JWST Near and Mid-Infrared Detectors and Instrumentation

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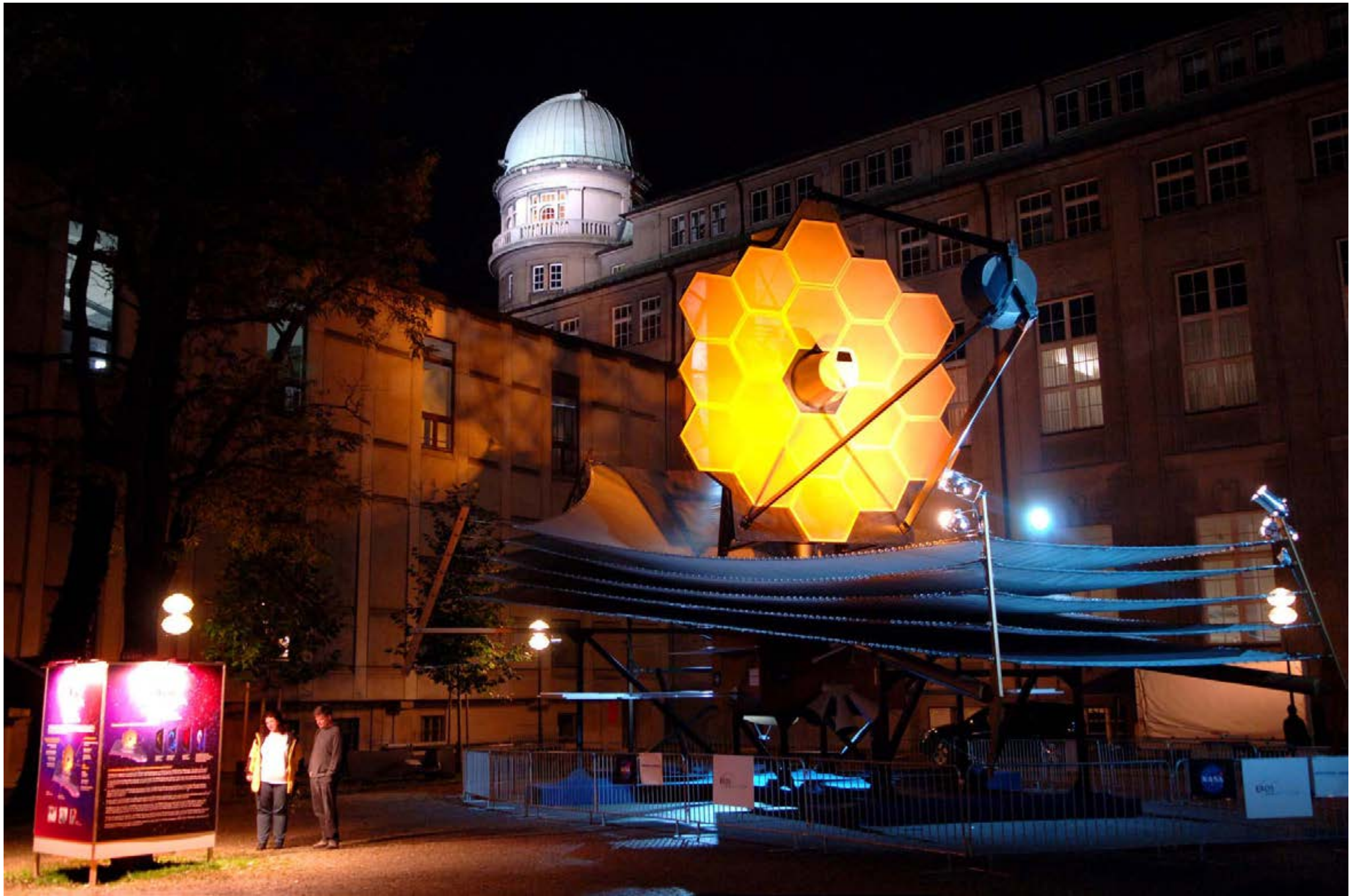
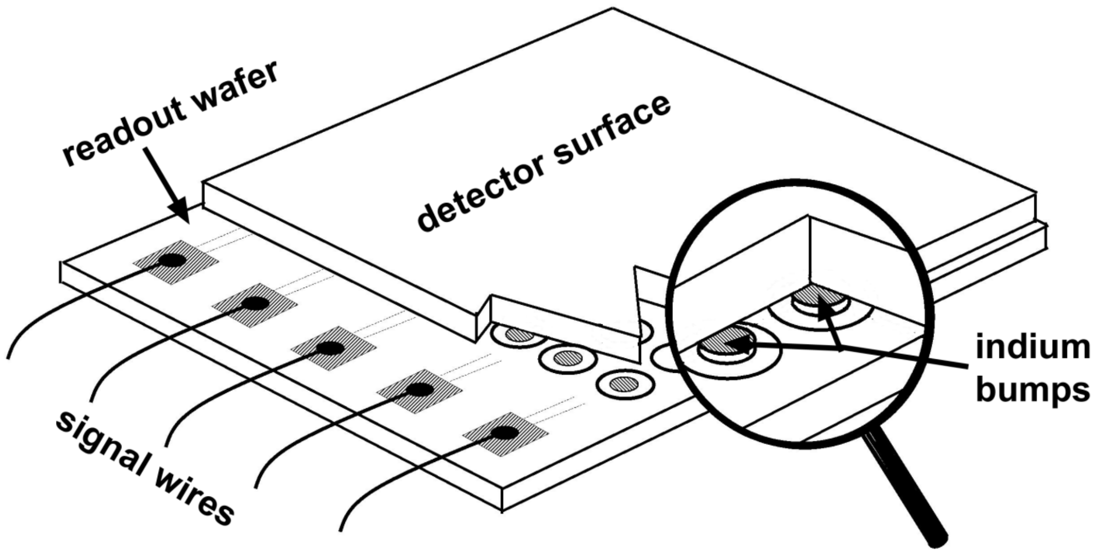


Topics

• Near-infrared (0.6 – 5 μm) detector arrays in HgCdTe

• Mid-infrared (5 – 28 μm) detector arrays in Si:As

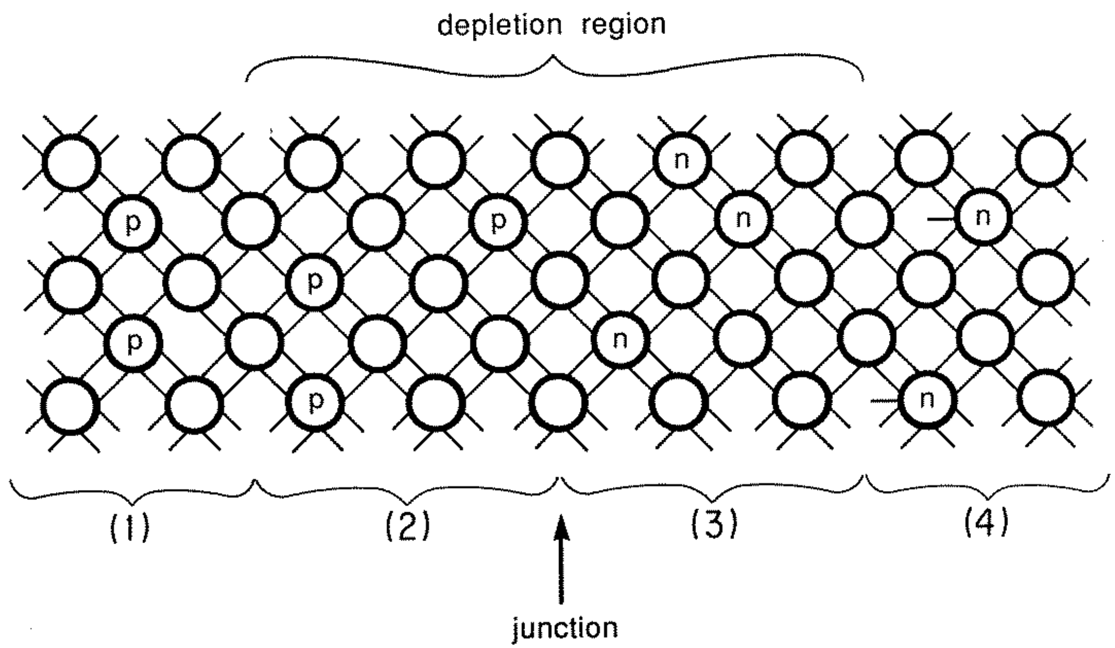
• Use of these devices in JWST* instruments



* The James Webb Space Telescope is a 6.5-m cooled (40K) telescope to be launched in 2018, built as a collaboration among NASA and the European and Canadian Space Agencies.

JWST Near-Infrared Arrays Use HgCdTe Photodiodes

provided by Teledyne Imaging Systems

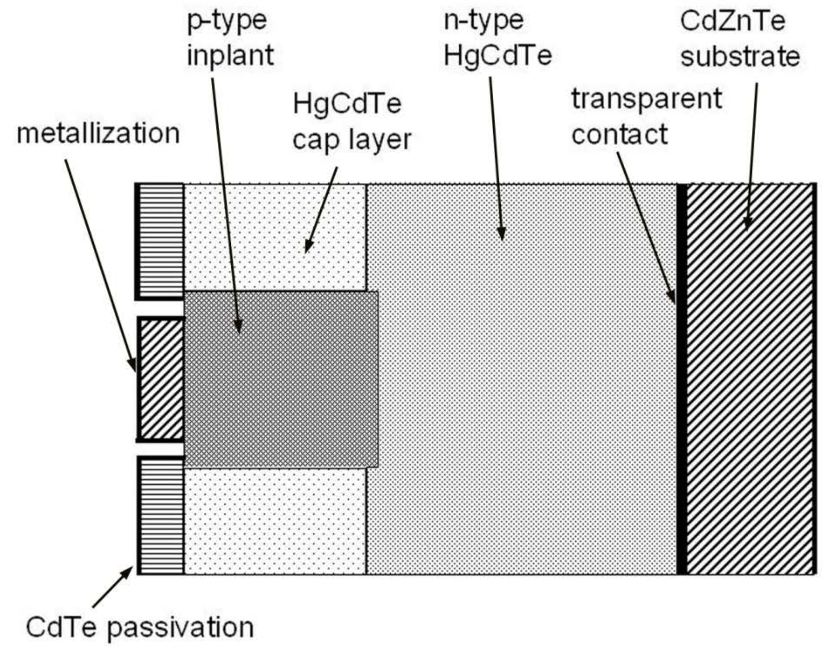


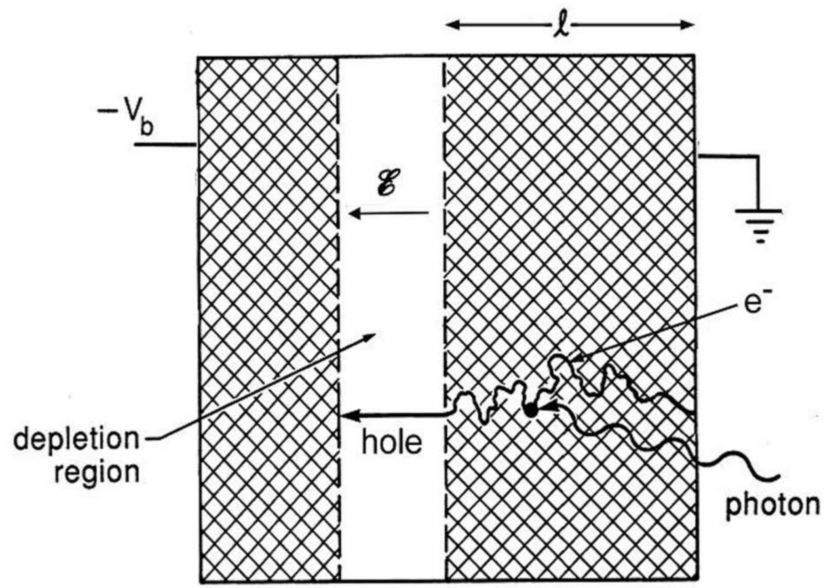
Why use photodiodes?

