Planet Formation
traced with interferometry

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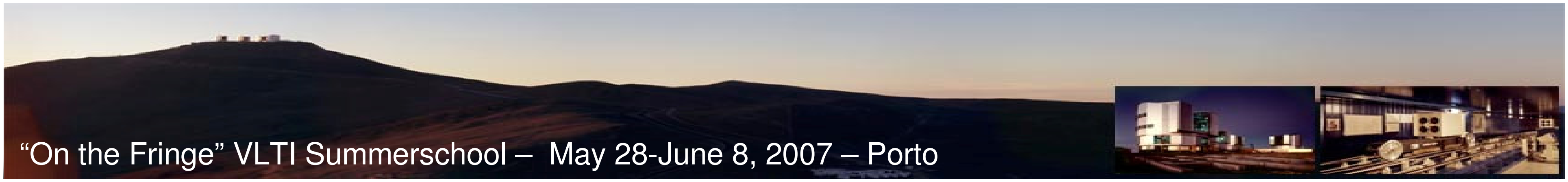
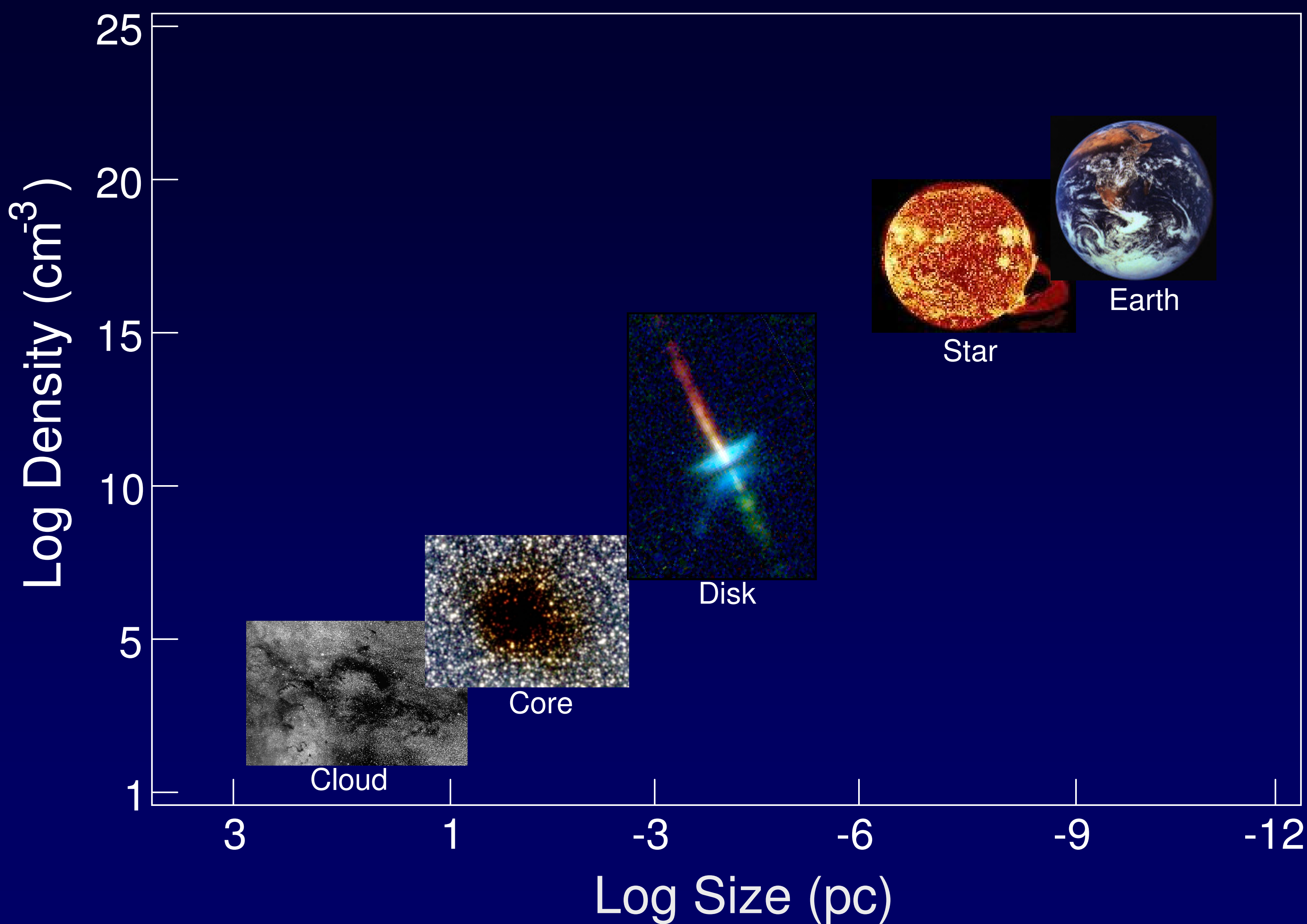
Emmy Noether Research Group
“Evolution of Circumstellar Dust Disks to Planetary Systems”
Max Planck Institute for Astronomy

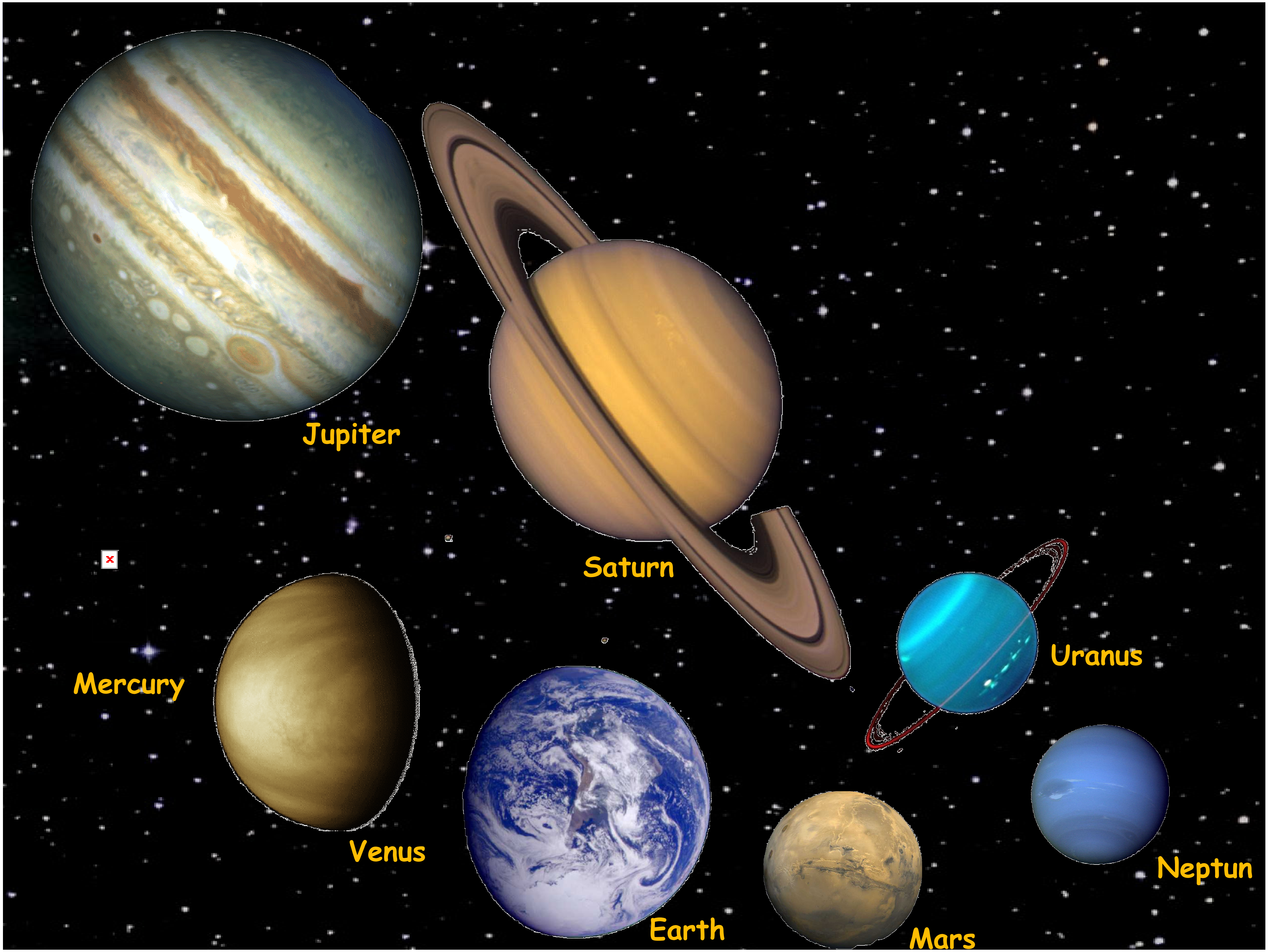


Clouds – Stars – Planets



Sources of Information

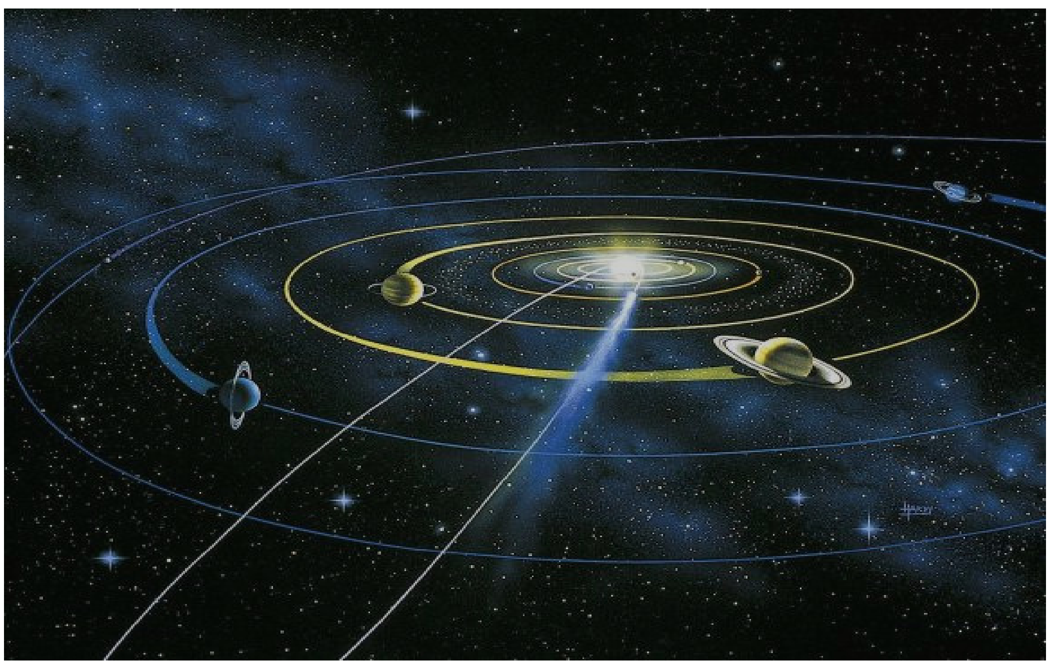
- Solar System
- Observations of other Systems
  - Protoplanetary and debris disks
  - Extrasolar planets/planetary systems
- Numerical Simulations
- Experiments
  (Laboratory Astrophysics)


Jupiter
Saturn
Mercury
Venus
Earth
Uranus
Mars
Neptun

The Solar System: Some striking facts

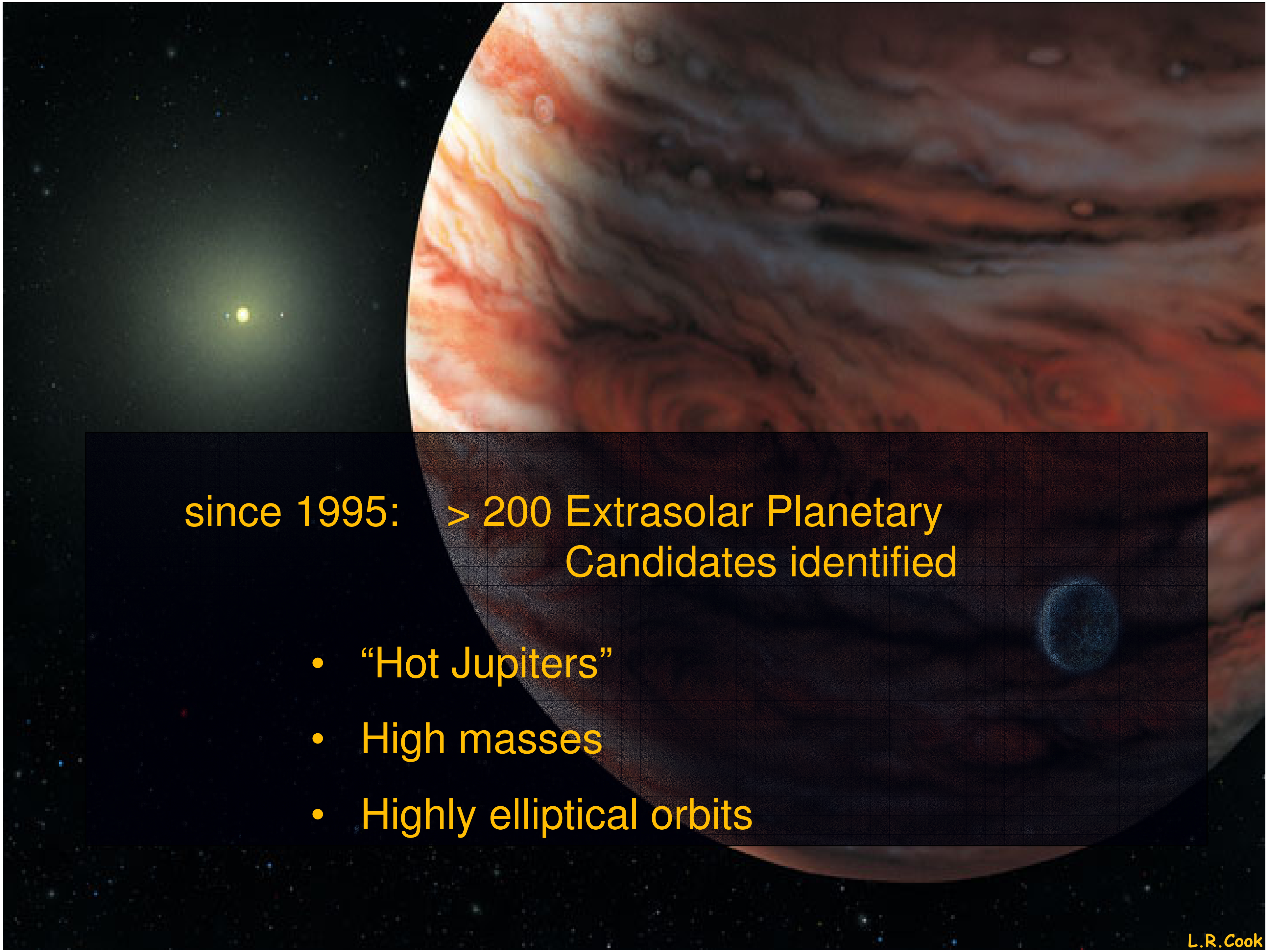
- **Planetary orbits are coplanar**
- **Planets orbit the sun in the same direction**
- **Distribution of Mass and Angular Momentum:**

  Sun Mass: 99.86%   but   Angular Momentum < 2%



- Age estimation:

  Sun and Planets have been formed at the same time



since 1995: > 200 Extrasolar Planetary Candidates identified

- "Hot Jupiters"
- High masses
- Highly elliptical orbits

Hot Jupiters

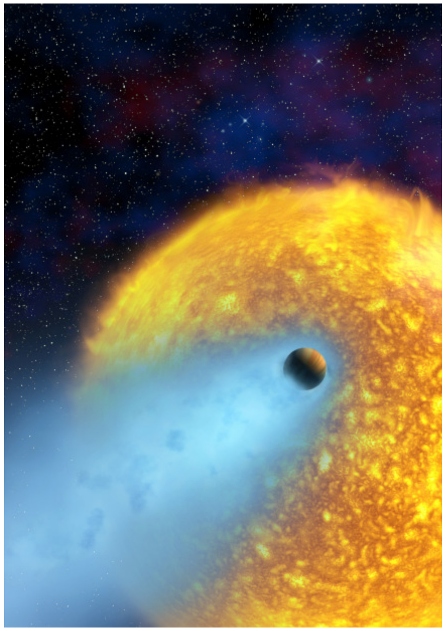
- Also called roasters, pegasids, Pegasi planets or Pegasean planets
- Class of extrasolar planets whose mass is close to or exceeds that of Jupiter
- Orbit: ~0.05 AU (eight times closer to its star than Mercury is to the Sun)

Why are Hot Jupiters unexpected?

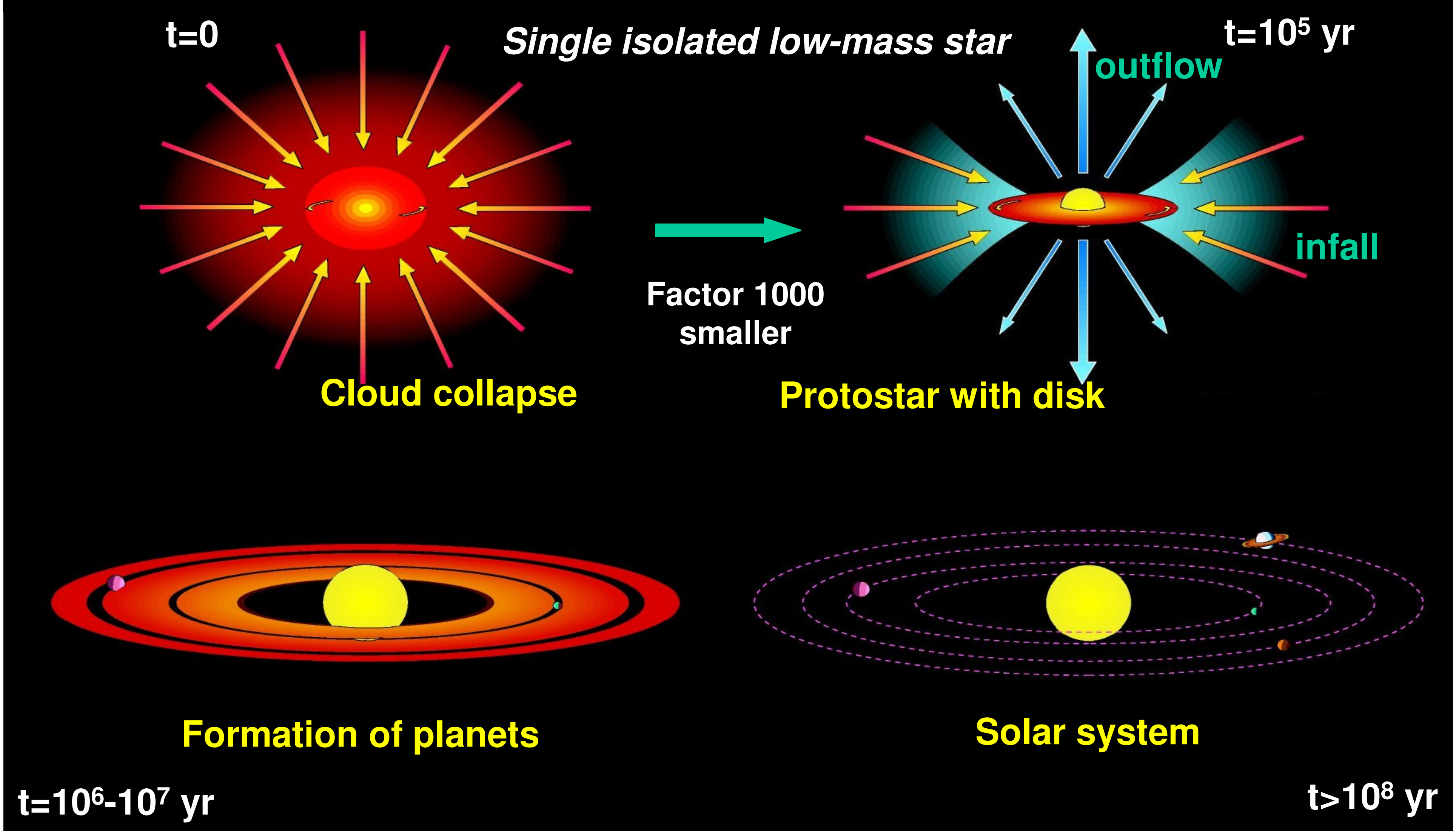
- Too hot (that close to the star) for significant condensation
- Too little material to build up a significant core (especially quickly)
- Gas is too hot to be held by a protoplanetary core

- *Solution I:*
  Planets form further out and migrate inwards (migration time ~10^6 yrs) [Ward 1981, Lin & Papaloizou 1986, Ward & Hourigan 1989, Artymowicz 1993]

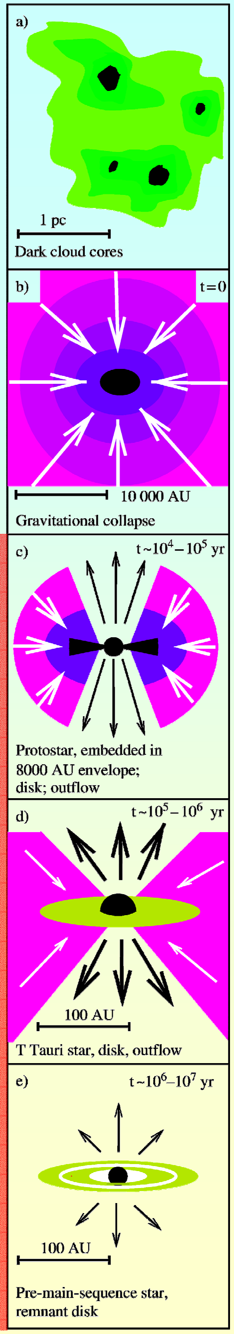
(• *Solution II: Planet form near its star in a disk instability (more massive disks, thermodynamics?)*)



The General Picture



Planet Formation in a Nutshell



(Waelkens 2001)

Star Formation Process → Circumstellar Disks → Planets

Core Accretion – Gas Capture

(sub)µm particles
↓
cm/dm grains
↓
Planetesimales
↓
Planets (cores)

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

- Agglomeration;
  Fragmentation

- Gravitational Interaction: Oligarchic Growth

- Gas Accretion

Alternativ: Gravitational Instability → Giant Planet

Agglomeration / Accretion Phase

~1 µm

Agglomeration

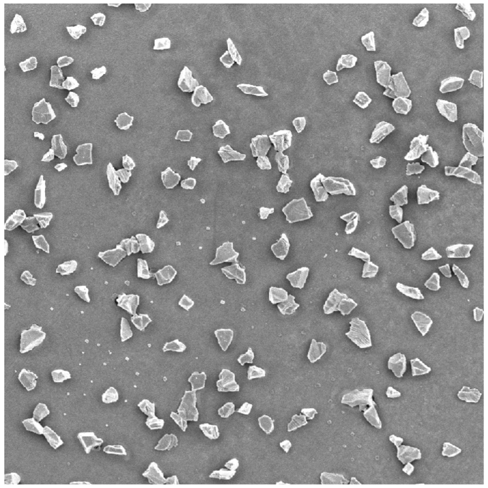
interaction with gas dominating
no gravity

~1 km

Accretion

no interaction with gas
gravity dominating

~10‘000 km



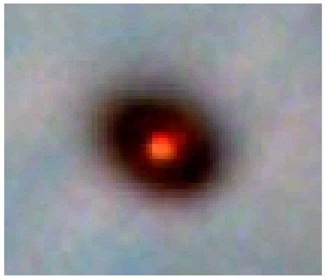
Preplanetary dust

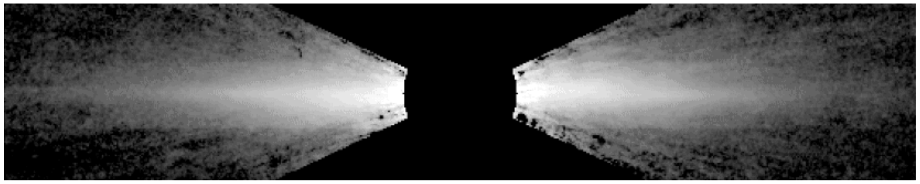
Planetesimals

Planets

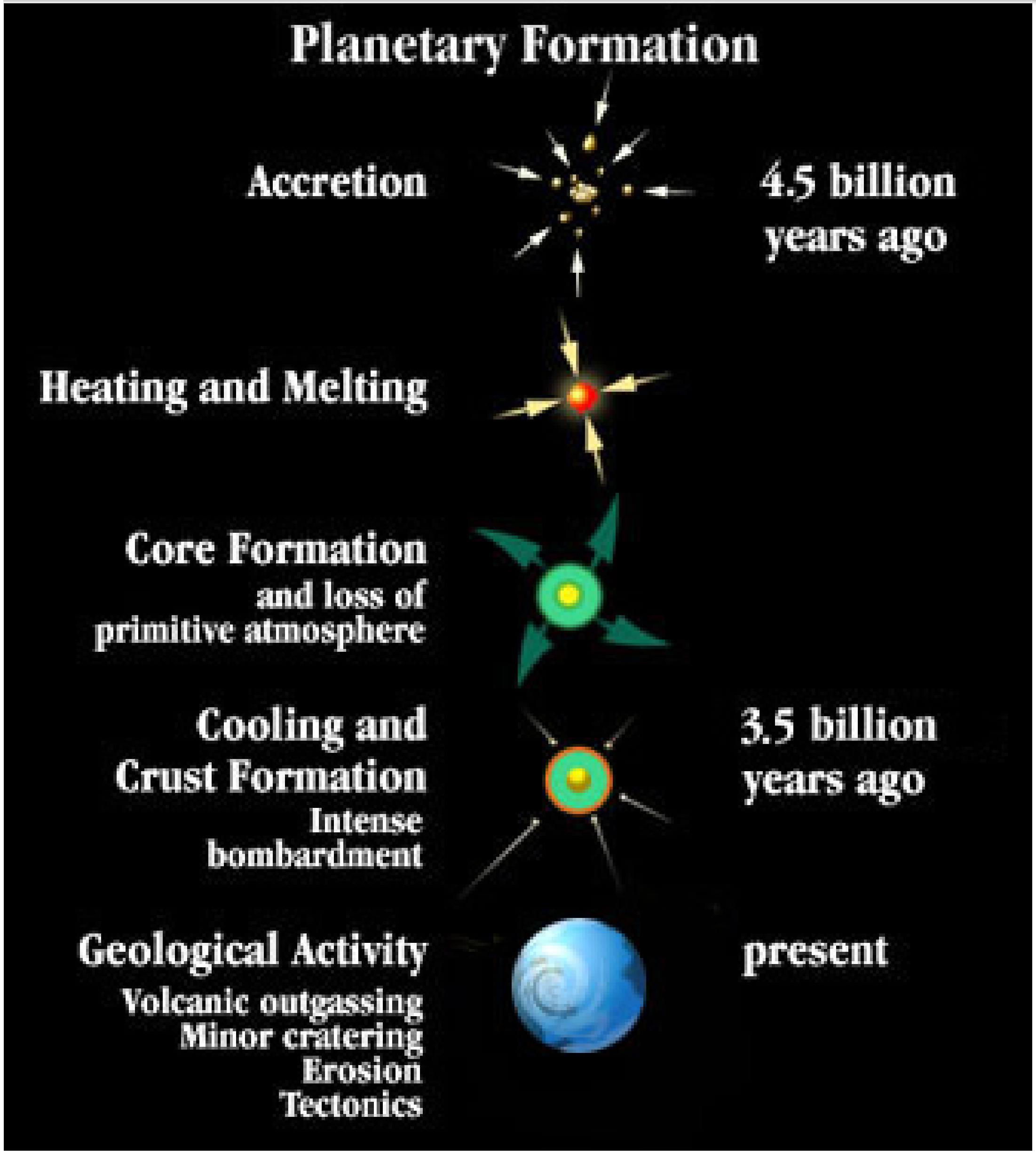
~ 10^4 - 10^6 years ?

