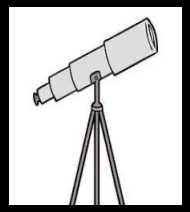
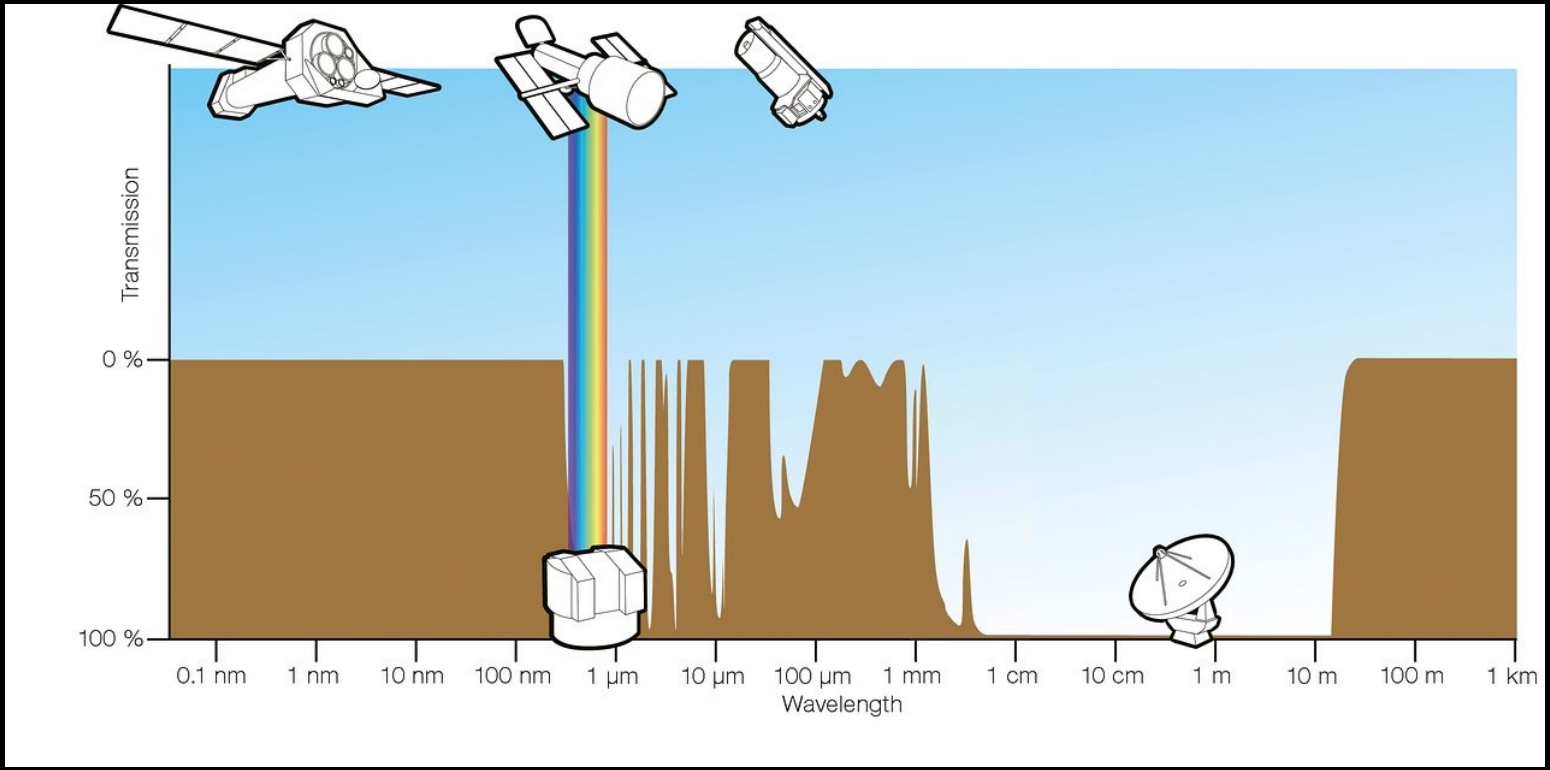
Purposes of disk observations



- Density
- Temperature
- Velocity
- Composition
- Global properties (e.g., total mass, size)

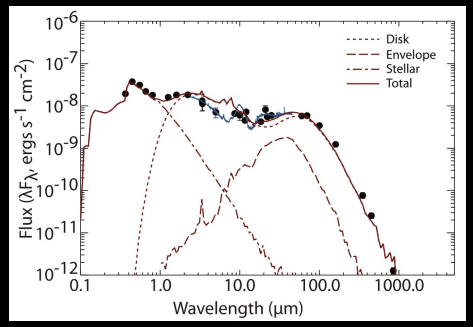
Transparency of the atmosphere, ground and space-based observations



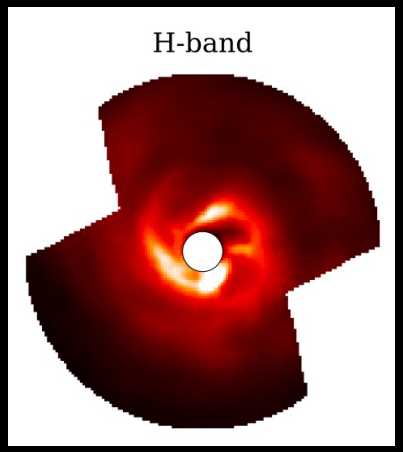
Credit: ESA/Hubble (F. Granato)

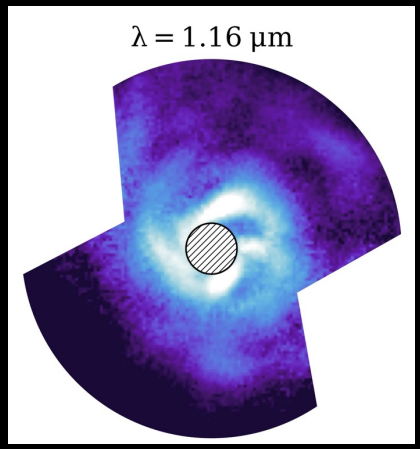
What information do we collect from photons

