The Fantastical Discoveries of Astronomy made possible by the Wonderful Properties of II-VI Materials

Presentation to the Rochester Institute of Technology
Virtual Detector Workshop
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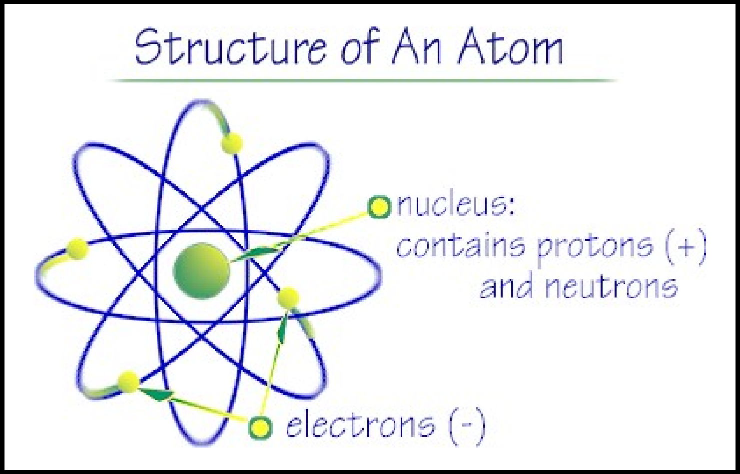
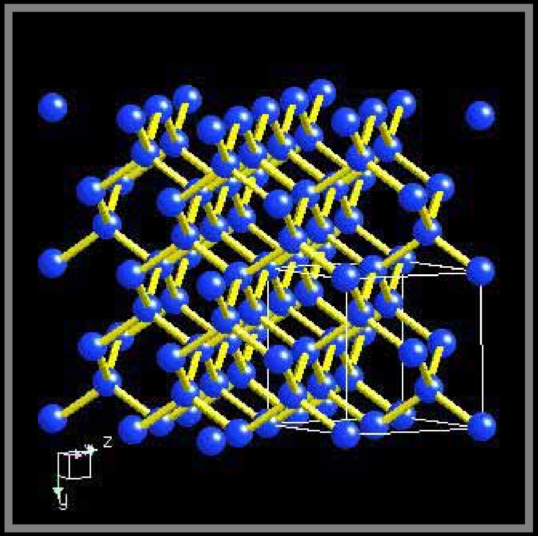
Teledyne Imaging Sensors

Crystals are excellent detectors of light



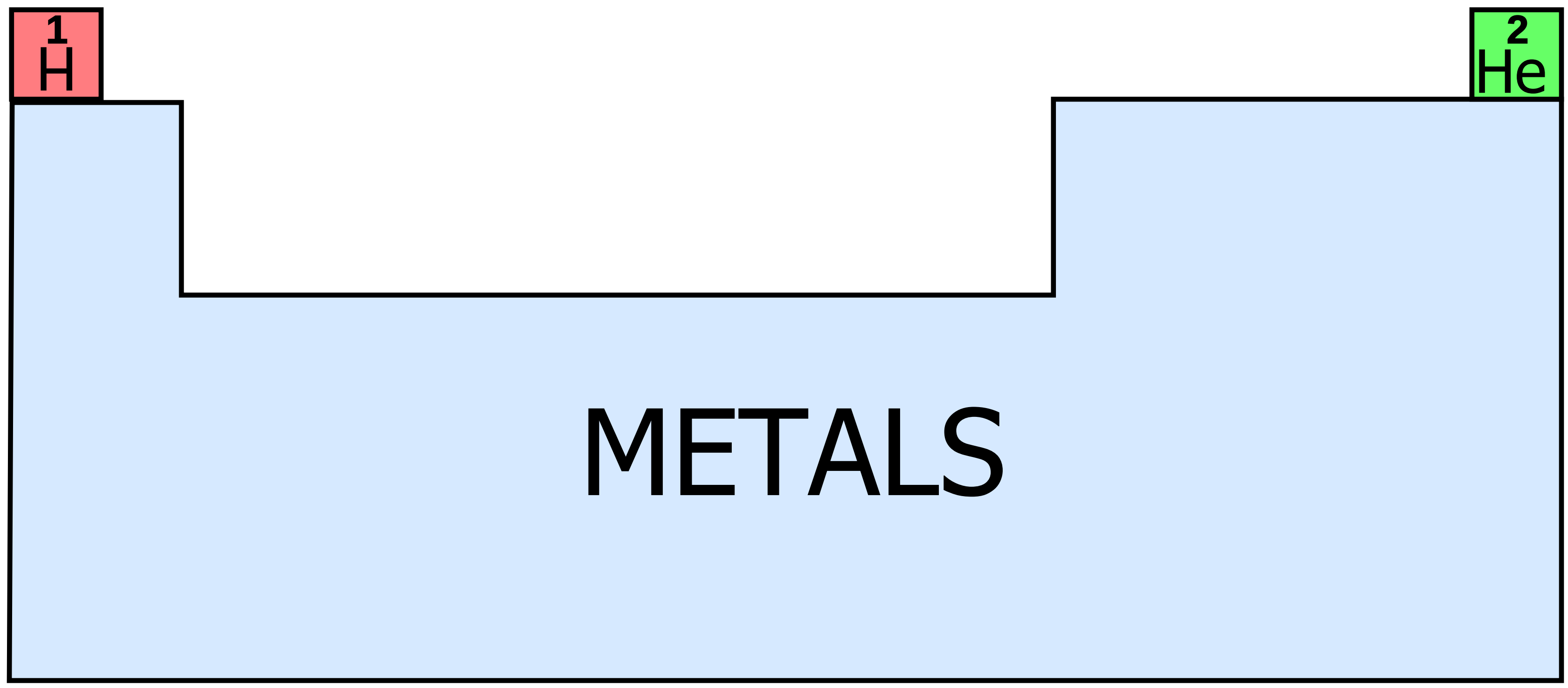
- Simple model of atom
  - Protons (+) and neutrons in the nucleus with electrons (-) orbiting



Silicon crystal lattice

- Electrons are trapped in the crystal lattice
  - by electric field of protons
- Light energy (or thermal energy) can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an "electron-hole" pair.
- The photocharge can be collected and amplified, so that light is detected
- The photon energy required to free an electron depends on the material.

The Astronomer's Periodic Table



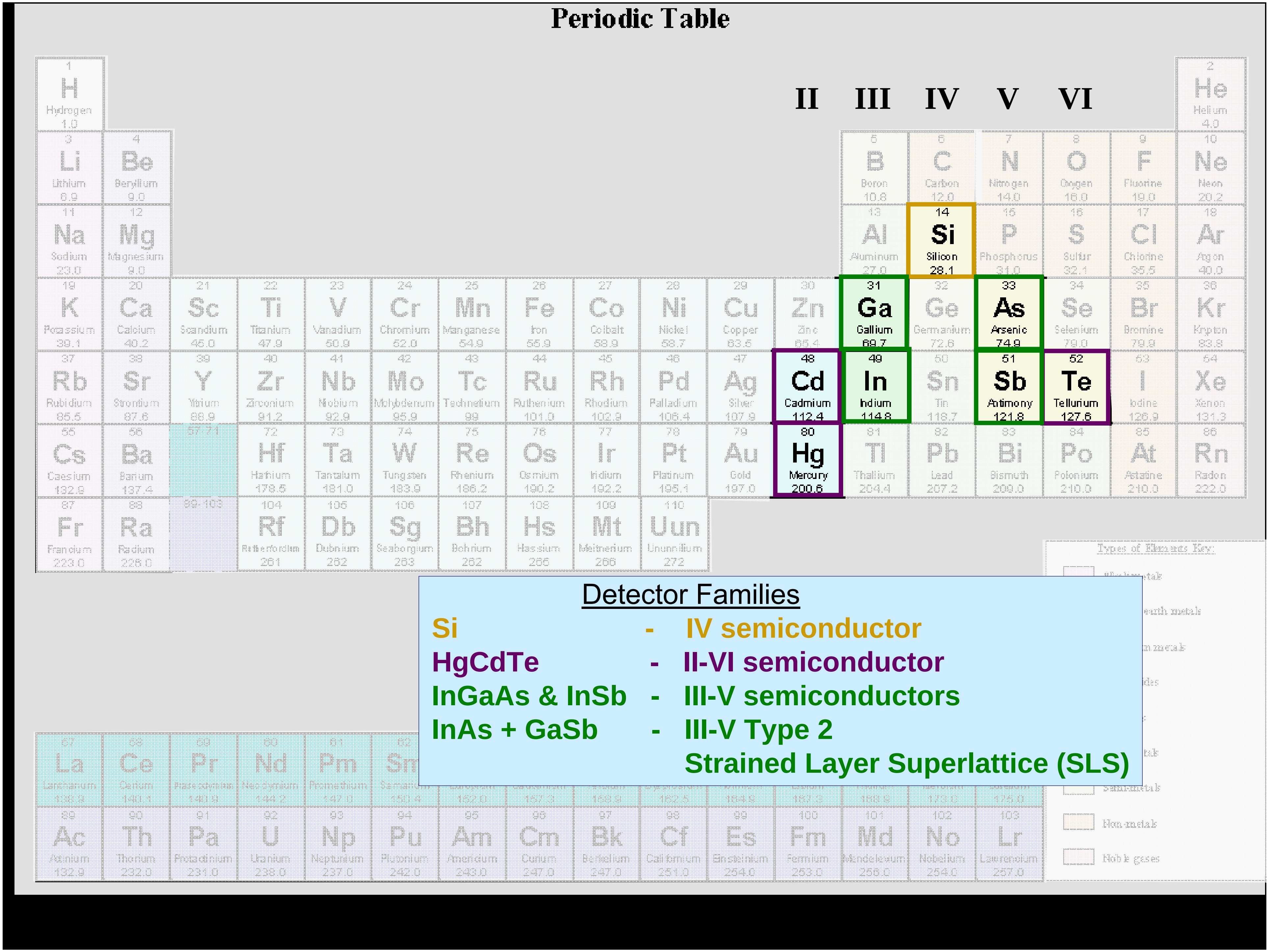
Periodic Table

1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 92.9	42 Mo Molybdenum 95.9	43 Tc Technetium 99	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.9	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
87 Fr Francium 223.0	88 Ra Radium 226.0	89-103	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 262	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium 147.0	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium 132.9	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium 237.0	94 Pu Plutonium 242.0	95 Am Americium 243.0	96 Cm Curium 247.0	97 Bk Berkelium 247.0	98 Cf Californium 251.0	99 Es Einsteinium 254.0	100 Fm Fermium 253.0	101 Md Mendelevium 256.0	102 No Nobelium 254.0	103 Lr Lawrencium 257.0

Types of Elements Key:

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Poor metals
- Semi-metals
- Non-metals
- Noble gases



Detector Families

Si - IV semiconductor

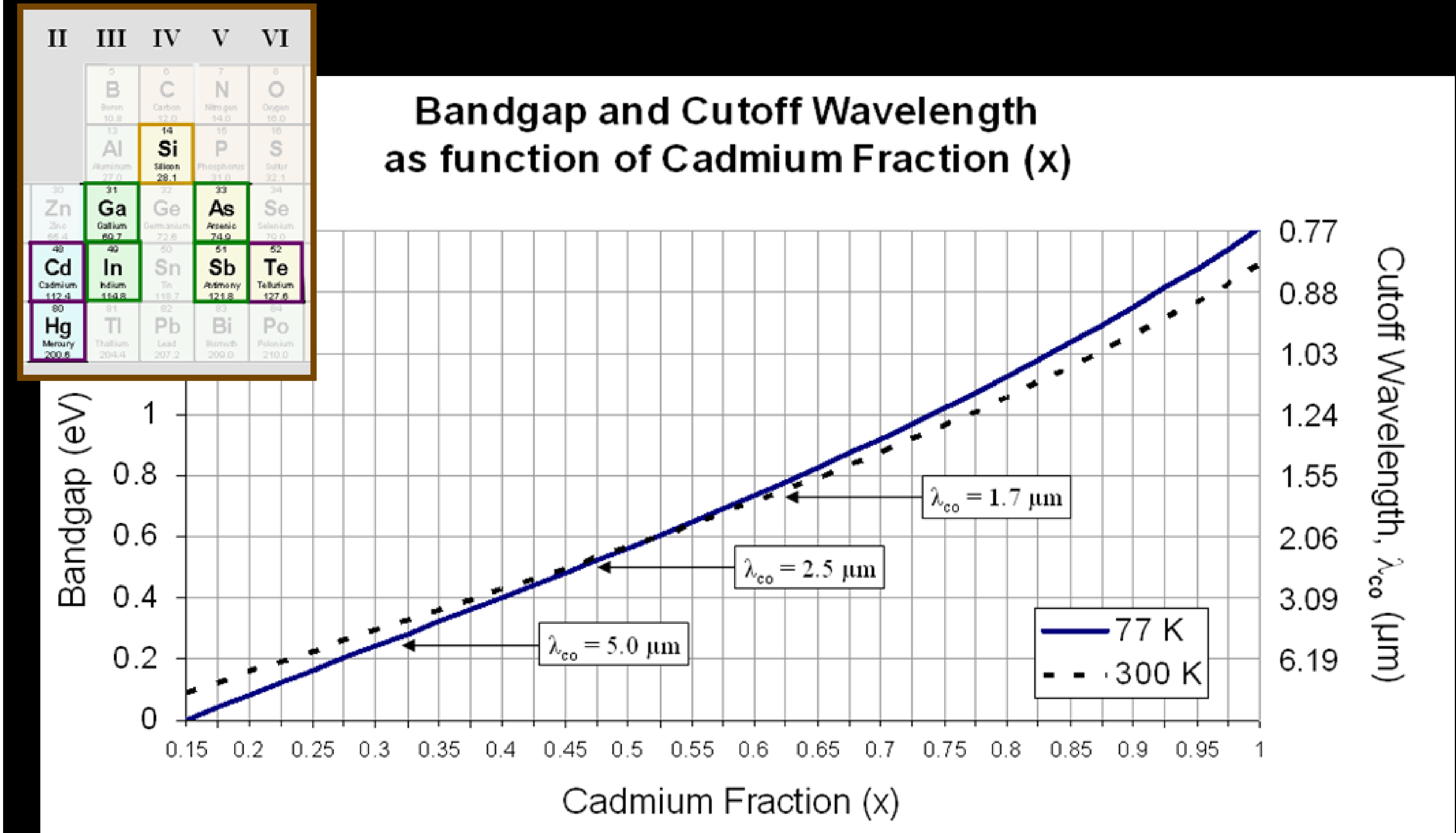
HgCdTe - II-VI semiconductor

InGaAs & InSb - III-V semiconductors

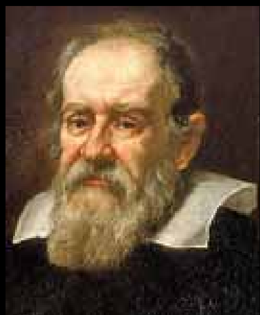
InAs + GaSb - III-V Type 2 Strained Layer Superlattice (SLS)

Tunable Wavelength: Valuable property of HgCdTe

$Hg_{1-x}Cd_xTe$ Modify ratio of Mercury and Cadmium to "tune" the bandgap energy



The Golden Age of Astronomy

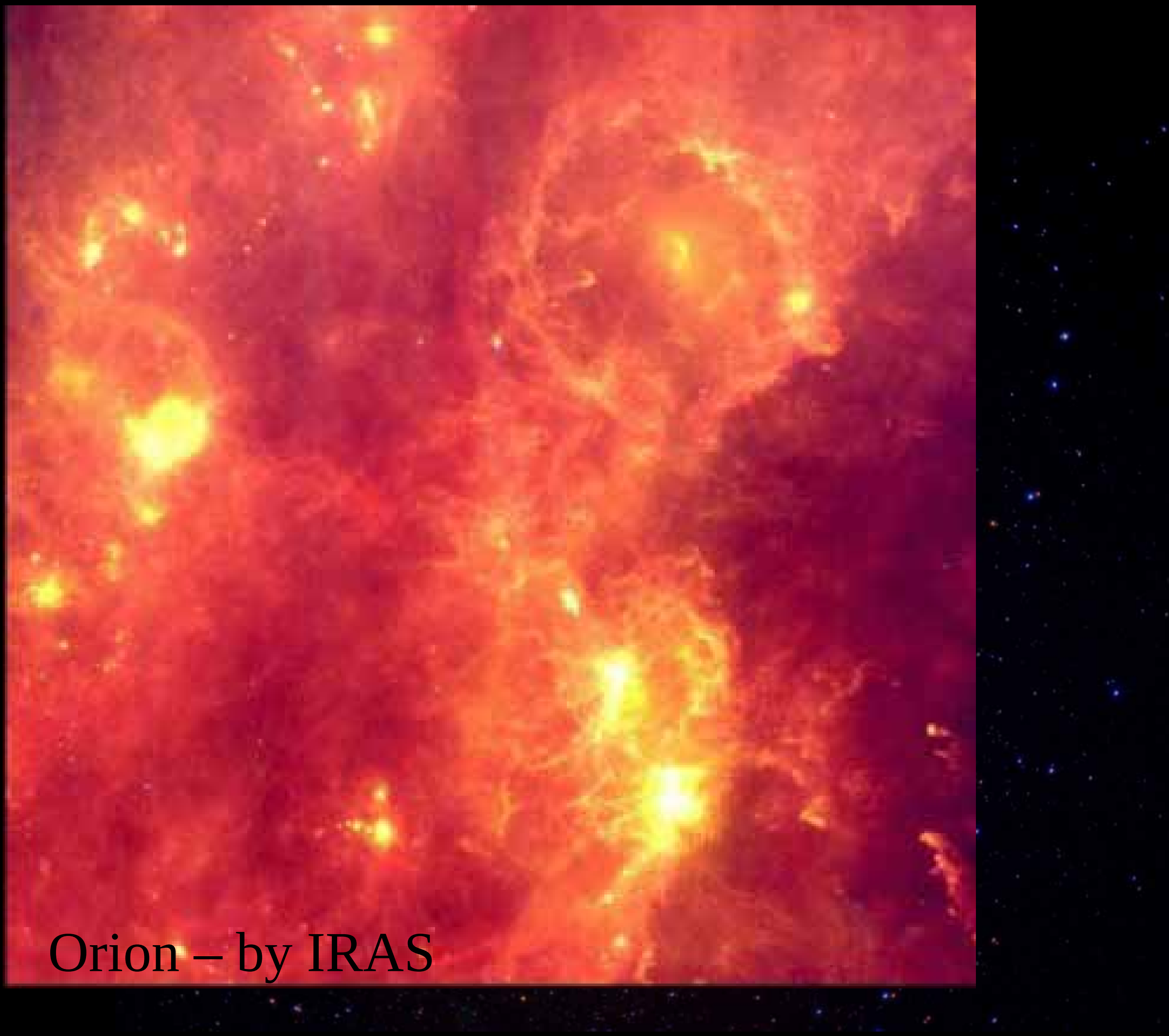


Galileo Galilei and 2 cm refractor (1609)

