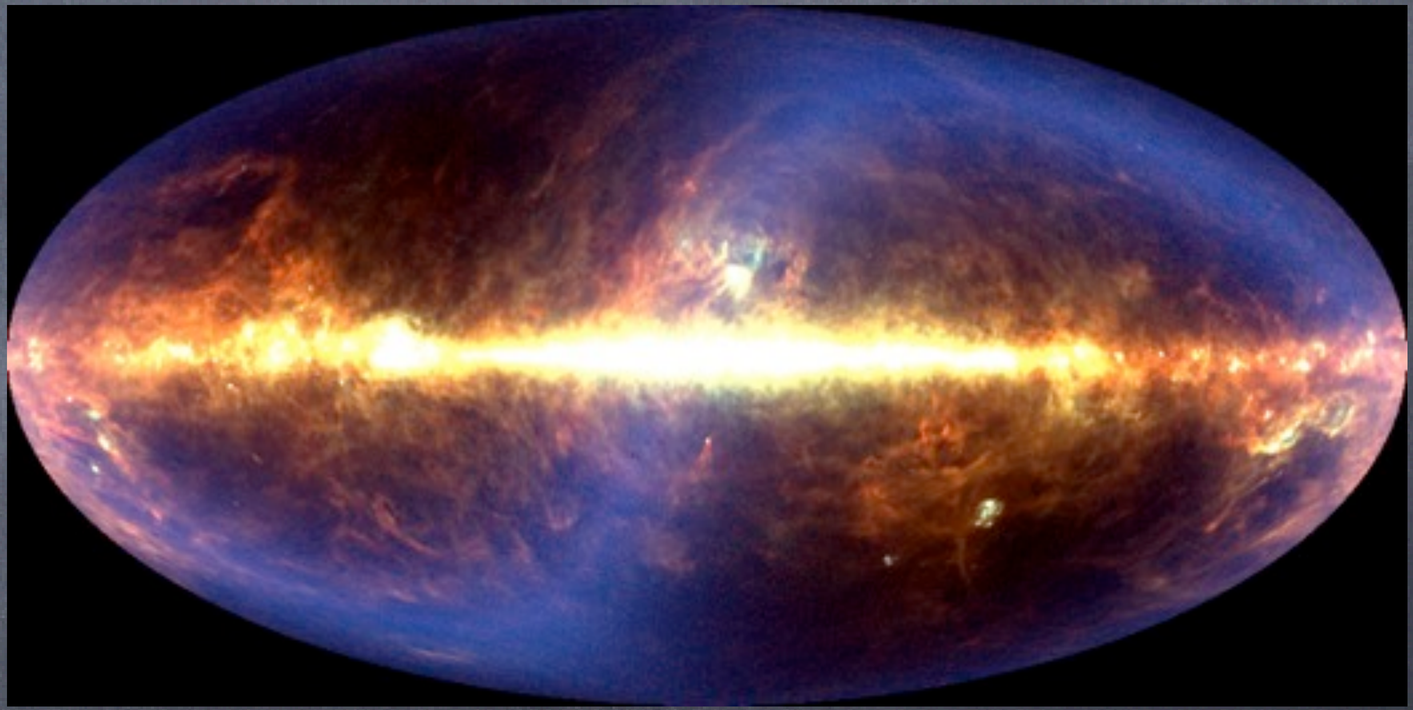
Infrared Astronomy



Some References

"Measuring the Universe" - G. Reike, Chapt. 3.2, 3.4, 3.5

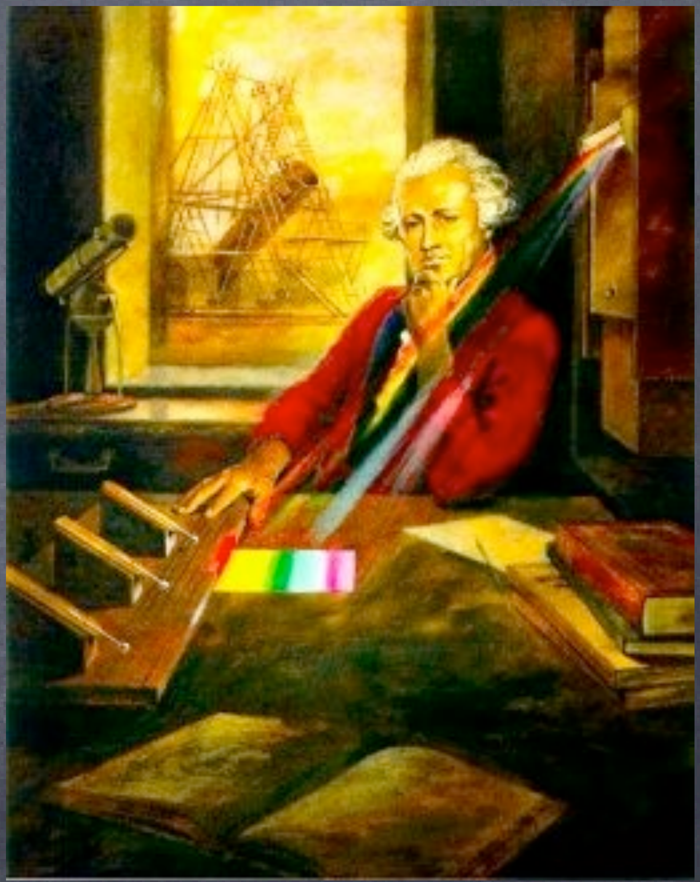
"Handbook of Infrared Astronomy" - I.S. Glass
(not my favorite book)

"Infrared Detector Arrays for Astronomy" - G.H. Reike, Annual Review of Astronomy and Astrophysics, 2007

NASA/IPAC's Cool Cosmos site: http://coolcosmos.ipac.caltech.edu/
(meant for a general audience)

Discovery of Infrared Radiation

The existence of infrared was discovered by William Herschel in 1800. Herschel measured the temperature of sunlight of different colors passing through a prism and found that the temperature increased just outside of the red end of the visible range. He later showed that these "calorific rays" could be reflected, refracted and absorbed just like visible light.



Sources of Emission

- Dusty regions (i.e. star forming regions)

  - emission from warm dust (for typical temperature of galaxies, dust emission peaks ~100 μm)
  - transparency of dust to IR radiation, longer wavelengths not scattered like visible radiation

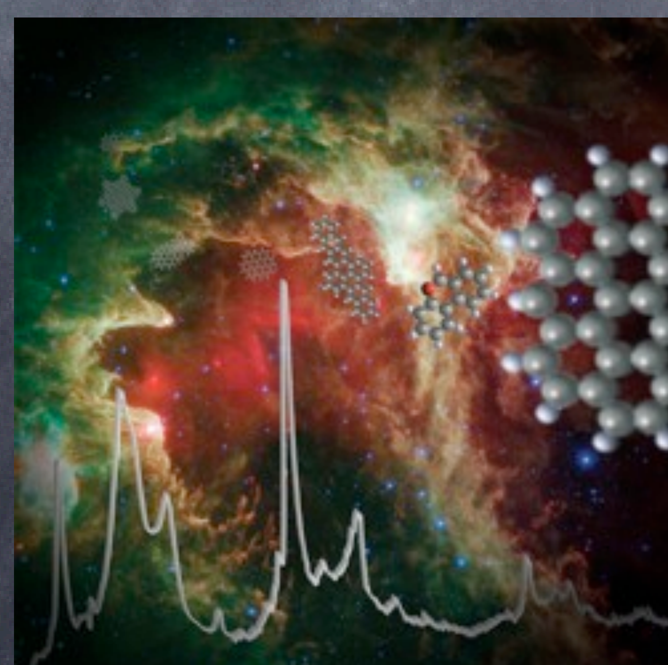
- Cool objects
  - small cool stars, red giants, brown dwarfs
  - planets, comets, asteroids
  - nebulae, interstellar dust, protoplanetary disks

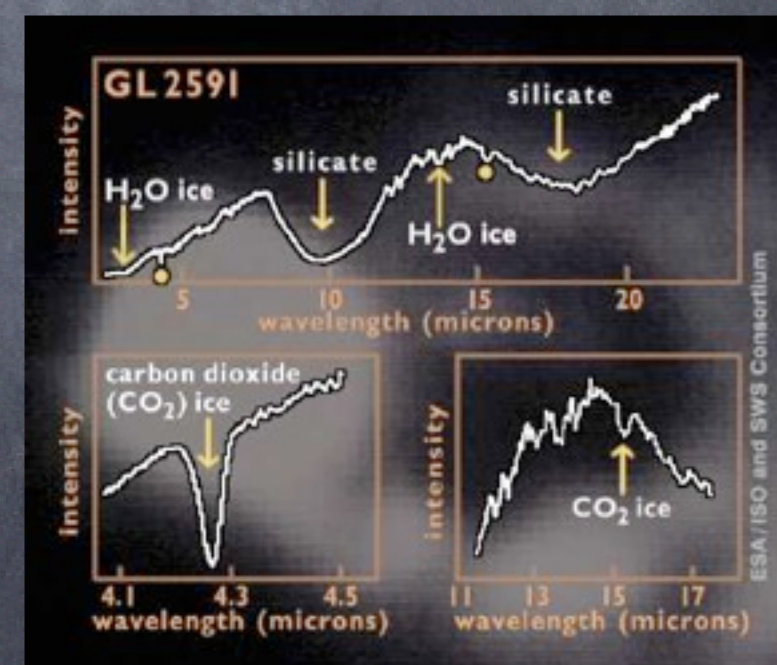
Cool stars energy peak ~ 1μm
Giant planets ~ 6-15μm
Dust re-radiation ~ 20-200μm

Sources of Emission

- High-redshift objects
  - can select high-z galaxies based on breaks in the spectrum leading galaxies to appear in red bands but not bluer bands (4000 Å z~2, Lyman limit at 912 Å z>7)

- Molecular vibrational and rotational lines
  - lines for CO, CO_2, H_2, H_2O, silicates
  - PAH features (polycyclic aromatic hydrocarbon)





Spectrum of a young star surrounded by a dense cloud, NASA IPAC "Cool Cosmos" site

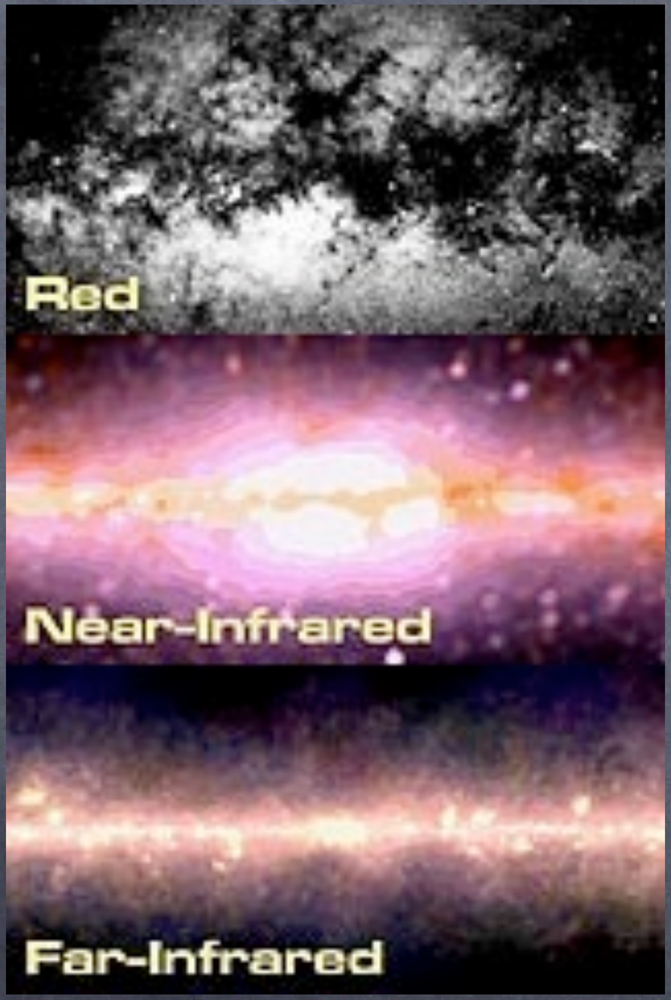
Sources of Emission

SPECTRAL REGION	WAVELENGTH RANGE (microns)	TEMPERATURE RANGE (degrees Kelvin)	WHAT WE SEE
Near-Infrared	(0.7-1) to 5	740 to (3,000-5,200)	Cooler red stars Red giants Dust is transparent
Mid-Infrared	5 to (25-40)	(92.5-140) to 740	Planets, comets and asteroids Dust warmed by starlight Protoplanetary disks
Far-Infrared	(25-40) to (200-350)	(10.6-18.5) to (92.5-140)	Emission from cold dust Central regions of galaxies Very cold molecular clouds

NASA IPAC "Cool Cosmos" site

Seeing Through Dust

Galactic Center



Cygnus Star-forming Region

NASA IPAC "Cool Cosmos" site

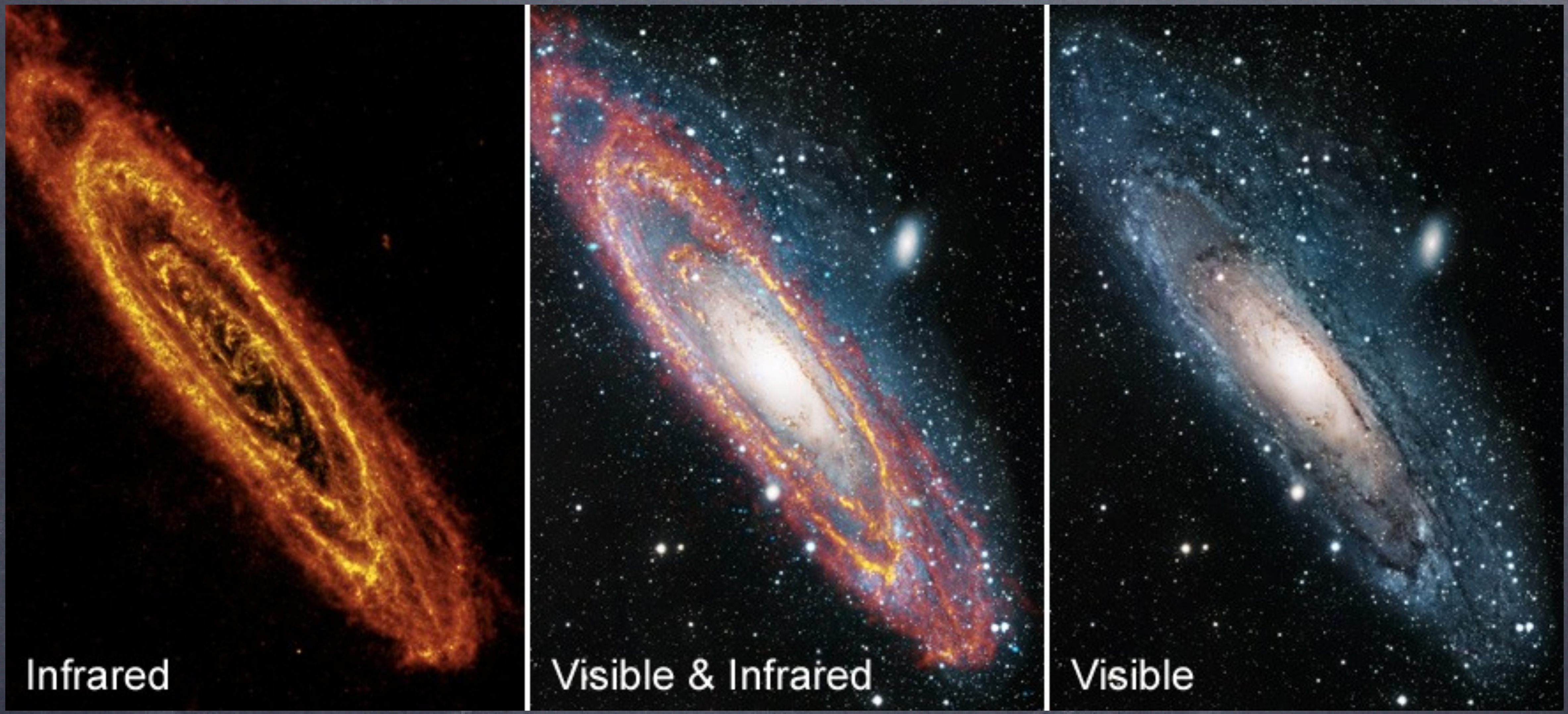


Image credit: Robert Gendler (visible) ; ESA / Herschel / SPIRE / HELGA (far-infrared)

