Spatially resolved observations of inner disc structure

Stefan Kraus

ESO Garching
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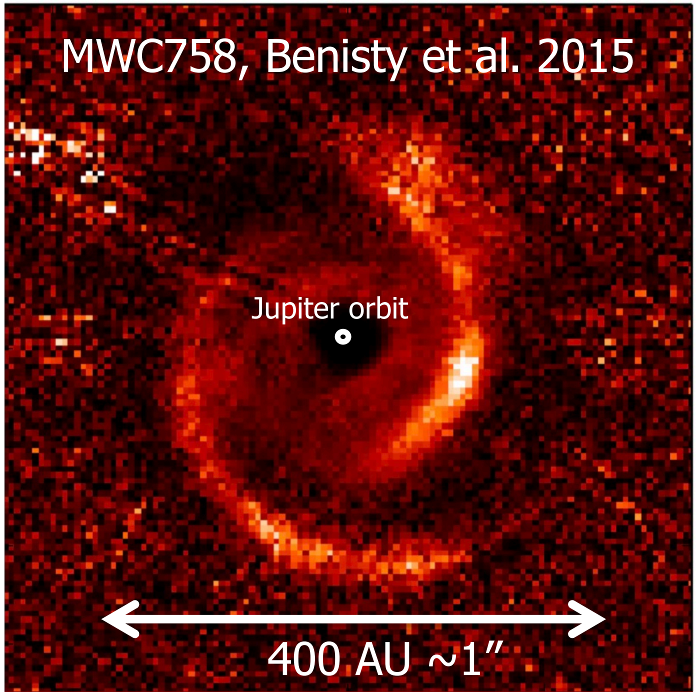
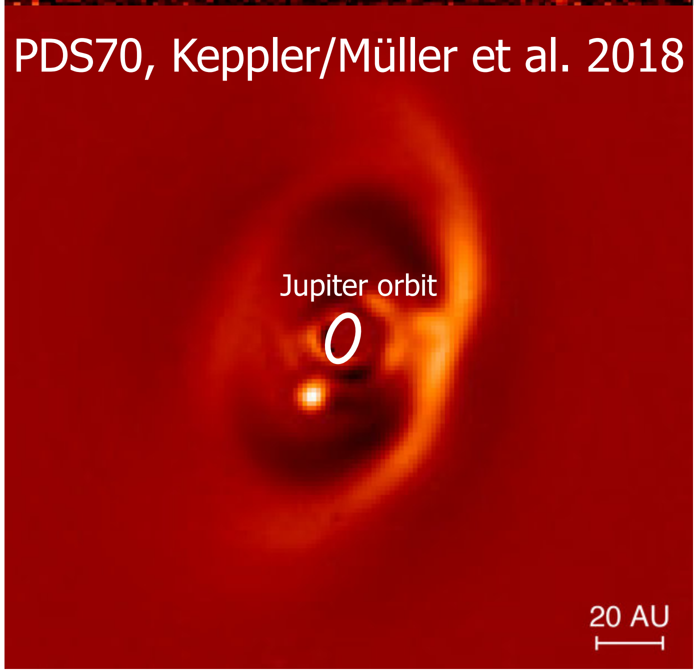
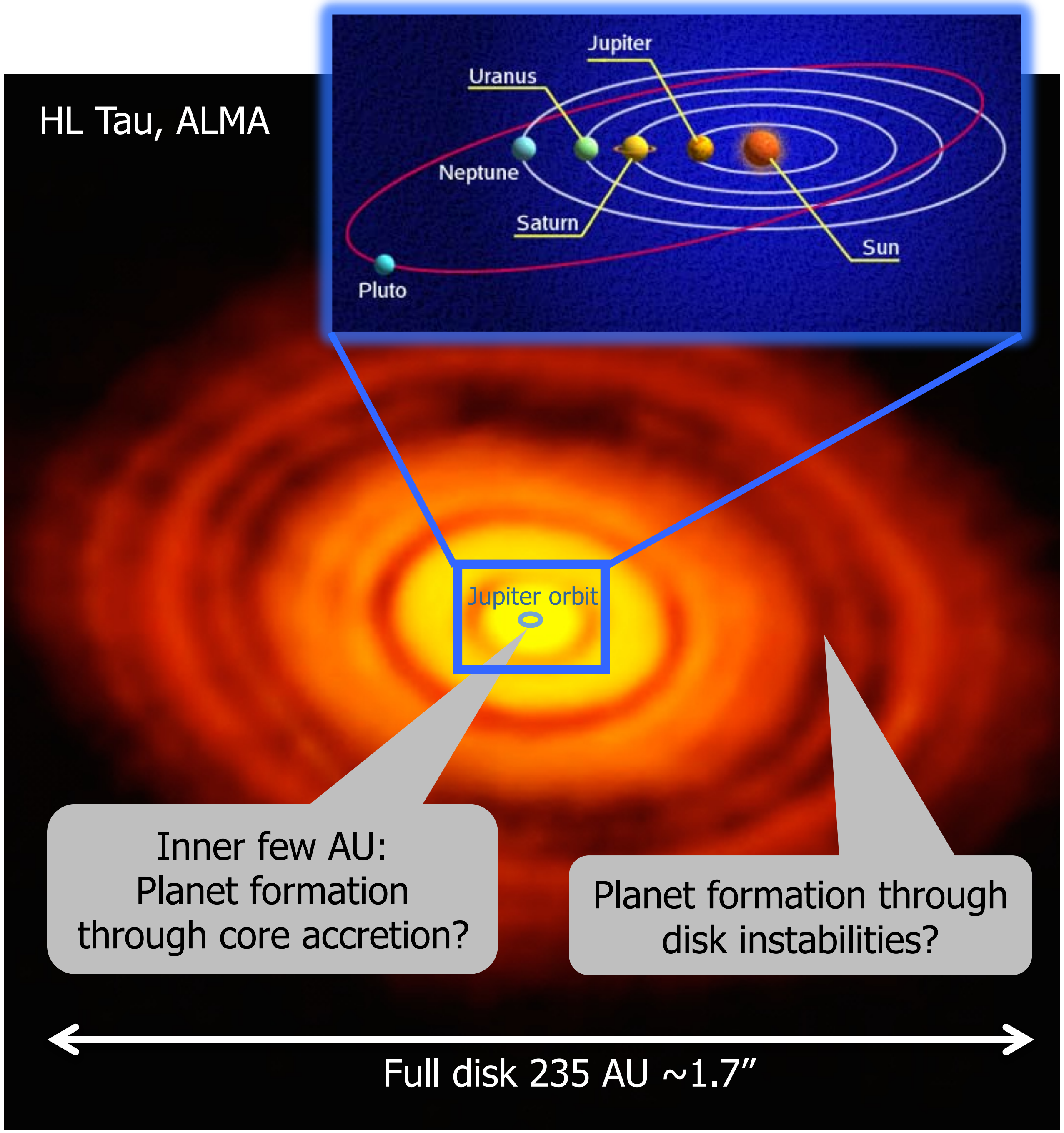
Outline

1. The need for high-angular resolution observations
2. Disk structure at/inside the dust sublimation radius
3. Multi-wavelength studies to constrain
   …global disk parameters
   …dust composition
   …disk gaps
4. Temporal variability
5. Gas kinematics in spectral lines
6. Multiplicity & disk structure in multiple systems
7. Conclusions

Exciting structures in intermediate/outer disk

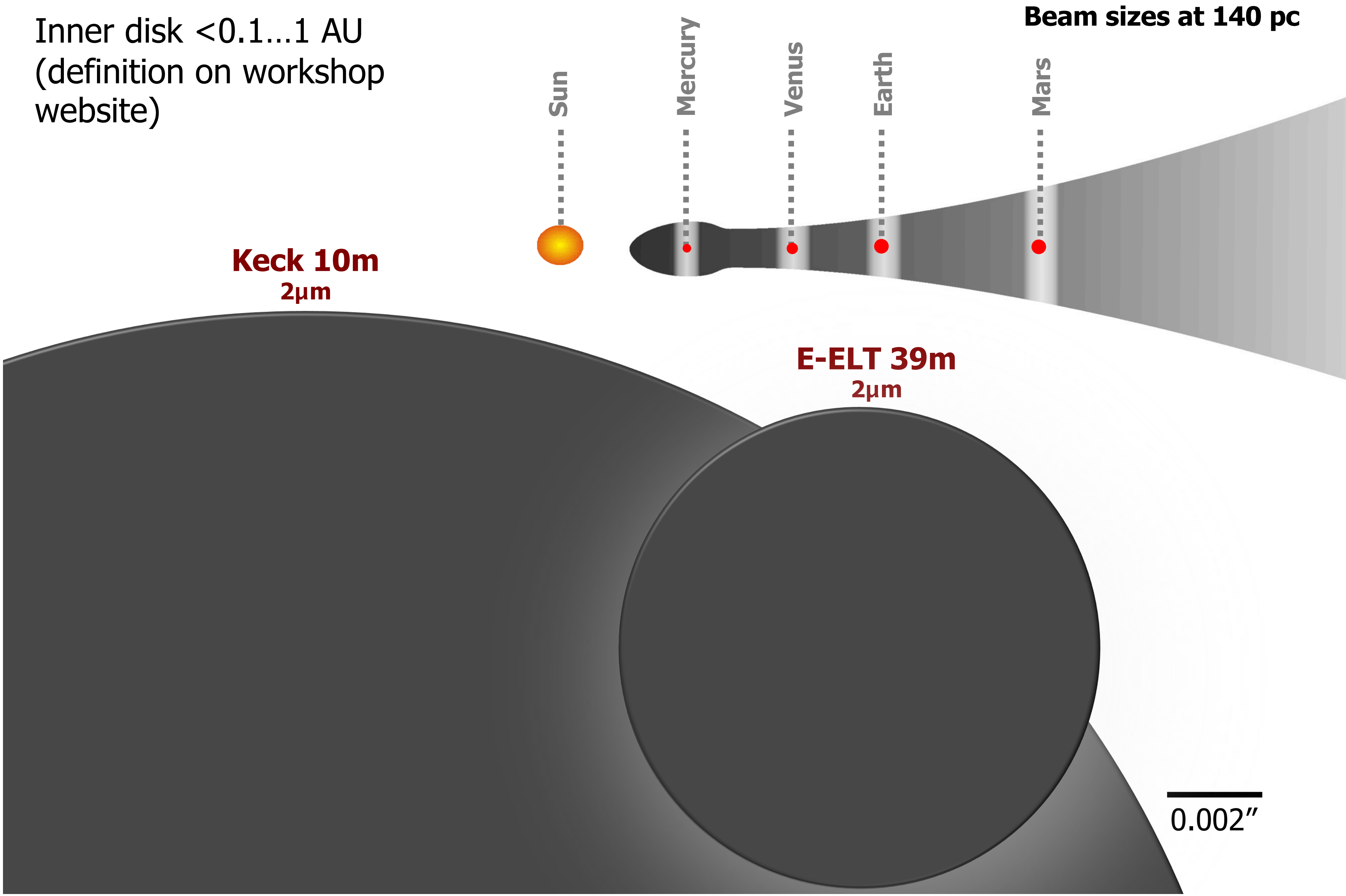




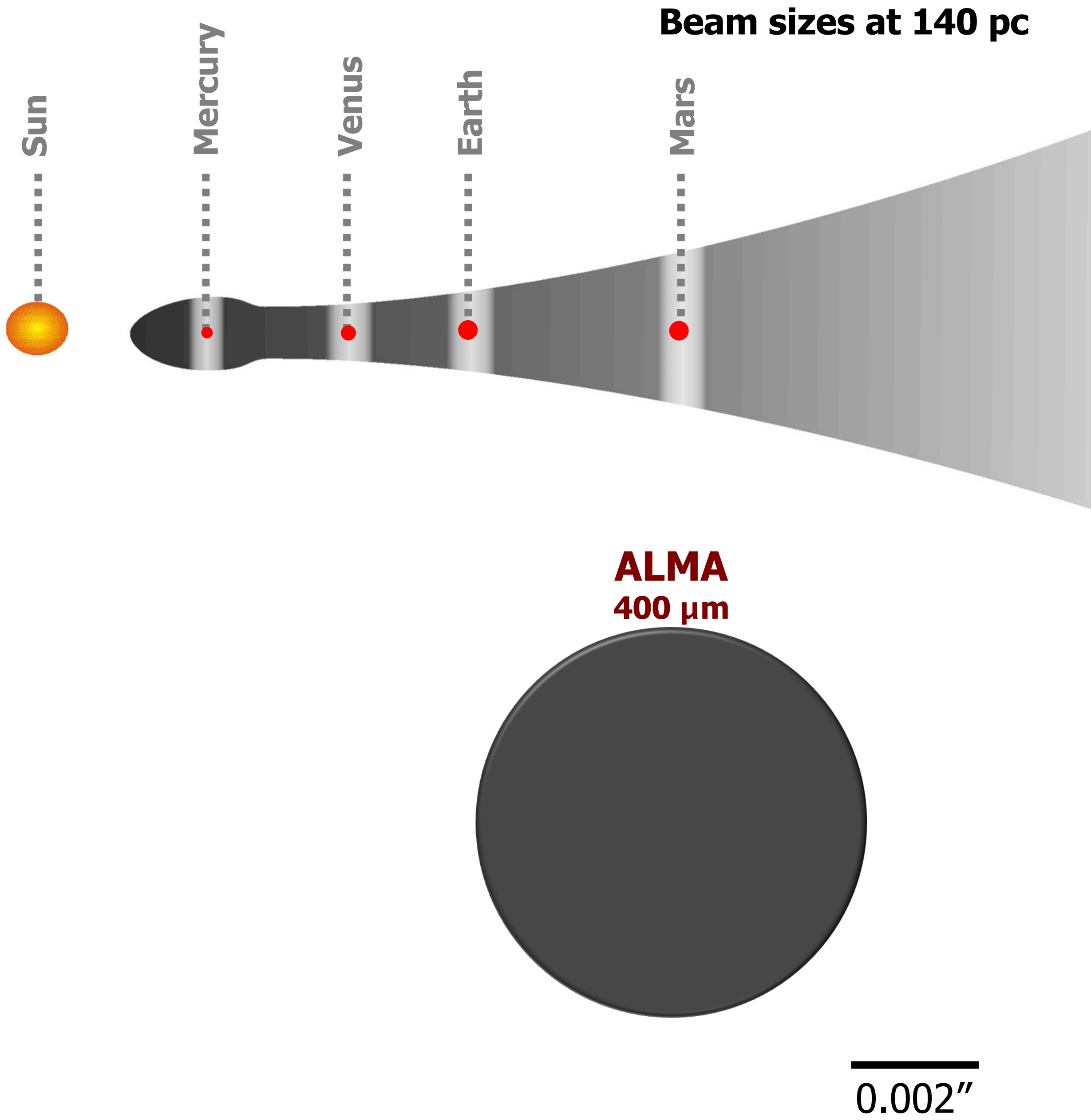


Resolving the “inner disk” environment

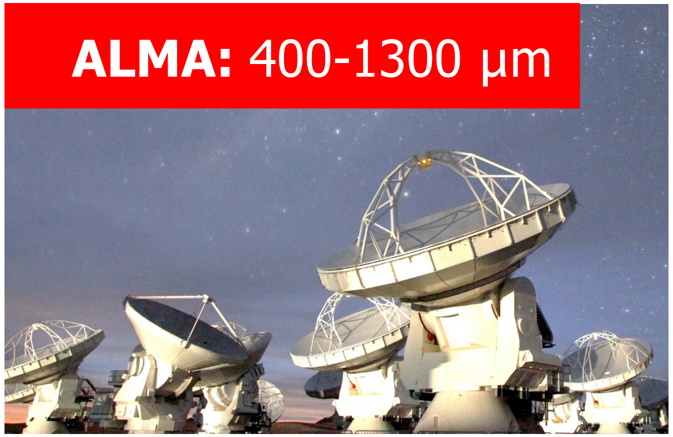
Inner disk <0.1…1 AU (definition on workshop website)



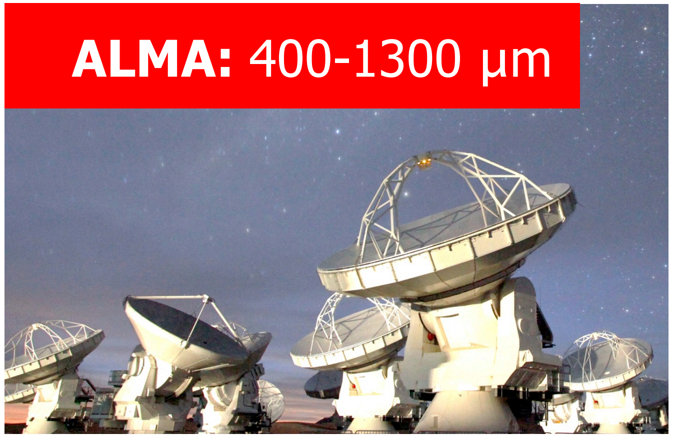
Resolving the "inner disk" environment

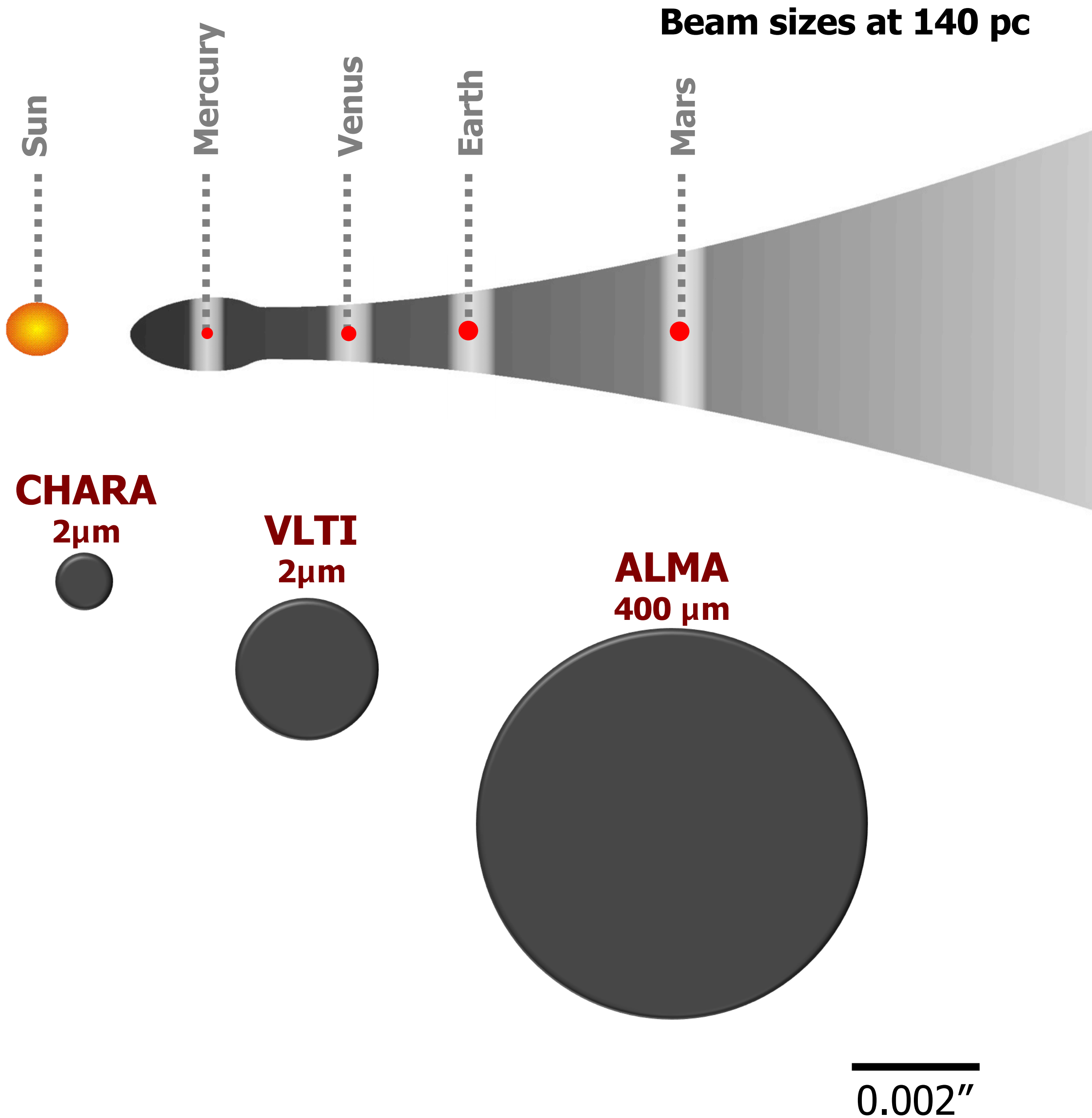


Interferometry breaks the resolution barrier imposed by diffraction (λ/D) and the atmosphere

