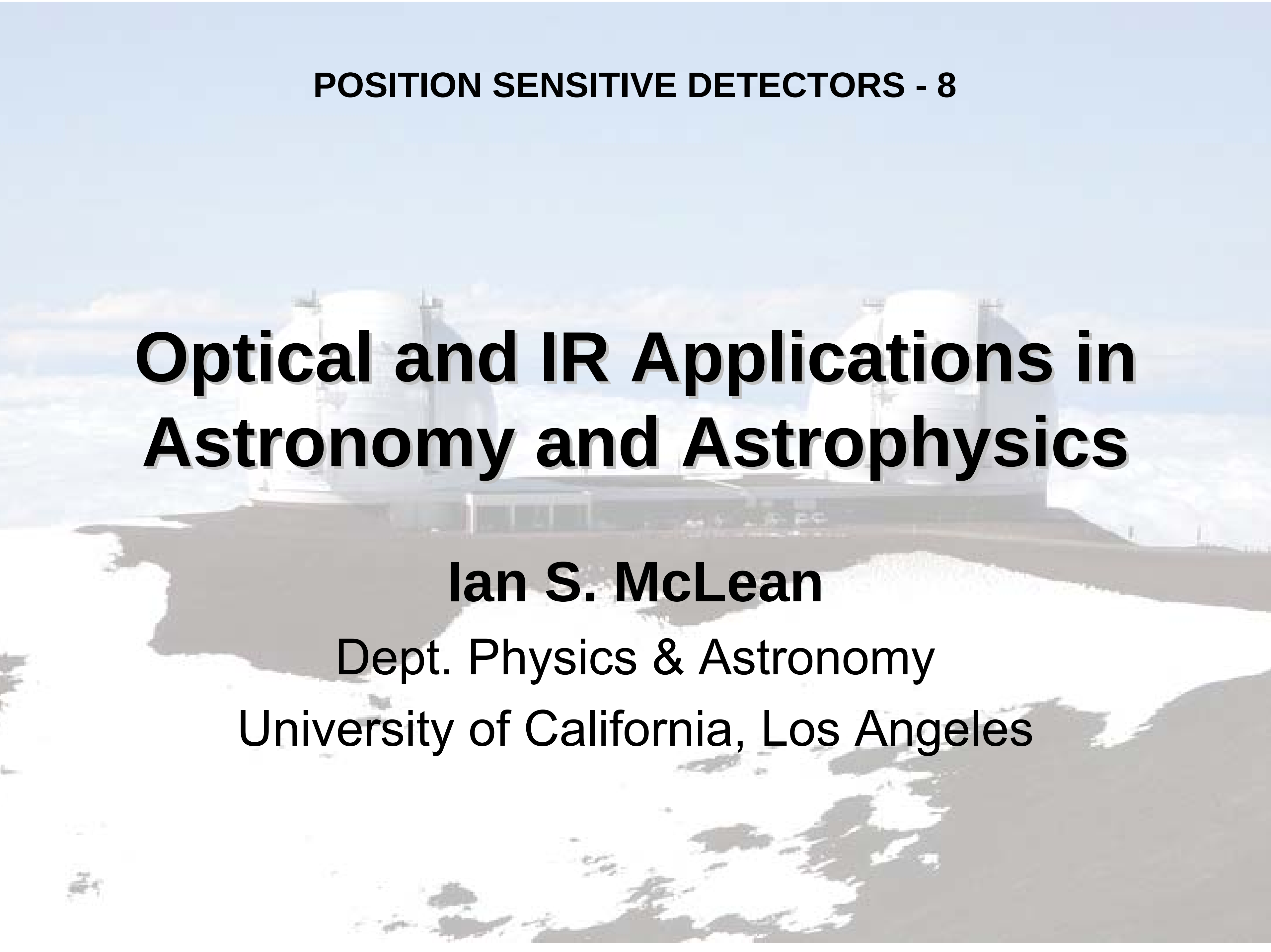


POSITION SENSITIVE DETECTORS - 8

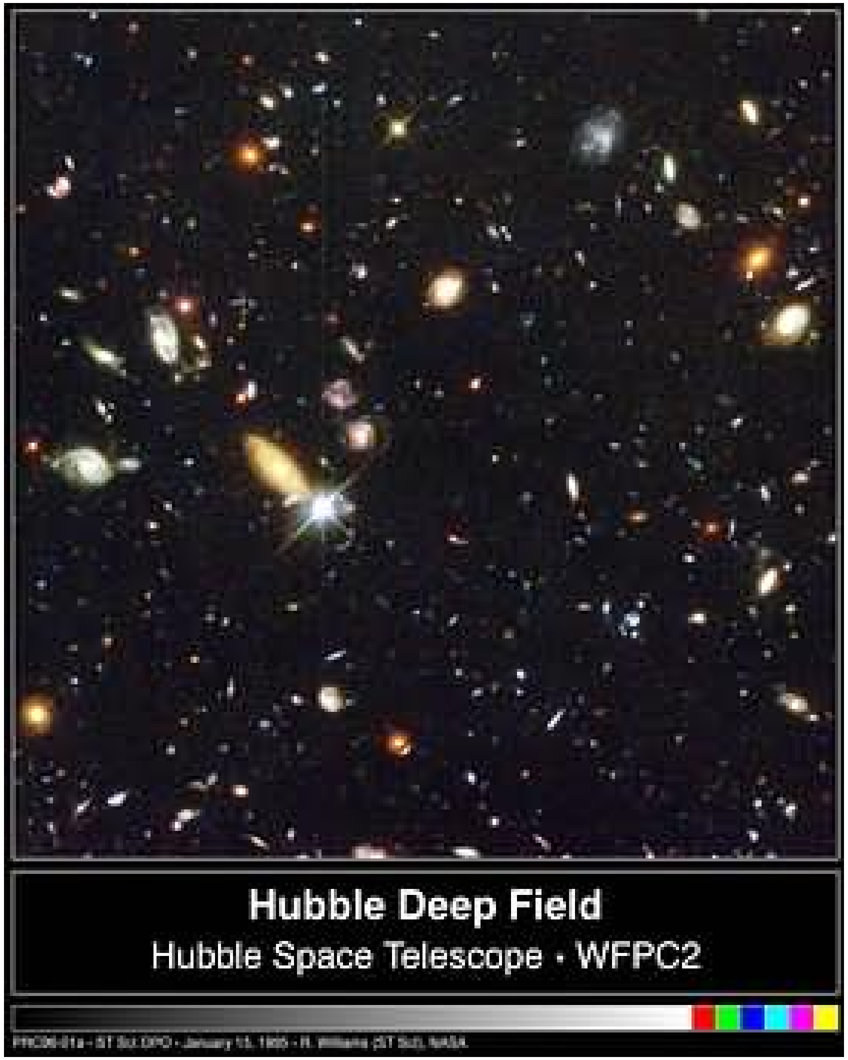
Optical and IR Applications in Astronomy and Astrophysics

Ian S. McLean

Dept. Physics & Astronomy

University of California, Los Angeles

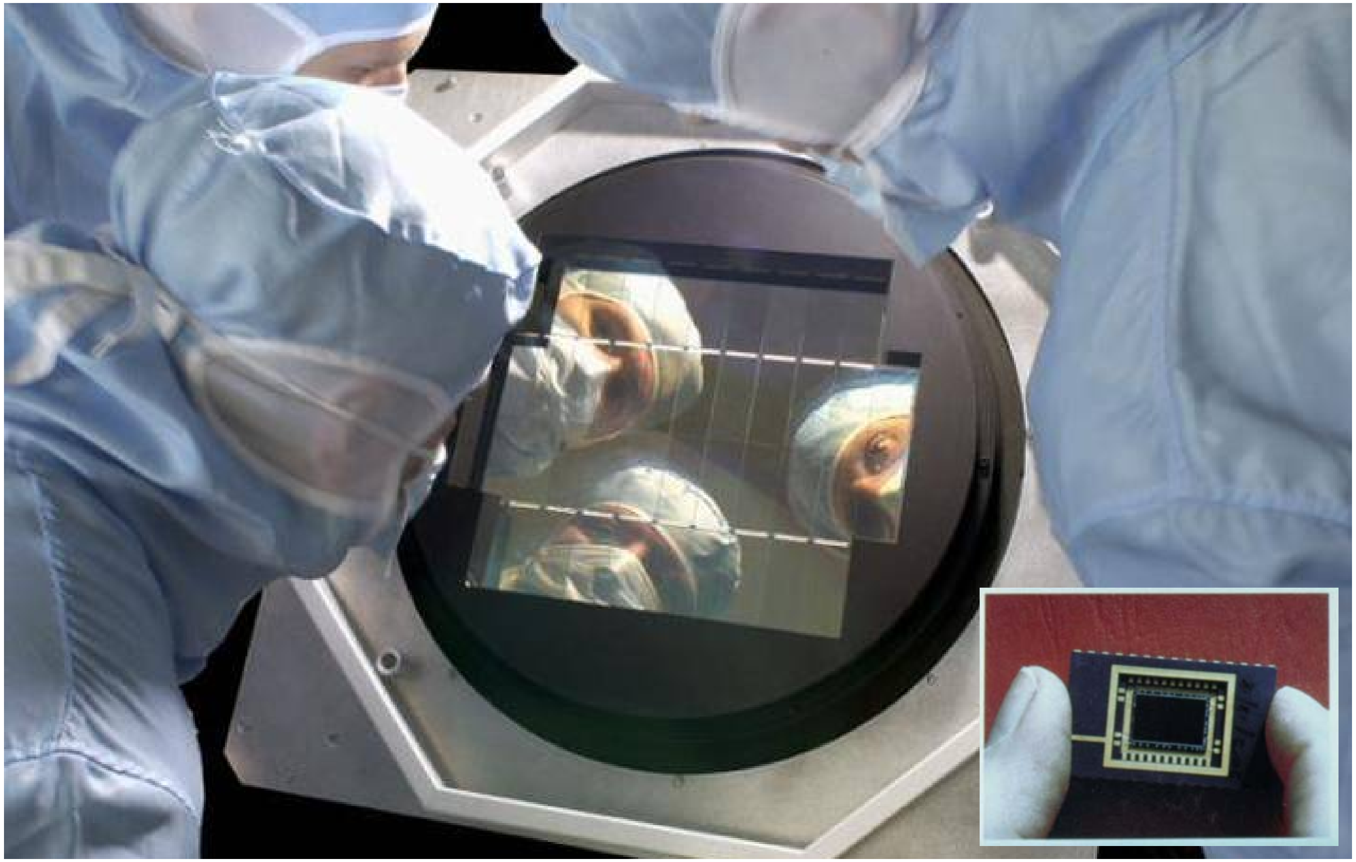
INTRODUCTION



- **400th anniversary of the telescope**, it is interesting to review the evolution of astronomical imaging
- For astronomers, **electromagnetic radiation** remains the dominant source of information about the cosmos
- Our understanding of the universe has always been related to
  - Deeper surveys of the cosmos reaching to ever fainter objects
  - Higher angular resolution yielding more fine detail
  - Larger statistical samples
  - Broader spectral response to sample all wavelengths
- Imaging (position-sensitive) devices have always been at the heart of all astronomical instruments – eyes, photography …

Charge-Coupled Devices

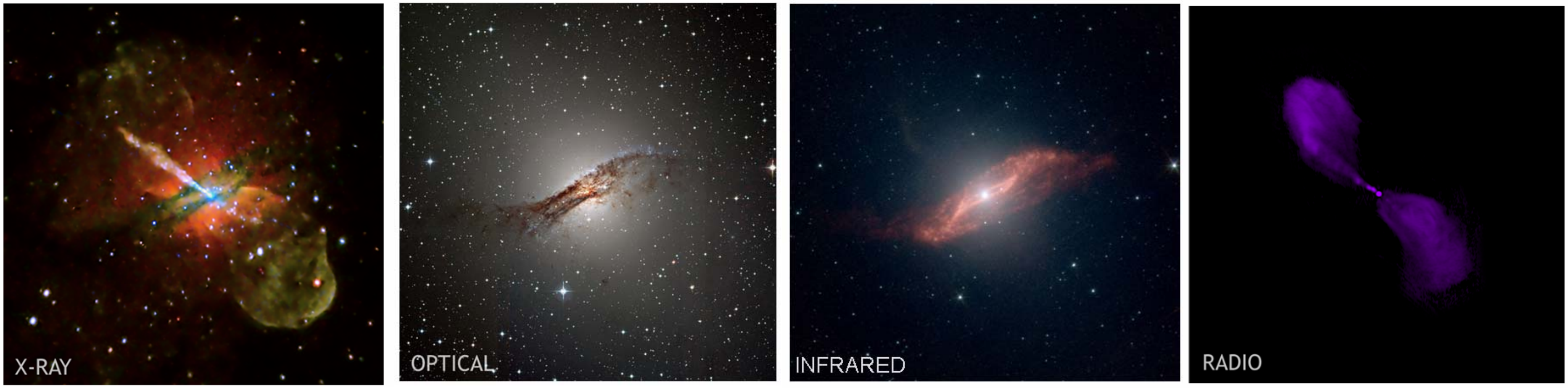
- Modern astronomical research is carried out using photo-electric equipment, but it was surely the introduction of the Charge-Coupled Device (CCD) in the late seventies that capped off the revolution from “**eyes to electronic sensors**”



