

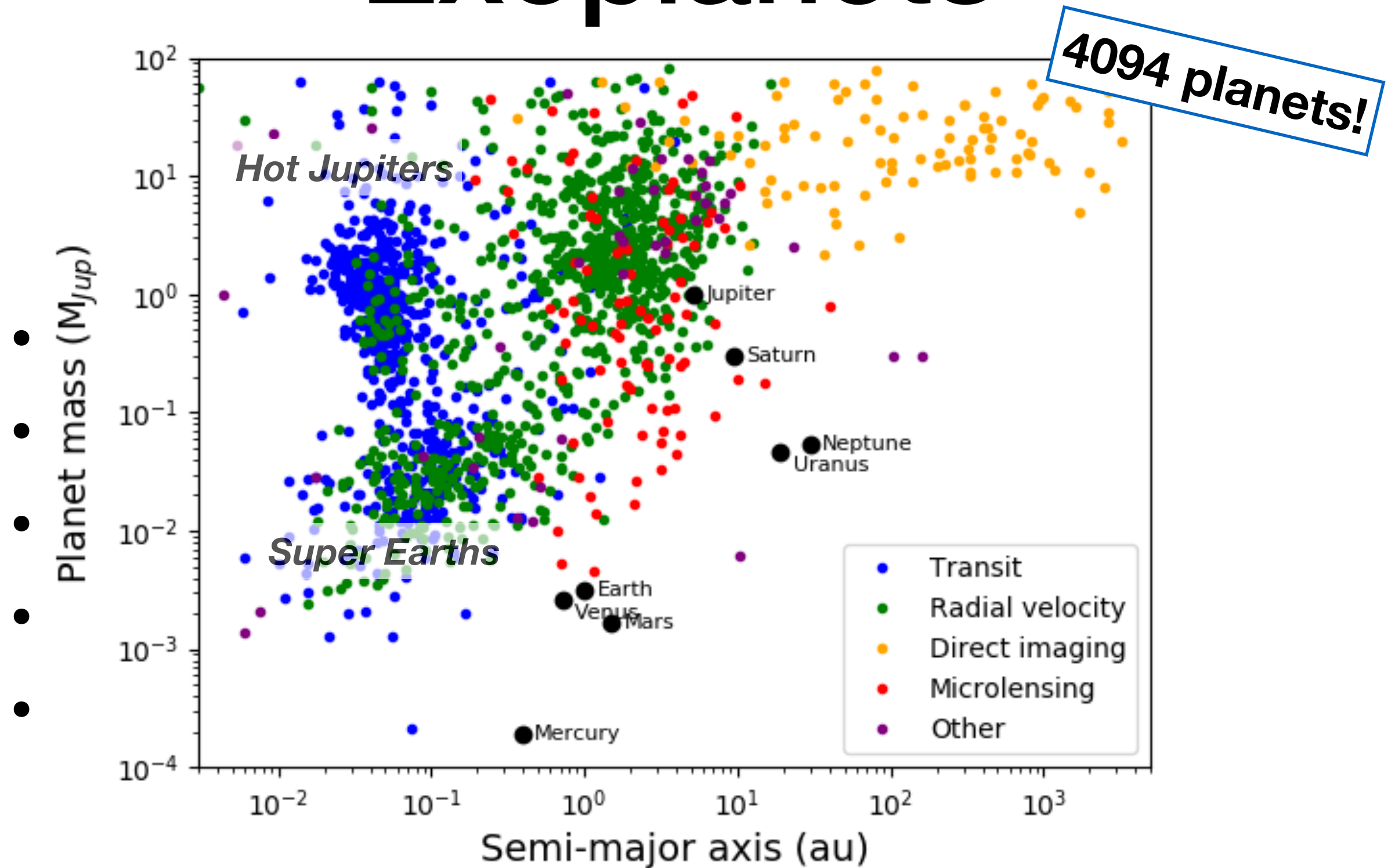
Introduction to protoplanetary disks

NBI Summer School Protoplanetary disks
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@NienkeMarel
August 5th 2019

Contents

- What are protoplanetary disks?
- How to observe dust and gas?
- Discovery and history of disks
- Evolution and lifetime
- Recent images

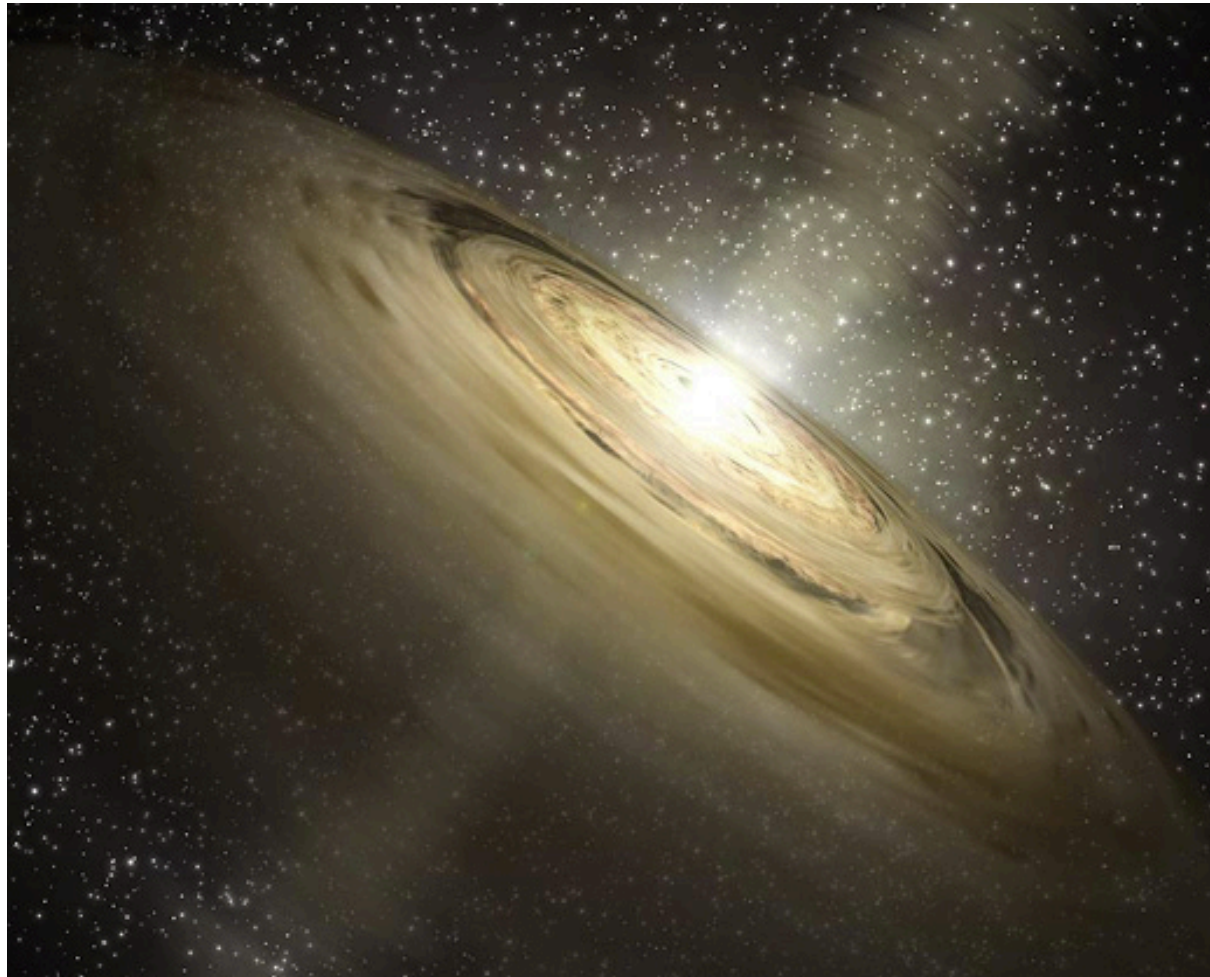
Exoplanets



Large diversity exoplanets, very different from Solar System:
motivation for studying protoplanetary disks to understand
planet formation

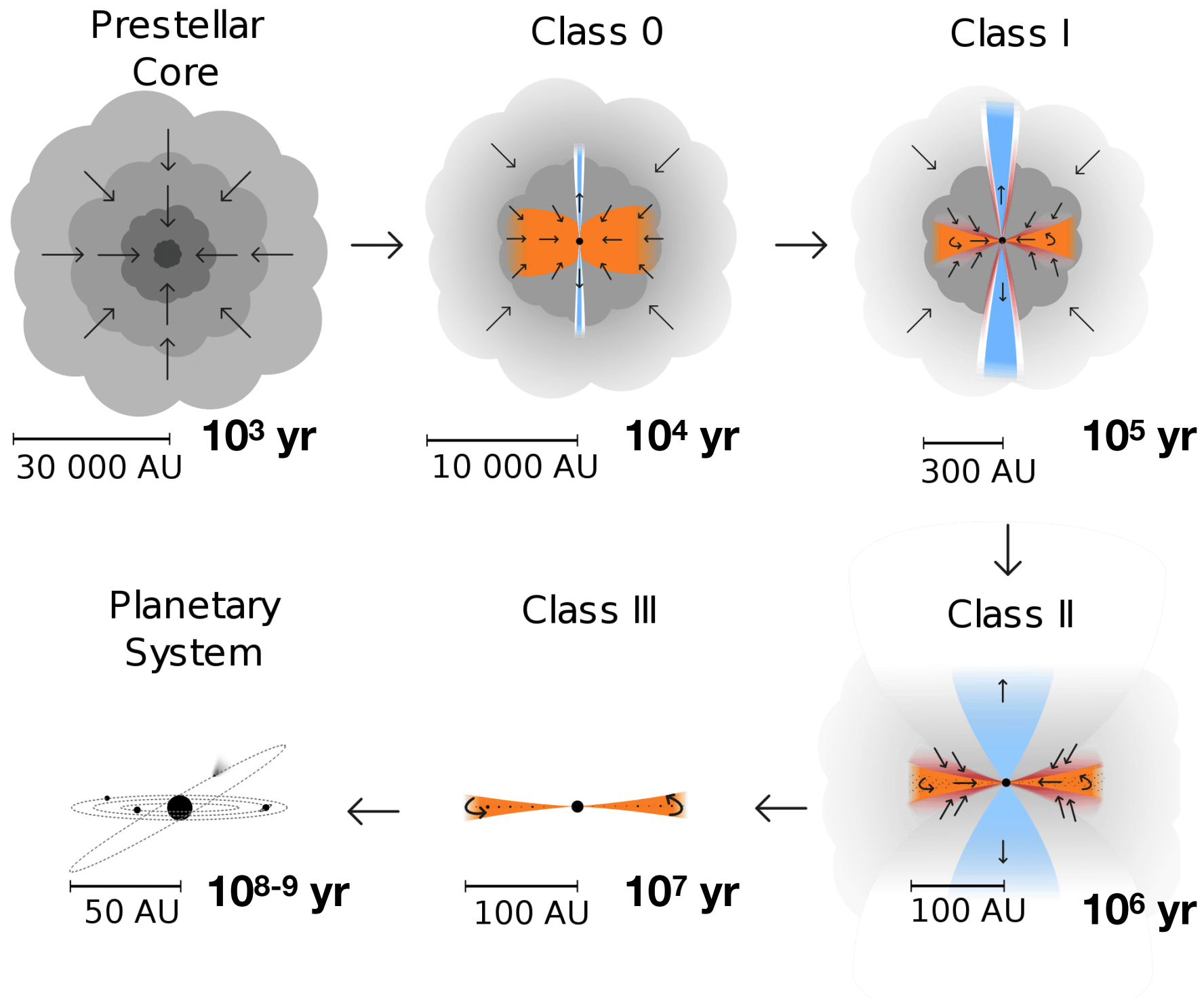
<http://exoplanet.eu>, June 2019

What are protoplanetary disks?



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

What are protoplanetary disks?



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

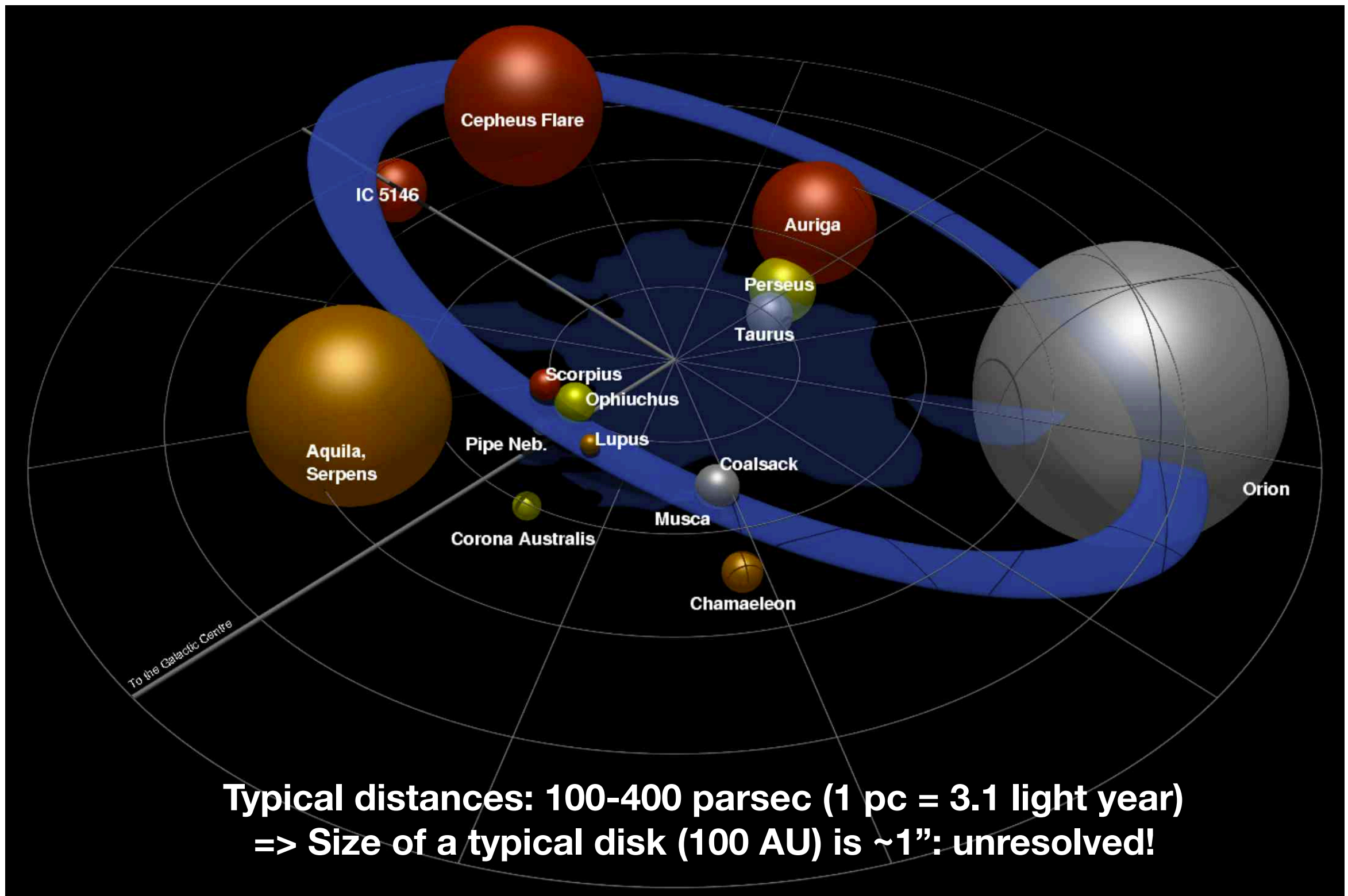
Where do we find disks?

- 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?



What's it like out there?

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

How do we observe?



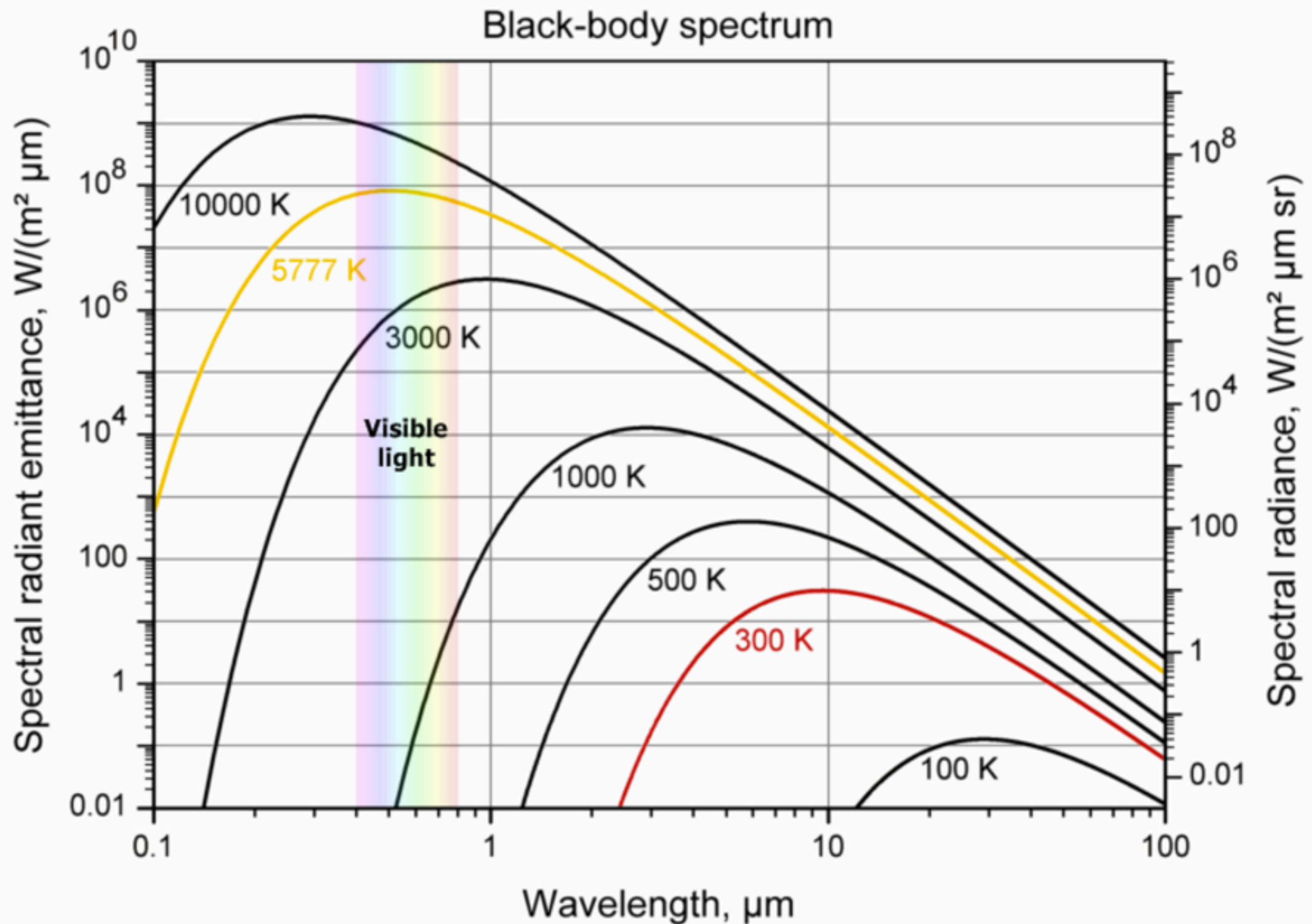
Visible . WFC3 . 2015



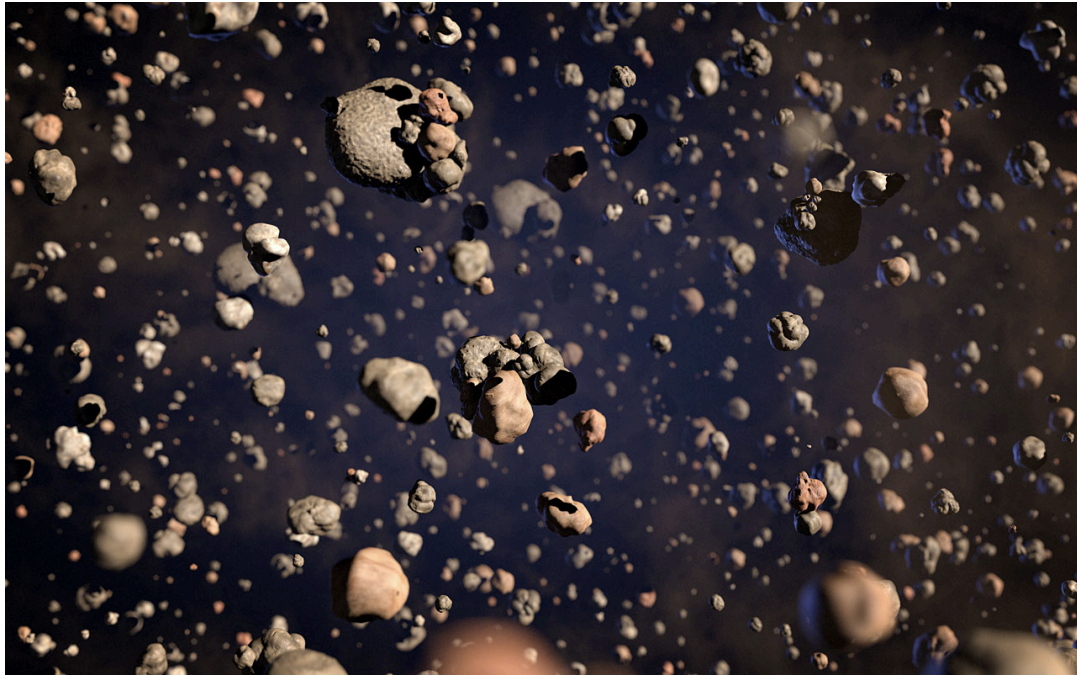
Infrared . WFC3 . 2015

At longer wavelengths we see colder material: why?

