# Planet formation with ALMA

AstroTwin Colombia School 2022
Planet formation and ALMA

dr. Nienke van der Marel
Leiden Observatory
@NienkeMarel

# About me

**3.** NRC & Banting fellow
Herzberg & University of Victoria
Canada (2017-2021)

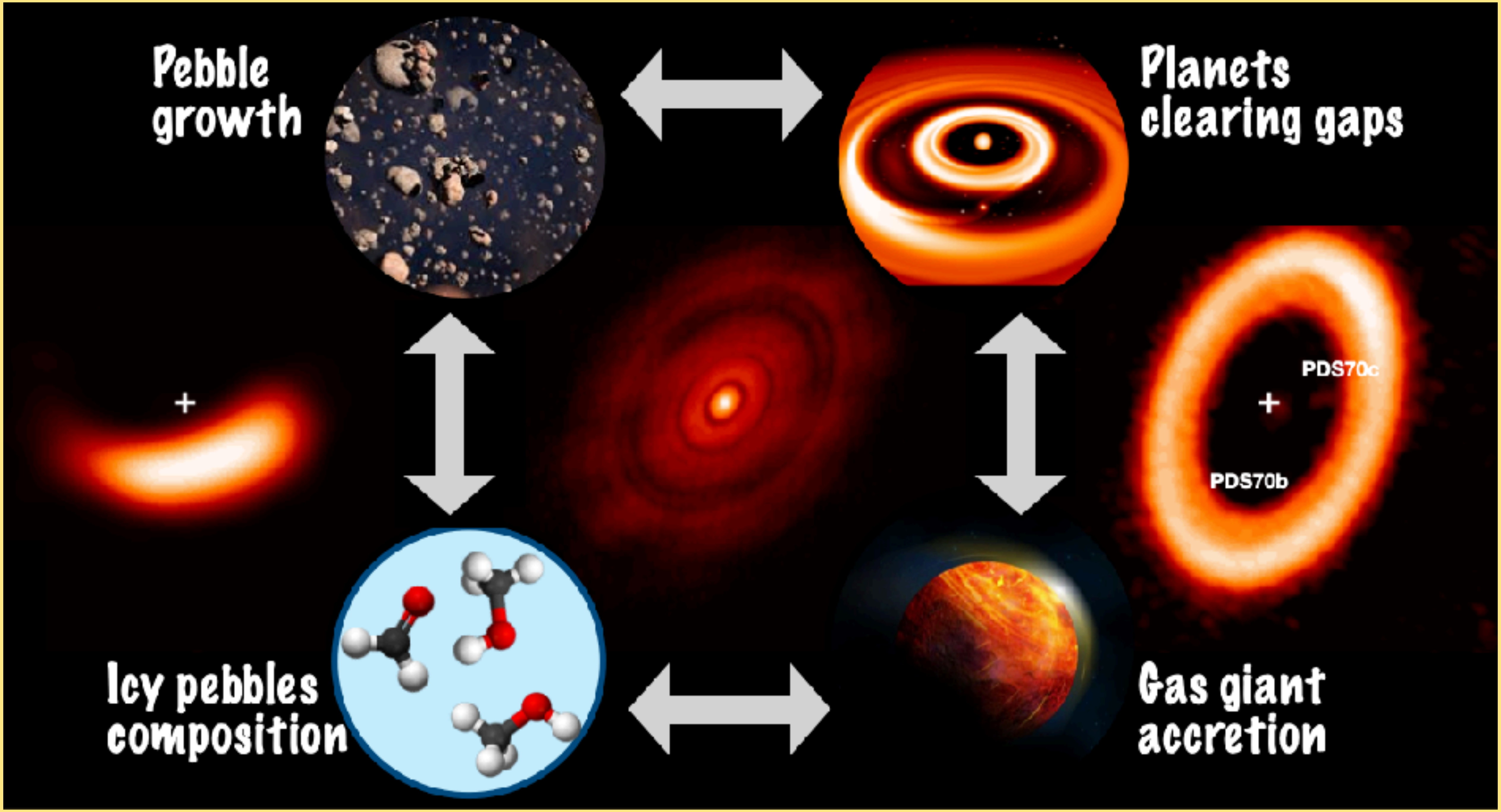
**1.** BSc+MSc+PhD Leiden University,
the Netherlands (2004-2015)

**4.** Assistant professor
Leiden University,
the Netherlands (2021-)

**2.** Parrent fellow,
University of Hawaii,
USA (2015-2017)

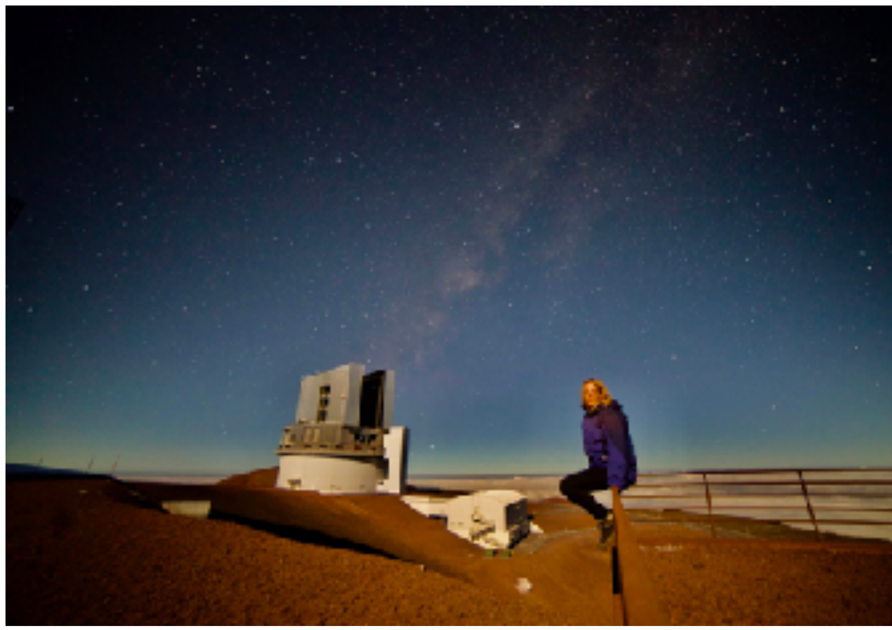

http://www.nienkevandermarel.com

# My research



Pebble growth
Planets clearing gaps
PDS70c
PDS70b
Icy pebbles composition
Gas giant accretion

# More about me







# More about me

**Hablo pocito Espanol…**

# This week

- 7 Lectures of 1.5 hours (with 15 minute break)
- ALMA tutorial
- ALMA data reduction project: work in pairs
- Paper presentation project: work in pairs
- Ask questions!

# This week

- Lectures
    1. Overview and history of the study of protoplanetary disks
    2. Basics of interferometry and ALMA
    3. Disk evolution and dust evolution
    4. Disk substructures and their connection to planets
    5. Disk mass in dust and gas
    6. Disk chemistry and kinematics
    7. Exoplanets and planet formation theory

# This week

**Monday December 5$^{th}$**

- 9.00 – 10.45 Lecture 1: Overview
- 11.00 – 12.45 Literature: divide in pairs, choose paper of interest
- 12.45 – 13.45 Lunch break
- 13.45 – 15.30 Lecture 2: Interferometry
- 15.45 – 17.30 ALMA tutorial

**Tuesday December 6$^{th}$**

- 9.00 – 10.45 Lecture 3: Evolution
- 11.00 – 12.45 ALMA: choose project and start imaging data
- 12.45 – 13.45 Lunch break
- 13.45 – 15.30 Lecture 4: Substructures
- 15.45 – 17.30 Literature/ALMA project

**Wednesday December 7$^{th}$:**

- 9.00 – 10.45 Lecture 5: Disk mass
- 11.00 – 12.45 ALMA: continue with ALMA project
- 12.45 – 13.45 Lunch break
- 13.45 – 15.30 Lecture 6: Chemistry and kinematics
- 15.45 – 17.30 Literature: prepare presentation for Friday

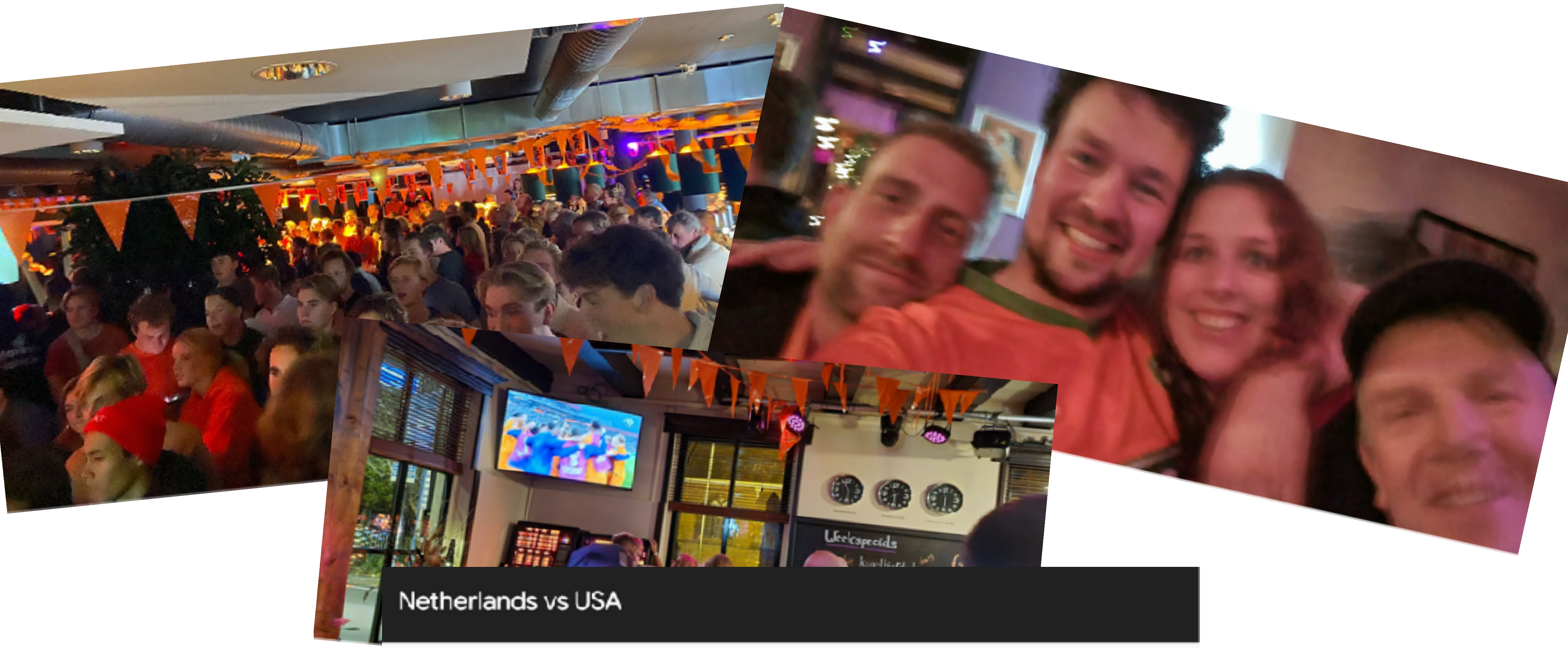
**Thursday December 8$^{th}$:**

Holiday

**Friday December 9$^{th}$:**

- 9.00 – 11.15 Student presentations literature (10 minutes each pair)
- 11.30 – 12.45 Lecture 7: exoplanets and planet formation theory
- 12.45 – 13.45 Lunch break
- 13.45 – 15.30 ALMA: continue project, prepare figures/slides
- 15.45 – 16.45 Student presentations ALMA (5 minutes each pair)
- 17.00 – 17.30 Summary and wrap up

# But this happened last Friday..



**Netherlands vs USA**

FIFA World Cup 2022™ · Sat, Dec 3 — Full-time

| Netherlands | 3 | - | 1 | USA |
|---|---|---|---|---|

Round of 16

Memphis Depay 10'
Daley Blind 45+1'
Denzel Dumfries 81'

Haji Wright 76'

# This week

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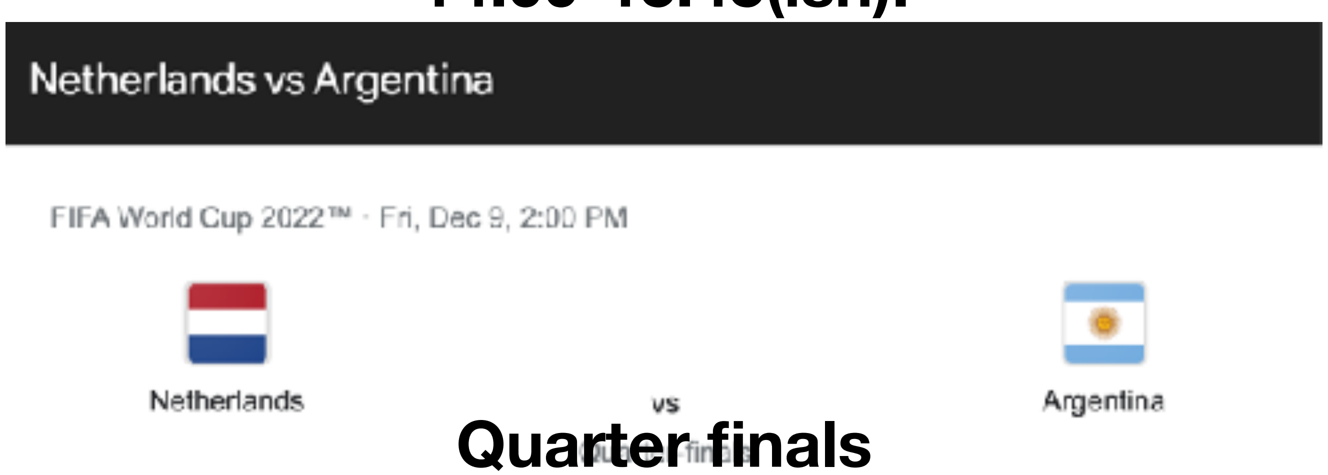
**14.00-15.45(ish):**




**Quarter finals**

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**What do you think about when I say planet formation?**

# Lecture 1
# Overview of protoplanetary disks

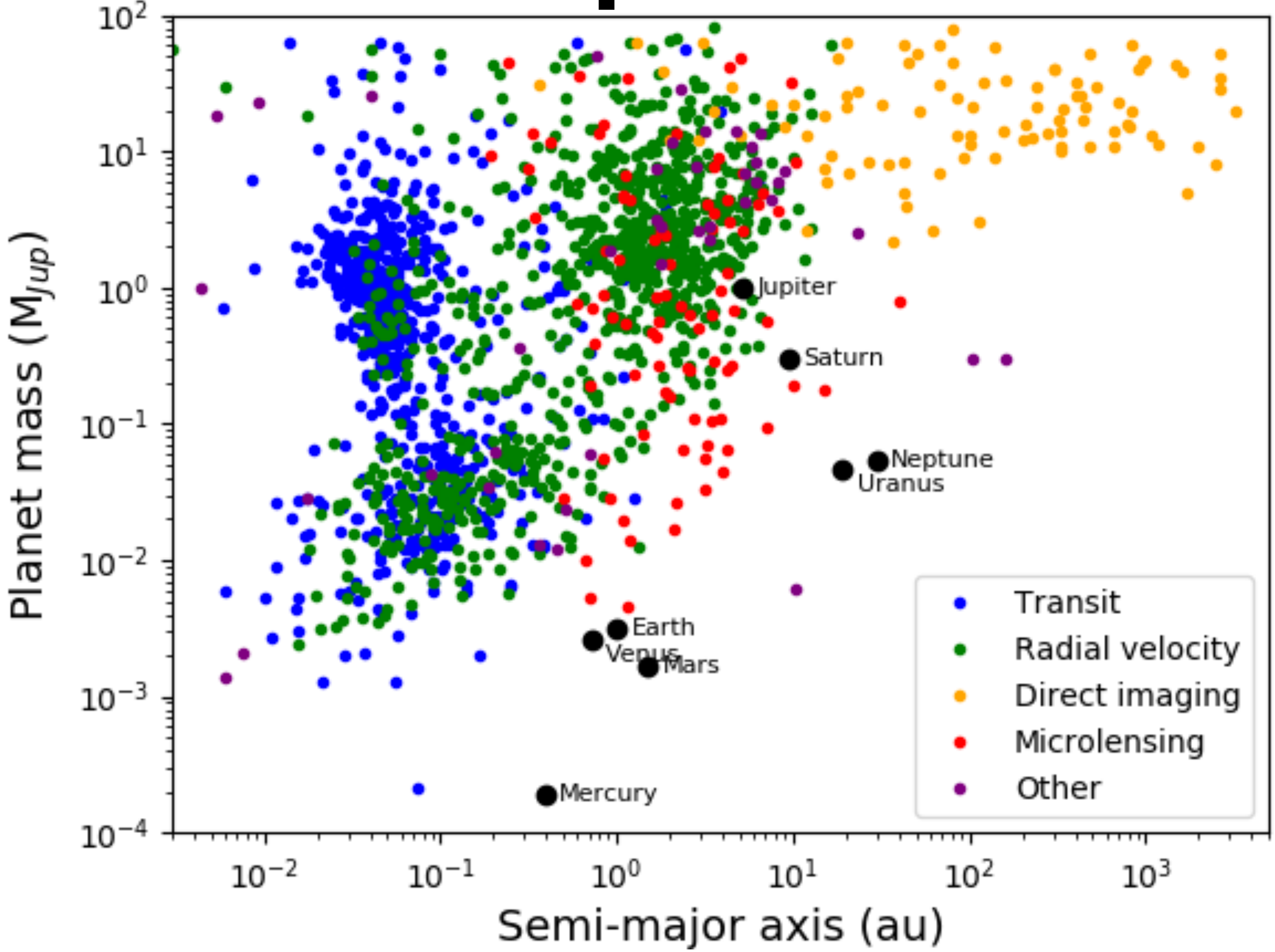
AstroTwin Colombia School 2022
Planet formation and ALMA
dr. Nienke van der Marel
Leiden Observatory

# Contents

- Exoplanets
- What are protoplanetary disks?
- How to observe dust and gas?
- Discovery and history of disks
- Evolution and lifetime
- A new era: spatially resolved observations of disks
- Disk processes

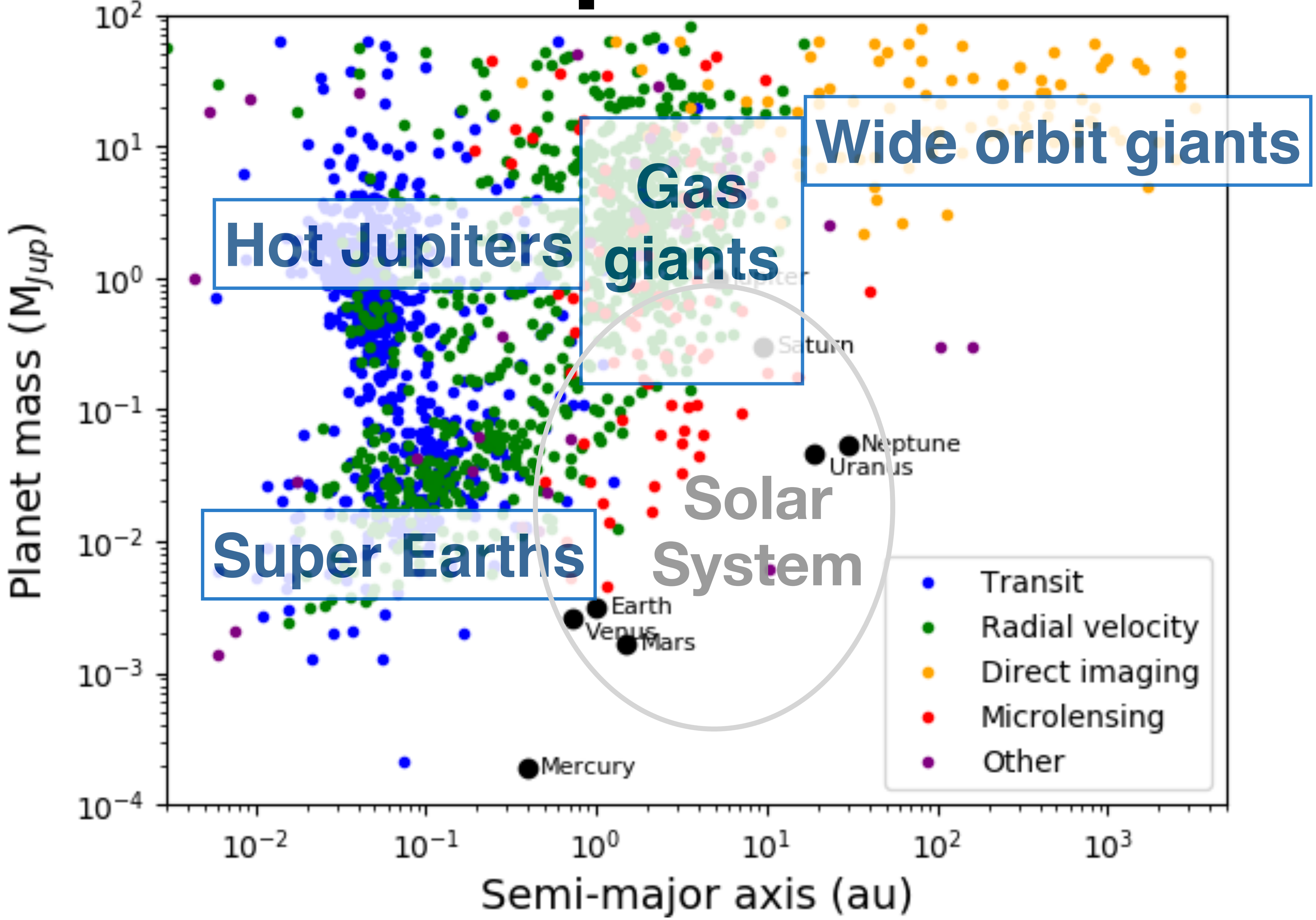
# Exoplanets

>5000 exoplanets!




*http://exoplanet.eu*
*NASA exoplanet archive*

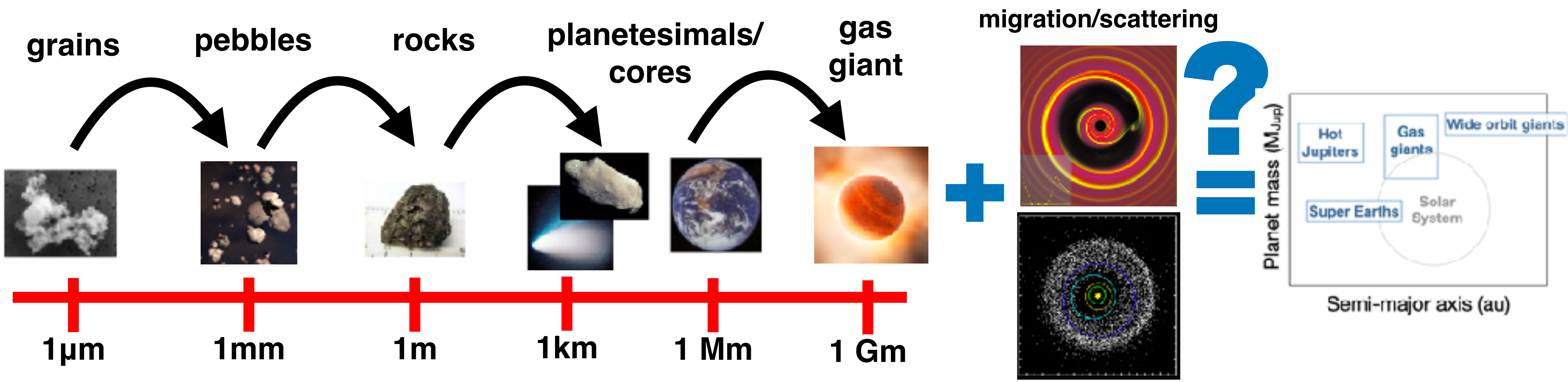
# Exoplanets



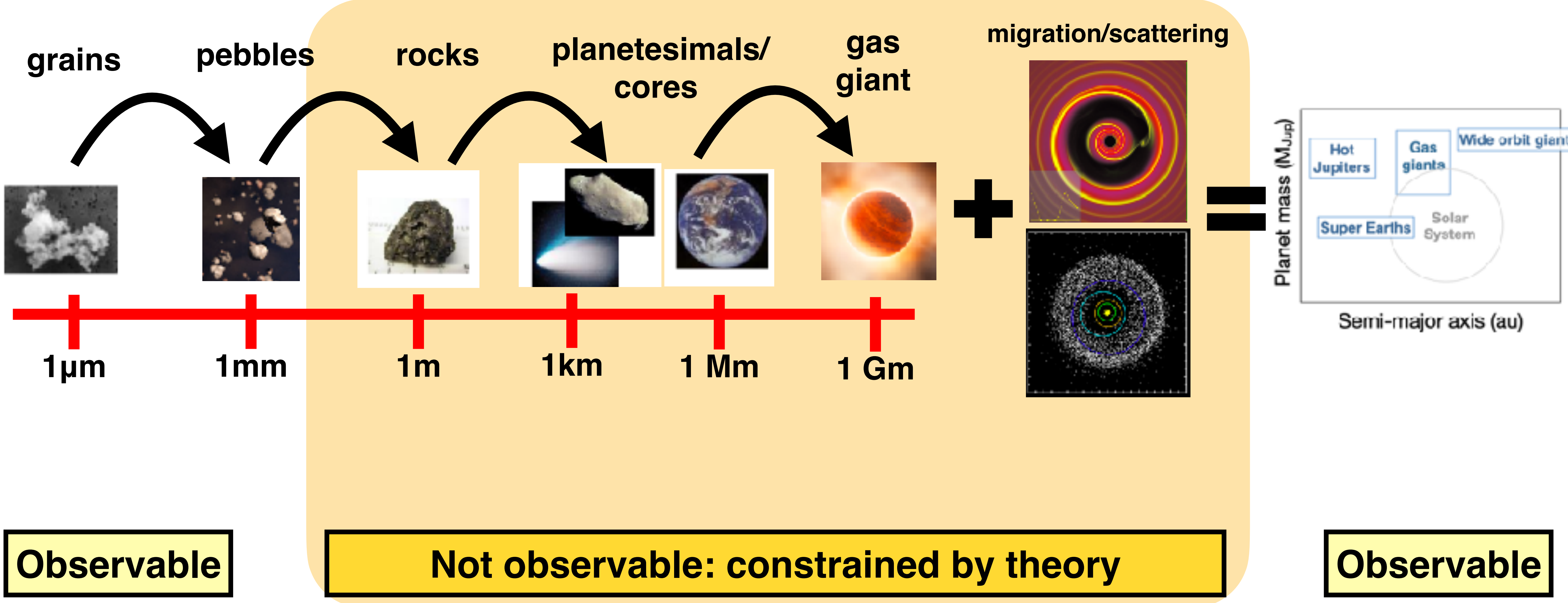

**Quite different from the Solar System…**

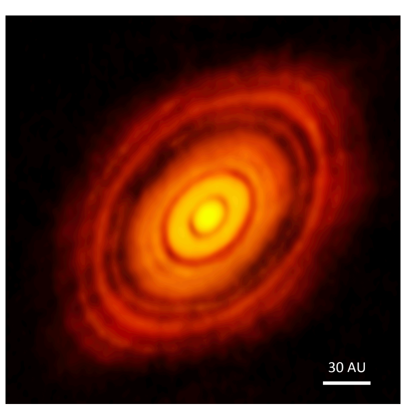
http://exoplanet.eu
*NASA exoplanet archive*

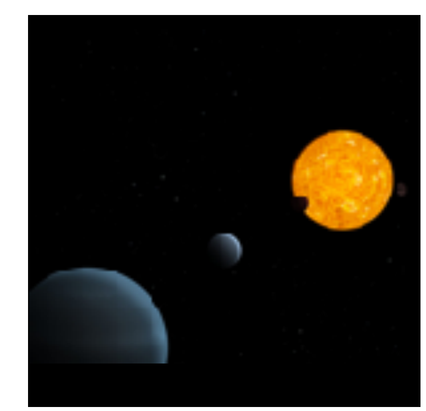
# Planet formation



# Planet formation

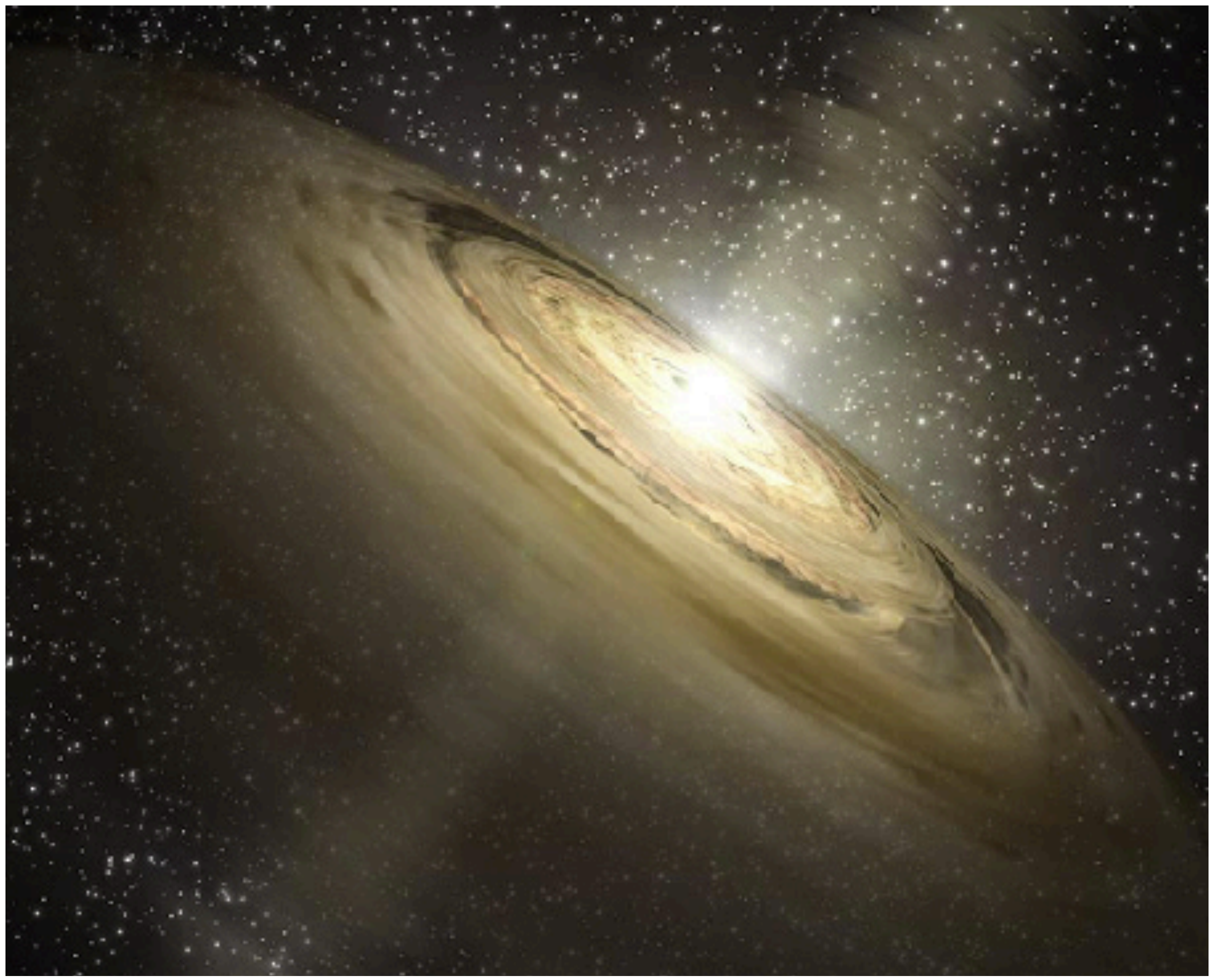


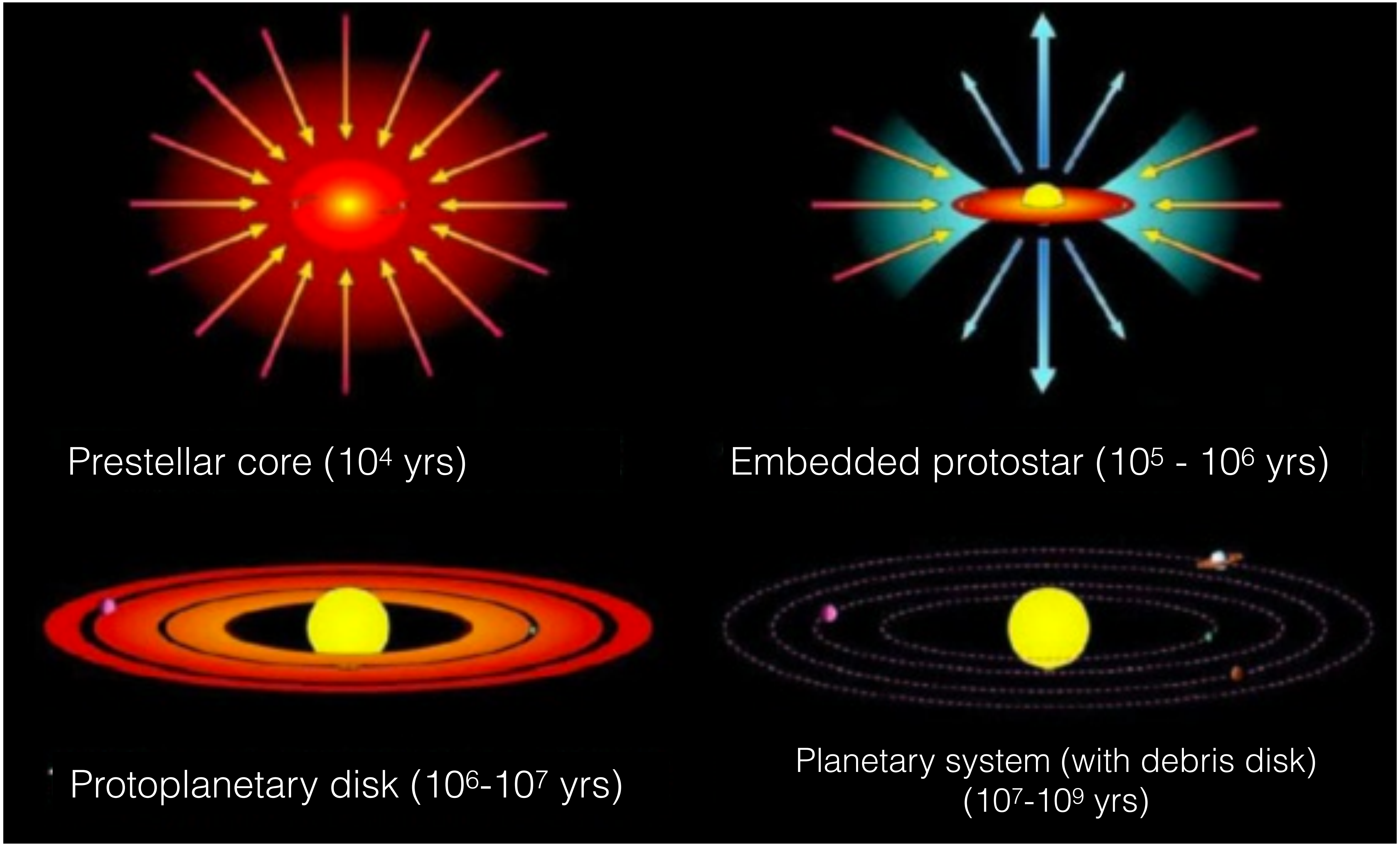
*Disk masses, time scales, radial scales, trends, exoplanet populations, occurrence rates, …*

