High-resolution Observations and Modeling of Circumstellar Disks

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(pre-)Summary

Goal

Conditions for planet formation:

Spatial (radial/vertical) distribution of dust and gas

Physical conditions (e.g., temperature/velocity/magnetic field structure)

More specifically…

Analysis of the global structure of circumstellar disks
at different stages of their evolution

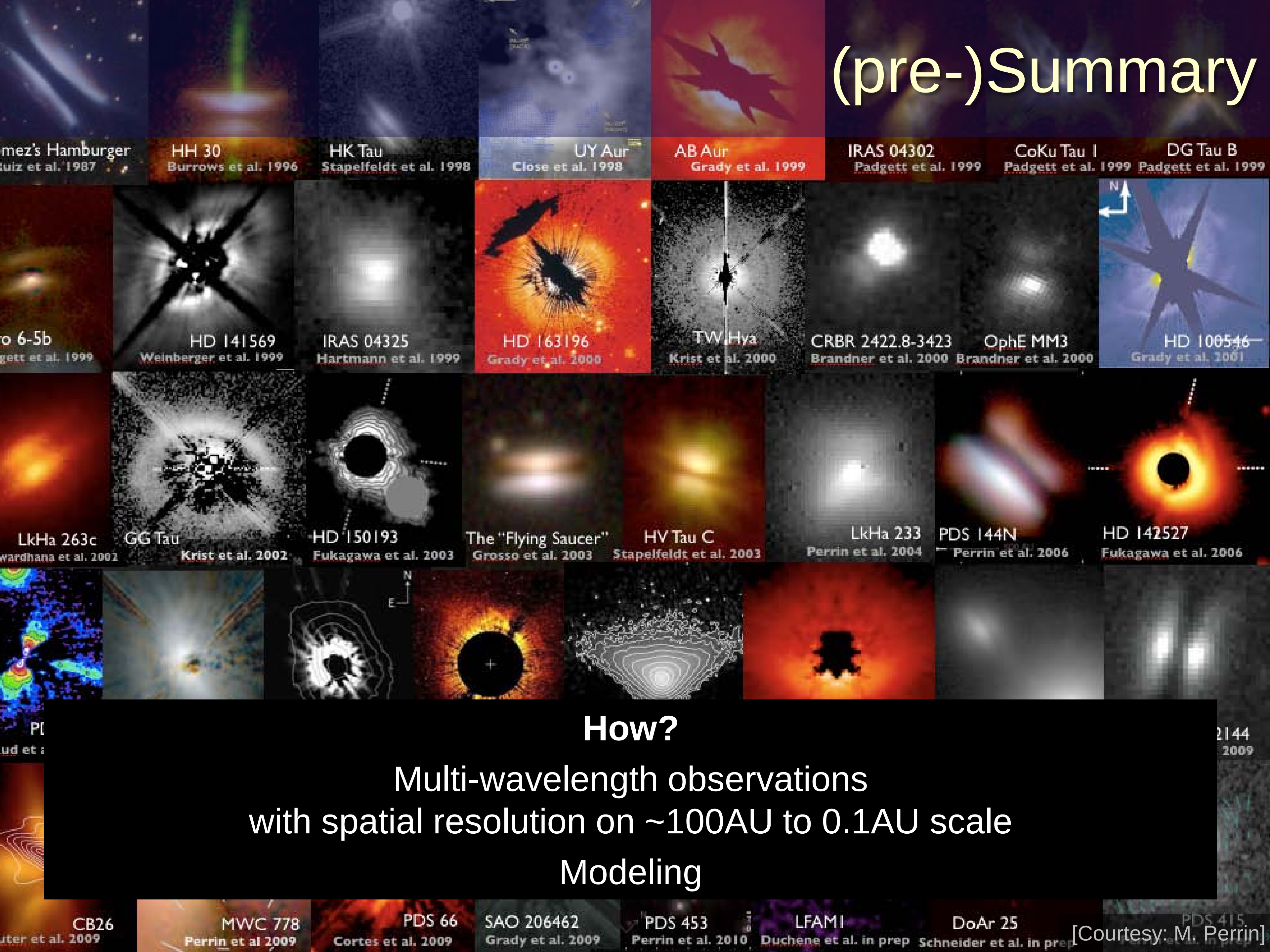
Small-scale structure, e.g. induced by planet-forming processes
or planet-disk interaction (temporal variations)

How?

Multi-wavelength observations
with spatial resolution on ~100AU to 0.1AU scale

Modeling

(pre-)Summary



How?

Multi-wavelength observations
with spatial resolution on ~100AU to 0.1AU scale

Modeling

[Courtesy: M. Perrin]

Overview

Large-scale structures in circumstellar disks @ various wavelengths:
Exemplary case studies

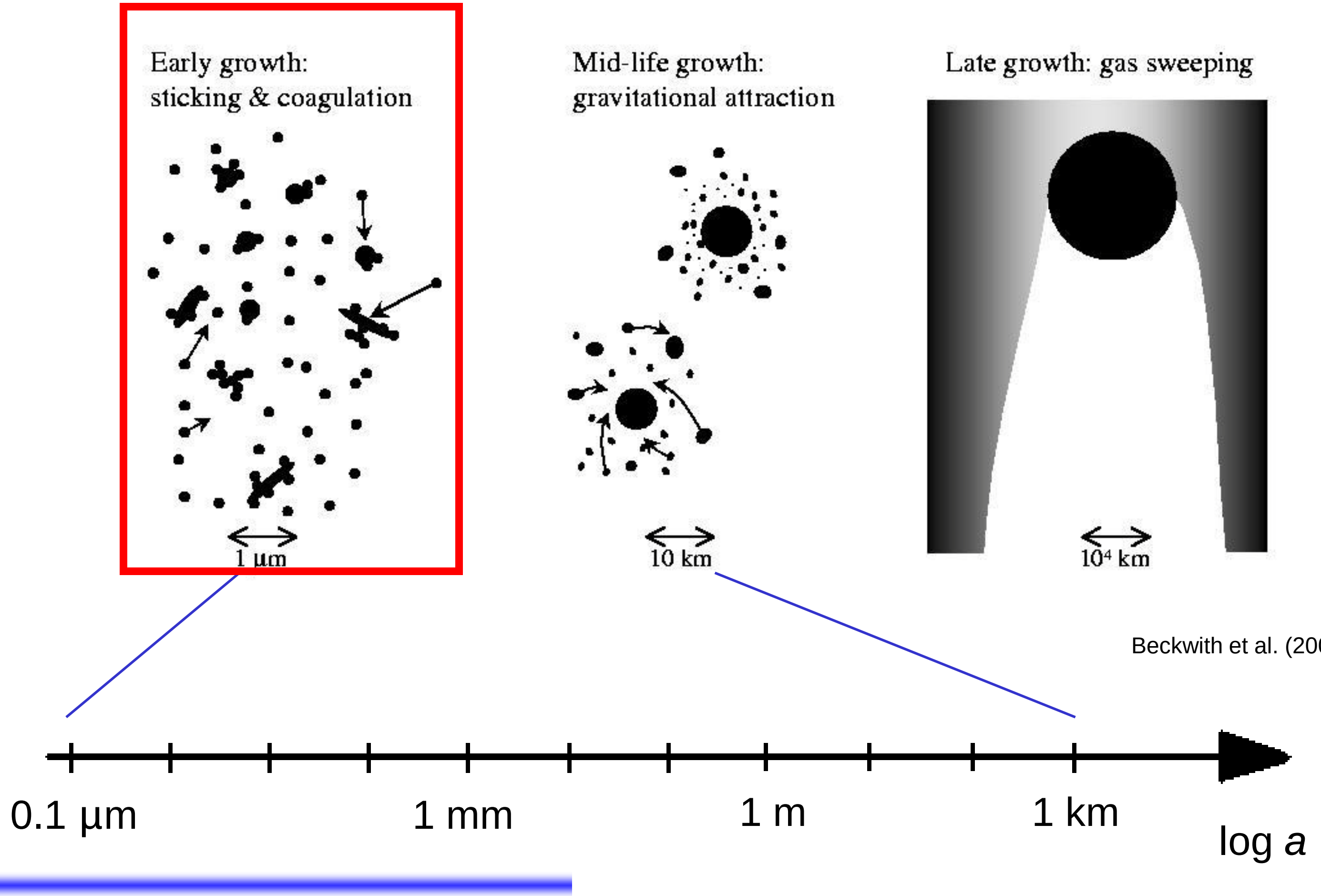
Small-scale structures in circumstellar disks @ various wavelengths:
Future prospects on disk-planet interaction observations

Debris disks

Focus: Dust

Various wavelengths

From dust to planets:
The importance of multi-wavelength observations

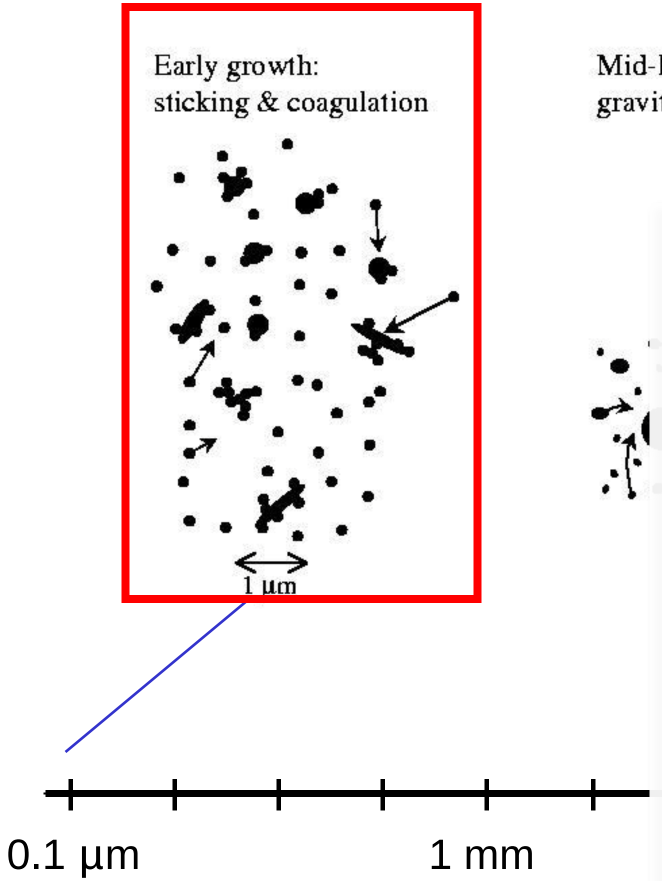


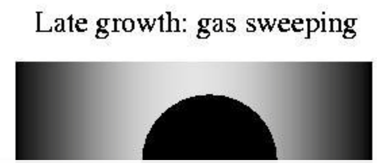
Particle size

≃

Observing wavelength

From dust to planets:
The importance of multi-wavelength observations





- Spectral Energy Distribution (SED)
  (sub)mm slope:

  $$F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$$

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

+ Radiative Transfer Modelling

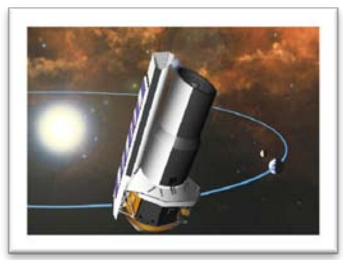
Particle size
≃
Observing wavelength

[First step] Sample the SED

Herschel [2009]

JCMT

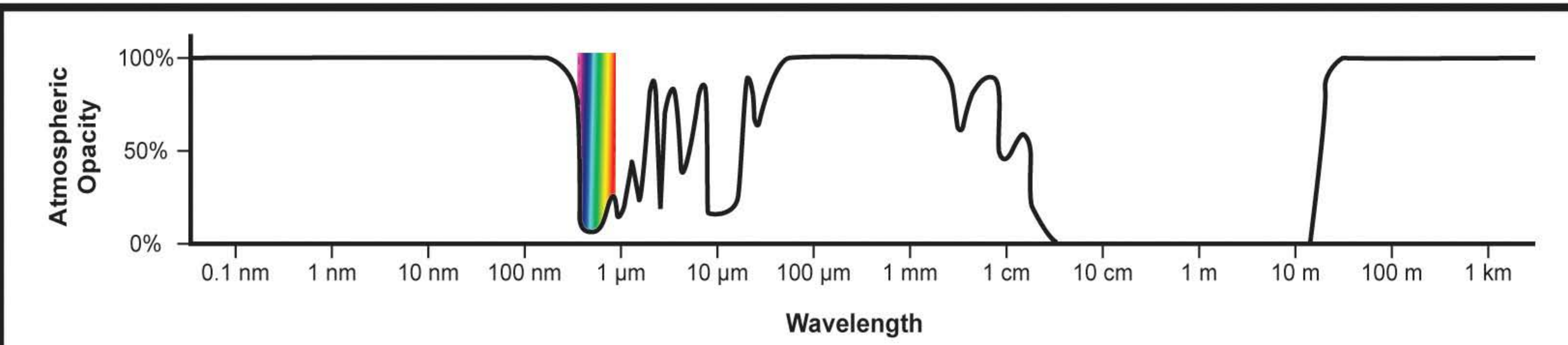
SUBARU



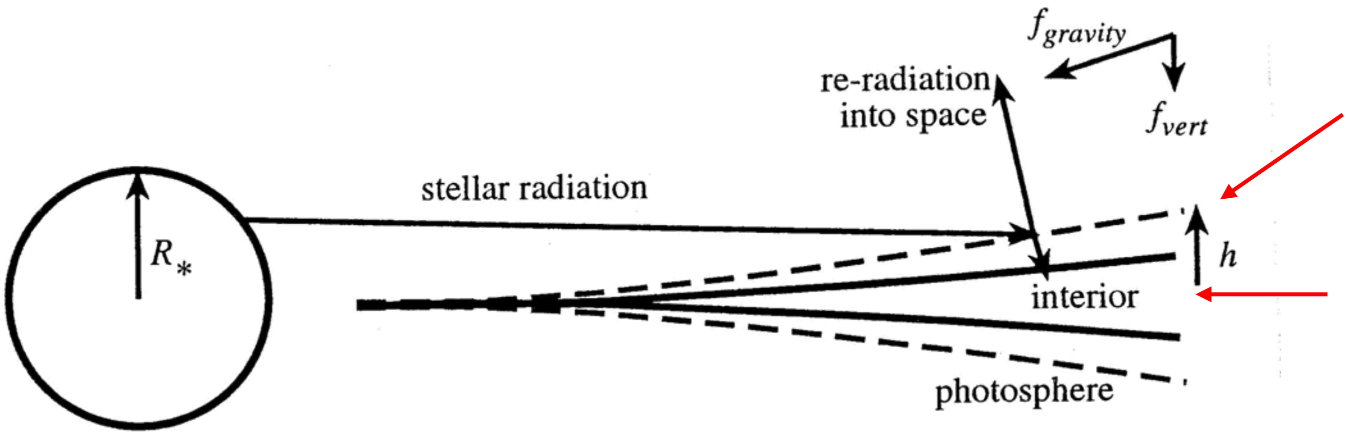
SOFIA
[201?]

Spitzer ST [2003]

APEX



[First step] Sample the SED



Warm Disk”atmosphere”

Cold inner disk region (high optical depth)

Figure 6. The flaring of a disk occurs naturally for a disk in hydrostatic equilibrium. The disk mass is assumed to be negligible; gravity from the star acts to keep the material in a plane. The scale height of the disk increases with radius, because the thermal energy decreases more slowly than the vertical gravitational energy as radius increases. The vertical gravitational force, f_{vert}, is shown as a component of the stellar gravitational force, $f_{gravity}$. The ray from the star shows the point at which short wavelength stellar radiation from the star is absorbed in the disk photosphere. The two other rays from this point show how the energy is reradiated into space and into the interior of the disk, thus heating the interior from the above.

[Beckwith, 2000]

Flaring => Star can illuminate / heat disk more efficiently

[First step] Sample the SED

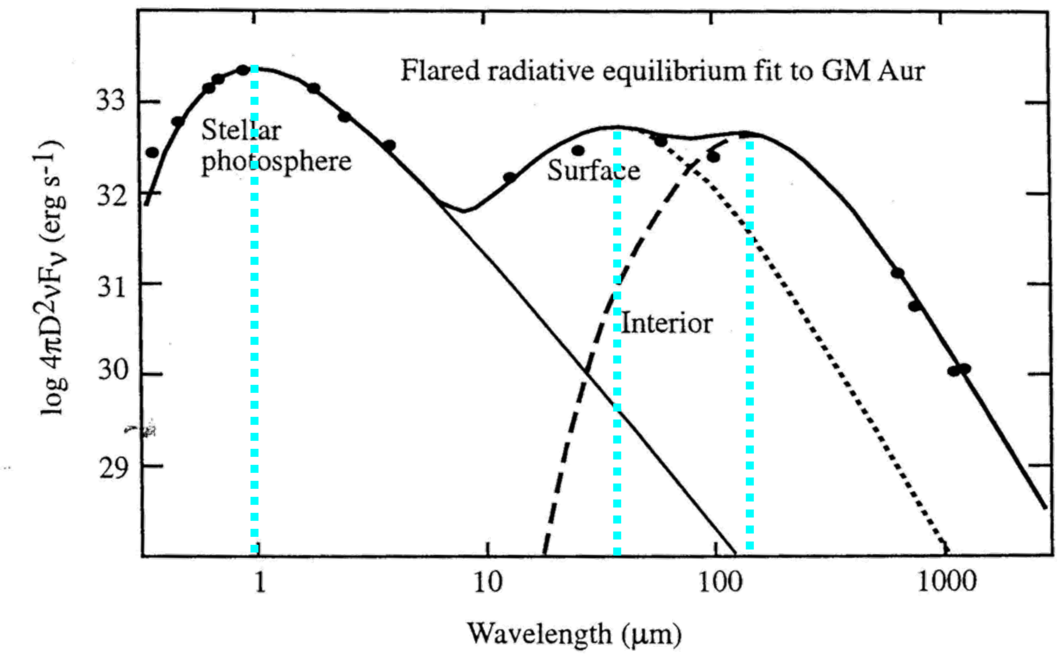
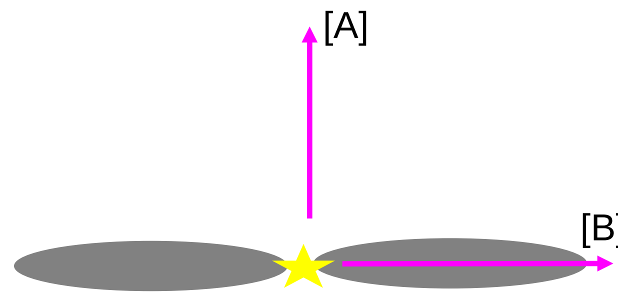
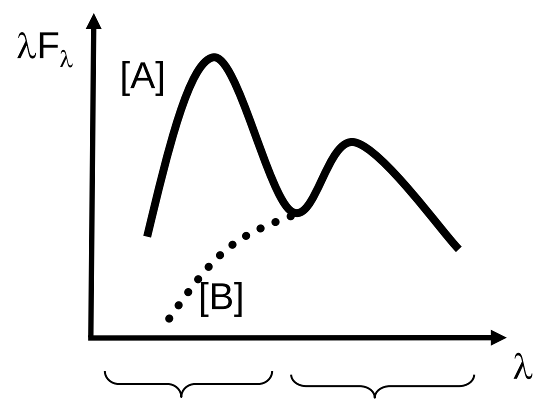


Figure 7. Figure 8 from Chiang and Goldreich (1997) showing how a flared disk with a photosphere reproduces one SED that differs substantially from a flat, black disk. They need a hole in the inner disk to account for the lack of disk emission short ward of about 5 μm.

