Exploring the signatures of planet formation with multi-wavelength interferometry

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EWASS
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Outline

Introduction

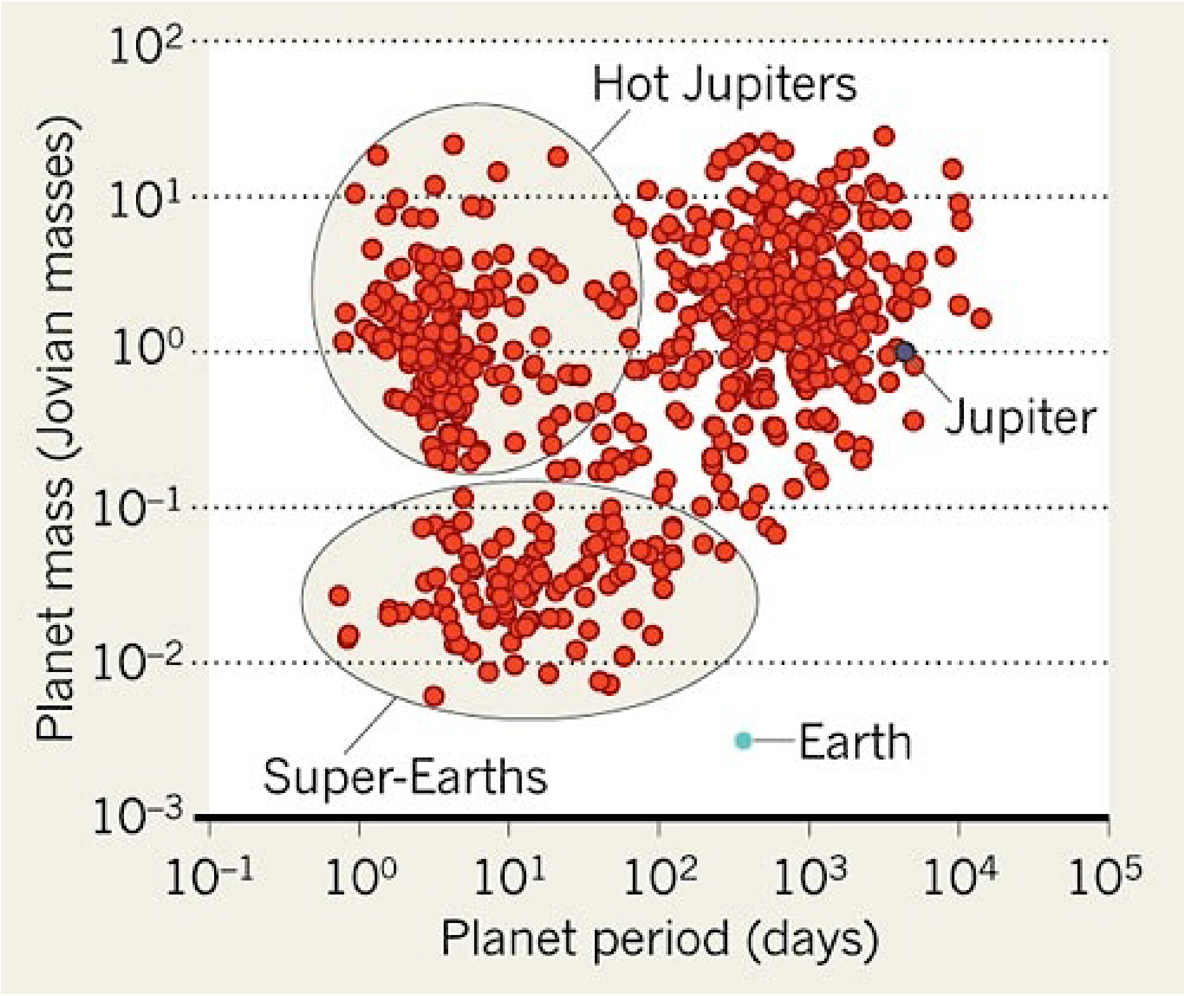
Planet formation scenarios and
the need for multi-wavelength interferometry

Study on the (pre-)transitional disk of V1247 Ori

Science prospects of VLTI/MATISSE

Conclusions

Exoplanetary systems



Exoplanetary systems show surprising diversity

Key questions:

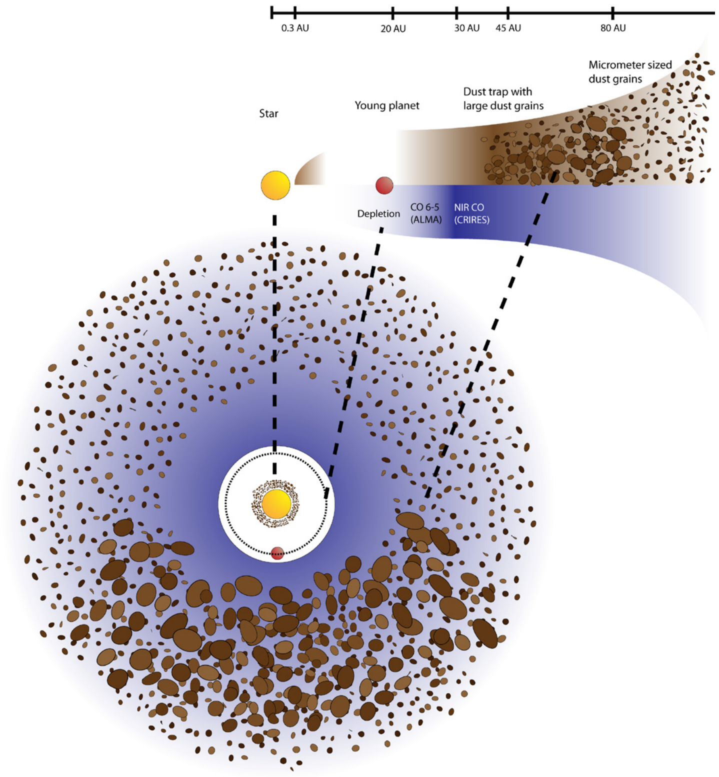
(1) What determines the architecture of planetary systems?

(2) Did the planets form where we observe them, or did they migrate due to planet-disk interaction?

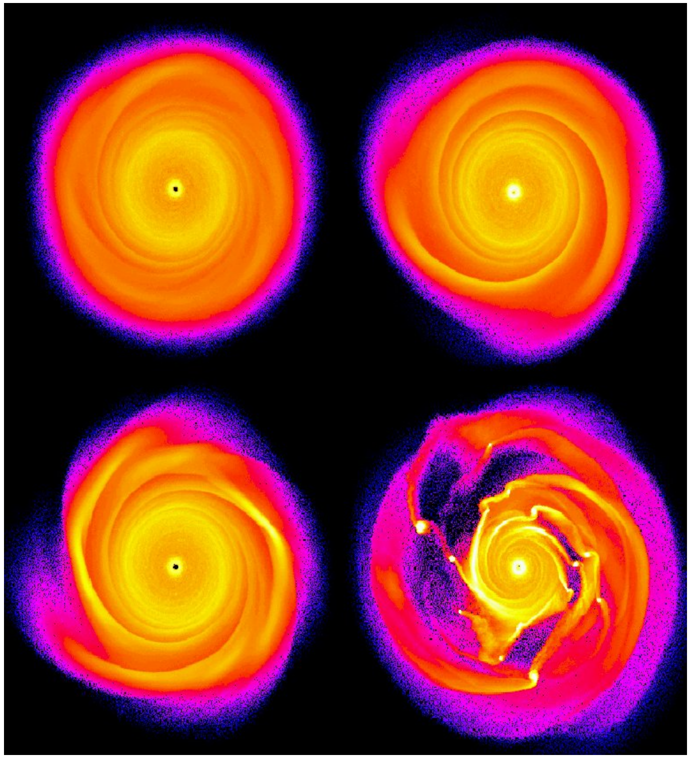
Hand 2011

Planet formation scenarios

Core accretion



Gravitational instabilities



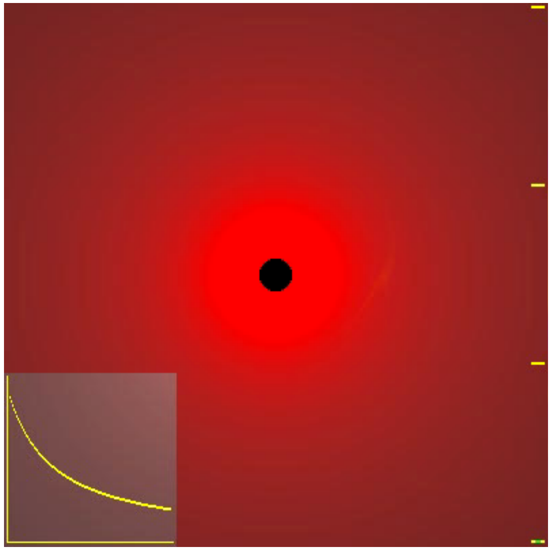
➜ Need to know **WHERE planets are forming** and **HOW they interact** with the disk material!

van der Marel 2013; Mayer et al. 2002

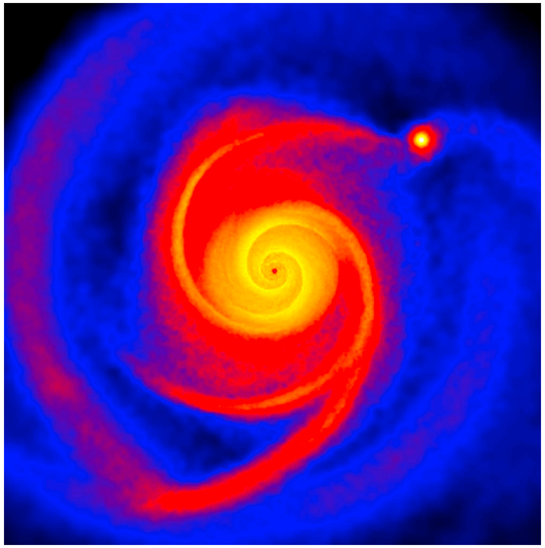
Signatures of planet formation

Planet formation alters the disk structure, causing
disk gaps, spiral arms, resonance effects, disk warping, …

Gap clearing



Disk fragmentation



Disk warping

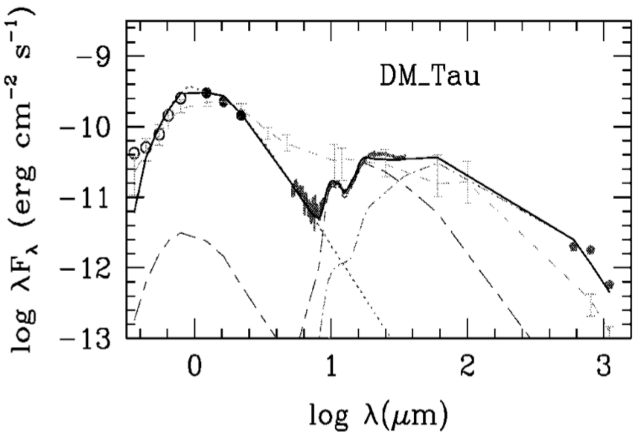
Gaps leave signatures
in the SED
(e.g. Calvet et al. 2004)

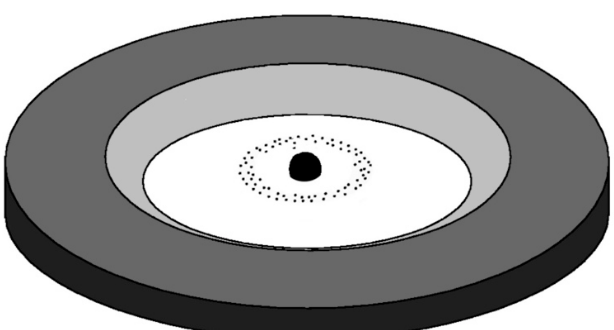
Asymmetric structures might cause
photometric/spectroscopic variability
(e.g. Muzerolle et al. 2009, Espaillat et al. 2011)

Armitage et al. 2005, Greaves et al. 2008

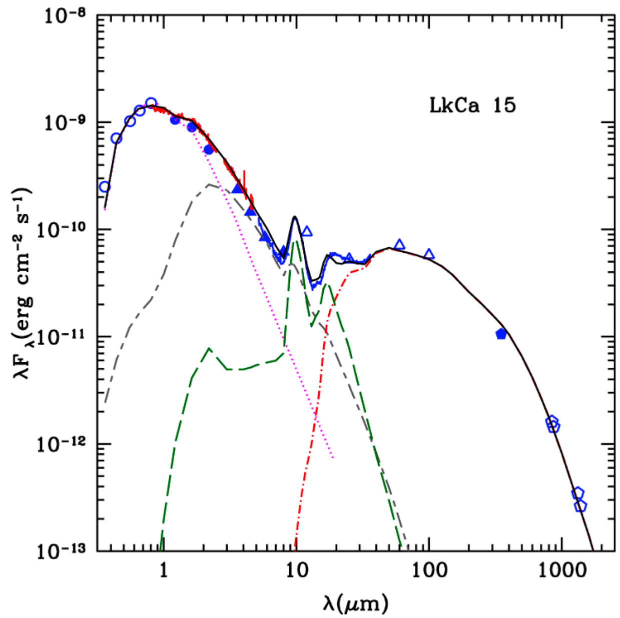
Disk structure in (pre-)transitional disks

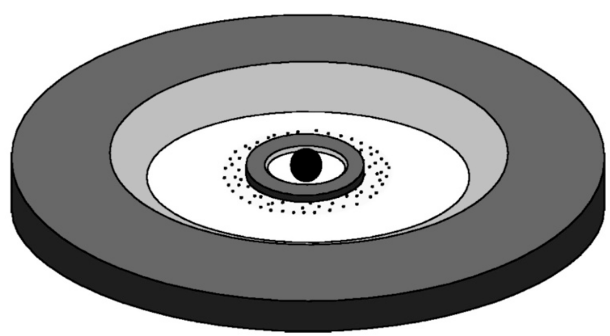
Transitional disks





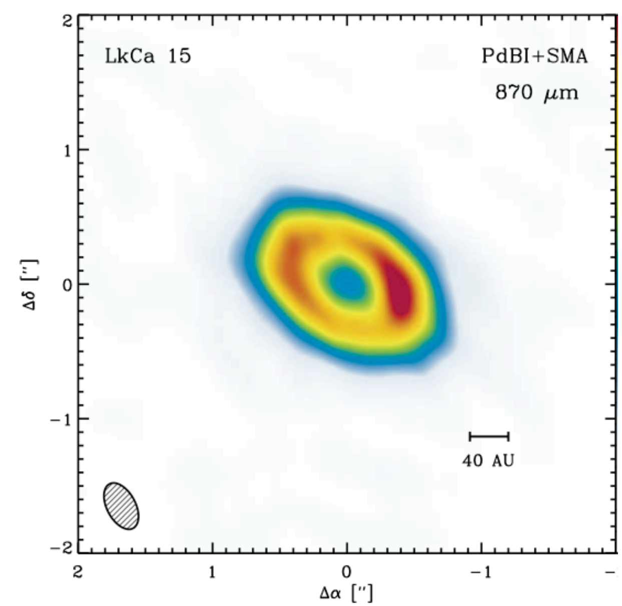
Pre-transitional disks





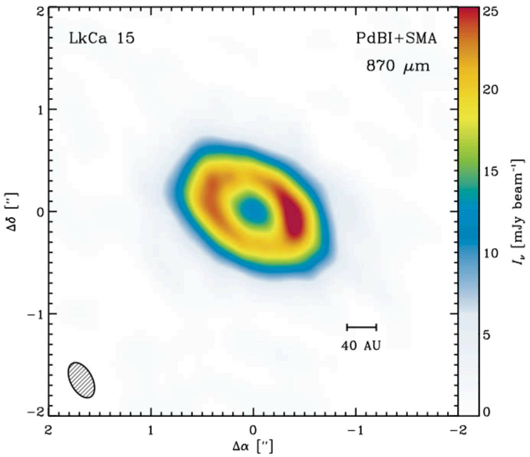
Disk-clearing mechanisms under discussion:

