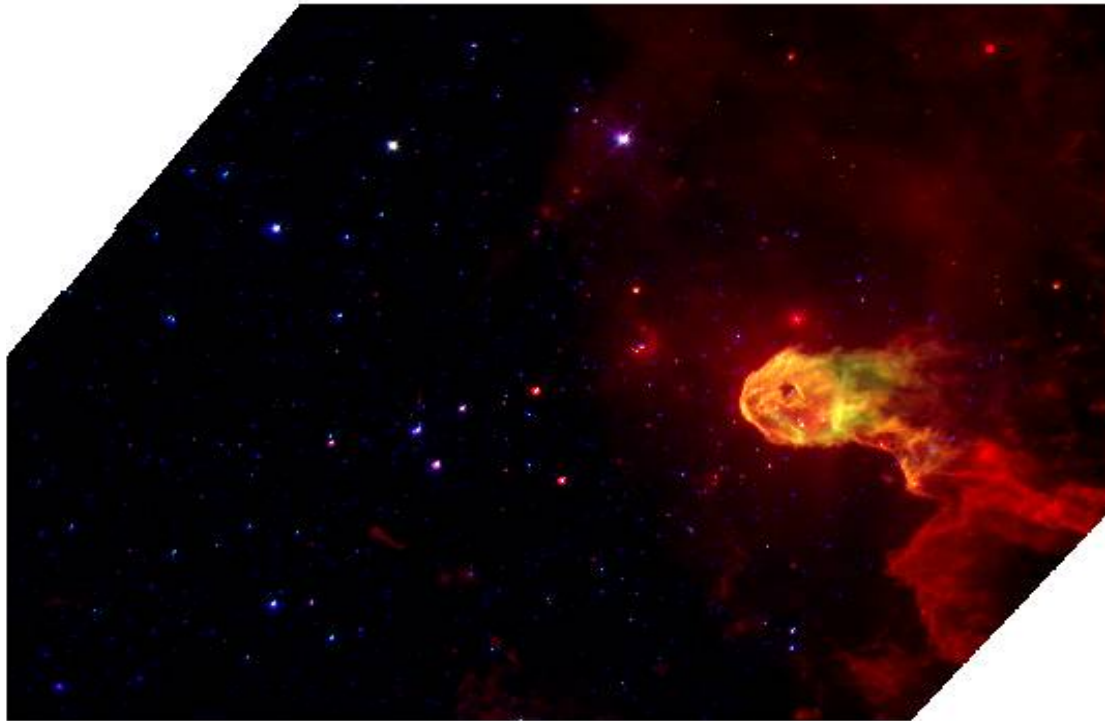


Multiwavelength Imaging of Stars, Disks and Newborn Planets



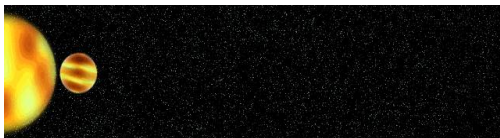
Aurora Sicilia-Aguilar, Max-Planck-Institut für Astronomie

Th. Henning, J. Bouwman, B. Merín, L. Hartmann, N. Calvet



Looking for the traces of planets: Is the Solar System a typical one?

- Planets are about a million times fainter than the star they orbit.
- The radius of a planet is about 100 times smaller than the stellar radius.
- The distance Sun-Earth is less than 1" even for the closer stars.



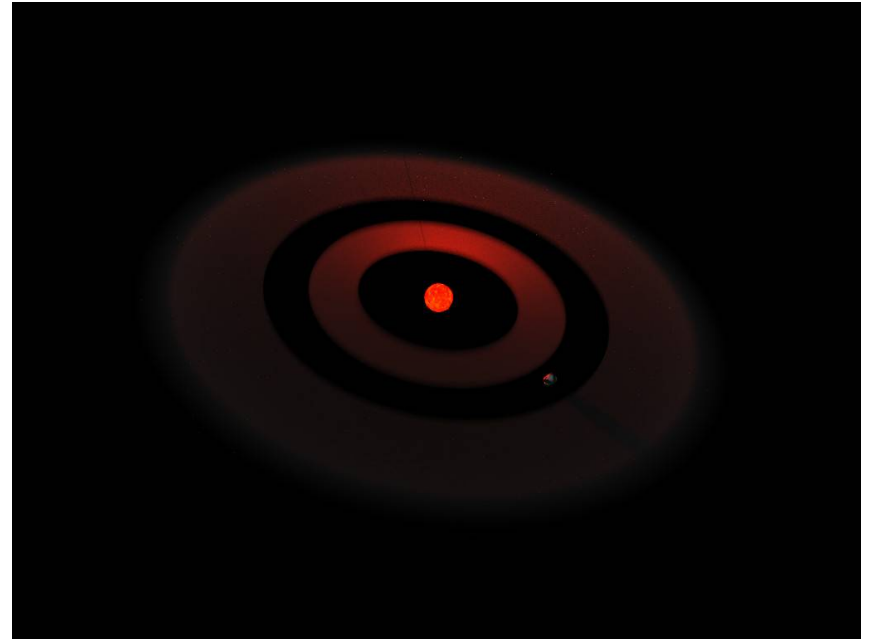
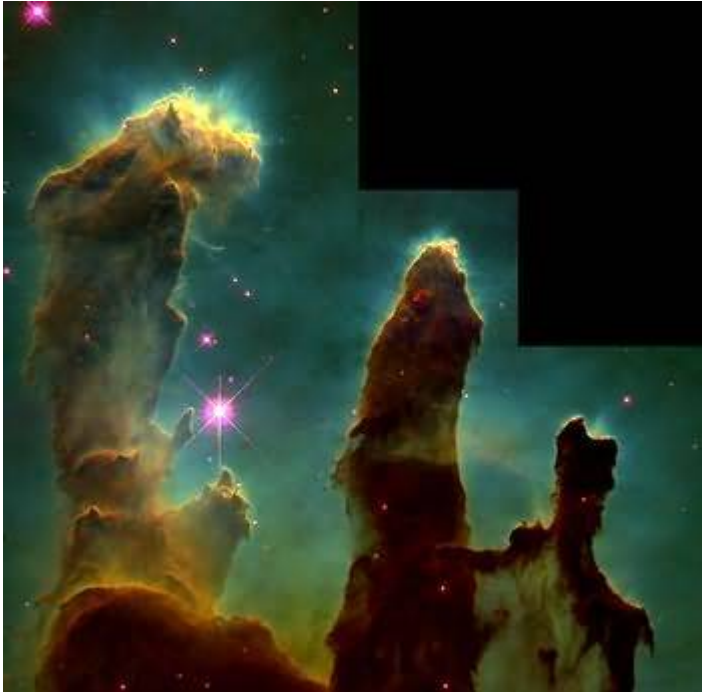
The planetary systems we found so far are very different from ours.

How frequent are planetary systems?

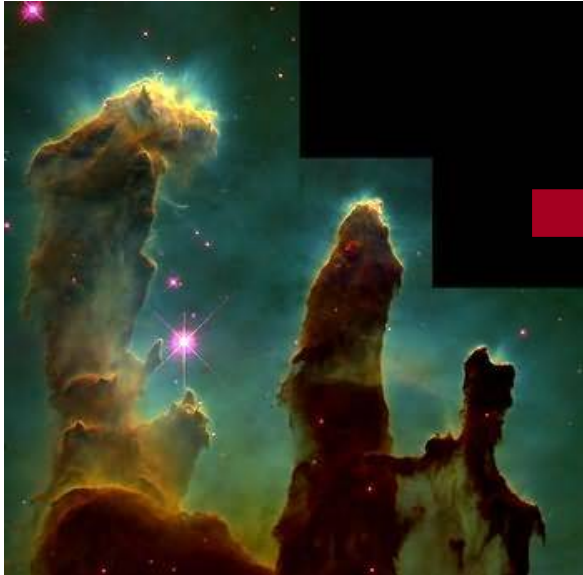
We find planets around 7% of the stars, but these are “special cases”.

Nearly all solar-type stars are formed with protoplanetary disks.

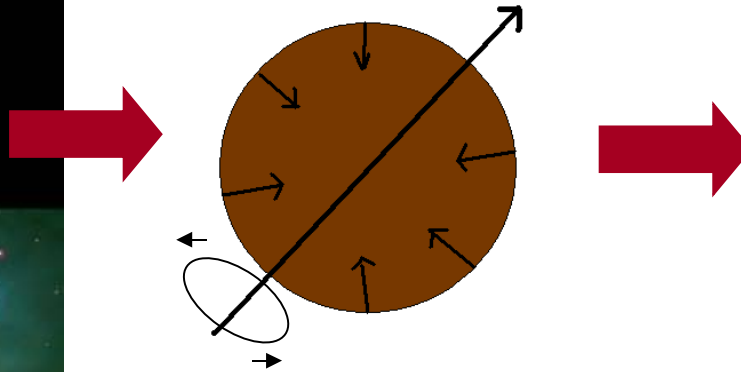
Disks disappear within 5-10 Myr, probably rendering planets.



