Astronomical observations in the infrared

Eric Hsiao
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Outline

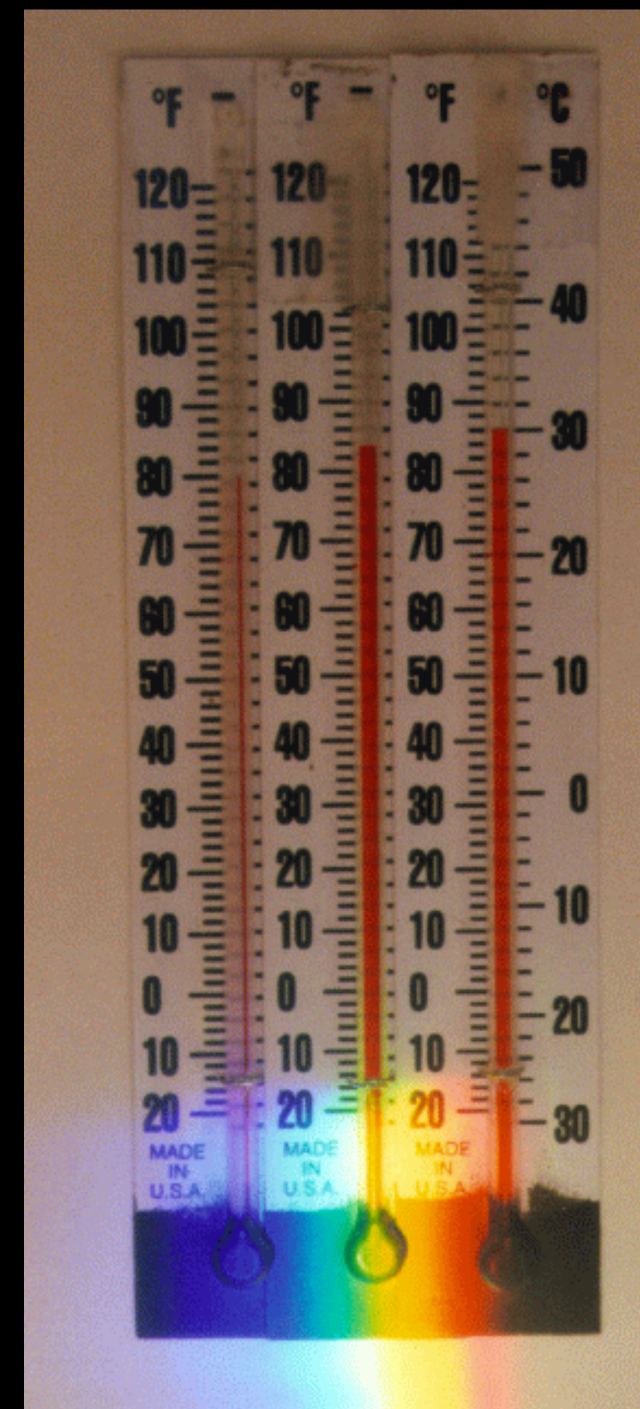
- Infrared radiation
- Infrared astronomy
- The Infrared sky
- Infrared detectors
- Infrared observations

Infrared radiation

- Discovered by William Herschel in 1800.
- First form of invisible electromagnetic radiation discovered!

Infrared radiation

- What is the temperature of each color?
- Temperature is the highest at “infra” red.
- But the Sun peaks at yellow. What’s going on here?



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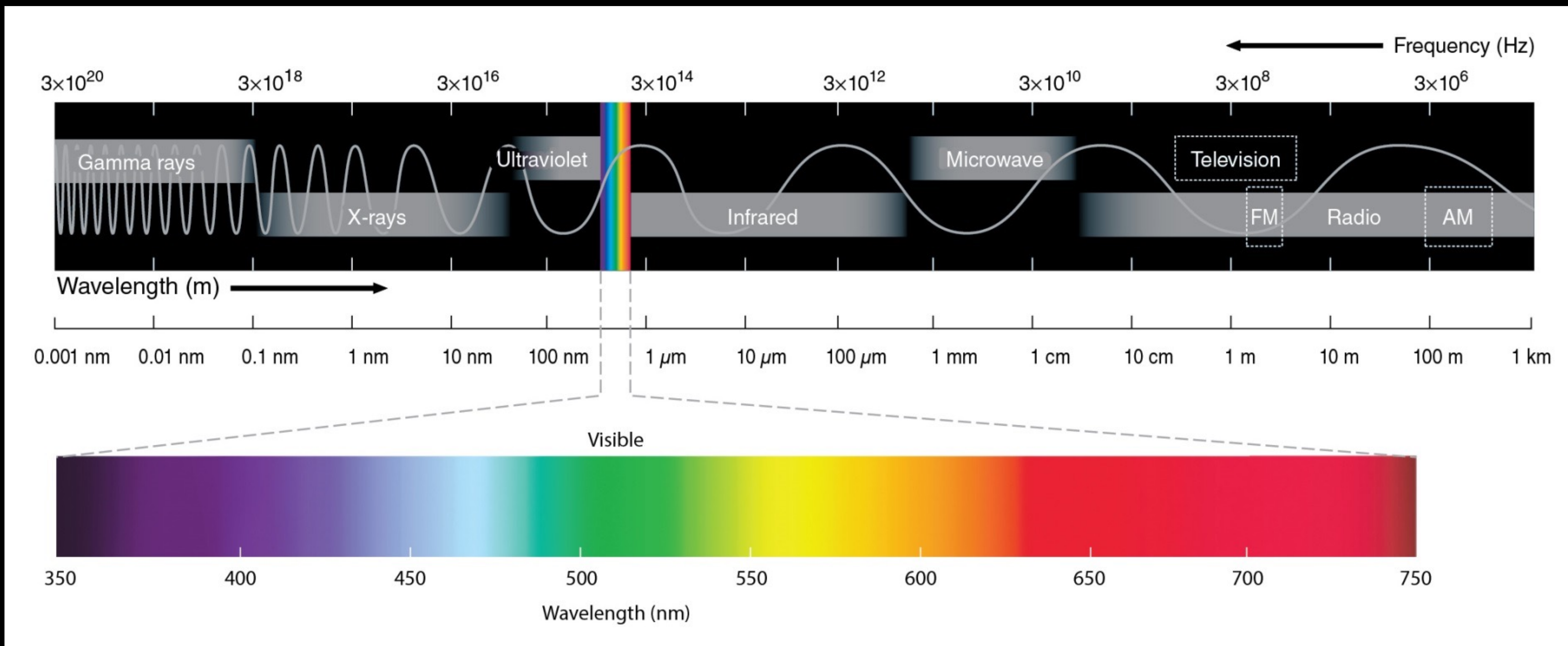
Infrared radiation

Infrared radiation



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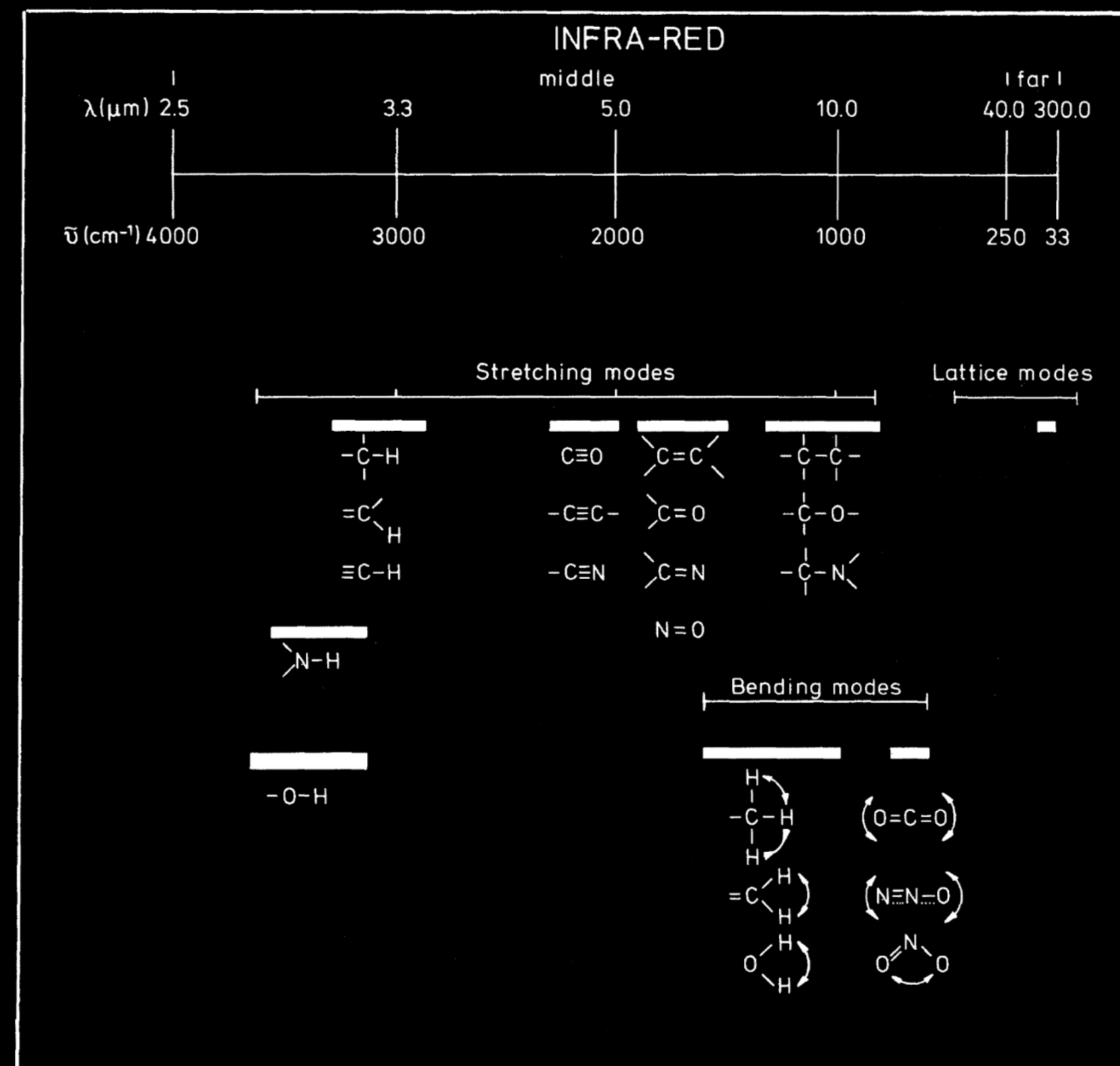
Infrared astronomy

- Fundamental vibrational frequencies for virtually all molecules made up of H, C, N, O are in the infrared.



Allamandola (1984)

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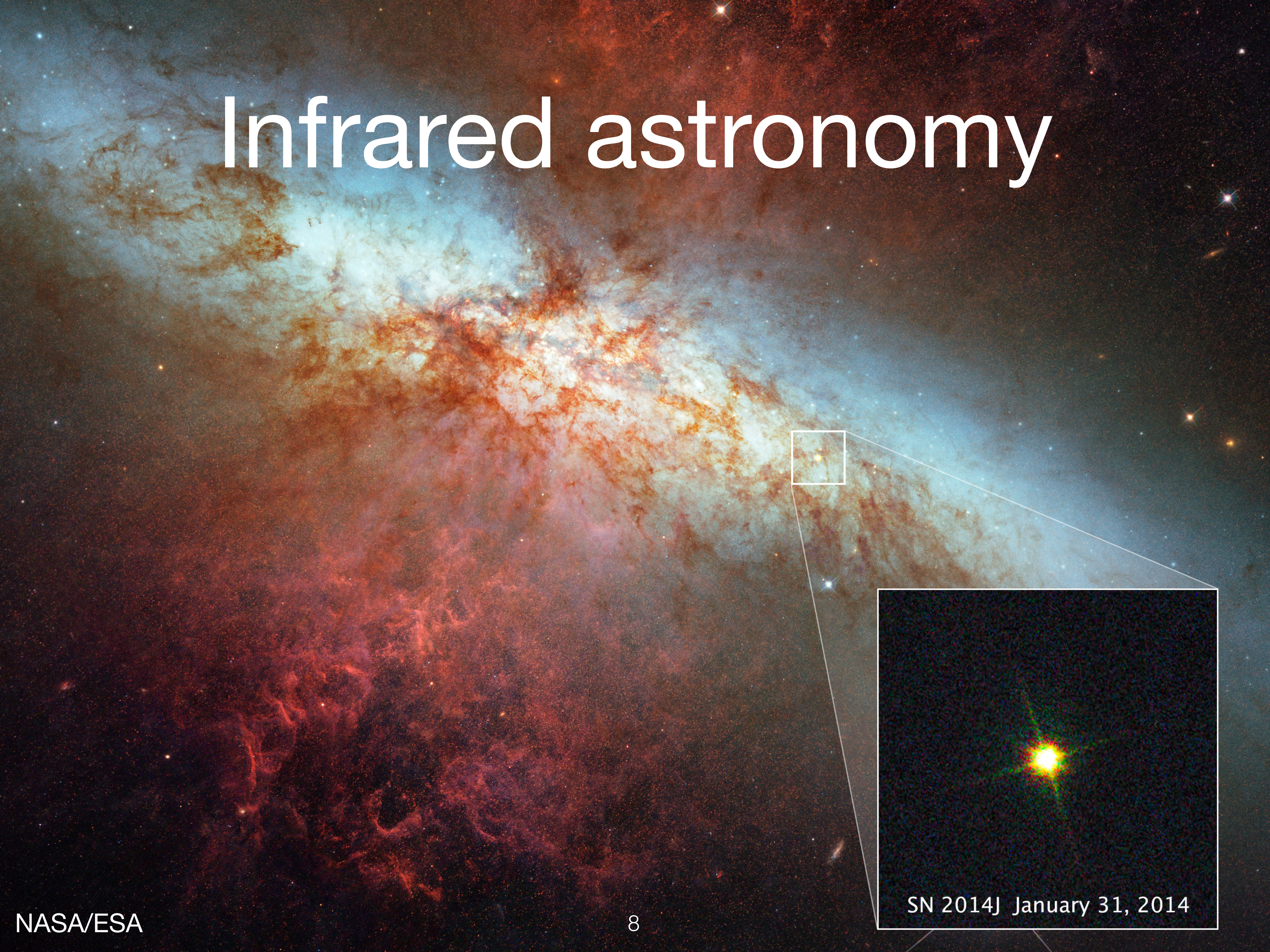
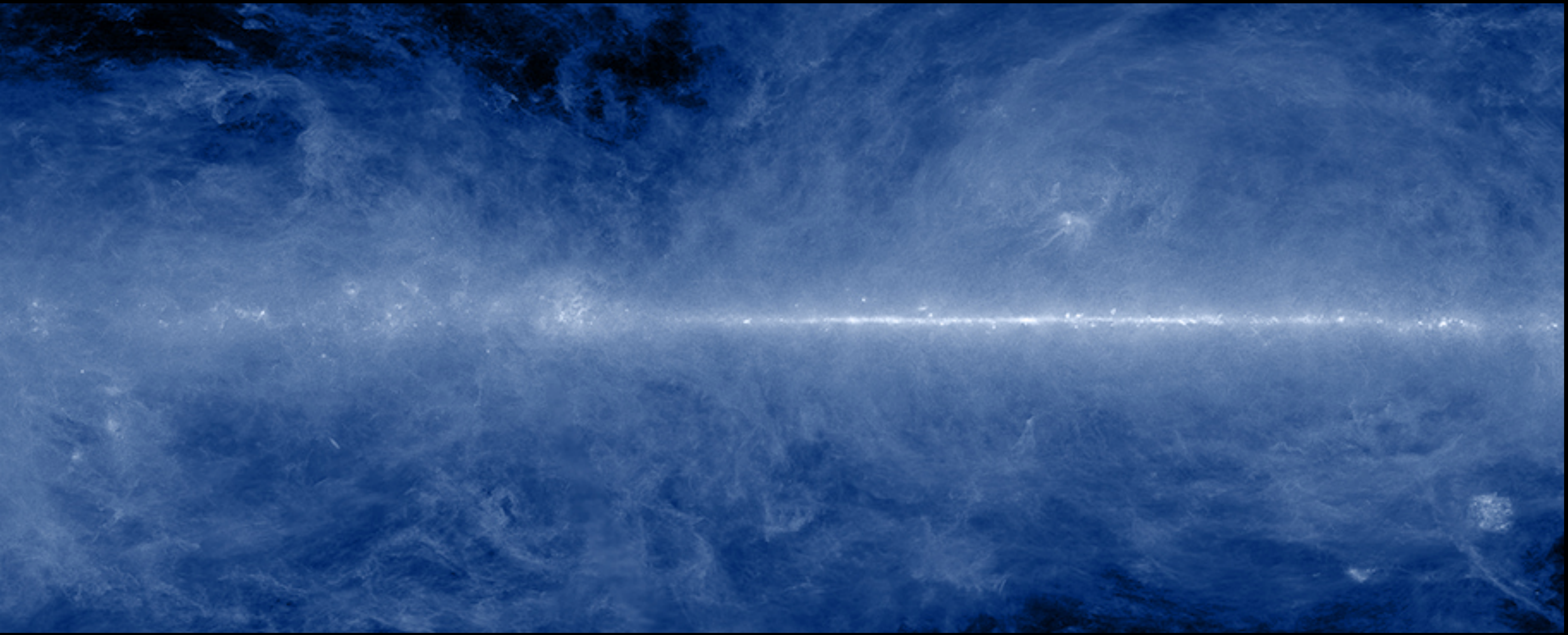
Infrared astronomy