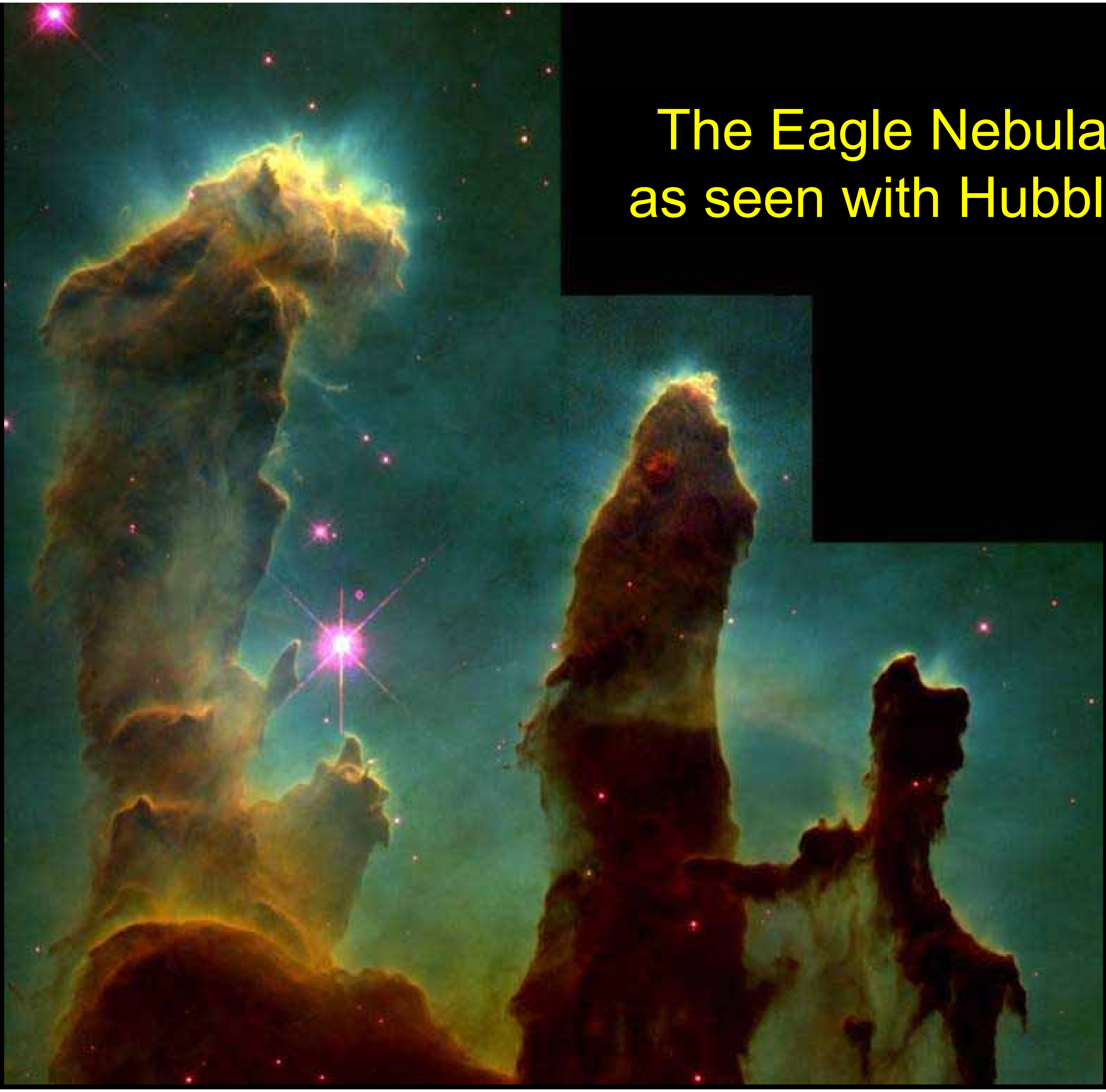
Hubble Space Telescope
- 2.4 meter

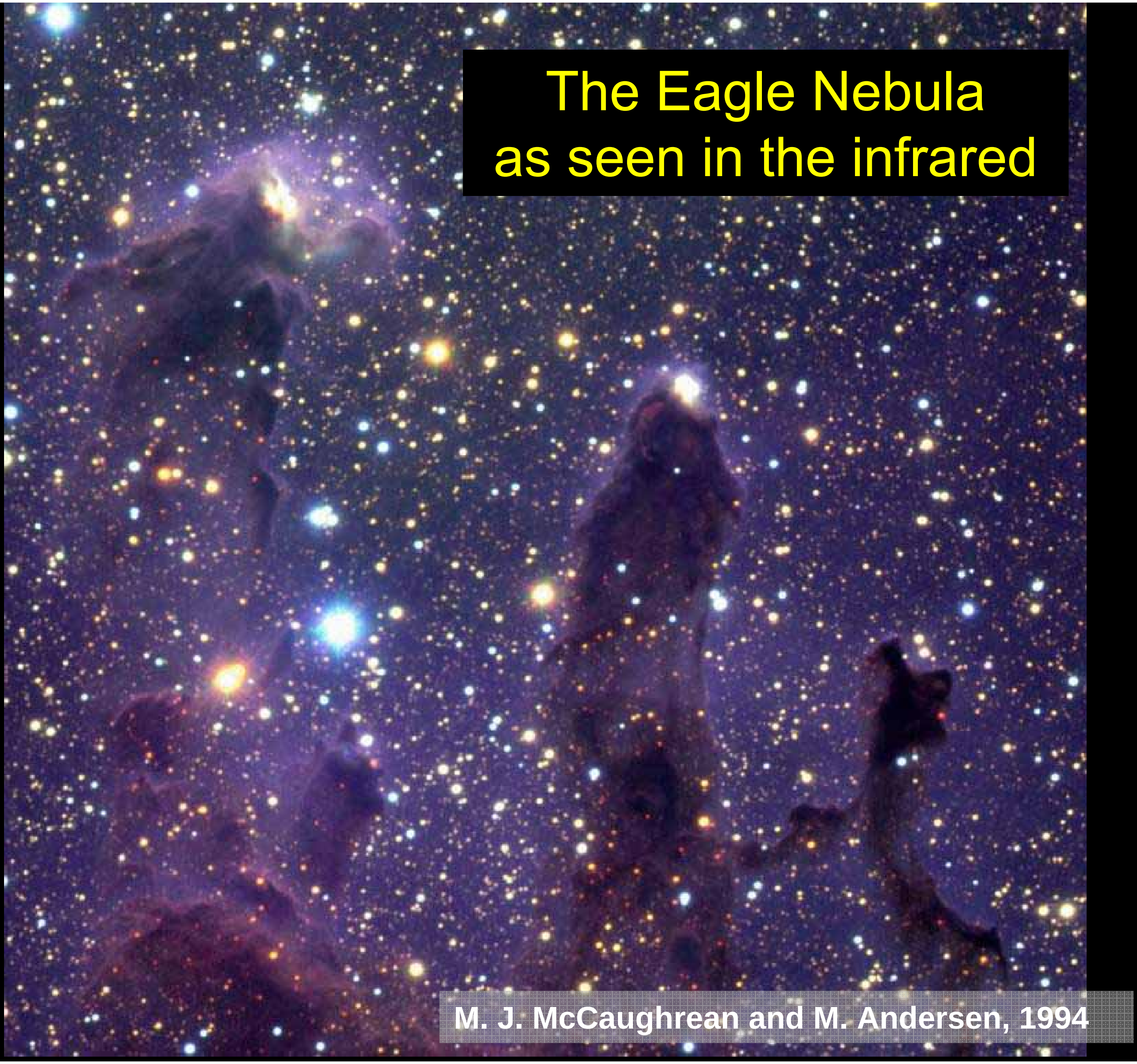
European Southern Observatory
Paranal Observatory
- Four 8.2 meter telescopes
- Four 1.8 meter auxiliary telescopes
- 4 meter infrared survey telescope
- 2.6 meter optical survey telescope

Orion – In visible and infrared light



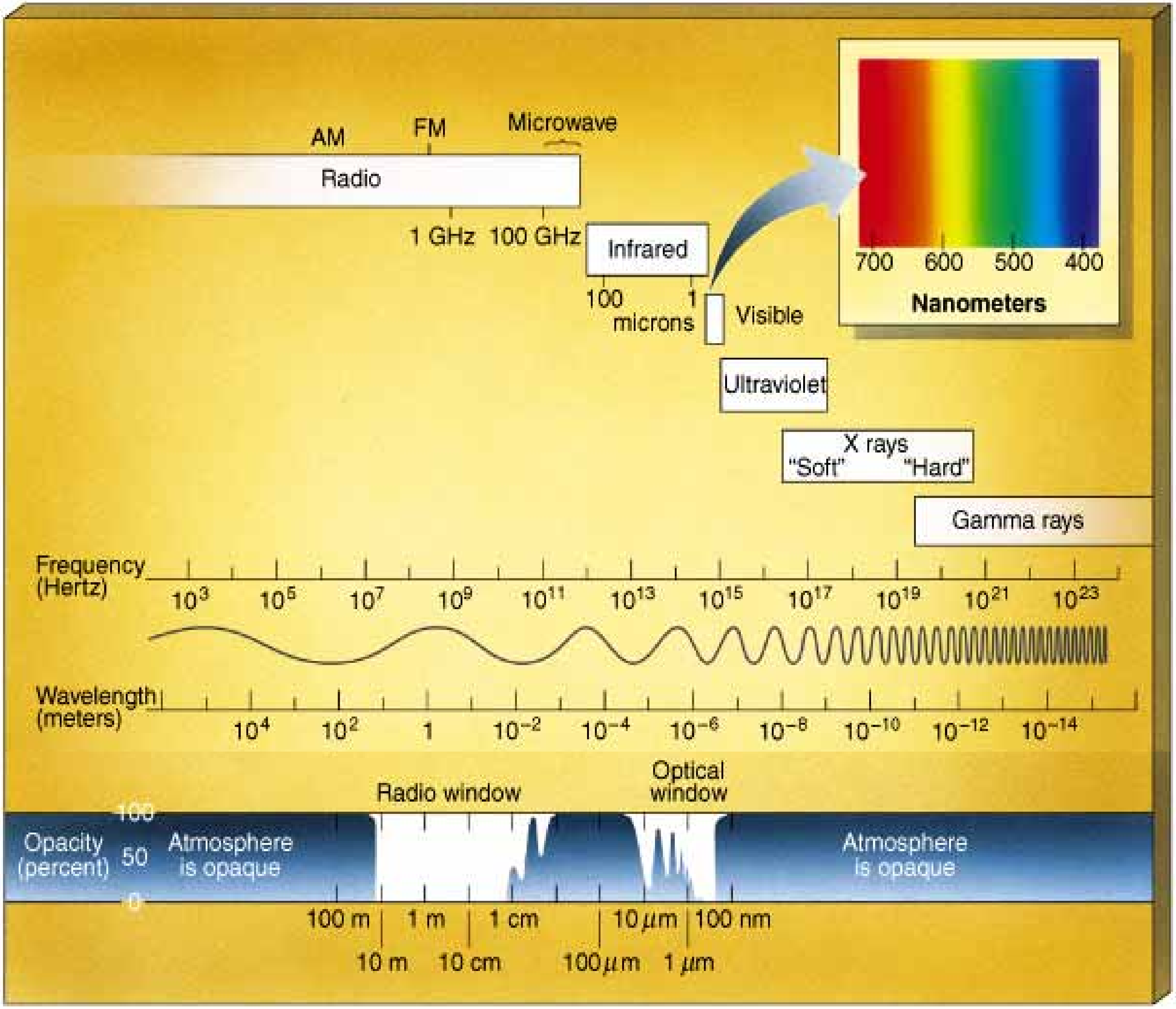
The Eagle Nebula as seen with Hubble




The Eagle Nebula
as seen in the infrared
M. J. McCaughrean and M. Andersen, 1994

European Southern Observatory

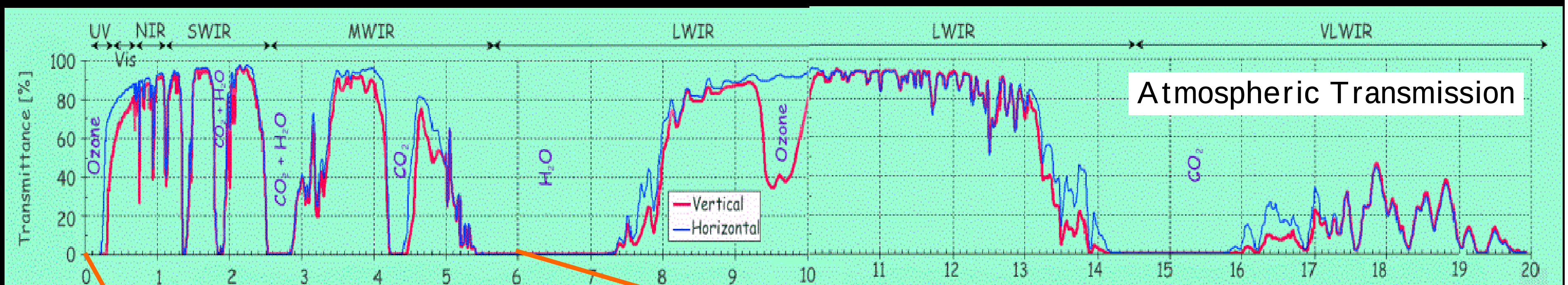
- 8.2 meter telescope



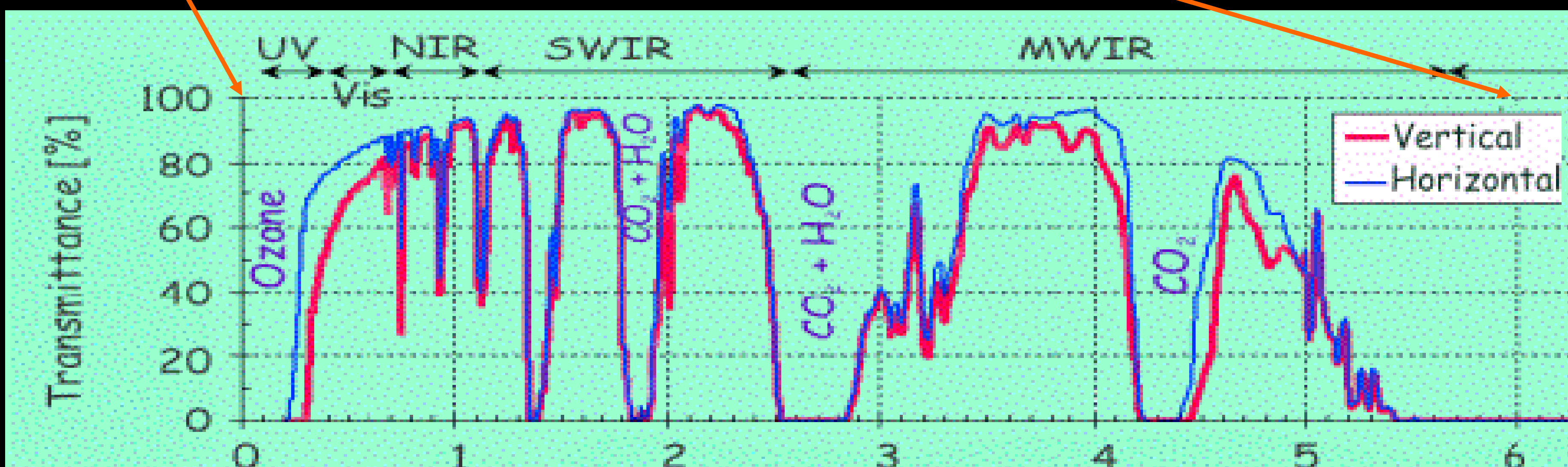
AM
FM
Microwave
Radio
1 GHz
100 GHz
Infrared
100 microns
1
Visible
Ultraviolet
X rays
"Soft"
"Hard"
Gamma rays
700
600
500
400
Nanometers
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^11 10^13 10^15 10^17 10^19 10^21 10^23
Wavelength (meters)
10^4 10^2 1 10^-2 10^-4 10^-6 10^-8 10^-10 10^-12 10^-14
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Atmosphere is opaque
100 m
1 m
1 cm
10 µm
100 nm
10 m
10 cm
100 µm
1 µm

Atmospheric transmission

Not all of the light gets through atmosphere to ground-based telescopes



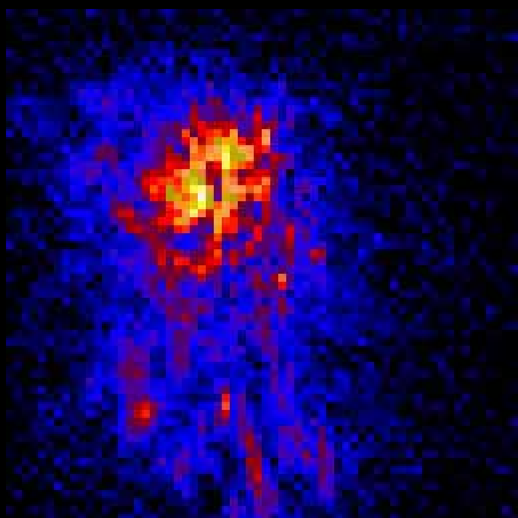
Wavelength (microns)