The phases of planet formation

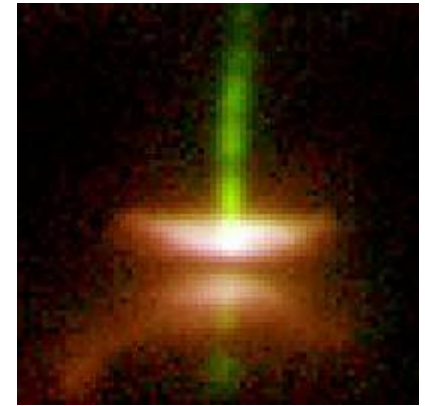


A **dust and gas** cloud contracts



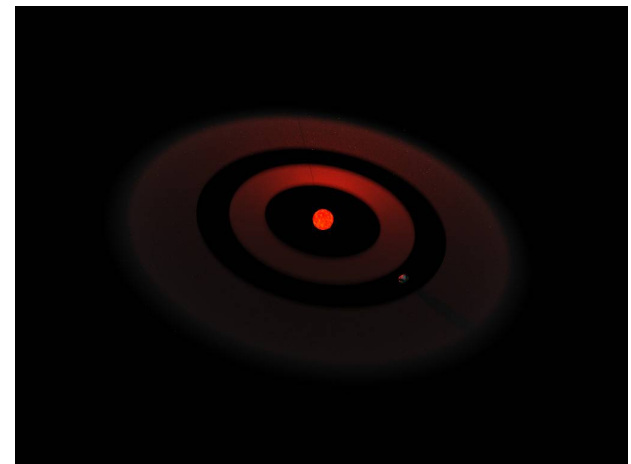
Gravitation detaches clumps, their **initial rotation flattens them**

A **star with a disk** is formed



HH 30, C. Burrows (STScI), the WFPC2 team, and NASA

The disk **coagulates**



The remaining disk is dissipated, and we are left with a **Planetary System**

The importance of studying young systems

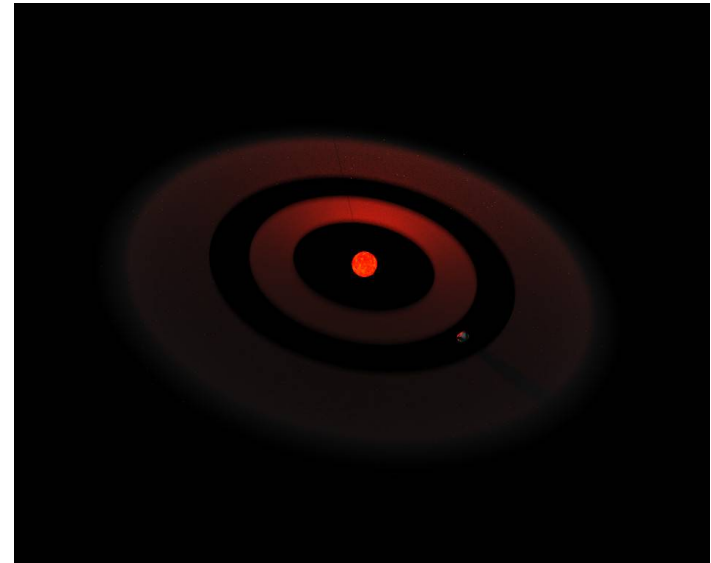
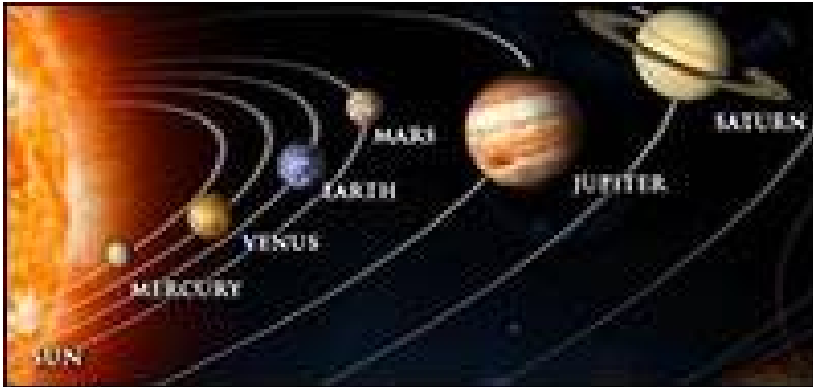
The planets and the disk are both heated by the star emitting at $\lambda \sim 3000 \mu\text{m} / T \text{ (K)}$, but...

~5 AU distance (Sun-Jupiter)

Planets are very faint
(compared to the star).

~300-500 AU radius

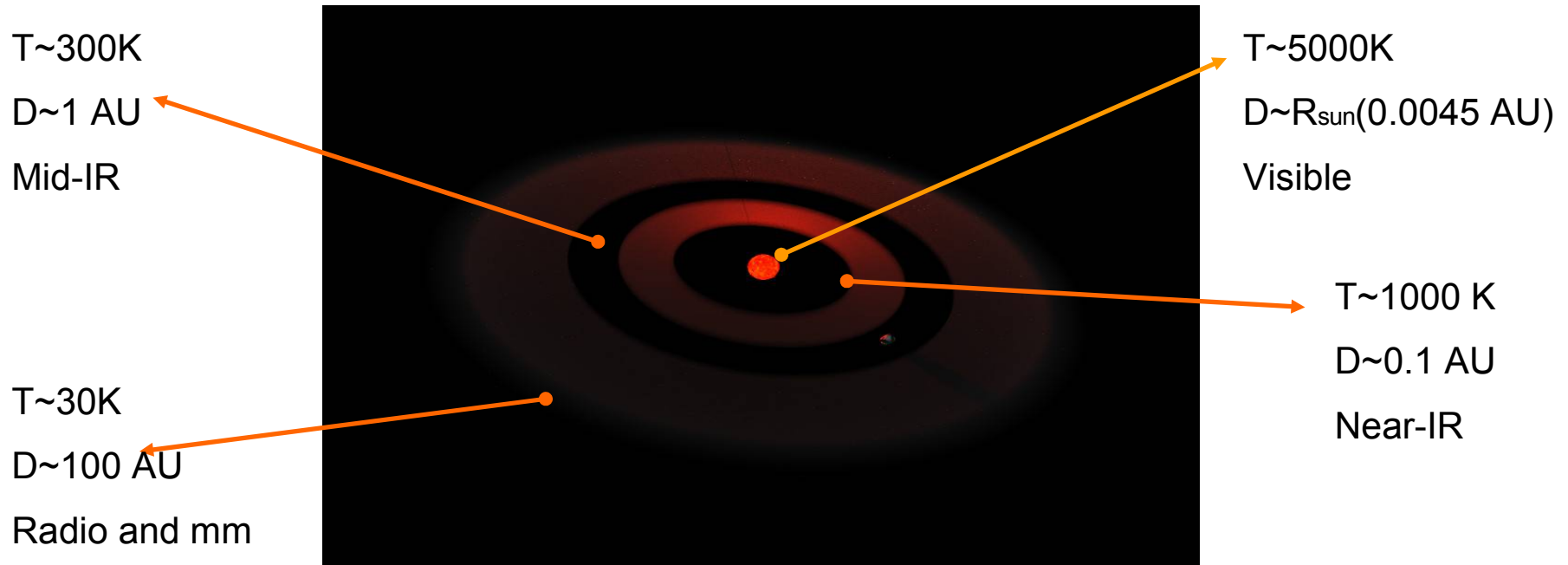
Very large surface:
large emission at long
wavelengths (IR-radio)



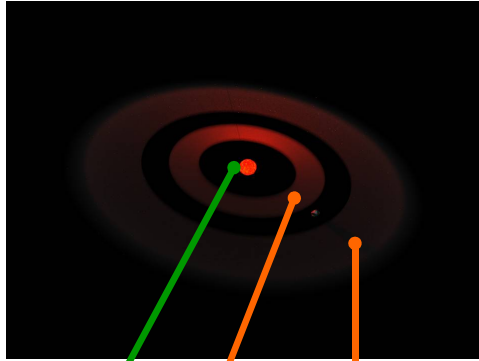
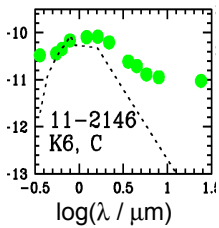
The importance of multiwavelength studies

How to get an “image” of what is too small to be spatially resolved?

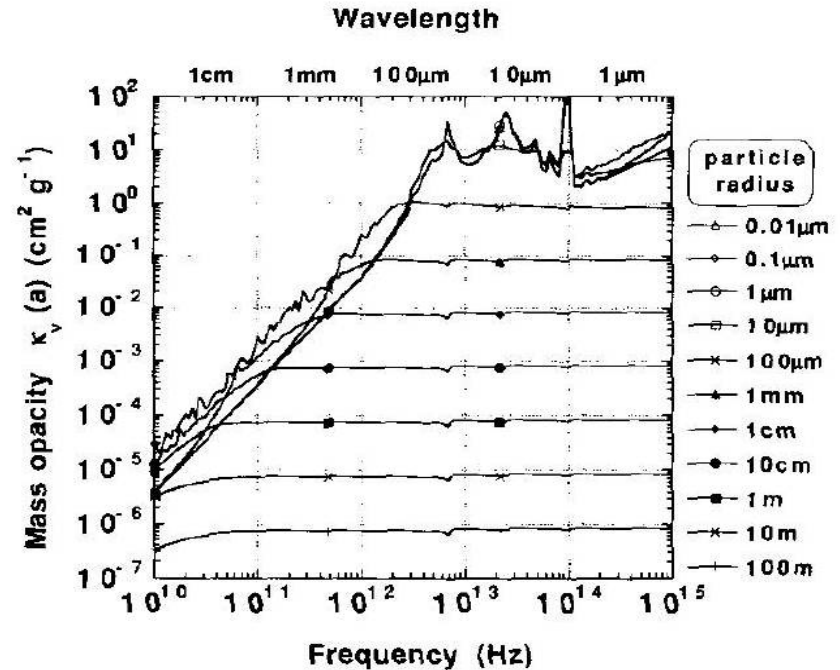
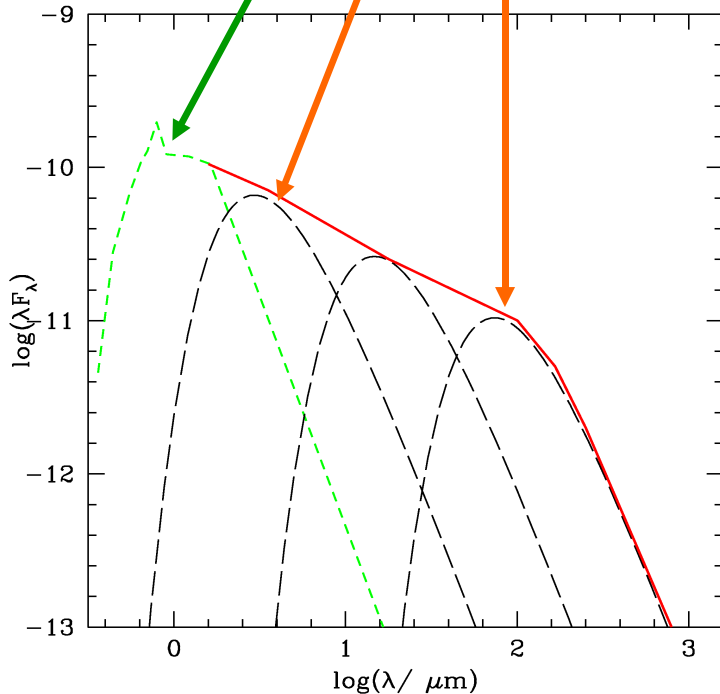
- ❖ Different temperatures → emission at different wavelengths → different distances.
- ❖ Different types of particles → emission at different wavelengths → materials.



