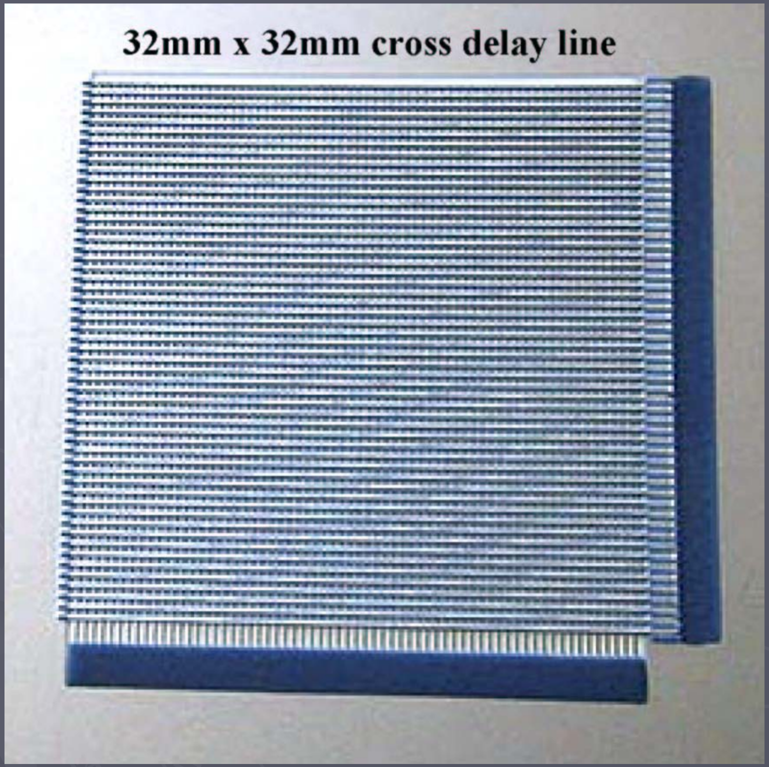
Cross delay line anode + time to digital converter



Cross strip anode + charge ratio centroiding

Udo Schühle
IMPRS Oct. 2010

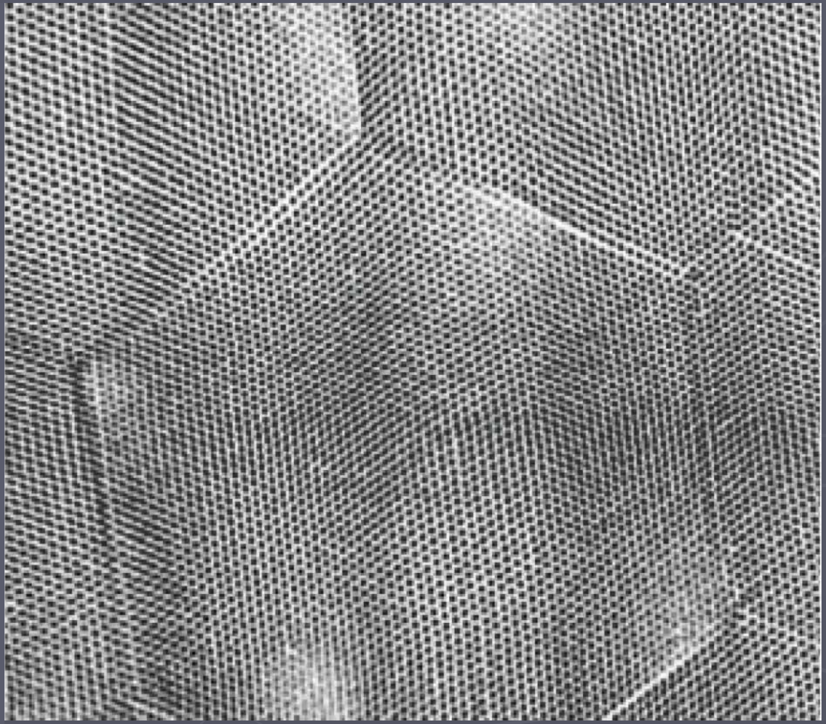
Anode design options



- Wedge and strip anode
- Cross Delay line anode
- Cross strip anode
- CCD sensor
- CMOS APS sensor

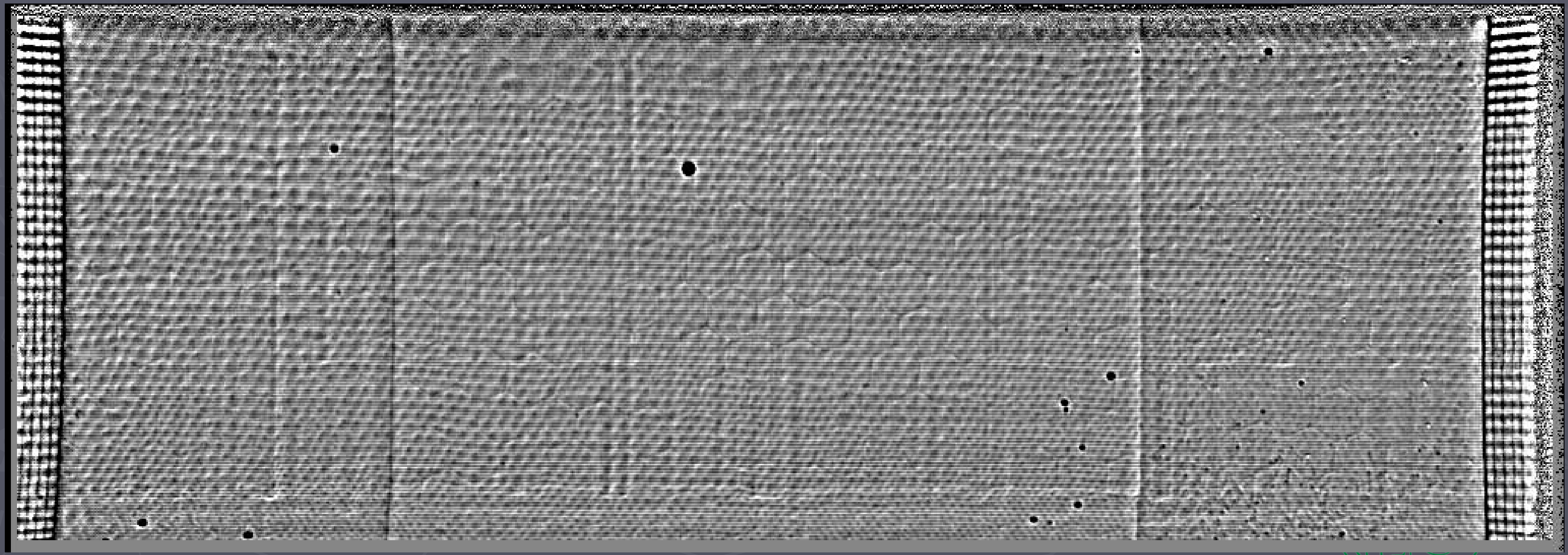
Flatfield pattern & resolution

- Pore structure limiting the resolution
- Multifiber bundle boundaries
- Moire pattern by superposition of MCPs