Common Astronomical Filters	J	H	K	L	M
	1.1-1.4	1.5-1.8	2.0-2.4	3.0-4.0	4.5-5.1

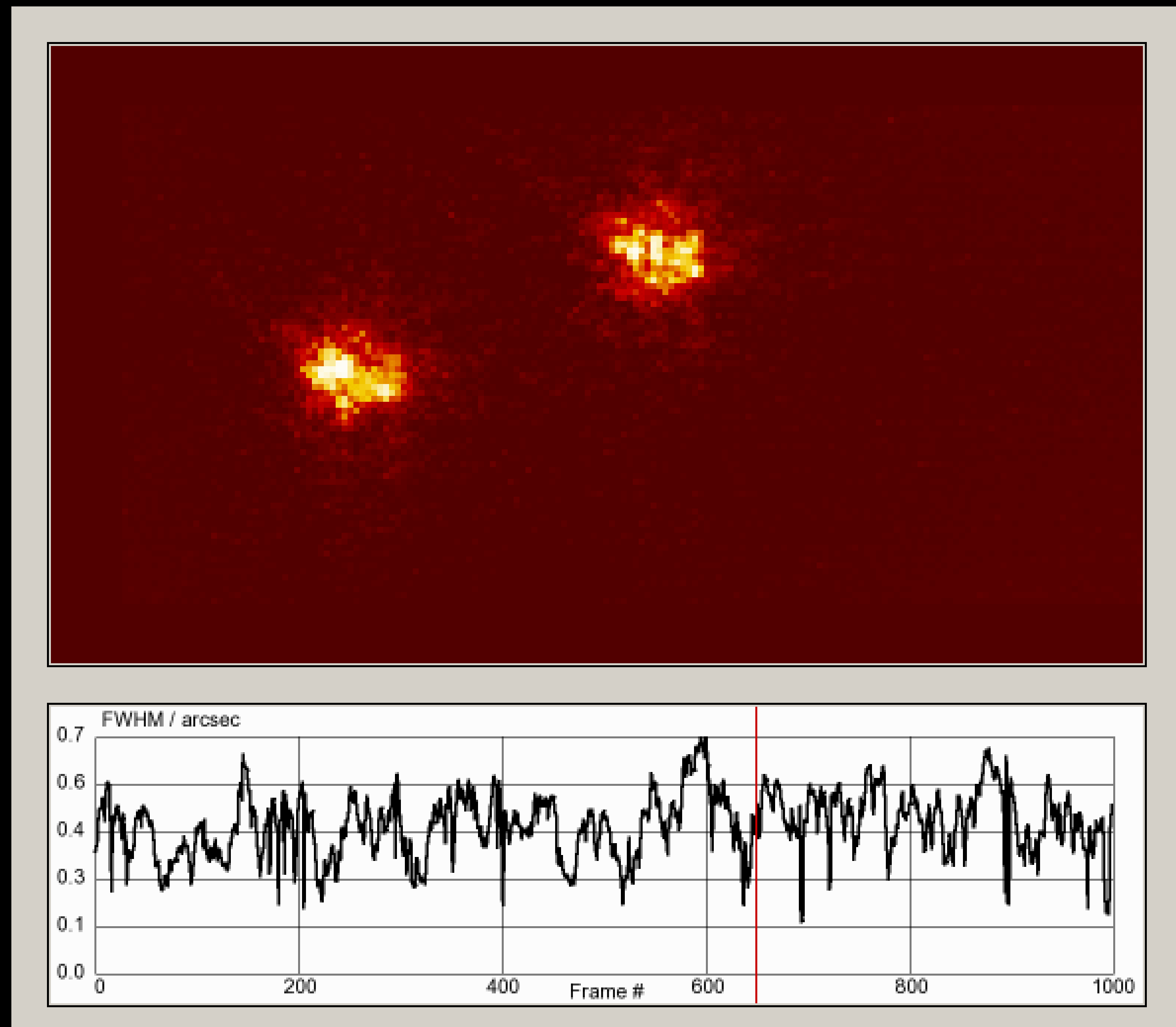
Atmospheric Blurring

The bane of ground-based astronomy



Long exposure image
is called the “seeing disk”

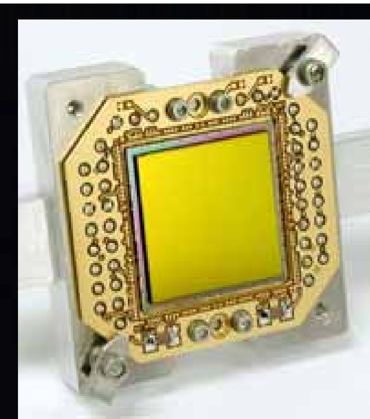
Long exposure image



Binary star pair 100 Her, 14 arc sec separation (V_{mag} = 6.0)
10 msec frame time

Hubble Space Telescope

- Quantum Efficiency = 85-90%
- Dark current (145K) = 0.02 e-/pix/sec
- Readout noise = 25 e- (single CDS)

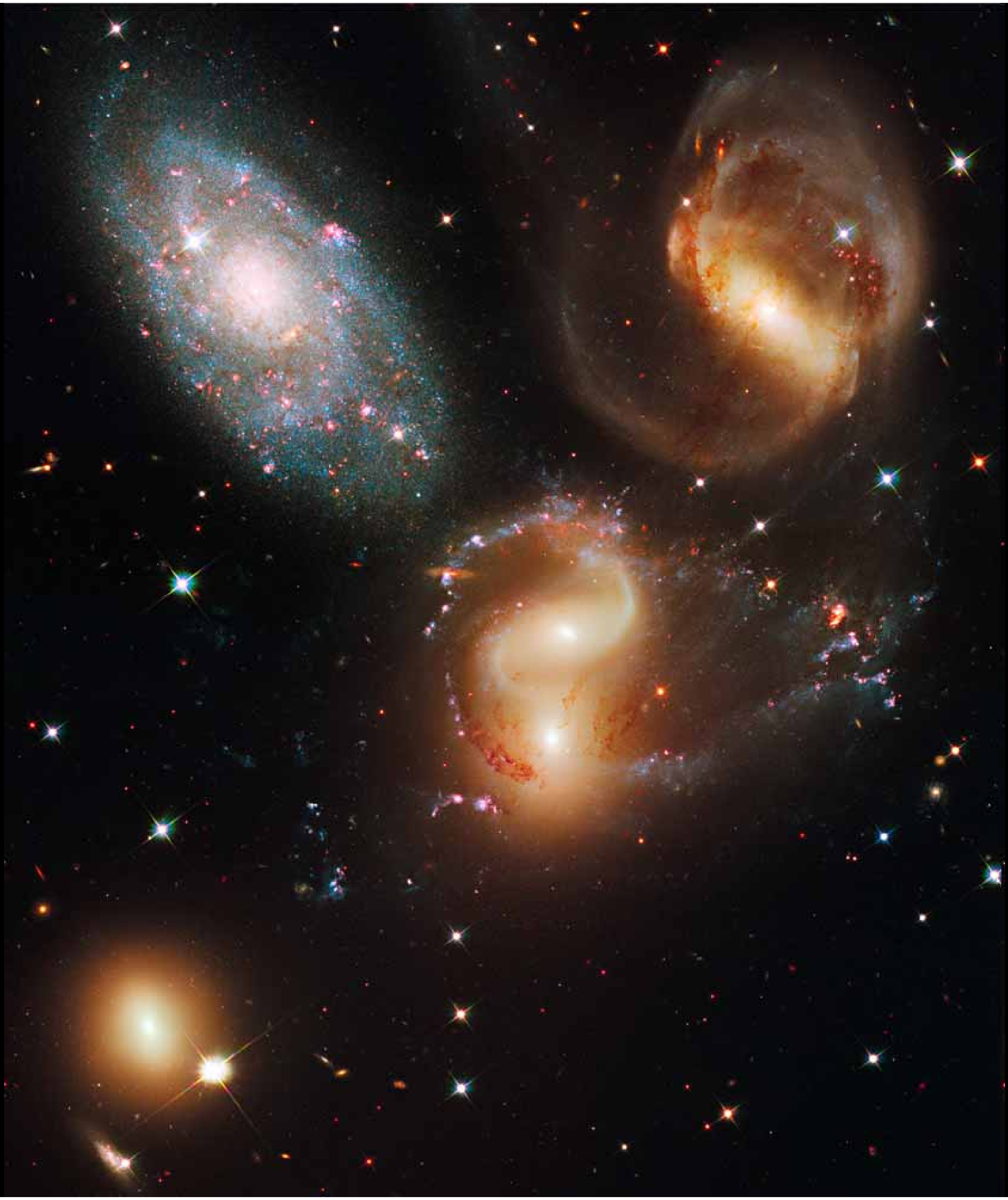


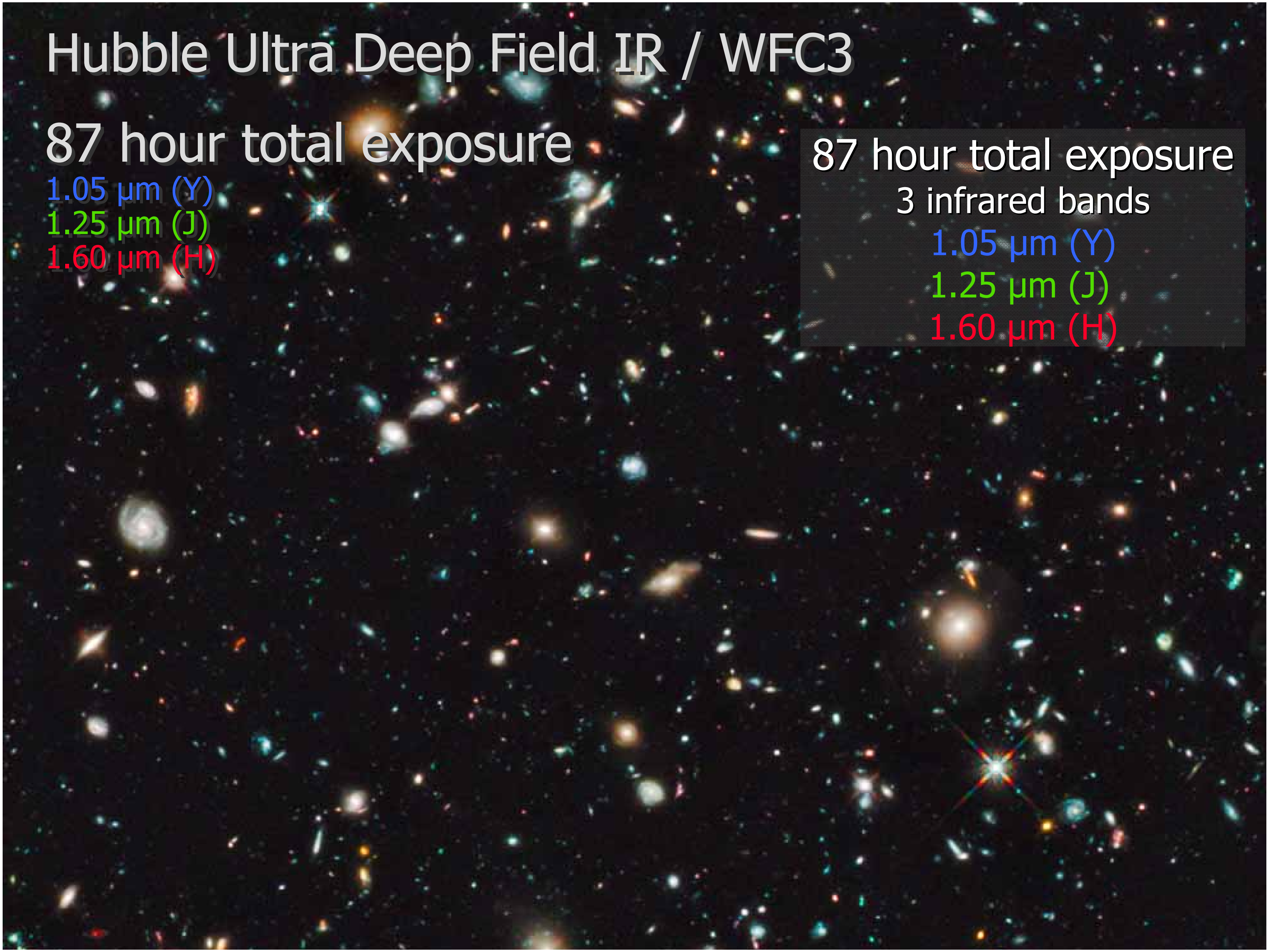
Infrared Detector

- 1024×1024 pixels
- 18 µm pitch
- 1.7 µm cutoff HgCdTe
- Substrate-removed

Stephan's Quintet

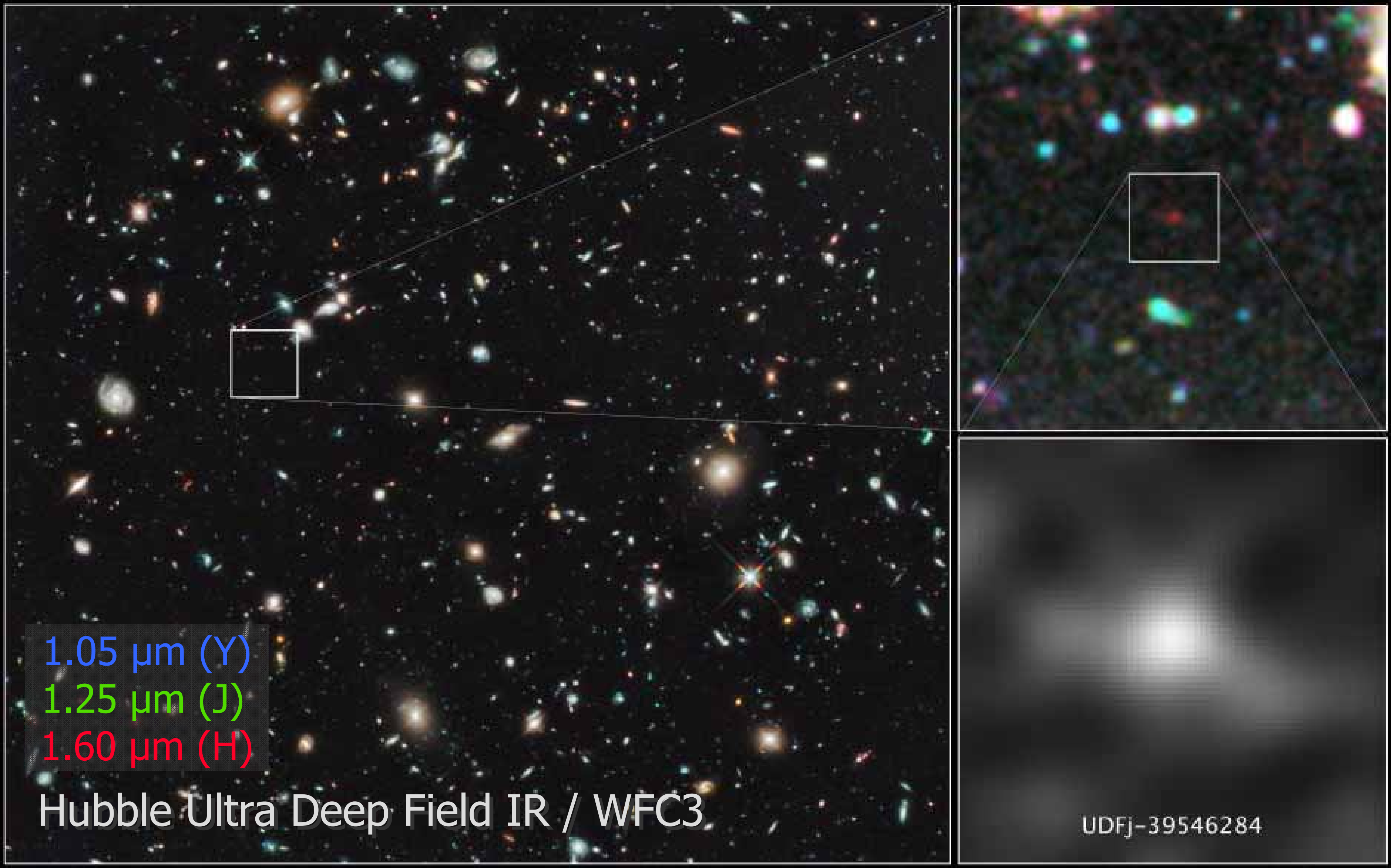
WFC3



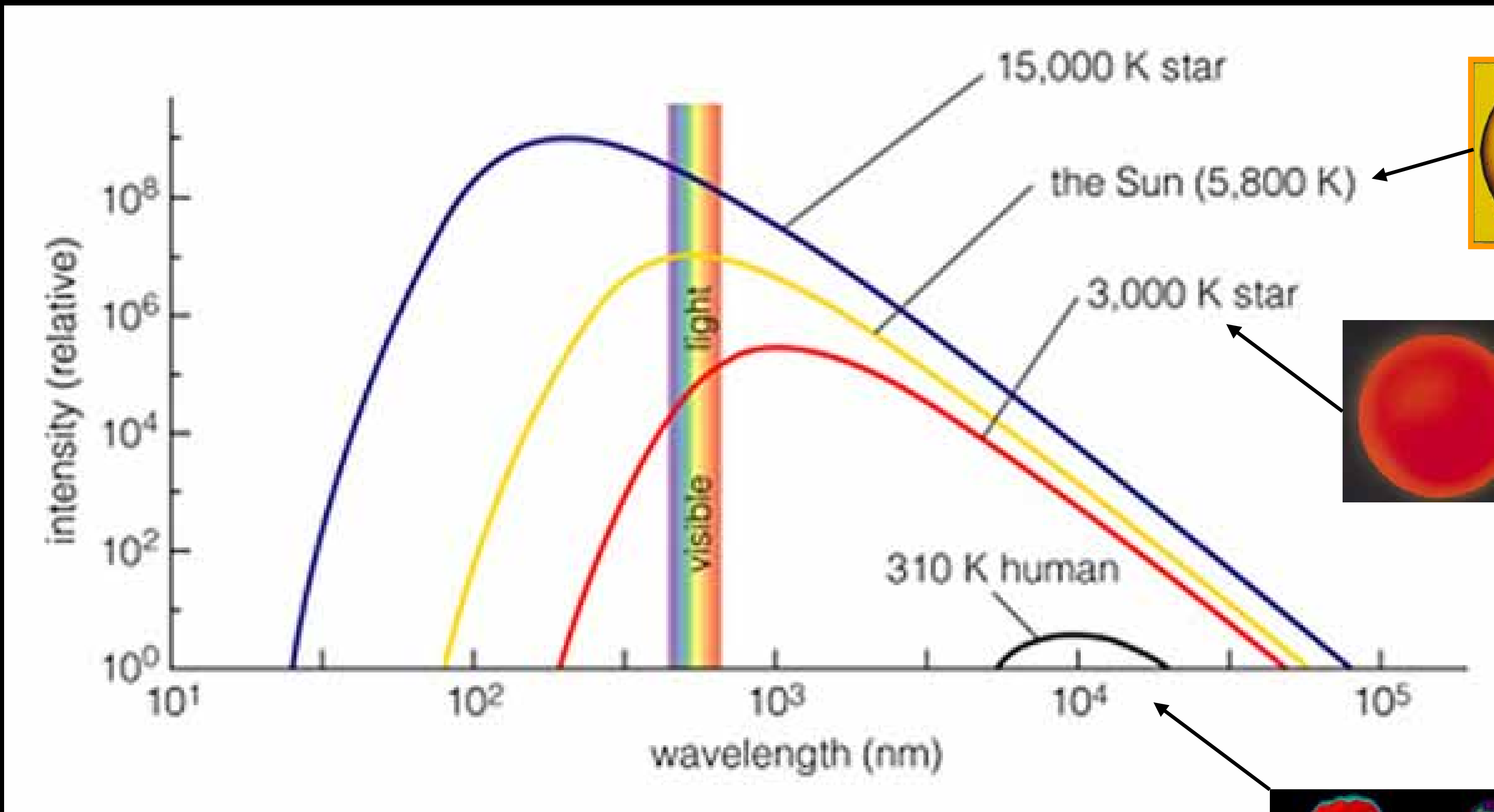

Hubble Ultra Deep Field IR / WFC3
87 hour total exposure
1.05 µm (Y)
1.25 µm (J)
1.60 µm (H)
87 hour total exposure
3 infrared bands
1.05 µm (Y)
1.25 µm (J)
1.60 µm (H)