The emission of the disk: Spectral Energy Distribution

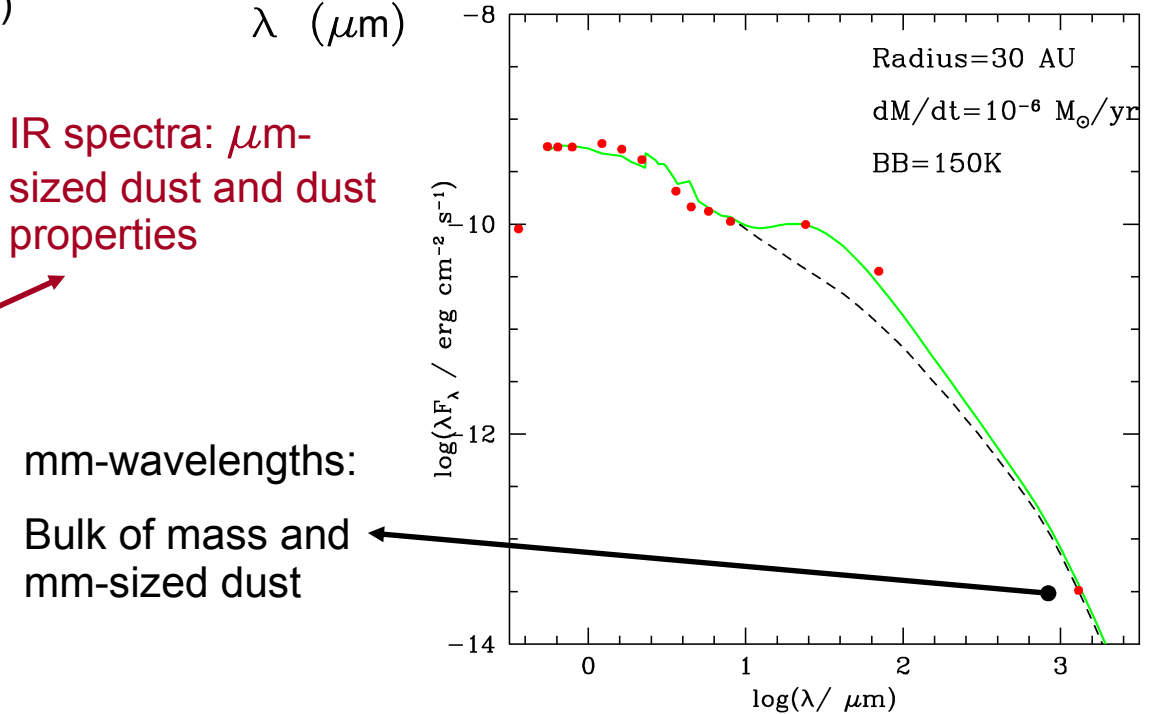
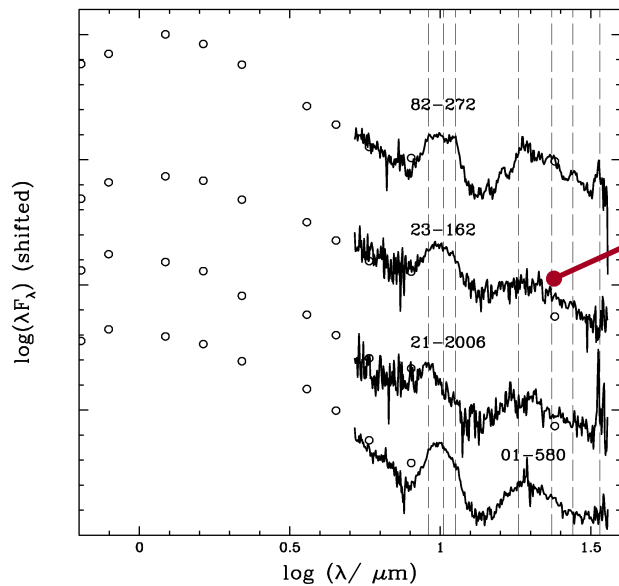
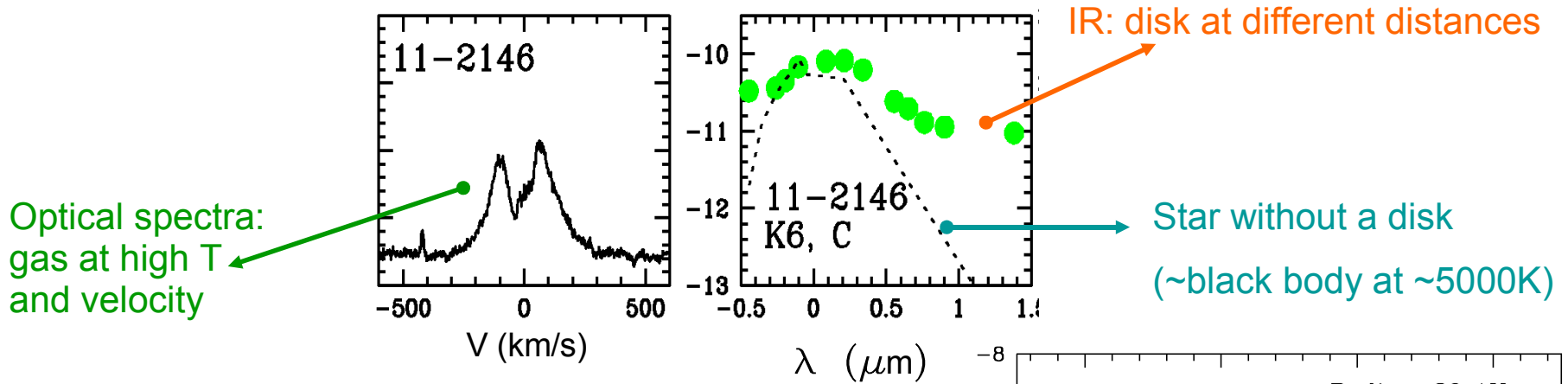


- Each part of the disk emits **approximately like a BB** at a certain **temperature** (depending on distance to the star).
- If there is a **gap**, we will **miss the BB** at that temperature.
- The total emission is \sim the sum of all BB... but...
- ... it also depends on the **dust size and properties**: we can know how the dust grains look like.



Miyake & Nakagawa (1993)

The multiwavelength picture we observe



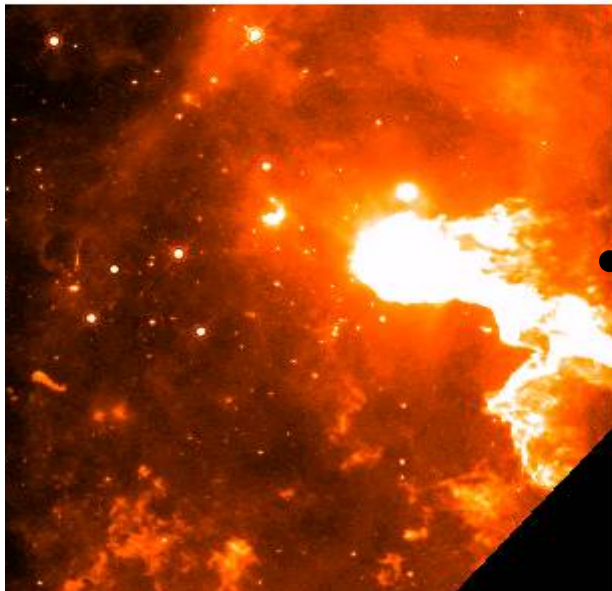
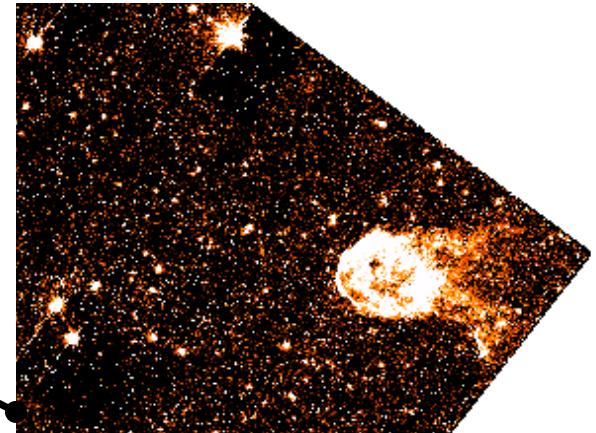
A journey through the cloud (in wavelength)