- Need high resistance to suppress Johnson noise $\langle I_J^2 \rangle = \dfrac{4kT\,df}{R}$
- At the diode junction, impurity charge carriers migrate to fill bonds
- Creates a *depletion* region with no free charge carriers
- Also results in a contact potential – a voltage that sweeps any free charge carriers across the junction region -- ~ 0.4 V for 2.5 μm detector
- Bandgap is energy needed to break a bond in the crystal – as in process of photon detection

Operation of a HgCdTe Photodiode Pixel

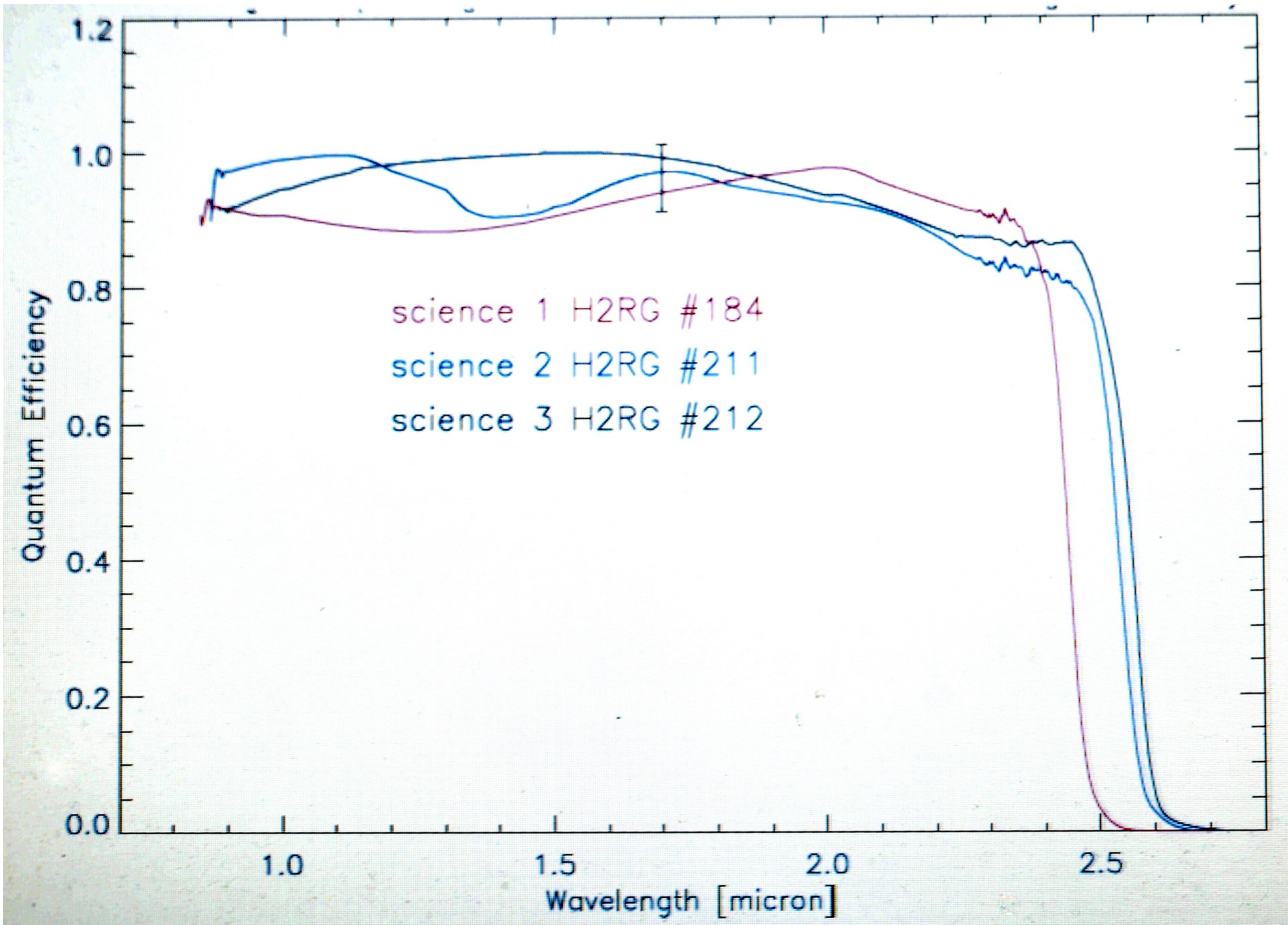
- **For infrared detection, need small bandgap material!**
- HgCdTe grown by molecular beam epitaxy (MBE): BG of 0.7 – 0.1 eV
- After hybridized to the readout (for strength) the substrate is removed for good quantum efficiency (QE) at short wavelengths
- Photon is absorbed in n-type layer if its energy is greater than the bandgap energy
- Photon absorption frees an electron and creates a hole
- Hole diffuses until gets swept across the junction by the contact potential
- Cap layer can have larger band gap to repel holes, pushing them toward junction
- Output to amplifier at metallized contact



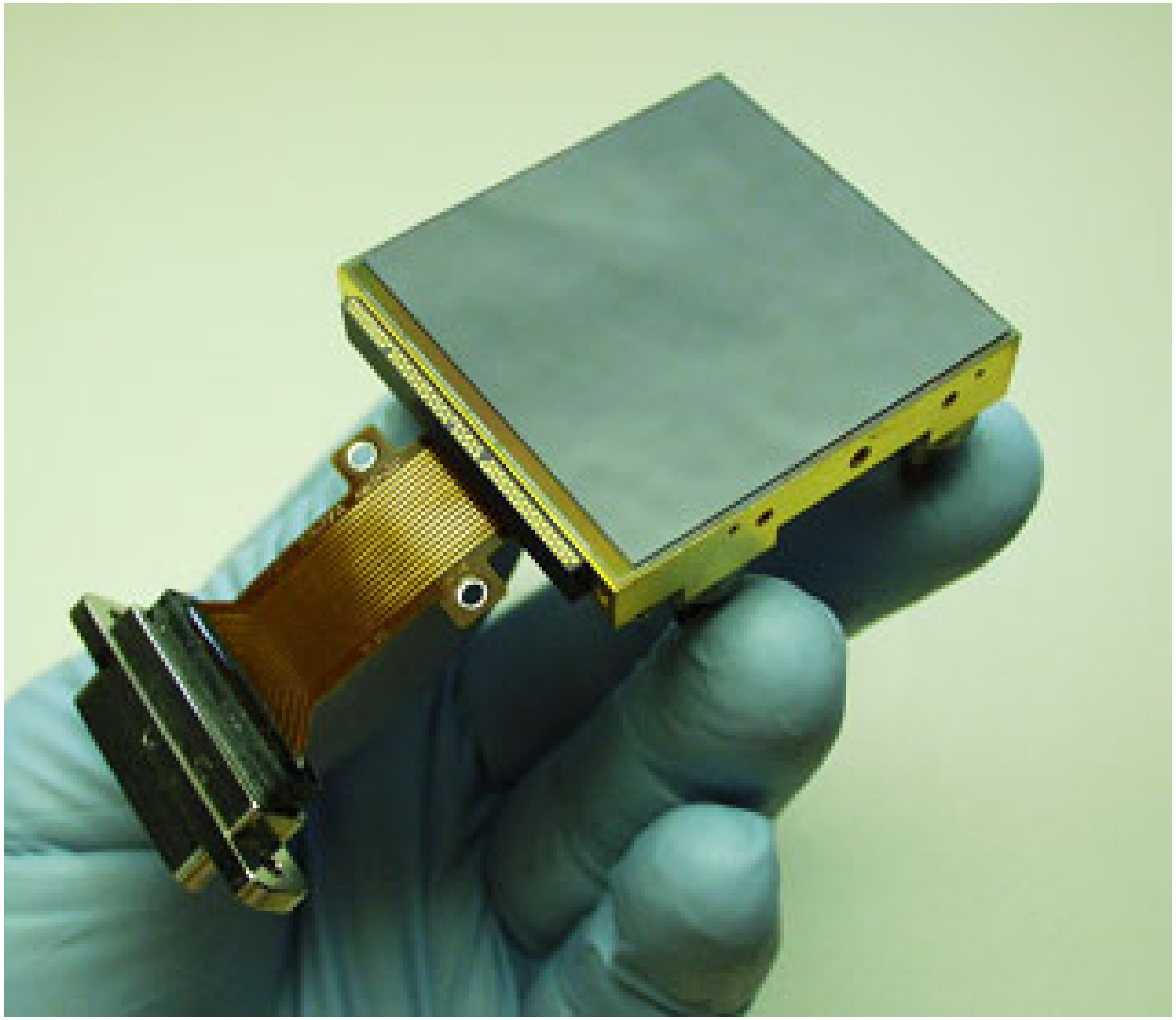


Have Excellent Broadband Quantum Efficiency

requires substrate removal



Arrays Are Buttable on Three Sides



Arrays in all three near-IR instruments, fully tested and ready for launch
Flight packaging for NIRCam at U. of Arizona under Rick Schnurr and Ken Don

Overall Properties are Excellent

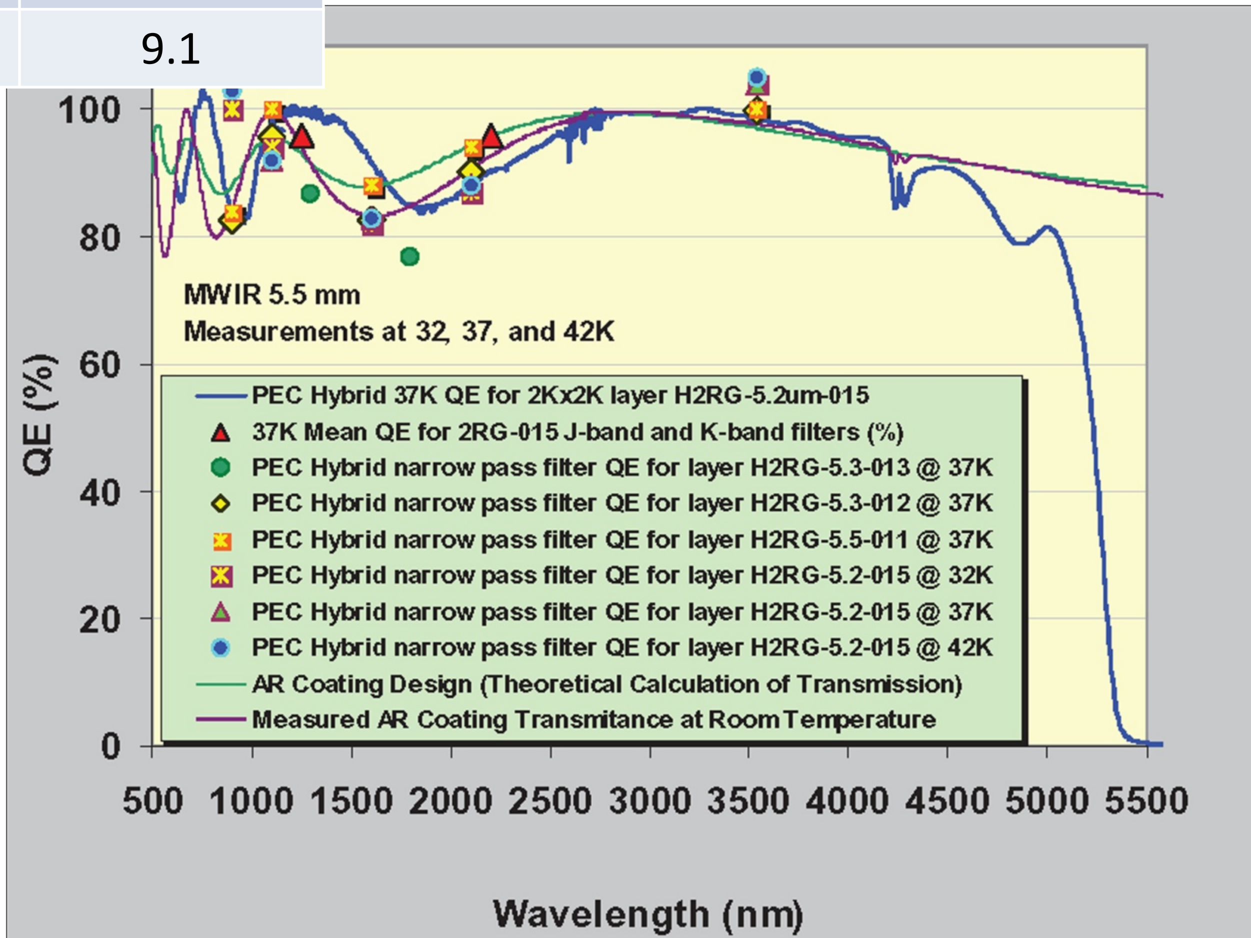
Format	**2048 X 2048**
Wavelength range	**0.6 – 2.5 μm**
Operating temperature	**$\leq$ 80 K**
Pixel size	**18 μm**
Read noise	**6 e rms**
Dark current	**$\sim$ 0.002 e/s**
Quantum efficiency	**> 80%**
Nominal bias	**0.25 V**
Well capacity	**90,000 e**

Spectacular Performance of HgCdTe Can Be Maintained with 5μm Cutoff Detectors

Cutoff wavelength	Dark current (e/s)	Read noise (e rms)
2.5 μm	0.002 ± 0.002	6.3
5 μm	0.036 ± 0.005	9.1

