Signatures of Planets and of their Formation Process in Circumstellar Disks

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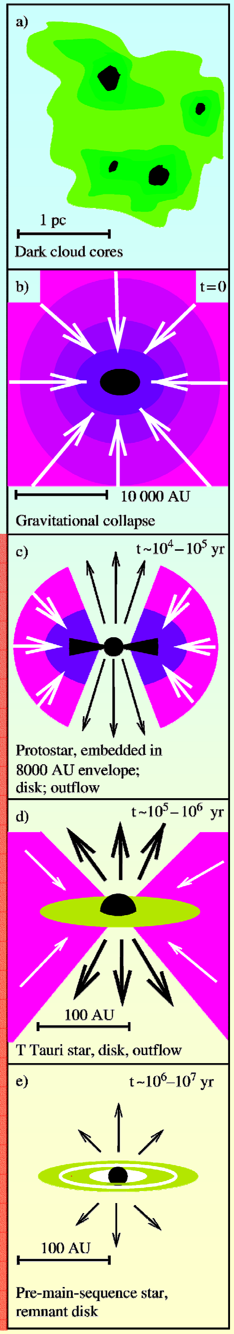
Emmy Noether Research Group
“Evolution of Circumstellar Dust Disks to Planetary Systems”
Max Planck Institute for Astronomy

Planet Formation in a Nutshell



(Waelkens 2001)

Star Formation Process → Circumstellar Disks → Planets

Core Accretion – Gas Capture

(sub)µm particles

↓

- Brownian Motion, Sedimentation, Drift
- Inelastic Collision → Coagulation

cm/dm grains

↓

- Agglomeration;
  Fragmentation

Planetesimales

↓

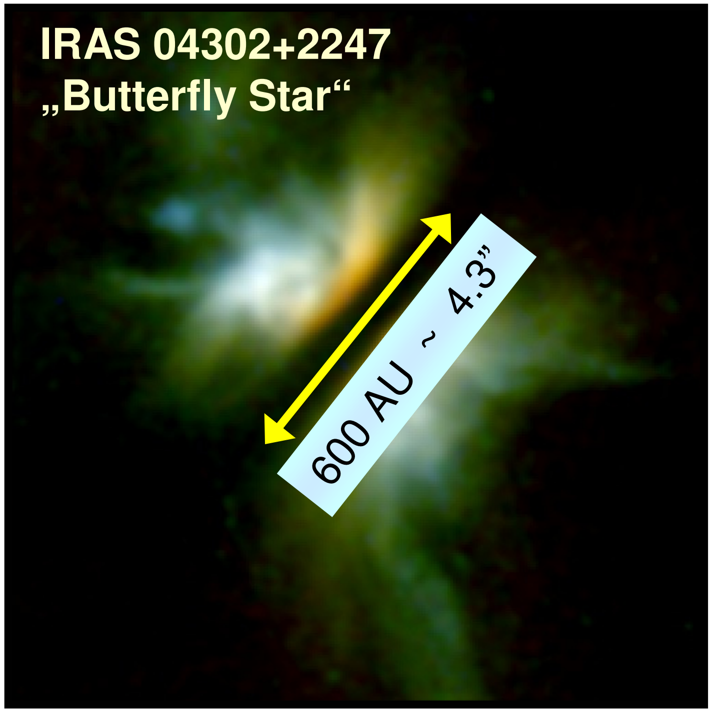
- Gravitational Interaction: Oligarchic Growth

Planets (cores)

- Gas Accretion

Alternativ: Gravitational Instability → Giant Planet

Size Scales



Solar System

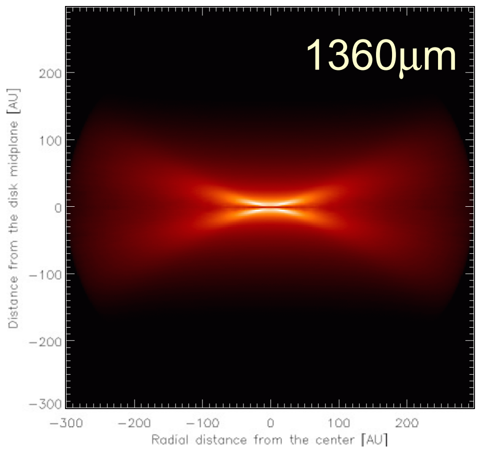
Angular diameter of the orbit of solar system planets in a distance of the Taurus star-forming region (140pc):

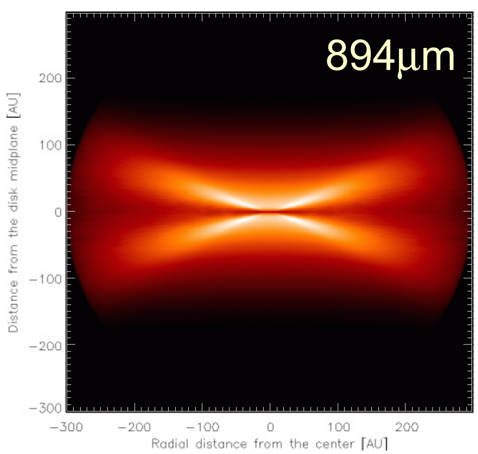
Neptune	-	0.43”
Jupiter	-	0.074”
Earth	-	0.014”

What is feasible?

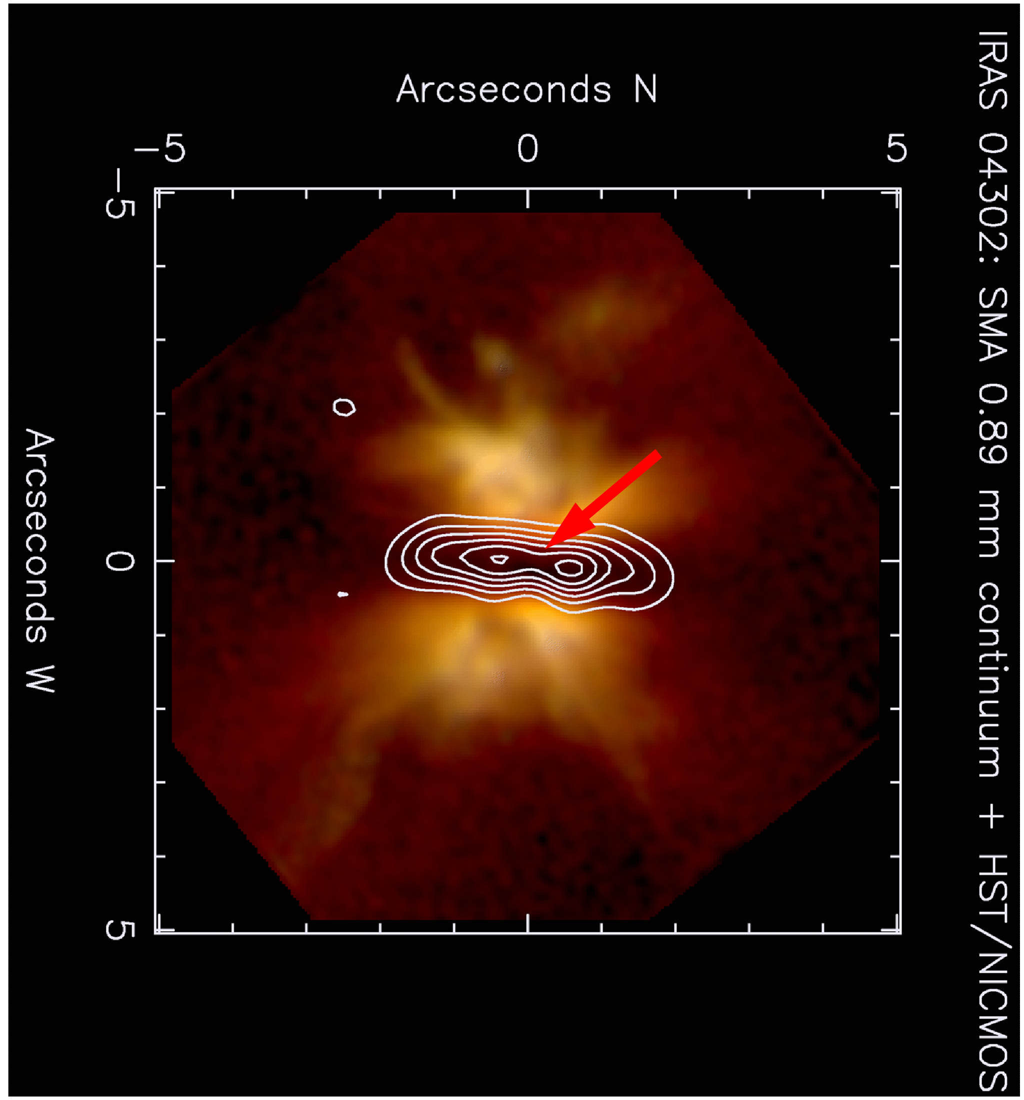
AMBER / VLTI	~ few mas	[near-IR]
MIDI / VLTI	~ 10 – 20 mas	[N band]
SMA	~ 0.3” (goal: 0.1”)	[~submm]

Submillimeter Disk Structure



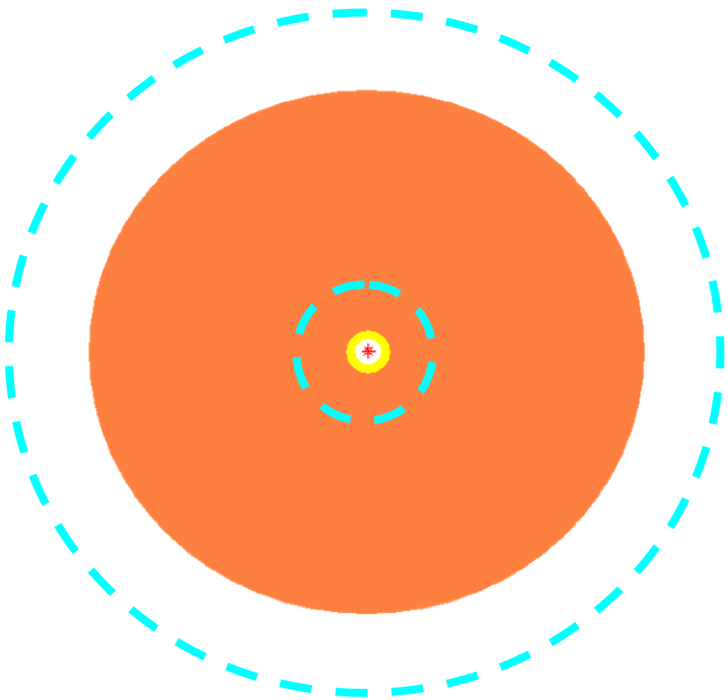


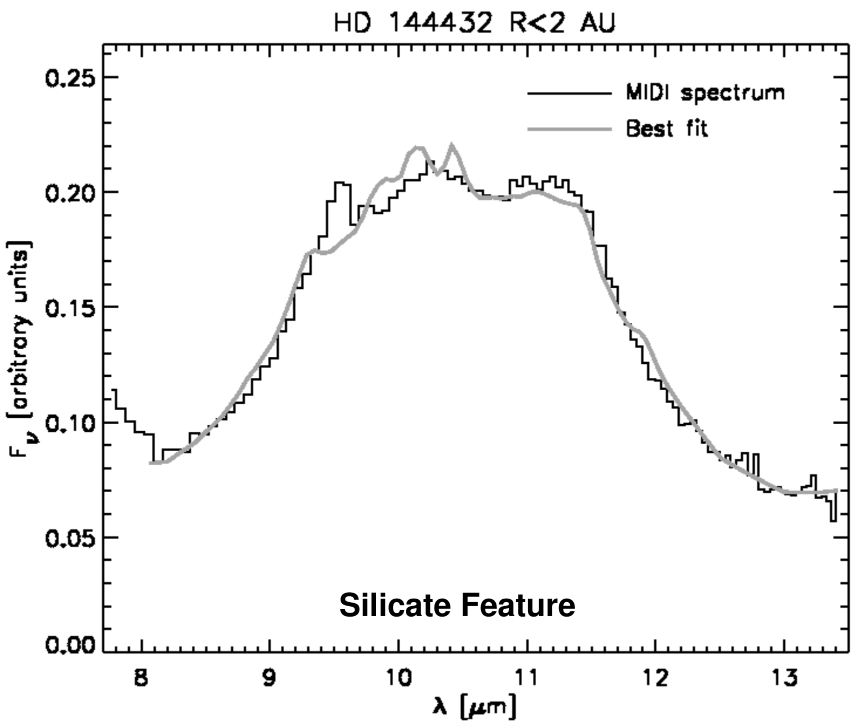
[Wolf et al., subm.]



