Very close environments of young stars

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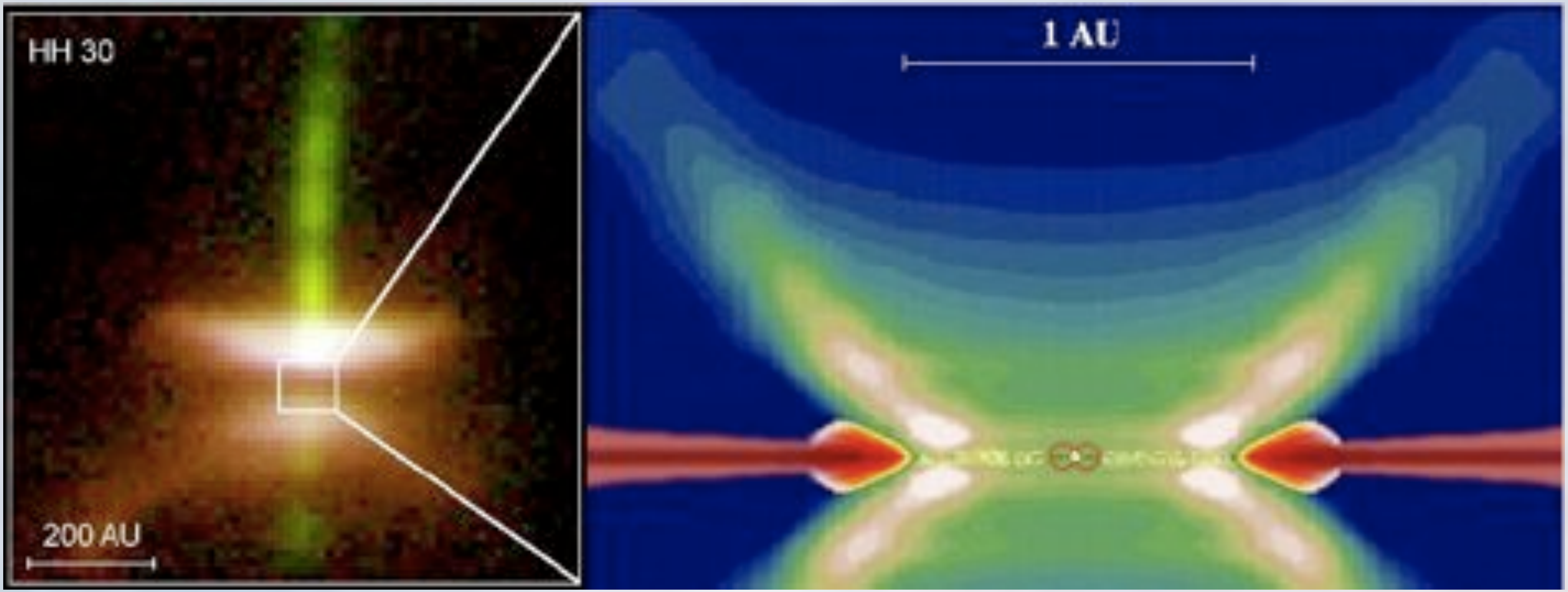
Inner regions of Young Stellar Objects



From Isella et al. (2007)

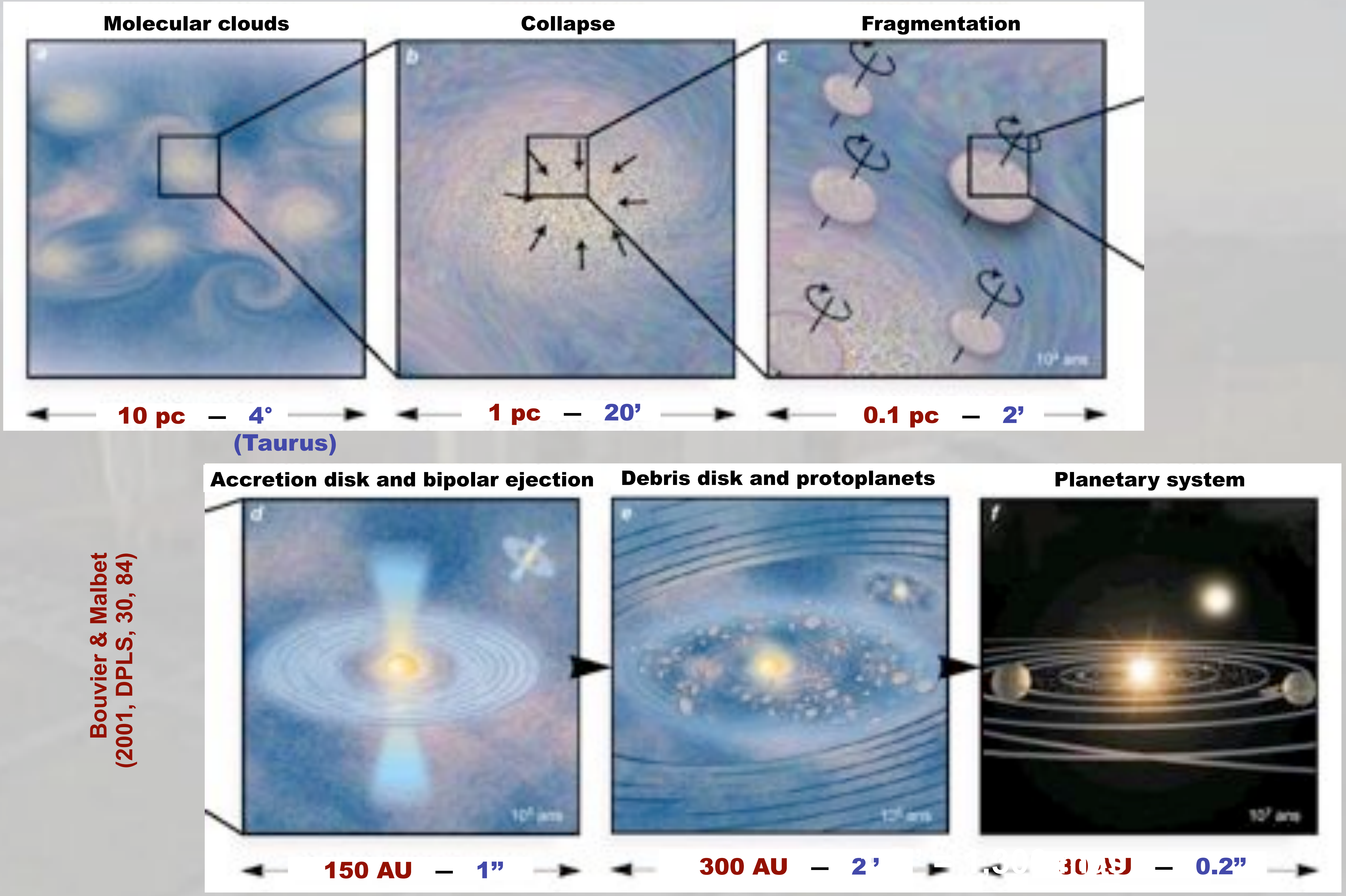
Outline

- **Introduction**
  - Physical conditions in the inner regions of YSOs
  - Need for very high angular resolution
  - Physical processes
- **Infrared interferometry**
  - Principles and observables
  - Instruments available for inner regions studies
  - Elements of bibliography
- **Inner disk physics**
  - Morphology of circumstellar structures
  - Constraints on disk structure (T, z,…)
  - Dust mineralogy
  - Gas/dust connection
  - Transition disks
- **Other AU-scale phenomena**
  - Hydrogen line emission : Outflows / winds or Magnetosphere?
  - Importance of Binaries and multiple systems
- **Future prospects**

INTRODUCTION

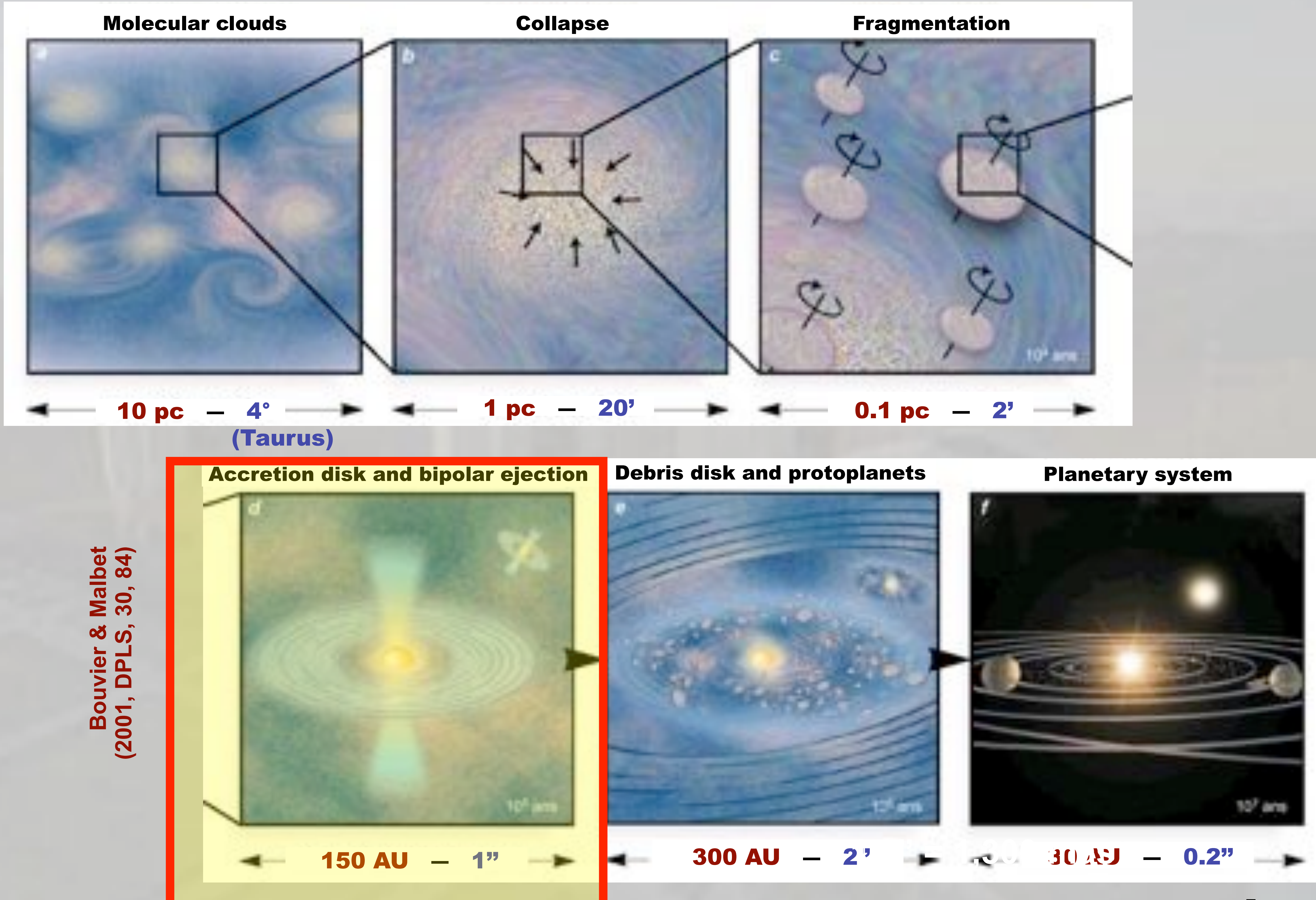
– Formation of stars, disks and planets
– Physical conditions in the inner regions of YSOs
– Need for very high angular resolution
– Physical processes

Formation of stars, disks and planets



Bouvier & Malbet
(2001, DPLS, 30, 84)

Formation of stars, disks and planets



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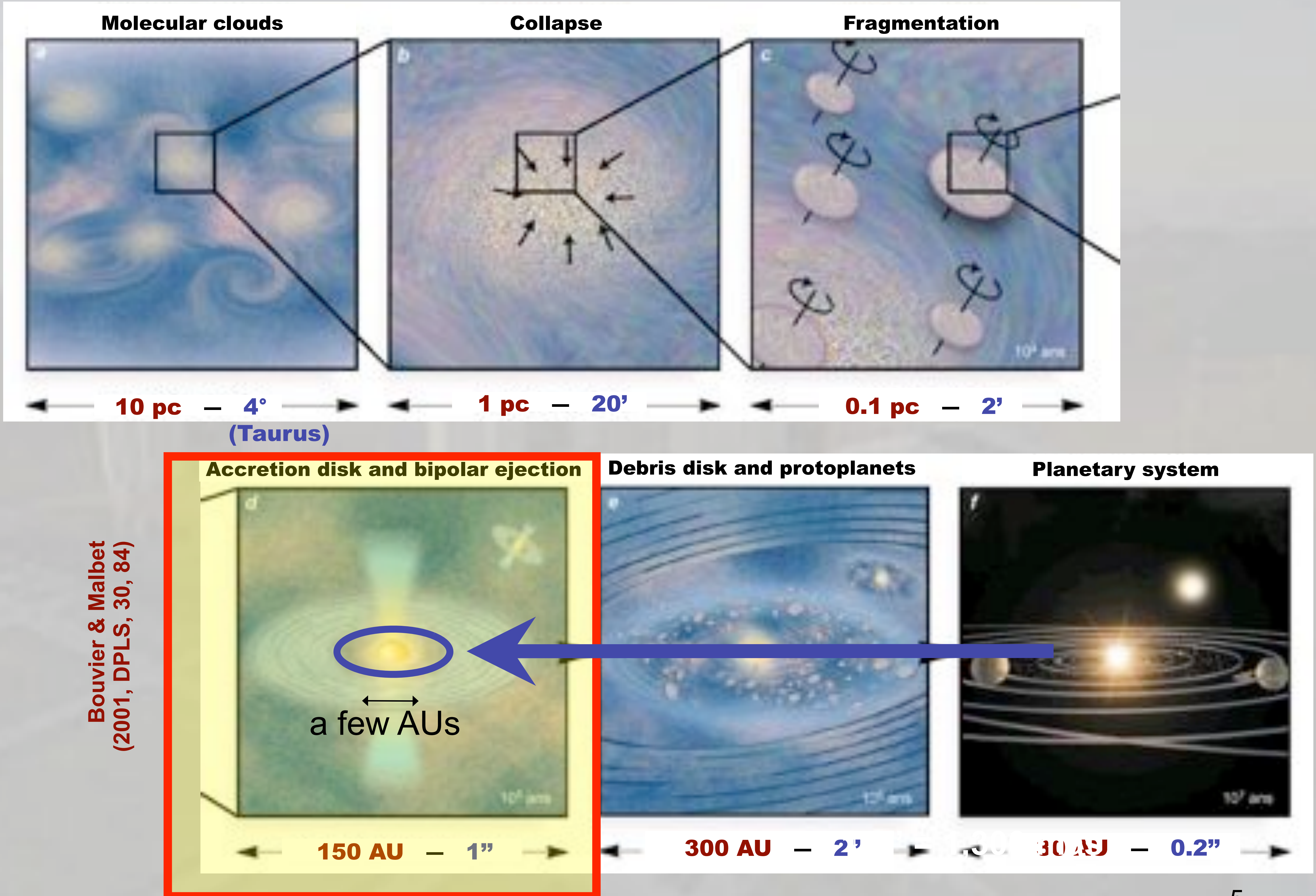
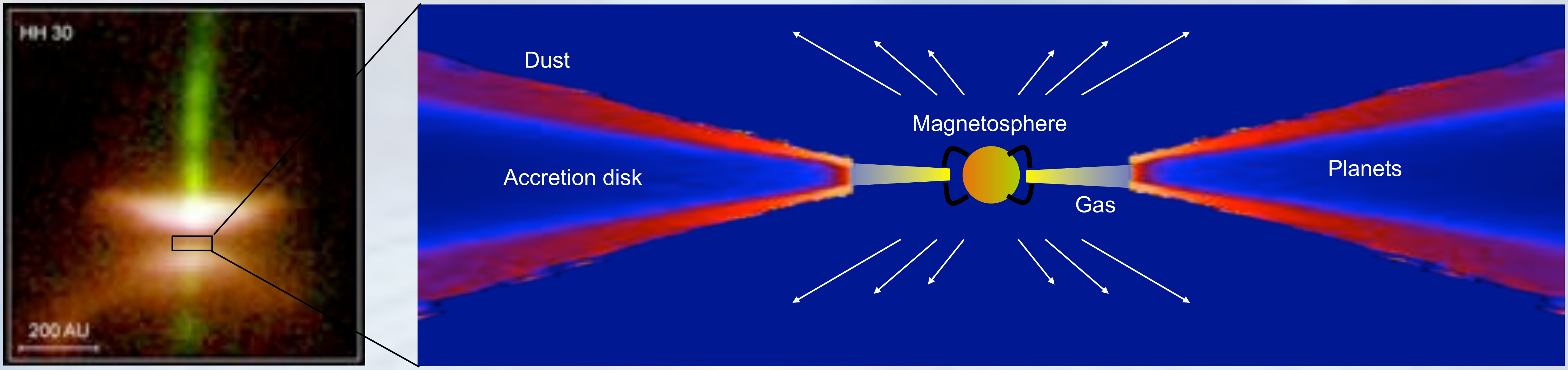


Bouvier & Malbet (2001, DPLS, 30, 84)

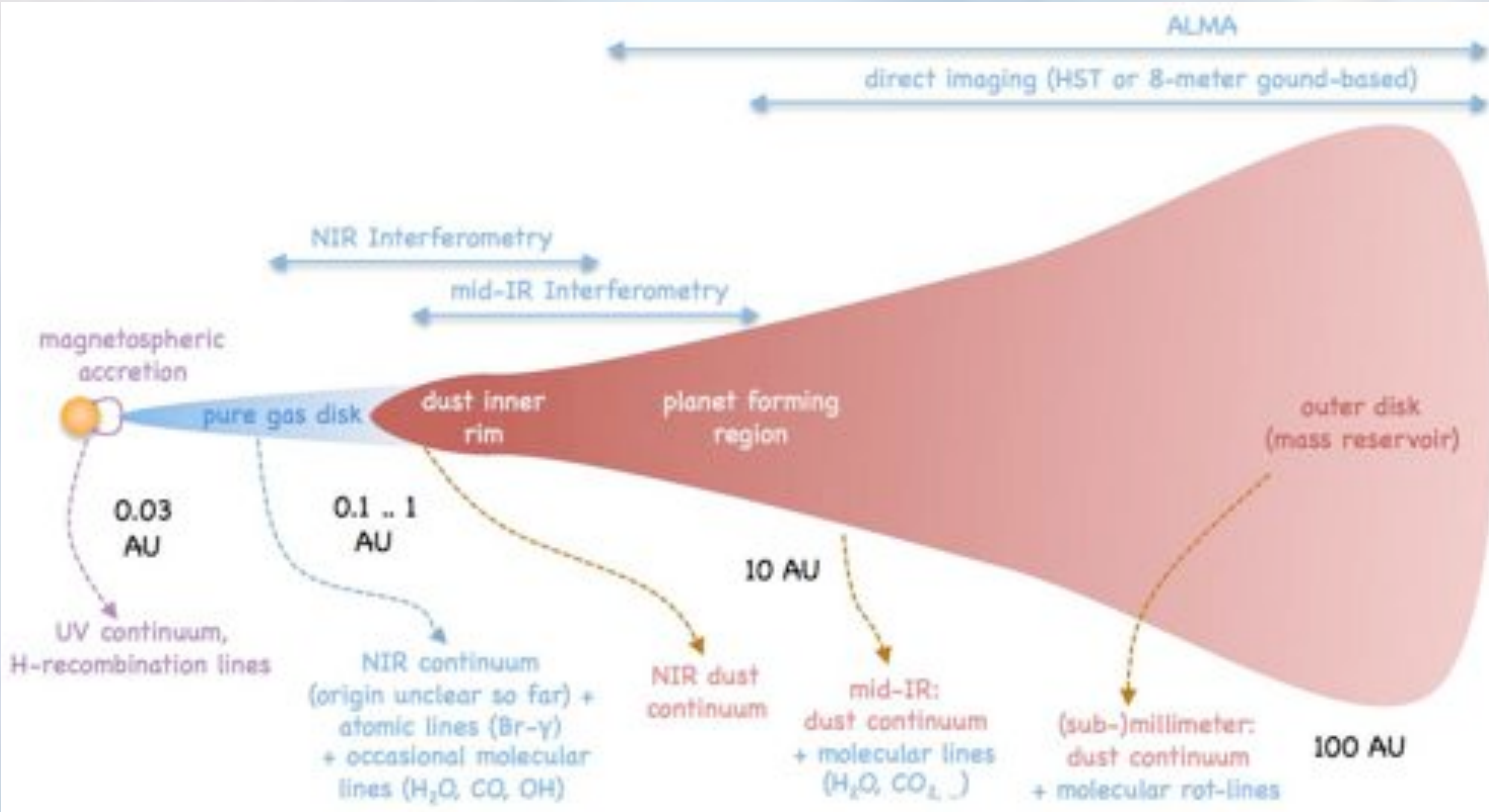
Physical conditions in the close environment of young stellar objects



- **Physical phenomena**
  - Keplerian accretion disk: gas + dust
  - Stars from K to B spectral types (4000K to 10000K)
  - Strong outflowing wind
  - Companions
  - Magnetophere
  - Protoplanets
- **Physical conditions**
  - Radius ranging from 0.1 AU to 10 AU
  - Temperature ranging from 150 K to 4000 K
  - Velocity ranging from 10 km/s to few 100 km/s

➡ **At 150 pc (Taurus), this corresponds to :**
$1\mu m \leq \lambda \leq 20\mu m$ and spatial scales between **0.5 et 70 mas**

Close environment of young stars



Dullemond & Monnier (2010, ARAA)

Instrumental requirements

- **Wavelength domain**

  Temperature ranges → **λ ~ 1 to 20 µm:**

- **Angular resolution**

  Spatial scales

1.22 λ/D	0.1 AU	1AU	5AU	10AU
75pc	1.5mas	15mas	70mas	150mas
150pc	0.7mas	7mas	30mas	70mas
450pc	0.2mas	2mas	10mas	20mas

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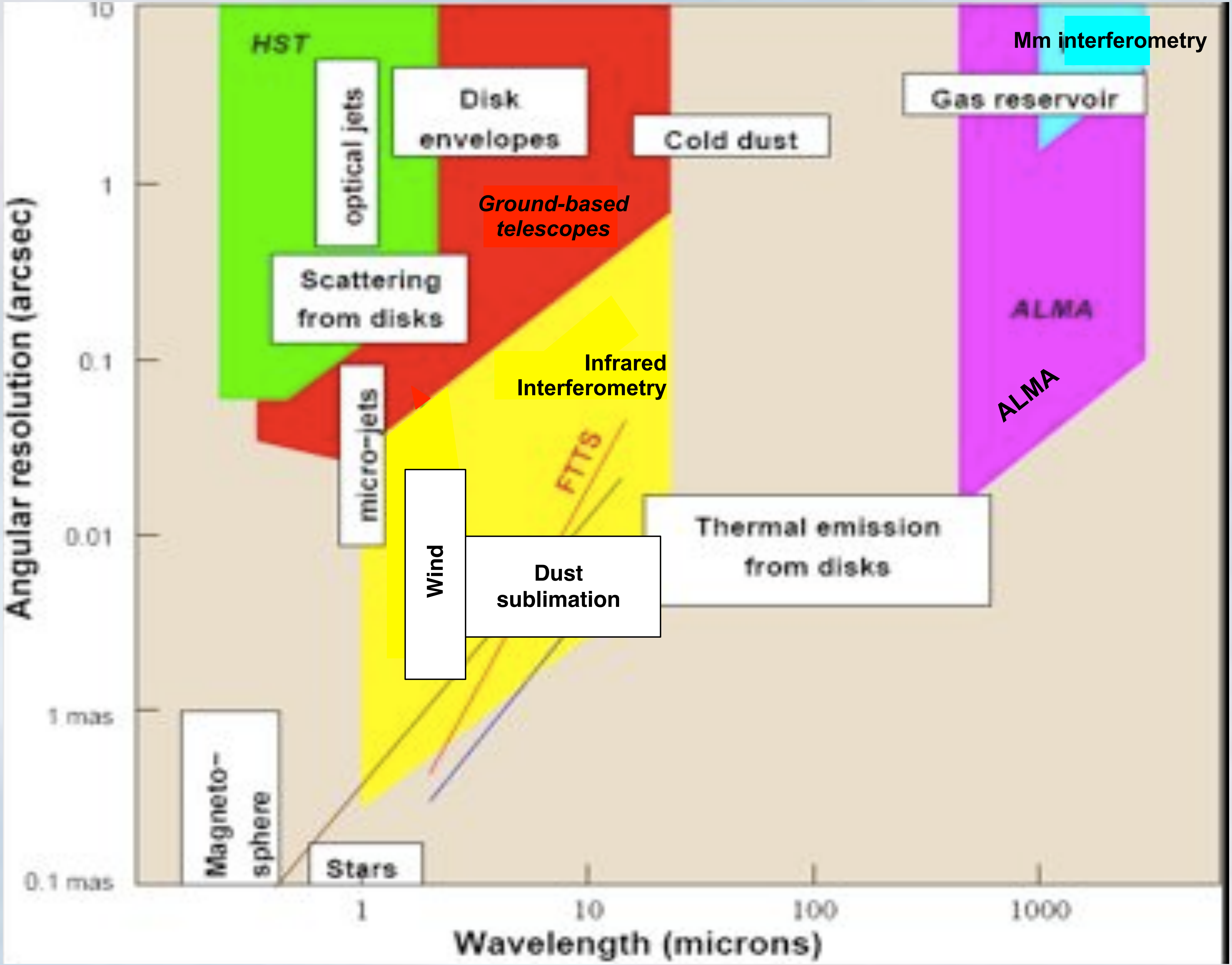
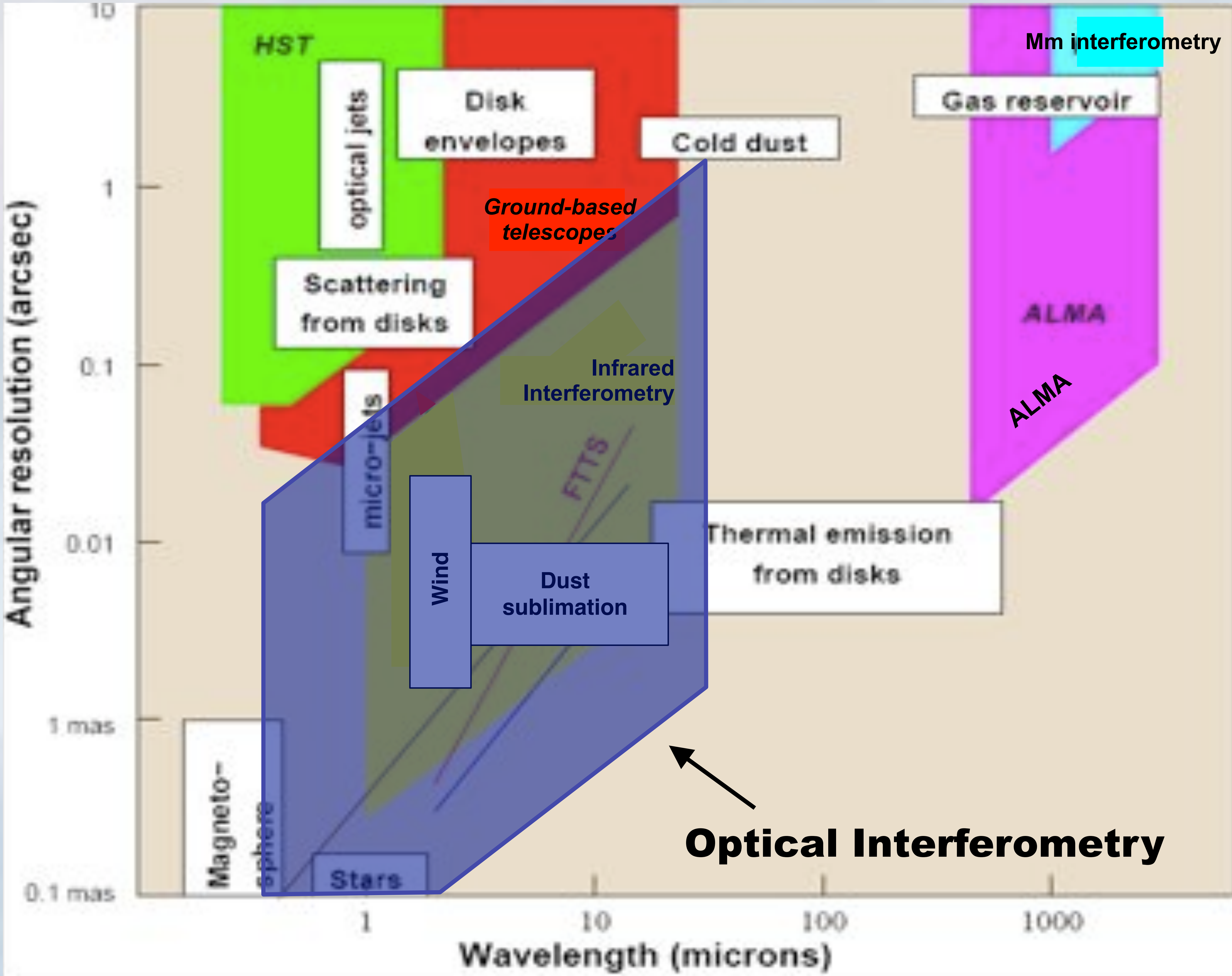
Spatial telescope