40 CCDs with 2Kx4K pixels compared with an early 512x320 CCD

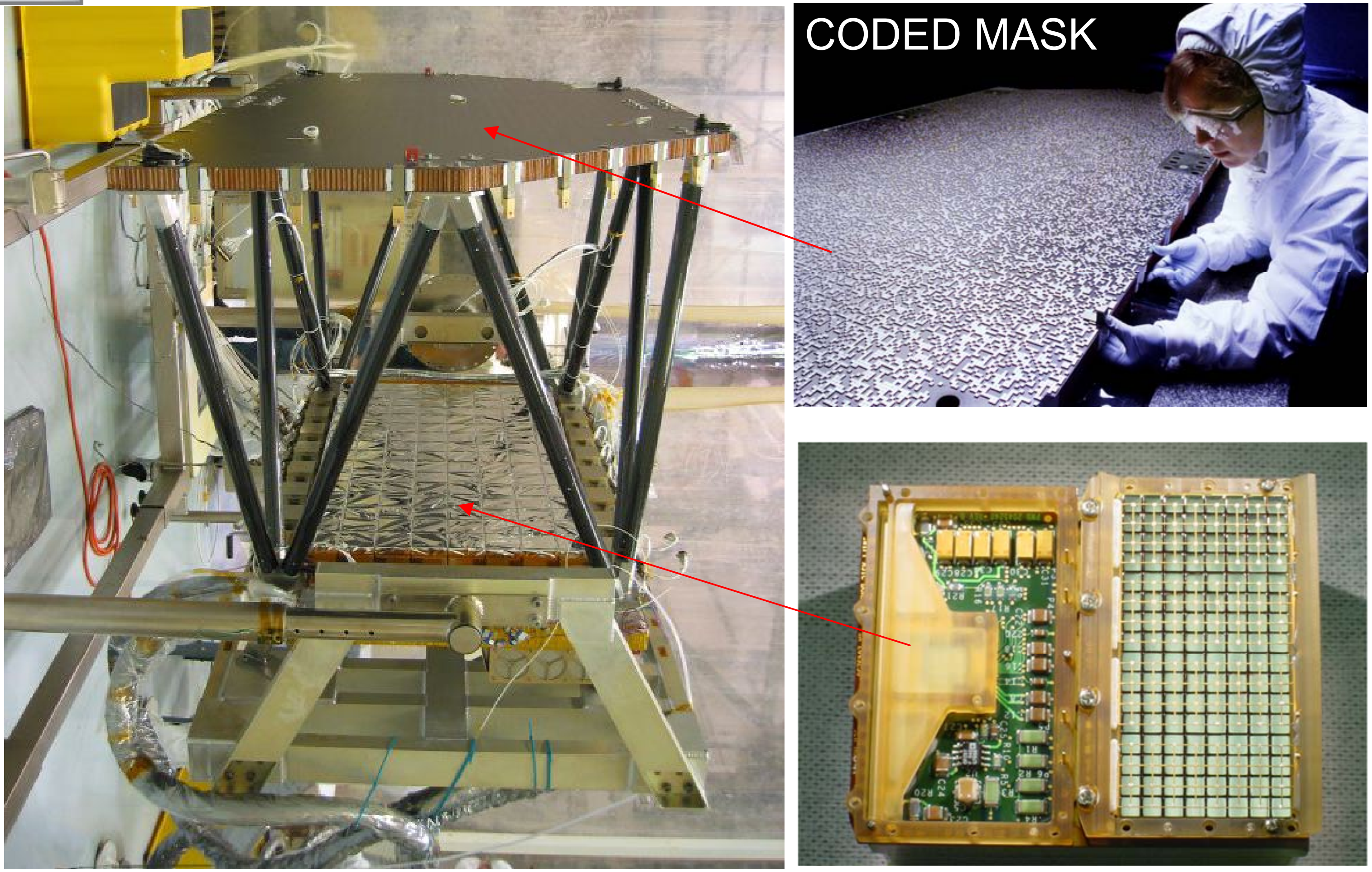
Imaging across the spectrum

- Over the last two decades a remarkable range of position-sensitive detectors have emerged e.g.
  - CZT arrays for gamma ray imaging
  - Silicon CCDs for X-ray, UV and visible imaging
  - HgCdTe, InSb, Si:As, Ge:Ga for infrared
  - Transition Edge Sensors for sub-mm

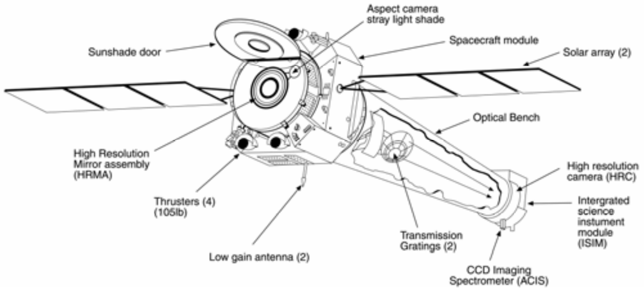


Centaurus A: X-ray, visible, infrared and radio images

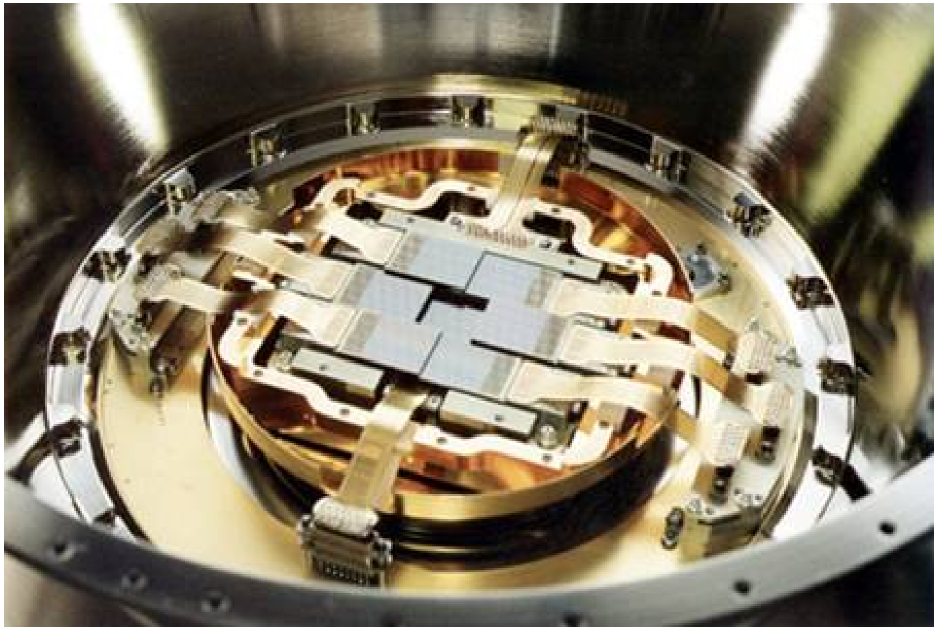
Examples: Gamma rays



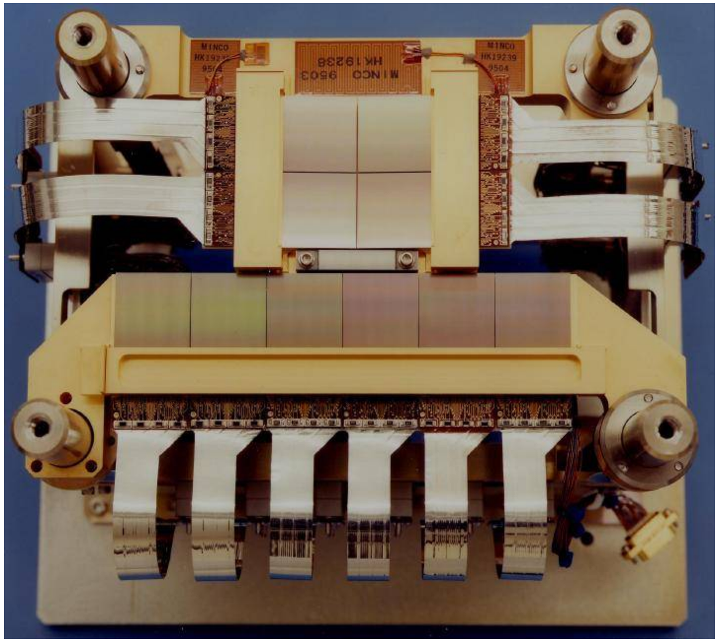
- A large mosaic of CZT “pixels” at the focus of the **SWIFT** gamma ray Burst Alert Telescope



X-rays



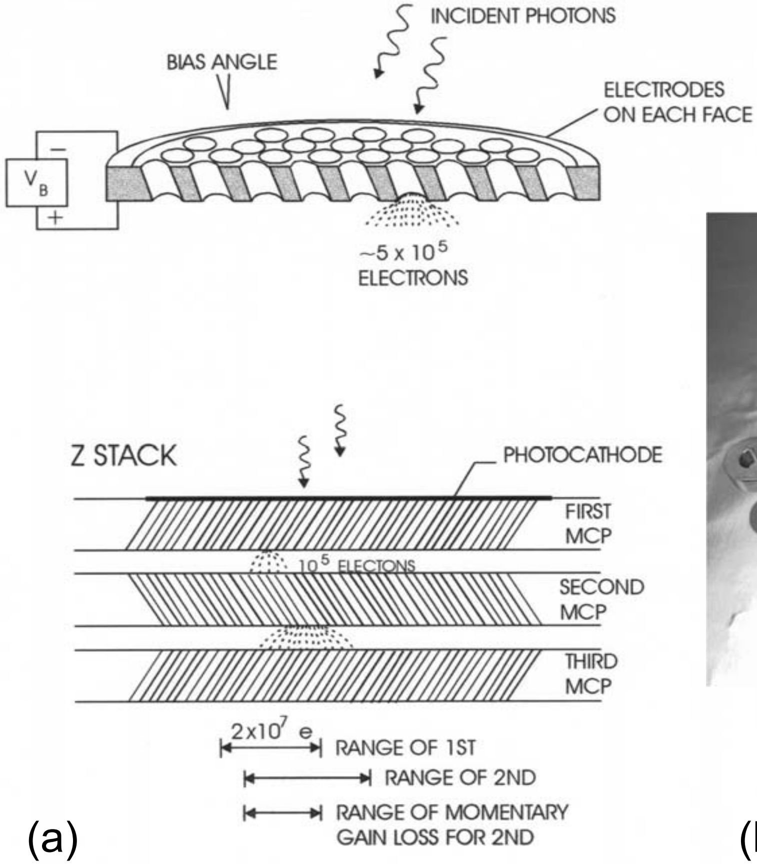
(a)



(b)

- One remarkable feature of the CCD is that it can also detect X-ray photons
- Figures (a) and (b) show the CCD cameras on XMM-Newton and the Chandra X-ray Observatory
- X-ray imaging with 0.5″ resolution on the sky is routinely possible

Ultra-Violet

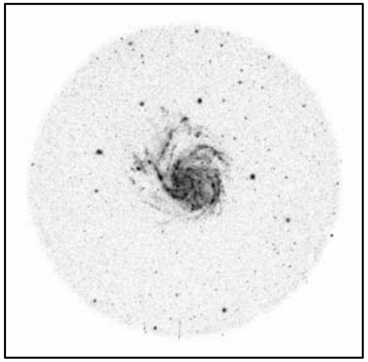


(a)

(b)

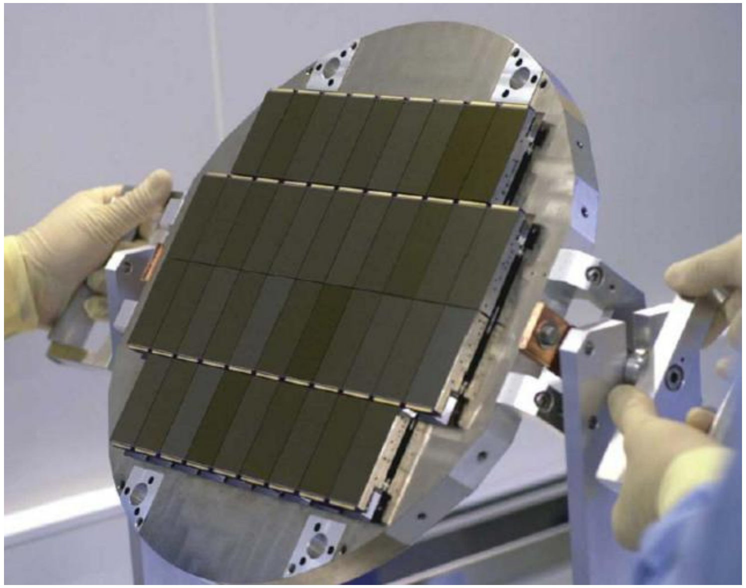
68 mm diameter MCP

GALEX UV image of “tail” behind the pulsating star Mira



- UV micro-channel plate cameras used on GALEX

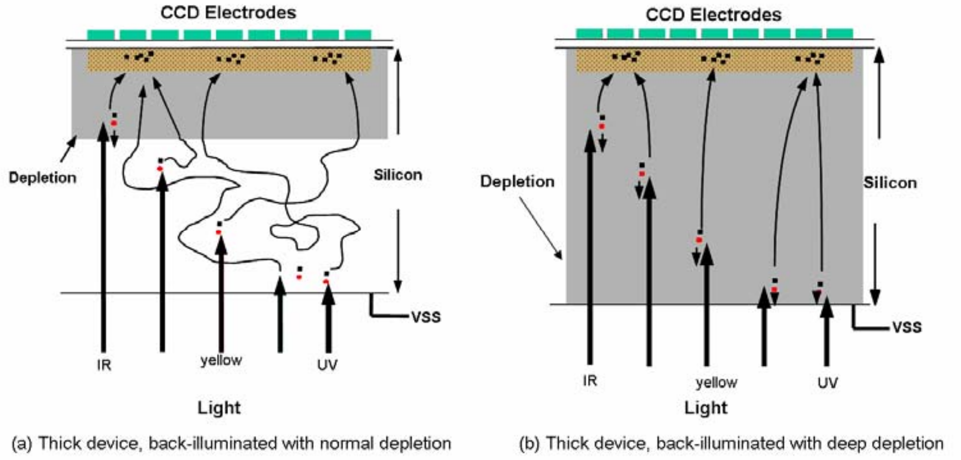
VISIBLE LIGHT



- CCDs are ubiquitous
- All telescopes – small to large
- Cameras
- Spectrometers
- Other instruments
- Large mosaics ➔ 40+ CCDs
- Many variations:
  - Deep depletion devices for excellent IR response
  - Electron-Multiplied CCDs for extremely low noise at high speeds
  - Orthogonal Transfer CCDs for active tracking of image tip/tilt

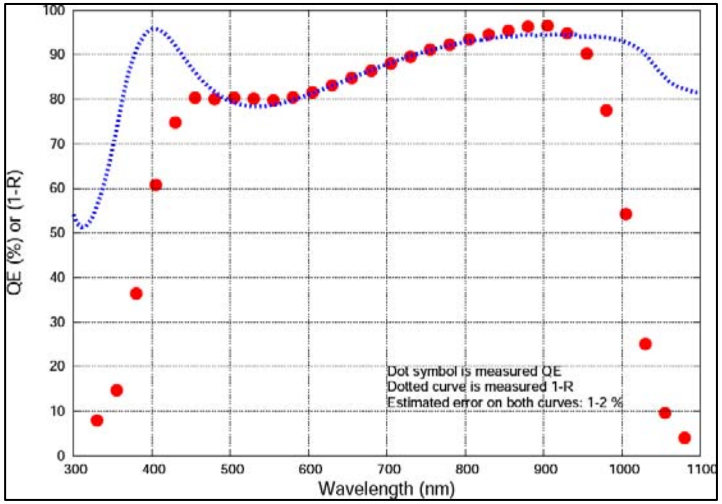
Varieties of CCDs in Use

Deep depletion



(a) Thick device, back-illuminated with normal depletion

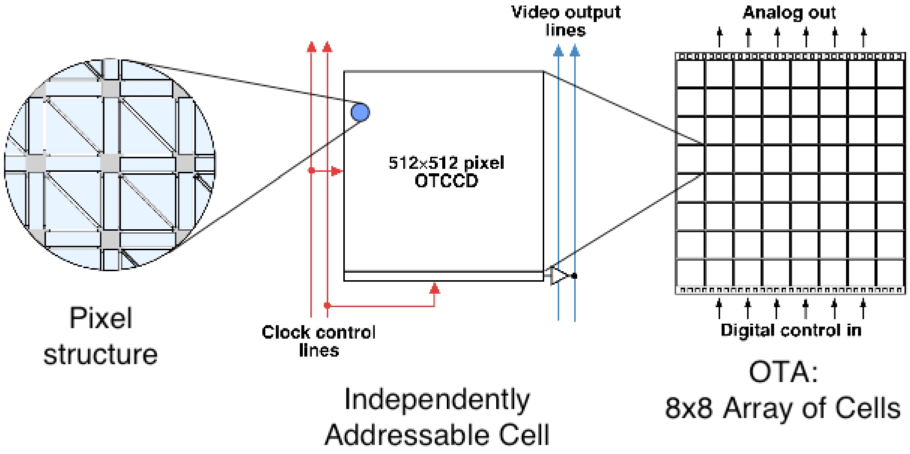
(b) Thick device, back-illuminated with deep depletion