constraints on radial + vertical disk structure
in the potential planet-forming region (r~80-120AU)

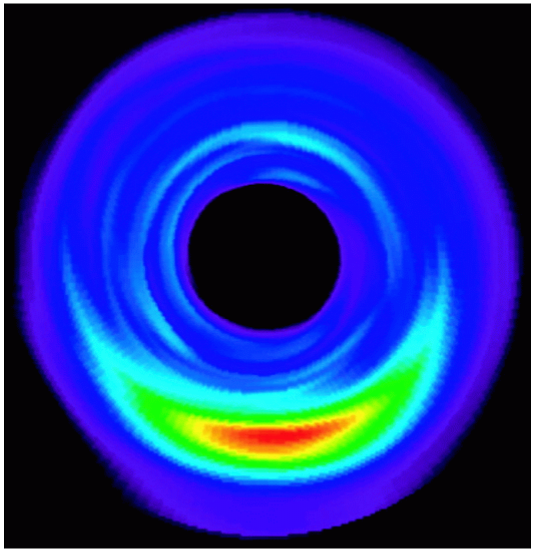
Dust Evolution – The Planet Forming Region





Van Boekel et al. (2004):	HAe/Be stars
Schegerer et al. (subm.):	T Tauri Stars

Vortices – Precursors of Protoplanets?



Klahr & Bodenheimer (2002)

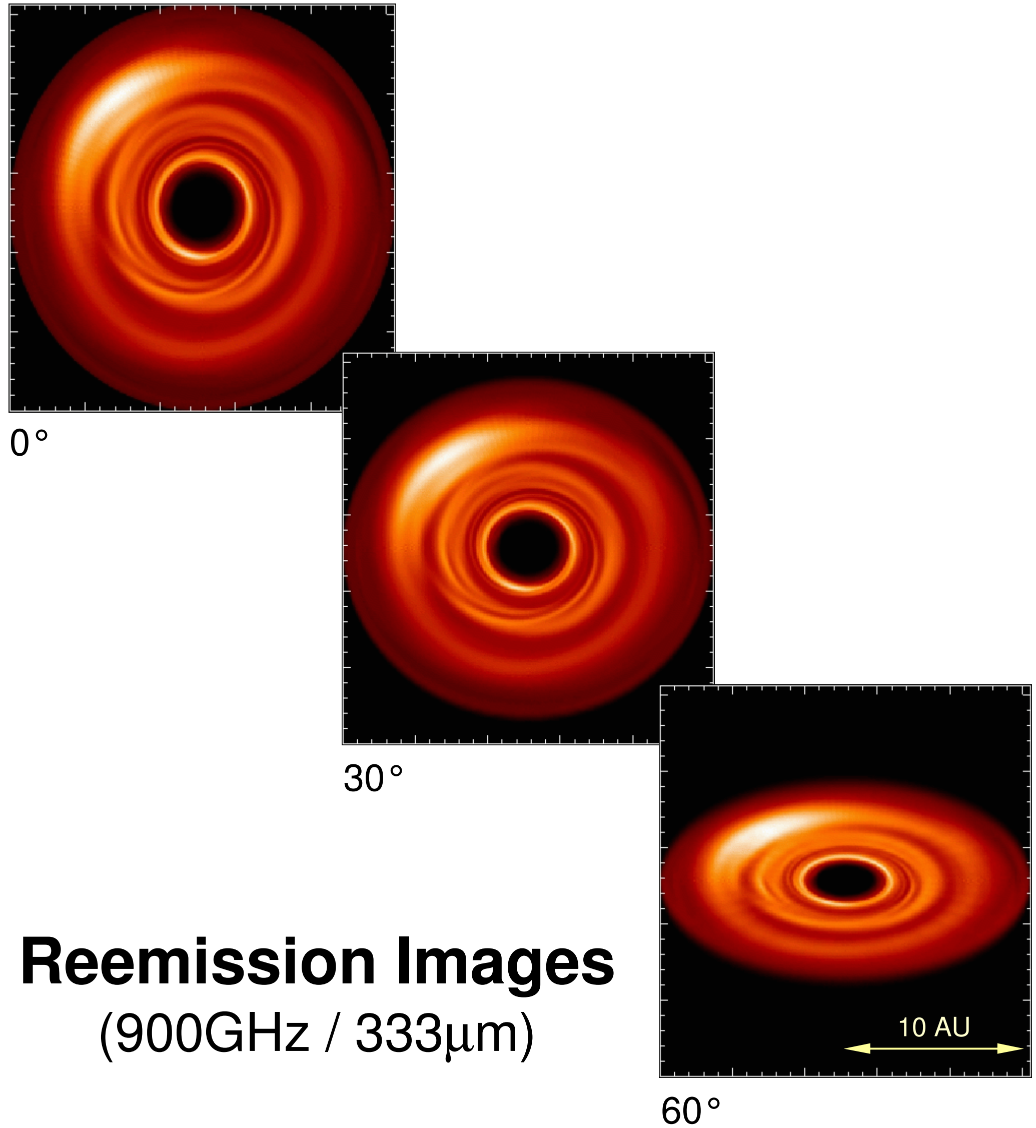
Global baroclinic instability

↓

Turbulence

↓

Long-lived high-pressure overdense anticyclones

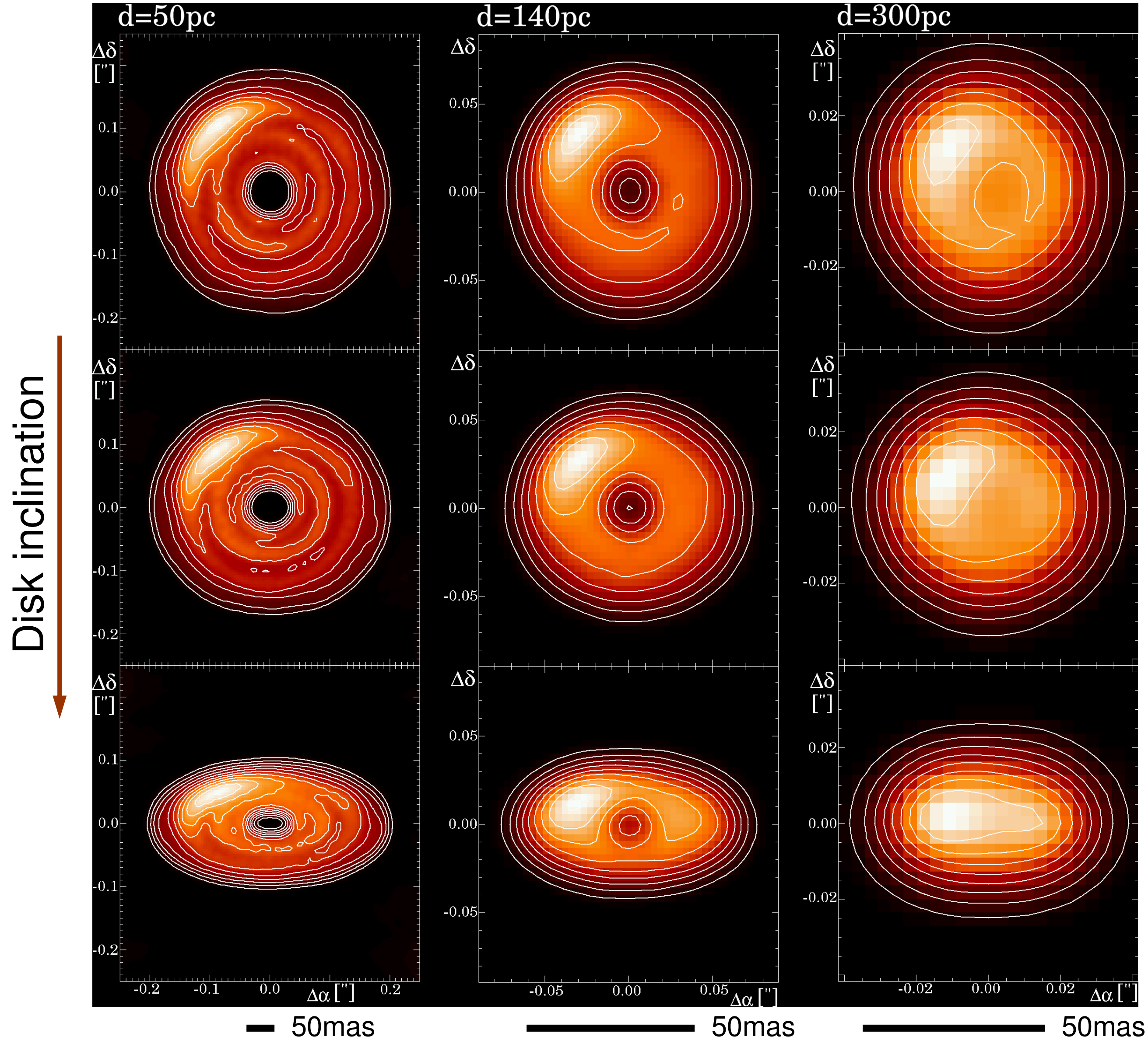


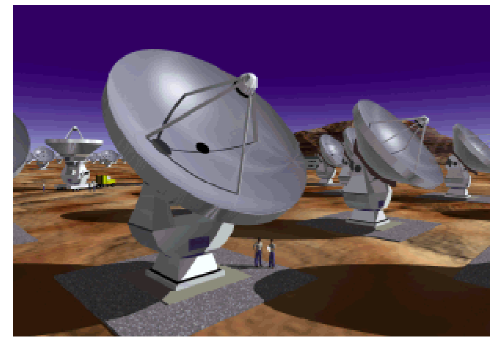
Reemission Images

(900GHz / 333µm)

[Wolf & Klahr 2002]

Vortices – Precursors of Protoplanets?