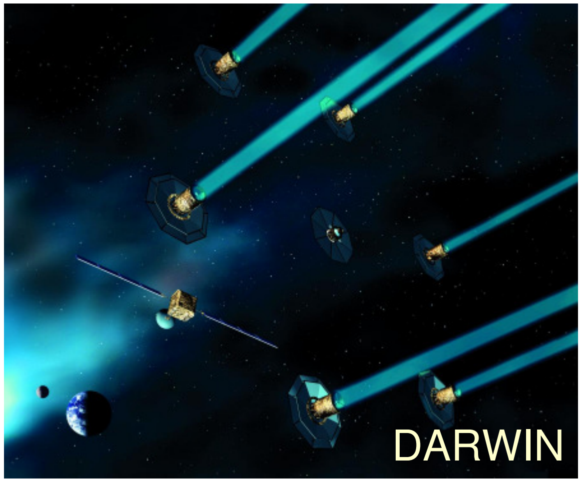
~ 10^7 - 10^8 years ?





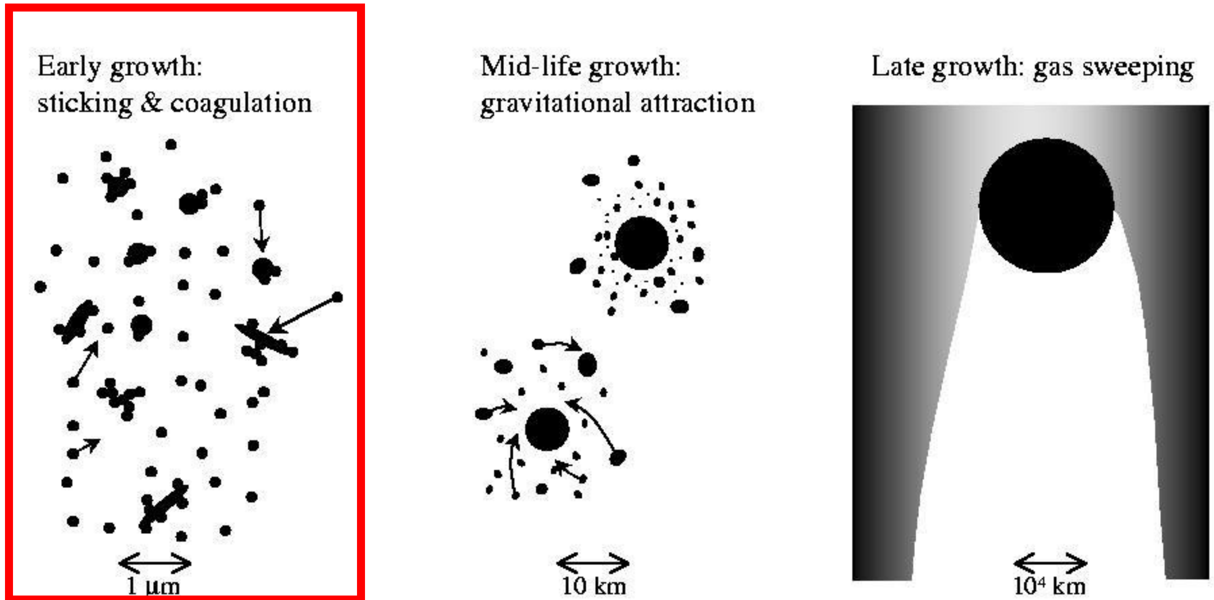
Planet Formation, Early Evolution



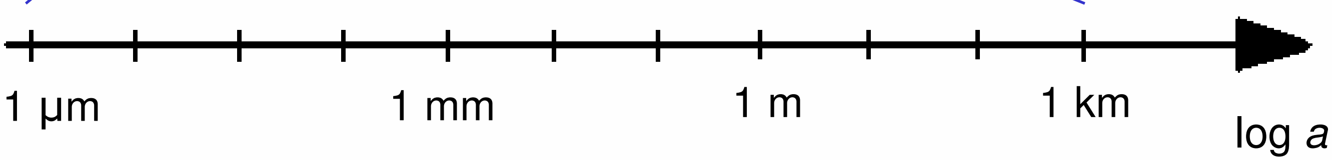


(e.g. Safronov, Wetherill, Ida, Benz)

Dust Grains => Planets

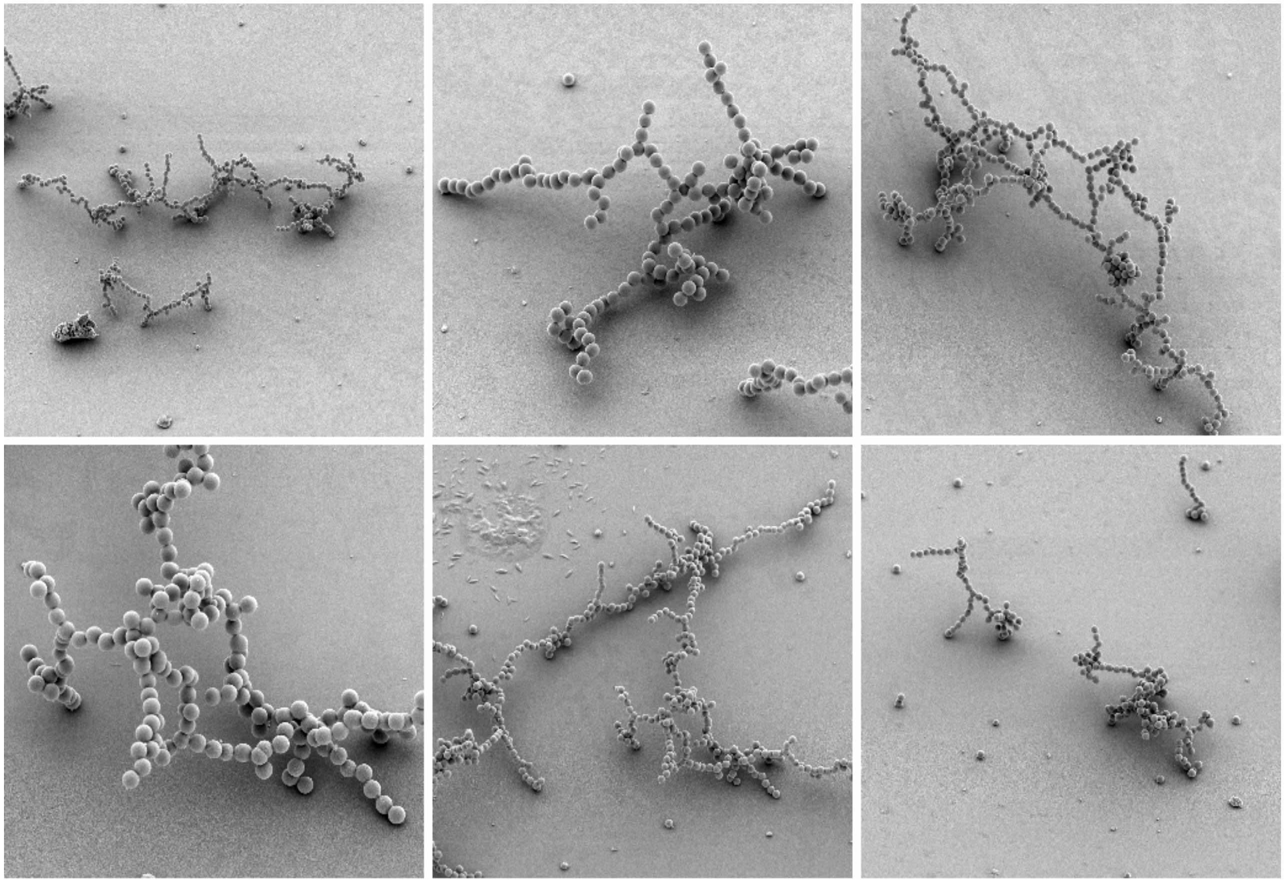


Beckwith et al. (2000)



particle size
≃
wavelength
of observation

Agglomerates in the Laboratory



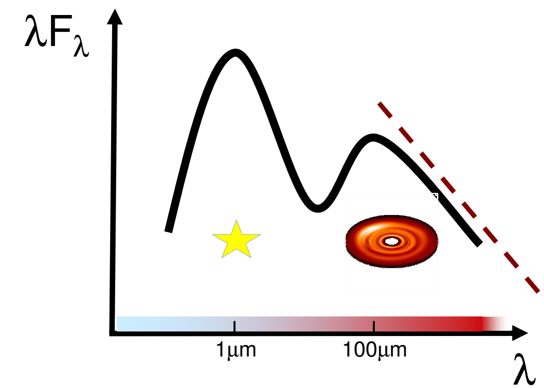
Silica Monospheres (1.9μm)

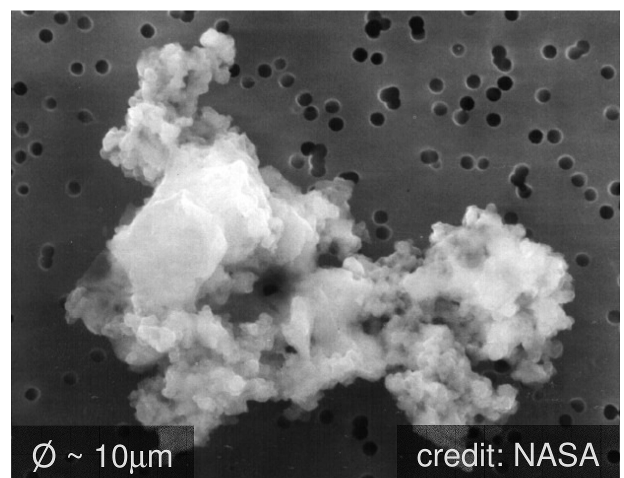
Particles stick and form open (fractal) structures

How to identify *grain growth*?

- Spectral Energy Distribution (SED)
  (sub)mm slope: $F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$
- Dust emission/absorption features
- Scattered light polarization
- Multi-wavelength imaging

+ Radiative Transfer Modelling





SED: (sub)mm slope

$$F_\nu \approx \kappa_\nu \frac{2k\nu^2}{c^2 D^2} \int_{R_{min}}^{R_{max}} T(r)\Sigma(r) 2\pi r dr$$

$\boxed{F_\nu \sim \kappa_\nu}$ – does not depend on disk structure

<u>Frequency dependence can be observed directly</u>

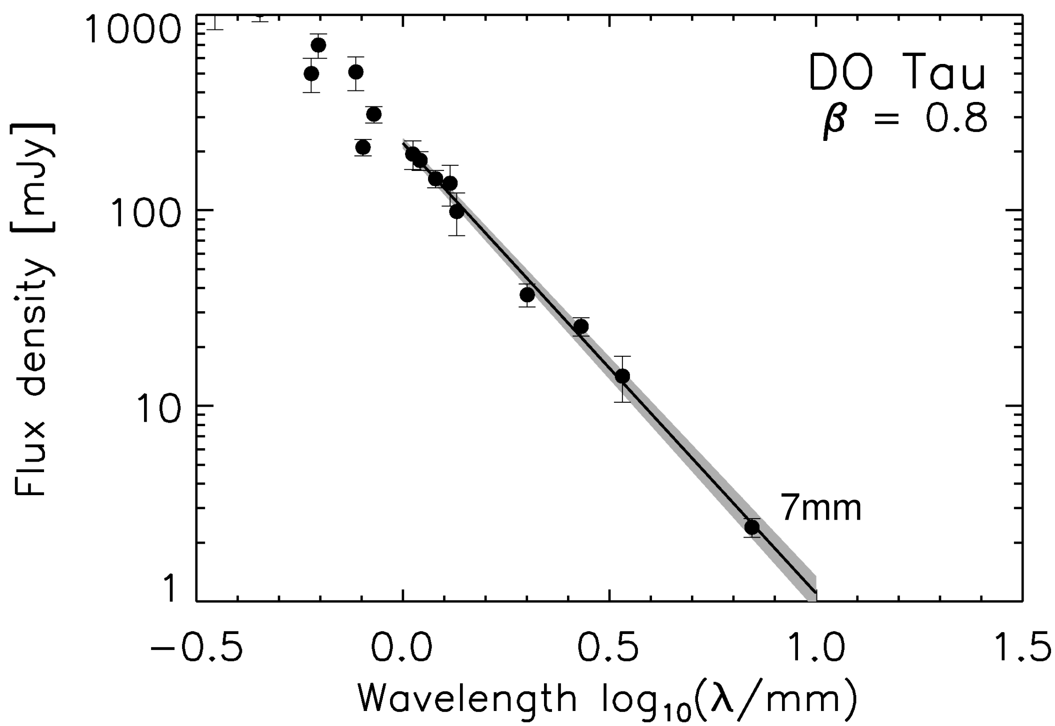
λ ~ (sub)mm wavelengths: $\kappa_\nu \sim \nu^\beta \sim \lambda^{-\beta}$

- Compact, spherical grains, r << λ : $\beta = 2$
- β ~ 1 for special materials (e.g. amorphous carbon), but for λ >> r: $\beta \rightarrow 2$
- r >> λ (rocks, asteroids) : $\beta = 0$ (opaque at mm wavelengths)
- Particles with r ~ 1mm: <u>**$0 < \beta < 2$**</u>

SED: (sub)mm slope

Observations:

- Interstellar Medium: β~2
- Circumstellar Disks: many disks with $\boxed{\beta \lesssim 1}$ observed



[Rodmann et al. 2005]

$\Longrightarrow$ Dust growth?

- Yes, if optically thin in the <u>entire</u> submm/mm region (disk inclination!)

- No, if optically thick: here the size/mass of the visible disk material increases with wavelength =>

$\beta = 2 \rightarrow 1$

i.e. 0 < β < 2 does not necessarily indicate dust grain growth!

How to identify *grain growth*?

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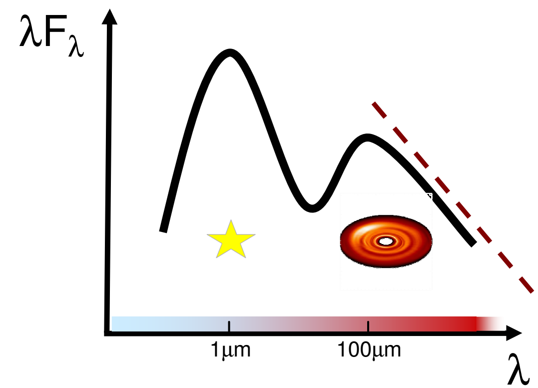
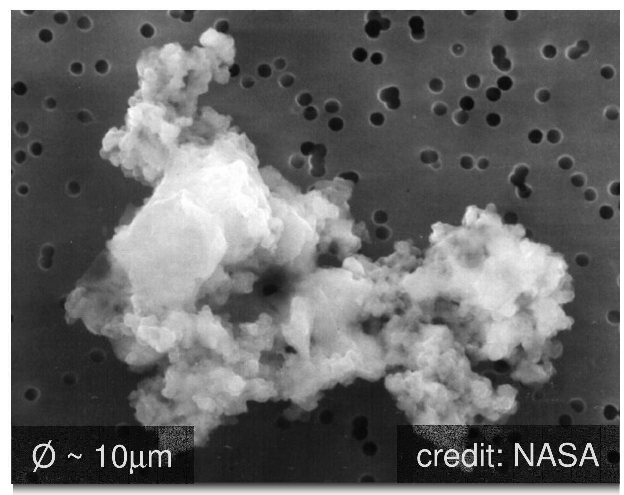
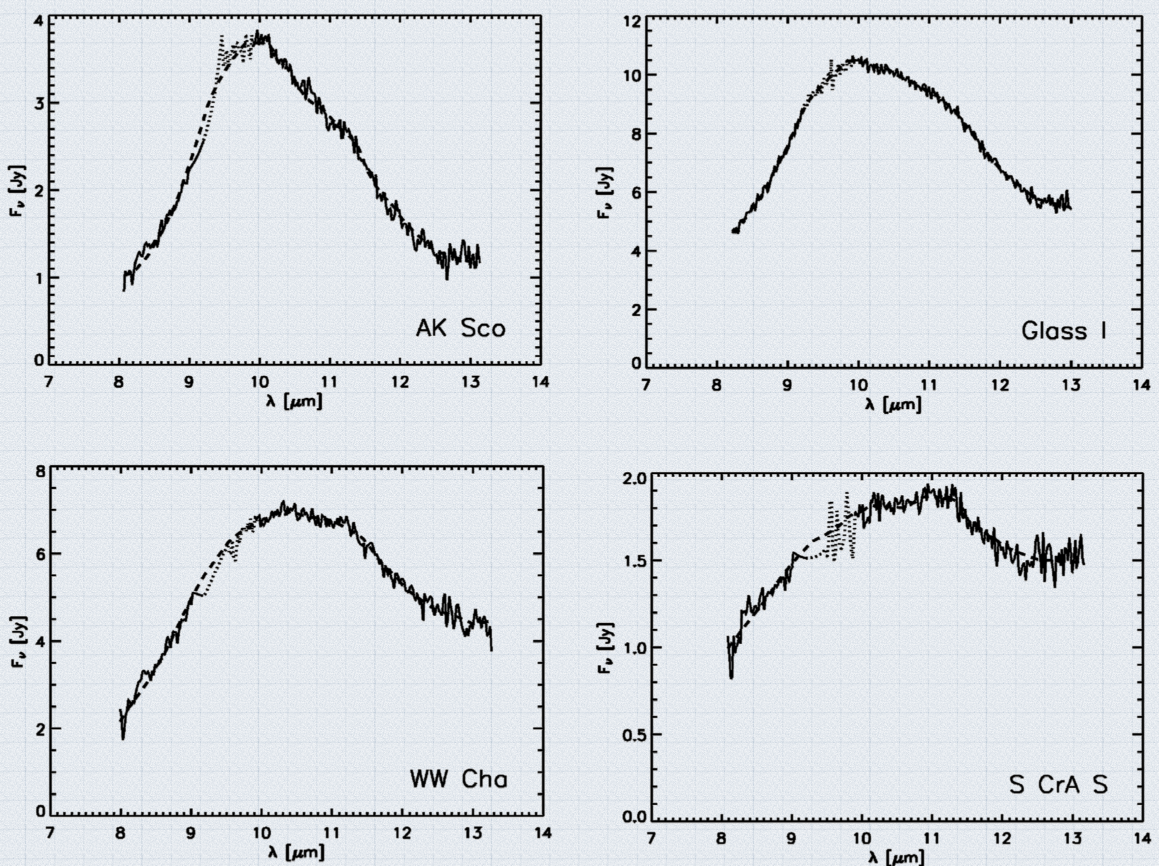




Characteristic Dust Emission Features



8-13micron spectra of 27 T Tauri stars

based on surveys by Przygodda et al. (2003) and
Kessler-Silacci et al. (2004) using TIMMI2/3.6m, LWS/Keck

Prominent Example:

~10μm Silicate Feature

Size + Shape

Chemical Composition

Crystallization degree

of Silicate grains

⇓

Grain Evolution

⇓

Physical Conditions

[Schegerer, Wolf, et al. 2006]

How to identify *grain growth*?

- Spectral Energy Distribution (SED)
  (sub)mm slope: $F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$
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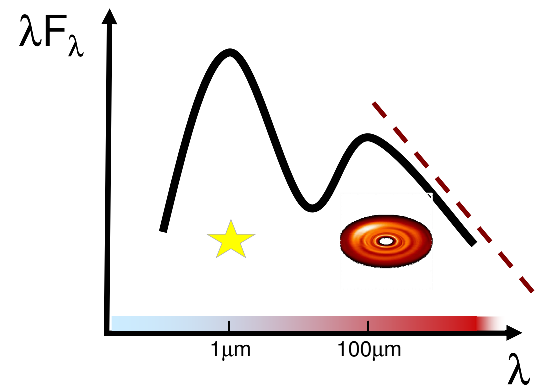
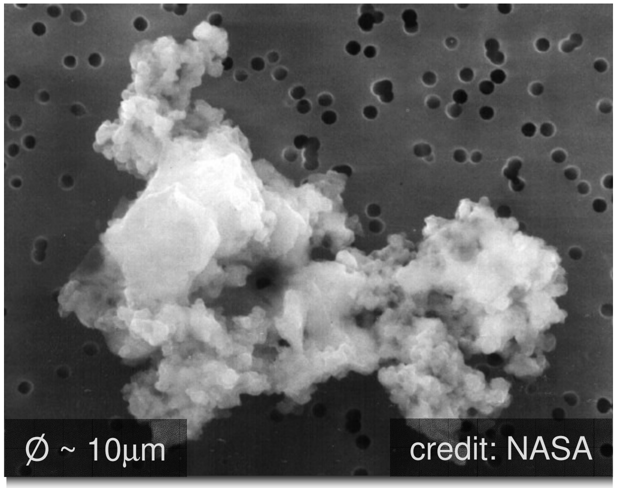
+ Radiative Transfer Modelling





Wolf et al. 1997-2000

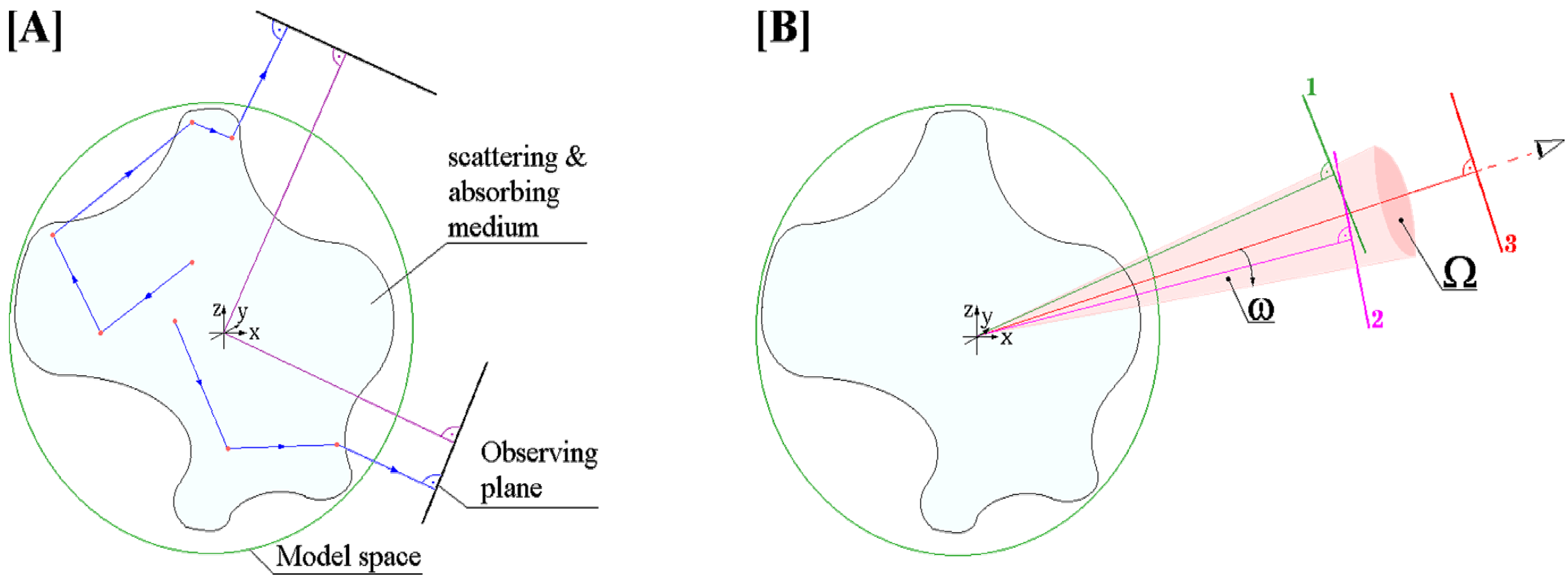
Wolf 2003

Monte Carlo Radiative Transfer

- Monte Carlo method:
  - Very powerful *(e.g., wide range of optical depths)* + flexible *(model)*
  - Direct Implementation of Physical Processes
    (e.g., Photon transport, Scattering, Absorption, Reemission)

- 3D continuum radiative transfer code MC3D
  - Well-tested, Former Applications:
    Globules, Disks, Clumpy circumstellar shells and AGN tori, ...
  - Models:
    - (almost) Arbitrary model geometry / density distribution
    - Arbitrary heating sources (e.g., Stars, Accretion disks)
    - Arbitrary optical properties
      of the absorbing/scattering medium
  - Output:
    - Self-consistent temperature distribution
    - Spectral energy distribution
    - Wavelength-dependent Images, Polarization Maps

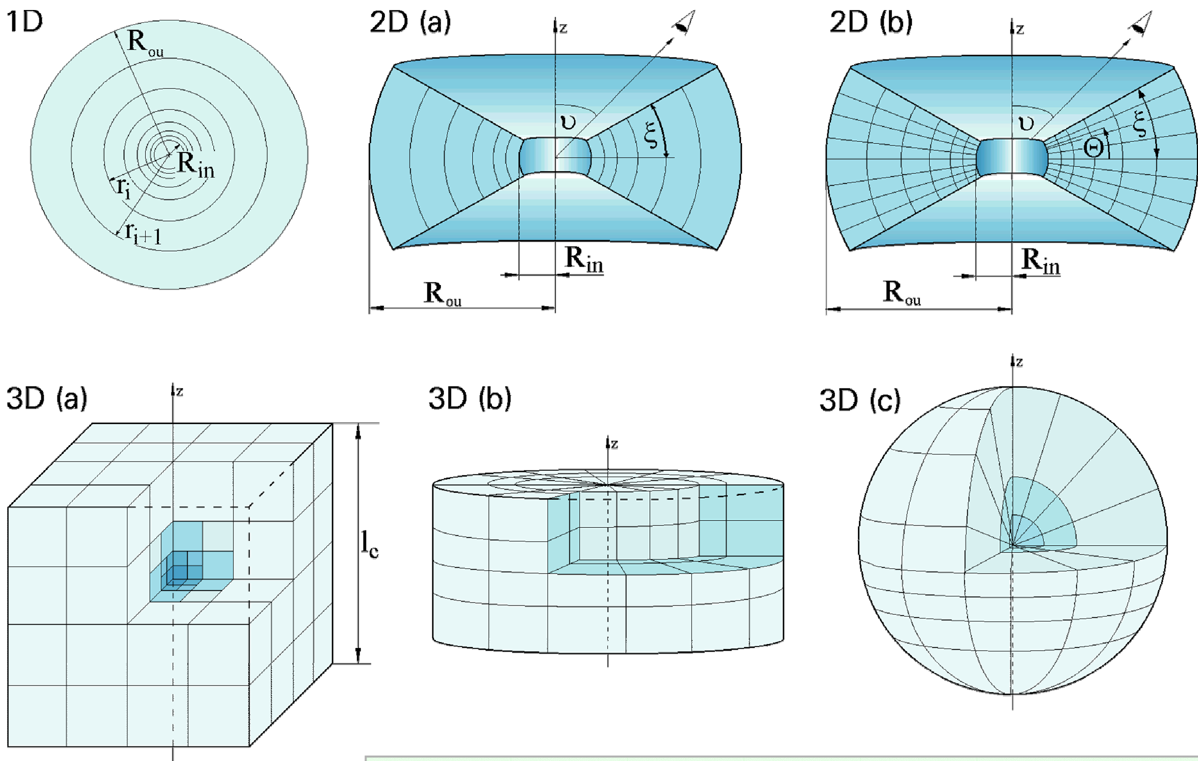
Monte Carlo Radiative Transfer



Weighted Photons:

- Wavelength
- Energy
- Stokes Vector (Polarization!)

