The (Infrared) Interferometric View on Herbig Ae/Be stars

Stefan Kraus
University of Exeter

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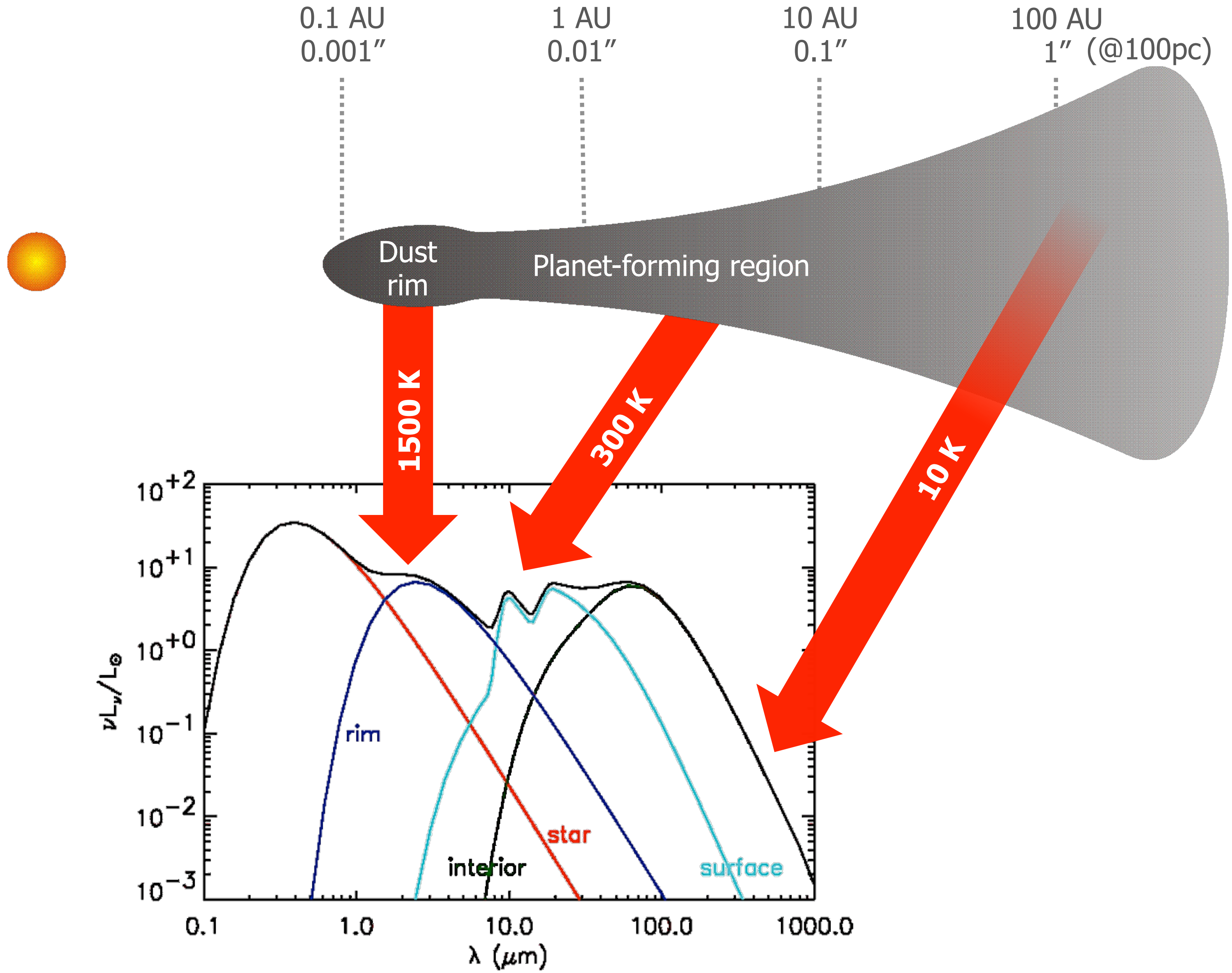
Outline

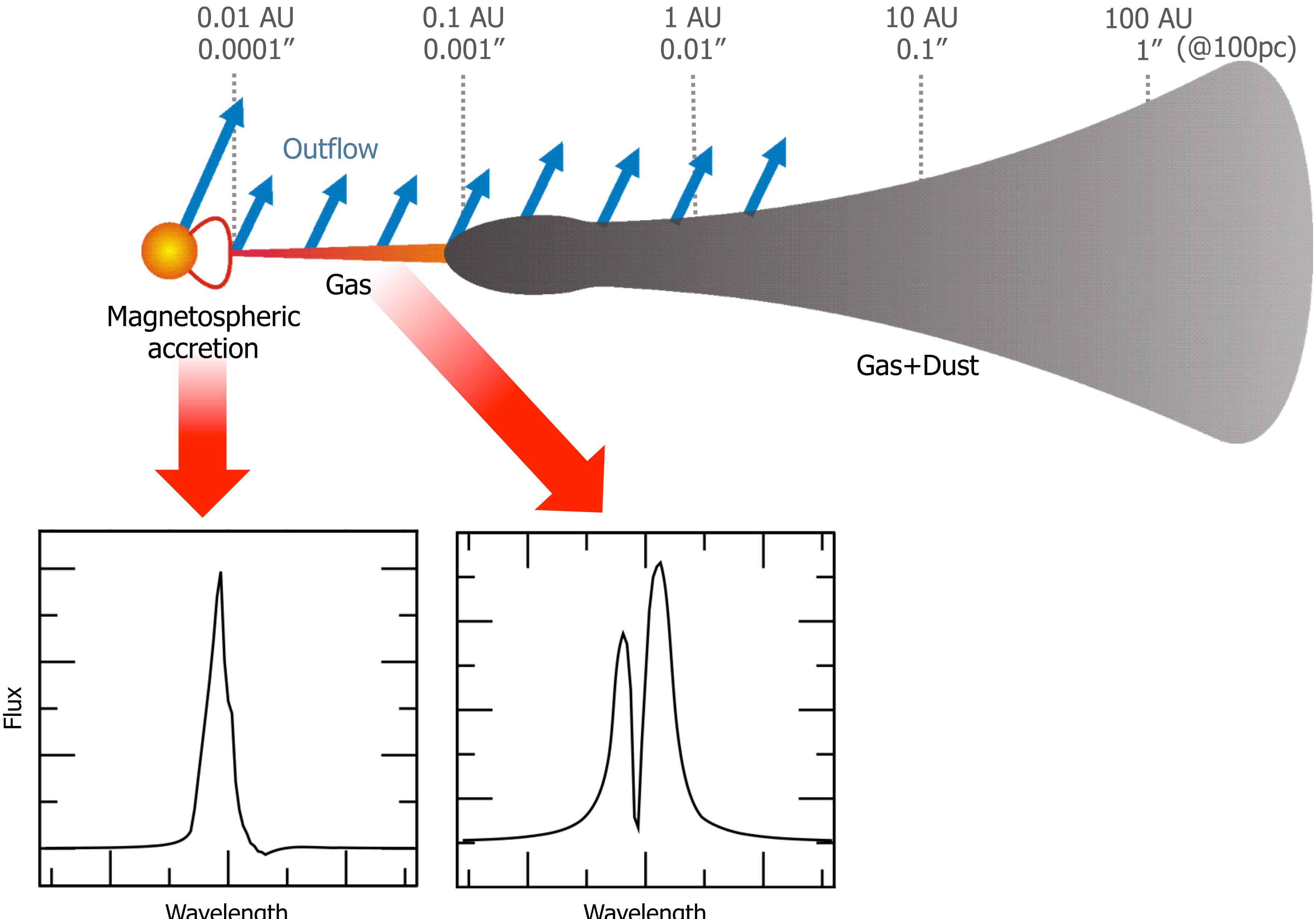
1. The need for high-angular resolution observations
2. Disk structure
   …near the dust sublimation radius
   ...in the extended disk
3. Disk gaps and asymmetries
4. Gas kinematics constraints
5. Multiplicity studies
6. Future opportunities

Disclaimer: I focus on Herbig Ae/Be stars and some early-type T Tauri stars, but do not cover typical T Tauri or supergiant-B[e] results

Protoplanetary disk structure – Continuum



Protoplanetary disk structure – Line emission



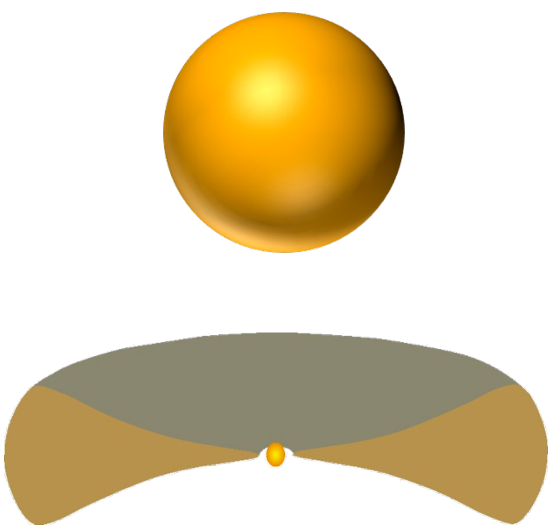
Kurosawa et al. 2006

The need for high-angular resolution observations

Spatially unresolved observations face severe limitations due to…

(1) Model ambiguities

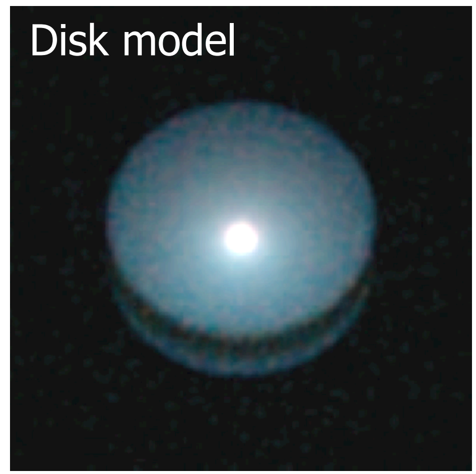
Different classes of models reproduce data equally well



Men'shchikov & Henning 1997

(2) Parameter ambiguities

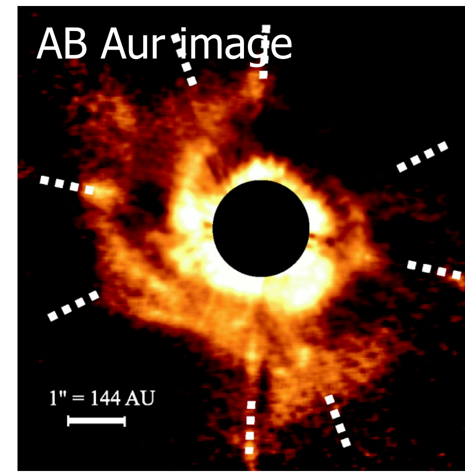
Diff. parameter combinations reproduce data equally well



Typical models require 18+ parameters (and dust composition assumptions)
Whitney et al. 2003
Robitaille et al. 2007

(3) Complexity!

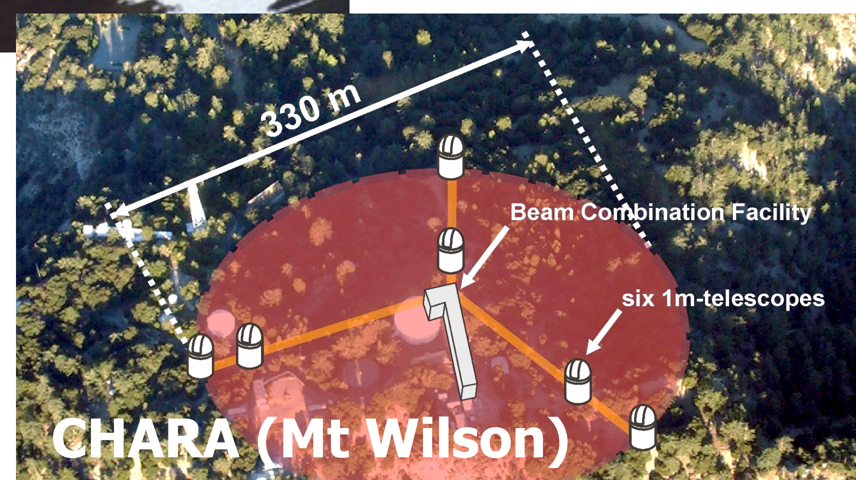
Models depend on simplifying assumptions



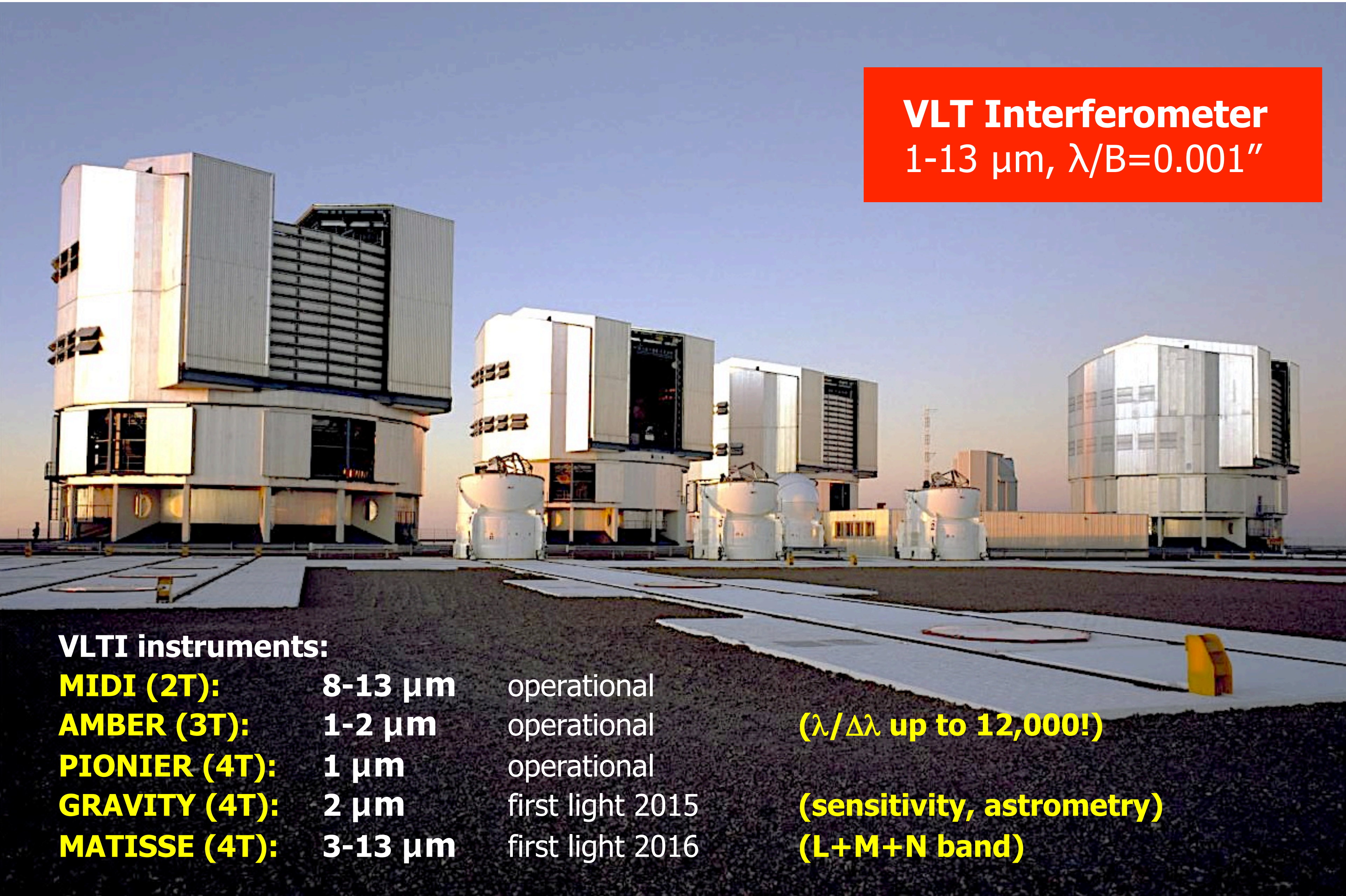
Stellar multiplicity, planet formation, gravitational instabilities, …
Piétu et al. 2005

➜ Spatially resolved observations needed

Optical interferometers used for YSO science



VLTI Interferometry

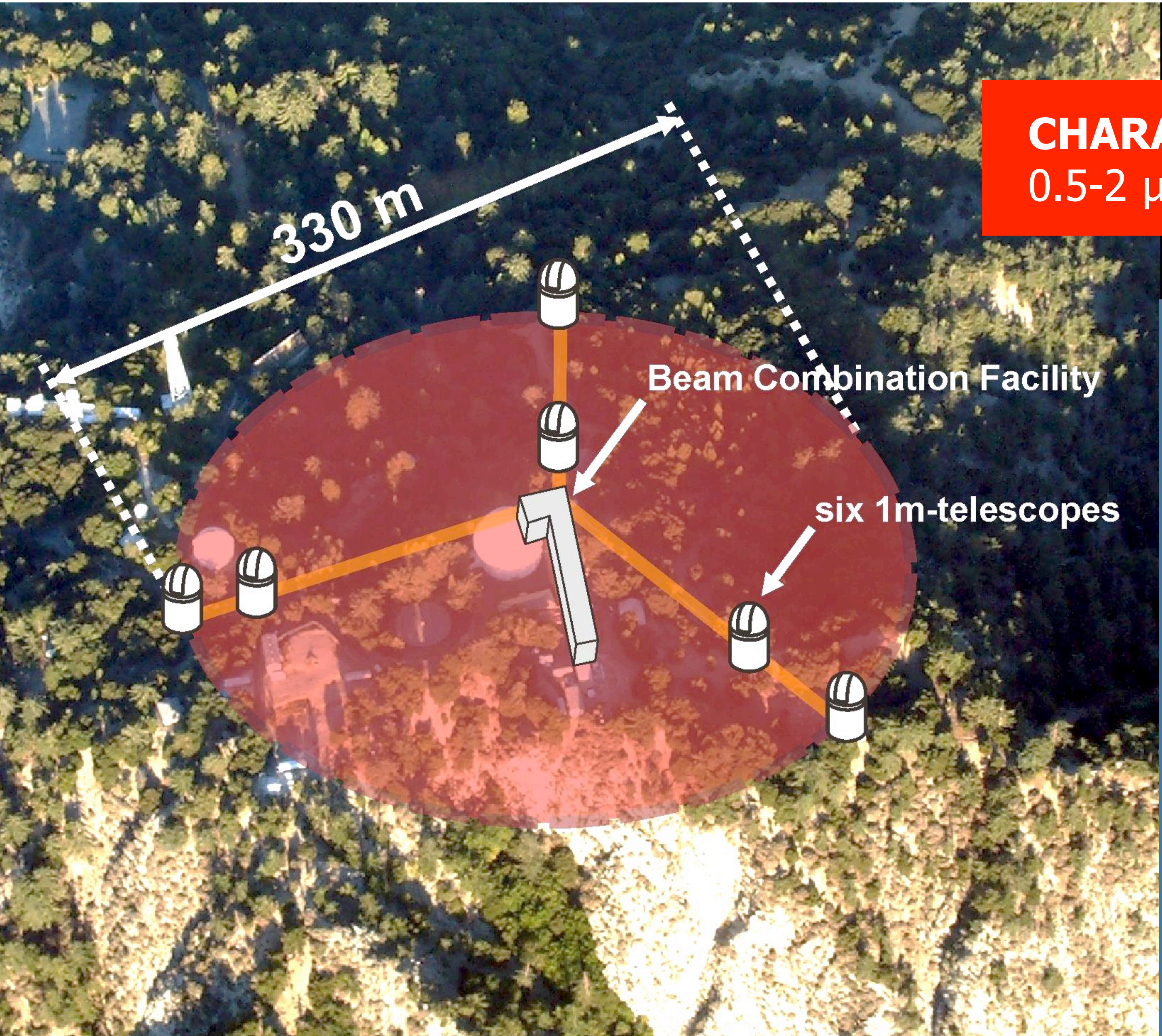


VLT Interferometer
1-13 µm, λ/B=0.001″

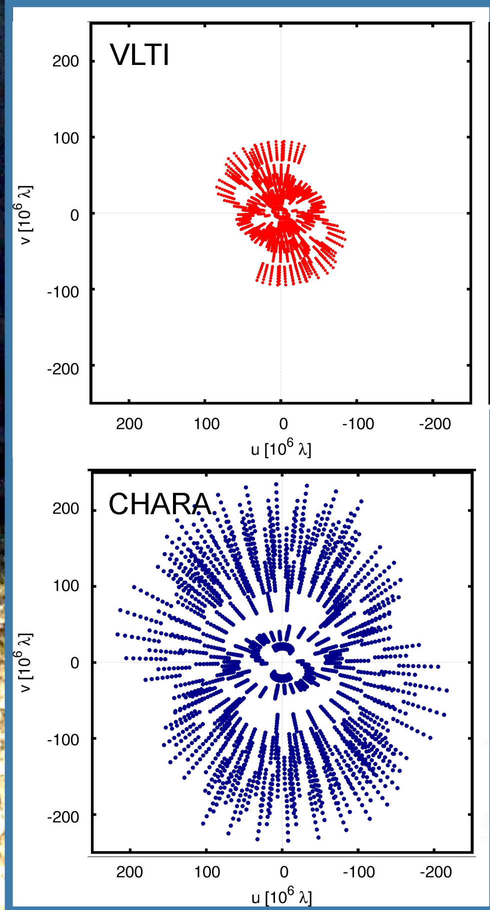
VLTI instruments:

MIDI (2T):	**8-13 µm**	operational	
AMBER (3T):	**1-2 µm**	operational	**(λ/Δλ up to 12,000!)**
PIONIER (4T):	**1 µm**	operational	
GRAVITY (4T):	**2 µm**	first light 2015	**(sensitivity, astrometry)**
MATISSE (4T):	**3-13 µm**	first light 2016	**(L+M+N band)**