Tr 37, star forming region, 4 million years old, 3000 light years distance



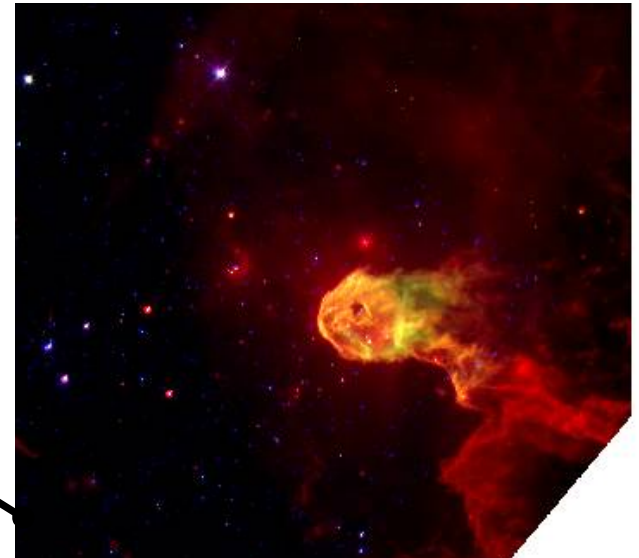
650 nm: stars and dust obscuration

3.6 μm : looking through the dust and dust BB "blue tail"

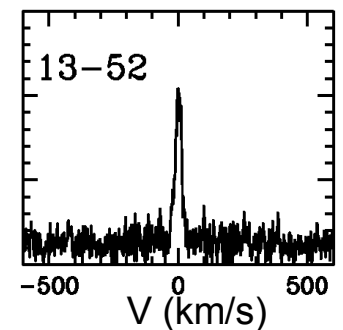
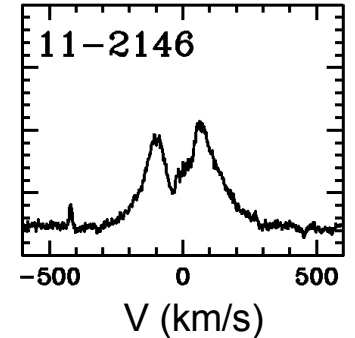
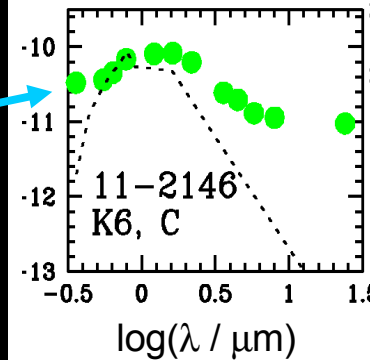
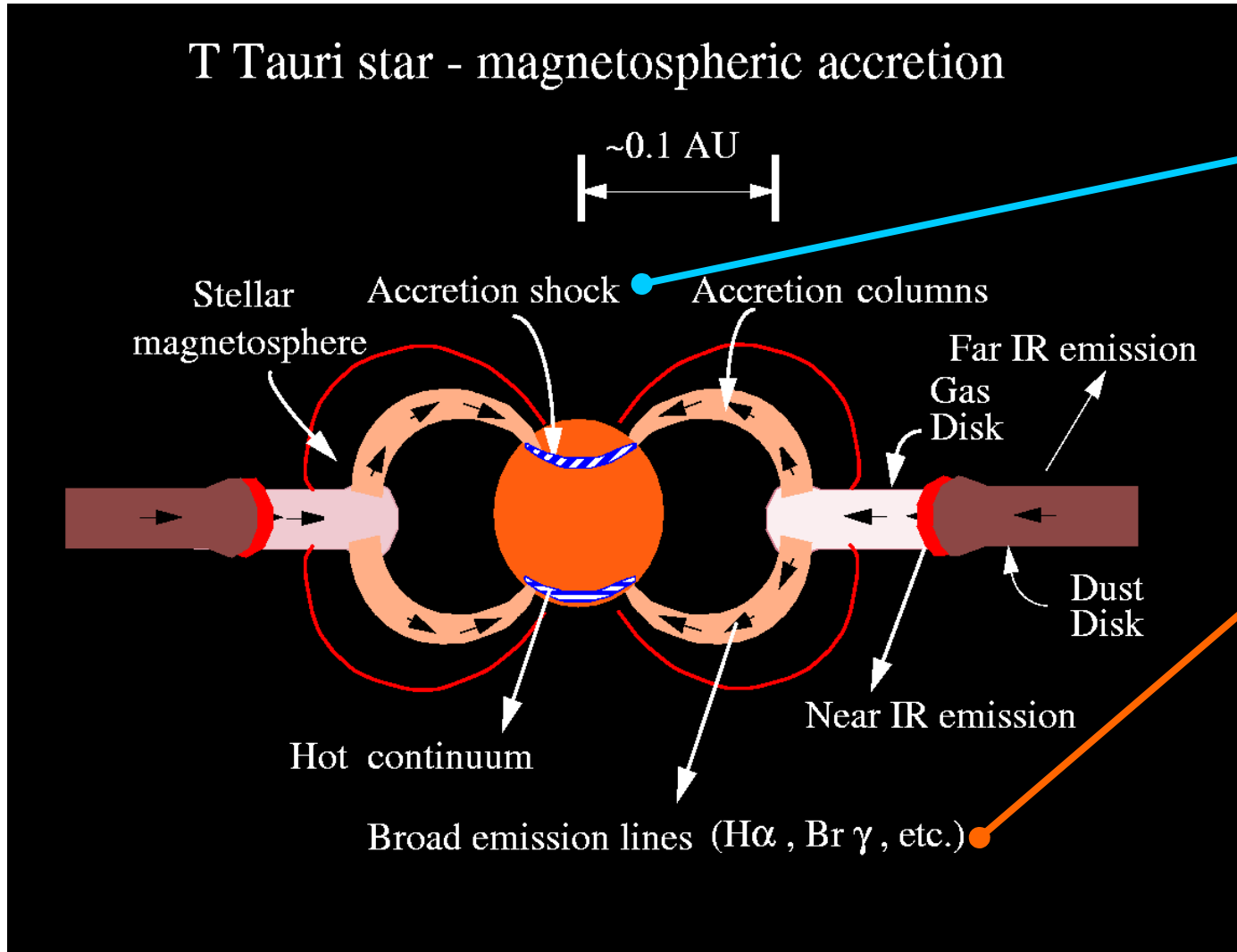


24 μm : near the peak of the warm dust BB emission

3.6, 8.0 and 24 μm : colorful journey through the cloud

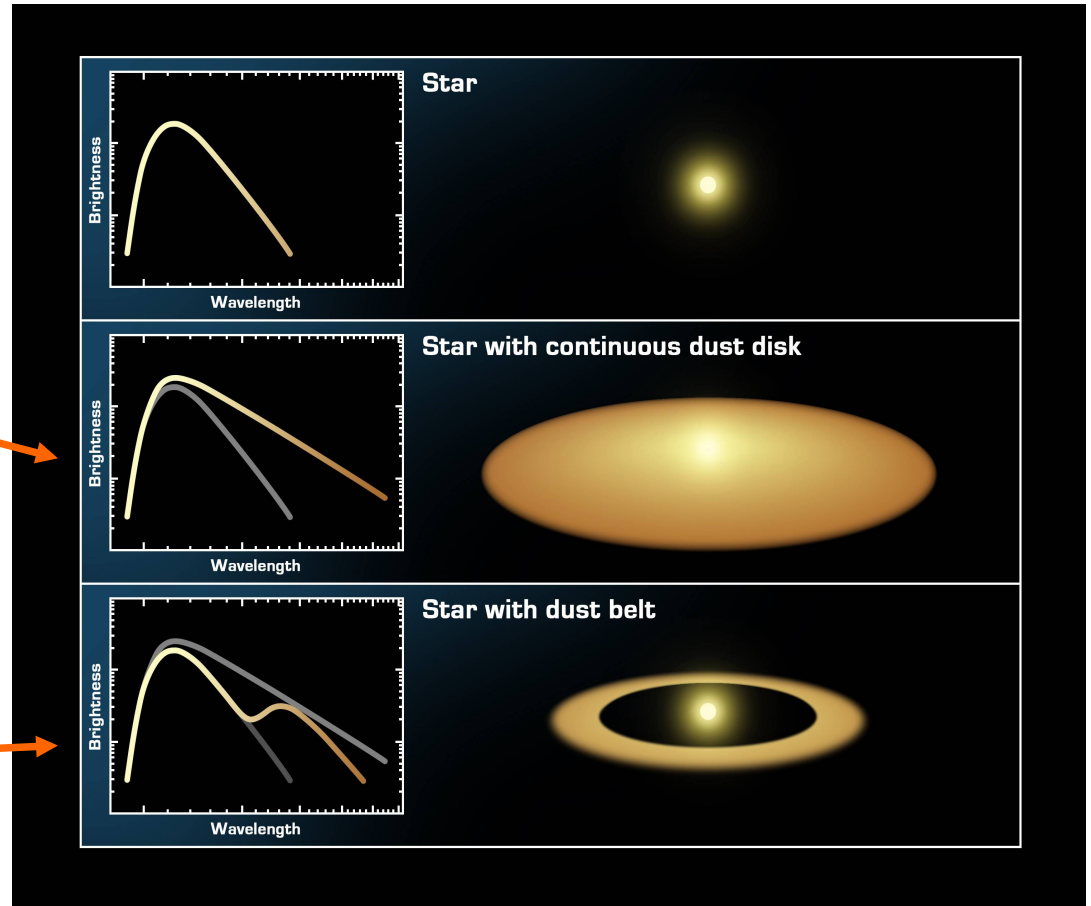
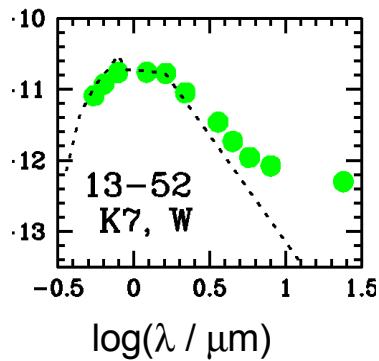
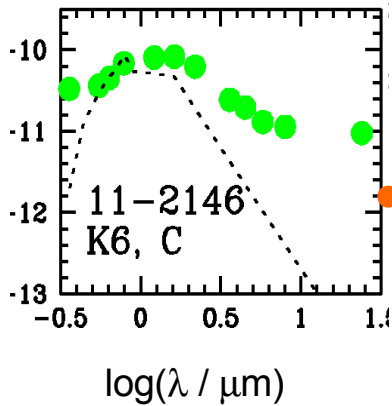
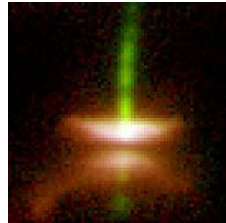


Optical and UV: The hot and active star





Near- and mid-IR: any planet there?