- planet-disk interaction
- photoevaporation
- grain growth
- stellar companions



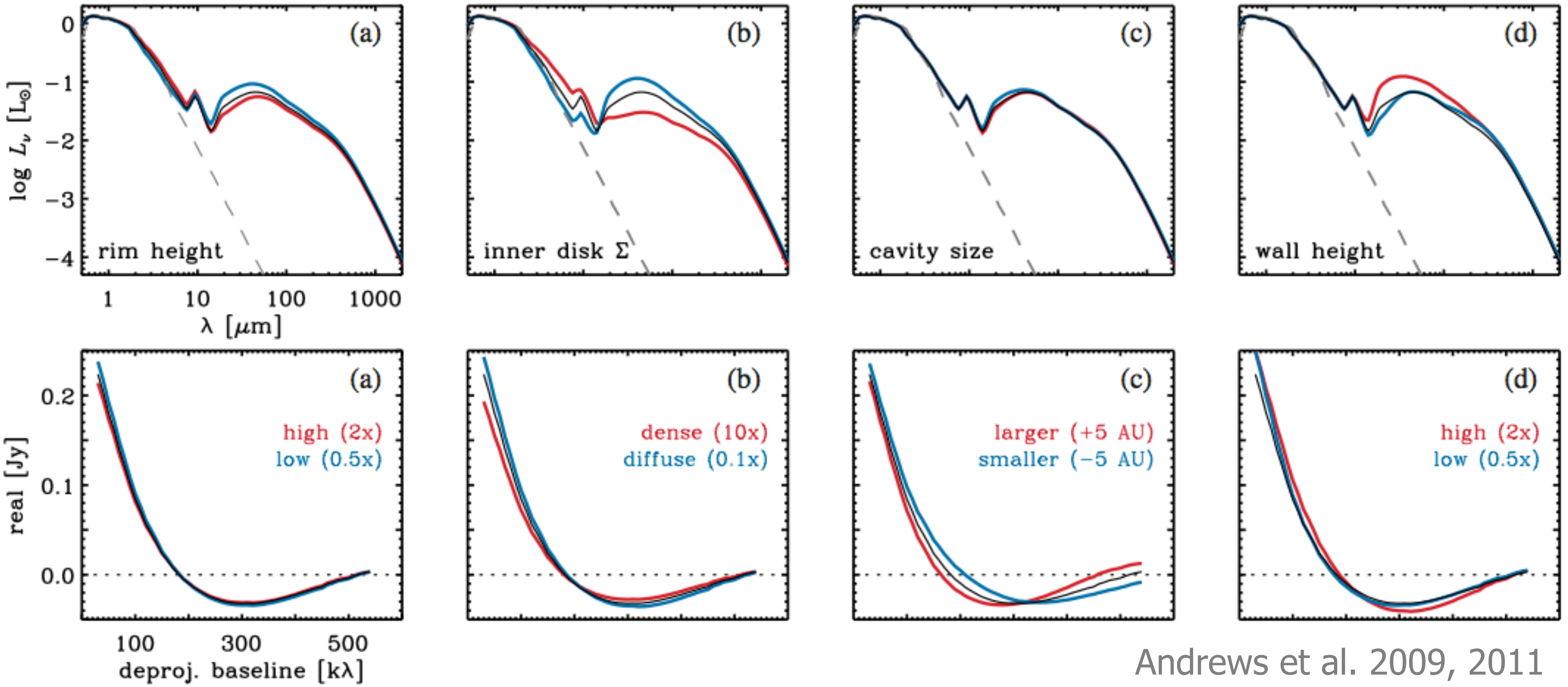
Calvet et al. 2002; Espaillat al. 2008, 2010; Andrews et al. 2011

Sub-mm interferometry of (pre-)transitional disks



Sub-mm interferometric imaging reveals
central density depressions in transitional disks,
but some key parameters remain difficult to constrain:

rim height, inner disk density,
cavity size, wall height, …



Andrews et al. 2009, 2011

Infrared interferometry

Interferometry breaks the resolution barrier imposed by diffraction (λ/D) and the atmosphere

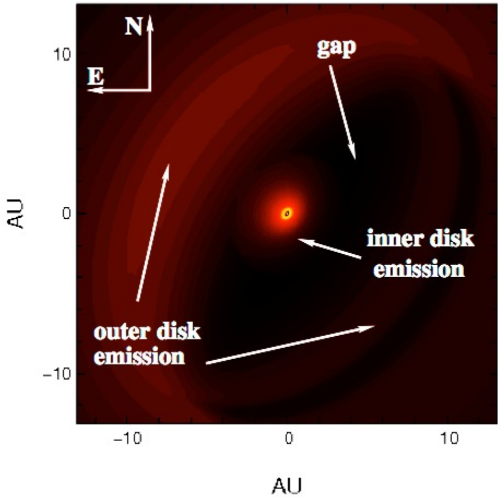
VLT Interferometer
1-13 µm, $\lambda/B=0.001''$

VLTI instruments:

MIDI (2T):	**8-13 µm**	operational
AMBER (3T):	**1-2 µm**	operational
PIONIER (4T):	**2 µm**	operational
GRAVITY (4T):	**2 µm**	first light 2014
MATISSE (4T):	**3-13 µm**	first light 2016

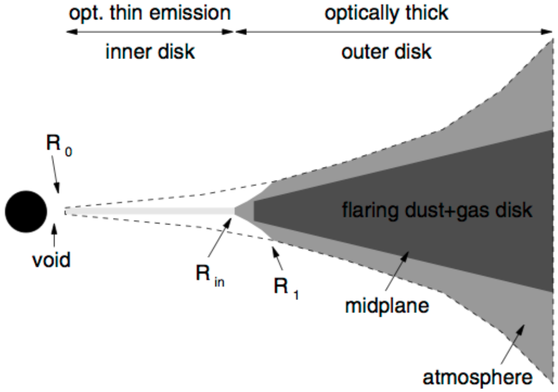
Infrared interferometry of (pre-)transitional disks

HD100546



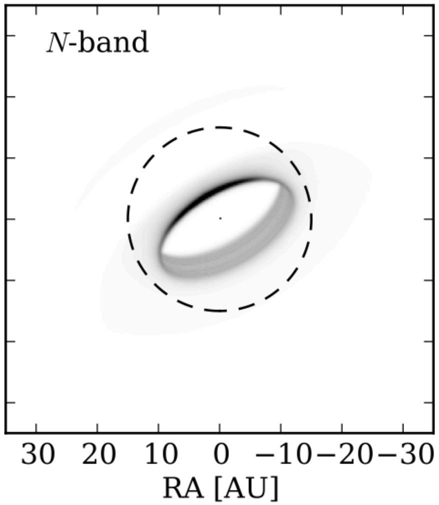
Benisty et al. 2010
Tatulli et al. 2011
Panic et al. 2012
Mulders et al. 2013

TW Hya



Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012

T Cha



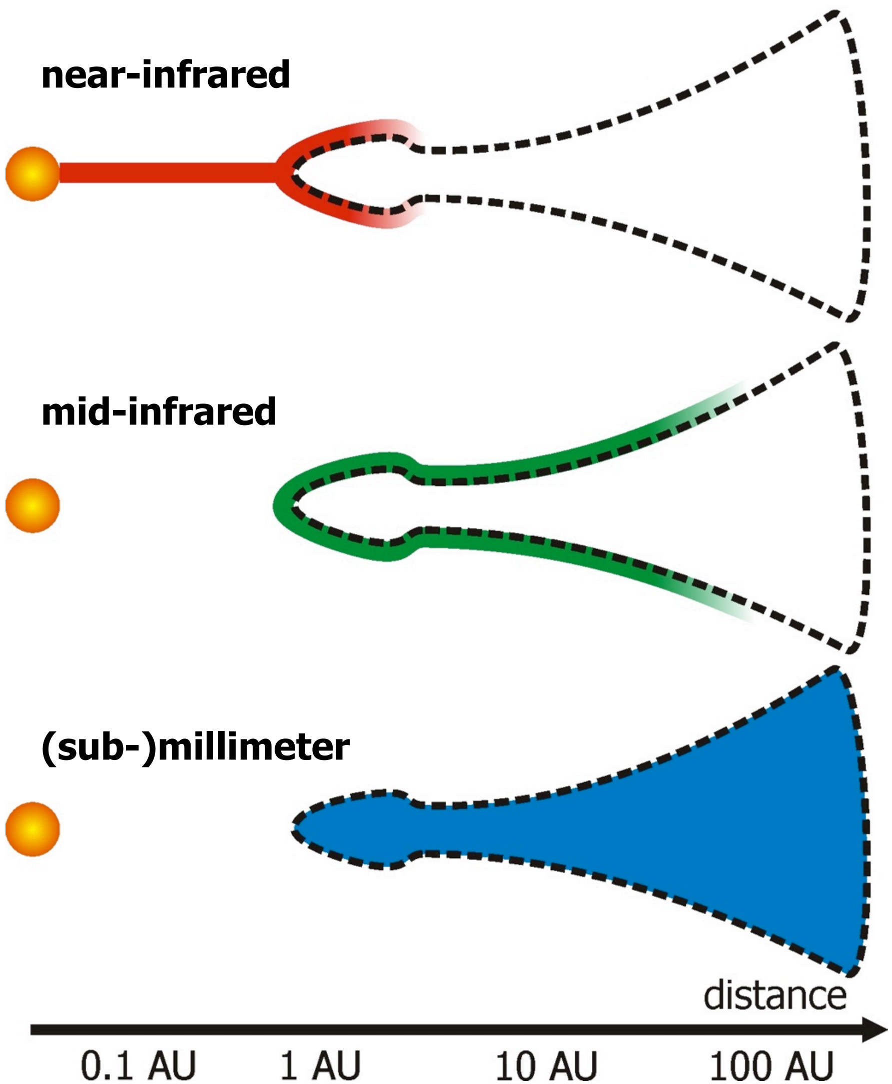
Olofsson et al. 2011, 2013

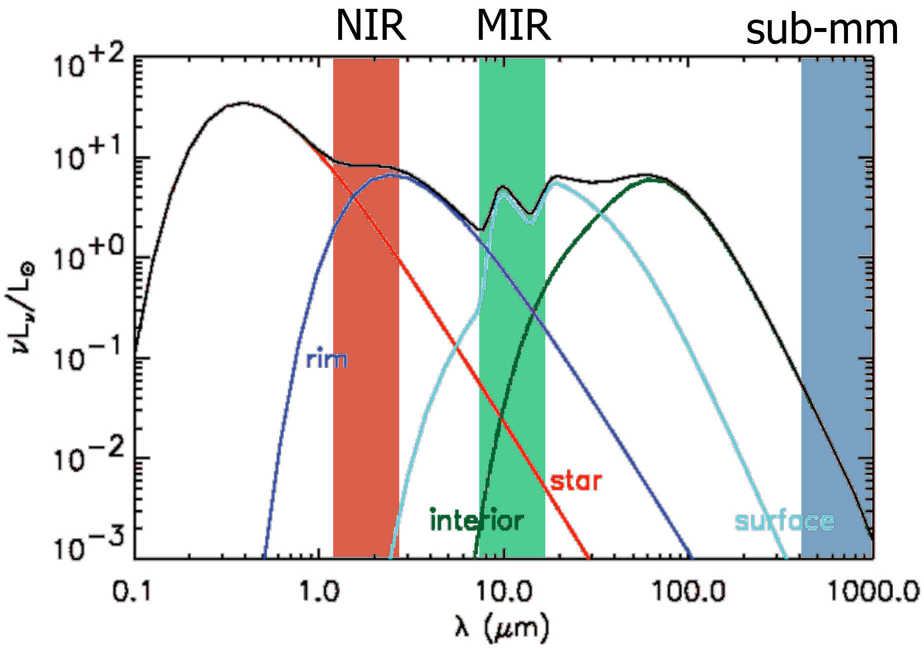
Open questions:

(1) Can we find evidence for disks with partially cleared gaps?
➜ establish evolutionary sequence of disk clearing

(2) How does the disk structure/clearing mechanism depend on stellar mass?
➜ larger object sample needed, in particular in intermediate-mass regime

Multi-wavelength interferometry

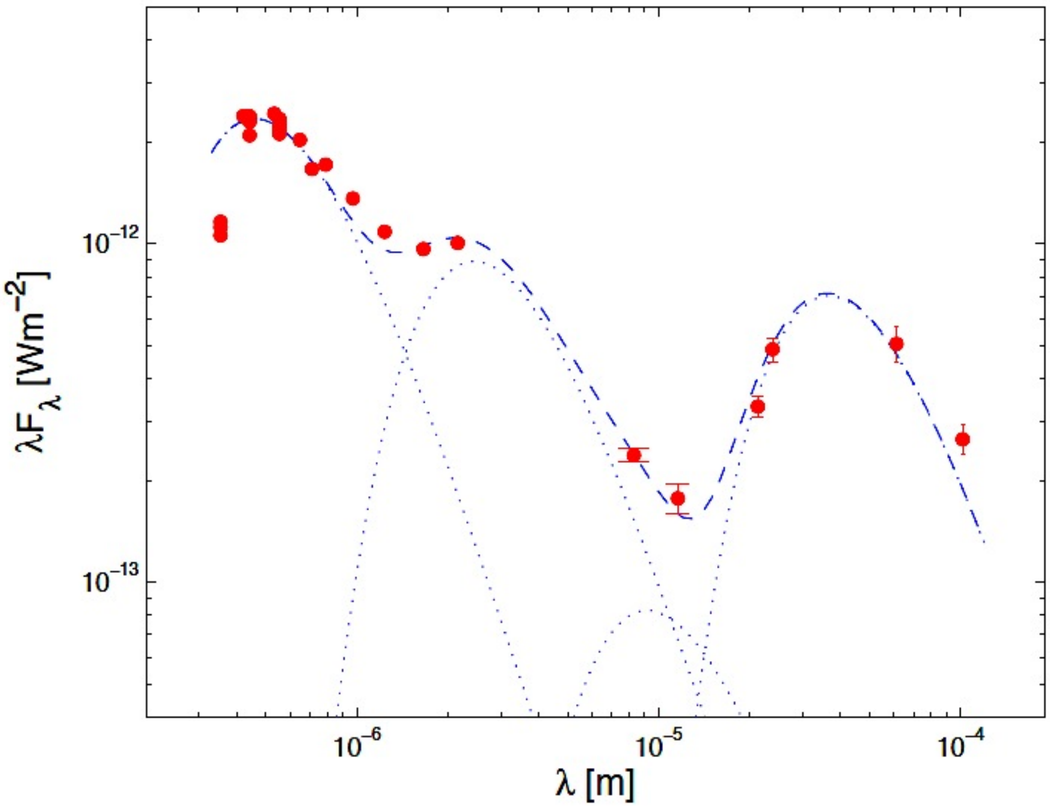




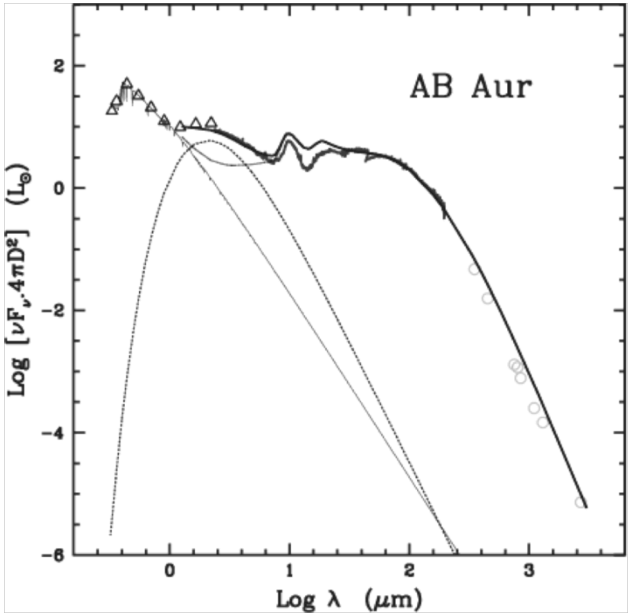
Combined NIR+MIR+sub-mm interferometry:

- Traces **all disk radii**
- Traces **disk surface & interior**
- Constrains **dust composition**
- **Solves ambiguities** by measuring the density & temperature structure directly