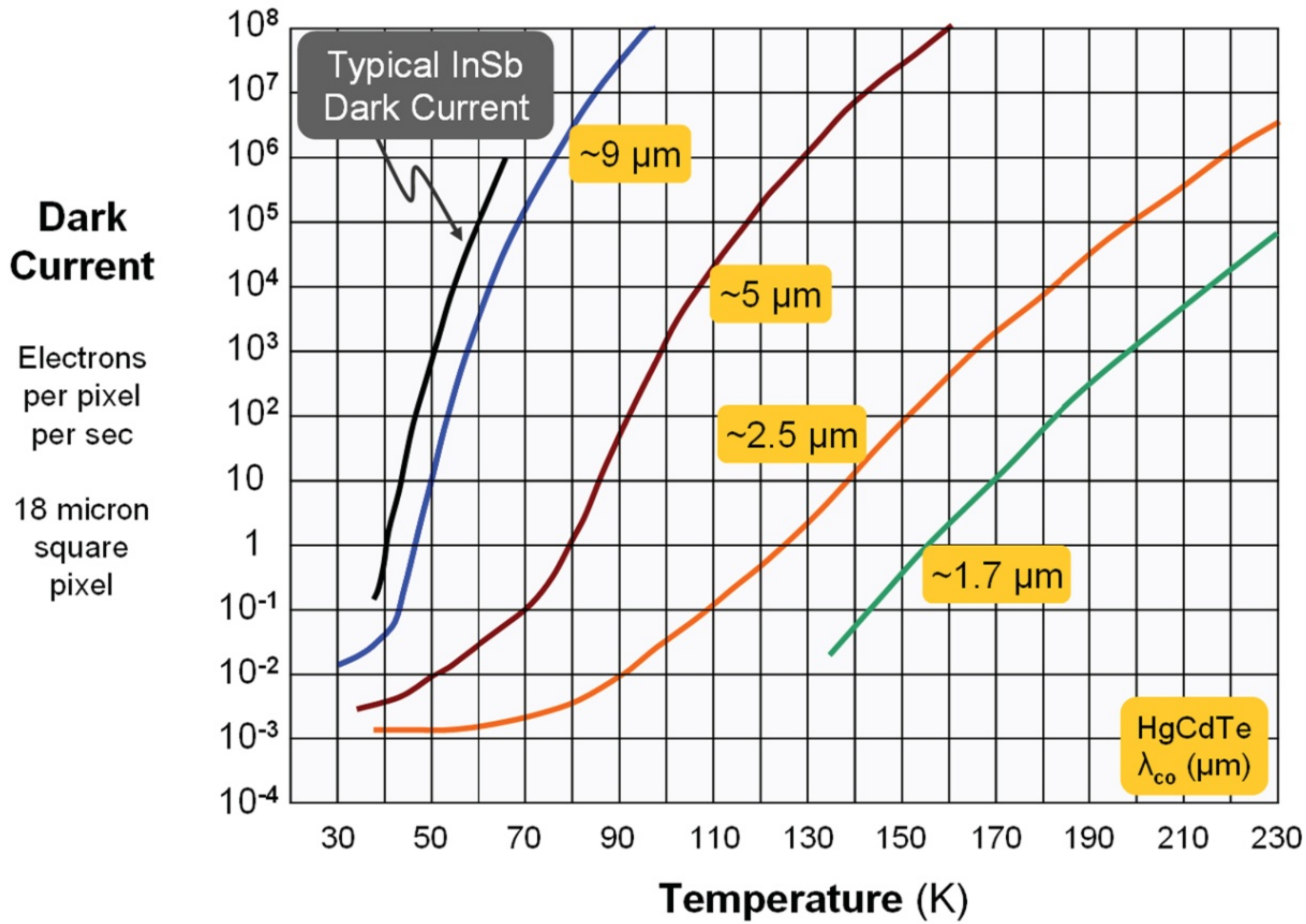
Longer wavelengths by changing x in $Hg_{1-x}\,Cd_x\,Te$

The 5 μm devices, supplied by Teledyne Imaging Systems, are used in all three of the shorter wavelength JWST instruments.



HgCdTe Technology Can Be Pushed to Somewhat Longer Wavelengths

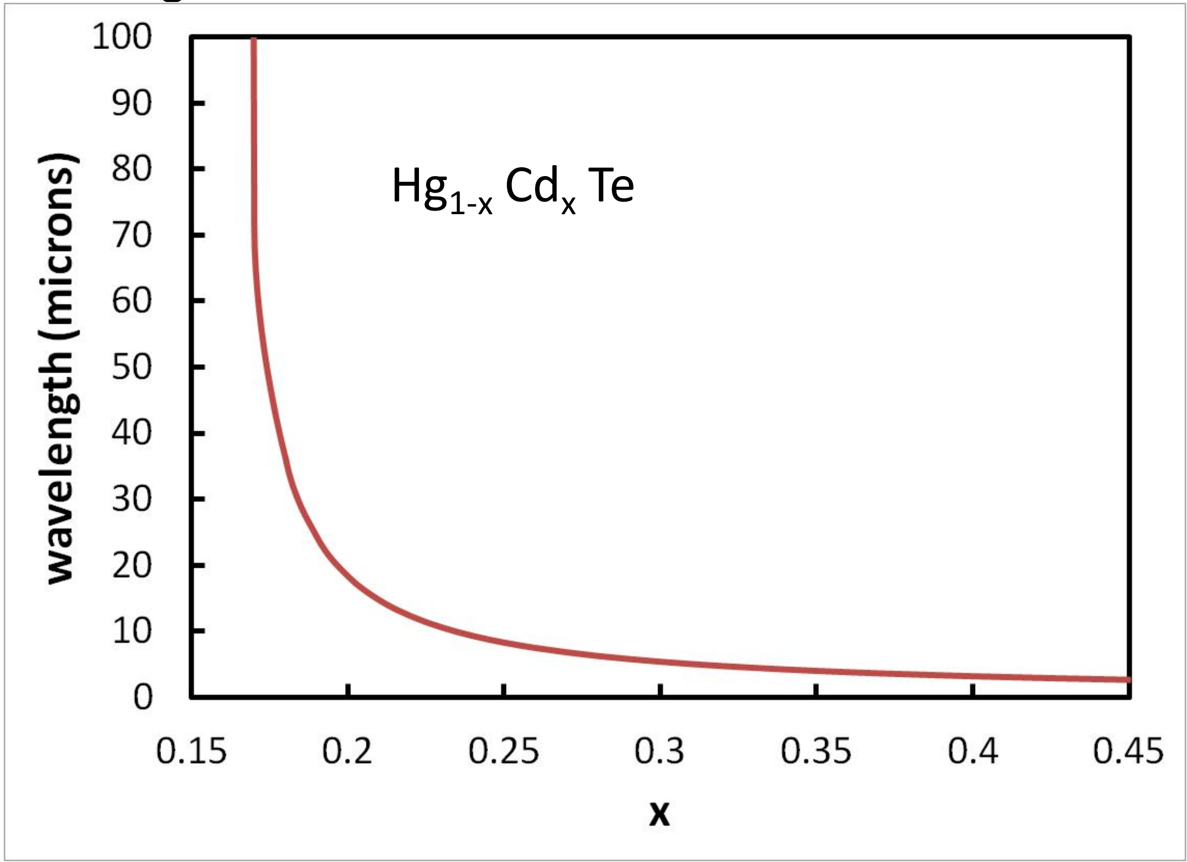
Raytheon also manufactures high performance HgCdTe. Avalanche diodes from, e.g., DRS, Raytheon, Sofradir, Selex. InSb is also useful where lower performance is OK and you do not have a very wealthy friend. See, e.g., L3-Cincinnati Electronics.



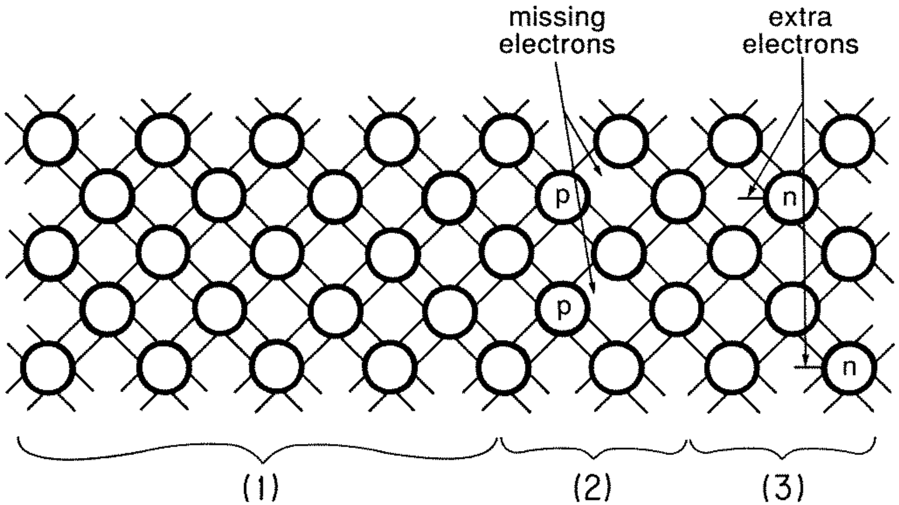
But There Is a Limit!

- Tests are about to begin on a 13 μm cutoff array, operating at ~ 30K (Judy Pipher and Craig McMurtry, private communication)
- But performance is not going to approach that with 2.5 μm devices
- There are three issues
  - Process control for accurate bandgap energy becomes very critical (below right)
  - Material becomes soft and fragile
  - Benefit from diode junction decreases with decreasing bandgap*

*Contact potential is proportional to bandgap and hence inversely proportional to cutoff wavelength! The internal diode field is proportional to the contact potential.



Solution: Use Extrinsic (doped) Material

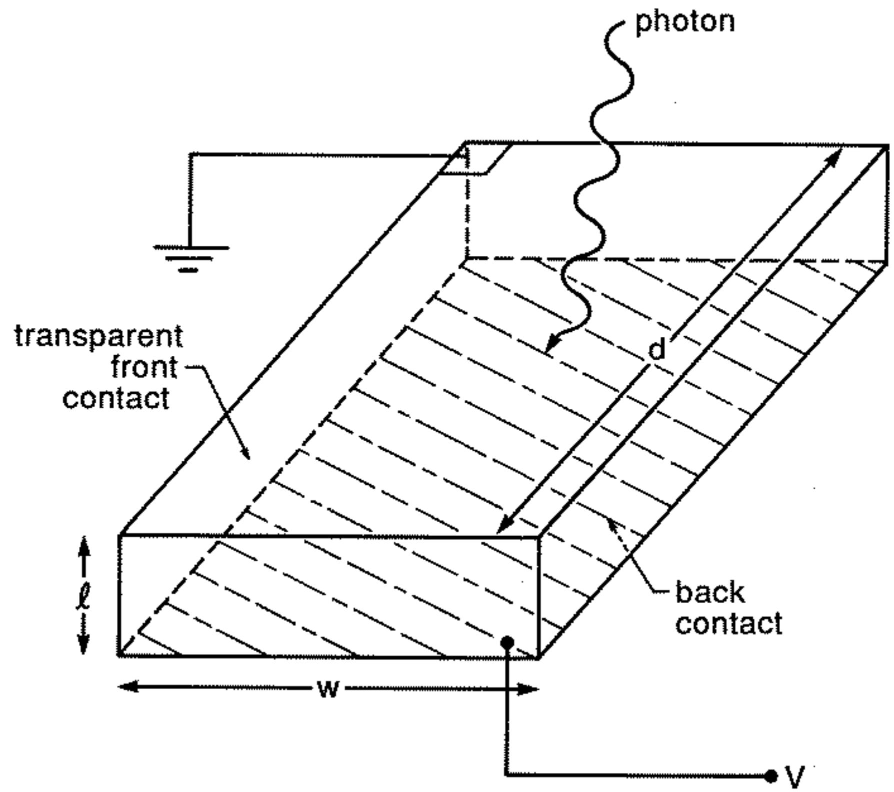


- Detector might be as to the right
- Must be operated very cold
- Large (for good absorption)
- Need high resistance to suppress Johnson noise

$$\langle I_J^2 \rangle = \frac{4kT\,df}{R}$$

- Result is very long RC time constant
- Example: 20 X 20 μm pixel, 500 μm thick, dark current 30 e/s will have $\tau \sim 100$ s!
- This leads to prompt (from charge carrier drift) response and slow (from RC adjustment in detector to changes
- And a bunch of really challenging calibration issues

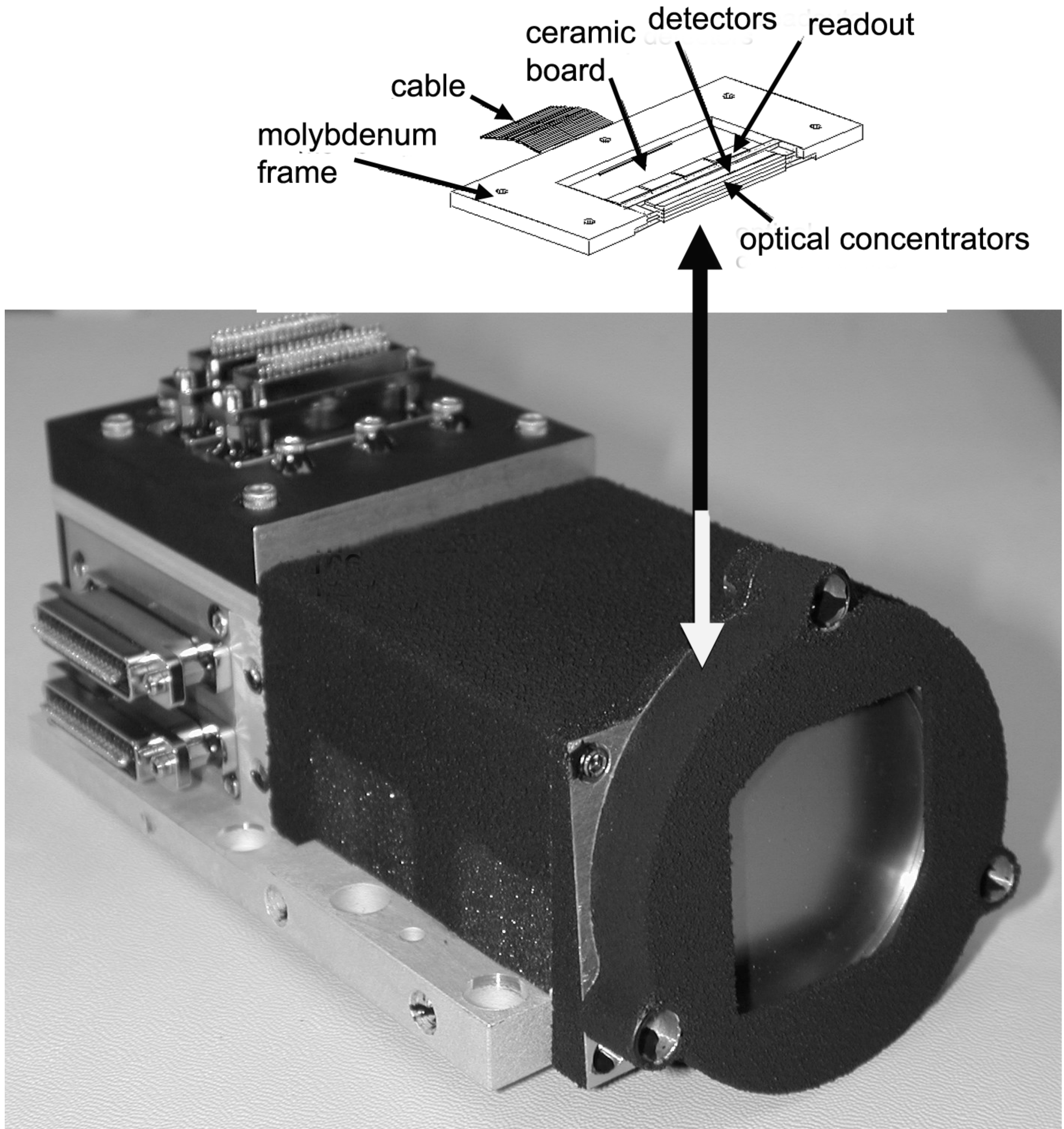
- The missing bonds (to left) require far less energy to free charge carriers
- But the impurity levels need to be low to limit dark current, so the photon absorption is not efficient