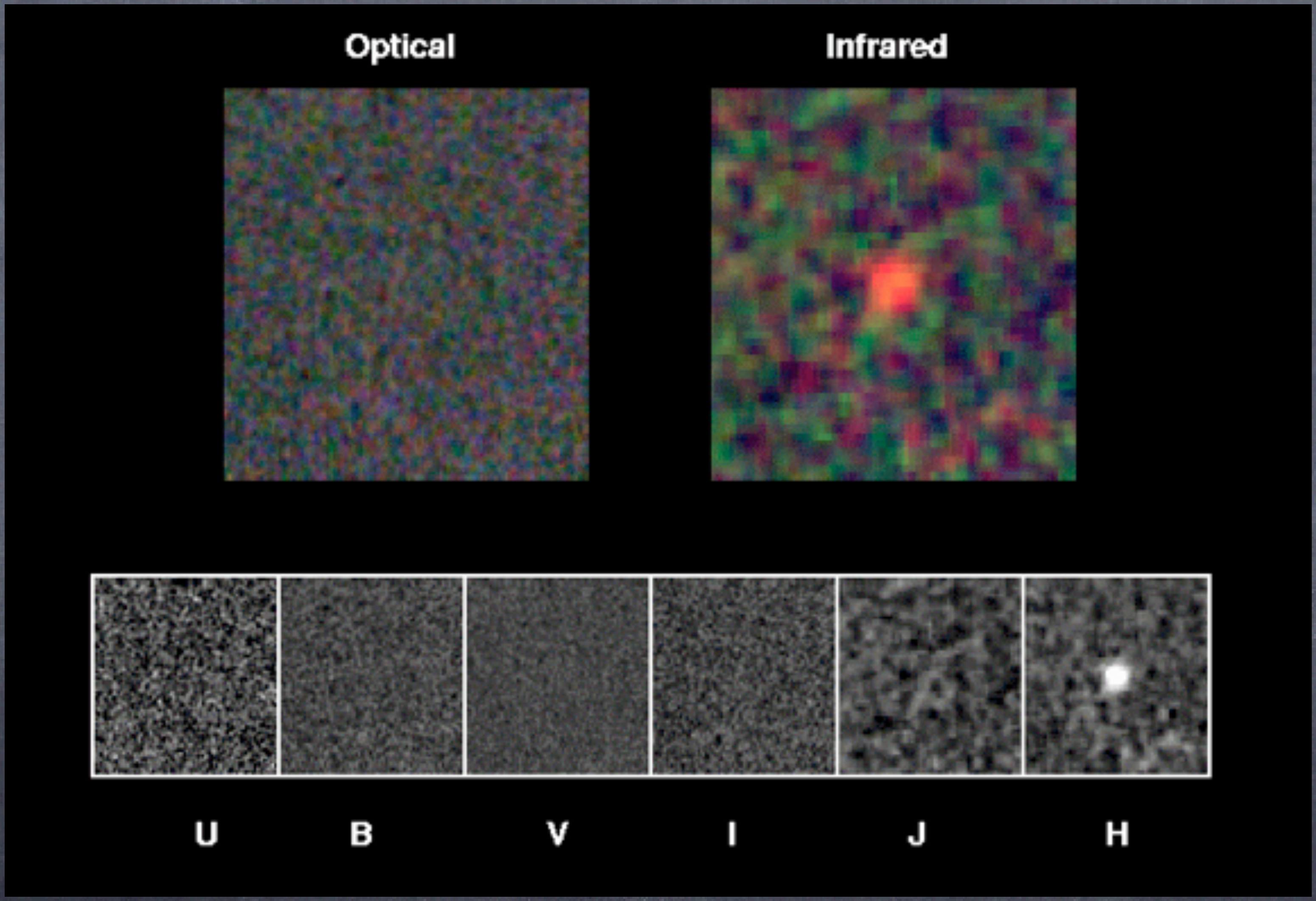
Herschel far-IR image of Andromeda compared to optical

Image credit: Robert Gendler (visible) ; ESA / Herschel / SPIRE / HELGA (far-infrared)

Herschel far-IR image of Andromeda compared to optical

High Redshift

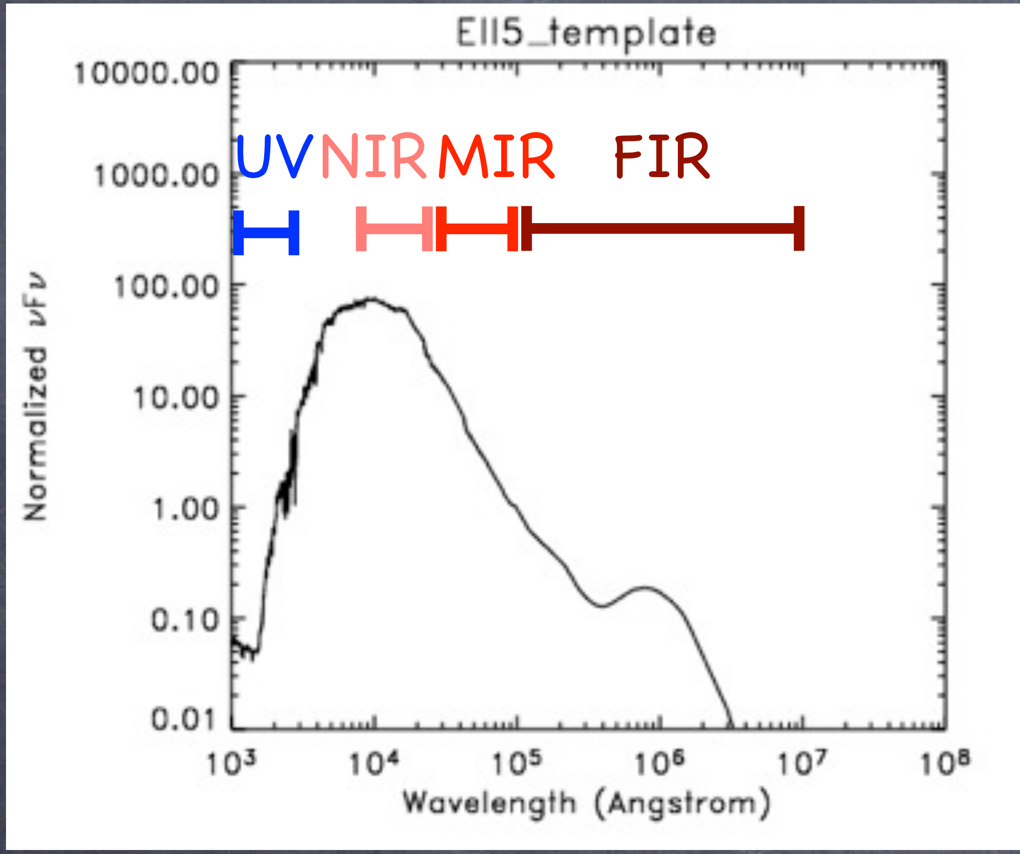
Example of a "J-band" dropout



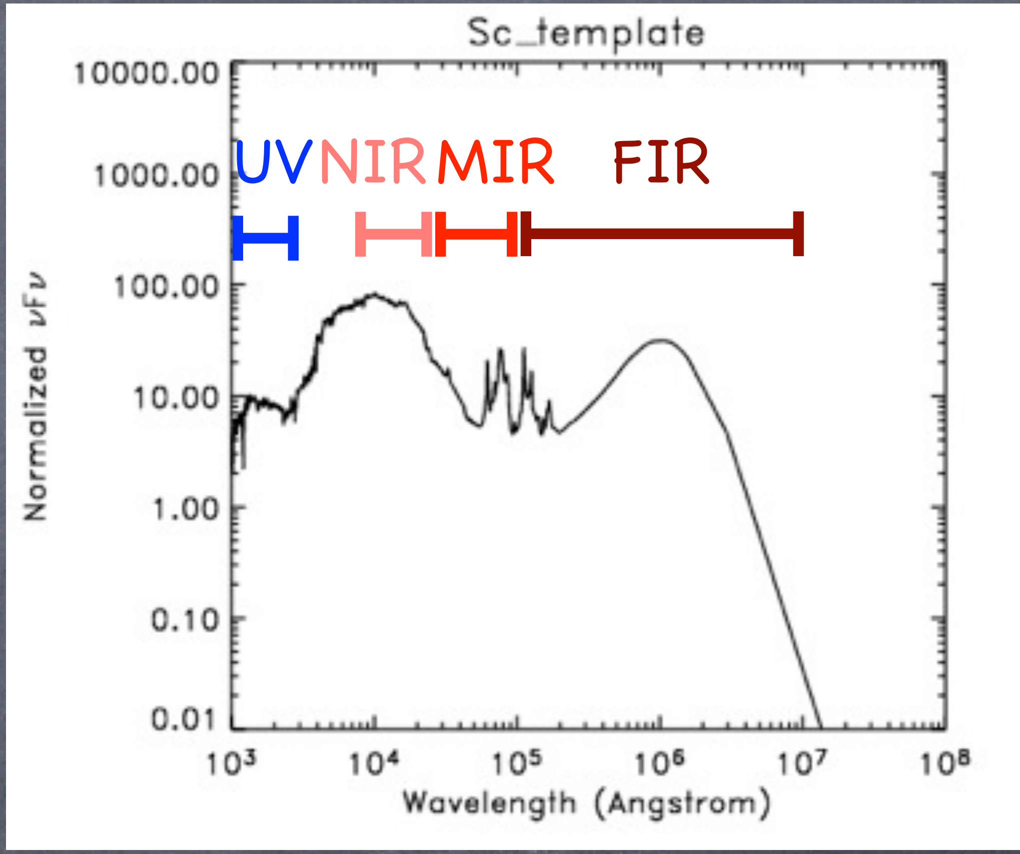
WFC3 White Paper Stiavelli and O'Connell

Example Galaxy SEDs

Elliptical Galaxy



Spiral Galaxy

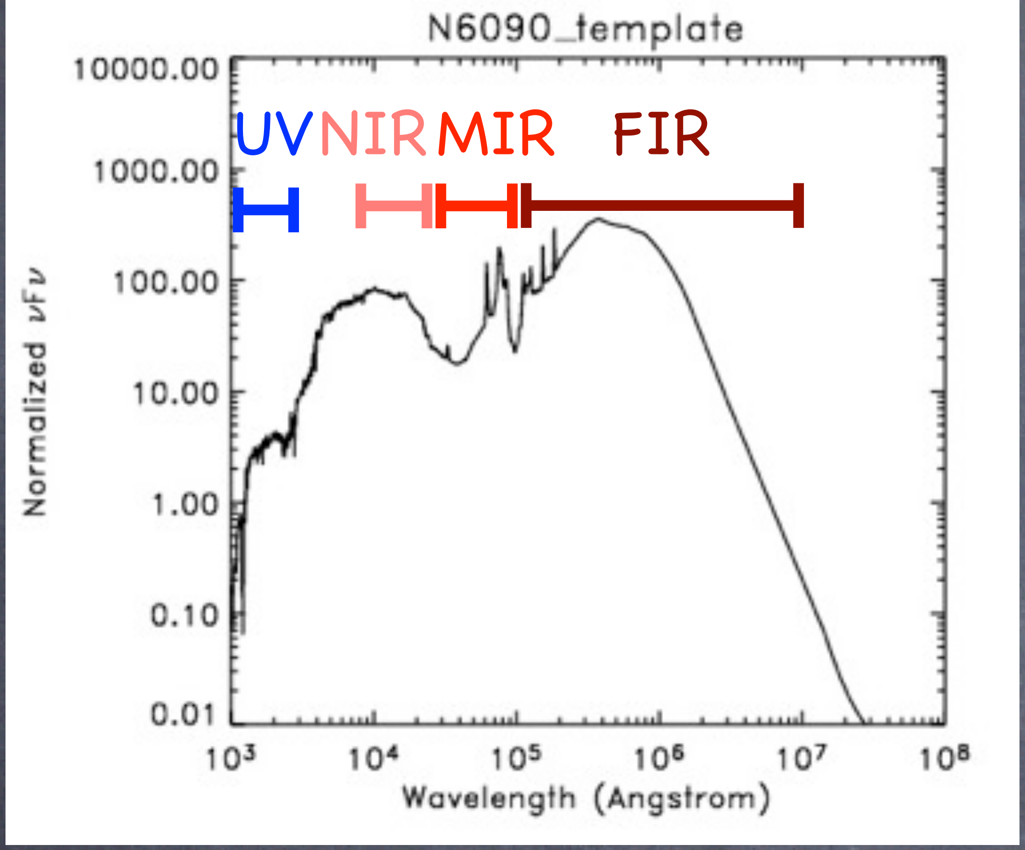


SWIRE Template Library

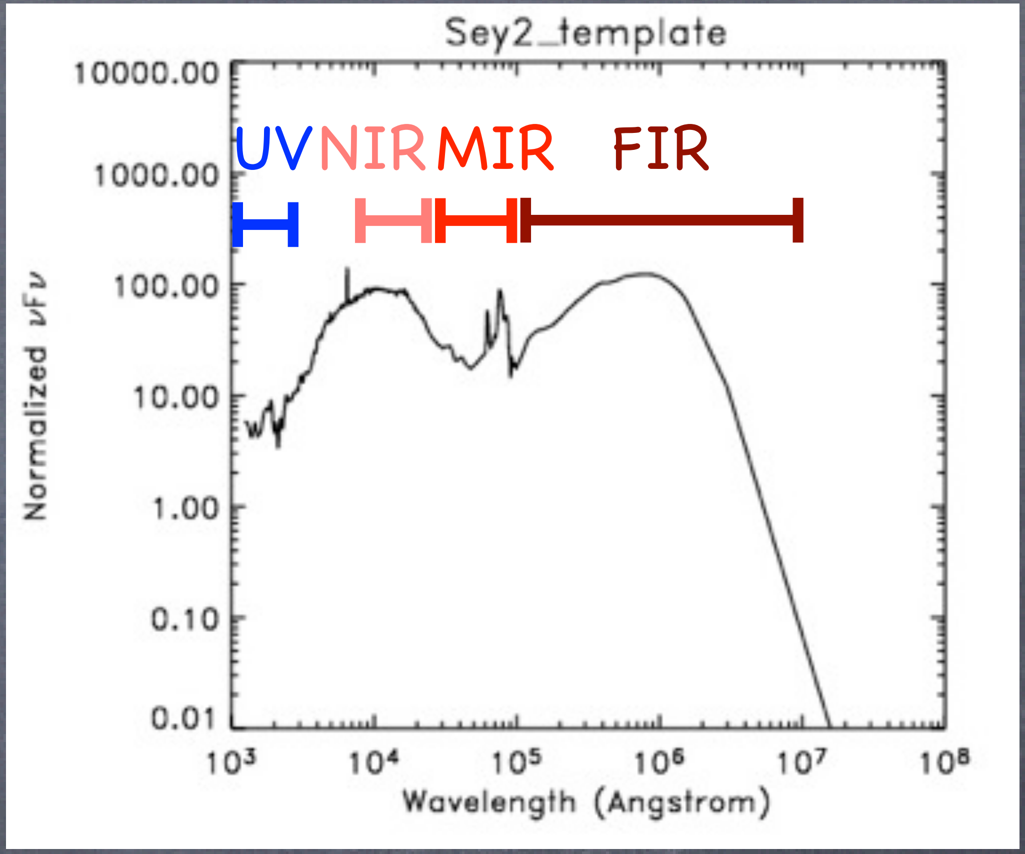
Elliptical galaxies are "red" in terms of optical colors, but star formation leads to significant IR emission in spiral galaxies

Example Galaxy SEDs

Starburst Galaxy



Seyfert 2 AGN



SWIRE Template Library

Significant IR emission from both AGN and star formation, may be distinguished using line features and multiwavelength data. For example, SF shows PAH and only low-ionization lines, where for AGN higher ionization lines are present.