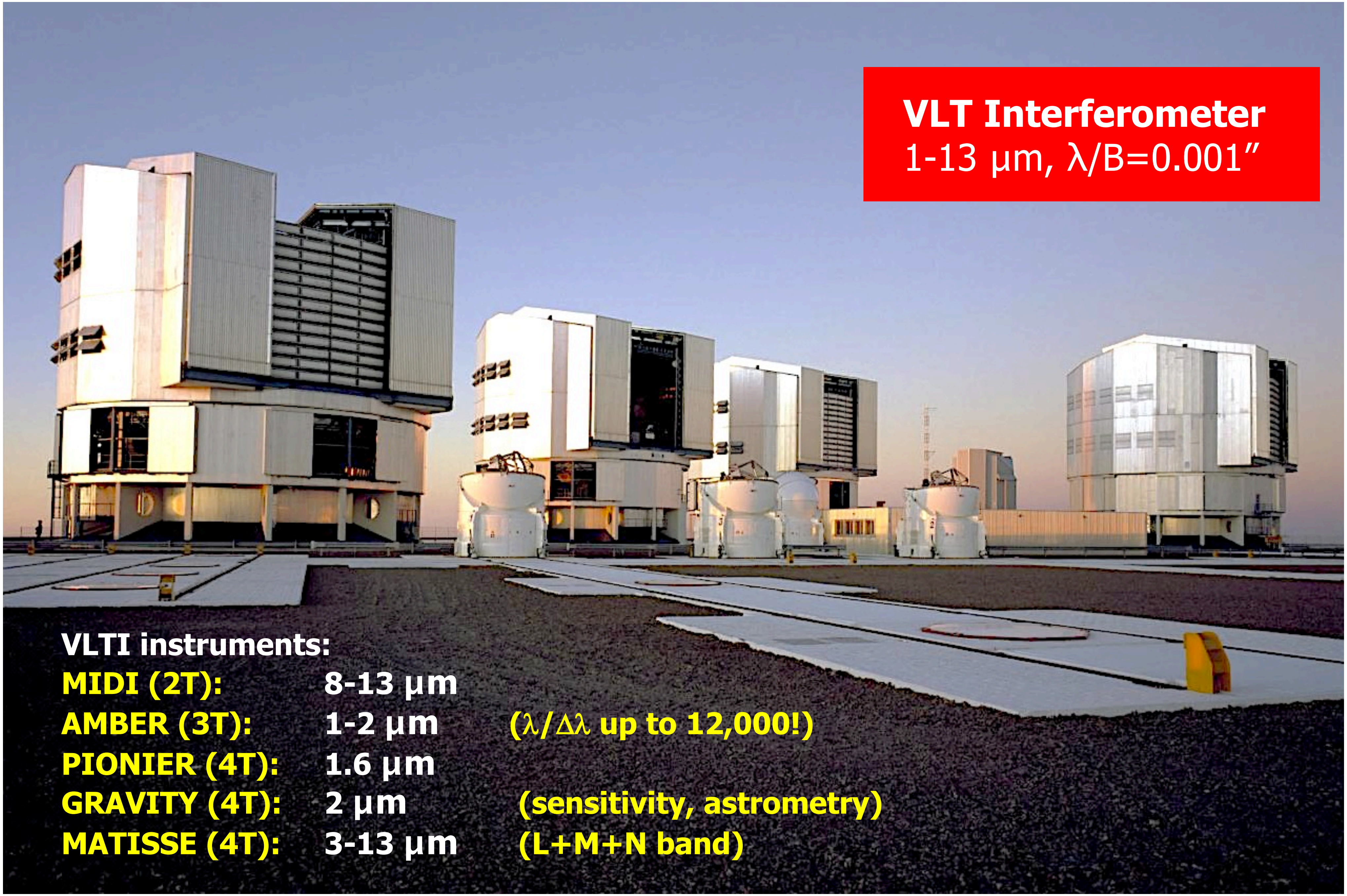


Resolving the "inner disk" environment

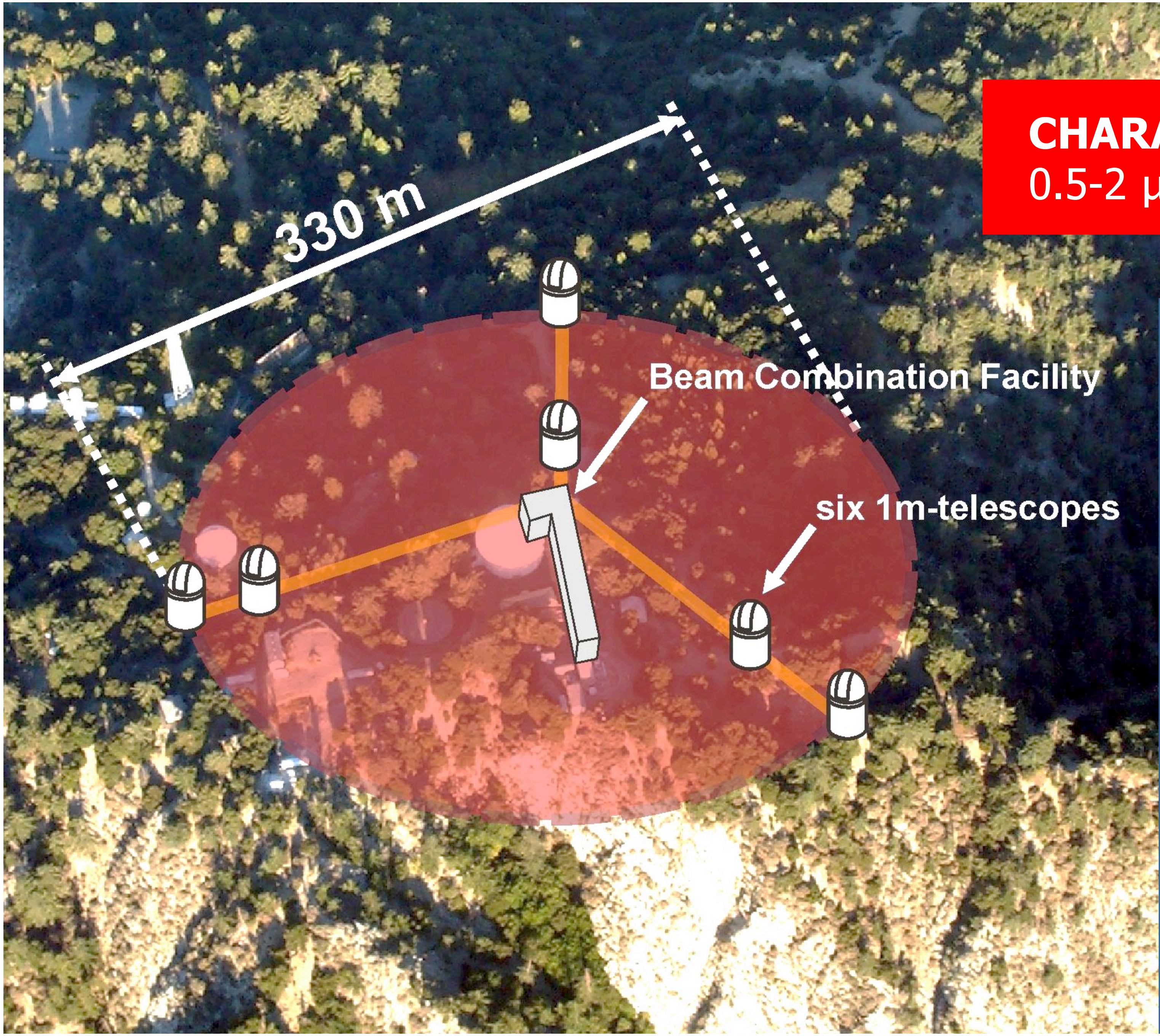




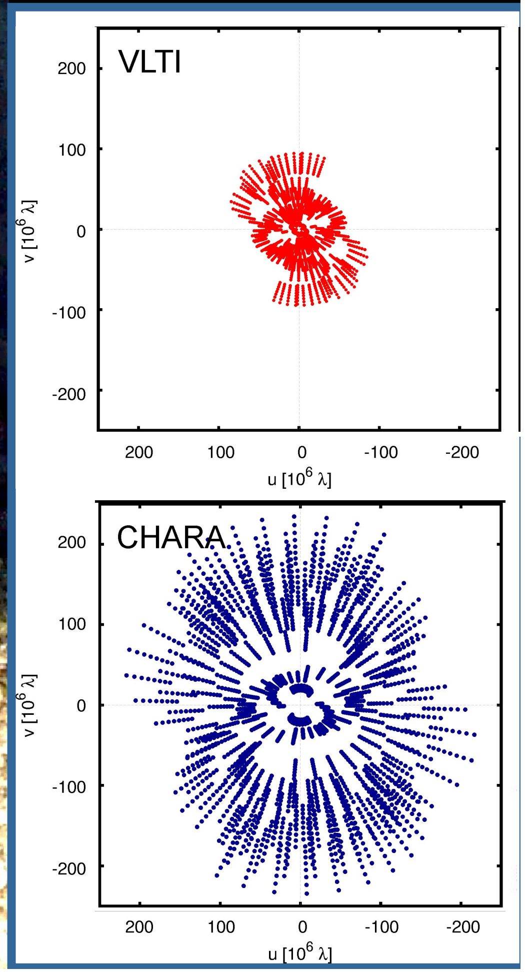
VLTI Interferometry



CHARA interferometry



CHARA array
0.5-2 μm, λ/B=0.0003″

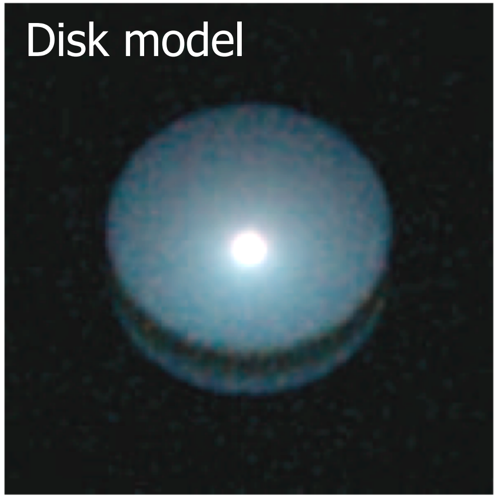


The need for high angular resolution

Spatially resolved observations essential in order to address:

(1) Parameter ambiguities

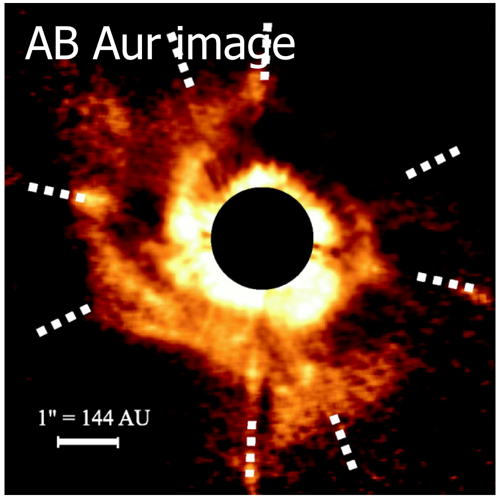
Diff. parameter combinations reproduce data equally well



Typical models require
18+ parameters
+ dust composition
assumptions
Whitney et al. 2003

(2) Complexity!

Models depend on simplifying assumptions



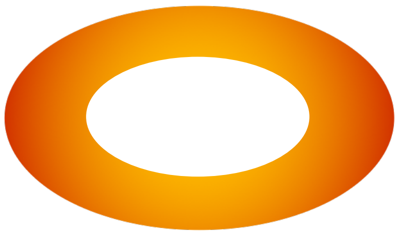
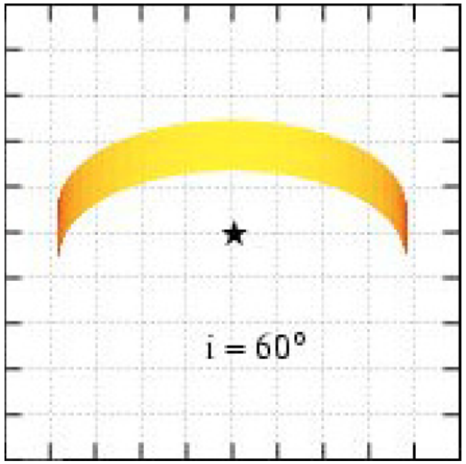
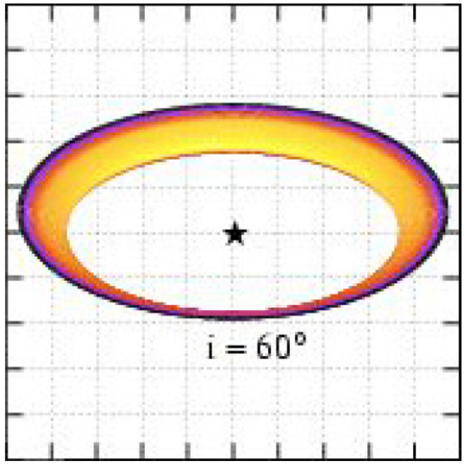
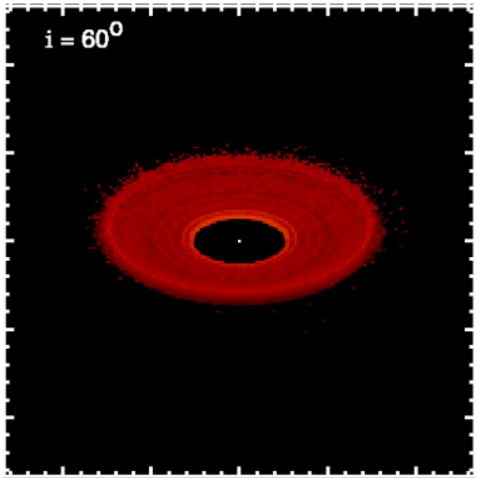
Stellar multiplicity,
planet formation,
gravitational instabilities, …
Piétu et al. 2005

Protoplanetary disk structure at/inside dust sublimation region

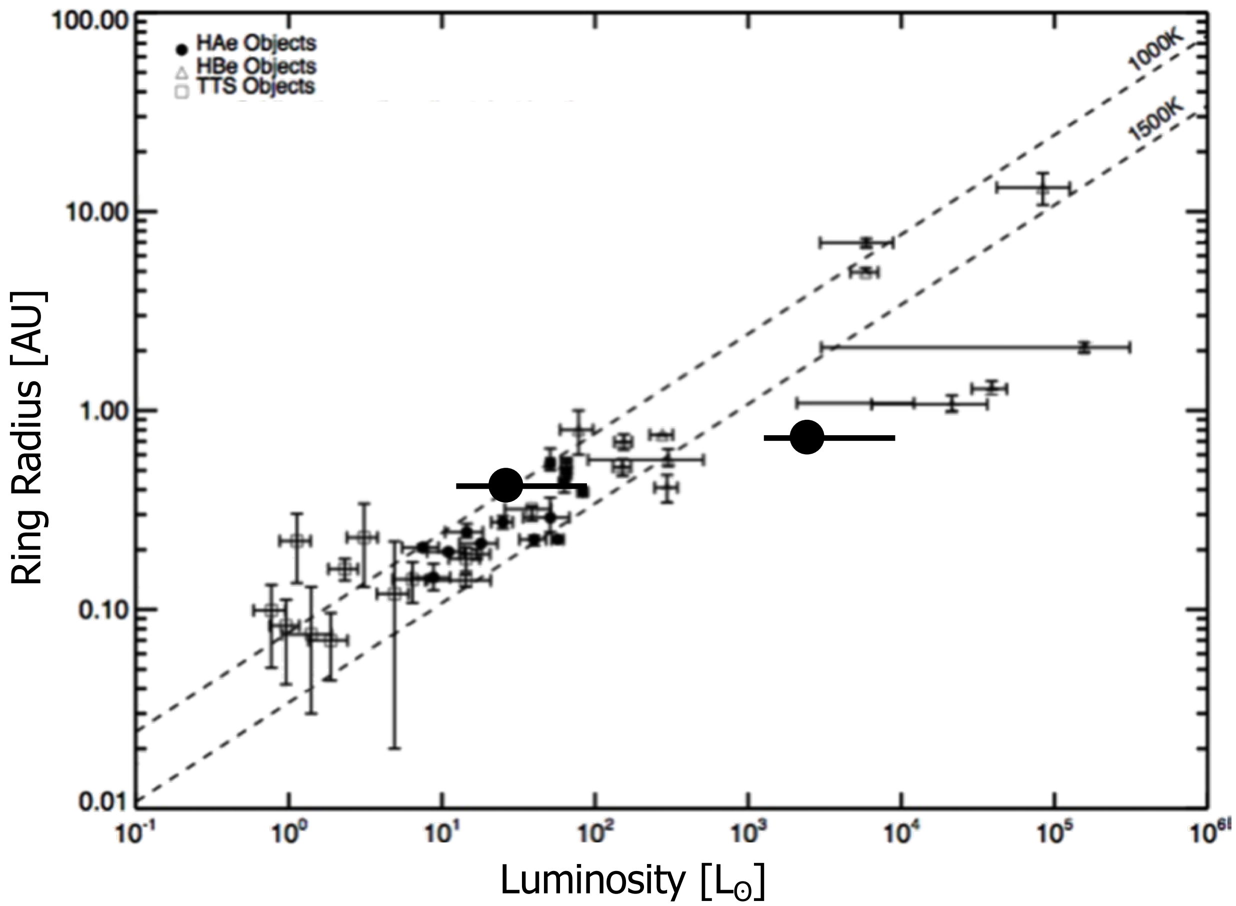
Interferometric observables

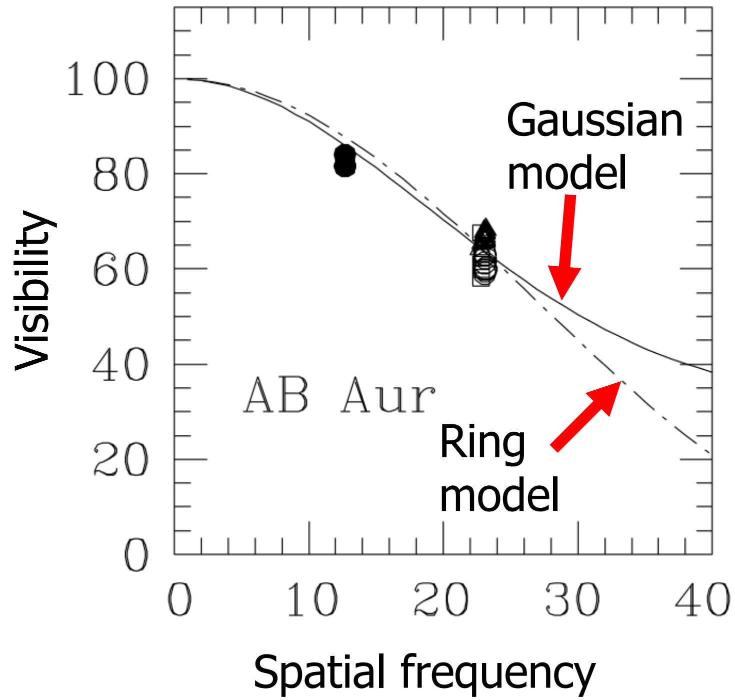
Interferometric observables:

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

GEOM. FLAT DISK	VERTICAL RIM	CURVED RIM	VERY CURVED RIM
			
e.g. temperature gradient models	Natta et al. 2001 Dullemond et al. 2001	Isella & Natta 2005 Flock et al. 2017, 2018	Tannirkulam et al. 2007 Kama et al. 2009
No asymmetries (CP $\equiv$ ZERO!)	Strong asymmetries (strong CP signal)	→	Weak asymmetries (weak CP signal)