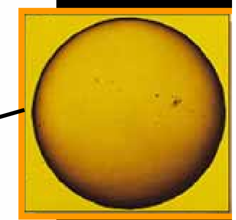
Most distant galaxy yet seen

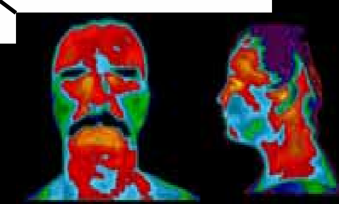
Light travelled for 13.2 billion years to reach the Earth



Thermal Radiation

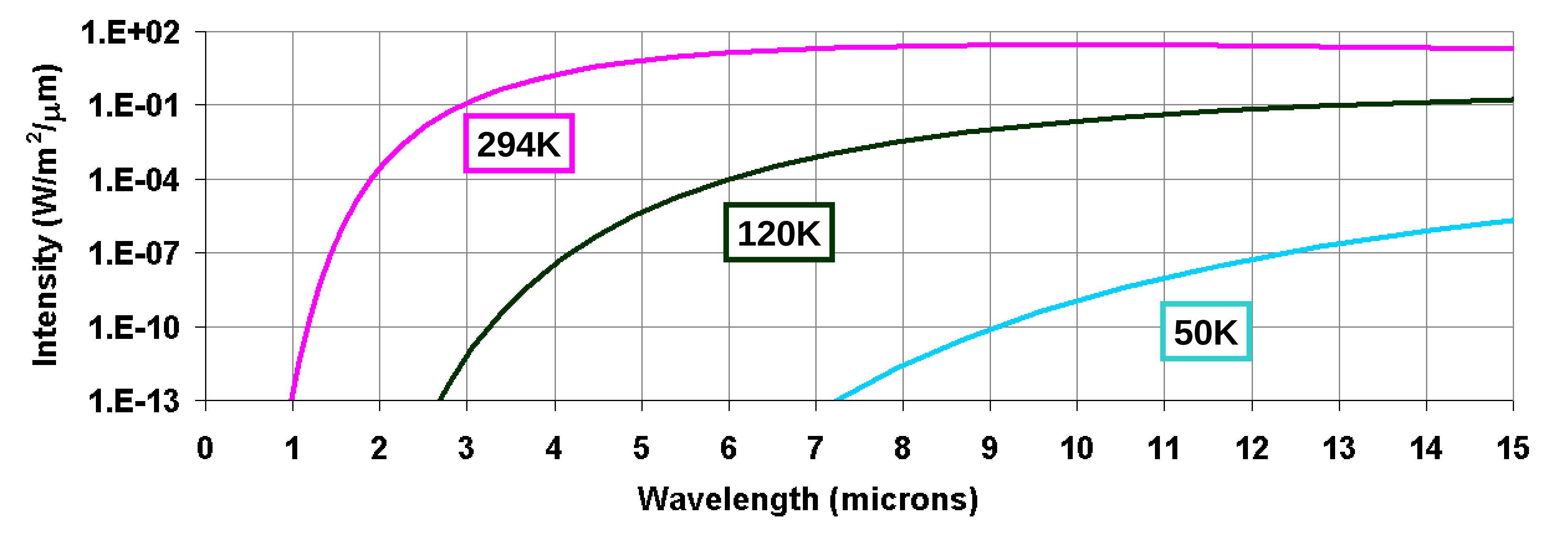






Ultraviolet ← → Infrared

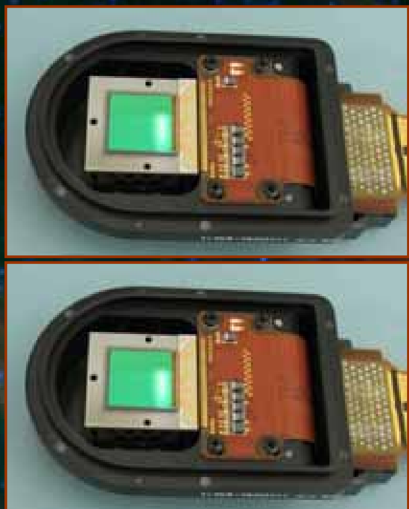
Thermal Radiation



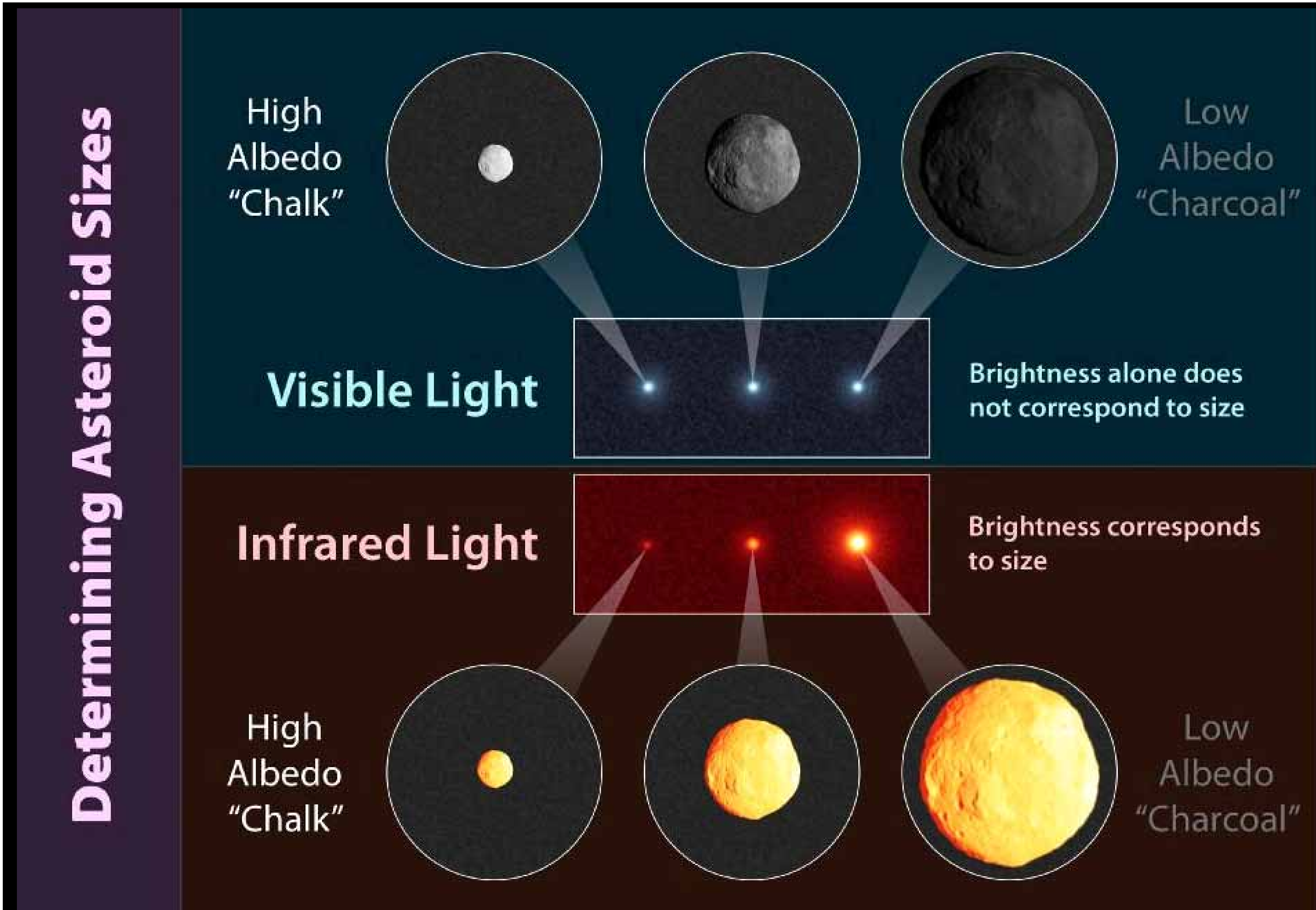
Hubble Space Telescope 2.4-m primary mirror is kept at 70 ºF (21C, 294K)

Wide-field Infrared Survey Explorer (WISE)

HgCdTe arrays for 2 of 4 infrared bands

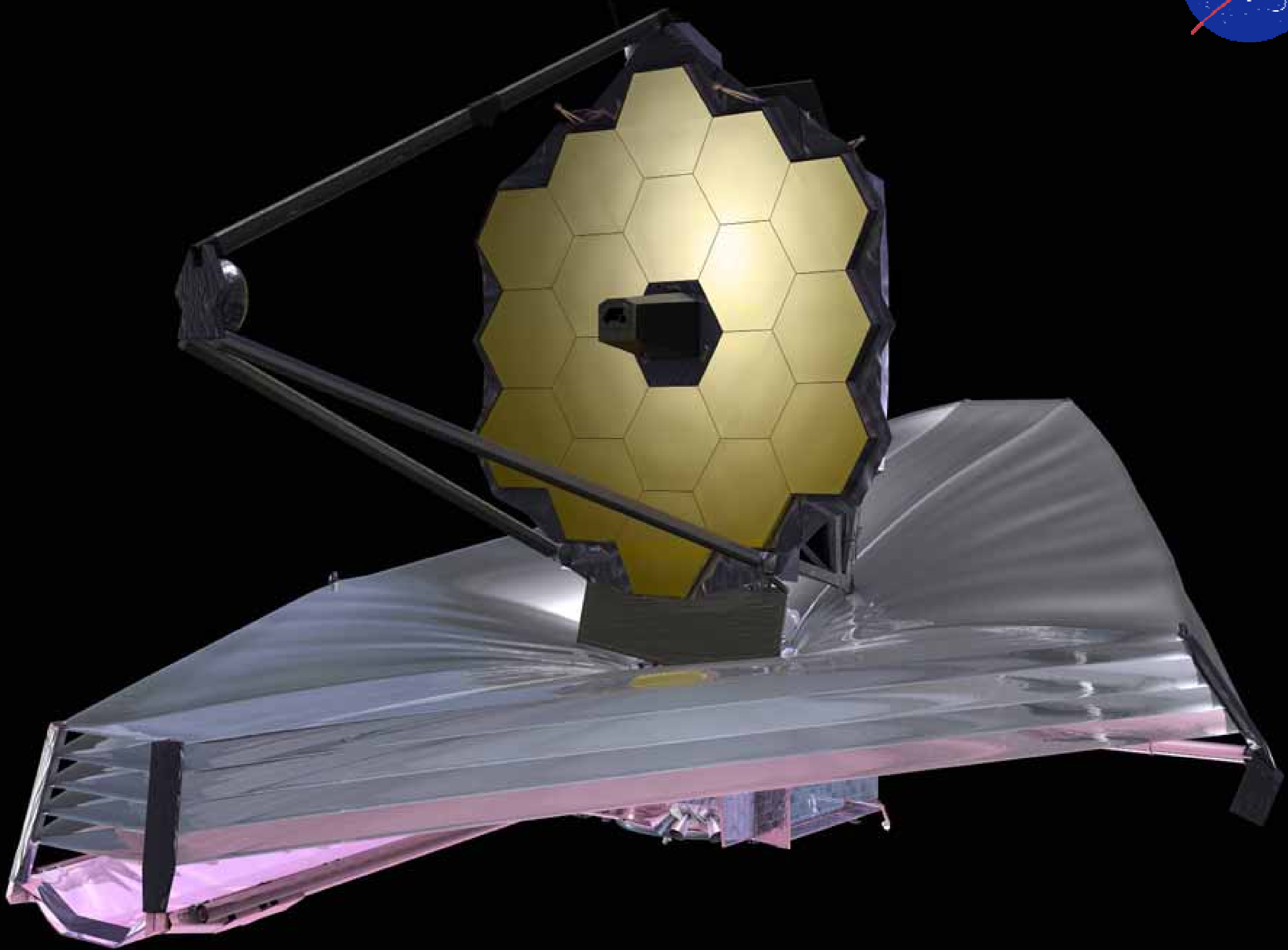


Two
1024×1024 pixel
infrared arrays
3.4 and 4.6 μm bands



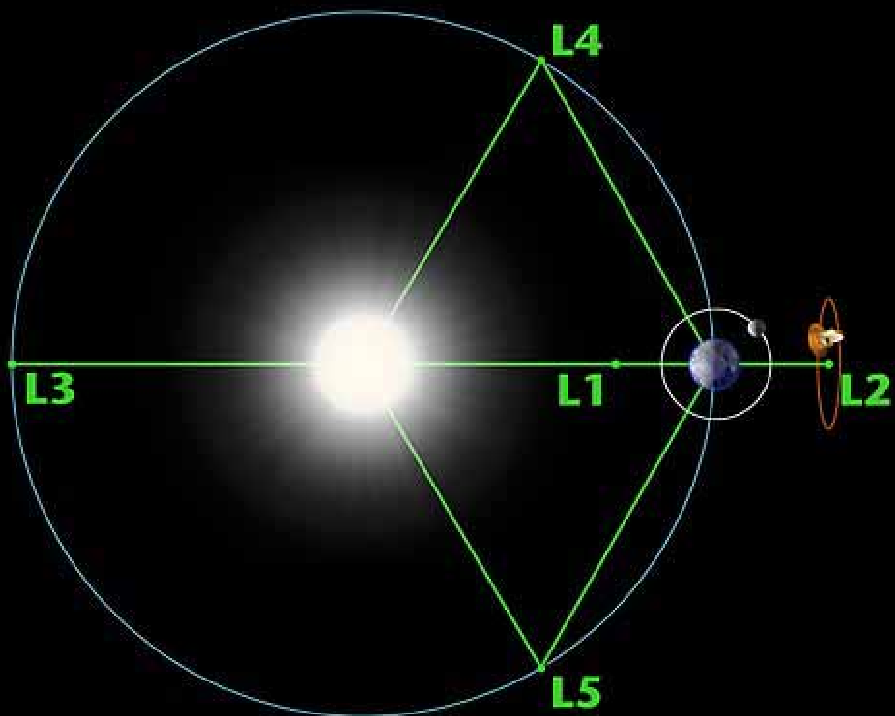
29 September 2011 Press Release

James Webb Space Telescope (JWST)



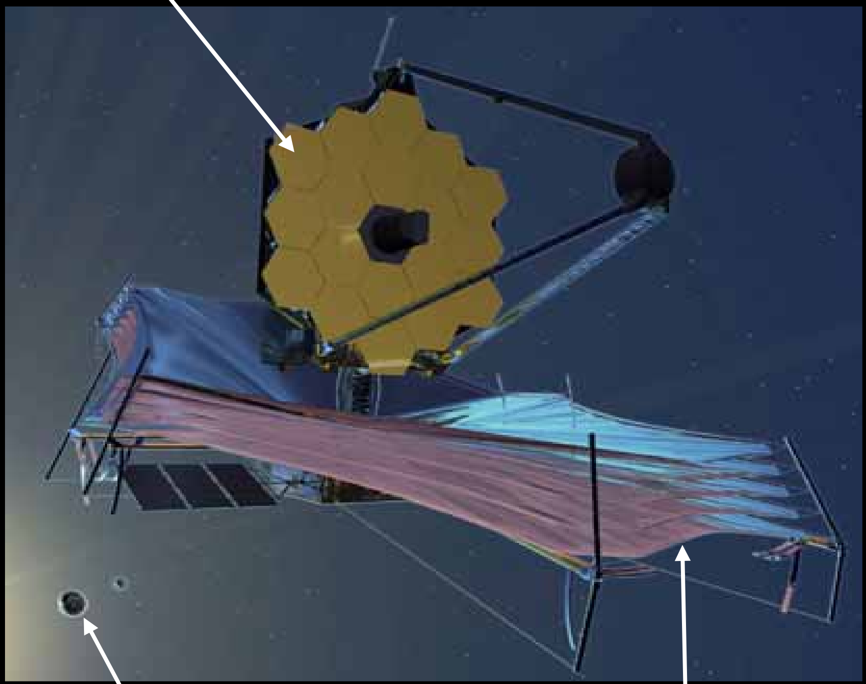
Lagrange Point 2 (L2)

Optimal Location for Infrared Space Telescope



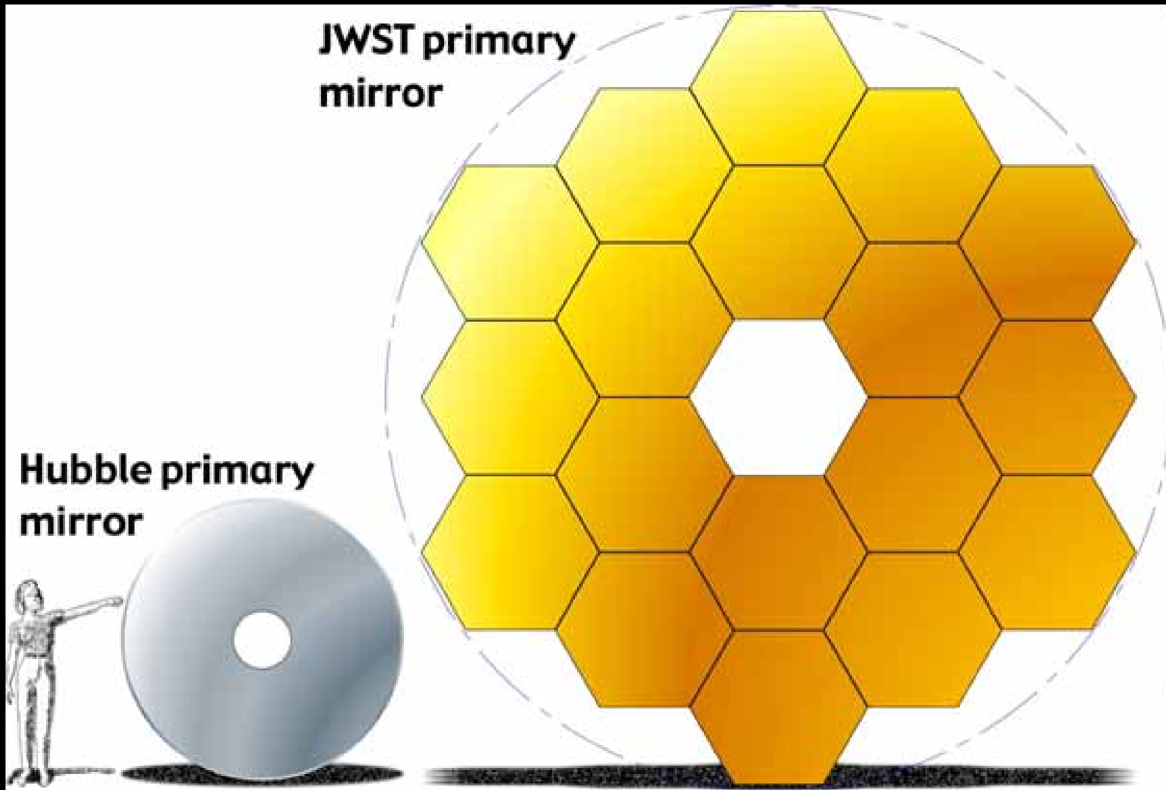
Lagrange Points of the Earth-Sun system
(not drawn to scale!)