Adaptive optics

Interferometry



Angular resolution (arcsec)
10
1
0.1
0.01
1 mas
0.1 mas
Wavelength (microns)
1
10
100
1000
HST
optical jets
Disk envelopes
Cold dust
Gas reservoir
Mm interferometry
Ground-based telescopes
Scattering from disks
micro-jets
Infrared Interferometry
ALMA
ALMA
FTTS
Wind
Dust sublimation
Thermal emission from disks
Magneto-sphere
Stars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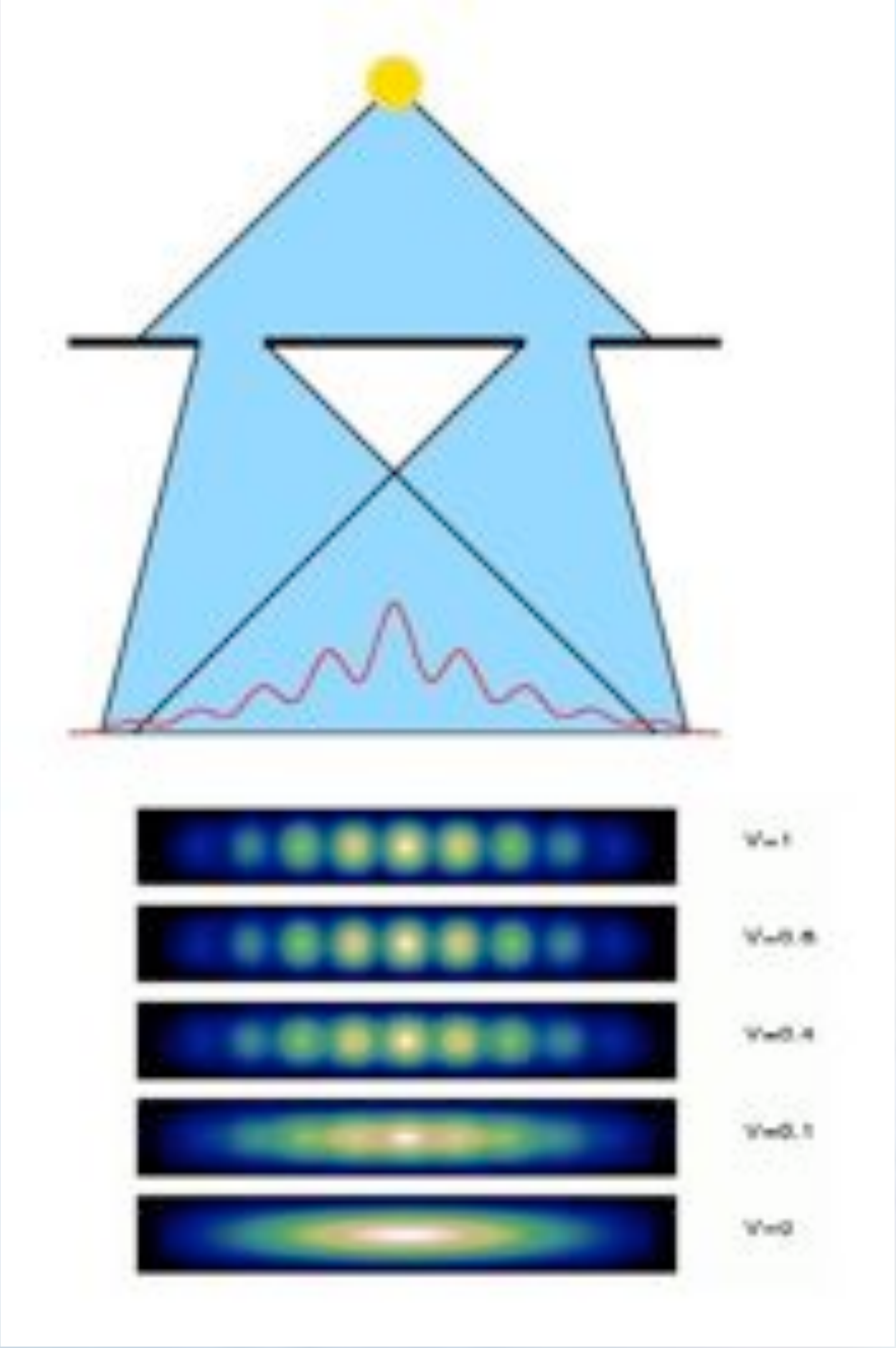
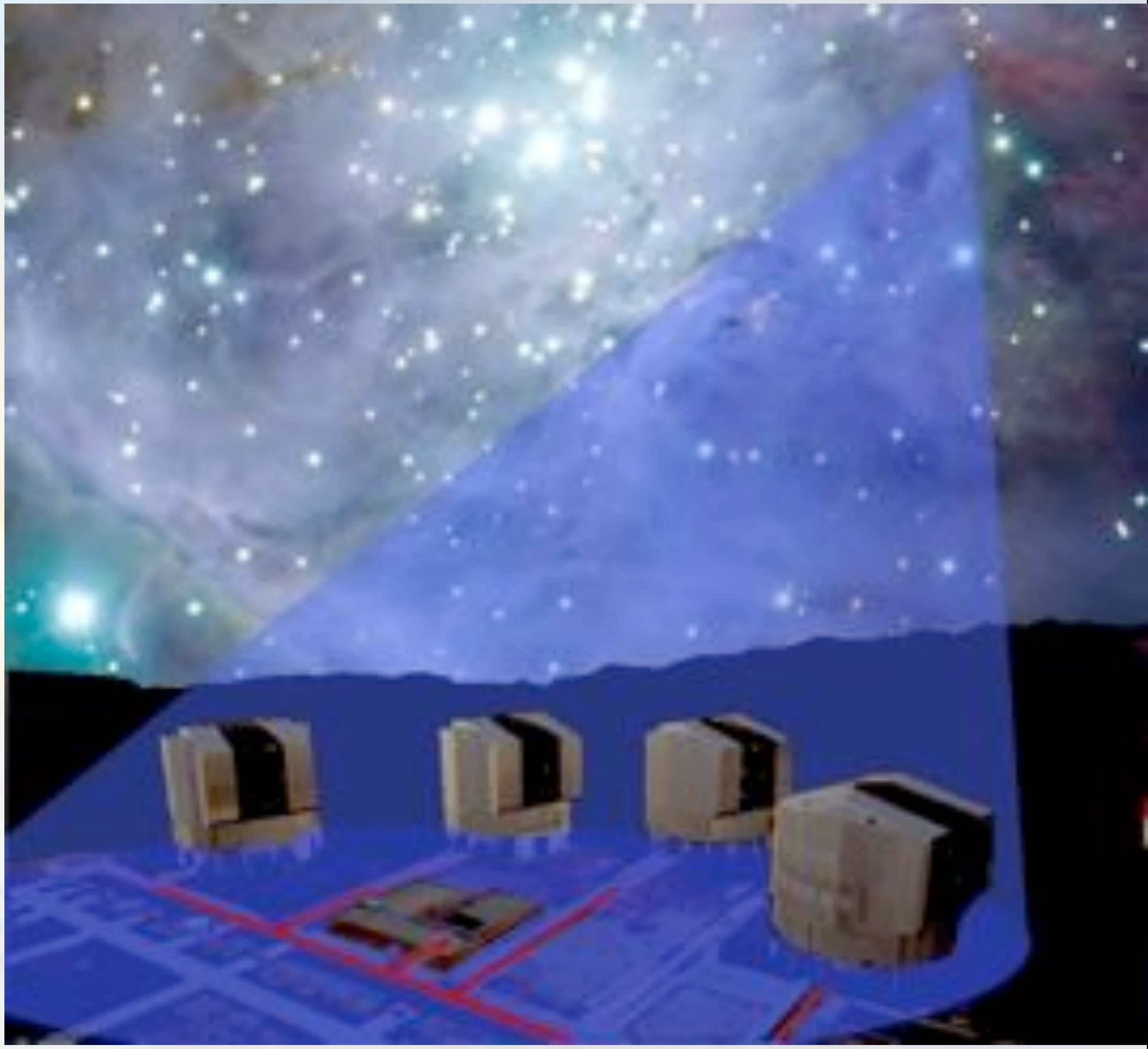
Dust sublimation
Thermal emission from disks
Magneto-sphere
Stars
Optical Interferometry
Angular resolution (arcsec)
10
1
0.1
0.01
1 mas
0.1 mas
1
10
100
1000
Wavelength (microns)

Infrared and visible Interferometry

- Principles and observables
- Instruments available for YSO studies
- Elements of bibliography on YSO science results

Basics of optical interferometry





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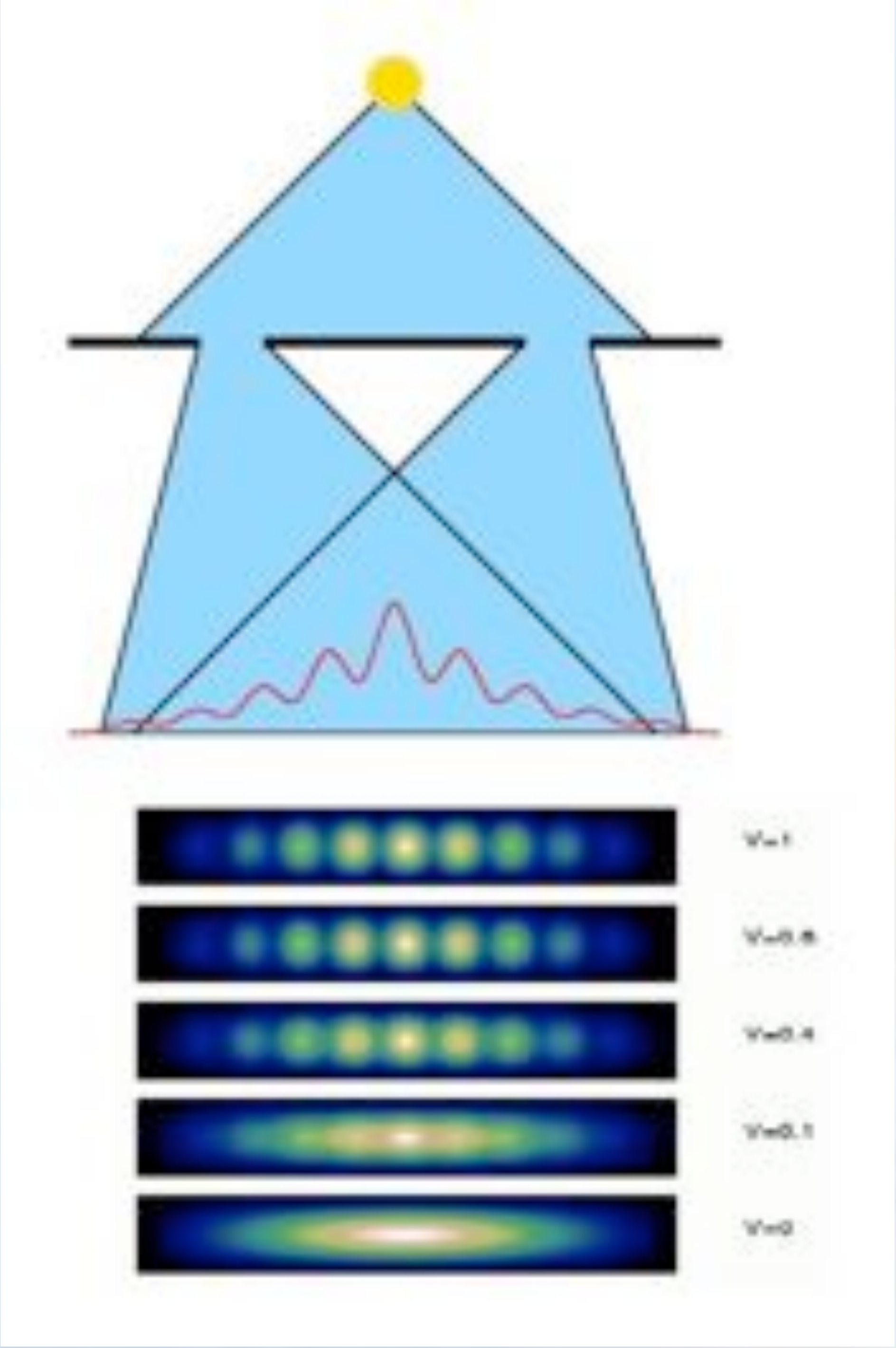
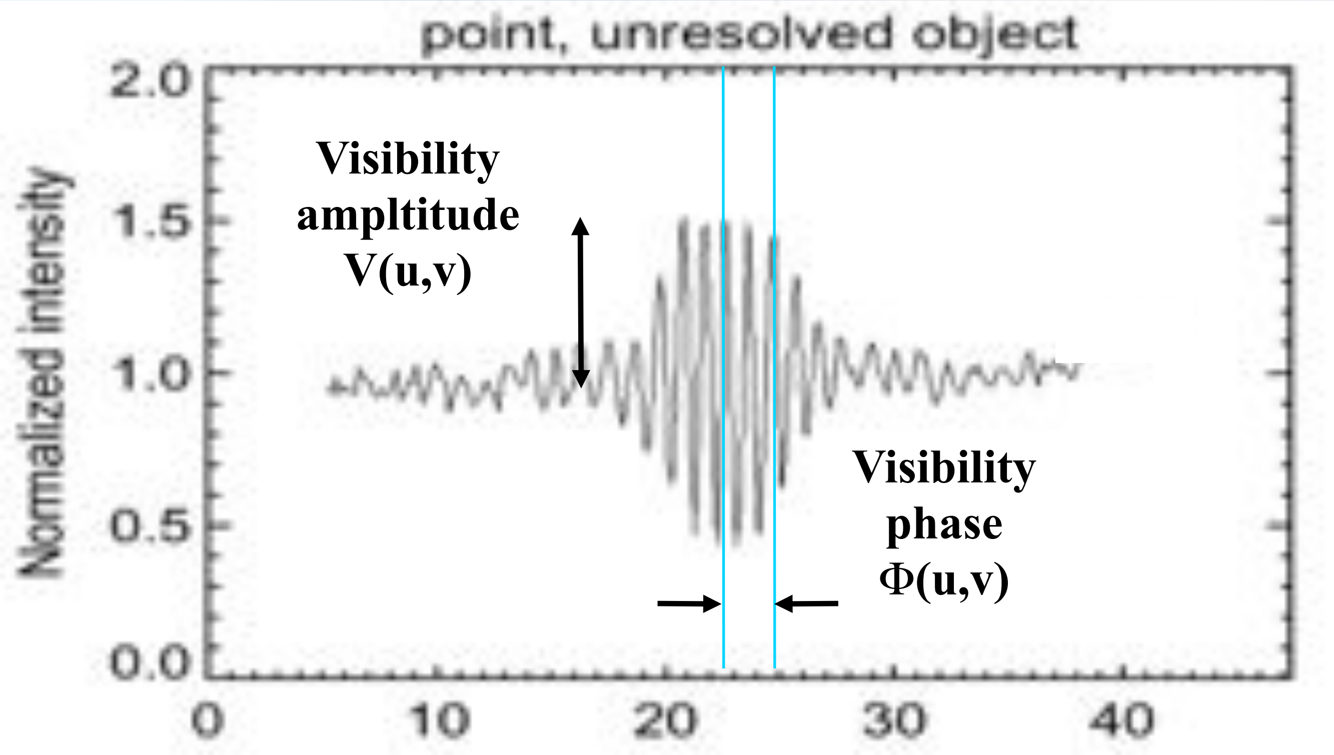
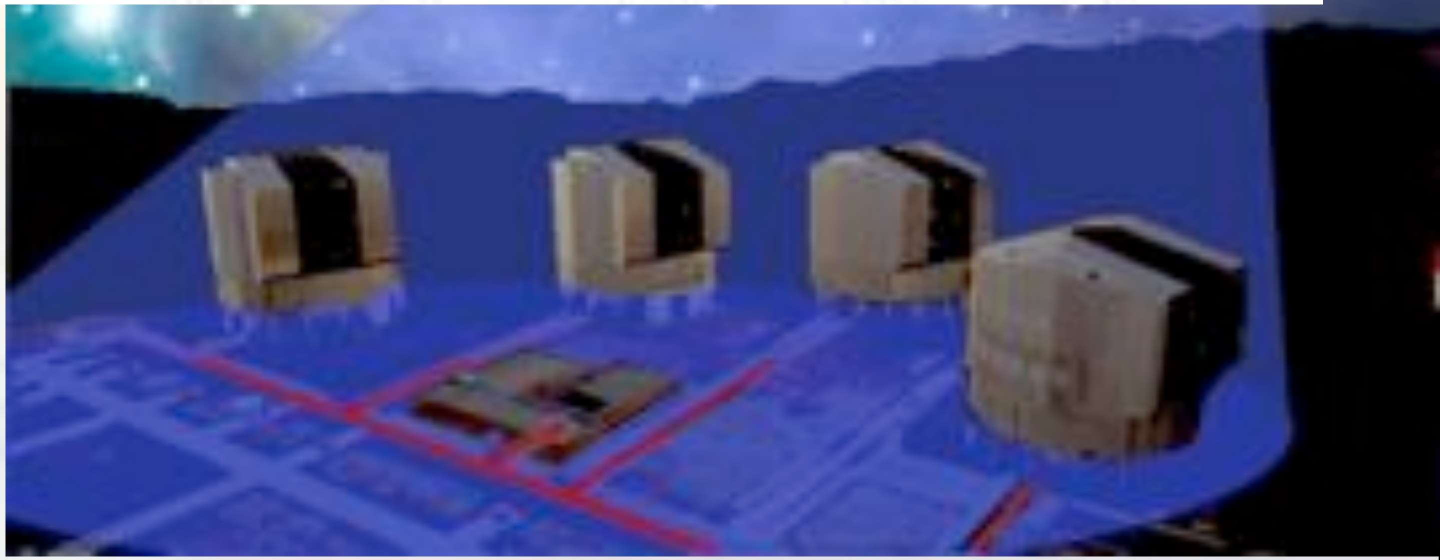
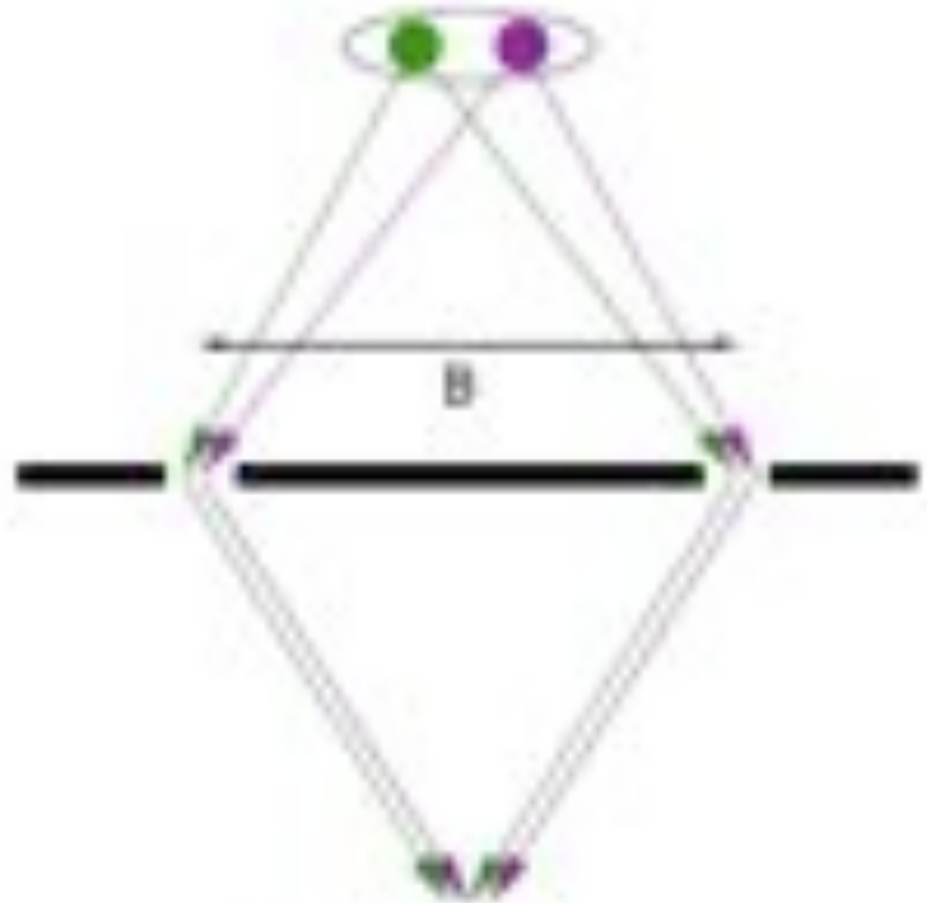
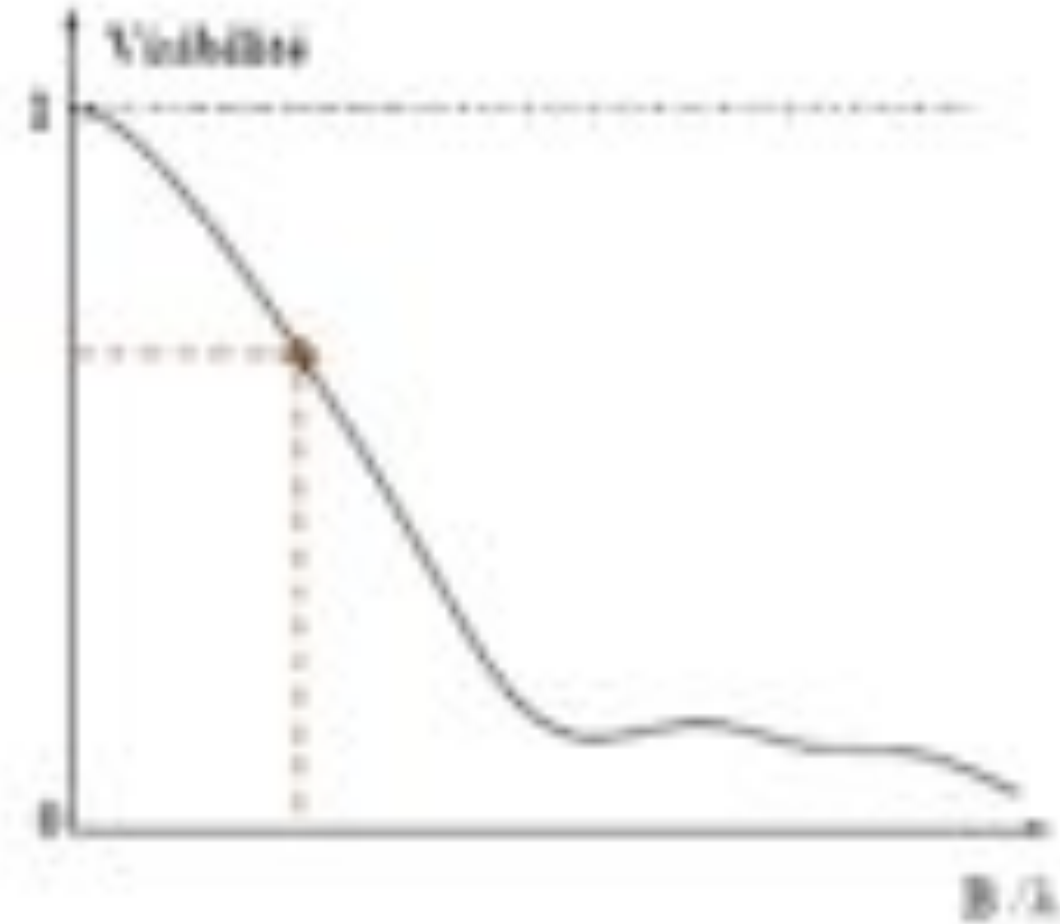






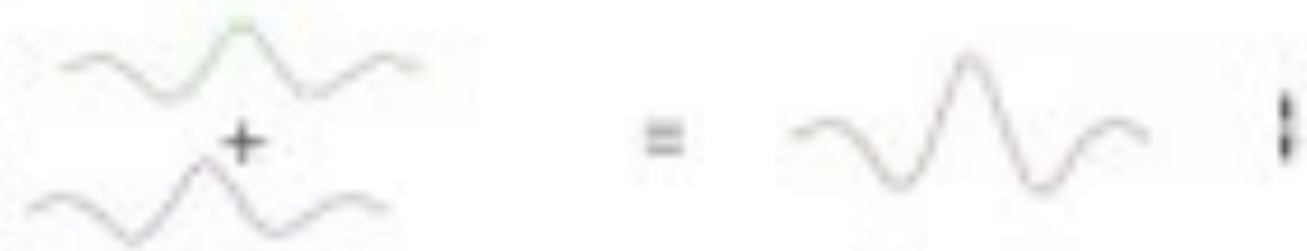
Spatial coherence





Interferogram 1

Interferogram 2

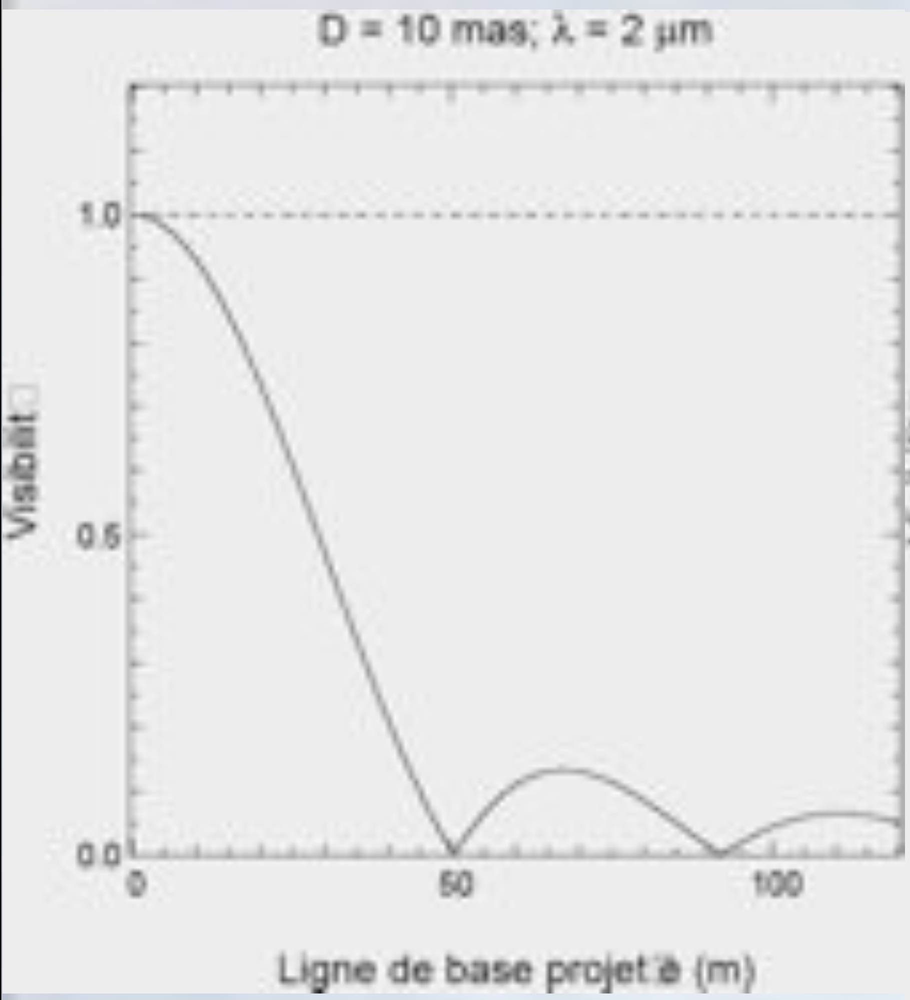


Reduced contrast
Shifted phase

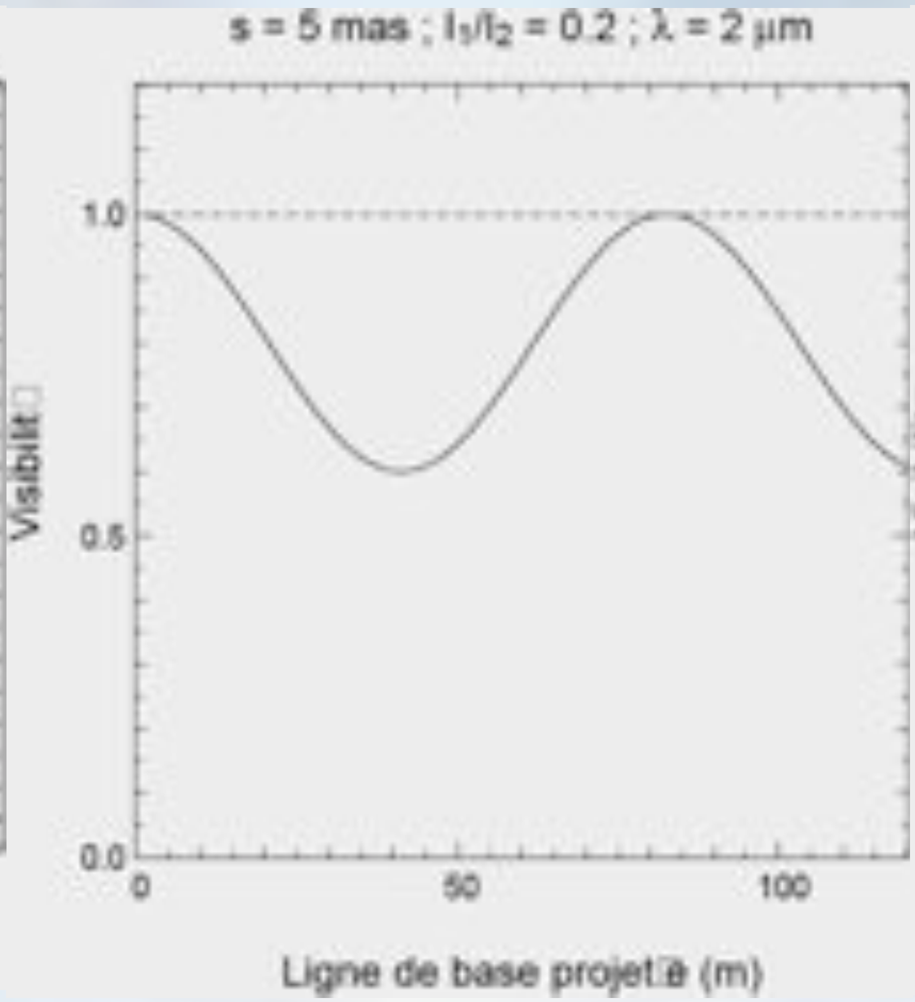
Zernicke-van Cittert theorem

Visibility = Fourier transform of the brightness spatial distribution

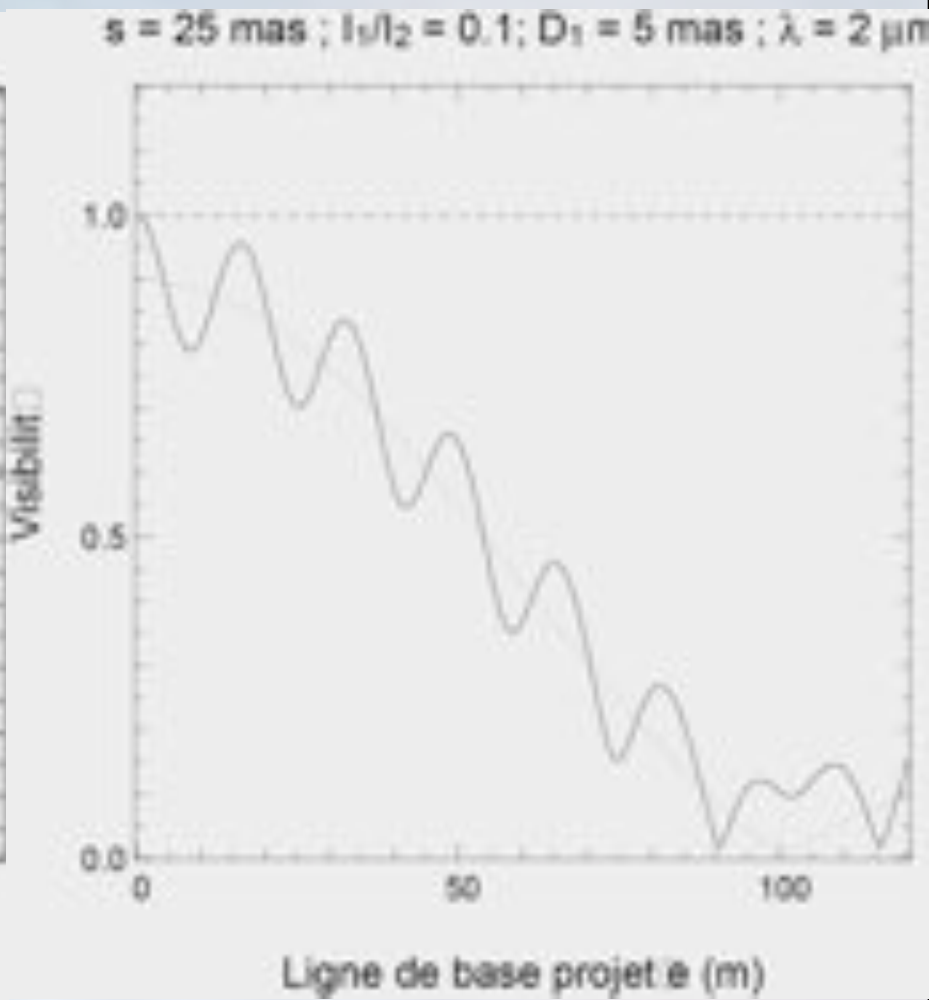
Visibilities



Uniform disk



Binary with unresolved components



Binary with resolved component

Interferometers involved in YSO research

Facility	Instrument	Wavelength (microns)	# tel.	Tel. Diam. (m)	Baseline (m)
Existing facilities					
PTI	V²	H, K	3	0.4	80-110
IOTA	V², CP	H, K	3	0.4	5-38
ISI	Heterodyne	11	2/3	1.65	4-70
KI	V²	K, L / spectral	2	10	80
	nulling	N			
VLTI	AMBER: V², CP	1-2.5 / spectral	3 / 4 (8)	8.2	40-130
	MIDI: V², V	8-13 / spectral	2 / 4 (8)	1.8	8-200
CHARA	V², CP, Imaging	1-2.5 (spectral)	2/4 (6)	1	50-350
Future facilities					
LBT	V², nulling	1-12 μm	2	8.4	6-23
MROI	V², CP, imaging	V, NIR	3/6 (10)	1.4	7.5-340

Interferometers involved in YSO research

<table>
<tr><th>Facility</th><th>Instrument</th><th>Wavelength (microns)</th><th colspan="2"># tel.</th><th>Tel. Diam. (m)</th><th>Baseline (m)</th></tr>
<tr><td colspan="7">Existing facilities</td></tr>
<tr><td><s>PTI</s></td><td><s>V²</s></td><td><s>H, K</s></td><td colspan="2"><s>3</s></td><td><s>0.4</s></td><td><s>80-110</s></td></tr>
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<tr><td rowspan="2">KI</td><td>V²</td><td>K, L / spectral</td><td colspan="2" rowspan="2">2</td><td rowspan="2">10</td><td rowspan="2">80</td></tr>
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Interferometers involved in YSO research

