Master in Space Sciences - Academic year 2021-2022

SPAT0063 Introduction to exoplanetology

Lecture 8: System architectures & circumstellar disks

May 17th, 2022

Olivier Absil

FNRS Senior Research Associate — STAR Institute
olivier.absil@uliege.be

Outline

I. System architectures & statistics

II. Protoplanetary disks

II.1. Theoretical picture

II.2. Imaging techniques

II.3. Results from imaging

II.4. Protoplanets

III. Debris disks

I. System architectures & statistics

— combining all detection methods —

Discovery spaces

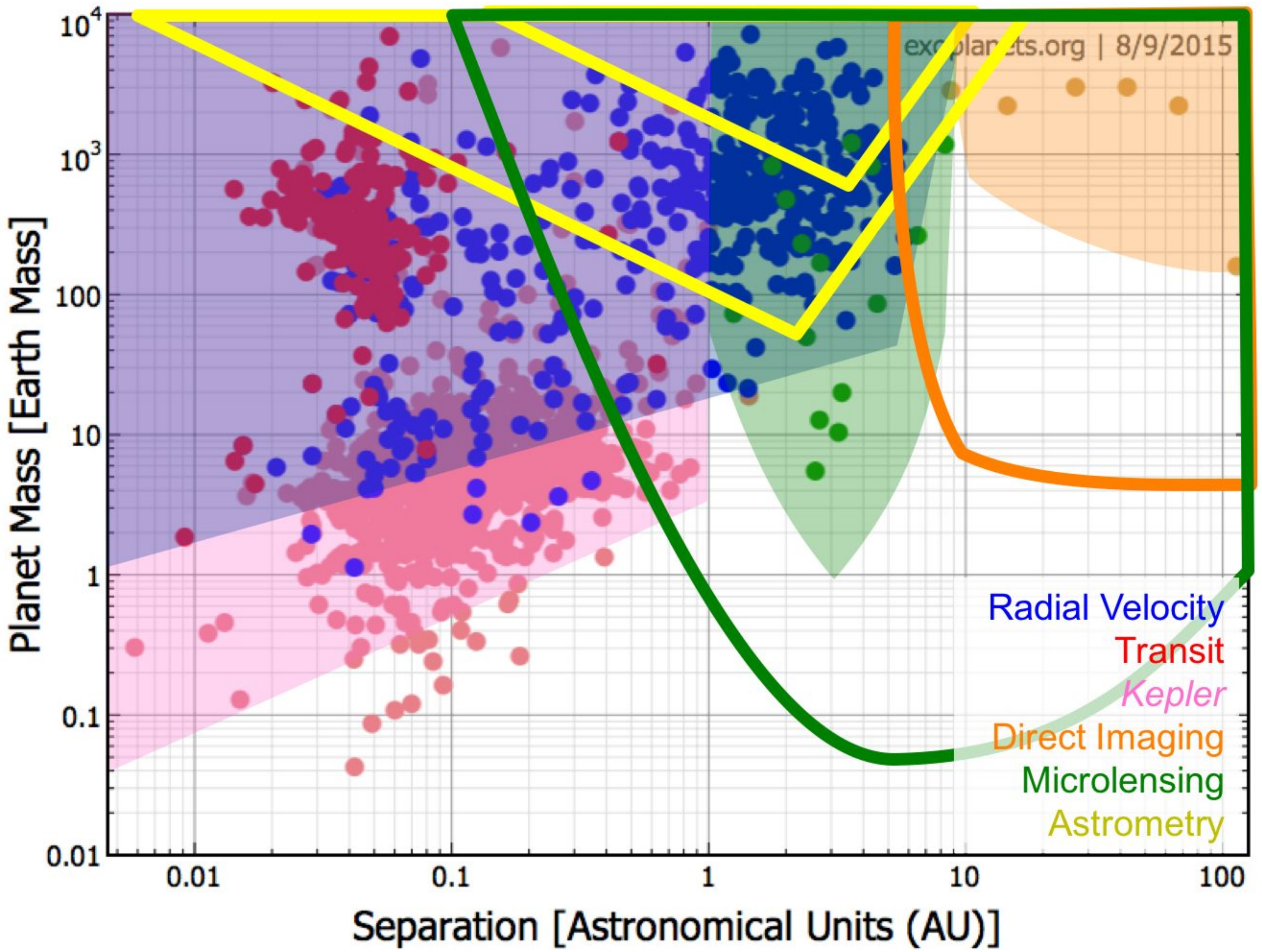
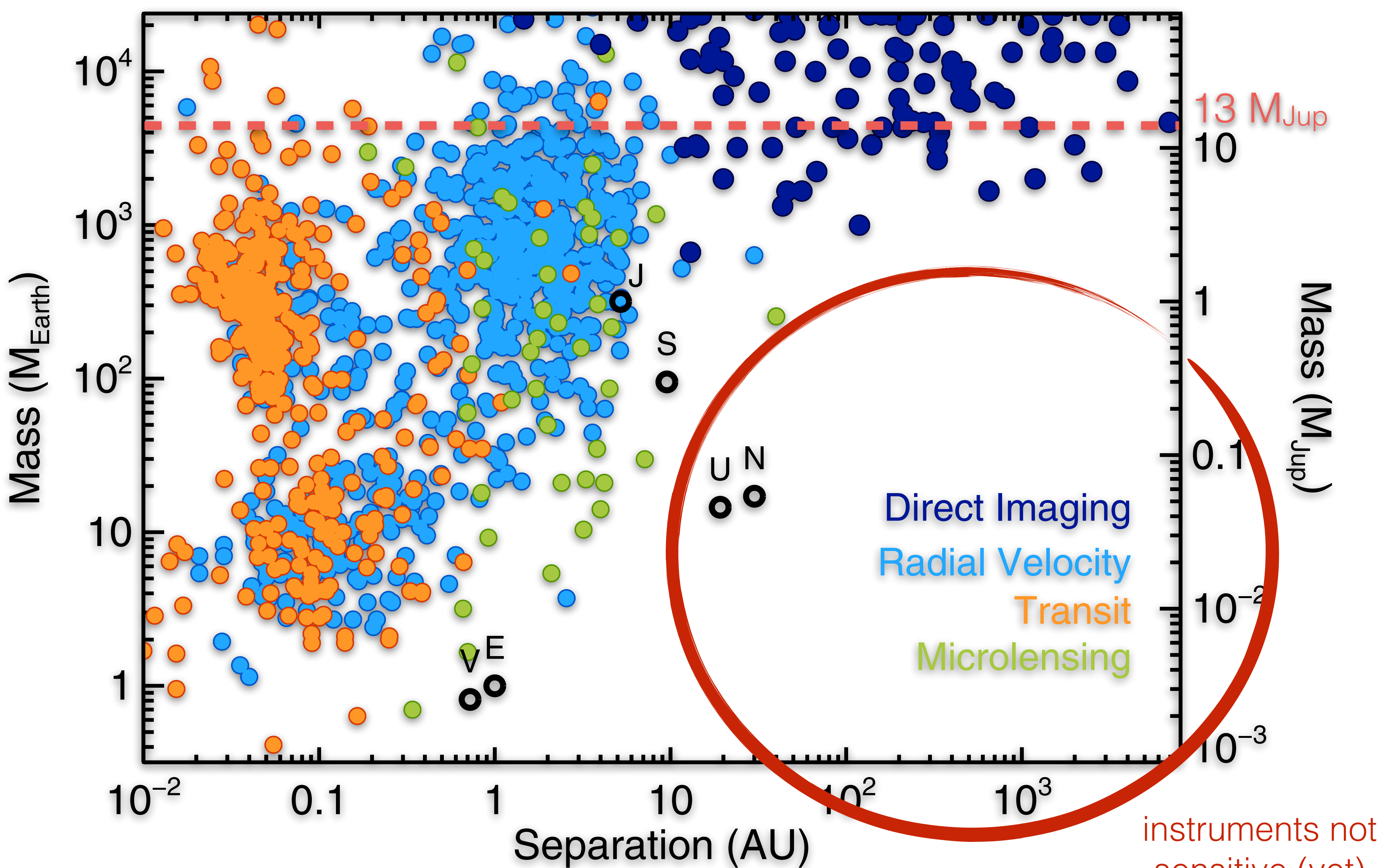


Figure 1. Approximate masses and orbital semi-major axes of known exoplanets. The color of each point indicates the detection technique used to discover each planet. Shaded regions indicate the approximate range of parameter space over which each detection technique is currently sensitive. Colored lines indicate the approximate sensitivity regimes of future/ongoing exoplanet surveys: the ground-based direct imaging GPI Exoplanet Survey[7] (orange line), the GAIA planet astrometry survey[8] for planets orbiting a 1 $M_\odot$ star at 200 pc (upper yellow line) and a 0.4 $M_\odot$ M dwarf at 25 pc (lower yellow line), and the WFIRST exoplanet microlensing survey[9] (solid green line). This data was taken from the Exoplanet Orbit Database.[10] Masses of *Kepler* planet candidates are roughly estimated from the measured planet radii.

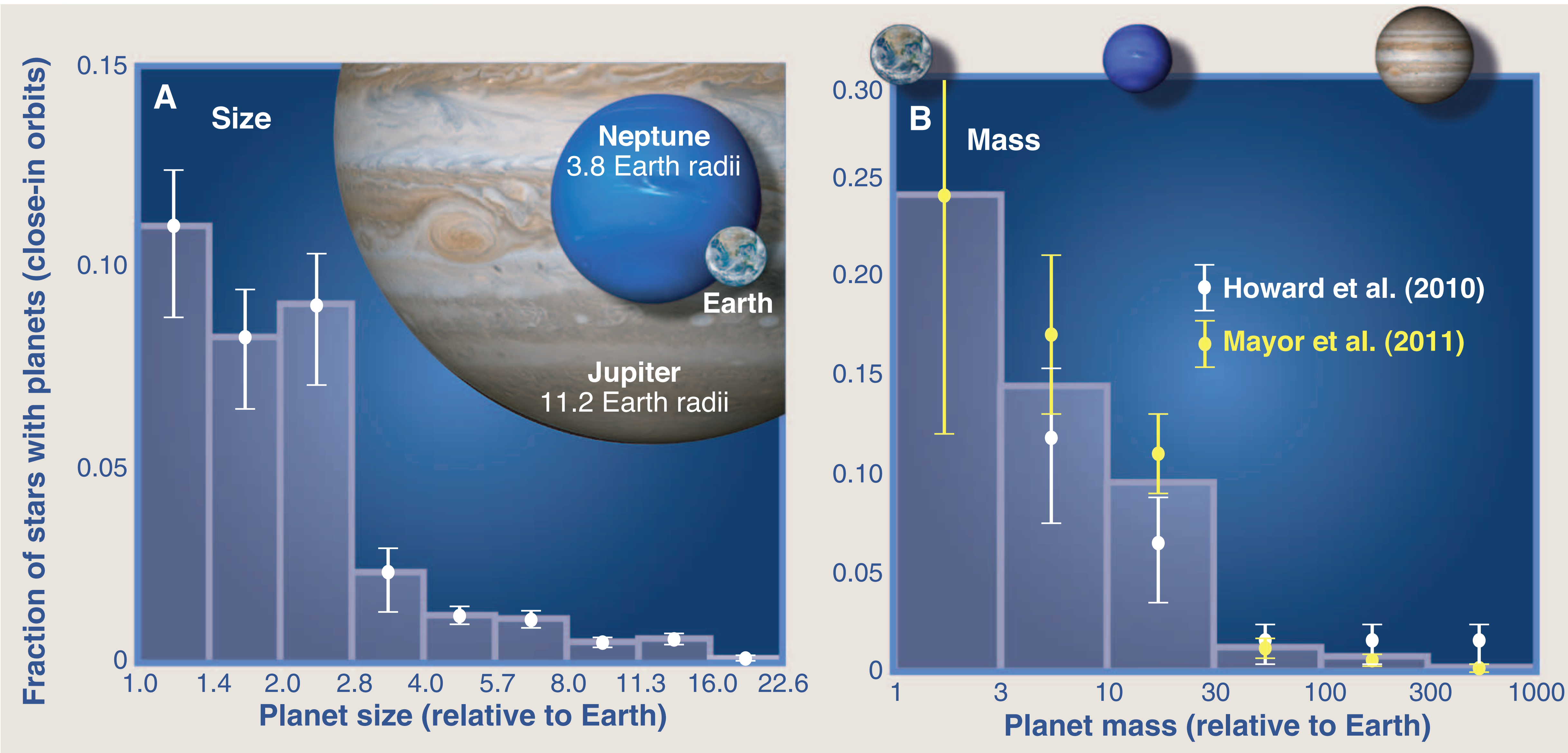
Statistics



Mass (M_{Earth})
10^4
10^3
10^2
10
1
Separation (AU)
10^{-2}
0.1
1
10
10^2
10^3
13 M_{Jup}
10
1
0.1
10^{-2}
10^{-3}
Mass (M_{Jup})
J
S
U
N
V
E
Direct Imaging
Radial Velocity
Transit
Microlensing
instruments not sensitive (yet)

Size/mass distribution

(only close-in orbits shown here, typically < 0.25 au)

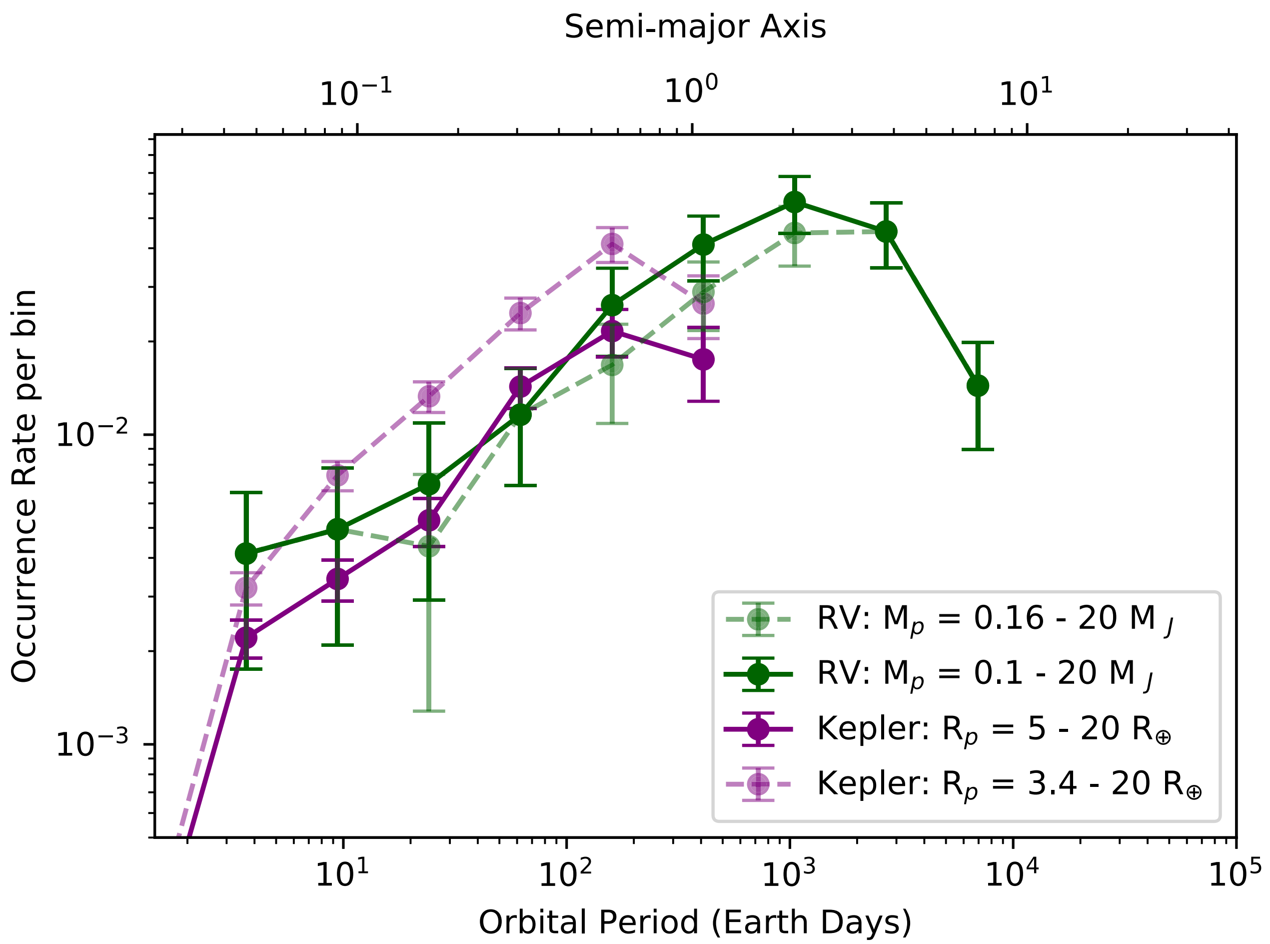


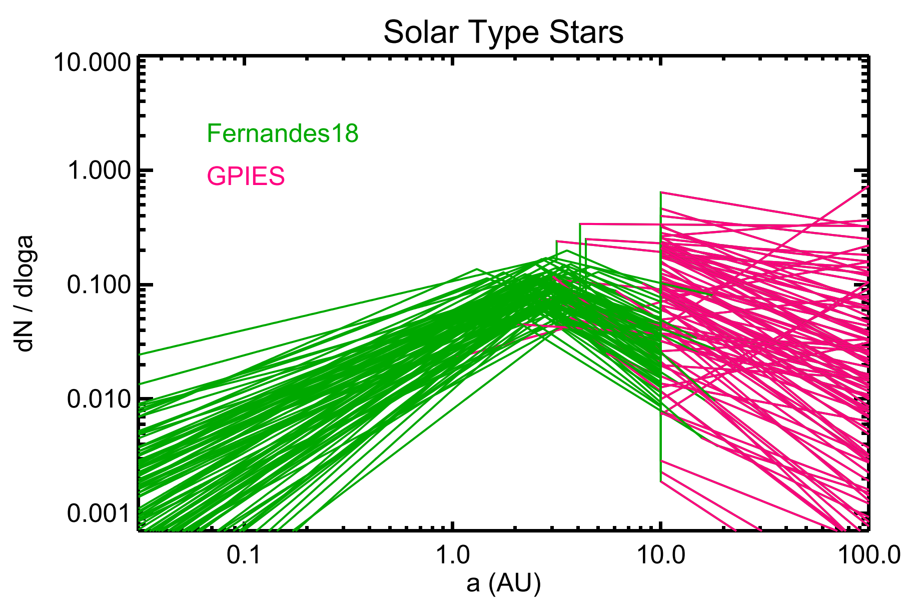
Frequency of planets decreases for increasing mass. Possible break at ~2R_{Earth}.

— Super-Earths are abundant in the galaxy! —

Period distribution

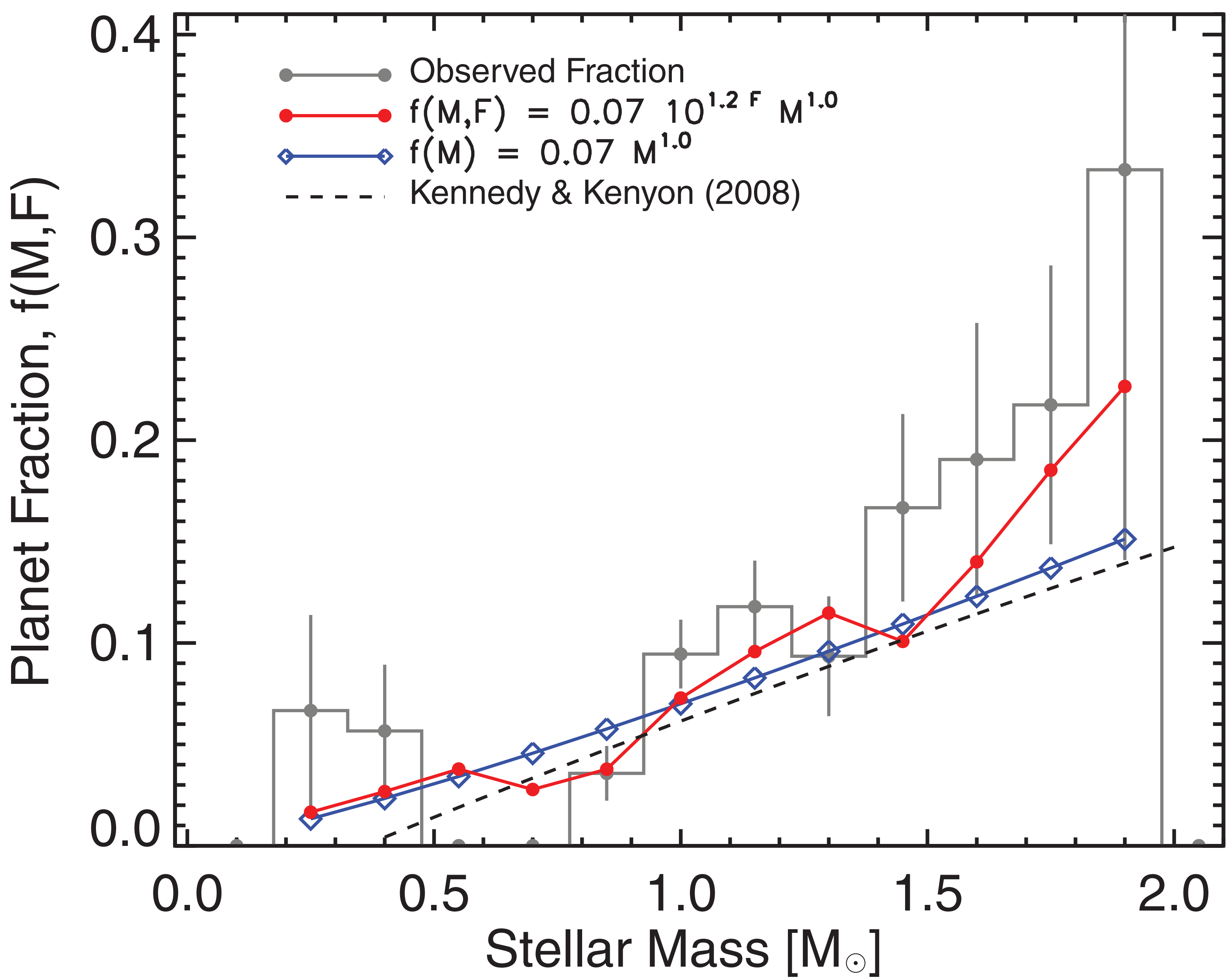
- Planet occurrence shown to increase with period
- Break in planet occurrence recently found (~2-3 au) thanks to long-period RV surveys
    - confirmed by direct imaging surveys
- Compatible with core-accretion scenarios
    - peak planet formation rate around snow lines



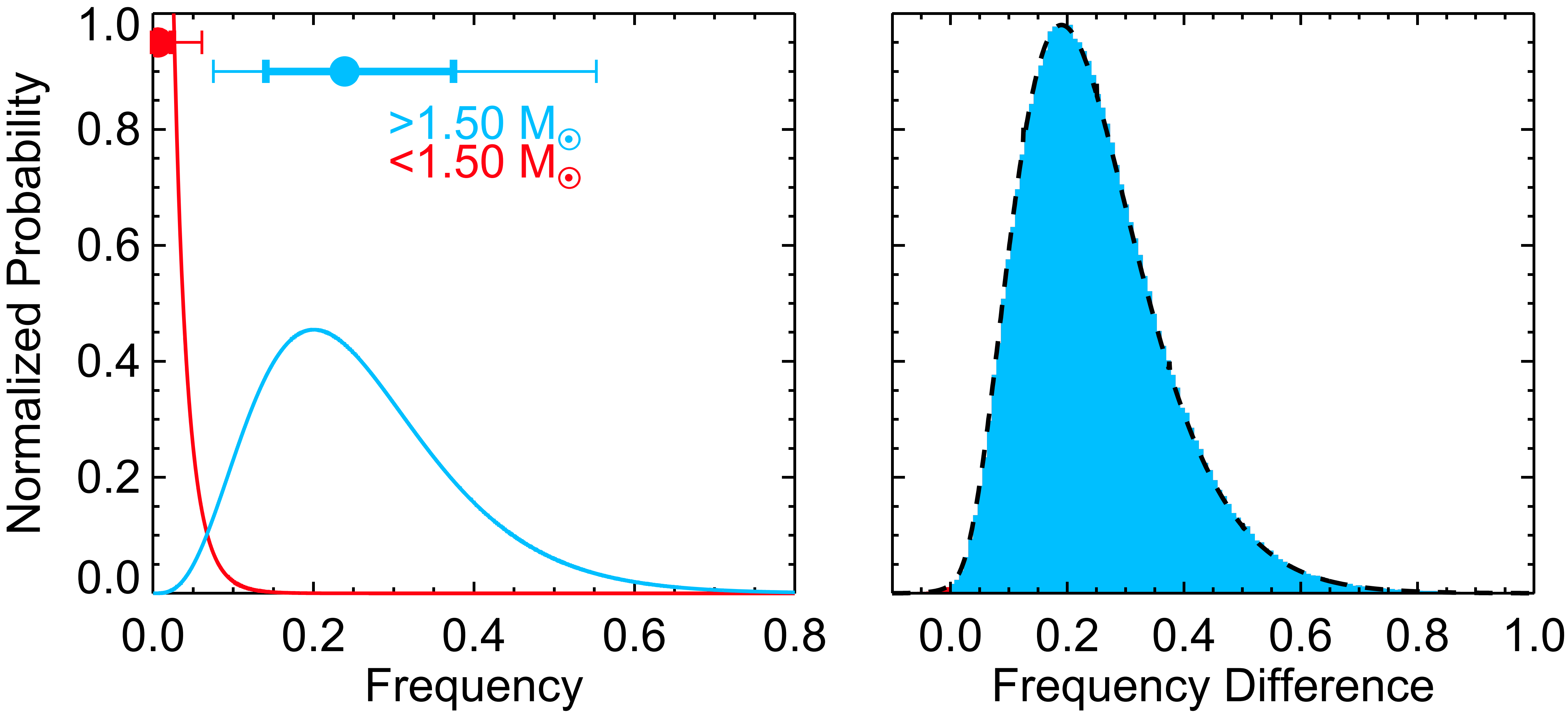


Effect of stellar mass (1/2)

Giant planets more abundant around massive stars



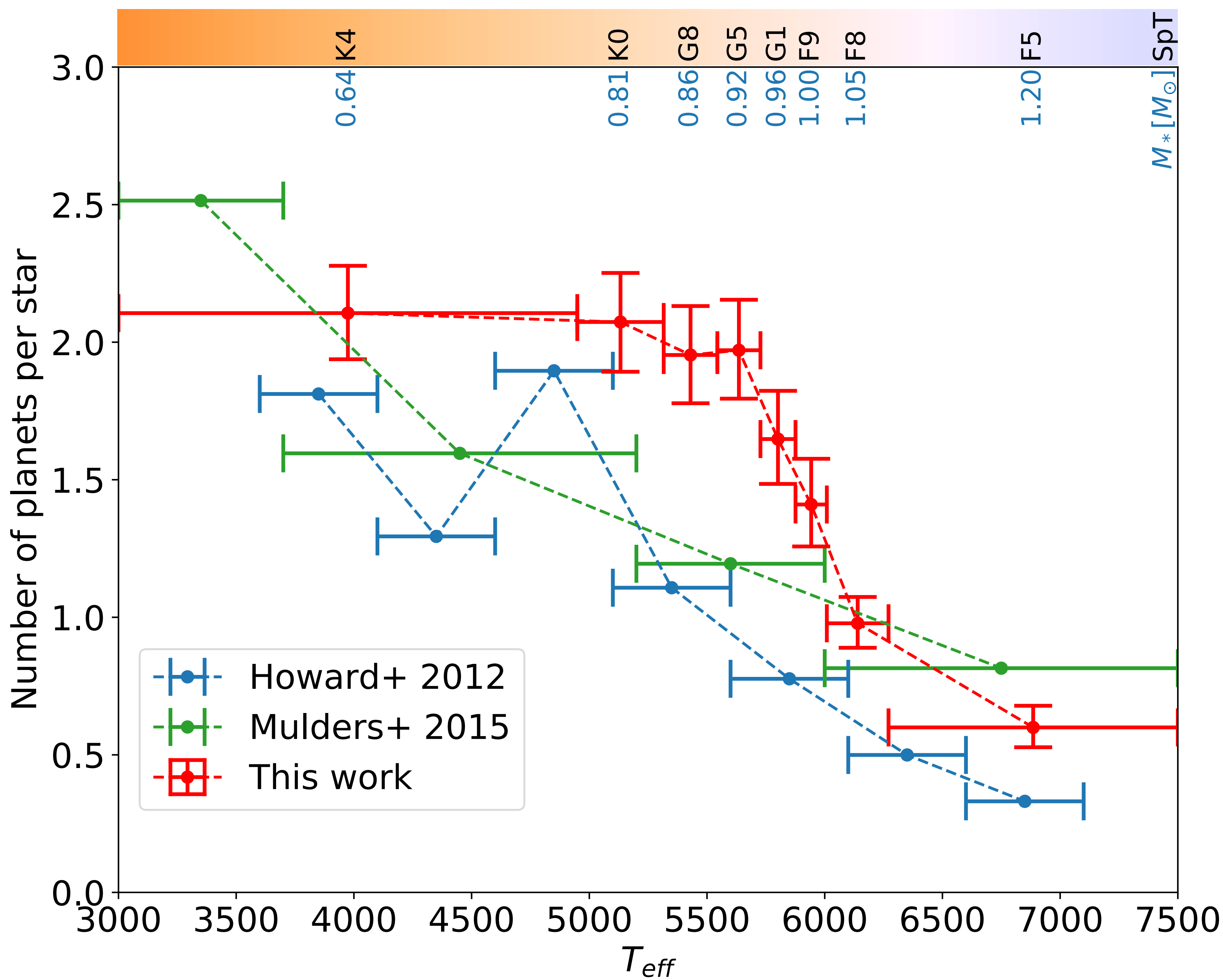
Effect also seen in direct imaging surveys



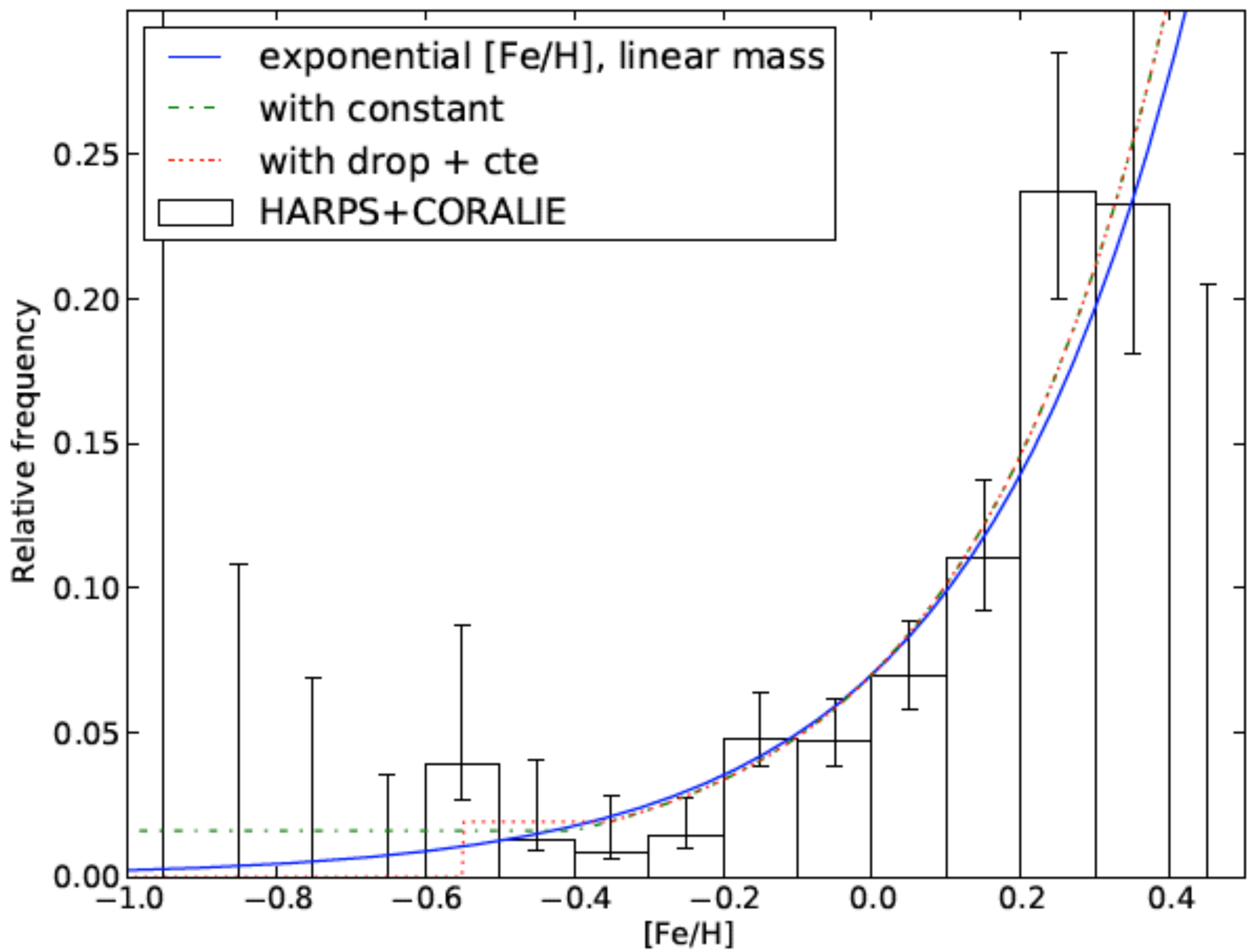
Most directly imaged planets around intermediate mass stars so far

Effect of stellar mass (2/2)