NASA/ESA

Infrared astronomy



IRAS/COBE

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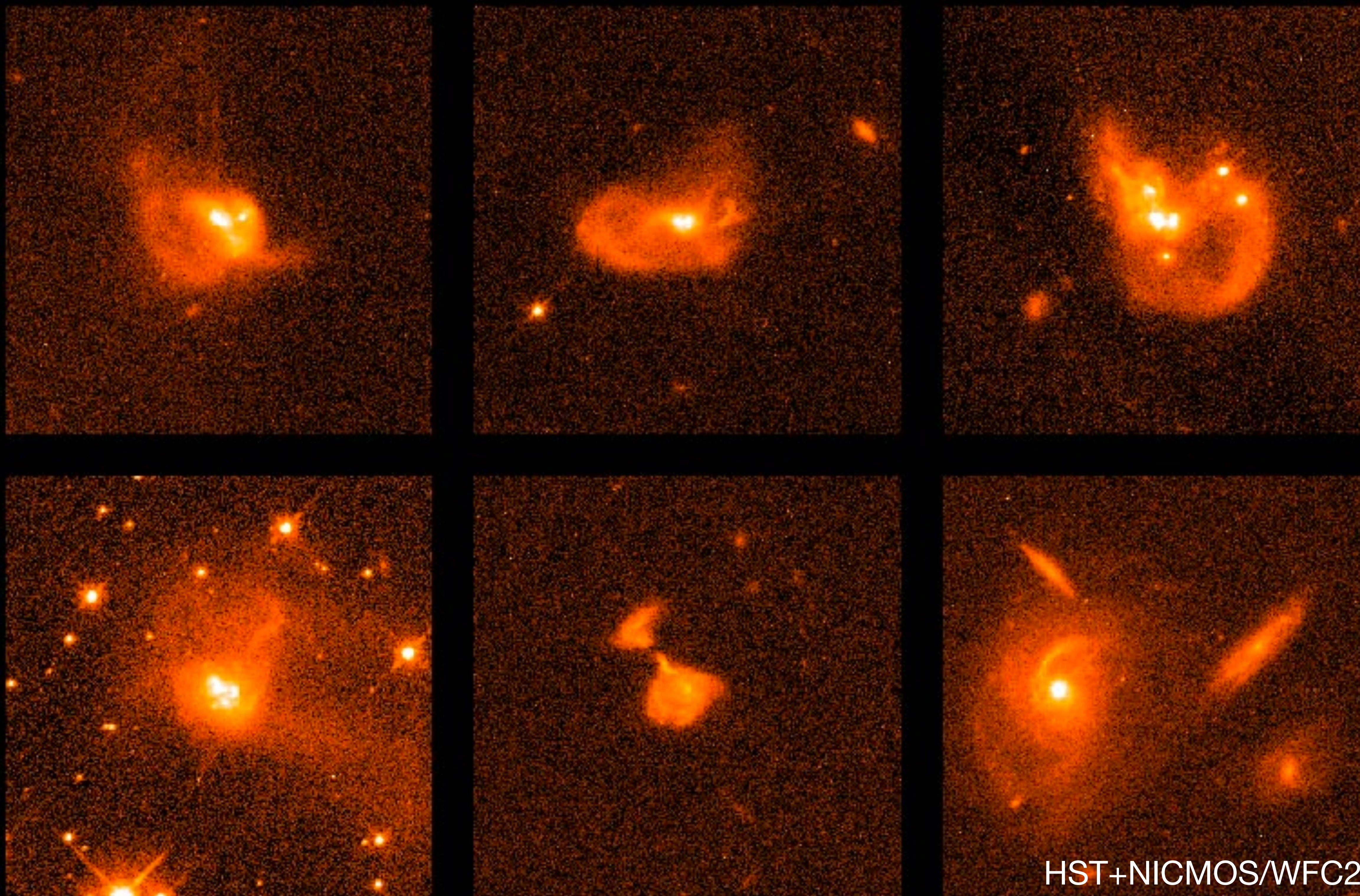
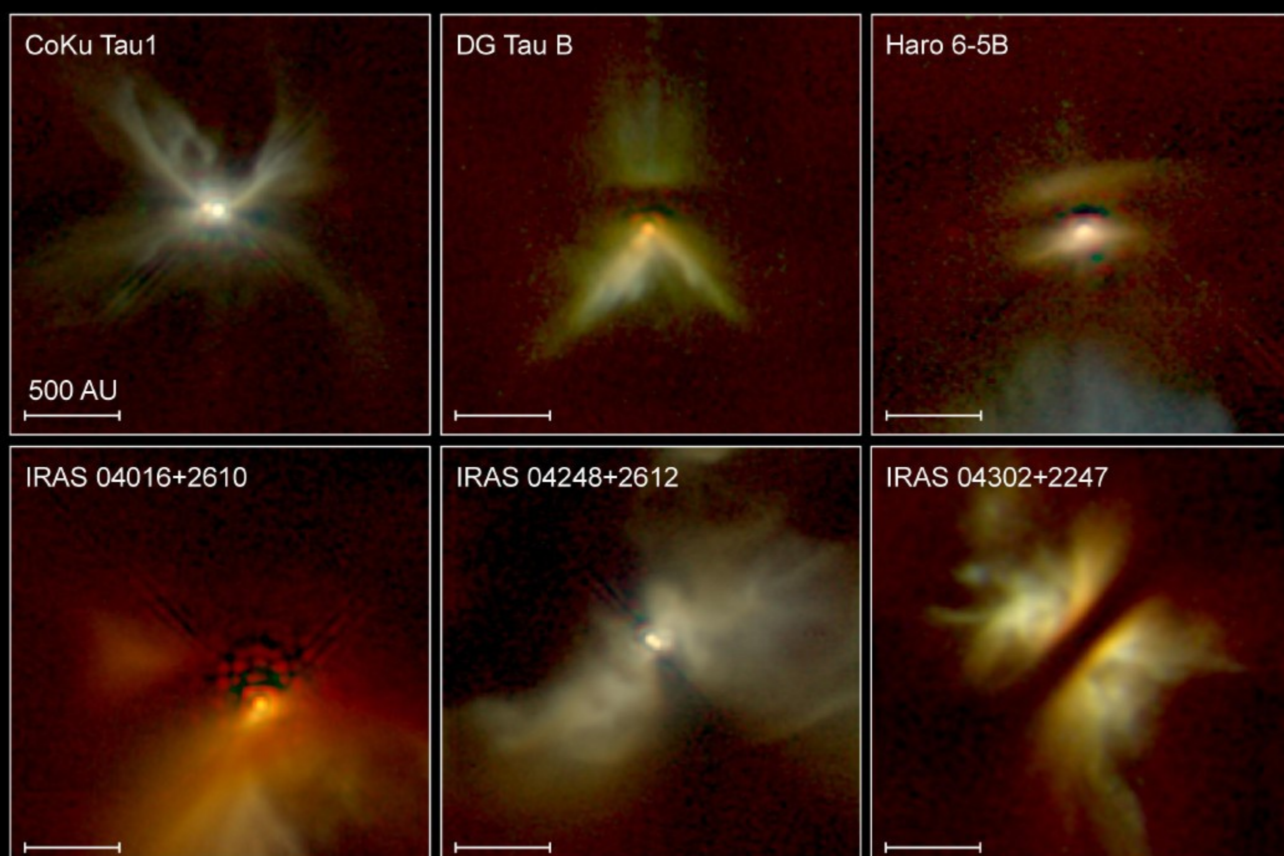
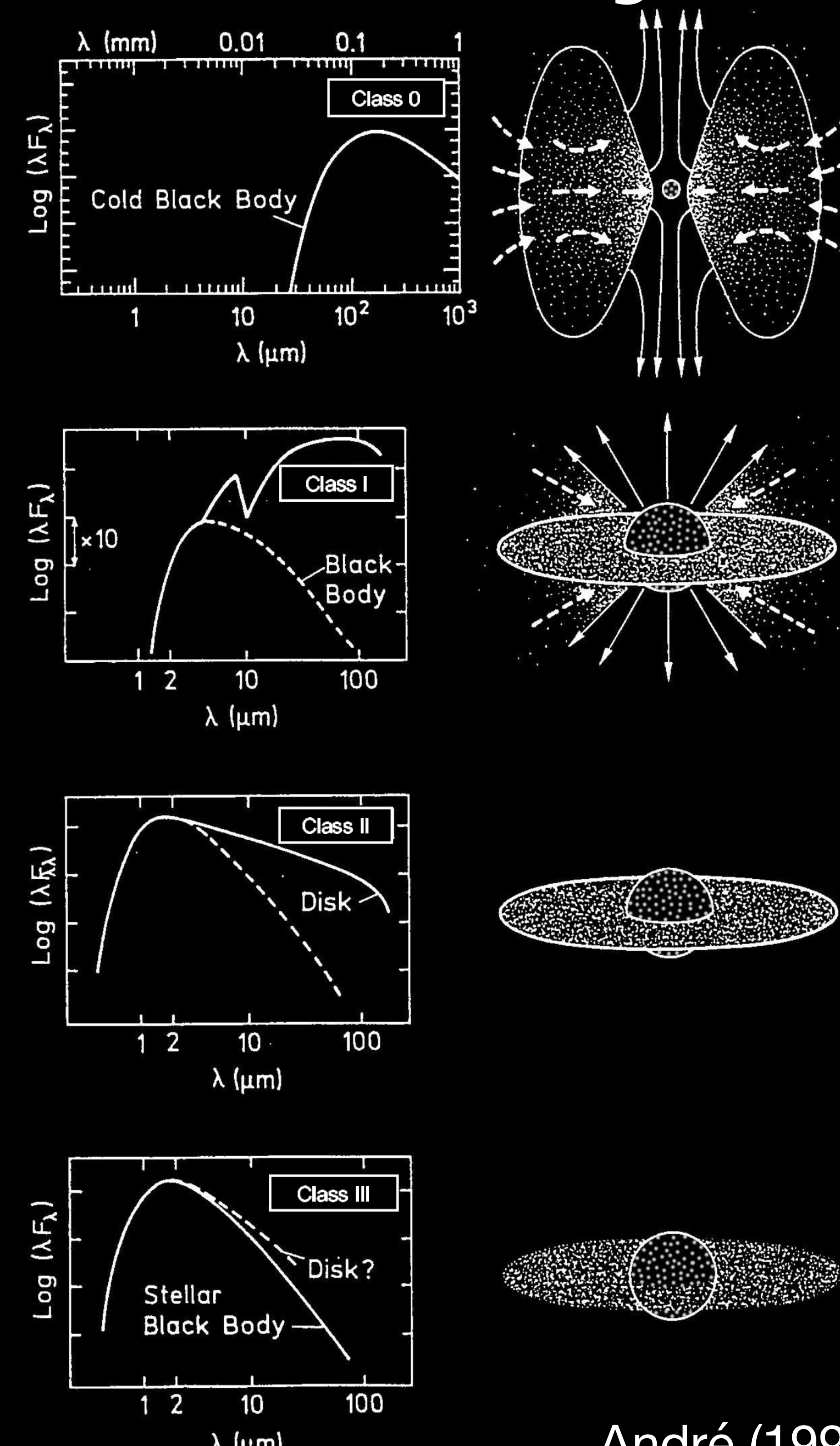
Infrared astronomy



Infrared astronomy



Caltech/IPAC/JPL/NASA



André (1994)

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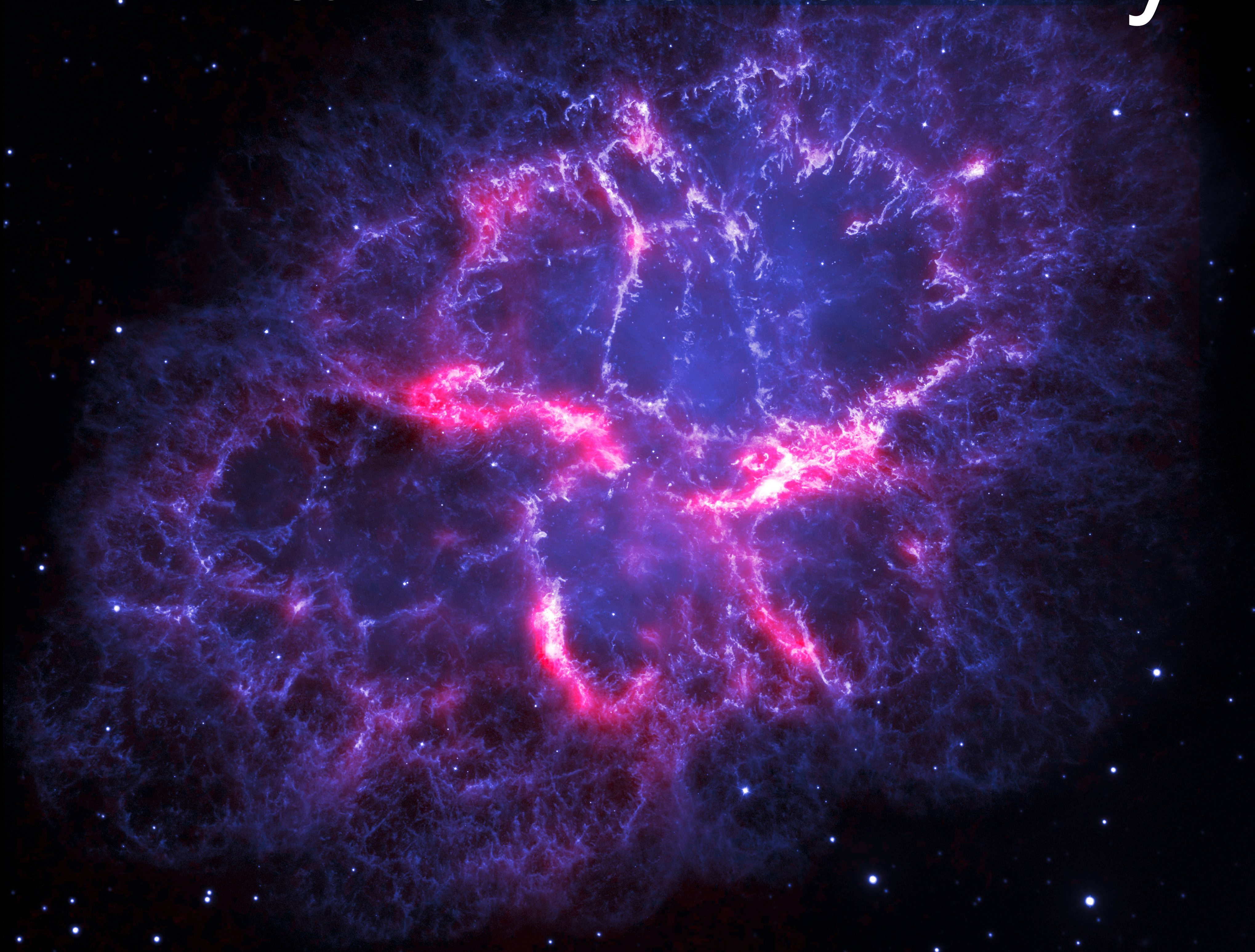
Infrared astronomy



ESA/Herschel

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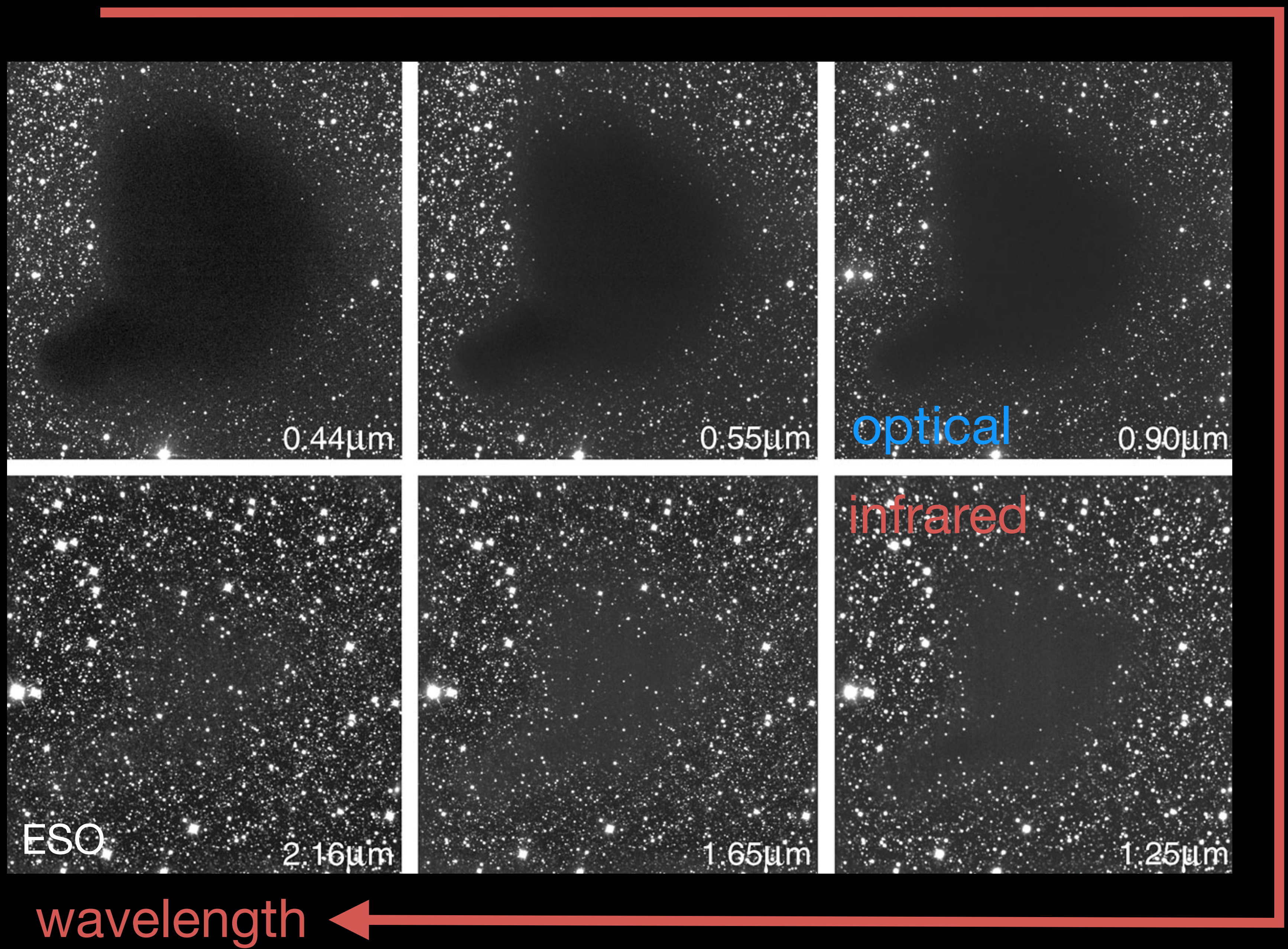
Infrared astronomy



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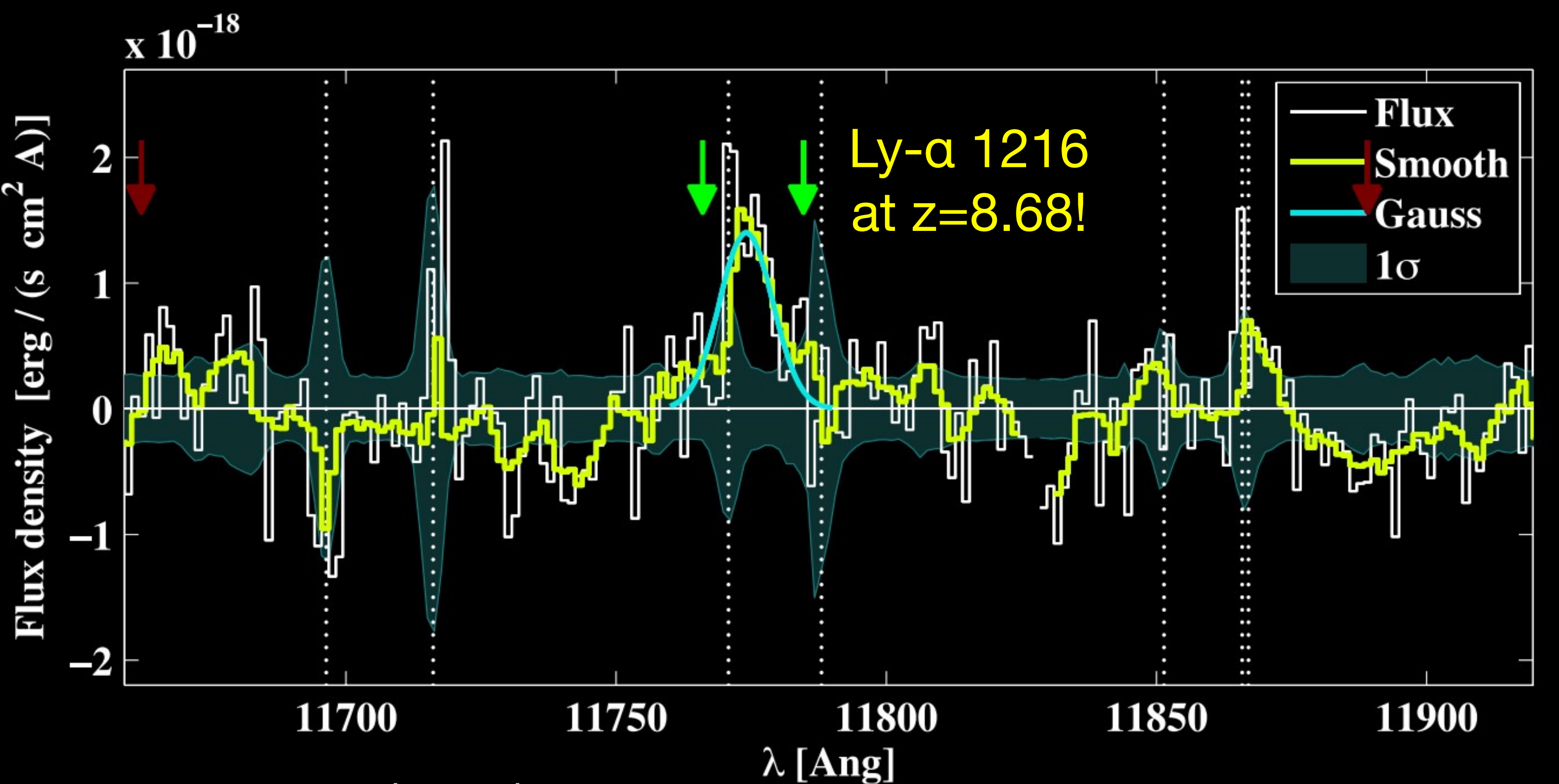
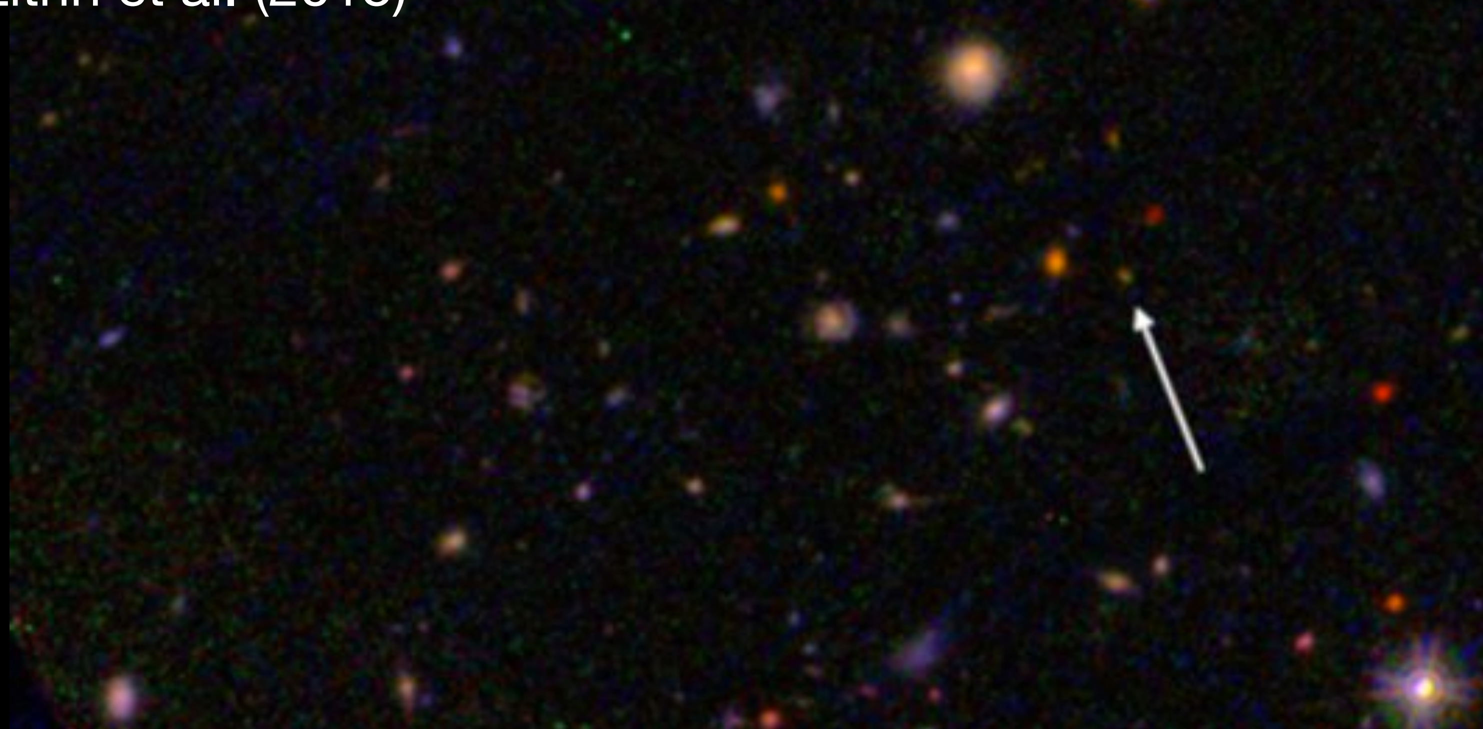
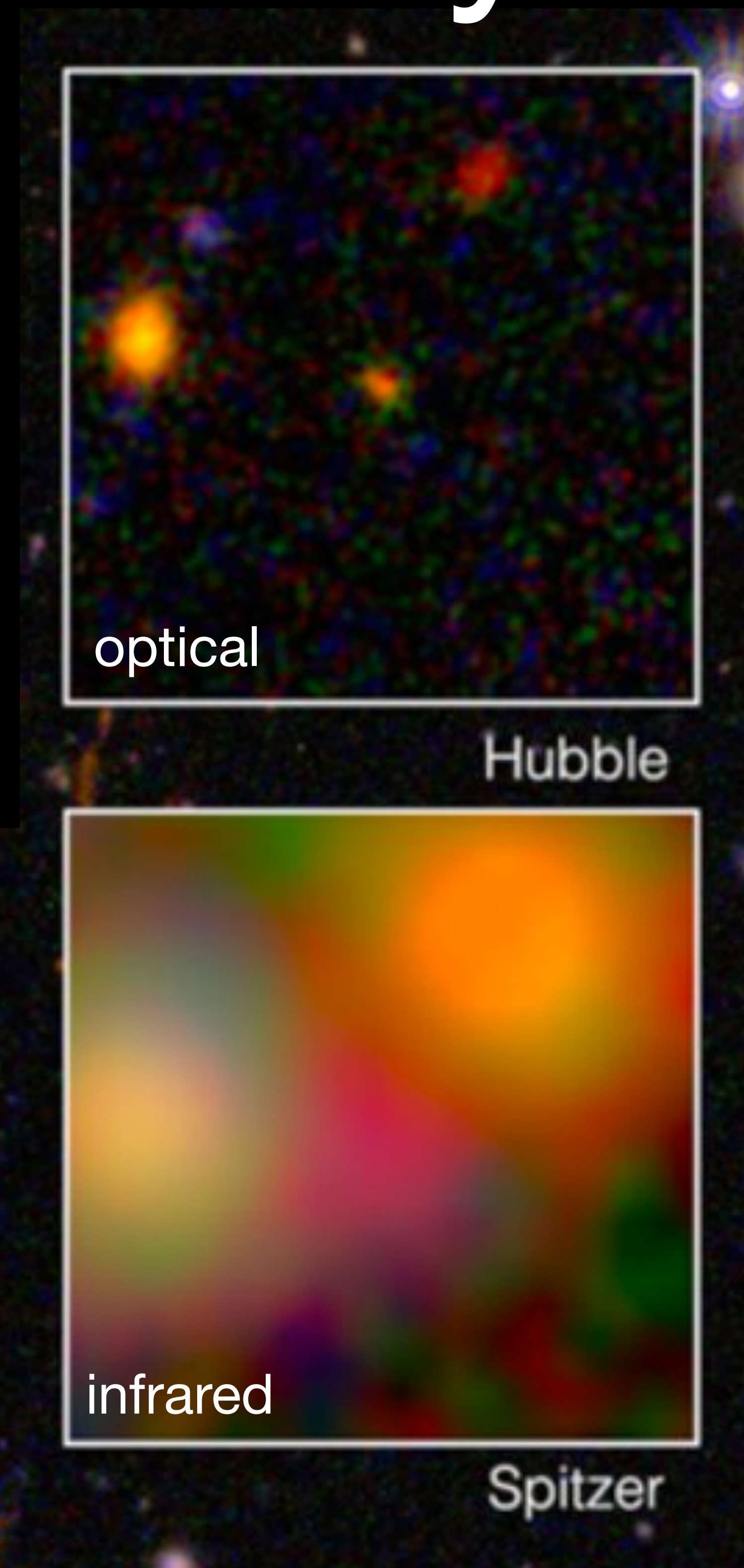
Infrared astronomy