Size-luminosity relation

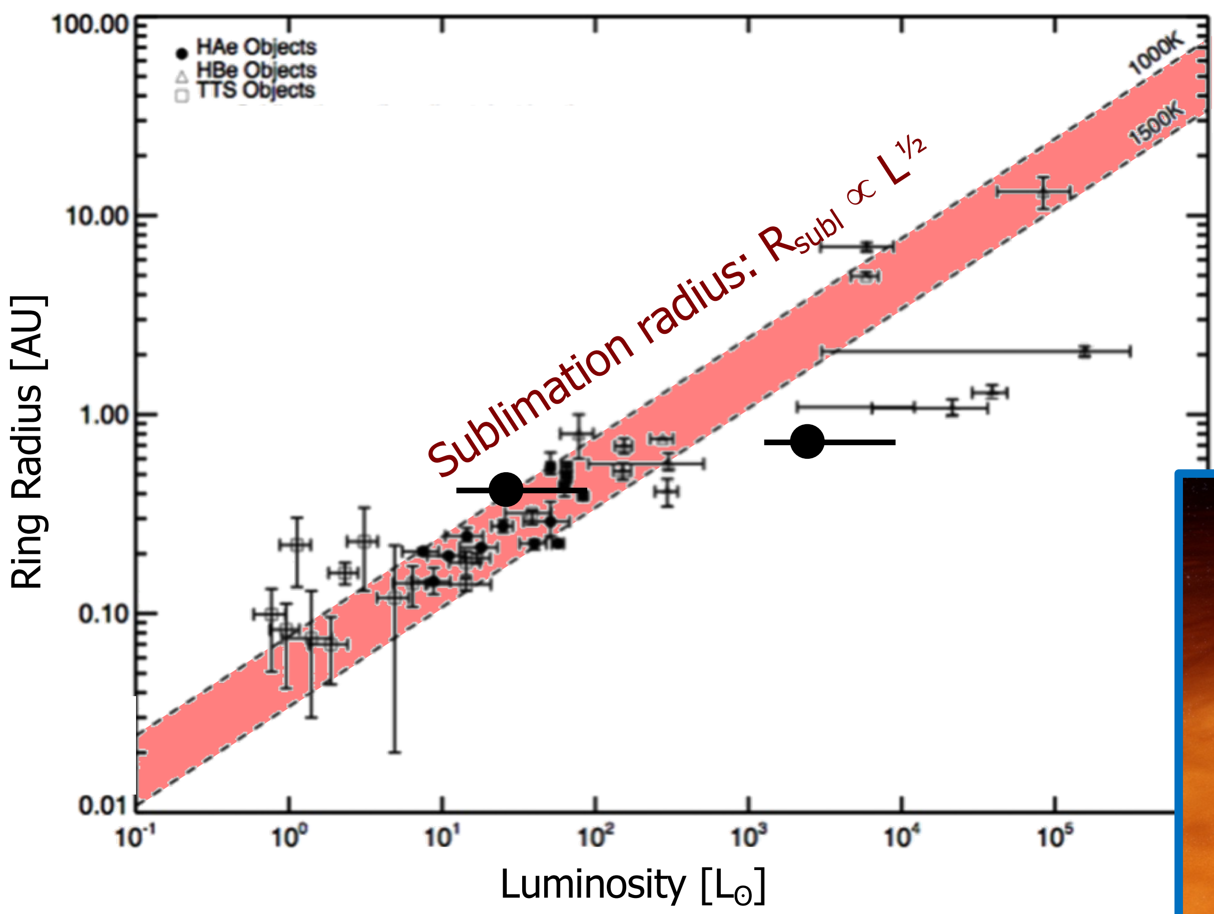




➜ Pionieering studies in early 2000‘s did not constrain the emission geometry, **but assumed a geometry and investigated how the size scaled with the stellar luminosity**

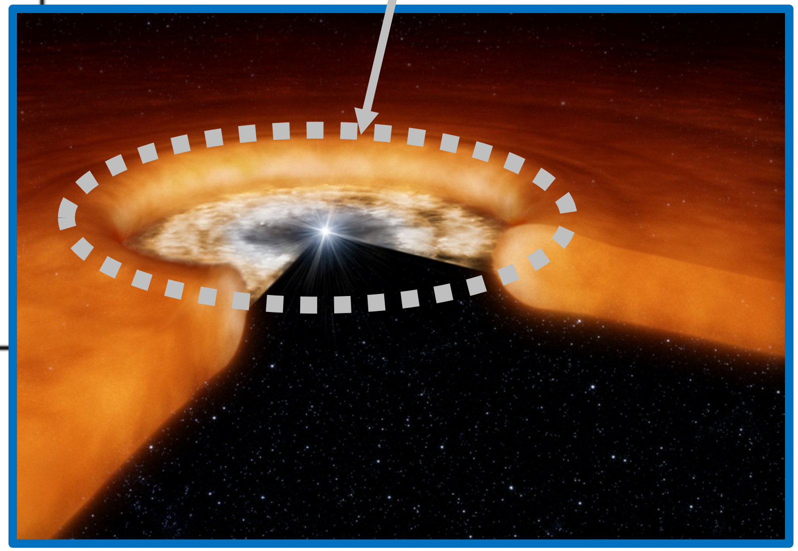
Millan-Gabet 2001, 2007 PPV; Monnier et al. 2002, 2005
also: Akeson et al. 2000; Eisner et al. 2003, 2004

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

Modeling the dust sublimation rim

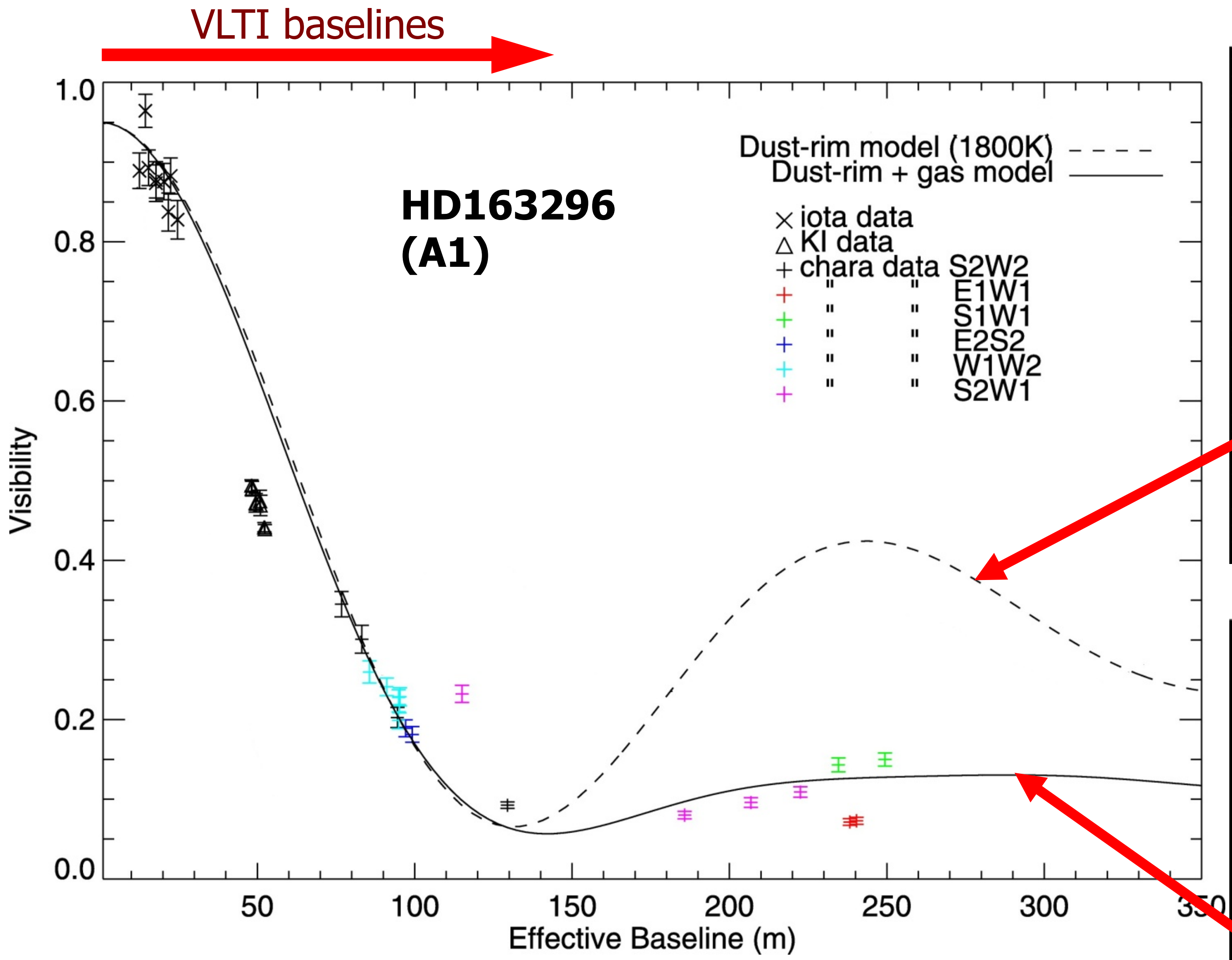
Conclusions from modelling PIONIER LP data on 27 Herbig stars (Lazareff et al. 2017):

- Ring shaped geometries preferred, but very wide (40%)
- Fraction of reprocessed light suggests z/h=0.2 at sublimation rim
- Dust temperature 1800K
- For few objects, azimuthal modulation (preferentially along minor axis) improves the fit

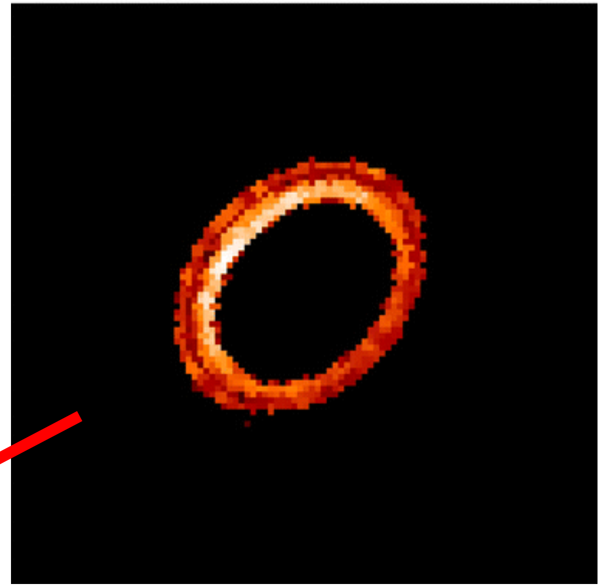
➜ Consistent with emission from curved dust sublimation rim

images in Kraus et al. 2010, Renard et al. 2010, Benisty et al. 2011

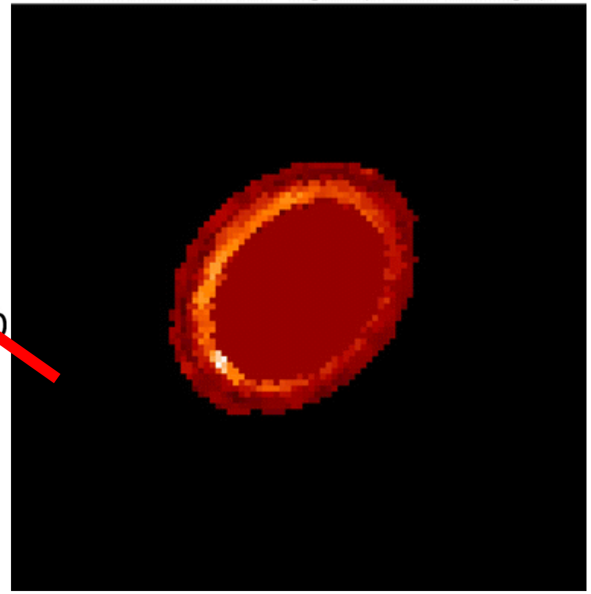
Need of long baselines



Standard (1800K) inner rim (K-band image)



Standard inner rim + gas (K-band image)

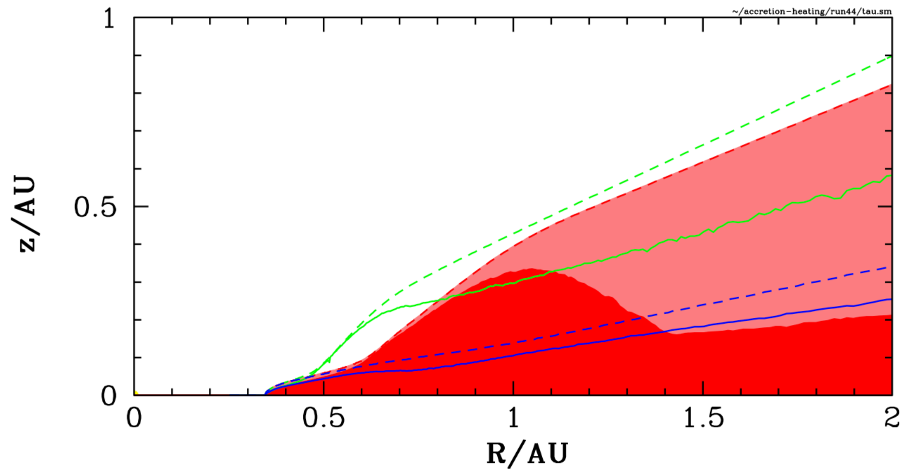


➜ Probing the detailed rim geometry and to characterize emission from inside the rim requires long CHARA baselines

Tannirkulam et al. 2008

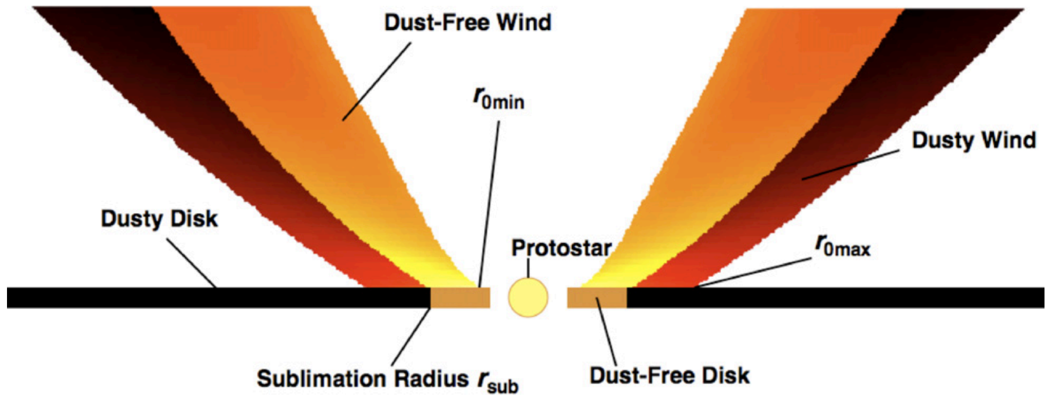
Beyond the puffed-up rim paradigm

Magnetically supported disk atmosphere



Turner et al. 2014

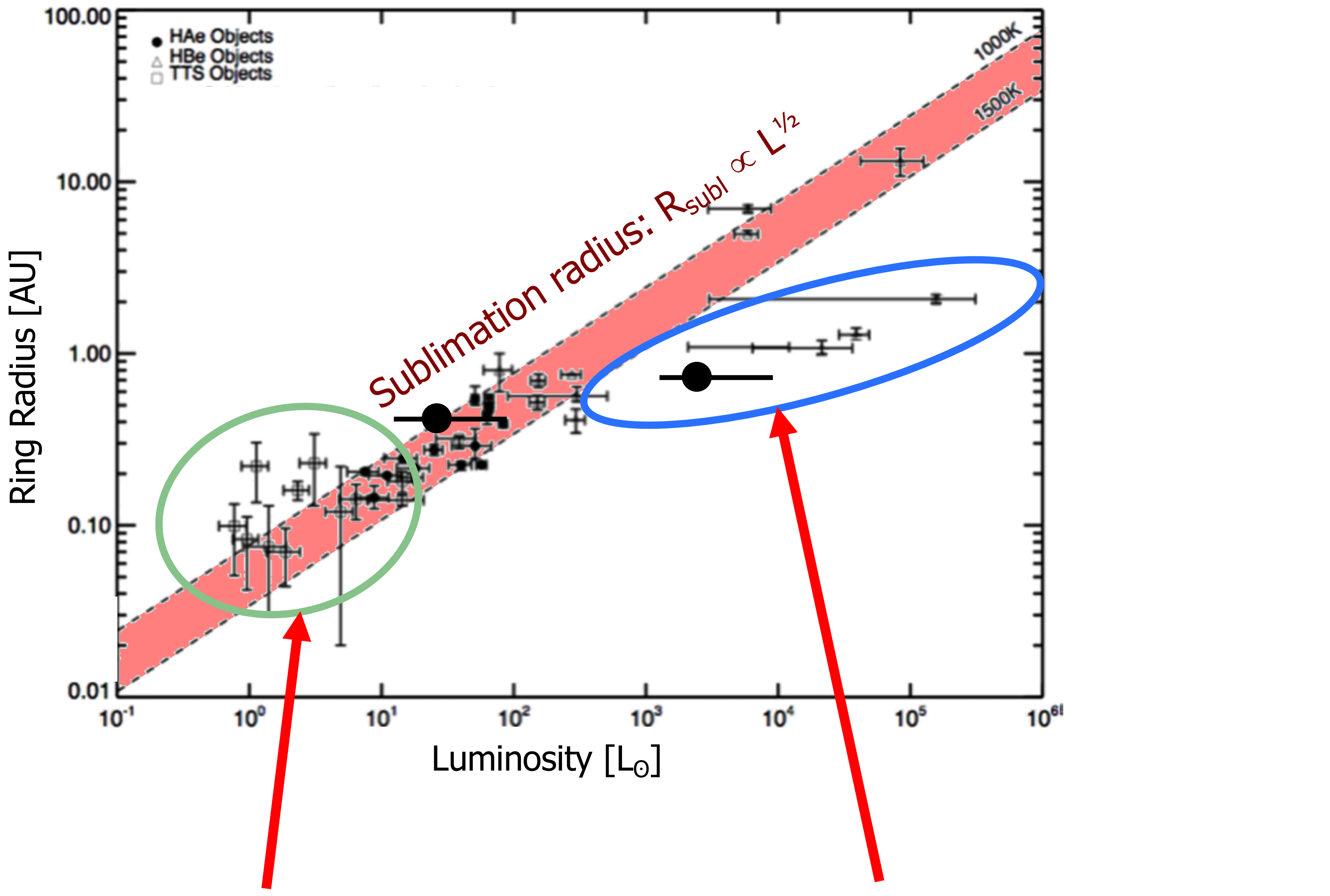
Dusty disk winds



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**

Size-luminosity relation



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

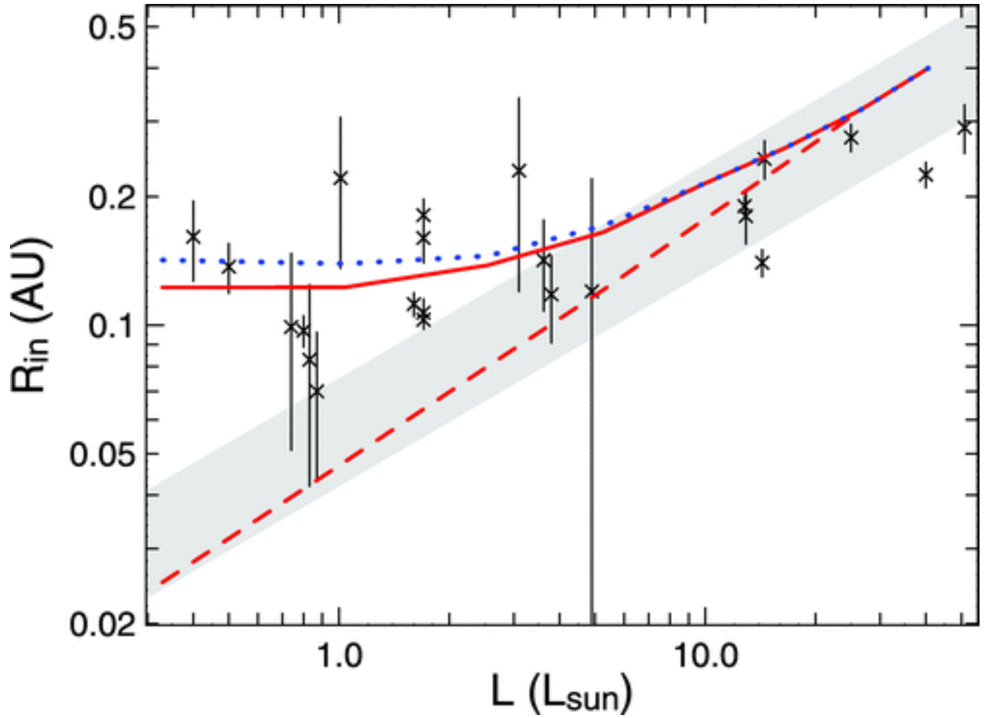
Herbig Be stars often appear **systematically smaller**

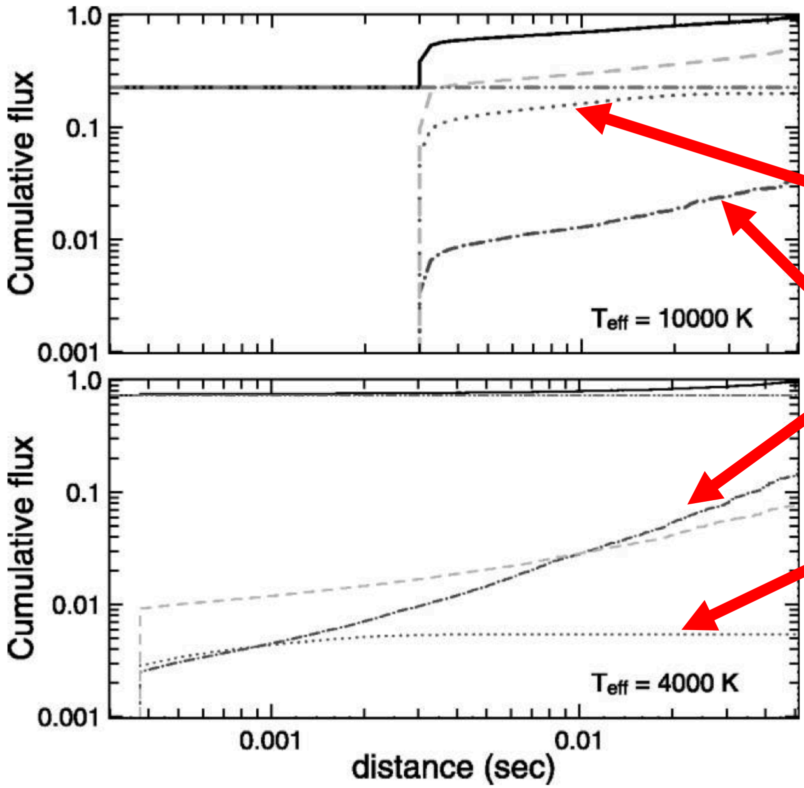
Millan-Gabet 2001, PPV; Monnier et al. 2002, 2005