Small planets more abundant around low-mass stars

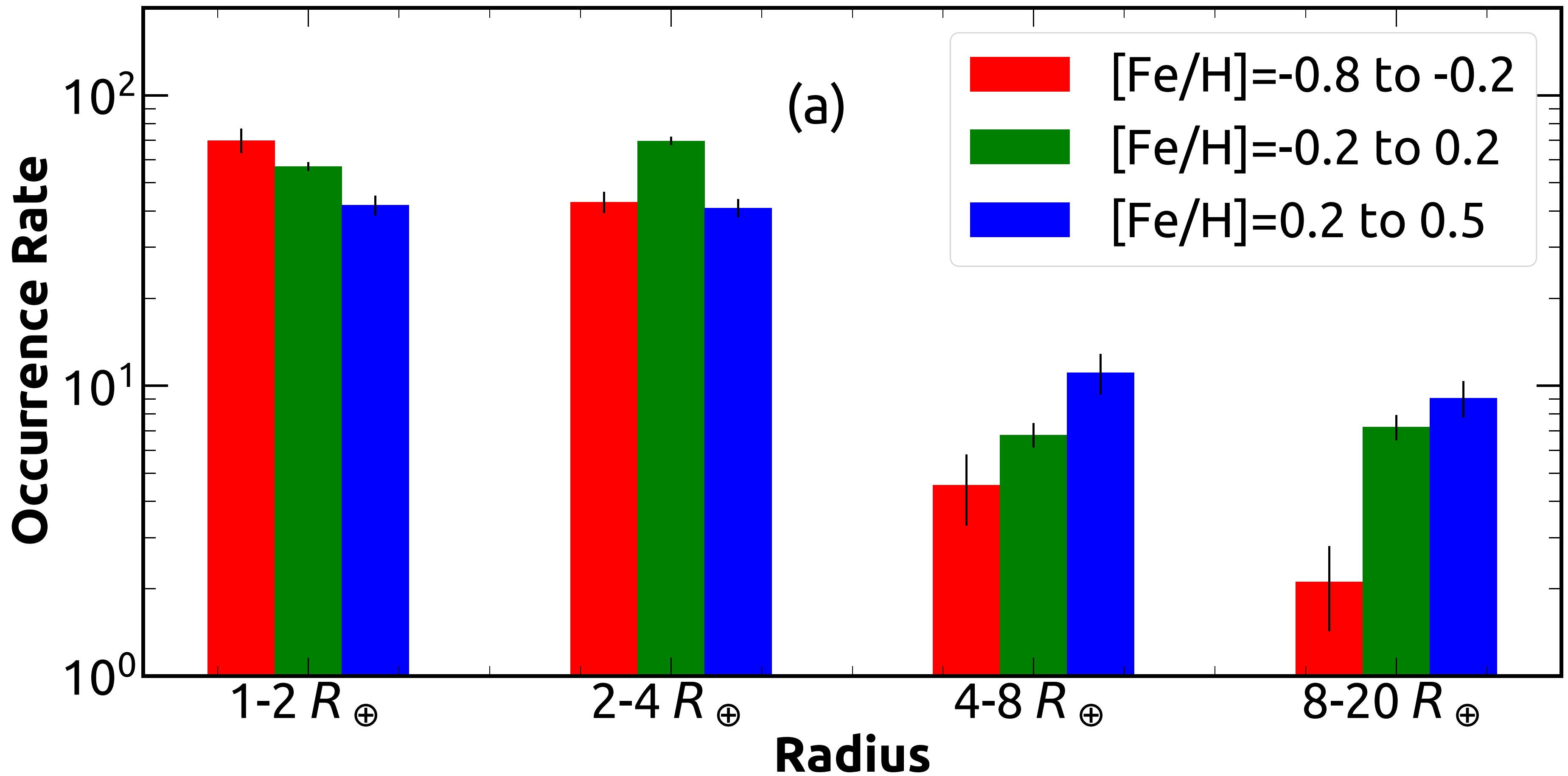


Effect of stellar metallicity



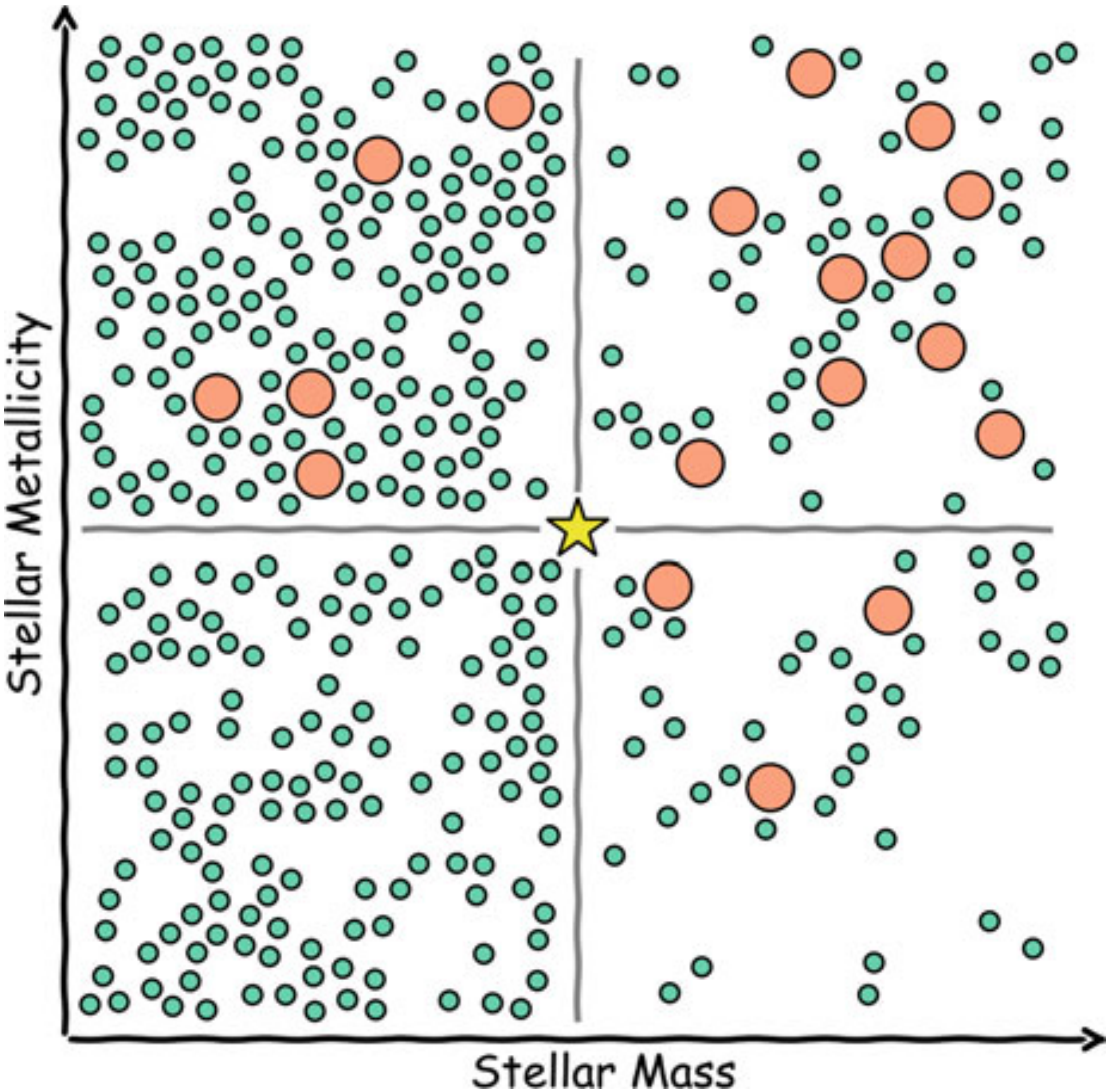
The frequency of exoplanets increases with stellar metallicity
(as expected from core-accretion)

Closer look at metallicity

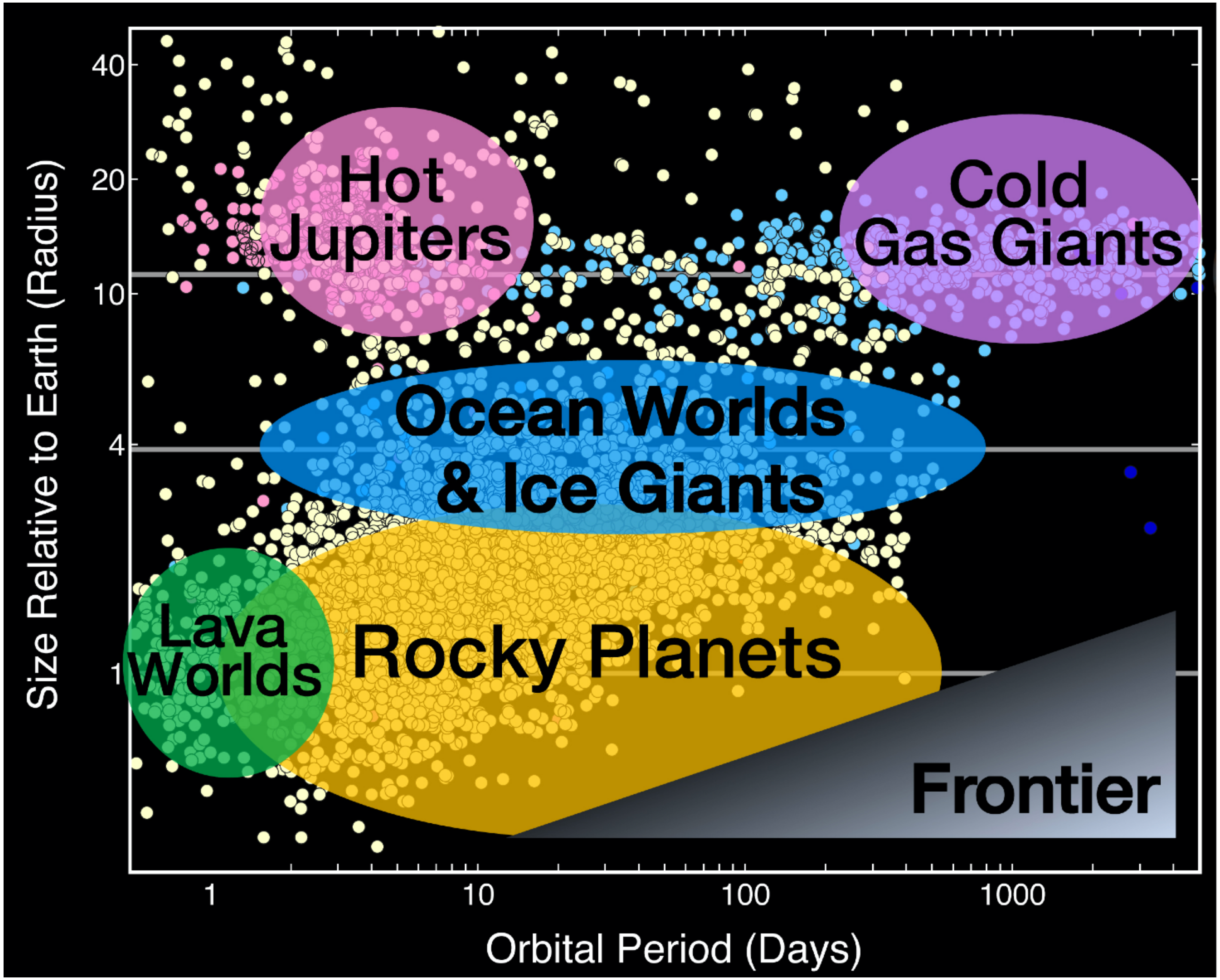


Metallicity matters only above Neptune size — not really for small planets

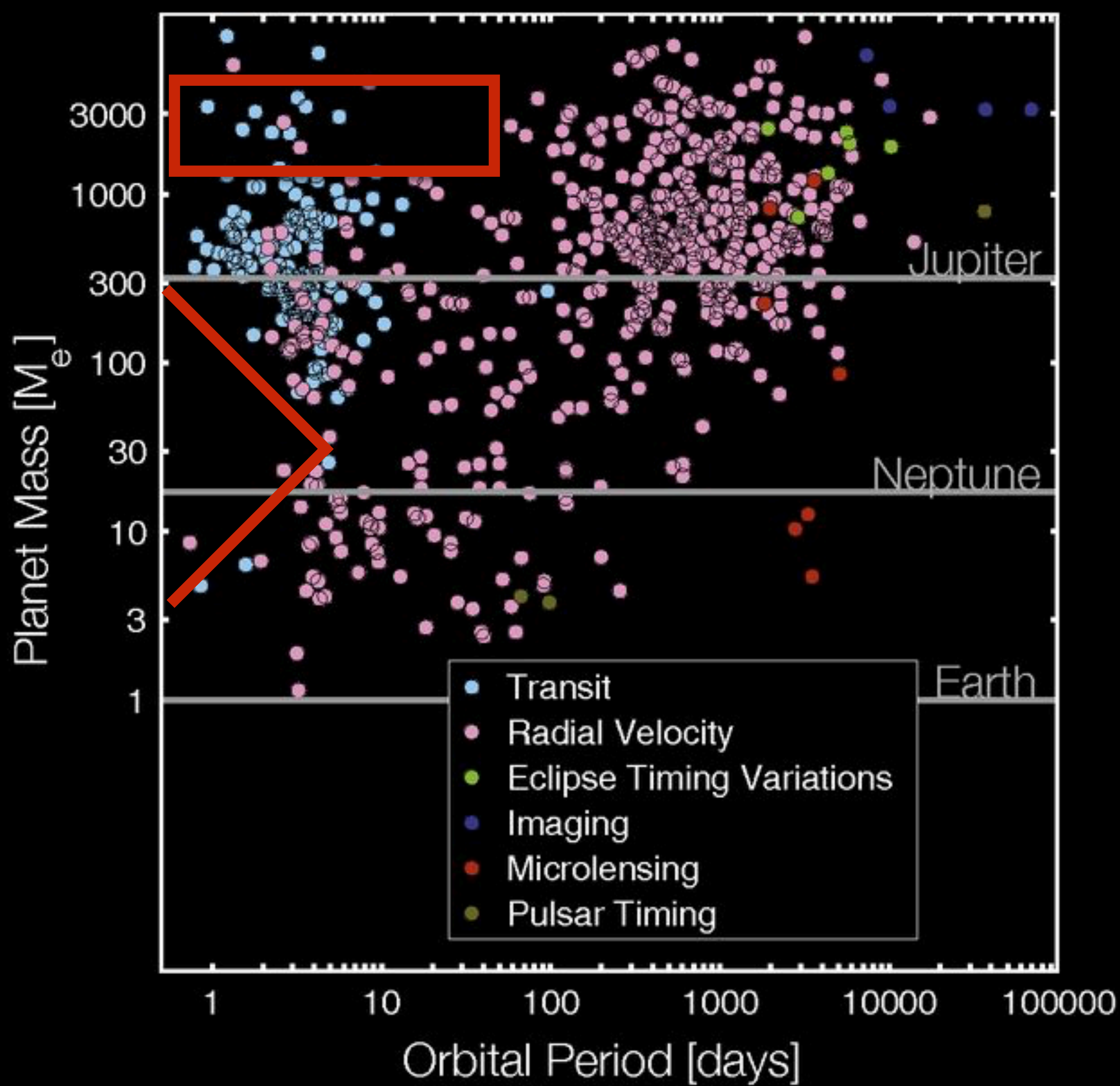
Effect of star: summary

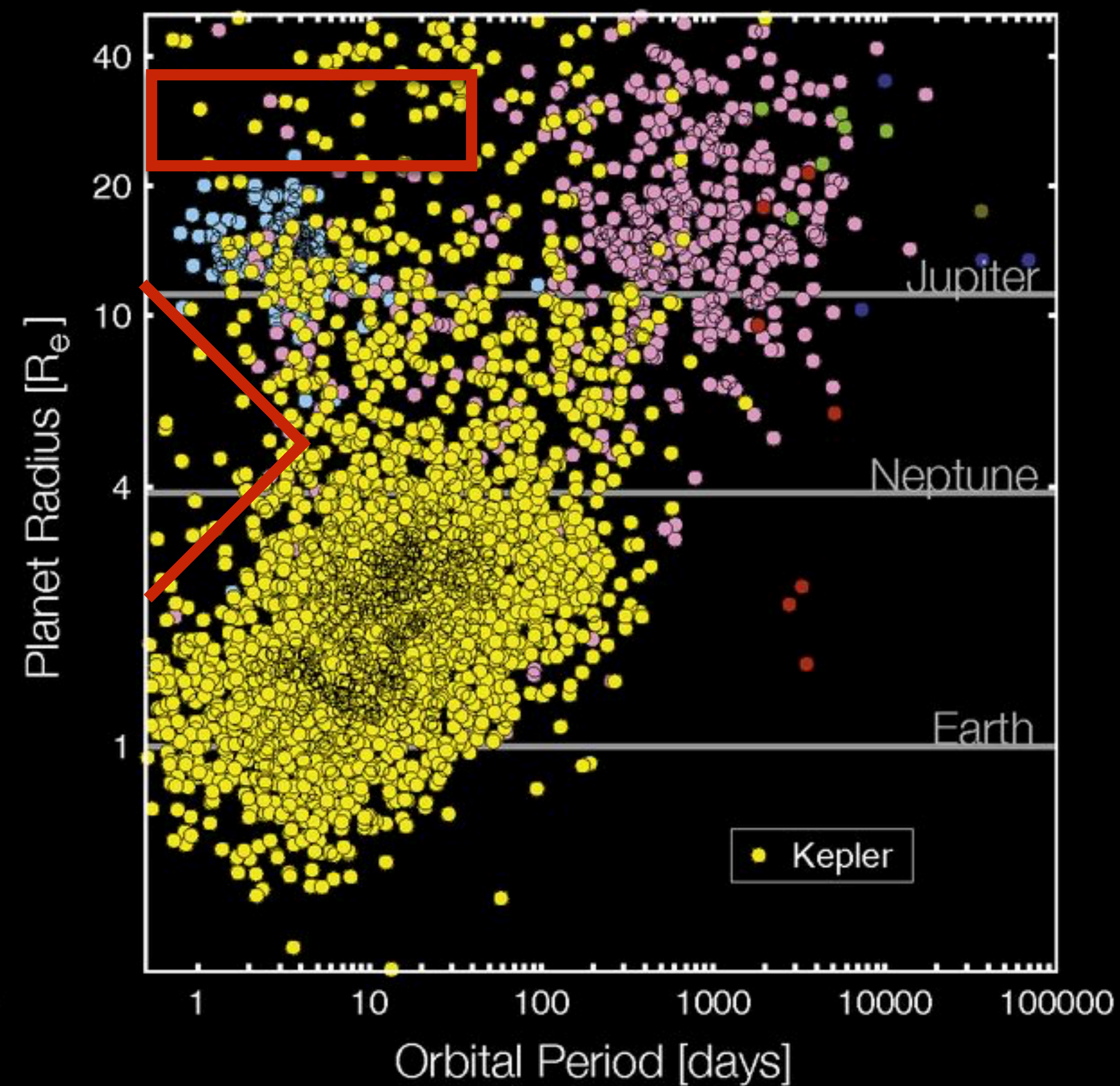


More detailed trends



Structures in M-P space

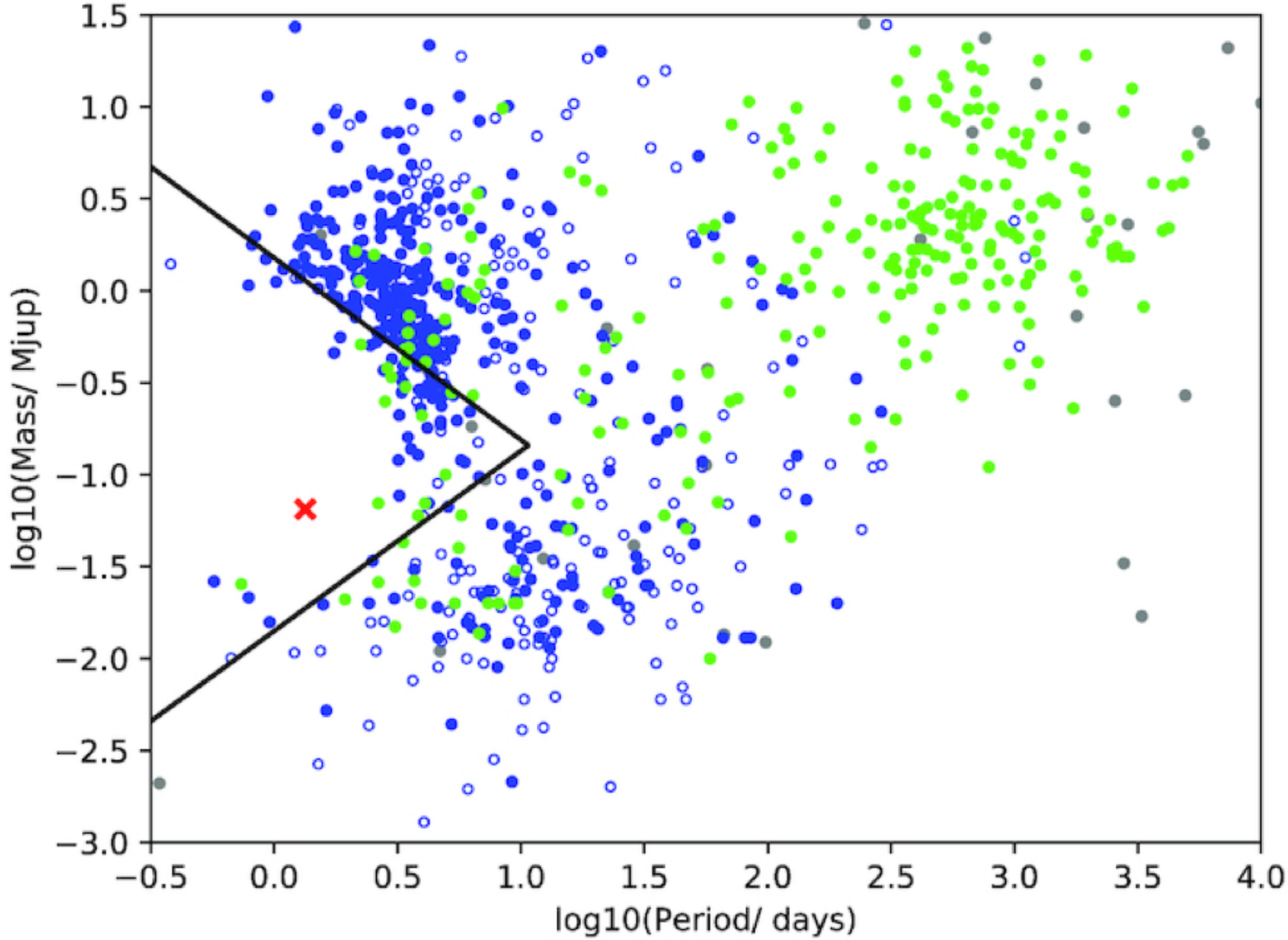




Neptunian desert

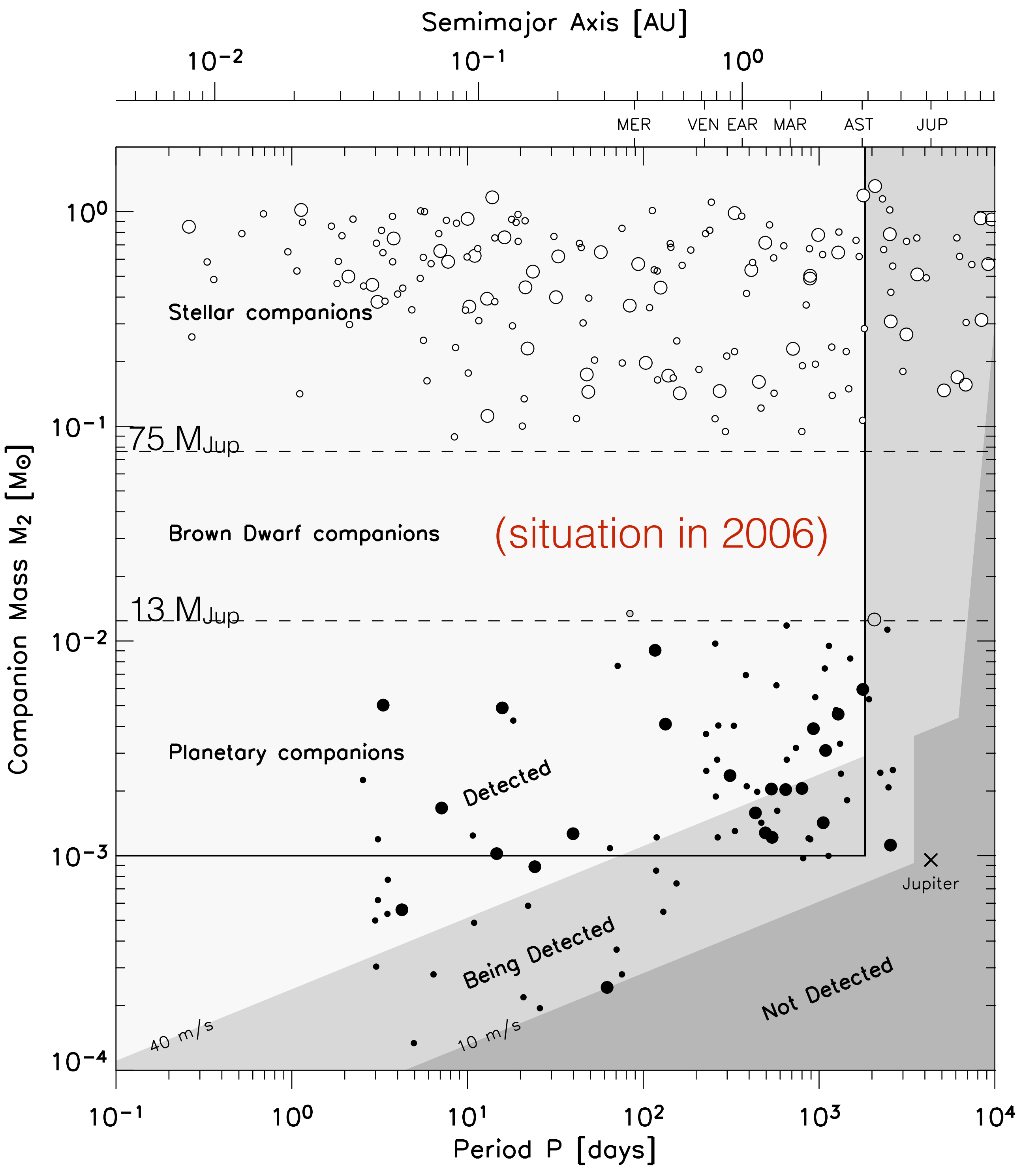
This area receives strong irradiation from the star, so that planets may lose their gaseous atmosphere as they evaporate, leaving just a rocky core.

Desert may also be (partly?) due to a different formation mechanism for short-period super-Earths and giant exoplanets.



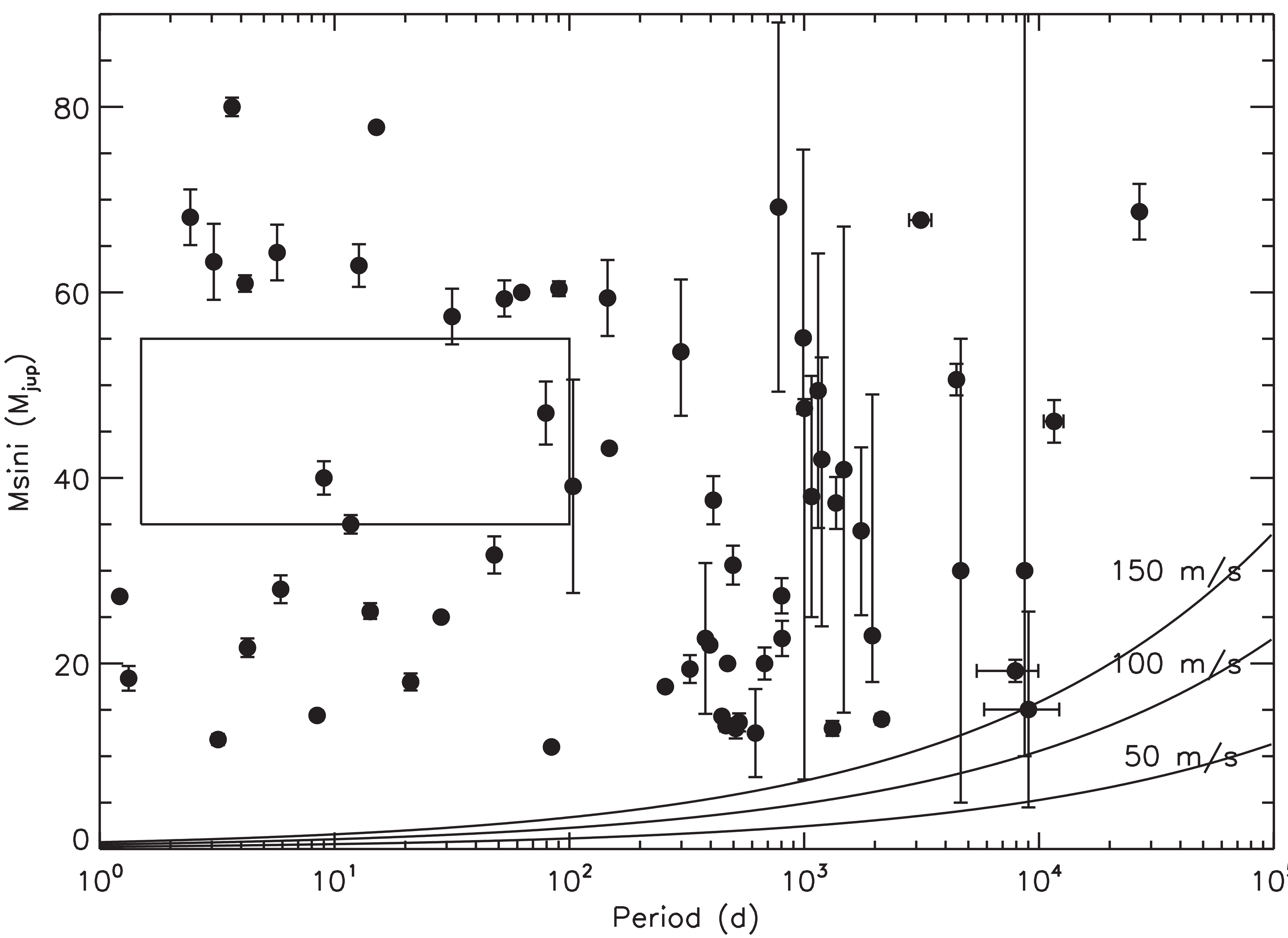
Brown dwarf desert

- Paucity of BD in close orbit identified in the early 2000s
  - driest part observed for masses 35 ≲ Msin i ≲ 55 M_J and orbital periods < 100 days
  - desert now partly filled with new discoveries, but trend remains
- Probably related to different formation mechanisms (and/ or migration mechanisms) between planets and BDs