Rough wavelength | Wavelength | Location | Wavelength AND Location



Lomax+16



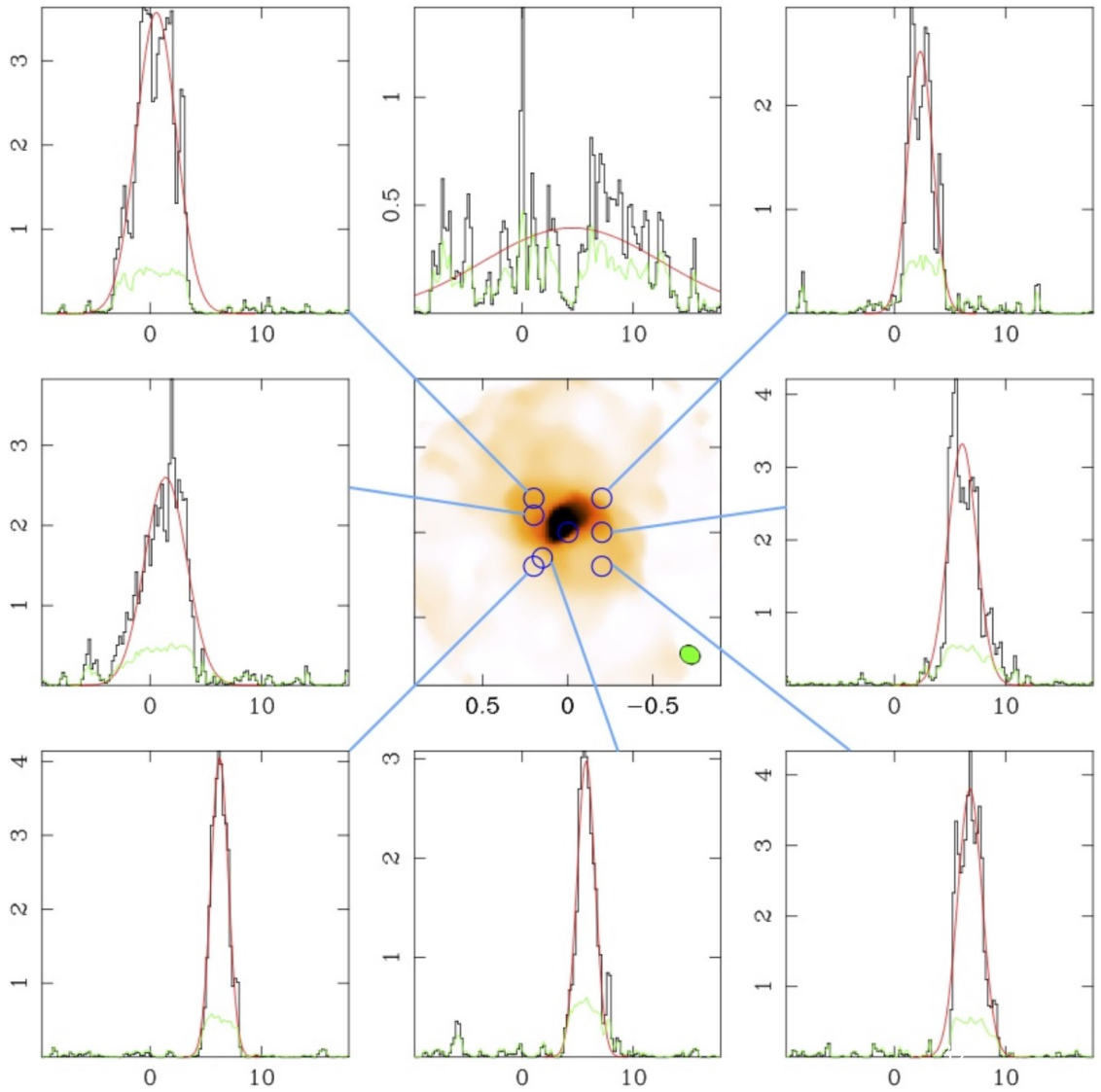


Lawson + 21

Photometry | Spectrum | Image | Channel Maps

Other possible information that you may care: polarization, etc

Another way to look at channel maps



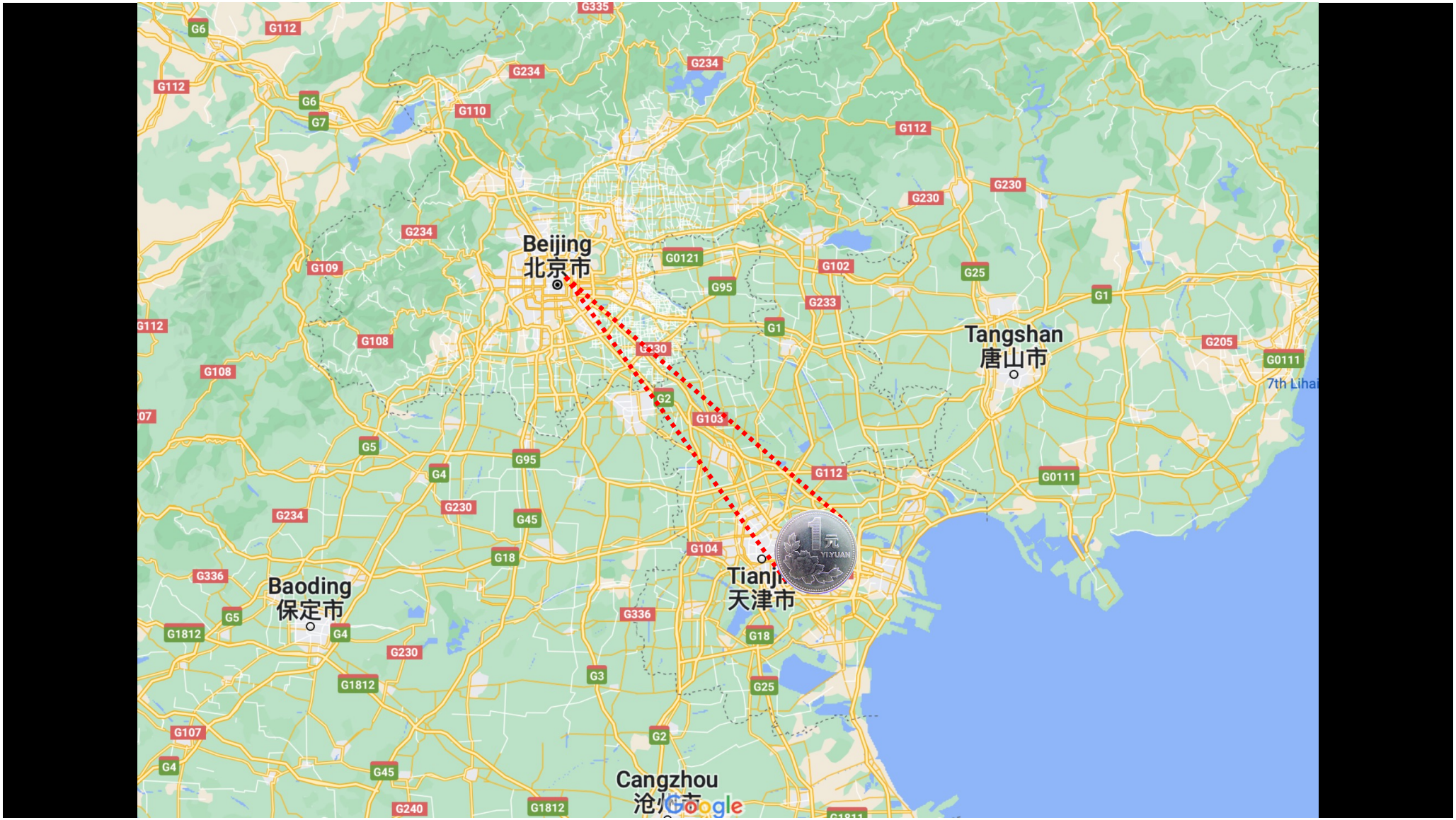
Casassus + 15

Disk Imaging Observations

- Nearby star forming regions:
  ~140 pc
- Solar-type planetary system:
  30 AU (Neptune's orbit)
- 1 AU at 140 pc:
  7 milliarcsecond (4×10^{-8} radian)

Requirements

- **Inner working angle:**
  $\lesssim$ 30 AU, or 0.2 arcsec
- **Angular resolution:**
  a few × 0.01 arcsec


Beijing
北京市
Tangshan
唐山市
Baoding
保定市
Tianjin
天津市
Cangzhou
沧州市
Google

High Contrast High Resolution Disk Imaging

$$\frac{\lambda}{D} = \frac{1\ \mu\text{m}}{10\text{-m mirror}} \quad \frac{1\ \text{mm}}{10\ \text{km baseline}} = \text{a few} \times 0''.01$$

