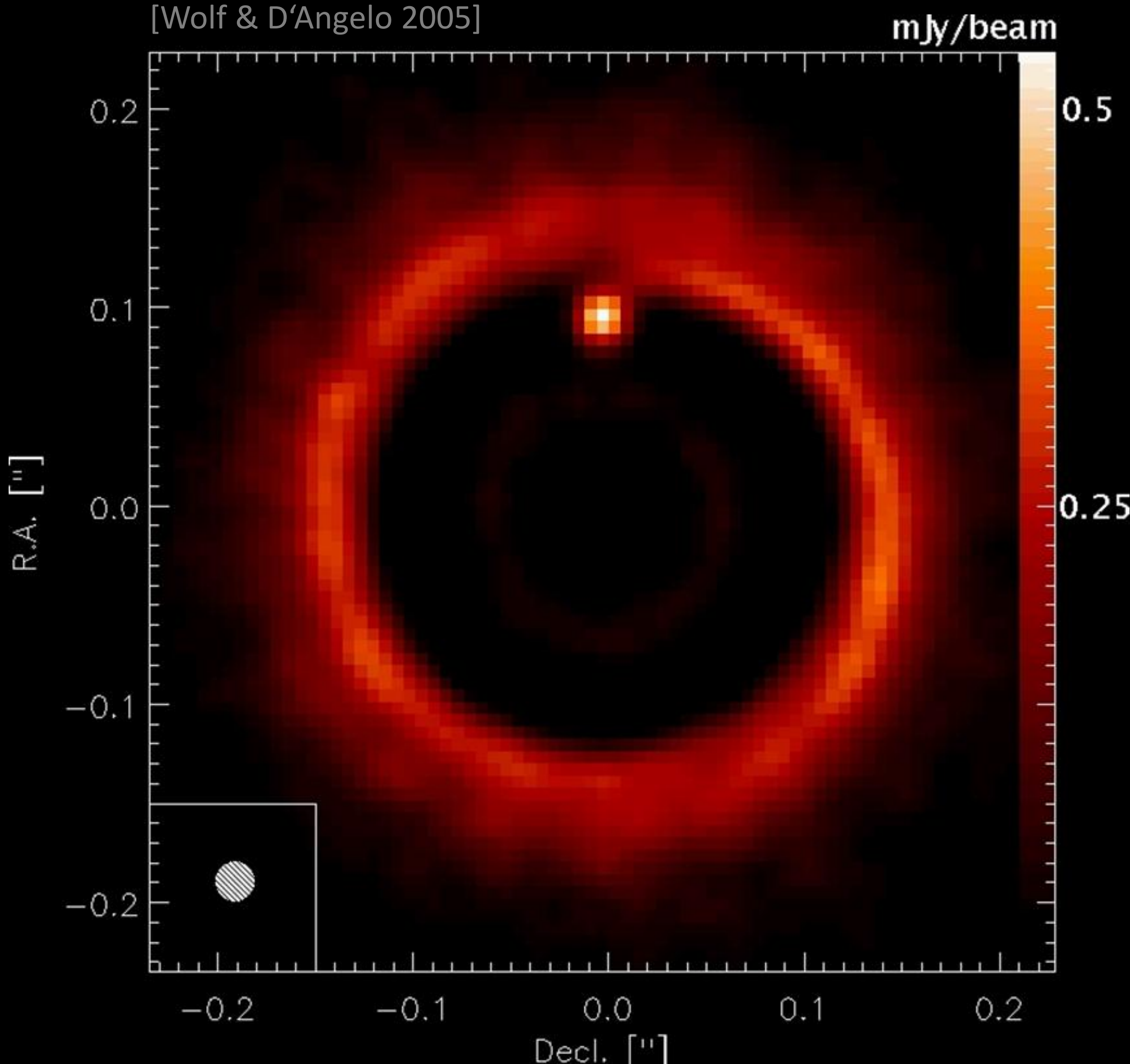
Searching for protoplanets

Sebastian Wolf
Kiel University, Germany

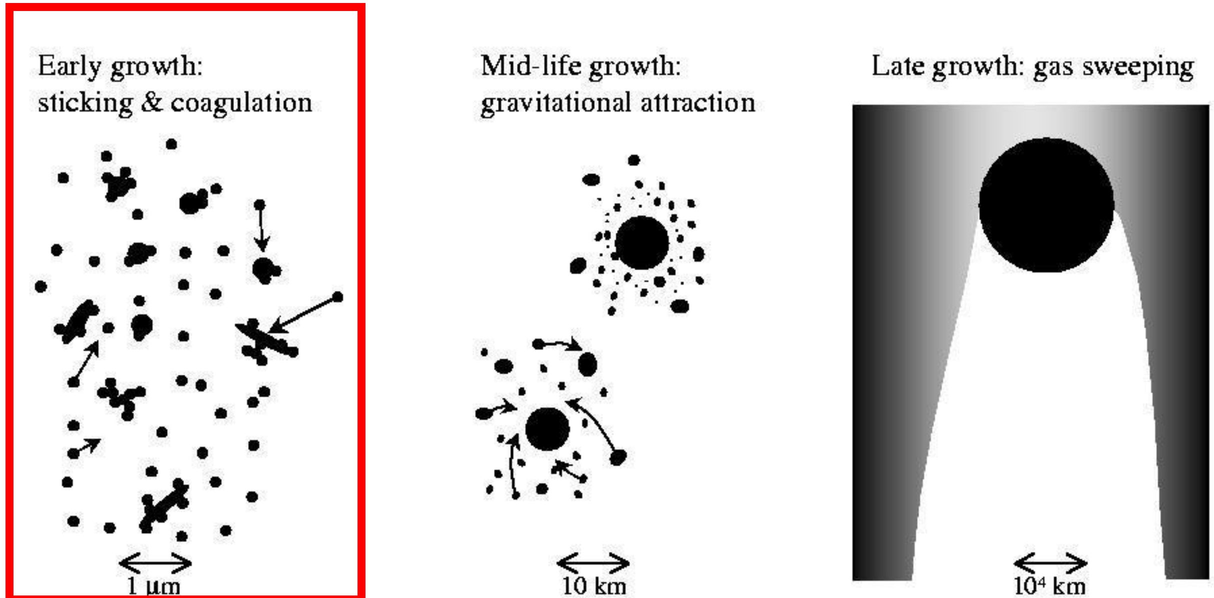
[Wolf & D‘Angelo 2005]



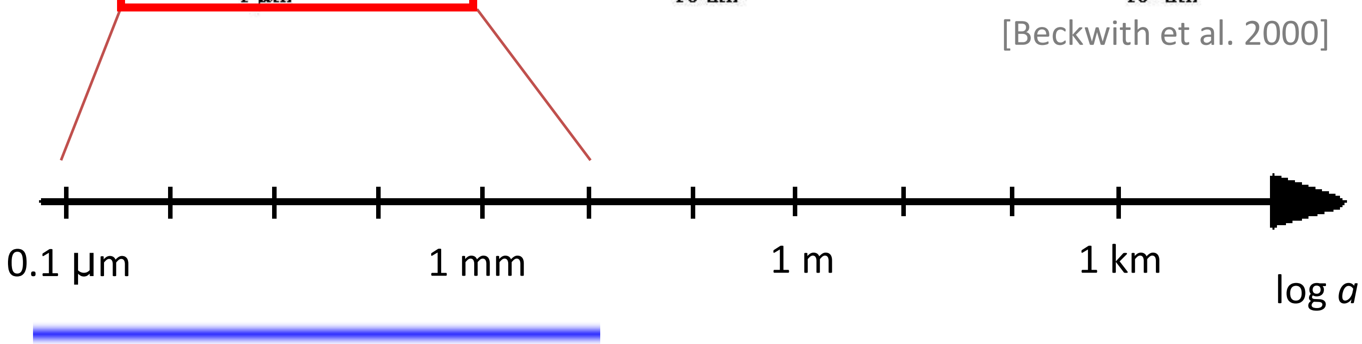
Constraints on the late stages of planet formation

Disk physics

Early stages



[Beckwith et al. 2000]



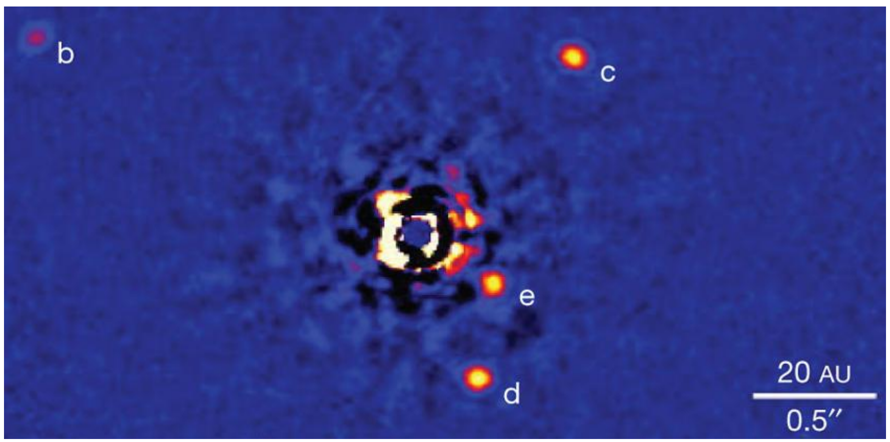
Particle size

≃

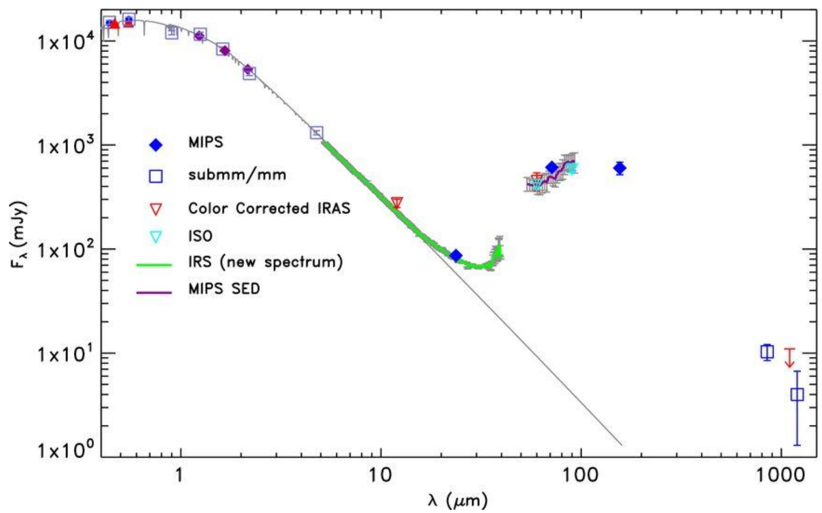
Observing wavelength

If the disk was less dominant …

- Problems:
  - UV/IR: Scattered stellar radiation; IR/mm: Thermal disk emission
  - Absorption (global: inclination dependent; local: circumplanetary environment)



HR 8799 [Marois et al. 2011]

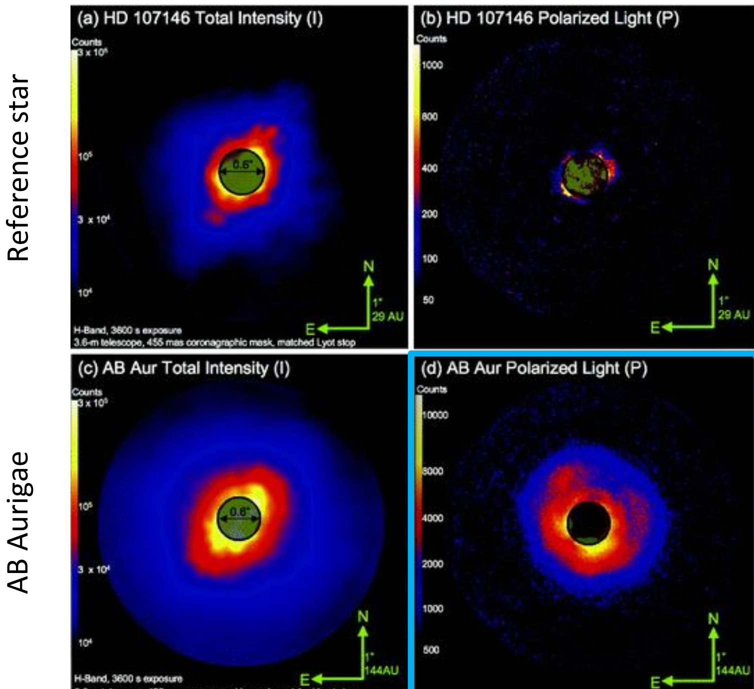


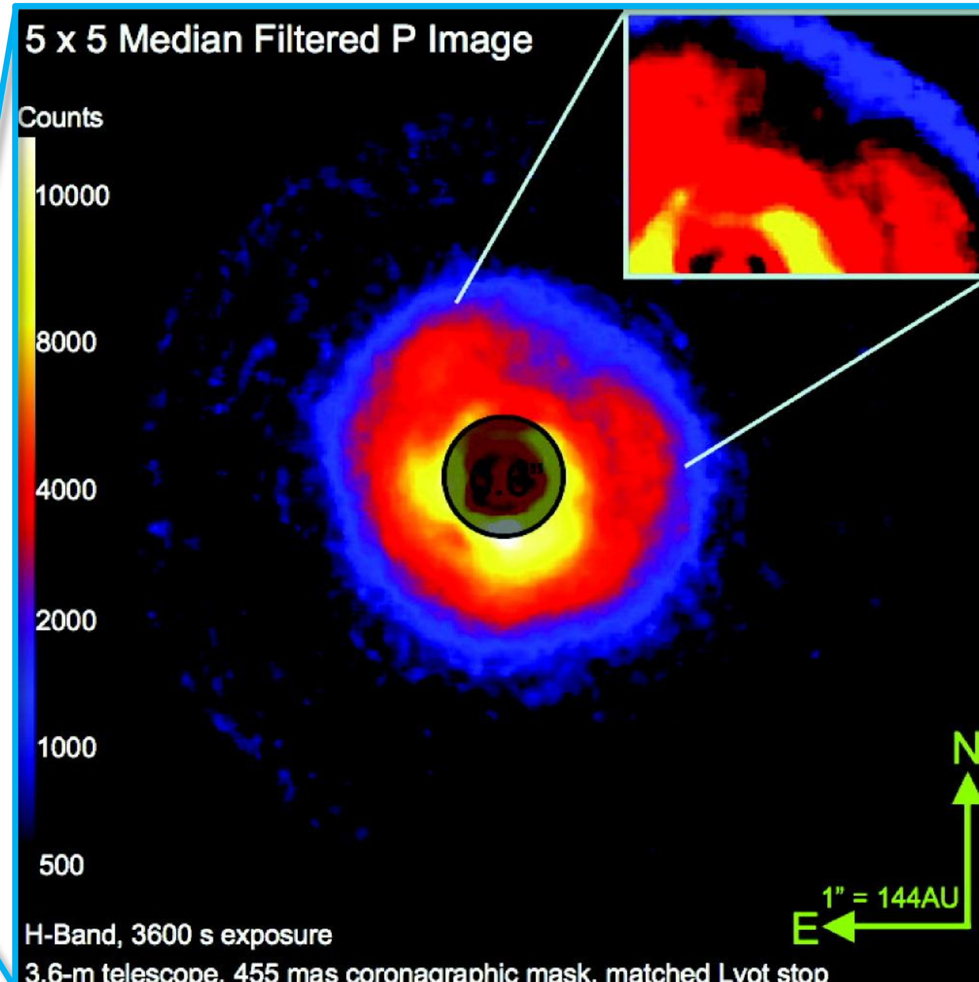
HR 8799 [Su et al. 2009]

- Direct detection throughout a broad wavelength range
  (even through radio wavelengths; attempts, e.g., HD 189733 b: Smith et al. 2009)

Status

Example 1: AB Aurigae





Geometrical scattering effect

[Perrin et al. 2009]

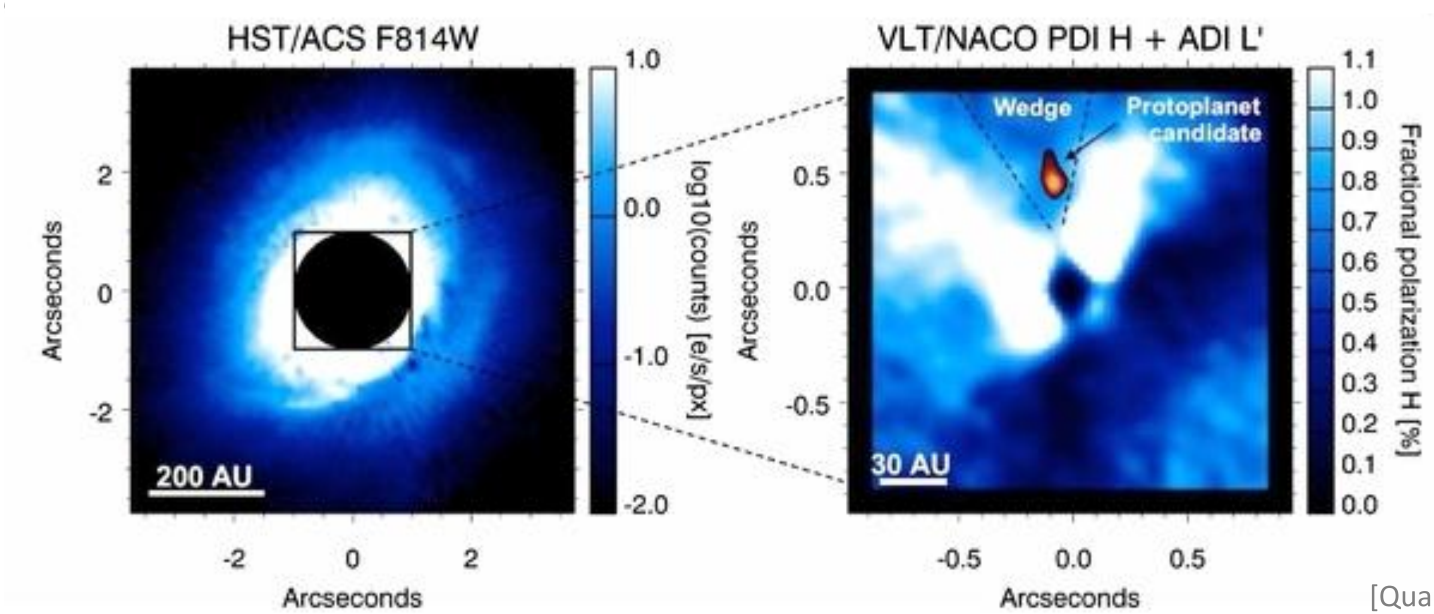
Polarized intensity: (color-coded) $P \cdot I = \sqrt{Q^2 + U^2}$

(Oppenheimer et al., 2008)

H band (3.63m AEOS telescope, Maui)

Status

Example 2: HD 100546

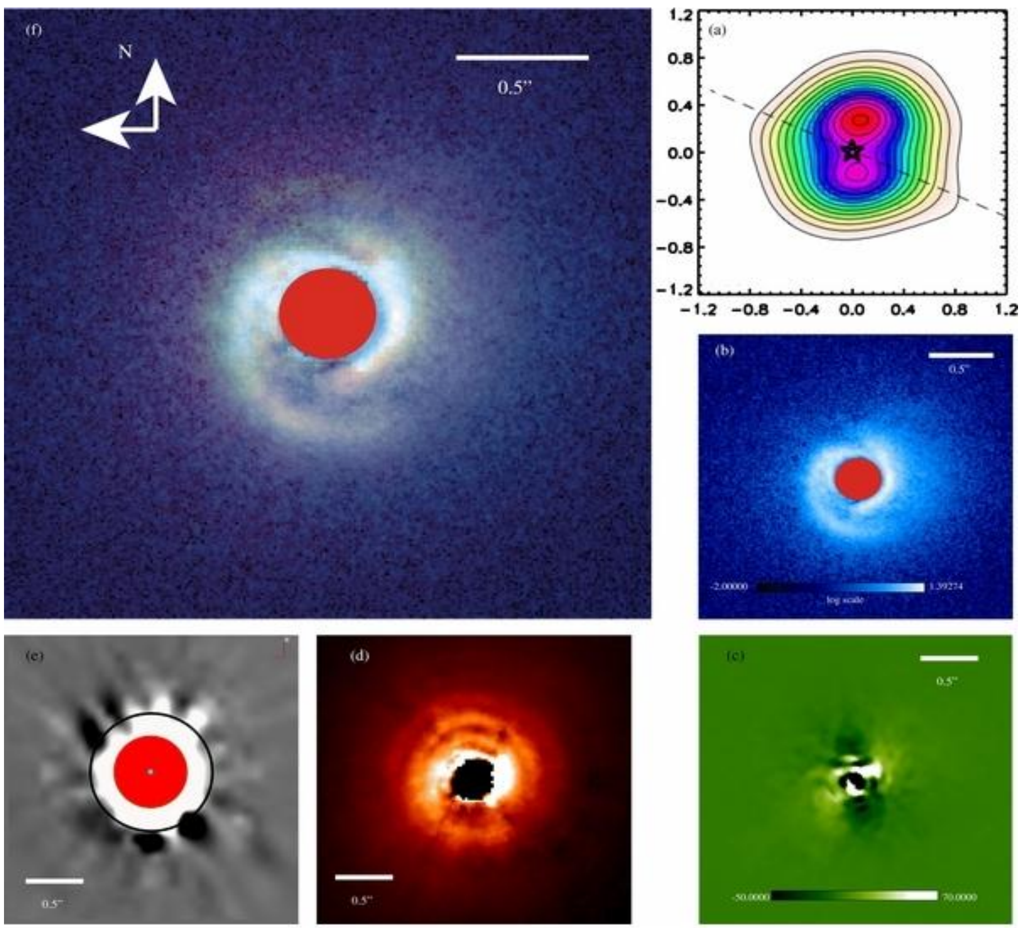


[Quanz et al. 2013]

- De-projected separation of the object ~68 AU
- L_{min} ~ 10^{-4} L_{Sun}
  - For comparison: 4 × 10^{-4}–10^{-2} L_{Sun} during the first few hundred-thousand years after gas runaway accretion sets in (Mordasini et al. 2012)
- To be confirmed:
  - Common proper motion
  - Orbital motion
  - ALMA: Azimuthal gap?