Zitrin et al. (2015)





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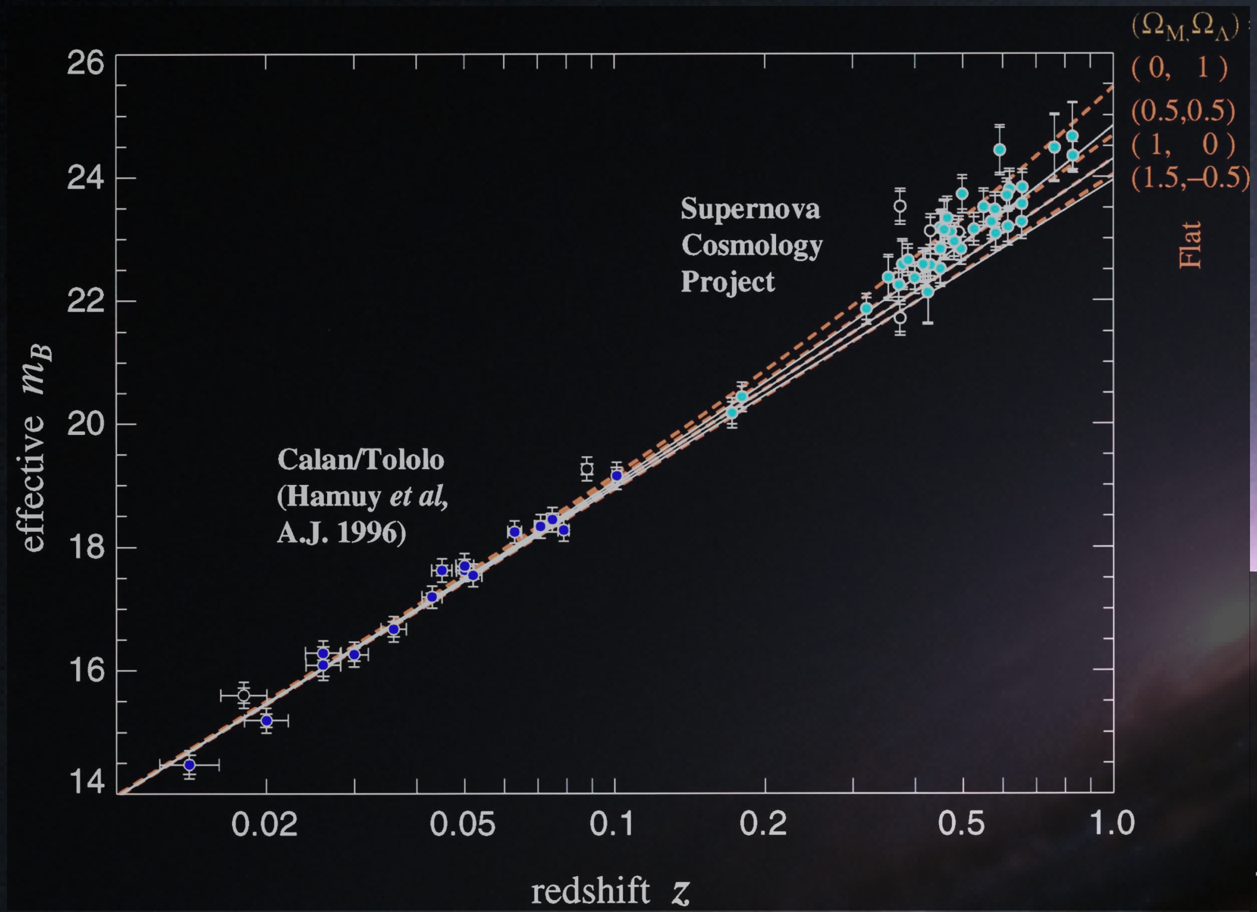
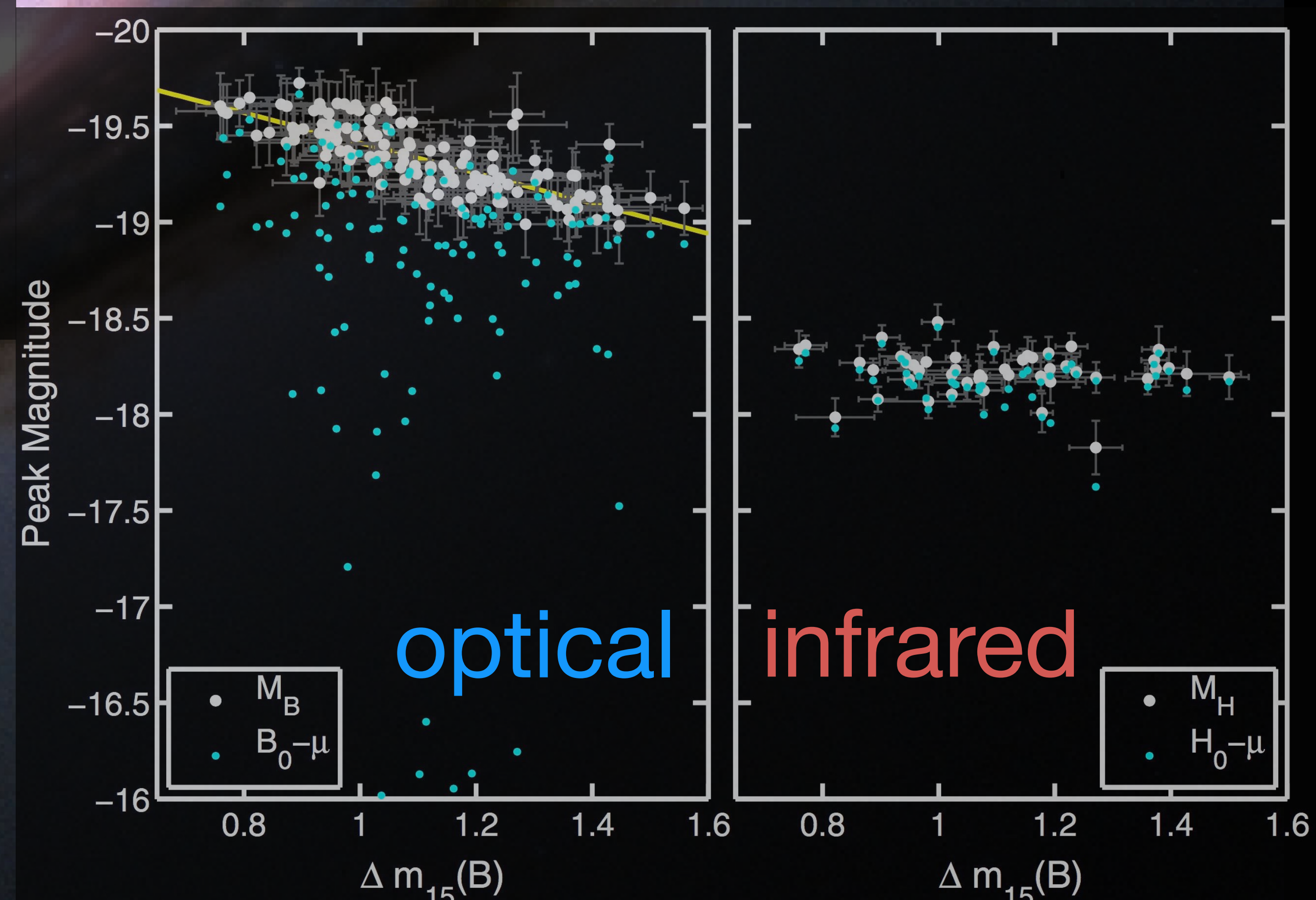
Infrared astronomy



Perlmutter et al. (1999)



Mandel et al. (2011)

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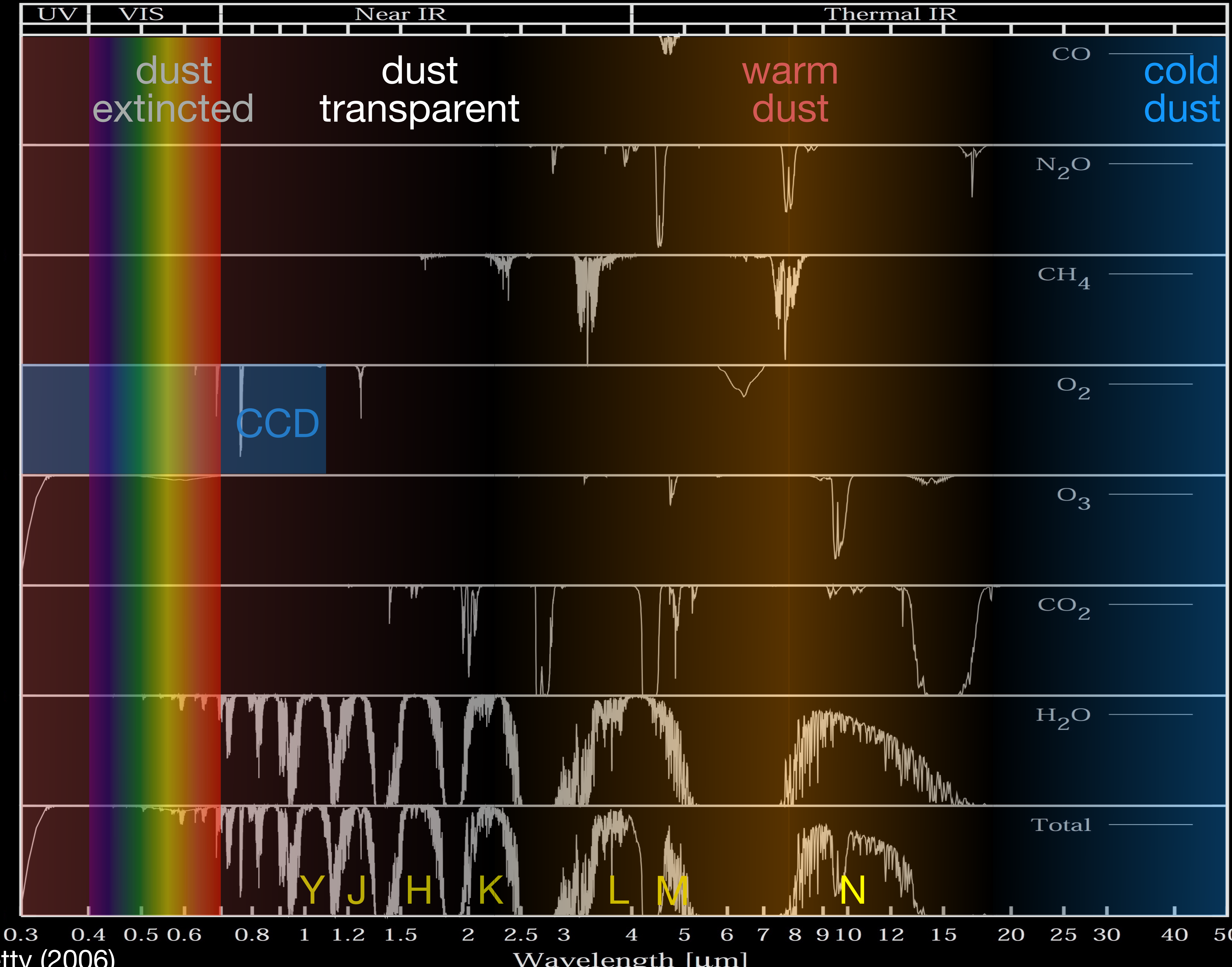

Petty (2006)

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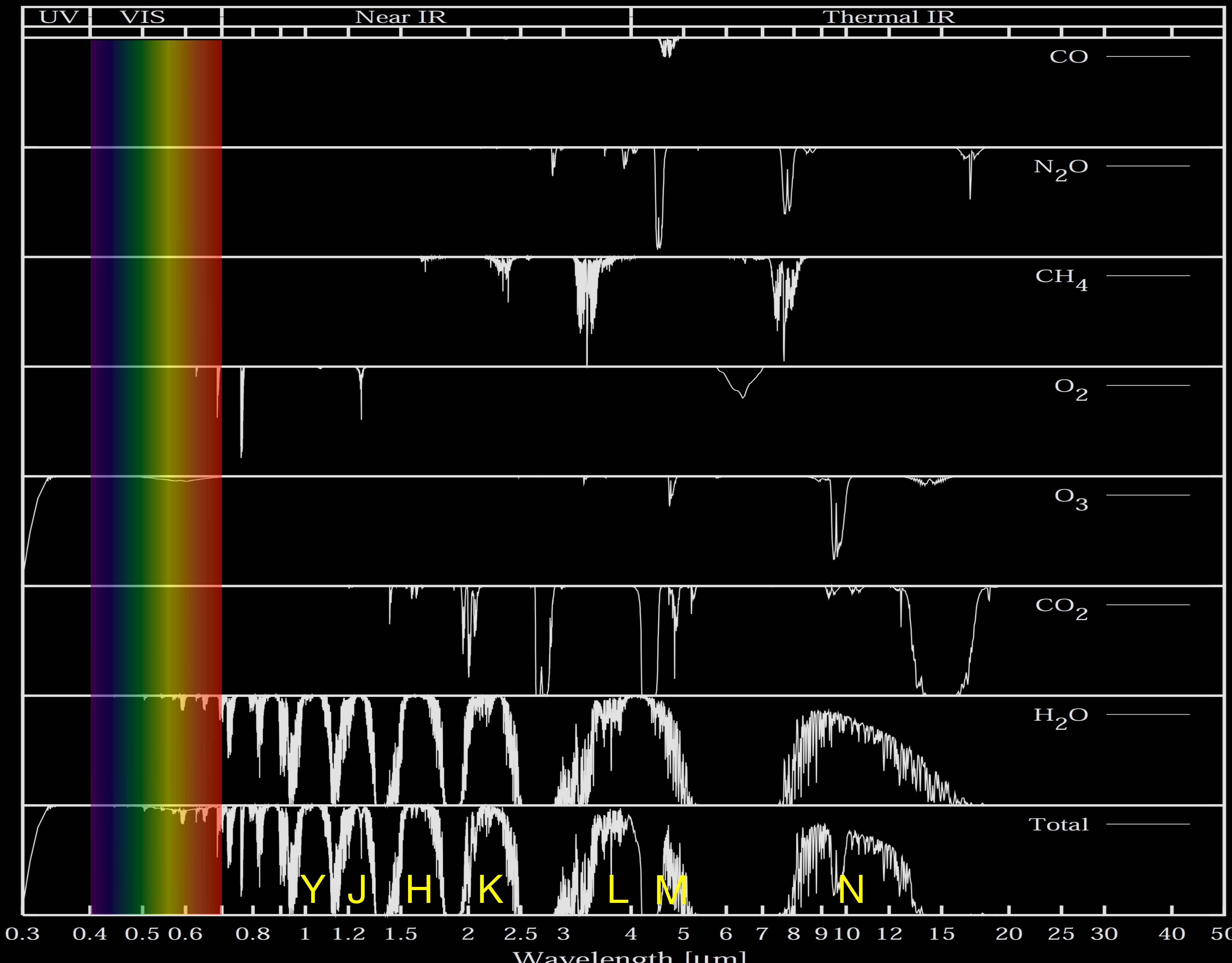
The infrared sky

Water vapor absorption

- H_2O is a main source of atmospheric opacity.
- Varies strongly with temperature.
- Falls off rapidly with altitude.
- The infrared sky is effectively opaque > 26 μm.



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The infrared sky

Airglow emission

- Meinel bands, radiated by OH.
- High up in the atmosphere.
- The strength varies with location and time.
- Can be used for wavelength calibration.