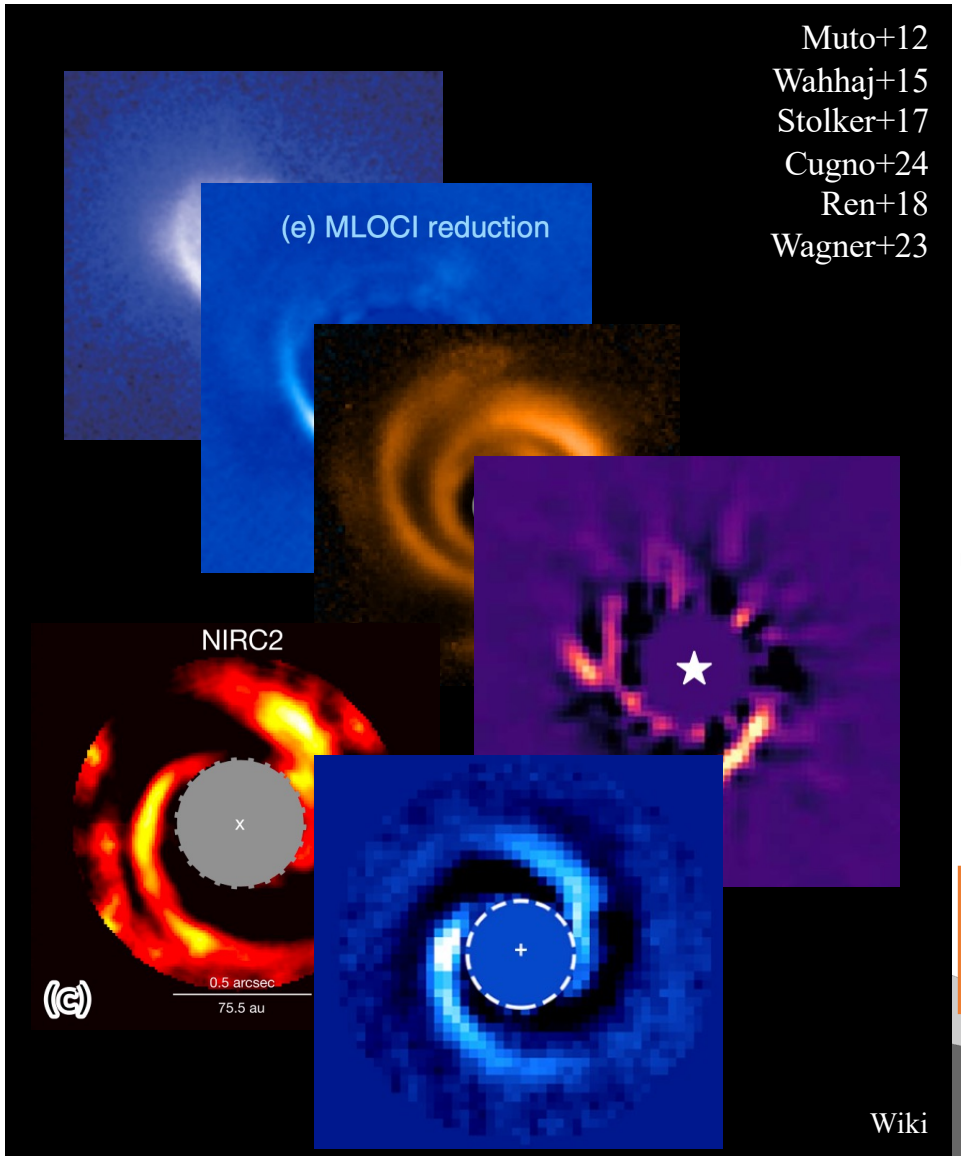
1 um
10-m ground based telescopes

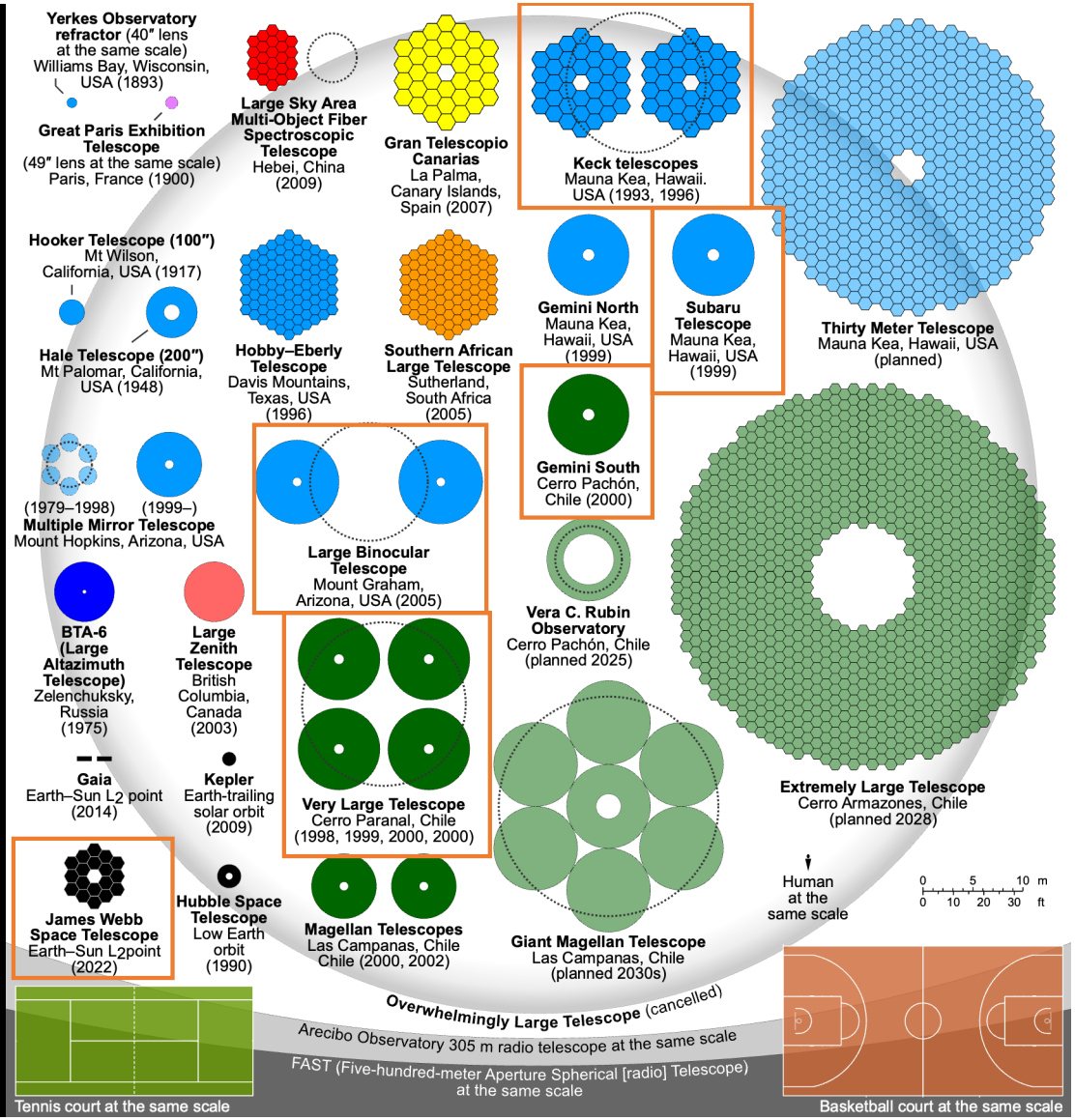
1 mm
Radio interferometers with baselines up to 10 km