IR Detectors

- IR instruments must be cooled to avoid excess dark current
  - Near-IR: cool to 77K (liquid nitrogen)
  - Mid-IR: cool to 4K (liquid helium)
  - Far-IR: as low as possible, down to 100 mK (using e.g. ^3He)

- The band gap for silicon is too large to detect light at wavelengths greater than about 1.1 μm, and materials with a narrower band gap need to be used. Common materials:
  - Mercury cadmium telluride (HgCdTe): 0.8-5 (25) μm
  - Indium antimonide (InSb): 1-5.5 μm
  - Silicon Arsenic (Si:As): 6-27 μm
  - Germanium Gallium (Ge:Ga): < 70 μm, < 160 μm (depending on stress)

Doping – Extrinsic Photoconductors

- Dopants are impurities that change the crystal structure of a semiconductor to either add extra electrons (n-type) or missing bonds (p-type).

semiconductor:dopant (Si:As, Ge:Ga)

- The effect is to add extra energy levels and change the band gap of the material.

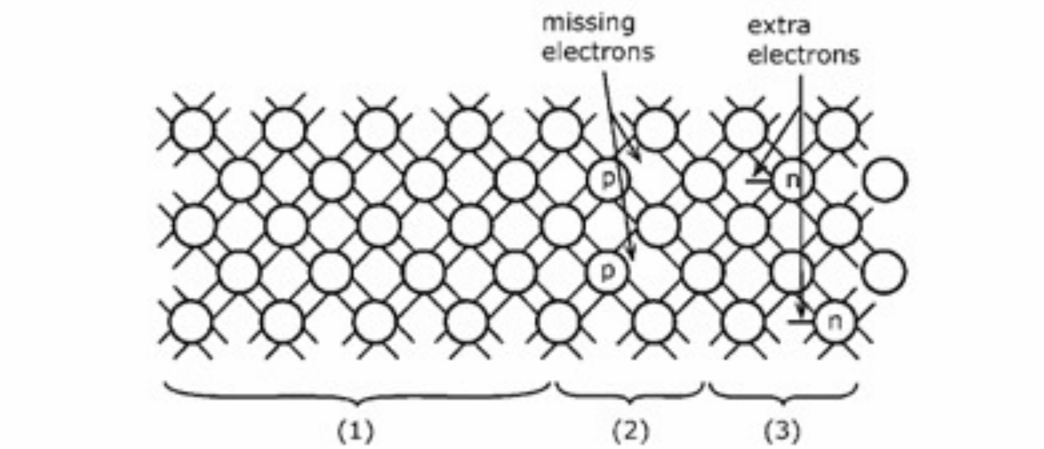


Figure 3.2. Crystal structure of (1) intrinsic, (2) p-type, and (3) n-type semiconductors.

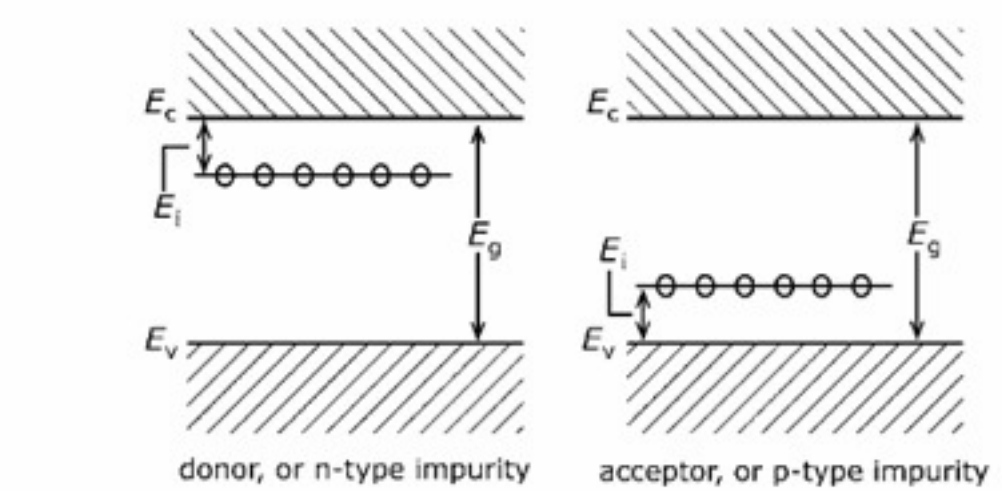
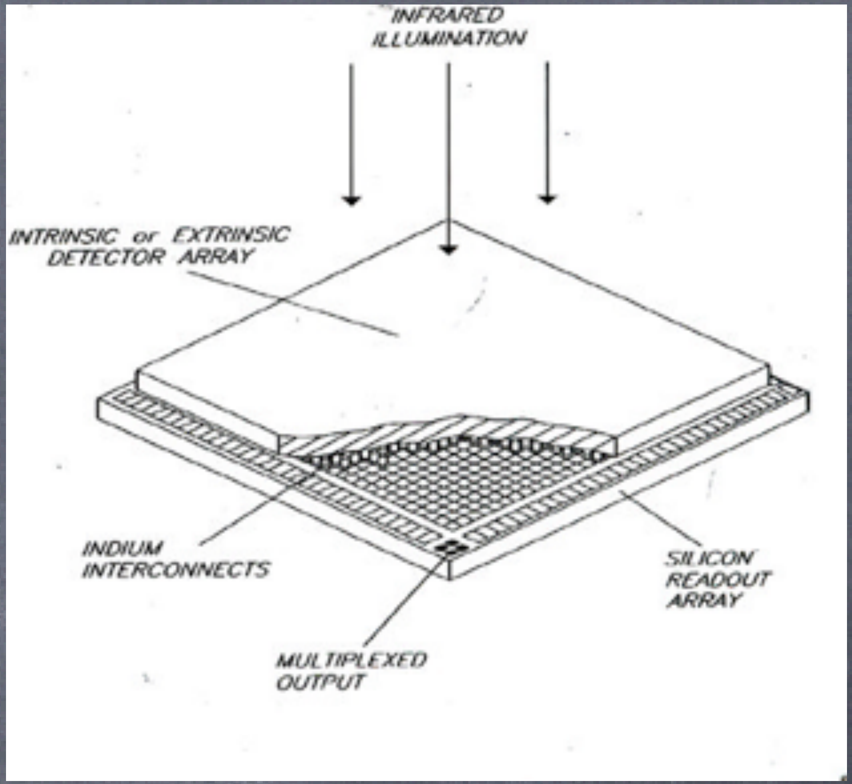


Figure 3.3. Bandgap diagrams for extrinsic photoconductors.

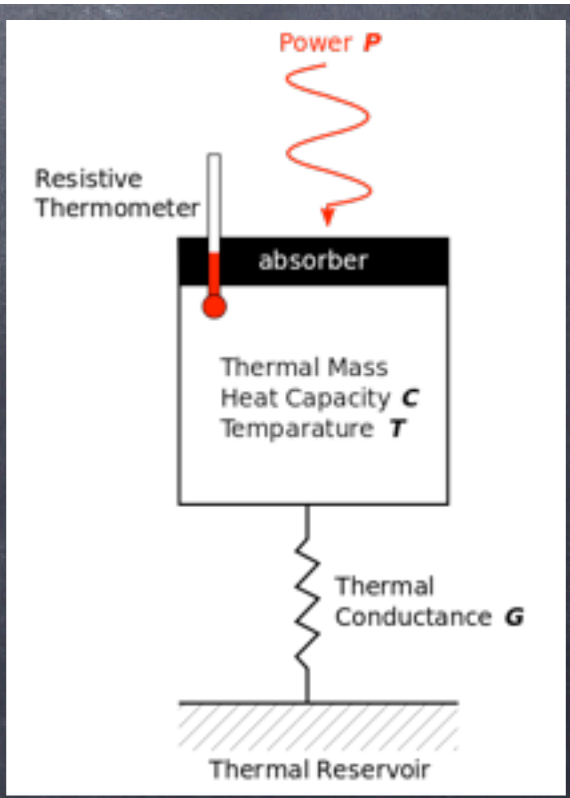
"Measuring the Universe" - G. Reike

IR Detectors



- IR arrays: detector layer (HgCdTe, etc.) mechanically bonded to a (silicon) multiplexed readout array. Unlike CCDs pixels can be readout individually; individual amplifier readouts are used.

- Bolometers: used in far-IR and submm range. In bolometers photons are thermalized raising the temperature of the material (such as Ge). This change in energy is detected with a sensitive resistive thermometer.



IR Spatial Resolution

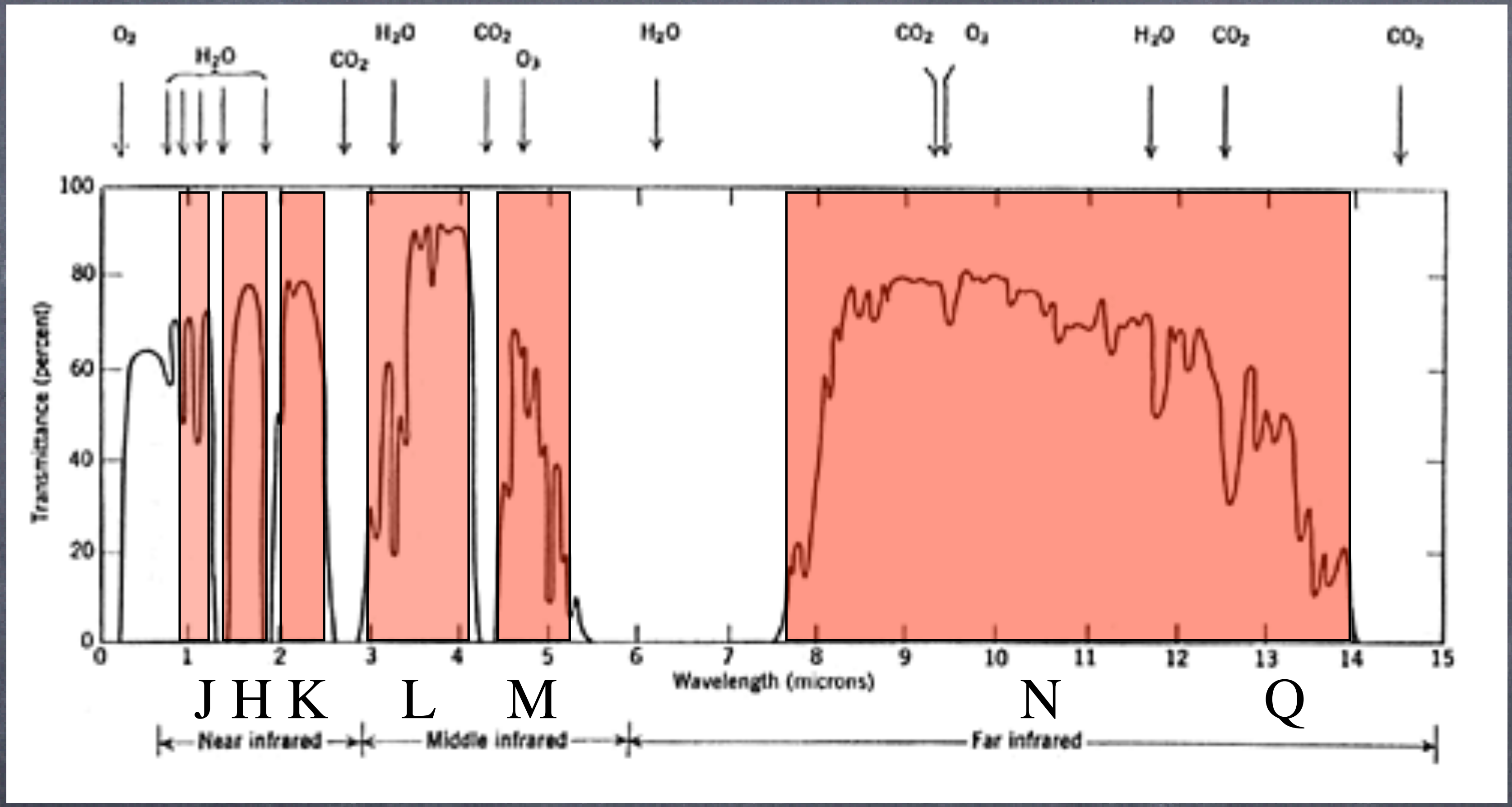
Diffraction limit: $\theta = 1.22\ \lambda/D$

The diffraction limit is larger for longer wavelengths. For mid-IR can get diffraction limited imaging from the ground.