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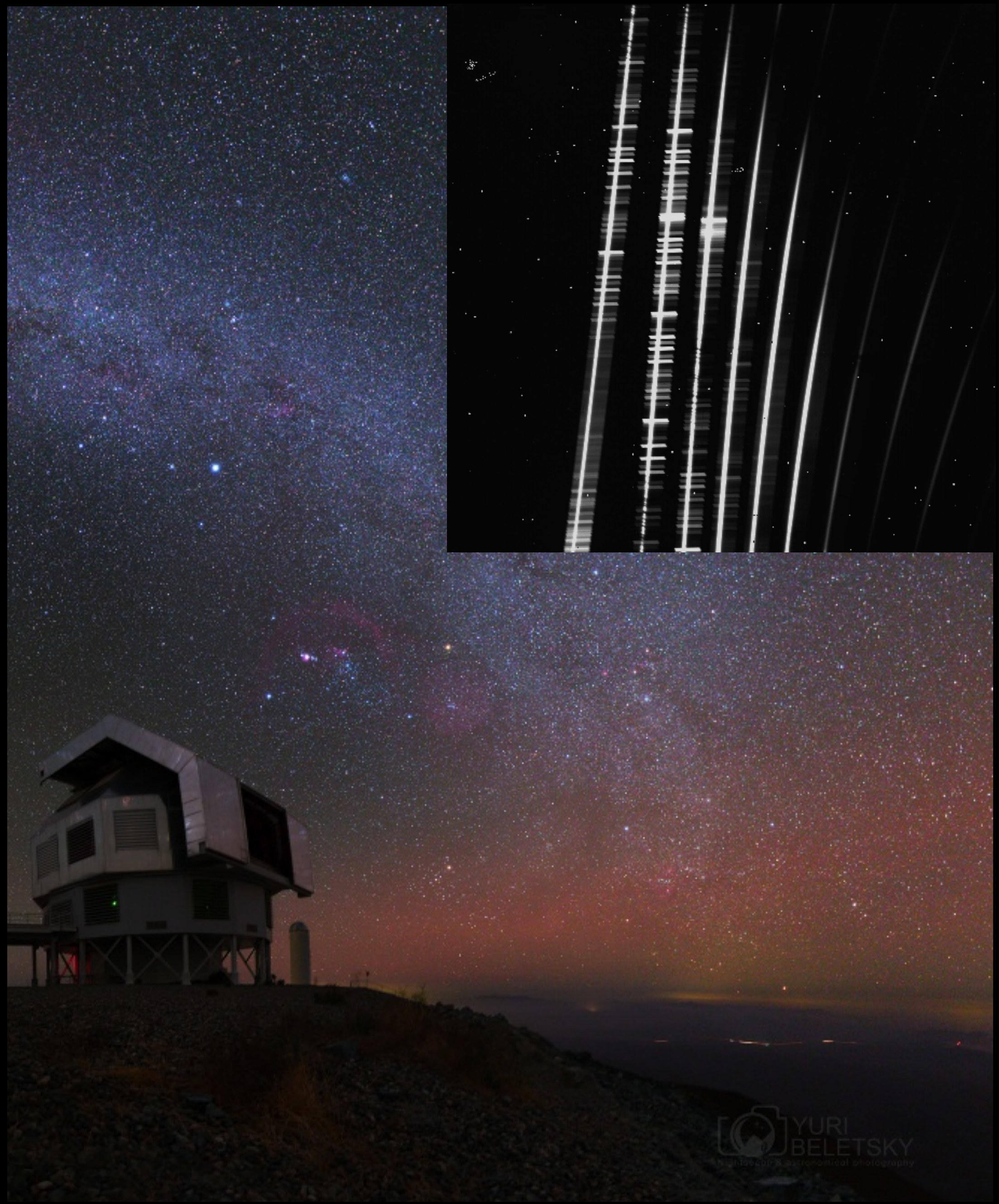

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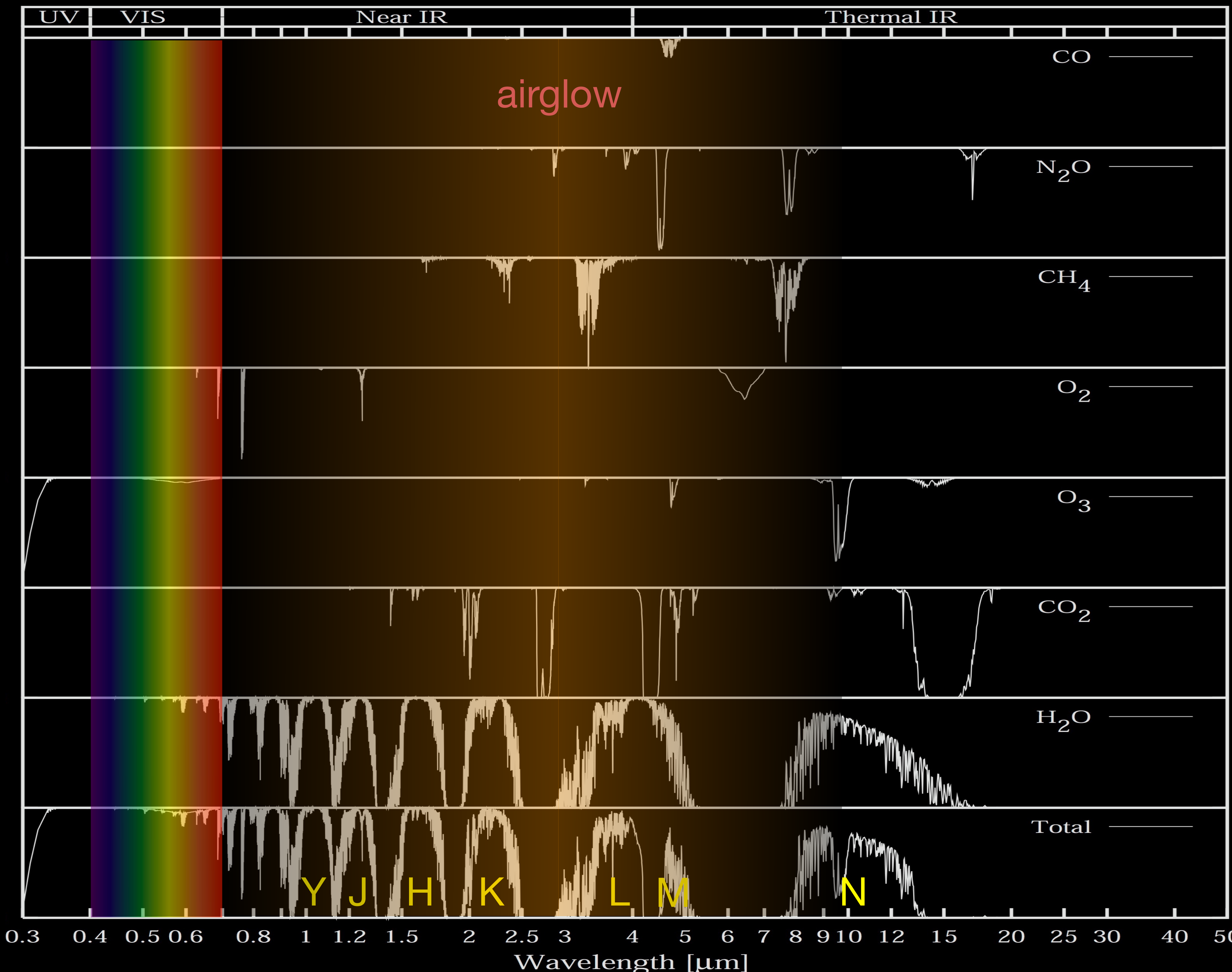

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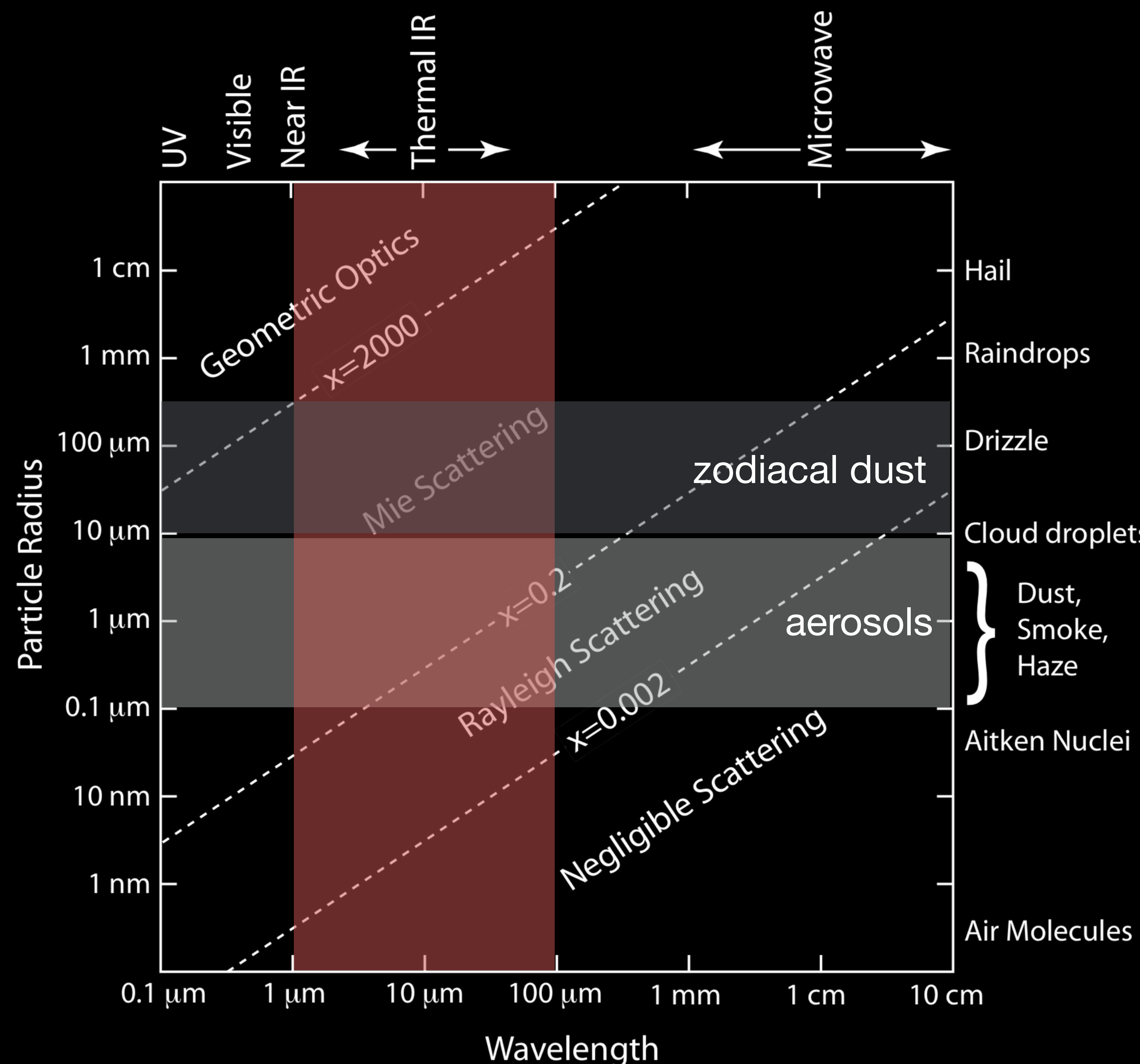
The infrared sky

- Rayleigh scattering of air molecules is negligible in the infrared.
- Aerosols and zodiacal dust scatter in the Mie regime.



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The infrared sky

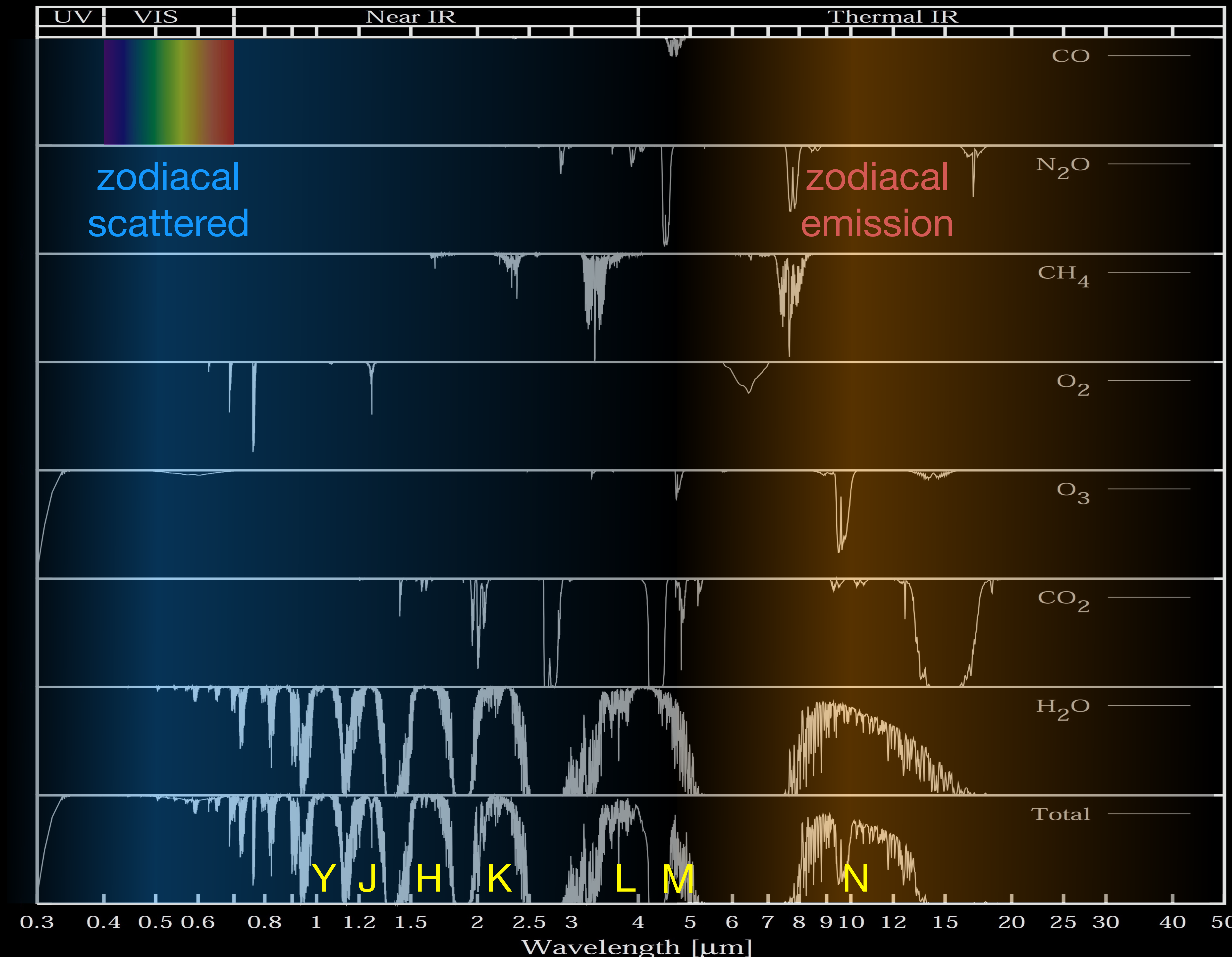
Aerosol scattering

- Mie scattering by sea salt, volcanic, and desert aerosols has weak dependence with wavelength.
- Aerosols live high up in the atmosphere.

The infrared sky

Zodiacal light

- Come from dust associated with the solar system.
- Two components:
  scattered light,
  warm dust emission.



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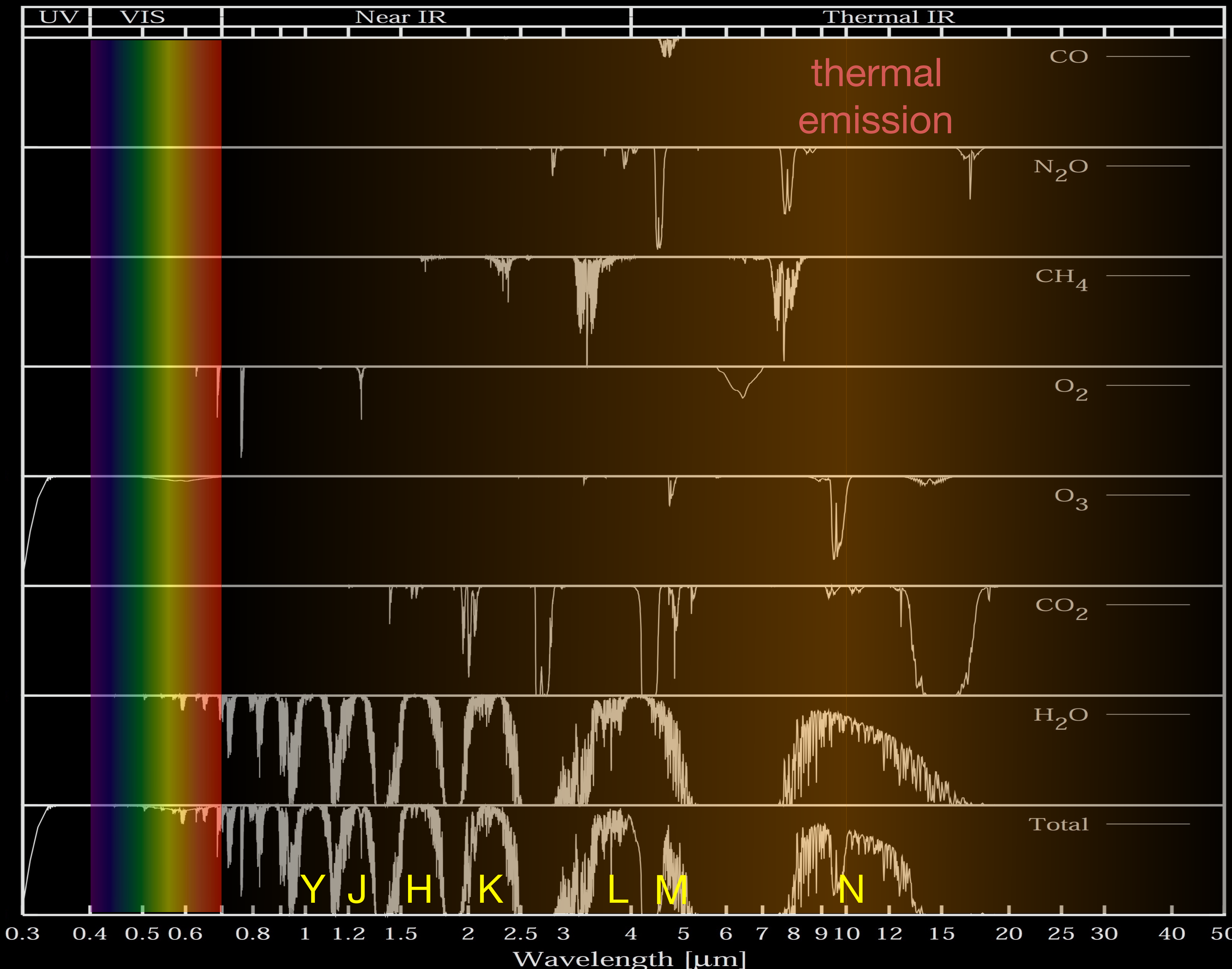
The infrared sky

Terrestrial sources

- 273 K blackbody corresponds to 10 μm peak.
- Detectors need to be cooled.
- Support structures and surfaces often coated with gold.



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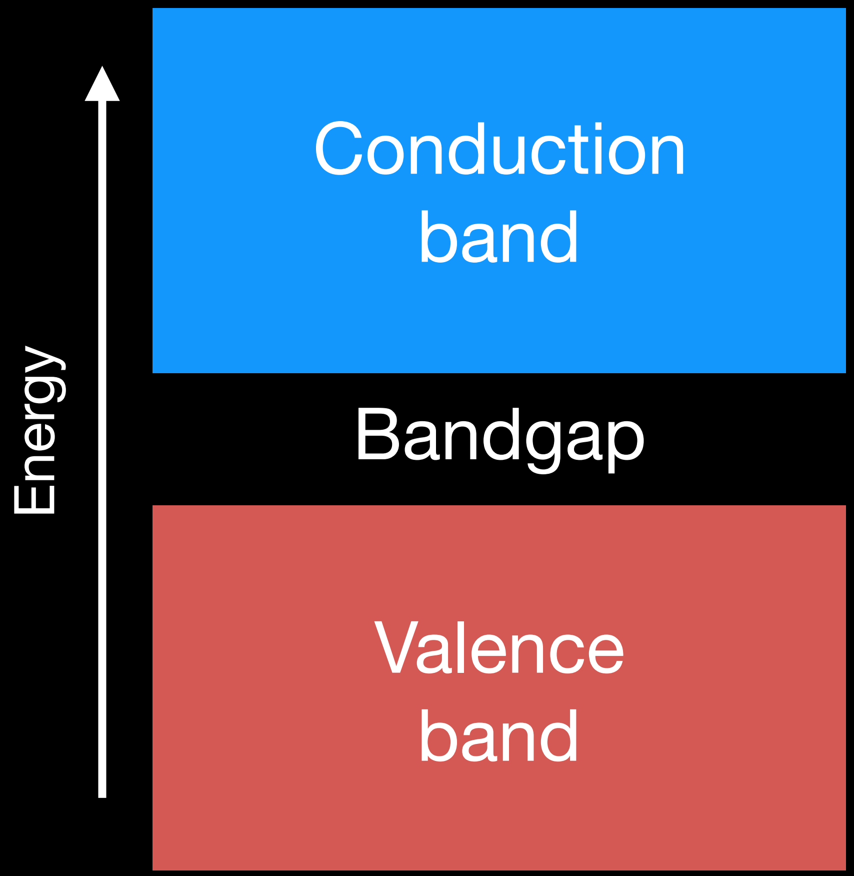
Infrared detectors

- Optical CCD detectors and infrared detectors are semiconductors.
- Operate on the excitation of electrons from an immobile to a free-moving energy band.
- The bandgap determines the minimum energy required for the incident photons.