NASA/JPL-Caltech/T. Pyle (SSC)

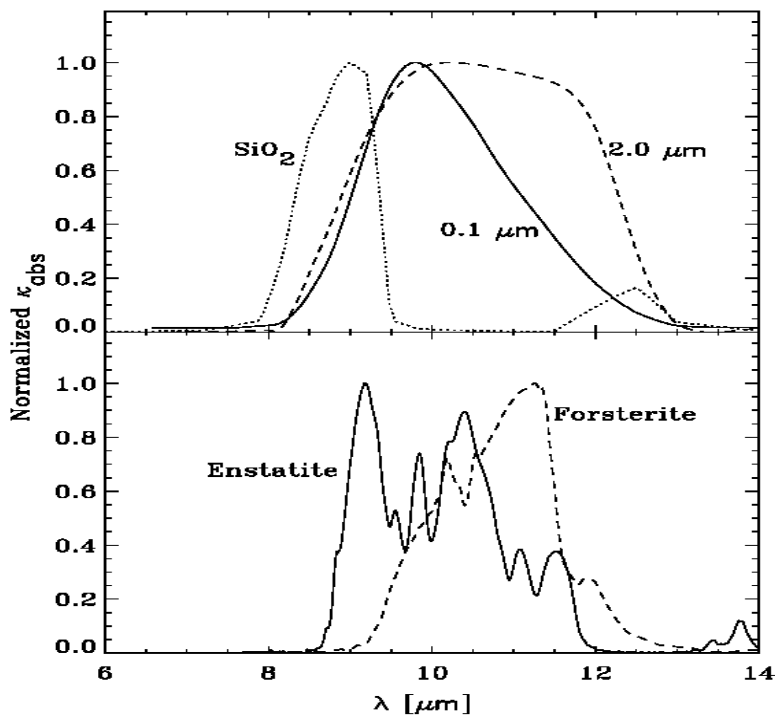


To keep the gap open, planets are required

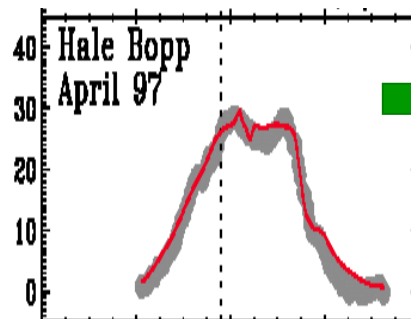
IR Spectra: dust mineralogy

The spectral lines in IR reveal:

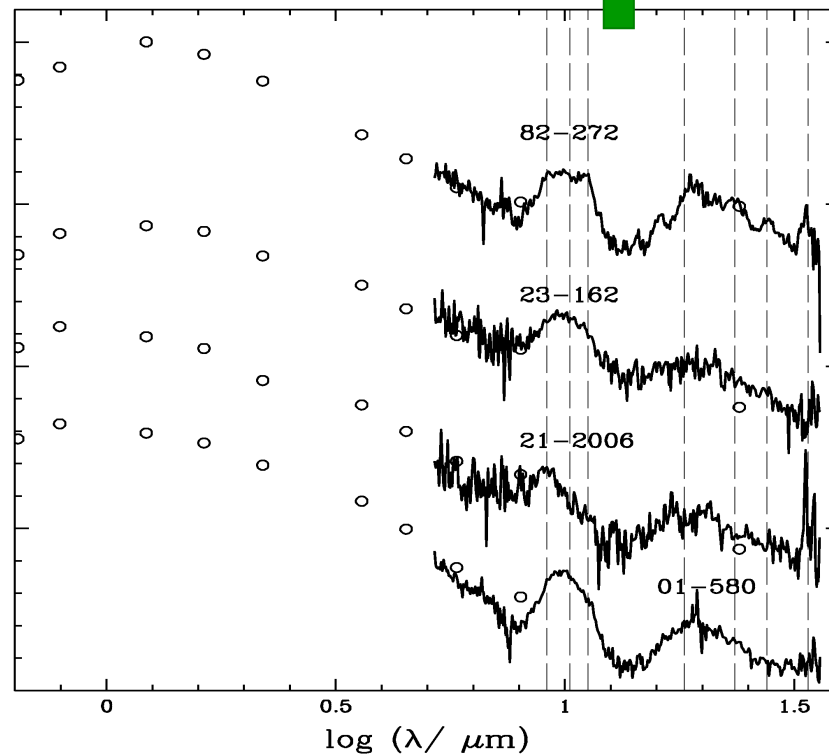
- **Temperature** (location in the disk).
- **Size** of the dust grains.
- **Composition**.
- **Solid state** (amorphous/ crystalline).



Bouwman et al. 2001



Disks around other stars have the same composition than our Solar System

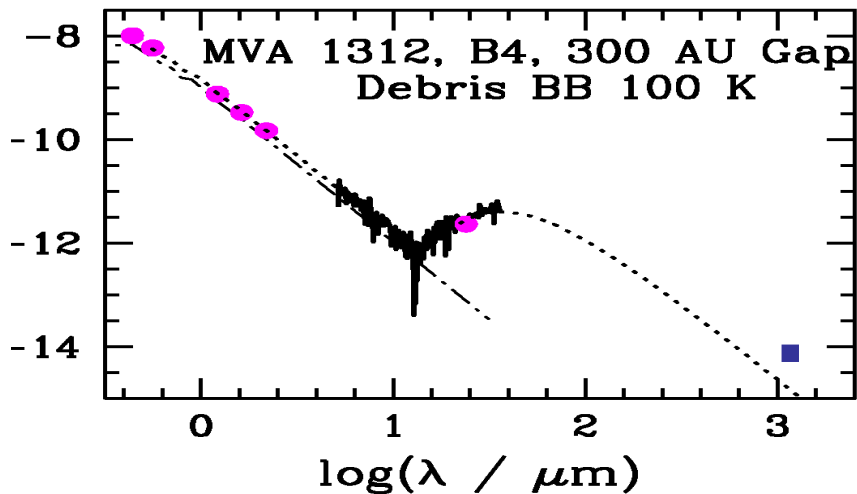
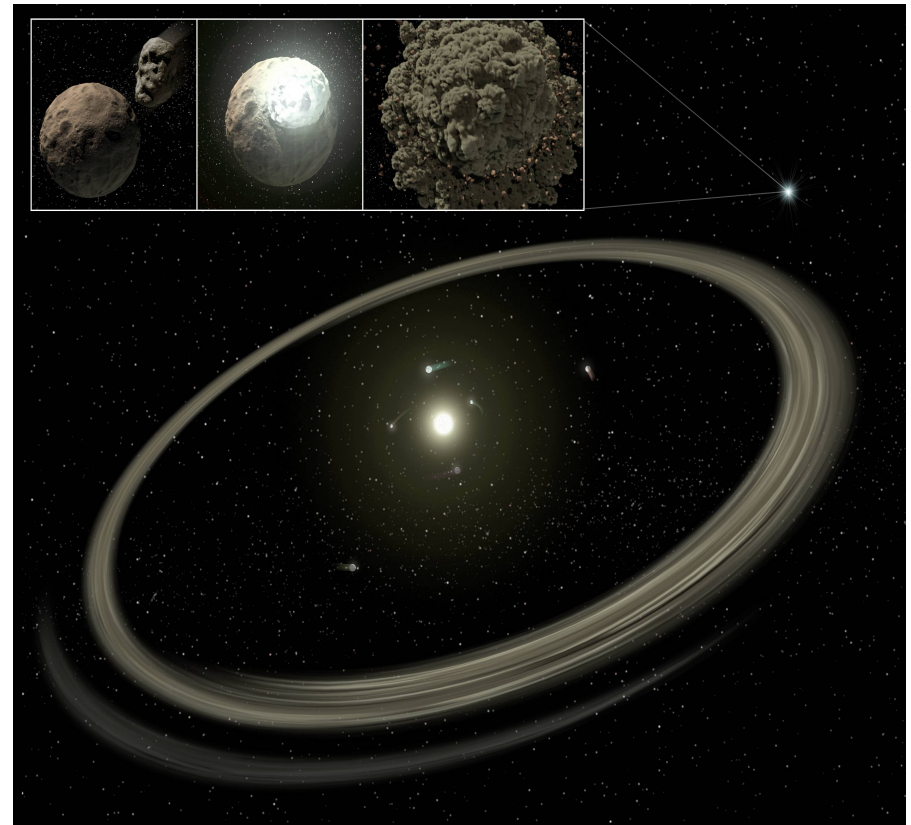




The mid- and far-IR

- **Trace colder material at larger distances:** Kuiper Belts, cometary belts and dusty rings remaining from planet formation.
- **Trace larger grains:** constraint grain size and composition.

