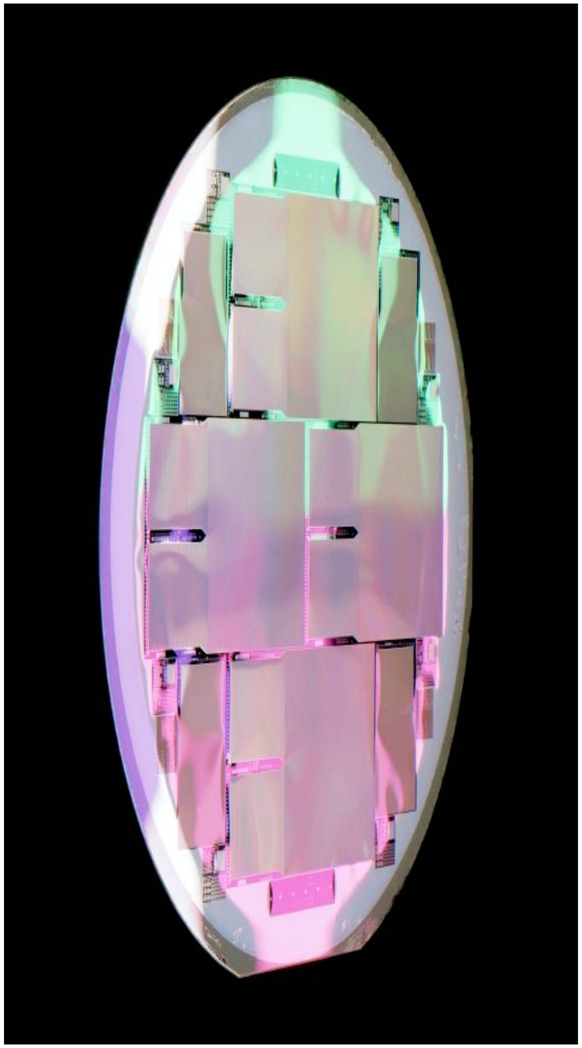


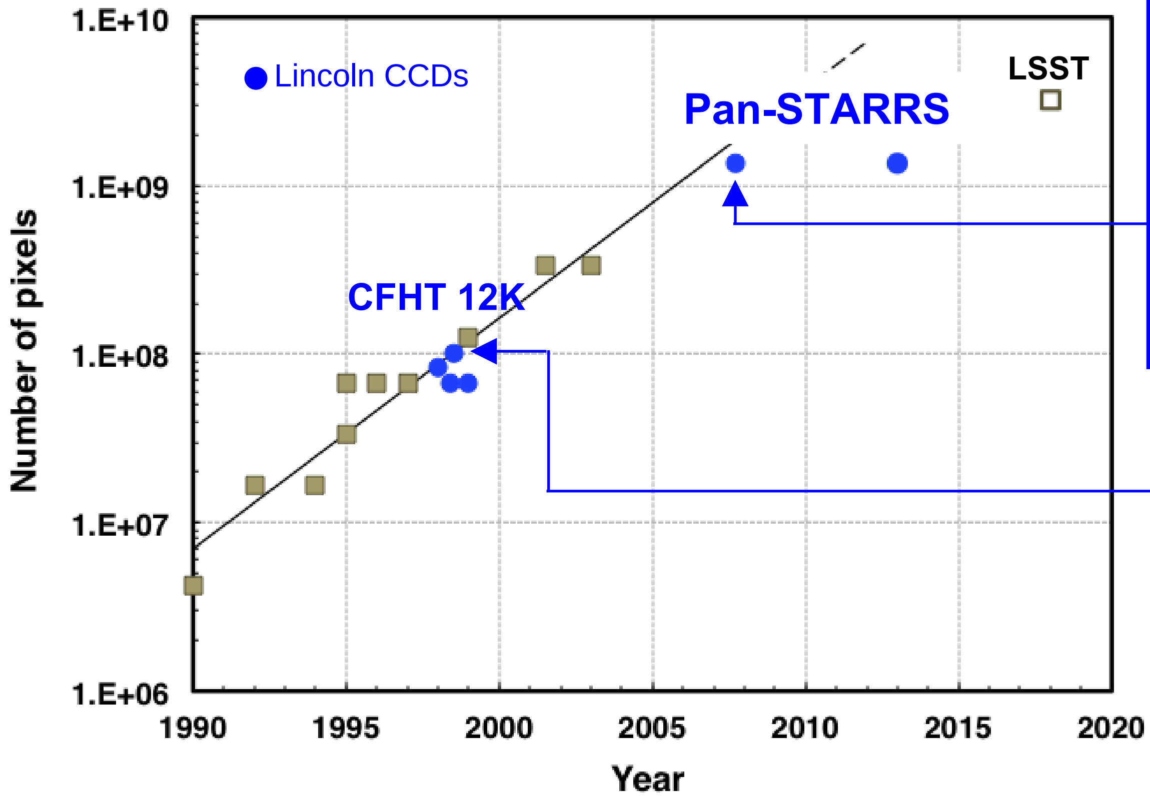
Advanced CCD and CMOS Image Sensor Technology at MIT Lincoln Laboratory

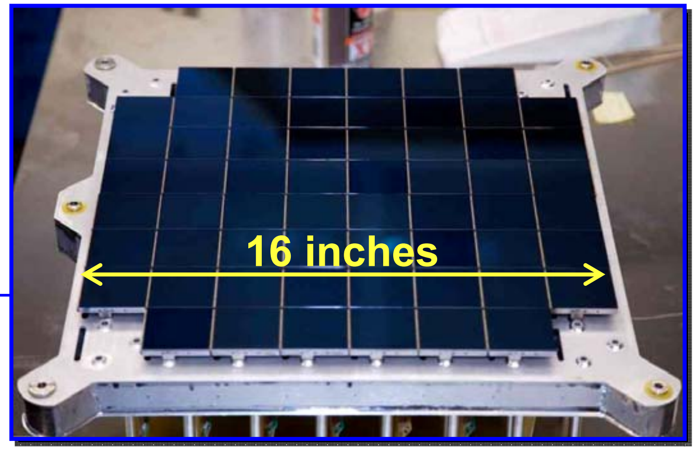
Vyshnavi Suntharalingam
American Physical Society March Meeting

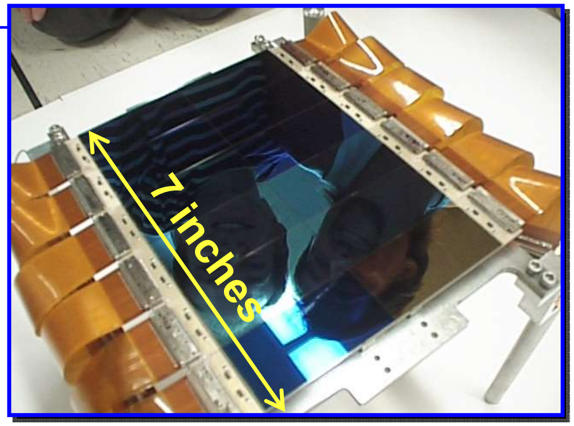
27 February 2012

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

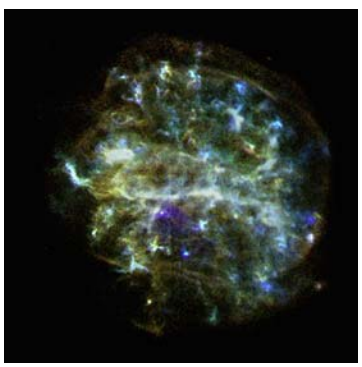
CCD Focal Planes on Astronomical Telescopes







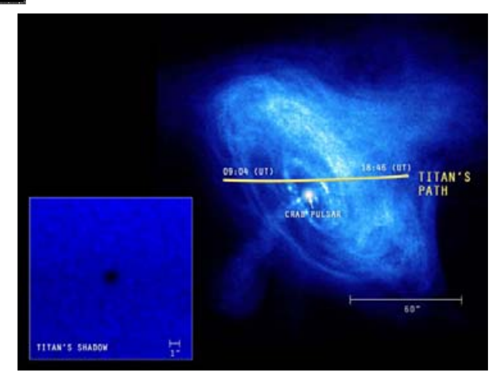
NASA Chandra X-ray Great Observatory
Launched July 1999



G292.0+1.8

Centaurus A

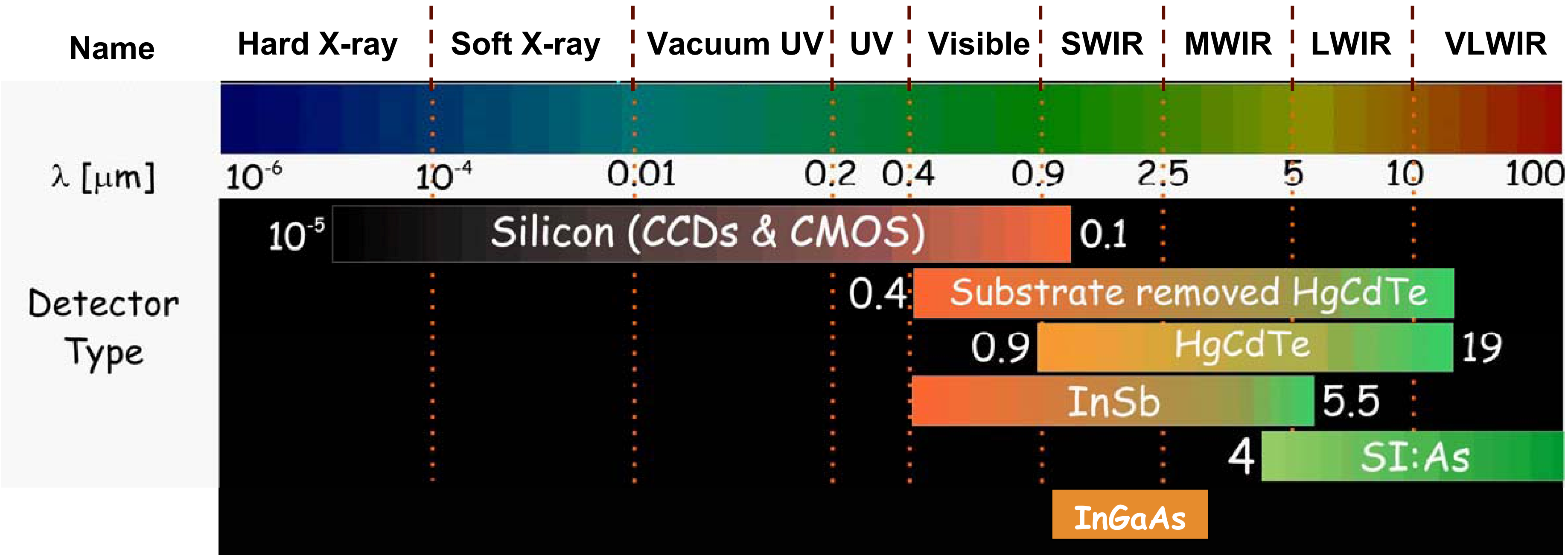
PSR B1509-58



Titan’s shadow

http://chandra.harvard.edu/

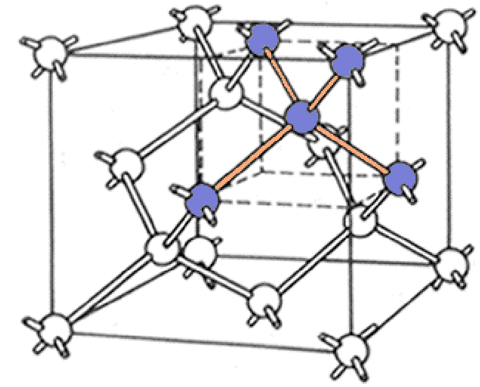
Wavelength Ranges for Detectors



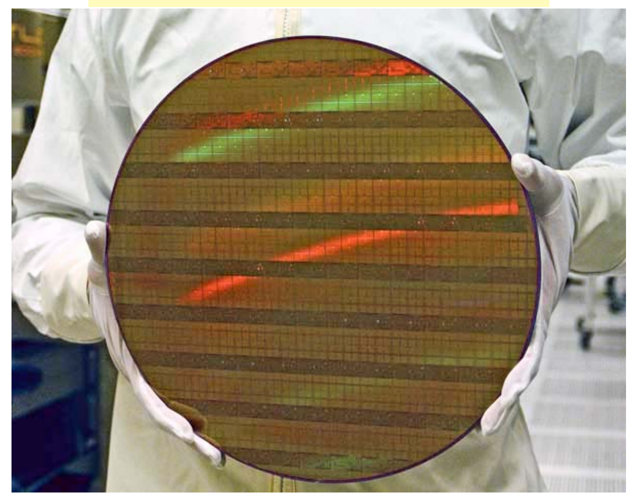
The Silicon Advantage

- **Abundant**
- **Elemental semiconductor**
- **Can be highly purified (<ppb)**
  - **Controlled amounted of impurities can be added**
- **Forms strong covalent bonds with itself and with Oxygen**
  - **High melting point**
    - **c-Si: 1440°C; SiO_2: 1700°C**
  - **SiO_2 can be used for isolation and protection**
- **Can combine with halogens and hydrogen if there is no oxygen**

Face-Centered Cubic Diamond Crystal Lattice



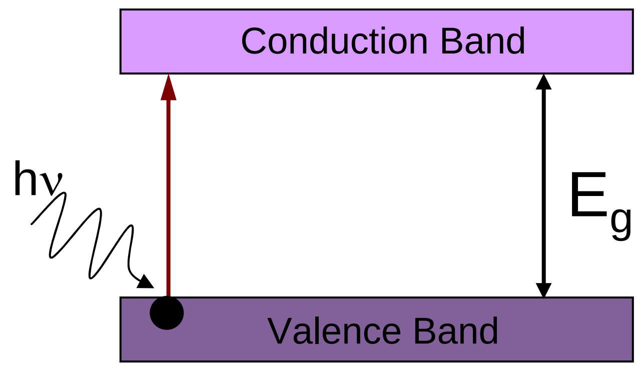
300-mm Wafer (Intel)



Photoelectron Creation

- **Photons striking the semiconductor excite electrons from the Valence band into the Conduction band**
- **Absorption occurs for hν ≥ Eg**
  - **Or $E_{photon} = hc/\lambda \geq Eg$**

Intrinsic Semiconductor



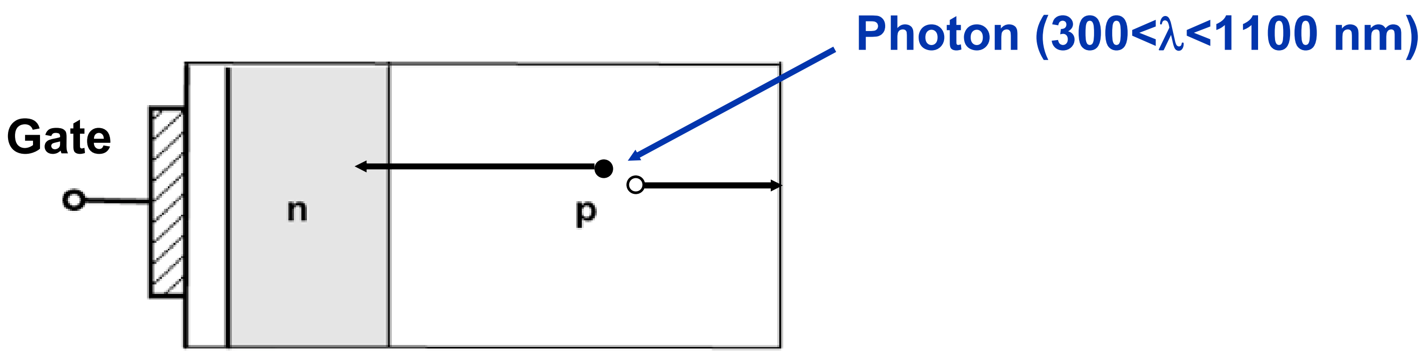
Symbol	E_g(eV)	λ_c (µm)
Si	1.12	1.1
InGaAs	0.73 - 0.48	1.68* - 2.6
HgCdTe	1.00 - 0.07	1.24 - 18
InSb	0.23	5.5
Si:As	0.05	25