Very high red QE from deep depletion chips

- **Partition a conventional large-area CCD imager into an array of independently addressable cells.**

OTCCDs

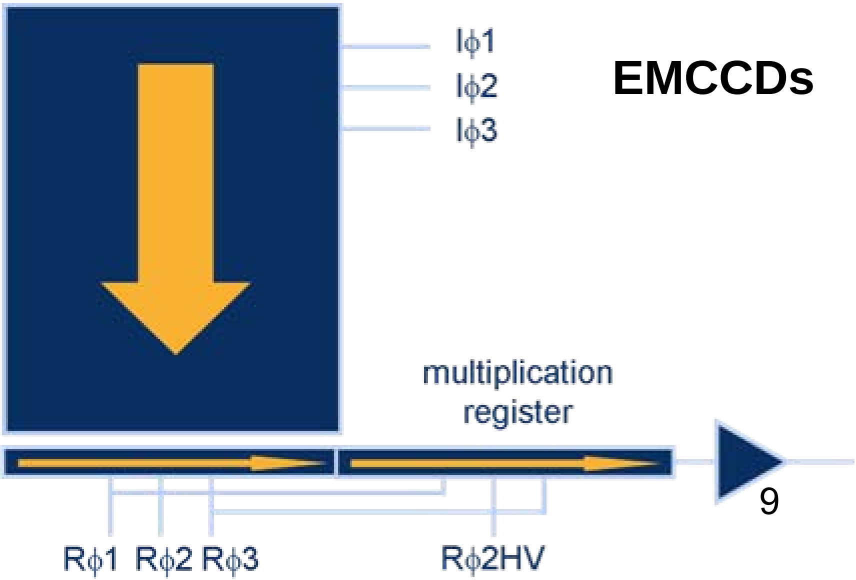


Pixel structure

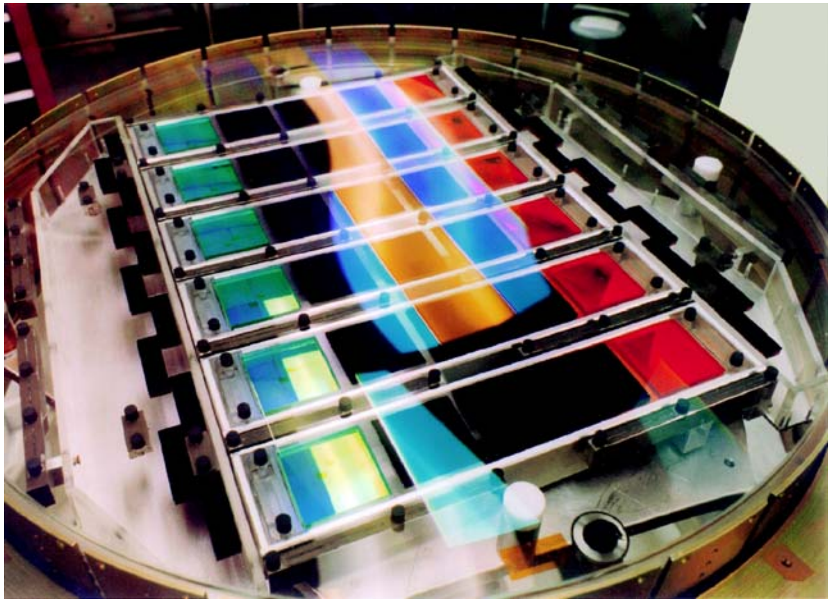
Independently Addressable Cell

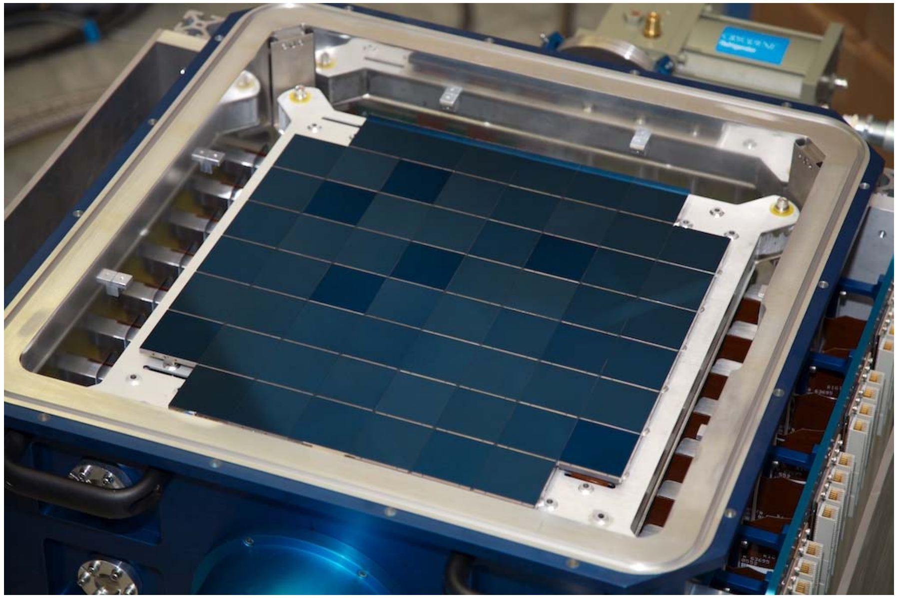
OTA:
8x8 Array of Cells

EMCCDs

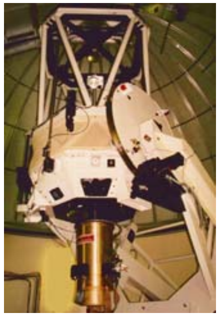


CCD mosaics - digital sky surveys

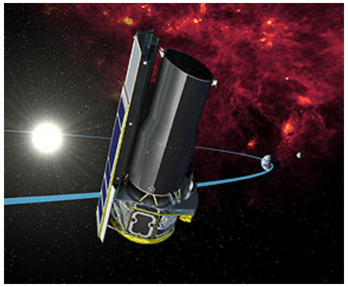




- Sky surveys are now digital
  - e.g. the Sloan Digital Sky Survey (SDSS)
- Visible light cameras now at Gigapixel levels
  - e.g. the orthogonal transfer CCDs for Pan-STARRS

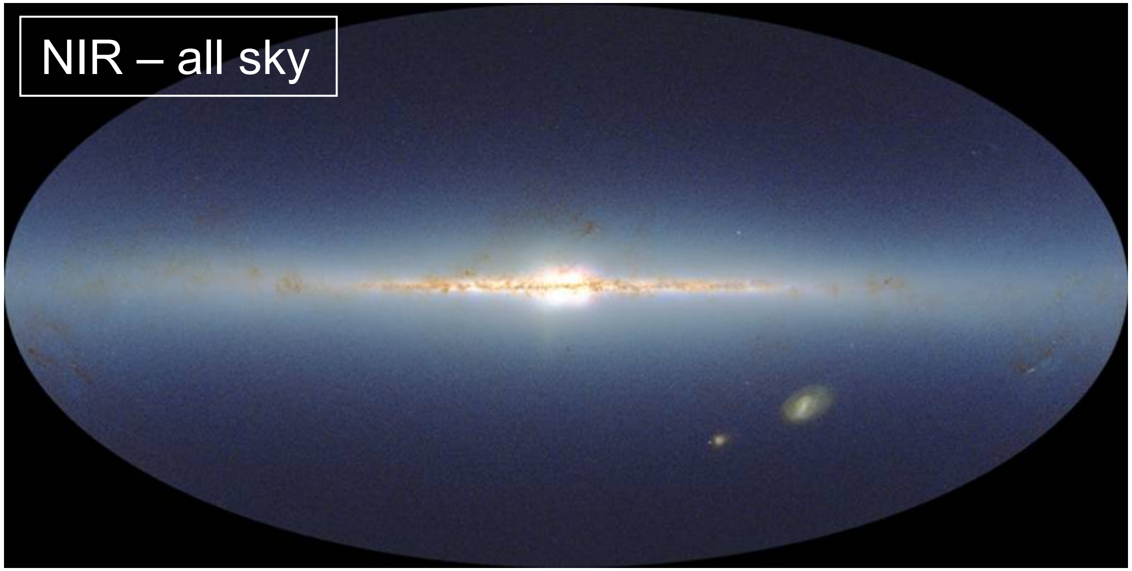


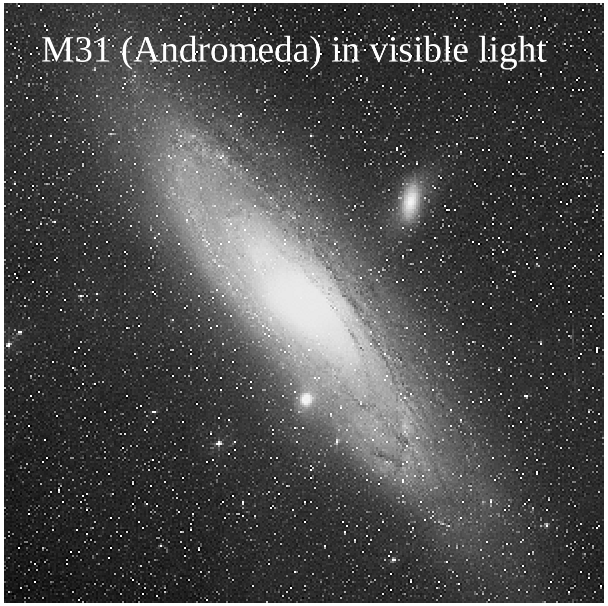
Infrared

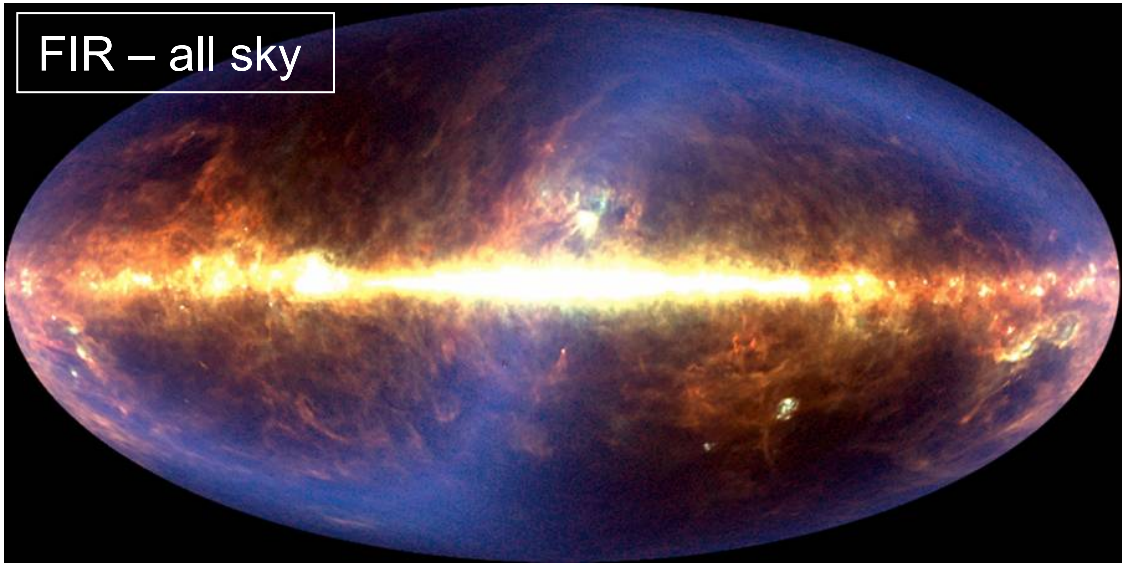


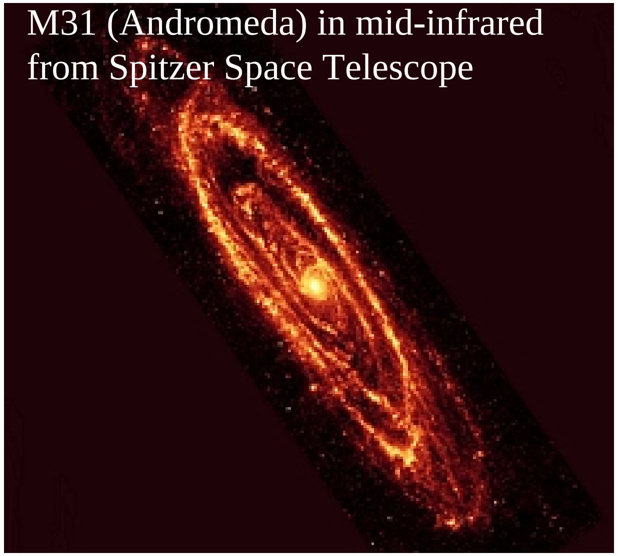
- Band-gap energy limits silicon CCDs to wavelengths less than 1100 nm
- No precursor like photographic emulsions ➔ the impact of infrared arrays was perhaps even greater than that of CCDs.
- All-sky surveys such as the 2 Micron All Sky Survey (**2MASS**) became possible in the near-infrared (1-2.5 μm) in late 90s
- Hubble-class infrared space missions such as the **Spitzer Space Telescope** (3-150 μm) became possible (2003).