6.5-m mirror



Earth

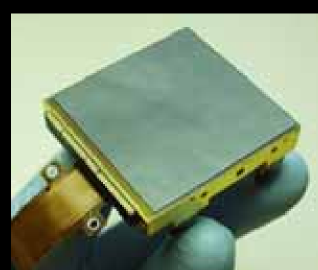
sunshield



294 K | Mirror Temp. | **50 K**

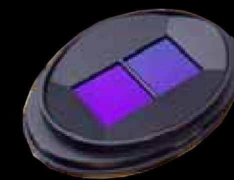
1 Mpixel | # Pixels | **63 Mpixel**

1 H1R
1024×1024



15 H2RG
2048×2048

JWST II-VI Sensors

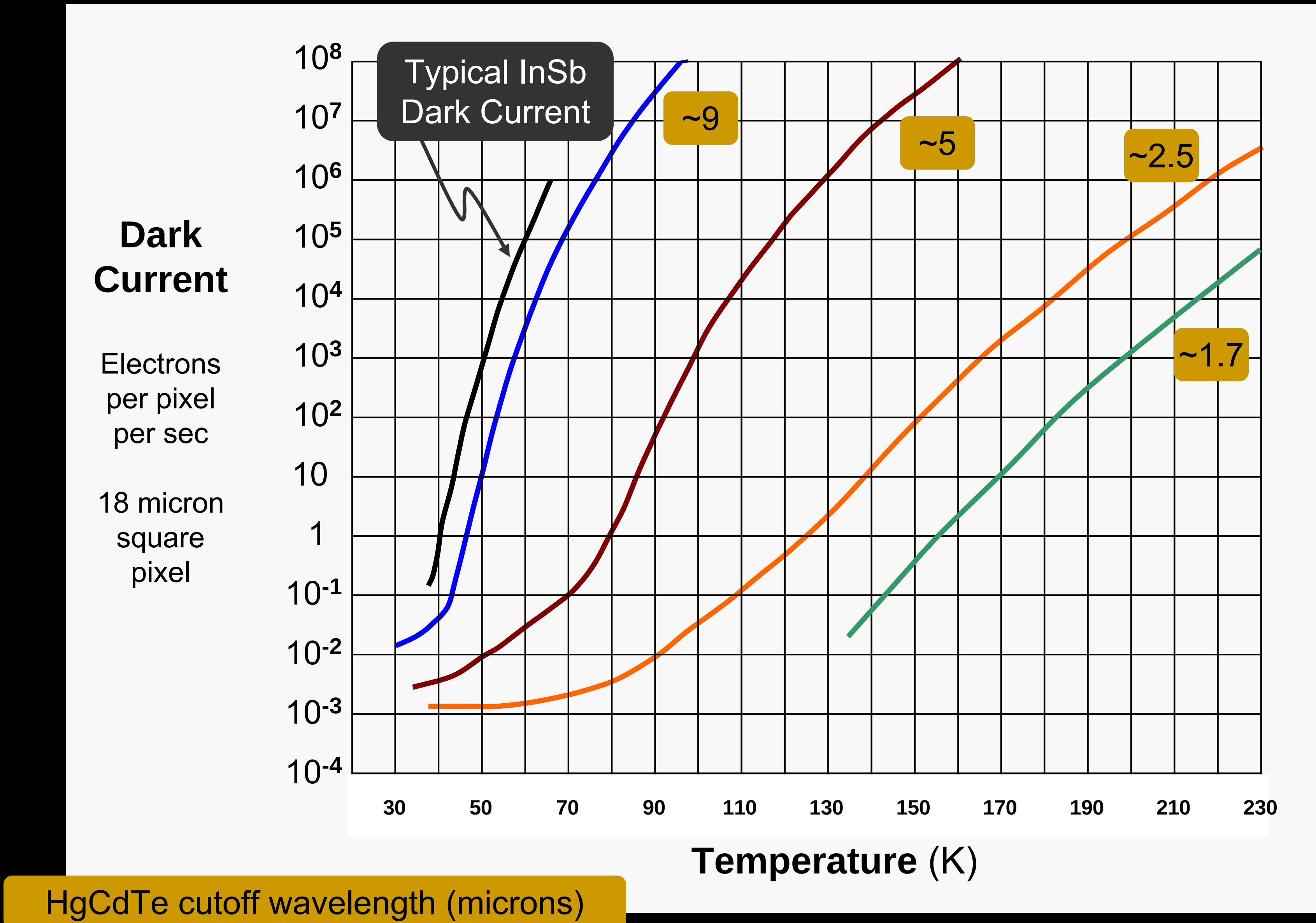


NIRSpec
(Near Infrared Spectrograph)
<6 e- noise for 1000 sec exposure

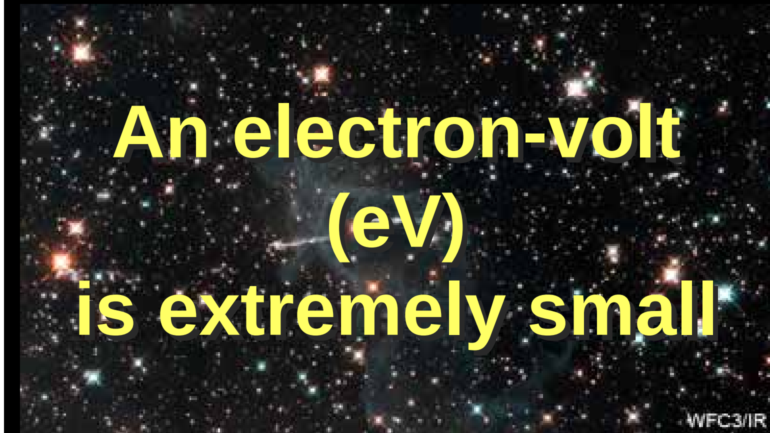
FGS
(Fine Guidance Sensors)

NIRCam
(Near Infrared Camera)

Dark Current of HgCdTe Detectors

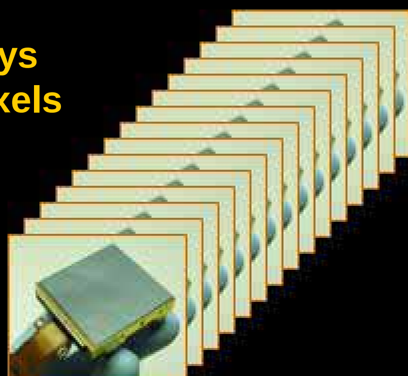


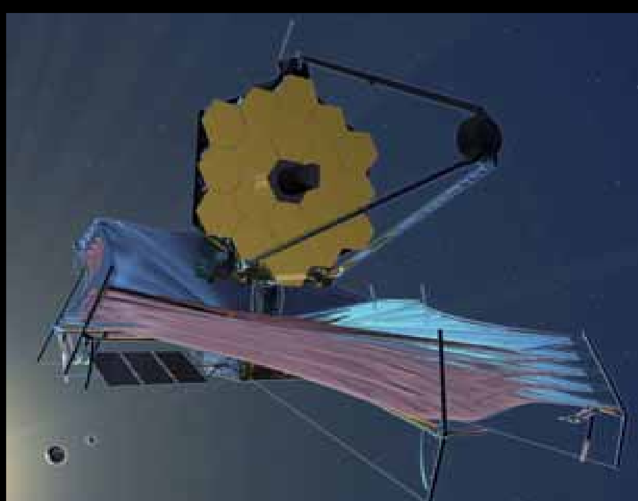
An electron-volt (eV) is extremely small



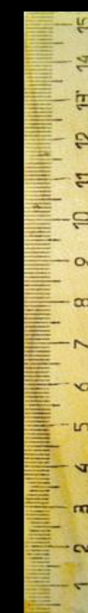
- The energy of a photon is **VERY** small
  - Energy of SWIR (2.5 μm) photon is 0.5 eV
- In 5 years, JWST will take ~1 million images
  - Total # SWIR photons detected ≈ 3.6×10^{16}
  - Total energy detected ≈ 1.8×10^{16} eV
- Drop peanut M&M® candy (~2g) from height of 15 cm (~6 inches)
  - Potential energy ≈ 1.8×10^{16} eV

15 H2RG
2K×2K arrays
63 million pixels

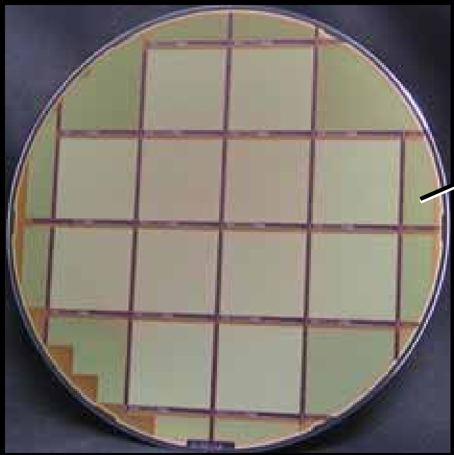


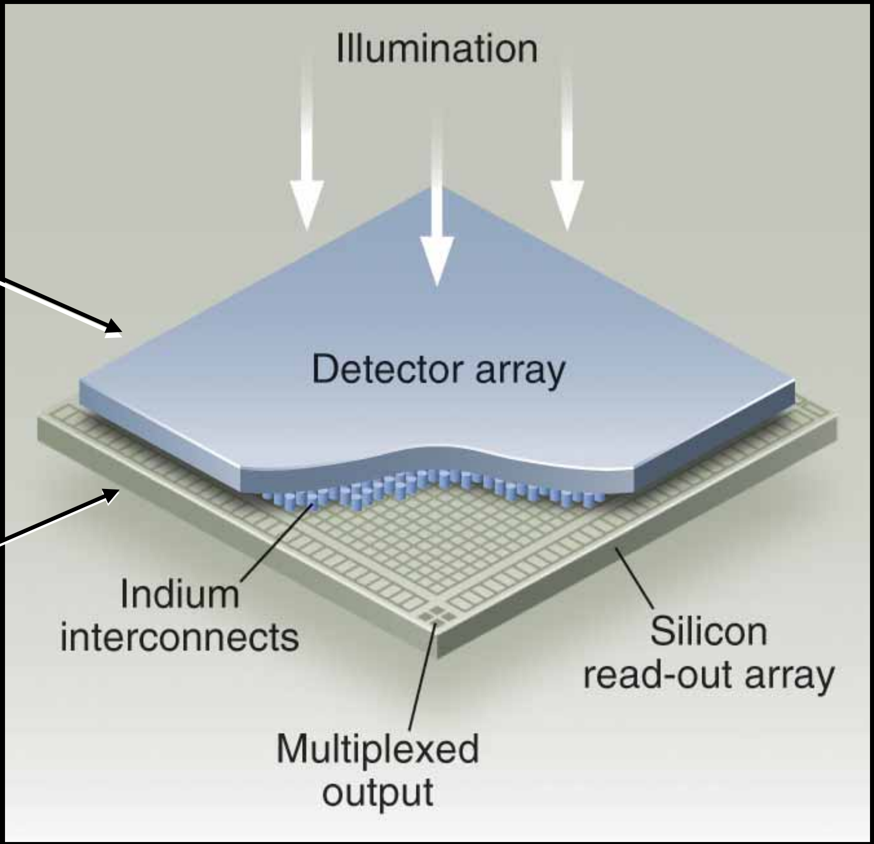


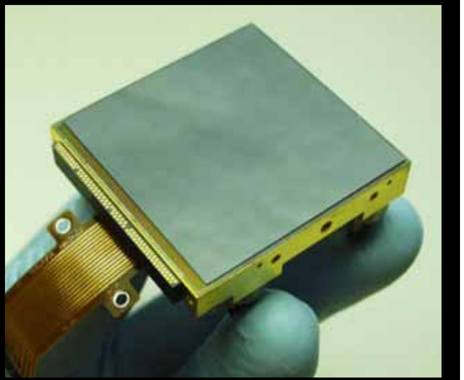
15 cm peanut M&M® drop is equal to the energy detected during 5 year operation of the James Webb Space Telescope!



Hybrid CMOS Infrared Imaging Sensors





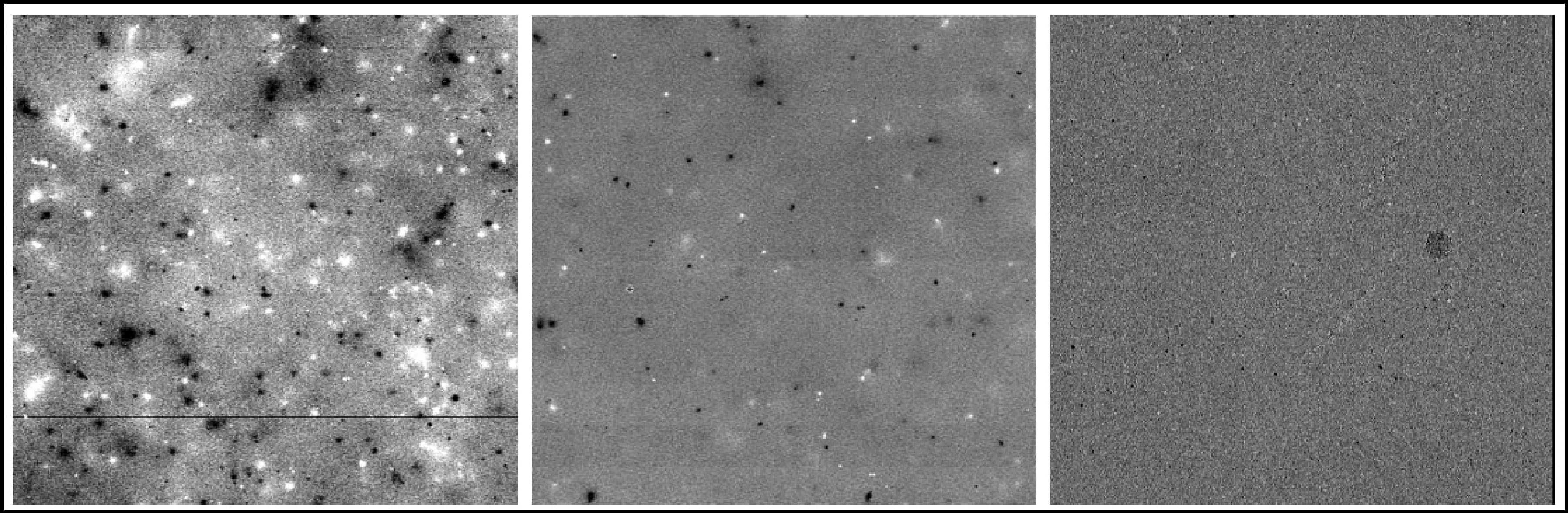


Three Key Technologies

- Growth and processing of the HgCdTe detector layer
- Design and fabrication of the CMOS readout integrated circuit (ROIC)
- Hybridization of the detector layer to the CMOS ROIC

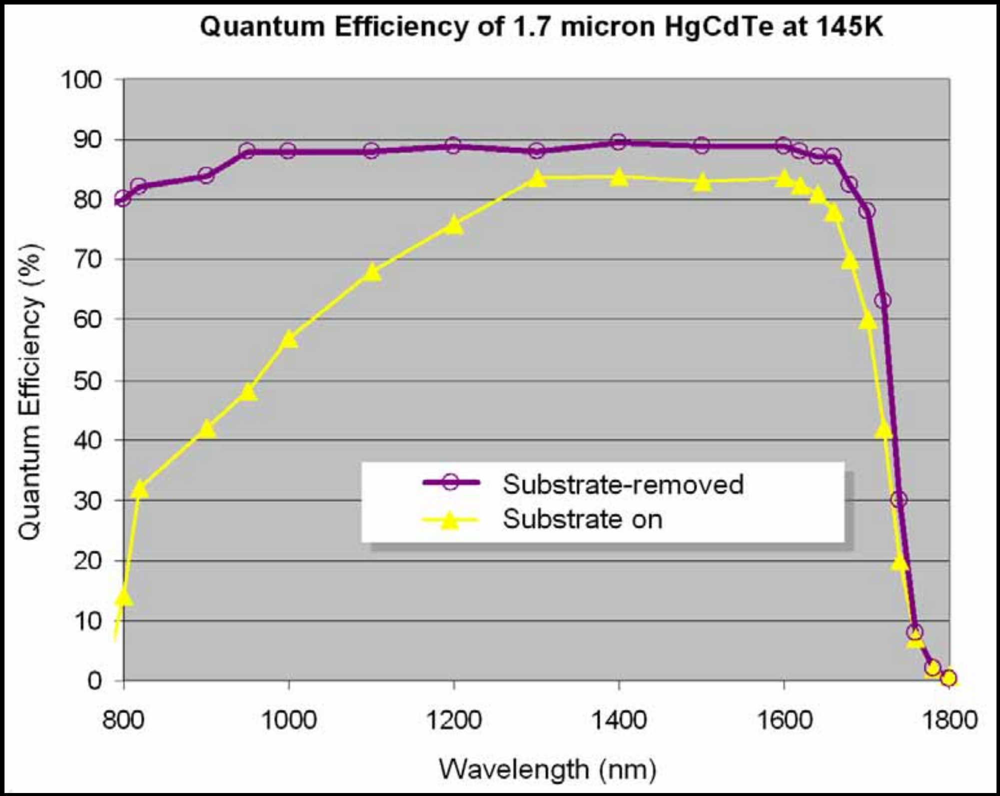
Cosmic Rays and Substrate Removal

- Cosmic ray events produce clouds of detected signal due to particle-induced flashes of infrared light in the CdZnTe substrate
- Removal of the substrate eliminates the effect

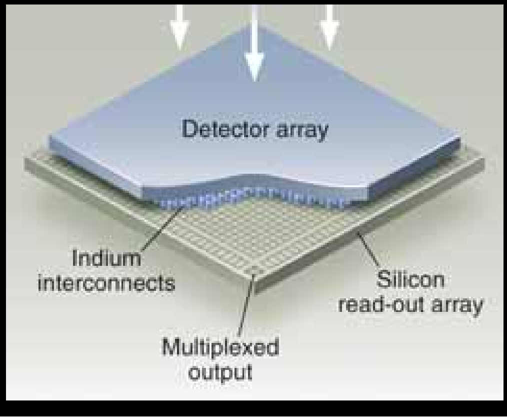


2.5 μm cutoff, substrate on — 1.7 μm cutoff, substrate on — 1.7 μm cutoff, substrate off