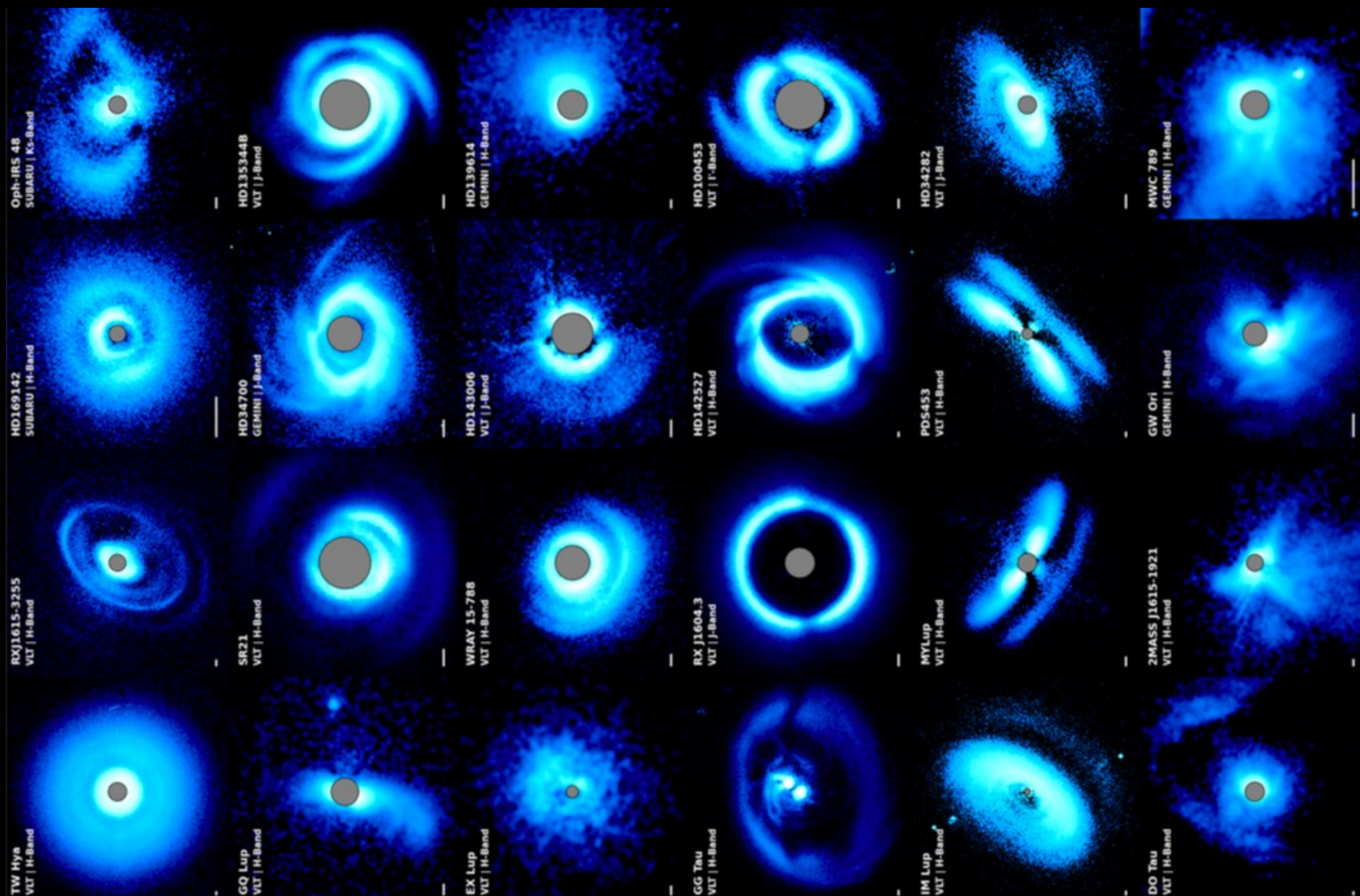
What are we looking at in these observations?

Scattered light imaging to probe the distribution of small (sub-micron-sized) grains

dust continuum and gas line emission observations to probe the distribution of big (mm-sized) dust grains and gas


Muto+12
Wahhaj+15
Stolker+17
Cugno+24
Ren+18
Wagner+23
(e) MLOCI reduction
NIRC2
0.5 arcsec
75.5 au
Wiki


Yerkes Observatory refractor (40″ lens at the same scale) Williams Bay, Wisconsin, USA (1893)
Great Paris Exhibition Telescope (49″ lens at the same scale) Paris, France (1900)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope Hebei, China (2009)
Gran Telescopio Canarias La Palma, Canary Islands, Spain (2007)
Keck telescopes Mauna Kea, Hawaii. USA (1993, 1996)
Thirty Meter Telescope Mauna Kea, Hawaii, USA (planned)
Hooker Telescope (100″) Mt Wilson, California, USA (1917)
Hale Telescope (200″) Mt Palomar, California, USA (1948)
Hobby–Eberly Telescope Davis Mountains, Texas, USA (1996)
Southern African Large Telescope Sutherland, South Africa (2005)
Gemini North Mauna Kea, Hawaii, USA (1999)
Subaru Telescope Mauna Kea, Hawaii, USA (1999)
Gemini South Cerro Pachón, Chile (2000)
(1979–1998) (1999–) Multiple Mirror Telescope Mount Hopkins, Arizona, USA
Large Binocular Telescope Mount Graham, Arizona, USA (2005)
Vera C. Rubin Observatory Cerro Pachón, Chile (planned 2025)
BTA-6 (Large Altazimuth Telescope) Zelenchuksky, Russia (1975)
Large Zenith Telescope British Columbia, Canada (2003)
Very Large Telescope Cerro Paranal, Chile (1998, 1999, 2000, 2000)
Extremely Large Telescope Cerro Armazones, Chile (planned 2028)
Gaia Earth–Sun L2 point (2014)
Kepler Earth-trailing solar orbit (2009)
Human at the same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope Earth–Sun L2point (2022)
Hubble Space Telescope Low Earth orbit (1990)
Magellan Telescopes Las Campanas, Chile Chile (2000, 2002)
Giant Magellan Telescope Las Campanas, Chile (planned 2030s)
Overwhelmingly Large Telescope (cancelled)
Arecibo Observatory 305 m radio telescope at the same scale
FAST (Five-hundred-meter Aperture Spherical [radio] Telescope) at the same scale
Tennis court at the same scale
Basketball court at the same scale