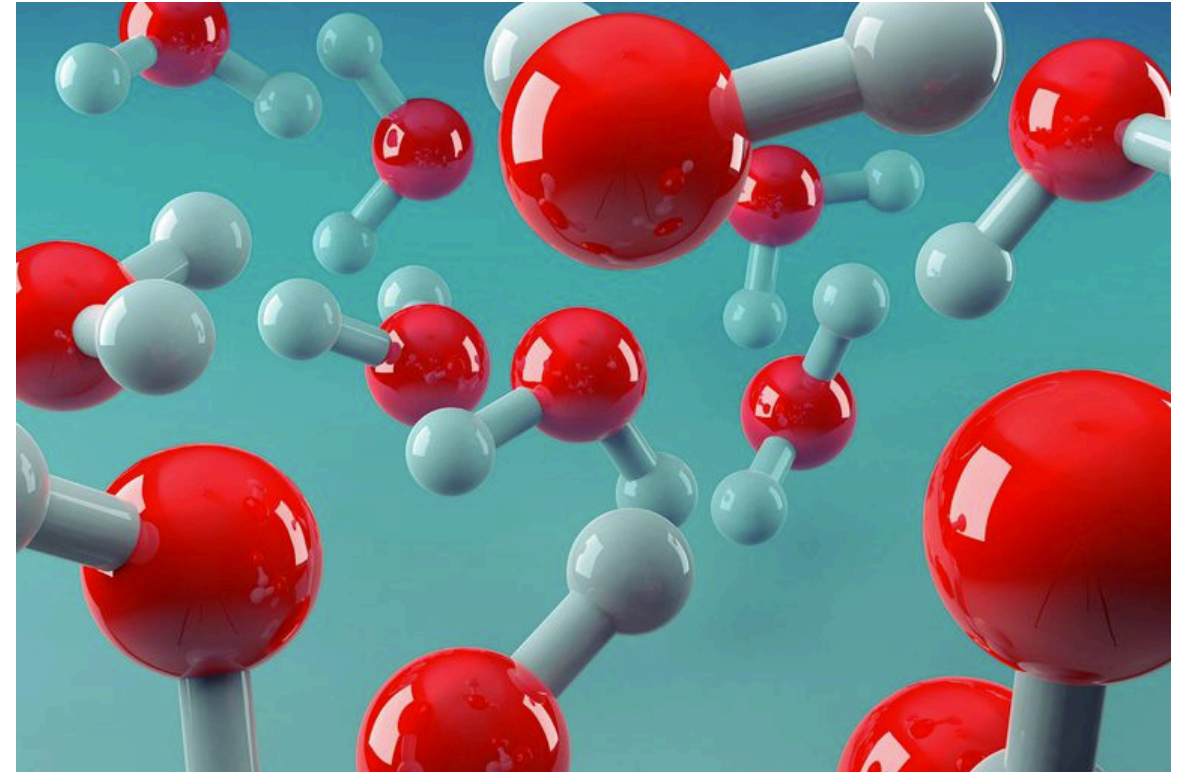
How do we observe?



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)**

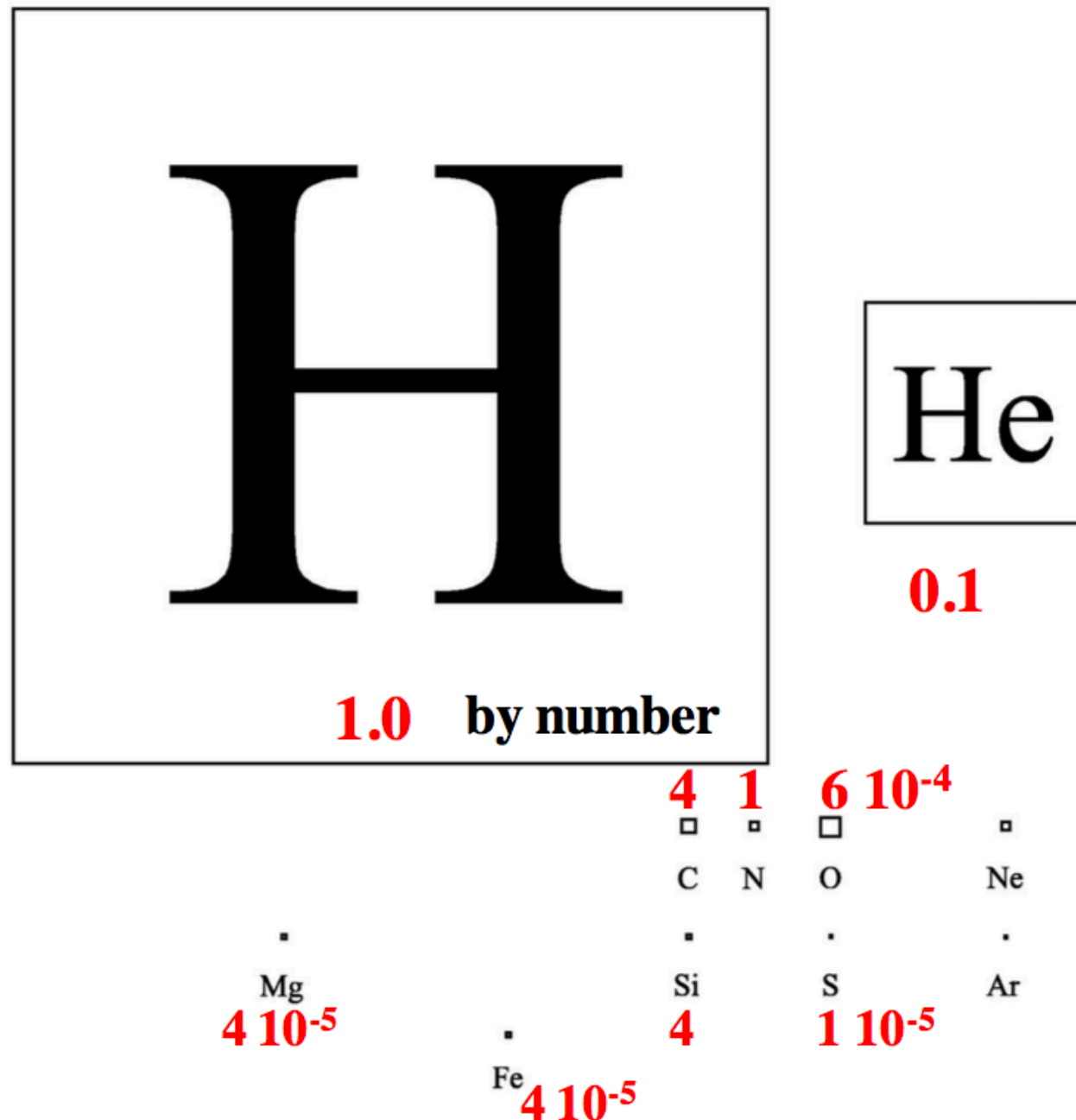


**Gas particles are molecules: emission through 'molecular lines'
(narrow emission)**

What are the most common molecules in the Universe?

What do we observe?

Periodical table of astronomy:

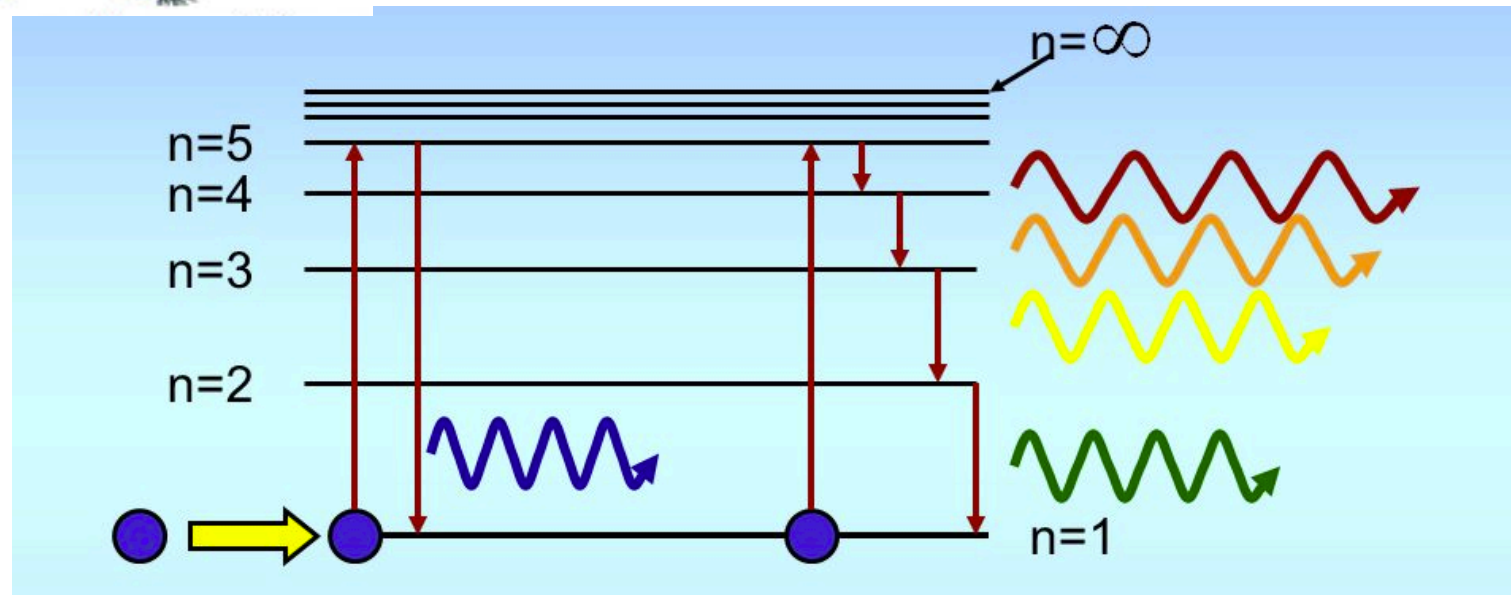
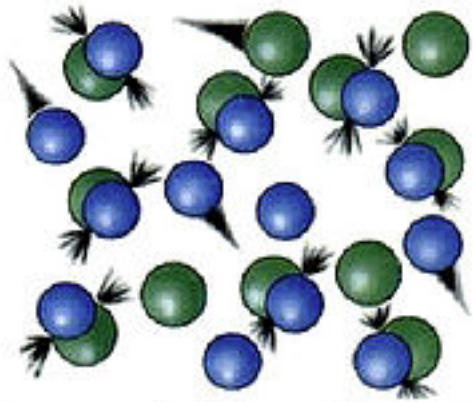


Simple molecules:

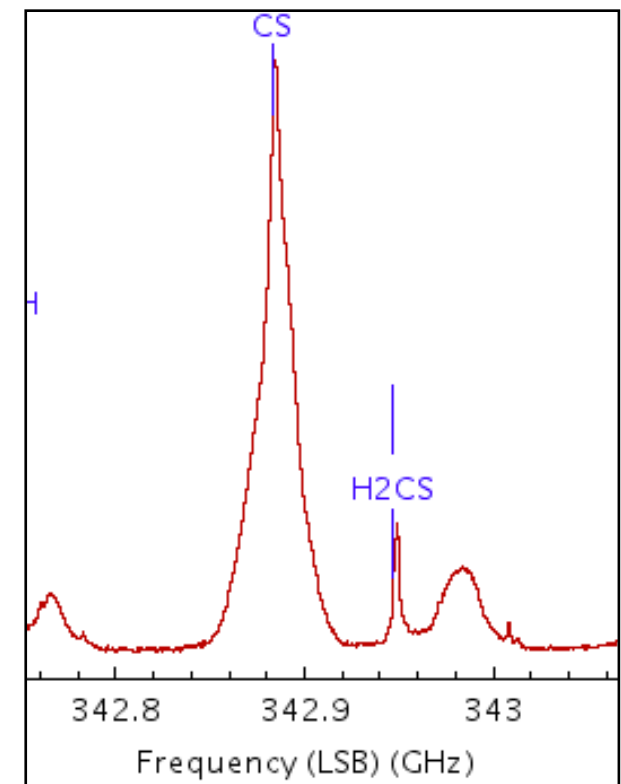
- H_2
- CO
- CO_2
- H_2O
- CN
- OH
- CH^+
- HCO^+
- H_2CO
- ...

What do we observe?

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



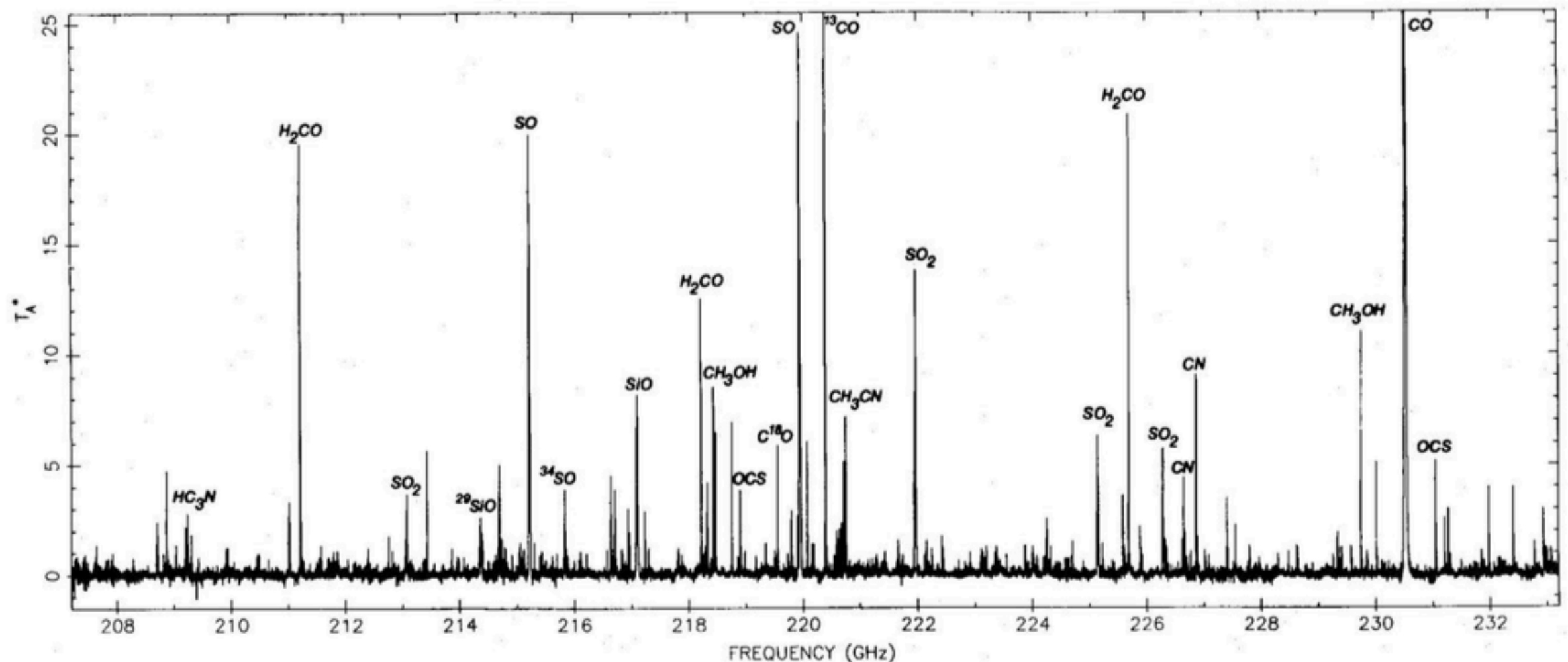
A collision brings a molecule in a higher energetic state



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?

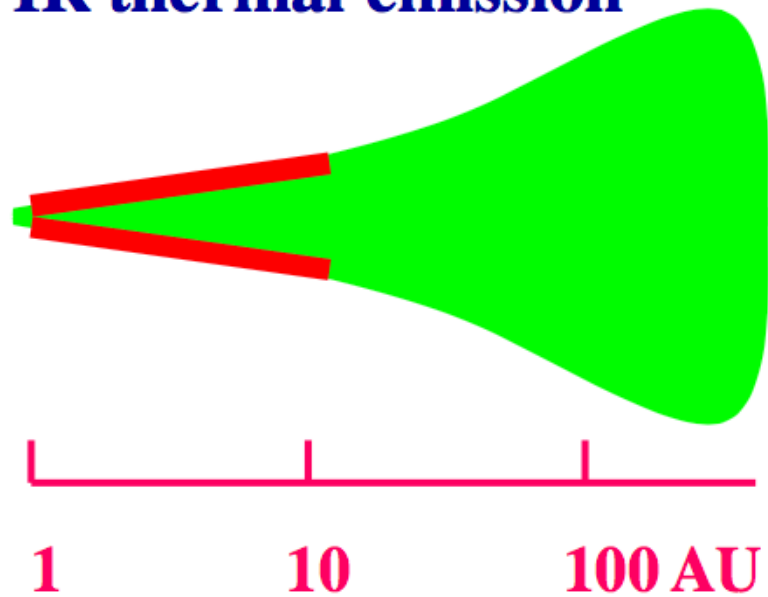
- Each molecular *line* is the result of millions of photons emitted by millions of molecules in this processes: a bulk of *gas*
- Molecular lines on top of *dust* continuum: *continuum* emission is the *averaged* emission at every frequency where there is no line!



NB Frequency and wavelength are used interchangeably: $c = \lambda * \nu$

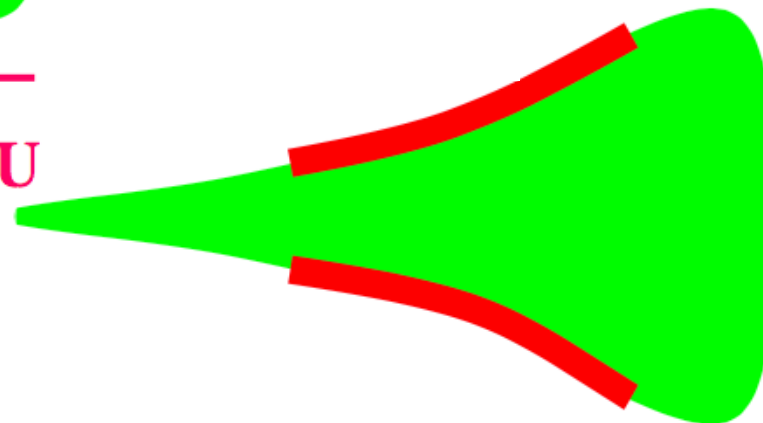
Wavelengths and disks

IR thermal emission

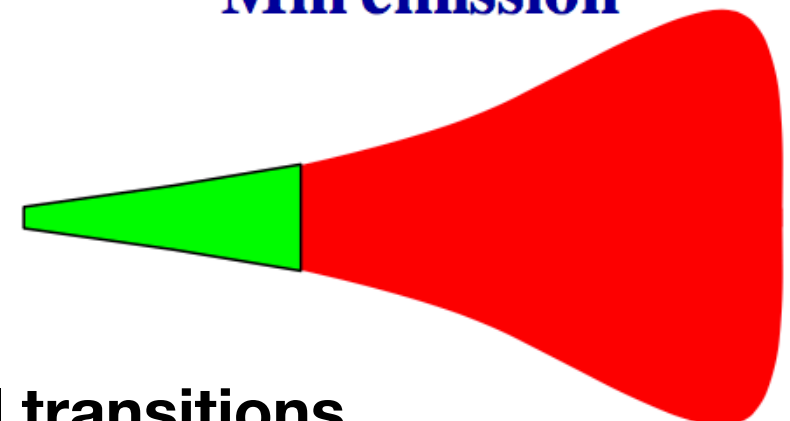


(Ro)vibrational transitions

FIR emission

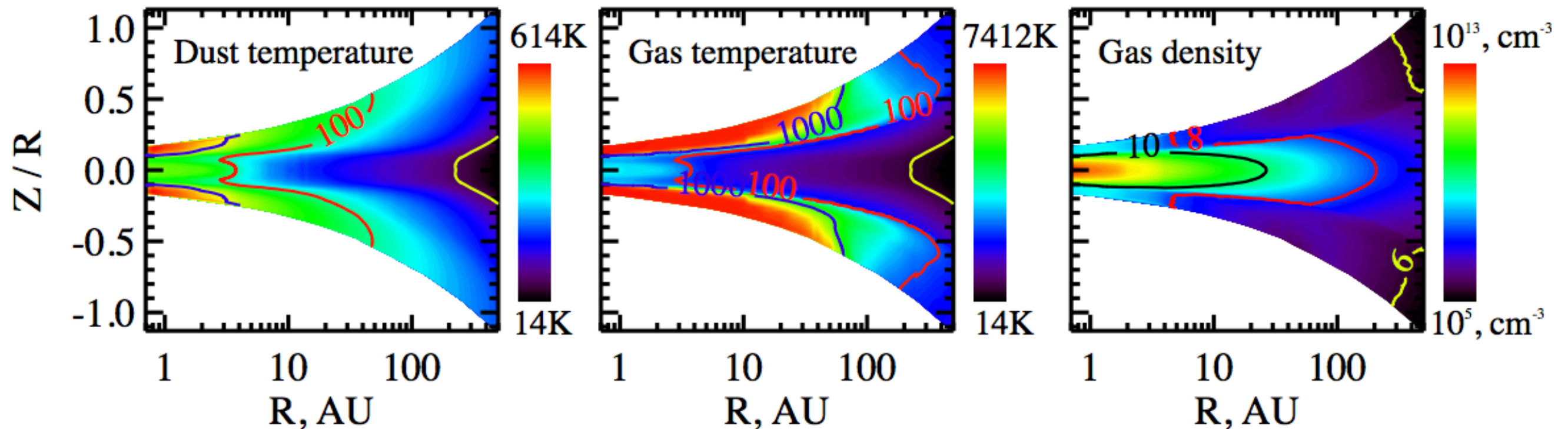


Mm emission



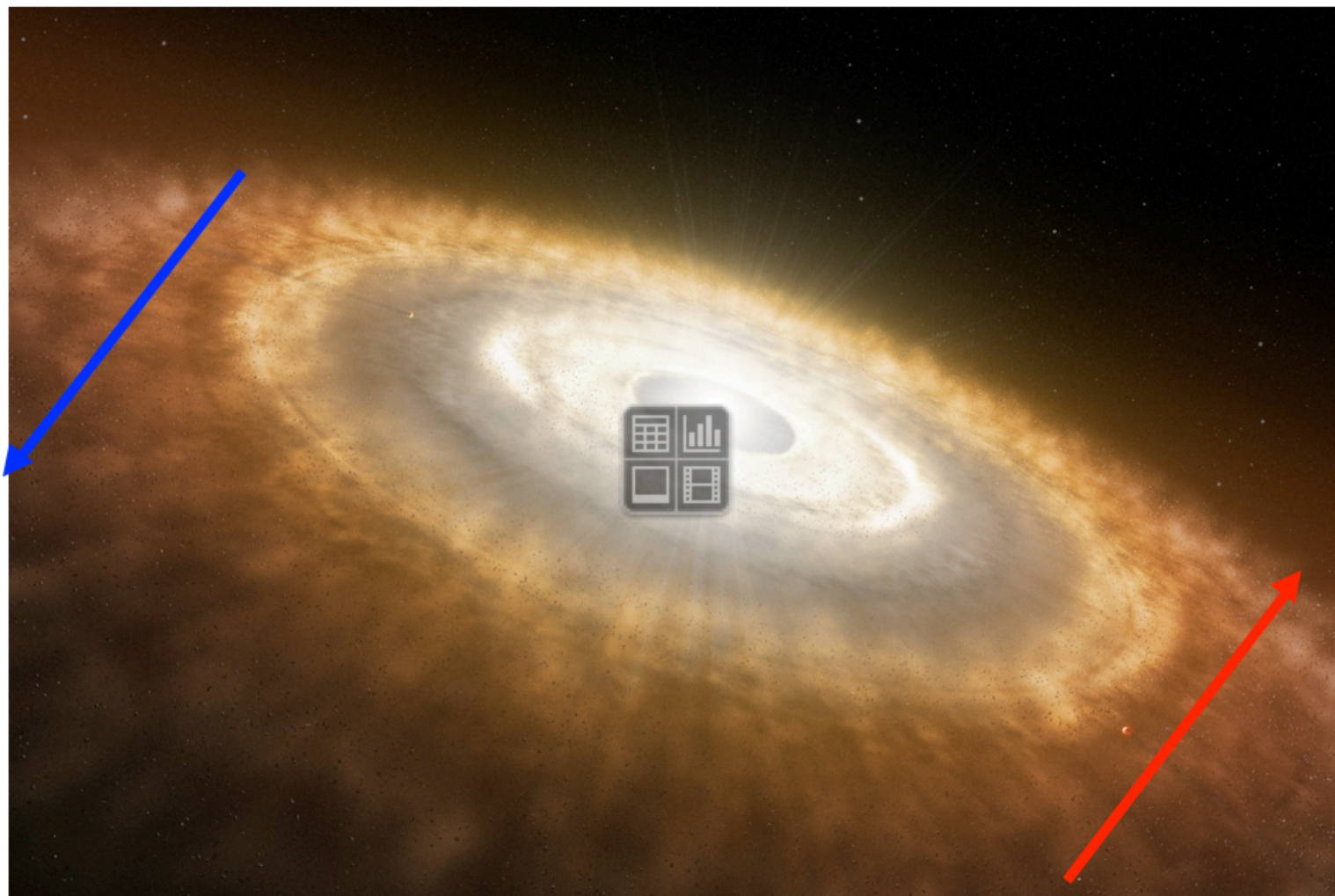
Rotational transitions

Disk density and temperature



What do we observe?

