Observations and Modeling of Circumstellar disks

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Goals & Methods

- Goal: Constrain conditions for planet formation
  - Spatial distribution of gas and dust
  - Physical conditions: Temperature, velocity, magnetic field structure
- Specific questions
  - Global disk structure = f(time)
  - Small-scale structure,
    e.g., induced by planet-formation or planet-disk interaction
- Approach
  - Multi-wavelength observations with spatial resolution of ~0.1AU – 100AU
  - Modeling

Overview

1. General remarks
   a) Multi-wavelength observations
   b) Spatially resolved disk images

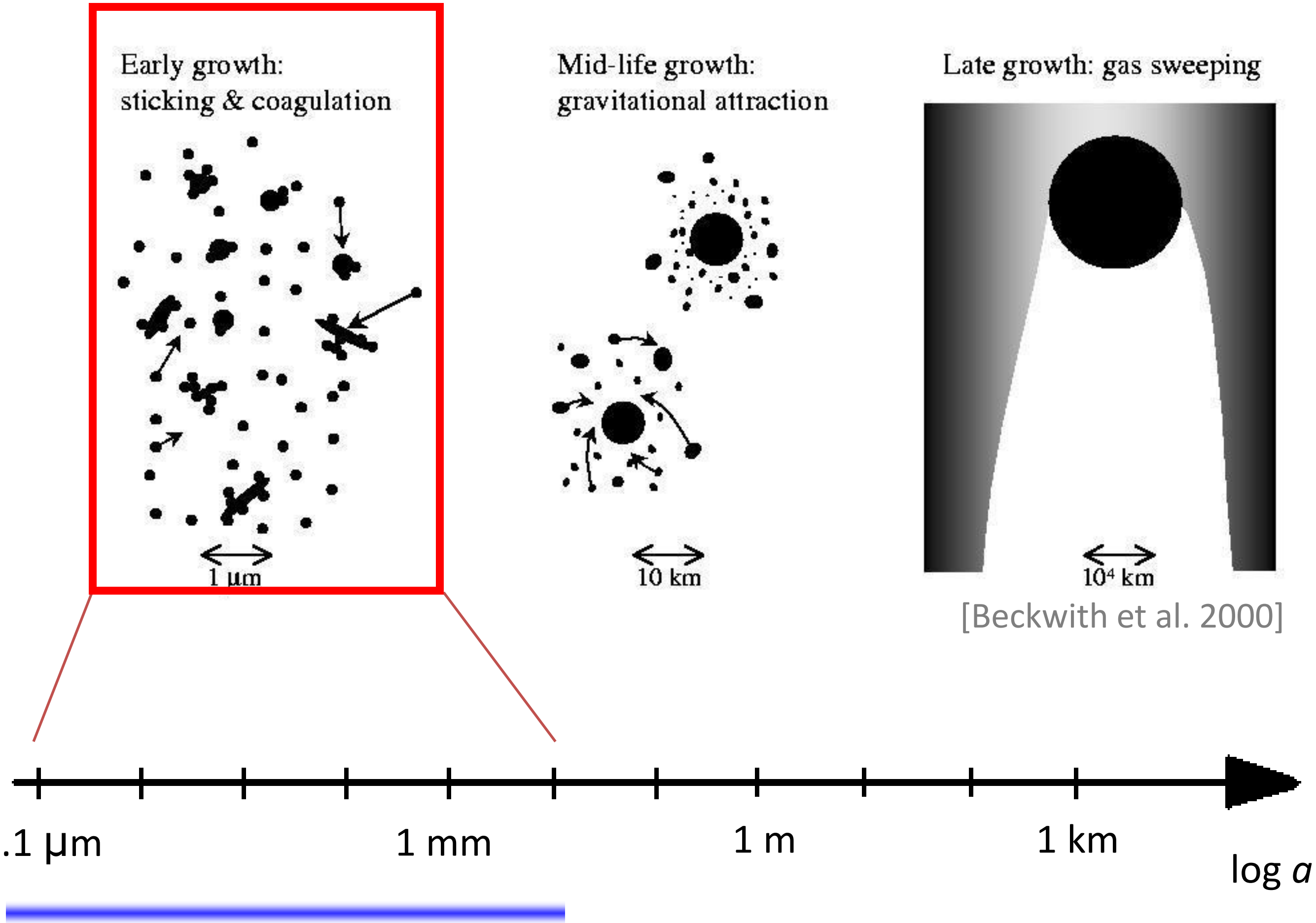
2. Exemplary studies
   a) Protoplanetary / Transitional Disks
   b) Debris disks

3. Tracing proto-planets (if time allows)

General remarks

a) Potential of multi-wavelength observations

From dust to planets

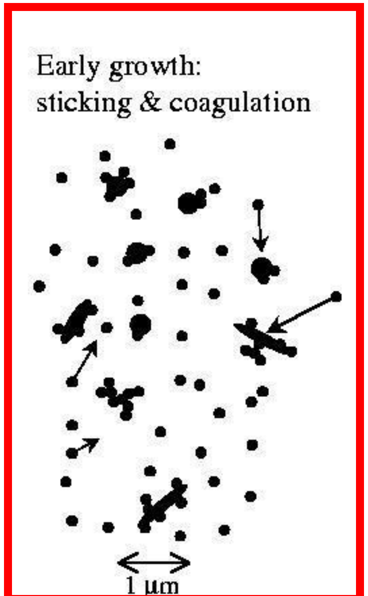


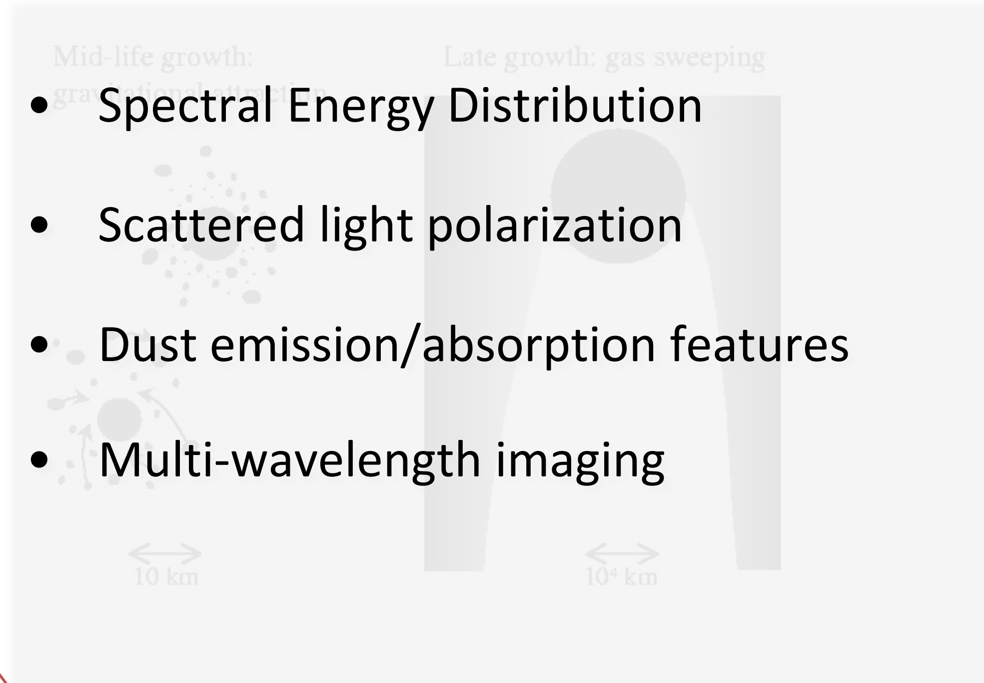
Particle size

≃

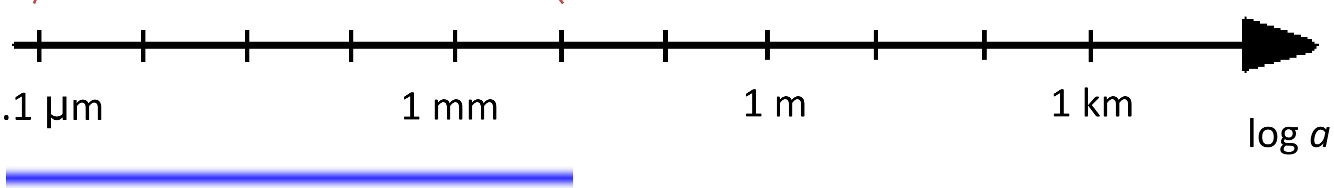
Observing wavelength

From dust to planets



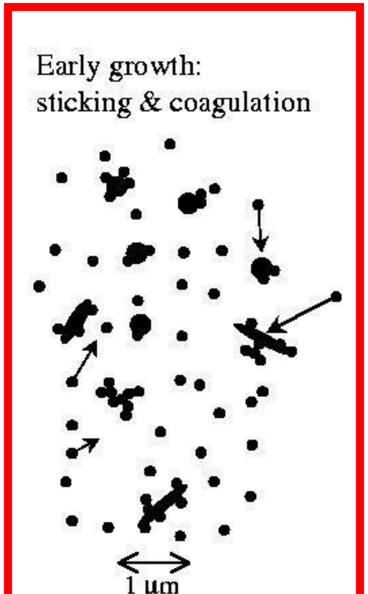


- Spectral Energy Distribution
- Scattered light polarization
- Dust emission/absorption features
- Multi-wavelength imaging



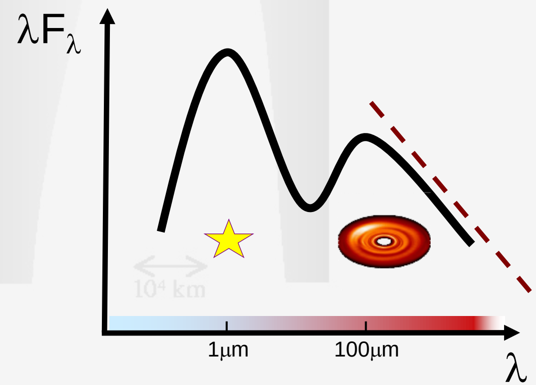
Particle size
≃
Observing wavelength

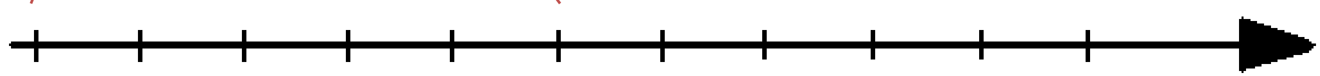
From dust to planets



"Save" parameters:
Total dust mass and **Grain size** derived from the (sub)mm (slope) of the SED: $F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$

Underlying assumption:
Optically thin disk

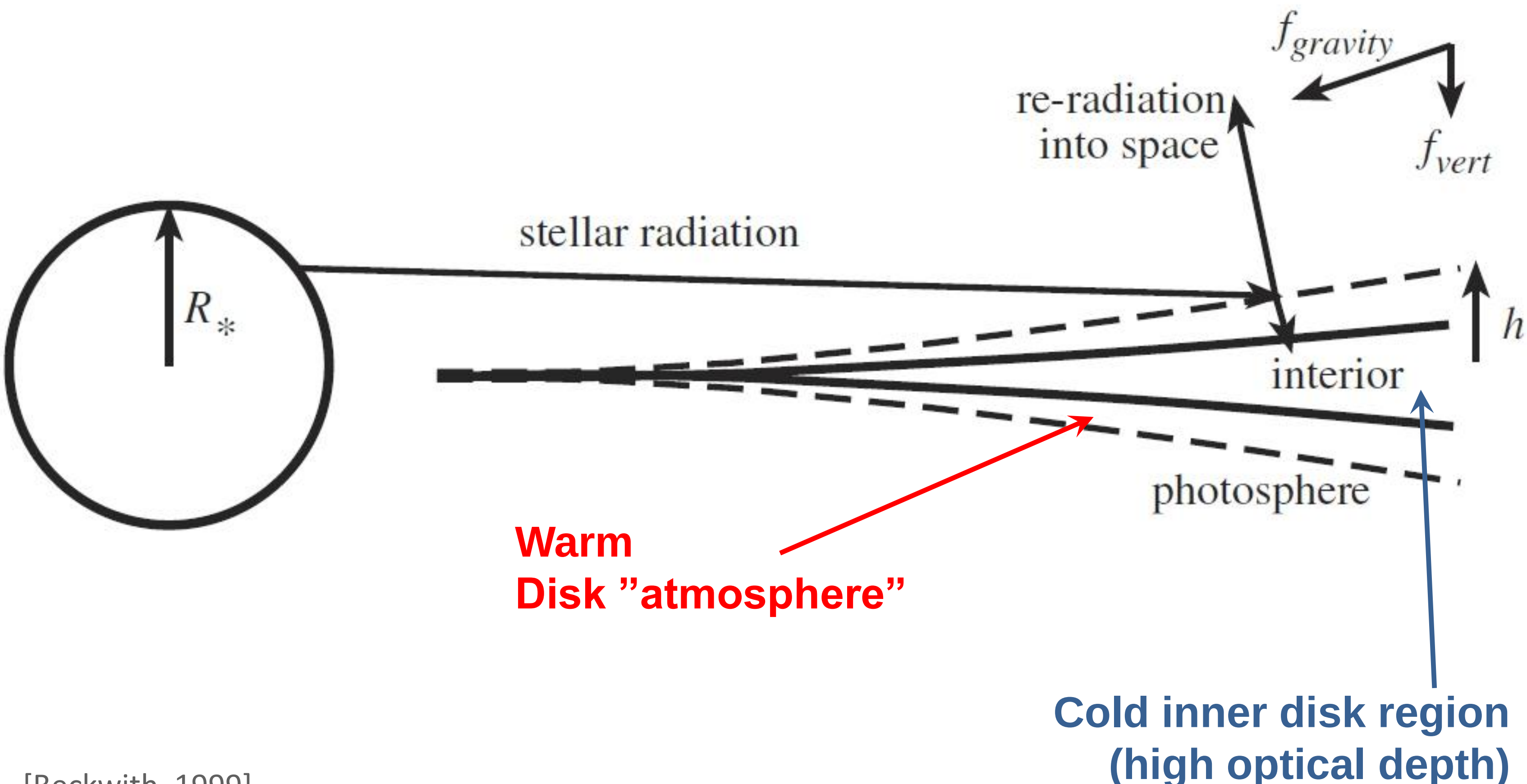




0.1 µm   1 mm   1 m   1 km   log *a*

Particle size
≃
Observing wavelength

Low-resolution SED / Disk structure

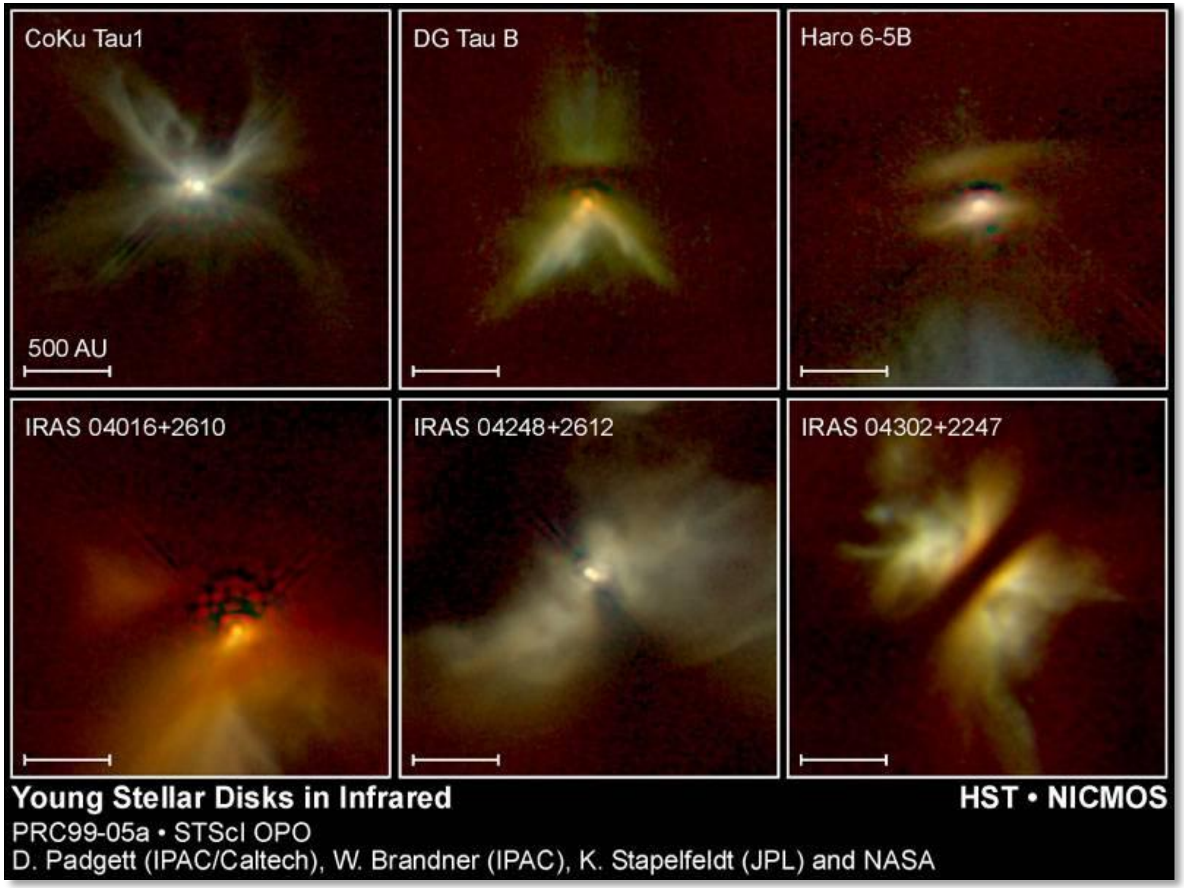


[Beckwith, 1999]

Flaring: Star can illuminate / heat disk more efficiently

SED analysis: Ingredients

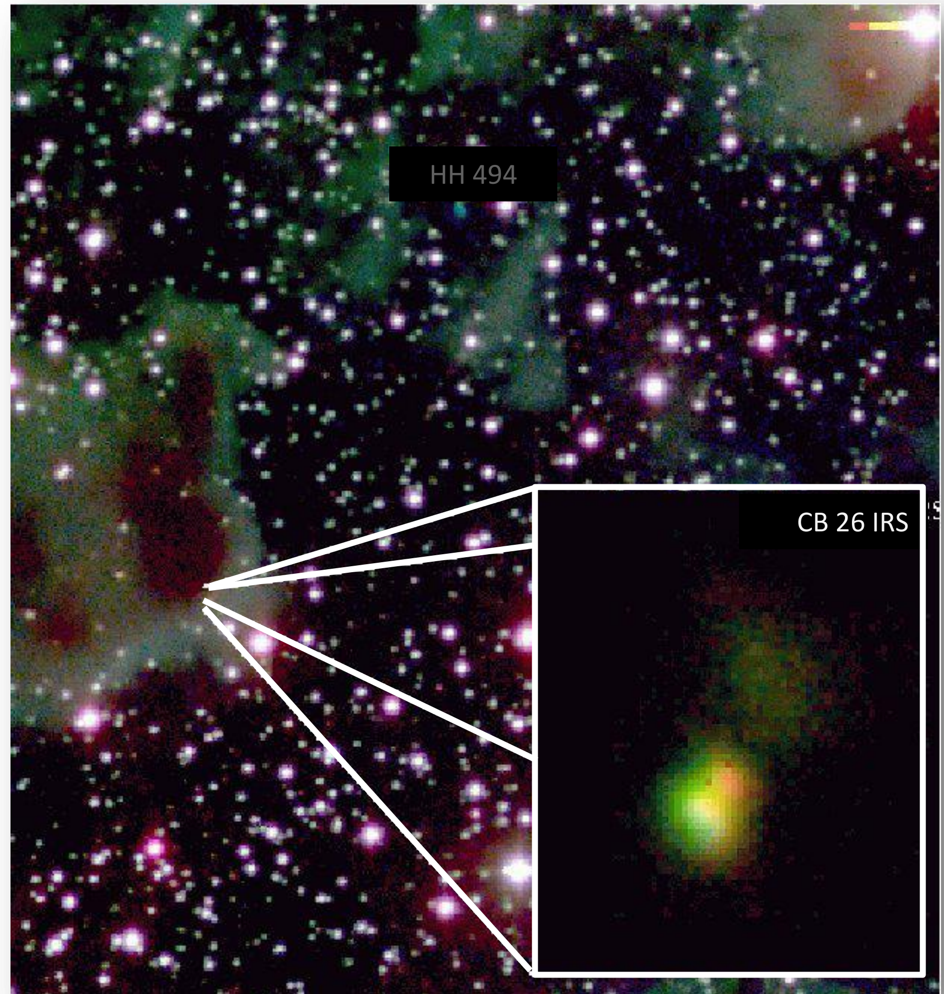
Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)



SED analysis: Ingredients

Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)



[courtesy of R. Launhardt]

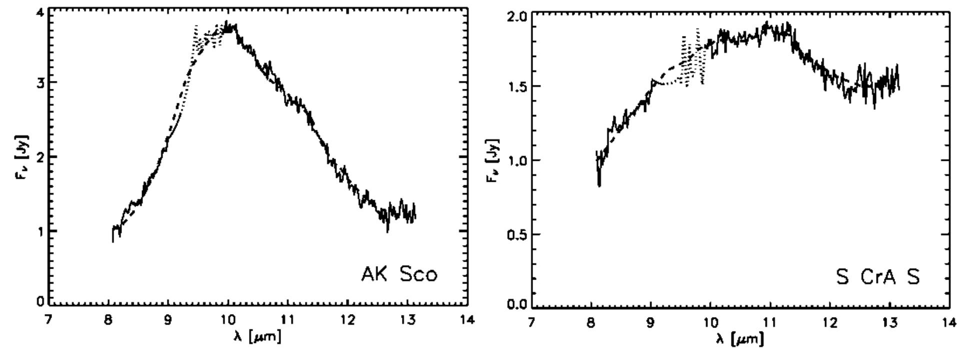
SED analysis: Ingredients

Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)

Dust characteristics (absorption/emission)

Prominent Example: ~10um Silicate Feature



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

[Schegerer, Wolf, et al., 2006]

Shape of feature =

f(Chemical Composition, Crystallization degree)

⇒ Grain Evolution

⇒ Physical Conditions

SED analysis: Ingredients

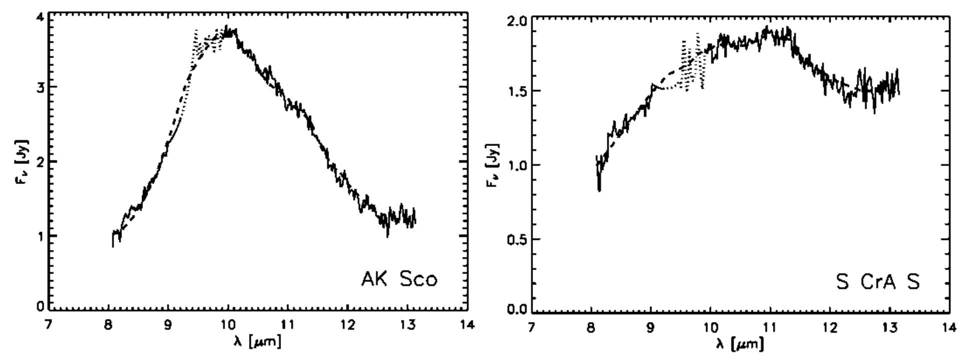
Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)

Dust characteristics (absorption/emission)

Characteristics of the illuminating/heating sources (stellar photosphere, accretion, single star vs. binary)

Prominent Example: ~10um Silicate Feature



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Shape of feature =

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⇒ Grain Evolution

⇒ Physical Conditions

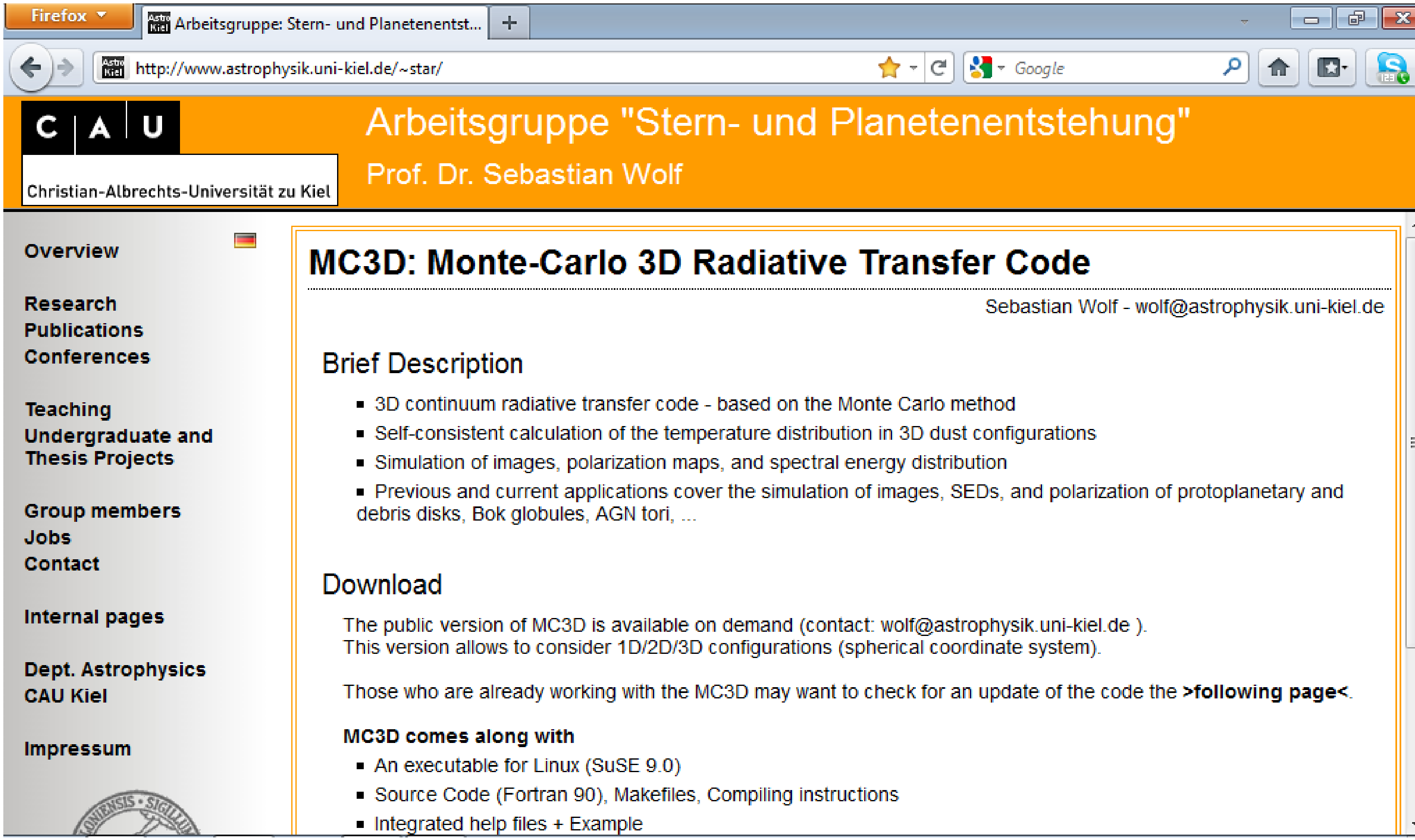
SED analysis: Conclusions

Proper analysis of multi-wavelength observations require

- **Radiative Transfer Simulations**
  - Detailed numerical modeling taking into account absorption / heating / reemission + scattering processes
  - Our approach: Monte-Carlo Method

- **Proper Fitting Techniques**
  Our approaches
  - Database fitting
  - Simulated annealing (Kirkpatrick et al. 1983)
    - Modification of Metropolis-Hastings algorithm for optimization
    - Implementation independent of problem dimensionality
    - Local optima overcome inherently

SED analysis: Conclusions



http://www.astrophysik.uni-kiel.de/~star

[Wolf et al. 1999; Wolf 2003]

SED analysis: Conclusions

but

SEDs can be well reproduced, but not unambiguously

$\Rightarrow$ Information about spatial brightness distribution required:

- Spatial disk structure
  (e.g., inner/outer radius, radial scale height distribution)
- Spatial distribution of Dust parameters (composition, size) and
  Gas phase composition/excitation

Note:

Appearance of circumstellar disks determined by both,

its **Structure** (density distribution) and **Dust properties**

General remarks

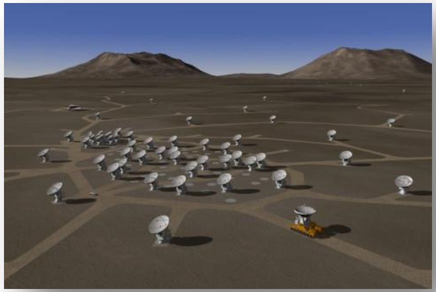
b) Spatially resolved images

Requirements – HST, AO, Interferometry


VLTI

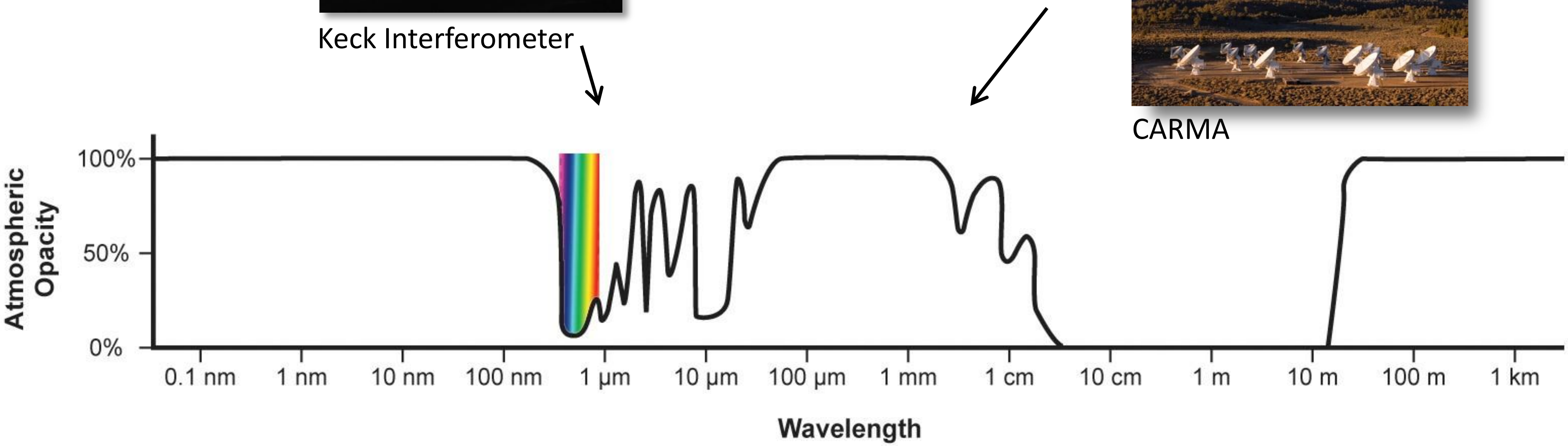

Keck Interferometer


SMA

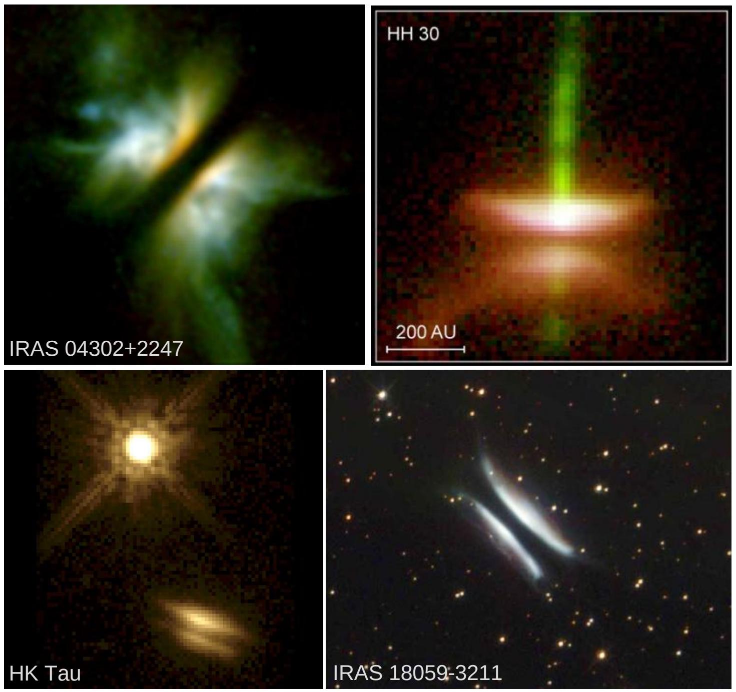

ALMA

IRAM


CARMA



Edge-on disks

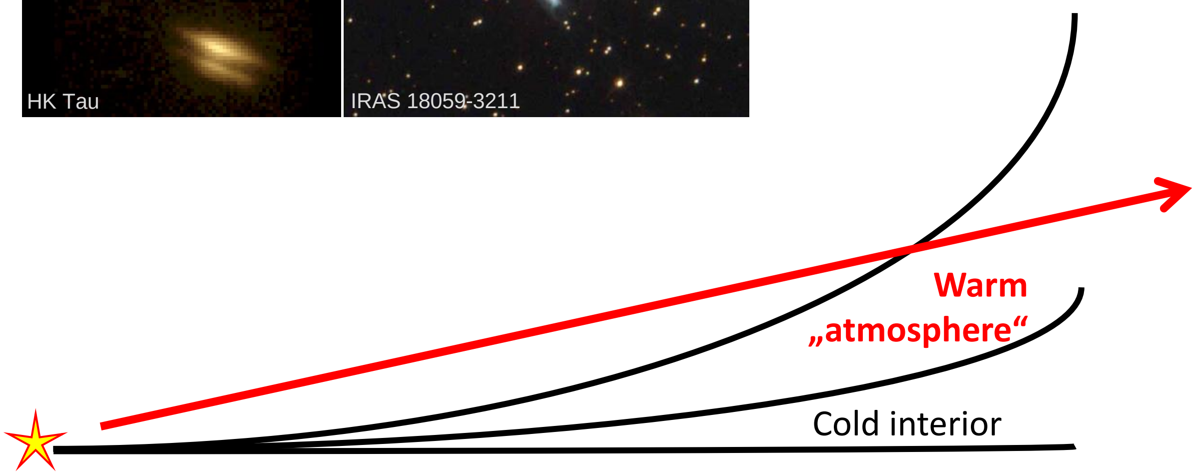


Optical/IR

Wavelength-dependence of the apparent *vertical* extent of the disk

⇒ *Vertical opacity structure*

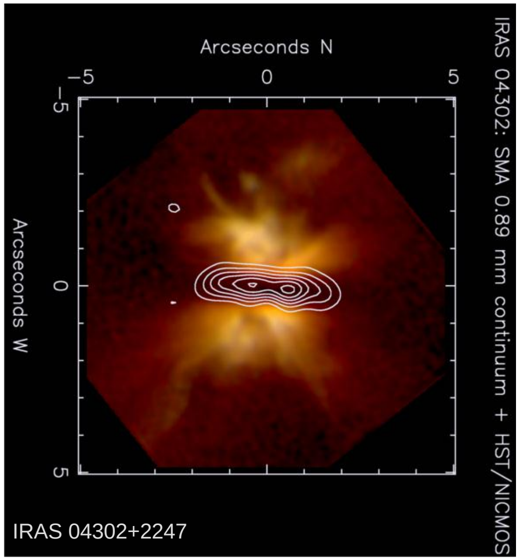
⇒ *Constraints on grain size in upper disk layers (dust settling?)*



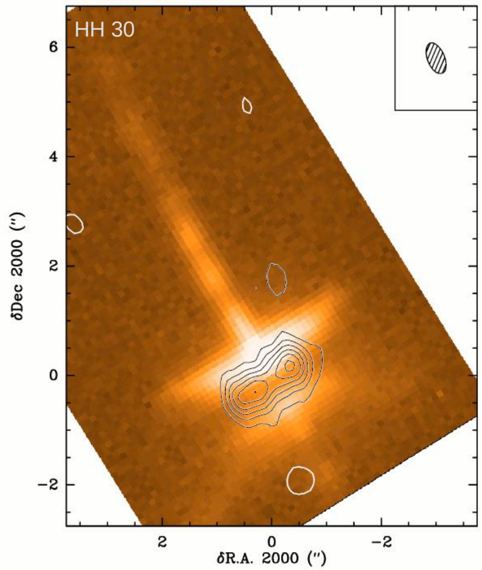
Approximate disk size (dust)

Disk flaring

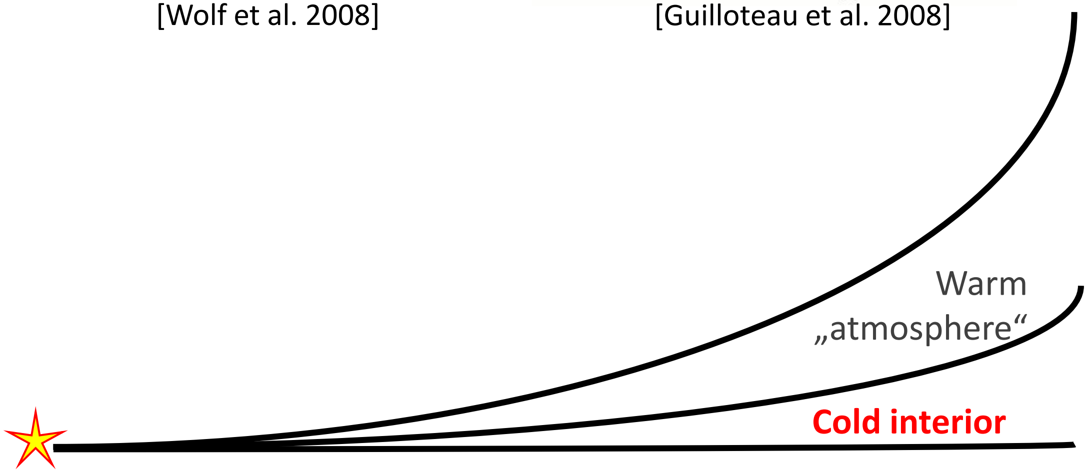
Edge-on disks



[Wolf et al. 2008]



[Guilloteau et al. 2008]



(Sub)mm

Wavelength-dependence of the *radial* brightness distribution

$\Rightarrow$ Radial disk structure

$\Rightarrow$ Radial distribution of dust grain properties; Abundance / Excitation of gas

$\Rightarrow$ Large inner gap?

$\Rightarrow$ Velocity structure (gas)

Face-on disks

Optical / IR

Wavelength-dependence of the radial brightness distribution

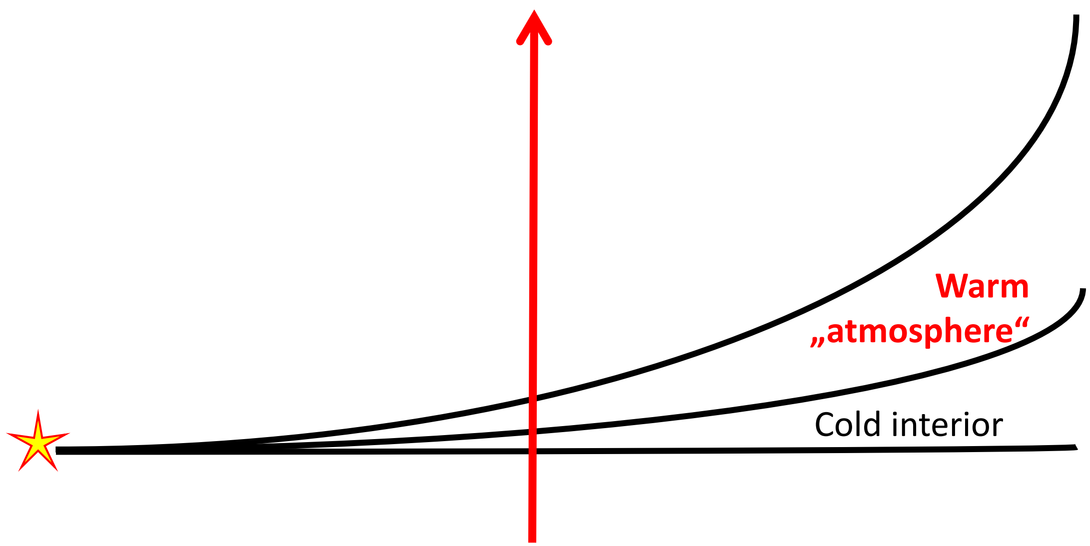
⇒ Disk:

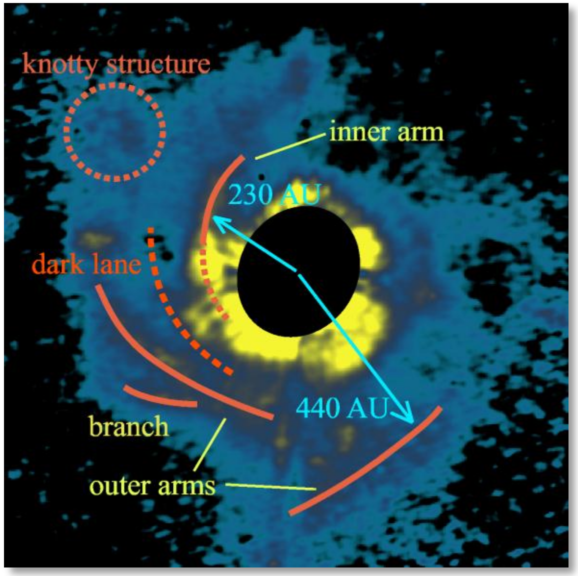
⇒ Flaring; Surface structure (local scale height variations)

⇒ Dust:

⇒ Scattering properties (scattering phase function) in different layers

⇒ Chemical composition = f (radial position); e.g., silicate annealing





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

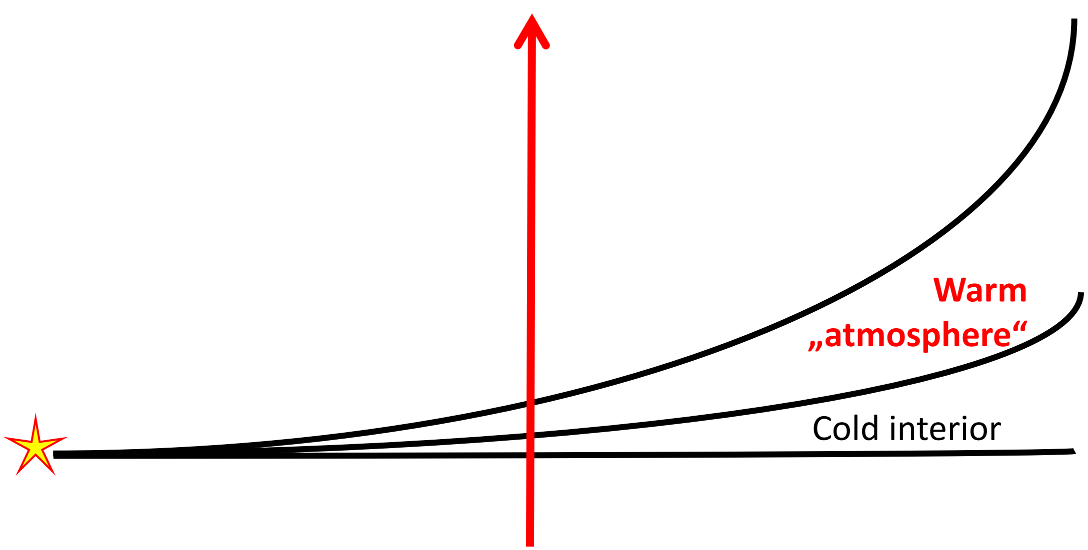
Face-on disks

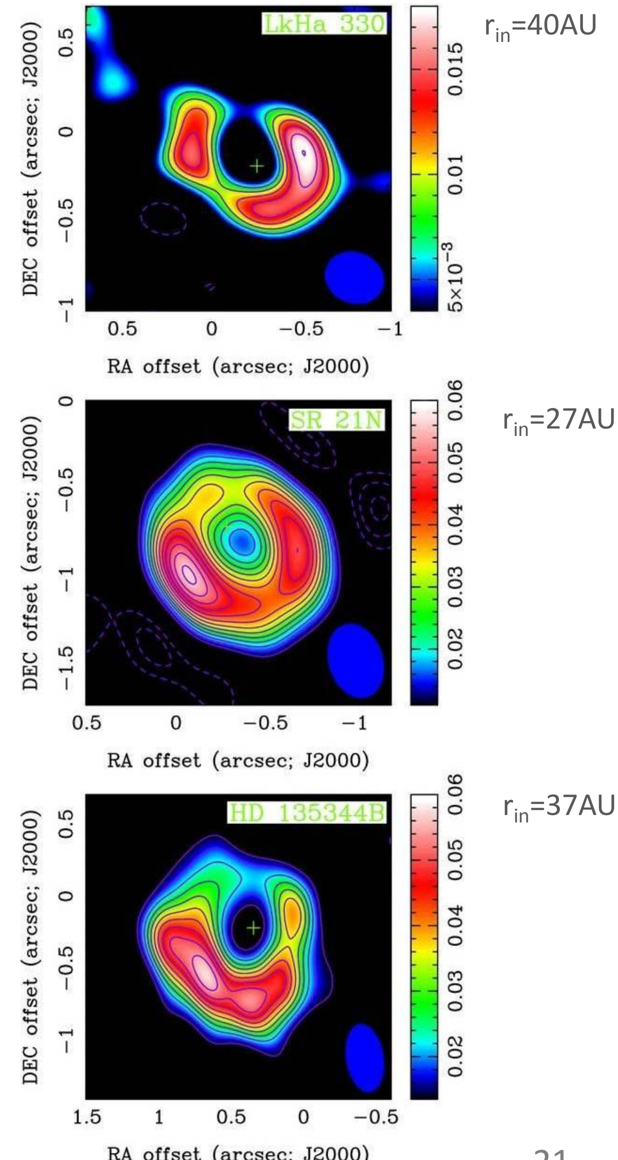
(Sub)mm

Radial/azimuthal disk structure

⇒ Asymmetries, Local density enhancements

⇒ Gaps, Inner dust-depleted regions



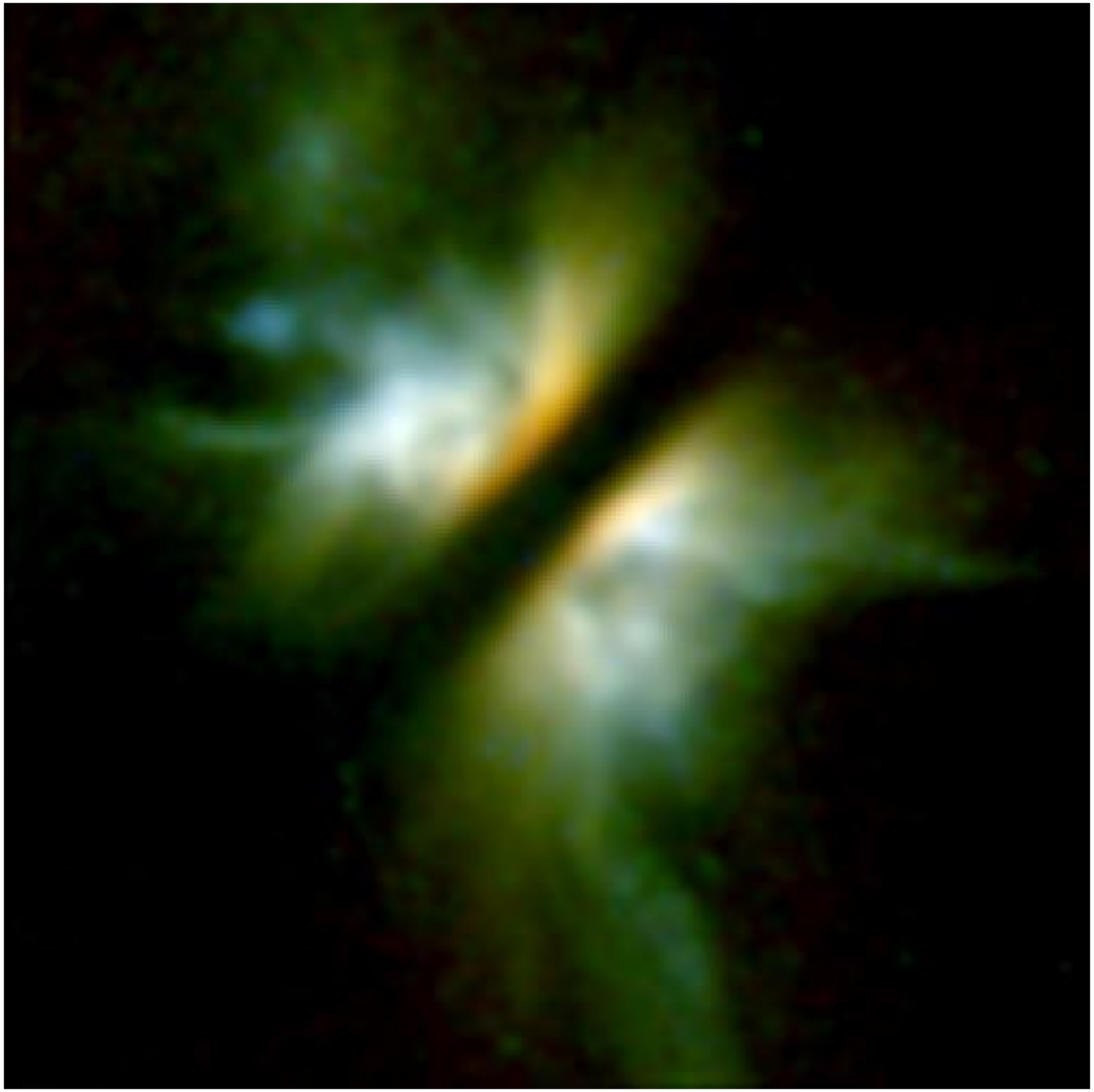


[Brown et al. 2009: 340GHz, continuum]

Exemplary studies

a) Protoplanetary / Transitional disks

IRAS 04302+2247 („Butterfly star“)



[Padgett et al. 1999]

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

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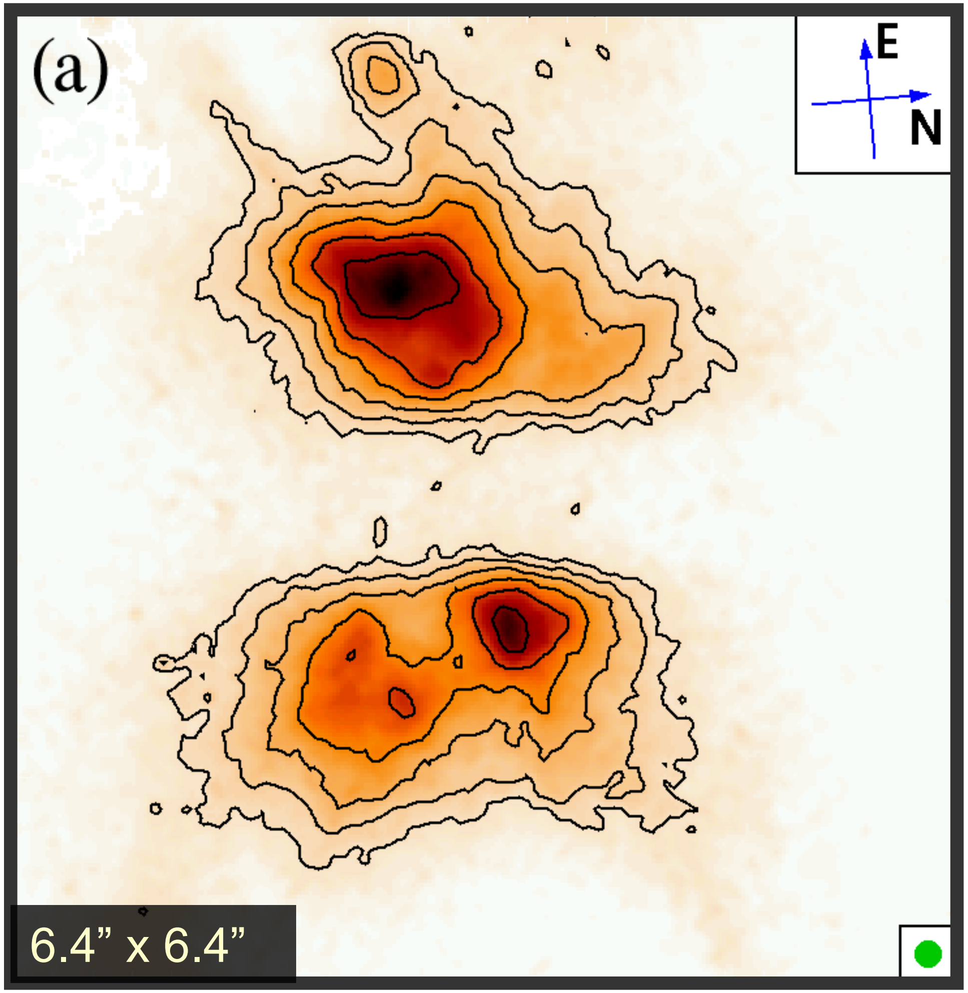

1.10 μm

[Wolf et al. 2003]

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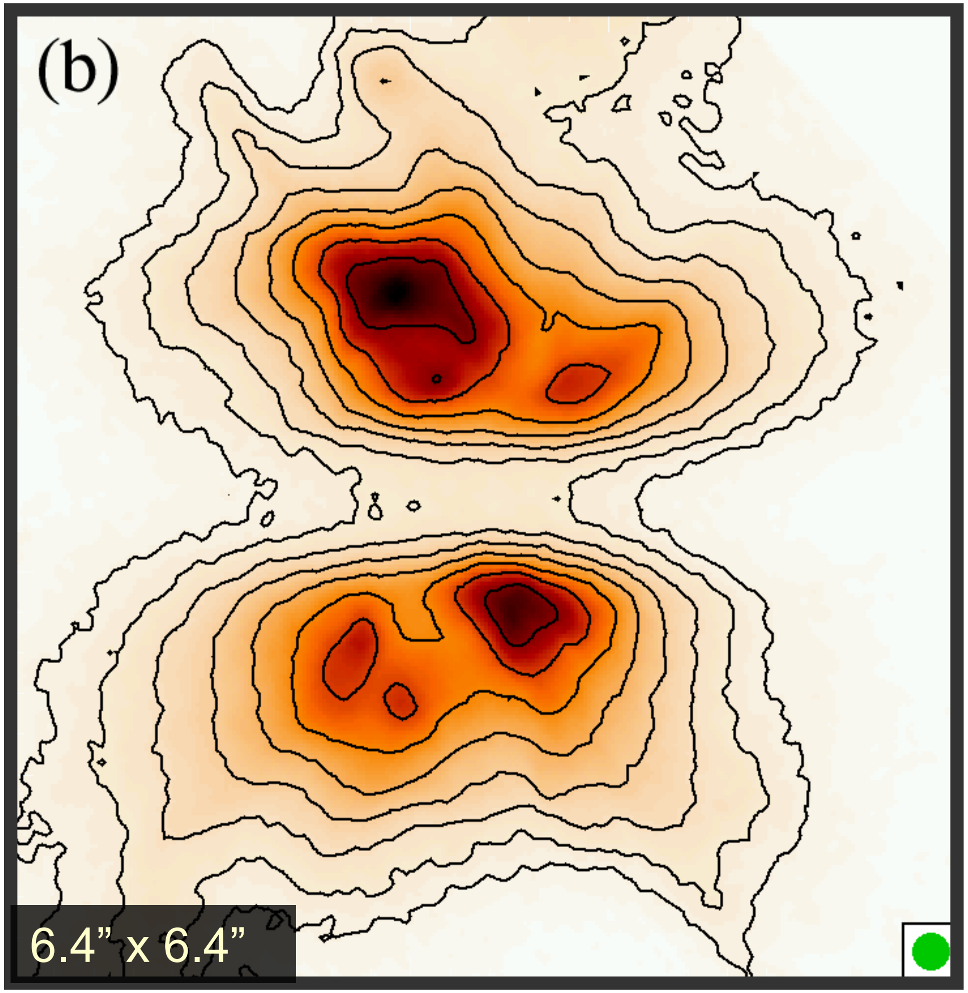

1.10 µm

1.60 µm

[Wolf et al. 2003]