Nonetheless:

32 X 32 Ge:Ga Detector Array for MIPS on Spitzer

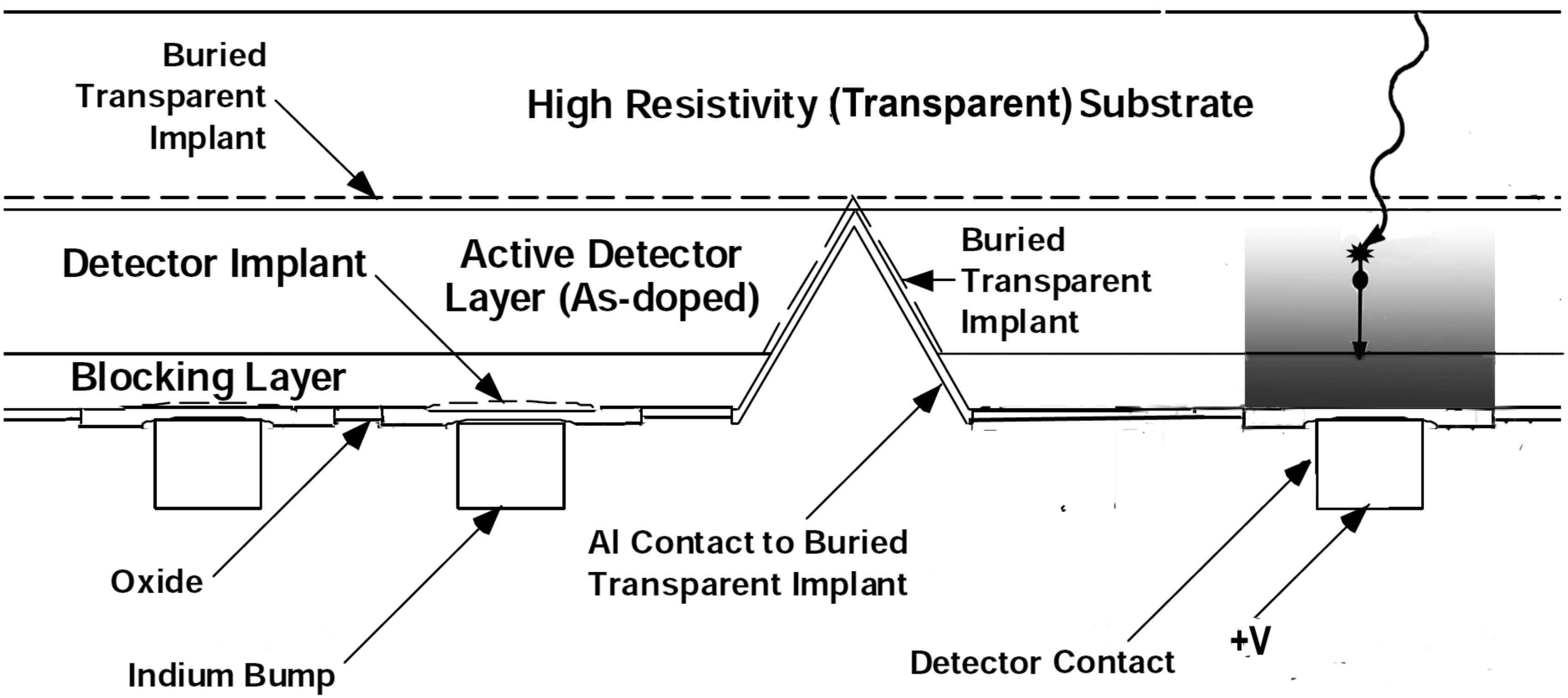
This is pretty cumbersome – is there some other approach, at least for wavelengths not too far beyond 10 μm?



Si:As Impurity Band Conduction Detectors

- Carried on transparent silicon substrate
- High resistance is supplied by blocking layer of much purer material
- Electric field (to far right grey scale) imposed by contact penetrates IR-active layer and causes photoelectrons to drift to contact
- Readout by amplifier-per-detector, similar to HgCdTe arrays

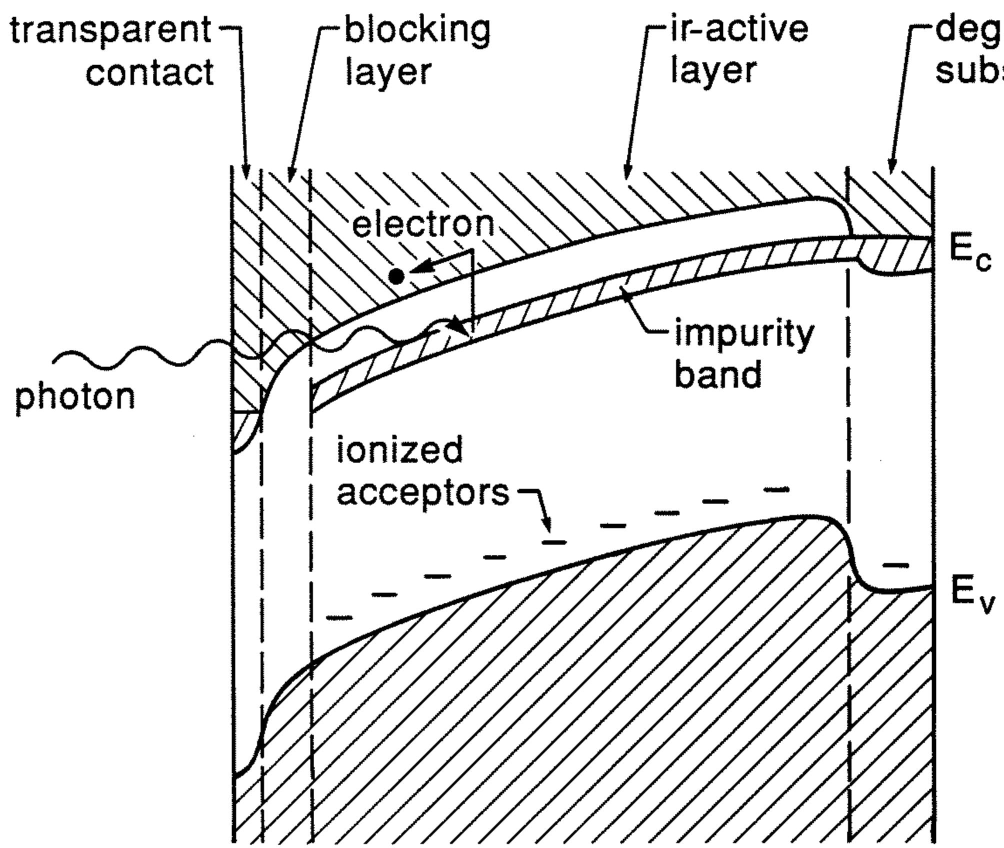
- **We will discuss this detector type with specific reference to the MIRI/JWST devices***



* Arrays made by Raytheon Vision Systems & have strong heritage to those used in IRAC/Spitzer

Low Dark Current Because Blocking Layer Has No Impurity Band

- Electrons must be elevated to conduction band to get to contact
- This sets limit on impurity concentration in IR-active layer, to keep band narrow enough
- MIRI detectors have 7 X 10^{17} As cm^{-3}, approaching the limit for good detectors
    - About 100 times higher than is permissible without a blocking layer
- Infrared active layer can be only 30-35 μm thick with good absorption



Only Works with Exquisite Control of Impurities

- Arsenic is a donor impurity; acceptor impurities in IR layer produce space charge
- This opposes the field created by the bias voltage on the contact
- Must keep impurity very low or will not be able to collect the photo charge
- Technically, to collect photo charge, the field needs to deplete the IR-active layer of all other free charge carriers
- Depleted depth *w* depends on bias voltage V_b, blocking layer thickness t_B, and acceptor impurity concentration N_A

$$w = \left[\frac{2\kappa_0 \varepsilon_0}{q\, N_A} |V_b| + t_B^2\right]^{1/2} - t_B$$

- V_b is limited to avoid avalanching of charge carriers, creating excess noise
- MIRI detectors have 1.5 X 10^{12} acceptors cm^{-3}, approaching the limit for good detectors

- Summary of the contents of a 25 μm X 25 μm X 35 μm (deep) MIRI detector volume:

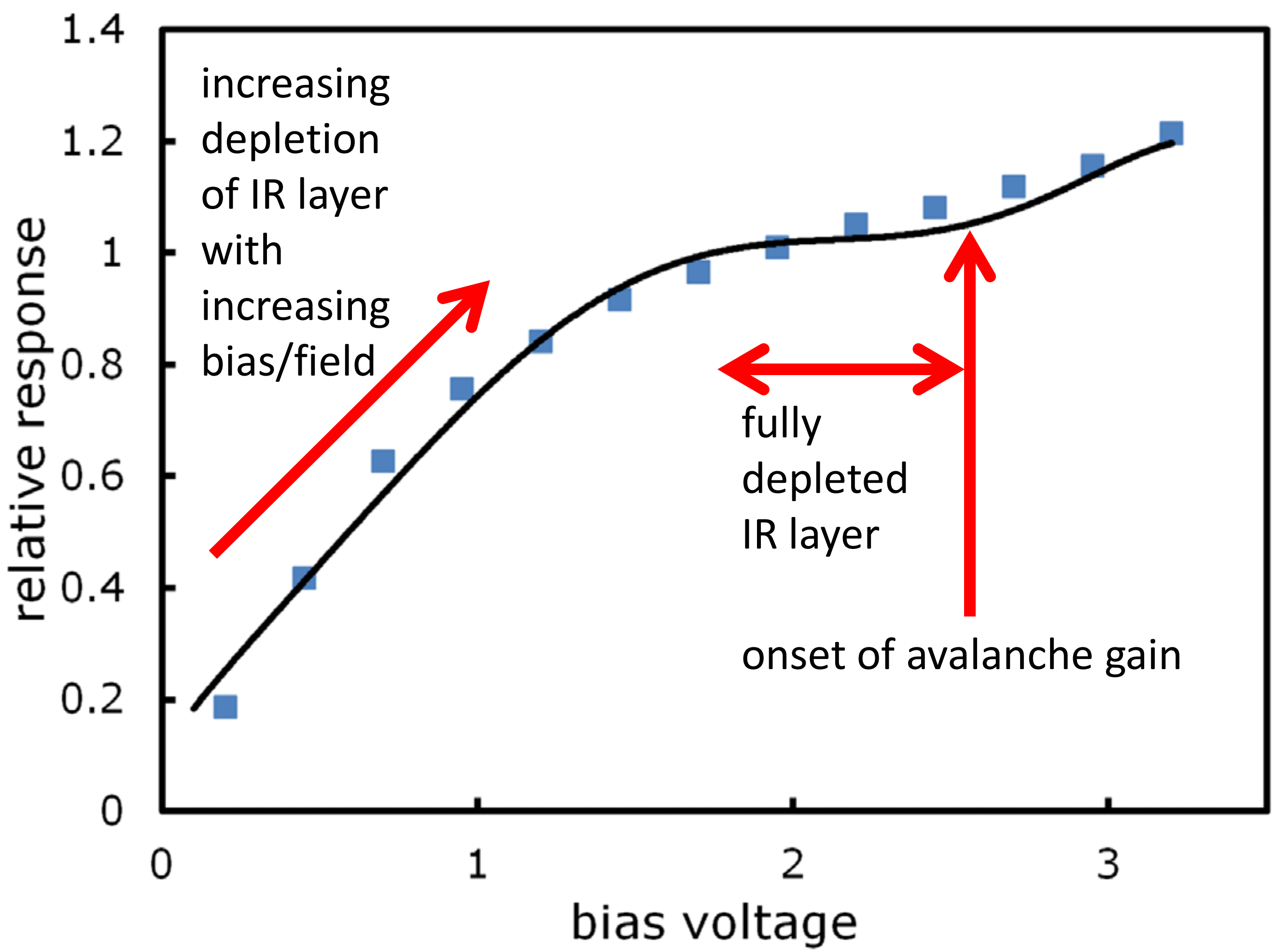
Silicon atoms	**1 X 10^{15}**
Arsenic atoms	**1 X 10^{10}**
Acceptors	**< 4 X 10^{4}**

- The statistical fluctuations in acceptor numbers actually contribute to the nonuniformity of an array!