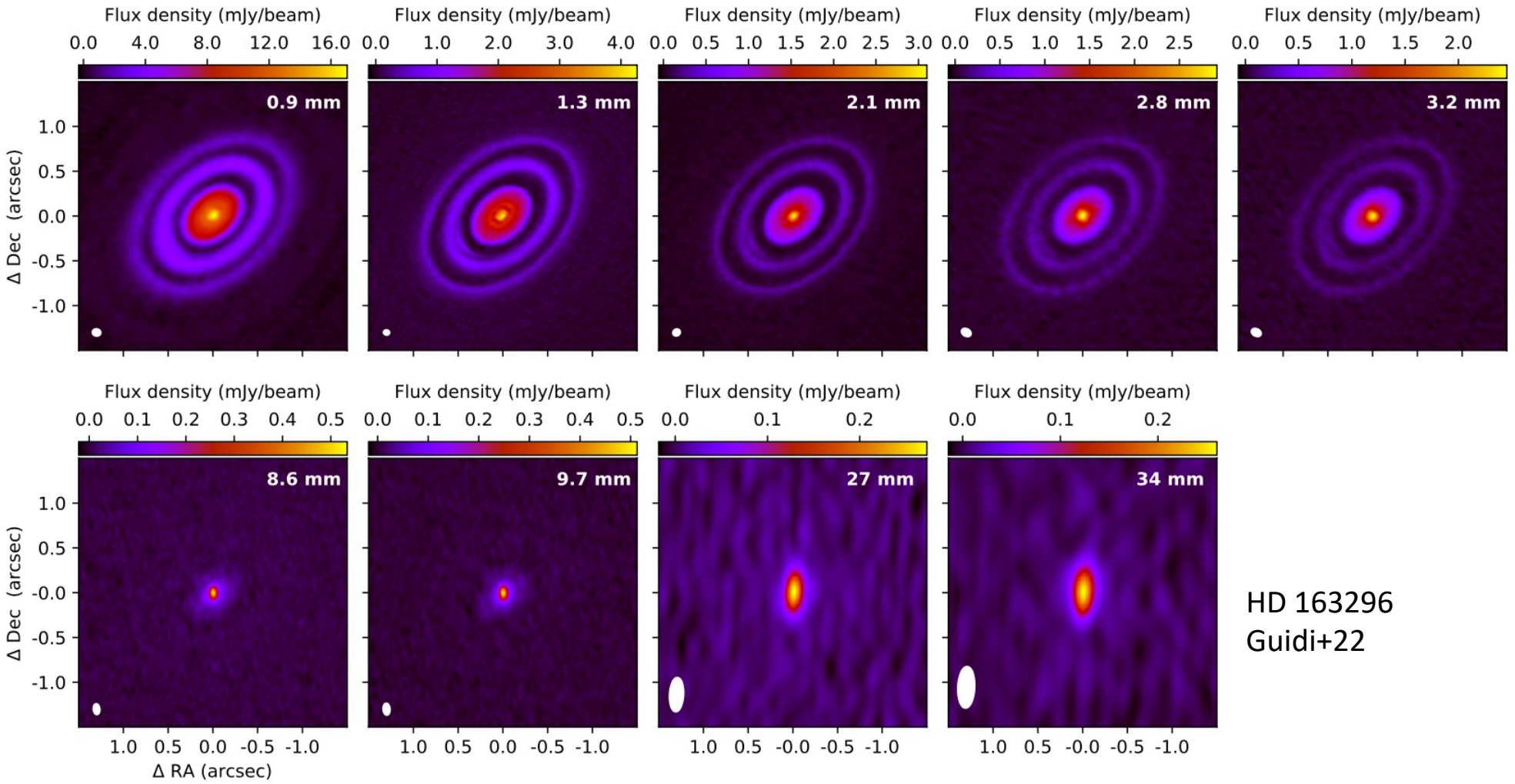
Scattered Light

Benisty+22

Millimeter / Centimeter Observations: Radio Interferometers

Atacama Large Millimeter Array (ALMA)

Jansky Very Large Array (JVLA)



HD 163296
Guidi+22

Fig. 1. Continuum maps of HD 163296 from ALMA observations (top row) and VLA (bottom row). The synthesized beams of the final maps are drawn as white ellipse at the bottom left corner of each panel and are listed in Table 1.

Observers' Workflow

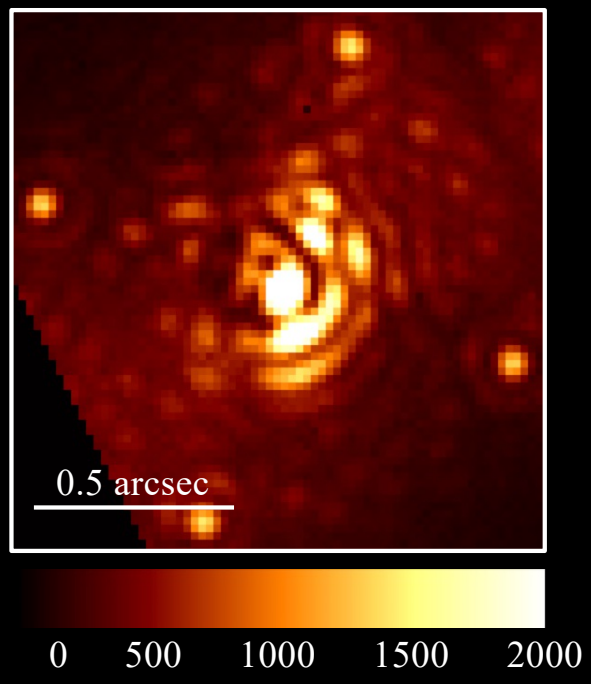
- Form a scientific hypothesis
- Choose the right telescope and instrument; write observing proposals
- Carry out observations (optional)
- Calibrate and reduce data
- Analysis data, deliver science results