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



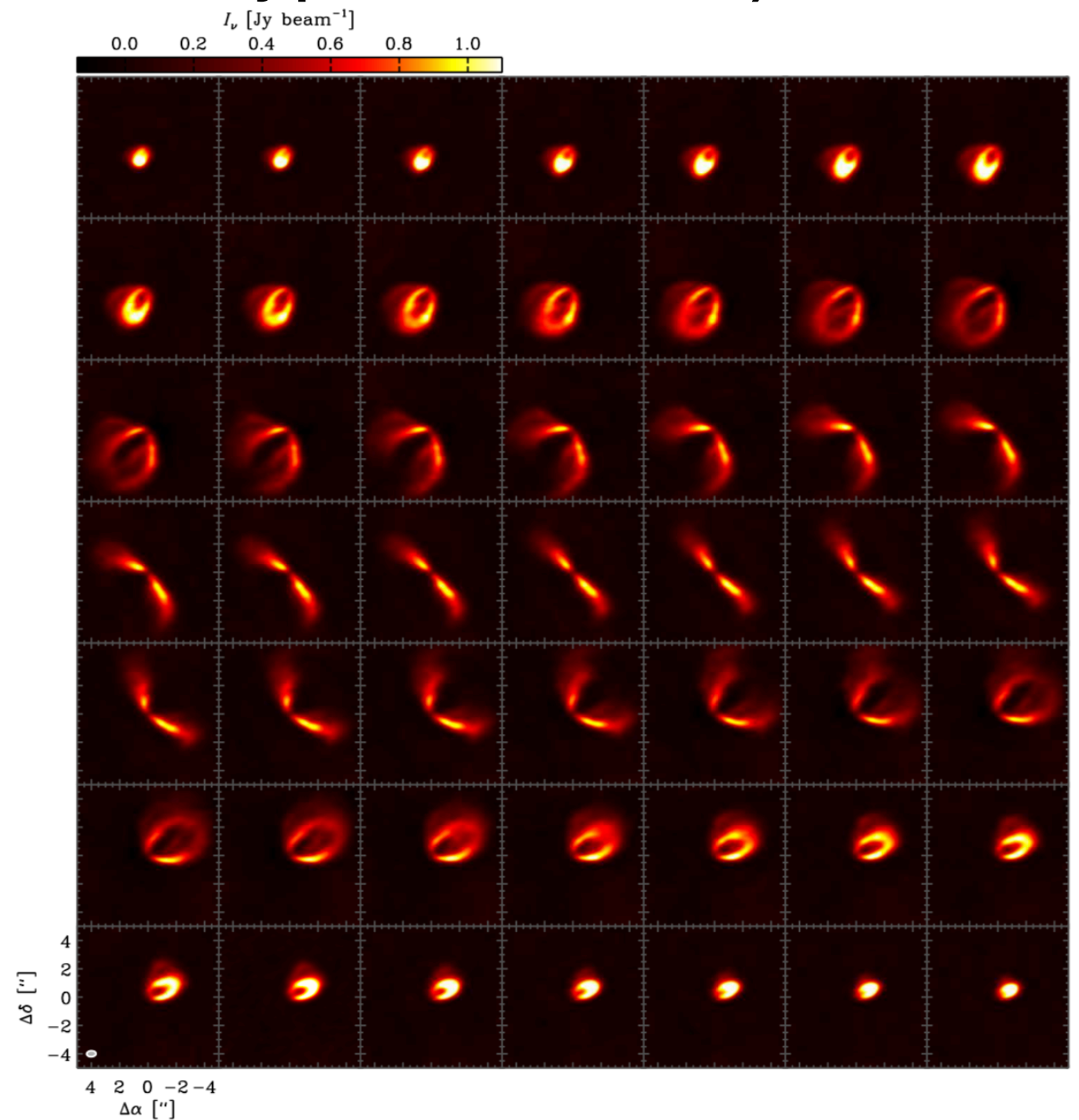
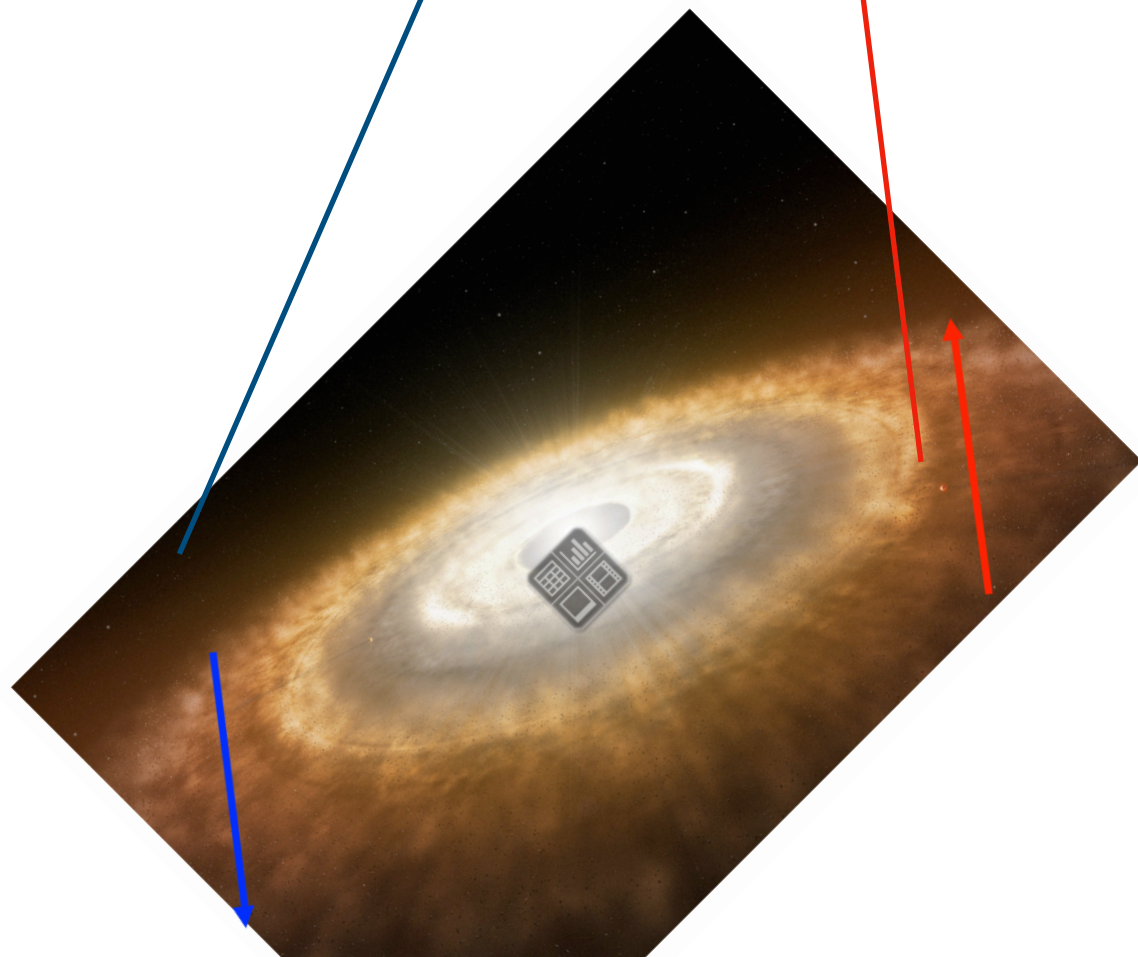
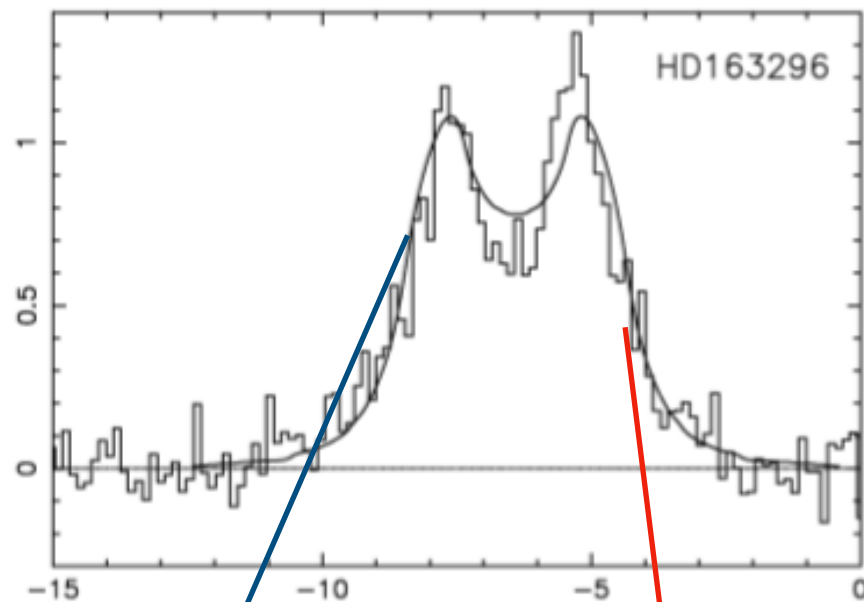
$$V(R) = \sqrt{\frac{GM}{R}}$$

Stellar mass

The disk rotates Keplerian:
what happens to the line?

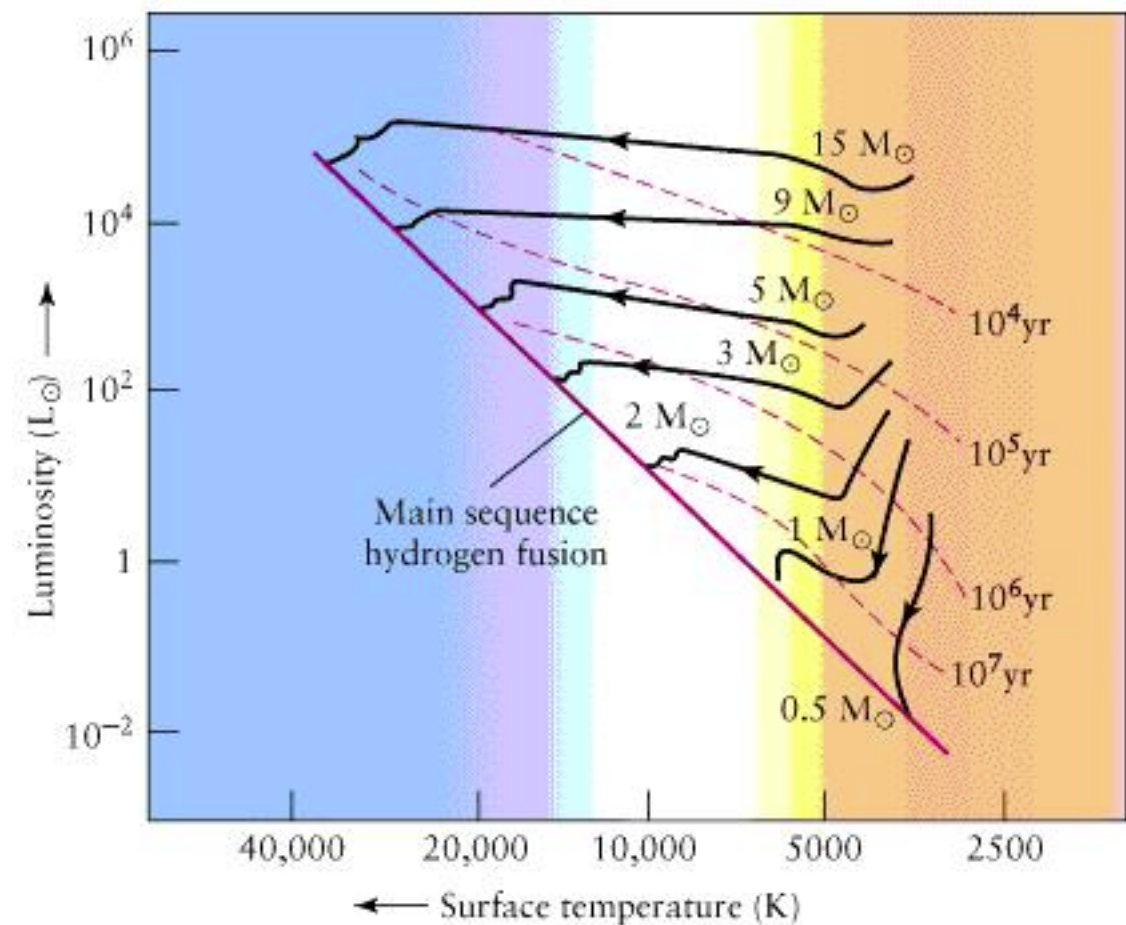
What do we observe?

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



History

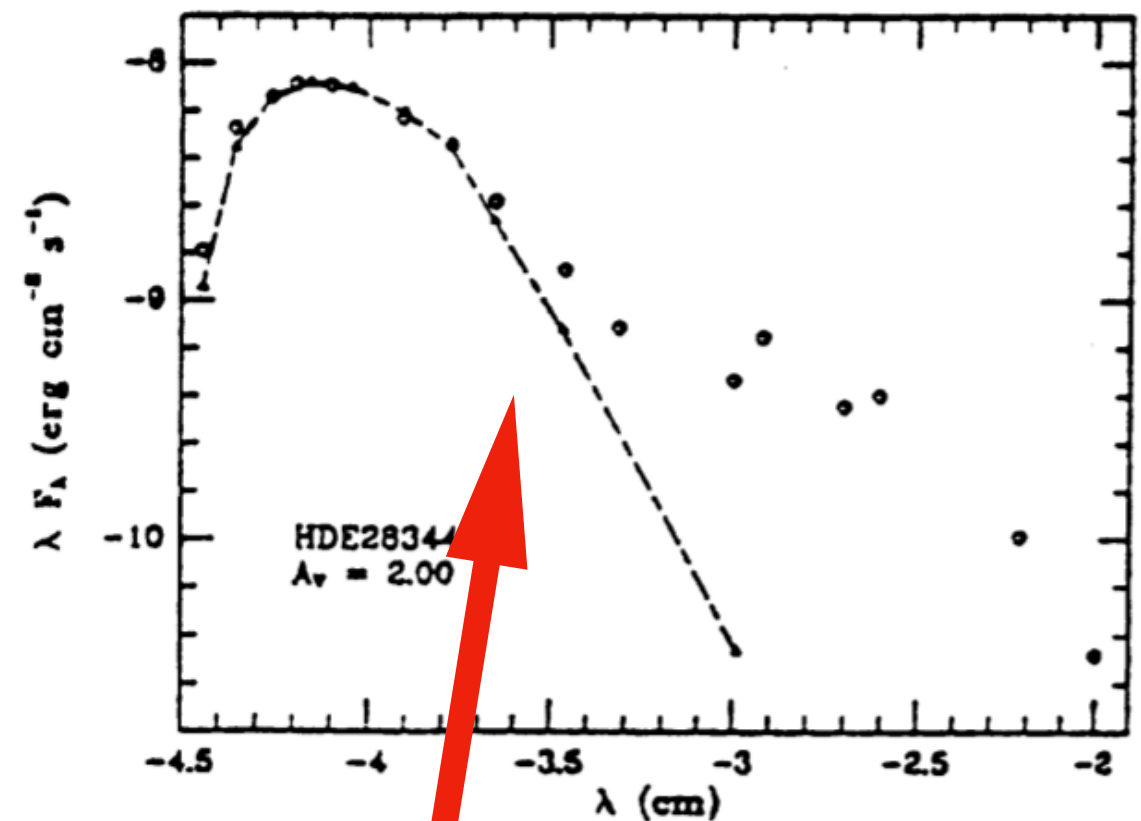
- History of astronomy largely driven by technology: until 1950s mostly limited to optical wavelengths!
- First discovery: young stars!
 - overluminous compared to stars of same spectral type (temperature)
 - found in particular in dark clouds
 - strong optical emission lines (H α) and UV excess: accretion



Why are young stars overluminous?

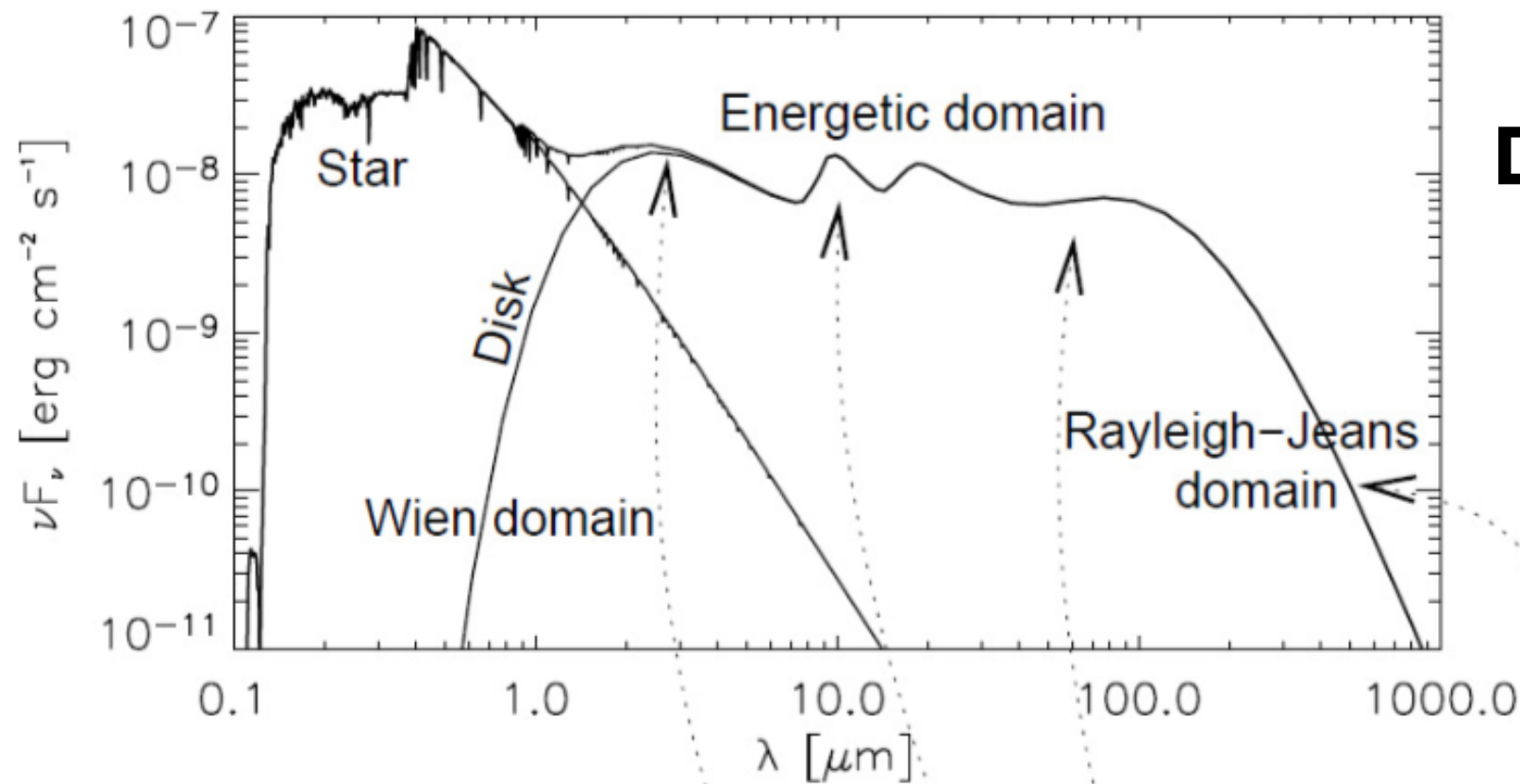
History

- 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 ($<2 M_{\text{sol}}$) and Herbig stars ($>2 M_{\text{sol}}$)
- 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