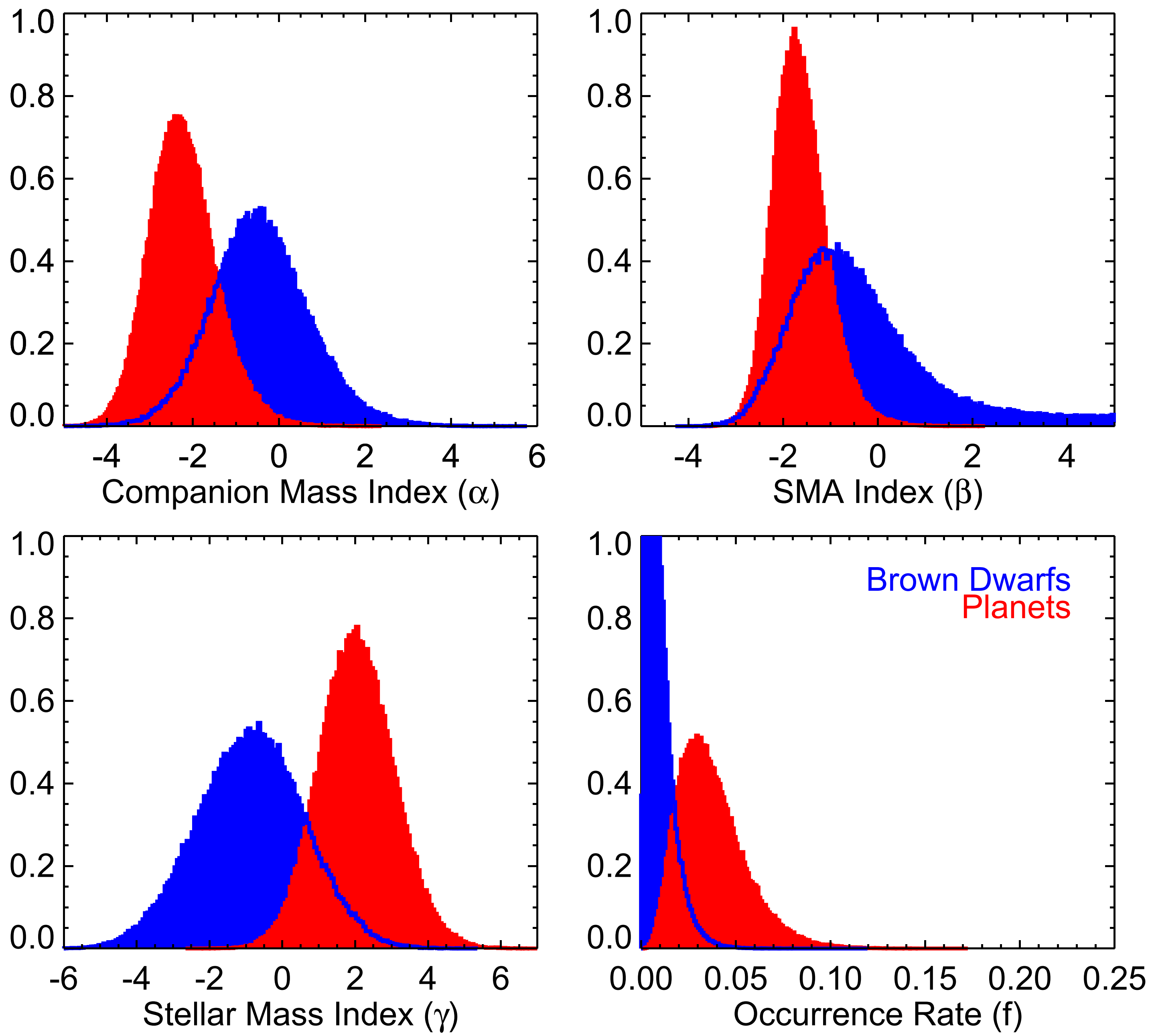


BD desert in 2014

The desert is slowly filling up…

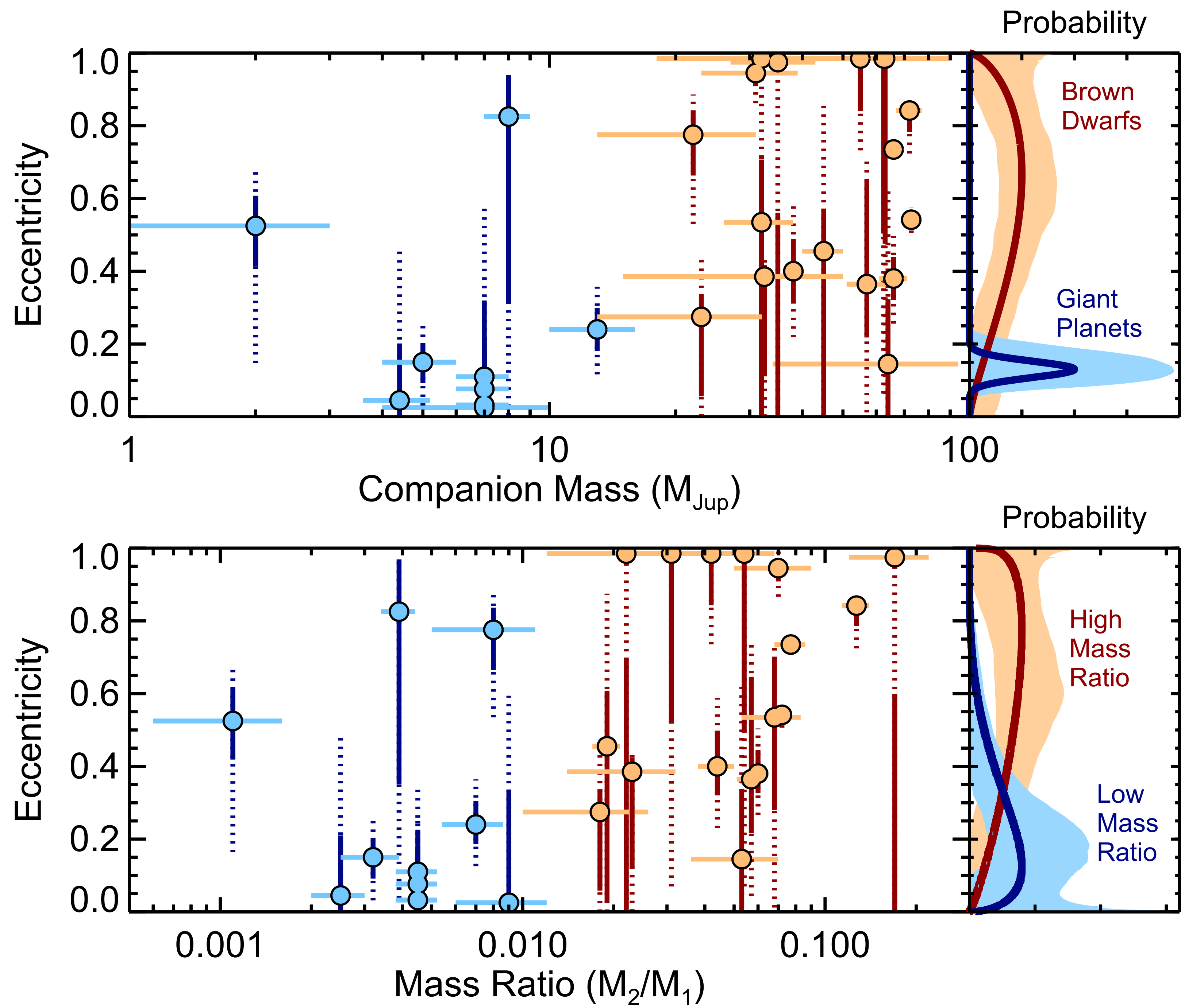


BDs and planets also look different in direct imaging surveys



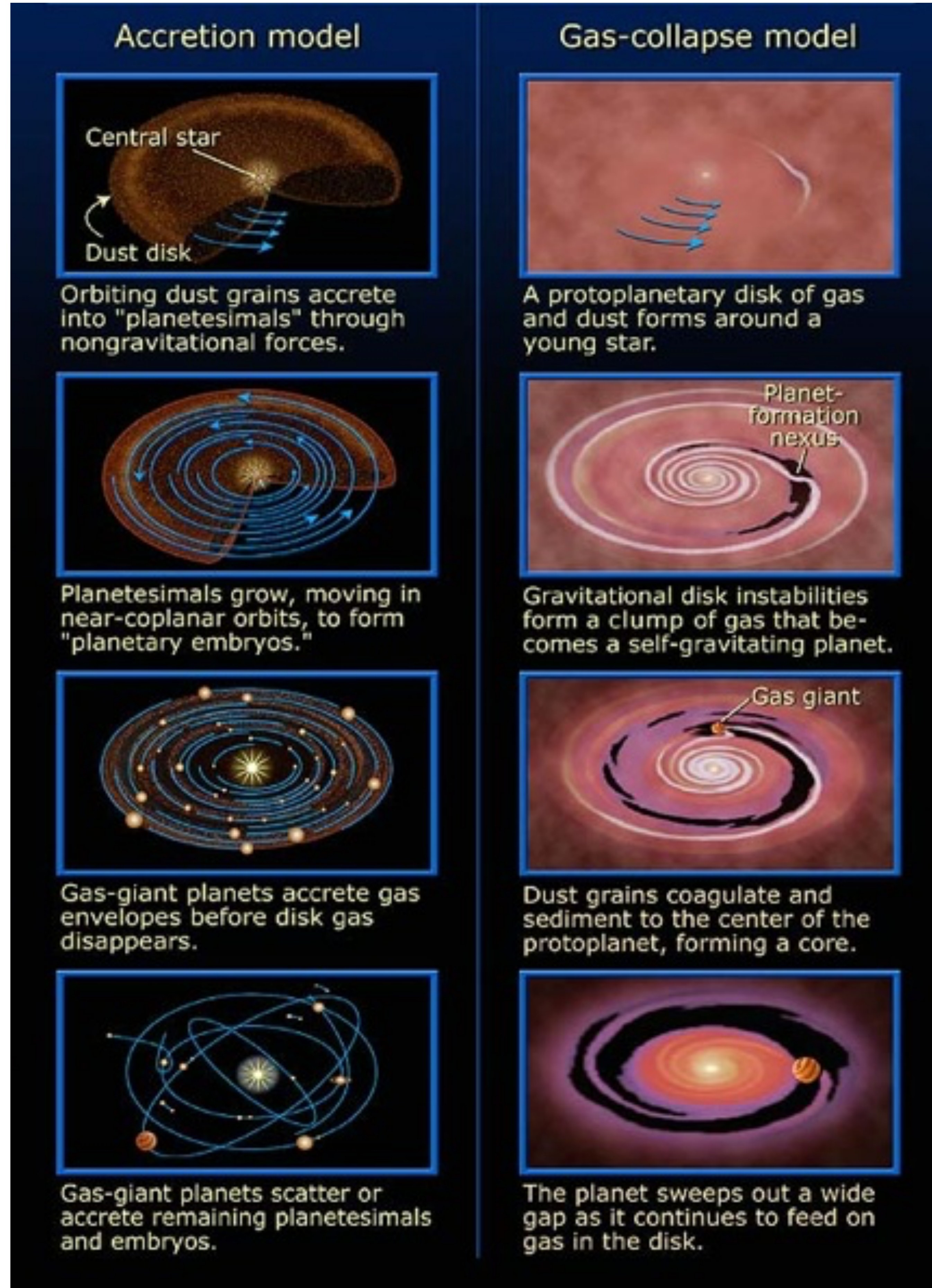
Brown dwarfs vs planets: an intrinsic difference?

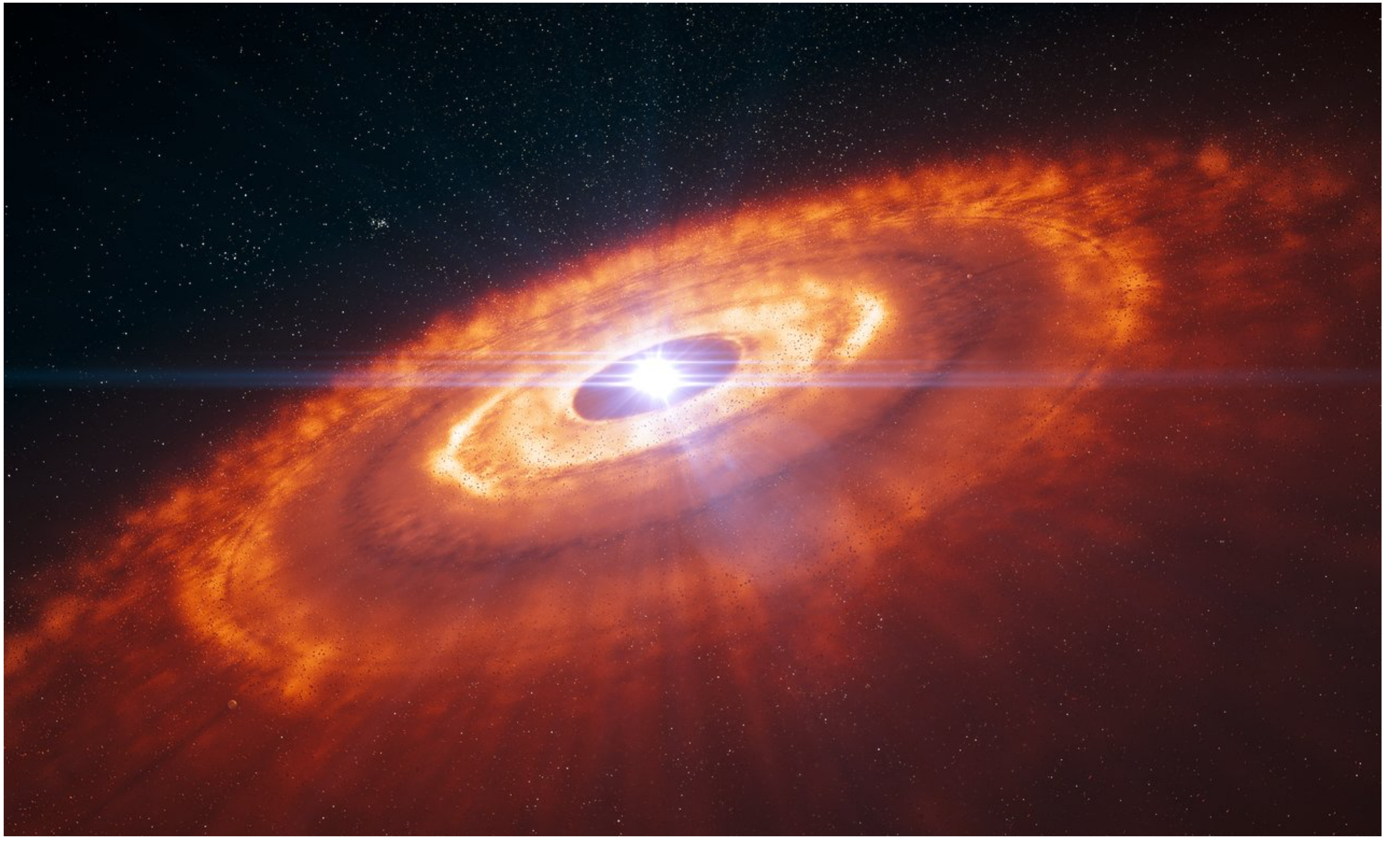
- Eccentricity distribution of directly imaged planets is skewed to low values compared to brown dwarfs
- May be directly linked to formation scenario



Core accretion vs gravitational instability

- Gravitation instability can explain more massive planets further away, but requires massive disk
- Dynamical evolution makes it hard to distinguish between the two scenarios
- Studying very young systems is key!





II. Protoplanetary disks

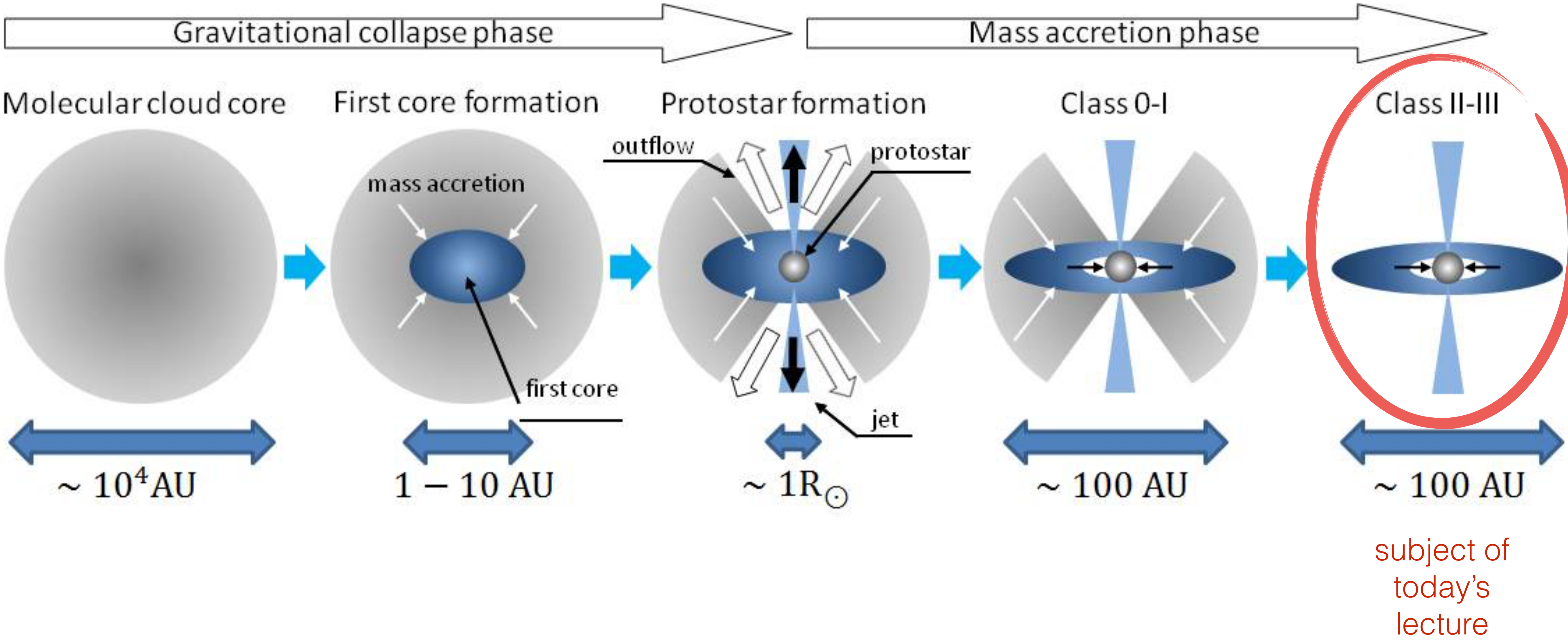
— an observational perspective —

II. Protoplanetary disks

II.1 Theoretical picture

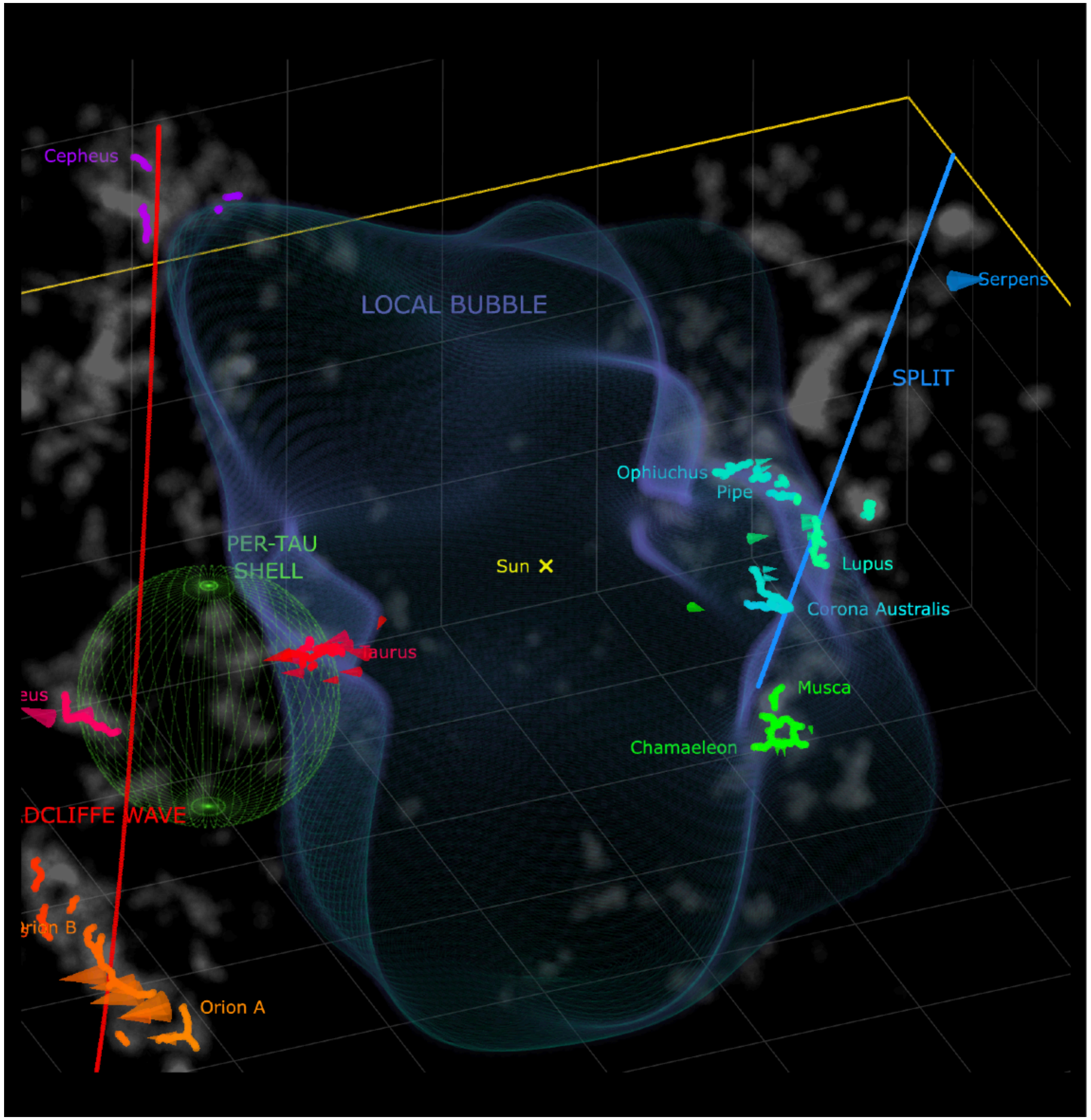
Protoplanetary disks

Disks are the consequence of angular momentum conservation



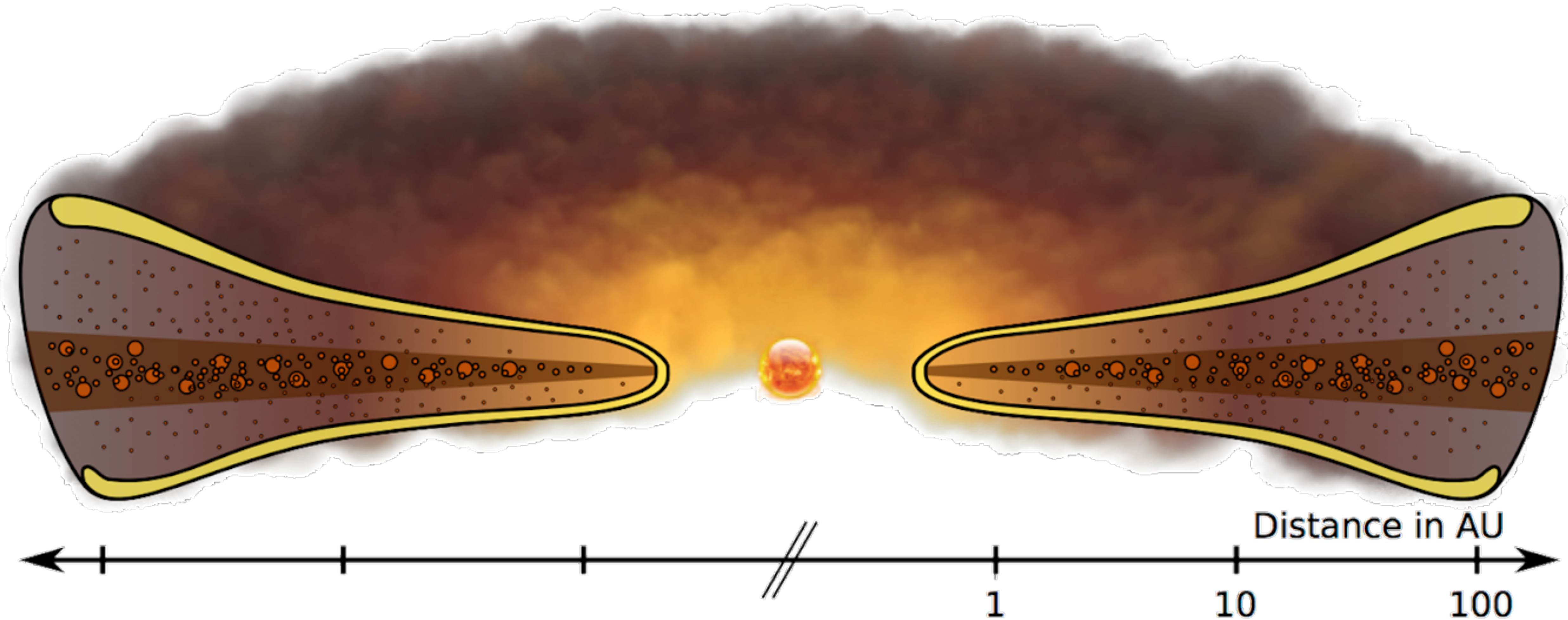
Star-forming regions

- By ‘chance’, our Sun is currently in the middle of the Local Bubble
- Nearest star forming regions at ~140 pc (Taurus)
- Need to go to Orion nebula (400 pc) to see massive star formation in action



Standard theoretical picture

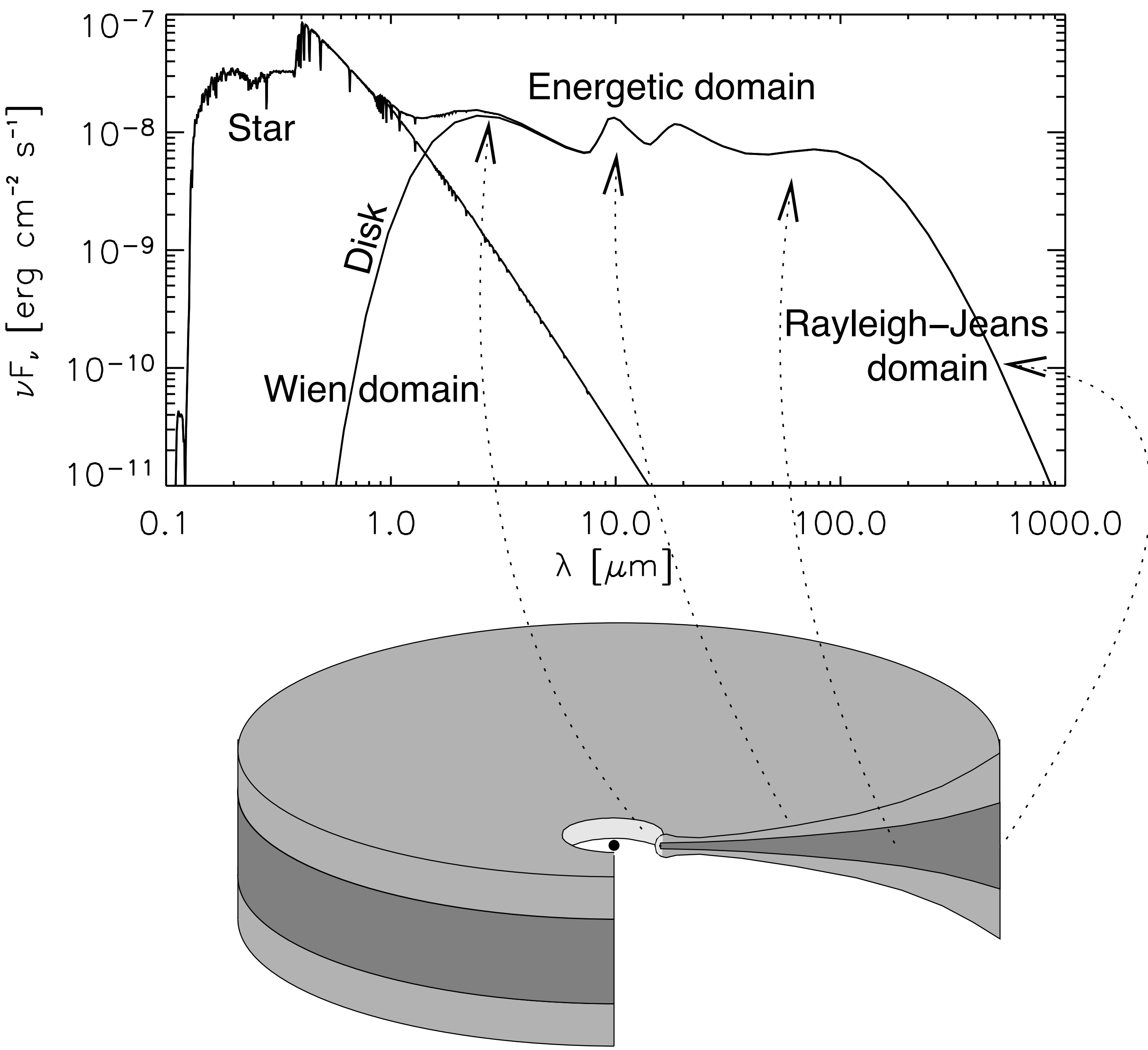
- Small grains coupled to gas —> gentle collisions
- Grain growth —> settling to mid-plane
- Decoupling from gas —> migration



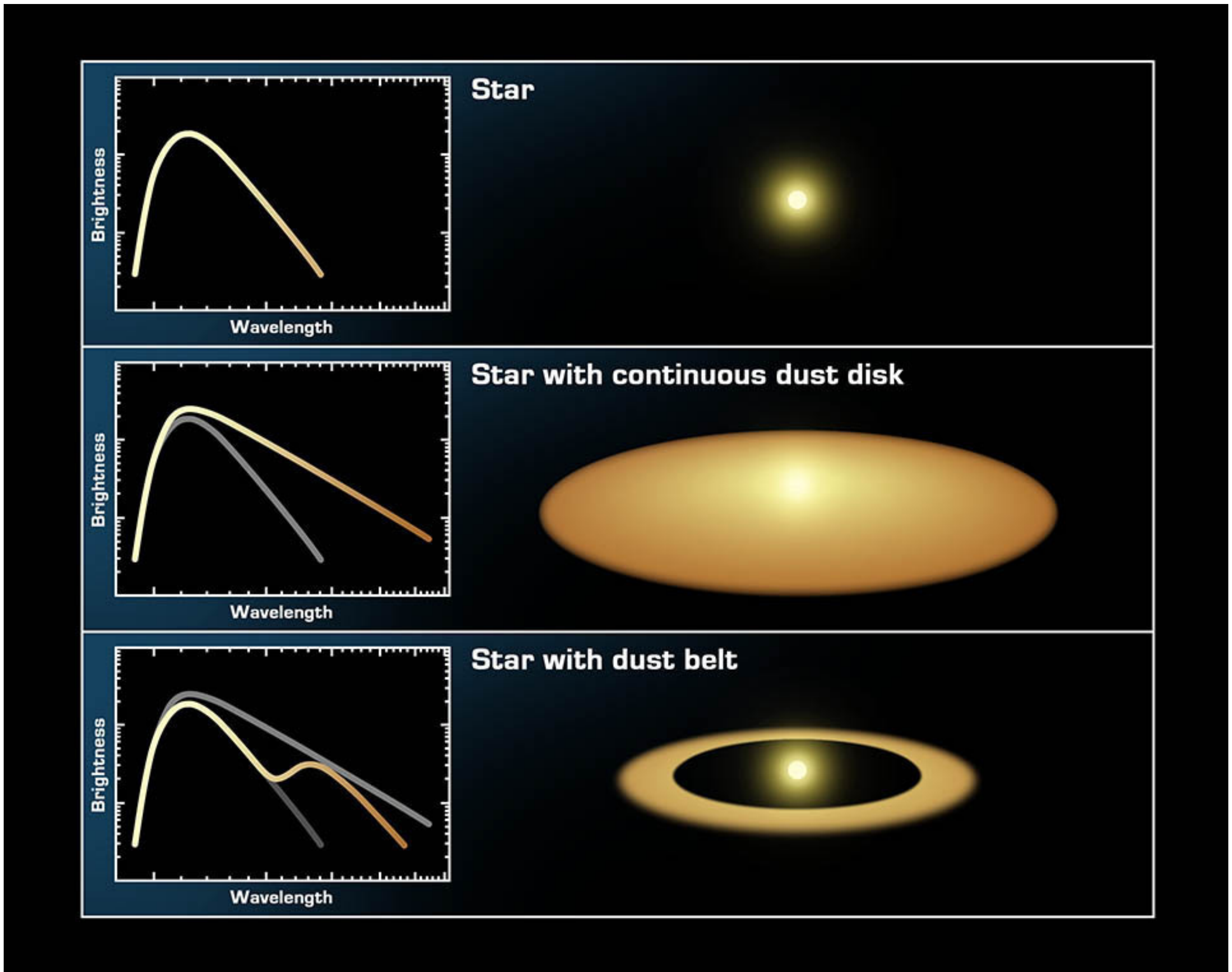
Key structure properties

- Protoplanetary disks mainly characterized by:
  - mass, radius, density, temperature
  - radial and vertical structure (flaring)
  - dynamics: transport mechanisms, magnetic fields, winds, etc
- Properties probed in a variety of ways
  - photometry (spectral energy distribution, sub-mm luminosity)
  - spectroscopy: dynamics through gas lines
  - imaging: size, morphology & structures
- These properties depend on host star, environment, evolution

Spectral energy distribution



SEDs: first hint on structure

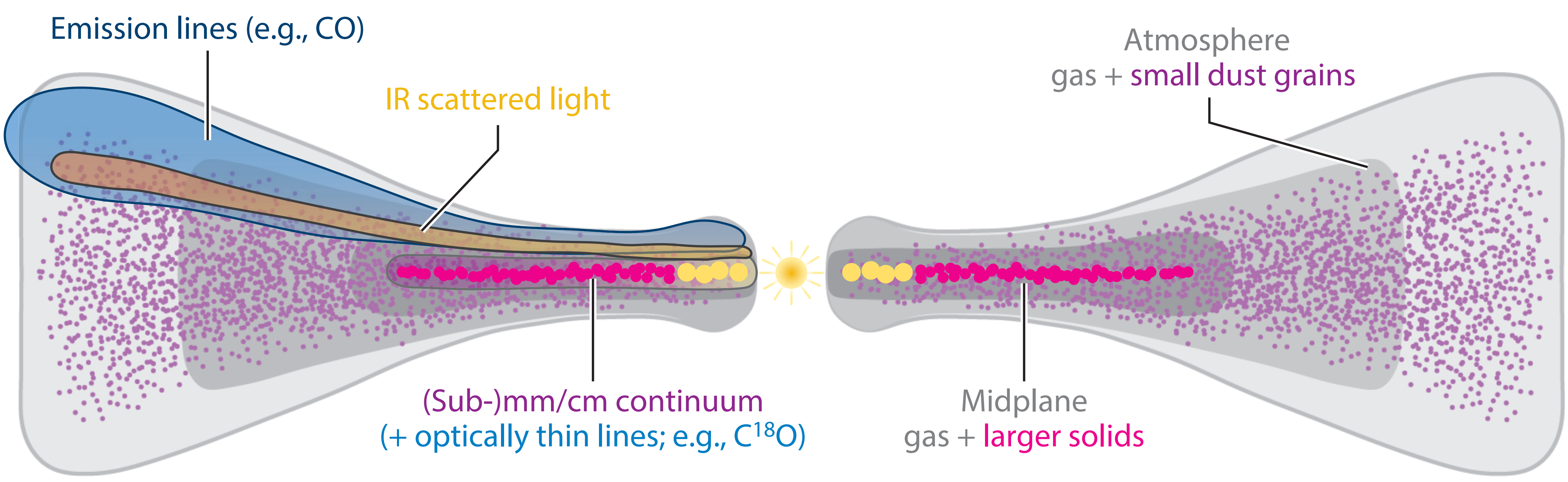


II. Protoplanetary disks

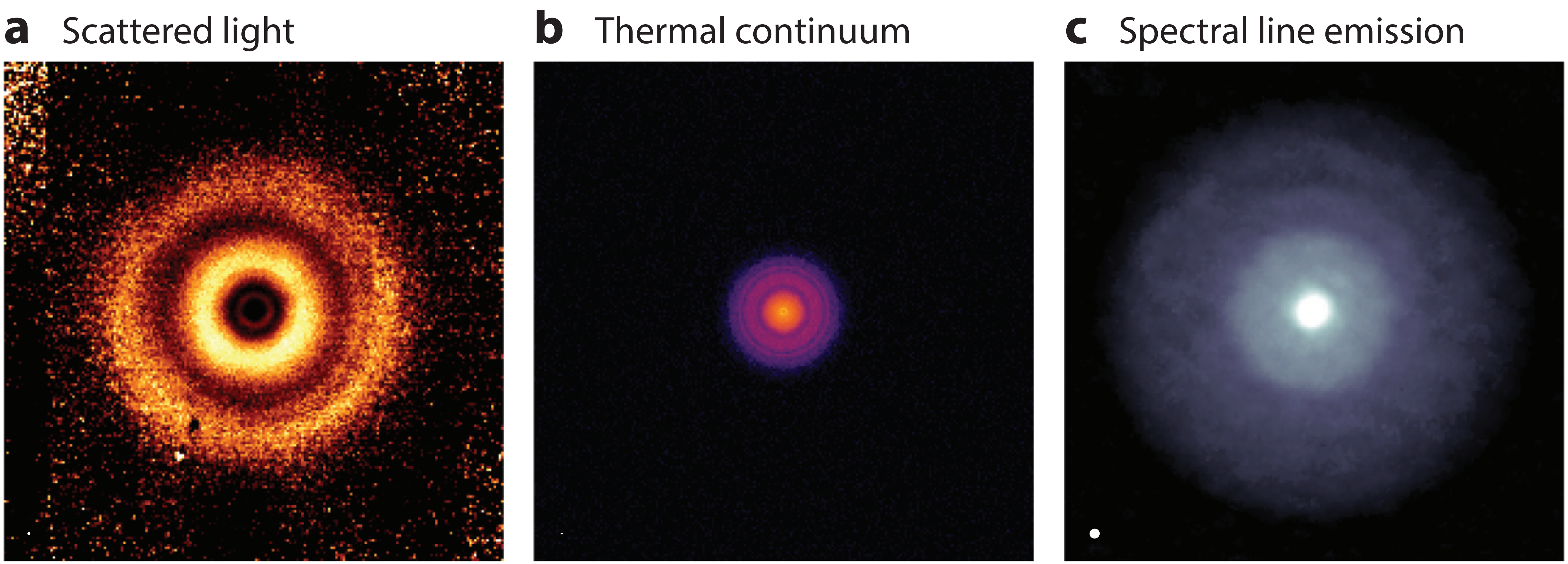
II.2 Imaging techniques

Three main tracers to study disk structures

- Scattered light: dust suspended in gas upper layers
- Thermal emission: disk solids
- Line emission: gas