“Oversized” T Tauri stars

NIR emitting zone is smaller, due to smaller R_{sub} and cooler disk

➜ Scattered light contributions are non-negligible for cool stars





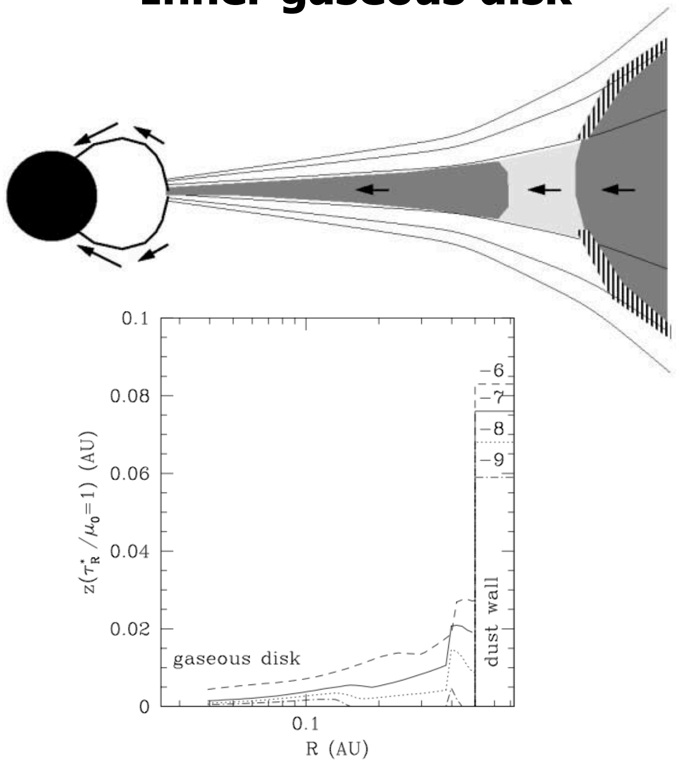
Scattered light

Thermal dust emission

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

"Undersized" Herbig Be stars

Inner gaseous disk

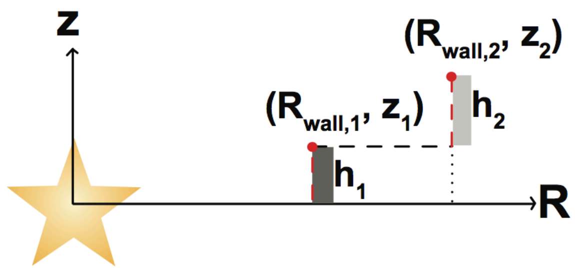


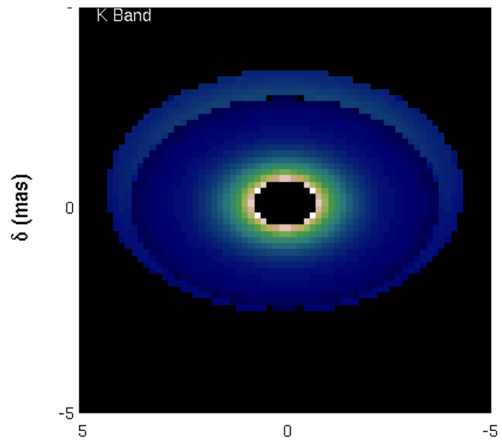
Idea: Gas emits free-free emission and/or shield dust rim, allowing dust to exist closer in

Challenge: Expected molecular line emission not observed (Benisty et al. 2009)

(Muzerolle et al. 2004, Monnier et al. 2005, Kraus et al. 2009)

Highly refractory dust grains





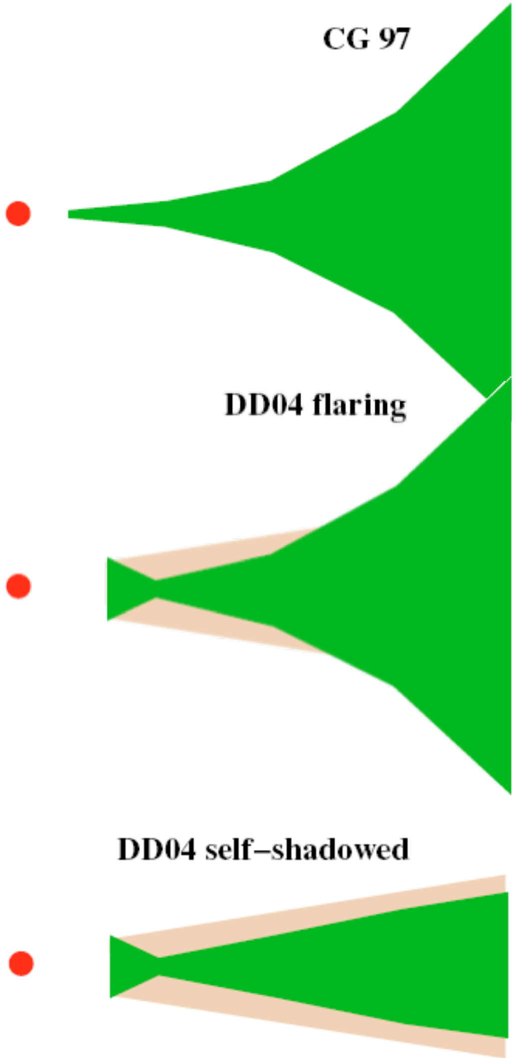
Idea: Highly refractory dust species (Graphite, Iron, …) can exist inwards of Silicate rim, resulting in complex, multi-layered rim structure

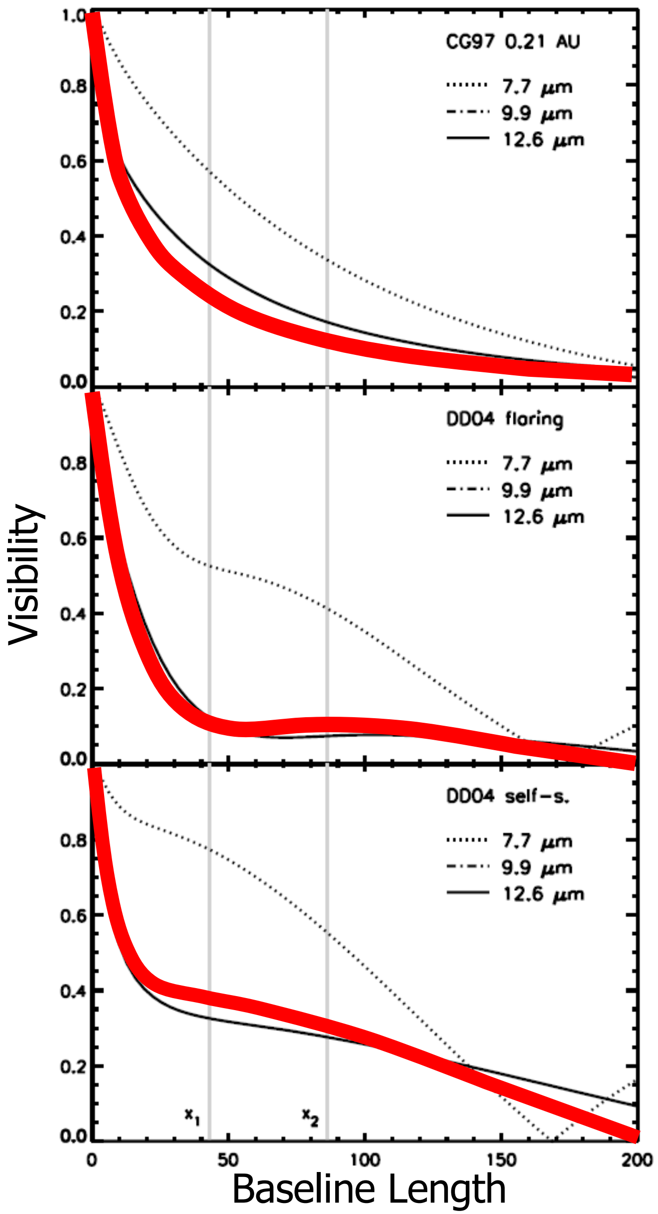
Challenge: Requires T_{subl}=2100…2300 K

(Benisty et al. 2009, Kama et al. 2009, McClure et al. 2013)

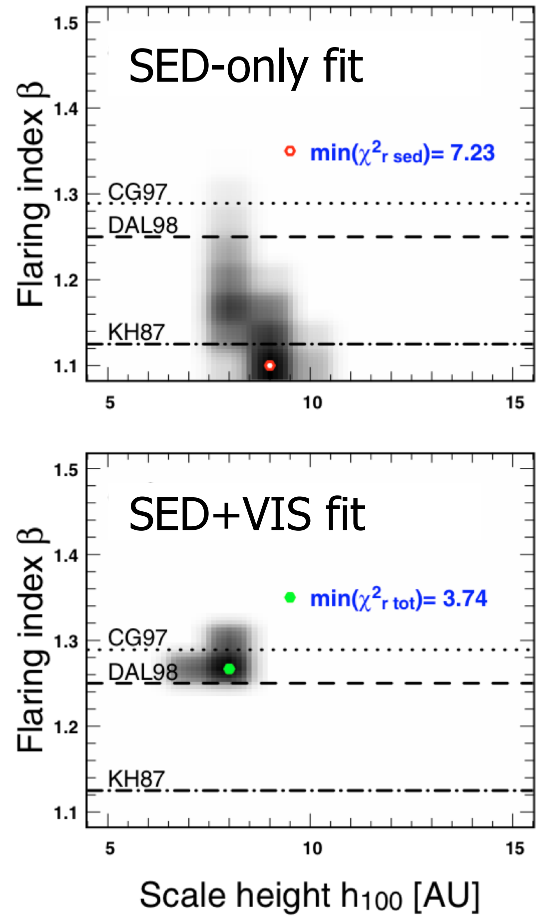
Multi-wavelength studies:
Disk gaps and dust composition

Constraints on disk flaring





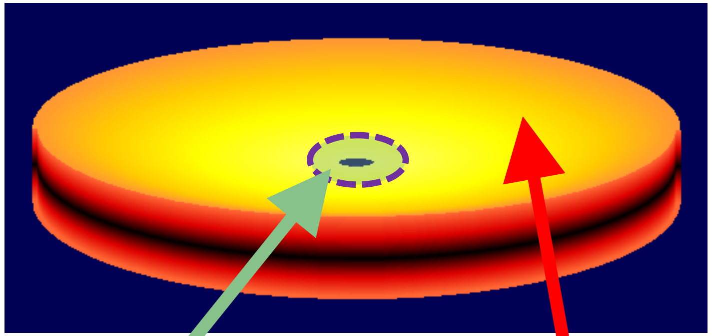
AB Aurigae VLTI/MIDI:



➜ MIR spectro-interferometry probes disk flaring properties

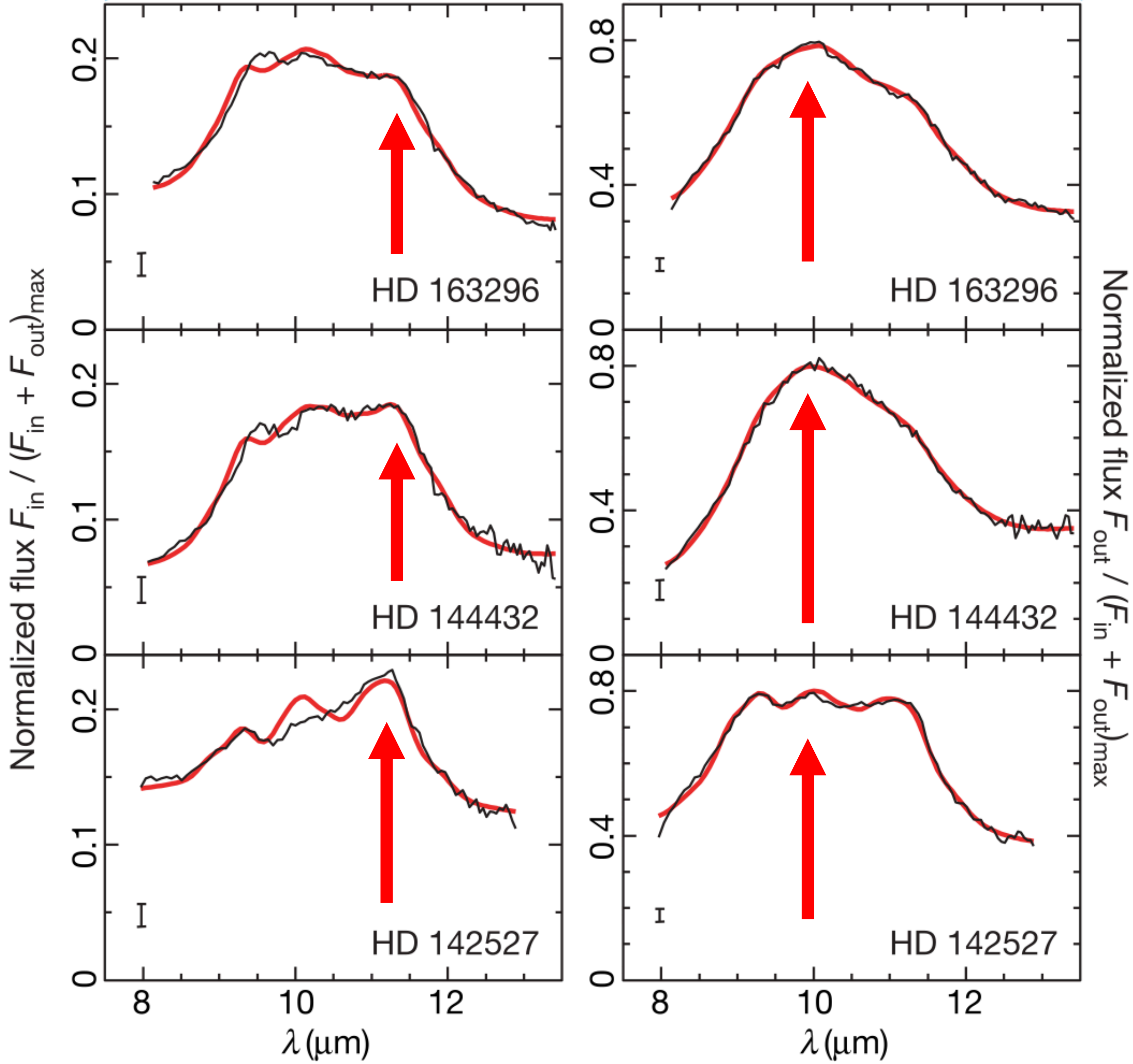
van Boekel et al. 2005, di Folco et al. 2009
also: Preibisch et al. 2005, Schegerer et al. 2009; Ragland et al. 2012

Dust mineralogy



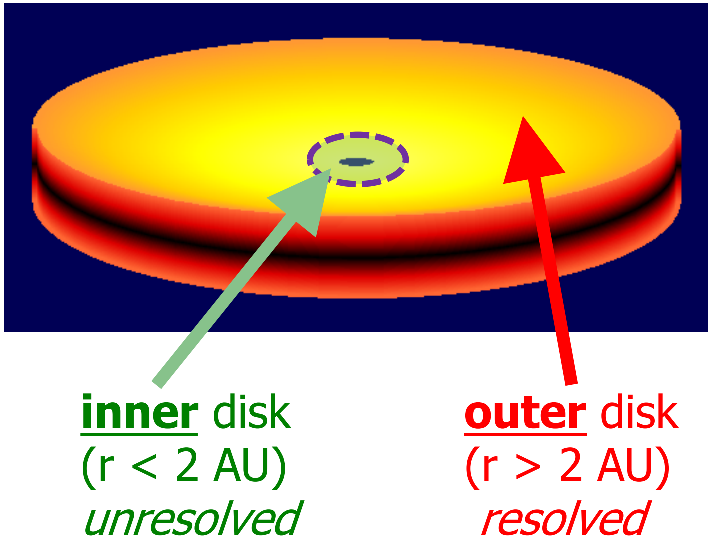
Mid-Infrared interferometry allows to separate the flux contributions from different spatial scales.

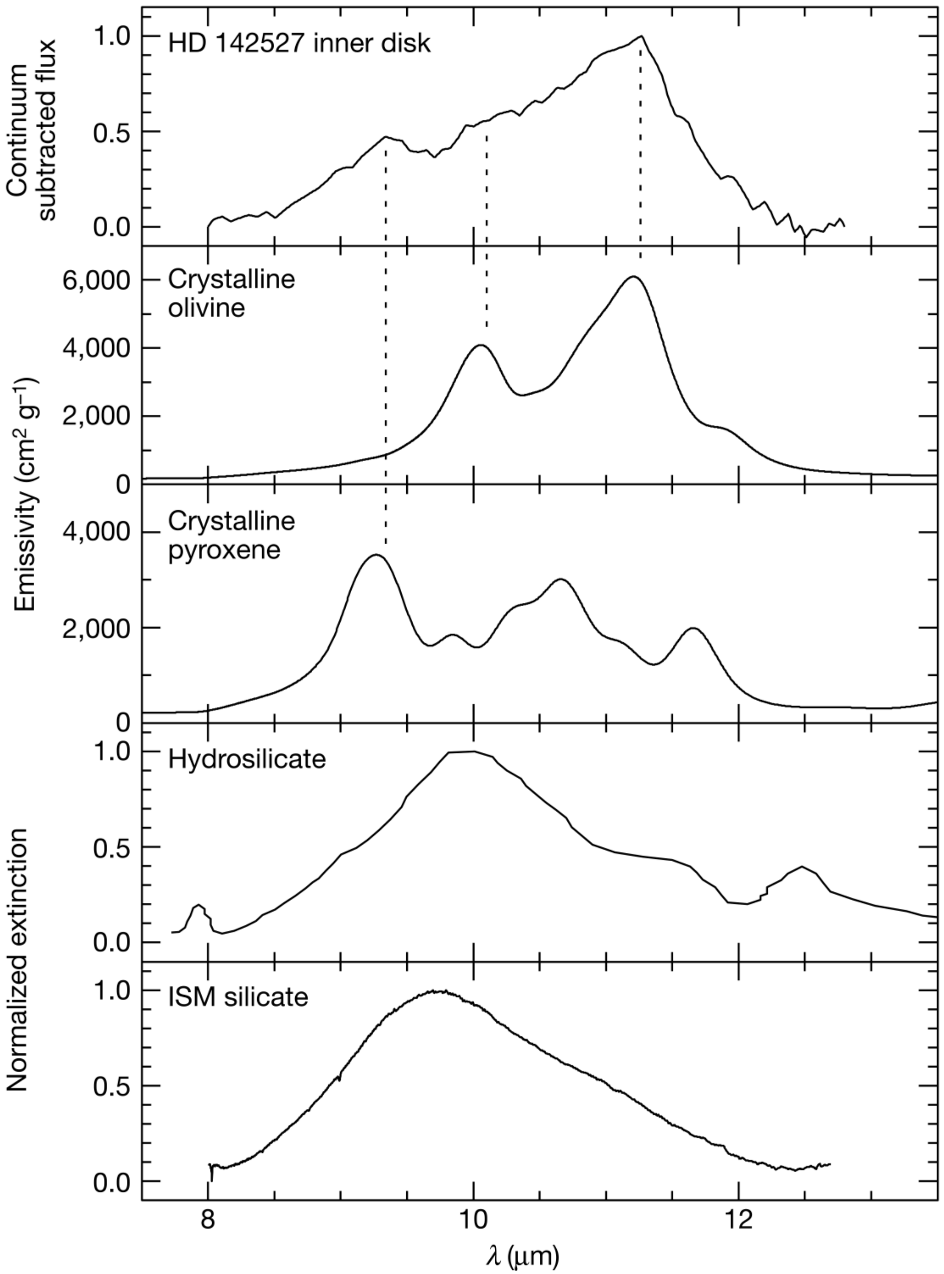
➜ Spectra from inner and outer disk regions differ significantly!



van Boekel et al. 2004, also: Varga et al. 2018

Dust mineralogy



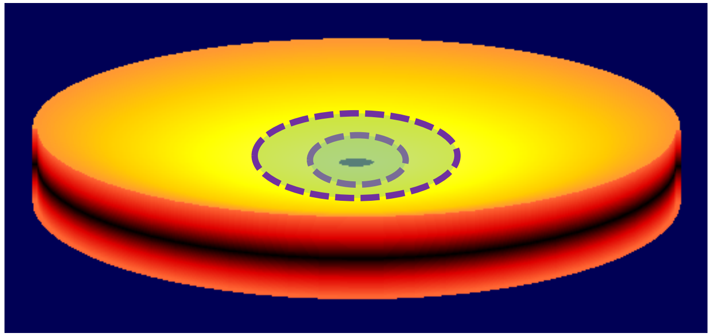


Dust in the inner disks is highly crystallized and consists of larger grains than dust in outer disk regions.