# What are protoplanetary disks?



**Rotating pancakes of gas and dust found around young stars (few Myr) in which planets are forming**

# Star and planet formation




**Disks (and planets) are a by-product of star formation!**

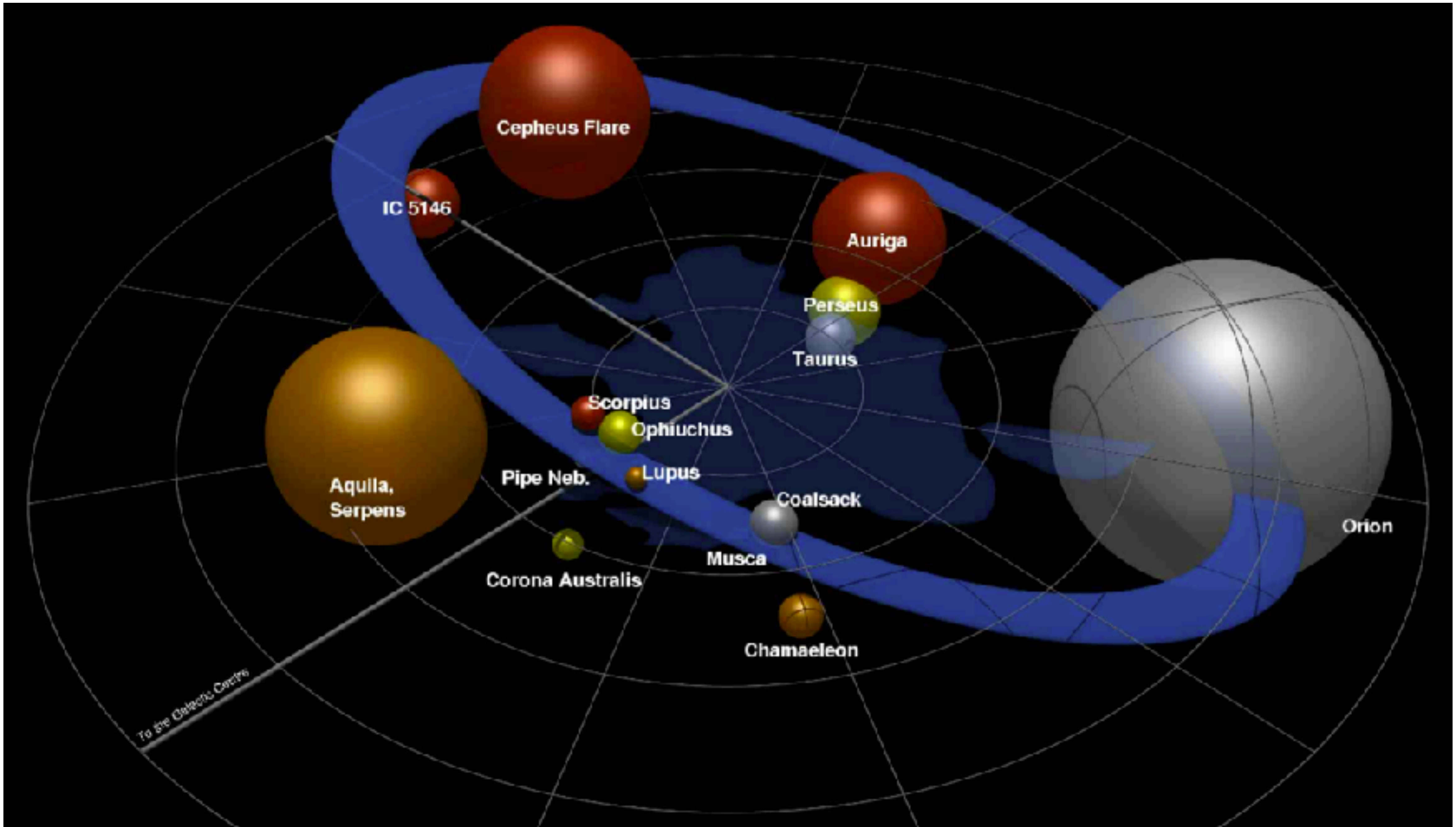
Credit: Shu

# Where do we find disks?

- Stars generally form in clusters, or *star-forming regions:* often named after the constellation that they are in (e.g. Orion, Taurus, Serpens, etc.)

**Optical images: so why is there so much black?**

# Where do we find disks?




**Typical distances: 100-400 parsec (1 pc = 3.1 light year)**
**=> Size of a typical disk (100 AU) is ~1”: unresolved!**

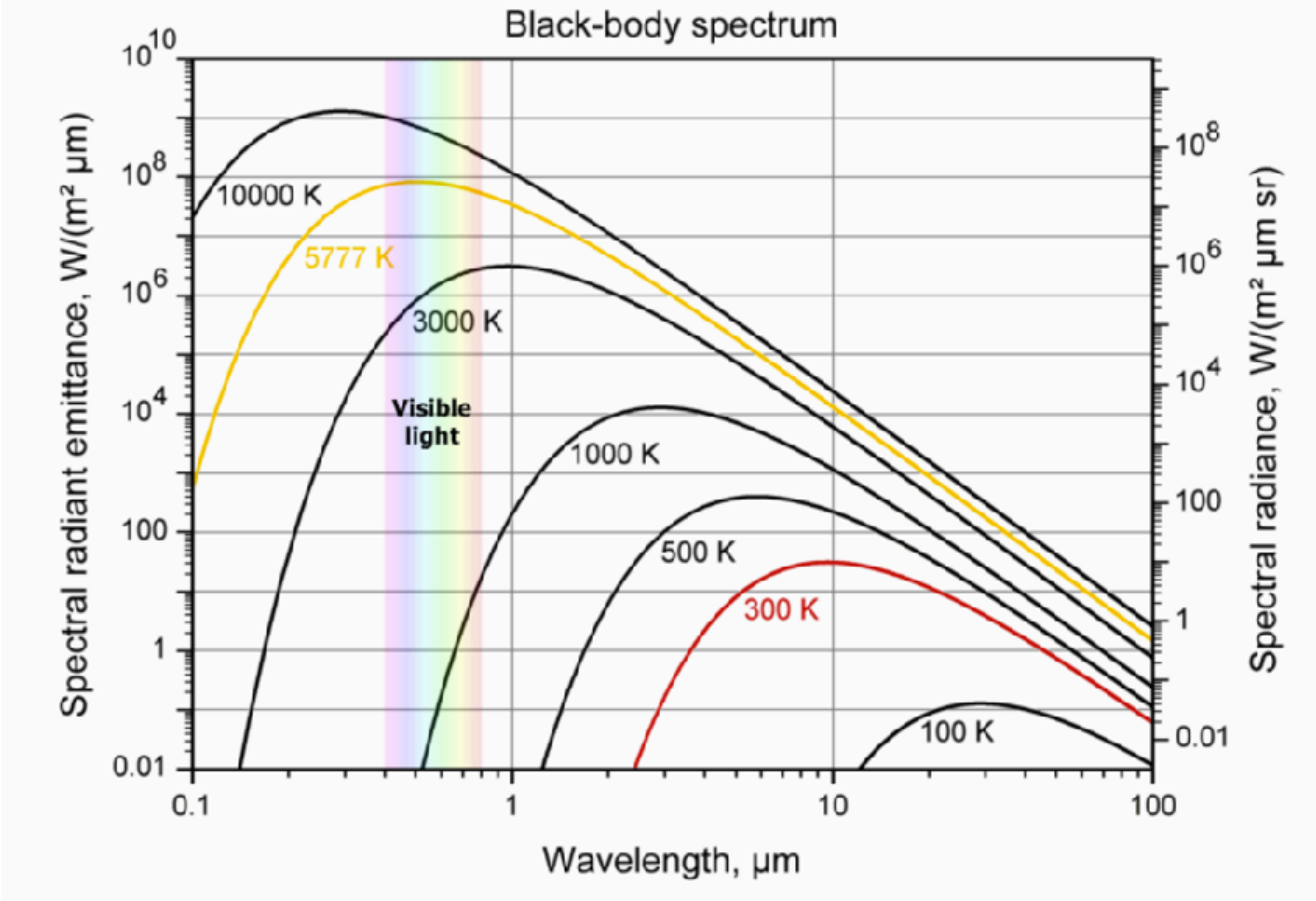
# What's it like out there?

- **Conditions very different from Earth!**
- Typical conditions:
  - Diffuse clouds: $T_{kin}$~100 K, n~100 $cm^{-3}$
  - Dense clouds: $T_{kin}$~10-100 K, n~$10^4$-$10^8$ $cm^{-3}$
  - Disk: $T_{kin}$~10-1000 K, n~$10^8$-$10^{13}$ $cm^{-3}$
- In clouds: 100 times more gas than dust!
- Compare atmosphere at sea level:
  $T_{kin}$~300 K, n~3 $10^{19}$ $cm^{-3}$

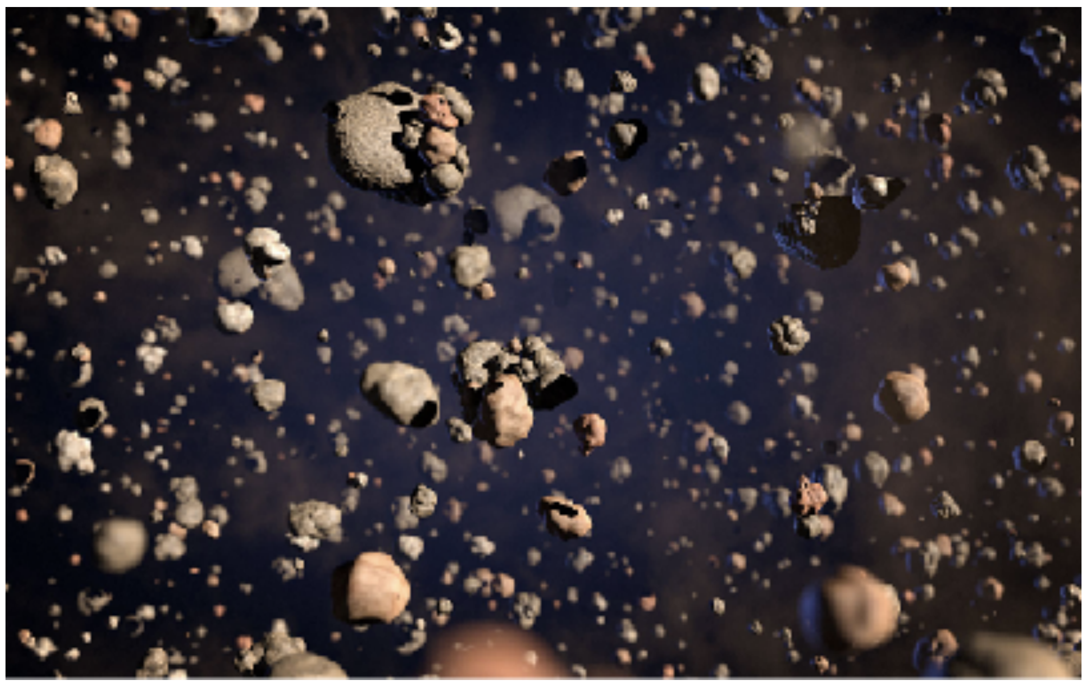
# How do we observe?

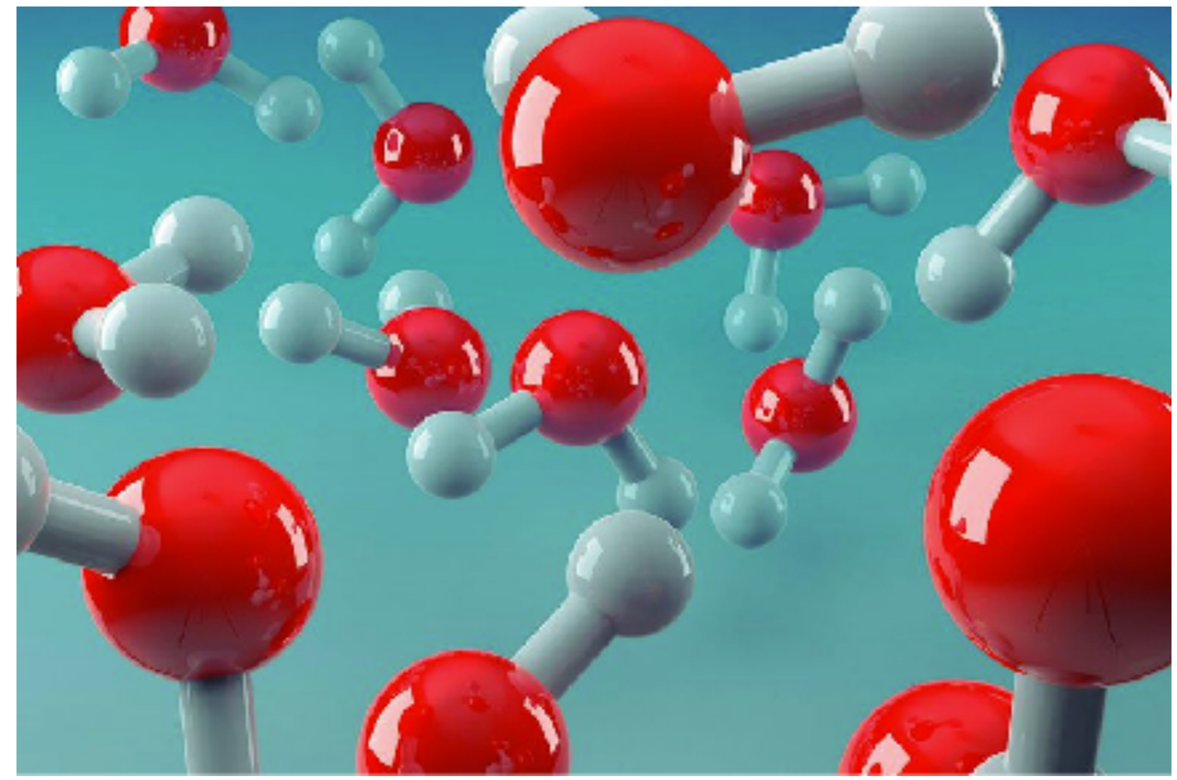

At longer wavelengths we see colder material: why?

# How do we observe?



# What do we observe?





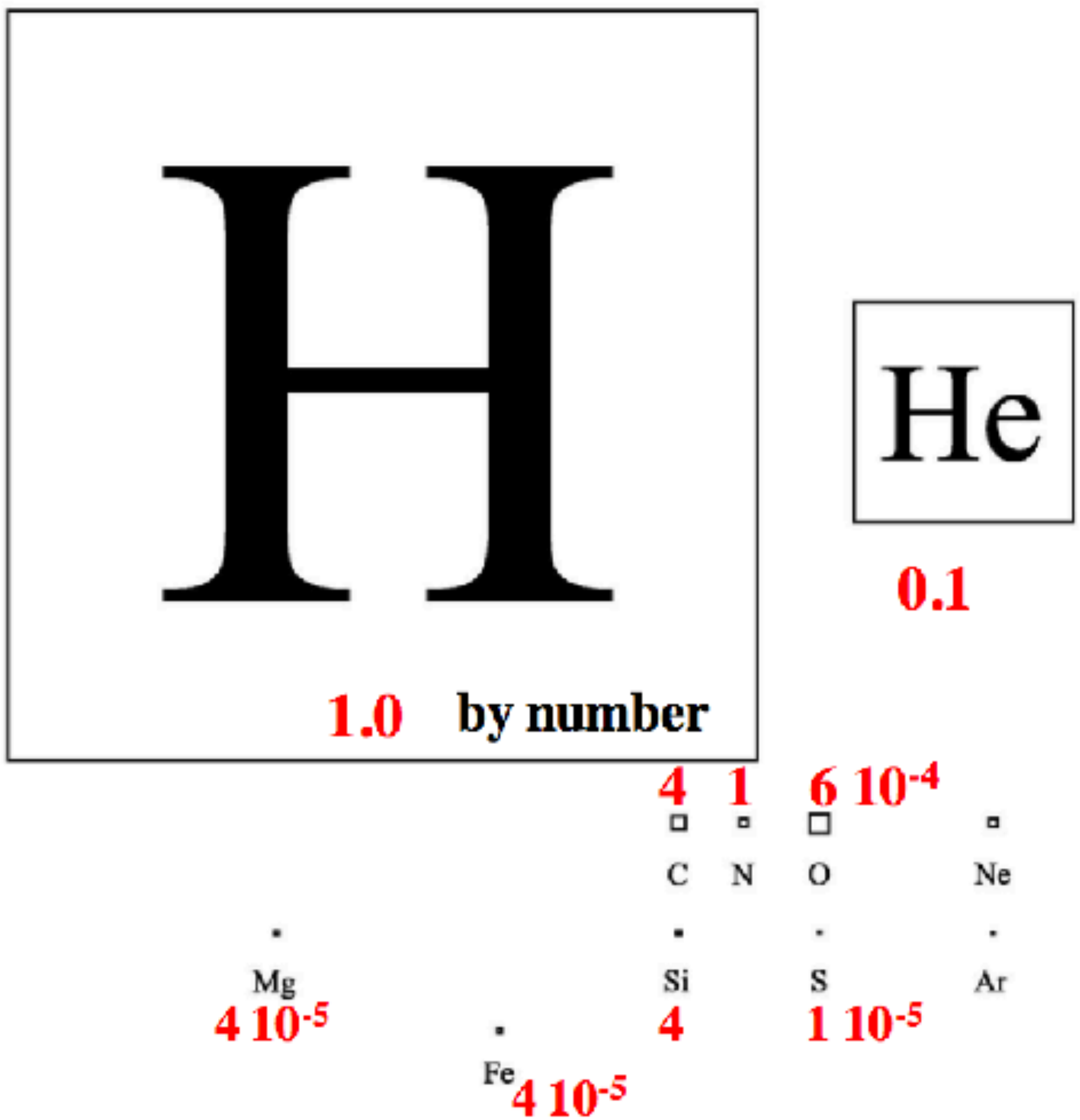
**Dust particles heat up by stellar radiation and become blackbodies: emit radiation at longer wavelengths depending on the temperature 'continuum emission' (broadband emission)**

**Gas particles are molecules: emission through 'molecular lines' (narrow emission)**

**What are the most common molecules in the Universe?**

# What do we observe?

**Periodical table of astronomy:**



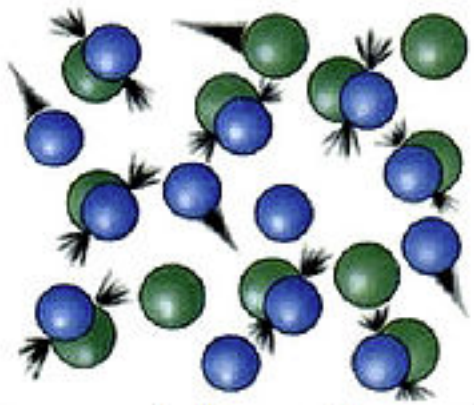

**Simple molecules:**

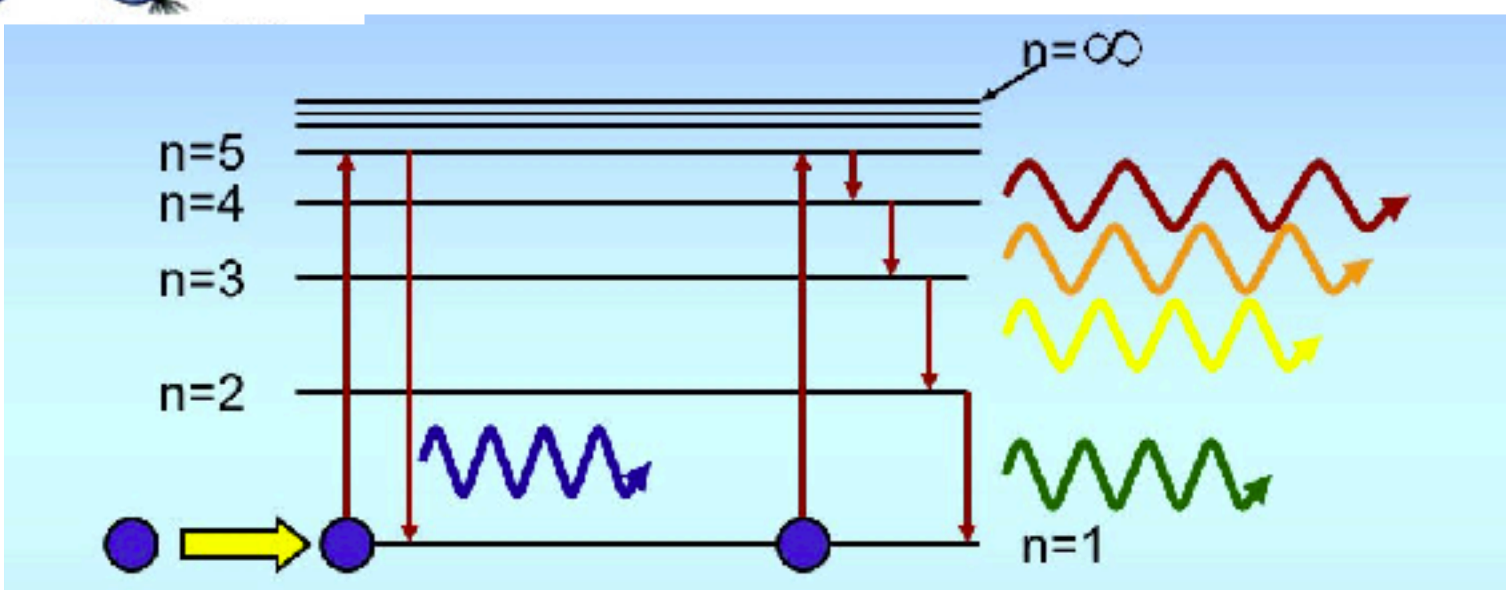
- $H_2$
- CO
- $CO_2$
- $H_2O$
- CN
- OH
- $CH^+$
- $HCO^+$
- $H_2CO$
- …

McCall 2001

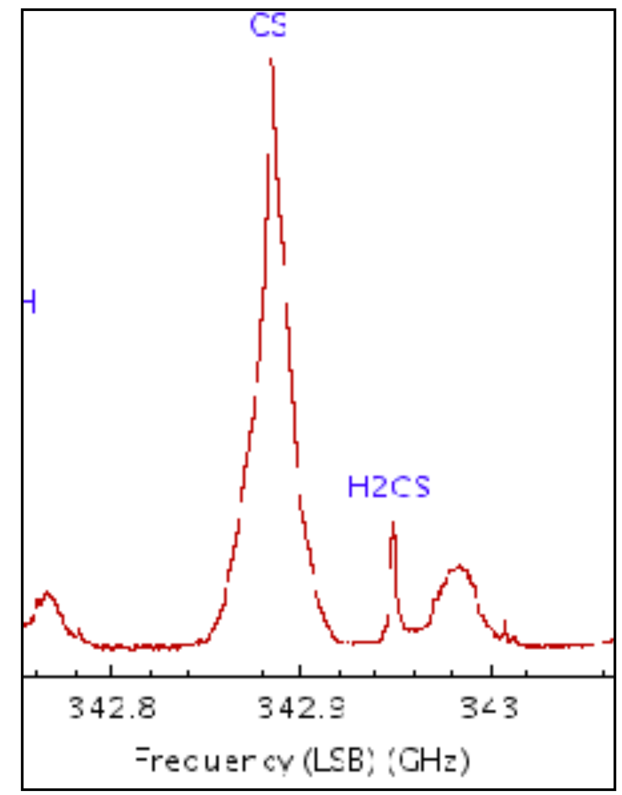
# What do we observe?

**Molecules move around randomly and occasionally collide (more collisions at higher temperature and/or higher density)**





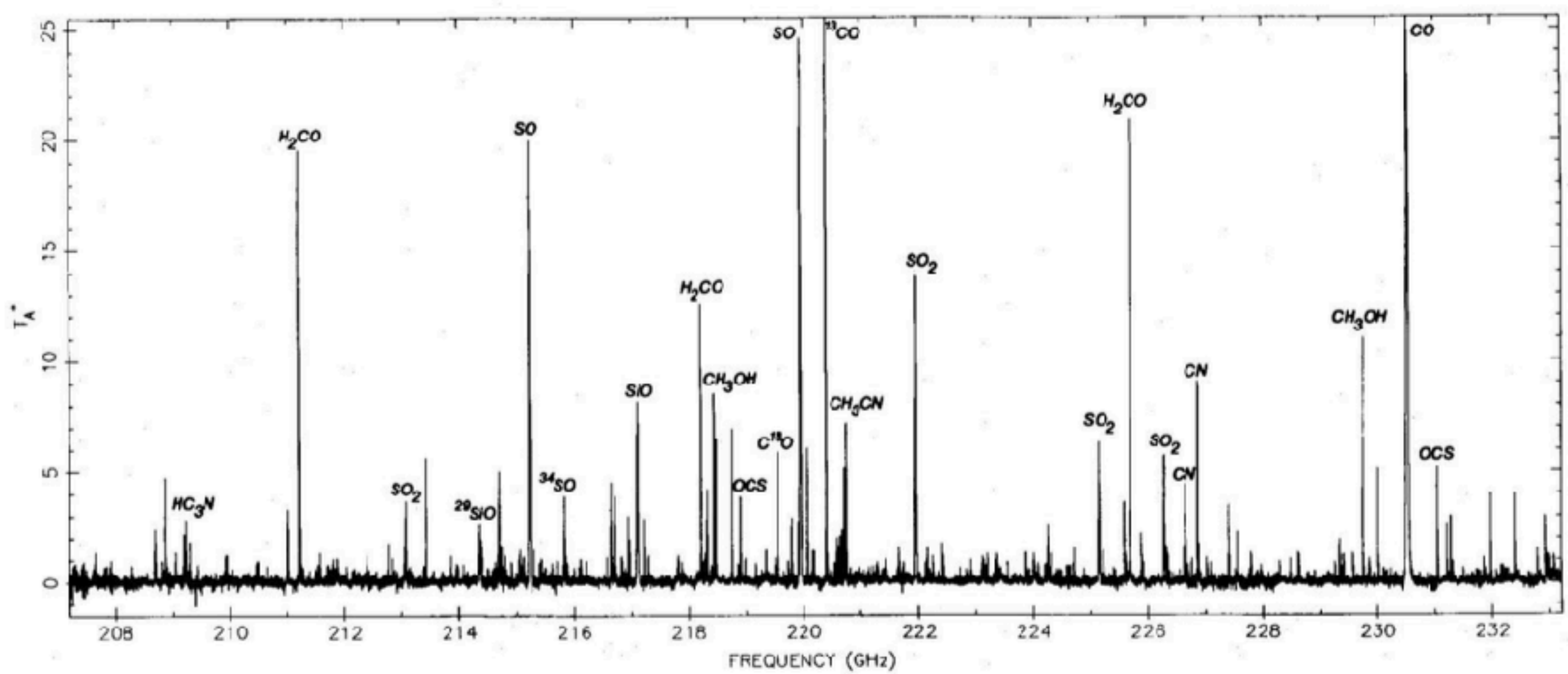

**A collision brings a molecule in a higher energetic state**




**The molecule emits a photon (spontaneous emission) at a specific frequency to get back to lower energy.**
**The frequency is unique for each molecule and each transition ('fingerprint')**

# What do we observe?

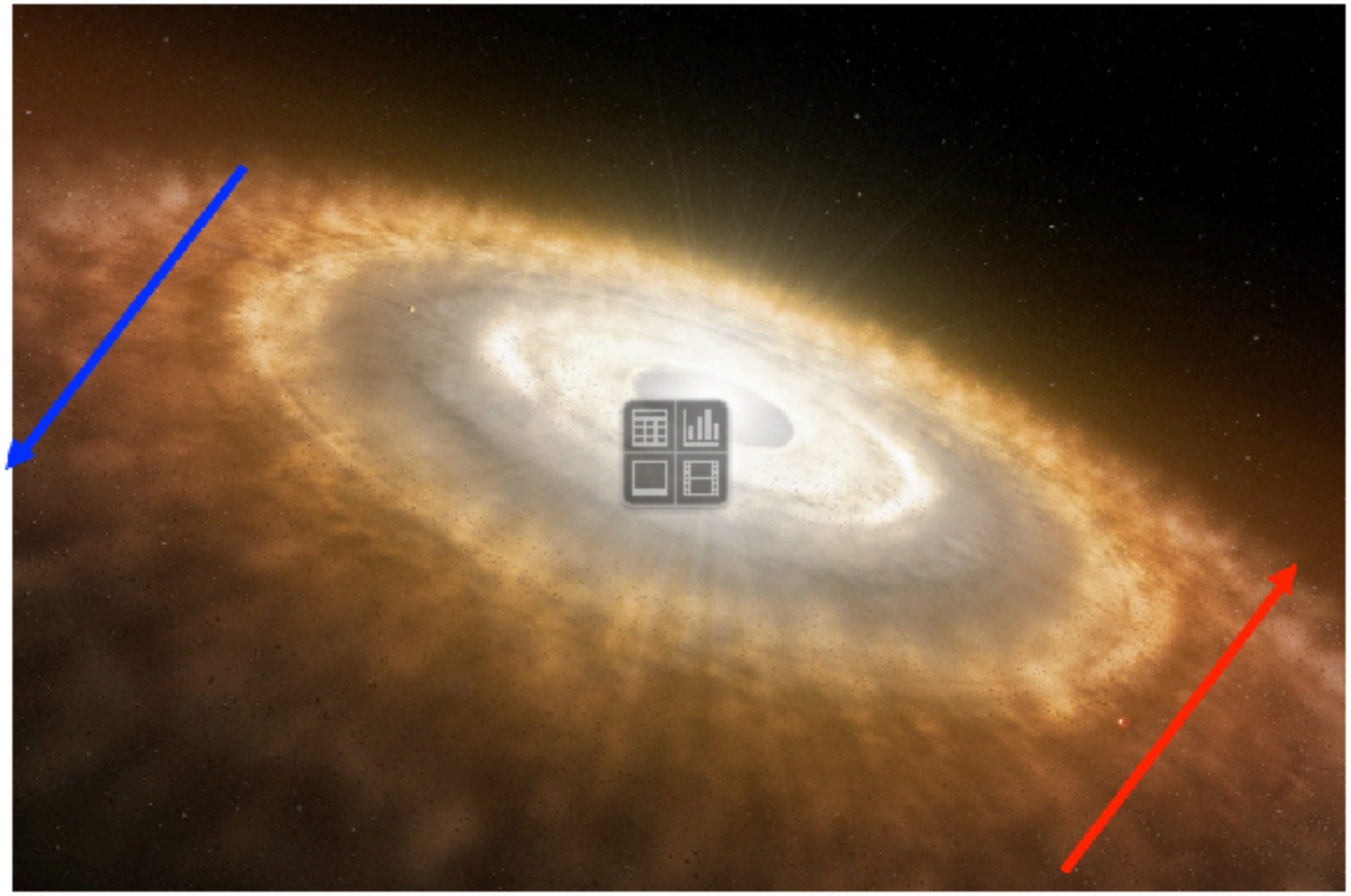
- Each molecular *line* is the result of millions of photons emitted by millions of molecules in this processes: a bulk of *gas*
- Molecular lines on top of *dust* continuum: *continuum* emission is the *averaged* emission at every frequency where there is no line!