Monte Carlo Radiative Transfer



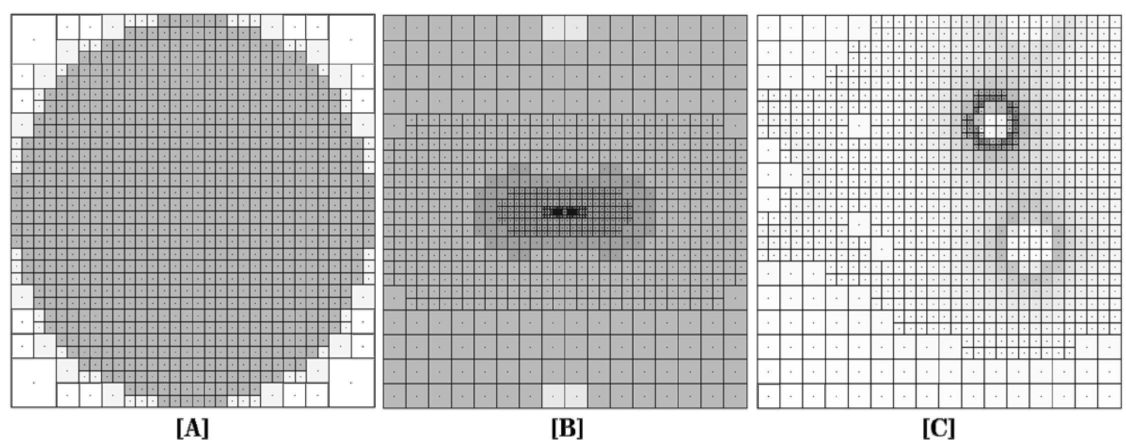
<u>Goal</u>

Spatially Resolved Dust Temperature Distribution

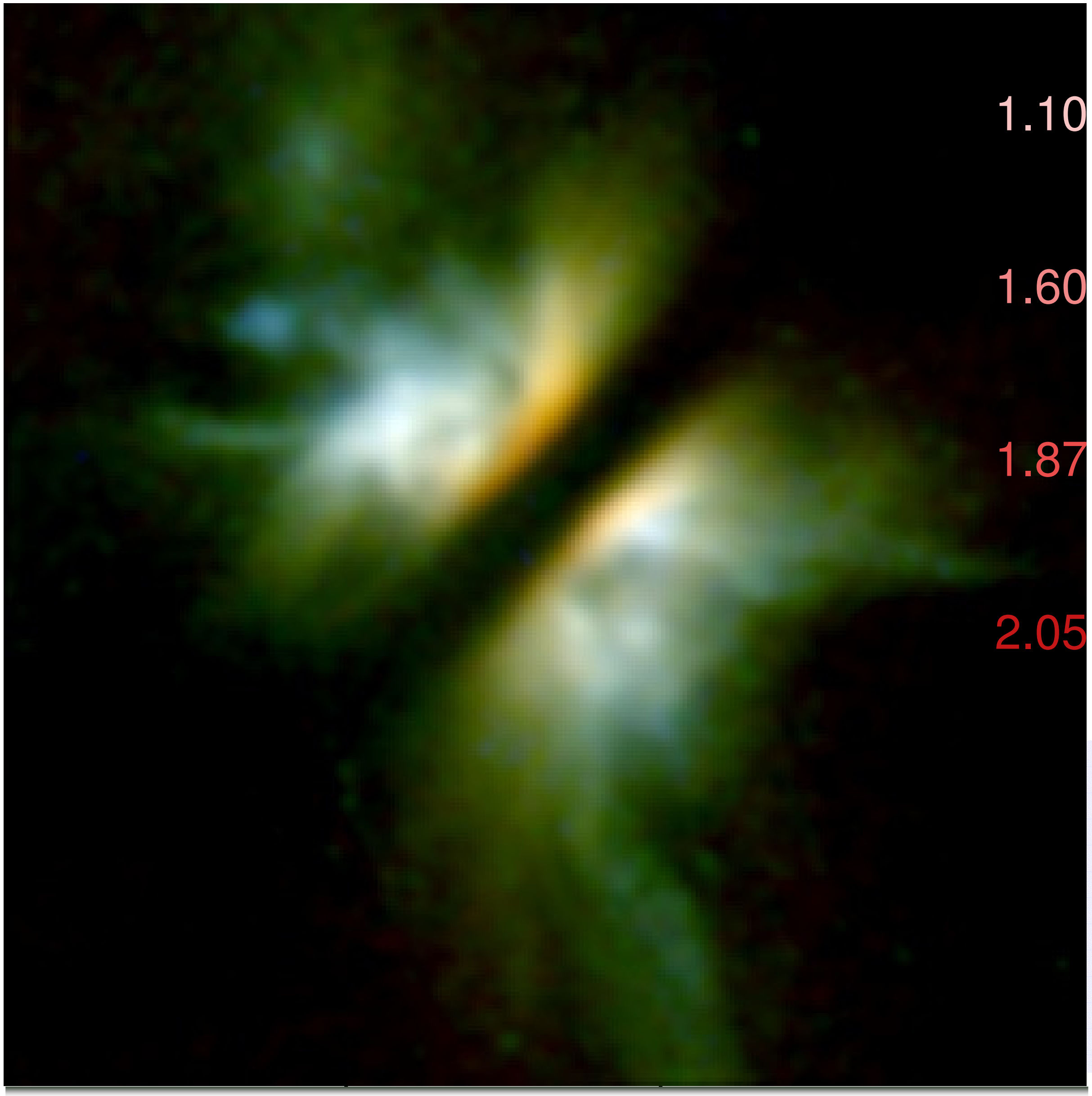
<u>Solution</u>

Local Energy Conservation in each cell

Example Adaptive Grid



The Butterfly Star in Taurus



1.10 μm

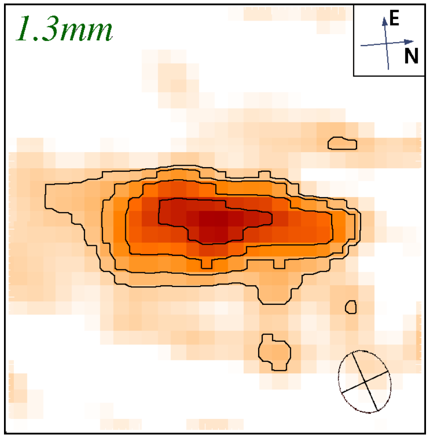
1.60 μm

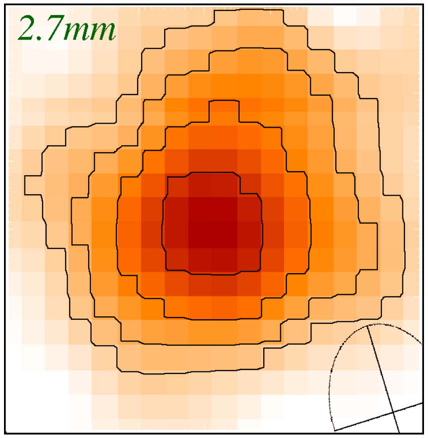
1.87 μm

2.05 μm

- Wavelength-dependence of the dust lane width
- Relative change of the brightness distribution from 1.1μm-2.05μm
- Slight symmetry of the brightest spots

The Butterfly Star in Taurus





- **Disk density profile** $$\rho_{\mathrm{disk}} = \rho_0 \left(\frac{R_*}{\varpi}\right)^{\alpha} \exp\left\{-\frac{1}{2}\left[\frac{z}{h(\varpi)}\right]^2\right\} \qquad h = h_0 \left(\frac{\varpi}{R_*}\right)^{\beta}$$
- **Envelope structure** Resulting from mass infall under consideration of envelope rotation *(Ulrich 1976)*
- **Heating Sources** Star (Blackbody), Accretion $$dL_{\mathrm{acc}} = \frac{3}{4\pi}\frac{GM_*\dot{M}}{\varpi^3}\left[1-\left(\frac{R_*}{\varpi}\right)^{1/2}\right] dA$$
- **Dust Properties** Grain size distribution: $n(a) \propto a^{-3.5}, \quad a_{\mathrm{min}} < a < a_{\mathrm{max}}$

  Chemical Composition: Astr. Silicate, Graphite

[Wolf et al. 2003]

The Butterfly Star in Taurus

Disk outer radius:
300 AU

Radial/Vertical density profile:
α=2.37, β=1.29

Disk scale height:
h(100AU) = 15AU

Disk Grain size distribution:
a_{Grain} = (0.005 – **100**) μm

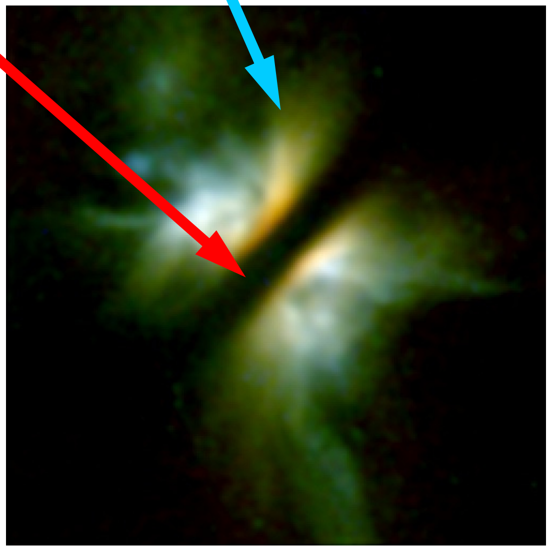
Disk Mass:
7 x 10^{-2} M_{sun}

Envelope Mass:
4.8...6.1 x 10^{-4} M_{sun}

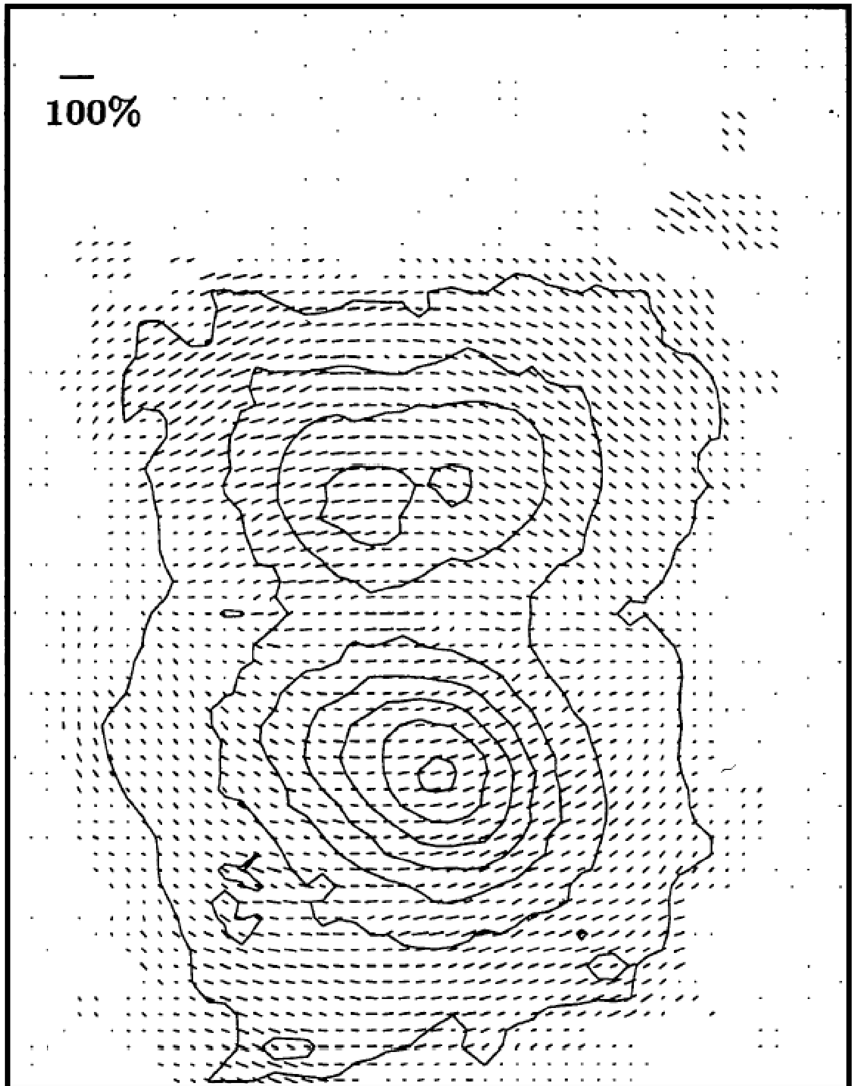
[Wolf et al. 2003]

Confirmation of
different dust evolution scenarios
in the circumstellar shell and disk:

1. Interstellarer dust (< 1μm) in the shell
2. Dust grains with radii up to ~100μm in the circumstellar disk!



Verification



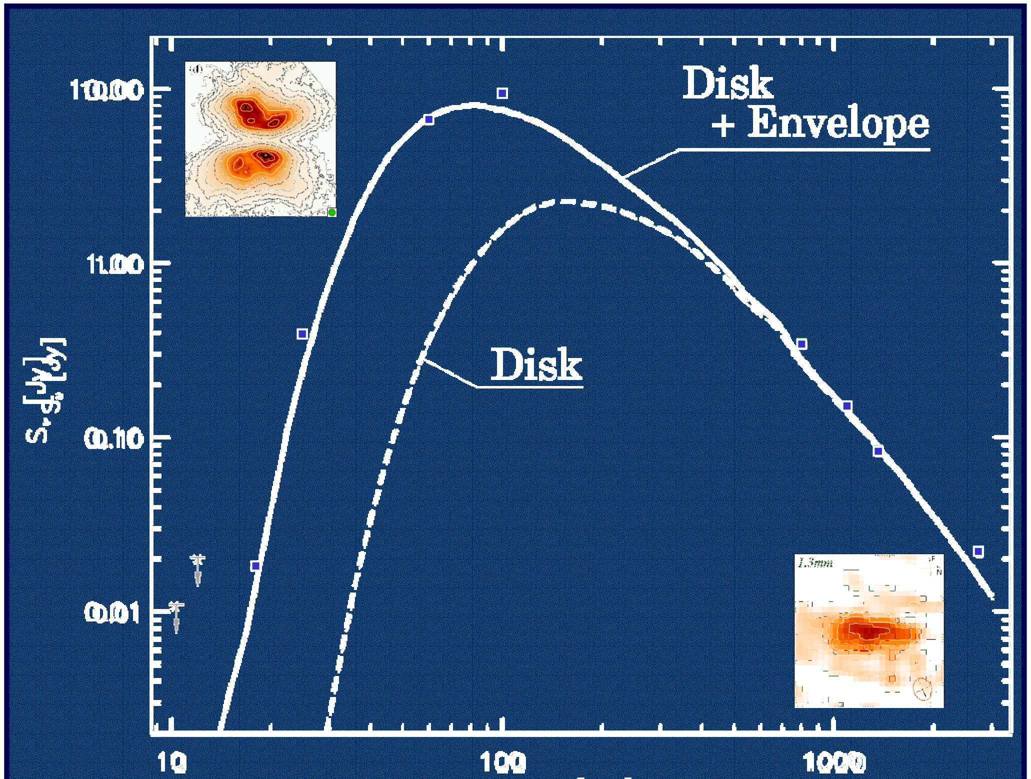
J band polarization map
(Lucas & Roche 1997 – IRCAM-3/UKIRT)

Very high degrees of **Linear Polarization** (up to 80%)

↓

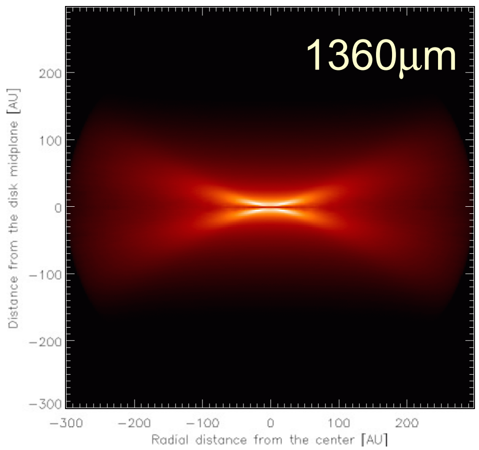
Scattering is dominated by small, interstellar-type dust grains

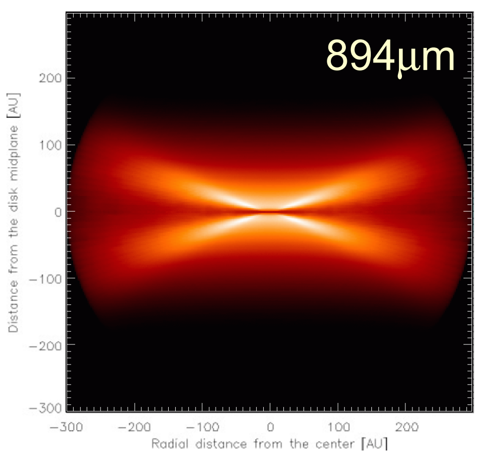
SED



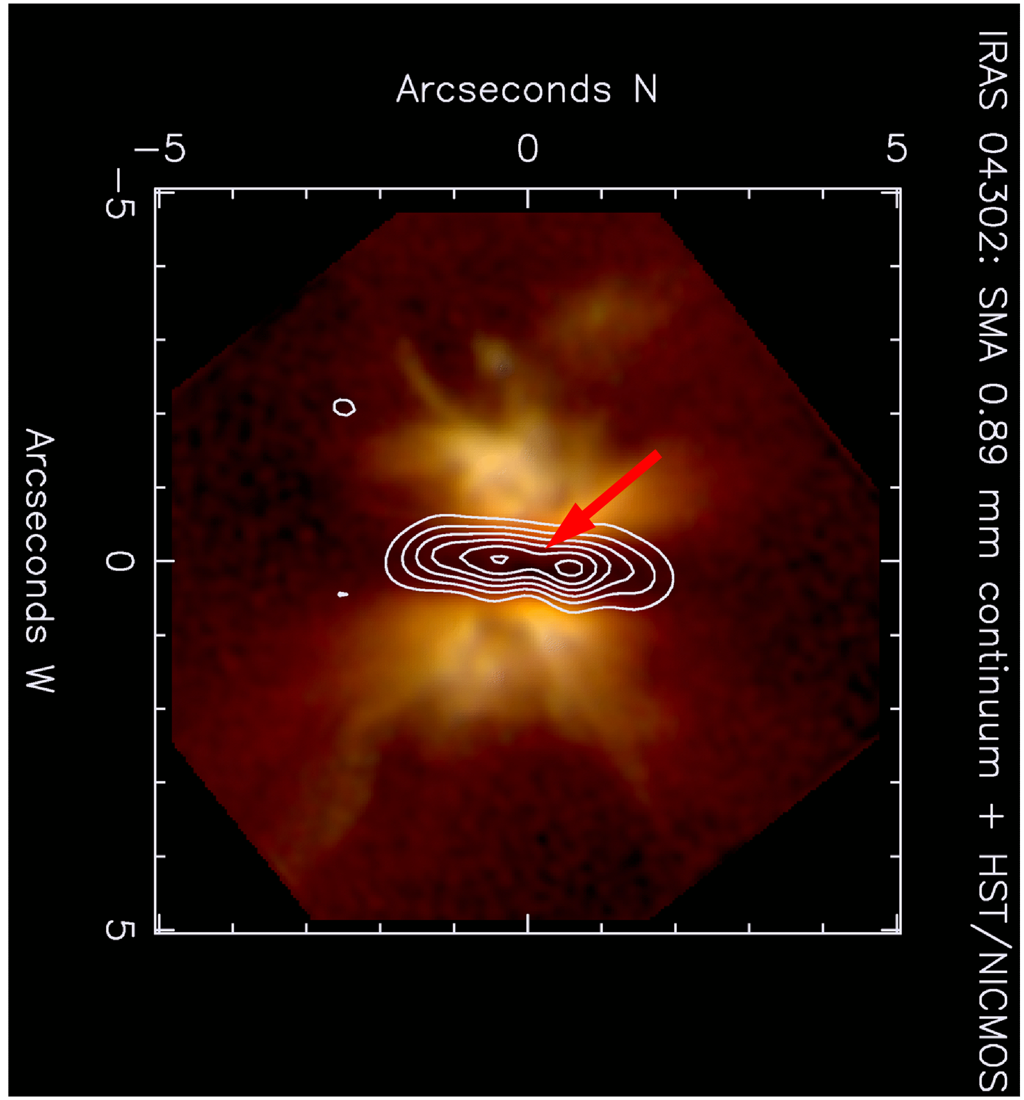
[Wolf et al. 2003]

Submillimeter Disk Structure



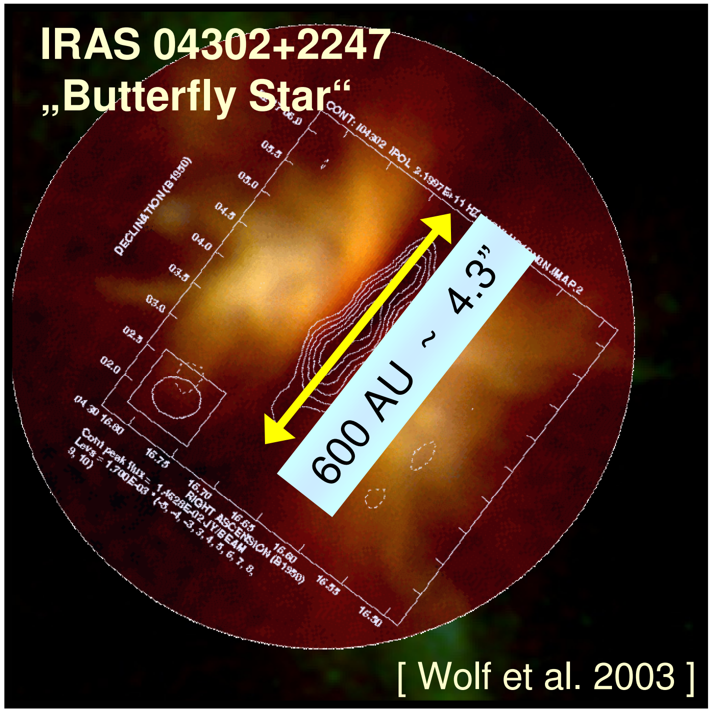


[Wolf et al., subm.]