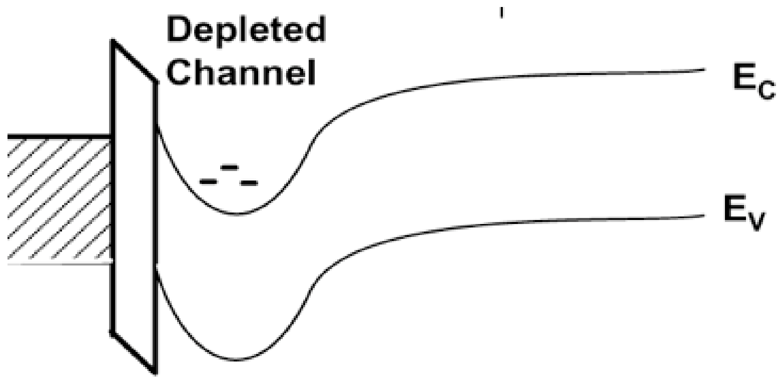
$\lambda_c = 1.238 / E_g$ (eV)

h = Planck's constant
ν = frequency of light = λ/c
E_g = Energy Gap

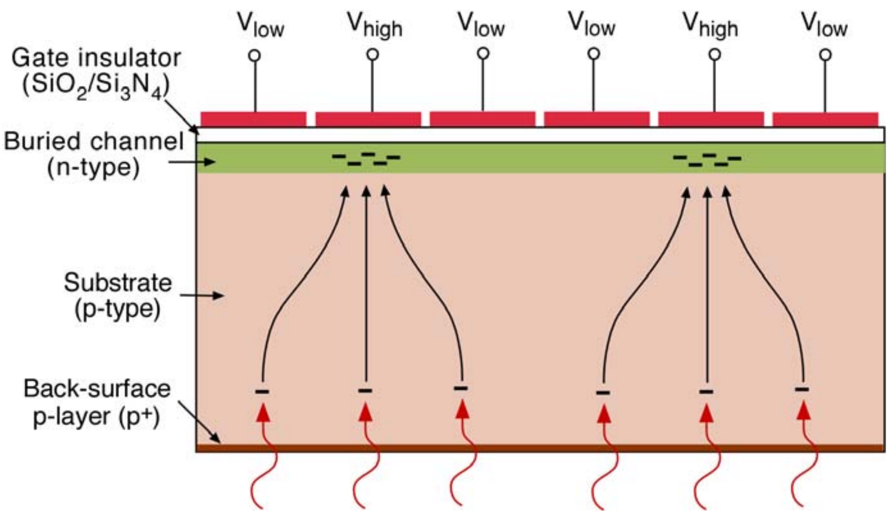
***Lattice matched InGaAs ($In_{0.53}Ga_{0.47}As$)**

Detection and Vertical Confinement

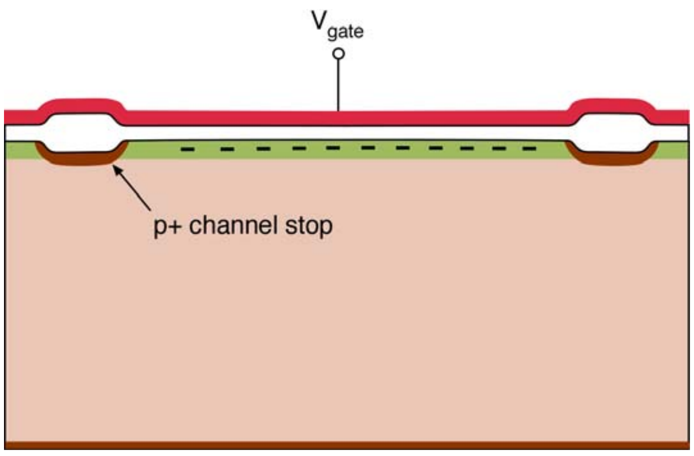




Basic CCD Structure



View along charge-transfer direction



View across CCD channel

CCD Operation

Device Cross Section

Potential Distribution

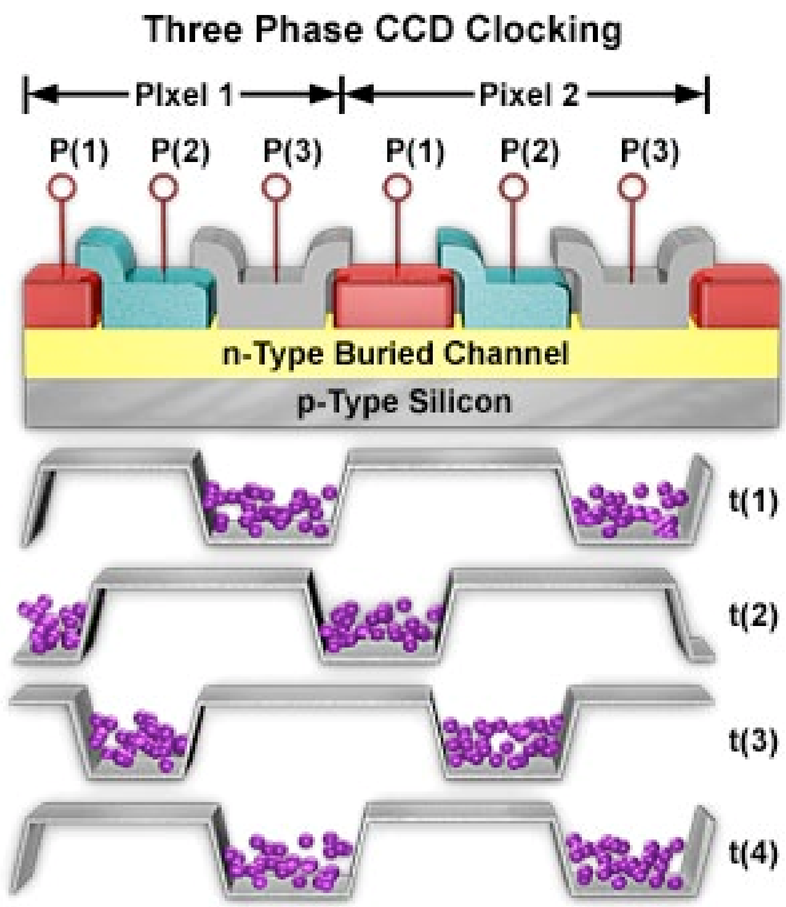
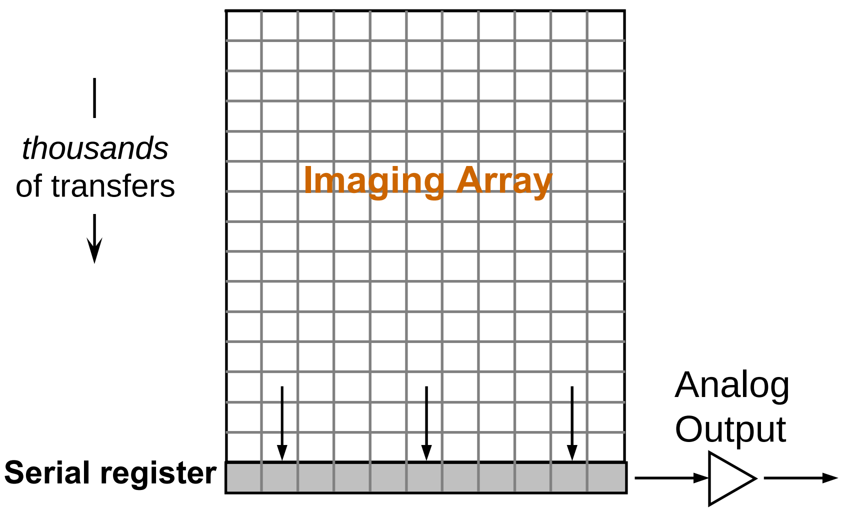


Figure 1

http://learn.hamamatsu.com/articles/threephase.html

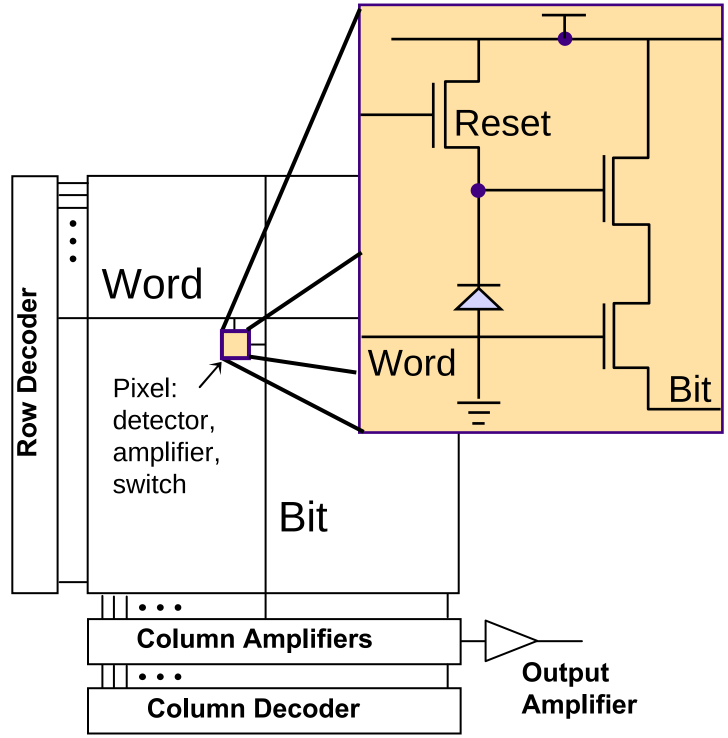
Comparison of CCD and CMOS Imagers

CCD imager



- **Pros**
  - **Still used in highest performance applications**
  - **Best QE, lowest noise**
- **Cons**
  - **Sensitive to proton damage in space applications**

CMOS Active Pixel Sensor (APS)

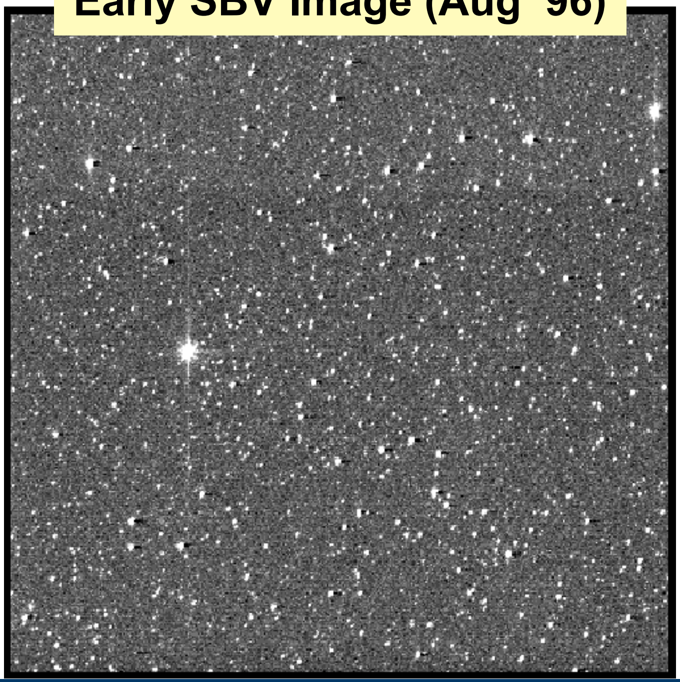


- **Pros**
  - **Provides on-chip electronics**
- **Cons**
  - **Modest imaging performance for monolithic**

Effect of Space Environment on CCD Performance:
SBV Image Comparison

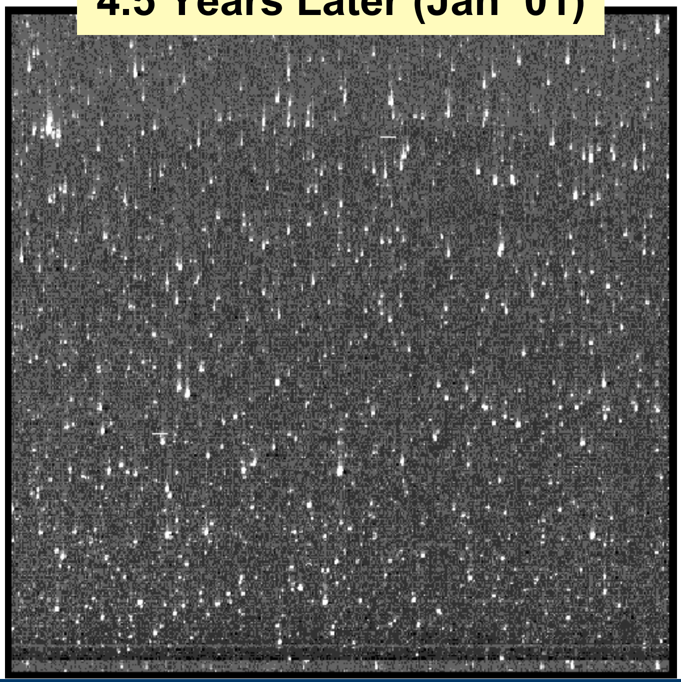
- Radiation-induced traps in silicon capture electrons during charge transfer and release as trailing charge
- Recent CCD performance improvements
  - Smaller transfer distances
  - Channel engineering
  - Lower temperature
- Better performance with CMOS devices with few/no transfers

Early SBV Image (Aug ’96)



Fabrication 1987

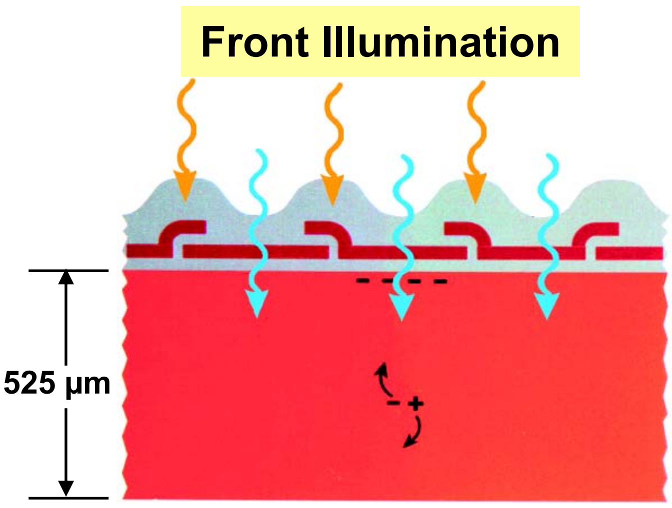
4.5 Years Later (Jan ’01)

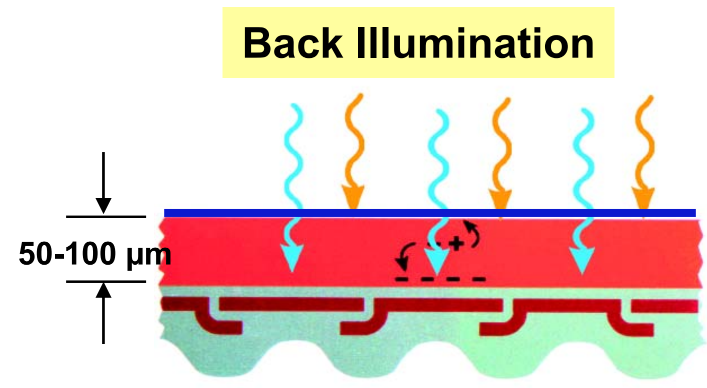


Back-Illuminated Structure

- Front illumination (FI)
  - Cheaper to build
  - Absorption in overlying films
  - Reflection losses
- Back illumination (BI)
  - More expensive, but becoming more common
  - Direct coupling of photons to active silicon volume
  - AR coatings enable nearly 100% QE

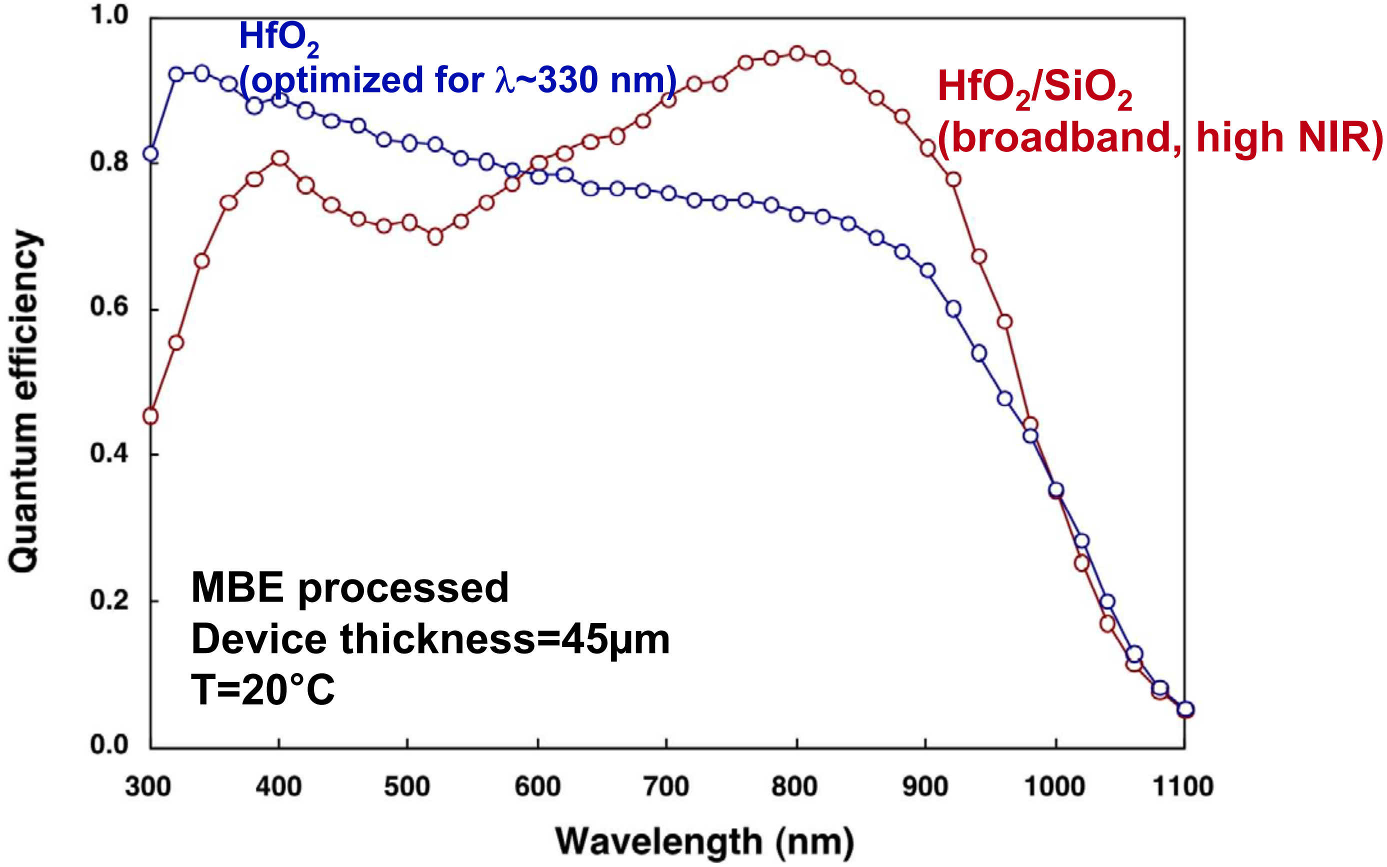
- Good back-surface treatment required to avoid photoelectron loss
  - Boron implant and laser anneal
    - e2V, MIT/LL
  - MBE
    - JPL, MIT/LL
  - Chemisorption coating that produces positive charge
    - University of Arizona (Lesser)