Simulation: ALMA

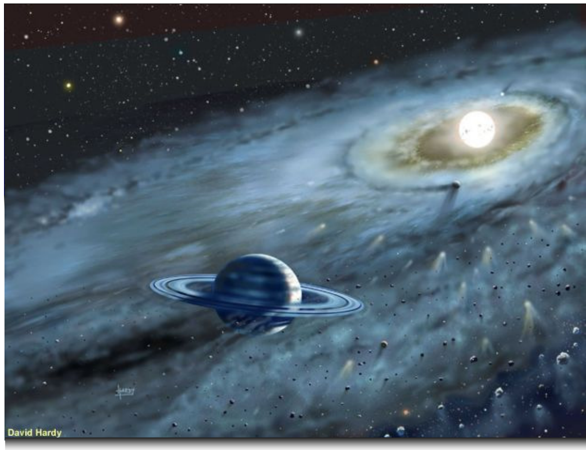
Baseline: 13km,
64 antennas

900GHz,
Integration time 2hrs

↓

Disk survey possible

[Wolf & Klahr 2002]



Finding Protoplanets - In Disks?

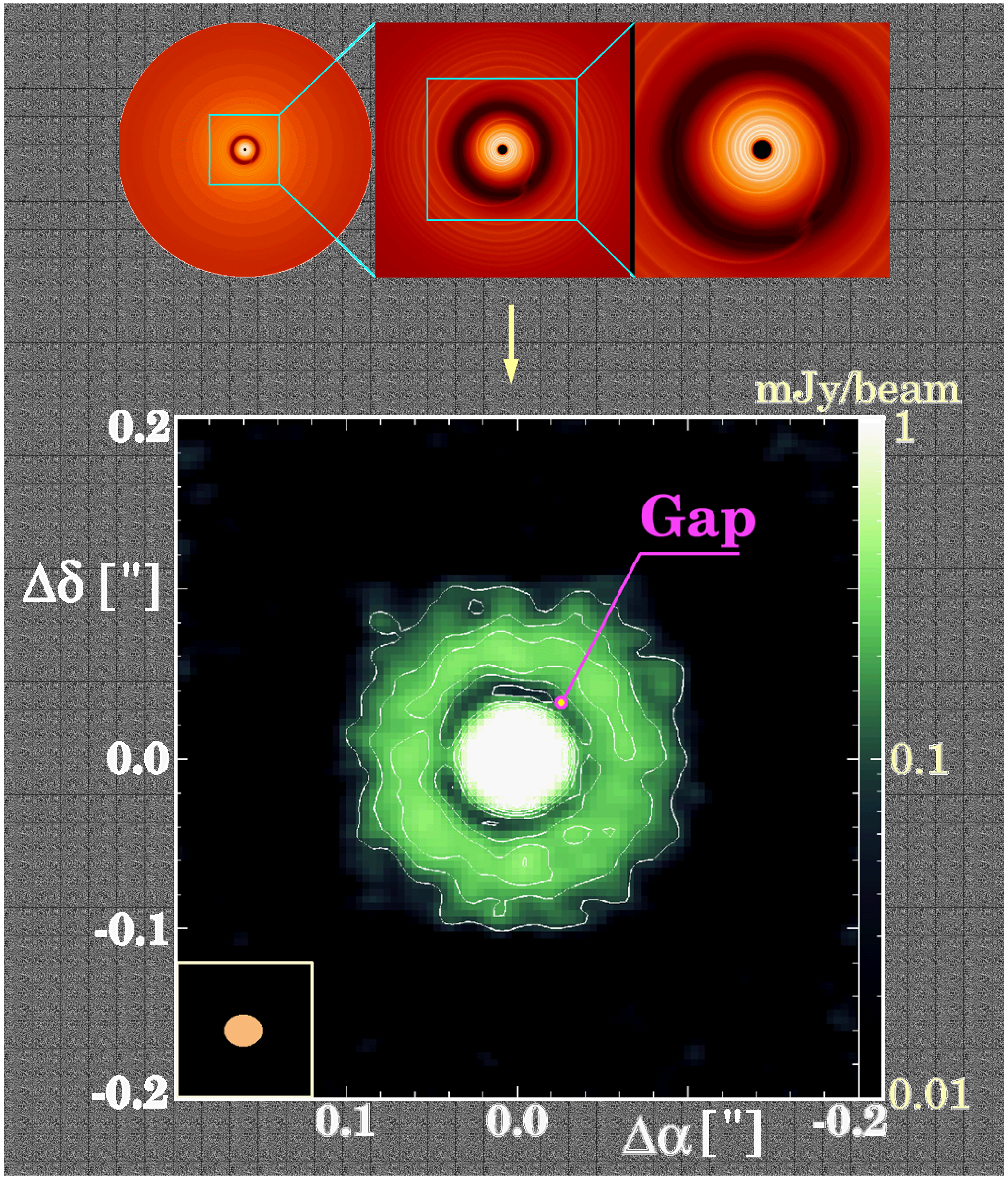
Additional Problems (Dust!)

UV – (N)IR	Scattering
IR – mm	Thermal Reemission
Young disks	Extinction (inclination-dependent)

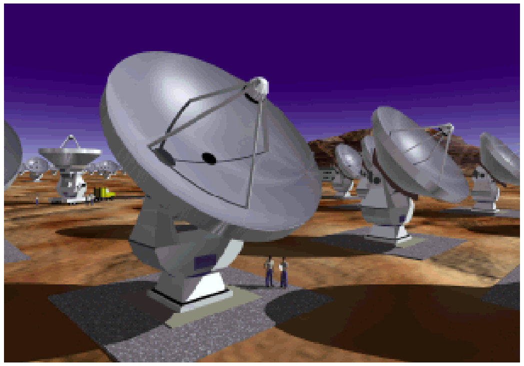
= *f (dust properties,* $\rho(r,\theta,\phi)$, $T(r,\theta,\phi)$)

Solution: High-resolution Imaging

ALMA: Gaps



Jupiter
in a 0.05 M_{sun} disk
around
a solar-mass star
as seen with ALMA



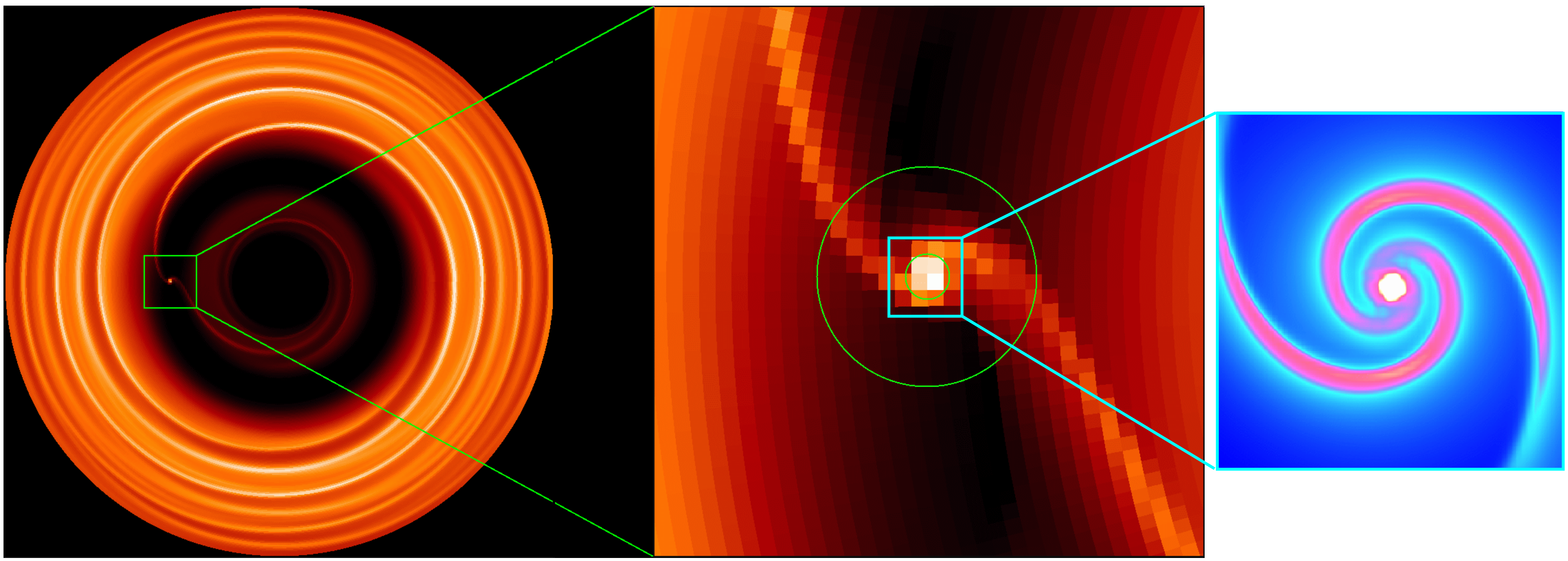
d=140pc

Baseline: 10km

λ=700µm, t_{int}=4h

[Wolf et al. 2002]

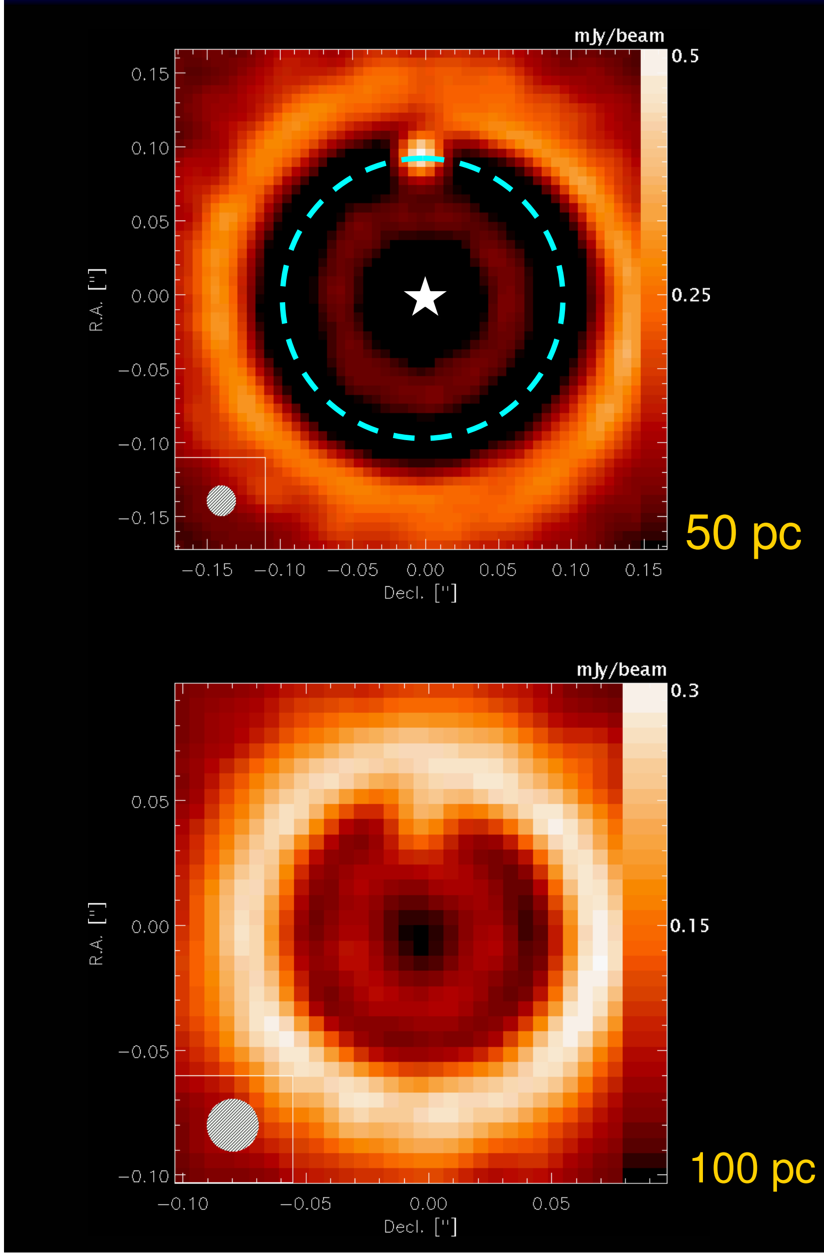
Planetary Accretion Region



[D'Angelo et al. 2002]