NB Frequency and wavelength are used interchangeably: c = λ * ν

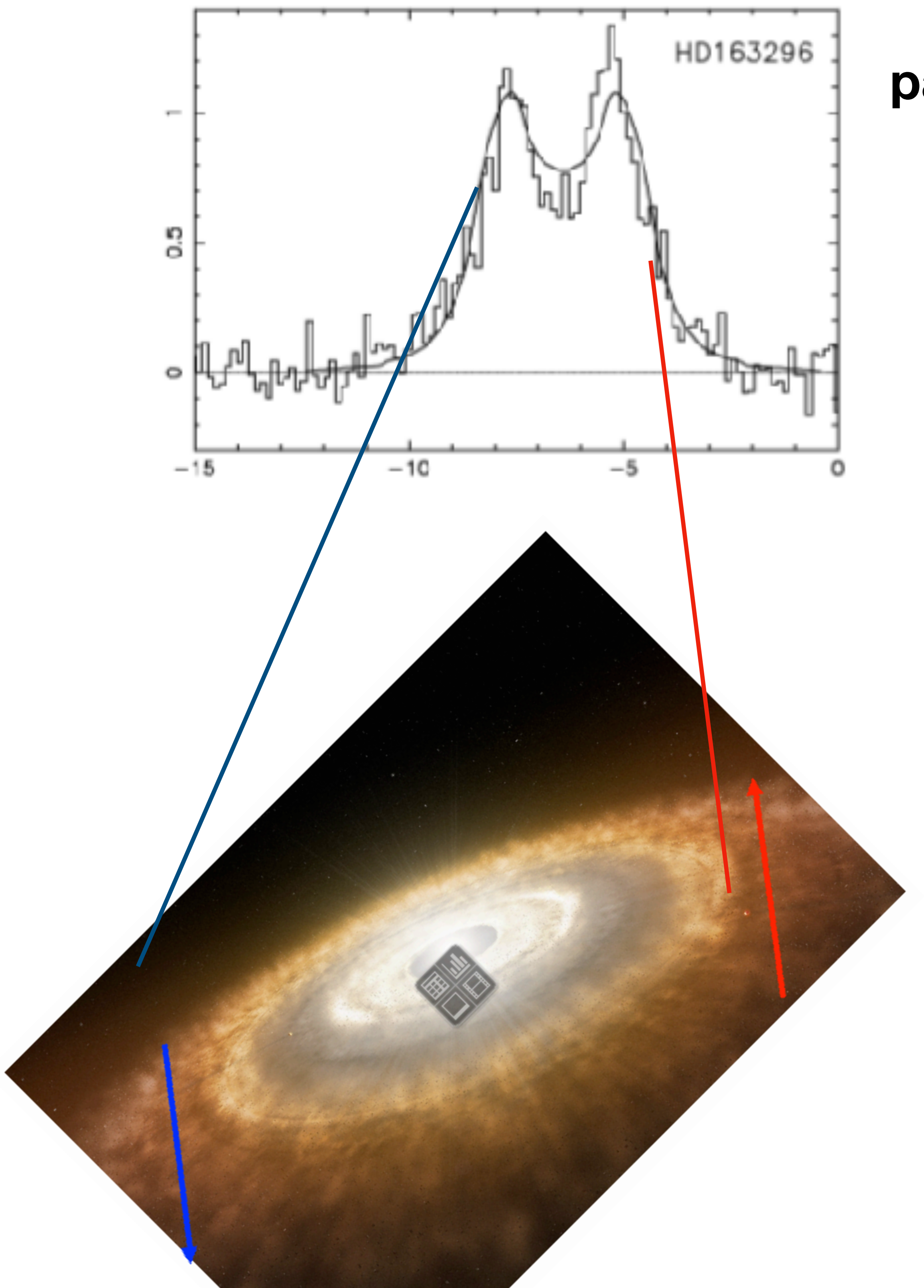
# What do we observe?

**What can we study with molecular lines other than chemistry and gas density: kinematics!**

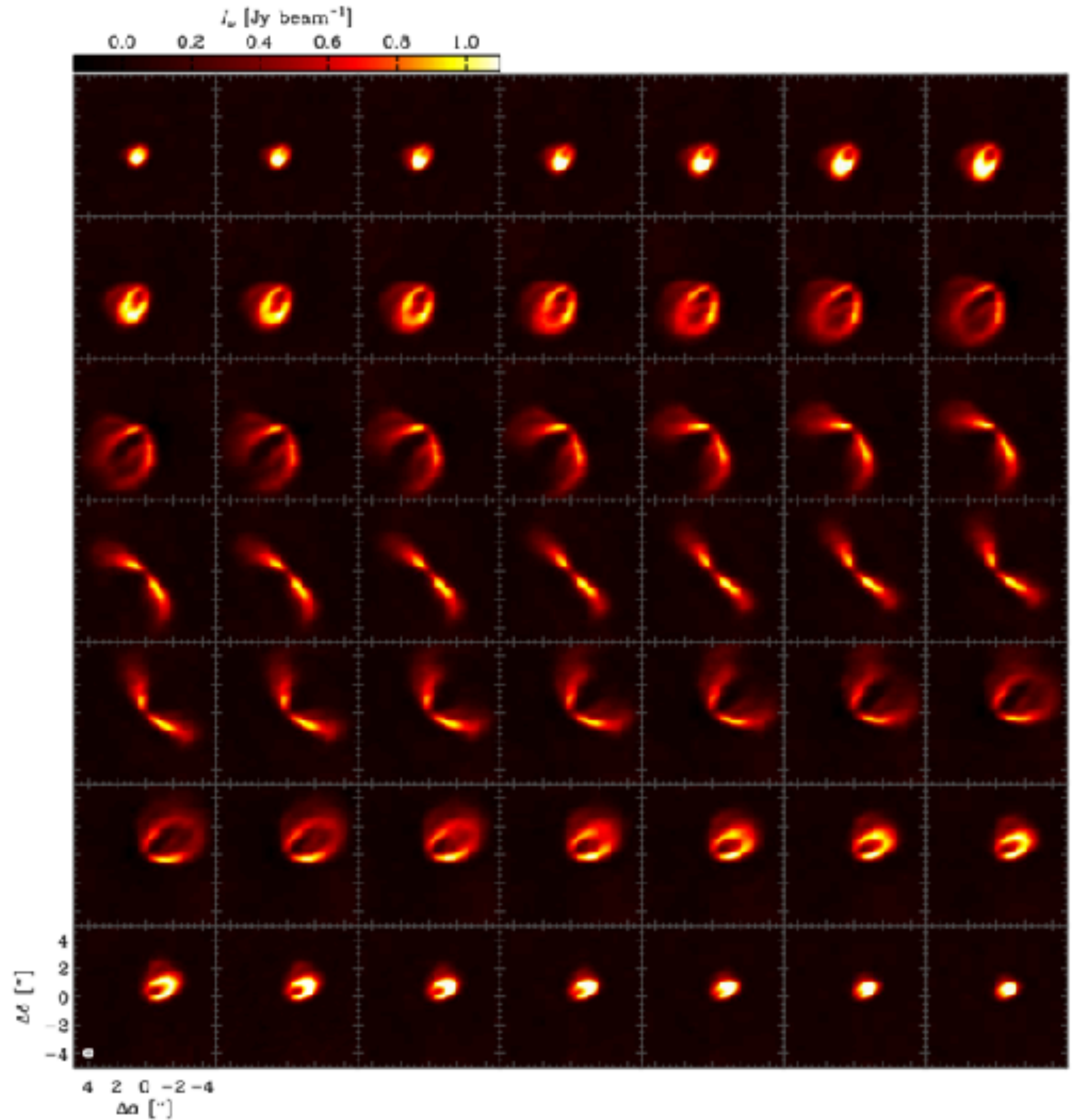


**The disk rotates Keplerian: what happens to the line?**

# What do we observe?

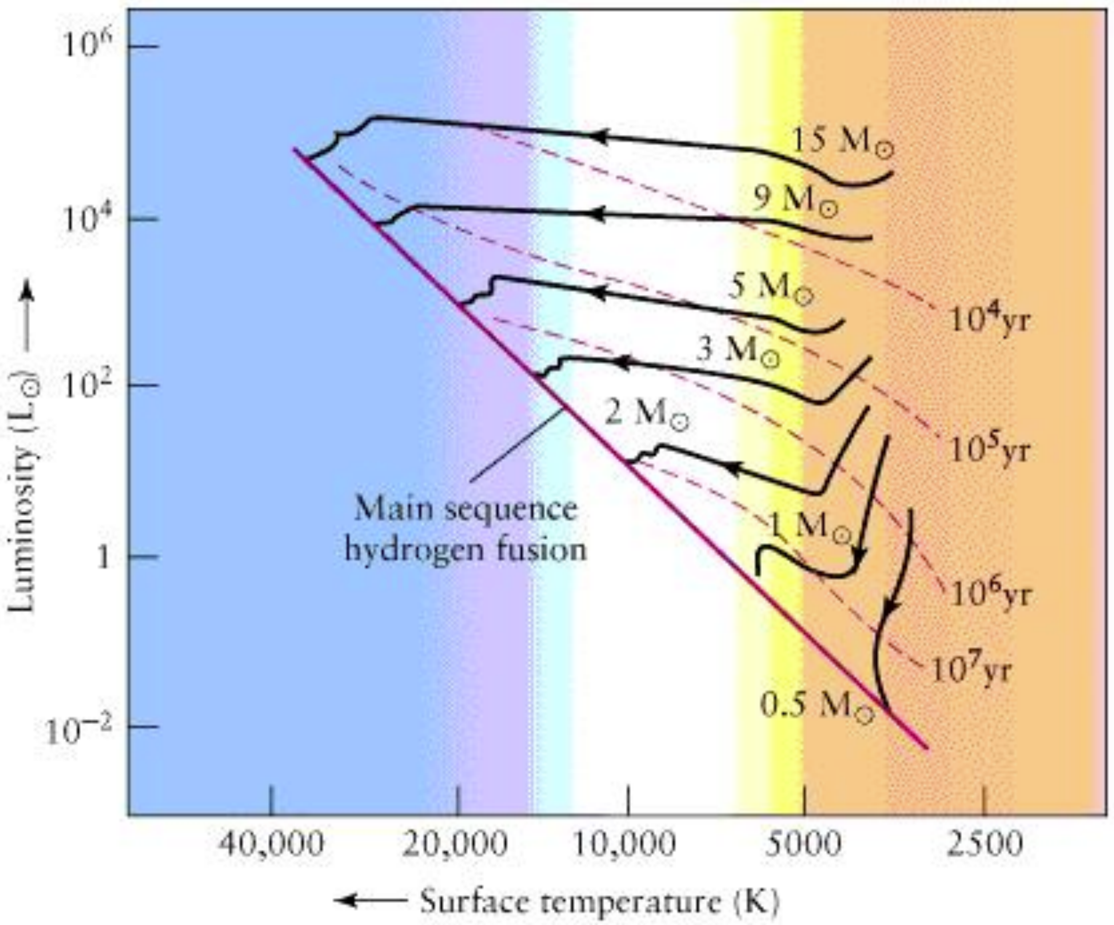



**Doppler effect: blue and red-shifted parts in the disk (double-peak spectrum or ‘butterfly pattern’ if resolved)**



# History

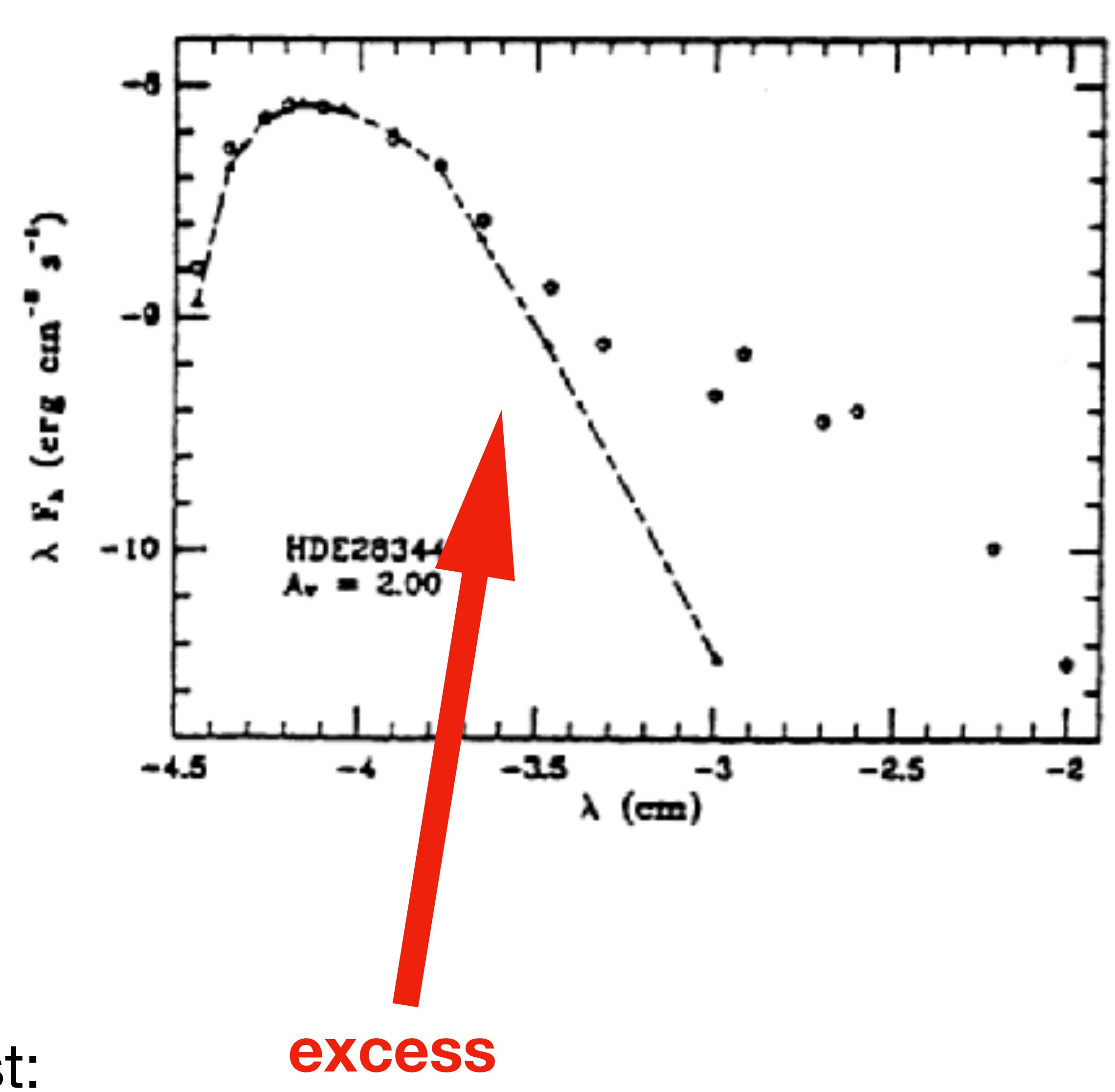
- History of astronomy largely driven by technology: until 1950s mostly limited to optical wavelengths!
- First discovery: young stars!
  - overluminous compared to stars of same spectral type (temperature)
  - found in particular in dark clouds
  - strong optical emission lines (Hα) and UV excess: accretion



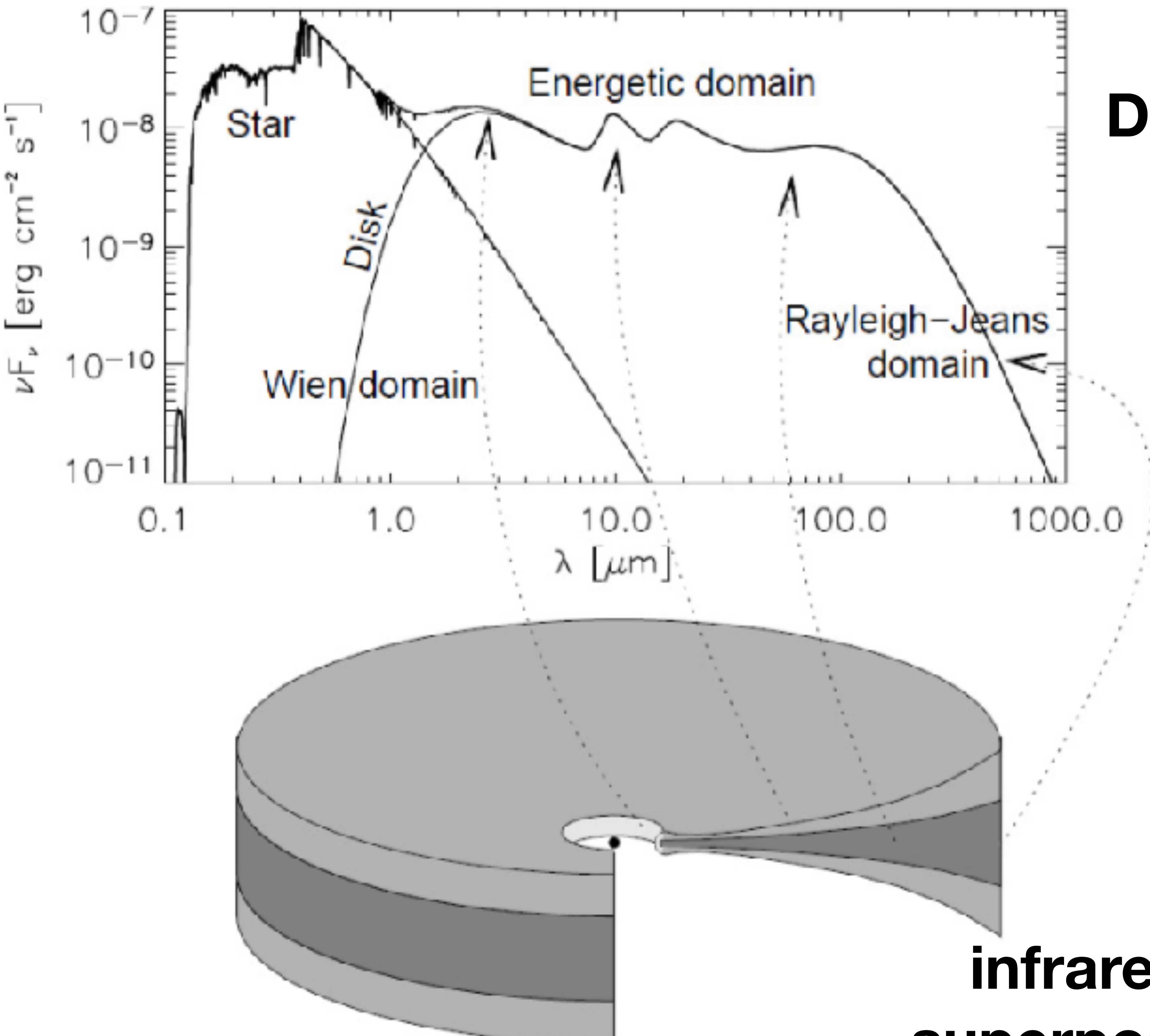

**Why are young stars overluminous?**

# History

- Young stars are still contracting: larger radius, hence more luminous
- Young stars are still accreting material: must be something feeding them
  - Terminology (historic):
    T Tauri stars (<2 $M_{sol}$) and Herbig stars (>2 $M_{sol}$)
- In 1960-1980s: ‘excess’ emission at infrared found in young stars
  => first evidence of a dusty disk
- Keep in mind
  - this is photometry:
    no resolved observations yet!
  - most information about the disk is from the dust:
    more sensitive to broadband emission than lines



# History




**Dust in disk gets heated up by the star: radial temperature gradient**

**infrared to mm emission: superposition of blackbodies**

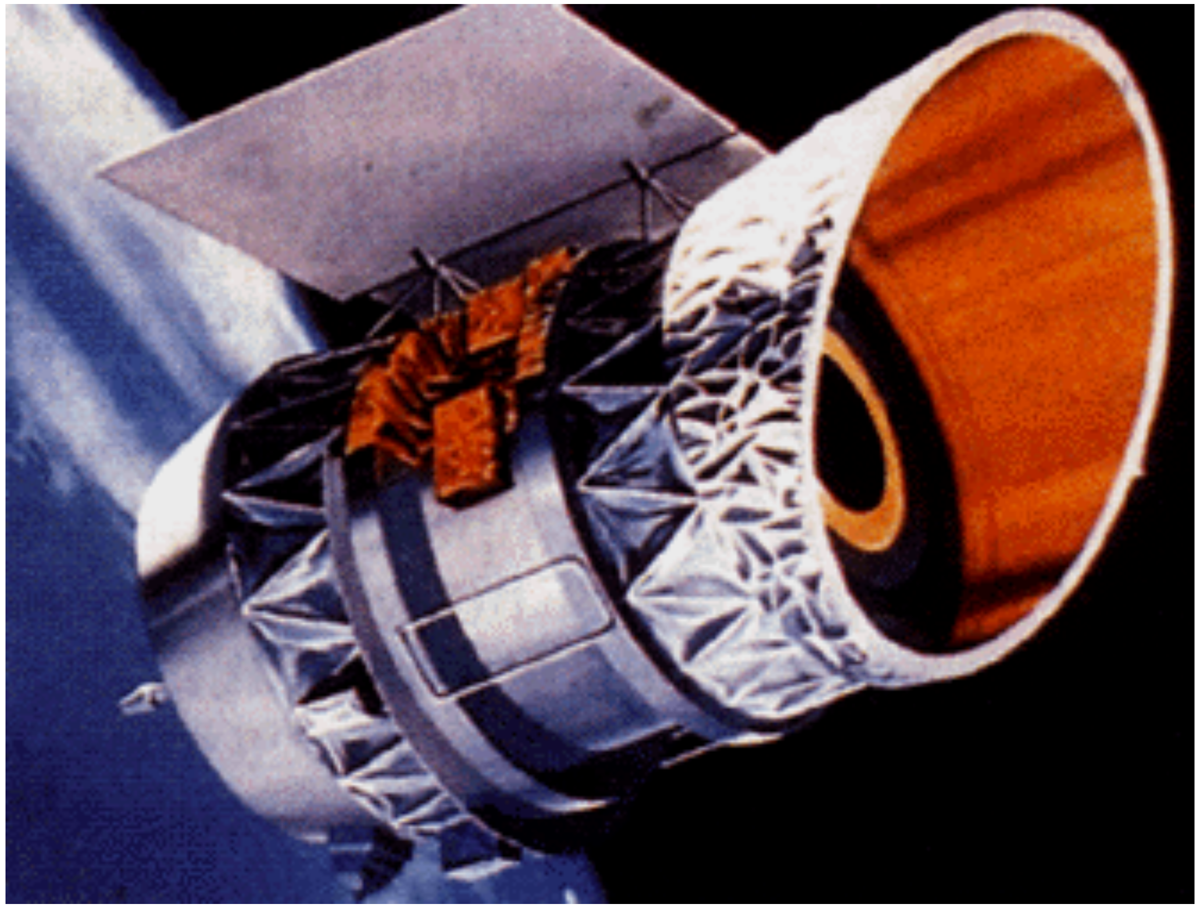
# History

- IRAS satellite 1983:
  full sky survey in infrared
  (12, 25, 60, 100 micron)

- Diameter: 57 cm (22 inch)

- >250 000 IR sources found

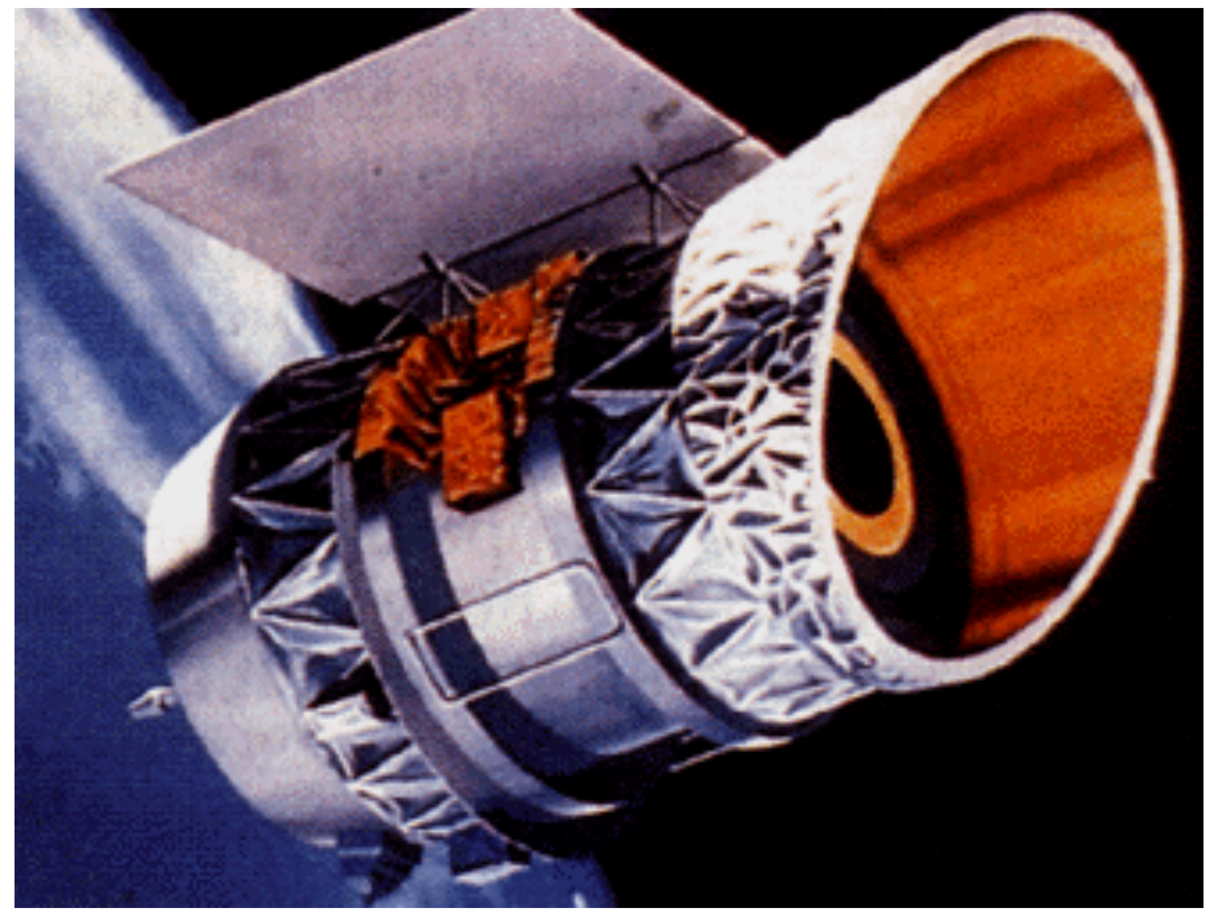
- Follow up:
  ISO satellite 1995-1997
  => deeper and including
  spectroscopy



**What is the problem with these observations if you think about the size of the telescope and the size of disks?**

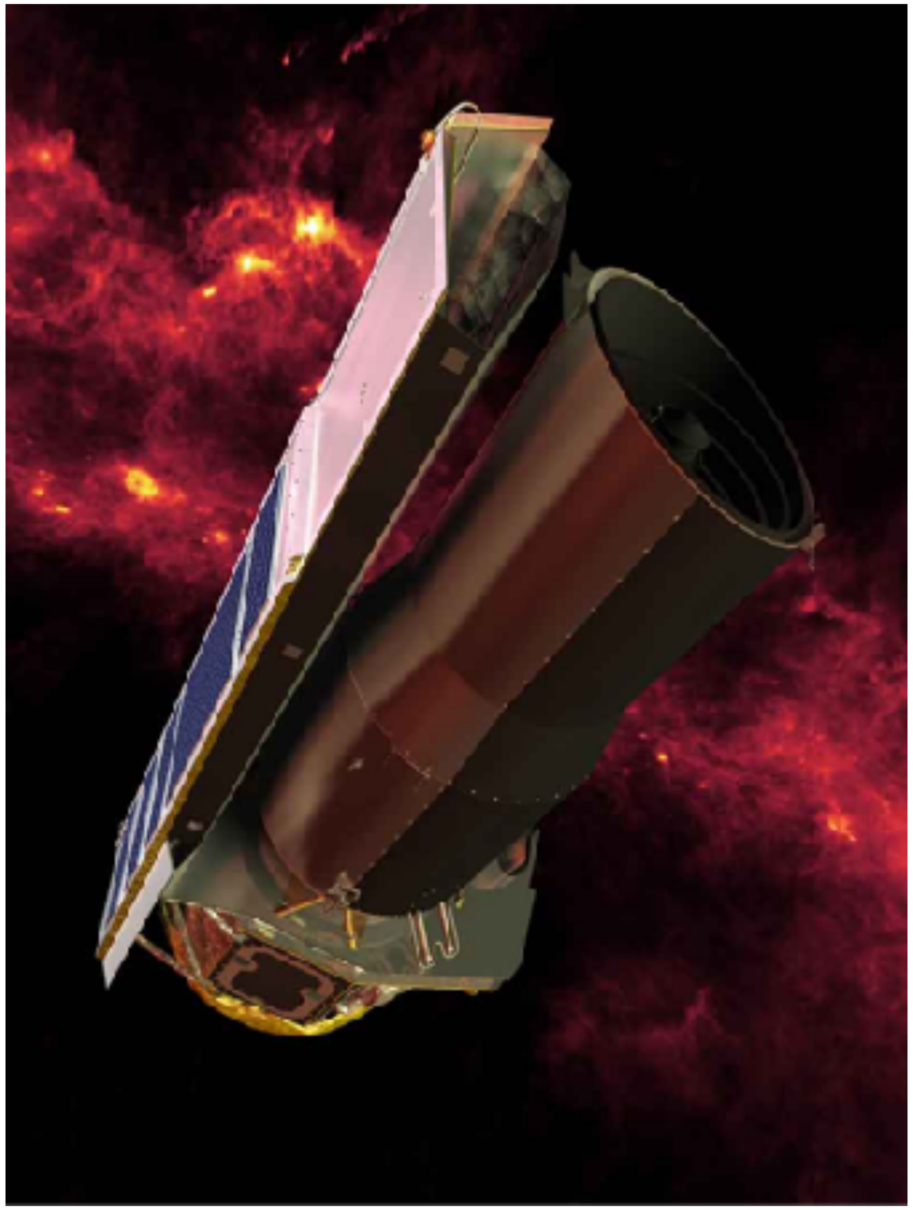
# History

- Diameter: 57 cm (22 inch)
- Telescope resolution: $\lambda$/D => 30-120” beam
- Disks are ~1”! Unresolved!
- Photometry is confused
- Full sky: short integrations (low sensitivity)