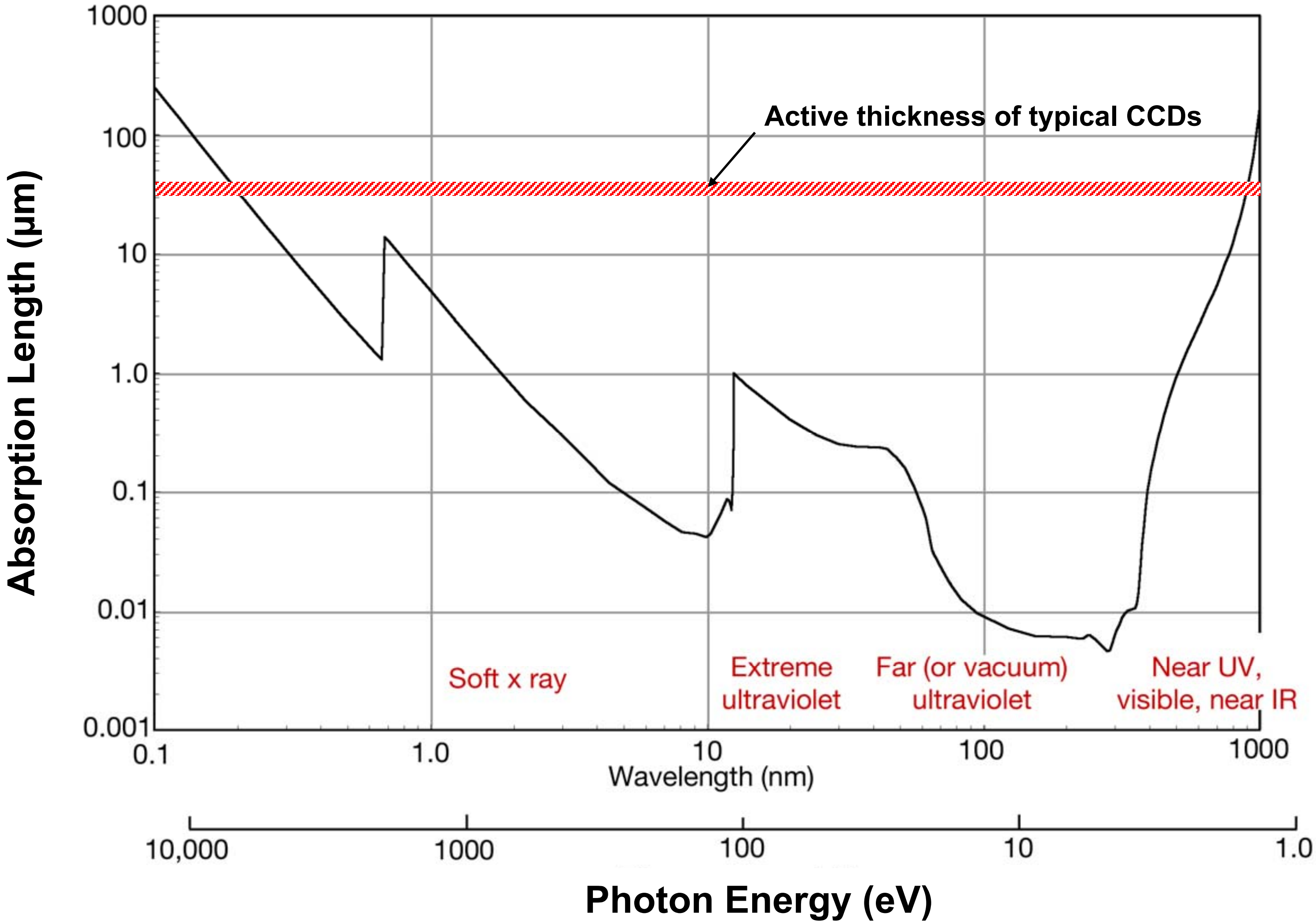


Anti-Reflection Coatings

- **Minimize reflection from air (n≈1)/ silicon (n≈4) interface**
  - **Typically Hafnium oxide for single layer (λ/4) coatings**
  - **Specialized coatings developed with two layers or graded thicknesses**

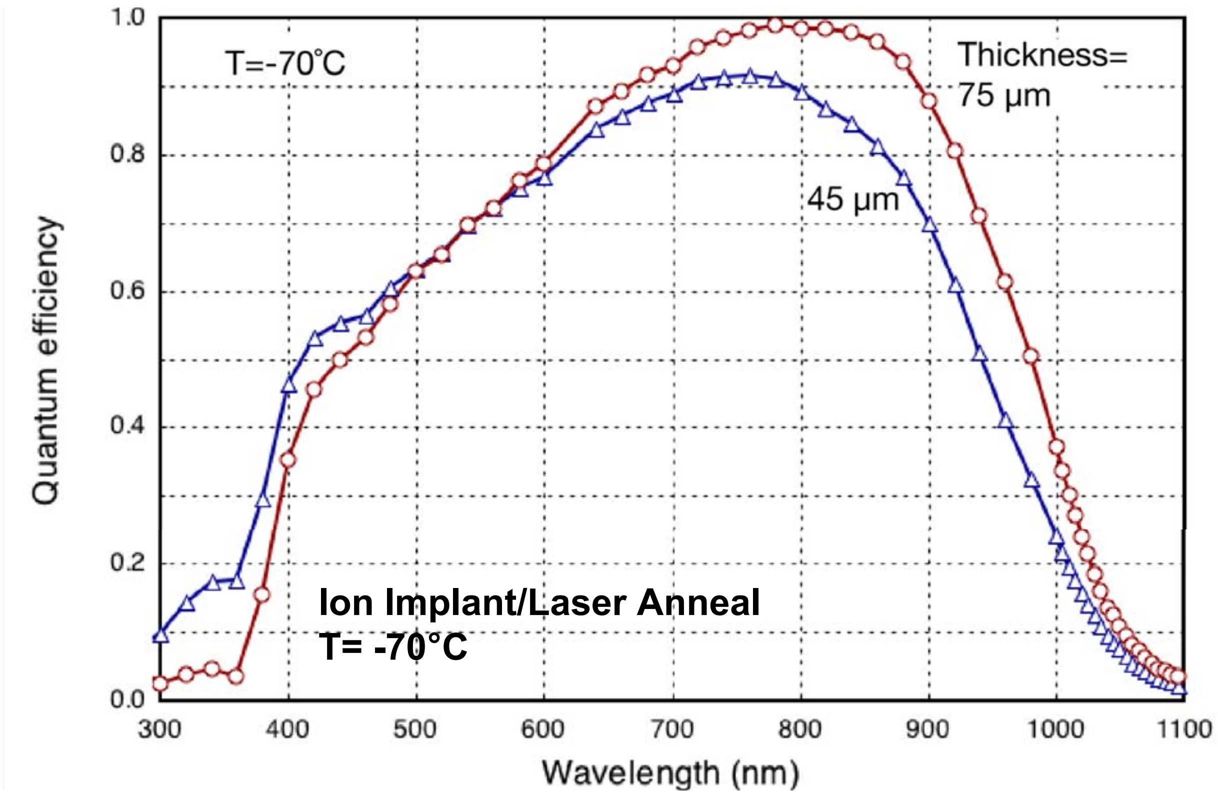


Photon Absorption Length in Silicon



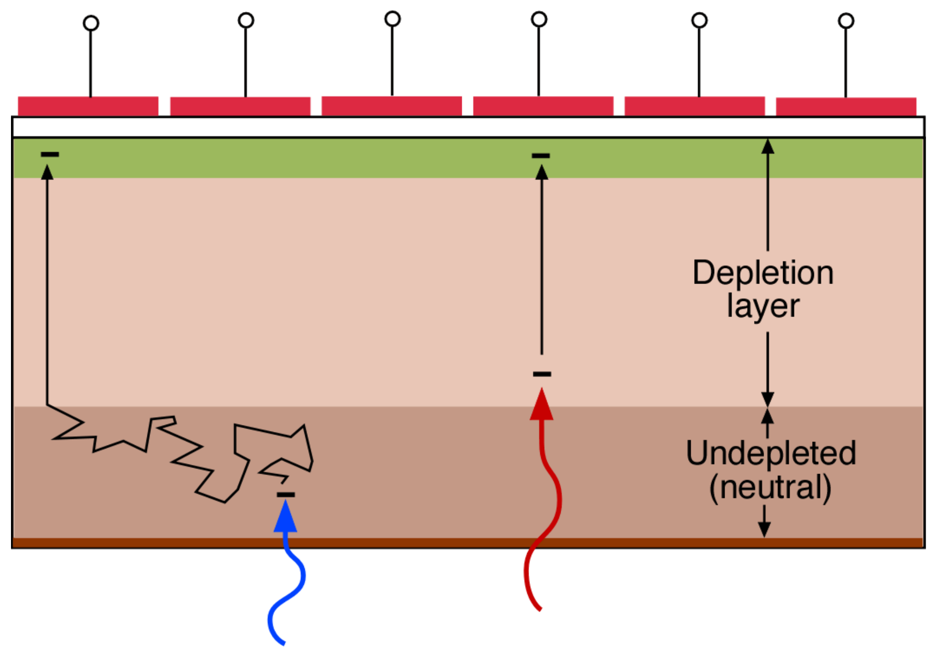
Effect of Silicon Thickness on NIR Spectral Response

- **Near-IR response requires thicker silicon**
  - **Specialized material with resistivity > 3000 ohm-cm**
- **Considerations:**
  - **Increased PSF with large undepleted depth**



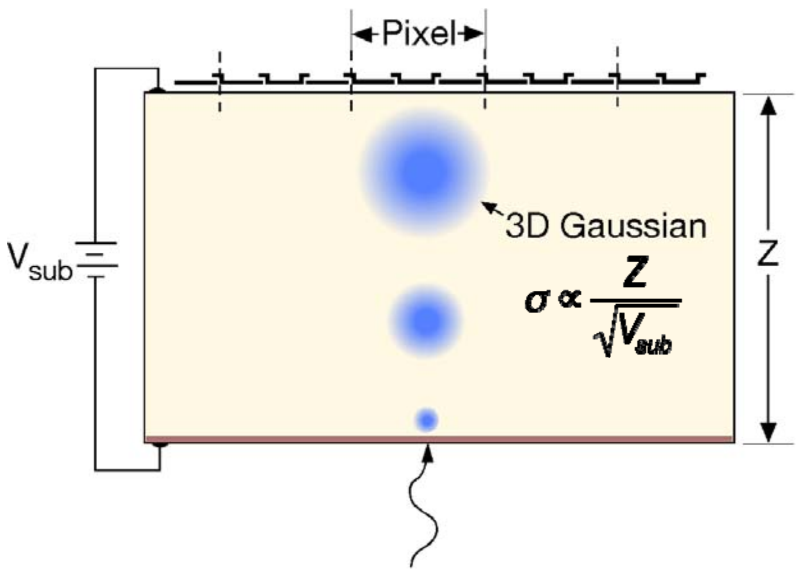
Effects of Partial Depletion

- **Full depletion essential for minimal charge spreading (high MTF)**
- **Methods to ensure full depletion**
  - **Thin device**
  - **High-resistivity substrate**
  - **High clock voltages**
  - **Bias back-surface p^+ negative**