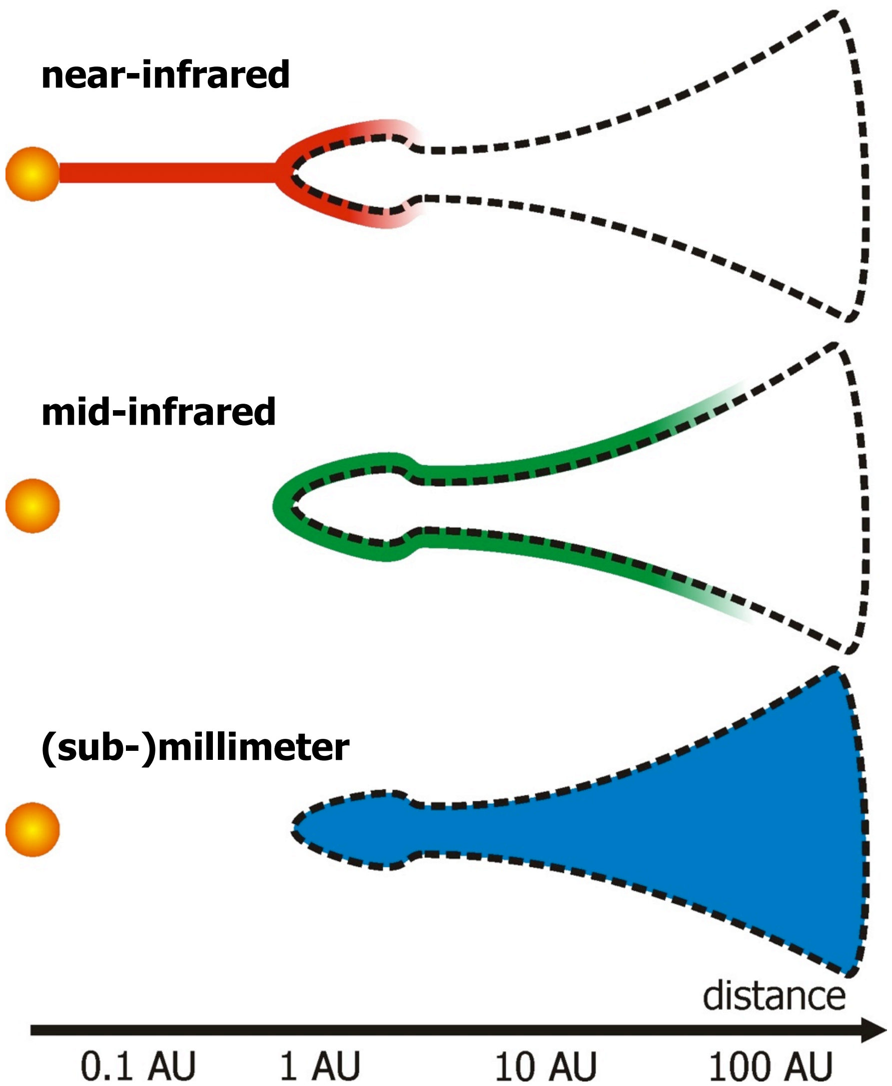
CHARA interferometry

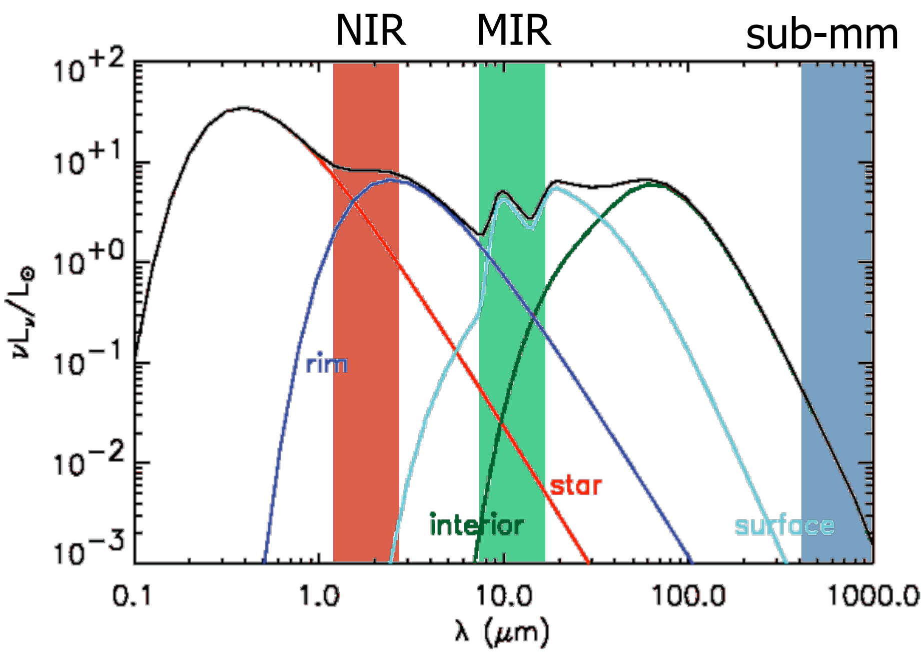


CHARA array
0.5-2 µm, λ/B=0.0003″



Multi-wavelength interferometry





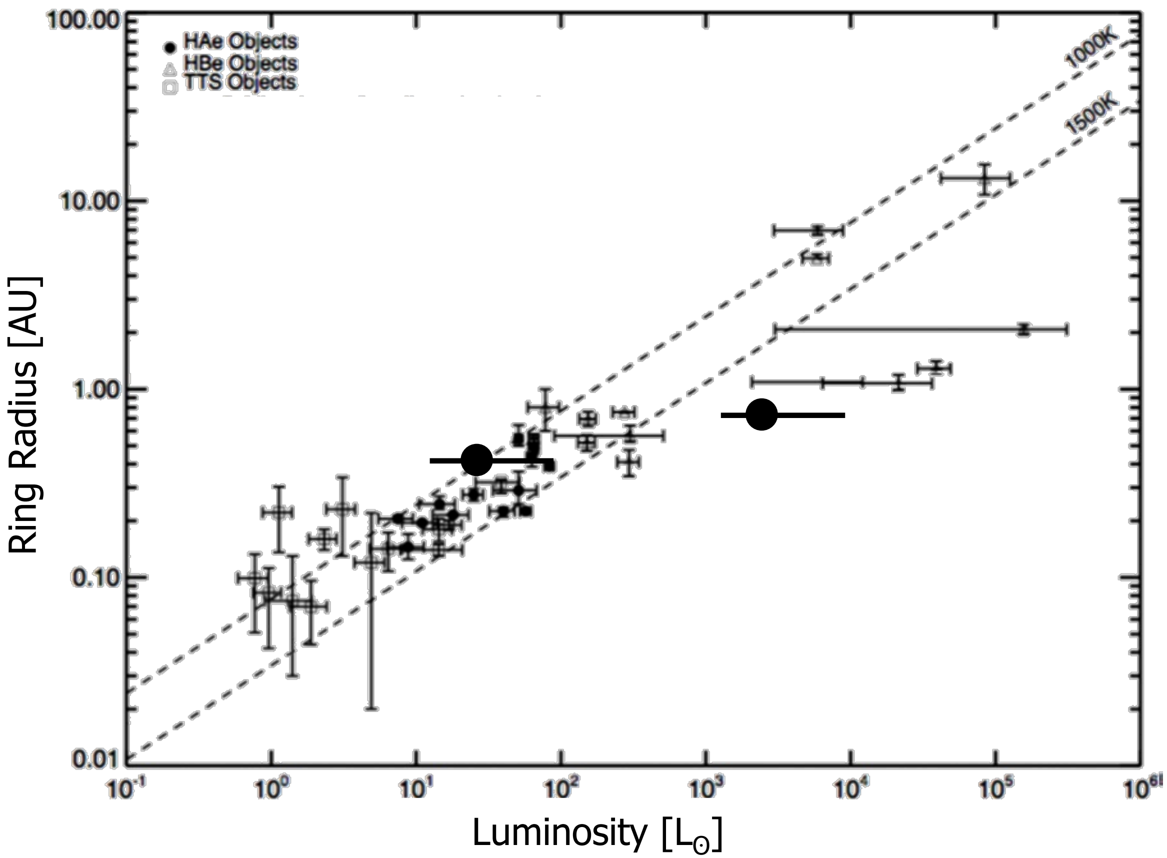
NIR/MIR/mm wavelength regimes…

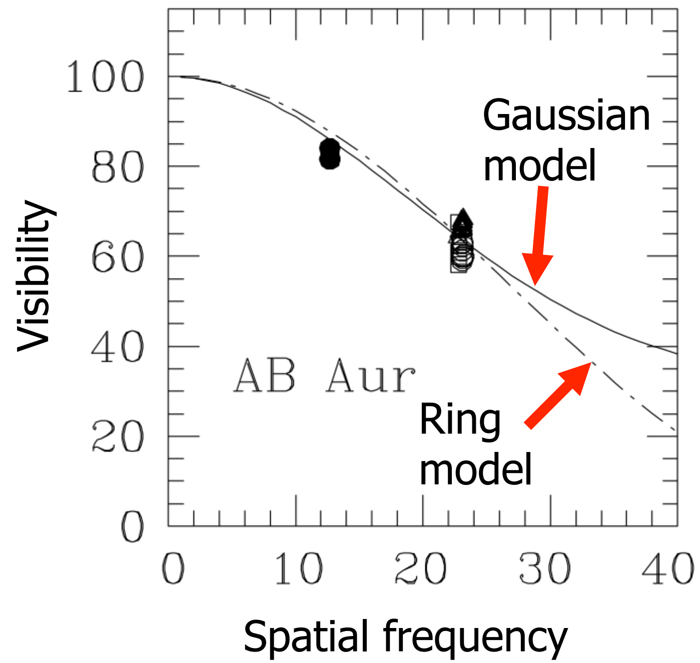
..trace **different disk radii**

…trace **disk surface & interior**

Disk structure near the dust sublimation radius

Size-luminosity relation

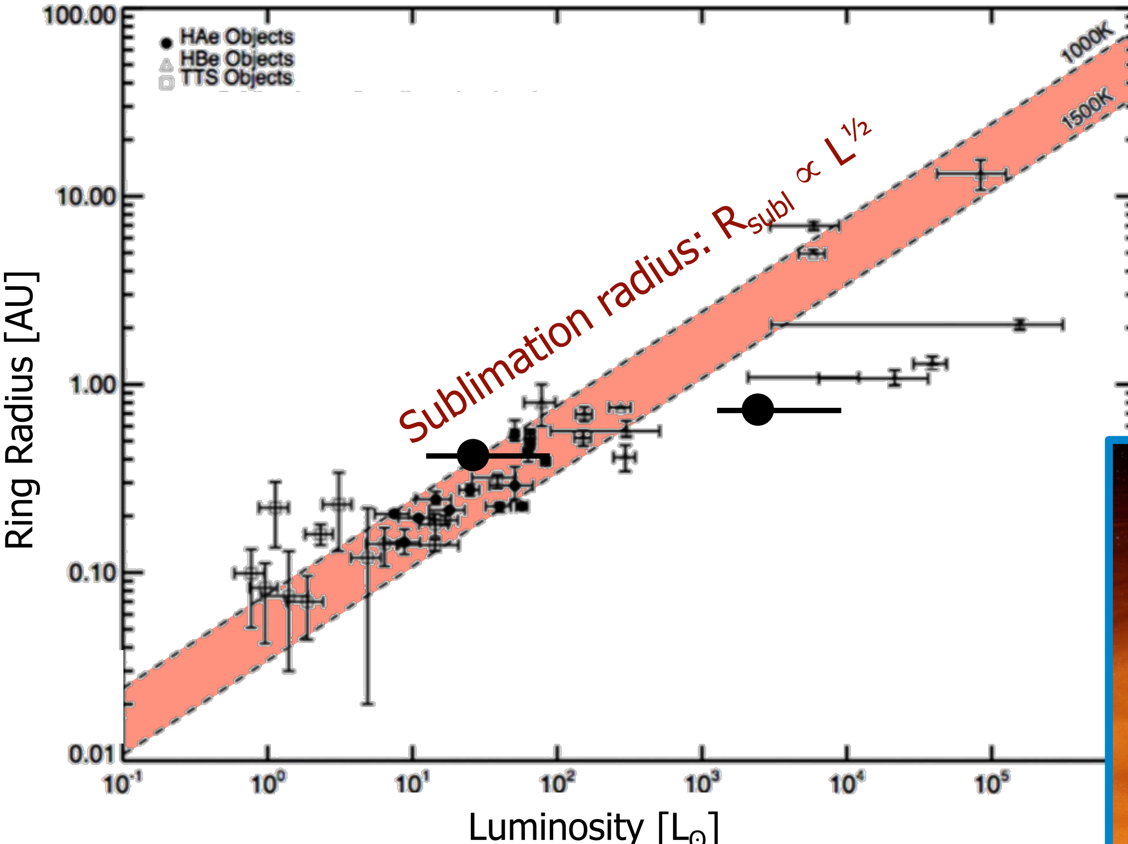




➜ Pioneering studies in the early 2000's did not constrain the emission geometry, **but assumed a geometry and investigated how the size scaled with the stellar luminosity**

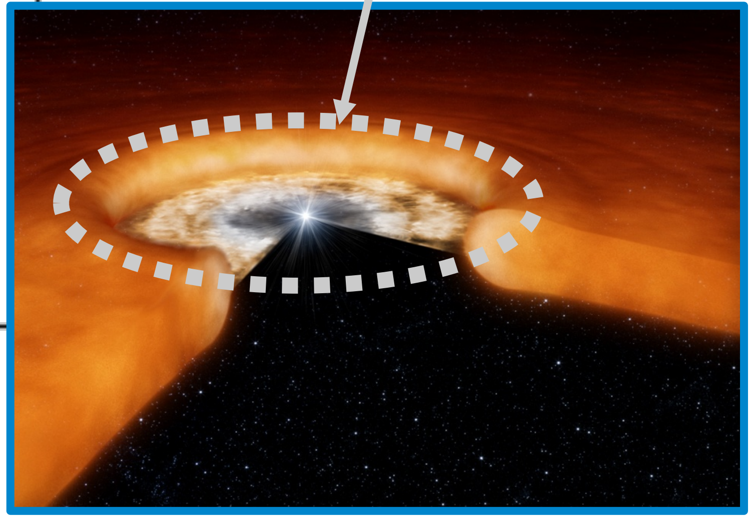
Millan-Gabet 2001, 2007 PPV; Monnier et al. 2002, 2005
also: Akeson et al. 2000; Eisner et al. 2003, 2004

Size-luminosity relation



The measured NIR disk sizes scale roughly with $L^{1/2}$

➜ Consistent with emission from the dust sublimation rim



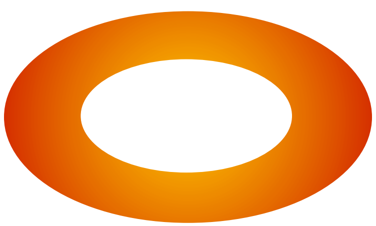
Millan-Gabet 2001, 2007 PPV; Monnier et al. 2002, 2005
also: Akeson et al. 2000; Eisner et al. 2003, 2004

Evidence for a puffed-up inner rim

Interferometric observables:

Visibility ➜ measures object extension (1st order)
Differential Phase (DP) ➜ measures photocenter displacements (1st order)
Closure Phase (CP) ➜ measures deviations from point-symmetry

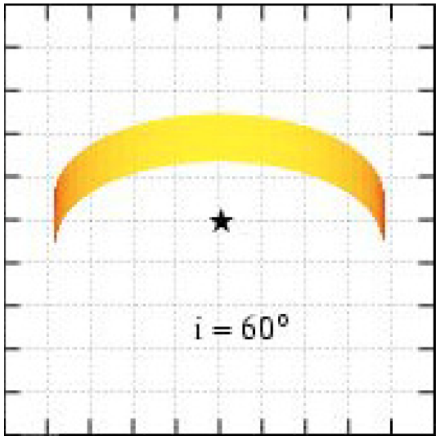
GEOM. FLAT DISK



e.g. temperature gradient models

No asymmetries (CP ≡ ZERO!)

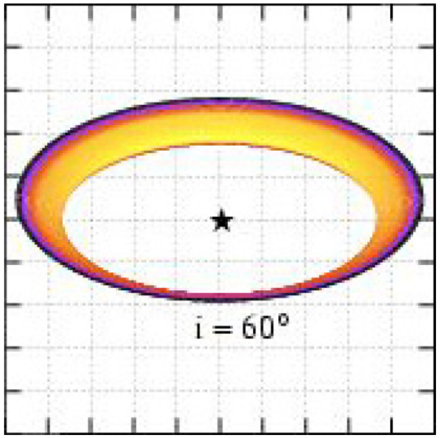
VERTICAL RIM



Natta et al. 2001
Dullemond et al. 2001

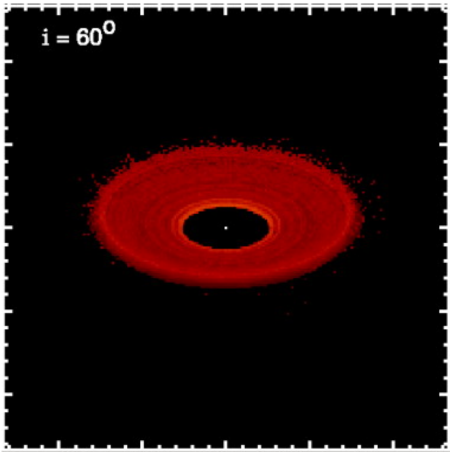
Strong asymmetries (strong CP signal)

CURVED RIM



Isella & Natta 2005

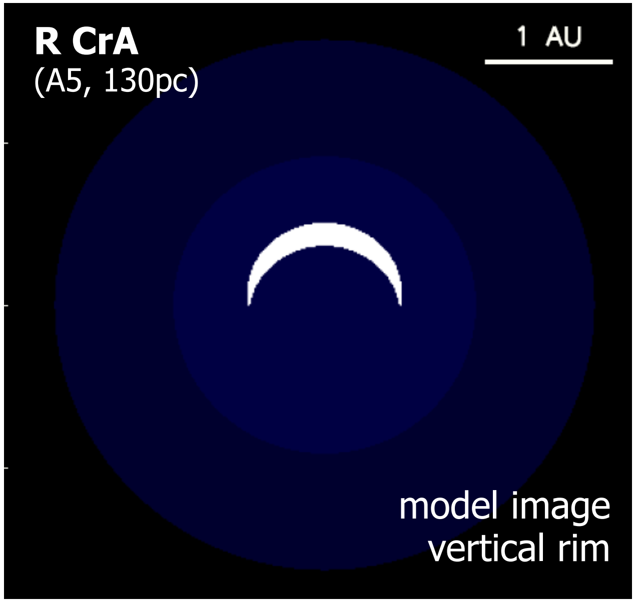
VERY CURVED RIM

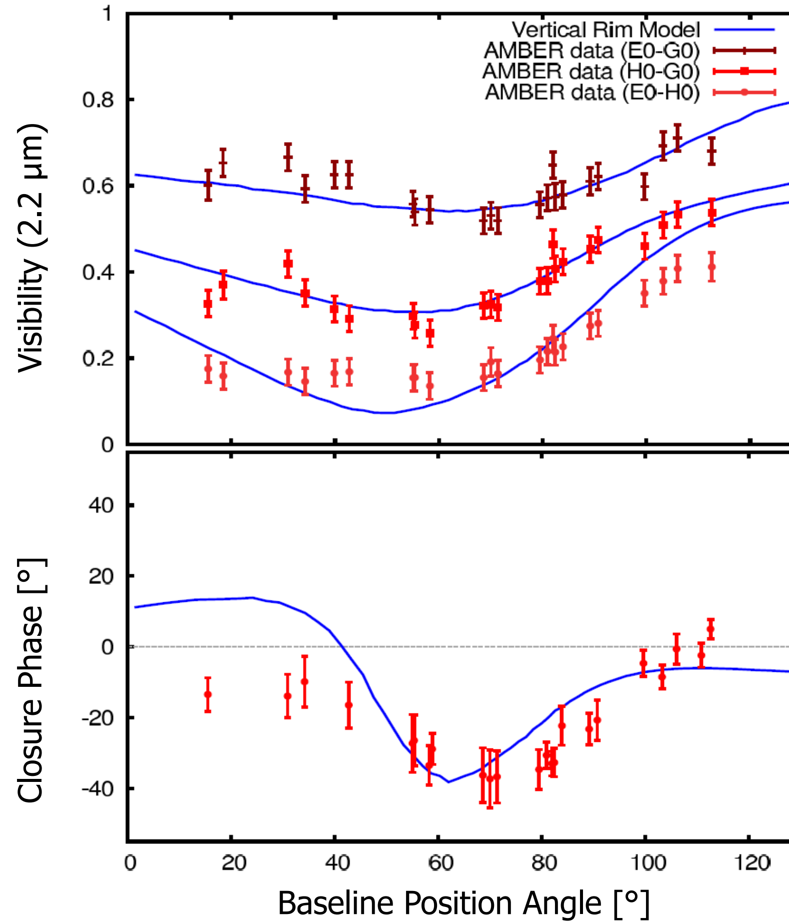


Tannirkulam et al. 2007
Kama et al. 2009

Weak asymmetries (weak CP signal)

Evidence for a puffed-up inner rim: Modelling

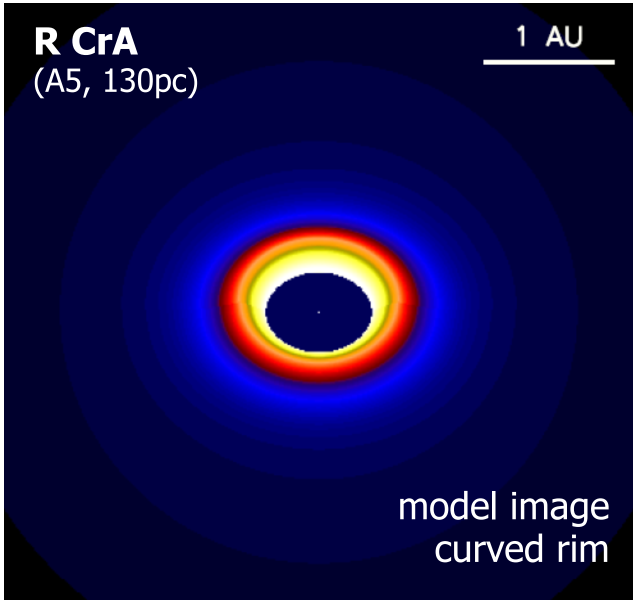


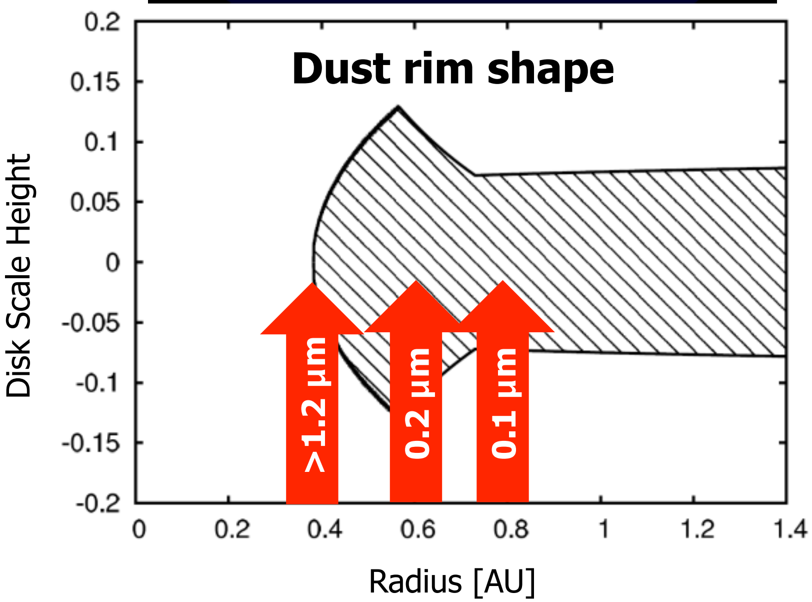


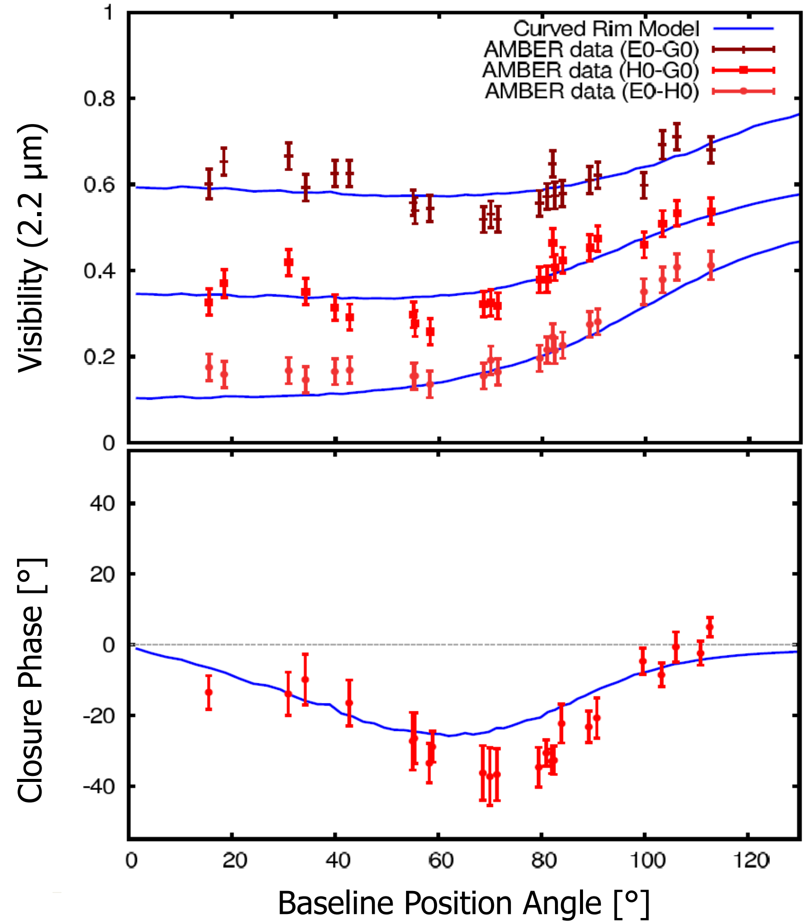
➜ Vertical rim model inconsistent with measured closure phases

Kraus et al. 2009

Evidence for a puffed-up inner rim: Modelling



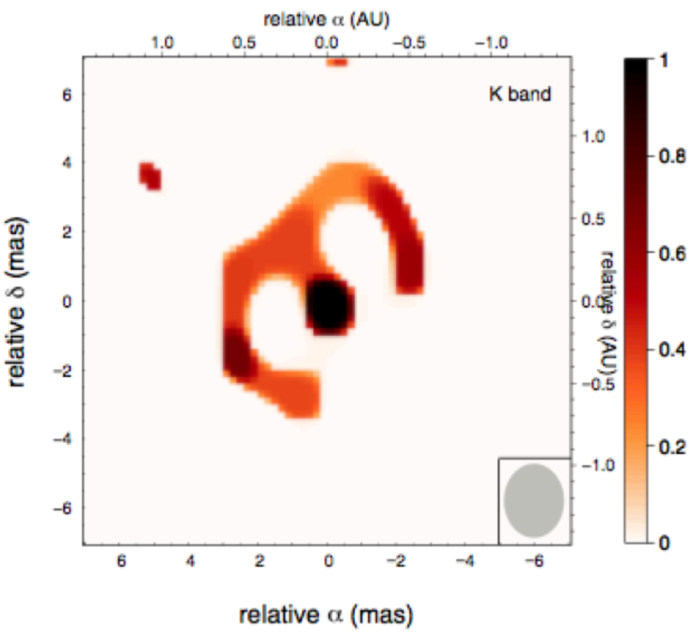


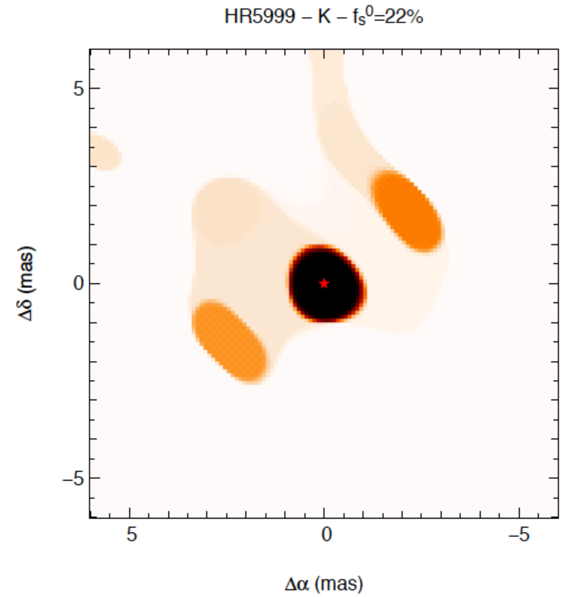


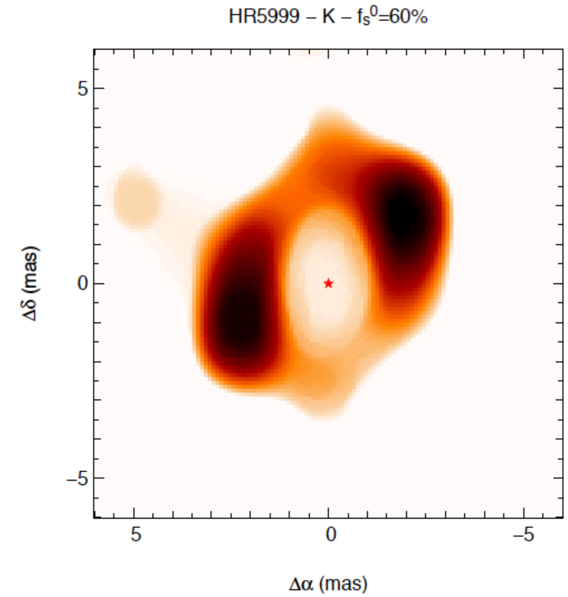
➜ Detected asymmetries constrain **puffed-up rim structure & dust grain properties**