V1247 Orionis

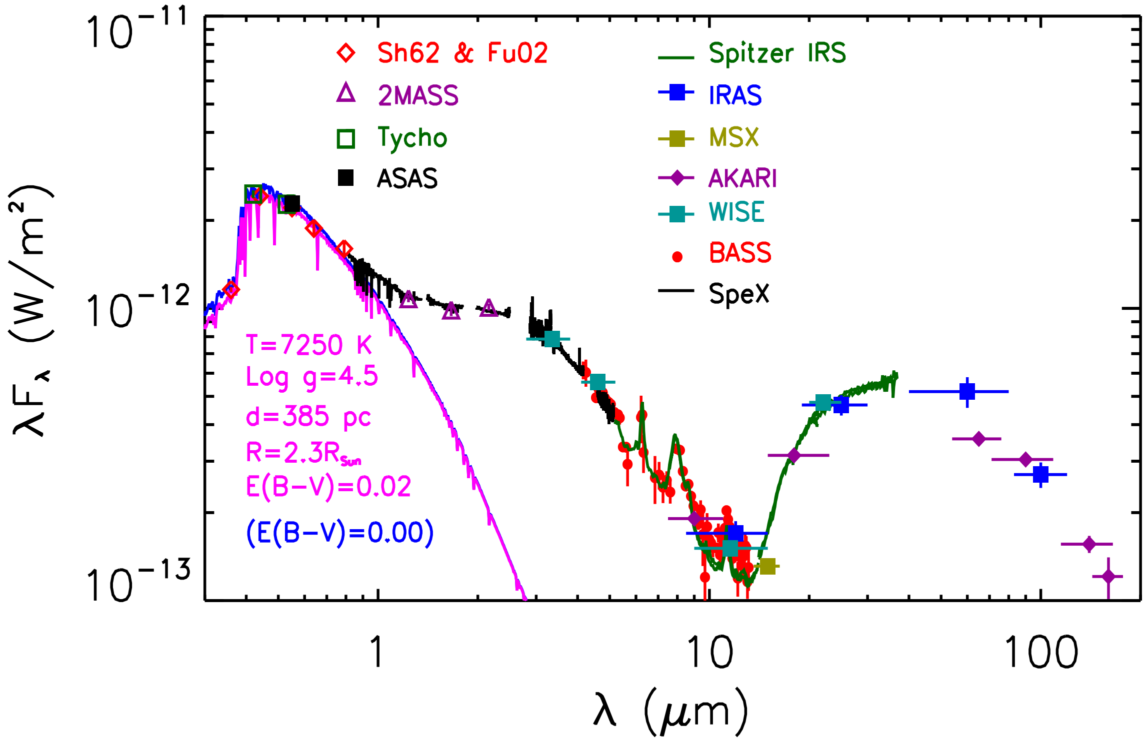


Typical "full" disk

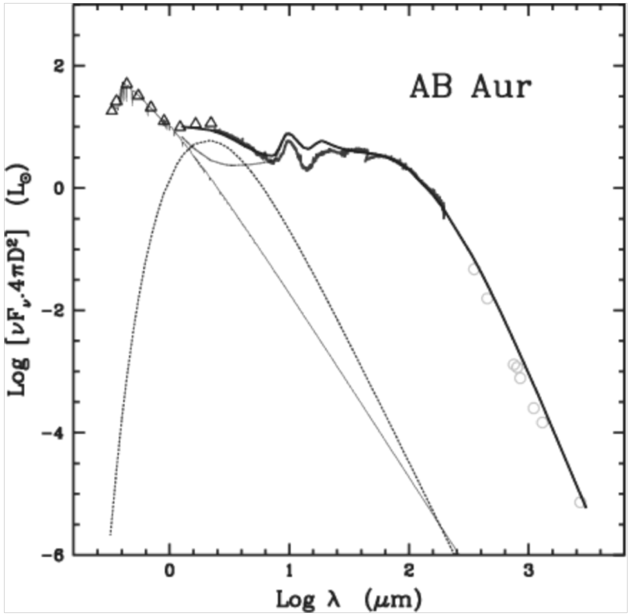


Caballero 2010

V1247 Orionis



Typical "full" disk

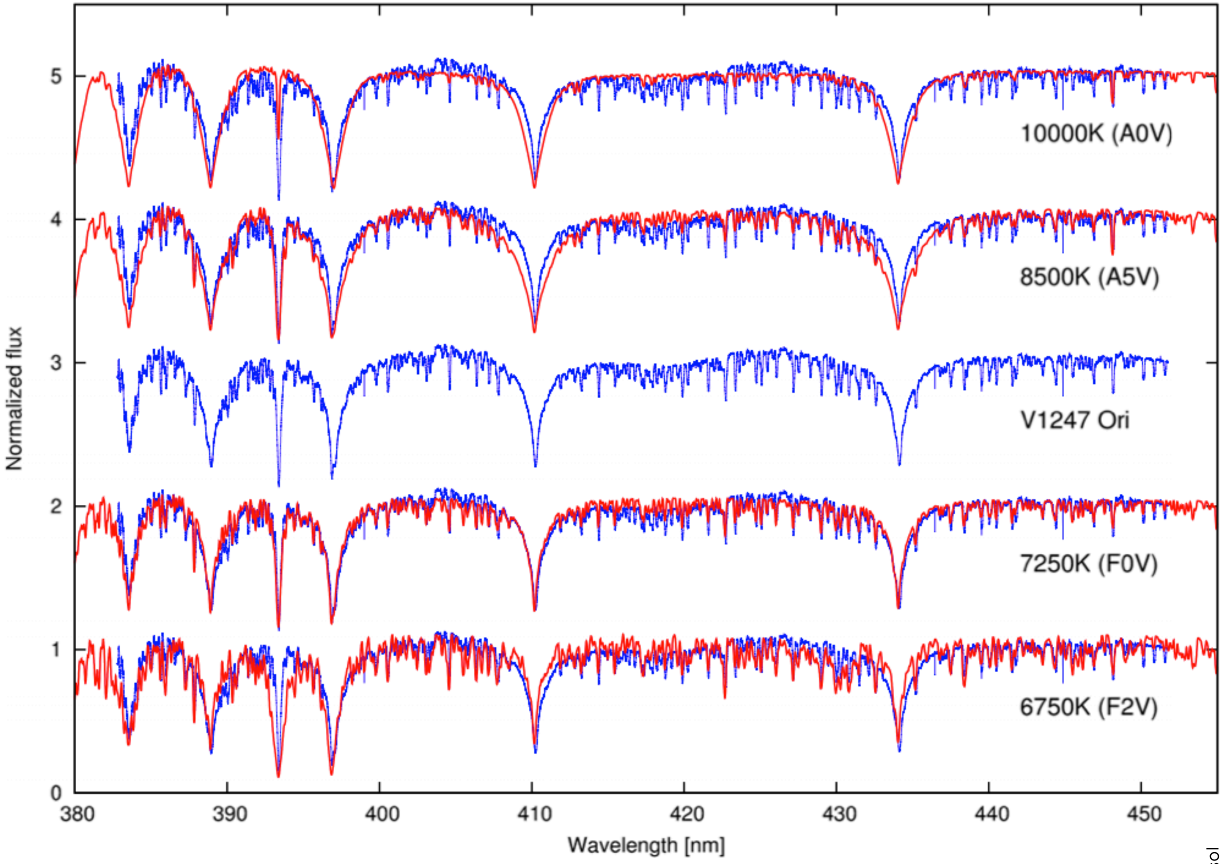


V1247 Ori exhibits MIR flux deficit compared to typical protoplanetary disks

➜ **Indirect evidence for a gapped disk structure**

Kraus et al. 2013

Stellar classification



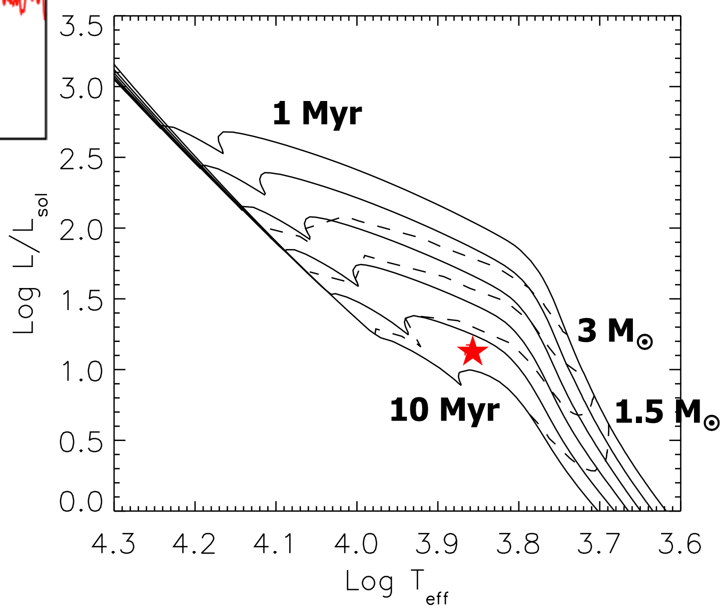
V1247 Ori:

Classification using synthetic spectra by Munari et al. (2005)

➜ **HARPS spectroscopy essential for spectral classification**

Spectral type F0V
T_{eff} = 7250±100 K
g = 4.5
v_{rot} = 60 km/s

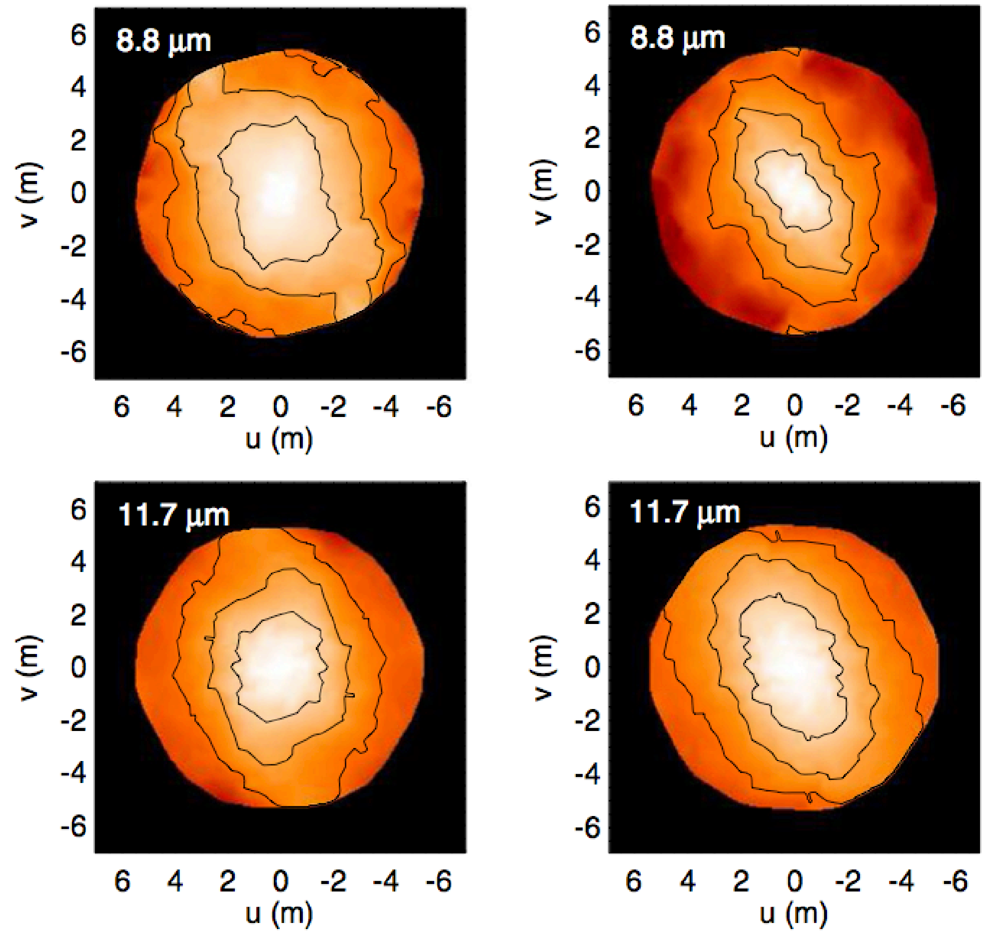
d = 385±15 pc
M = 1.86 $M_\odot$
Age = 7.4±0.4 Myr



Resolving the disk structure

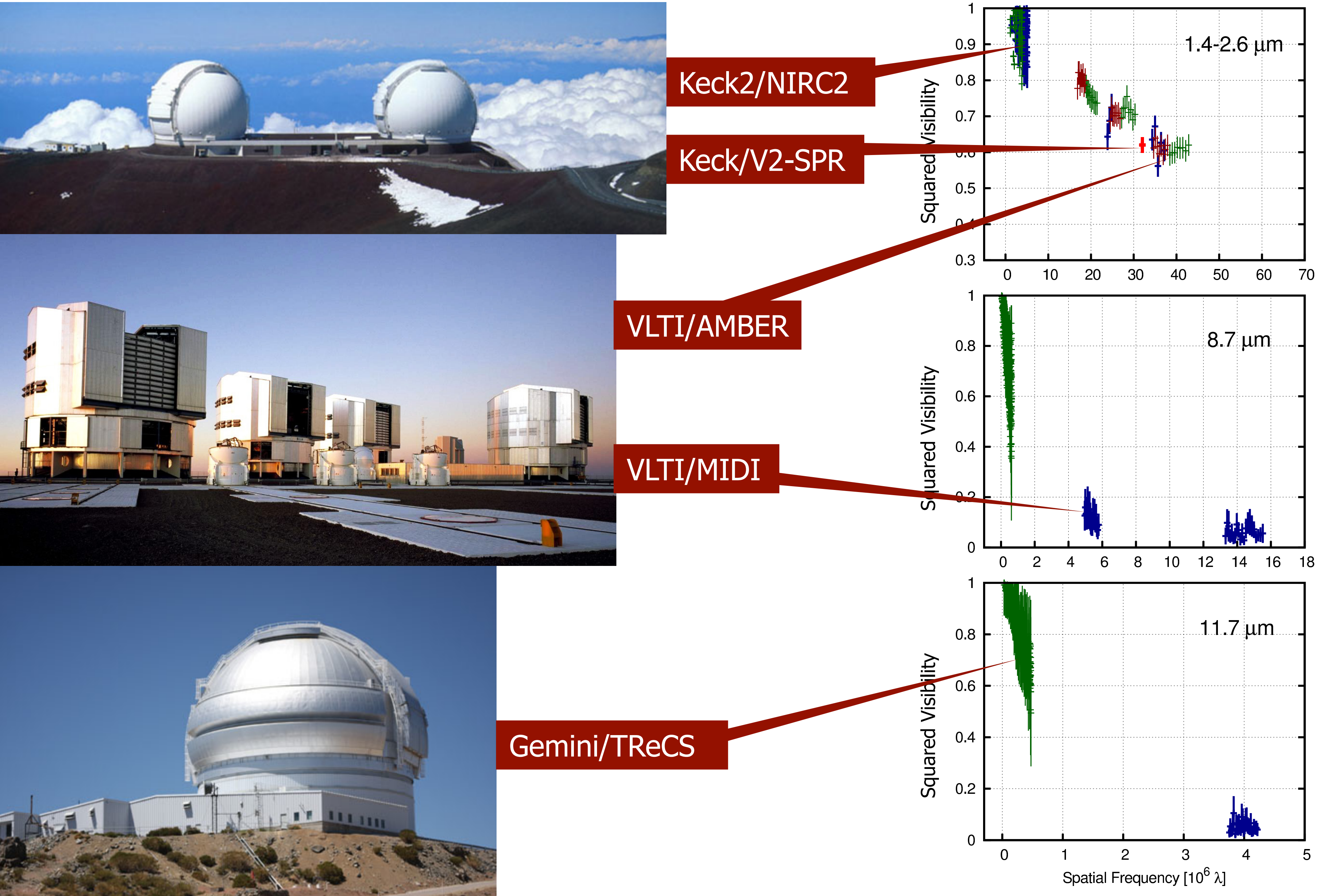
Gemini/TReCS speckle interferometry yields MIR 2-D power spectra