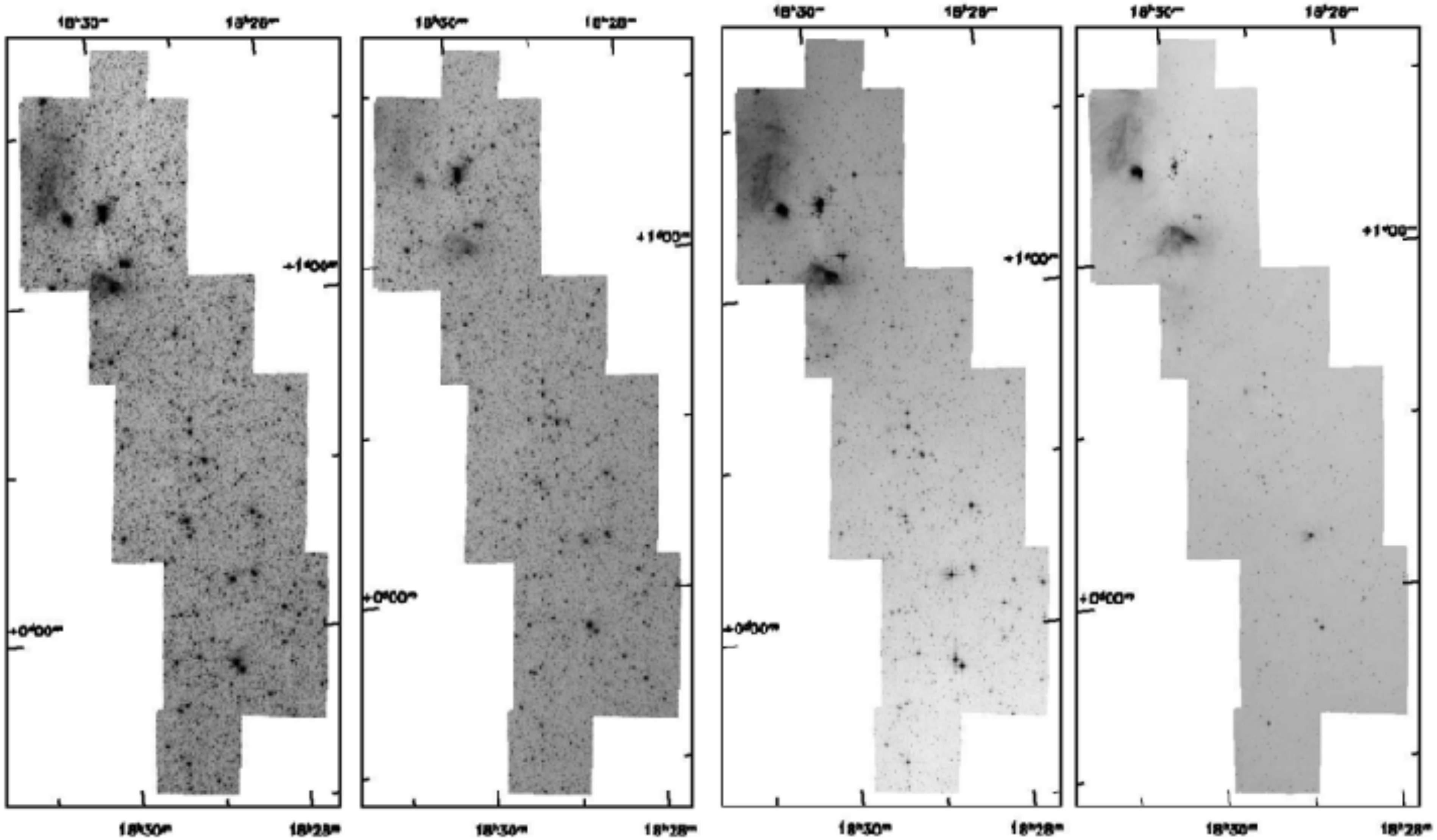
# History

- Next IR telescope: Spitzer!
- Cold mission: 2003-2009
  (but warm mission still on-going)
- Diameter 85 cm
- Targeted photometry and spectroscopy at 3-70 micron
- **Full mapping of nearby star-forming regions**

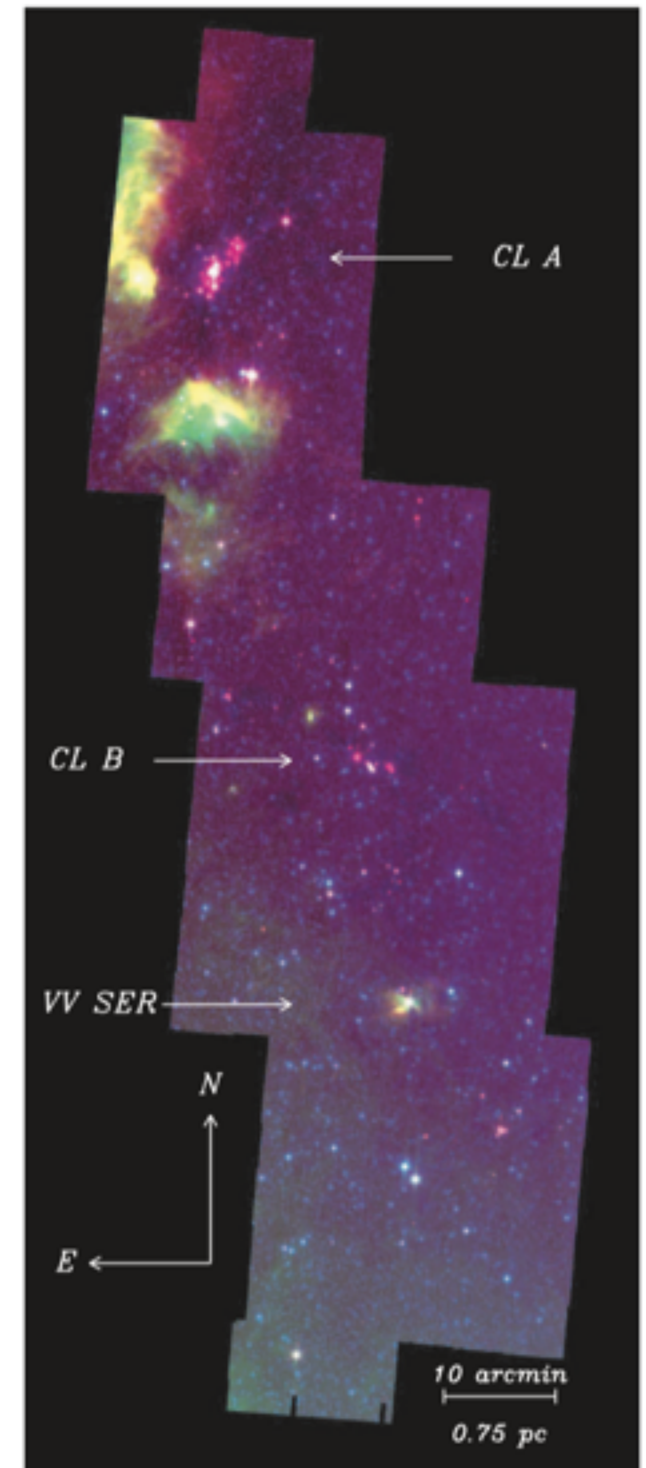


# History

**Identifying young stellar objects in star forming regions: tedious work!**



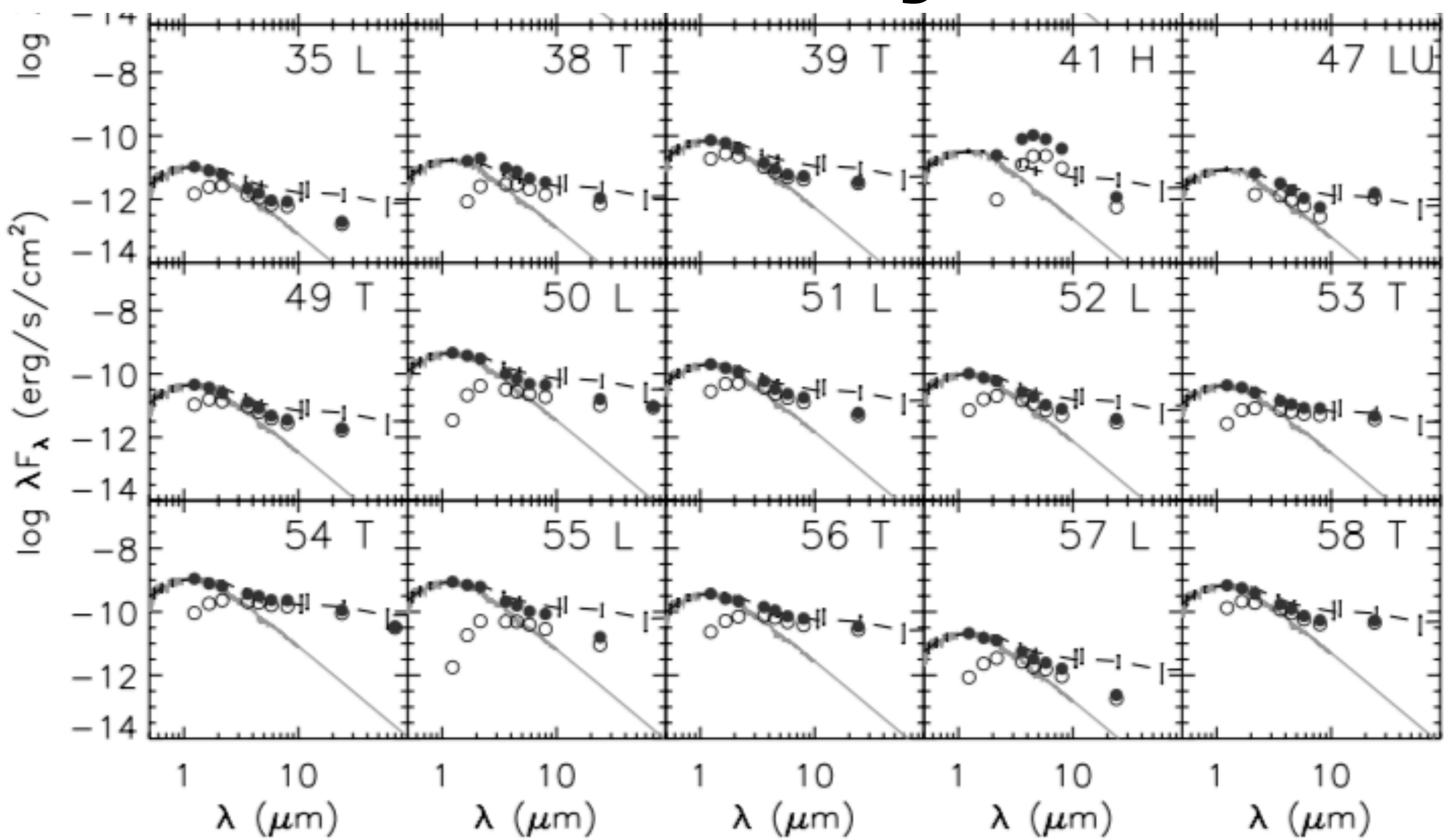
**IRAC bands: 3.6, 4.5, 5.8 and 8.0 micron**




**Composite image with IRAC2/4 and MIPS (24 micron)**

Harvey et al. 2006, 2007

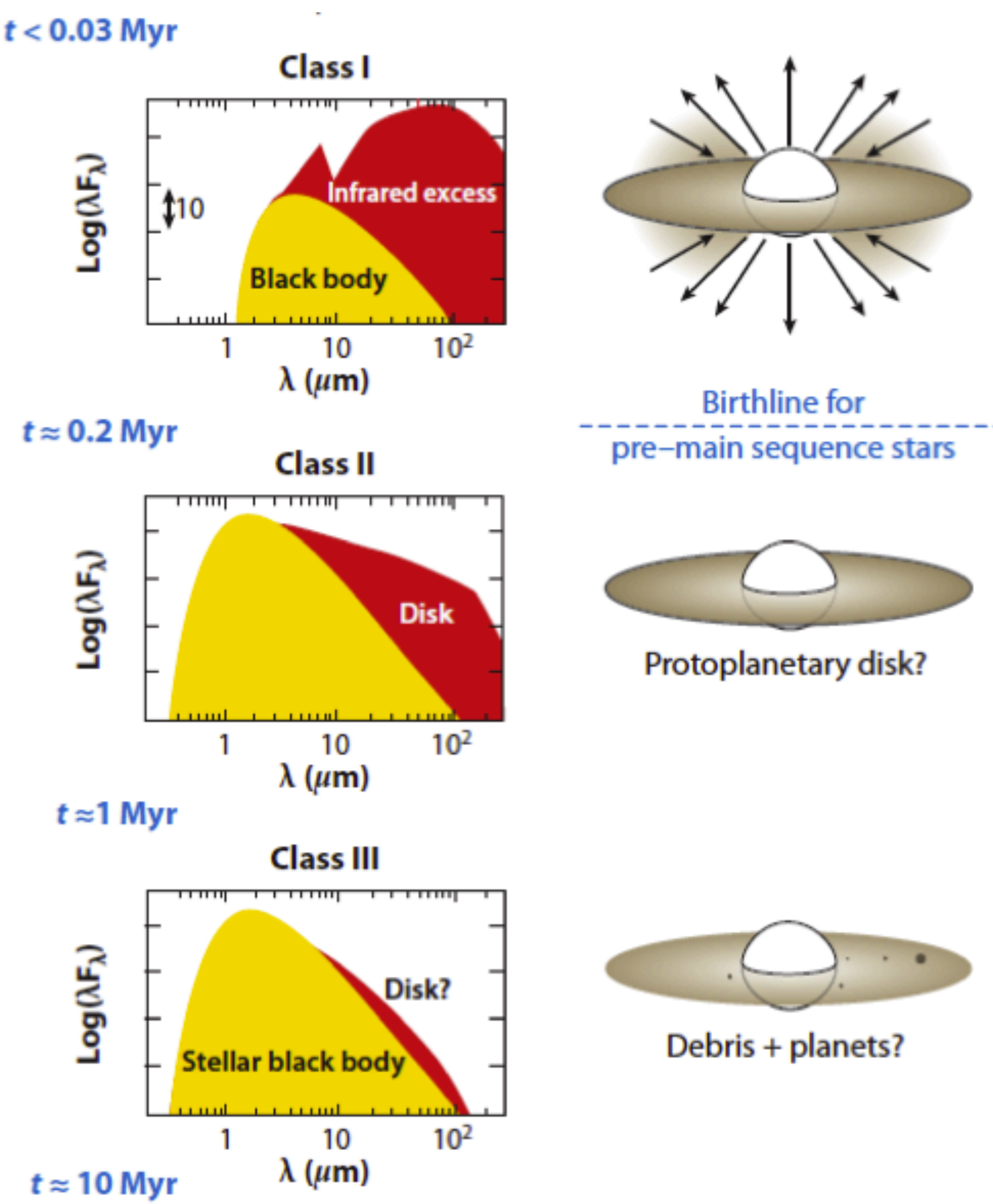
# History




**Results: thousands of SEDs of young stars, including many disks!**

**Relation with accretion measured in UV/Ha: disks with higher IR excess generally higher accretion => evolution!**

# Evolution




**Further classification by amount of infrared excess:**

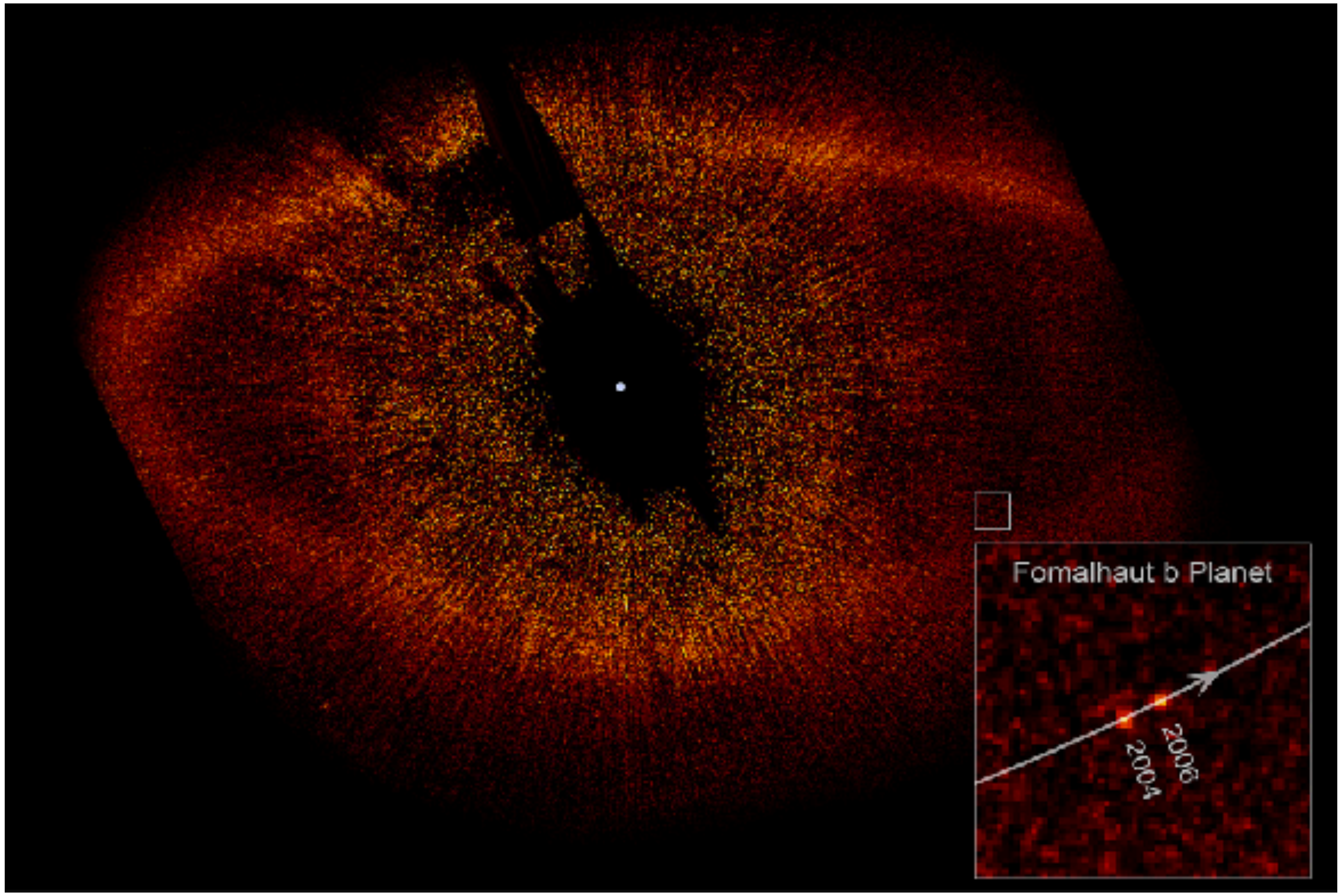
- **young systems still embedded in a cloud (Class 0/I);**
- **protoplanetary disks (Class II), still accreting;**
- **old debris disks (Class III), not accreting**

# Evolution

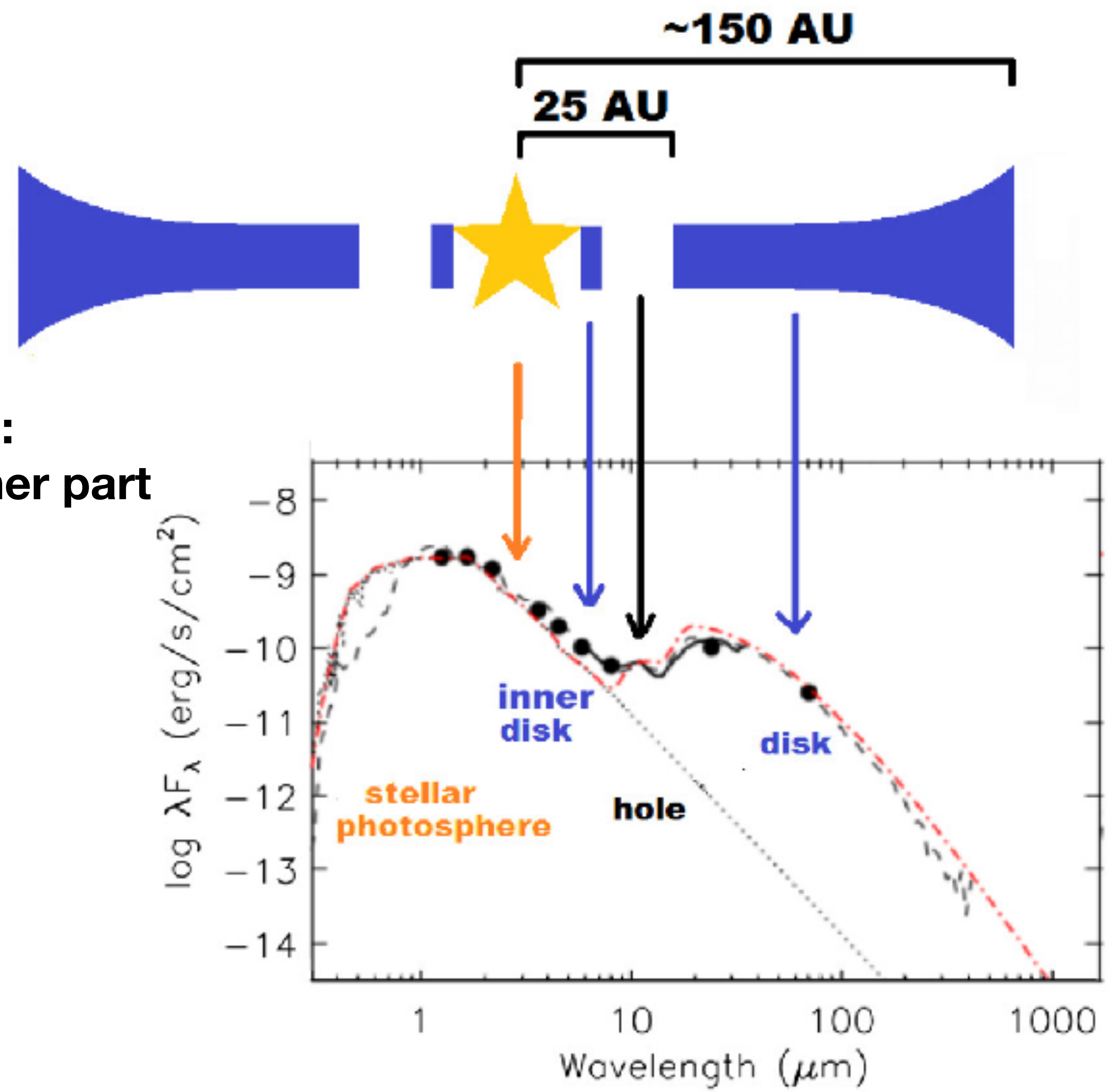
**Debris disks:**
**old protoplanetary disks or remnants of collisions of planetesimals and comets (like Kuiper Belt)**

**Debris disks are found at much closer distances to us: not limited to star forming regions and much longer lifetimes (~Gyr)**

**Famous example: Formalhaut (Hubble image) at 8 pc**

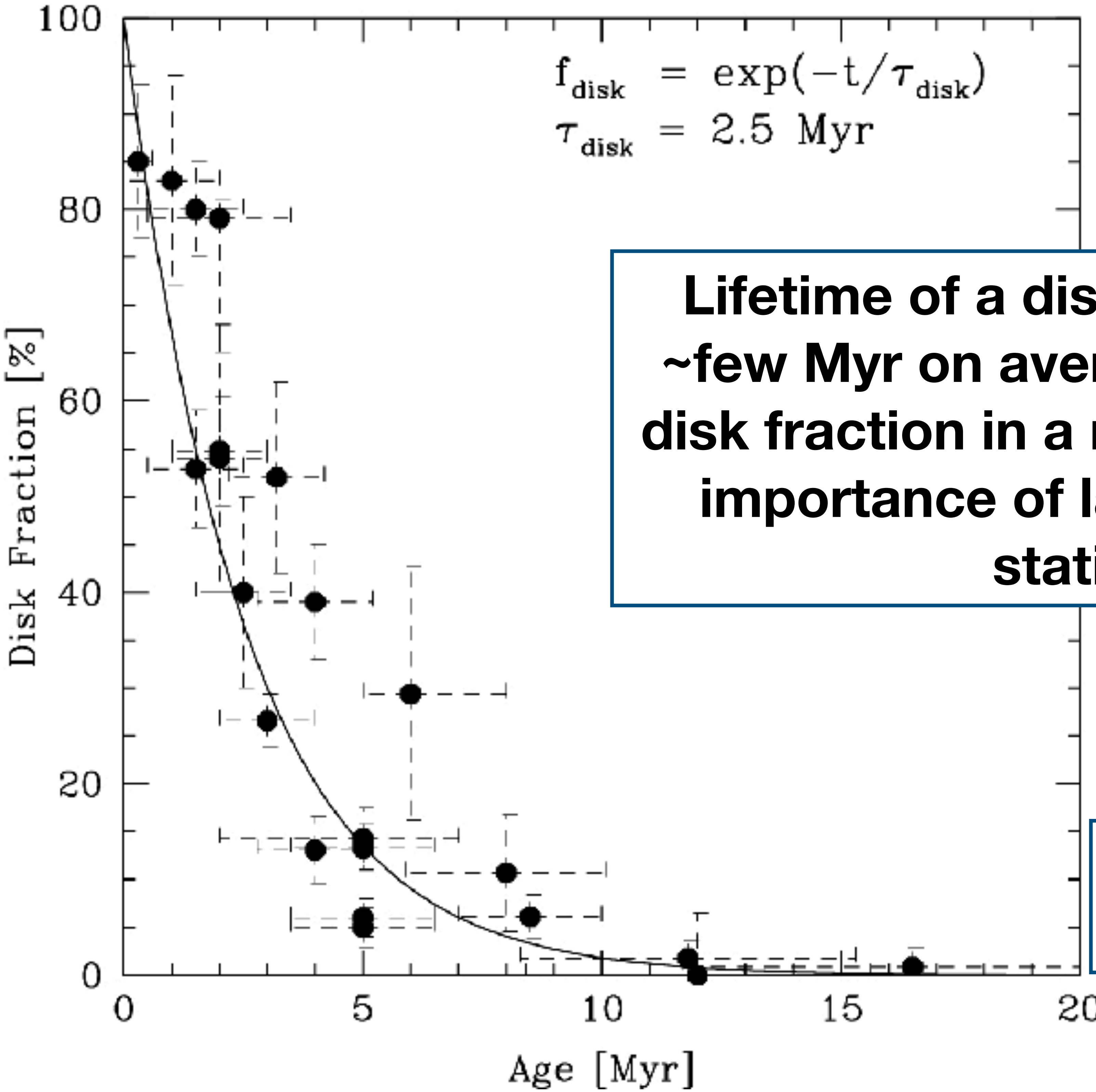


# Evolution




**Discovery transition disks: disks with a gap in the inner part of their dust disk!**

# Evolution and lifetime

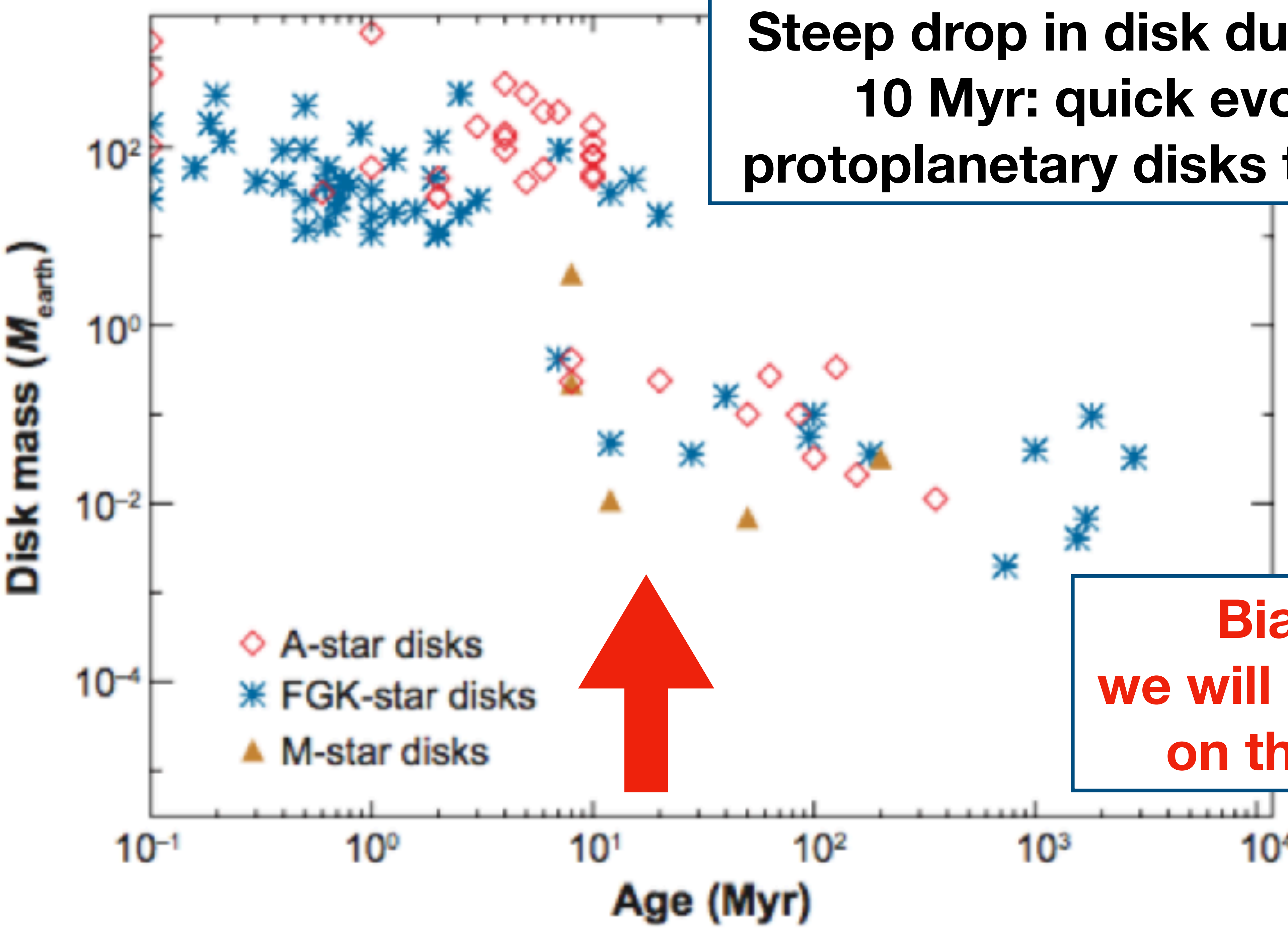



**Lifetime of a disk is thought to be ~few Myr on average, based on the disk fraction in a number of clusters: importance of large surveys and statistics!**

**We will see some update on this tomorrow…**

Mamajek et al. 2009

# Evolution and lifetime




**Steep drop in disk dust mass around 10 Myr: quick evolution from protoplanetary disks to debris disks?**

**Biased sample: we will see some update on this tomorrow…**

Wyatt et al. 2008

So what do we know so far about disks?

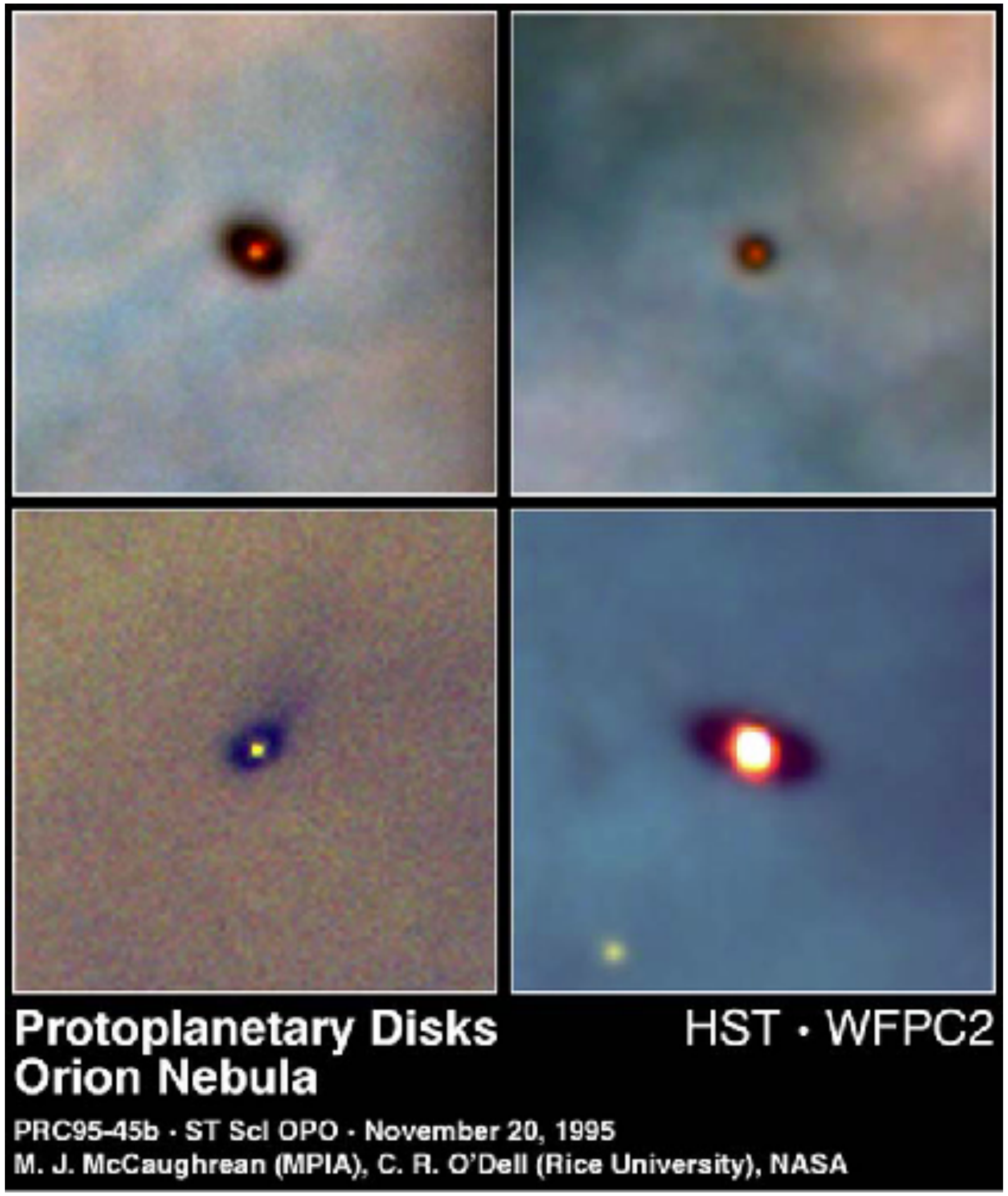
# So what do we know so far about disks?