NIR Scattered Light Imaging of Protoplanetary Disks

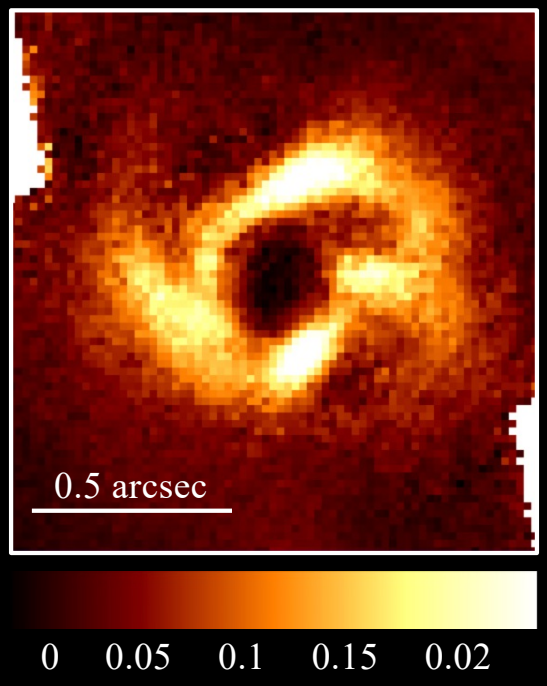
Subaru SCExAO Observations of AB Aur

Subaru Telescope

(Calibrated) Raw Image



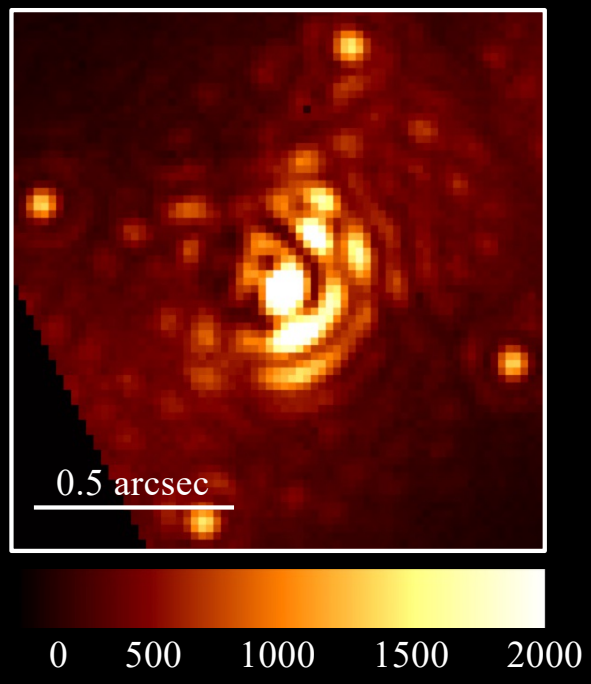
Starlight Removed Image



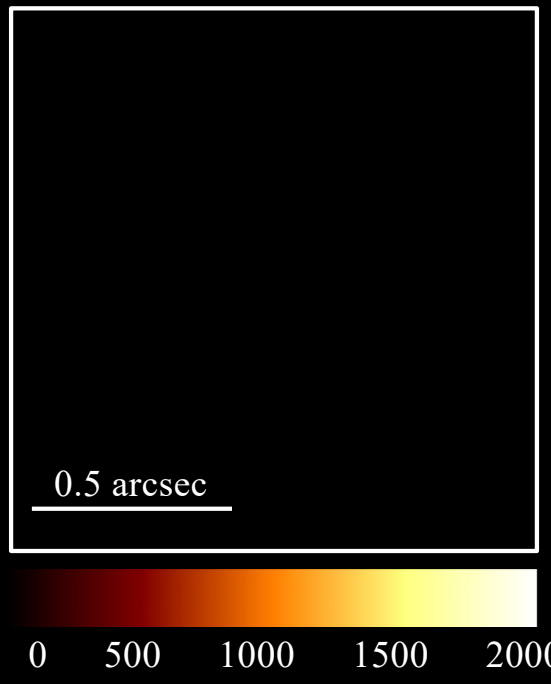
Subaru SCExAO Observations of AB Aur

Subaru Telescope

(Calibrated) Raw Image



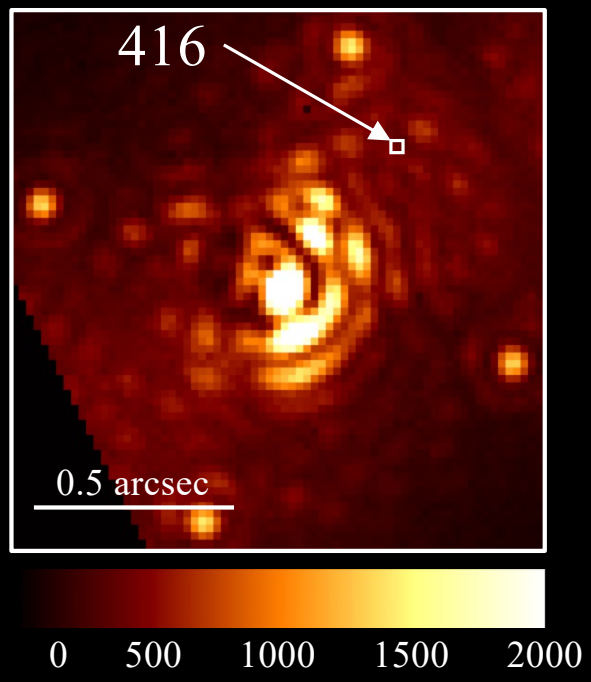
Starlight Removed Image



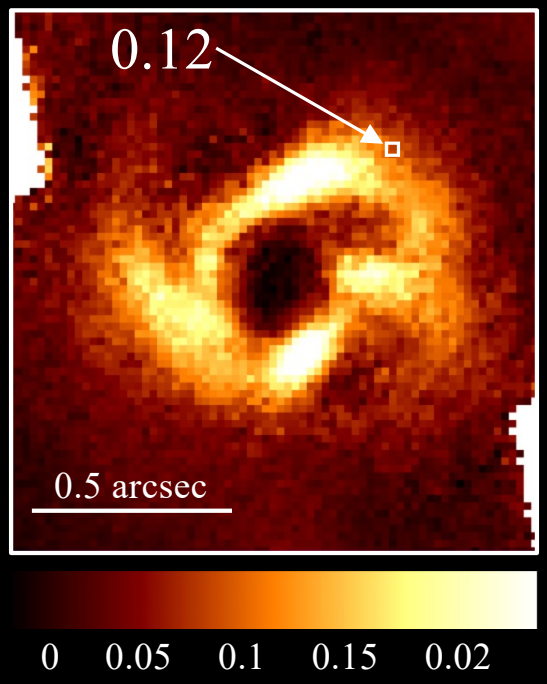
Subaru SCExAO Observations of AB Aur

Subaru Telescope

(Calibrated) Raw Image



Starlight Removed Image



NIR Imaging: remove starlight, retain disk/planet light

Total Intensity Imaging

- RDI: reference-star differential imaging
- ADI: angular differential imaging
- SSDI: spectroscopic spectral differential imaging
- SDI: spectral differential imaging

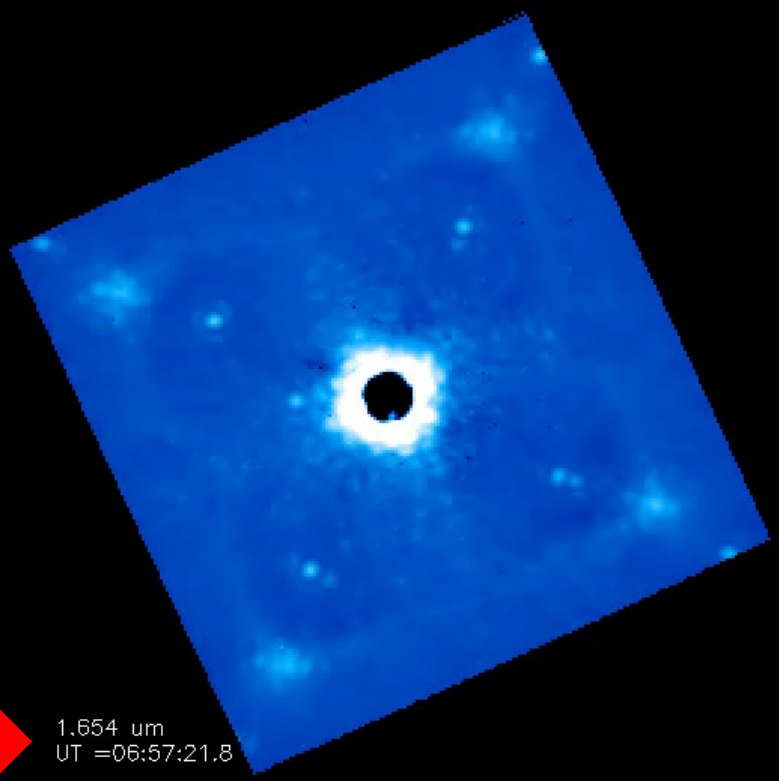
Polarized Intensity Imaging

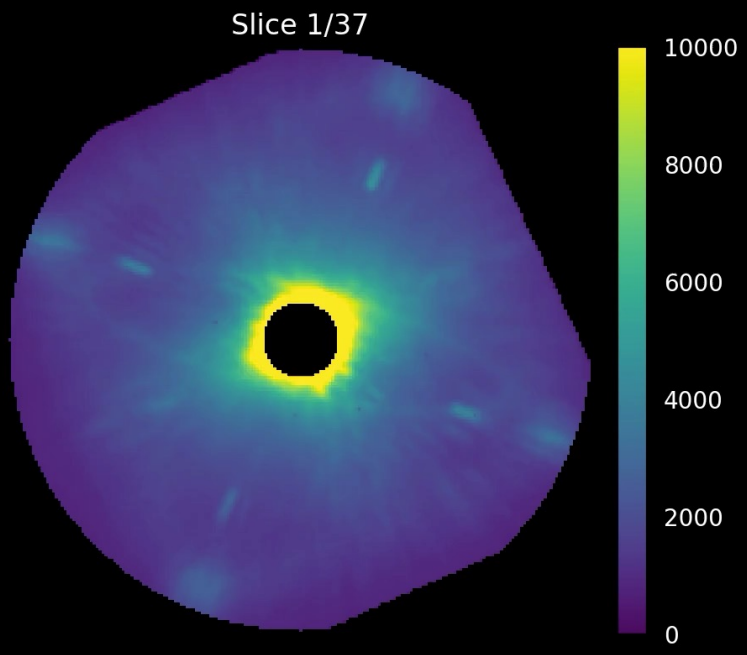
- PDI: polarization differential imaging