3 component SED

Inclination dependence:





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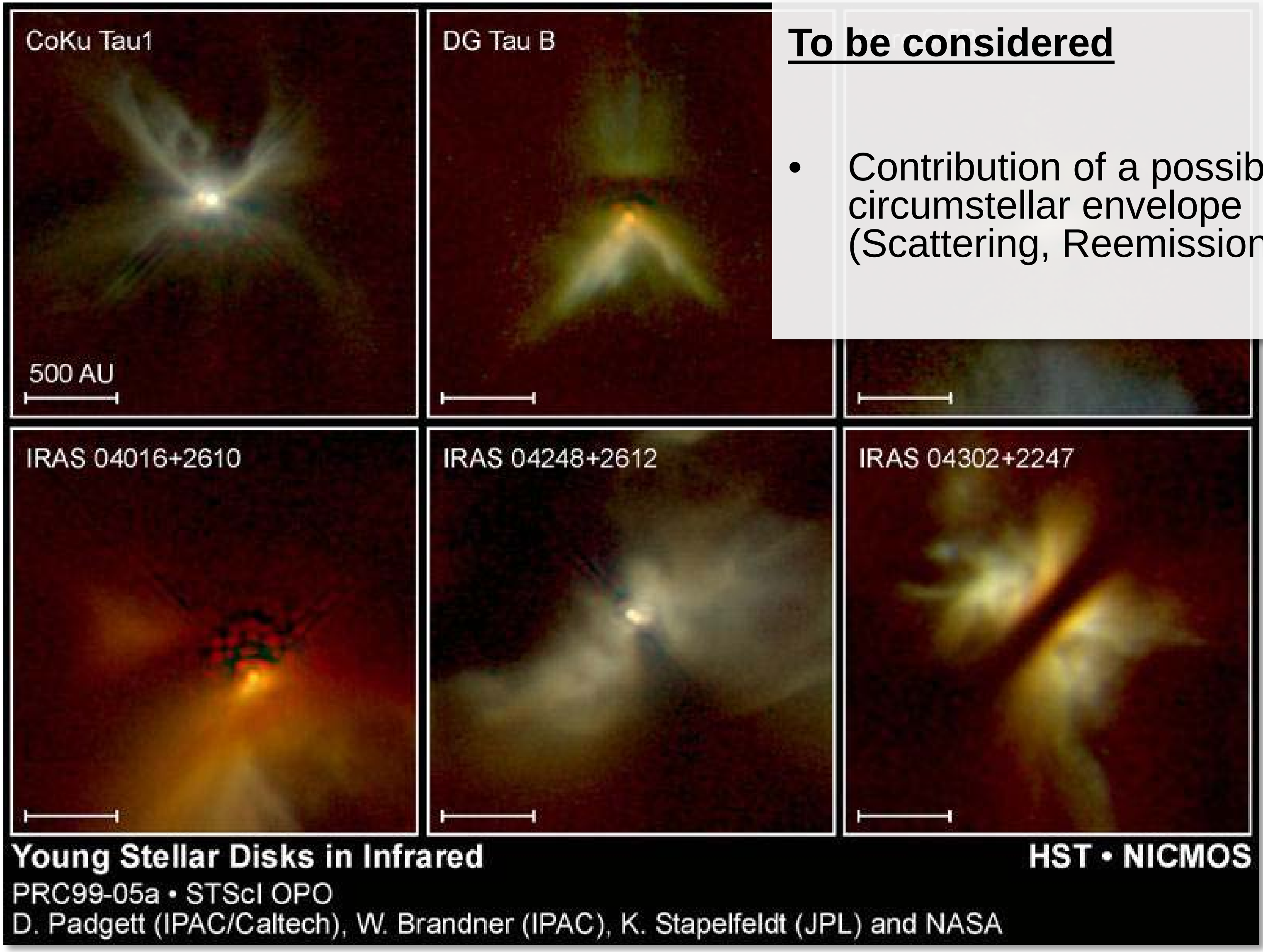
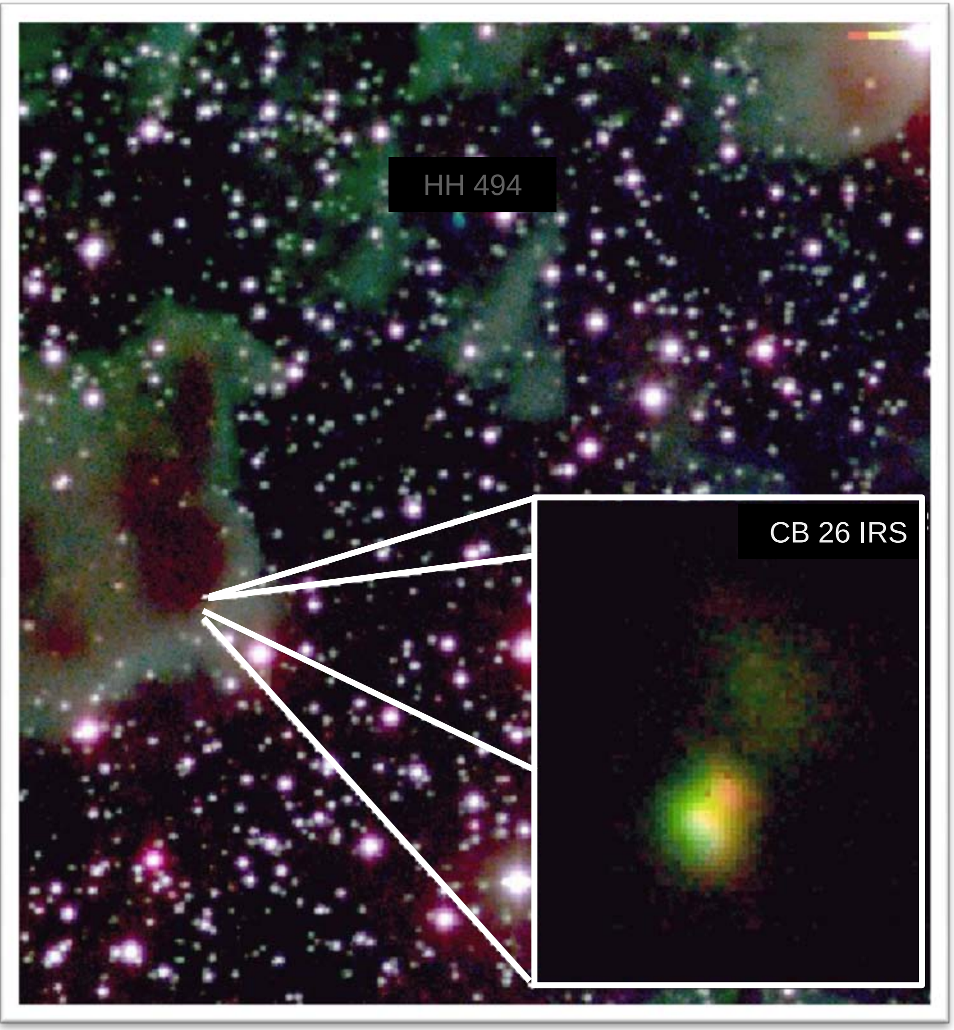


To be considered

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

[First step] Sample the SED



[courtesy of R. Launhardt]

To be considered

- Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)
- Significant foreground extinction (wavelength-dependent!);

  Interstellar Polarization

[First step] Sample the SED

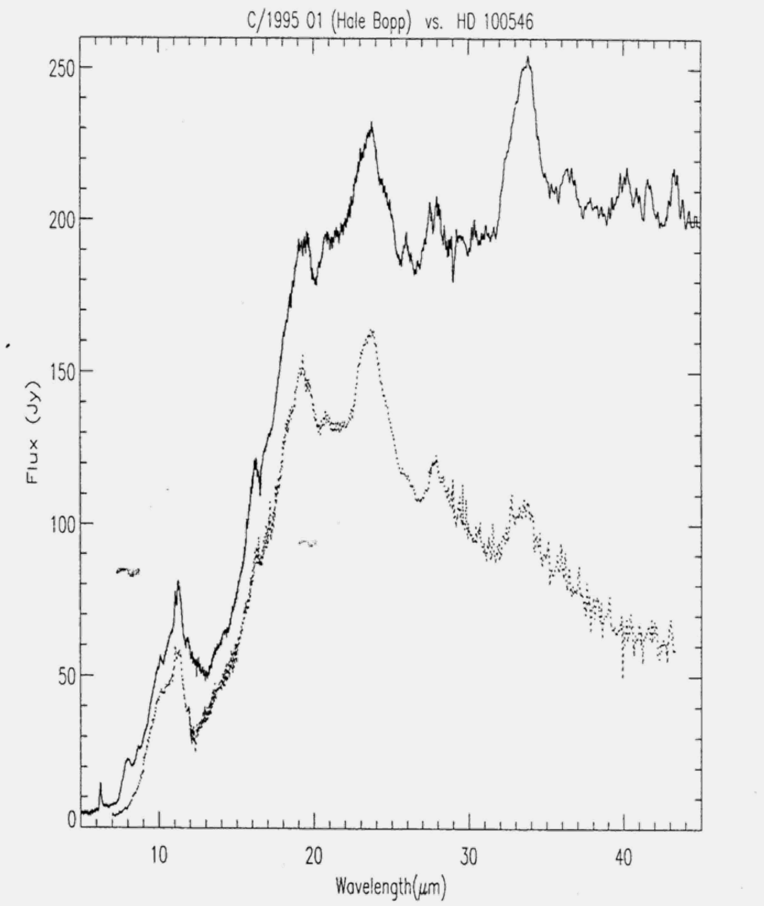


Figure 9. This is Figure 5 from Malfait et al. (1998) showing the detection of emission features in the disk around the Herbig Ae/Be star, HD 100546, (solid line at top) as predicted if the disk is heated by radiation from the central source. It is compared with the spectrum of comet Hale-Bopp (dotted line underneath). Notice the close correspondence between emission features in the comet and in the disk spectrum, indicating that the particles in the disk are made from similar material as particles in the early solar system that made up the comet.

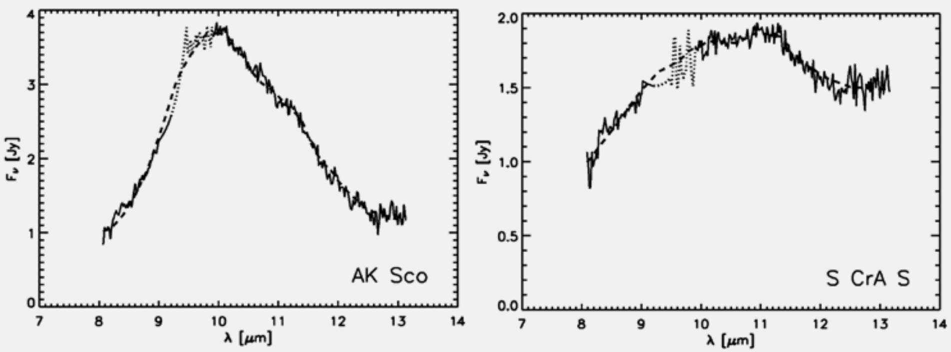
To be considered

- Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)
- Significant foreground extinction (wavelength-dependent!);

  Interstellar Polarization
- Dust characteristics (constraints from emission/absorption features)

[First step] Sample the SED

Analysis of individual features



8-13micron spectra of 27 <u>T Tauri stars</u>

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]

Prominent Example: ~10μm Silicate Feature

Size + Shape, Chemical Composition

Crystallization degree of Silicate grains

$\Rightarrow$ **Grain Evolution**

$\Rightarrow$ **Physical Conditions**

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[First step] Sample the SED

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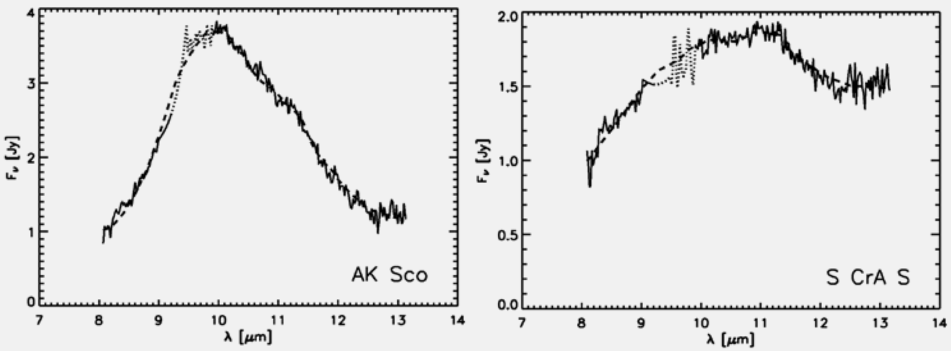

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⇒ **Physical Conditions**

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- Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)
- Significant foreground extinction (wavelength-dependent!);

  Interstellar Polarization
- Dust characteristics (constraints from emission/absorption features)
- Characteristics of the illuminating / heating sources:
  - Spectrum of stellar photosphere
  - Accretion
  - Single star vs. binary

    Taurus-Auriga Star forming region: 80-100% (Ghez et al. 1993, Leinert et al. 1993, Reipurth & Zinnecker 1993)

[First step] Sample the SED

Conclusion (I)

Proper analysis of multi-wavelength observations require

Radiative Transfer Simulations:

Detailed numerical modeling taking into account
absorption / heating / reemission + scattering processes

Approaches:

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

Conclusion (II)

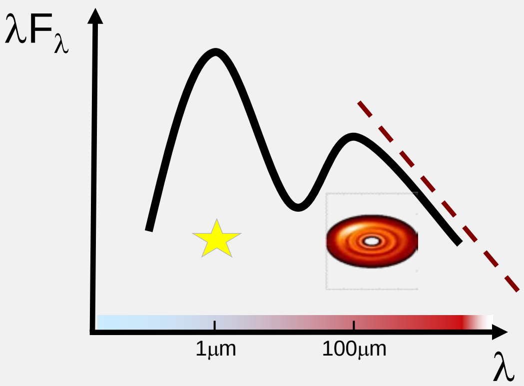
SEDs can be well reproduced, but not unambiguously

Example (a):

Young, gas-rich ("protoplanetary") disks

Disk (dust) mass and
Grain growth derived form the (sub)mm slope of the Spectral Energy Distribution $F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$

underlying assumption: optically thin disk



Thamm et al. 1994, A&A 287, 493,
"Ambiguities of parameterized dust disk models for young stellar objects"

Goal: Finding the best fit for the SED of FU Ori, DN Tau;
(8 free parameters, Metropolis algorithm)

Result: "… In all cases we find a global ambiguity in acceptable fits."

[First step] Sample the SED

Conclusion (II)

SEDs can be well reproduced, but not unambiguously

Example (b):

Debris disks

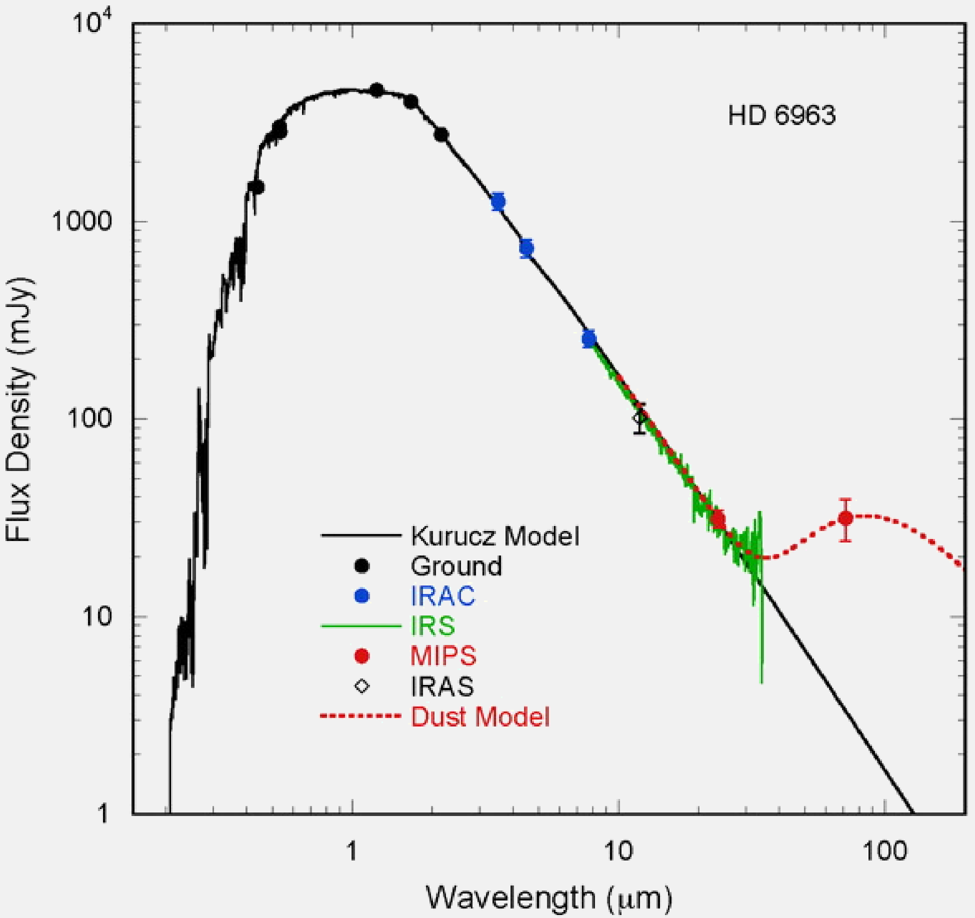
(1) Optically thin => SED = f (T(R), $Q_{abs, sca}$)

⇒ Azimuthal structure (e.g., patterns indicating embedded planets) can *not* be derived

(2) Many of the debris disks which were observed with the Spitzer Space Observatory show no or only very weak emission in the range < 20…30μm

⇒ Often only weak constraints for the chemical composition of dust can be derived

(3) Unambiguous dust/geometrical parameters difficult to derive
(e.g., Wolf & Hillenbrand 2003)



[Kim, et al. 2005]

<u>Conclusion (II)</u>

SEDs can be well reproduced, but not unambiguously

=> Information about the spatial brightness distribution required

Techniques: Direct Imaging, Interferometry

Goals:

- Constraints for spatial structure of disks
  (e.g., inner / outer radius, radial scale height distribution)
- Constraint for spatial distribution of
  - Dust parameters (composition, size)
  - Gas phase composition (+ excitation conditions)

Requirement

(typical) Disk diameter: ~ a few hundred AU,

Distance of nearby star-forming region (e.g., in Taurus): 140pc

=> typical angular diameter: ~ a few arcseconds

with $d \approx 1{,}22 \frac{\lambda}{D}$

$\Rightarrow$ *optical / near-IR imaging:*

- *Ground-based large aperture AO telecopes*
- *HST*

$\Rightarrow$ *(sub)mm mapping:*

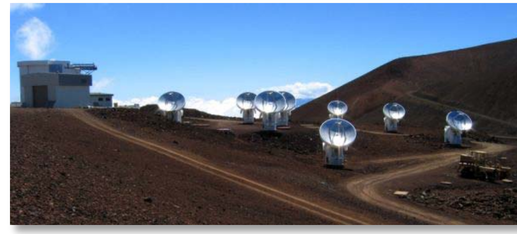
- *Interferometry*

Various wavelengths

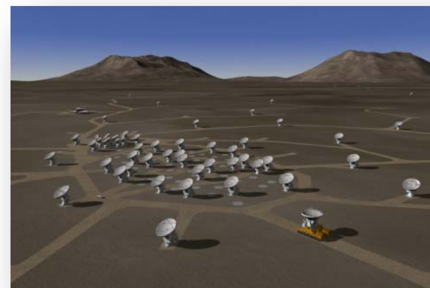
Spatial structures at various scales and wavelengths

Interferometry

VLTI



SMA

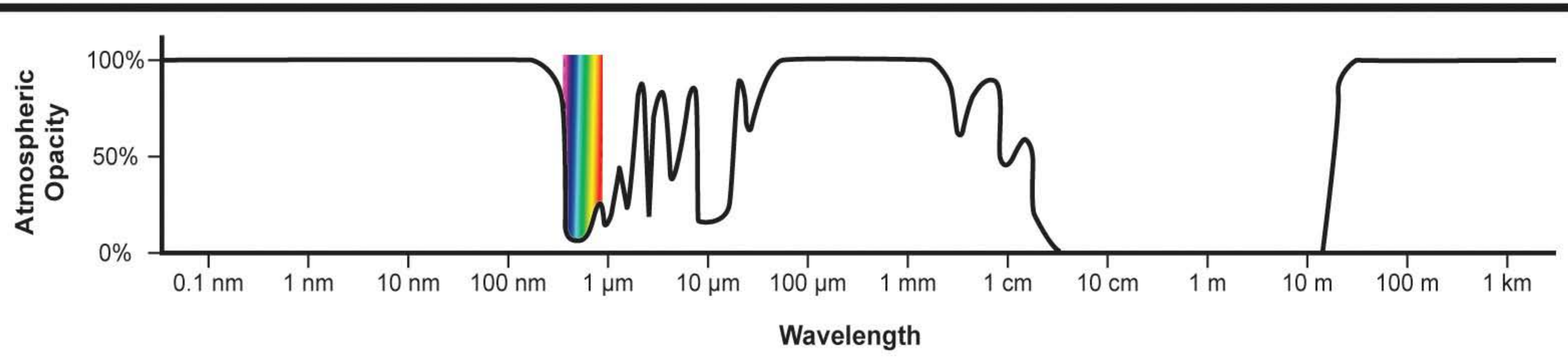


ALMA [2011]