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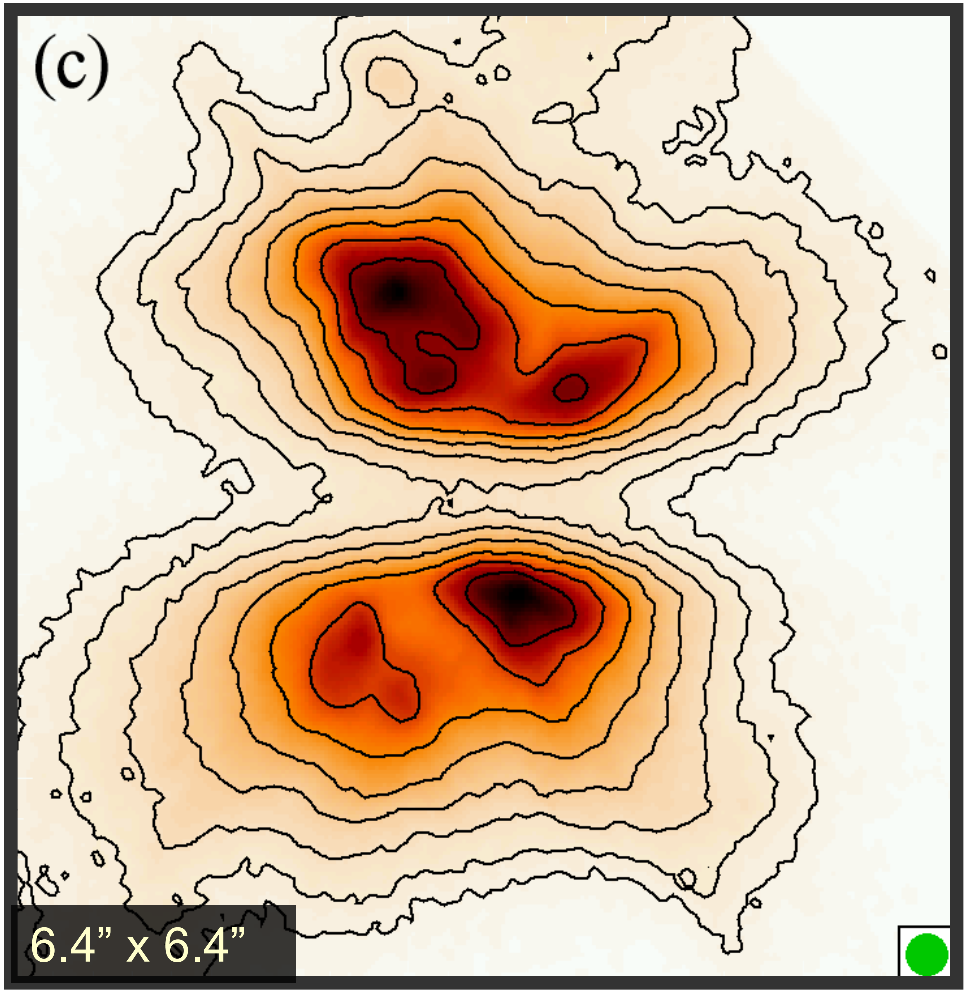

1.10 µm

1.60 µm

1.87 µm

[Wolf et al. 2003]

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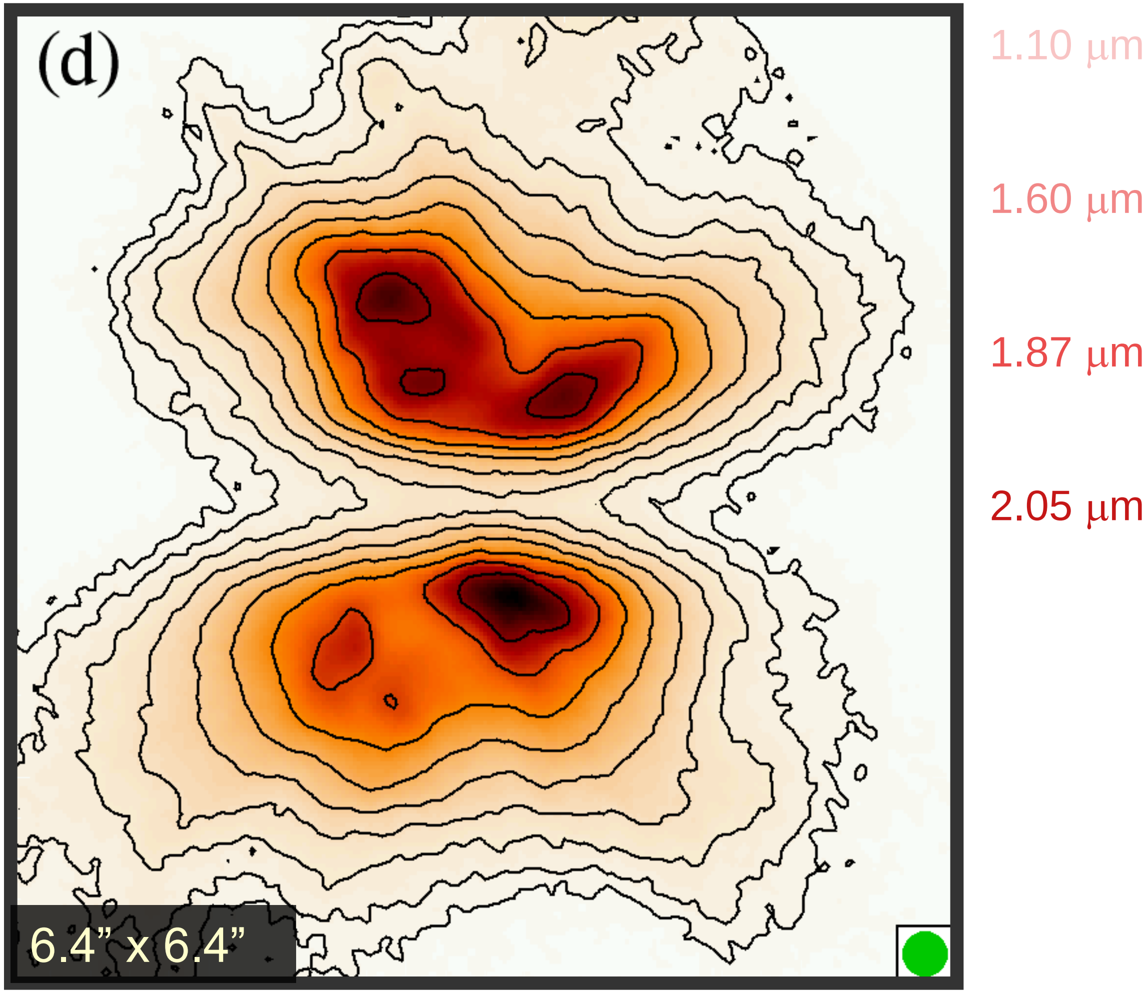

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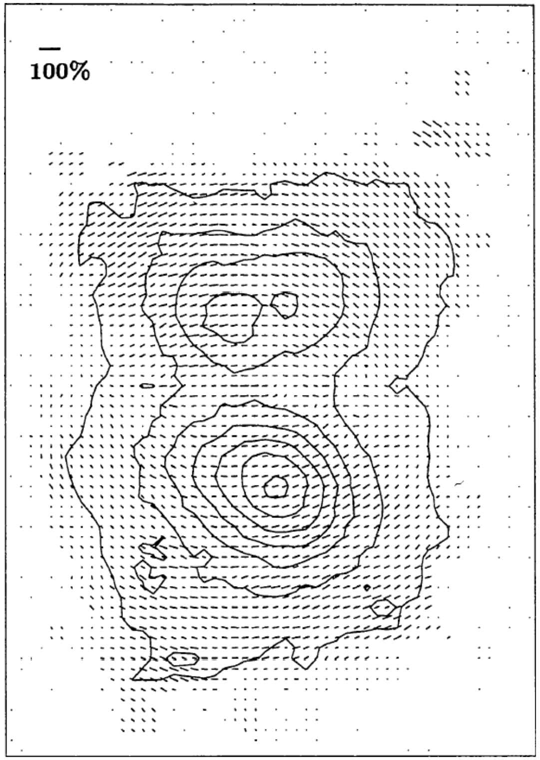


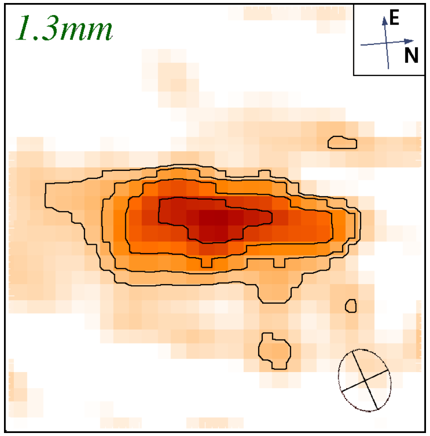
J band polarization map:
Linear Polarization: **Up to 80%**

[Lucas & Roche 1997]

- Conclusion:

  Optically thin (upper) disk layers +
  envelope dominated by ISM-type grains

- Disk reemission
  - Constraints on disk interior
  - Early measurement with OVRO:



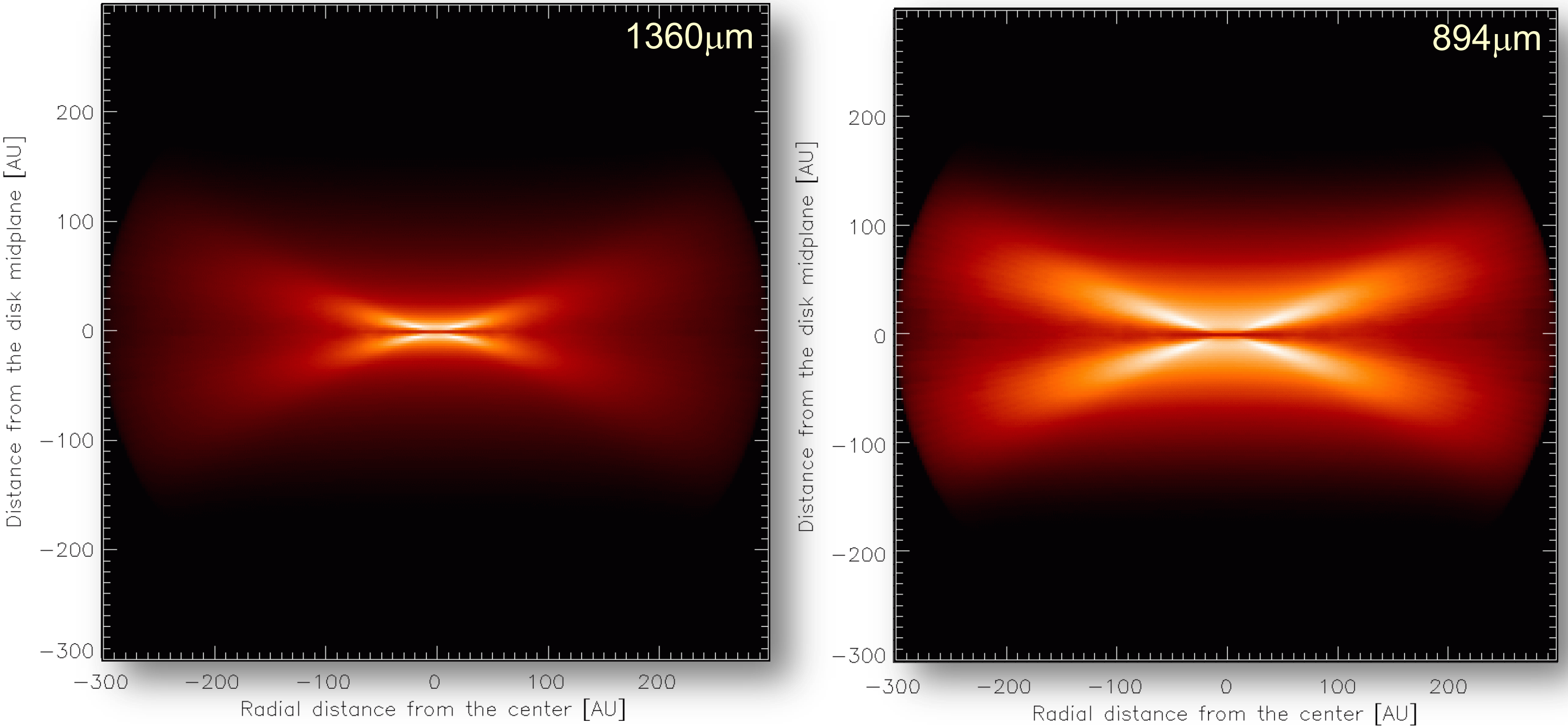
1.3mm, 600AU x 600AU
[Wolf et al. 2003]

Dust grains with radii up to ~100μm in the circumstellar disk!

Confirmation of **different dust evolution** in the shell vs. disk

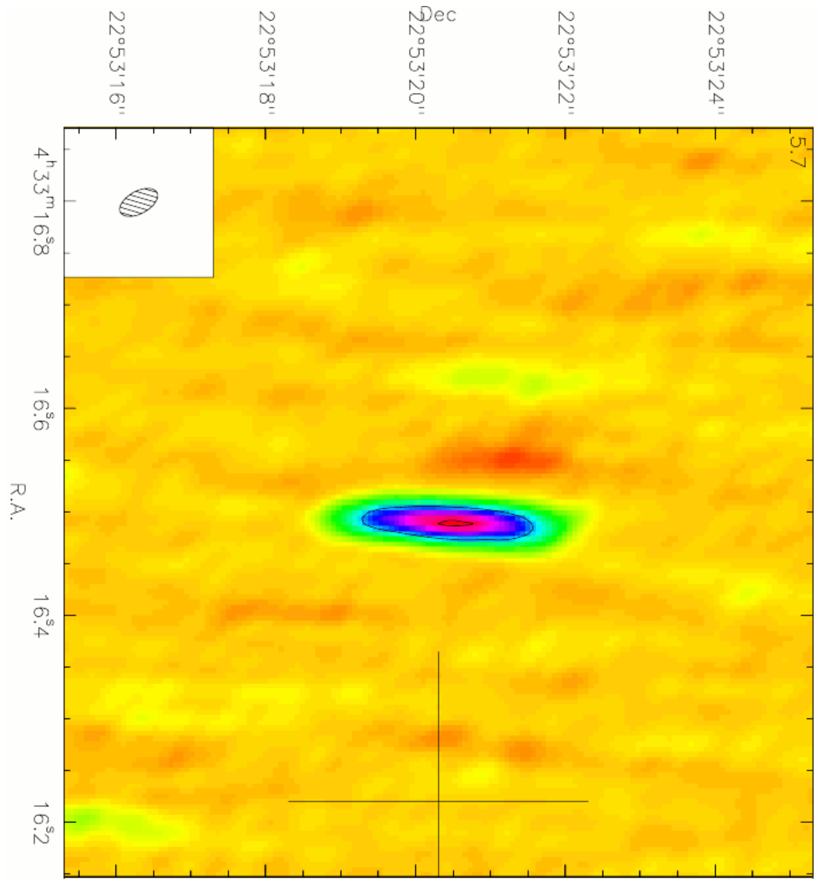
IRAS 04302+2247 („Butterfly star“)

- Verification of the previous analysis

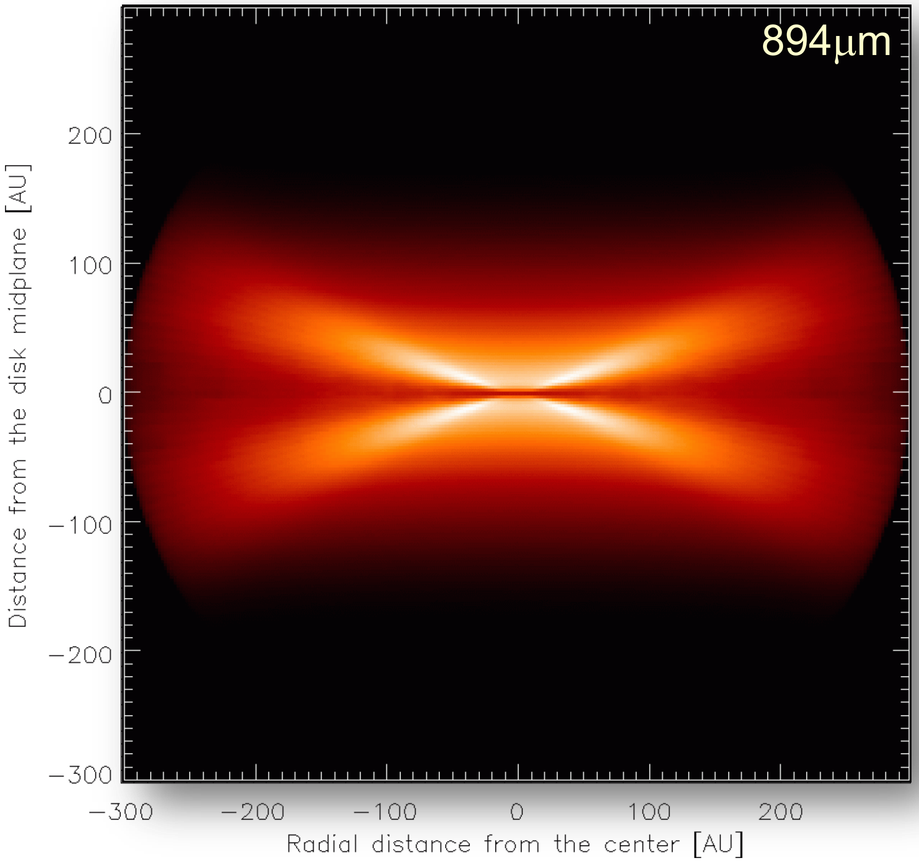


[Wolf et al. 2003, 2008]

IRAS 04302+2247 („Butterfly star“)



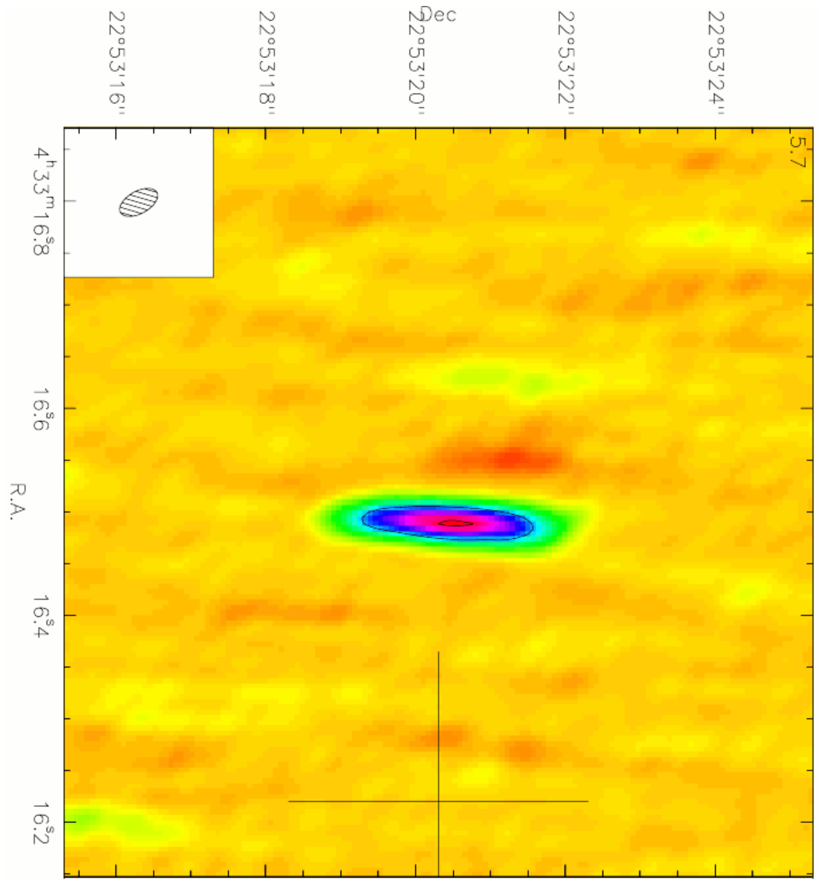
IRAS / PdBI: **1.3mm**, continuum



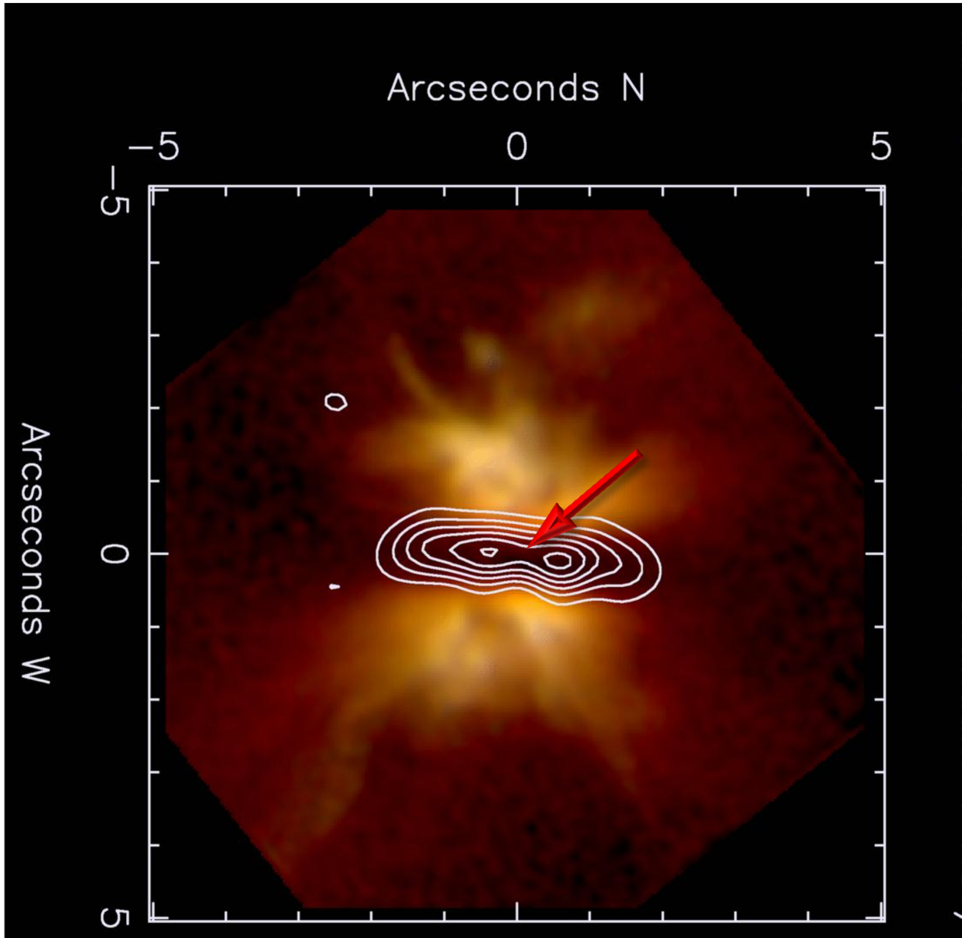
[Gräfe, Wolf, et al., in prep.]

[Wolf et al. 2003, 2008]

IRAS 04302+2247 („Butterfly star“)



IRAM / PdBI: **1.3mm**, continuum



SMA: **0.89 mm**, continuum

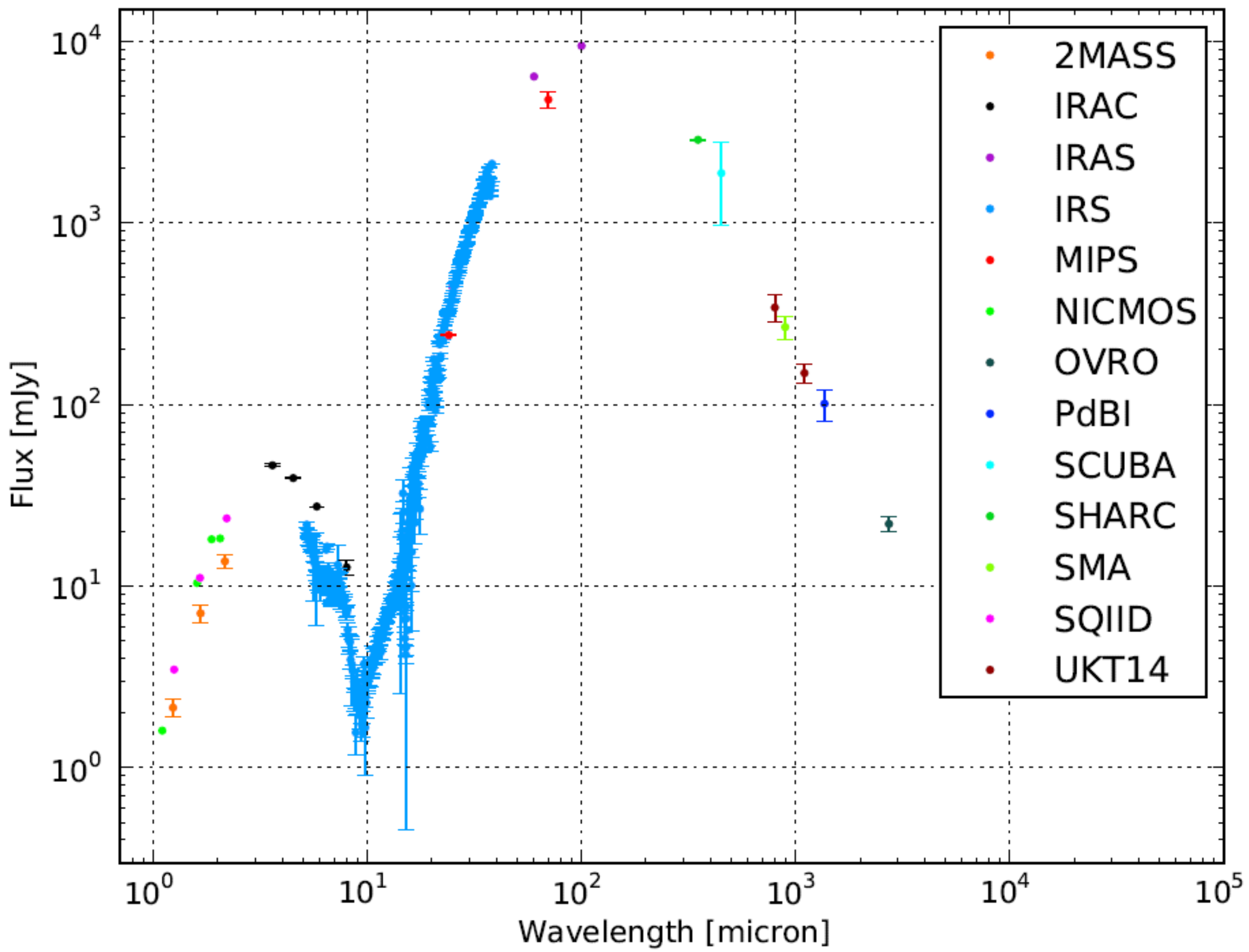
+ HST/NICMOS

[Gräfe, Wolf, et al., in prep.]

[Wolf et al. 2008]

IRAS 04302+2247 („Butterfly star“)

- New observations – Reduction of Degeneracies – New Constraints



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- New observations –

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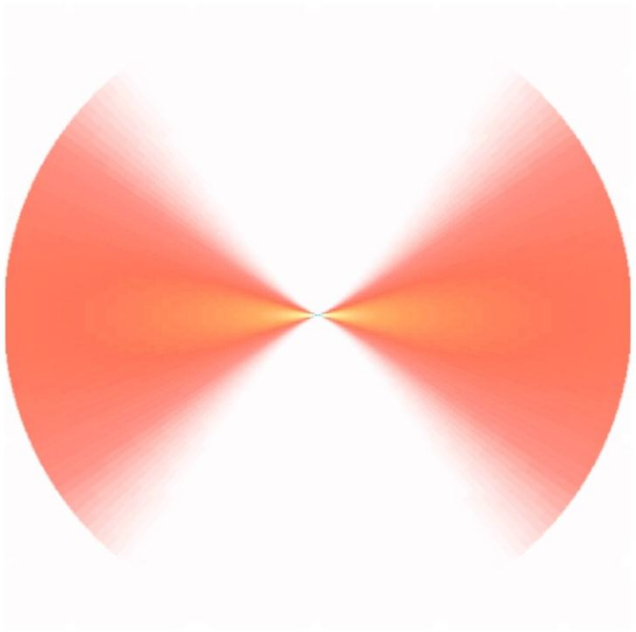

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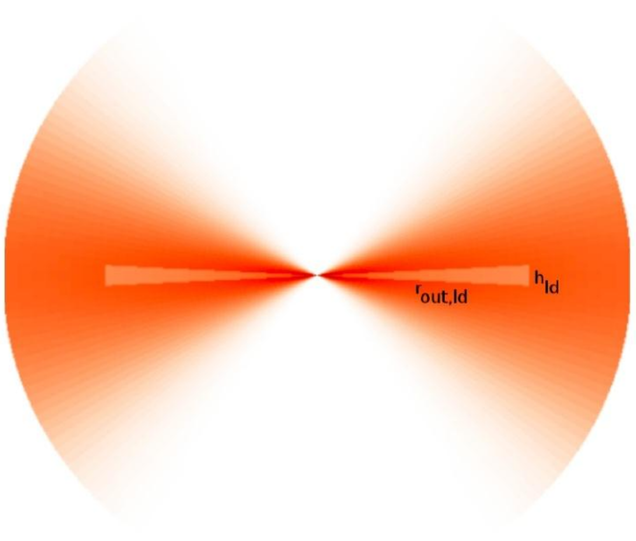
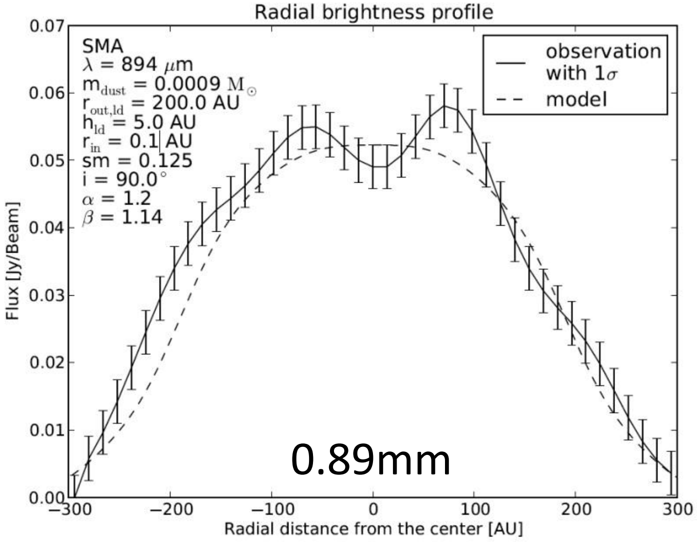
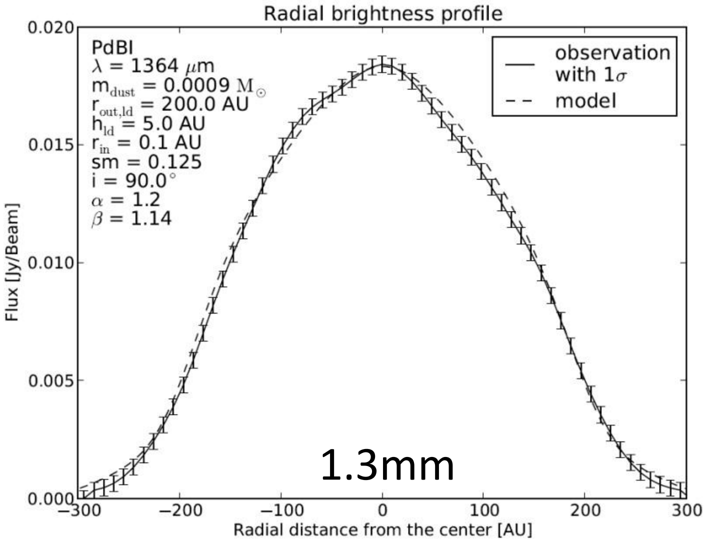






[Gräfe, Wolf, et al., in prep.]