Kraus et al. 2009

Evidence for a puffed-up inner rim: Imaging







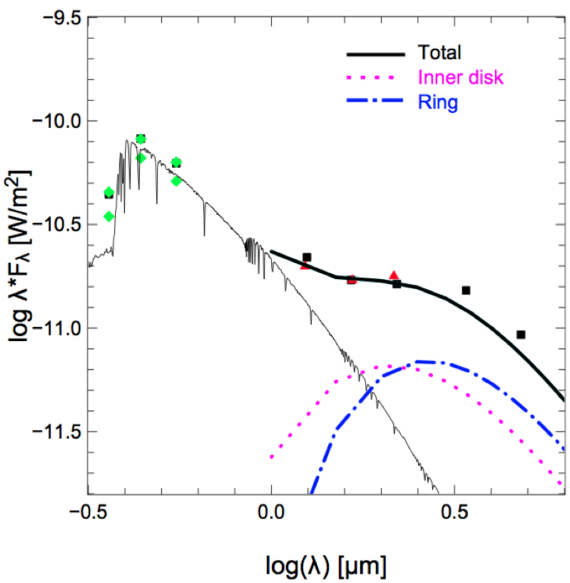
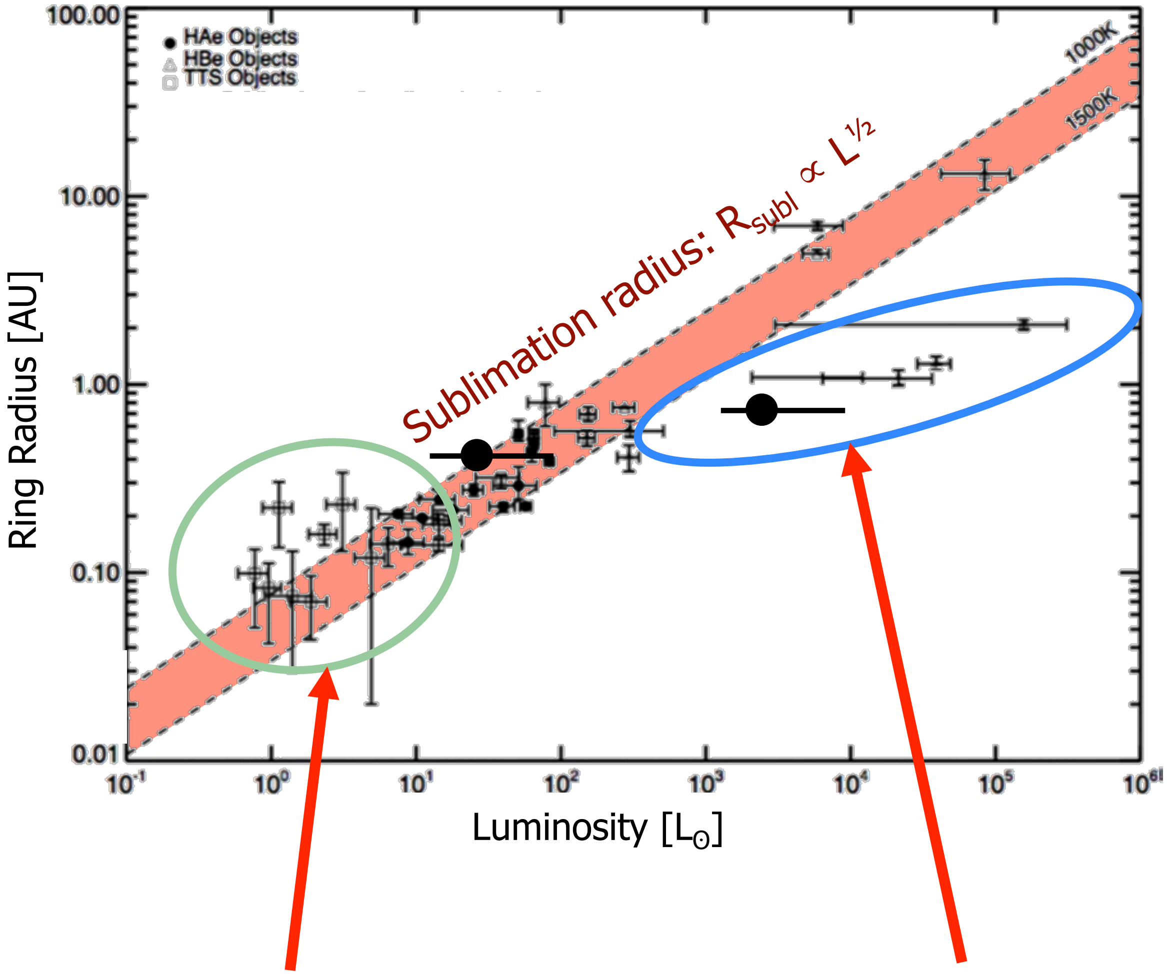


Image after removing the photospheric contributions

Image after removing photospheric and inner disk contributions

Benisty et al. 2011, Kluska et al. 2014
also: Renard et al. 2010; talk today by J. Kluska

Size-luminosity relation



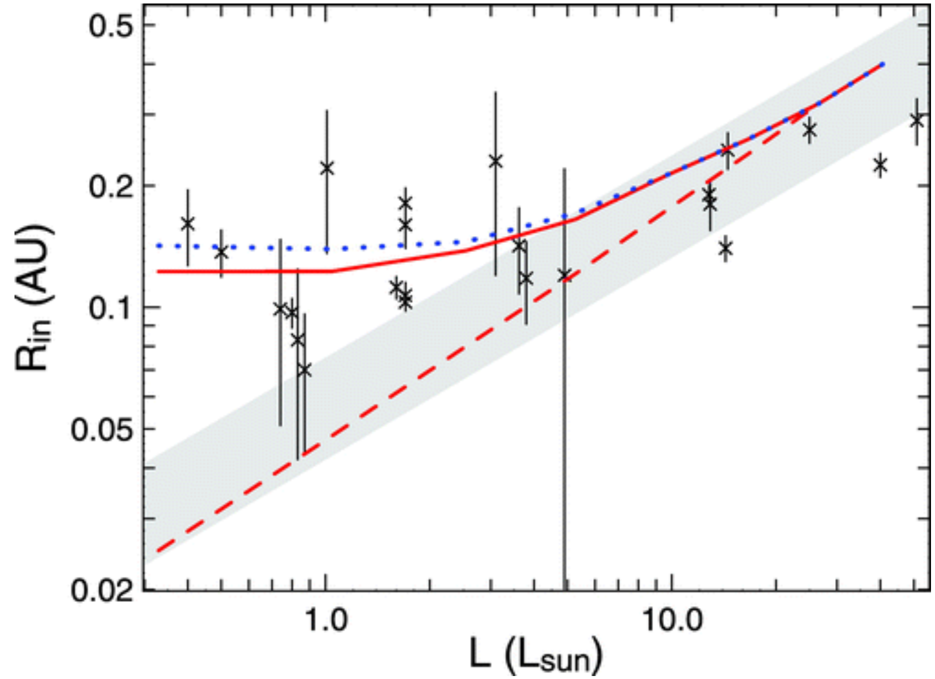
T Tauri stars often appear **systematically larger** than suggested by $R_{subl} \propto L^{1/2}$ relation

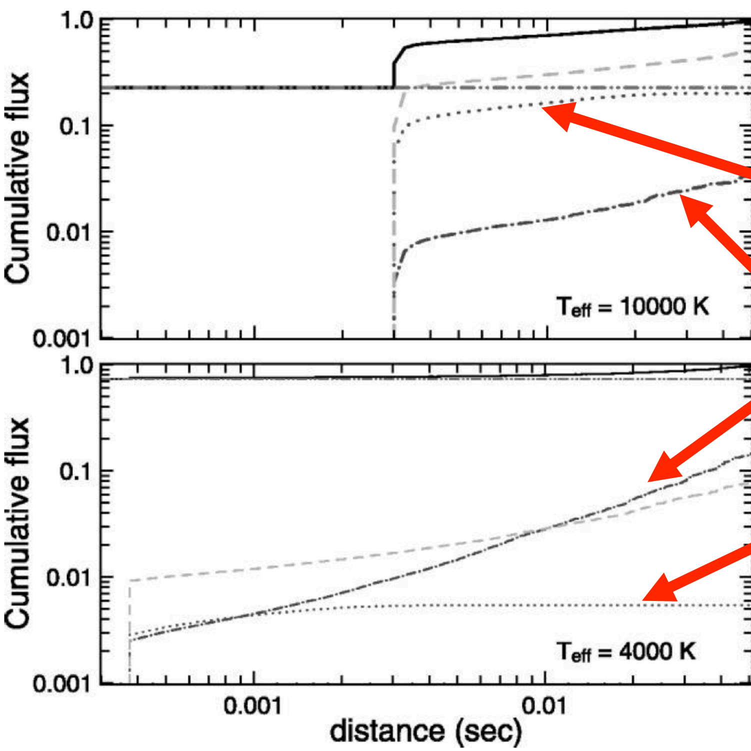
Herbig Be stars often appear **systematically smaller**

Millan-Gabet 2001, PPV; Monnier et al. 2002, 2005

“Oversized” T Tauri stars

Scattered light contributions are non-negligible for cool stars



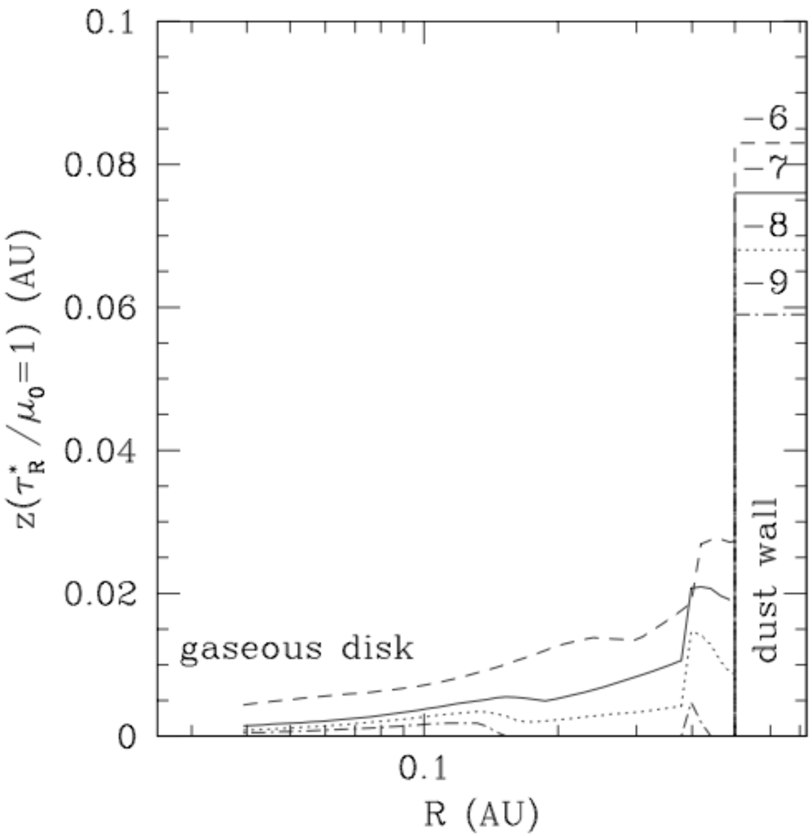


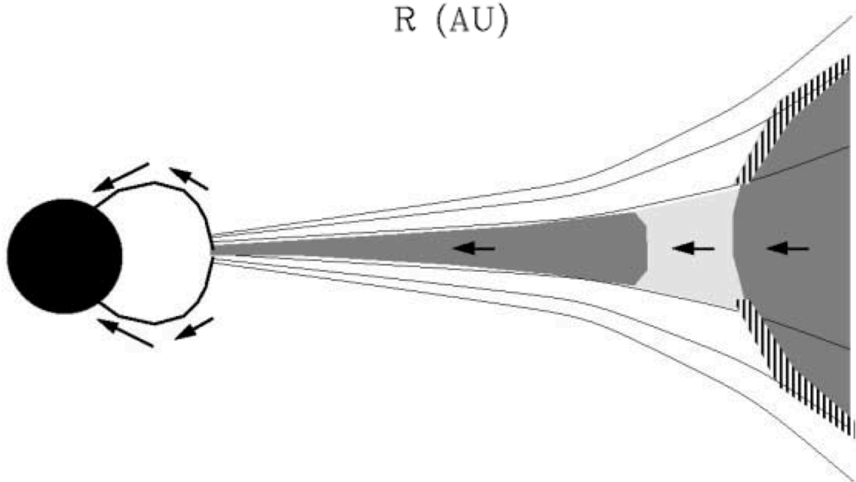
Scattered light

Thermal dust emission

Pinte et al. 2008
also: Eisner et al. 2007

"Undersized" Herbig Be stars: Gas absorption?



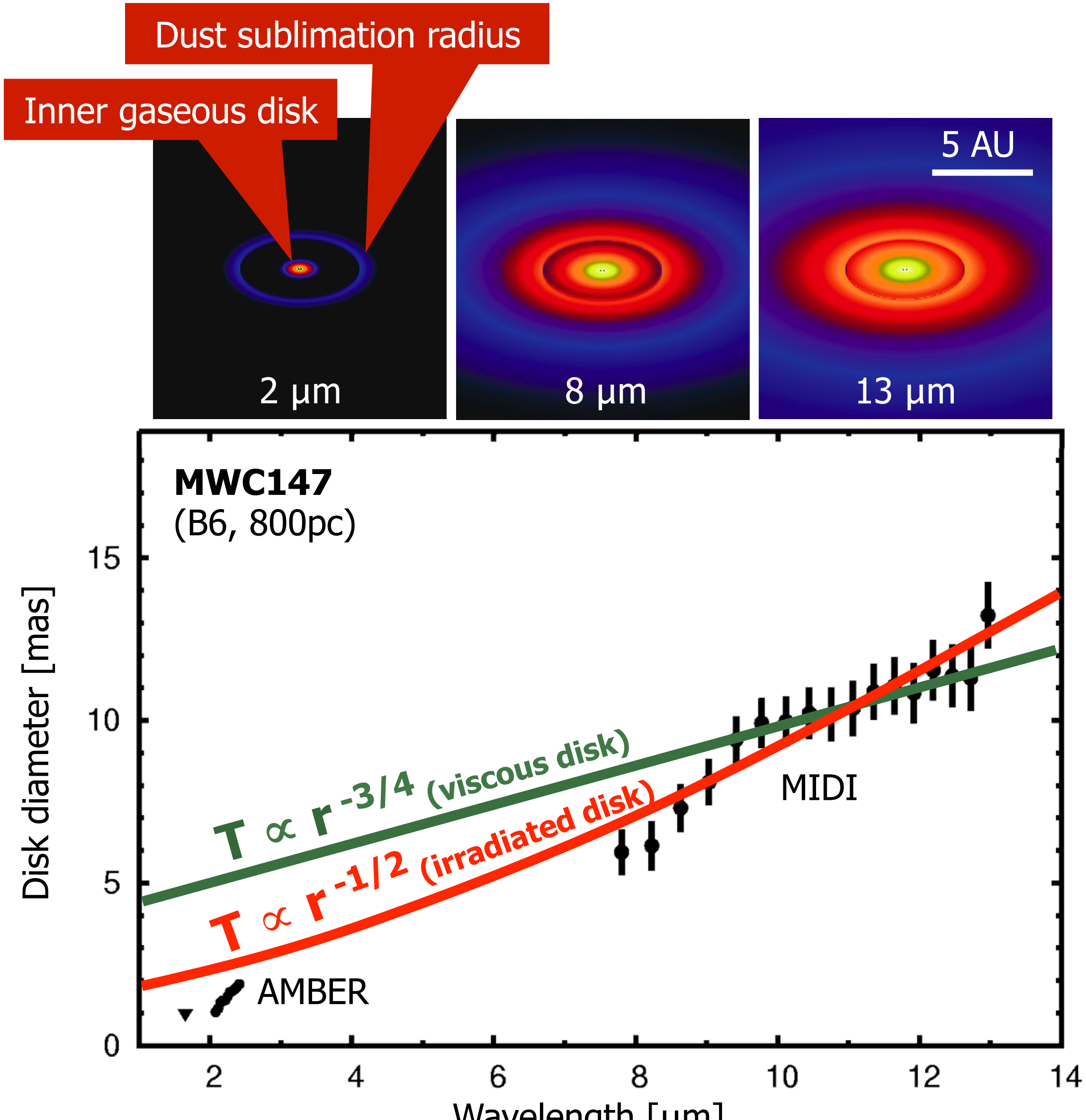


Gas absorption by an inner gaseous disk could shield dust from stellar irradiation

➜ Scale height possibly to low (Muzerolle et al. 2004)

Muzerolle et al. 2004
also: Monnier et al. 2005

"Undersized" Herbig Be stars: Optically thick gas?



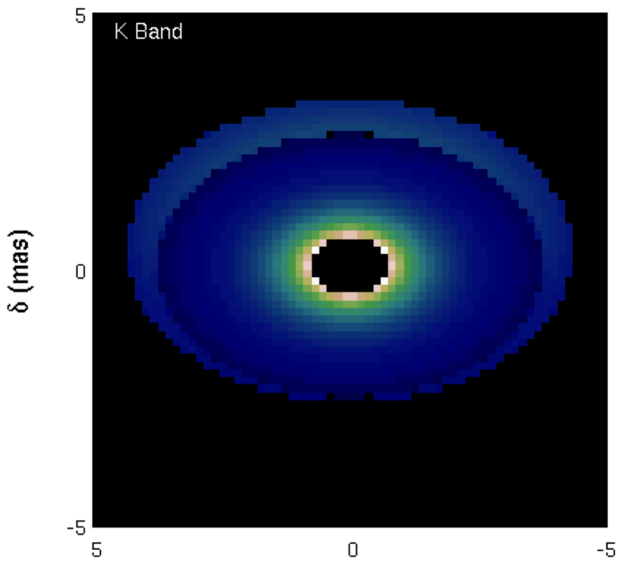
Temperature power law profiles ($T \propto r^{-1/2}$, irradiated disks, or $T \propto r^{-3/4}$, viscous disks) cannot reproduce the measured wavelength-dependent disk size

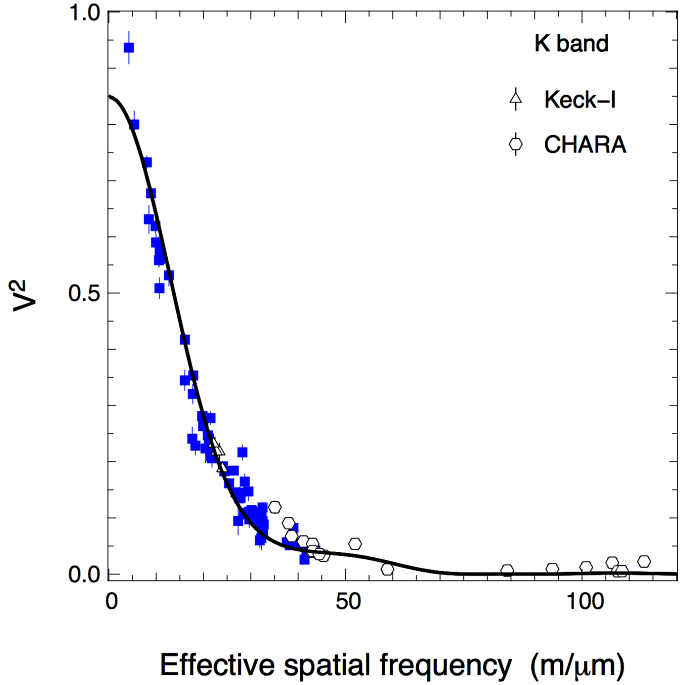
→ **Hot gas emission inside dust sublimation radius**

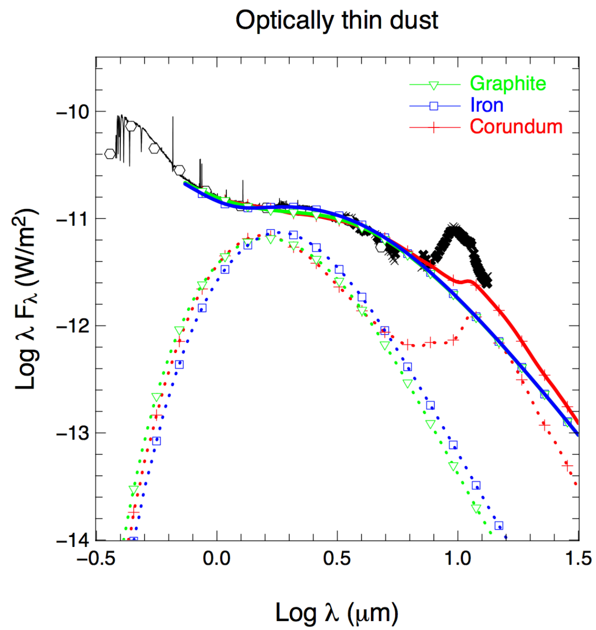
→ **Multi-wavelength interferometry enables physical characterization**

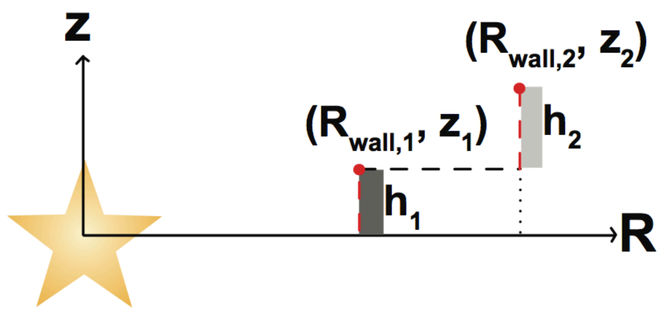
Kraus et al. 2008
also: Isella et al. 2008, Eisner et al. 2005

“Undersized” Herbig Be stars: Highly refractory grains?









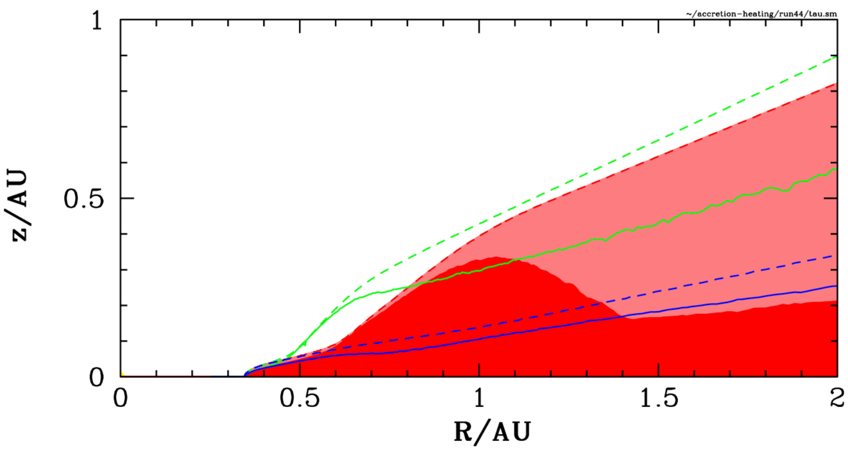
Highly refractory dust grain species (Graphite, Iron, …) could move dust sublimation radius inwards (requires T_{subl}=2100…2300 K)

➜ **Complex, multi-layered rim geometry**

Benisty et al. 2010, Kama et al. 2009, McClure et al. 2013

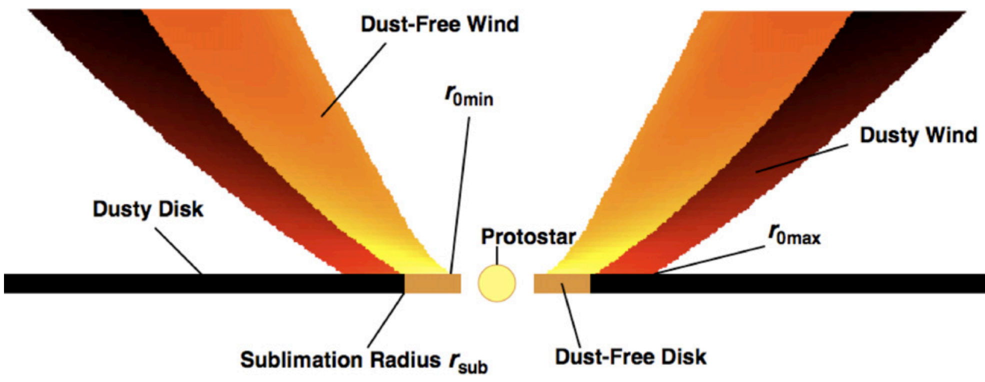
Beyond the puffed-up rim paradigm

Magnetically supported disk atmosphere



Turner et al. 2014

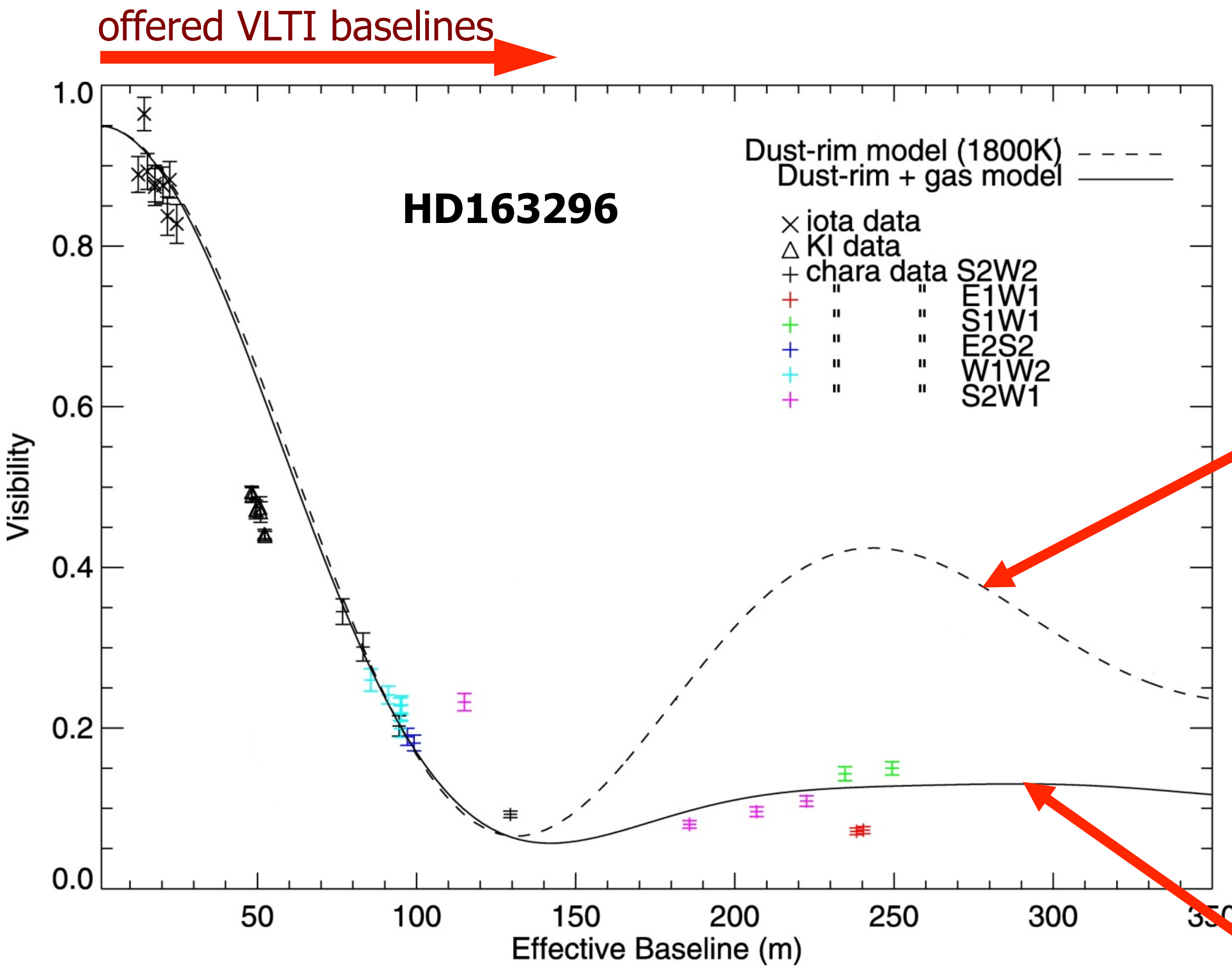
Dusty disk winds

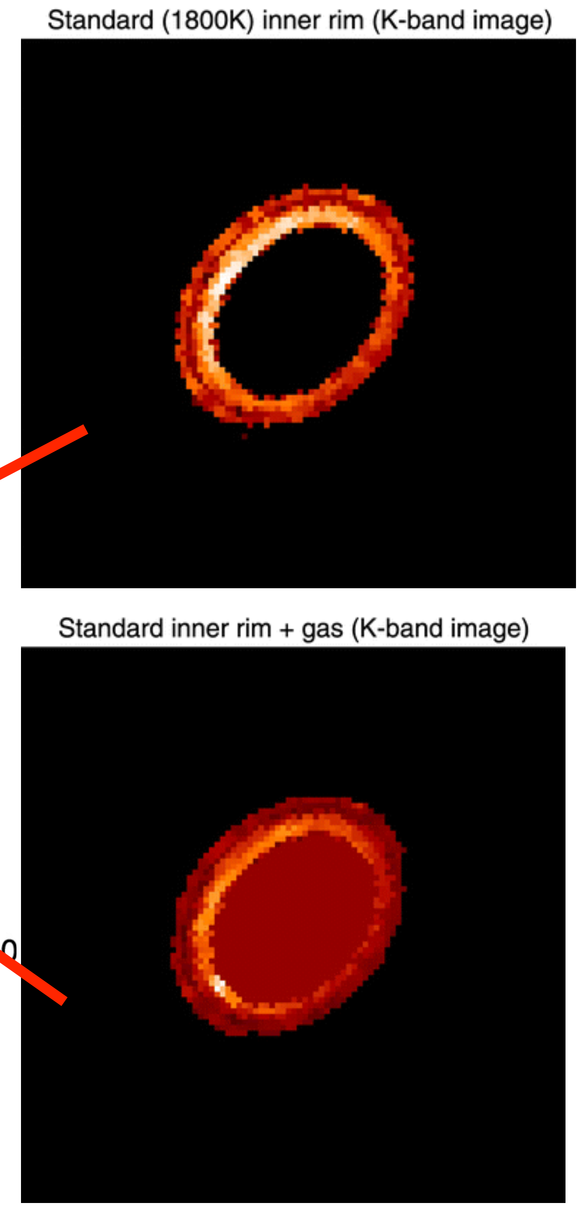


Vinković & Jurkić 2007
Bans & Koenigl 2012

New models are able to reproduce the SED without conventional puffed-up inner rim
➜ Need to be tested with interferometry