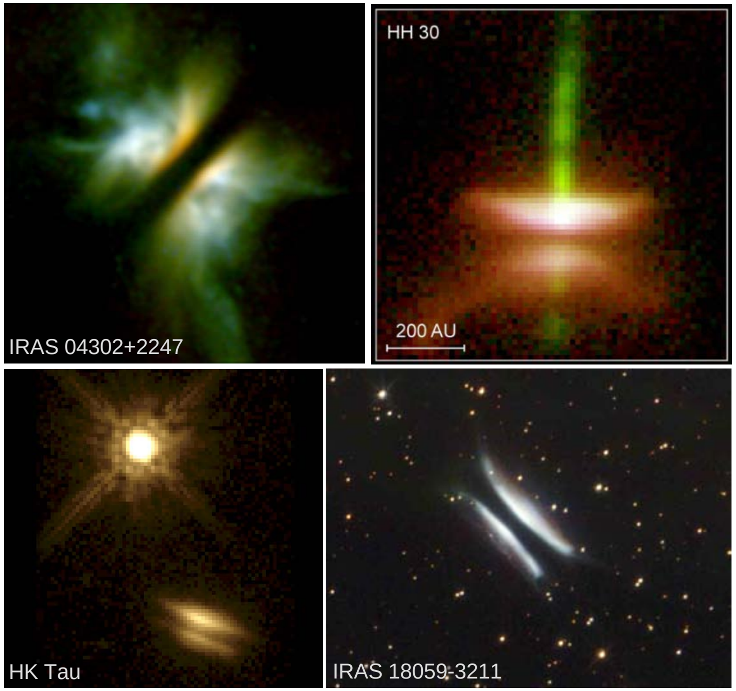
IRAM

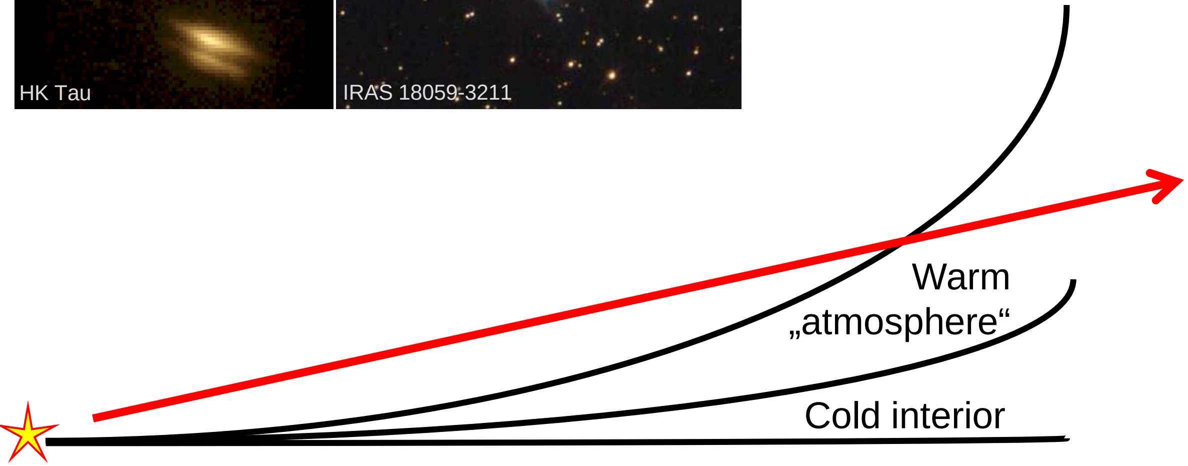
Keck Interferometer

VLA



Various wavelengths – Various disk regions





Edge-on disks

Optical / IR

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

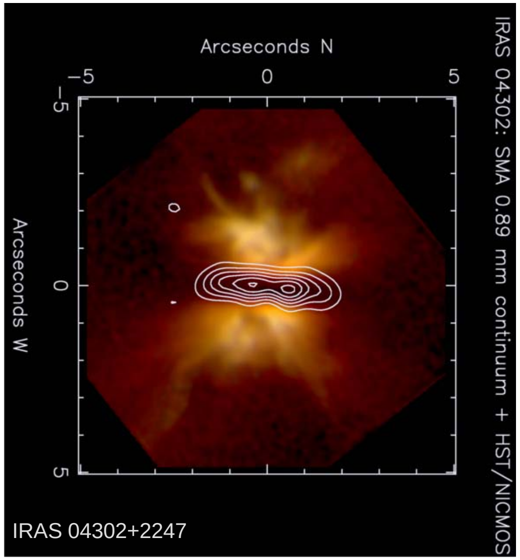
⇒ *Vertical opacity structure*

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

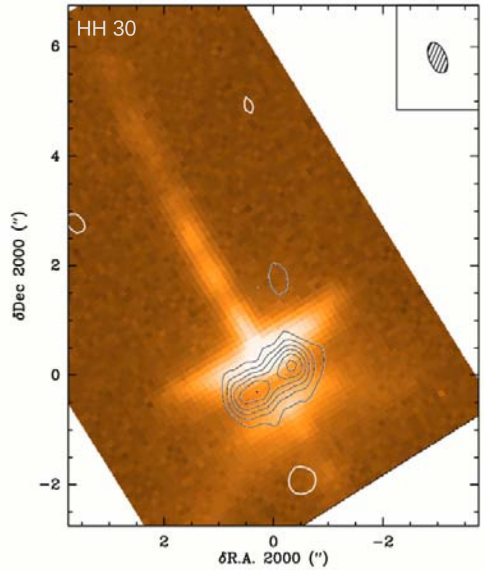
Approximate (dust) disk size

Disk flaring

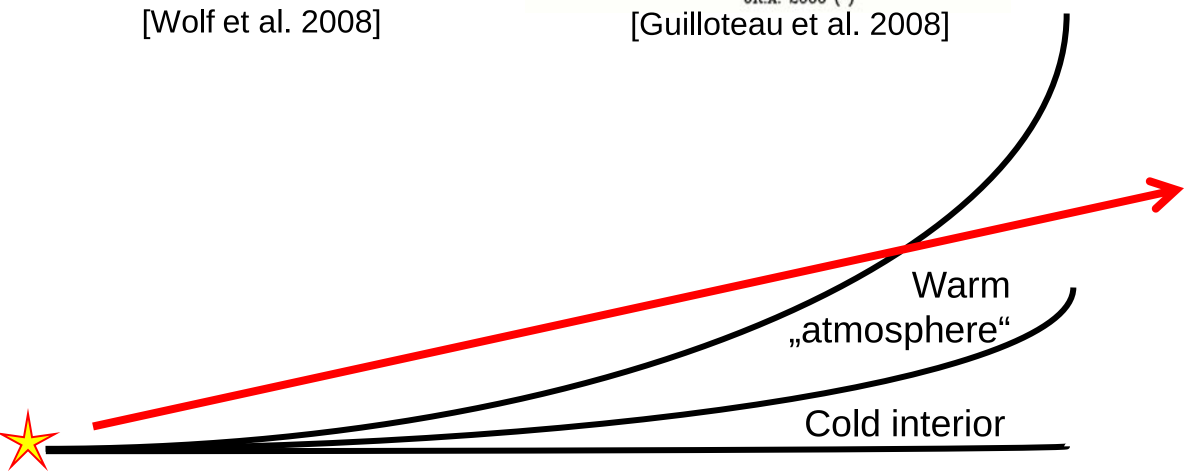
Various wavelengths – Various disk regions



[Wolf et al. 2008]



[Guilloteau et al. 2008]



Edge-on disks

(Sub)mm

Wavelength-dependence of the *radial* brightness distribution

⇒ Radial disk structure

⇒ Radial distribution of dust grain properties; Abundance / Excitation conditions of gas species

⇒ Large inner gap?

⇒ Velocity structure (gas)

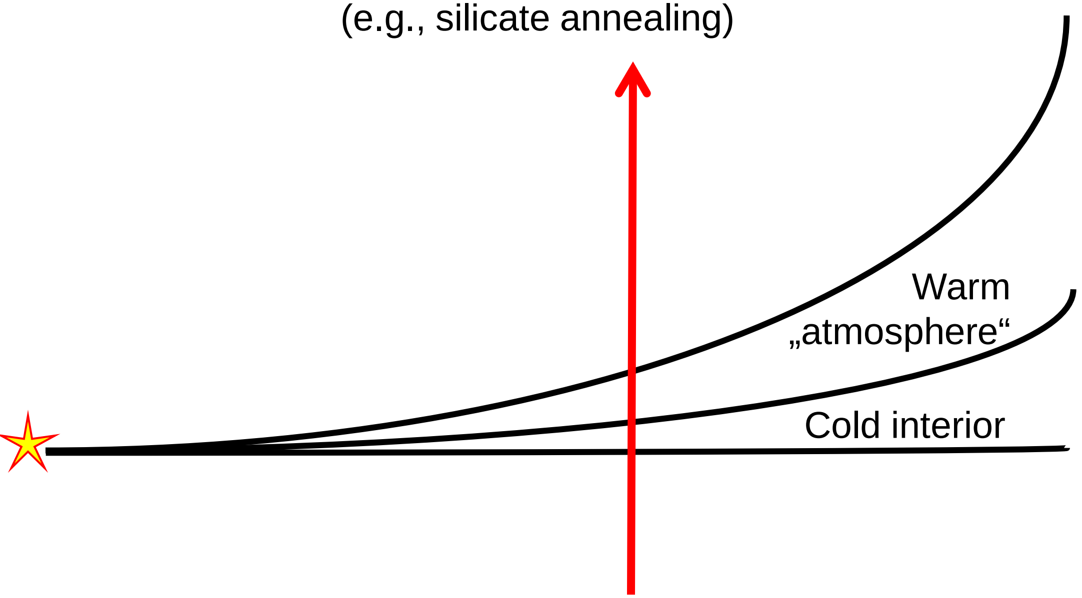
Various wavelengths – Various disk regions

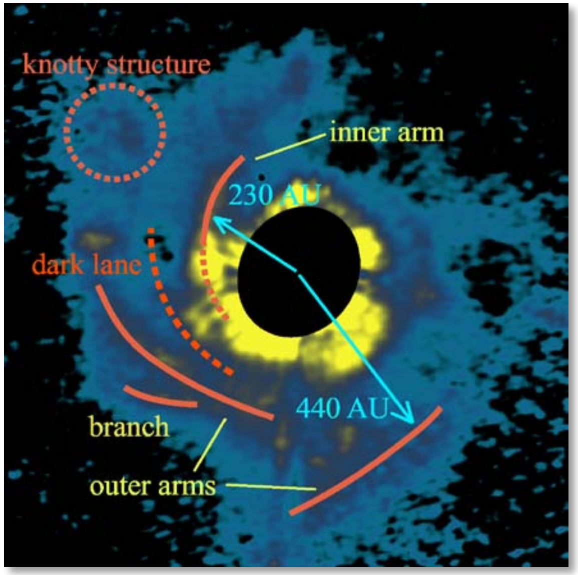
Face-on disks

Optical / IR

Wavelength-dependence of the *radial* brightness distribution

⇒ Disk: 1) Flaring; 2) Surface structure (local scale height variations)
⇒ Dust: 1) Scattering properties (scattering phase function) in different layers
2) Chemical composition = f (radial position)
(e.g., silicate annealing)





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

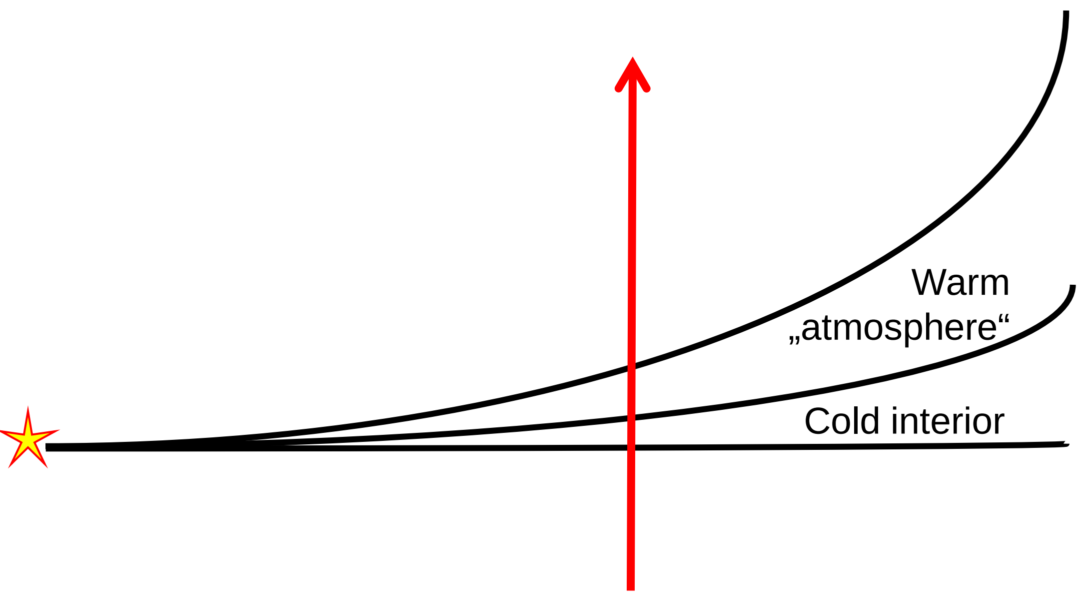
Various wavelengths – Various disk regions

Face-on disks

(Sub)mm

Radial / azimuthal disk structure

⇒ Asymmetries, Local density enhancements
⇒ Gaps, Inner Holes



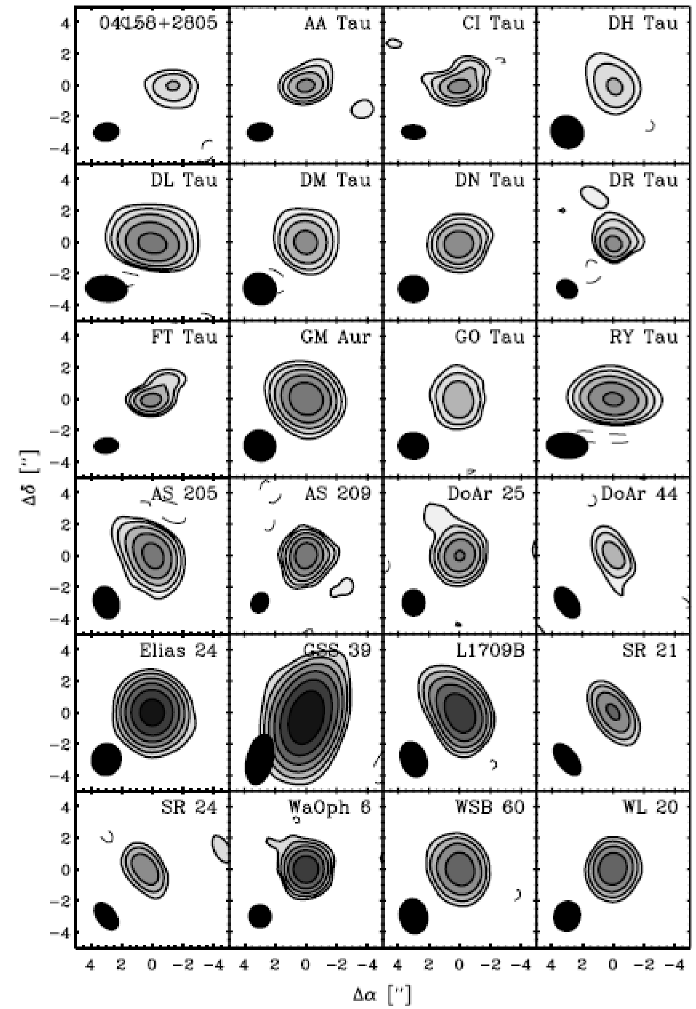


Fig. 2 Submillimeter continuum images from an SMA survey of T Tauri disks (Andrews and Williams 2007). Each panel is 10″ (∼1500 AU) on a side

[Andrews & Williams 2007 / 2008]

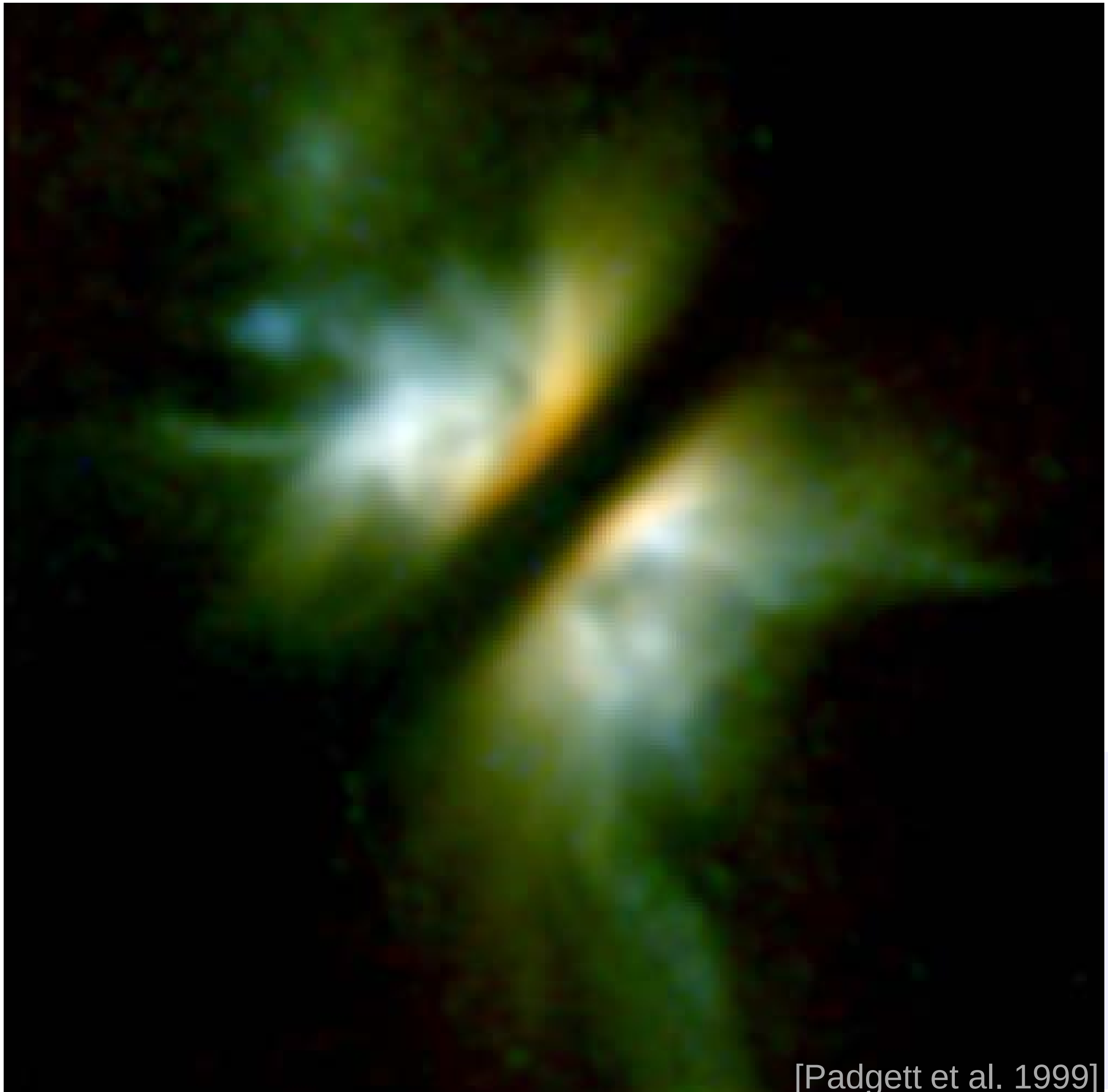
Exemplary studies

Large-scale structures
in circumstellar disks
@ various wavelengths

(~10 AU – a few 100 AU, i.e., > 0.1“)

Example #1: Butterfly star in Taurus

Example #1 The Butterfly Star in Taurus



[Padgett et al. 1999]