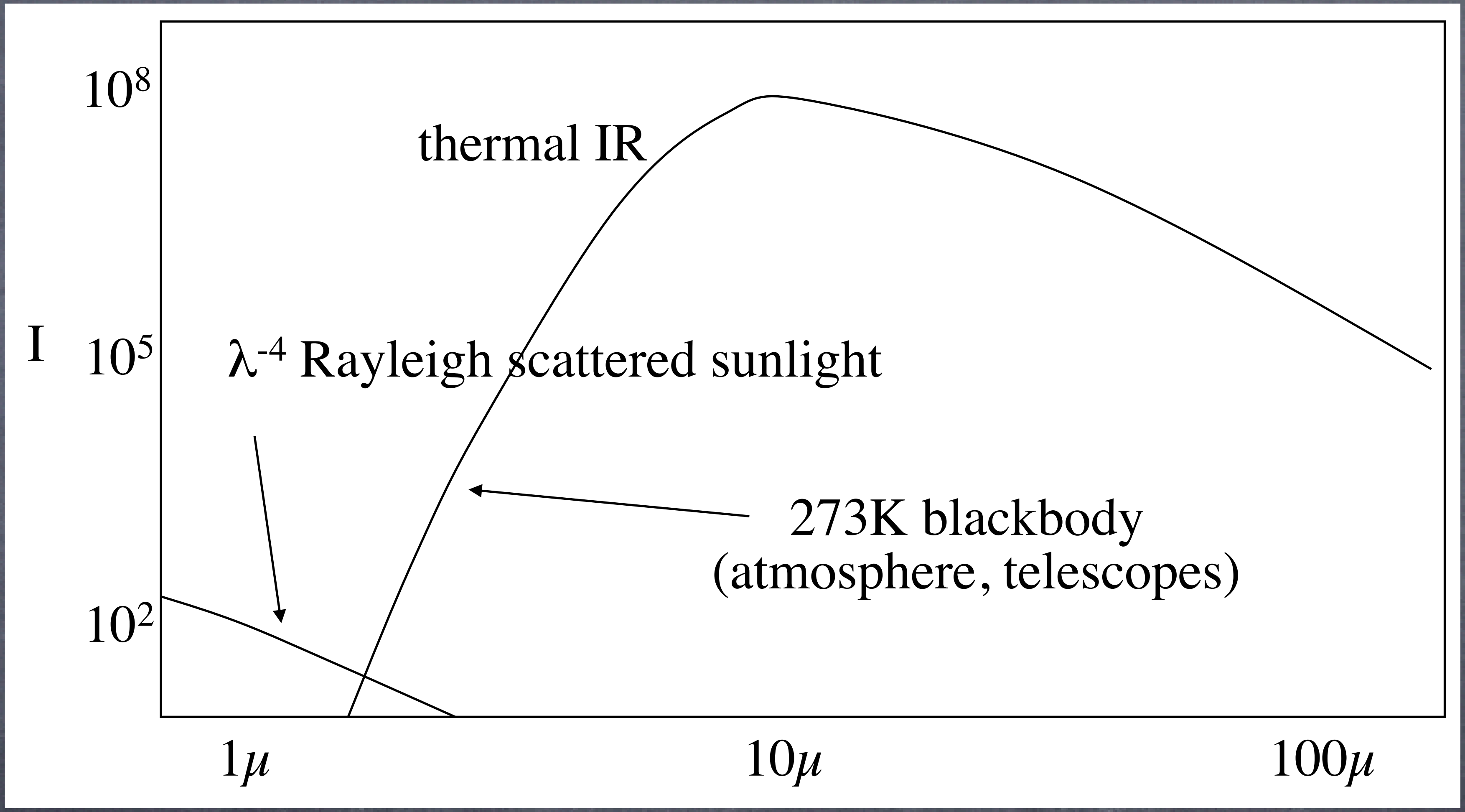
Seeing: seeing disk diameter $\propto \lambda^{-0.2}$

Seeing on the other hand is somewhat better in the red and IR. 0.35″ at 2 μm compared to 0.5″ at 4000Å.

Atmospheric Windows

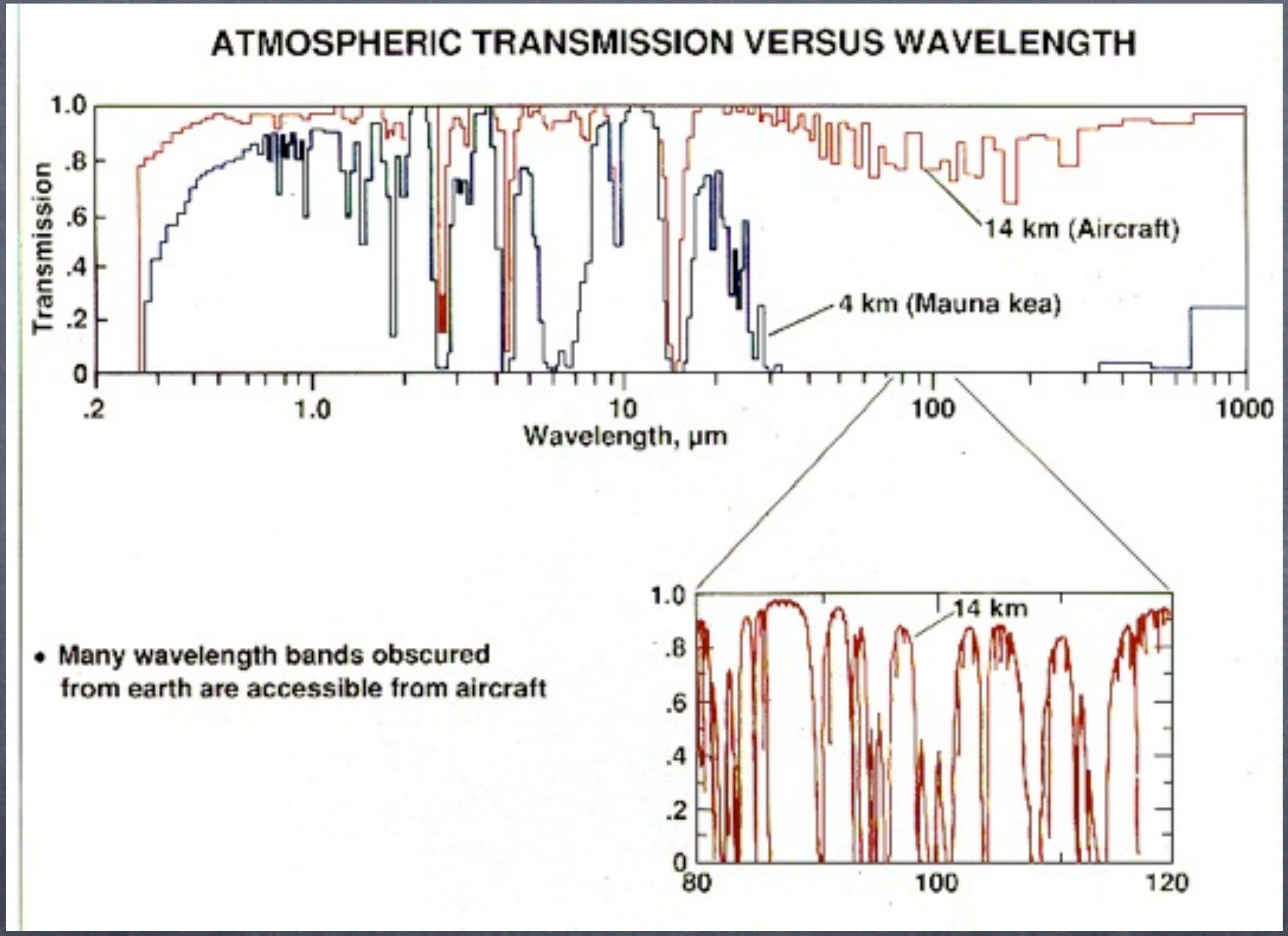


Atmospheric Background



While there are bands in mid-IR with reasonable atmospheric transmission, the thermal sky background is very bright and changes on short timescales.

Using Aircraft

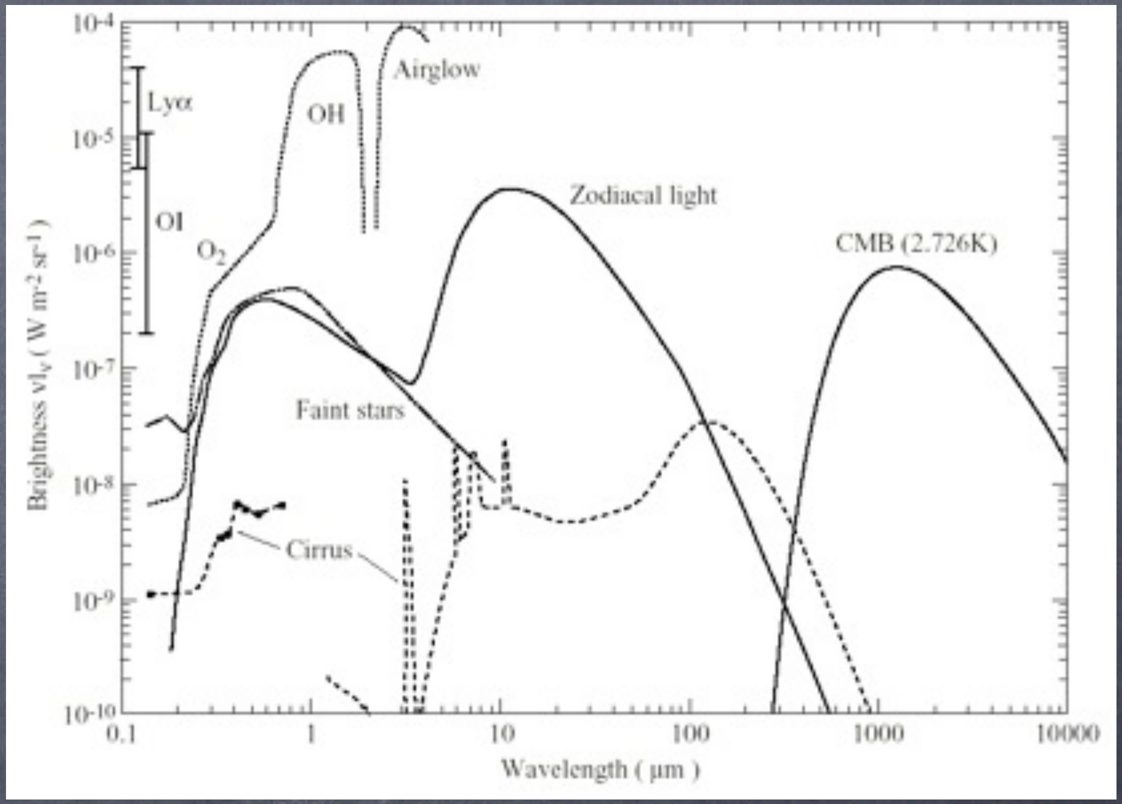


Cosmic IR background

Zodiacal light: background associated to dust in the solar system. In near-IR scattered sunlight dominates, and at longer wavelengths emission from the dust itself.

Cirrus: emission from dust in the ISM dominates in far-IR at high galactic latitudes and in all IR bands in the Galactic plane

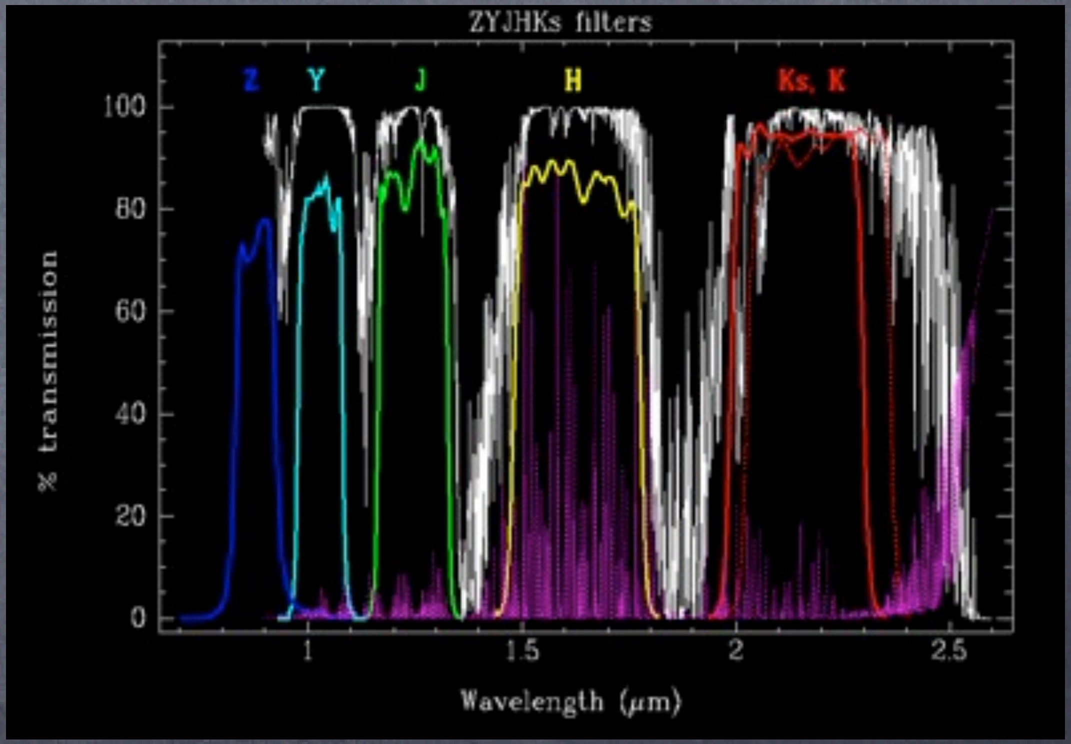
Cosmic IR background: summed emission from distant, unresolved galaxies. Traces history of star formation.



Leinert et al. 1998

Ground Based Telescopes - Near-IR

- Most major telescopes have instruments for imaging and spectroscopy in the near-IR (J, H, K band)
- Adaptive optics systems typically work in the IR where the seeing is better.



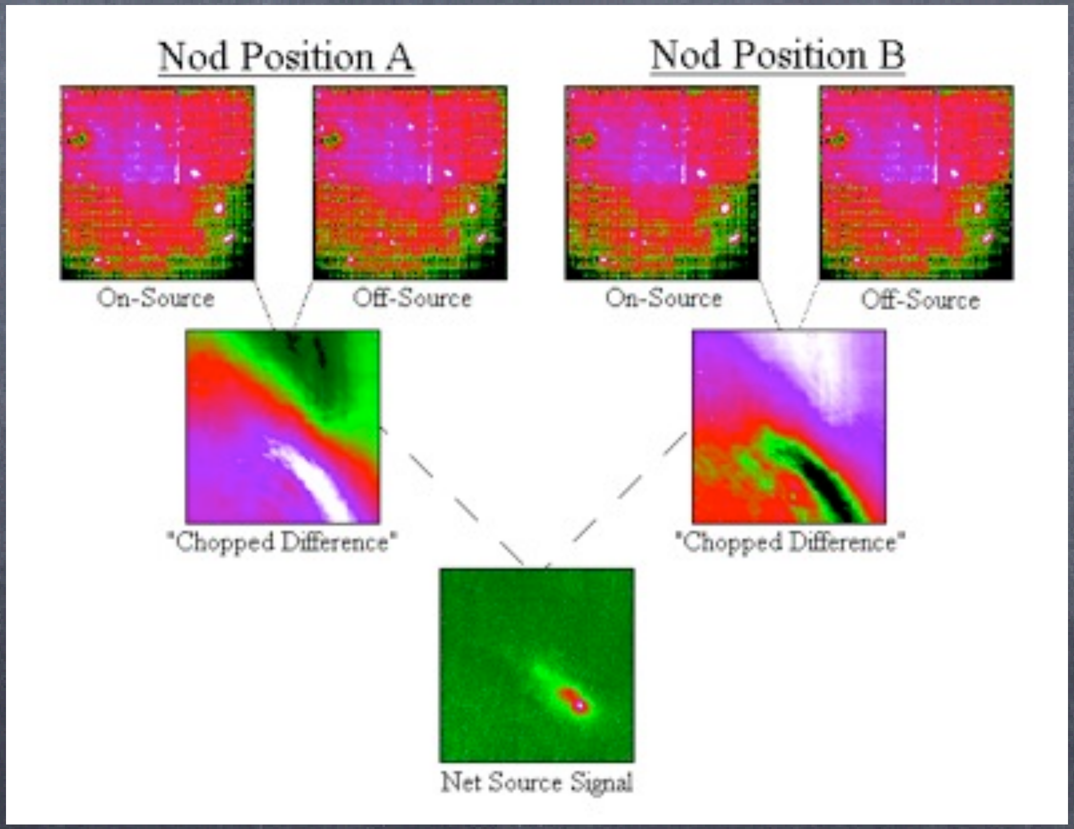
Ground Based - Mid-IR

- In the mid-IR often get diffraction limited seeing, meaning ground based resolution better than small mirrors in space.
- However, the sky background is very high (~0 mag/arcsec^2) and the telescope itself is bright, meaning that ground based observations are typically less sensitive than space.
- Sky brightness also changes rapidly, so mid-IR imaging from the ground is typically done through "chop and nod" observing.