Need of long baselines



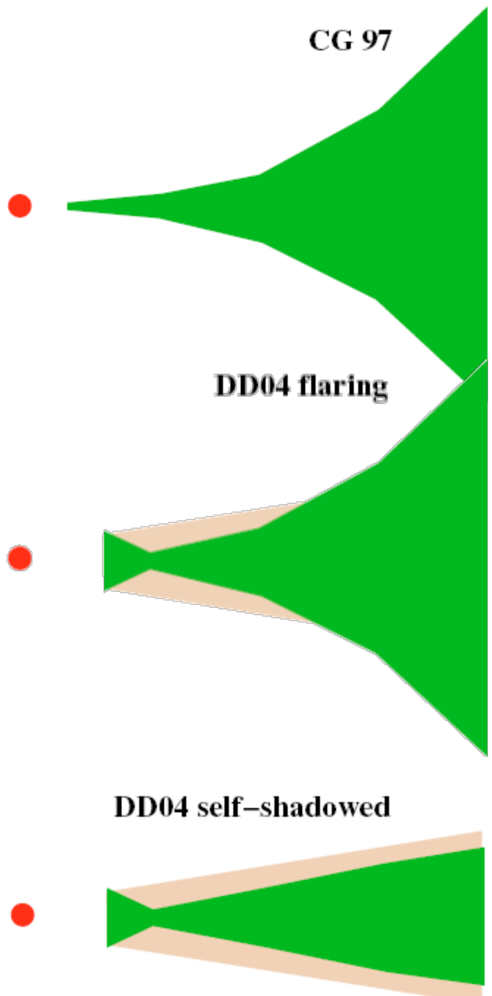


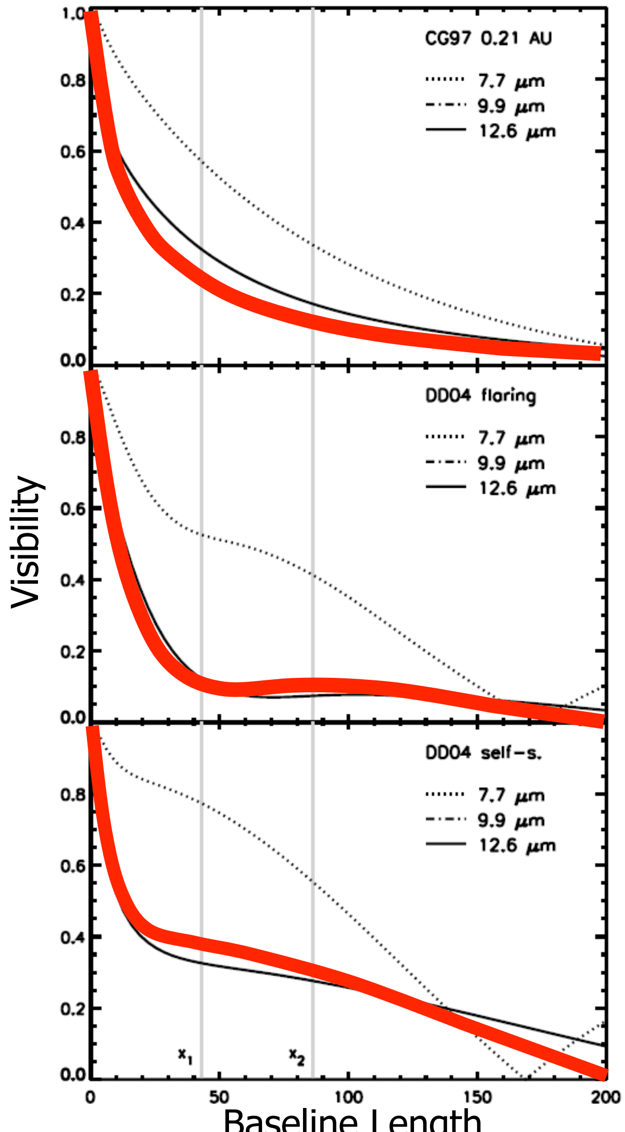
➜ Probing the detailed rim geometry and to characterize emission from inside the rim requires long CHARA baselines

Tannirkulam et al. 2008

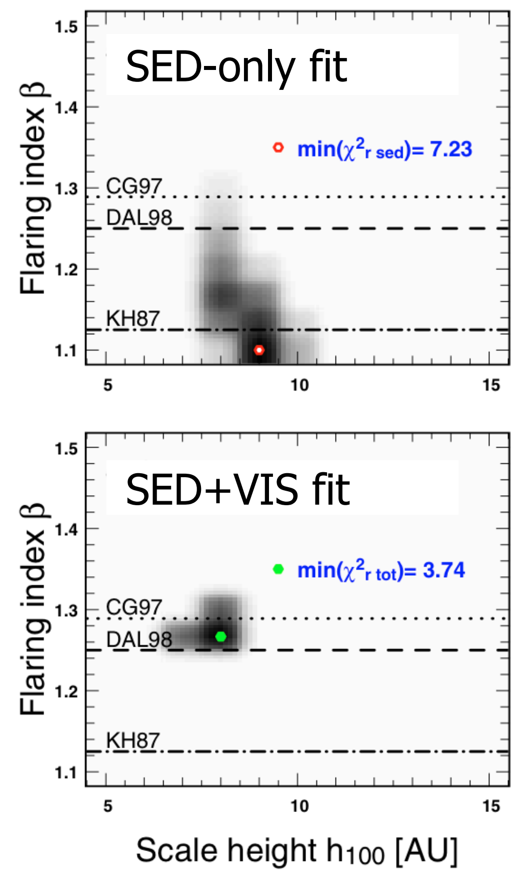
Disk structure
in the extended disk

MIR interferometry: Constraints on disk flaring





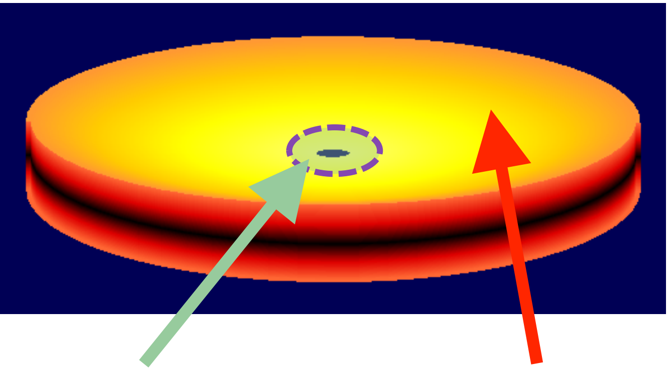
AB Aurigae VLTI/MIDI:



→ MIR spectro-interferometry probes disk flaring properties

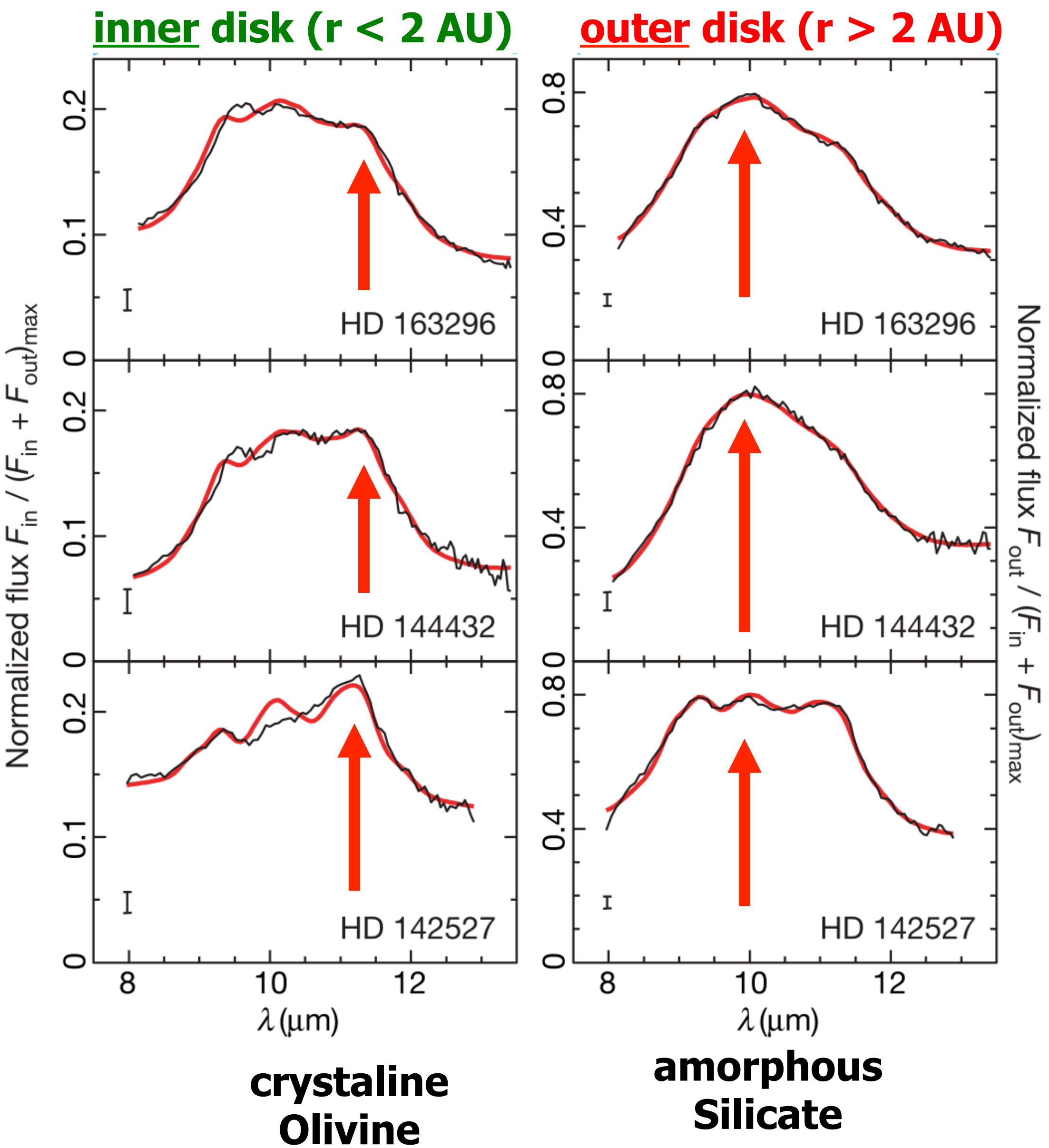
van Boekel et al. 2005, di Folco et al. 2009
also: Preibisch et al. 2005, Schegerer et al. 2009; Ragland et al. 2012

Dust mineralogy



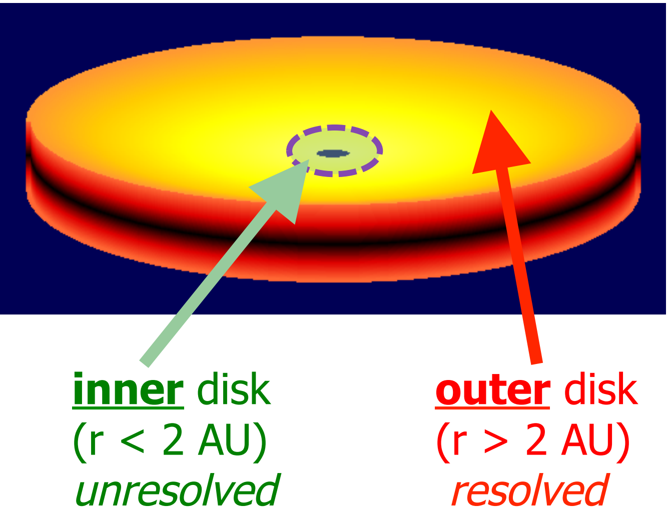
Mid-Infrared interferometry allows to separate the flux contributions from different spatial scales.

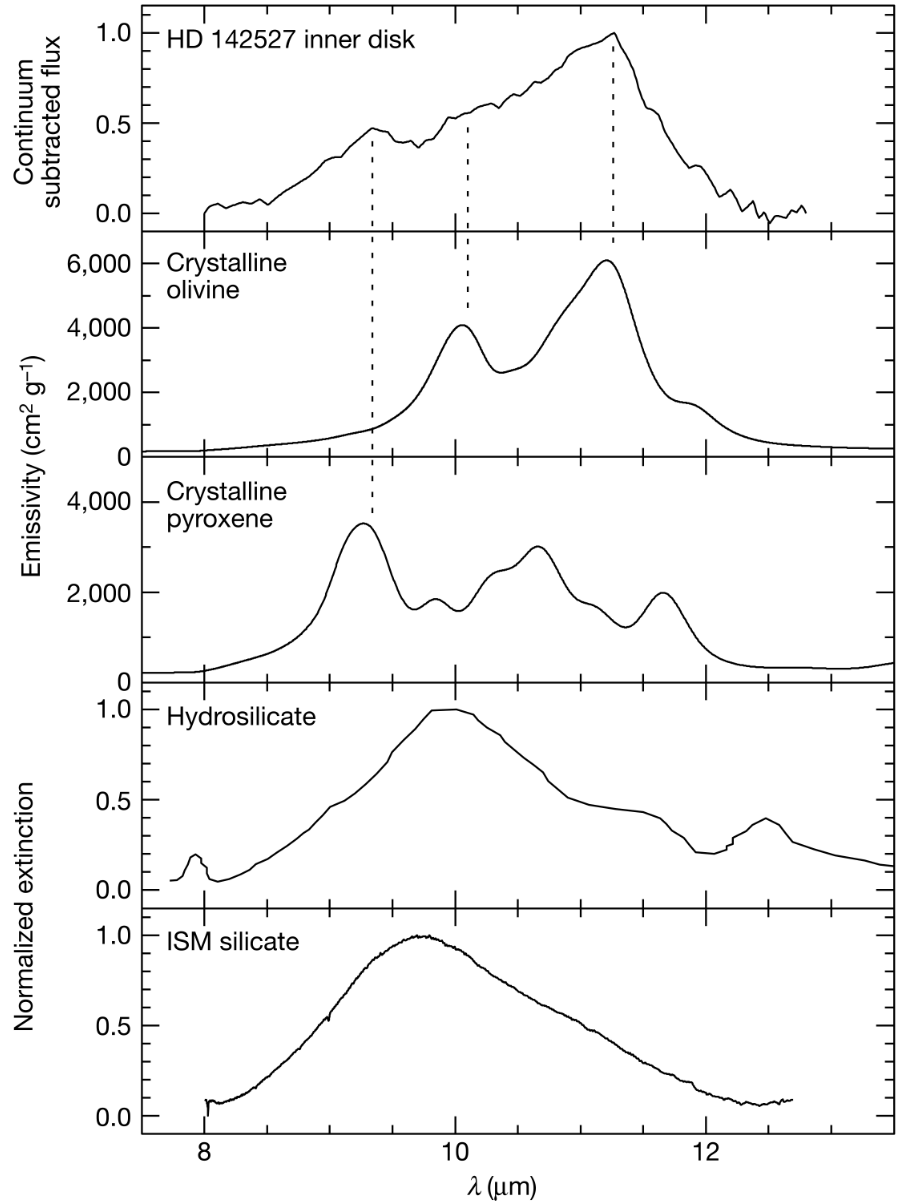
➜ Spectra from inner and outer disk regions differ significantly!



van Boekel et al. 2004

Dust mineralogy



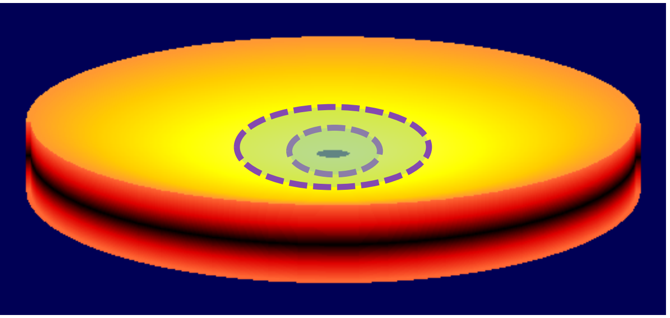


van Boekel et al. 2004

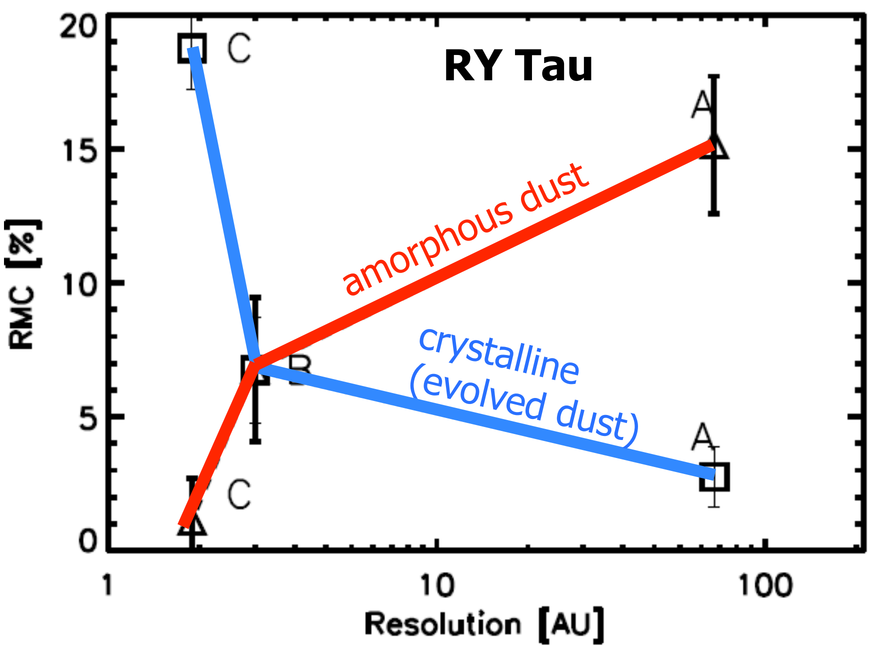
Dust in the inner disks is highly crystallized and consists of larger grains than dust in outer disk regions.

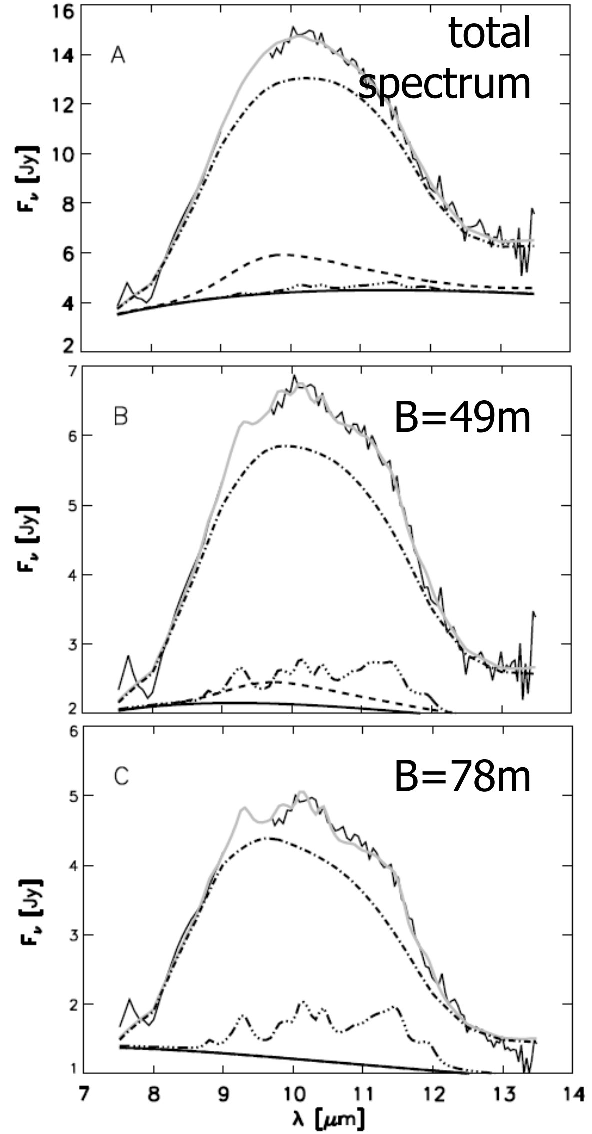
➜ Evidence for radial differences in dust mineralogy (grain growth)

Dust mineralogy



Using different baseline lengths allows one to probe dust mineralogy as function of radius
➜ separate crystalline and amorphous silicate contributions





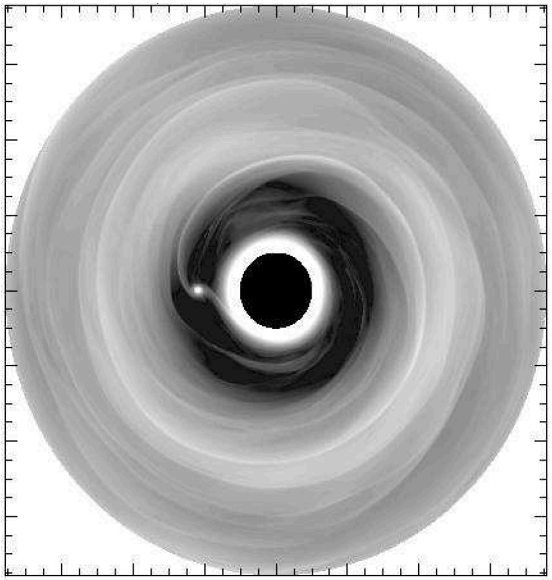
Schegerer et al. 2008
also: Ratzka et al. 2007