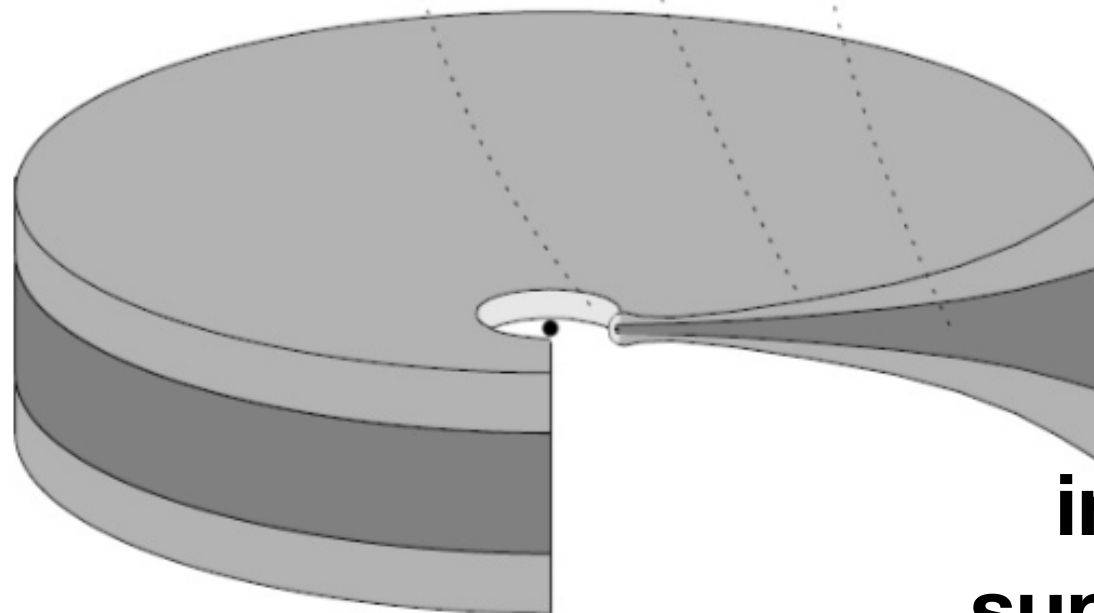


excess

History



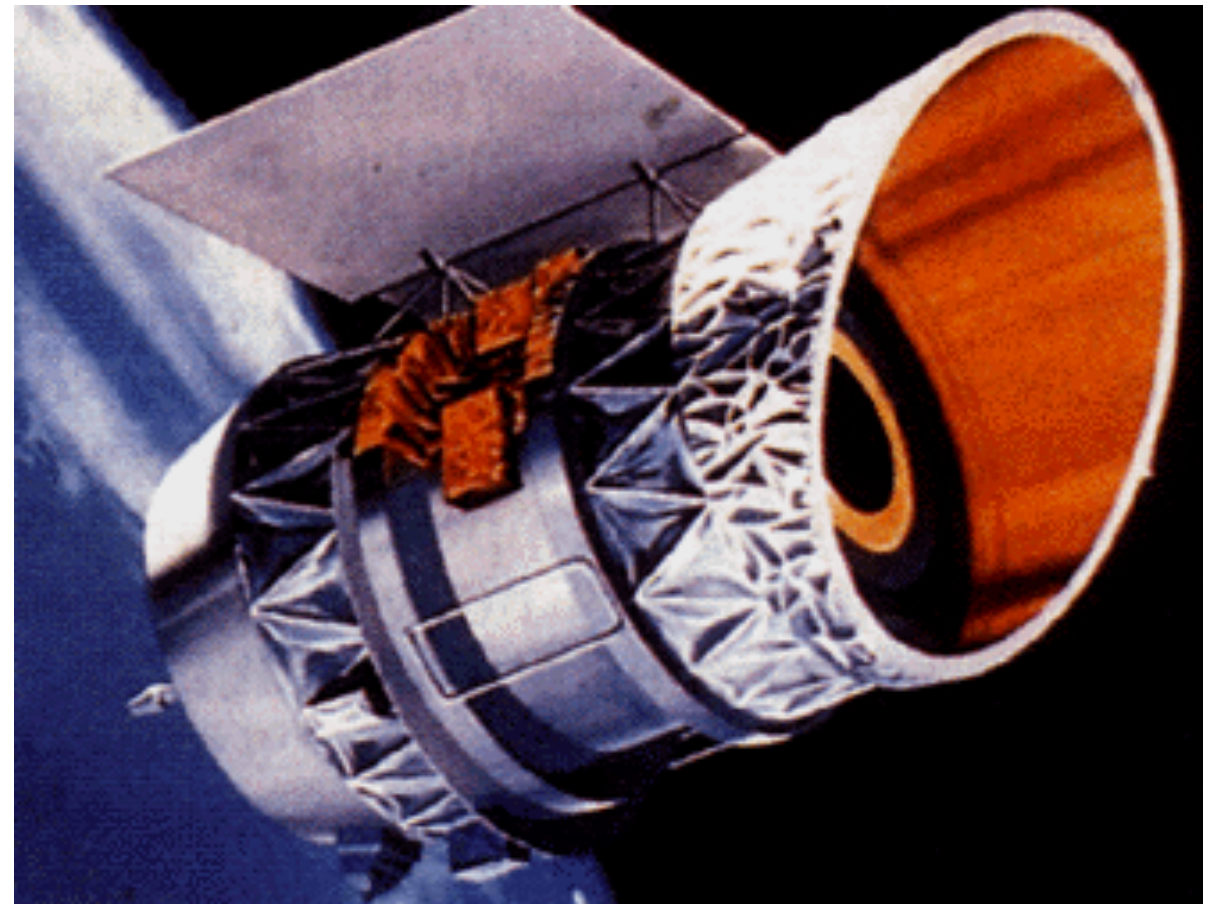
**Dust in disk gets heated up by the star:
radial temperature gradient**



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

History

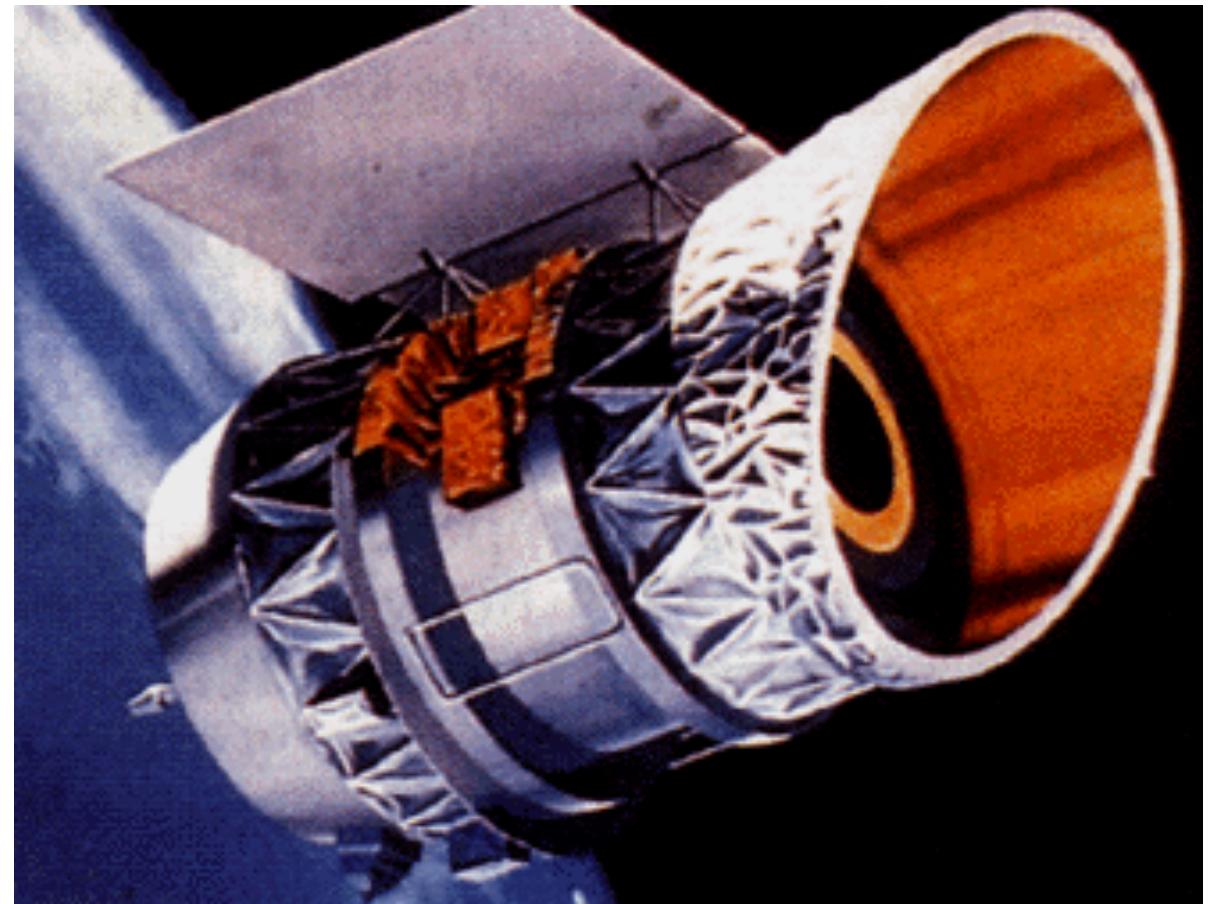
- IRAS satellite 1983:
full sky survey in infrared
(12, 25, 60, 100 micron)
- Diameter: 57 cm (22 inch)
- >250 000 IR sources found
- Follow up:
ISO satellite 1995-1997
=> deeper and including
spectroscopy



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

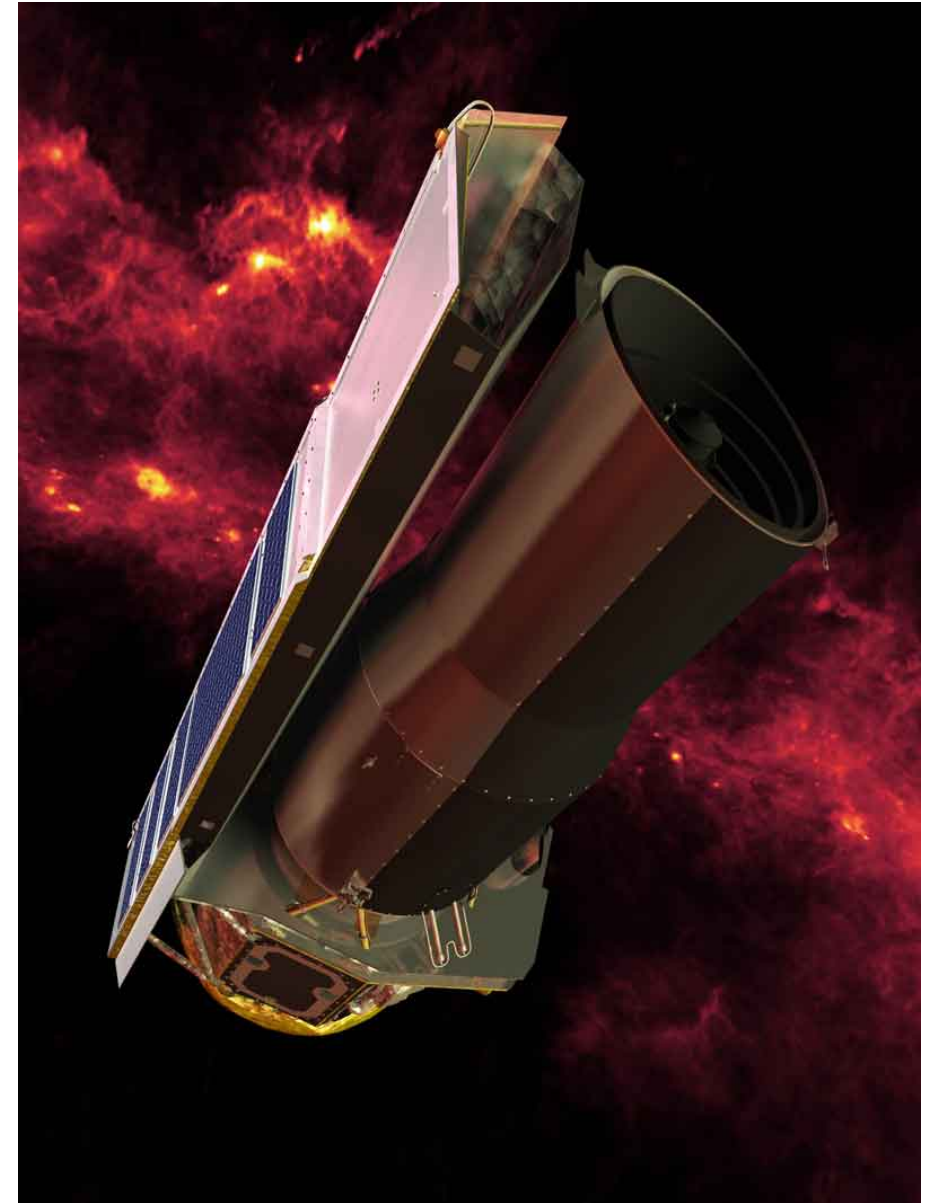
History

- Diameter: 57 cm (22 inch)
- Telescope resolution: λ/D
 $\Rightarrow$ 30-120" beam
- Disks are $\sim 1''$! Unresolved!
- Photometry is confused
- Full sky: short integrations
(low sensitivity)



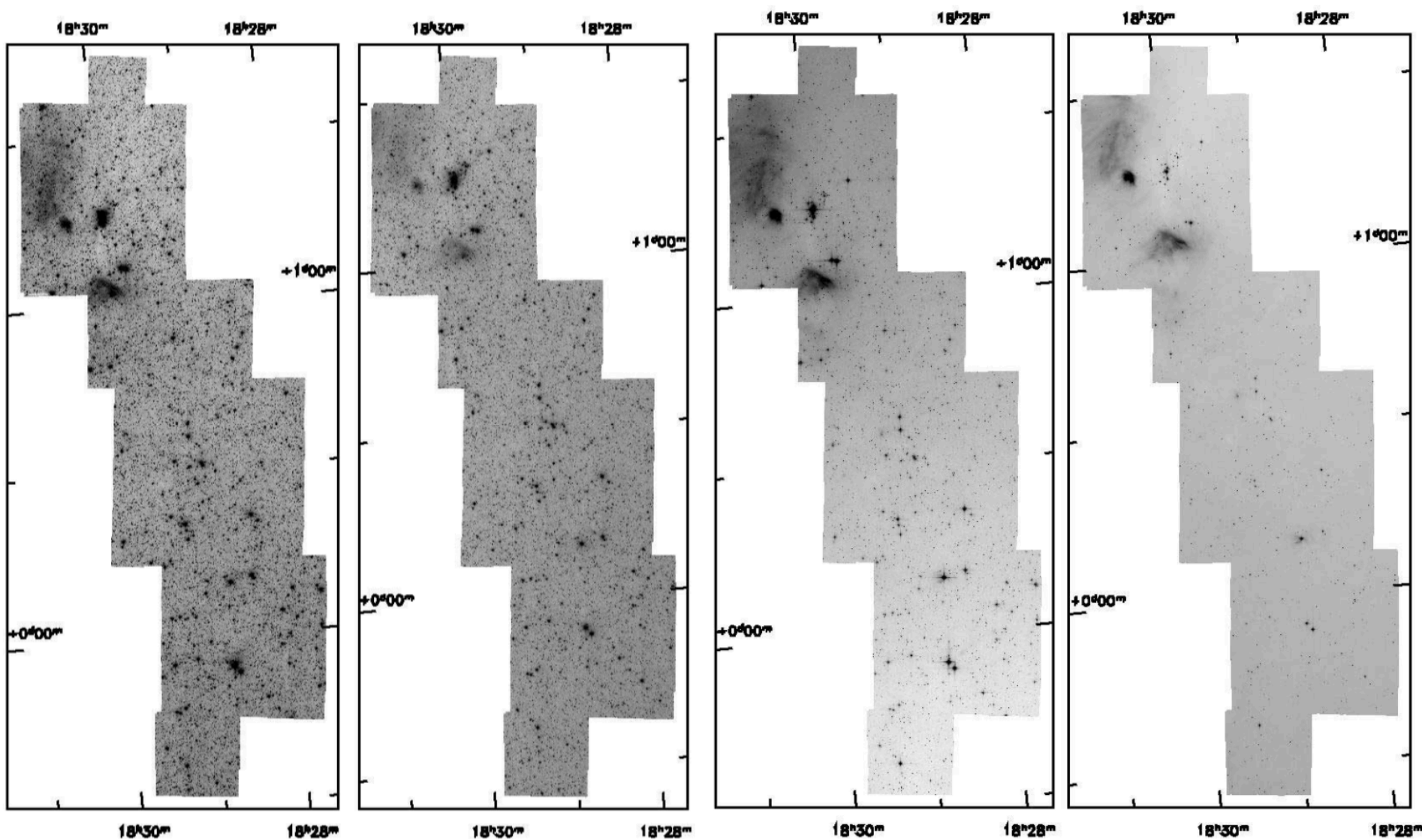
History

- 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**



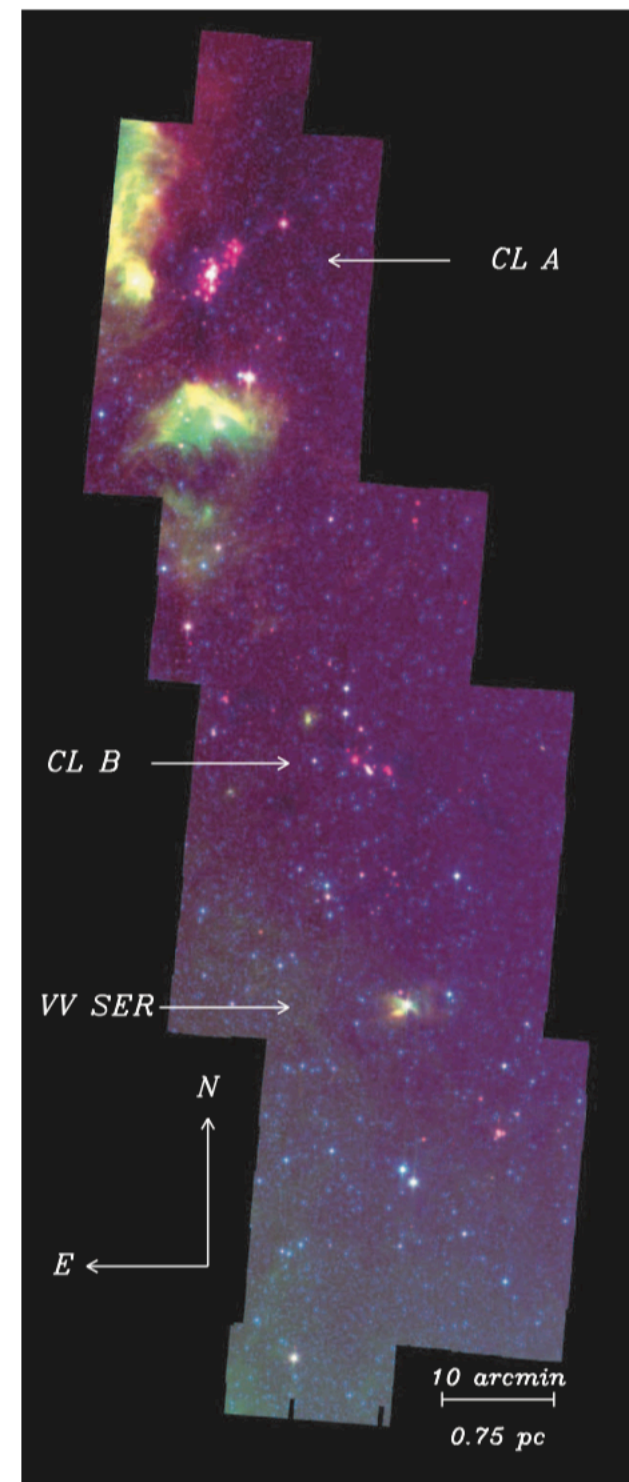
History

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



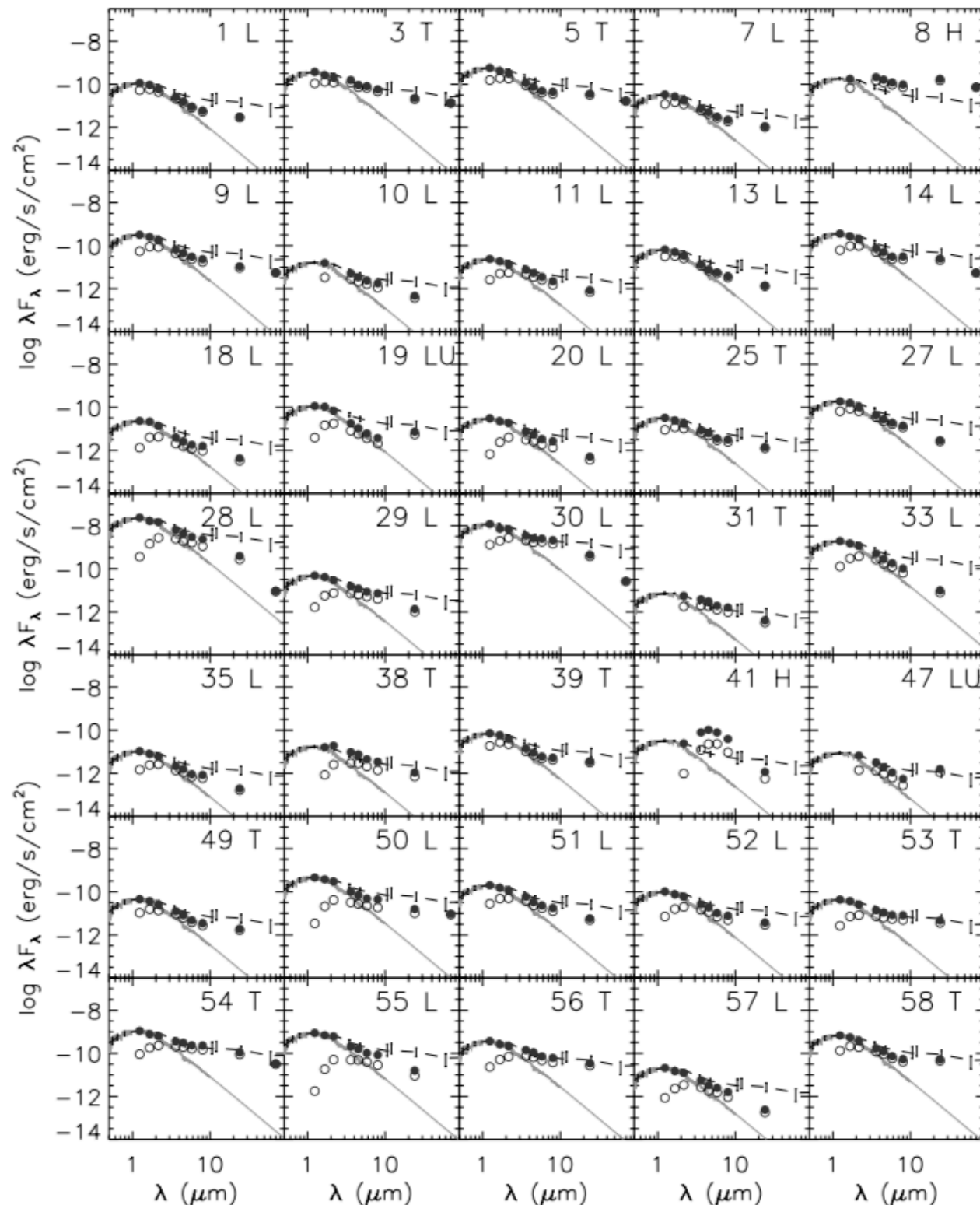
IRAC bands: 3.6, 4.5, 5.8 and 8.0 micron

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



Harvey et al. 2006, 2007

History

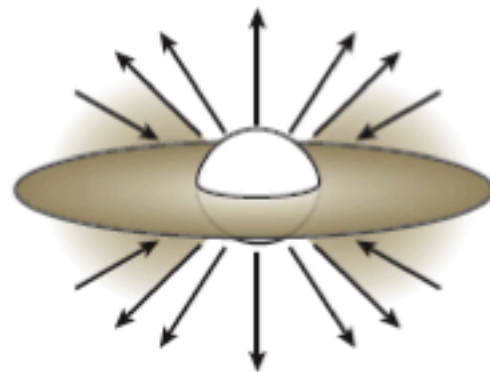
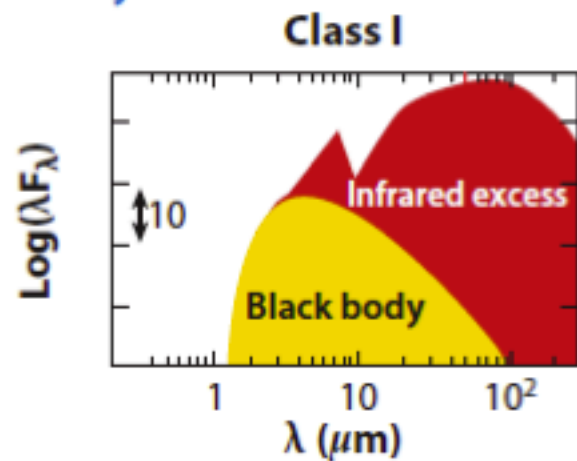


Results: thousands of SEDs of young stars, including many disks!