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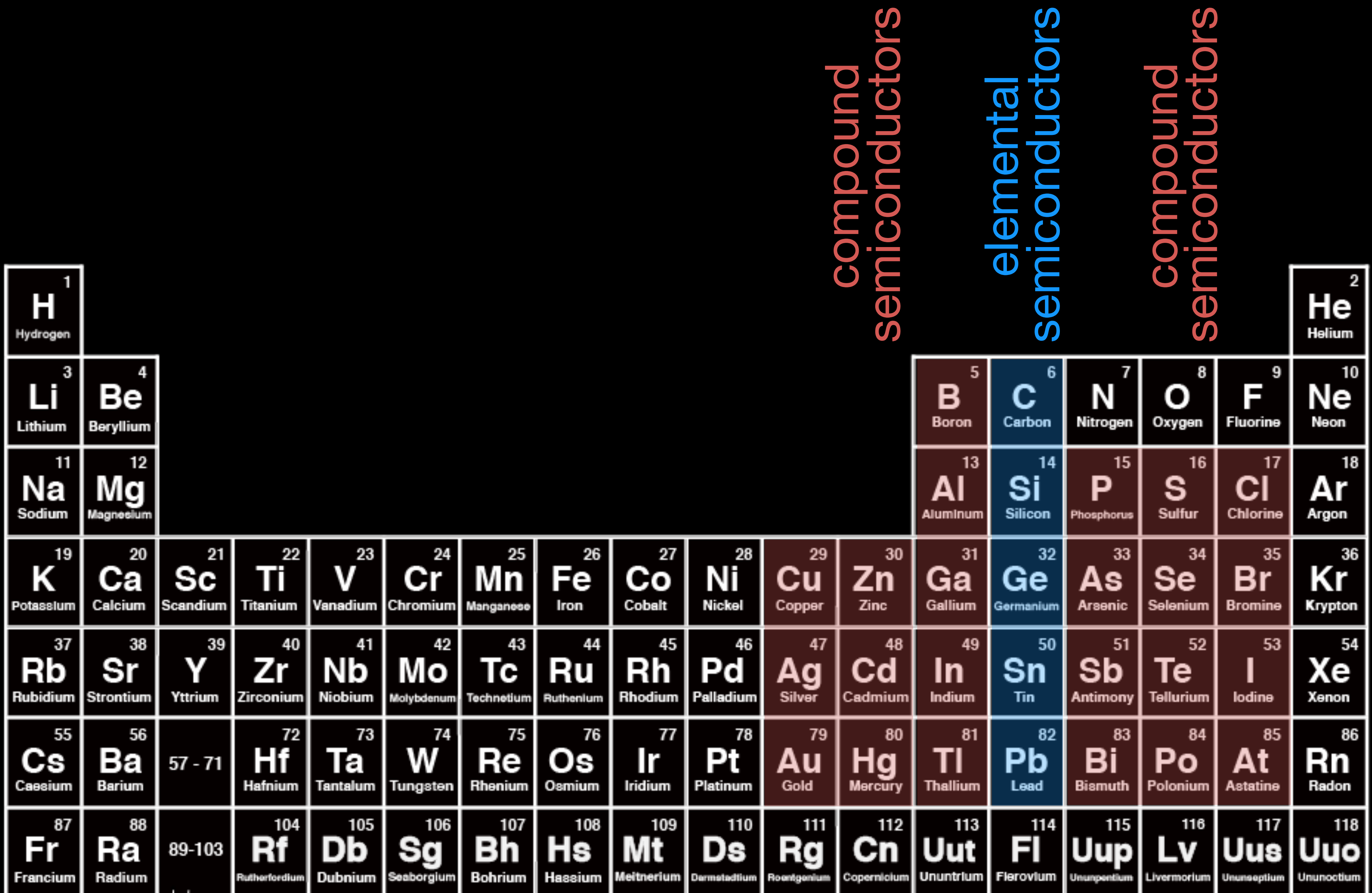
Infrared detectors



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Infrared detectors

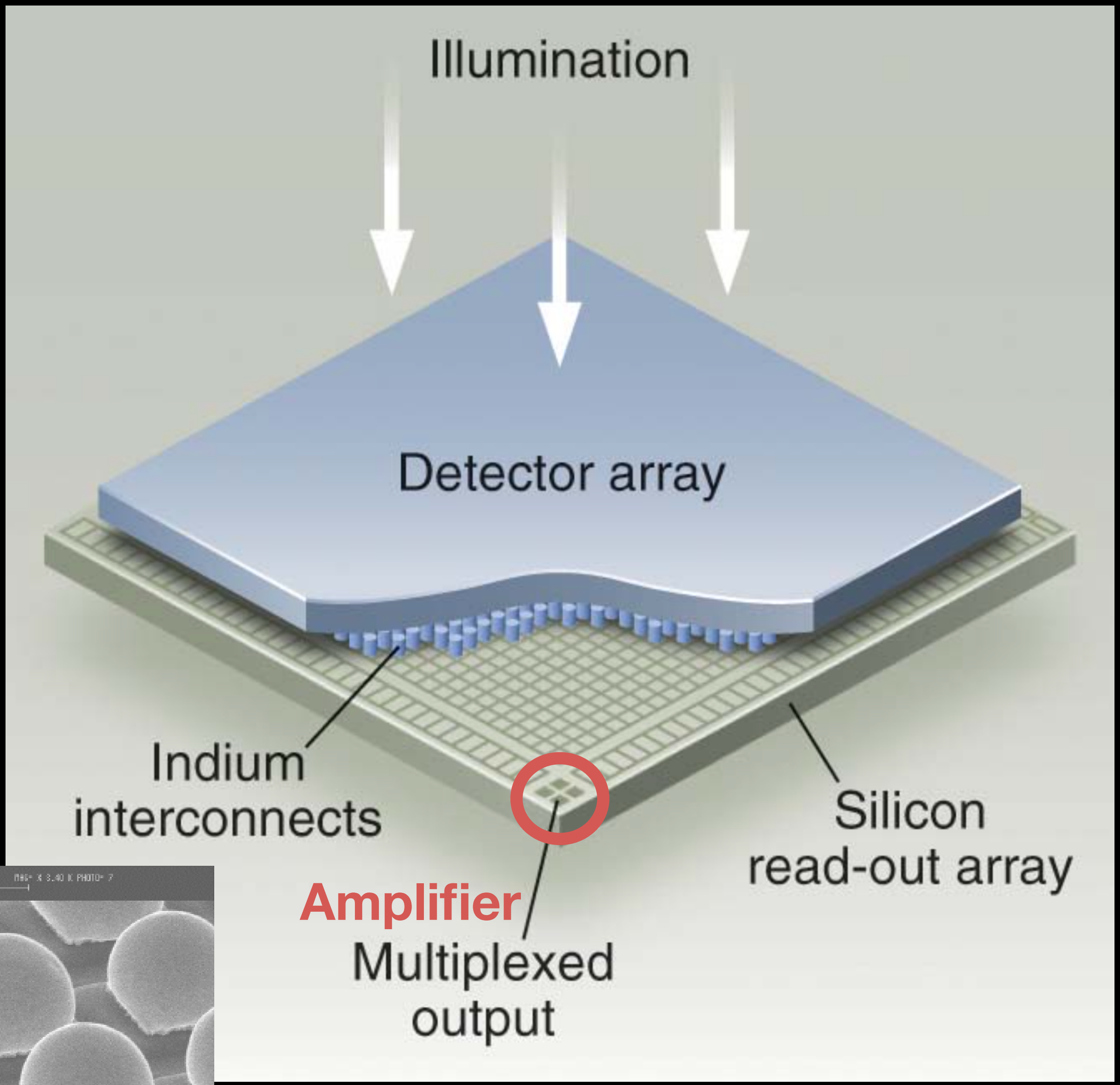
- Minimum energy for the bandgap jump translates to a maximum wavelength cutoff.
- Infrared detector materials have smaller bandgap than Si.
- Can tune the bandgap by changing the ratio of Hg/Cd in HgCdTe detectors.
- Smaller bandgaps means larger <u>dark current</u>.

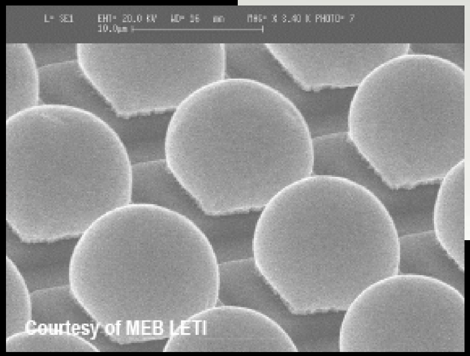
Material	Temperature (K)	Cutoff wavelength (μm)
Si	295	1.11
Ge	295	1.85
InSb	77	5.4
InGaAs	77	2.6
HgCaTe	77	1.2—18
Si:As	5	23
Si:Sb	5	36
Si:Ga	10	17.5
Ge:Ga	10	115

Glass (1999)

Infrared detectors

- Because readout electronics are Si-based, infrared detectors have largely adopted the two-layer, CMOS architecture.
- Detector layer is connected to the Si readout layer by "indium bumps."





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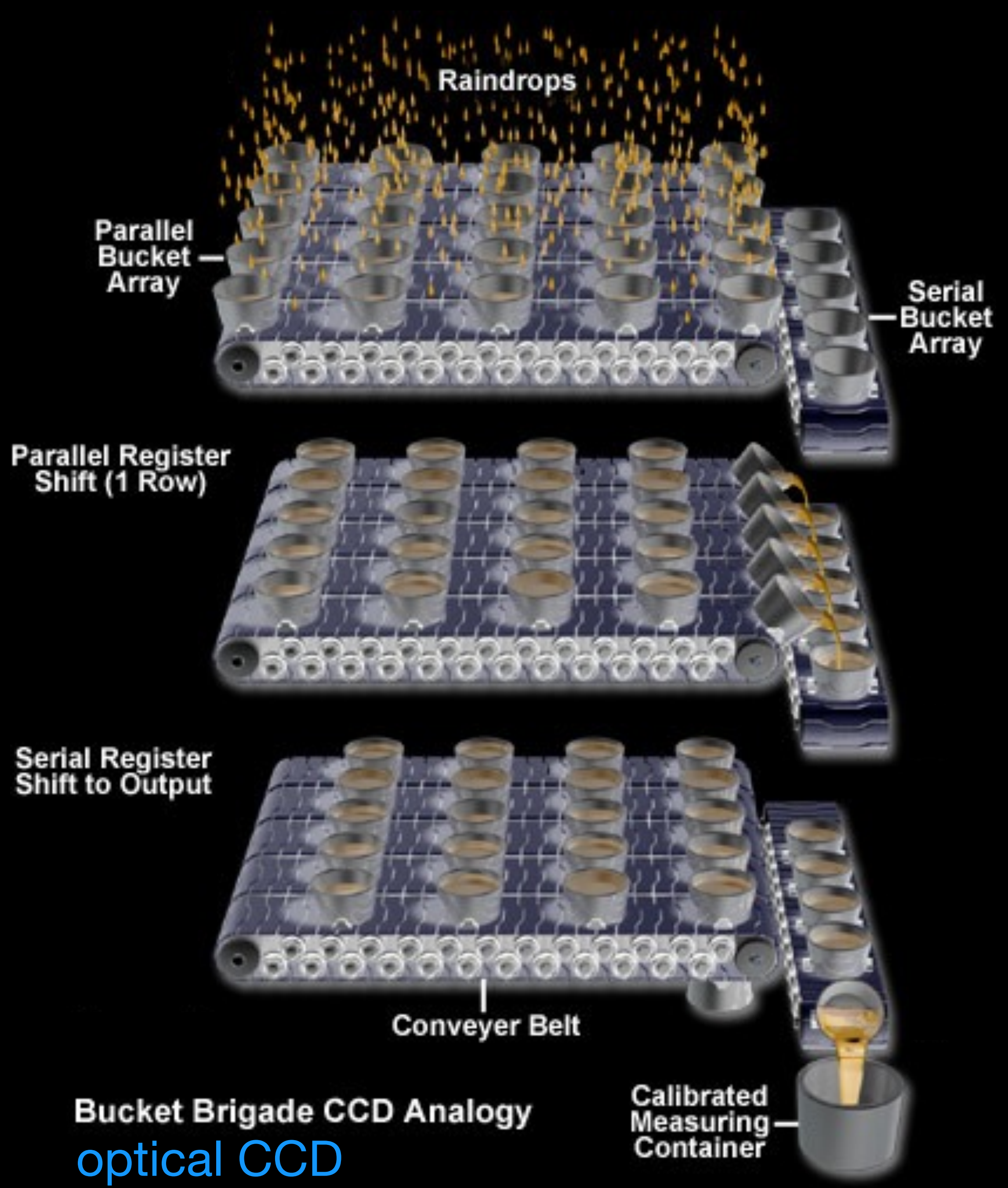
Infrared detectors

- The readout of CCD for optical light works like "bucket brigade."
- Parallel register shifts a row of charges into the serial register.
- Serial register then transfer charges sequentially to amplifier.
- Repeat.



optical CCD

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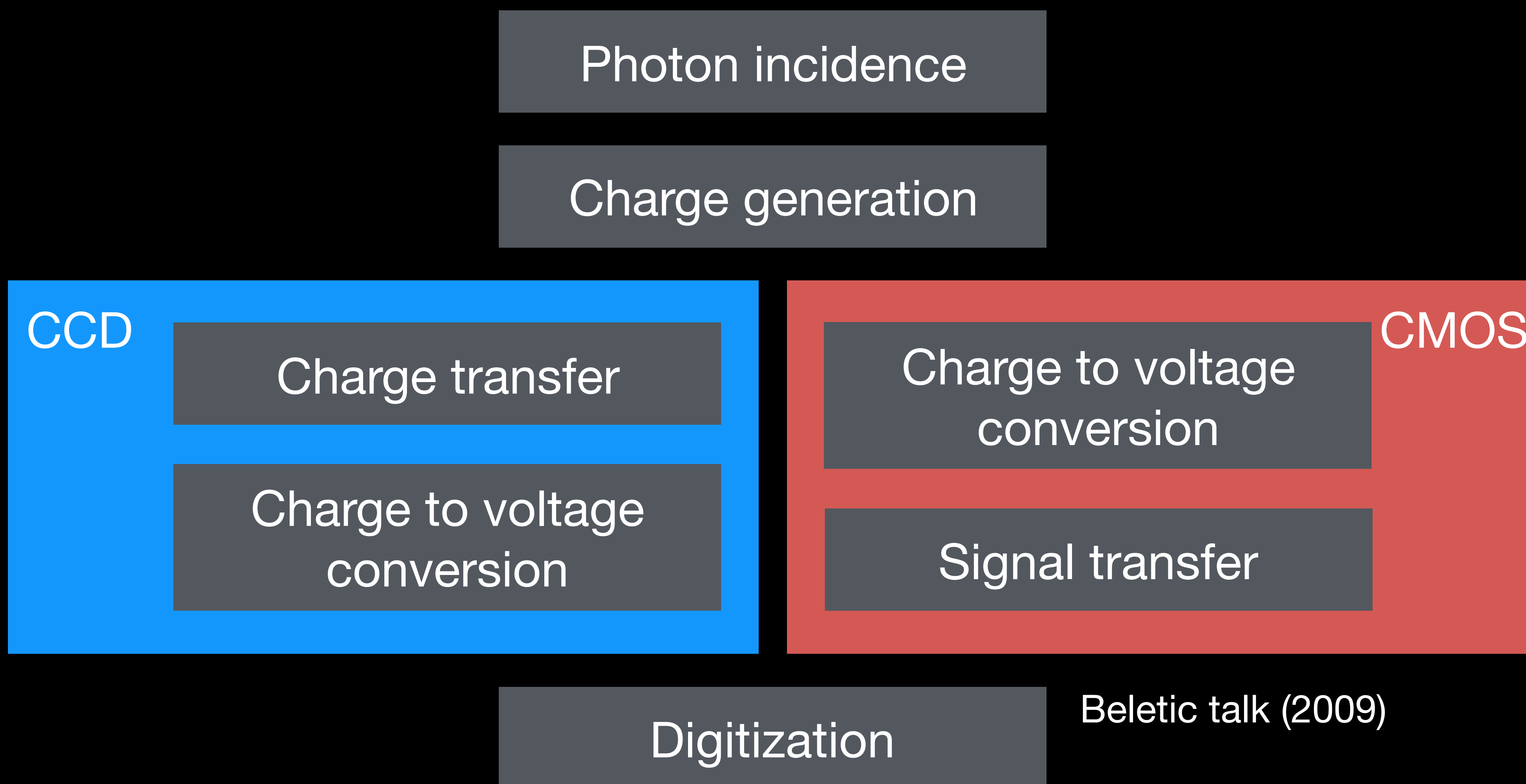
Infrared detectors



Beletic talk (2009)

Infrared detectors

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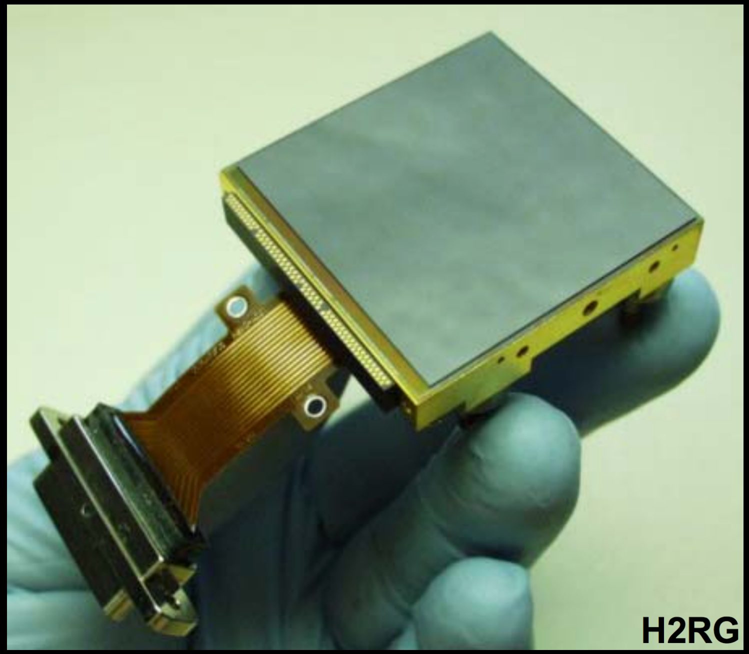
Advantages

- No mechanical shutter needed.
- Readout is nondestructive.



Disadvantages

- Pixel-level charge-to-voltage conversion causes higher readout noise.
- Signal accumulates with slight nonlinearity.
- Readout amplifier glows in the infrared.
- Individual signal paths cause pixel-to-pixel bias jumps.
- Discharging trapped electrons and holes is slow which causes persistence.

Infrared observations

optical	infrared	data reduction
Bias subtraction		imaging
	Sky subtraction	imaging
	Dark subtraction	imaging
Flat field division	Flat field division	imaging
Spectrum extraction	Spectrum extraction	spectroscopy
(Telluric correction)	Telluric correction	spectroscopy
Wavelength calibration	Wavelength calibration	spectroscopy

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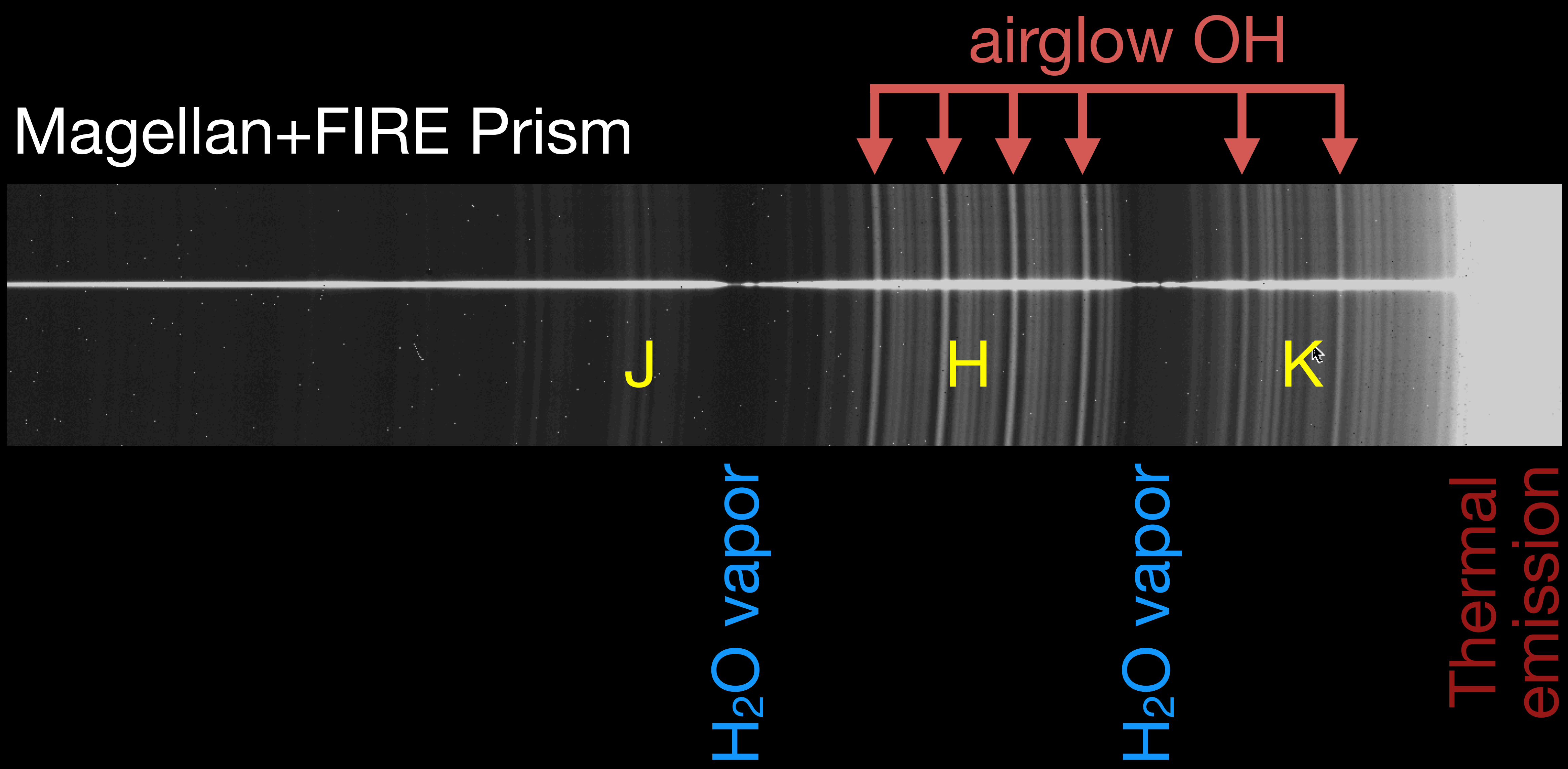
Infrared observations