IRAS 04302+2247 („Butterfly star“)

Best Fit

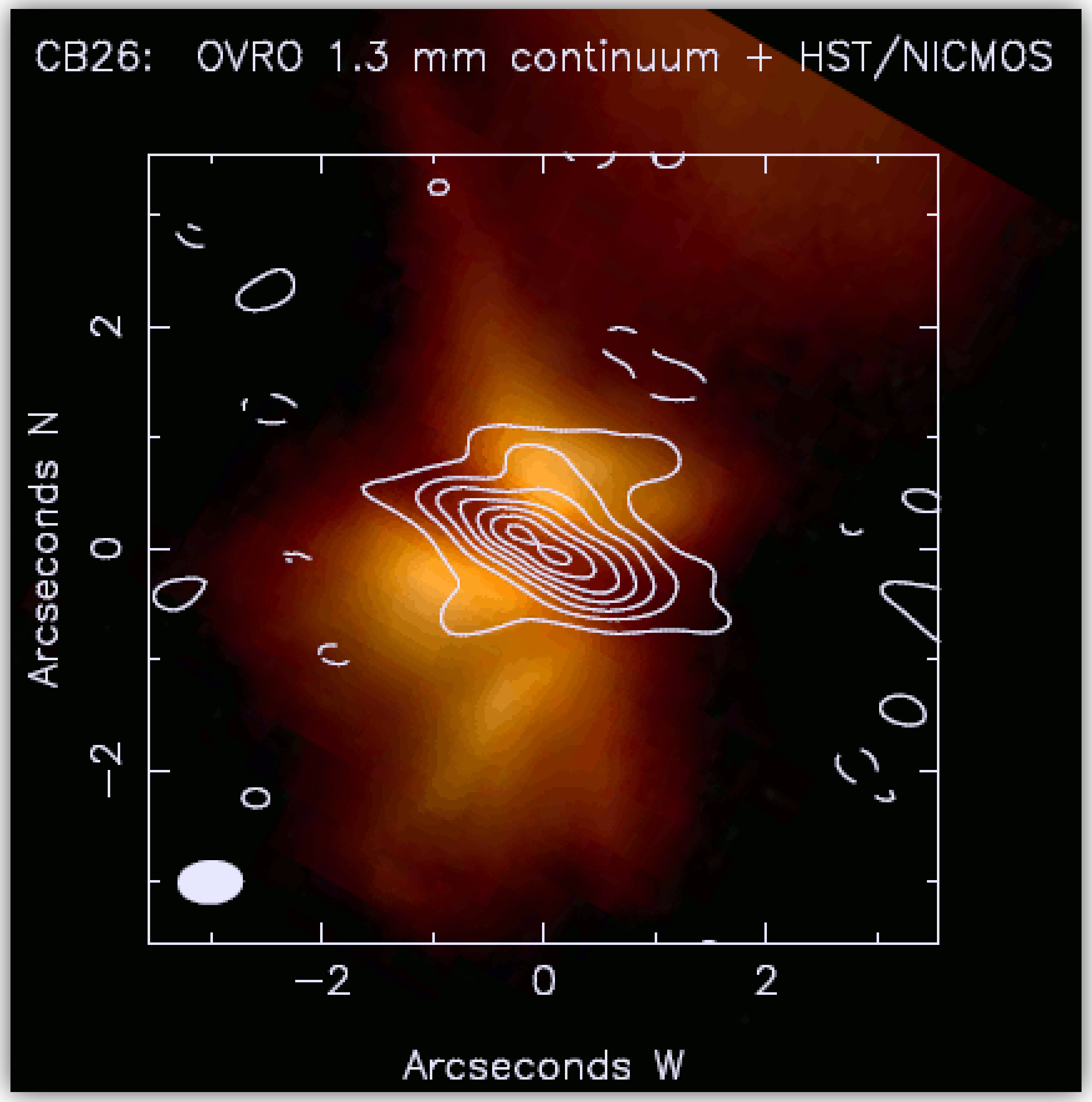
$a_{\mathrm{max,ld}}$	$= 100\,\mu\mathrm{m}$,	i	$= 90°$
α	$= 1.2$,	β	$= 1.14$
h_{ld}	$= 5.0\,\mathrm{AU}$,	$r_{\mathrm{out,ld}}$	$= 200.0\,\mathrm{AU}$
M_{ld}	$= 0.00025\,\mathrm{M}_\odot$,	M_{sd}	$= 0.00065\,\mathrm{M}_\odot$

Constraints

$a_{\mathrm{max,ld}} = 100\,\mu\mathrm{m}$,	$i = 90°$
$1.2 \leq \alpha < 1.8$,	$\delta\alpha = 0.2$
$1.12 < \beta < 1.17$,	$\delta\beta = 0.01$
$4.0\,\mathrm{AU} \leq h_{\mathrm{ld}} \leq 7.0\,\mathrm{AU}$,	$\delta h_{\mathrm{ld}} = 1.0\,\mathrm{AU}$
$175.0\,\mathrm{AU} \leq r_{\mathrm{out,ld}} \leq 225.0\,\mathrm{AU}$,	$\delta r_{\mathrm{out,ld}} = 25.0\,\mathrm{AU}$
$0.0008\,\mathrm{M}_\odot \leq \mathrm{M}_{\mathrm{dust}} \leq 0.001\,\mathrm{M}_\odot$,	$\delta M_{\mathrm{dust}} = 0.0001\,\mathrm{M}_\odot$

[Gräfe, Wolf, et al., in prep.]

CB 26



[Sauter, Wolf et al. 2009]

Observations considered

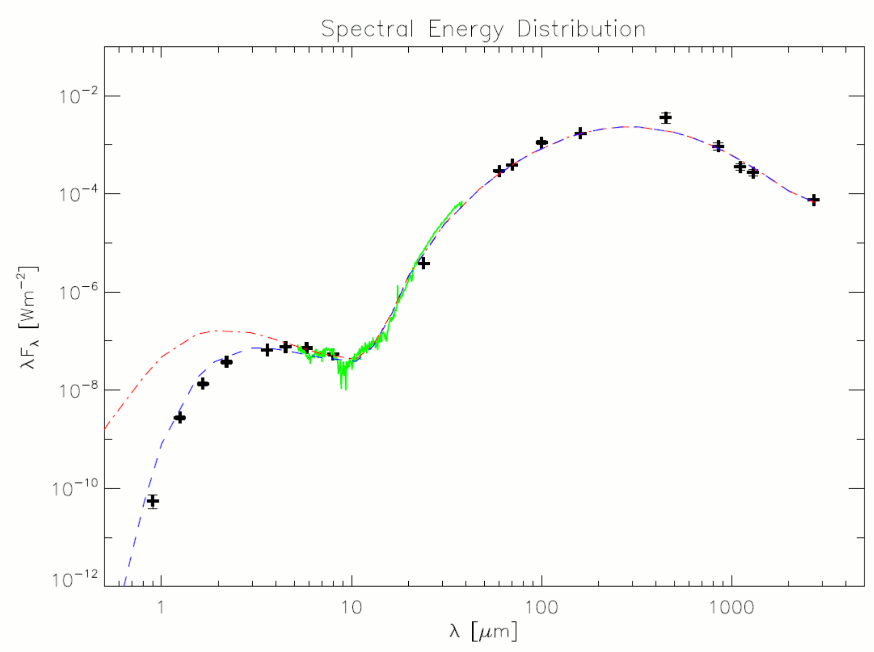
HST NICMOS NIR imaging

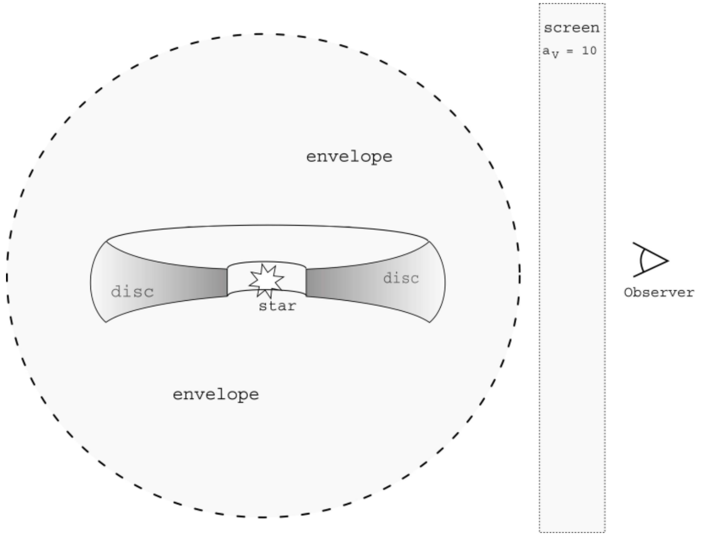
Submm single-dish:
SCUBA/JCMT,
IRAM 30m

Interferometric mm cont. maps:
SMA (1.1mm), OVRO (1.3/2.7mm)

SED, including IRAS, ISO, Spitzer

CB 26





Main Conclusions

- **Dust**
  - ISM dust grains in the envelope and „upper" disk layers
  - Dust grains in the disk midplane only slightly larger than in the ISM
- **Disk**
  - **Inner disk radius: ~ 45 +/- 5 AU**

[Sauter, Wolf et al. 2009]

HH30

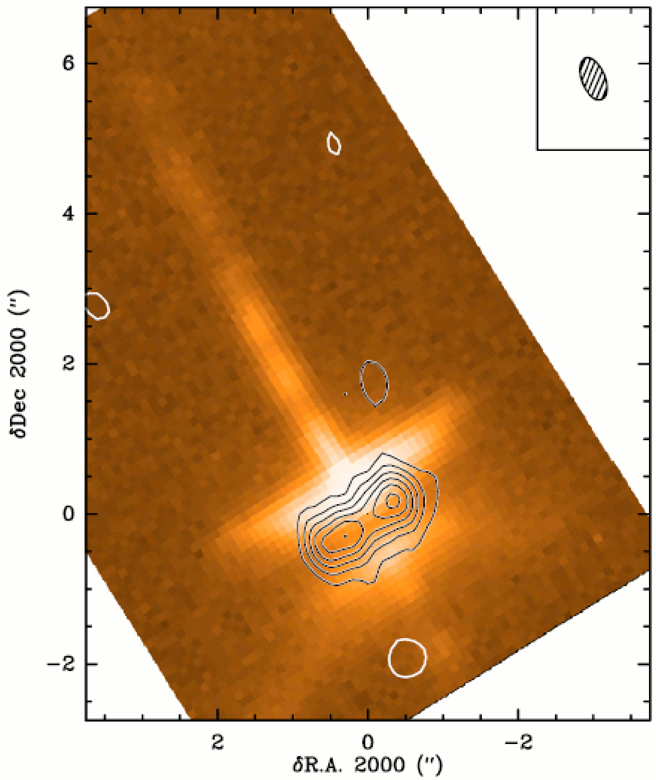


Fig. 1. Superimposition of the PdBI 1.30 mm continuum map on the HST data. The spatial resolution is $0.59 \times 0.32''$ at PA 22°. The center of projection is RA = $04^h31^m37\overset{s}{.}469$ and Dec = $18°12'24\overset{''}{.}22$ in J2000. Contour levels start at and are spaced by 3σ = 0.56 mJy/beam, corresponding to 68 mK. The registration of the HST image is approximate, as the positions given by Anglada et al. (2007) and Cotera et al. (2001) differ by $1''$.

Observation
IRAM interferometer, 1.3mm,
beam size ~0.4”

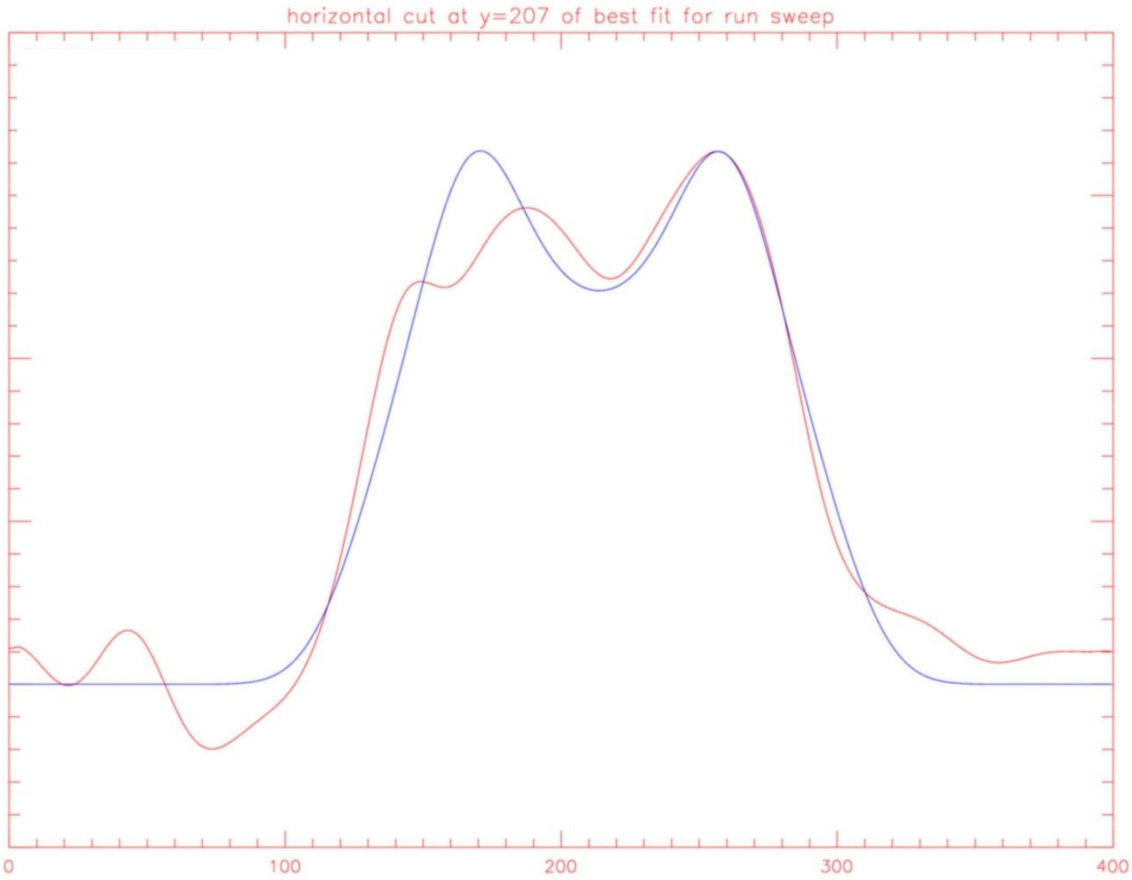
Results
Disk of HH30 is truncated at an inner radius 37 ± 4 AU

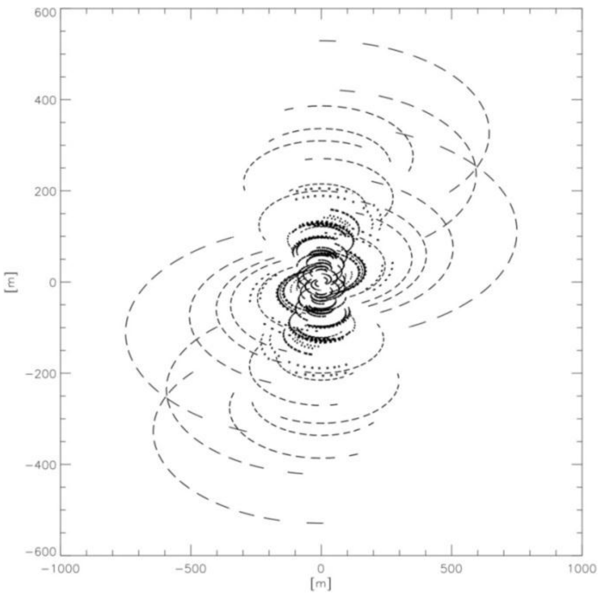
Interpretation

- Tidally truncated disk surrounding a binary system (two stars on a low eccentricity, 15 AU semi-major axis orbit)
- Additional support for this interpretation: Jet wiggling due to orbital motion
- The dust opacity index, β ≈ 0.4, indicates the presence of cm size grains (assuming that the disk is optically thin at 1.3mm)

[Guilloteau et al. 2008]

HH30





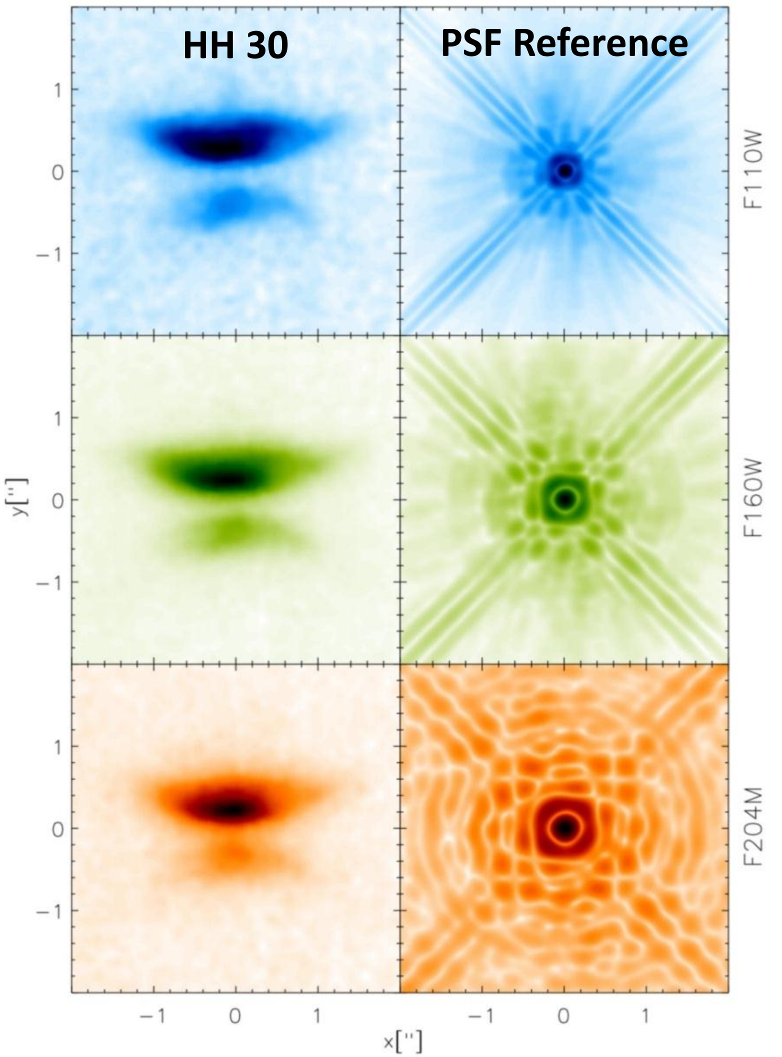
[uv coverage]

Fitting of
a) reconstructed map
b) uv data

Resulting inner radius: 50 +/- 10 AU

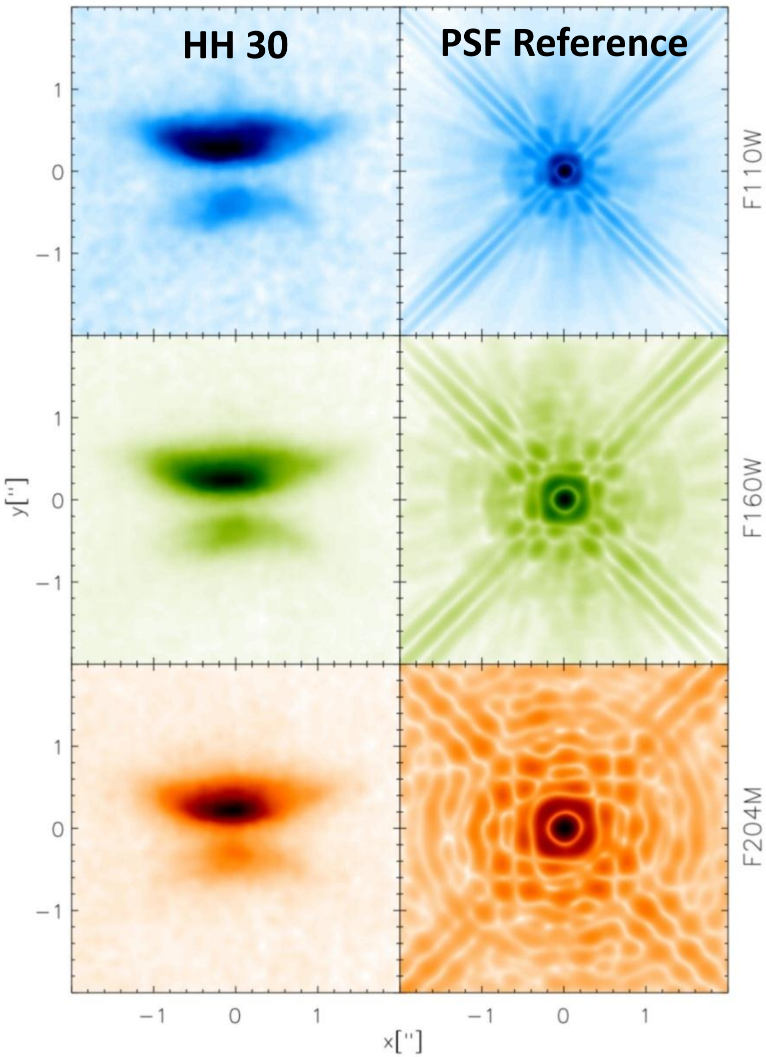
[Madlener, Wolf, et al., subm.]

HH30

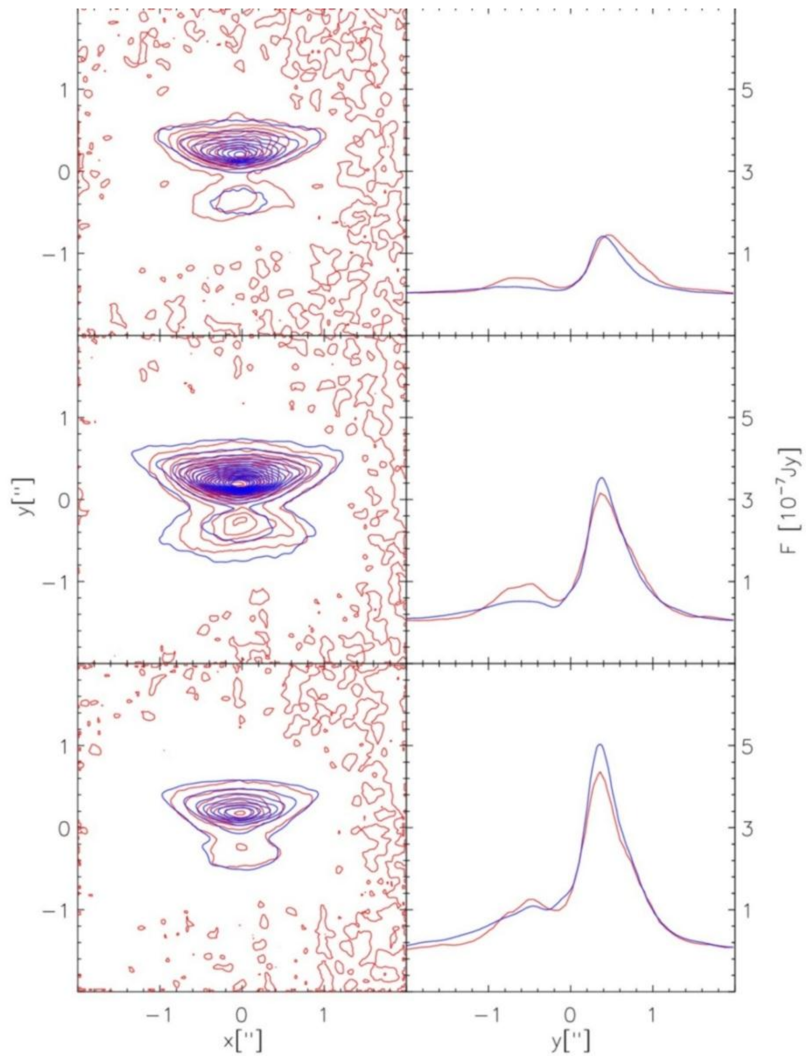


[based on observations published
by Cotera et al. 2001]

HH30

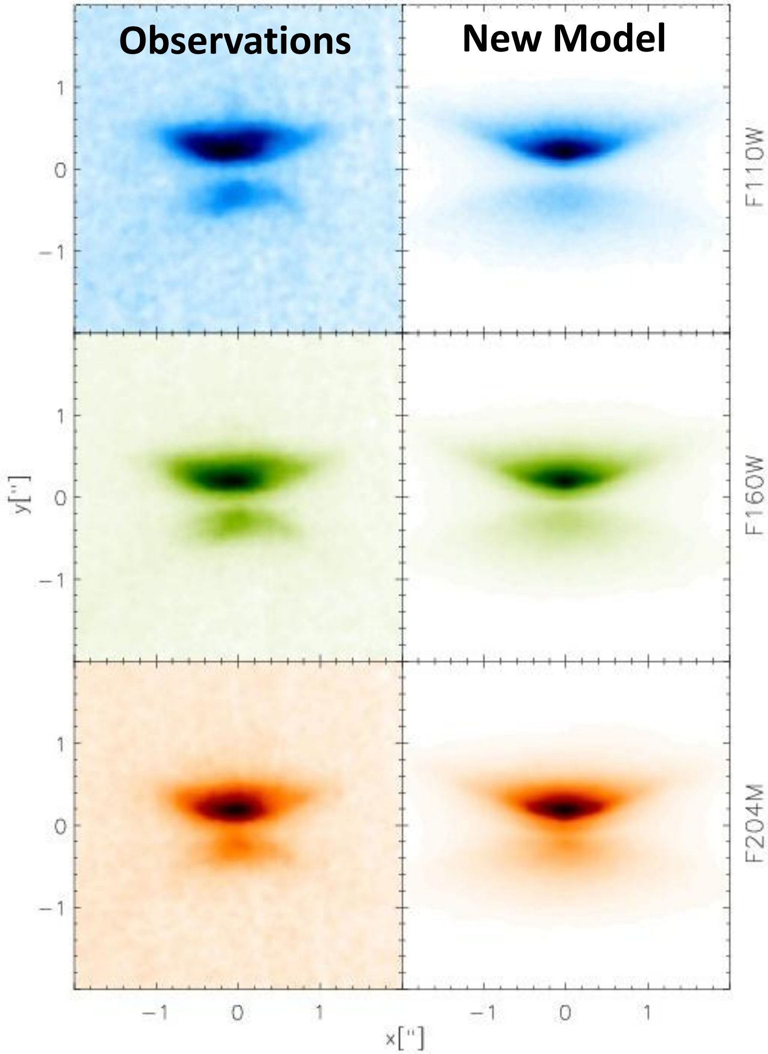


[based on observations published by Cotera et al. 2001]

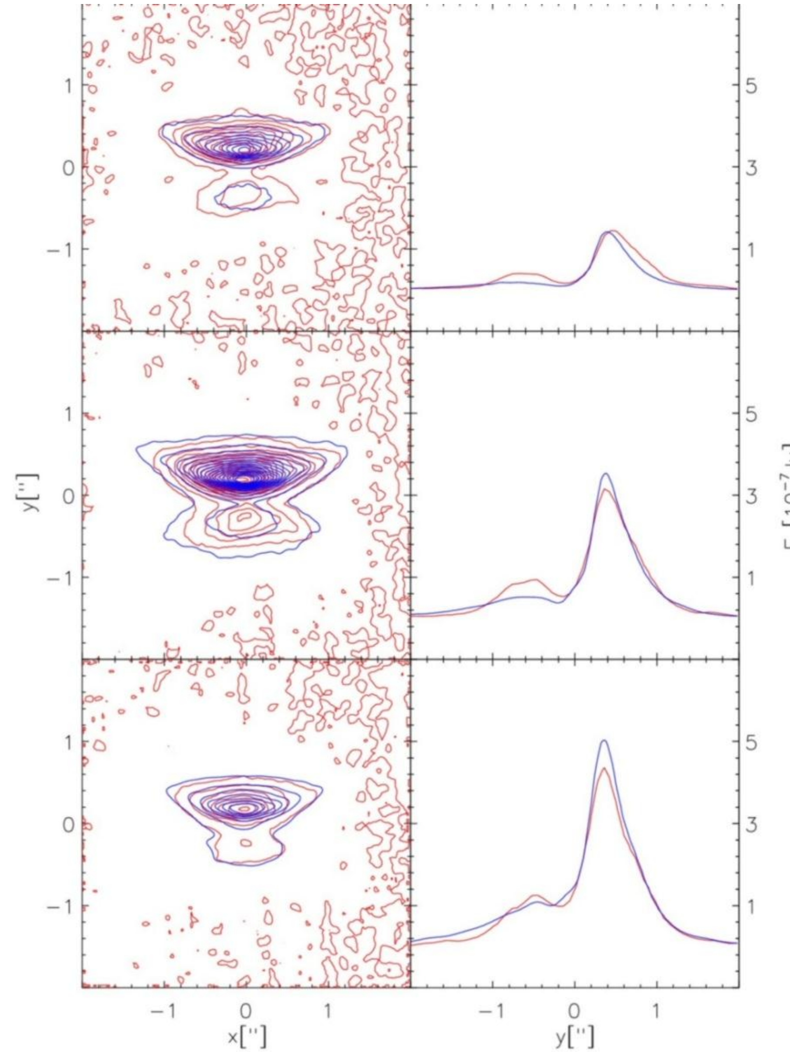


[Madlener, Wolf, et al., subm.]