Small apertures

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Interferometers involved in YSO research

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Large apertures

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Spectral resolution

Interferometers involved in YSO research

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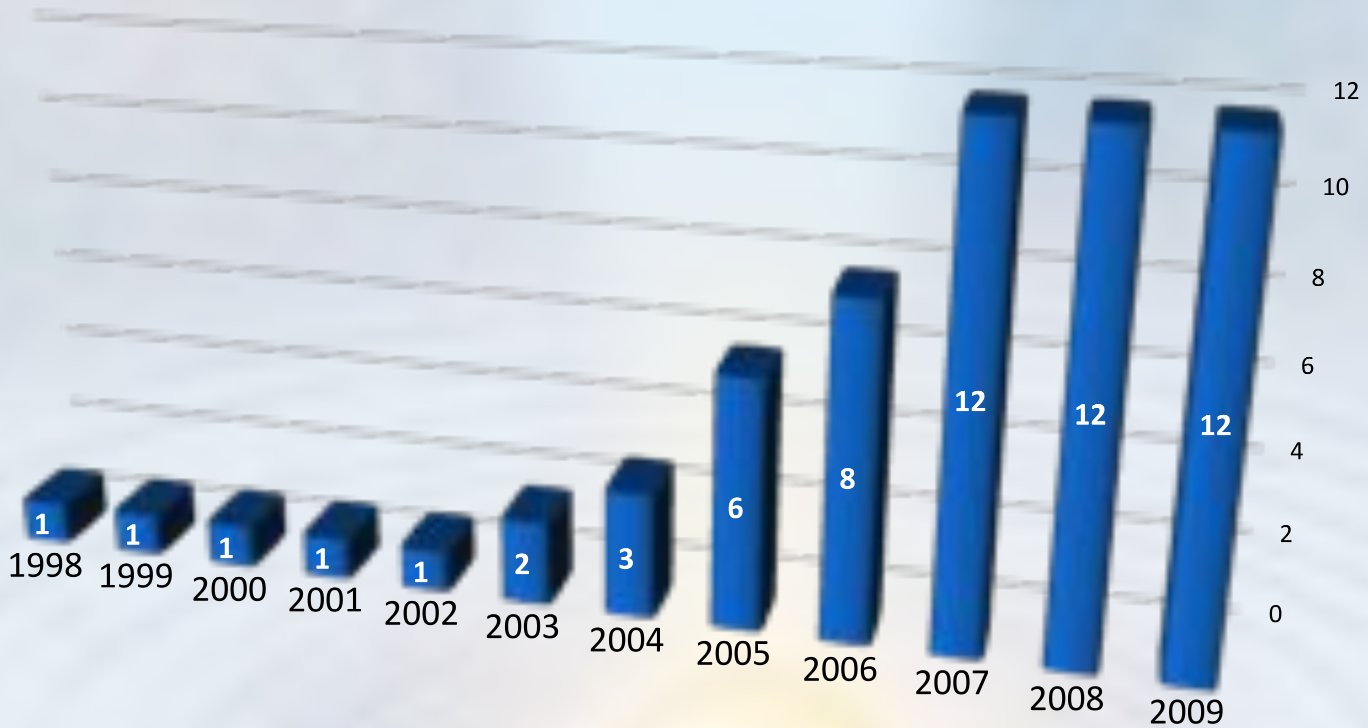
Interferometry publication OLBIN database

http://olbin.jpl.nasa.gov

→ **71 astrophysical results published to date, ~100 objects observed.**

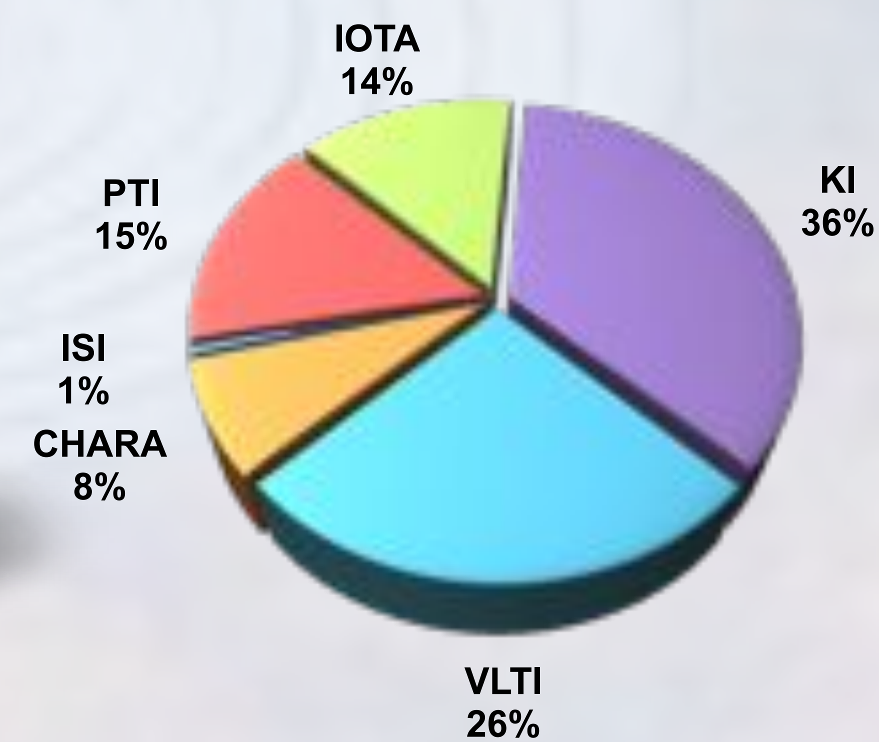
YSOs + Debris disks observed (1998-2009)

Refereed papers



Number of observations

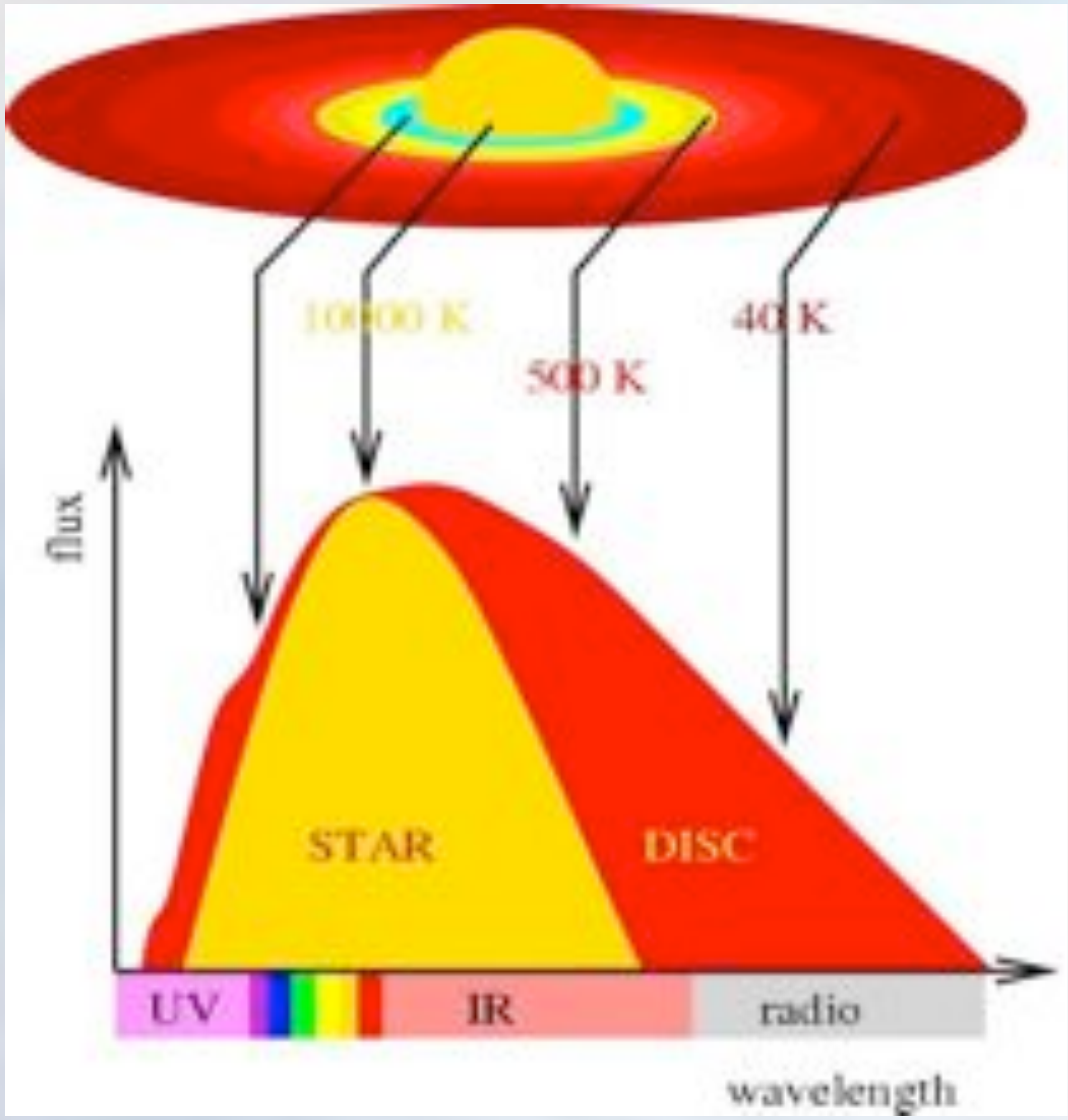
Interferometers

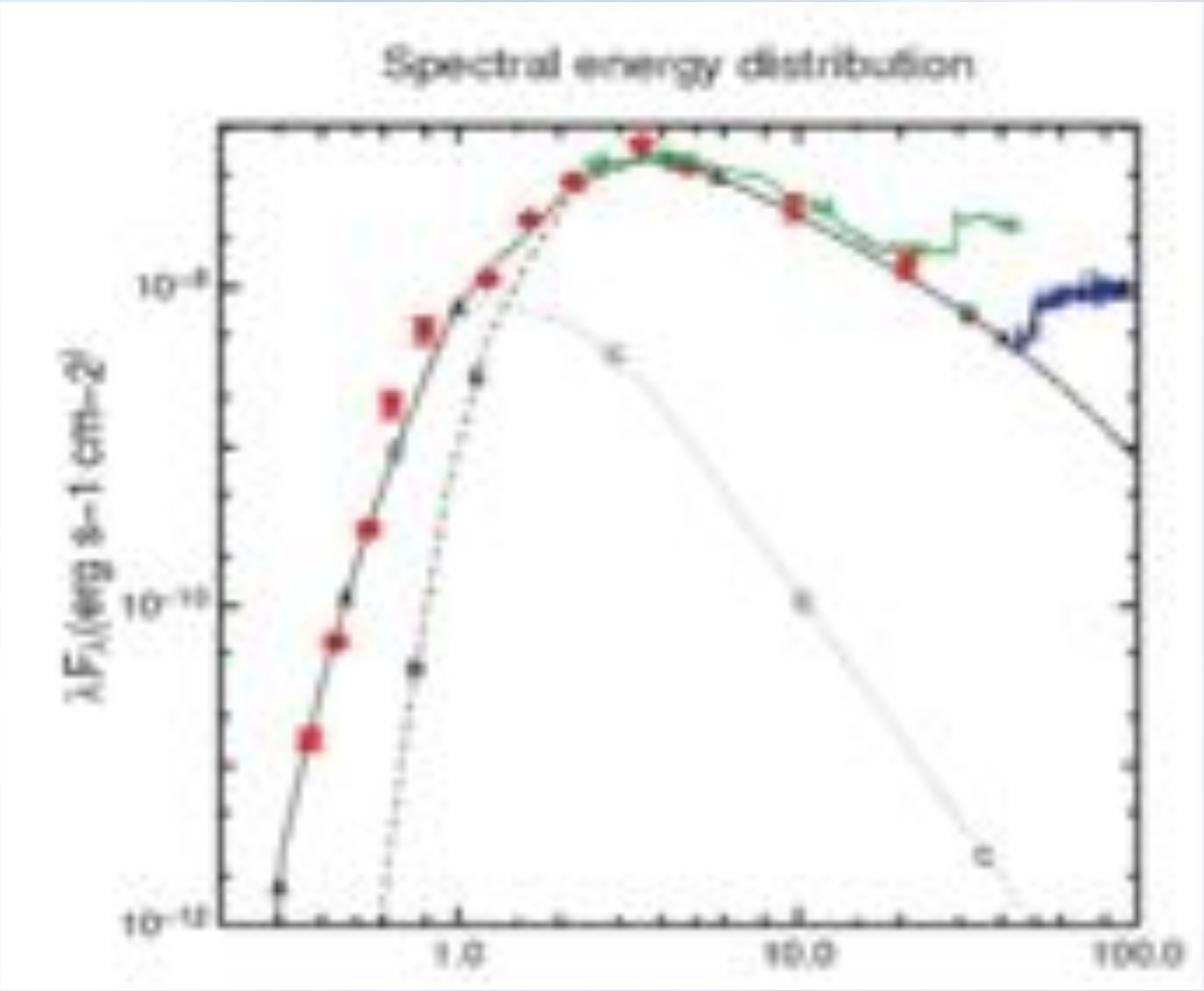


INNER DISK PHYSICS

- – Disk structures
- – Constraints on disk structure (T, z,…)
- – Dust mineralogy
- – Gas/dust connection

UV and IR excesses in Spectral Energy Distribution

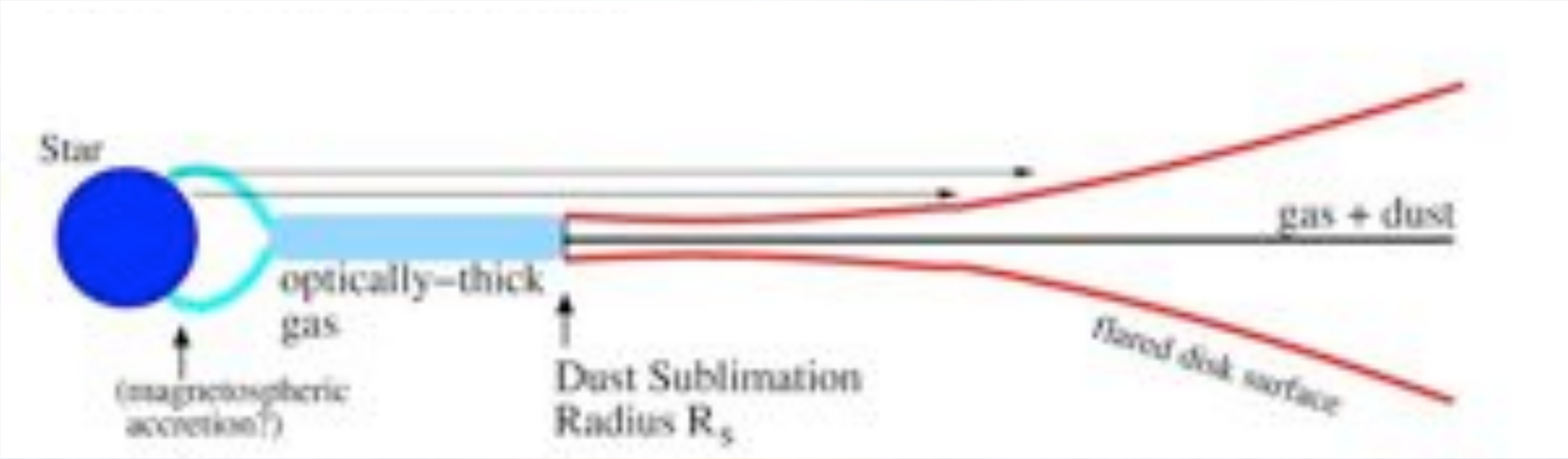




Geometrically thin optically thick accretion disk + irradiation
= « classical » accretion disk model

Malbet & Bertout (1995, A&AS)

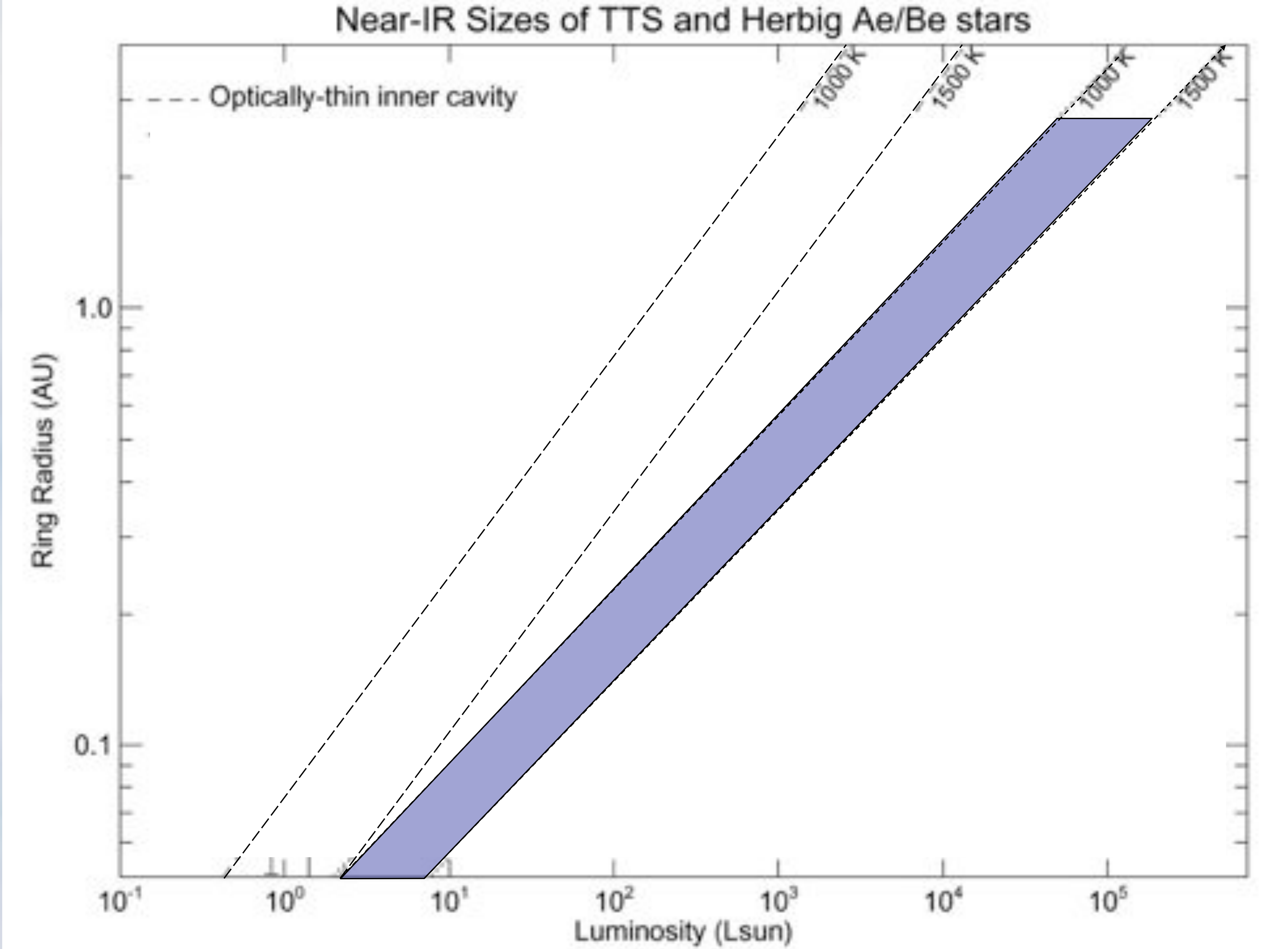
Original disk concept



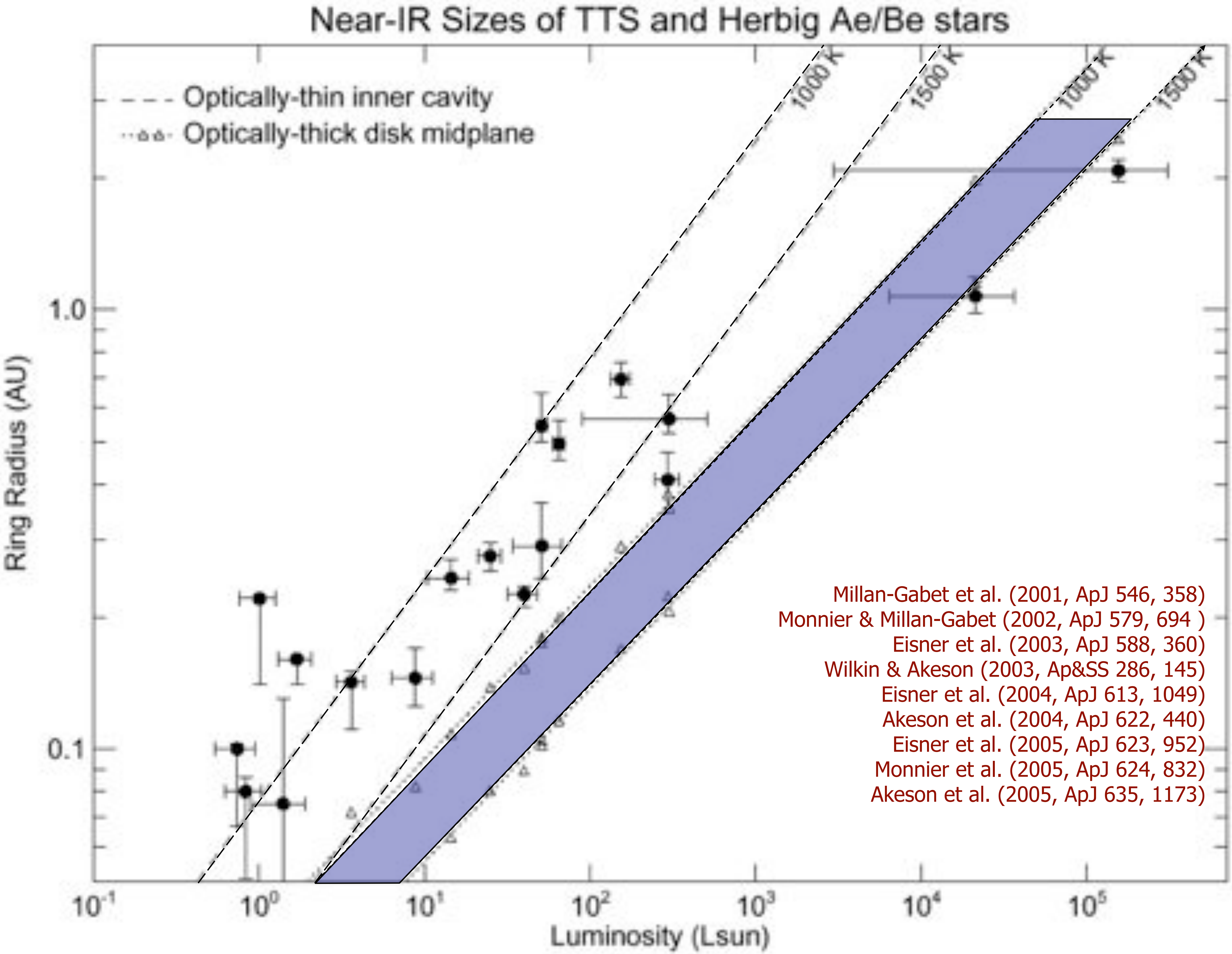
e.g. Malbet & Bertout (1995, A&AS 113, 369)

- **Optically thick disk both for inner gas and outer dust**
- **Simple power-law temperature distribution ($T \propto r^{-0.75}$, $T \propto r^{-0.5}$)**
- **Oblique disk heating**

→ fits rather well **spectral energy distributions (SEDs)**



Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
1000 K
1500 K
1000 K
1500 K
Ring Radius (AU)
1.0
0.1
Luminosity (Lsun)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



Millan-Gabet et al. (2001, ApJ 546, 358)
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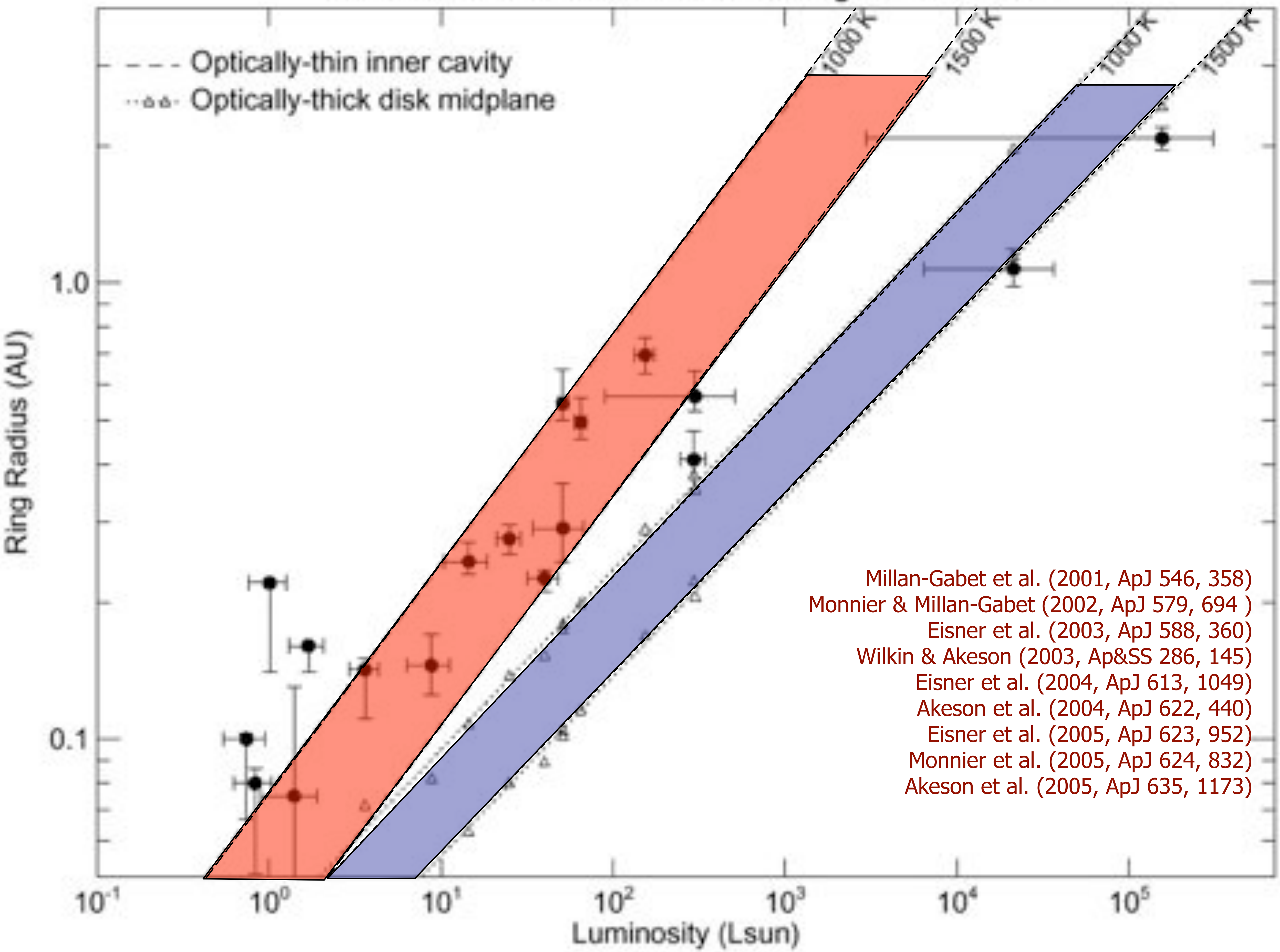
Near-IR Sizes of TTS and Herbig Ae/Be stars



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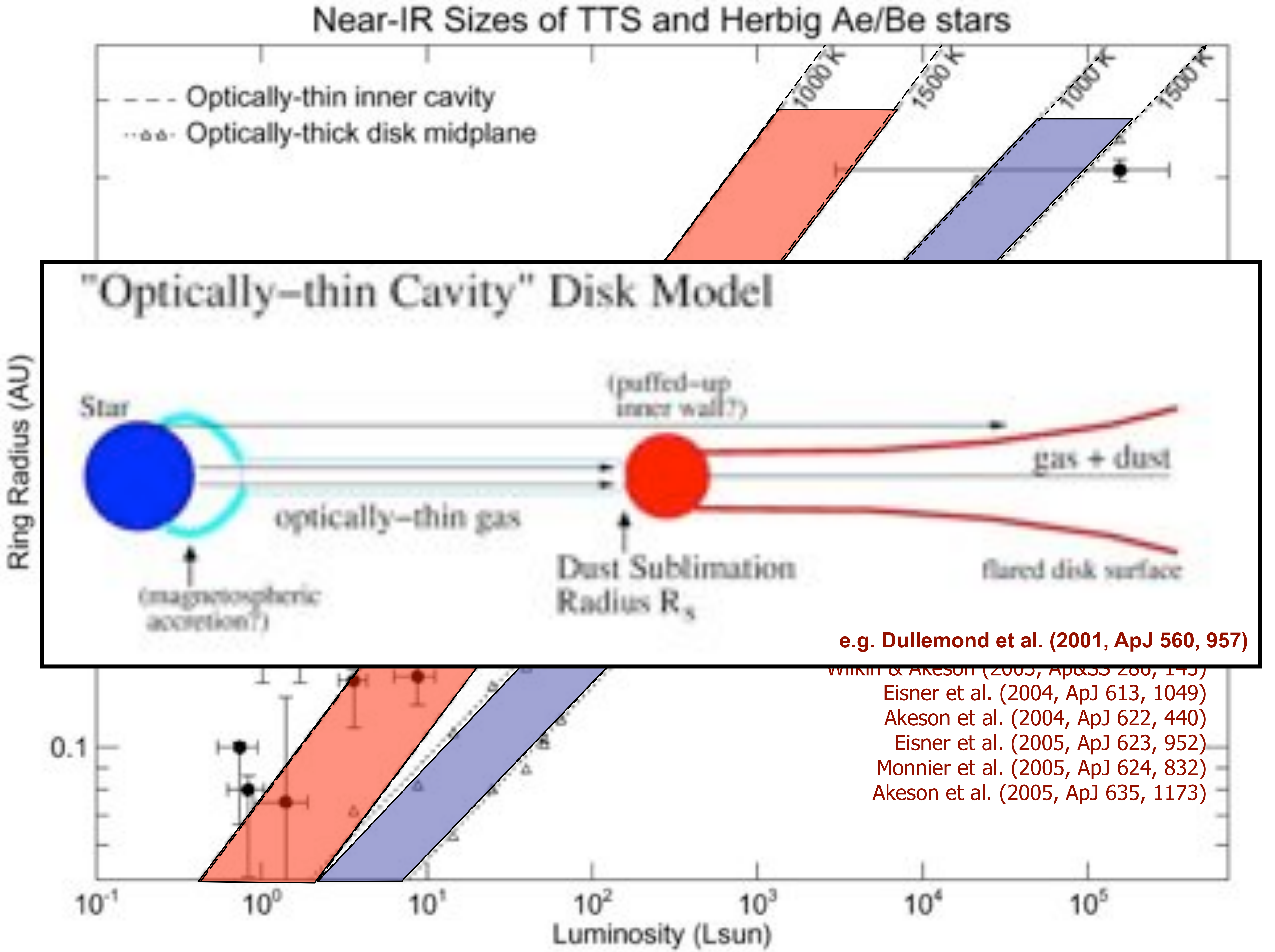

Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
Optically-thick disk midplane
1000 K
1500 K
1000 K
1500 K
"Optically–thin Cavity" Disk Model
Star
(puffed-up inner wall?)
gas + dust
optically–thin gas
(magnetospheric accretion?)
Dust Sublimation Radius R_s
flared disk surface
e.g. Dullemond et al. (2001, ApJ 560, 957)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
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Ring Radius (AU)
0.1
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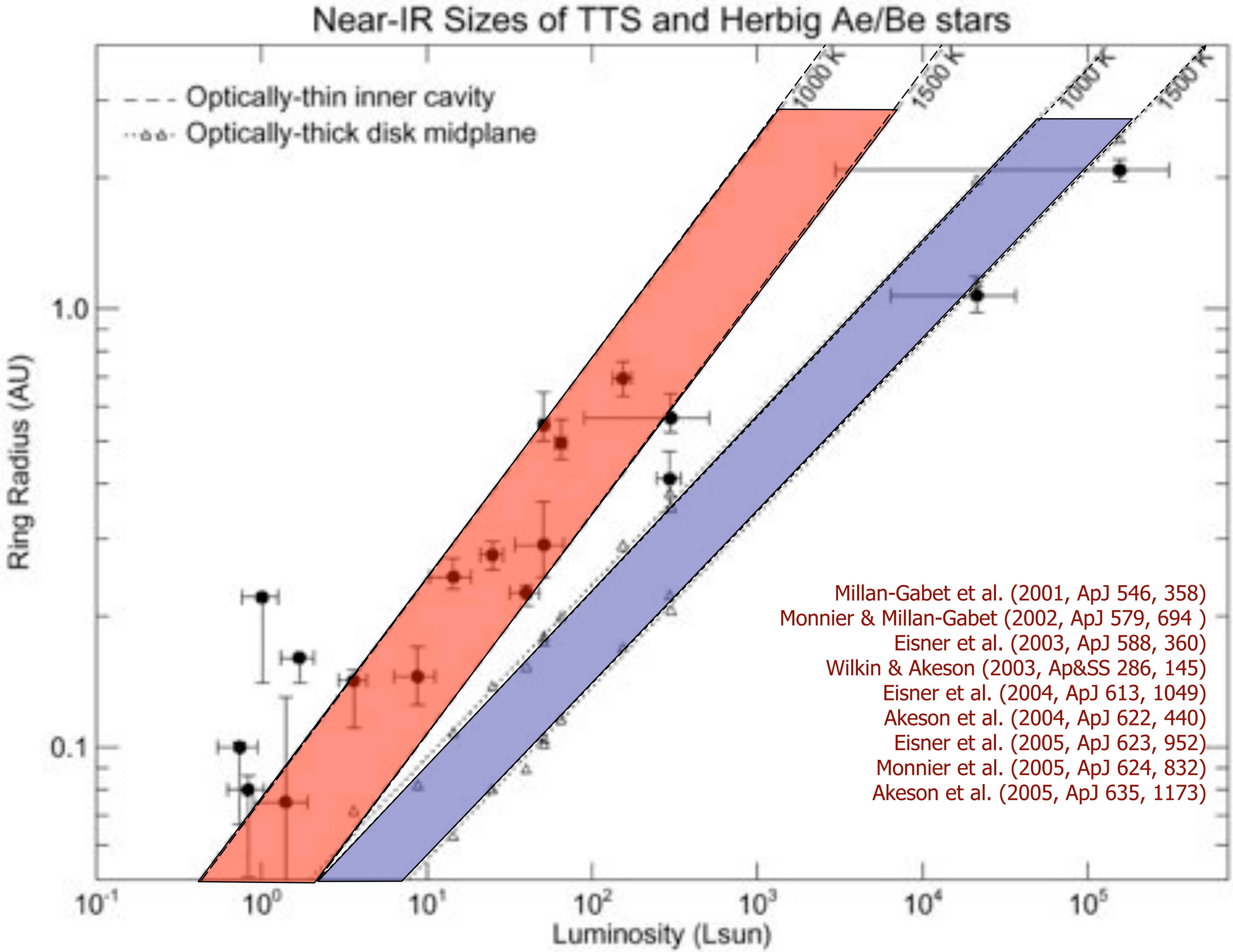
10^{5}
Luminosity (Lsun)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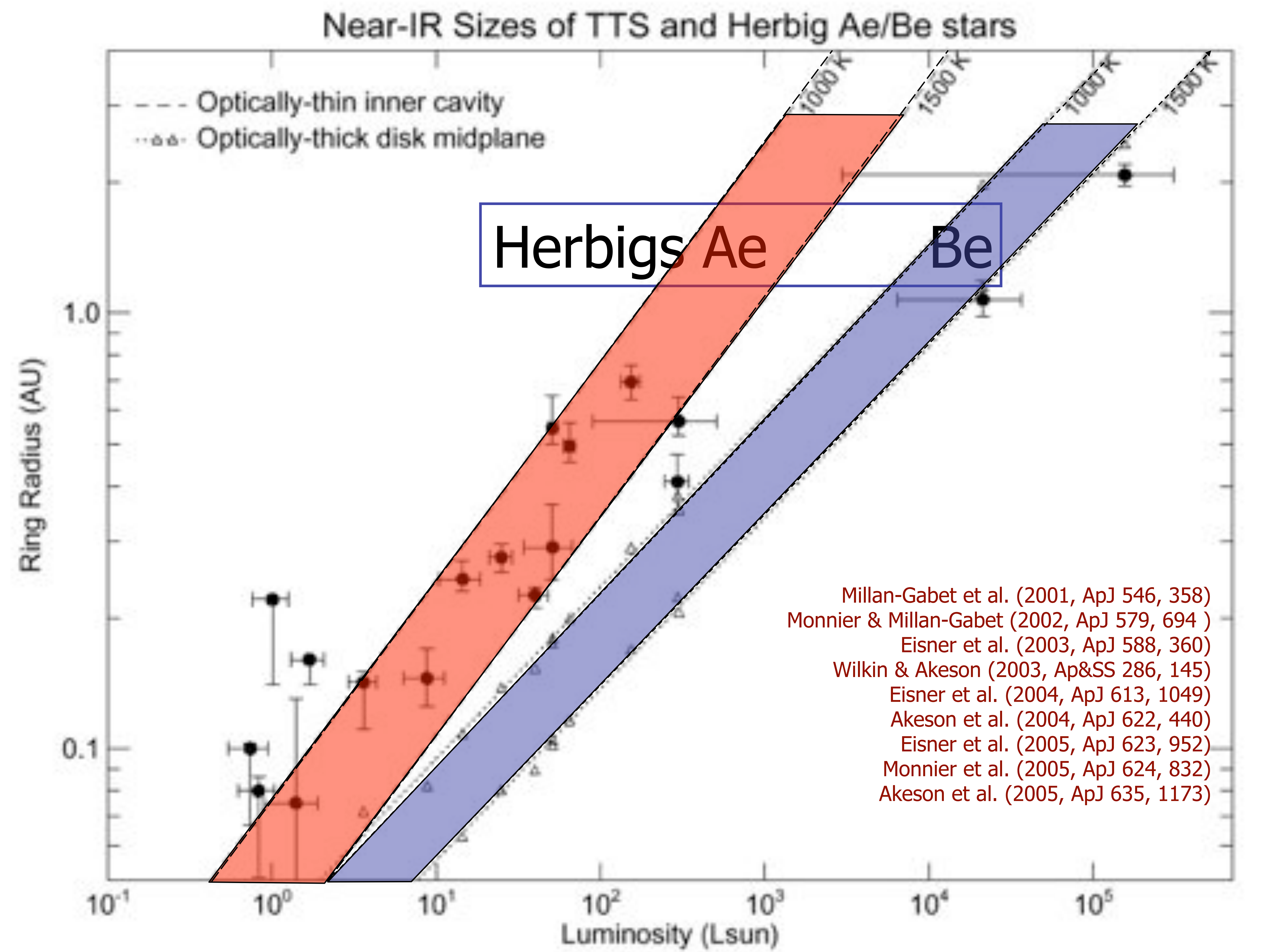

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10^{4}
10^{5}
Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
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Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
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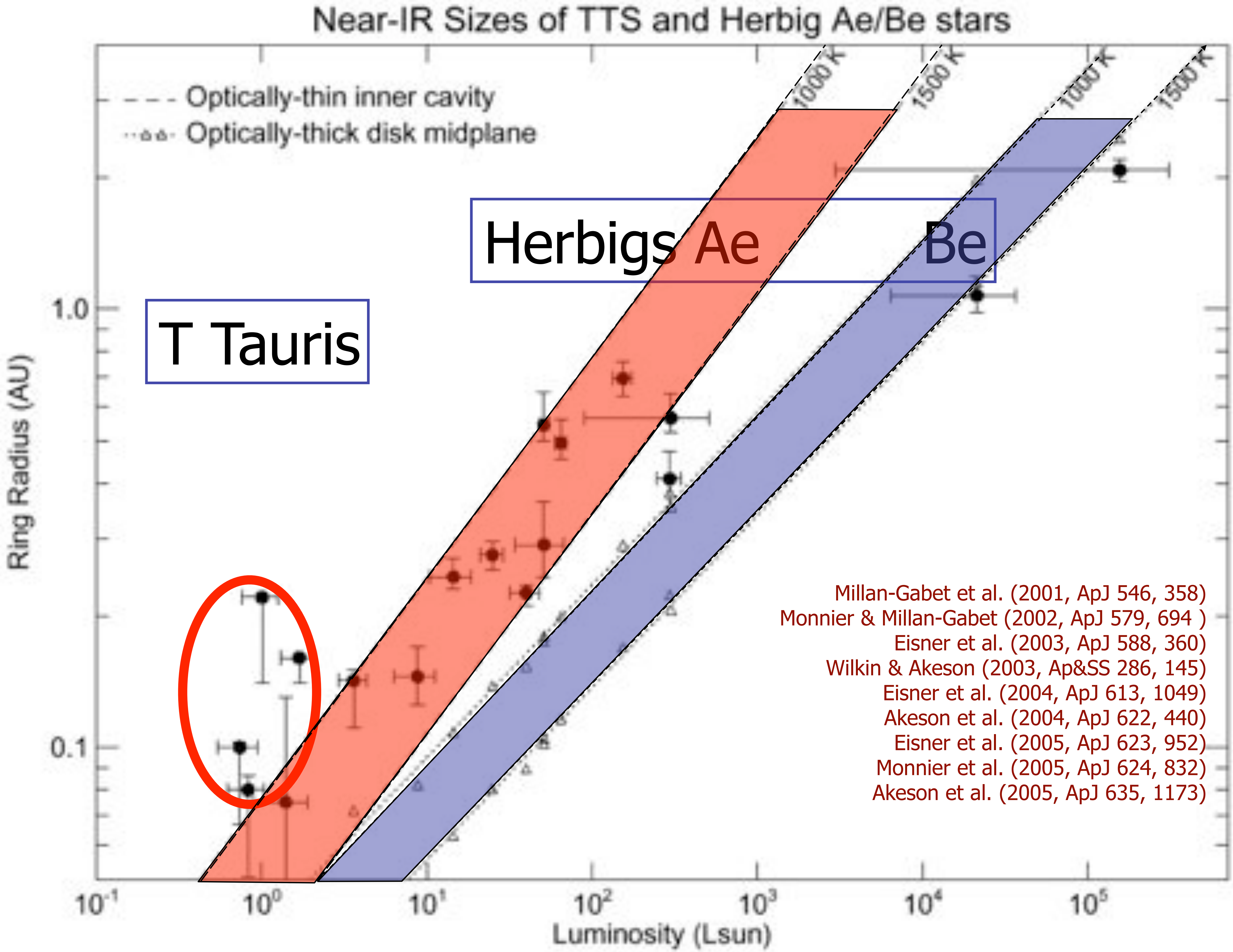
Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
Optically-thick disk midplane
1000 K
1500 K
1000 K
1500 K
Herbigs Ae Be
T Tauris
Ring Radius (AU)
1.0
0.1
Luminosity (Lsun)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
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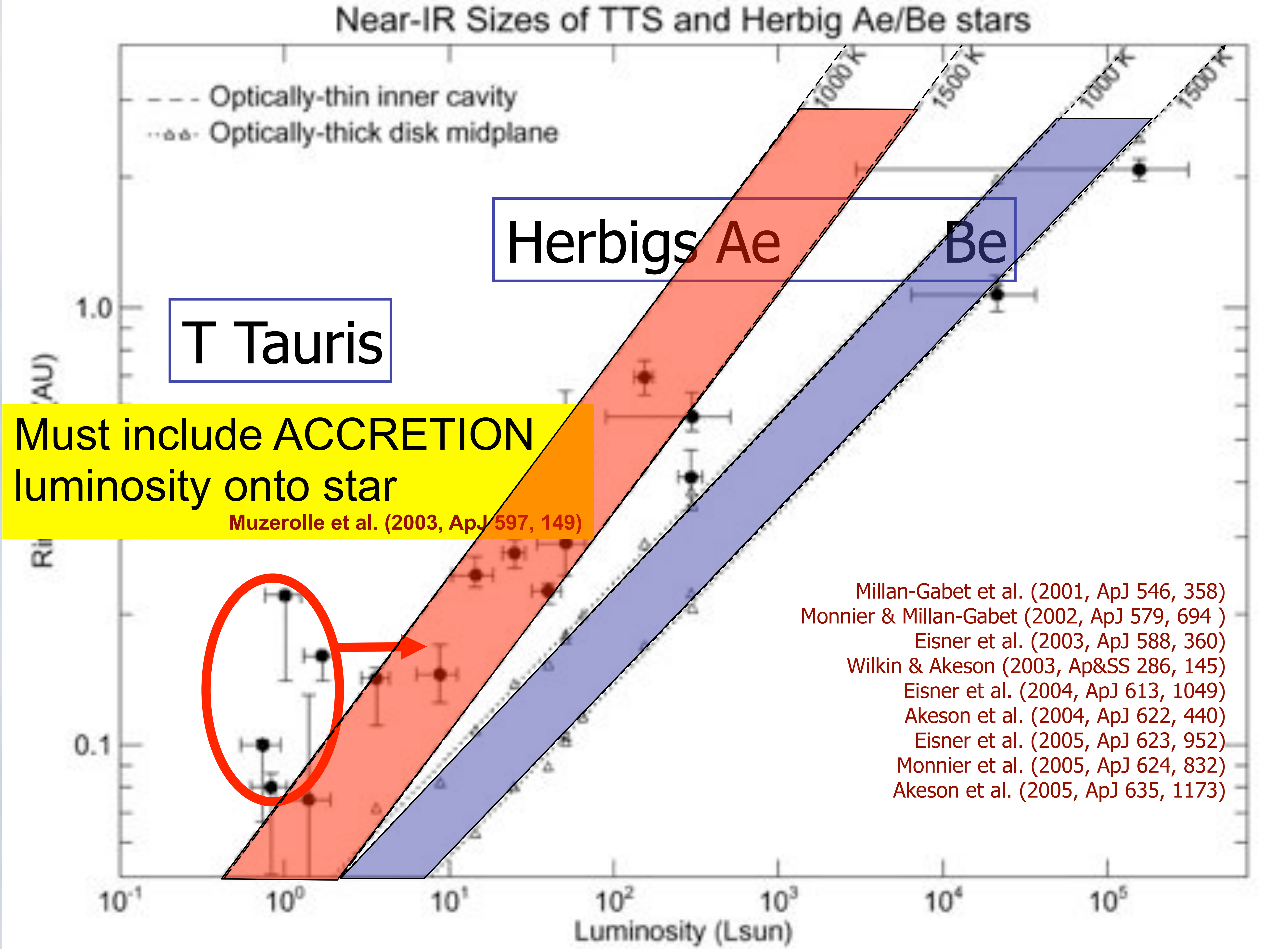

Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
Optically-thick disk midplane
1000 K
1500 K
1000 K
1500 K
Herbigs Ae Be
T Tauris
Must include ACCRETION luminosity onto star
Muzerolle et al. (2003, ApJ 597, 149)
1.0
0.1
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Luminosity (Lsun)
Millan-Gabet et al. (2001, ApJ 546, 358)
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Akeson et al. (2005, ApJ 635, 1173)

Inner region discussion

- Inner rim shapes: how sharp is it?
  Dust sublimation **Isella & Natta (2005, A&A 438, 899)**
  vs Dust settling & grain growth **Tannirkulam et al. (2007, ApJ 661, 374)**

- Inner hole? but
  - optically thick disk beyond the dust sublimation barrier
    e.g. TTS **Akeson et al. (2006, ApJ 635, 1173)**
  - disk halo with 0.15-0.8 optical depths

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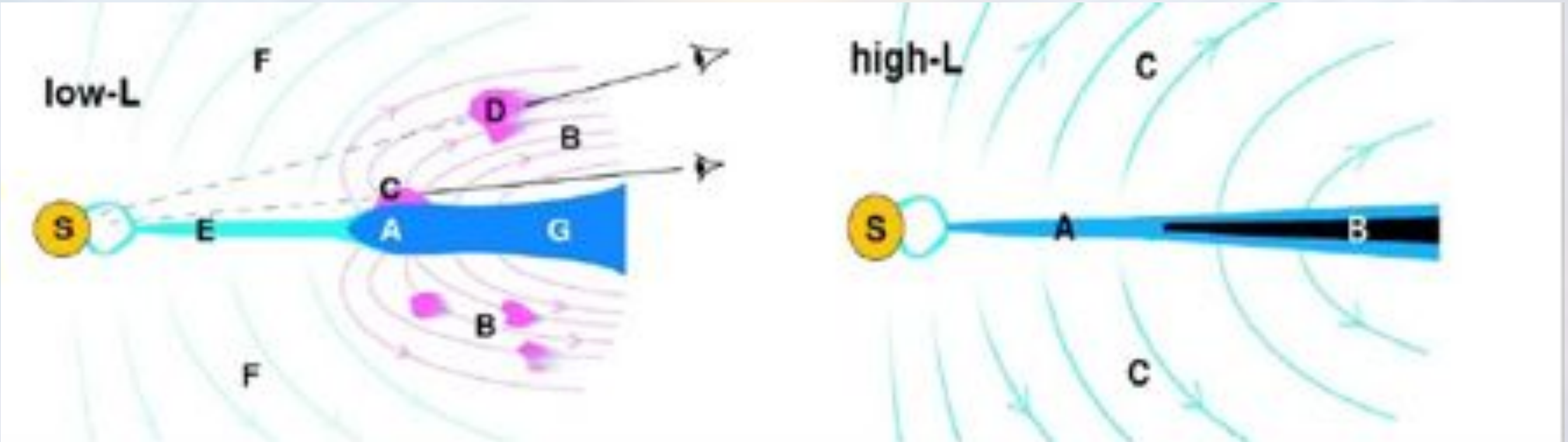
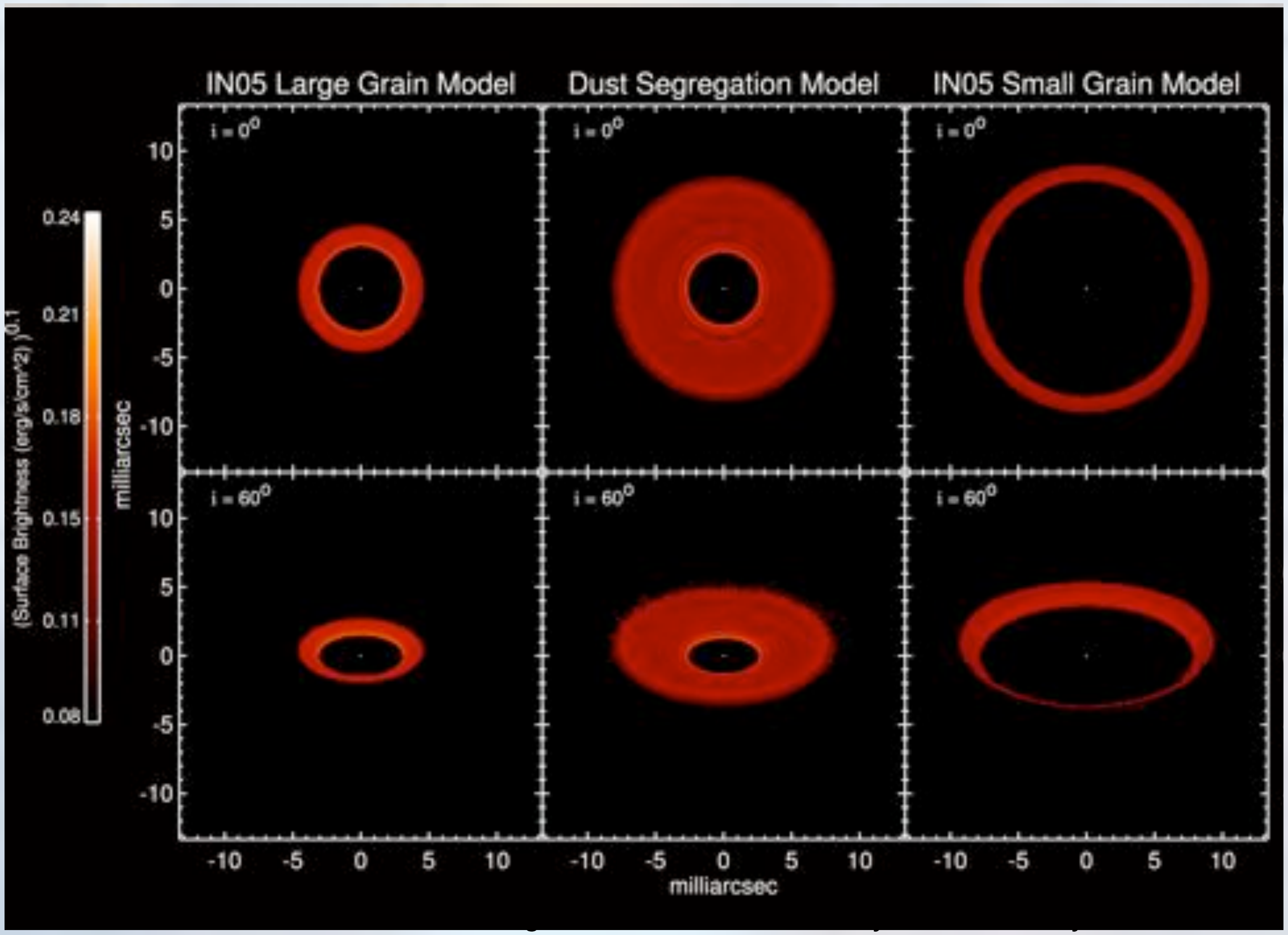
    Vinkovic & Jurkic (2007, ApJ 658..462)



The geometry of the inner rim

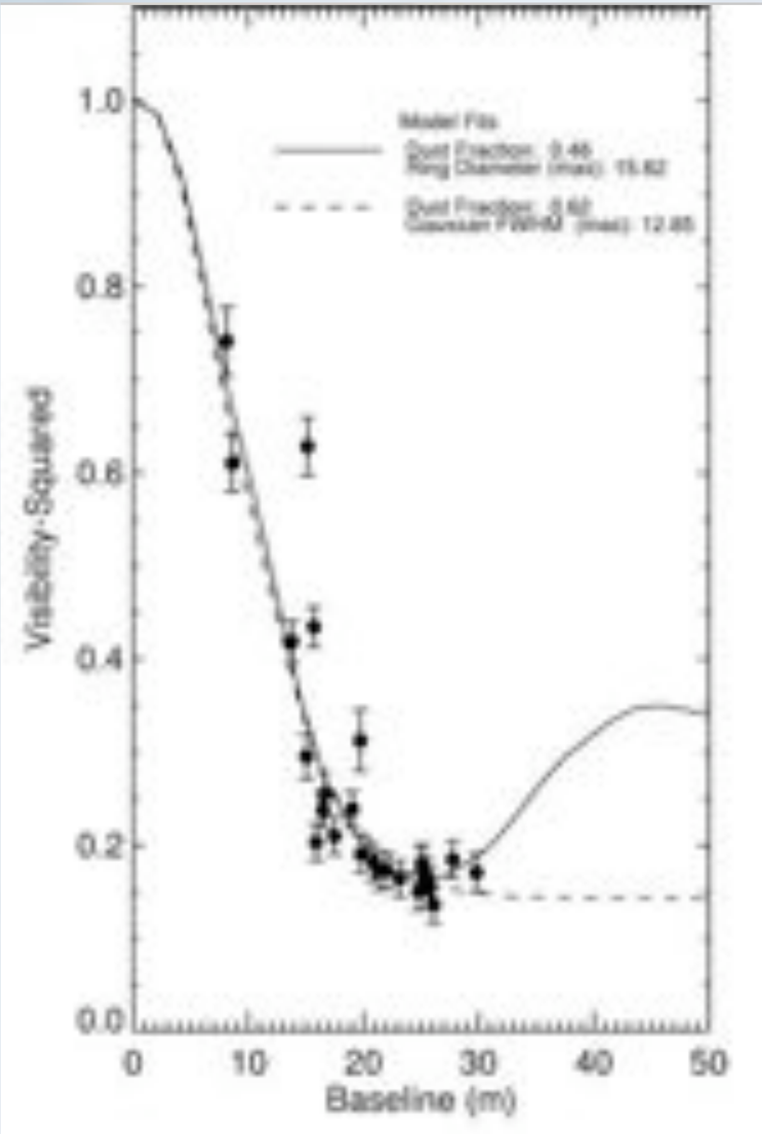
The geometry of the inner rim

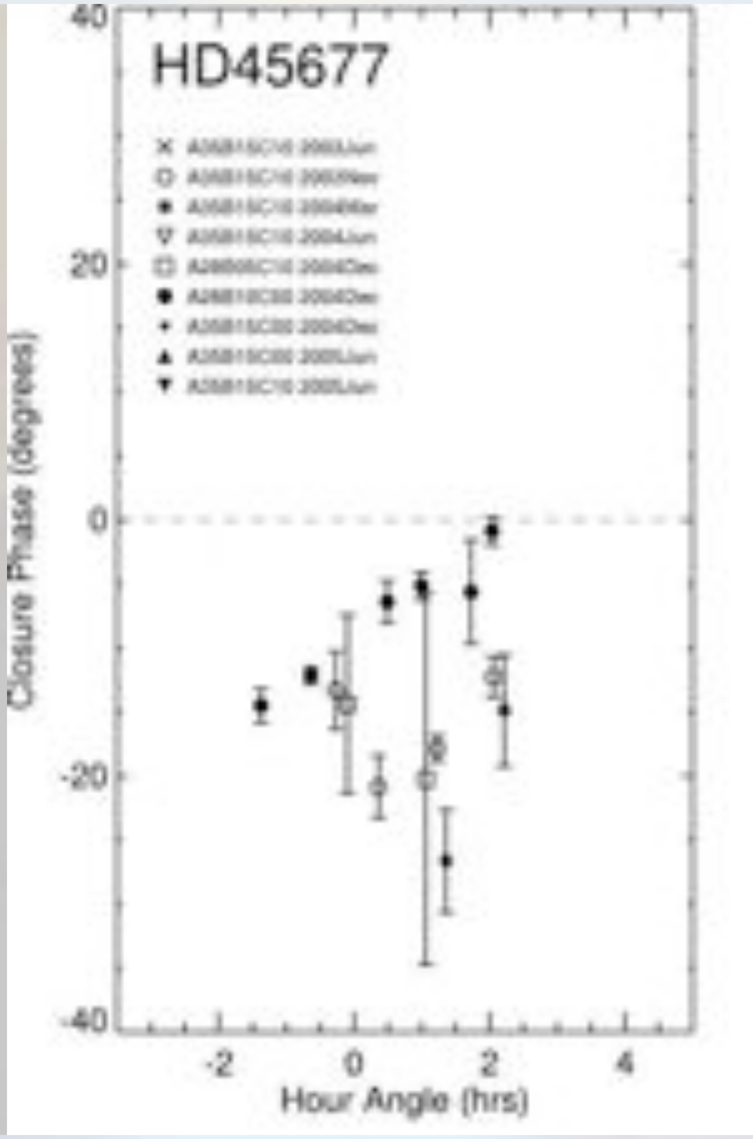
- If inclined disk: asymmetries (skewness) depending on dust characteristics Tannirkulam et al. (2007, ApJ 661, 374)

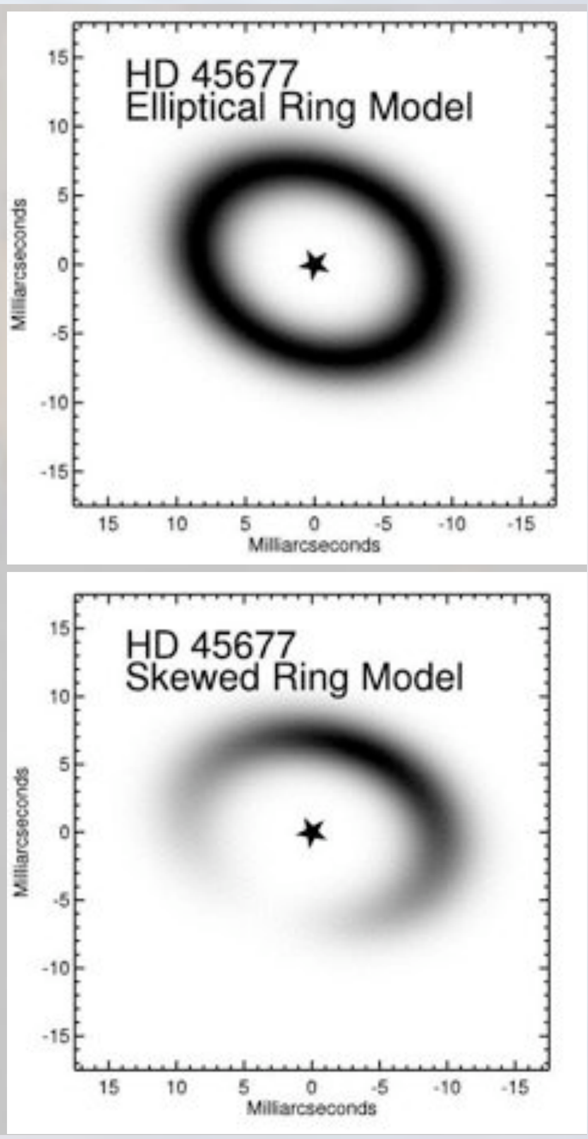


The geometry of the inner rim

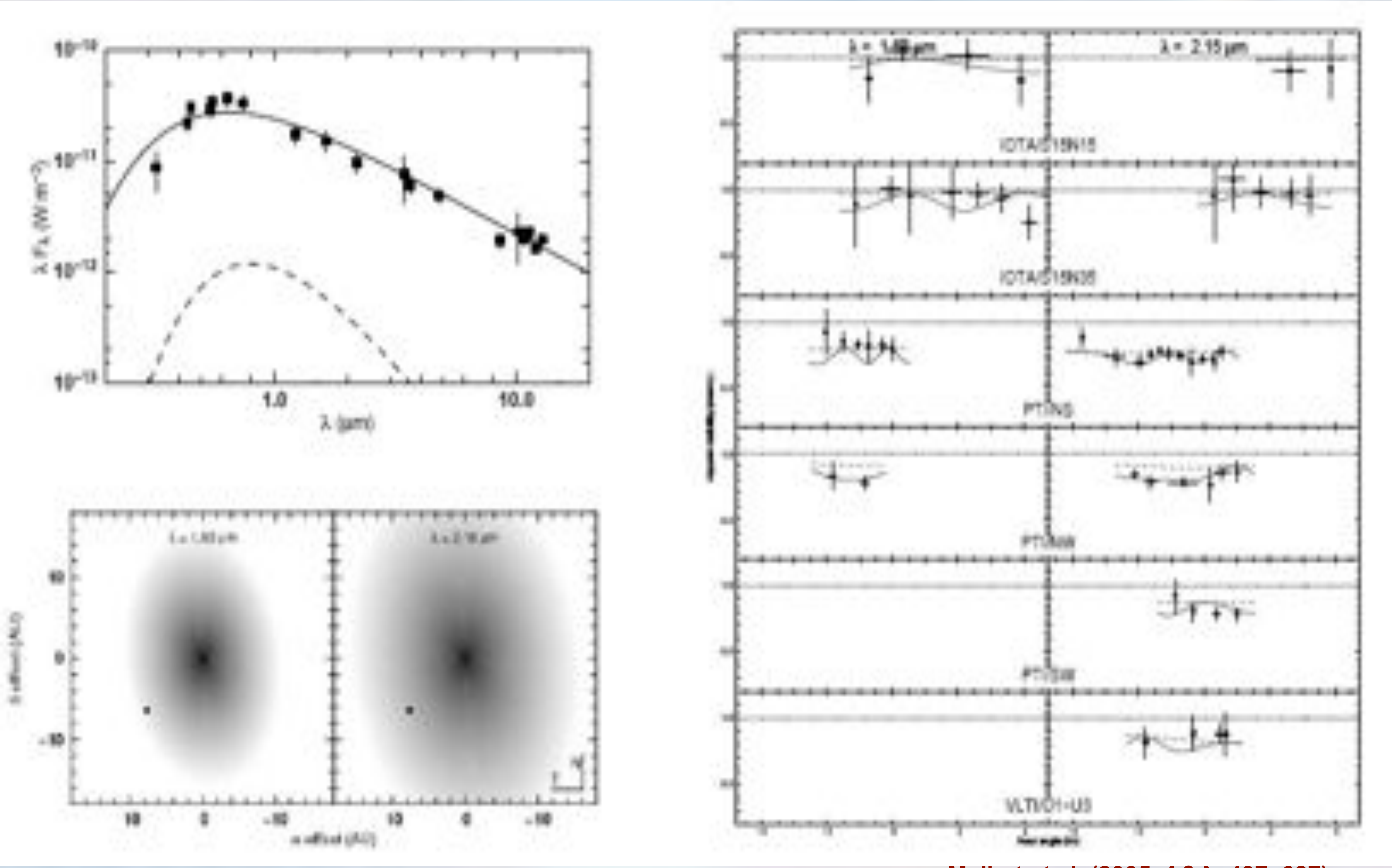
- If inclined disk: asymmetries (skewness) depending on dust characteristics **Tannirkulam et al. (2007, ApJ 661, 374)**
- Closure phase is a powerful observable to probe such asymmetries **Monnier et al. (2006, ApJ 646, 444)**