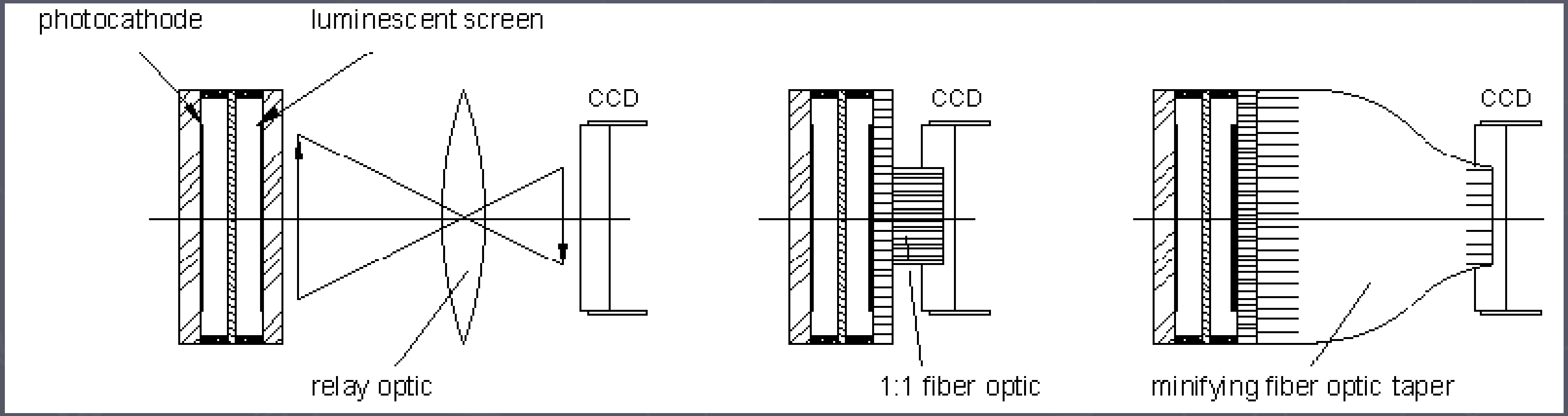
Example: flatfield of SUMER XDL detector

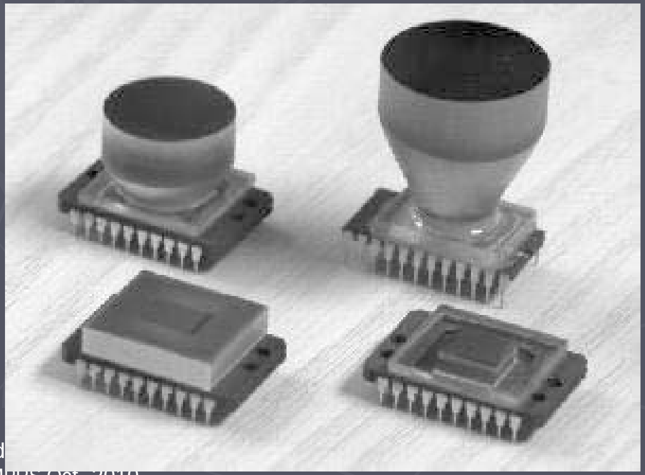
- Image geometric distortion
- ADC nonlinearity
- Multifiber bundles (hexagonal)
- Moire pattern (from 3 MCPs)
- Dead pores



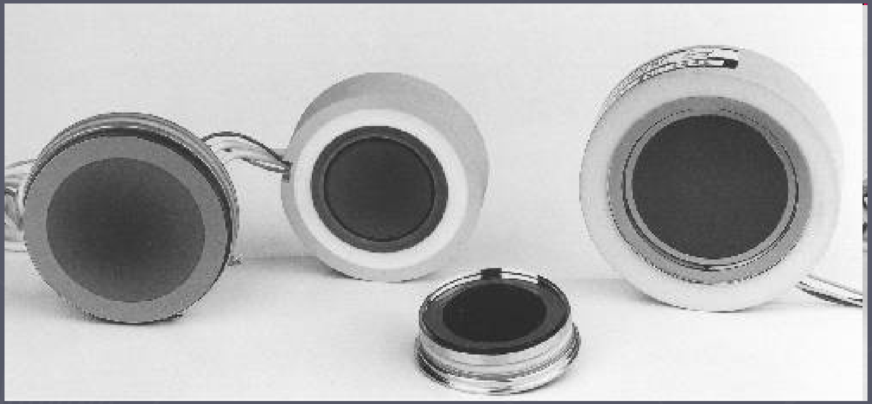
Intensified CCD

MCP coupled to CCD via lens or fiber-optic taper

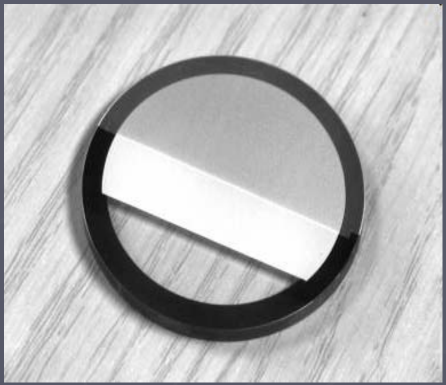




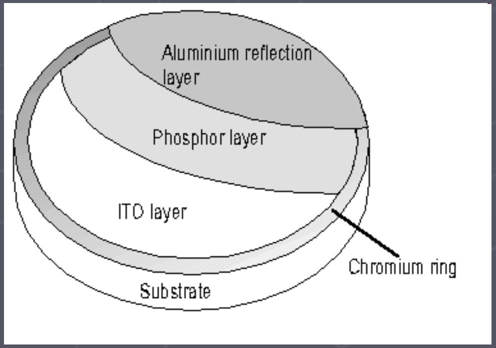
Microchannel plate intensifiers



MCP based intensifiers



Phosphor screen anode



Phosphor screen anode on fiber optic coupler

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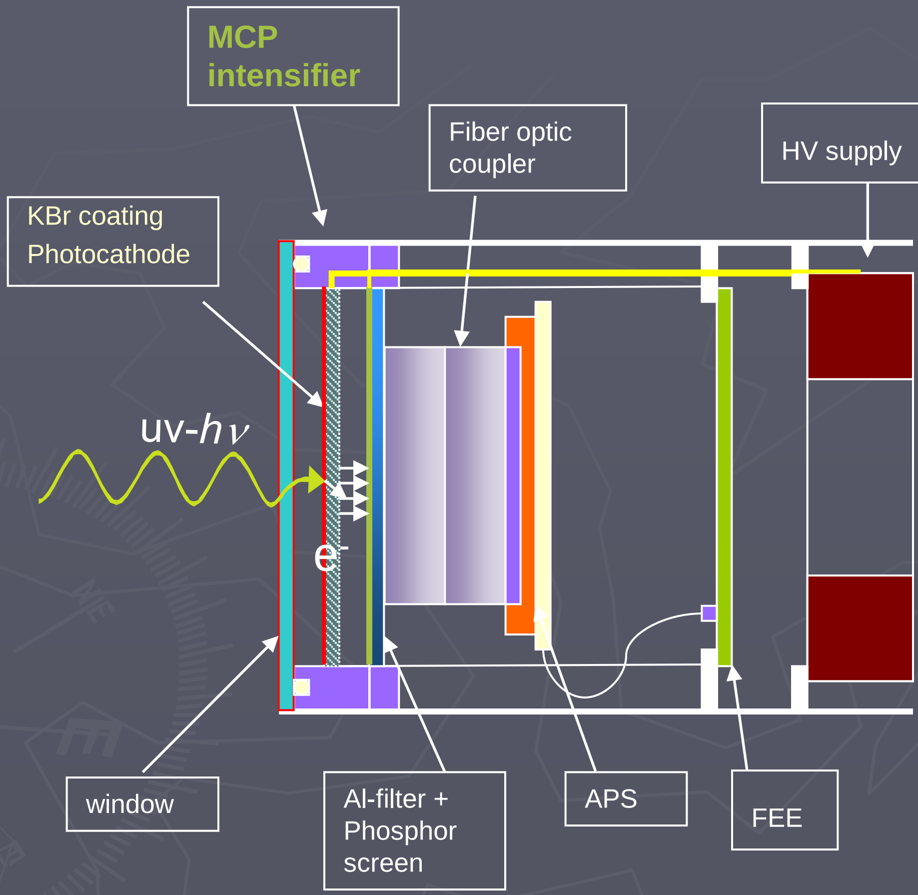
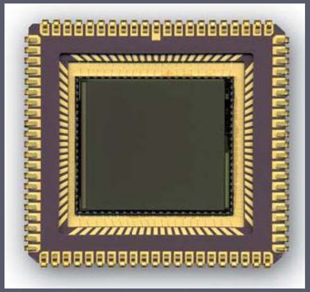
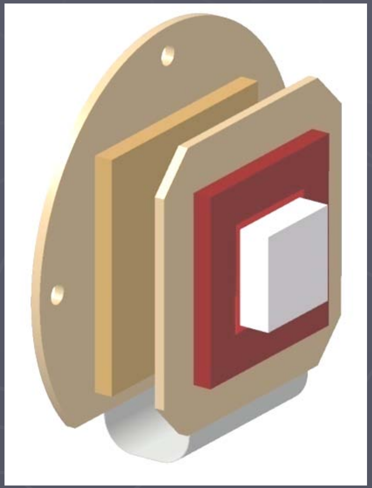
Solar-blind intensified imaging array detector