HH30



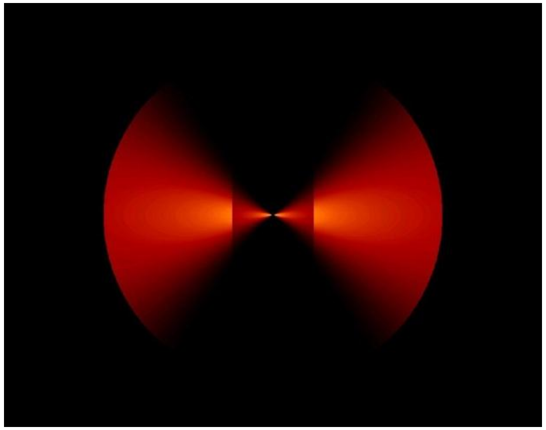
[based on observations published by Cotera et al. 2001]



[Madlener, Wolf, et al., subm.]

HH30

model	A (NIR)	B (SED)	C (SED/mm)
η	0.019	$0.029^{+0.024}_{-0.005}$	0.03
α	2.45	$2.39^{+0.28}_{-0.23}$	2.3
β	1.09	$1.21^{+0.01}_{-0.13}$	1.16
$R_{\rm in}$ [AU]	2.1	$0.27^{+0.98}_{-0.17}$	0.56
$R_{\rm att}$ [AU]	59.6	$47.1^{+2.7}_{-16.7}$	44.4
$R_{\rm out}$ [AU]	455	485^{+15}_{-360}	175
h_{100} [AU]	14.8	$14.9^{+0.5}_{-1.4}$	14.7
$m_{\rm dust}$ $[10^{-5} M_\odot]$	0.734	$7.4^{+10.1}_{-2.8}$	5.04
$T_{\rm eff}$ [K]	3300	3200^{+700}_{-200}	3300
L_* $[L_\odot]$	0.6	$0.38^{+0.48}_{-0.11}$	0.48
$a_{\rm min}$ [μm]	0.006	$0.009^{+0.003}_{-0.008}$	0.003
$a_{\rm max}$ [μm]	1.87	19000^{+31000}_{-9400}	20200
d	3.4	$3.71^{+0.11}_{-0.19}$	3.58
i[°]	83.6	$83.4^{+2.2}_{-3.0}$	85.1

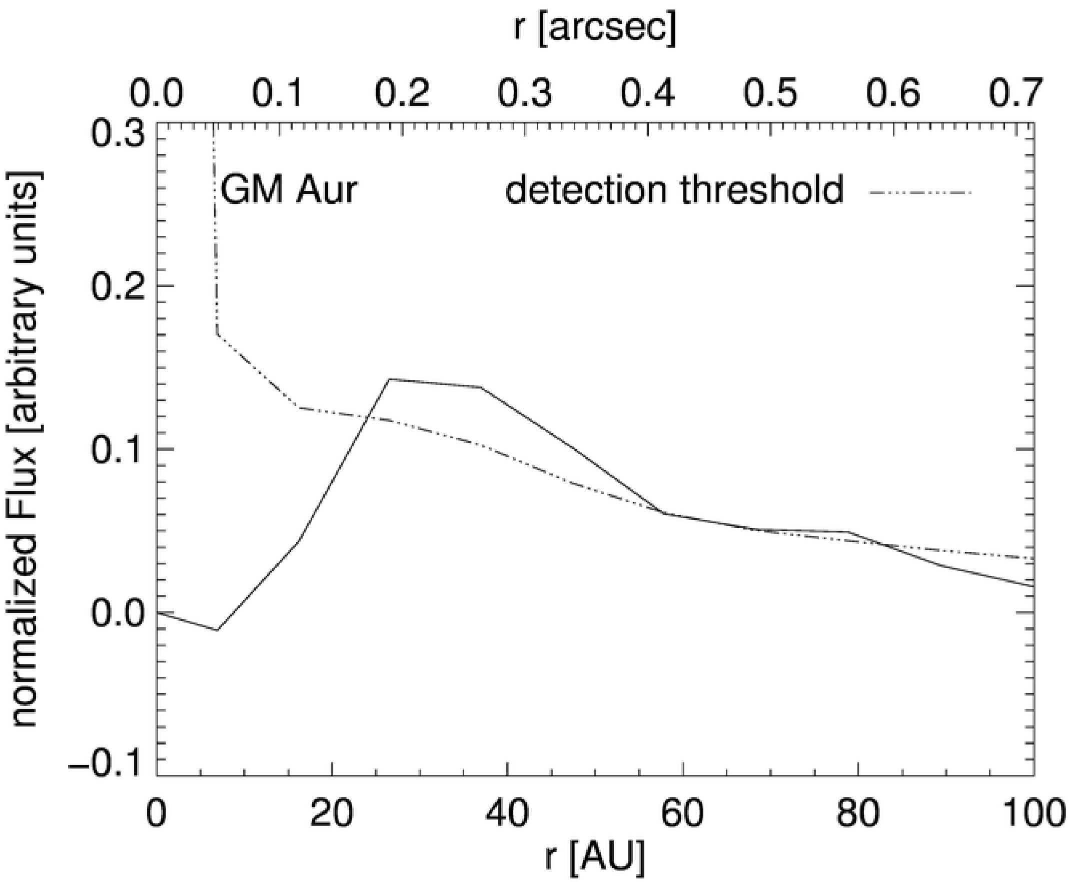


Spatially resolved millimeter images reveal large inner hole

but
Combination with SED (and constraints from scattered ligt images) show that **inner region is not entirely cleared**

[Madlener, Wolf, et al., subm.]

GM Aurigae



Observed flux residuals of GM Aur

Goal

Direct imaging of the inner disk rim of transitional disks

Technique

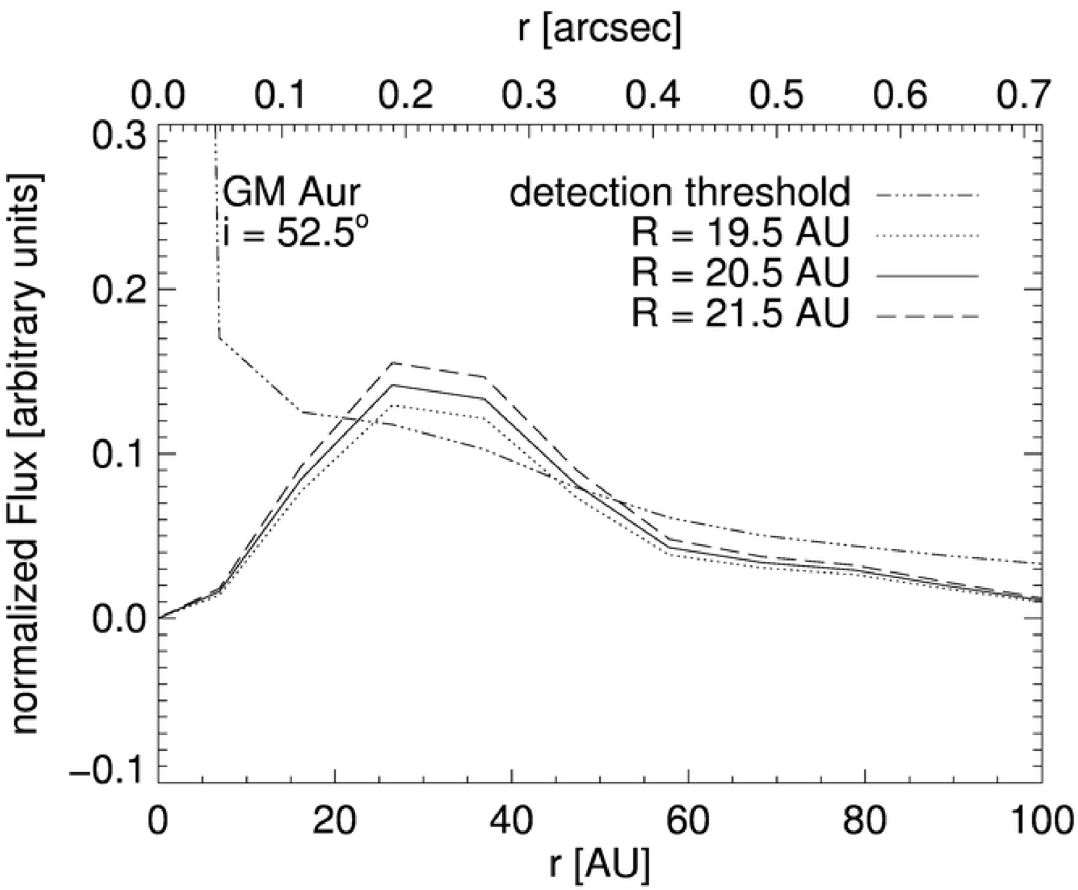
VISIR (N band) imaging

Targets

GM Aur,
DH Tau,
DM Tau

[Gräfe, Wolf, et al., 2011]

GM Aurigae



Modeled flux residuals of GM Aur

Results

- Transitional disk around GM Aur spatially resolved
- Inner disk radius: 20.5(+1.0,-0.5) AU

- Disks around DH Tau and DM Tau not spatially resolved (consistent with literature values)
  - DH Tau
    <15.5 (+9.0,-2.0) AU
  - DM Tau
    <15.5 (+0.5,-0.5)

[Gräfe, Wolf, et al., 2011]

Inner disks – Open questions

Hypotheses / Theoretical model to be tested

- Accretion: Viscosity, Angular momentum transfer, Accretion geometry on star(s)
- Snow-line (location / surface density profile)
- Planets: Luminosity, induced gaps
- Puffed-up inner rim and associated shadowed region
- Gas within the inner rim
- Gas-to-dust mass ratio; Empty(?) holes in transition disks

The general context (exemplary questions):

- How do inner and outer disk relate to each other?
- Where and when do planets form?

Required

Empirically-based input to improve our general understanding and thus to better constrain planet formation / disk evolution models

Approach

Imaging the inner disk

Mid-IR Spectro-Interferometry

- Goal
  - Spectrally resolved (R=30) N band visibilities for various T Tauri disks
  - MIDI: $\lambda/B \geq$ 1AU @ 140pc with B ≤ 130m

- Results
  - **SED** (global appearance of the disk) + spectrally resolved **visibilities** can be fitted **simultaneously**
  - Best-fit achieved in most cases with an **active accretion disk and/or envelope**
  - Decompositional analysis of the 10μm feature confirms effect of **Silicate Annealing** in the inner disk (~ few AU)

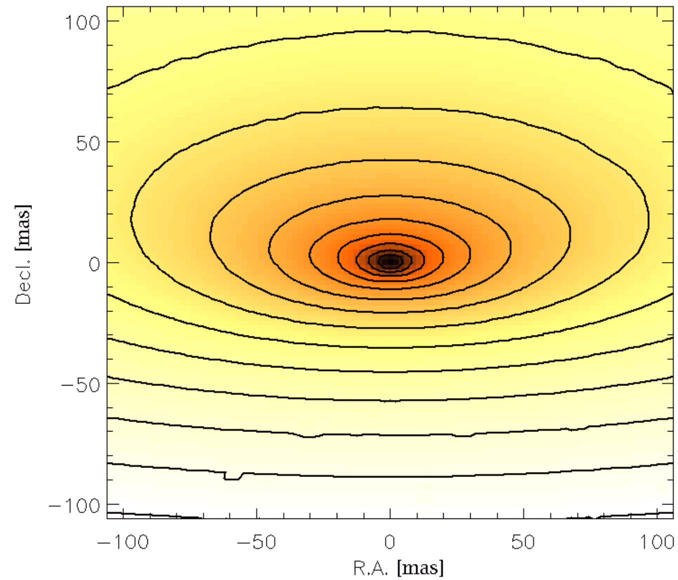
- References
  - Schegerer, Wolf, et al. 2008, A&A 478, 779 „The T Tauri star RY Tauri as a case study of the inner regions of circumstellar dust disks "
  - Schegerer, Wolf, et al. 2009, A&A, 502, 367 „Tracing the potential planet-forming region around seven pre-main sequence stars"

Limitation of two-beam interferometers

- Goal:
  True surface brightness profile
  of circumstellar disks

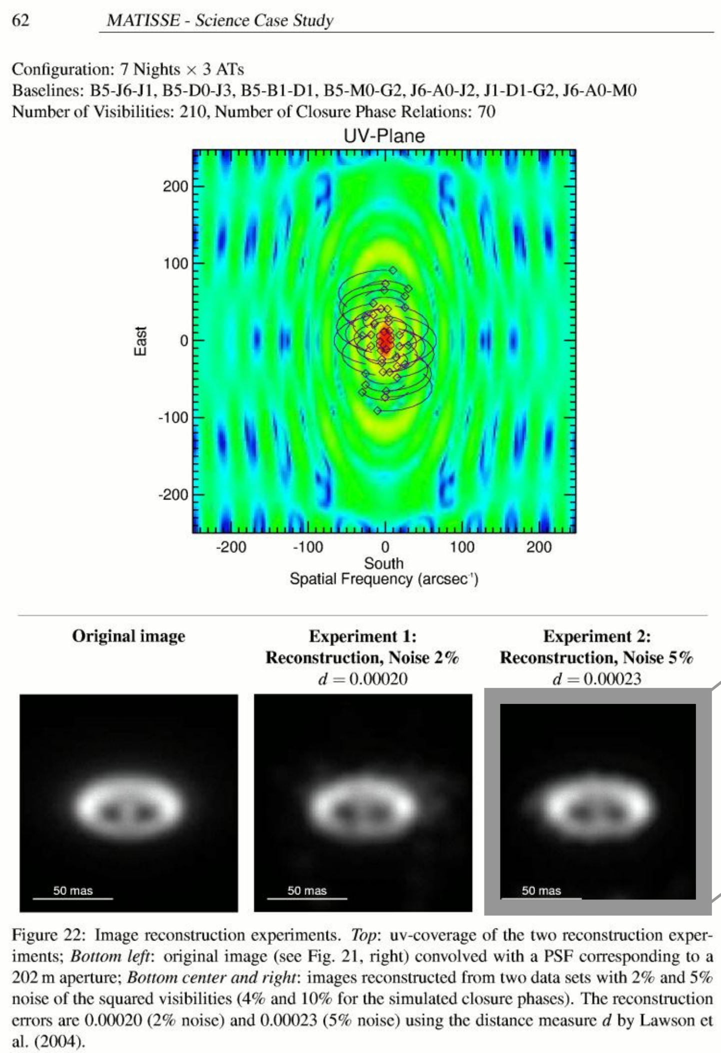
- Problem
  - Two-telescope interferometers: “Mean” disk size & approximate disk inclination
  - Assumption: Iso-brightness contours are centered on the location of the central star

- Solution
  - **MATISSE:** Multi-AperTure Mid-Infrared SpectroScopic Experiment
  - Second generation VLTI beam combiner
  - L, M, N bands: ~ 3 – 13 mm
  - Spectral resolution: 30 / 100-300 / 500-1000
  - Simultaneous observations in 2 spectral bands



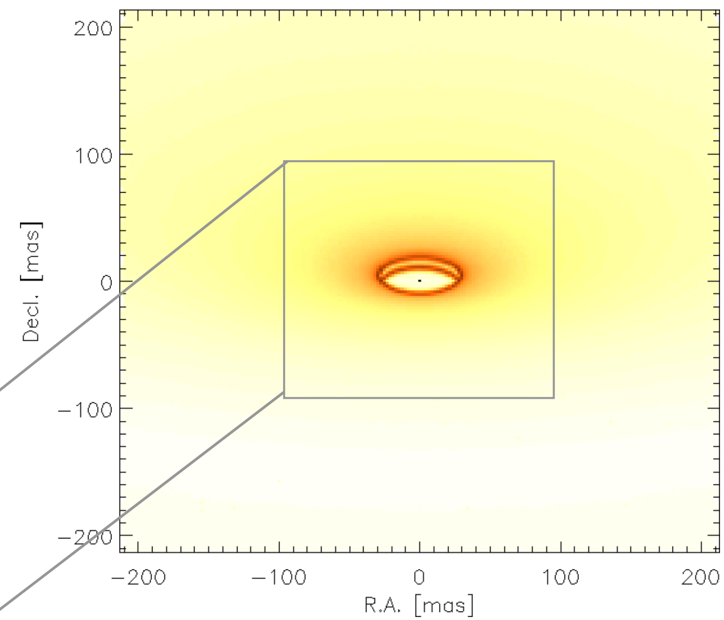
Simulated 10µm intensity map of the inner 30AU×30AU region of a circum-stellar T Tauri disk at an assumed distance of 140 pc; inclination: 60◦.

MATISSE / Circumstellar disks


62 *MATISSE - Science Case Study*

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).



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

[Wolf et al. 2007]

MATISSE / Circumstellar disks

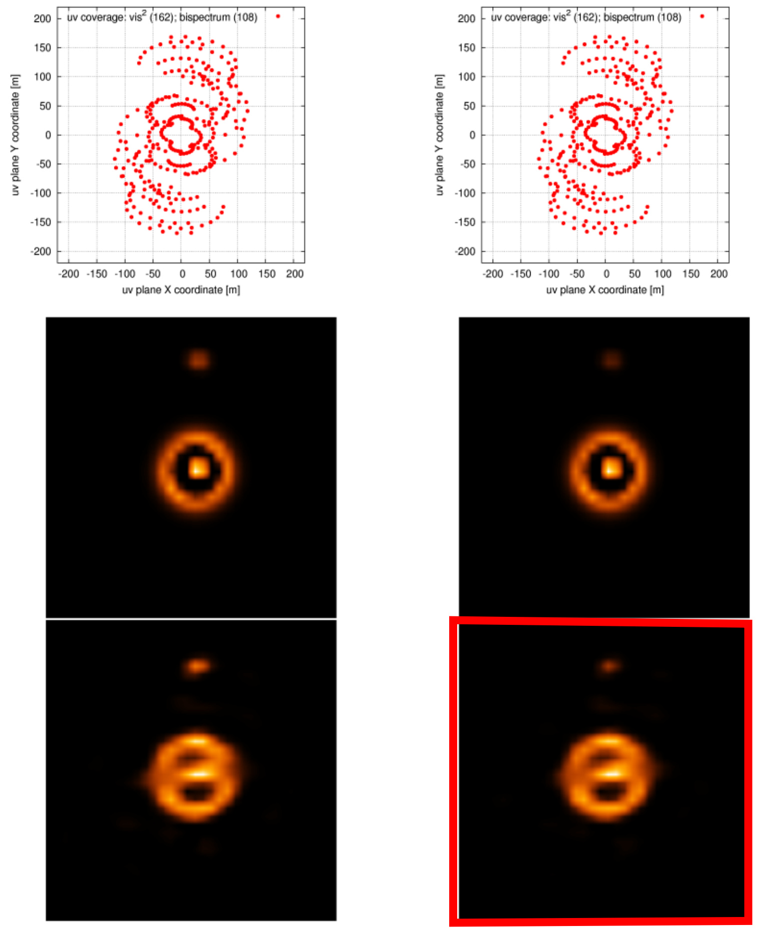
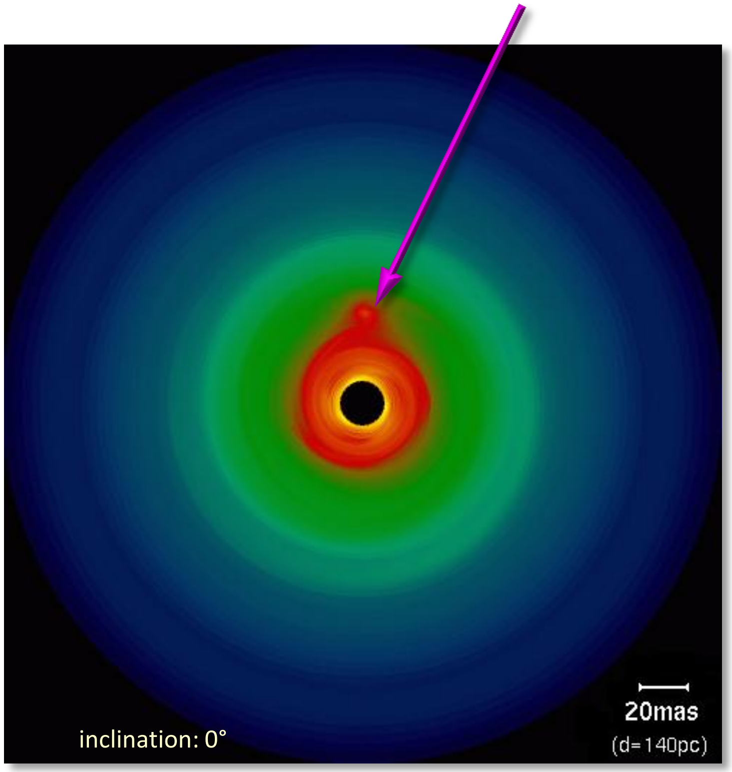


Figure 6: Reconstructed N band images (3x4ATs; ~ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5[right]). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and 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 Proto-Planet

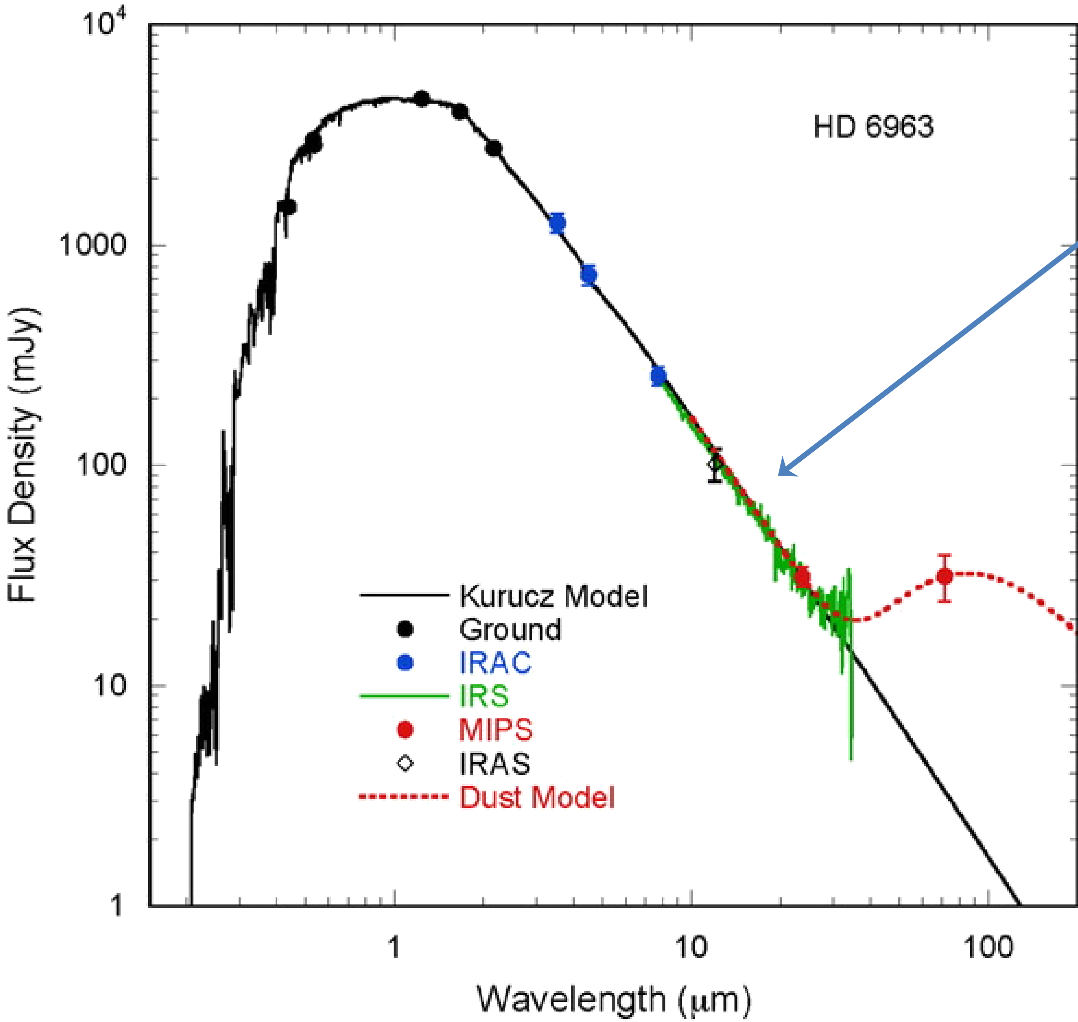


[Wolf et al. 2007]

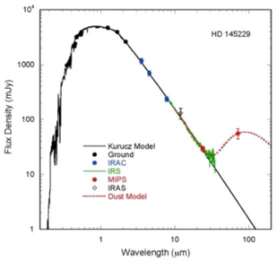
Exemplary studies

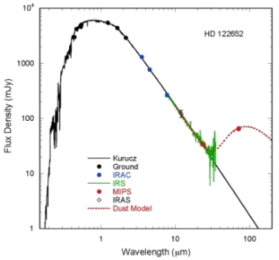
b) Debris disks

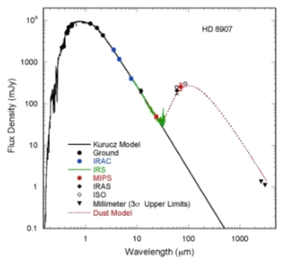
Problems with SEDs

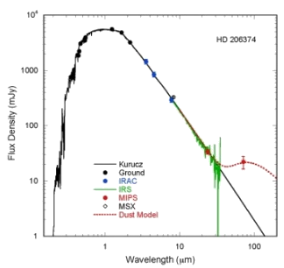


Weakly constrained dust properties









[Kim et al. 2005]