See Poster #7:
A. Hales & R. Reid

Close-up view: Planetary Region

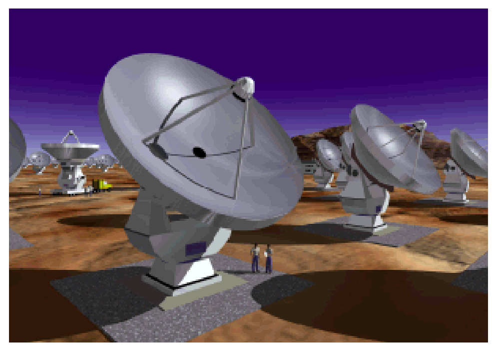


[Wolf & D'Angelo 2005]

$M_{planet} / M_{star} = 1M_{Jup} / 0.5\ M_{sun}$

Orbital radius: 5 AU

Disk mass as in the circumstellar disk as around the Butterfly Star in Taurus



Maximum baseline: 10km, 900GHz, t_{int}=8h

Random pointing error during the observation: (max. 0.6") ;
Amplitude error, "Anomalous" refraction;
Continuous observations centered on the meridian transit;
Zenith (opacity: 0.15); 30° phase noise;
Bandwidth: 8 GHz

Shocks & MRI

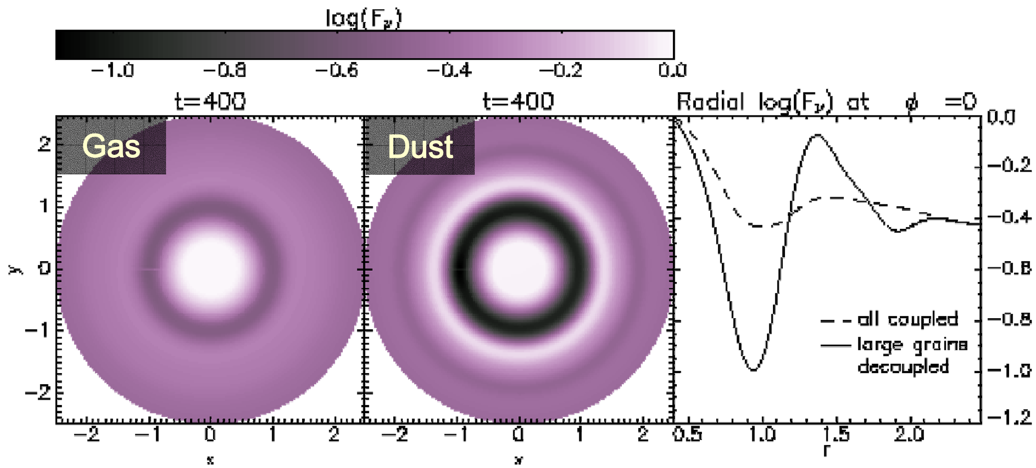
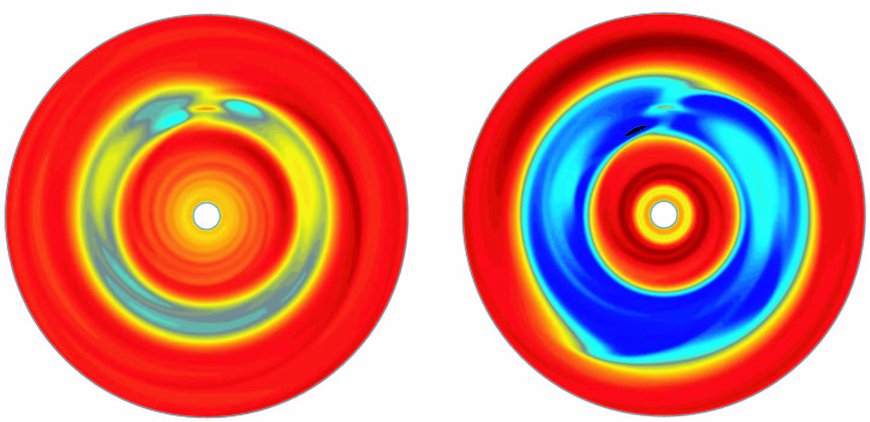


Fig. 3. Logarithm of flux densities at 1 mm, normalized by the maximum and convolved with a Gaussian of FWHM 2.5 AU, corresponding to a resolution of 12 mas at 140 pc. Left panel: all particles follow the gas exactly (static dust evolution). Middle panel: particles larger than the critical size decouple from the gas (dynamic dust evolution). Right panel: the corresponding radial flux densities.

(Paardekooper & Mellema 2004)

Strong spiral shocks near the planet are able to decouple the larger particles (>0.1mm) from the gas

→ **Formation of an annular gap in the dust, even if there is no gap in the gas density.**



Log Density in MHD simulations after 100 planet orbits for planets with relative masses of q=1x10^{-3} and 5x10^{-3} (Winters et al. 2003)

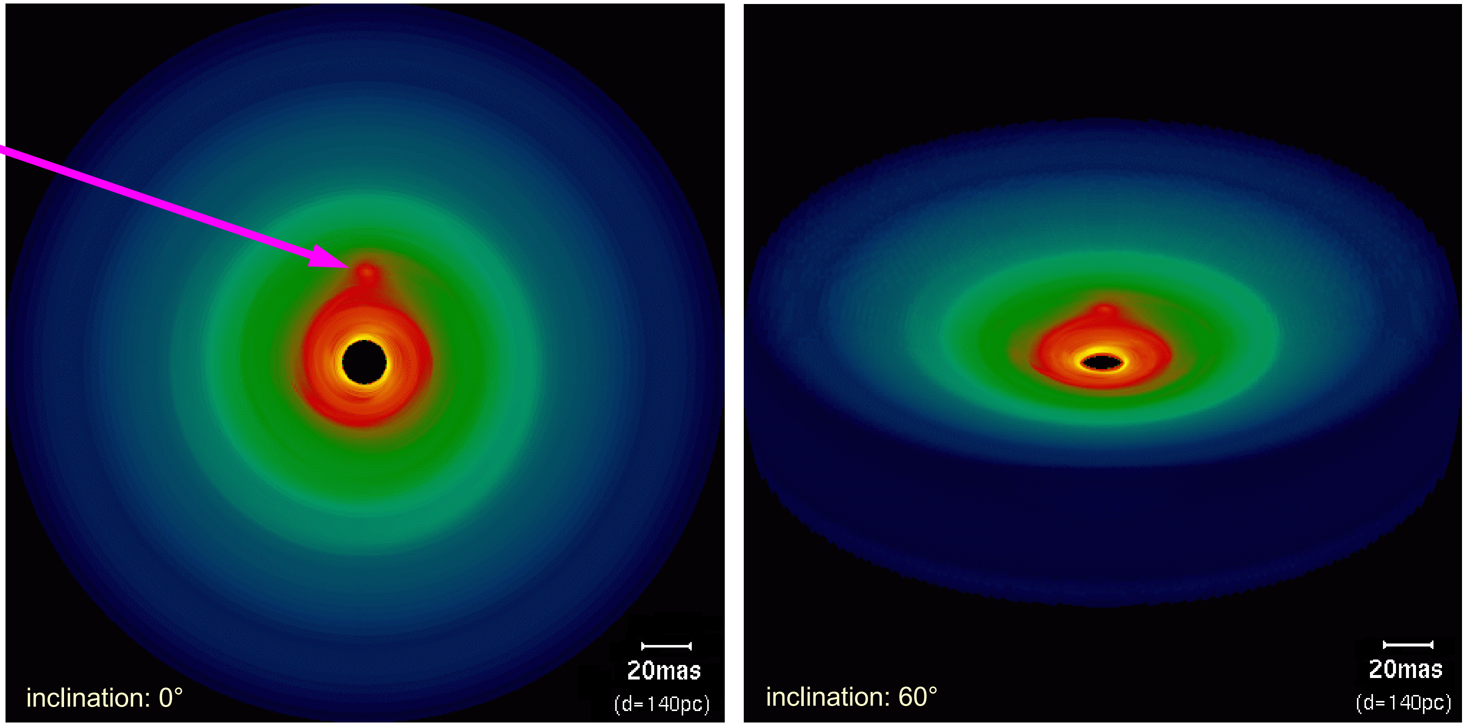
MHD simulations - Magnetorotational instability

- gaps are shallower and asymmetrically wider
- rate of gap formation is slowed

→ Observations of gaps will allow to constrain the physical conditions in circumstellar disks