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

Size Scales



Solar System

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

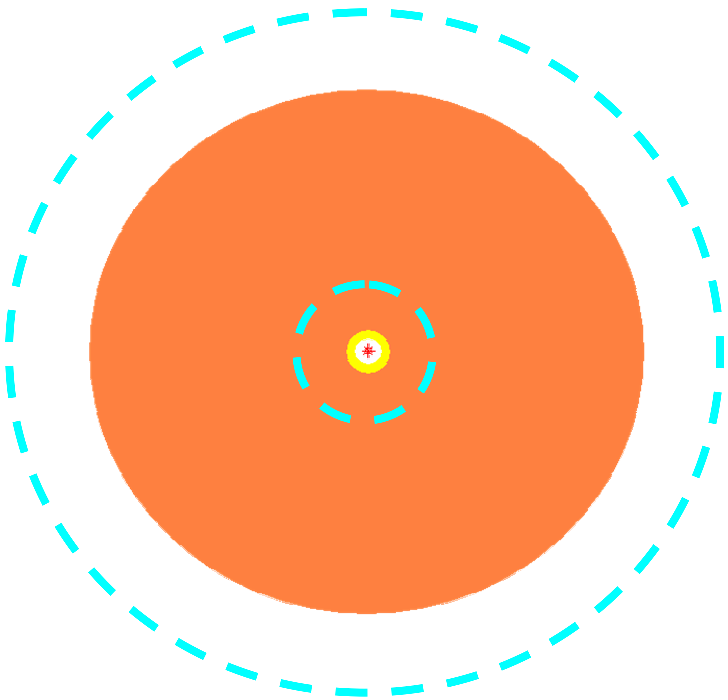
Neptune	-	0.43”
Jupiter	-	0.074”
Earth	-	0.014”

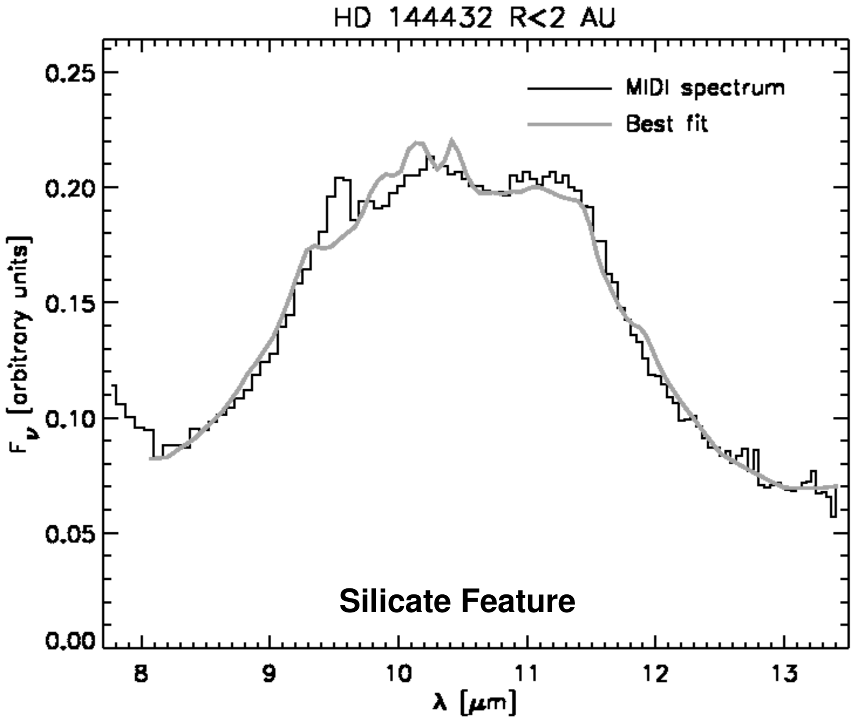
What is feasible?

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

Dust Evolution – The Planet Forming Region

Herbig Ae/Be Stars

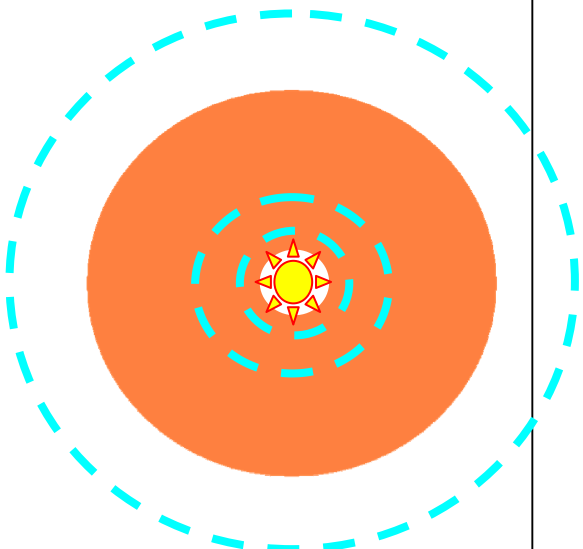


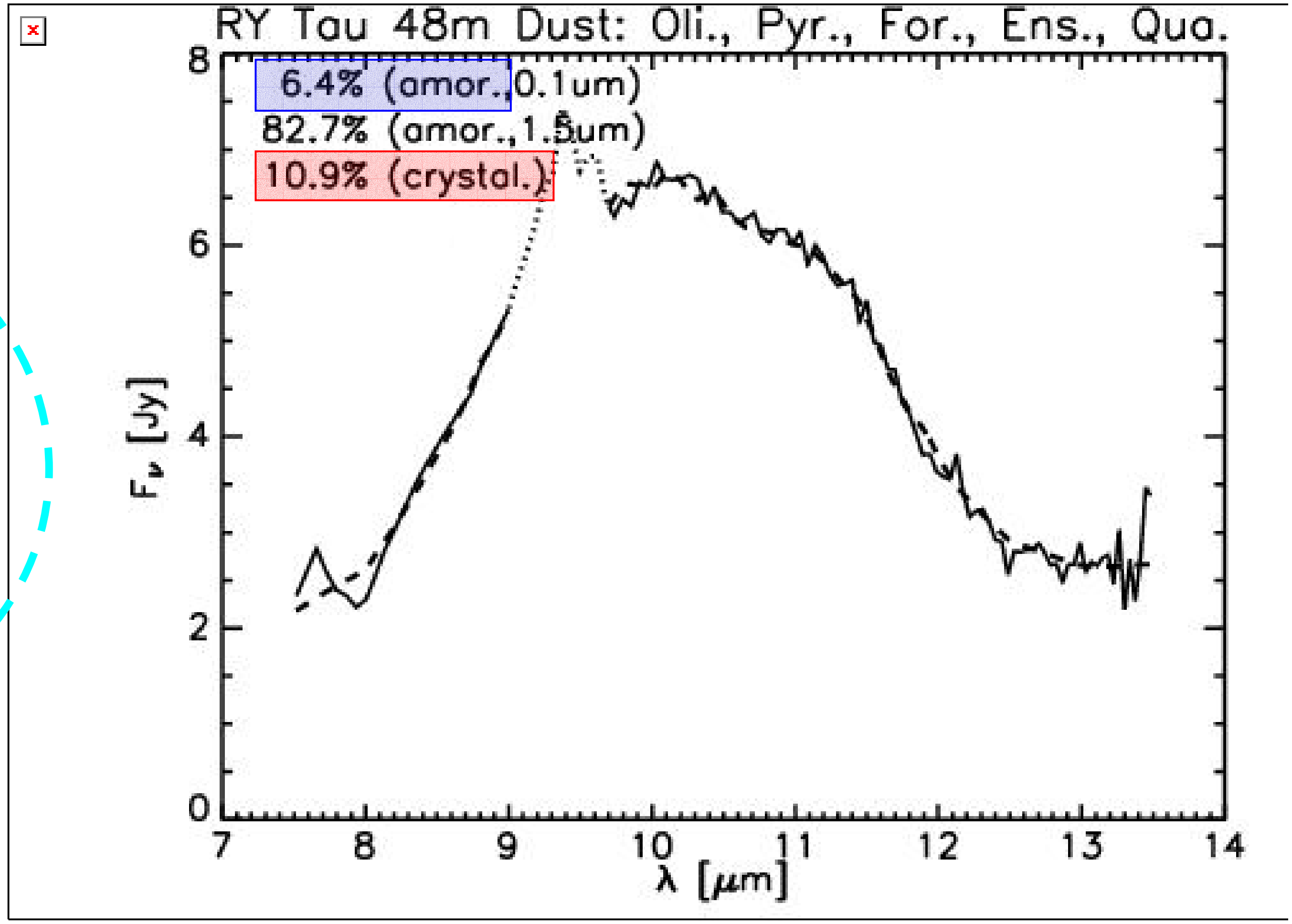


[Leinert et al. 2004]

Dust Evolution – The Planet Forming Region

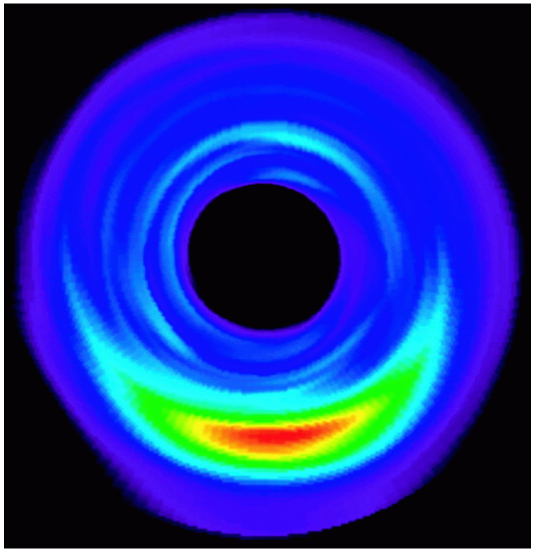
T Tauri Stars
(M < 2-3 M_{sun})





[Schegerer, et al., subm.]

Vortices – Precursors of Protoplanets?



Klahr & Bodenheimer (2002)

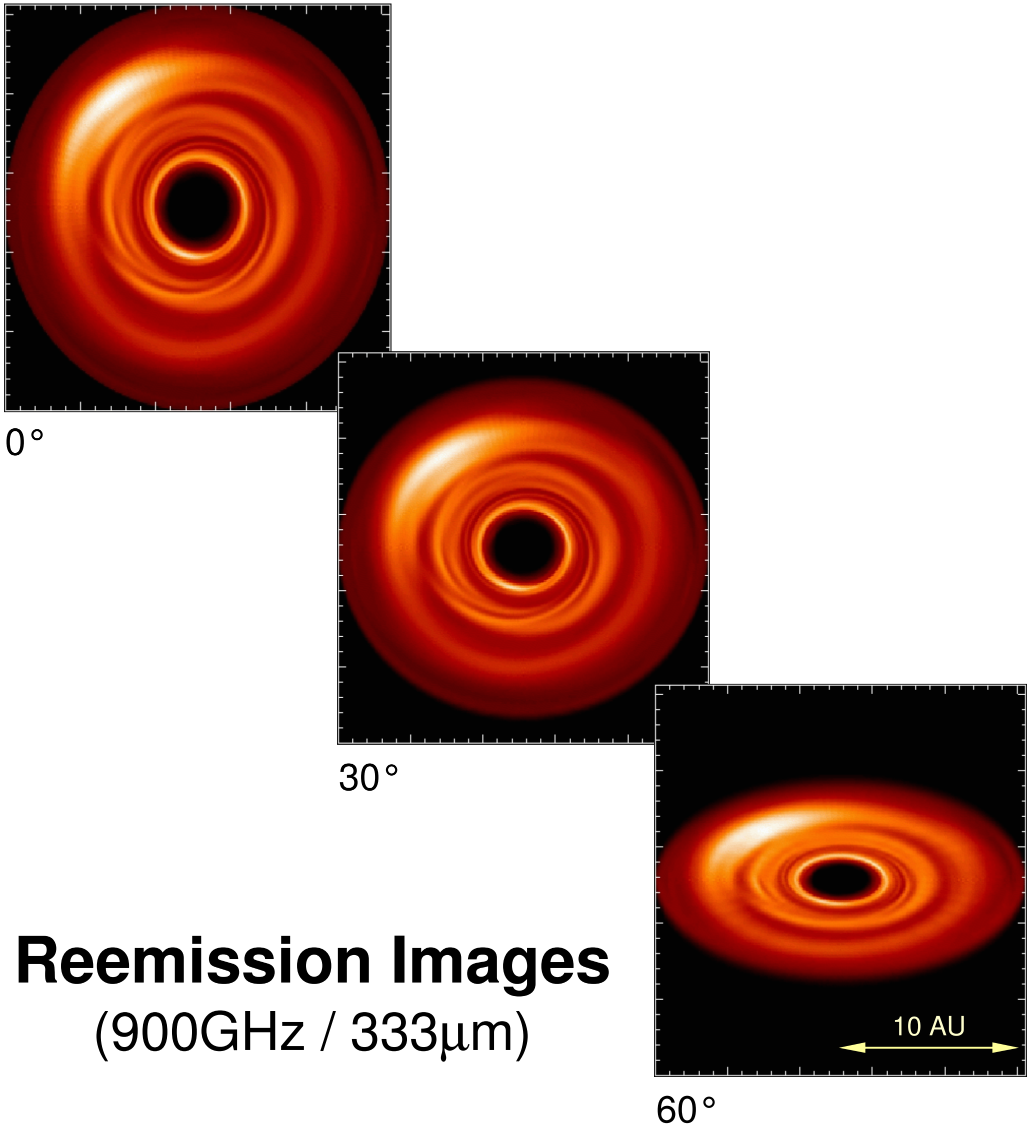
Global baroclinic instability

↓

Turbulence

↓

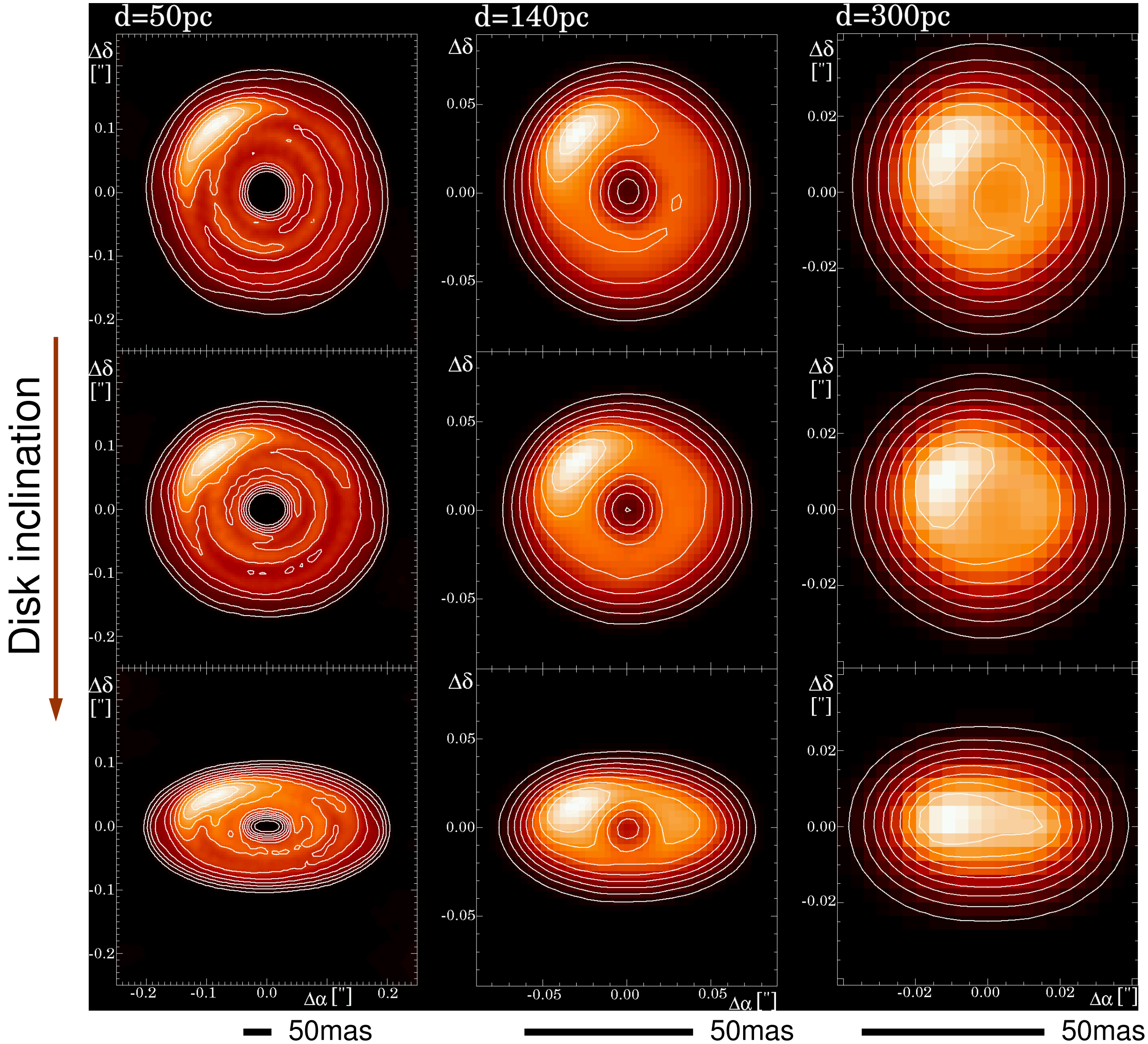
Long-lived high-pressure overdense anticyclones

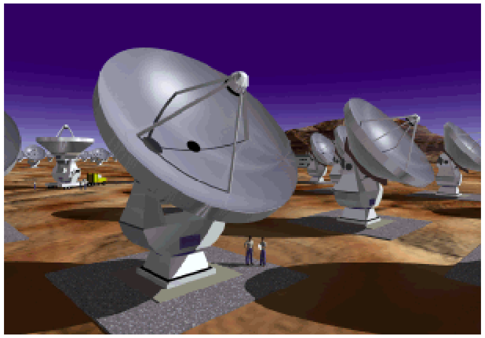


Reemission Images
(900GHz / 333μm)

[Wolf & Klahr 2002]

Vortices – Precursors of Protoplanets?





Simulation: ALMA

Baseline: 13km, 64 antennas

900GHz, Integration time 2hrs

↓

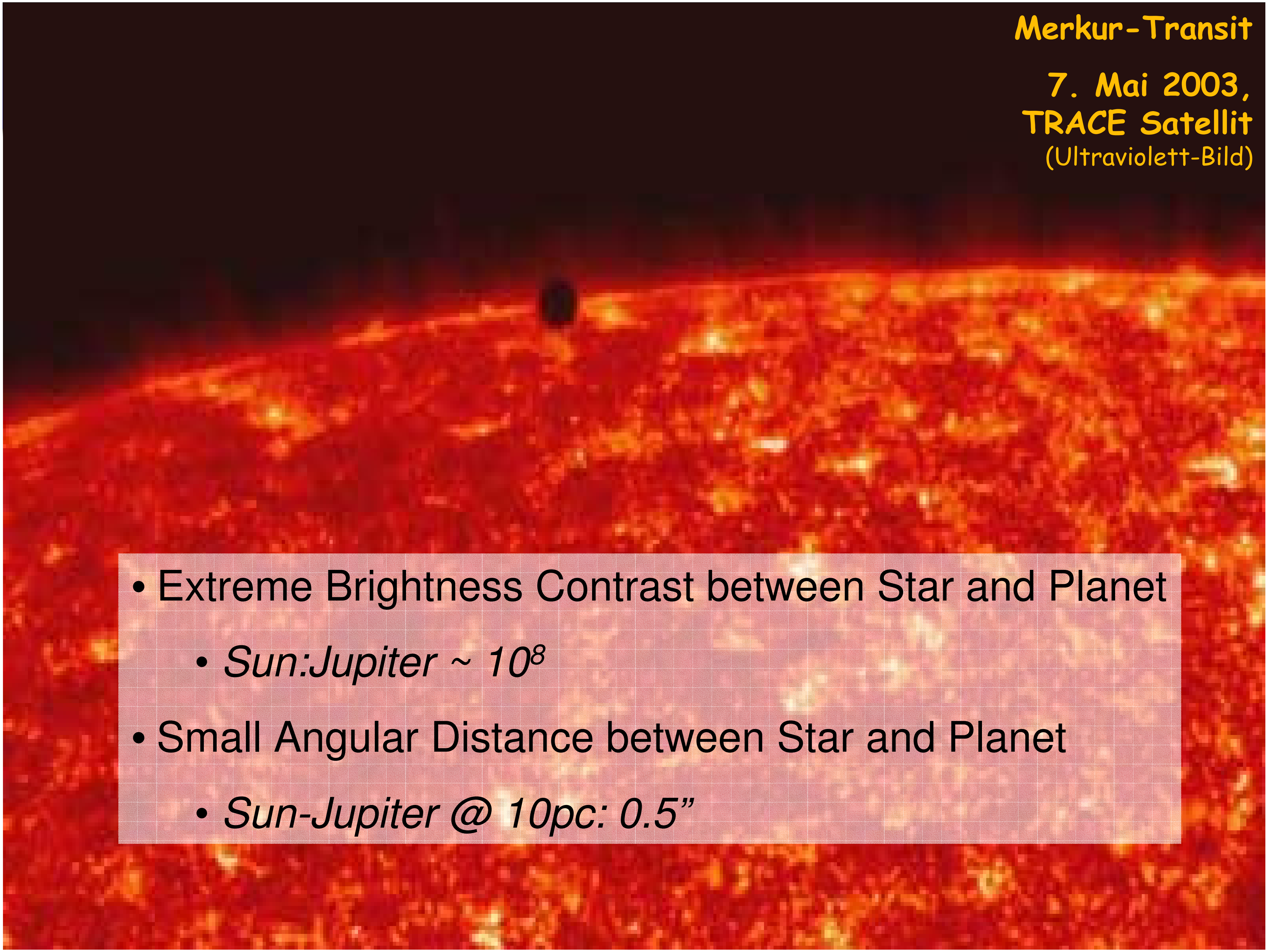
Disk survey possible

[Wolf & Klahr 2002]

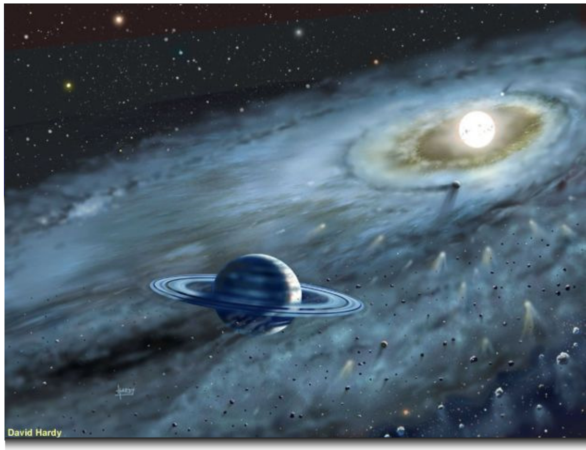
Protoplanets

In Circumstellar Disks


Approximate Size of the Earth



- Extreme Brightness Contrast between Star and Planet
  - *Sun:Jupiter ~ 10^8*
- Small Angular Distance between Star and Planet
  - *Sun-Jupiter @ 10pc: 0.5”*



Finding Protoplanets - In Disks?

Additional Problems
(Dust!)