HD 107146

Observations

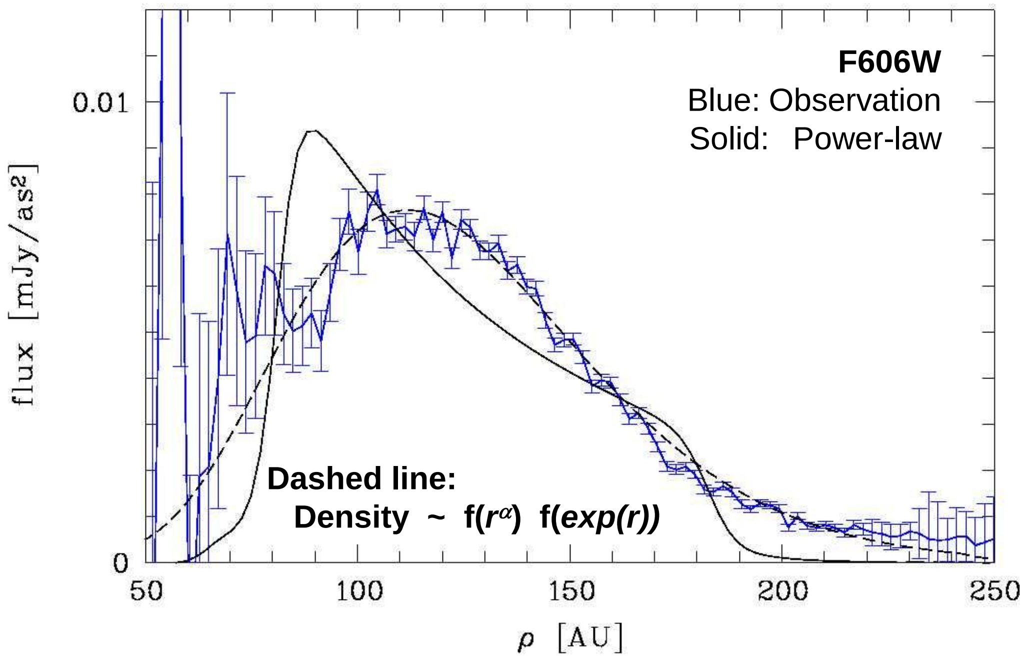
- G2 V, 28.5pc
- Spatially resolved maps
  - HST/ACS (F606W)
  - HST/NICMOS (F110W,F814W)
  - CARMA (1.3mm)
- SED
  - 3.5μm - 3.1mm
  - in particular: Spitzer / IRS (7.6μm - 37μm)

Modeling

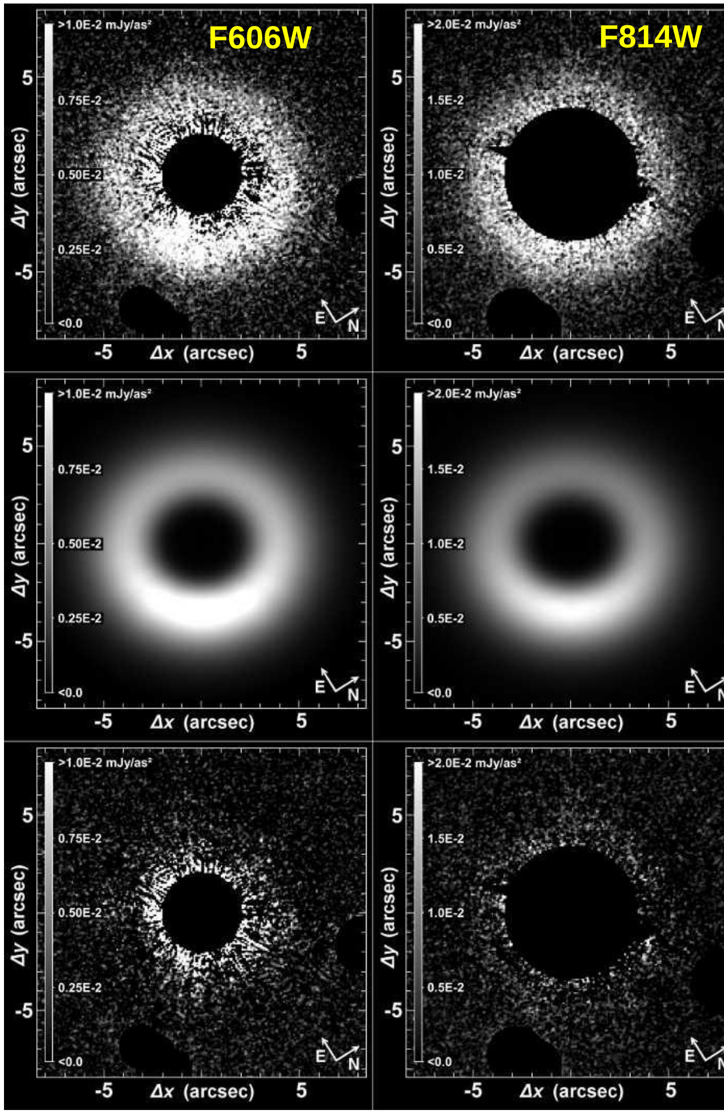
- Approach:
  Simultaneous fitting of images and SED
- Fitting tool: SAnD
  - Simulated annealing minimization scheme
  - Fast: finds fit among ~10^{11} models in ~70 hours
  - Large number of free parameters possible
  - Limited initial constraints on disk physics

[Ertel, Wolf, et al. 2011]

HD 107146



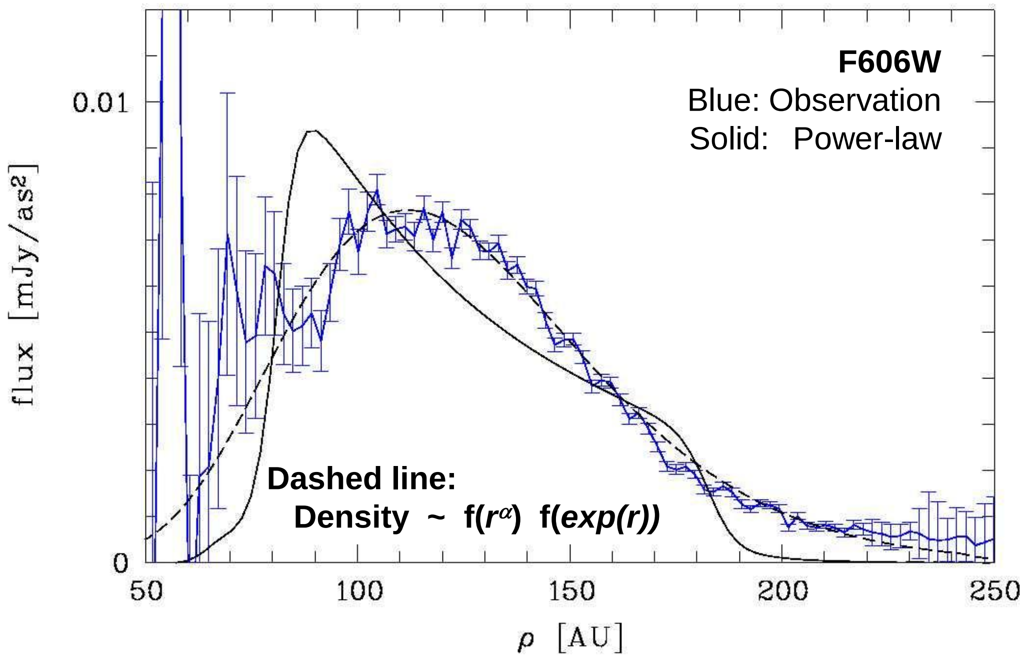
- Broad disk, not a narrow ring
  (surface density: FWHM = 91 AU,
  peak radius = 131 AU)
- Radial density distribution: No simple power-law

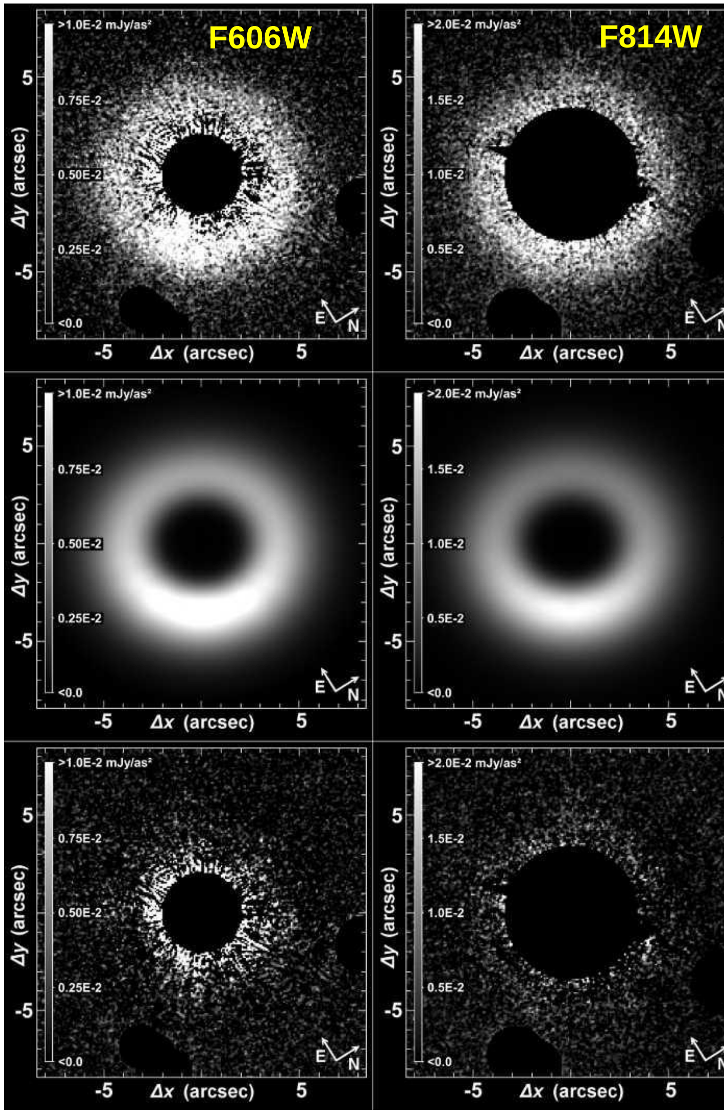


HST/ACS

[Ertel, Wolf, et al. 2011]

HD 107146





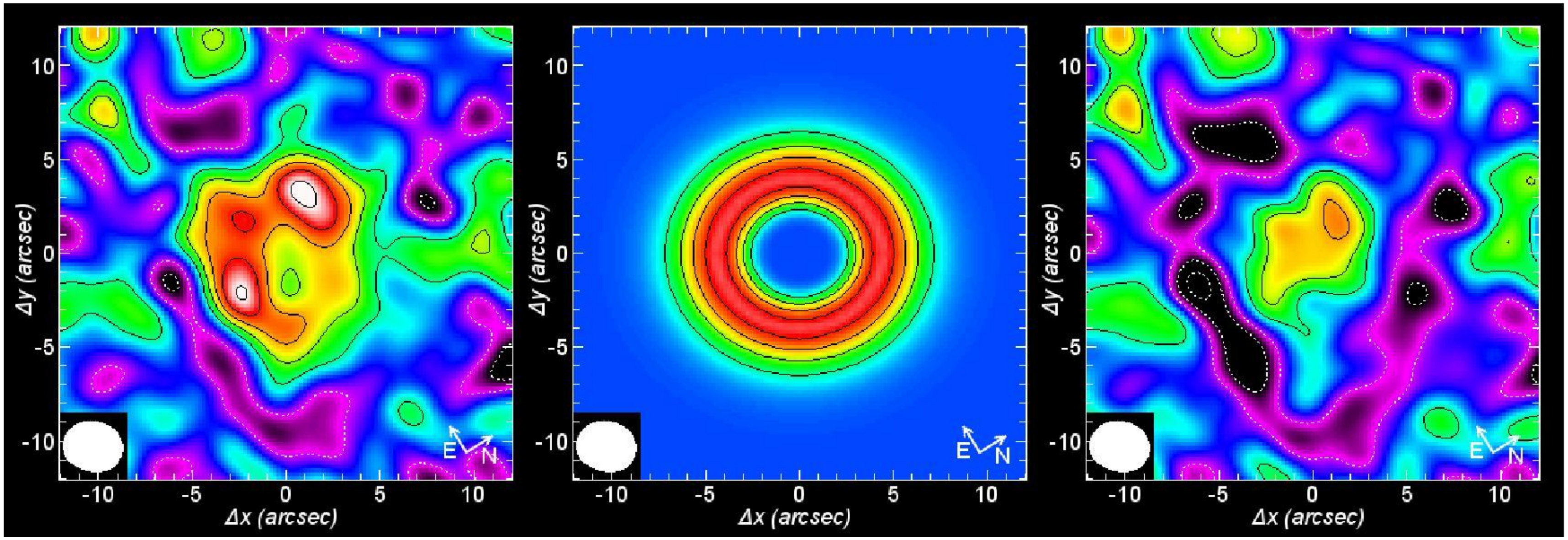
HST/ACS

- Consistent mass estimate from scattered light data and millimeter measurements (6.4+/-0.3 x 10^{-7} M_{Sun})

- Large lower grain size (5 x expected blow-out size), robust against uncertainties in model parameters

[Ertel, Wolf, et al. 2011]

HD 107146



CARMA, 1.3mm (Corder et al. 2009) — (our) Model image — Observation - Model

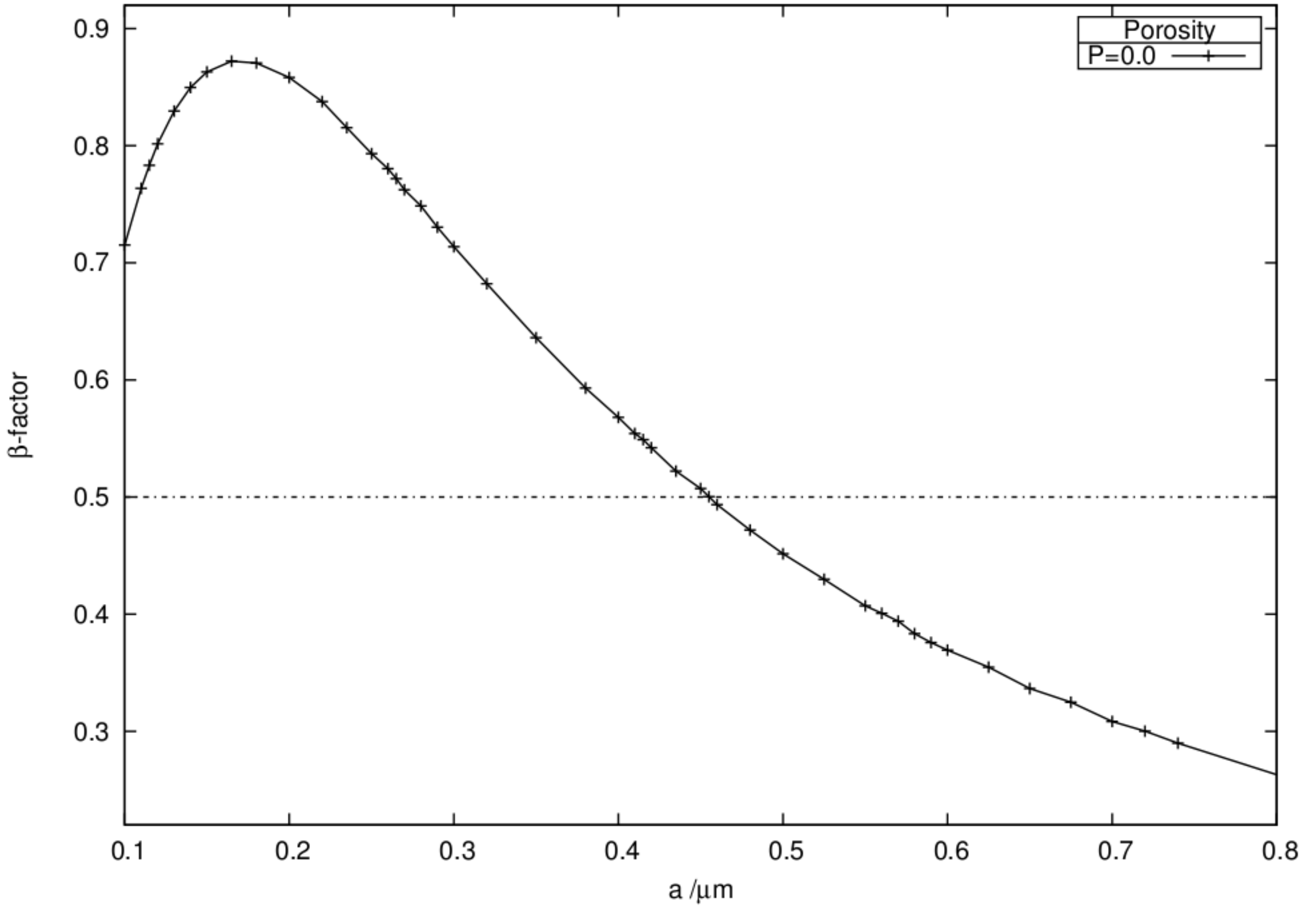
[Contours start at -1σ (white, dashed) and 1σ (black, solid) and have increments of 1σ, respectively, where 1σ = 0.35 mJy/beam]

Model subtraction: In u-v domain

Two peaks: Artefacts of image reconstruction

[Ertel, Wolf, et al. 2011]

Porous grains: Blow-out size

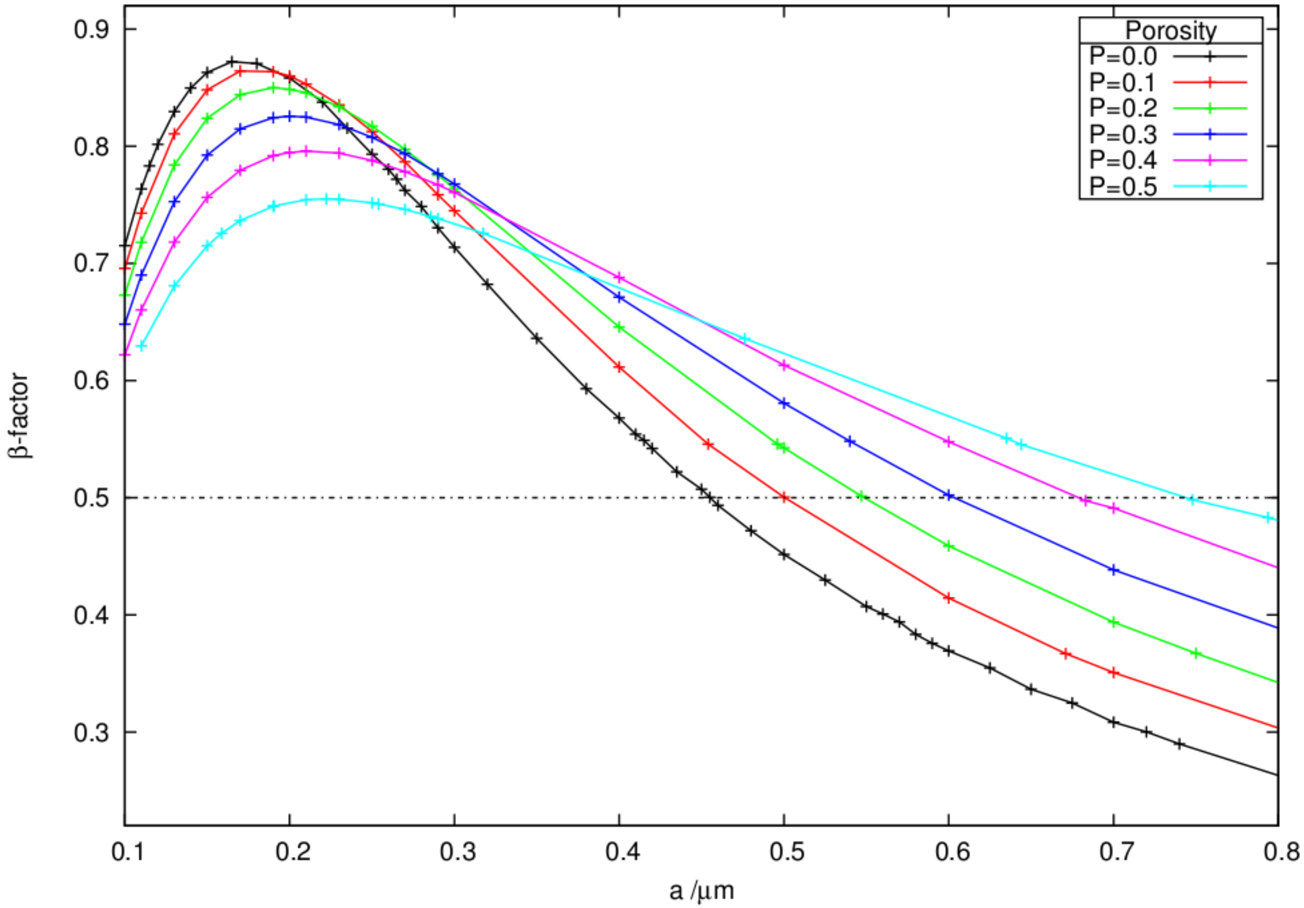


[Kirchschlager & Wolf, in prep.]

Porous grains in the Solar system

- T = 5777K, Astrosilicate
- a_{min} = 0.45 μm

Porous grains: Blow-out size



[Kirchschlager & Wolf, in prep.]

Porous grains in the Solar system

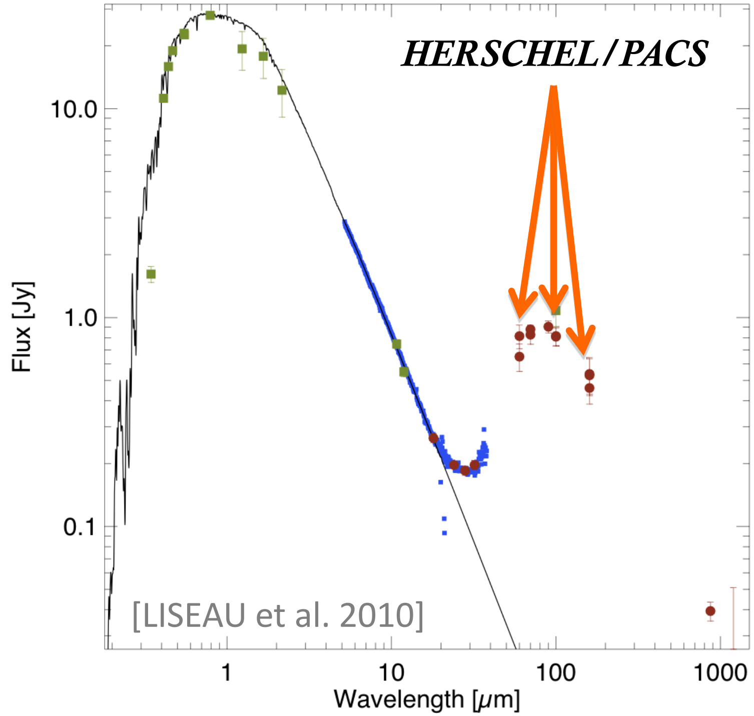
- T = 5777K, Astrosilicate
- a_{min} = 0.45 μm

But for

- Hole size H = 1/100
- a_{min} = 0.74μm for P=0.5

q1 Eri

- Stellar parameters
  - Spectral type: F8
  - Distance : 17.4 pc
  - Age : ~ 2 Gyr

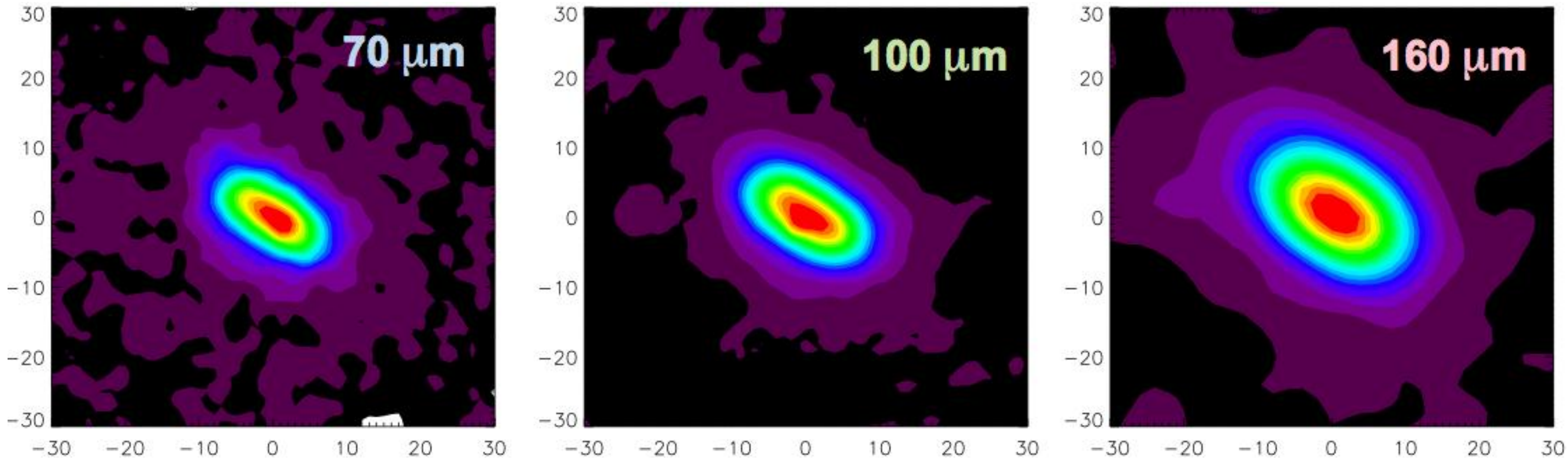


- Planet
  (Mayor et al. 2003, Butler et al. 2006)
  - M sin i: 0.93 $M_{Jupiter}$
  - Semi-major axis: 2.03 AU
  - Eccentricity : 0.1

- Dust ring
  - IRAS, ISO and Spitzer: cold dust; L ~ 1000 L(Kuiper Belt)
  - Sub-mm APEX/LABOCA images:
    Disk extent up to several tens of arcsec (Liseau et al. 2008)
  - HST images suggest a peak at 83 AU (4.8”, Stapelfeldt et al., in prep.)

q1 Eri

- Herschel observations (Key project *DUNES*):



  - Disk spatially resolved at all PACS wavelengths
  - Disk marginally resolved along the minor axis: inclination > 55°

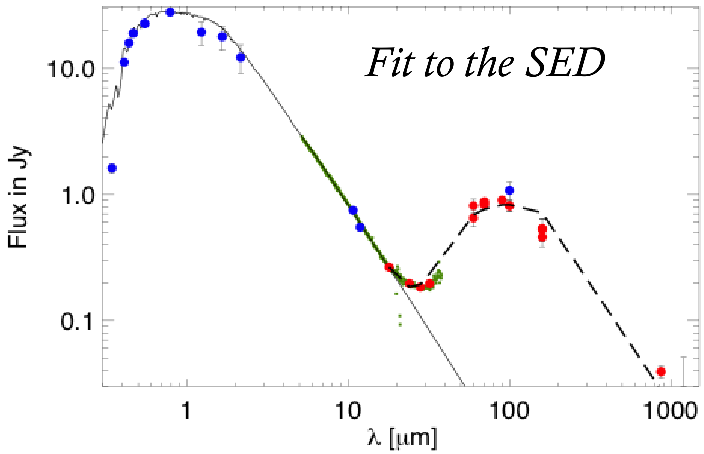
- Detailed simultaneous modeling of the SED and PACS images required to unveil the disk structure, dust properties and dynamical history

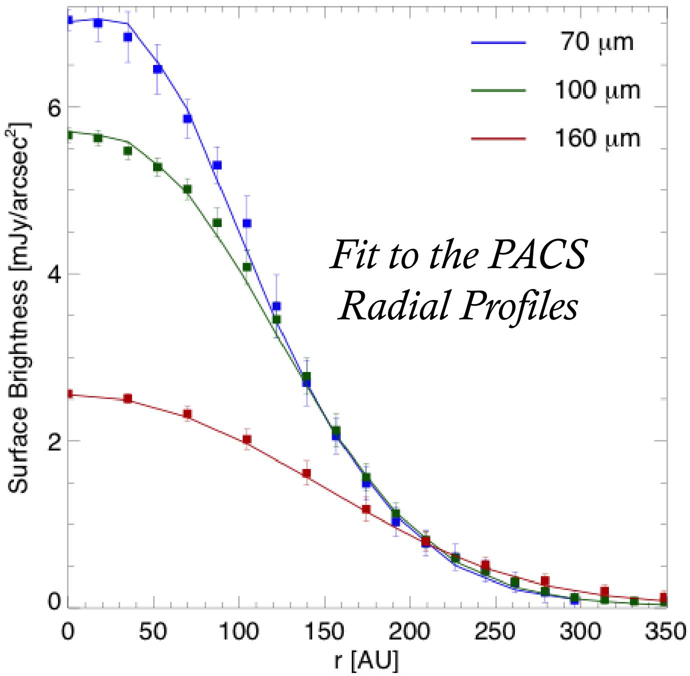
q1 Eri

No initial constraints on outer disk radius

Best fit (χ_r^2 = 1.24):