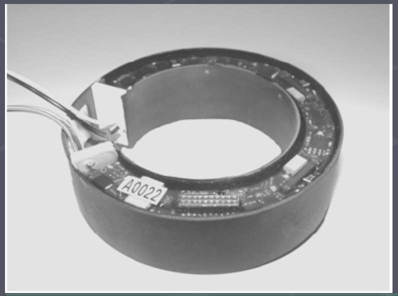
= MCP intensifier coupled with a pixel sensor







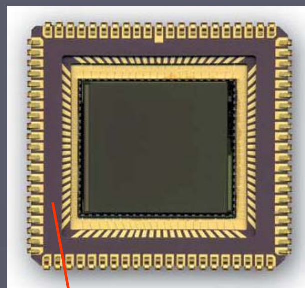
APS sensor array on PCB

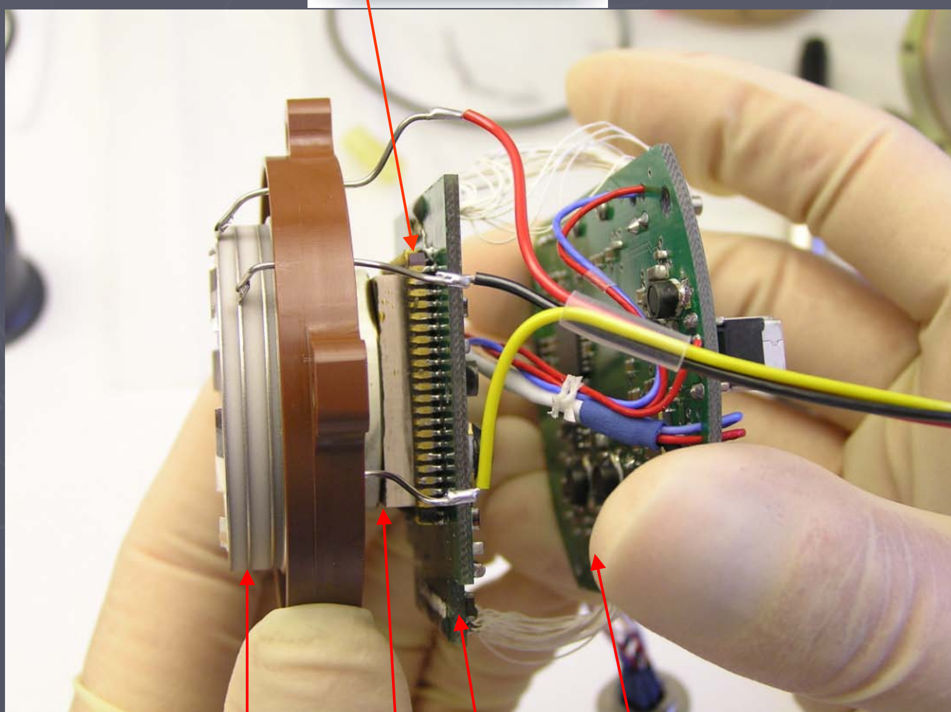


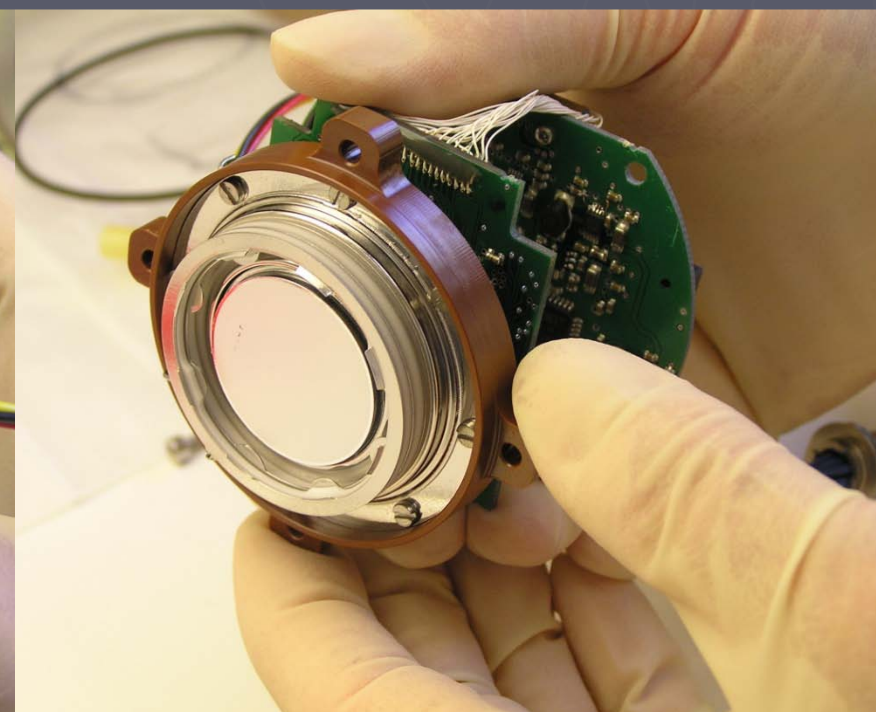
HV power supply

Intensified APS

STAR 1000
visible CMOS-APS sensor







MCP stack

fiber optic blocks

APS sensor board

FEE board

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Fiber optic coupling

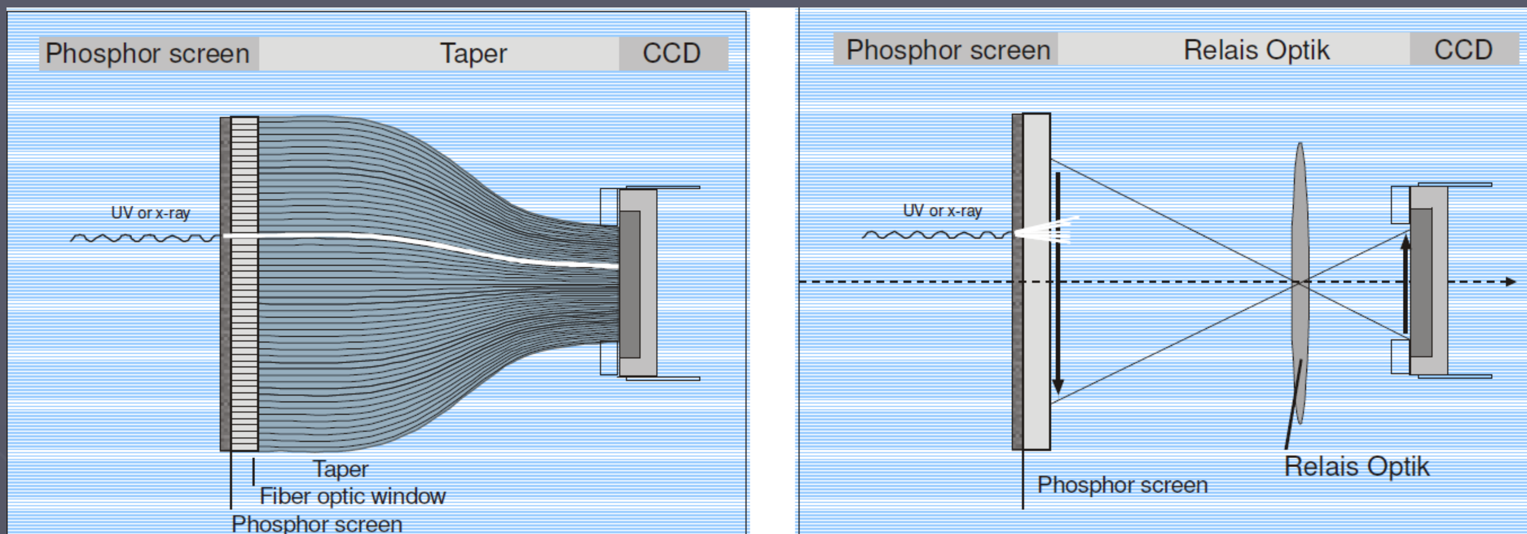


Image intensifier can be coupled to any sensor (CCD or APS) on the market

Fiber optic tapers

Typical Taper Specifications	
Glass Type	SCHOTT 24 Glass
Element Size (μm)	6, 10, 18, 25
Numerical Aperture – small end	1.0
Stray Light Control (EMA)	Available with or without EMA
Collimated Transmission White Light for Base Material: 3mm thick 10mm thick	 85% 44%
Coefficient of Thermal Expansion (x10 –7 / °C)	68
Phosphor Compatible	Yes