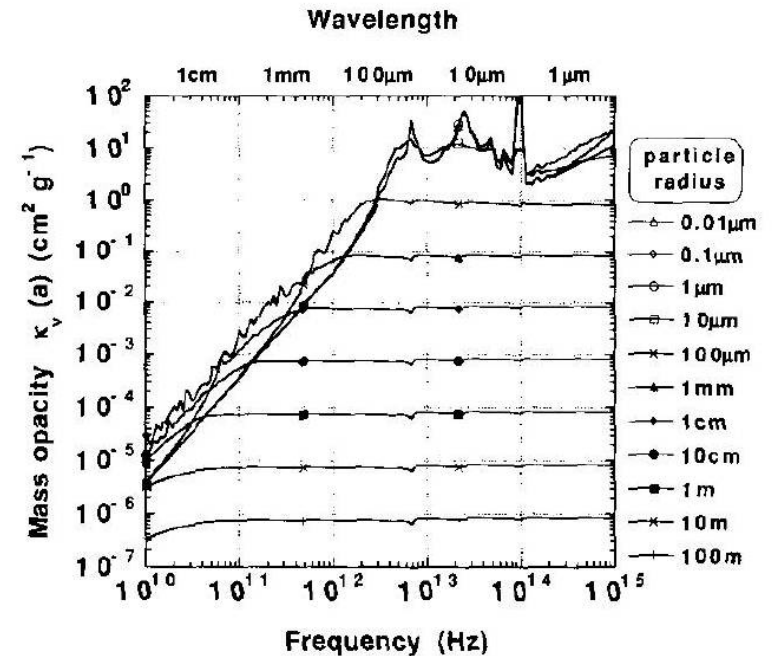
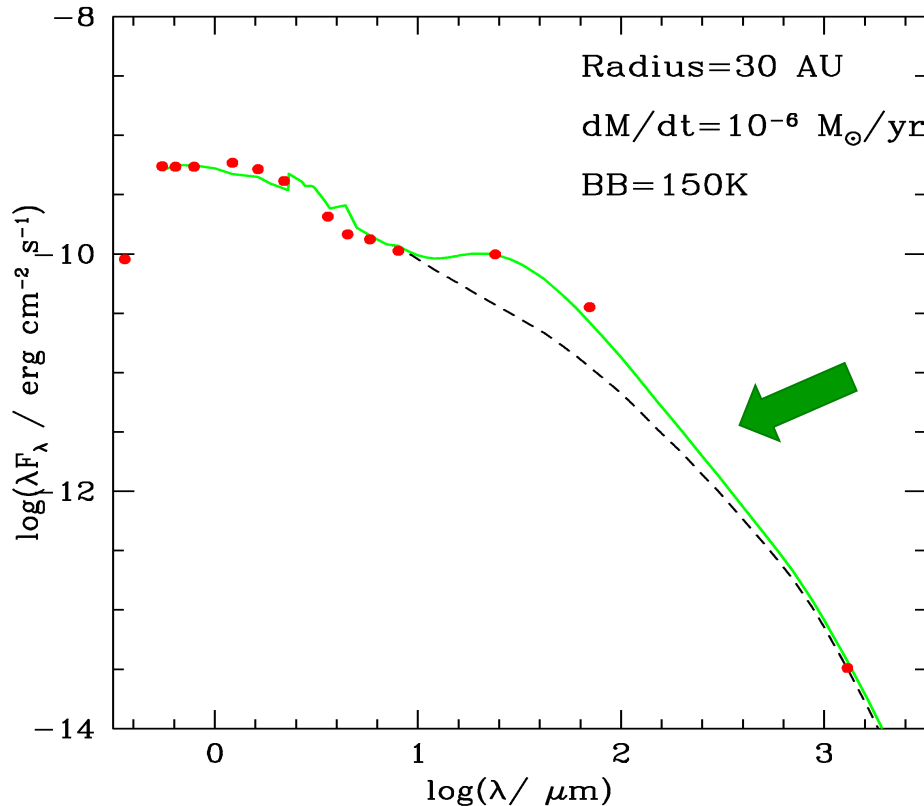
Artist picture of an extra-solar Kuiper belt.





Far-IR

- At longer wavelengths, we trace **larger grains** and **colder matter**; $\lambda \sim 3000 \mu\text{m} / T(\text{K})$.
- The far-IR is very important to determine the **sizes of the dust particles** and the **disk structure** at large scale.
- **Herschel** will be a very important instrument to reveal the disk structure: and to detect grain growth.

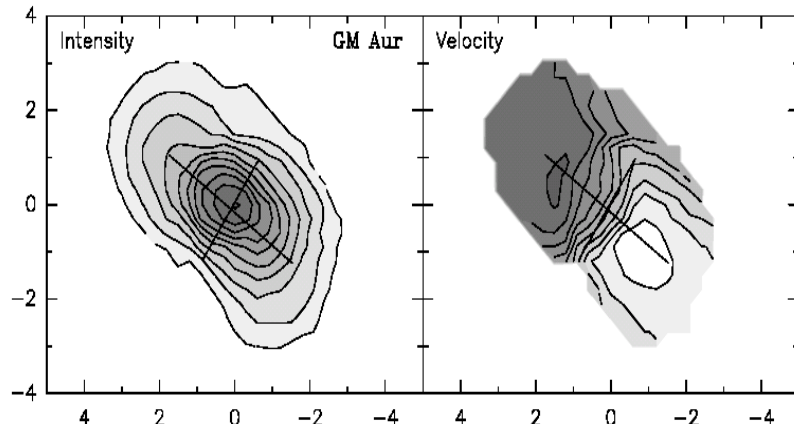
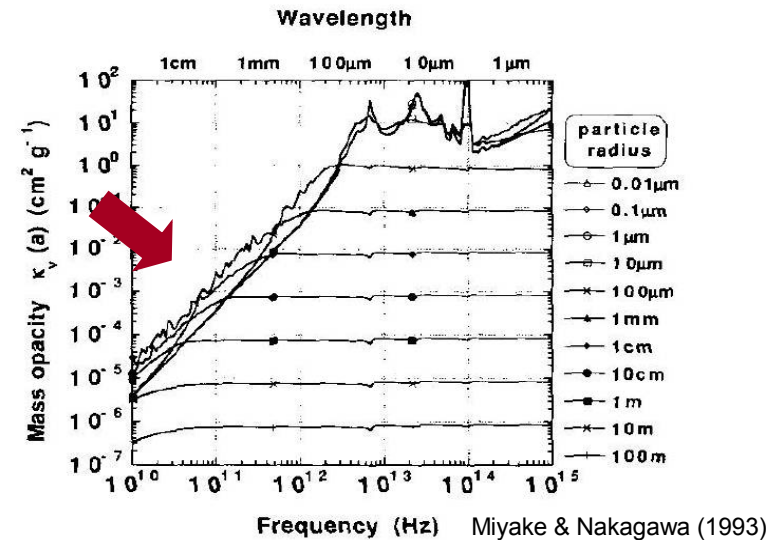


Miyake & Nakagawa (1993)

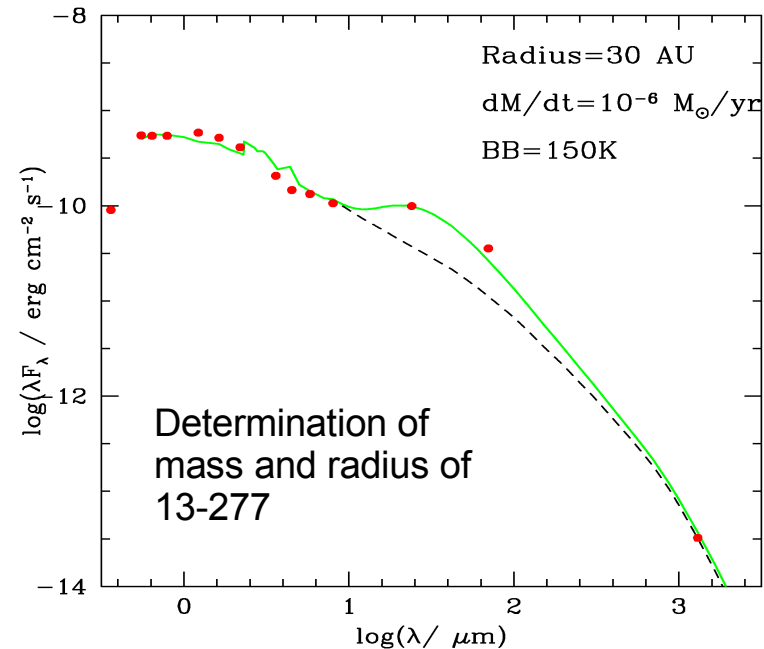


Millimetre and sub-millimetre regime

- Trace **large particles** (mm sizes) and the **total mass**: the disk is “transparent” at mm wavelengths.
- Resolving **disk rotation** via Doppler shifts in CO lines.
- Resolving **disk size** (interferometry).

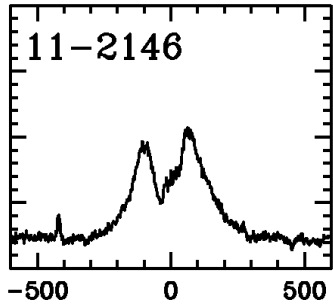


¹²CO(2-1) transition for the GM Aur disk, observed with 4 IRAM antennae (Dutrey et al. 1998).