Tabula rasa …

- Star + Planet + Disk: Gravitational interaction
- Result: Characteristic disk structures



Disk of MWC 758:

(a) 880 µm continuum after Isella et al. (2010), the dashed line indicates the disk semimajor axis,

(b) *H*-band polarized intensity,

(c) K_s data with conservative LOCI processing,

(d) *K*' intensity with conservative LOCI processing,

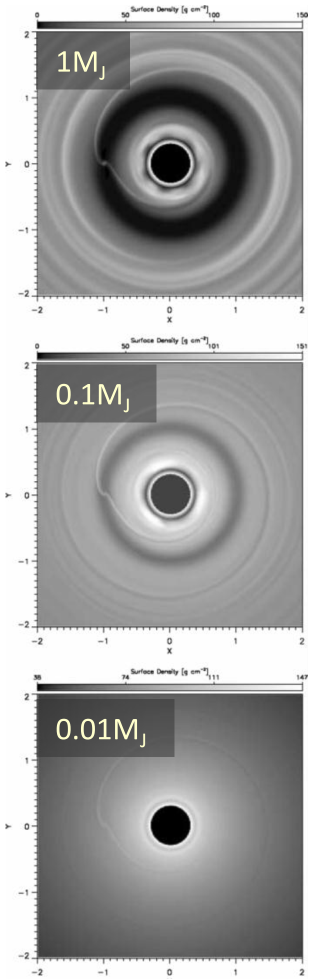
(e) *HST*/NICMOS total intensity data following PSF subtraction,

(f) Color composite of H PI and *K*' data.

[Grady et al. 2013]

Tabula rasa …

- Gaps, spiral density waves
- Structures = f (stellar, planetary, and **disk parameters**)



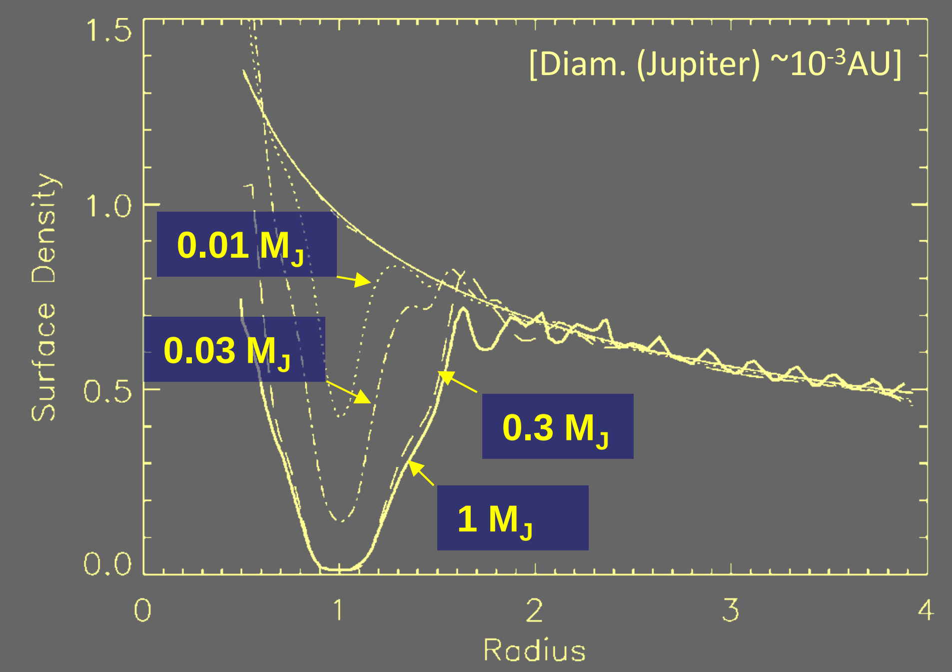
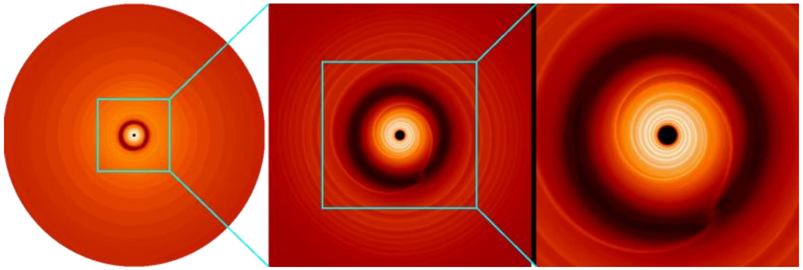
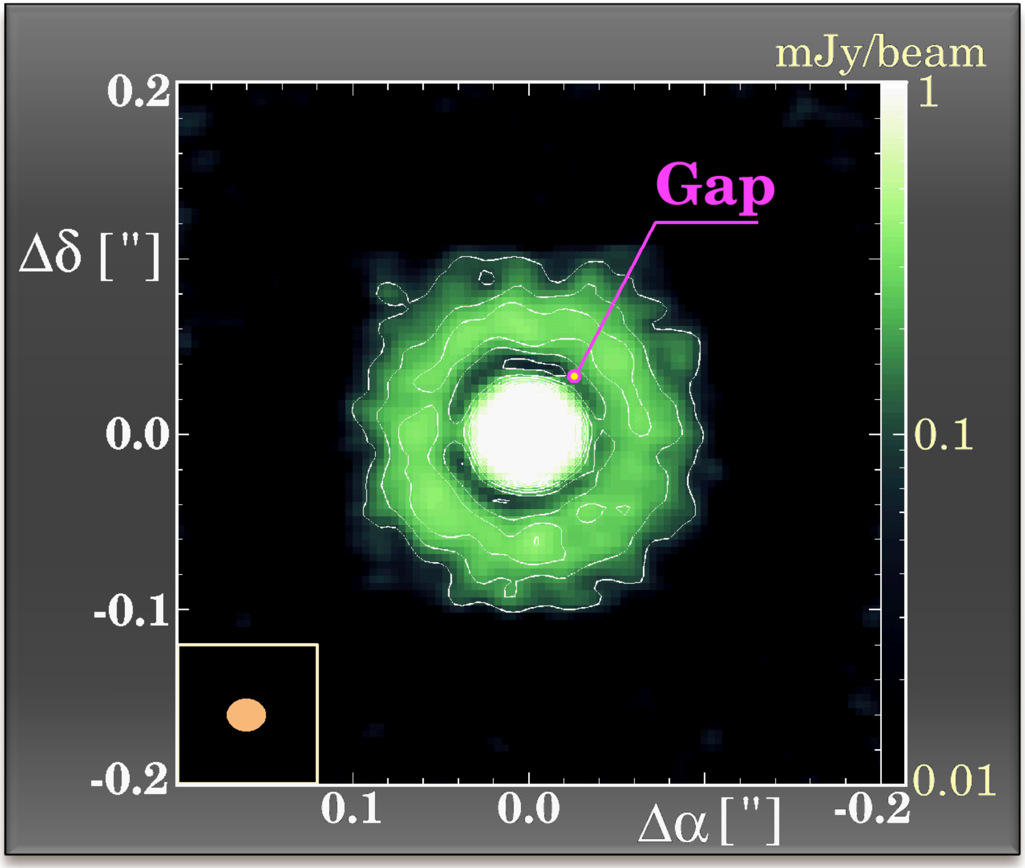


Figure 2. The final azimuthally averaged disc surface density for planets with masses of 1 (long-dashed), 0.3 (dot-dashed), 0.1 (dotted), 0.03 (short-dashed) and 0.01 (thin solid) M_J. Only planets with masses $M_p \gtrsim 0.1\ M_J$ ($M_p \gtrsim 30\ M_\oplus$) produce significant perturbations. The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

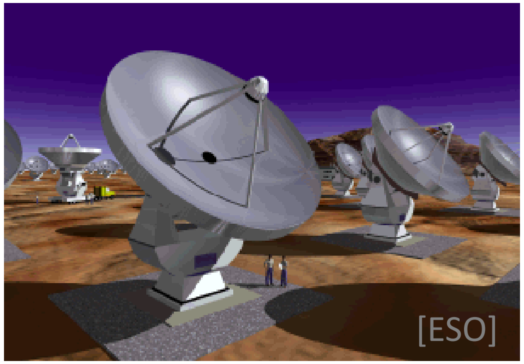
[Bate et al. 2003]

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

[Wolf et al. 2001]

Gaps: A systematic preparatory study

[Ruge, et al., 2013]

1. 3D HD- and MHD disc models (PLUTO)
2. Follow-up radiative transfer (MC3D)
3. Predictions on the observability (CASA)

Model space

Self-similar disc models

Disc size is scaled (outer radius: 9AU … 225AU)

Disc mass:

1. $M = 2.67 \times 10^{-7 \cdots -2}\,\mathrm{M}_\odot$
2. Masses from cut-outs of the Butterfly-star disc ($M_{\mathrm{total}} = 0.07\,\mathrm{M}_\odot$) (Wolf et al. 2003)

Central stars

Spectral type	**L** [$L_\odot$]	**T**$_{\mathrm{eff}}$ [K]
K	0.35	4500
G	1	6000
F	7.5	6900
A	20	8500
T Tauri	0.95	4000
Herbig Ae	43	9500

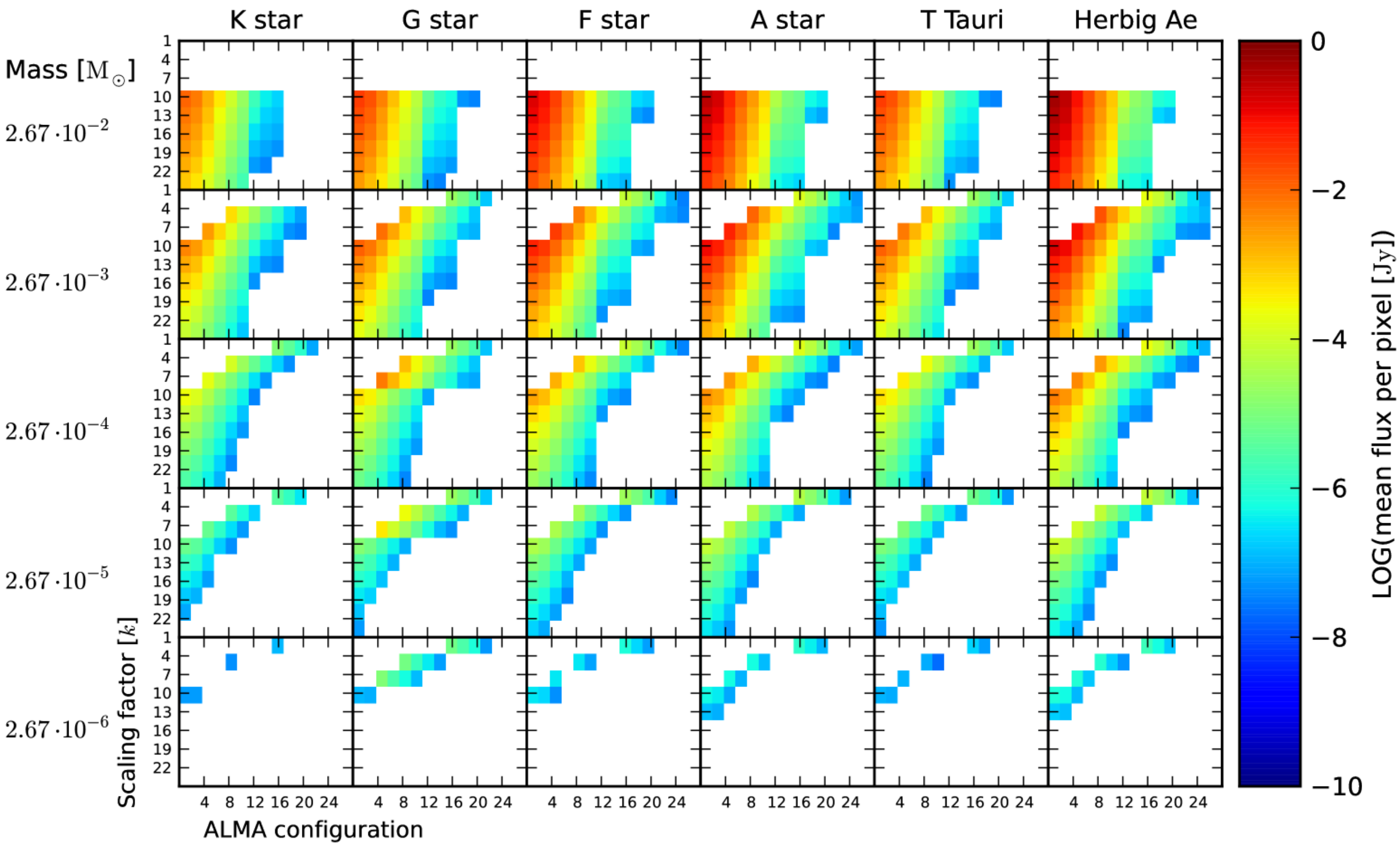
Additional parameters

Parameter	**Value**
Exp. time	$^1/_2$h, 2h, 8h
14 ALMA conf.	just even
7 wavelengths	$\lambda_{\mathrm{min}} = 330\,\mu\mathrm{m}$
	$\lambda_{\mathrm{max}} = 3300\,\mu\mathrm{m}$

+ further variable parameters *(e.g., grain size distribution, Star/Planet mass ratio)*

Detect and resolve an unperturbed disc at 430μm

[Ruge, et al., 2013]



[HD disc model, large dust grains, 2h exposure time]

Detect and resolve an unperturbed disc at 430μm

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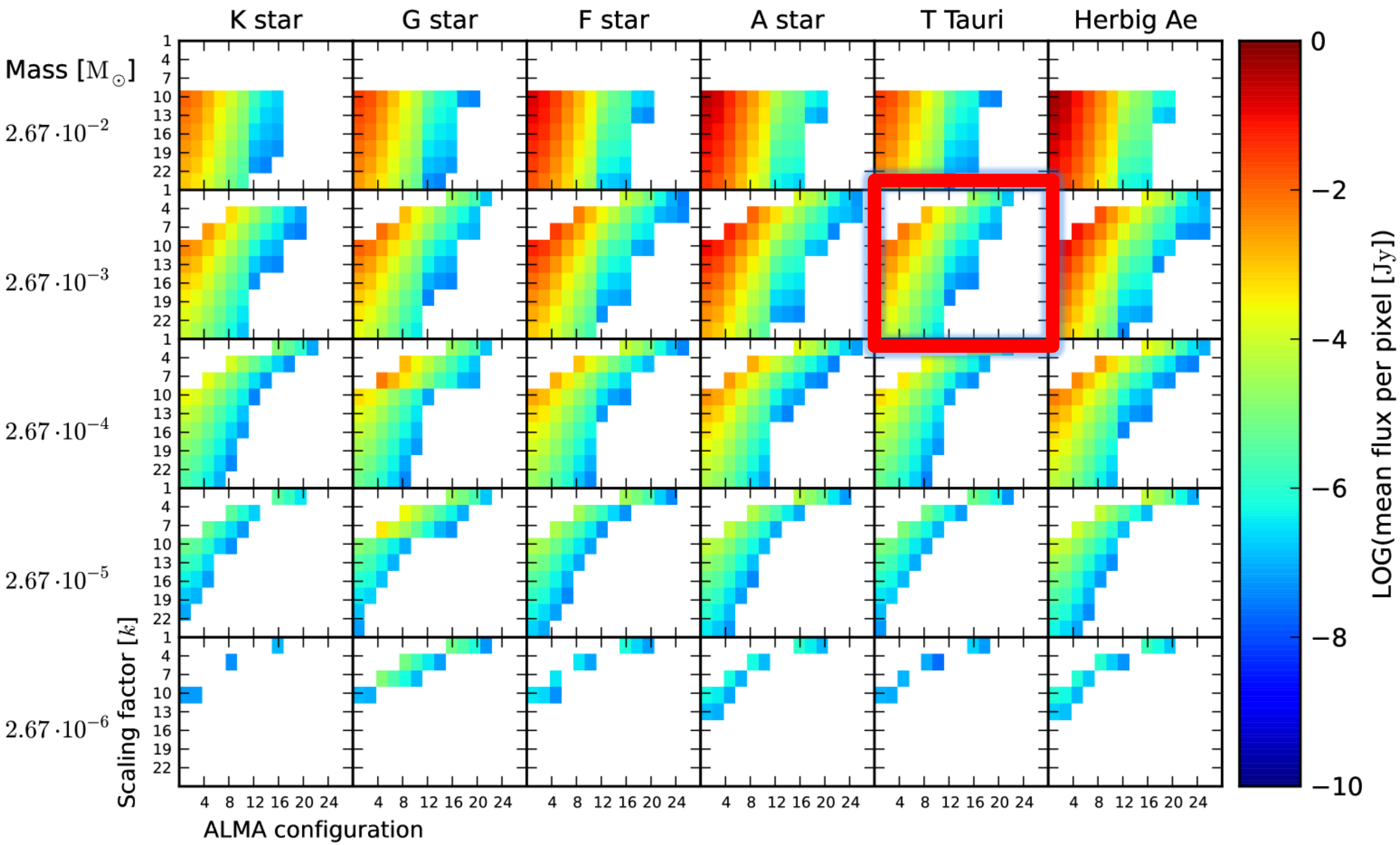
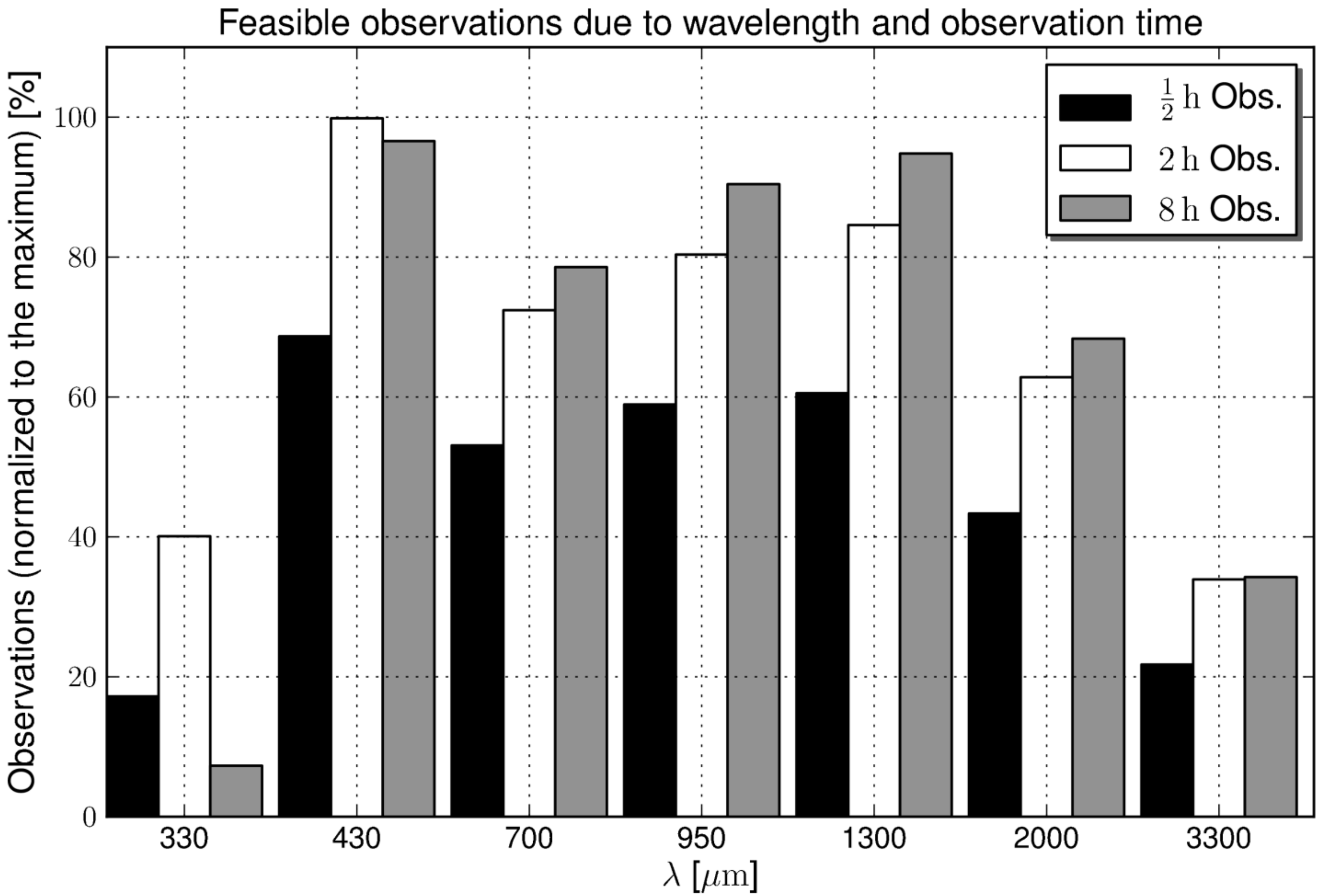


[HD disc model, large dust grains, 2h exposure time]