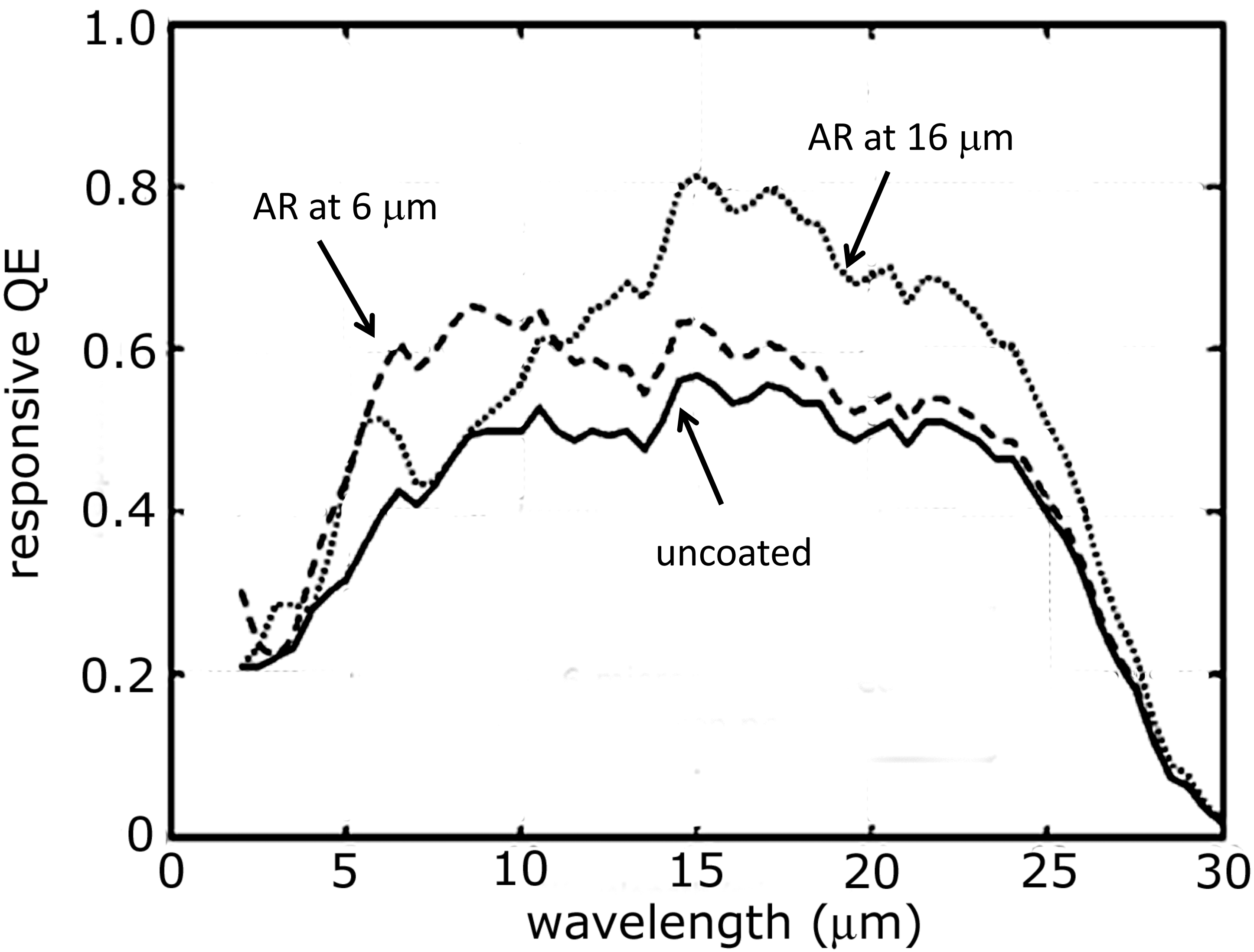
Detectors Meeting These Requirements Behave as Expected

- Original theory developed in ~ 1985 (Petroff & Stapelbroek) , when $N_A > 10^{13}$ cm^{-3} and consequently IR-active layers were perhaps 15 μm thick
- Still valid, but advances in detectors expose some shortcomings
- Lower right shows expected response vs. bias voltage, V_b

- Blue squares are measured response
- Line is theoretical fit
- Theory is updated from 1985 original papers
- Includes diffusion of charge carriers from production sites
- Critical to account for low-bias behavior
- Rieke et al. 2015, PASP, 127, 665 for details



Quantum Efficiency is High

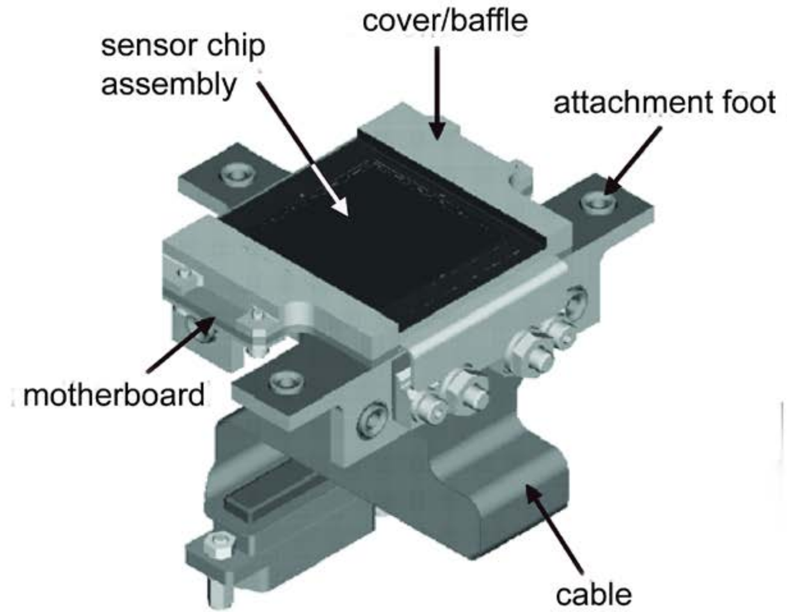


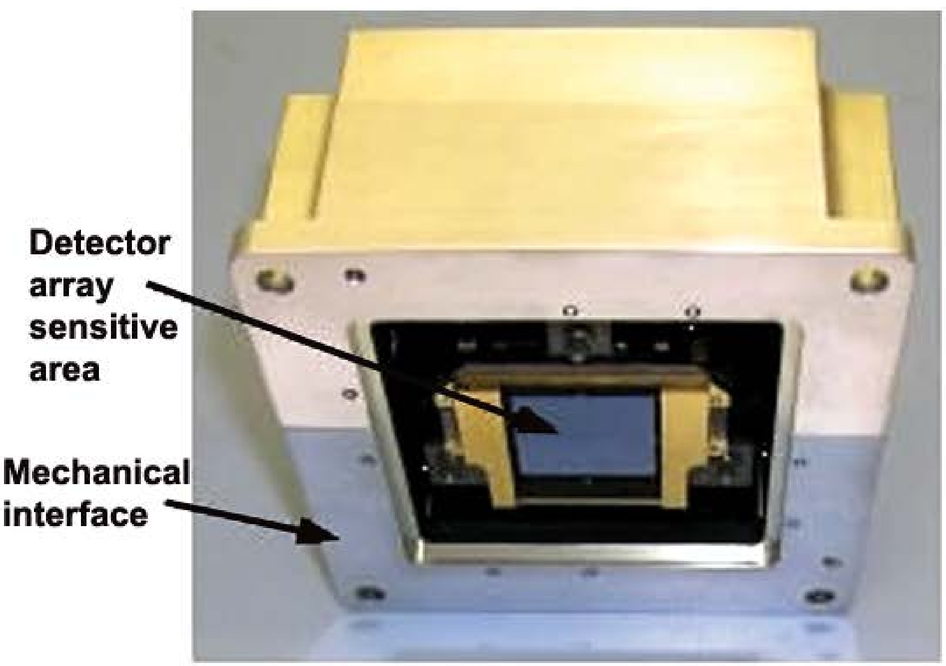
Overall Properties are Excellent

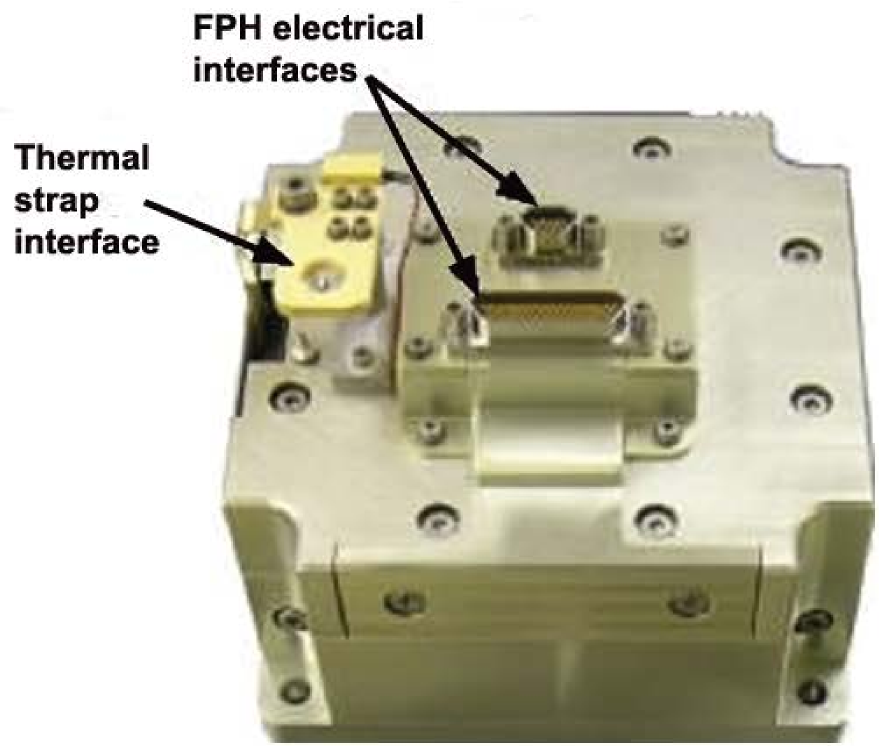
Format	1024 X 1024
Wavelength range	5 – 28 μm
Operating temperature	$\leq$ 6.7 K
Pixel size	25 μm
IR layer thickness	35 μm
As doping	7 X 10^{17} cm^{-3}
Acceptor concentration	1.5 X 10^{12} cm^{-3}
Read noise	14 e rms
Dark current	0.2 e/s
Quantum efficiency	> 60%
Nominal bias	2.6 V
Well capacity	250,000 e

Arrays Are Ready for Launch

- Array development at JPL, under leadership of Mike Ressler and Kalyani Sukhatme
- Flight packaging to right
- Mounted and aligned in instrument (housing below)
- Instrument delivered
- JWST instrument package has completed final cryo test

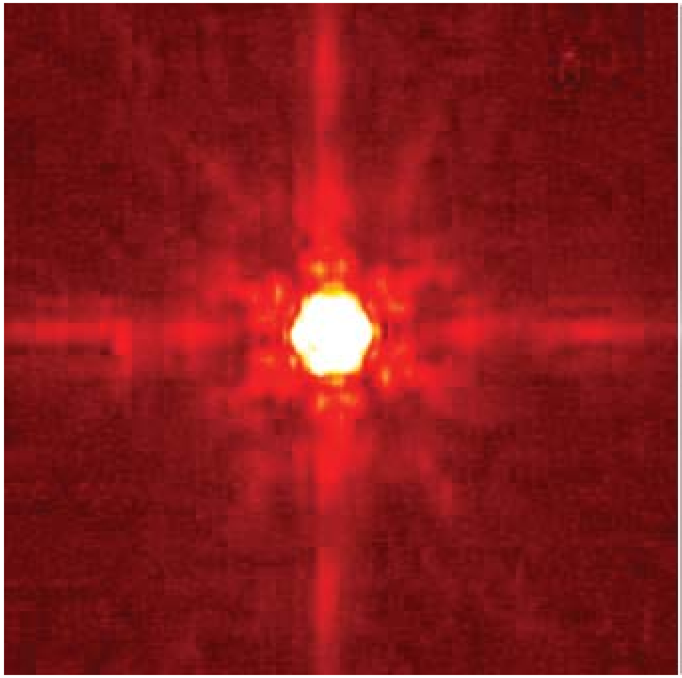
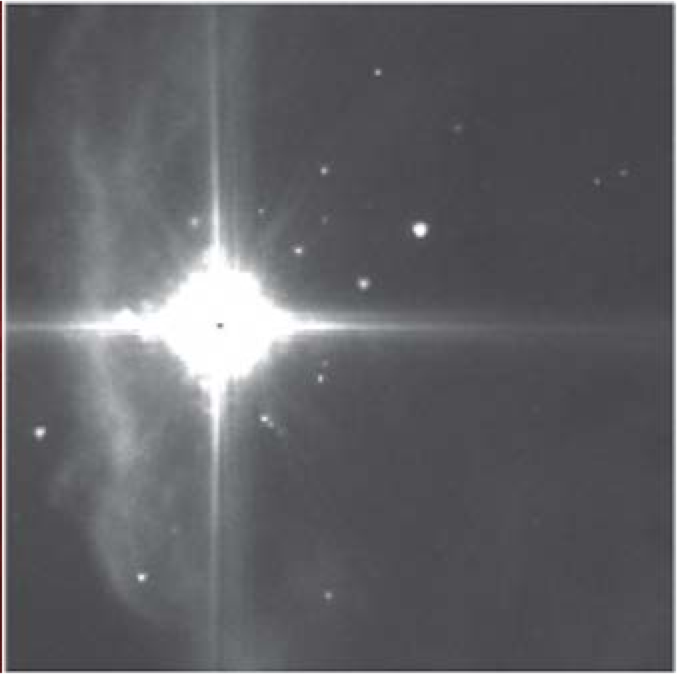