Complementary Observations: Mid-IR

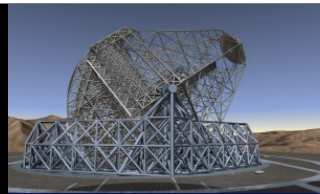
Hot Accretion
Region
around the Planet

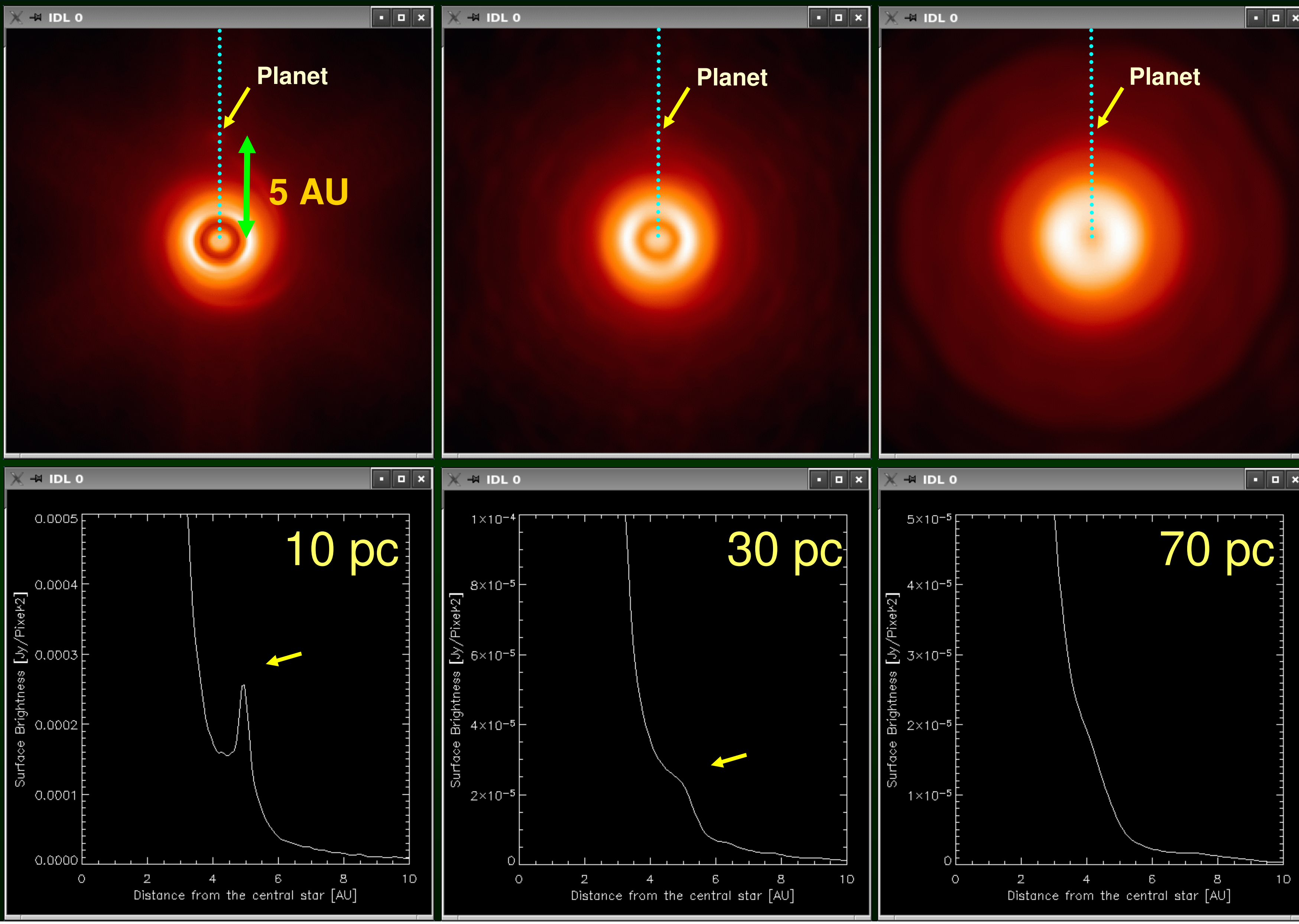


10μm surface brightness profile of a T Tauri disk
with an embedded planet
(inner 40AUx40AU, distance: 140pc)

[Wolf & Klahr, in prep.]

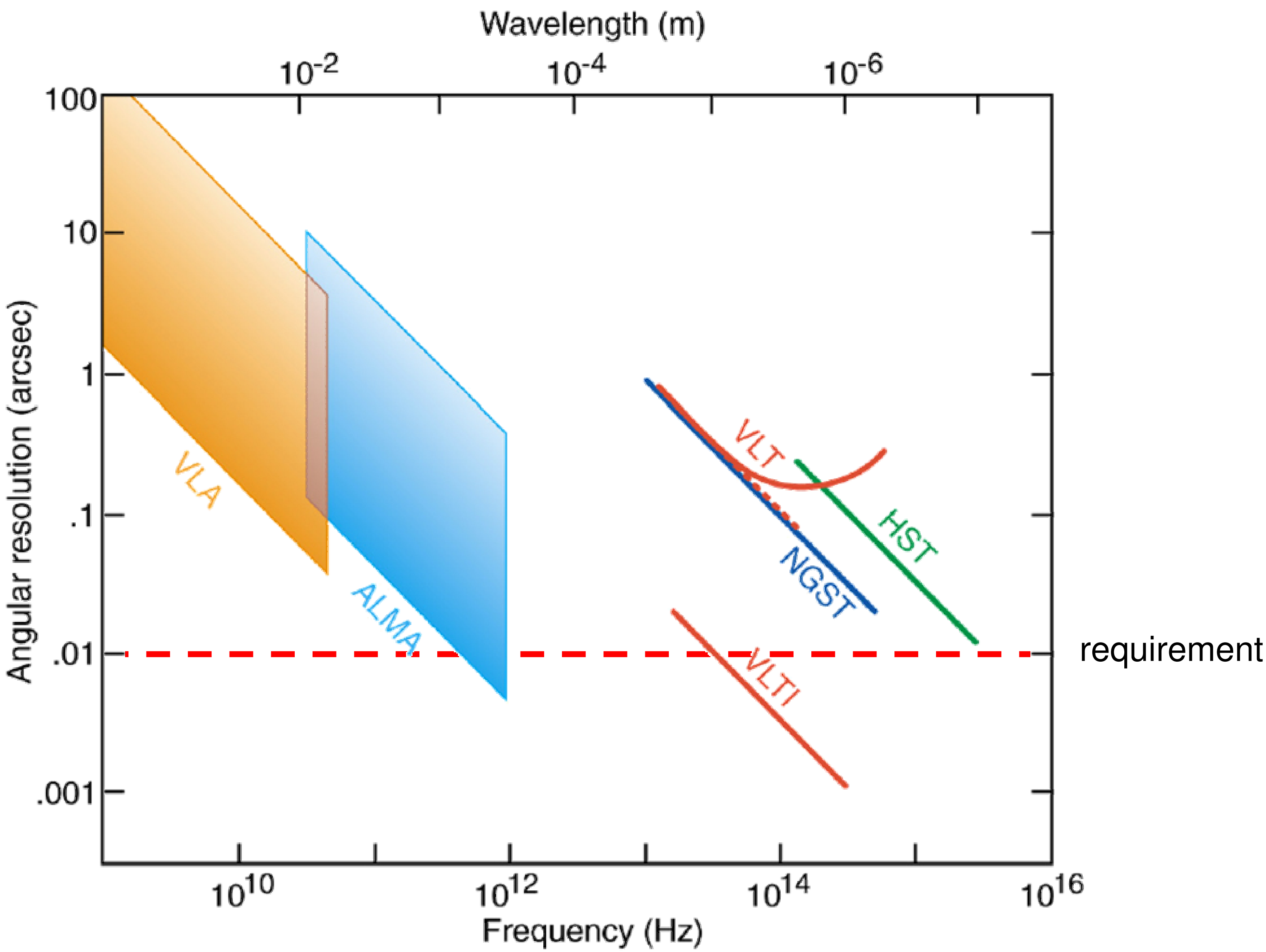
T-OWL





[Wolf, Klahr, Egner, et al. 2005 in Lenzen et al. 2005]

High Resolution!



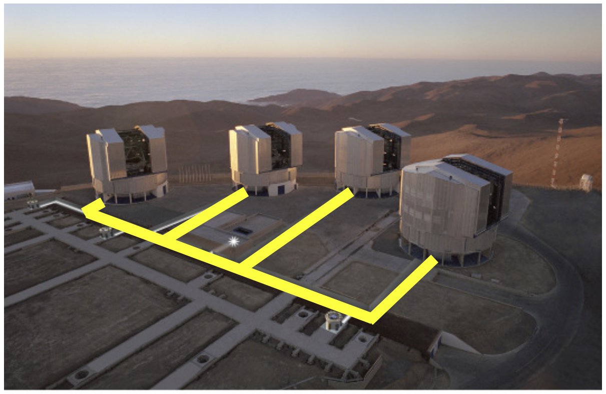
MATISSE

Multi-AperTure Mid-Infrared SpectroScopic Experiment

High-Resolution Multi-Band Image Reconstruction + Spectroscopy in the Mid-IR

2nd Generation VLTI Instrument

PI : Lopez (OCA,Nice)
Co-PI+Proj.Scient. : Wolf (MPIA,HD)



Aerial View of Paranal Observing Platform with VLTI Light Paths

ESO PR Photo 10f/01 (18 March 2001) © European Southern Observatory

Specifications:

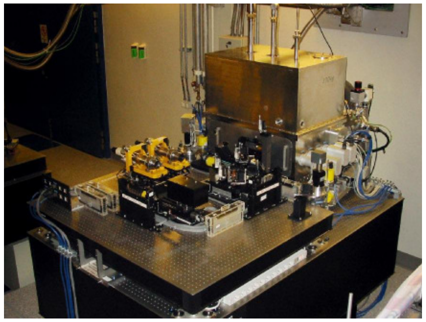
- *L, M, N, Q band: ~ 2.7 – 25 μm*
- *Spectral resolutions: 30 / 100-300 / 500-1000*
- *Simultaneous observations in 2 spectral bands*

What's new?

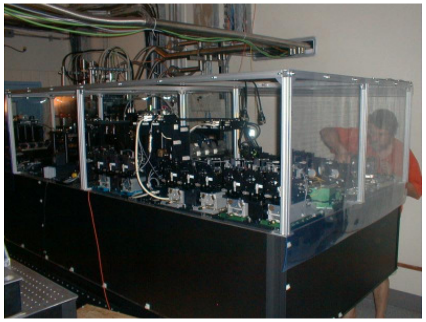
- Image reconstruction
  on size scales of ***3*** */ 6 mas (L band)* ***10*** */ 20mas (N band) using* ***ATs*** */ UTs*
- Multi-wavelength approach in the mid-infrared
  3 new mid-IR observing windows for interferometry (L,M,Q)
- Improved Spectroscopic Capabilities

Multi-AperTure Mid-Infrared SpectroScopic Experiment MATISSE

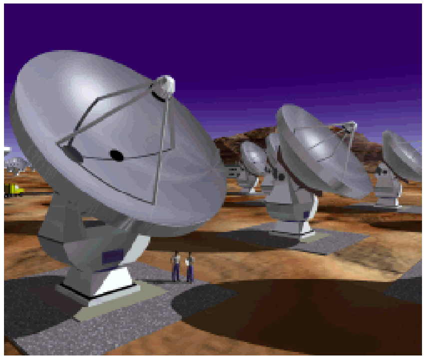
High-Resolution Multi-Band Image Reconstruction
+ Spectroscopy in the Mid-IR



Successor of **MIDI**:
Imaging capability in the L, M, N bands

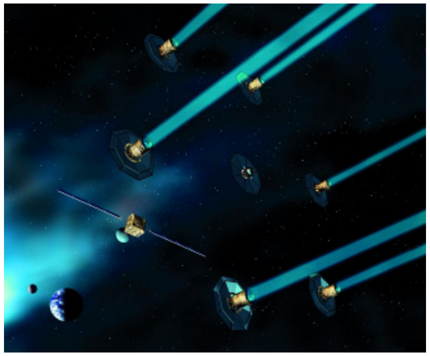


Successor + Extension of **AMBER**:
Extension down to 2.7μm
+ General use of closure phases