Impact of the observing wavelength and exposure time

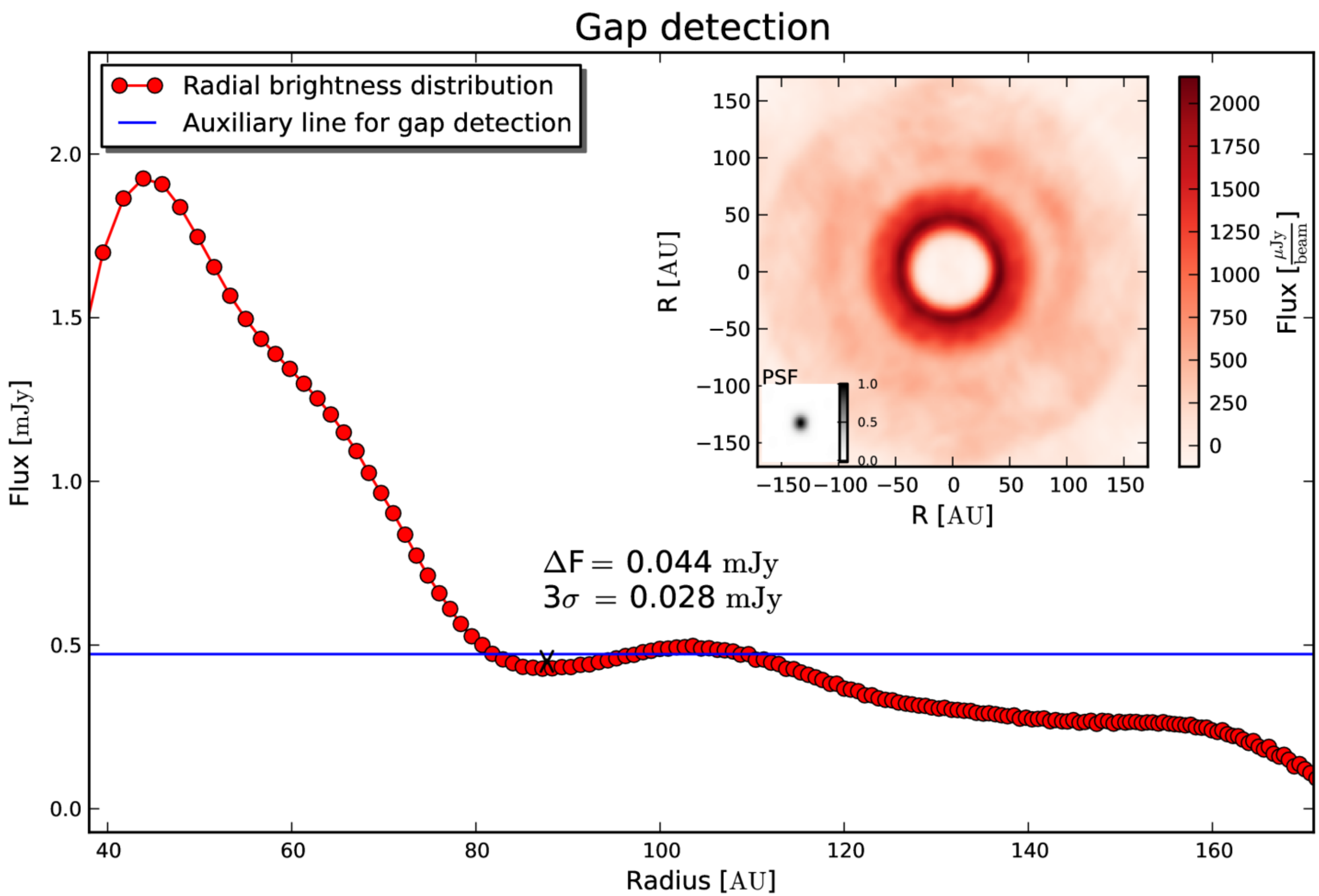
[Ruge, et al., 2013]



[all disc models, central stars, disc sizes and masses and both grain sizes]

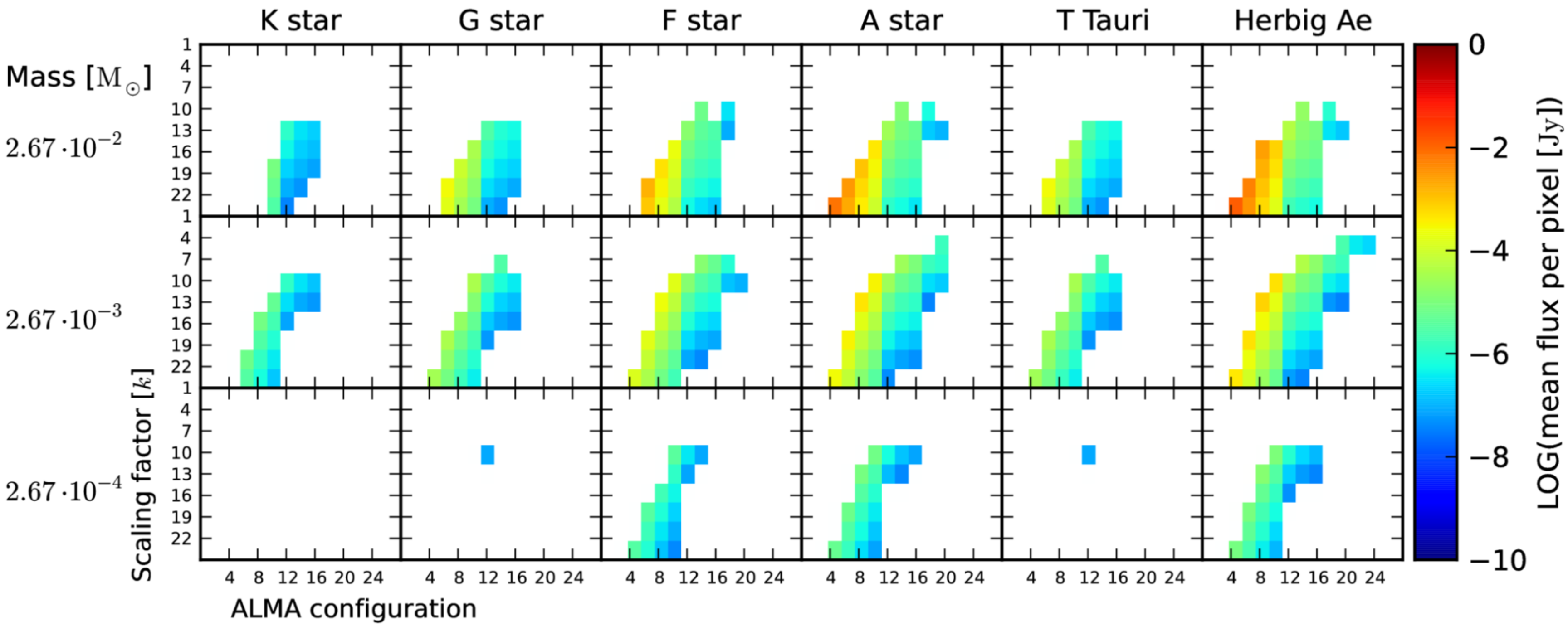
How to detect a gap?

[Ruge, et al., 2013]



Trace a planet-induced gap at 430μm

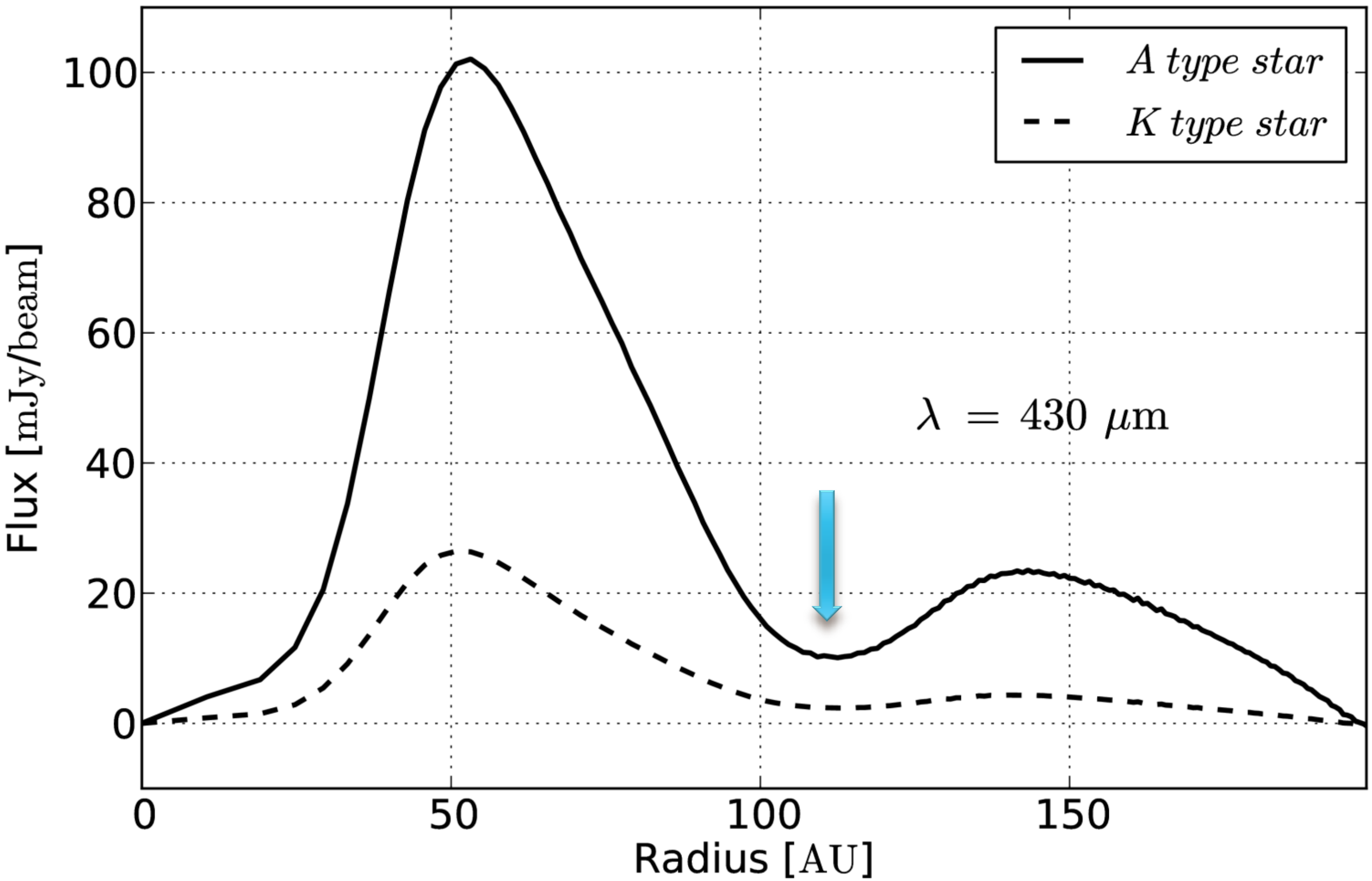
[Ruge, et al., 2013]



Large dust grains, 2h exposure time, $M_P/M_* = 10^{-3}$ (HD)

Impact of the central star

[Ruge, et al., 2013]



Observing gaps in disks: Summary

Results of this study are available at

Ruge, et al. (2013) A&A 549, A97

Database: **www1.astrophysik.uni-kiel.de/~placid**

Further issues to consider:

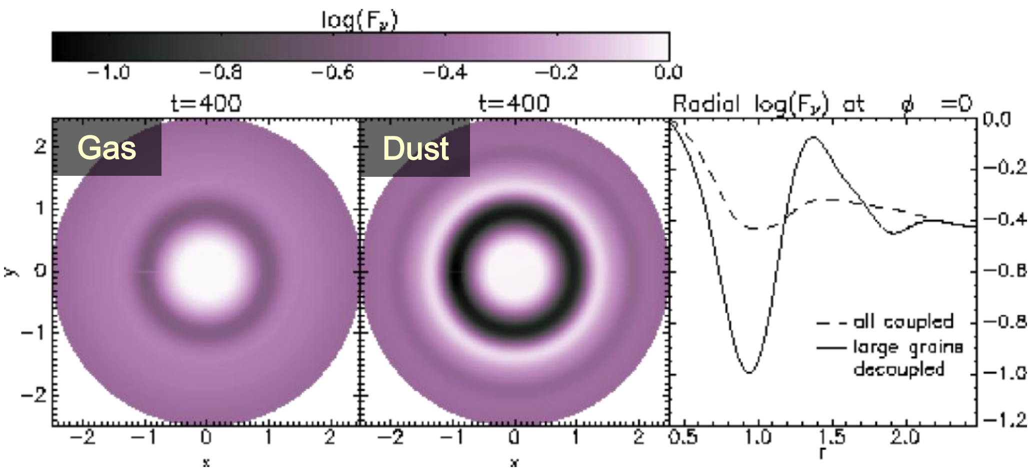


Fig. 3. Logarithm of flux densities at 1 mm, normalized by the maximum and convolved with a Gaussian of FWHM 2.5 AU, corresponding to a resolution of 12 mas at 140 pc. Left panel: all particles follow the gas exactly (static dust evolution). Middle panel: particles larger than the critical size decouple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

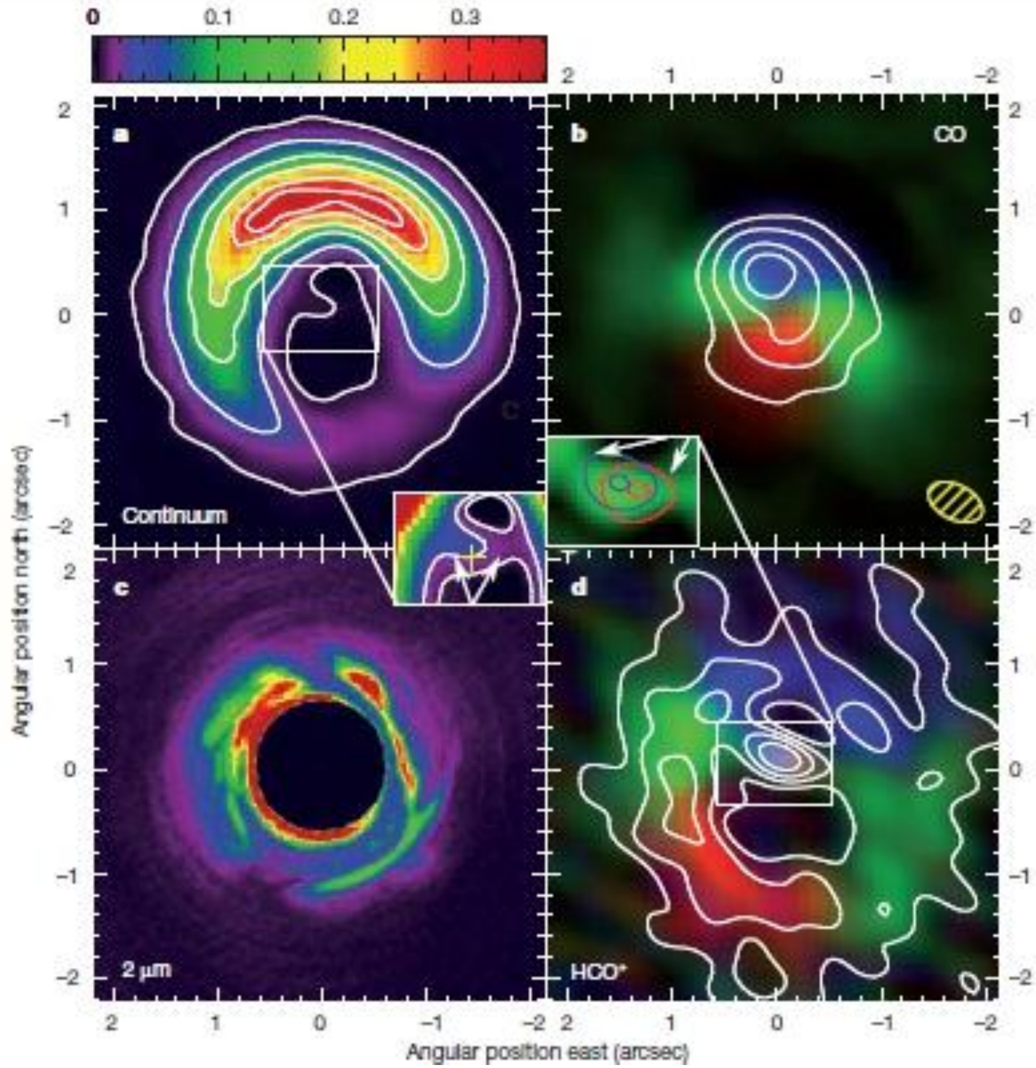
see also

Fouchet et al. (2010), Gonzales et al. (2012; ALMA case study)

Gas vs. dust distribution: Flow through gap

HD 142527
(d=140pc)

- Inner disk r~10AU, surrounded by a particularly large gap, and a disrupted outer disk beyond 140 AU
- Disruption is indicative of a perturbing planetary-mass body at ~90 AU
- Observations of diffuse CO gas inside the gap, with denser HCO^+ gas along gap-crossing filaments



[Casassus et al., 2012]

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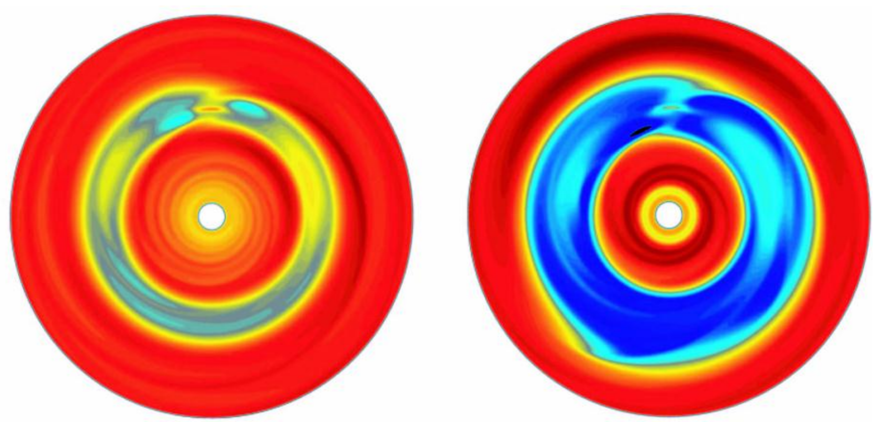


Log Density in MHD simulations after 100 planet orbits for planets with relative masses of $q=1x10^{-3}$ and $5x10^{-3}$

[Winters et al. 2003]

(see also Ruge et al. 2013)

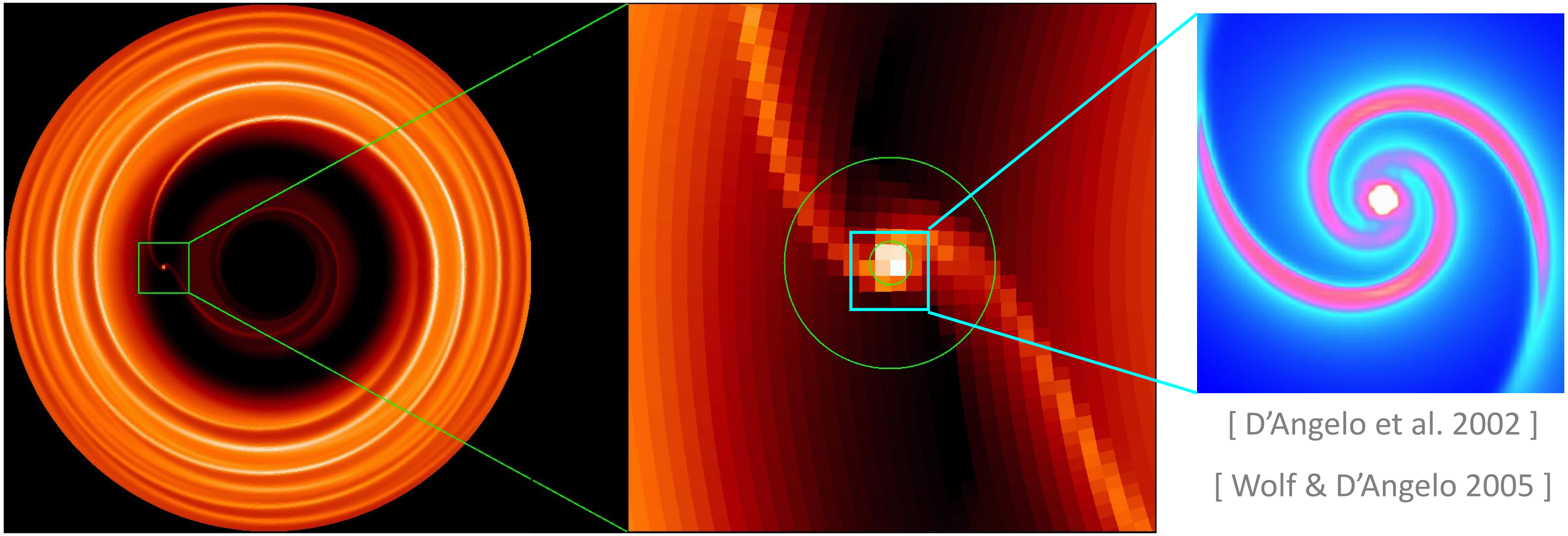
MHD simulations :

Gaps are shallower and asymmetrically wider;

Rate of gap formation is slowed

Observations of gaps will allow constraining the physical conditions in circumstellar disks

Local environment of proto-planets

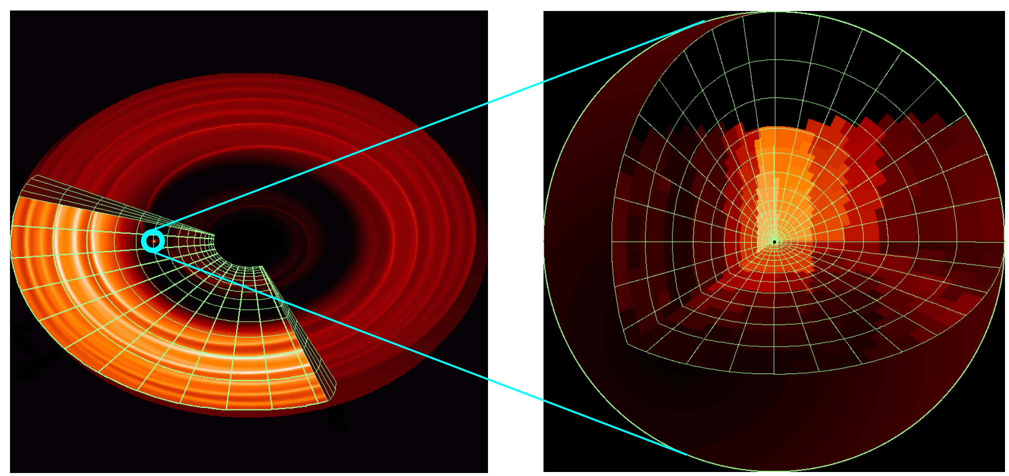


[D'Angelo et al. 2002]

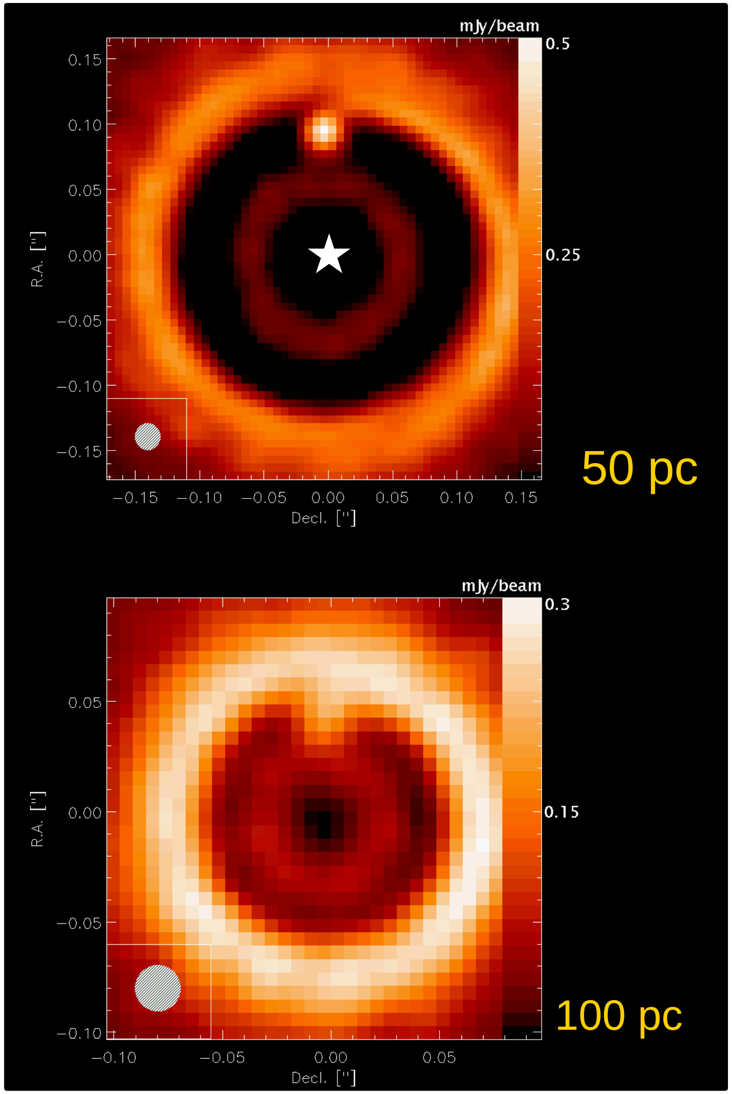
[Wolf & D'Angelo 2005]

Procedure

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



Tracing proto-planets with ALMA



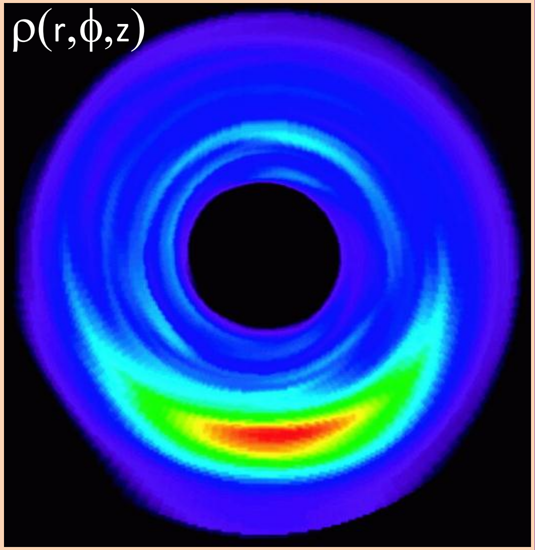
[Wolf & D'Angelo 2005]

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

Vortices – Precursors of Protoplanets?