Although These Arrays Are Great, They are Not Quite Perfect

- Short wavelength (5 – 8 μm) shows cross artifact
- MIRI array to left from test campaign, IRAC array from space to right
- Root cause is poor absorption of Si:As at these wavelengths

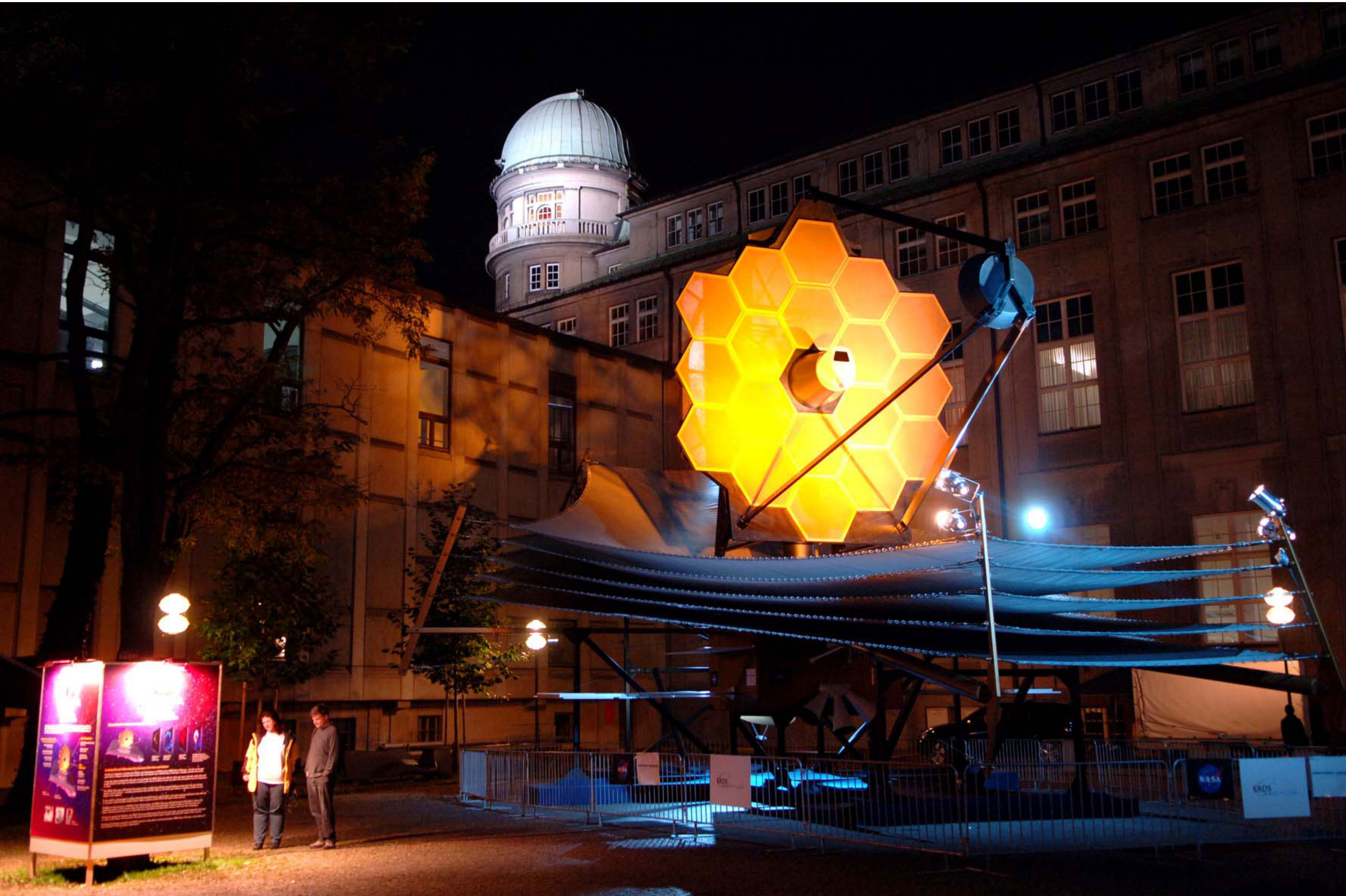
Future development of HgCdTe may make it the detector material of choice in this region.

Nonetheless, detectors for 1 – 28 μm are superb!!

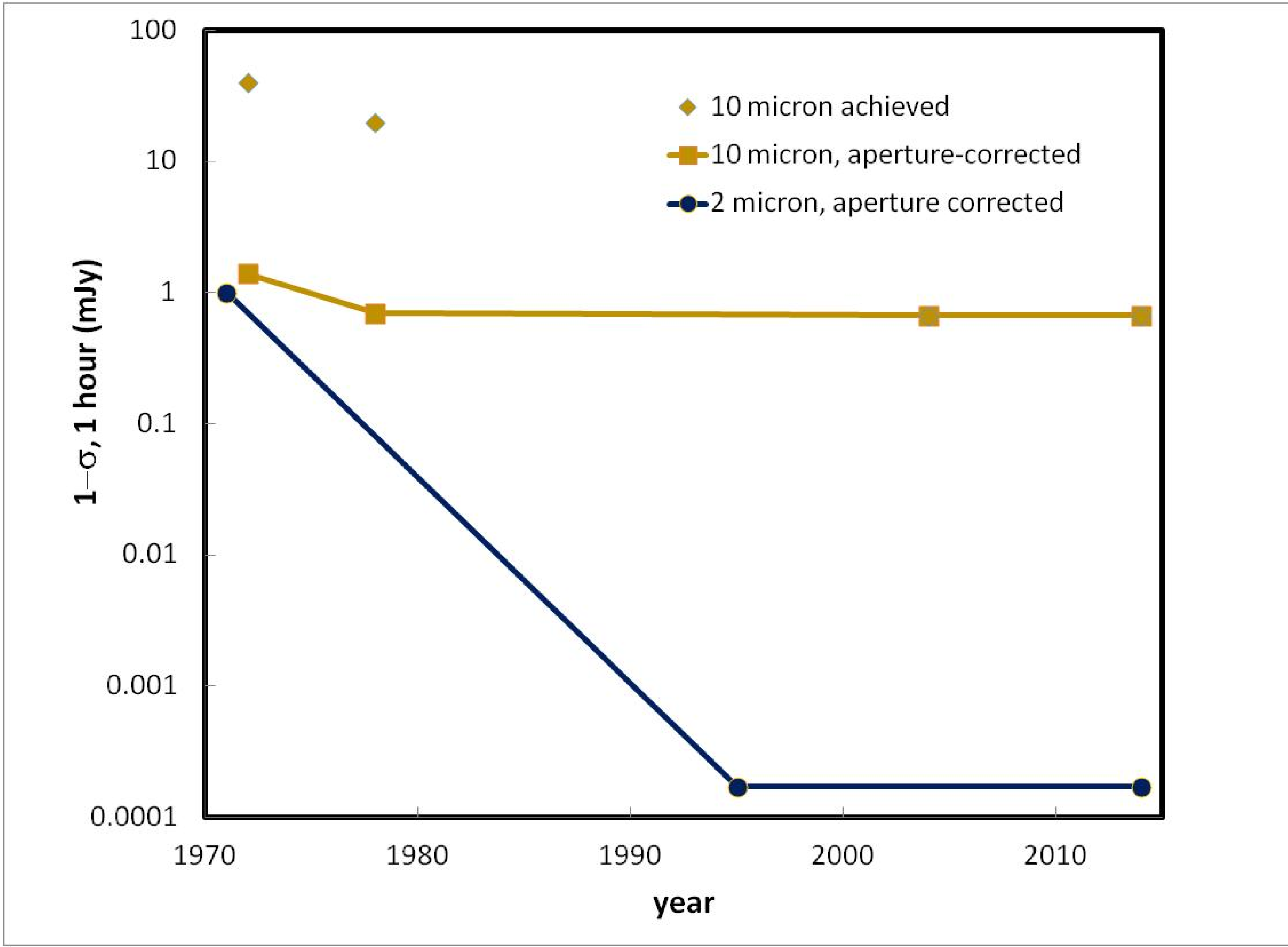
- Low noise: < 15 electrons rms
- Low dark current: << 1 e/s
- High quantum efficiency: > 60%
- Large format arrays: $\geq$ 1 Mpixel
    - Fill factor ~ 100%
    - Low crosstalk, ~ 2%
- Well-behaved photometrically – with suitable data pipeline processing

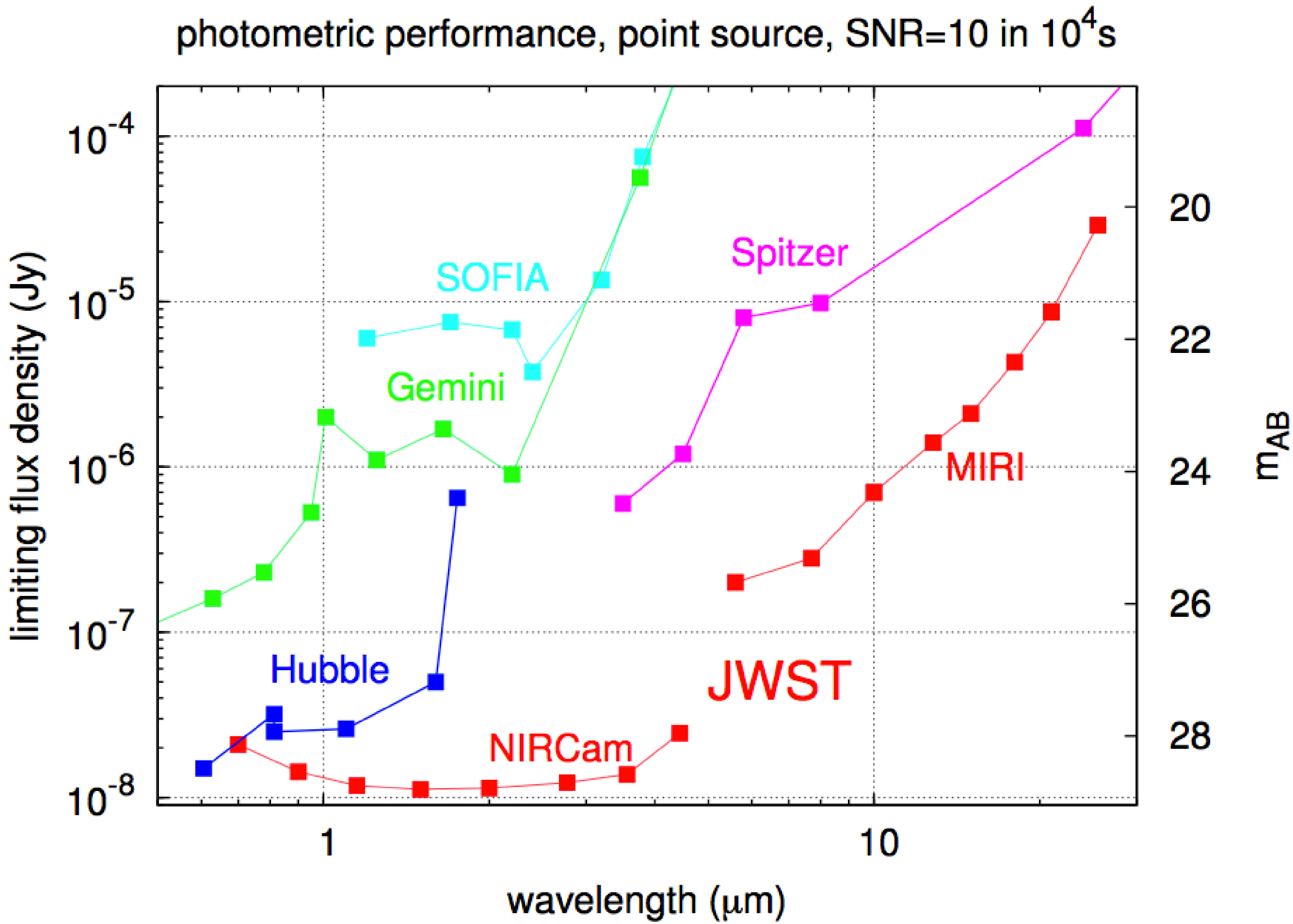
This is a recent technological development: 40 years ago the best we had was single pixels, each 1000 times less sensitive!