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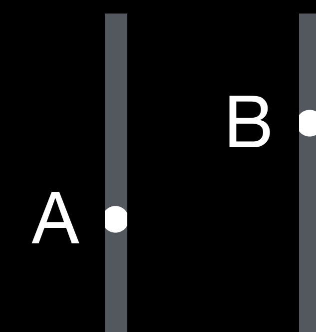
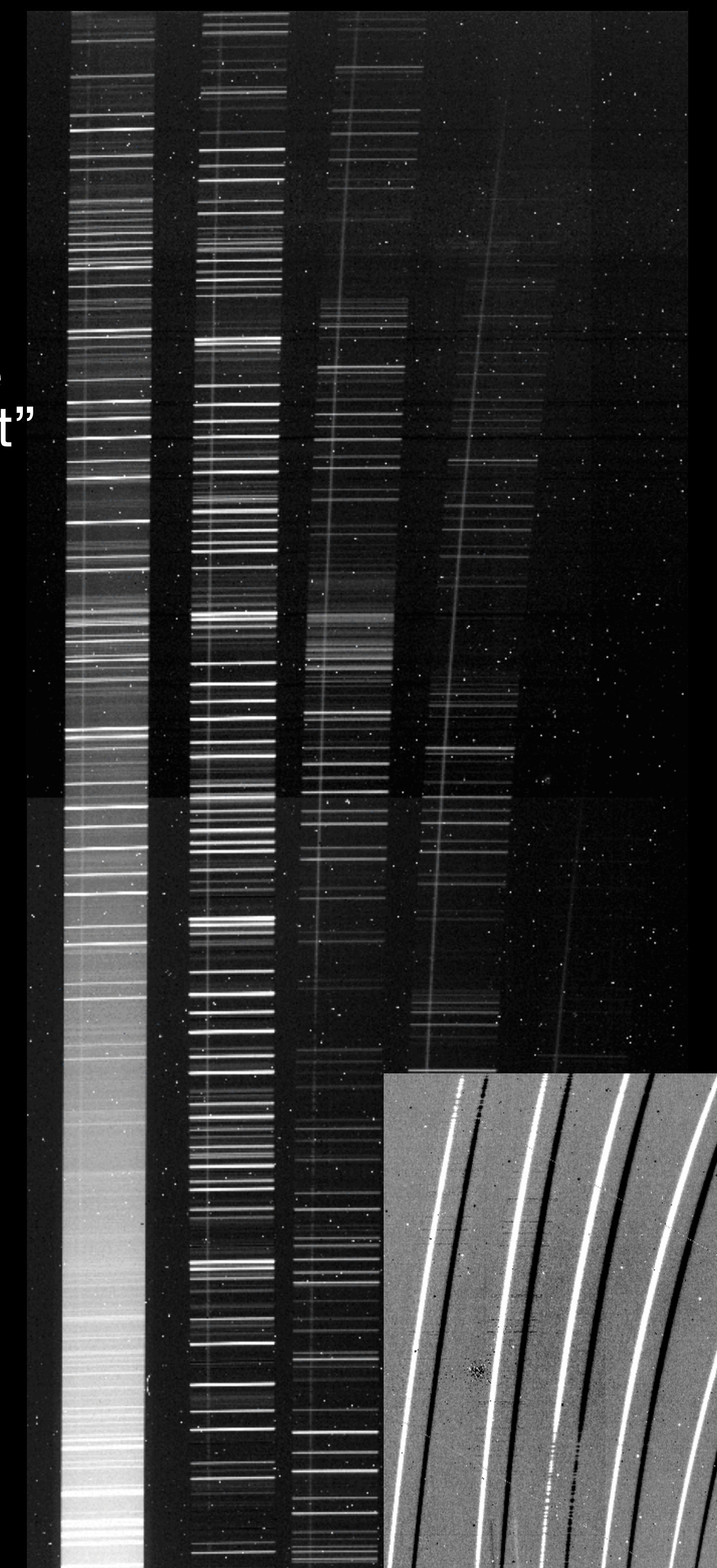
Infrared observations

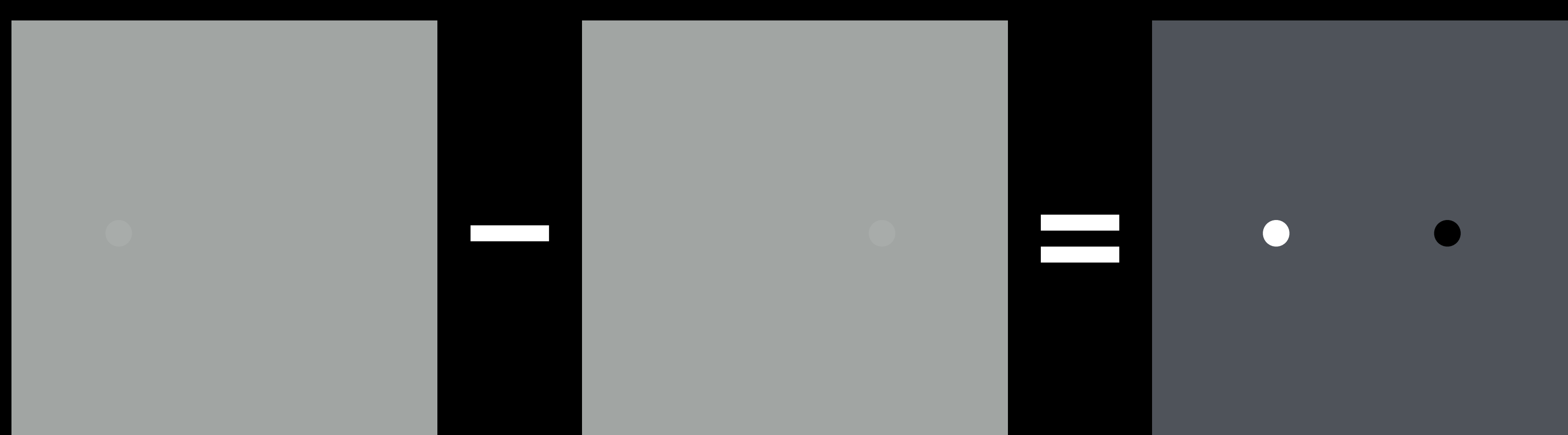
Nodding and dithering

- Remove airglow and thermal emissions by practicing the nodding (spectroscopy) and dithering (imaging) techniques.



ABBA sequence
"nod along the slit"





dithering

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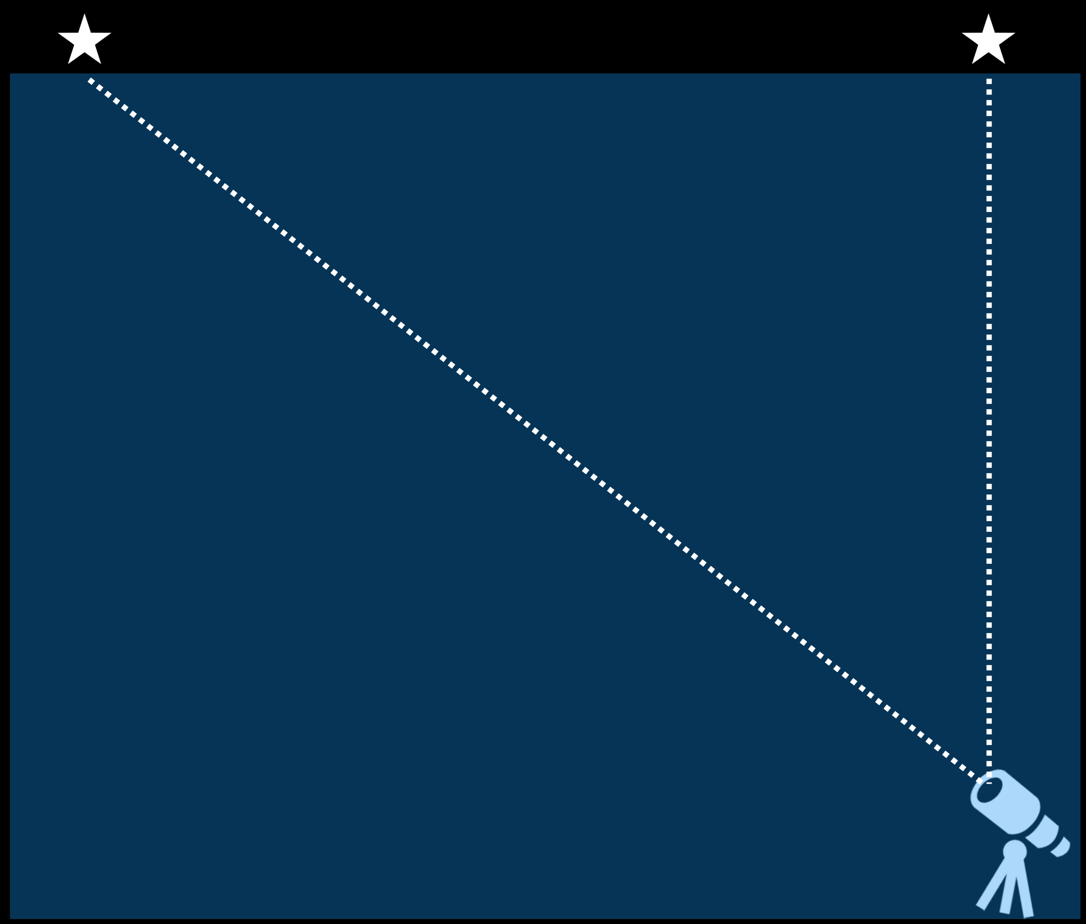
Infrared observations

Photometric standards

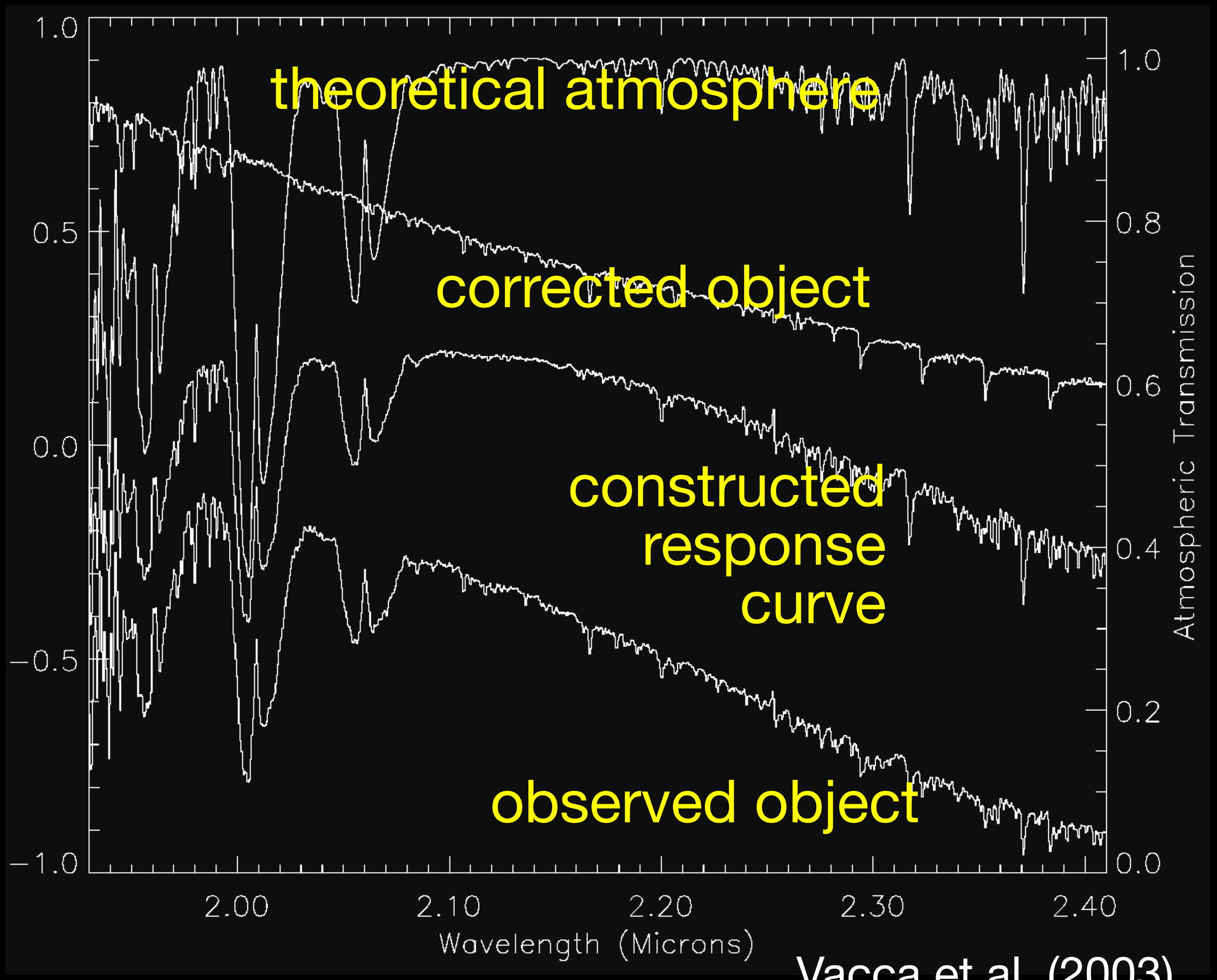
- To combat variable atmospheric absorptions, photometric standard stars are taken at a range of airmasses.



Infrared observations

Telluric standards

- A telluric standard star is taken close in time, airmass and angular distance to the science target.
- A response curve, including the atmosphere and the system response, is constructed by modeling the stellar spectrum.



Vacca et al. (2003)

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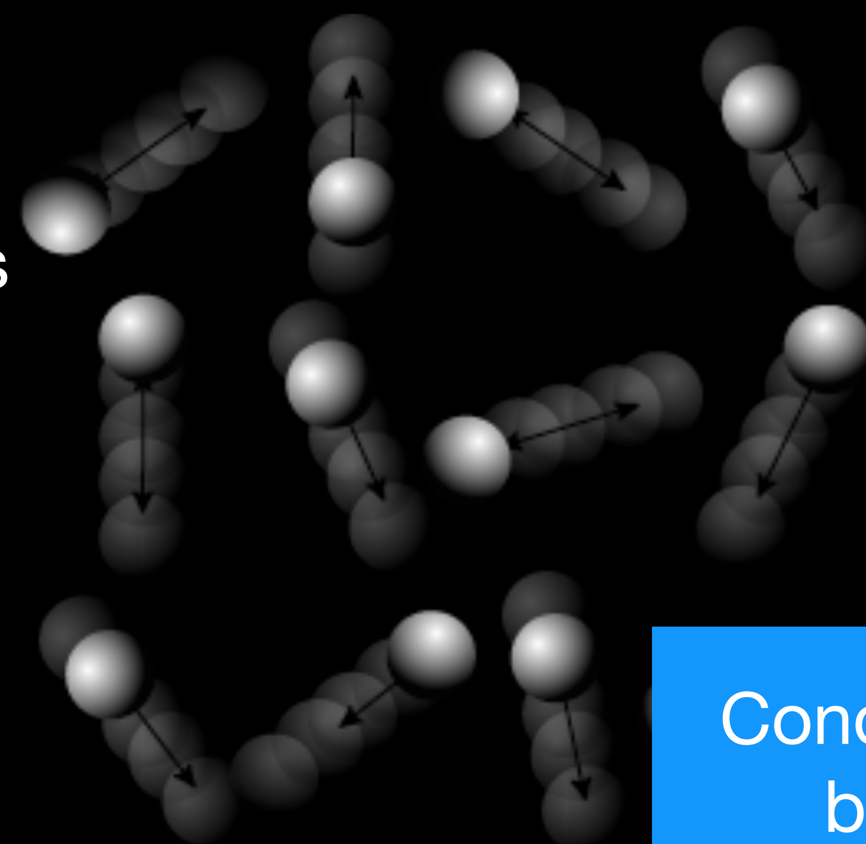
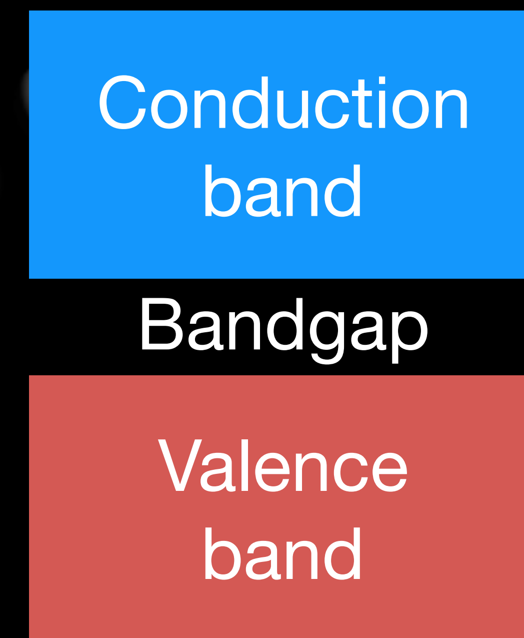
Infrared observations

Dark current

- If vibrational energy of particles is larger than the bandgap, dark current flows in absence of light.
- In general, smaller the bandgap, cooler temperature is required to limit dark current.
- Use dark images with the same exposure time as observations.





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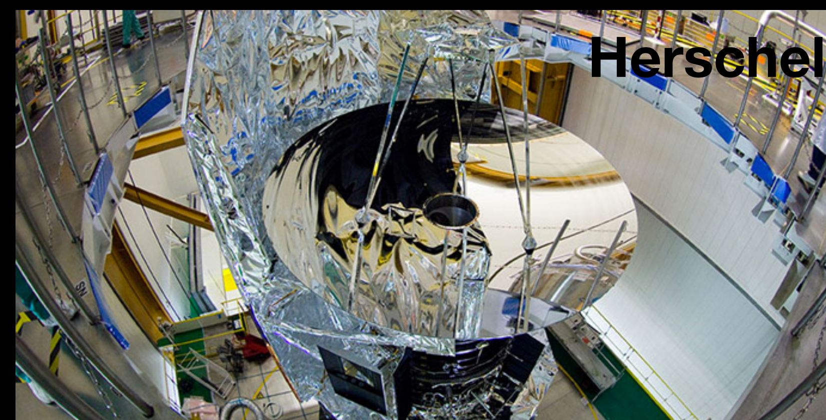
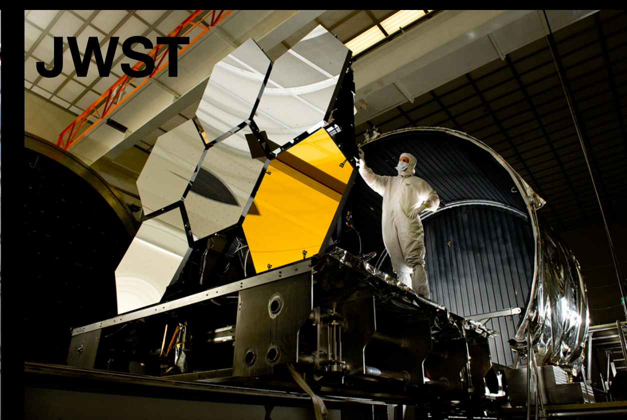
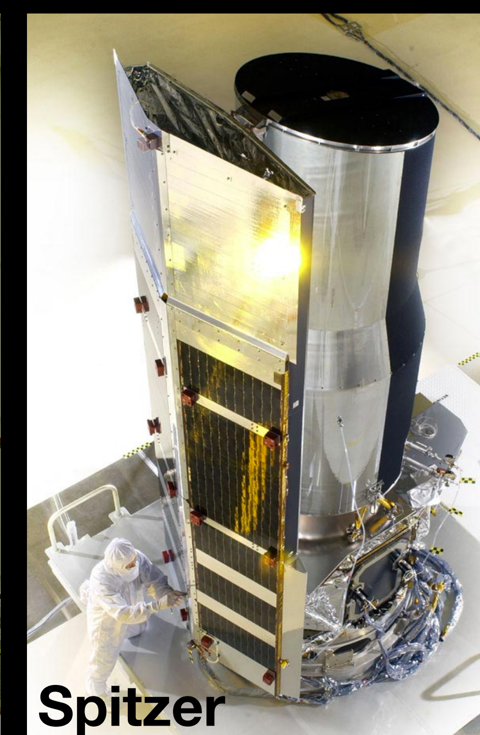
Infrared observations





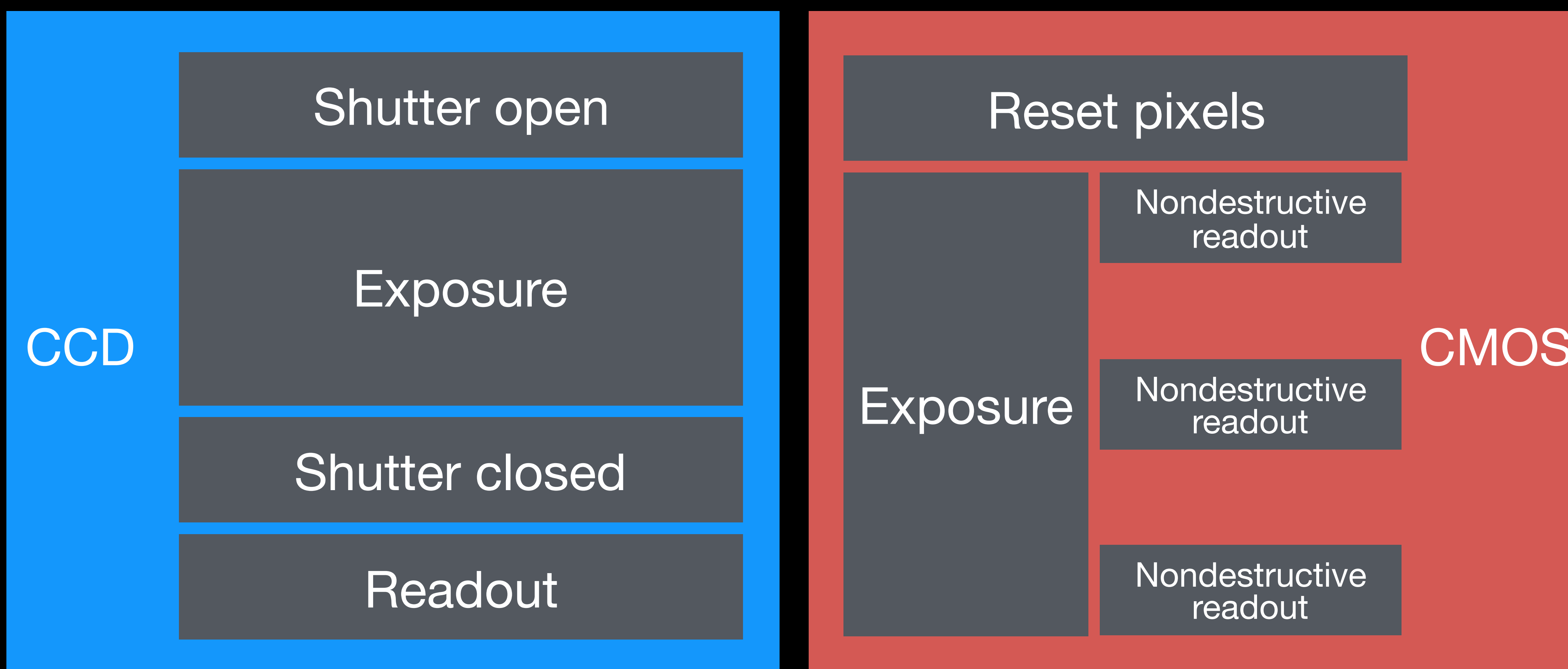
Going into space

- Avoid atmospheric absorption and emission.
- Access longer wavelength.
- Cool detector and optics to limit dark current and thermal emission.