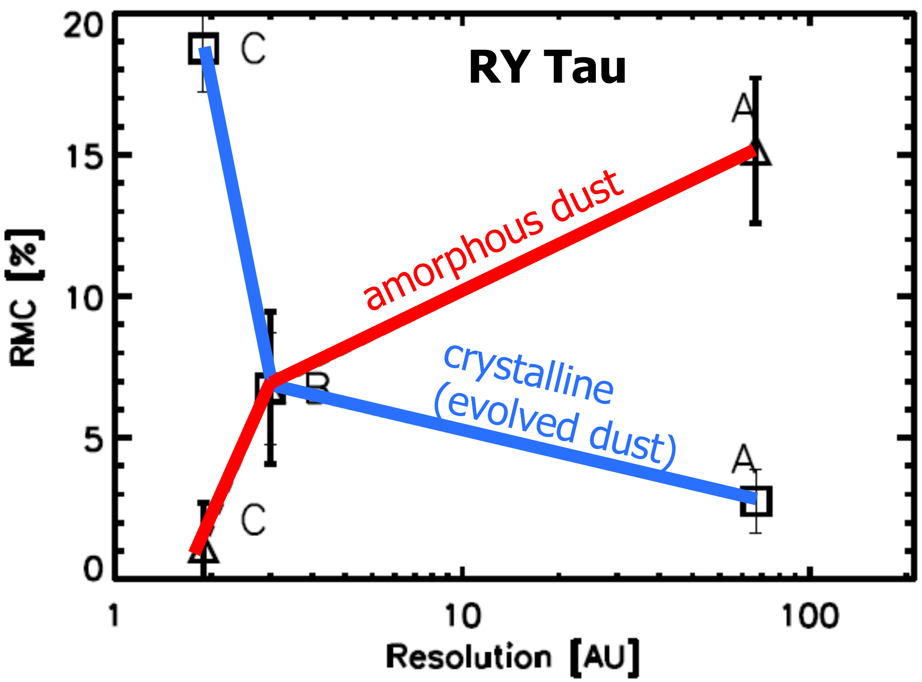
➜ Evidence for radial differences in dust mineralogy (grain growth)

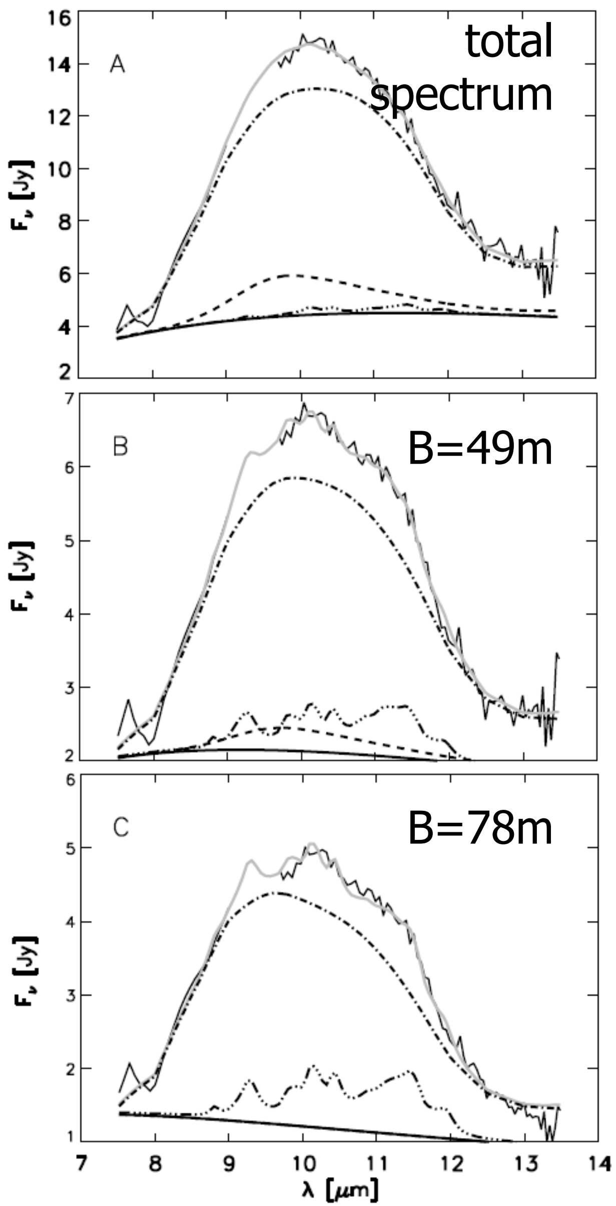
van Boekel et al. 2004, also: Varga et al. 2018

Dust mineralogy



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



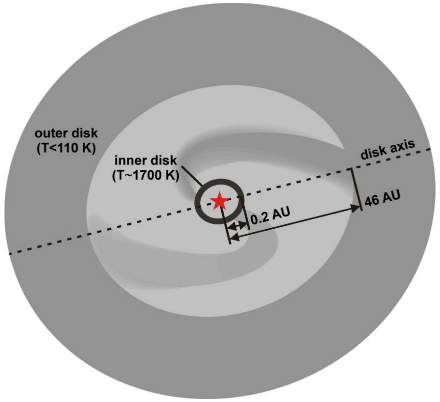


Schegerer et al. 2008
also: Ratzka et al. 2007,

Gaps and disk evolution

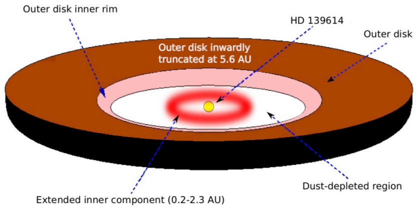
V1247 Ori	HD139614	HD100546	T Cha	TW Hya

V1247 Ori



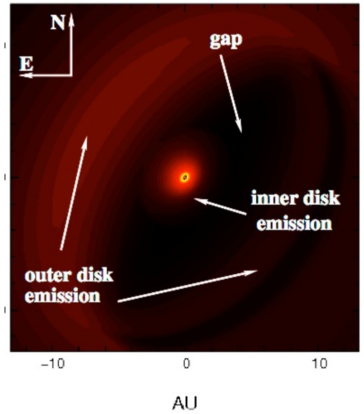
- Gap 0.2–46 AU, partially depleted
- Gap contains optically thin carbonaceous dust

HD139614



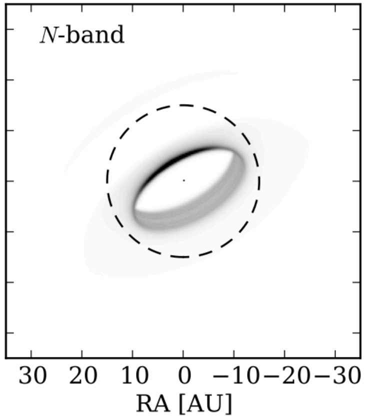
- Gap 0.2–5.6 AU, fully depleted

HD100546



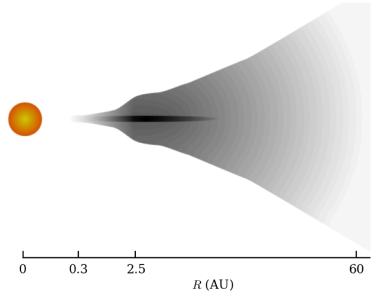
- Gap 0.3–29 AU, fully depleted
- Companion candidate (Quanz et al. 2013, Currie et al. 2015, Rameau et al. 2018)

T Cha



- Gap 0.1–25 AU, fully depleted

TW Hya



- Depleted region <2.5 AU with very large settled grains

time??

Kraus et al. 2013

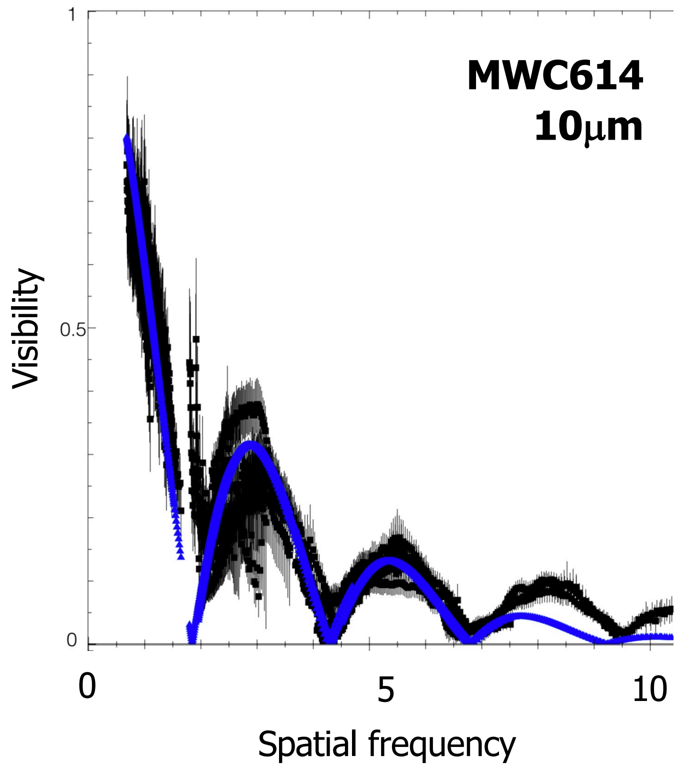
Matter et al. 2014
Carmona et al. 2016

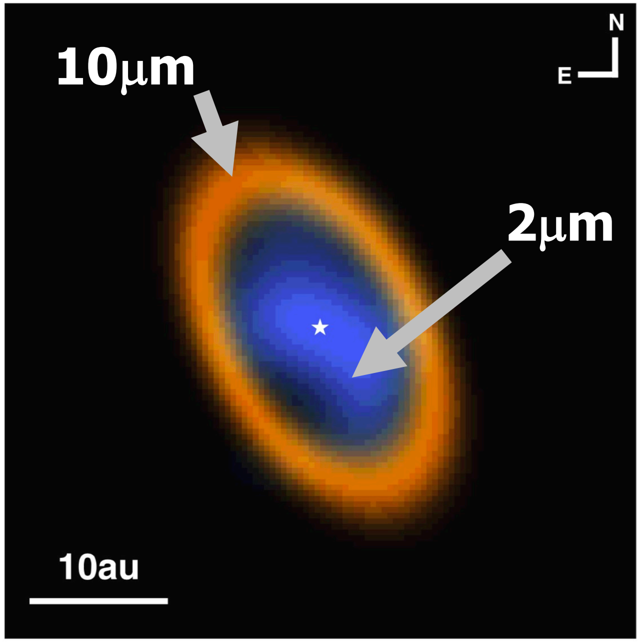
Benisty et al. 2010
Tatulli et al. 2011
Panic et al. 2012
Mulders et al. 2013
Jamialahmadi et al. 2018

Huelamo et al. 2011,
Olofsson et al. 2011, 2013

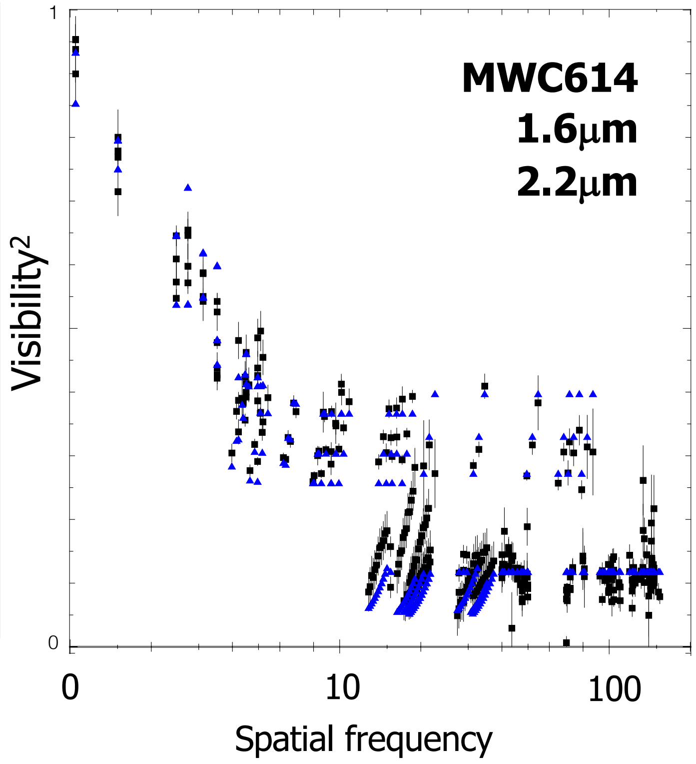
Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012
Menu et al. 2014

Evidence for quantum-heated particles





Kluska et al. 2018

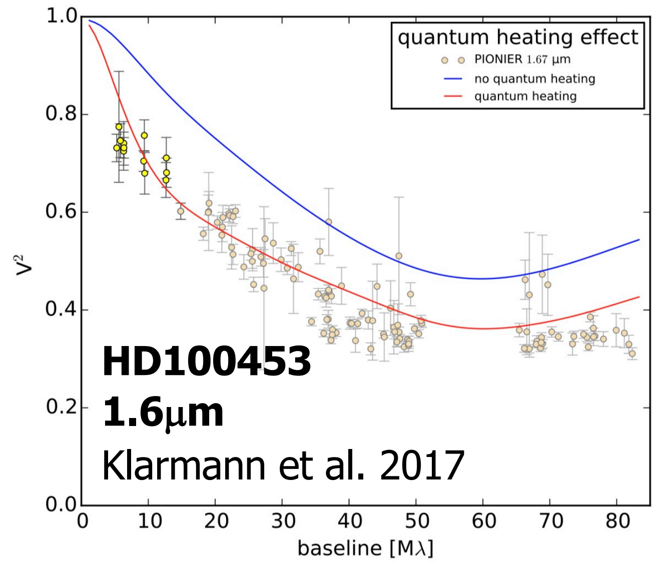


<u>MWC614 (Kluska et al. 2018):</u>

10µm : sharp ring structure @ 12.3± 0.4 AU

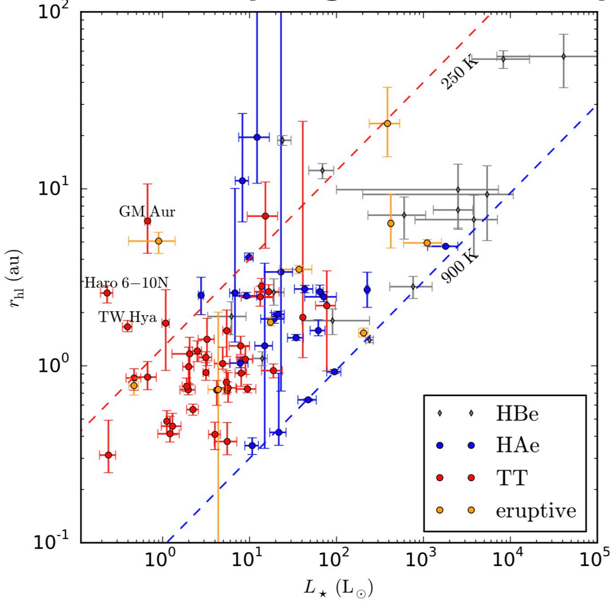
2µm : extended smoothly <10 AU (T=1812 ± 71 K)

➜ Possibly quantum-heated particles, pumped by stellar UV flux (HD100453: Klarmann et al. 2017)

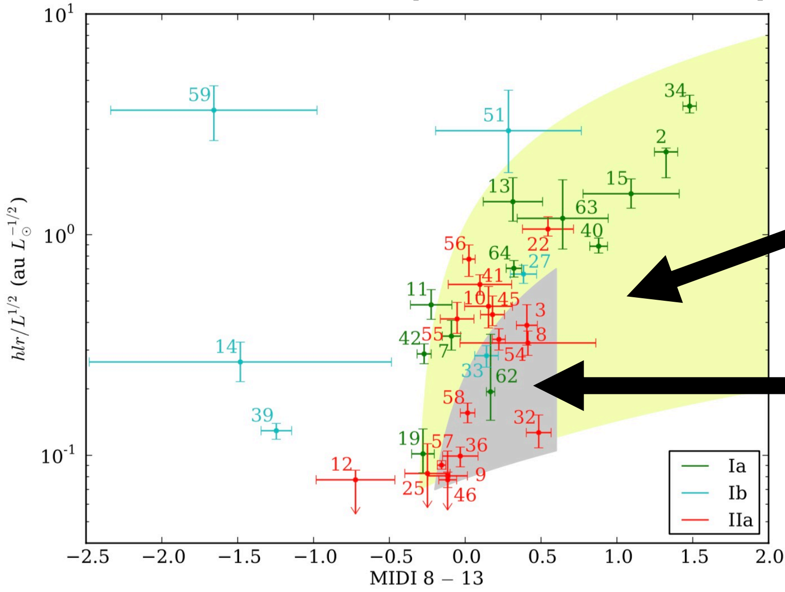


Systematic search for gaps

82 YSO (Varga et al. 2018)

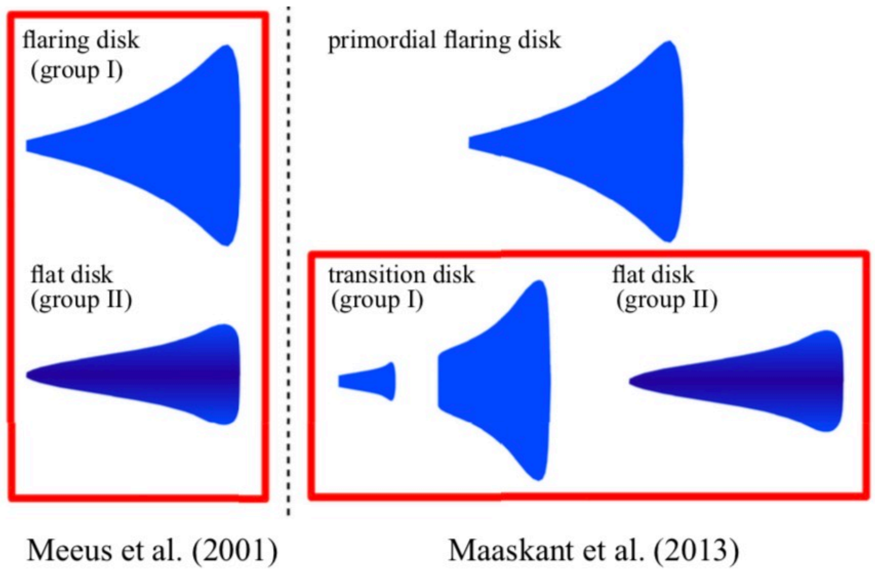


38 HAeBe stars (Menu et al. 2015)



Gapped disks?