μm

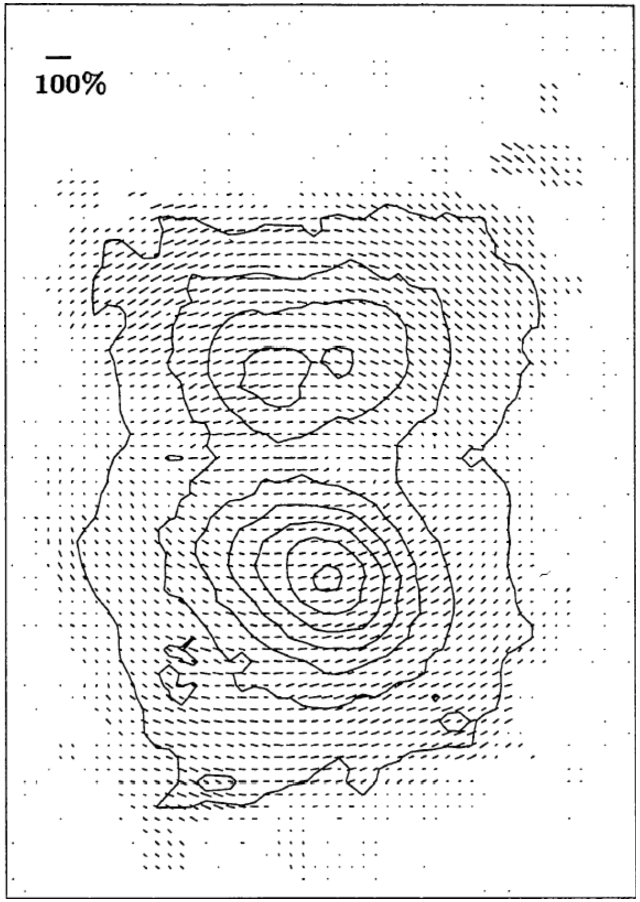
μm

μm

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

Example #1 The Butterfly Star in Taurus



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

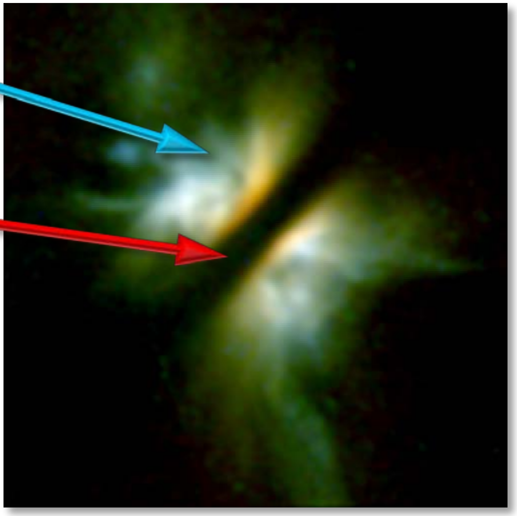
Linear Polarization:up to 80%

Scattering dominated by interstellar-type grains

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}

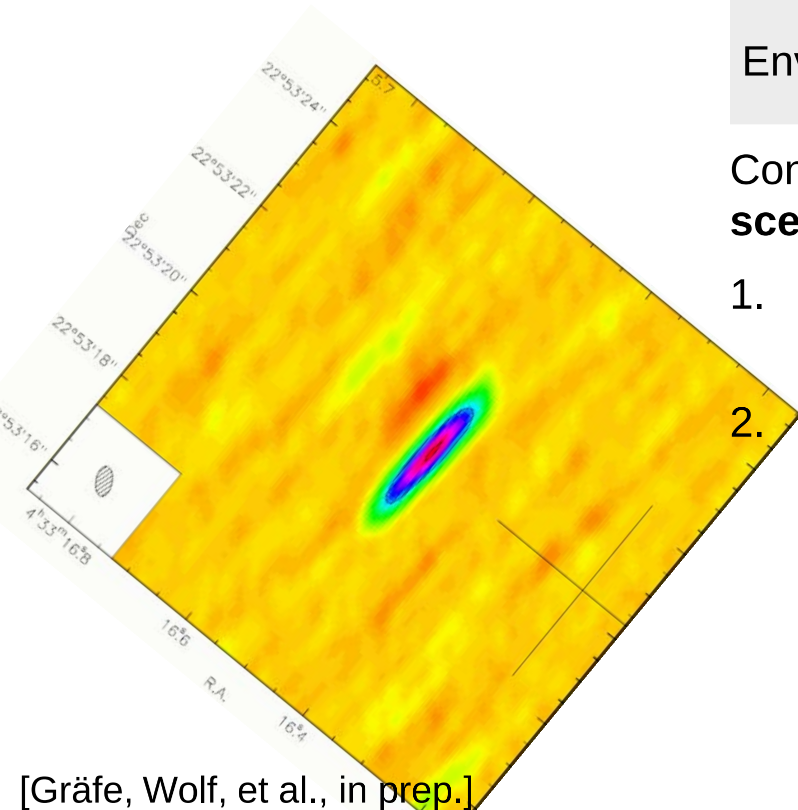
Confirmation of **different dust evolution scenarios** in the circumstellar shell and disk:

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



Example #1 The Butterfly Star in Taurus

IRAM / PdBI



[Gräfe, Wolf, et al., in prep.]

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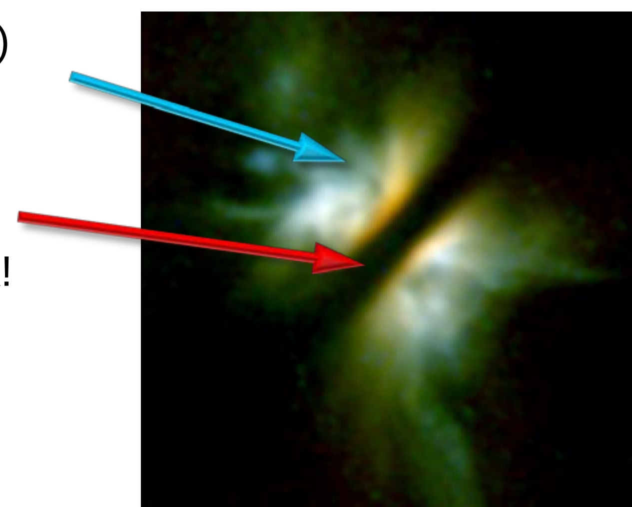

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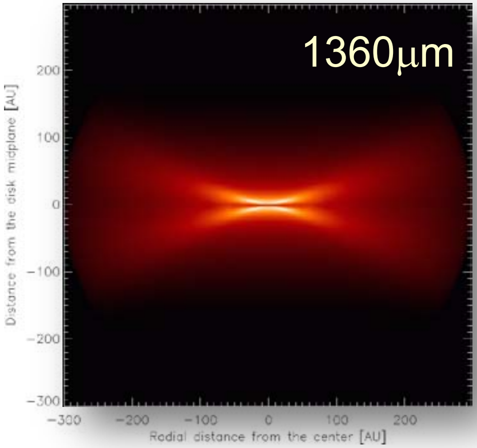
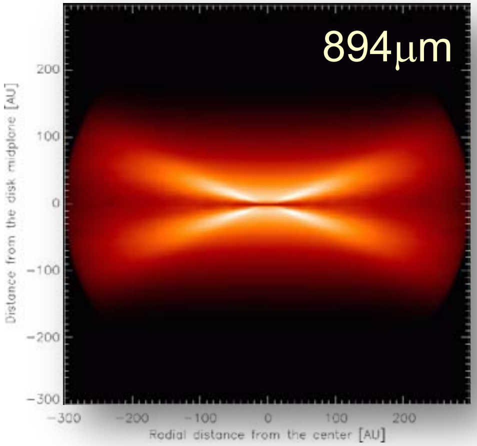
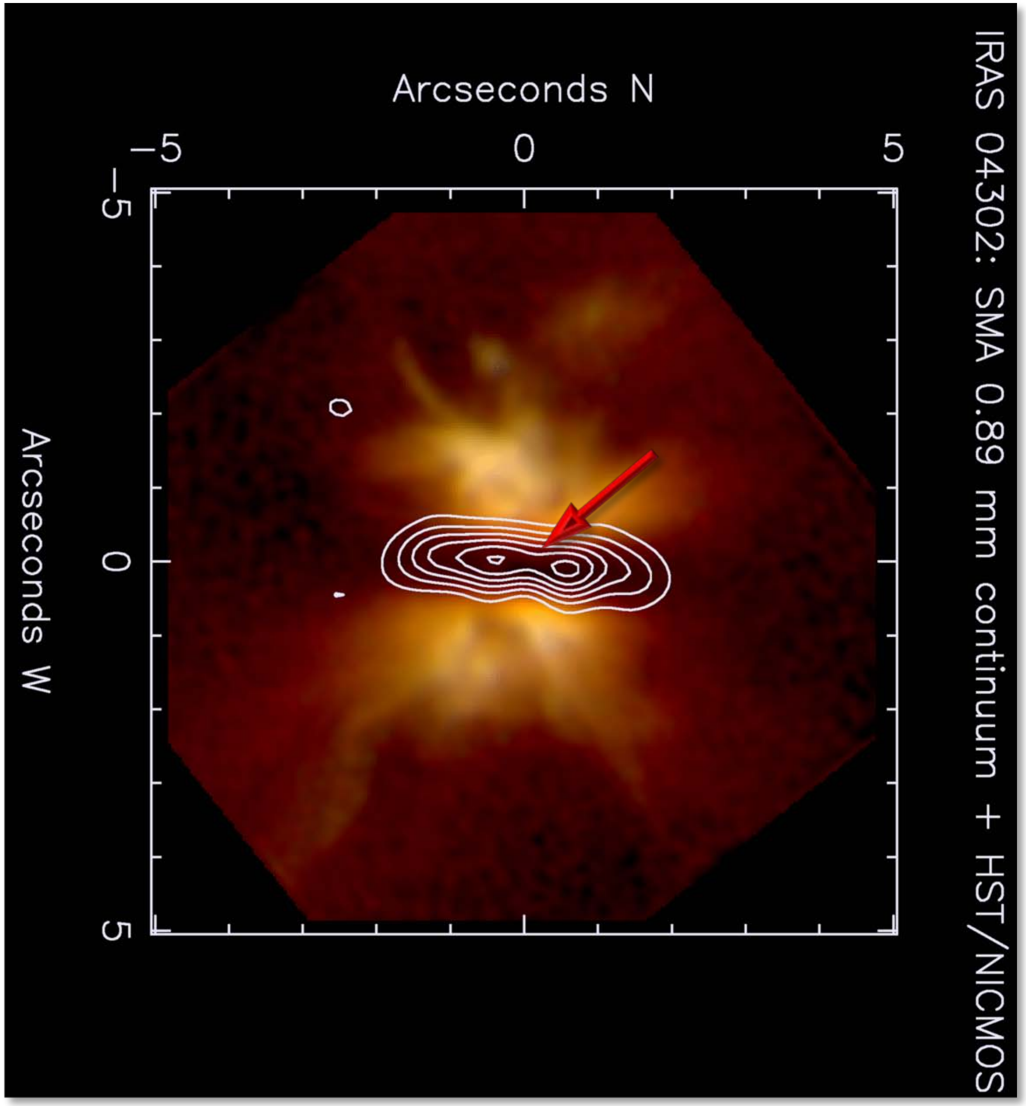






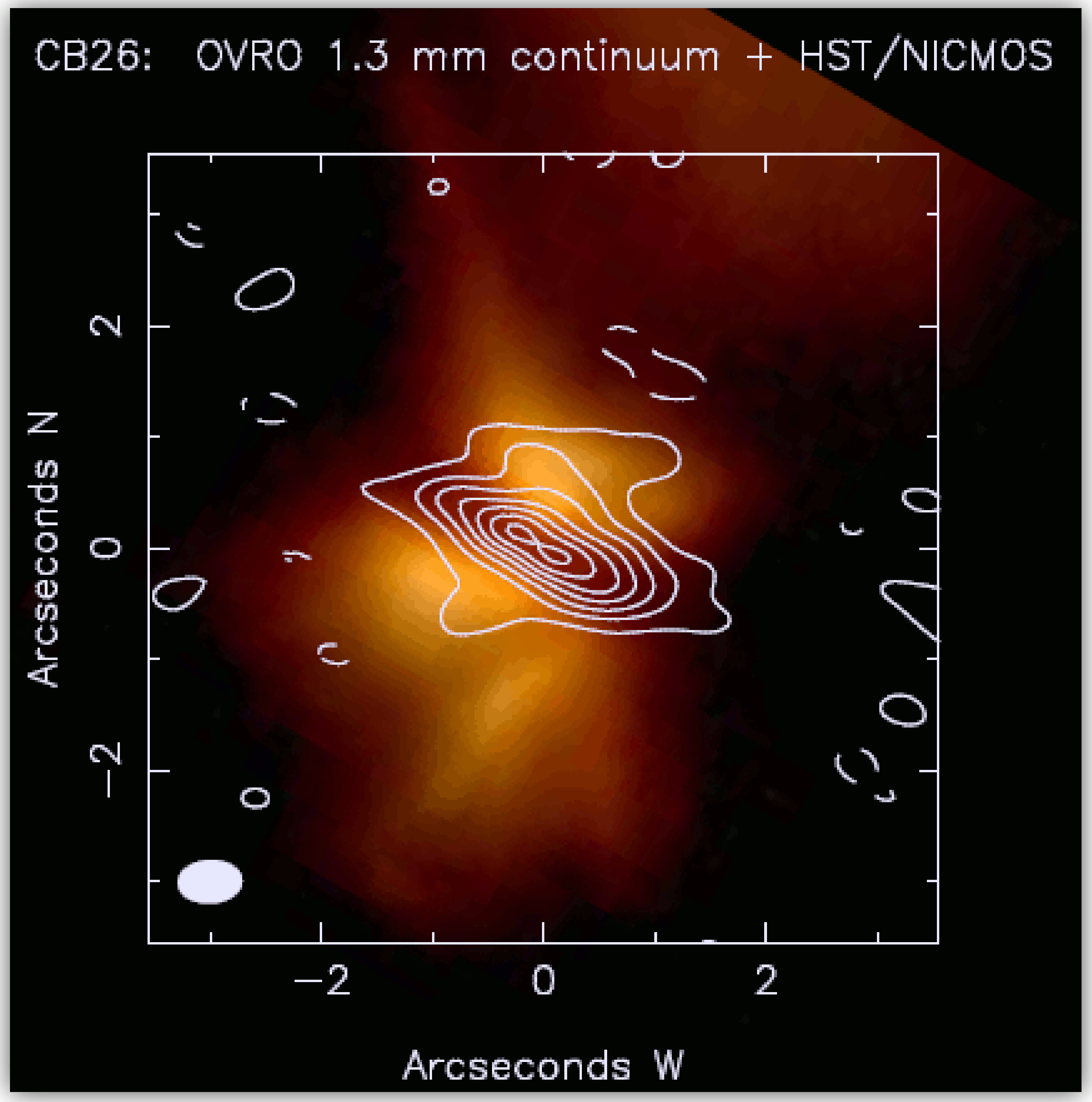
[Wolf et al. 2008]

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

Exemplary studies

Example #2: CB 26 (Taurus)

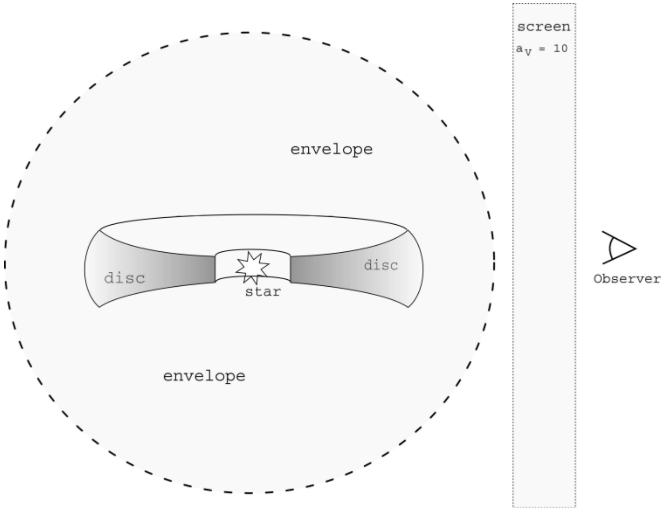
Example #2 Disk in the Bok Globule CB26



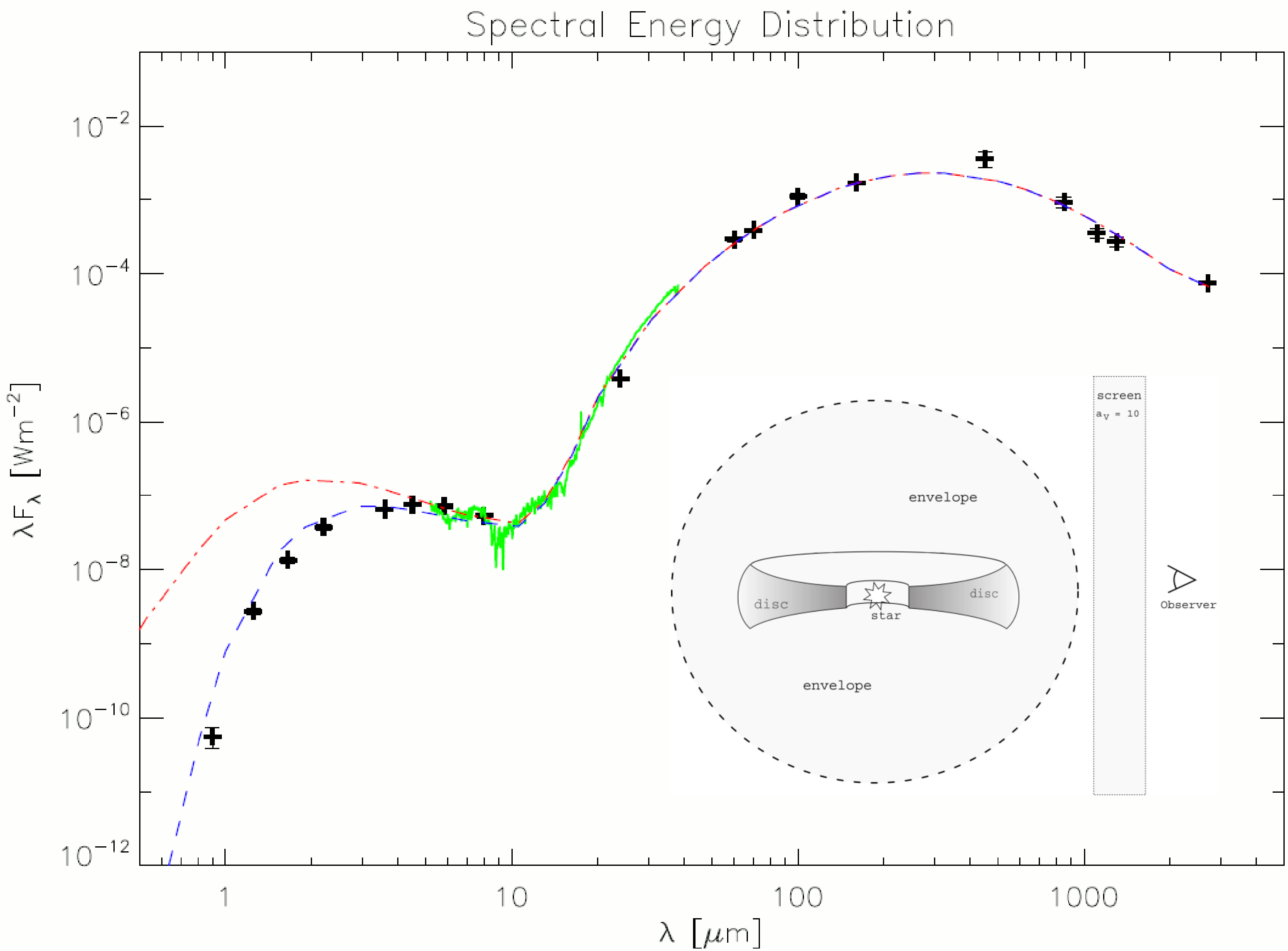
[Sauter, Wolf, et al., 2009]