Infrared (1-150 μm)

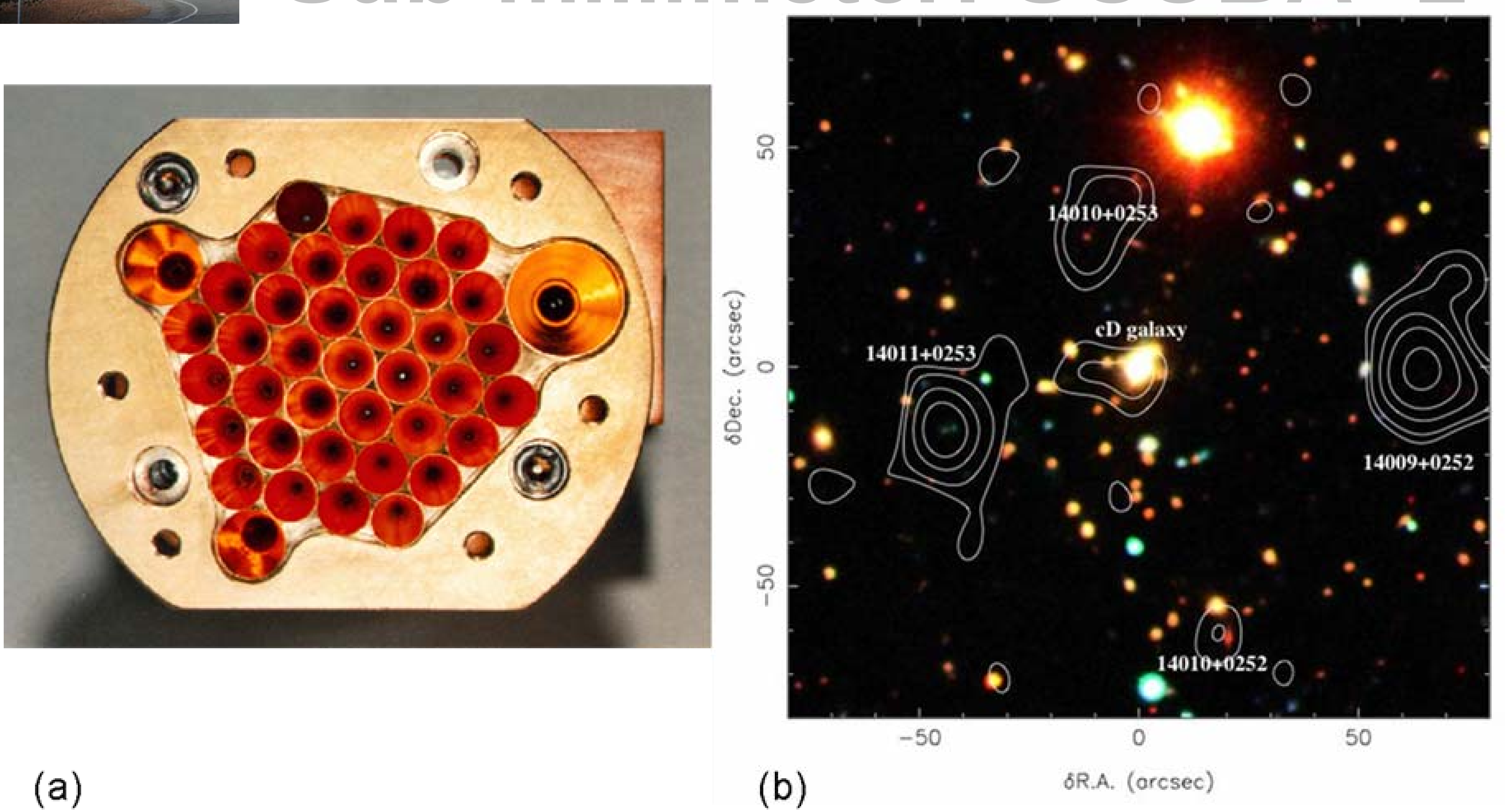

NIR – all sky


M31 (Andromeda) in visible light


FIR – all sky

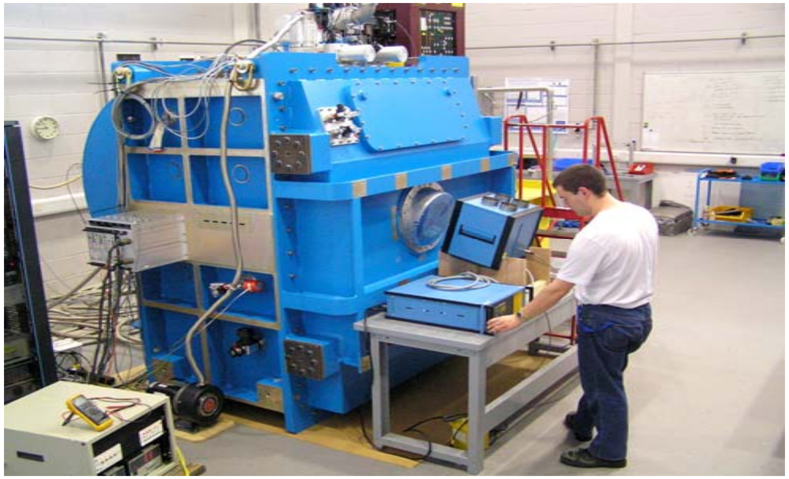

M31 (Andromeda) in mid-infrared
from Spitzer Space Telescope

Sub-millimeter: SCUBA -1



Bolometer arrays have extended the imaging capability to 850 μm

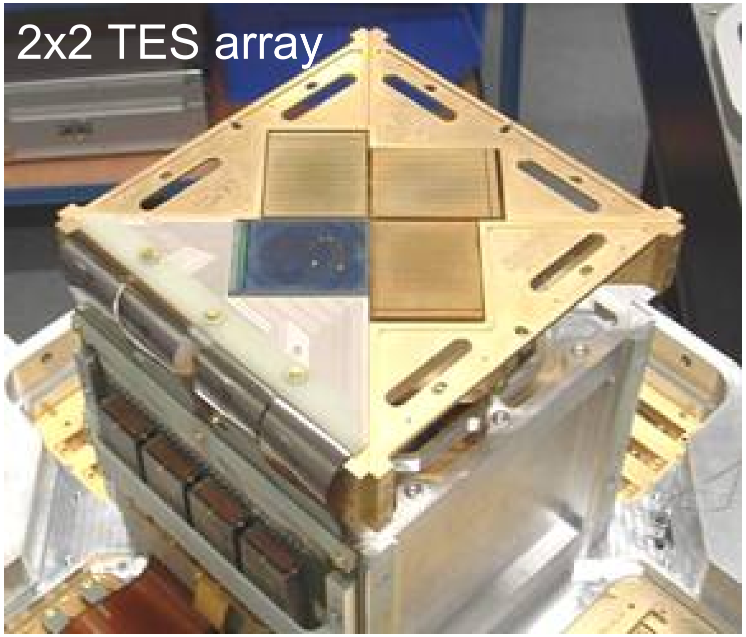
SCUBA-2

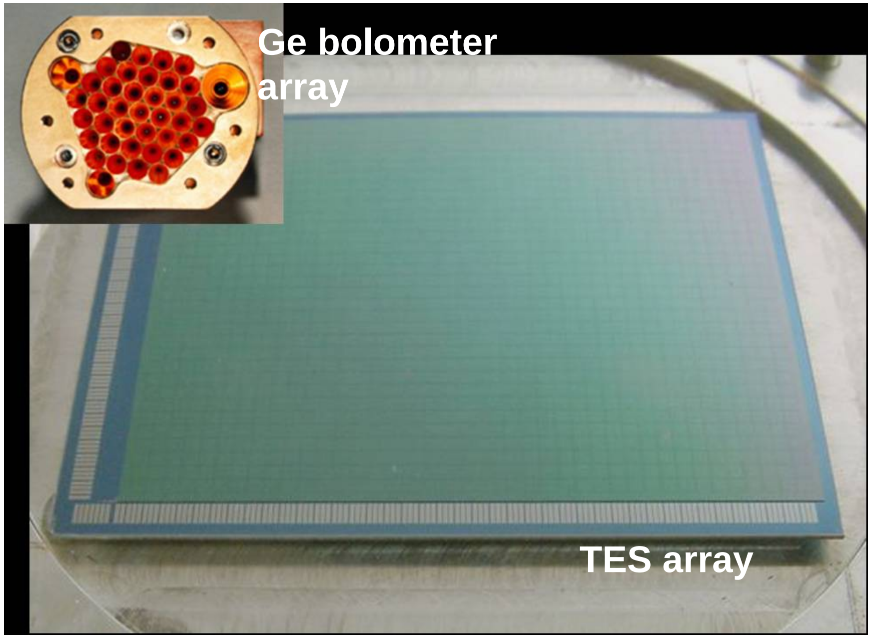


CCD-like imaging is now possible in the sub-mm regime using an array of Transition Edge Sensors

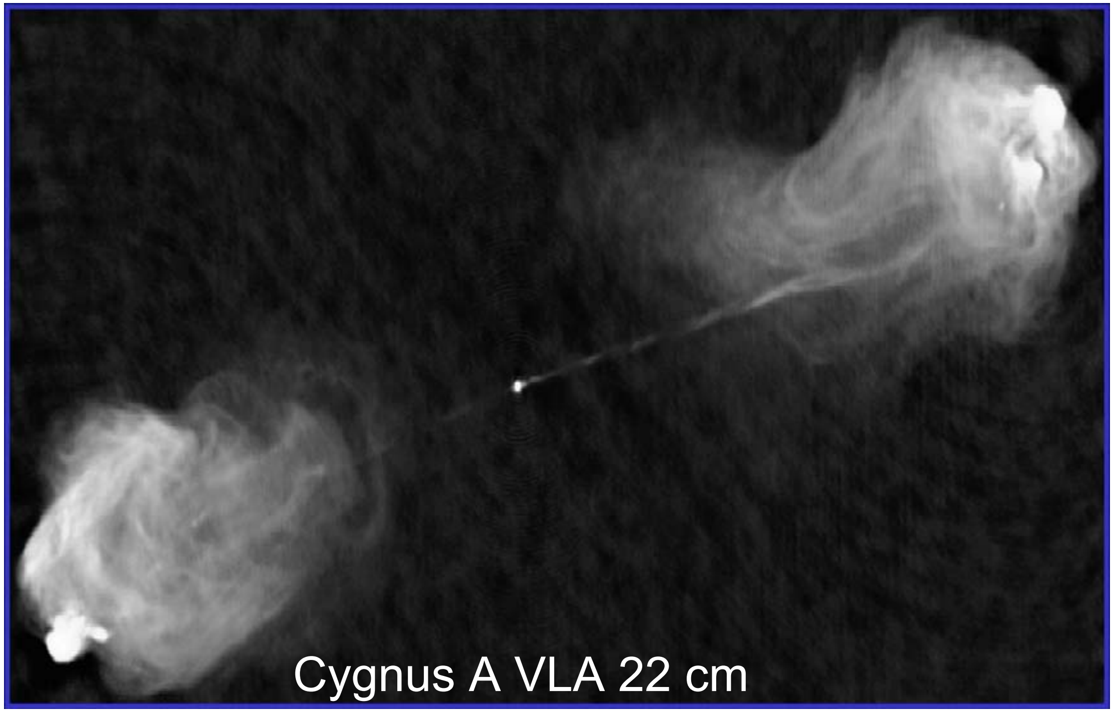
This 2 x 2 mosaic will have about 4000 pixels