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

Evolution and lifetime

$t < 0.03$ Myr

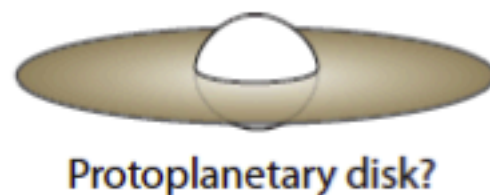
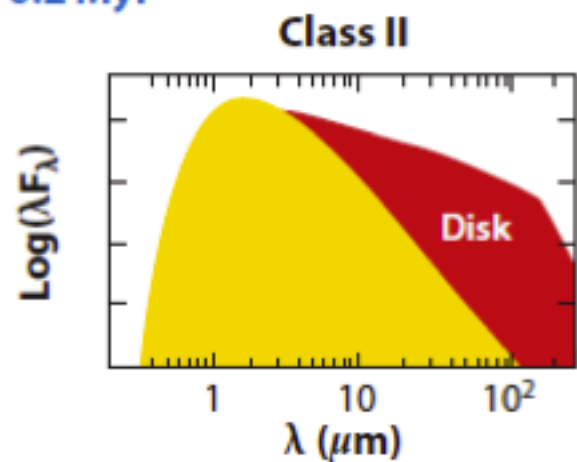


Birthline for
pre-main sequence stars

Further classification by amount of infrared excess:

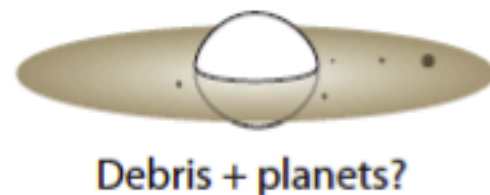
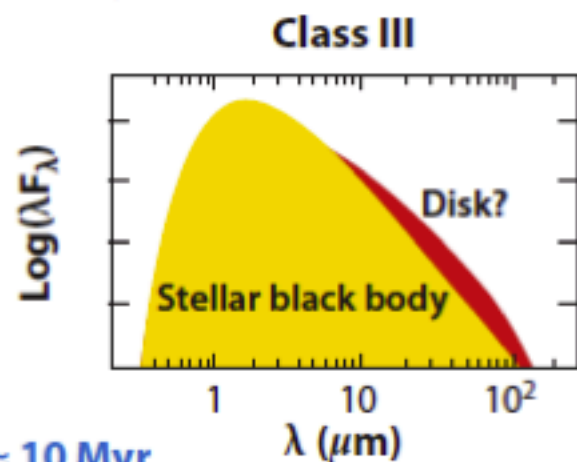
- young systems still embedded in a cloud (Class 0/I);
- protoplanetary disks (Class II), still accreting;
- old debris disks (Class III), not accreting

$t \approx 0.2$ Myr



Protoplanetary disk?

$t \approx 1$ Myr



Debris + planets?

$t \approx 10$ Myr

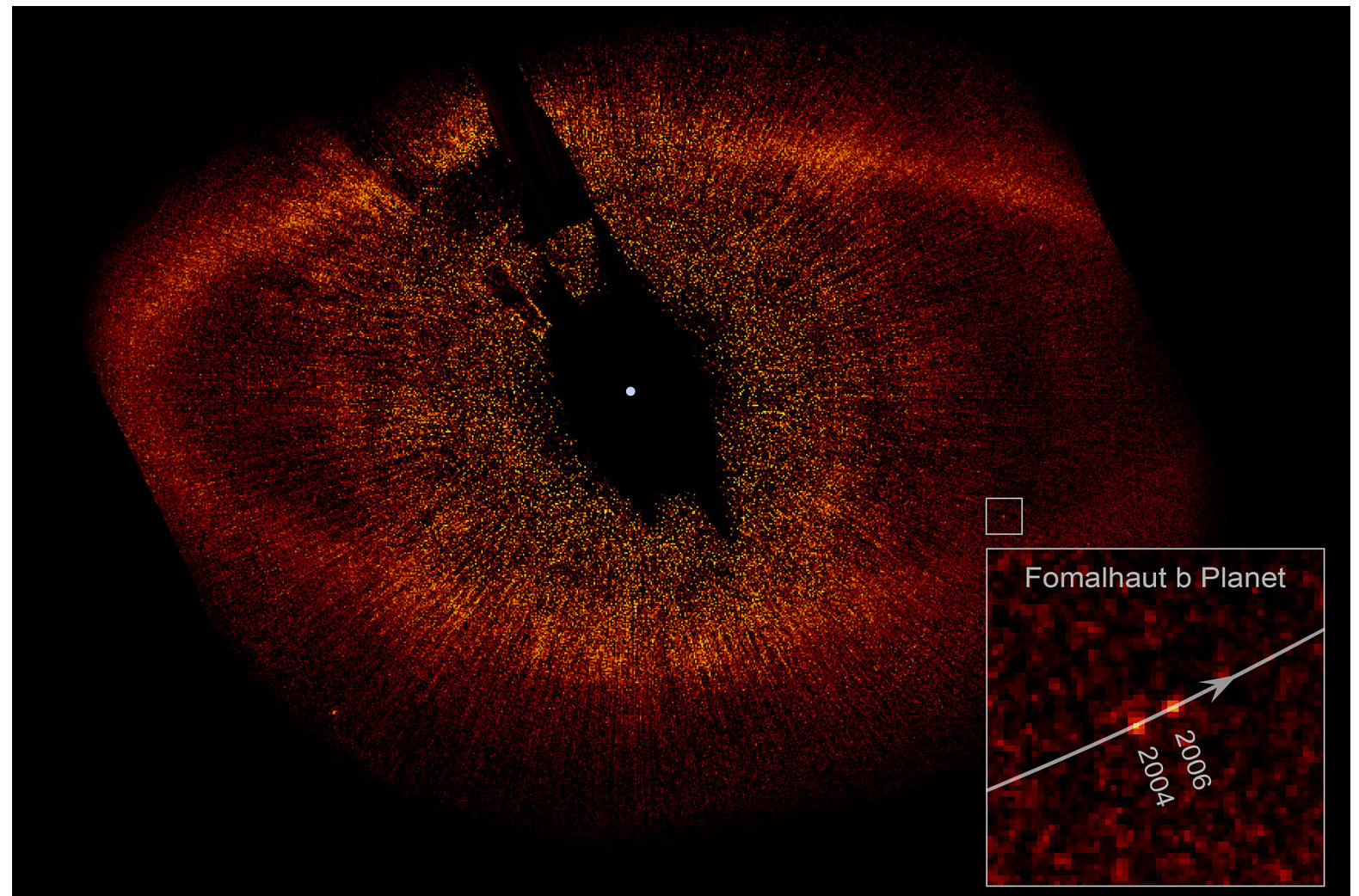
Lecture Jorgensen
Monday

Evolution and lifetime

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

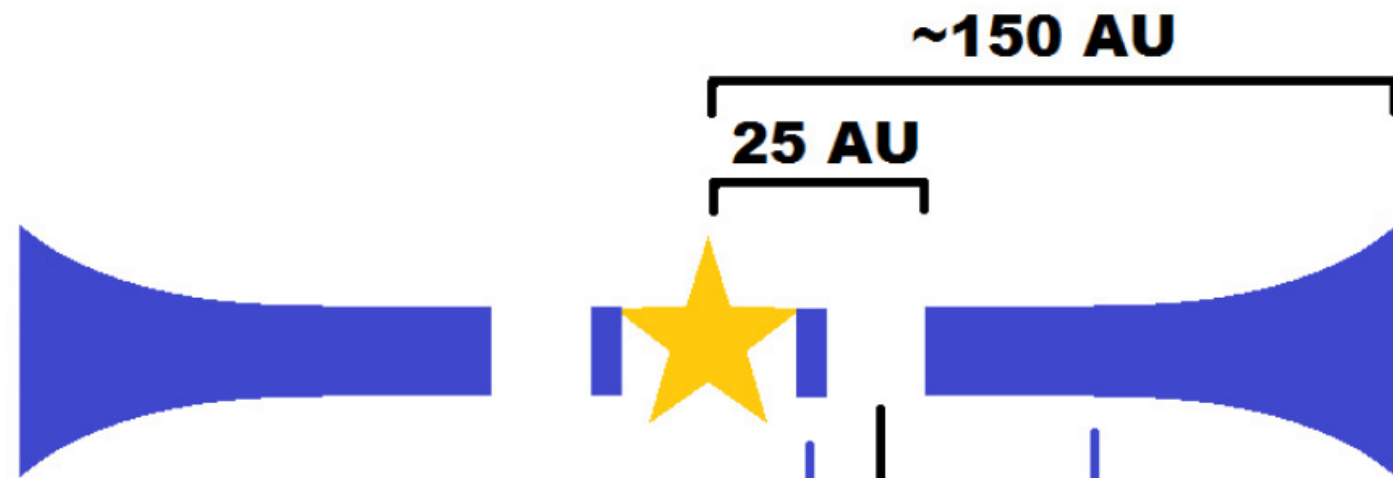
**Debris disks are found at
much closer distances to us:
not limited to star forming
regions and much longer
lifetimes (~100 Myr)**