The Promise of JWST



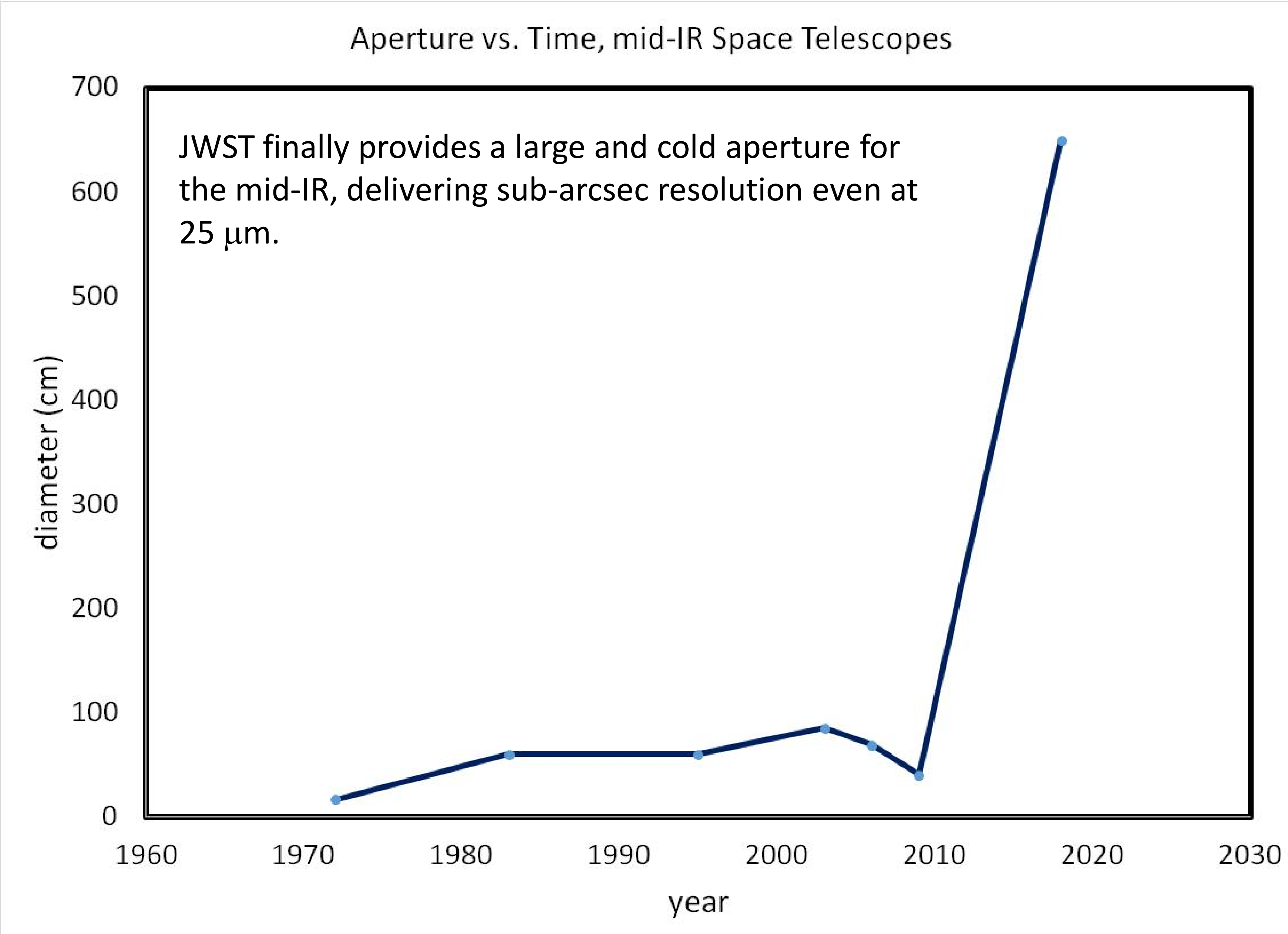
Background limit has stopped sensitivity gains from the ground.





photometric performance, point source, SNR=10 in 10^4 s
limiting flux density (Jy)
10^-4
10^-5
10^-6
10^-7
10^-8
m_AB
20
22
24
26
28
1
10
wavelength (μm)
SOFIA
Gemini
Spitzer
Hubble
MIRI
NIRCam
JWST

Previous space telescopes were small with low angular resolution



JWST and Its Instruments

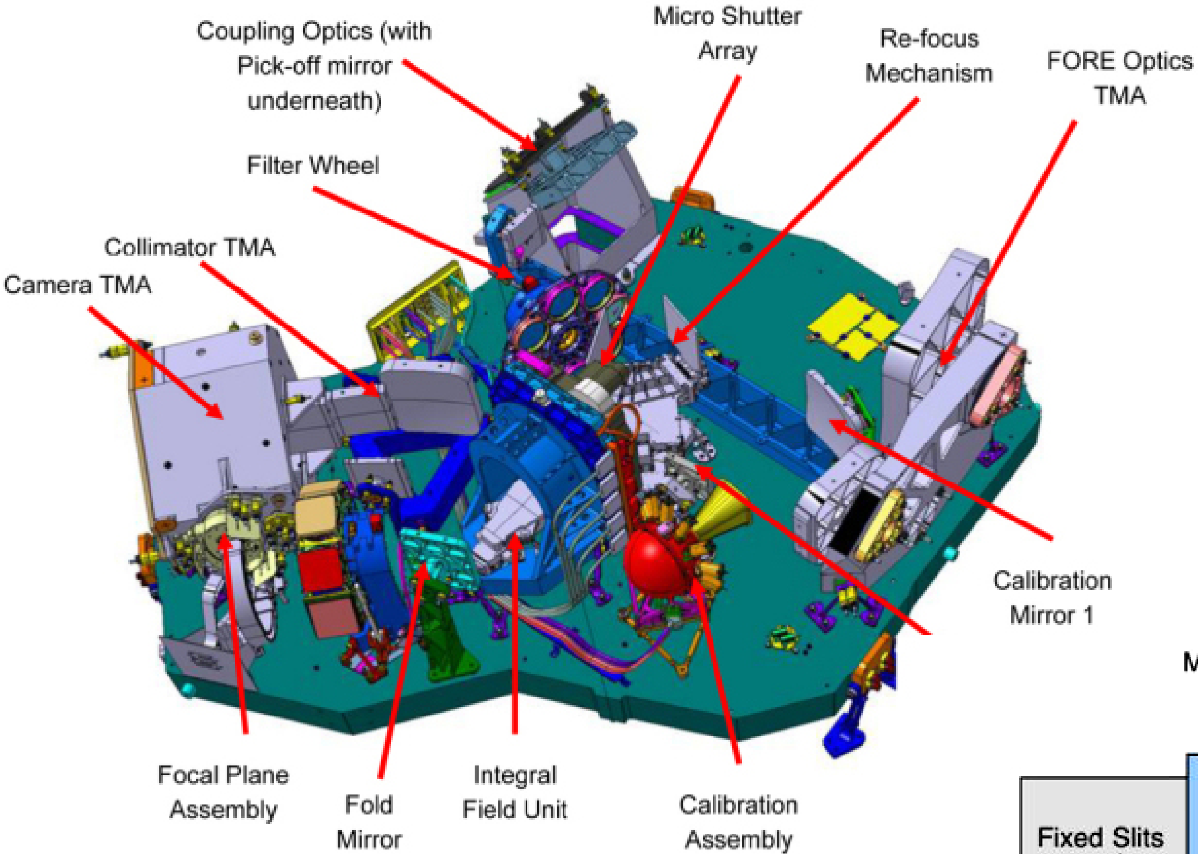
- **With JWST, IR astronomy will have doubled its "astronomical capability*" every 10 months for 50 years!!!**

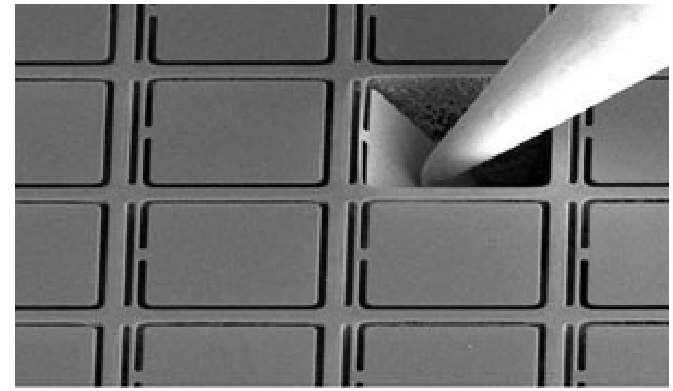
- These gains are powered by 1.) putting cryogenic telescopes into space; and 2.) developing infrared arrays with the performance to take advantage of the space environment

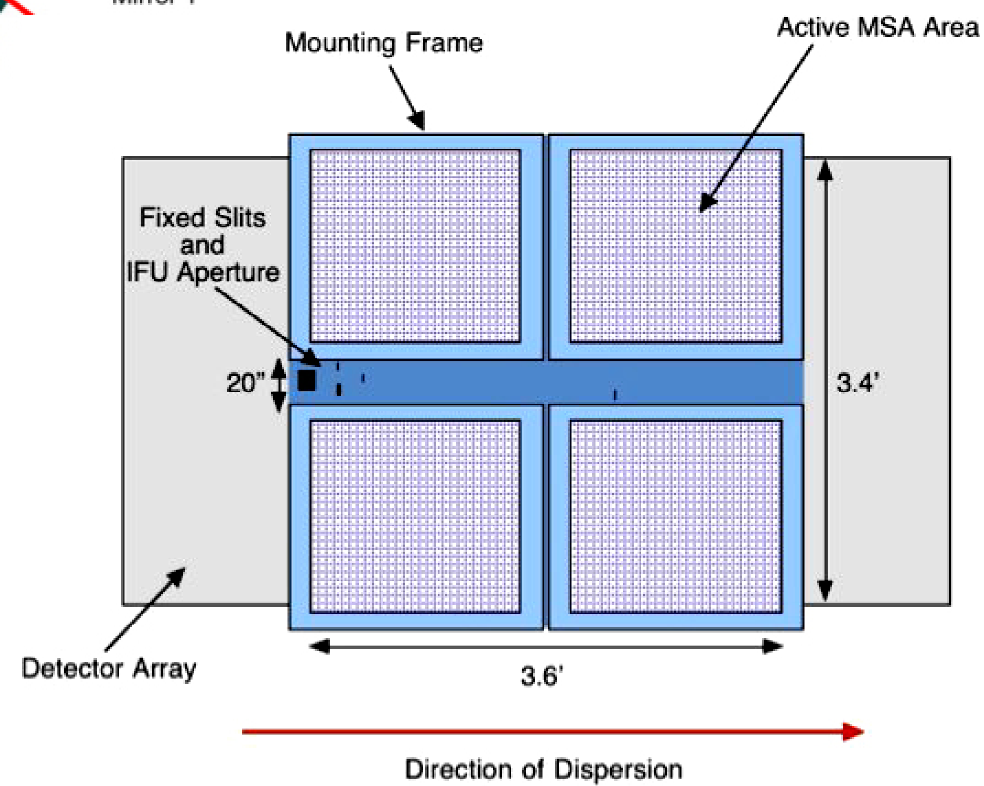
- JWST combines this potential with sophisticated instrumentation
    - NIRSpec: multi-object, integral field, and long slit spectroscopy, spectral resolutions of $\lambda/\Delta\lambda$ = 100, 1000, and 2700, uses two 5 μm cutoff HgCdTe arrays
    - NIRCam: Imager and coronagraph (with some spectroscopic capability) with 10 square arcmin field, operated from 0.6 to 5 μm with short and long wavelength channels; uses eight 2.5 μm cutoff and two 5 μm cutoff HgCdTe arrays
    - NIRISS: slitless and single object spectroscopy 1 to 3 μm, nonredundant mask interferometry 3.8 -4.8 μm; uses one 5 μm cutoff HgCdTe array
    - MIRI: imaging, coronagraphy, low and high resolution spectroscopy from 5 to 29 μm; uses three Si:As IBC arrays
- More information at (among other sites): http://www.stsci.edu/jwst/instruments

* Astronomical capability is a metric proportional to the integration time for a survey. It goes as the number of pixels divided by the detection limit per pixel squared (Bahcall 1990)