UV – (N)IR — Scattering

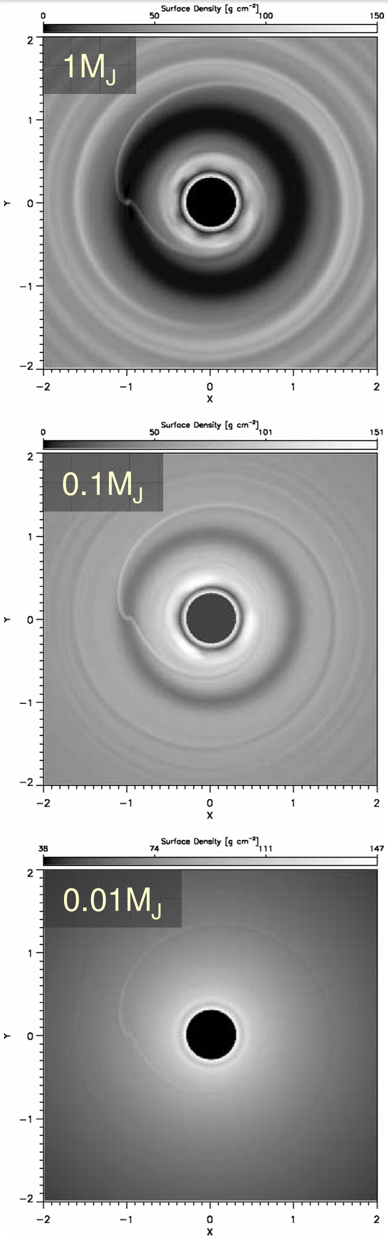
IR – mm — Thermal Reemission

Young disks — Extinction (inclination-dependent)

$= f\,(\,\text{dust properties},\ \ \rho(r,\theta,\phi),\ \ T(r,\theta,\phi)\,)$

Solution: Interferometry / High-resolution Imaging

Disk-Planet Interaction



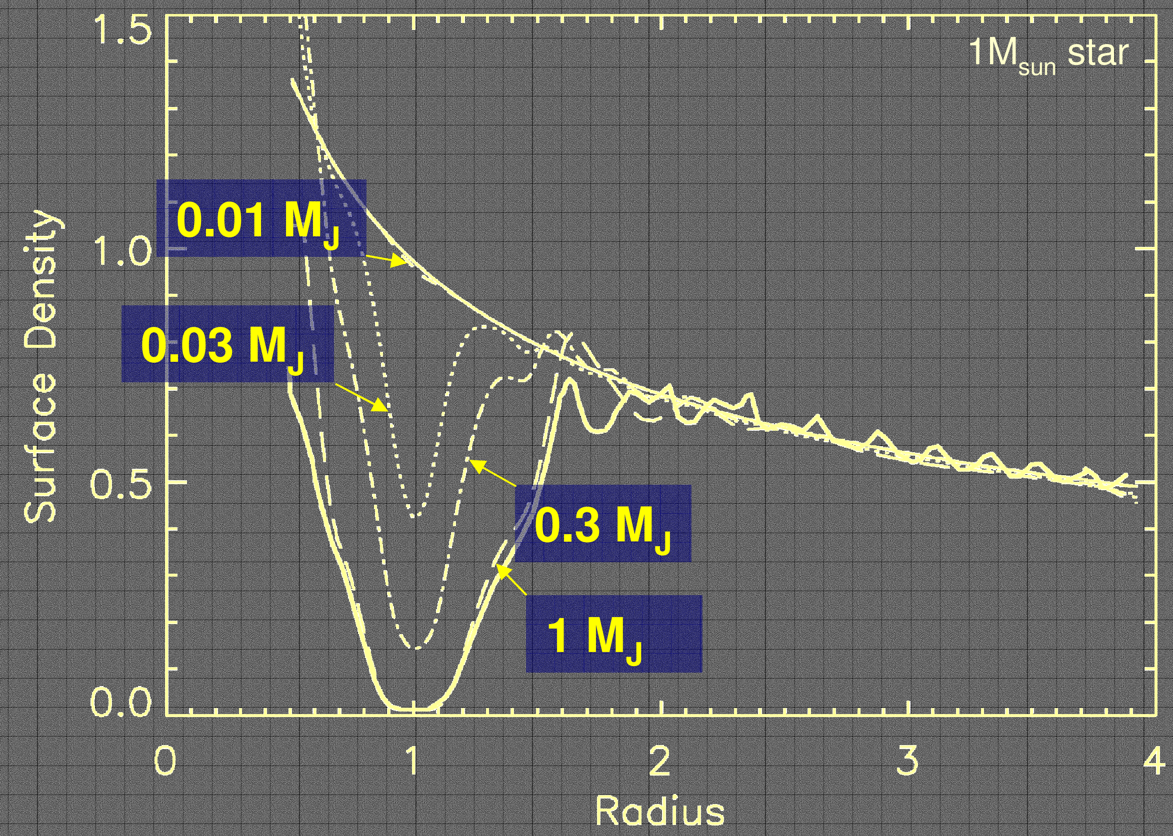
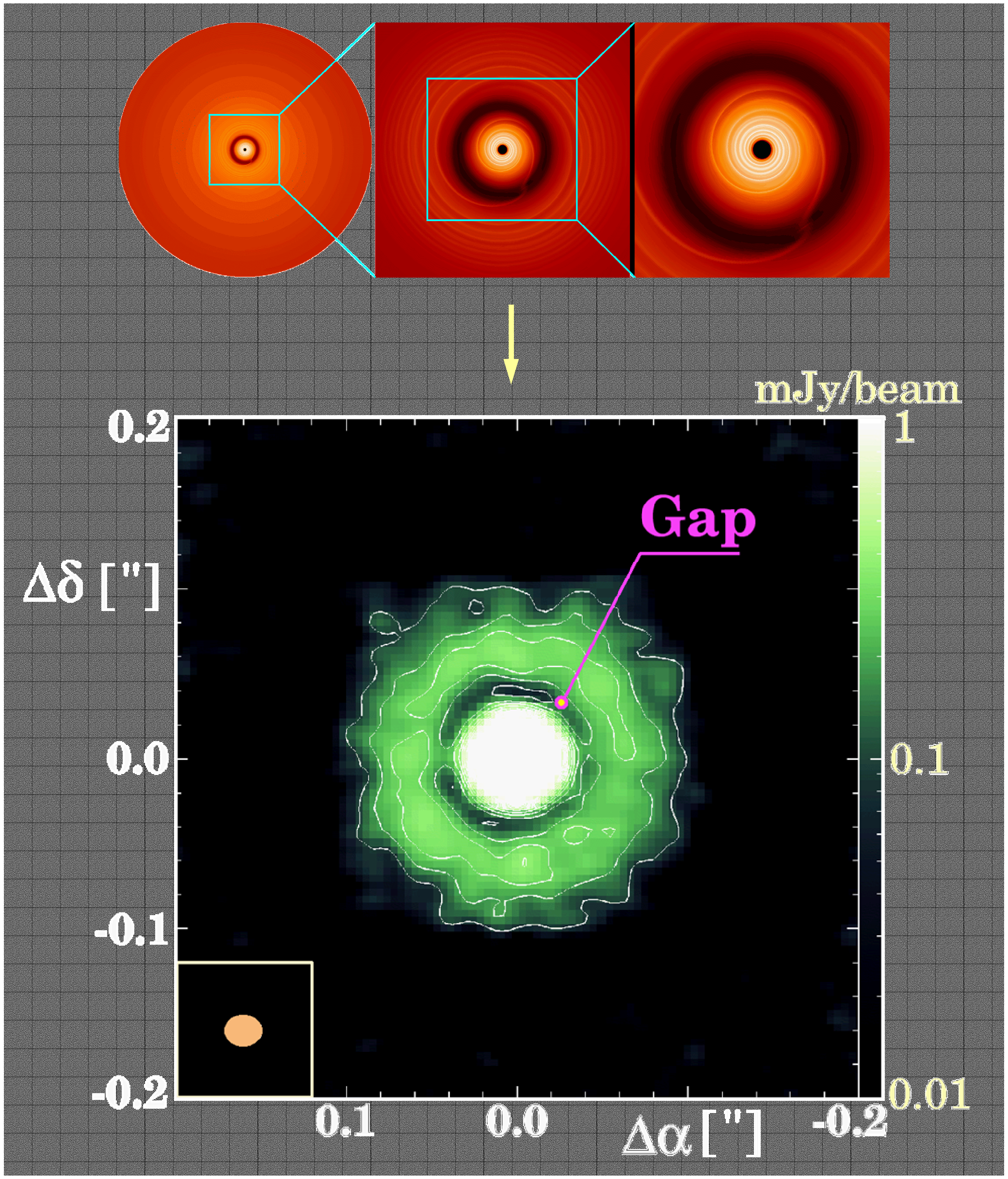


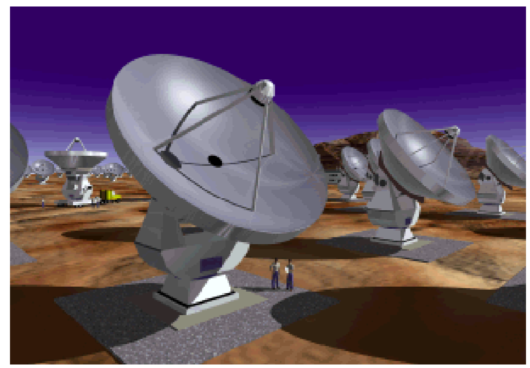
Figure 2. The final azimuthally averaged disc surface density for planets with masses of 1 (long-dashed), 0.3 (dot-dashed), 0.1 (dotted), 0.03 (short-dashed) and 0.01 (thin solid) M_J. Only planets with masses $M_p \gtrsim 0.1\ M_J$ ($M_p \gtrsim 30\ M_\oplus$) produce significant perturbations. The thick solid line gives the result for a 1-M_J planet from the two-dimensional calculations of Lubow et al. (1999).

(Bate et al. 2003)

ALMA: Gaps



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



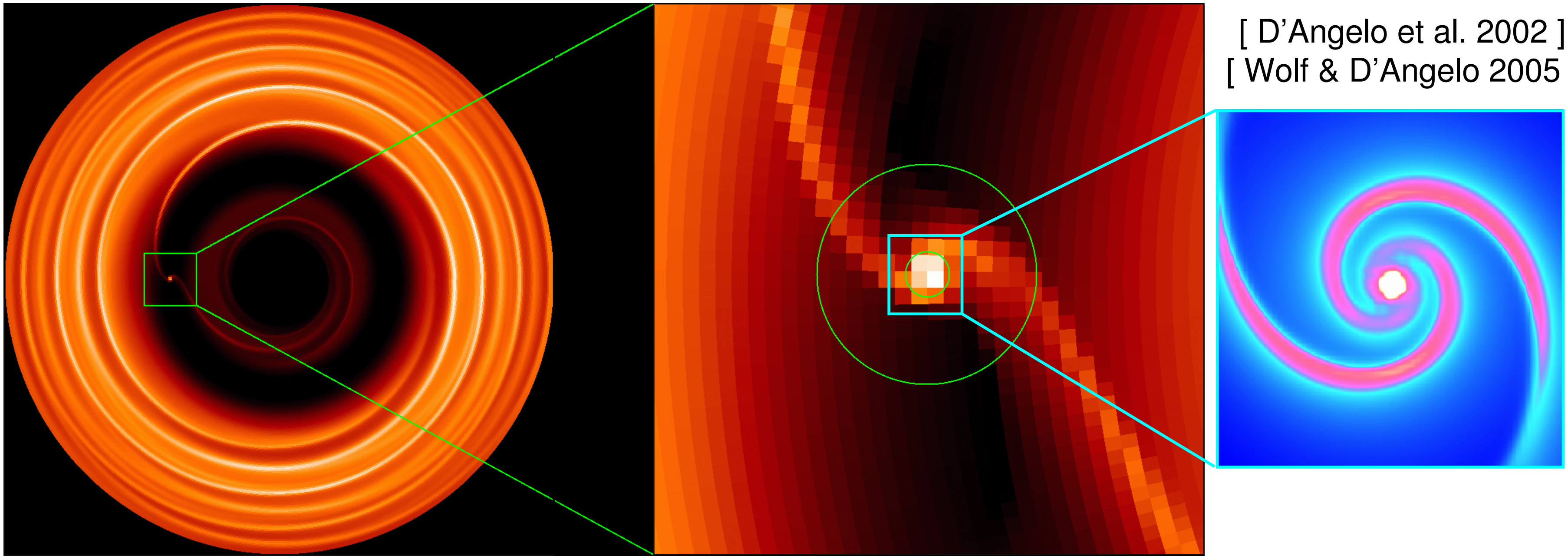
d=140pc

Baseline: 10km

λ=700µm, t_{int}=4h

[Wolf et al. 2002]

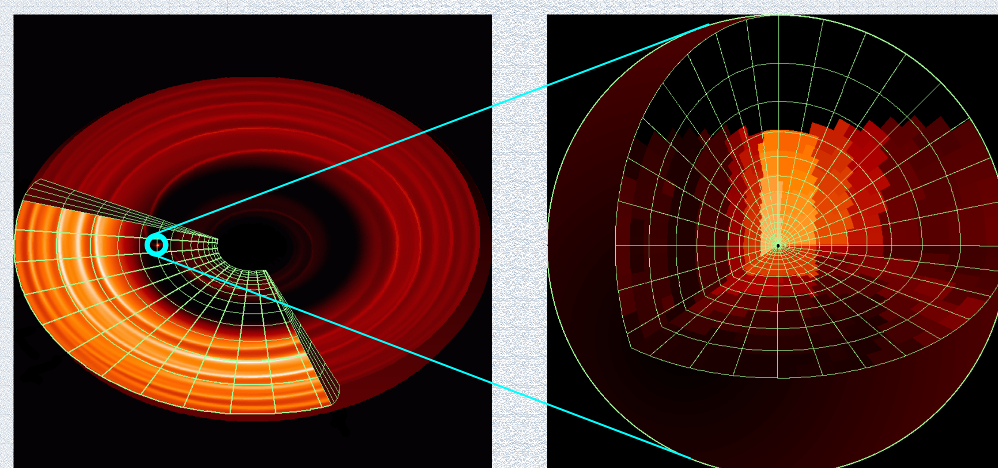
Planetary Accretion Region



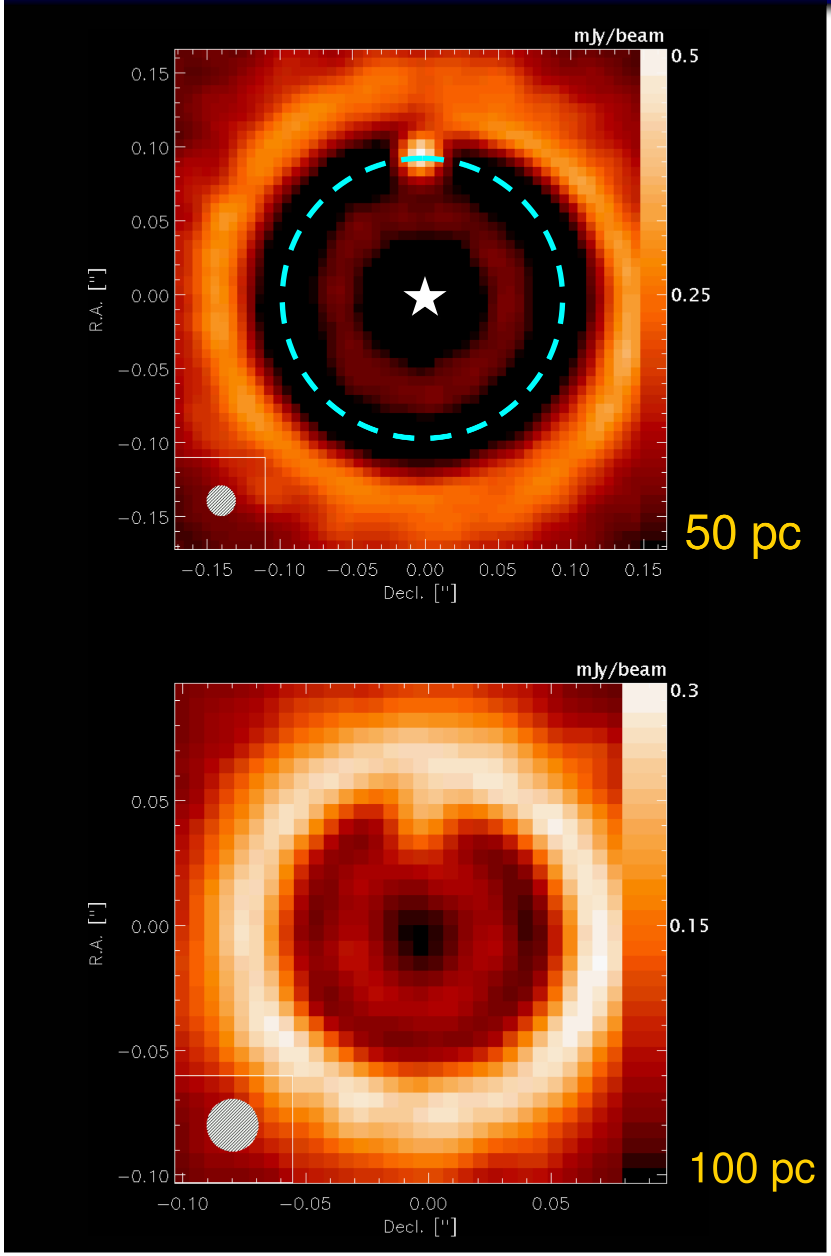
[D'Angelo et al. 2002]
[Wolf & D'Angelo 2005]

Procedure

Density Structure
↓
Stellar heating
↓
Planetary heating
↓
Prediction of Observation



Close-up view: Planetary Region

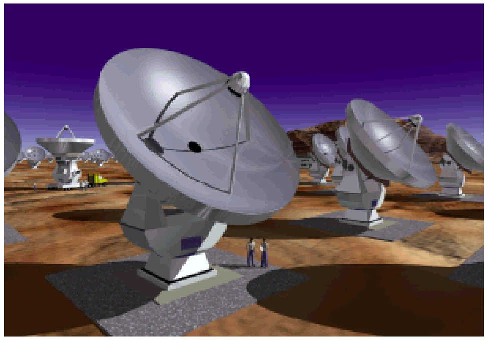


[Wolf & D'Angelo 2005]

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

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); 30º phase noise;
Bandwidth: 8 GHz

Shocks & MRI

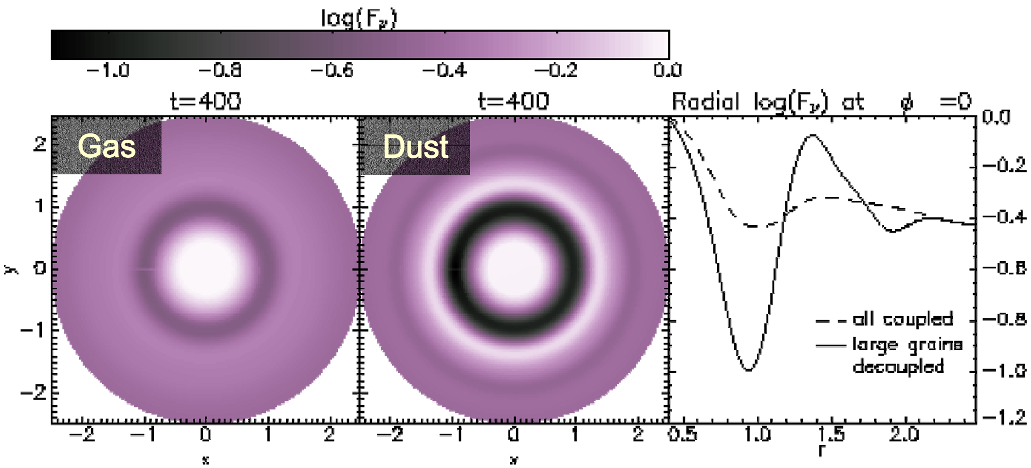
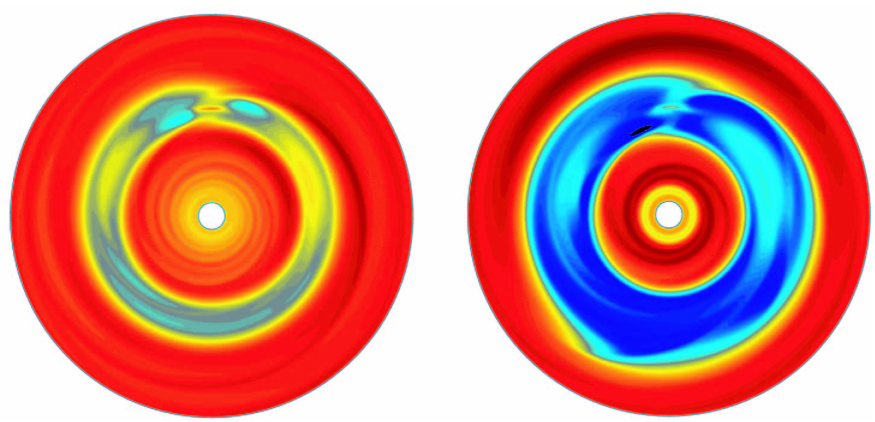


Fig. 3. Logarithm of flux densities at 1 mm, normalized by the maximum and convolved with a Gaussian of FWHM 2.5 AU, corresponding to a resolution of 12 mas at 140 pc. Left panel: all particles follow the gas exactly (static dust evolution). Middle panel: particles larger than the critical size decouple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

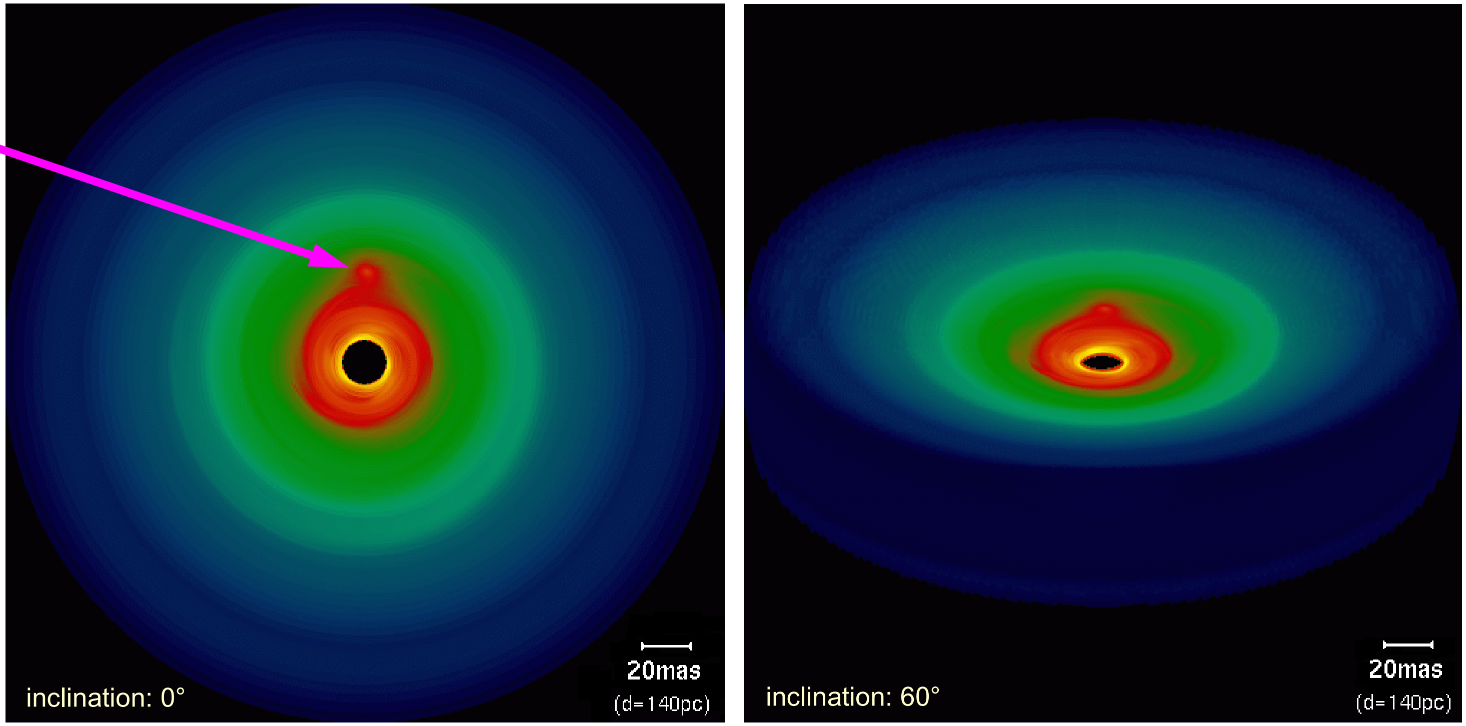
MHD simulations - Magnetorotational instability

- 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

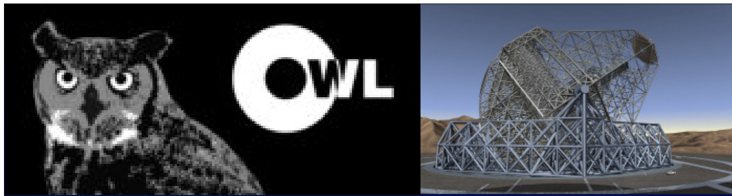
Hot Accretion Region around the Planet

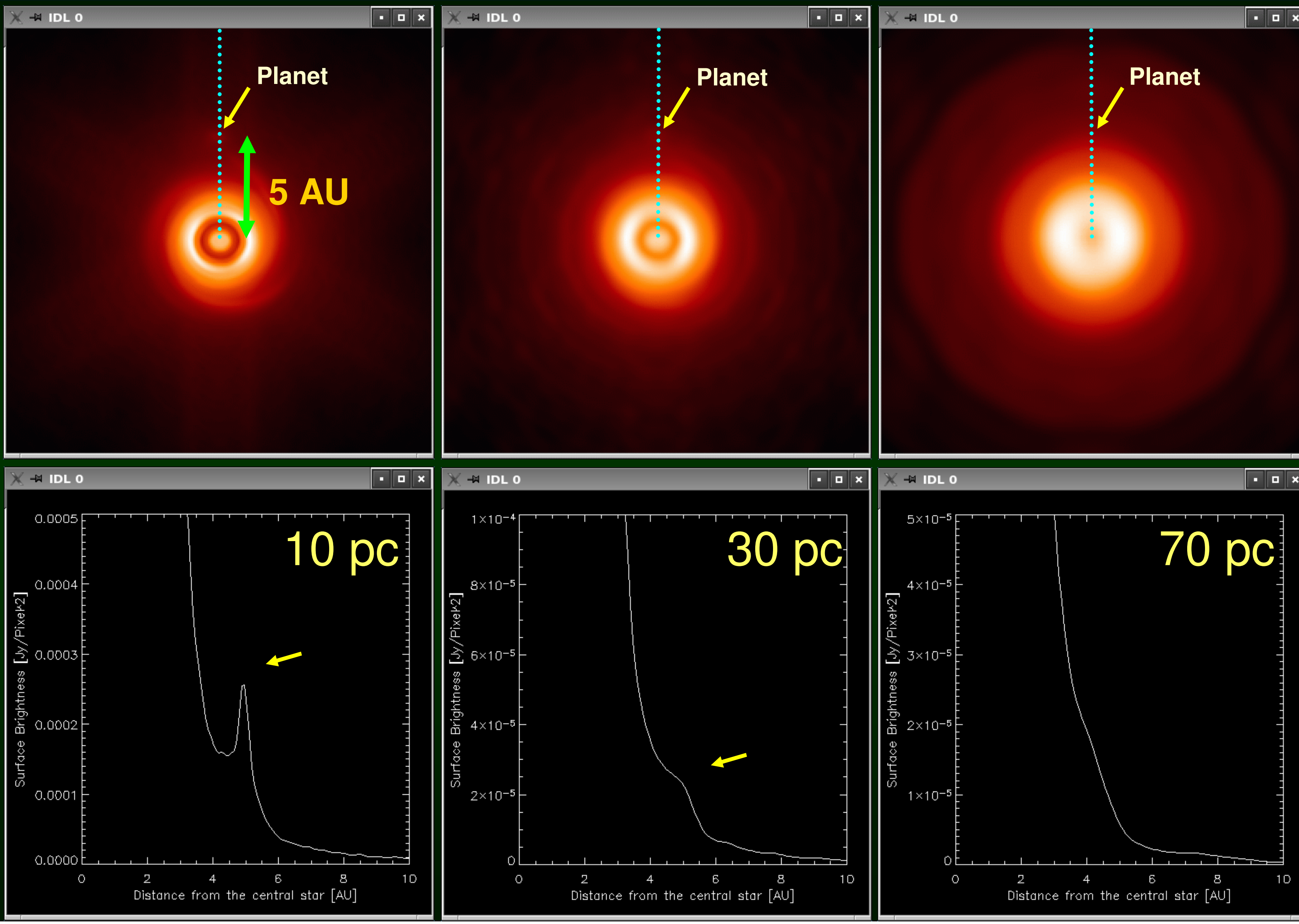


10μm surface brightness profile of a T Tauri disk with an embedded planet (inner 40AUx40AU, distance: 140pc)

[Wolf & Klahr, in prep.]