➜ **Inclination: 31±7°**
PA: 104±15°



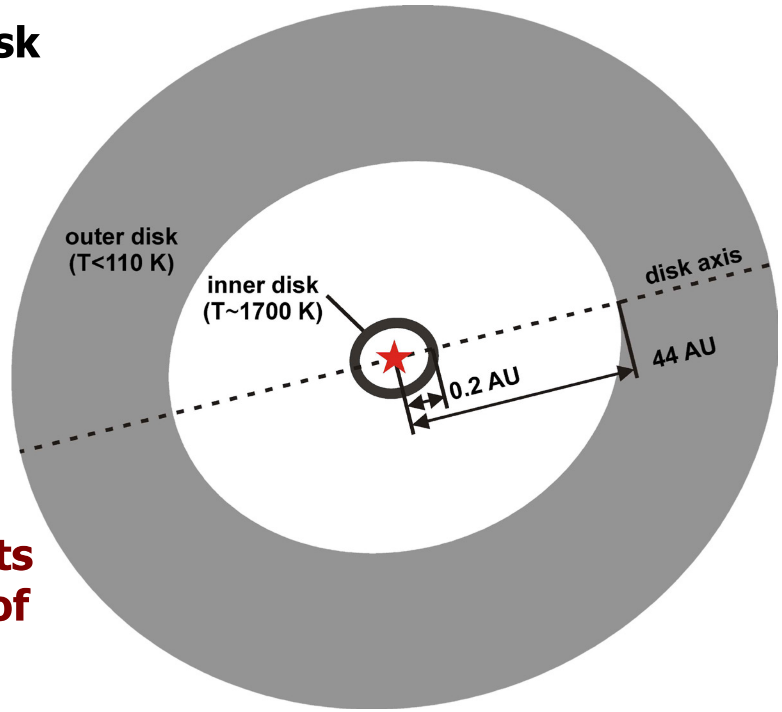
Gemini/TReCS

Resolving the disk structure

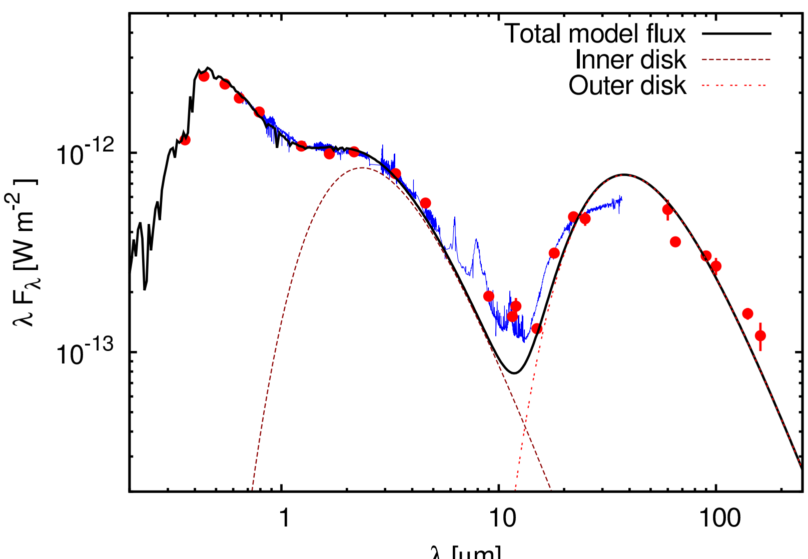


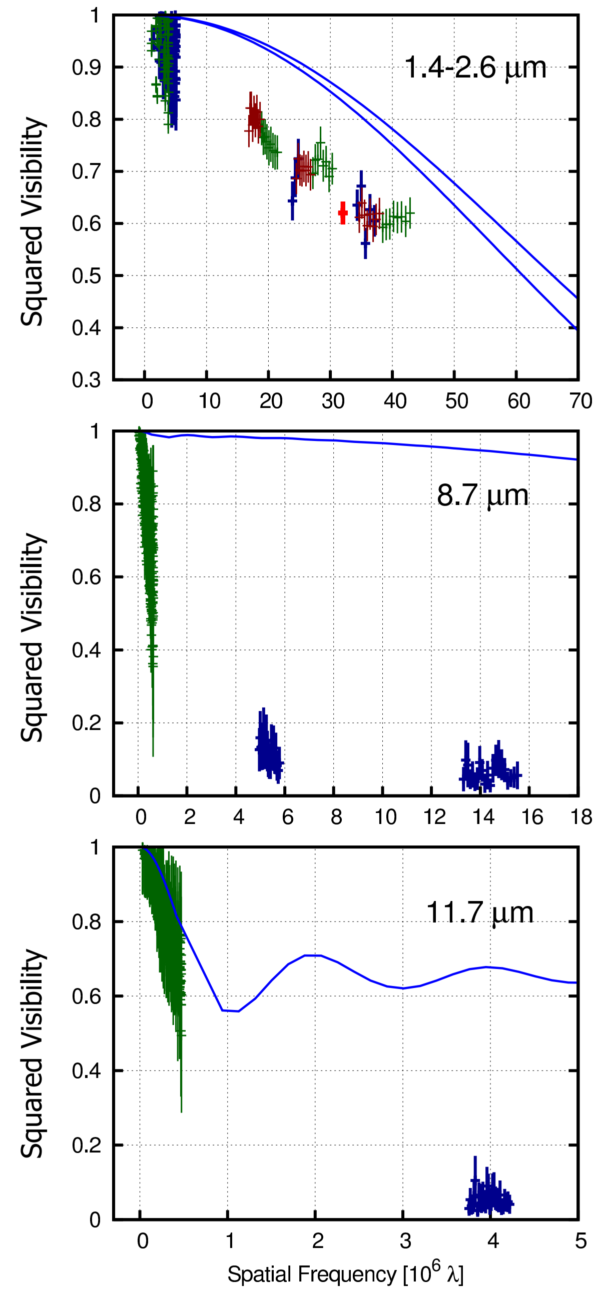
Resolving the disk structure

Scenario 1: Gapped disk



➜ **Model underpredicts MIR-size by order of magnitude**





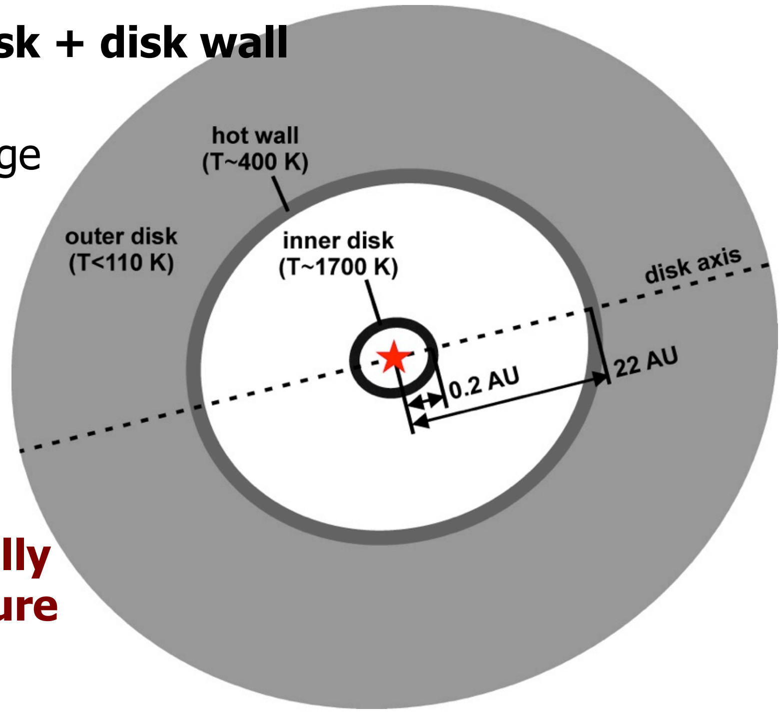
Resolving the disk structure

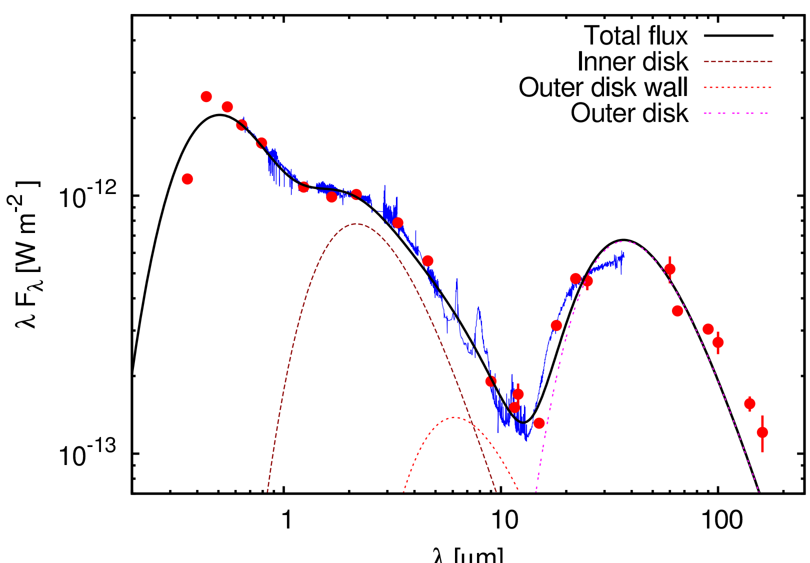
Scenario 2: Gapped disk + disk wall

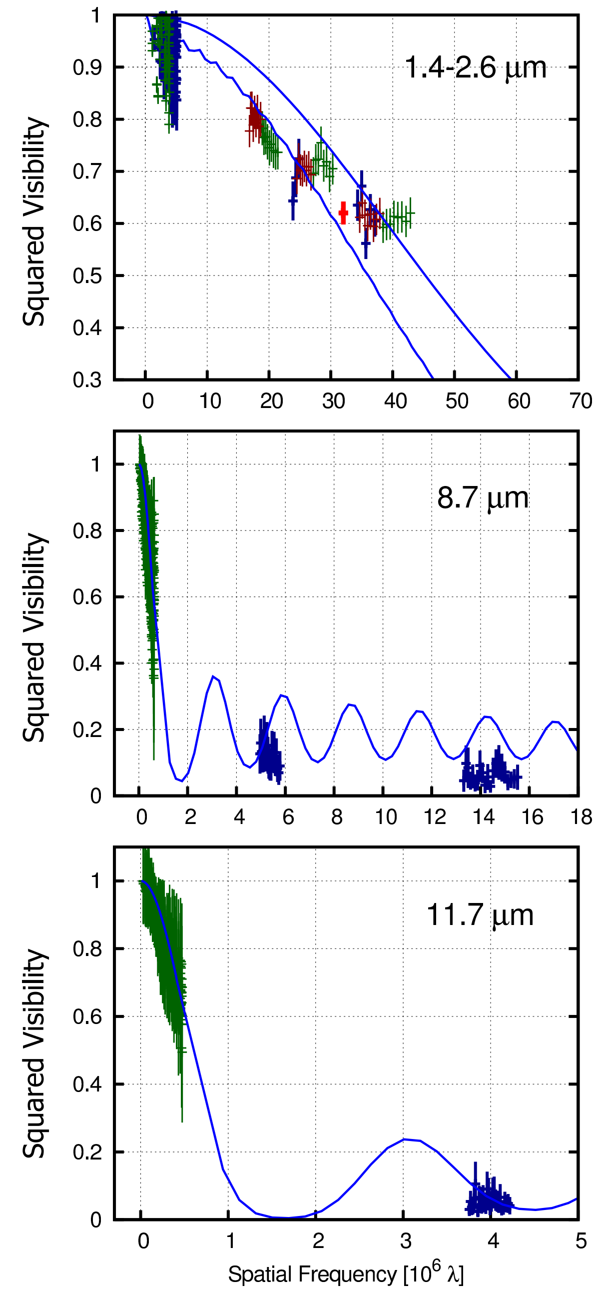
Realistic temperature range for wall @ 22 AU:

90K for grey dust
160K for 0.1μm grains

➜ **Requires unphysically high wall temperature of 400 K @ 22 AU**

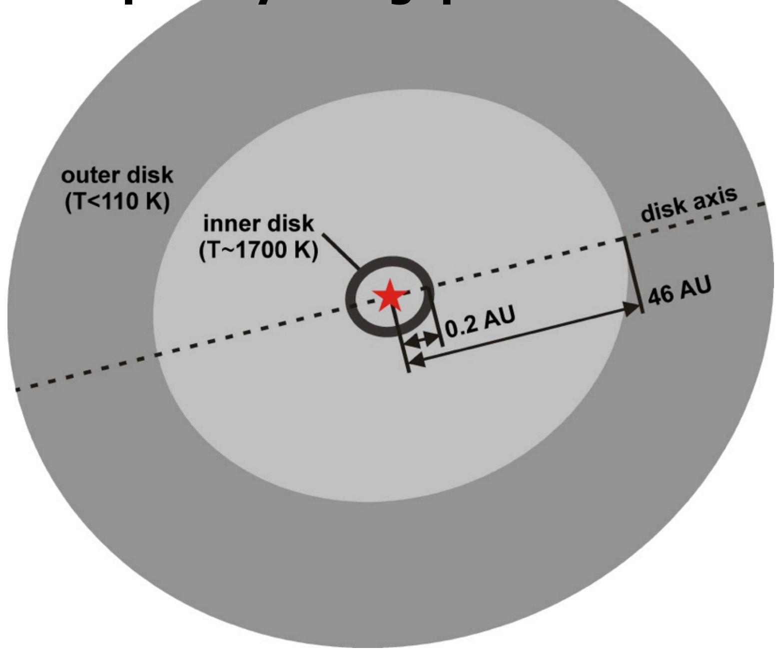






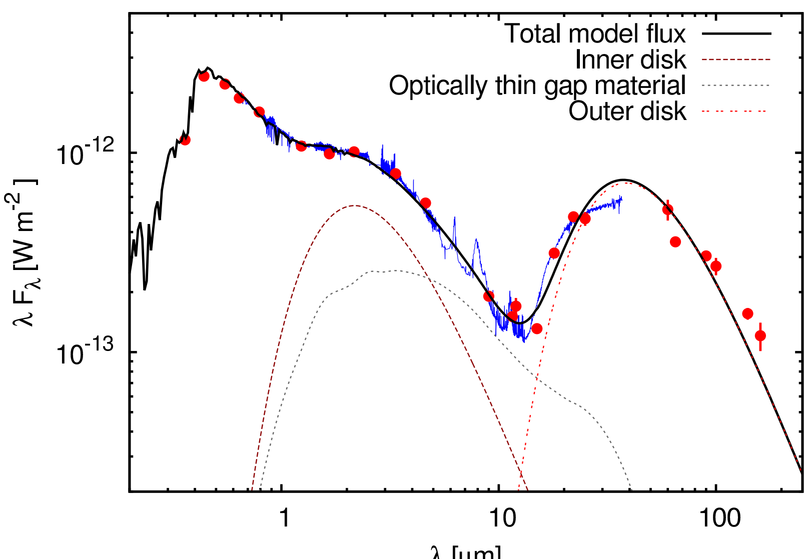
Resolving the disk structure

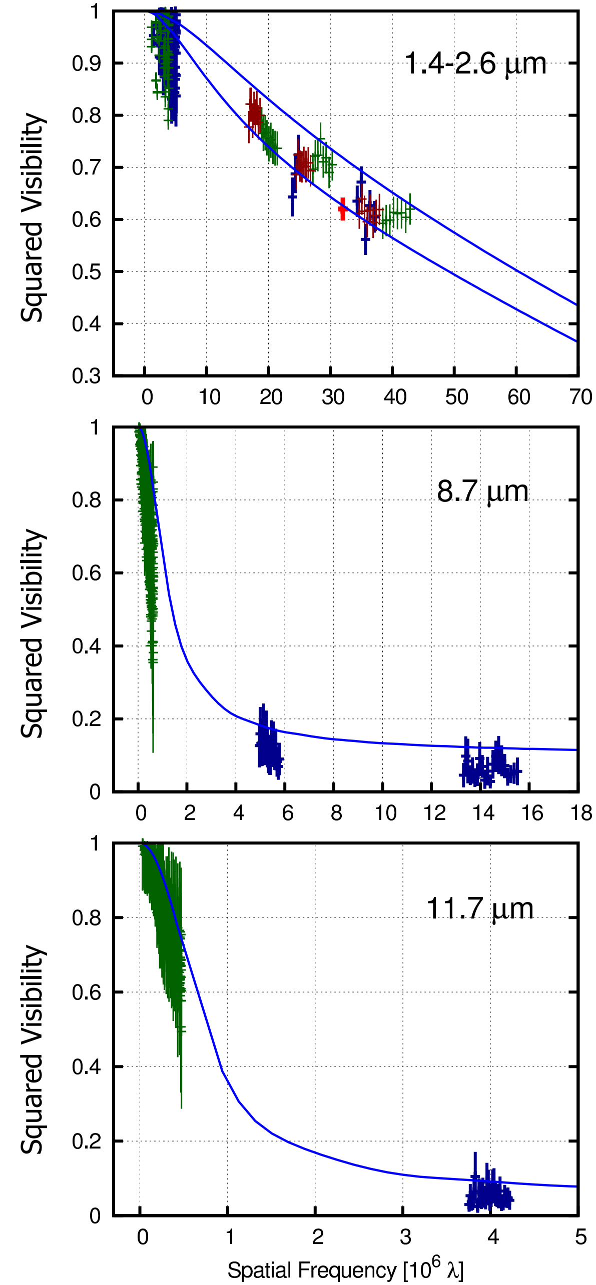
Scenario 3: Gapped disk + optically thin gap material