Disk gaps and asymmetries

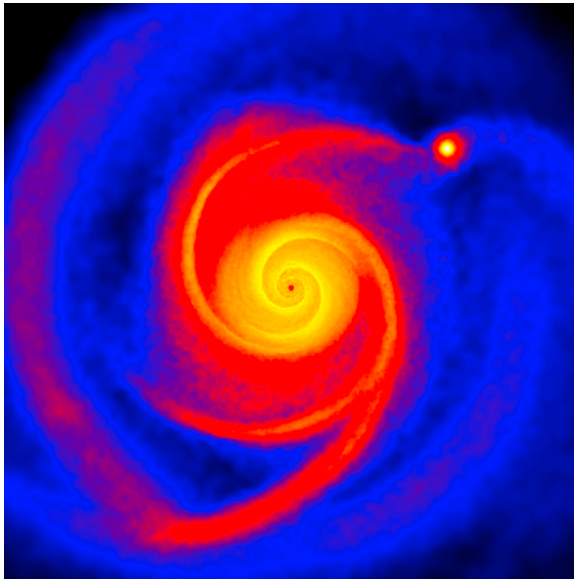
Planet formation signatures

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

Gap clearing



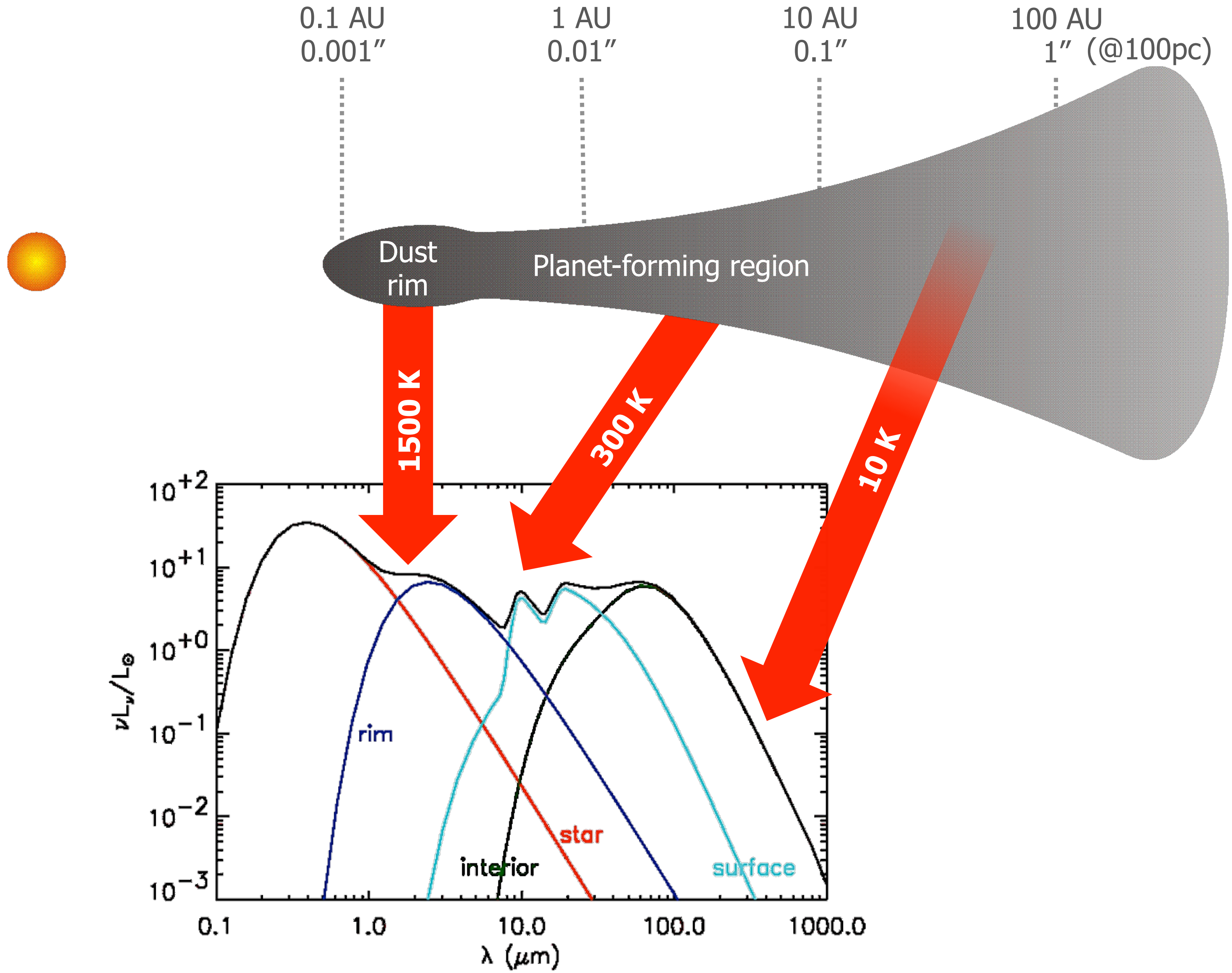
Disk fragmentation



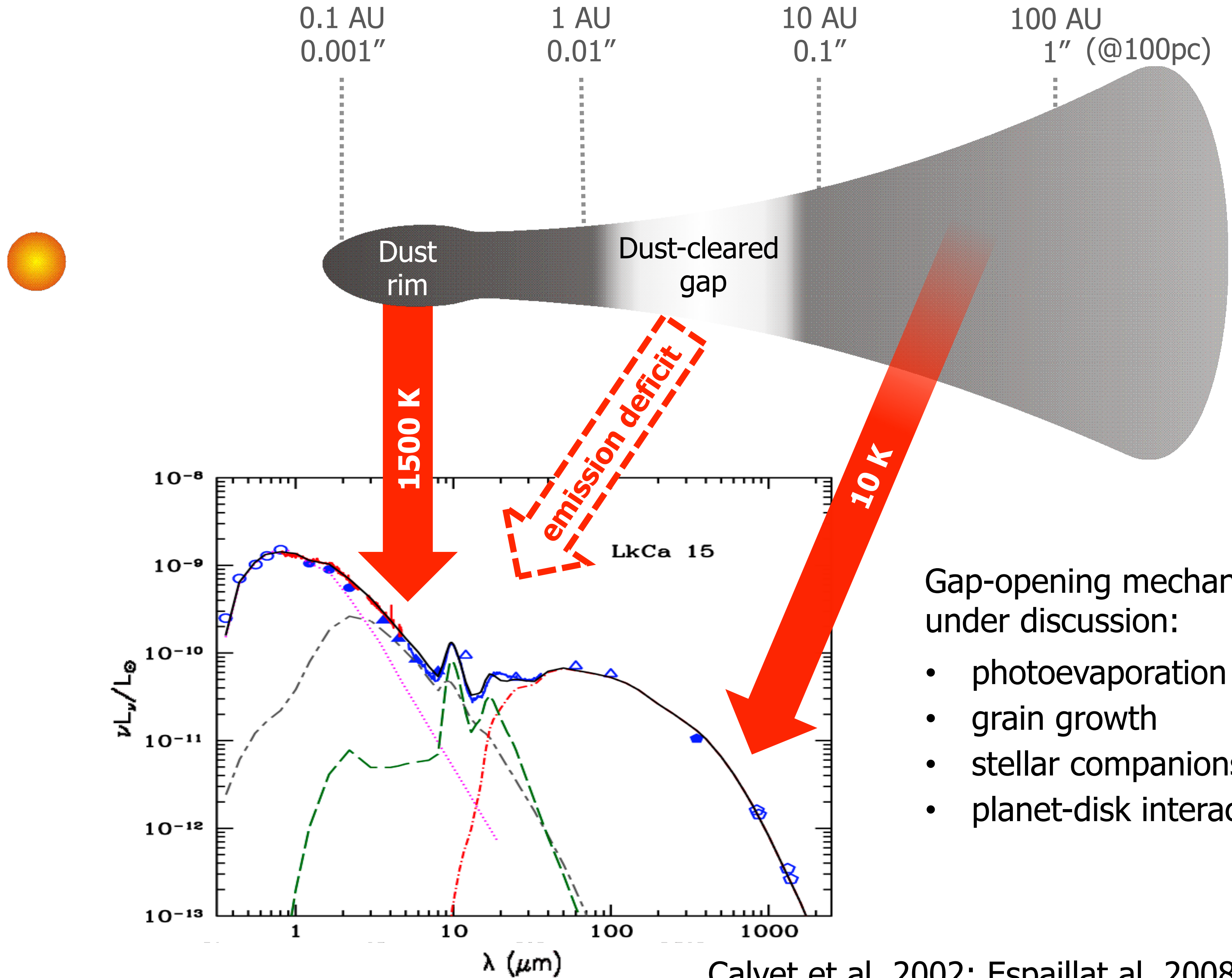
Disk warping

Papaloizou et al. 2007, Greaves et al. 2008, Muzerolle et al. 2009

Disk structure – Protoplanetary disks



Disk structure – Transitional disks



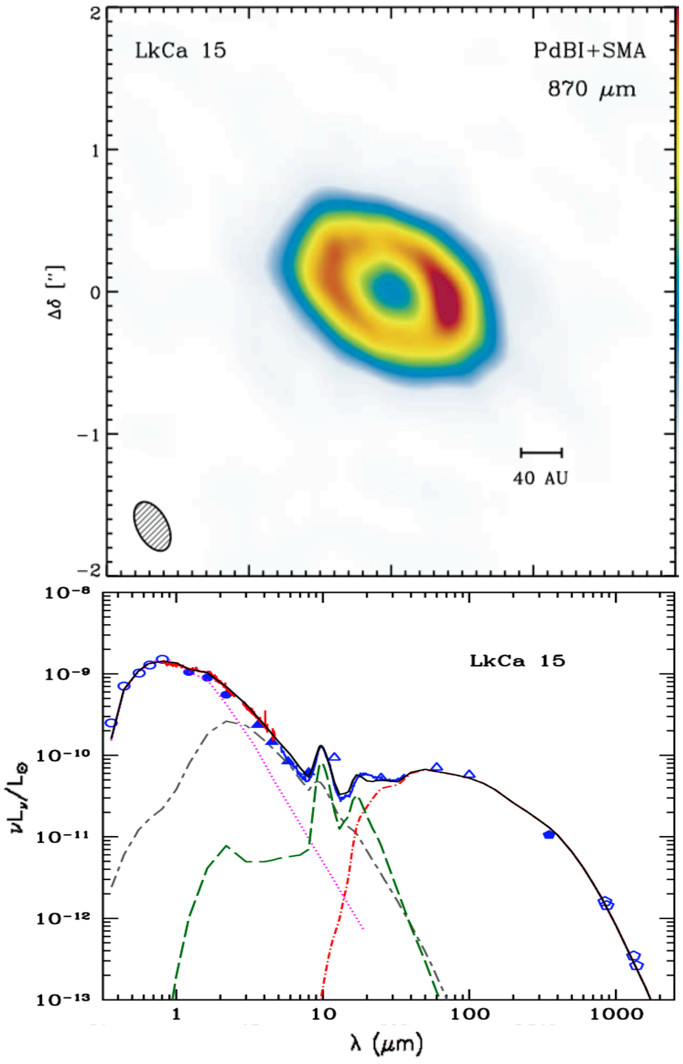
Gap-opening mechanisms under discussion:

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

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

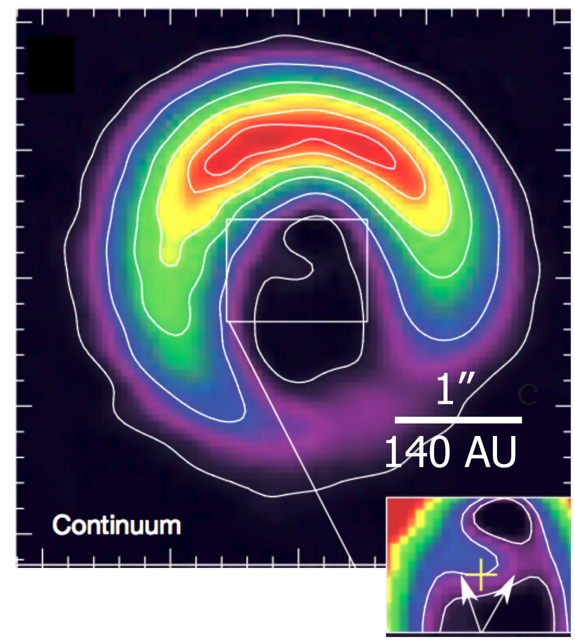
Disk structure – Transitional disks

LkCa15



Andrews et al. 2011

HD142527

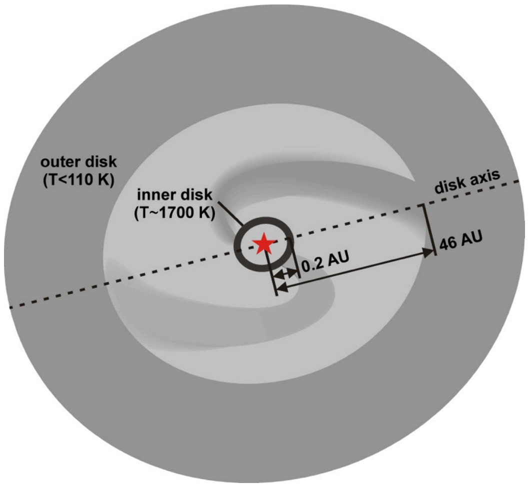


Casassus et al. 2013

(Sub-)millimeter interferometry
reveals central density depressions

IR Interferometric studies on transitional disks

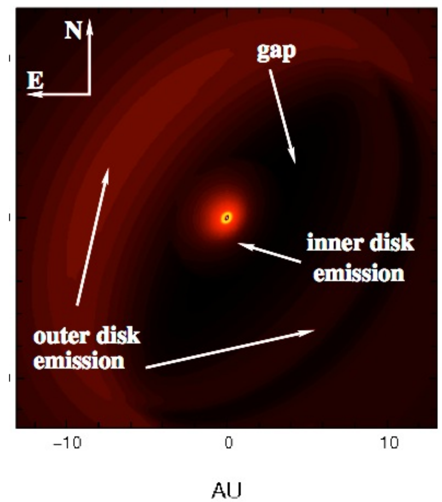
V1247 Ori



- Gap 0.2 – 46 AU, partially depleted
- Gap contains optically thin carbonaceous dust

Kraus et al. 2013

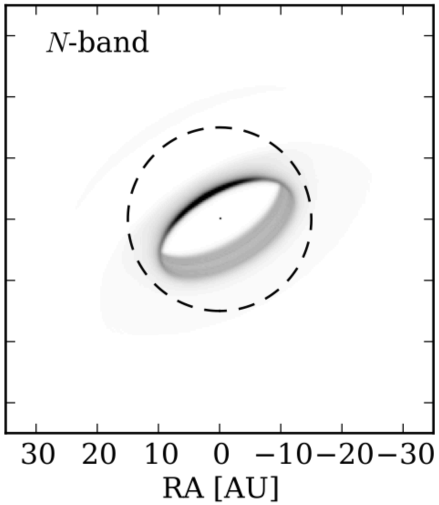
HD100546



- Gap 0.3 – 29 AU, fully depleted
- Companion candidate (Quanz et al. 2013)

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

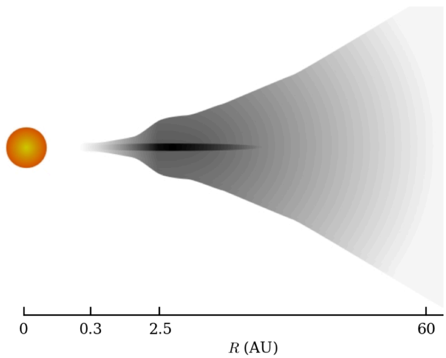
T Cha



- Gap 0.1 – 25 AU, fully depleted
- Companion candidate (Huelamo et al. 2011)

Olofsson et al. 2011, 2013

TW Hya



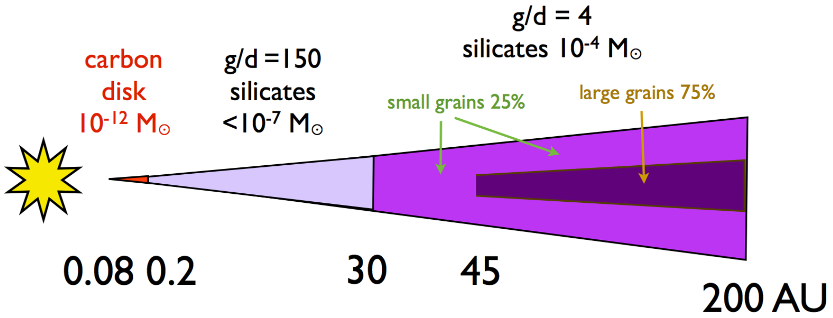
- Depleted region <2.5 AU with very large settled grains

Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012
Menu et al. 2014

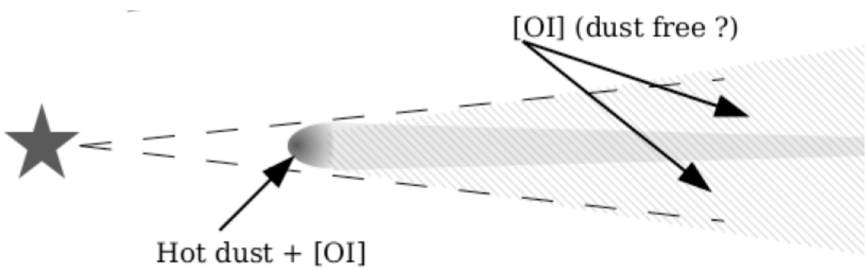
time??

IR Interferometric studies on transitional disks

Studies combining IR interferometry + Gas tracers:

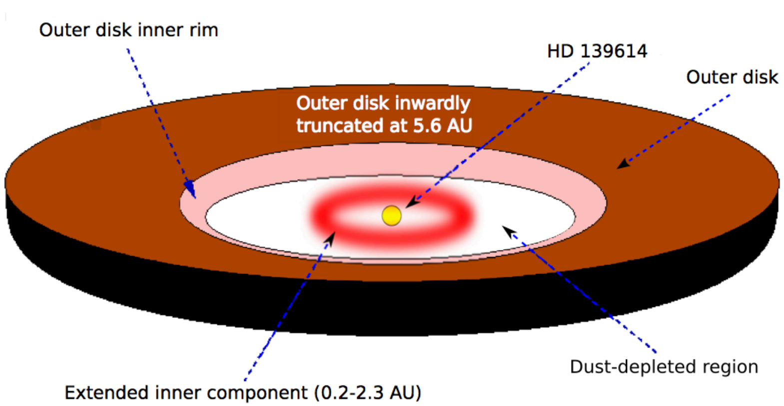


SAO 206462, CO fund. line
Carmona et al. 2014



HD101412, [OI] line
Fedele et al. 2008

Detection of gaps in "classical" disks:



HD139614
Matter et al. 2014

Detection of AU-scale discontinuities in "classical" disks (based on SED)

➜ Early stages of disk clearing?

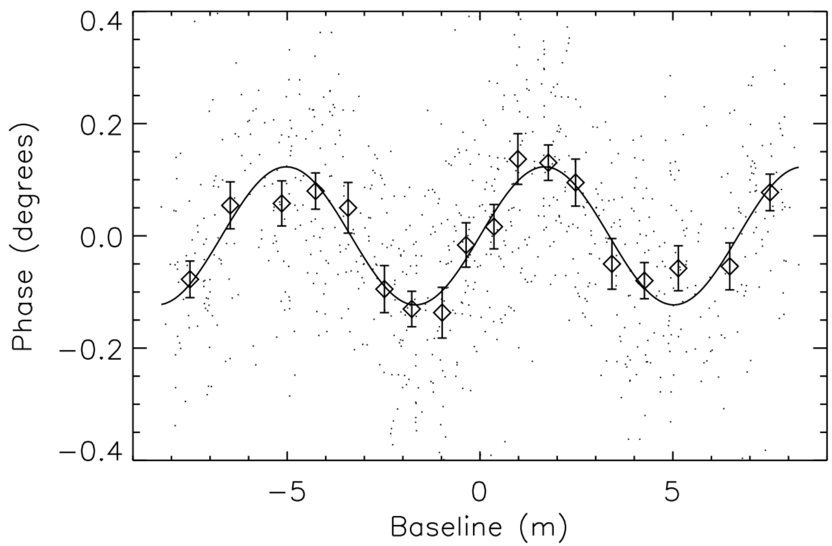
➜ Gaps characteristic of all Group I sources? (Maaskant et al. 2013)

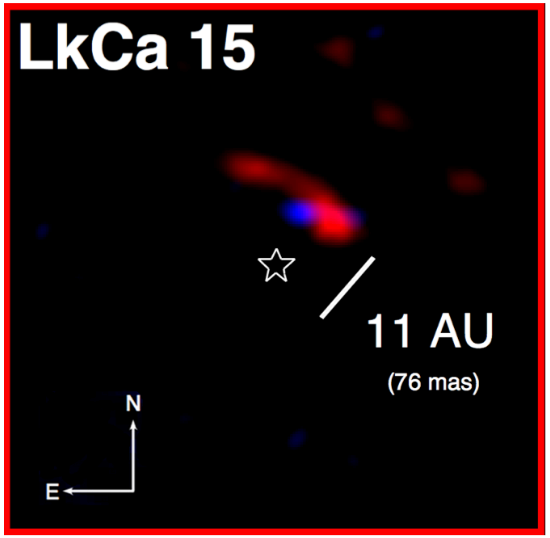
also: Chen et al. 2010; Schegerer et al. 2013

AU-scale asymmetries

Asymmetries might trace:

1. **Companions**



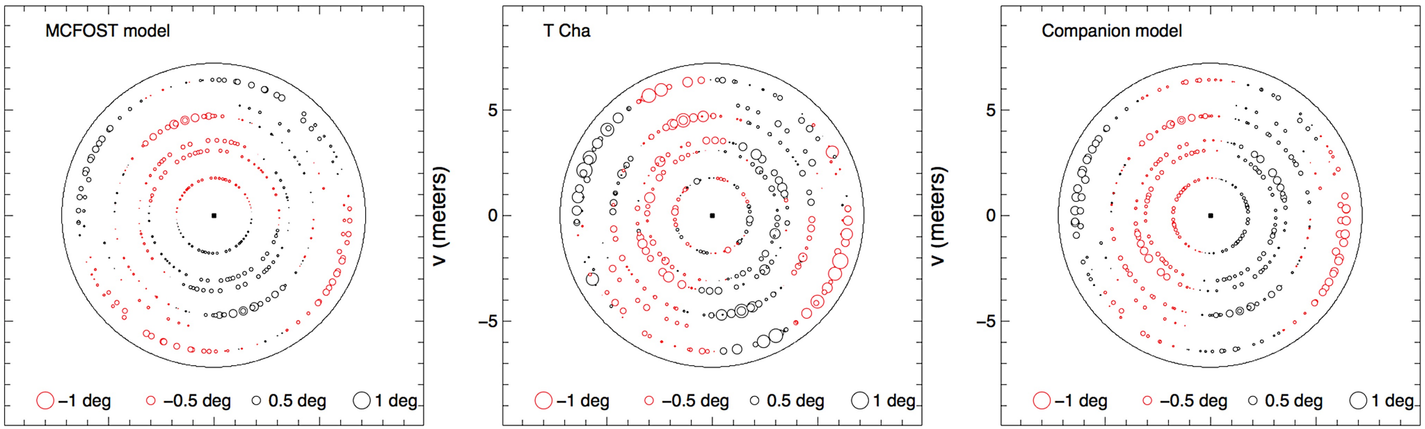


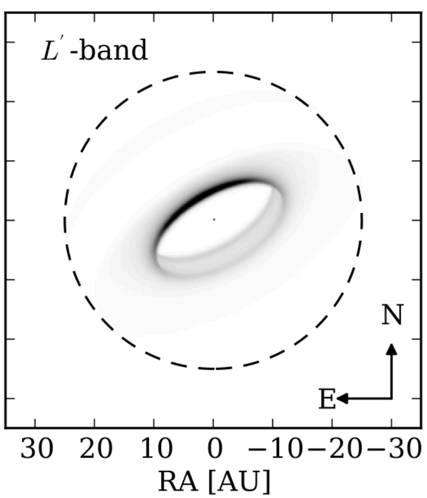
Kraus & Ireland 2012

AU-scale asymmetries

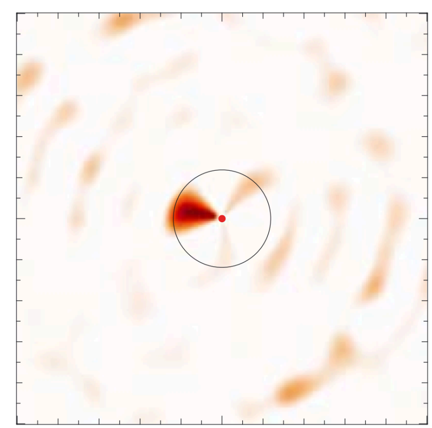
Asymmetries might trace:

2. **Vertically extended structures in an axial-symmetric disk seen under inclination**, e.g. at the inner edge of the outer disk





T Cha



Olofsson et al. 2013; Huelamo et al. 2011

AU-scale asymmetries

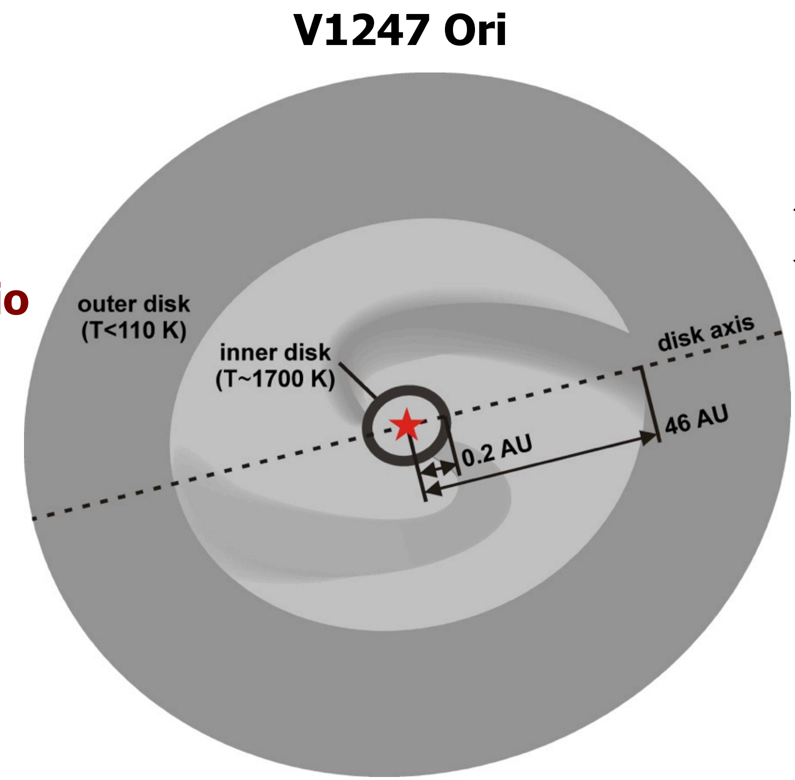
Asymmetries might trace:

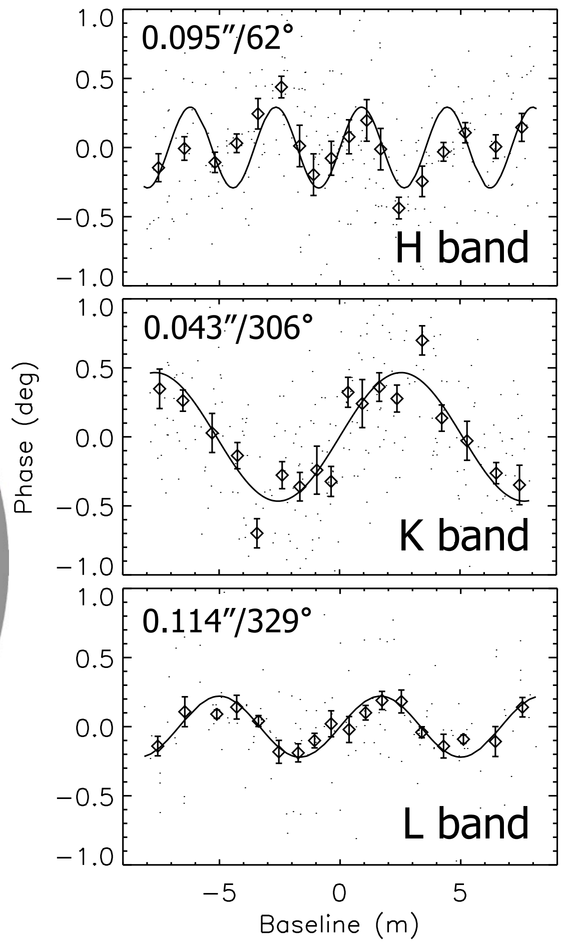
3. Complex, non-axialsymmetric structure