Substrate Removal allows HgCdTe to detect UV and Visible Light

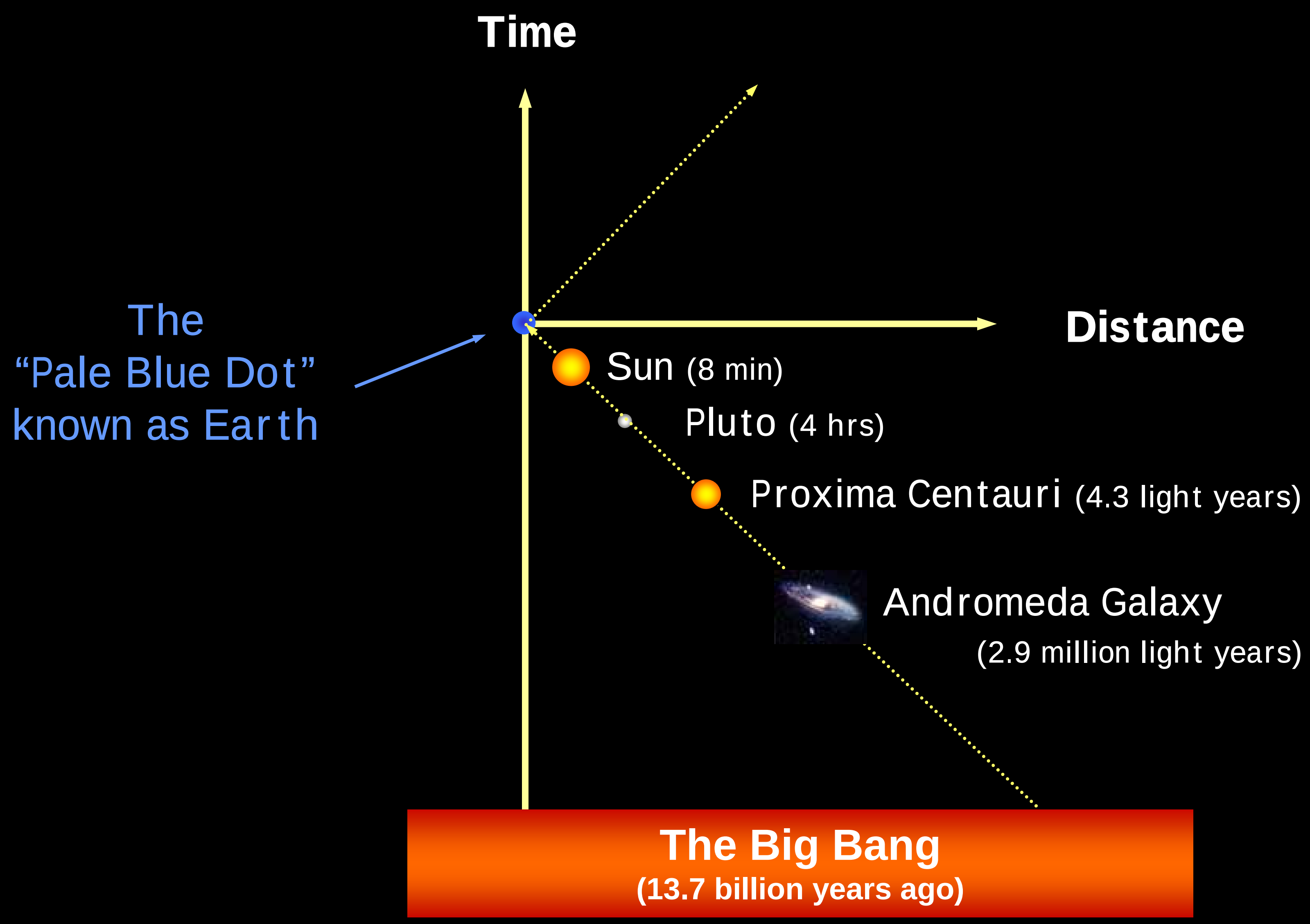


Quantum Efficiency of 2.3 micron HgCdTe



Astronomy is a Time Machine

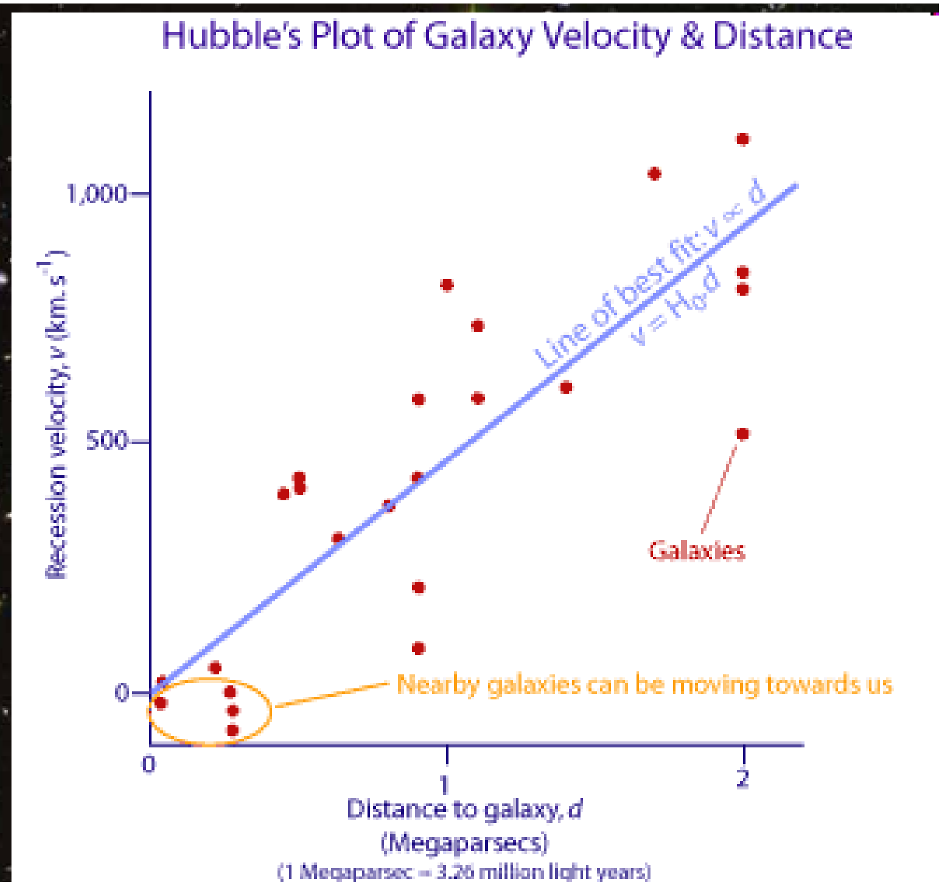
Thank heavens for the finite speed of light



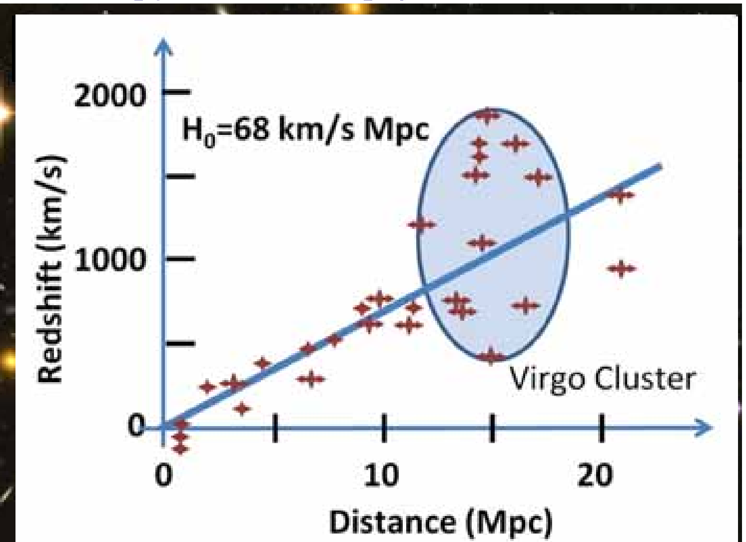
Edwin Hubble
1889 – 1953

Worked at Mt. Wilson
1919 - 1953

Mt Wilson 100-inch telescope
(completed 1916)



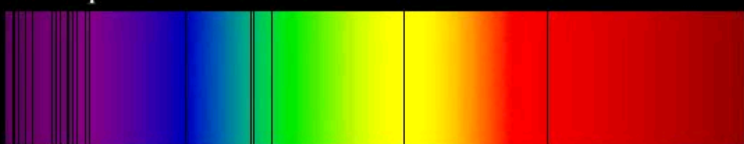
Albert Einstein & Edwin Hubble
Mt. Wilson 100-inch telescope
(1931)



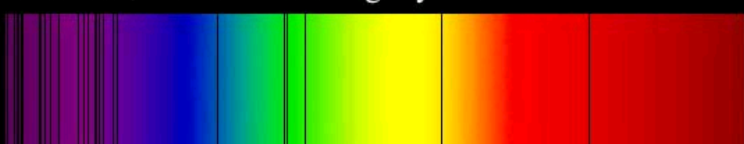
Redshift (z) due to Expansion of the Universe

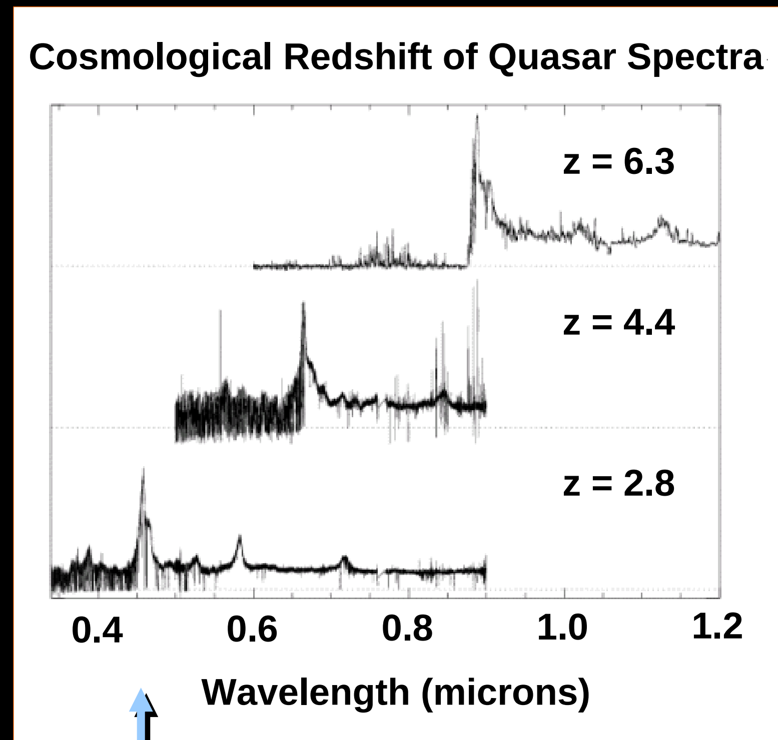
$$z = \frac{\lambda_{\rm obsv} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$

Absorption Lines from our Sun



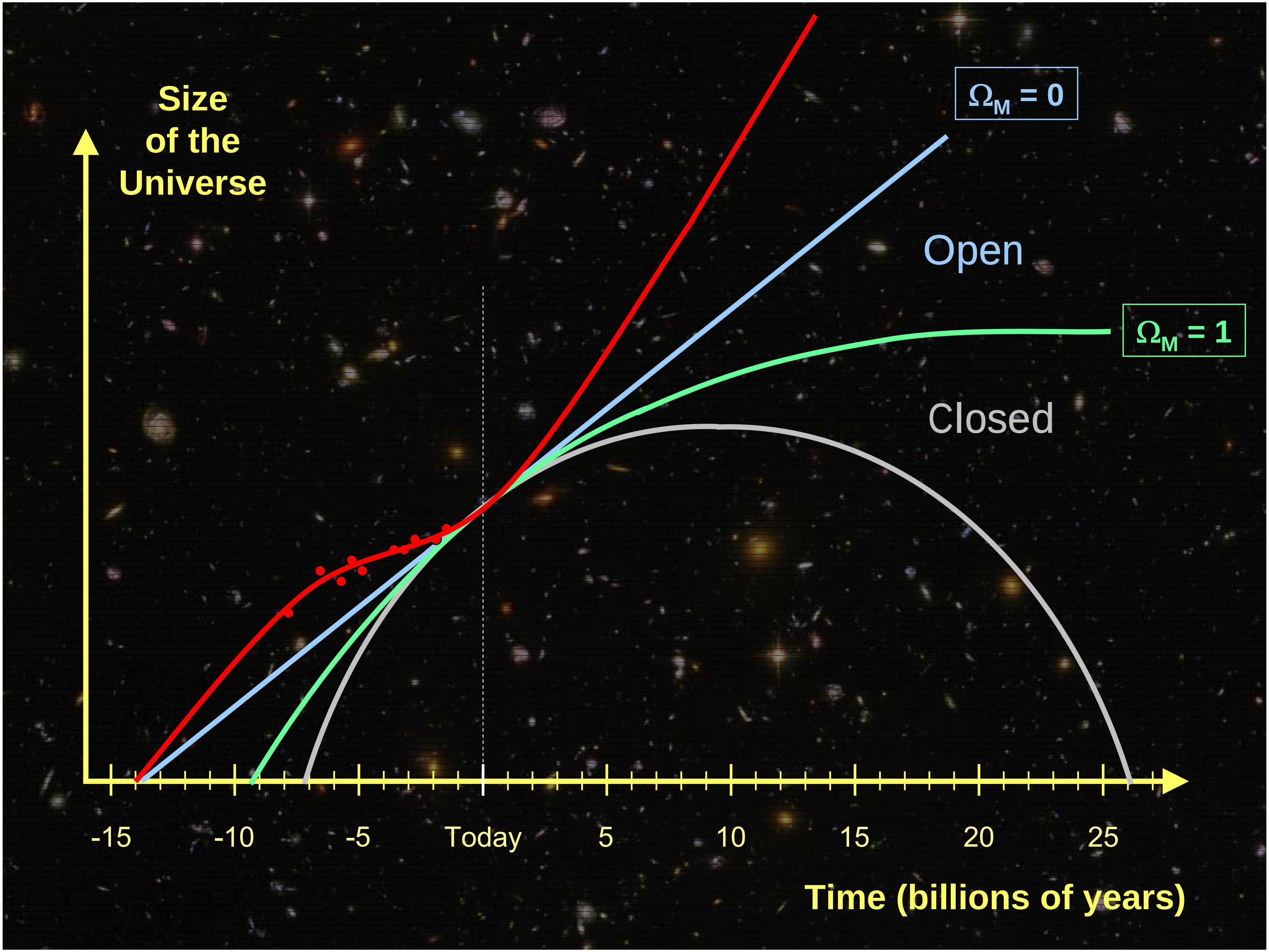
Absorption Lines from a supercluster of galaxies, BAS11
$v = 0.07\,c$, $d = 1$ billion light years

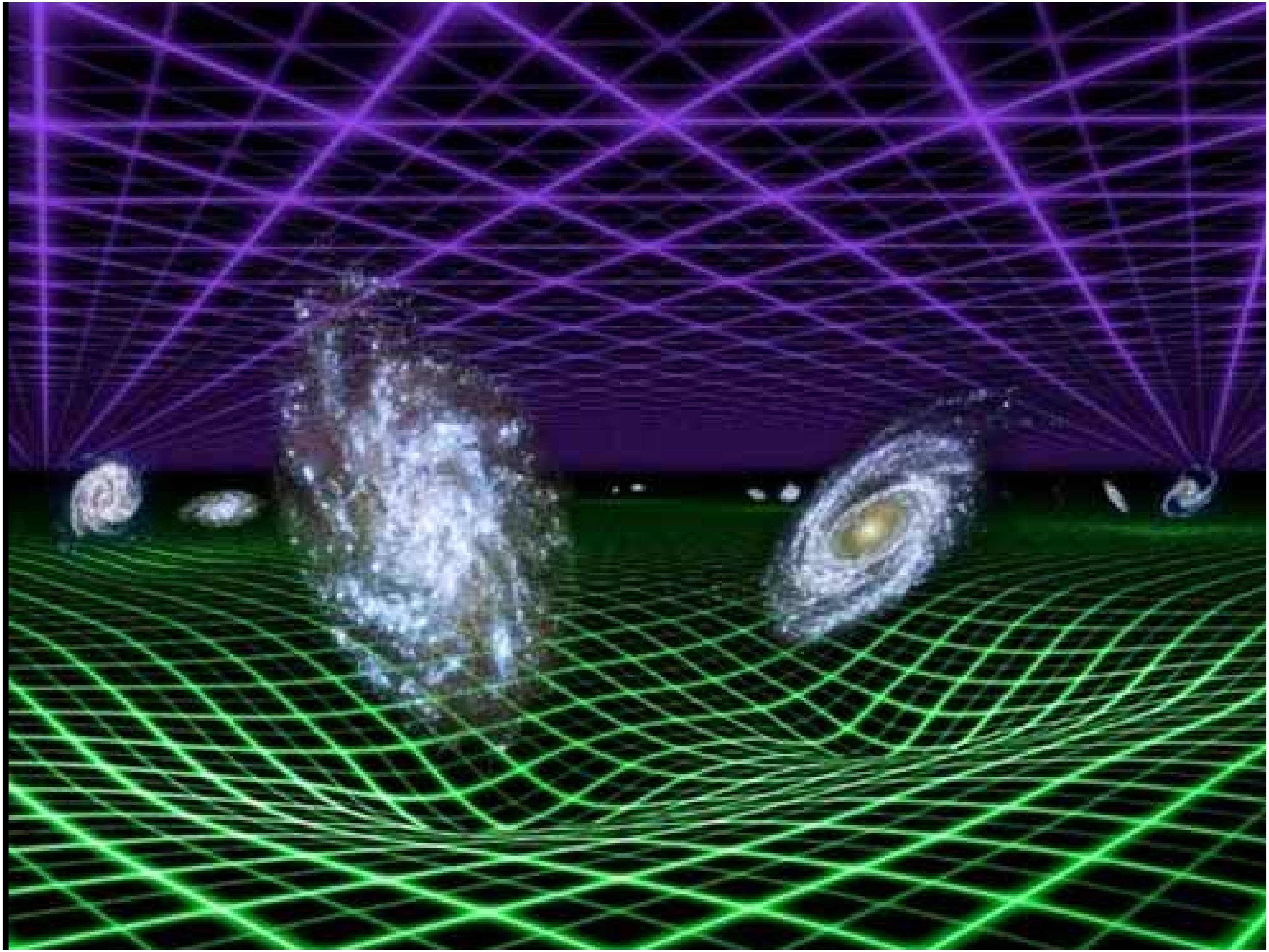




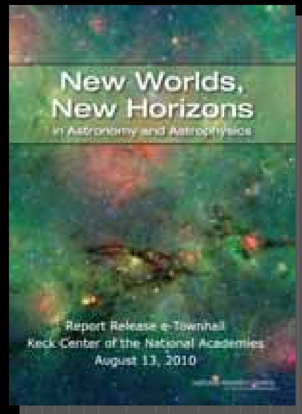
Lyman Alpha emission of hydrogen 1216Å in rest frame