ADI (angular differential imaging)

https://www.youtube.com/watch?v=lV8PVzPZcBk

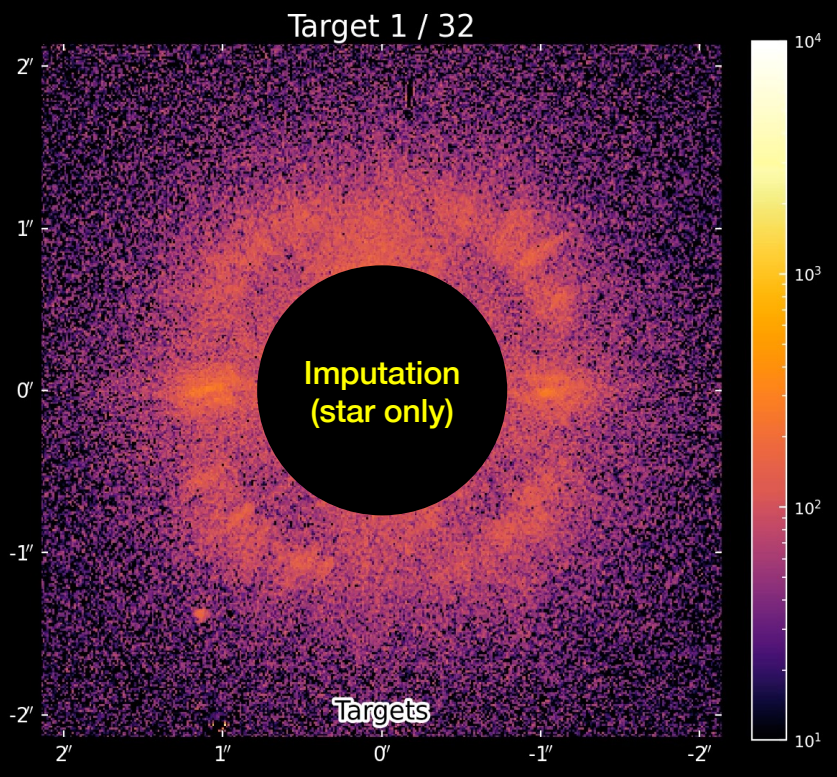
ADI (angular differential imaging)

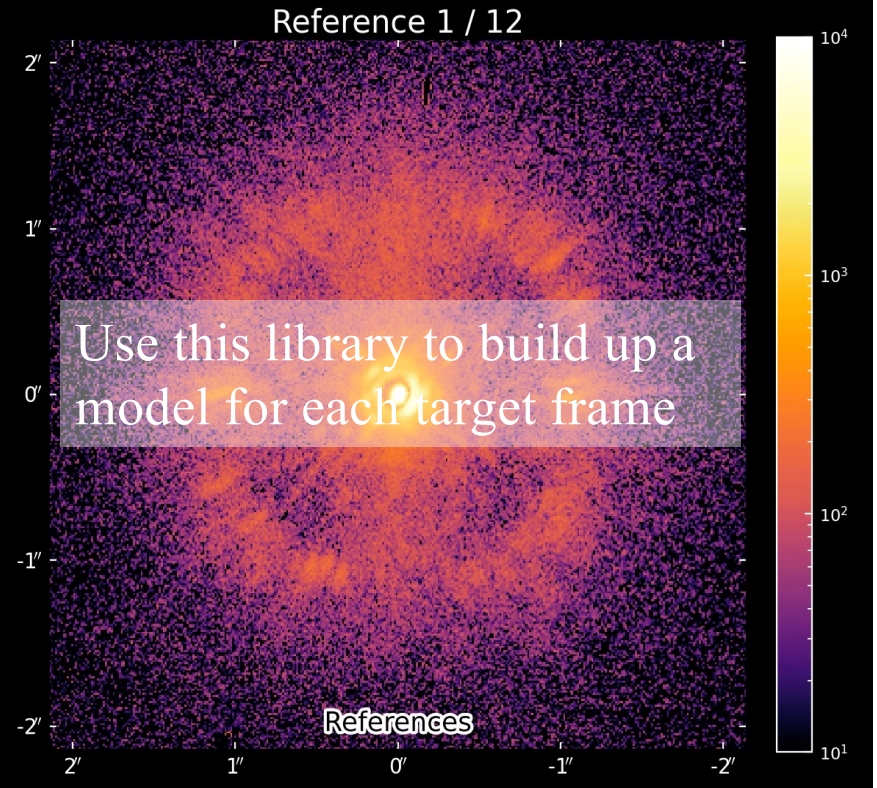




GPI data on Beta Pictoris b: Christian Marois

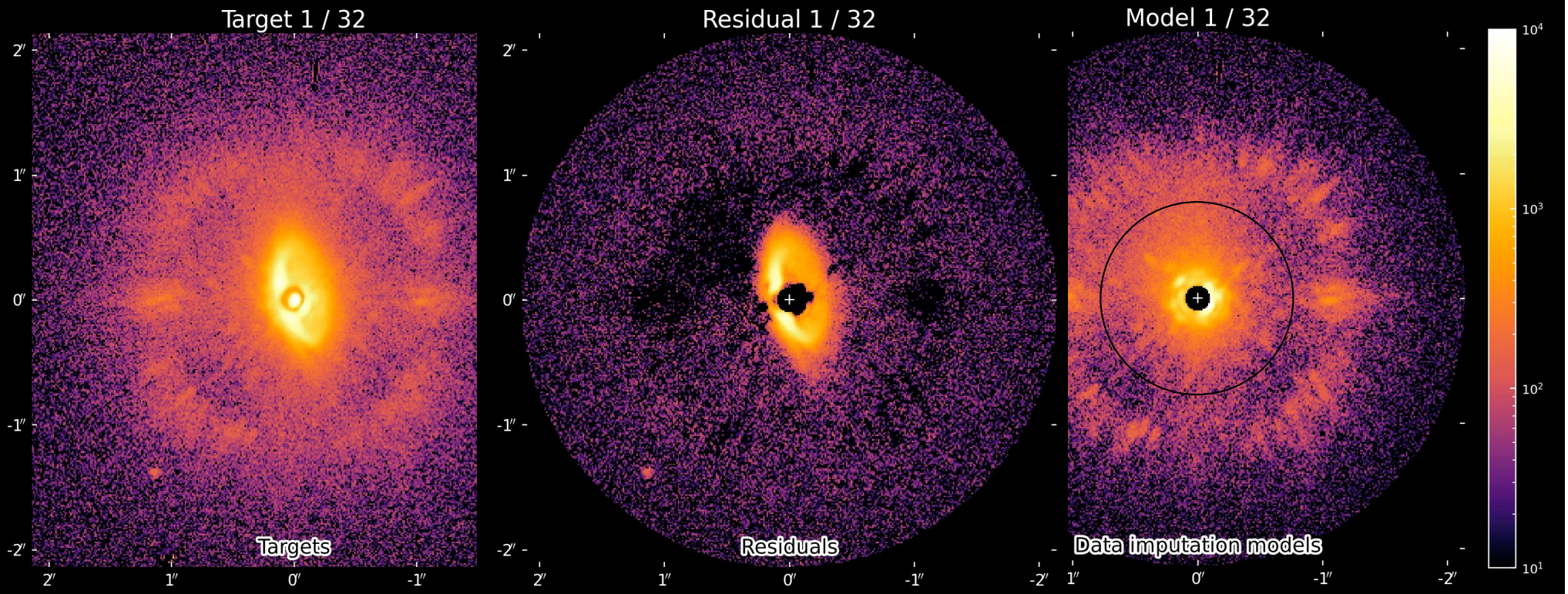
RDI (reference-star differential imaging)