- Dust disk :
  - Mass : 0.05 M_{Earth}
  - Surface density: **$r^{+0.9}$**
  - Disk extent: 17-210 AU
- Grain properties:
  - 50-50 silicate-ice mixture
  - Minimum grain size ~ 0.7 μm
  - Size distribution: -3.3 power law index





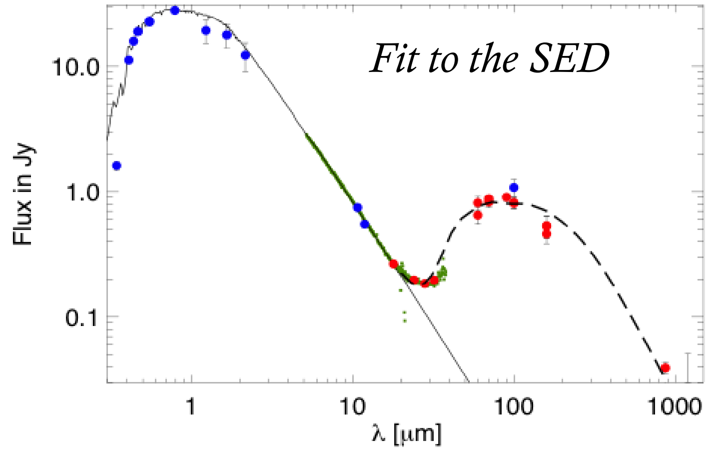
q1 Eri

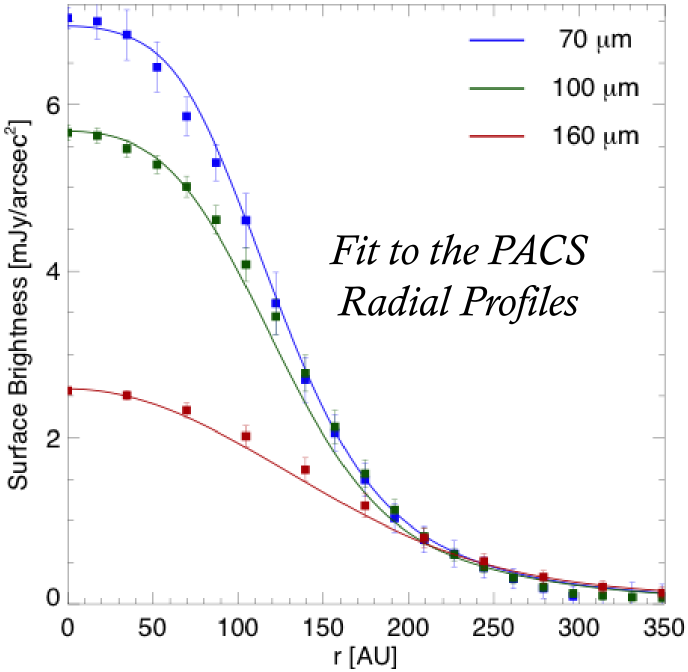
Constraint:

Fixed outer disk radius to large value (600AU)

Best fit (χ_r^2 = 1.4):

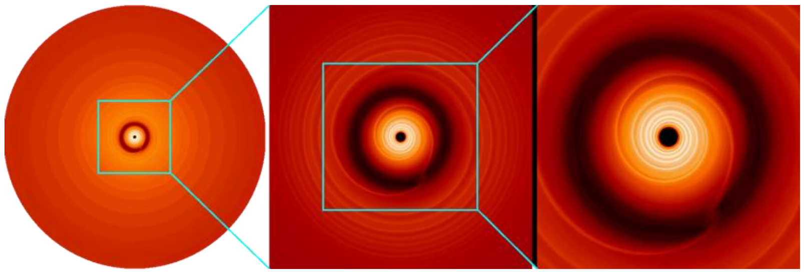
- Dust disk :
  - Mass : 0.055 MEarth
  - Surface density: **r $^{-2}$**
  - Belt peak position: 75-80 AU
- Grain properties:
  - 50-50 silicate-ice mixture
  - Minimum grain size ~ 0.4 μm
  - Size distribution: -3.3 power law index

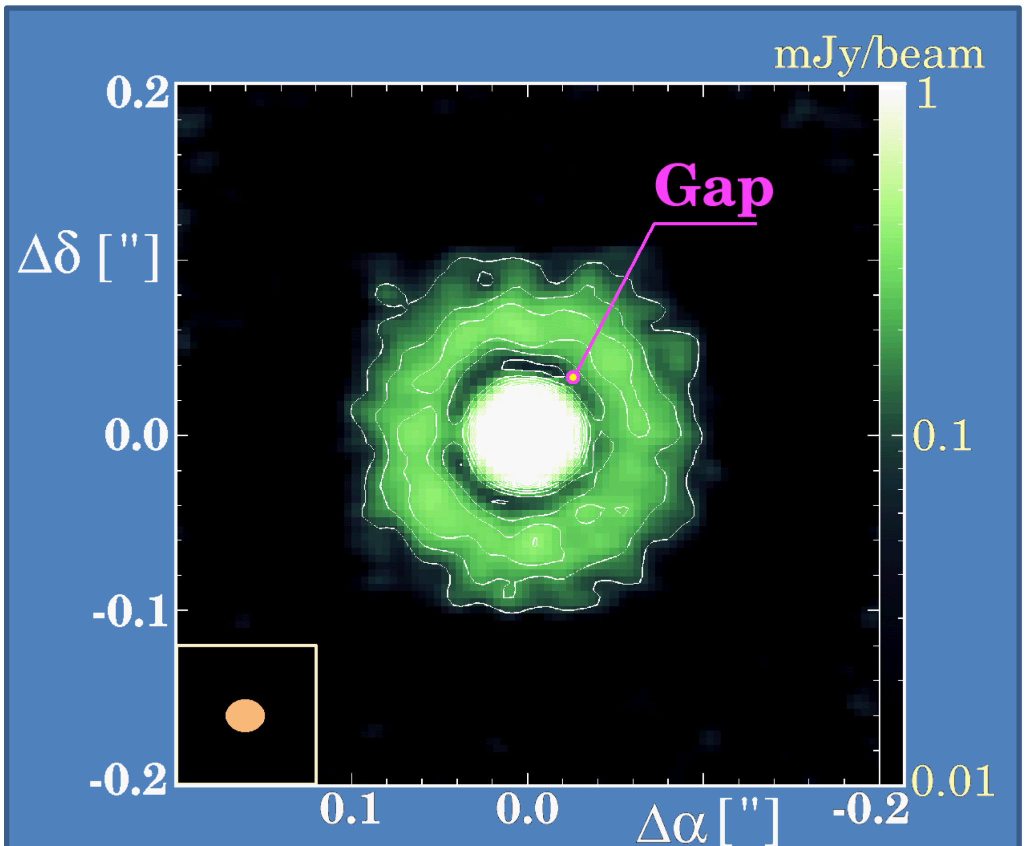




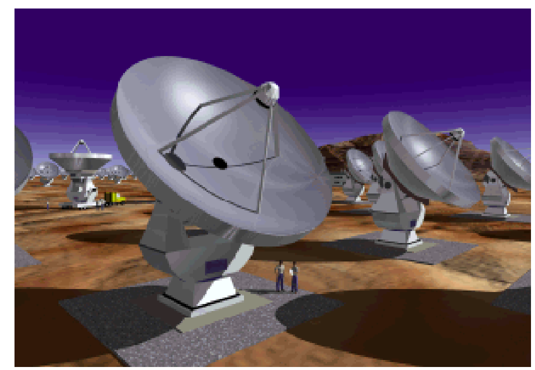
Tracing proto-planets

Tracing gaps with ALMA





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

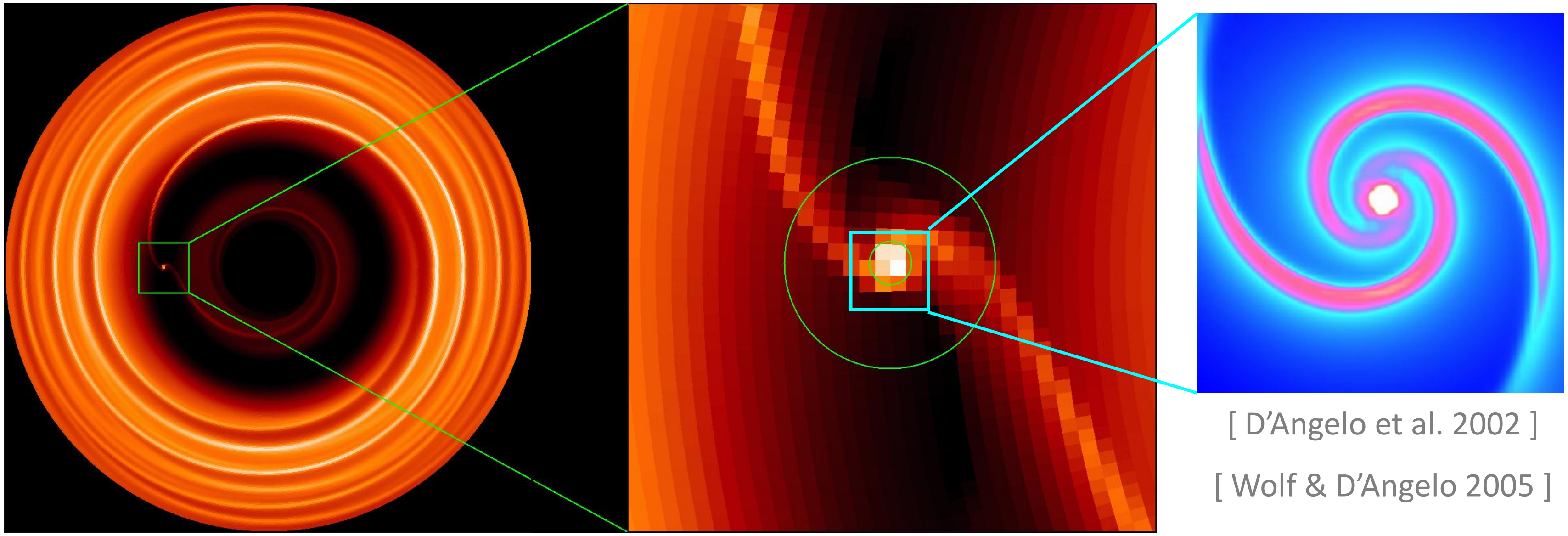


d=140pc

Baseline: 10km

λ=700μm, t_{int}=4h

Local environment of proto-planets

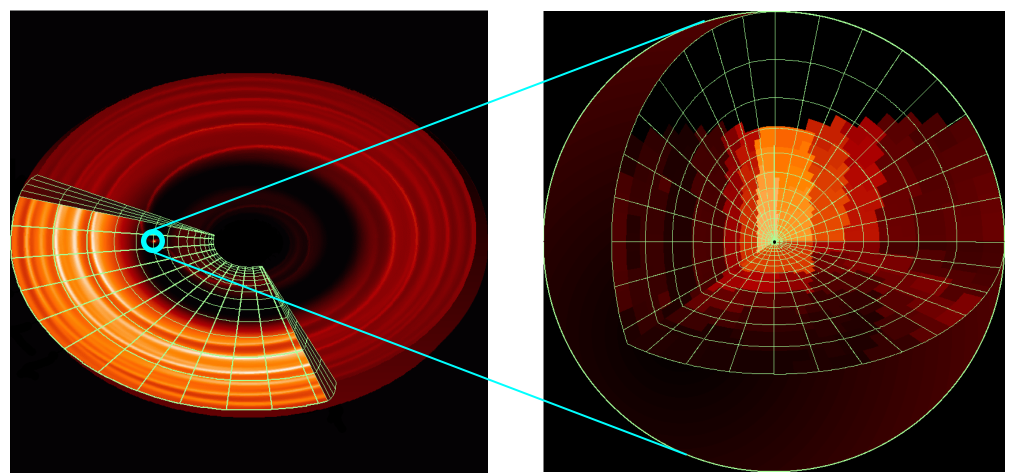


[D'Angelo et al. 2002]

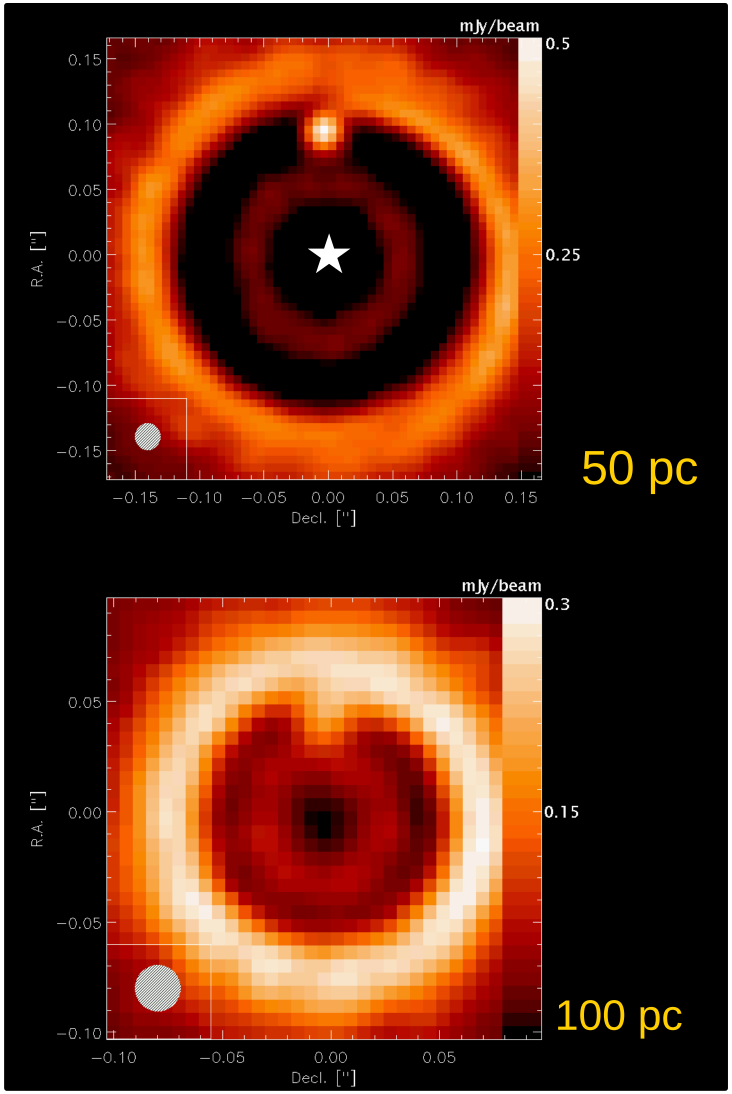
[Wolf & D'Angelo 2005]

Procedure

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



Tracing proto-planets with ALMA



[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 around the Butterfly Star in Taurus
- Observing conditions
  - Maximum baseline: 10km
  - 900GHz
  - Integration time = 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

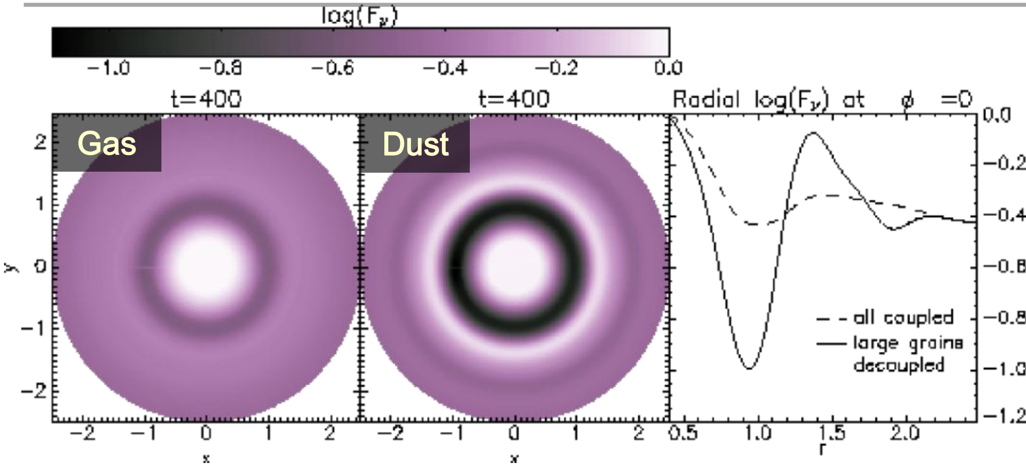
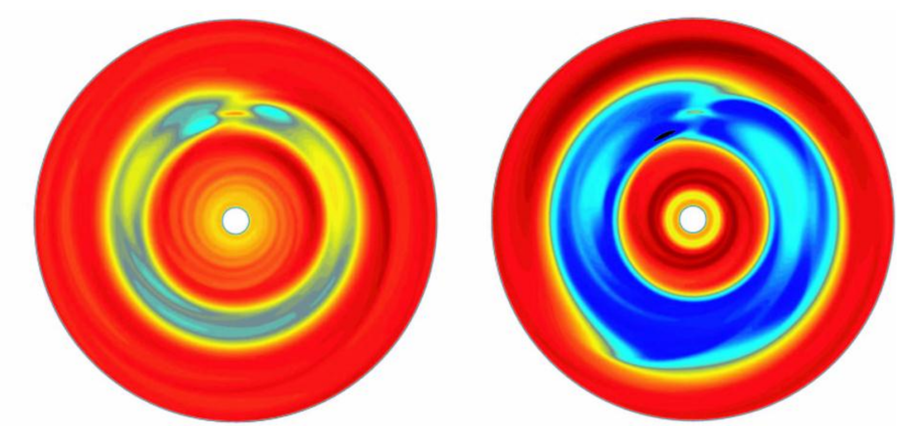


Fig. 3. Logarithm of flux densities at 1 mm, normalized by the maximum and convolved with a Gaussian of FWHM 2.5 AU, corresponding to a resolution of 12 mas at 140 pc. Left panel: all particles follow the gas exactly (static dust evolution). Middle panel: particles larger than the critical size decouple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



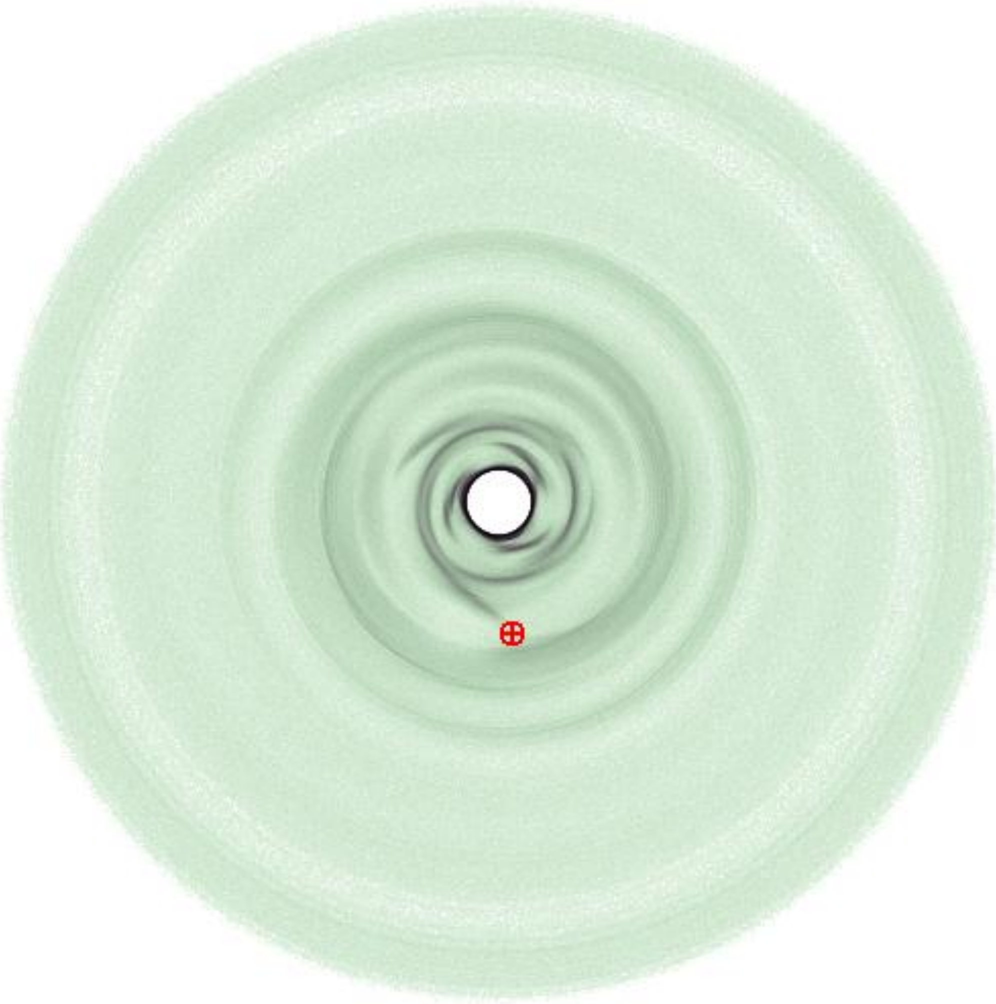
Log Density in MHD simulations after 100 planet orbits for planets with relative masses of $q=1\times10^{-3}$ and 5×10^{-3}

[Winters et al. 2003]

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

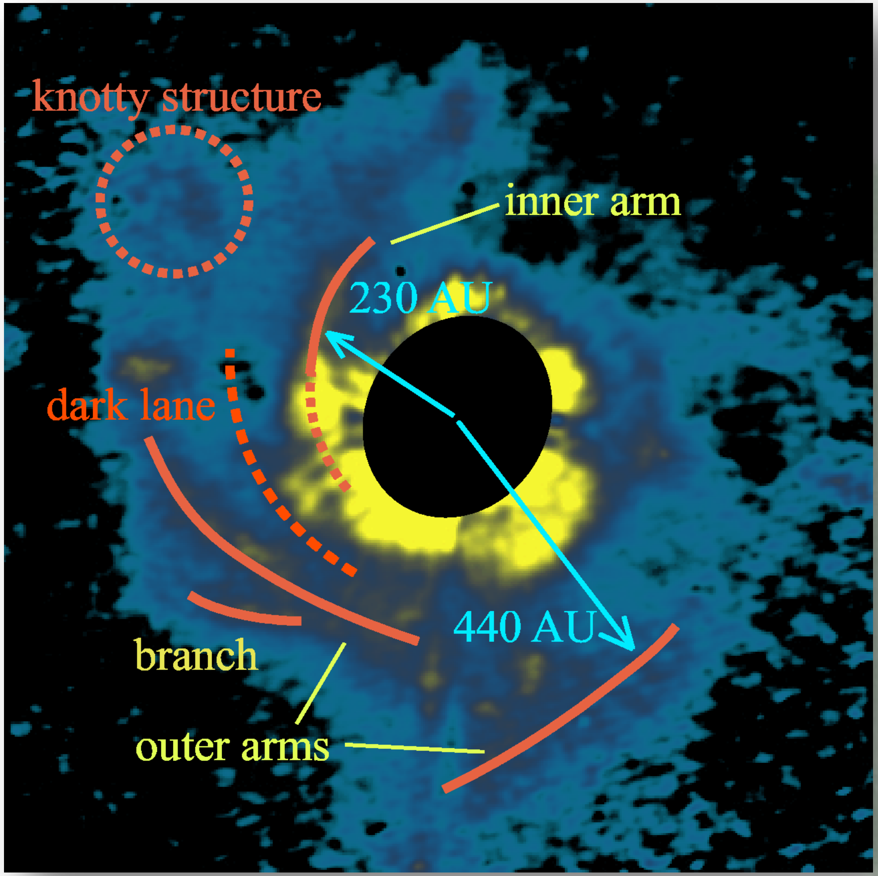
Observations of gaps will allow to constrain the physical conditions in circumstellar disks

Multi-wavelength search for disk structures



K band scattered light image (Jupiter/Sun + Disk)
[Disk radius: 20AU] [Wolf, 2008]

Multi-wavelength search for disk structures



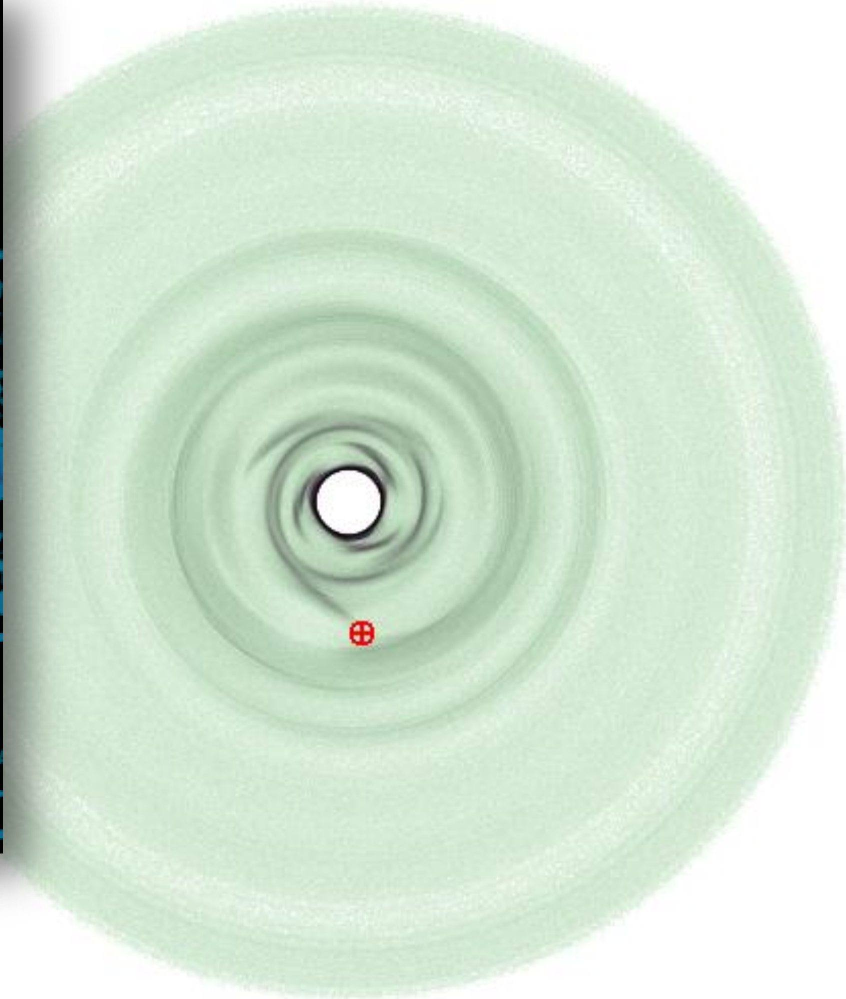
AB Aurigae

Spiral arm structure: H band

(Herbig Ae star; SUBARU)

Distance: ~140 pc

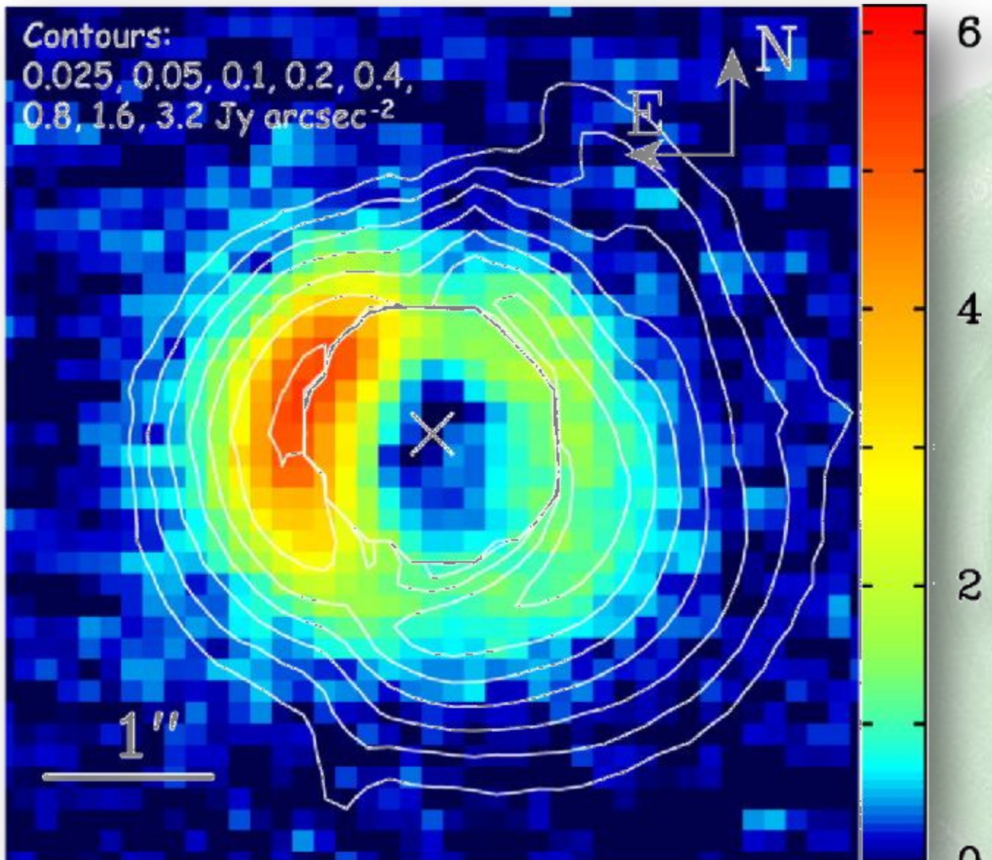
[Fukagawa et al. 2004]