➜ **Gap filled with optically thin dust**
$\Sigma_{gap}=9\times10^{-6}$ g/cm^2

➜ **Gap material dominates MIR emission**

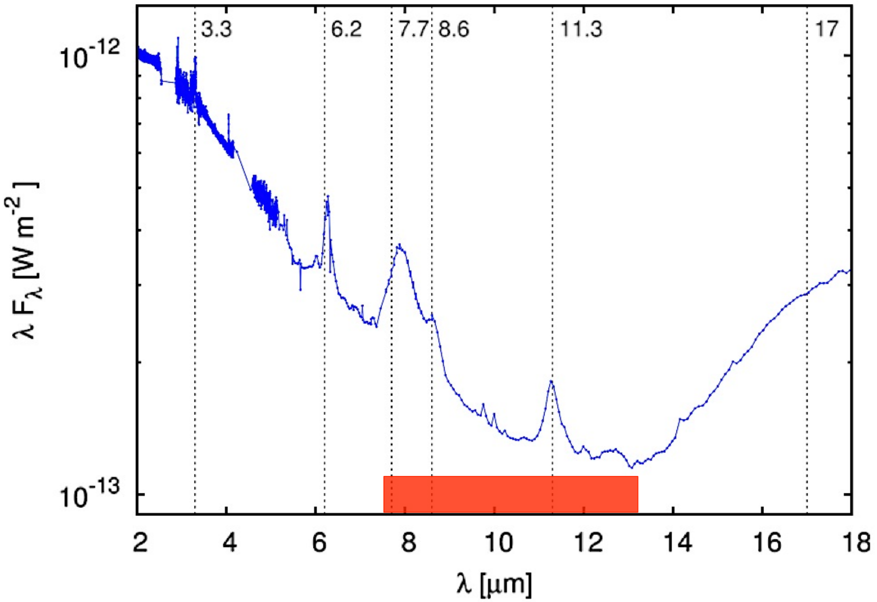


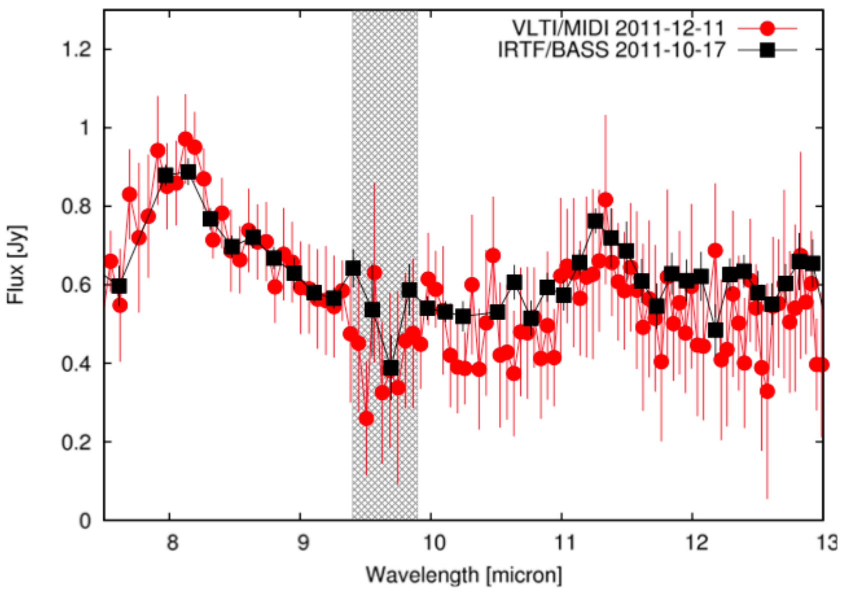


Dust mineralogy

➜ **Carbon-dominated dust mineralogy required** (other carbon-rich systems: Fomalhaut, 55 Cnc e, …)

➜ **Strong PAH emission origins within the gap region**

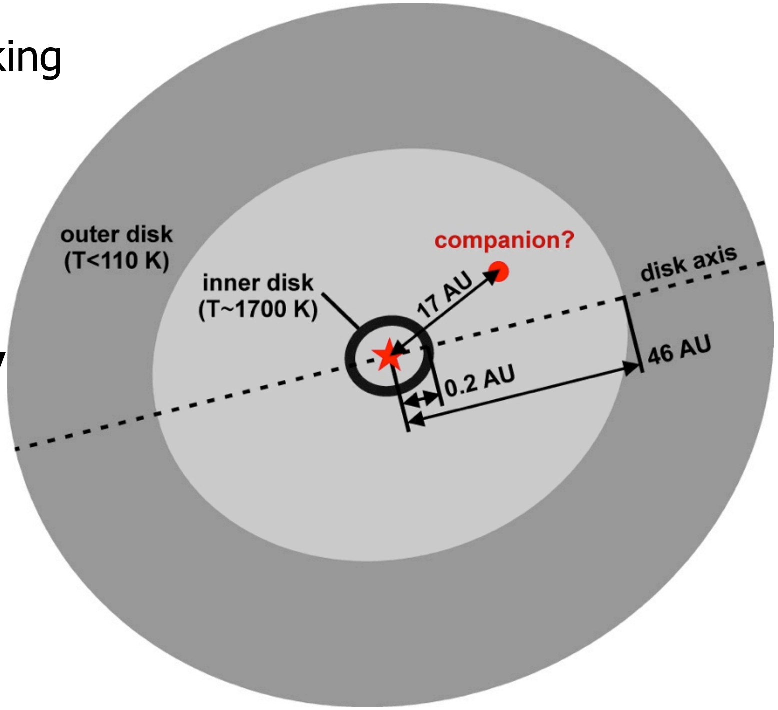




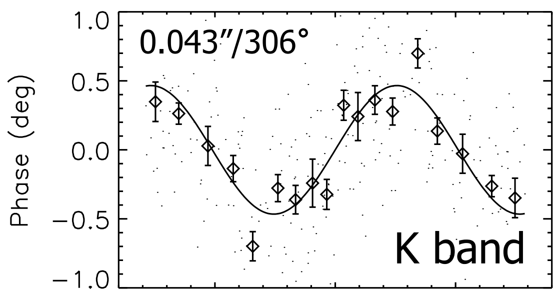
AU-scale asymmetries: The gap-opening body?

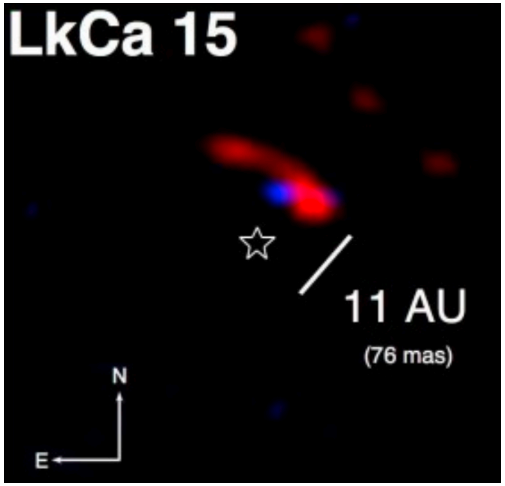
Keck/NIRC2 aperture masking reveals asymmetries

➜ **K-band detection consistent with companion discovery (10σ-level)**

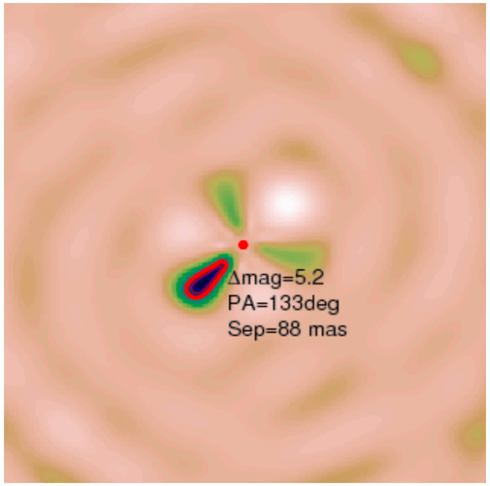


Keck/NIRC2 aperture masking

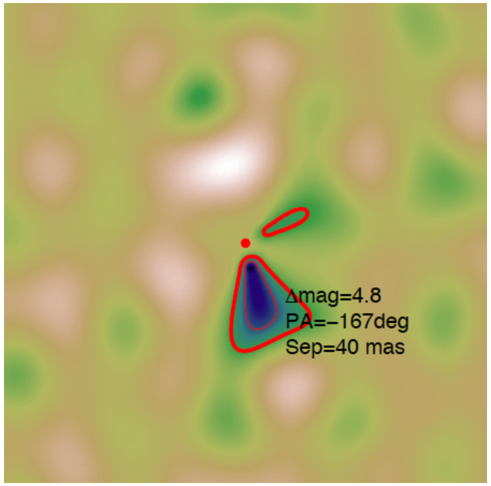




LkCa 15, Kraus & Ireland 2011



HD142527, Biller et al. 2012

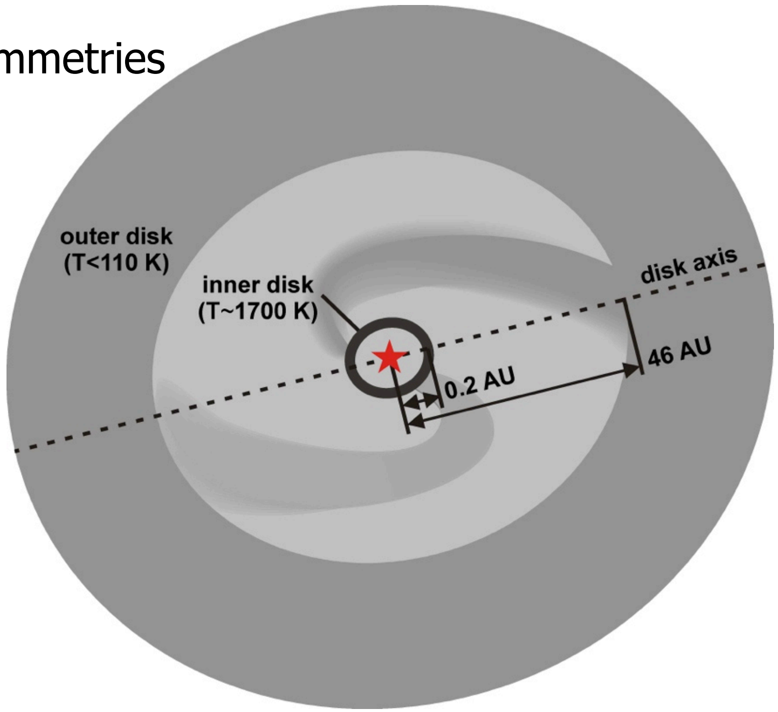


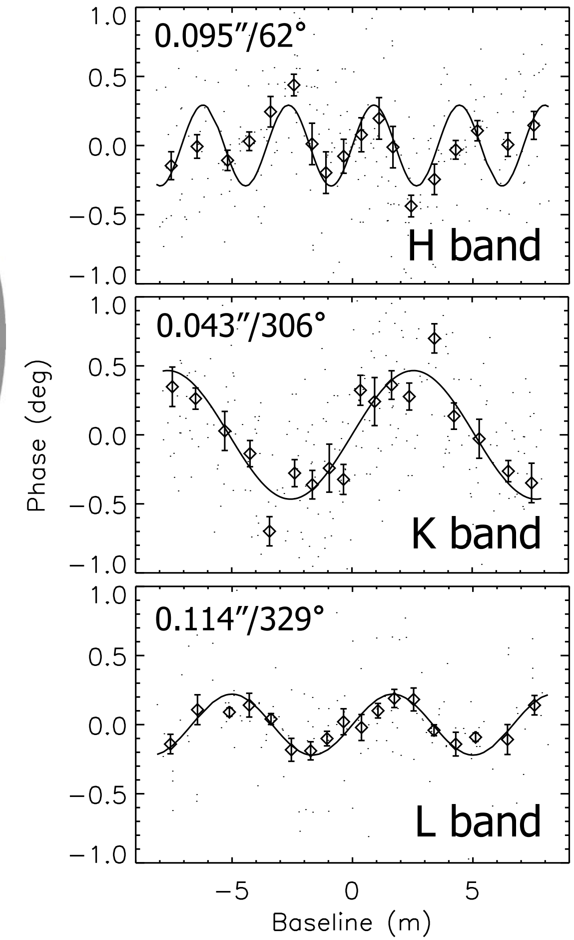
FL Cha, Cieza et al. 2013

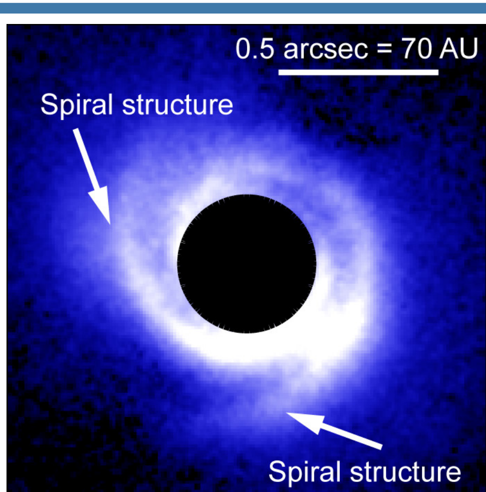
AU-scale asymmetries: Disk inhomogeneities

Amplitude/direction of asymmetries changes with wavelength

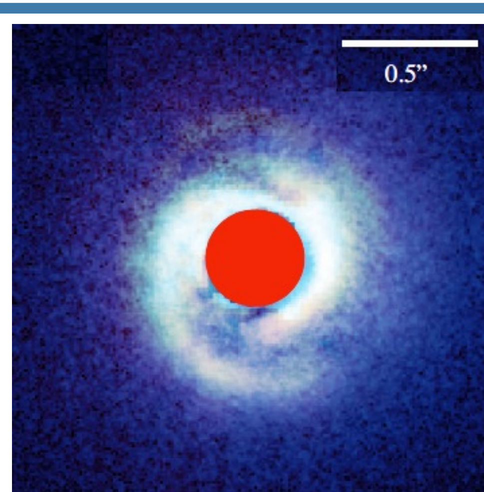
- ➜ **Not consistent with companion scenario**
- ➜ **Complex density structures in the gap region, possibly due to dynamical interaction with gap-opening planets**