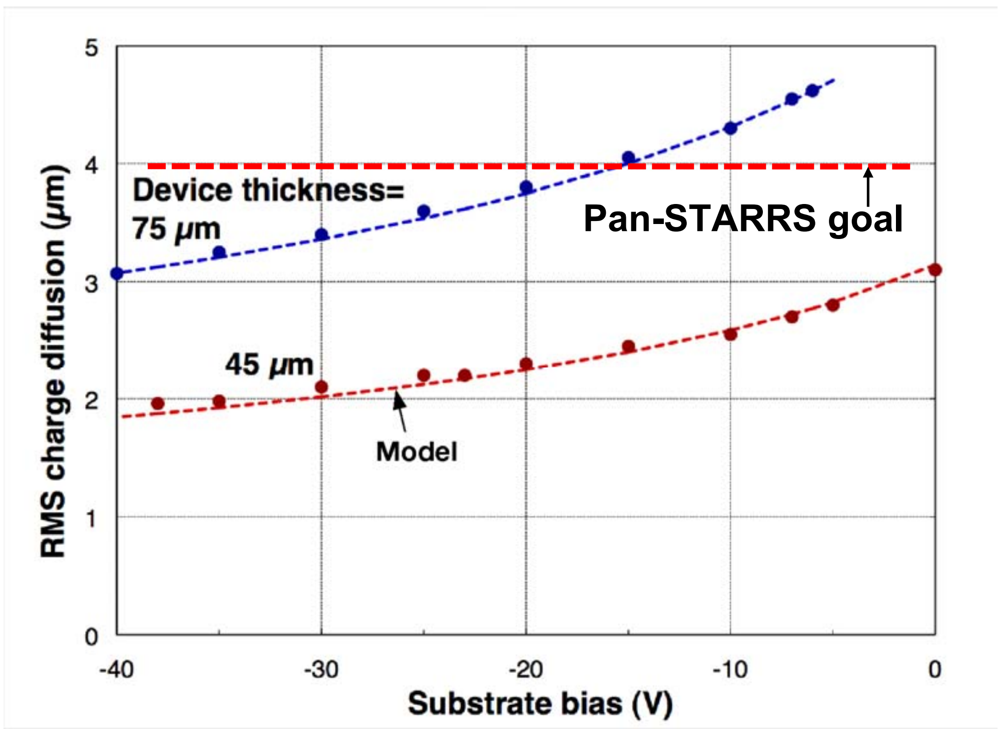


Tradeoff: High QE vs. Imager Resolution

- Voltage bias across sensor produces high resolution in thick imagers

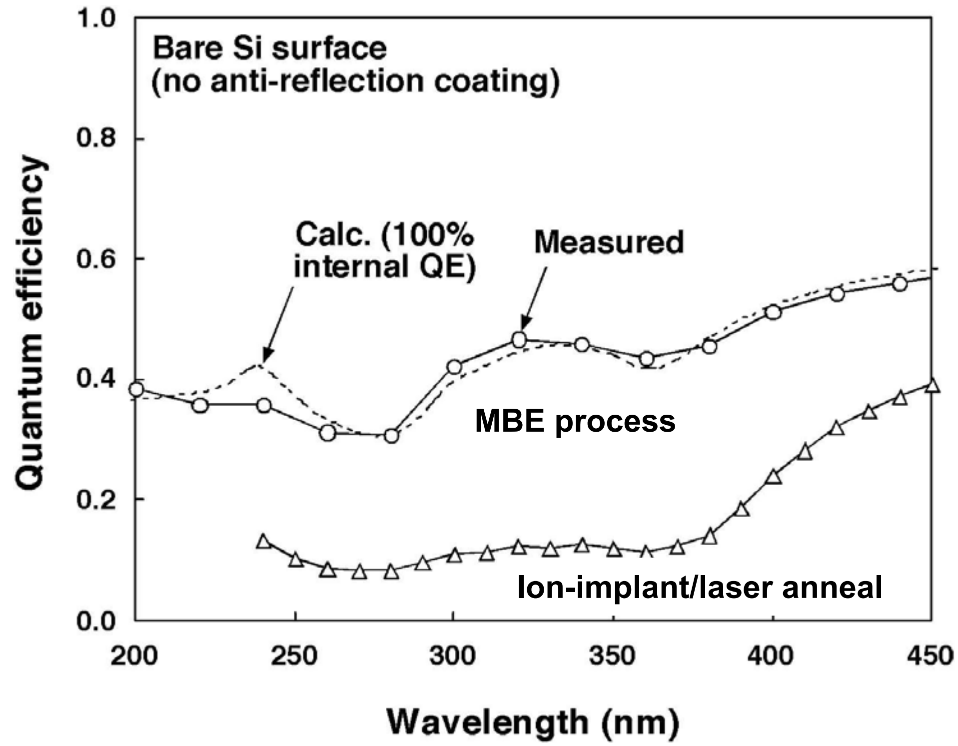


Measured charge diffusion vs. substrate bias and device thickness



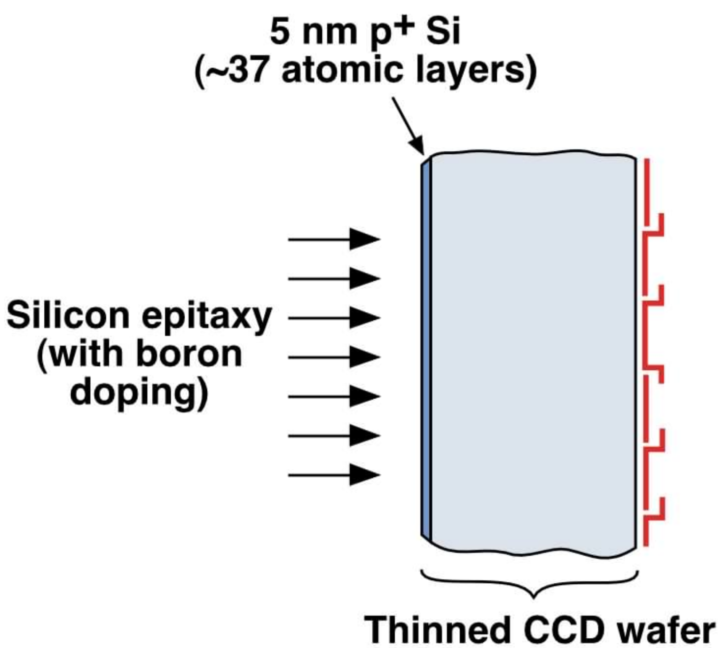
UV-Sensitive Silicon Detectors

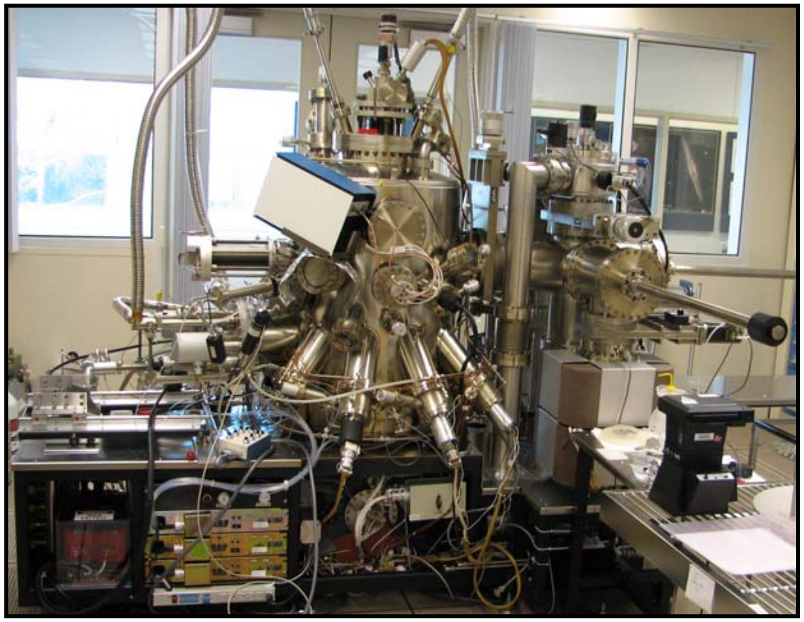
- UV (<400 nm) is challenging
  - Shallow penetration depth of radiation
  - Requires extremely thin, doped surface layer
- Demonstrated near 100% internal quantum efficiency, temporally stable
- Applicable to improved soft-x-ray response below 500 eV



Molecular Beam Epitaxy Backside Treatment

- **Fully processed imager wafers are chemically thinned to typically 40-50µm**
- **Grow 5nm of p+ Si epitaxially on the back surface at ~430°C**
  - **Epitaxially doped layer << absorption length**
  - **Absorption length <10 nm at λ=200-350 nm**





Ultra-high-vacuum molecular-beam epitaxy system

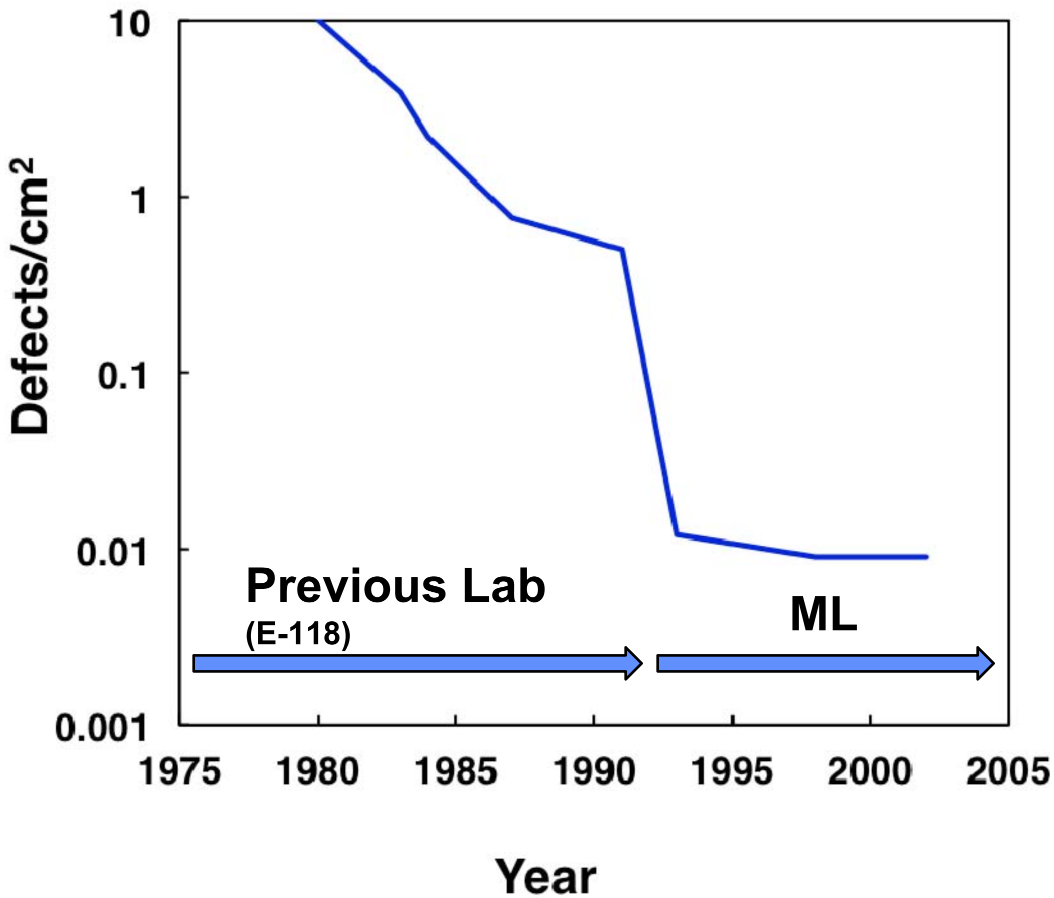
Lincoln Microelectronics Laboratory

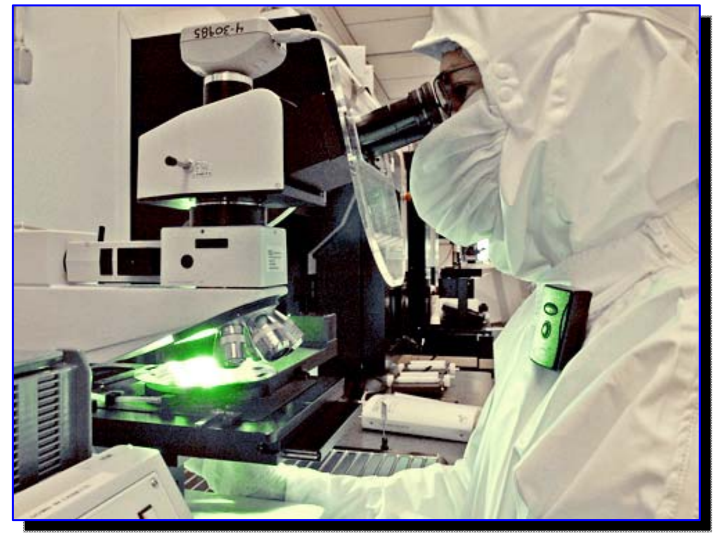
70,000 ft^2 total:
8,100 ft^2 class 10; 10,000 ft^2 class 100

Application Areas

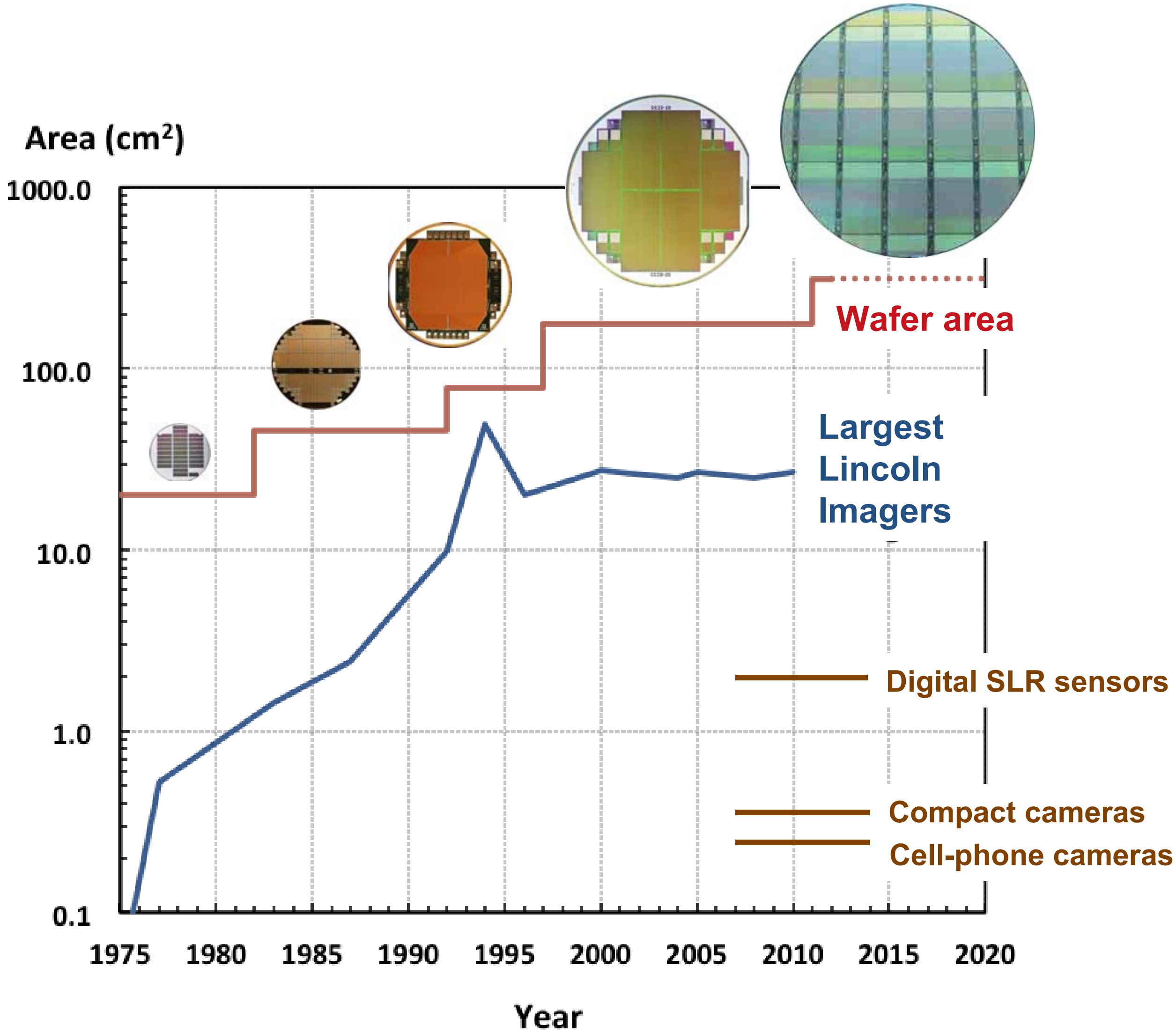
- **High performance CCD imagers**
- **Photon-counting APD arrays**
- **Low power silicon-on-insulator CMOS**
- **Rad-hard and space electronics**
- **Superconducting electronics**
- **Microelectromechanical RF/optical switches**

Impact of the Microelectronics Lab





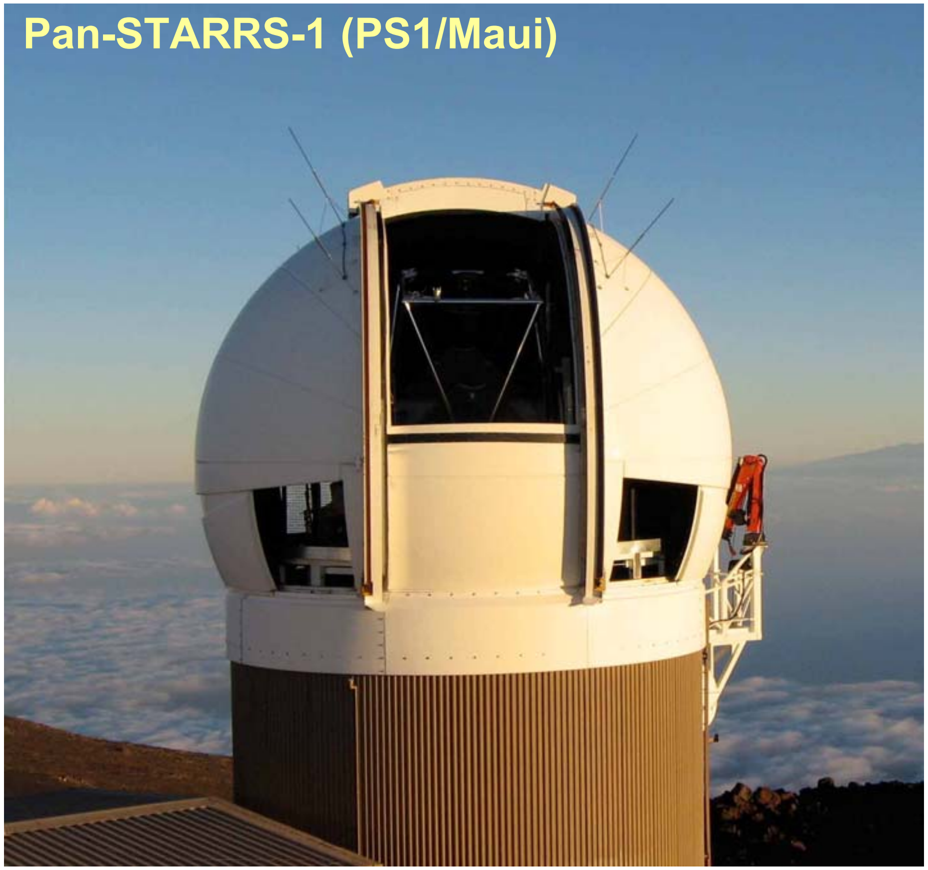
Growth in Wafer and Device Sizes



Pan-STARRS Mission
(Panoramic Survey and Rapid Response System)