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



Example #2 Disk in the Bok Globule CB26



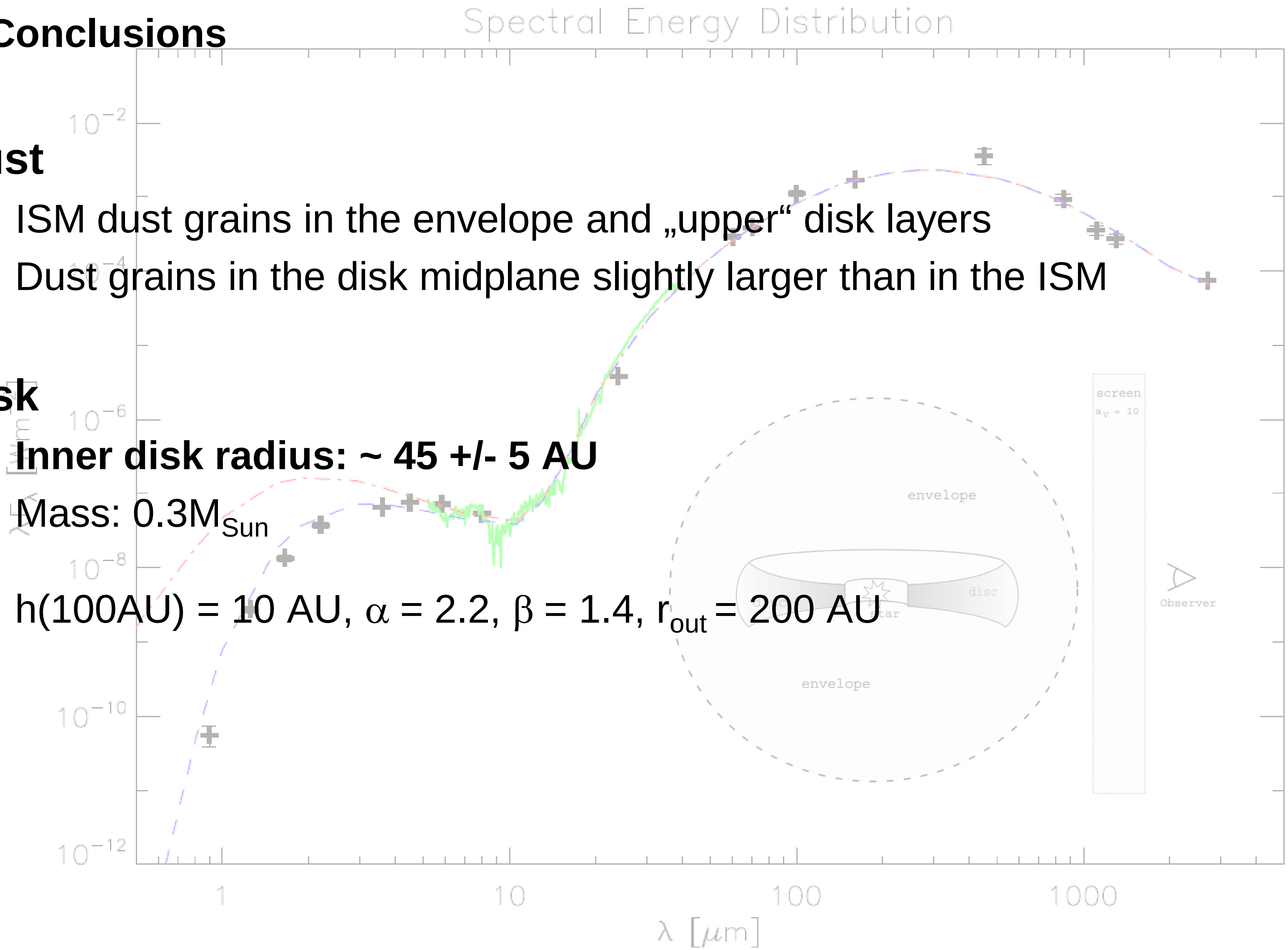
[Sauter, Wolf, et al., 2009]

Example #2 Disk in the Bok Globule CB26

Main Conclusions

- **Dust**
  - ISM dust grains in the envelope and „upper“ disk layers
  - Dust grains in the disk midplane slightly larger than in the ISM

- **Disk**
  - **Inner disk radius: ~ 45 +/- 5 AU**
  - Mass: $0.3M_{Sun}$
  - $h(100AU) = 10$ AU, $\alpha = 2.2$, $\beta = 1.4$, $r_{out} = 200$ AU



[Sauter, Wolf, et al., 2009]

Example #3: HH30

Example #3 HH30

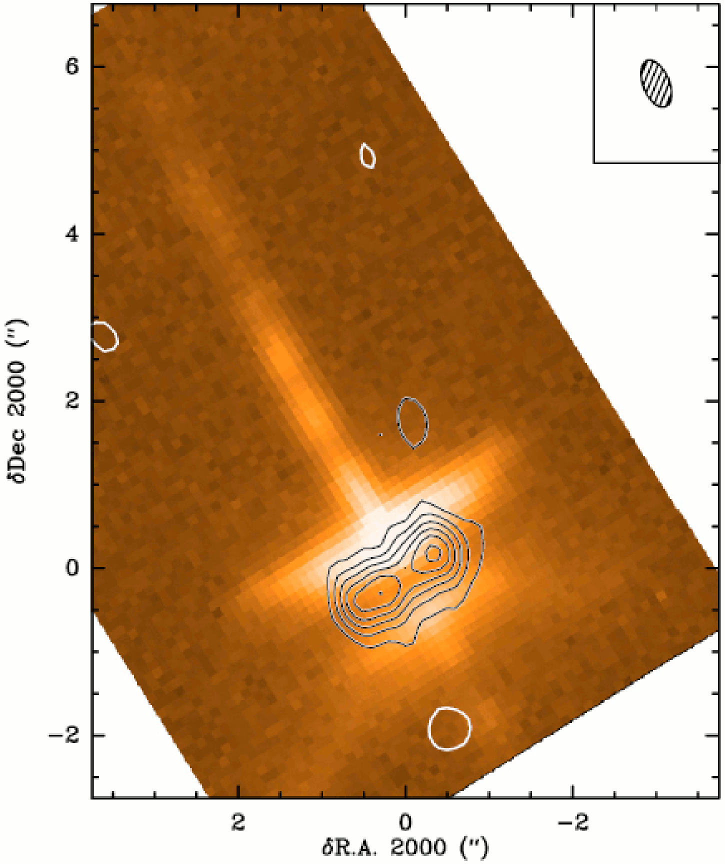


Fig. 1. Superimposition of the PdBI 1.30 mm continuum map on the HST data. The spatial resolution is 0.59 × 0.32″ at PA 22°. The center of projection is RA = $04^h31^m37\overset{s}{.}469$ and Dec = 18°12′24.″22 in J2000. Contour levels start at and are spaced by 3σ = 0.56 mJy/beam, corresponding to 68 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″.

[Guilloteau et al. 2008]

<u>Observation</u>

• IRAM interferometer, 1.3mm, beam size ~0.4"

<u>Results</u>

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

<u>Interpretation</u>

• Tidally truncated disk surrounding a binary system (two stars on a low eccentricity, 15 AU semi-major axis orbit)

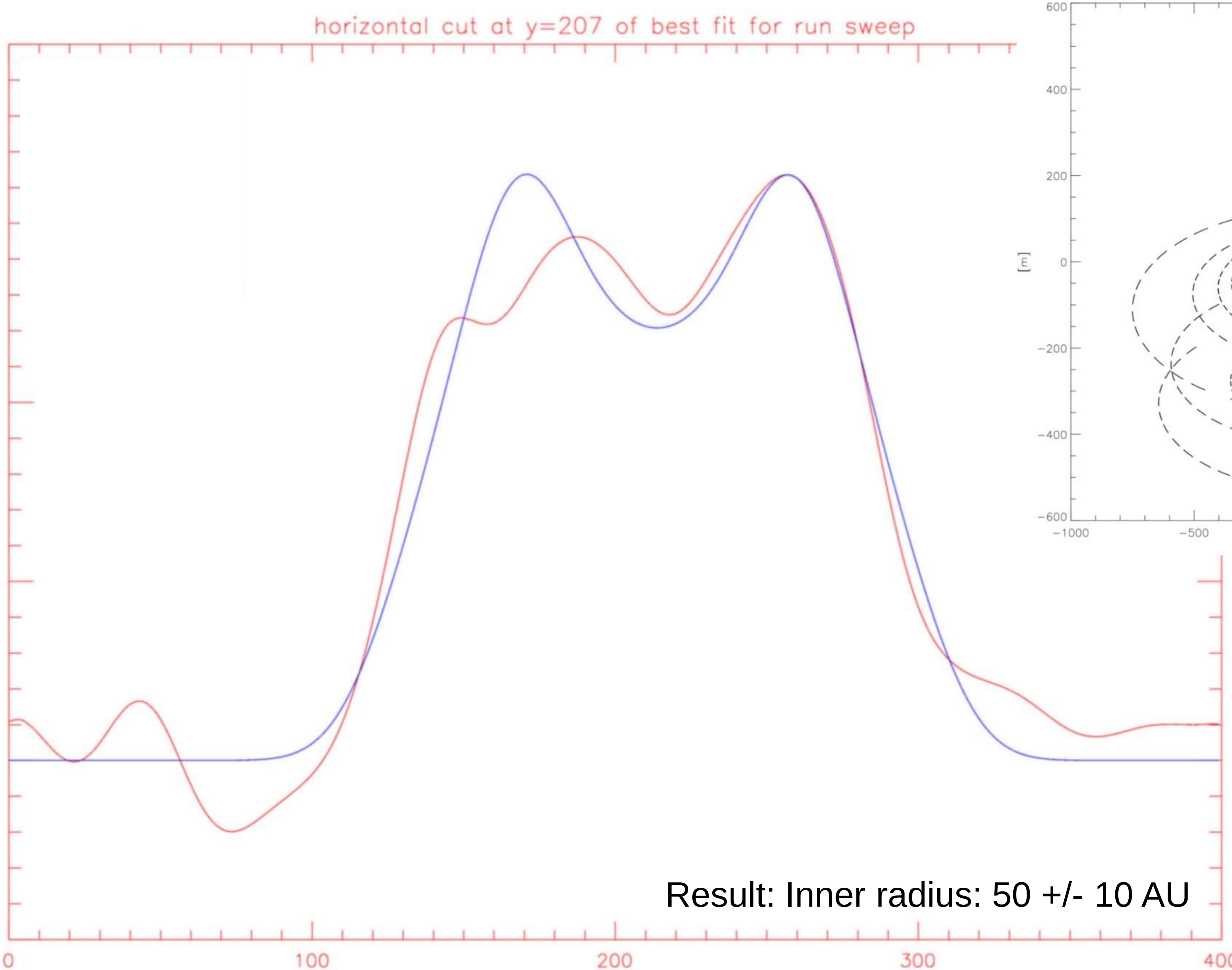
• Additional support for this interpretation: Jet wiggling due to orbital motion

• The dust opacity index, β ≈ 0.4, indicates the presence of cm size grains (assuming that the disk is optically thin at 1.3mm)

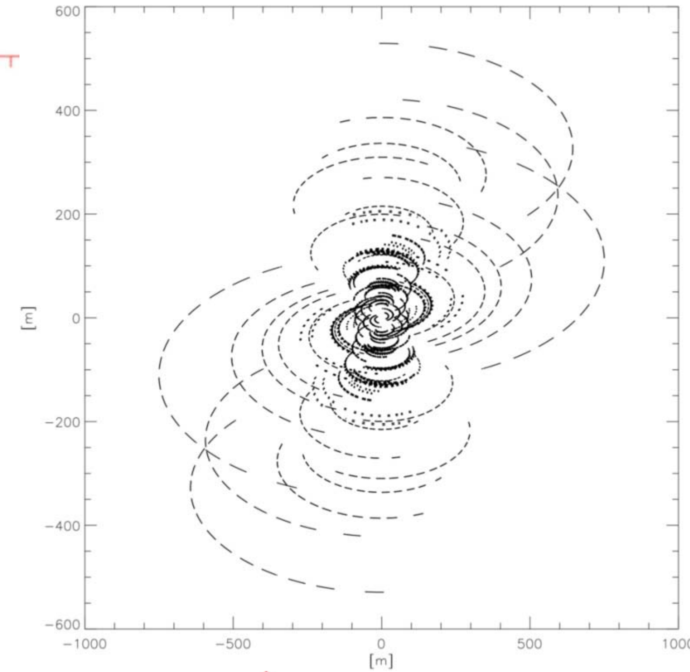
"… In this domain, ALMA will likely change our observational vision of these objects."

Example #3

HH30



Result: Inner radius: 50 +/- 10 AU

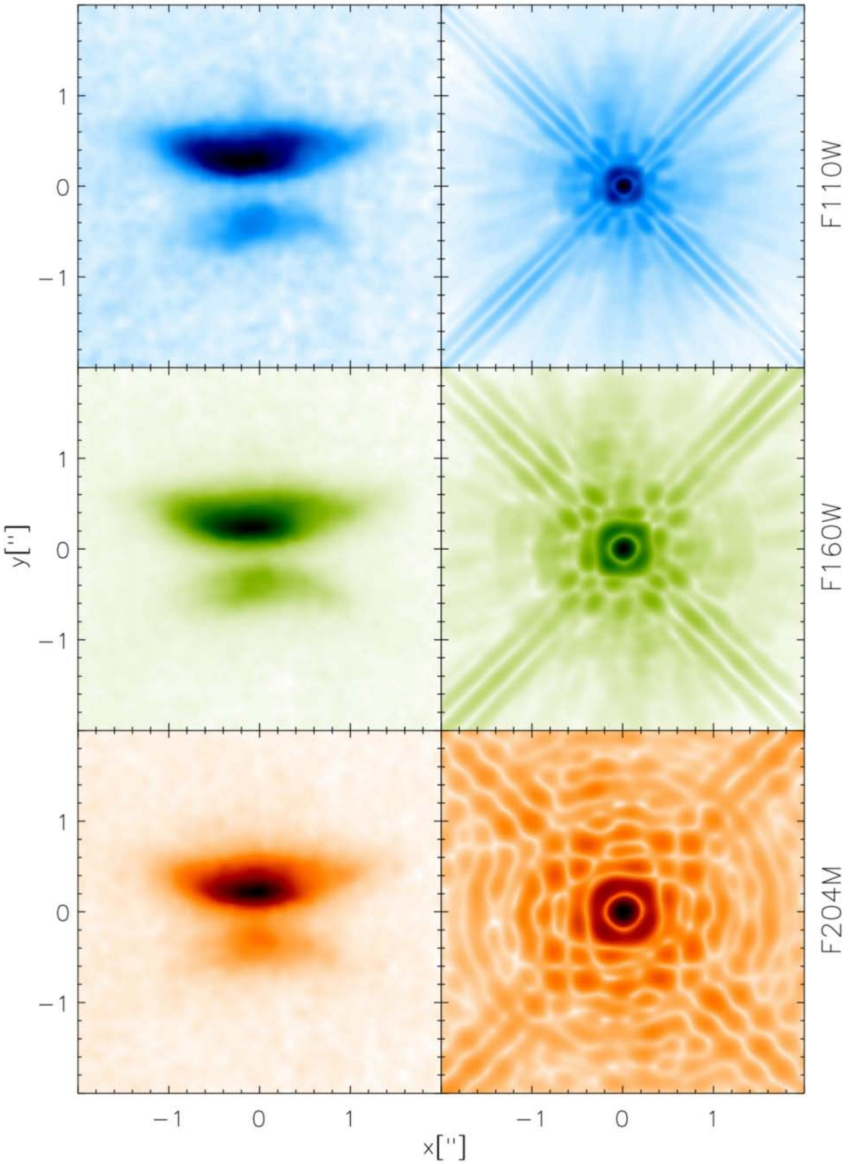


[uv coverage]

Fitting of
a) reconstructed map
b) uv data

(Madlener, Wolf, et al., in prep.)

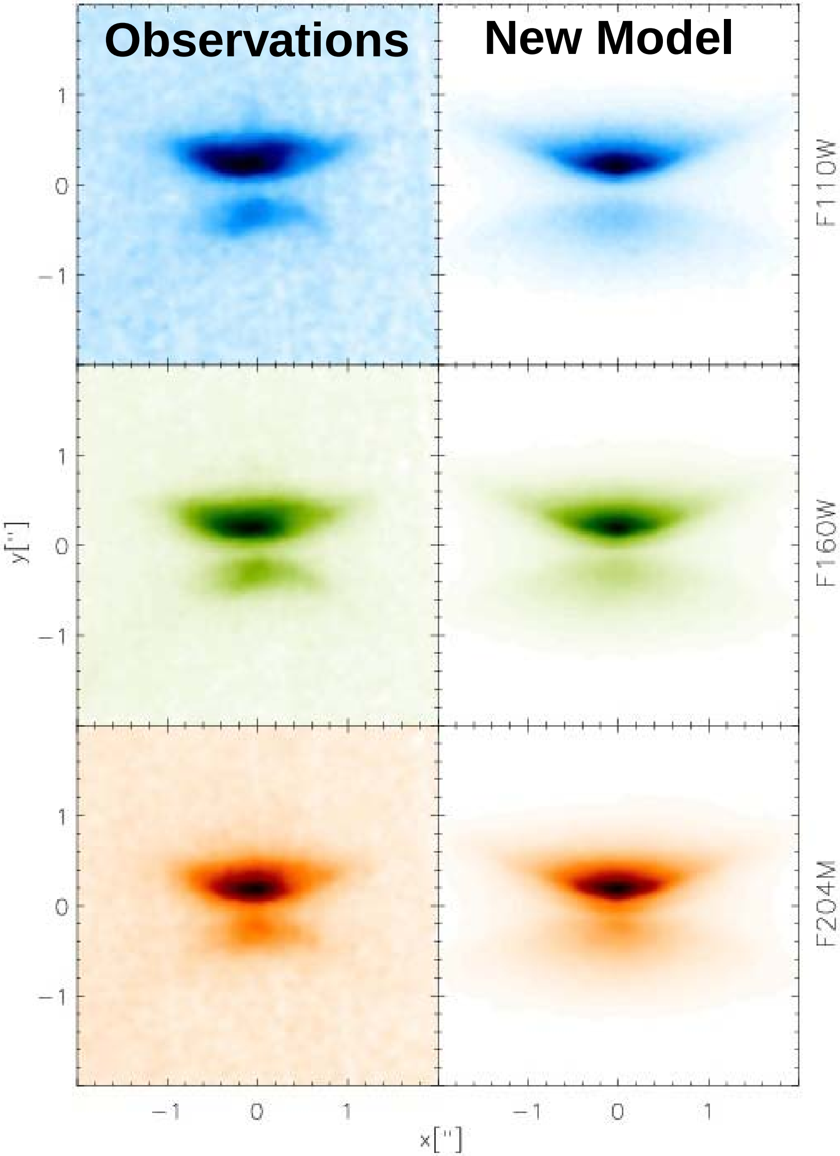
Example #3 HH30



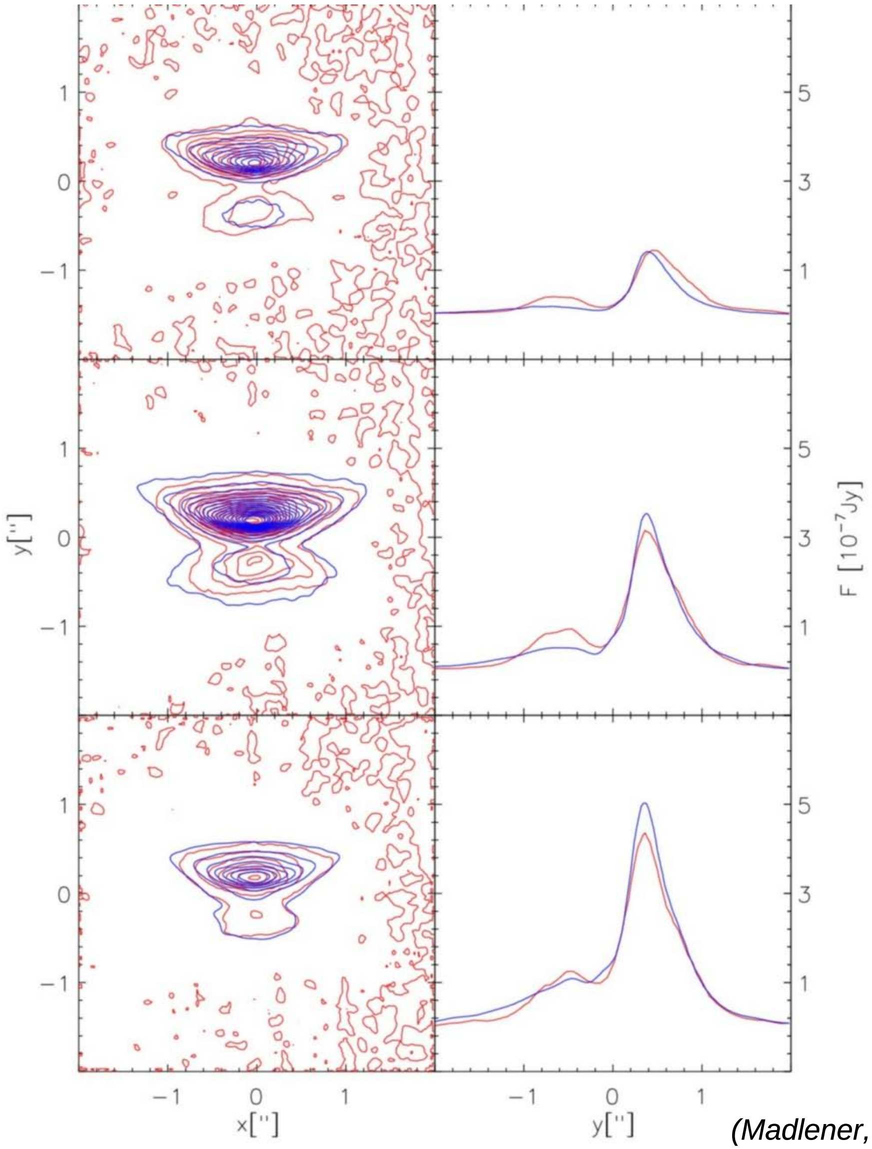
[based on observations published by Cotera et al. 2001]

(Madlener, Wolf, et al., in prep.)