Morphology depends on chosen tracer



The TW Hya disk seen with different tracers

Continuum emission

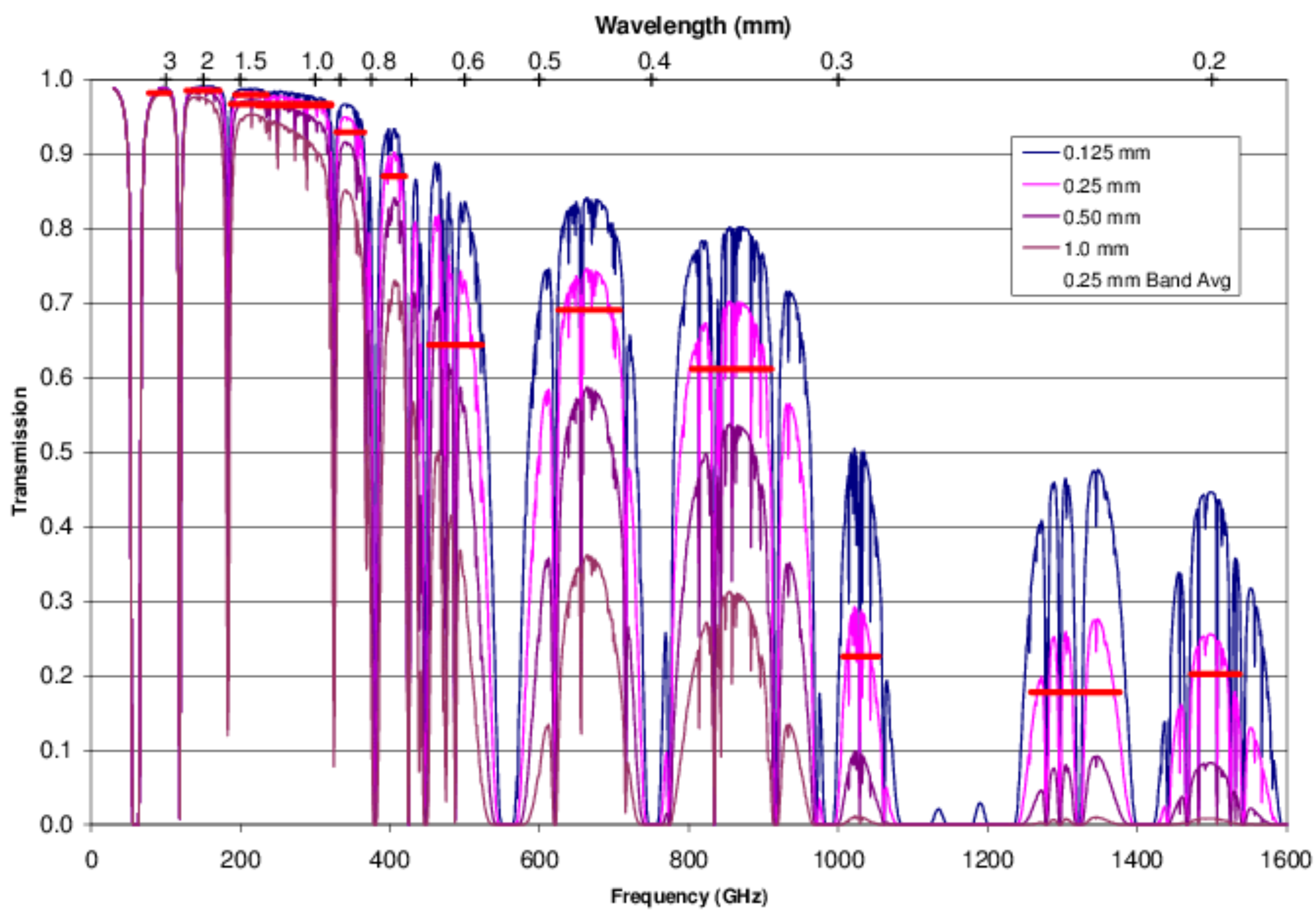
- Optical depth decreases with λ, providing direct view of disk mid-plane in the sub-mm
  - sub-mm range is also required to address thermal emission at low temperatures, far away from the star
- Particle size probed in thermal emission mostly ~ λ
  - smaller particles do not emit efficiently
  - larger particles give less emission per mass, although all sizes contribute (—> ambiguity)
- Sub-mm appropriate to study grain growth

Continuum observations

- Single-dish observations strongly limited in angular resolution
  - Largest antenna (JCMT): 15 m —> resolution > 5 arcsec at 450 μm
  - Disks are typically < 1 arcsec (100 au @ 100 pc)
- Interferometry: angular resolution limited by antenna separation
  - ALMA: 64 antennas, baselines up to 16 km —> resolution ~ 20 mas!
  - Electric field recorded through local oscillators in each antenna
  - Interferometric signal produced offline by correlation
  - Images reconstructed with specific algorithms

Continuum observations

- Sub-mm observations require extremely dry sites



ALMA

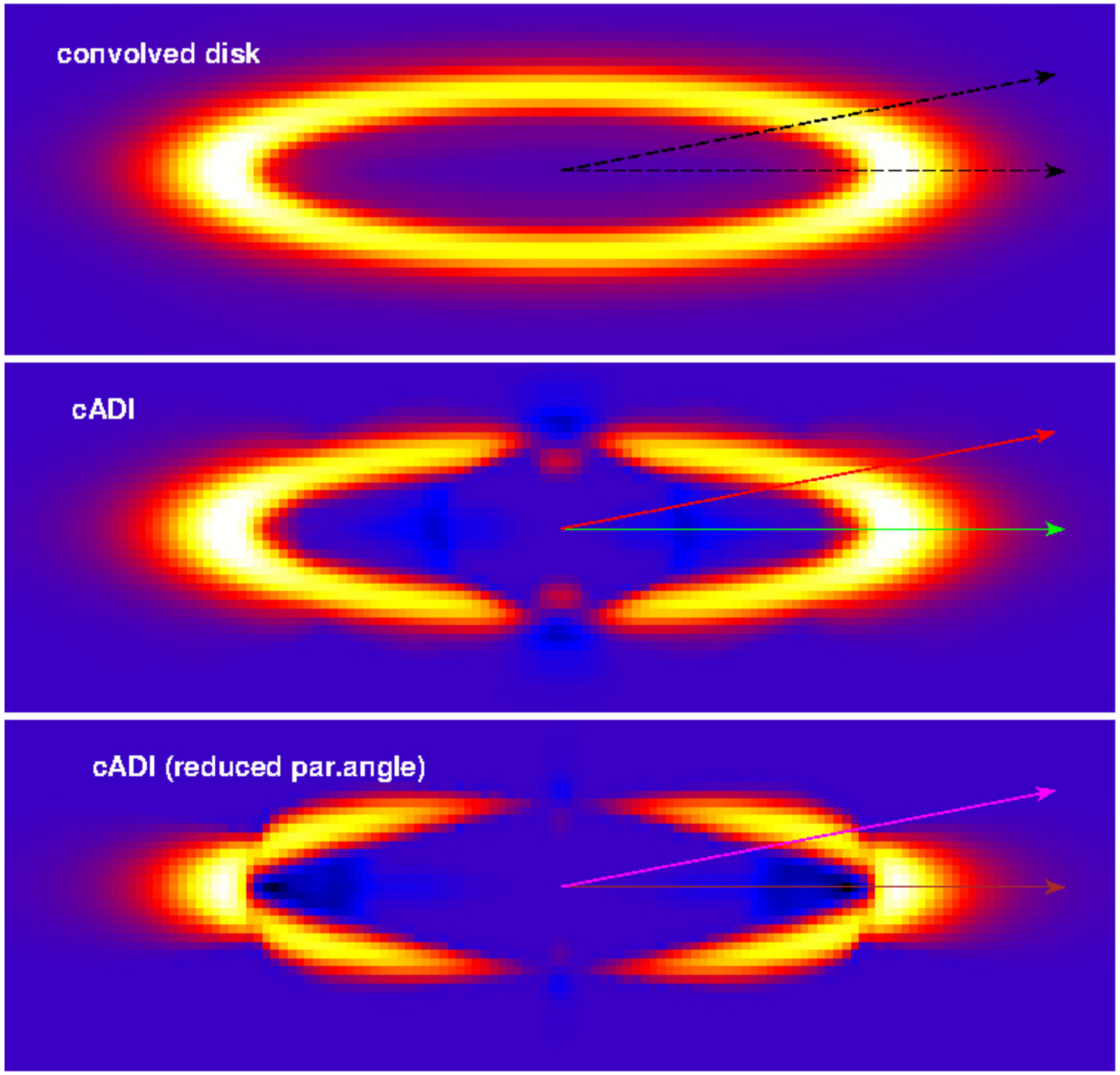
Scattered light

- Starlight reflected from disk surfaces is typically faint, gray or red, and forward scattered
    - those properties indicate dust aggregates with a_{max} ~ 10 μm in disk atmospheres, representing the early steps in the growth sequence or possibly tracing collision fragments mixed up from the midplane
    - settling induces a vertical stratification of particle sizes, which makes the height of the scattering surface decrease with λ
- Scattered light is partly polarized, depending on the size, shape, and composition of grains

Scattered light observations

- Required high-contrast imaging techniques

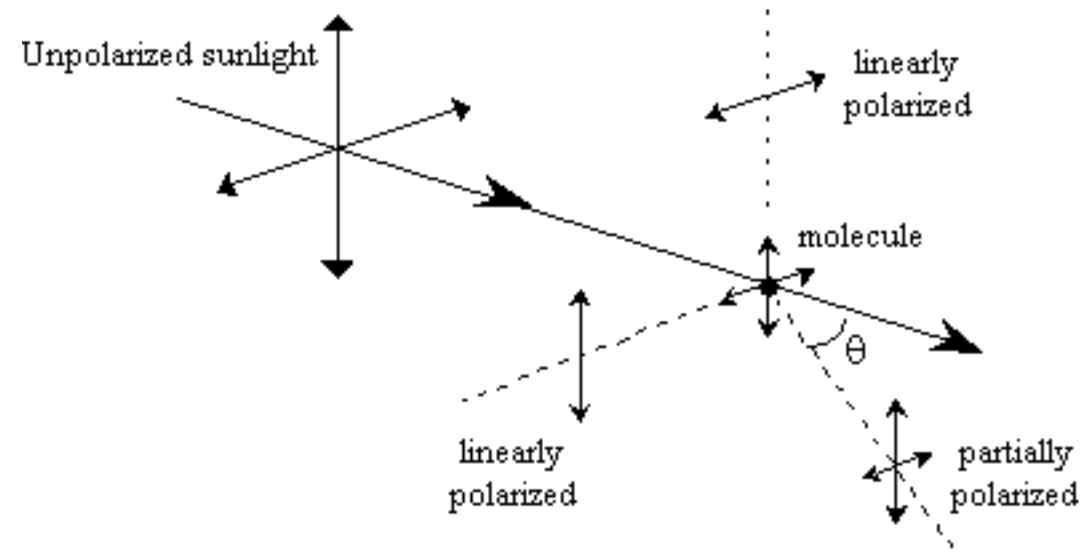
- Imaging disks with ADI is complicated
  - extended source can be confused with stellar halo
  - standard ADI processing techniques not designed to preserve the morphology of disks

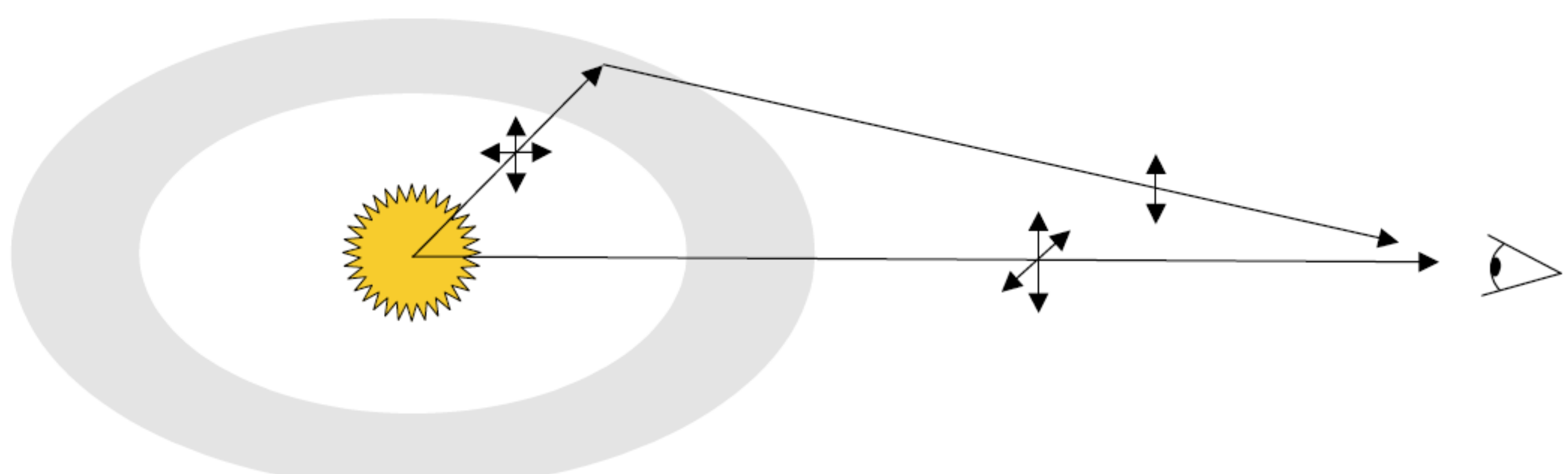


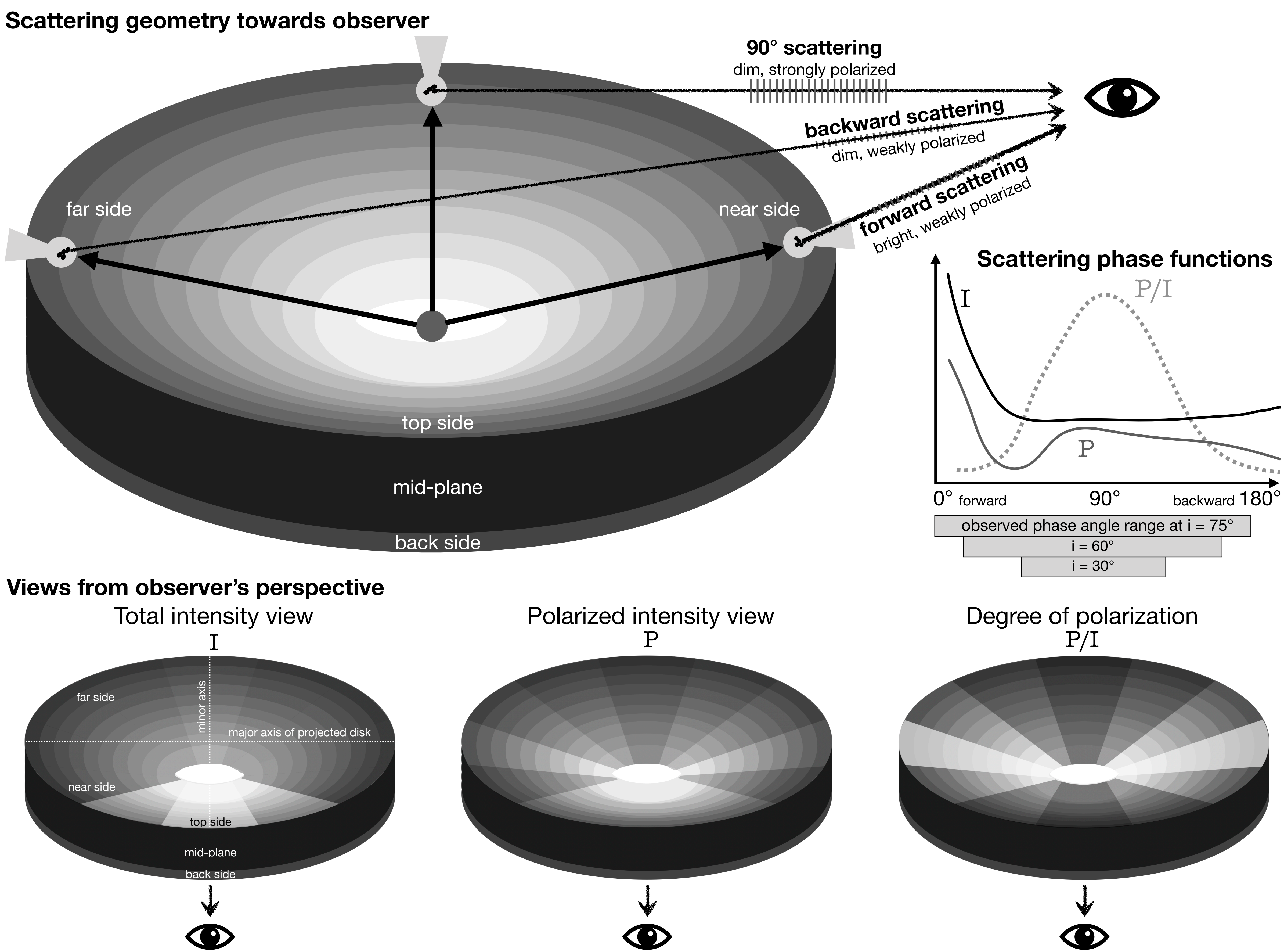
Scattered light observations: polarimetric differential imaging

- Reflected light from dust is partially polarized
  - same phenomenon explains why our blue sky is partly polarized
- Star produces unpolarized light
- Can be exploited by polarimetric imager

our blue sky is polarized!







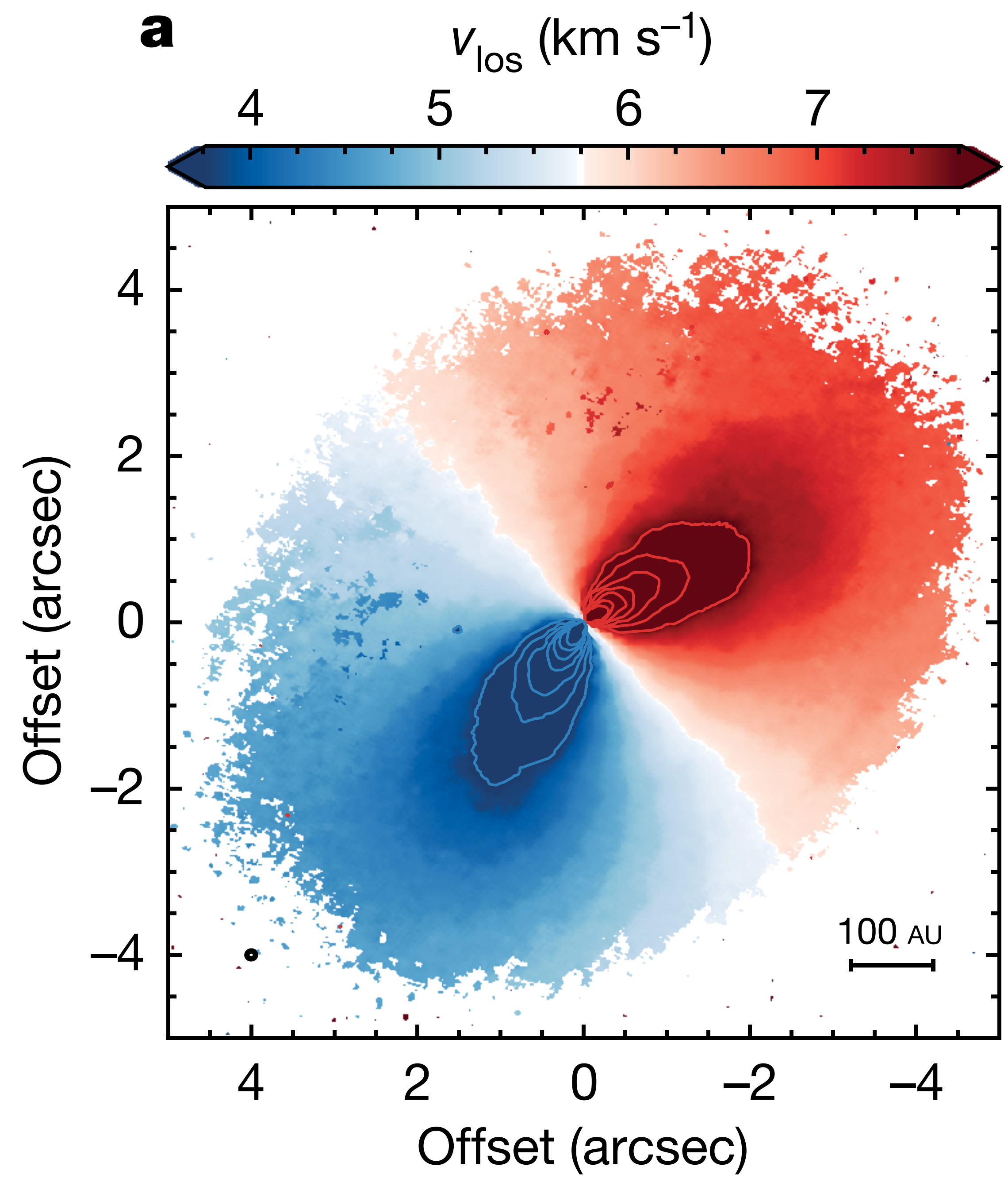
Scattering geometry towards observer
90° scattering
dim, strongly polarized
backward scattering
dim, weakly polarized
forward scattering
bright, weakly polarized
far side
near side
top side
mid-plane
back side
Scattering phase functions
I
P/I
P
0° forward
90°
backward 180°
observed phase angle range at i = 75°
i = 60°
i = 30°
Views from observer's perspective
Total intensity view
I
far side
minor axis
major axis of projected disk
near side
top side
mid-plane
back side
Polarized intensity view
P
Degree of polarization
P/I

Spectral line emission

- Main gas species (H_2) has very little signature (no dipole moment, inefficient emission)
- Measurements rely on the spectral line emission from (sub-)mm rotational transitions of rare tracer molecules
  - mainly CO (high optical depth)
  - mass can be studied with rarer isotopologues (^{13}CO, $C^{18}O$)
- Mostly done in sub-mm, although mid-IR can also be used

Spectral line observations

- Reconstruct ALMA images in individual spectral channels around a gas line
- Blue/red-shift due to rotation slightly changes the wavelength of the emission line
- Wavelength shift corresponds to gas velocity —> can be used to probe disk dynamics

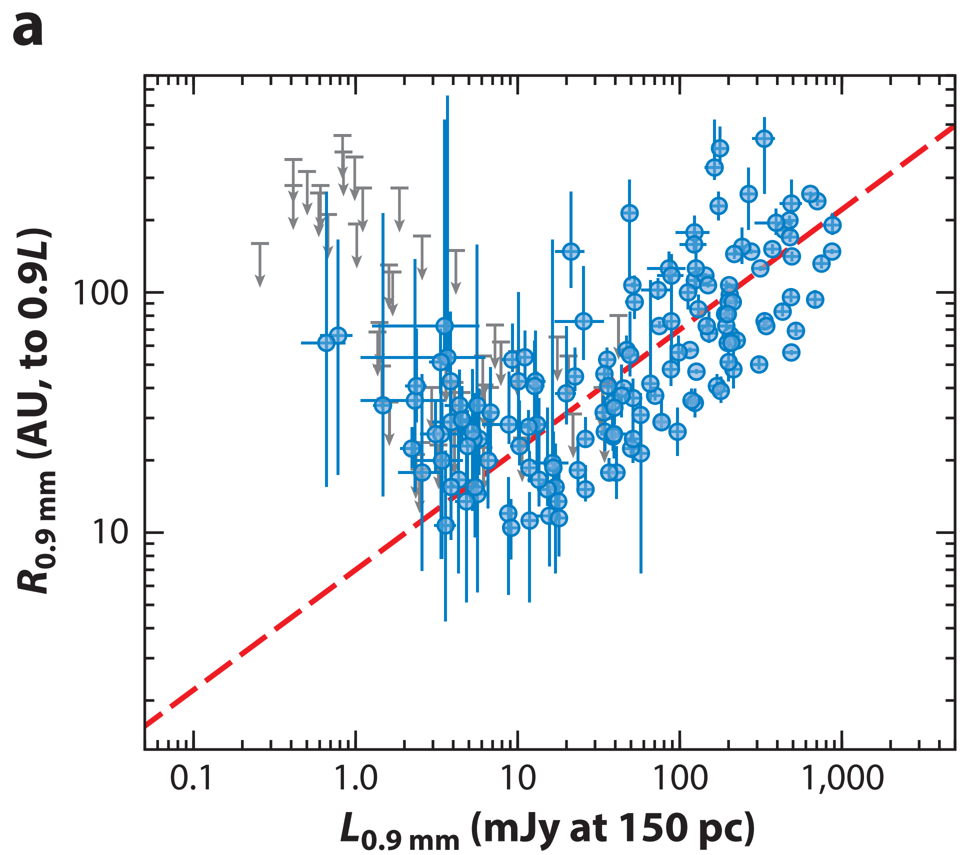


II. Protoplanetary disks

II.3 Results from imaging

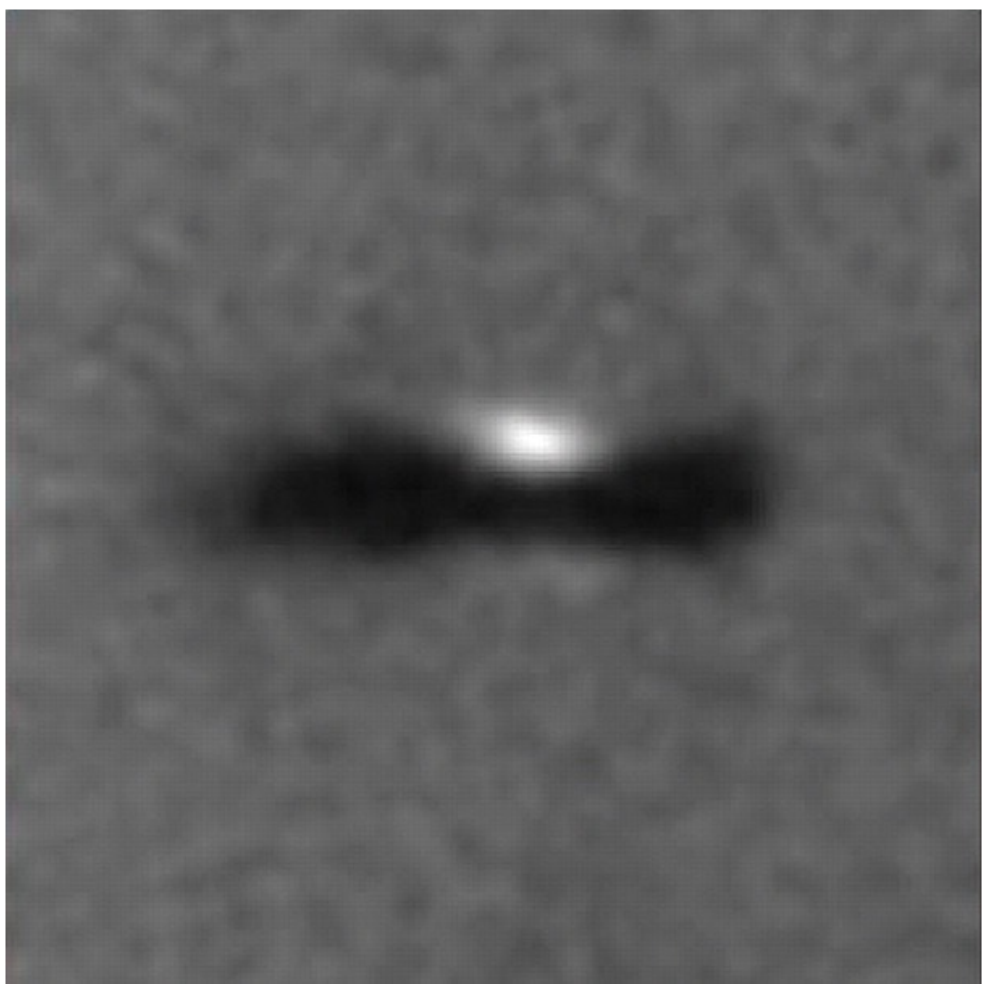
Disk sizes

- Maximum disk extension (sometimes >> 100 au) measured in:
    - scattered light
    - gas lines
- Reduced disk sizes generally measured in:
    - sub-mm (radial drift, reduced brightness, optical depth, evolution of solids, …?)
    - polarized scattered light (partial polarization reduces sensitivity)

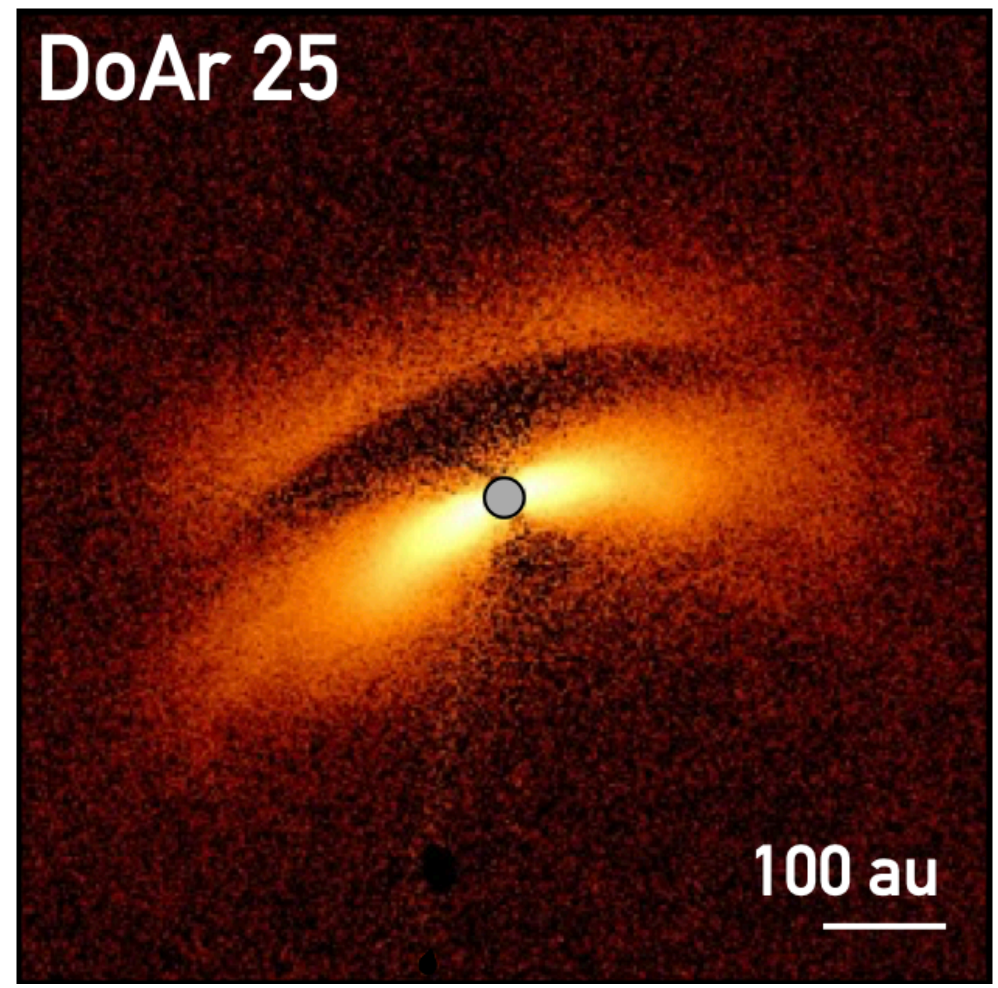


Disk shapes: flaring

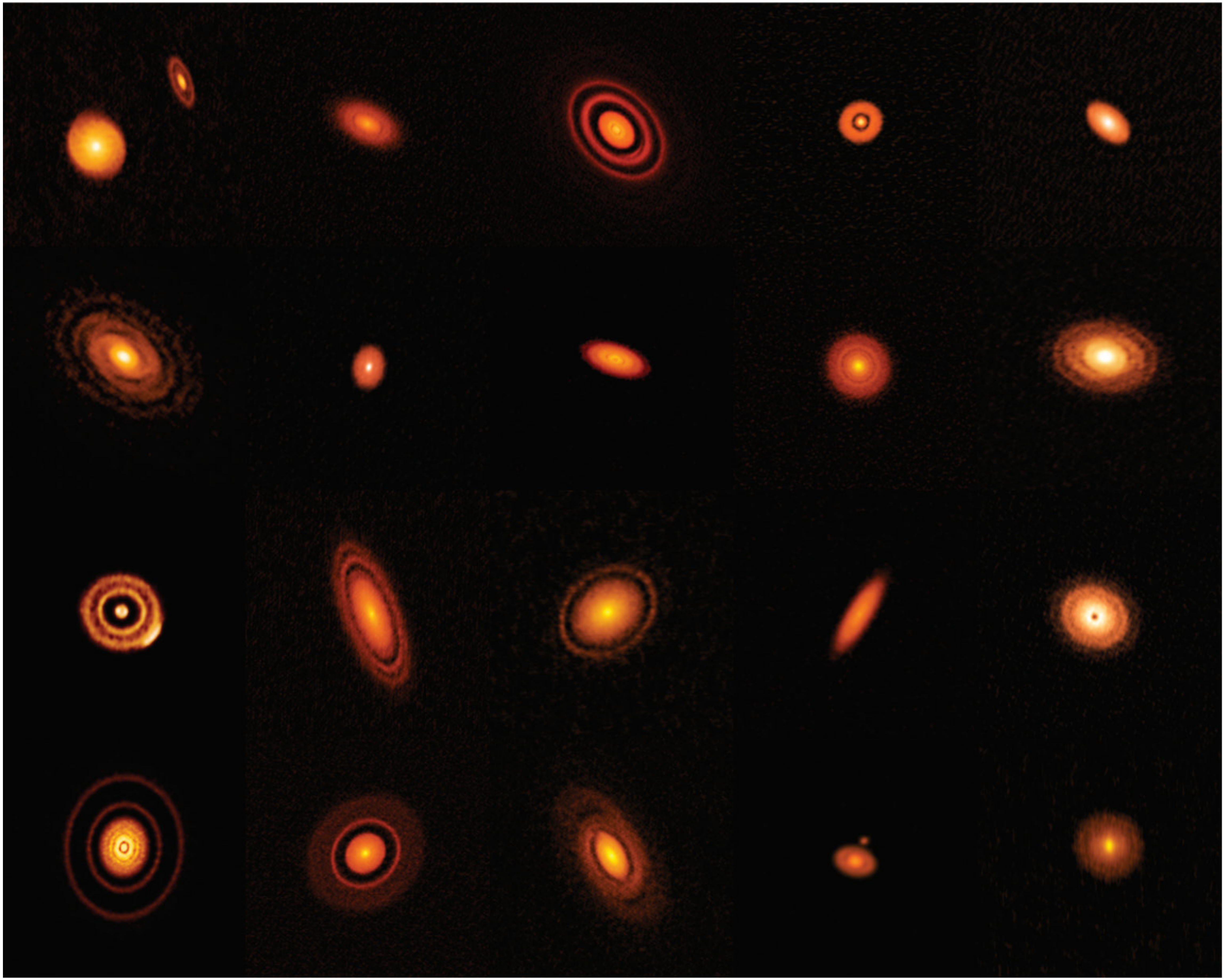
early days: silhouette (HST)