- They are made of gas and dust and rotate
- They can be observed anywhere between UV and mm wavelengths
- They are accreting material onto the star
- They are (mostly) several 100 light years away and clustered in star forming regions
- They are (mostly) unresolved in infrared data implying they are ~1” or smaller in size (~100s AU)
- They live several million years
- They may have substructure such as gaps
- They form planets

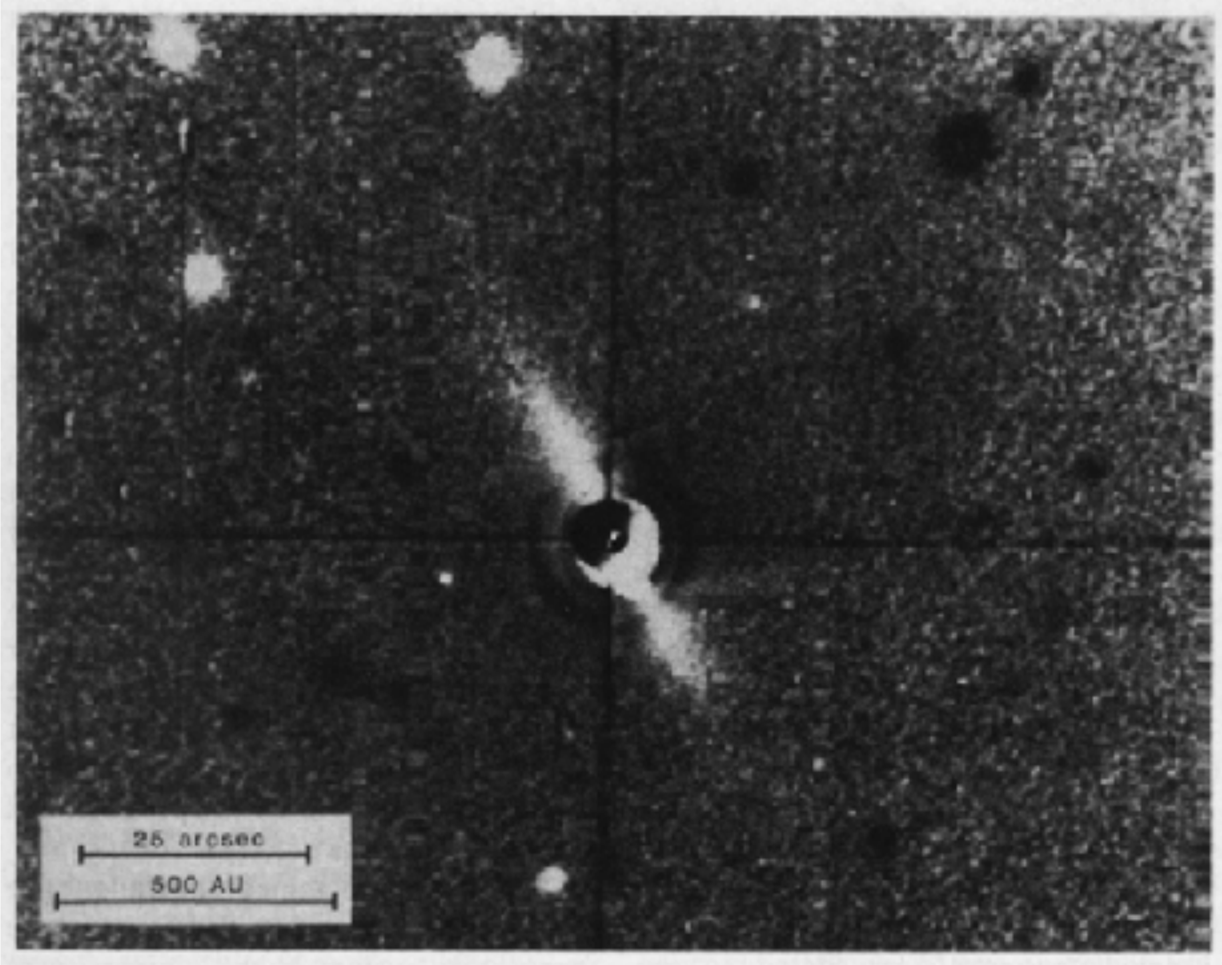
**Let’s get to disk images!**

# First disk images

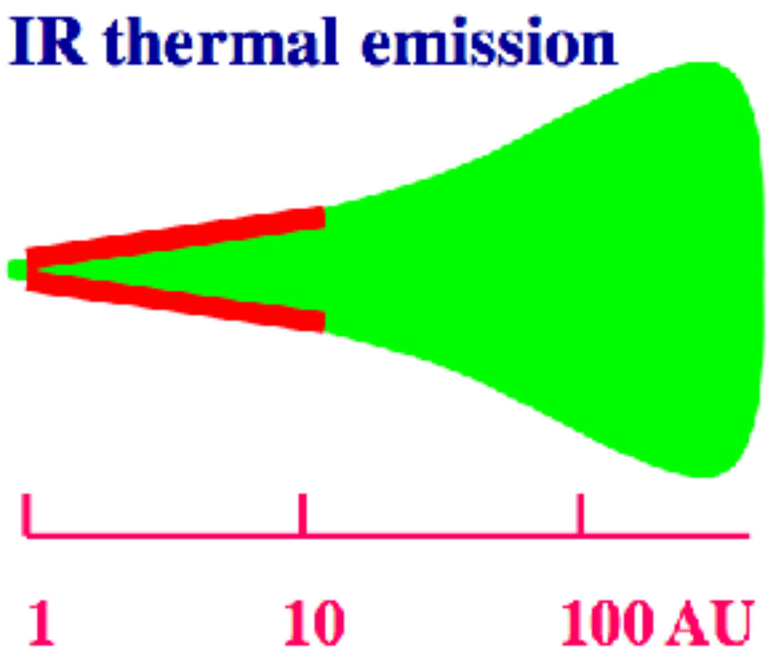
**1995: ‘proplyds’ seen with Hubble in Orion**

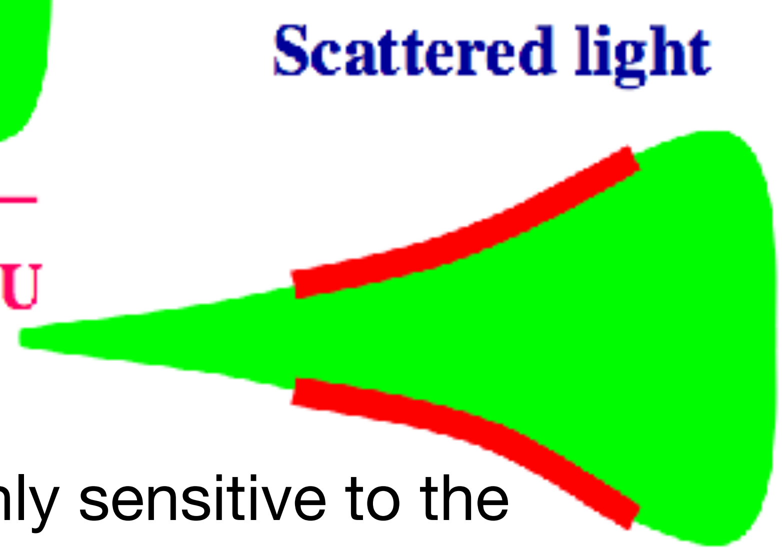


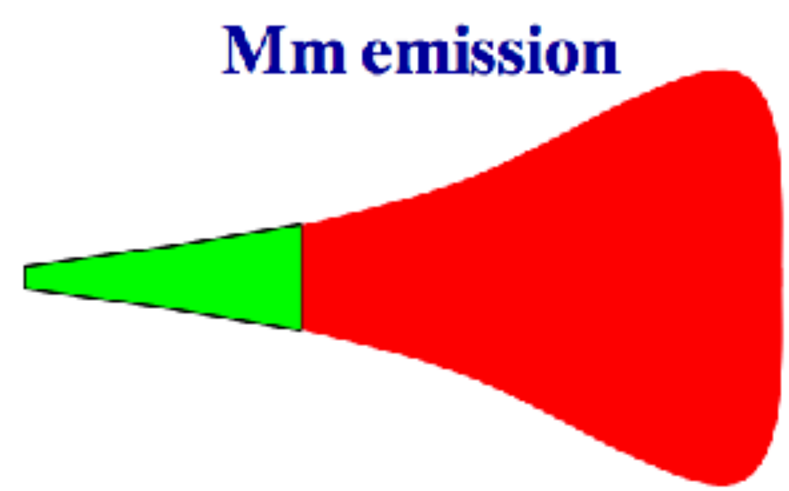

**1984: Beta pic (debris disk) in optical scattered light: edge-on**



# First disk images



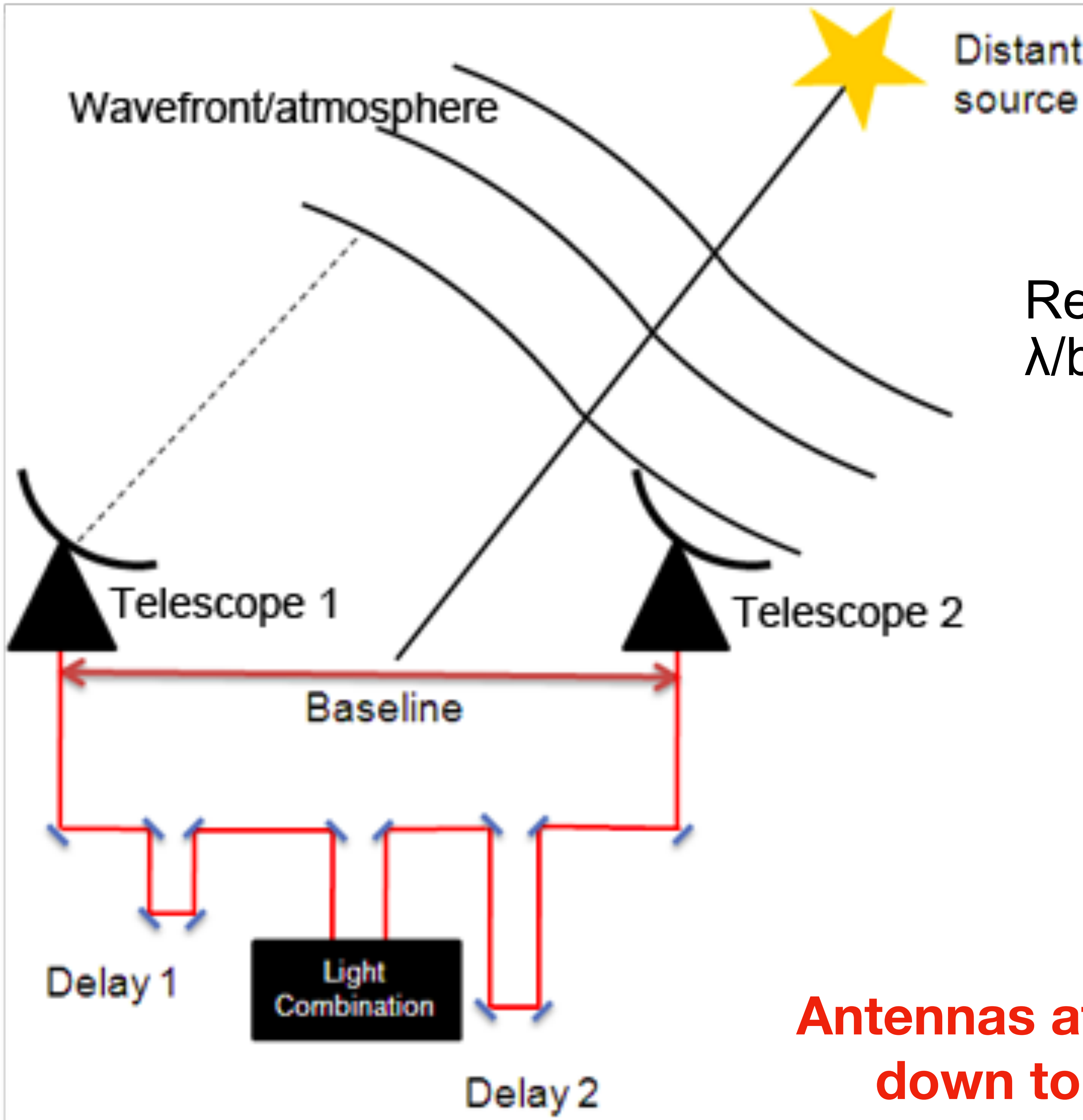

- Problem with scattered light: only sensitive to the upper layers of the disk (‘optically thick’)
- Optically thick means that photons at deeper layers in the disk are *reabsorbed* in the upper layers, so you only observe the *upper layers*
- Optical depth is lower at *longer wavelengths* (millimeter), so we need to observe at millimeter wavelengths at high *resolution*, but res ~ λ/D => >10” even for 30m telescopes

# A new era of disk imaging: millimeter interferometry




What is interferometry?

# Interferometry

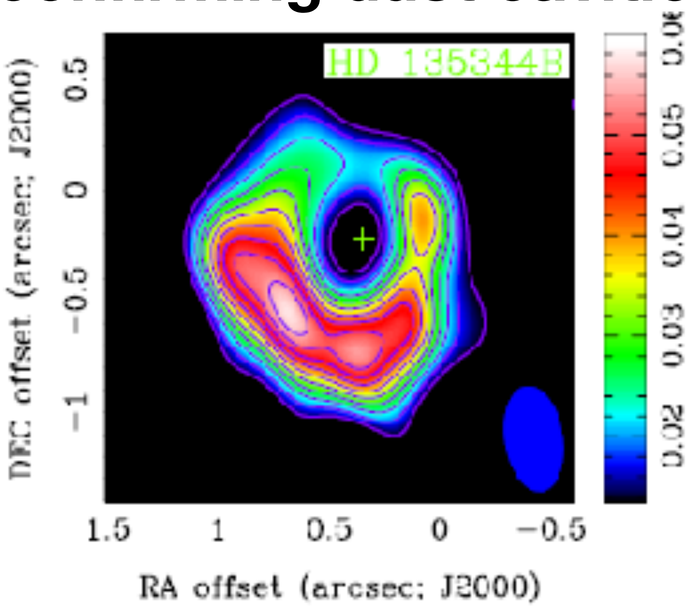


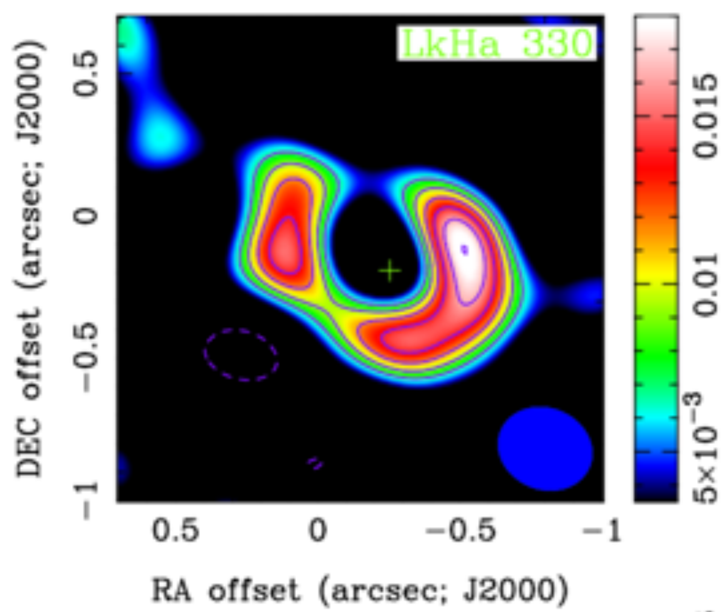

Resolution:
λ/baseline length

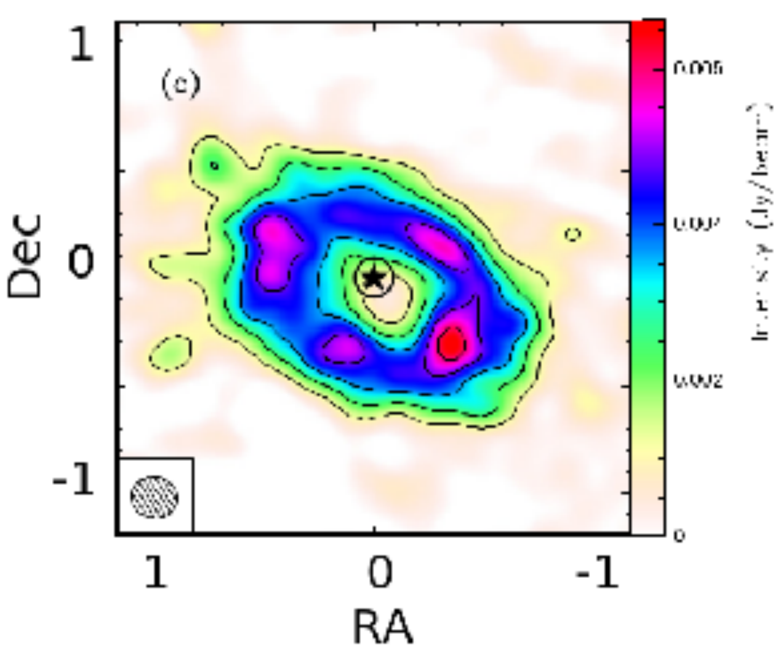
**Antennas at ~500 m distances:**
**down to ~0.4” resolution**

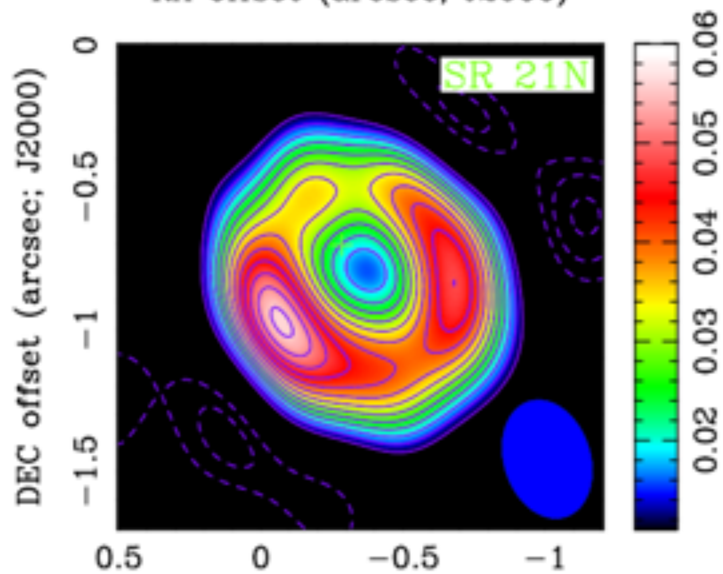
# Interferometry

**continuum images of transition disks, confirming dust cavities**



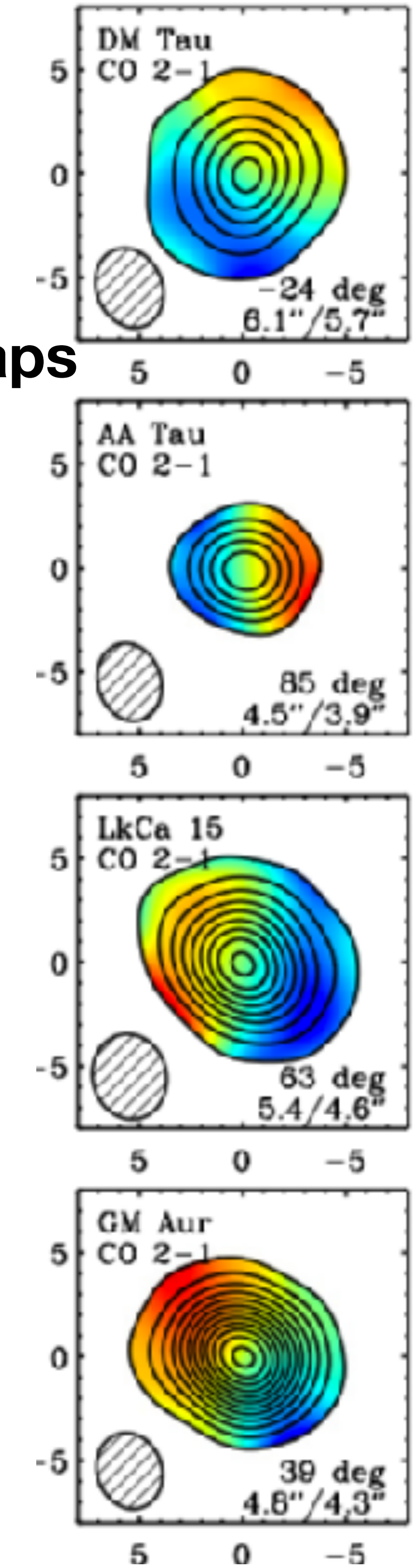




Brown et al. 2009
Isella et al. 2010
Oberg et al. 2010

**Velocity maps of CO**




**What kinematics do we see in velocity maps?**

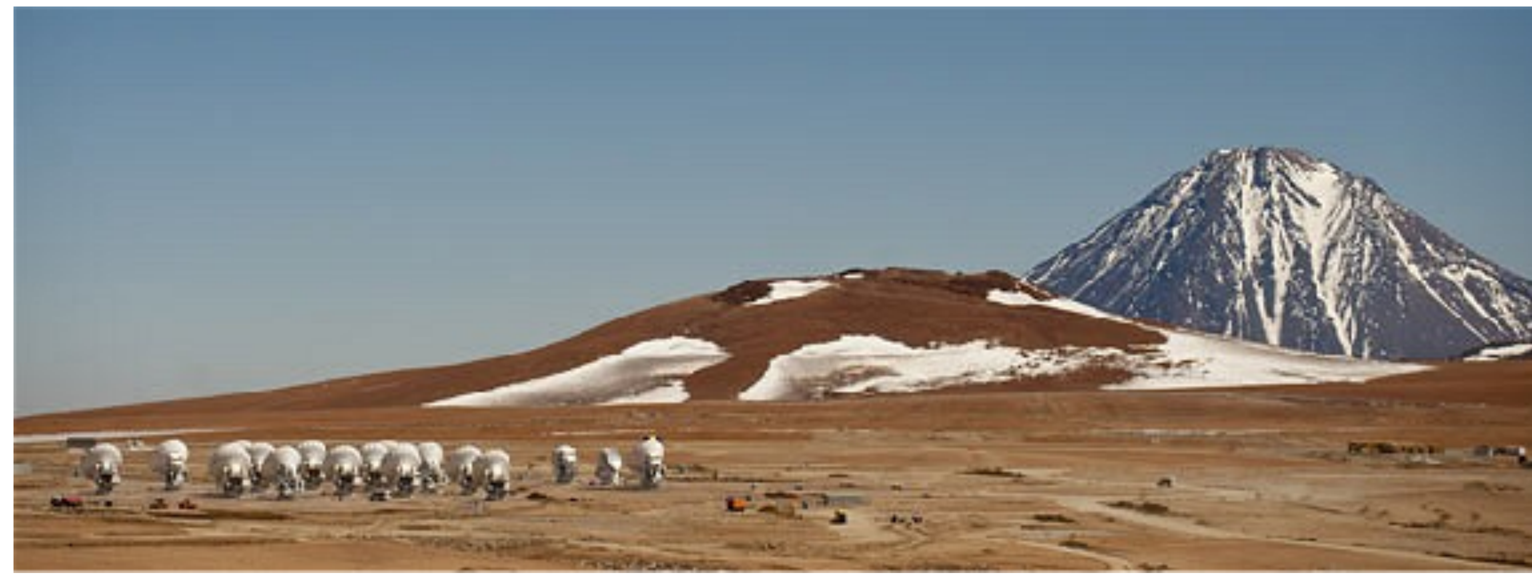
# Interferometry

- Results pioneering interferometers still limited due to small number of antennas and relatively low elevation
    - Low sensitivity: only observations of the brightest disks
    - Low sensitivity: mainly dust continuum observations
    - Short baselines: only marginally resolved disks
    - Limited number of baselines: bad image quality after Fourier transform of data

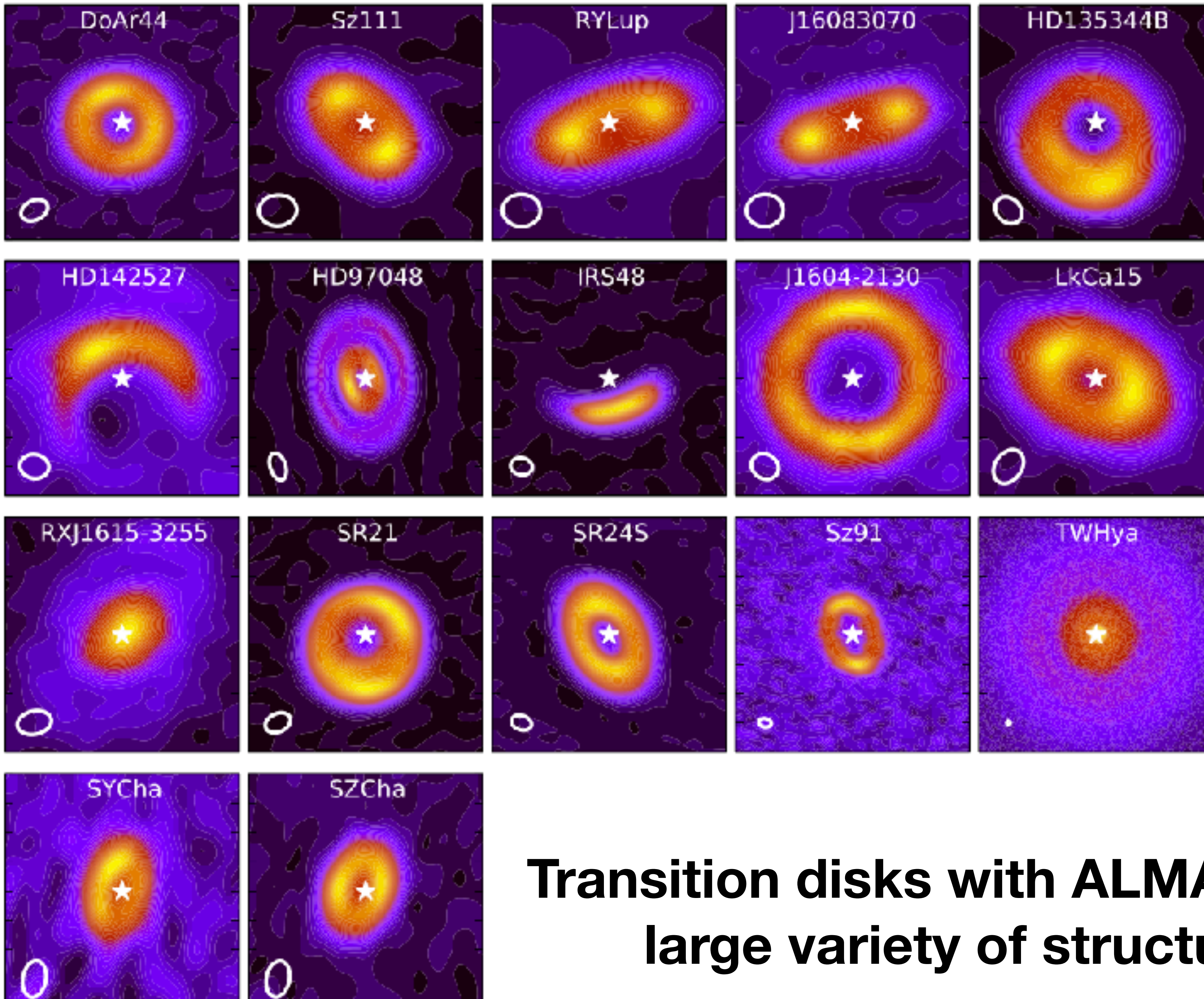
# ALMA

# ALMA


North Atlantic Ocean
VENEZUELA
COLOMBIA
BRAZIL
PERU
BOLIVIA
South Pacific Ocean
PARAGUAY
CHILE
ARGENTINA
Santiago
Buenos Aires
Montevideo
South Atlantic Ocean



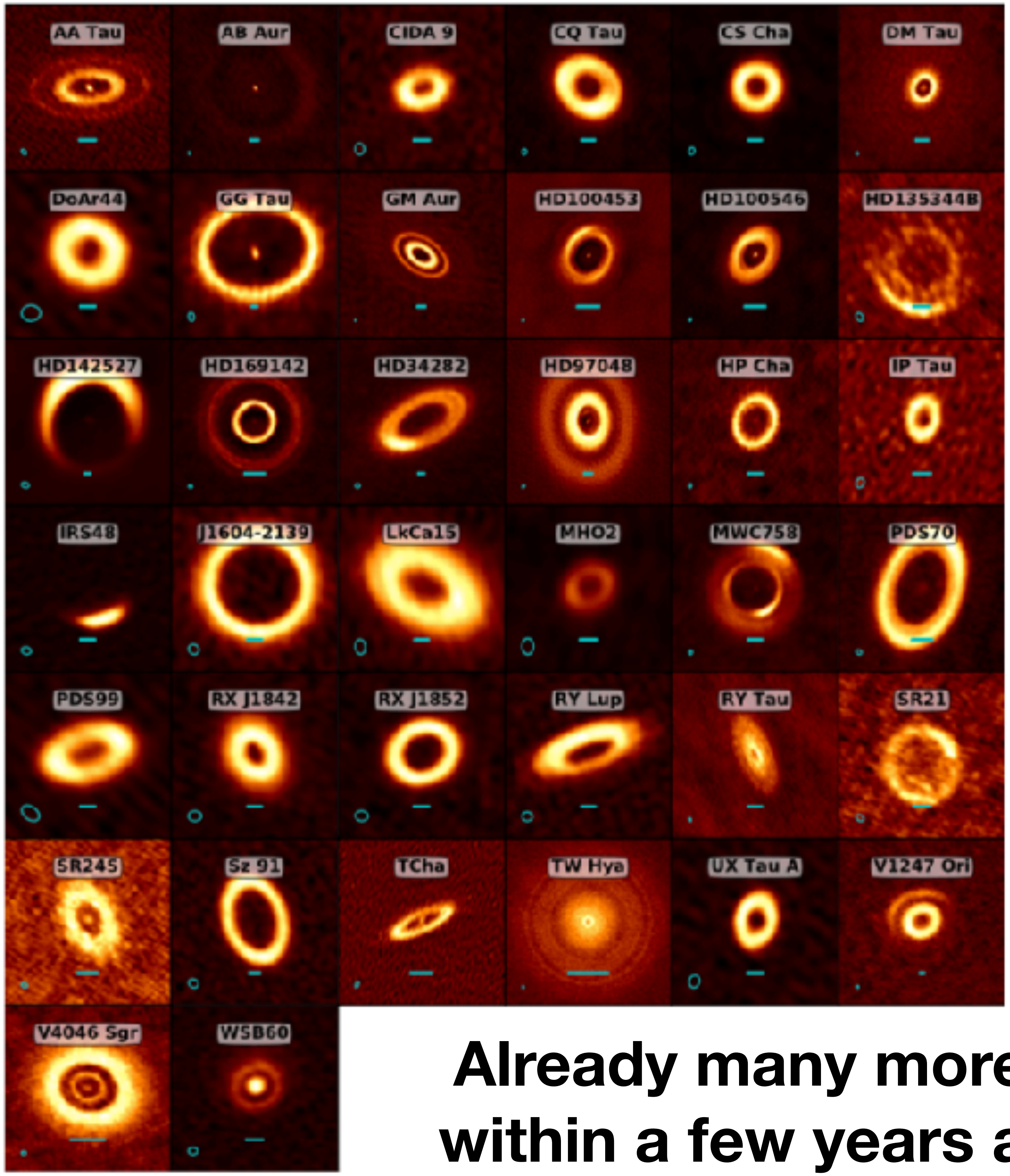
# ALMA




**Transition disks with ALMA at 0.2" : large variety of structures!**

Gallery by van der Marel in 2016 (early ALMA)