Example #3 HH30



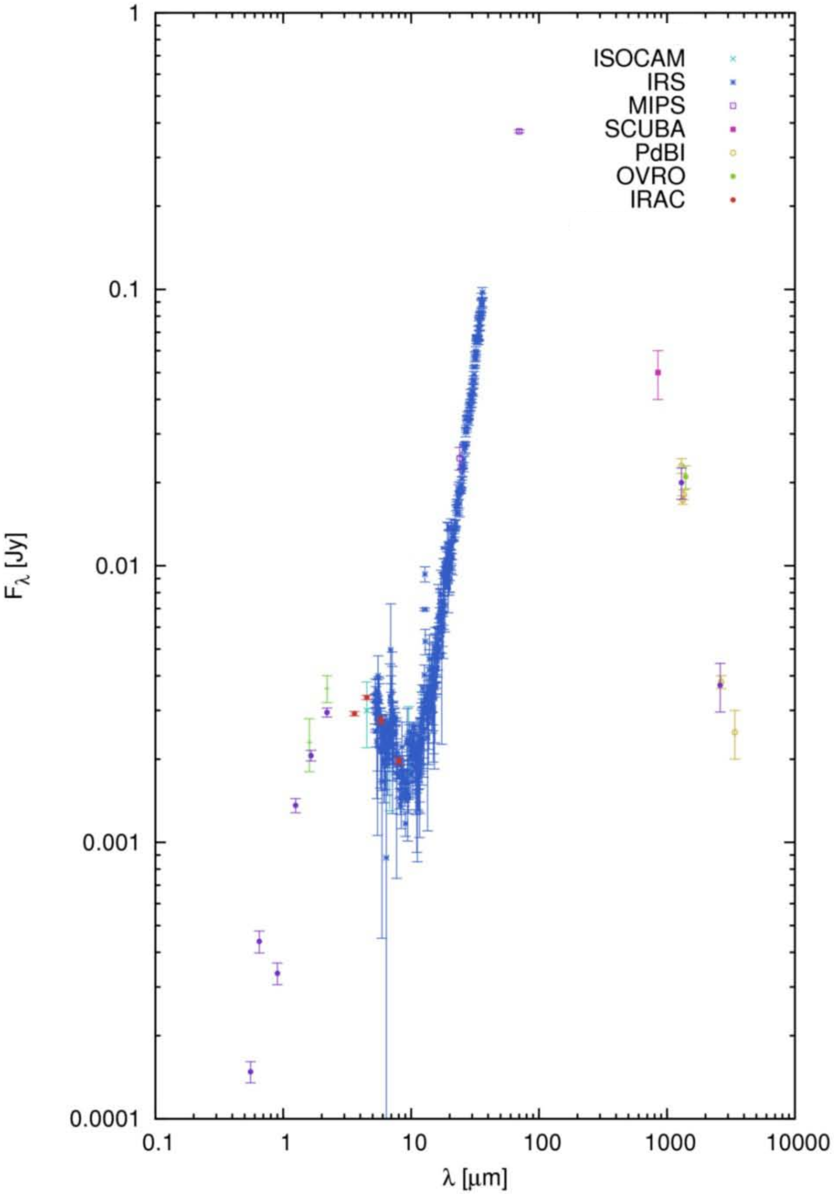
[based on observations published by Cotera et al. 2001]

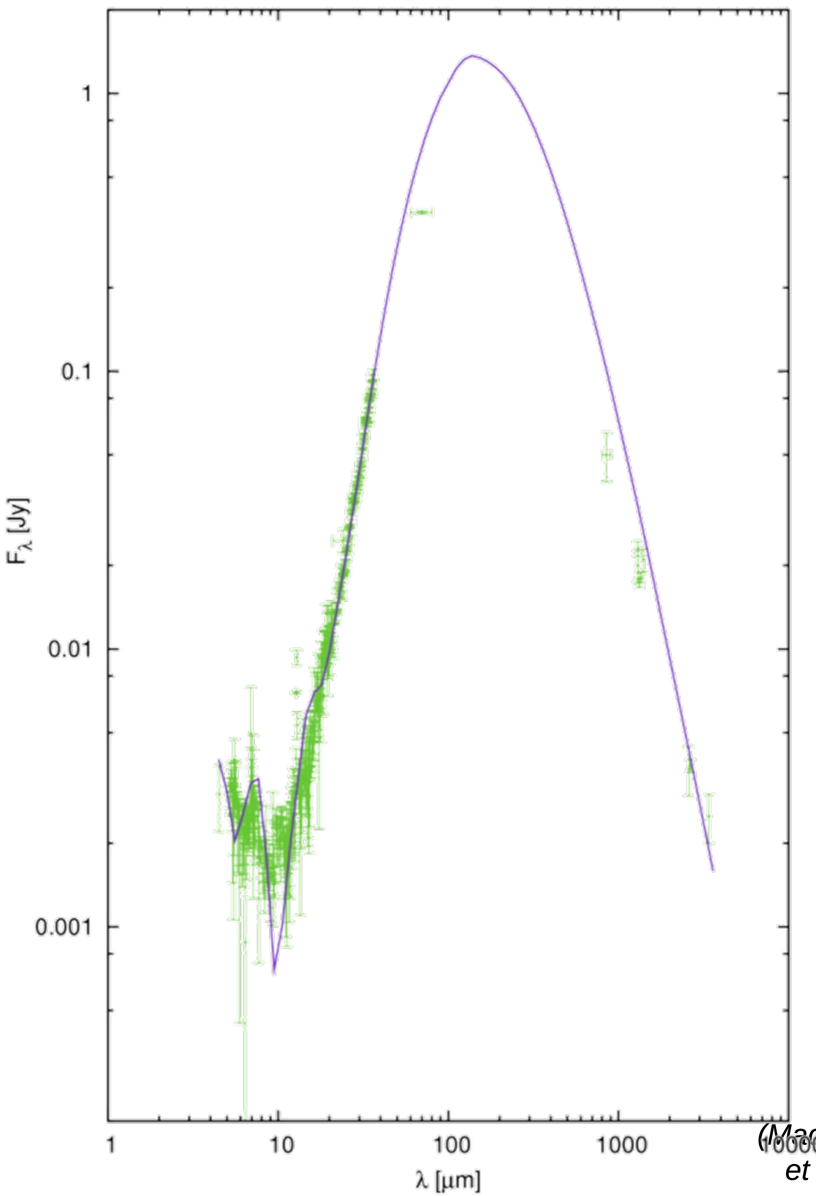


(Madlener, Wolf, et al., in prep.)

Example #3

HH30





(Madlener, Wolf, et al., in prep.)

Example #3 HH30

Mass distribution

- α = 2.3 +/- 0.2
- β = 1.2 +/- 0.1
- h_{100} = (14.8 +/- 1.0) AU
- R_{in} = (0.5 +/- 0.4) AU
- **R_{att} = (50 +/- 10) AU**
- R_{out} = (200 +/- 30) AU
- q = 0.03 +/- 0.01
- m_{dust} = (9 +/- 6)E-5 M_sun

Star

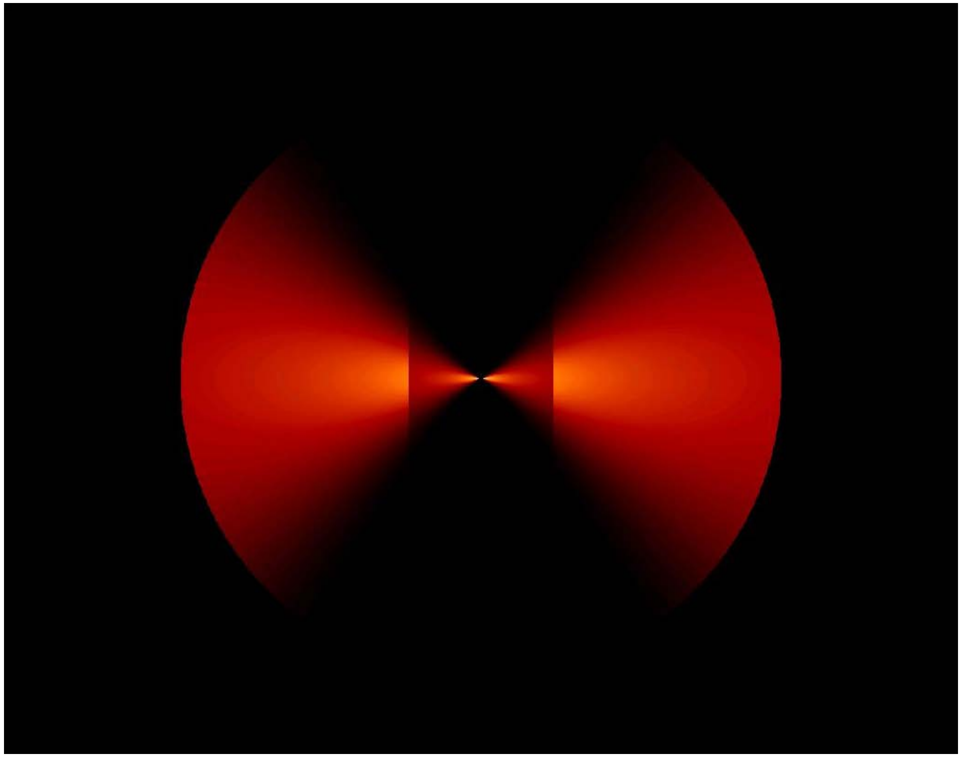
- L = (0.4 +/- 0.2) L_sun
- T_{eff} = (3400 +/- 300) K

Grain size distribution

- a_{min} = (5 +/- 3) nm
- **a_{max} = (8 +/- 7) mm**
- d = (3.6 +/- 0.2)

Disk inclination

- i = (82 +/- 2)°



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., in prep.)

Exemplary studies

Small-scale structures
of circumstellar disks
@ various wavelengths

(<10 AU, i.e., <0.1“)

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 to 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

Spectro-Interferometry in the mid-infrared

The VLT Array on the Paranal Mountain

<u>Mid-Infrared Interferometric Instrument (MIDI)</u>

Spatial resolution: $\lambda/B \geq 1AU$ @ 140pc with $B \leq 130m$

Spectrally resolved (R=30) data in N band:
- Silicate feature + (relative) radial distribution
- Inner disk region $\leq$ 40 AU

<u>General results</u>

(1) **SED** (global appearance of the disk) + spectrally resolved **visibilities** can be fitted **simultaneously**

(2) Best-fit achieved in most cases with an **active accretion disk and/or envelope**

(3) Decompositional analysis of the 10 μm feature confirms effect of **Silicate Annealing** in the inner disk (~ few AU)

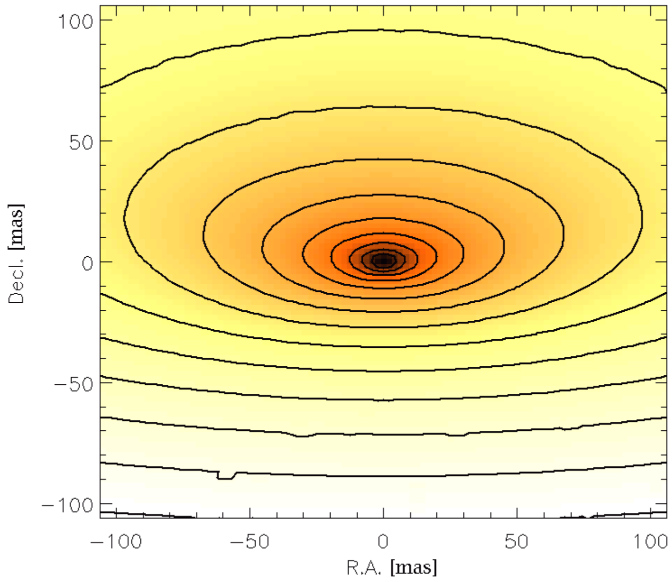
Schegerer, Wolf, et al. 2008, A&A 478, 779
„The T Tauri star RY Tauri as a case study of the inner regions of circumstellar dust disks “

Schegerer, Wolf, et al. 2009, A&A, 502, 367
„Tracing the potential planet-forming region around seven pre-main sequence stars“

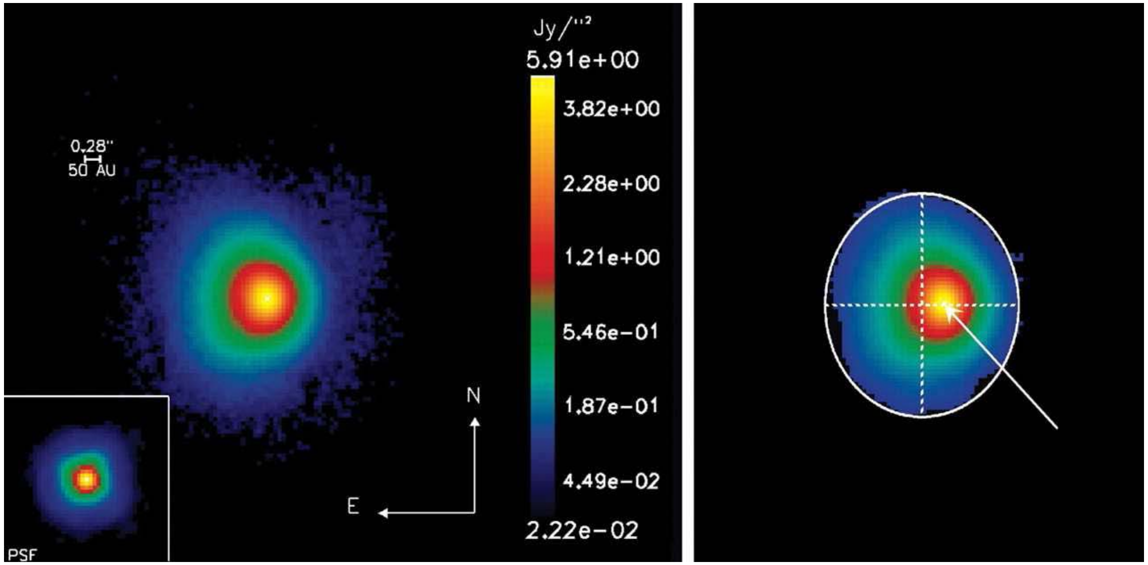
Limitation of 2-beam interferometers [Example]

True surface brightness profile in circumstellar disks around TTauri / HAe/Be stars

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

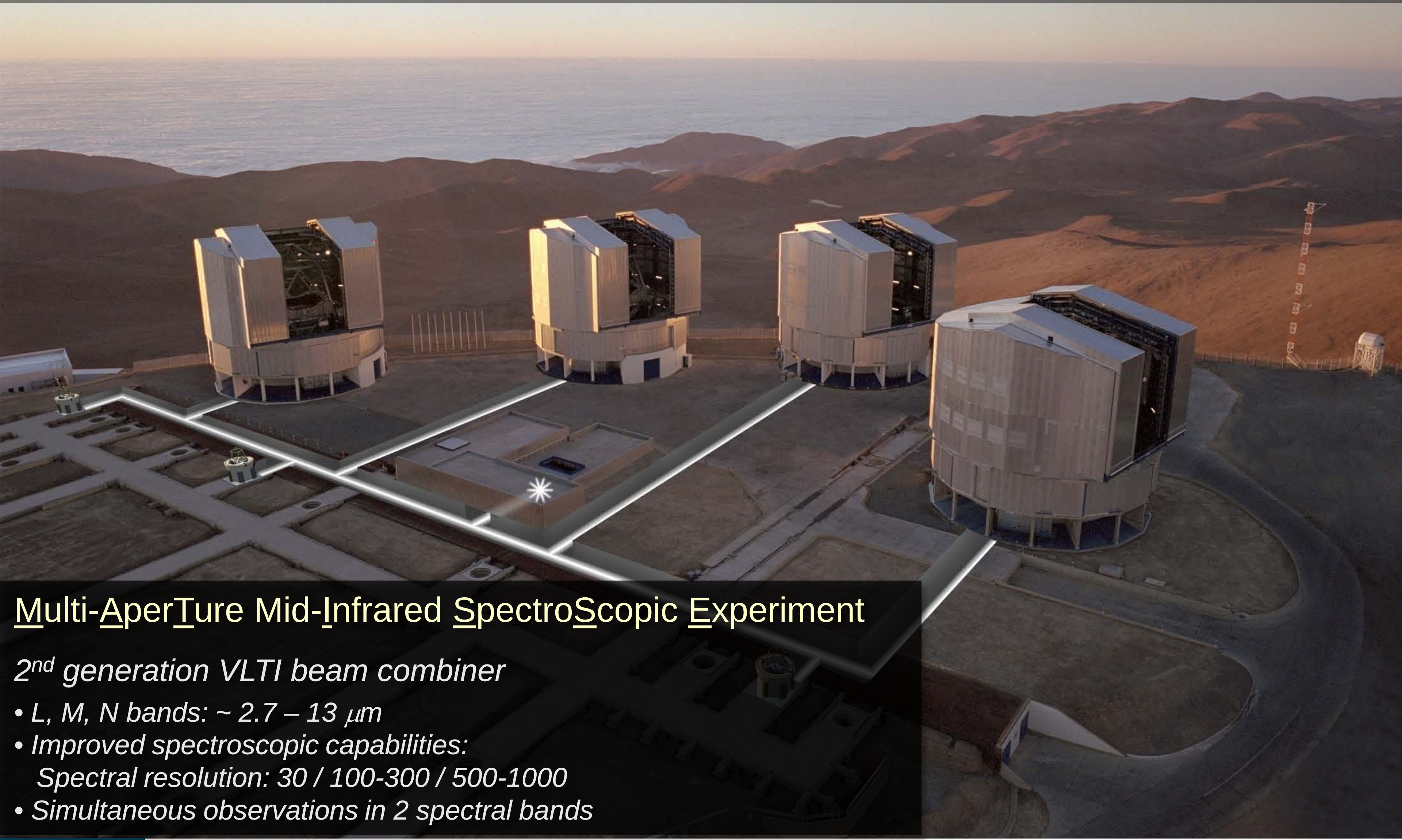


Simulated 10μm intensity map of the inner 30AU×30AU region of a circumstellar T Tauri disk at an assumed distance of 140 pc; inclination angle: 60◦.



Left: VISIR false-color image of the emission from the circumstellar material surrounding the HAe star HD97048. The emission is widely extended, as compared with the point spread function (inset) obtained from the observation of a pointlike reference star.
Right: Same image as in the middle, but with a cut at the brightness level and a fit of the edge of the image by an ellipse (Lagage et al. 2006).