Fused Fiber Optic Tapers by Schott

Image Minification or Magnification

typical de-magnfication of 3:1 is standard (5:1 possible)

http://www.schott.com/lightingimaging/english/products/healthcare/imagingfiberoptics/fusedcomponents/tapers.html

Performance of the sensor array with readout electronics (without intensifier)

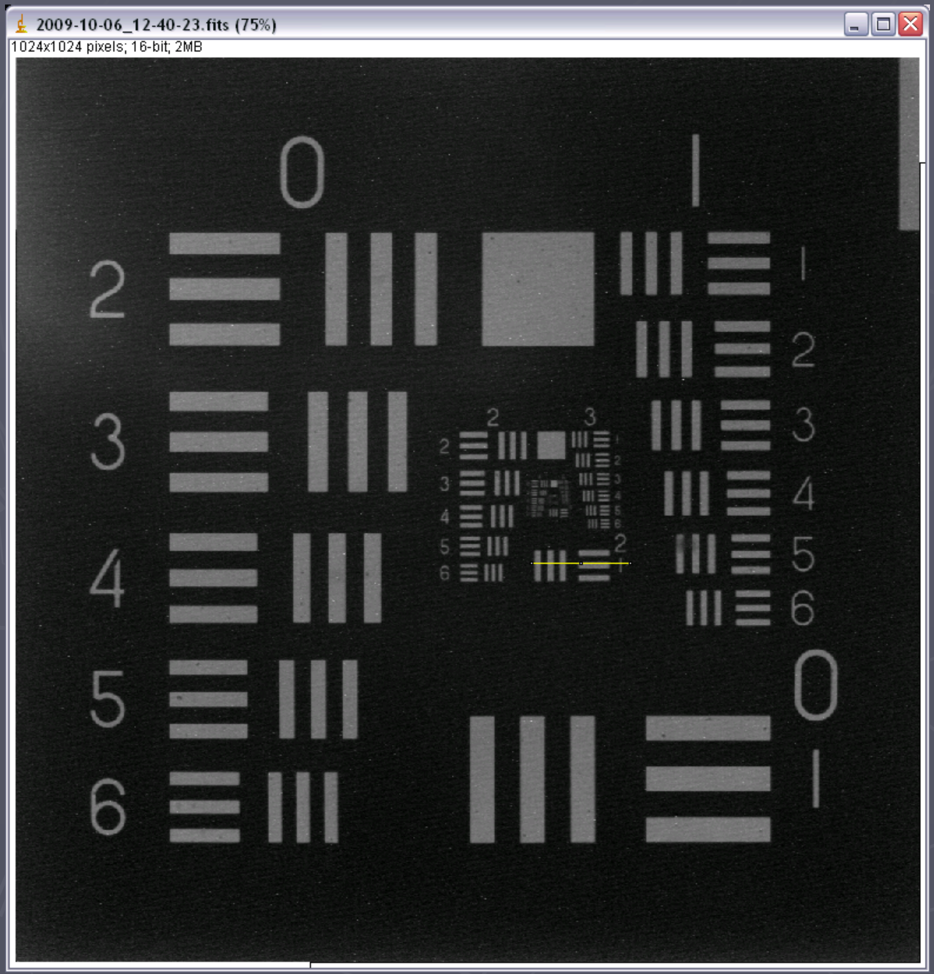
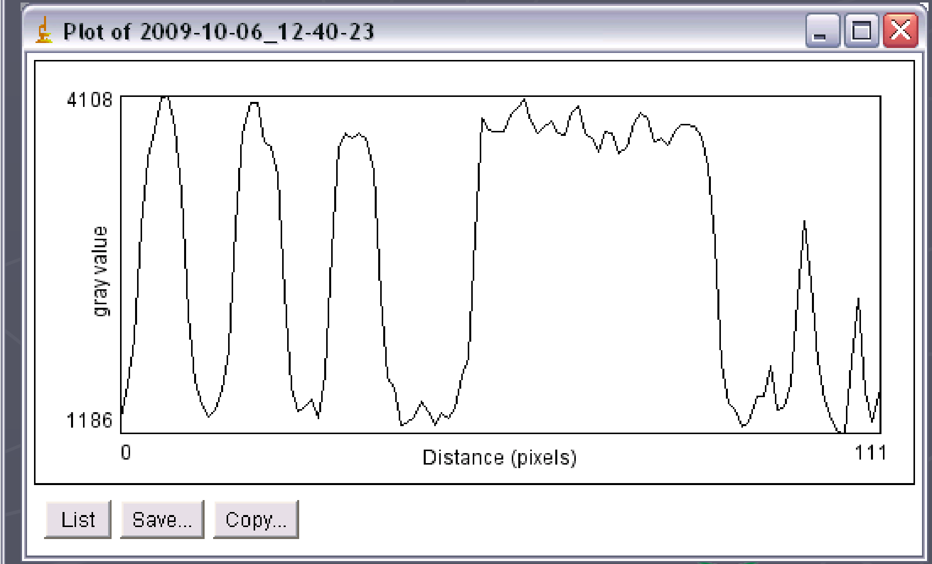
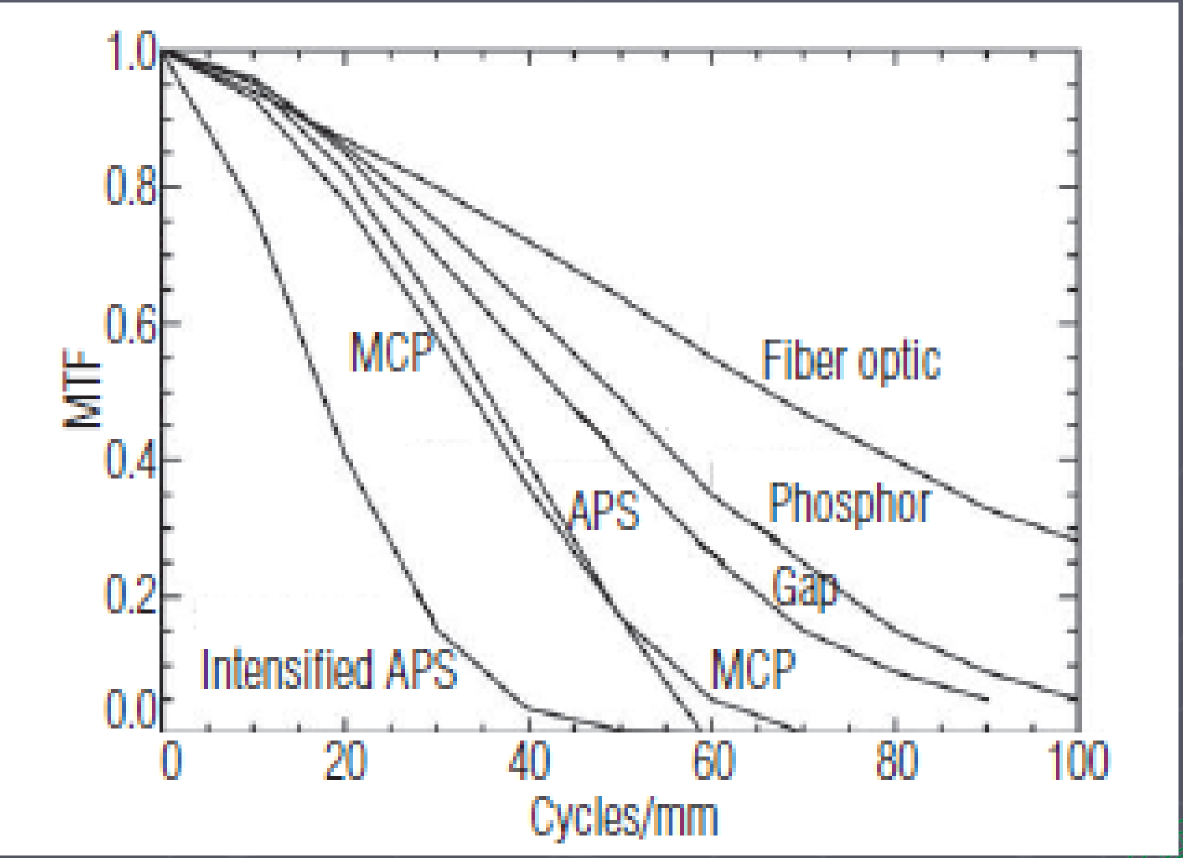