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

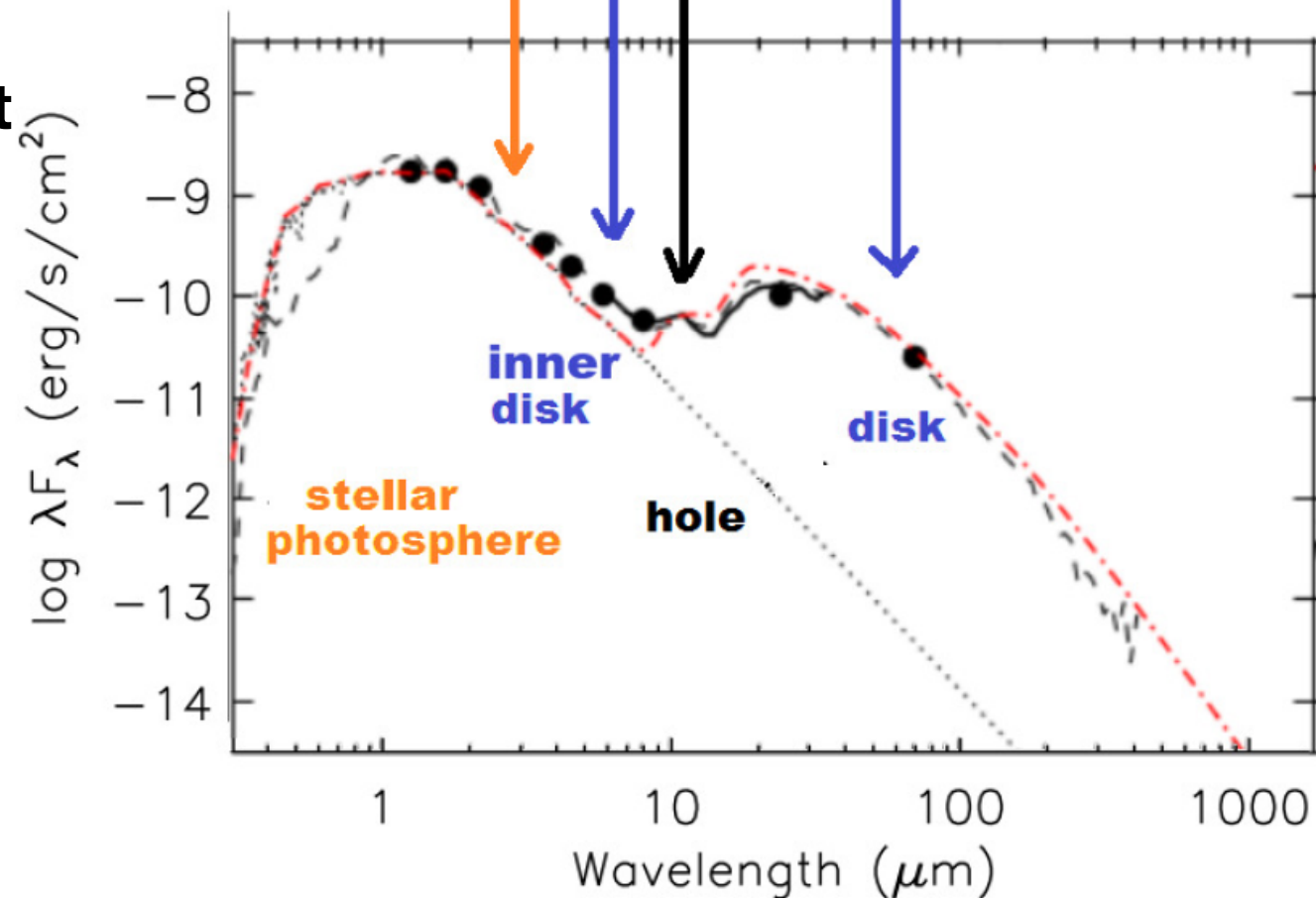


**Lecture Maddison
Wednesday**

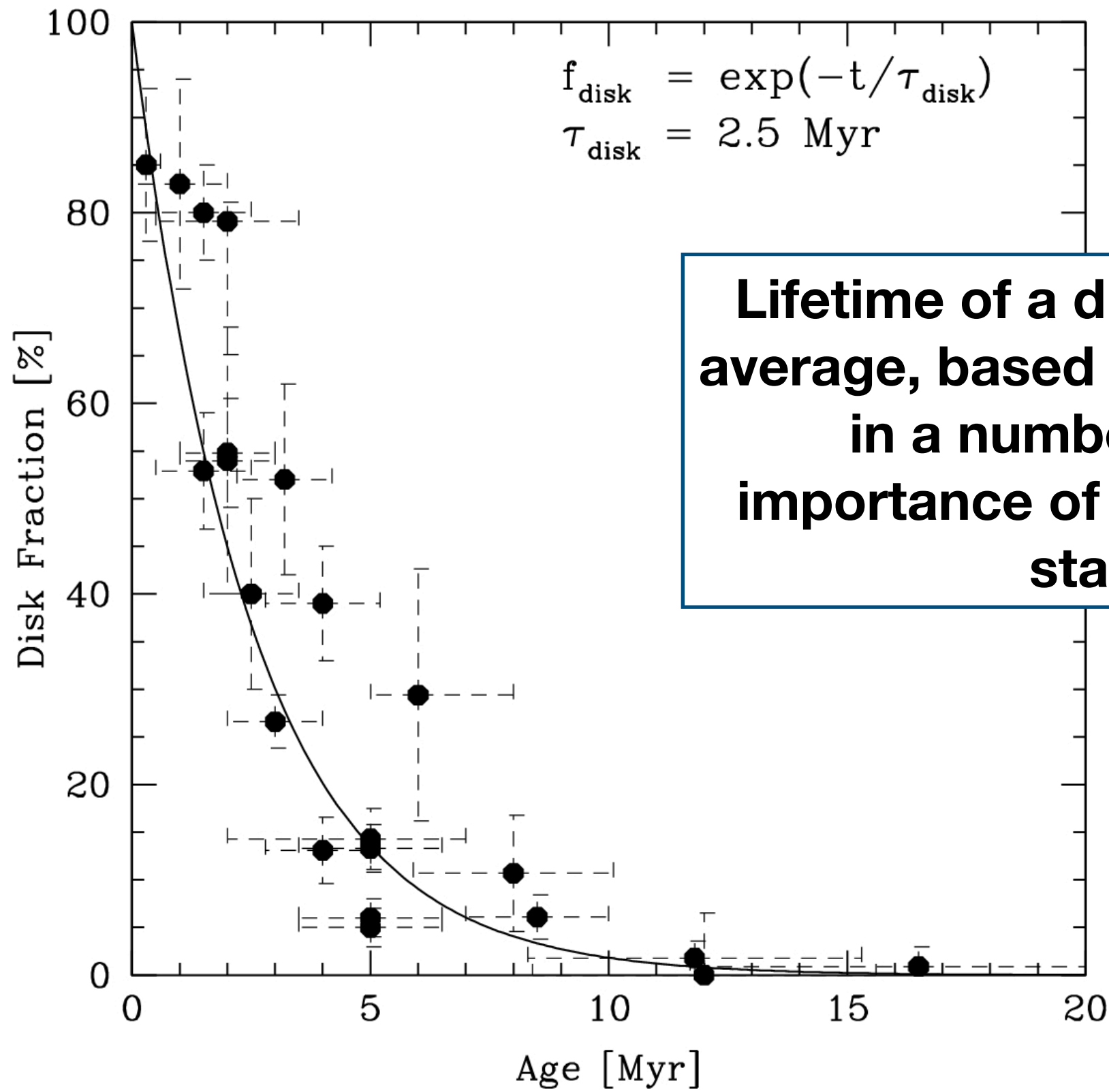
Evolution and lifetime



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

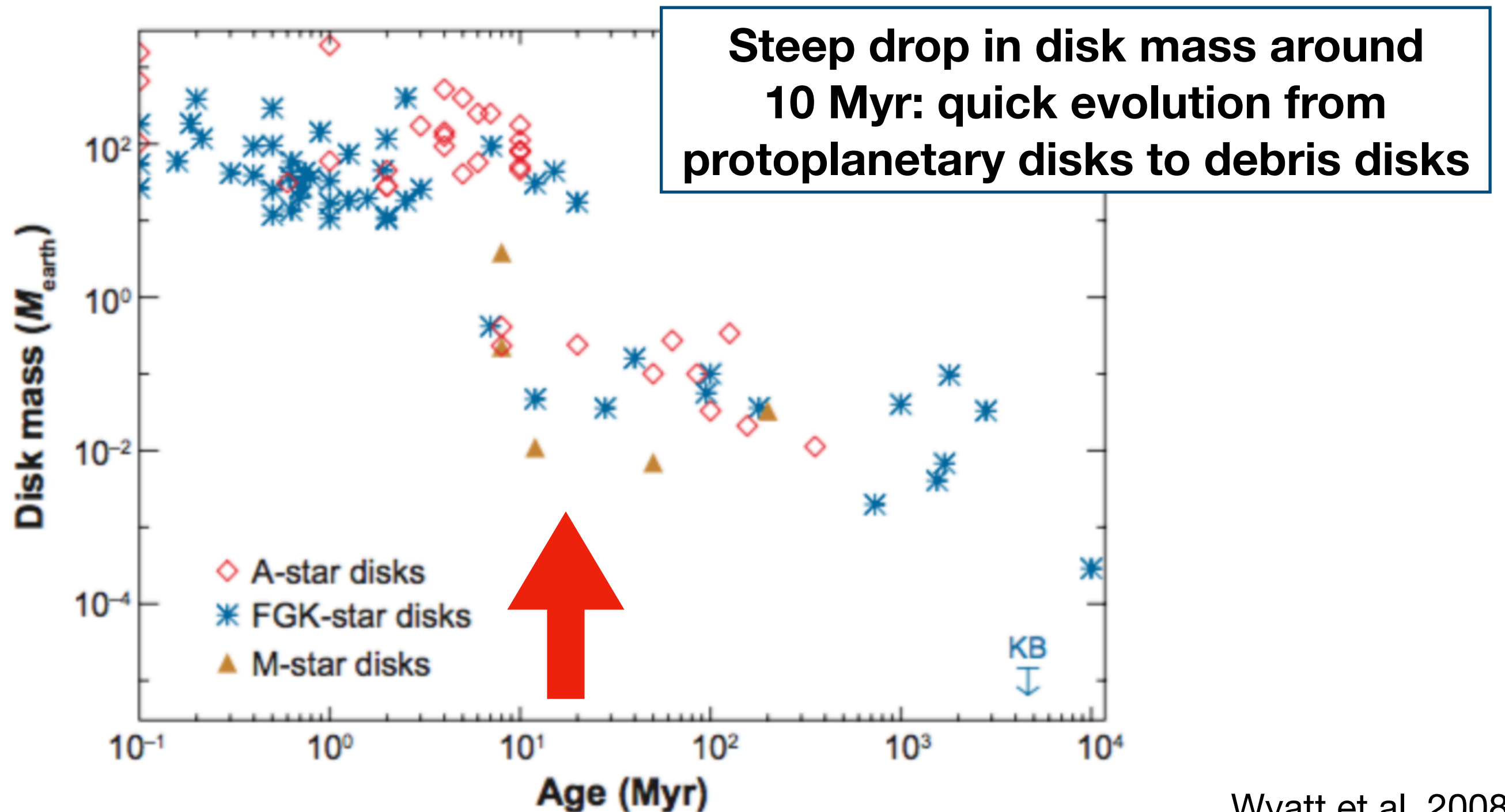


Evolution and lifetime



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

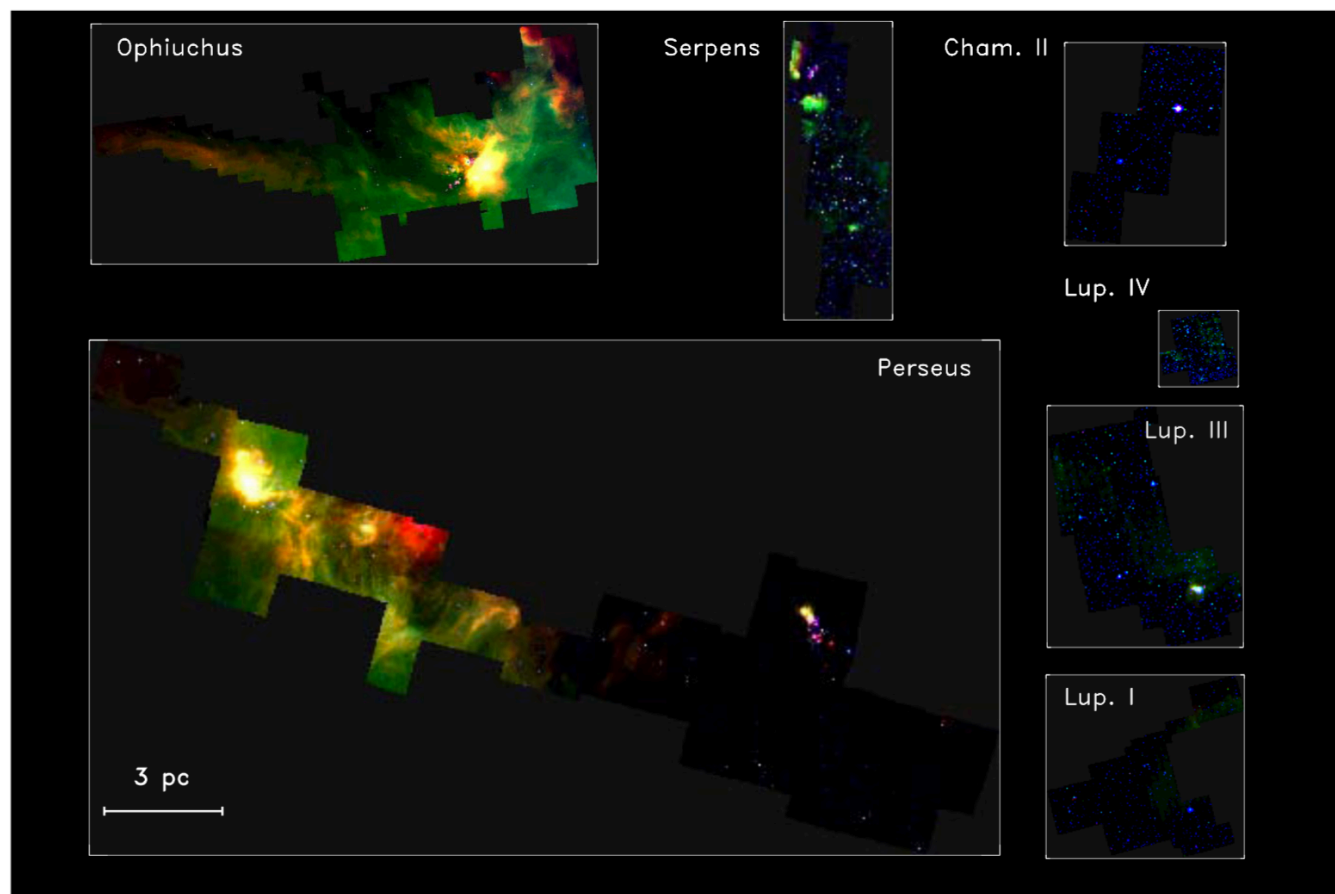
Evolution and lifetime



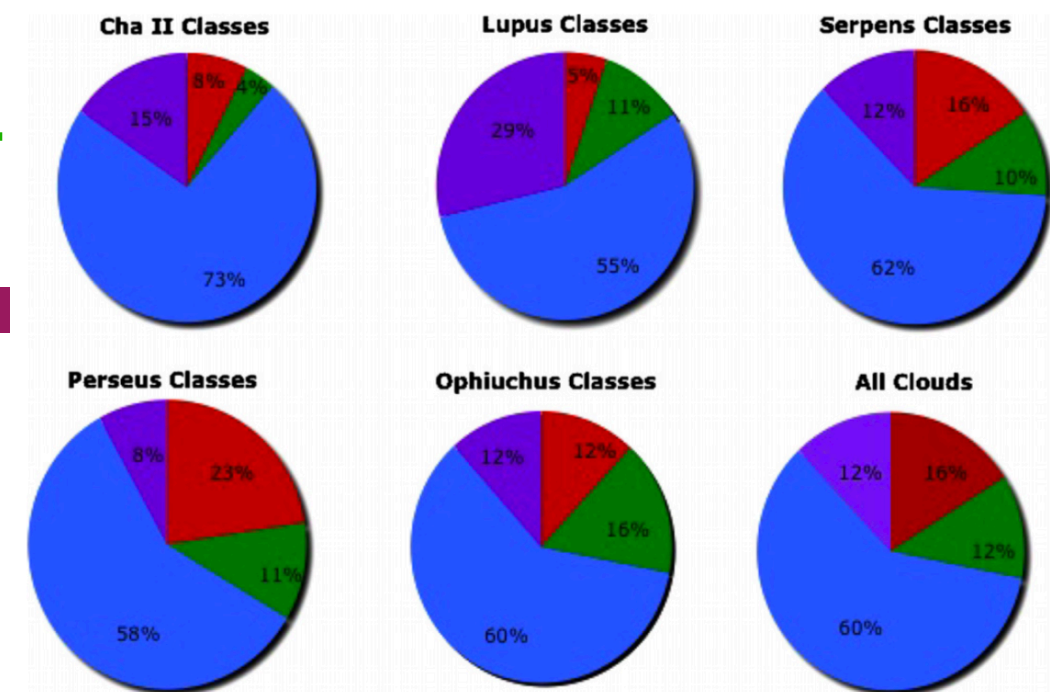
Evolution and lifetime

c2d: 'Cores to Disks':

=> Large Spitzer program targeting YSOs in nearby star forming regions



Class I
Class F
Class II
Class III

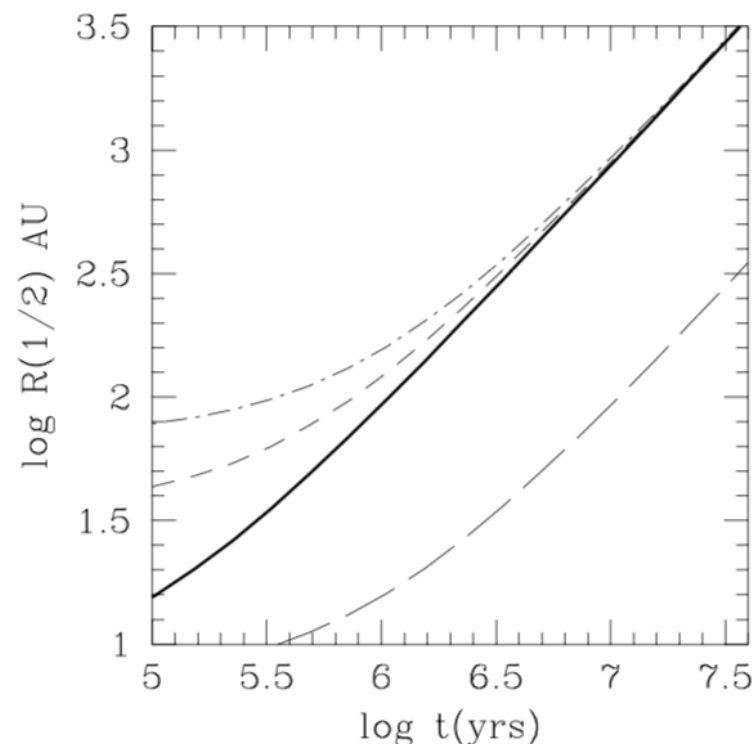
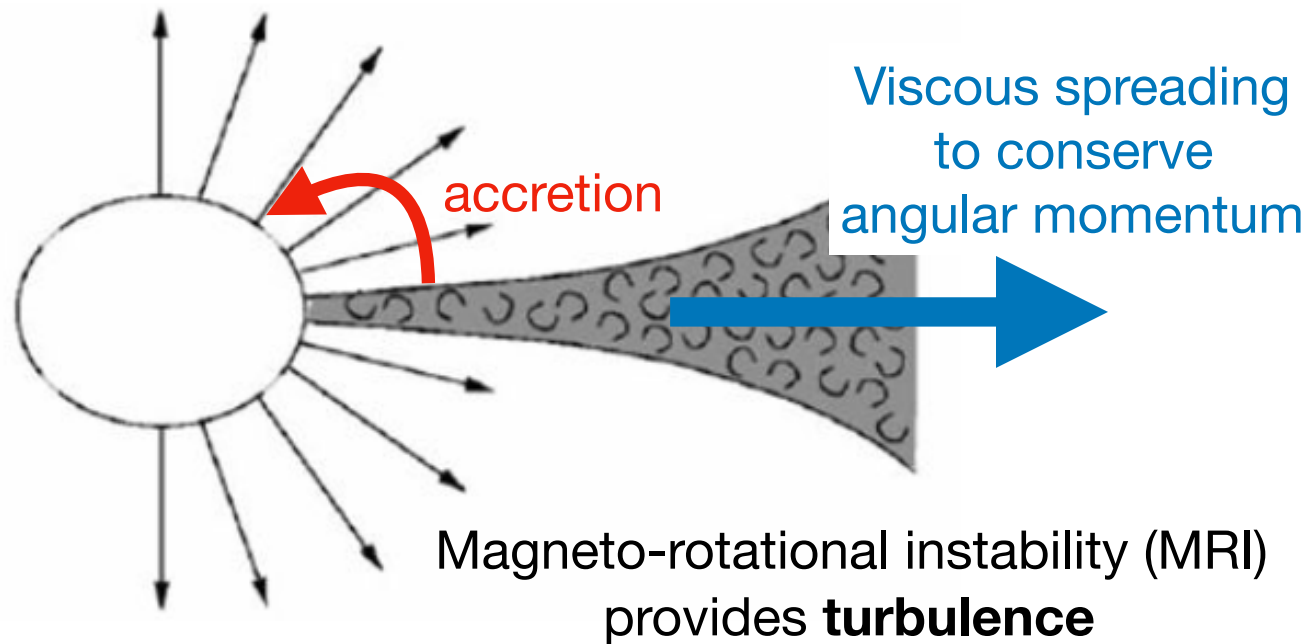


5 nearby clouds (100-260 pc), ~1000 YSOs

Statistics used to derive lifetimes:
Class 0+I: ~0.5 Myr

Evolution and lifetime

Classical picture of viscous accretion disk:



Recent results:

- MRI not as active as thought (non-ideal MHD)
- Turbulence lower than thought (observations)
- Alternative: angular momentum removed by disk winds (Bai 2016)

Lecture Shang
Tuesday

Lynden-Bell & Pringle 1974
Hartmann et al. 1998
Turner et al. 2014 (PPVI)

**So what do we know so far
about disks?**

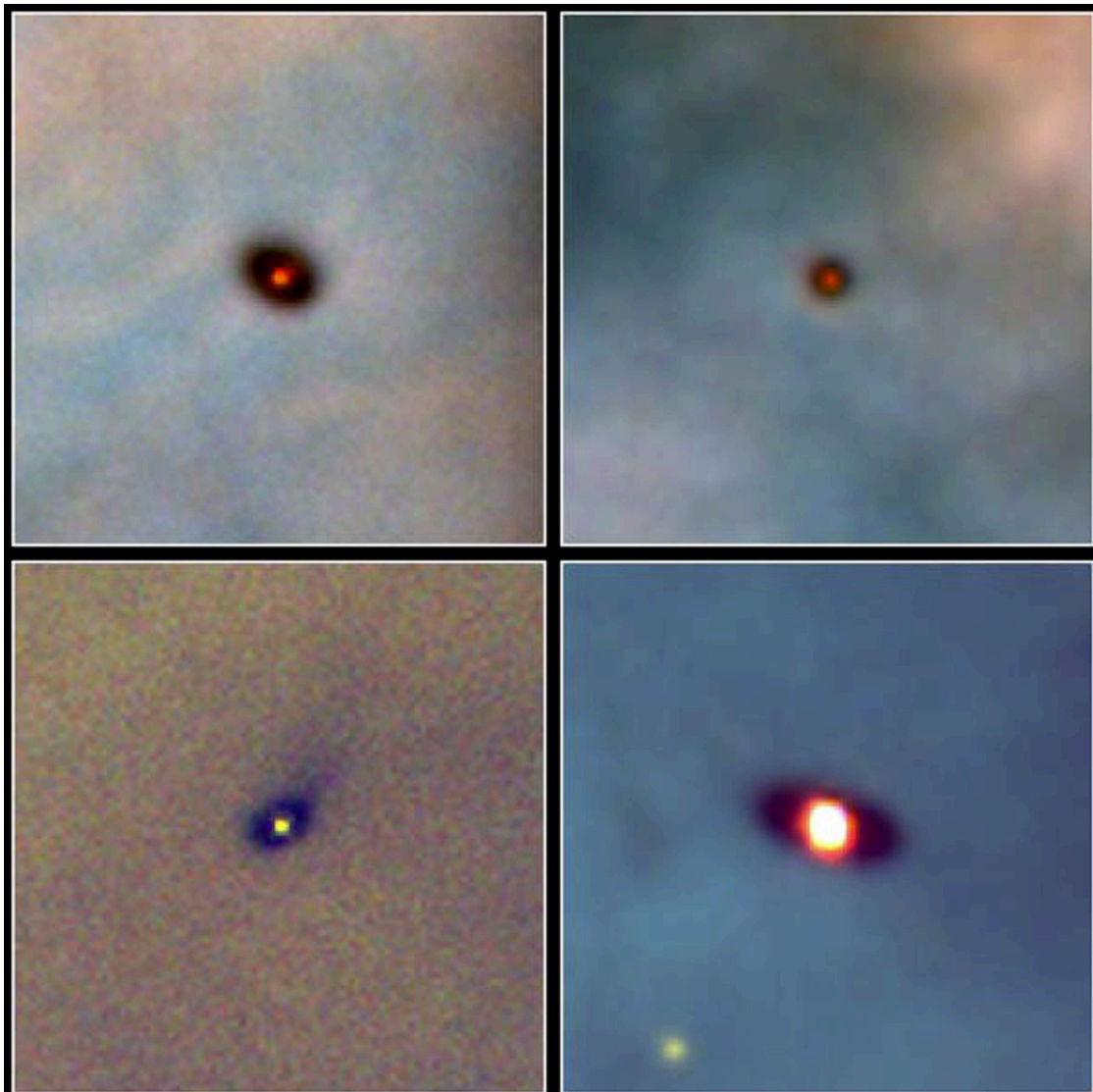
So what do we know so far about disks?

- 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 $\sim 1''$ or smaller in size (~ 100 s AU)
- They live several million years
- They quickly dissipate by the end of their lifetime
- 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



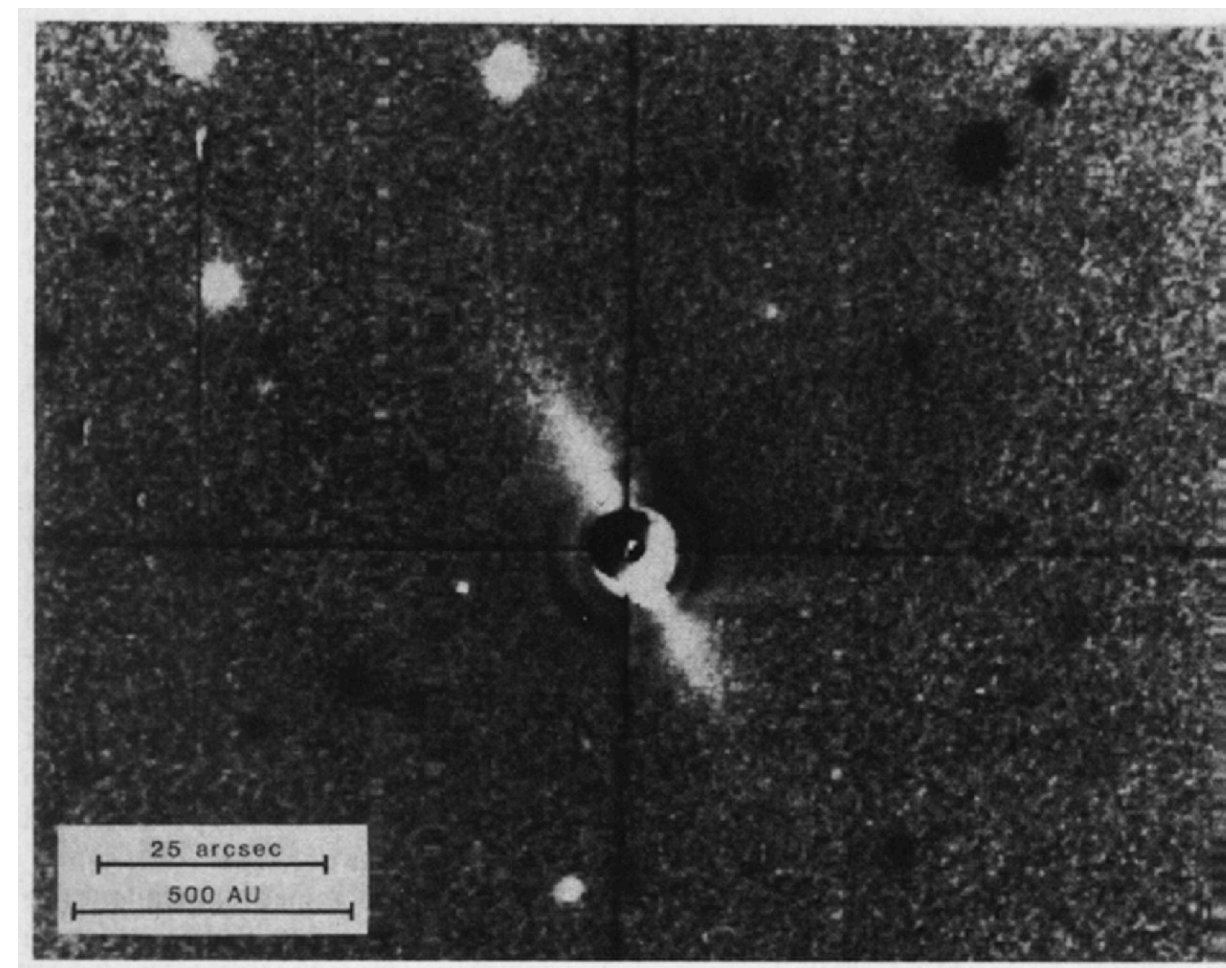
**Protoplanetary Disks
Orion Nebula**

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995

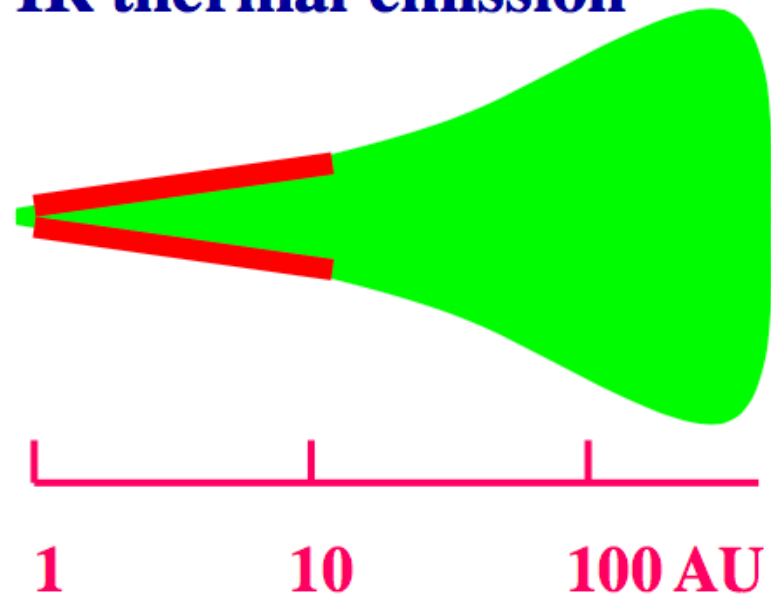
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

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

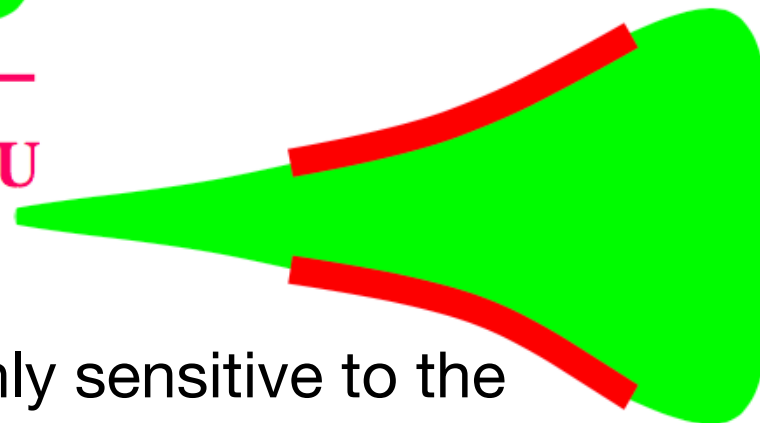


First disk images

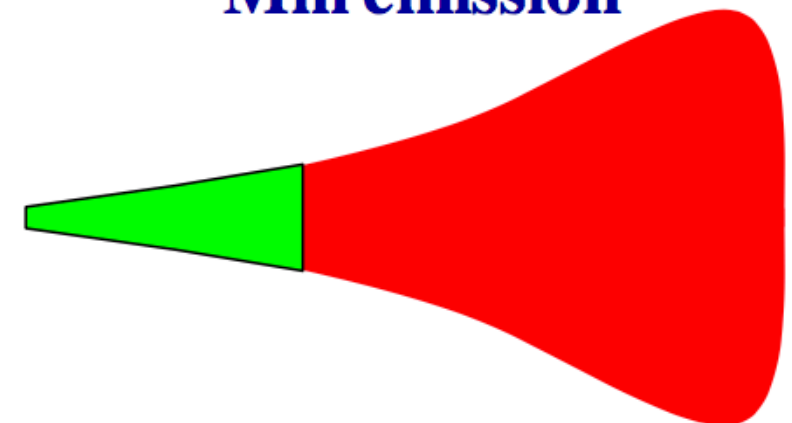
IR thermal emission



Scattered light



Mm emission



- 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 $\text{res} \sim \lambda/D \Rightarrow >10''$ even for 30m telescopes

A new era of disk imaging: millimeter interferometry

SMA (Maunakea) since 2003



PdBI (France) since 1990

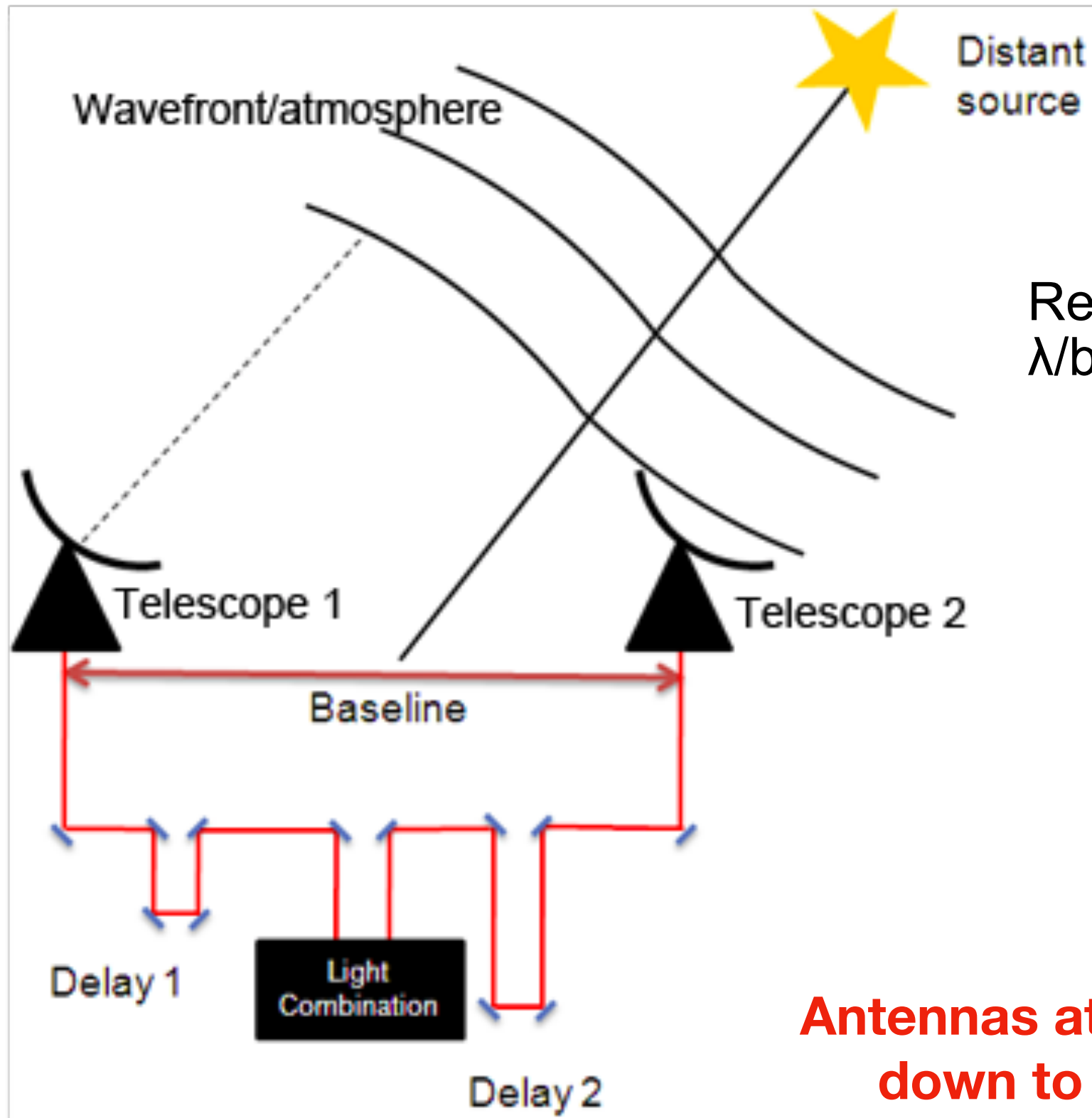


CARMA (California) 2006-2015



What is interferometry?