Klahr & Bodenheimer (2002)

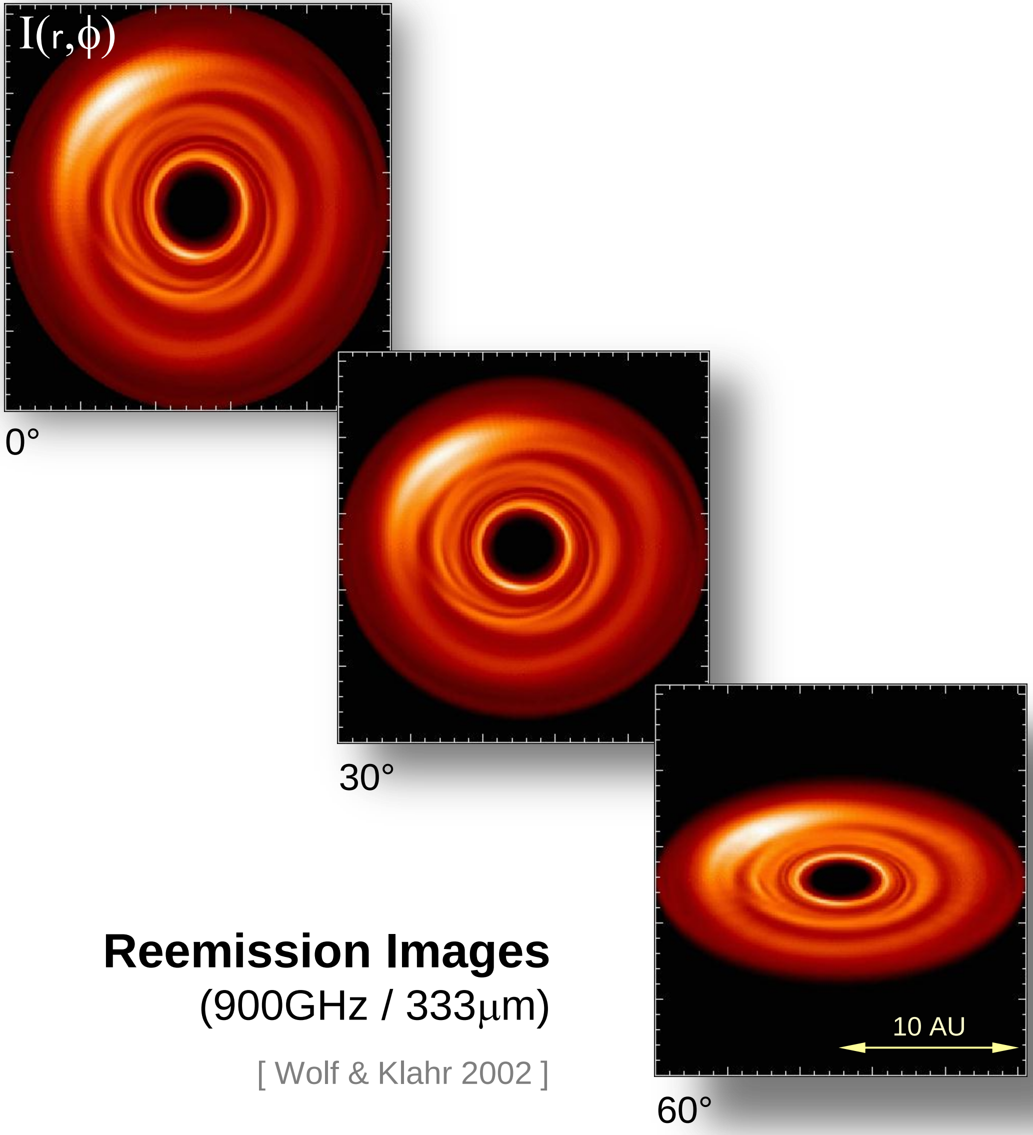
Global baroclinic instability

↓

Turbulence

↓

Long-lived high-pressure overdense anticyclones



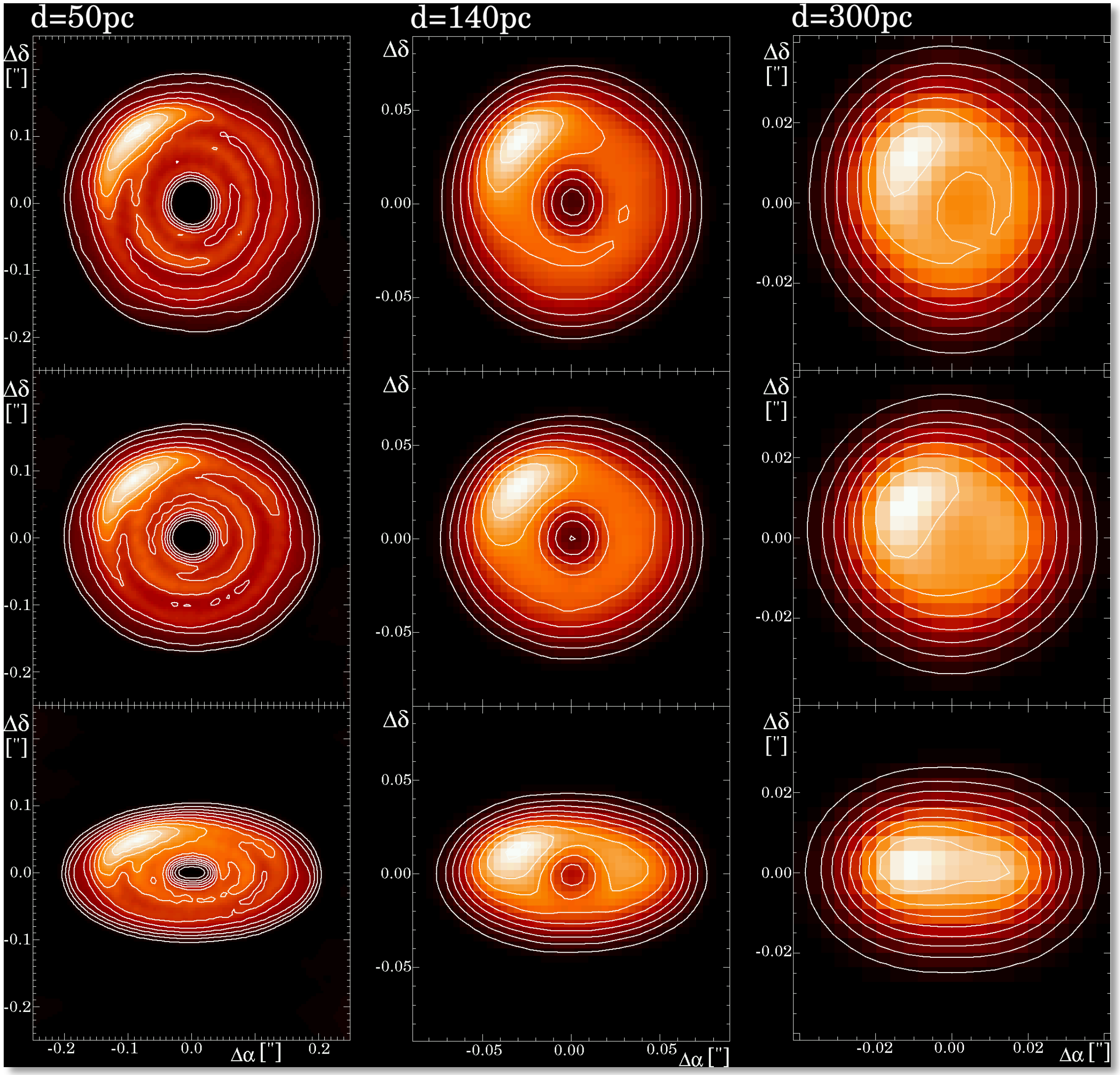
Reemission Images
(900GHz / 333μm)

[Wolf & Klahr 2002]

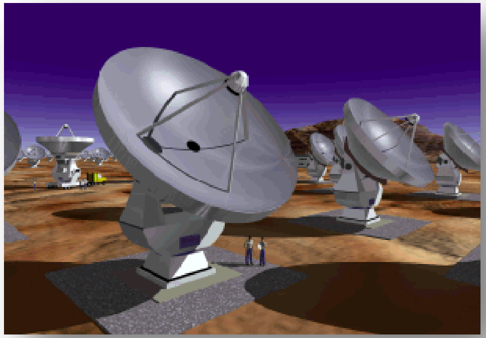
Vortices – Precursors of Protoplanets?

[Wolf & Klahr 2002]

Disk inclination



50mas 50mas 50mas



Simulation: ALMA

Baseline: 13km, 64 antennas

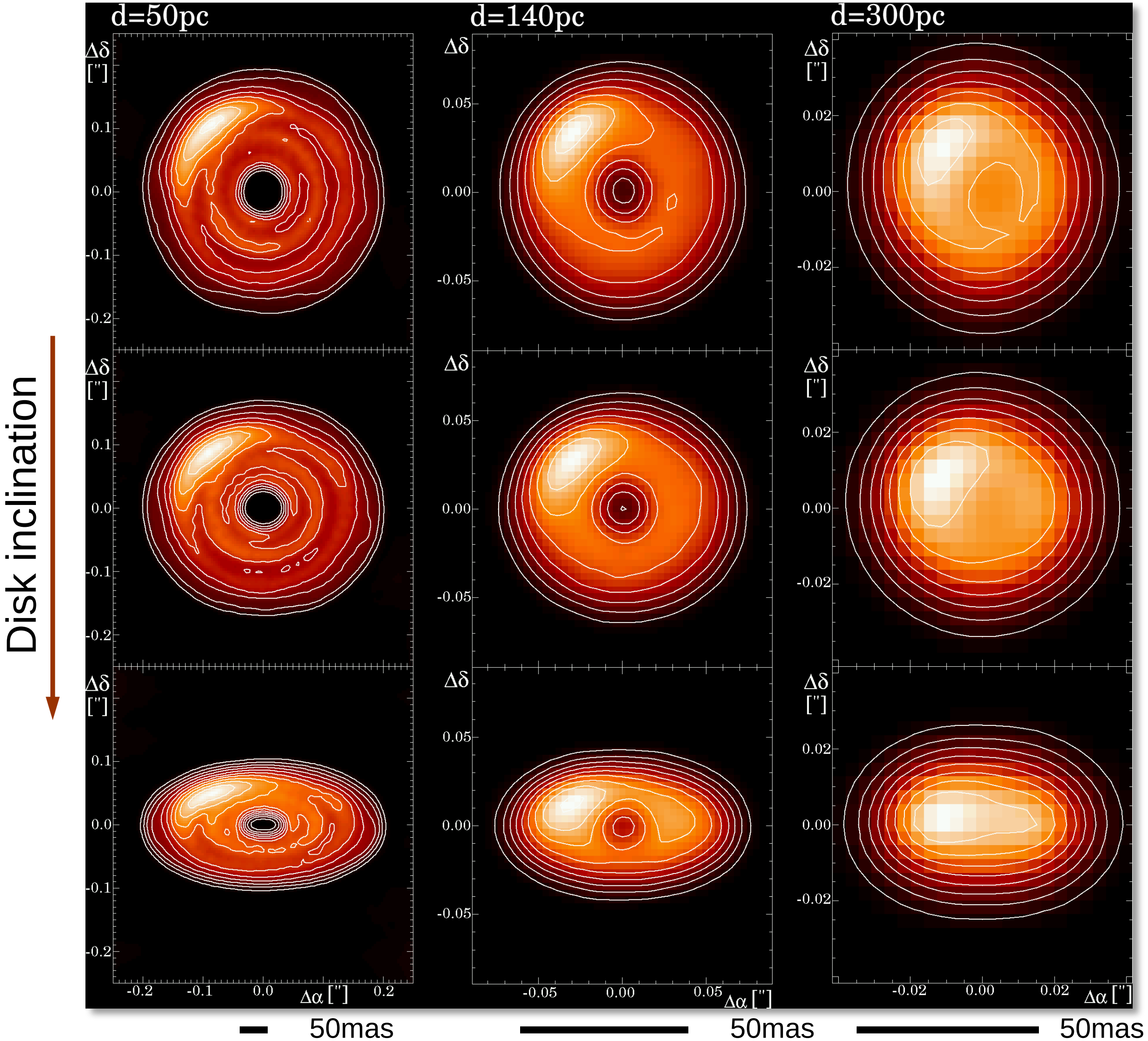
900GHz, Integration time 2hrs

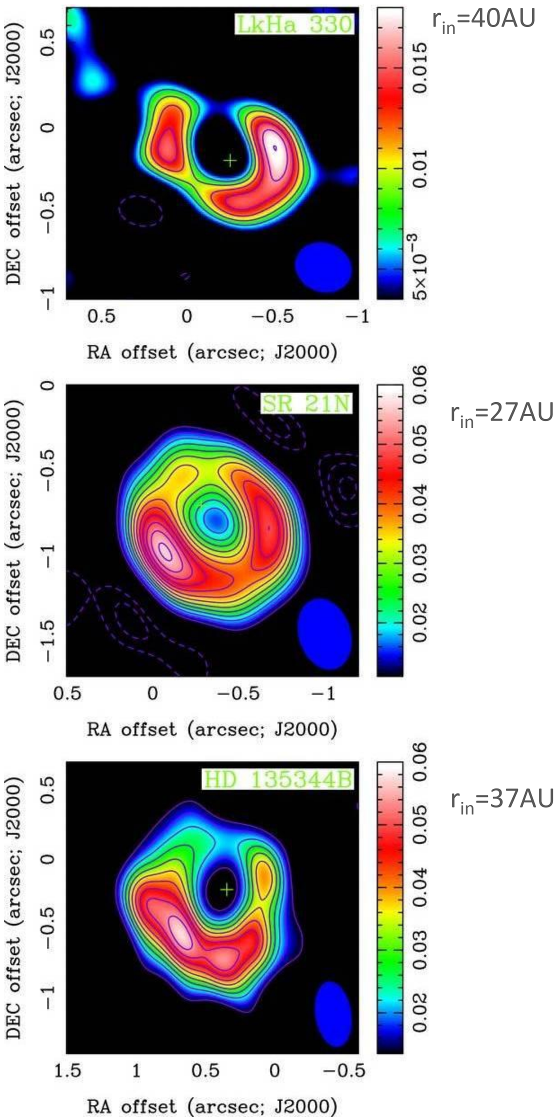
↓

Disk survey possible

Vortices – Precursors of Protoplanets?

[Wolf & Klahr 2002]

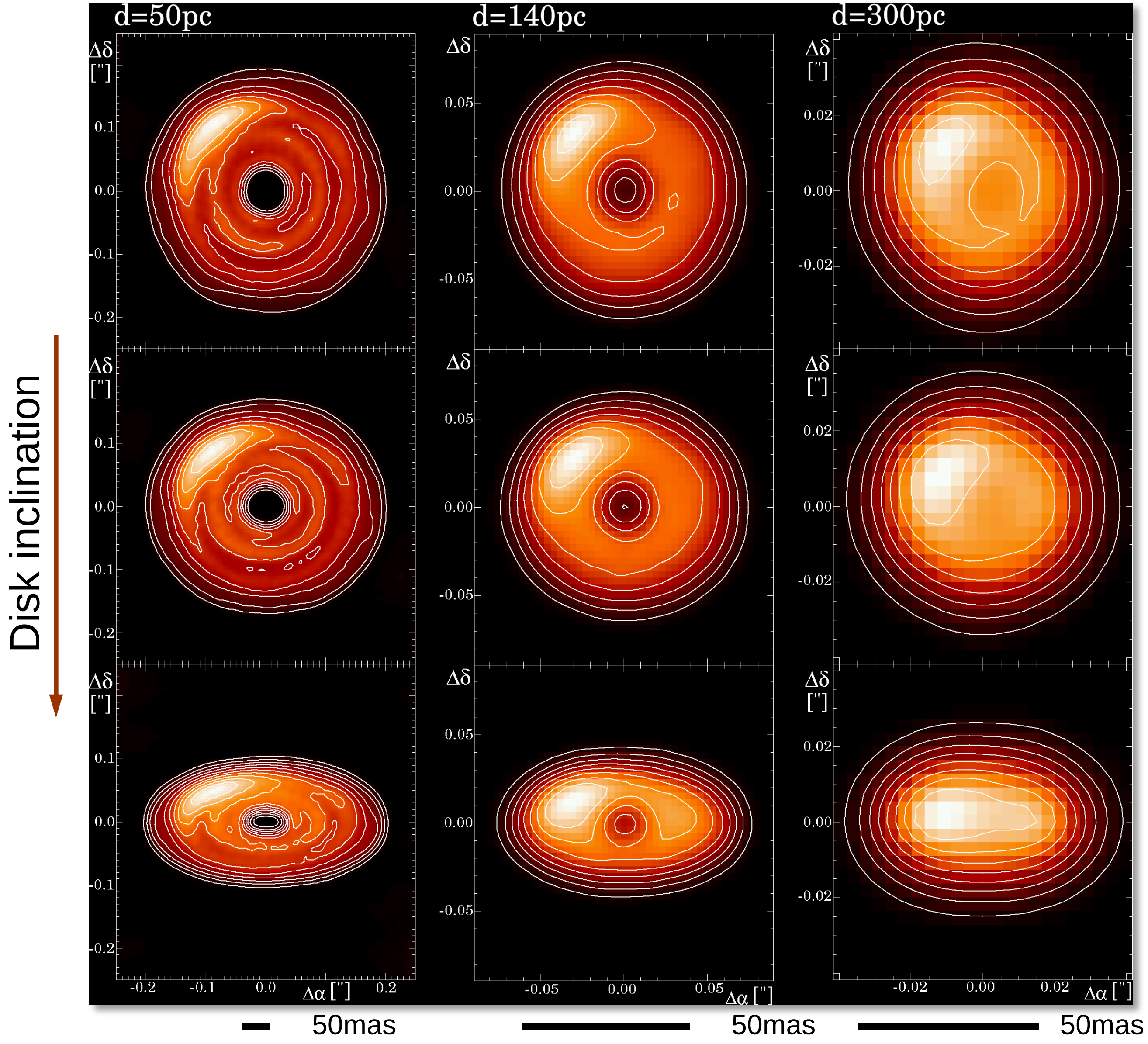




[Brown et al. 2009: 340GHz; see also Andrews et all. 2011]

Vortices – Precursors of Protoplanets?