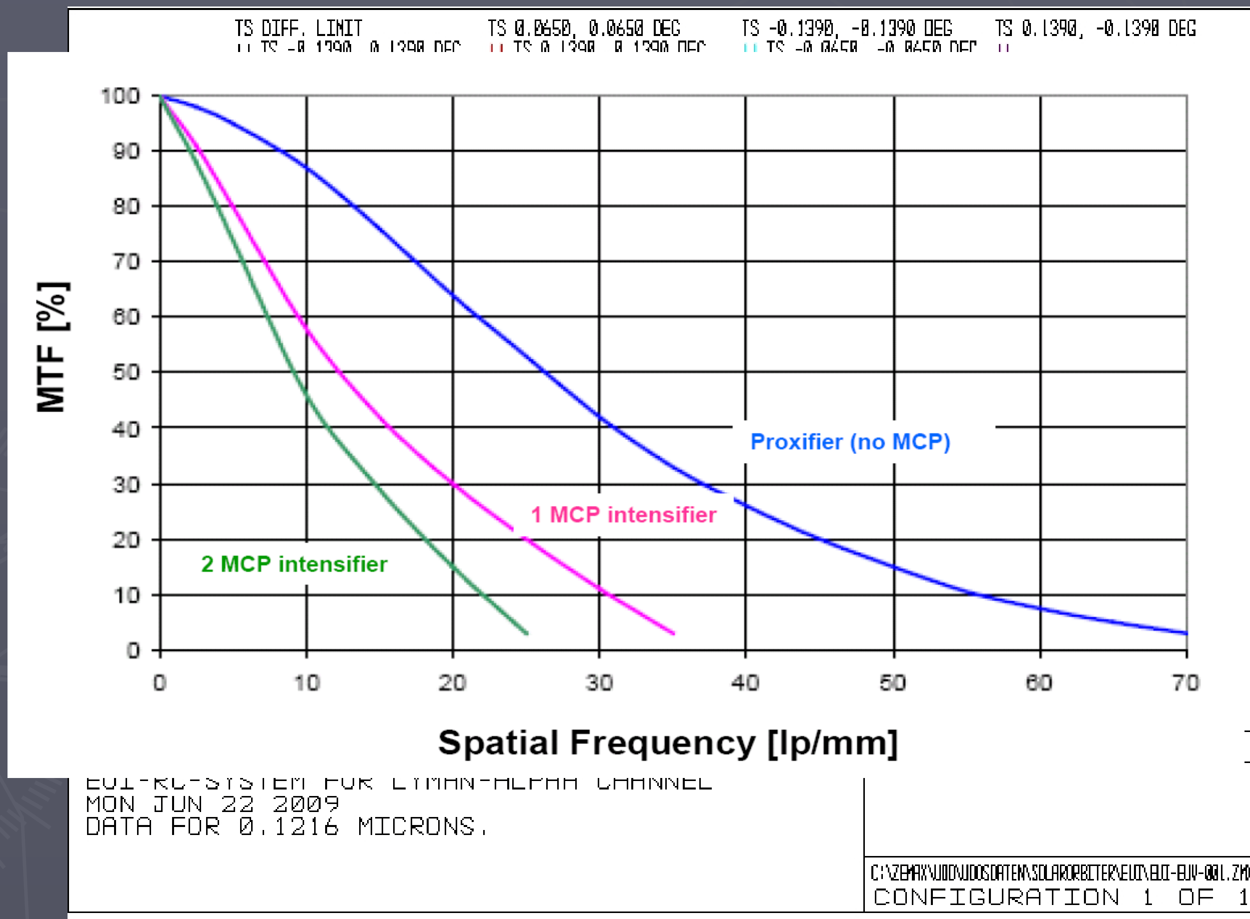
Image of a target. The yellow line is the location of the profile shown below



Resolution limitations of intensifier



Resolution of the optical system adapted to I-APS detector



optical transfer function match telescope with detector

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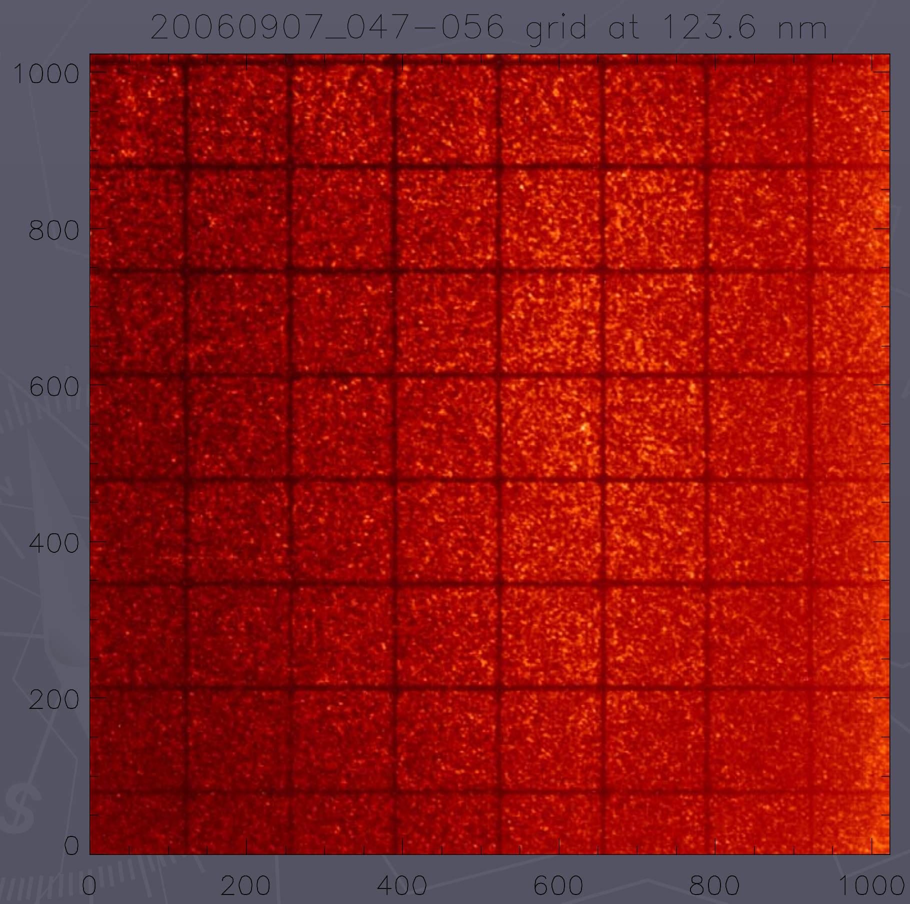
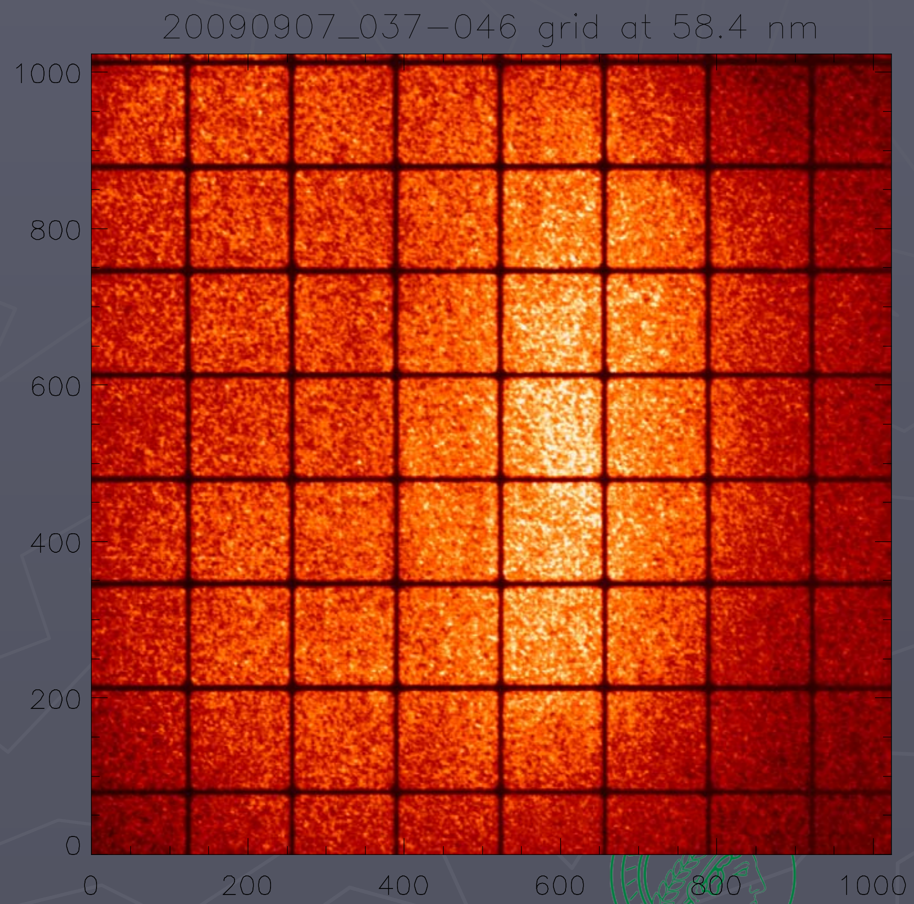
test images with extreme UV lamp