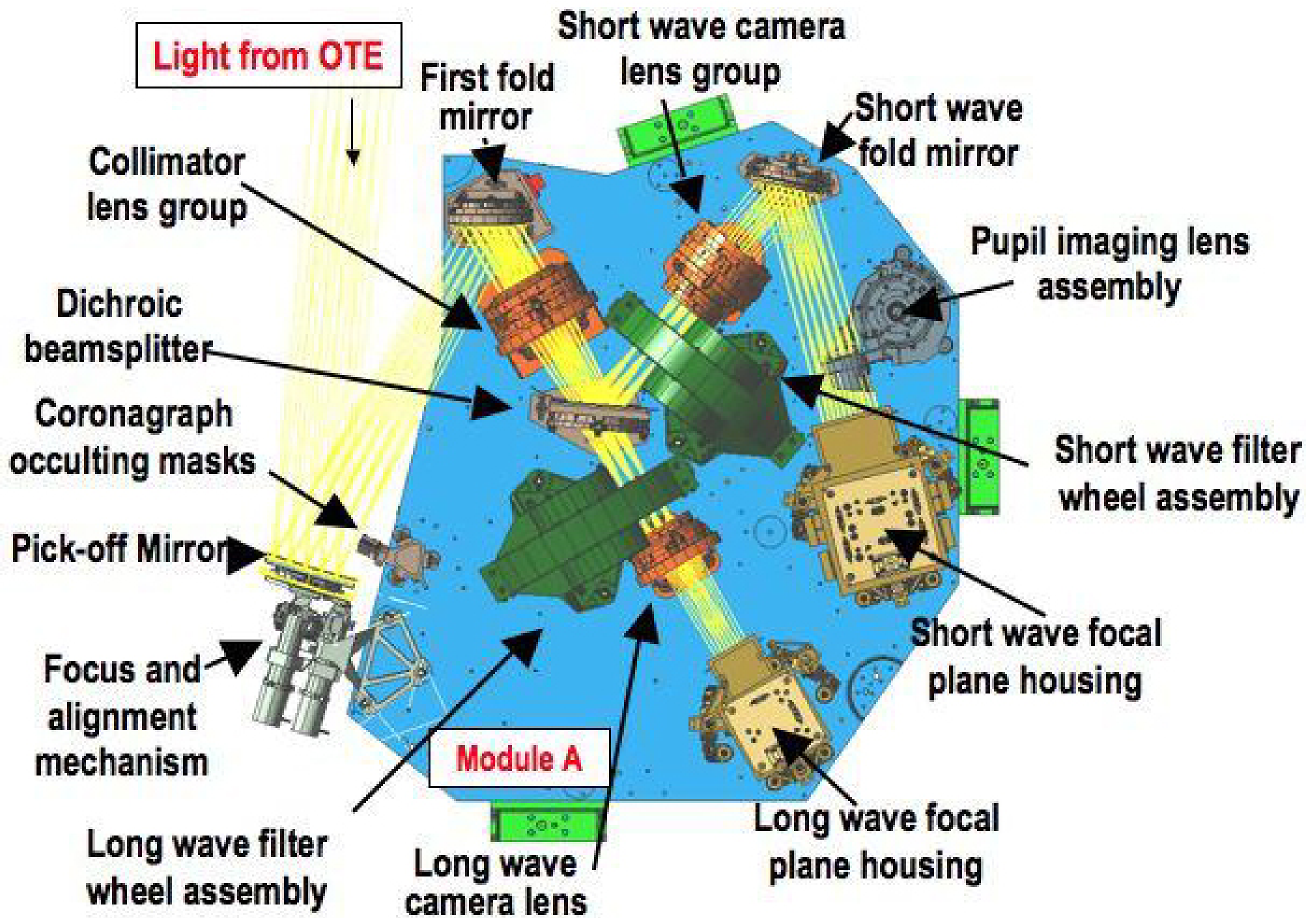
NIRSpec Key Features





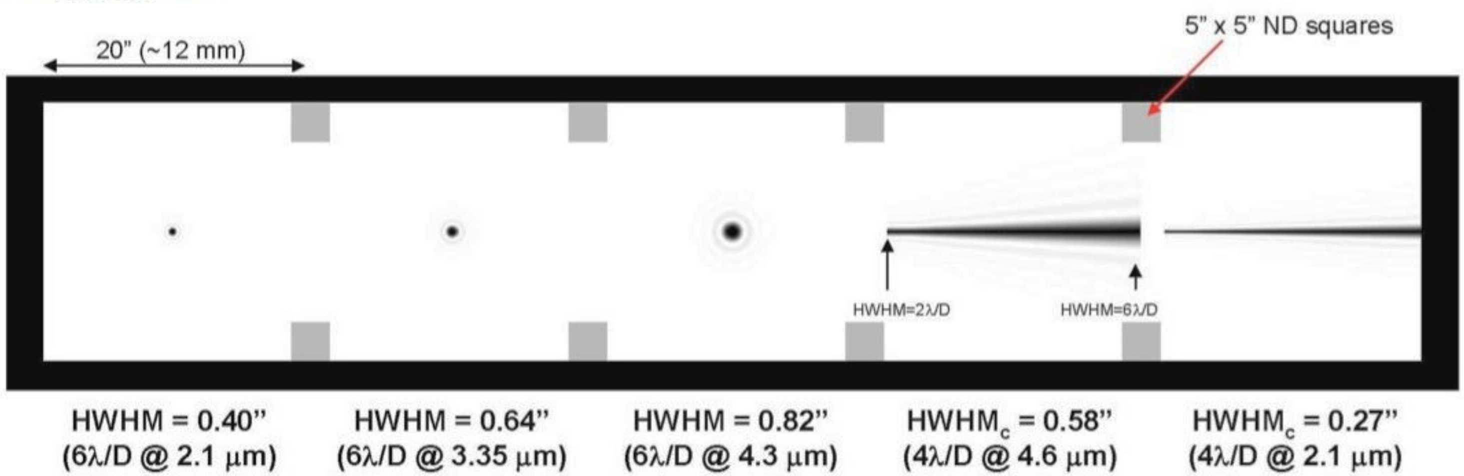


- Silicon carbide optical bench and optics
- All reflective design
- Microshutter arrays that allow multi-object spectroscopy, 0.6 – 5 μm



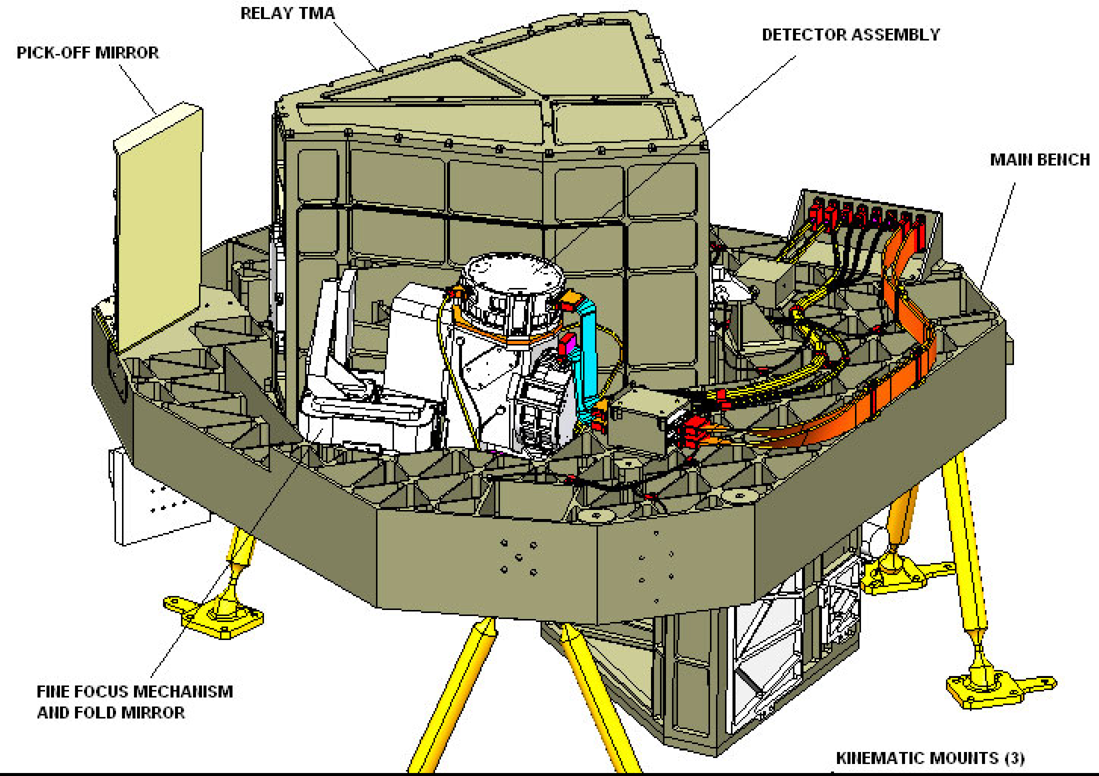
NIRCam Key Features

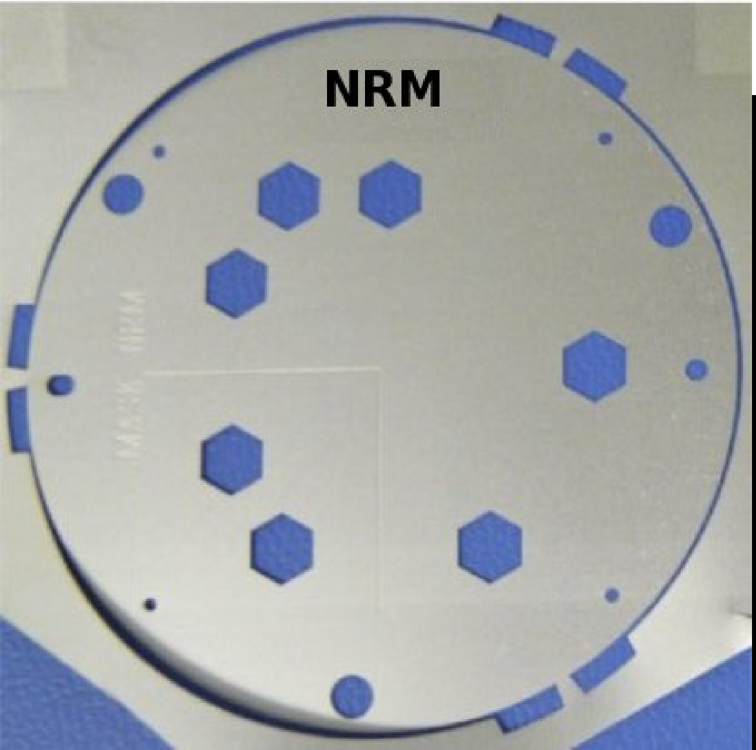
- Two identical cameras provide high reliability
    - Critical because NIRCam does wavefront sensing
- Dichroic division into short and long wavelengths supports high observing efficiency, 0.6 – 5 μm
- Extensive coronagraphic capabilities

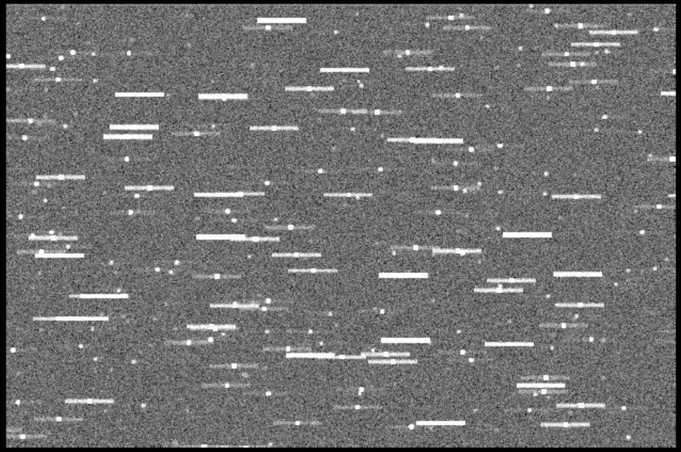


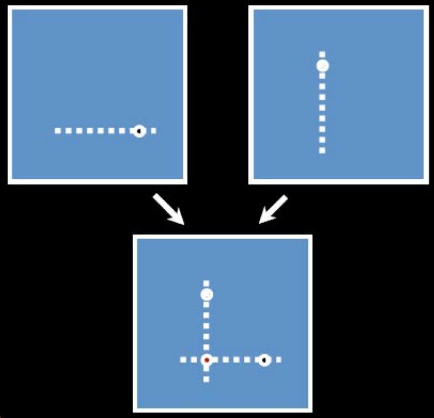
NIRISS Key Features

- Combined with guide camera
- Nonredundant interferometric mask provides highest possible resolution at 3.8 – 4.8 μm
- Slitless grisms give efficient spectroscopy over entire field of view, 1 – 2.5 μm
    - Orthogonal grisms reduce spectral overlap

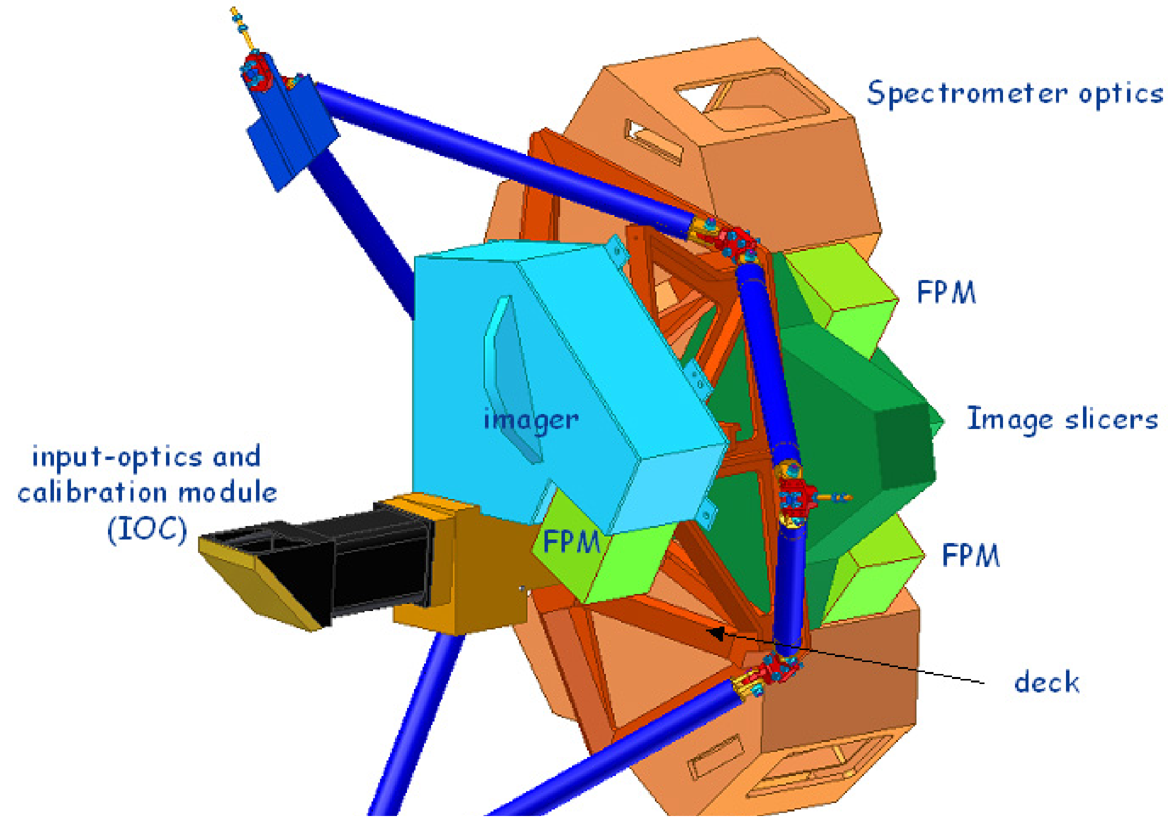








- A spectrum for every source in the field of view.
- Not restricted



MIRI Key Features

- Cooled to < 6.5 K with cryocooler
- Combines imaging, coronagraphy, low and high resolution spectroscopy, 5 – 28.5 μm
- Highly efficient IFU spectrometer – covers 5 – 28.5 μm at $\lambda/\Delta\lambda \sim 2500$ in three exposures
- 4-quadrant phase masks provide small inner working angle coronagraphy