Compare the layout to the bolometer array from SCUBA-1

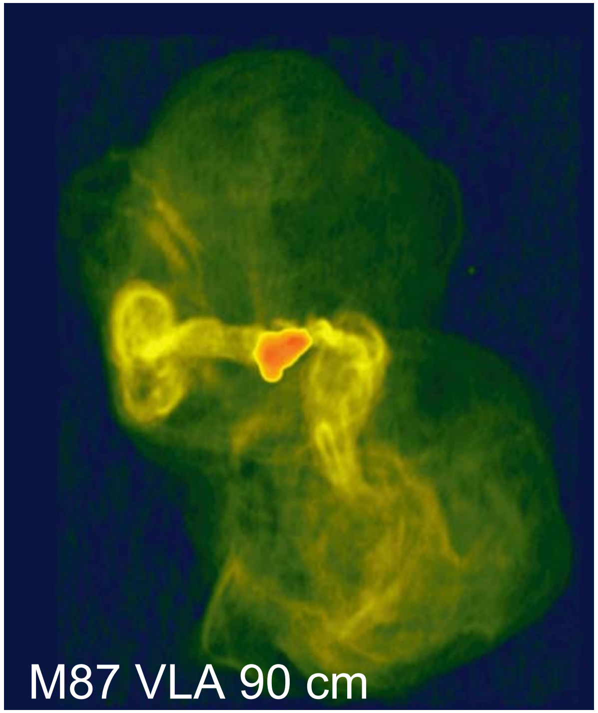




Radio mapping



Cygnus A VLA 22 cm

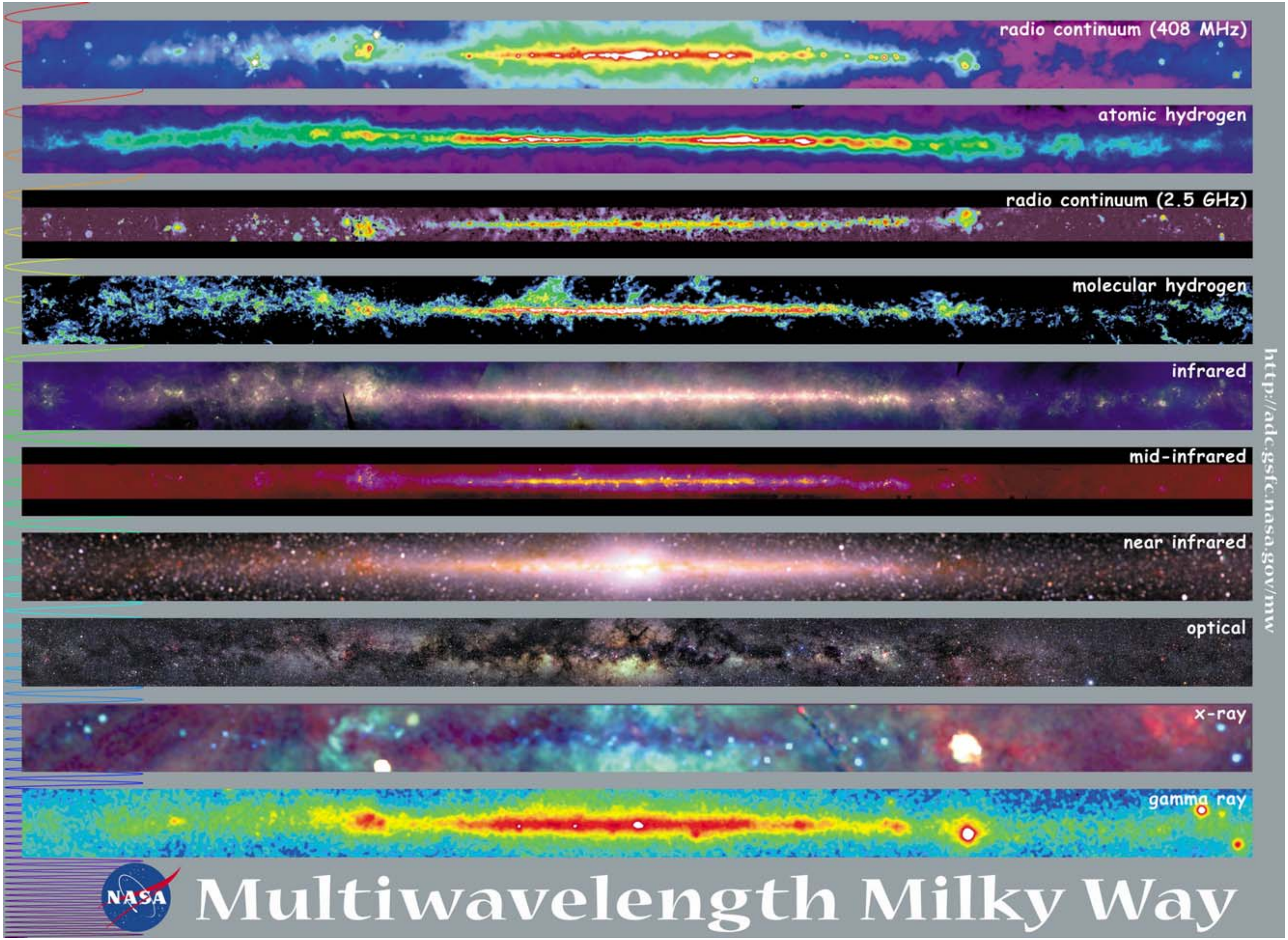


M87 VLA 90 cm

Mostly mapping by single apertures or interferometer arrays

Increasing use of multiple horns and SIS mixers

MULTI-WAVELENGTH IMAGING



BUT THERE IS MORE …

ACHIEVING THE DIFFRACTION LIMIT

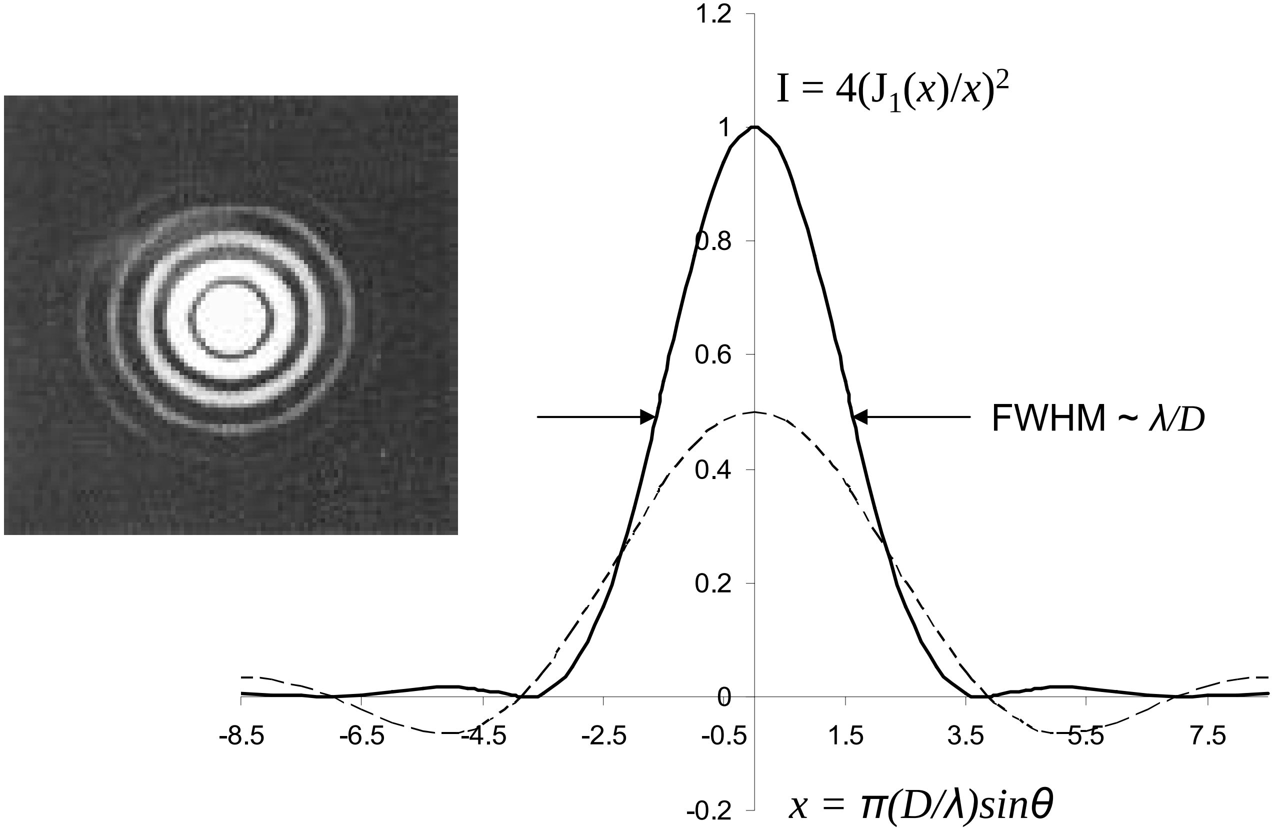
- The twin 10-meter telescopes of the W. M. Keck Observatory
- Operated by the California Association for Research in Astronomy (CARA) on behalf of the University of California and Caltech, in collaboration with NASA

Collecting area scales as the area D^2

Angular resolution is inversely proportional to D ($\sim\lambda/D$)

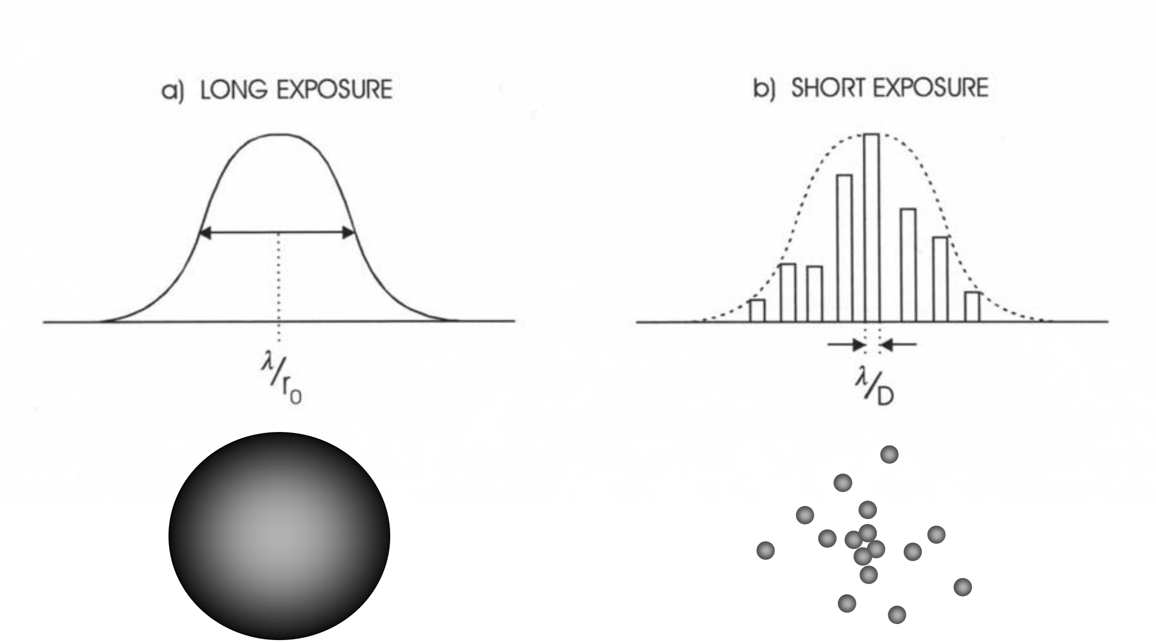
But “seeing” limits angular resolution to ($\sim\lambda/r_0$) where $r_0 << D$

DIFFRACTION LIMIT



- The Airy diffraction pattern for a circular aperture
- For the Keck telescope at λ = 1 μm the FWHM = 0.020″

THE ORIGIN OF SEEING



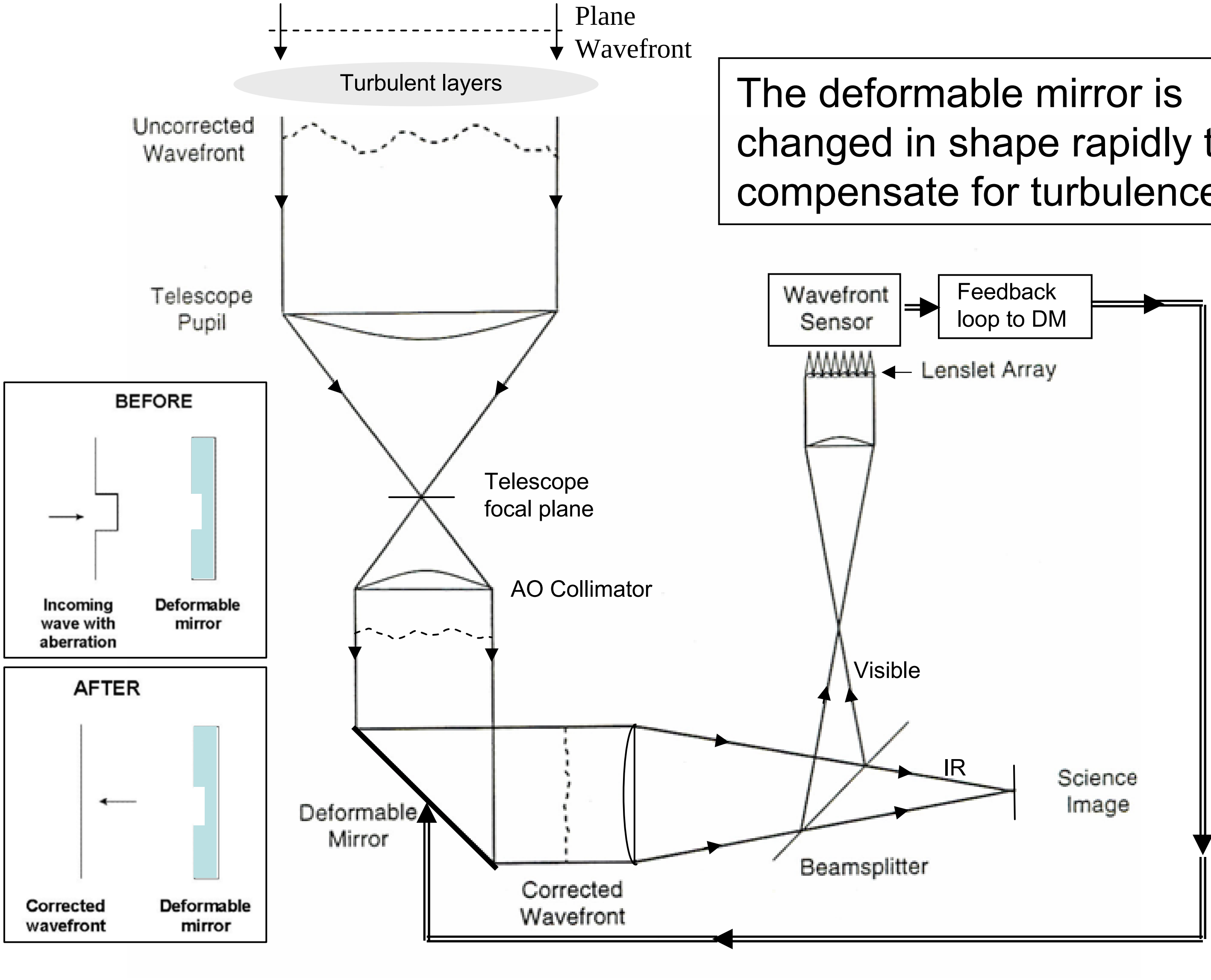
SEEING DISK

SPECKLES

- Turbulence displaces and blurs out all the instantaneous, diffraction-limited images into a “seeing disk”
- Size of seeing disk is determined by Fried parameter (r_0) which gives equivalent aperture for diffraction-limited performance
- Typically r_0 ~ 20 cm so the seeing is ~1″

ADAPTIVE OPTICS SYSTEMS

The deformable mirror is changed in shape rapidly to compensate for turbulence



)

LASER GUIDE STARS

Sodium laser beacon projecting from the Keck 2 telescope

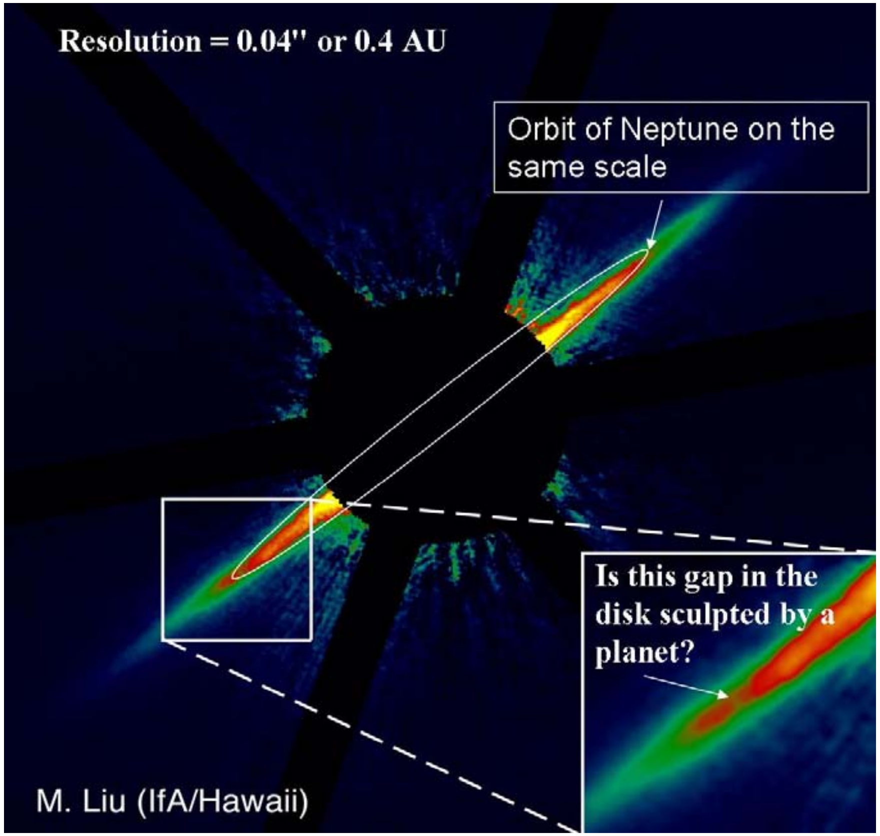
An artificial star is produced because of the thin sodium later at 92 km