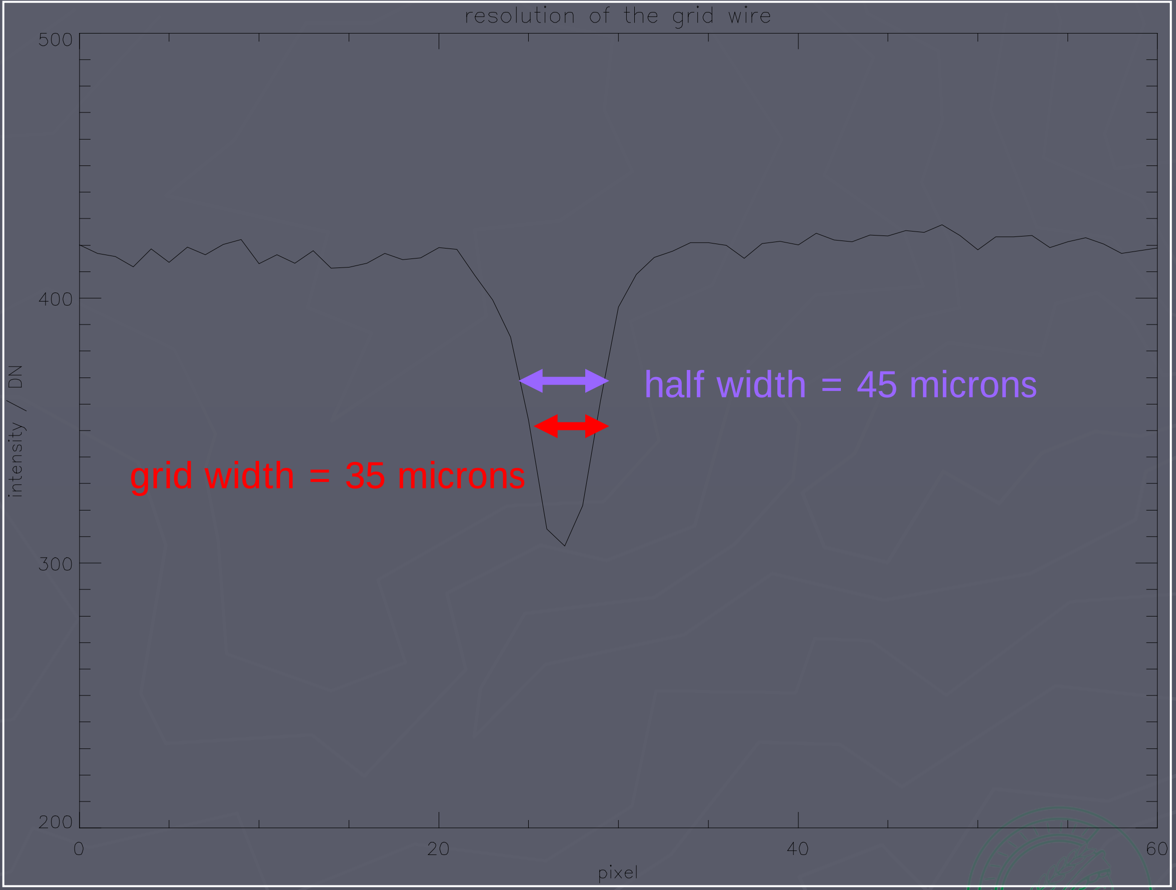
grid mask image at 123.6 nm



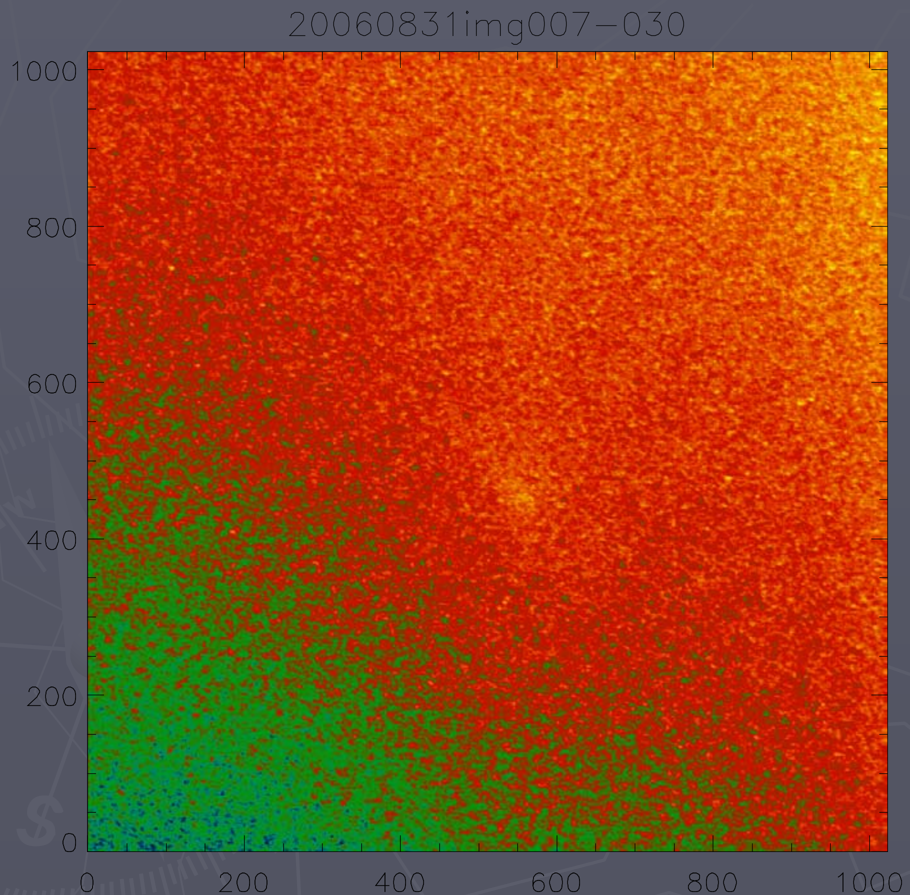
grid mask image at 58.4 nm

Resolution test with I-APS Detector

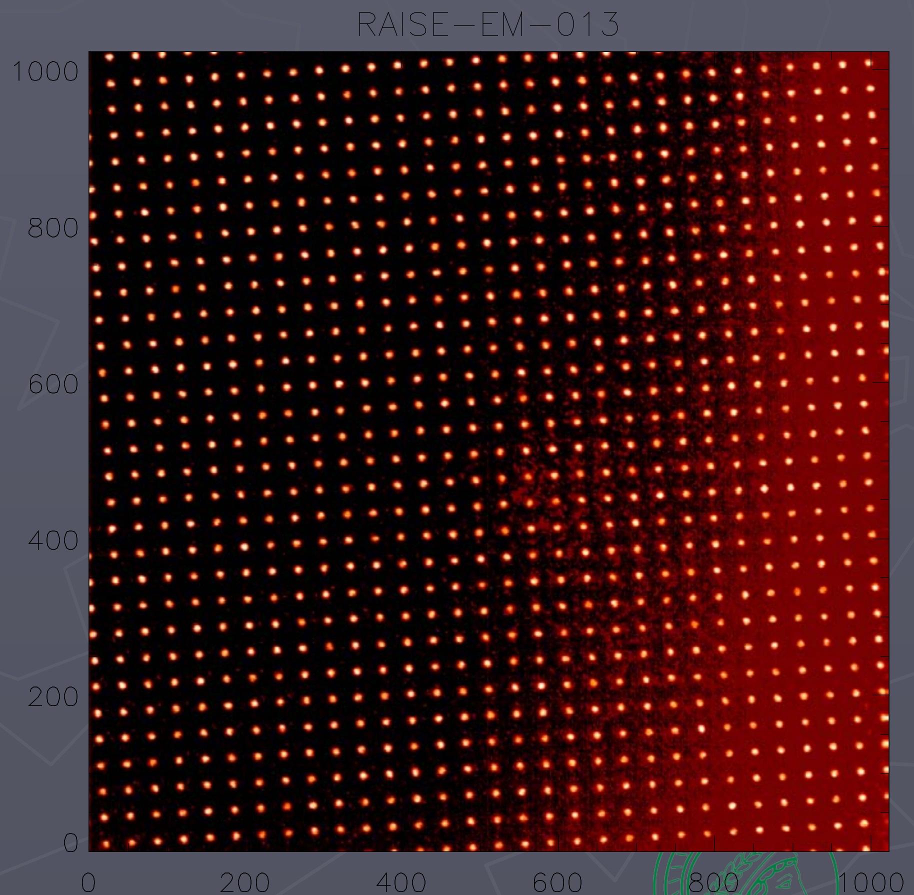
- imaging a wire grid
- 35 μm wire width
- 12 μm pore MCPs
- 15 μm APS pixels