# ALMA

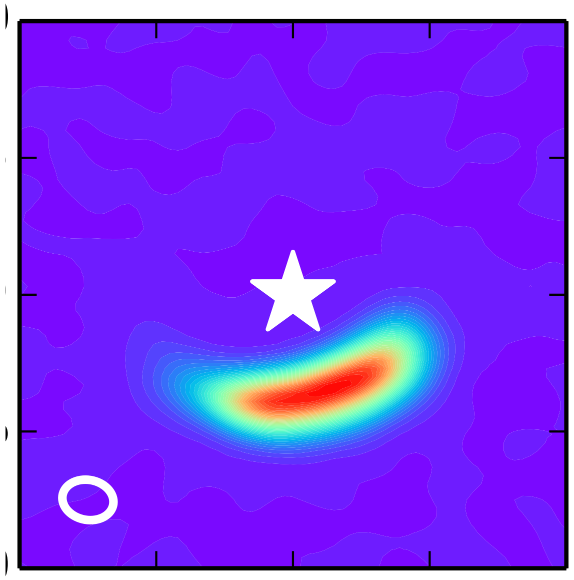



Francis & van der Marel 2020

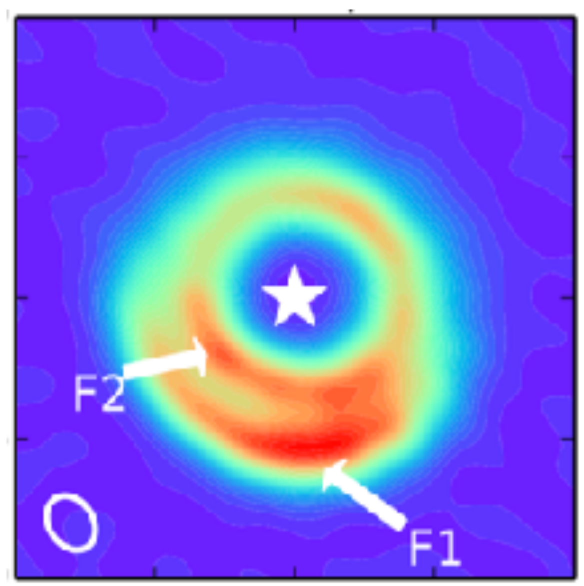
**Already many more structures visible within a few years at higher resolution**

# ALMA

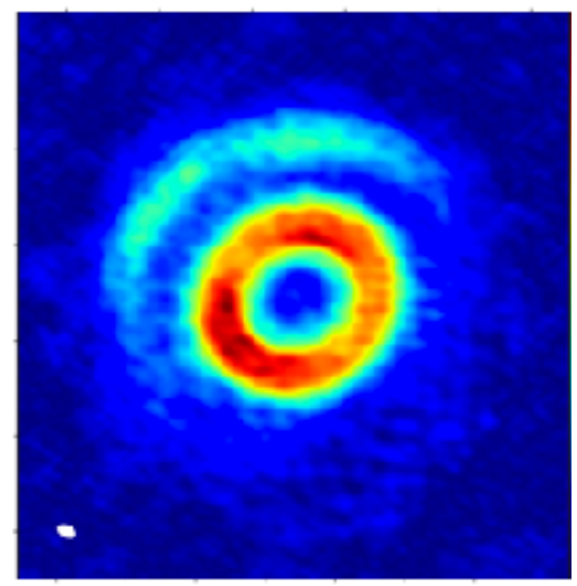
**IRS48**



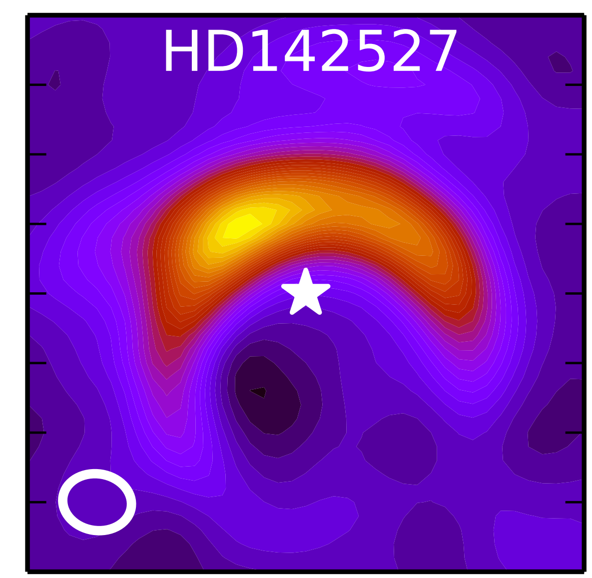
**HD135344B**




**V1247 Ori**



**HD142527**

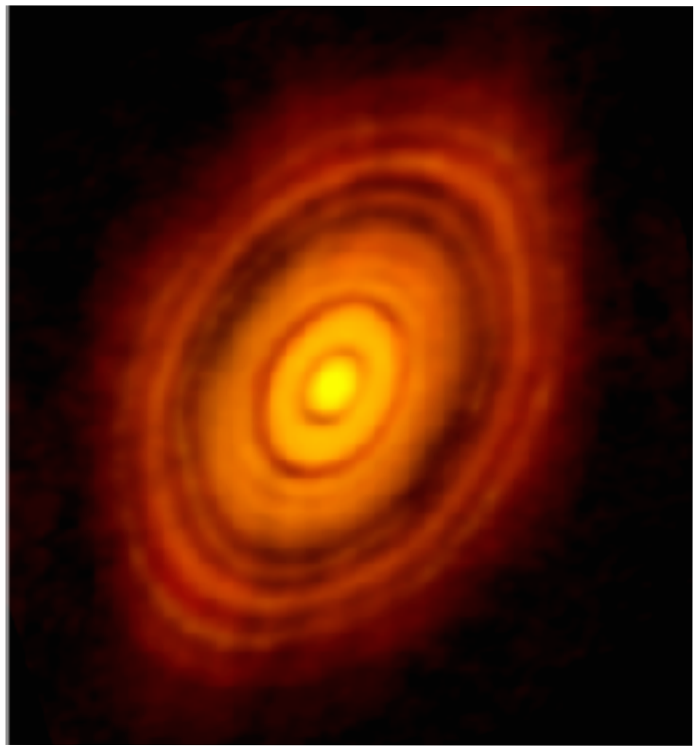



**Disks with millimeter asymmetries: vortices?**

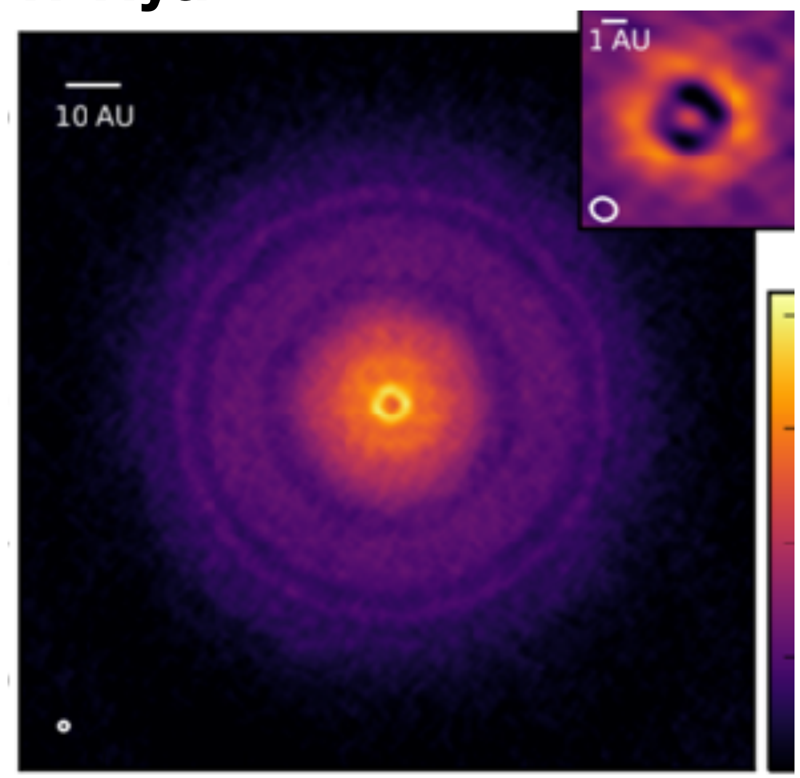
van der Marel et al. 2015, 2016
Kraus et al. 2017

# ALMA

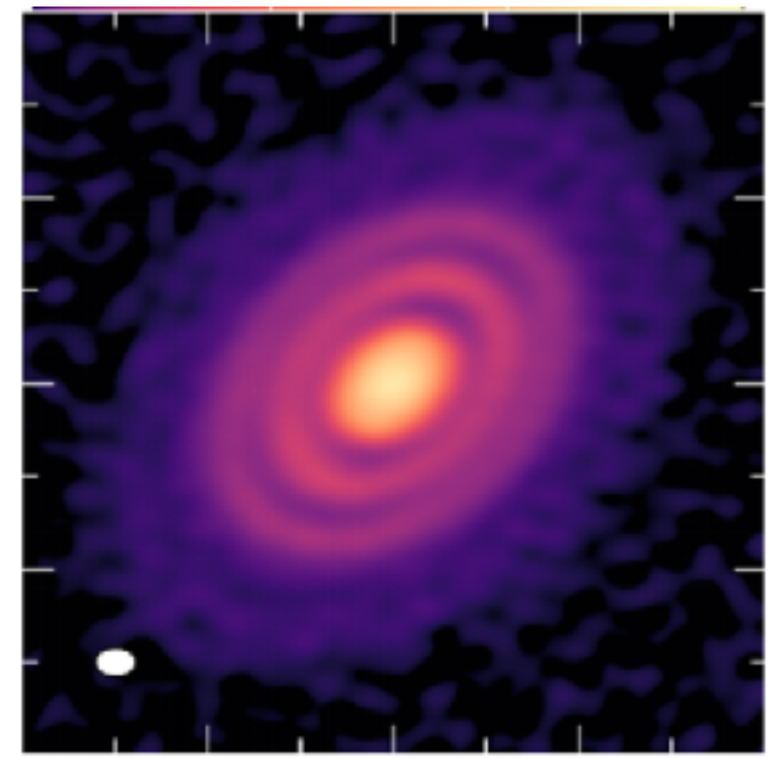
**HL Tau**

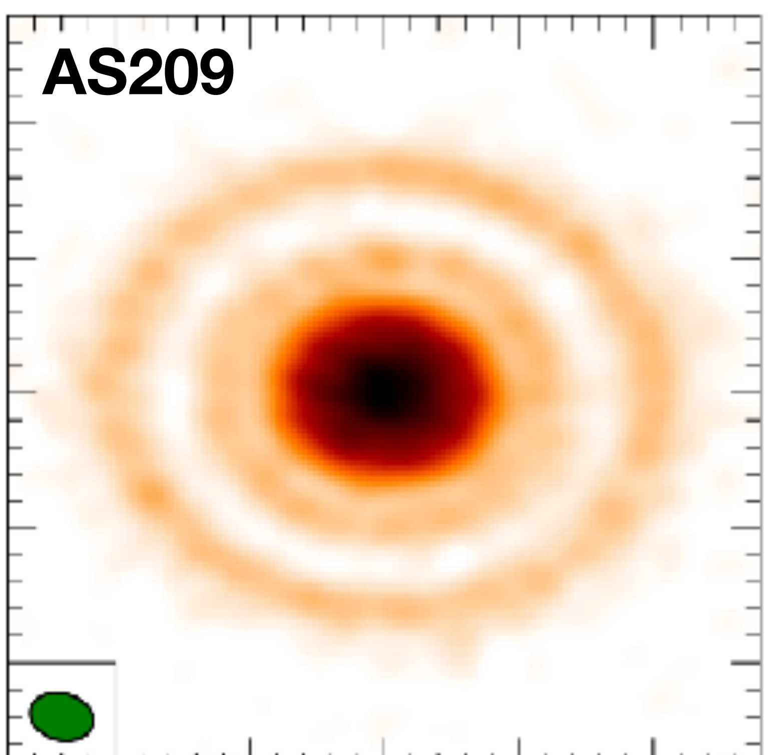


**TW Hya**




**HD163296**



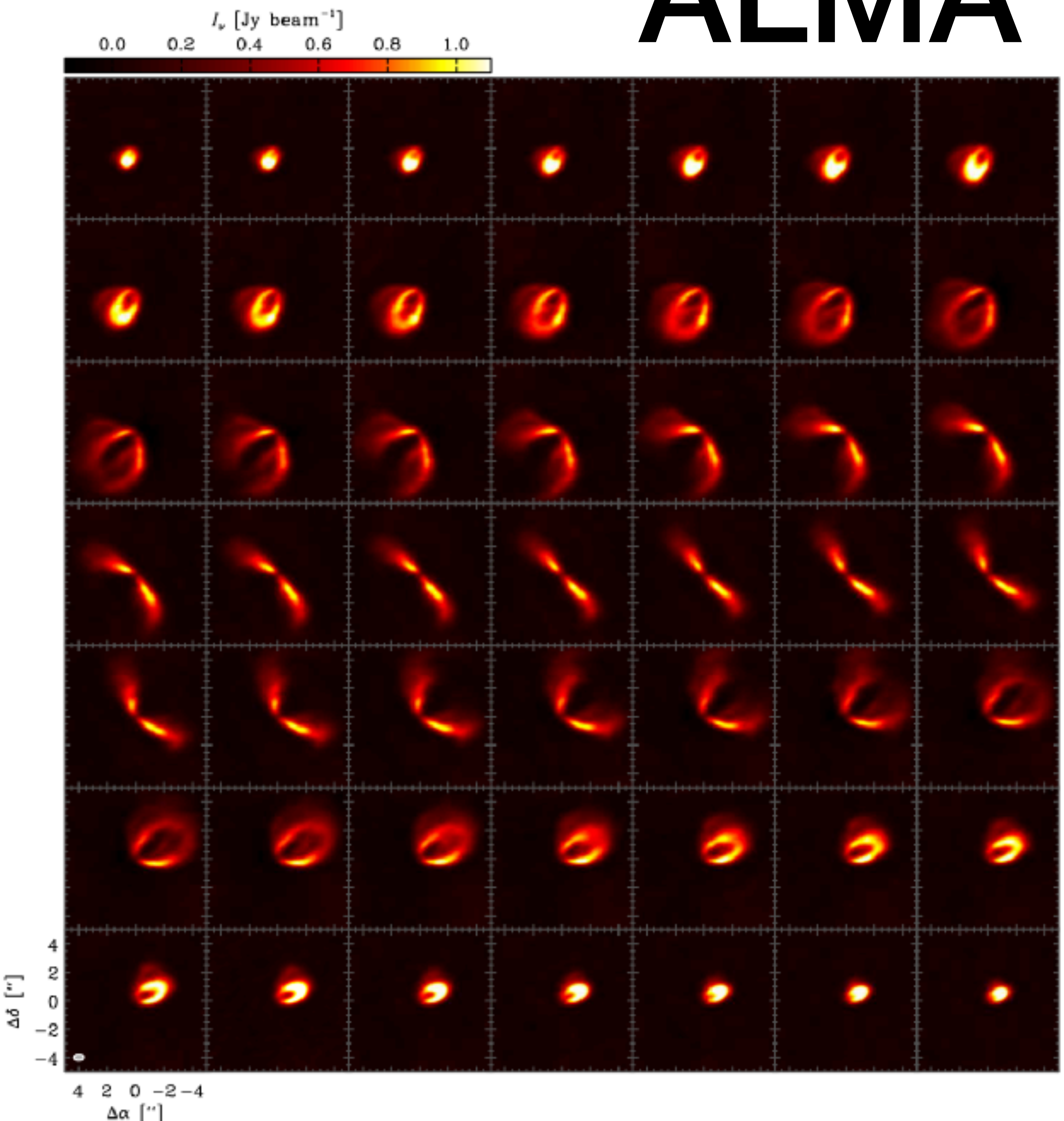




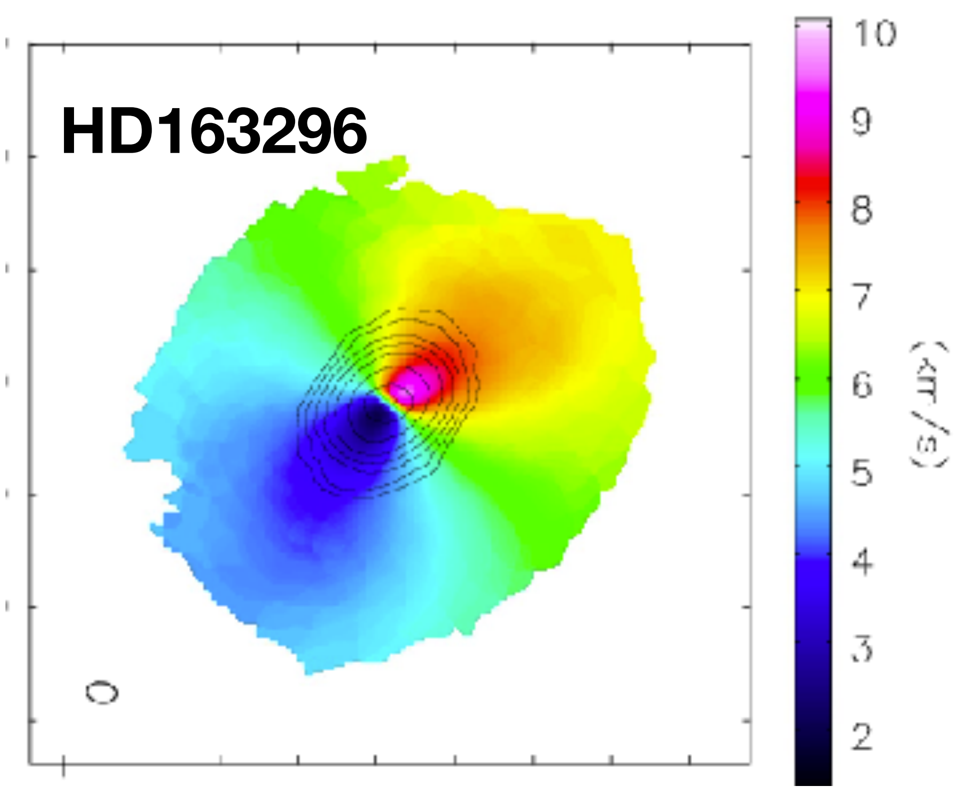
**High resolution dust images down to 0.004” resolution: rings and spiral arms!**

ALMA consortium et al. 2015,
Andrews et al. 2016, Isella et al. 2016,
Fedele et al. 2017, Perez et al. 2017