[Wolf & Klahr 2002]



see also

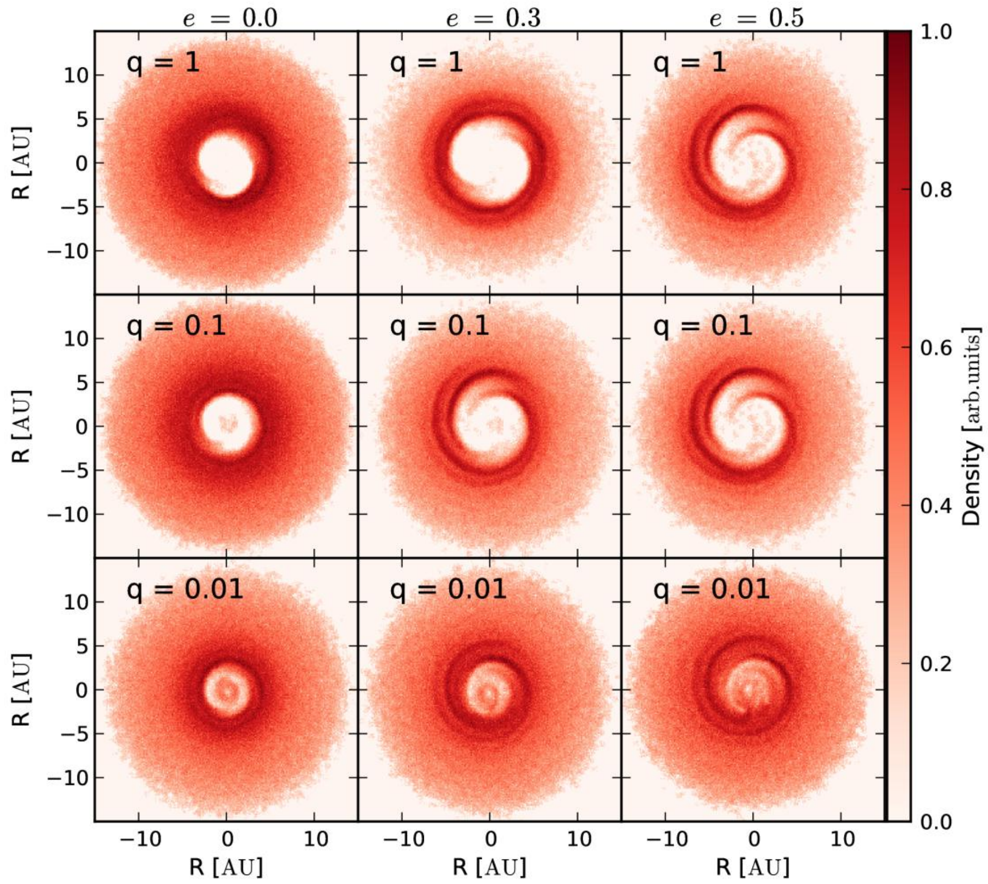
F. Menard
this conference

Regaly et al. (2012)
Submm imaging (Simulations)

Jang-Condell & Boss (2007):
Simulated scattered light images of a disk in which a planet is forming by gravitational instability. Simulated images bear no correlation to the vertically integrated surface density of the disk, but rather trace the density structure in the tenuous upper disk layers

Planets – Vortices – Binary systems

[Ruge, et al., in prep.]



Exemplary disk density distributions

Large-scale disk structures resulting from binary-disk interaction

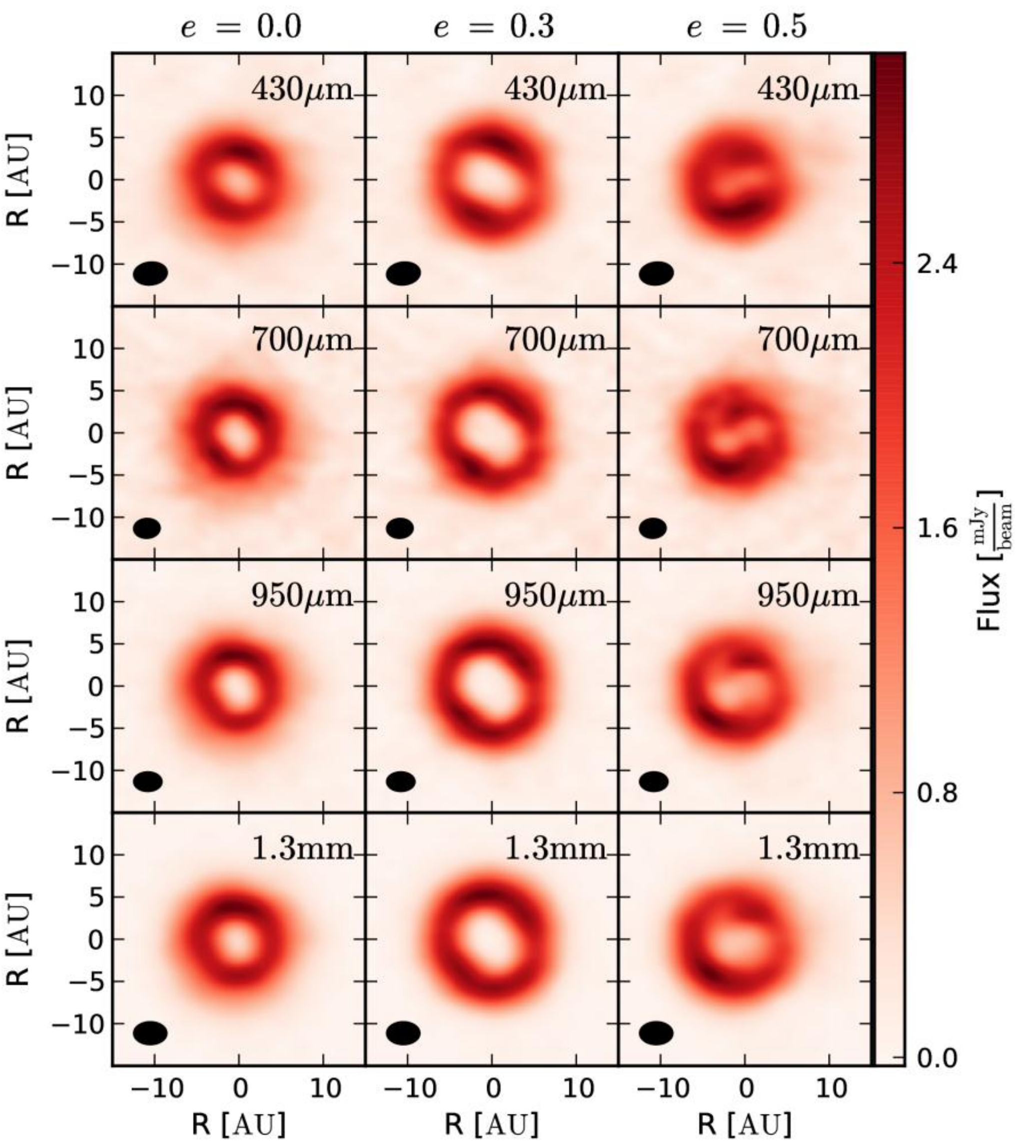
- Density distribution from SPH simulations
- D~ 140 pc, declination: 20°

- ALMA: Asymmetries at the inner edge of the disks + *potentially* resolve spiral arms if the disk is seen face-on

- ALMA will allow one also to detect perturbations in the disk density distribution through asymmetries in the edge-on brightness profile

Planets – Vortices – Binary systems

[Ruge, et al., in prep.]



Simulated ALMA maps

Large-scale disk structures resulting from binary-disk interaction

- Density distribution from SPH simulations
- D~ 140 pc, declination: 20°

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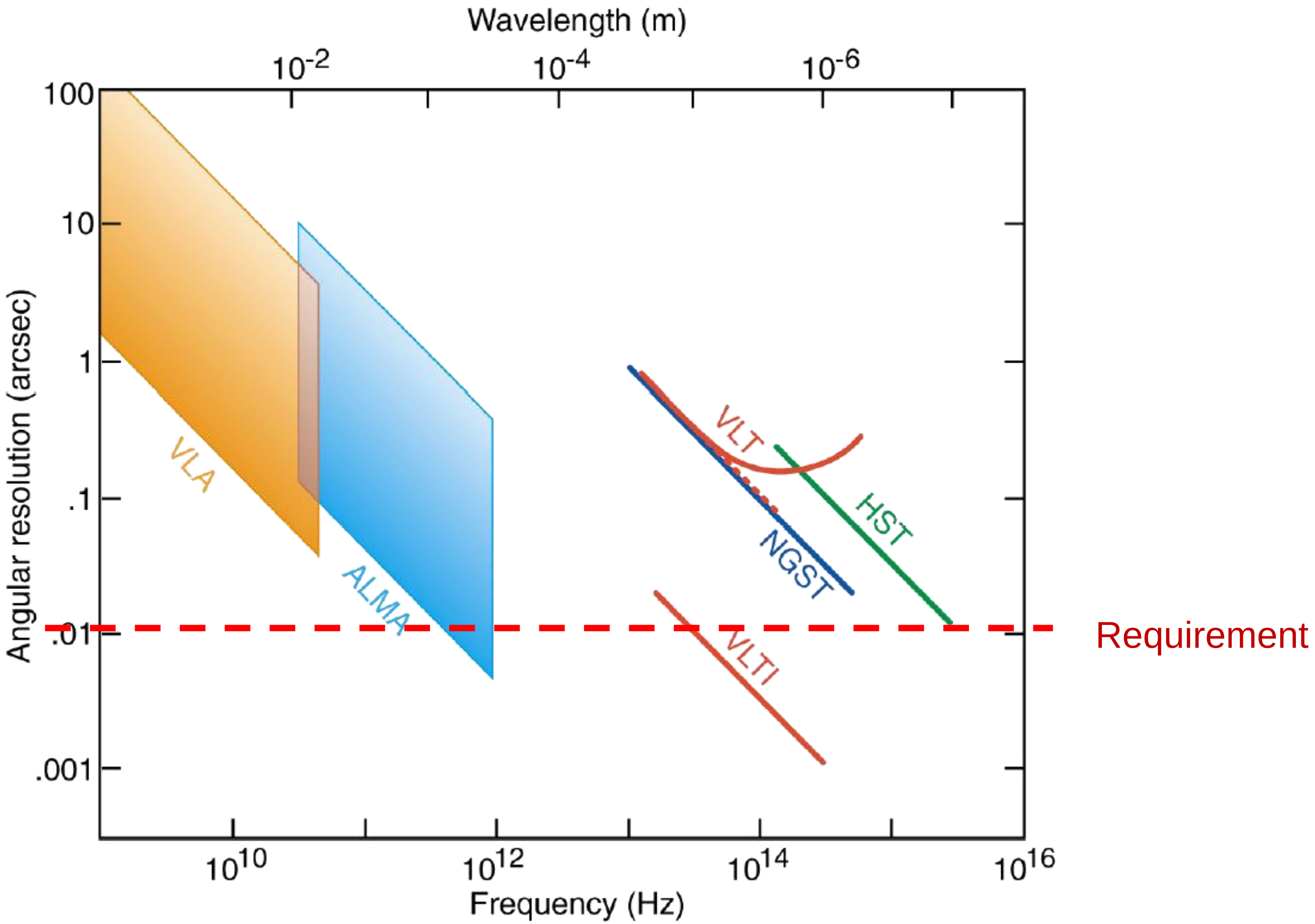
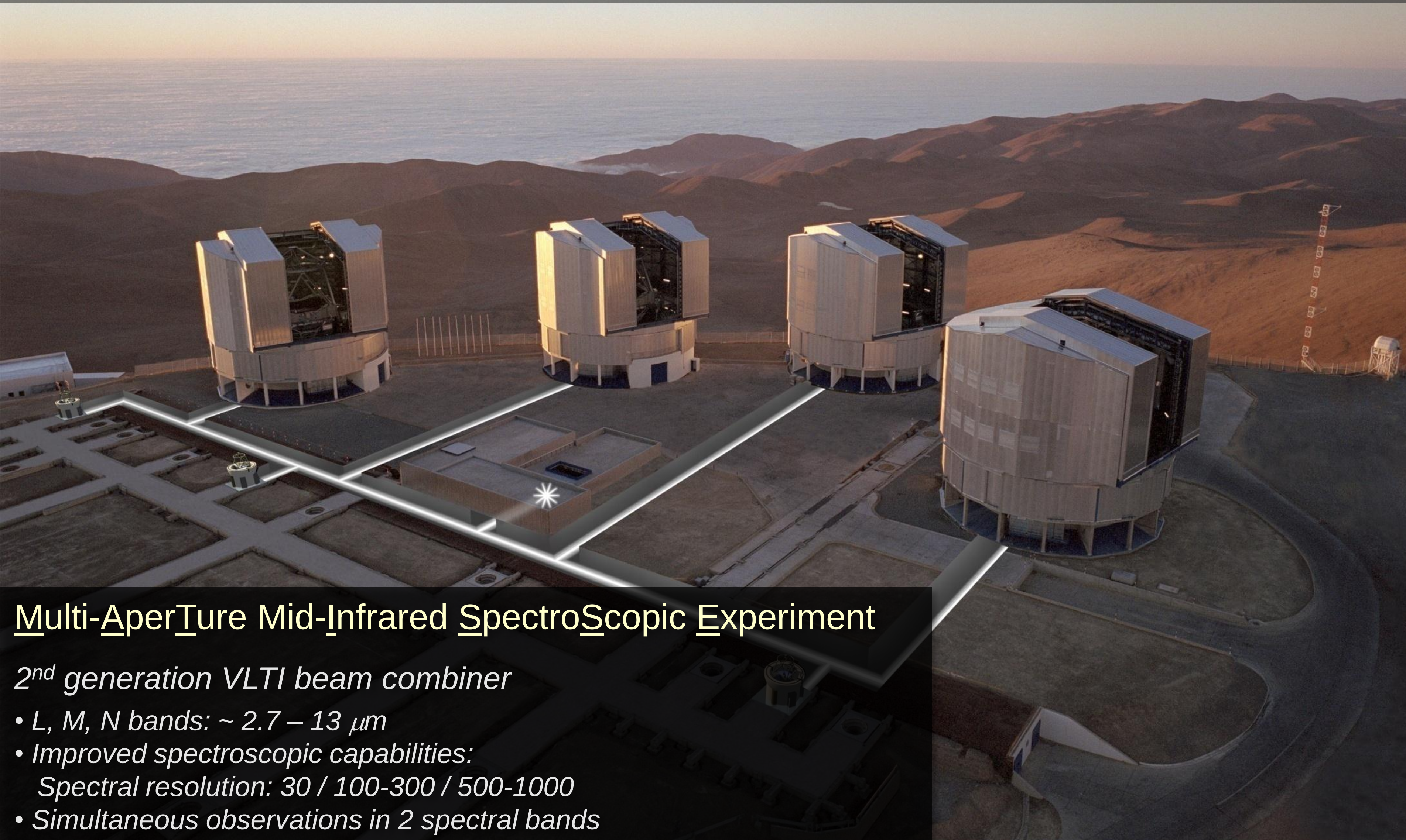
High Resolution!



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*

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

MATISSE / Embedded proto-planets

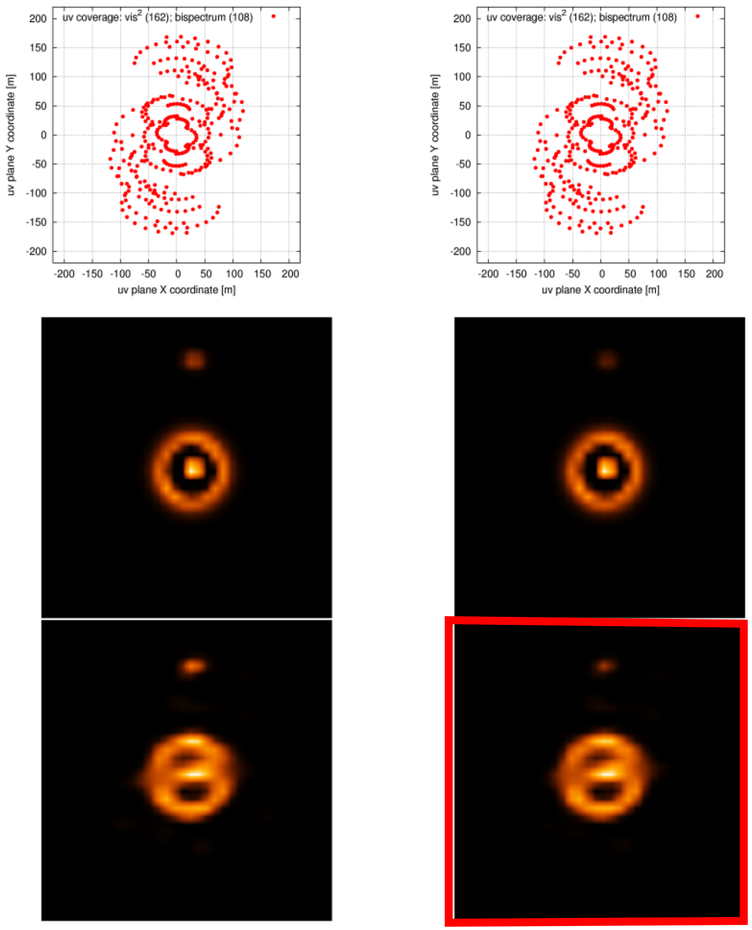
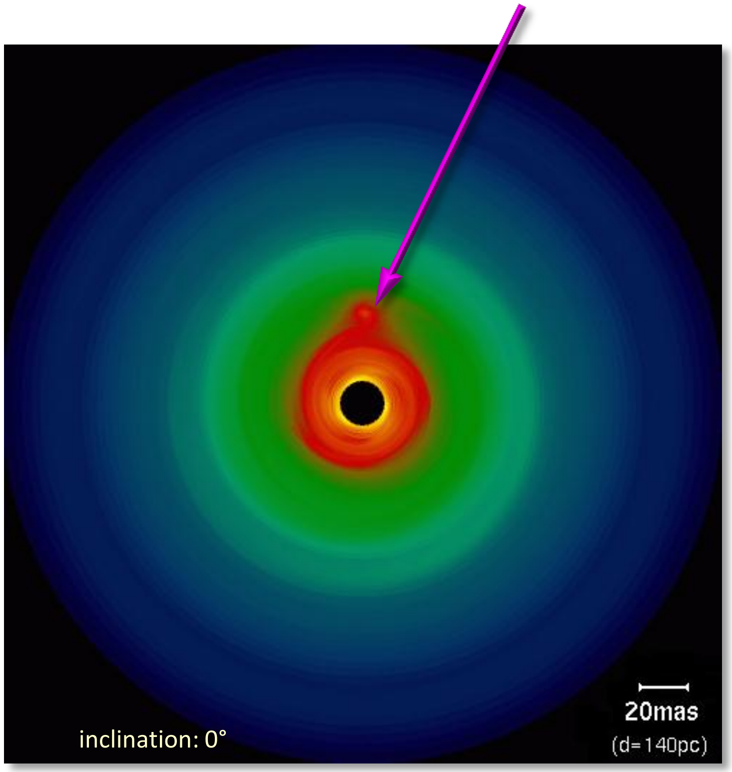


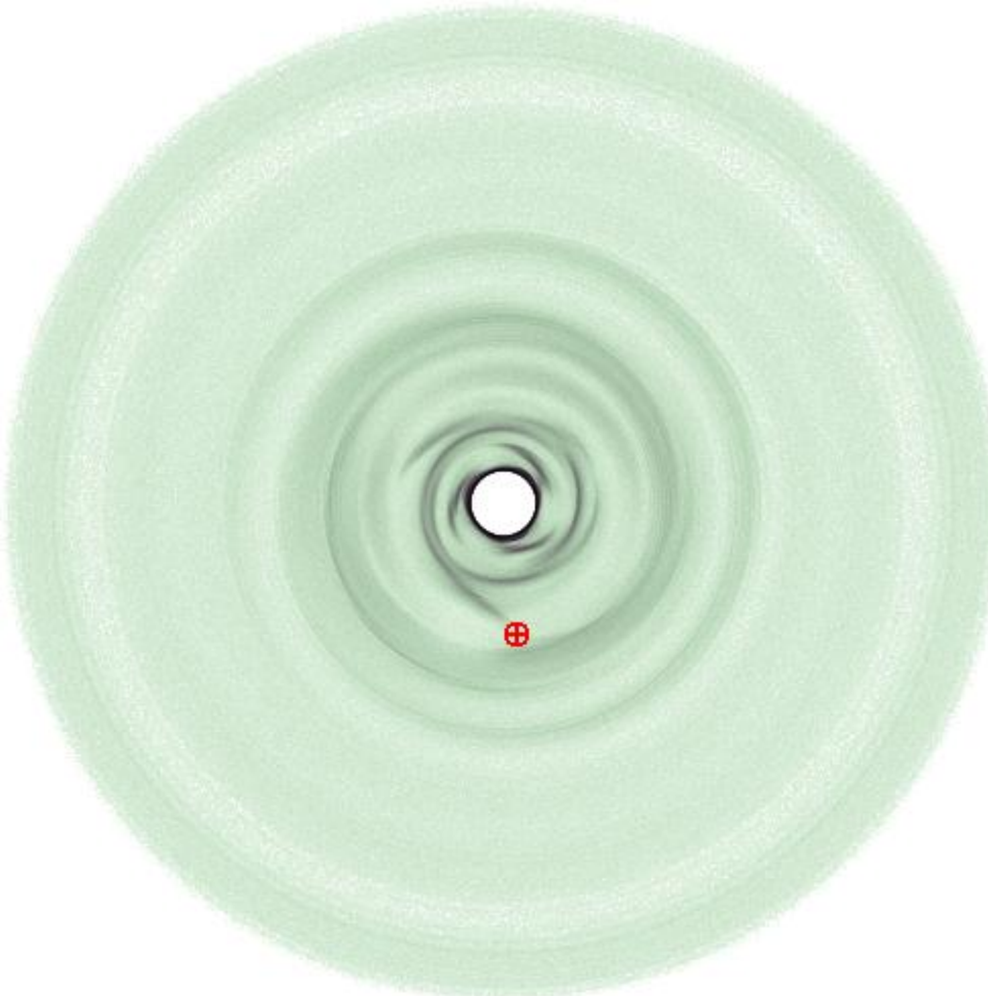
Figure 6: Reconstructed N band images (3x4ATs; ~ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5[right]). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and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

[Wolf et al. 2007]