The sodium beacon provides a bright reference star for any point on the sky

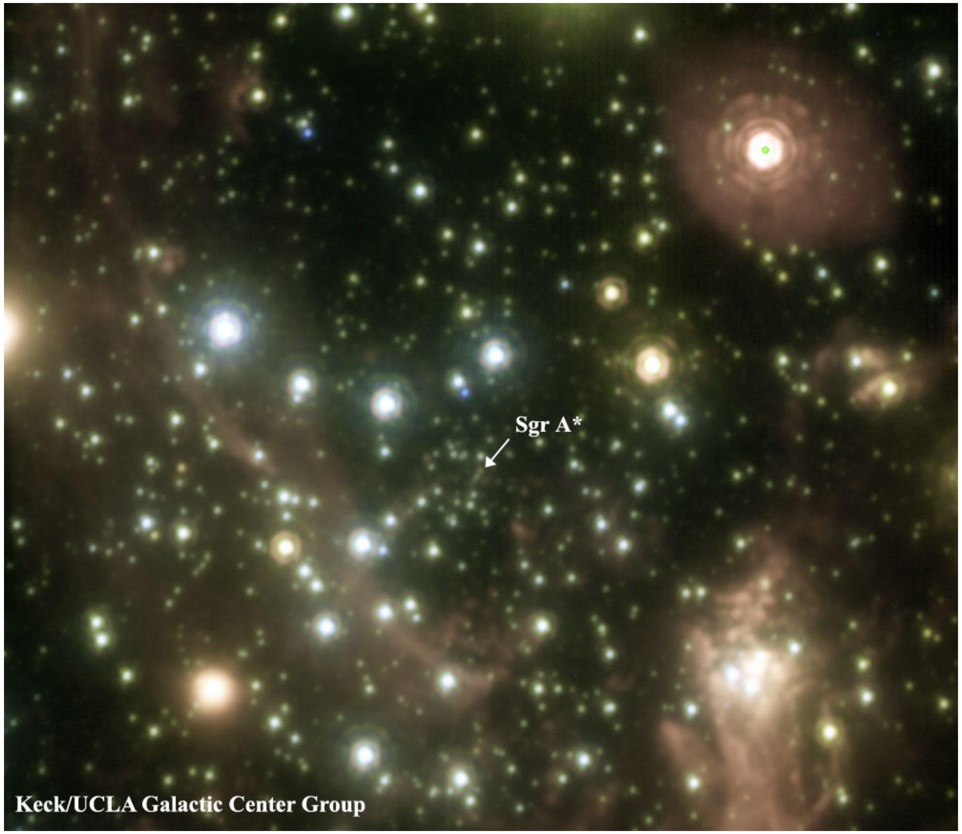
AO correction can now routinely put over 50% of the light into the central peak of the Airy pattern in the near IR

INFRARED ASTRONOMY BENEFITS: IR arrays on diffraction-limited telescopes

The Power of Adaptive Optics



M. Liu (IfA/Hawaii)



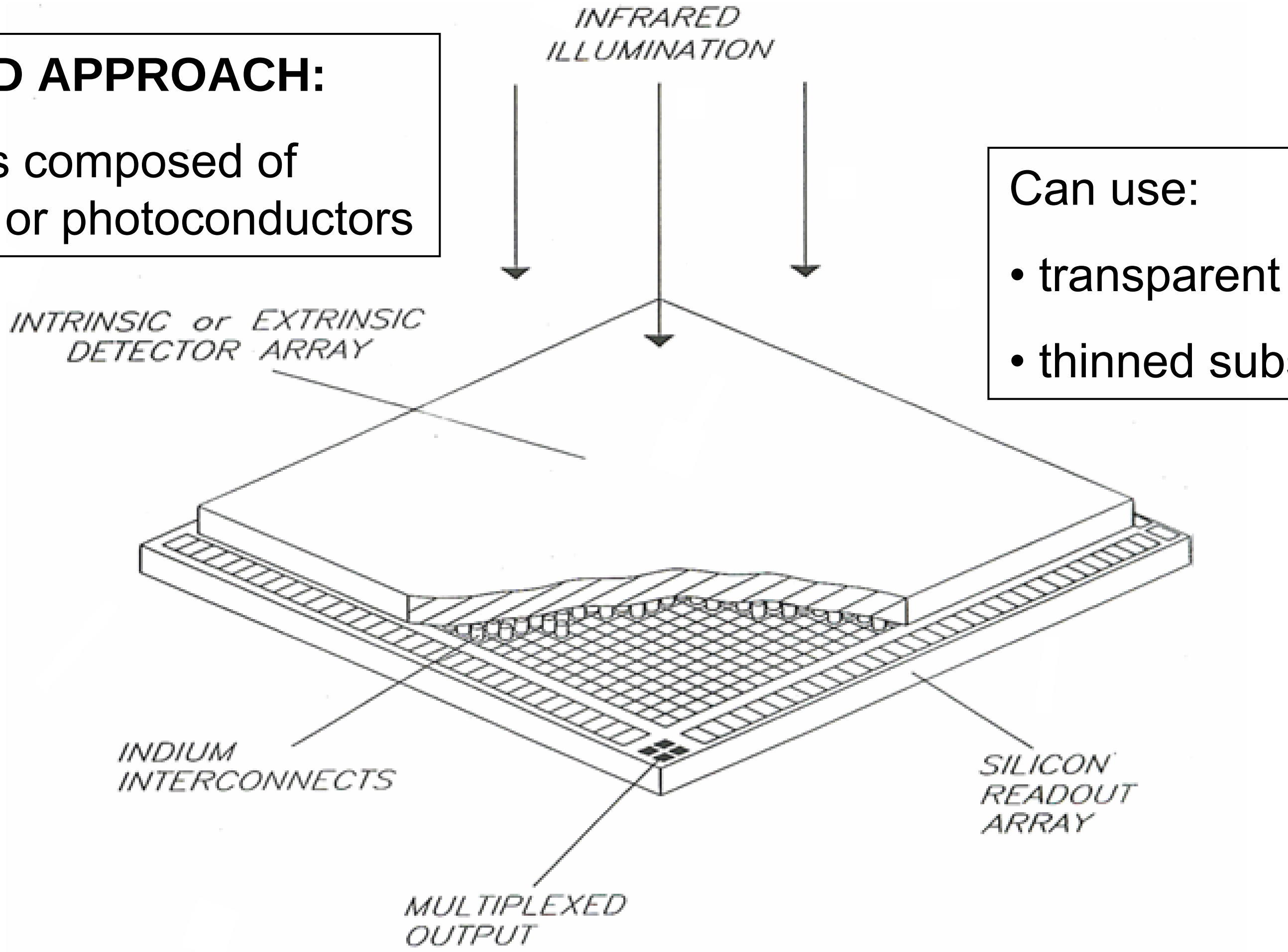
Keck/UCLA Galactic Center Group

- AU Mic – a very nearby star with a pre-planetary disk
- Galactic Center – central parsec of Galaxy at distance of ~26,000 light years – track orbital motions of stars around Black Hole

INFRARED DETECTORS

THE HYBRID APPROACH:

Upper slab is composed of photodiodes or photoconductors



Can use:

- transparent substrate
- thinned substrate

Lower slab (silicon) could be a CCD but is usually an array of source followers per detector multiplexed by CMOS shift registers

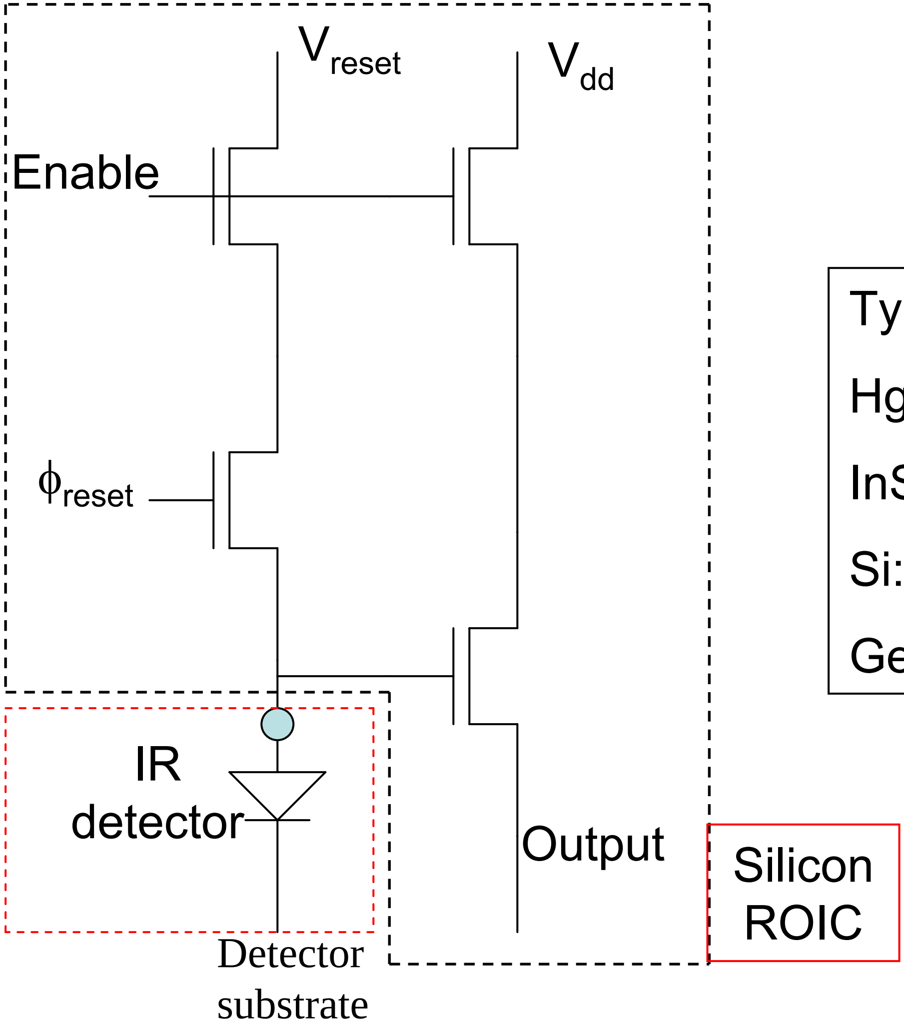
Typical Unit Cell

Basic properties are the same as those of CCDs:

Read noise

Quantum efficiency

Dark current



Typical materials:

HgCdTe (< 5 μm)

InSb (< 5 μm)

Si:As (< 30 μm)

Ge:Ga (< 150 μm)

FORMATS:

2K x 2K for < 5 μm

1K x 1K for Si:As

32 x 32 for Ge:Ga

Infrared Detectors

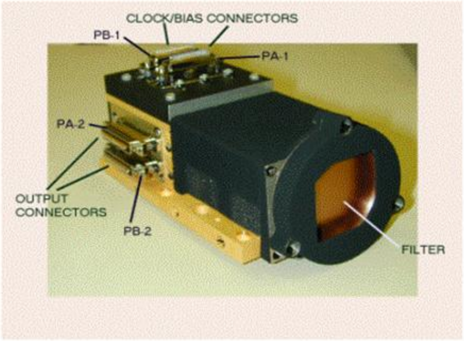
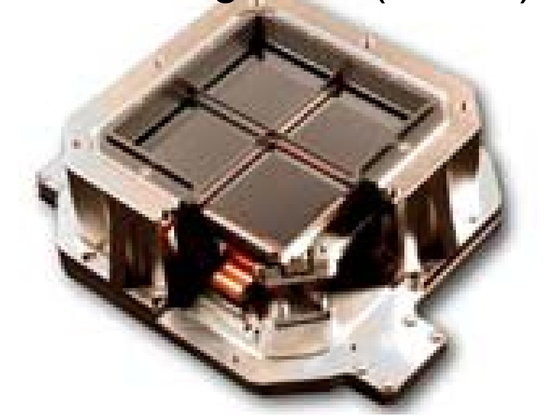


Figure 5. MIPS Flight 70 µm Array

Ge:Ga array (32 x 32) on Spitzer

2 x 20 Ge:Ga stressed

4k x 4k HgCdTe (JWST)



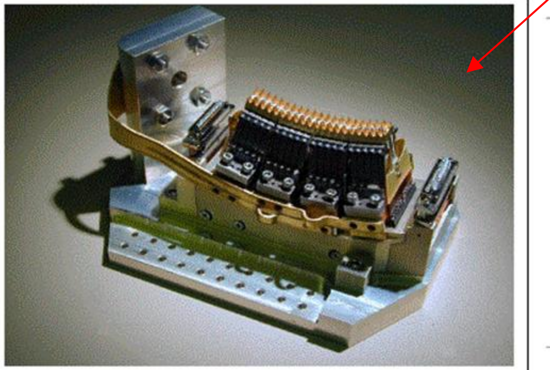
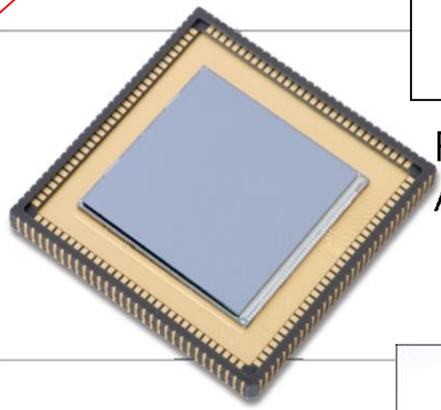
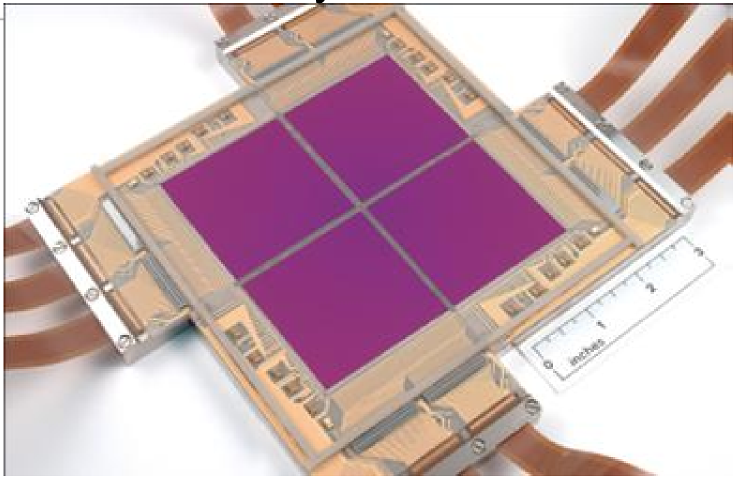


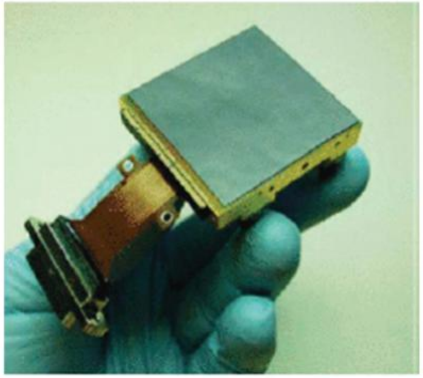
Figure 6. MIPS 160 µm Stressed Ge:Ga Array