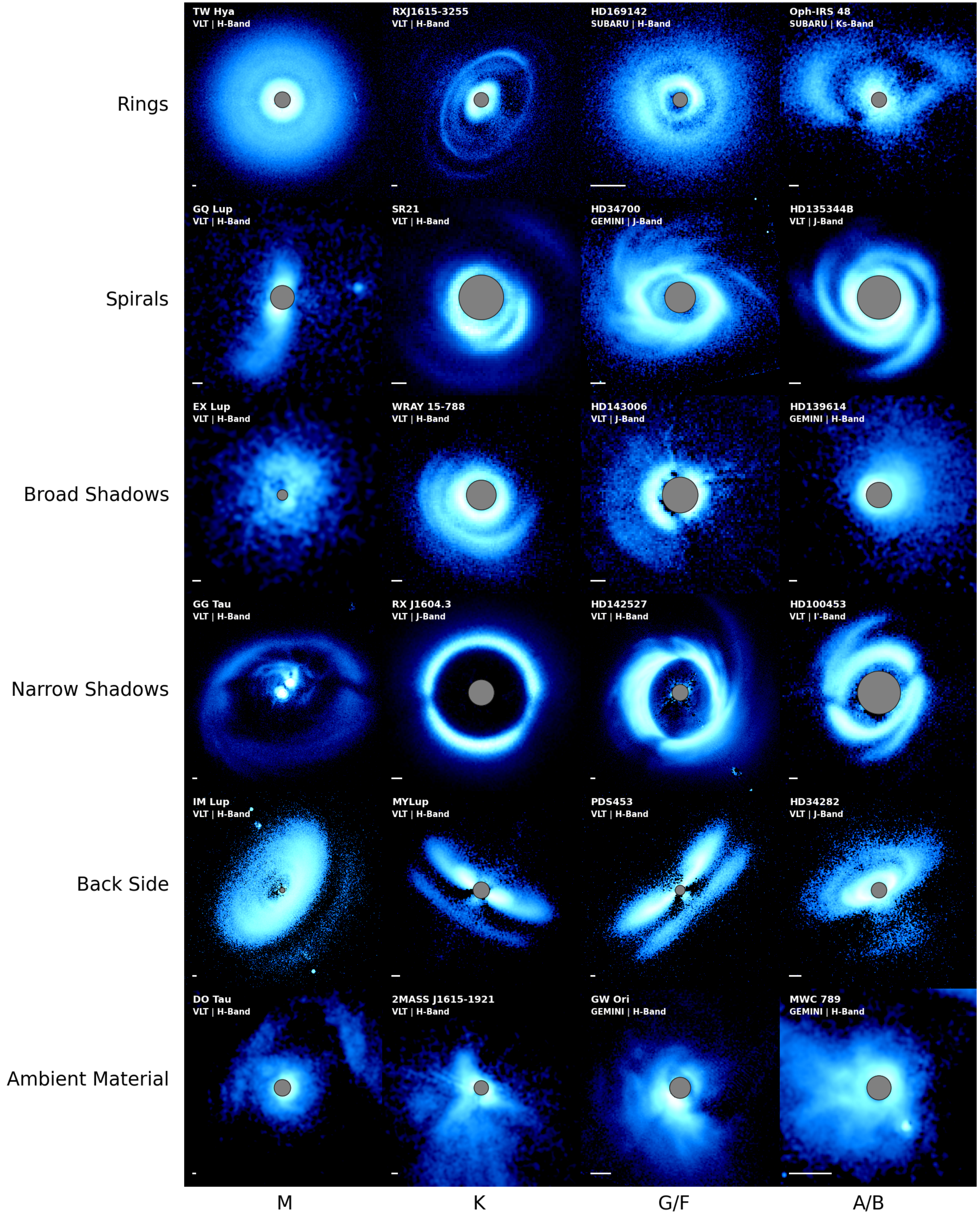
today: scattered emission from both sides



A variety of structures: the ALMA view



A variety of structures: the optical polarization view

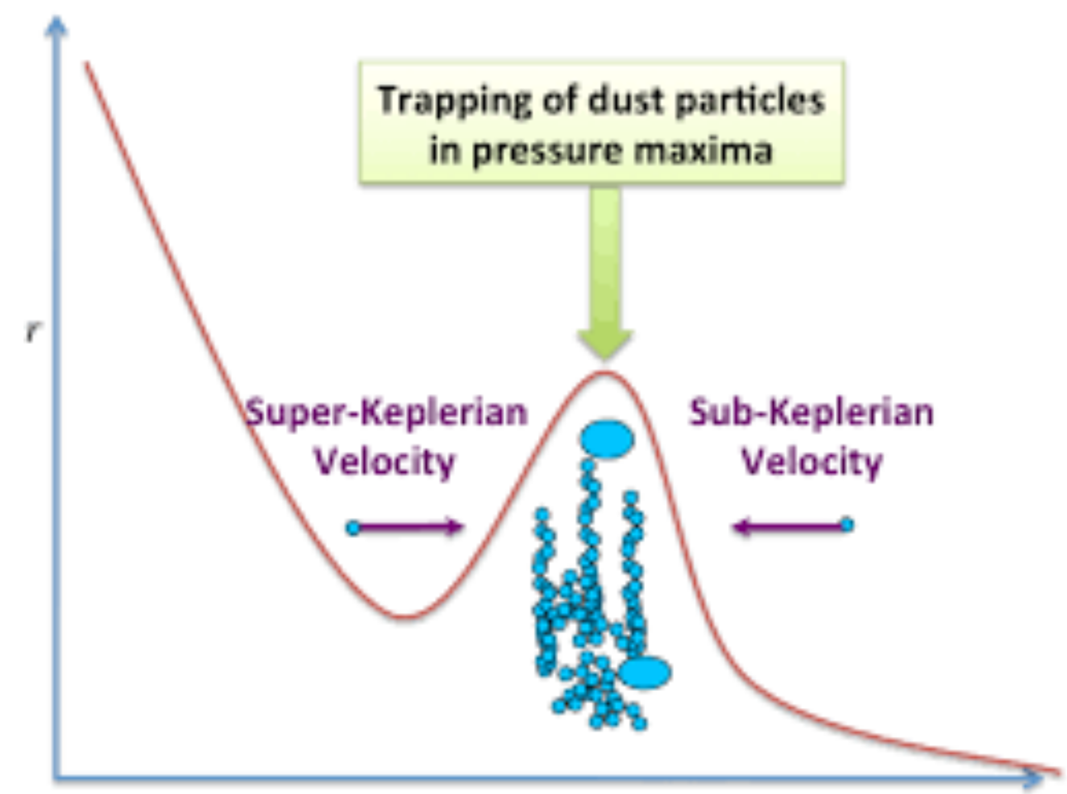


The crucial role of disk structures

- Standard model has monotonically decreasing P(r) —> negative force —> gas has sub-Keplerian motion

- Migration of solids due to gas sub-Keplerian motion, which creates « head wind »

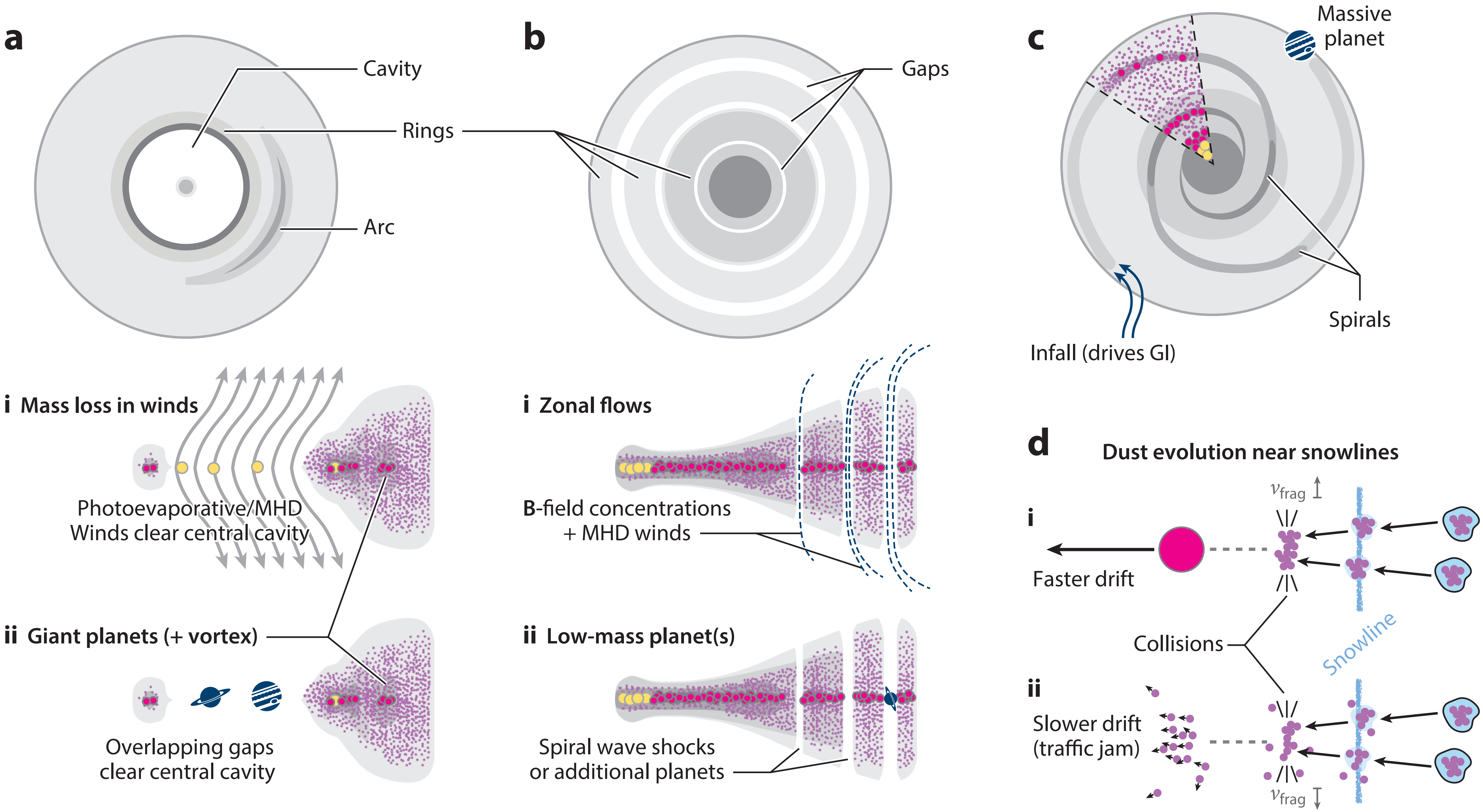
- Non-monotonic pressure profile can create dust trap, which promotes growth



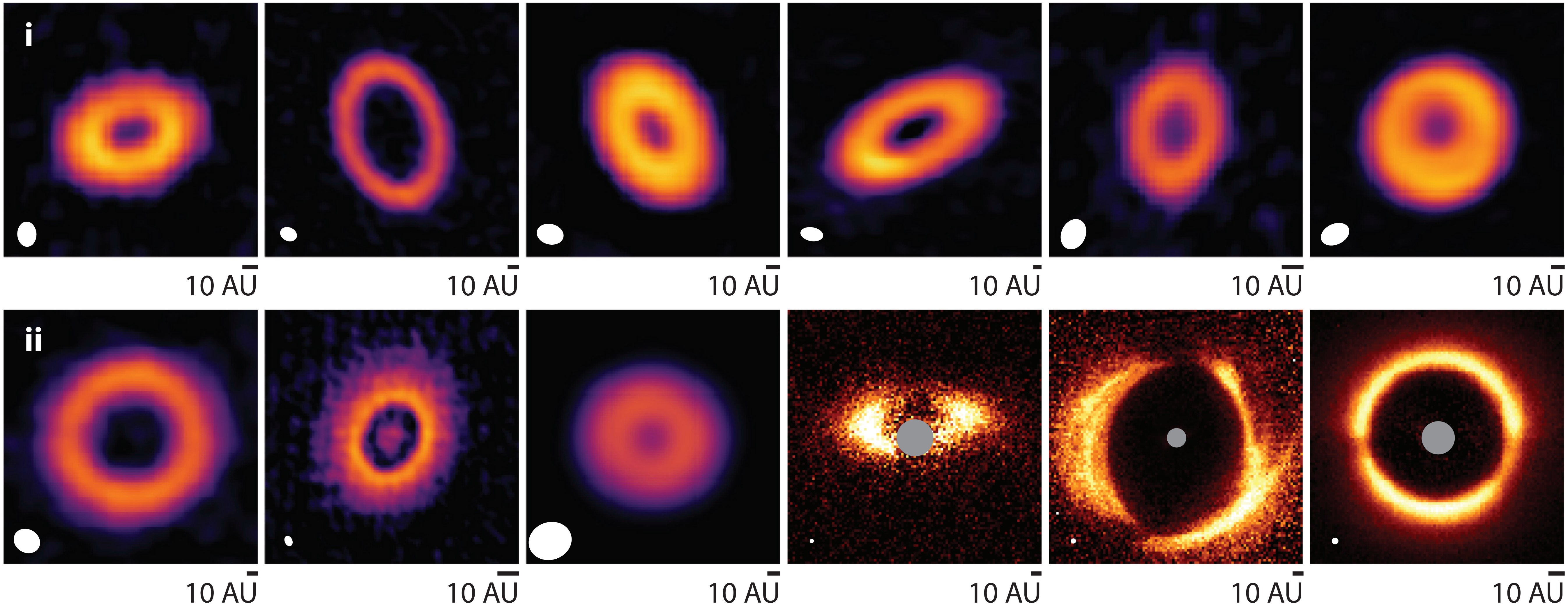
Possible origins of substructures

- Fluid mechanics
  - photoevaporation / winds —> cavities
  - magneto-hydro dynamic flows & turbulence —> gaps, vortices
  - self-gravity —> spiral patterns
- Dynamical interactions with companions
  - low-mass companions —> gaps, spirals
  - massive companions —> cavities, vortices, warps
- Condensation fronts (snow lines) affect density of solid and gas, and outcome of collisions

Possible shapes

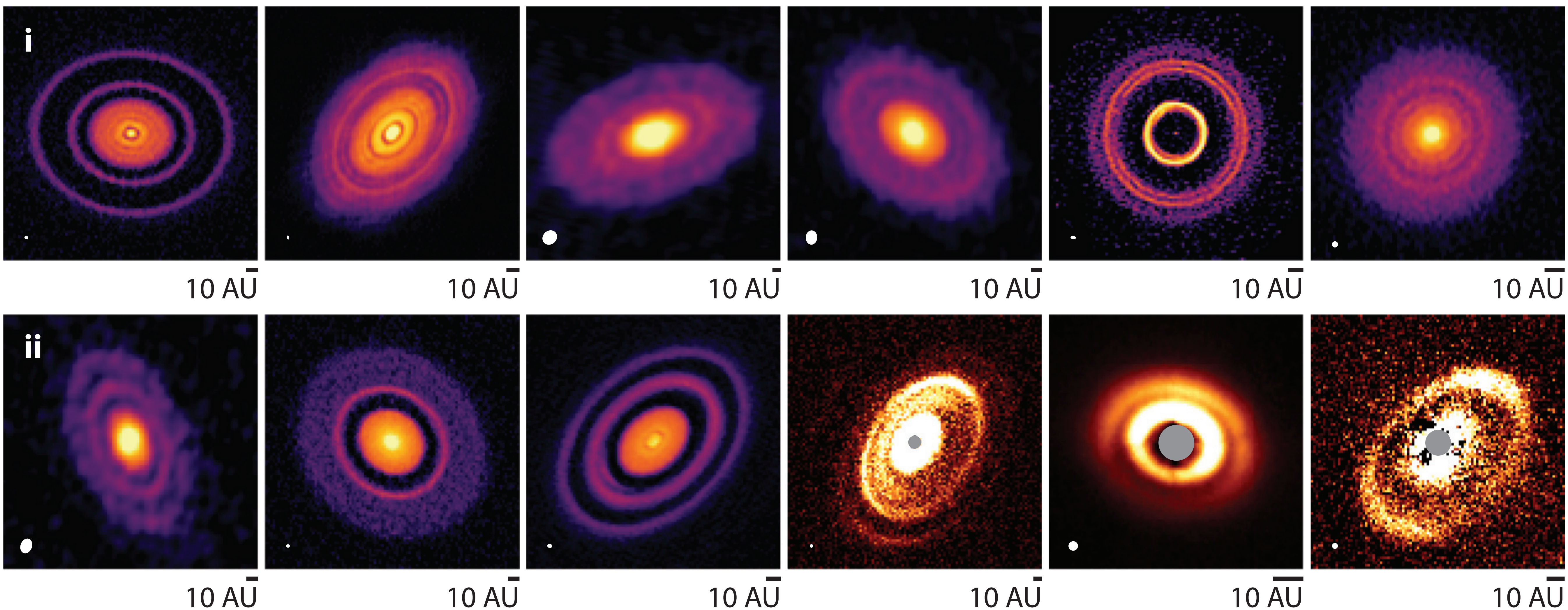


Rings - cavities



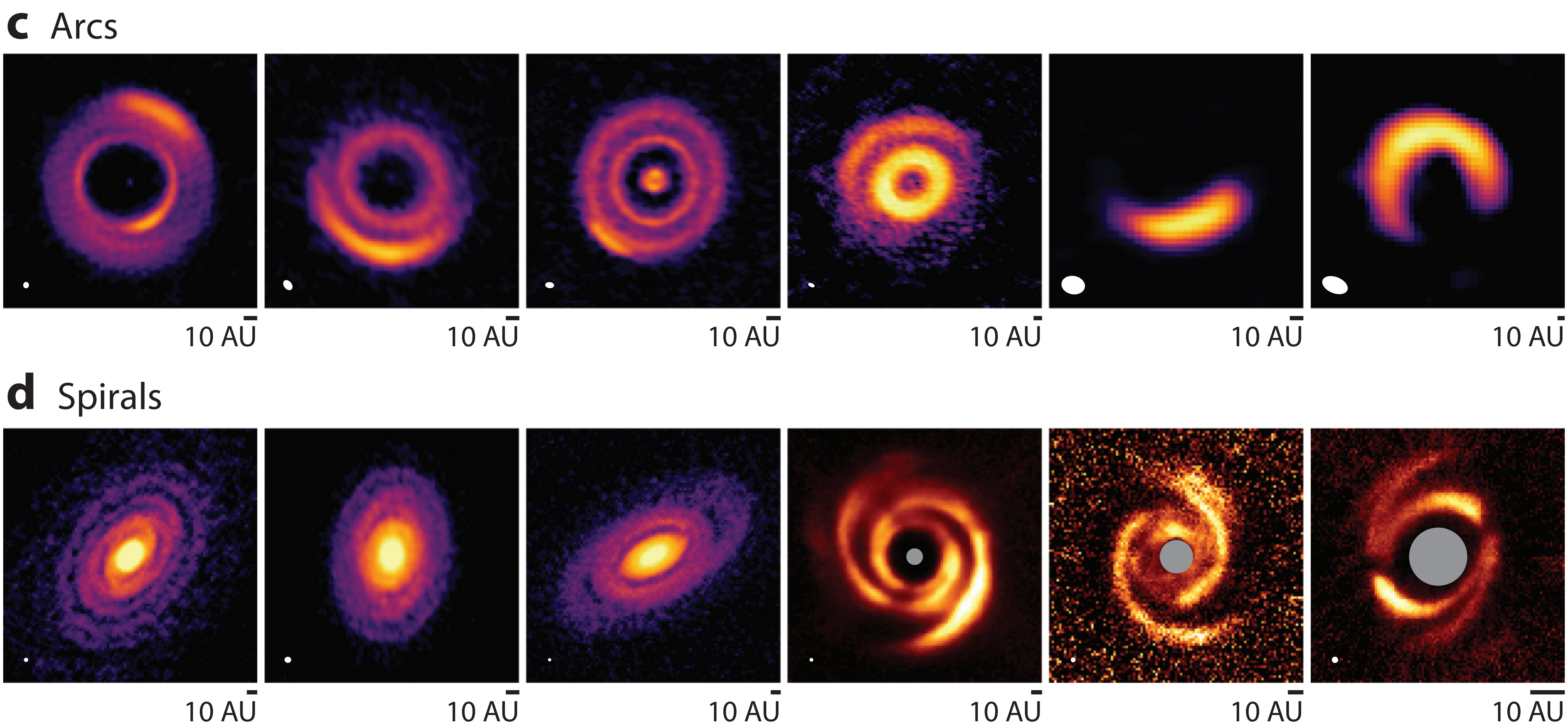
Cavities more prominent in sub-mm. Could be due to big grains being trapped, while gas and small dust still flowing through cavity.

Rings - gaps



No direct relationship found so far between the position and number of gaps in sub-mm and optical observations.

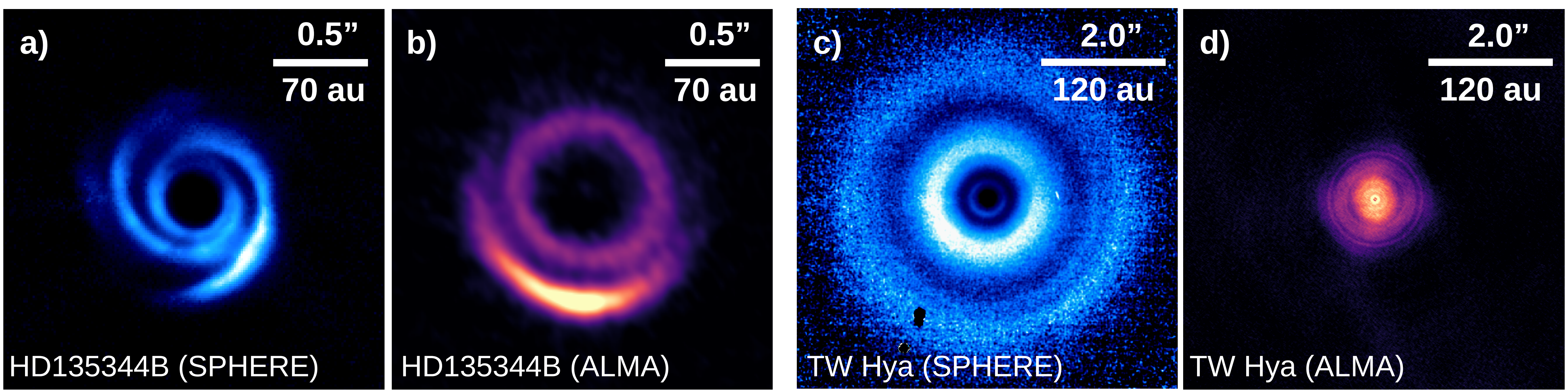
Arcs, spirals



Sub-mm spirals trace density, while optical spirals are more likely due to disk scale height variations.

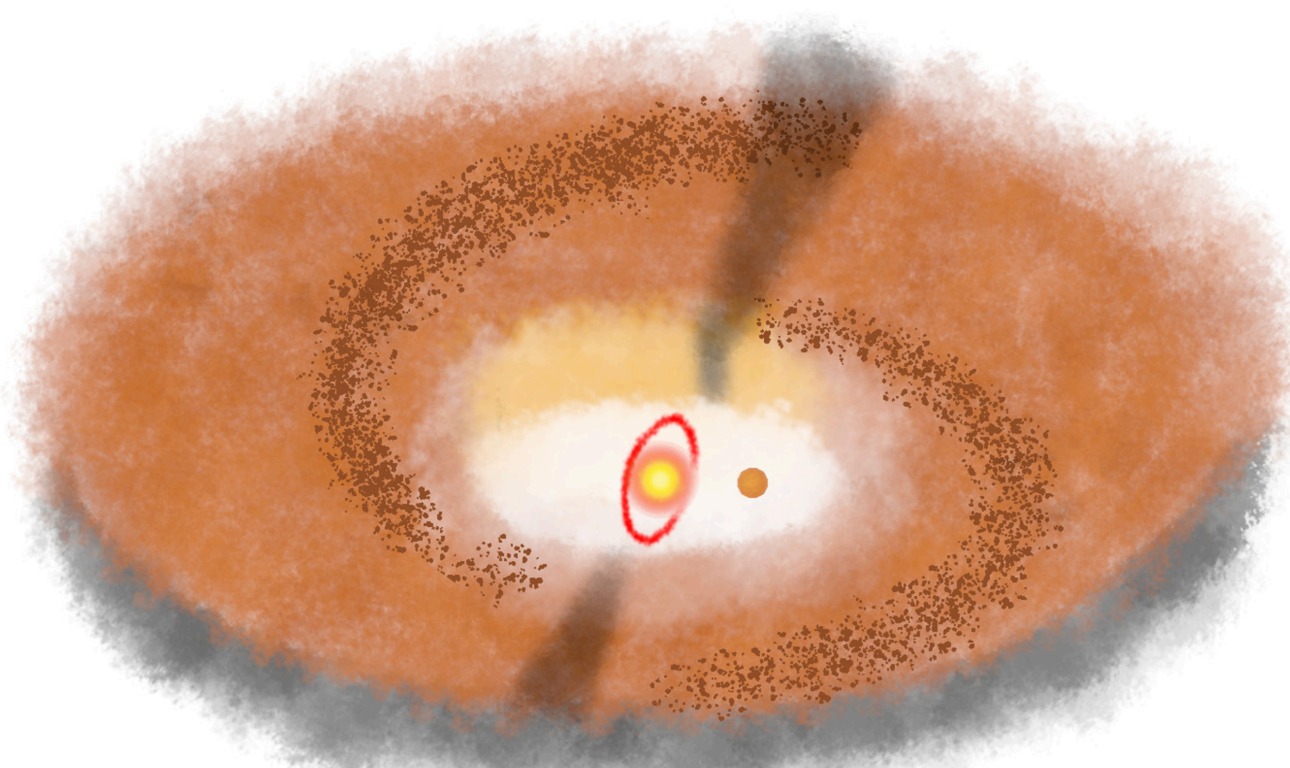
Sub-mm vs optical images

- Multi-wavelength view required to understand disk structure and constrain mechanisms at play

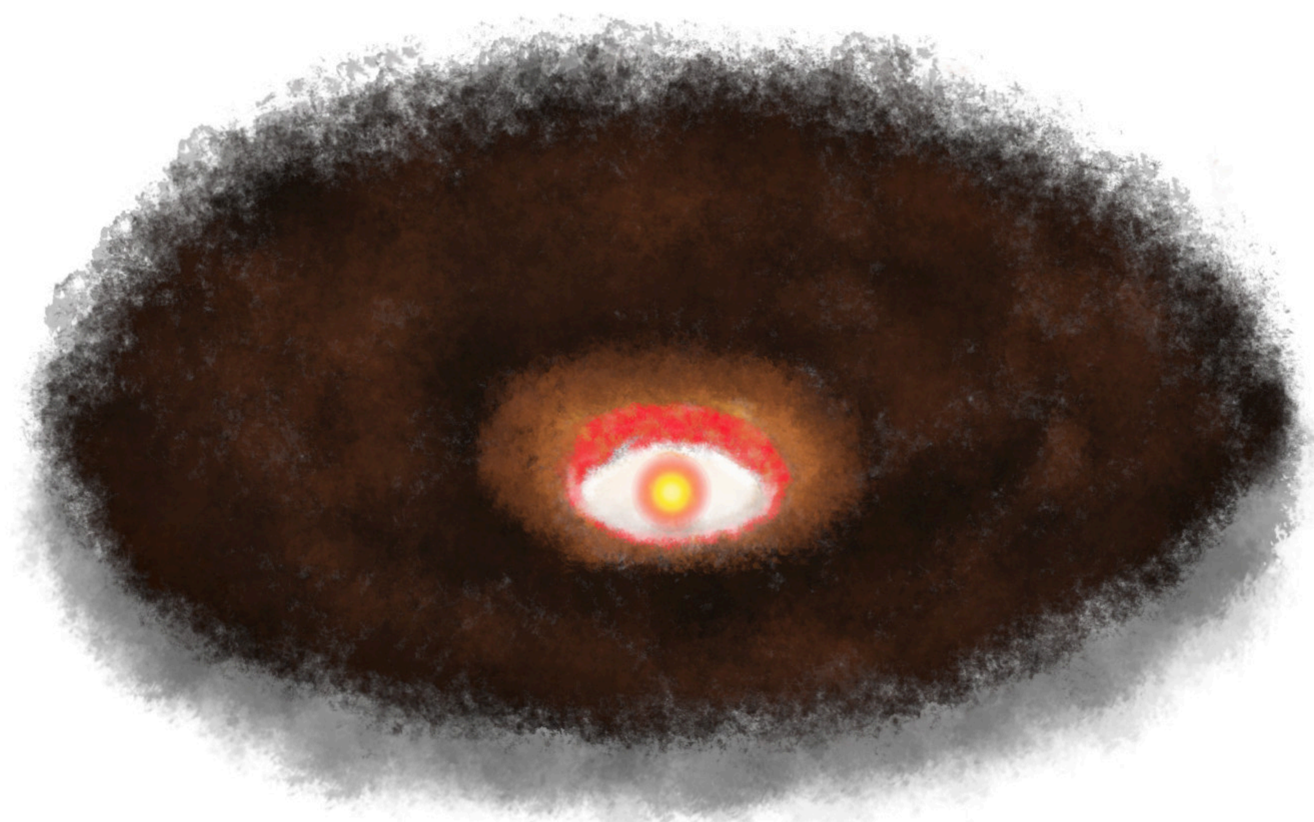


Vertical structures: shadows and warps

Inner disks can project shadows onto outer disks, which affect its appearance in scattered light. Shadows can be local, extended, or global.