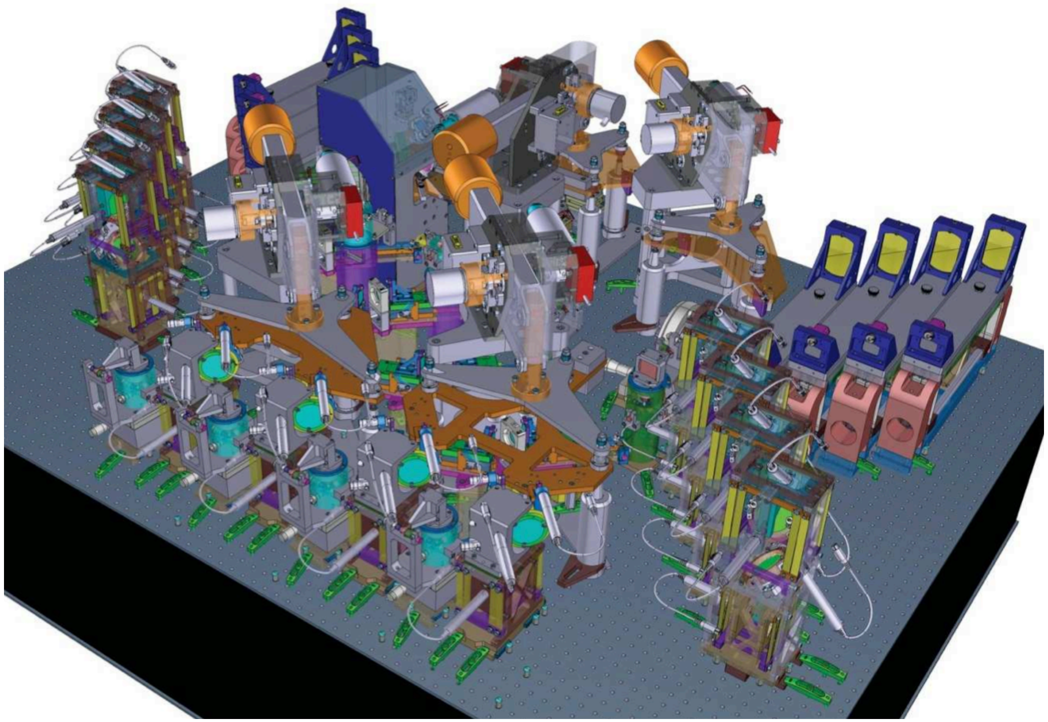
SAO206462, Dong et al. 2012



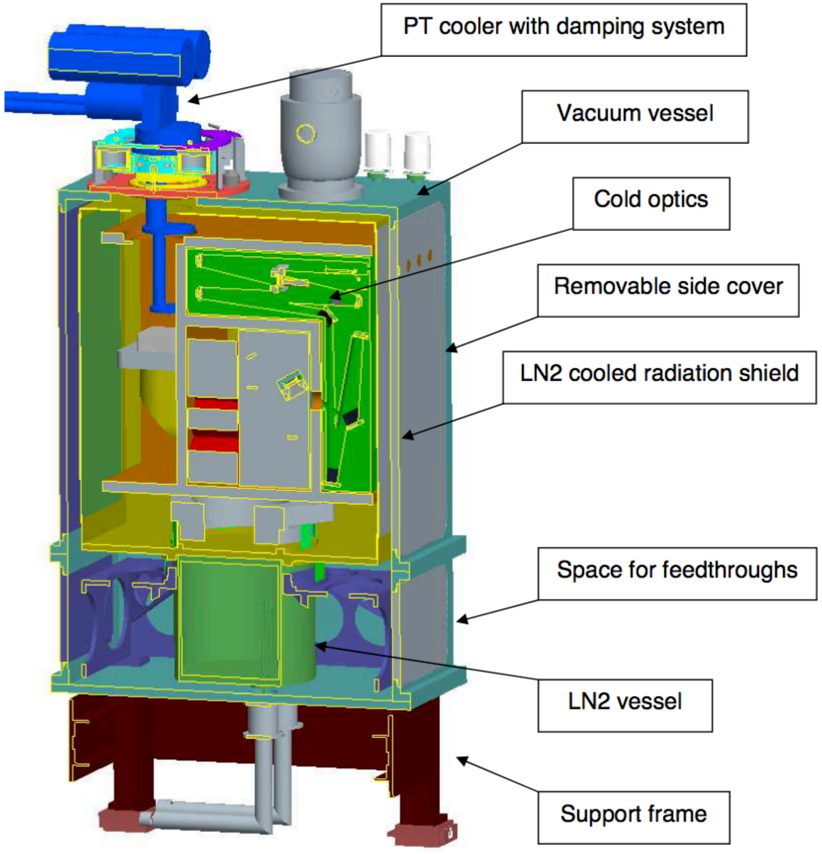
MWC758, Grady et al. 2013

VLTI/MATISSE

Warm optics



Cold optics

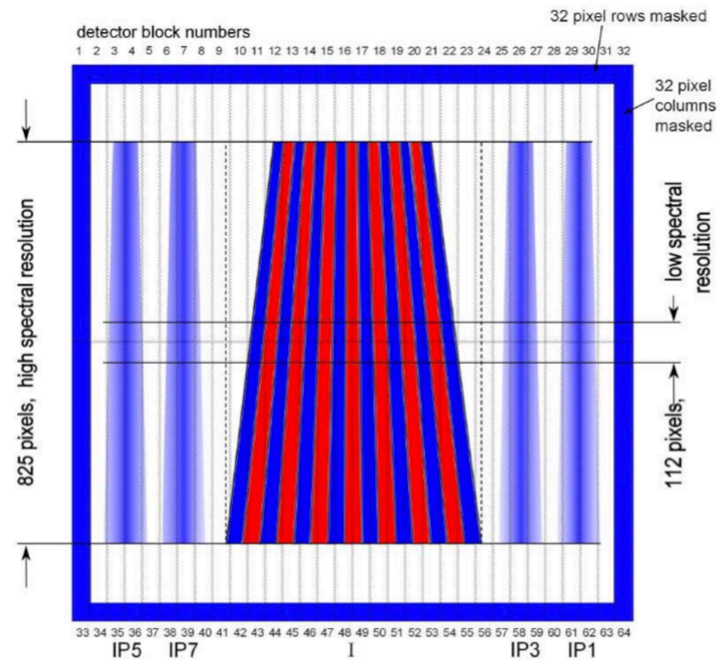


4T beam combiner, 2 detectors:

L / M / L+M band:	R=30, 500, 950	Hawaii-2RG
N-band:	R=30, 220	Aquarius FPA

VLTI/MATISSE design

- Multi-axial layout
- photometric beams (HighSens / SciPhot)
- chopping to separate sky background



Sensitivity goals:

Telescope/Bands	L-band	M-band	N-band
AT	1.9 Jy	5.7 Jy	11.6 Jy
UT	0.18 Jy	0.44 Jy	0.7 Jy

Accuracy goals L band:

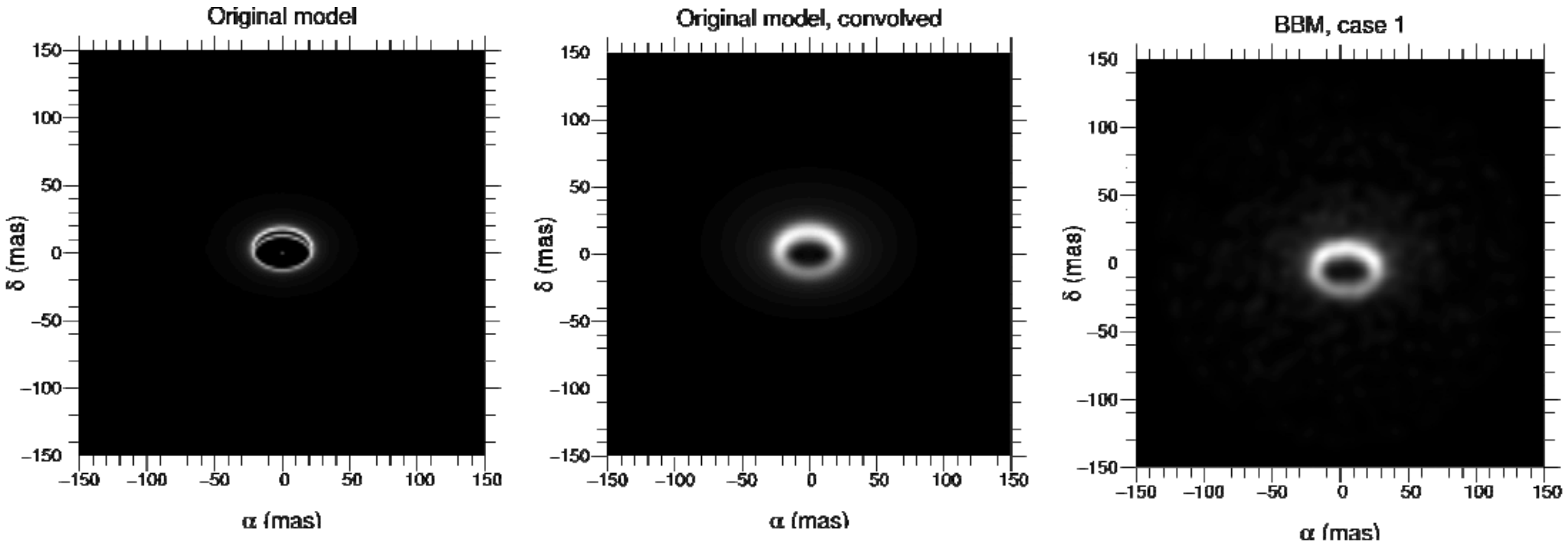
L band 20 Jy Low resolution		Technical Specifications	
		Specifications	Goals
Visibility	AT	≤ 7.5 %	≤ 2.5 %
	UT	≤ 7.5 %	≤ 2.5 %
Closure Phase	AT	≤ 80 mrad	-
	UT	≤ 40 mrad	≤ 1 mrad
Differential Visibility	AT	≤ 3 %	≤ 1 %
	UT	≤ 1.5 %	≤ 0.5 %
Differential Phase	AT	≤ 60 mrad	-
	UT	≤ 30 mrad	≤ 1 mrad

Accuracy goals N band:

N band 20 Jy Low resolution		Technical Specifications	
		Specifications	Goals
Visibility	AT	≤ 30 %	≤ 10 %
	UT	≤ 7.5 %	≤ 2.5 %
Closure Phase	AT	≤ 80 mrad	-
	UT	≤ 40 mrad	-
Differential Visibility	AT	≤ 30 %	≤ 10 %
	UT	≤ 5 %	≤ 2 %
Differential Phase	AT	≤ 60 mrad	-
	UT	≤ 30 mrad	-

MIR interferometric imaging

Simulation assuming full tracks on 7 configurations in 4T mode

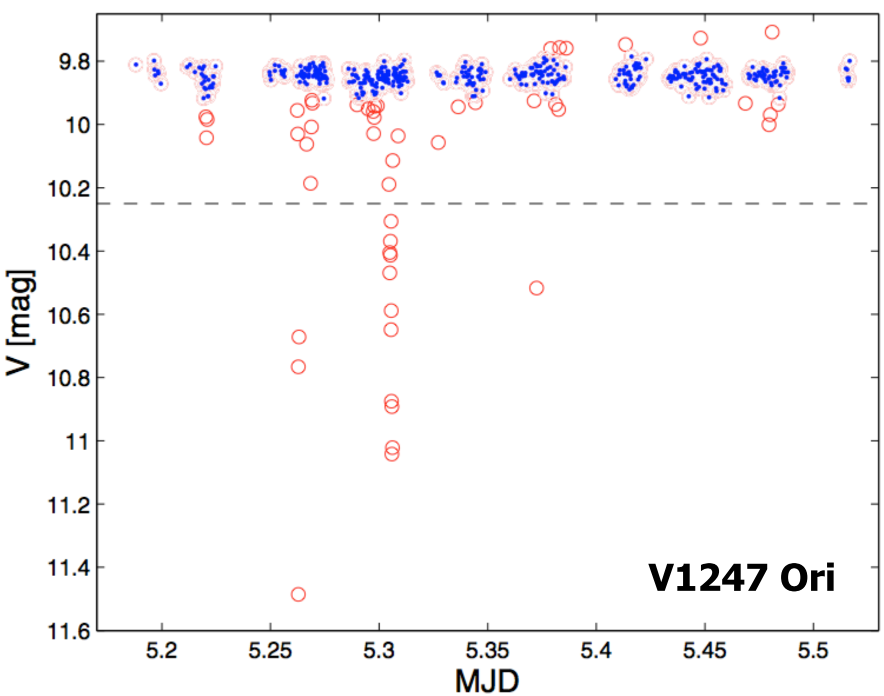


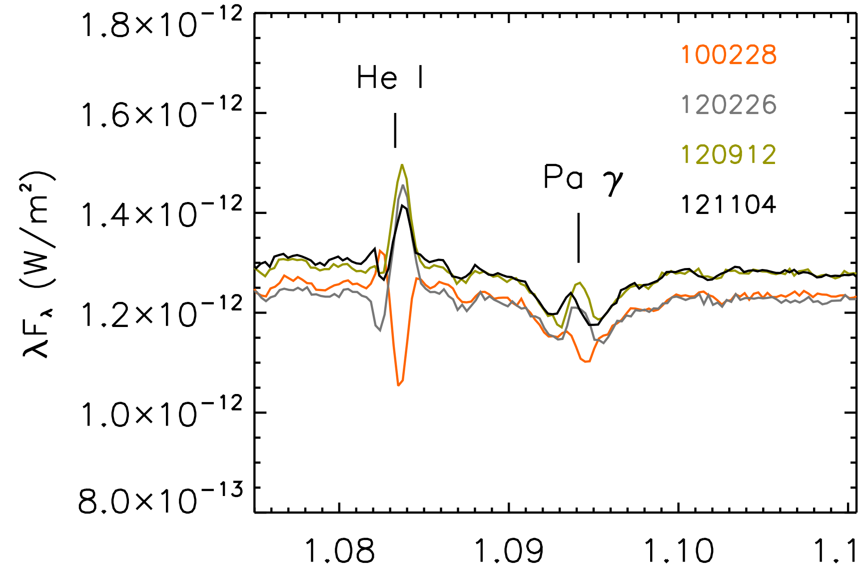
4T beam combination will enable **efficient image reconstruction**

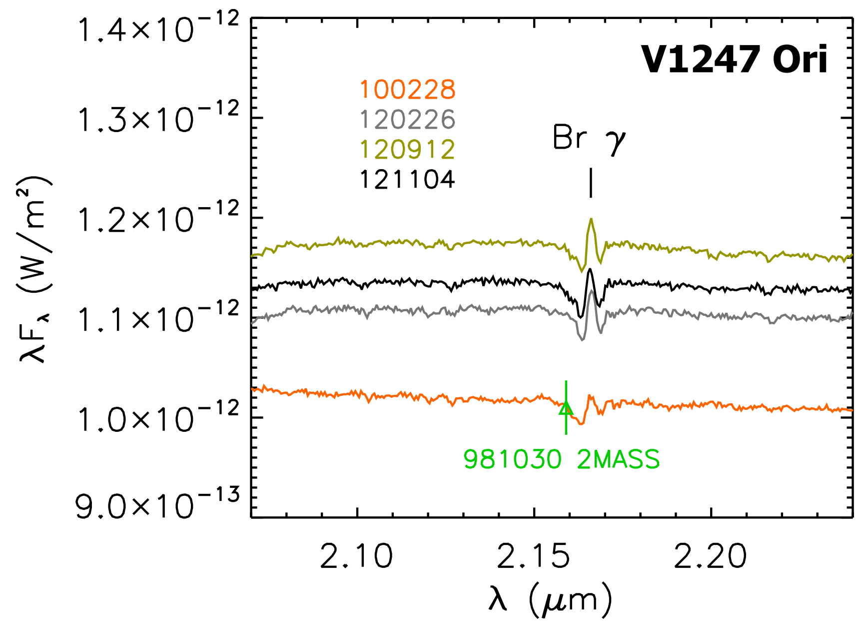
- ➜ study complex structures
- ➜ model-independent constraints
- ➜ important to extend user base

MIR interferometric imaging

Many pre-transitional disks show photometric & spectroscopic variability, possibly reflecting structural changes in the inner disk regions