Direction of asymmetries changes with wavelength

➜ Not consistent with 1-companion scenario nor symmetric disk

➜ Complex density structures in the gap region, possibly due to dynamical interaction with gap-opening planets





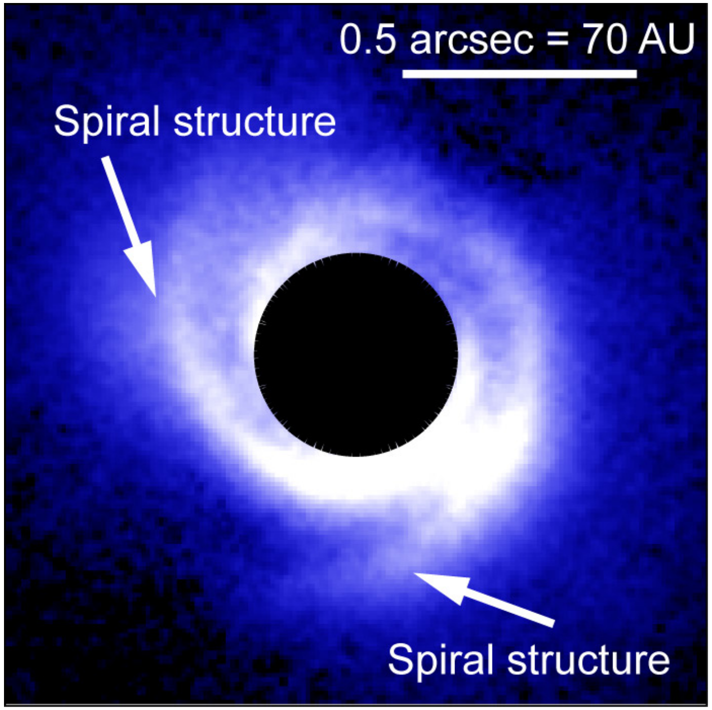
Kraus et al. 2013

AU-scale asymmetries

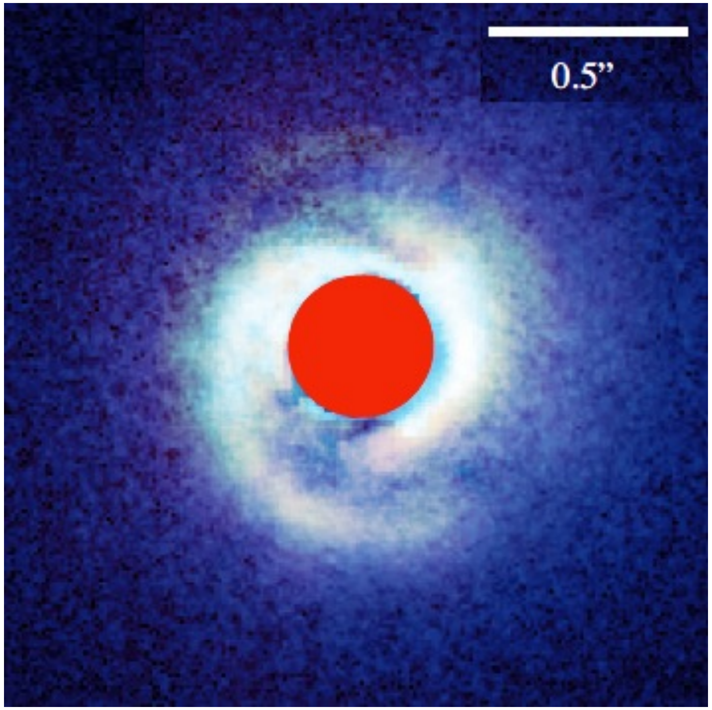
Asymmetries might trace:

3. Complex, non-axialsymmetric structure

SAO206462



MWC758

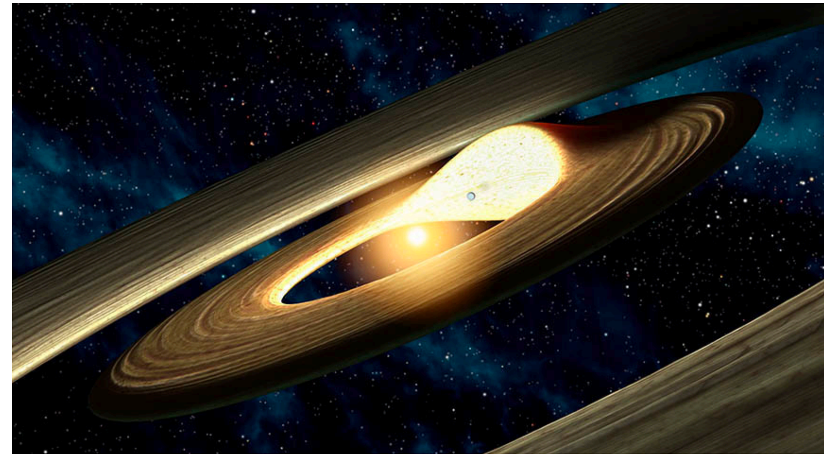


Dong et al. 2012, Grady et al. 2013

AU-scale asymmetries

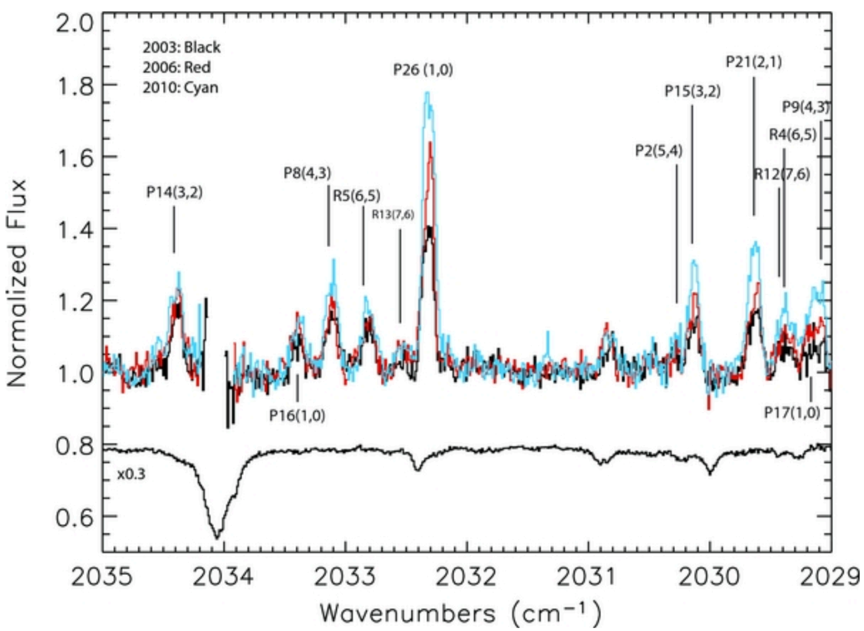
For some objects, both structural and spectroscopic variability has been detected

➜ Good uv-coverage needed for imaging

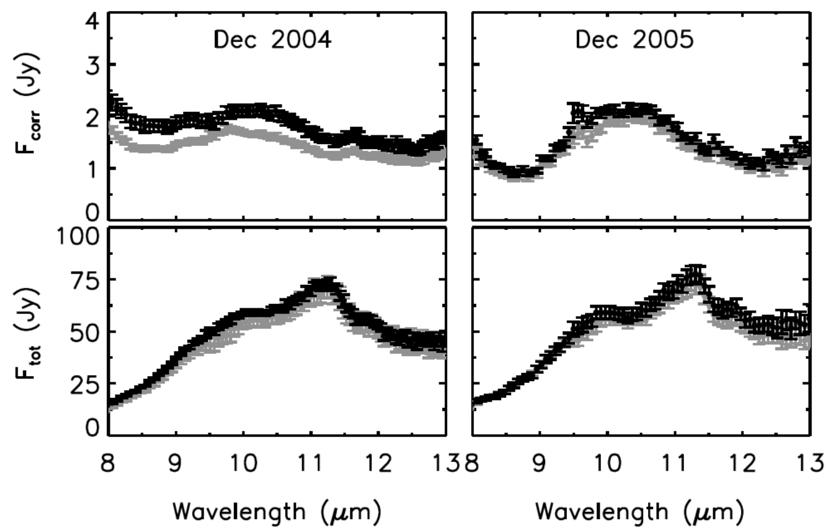


Artists Impression, Muzerolle et al. 2009

Spectroscopic variability
(HD100546)



Structural variability
(HD100546)



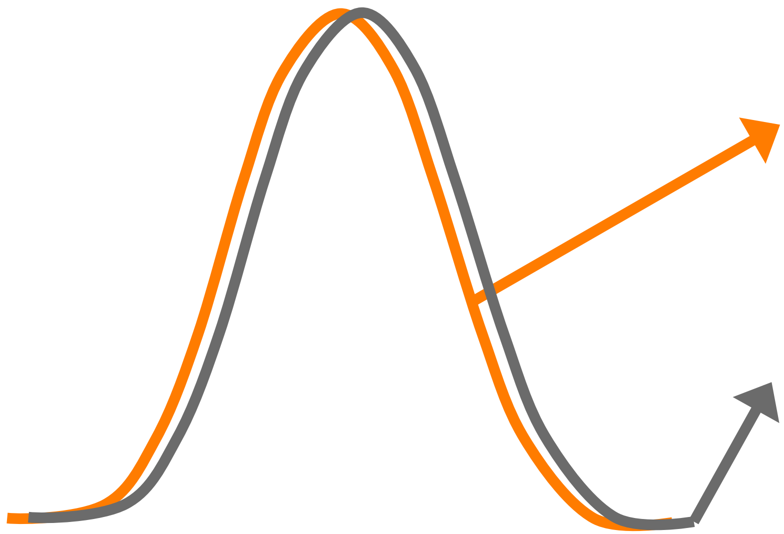
Panić et al. 2014; Brittain et al. 2013
also: Mosoni et al. 2013

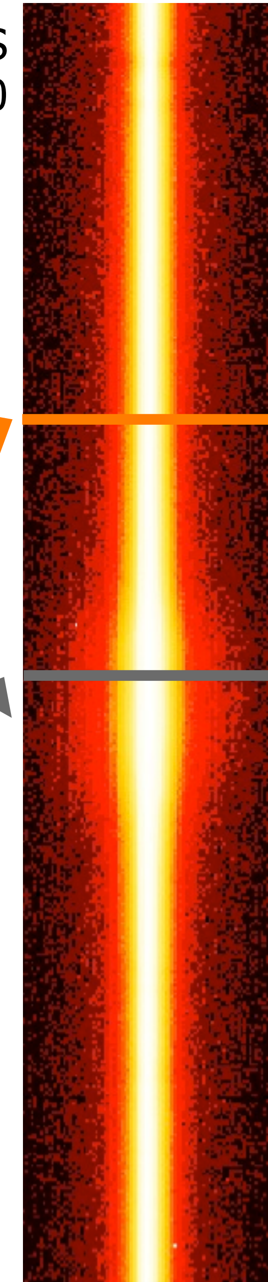
Gas kinematics studies

Spectro-interferometry vs. spectro-astrometry

VLT/CRIRES
R=100,000

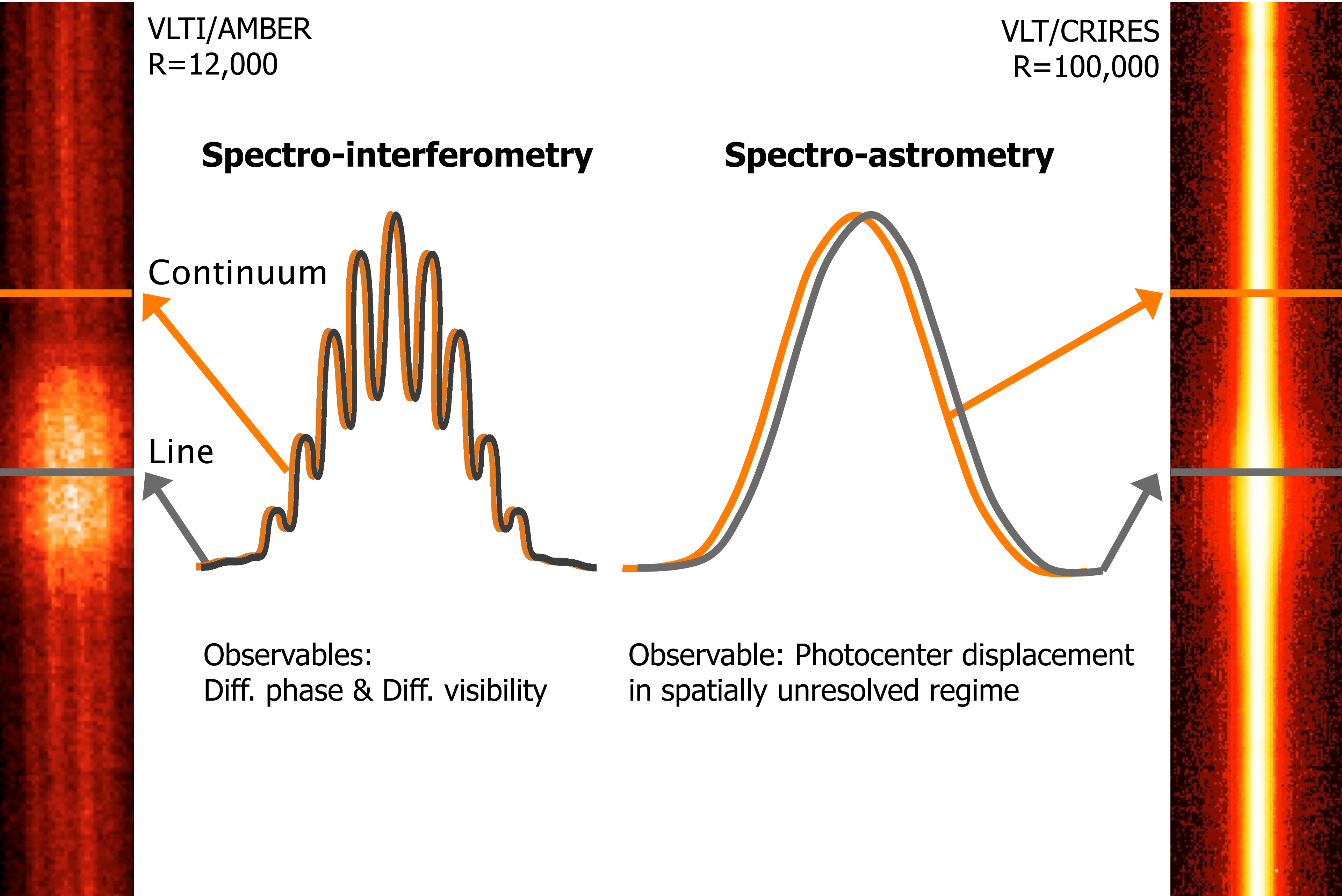
Spectro-astrometry



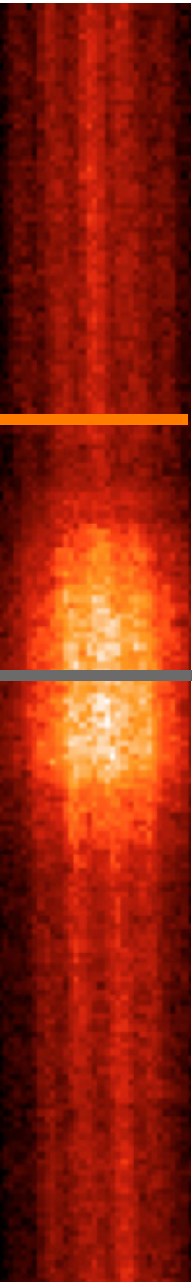


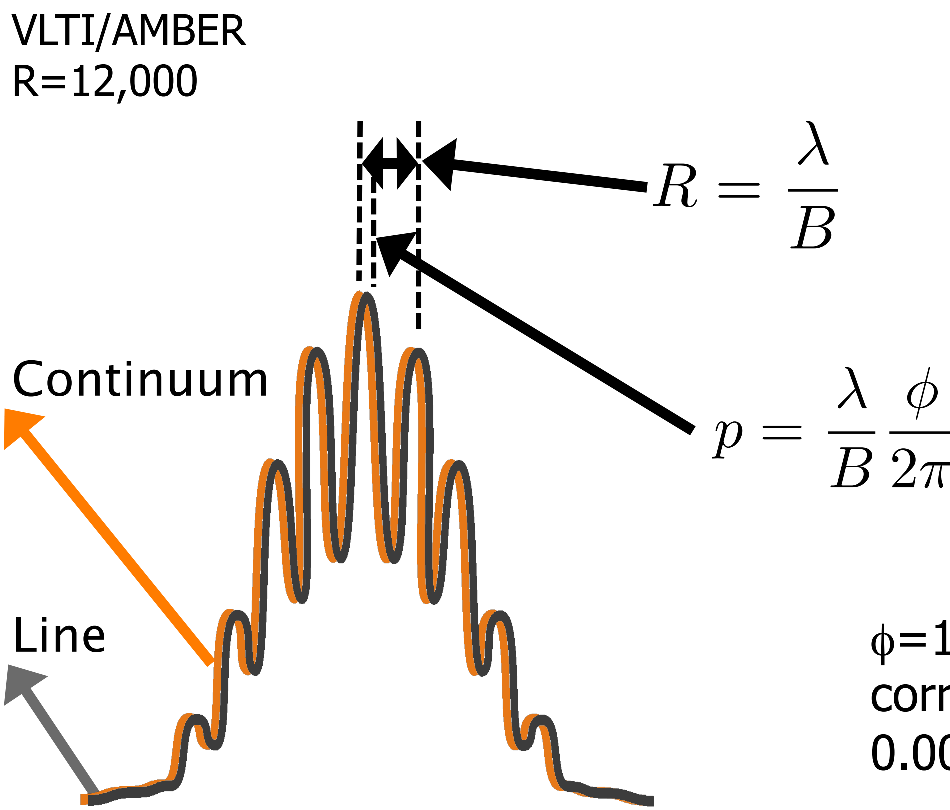
Observable: Photocenter displacement
in spatially unresolved regime

Spectro-interferometry vs. spectro-astrometry



Spectro-interferometry





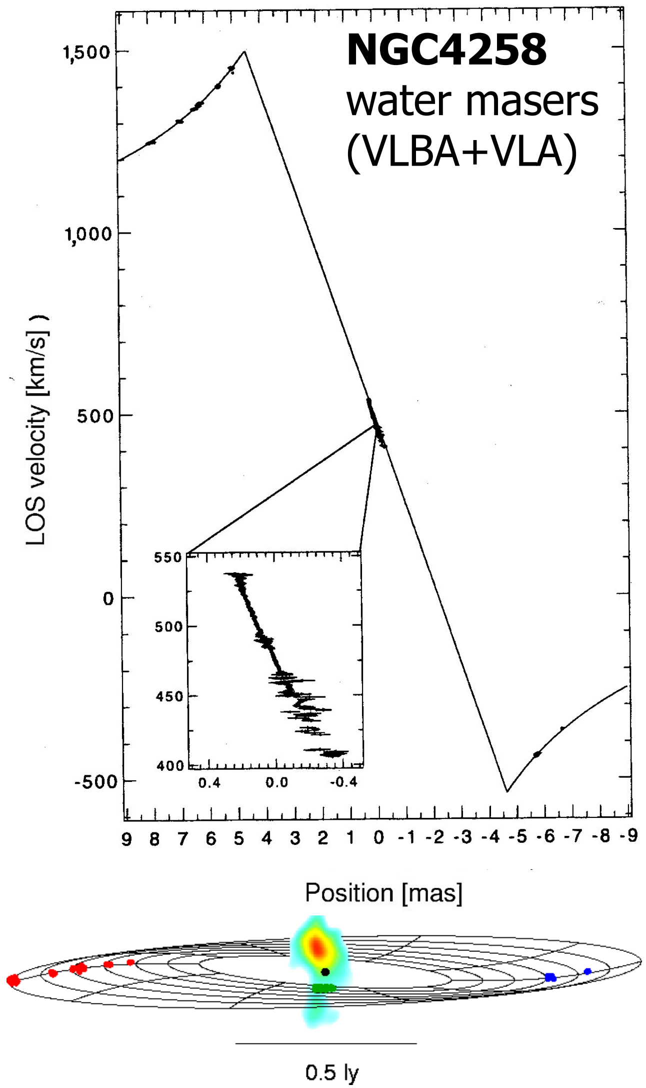
ϕ=1° for 2µm, B=100m corresponds to **0.012 mas** or 0.002 AU=0.5 $R_\odot$ in Taurus

➜ Short baselines: Differential phases measure photocenter displacements between the continuum and line-emitting region

➜ Long baselines: Constrains the **geometry** of the line-emitting region

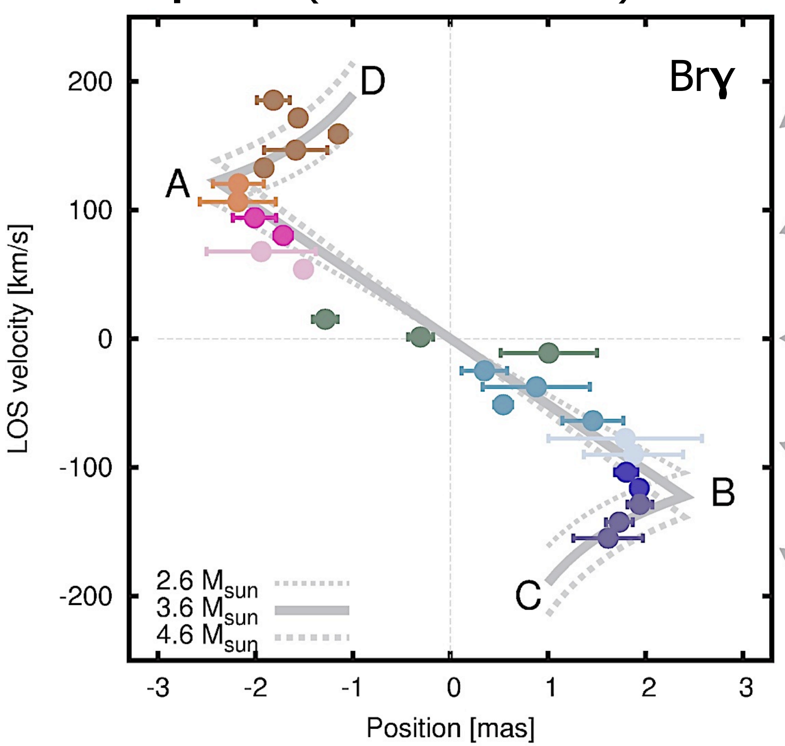
Gas kinematics studies

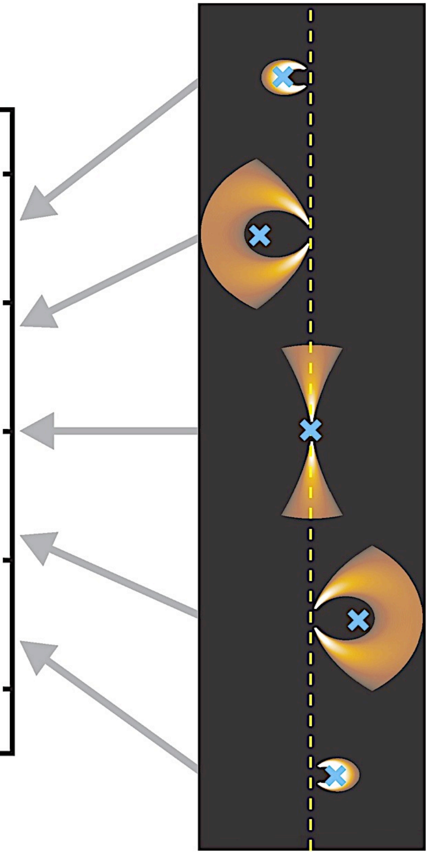
Disk rotation profile:



Miyoshi et al. 1995
Herrnstein et al. 1997

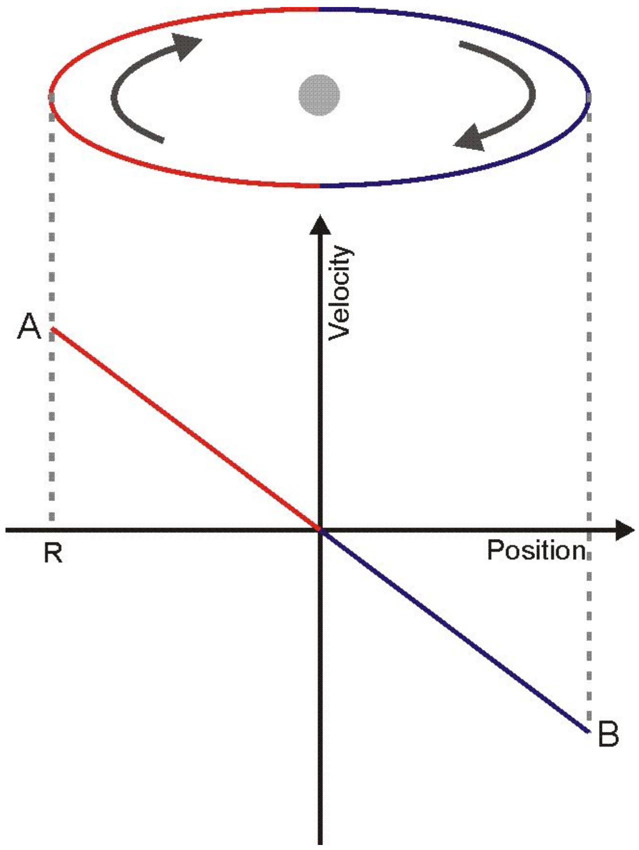
β CMi (classical Be star)