Chopping and Nodding

chop1 = source + sky1, chop2 = sky2 (secondary moved at a few Hz)
nod1 = sky1, nod2 = source + sky2 (telescope moved 2-4x per minute)

(chop1-chop2)+(nod2-nod1) = 2*source



Example OSCIR images taken in the chop & nod mode at IRTF (provided by C. Telesco, R. Pina, and R.S. Fisher, then at the University of Florida.)

Differences in IR and Optical Observing (some)

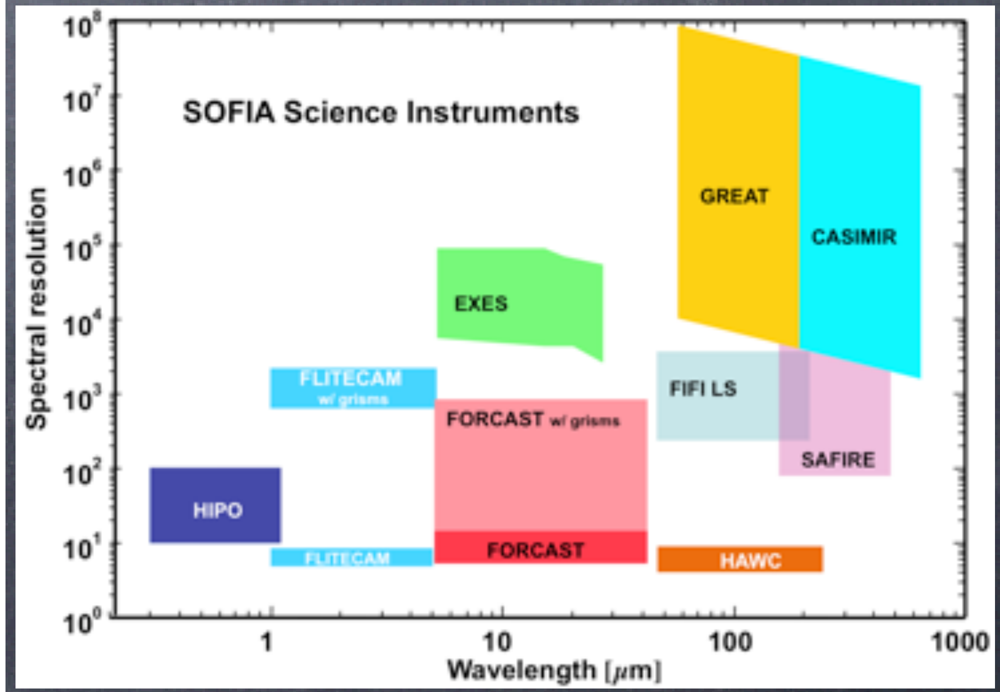
- Dark current more likely to be important -- take dark frames
- Response of IR arrays more non-linear than CCDs, reduced response by a few percent for bright sources
- The sky is bright and variable, you want flats taken under the same conditions as observations -- Use night-sky flats, readout often/dither, chopping and nodding
- Residual images persist on later readouts -- try not to saturate
- Can have bad pixels but likely not bad columns

SOFIA

- Basic info: 2.5-m mirror, can make up to 100 8-10 hour flights per year, designed to work for 20 years

- Instruments: 7 first generation instruments

SOFIA Instrument	Description	Built by / PI	λ range (μm) spec res ($\lambda_o/\Delta\lambda$)	Field of View Array Size	Available
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope Facility Instrument - Mid IR Camera and Grism Spectrometer	Cornell T. Herter	5 - 40 R ~ 200	3.2' x 3.2' 256 x 256 Si:As, Si:Sb	2010
GREAT	German Receiver for Astronomy at Terahertz Frequencies PI Instrument - Heterodyne Spectrometer	MPIfR, KOSMA DLR-WS R. Güsten	60 - 200 R = 10^6 - 10^8	Diffraction Limited Single pixel heterodyne	2010
FIFI LS	Field Imaging Far-Infrared Line Spectrometer PI Instrument w/ facility-like capabilities - Imaging Grating Spectrometer	MPE, Garching A. Poglitsch	42 - 210 R = 1000 - 3750	30"x30" (Blue) 60"x60" (Red) 2 - 16x5x5 Ge:Ga	2010
HIPO	High-speed Imaging Photometer for Occultation Special PI Instrument	Lowell Obs. E. Dunham	.3 - 1.1	5.6' x 5.6' 1024x1024 CCD	2012
FLITECAM	First Light Infrared Test Experiment CAMera Facility Instrument - Near IR Test Camera and Grism Spectrometer	UCLA I. McLean	1 - 5 R~2000	8.2' x 8.2' 1024x1024 InSb	2012
~~CASIMIR~~	~~CAltech Submillimeter Interstellar Medium Investigations Receiver~~ PI Instrument - Heterodyne Spectrometer	~~Caltech~~ J. Zmuidzinas	~~[illegible]~~ R = $3x10^4$ - $6x10^6$	~~Diffraction Limited~~ Single pixel heterodyne	~~[illegible]~~
HAWC	High-resolution Airborne Wideband Camera Facility Instrument - Far Infrared Bolometer Camera	Univ of Chicago D. Harper	50 - 240	Diffraction Limited 12x32 Bolometer	2013
EXES	Echelon-Cross-Echelle Spectrograph PI Instrument - Echelon Spectrometer	UT/UC Davis NASA Ames M. Richter	5 - 28 R = 10^5, 10^4, or 3000	5" to 90" slit 1024x1024 Si:As	2013
~~SAFIRE~~	~~Submillimeter And Far InfraRed Experiment~~ PI Instrument - Bolometer array spectrometer	~~GSFC~~ H. Moseley	~~[illegible]~~ R ~ 2000	~~[illegible]~~ 32x40 Bolometer	~~[illegible]~~



Spitzer

- Launched 2003, warm mission 2009
- Basic info: 85 cm Beryllium primary mirror, liquid helium cryogen, Earth-trailing solar orbit
- Instruments:

  InfraRed Array Camera (IRAC): 4 band, near-IR imager
  InfraRed Spectrograph (IRS): mid-IR spectrograph
  Multiband Imaging Photometer for Spitzer (MIPS): far-IR imager

Spitzer Instrument summary

	λ (microns)	Array Type	λ/Δλ	Field of View	Pixel Size (arcsec)	Sensitivity (μJy) (5 σ in 500 sec, incl. confusion)
IRAC	3.6	InSb	4.7	5.21'x5.21'	1.2	1.6 (3.4)
IRAC	4.5	InSb	4.4	5.18'x5.18'	1.2	3.1 (4.3)
IRAC	5.8	Si:As(IBC)	4.0	5.21'x5.21'	1.2	20.8 (21)
IRAC	8.0	Si:As(IBC)	2.8	5.21'x5.21'	1.2	26.9 (27)
IRS	5.2–14.7	Si:As(IBC)	64–128	3.7''x57''	1.8	250
IRS	13.5–18.5 18.5–26	Si:As(IBC) Peak-Up	~3	54''x80''	1.8	116 80
IRS	9.9–19.5	Si:As(IBC)	~600	4.7''x11.3''	2.3	1.2×10^{-18} W/m^2
IRS	14.3–35.1	Si:Sb(IBC)	64–128	10.6''x168''	5.1	1500
IRS	18.9–37.0	Si:Sb(IBC)	~600	11.1''x22.3''	4.5	2×10^{-18} W/m^2
MIPS	24	Si:As(IBC)	5	5.4'x5.4'	2.55	110
MIPS	70	Ge:Ga	4	2.7'x1.4' 5.2'x2.6'	5.20 9.98	14.4 mJy 7.2 mJy
MIPS	55-95	Ge:Ga	15–25	0.32'x3.8'	10.1	57, 100, 307 mJy (@60, 70, 90 μm)
MIPS	160	Ge:Ga (Stressed)	5	0.53'x5.33'	16×18	29 (40) mJy

- Warm mission: telescope is now at 27.5 K and the lowest two IRAC channels are still operational with little loss in sensitivity, By the end of 2013, Spitzer will have drifted too far from Earth for two-way communication

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Science Highlights (some)

- First detection of light from an extrasolar planet, also studies of planet atmospheres.
- Studies of planetary disks and very young stars
- Studies of the Milky Way bar structure and the Double Helix Nebula indicating strong magnetic fields in the center of the Galaxy
- Discovery of surprisingly massive and mature galaxies at high redshifts
- Discovery and study of high-redshift clusters of galaxies

Herschel: Far-IR

- Launched May 2009, planned 3-year mission

- Basic info: 3.5-m mirror, liquid helium cryogen plus individual cooling systems for each instrument, orbit at L2

- Instruments:

PACS (Photodetecting Array Camera and Spectrometer): imaging in 3 bands and spectroscopy 55-210 μm, 1.75′x3.5′ FOV
SPIRE (Spectral and Photometric Imaging Receiver): imaging in 3 bands and spectroscopy 194-672 μm, 4′x8′ FOV
HIFI (Heterodyne Instrument for the Far Infrared): very high resolution heterodyne spectrometer: signal is translated to a lower frequency through combining it with a stable second frequency

HERSCHEL and his instruments

PACS

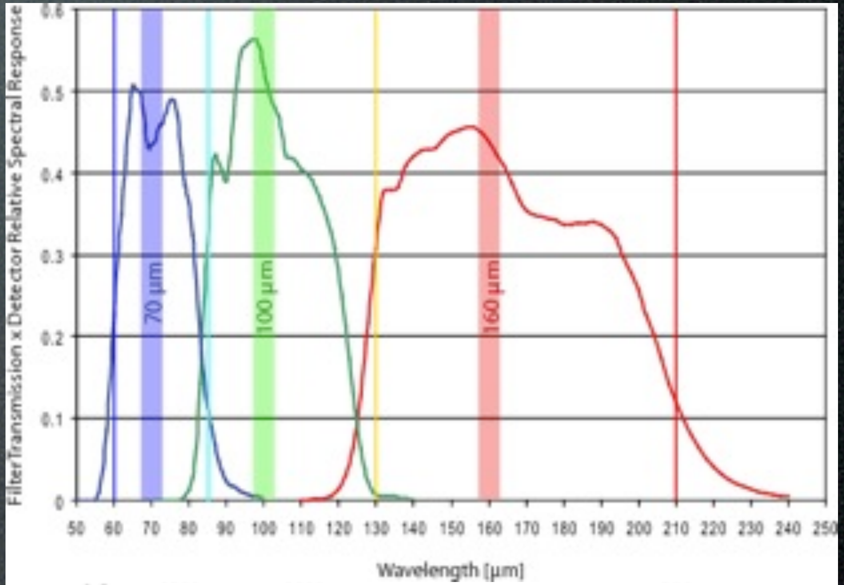
- Three FIR bands: 70, 100, 160 μm.
- Imaging & Spectroscopic capability

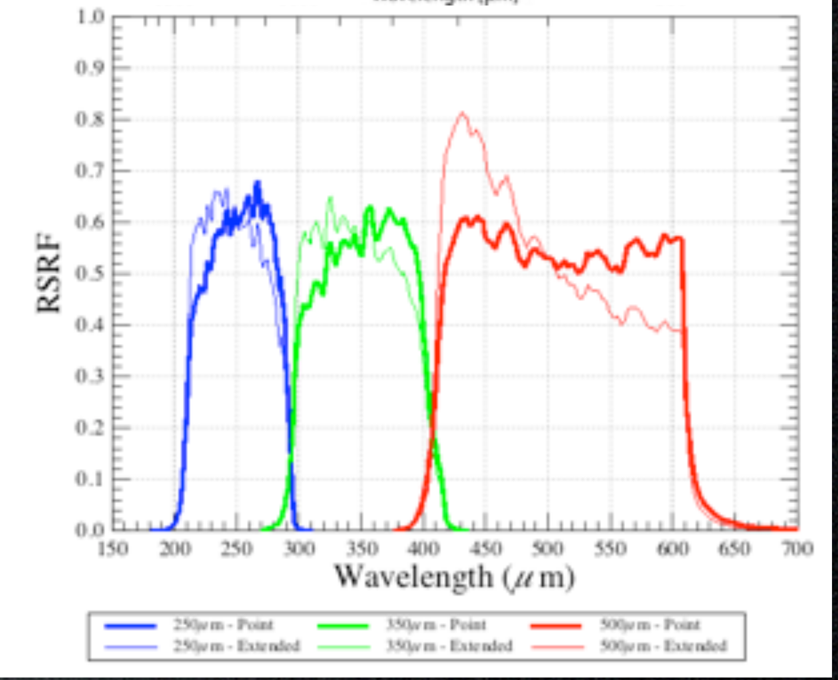
Poglitsch+ 2010

SPIRE

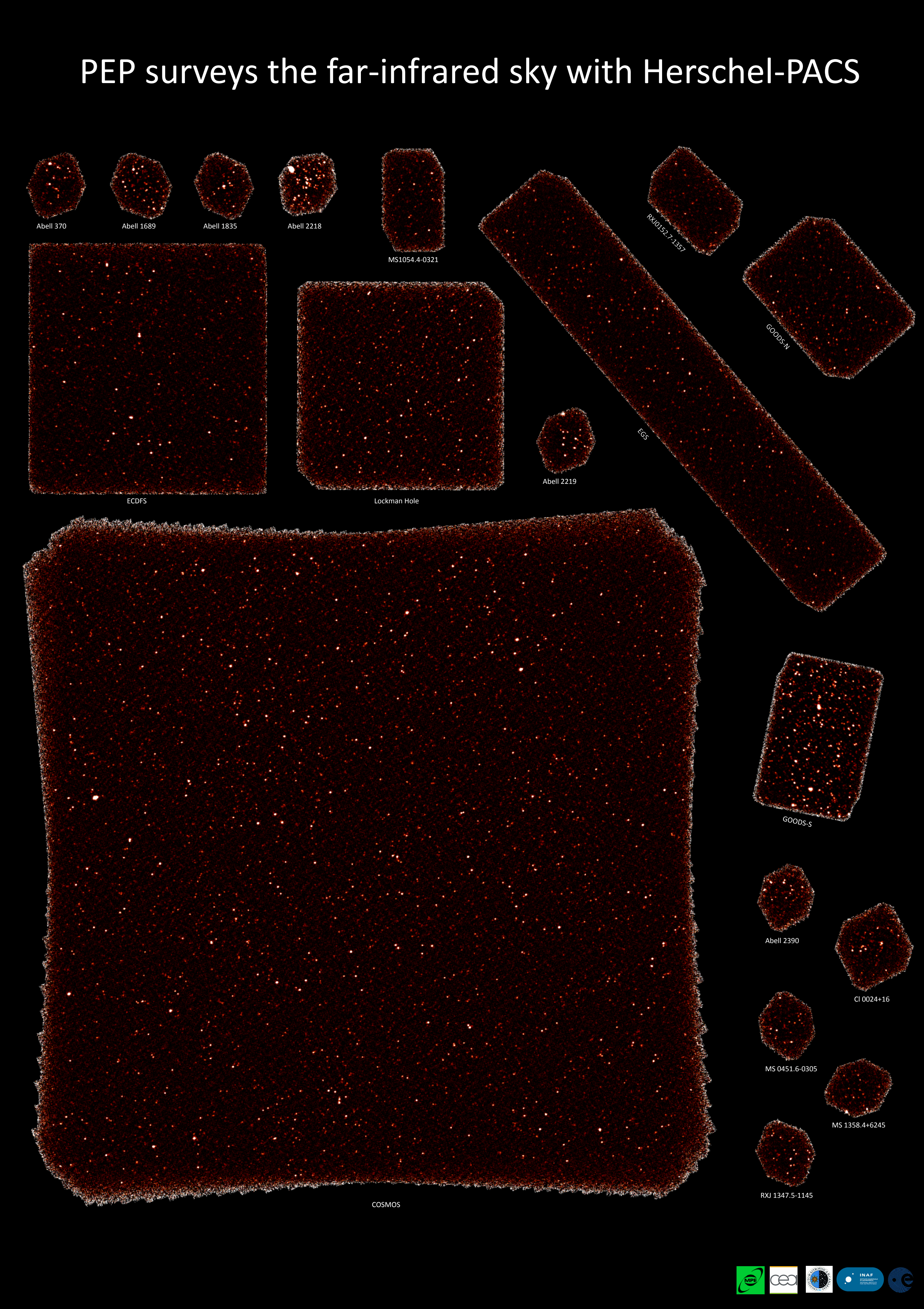
- Imaging and FT spectroscopy: 250, 350, 500 μm.