Infrared observations

- To push the readout noise below the Poisson noise, multiple measurements are typically made.



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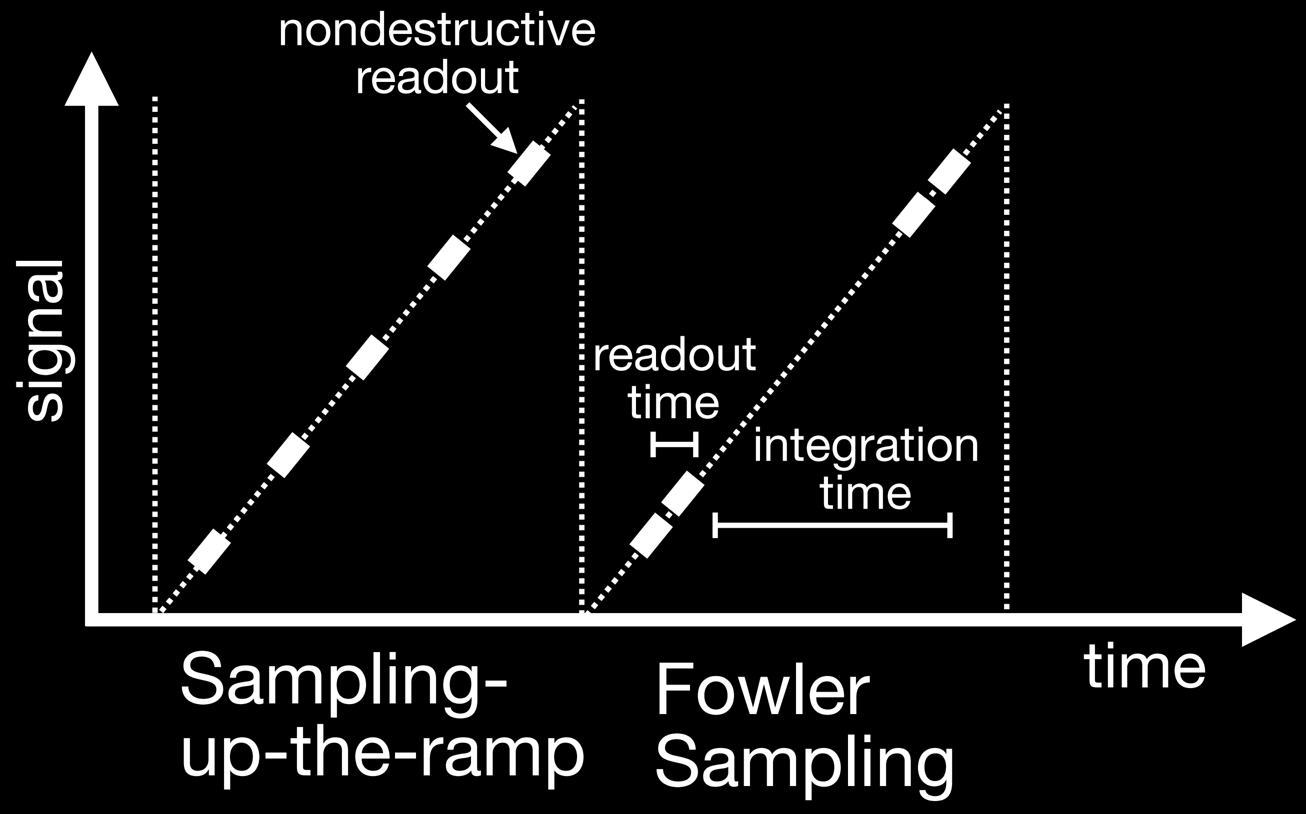

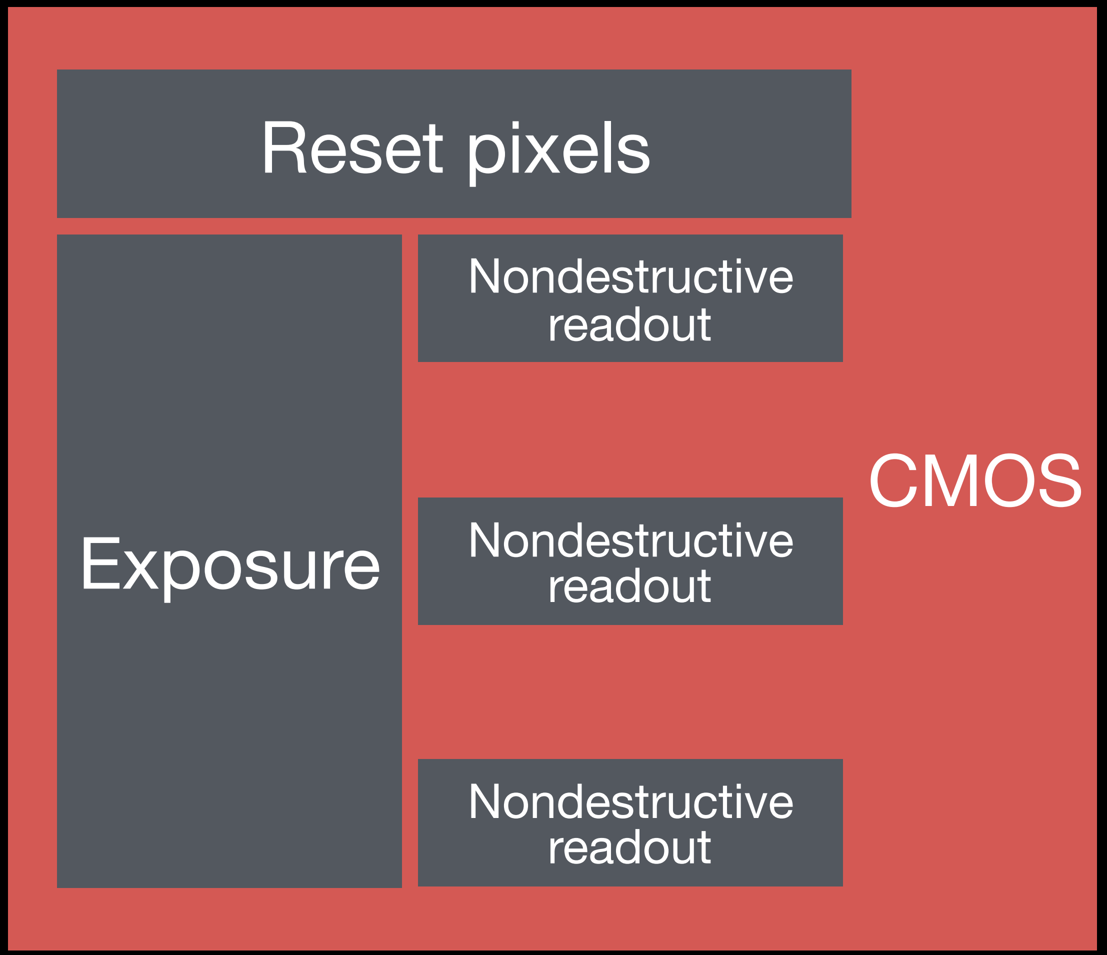

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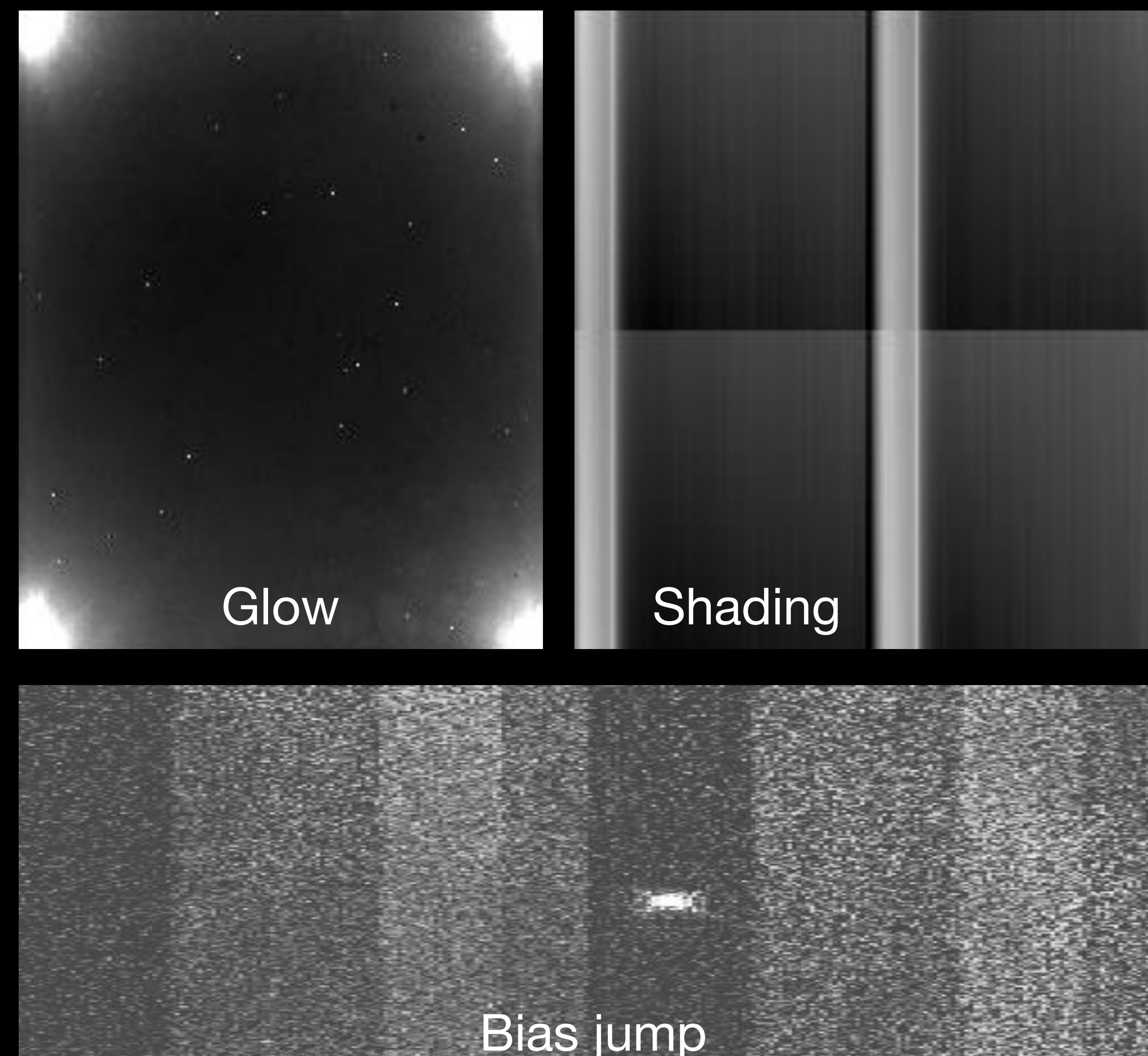
Infrared observations

Amplifier induced anomalies

- Additive.
- “Glow” caused by amplifier temperature.
- “Shading” caused by temperature change across the array.
- “Bias jump” caused by amplifier of another instrument nearby.



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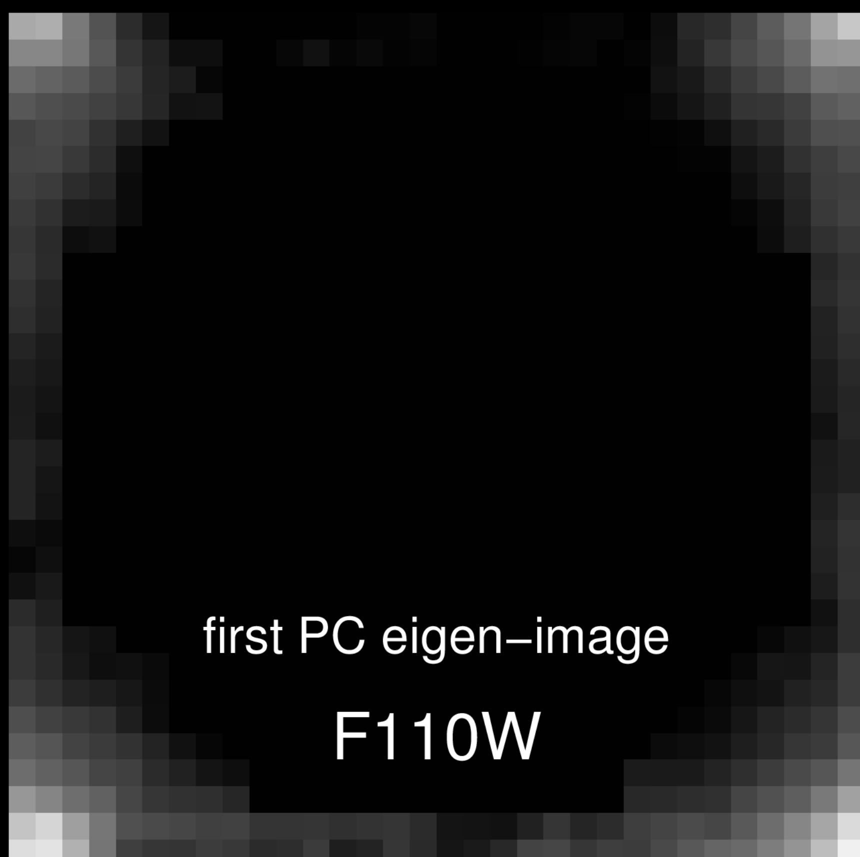
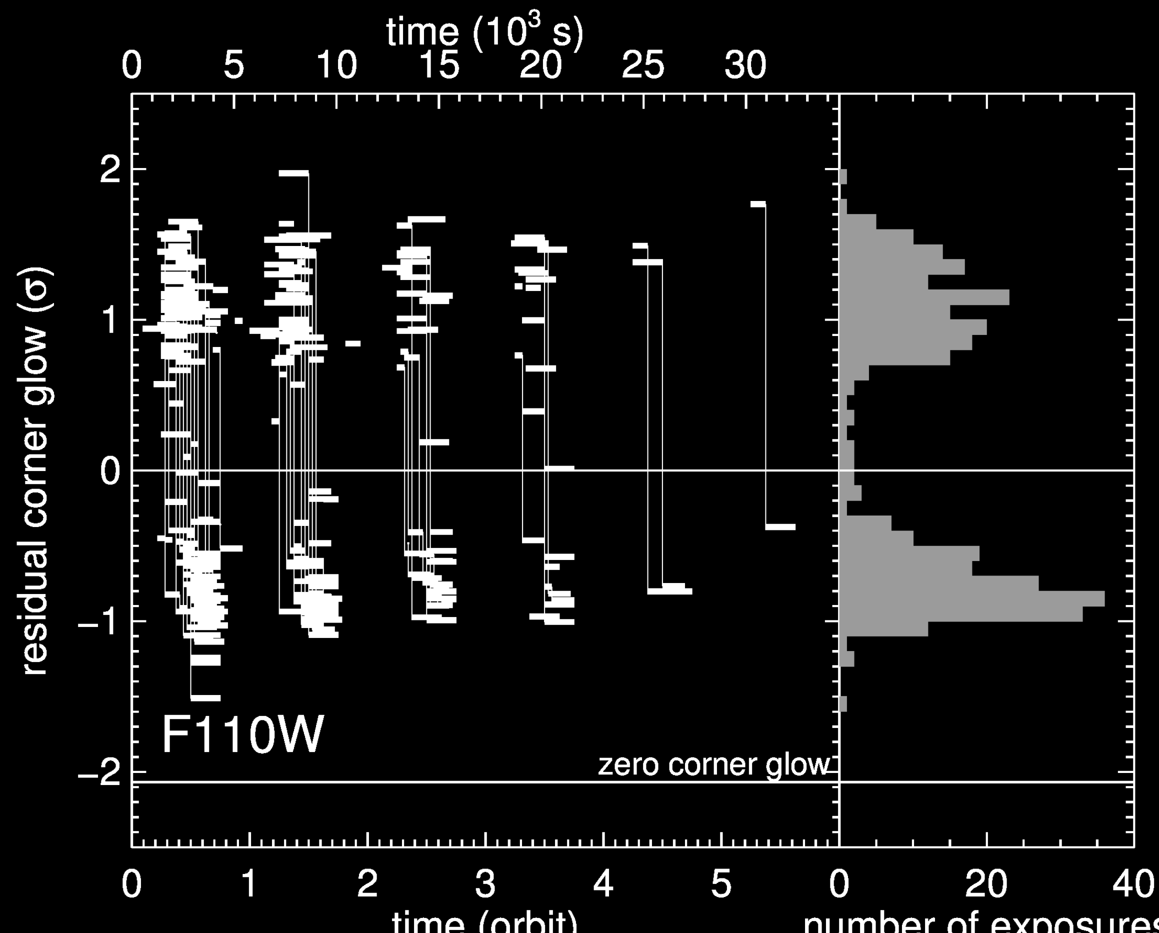
Infrared observations

Amplifier glow





Hsiao et al. (2010)