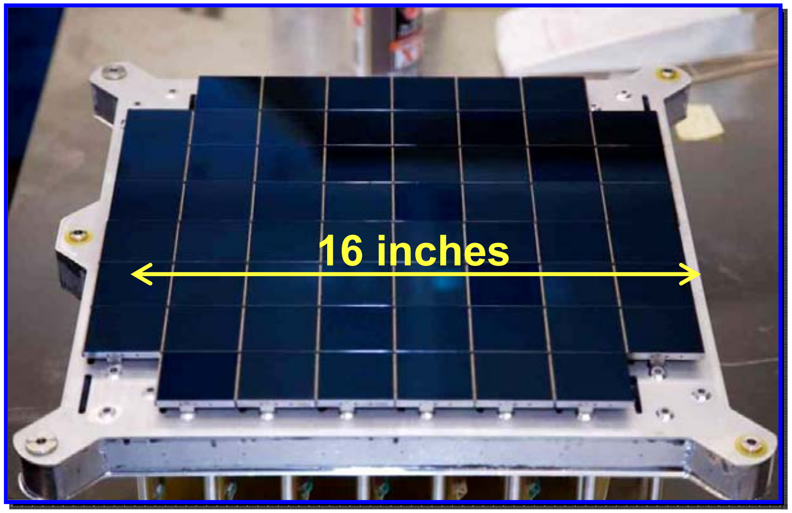
High-cadence, wide-field surveys for detection of asteroids and transient phenomena

- **Four, 1.8-m aperture telescopes**
  - **m_v ~24**
  - **30-60 sec exposure**
  - **FOV: 3 degrees**
  - **Spatial sampling: 0.3 arcsec**
  - **Survey Mode: 6,000deg^2 /night**



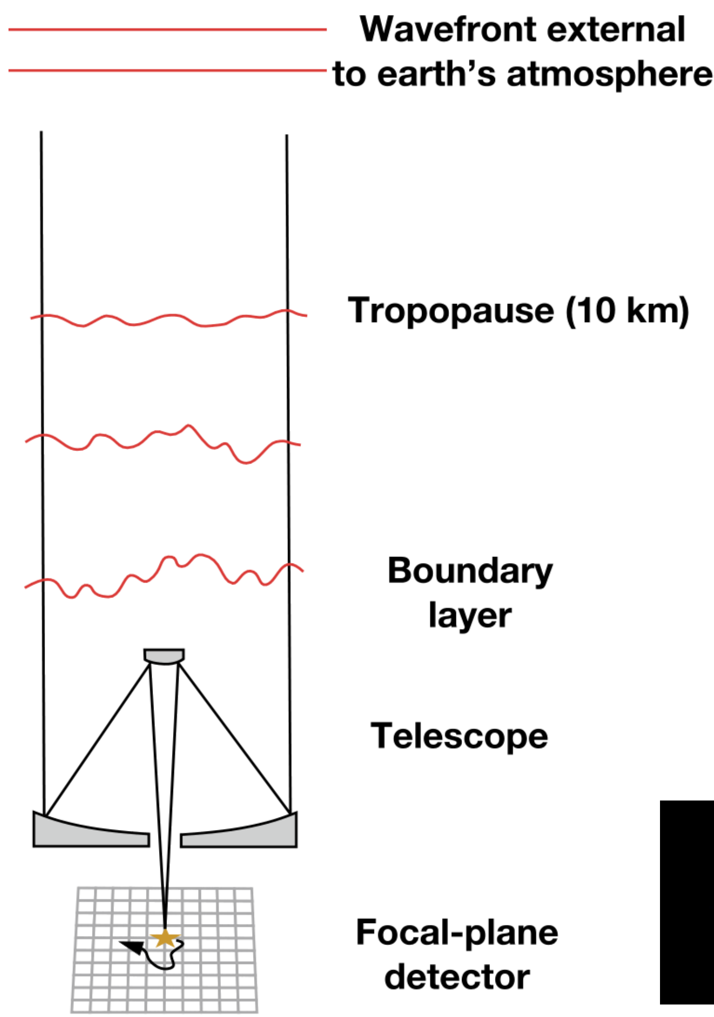
Gigapixel Astronomy: Technology Goals

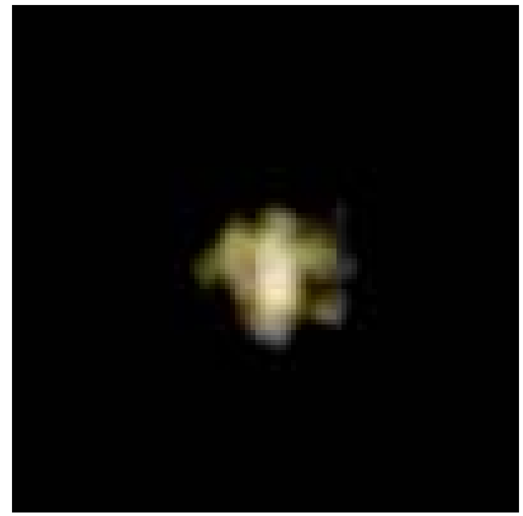
- **Goal 1: Build the largest and most cost effective astronomy CCD focal planes made**
  - Large CCD imager tiles
  - High yield
  - Redundant optics design
    - Allow for missing cells and seam loss



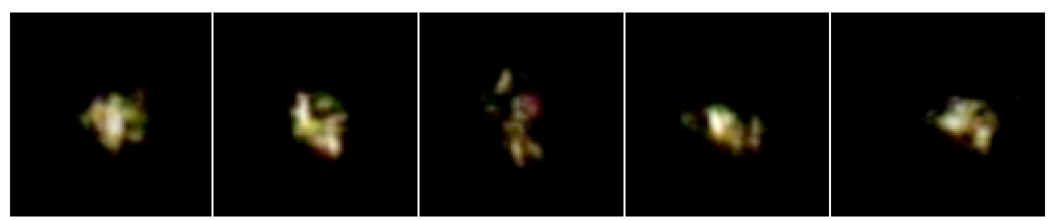
- **Goal 2: Remove translational atmospheric distortions ("de-twinkle")**
  - Use Orthogonal CCD structure
  - Organize imager chip into independently operable Orthogonal Transfer CCD (OTCCD) cells

Image Motion from Atmospheric Turbulence (de-Twinkle)



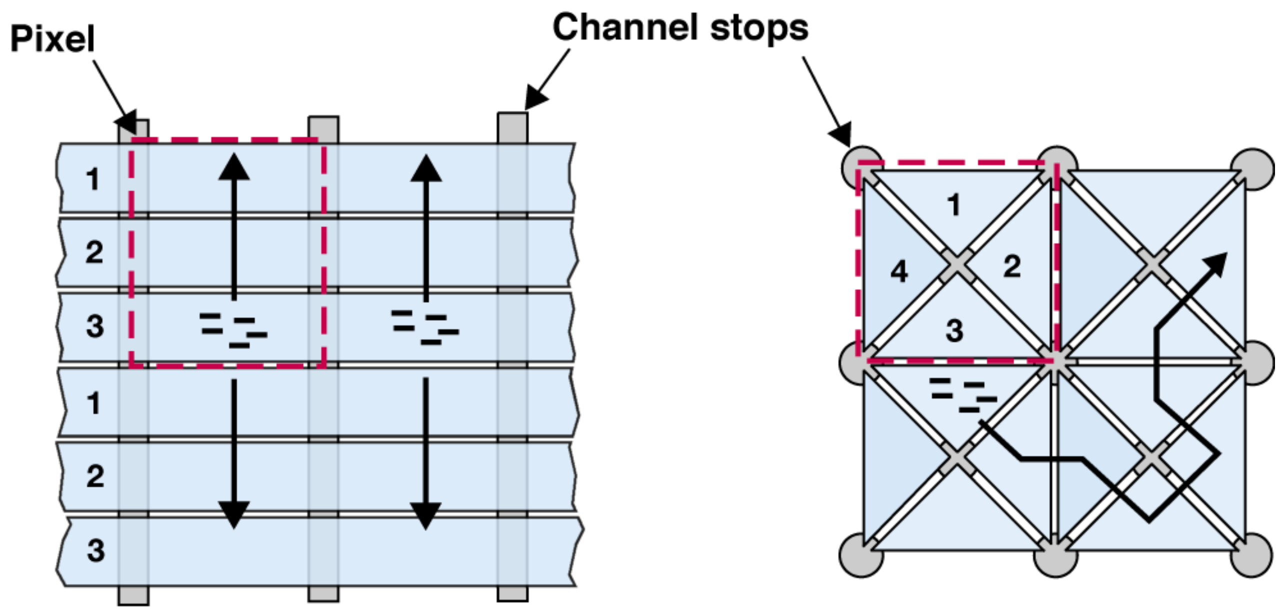


http://www.noao.edu/education/gsmt/seeing



1995: Orthogonal Transfer CCD (OTCCD)

- **Charge transfer in arbitrary directions**
- **Can noiselessly remove blur due to scene or platform motion**
  - **Ground-based astronomy (atmospheric effects)**
  - **Imaging from unstable platforms (e.g., satellites)**

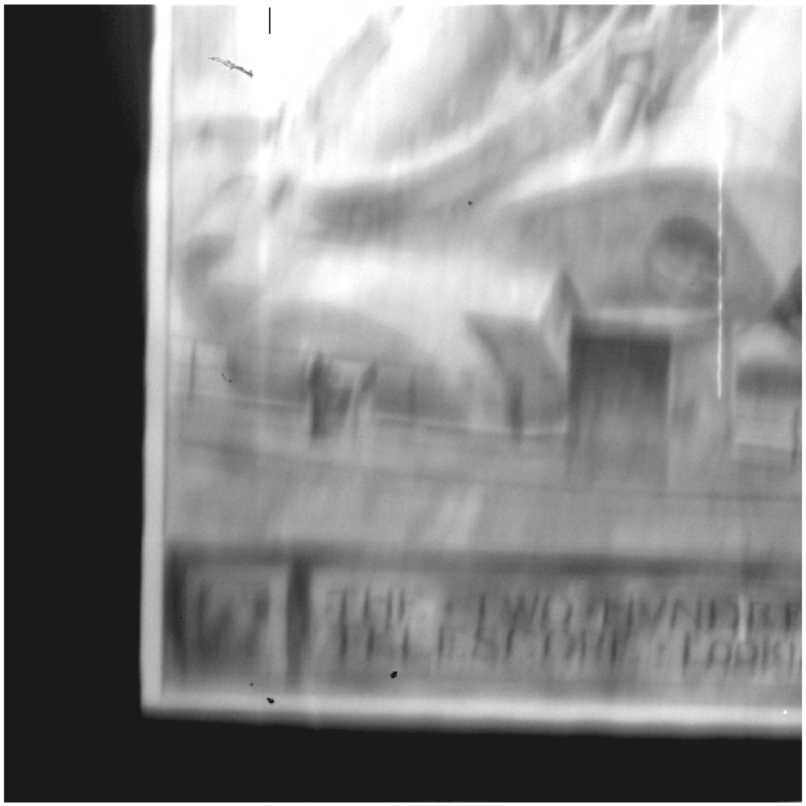


Conventional CCD: charge transfer in two directions

OTCCD: charge transfer in all directions

Laboratory Demo of Motion Compensation

CCD camera spring mounted

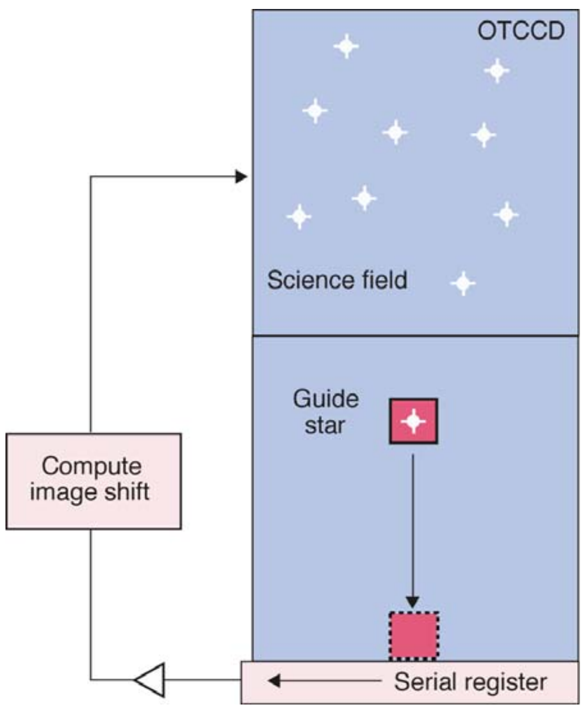


OTCCD gates fixed
during image acquisition

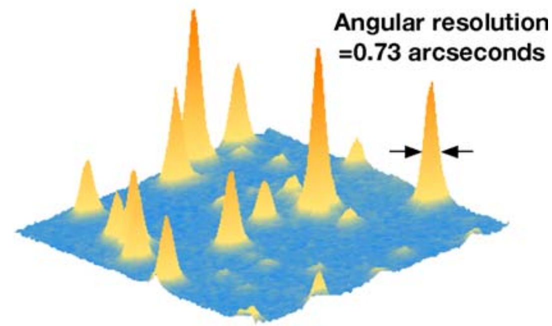
OTCCD gates tracking
image motion

1997: Application of OTCCDs in Astronomy

- **Electronic image-motion compensation**
  - Wavefront distortion (electronic tip/tilt correction)
  - Telescope shake

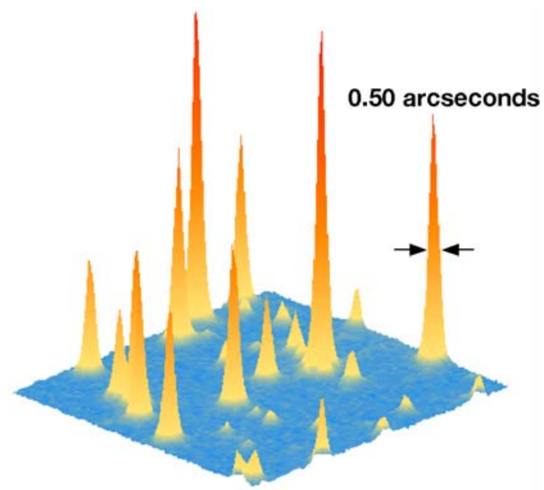


Star-cluster imagery (M71)



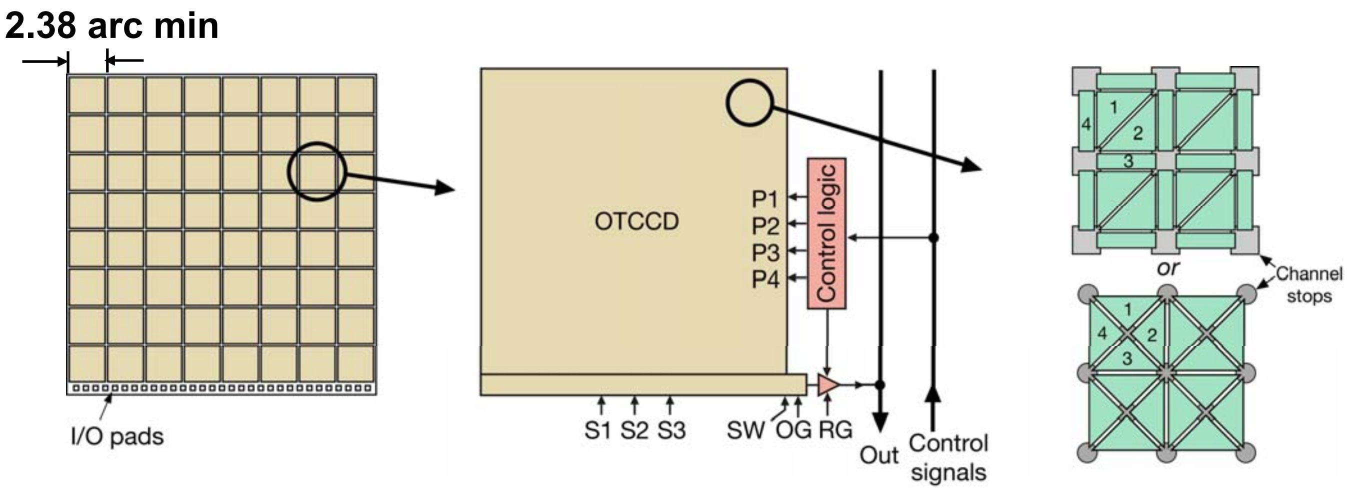
No motion compensation

SNR increase: 1.7x



With motion compensation

Orthogonal Transfer Array

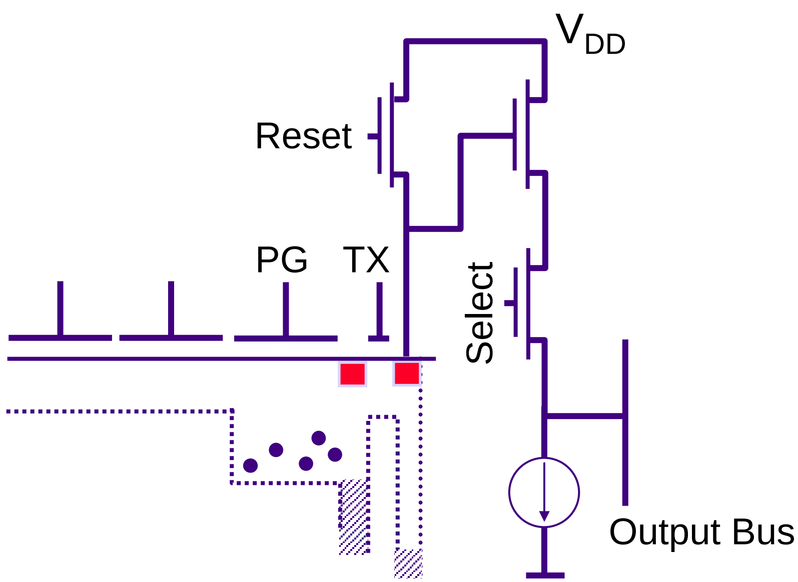


OTA: 8×8 array of OTCCD cells	OTA cell with I/O control	Four-phase OTCCD pixels

- **New device paradigm**
  - **2D array of independent OTCCDs**
  - **Independent clocking and readout of OTCCDs**
- **Advantages**
  - **Enables spatially varying image motion correction**
  - **Isolated defective cells tolerable (higher yield)**