Griffin+ 2010





courtesy of David Rosario



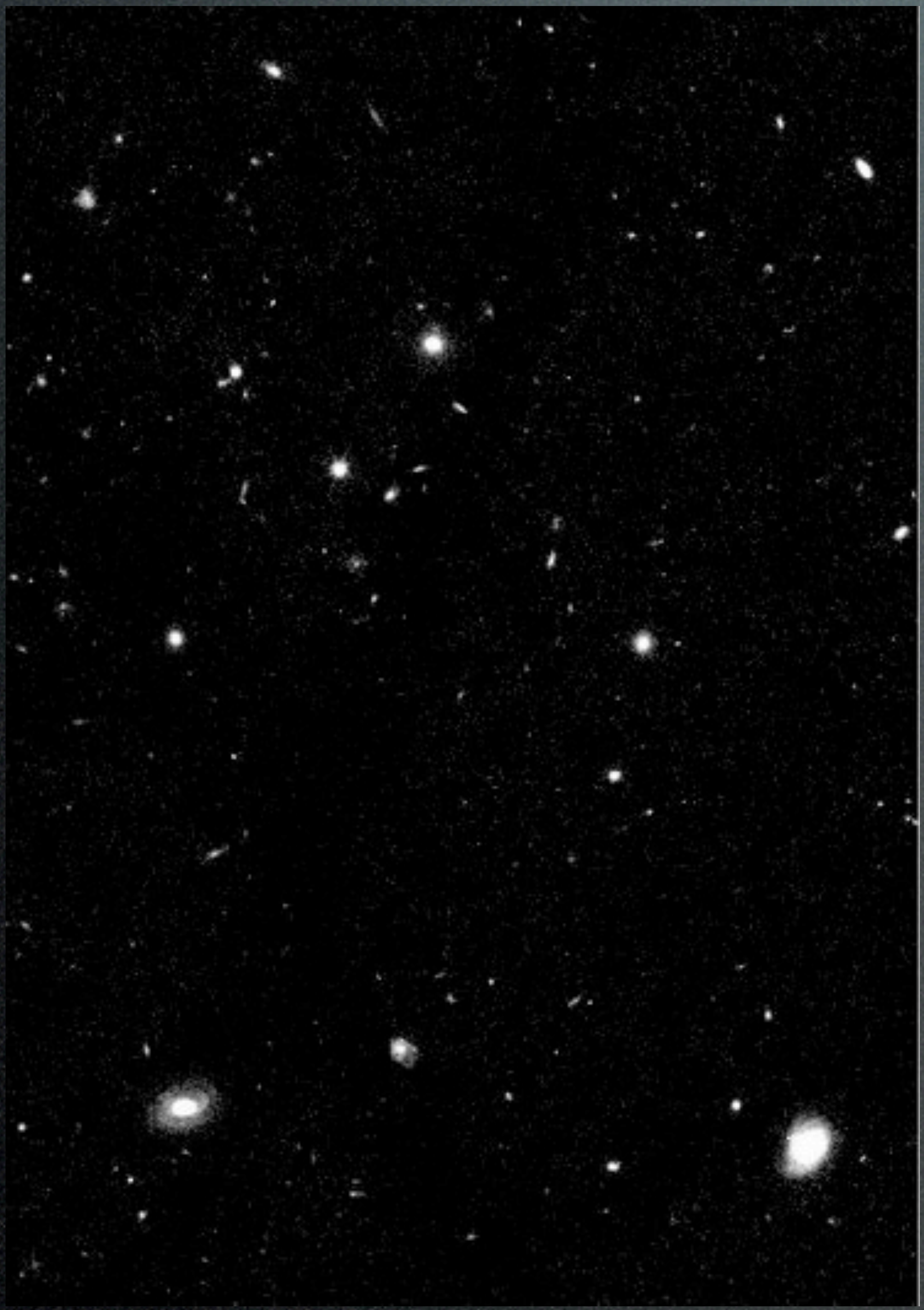
PEP:

PACS Evolutionary probe

Herschel GTO survey covering six key survey fields and several massive galaxy cluster fields