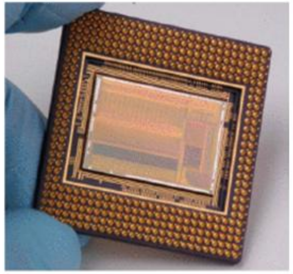


Raytheon IBC
Aquarius 1kx1k Si:As

Raytheon 4k x 4k InSb

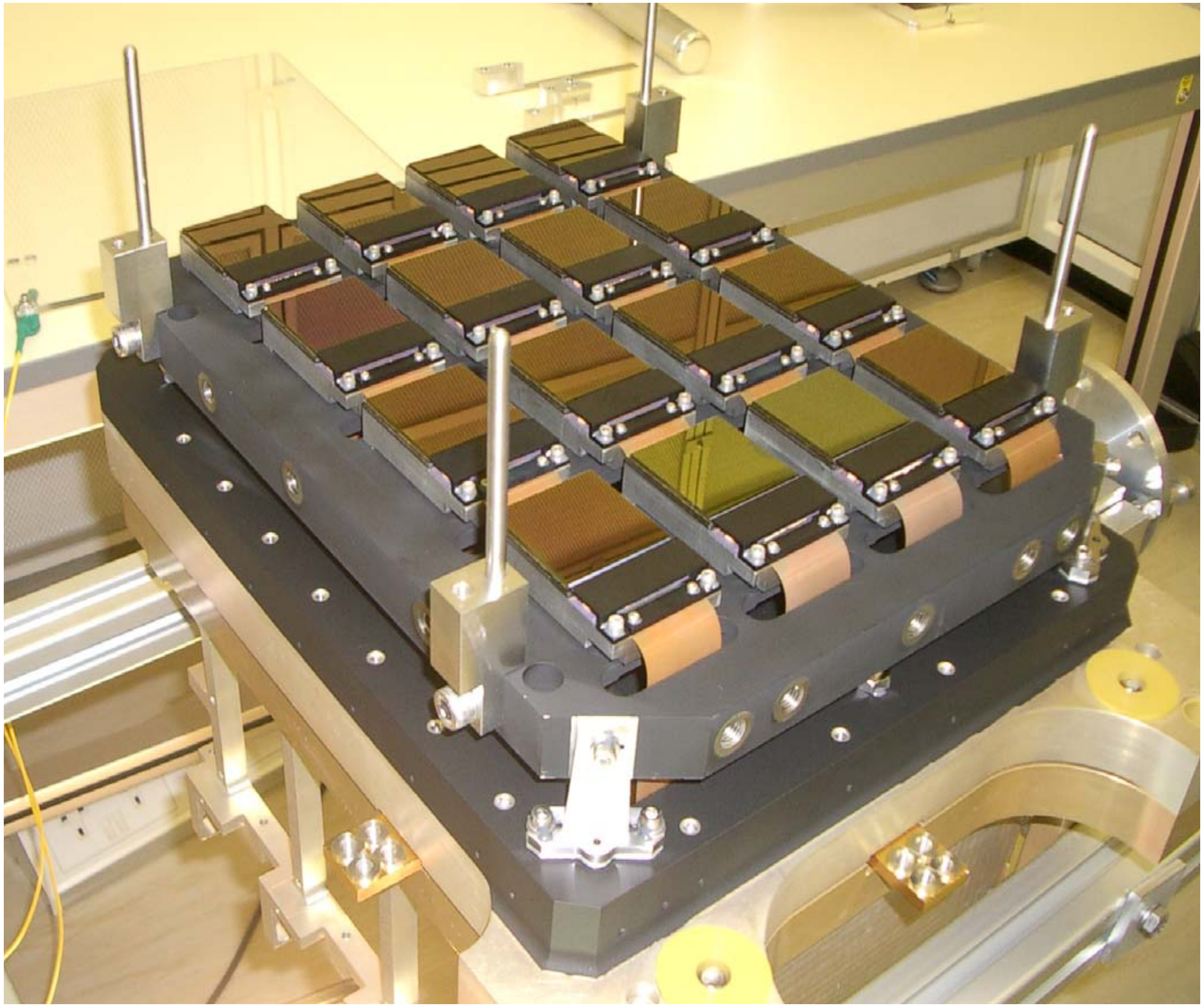






Teledyne H2-RG HgCdTe
2k x2k and SIDECAR ASIC

VISTA Camera array of 16 2K x 2K HgCdTe detectors: the largest mosaic so far



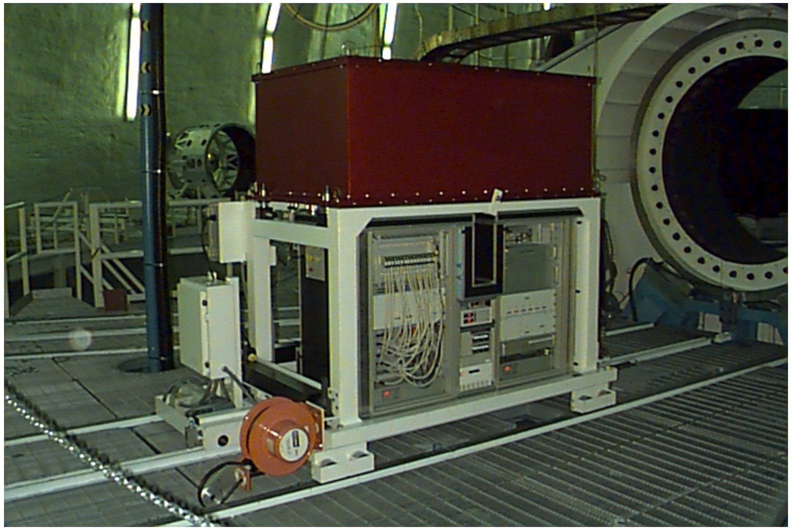
INFRARED INSTRUMENTS

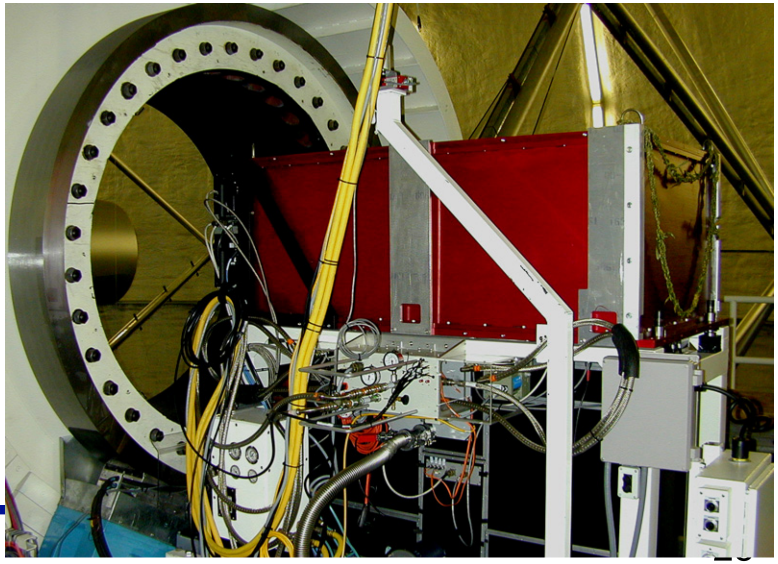
made possible by advances in IR detectors

- High-resolution spectrometers
- Integral field and AO-corrected spectrometers
- Multi-object spectrometers

- **Examples from the Keck Observatory:**
  - NIRSPEC
  - OSIRIS
  - MOSFIRE

NIRSPEC: Near IR Spectrometer

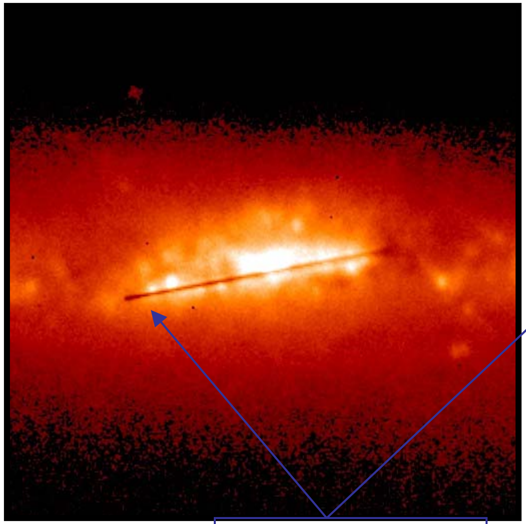




- **RNAS (**shares with DEIMOS**) or**
- **LNAS (**behind AO with OSIRIS**)**
- **IR Slit-Viewer (SCAM) FOV=46″x 46″**
  - **λ range 0.95 – 2.5 μm**
  - **256 x 256 HgCdTe array**
- **Spectrograph:**
  - **Low-Res ~2,000 (long slit)**
  - **High-Res ~25,000 (echelle)**
  - **λ range 0.95 - 5.5 μm**
  - **1024 x 1024 InSb array**

NIRSPEC Illustration: M82 rotation curves

M82 (I band) in the CCD guide camera; central hole allows light to slit.



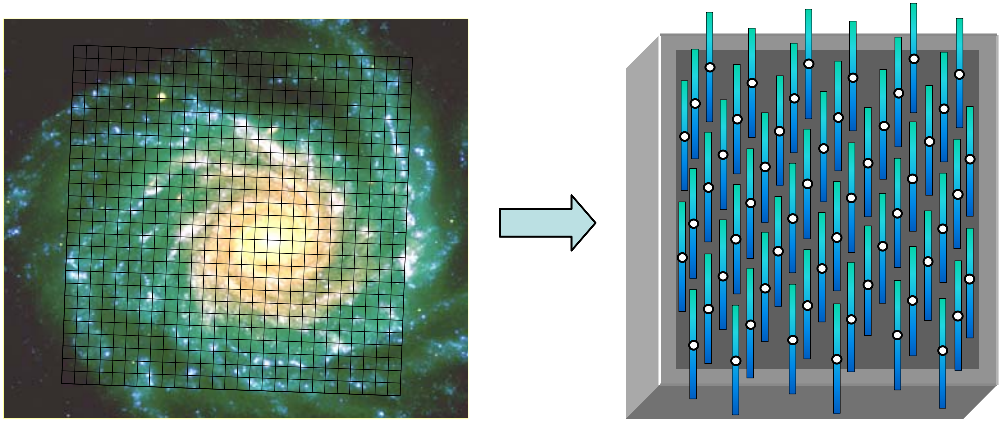
Blue Shift

Core of M82 on the 0.58´´ (4 pixels) x 24´´ reflective slit; K band.

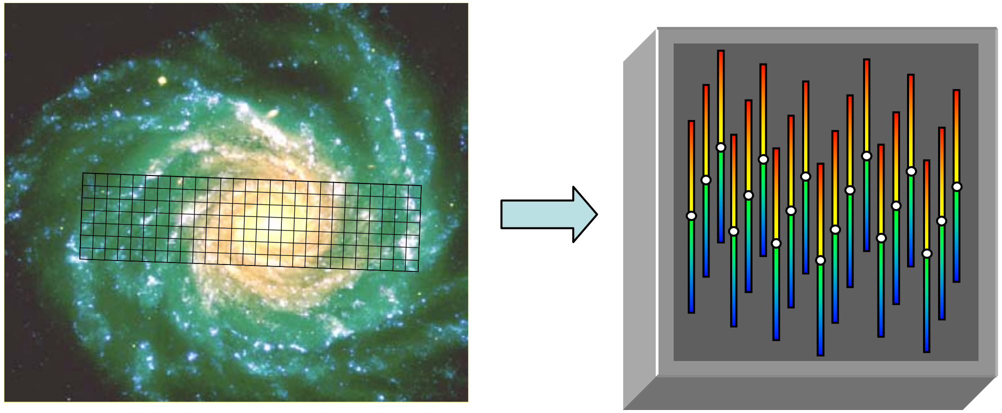
Raw K band echellogram R~18000 (16.7 km/s); Brγ (2.16) µm at left; dark lines are telluric H2O.

- **OSIRIS has an array of lenses in the telescope focal plane**
- Two operational modes selected by a mask over the lenslets
- Spectral resolution R=3900

- Square FOV
  - 64x64 lenslets
  - up to 4096 spectra
  - 400 spectral pixel each
  - Narrow band filters (19)



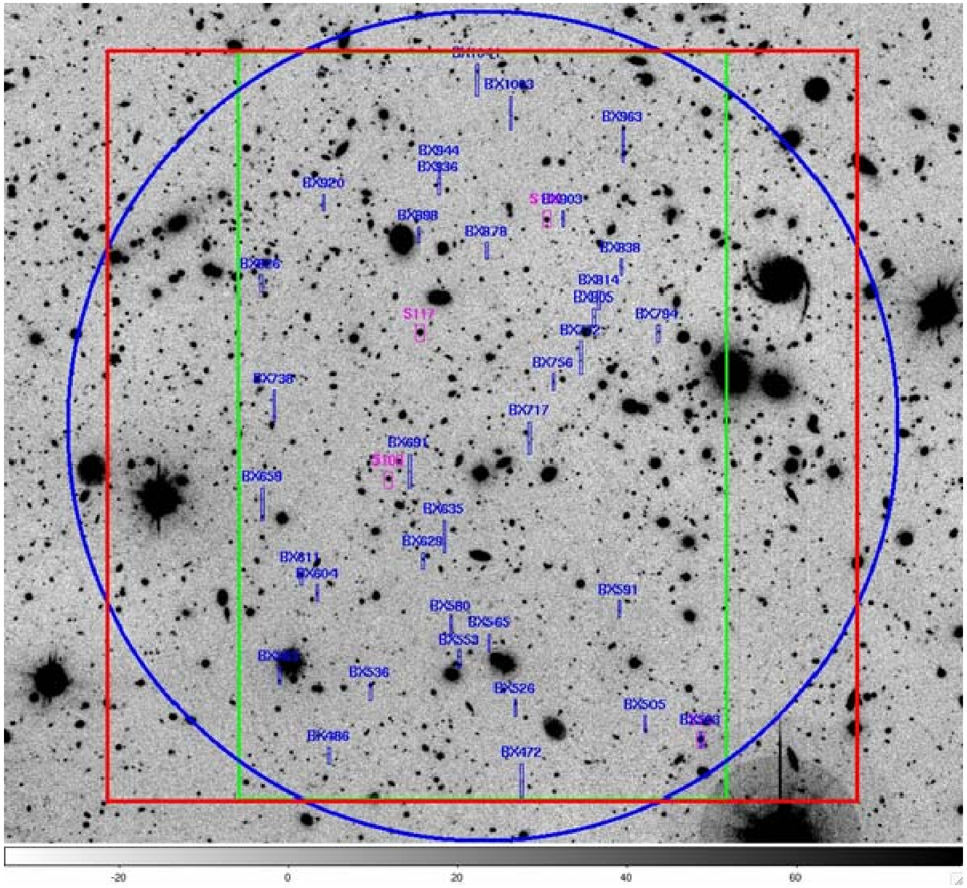
- Rectangular 4:1 FOV
  - 16x64 lenslets
  - 1024 spectra
  - 1700 spectral pixel each
  - Broad band filter
    (z, J, H or K)