The distant universe is an infrared universe

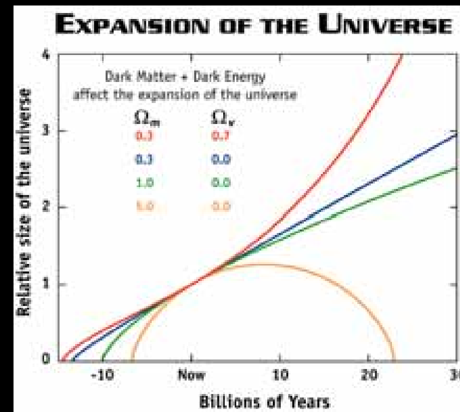

Size
of the
Universe
$\Omega_M = 0$
Open
$\Omega_M = 1$
Closed
-15
-10
-5
Today
5
10
15
20
25
Time (billions of years)



Dark Energy Missions

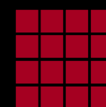


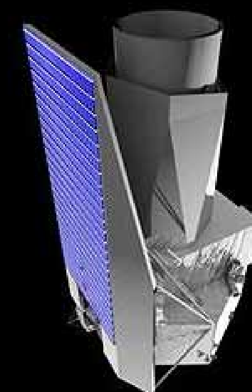
The Decadal Review ranked Dark Energy as the #1 priority for NASA's next major space astronomy mission



2011 Nobel Prize in Physics

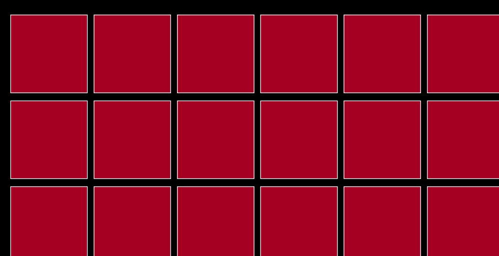
Euclid dark energy mission





- Euclid selected by ESA for 2019 launch !
- Teledyne's H2RG IR detector and SIDECAR ASIC are baseline for the infrared instrument

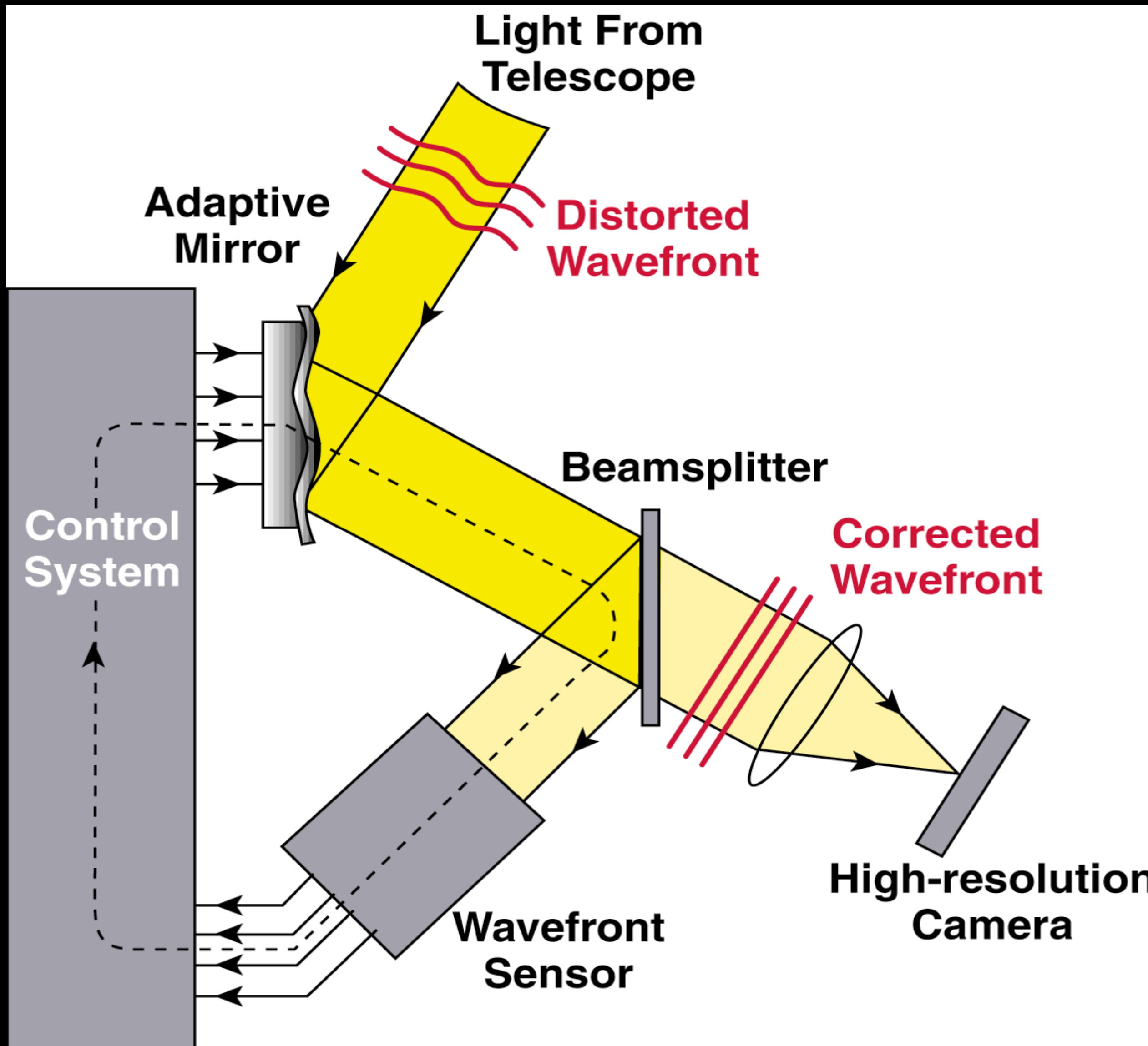
WFIRST – Wide Field Infrared Survey Telescope

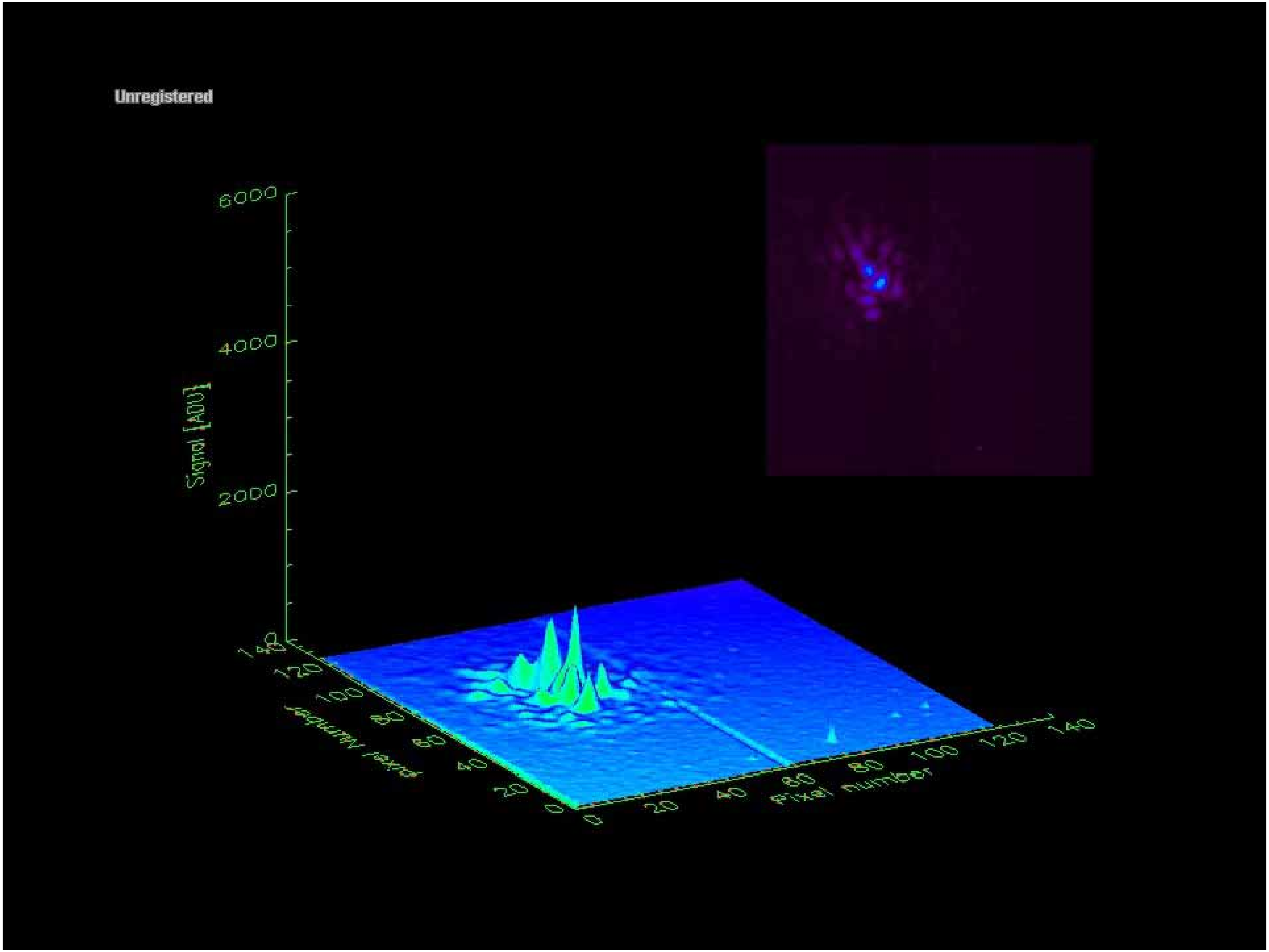


Eighteen
2K×2K arrays
75 Mpixel mosaic

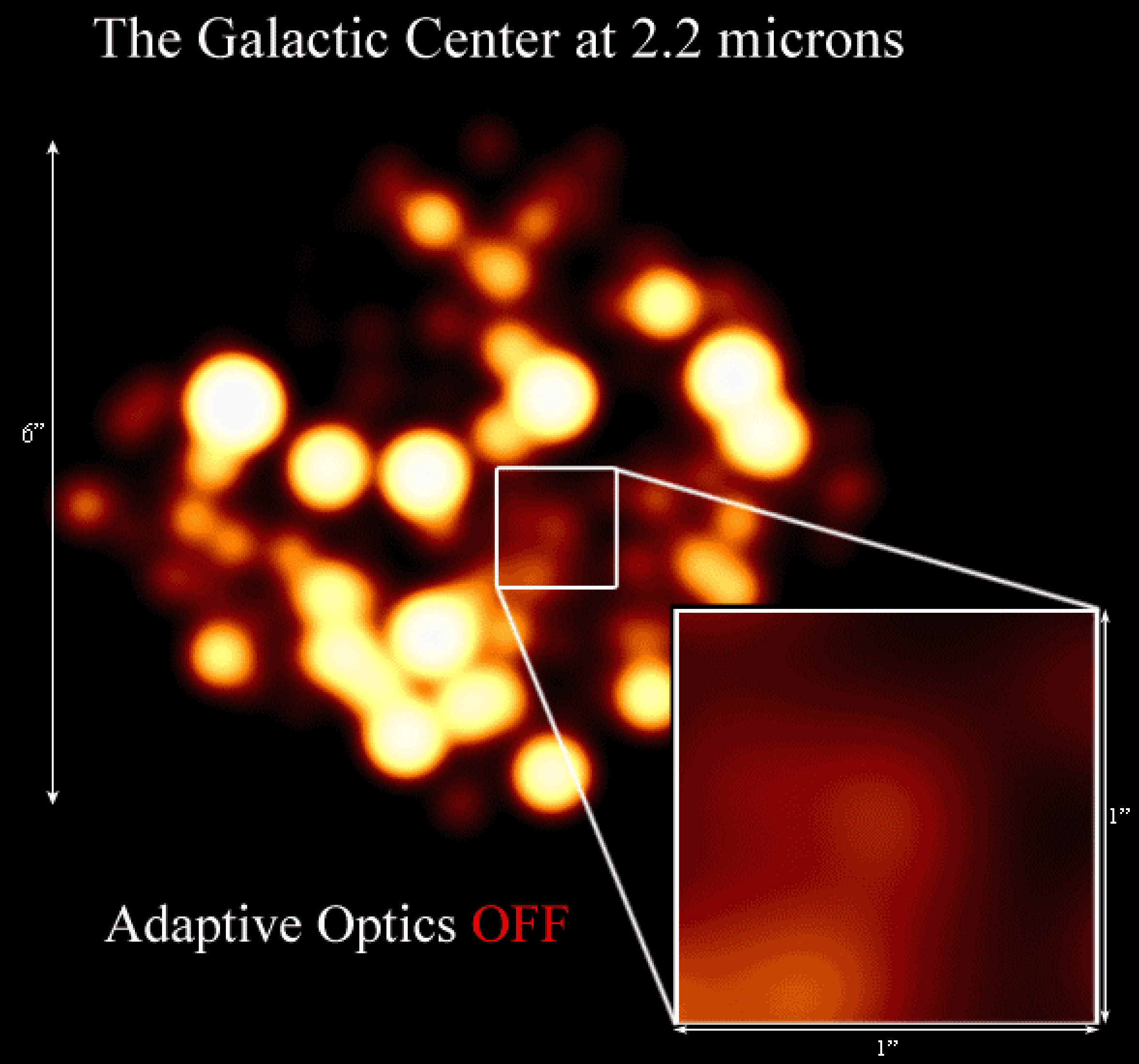
Mauna Kea, Hawai'i
The Northern Hemisphere's best astronomical site

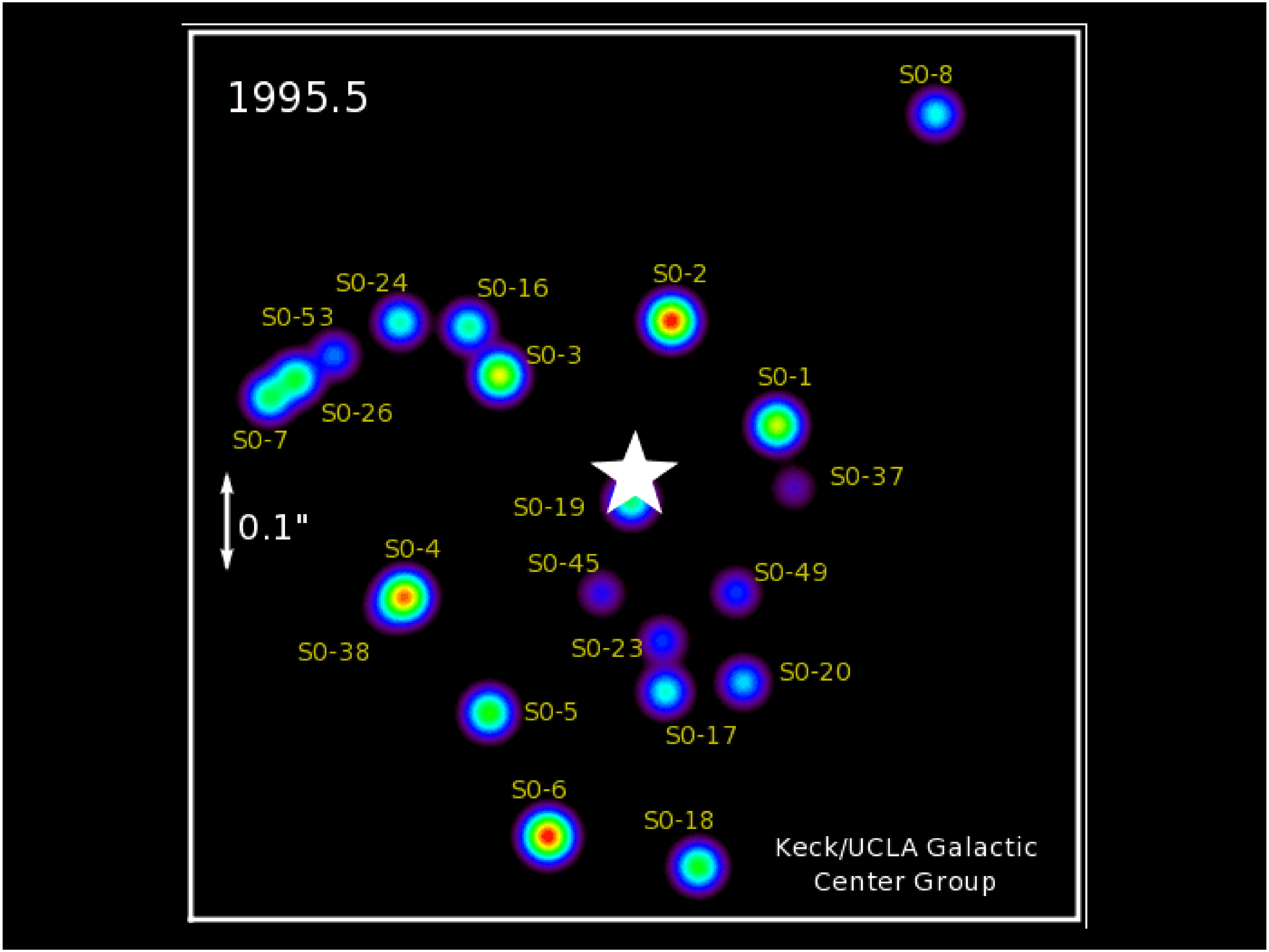
Simplified AO system diagram



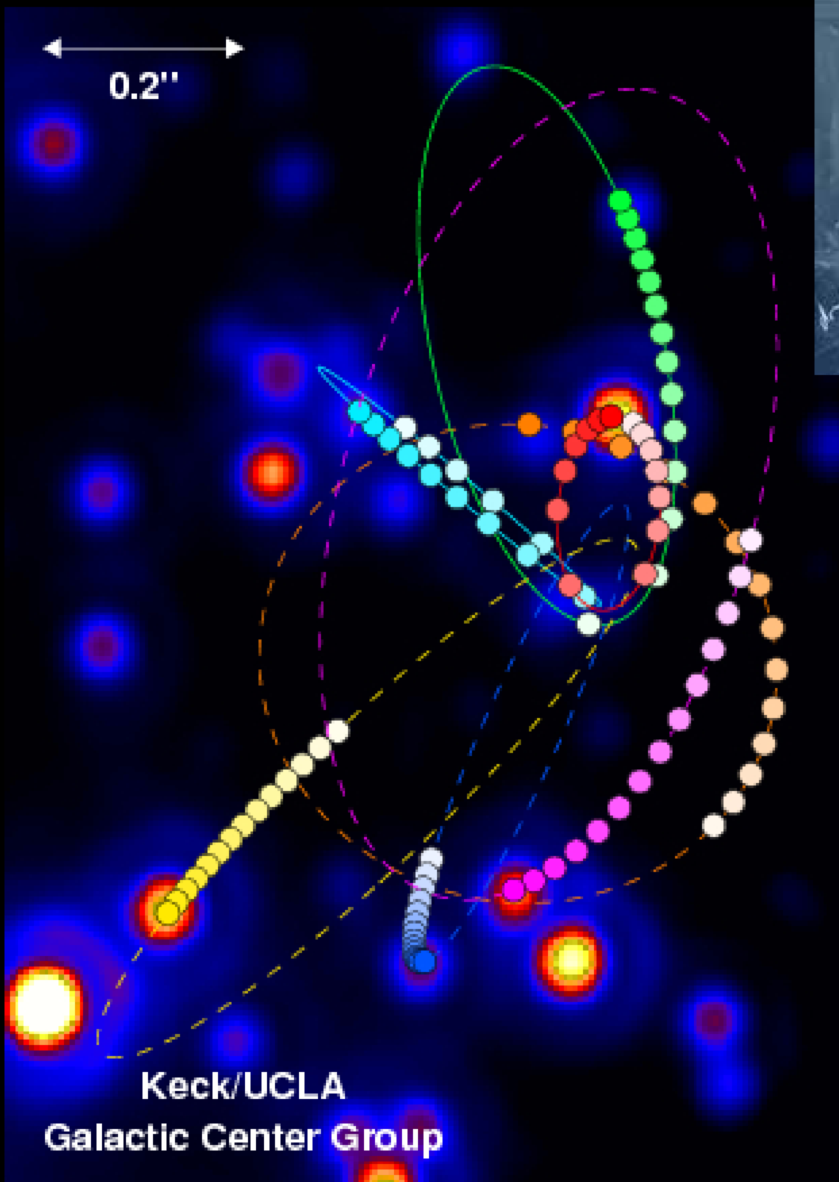

Unregistered
6000
4000
Signal [ADU]
2000
0
140
120
100
80
60
40
20
0
Pixel number
0
20
40
60
80
100
120
140
Pixel number