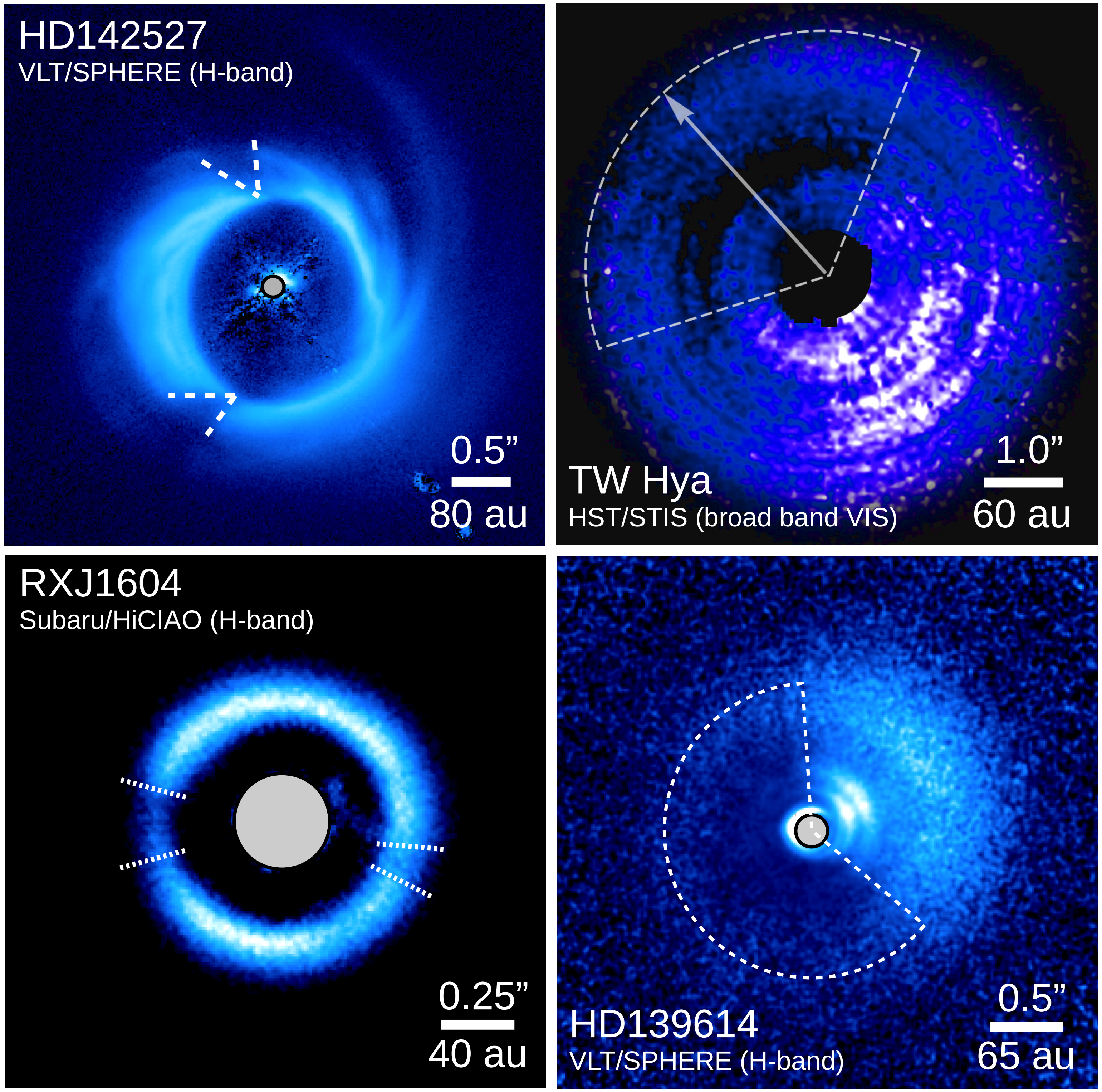


Spirals, shadow lanes, misaligned inner disk



Global shadow

Shadows


HD142527
VLT/SPHERE (H-band)
0.5"
80 au
TW Hya
HST/STIS (broad band VIS)
1.0"
60 au
RXJ1604
Subaru/HiCIAO (H-band)
0.25"
40 au
HD139614
VLT/SPHERE (H-band)
0.5"
65 au

II. Protoplanetary disks

II.4 Protoplanets

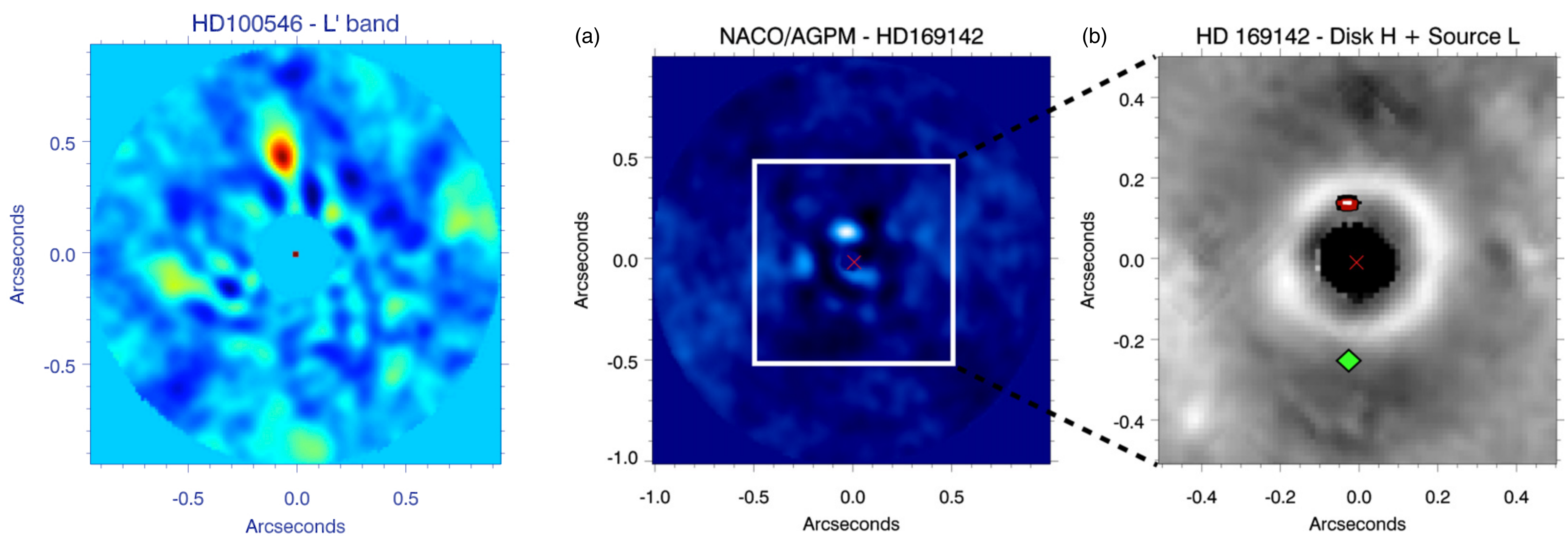
Goal: find the planets supposed to create these structures

Young planets should be bright, inside low-brightness gaps / cavities

Detecting protoplanets

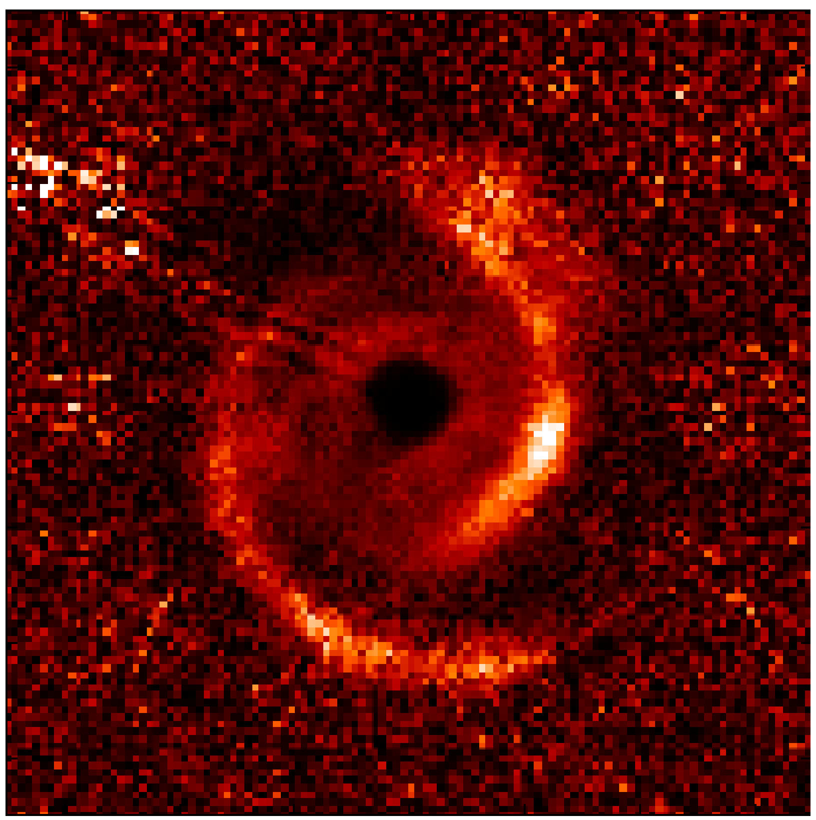
- Young planets still in the process of accreting material for circumstellar disk

- Image processing complicated by presence of disk (—> several false positives)

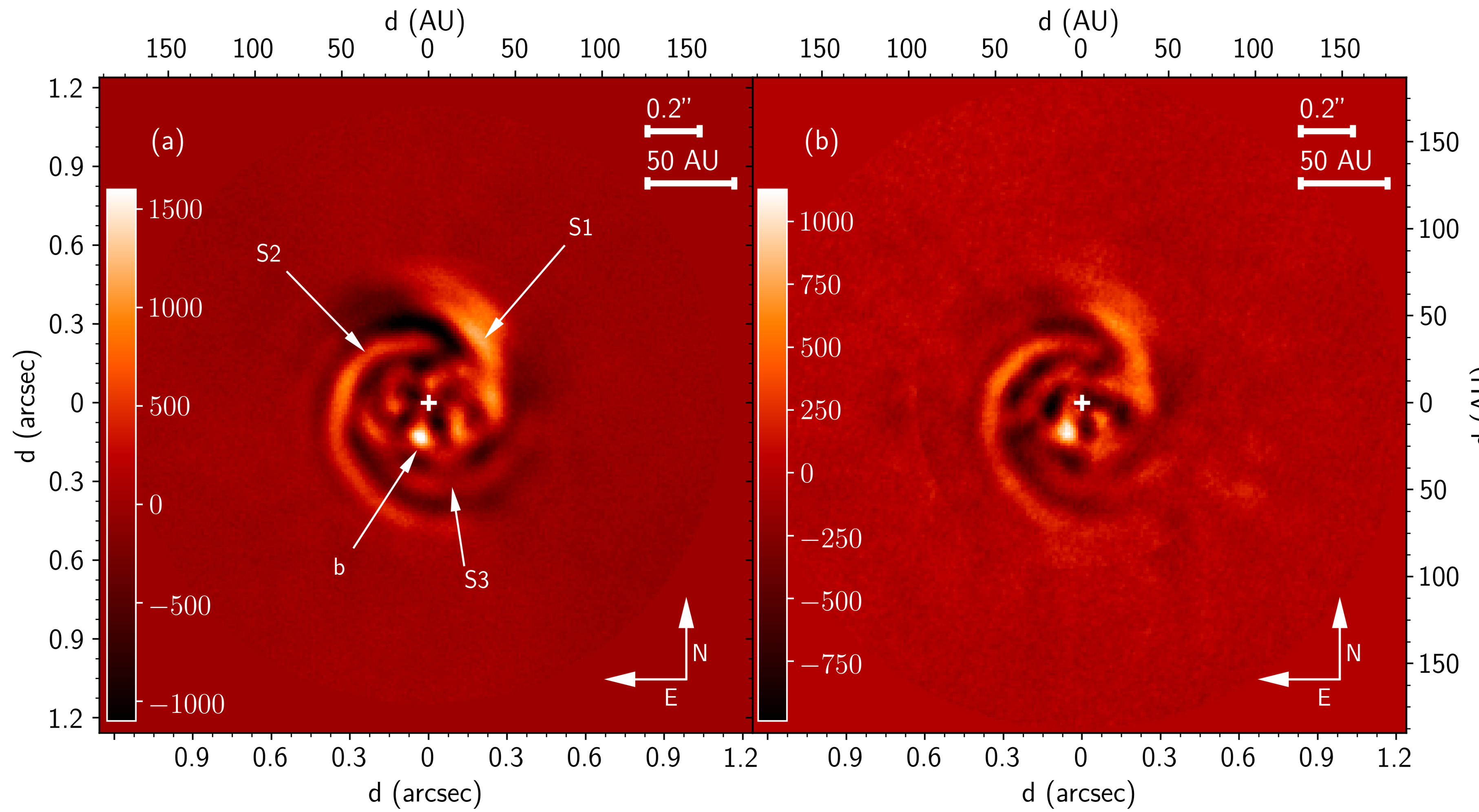


Some promising candidates

SPHERE/IRDIS Y band polarimetry (2014)



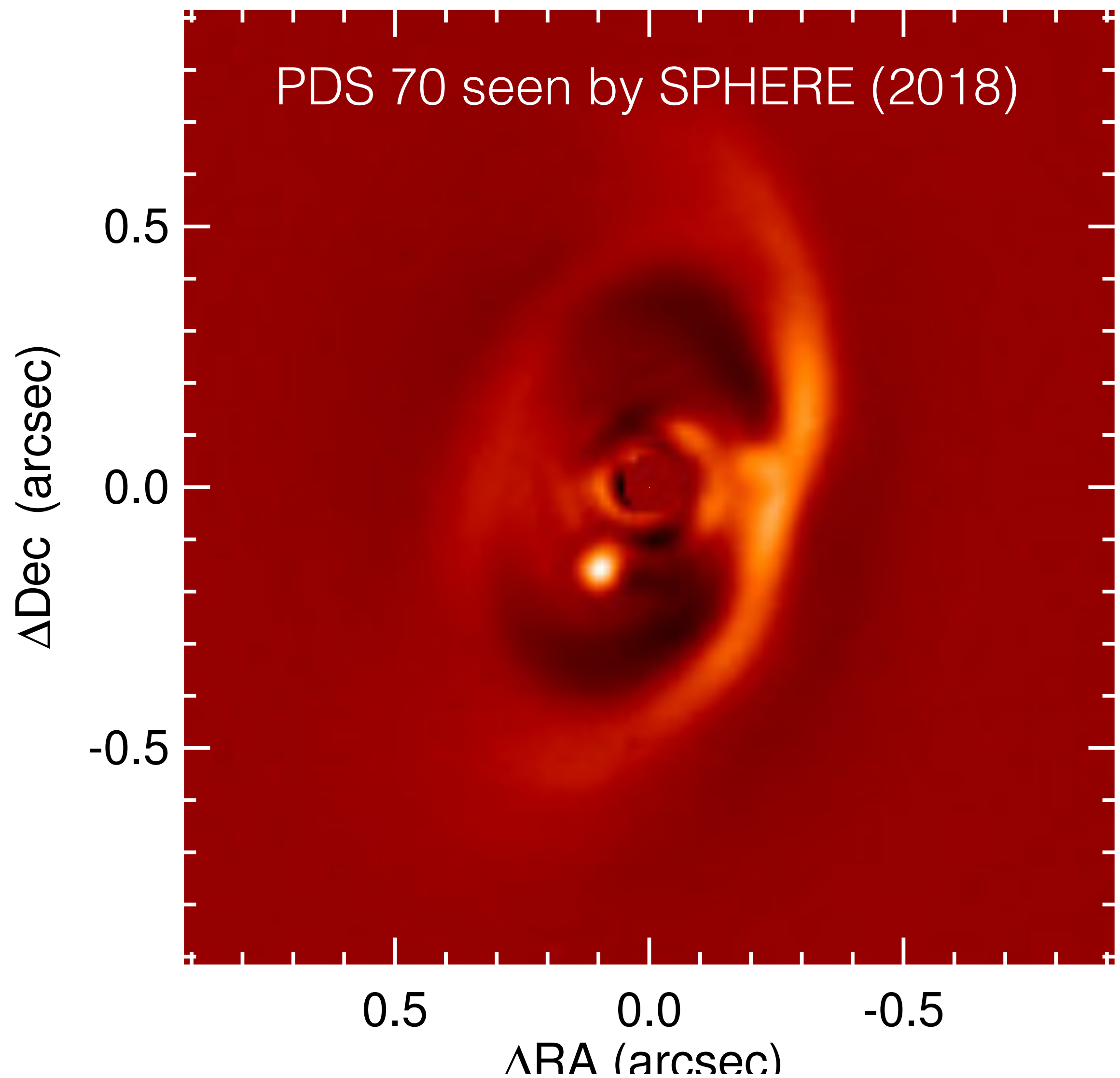
Keck/NIRC2 L- band imaging (2015 & 2016)



MWC 758 — a young star with a protoplanetary disk, and a companion candidate that could create the spiral arms

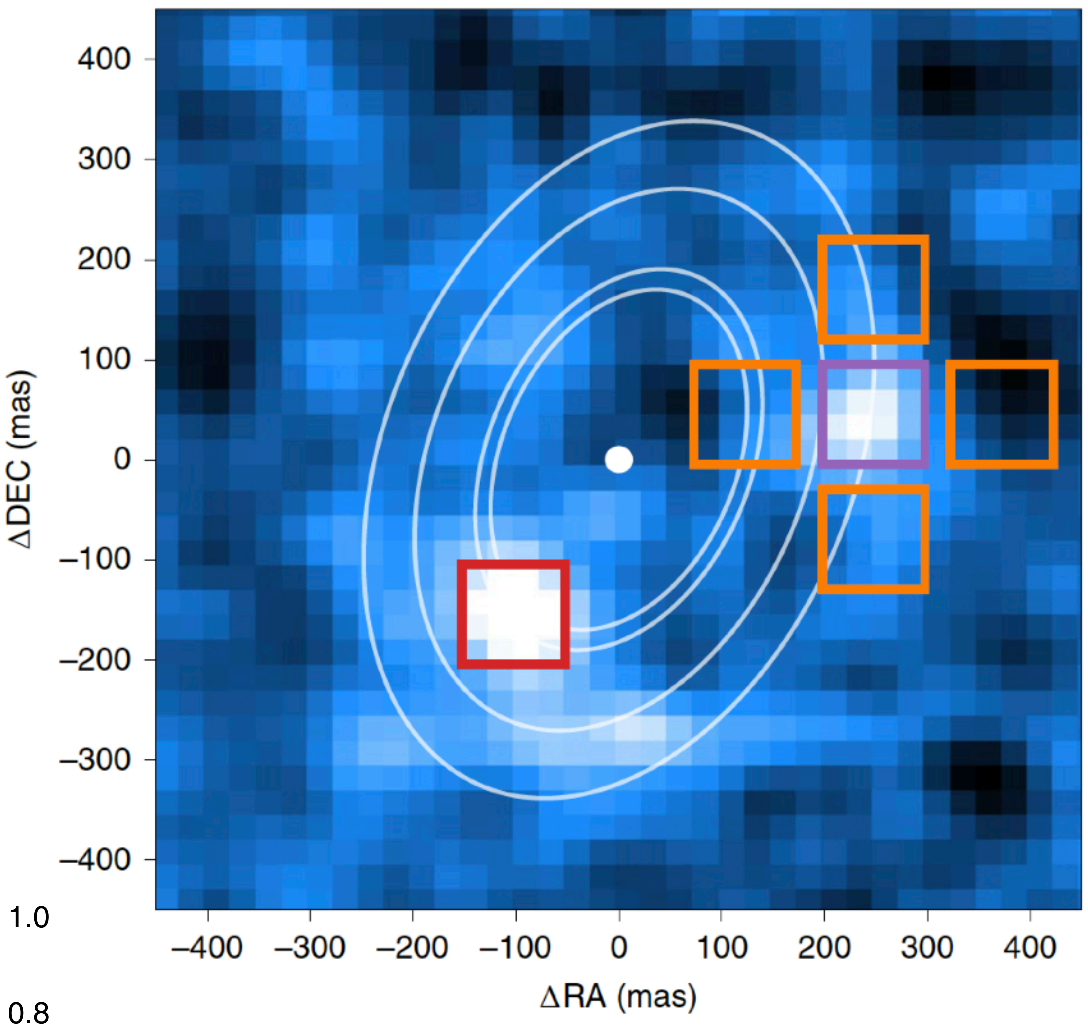
Then comes PDS70!

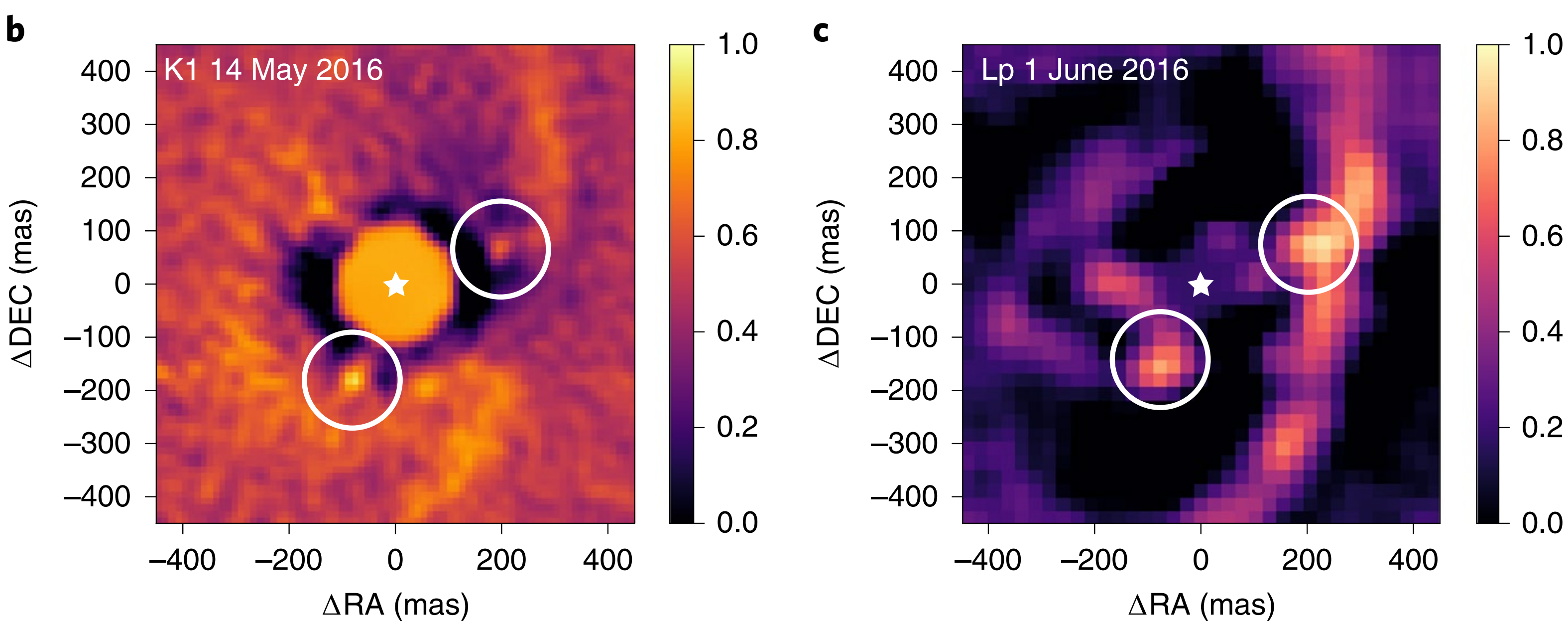
- PDS70 = low-mass young star in Taurus (~5 Myr)
- First robust detection of a forming protoplanet: PDS70b
- Located at 22 au, inside the large gap of the PDS70 disk



Accretion signature in Hα

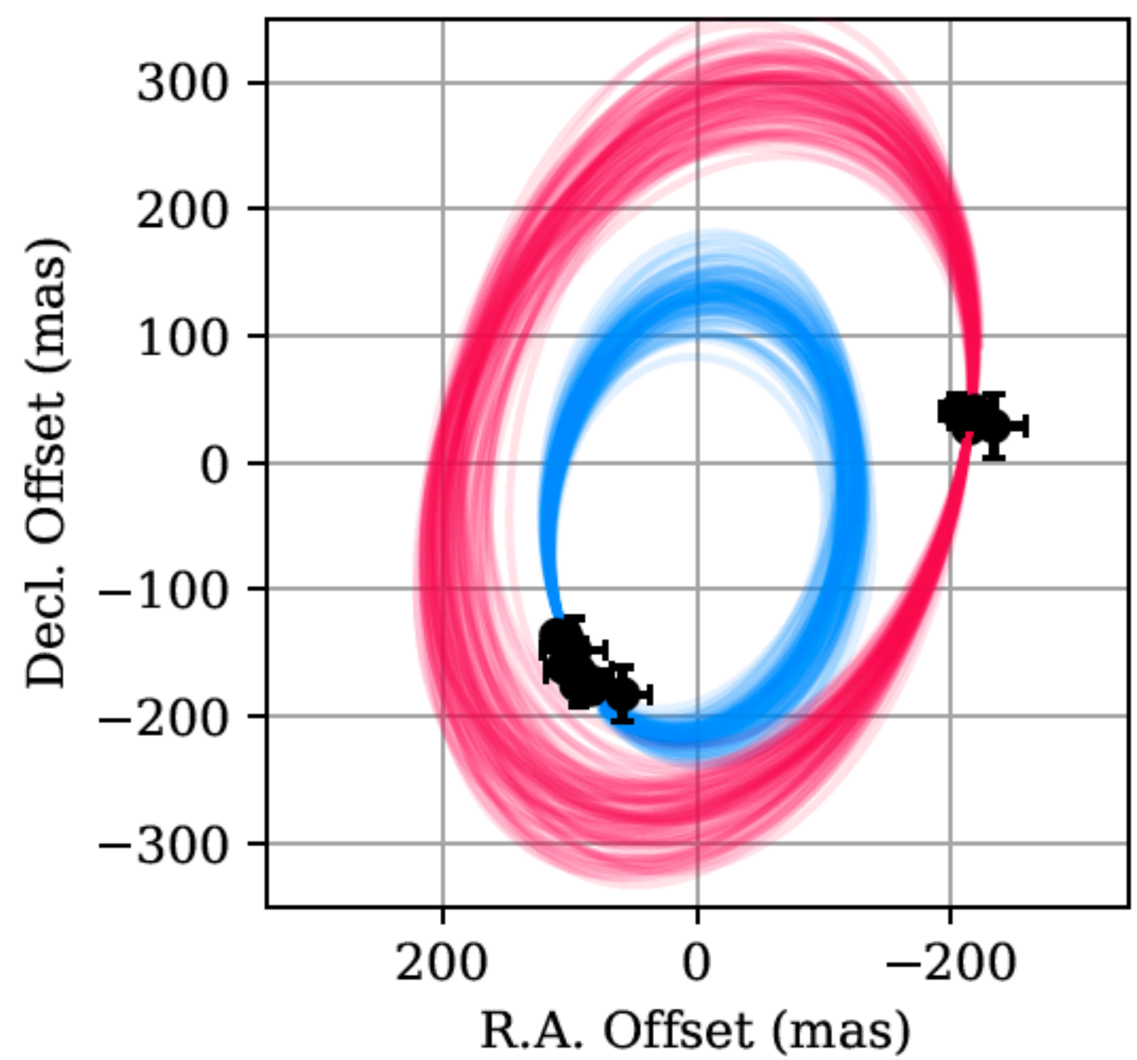
- Confirmation of PDS70b using accretion emission line (hot hydrogen gas)
- Detection of PDS70c, which was initially missed due to confusion with the disk





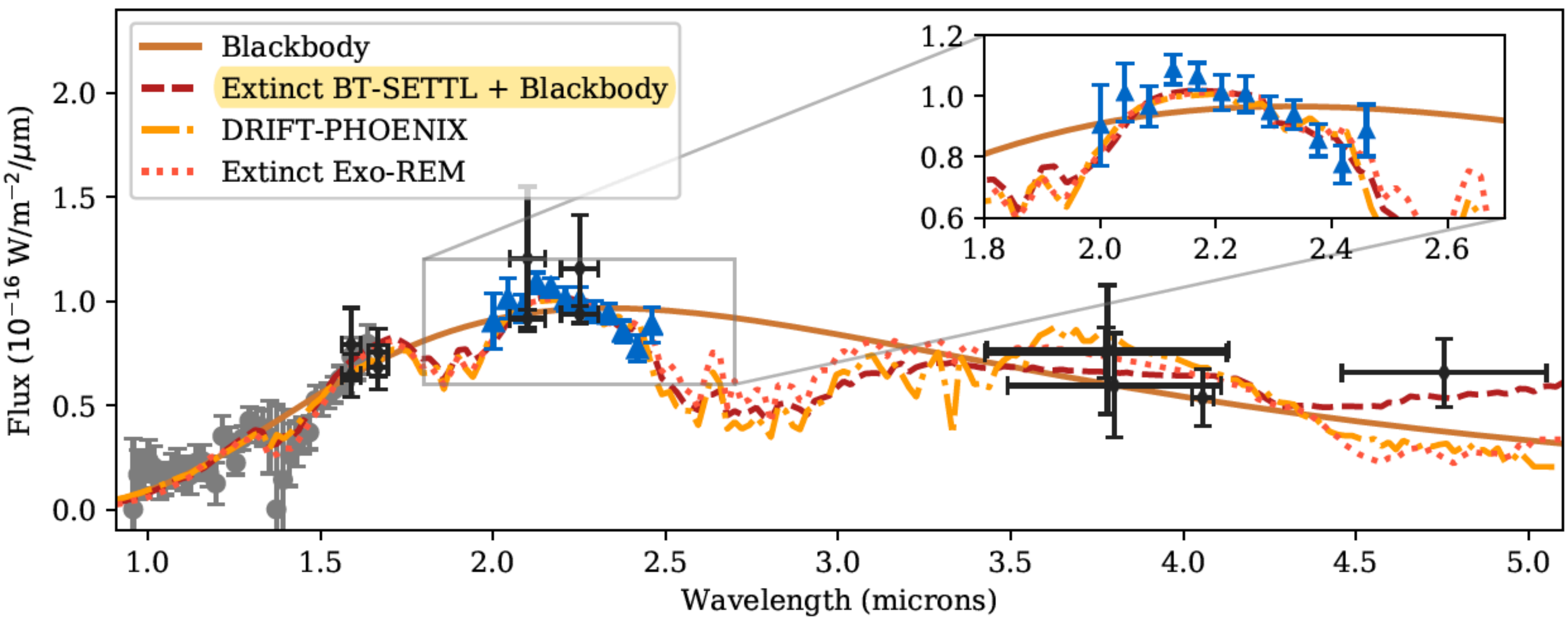
Orbits constrained

- Already 7 years of coverage (incl. archives)
- Planets most probably in 2:1 resonance
- Masses constrained to be below 10 M_{Jup}



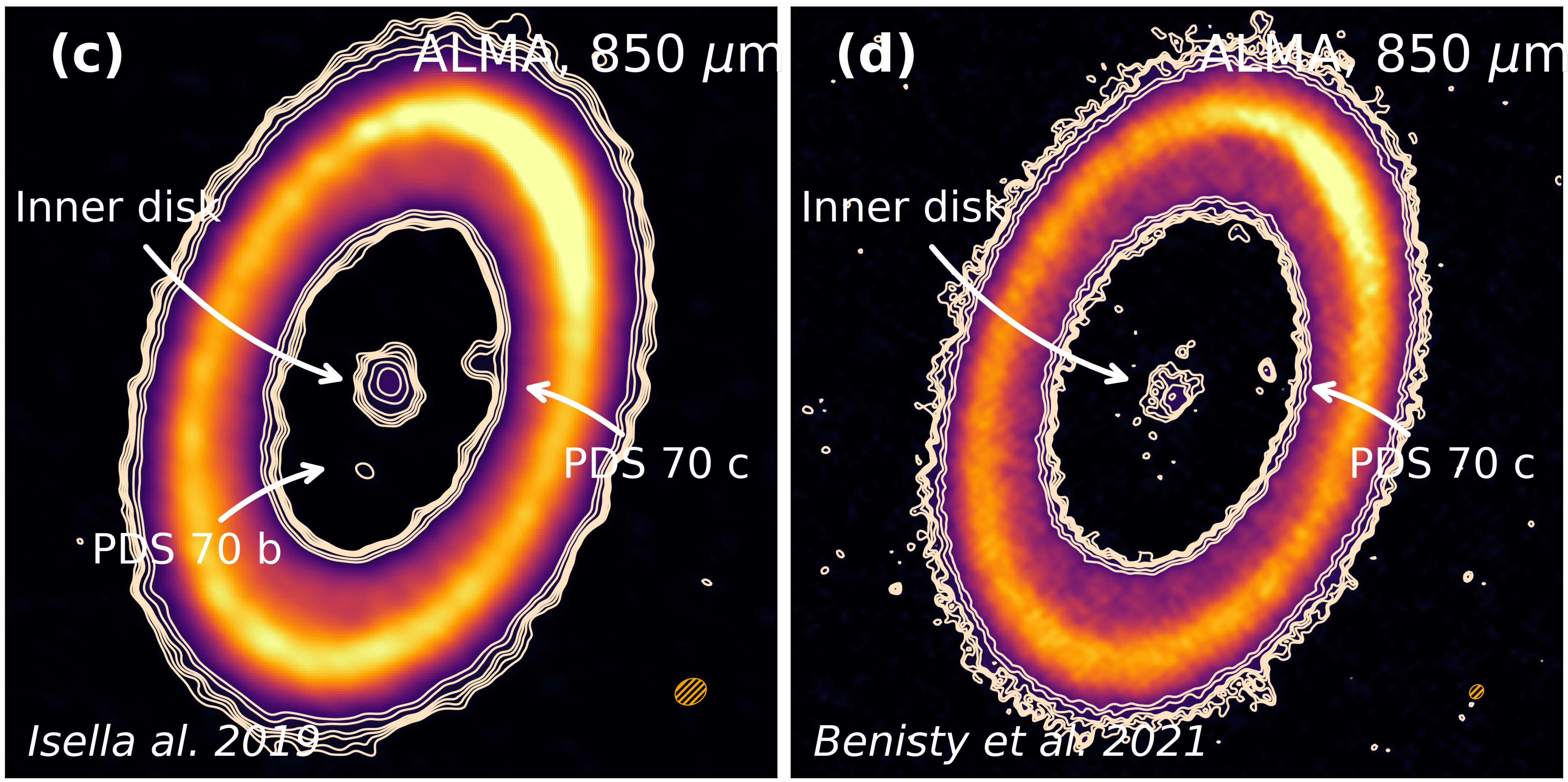
Spectrum: a circumplanetary disk?

- Very red, almost featureless spectrum —> planet photosphere hidden by dust. Is it in the planetary atmosphere, accretion column, or CPD?