Charge Sensing

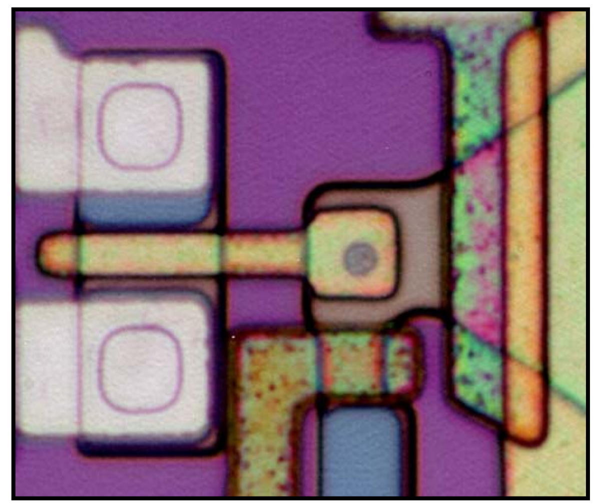
- **Similar techniques for achieving low noise in CCD or CMOS sensors**
  - **Minimize sense node capacitance**
  - **Minimize sense FET noise voltage**
  - **Employ correlated double sampling to correct for reset noise**



PG = Photogate

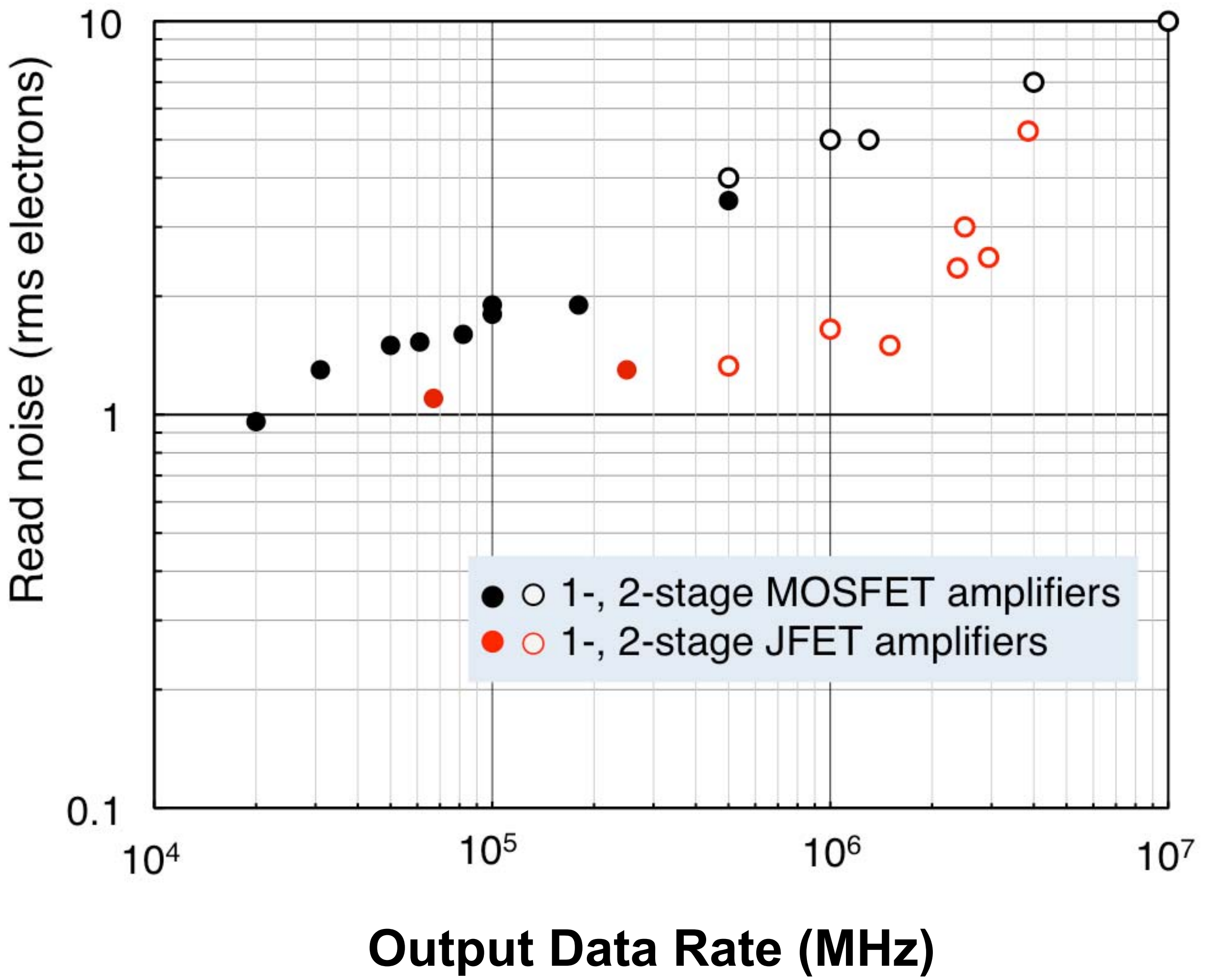
TX = Transfer gate

Charge-sensing Amplifier



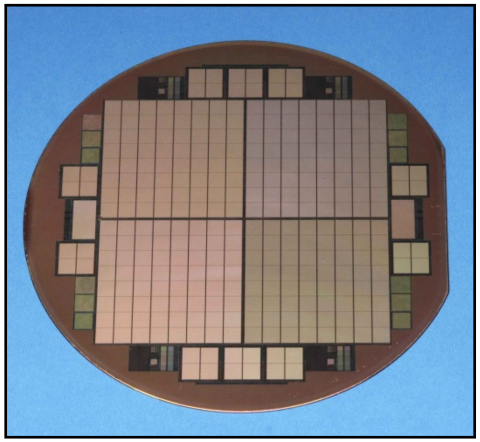
Sense-node Capacitance ~ 5 fF
(20 µV/e$^-$)

Comparison of MOSFET and pJFET-based Output Circuits



Device Fabrication and Sample Imagery

- **Four OTAs on 150-mm wafer (die size 49.5×50.1 mm)**
- **Four-poly, n-buried-channel process**
- **Fabricated on 5,000 Ω·cm float-zone silicon wafers**
- **Back-illuminated devices thinned to 75 µm**



150-mm wafer with four OTAs

Image from back-illuminated OTA 10-µm pixel, 22.6 Mpixels

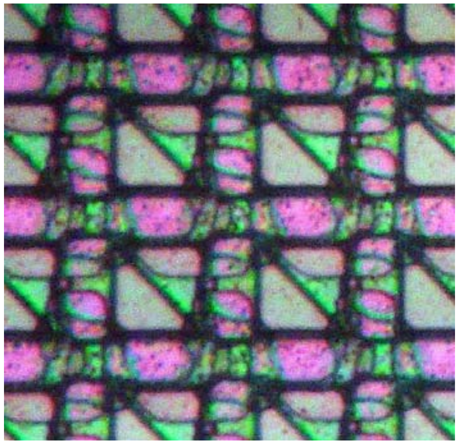
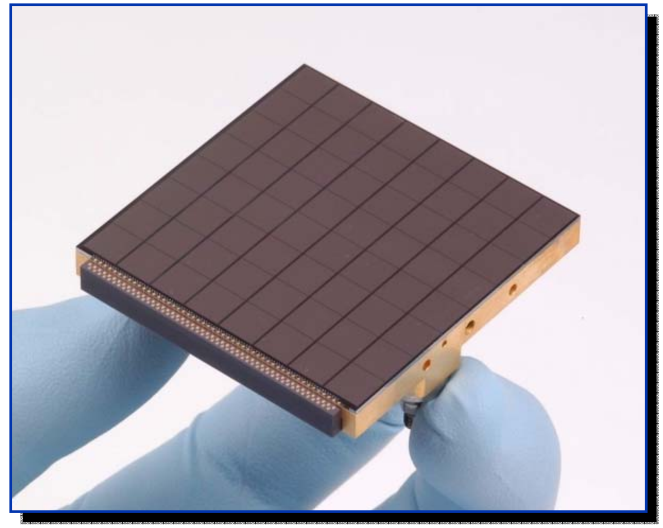
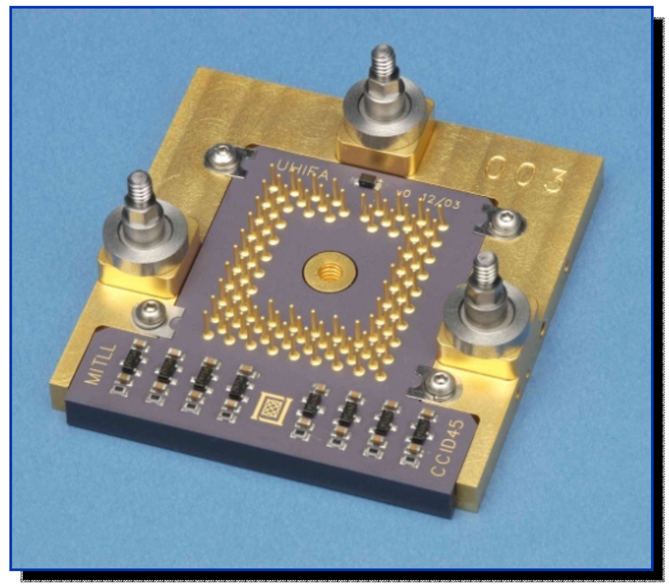


Photo of pixel array

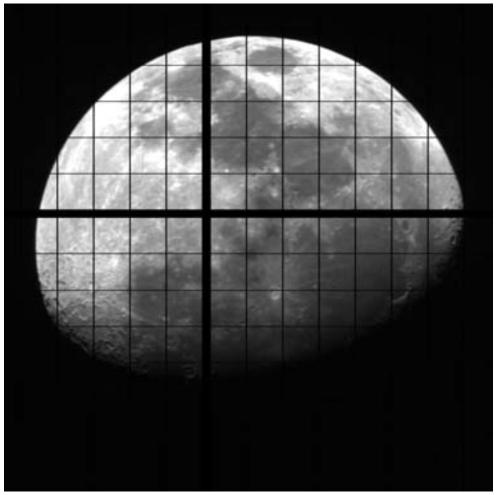
Very large focal plane arrays: Packaging requirements

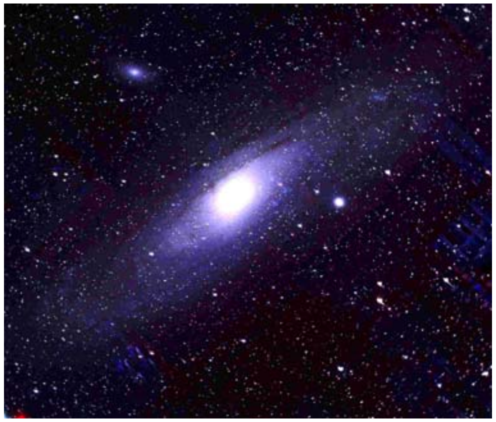
- **Large number (60) of chips**
- **Minimal seam loss**
  - Four-side abuttable
  - Repairable
- **Array flatness (+/- 20 microns) under cryogenic operation**
- **Low noise operation**
  - Good electrical isolation
- **Moderate wire count**



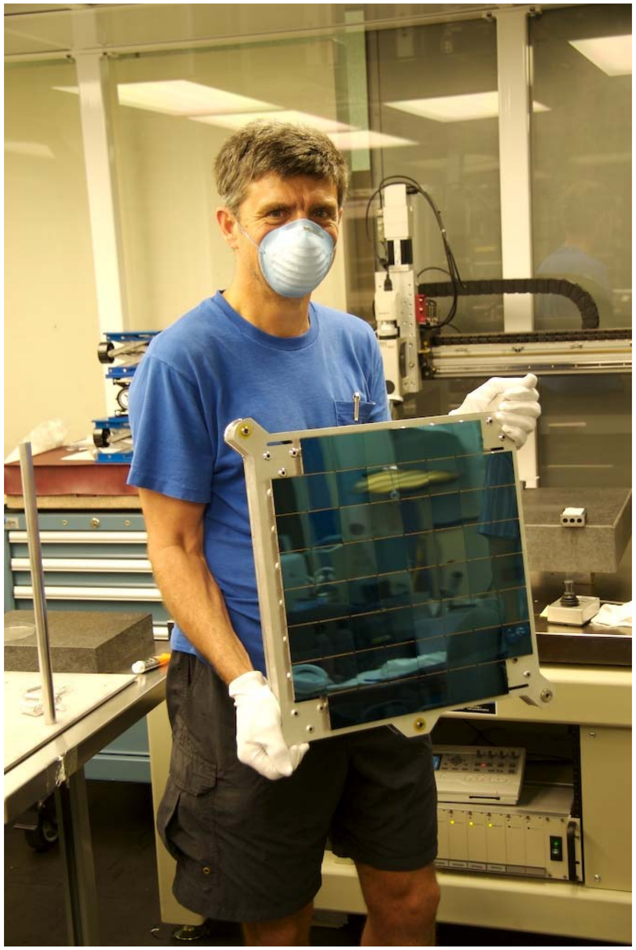


Pan-STARRS Gigapixel Camera





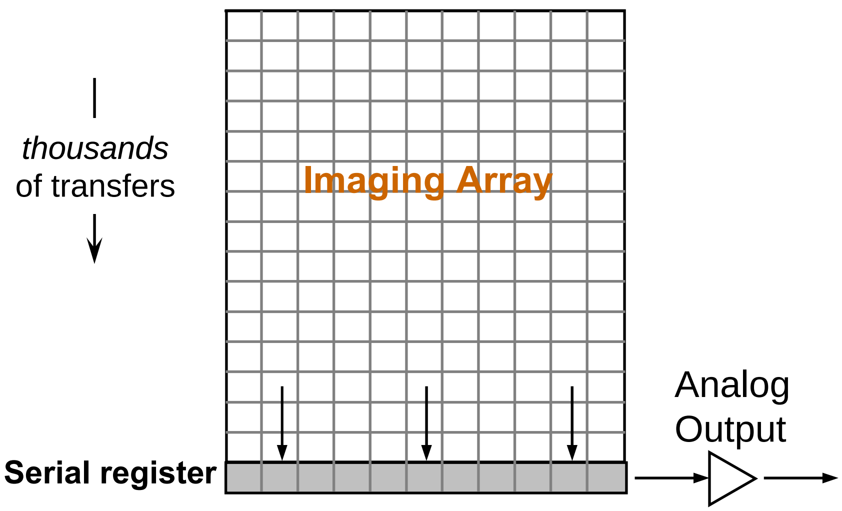
Images from first light (August 2007)



60 OTAs; 1.36 Gpixels

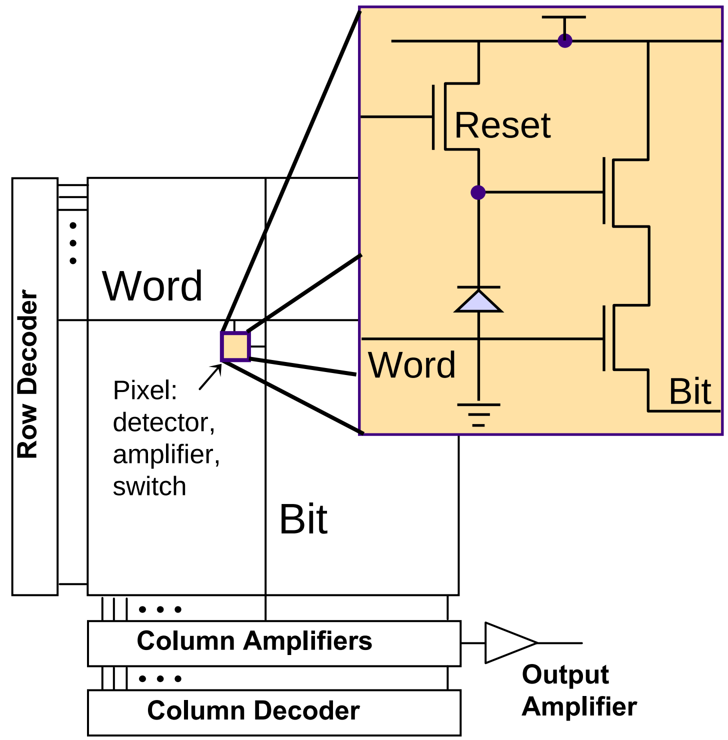
Comparison of CCD and CMOS Imagers

CCD imager



- **Pros**
  - **Still used in highest performance applications**
  - **Best QE, lowest noise**
- **Cons**
  - **Sensitive to proton damage in space applications**