Full disk

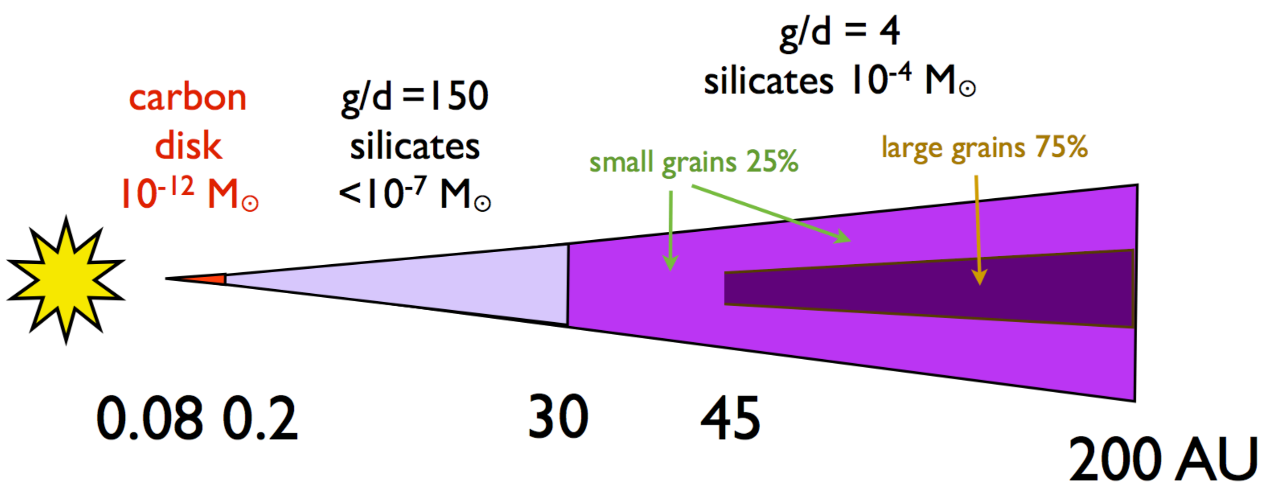


Some of scatter in MIR size-L diagram could be due to disk sub-structure, such as gaps

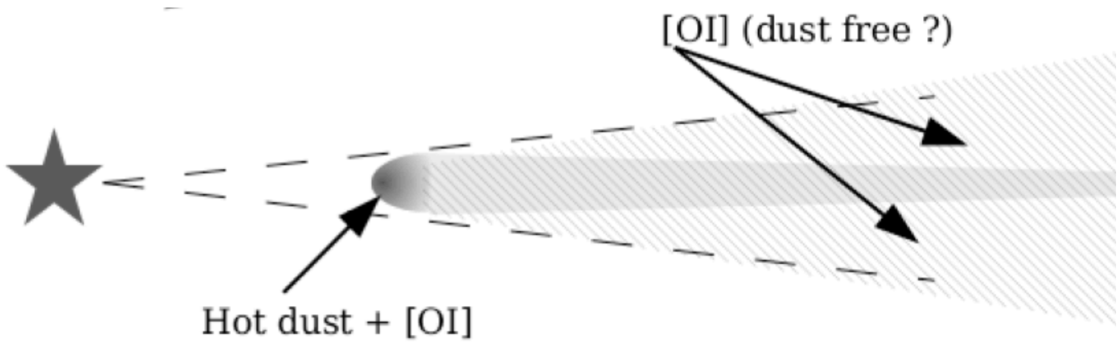
Herbig stars:
Size-color diagram suggests that Meeus Group I sources might be more likely to exhibit such sub-structure than Group II sources

also: Schegerer et al. 2013, Chen et al. 2012, 2016

Linking continuum geometry + molecular gas tracers



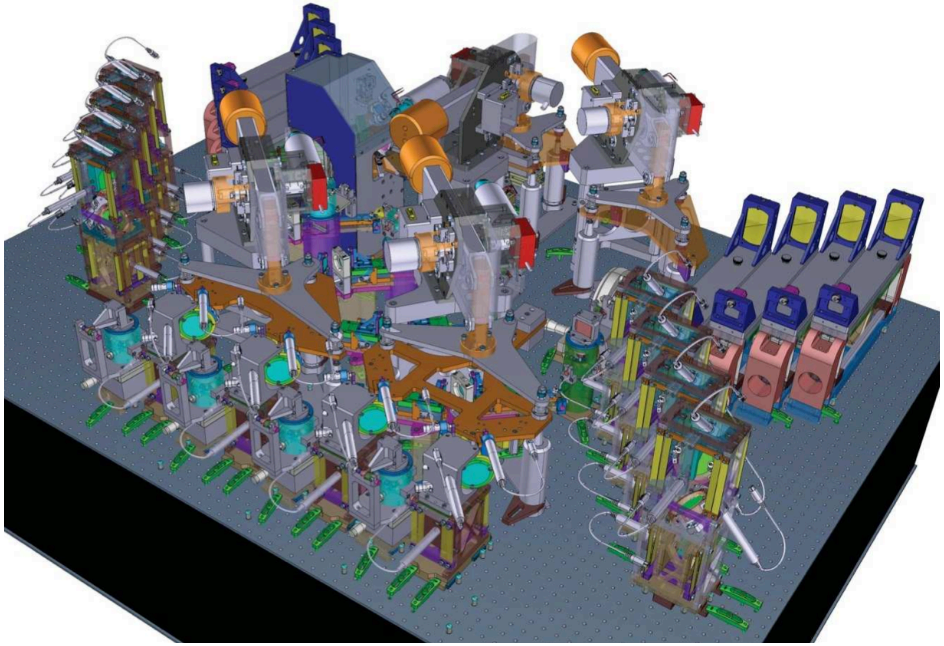
SAO 206462, CO fund. line
Carmona et al. 2014



HD101412, [OI] line
Fedele et al. 2008

also: Chen et al. 2010; DIANA project

Prospect: MATISSE imaging



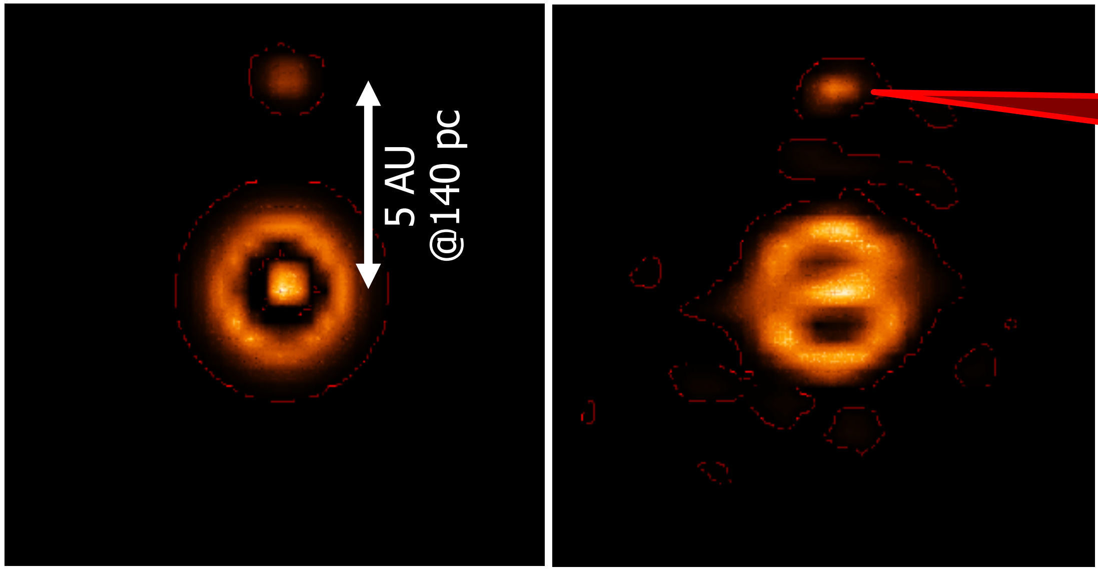
New 4T beam combiner

L/M band: R=30, 500, 950, 5000

N-band: R=30, 220

Covers important new line tracers, e.g. fundamental CO

Simulated image (10 µm) Reconstructed image



Protoplanet (1 M_J) around T Tauri star

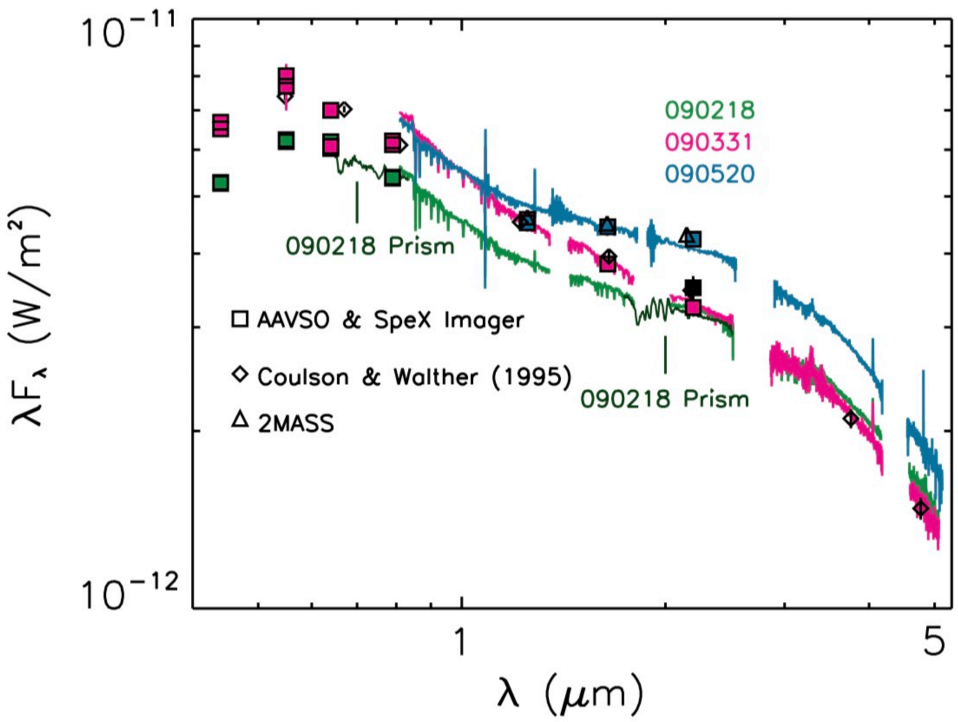
Fortney et al. 2008

Wolf & D’Angelo 2005

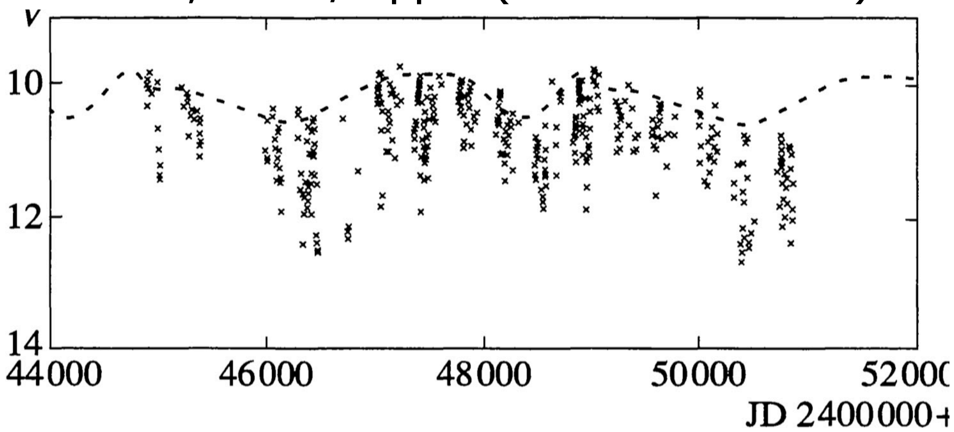
Temporal variability

Evidence for variability in the inner disk environment

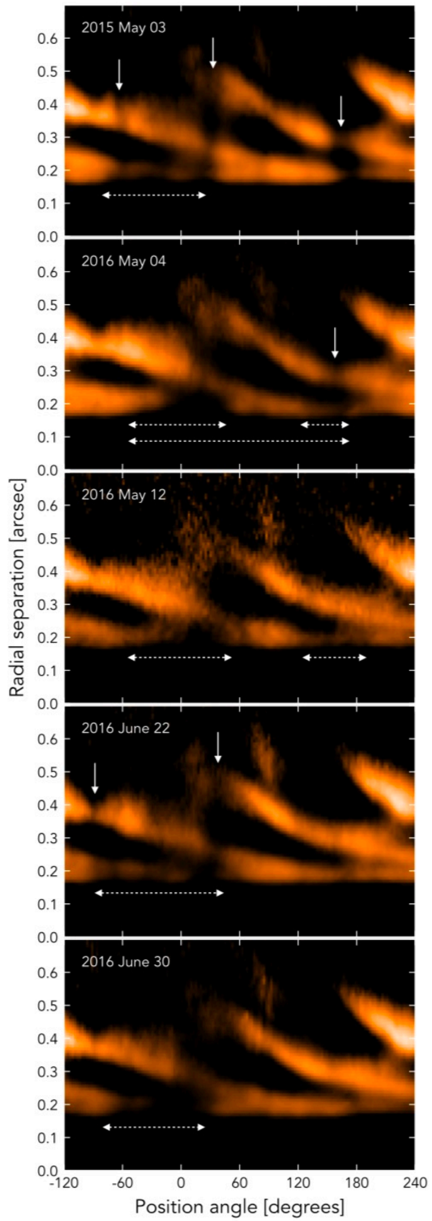
SAO206462, SED variability
Sitko et al. 2009



CO Ori, UXors/Dipper (Grinin et al. 1998)

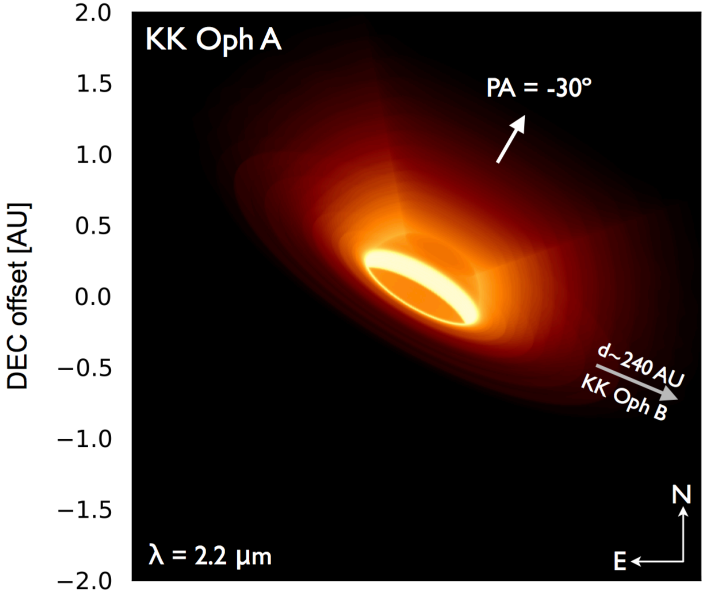


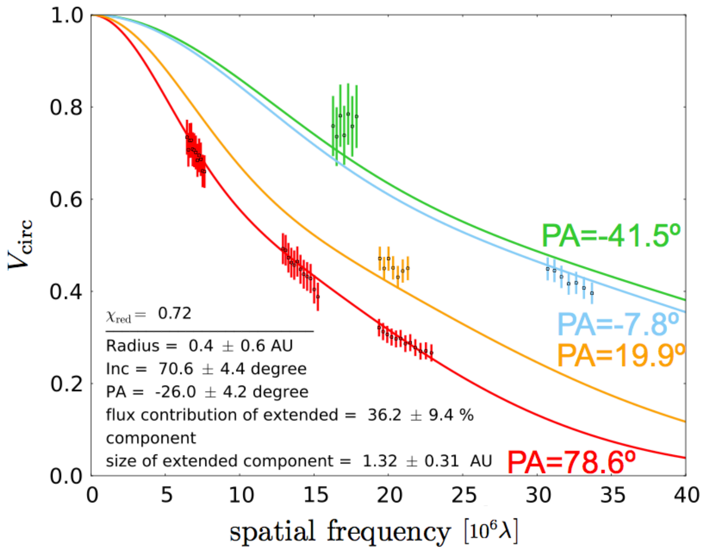
SAO206462, SPHERE (J-band)
Stolker et al. 2017



also: Benisty et al. 2017, 2018, Pinilla et al. 2018

UX Ori / Dipper stars: Disk inclination constraints





Kreplin et al. 2016

Most scenarios predict near-edge viewing geometry:

- Orbiting dust clouds
- Scale height variations near dust rim
- Dusty disk winds
- Disk warps induced by companions/planets

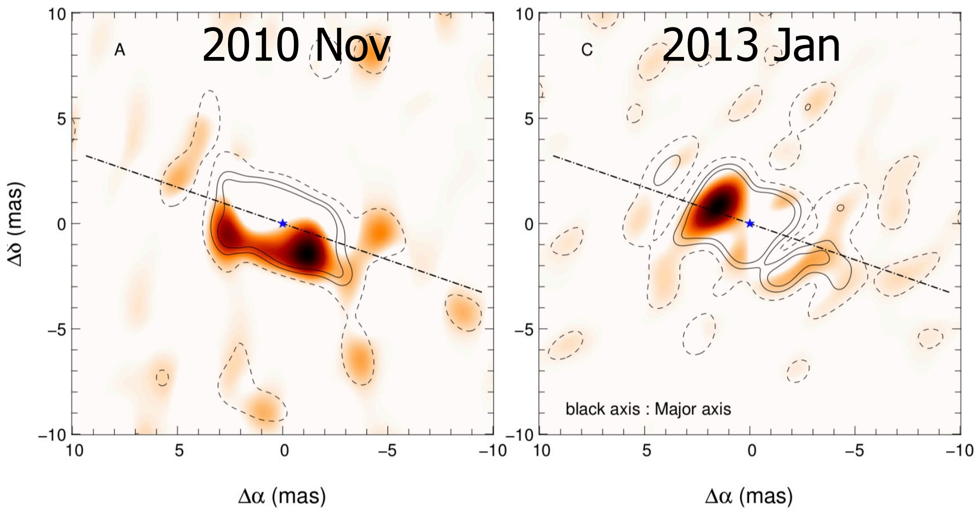
Interferometry provides inclination estimates for inner disk:

CO Ori:	~30°
CQ Tau:	~30–50°
V1026 Sco:	~50°
UX Ori:	~60–70°
VV Ser:	~70°
KK Oph:	~70°

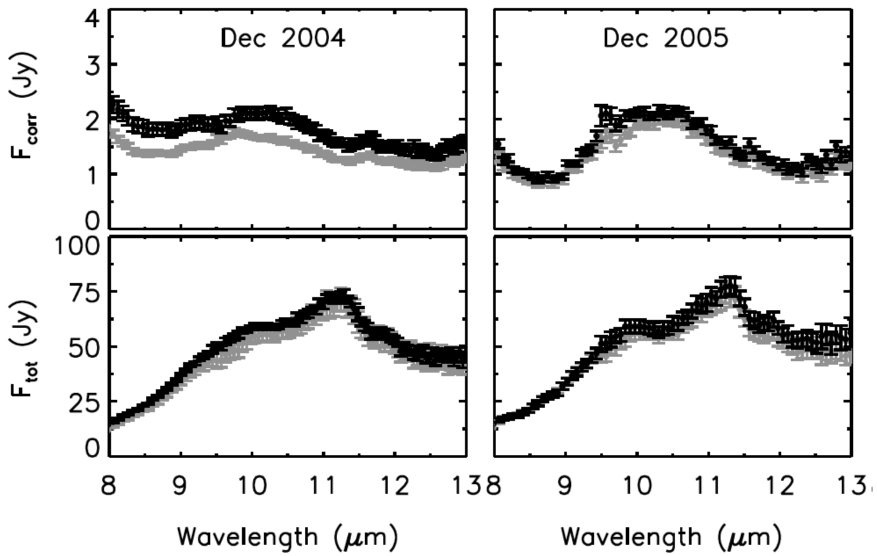
Eisner et al. 2004, Pontoppidan et al. 2007, Chapillon et al. 2008, Vural et al. 2014, Kreplin et al. 2013, 2016, Davies et al. 2018

Changing inner disk structures

MWC158 (NIR contour: image, color: asymmetry)
Kluska et al. 2016



HD100546 (MIR)
Panic et al. 2012

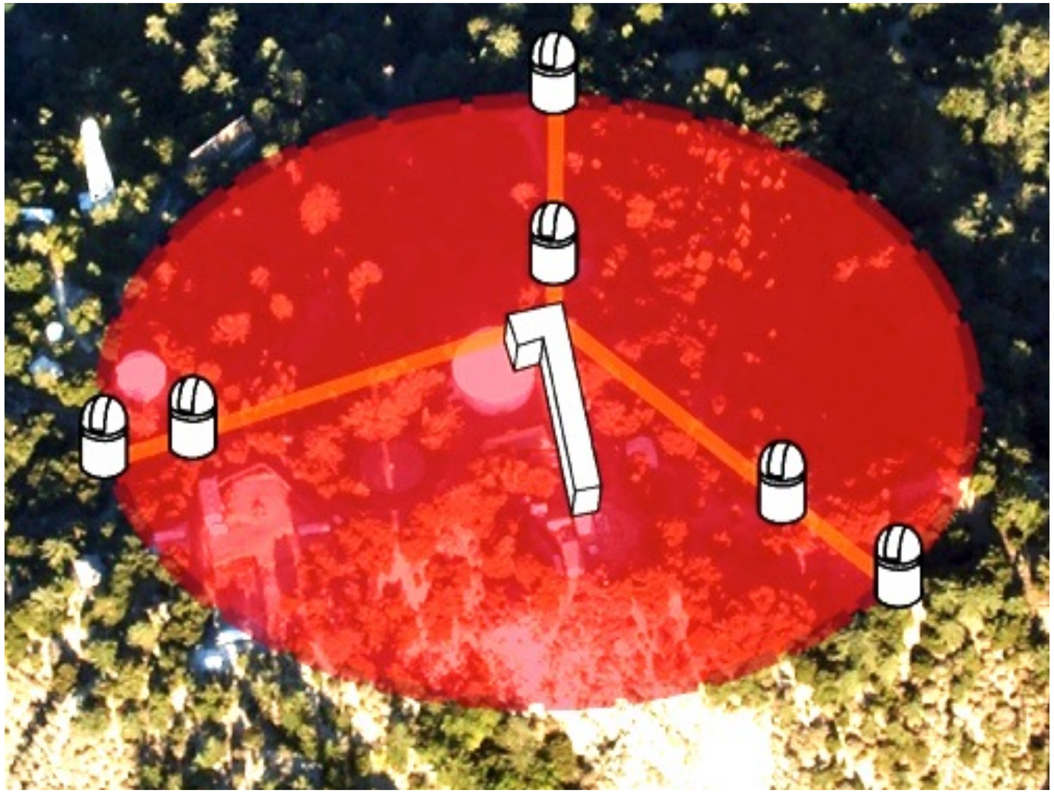


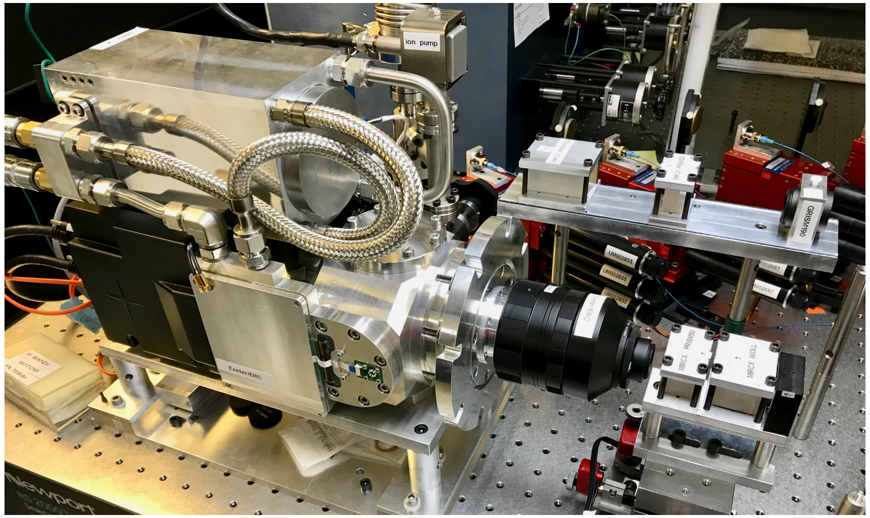
Keplerian period (140pc, 2 M_{sun})
@3mas (VLTI): **2 month**
@1mas (CHARA): **14 days**