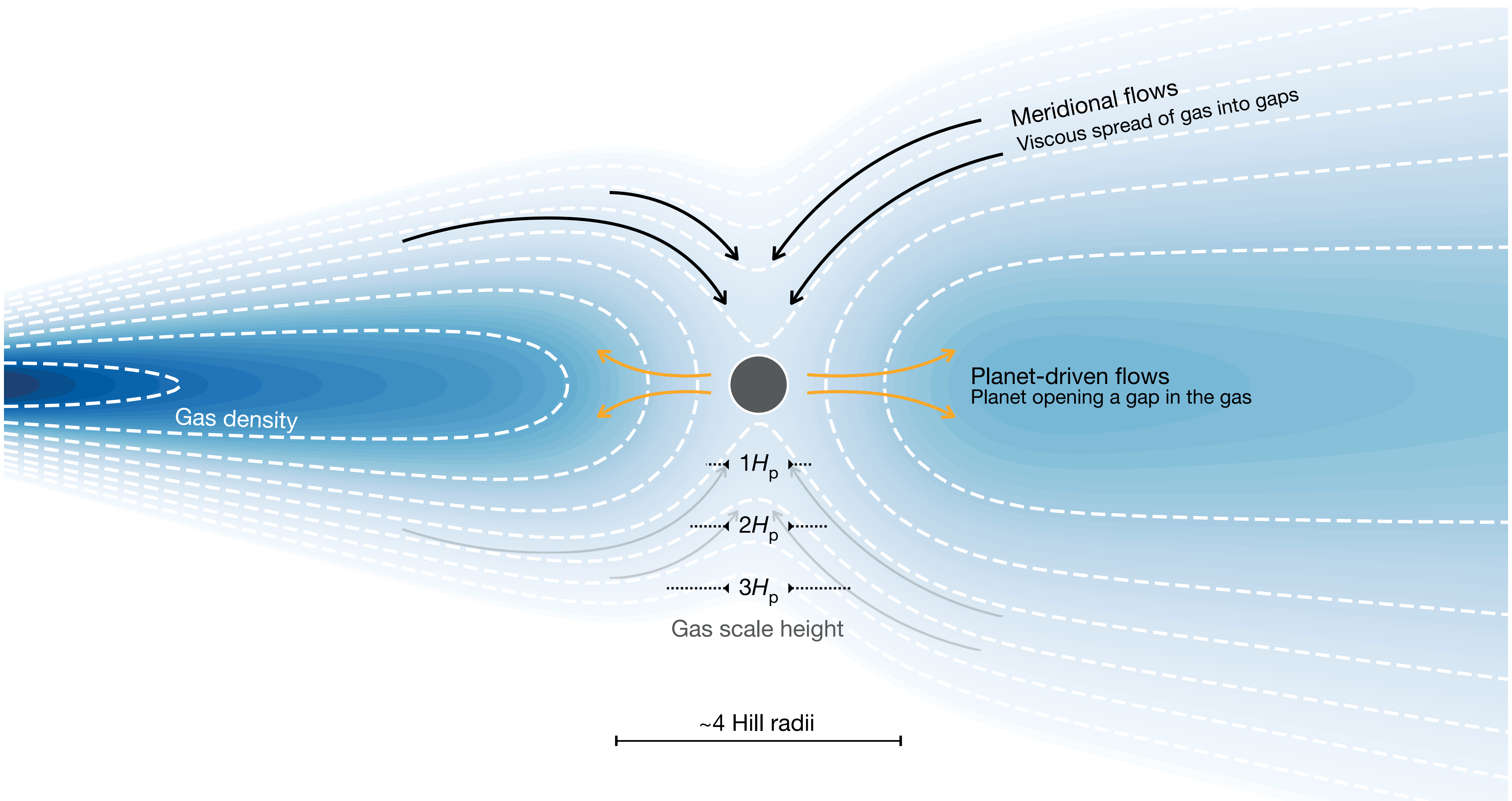


CPD around PDS70 planets: ALMA confirmation

- Compact emission colocated with PDS70b & c
- About 0.01 M_{Earth} of dust (in large grains)

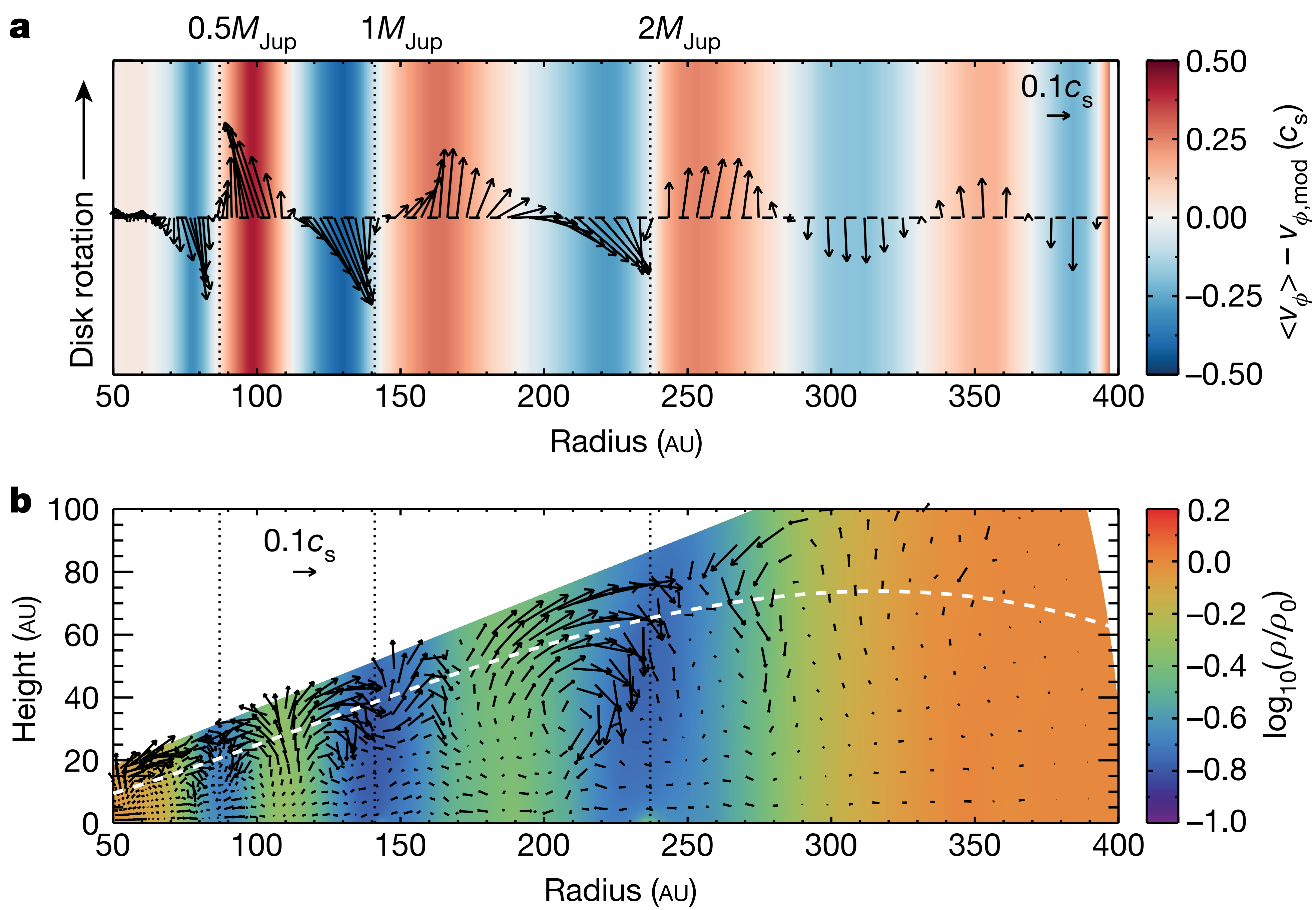


Gas dynamics perturbations due to protoplanets



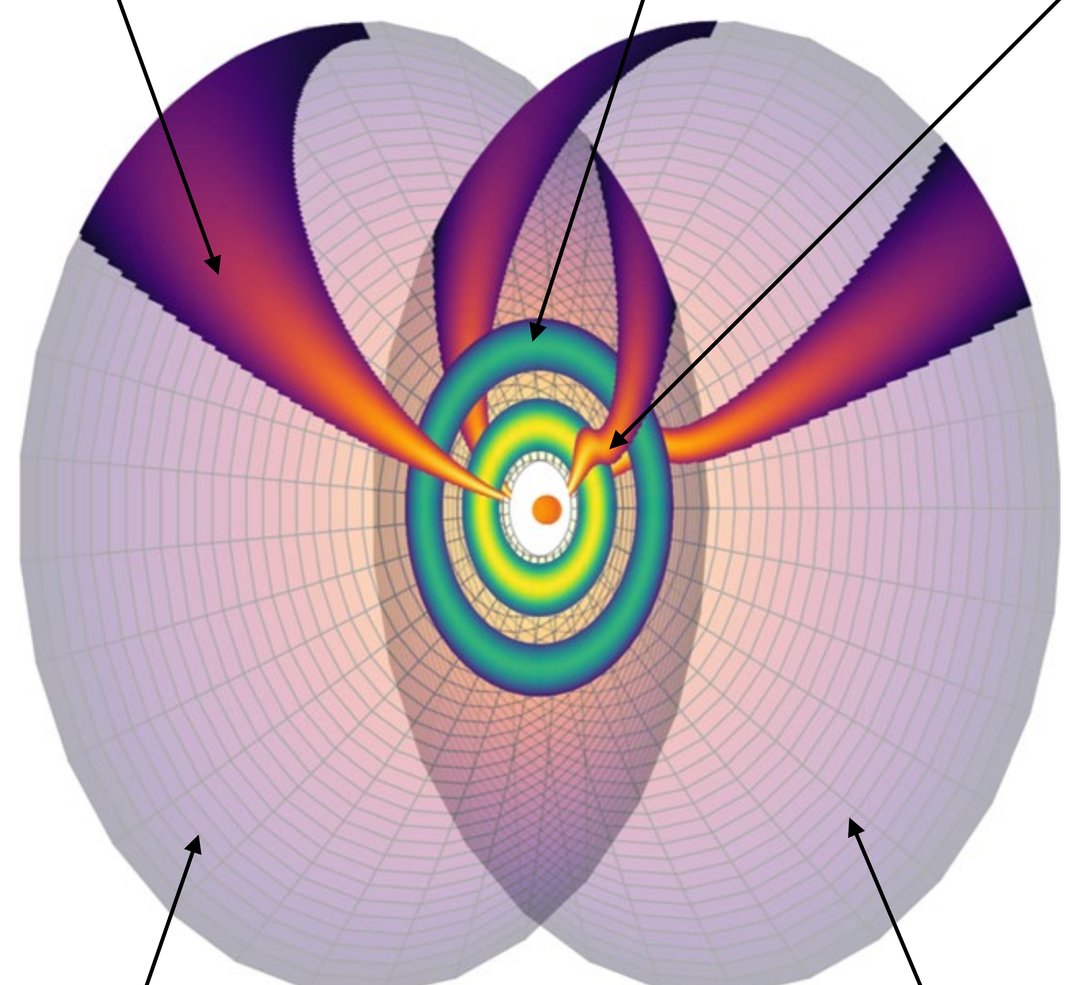
Another potential way of using ALMA, in addition to CPD detection

Gas meridional flows

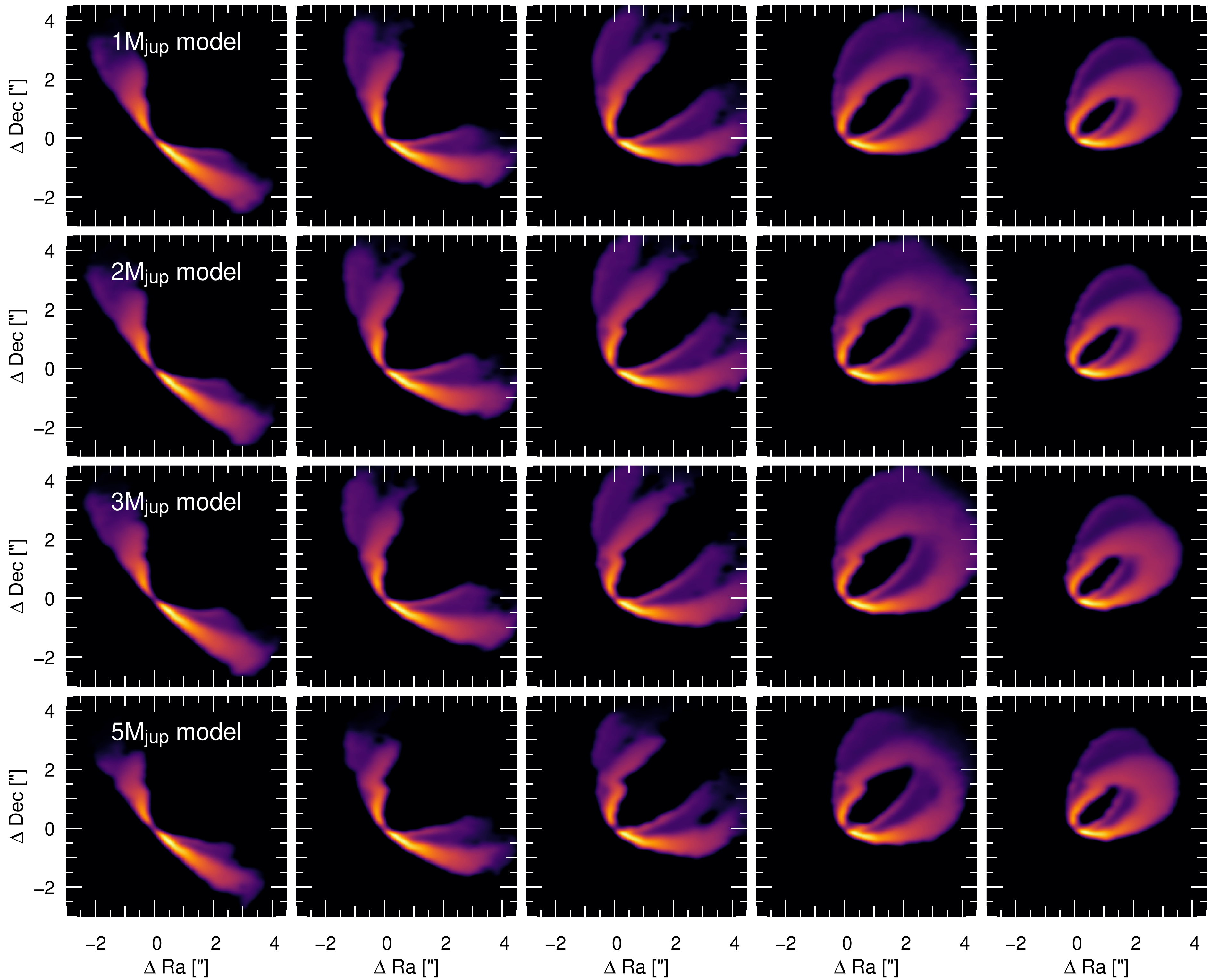


Gas kinks

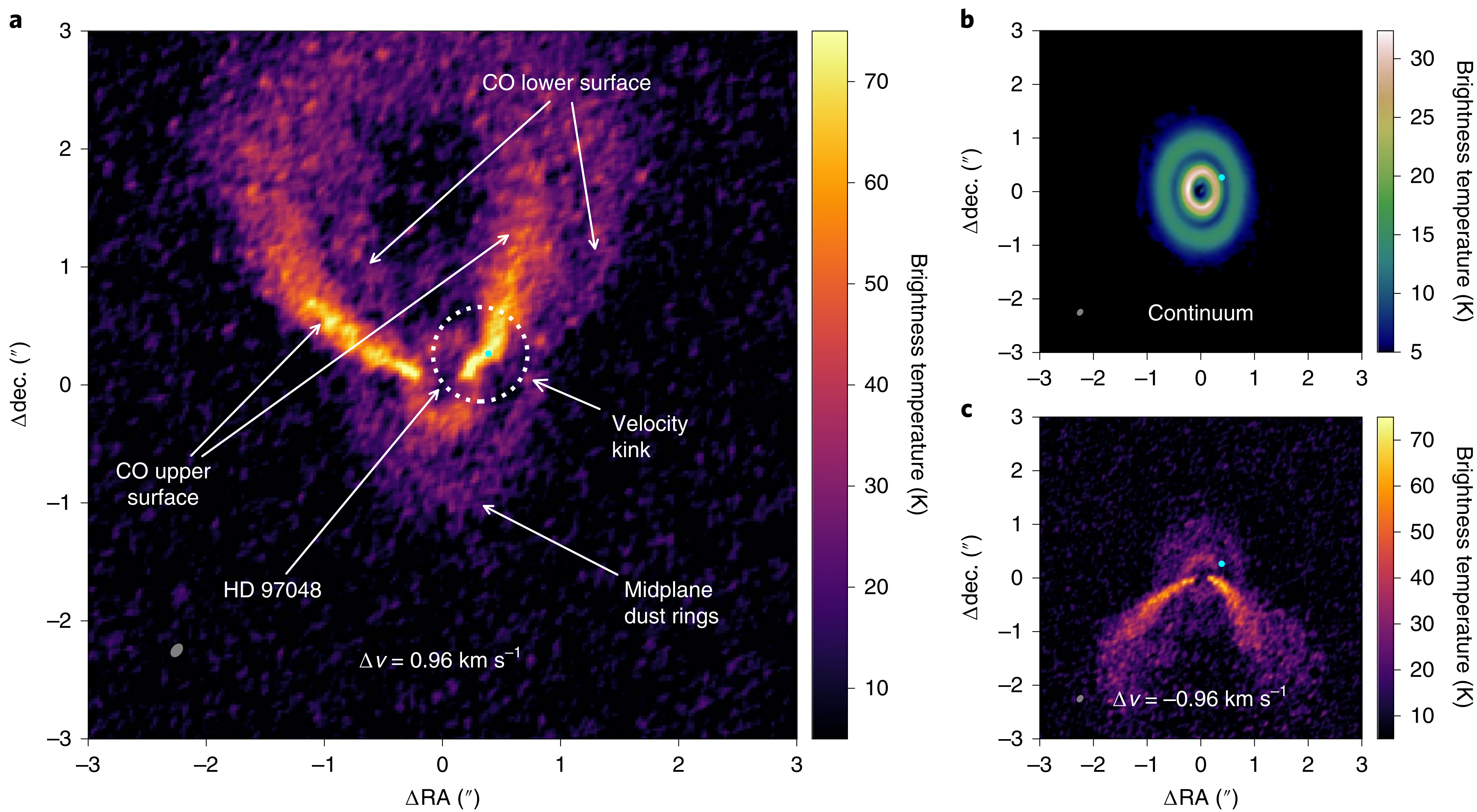
- Probing disk surface with ^{12}CO
- Forming protoplanet distorts the gas velocity pattern
    - spiral waves launched by planet

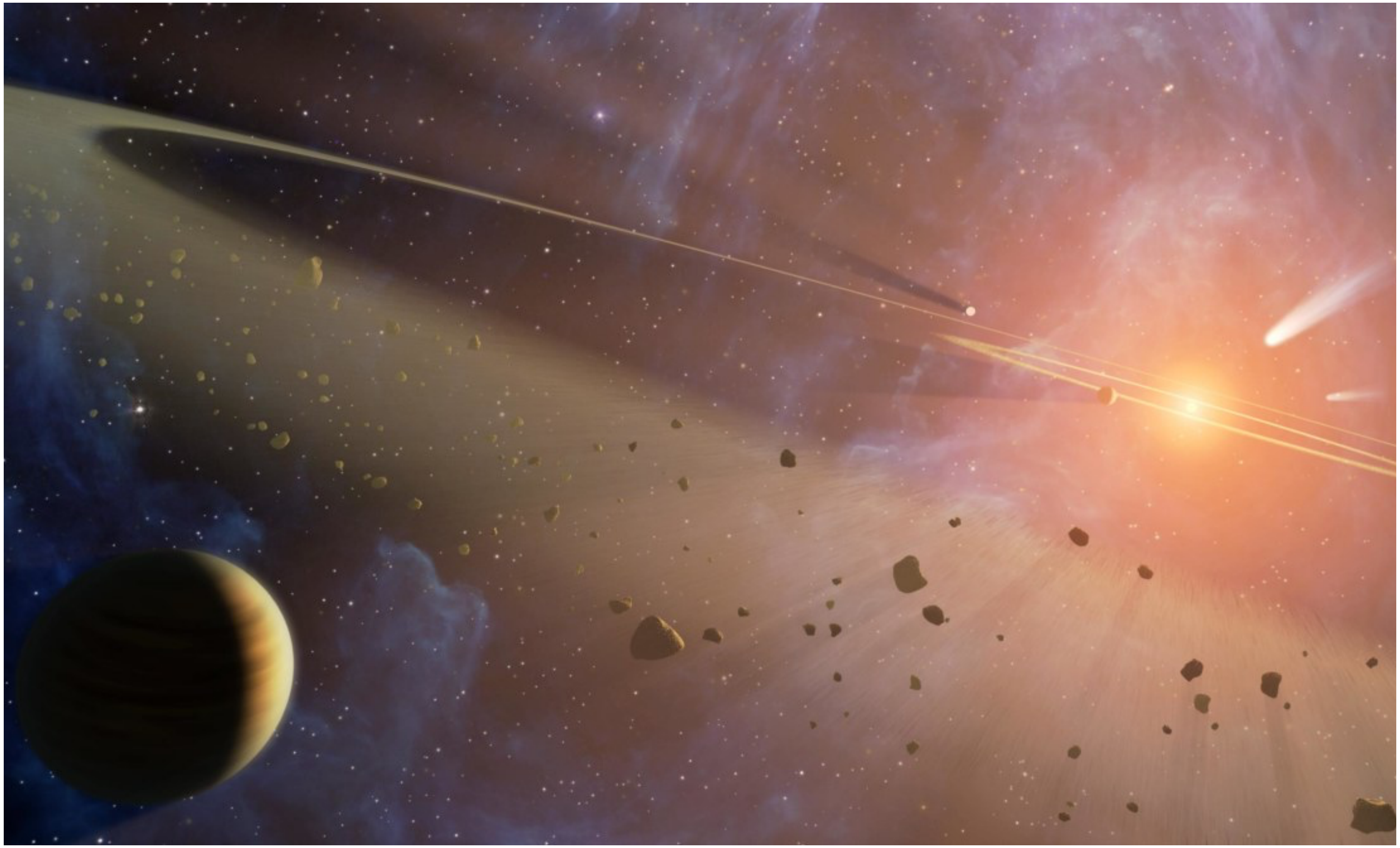


Gas kink: model



Gas kink: observation

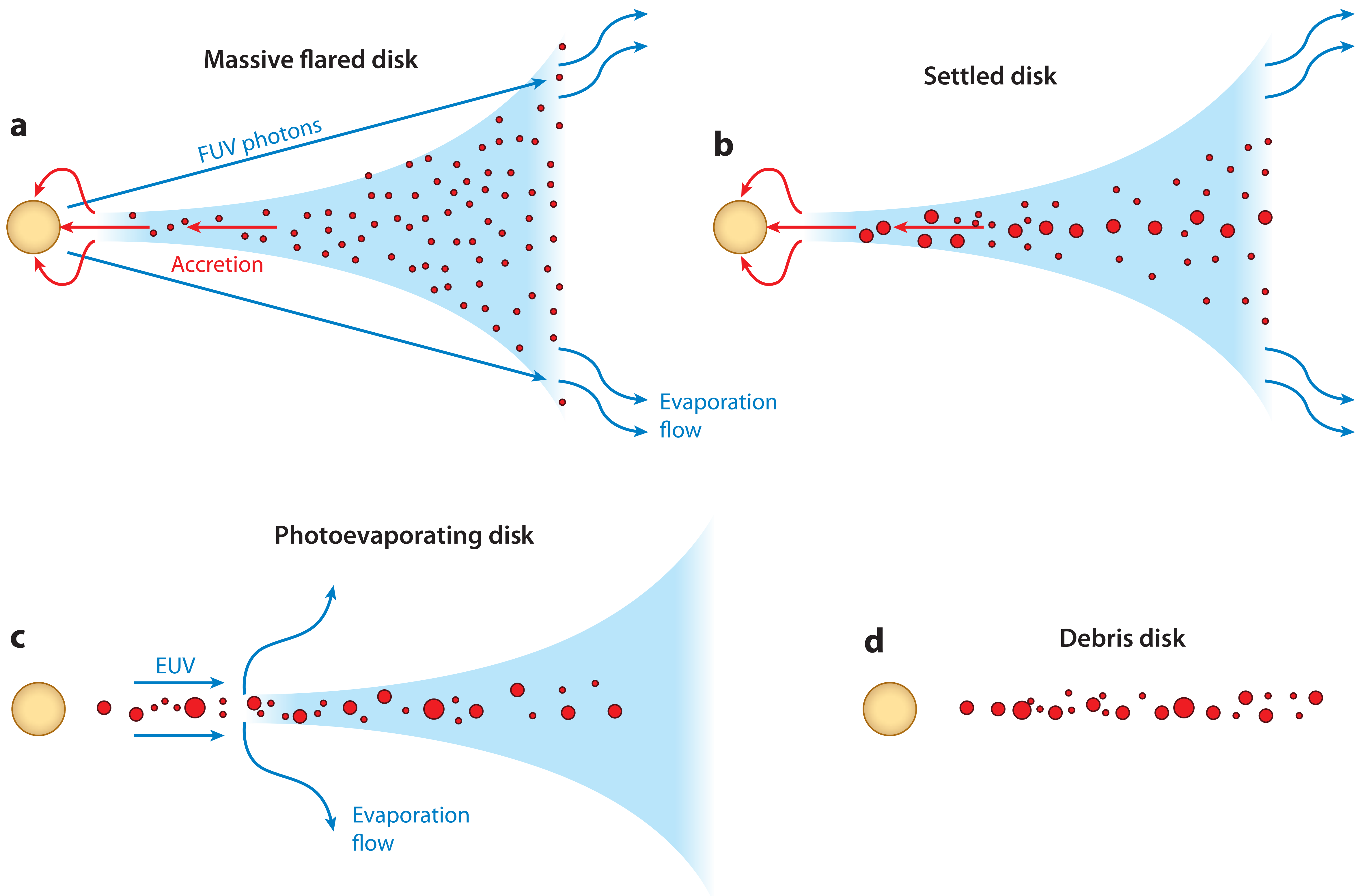




III. Debris disks

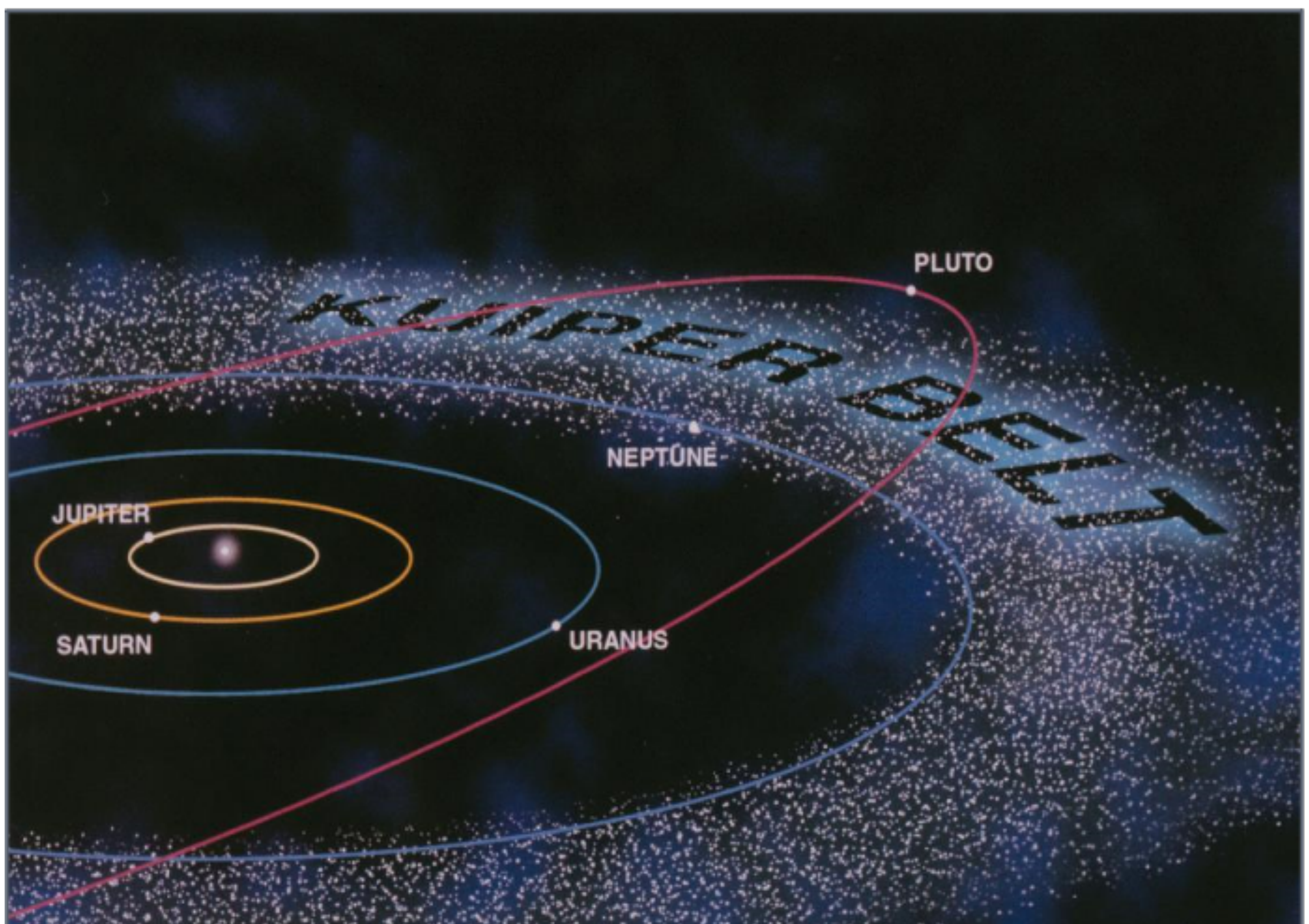
— the leftovers of planetary formation —

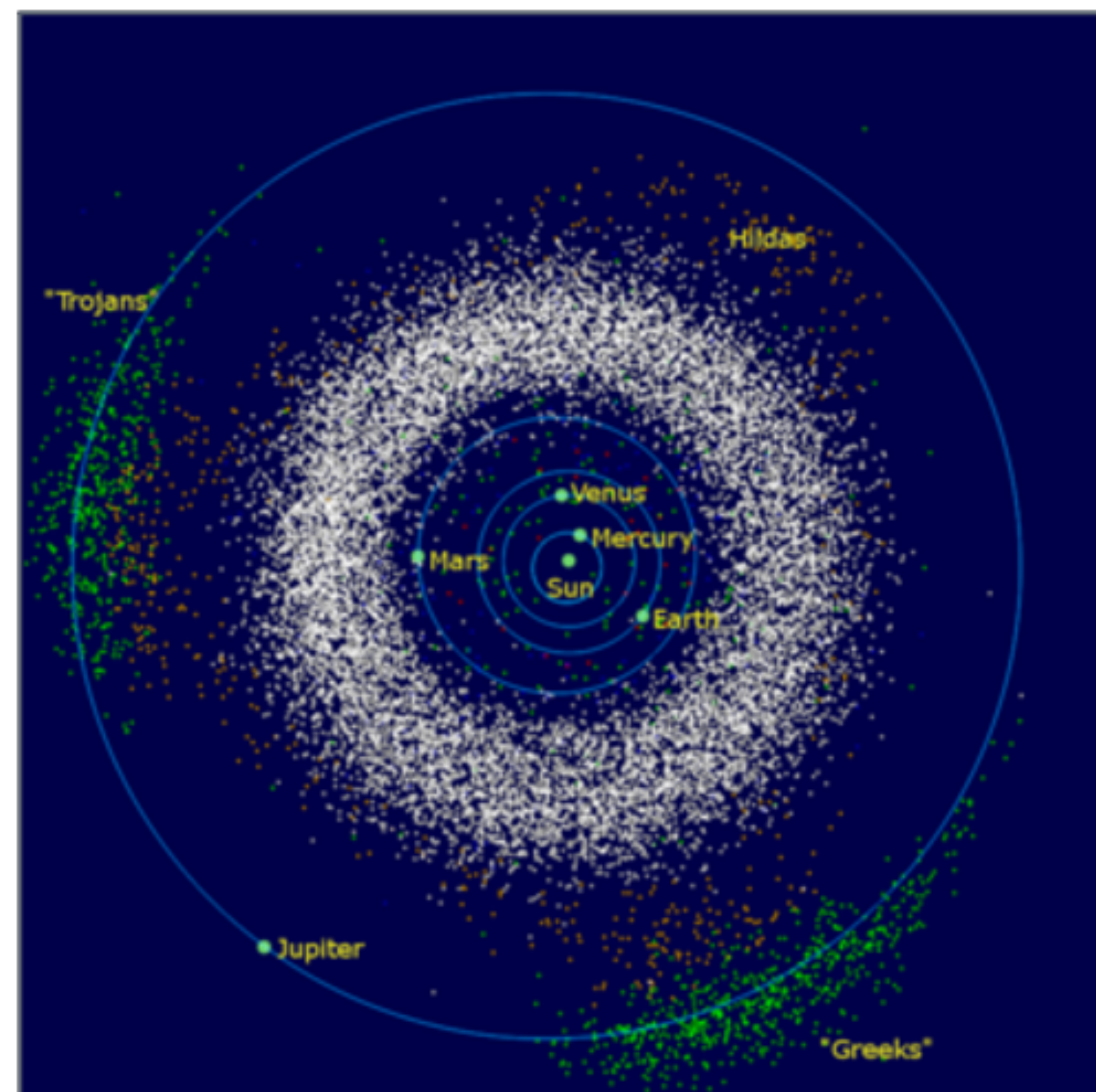
Evolution of disks



We all live in a debris disk

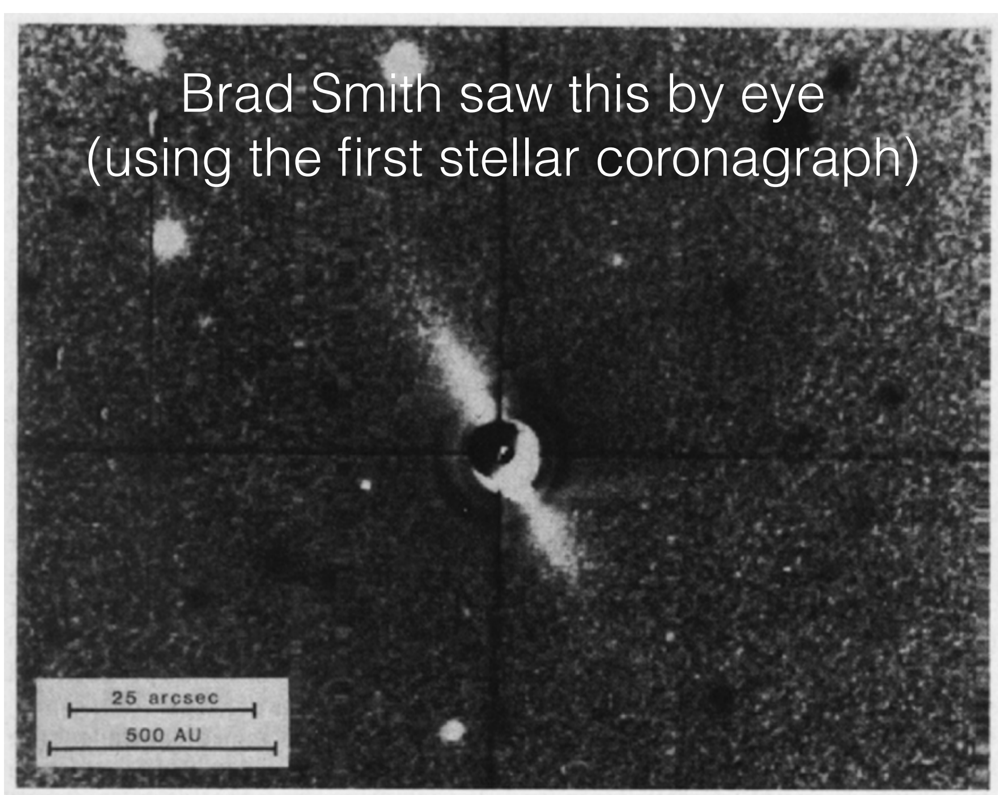
- Asteroid and Kuiper belts are our own debris disk