courtesy of David Rosario

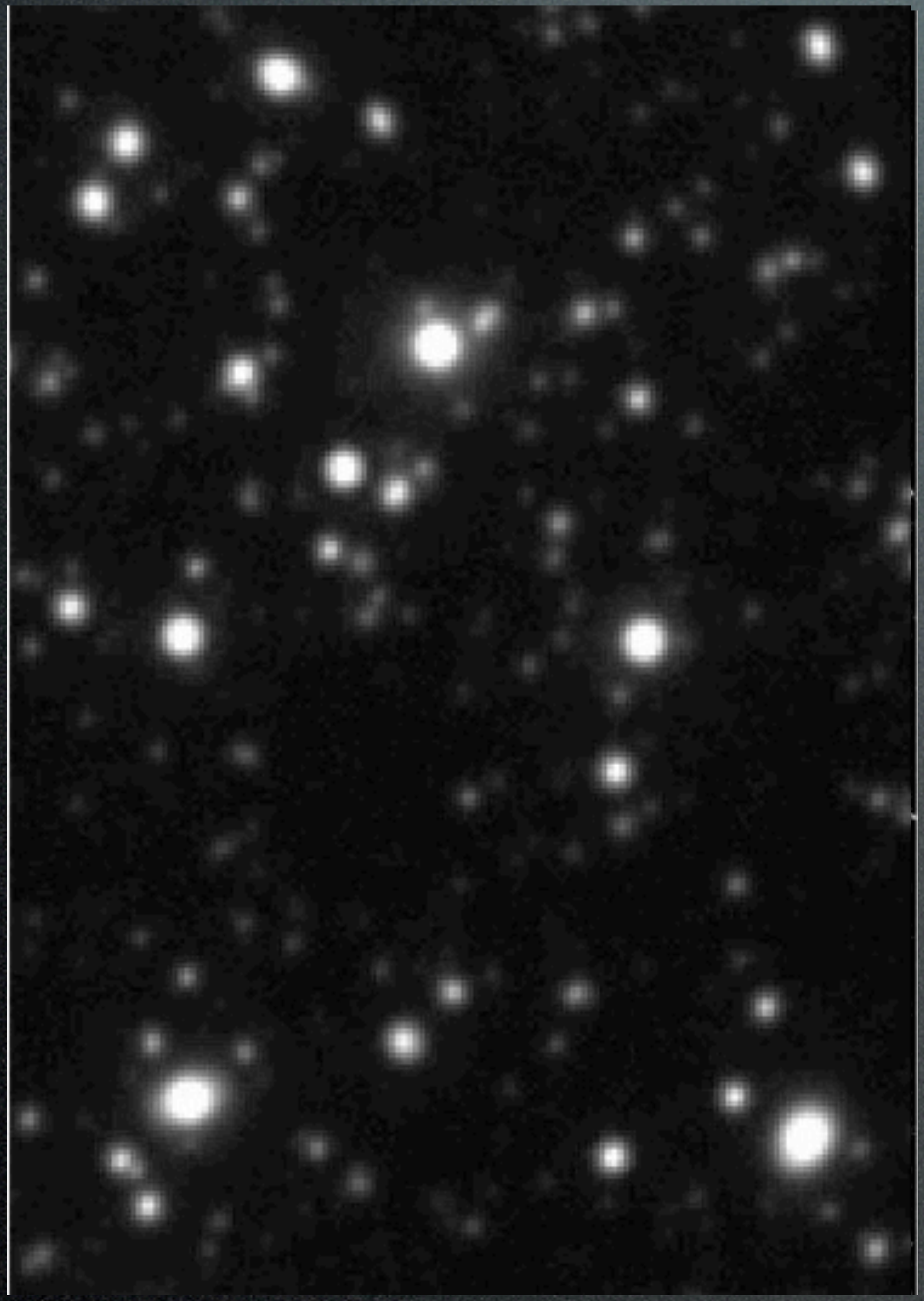
Working with HERSCHEL imaging data



HST/ACS
z-band

courtesy of David Rosario

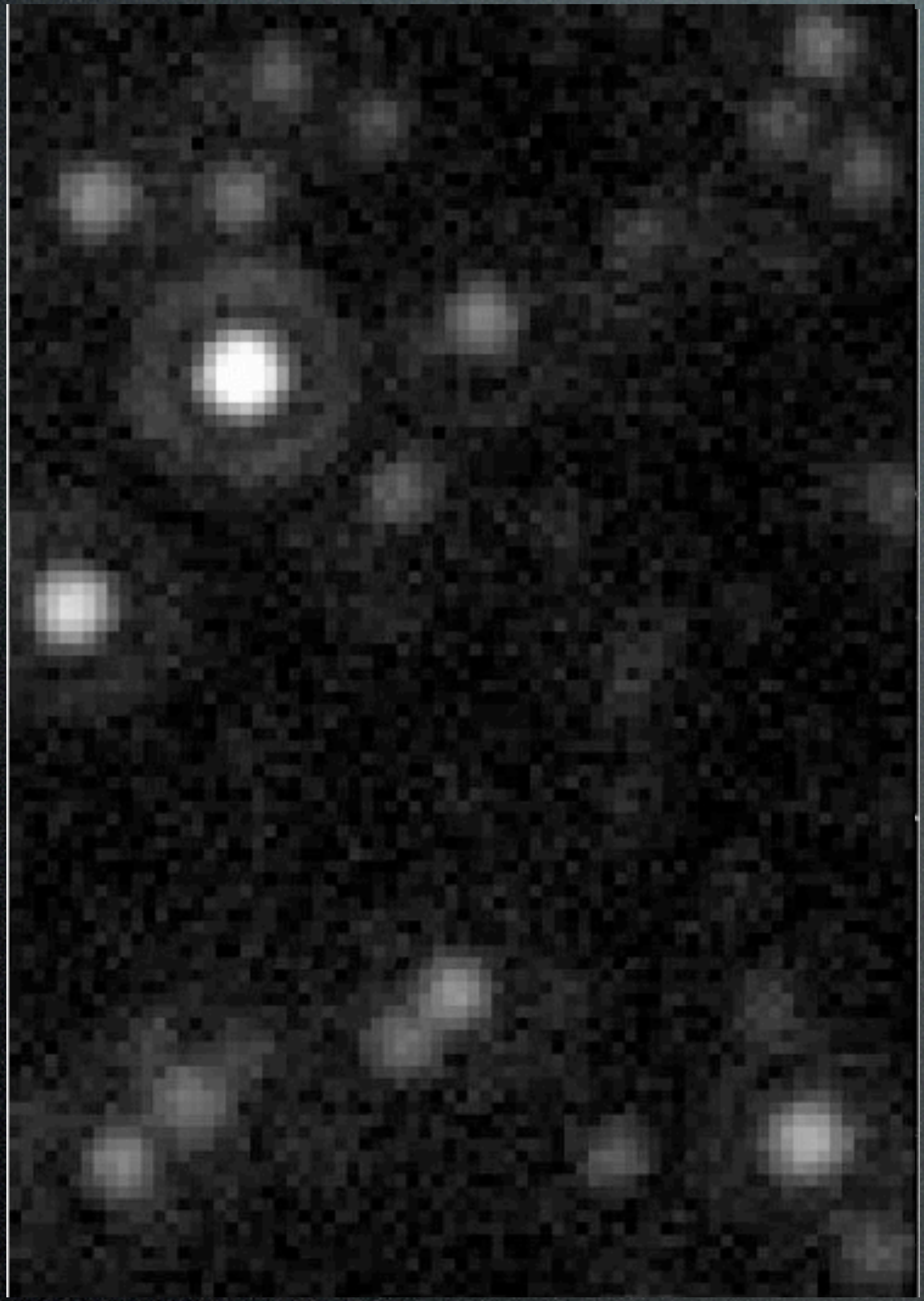
Working with HERSCHEL imaging data



Spitzer/IRAC
3.6 μm

courtesy of David Rosario

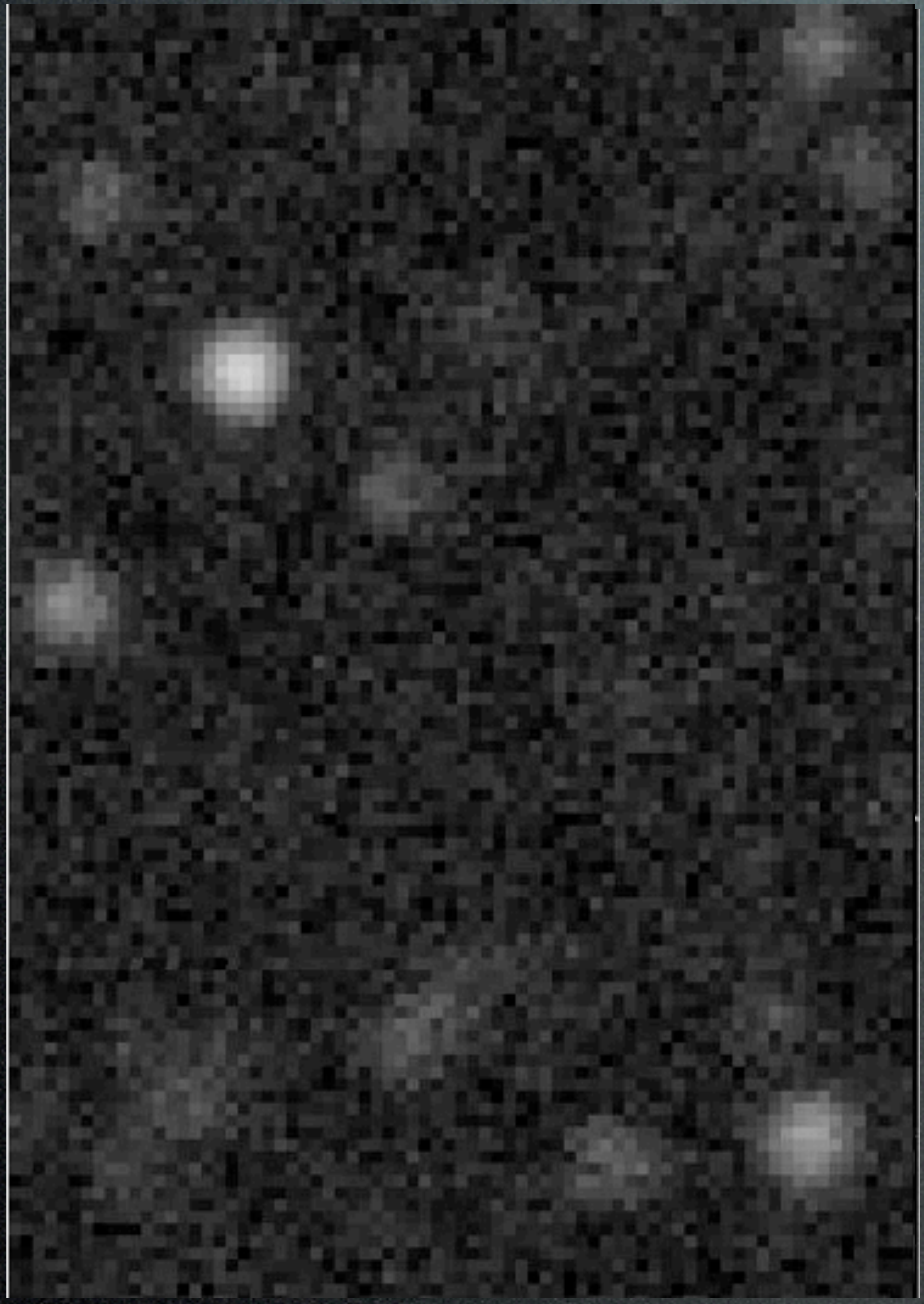
Working with HERSCHEL imaging data



Spitzer/MIPS
24 μm

courtesy of David Rosario

Working with HERSCHEL imaging data



Herschel/PACS
100 μm

courtesy of David Rosario

Herschel Science

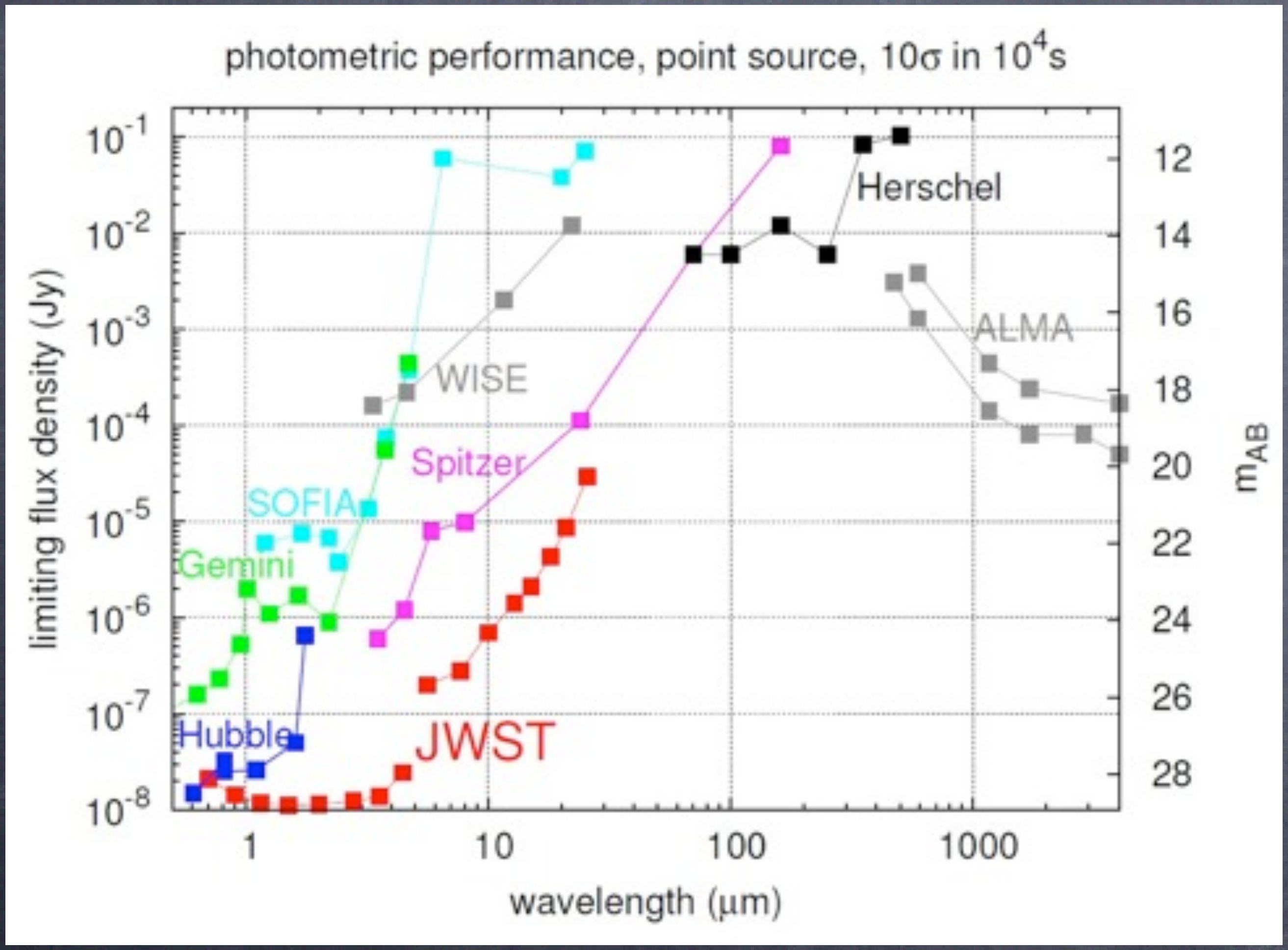
Science themes:

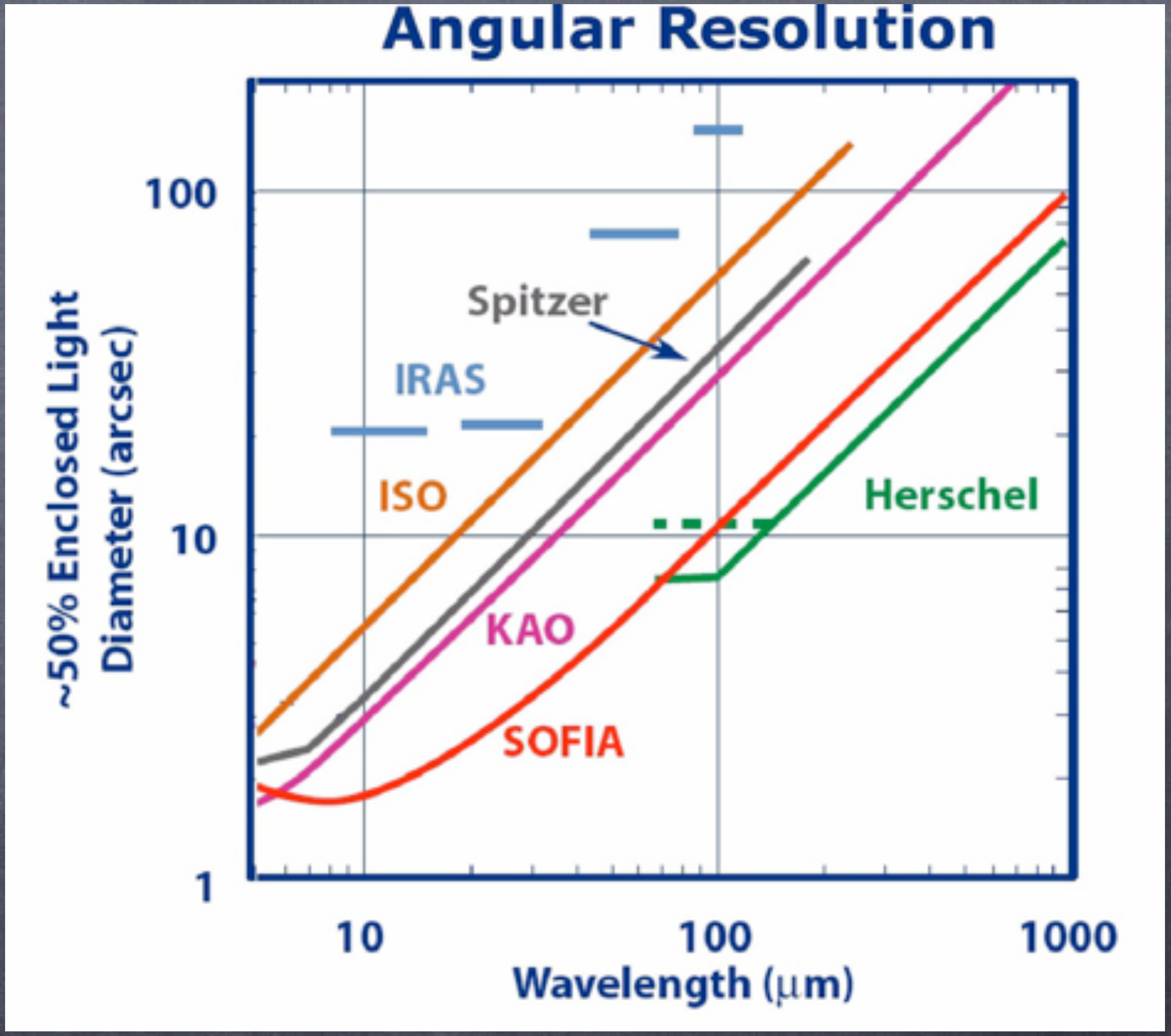
- High-z galaxies and galaxy evolution
- Star formation and its interaction with the ISM
- Chemical composition of planets, comets, moons
- Molecular chemistry

Some science highlights:

- Detection of significant water/ice in both proto-planetary disk and comet
- Studies of star forming galaxies near the peak of the SFR ($z \sim 2$) showing that starburst galaxies do not dominate SF.
- Discovery of molecular oxygen in Orion (first firm detection)
- Detection of FIR emission from black hole jets

Instrument Comparisons

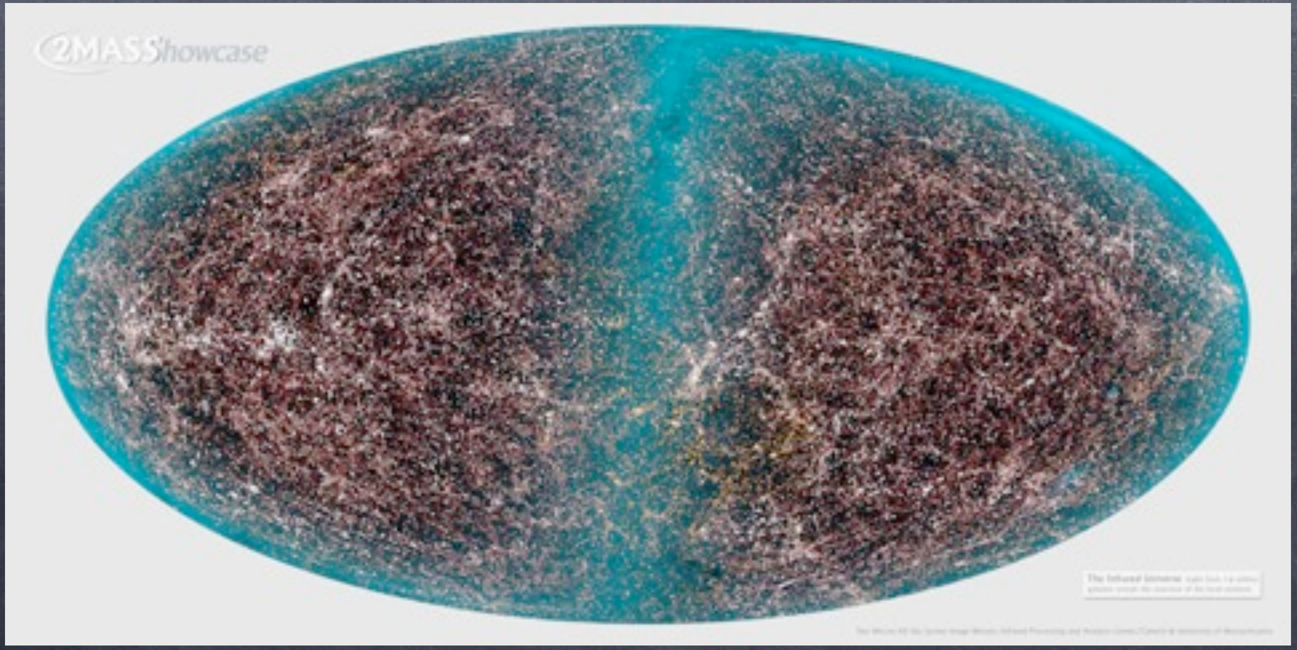




Two Micron All-Sky Survey (2MASS)

- All-sky survey in the J (1.25 μm), H (1.65 μm), and K_s (2.17 μm) bands using two 1.3-m telescopes one on Mt. Hopkins, AZ and one at CTIO, Chile. Ran from 1997-2001.

- Complimented by the 2MASS redshift survey which is complete to a limiting magnitude of K=11.75 over 91% of the sky, and contains ~45,000 galaxies.



WISE

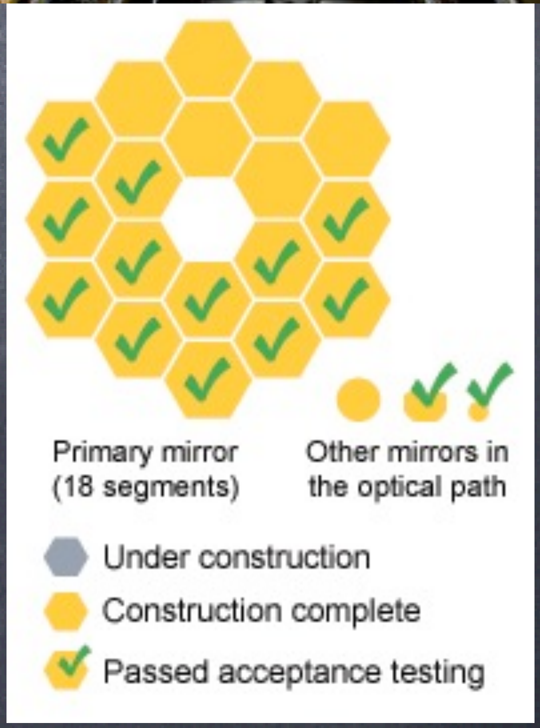
- Dec. 2009-Oct. 2010, warm mission to Feb. 2011
- 0.4-m telescope, frozen hydrogen cooled, HgCdTe and Si:As detectors
- All-sky survey in 4 bands 3, 5, 12 and 22 μm, about 1000 times deeper than previous space surveys, also discovered tens of thousands of asteroids

WISE mosaic of Milky Way, Image credit: NASA/JPL-Caltech/UCLA

Future Telescopes - JWST

- Launch planned for 2018
- Basic info: 6.5-m mirror with tennis court size sunshade which will unfold in orbit, 5-10 year lifetime, orbit at L2
- Instruments:

  Near-IR Camera: 0.6-5 μm, two 2.1'x2.1' FOV
  Near-IR Spectrograph: multi-object spectrograph with 3'x3' FOV (micro-shutter array allows targeting multiple objects)
  Mid-IR Instrument: imaging and spectroscopy from 5-28 μm, cooled with an additional cryogenic cooler