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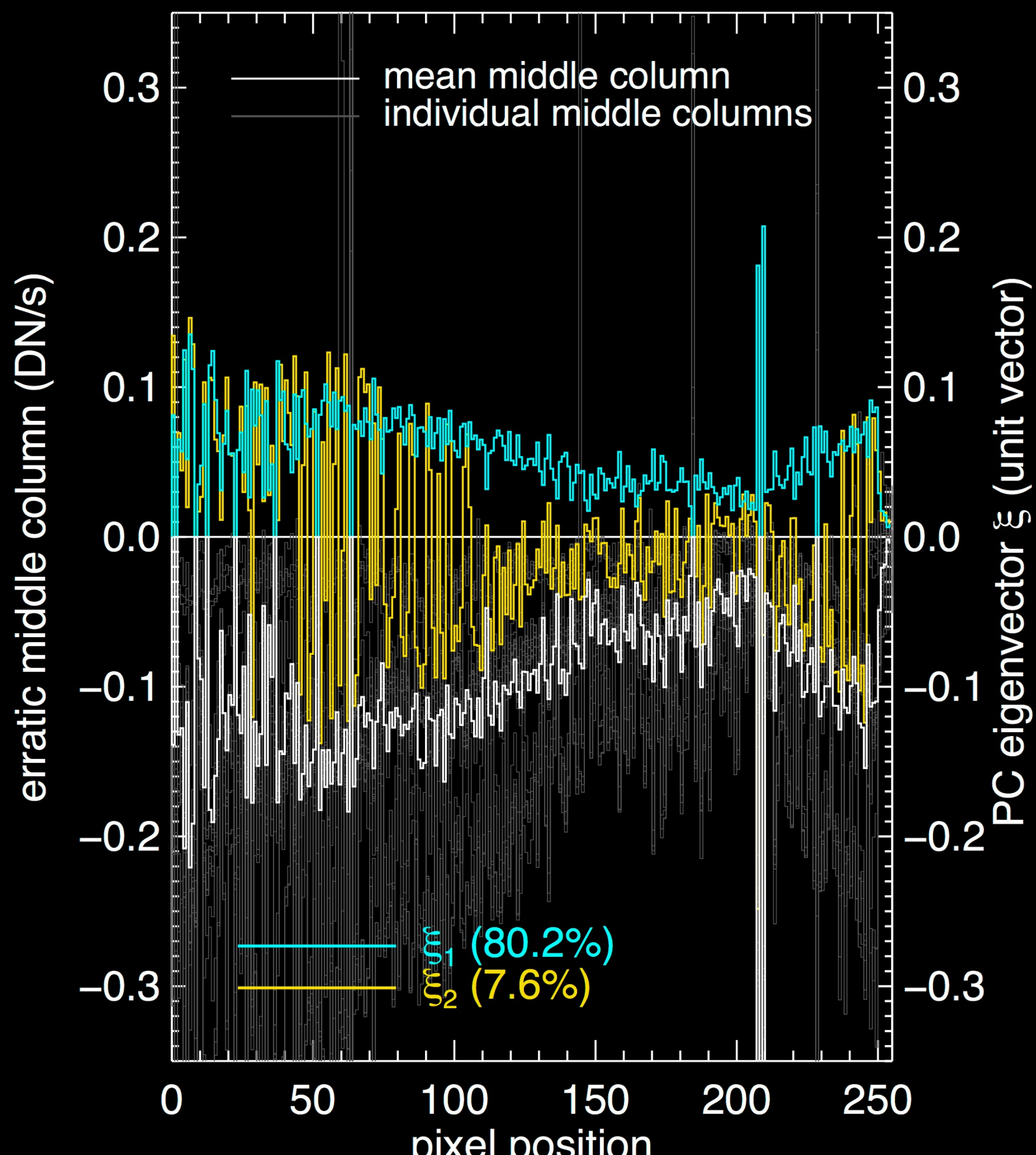
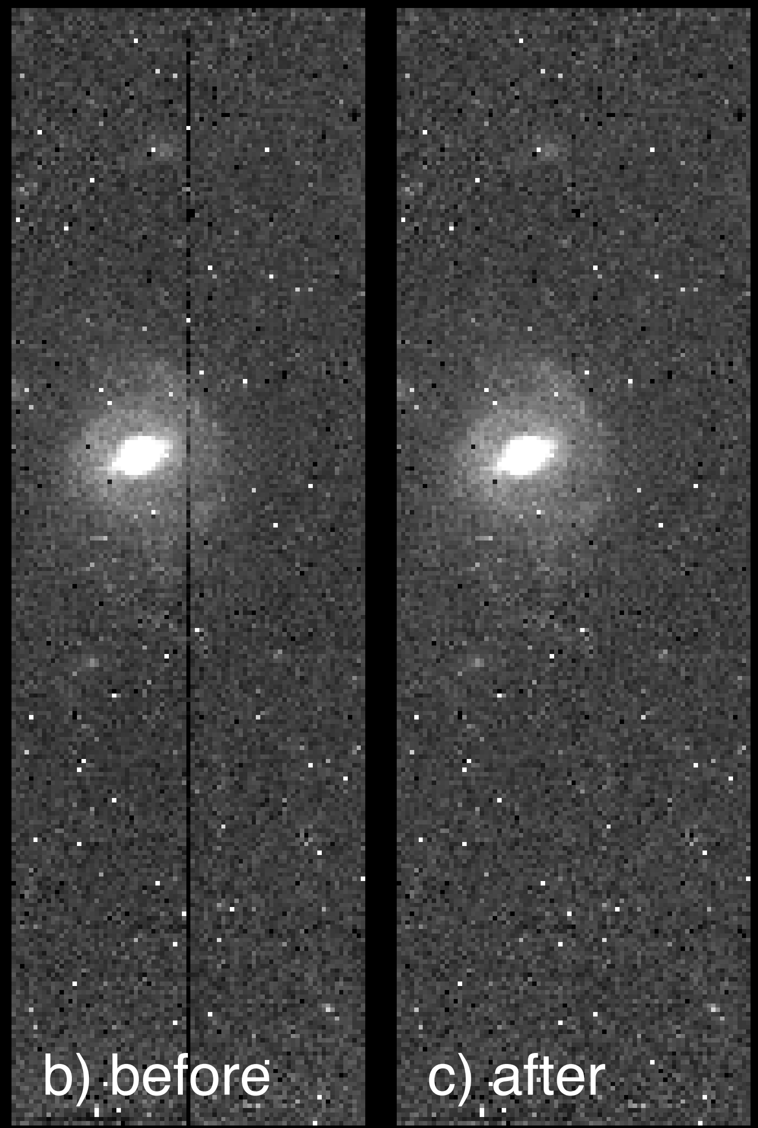
Infrared observations

Erratic middle column





Hsiao et al. (2010)

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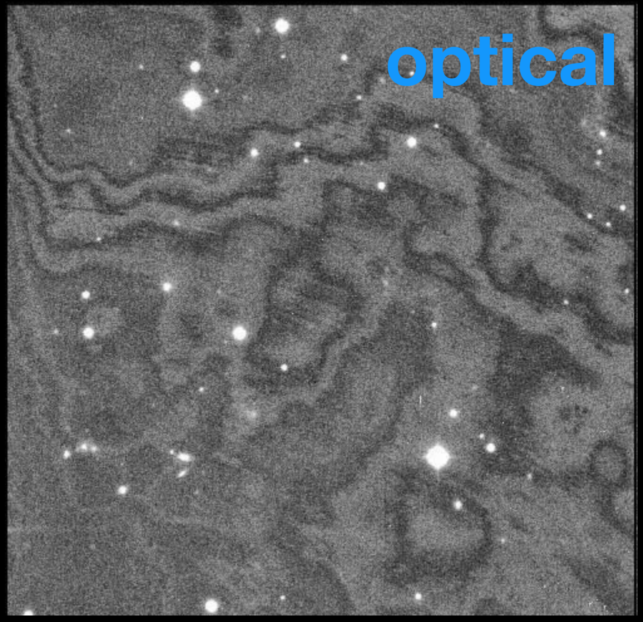
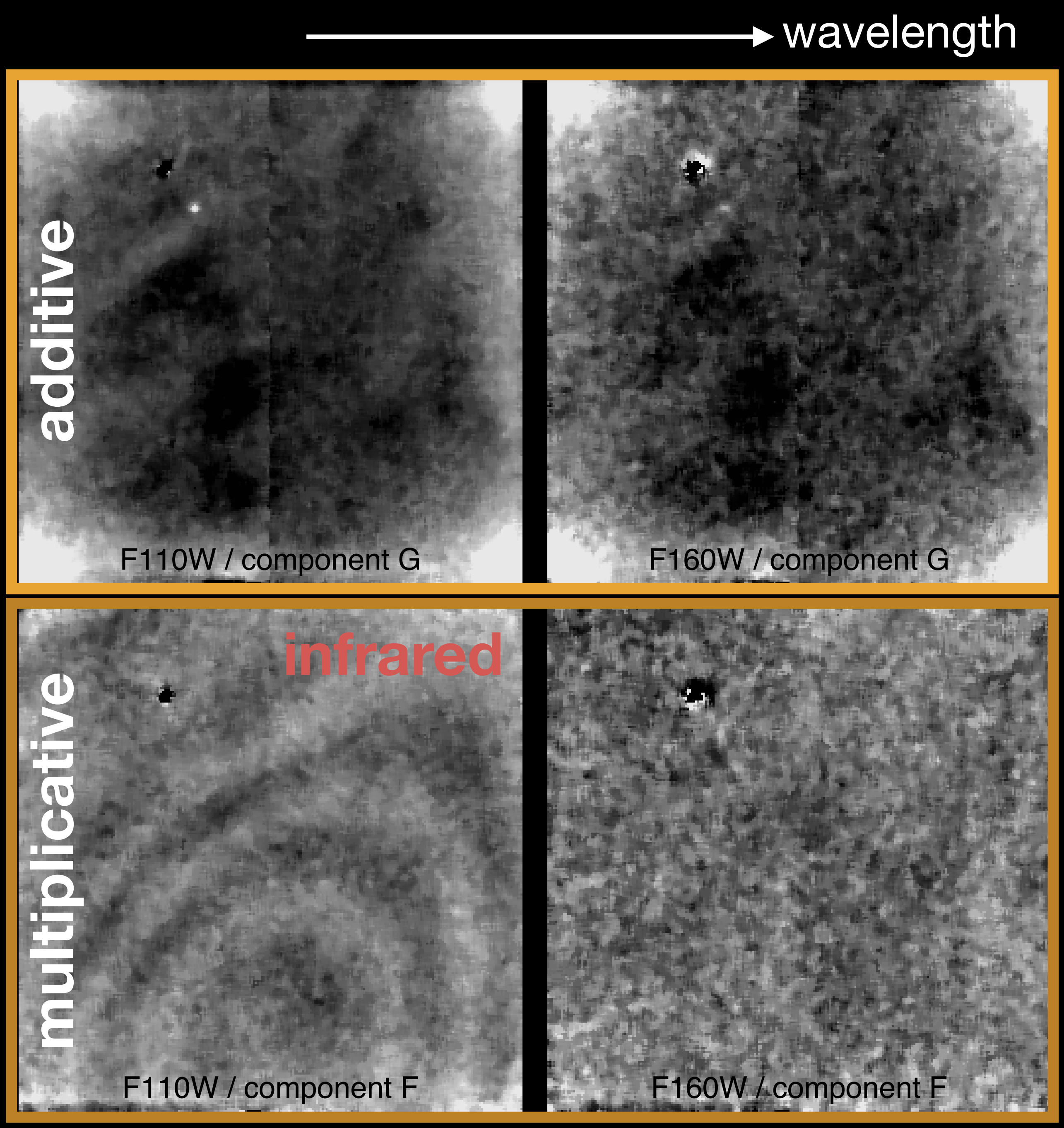
Infrared observations

Fringing?

- Fringing is common in CCDs, but unheard of in infrared detectors.
- The pattern is usually time and wavelength dependent.





Hsiao et al. (2010)

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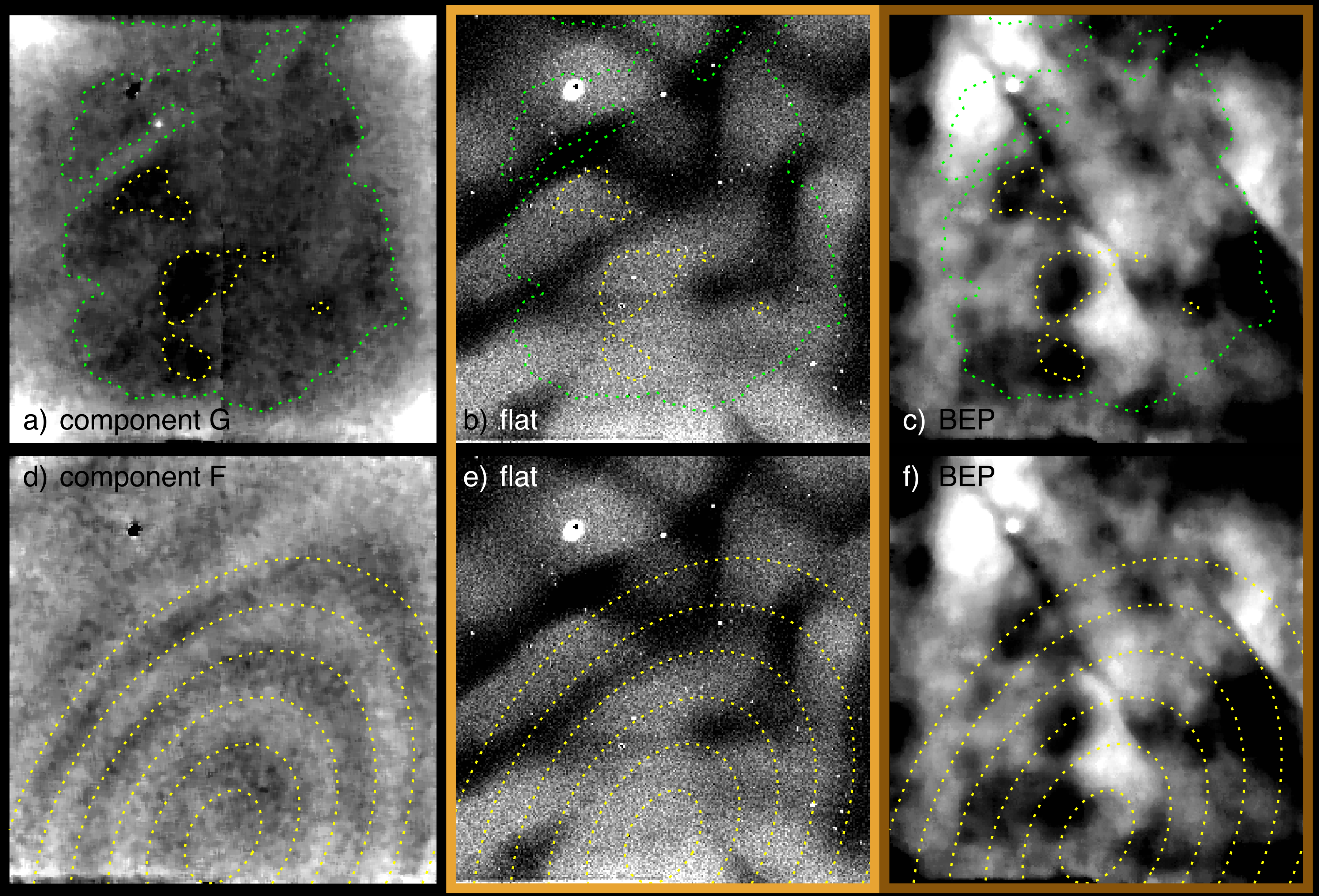

Hsiao et al. (2010)

Does not match flat image.

Does not match bright Earth persistence.

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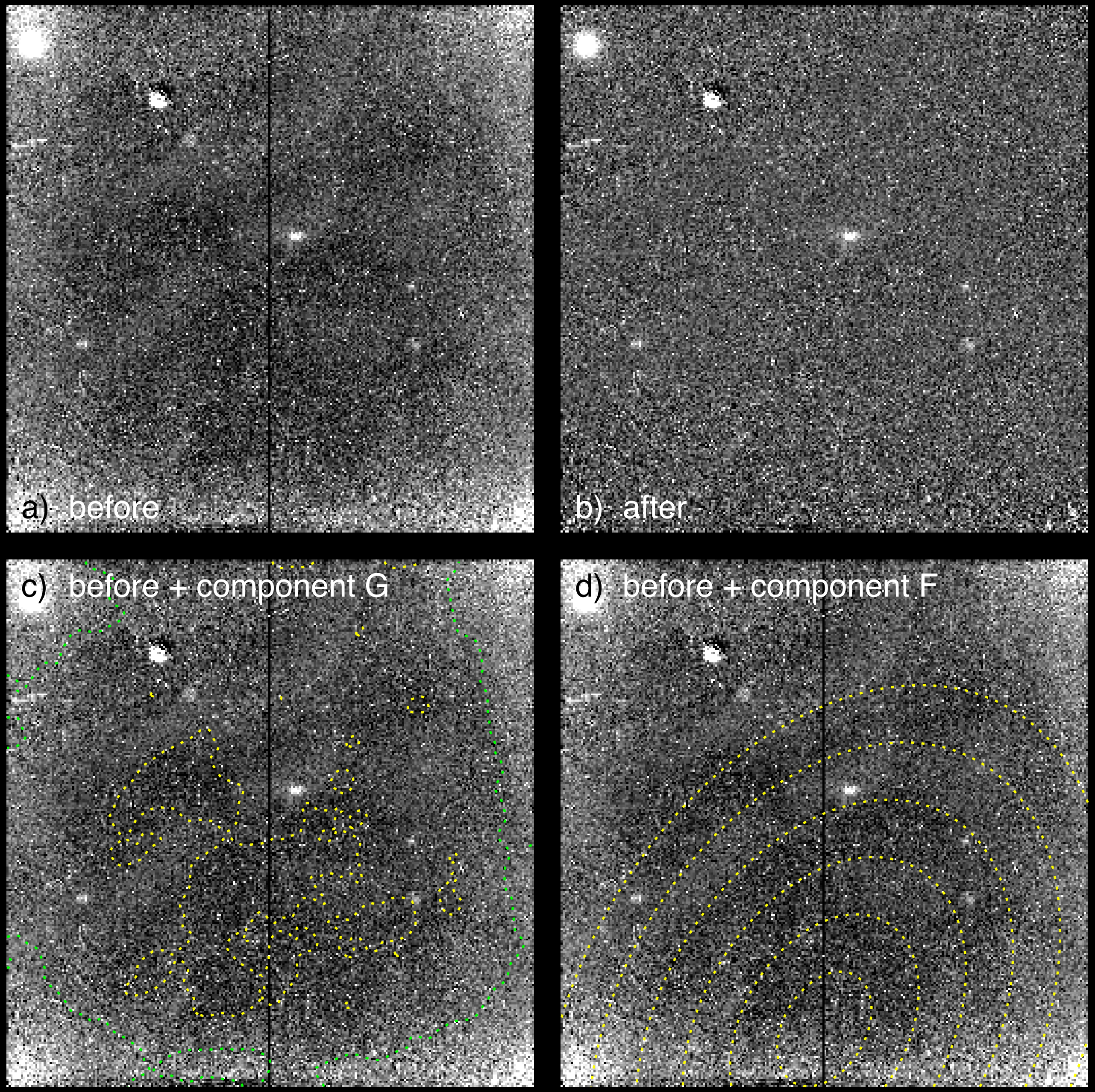
Infrared observations

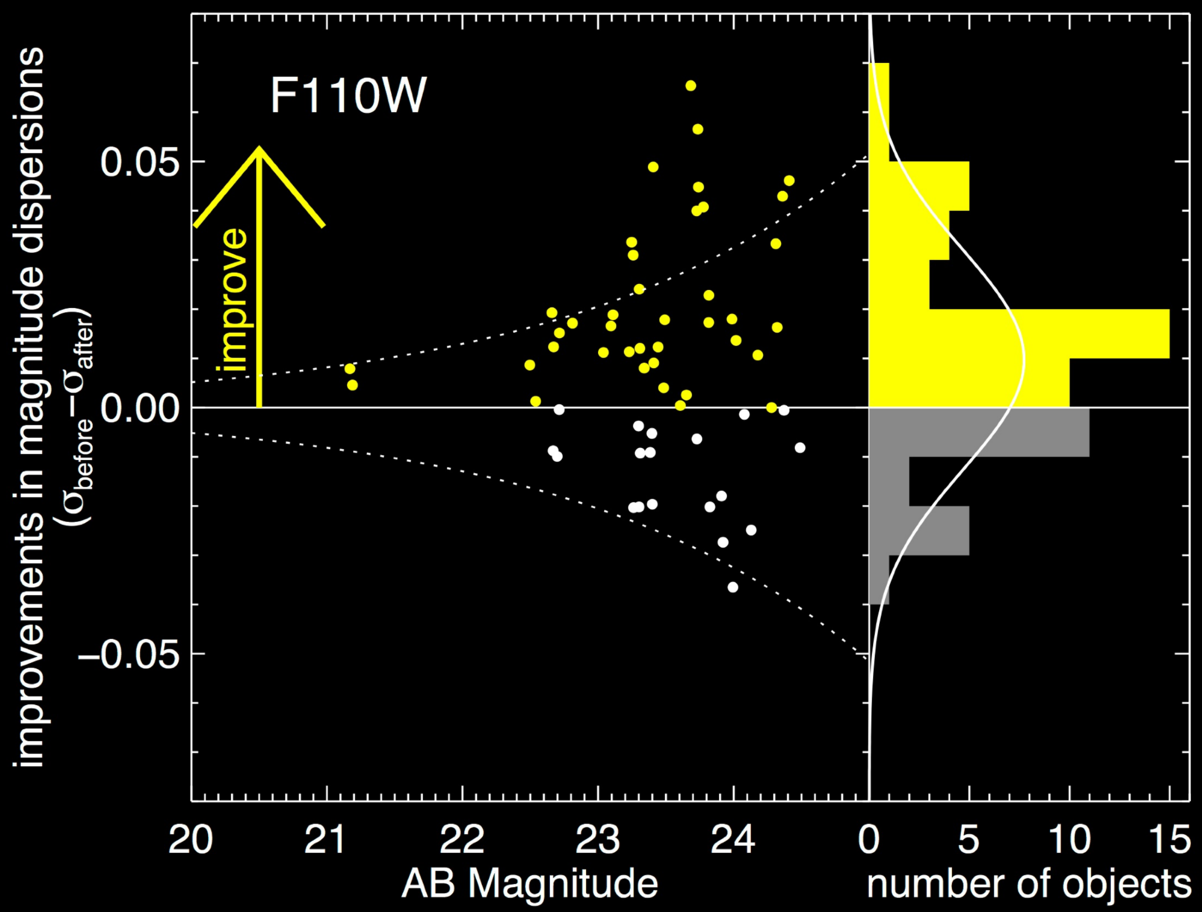
- Fringe pattern is in all images and is multiplicative, so persistence is ruled out.
- Mismatches with flats and darks rule out a temperature effect.
- Intensity follows zodiacal light.
- Spatially wide pattern could be produced by a sub-milliradian wedge in the detector layer.



Hsiao et al. (2010)

Infrared observations

- Removing these anomalies represents a 20% improvement in photometry.



Hsiao et al. (2010)

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Summary

- Environmental challenges
  - Atmospheric absorption
  - Airglow emission
  - Thermal/scattering
- Solutions
  - Photometric, telluric standards
  - Short exptime, nodding, dithering
  - Short exptime, cool detector, space
- Detector challenges
  - Dark current
  - Readout noise
  - Nonlinearity
  - Amplifier glow
  - Fringing?
  - Bad middle column
- Solutions
  - Cool detector, dark images
  - Sampling techniques
  - Nonlinearity correction, hardware
  - Master glow images, hardware
  - Master fringe images
  - Principal component modeling