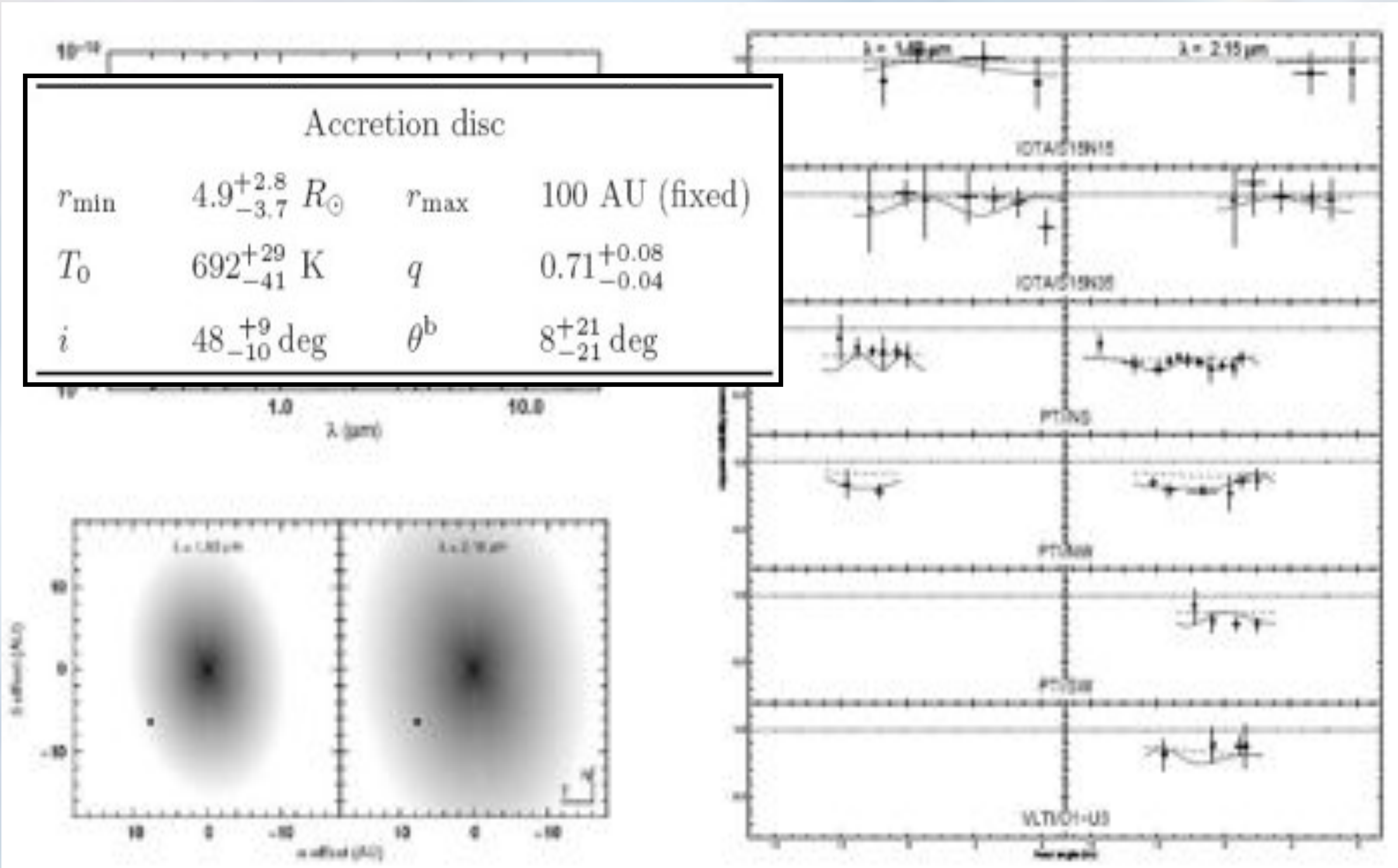


FU Orionis



Malbet et al. (2005, A&A, 437, 627)

FU Orionis



Accretion disc			
$r_{\rm min}$	$4.9^{+2.8}_{-3.7}\ R_\odot$	$r_{\rm max}$	100 AU (fixed)
T_0	692^{+29}_{-41} K	q	$0.71^{+0.08}_{-0.04}$
i	48^{+9}_{-10} deg	$\theta^{\rm b}$	8^{+21}_{-21} deg

Malbet et al. (2005, A&A, 437, 627)

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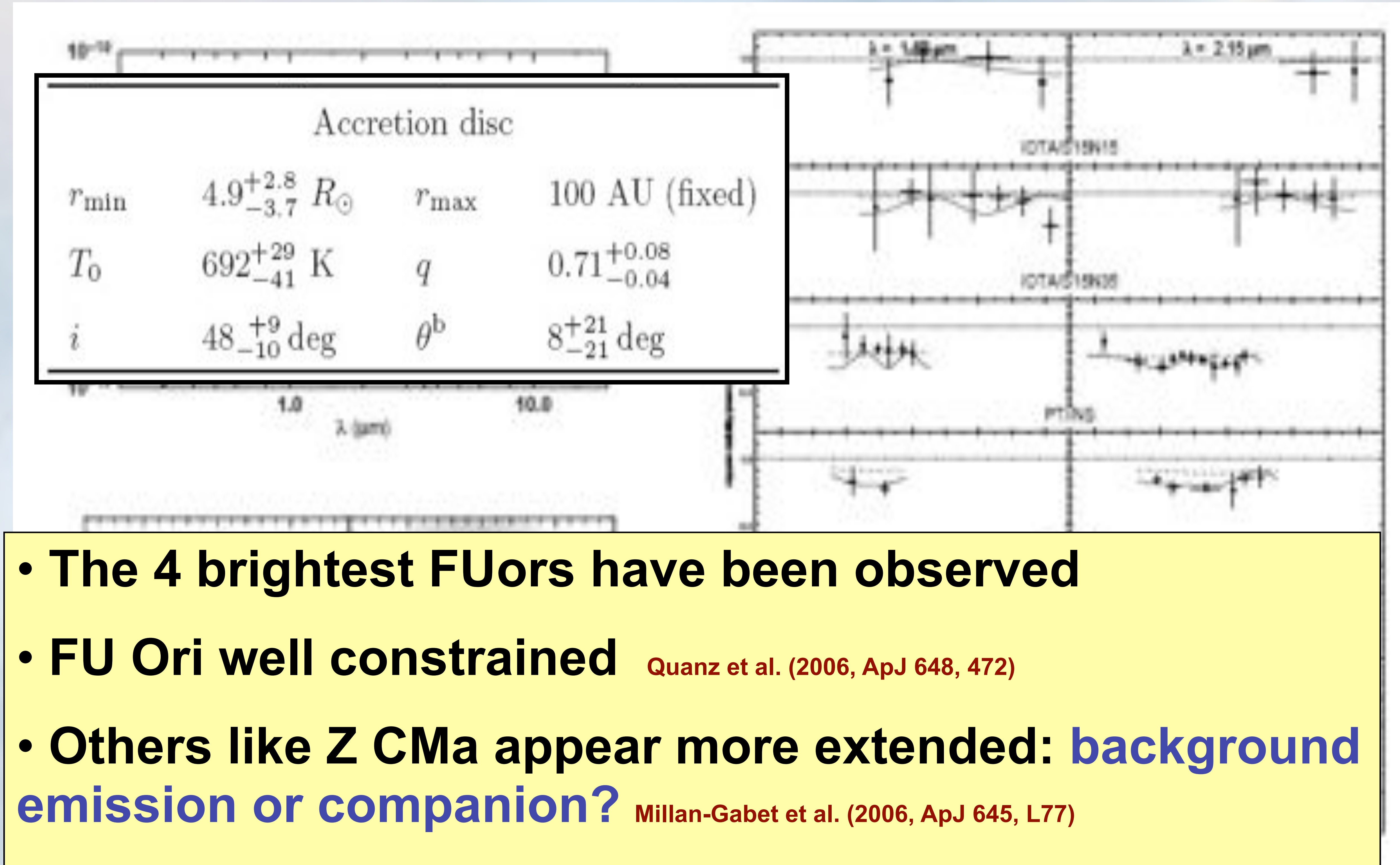

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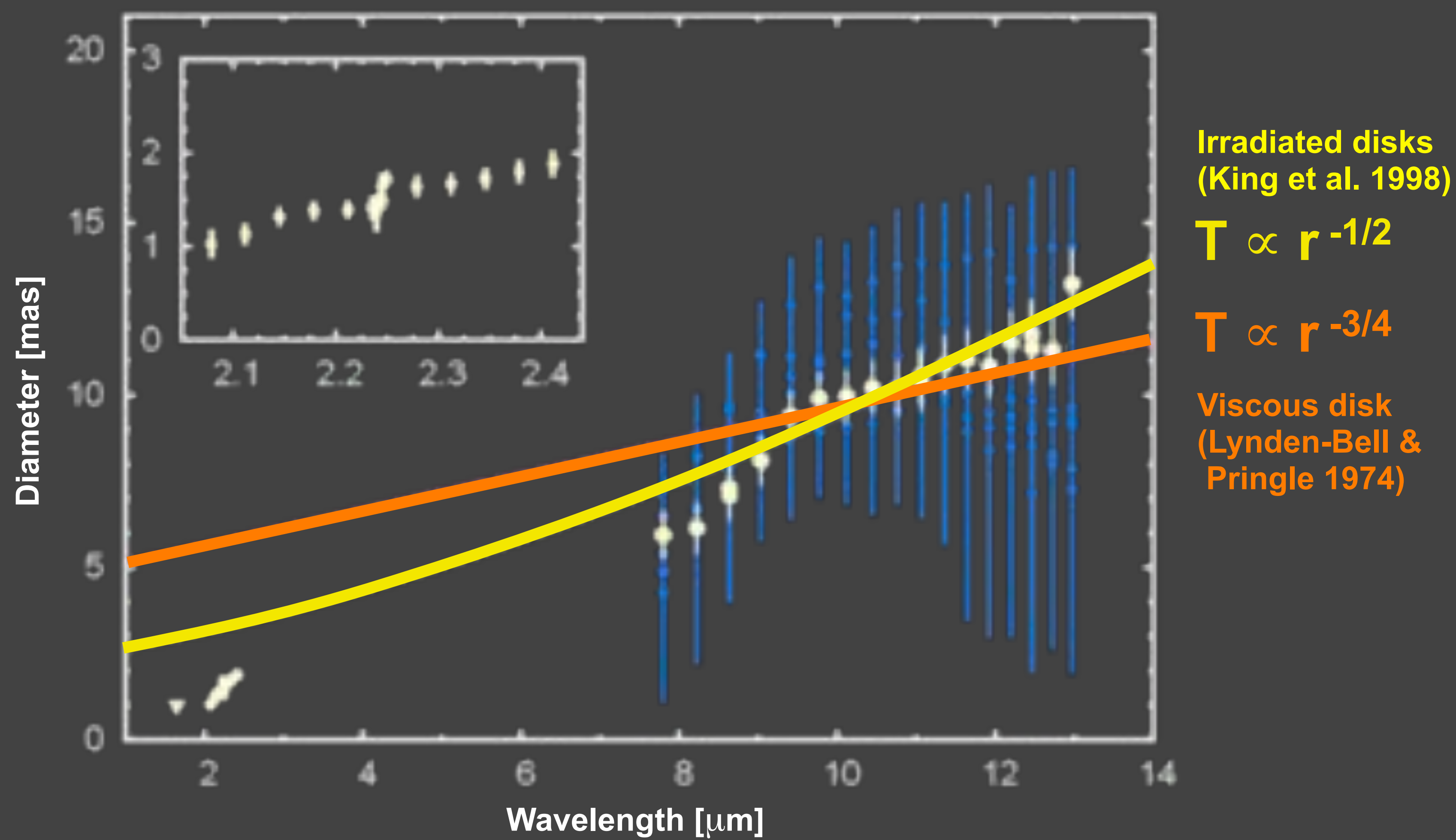
- **The 4 brightest FUors have been observed**
- **FU Ori well constrained** **Quanz et al. (2006, ApJ 648, 472)**
- **Others like Z CMa appear more extended: background emission or companion?** **Millan-Gabet et al. (2006, ApJ 645, L77)**
- **Recent FUOr: V1647 Ori** **Ábrahám, Mosoni, Henning et al. (2006, A&A 449, L13)**

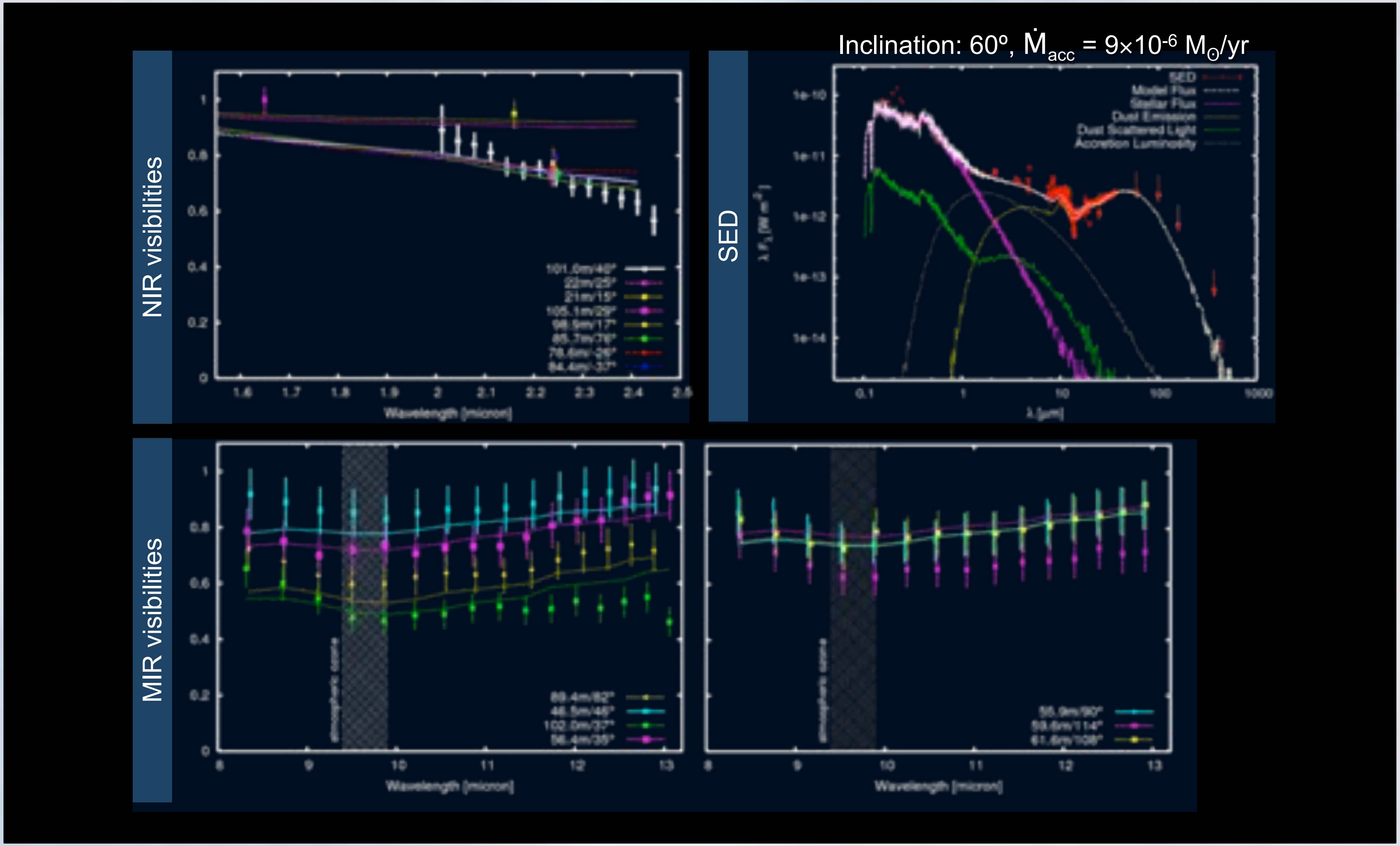
Radial temperature distribution of disks



Commonly used analytic temperature-power-law disk models ($T \propto r^{-1/2}$ or $T \propto r^{-3/4}$) cannot describe the measured wavelength-dependence of the apparent size
→ Detailed physical modeling required

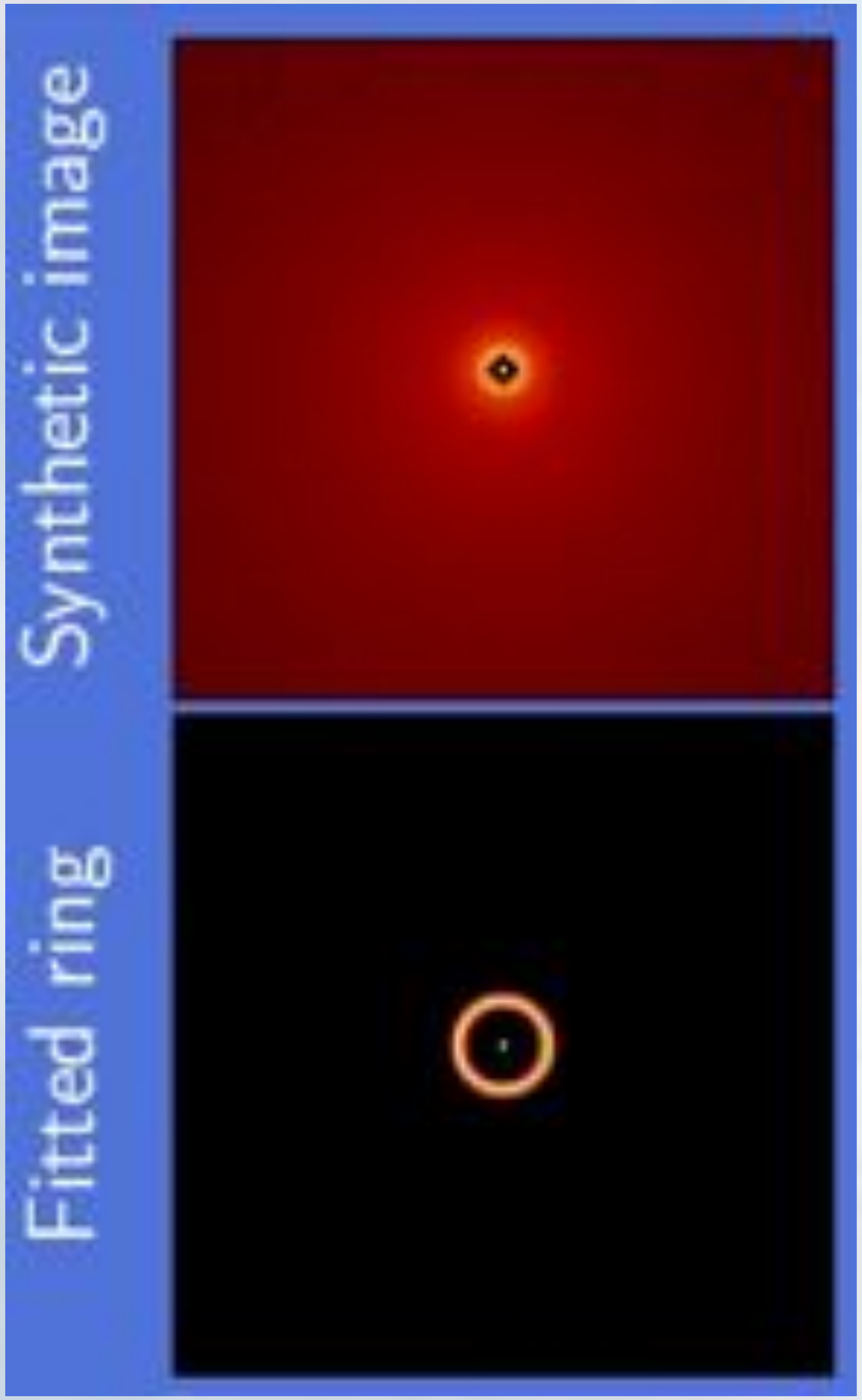
Kraus et al. (2007, ApJ 676, 490)

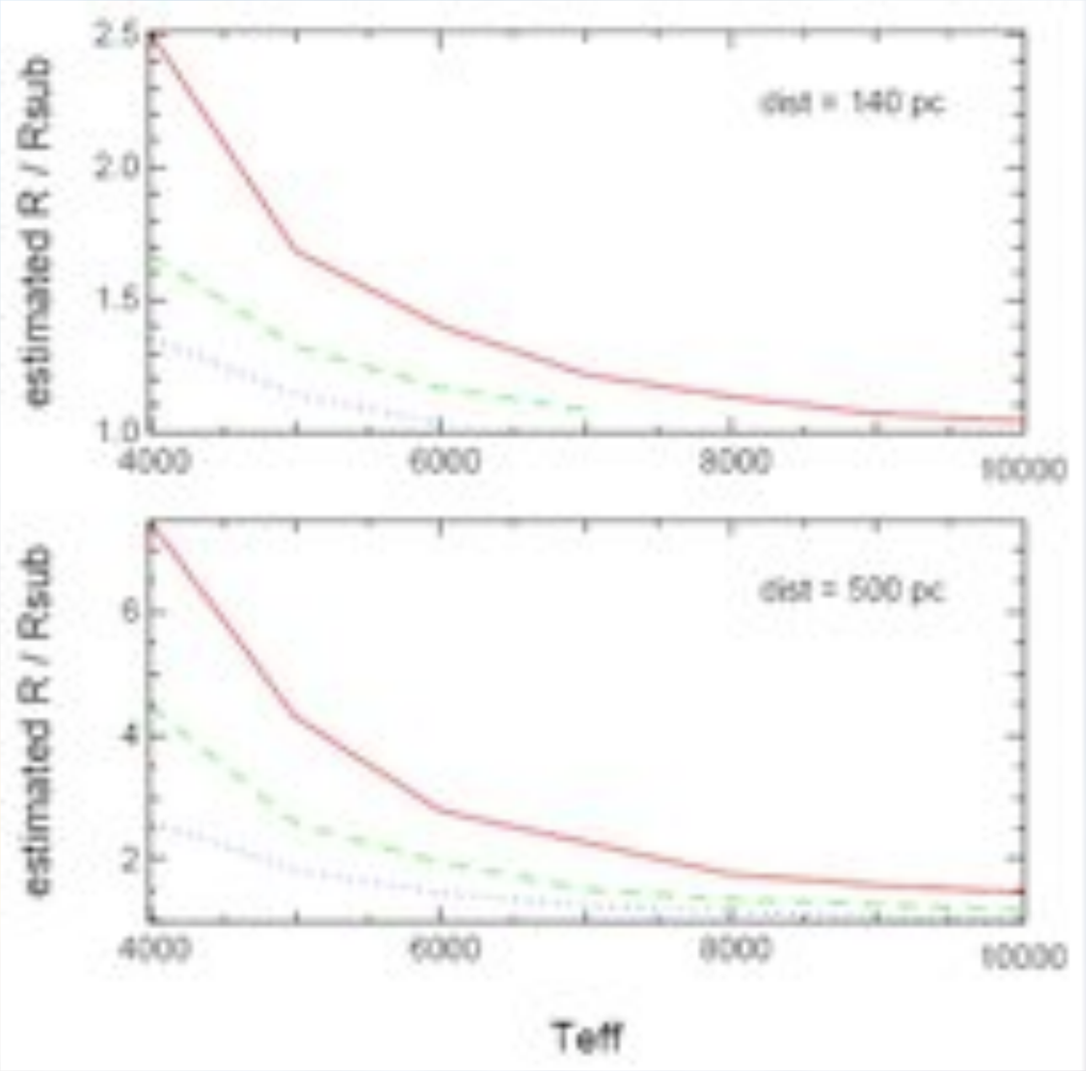
MWC 147: a full disk model to understand NIR and MIR measurements



Kraus et al. (2007, ApJ 676, 490)

Effect of extended scattered light

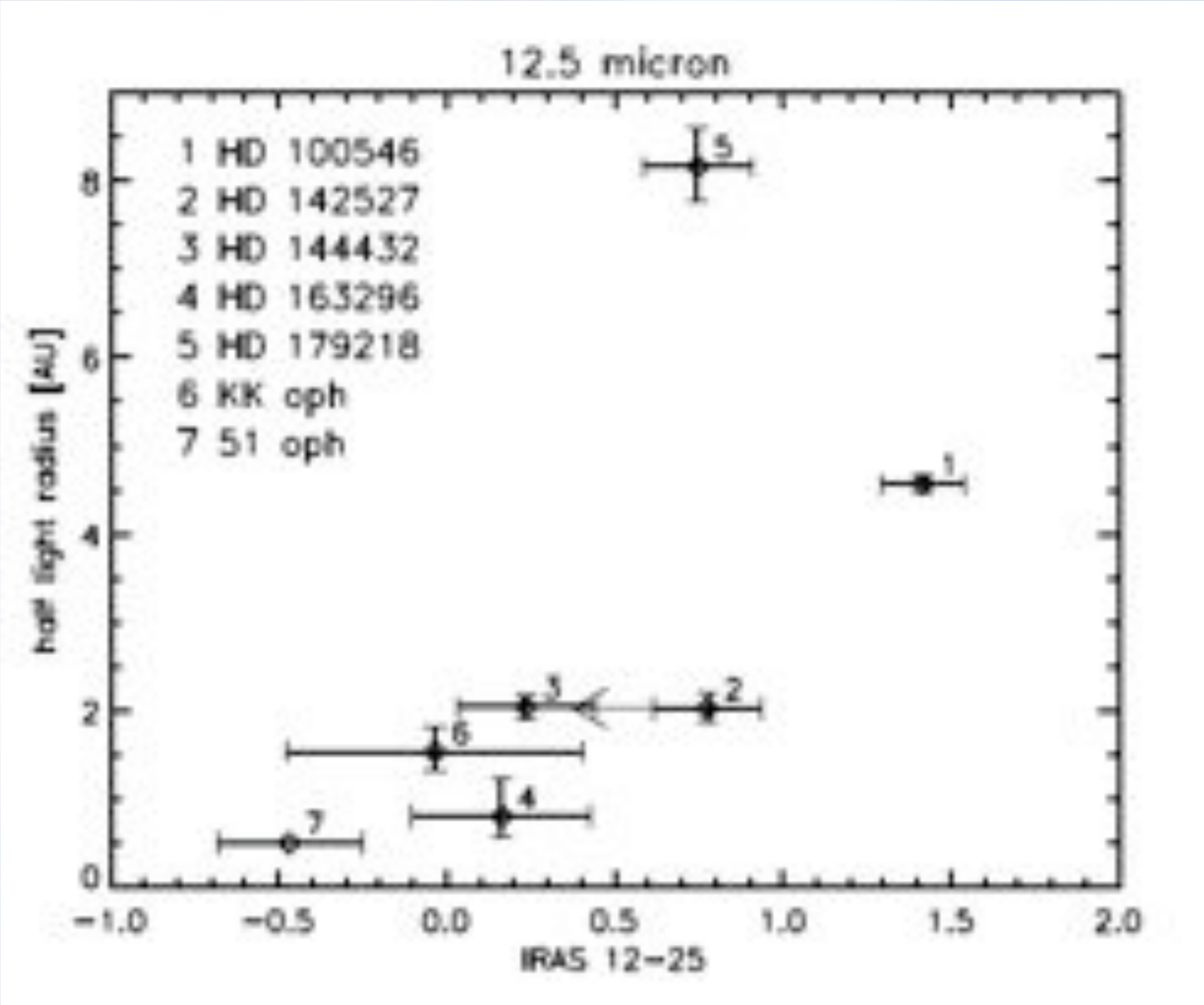




- Ring radius fitting can lead to overestimated sizes
- Careful modeling must be performed including all sources of radiation

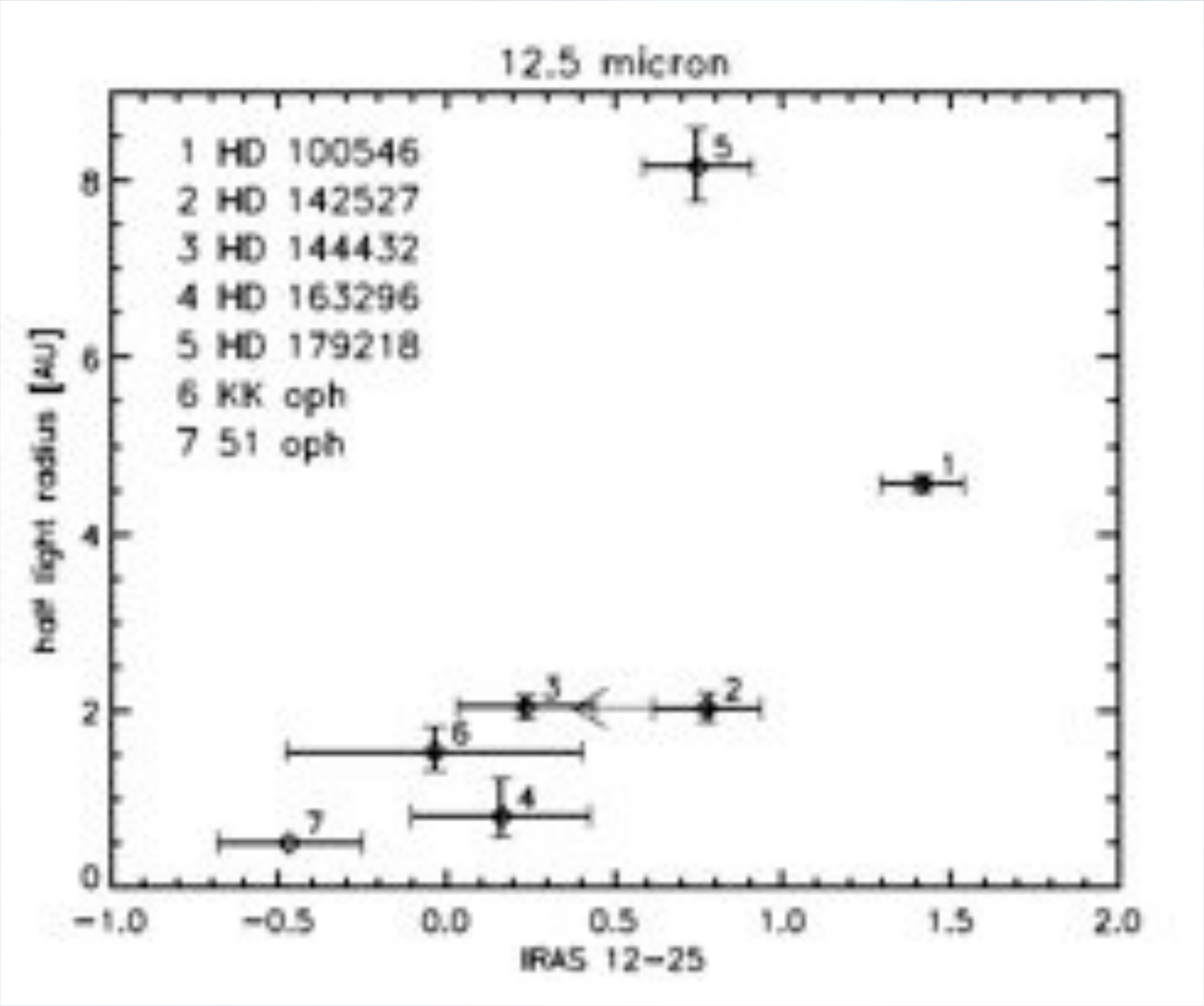
Pinte et al. (2007, ApJ 673, L63)