Hot Accretion Region
around Proto-Planet

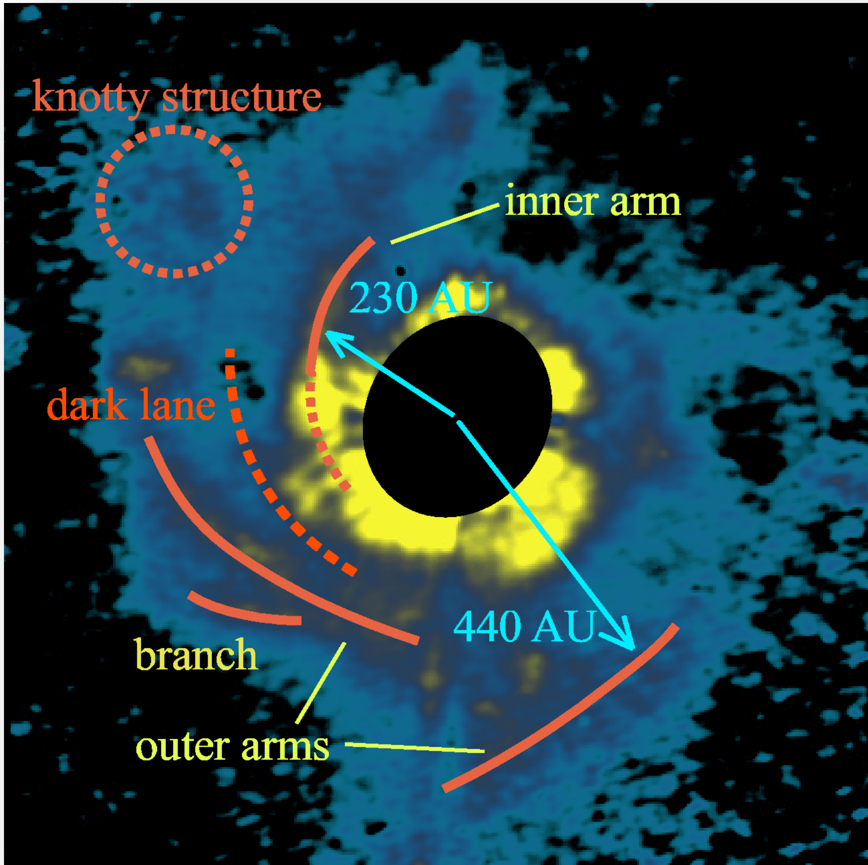


Optical/Near-IR: Scattered radiation



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

Optical/Near-IR: Scattered radiation



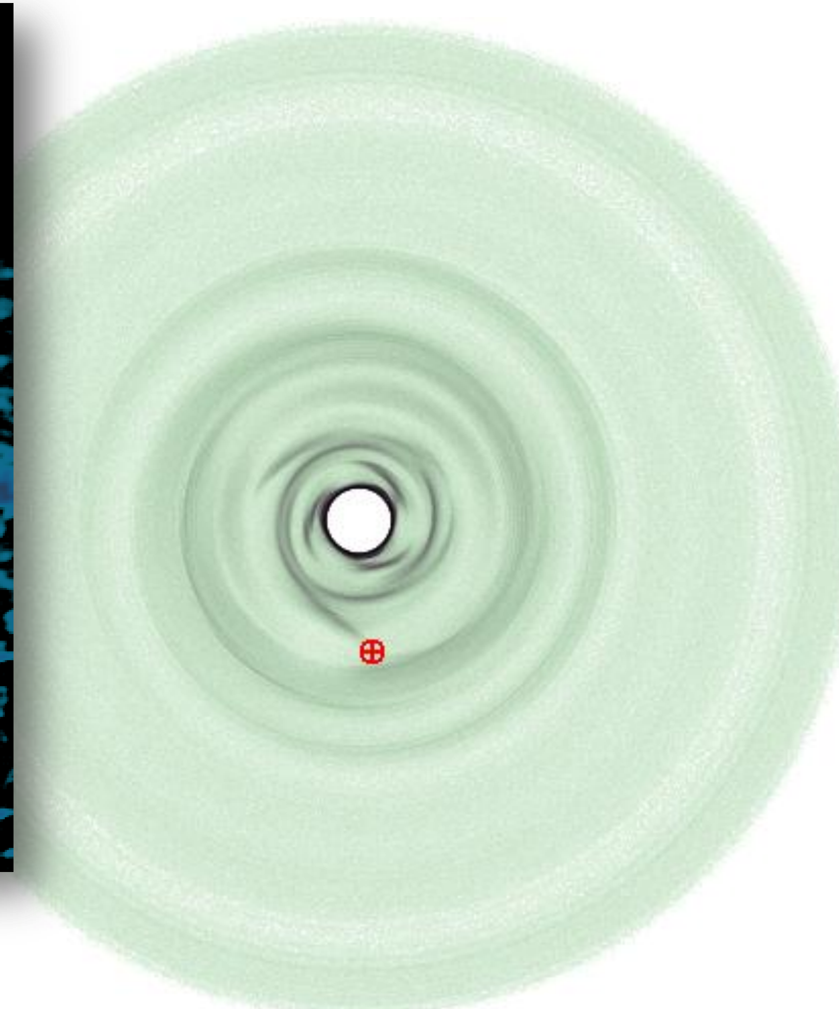
AB Aurigae

Spiral arm structure: H band

(Herbig Ae star; SUBARU)

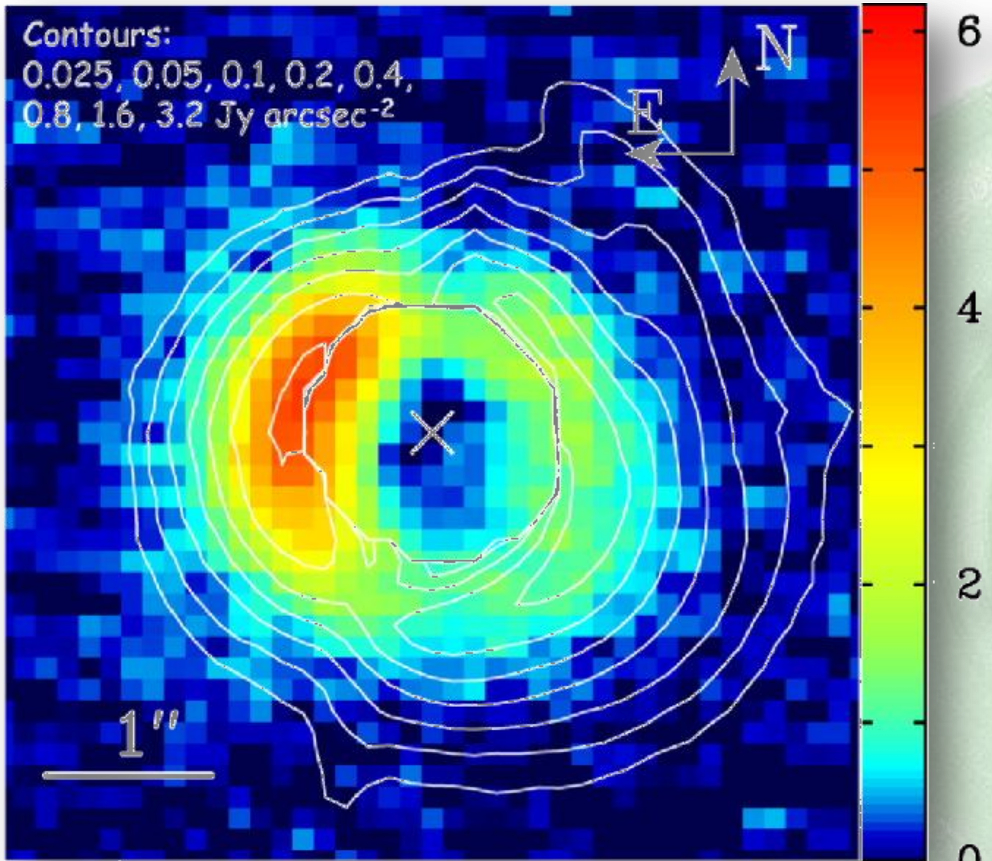
Distance: ~140 pc

[Fukagawa et al. 2004]



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

Optical/Near-IR: Scattered radiation



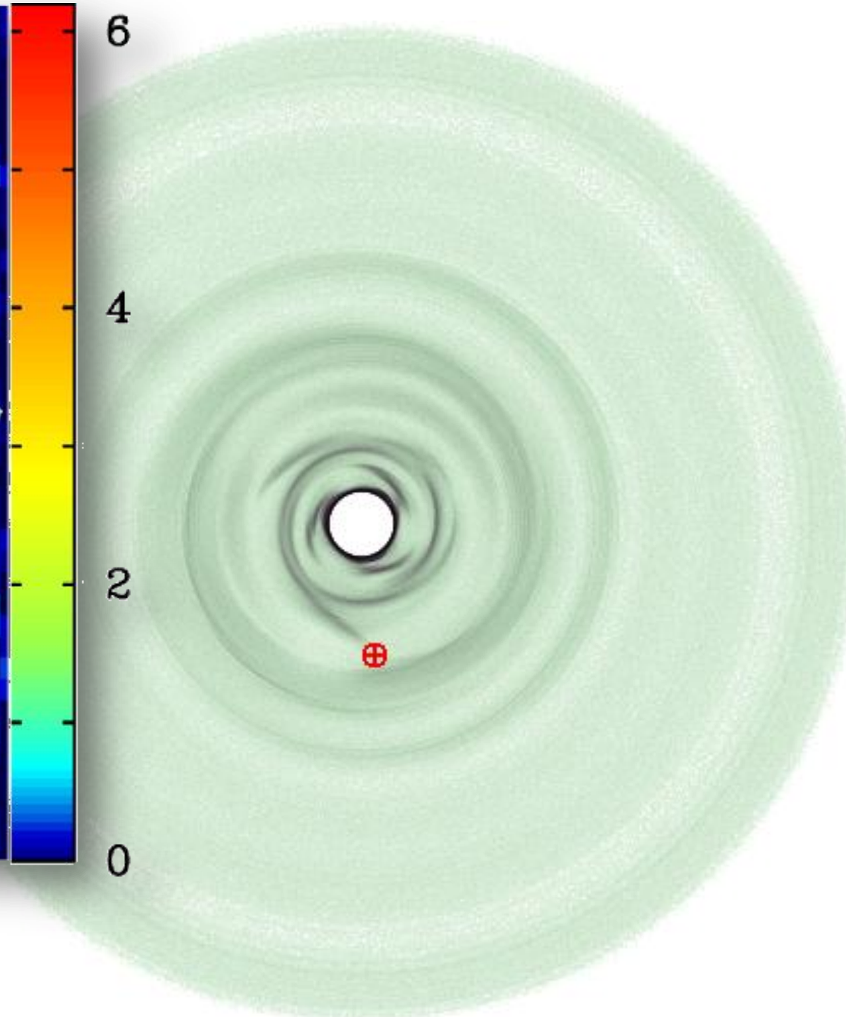
AB Aurigae

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

(Herbig Ae star; SUBARU)

Distance: ~140 pc

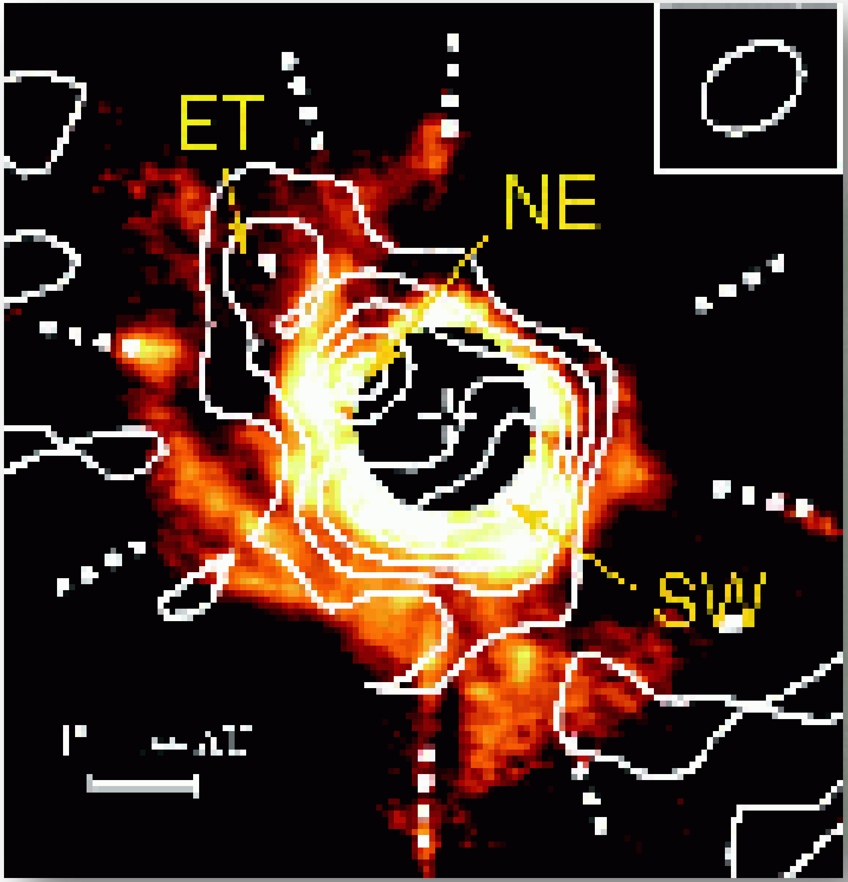
[Fujiwara et al. 2006]



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

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

Optical/Near-IR: Scattered radiation



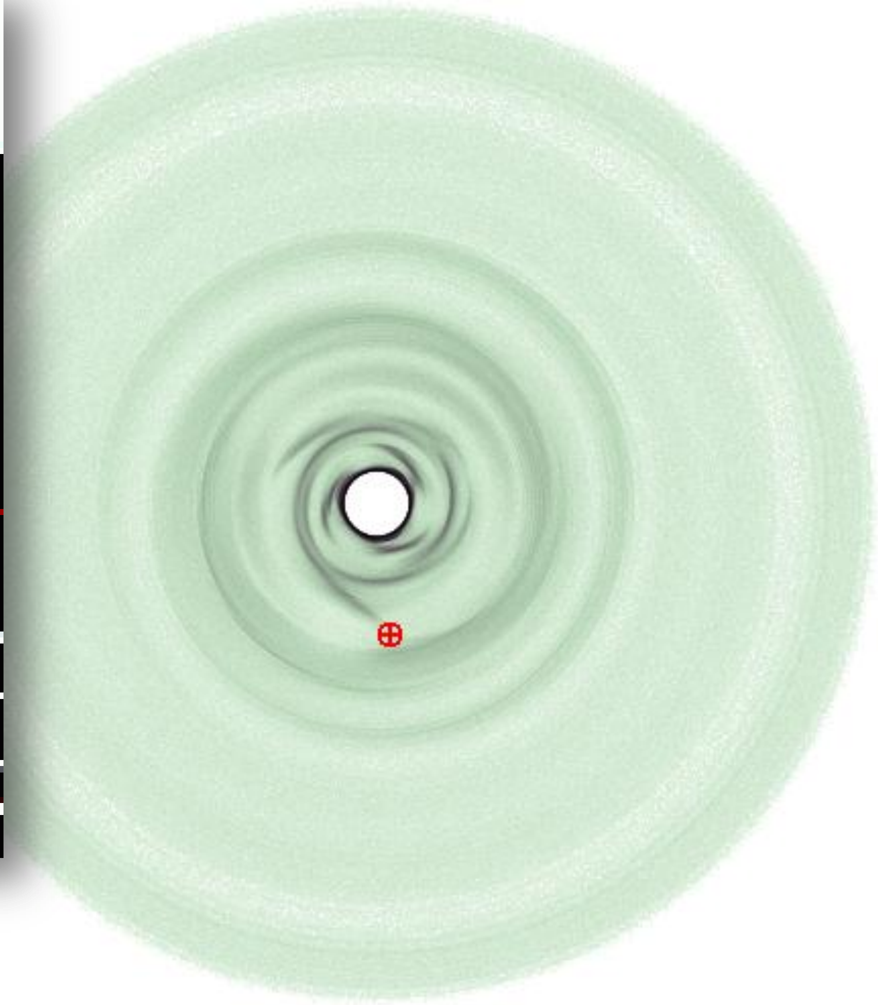
AB Aurigae

Spiral (345 GHz, continuum)

(Herbig Ae star; SMA)

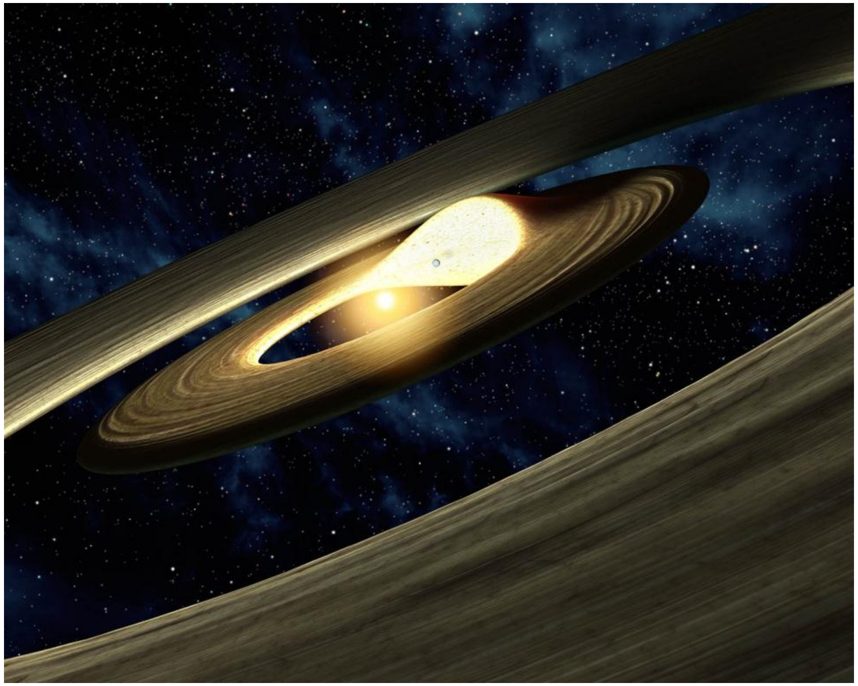
Distance: ~140 pc

[Lin et al. 2006]



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

Further planetary signatures in the near-IR?



Artist impression of the disk around LRLL 31. A planet in the innermost region influences the disk to cast a large shadow on the outer region. The orbit of the planet, and thus the shadow, causes the disk to be variable in the near infrared on timescales on the order of one week. Picture credits: NASA.

Observational basis: Spitzer/IRS 5-40μm observations, 6 months (Houck et al. 2004);
Further Spitzer/MIPS observations (Muzerolle et al. 2009) + SpeX/IRTF, SPOL (Spectro-polarimeter; Steward observatory) spectroscopic measurements

Observation

- Variability of T Tauri stars
  on time scales < 1 year

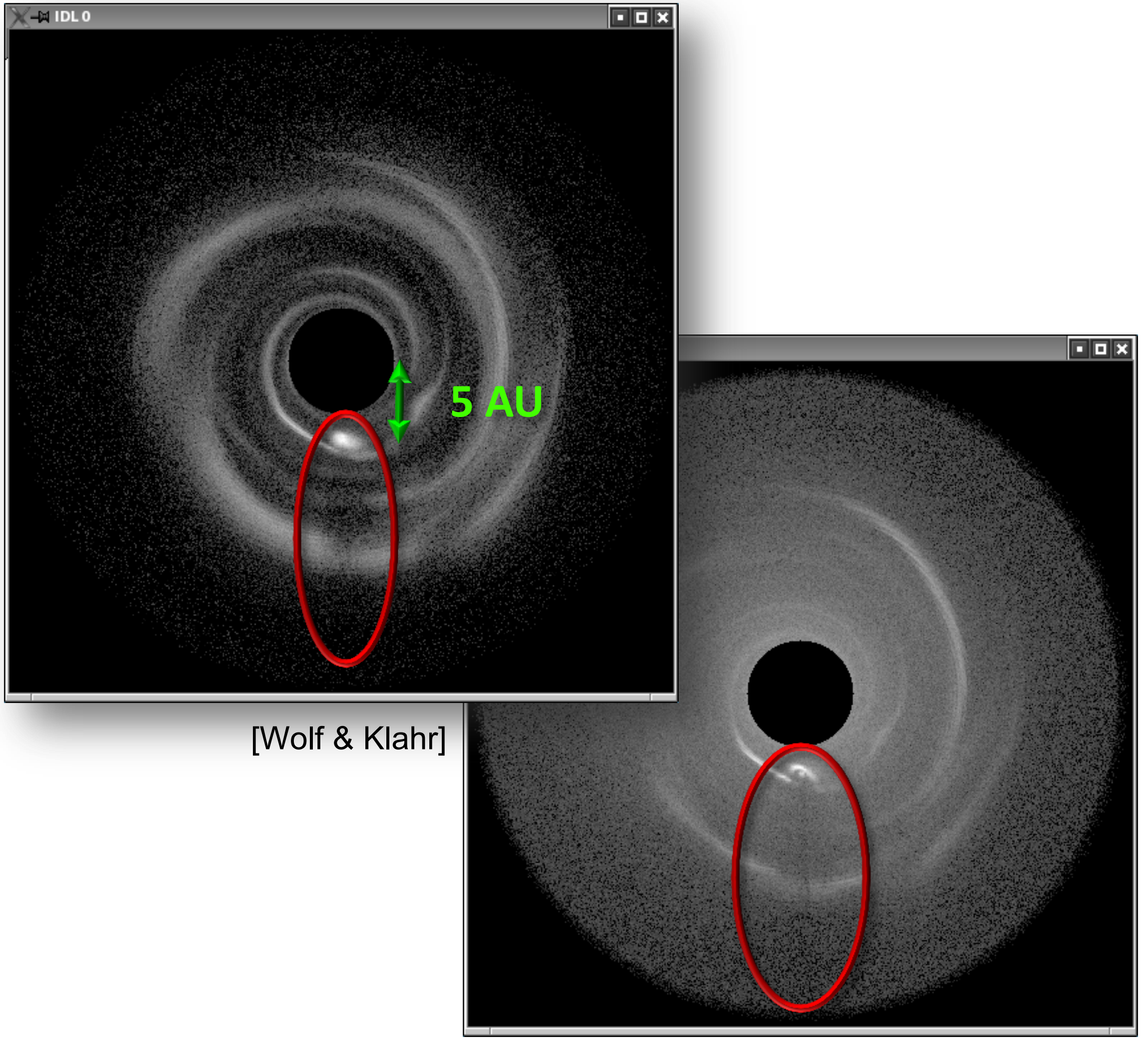
Various interpretations

- Clumpy inner circumstellar shell/disk structure
- Variable stellar accretion rate
  ⇒ variable net luminosity
  ⇒ variable inner disk structure / disk illumination
- Embedded stellar or planetary companion
  => dynamical perturbation (short-term)

Example

- Transitional disk LRLL 31 in the 2-3Myr old star-forming region IC 348:
  - Variations of the near-IR and N band spectra on a few months timescale [Muzerolle et al. 2009]