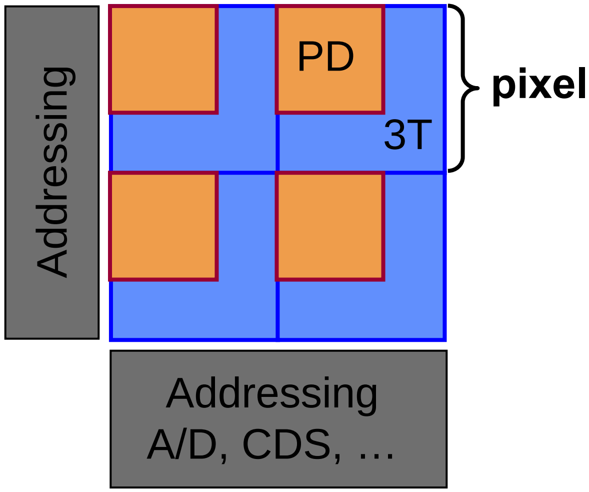
CMOS Active Pixel Sensor (APS)



- **Pros**
  - **Provides on-chip electronics**
- **Cons**
  - **Modest imaging performance for monolithic**

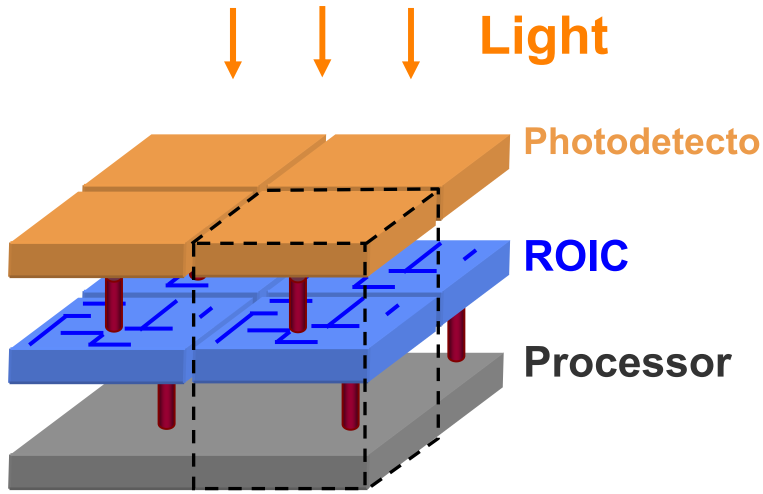
Four-Side Abuttable 3-D CMOS Image Sensor Development

Conventional Monolithic CMOS Image Sensor



- **Pixel electronics and detectors share area**
- **Fill factor loss**
- **Co-optimized fabrication**
- **Control and support electronics placed outside of imaging area**

3-D Pixel



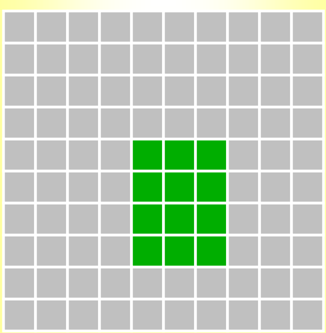
- **100% fill factor detector**
- **Fabrication optimized by layer function**
- **Local image processing**
  - **Power and noise management**
- **Scalable to large-area focal planes**

Special Scanning Techniques Supported by CMOS

- **Different scanning methods are available to reduce the number of pixels being read:**
  - **Allows for higher frame rate or lower pixel rate (reduction in noise)**
  - **Can reduce power consumption due to reduced data**

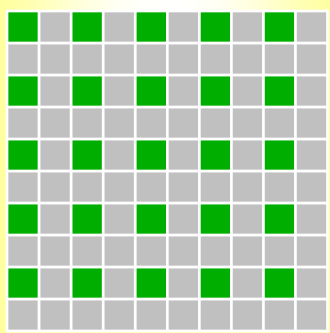
Windowing

- Reading of one or multiple rectangular subwindows
- Used to achieve higher frame rates (e.g. AO, guiding)



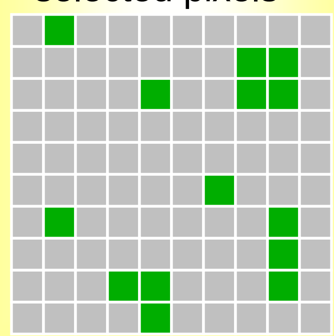
Subsampling

- Skipping of certain pixels/rows when reading the array
- Used to obtain higher frame rates on full-field images



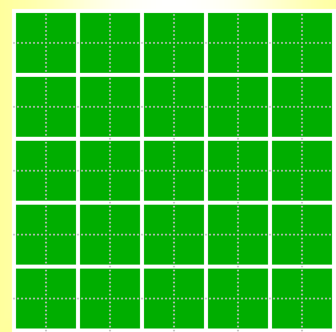
Random Read

- Random access (read or reset) of certain pixels
- Selective reset of saturated pixels
- Fast reads of selected pixels



Binning*

- Combining several pixels into larger super pixels
- Used to achieve lower noise and higher frame rates

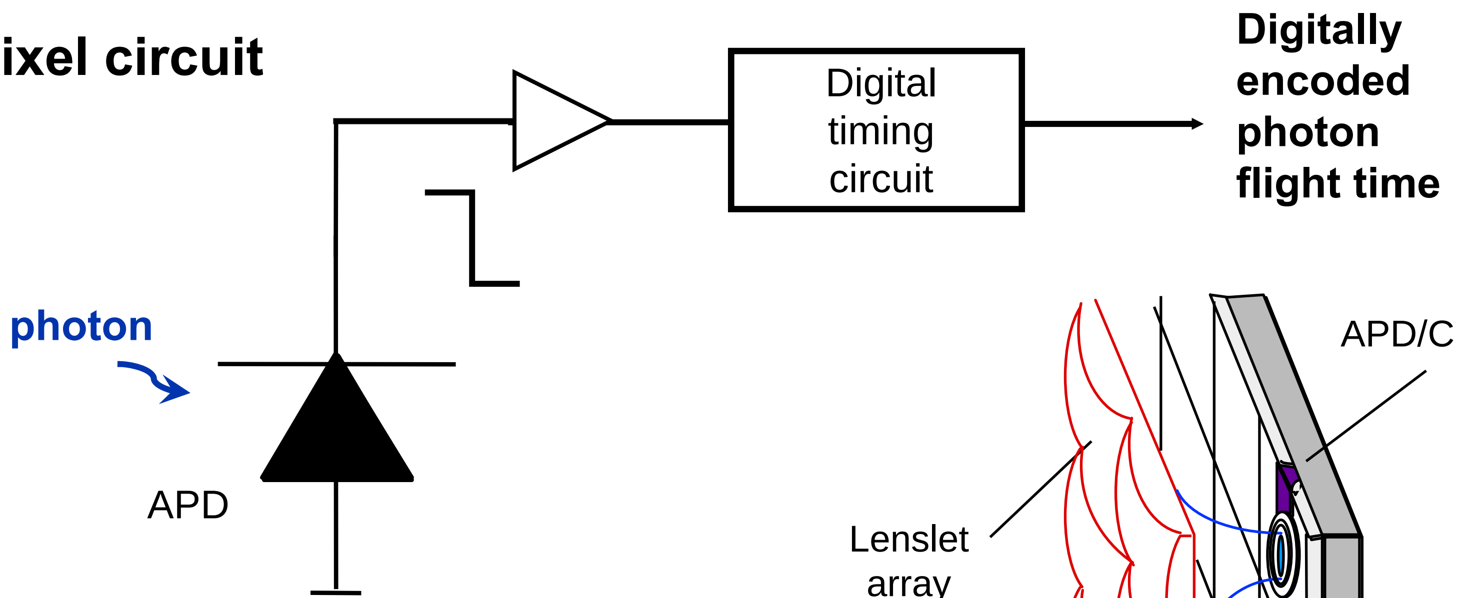


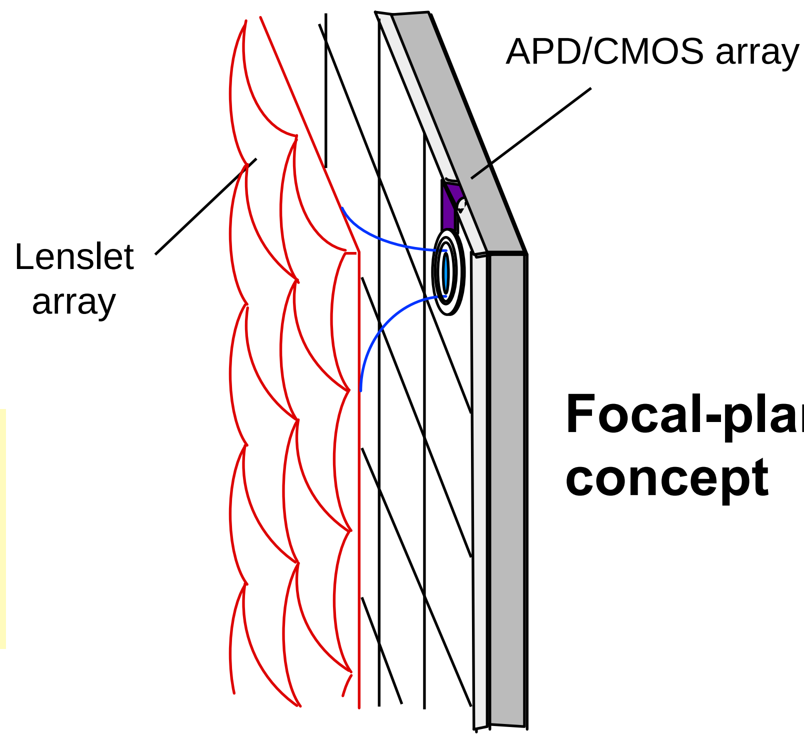
From Hoffman, Loose, Suntharalingam, SDW 2005

* Binning is more difficult to implement in CMOS than in CCDs.

Geiger-Mode Imager: Photon-to-Digital Conversion

Pixel circuit

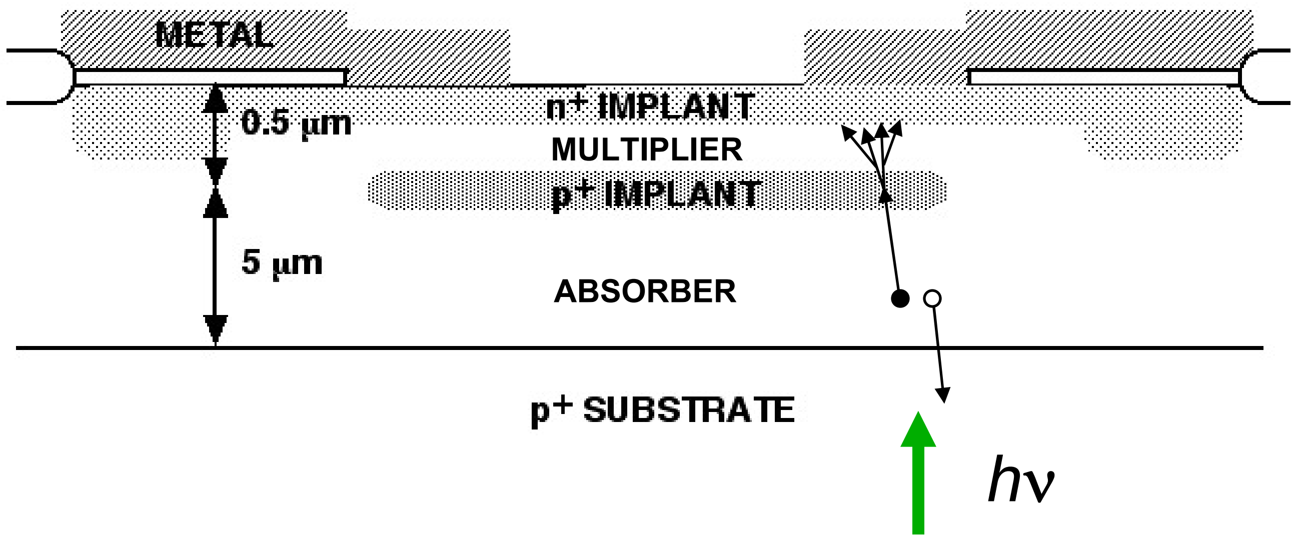




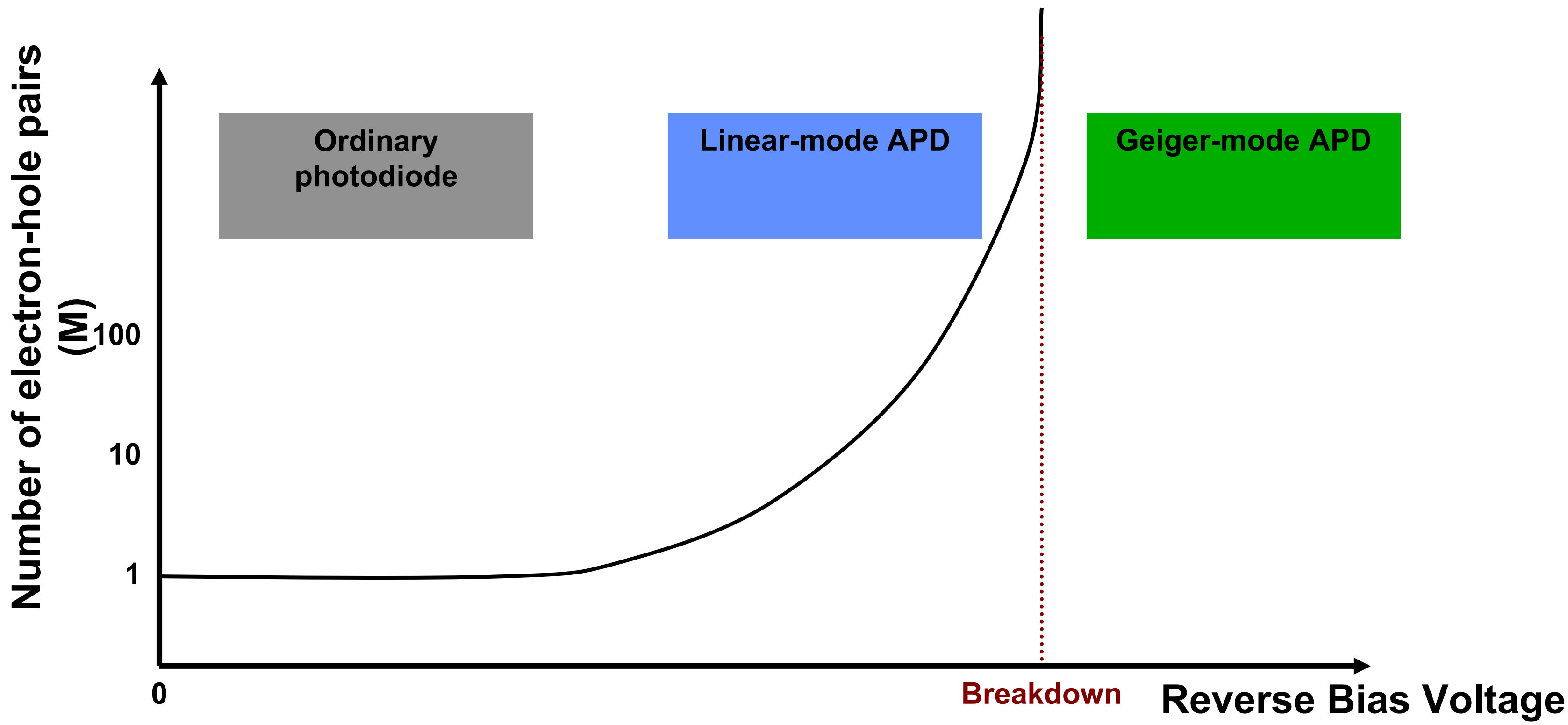
Focal-plane concept

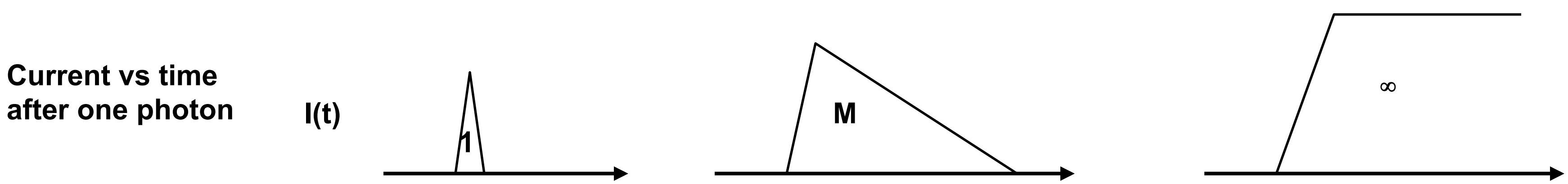
Quantum-limited sensitivity
Noiseless readout
Photon counting or timing