Vertical structure @ 10 microns

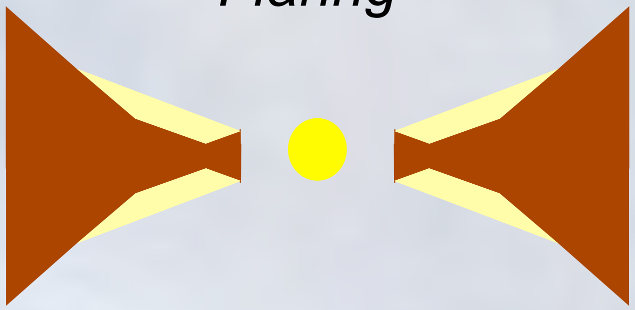


Leinert et al. (2004, A&A, 423, 537)

Vertical structure @ 10 microns



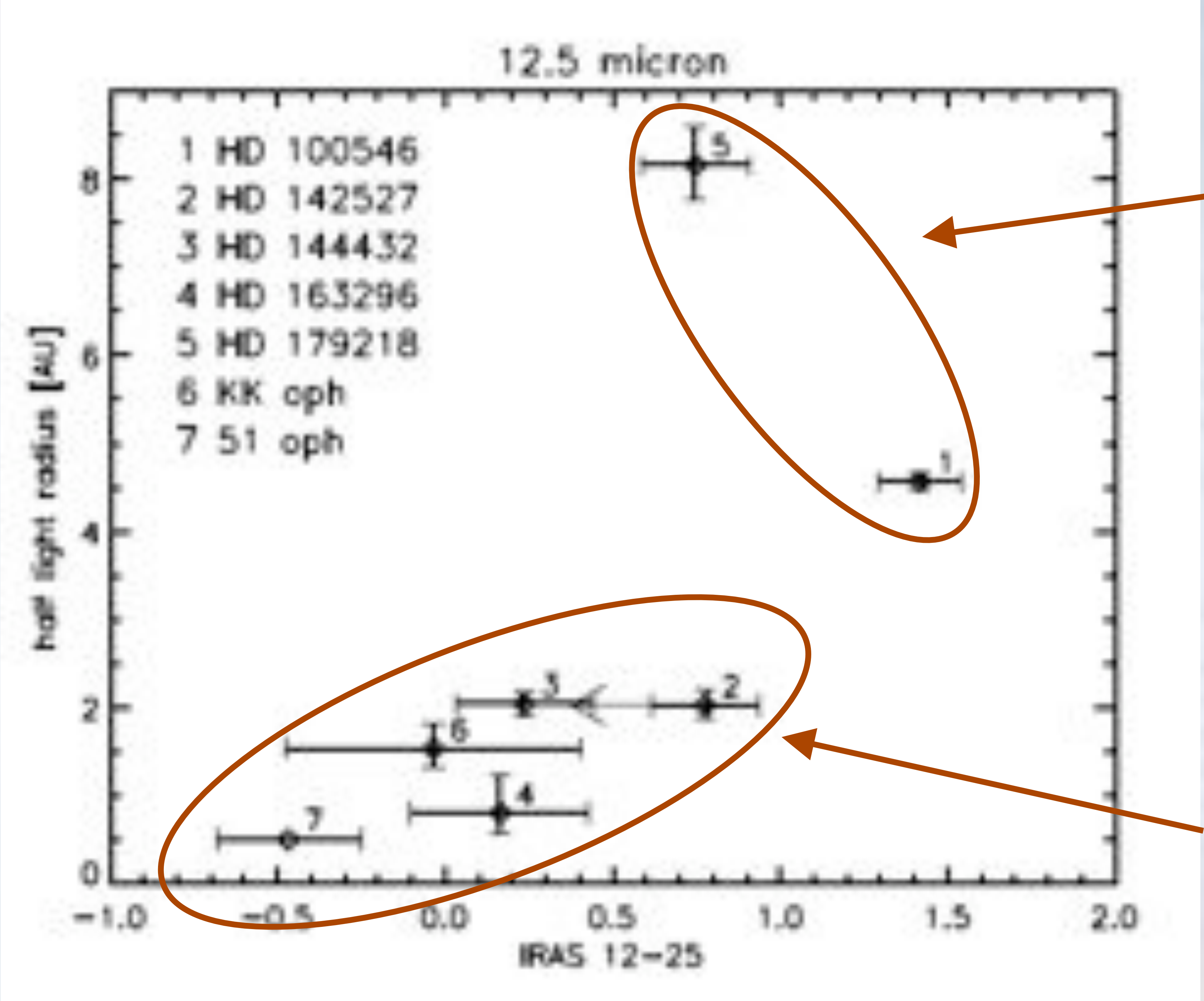
Flaring



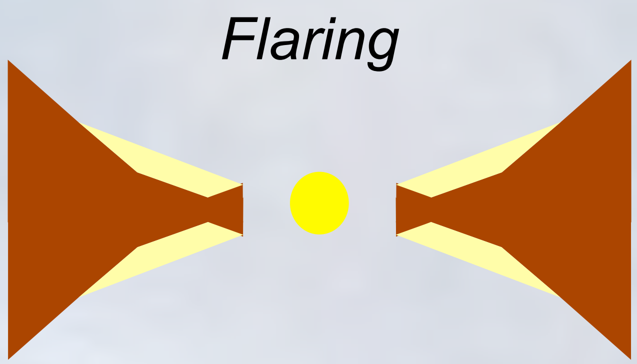
Self-shadowed

Leinert et al. (2004, A&A, 423, 537)

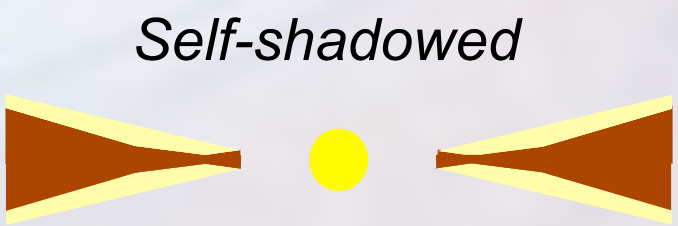
Vertical structure @ 10 microns



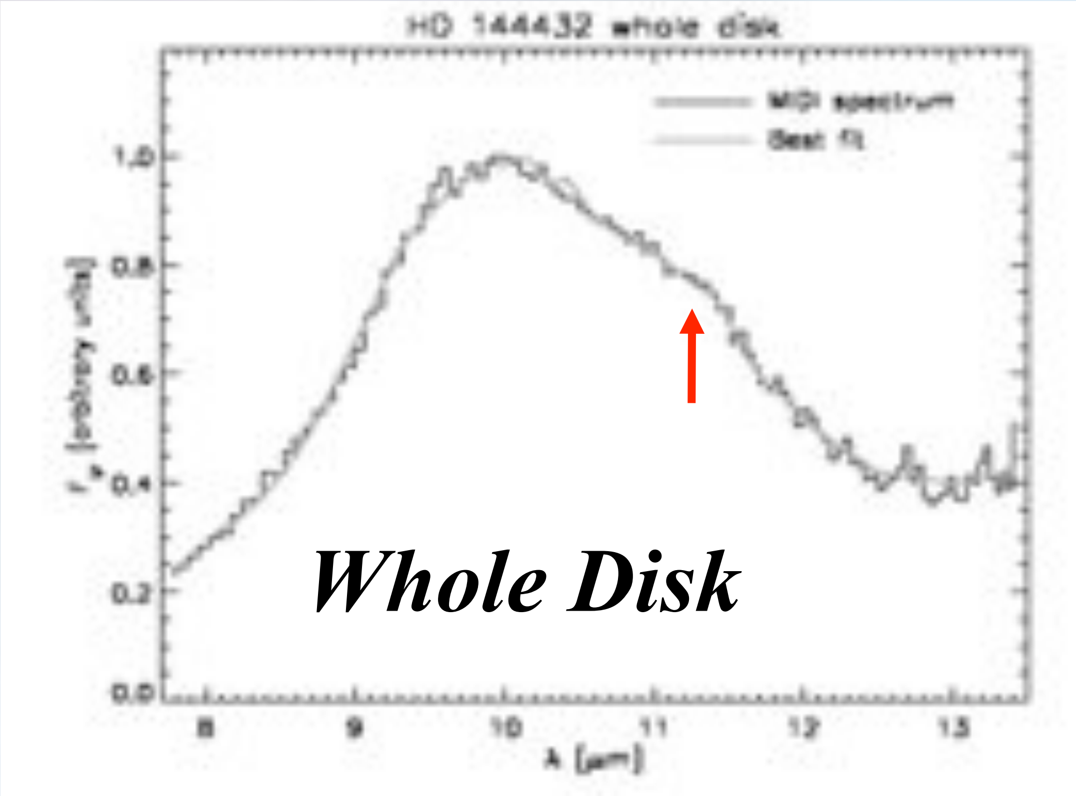
Leinert et al. (2004, A&A, 423, 537)

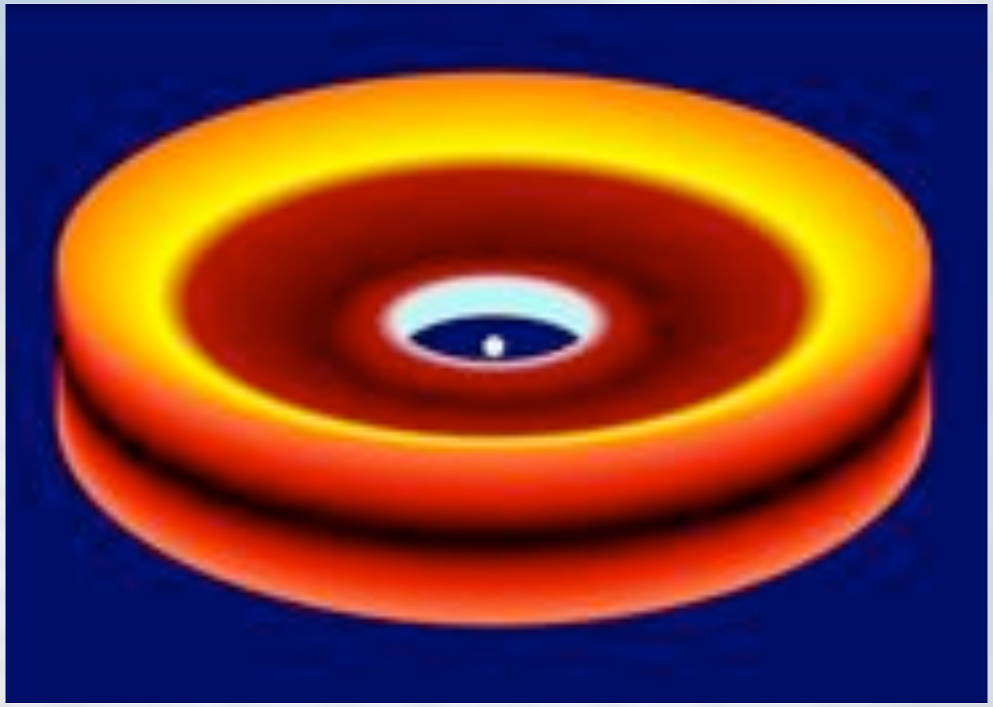


Sizes consistent with flat self-shadowed / flaring disk model SED classification



Dust mineralogy in HAeBe





Van Boekel et al. (2004, Nature, 432, 479)

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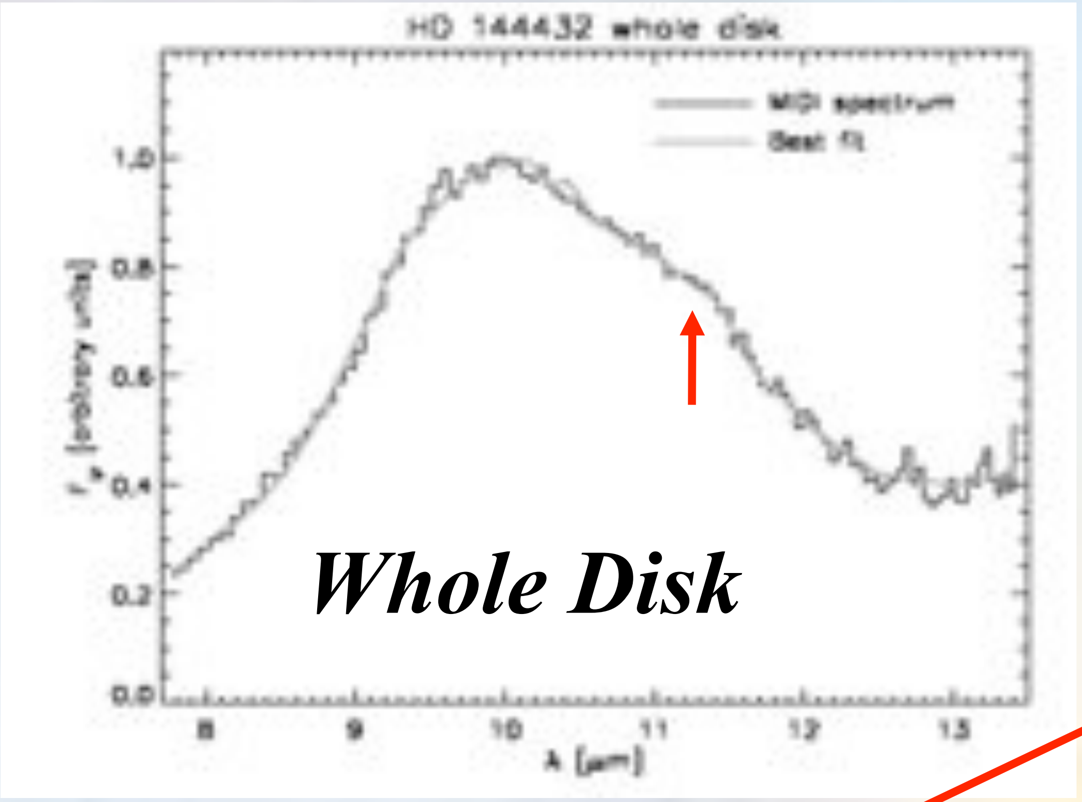

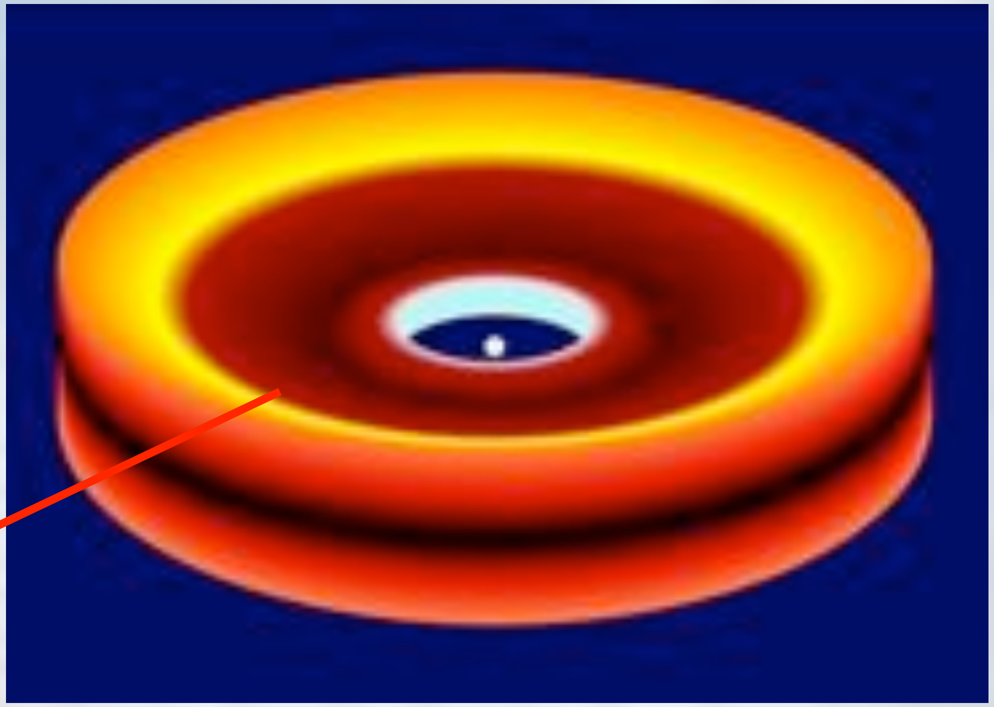

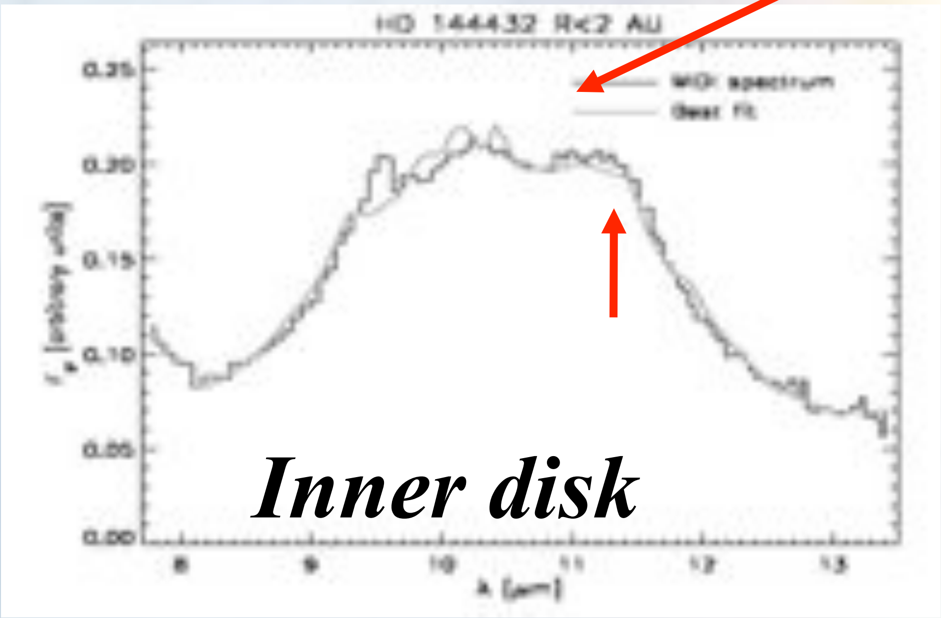

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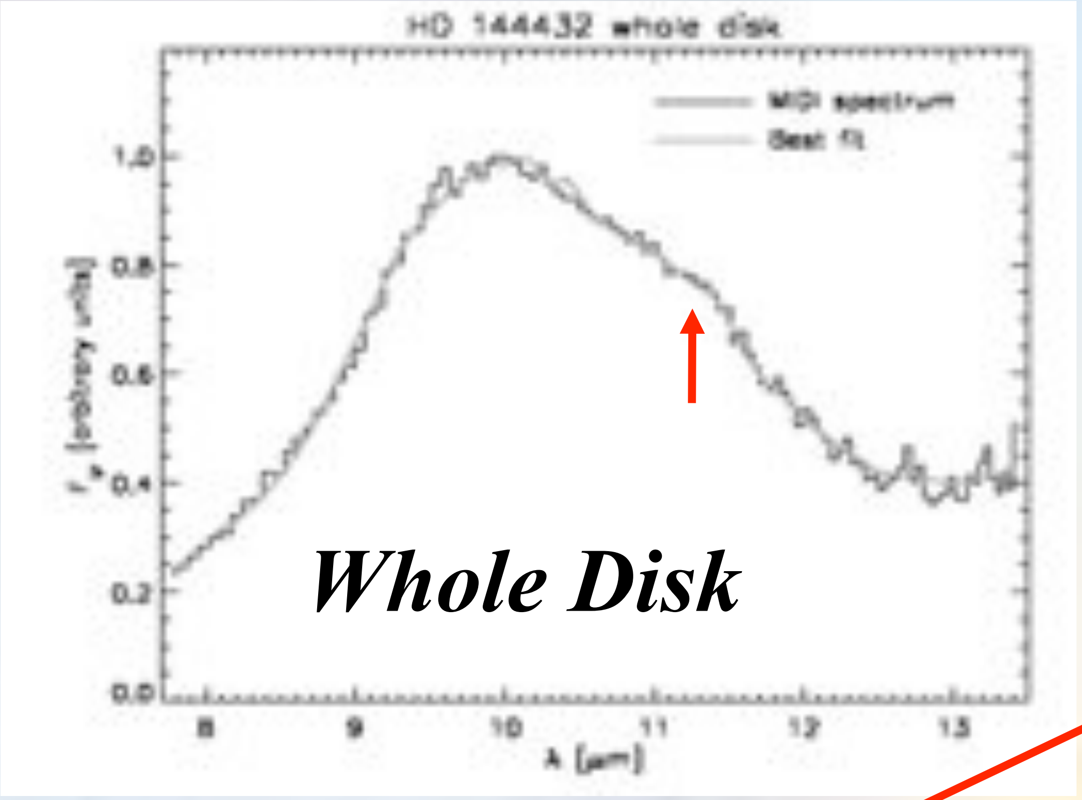
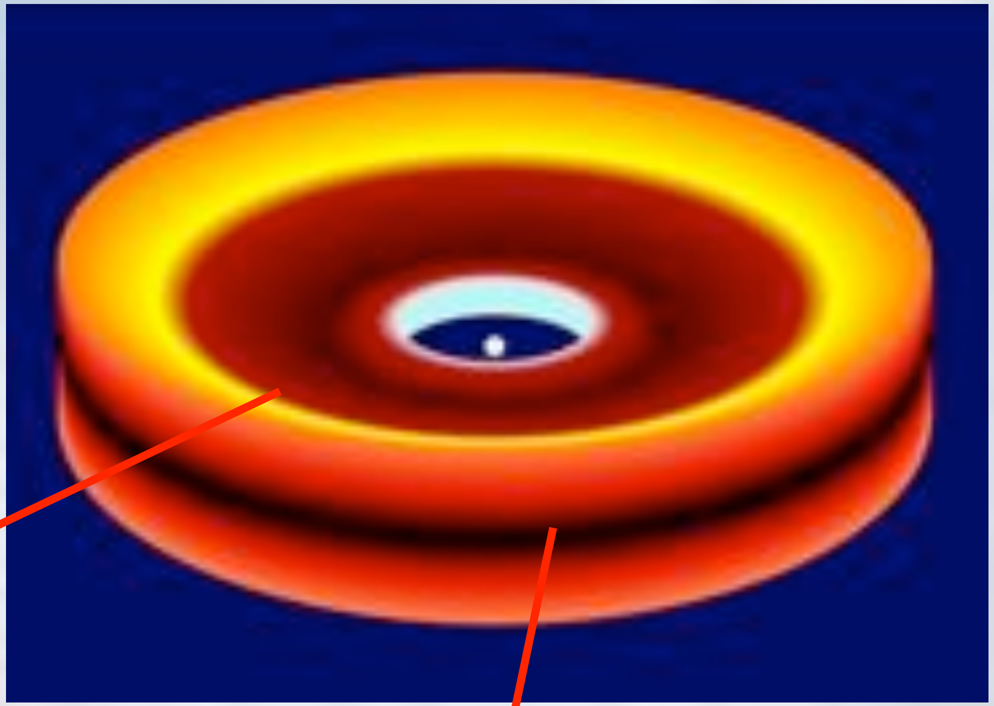
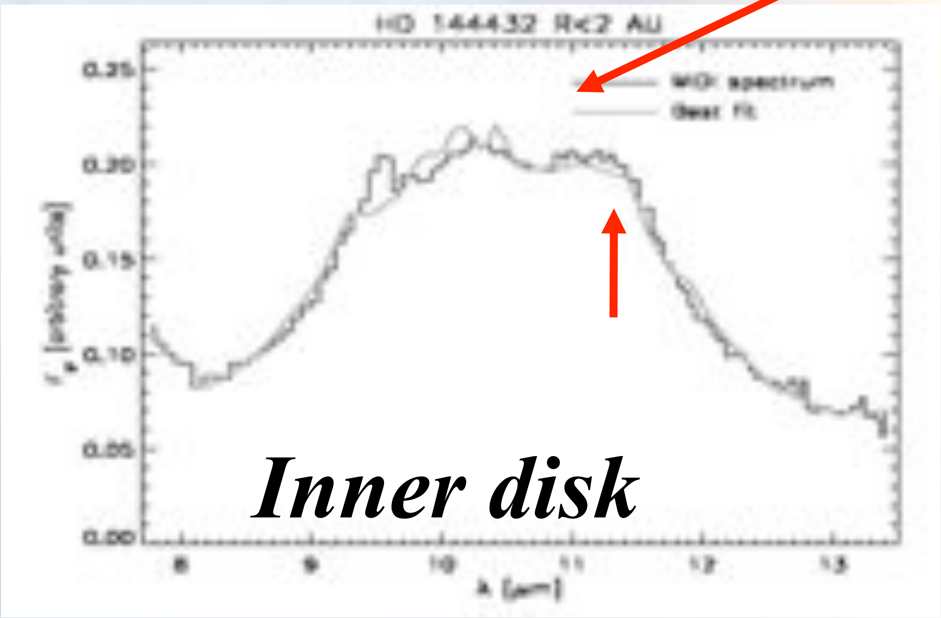
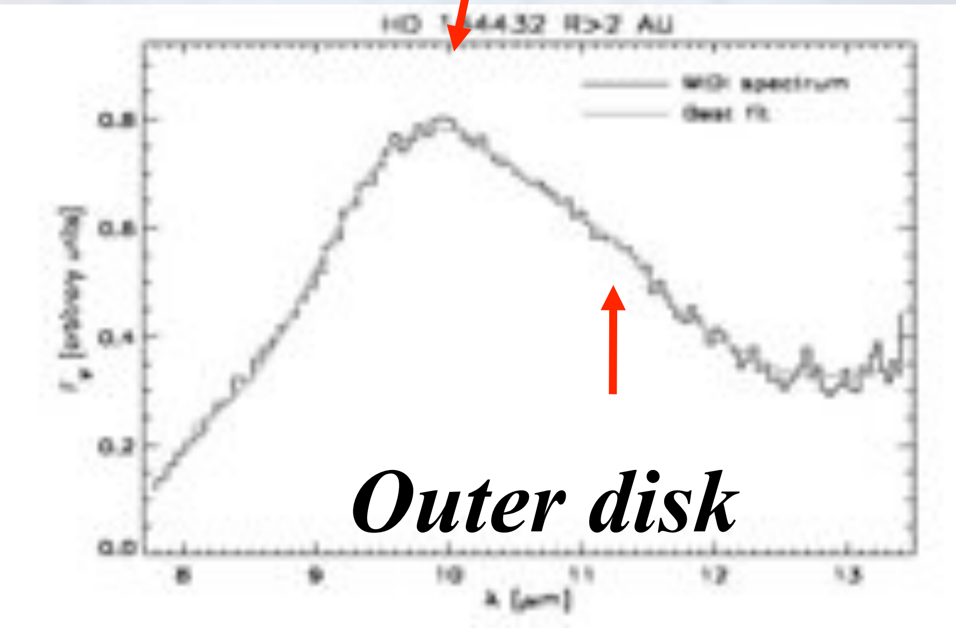


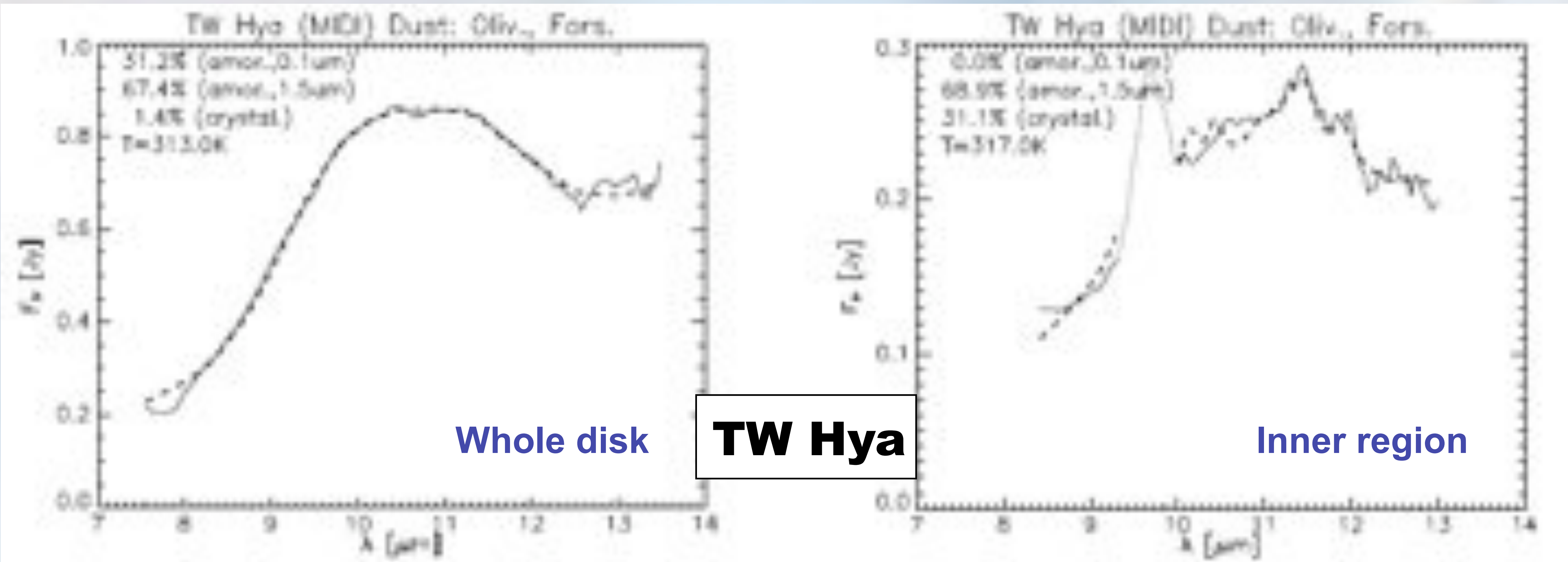






Van Boekel et al. (2004, Nature, 432, 479)

… also in T Tauri disks!