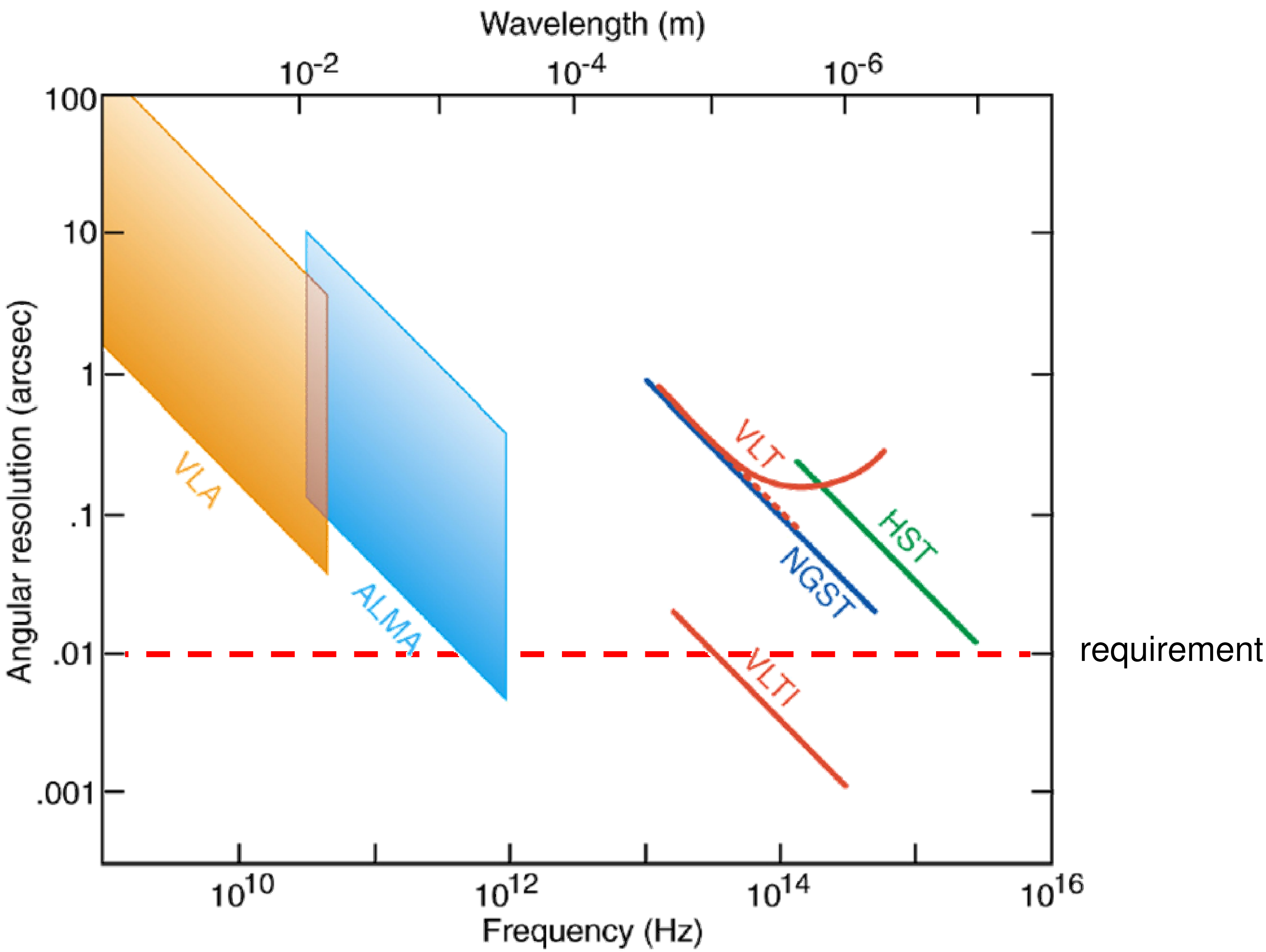
T-OWL





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

High Resolution!



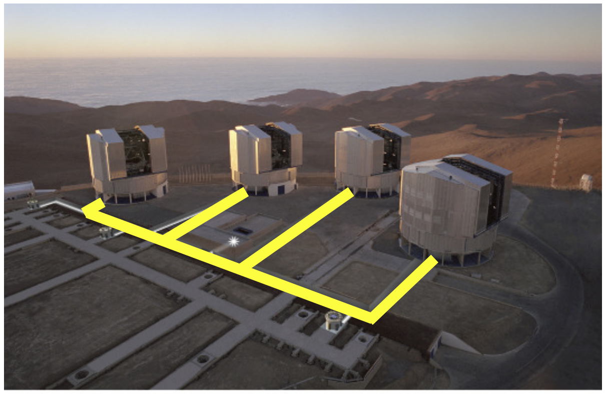
Multi-AperTure Mid-Infrared SpectroScopic Experiment **MATISSE**

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

2nd Generation VLTI Instrument (Status: Phase A)

Specifications:

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



Aerial View of Paranal Observing Platform with VLTI Light Paths

ESO PR Photo 10f/01 (18 March 2001)

What's new?

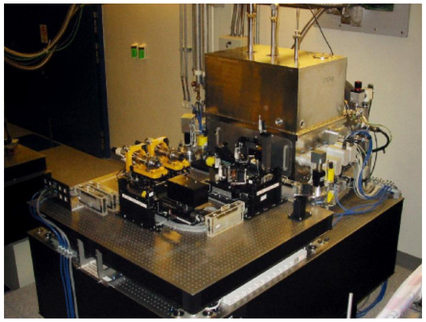
- Image reconstruction

  on size scales of ***3*** */ 6 mas (L band)* ***10*** */ 20mas (N band) using* ***ATs*** */ UTs*
- Multi-wavelength approach in the mid-infrared

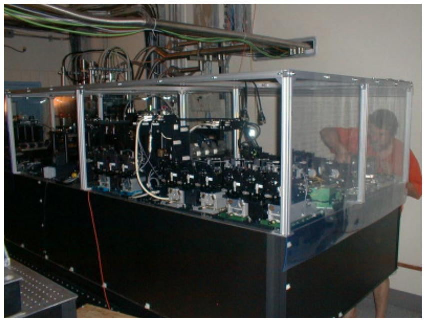
  3 new mid-IR observing windows for interferometry (L,M,Q)
- Improved Spectroscopic Capabilities

Multi-AperTure Mid-Infrared SpectroScopic Experiment MATISSE

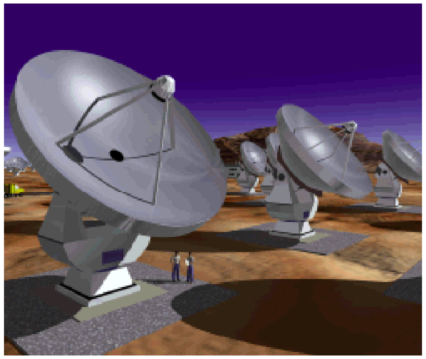
High-Resolution Multi-Band Image Reconstruction + Spectroscopy in the Mid-IR



Successor of **MIDI**:
Imaging capability in the entire mid-IR accessible from the ground

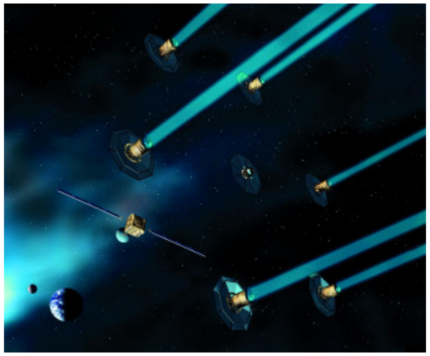


Successor of **AMBER**:
Extension down to 2.7μm
+ General use of closure phases



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

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



MATISSE – Planets

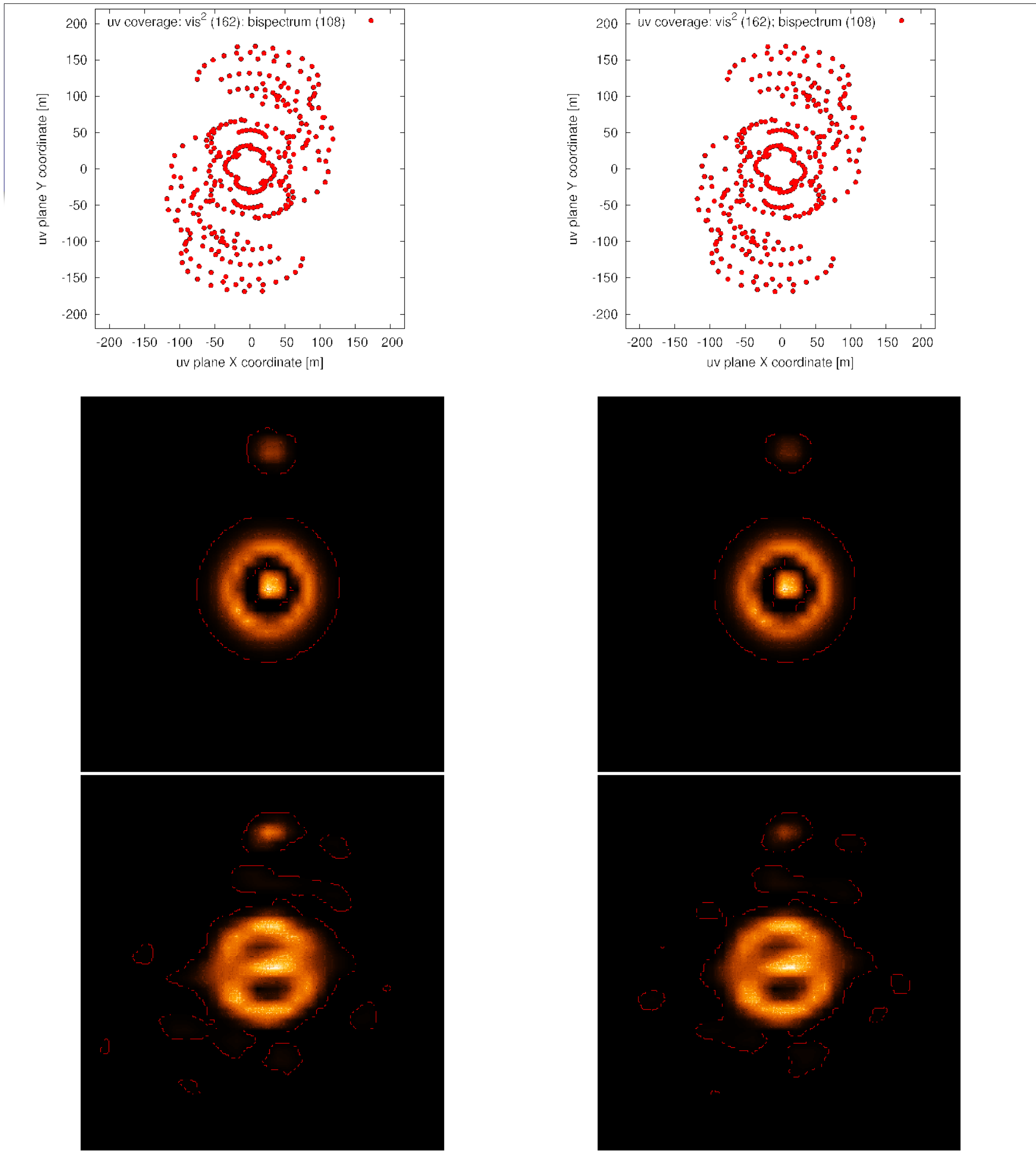
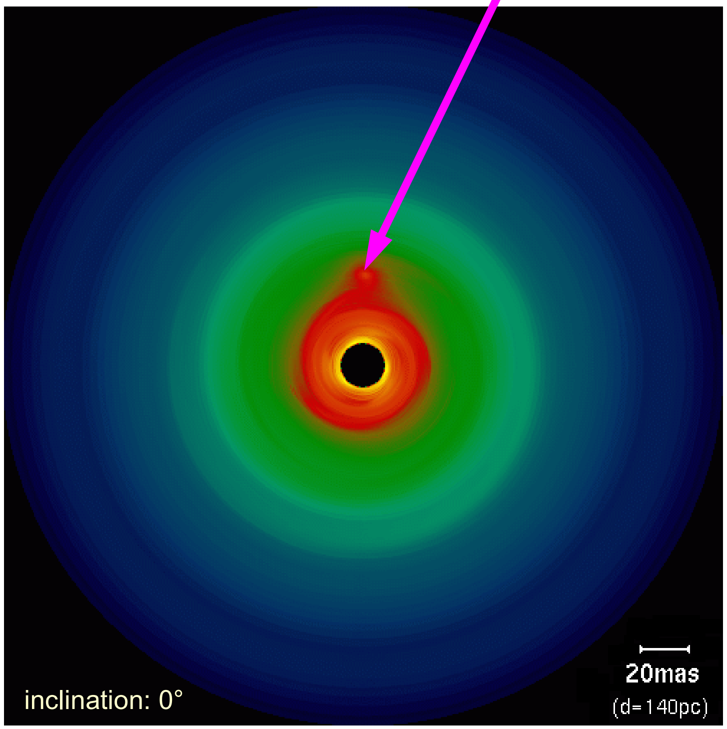


Figure 6: Reconstructed N band images (3x4ATs; ~ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5[right]). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and reconstructions, respectively. The images are not convolved (2x super resolution). Simulation parameter: modelled YSO with planet (declination -30°; observing wavelength 9.5 μm; FOV = 104 mas; 1000 simulated interferograms per snap shot with photon and 10 μm sky background noise (average SNR of visibilities: 20). See Doc. No. VLT-TRE-MAT-15860-5001 for details.

Hot Accretion
Region
around the Planet



[Wolf et al. 2005-2007]

Disk clearing?

Sublimation radius ~ 0.1-1AU (TTauri HAe/Be stars)

but:

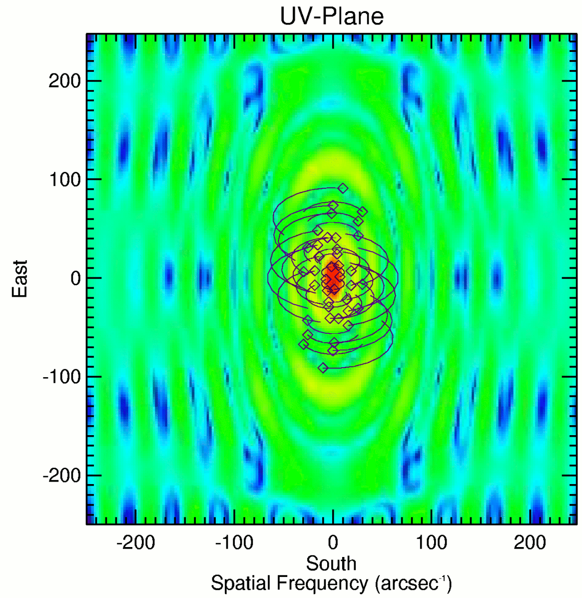
Observations: Significant dust depletion >> Sublimation Radii

TW Hydrae : ~ 4 AU (Calvet et al. 2002)

GM Aur   : ~ 4 AU (Rice et al. 2003)

CoKu Tau/4 : ~10 AU (D'Alessio et al. 2005, Quillen et al. 2004)

Configuration: 7 Nights × 3 ATs
Baselines: B5-J6-J1, B5-D0-J3, B5-B1-D1, B5-M0-G2, J6-A0-J2, J1-D1-G2, J6-A0-M0
Number of Visibilities: 210, Number of Closure Phase Relations: 70



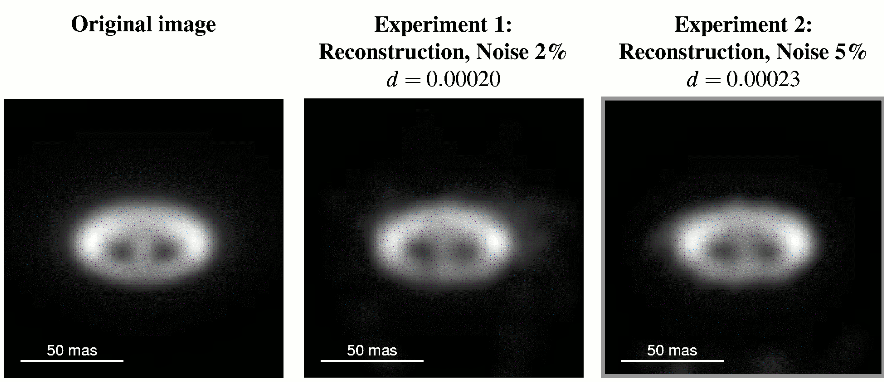
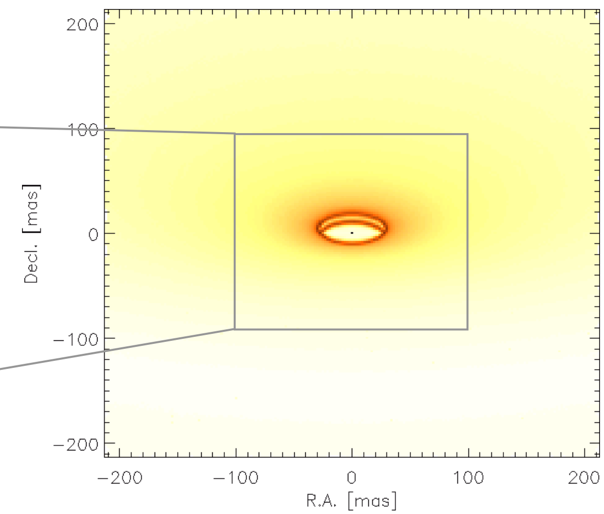


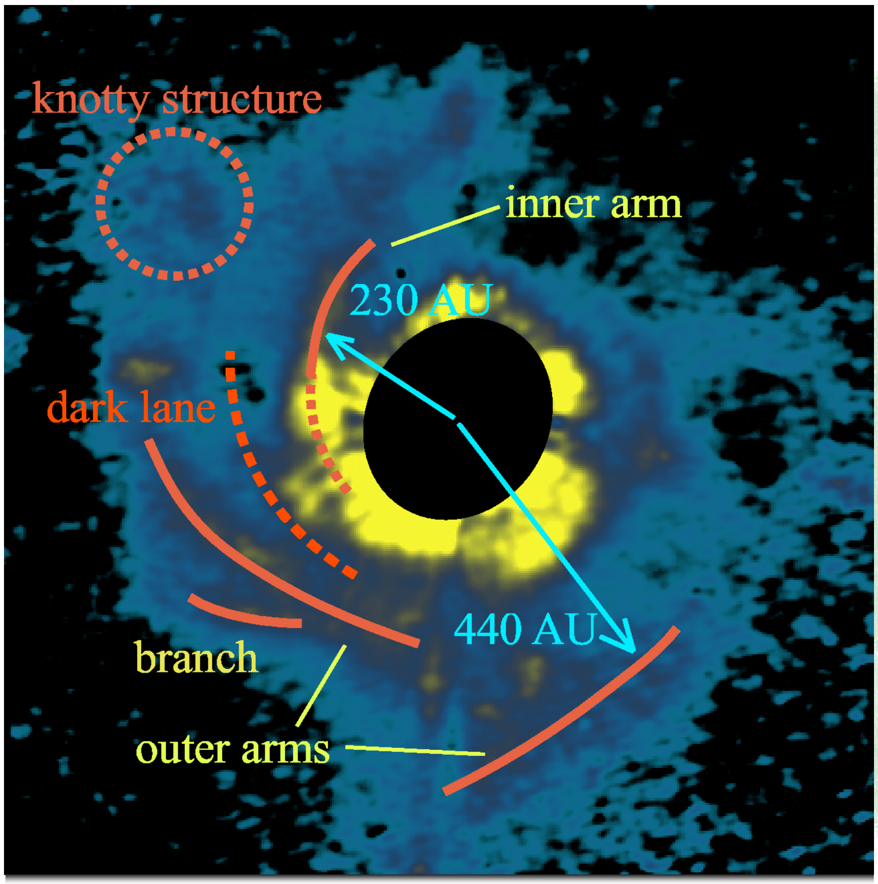
Figure 22: Image reconstruction experiments. *Top*: uv-coverage of the two reconstruction experiments; *Bottom left*: original image (see Fig. 21, right) convolved with a PSF corresponding to a 202 m aperture; *Bottom center and right*: images reconstructed from two data sets with 2% and 5% noise of the squared visibilities (4% and 10% for the simulated closure phases). The reconstruction errors are 0.00020 (2% noise) and 0.00023 (5% noise) using the distance measure *d* by Lawson et al. (2004).

[Wolf et al. 2005, 2006]

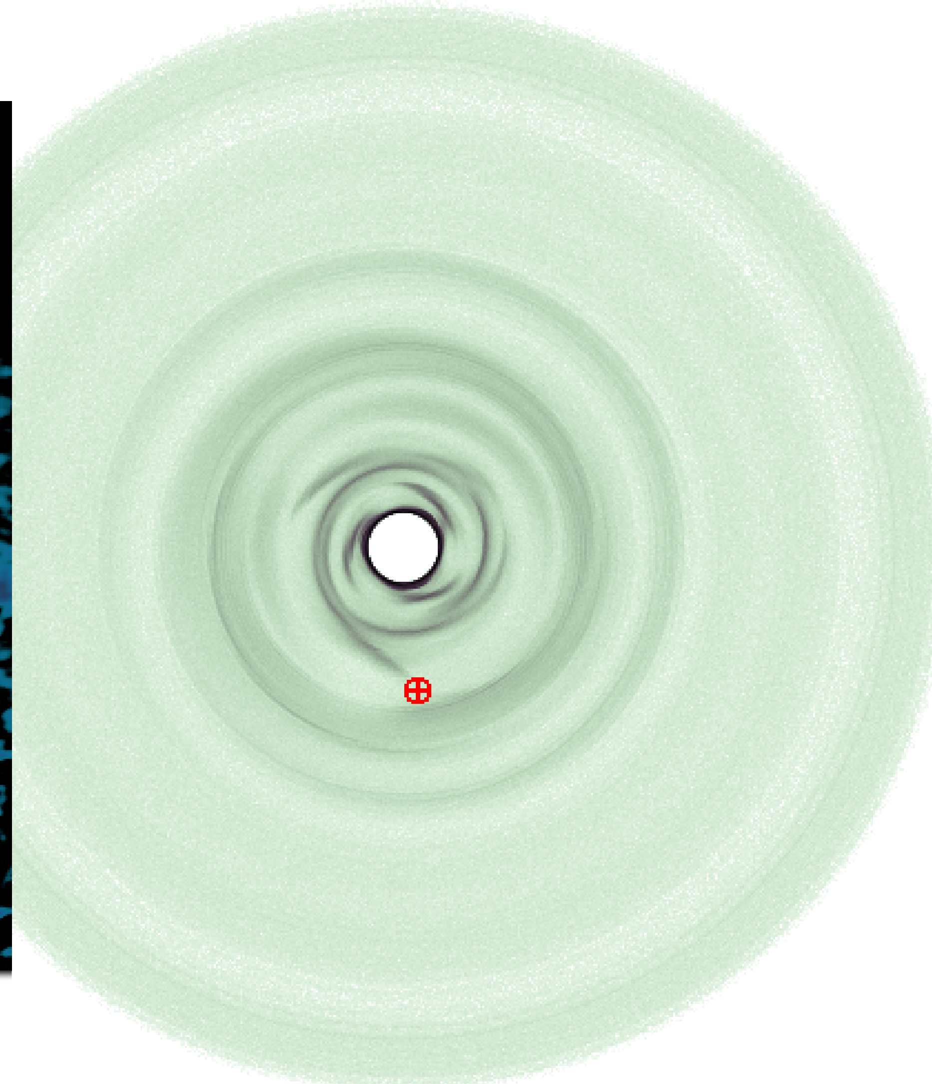


10µm image of a circumstellar disk
with an inner hole; radius 4AU
(inclination: 60°; distance 140pc;
inner 60AU x 60AU)

Surface Structure

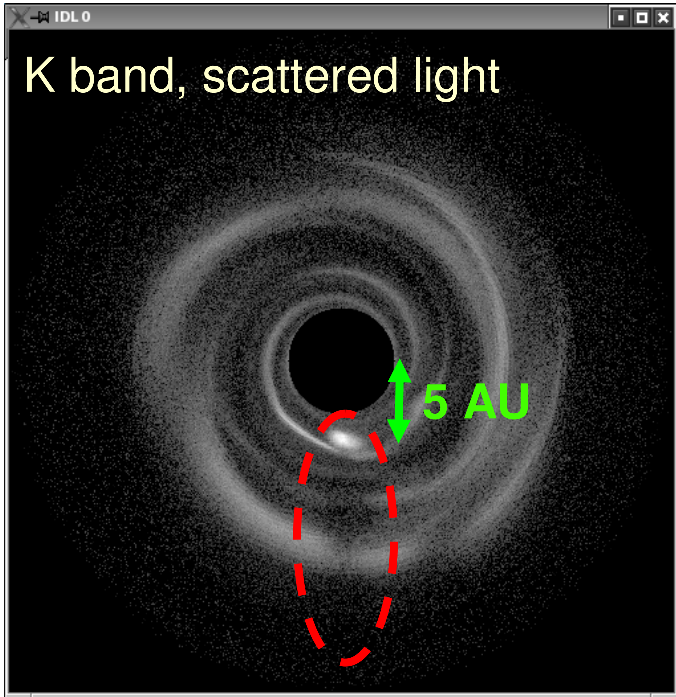


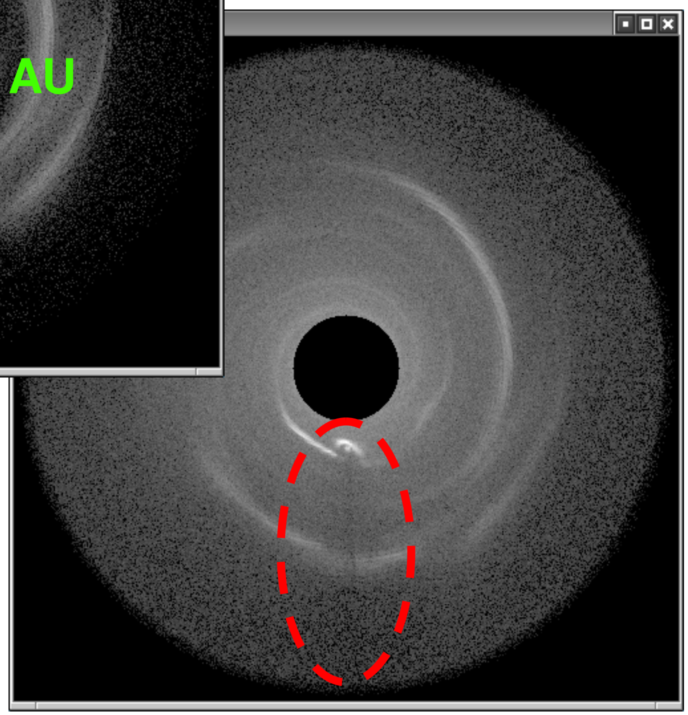
AB Aurigae - Spiral arm structure
(Herbig Ae star; H band; Fukagawa, 2004)



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

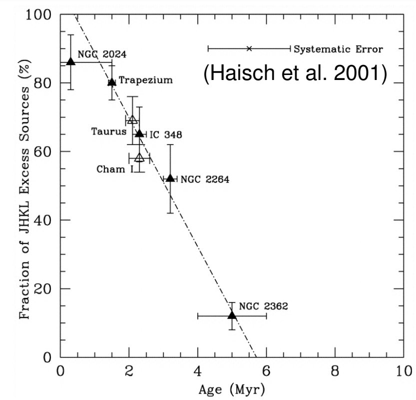
Narrow Angle Field: 1 °

Narrow Angle Astrometry
1μas mission accuracy

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

[G. Bryden, priv. comm.]