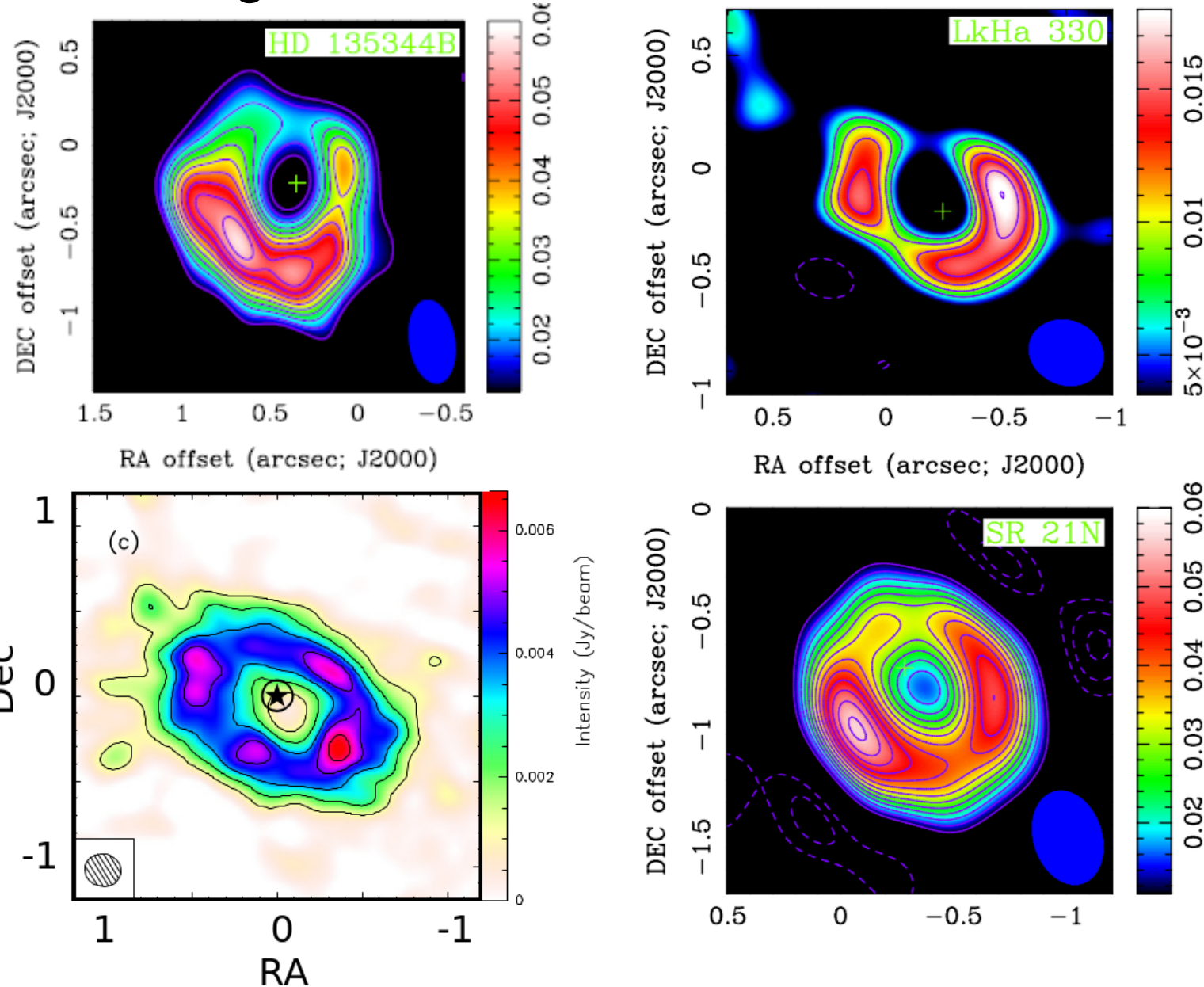
Interferometry



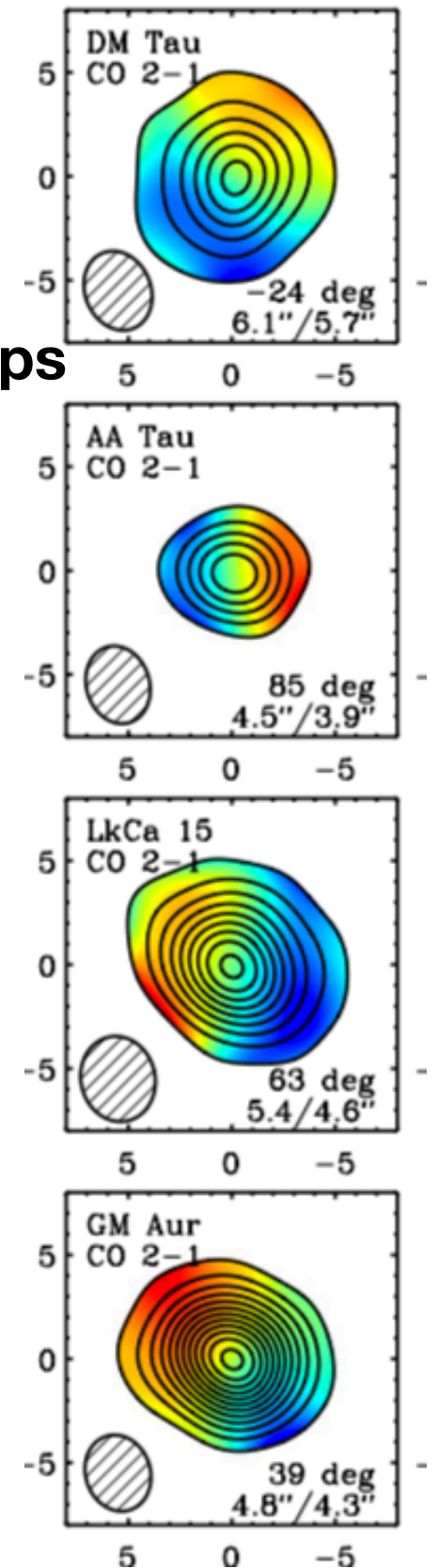
**Antennas at ~500 m distances:
down to ~0.4'' resolution**

Interferometry

continuum images of transition disks,
confirming dust cavities



Velocity maps
of CO



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

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 ($\sim 0.35''$ resolution)
 - Limited number of baselines: bad image quality after Fourier transform of data

ALMA

ALMA: Atacama Large Millimeter/submillimeter Array



ALMA



ALMA

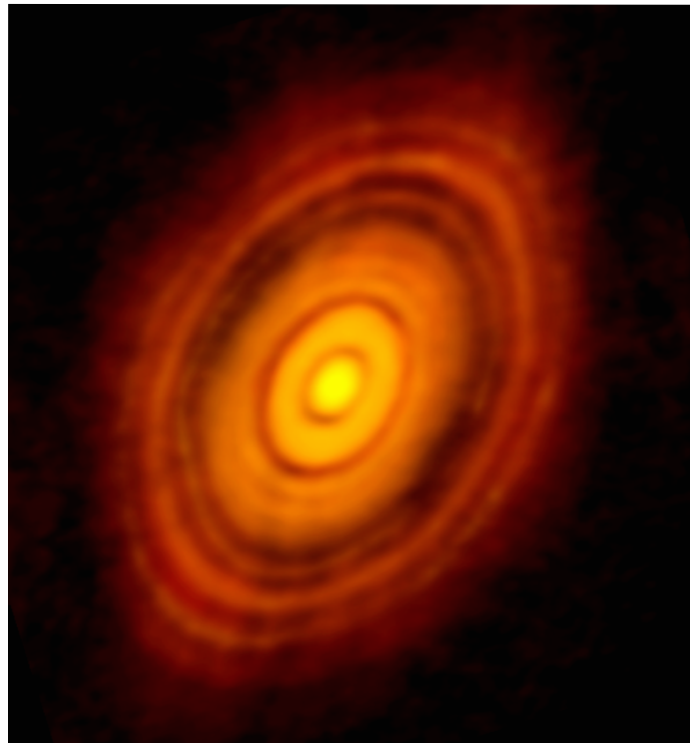
- Array of 66 antennas in Atacama desert in Chile at 5100m elevation
- Started operations in 2011
- Global collaboration between Europe, North America, Chile and East Asia
- Budget 1.3 billion \$ for operation of 30 years
- Sensitivity 100 times higher and resolution 200 times better than previous interferometers
- Resolution down to 0.01''!



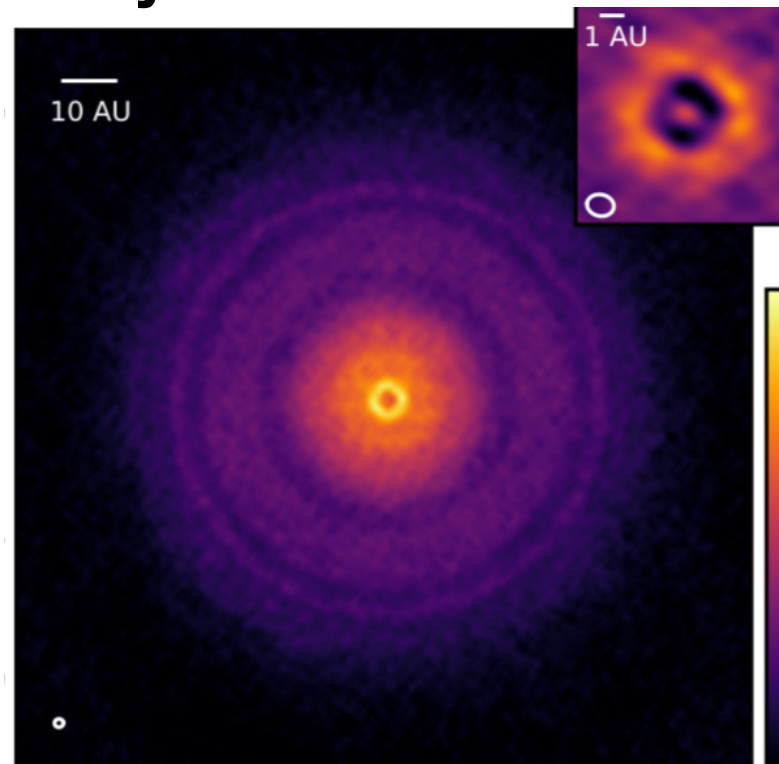
What is the advantage of high elevation?

ALMA

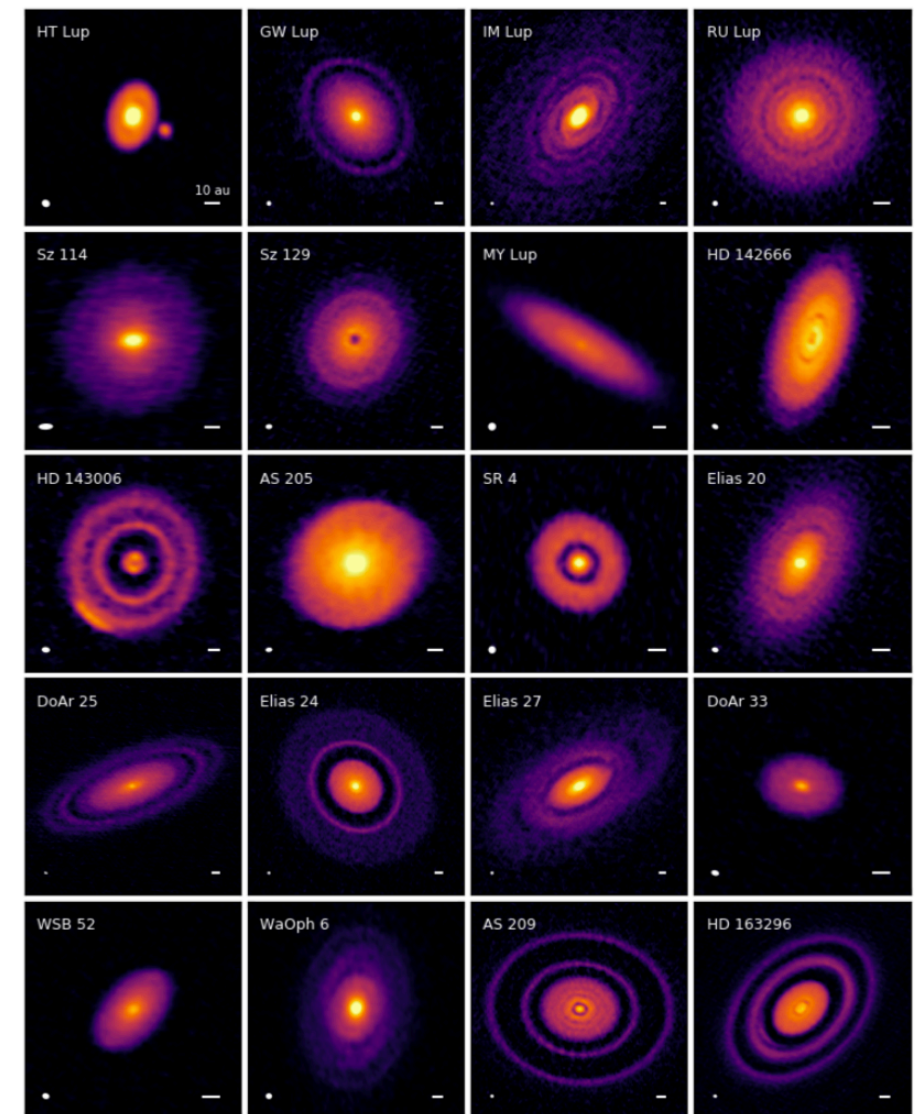
HL Tau



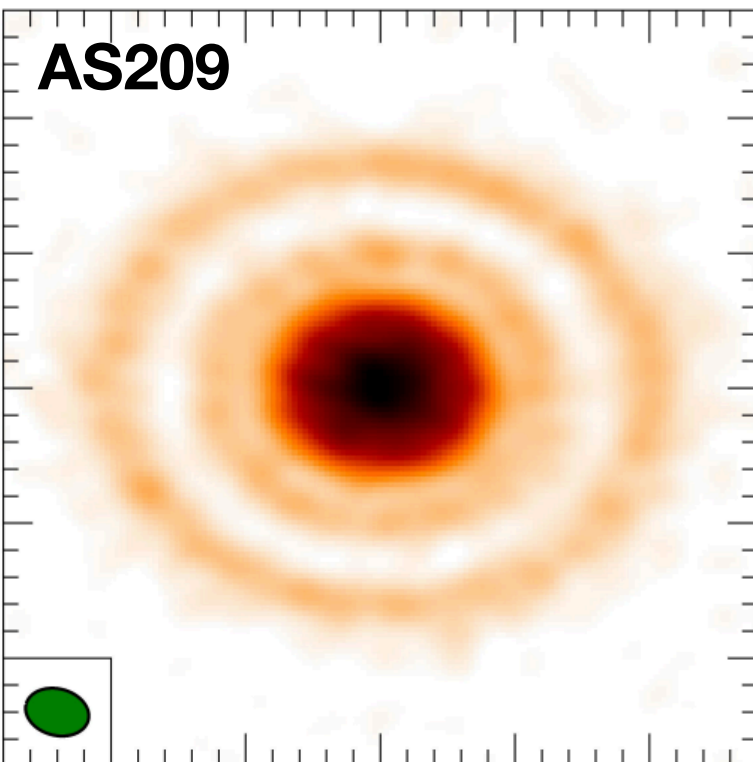
TW Hya



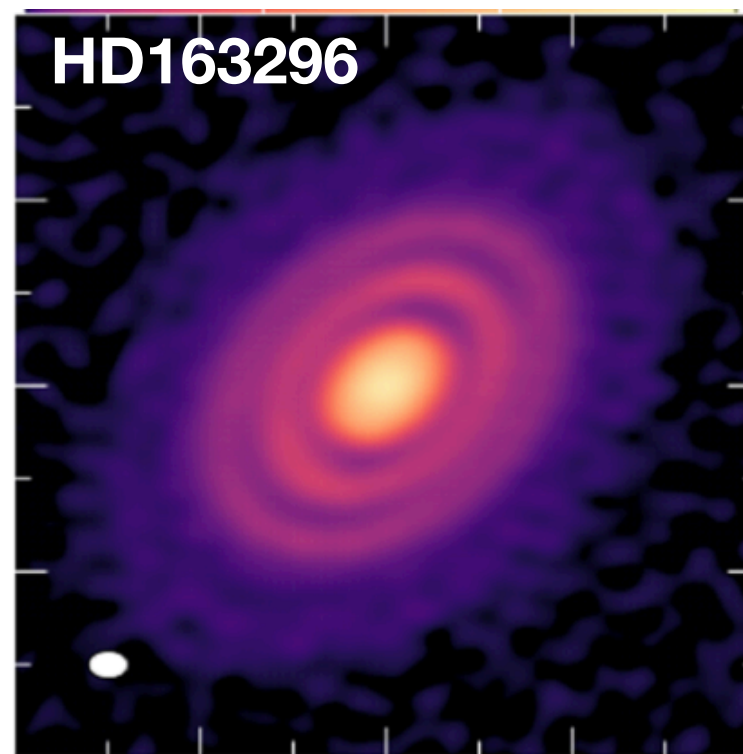
DSHARP



AS209



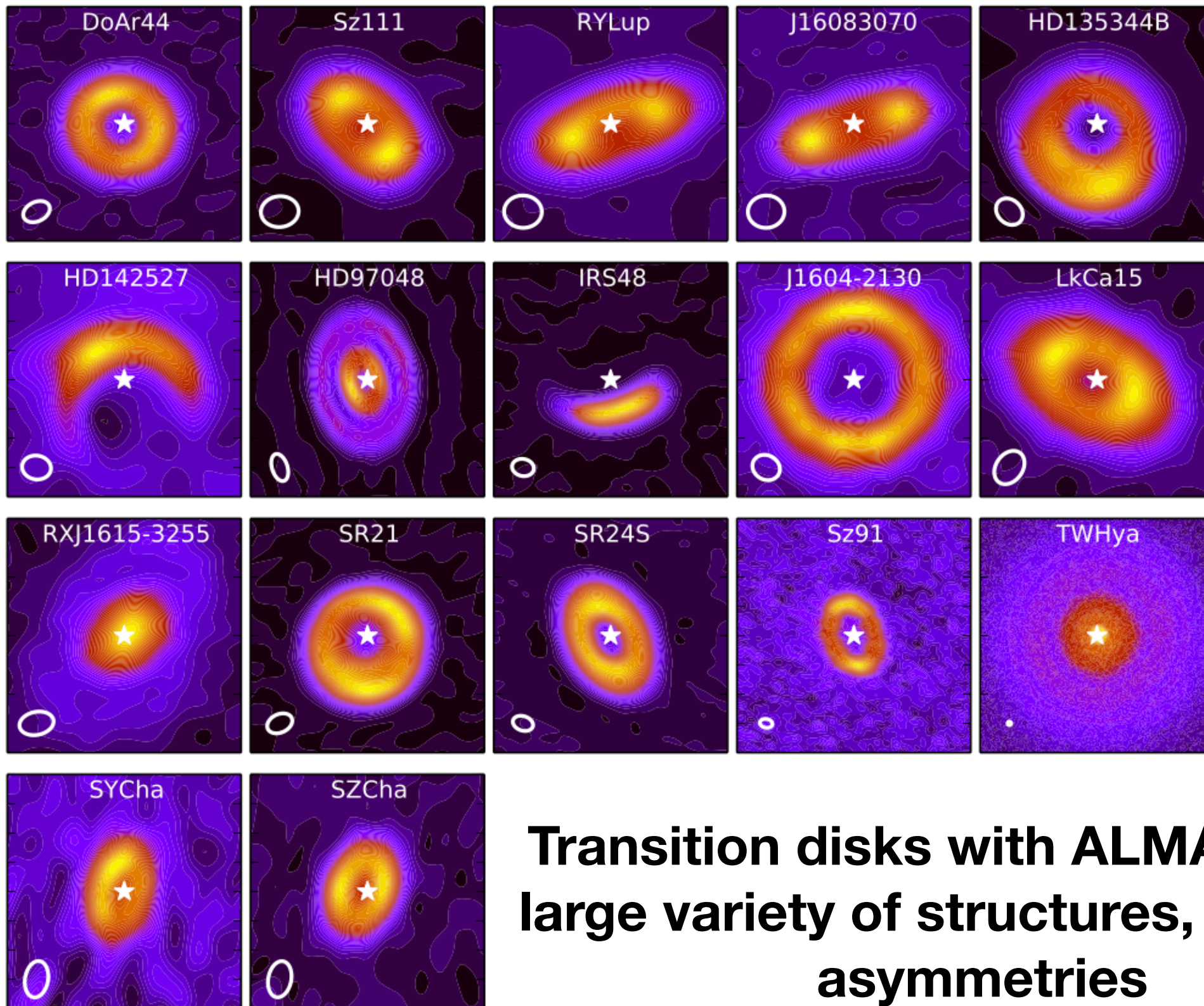
HD163296



**High resolution (0.04")
dust images: rings!
(even at <1 Myr)**

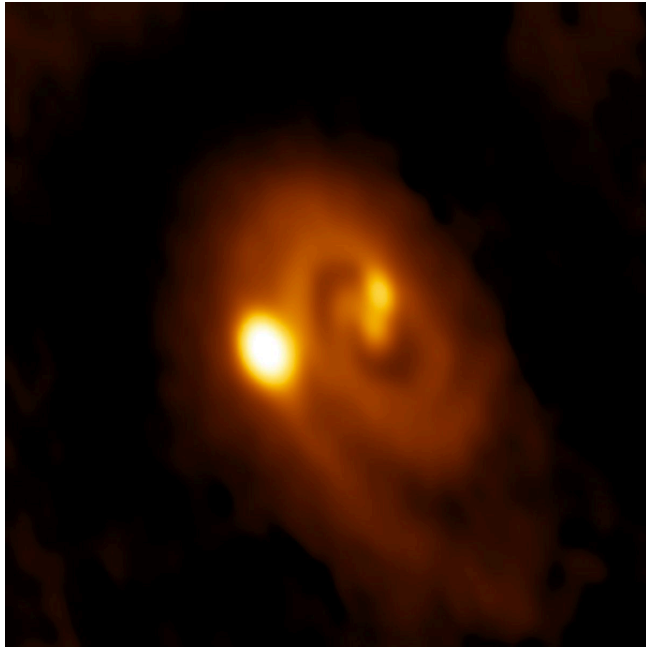
ALMA consortium et al. 2015, Andrews et al. 2016+2018, Isella et al. 2016, Fedele et al. 2017