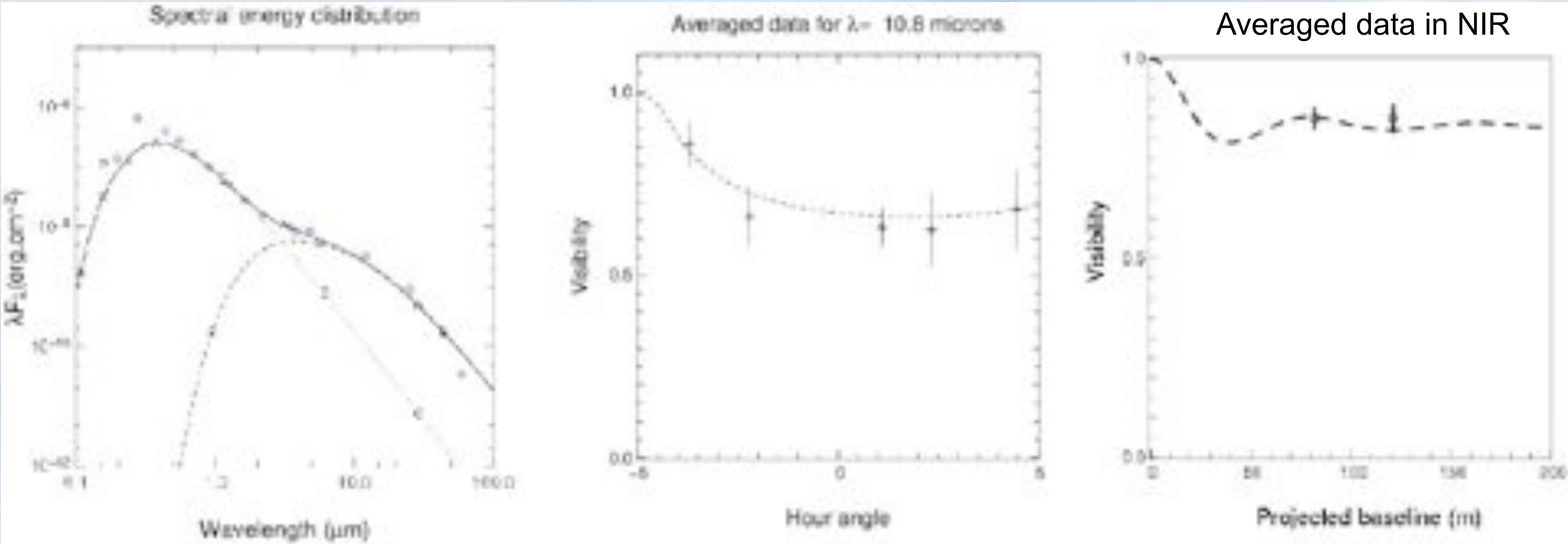
Ratzka et al. (2007, A&A 471, 173)

→ Inner disks (< 2 AU) have:

– larger silicate grains

– higher fraction of silicates is **crystalline** (40-100%)

51 Oph: NIR CO overtone emission



Parameter	Best fit Value
Distance	131 pc
R_*	$7\ R_\odot$
M_*	$3.8\ M_\odot$
T_{eff}	10000 K
Av	0.15
Accretion rate	$7.10^{-5}\ M_\odot/yr$
Disk outer radius	7 AU
Disk inner radius	0.55 AU
Inclination	88°
Position Angle	78°

Tatulli, et al. (2008, A&A 489, 1151)

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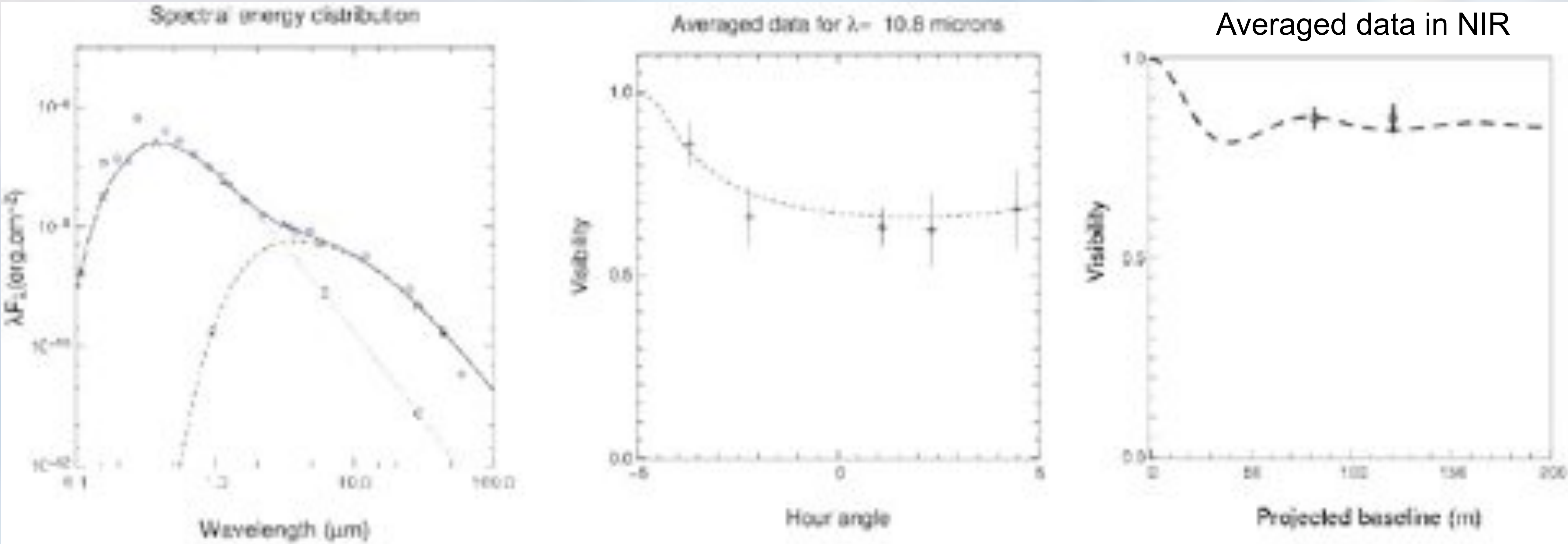

All observations fitted by the standard disk model!

but it seems not to be physically possible

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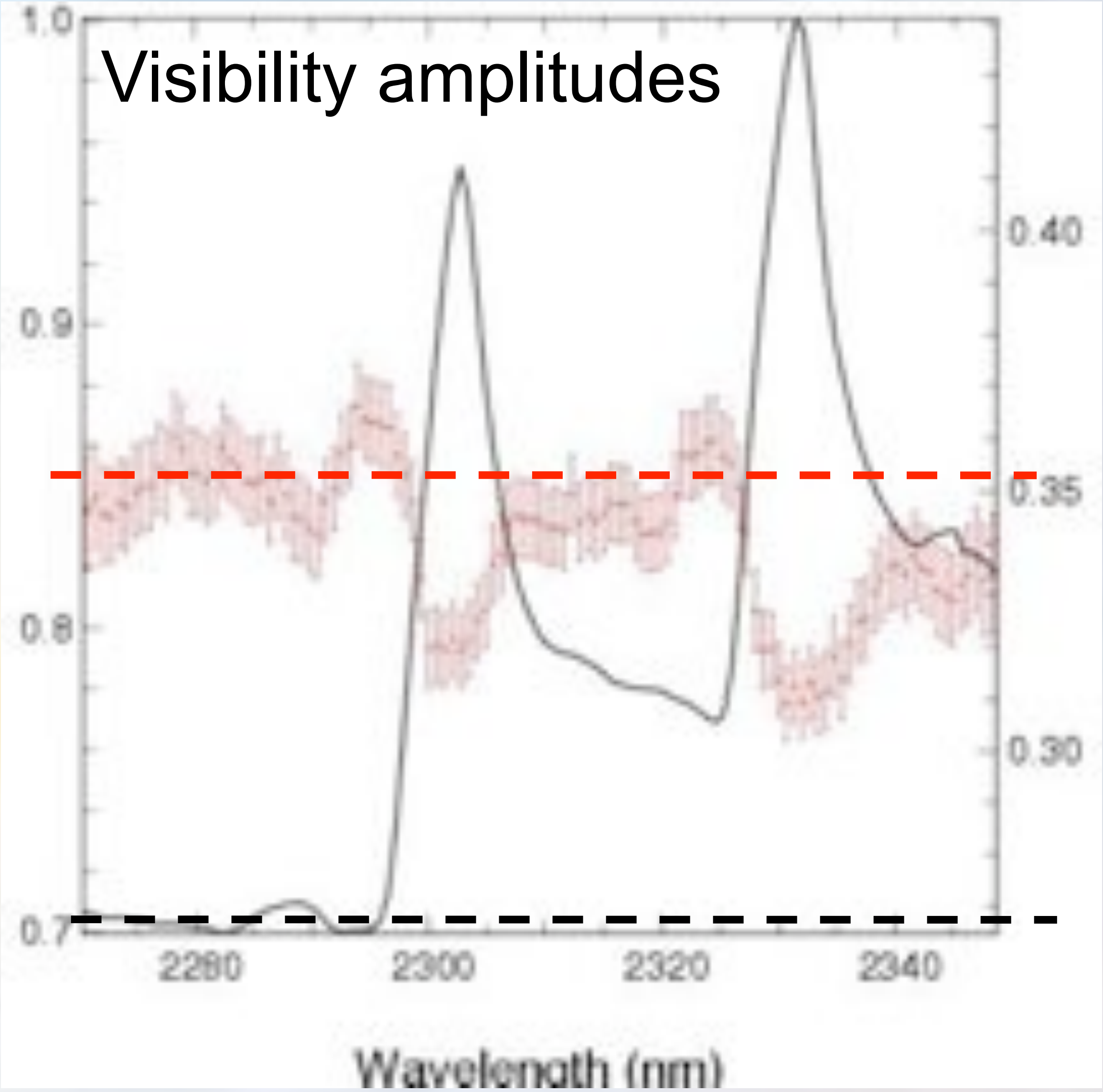
Tatulli, et al. (2008, A&A 489, 1151)

Region of CO emission in 51 Oph

NIR excess continuum



Tatulli, et al. (2008, A&A 489, 1151)

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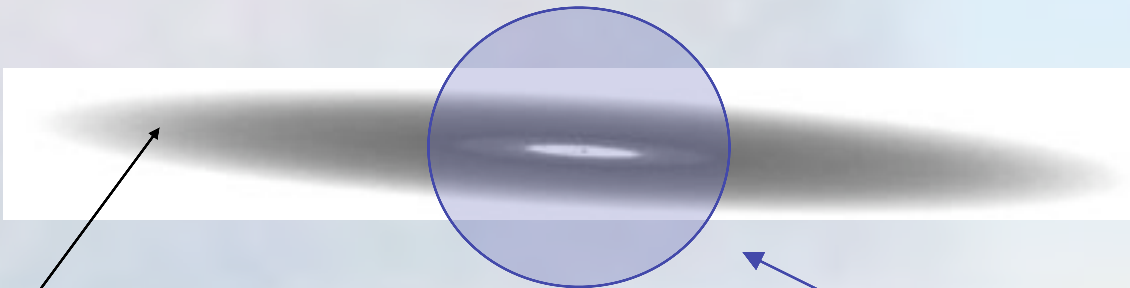
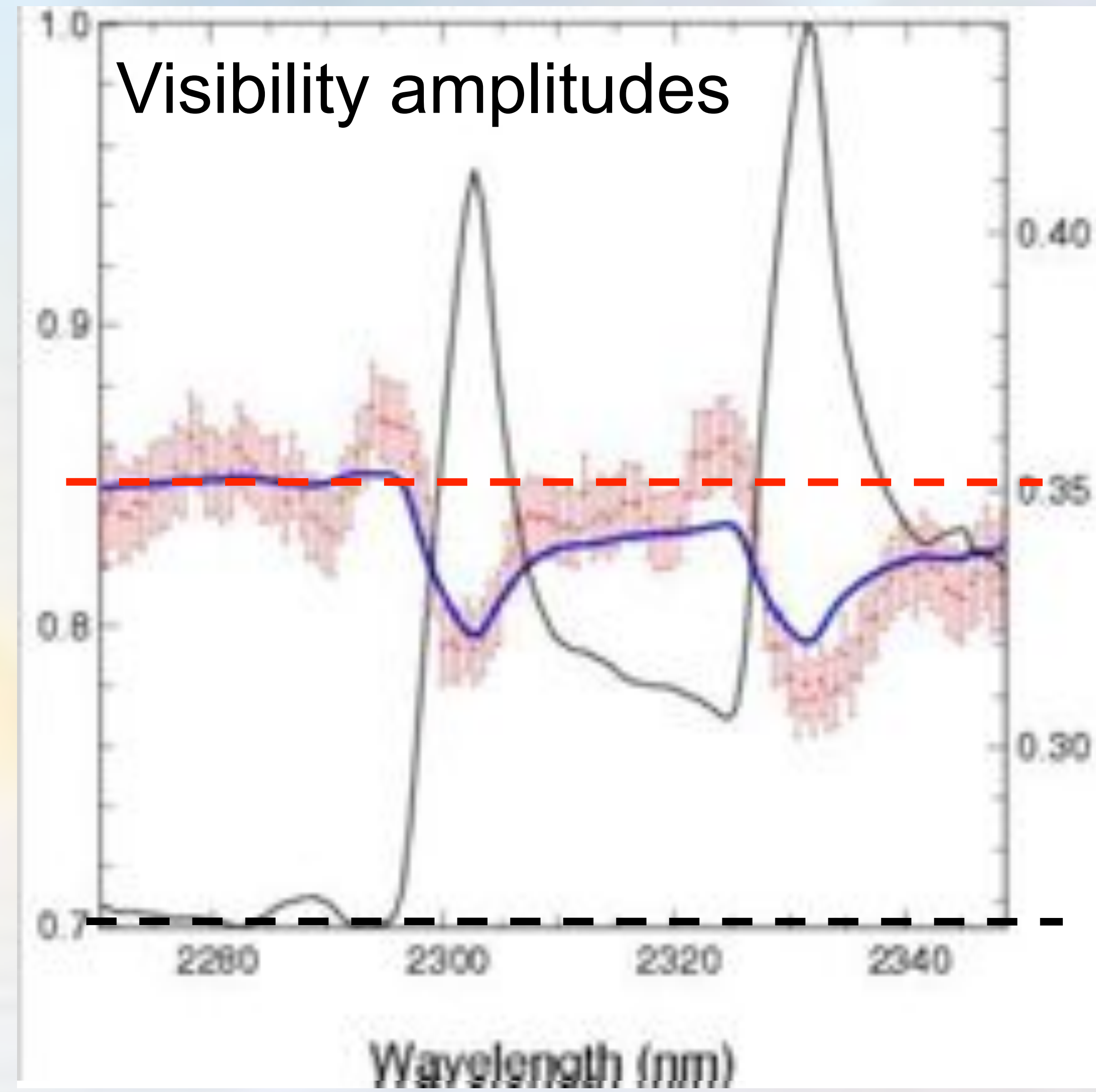


NIR excess continuum

CO emission
0.3AU size



Tatulli, et al. (2008, A&A 489, 1151)

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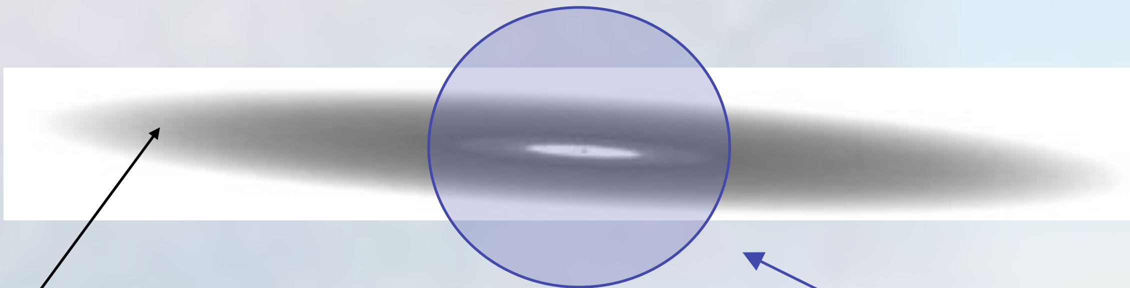

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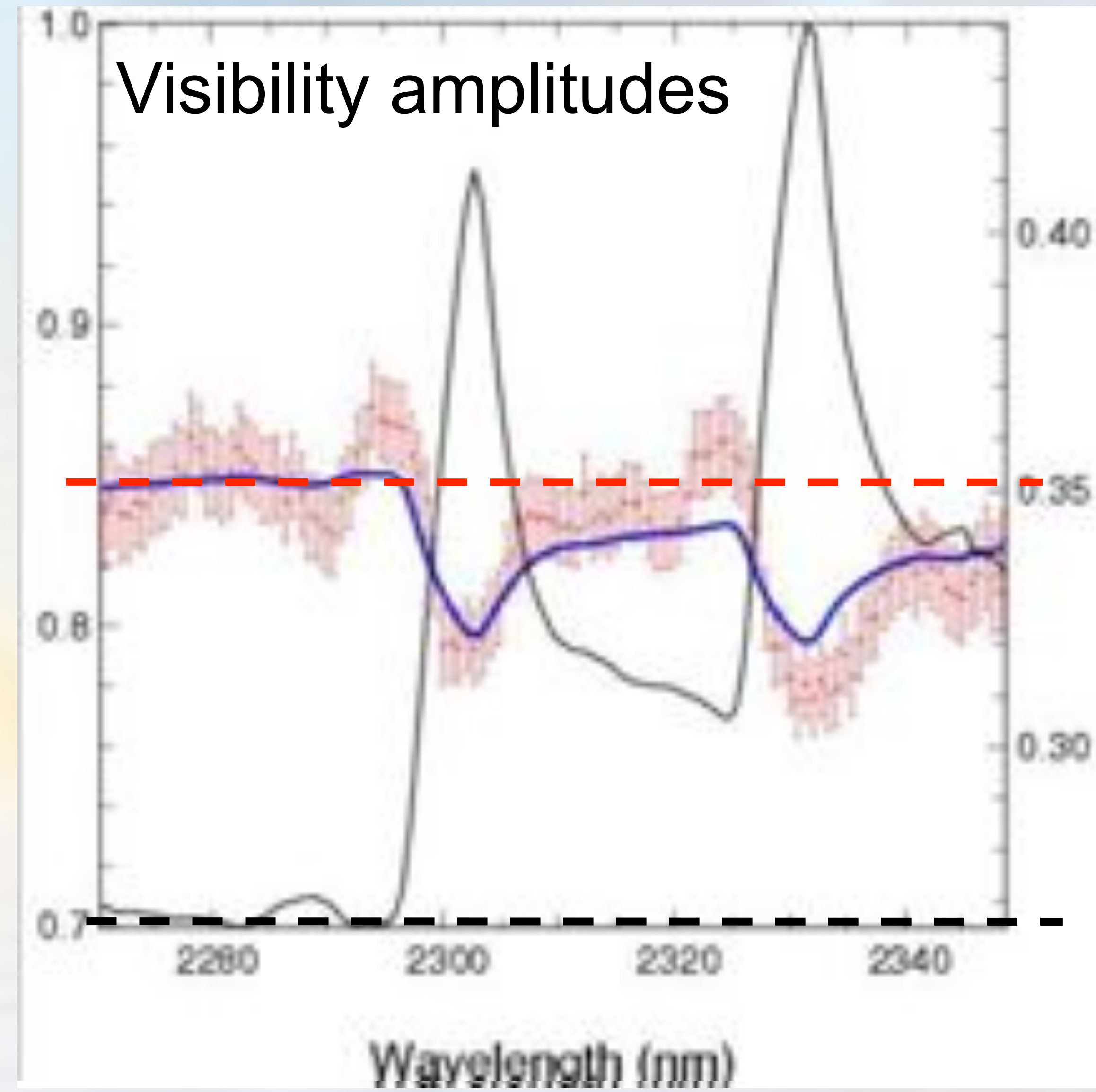

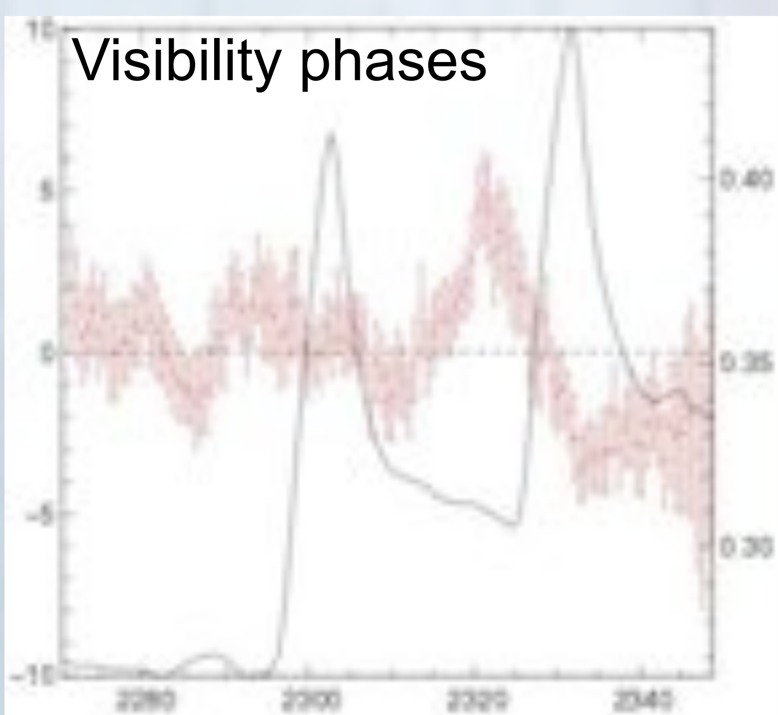

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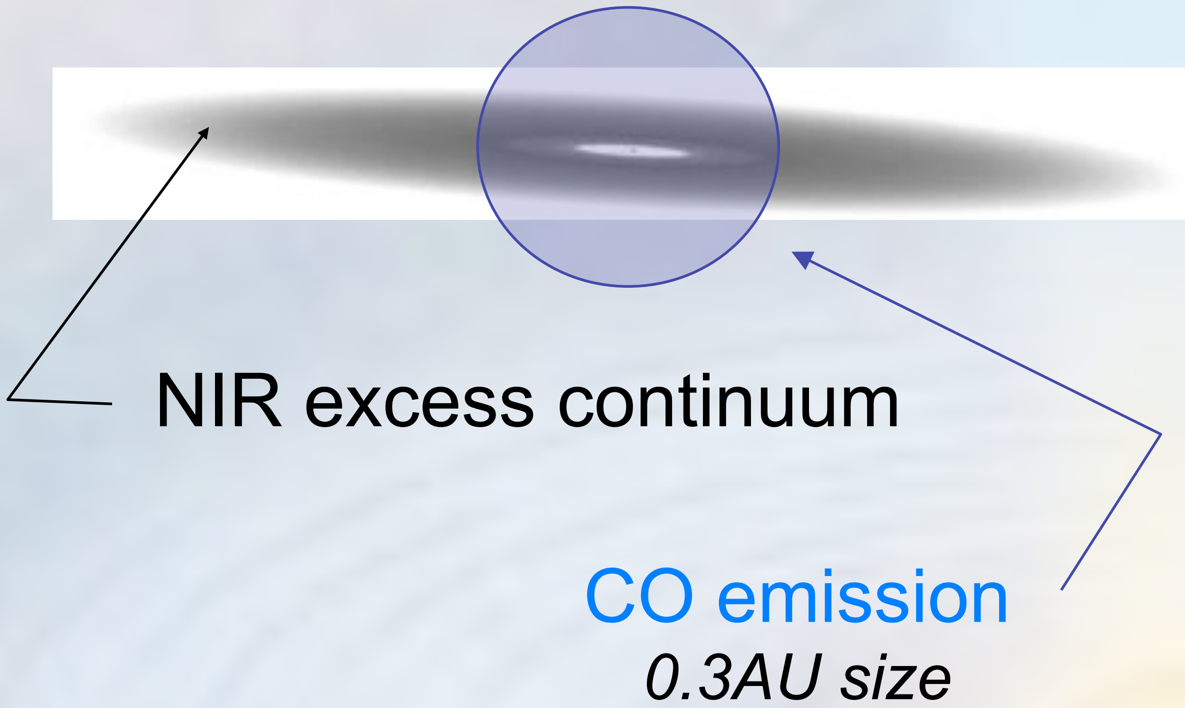
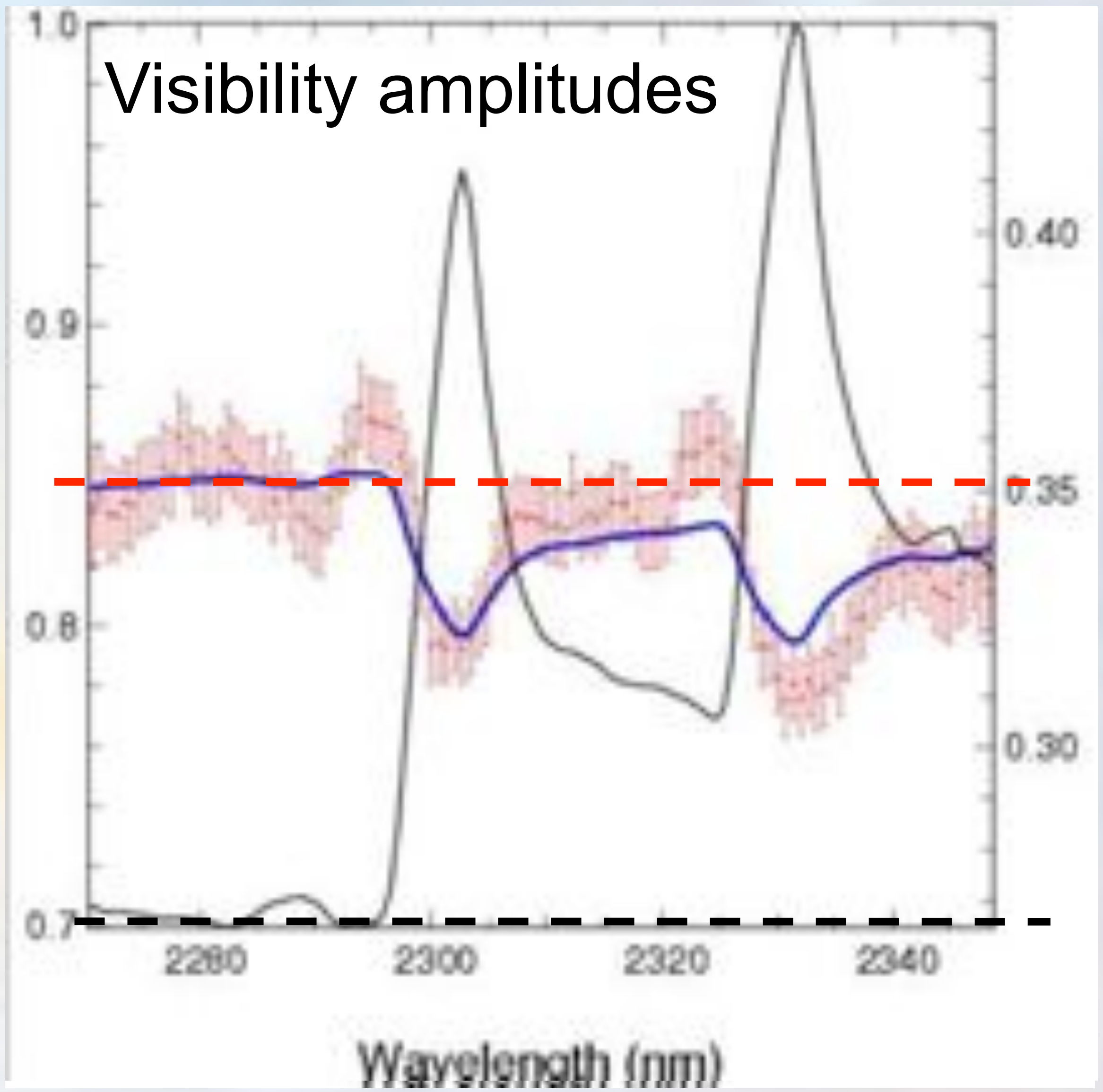
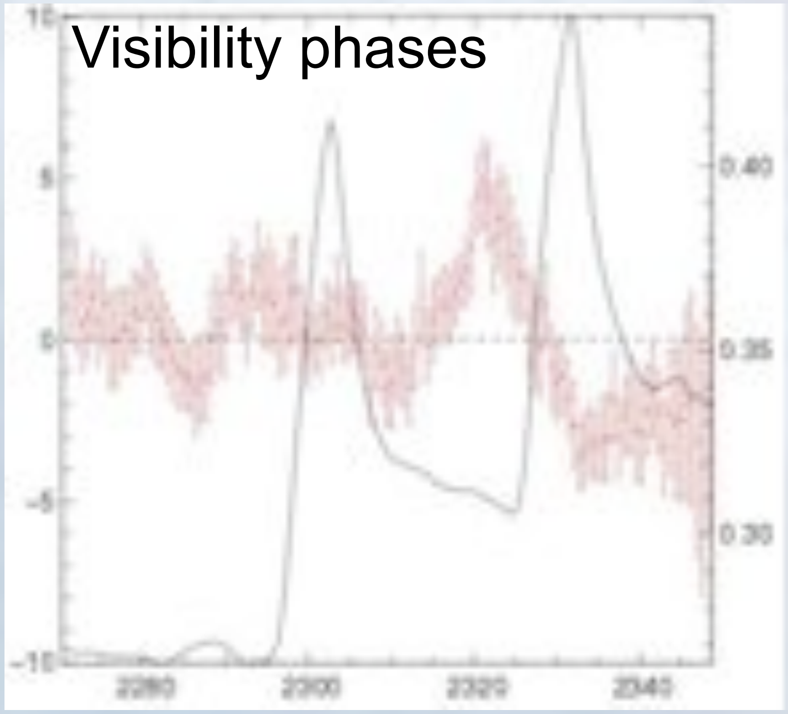


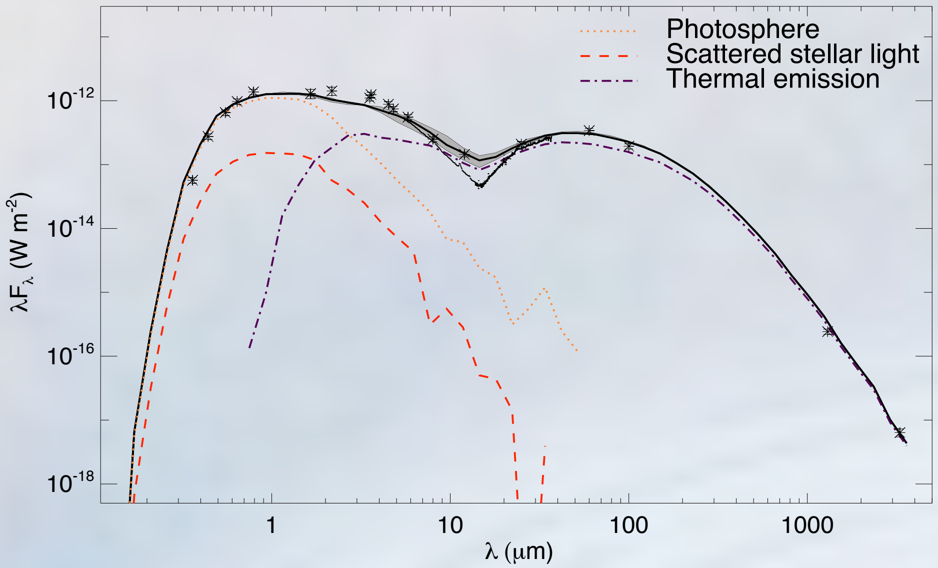


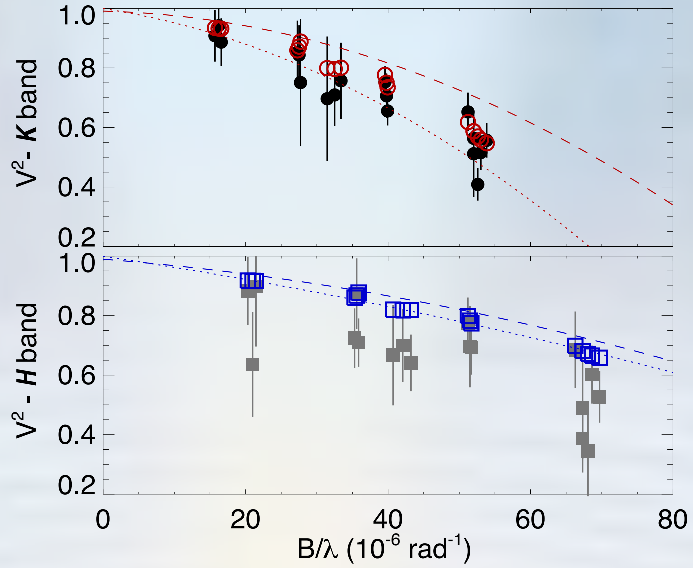


Comprehension of the dust vs gas morphology will increase with better coverage.