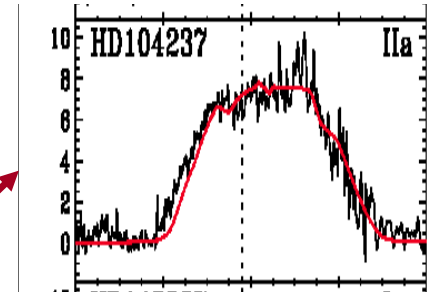


The multiwavelength spatial picture

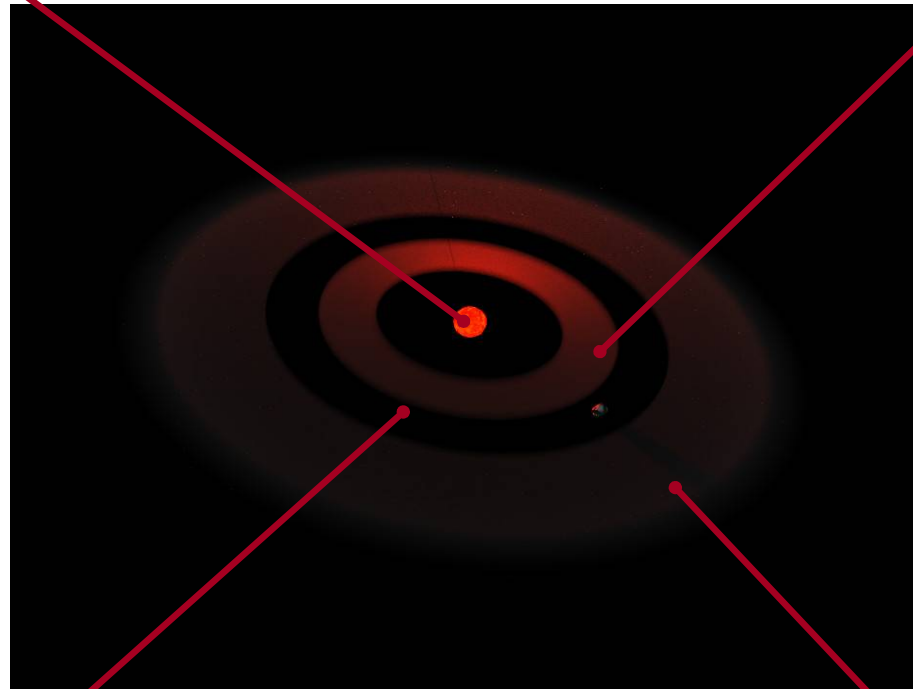
Bouwman et al. 2001



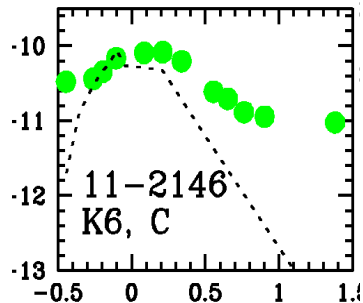
Optical and UV: stellar properties, accretion, chromospheric activity



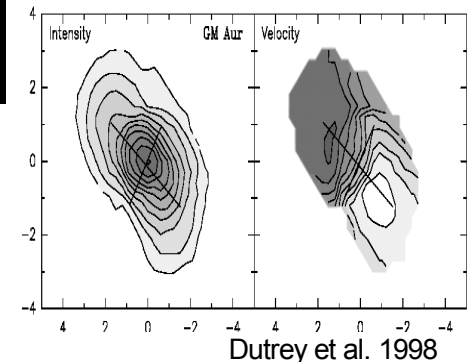
IR spectra: mineralogy, disk structure



IR photometry: inner disk structure, presence of gaps

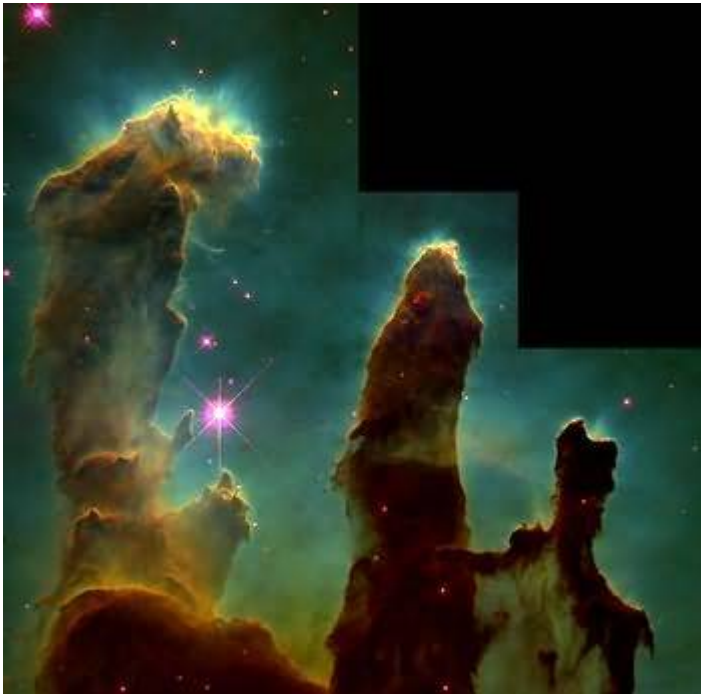


mm and radio: total mass, whole disk spatial resolution, disk rotation

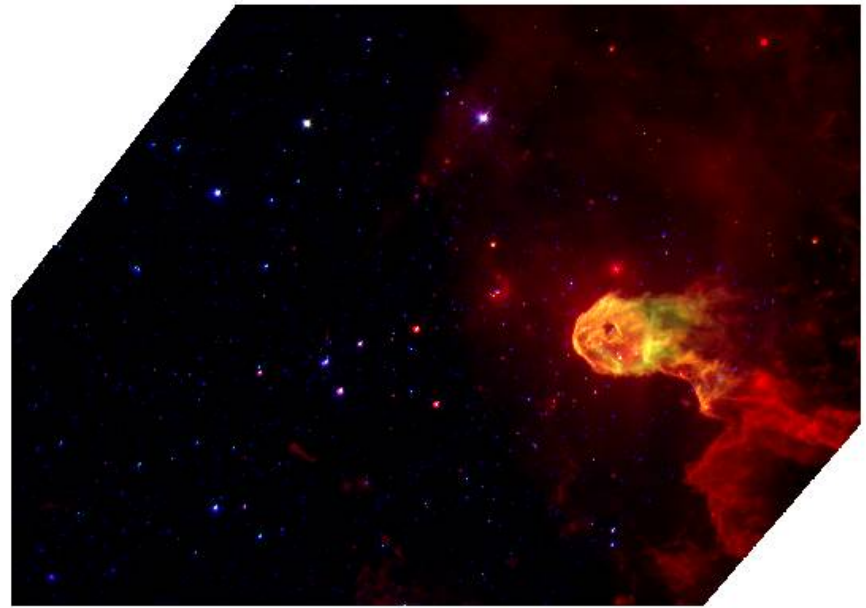


Witnessing the formation of our Solar System

4600 million years ago...



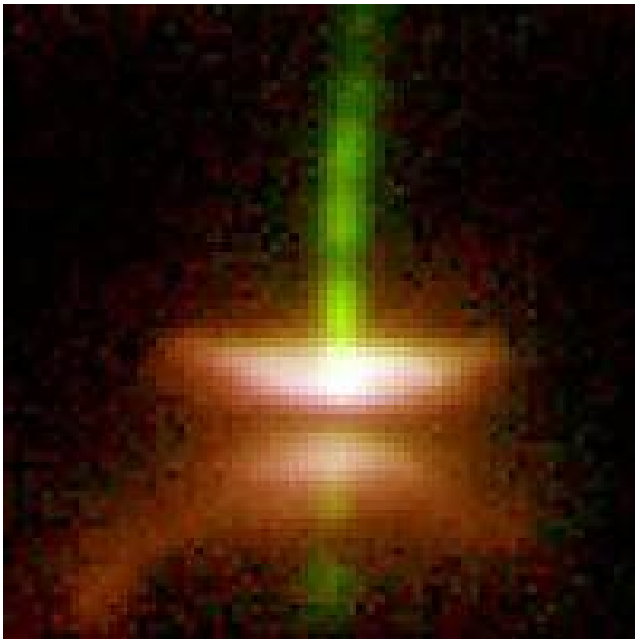
Eagle Nebula, J. Hester & P. Scowen, Arizona State University, NASA, ESA, STScI



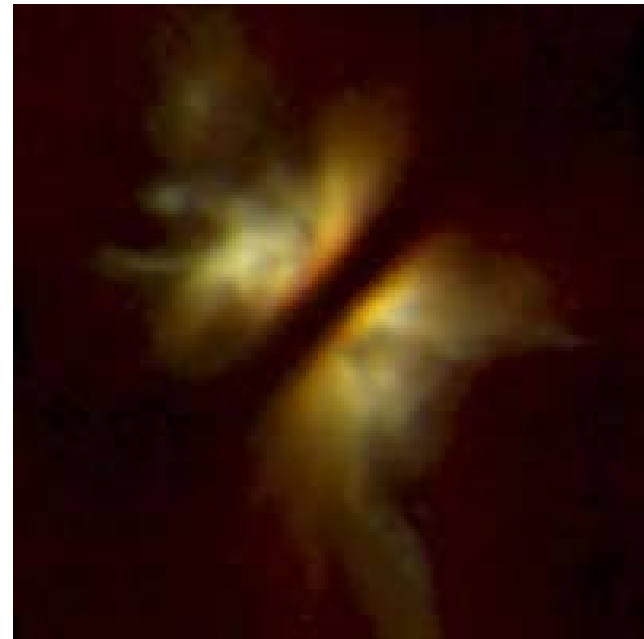
Tr 37, Spitzer Space Telescope, Sicilia-Aguilar et al.

Witnessing the formation of our Solar System

After 500,000 years...