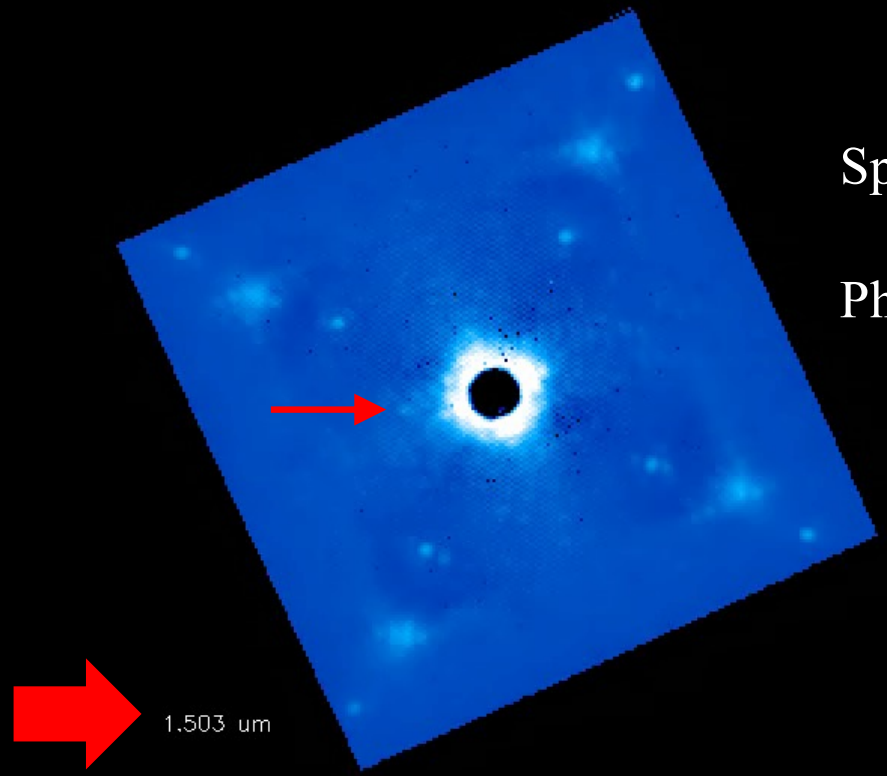
Star hopping (Wahhaj + 21): Target - reference - target - reference, …

RDI (reference-star differential imaging)



Non-negative matrix factorization (NMF): Ren et al. (2018)

SSDI (spectroscopic spectral differential imaging)

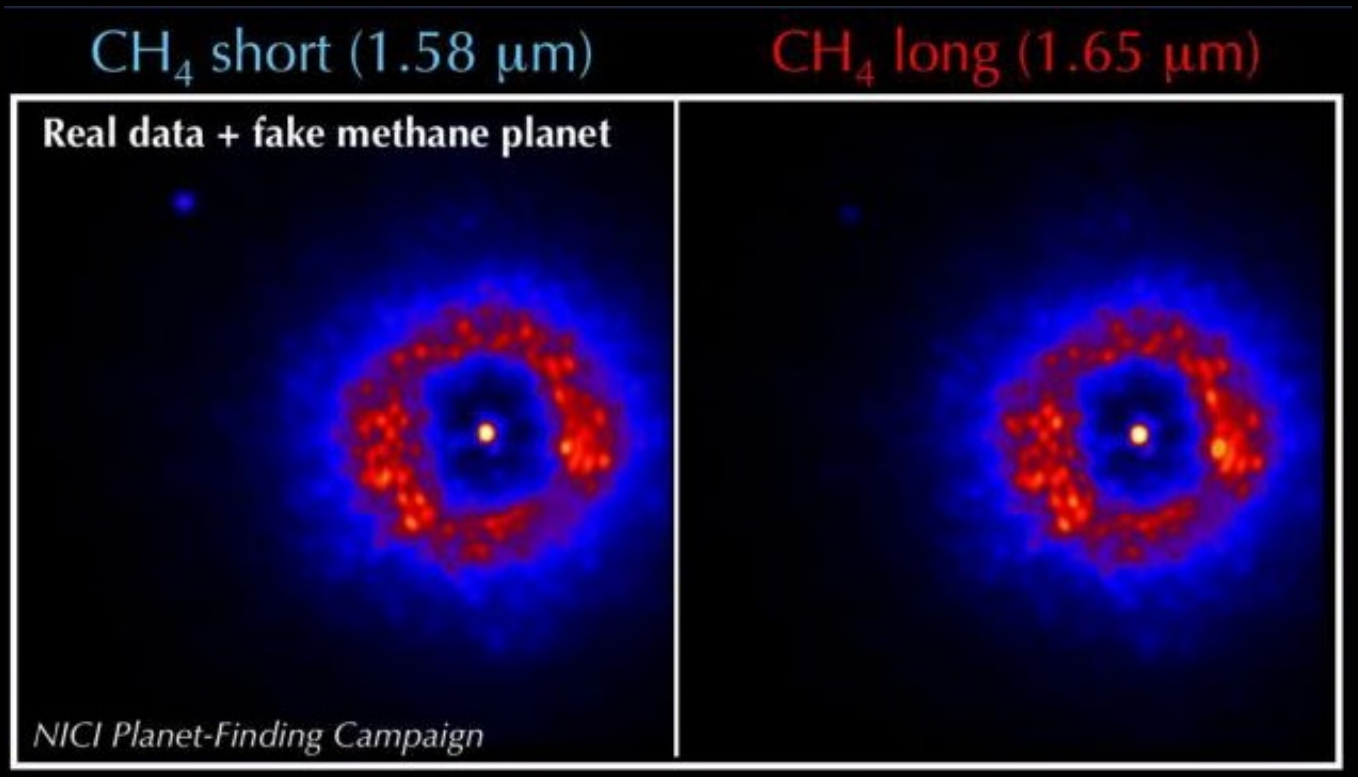


Speckles go out with λ/D

Physical structures stay

GPI data on Beta Pictoris b: Christian Marois

SDI (spectral differential imaging)



Julian C. Christou

PDI (polarimetry differential imaging)