MATISSE @ Very Large Telescope Interferometer



Multi-AperTure Mid-Infrared SpectroScopic Experiment

2nd generation VLTI beam combiner

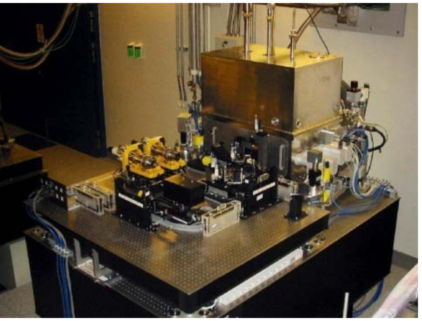
- *L, M, N bands: ~ 2.7 – 13 μm*
- *Improved spectroscopic capabilities:*
  Spectral resolution: 30 / 100-300 / 500-1000
- *Simultaneous observations in 2 spectral bands*

MATISSE

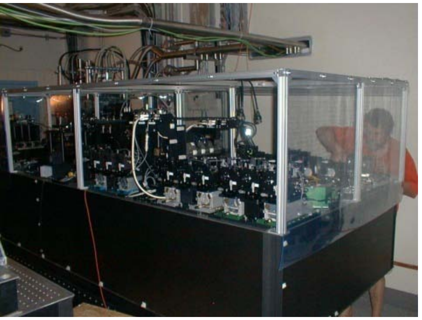
Goal: Thermal reemission images
with an angular resolution of 0.003“

ESO

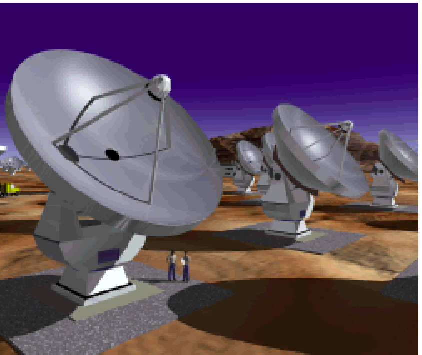
High-Resolution Multi-Band Image Reconstruction
+ Spectroscopy in the Mid-IR



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

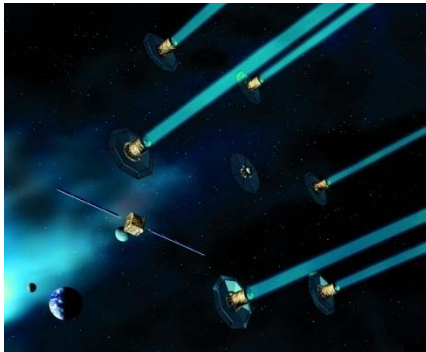


Successor / Extension of **AMBER**:
Extension down to 2.7μm
+ General use of closure phases



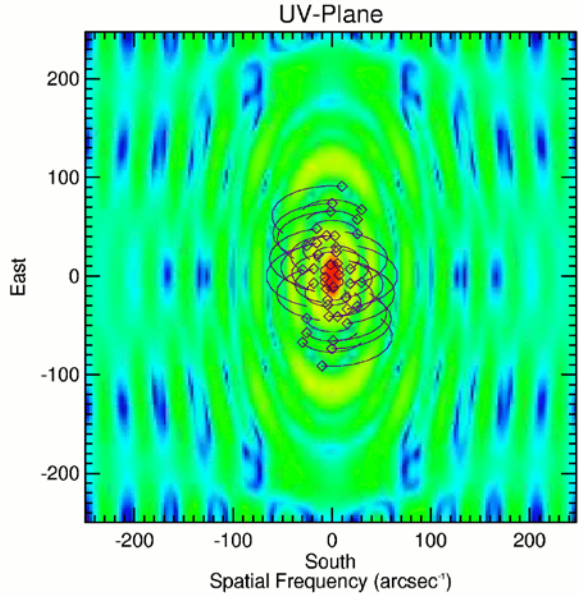
Complement to **ALMA** + **TMT/ELT**

Ground Precursor for
mid-IR space missions



Disk clearing?

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



Original image	Experiment 1: Reconstruction, Noise 2% $d = 0.00020$	Experiment 2: Reconstruction, Noise 5% $d = 0.00023$

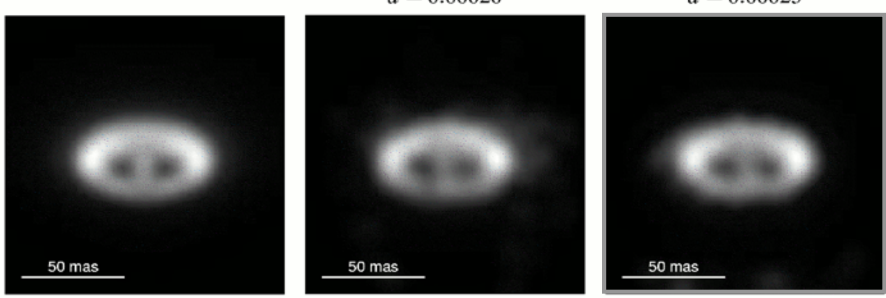


Figure 22: Image reconstruction experiments. *Top*: uv-coverage of the two reconstruction experiments; *Bottom left*: original image (see Fig. 21, right) convolved with a PSF corresponding to a 202 m aperture; *Bottom center and right*: images reconstructed from two data sets with 2% and 5% noise of 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]

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

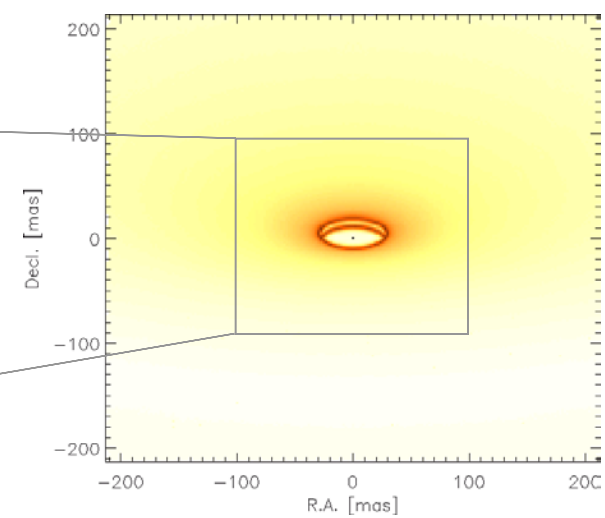
but:

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)



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

MATISSE – Planets

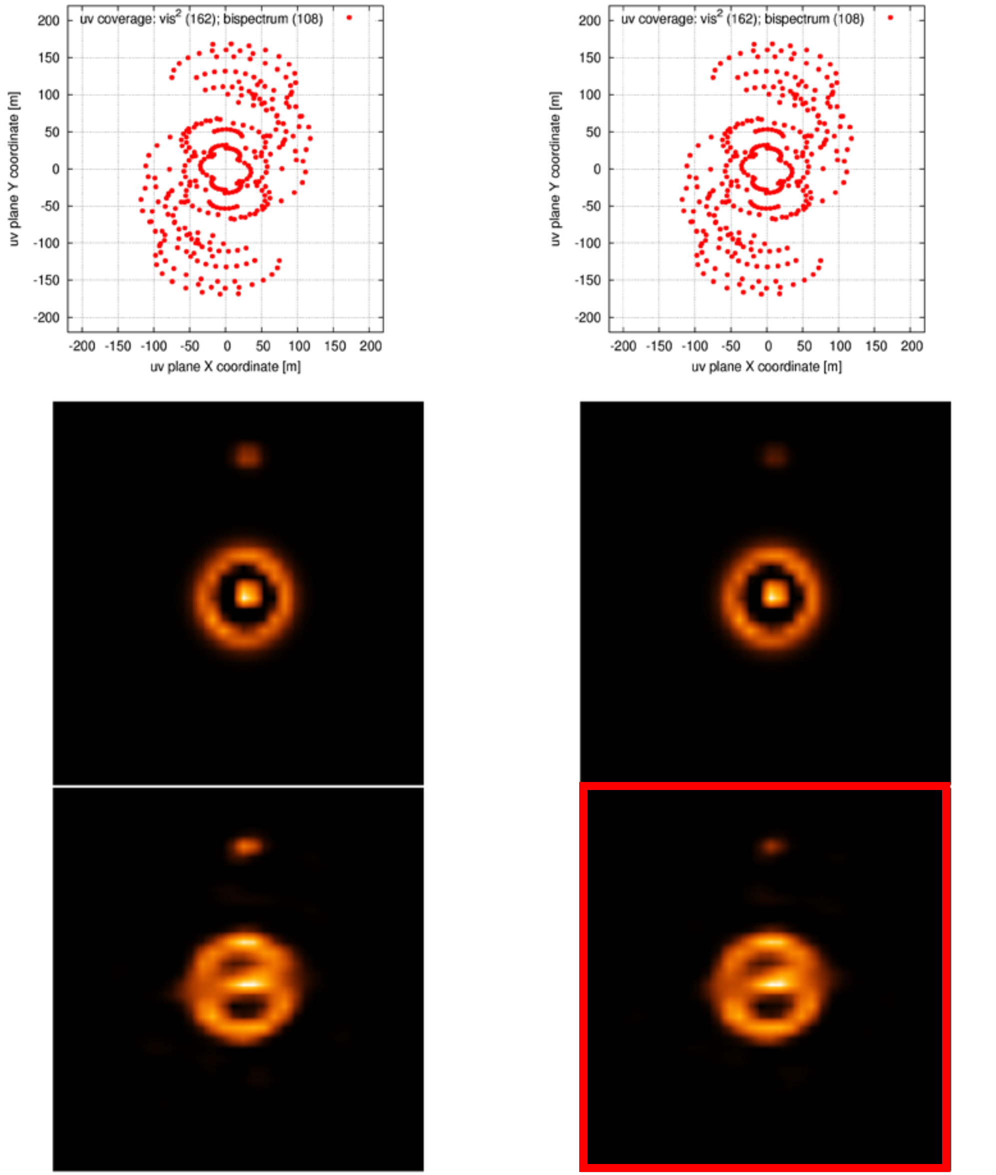
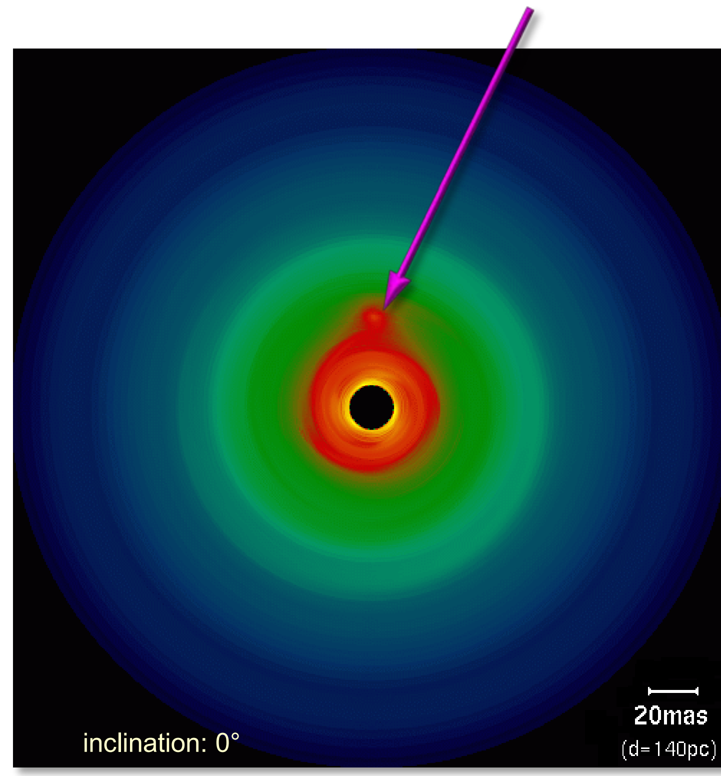


Figure 6: Reconstructed N band images (3x4ATs; ∼ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5[right]). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and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

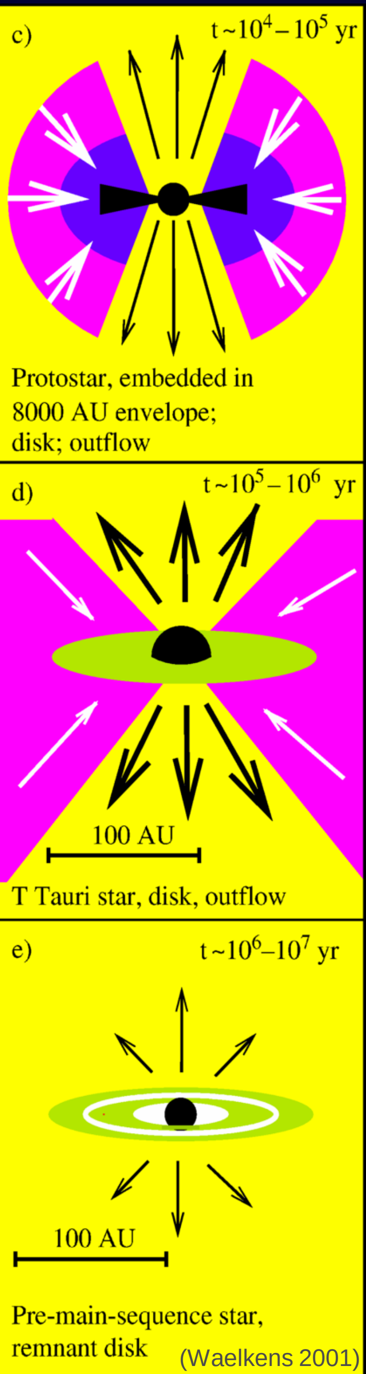


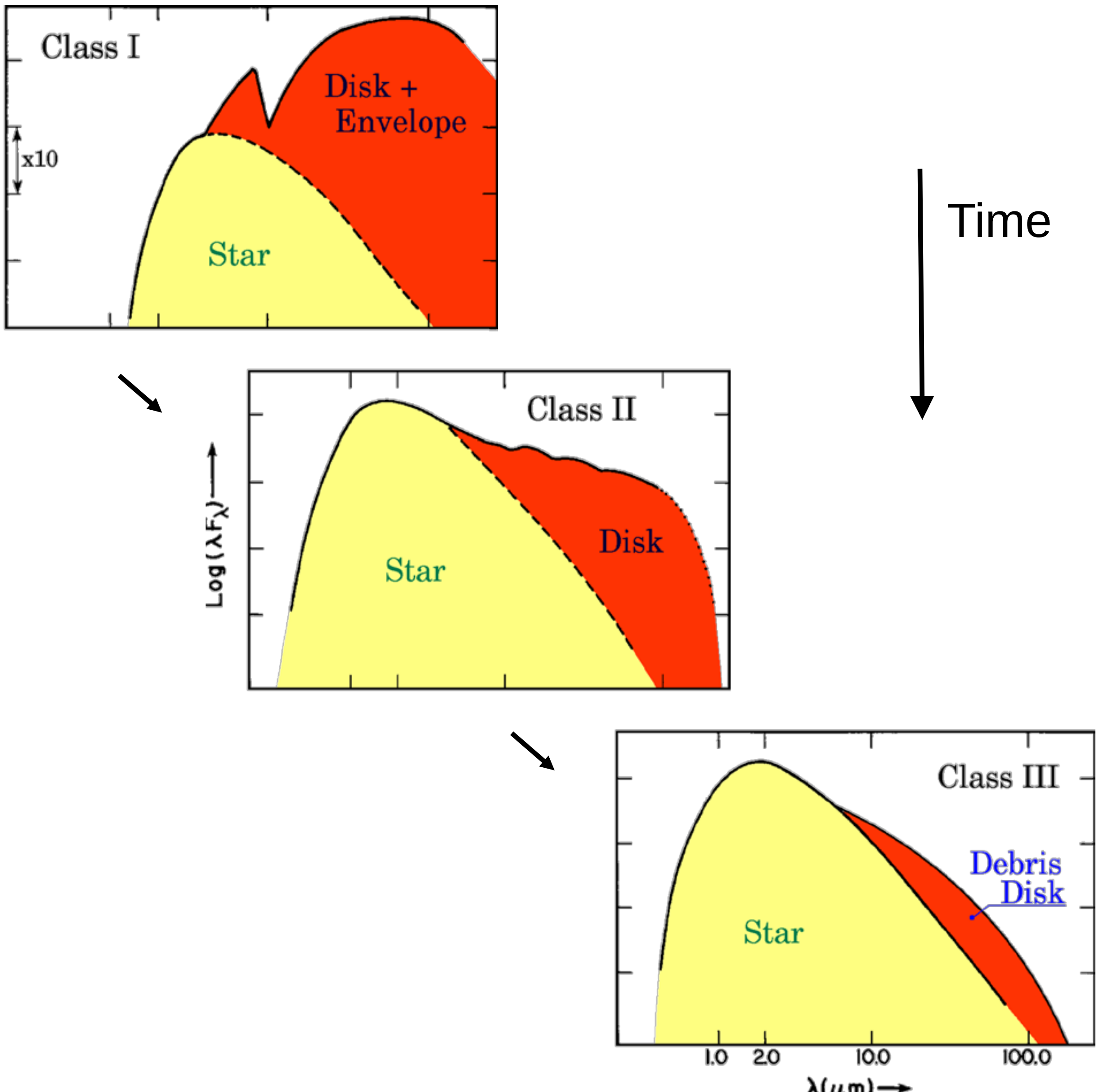
[Wolf et al. 2005-2007]