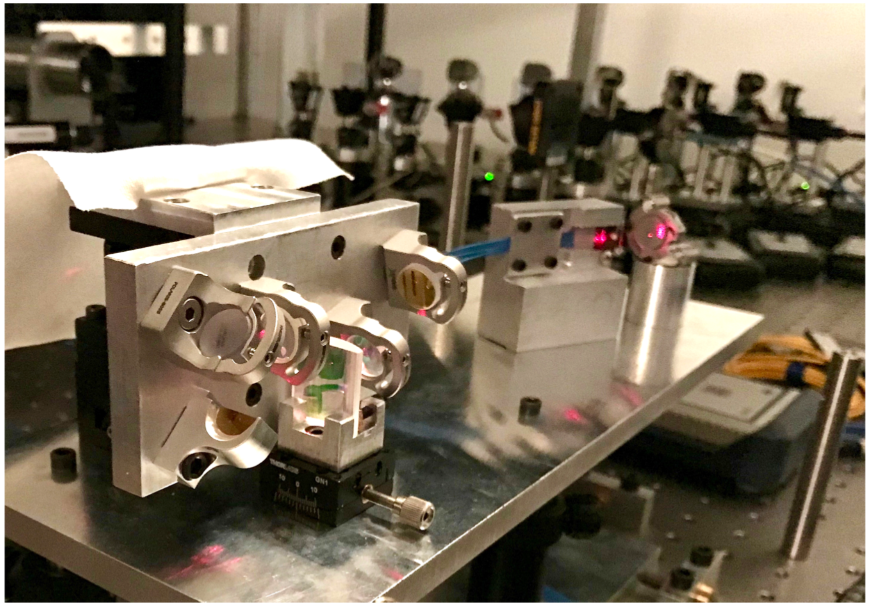
➜ Tough requirement on scheduling, challenging for reconfigurable arrays

also: Jamialahmadi et al. 2018
Chen et al. 2018

Prospects for imaging moving inner disk structures





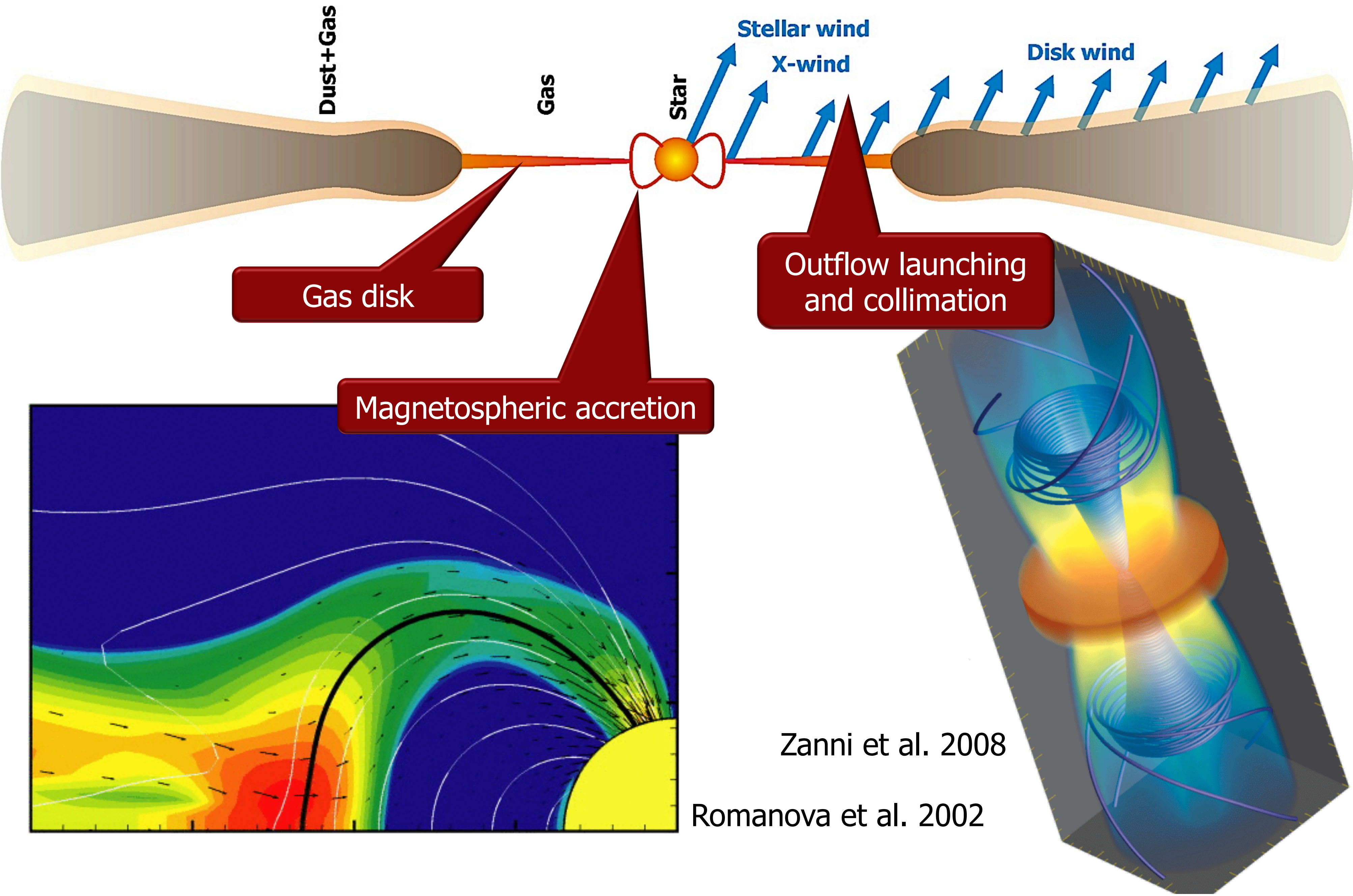


CHARA array: 6 one-meter telescopes, forming baselines up to 330m

MIRC-X: New 6T near-infrared imager that aims to image protoplanetary discs with 0.001" resolution

Gas kinematics in spectral lines

Accretion/ejection in YSOs

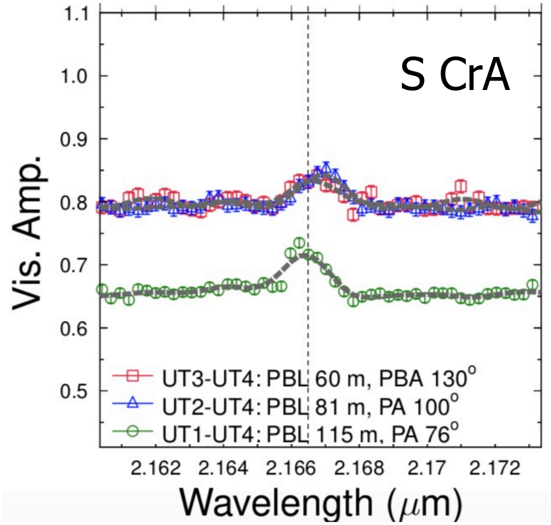


Zanni et al. 2008

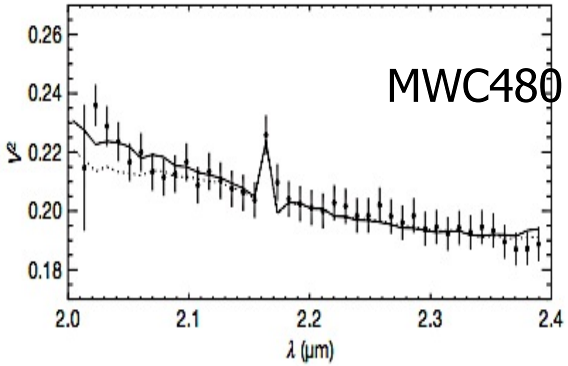
Romanova et al. 2002

Brγ: Does it trace accretion or outflow?

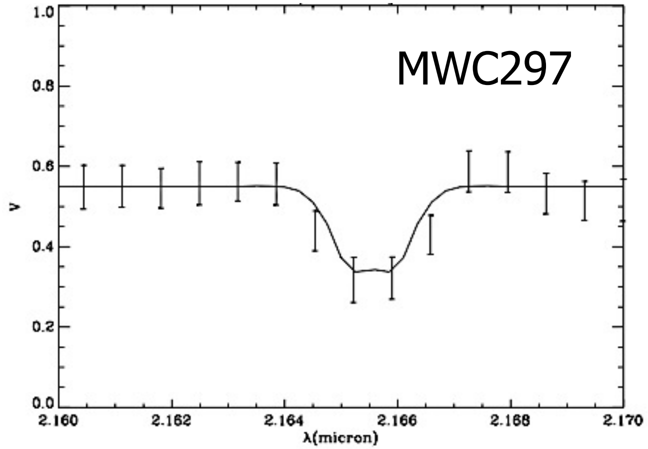
GRAVITY collab./
Garcia Lopez et al. 2017



Eisner et al. 2007



Malbet et al. 2007



No tight correlation has been found, but general trends:

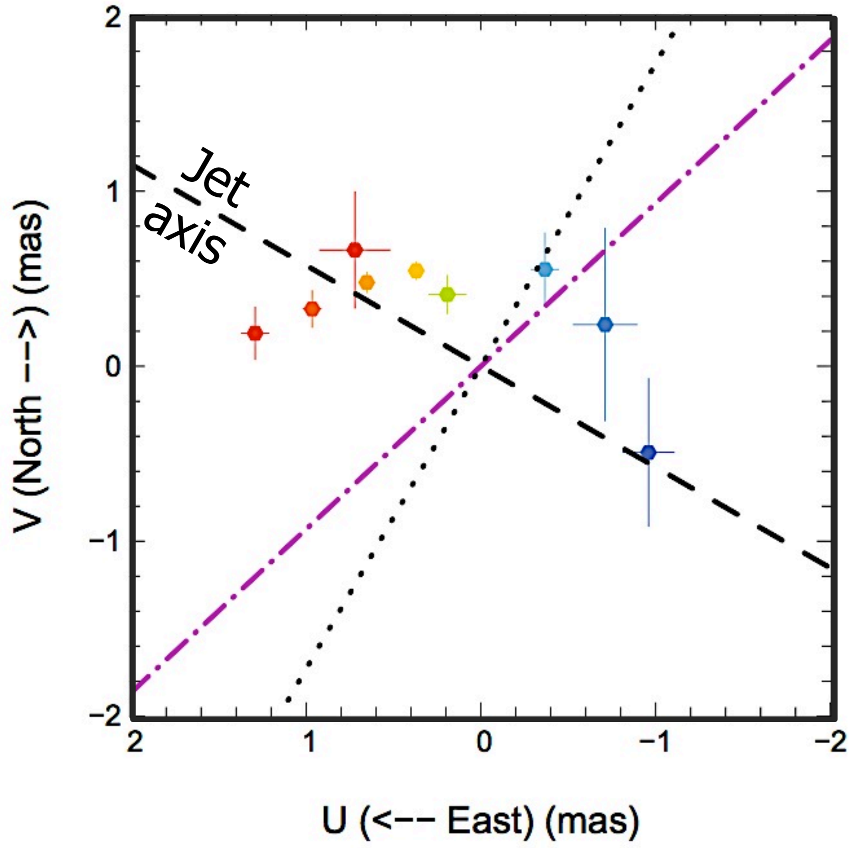
Compact Brγ-emitting region in most low-L sources (T Tauri, most Herbig Ae)
➜ **consistent with magnetospheric accretion**

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

also: Tatulli et al. 2007, Kraus et al. 2008, Eisner et al. 2009,2010

Brγ: Does it trace accretion or outflow?

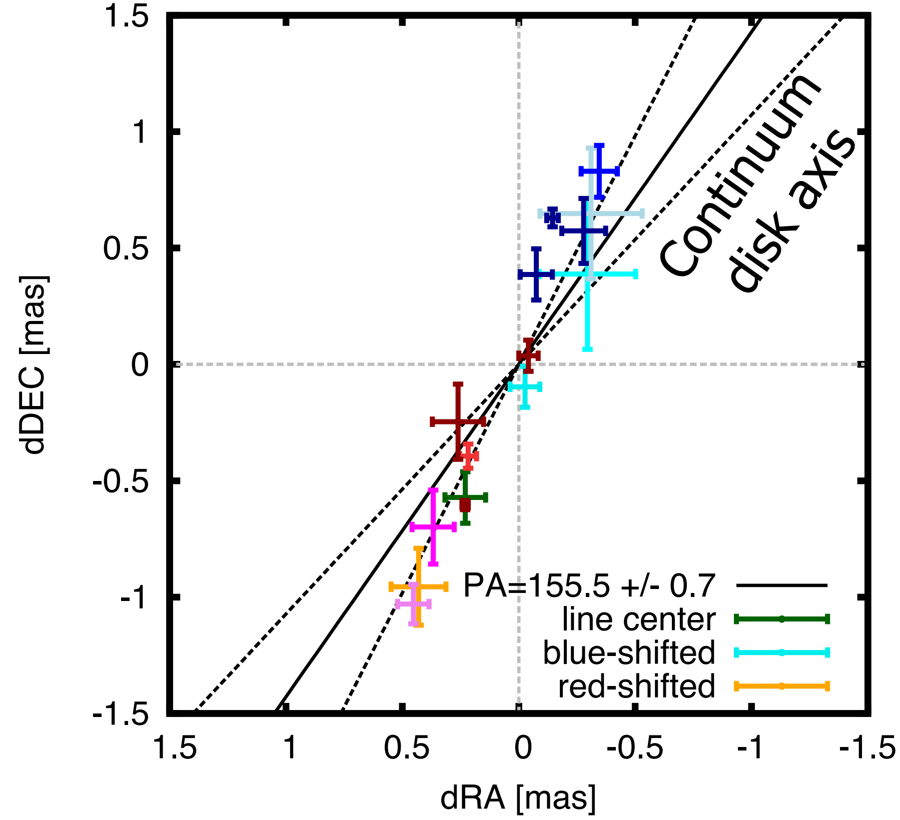
Z CMa (Benisty et al. 2010)



Herbig Be (+FU Ori), d=930-1150 pc

➜ Gas ejected in polar direction

V921 Sco (Kraus et al. 2012)



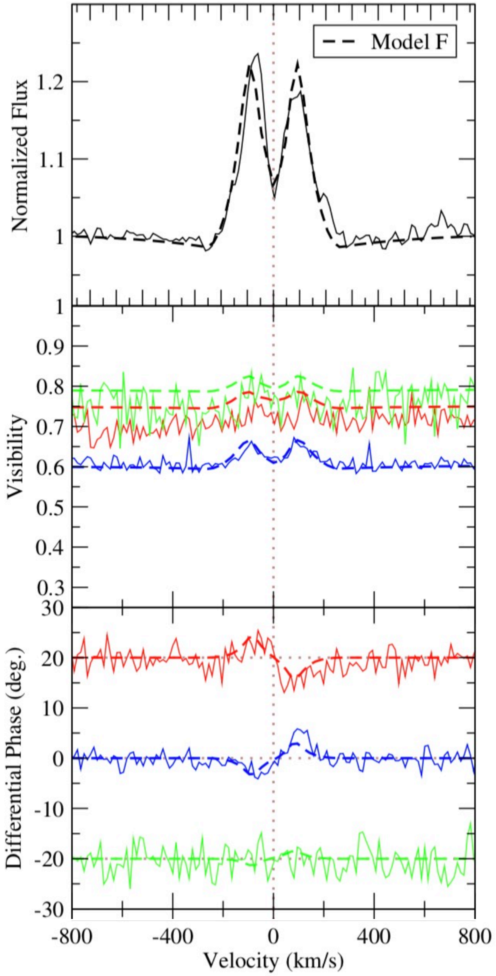
B[e], d=1150 pc (literature: 160-2600 pc)

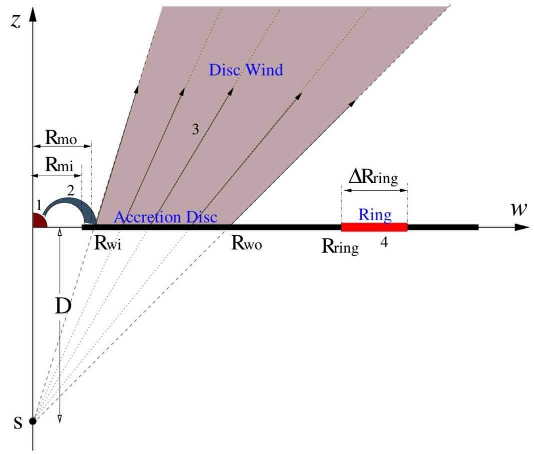
➜ Gas rotating in disk plane

➜ There is no unique Brγ emission-mechanism in YSOs

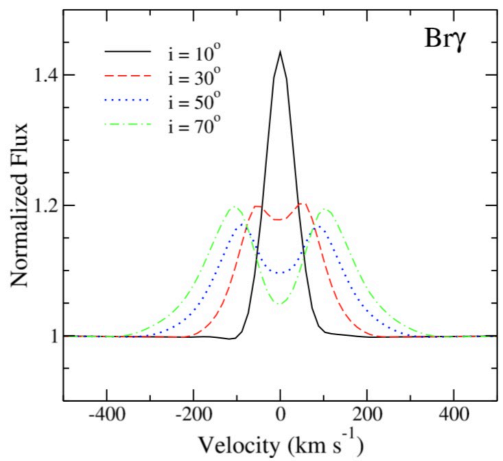
Brγ: Magneto-centrifugally driven disk wind models

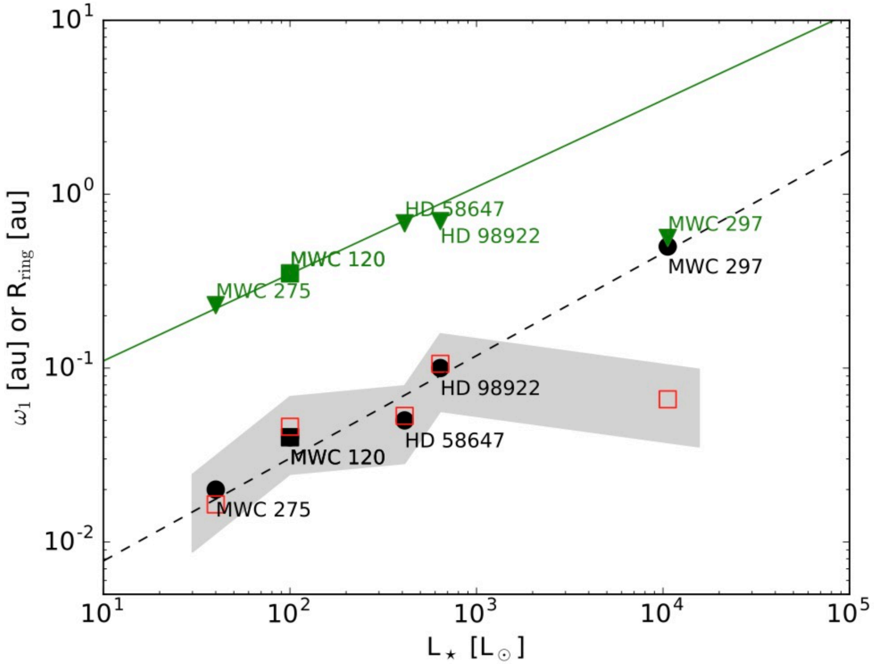
HD58647 (Kurosawa et al. 2016)