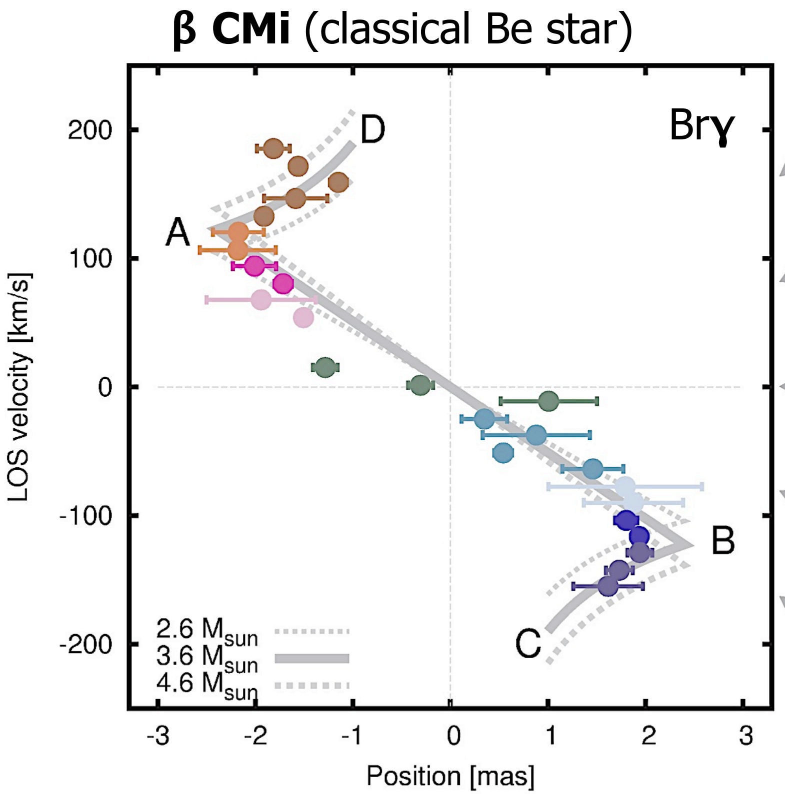


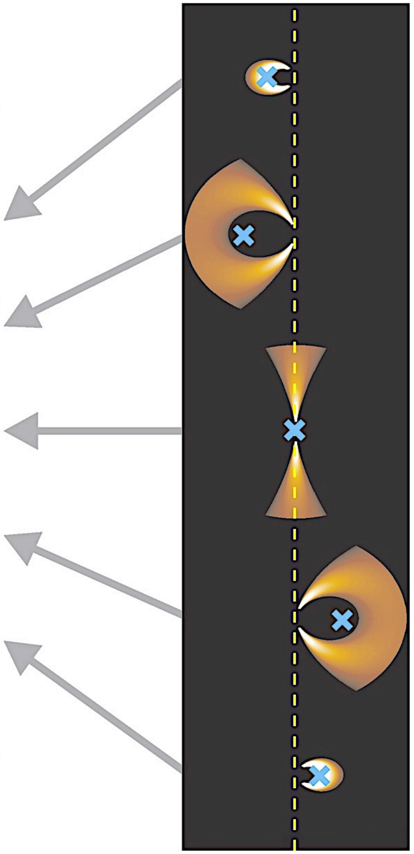
Kraus et al. 2012a

Gas kinematics studies



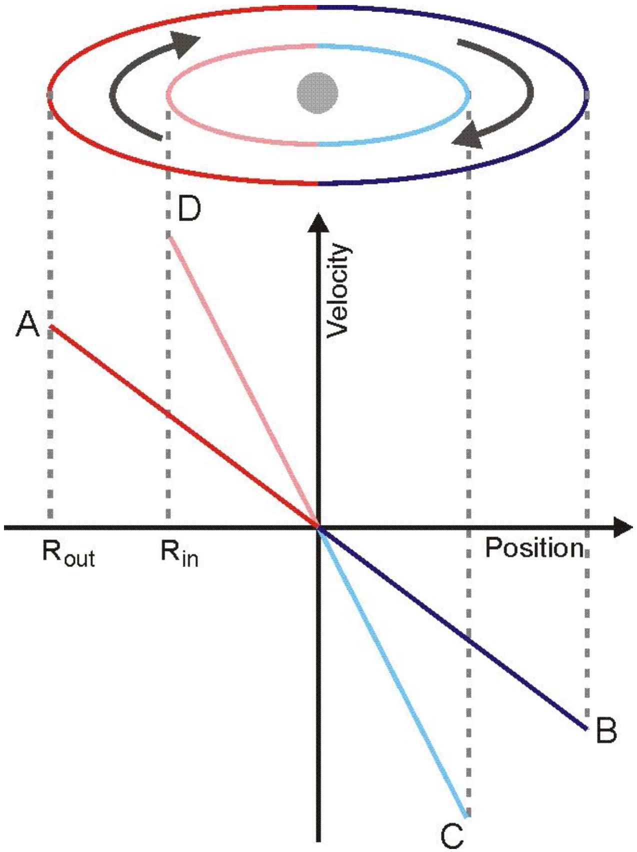
$$v_{\mathrm{kep}}(r, \vartheta) = \sqrt{\frac{GM_\star}{r}} \sin\vartheta \cdot \cos i$$





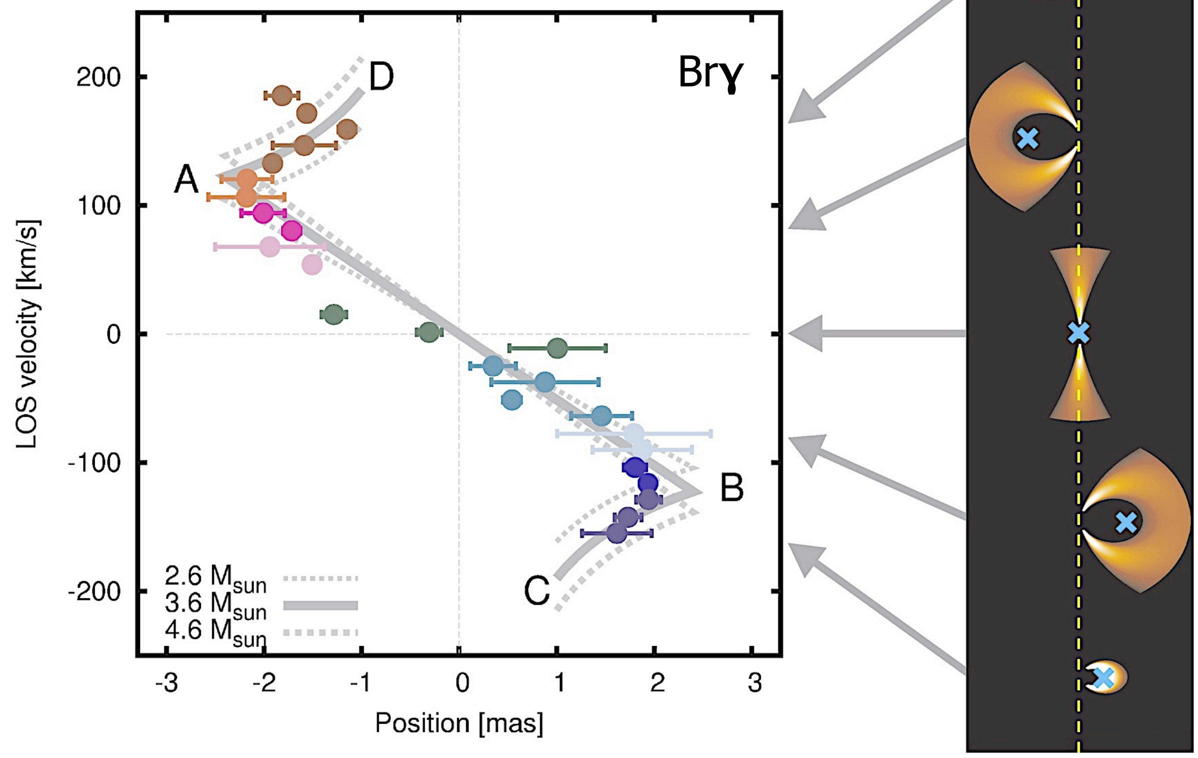
Kraus et al. 2012a

Gas kinematics studies



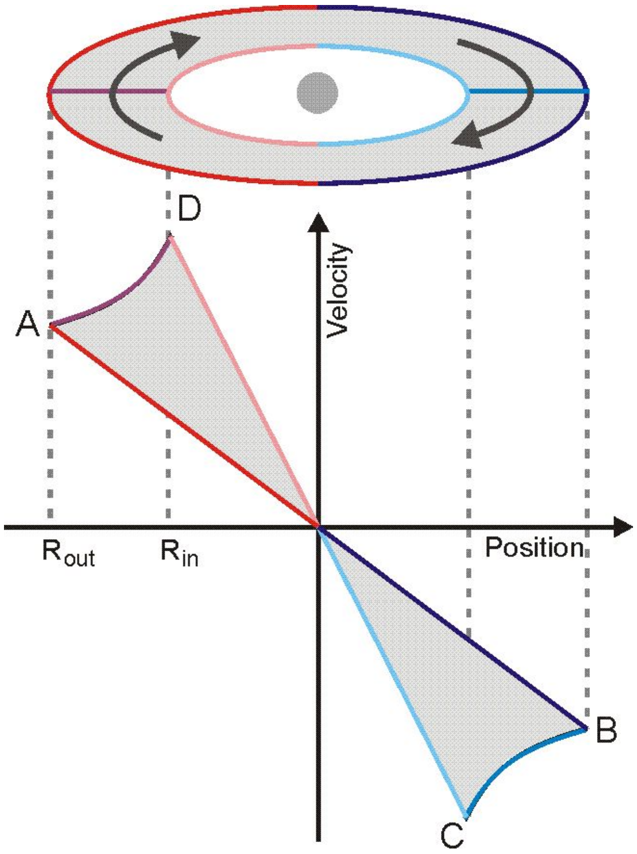
$$v_{\rm kep}(r,\vartheta) = \sqrt{\frac{GM_\star}{r}}\,\sin\vartheta\cdot\cos i$$

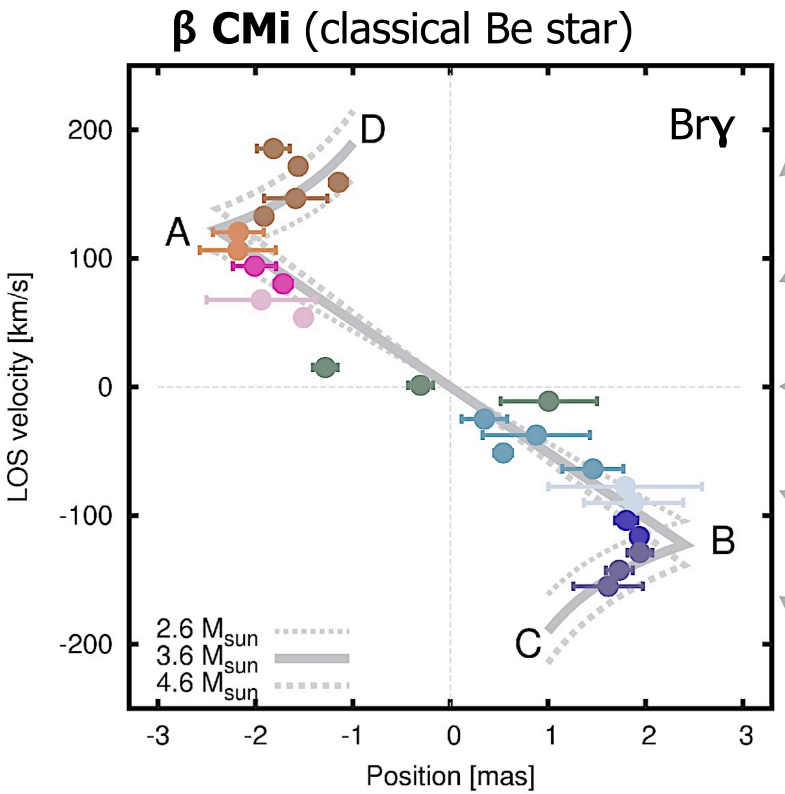
β CMi (classical Be star)

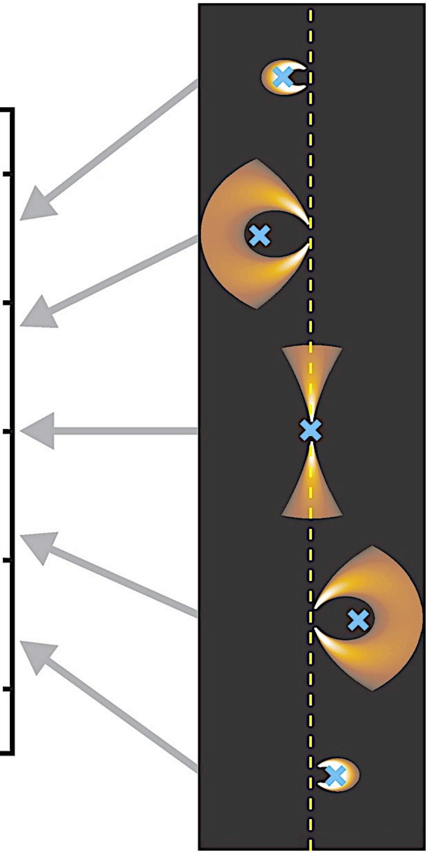


Kraus et al. 2012a

Gas kinematics studies



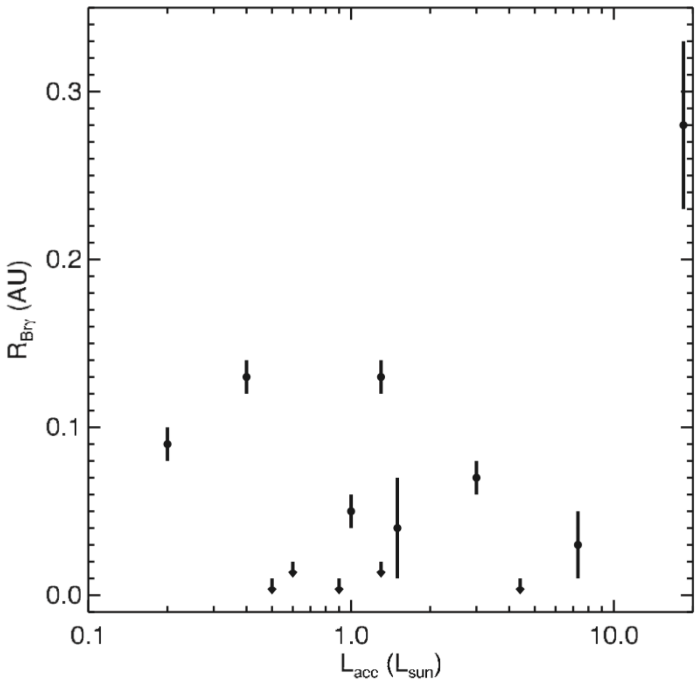


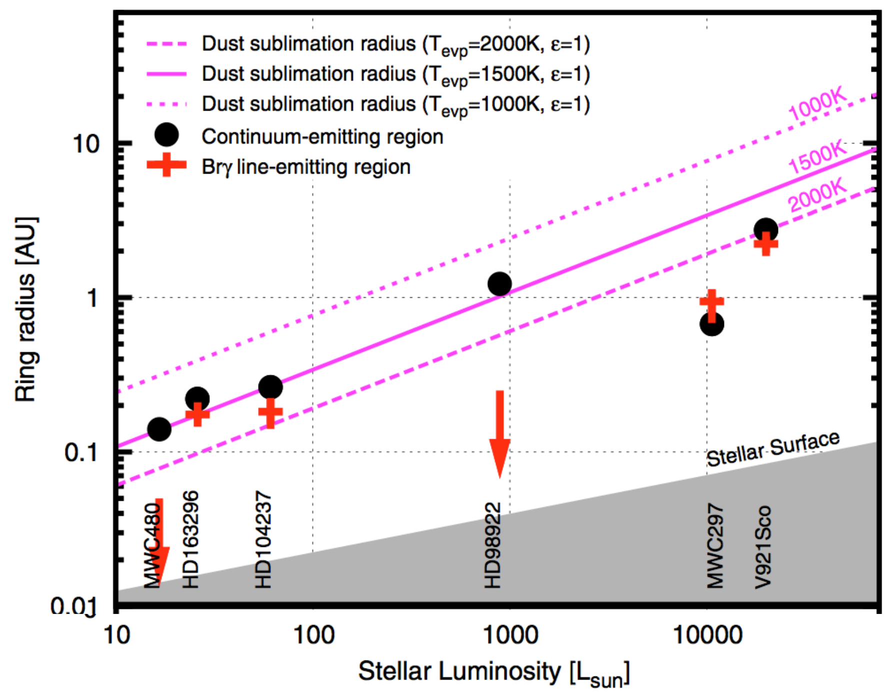


$$v_{\mathrm{kep}}(r, \vartheta) = \sqrt{\frac{GM_\star}{r}} \sin\vartheta \cdot \cos i$$

Kraus et al. 2012a

Gas kinematics studies: Brγ





No tight correlation has been found, but general trends:

Compact Brγ-emitting region in most low-L sources (T Tauri, most Herbig Ae)

➜ **consistent with magnetospheric accretion**

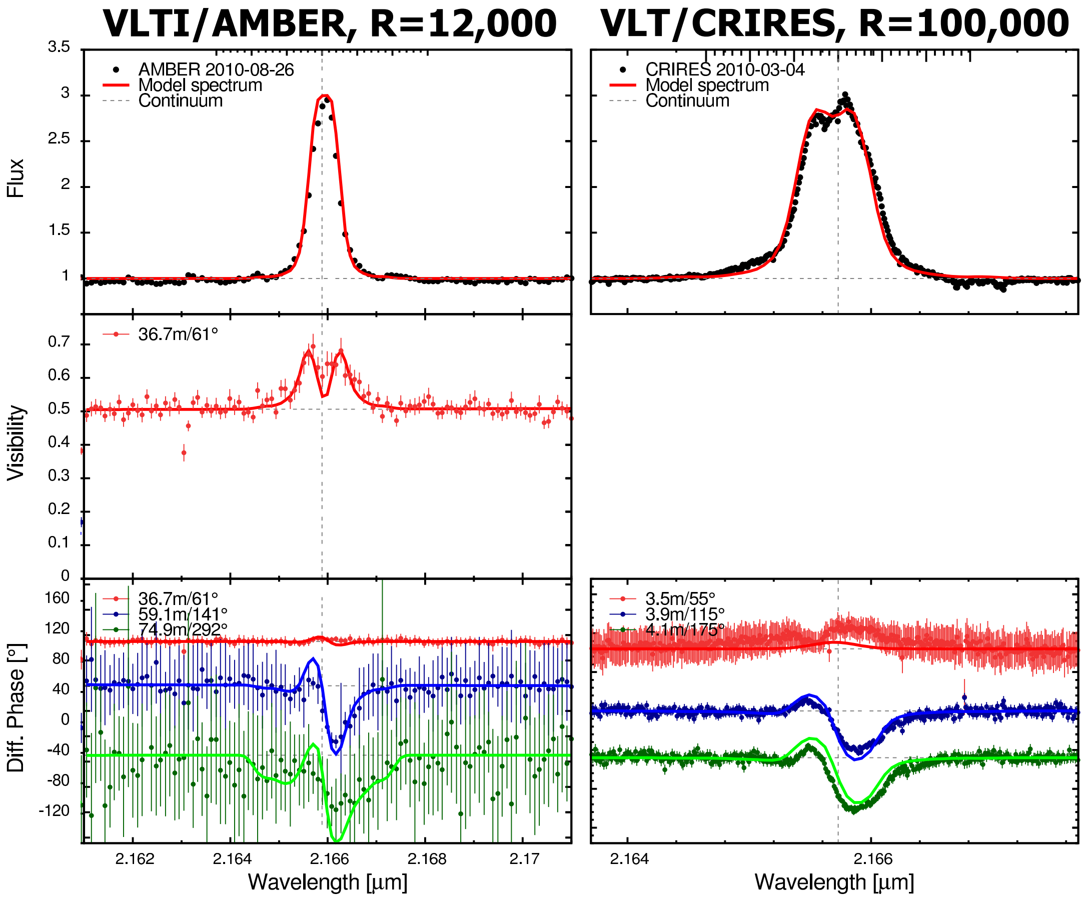
Extended Brγ-emitting ($R_{Br\gamma} \approx R_{sub}$) in some medium/high-L sources

➜ **wind contributions**

Kraus et al. 2008, Eisner et al. 2010

also: Tatulli et al. 2007, Eisner et al. 2009; Benisty et al. 2010

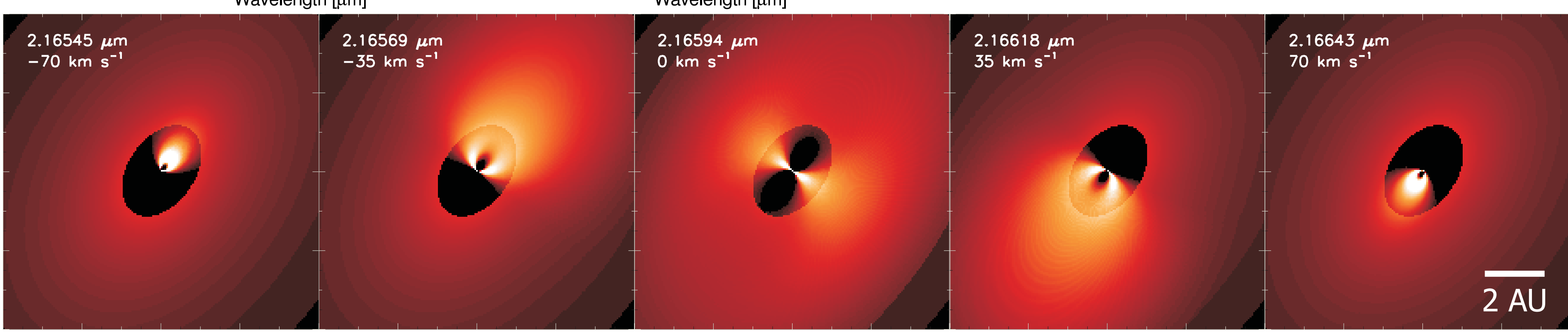
Gas kinematics studies: Brγ



Detailed modeling constraints the velocity field and fundamental stellar parameters:

$R_{\rm in}$	[mas]	$\lesssim 0.5$
$R_{\rm out}$	[mas]	5.8 ± 0.3
θ	[°]	$145.26 \pm 1.3^{\rm a}$
i	[°]	54 ± 2
$M_\star$	$[M_\odot]$	$(5.4 \pm 0.4) \cdot (d/1150\ {\rm pc})$
q		-1.0 ± 0.1

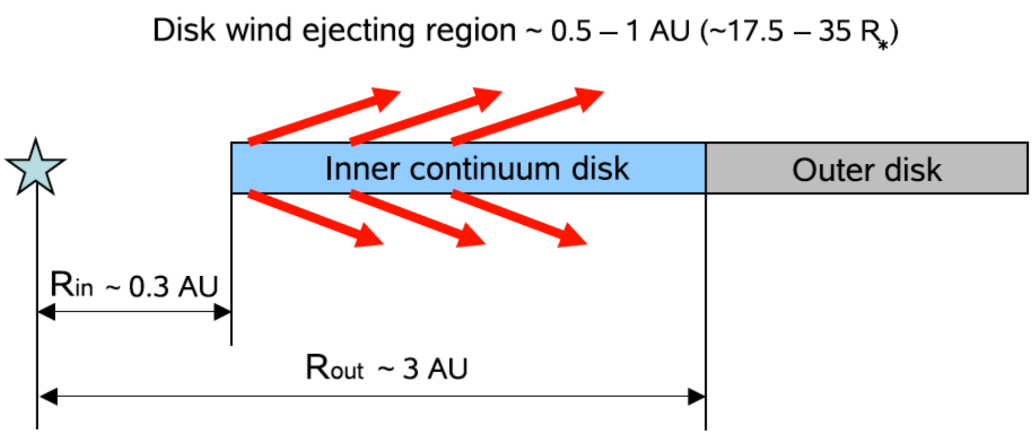
Kraus et al. 2012c

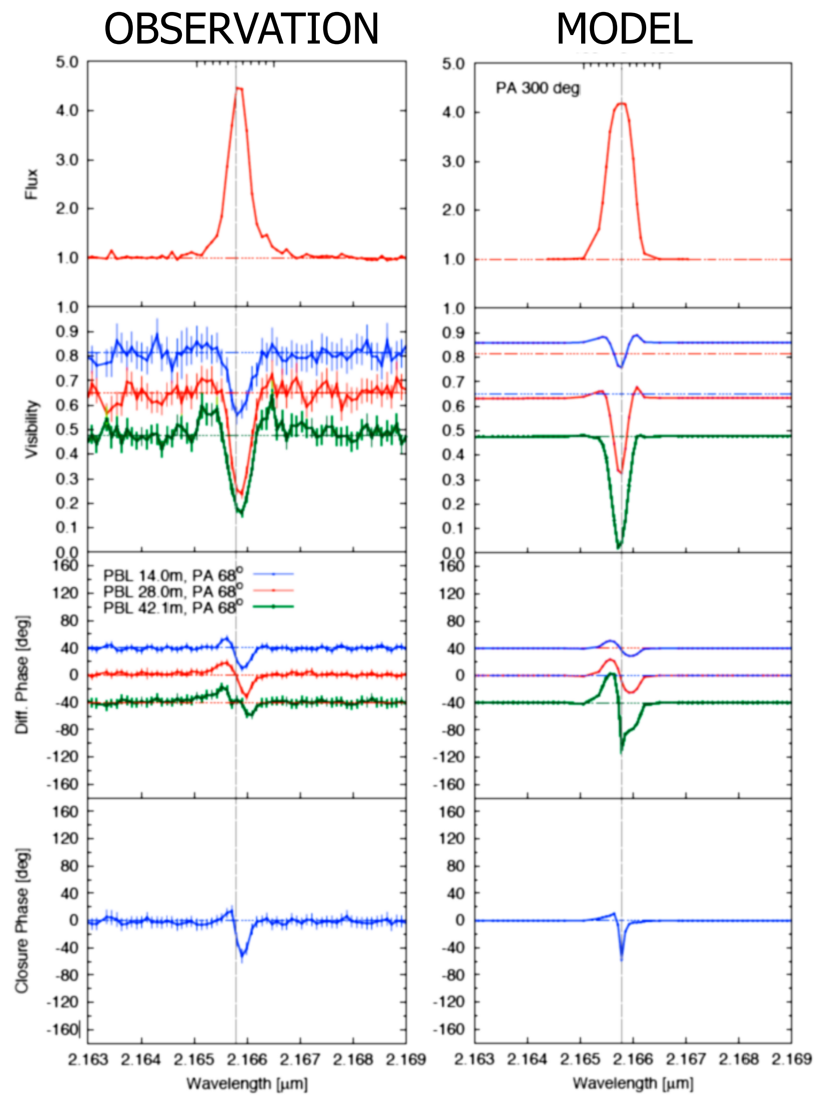


Gas kinematics studies: Brγ

MWC297:

Spectra and interferometric observables modeled with magneto-centrifugally driven disk wind

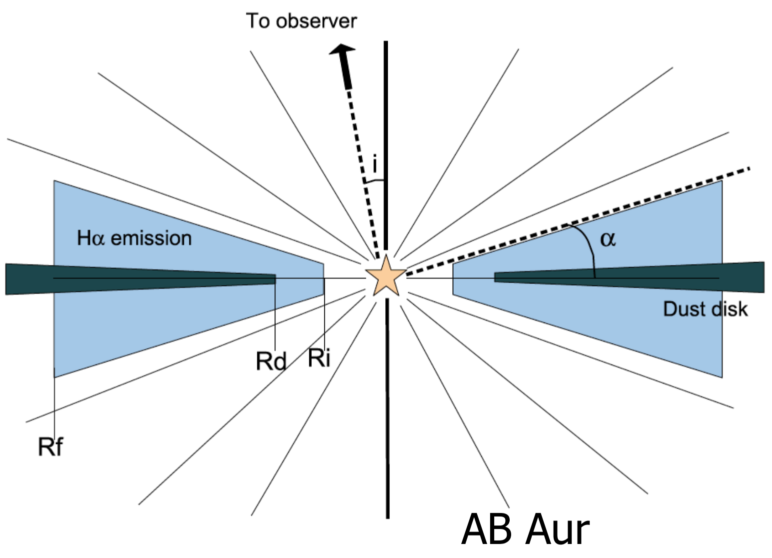




Weigelt et al. 2011, Grinin et al. 2012
also: Malbet et al. 2007

Gas kinematics studies: Hα, CO

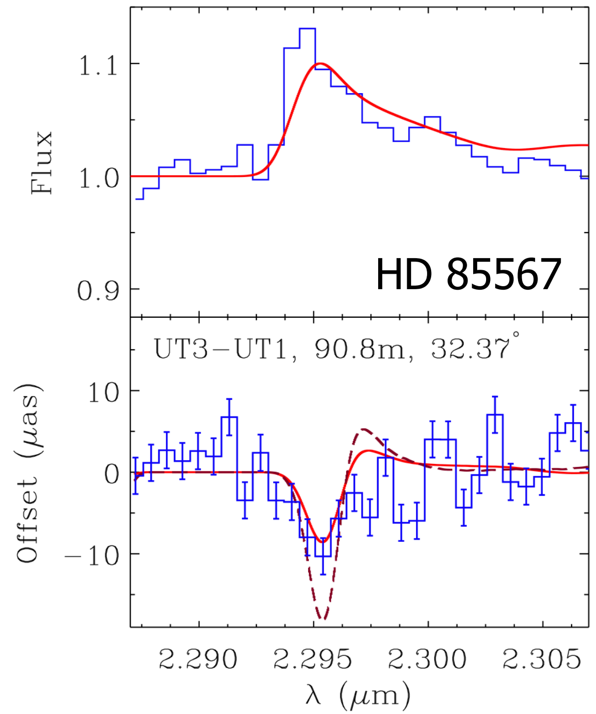
Hα line



Extended Hα region
➜ Consistent with disk wind origin

Rousselet-Perraut et al. 2010

CO 2.3 μm bandhead emission



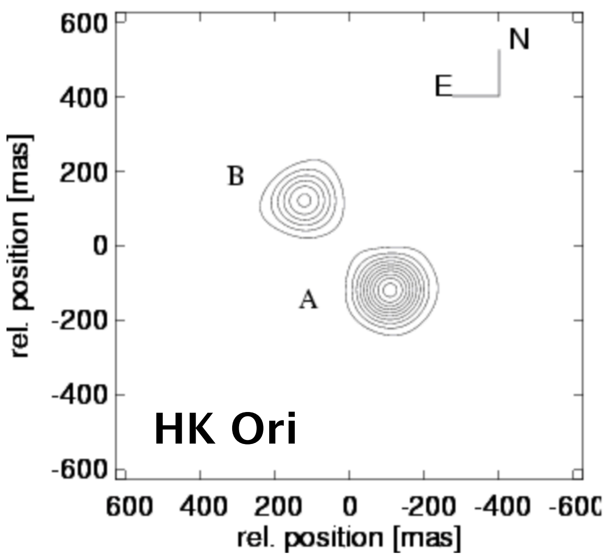
Gas disk inside of sublimation radius

Wheelwright et al. 2013
also: Tatulli et al. 2009, Eisner et al. 2011

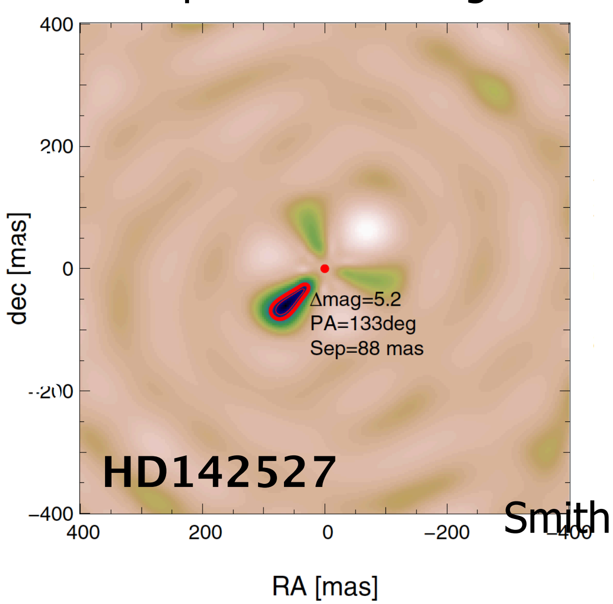
Multiplicity studies

Detecting companions

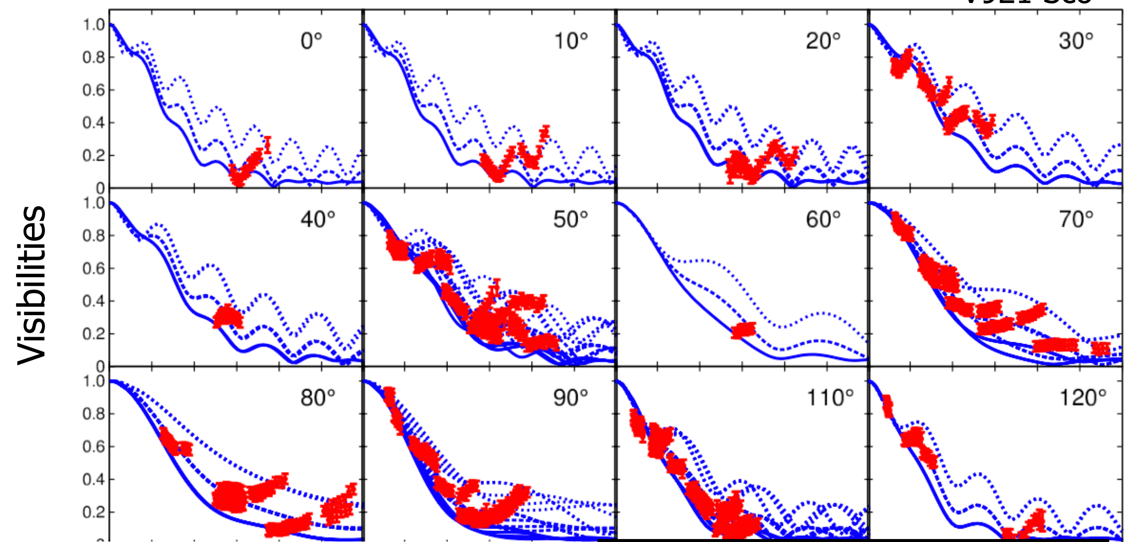
Speckle interferometry

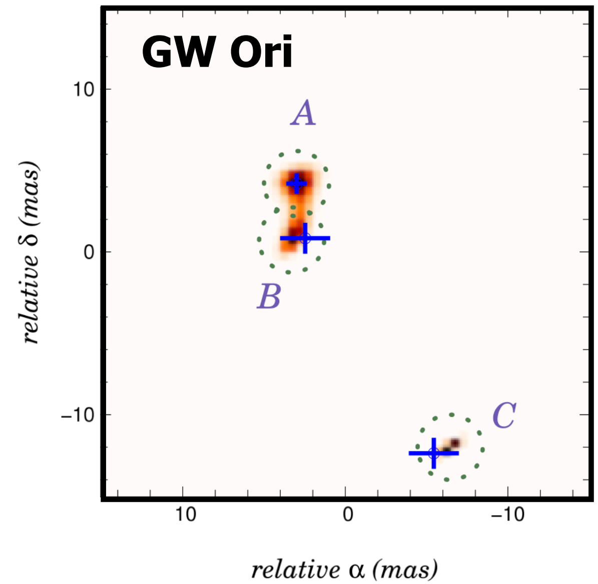


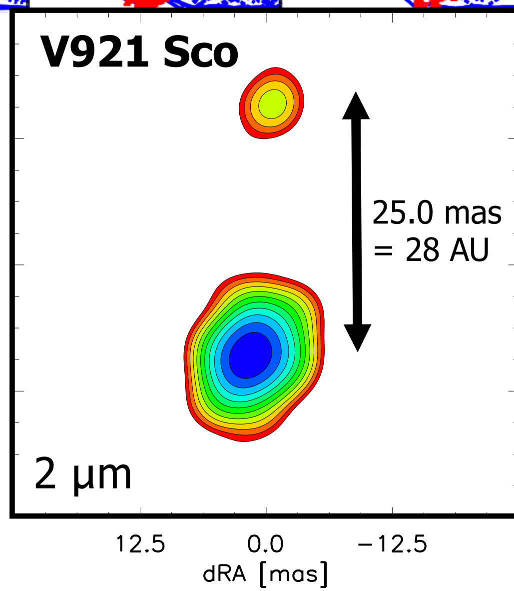
Aperture masking



V921 Sco

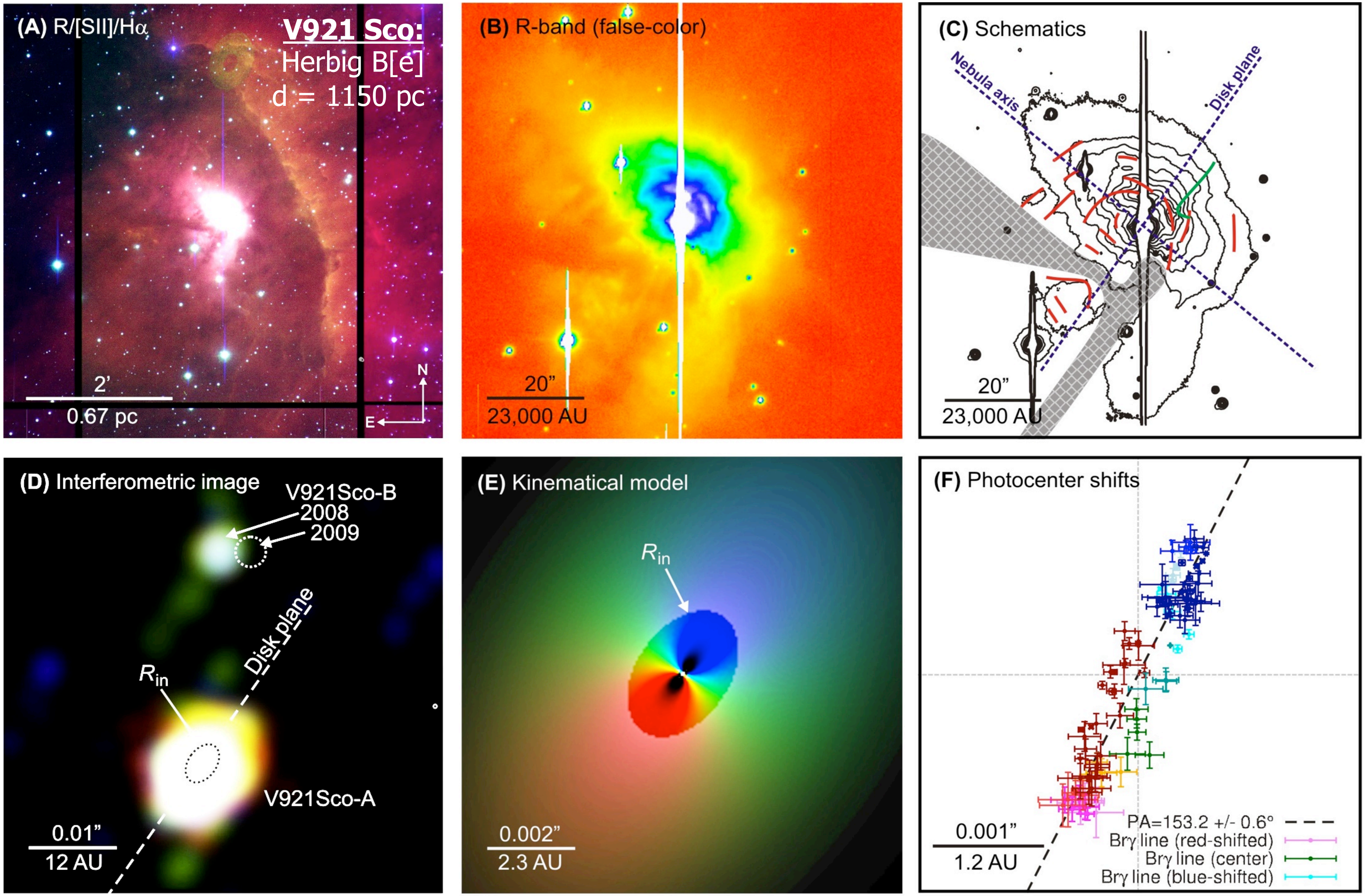






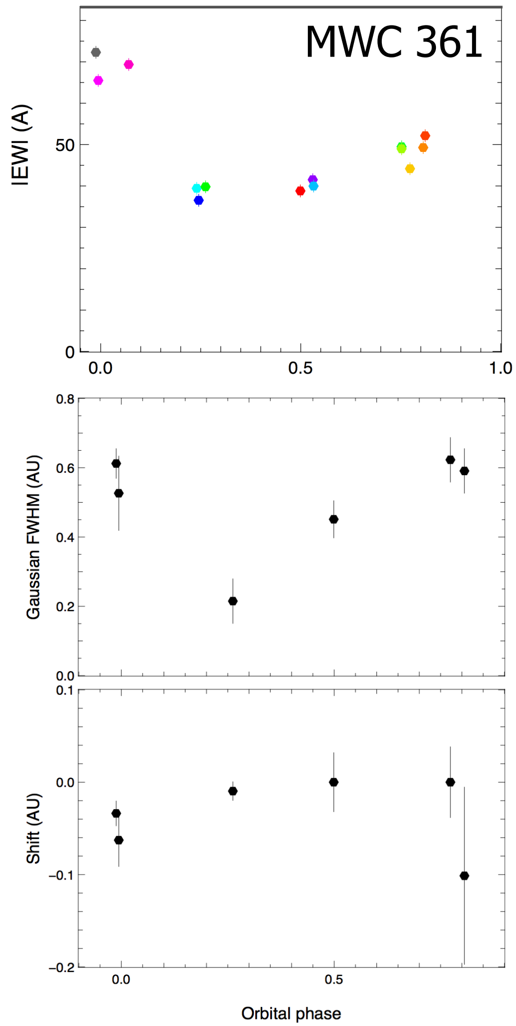
Smith et al. 2005, Biller et al. 2012, Berger et al. 2010, Kraus et al. 2012
also: Ratzka et al. 2009, Wang et al. 2012

Relating newly detected companions with large-scale structures



Kraus et al. 2012

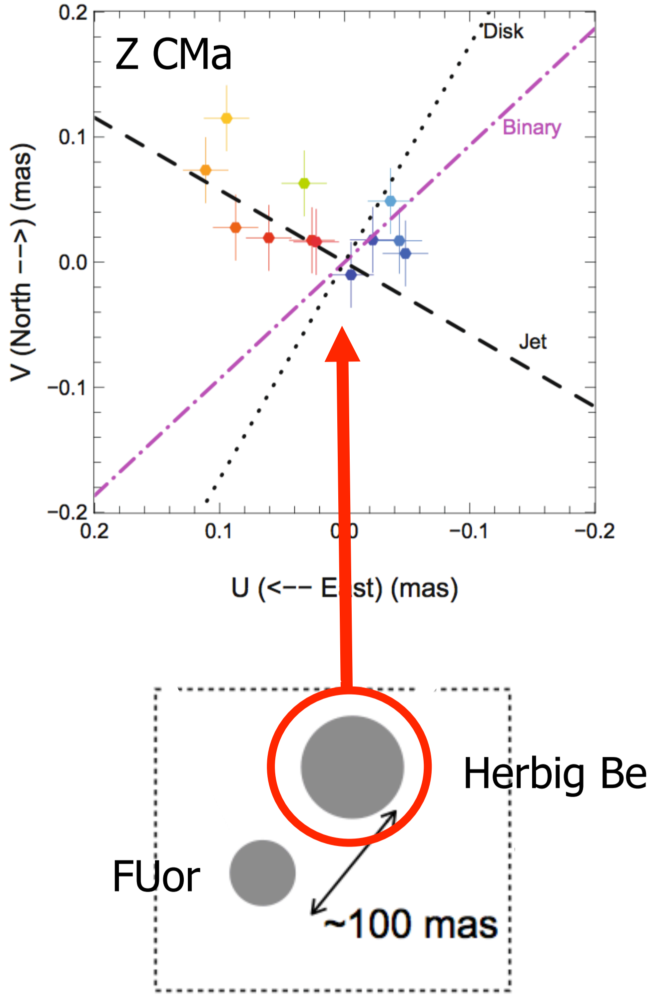
Characterizing disks & outflows in binary systems



Benisty et al. 2013

Increase in Hα EW and emitting radius near periastron passage

➜ Companion might trigger enhanced mass-loss in disk wind or stellar wind



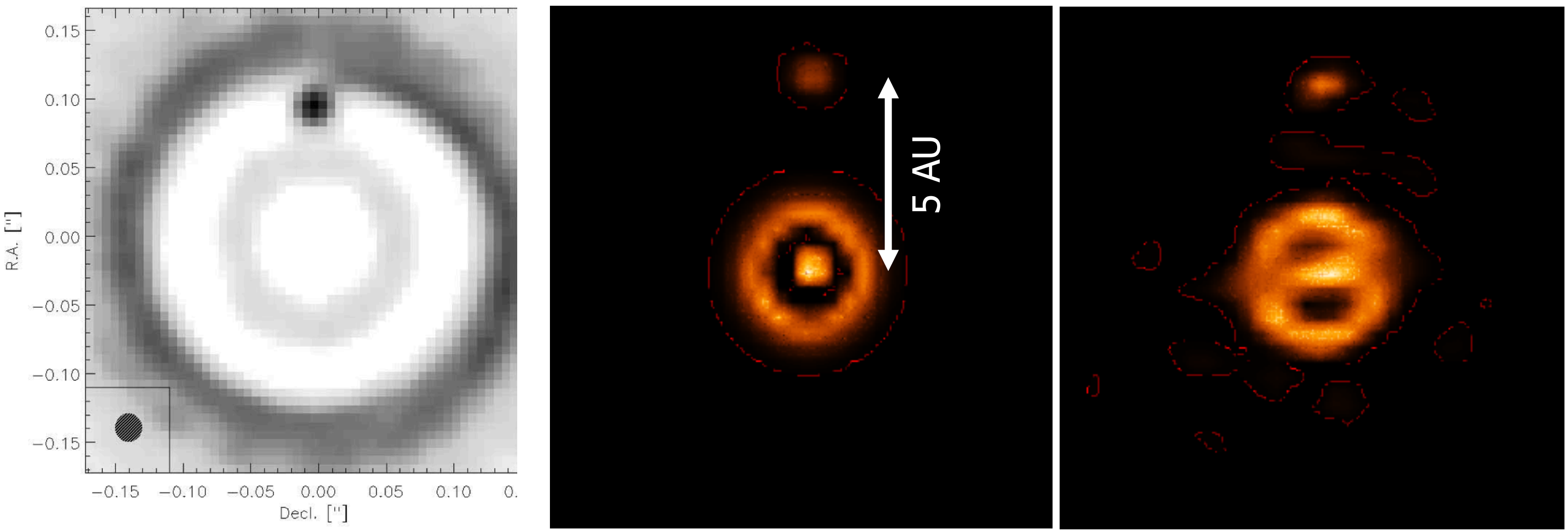
Benisty et al. 2012

also: Garcia et al. 2013, LeBouquin et al. 2014

Future opportunities

Prospects: MIR interferometric imaging

Simulated image (300 µm) | Simulated image (10 µm) | Reconstructed image



d=50 pc

d=140 pc

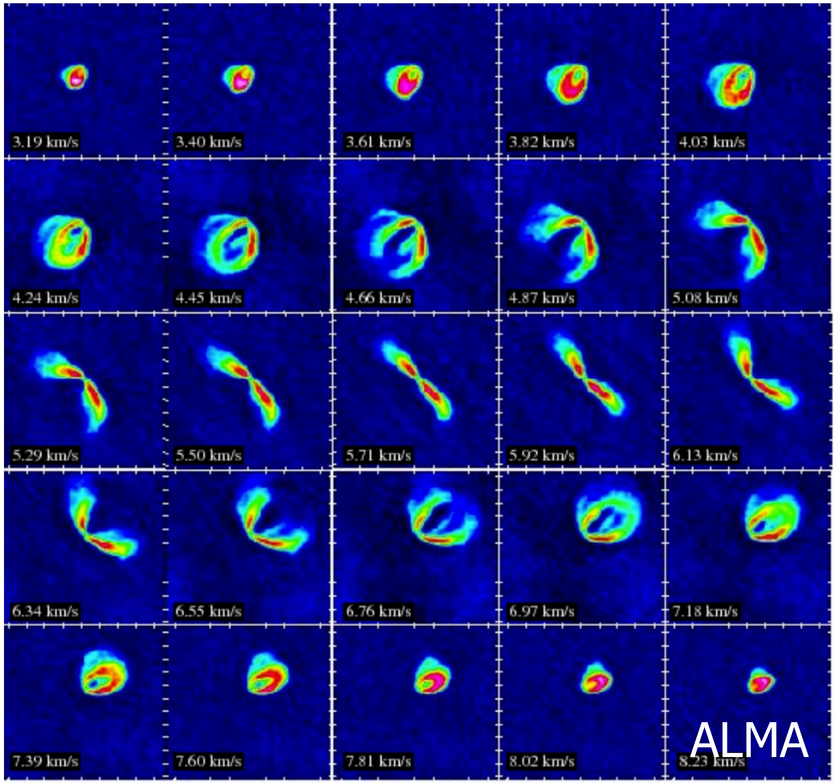
Wolf & D'Angelo 2005

VLTI/MATISSE (4T) will do imaging in 3 spectral bands (L/M/N-band), probing shadowing behind the rim, disk flaring, disk gaps, possibly young accreting planets

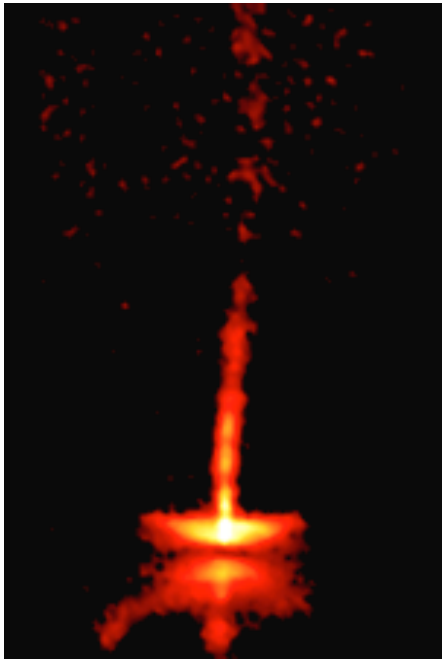
Prospects: Velocity-resolved imaging

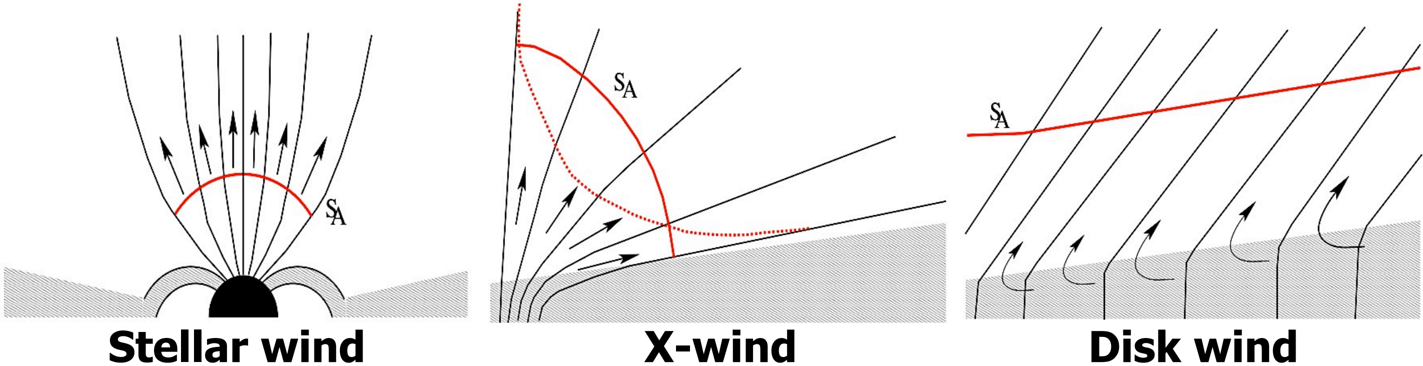
Velocity-resolved imaging in spectral lines can test theories of outflow-launching and magnetospheric accretion

VLTI/GRAVITY (4T): Brγ, (CO)
Future combiner (4T-6T): J-band? V-band?



de Gregorio-Monsalvoet al. 2013





Burrows et al. 2006, Ferreira et al. 1997

Conclusions

NIR+MIR interferometry constraints **dust distribution, composition, and physical conditions** from sub-AU to tens of AU

Disk geometry near the **dust sublimation region** still poorly understood, in particular for Herbig Be stars

Unique constraints on **disk gaps, disk asymmetries, and multiple systems**

Interferometry with high spectral dispersion allows us to study the **gas kinematics** in the inner disk regions, constraining the disk parameters, stellar mass, velocity field (Keplerian, infall, outflow, ...), and gas excitation structure.

Studies are strongly limited by uv-coverage (both for modeling & imaging)
➜ **Huge potential** for upcoming 4T and 6T beam combiners