K band scattered light image (Jupiter/Sun + Disk)

[Disk radius: 20AU] [Wolf, 2008]

Multi-wavelength search for disk structures



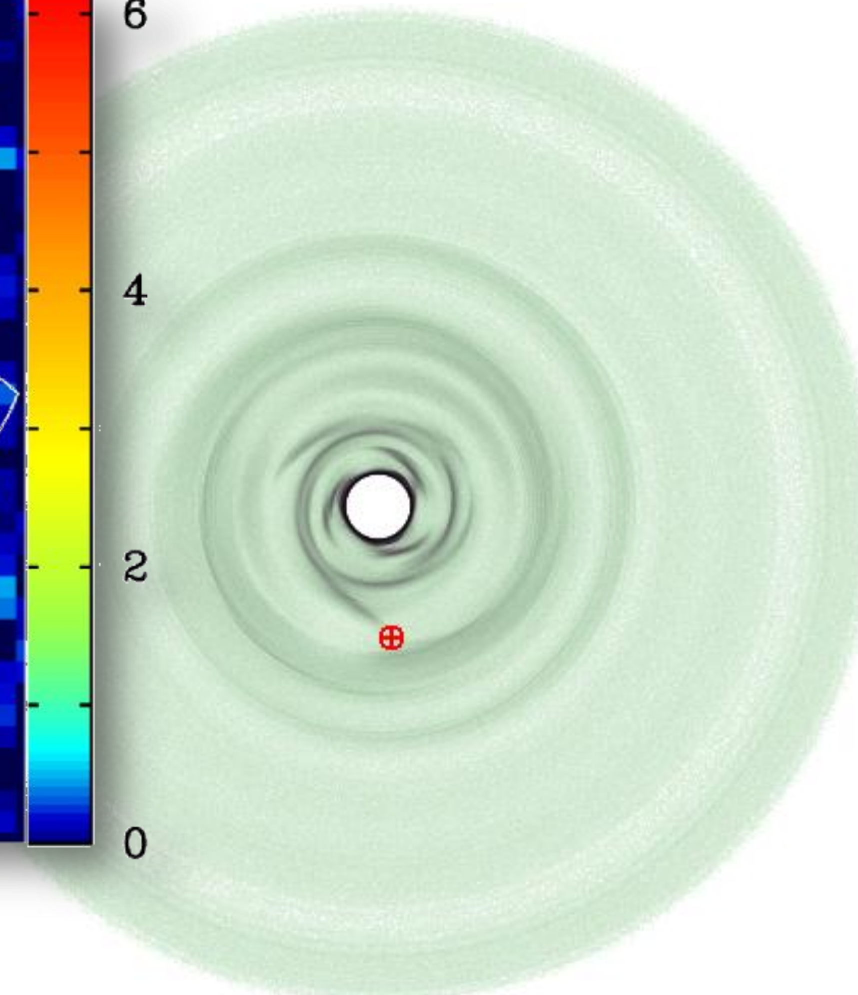
AB Aurigae

Asymmetry (Color: 24.5µm, Contours: H Band)

(Herbig Ae star; SUBARU)

Distance: ~140 pc

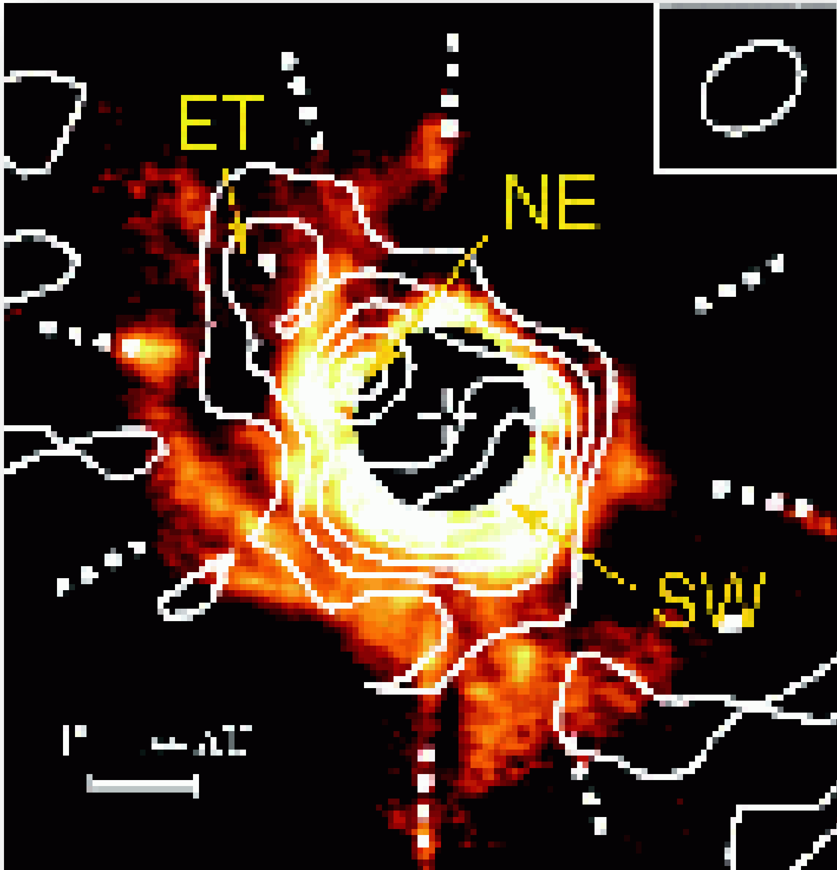
[Fujiwara et al. 2006]



K band scattered light image (Jupiter/Sun + Disk)

[Disk radius: 20AU] [Wolf, 2008]

Multi-wavelength search for disk structures



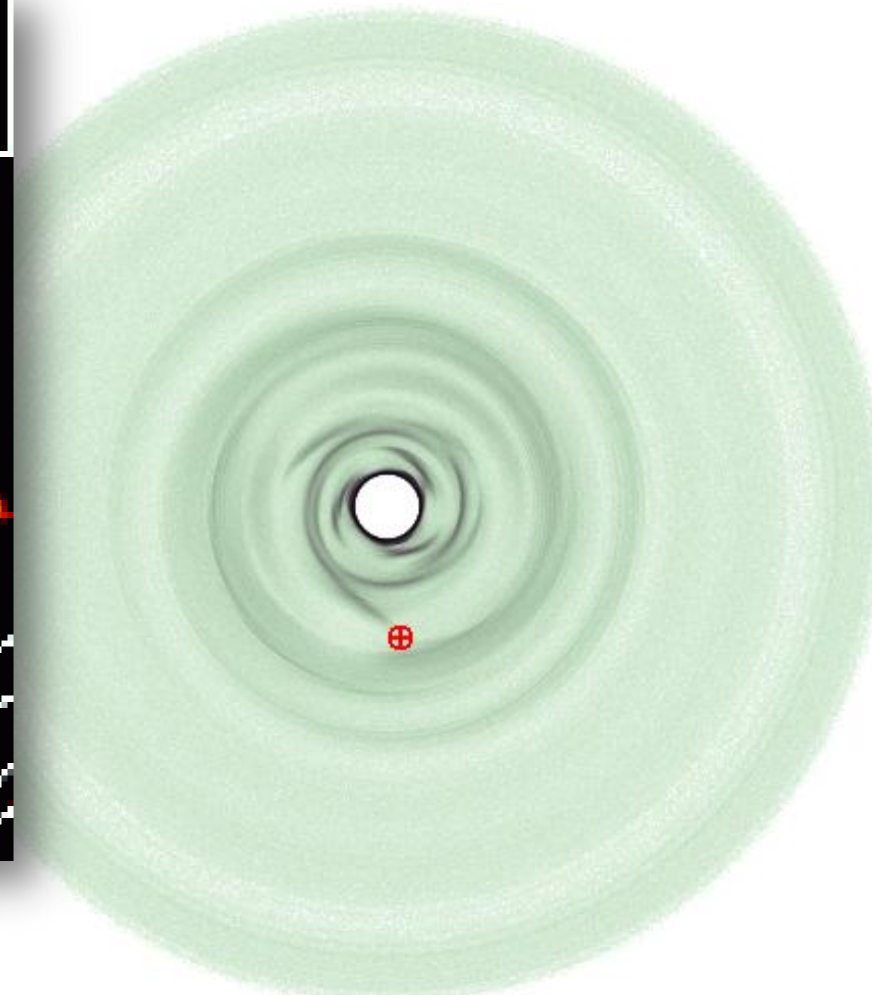
AB Aurigae

Spiral (345 GHz, continuum)

(Herbig Ae star; SMA)

Distance: ~140 pc

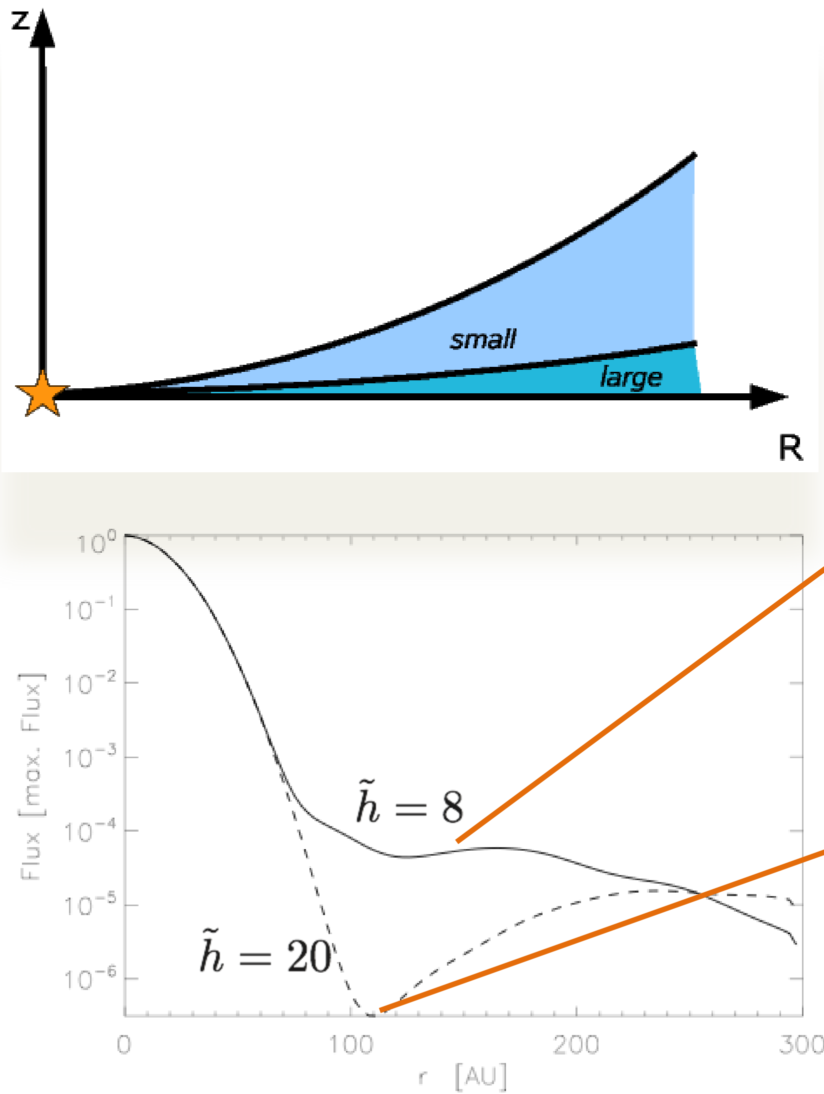
[Lin et al. 2006]

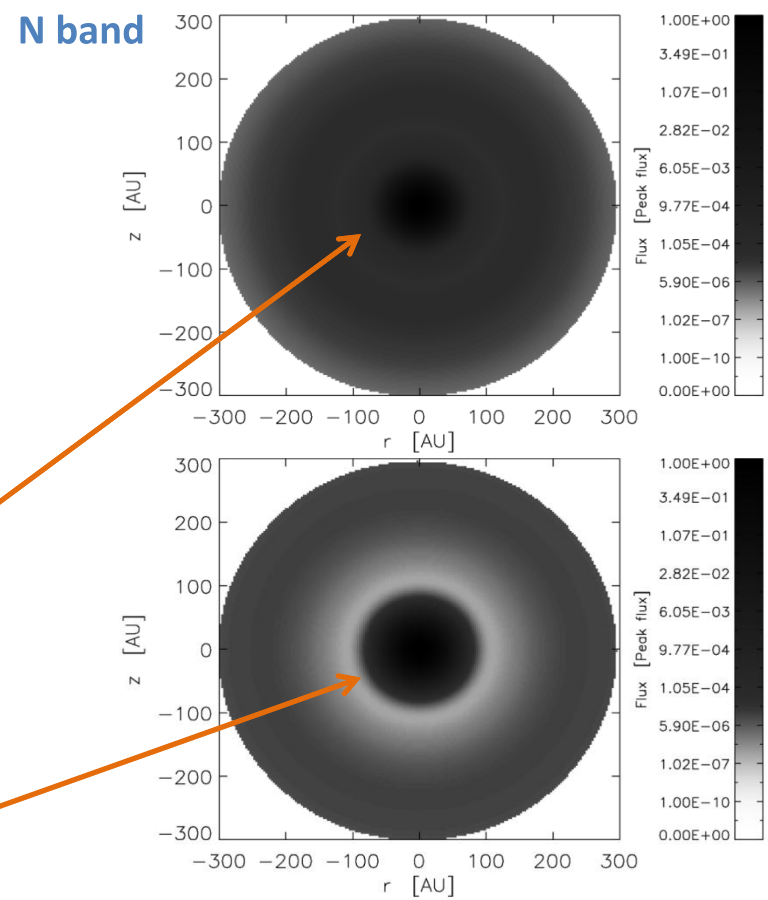


K band scattered light image (Jupiter/Sun + Disk)

[Disk radius: 20AU] [Wolf, 2008]

Gaps: The importance of multi-λ observations

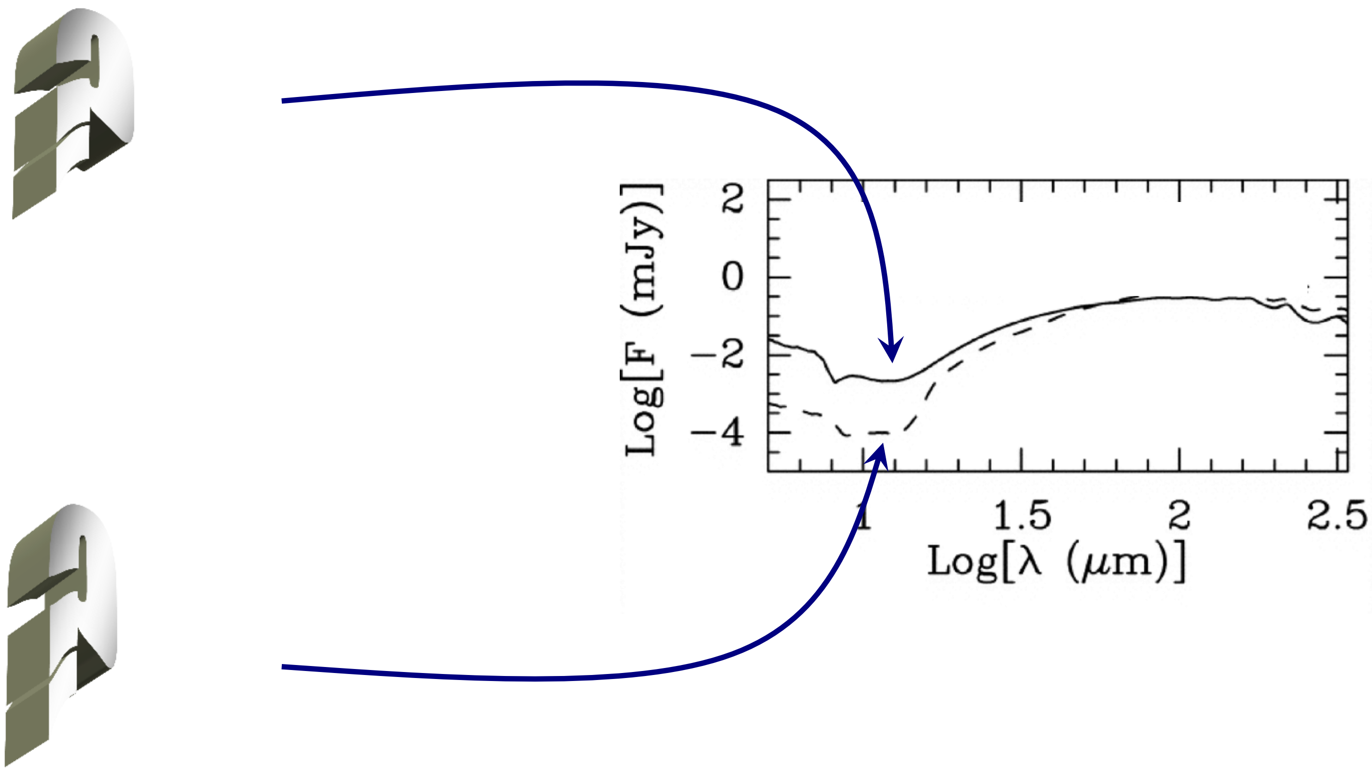




Gaps as indicators for dust sedimentation height

[Sauter & Wolf 2011]

Tracing planets in debris disks: Imaging required

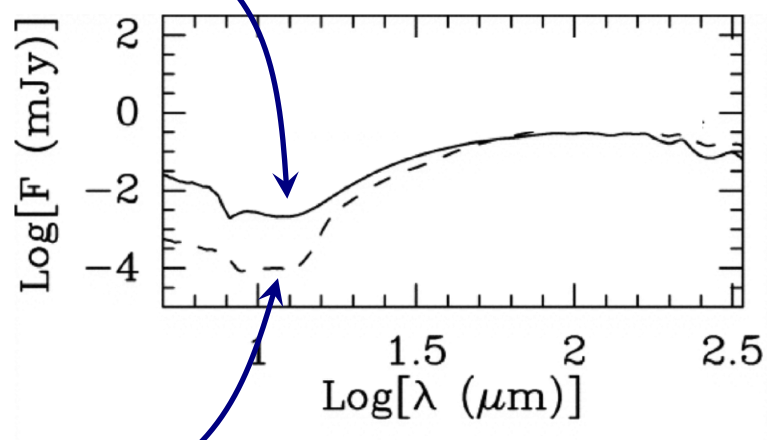


[Moro-Martin, Wolf, & Malhotra 2005]

Tracing planets in debris disks: Imaging required

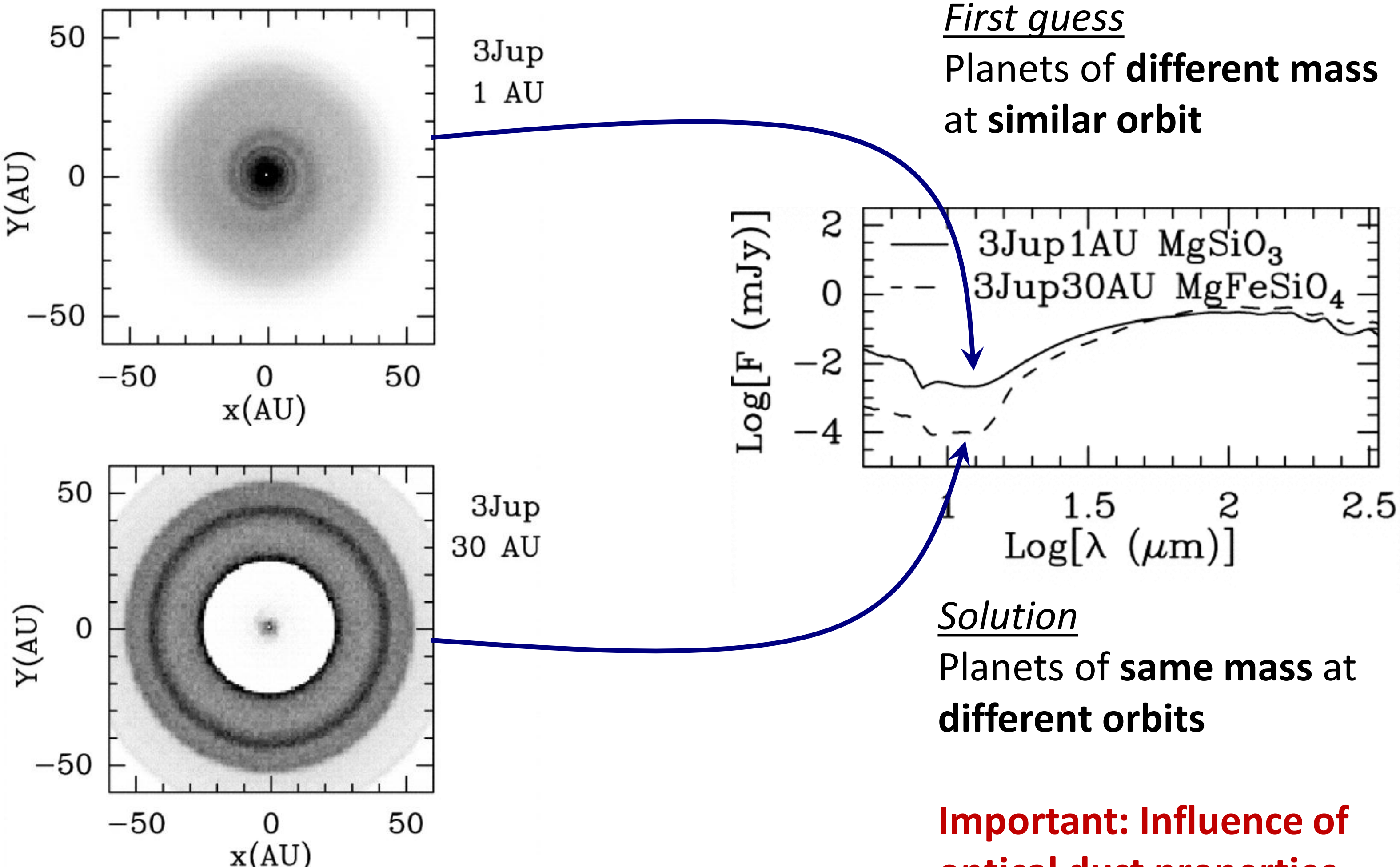
First guess

Planets of **different mass**
at **similar orbit**



[Moro-Martin, Wolf, & Malhotra 2005]

Tracing planets in debris disks: Imaging required



First guess

Planets of **different mass** at **similar orbit**

Solution

Planets of **same mass** at **different orbits**

Important: Influence of optical dust properties

[Moro-Martin, Wolf, & Malhotra 2005]

What comes next?

- Multi-wavelength / Multi-scale intensity measurements
  - Inner (<10AU) disk structure: Test of disk / planet formation evolution models
  - Distribution of gas species
- Polarimetry
  - High-contrast observing techniques
  - Break degeneracies, Magnetic field measurement
- Near-future goal: Planet-disk interaction
  - Usually much larger in size than the planet
  - 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.

What comes next?

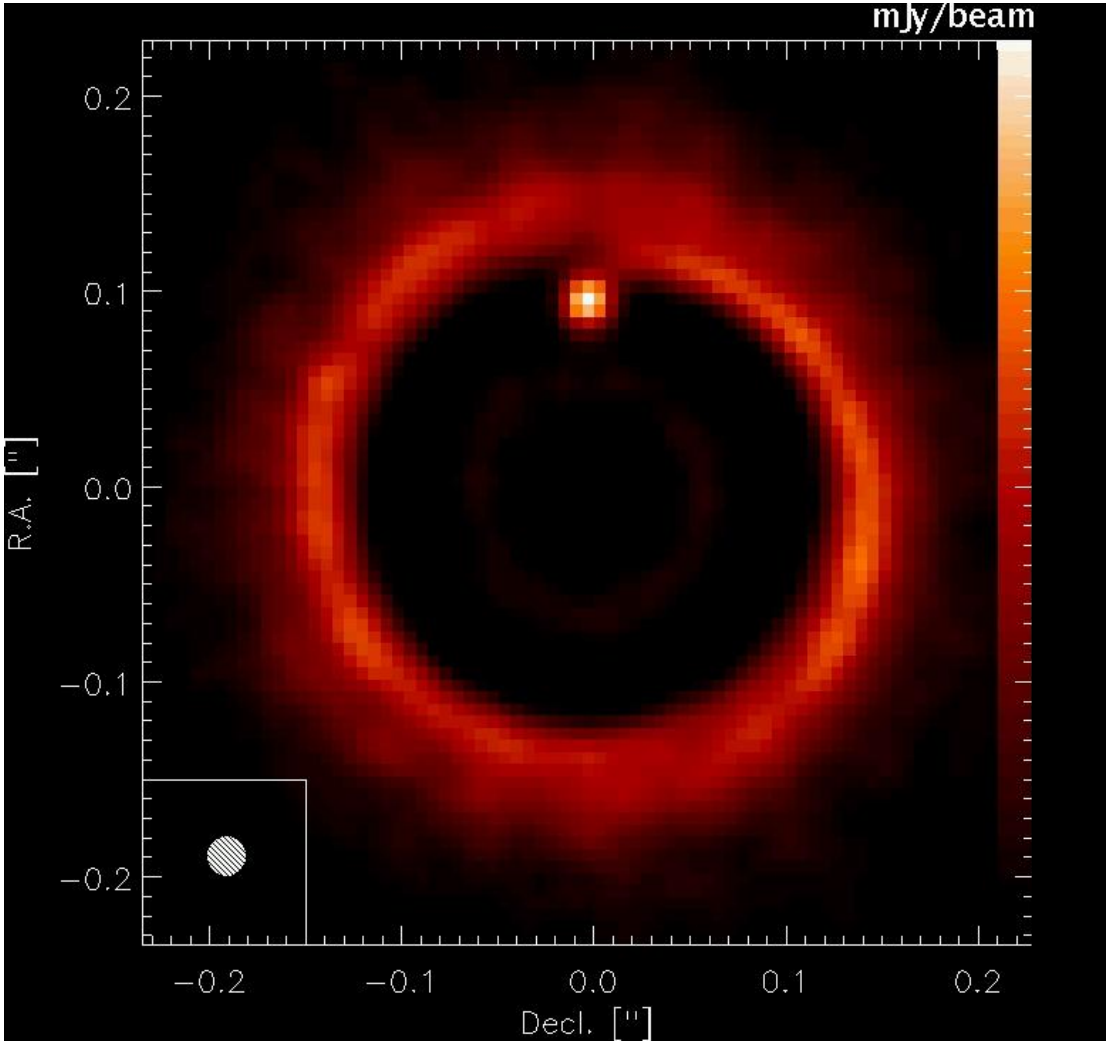
- Self-consistent modeling of dust / gas density & temperature distribution

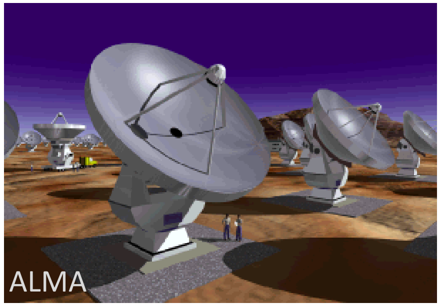
- Dust properties = f(**r**,z)

- Additional, independent observables

  Examples:
  - Polarization: High-angular resolution
  - ALMA: High-angular resolution maps
  - ALMA: Submm-wavelengths
  - ALMA: Gas

And hopefully soon …





Thank you.