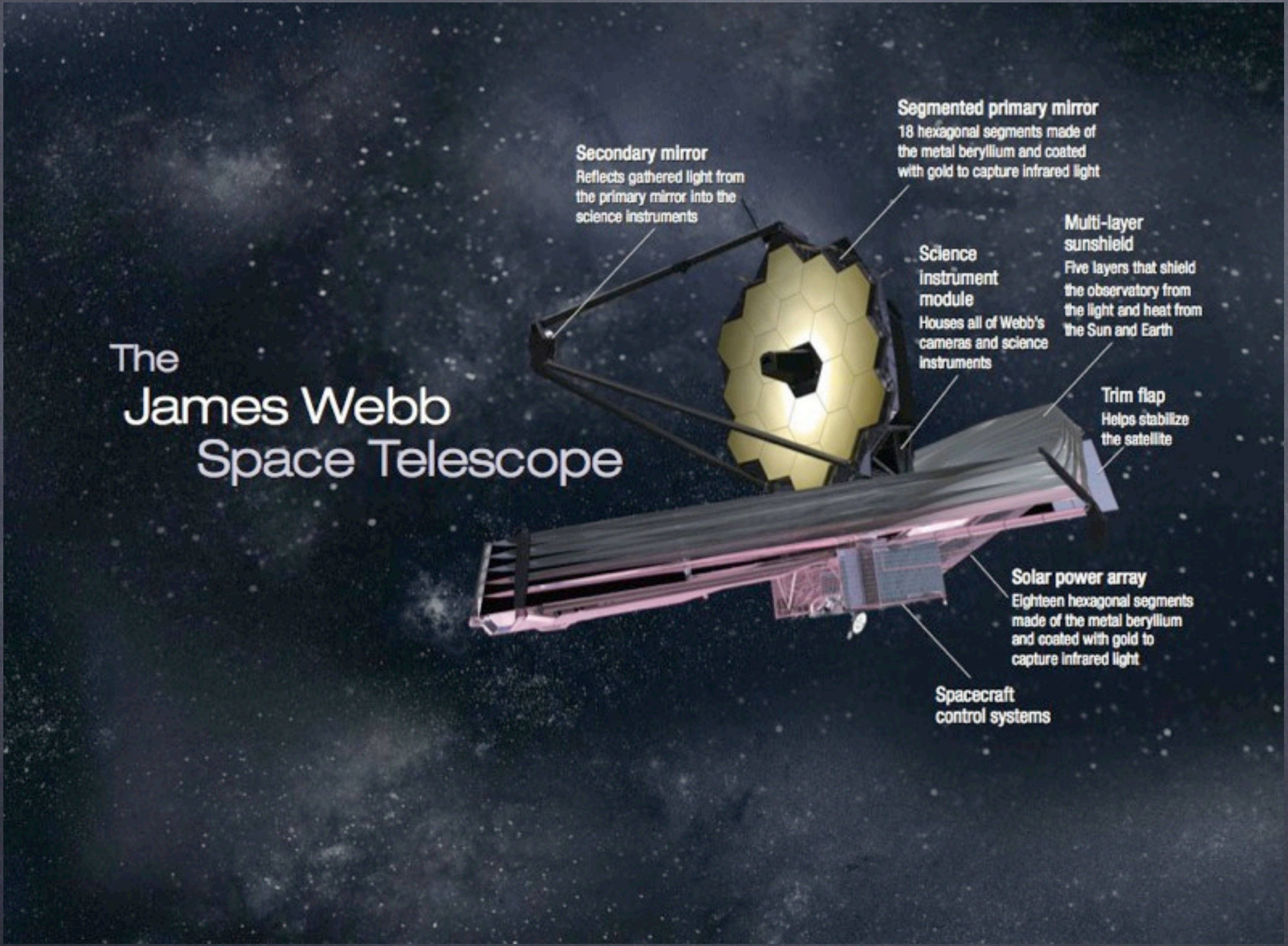
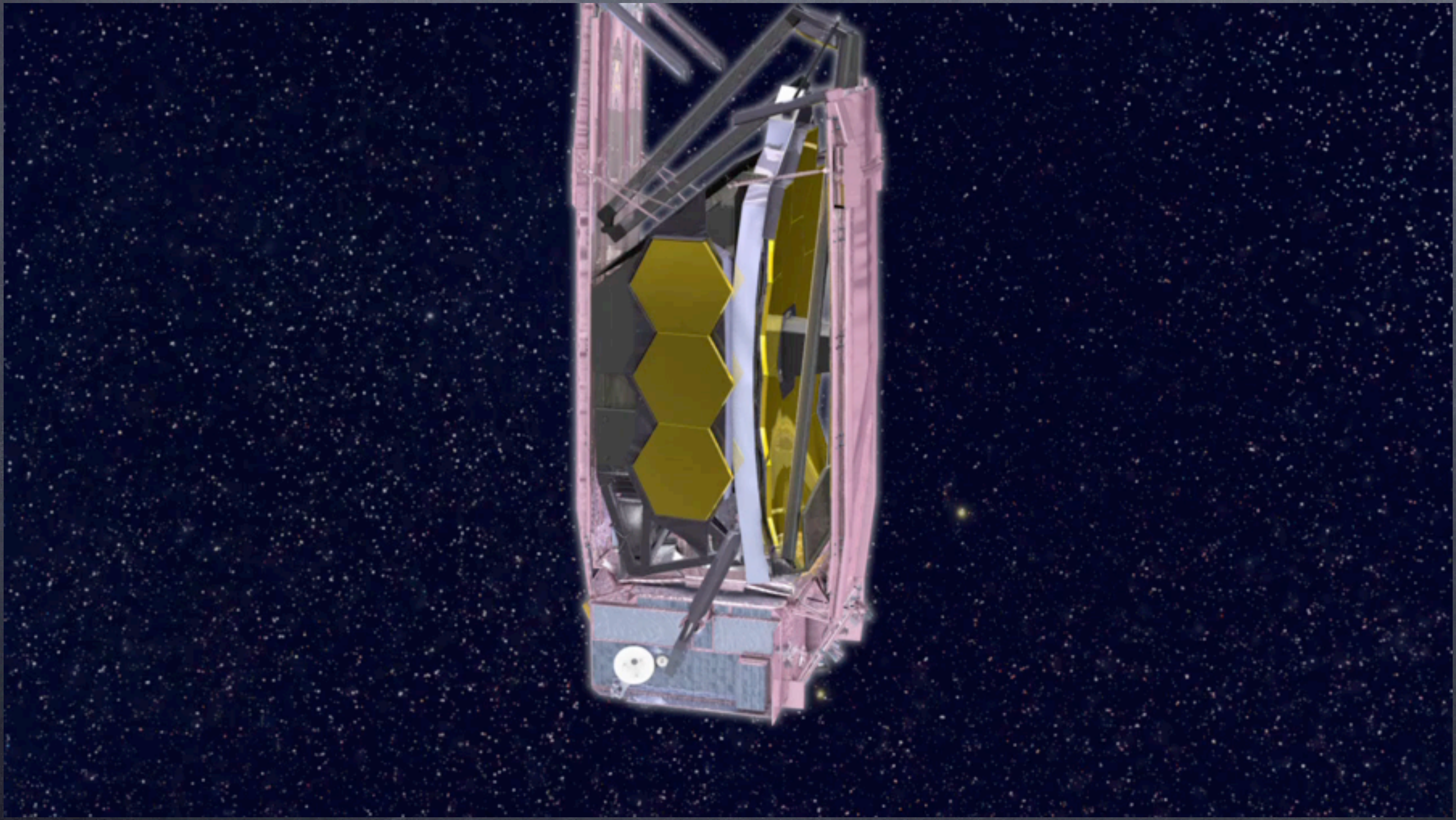


Image credit: NASA/STScI

JWST Deployment



JWST Science

Four major science themes:

- The End of the Dark Ages: First Light and Reionization
- Assembly of Galaxies
- The Birth of Stars and Protoplanetary Systems
- Planetary Systems and the Origins of Life

Comparison of UV/Vis/IR

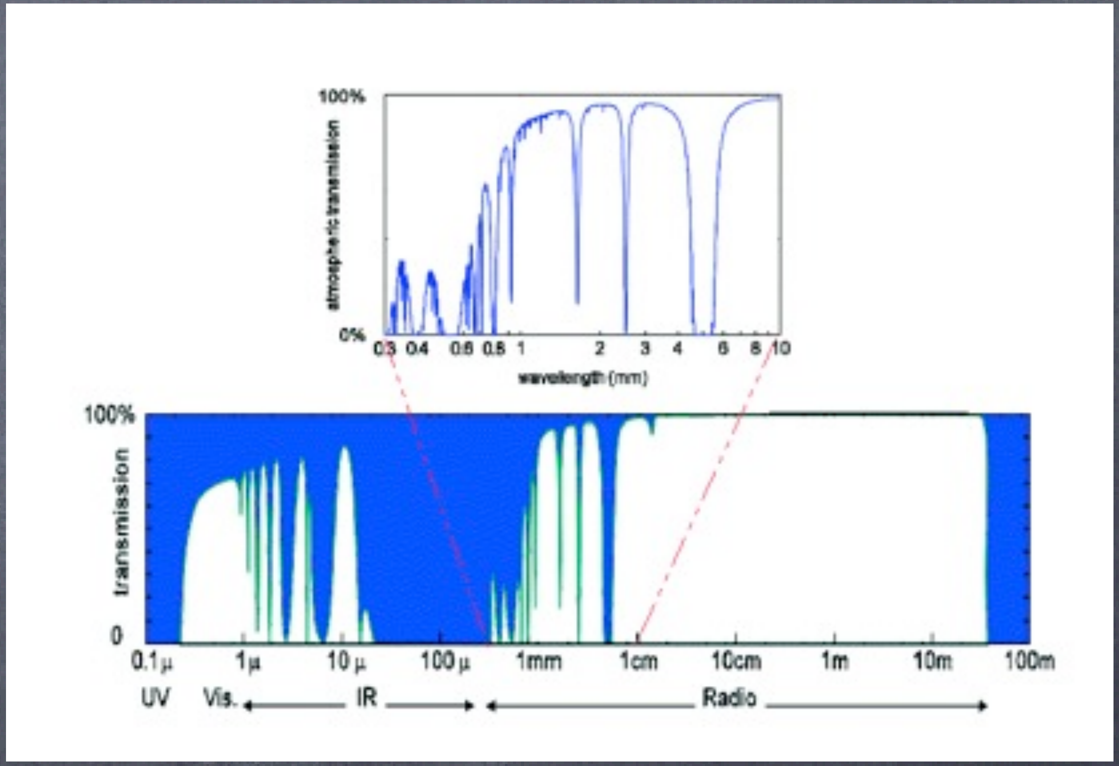
	UV	Optical	IR
sources of emission	massive stars, WHIM, Ly α	many	dust, cool objects, molecules
detectors	based on microchannel plates	CCDs	HgCdTe etc. arrays, bolometers
major telescopes	GALEX, HST	many	Spitzer, Herschel, ground
surveys	GALEX	SDSS	2MASS, WISE

Sub-mm Astronomy

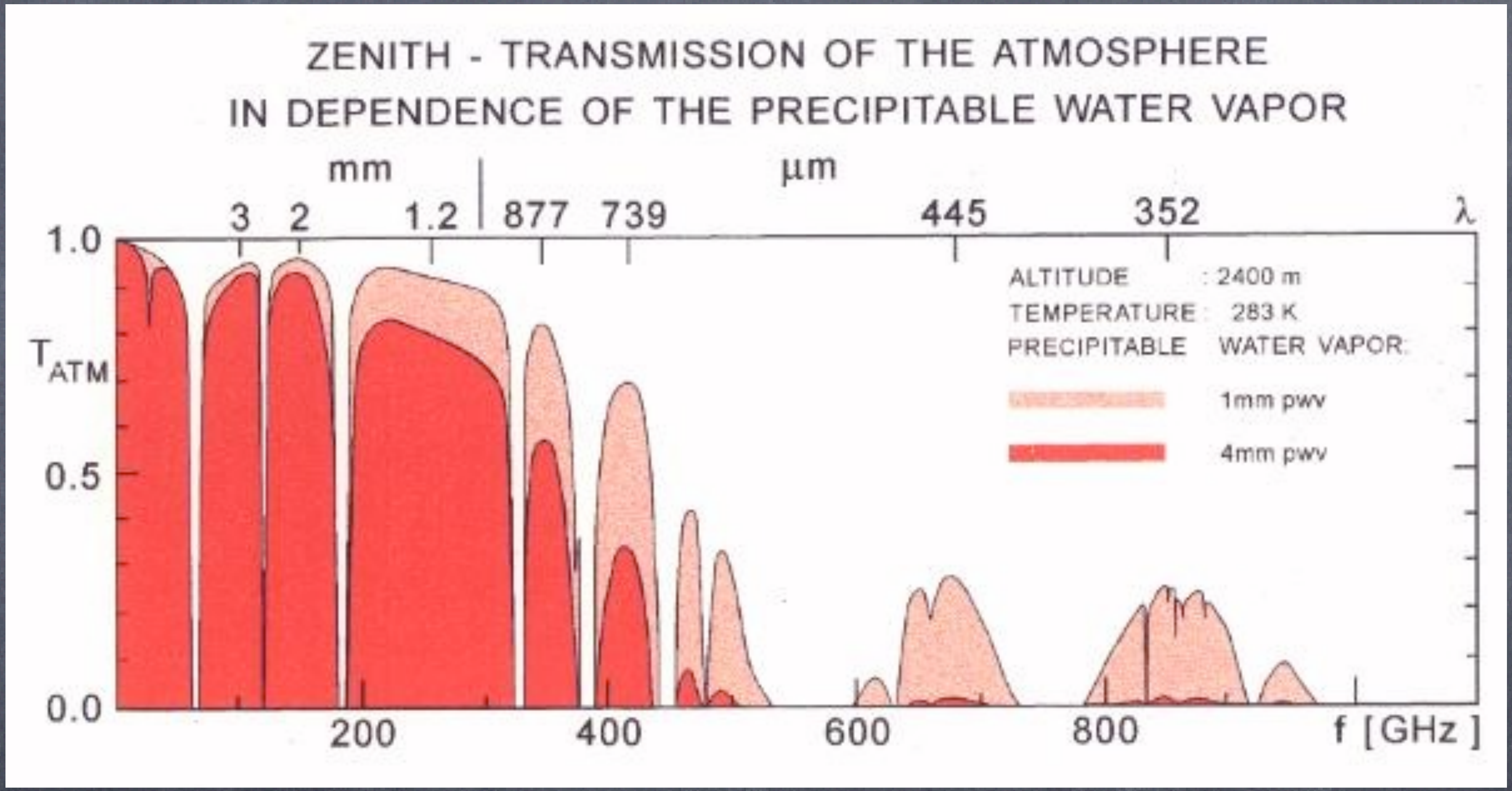
- Sub-mm refers to roughly 0.3-1 mm wavelengths somewhere in the far-IR, microwave, radio range (Herschel covers some sub-mm)

- Instruments are bolometers for imaging and heterodyne receivers for spectroscopy

- Science: molecular clouds/star formation, high-redshift dusty/star forming galaxies



Need a dry site!



Ground Based sub-mm

- Good sites include Mauna Kea, the Atacama desert in Chile, and the South Pole.

- Ground based telescopes:

  Atacama Pathfinder Experiment (APEX), 12-m dish with 264 aluminum panels, a modified ALMA prototype

  Submillimeter Array (SMA) interferometer on Mauna Kea with 8, 6-m telescopes

  James Clerk Maxwell Telescope, 15-m

  Caltech Submillimeter Observatory, 10.4-m

Atacama Large Millimeter Array (ALMA)

- 66 12-m and 7-m radio telescopes with varying baseline from 150 m to 16 km
- On a plateau in the Atacama desert at 5000 meters
- 0.3-9.6 mm, FOV ~21" at 300 GHz, resolution as good as 6 mas depending on wavelength and configuration
- Cost around $1.3 billion
- Science: first stars and galaxies, star and planet formation, composition of molecular clouds

ALMA (ESO/NAOJ/NRAO), Visible: HST