APD Structure and Operation

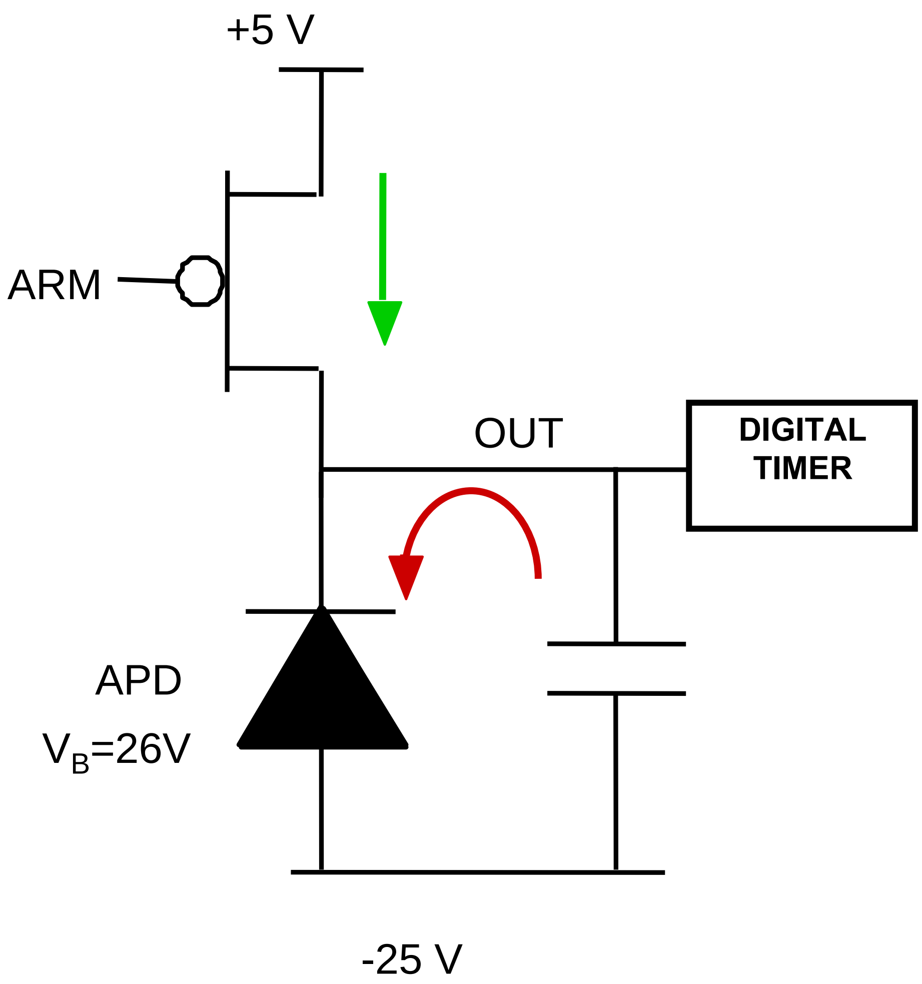


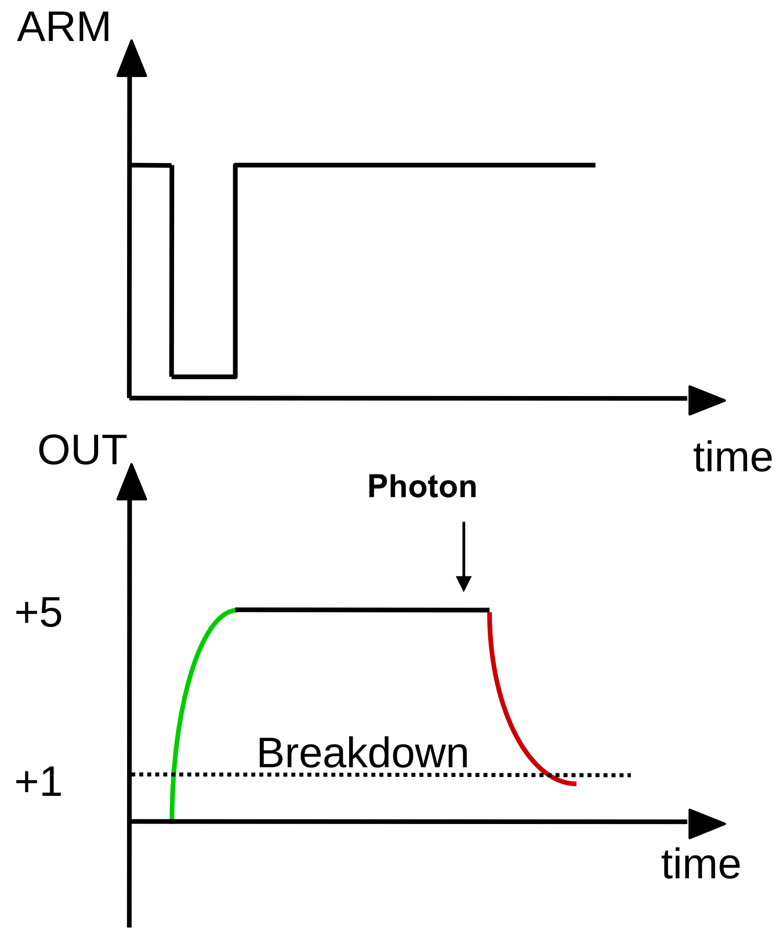
Gain of an APD



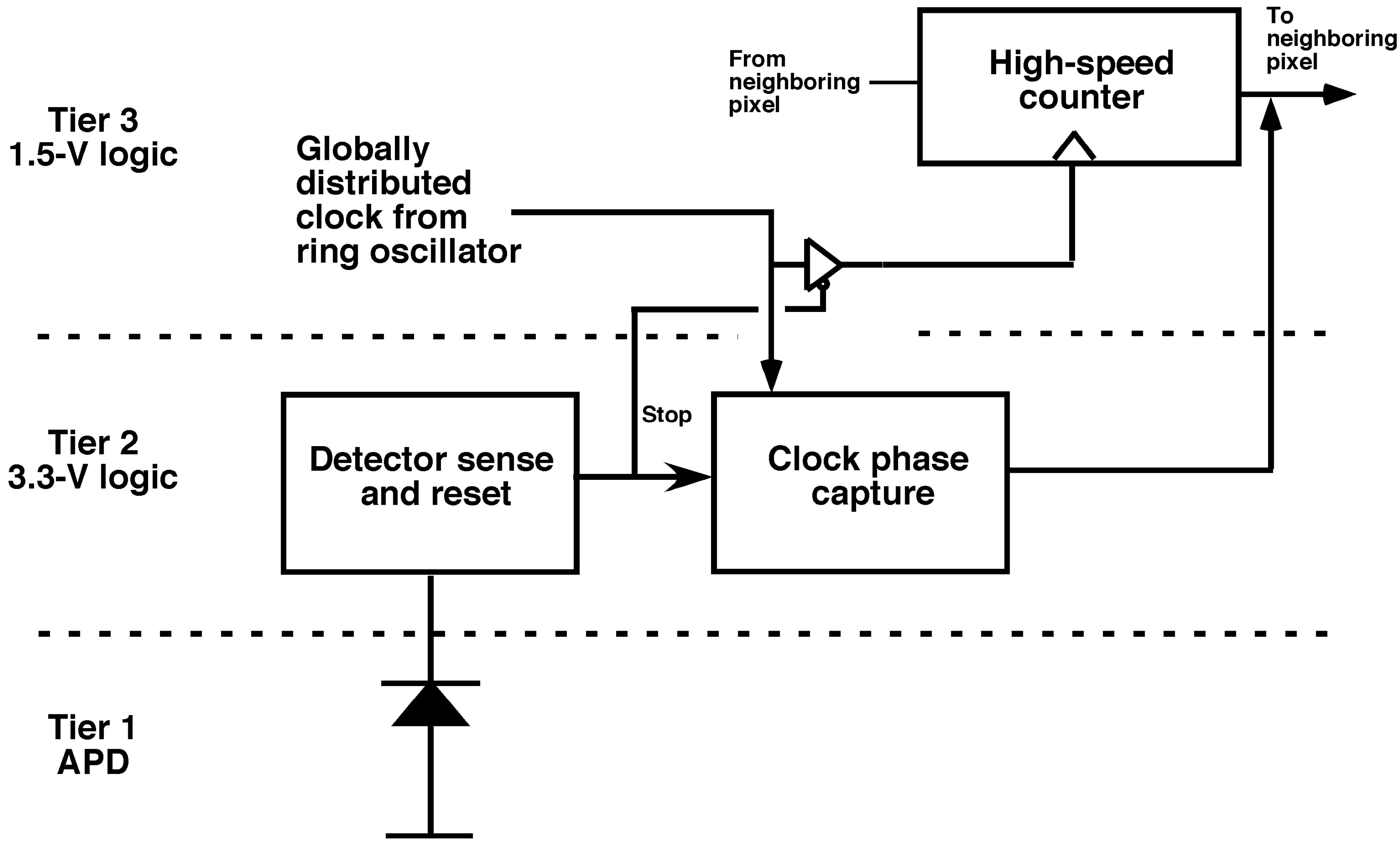


Reset and Quenching

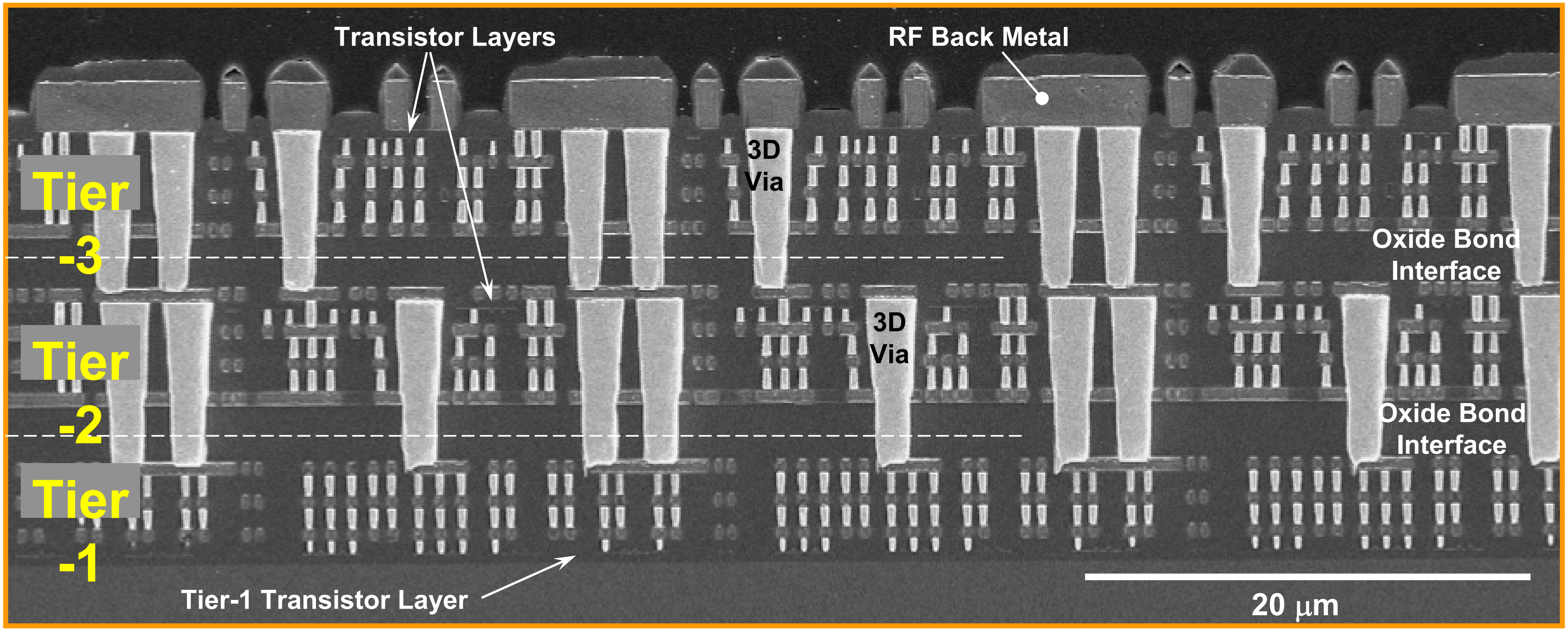




Pixel Block Diagram



3-Tier 3DIC Cross-Section



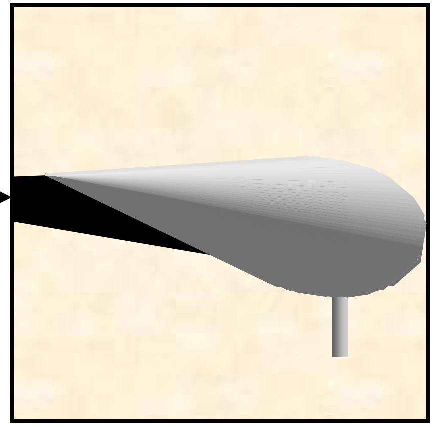
Three FDSOI CMOS Tiers, total active circuit height ~ 21 um

Tier 1 bottom, Tier 2 and Tier 3 inverted and bonded on top, substrates removed

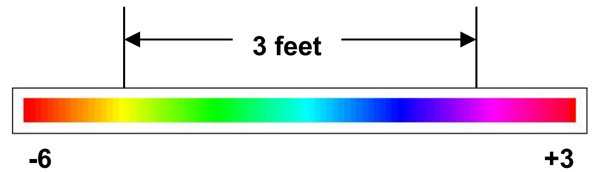
11 metal interconnect layers thick RF top metal

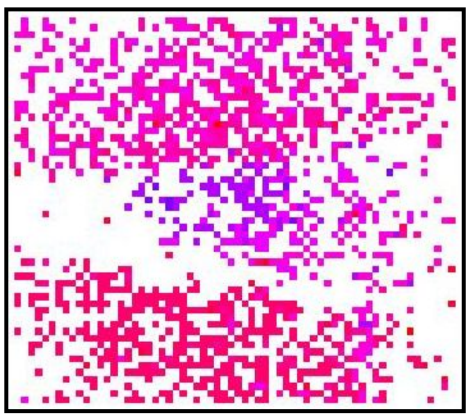
Dense unrestricted 3D vias for electrical connections between tiers

Example of Multiframe Processing

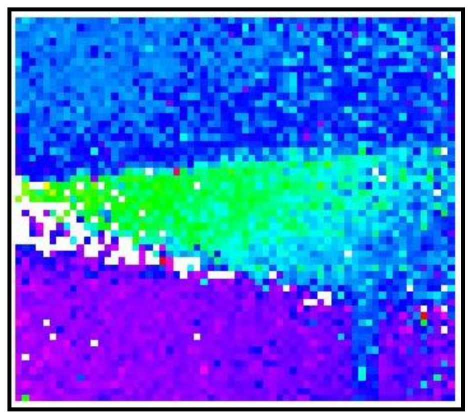


Target:
Cone and Support Post
In Front of Flat Plate

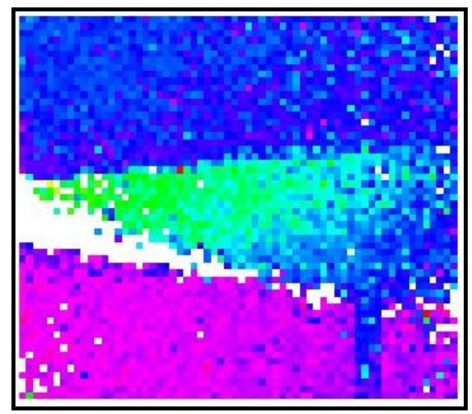




Each frame is filtered to eliminate out-of-range vales. Then frame-to-frame jitter is measured and subtracted out using average timing value over the top ten rows.



21 frames combined by averaging the timing value for each pixel



10 of these 21-frame averages are combined by picking the most common timing value at each pixel (mainly eliminates spurious counts)

Summary

- **CCD imagers continue to demonstrate the highest performance for large-format, broad spectral response, scientific applications**
  - **Leverage enormous investment in silicon-based microelectronics**

- **CMOS technology can bring many attractive features to astronomical detectors via 3D integration**
  - **Gm-APDs for Quantum-limited sensitivity**
  - **Pixel-level digitization and noiseless readout**
- **Continued and desired improvements**
  - **Higher data rates without a noise penalty**
  - **Flexible readout modes with electronic shuttering**
  - **On-chip computation and data thinning**
  - **Design for yield**
- **Will we soon enter the era of smaller, smarter telescopes?**