Shadow / Center-of-light wobble

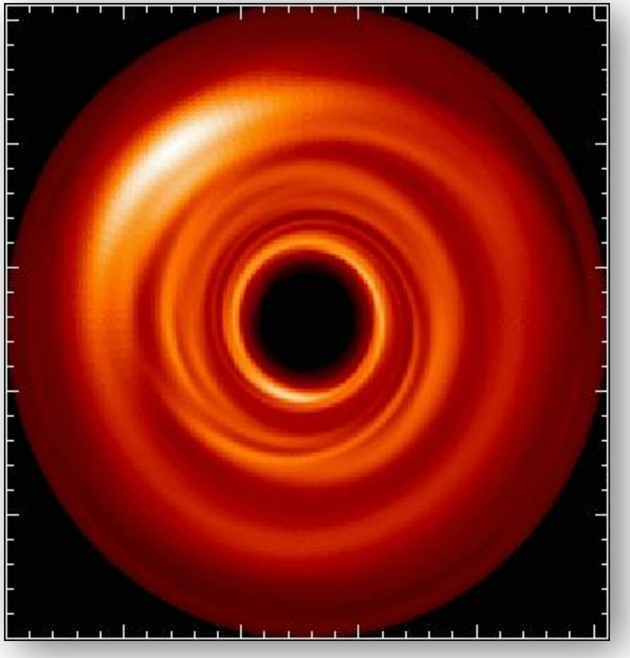


[Wolf & Klahr]

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

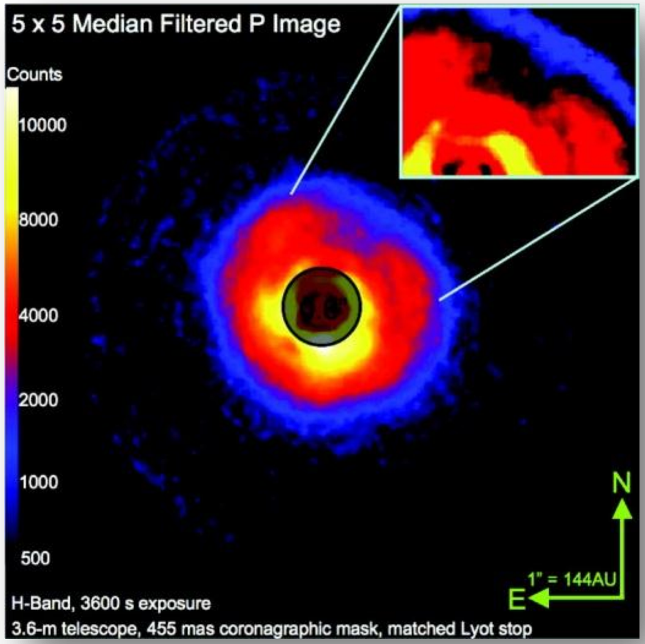
All that glitters is not gold…

- Remember:



Other mechanisms creating similar asymmetric, large-scale density structures

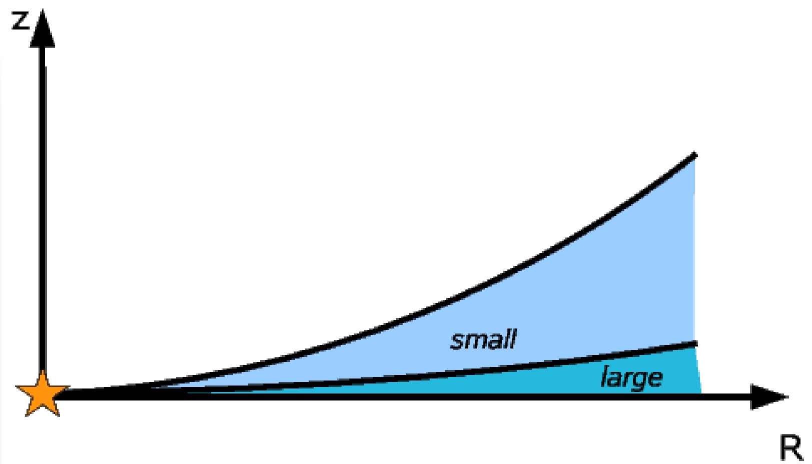
Examples:
Vortices, Binary systems

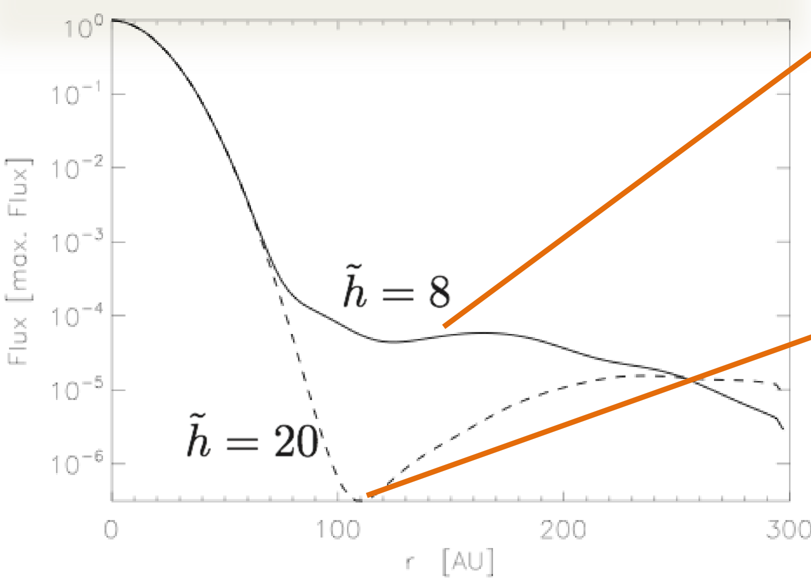


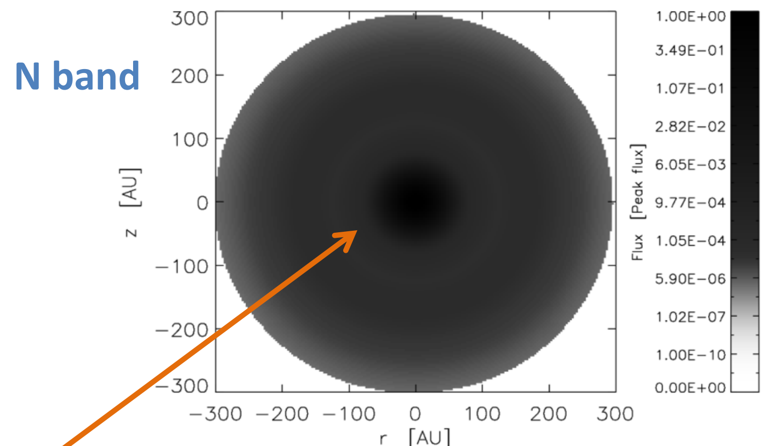
Apparent structures
due to applied observing technique

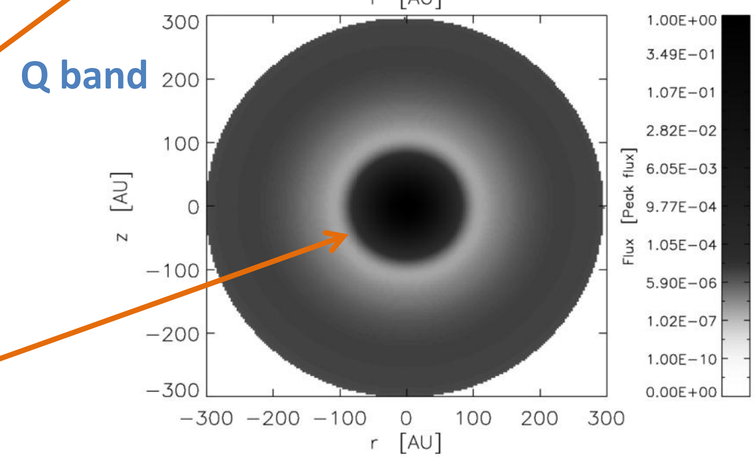
Example:
Polarization x Intensity

„Gaps“: The importance of multi-λ observations





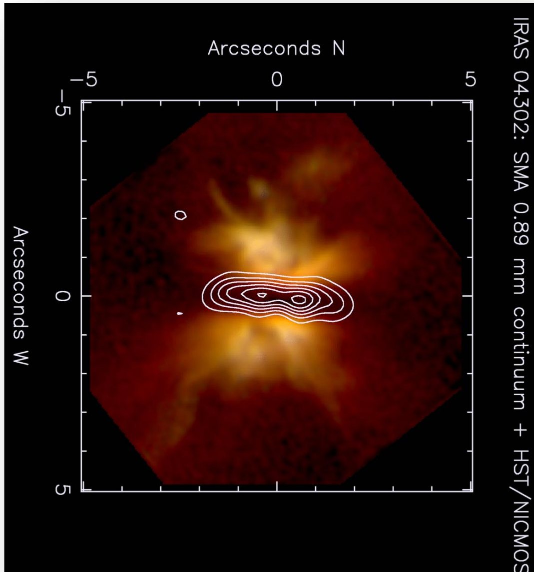


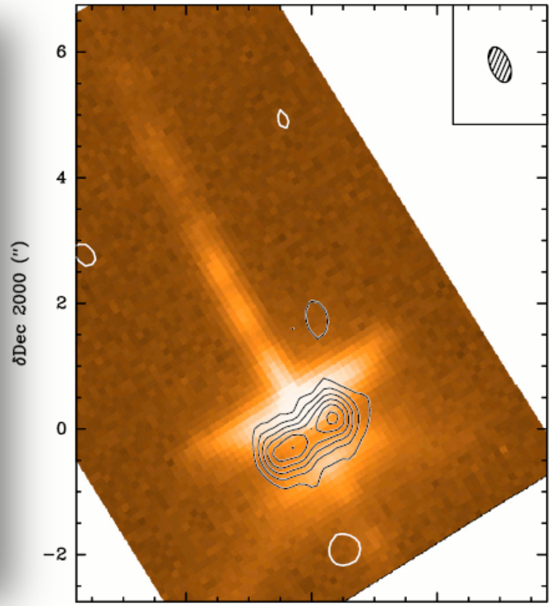


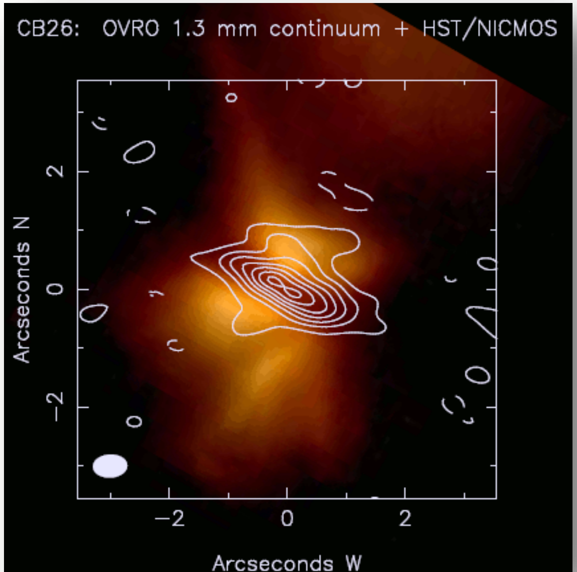
Gaps as indicators for dust sedimentation height

[Sauter & Wolf 2011]

Inner holes?







IRAS 04302+2247
(„Butterfly star“)

[Wolf, et al. 2003, 2008, Gräfe, et al. 2013]

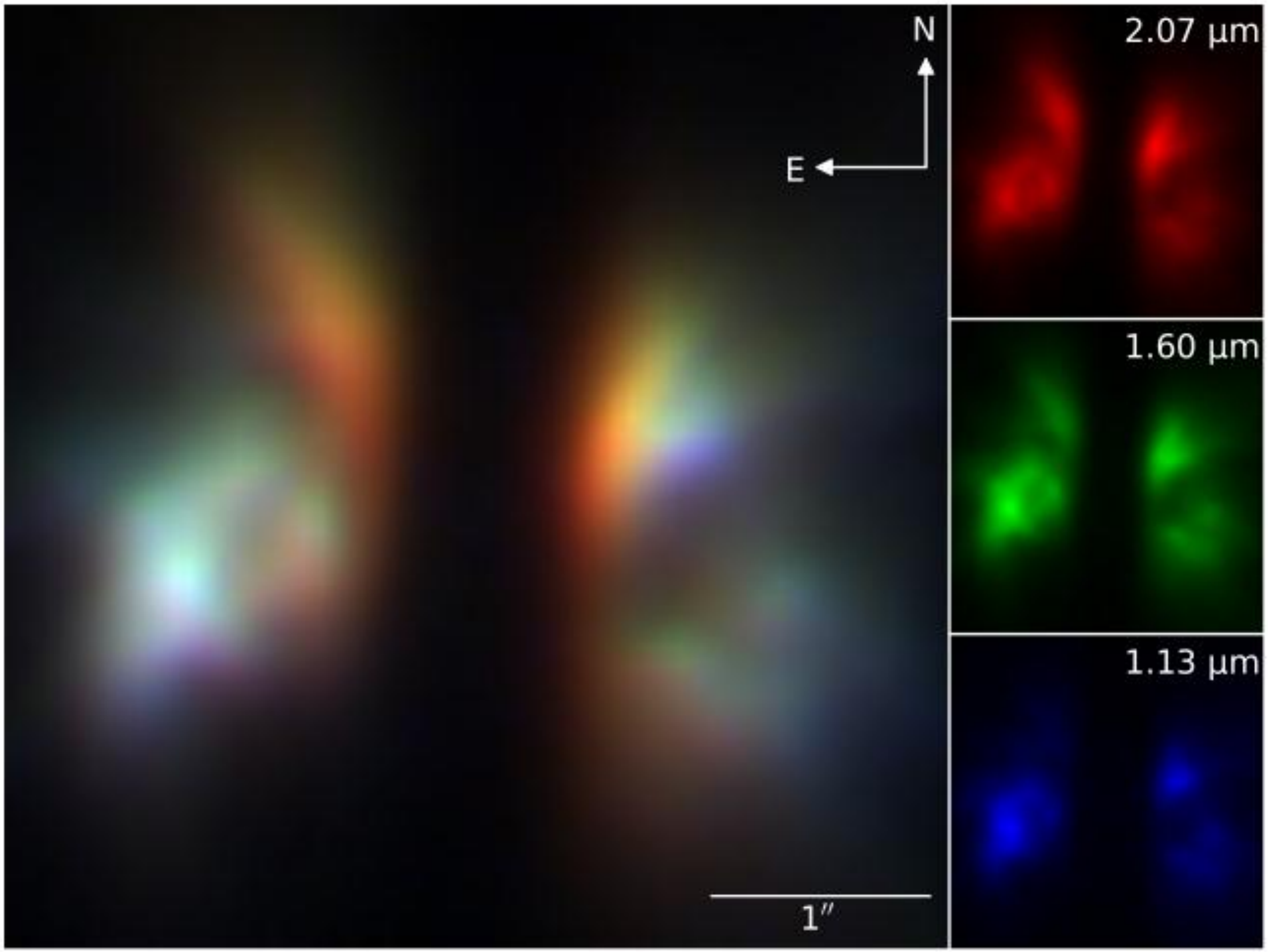
HH 30

[Guilloteau et al. 2008; Madlener, et al. 2012]

CB 26

[Sauter, et al. 2011]

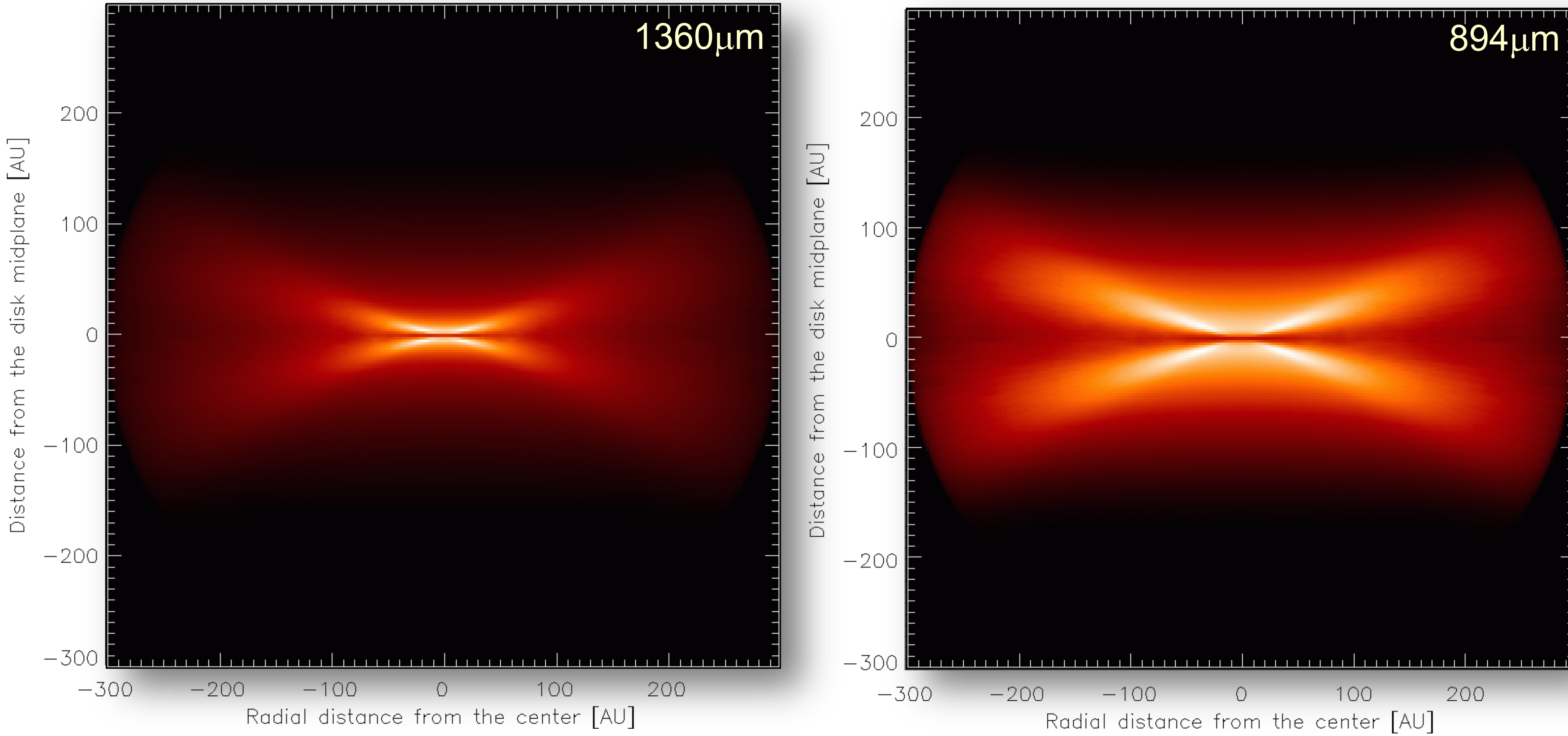
IRAS 04302+2247 („Butterfly star“)



[Gräfe et al. 2013]

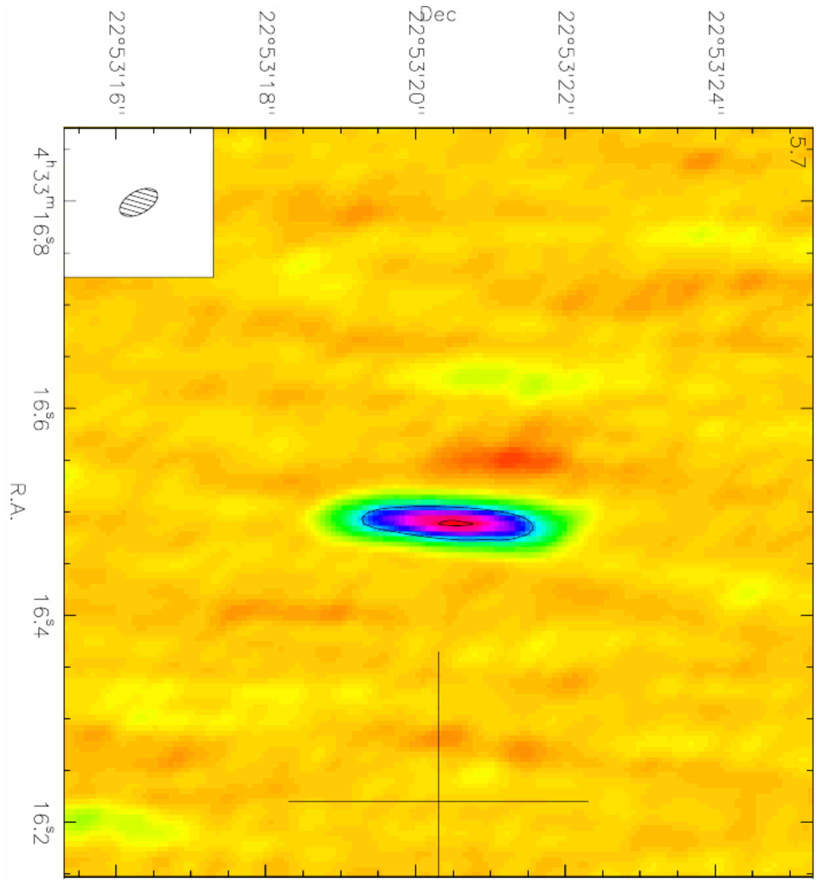
IRAS 04302+2247 („Butterfly star“)