# ALMA

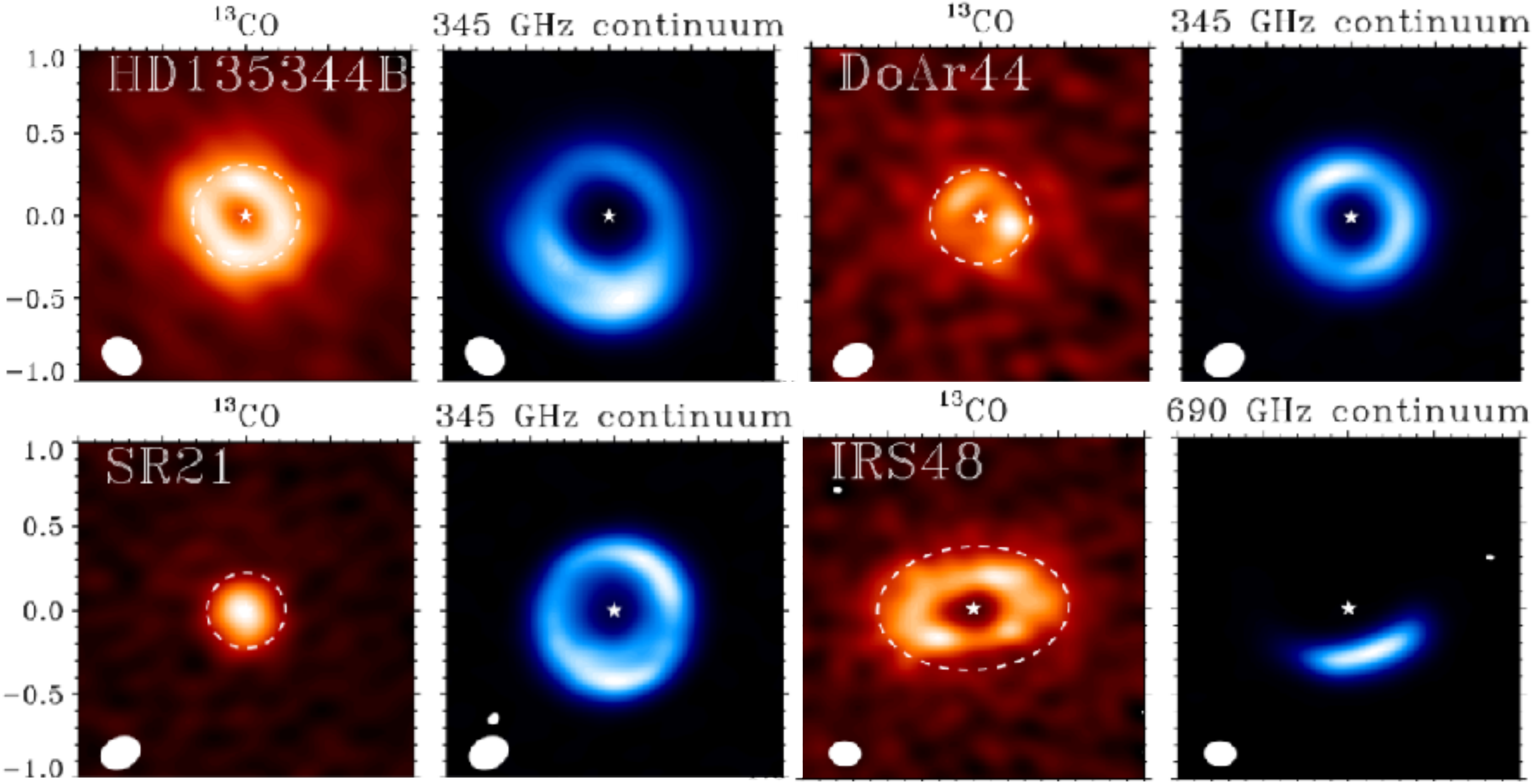



**High resolution velocity maps of molecules**




Rosenfeld et al. 2013

# ALMA

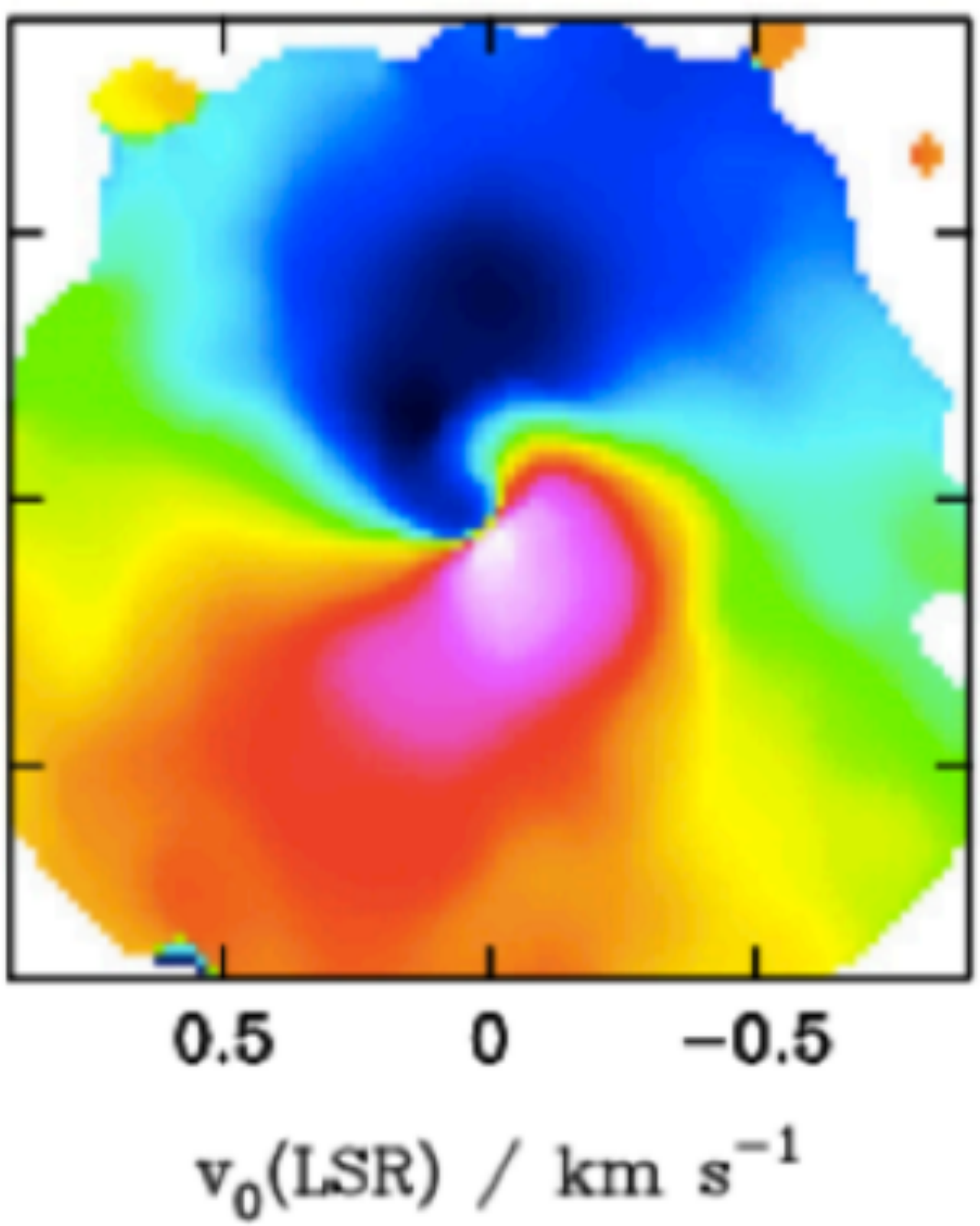



**Clear difference in morphology between dust (blue) and gas density (red): evidence for planets clearing the gaps**

van der Marel et al. 2016

# ALMA

HD142527

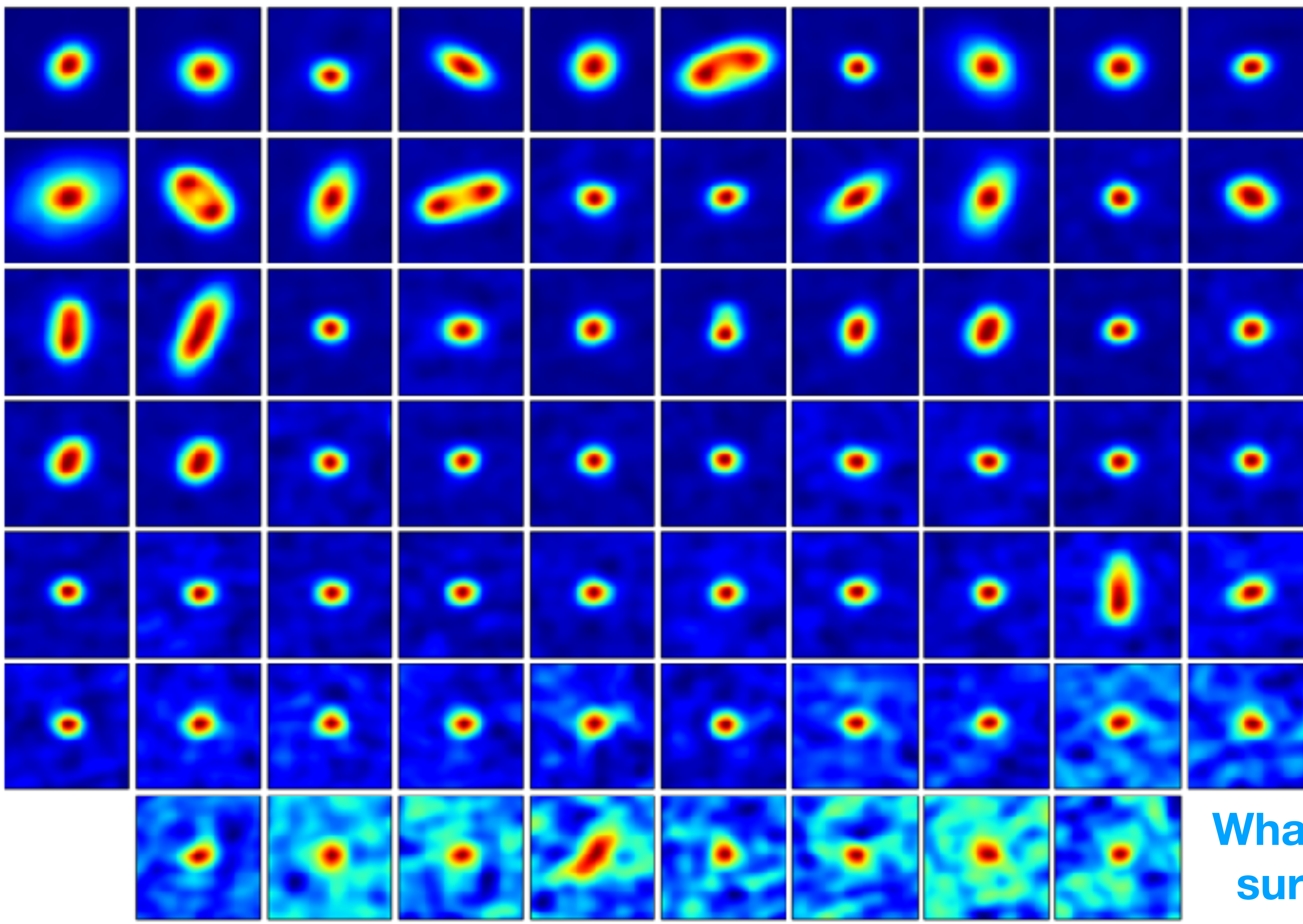



**Disk with non-Keplerian motion: accreting gas onto the star?**

Casassus et al. 2015

# ALMA

**Disk surveys of entire star forming regions in 1-2 minutes per source!**

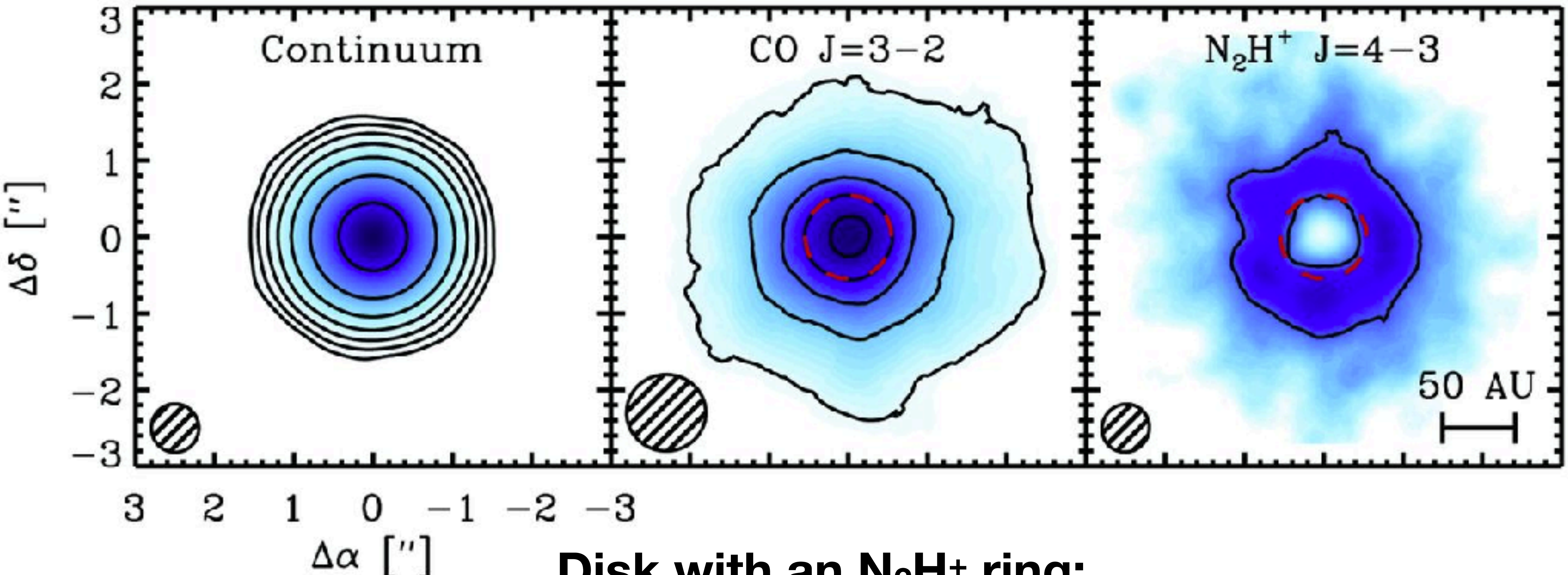


Ansdell et al. 2016

**What is the advantage of these surveys compared to Spitzer surveys?**

# ALMA

**TW Hya**

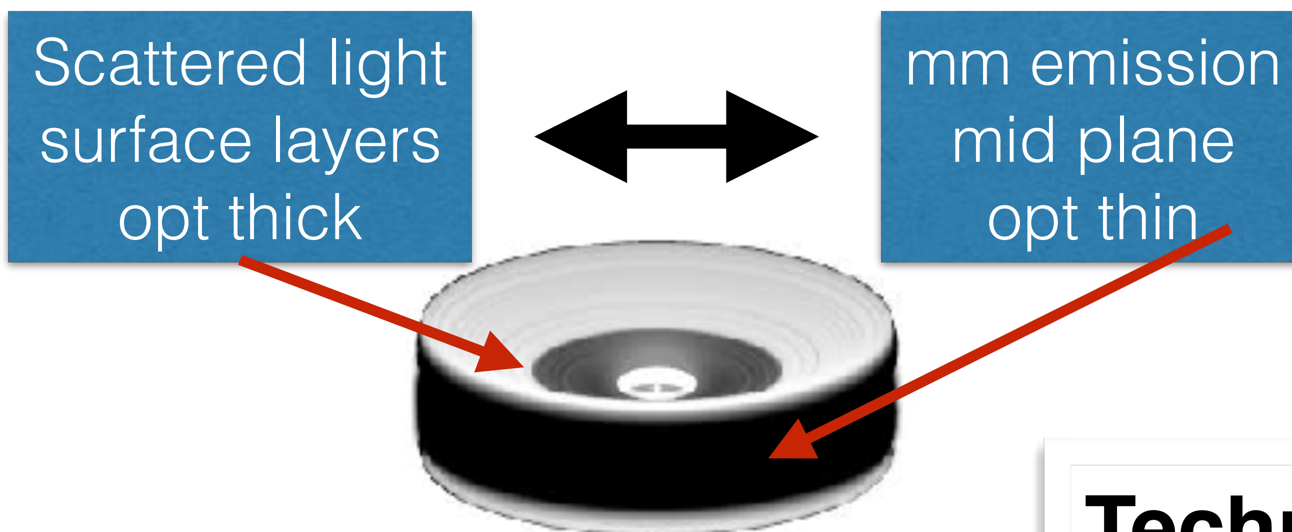



**Disk with an $N_2H^+$ ring:**
**CO snowline**
**($N_2H^+$ can only form when CO is frozen out)**

Qi et al. 2013

# NIR imaging

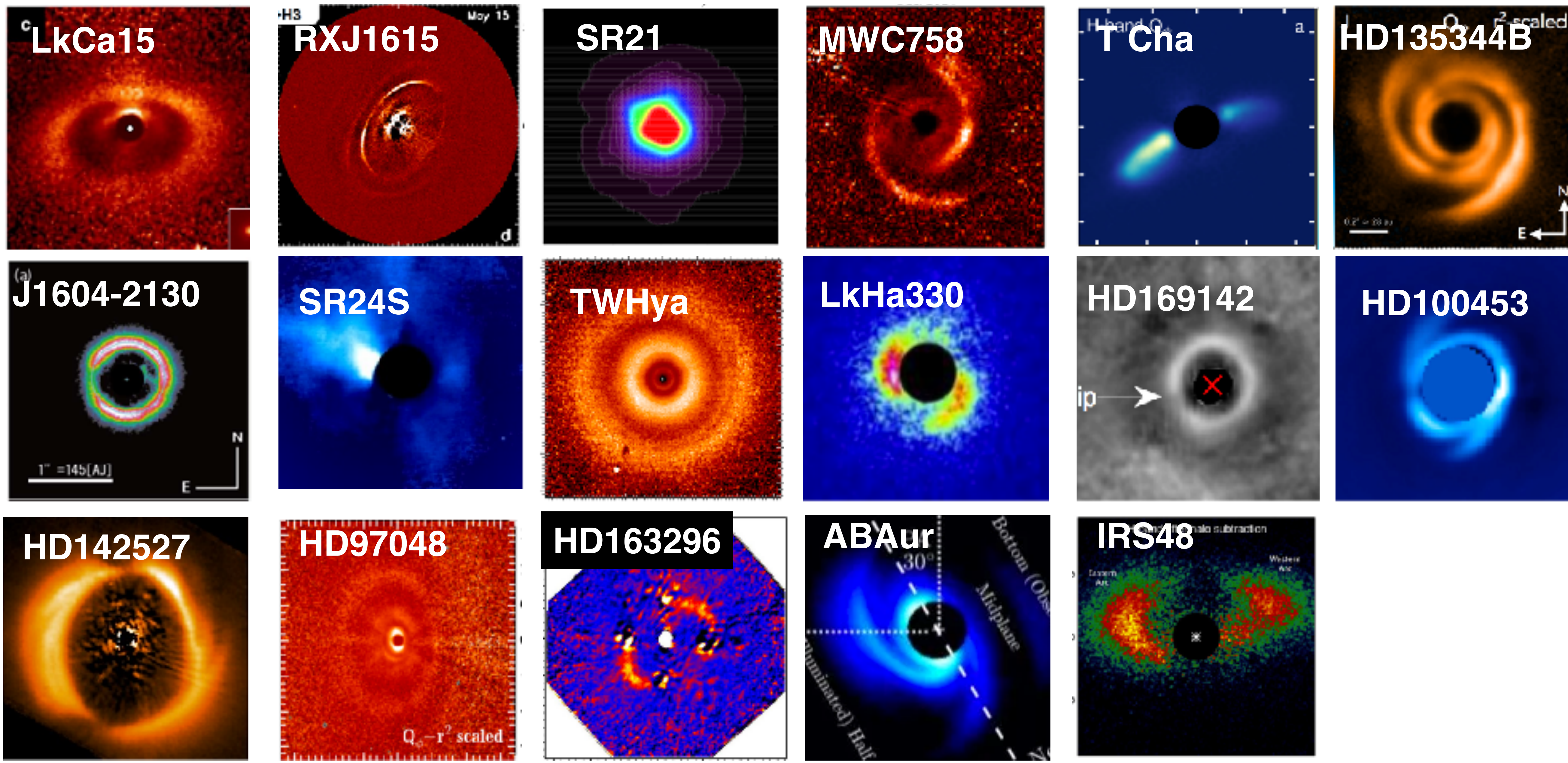
- Scattered light imaging is sensitive to upper layers of the disk => different perspective




**Technique also used to detect protoplanets**

- Difficulties:
  - need for adaptive optics system
  - need for small coronograph blocking the stellar light
  - need for observing techniques removing diffraction patterns

# NIR imaging

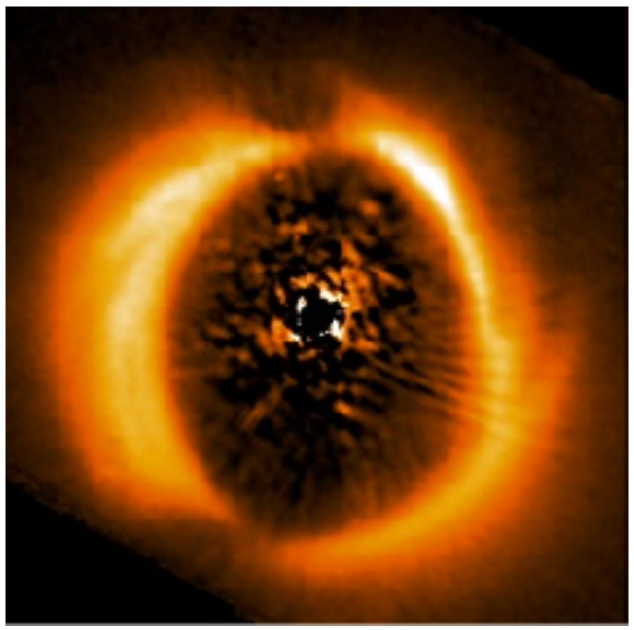



**Also here a wide variety of structures: rings and spiral arms**

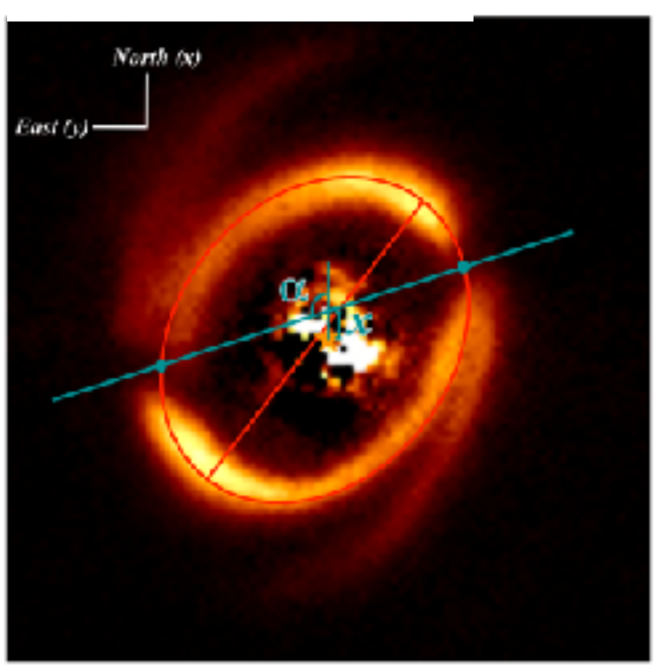
Credits: SPHERE and SEEDS teams

# NIR imaging

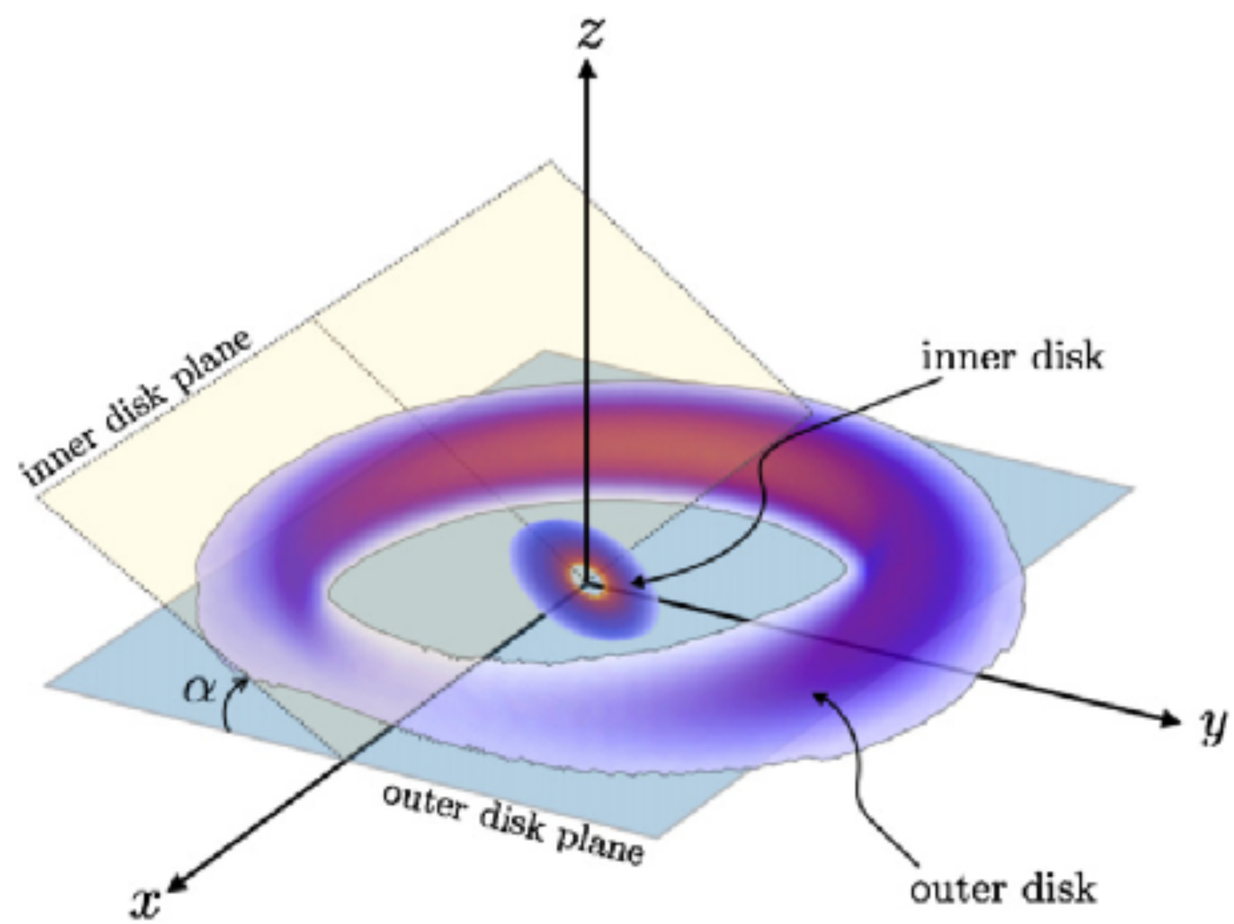
**HD142527**



**HD100453**

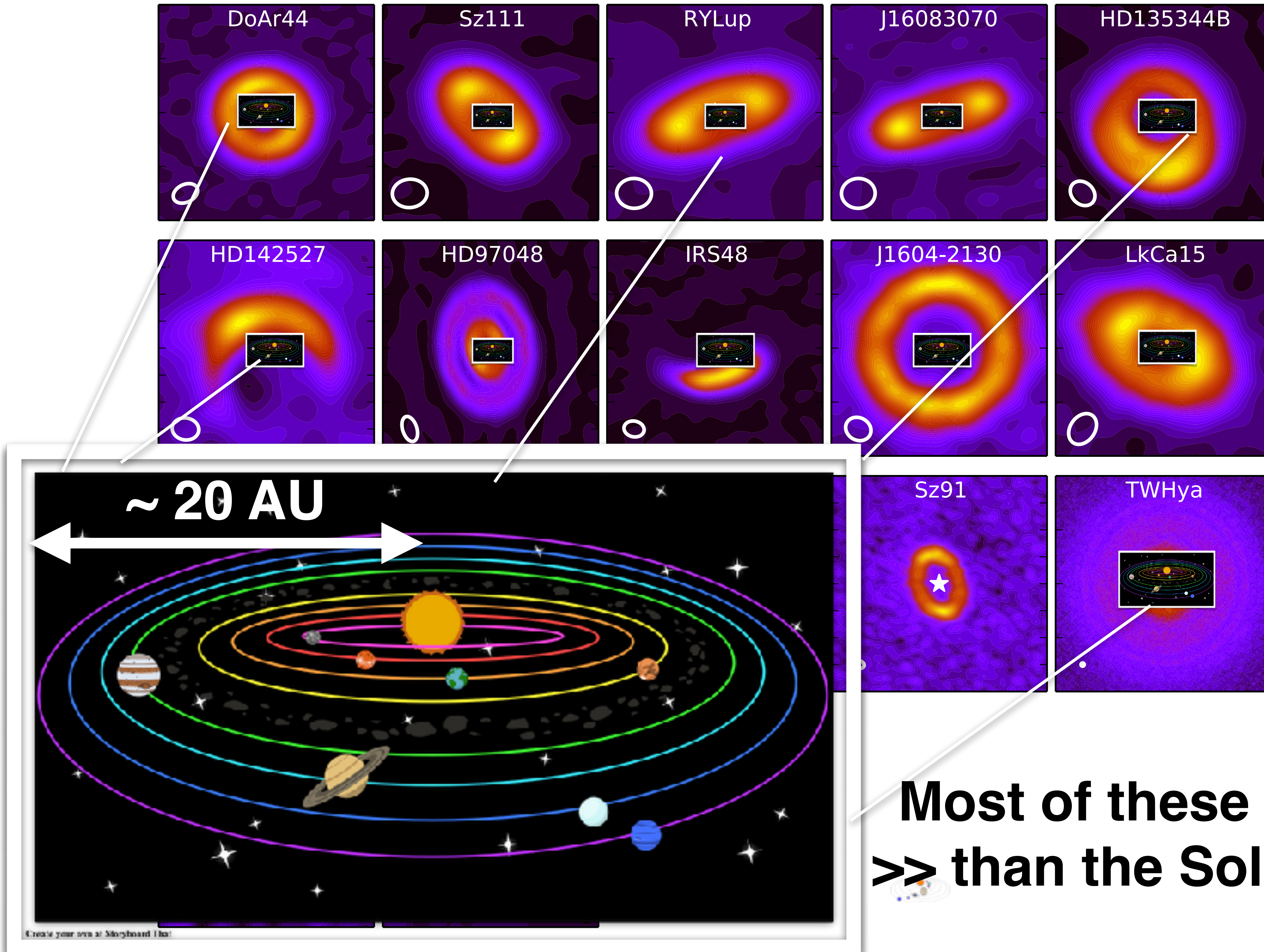



**Shadows along the ring:**
**Misalignment between inner and outer disk**




Marino et al. 2015
Benisty et al. 2017

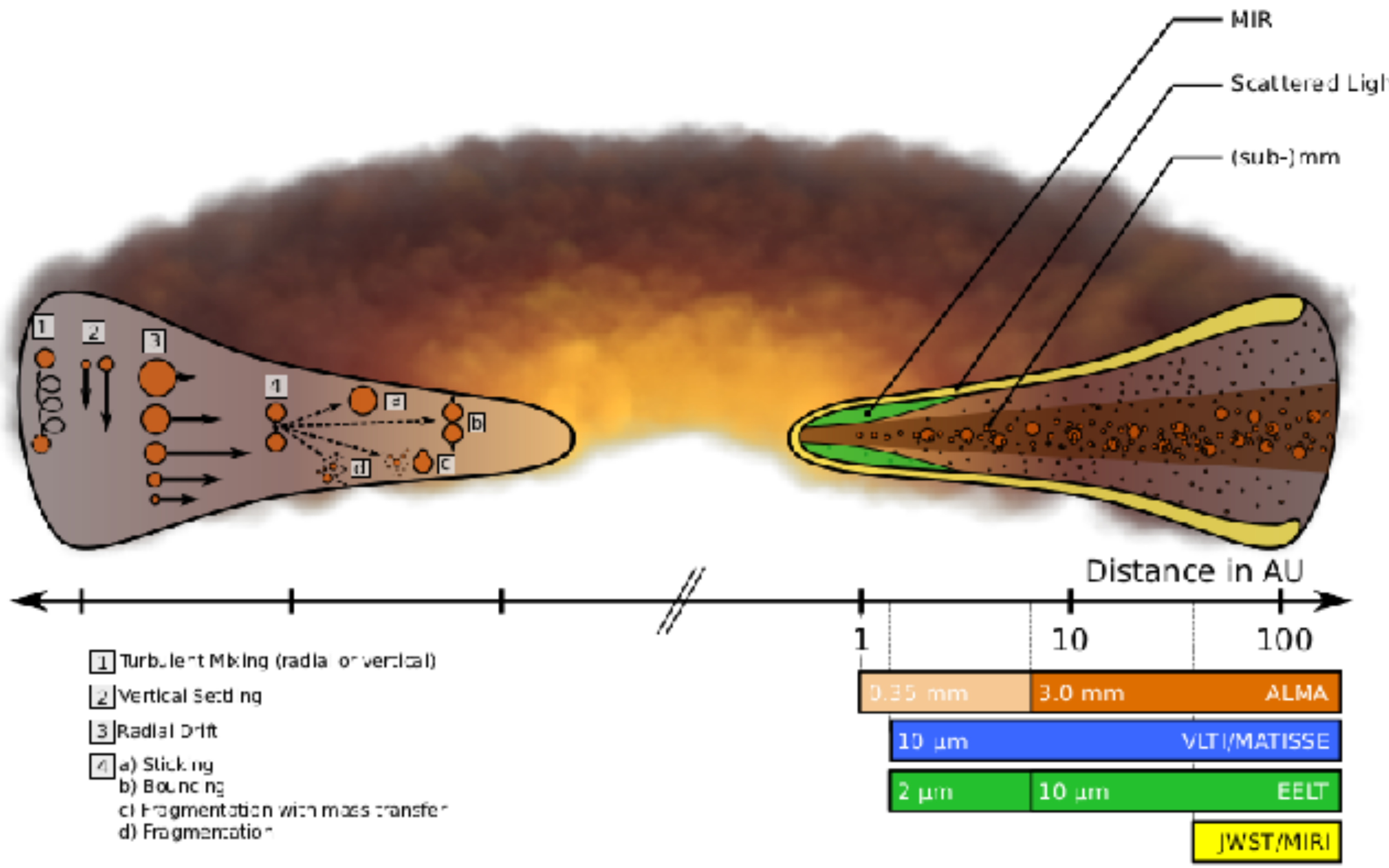
# Something to keep in mind…




**Most of these disks are >> than the Solar System!**

# Disk processes

- dust growth
- accretion and photoevaporation
- dynamics and instabilities
- planet disk interaction
- chemistry

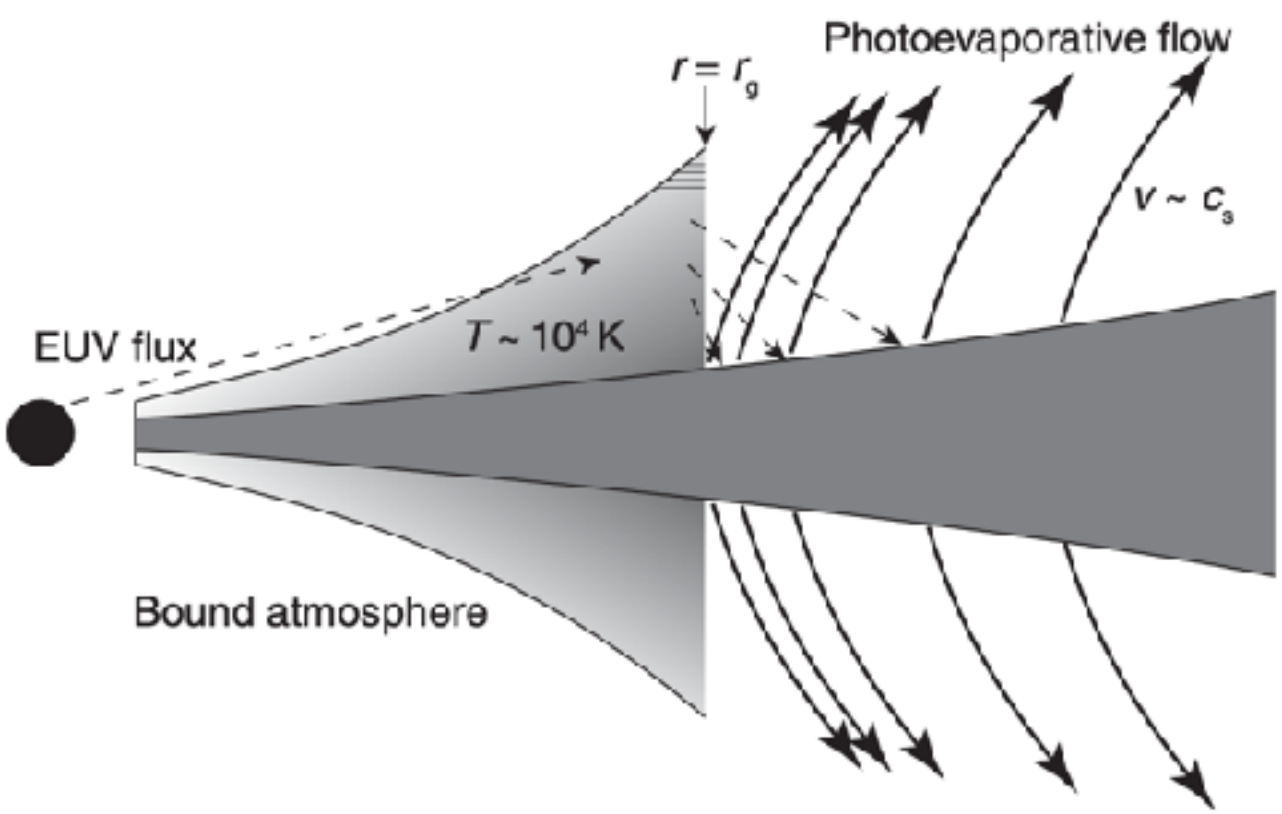


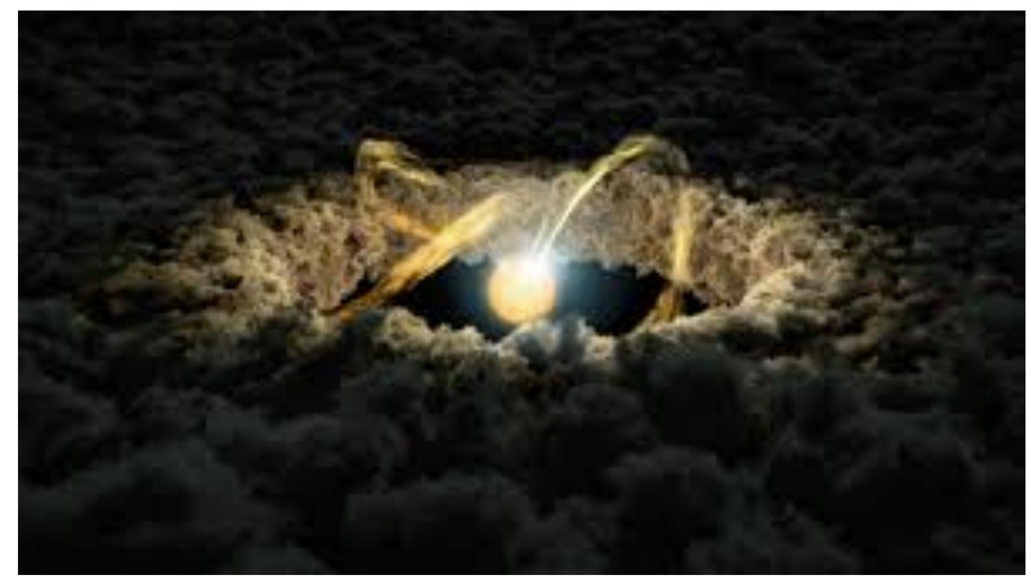

Testi et al. 2014

# Accretion and photo evaporation

**Photoevaporative wind: stellar radiation heats up upper layers inner disk beyond escape velocity: photoevaporative wind (measured in infrared line profiles)**

**Accretion: material is transported through the disk inwards onto the star (measured through broad Hα line).**

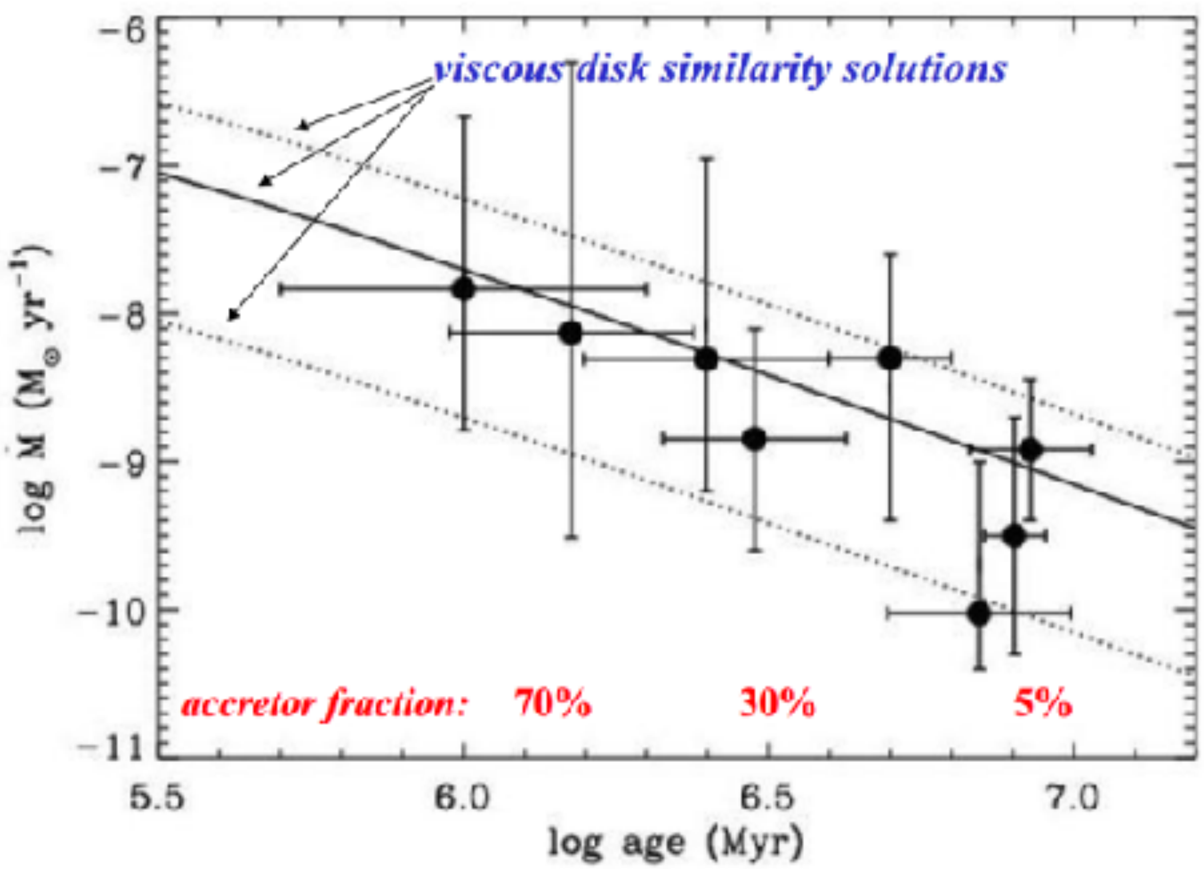


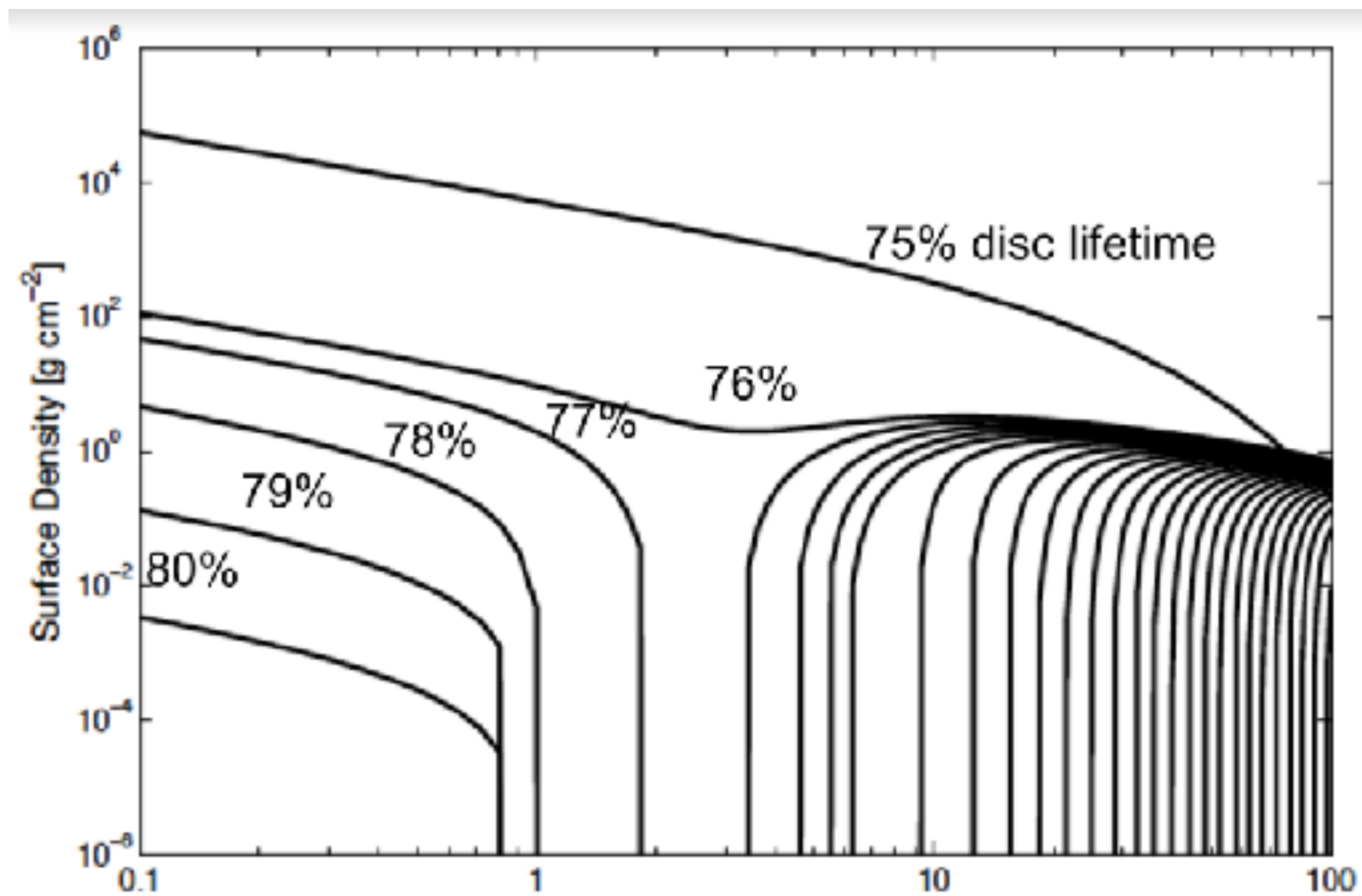
**Balance between accretion and photo evaporation**