Disks evolve …



Near-infrared photometric studies:
sensitive to the inner ~ 0.1 AU around solar-type stars:

- Excess rate decreases from ~80% at an age of ~1 Myr to about 50% by an age of ~3 Myr (Haisch et al.~2001)
- By ages of ~10-15 Myr, the inner disk has diminished to nearly zero (Mamajek et al.2002).

- **Far-infrared / millimeter continuum observations** probe the colder dust and thus the global dust content in disks:
  - Beckwith et al. (1990): no evidence of temporal evolution in the mass of cold, small (<1mm) dust particles between ages of 0.1 and 10Myr
  - By an age of 300 Myr the dust masses were found to by decreased by at least 2 orders of magnitude (Zuckerman & Becklin 1993).
  - Based on studies with the Infrared Space Observatory (ISO), the disk fraction amounts to much less than 10% for stars with ages > 1 Gyr (e.g., Spangler et al. 2001; Habing et al. 2001; Greaves et al. 2004; Dominik & Decin 2003).

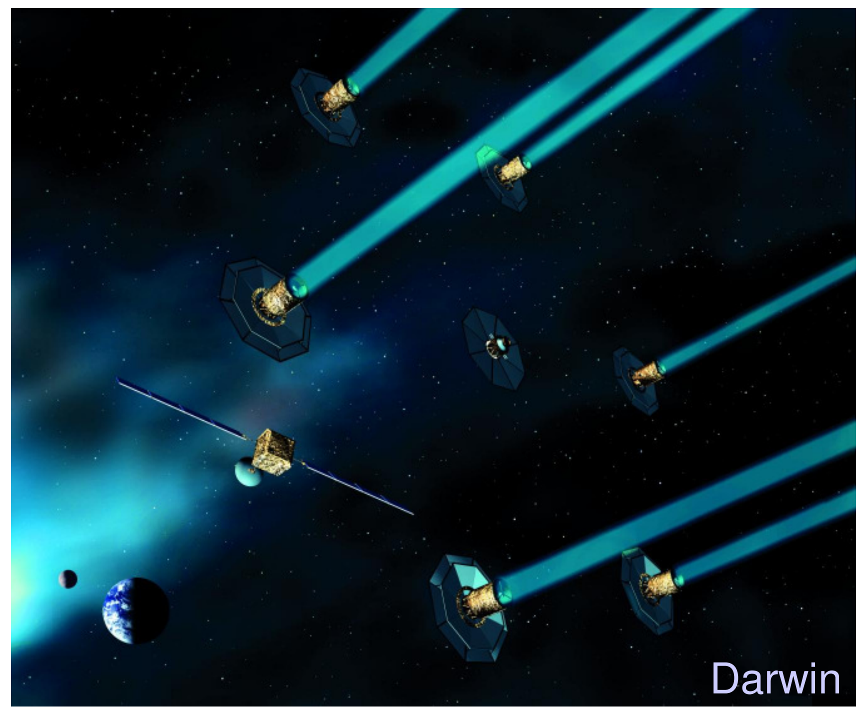
… but might still outshine embedded planets

The exozodiacal dust disk around a target star, even at solar level, will likely be the dominant signal originating from the extrasolar system:

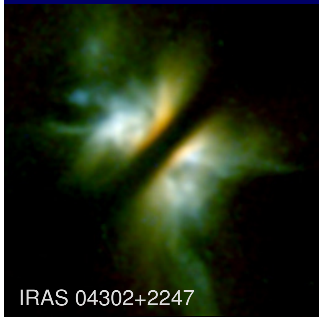
- Solar system twin: overall flux over the first 5 AU is about 400 times larger than the emission of the Earth at 10µm

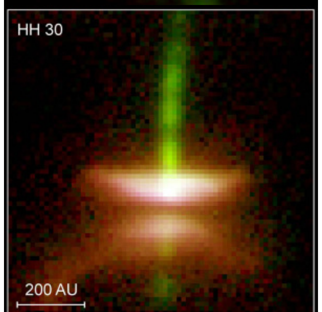
Zodiacal light of our own solar system:

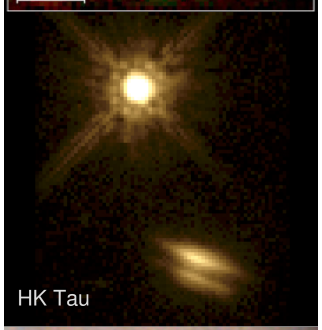
- Potential serious impact on the ability of space-born observations (e.g. DARWIN)
- Attributed to the scattering of sunlight in the UV to near-IR, and the thermal dust reemission in the mid to far-IR
- > 1µm: signal from the zodiacal light is a major contributor to the diffuse sky brightness and dominates the mid-IR sky in nearly all directions, except for very low galactic latitudes (Gurfil et al. 2002).



Planet Disk Interaction







Young circumstellar disks around T Tauri / HAe/Be stars

optically thick

Debris disks

optically thin

Density structure dominated by

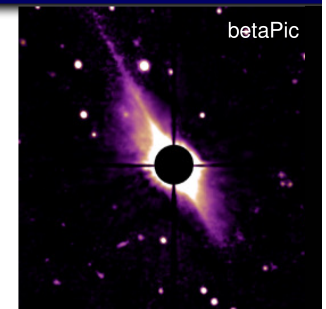
Gravitation

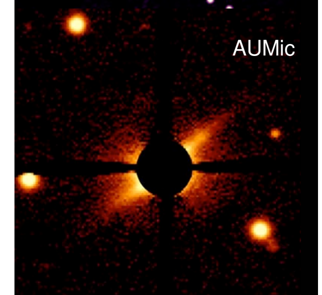
+

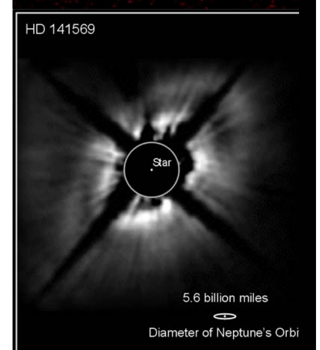
Gas dynamics

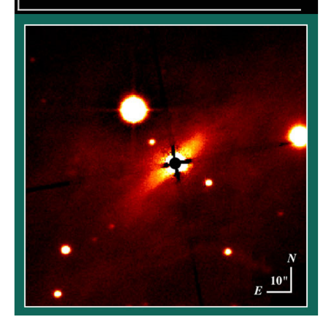
Radiation Pressure

Poynting-Robertson effect

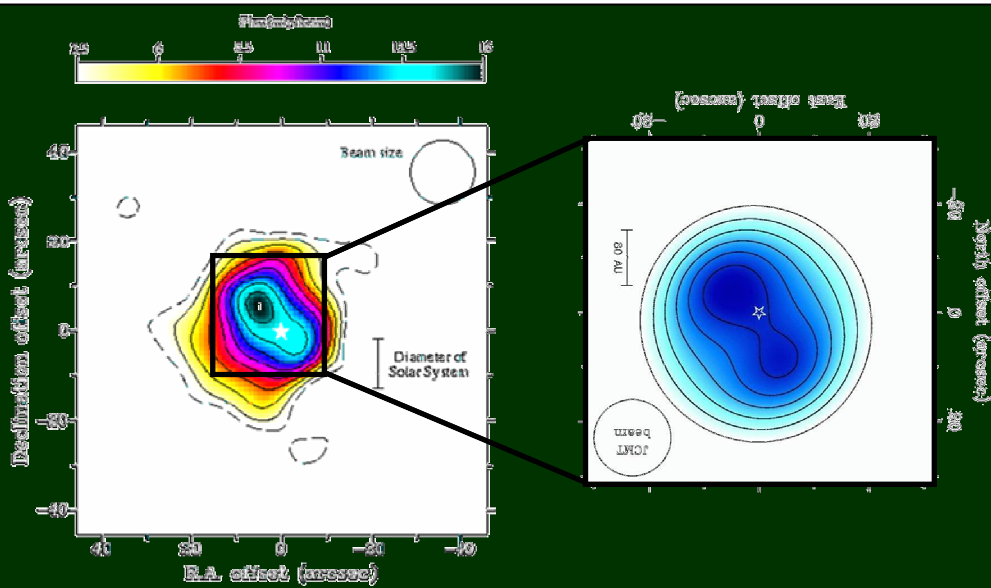


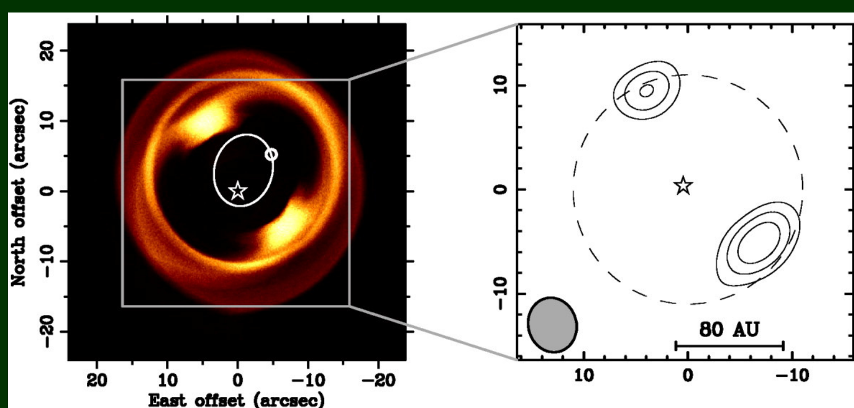






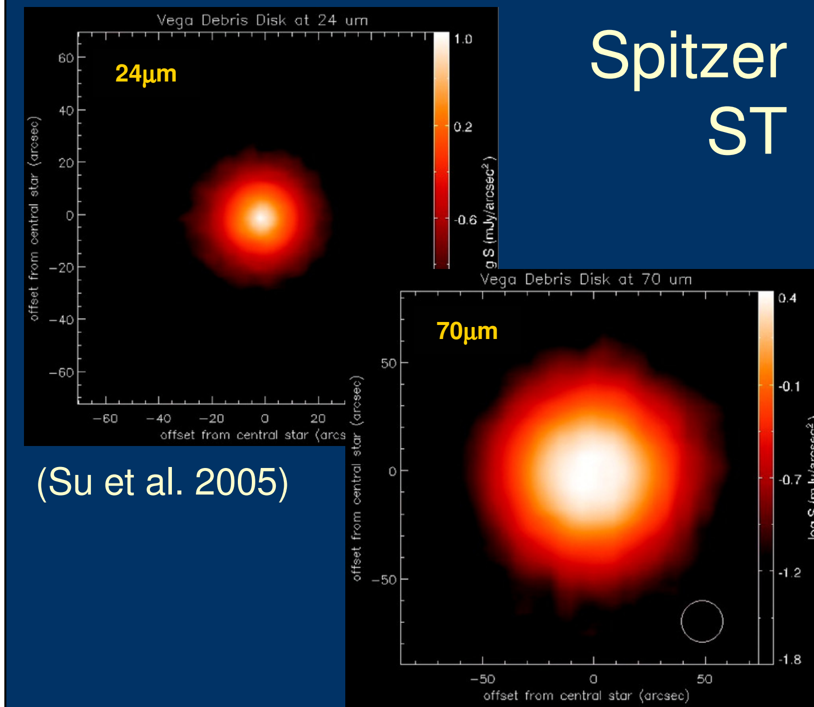
Debris Disks around Vega





Dust reemission ⟶ SOFIA, JWST

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

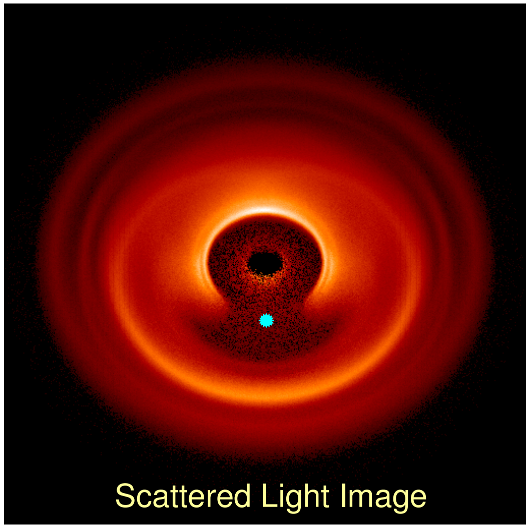


Spitzer ST

(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

Giant Planets in Debris Disks



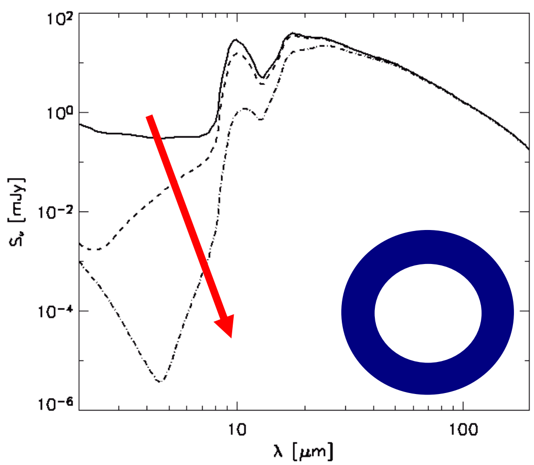
[Rodmann & Wolf]

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]

aida28.mpia.de/~swolf/dds

- Resonance Structures: **Indicators of Planets**

→ [1] Location

[2] Major orbital parameters

[3] Mass of the planet

- Decreased Mid-Infrared SED

DDS (Debris Disk Simulator)

Debris Disk Radiative Transfer Simulator

(last update : August 09, 2004)

Introduction | Manual | FAQs

Star

Blackbody Radiator | Predefined Stellar SED | Stellar SED Upload

5780.0 Effective Temperature [K] | Sun | Browse...

1.0 Luminosity [L(sun)]

Disk Size

Inner Radius

Given by the dust sublimation temperature

Fixed, Radius [AU] = 10.0

Outer Radius

Radius [AU] = 100.0

Disk Density Distribution

Analytical Description

$n(r) \sim r^{-a}$, half opening angle of the disk: g

a = 1.5 , g[°] = 45.0

Density Distribution Upload

Browse...

Disk Dust Mass

1.0e-5 M [M(Earth)]

1.0e-10 M [M(Sun)]

Dust Grain Size Distribution

5.0 min. grain radius [micron]

5.0 max. grain radius [micron]

Distribution: $n(\text{radius}) \sim \text{radius}^{-x}$, x = 3.5

Abundances of Chemical Components

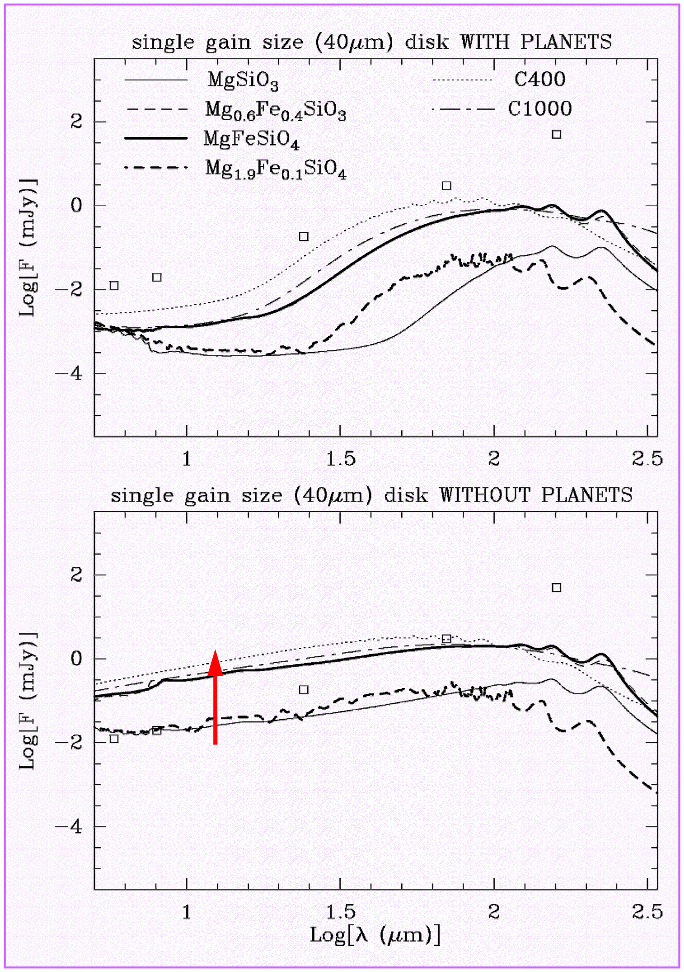
Silicates

aida28.mpia.de/~swolf/dds

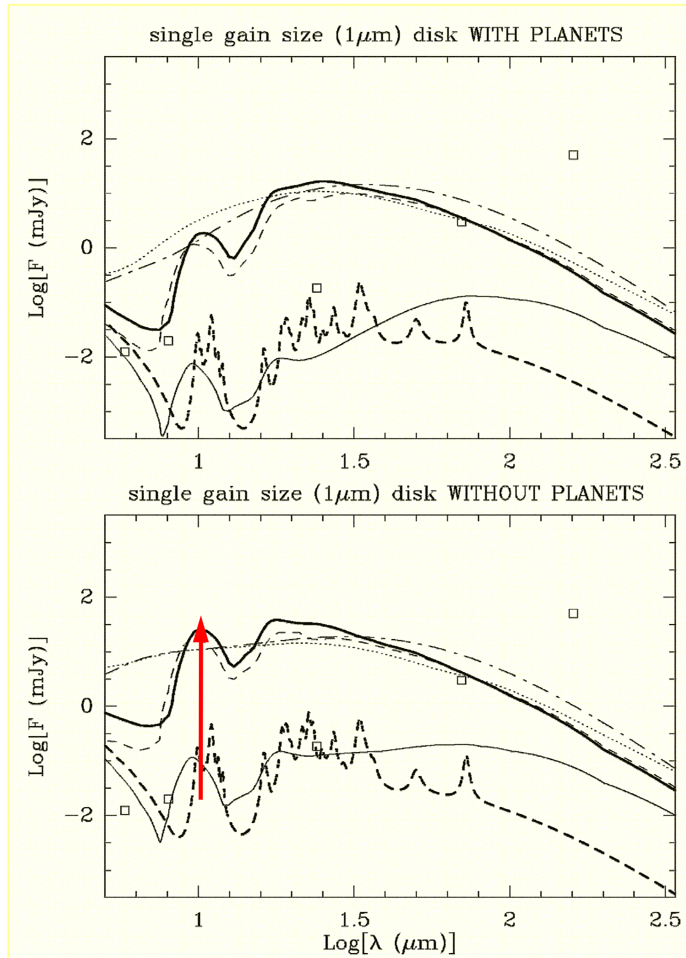
or www.mpia.de/ASD

The young Solar System

40μm



1μm



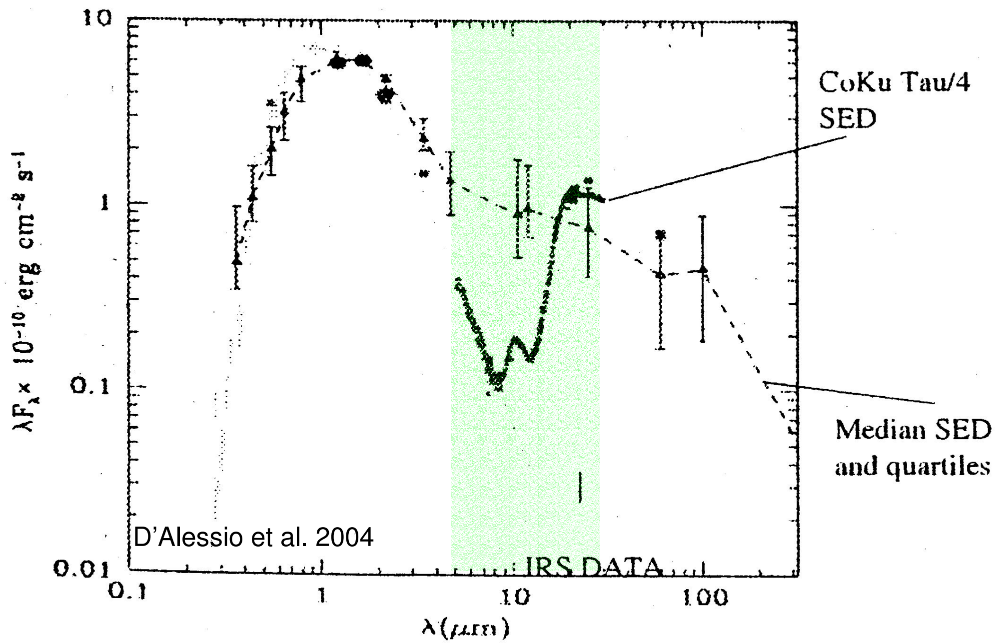
with planets

without planets

(distance: 50 pc, dust mass: 10^{-10} M_{sun})

[Moro-Martin, Wolf, & Malhotra 2004]

Dust evolution vs. Planet clearing



BBC NEWS WORLD EDITION

Last Updated: Thursday, 27 May, 2004, 21:26 GMT 22:26 UK

E-mail this to a friend | Printable version

Telescope spies 'youngest' planet

Nasa's Spitzer telescope has found evidence around a distant star for a planet that may be less than one million years old.

The infrared space observatory studied five stars in the constellation Taurus, about 420 light-years away.

All had dusty discs around them in which new planets are presumed to be forming out of accreting material.

An impression of what it might be like in the CoKu Tau 4 system

see talk by Richard Alexander
for the formation of inner holes in disks

(clearing by planets, photoevaporation, etc.)

Gaps => SED

Inner cavity in an optically thin disk surrounding a solar-type star

Fe content

Grain size

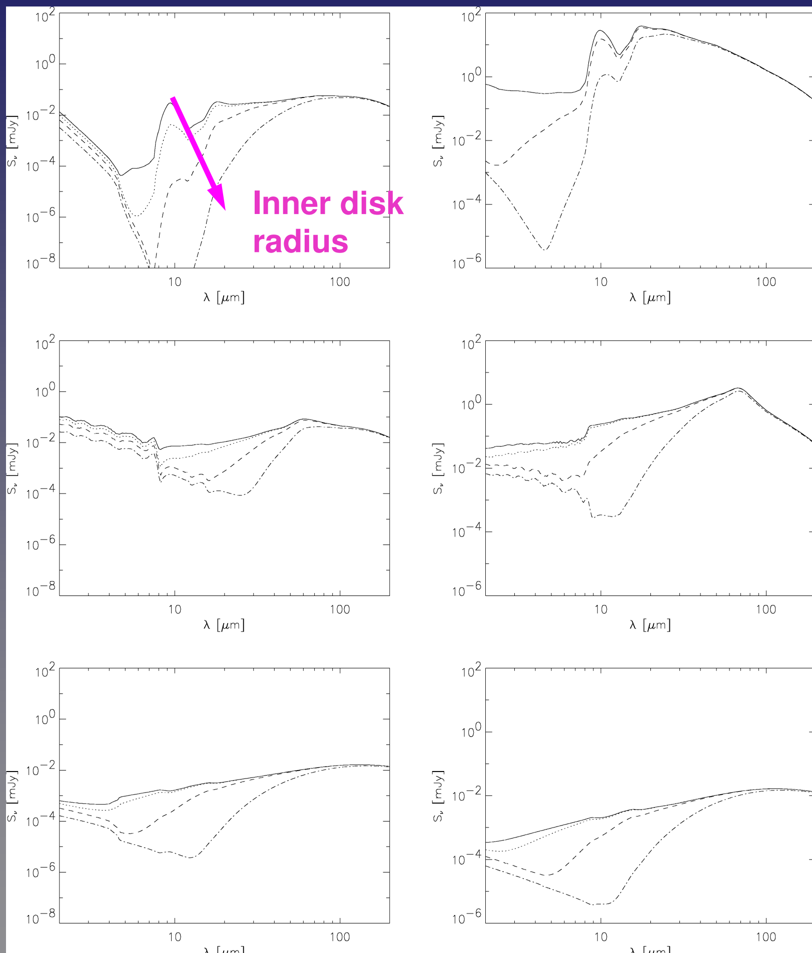


Fig. 10.— Influence of inner gaps on the SED. Inner disk radius: dust sublimation radius (solid line), 0.1 AU (dotted), 1 AU (dashed), and 10 AU (dash-dotted).
Left column: Fe-less Silicate ($MgSiO_3$).
Right column: Fe-rich (amorphous Olivine, $MgFeSiO_4$).
Top: $a_{\rm Grain} = 0.1\mu$m, *Middle:* $a_{\rm Grain} = 10\mu$m, *Bottom:* $a_{\rm Grain} =$ 1mm. Assuming a dust sublimation temperature of 1550 K, the sublimation radius of $MgFeSiO_4/MgSiO_3$ amounts to 1.3×10^{-1} AU/7.3×10^{-3} AU ($a_{\rm Grain} = 0.1\mu$m), 3.5×10^{-2} AU/1.2×10^{-2} AU ($a_{\rm Grain} = 10\mu$m), and 3.2×10^{-2} AU/3.3×10^{-2} AU ($a_{\rm Grain} =$ 1mm). Disk mass: $10^{-10} M_{\rm sun}$.