- Verification of the previous analysis

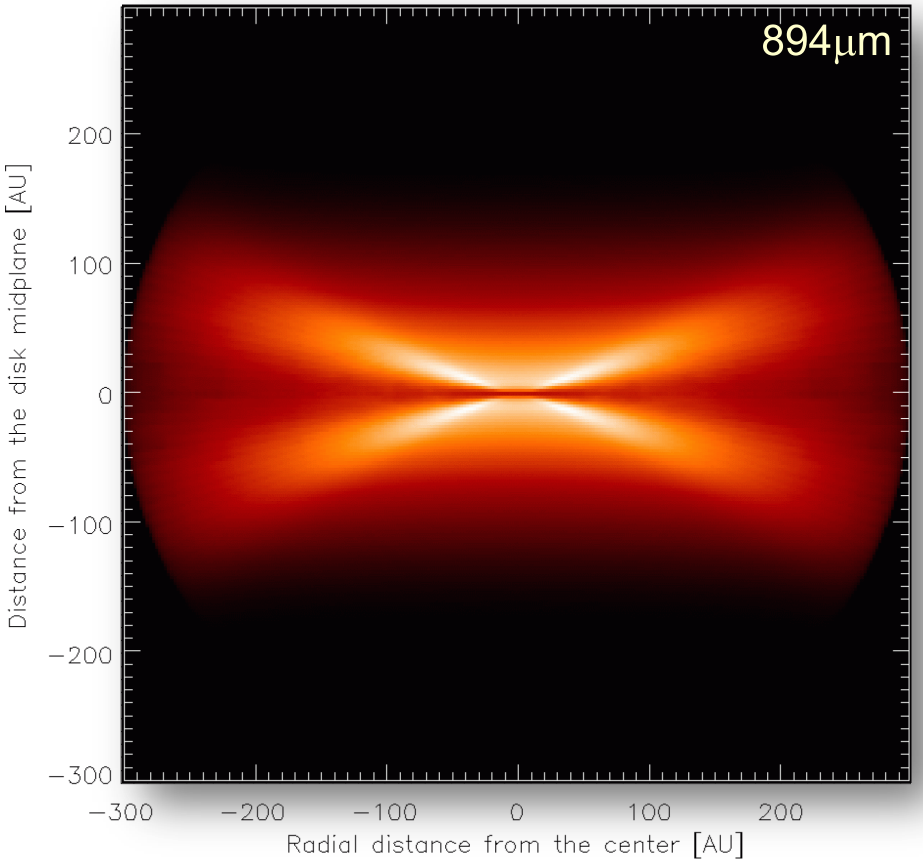


[Wolf et al. 2003, 2008]

IRAS 04302+2247 („Butterfly star“)



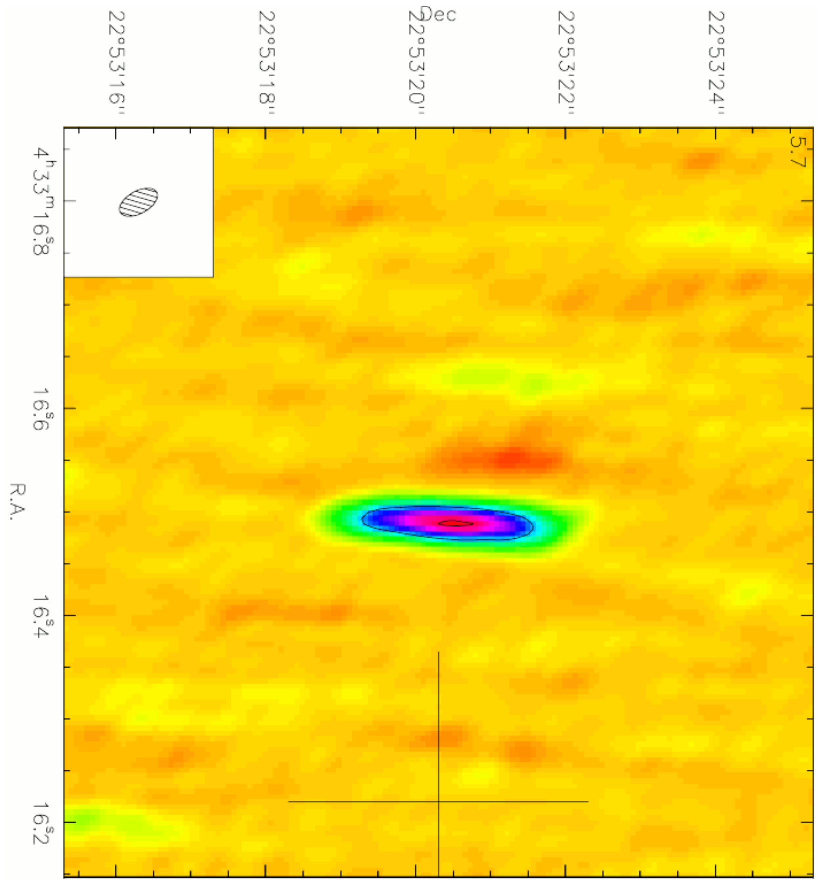
IRAM / PdBI: **1.3mm**, continuum



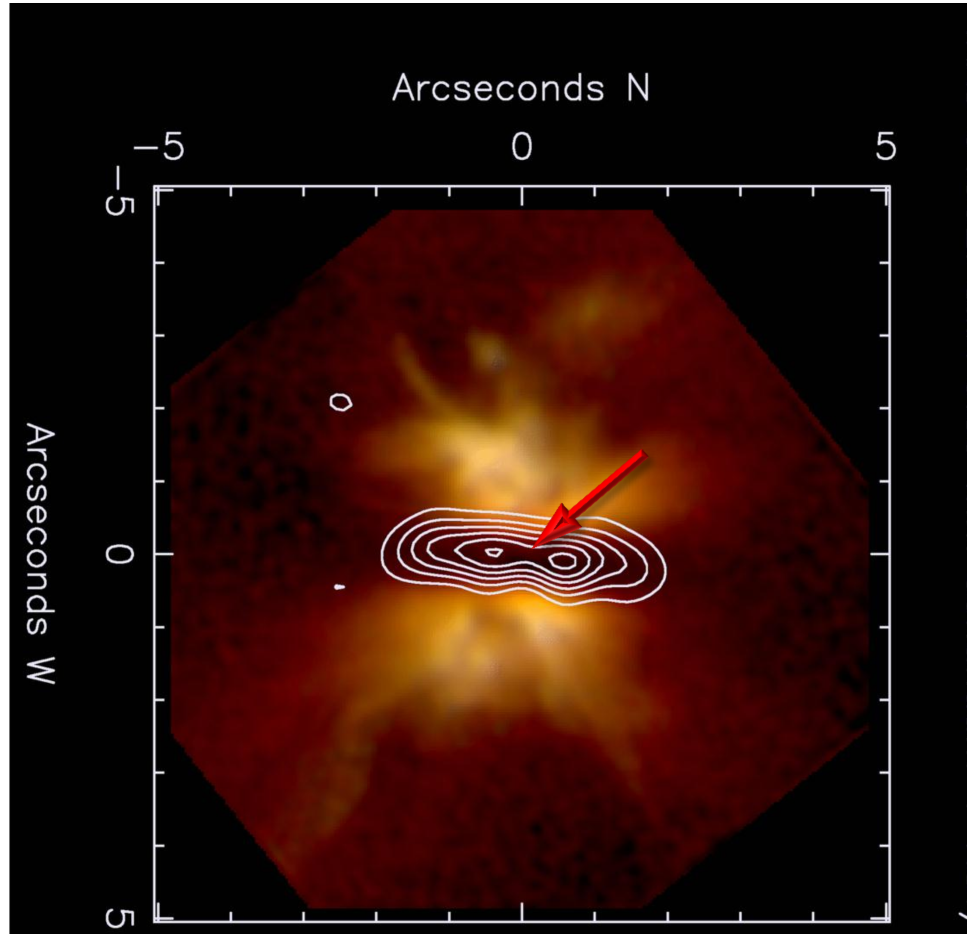
[Gräfe, et al., 2013]

[Wolf et al. 2003, 2008]

IRAS 04302+2247 („Butterfly star“)



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



SMA: **0.89 mm**, continuum

+ HST/NICMOS

[Gräfe, et al., 2013]

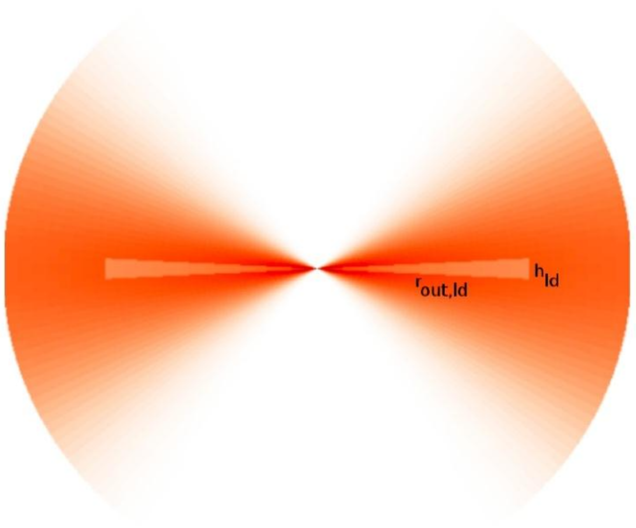
[Wolf et al. 2003, 2008]

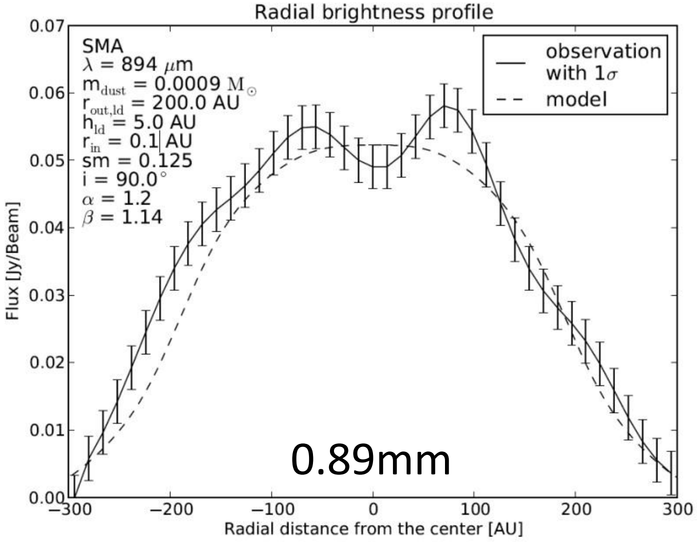
IRAS 04302+2247 („Butterfly star“)

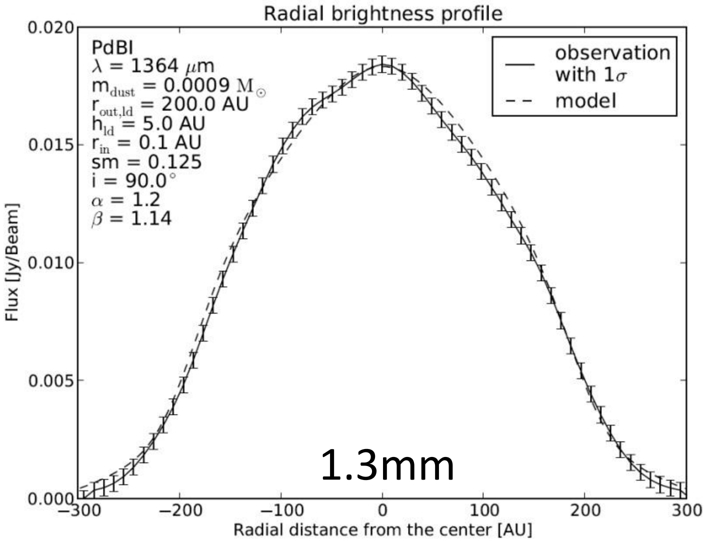
- New observations –

  Reduction of Degeneracies –

  New Constraints



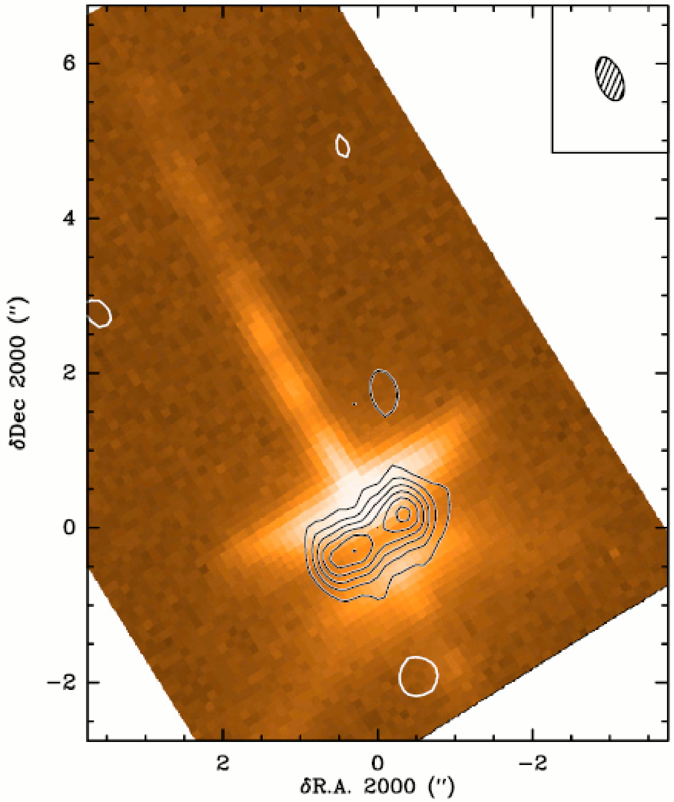




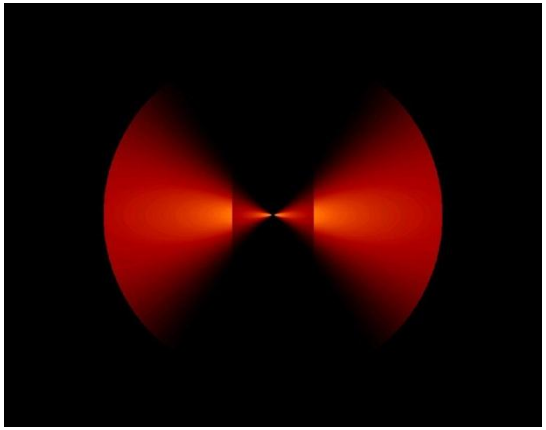
h_{ld}	= 5+/-1.5 AU	[h_{disk} = 15AU]
$r_{out,\,ld}$	= 200+/-25 AU	[r_{disk} = 300AU]
m_{ld}	= 28% m_{disk}	

[Gräfe, et al., 2013]

HH30



[Guilloteau, et al., 2008]



Spatially resolved millimeter images reveal large inner hole

but

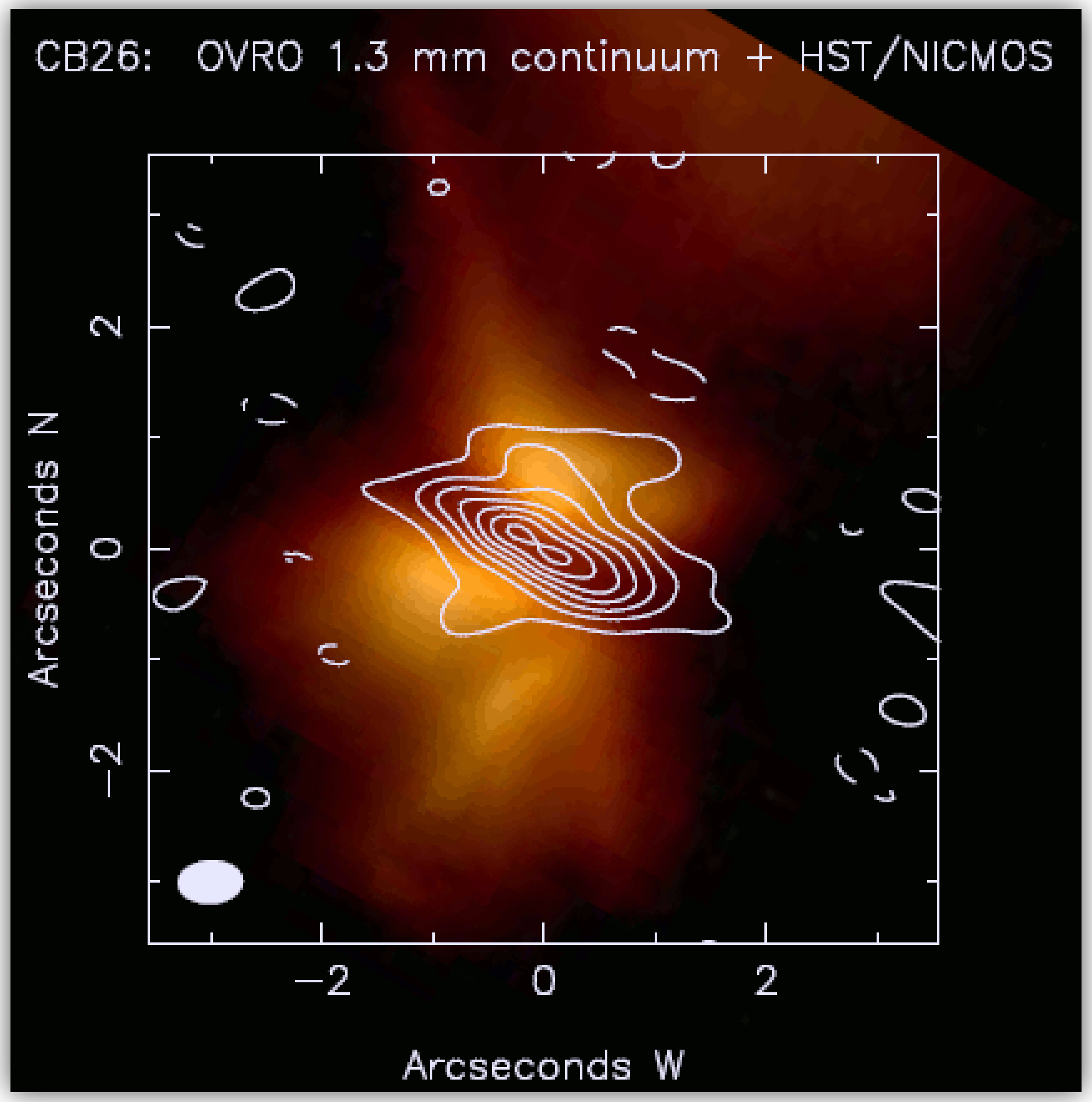
Combination with SED (and constraints from scattered light images) show that **inner region is not entirely cleared**

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

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

[Madlener, et al., 2012]

CB 26



Disk

Inner disk radius:

~ 45 +/- 5 AU

Dust

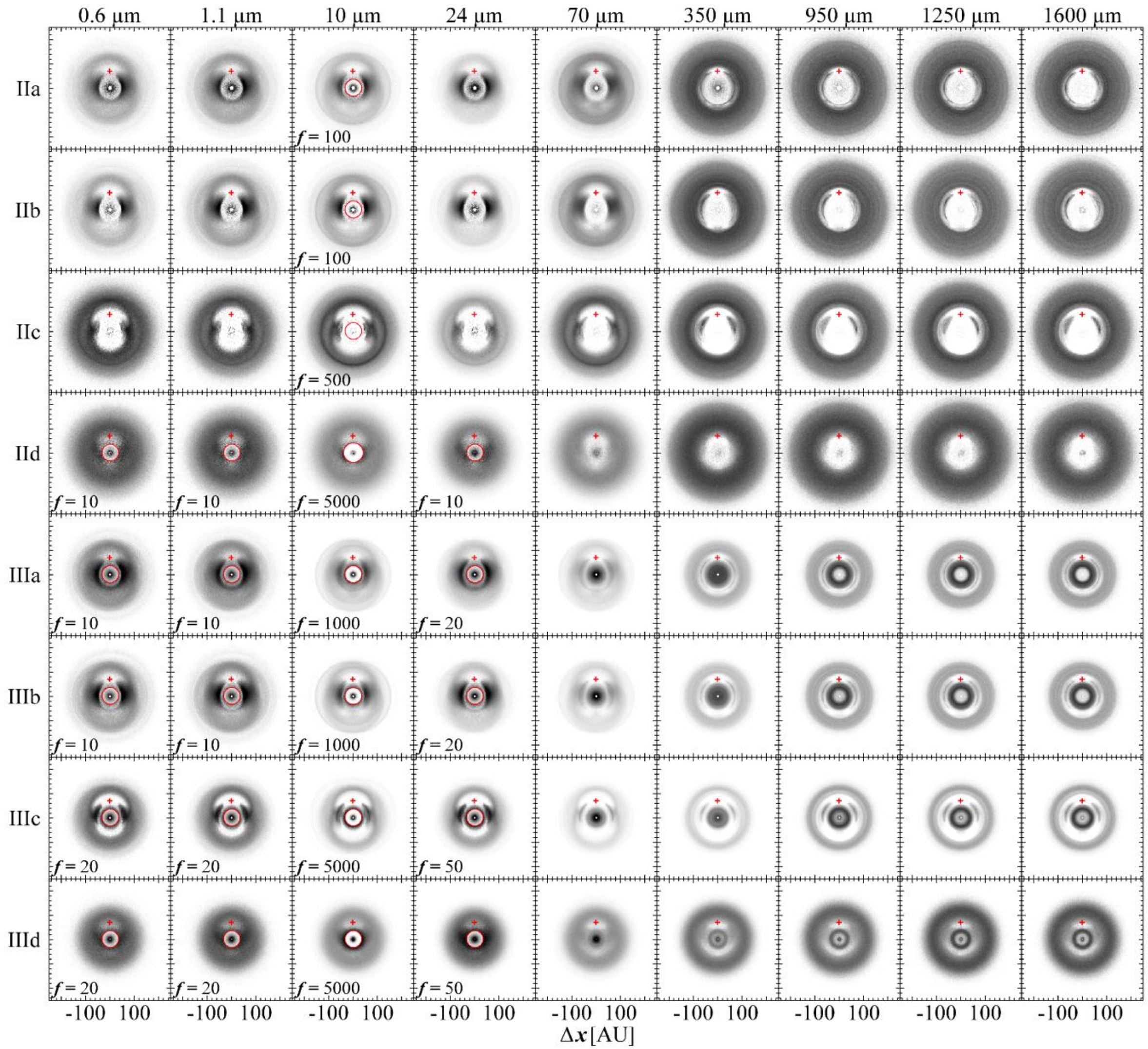
ISM dust grains
in the envelope
and „upper“ disk layers

Dust grains in the disk midplane only slightly larger than in the ISM

[Sauter, et al. 2009]

Structures in debris disks

Planet-induced structures in debris disks



[Ertel, Wolf, Rodmann, 2012]

High-angular resolution observations = f (λ, planetary mass/orbit)

ALMA

Limited by its sensitivity => trade-off between sensitivity and spatial resolution

Space-based mid-infrared observations

Able to detect and spatially resolve regions in debris disks even at a distance of several tens of AU from the star

What comes next?

- Multi-wavelength / Multi-scale intensity measurements
  - Inner (<10AU) disk structure: Test of disk / planet formation evolution models
  - ALMA + VLTI + …
  - Distribution of gas species

- Near-future goal: Planet-disk interaction

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

  $= f(\mathbf{r},z)$

Thank you!