# Accretion and photo evaporation

**Accretion rate is thought to drop with age: at some point photo evaporation becomes dominant and disk dissipates quickly**

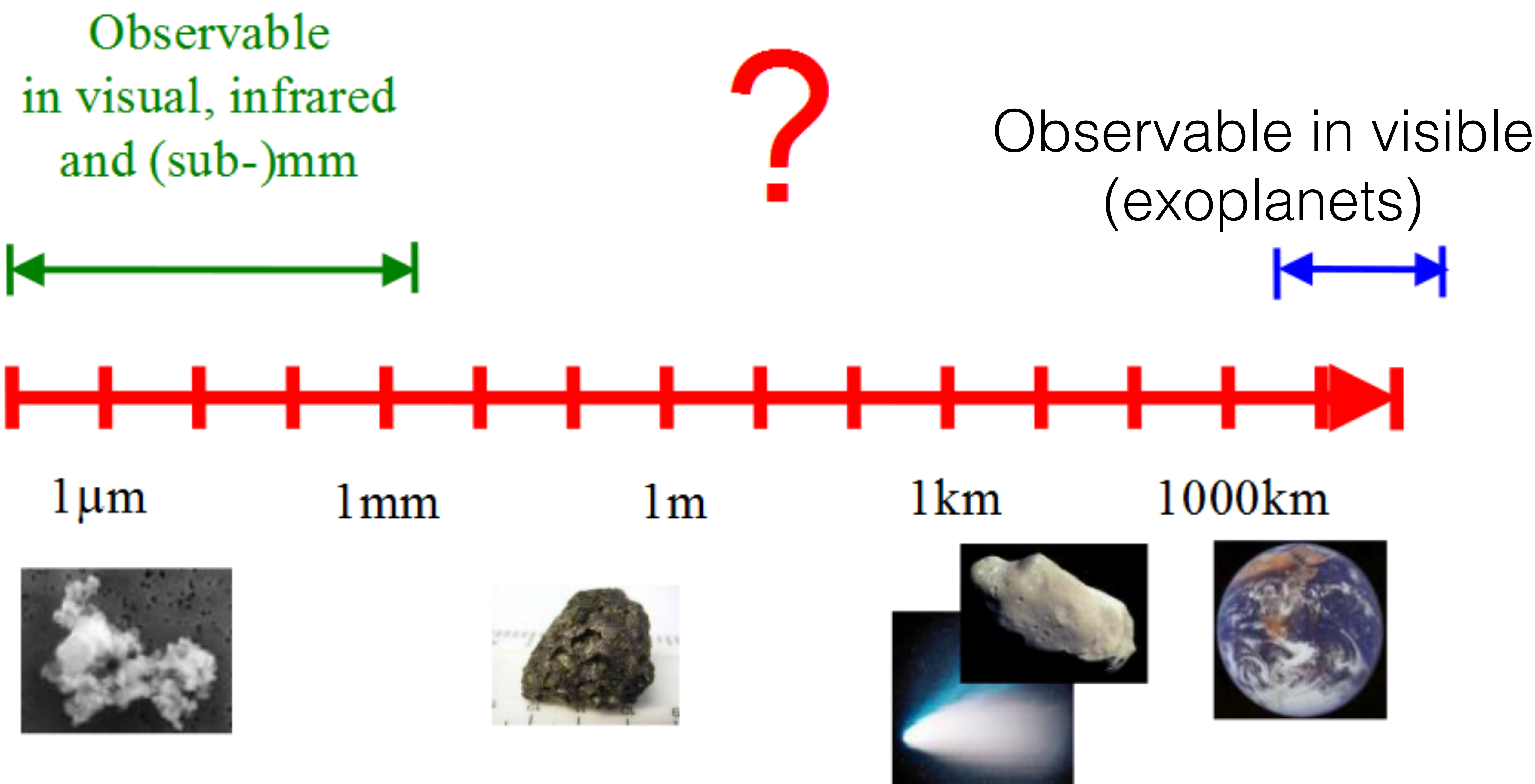



**Photoevaporative model by Owen et al. 2015**



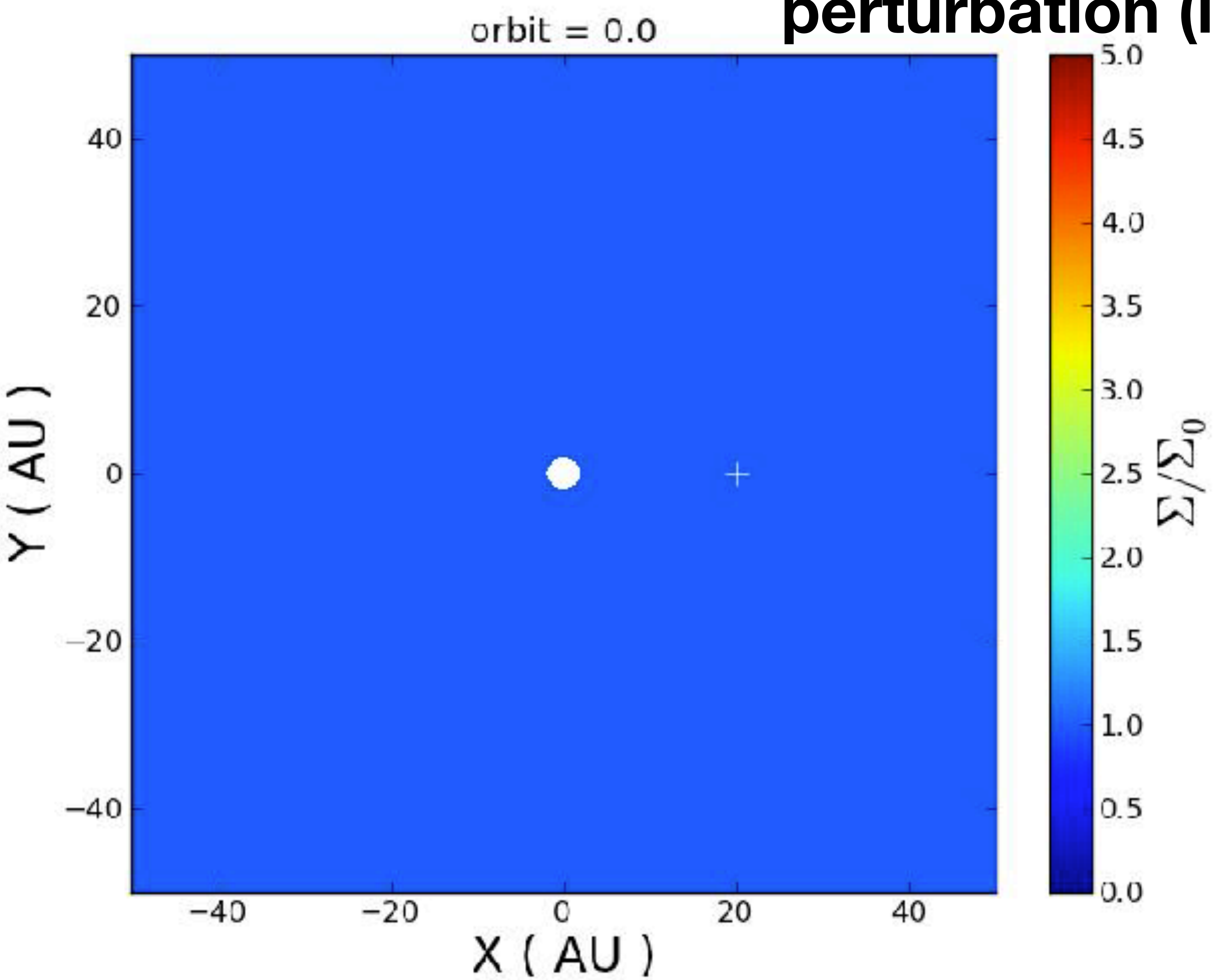
# Dust growth

- **Dust particles grow by collisions in a balance between coagulation and fragmentation**



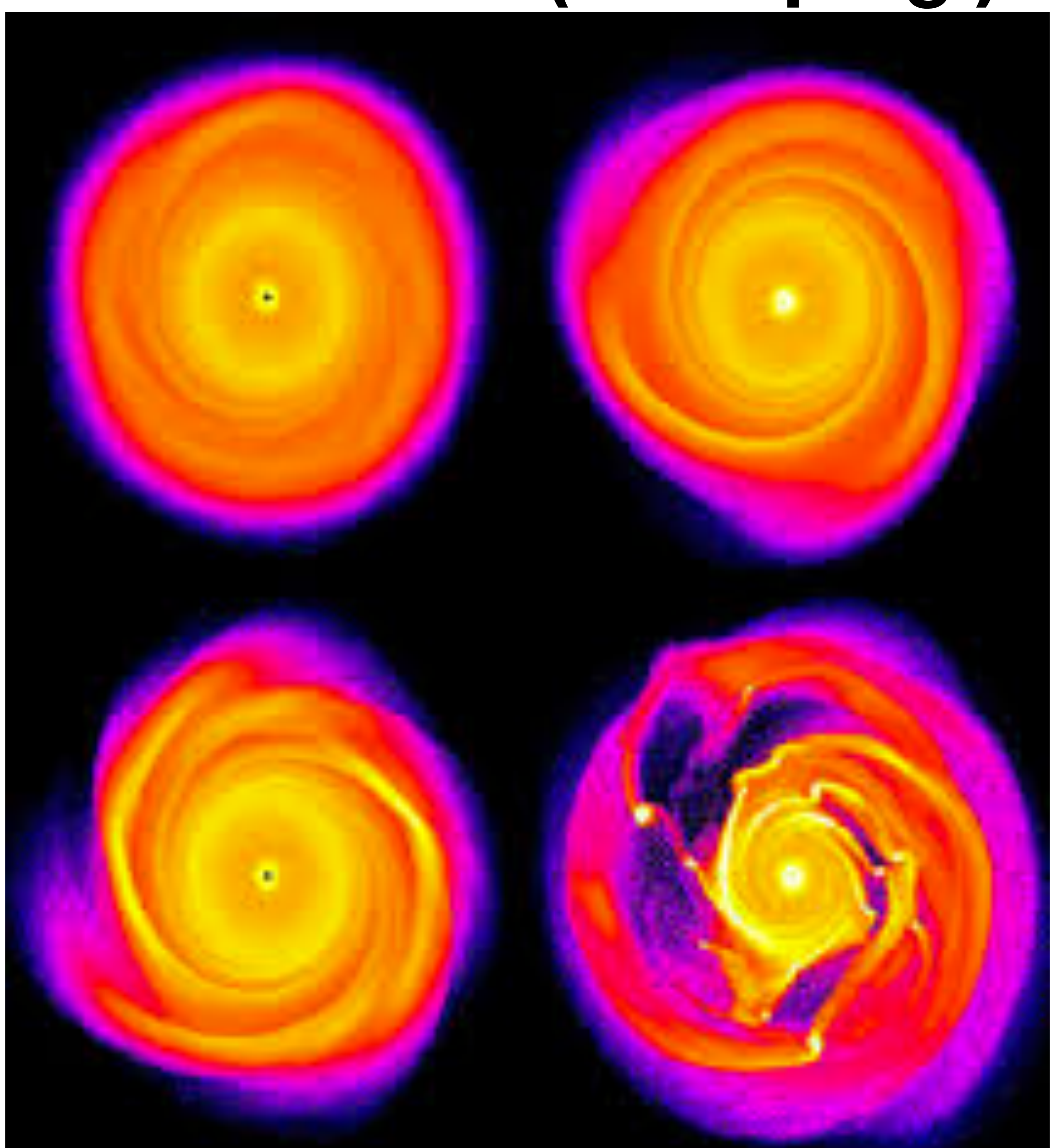
# Dynamics and instabilities

**Hydrodynamics in a gas disk: formation of gaps, spiral arms, vortices due to a perturbation (in this case a planet)**



# Dynamics and instabilities

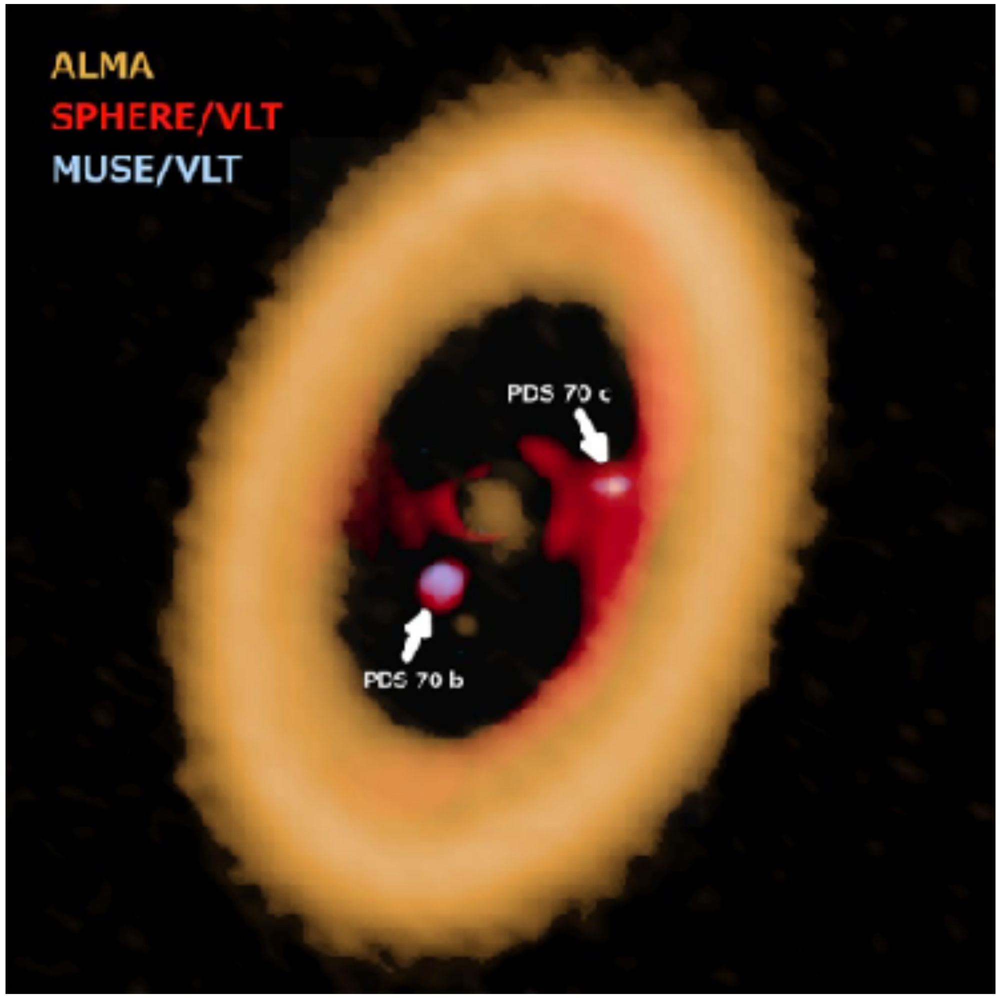
**Planet formation and spiral arms due to gravitational instability of the disk ('clumping')**

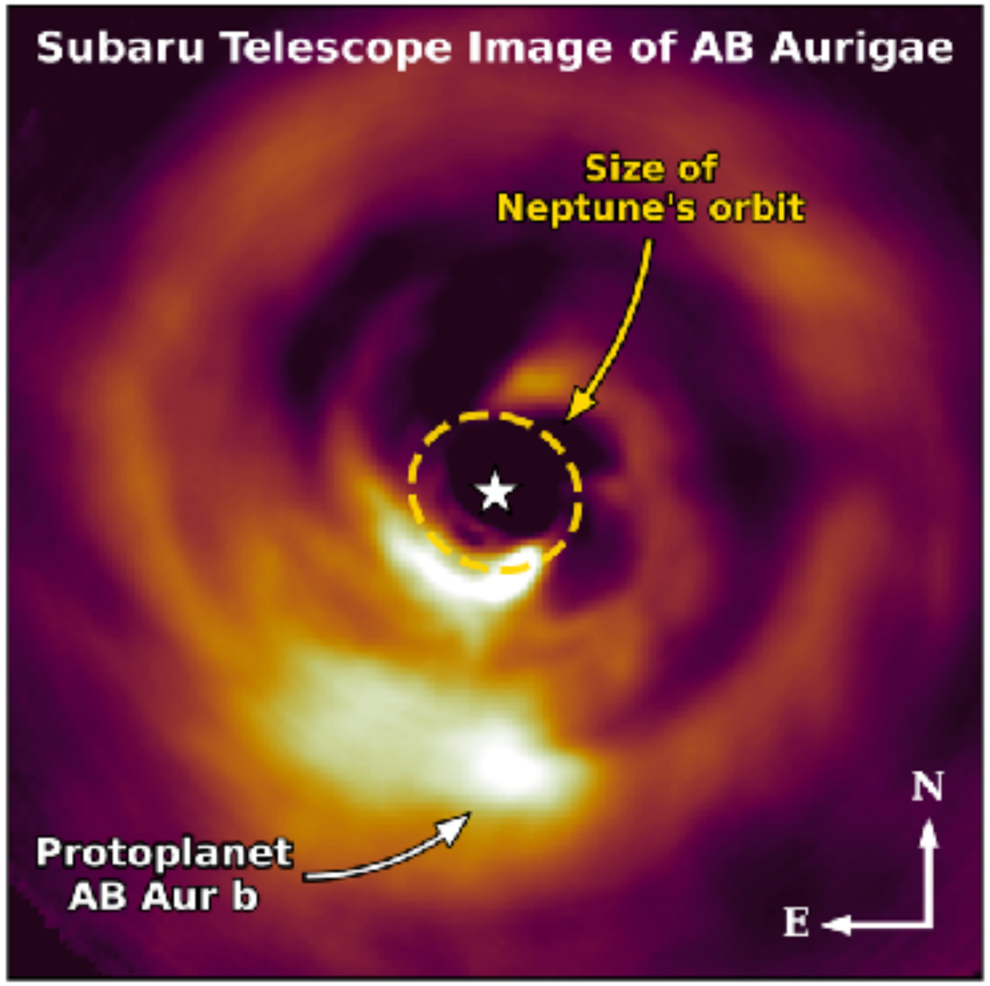


*=> Estimated disk masses are often too low for this process*

# Detected protoplanets in gaps!

**<u>PDS70: two planets and AB Aur: one planet</u>**




e.g. Keppler et al. 2018, 2021,
Haffert et al. 2019, Currie et al. 2022

# Planet disk interaction

- **When a planet is formed in a disk…**
  - **…it may create a gap**
  - **…it may create pressure bumps (dust traps)**
  - **…it may create vortices (dust traps)**
  - **…it may trigger spiral arms**
  - **…it may migrate inwards (or outwards)**

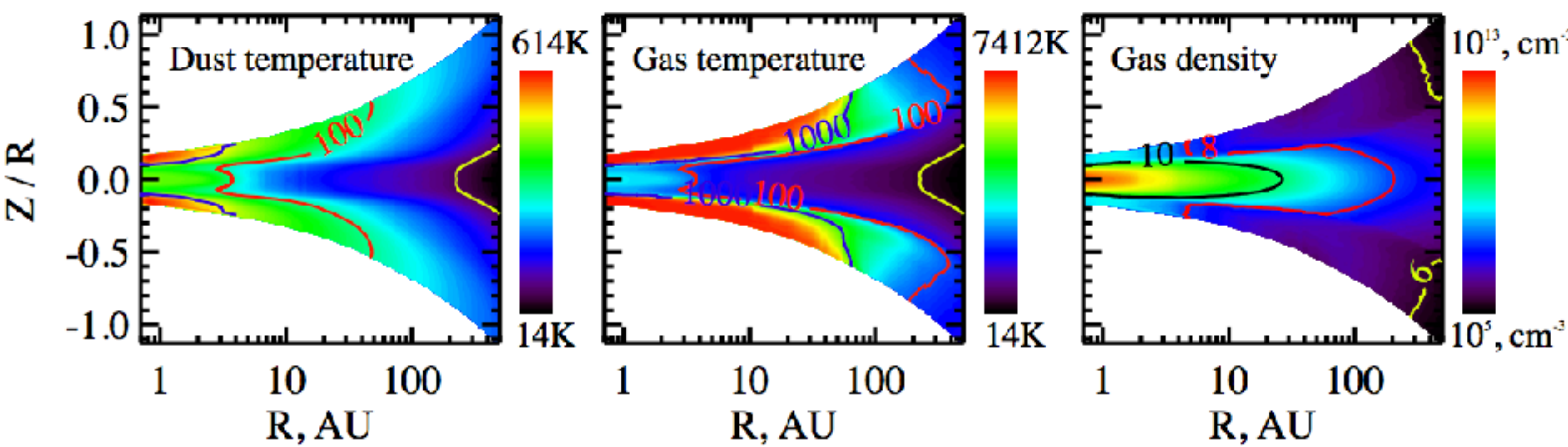
# Planet disk interaction

- Whe
  - …
  - …
  - …
  - …
  - …it may migrate inwards (or outwards)

**All these indications of the presence of a planet in the disk morphology are important, because detecting a planet in the disk itself is extremely difficult (and so far unsuccessful)**

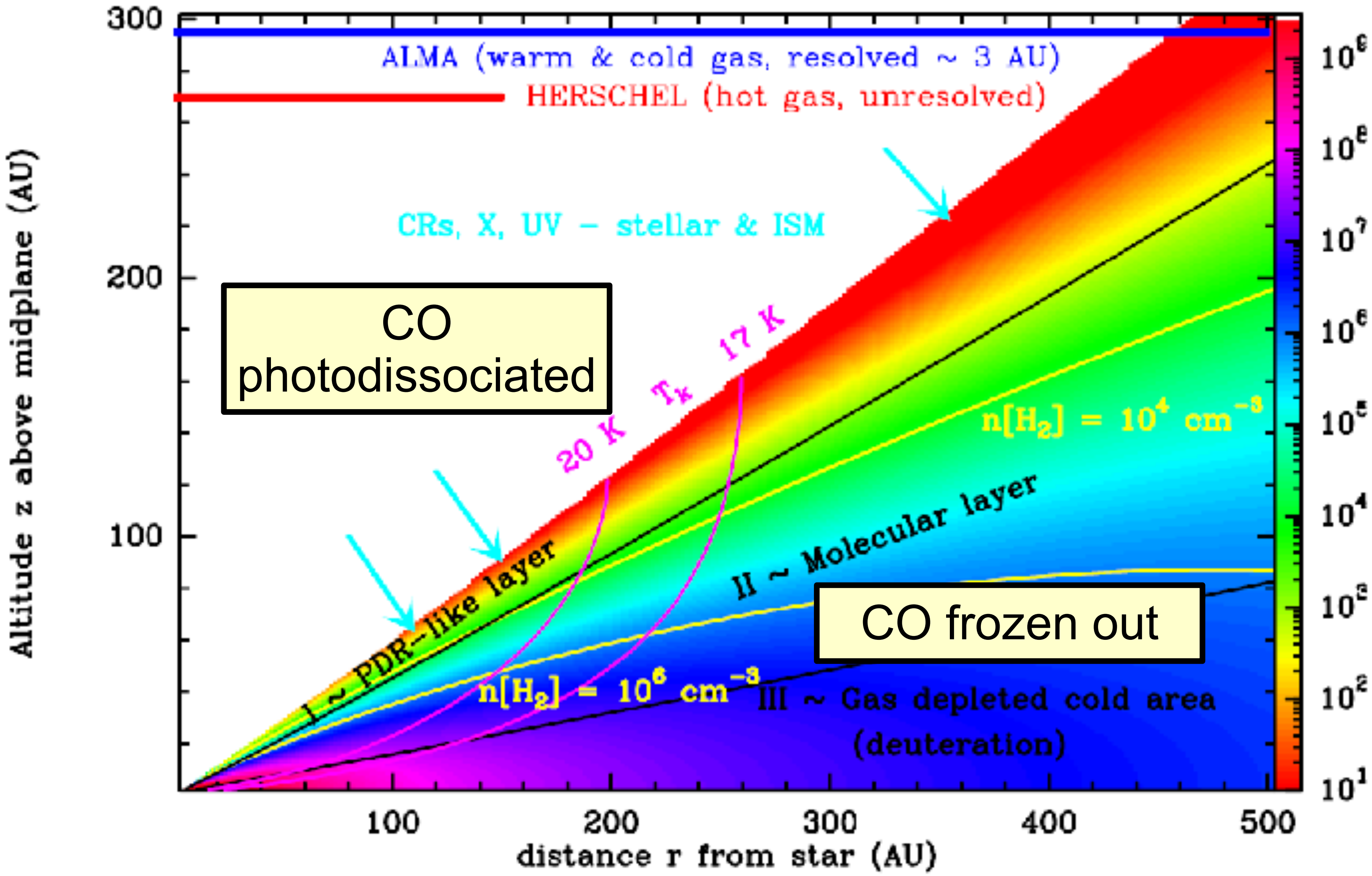
# Chemistry

- Chemistry is extremely useful in disks : biomolecules (origin of life), gas density tracer, snow lines, tracer physical conditions
- But interpreting molecular line emission is challenging:
  - large gradients in temperature, density and UV radiation field which all influence the local chemistry
  - chemical networks include thousands of reactions even for simple molecules
  - line emission relatively weak



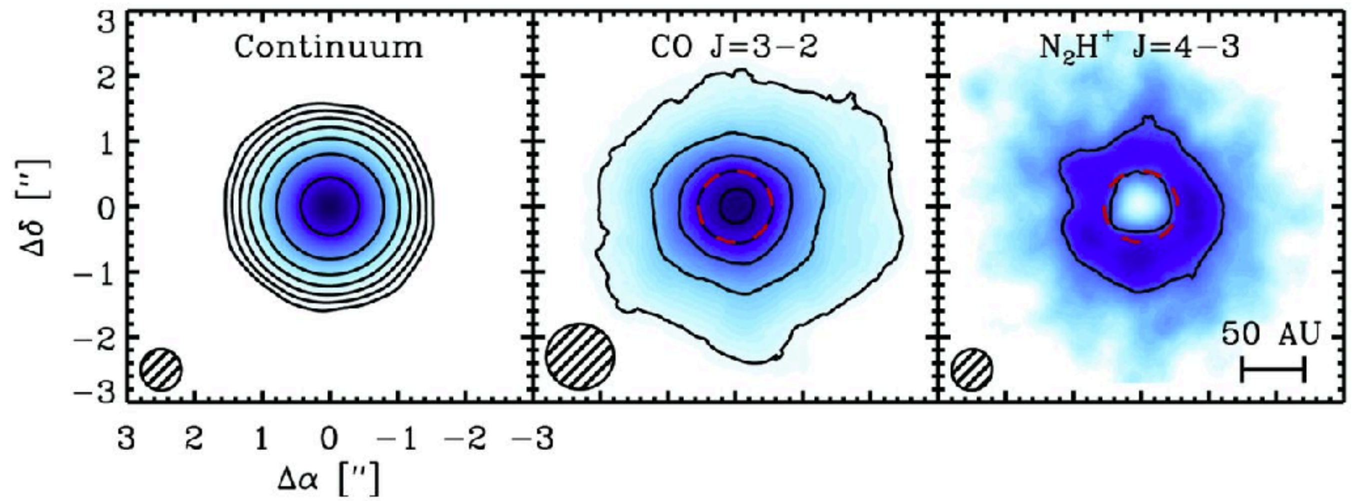
# Chemistry

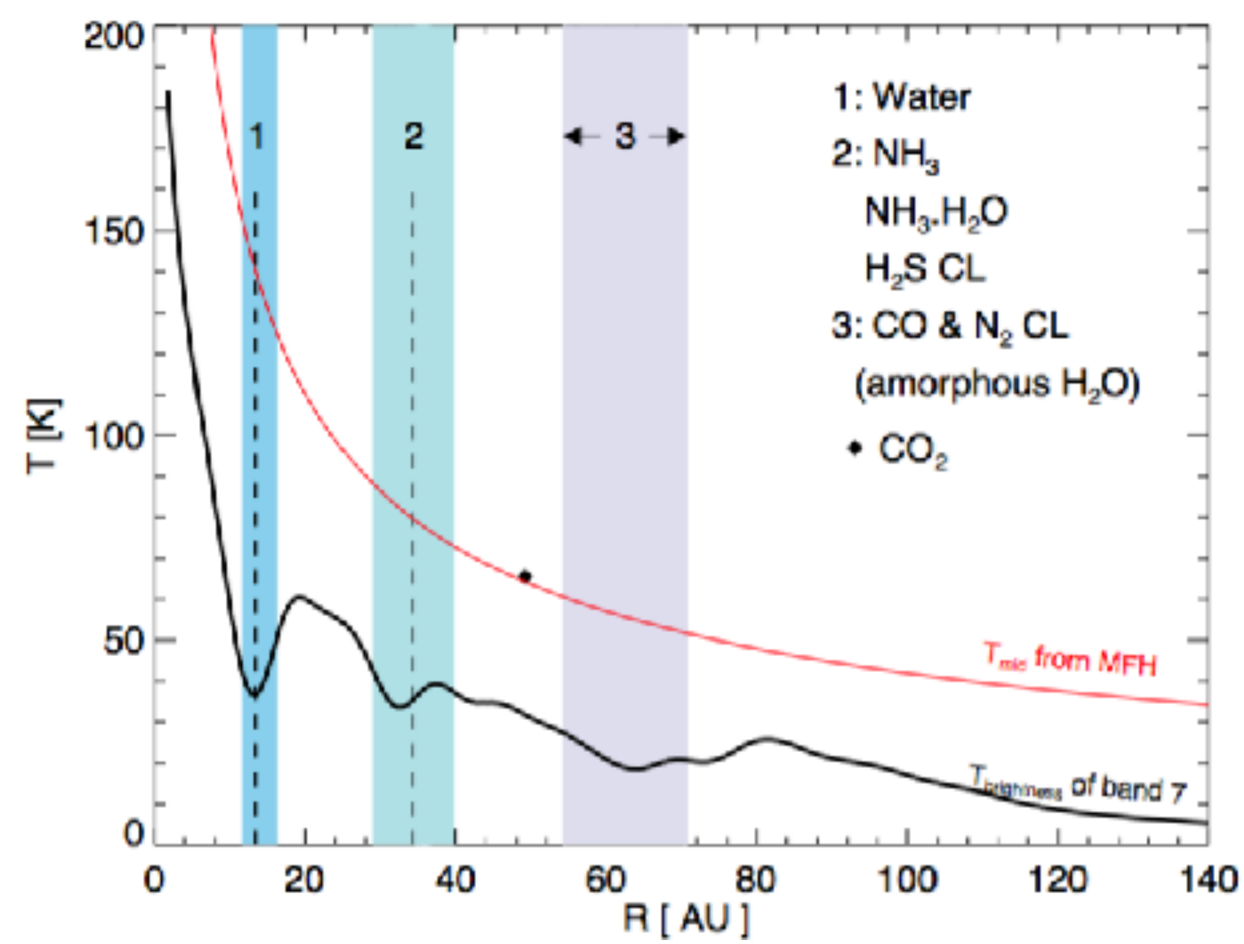
**Example: interpreting CO emission (gas density tracer)**



# Chemistry

- **Snow lines: radius/temperature where a molecule freezes out**
- **CO snow line through $N_2H^+$ or $DCO^+$**
- **Snow lines are particularly interesting as dust is expected to grow more efficiently due to increased stickyness: start of planet formation?**
- **Proposed idea: ring systems due to freeze out of different molecules?**




Zhang et al. 2015

# Final remarks

- Disk structures are much more complex than previously thought

- These structures may help to solve some issues, but also raise new questions

- While planet formation itself remains poorly understood, disks can help to constrain the environments where planets form or have recently been formed

**Questions?**

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