Garcia Lopez et al. 2016





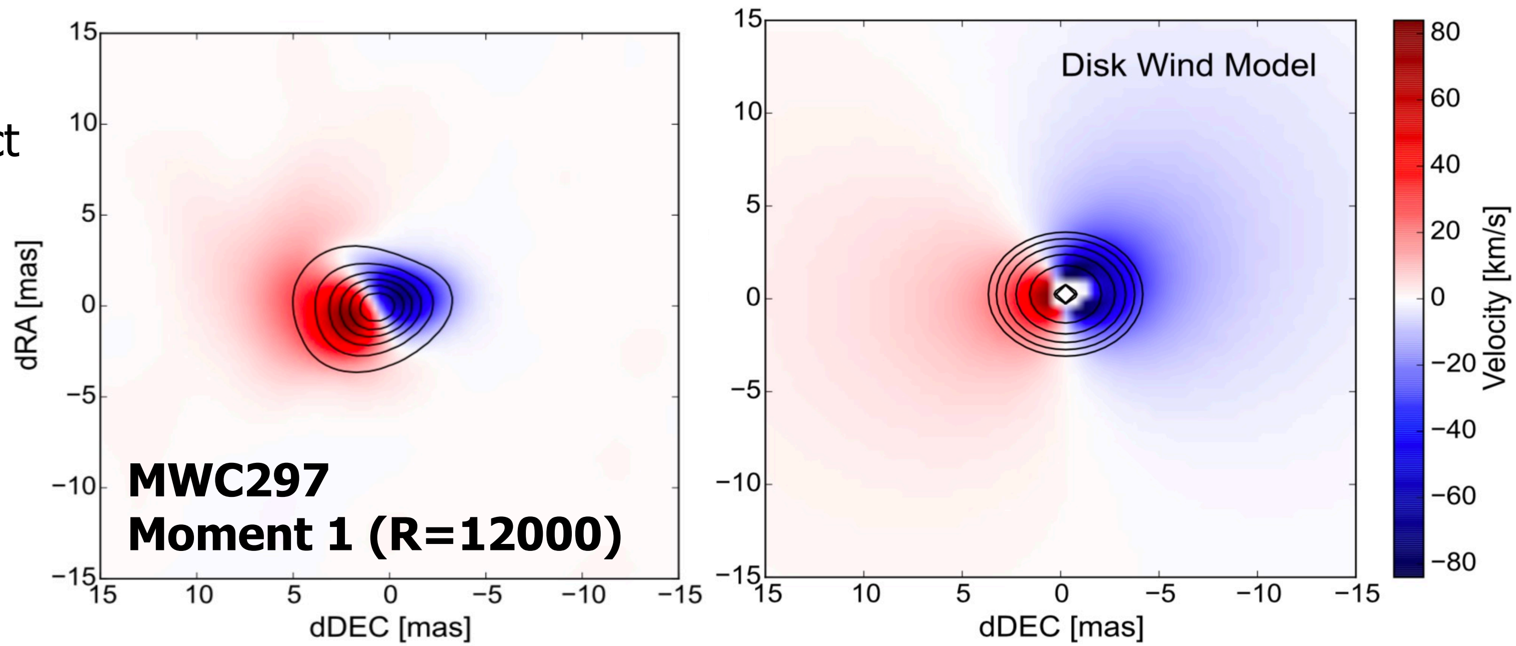
Disk wind inner radius consistent with Alfven radius, assuming B=25…150G (Kreplin et al. 2018)

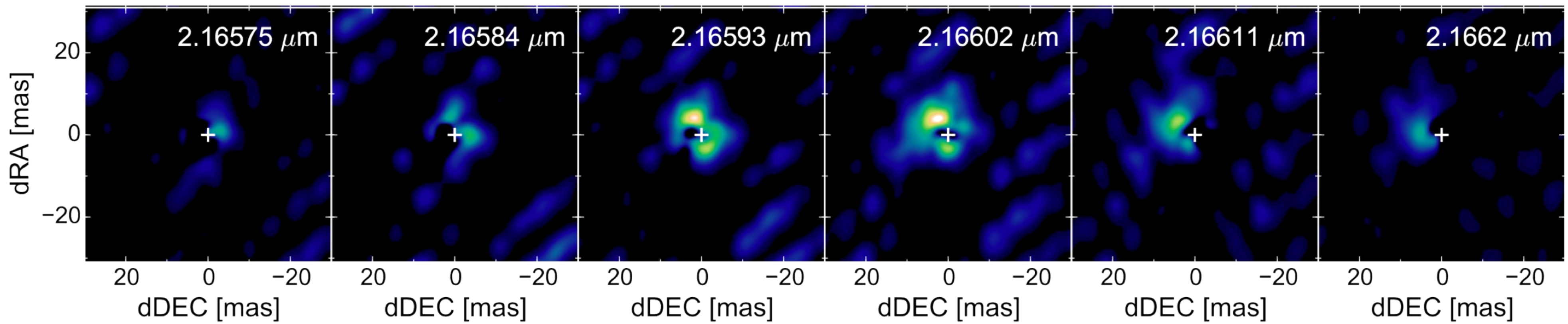
also: Weigelt et al. 2011, Grinin et al. 2012, Caratti o Garatti et al. 2015, 2016, Garcia-Lopez et al. 2015

Brγ: Velocity-resolved imaging

VLTI/AMBER Brγ observations can be used to reconstruct velocity-resolved channel maps

➜ interferom. “IFS”, 3D image cube

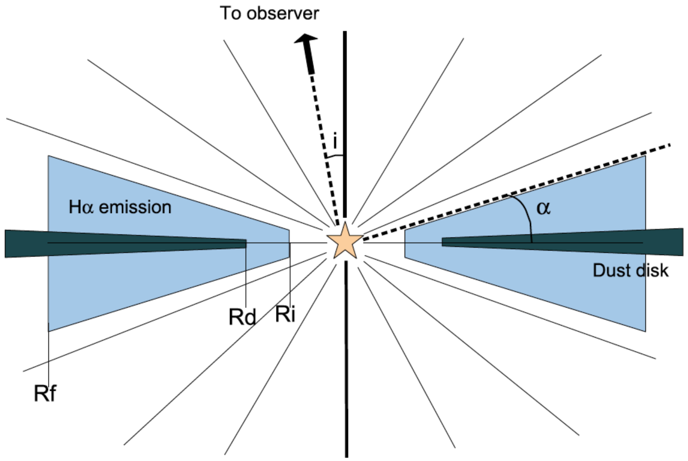




Hone et al. 2017

Gas kinematics studies: Hα, Pfund, CO

Hα line



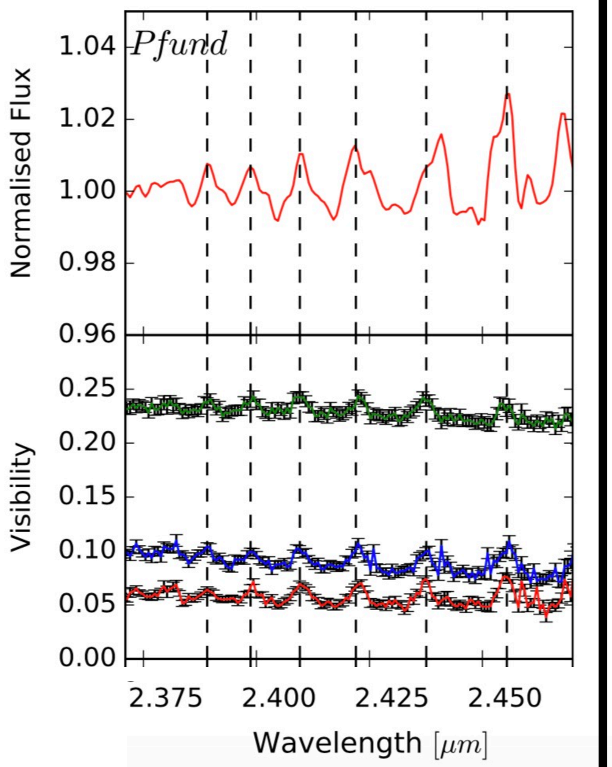
AB Aur

Rousselet-Perraut et al. 2010

Extended Hα region
➜ Consistent with disk wind origin

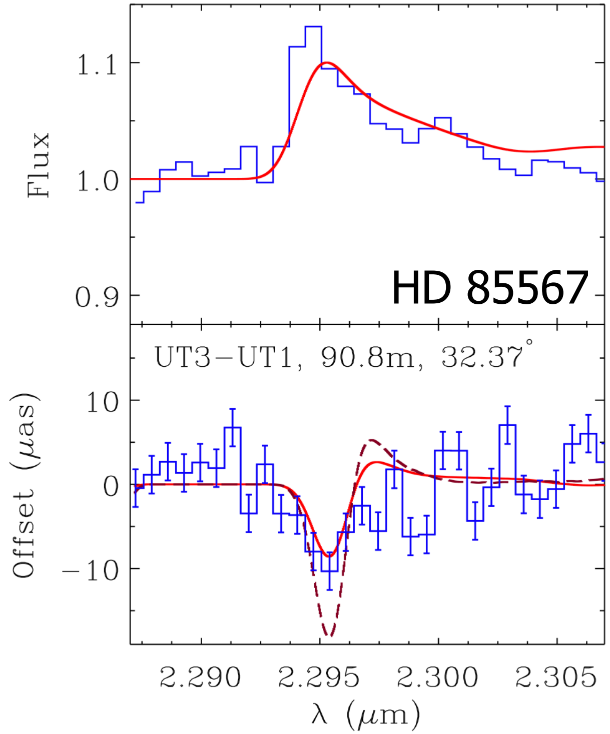
also: Perraut et al. 2016,
Mendigutia et al. 2017

Pfund lines



Koutoulaki et al. 2018

CO 2.3 μm bandhead emission



Wheelwright et al. 2013

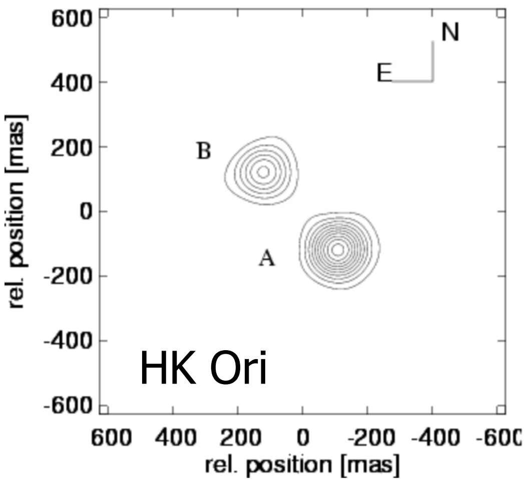
Gas disk inside of sublimation radius

also: Tatulli et al. 2009, Eisner et al. 2011,
Kraus et al. 2017

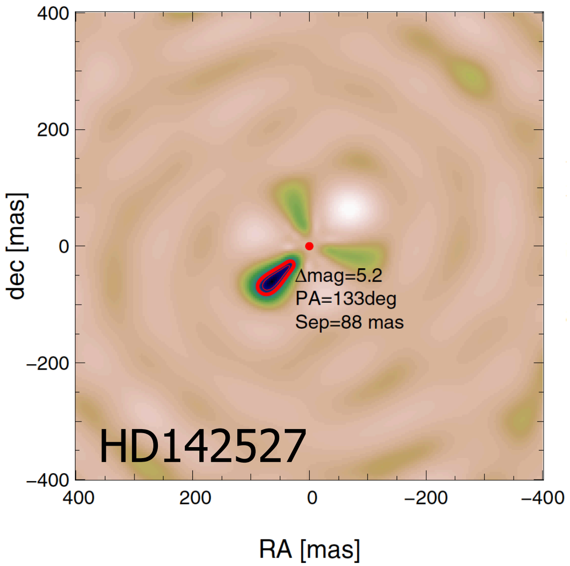
Multiplicity and
disk structure in multiple system

Detecting companions

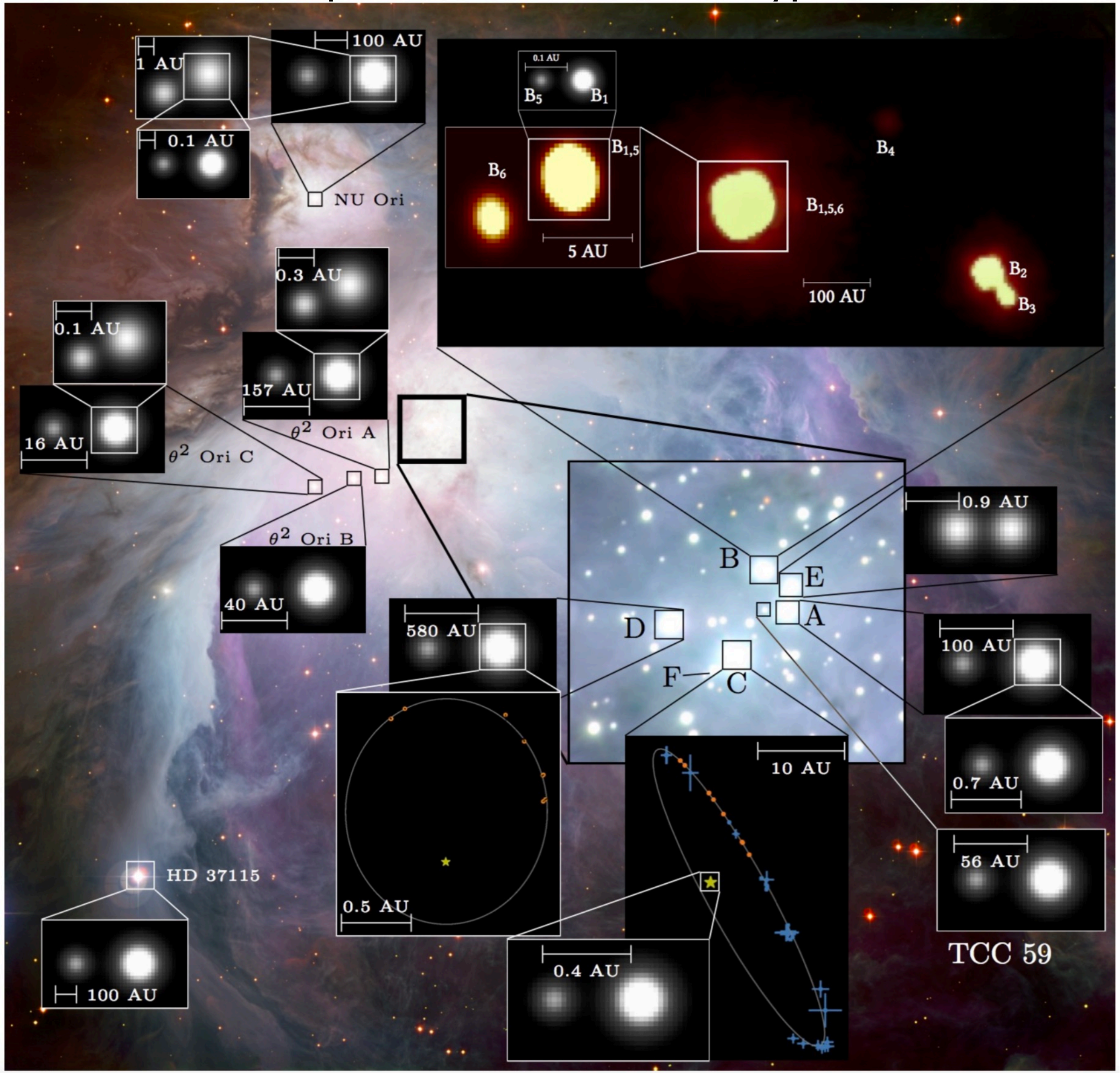
Speckle interferometry



Aperture masking



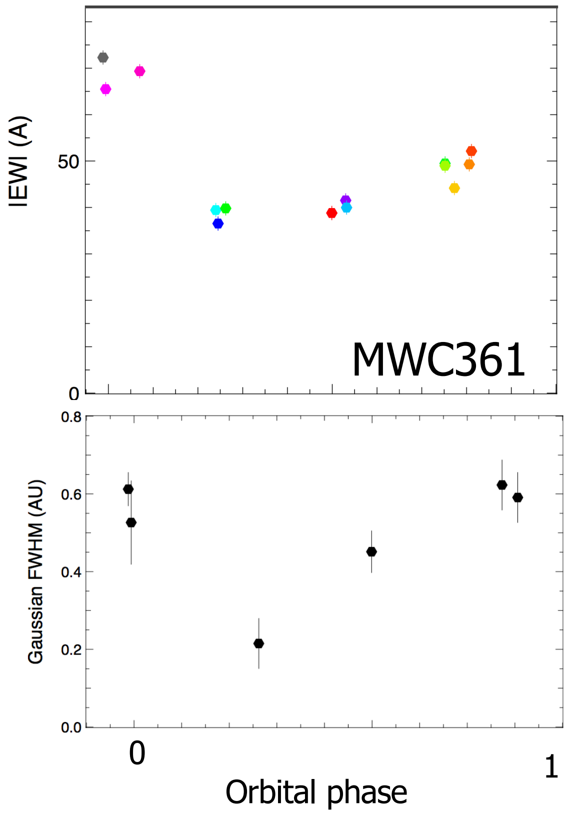
GRAVITY: 22 companions around 16 OB-type stars in Orion



Smith et al. 2005, Biller et al. 2012, GRAVITY-collab./Karl et al. 2018
also: Monnier et al. 2008, Ireland+Kraus 2008, Ratzka et al. 2009, Wang et al. 2012, Berger et al. 2010, Kraus+Ireland 2012, Kraus et al. 2012, many more…

Characterizing disks & accretion processes in PMS binaries

MWC361 (Benisty et al. 2013)

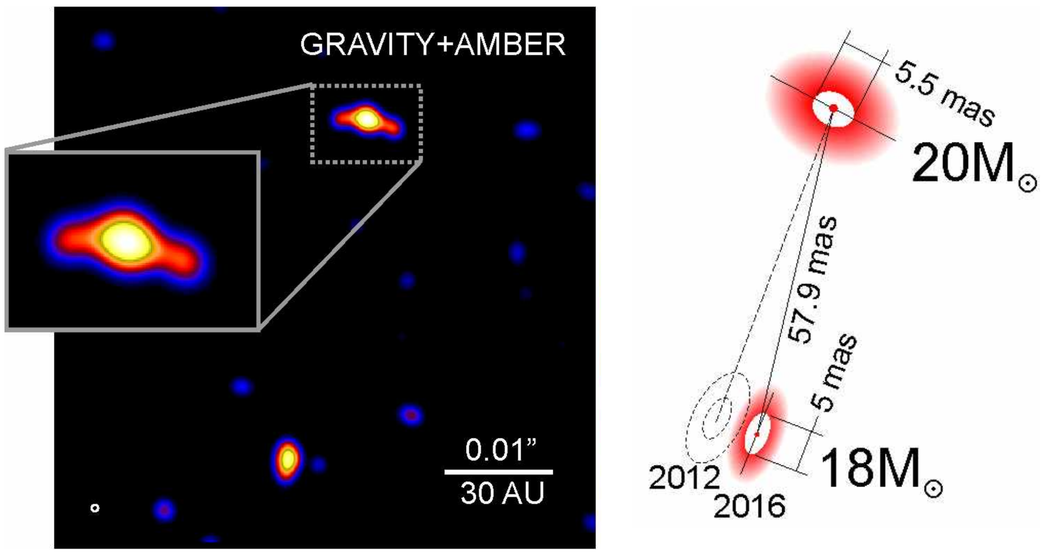


Increase in Hα EW and emitting radius near periastron passage

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

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

IRAS17216-3801 (Kraus et al. 2017)



Disk (mis)alignment information provides insights on dynamical history of system

- Tidal forces work towards realigning disks w.r.t. orbital plane on precession timescale (< 200,000 yrs for circumprimary disk)
  ➜ **Tidal realignment is still ongoing**
- Estimate individual accretion rates: $\frac{\dot{M}_B}{\dot{M}_A} = 1.6$
  Secondary interrupts accretion stream, channeling material onto circumsecondary disk (e.g. Whitworth et al. 1995)

Conclusions

Interferometry can resolve large sample of T Tauri, Herbig Ae/Be stars and mYSOs in the NIR (~60 w/PIONIER) and MIR (~100 w/MIDI)

Primary limitation for many VLTI studies: Baseline coverage + few apertures
➜ CHARA, NPOI, MROI ➜ plan for VLTI expansion & next-generation facility

- **Rim geometry:**
  Consistent with curved rim, but best-studied objects hint at material closer in
- **Multi-wavelength interferometry:**
  Fantastic tool to characterise dust properties and to study global disk structure
- **Multi-epoch observations:**
  Prospect to link inner+outer disk and to study origin of variability in YSO
- **Interferometry in spectral lines:**
  Constrain mass transport and gas kinematics in outflow-launching region