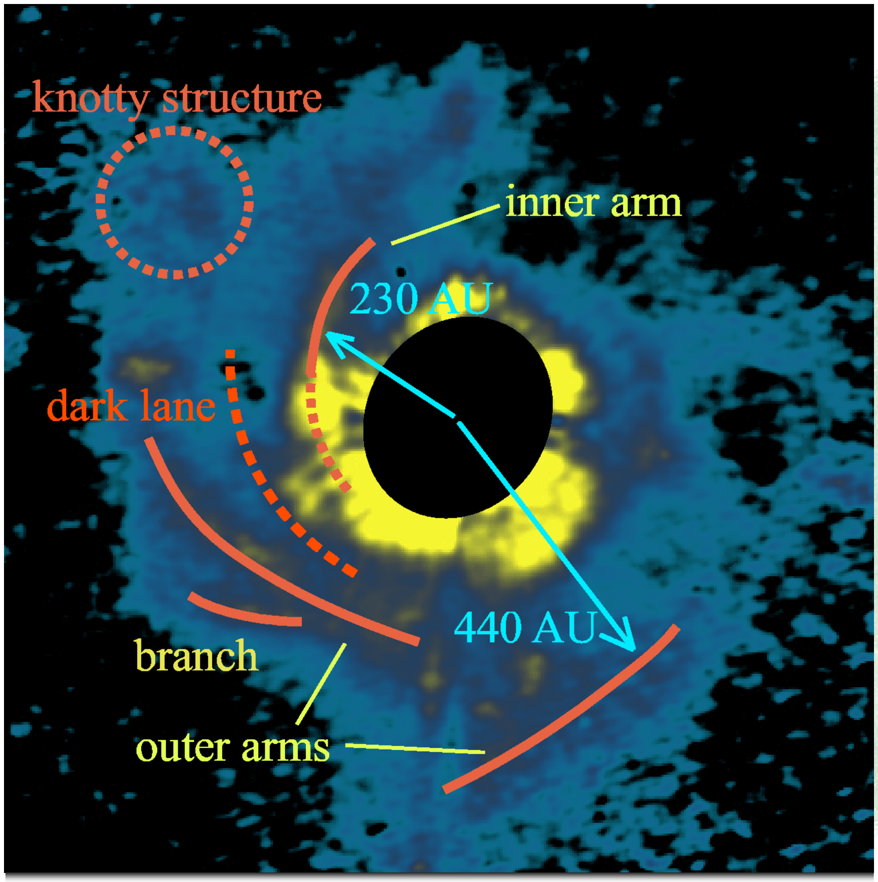


Complement to **ALMA** + **TMT**/**ELT**

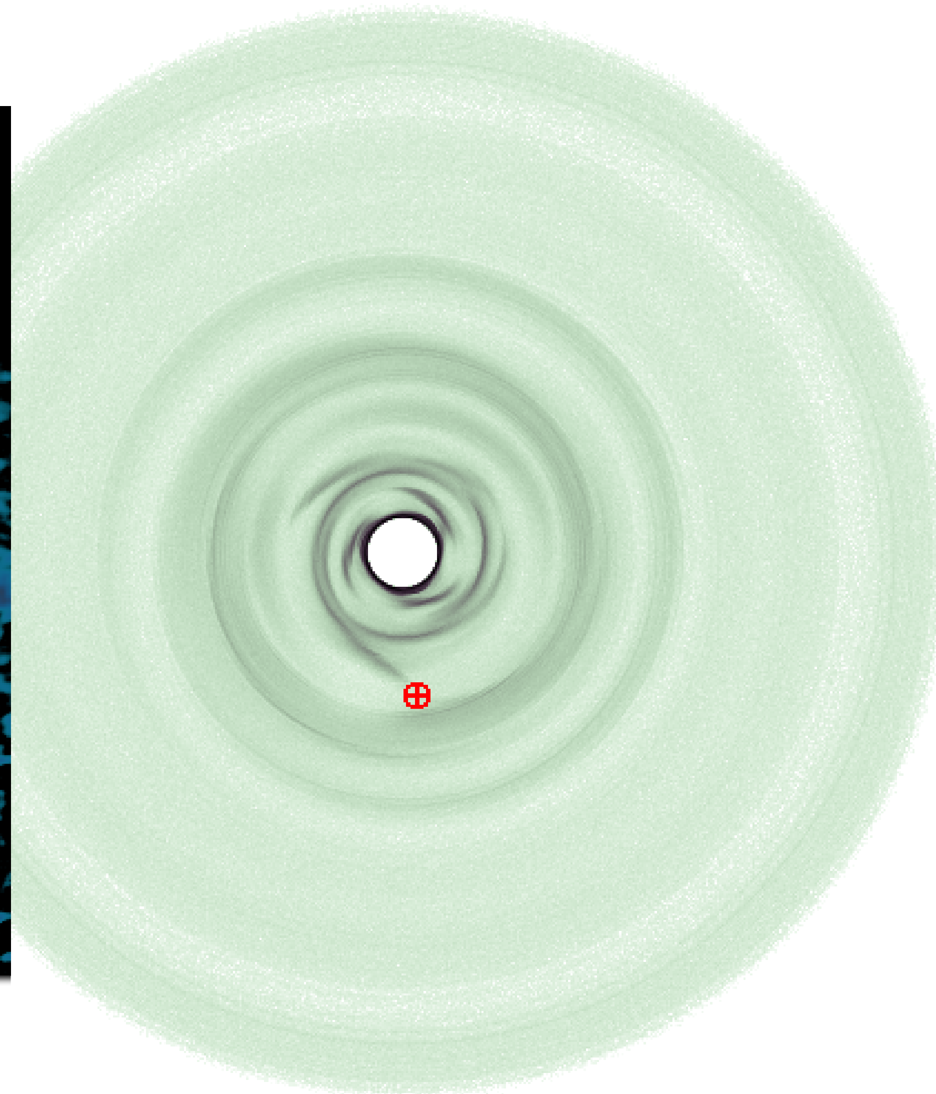
Ground Precursor of **DARWIN**
Wavelength range 6-18μm



Surface Structure

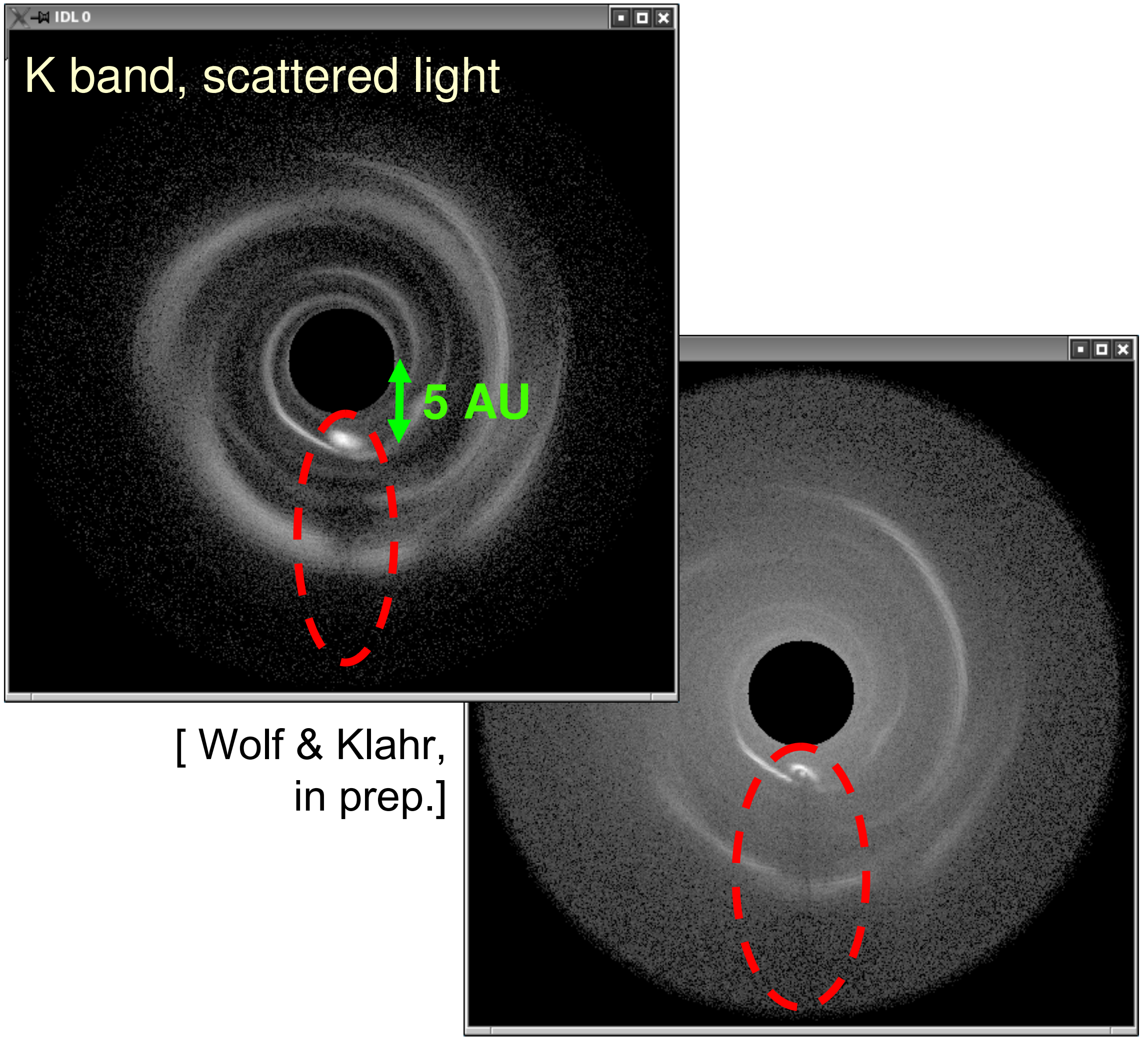


AB Aurigae - Spiral arm structure
(Herbig Ae star; H band; Fukagawa, 2004)



K band scattered light image (Jupiter/Sun + Disk)
[Wolf & Klahr, in prep.]

Shadow – Astrometry



[Wolf & Klahr, in prep.]