Wolf & Hillenbrand (2003)

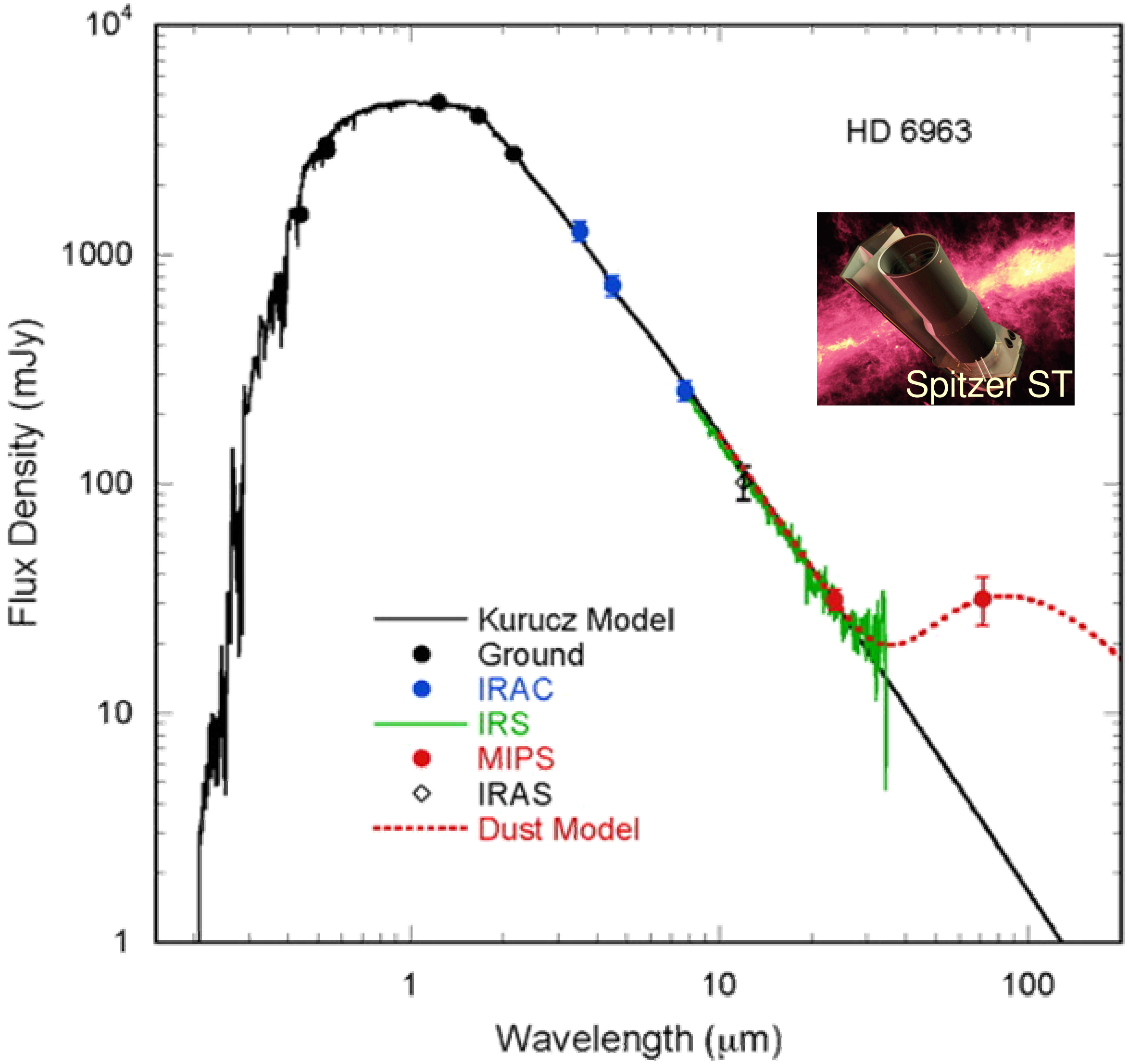
T Tauri Disks

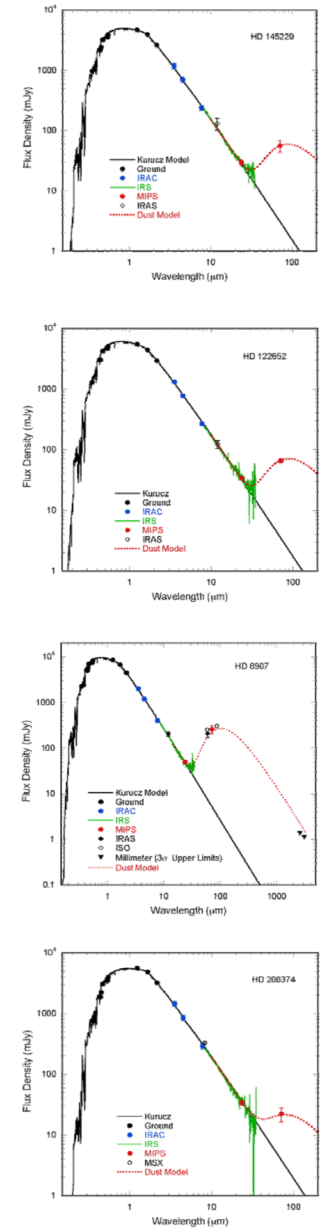
GM Aurigae, TW Hya
[Koerner et al. 1993, Rice et al 2003, Calvet et al. 2002]

Debris Disks

β Pic (20AU), HR 4796A (30-50AU), ε Eri (50AU), Vega (80AU), Fomalhaut (125AU) + „new“ Spitzer Debris Disks
[Dent et al. 2000, Greaves et al. 2000, Wilner et al. 2002, Holland et al. 2003]

Some Problems with SEDs





[Kim, et al. 2005]

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)

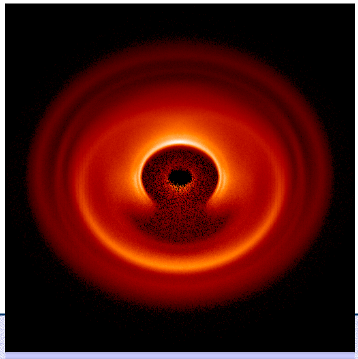
⇒ No / weak constraints on the chemical composition of the dust

Debris disks: Difficult to observe

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

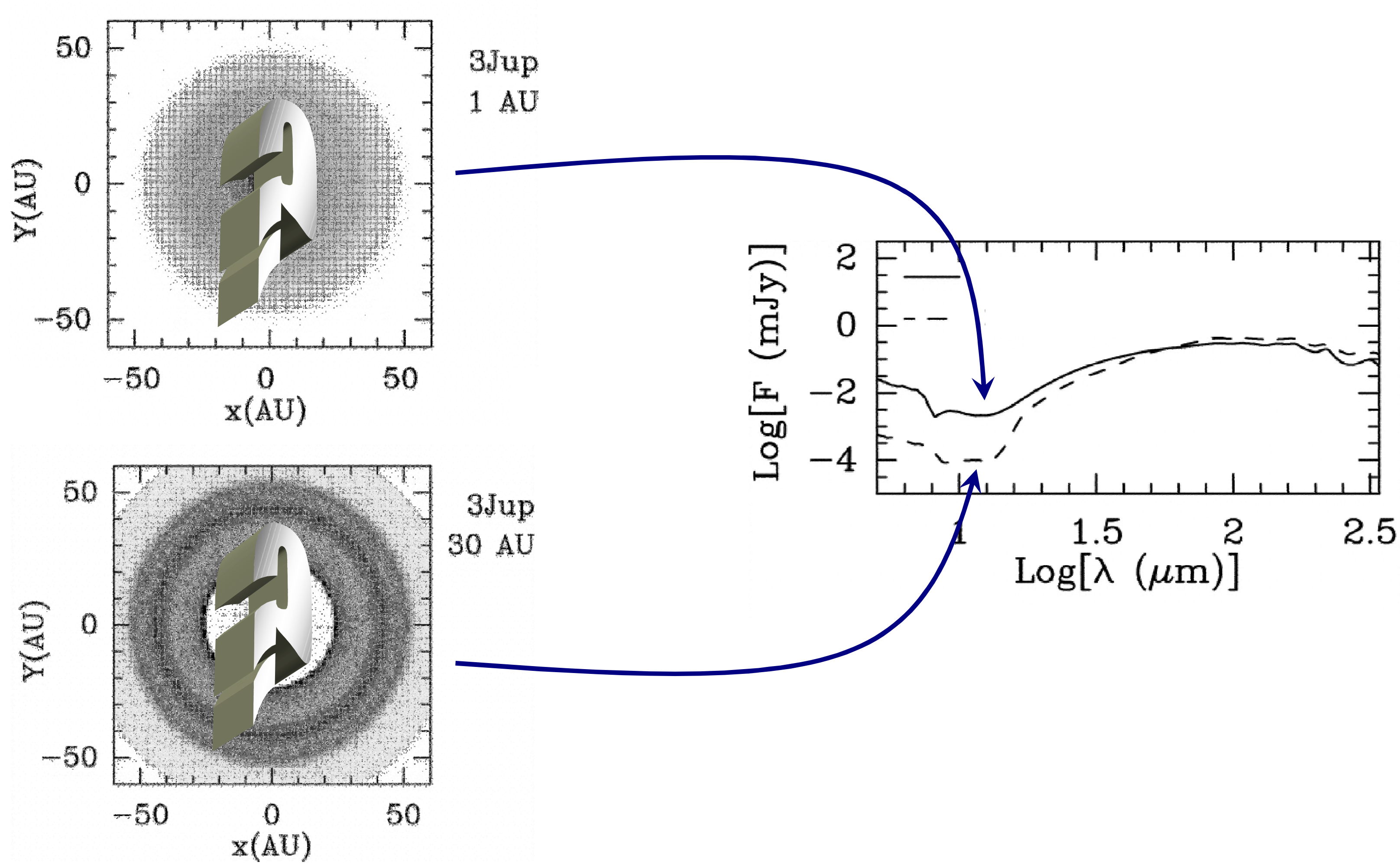
  but even here degeneracies are difficult to resolve (e.g., planet mass, orbit, grain size)

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



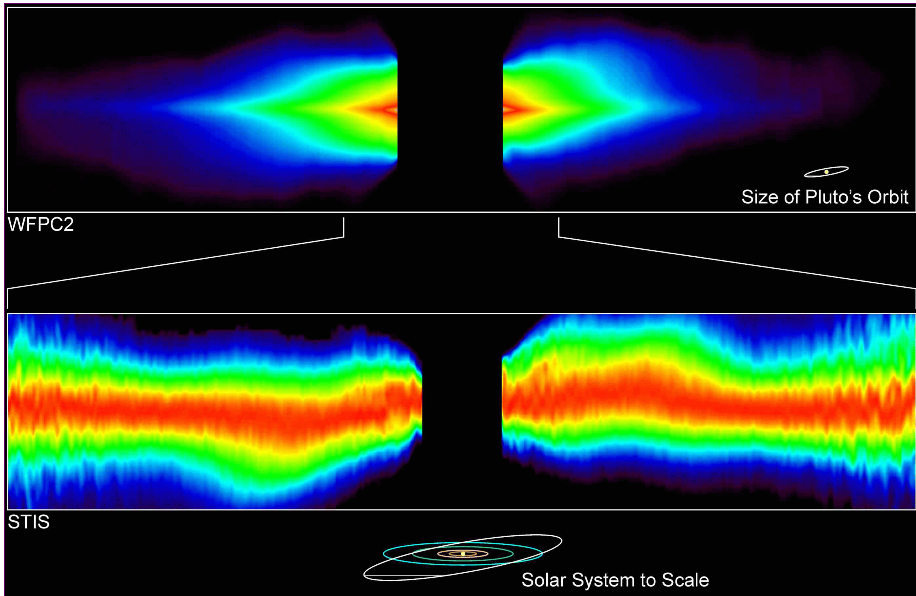
Imaging is required!

Imaging required!



[Moro-Martin, Wolf, & Malhotra 2005]

Warp in the βPic disk



(Schultz, Heap, NASA 1998)

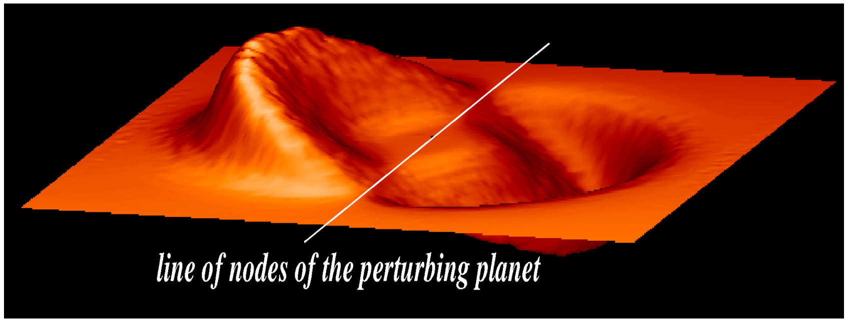
β Pictoris dust disk:

- Orientation : nearly edge-on
- Total mass :
  few tens ... few lunar masses
- Maximum of the dust surface
  density distribution located
  between 80AU and 100AU

(Zuckerman & Becklin 1993, Holland et al. 1998, Dent et al. 2000, Pantin et al. 1997)

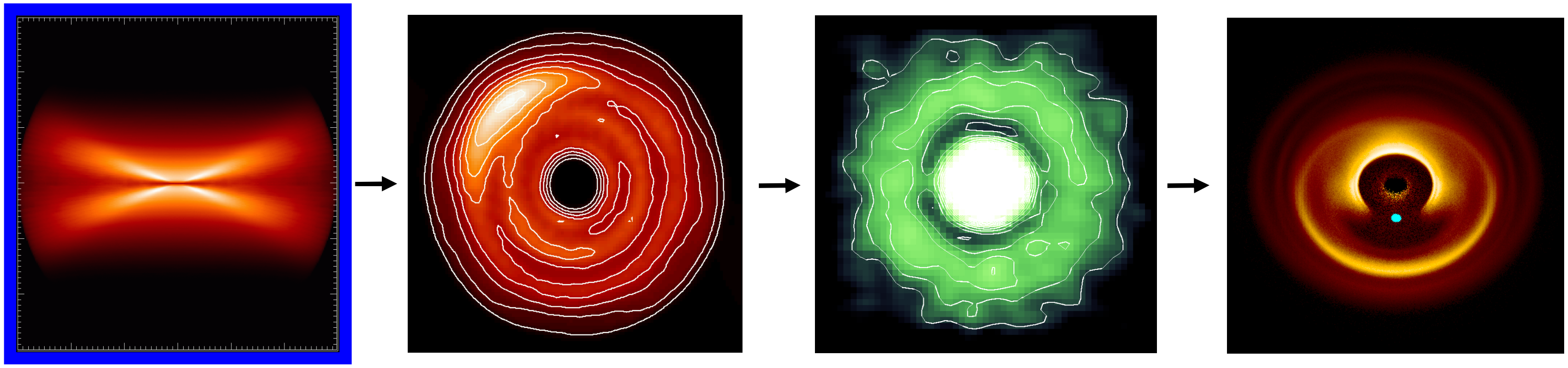
Model includes a Disk of Planetesimals

- **Extending out to 120-150AU, perturbed gravitationally by a giant planet on an inclined orbit**
- **Source of a distribution of grains produced through collisional evolution**

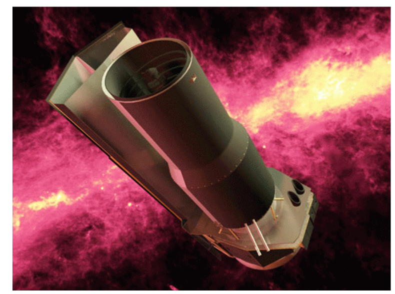


(Augereau et al. 2001, see also Mouillet et al. 1997)

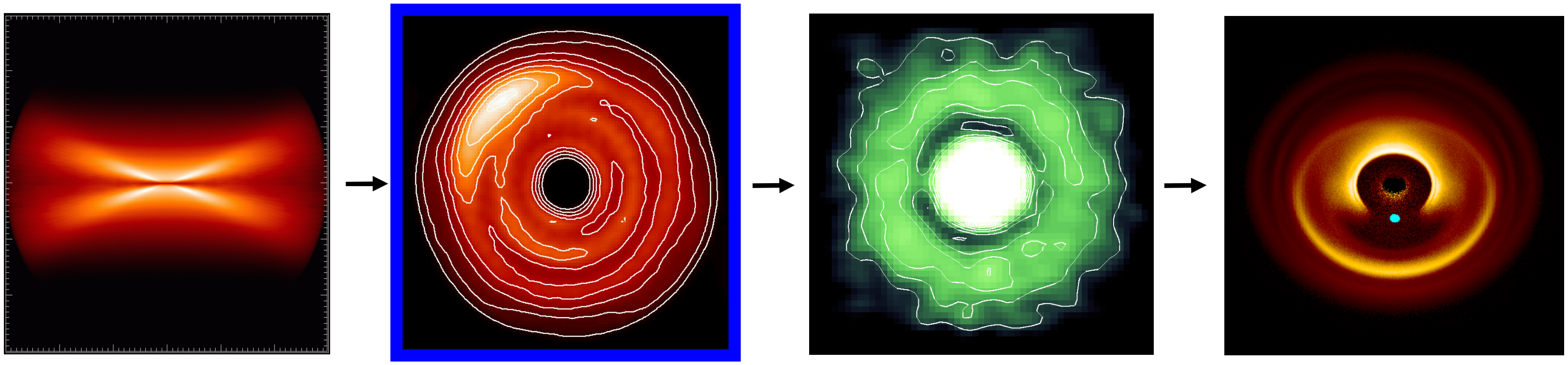
Concluding remarks



1. SED: (sub)mm slope
2. Shape of 10μm silicate feature
3. Scattered light polarization
4. Multi-wavelength imaging
   (Example: Butterfly Star)

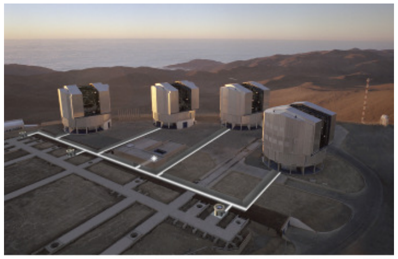


Concluding remarks



1. Imaging of the planet-forming Region
   (disk structure, e.g., Vortices)
2. Spectro-Interferometry

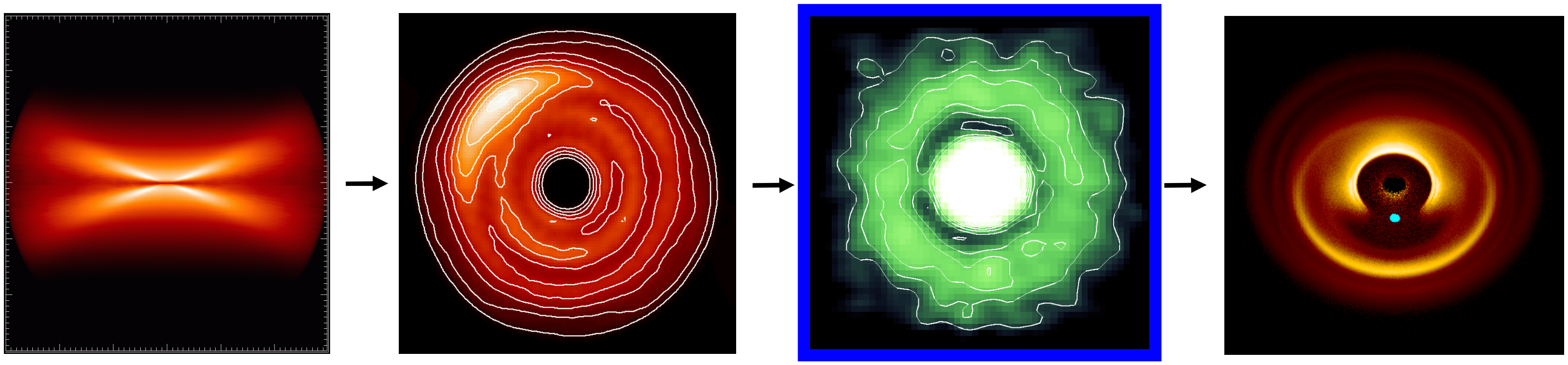
ALMA
ATACAMA LARGE MILLIMETER ARRAY



Aerial View of Paranal Observing Platform with VLTI Light Paths

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

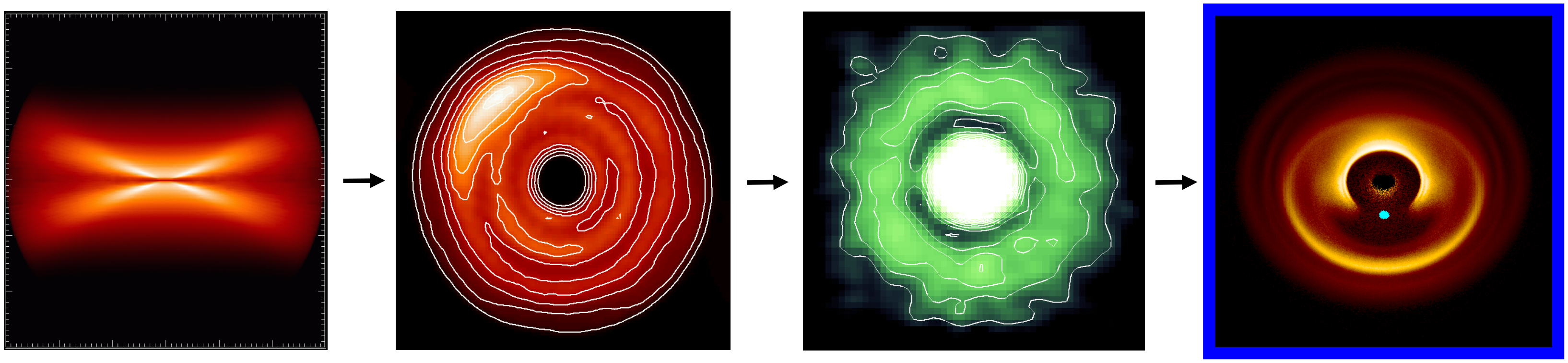
Concluding remarks



1. Gaps
2. Global Spiral Structures
3. Planetary Accretion Region
4. Inner holes
5. Shadow / Center-of-light-wobble

ALMA
ATACAMA LARGE MILLIMETER ARRAY

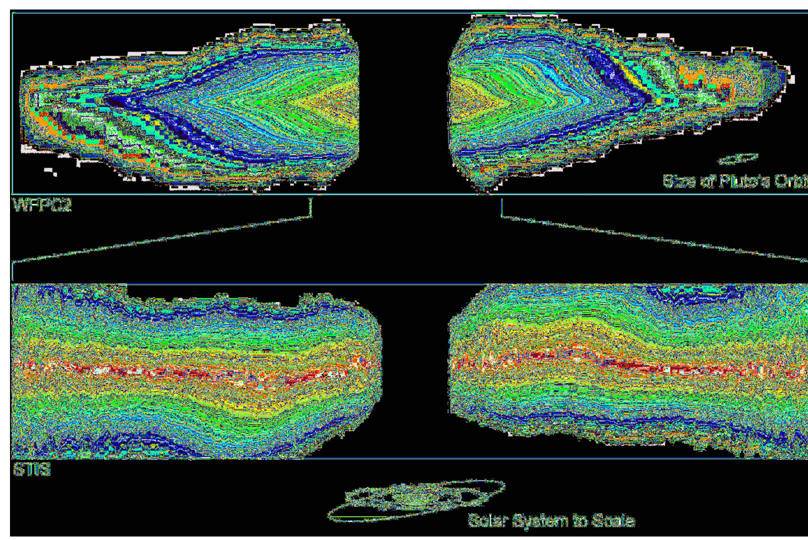
Concluding remarks



1. Characteristic Large-Scale Asymmetric Patterns

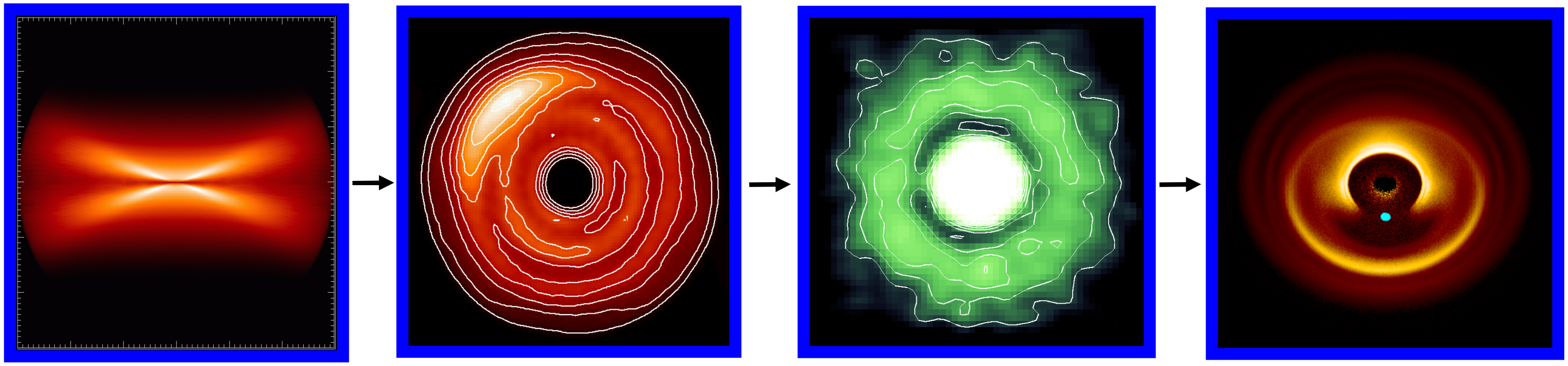
2. Shape of the mid-infrared SED

3. Warps (β Pic)



(Schultz, Heap, NASA 1998)

Concluding remarks



Theoretical investigations show that the planet-disk interaction causes **structures** in circumstellar disks, which are usually **much larger in size than the planet** itself and thus more easily detectable. The specific result of the planet-disk interaction depends on the evolutionary stage of the disk.

Numerical simulations convincingly demonstrate that **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 of planets.

These observations will provide a deep **insight into specific phases** of the formation and early evolution of planets in circumstellar disks.

Literature – Acknowledgements

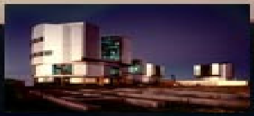
Extrasolar Planets

http://www.mpia-hd.mpg.de/EXTRA2005/

Software

www.mpia.de/ASD

Marie Curie Program "On The Fringe"



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