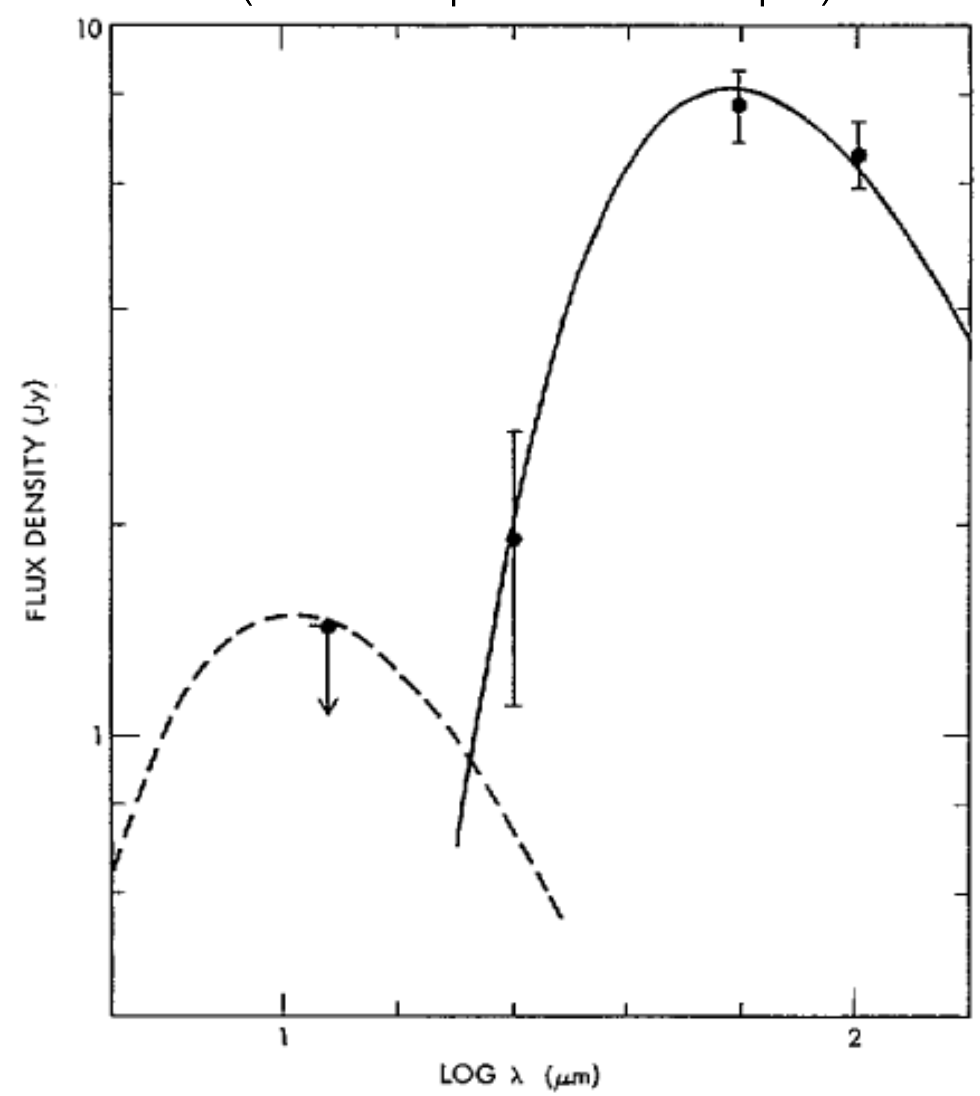


Debris disks: detection

- First planetary system detected in 1984
  - A circumstellar disk around beta Pictoris



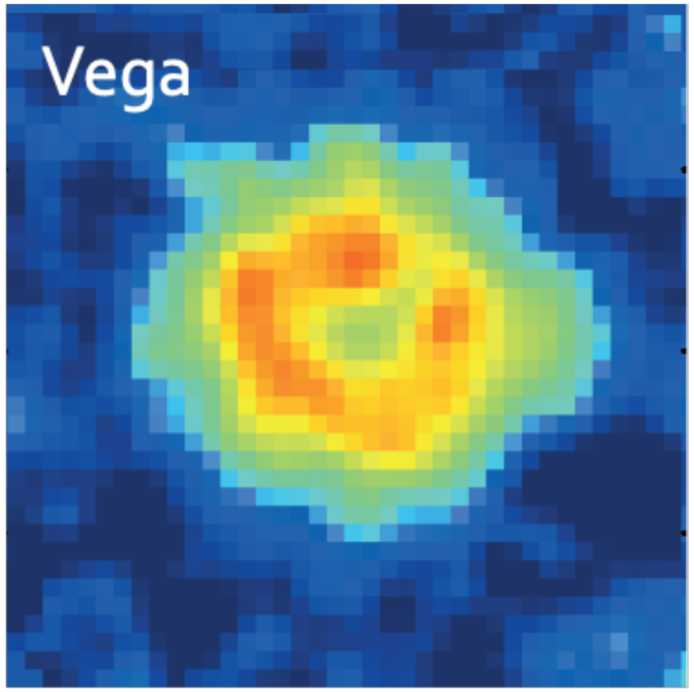
Infrared excess detected by IRAS
(first IR space telescope)

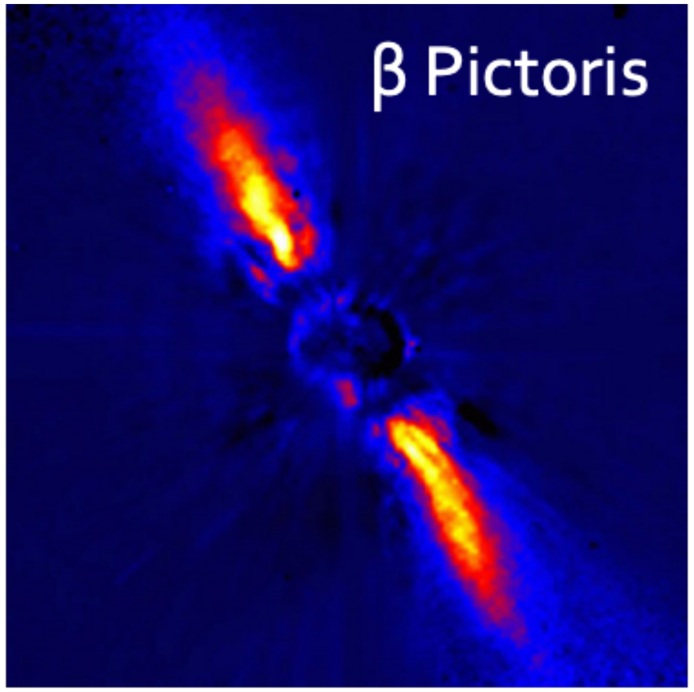


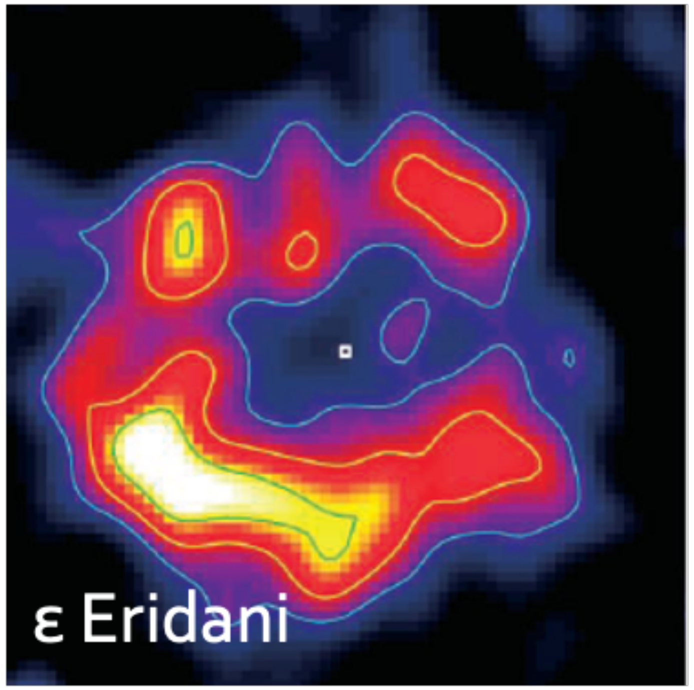
Debris disk imaging: optical and sub-mm

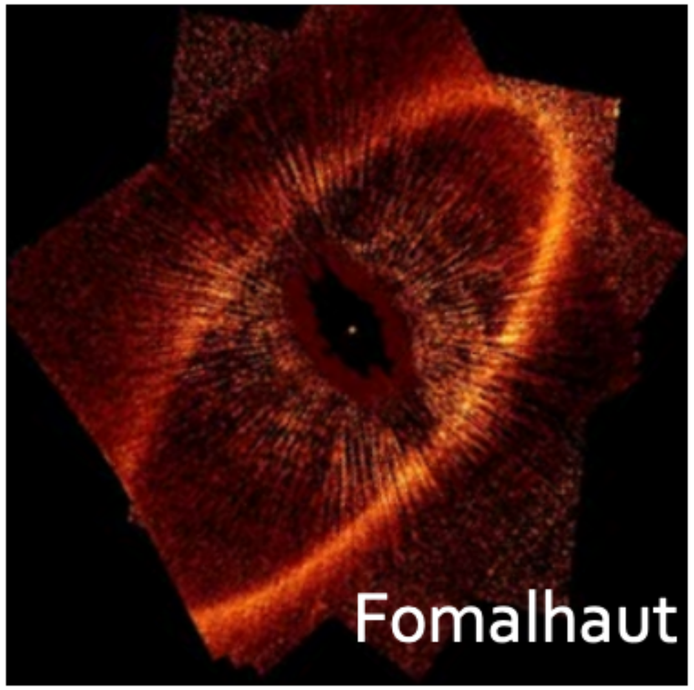
- Several images in the 2000's with HST and sub-mm antennas

- Now also studied with ground-based HCI

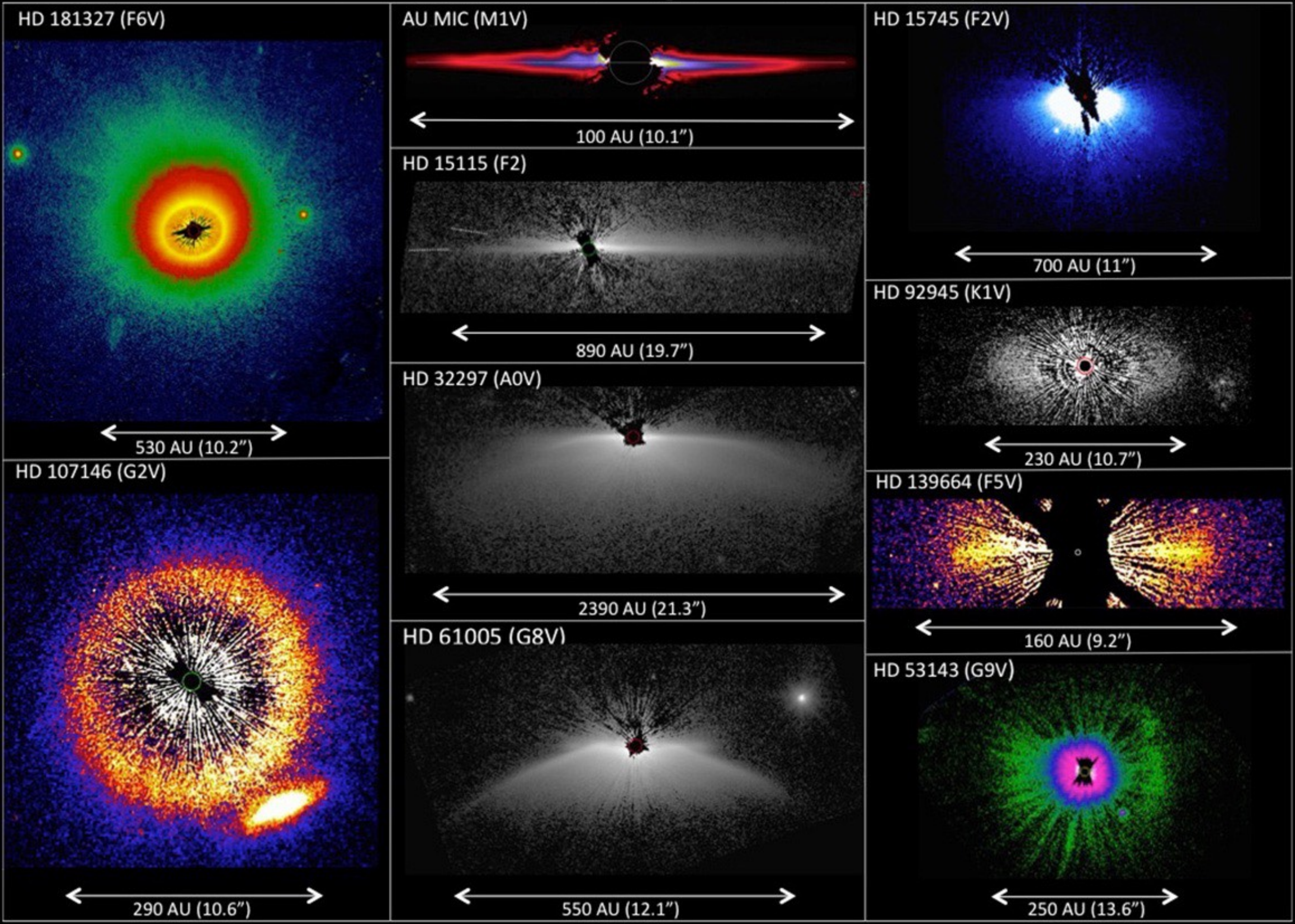






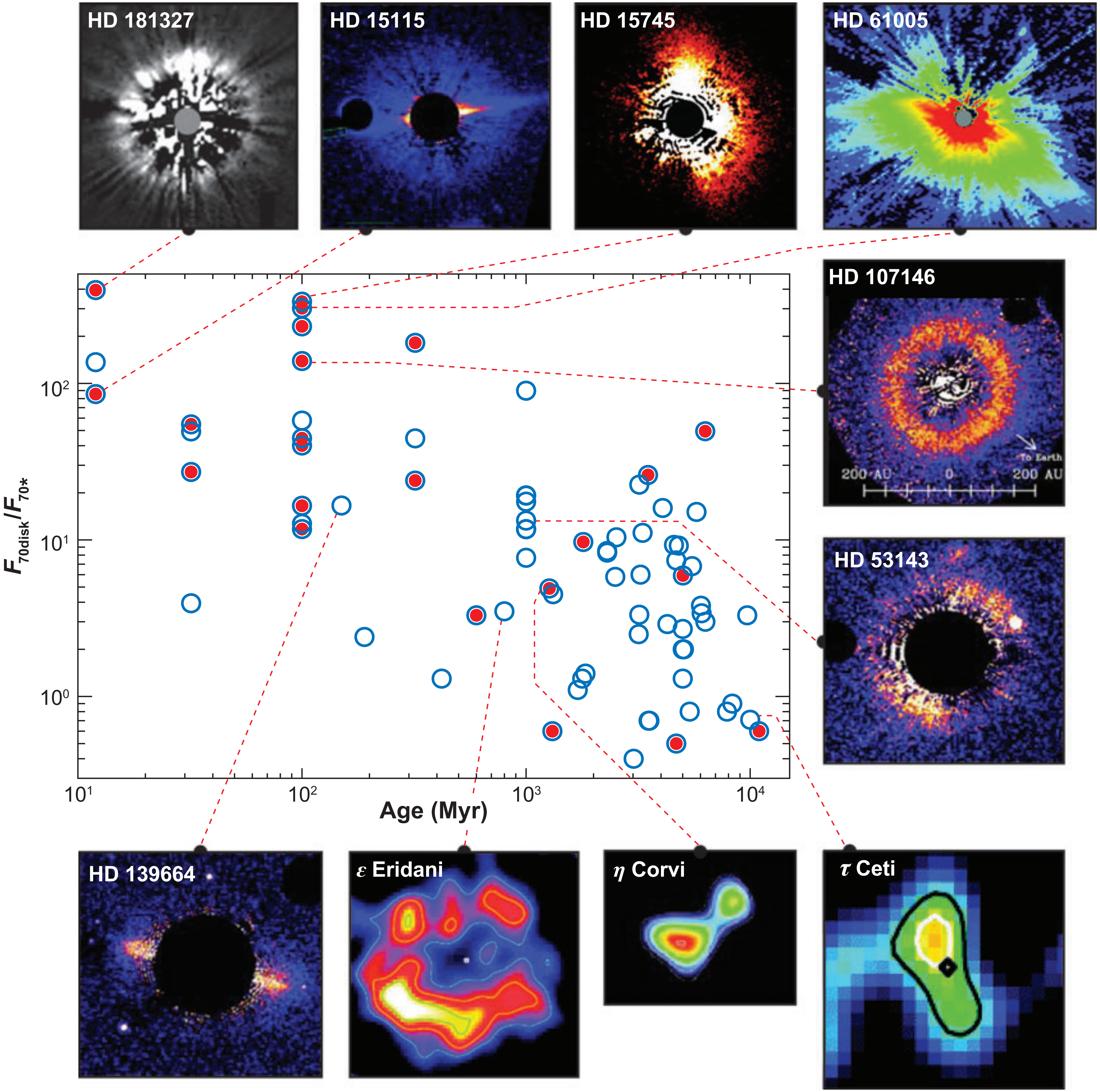


The Hubble GO/12228 Program Debris Disk Sample

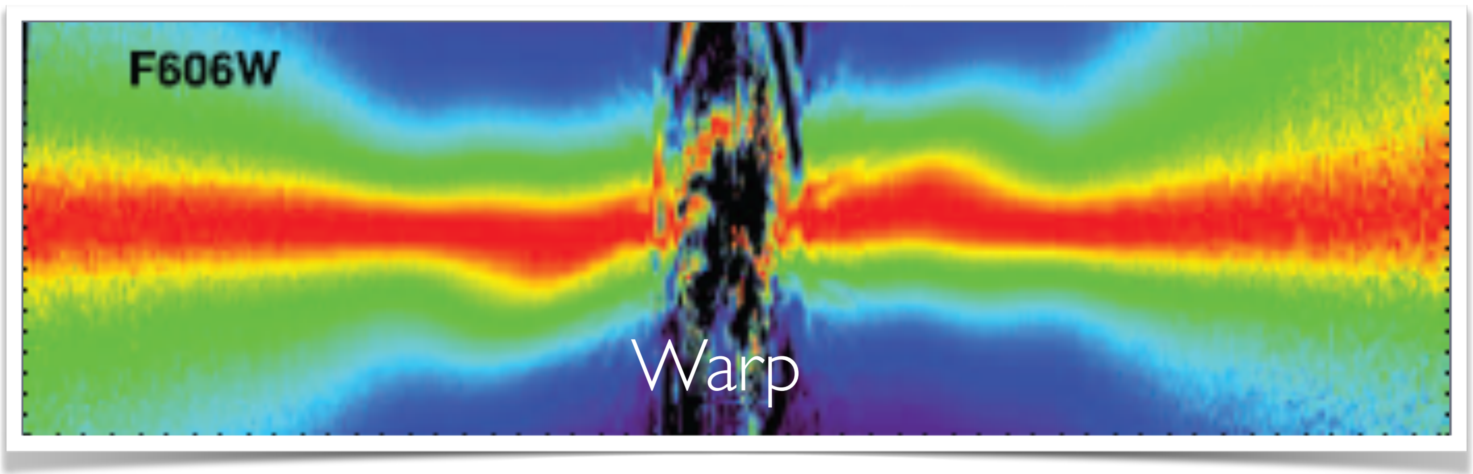


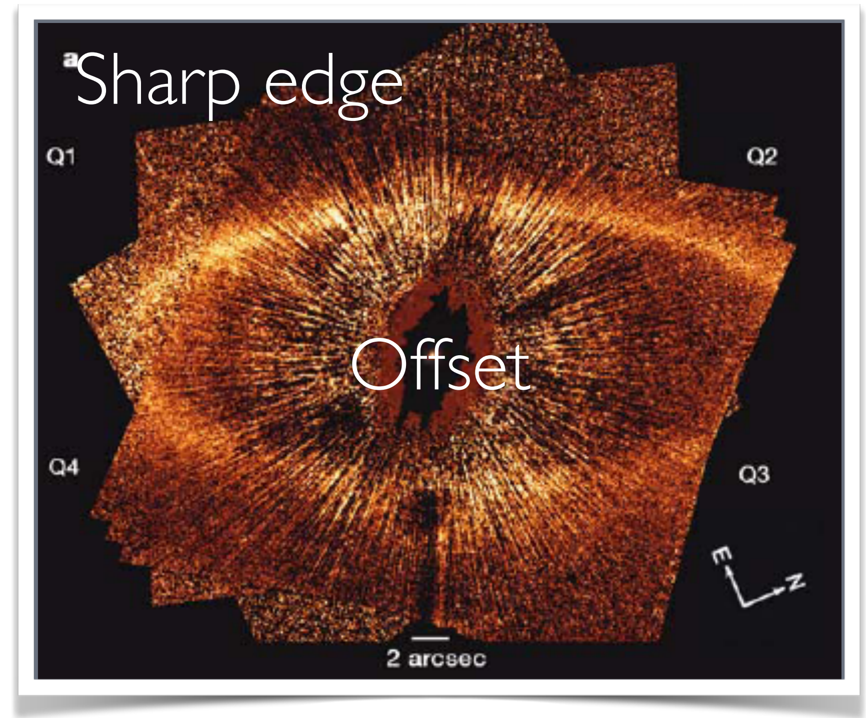
Disk luminosity slowly decreasing with time as planetesimals are ground down to dust, and radiation pressure expels small grains.

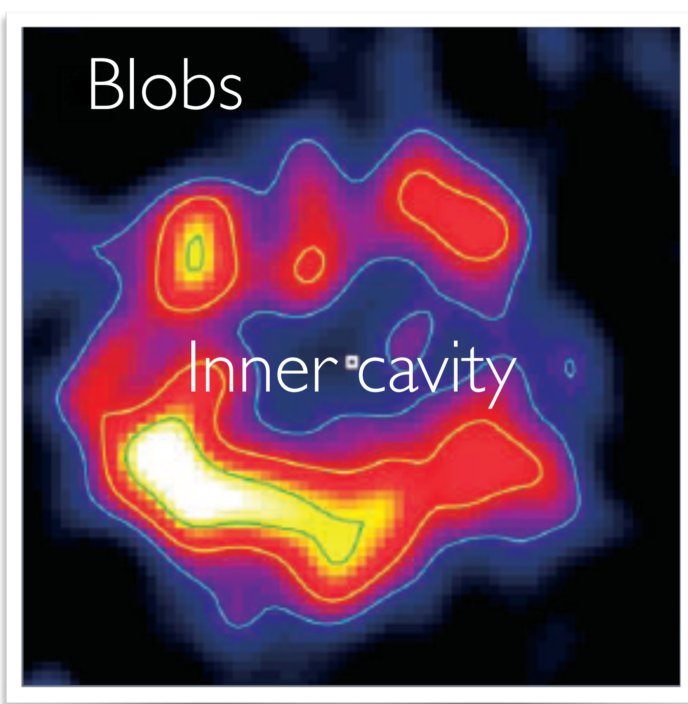
Nevertheless, bright debris disks have been detected and resolved at all ages.

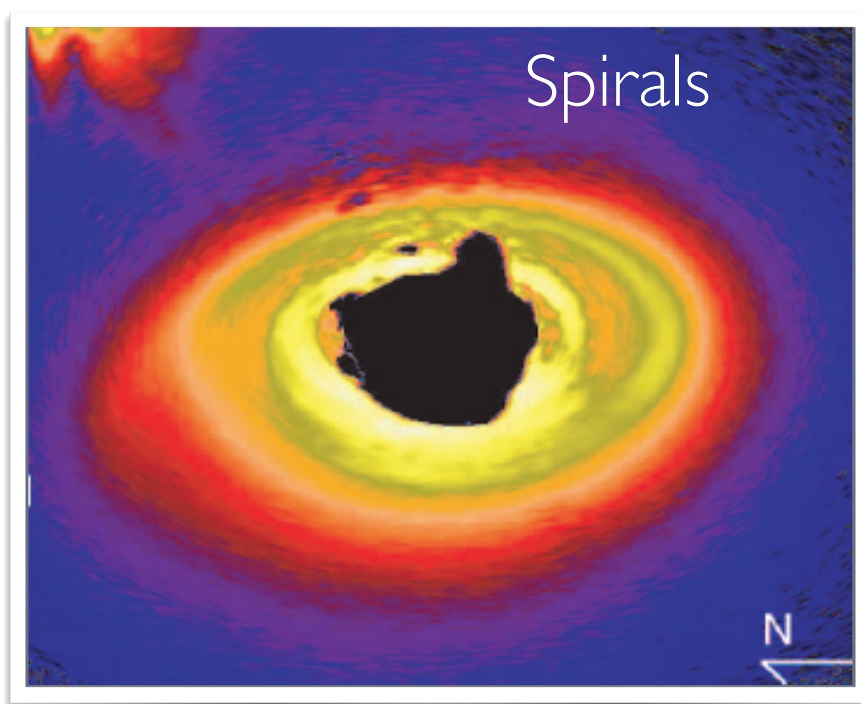


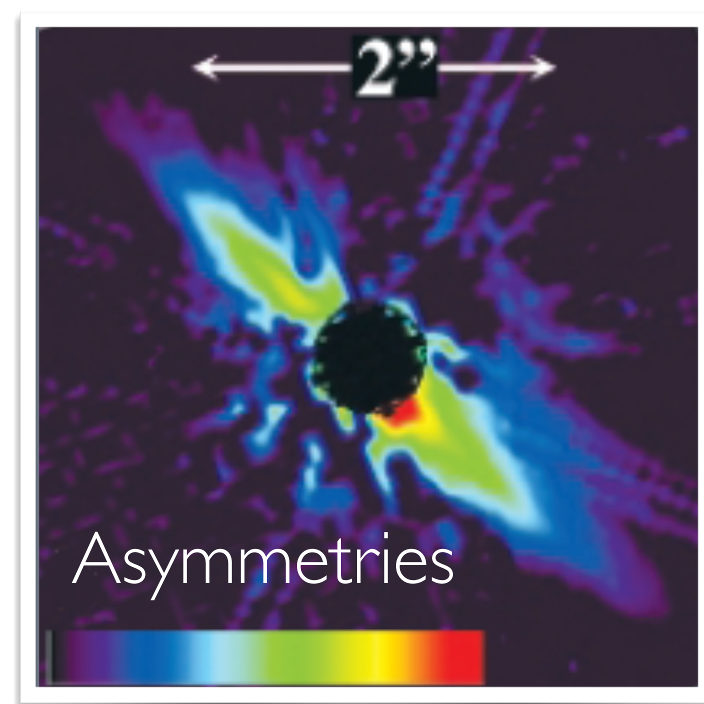
Many traces of planets



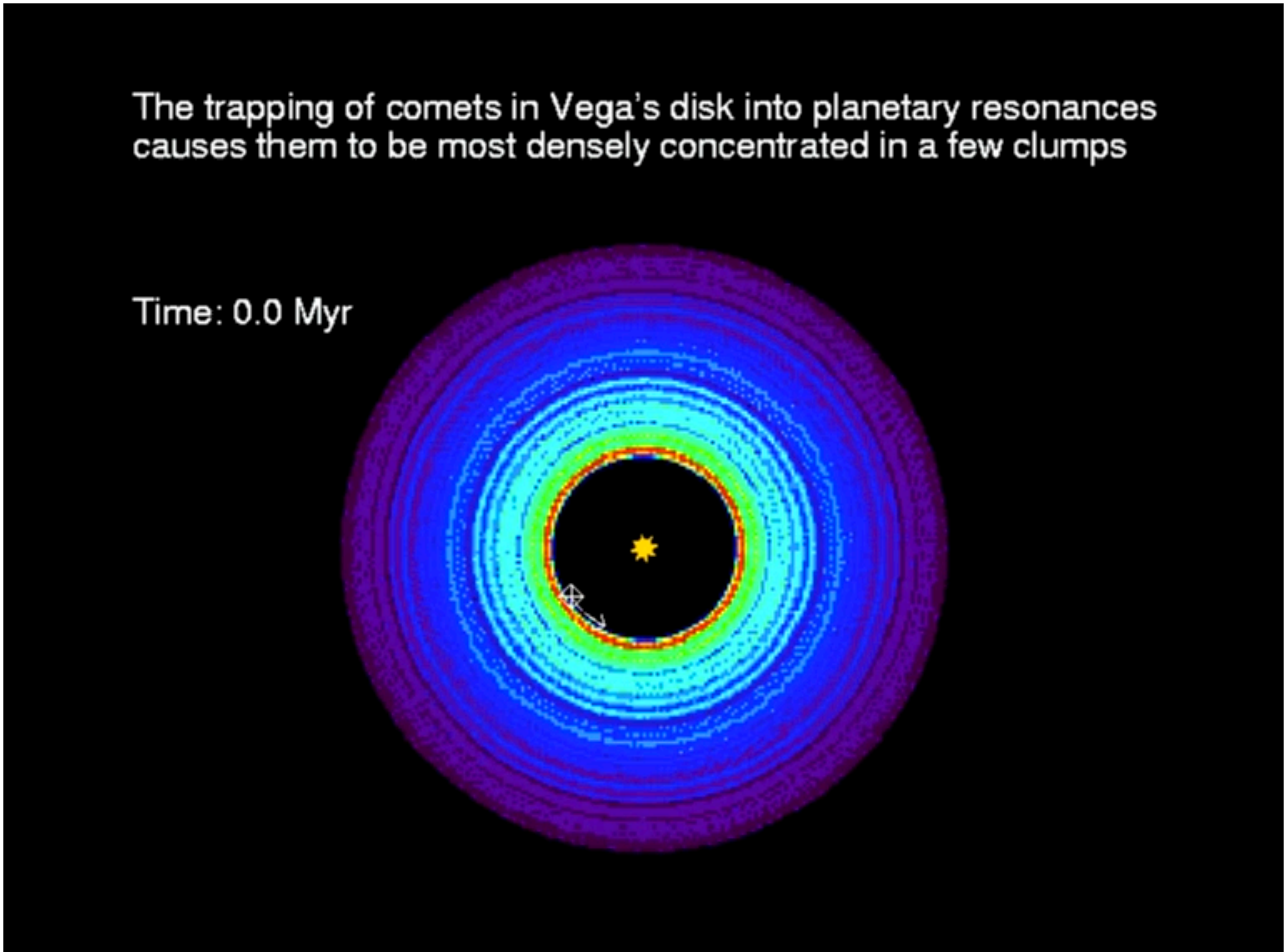






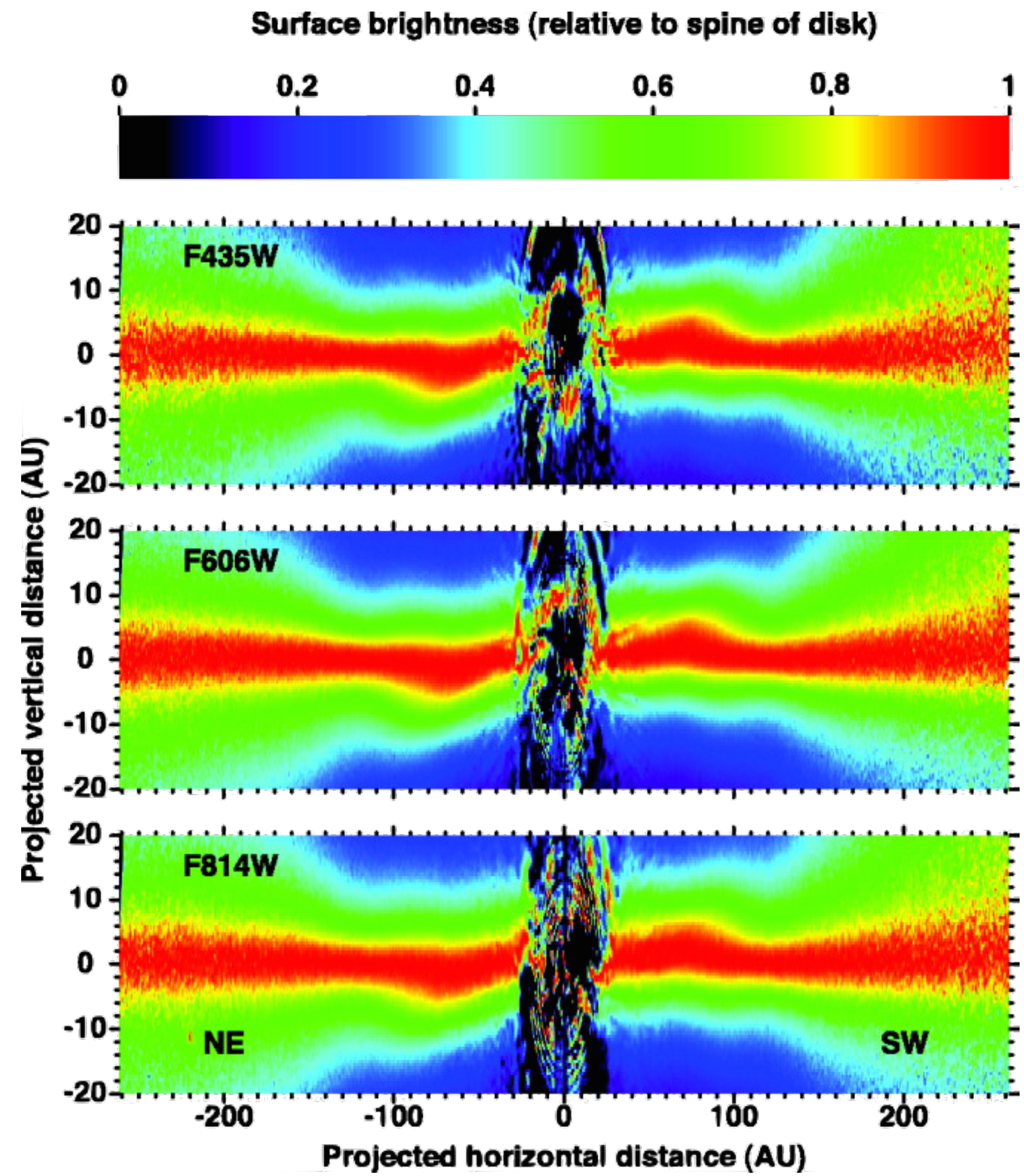


Dynamical interactions



Planet-disk interactions

- beta Pic b orbit consistent with production of warp
- … but what caused beta Pic b to move out of the main disk plane in the first place?
- 2019: RV data suggest presence of 9 M_{Jup} planet orbiting at 2.7 au
- 2020: confirmed with direct detection (interferometry)



Golimowski et al. 2006

Conclusions

- Detection of exoplanets has profoundly changed our understanding of planet formation
- Most of the ingredients leading from molecular core collapse to planet formation have been identified
  - many details still remain open / unsolved, including the connection between disk structures and forming planets
- Directly imaging planet formation in young systems at optical and sub-mm wavelengths is key to obtain a consistent picture, and connect all the dots
  - soon: boost in angular resolution with extremely large telescopes!