Performance testing with Lyman-α lamp



quasi flat image at 121.6 nm



pinhole mask image

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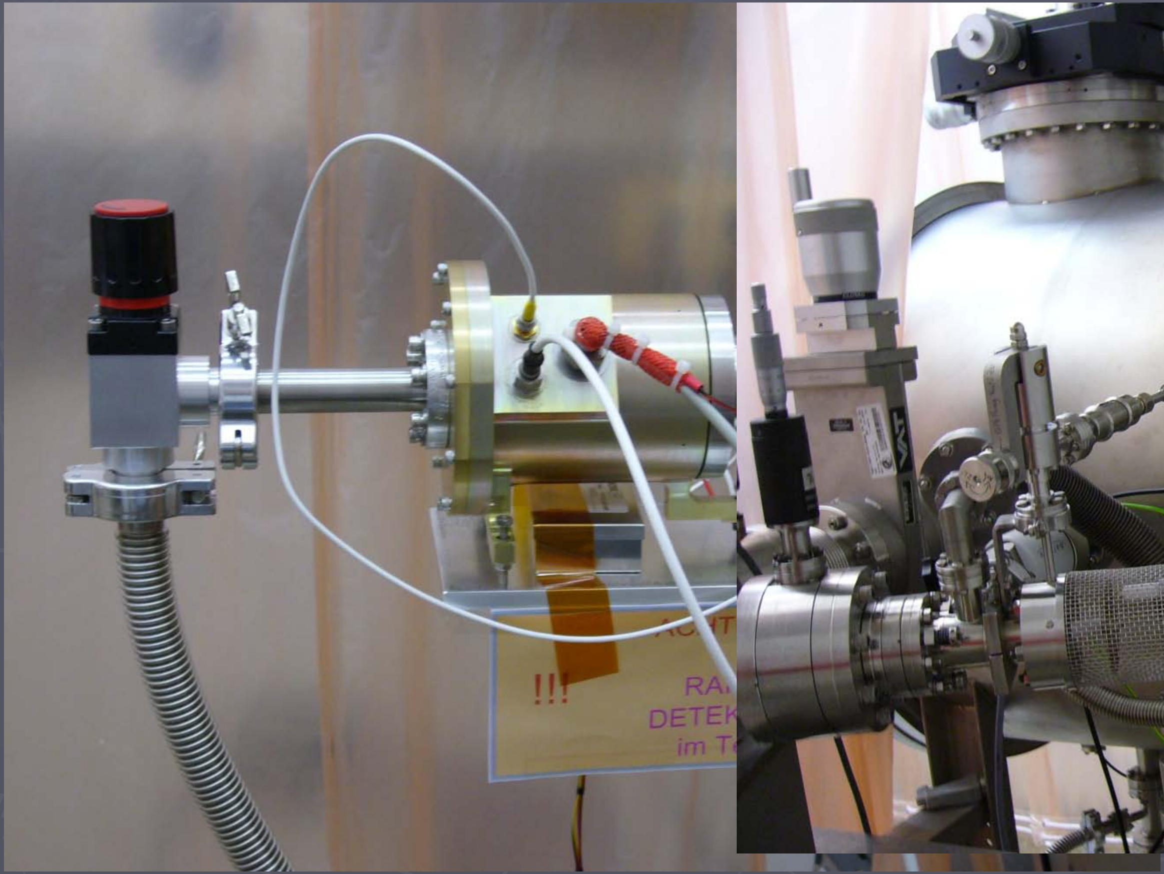
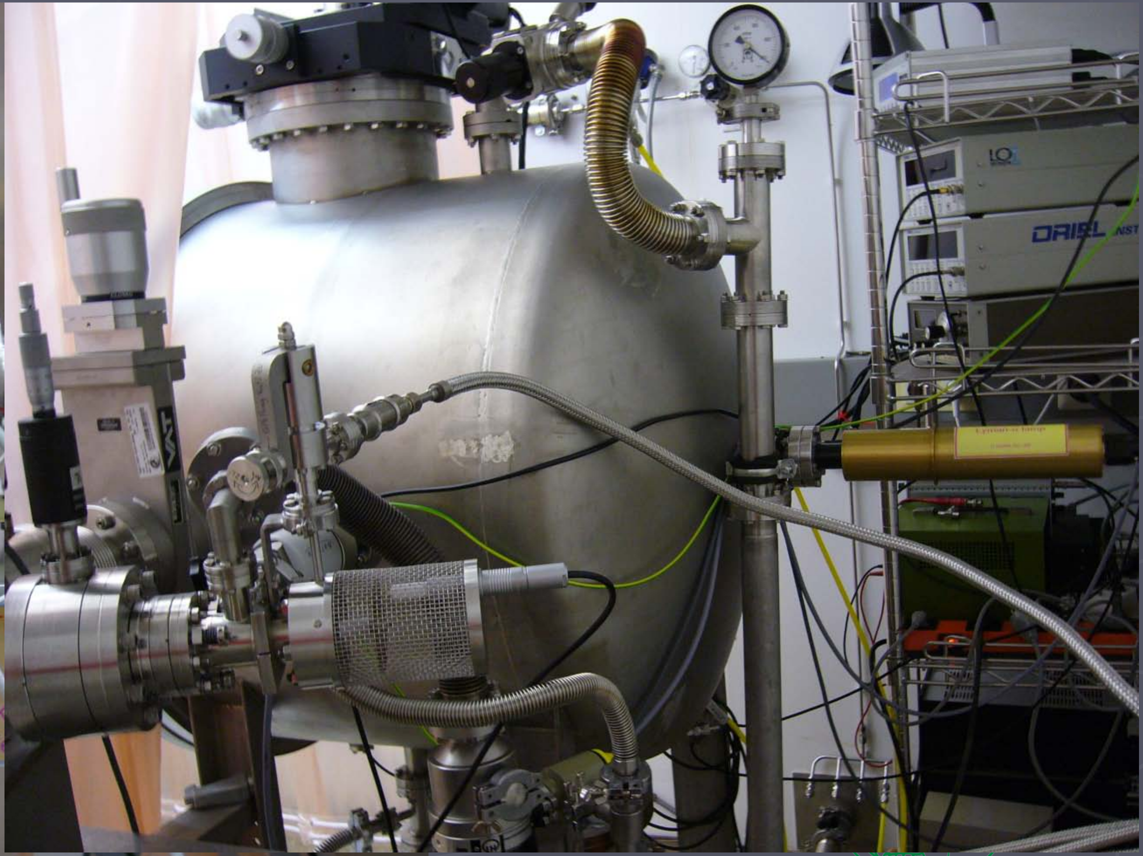
perfomance test with Lyman-α lamp and extreme UV lamp