Conditions for the occurrence of a significantly large / strong shadow still have to be investigated

Space Interferometry Mission (SIM)

Wavelength range 0.4-0.9µm

Baseline: 10m

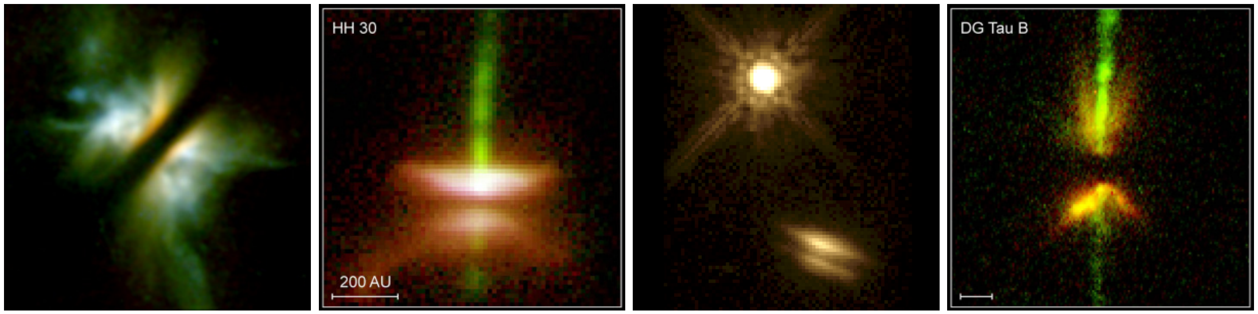
Narrow Angle Field: 1°

Narrow Angle Astrometry
1µas mission accuracy

<u>Strategy</u>
Center of Light Wobble

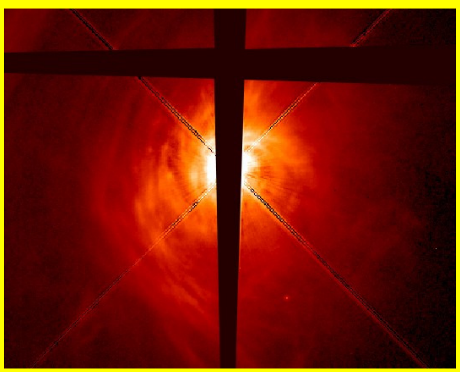
[G. Bryden, priv. comm.]

What disks to study?

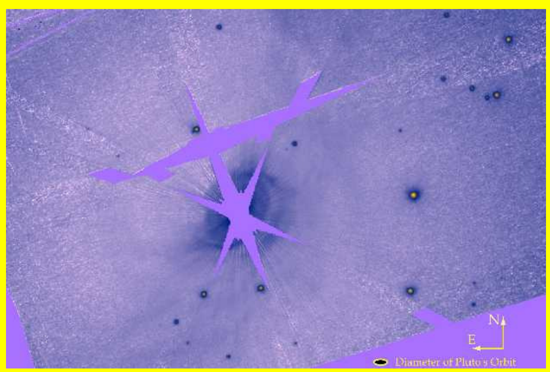


Etc. ...

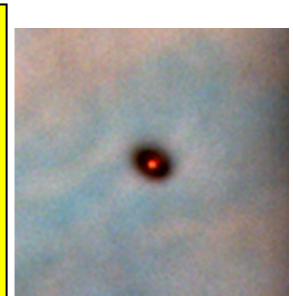
Clearly identified disks, well studied, but …
potentially ”planet-building sites” well hidden…



AB Aurigae



HD 100546



Very distant …

(Grady 2001 / 2003)

Preparatory studies, concentrating on face-on disks

Useful techniques:

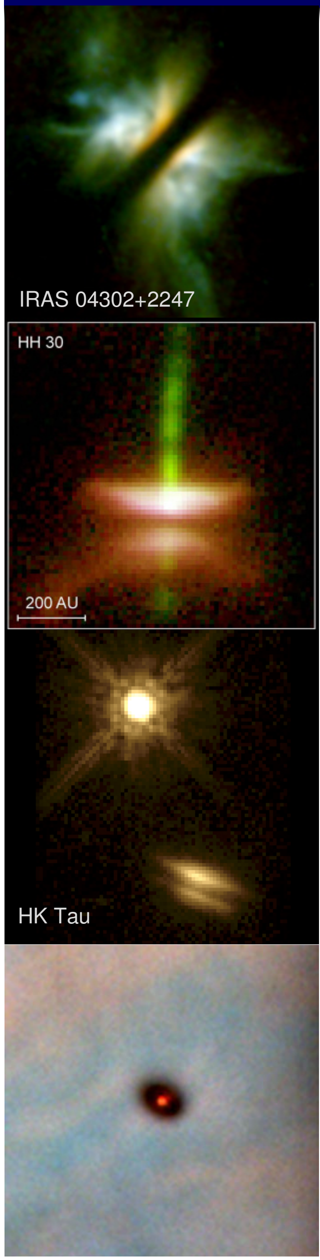
Coronography;

Differential polarimetric imaging;

hires mm maps

=> optical, nearIR, midIR;

Planet Disk Interaction



Young circumstellar disks around T Tauri / HAe/Be stars

optically thick

Debris disks

optically thin

Density structure dominated by

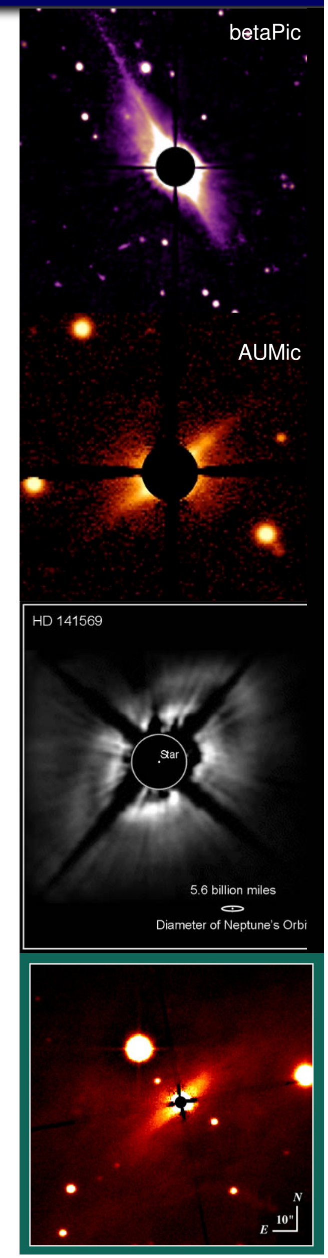
Gravitation

+

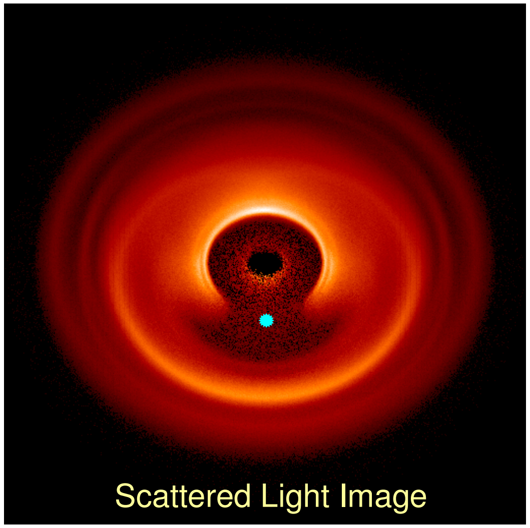
Gas dynamics

Radiation Pressure

Poynting-Robertson effect



Giant Planets in Debris Disks



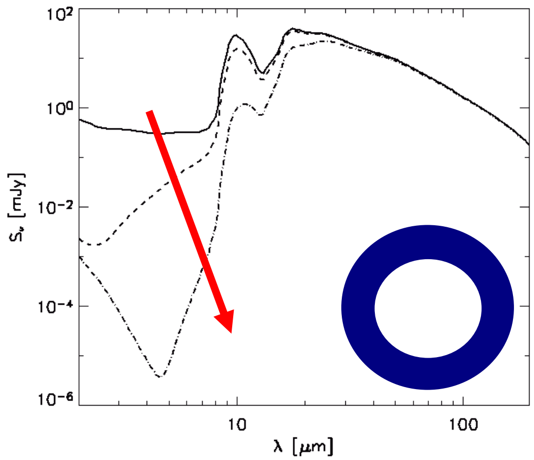
[Rodmann & Wolf]

Planet → Resonances and gravitational scattering →

Asymmetric resonant dust belt with one or more clumps, intermittent with one or a few off-center cavities

+

Central cavity void of dust.



[Wolf & Hillenbrand 2003, 2005; Moro-Martin, Wolf, Malhotra 2005]