Imaging the galactic center



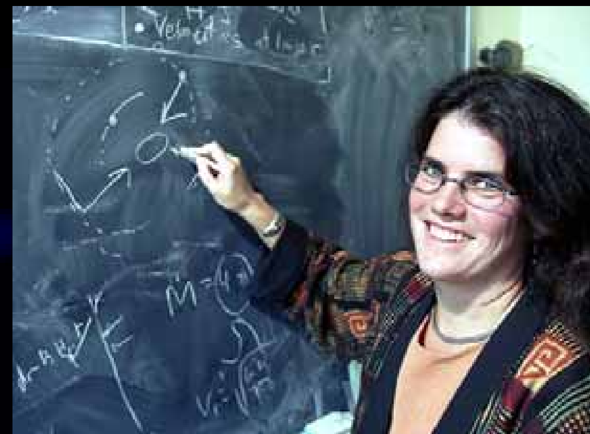


1995.5
S0-8
S0-24
S0-16
S0-2
S0-53
S0-3
S0-1
S0-26
S0-7
S0-37
S0-19
0.1"
S0-4
S0-45
S0-49
S0-38
S0-23
S0-20
S0-5
S0-17
S0-6
S0-18
Keck/UCLA Galactic
Center Group



S0-1
S0-2
S0-4
S0-5
S0-16
S0-19
S0-20

1995-2008

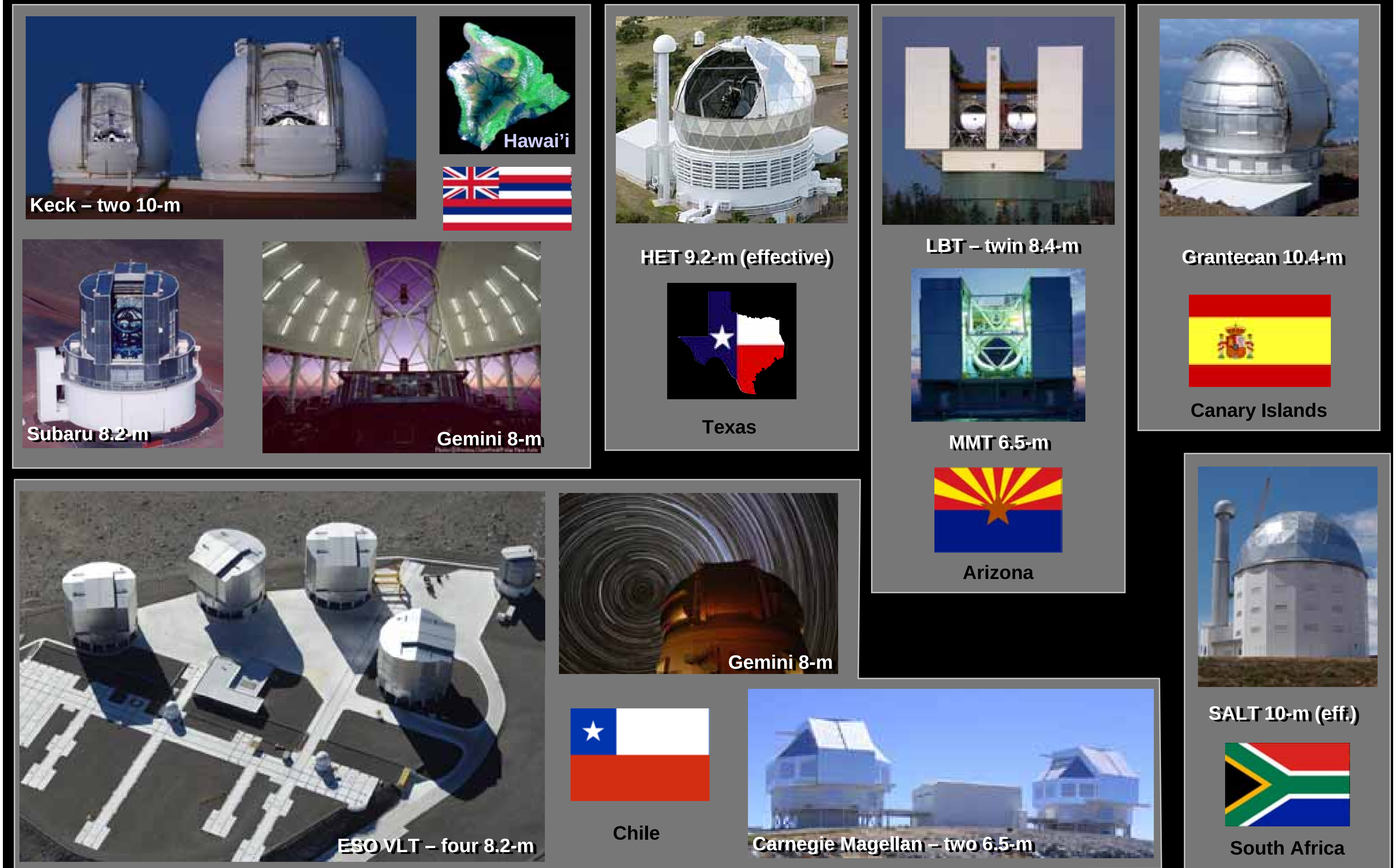


Andrea Ghez
University of California,
Los Angeles

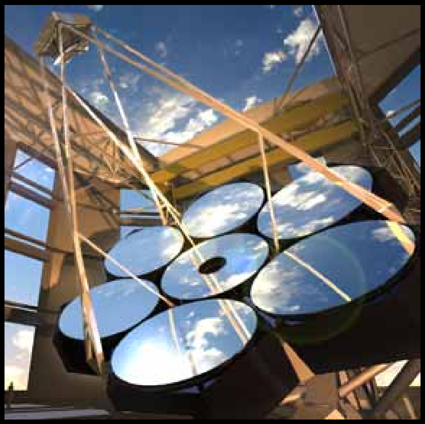
Reinhard Genzel
Max-Planck-Institut für
extraterrestrische Physik

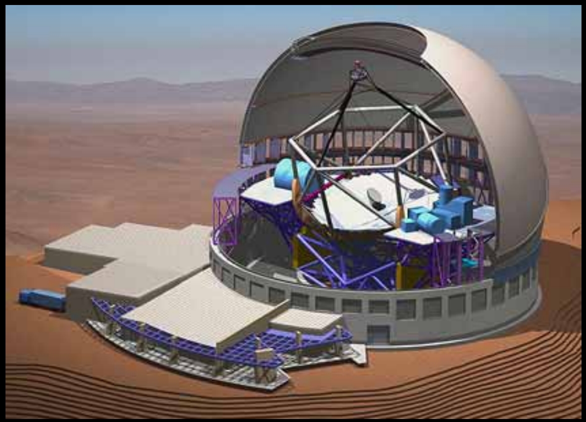
Mass of black hole at center of the Milky Way = 4.1±0.6 million solar masses

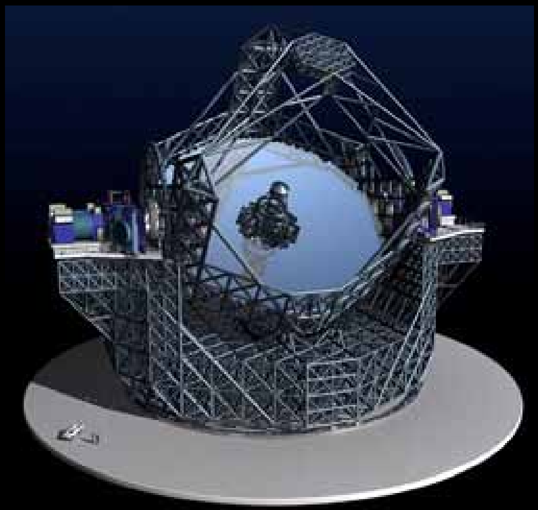
2011 - 17 telescopes with 6.5-meter aperture or larger

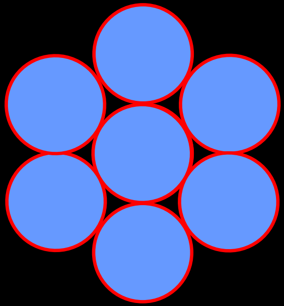


The era of the Extremely Large Telescopes (ELTs) is imminent









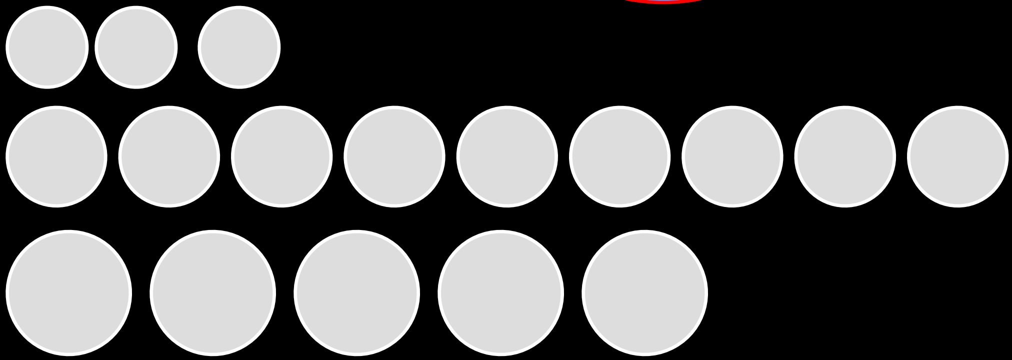
Giant Magellan
Telescope
GMT
24.5-m
359 m^2

Thirty Meter
Telescope
TMT
30-m
707 m^2

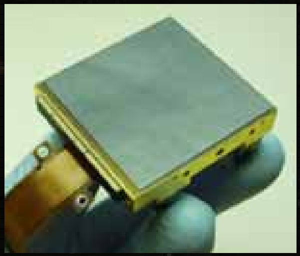
European Extremely
Large Telescope
E-ELT
39-m
1194 m^2

Existing Large
Telescopes
944 m^2 of
collecting area

3 6.5-m
9 8-m
5 10-m

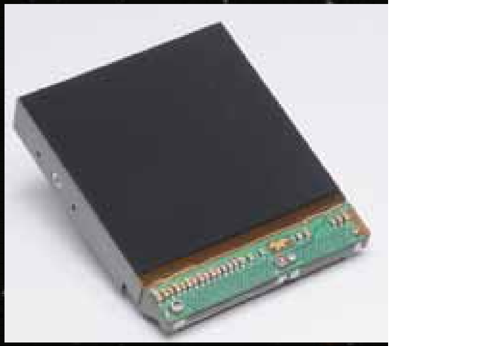


HgCdTe Sensors for Astronomy
State-of-the-art



Teledyne H2RG 2K×2K

Raytheon VIRGO 2K×2K



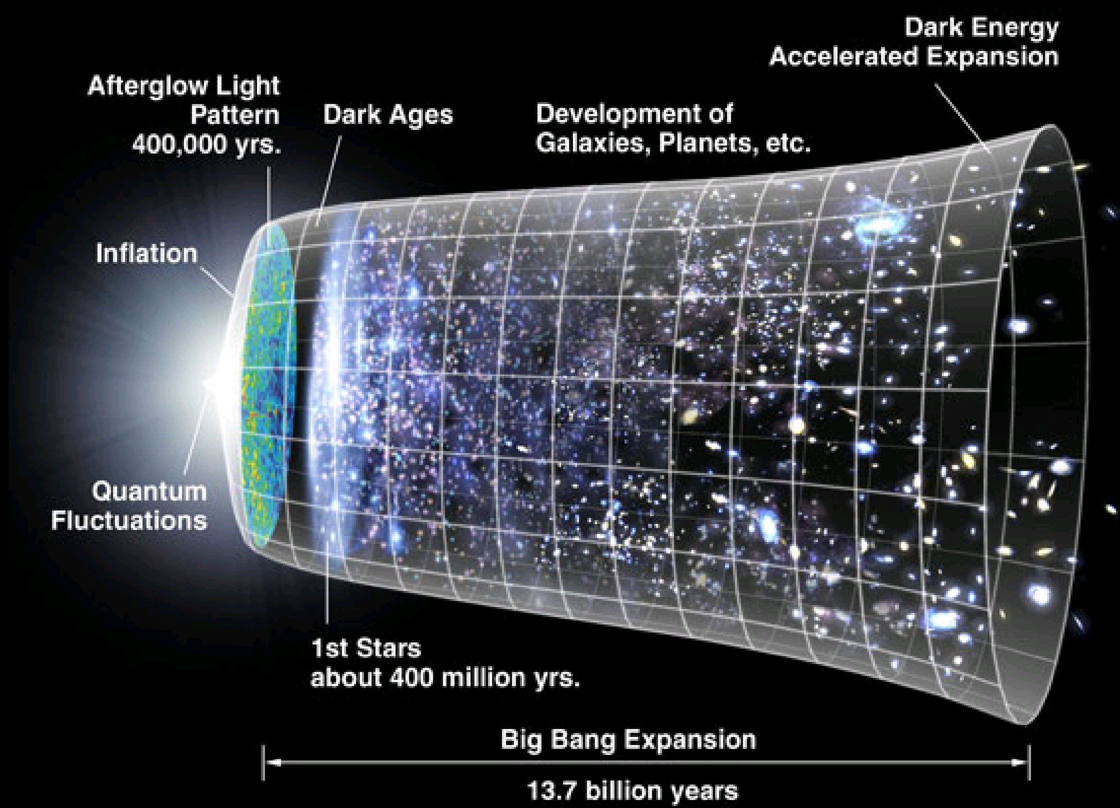
Teledyne H4RG-15 4K×4K

- Large format
  - 2048×2048 pixels is standard
  - 4096×4096 pixels is in development
- Quantum efficiency
  - 70-90% over wide bandpass; UV through infrared
- Noise
  - Dark current can be made negligible with cooling
  - Readout noise as low as 2-3 electrons with multiple sampling
  - Dynamic range (full well / total noise) of ~10,000 for the best sensors

- What astronomers want to be improved in HgCdTe sensors
  - Latency / Persistence: 0.1% degrades science
  - Operability: 95% to 99% specs set by cost
  - LWIR Producibility: LWIR more difficult, with lower yield
  - High speed, low noise: 500 Hz frame rate, 128^2, 3 e- noise
  - Cost: IR detectors are ~10× visible CCDs

Future Astronomy Discoveries to be made by II-VI materials

- Understand the end of the dark ages
- Determine how galaxies evolve
- Solve the mysteries of dark matter and dark energy



- Find and study planets in the habitable zone around other stars

- Find the killer asteroid before it hits the Earth !

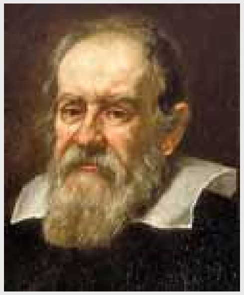
Thank you for your attention

Teledyne

Enabling humankind to understand the Universe and our place in it

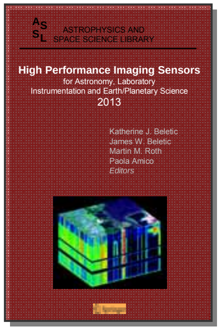
High Performance Imaging Sensors for Astronomy, Laboratory Instrumentation & Earth / Planetary Science

October 7-11, 2013 - Florence, Italy



A workshop for the leaders in sensor technologies that enable cutting edge science in the X-ray, UV, Visible and Infrared

- Status and plans for astronomical facilities and instrumentation (ground & space)
- Laboratory instrumentation (physical chemistry, synchrotrons, etc.)
- Earth and Planetary Science missions and instrumentation
- Detector materials (from Si and HgCdTe to strained layer superlattices)
- Sensor architectures – CCD, monolithic CMOS, hybrid CMOS
- Sensor electronics; Sensor packaging and mosaics
- Sensor testing and characterization



- ➢ **No parallel sessions; poster pops ensure visibility for all papers**
- ➢ **Workshop proceedings distributed in electronic and hardcover versions**
- ➢ **Group activities: Galileo Museum visit, Florence walking tour, Workshop receptions & dinners, catered lunches**
- ➢ **Guest program: Experience the culture of Tuscany; join group activities**
- ➢ **Workshop attendance limited; early registration is recommended**

Host Organizations

ESO

UNTERNEHMEN REGION

innoFSPEC

TELEDYNE