ALMA

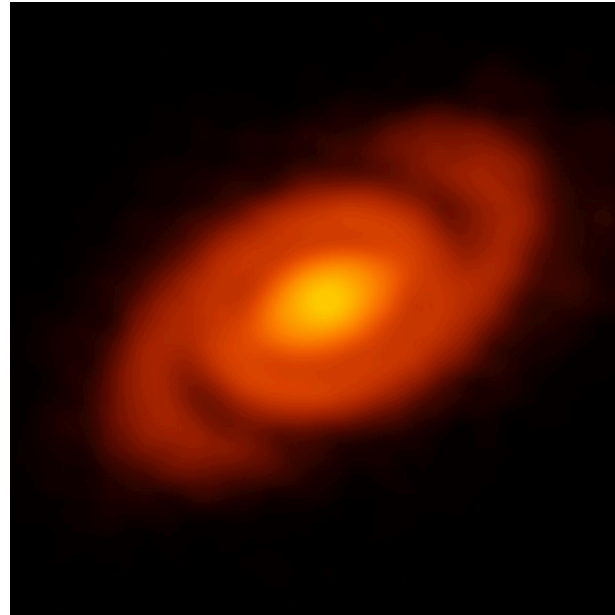


ALMA

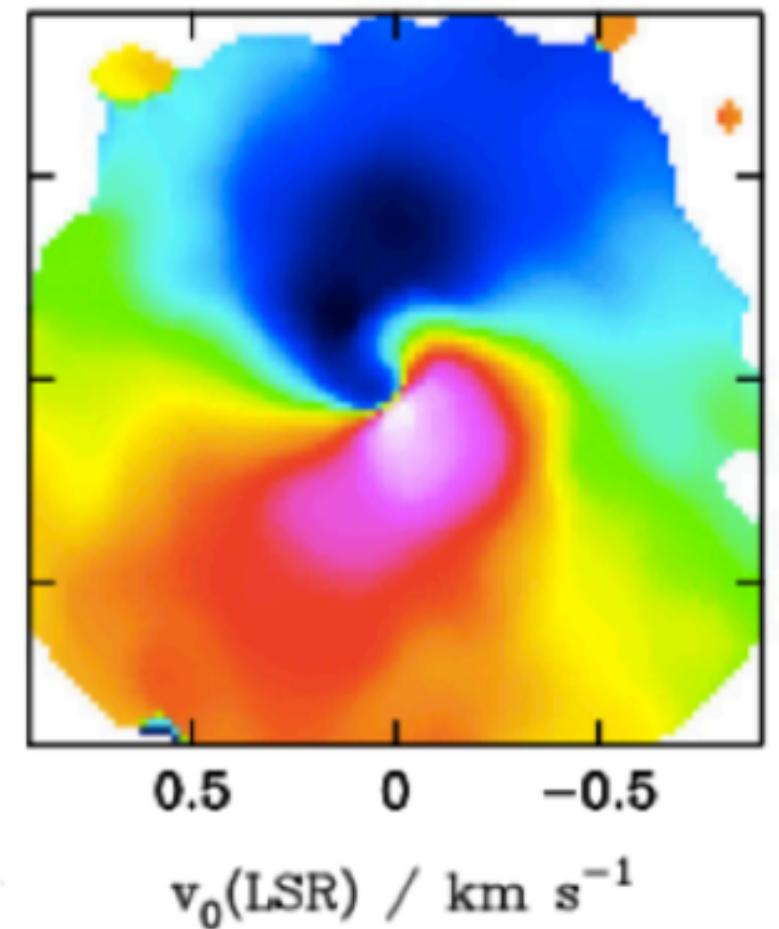
**Triple system with
disk fragmentation**



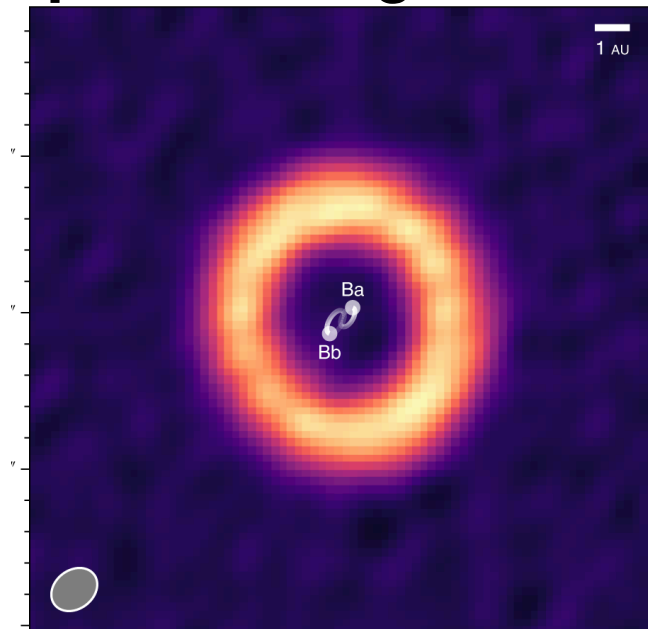
Spiral arms



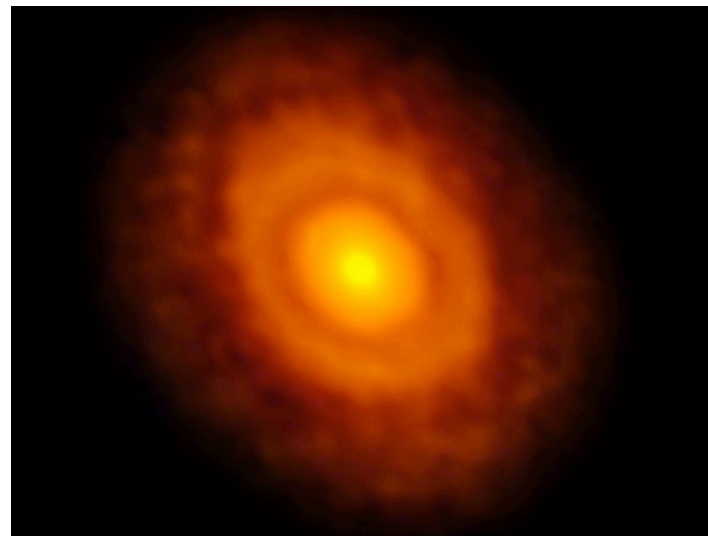
Non-Keplerian motion



**Circumbinary disk in
polar configuration**



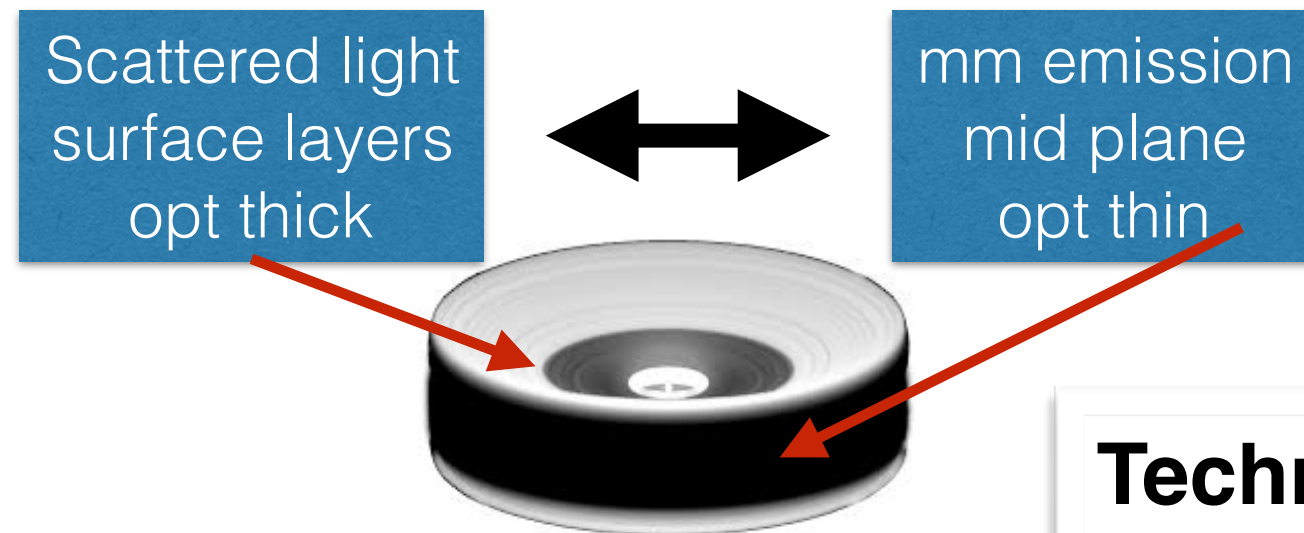
**Signature water snowline
after stellar outburst**



Kennedy et al. 2019
Tobin et al. 2016
Perez et al. 2016
Cieza et al. 2018
Casassus et al. 2015

NIR imaging

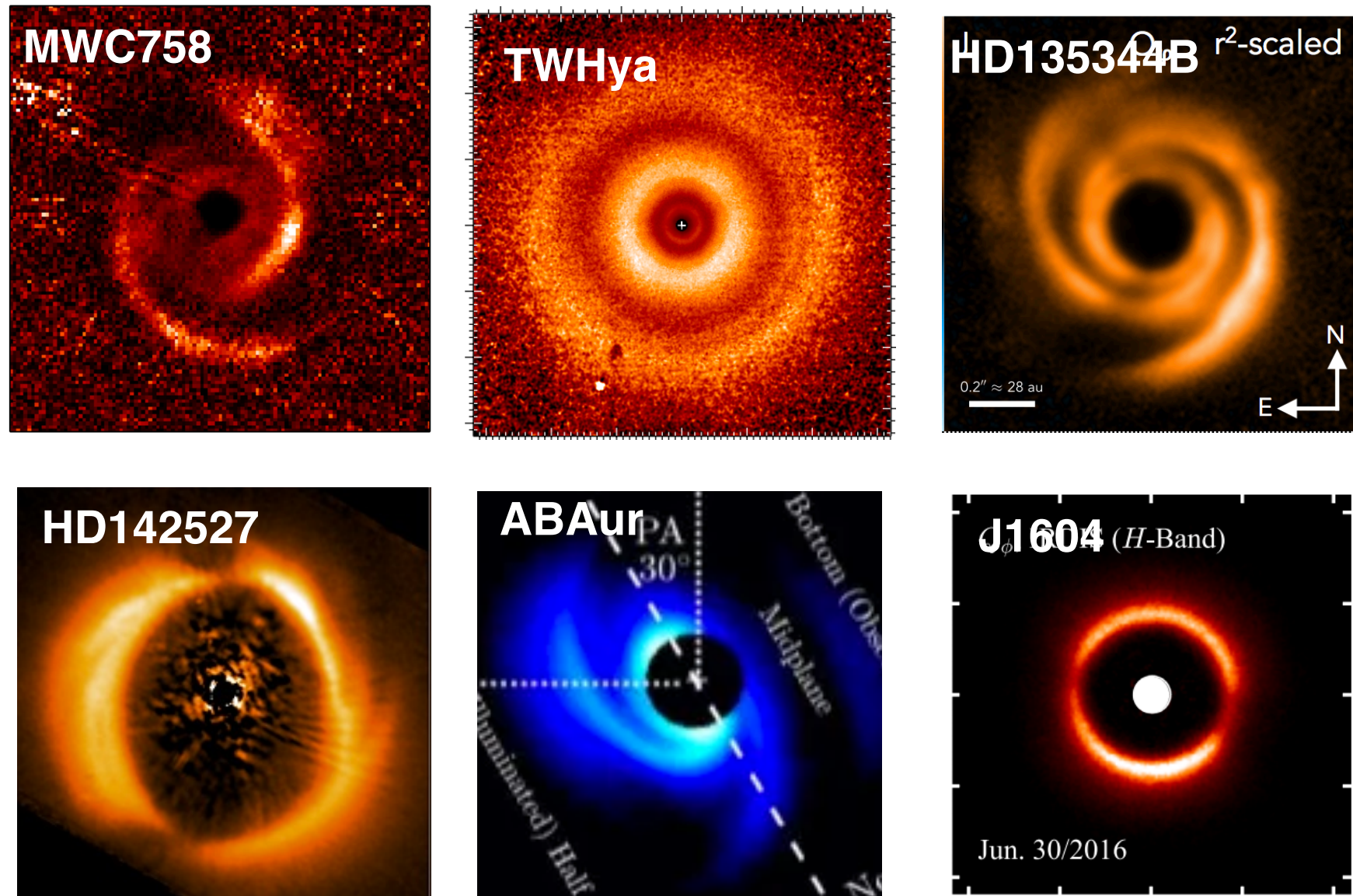
- Scattered light imaging is sensitive to upper layers of the disk => different perspective



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

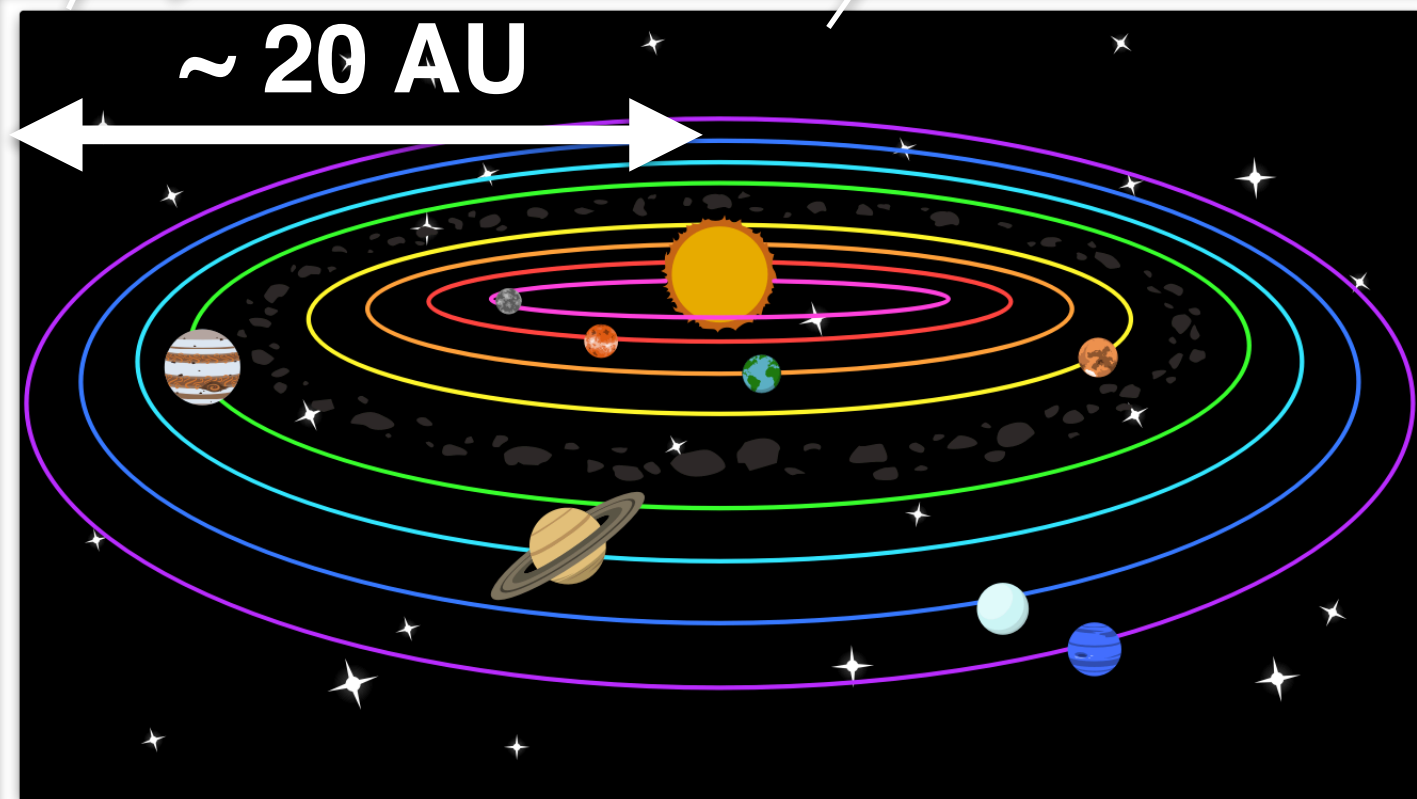
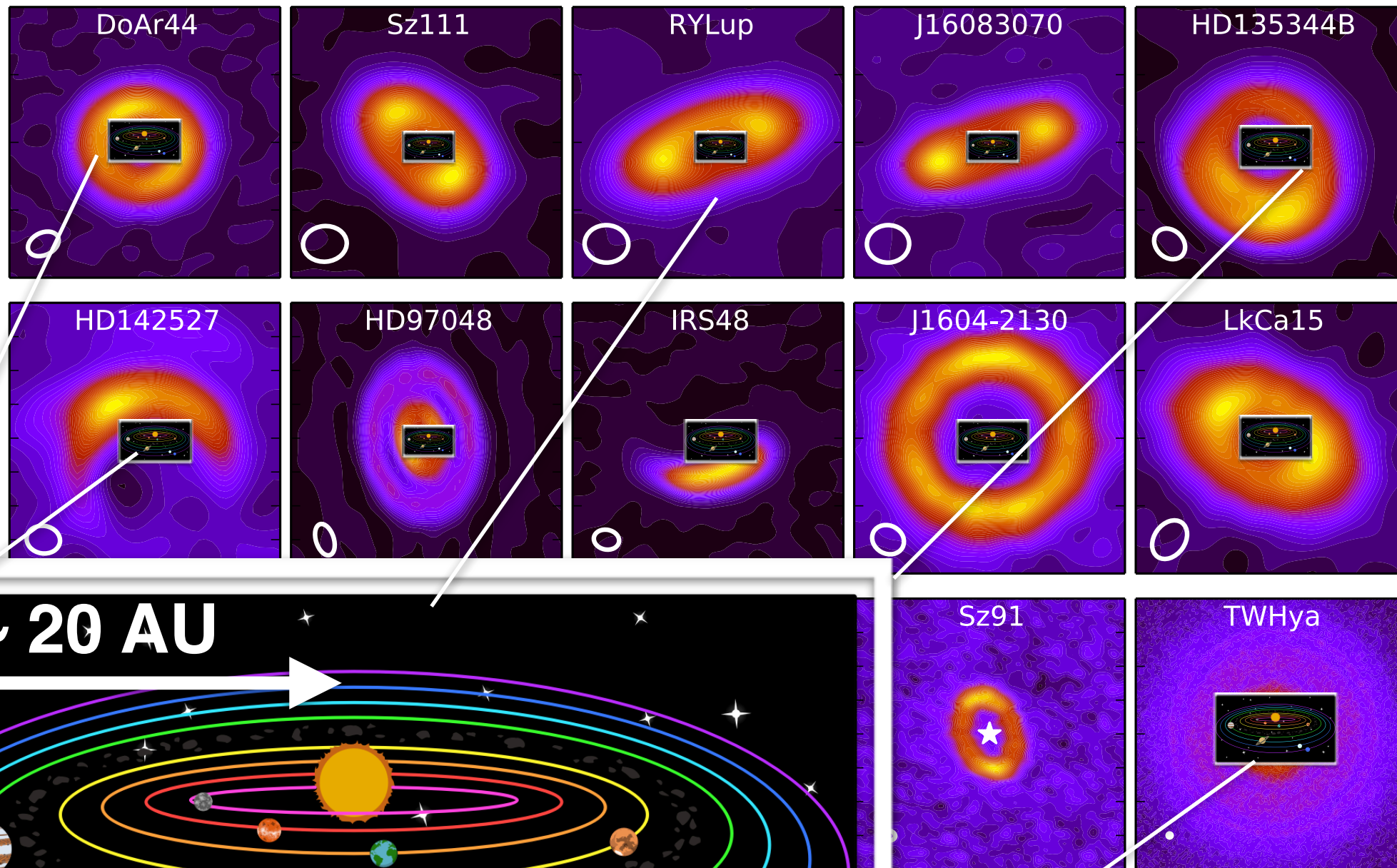
Technique also used to detect exoplanets (see lecture Henry Ngo)

NIR imaging



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

Something to keep in mind...



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

Something to keep in mind...

- 1. Historically, observational astronomy is split in different wavelength regimes, with different technologies: communities not necessarily talking with each other.**
- 2. Historically, disk theory, planet formation theory and disk observations developed almost independently due to lack of observational constraints. This has changed with ALMA!**
- 3. This is a rapidly evolving field: many classic ideas currently under debate. Make sure you know the historic context when reading publications and the contents of this summer school!**

Questions?

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