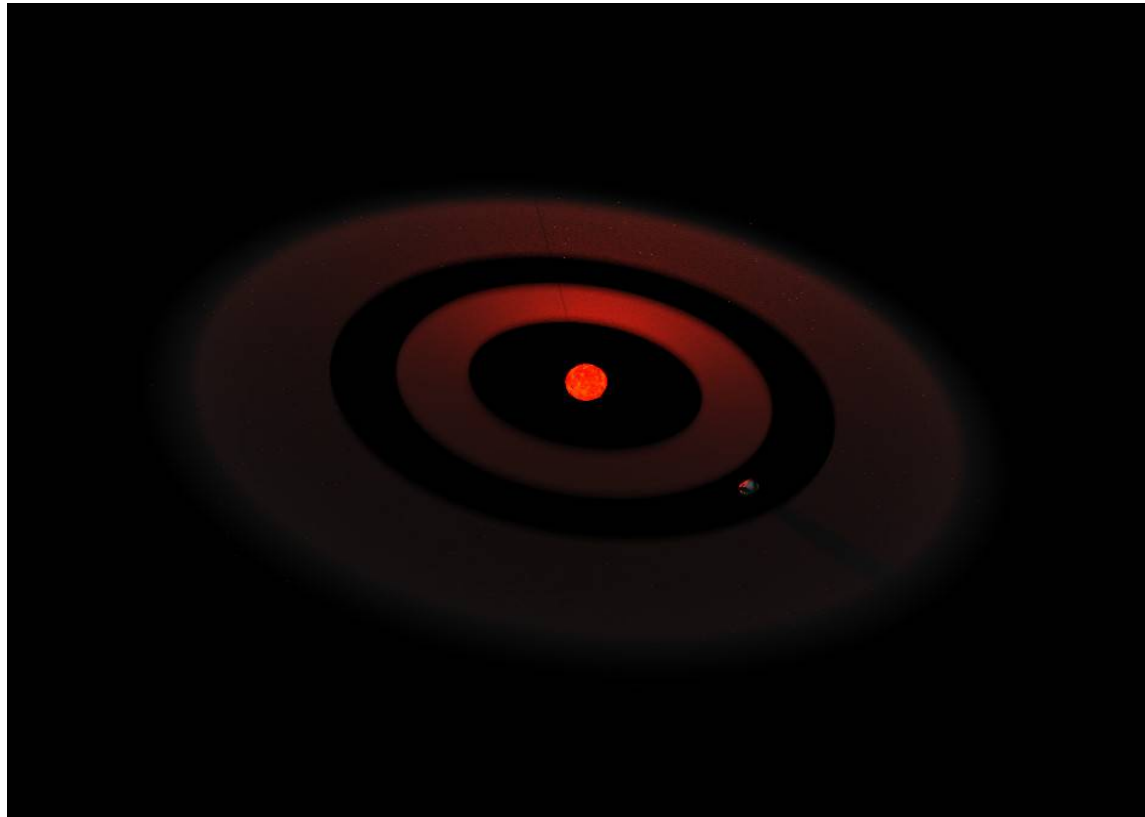
HH 30, C. Burrows (STScI), the WFPC2 team, and NASA



IRAS 04302 disk: D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

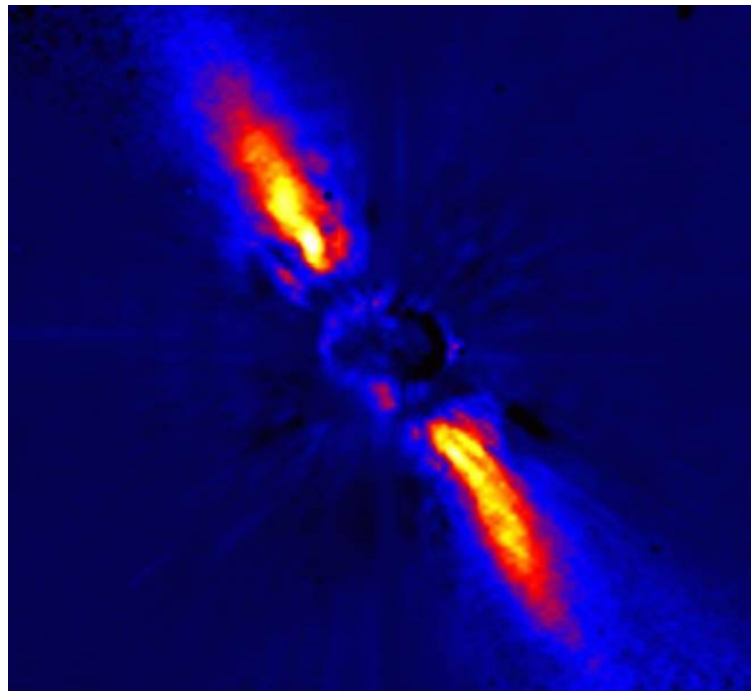
Witnessing the formation of our Solar System

After ~3 million years...



Witnessing the formation of our Solar System

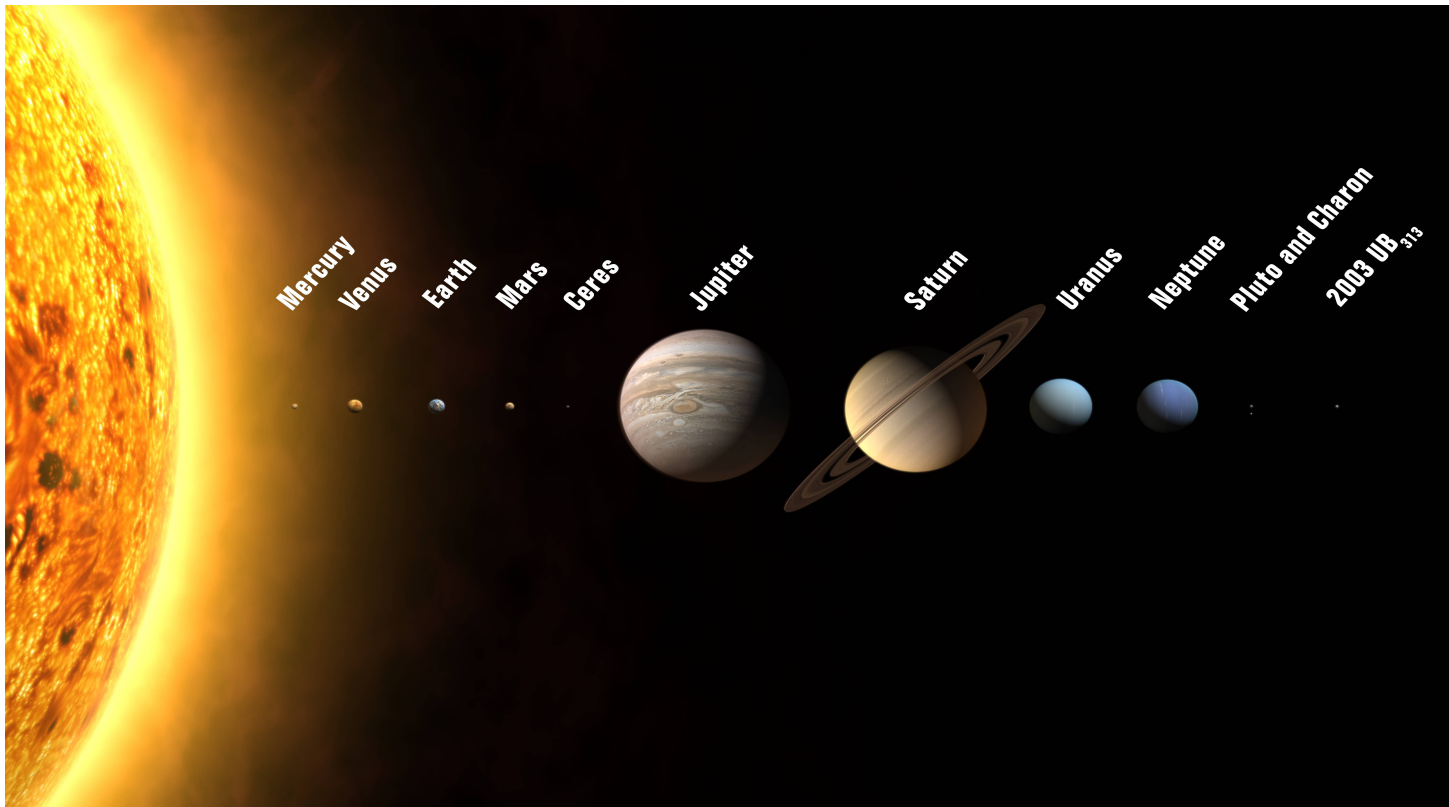
After ~8 million years...



Near-IR image of β Pictoris, by J-L Beuzit et al., using the ADONIS adaptive optics system at the 3.6-m telescope and the Observatoire de Grenoble, ESO, coronagraph.

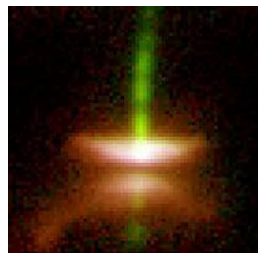
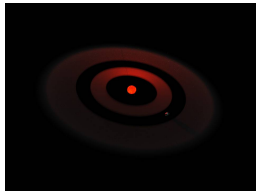
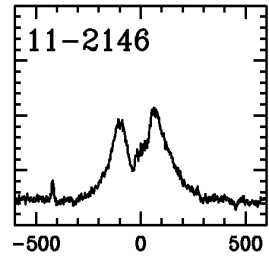
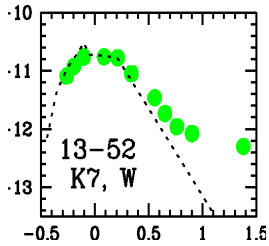
Witnessing the formation of our Solar System

After ~300 million years and until now...



The International Astronomical Union/Martin Kornmesser

Summary



- Multiwavelength images **resolve what is spatially unresolved**, being sensitive to different T (distance).
- **Visible wavelengths** trace hot matter (star and stellar chromosphere) and scattered light.
- **Near- and mid-IR** trace small grains in the terrestrial planet forming region.
- **Mid- and far-IR** trace larger grains the gaseous planet forming region.
- **Millimetre and radio** trace small sand and pebbles in the whole disk.
- **Young systems** are easier to detect and let us witness the formation of our own Solar System.