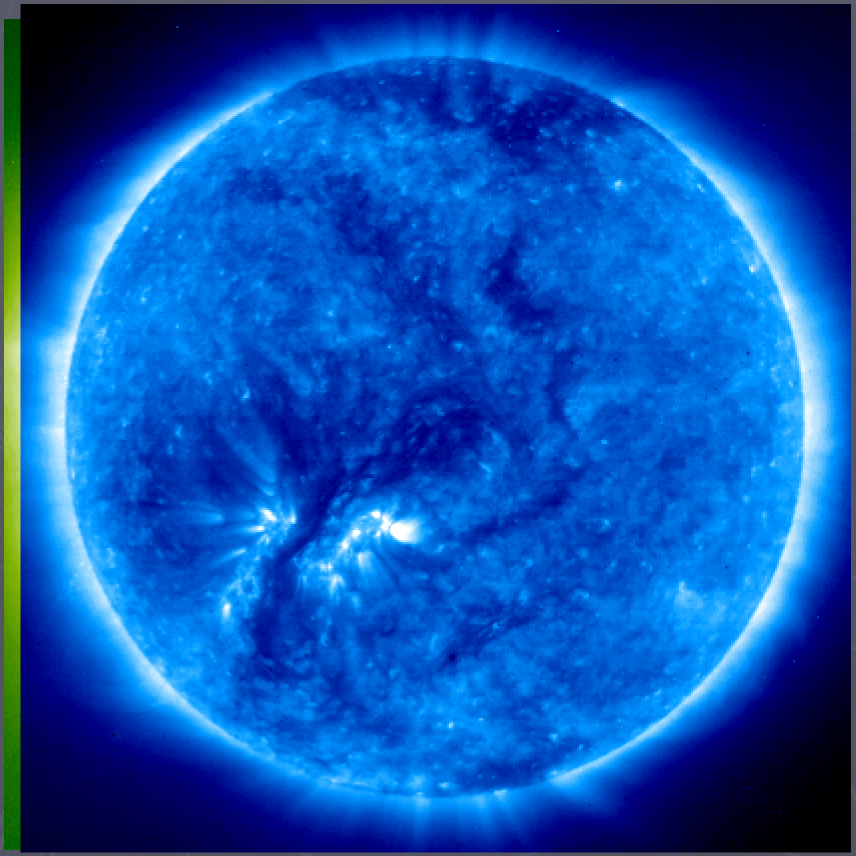
(tests possible under vacuum only!)



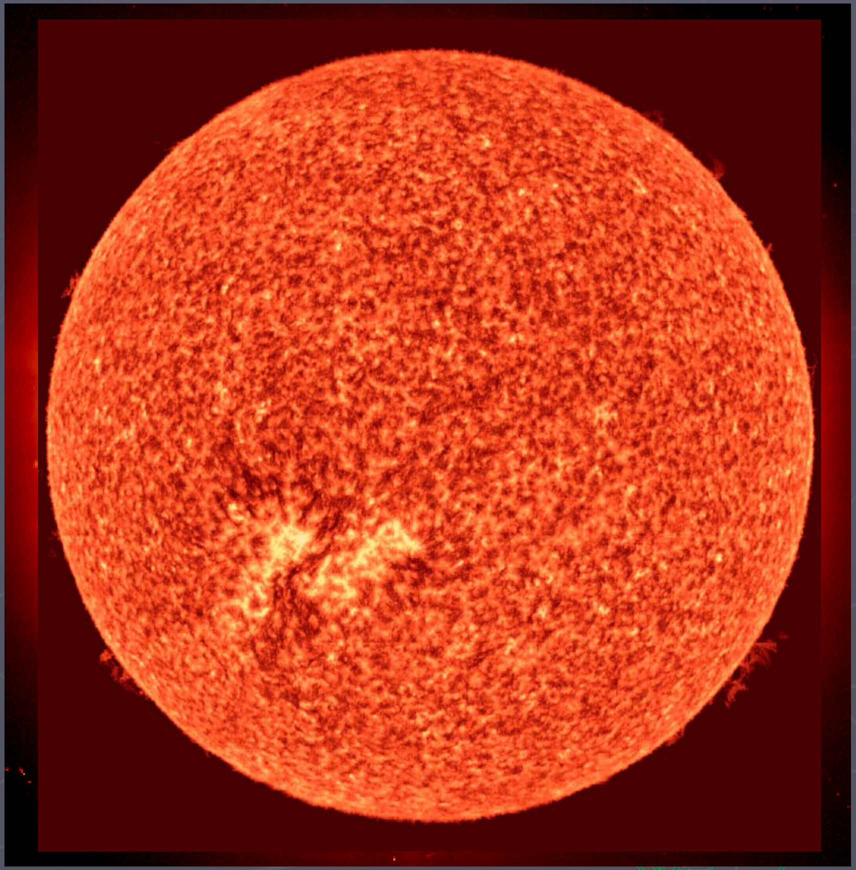


The Sun on 24 September 1996

Fe IX/X 17.2 nm
(SOHO/EIT)



H I Lyman-ε
(SOHO/SUMER)



Who is doing what?

Industial company (e.g., Proxitronic):

- Intensifier
- Fiber optic block
- Coupling of intensifier with fiber optic block and image sensor

MPS:

- Coating of MCP photokathode
- Front-end readout electronics
- Mechanical housing
- Space qualification (vibration, thermal vac, thermal balance)
- Performance characterization
- Calibration

Performance Parameters (1)

- Array size (pixel size and # of pixels)
- Frame rate (speed, determines image cadence)
- Radiation hardness
- Power requirements
- Technology
- Price (may be 0.5 million €)

Performance Parameters (2)

- Spectral range
- Radiometric response (QE)
- Flat field response (uniformity)
- Linearity of response
- Dark current / dark signal (need cold T)
- Noise (dark noise, read-out noise, photon noise)
- Dynamic range (full well capacity – dark signal)
- CTE = Charge Transfer Efficiency (for CCDs)