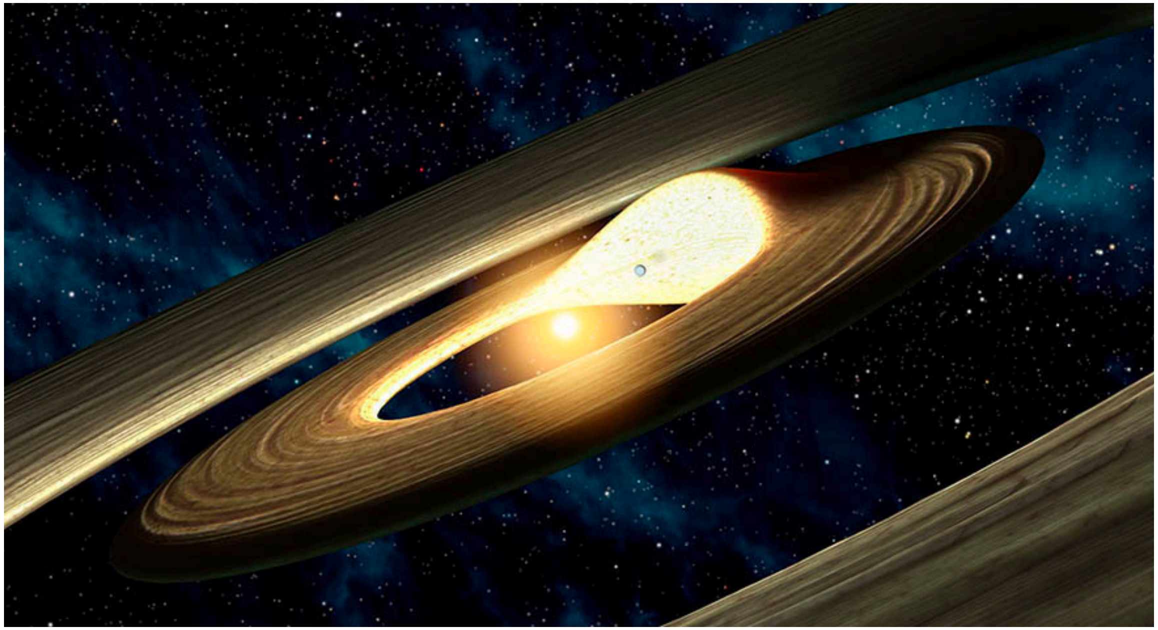




Cabellaro 2010, Kraus et al. 2013

MIR interferometric imaging

Many pre-transitional disks show photometric & spectroscopic variability, possibly reflecting structural changes in the inner disk regions



Artists Impression

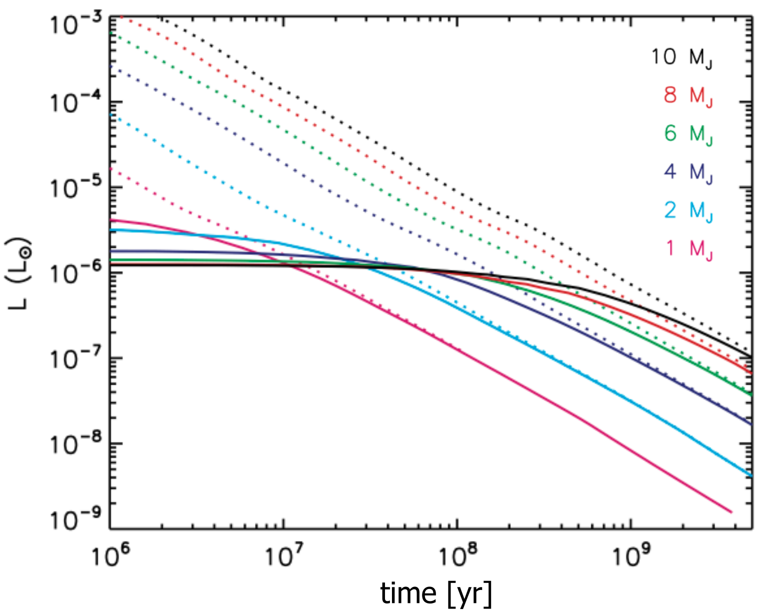
➜ **Multi-epoch interferometric imaging could reveal origin of variability**

New challenges:

- ➜ Coordinated spectroscopic + interferometric observations necessary
- ➜ Frequent & rapid configuration changes necessary to achieve uv-coverage

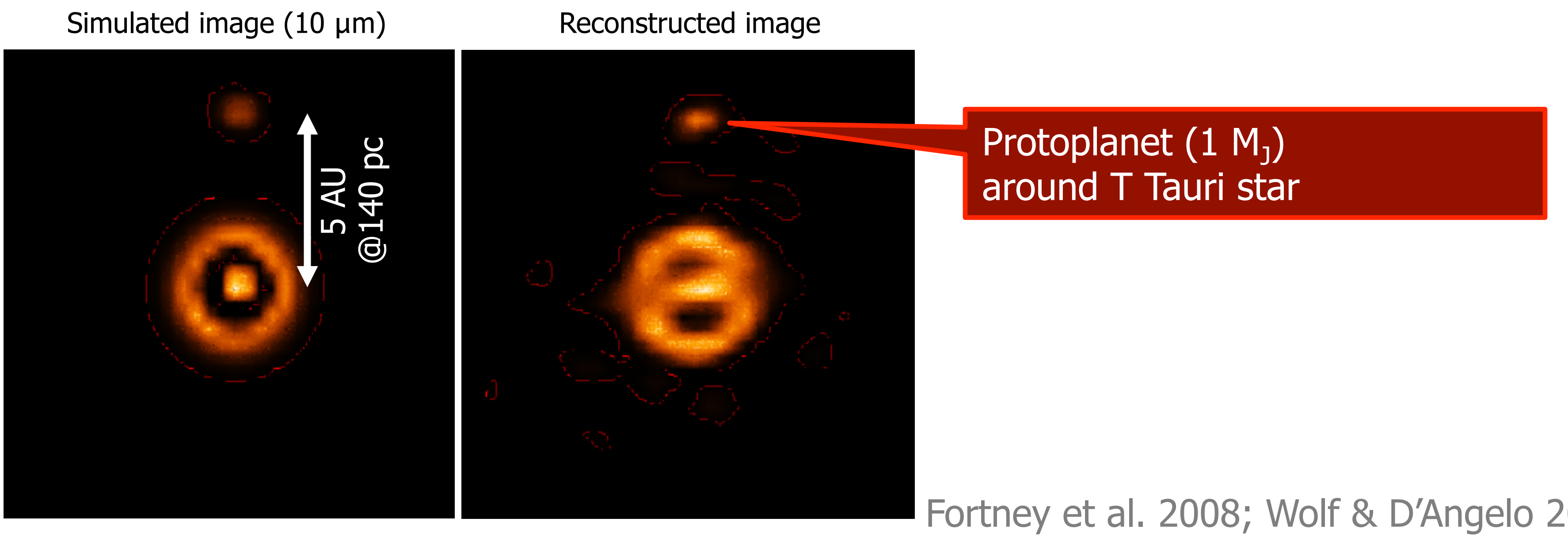
Muzerolle et al. 2009

MIR interferometric imaging



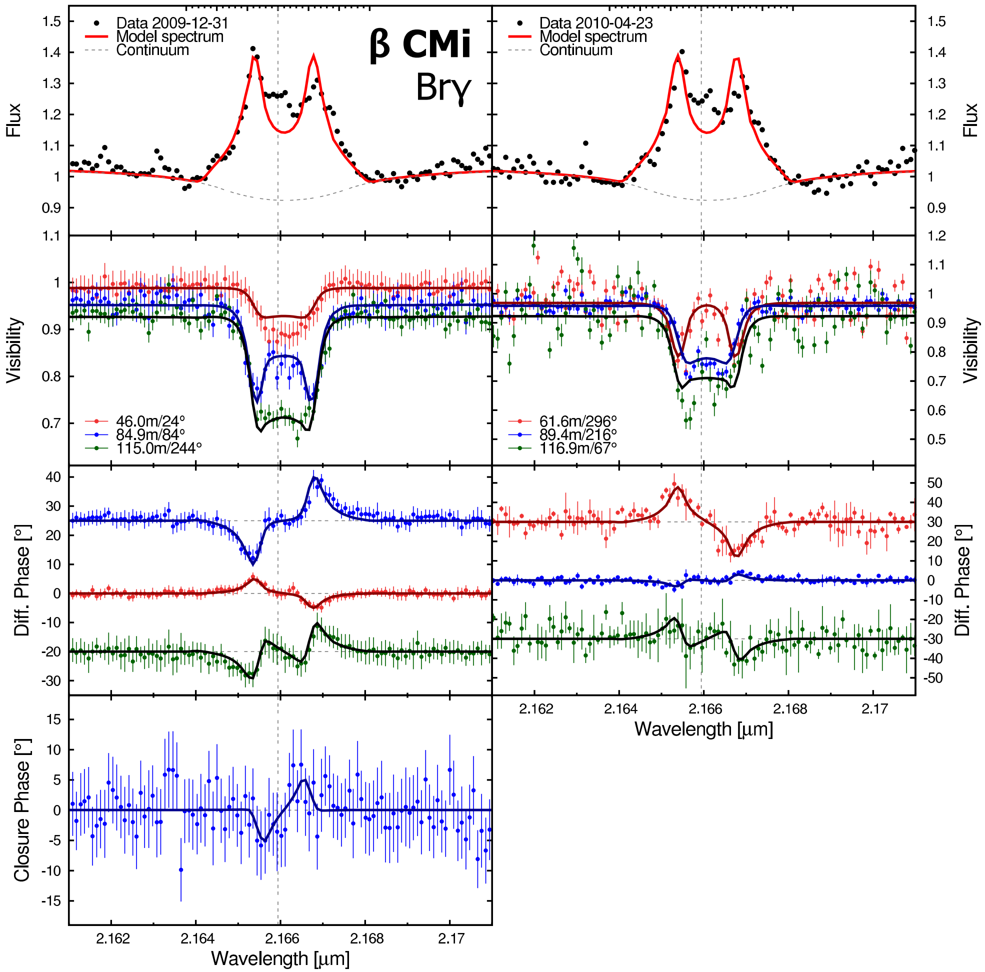
Young accreting planets emit significantly at mid-infrared wavelengths

➜ MATISSE could detect protoplanets on scales of a few AU



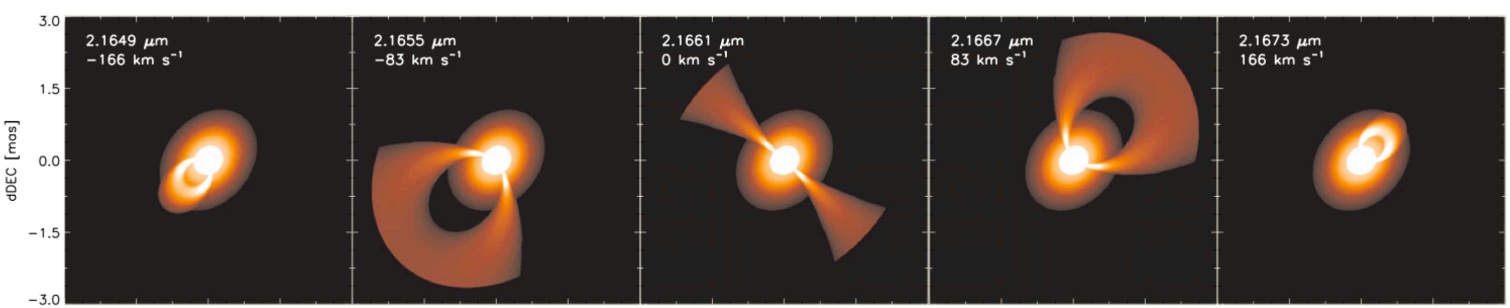
Fortney et al. 2008; Wolf & D'Angelo 2005

Interferometry in spectral lines



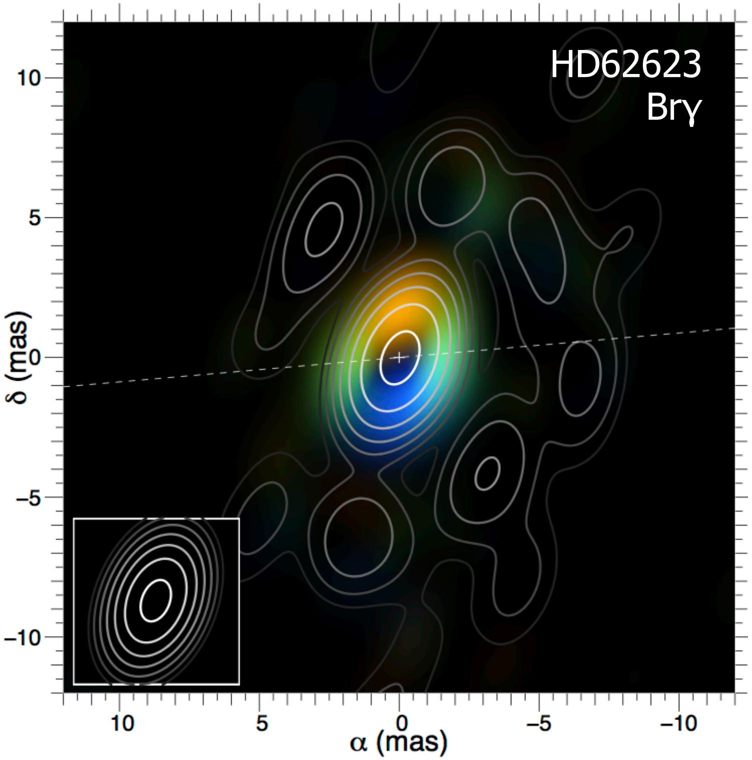
Interferometry with high spectral dispersion reveals gas distribution and kinematics

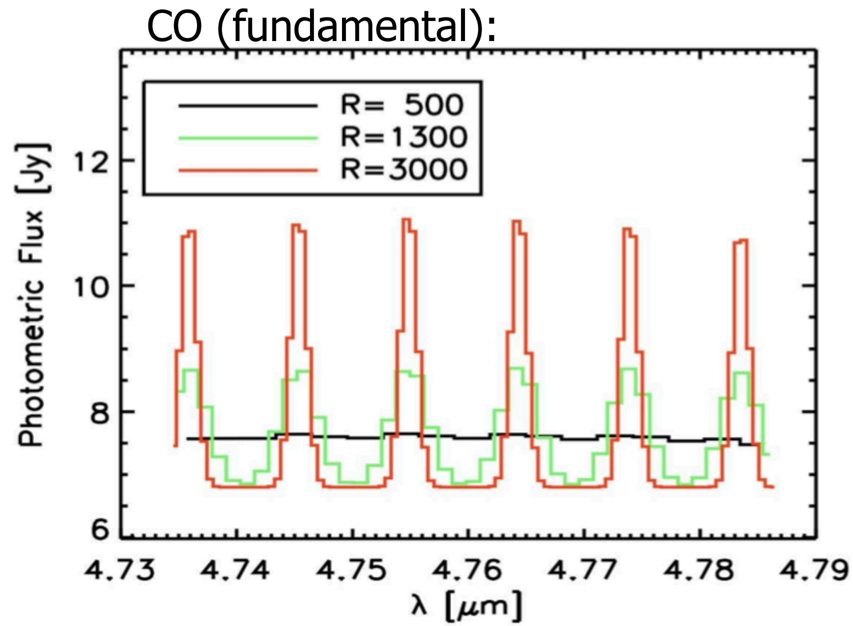
$$v(r) = r^{-0.5\pm0.1} (\text{=Keplerian})$$
$$M_\bigstar = 3.6 \pm 0.2 M_\odot$$
$$i = 38.5 \pm 1.0^\circ$$
$$\text{PA} = 140.0 \pm 1.7^\circ$$



Kraus et al. 2012a

Interferometry in spectral lines



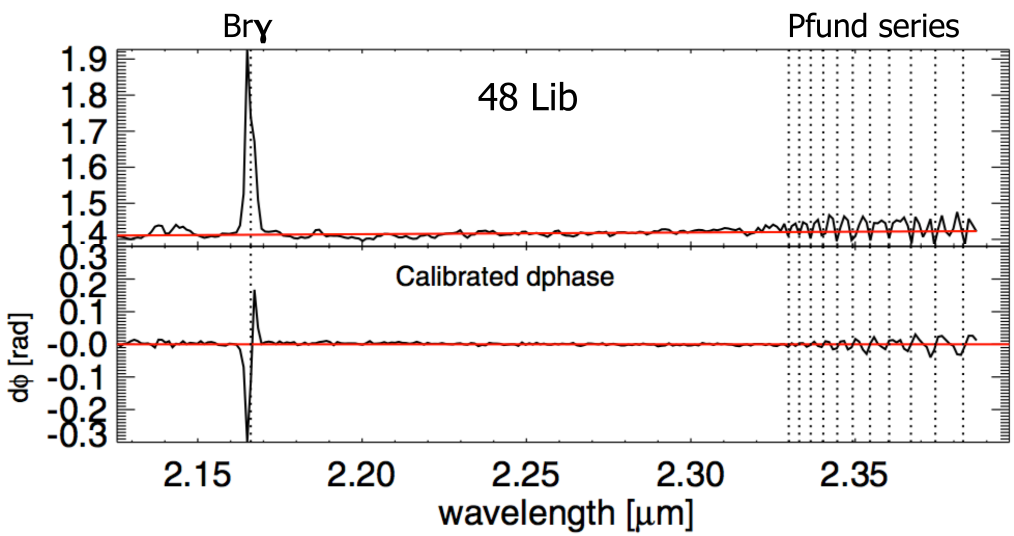


MATISSE will allow efficient imaging in spectral lines, enabling studies on more complex velocity fields (even though at relatively low spectral resolution)

Important new gas phase tracers:
HI (Pfund δ, γ), CO (fundamental, 4.7μm), H_2O (3.0μm, 5.0μm), HCN (3.1μm, 3.8μm), H_2C_2 (3.1μm, 3.8μm), OH (2.8μm), SiO (4.1μm)

Millour et al. 2011; MATISSE SC doc.