Exemplary studies

Debris disks

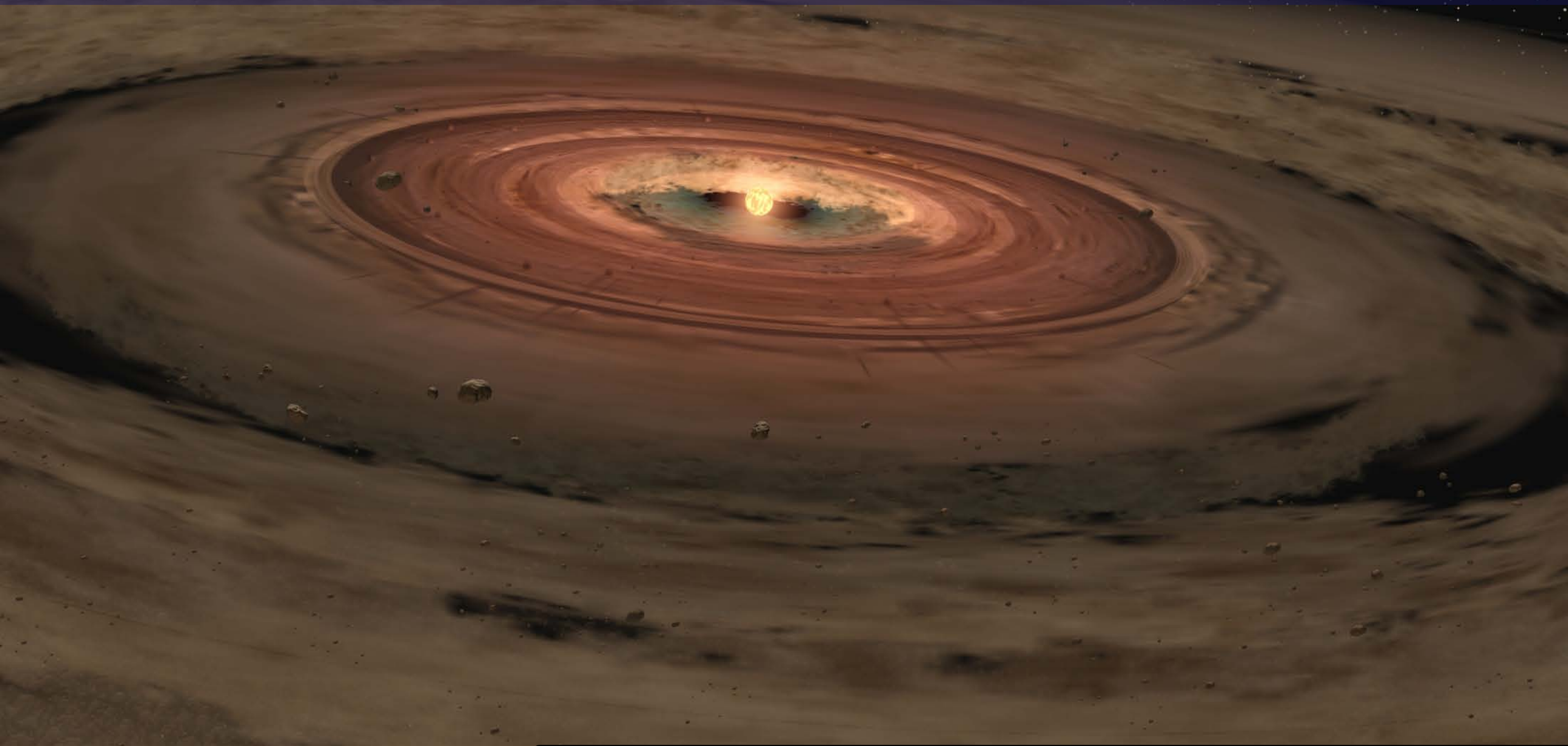
Disk Evolution

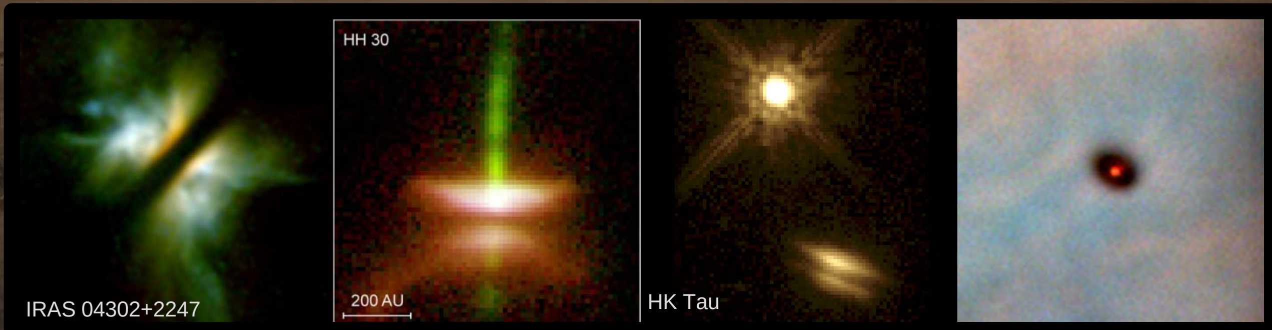




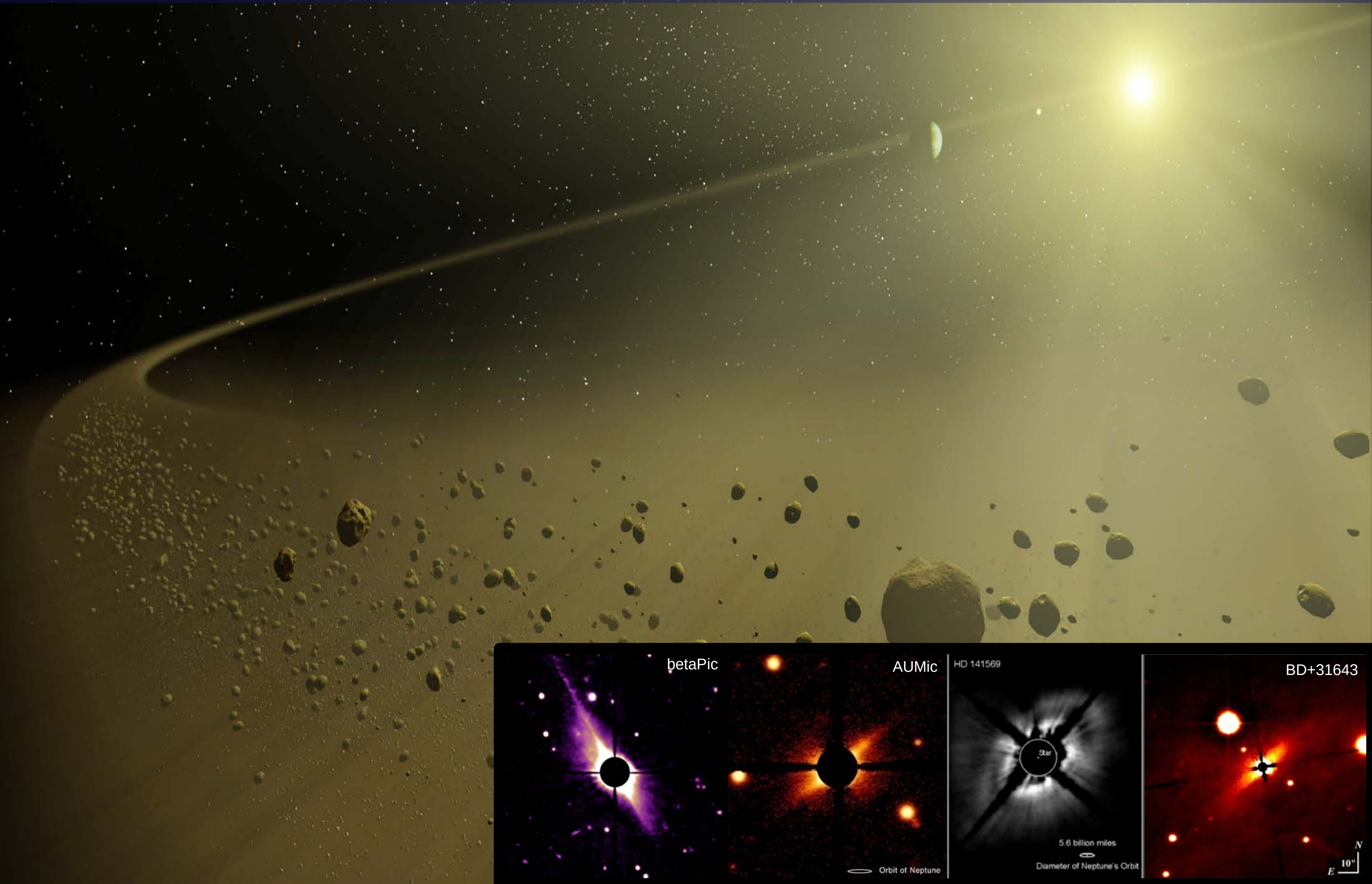
(Lada 1987)

Young circumstellar disks





Debris disks



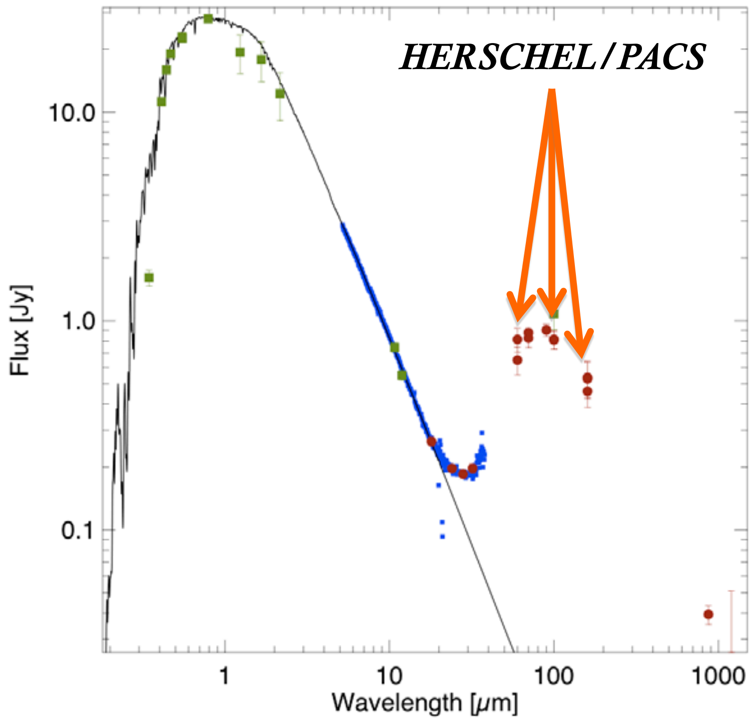
Exemplary study: q1 Eri

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

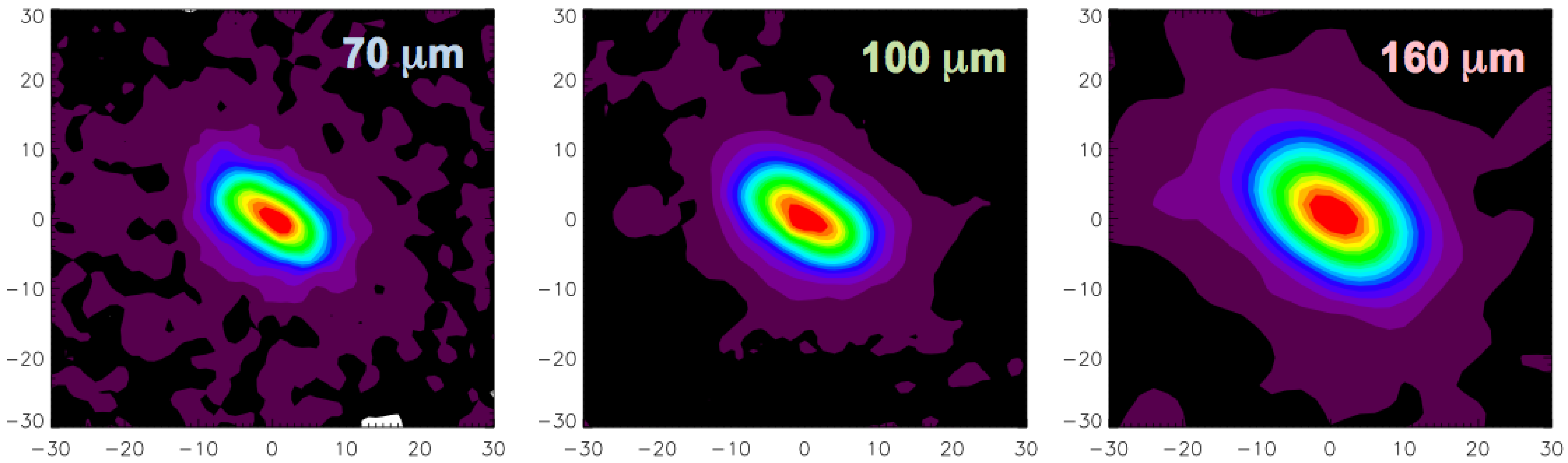


(LISEAU et al. 2010)

Dust ring

- IRAS, ISO and Spitzer: cold dust, with a luminosity ~1000 times that of the 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.)

Exemplary study: q1 Eri



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

Detailed <u>simultaneous</u> modeling of the SED and PACS images required to unveil the disk structure, dust properties and dynamical history

q1 Eri

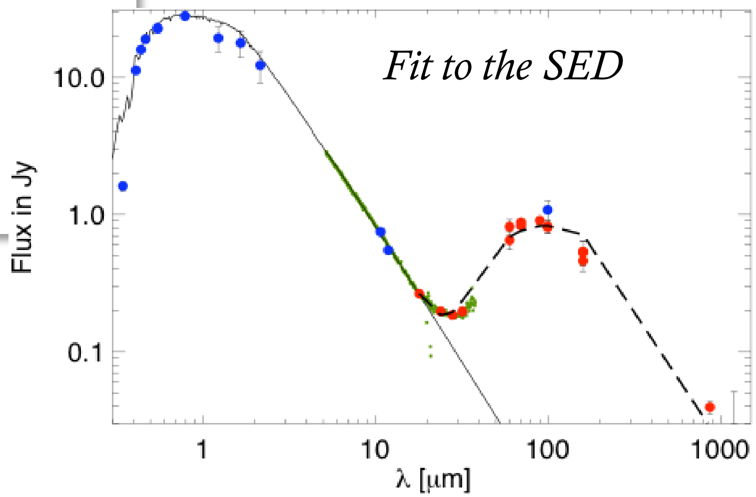
SAND

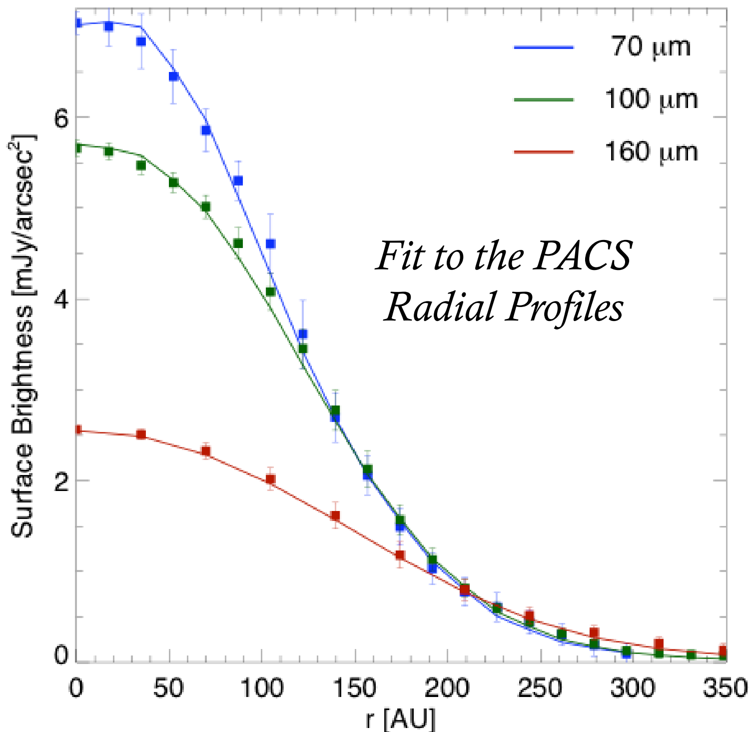
- Simulated annealing minimization scheme
- Fast: finds fit among ~10^{11} models in ~70 hours
- Large number of free parameters possible
- Limited initial constraints on disk physics

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

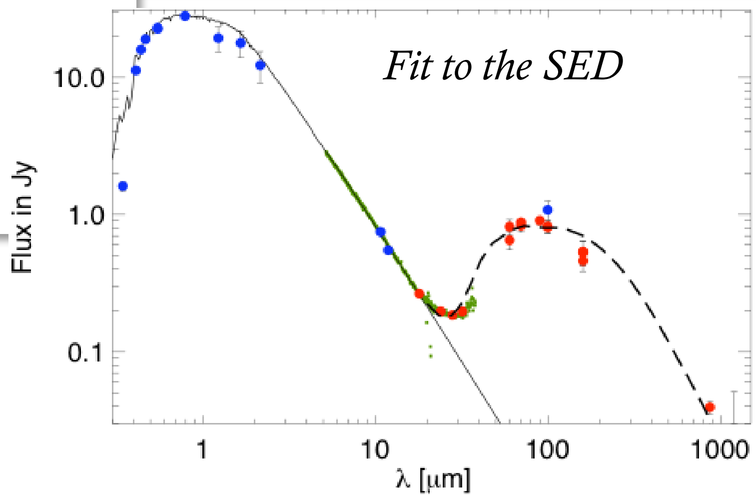




SAND

- 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

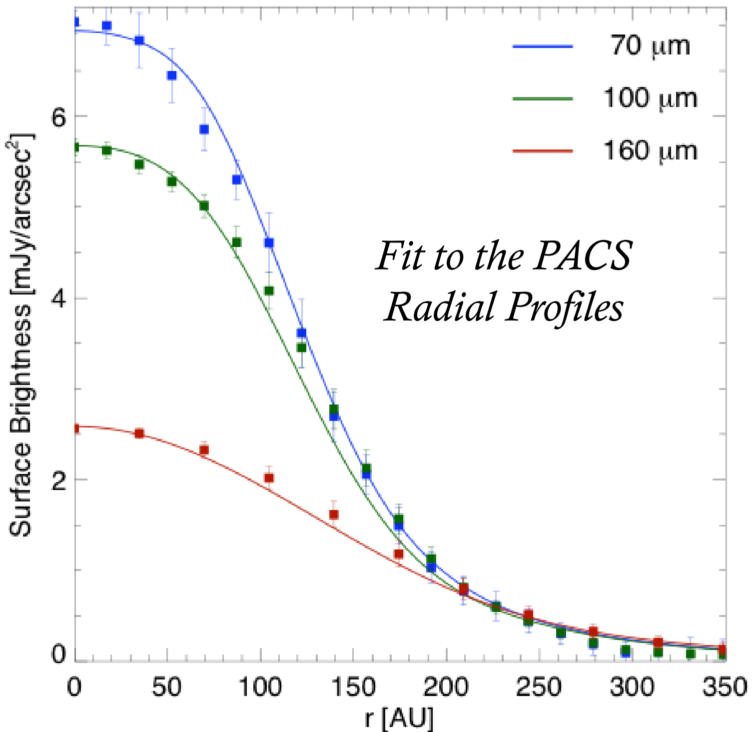
q1 Eri



Constraint:
Outer disk radius fixed to large value (600AU)

Best fit (χ_r^2 = 1.4):

- Dust disk :
  - Mass : 0.055 M_{Earth}
  - **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



What's next?

Multi-wavelength / Multi-scale intensity measurements

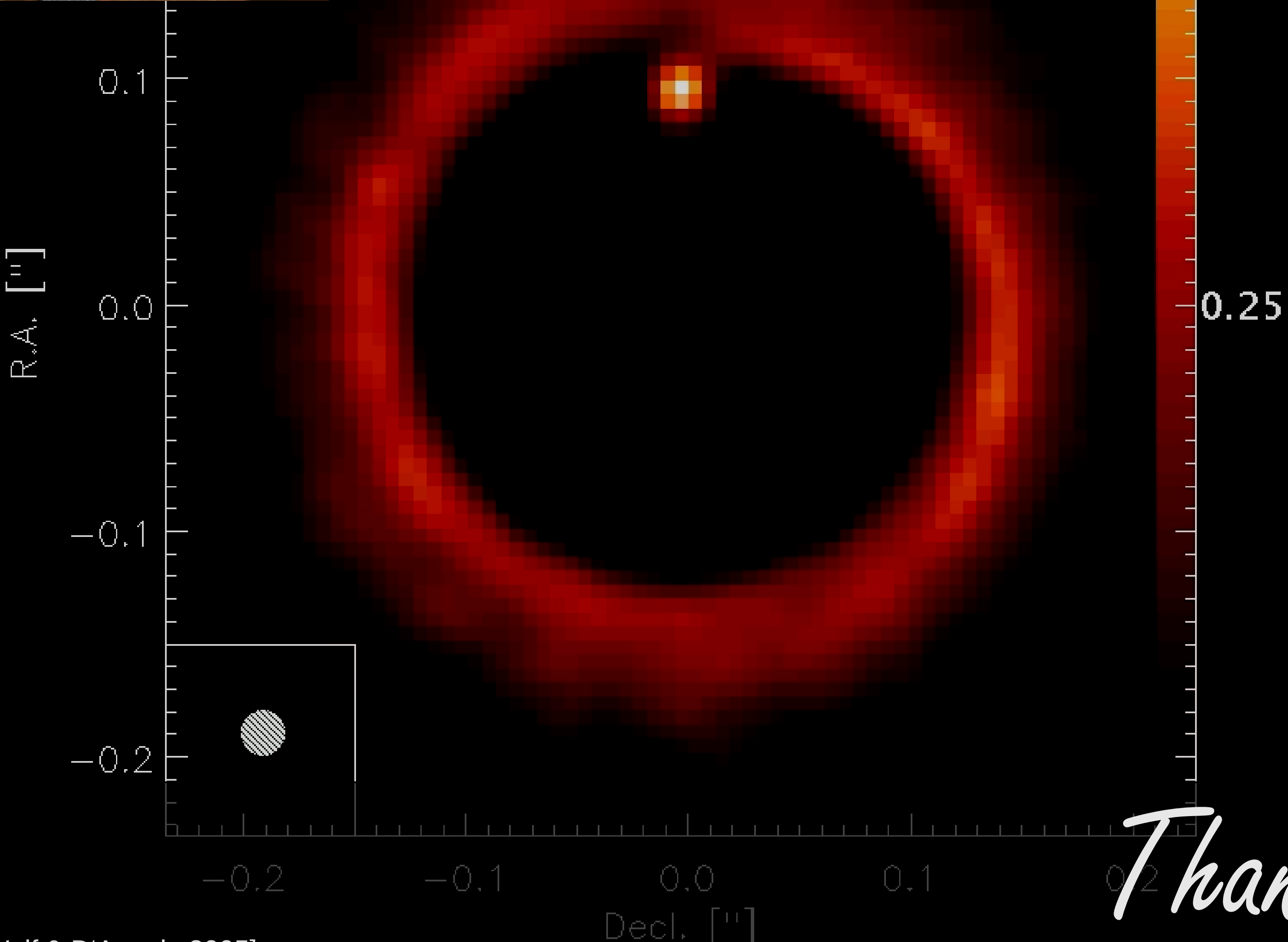
- Inner (<10AU) disk structure: Test of disk / planet formation evolution models
- Distribution of gas species

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.



[Wolf & D‘Angelo 2005]

Thank you.