- Resonance Structures: **Indicators of Planets**

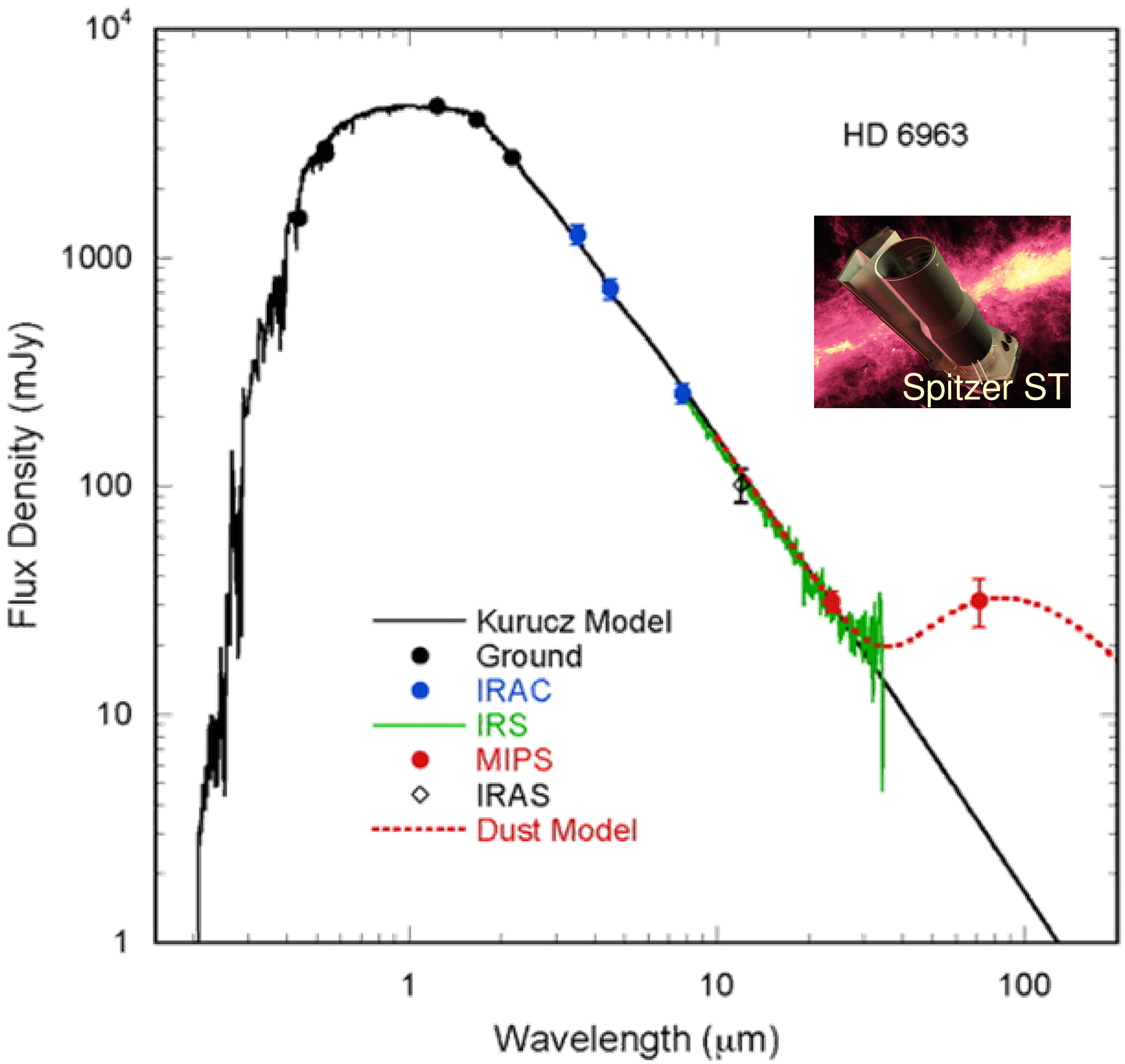
→ [1] Location

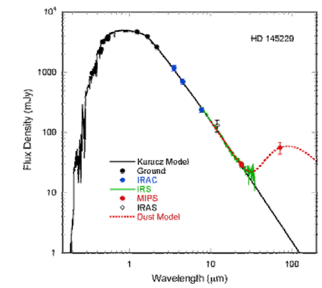
[2] Major orbital parameters

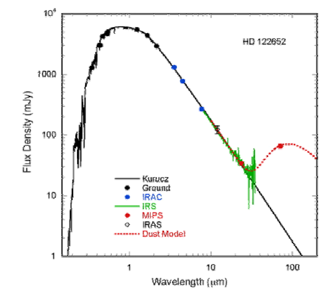
[3] Mass of the planet

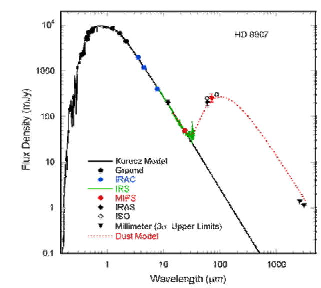
- Decreased Mid-Infrared SED

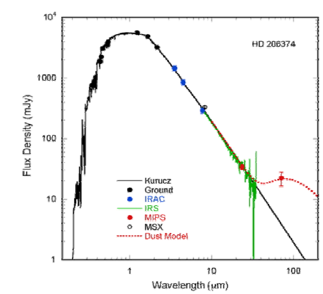
Some Problems with SEDs





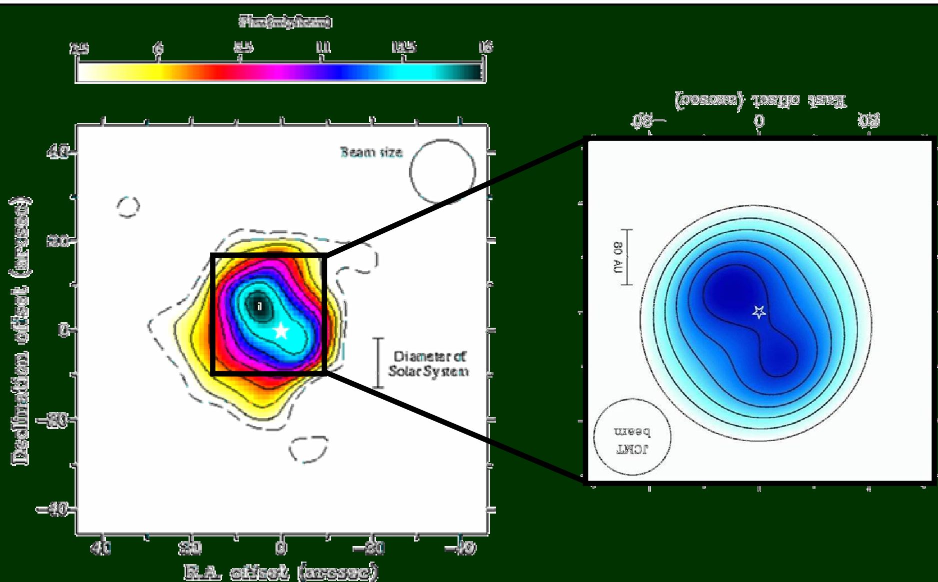


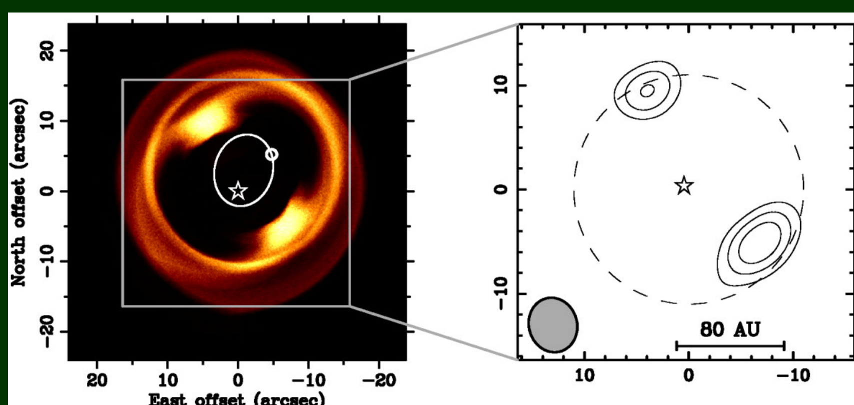




[Kim, …, Wolf, et al. 2005]

Example: Debris Disks around Vega

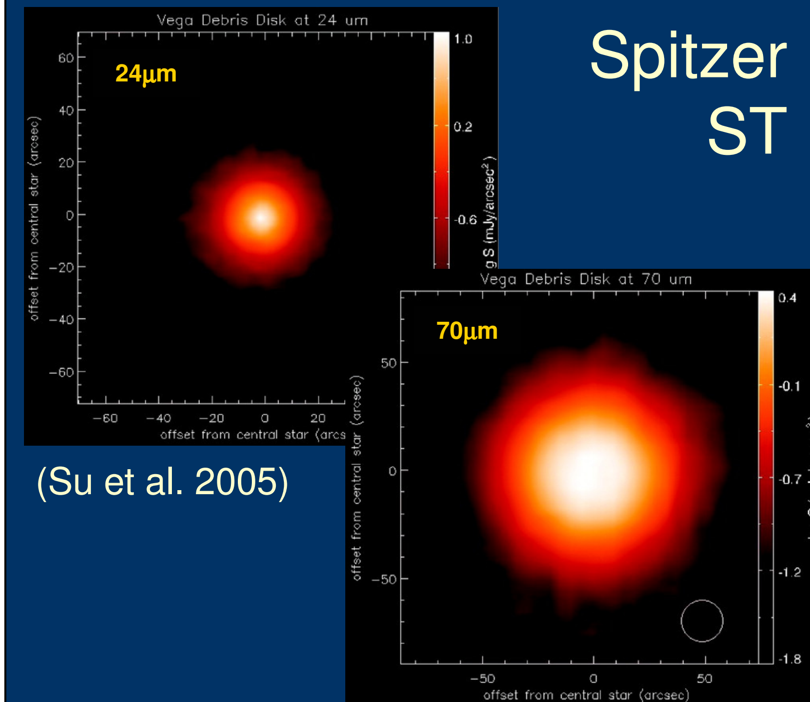




Dust reemission ⟶ SOFIA, JWST

(Holland et al. 1998, Wilner et al. 2002)

Spitzer
ST



(Su et al. 2005)

- **No clumpy structure**
- Inner disk radius: 11”+/-2”
- Extrapolated 850μm flux << observed
- Explanation:
  Grains of different sizes
  traced by Spitzer/SCUBA

Some Problems with SEDs

Many of the debris disks observed with the Spitzer ST,
show no or only very weak emission at wavelengths < 20…30µm
(e.g. Kim et al. 2005)

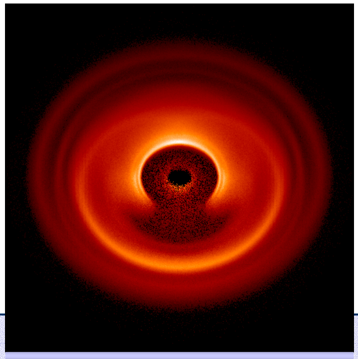
$\Rightarrow$ No / weak constraints on the chemical composition of the dust

Debris disks: Difficult to observe

- Low Surface Brightness
- Optically thin: Only constraints on radial structure can be derived: SED = f (T(R))

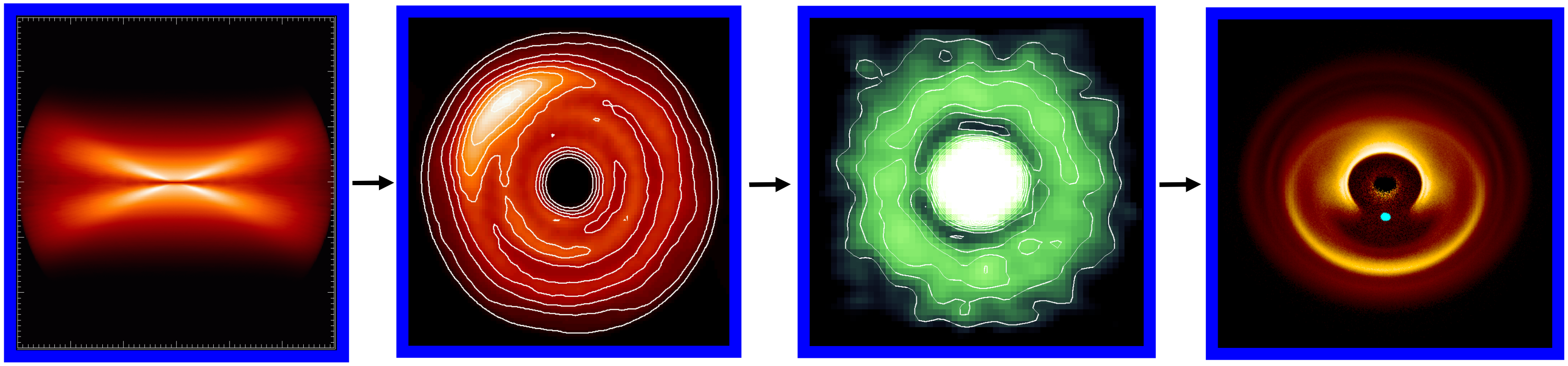
  but even here degeneracies are difficult to resolve (e.g., planet mass, orbit, grain size)

- Azimuthal (and vertical) disk structure <u>can not</u> be traced via SED observations / modelling



Imaging is required!

Concluding remarks



Planet-disk interaction: Signatures in circumstellar disks

- Usually much larger in size than the planet more ➡ easily detecable
- Specific structure depends on the evolutionary stage of the disk

High-resolution imaging

- performed with observational facilities which are already available or will become available in the near future will allow to trace these signatures.

➡ **Insight into specific phases of the formation and early evolution of planets in circumstellar disks.**

Acknowledgements

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Emmy Noether-Programm

Deutsche Forschungsgemeinschaft

DFG

Max-Planck-Institut für Astronomie Heidelberg

Max Planck Institute for Astronomy Heidelberg

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