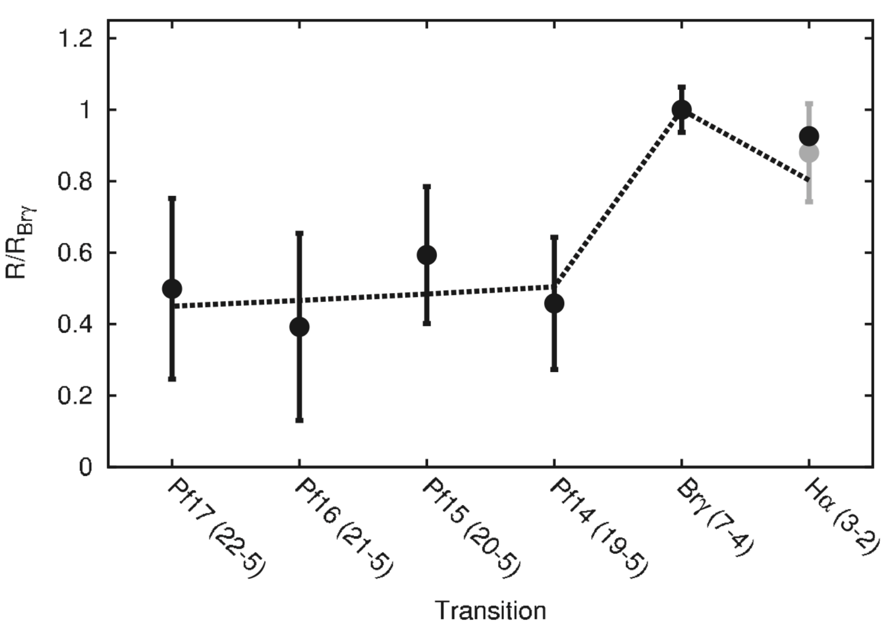
Interferometry in spectral lines

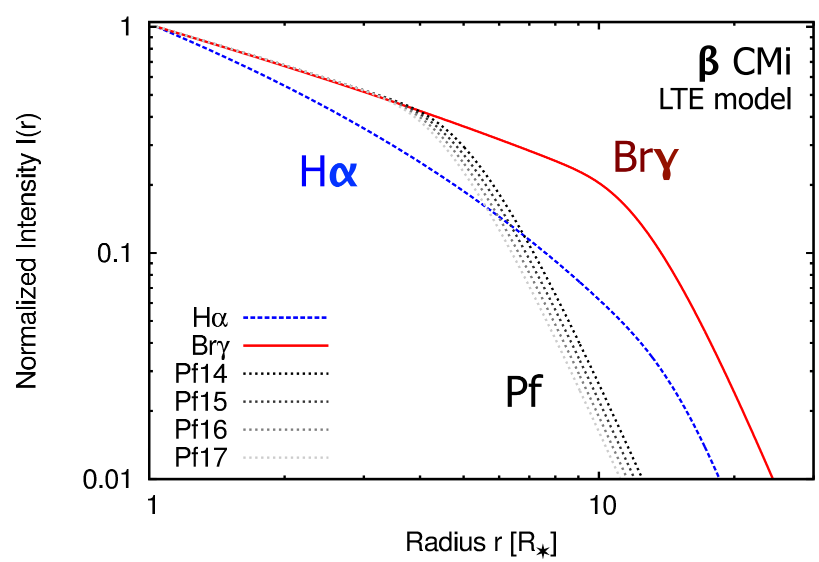


Multi-line-transition interferometry provides powerful constraints on disk ionization, temperature & density structure

For Be star **β** CMi we find:

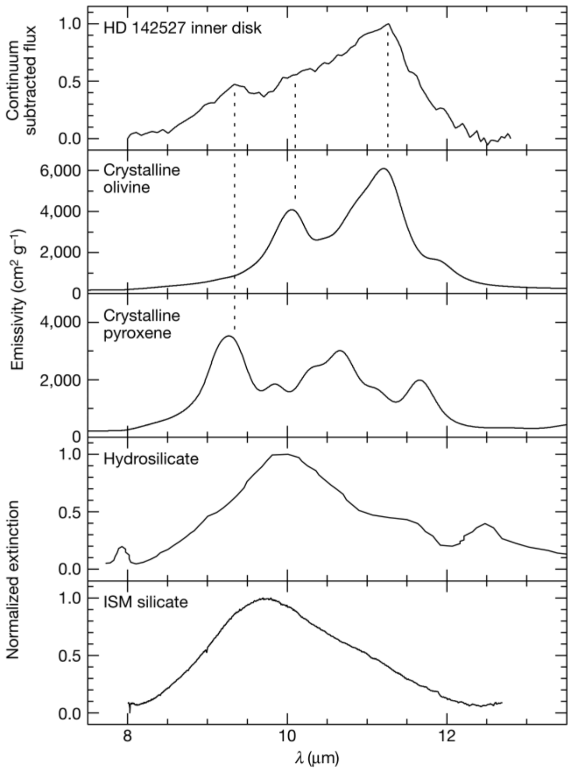
$$R_{\mathrm{cont}} < R_{\mathrm{Pf}} < R_{\mathrm{Br}\gamma} \approx R_{\mathrm{H}\alpha}$$

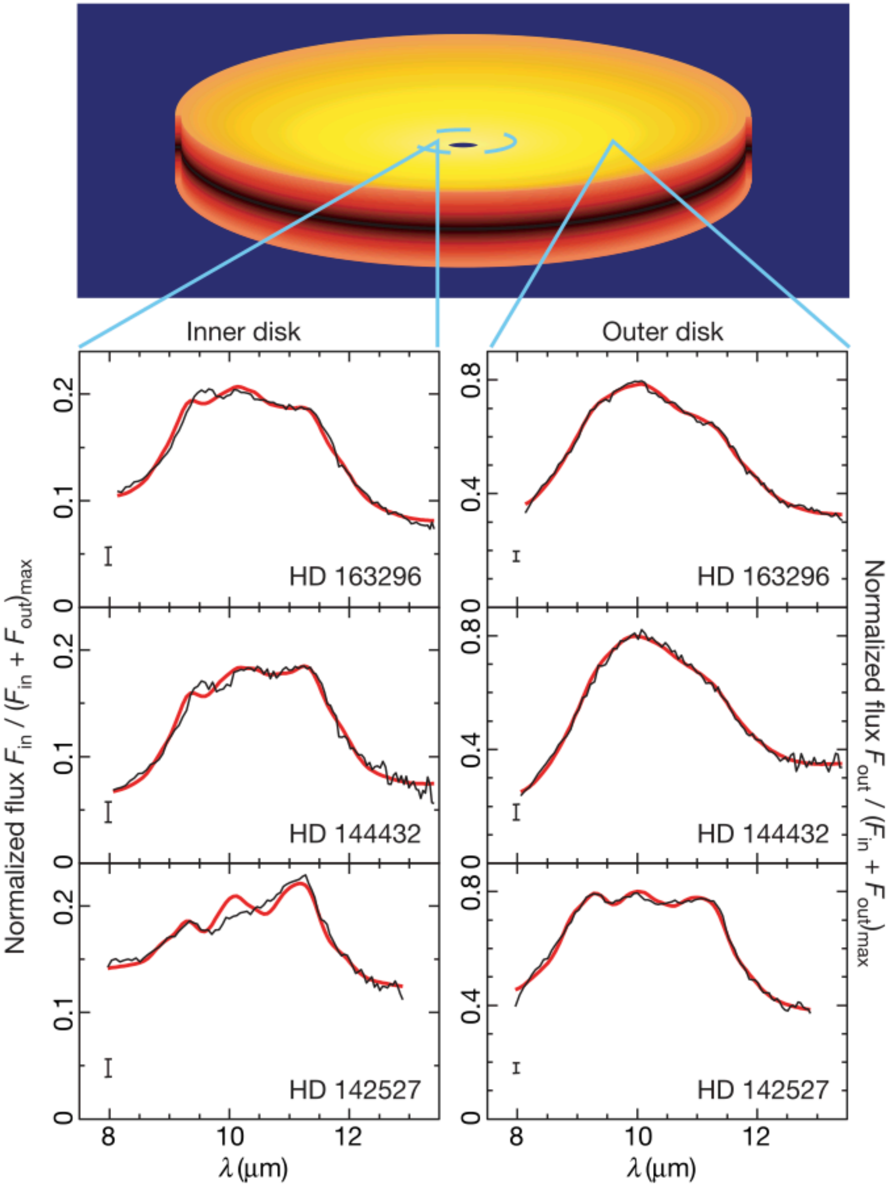




Pott et al. 2010; Kraus et al. 2012a

Radial probes of dust mineralogy



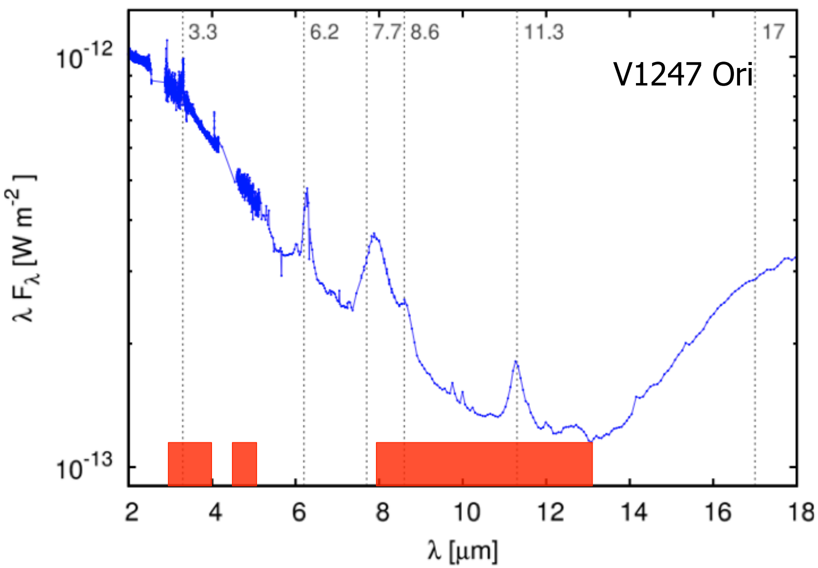


MIR interferometry can reveal spatial gradients in dust composition

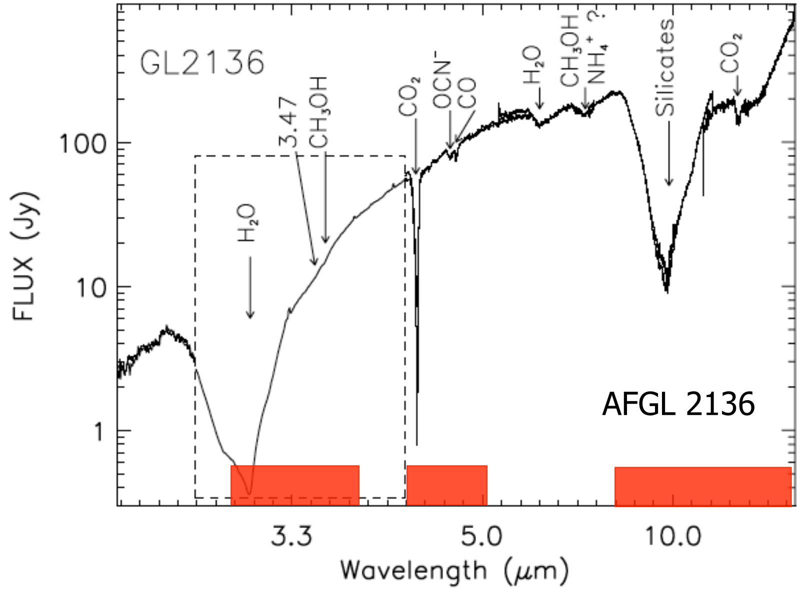
van Boekel et al. 2004

Dust / Ice features

PAH features:



Ices:



Important dust spectroscopic features covered by MATISSE:

Silicate, fosterite, enstatite, … (N band)

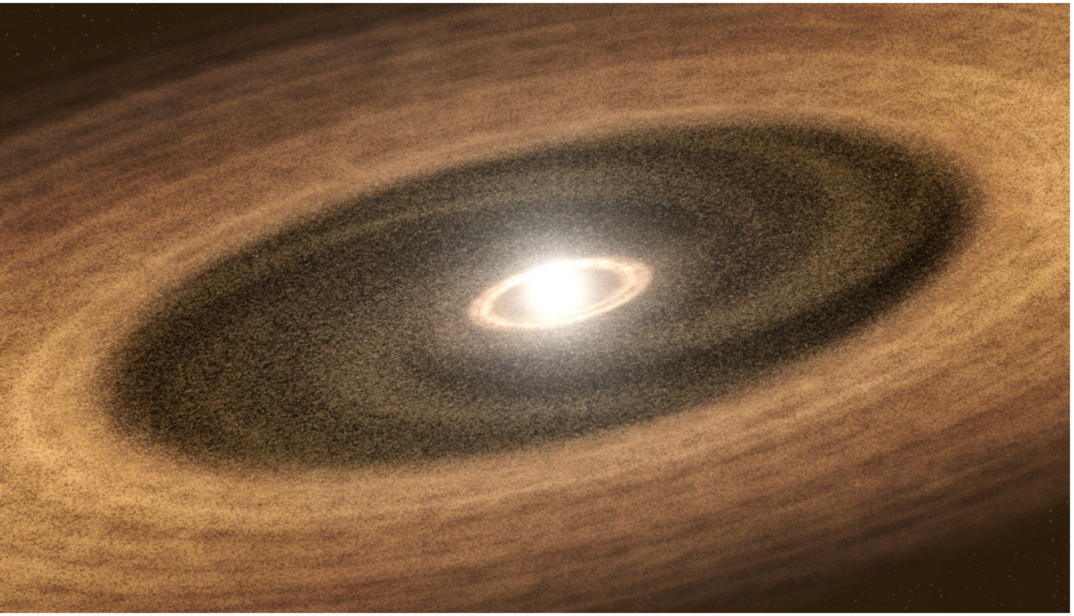
H_2O ice (3.1µm), CH_3OH ice (3.5µm), NH_3 ice (3.0µm)

PAH stretching/bending/vibration modes (3.3µm, 7.7µm, 8.6µm, 11.3µm)

C-H nanodiamonds (3.4-3.5µm)

Kraus et al. 2013; Dartois et al. 200.

Conclusions


V1247 Ori, Artist Impression, PlanetQuest

V1247 Orionis:

- NIR+MIR+sub-mm interferometry constrains gap geometry and composition
- **Gap filled with large amounts of optically thin carbonaceous dust,** whose emission dominates at MIR wavelengths
- Detected asymmetries trace density inhomogeneities, possibly related to dynamical interaction with the gap-opening bodie(s)

- Combining interferometric data at different wavelengths / facilities opens new science prospects
- MATISSE will introduce efficient **interferometric imaging in the L+M+N band** and provide access to **important new spectral lines and tracers of dust/ice species**