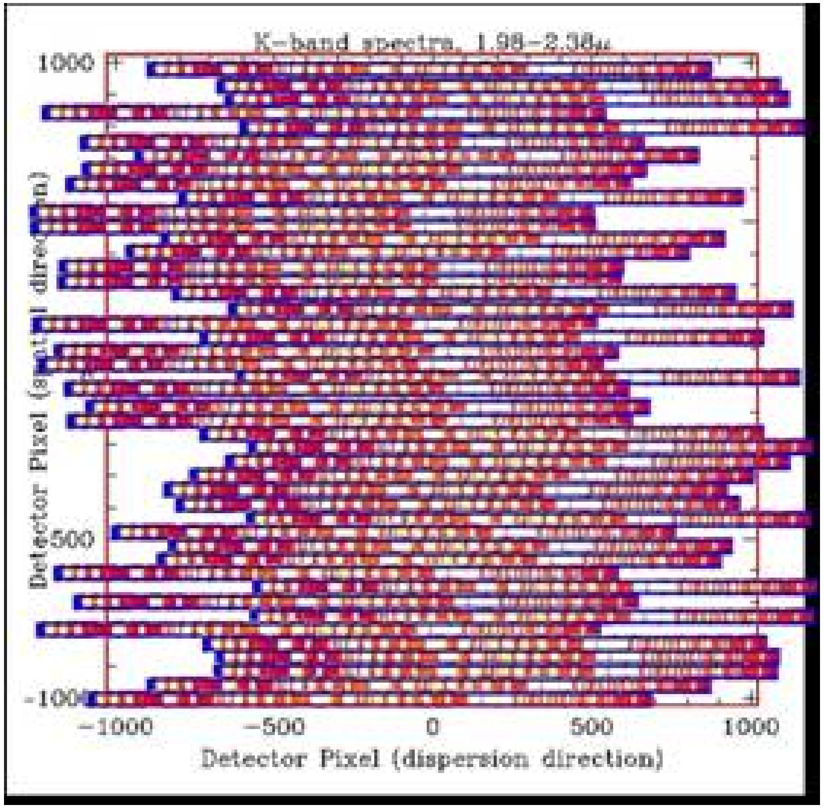


MOSFIRE – a multi-object spectrometer

deploys slits over a 6′ x 6′ field

Excellent field of view for imaging (blue circle) and spectroscopy (green rectangle)





Slits placed within the green rectangle produce spectra (cartoon) that fall mostly on the detector (red square); randomly oriented spectra are illustrated (right)

MOSFIRE is currently under construction

CHALLENGES FOR FUTURE
ASTRONOMICAL INSTRUMENTATION

- Important considerations when applying position-sensitive detectors such as CCDs and infrared arrays to astronomy are:
  - Matching to the angular scale
    - seeing or diffraction
  - Matching to the spectral resolution
  - Maximizing signal-to-noise ratio
- As telescopes get larger it is harder to match to a pixel of a given size (d_{pix})

Useful Relationships

$$\theta_{pix} = 206265 \frac{d_{pix}}{D_{tel}(f/number)_{cam}}$$

Example: If dpix = 27 μm and Dtel = 10 m (Keck telescope), then θpix = 0.56″/(f/number)cam.

Assuming seeing of 0.5″ (on Mauna Kea) and 2-pixel sampling, this implies θpix = 0.25″ which leads to Fcam = 2.2.

For 18.5 μm pixels however, we would need an f/1.5 camera!

As CCD pixels get smaller and telescope mirrors get larger, it becomes more challenging to invent an optical re-imaging (or matching) system.

Another useful relation

Slit-limited grating spectrometers have a resolving power R = λ/Δλ given by

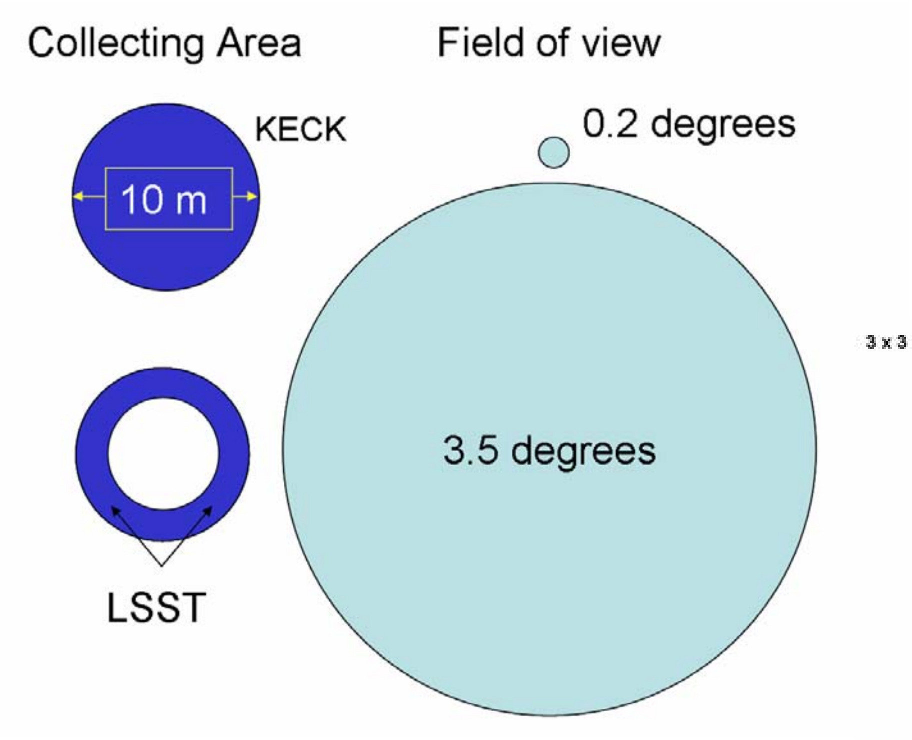
$$R = \left(\frac{\sin i + \sin \theta}{\cos i} \right) \frac{D_{coll}}{D_{tel}} \frac{206265}{p\,\theta_{pix}}$$

This important formula makes it clear that as telescopes get larger (D_{tel}) the spectrograph (defined essentially by the collimated beam unto the grating, D_{coll}) gets larger too, all else being equal.

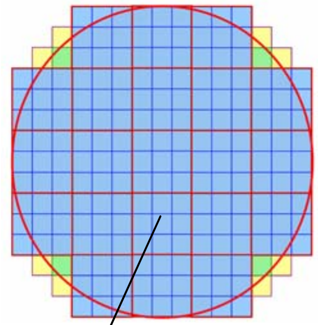
ALWAYS DIFFRACTION-LIMITED?

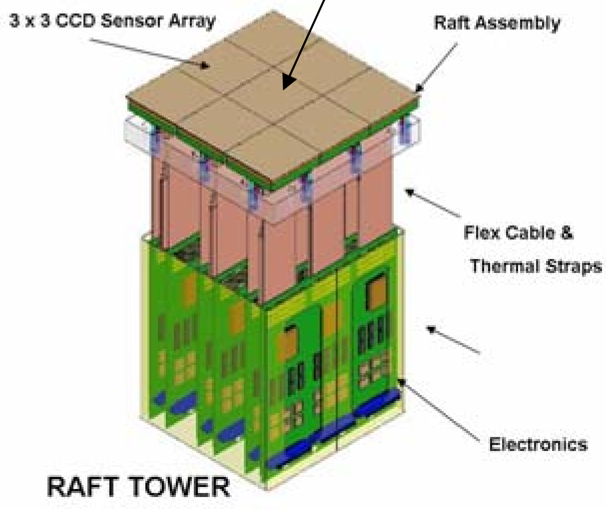
- Optical matching problems are relaxed when AO systems provide very small images e.g. 0.02″ instead of 0.2″ per pixel
- But the field of view has been reduced by a factor of 10 in linear dimension
- A 2K x 2K detector would need to be replaced by a 20K x 20K or a mosaic of **100** 2K x 2K chips
- This is feasible for silicon CCDs, but for IR arrays there is a cost problem because each 2Kx2K is already ~$350,000
- Deploy a number of AO-corrected fields over a much larger field of regard

Three billion pixels



LSST
Focal
Plane





Can the infrared, or any other wavelength band compete?

That is the next challenge!

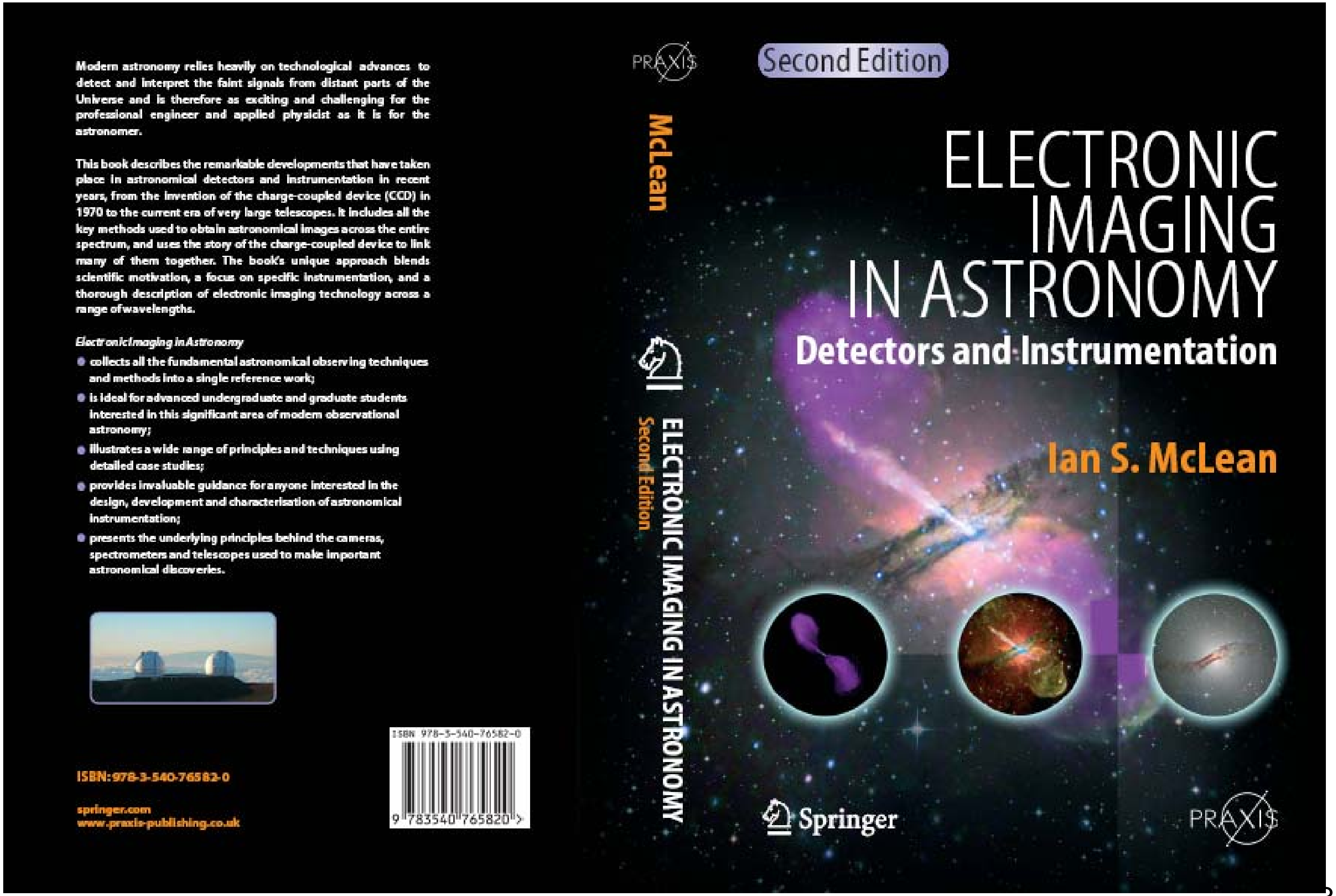
CONCLUSIONS

- Golden Age with outstanding position-sensitive detectors spanning most of the e-m spectrum
- CZT arrays for gamma-ray imaging, CCDs for X-ray imaging & micro-channel plates (+CCDs) for UV imaging
- The optical regime, far from becoming entrenched, is booming with
  - very large telescopes and special survey telescopes, large mosaics of CCDs and specialized CCDs
- The IR regime is even better off despite difficulties of ground-based infrared observations because
  - IR arrays have essentially “caught up” with CCDs in terms of basic formats & AO correction in the NIR has allowed big telescopes to operate at their diffraction limits
- The sub-mm regime is poised to explode due to the advent of large arrays of transition edge sensors

CONCLUSIONS

- Due to rapid advances in Adaptive Optics, many 8-10 meter telescopes now have diffraction-limited cameras and spectrometers for near-infrared wavelengths
- Work is continuing to bring these benefits to shorter wavelengths too.
- Unique CCDs, such as electron-multiplied (EM) and orthogonal transfer (OT) CCDs, will make a big impact
- Despite the many challenges in designing instruments to capitalize on the panoply of position-sensitive detectors, many spectacular discoveries can be traced back to the enabling power of the electronic imaging detector itself
- Perhaps the best is yet to come!

Want more about “Electronic Imaging in Astronomy”?



Modern astronomy relies heavily on technological advances to detect and interpret the faint signals from distant parts of the Universe and is therefore as exciting and challenging for the professional engineer and applied physicist as it is for the astronomer.

This book describes the remarkable developments that have taken place in astronomical detectors and instrumentation in recent years, from the invention of the charge-coupled device (CCD) in 1970 to the current era of very large telescopes. It includes all the key methods used to obtain astronomical images across the entire spectrum, and uses the story of the charge-coupled device to link many of them together. The book's unique approach blends scientific motivation, a focus on specific instrumentation, and a thorough description of electronic imaging technology across a range of wavelengths.

Electronic Imaging in Astronomy

- collects all the fundamental astronomical observing techniques and methods into a single reference work;
- is ideal for advanced undergraduate and graduate students interested in this significant area of modern observational astronomy;
- illustrates a wide range of principles and techniques using detailed case studies;
- provides invaluable guidance for anyone interested in the design, development and characterisation of astronomical instrumentation;
- presents the underlying principles behind the cameras, spectrometers and telescopes used to make important astronomical discoveries.

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Detectors and Instrumentation

Ian S. McLean

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