Tatulli, et al. (2008, A&A 489, 1151)

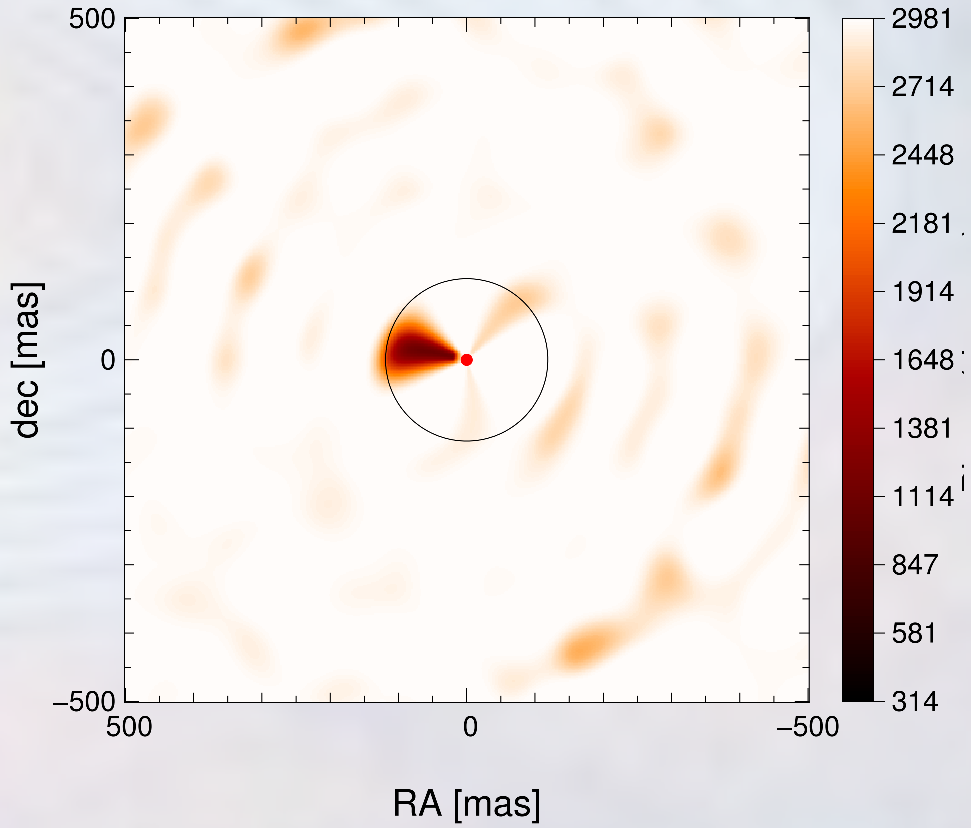
Transition disks: the case of T Cha





Olofsson et al. (2011, A&A 528, L6)

- Transition disks are disks with lack of MIR emission compared to FIR (discovered by Spitzer)
- Believe to have disk holes and therefore having starting planetary formation
- Discovery of disk gap between 0.17 and 7.5 AU (Olofsson et al. 2011)
- Discovery of a planet by Huelamo et al. (2011) at 62mas +/- 7mas, i.e. 6.7AU

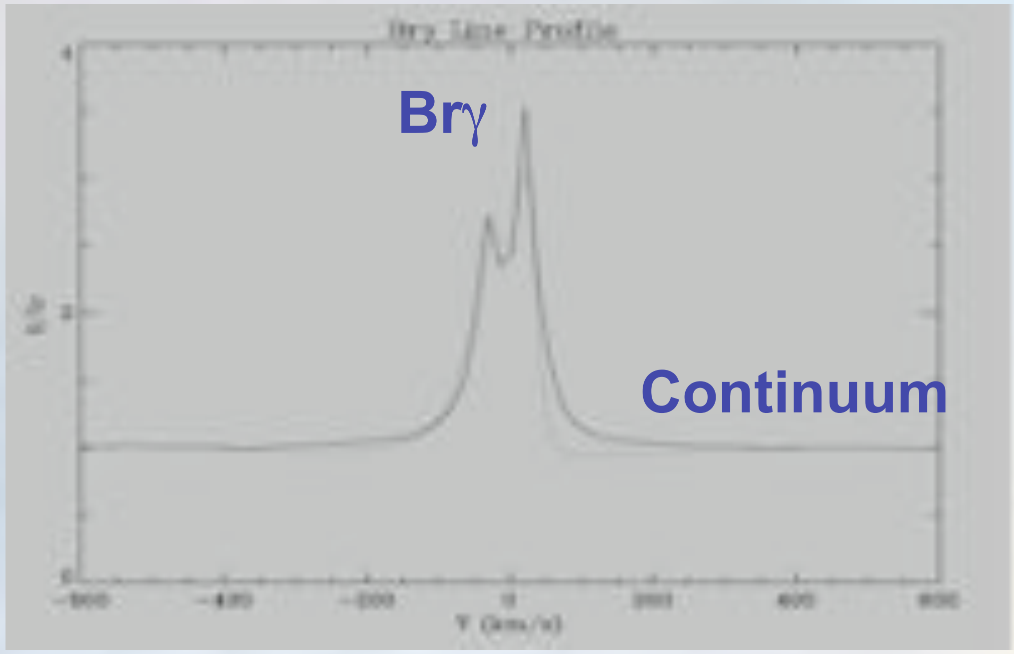


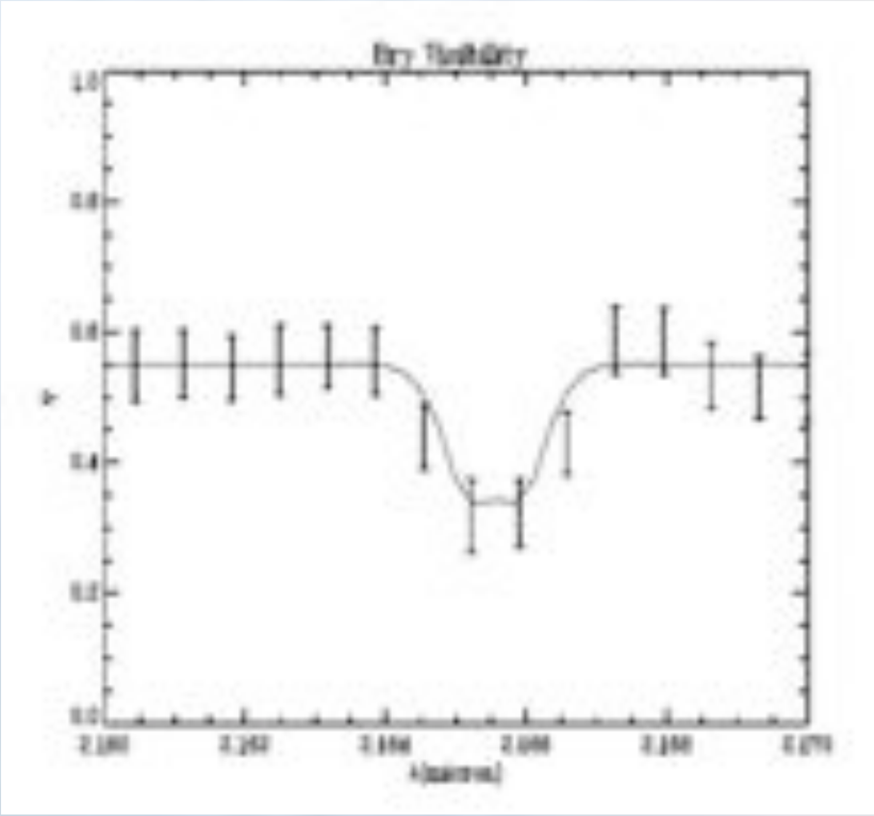
Huélamo et al. (2011, A&A 528, L7)

HYDROGEN LINE EMISSION

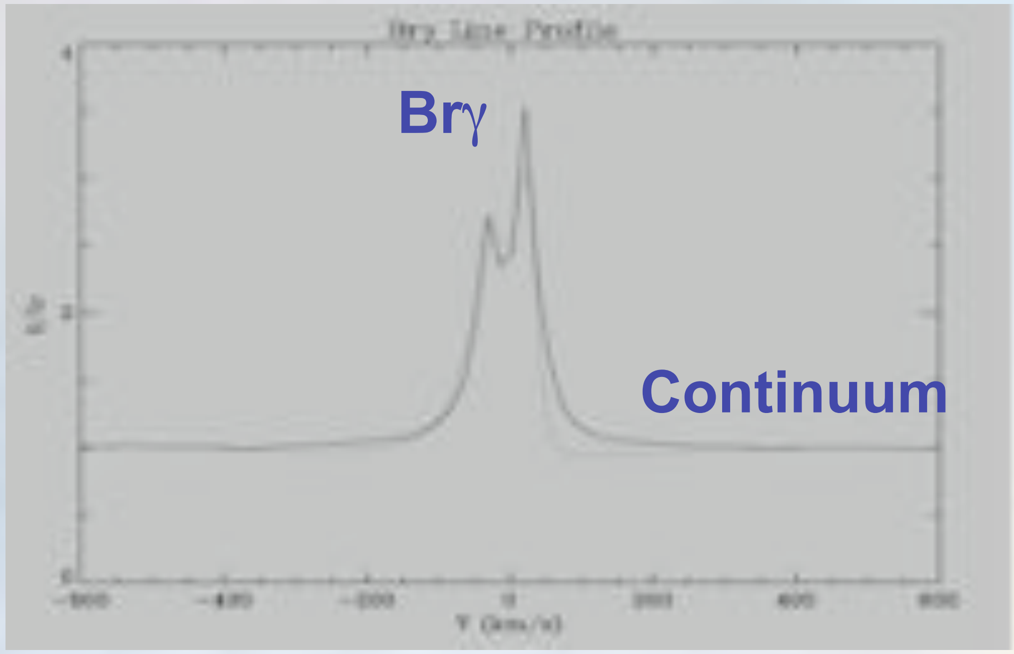
- Outflowing winds?
- Magnetospheres?

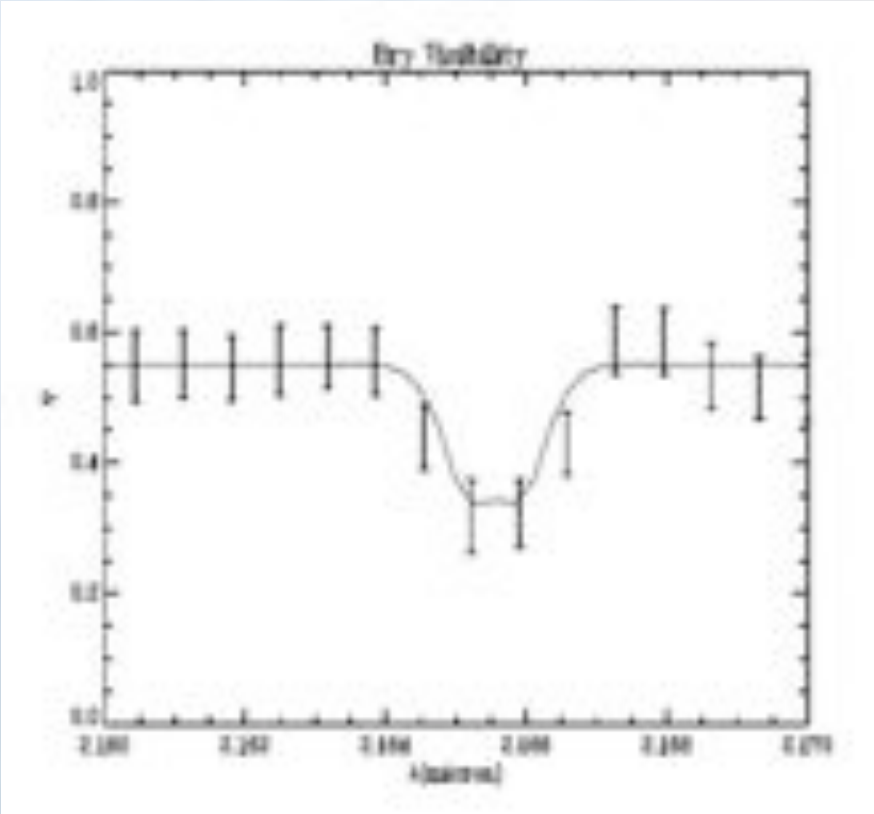
Disk and wind spatially are spectrally resolved in MWC 297

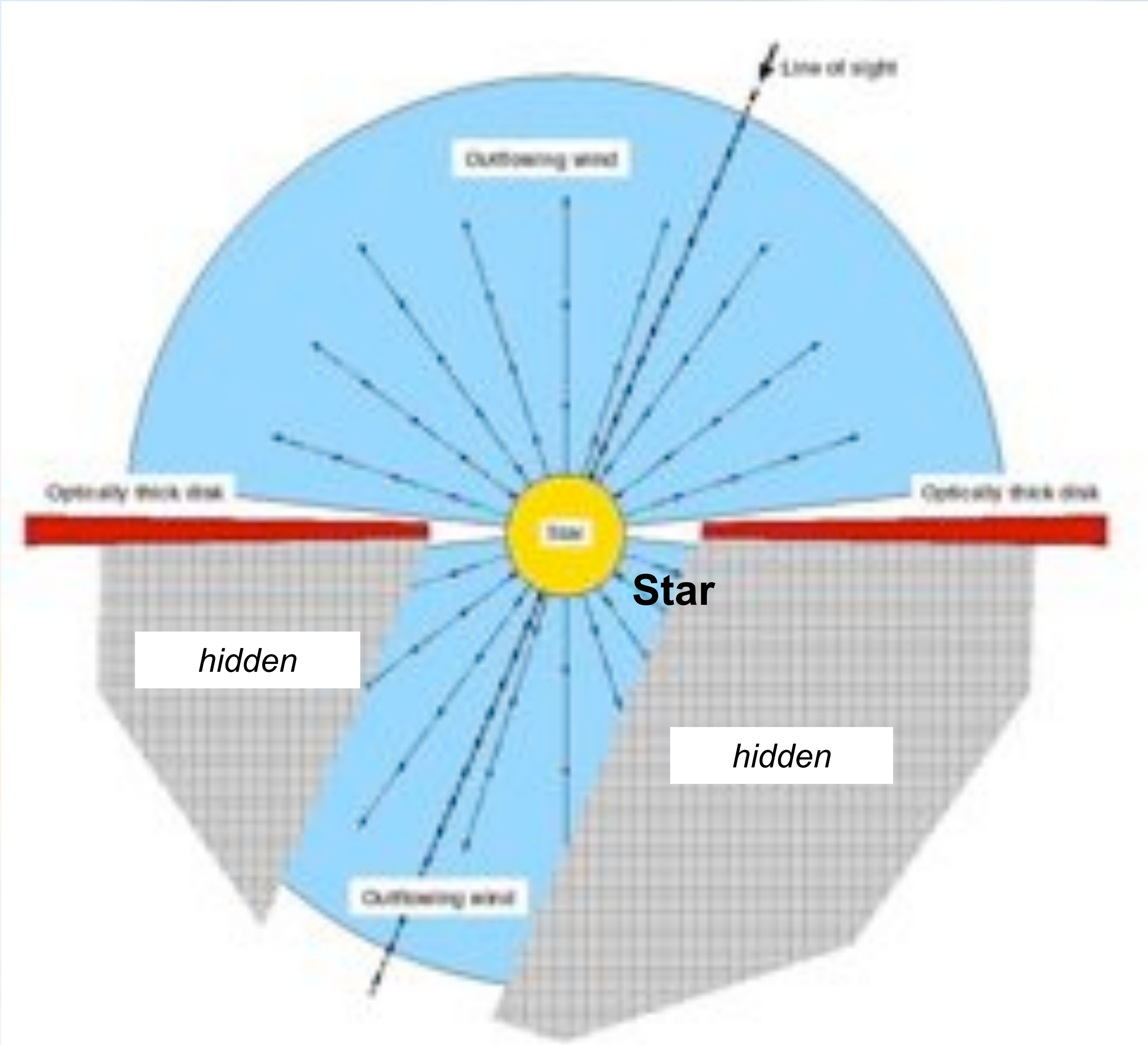




Disk and wind spatially are spectrally resolved in MWC 297

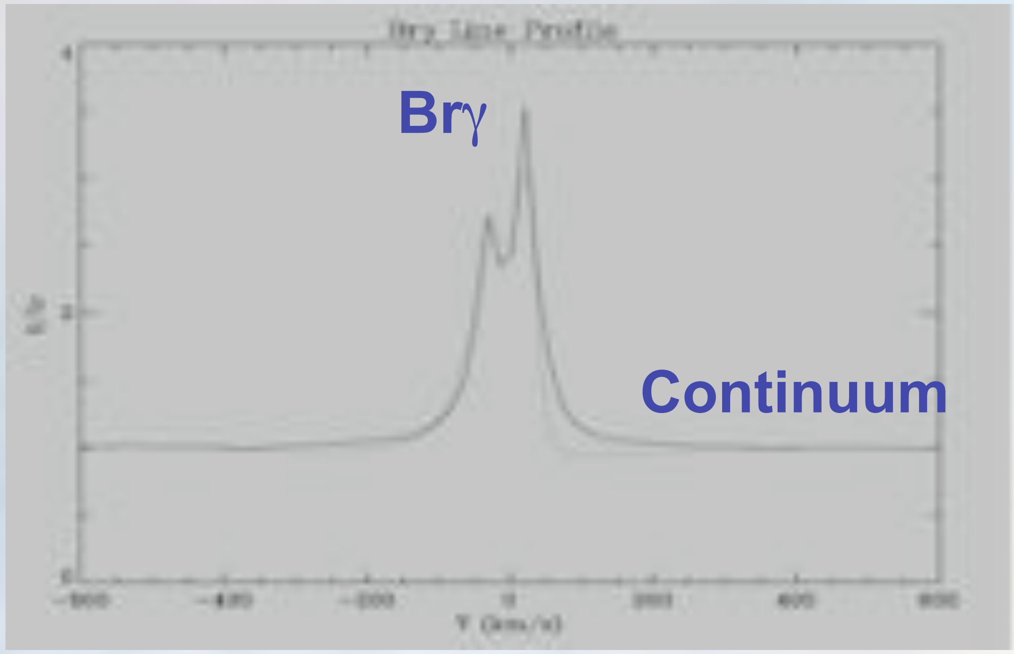


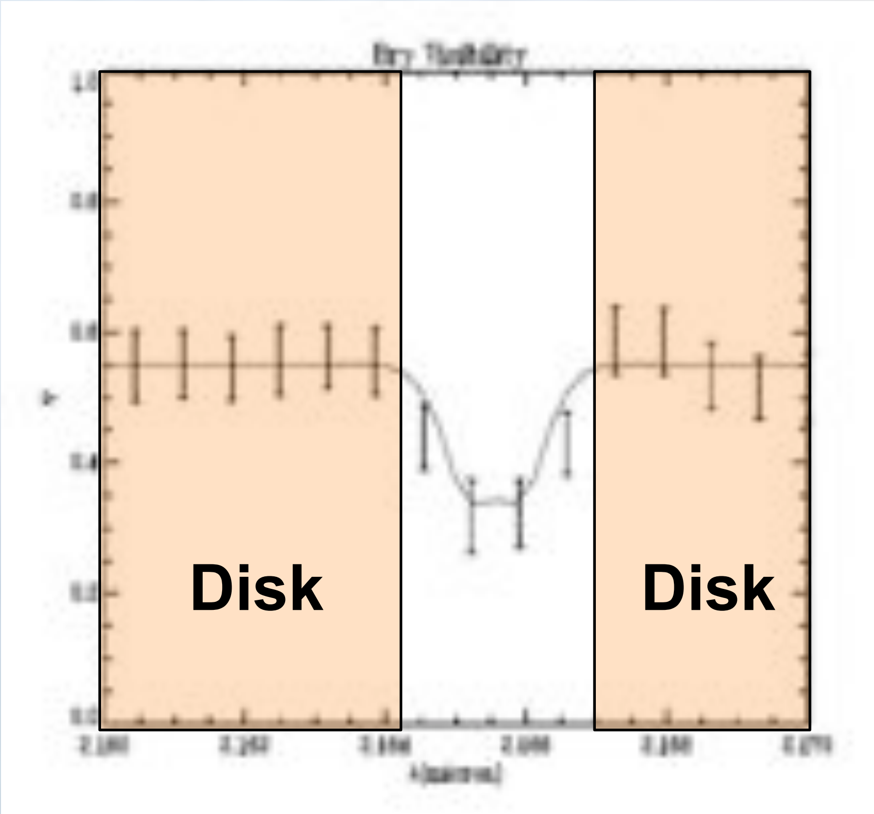


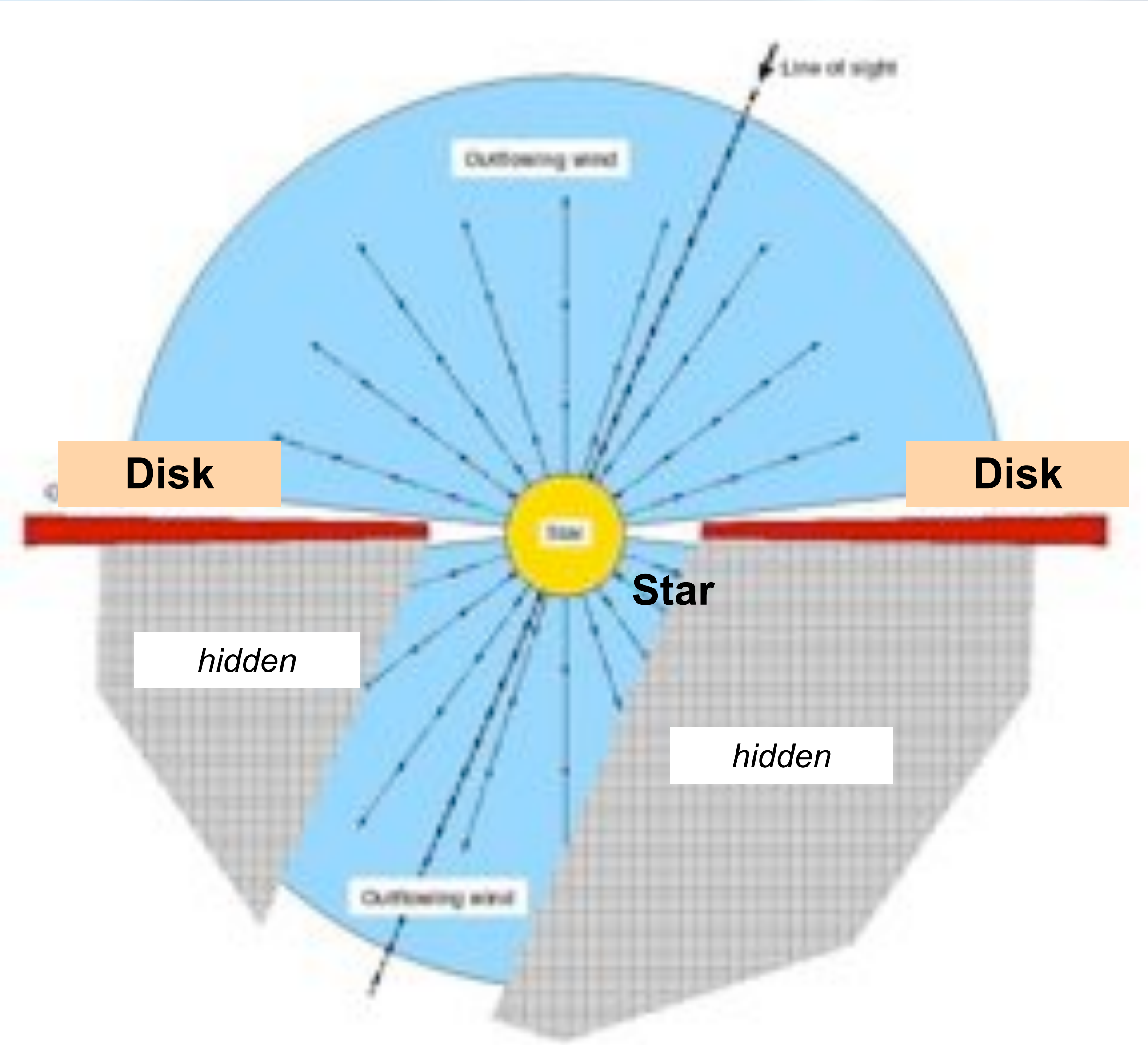


Malbet et al. (2007, A&A 464, 43)

Disk and wind spatially are spectrally resolved in MWC 297

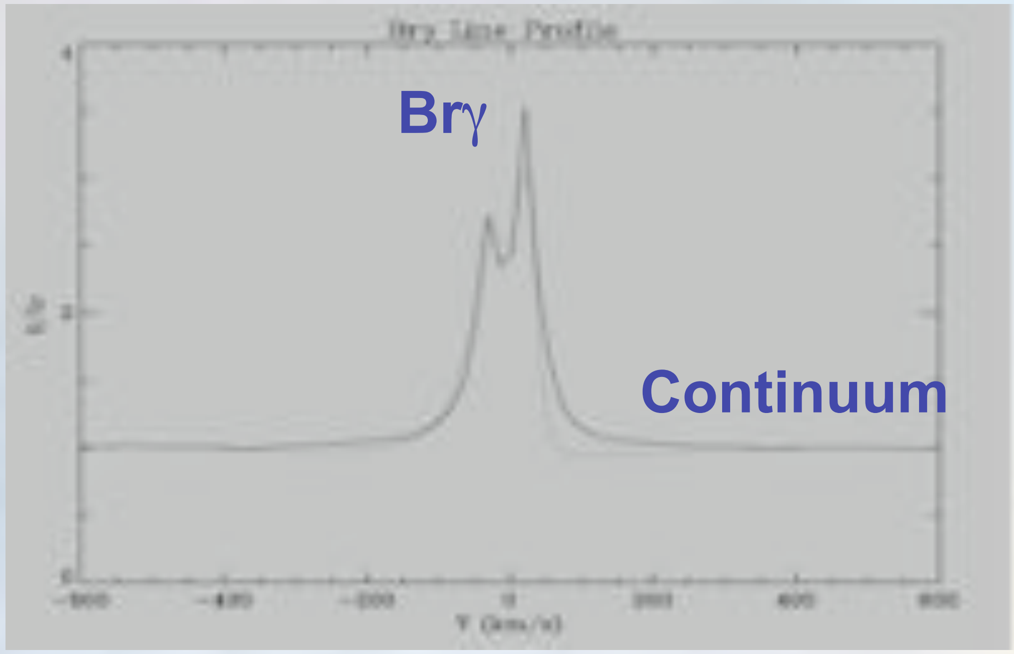


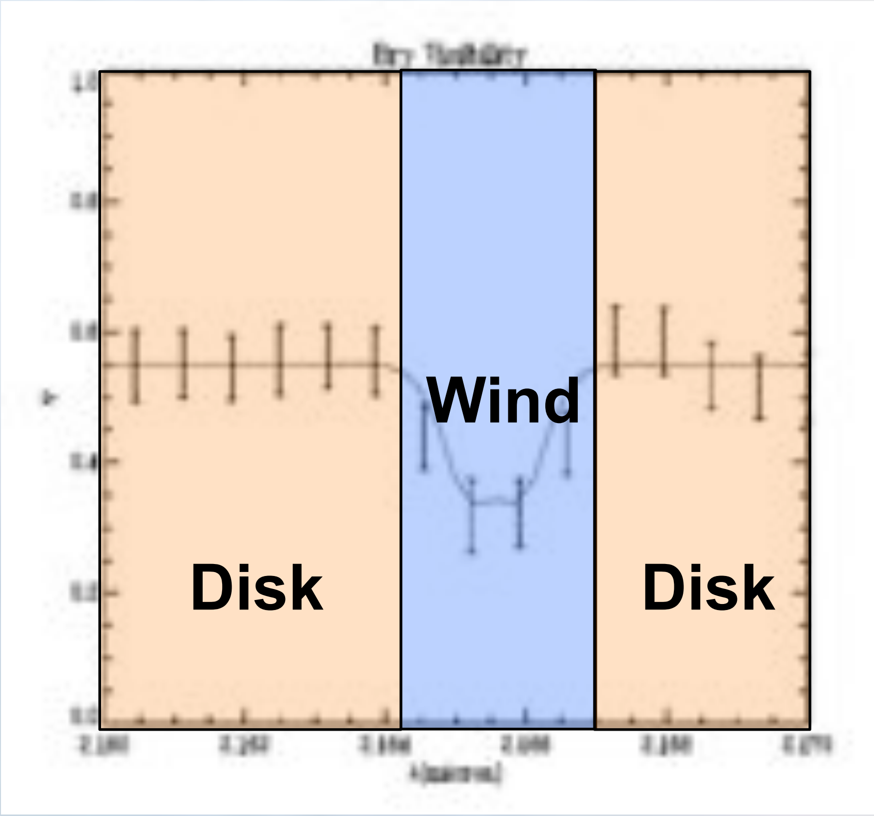


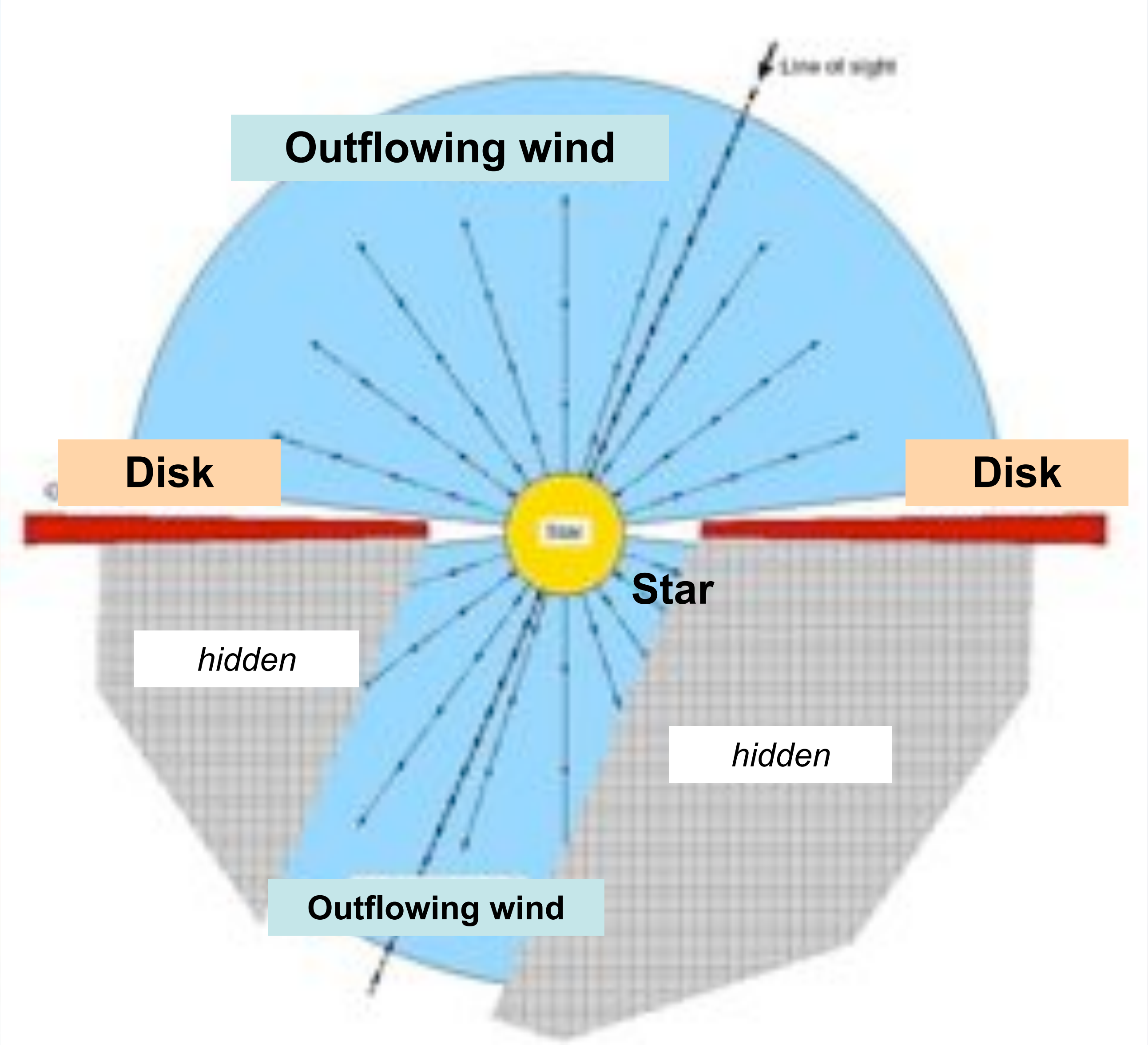


Malbet et al. (2007, A&A 464, 43)

Disk and wind spatially are spectrally resolved in MWC 297

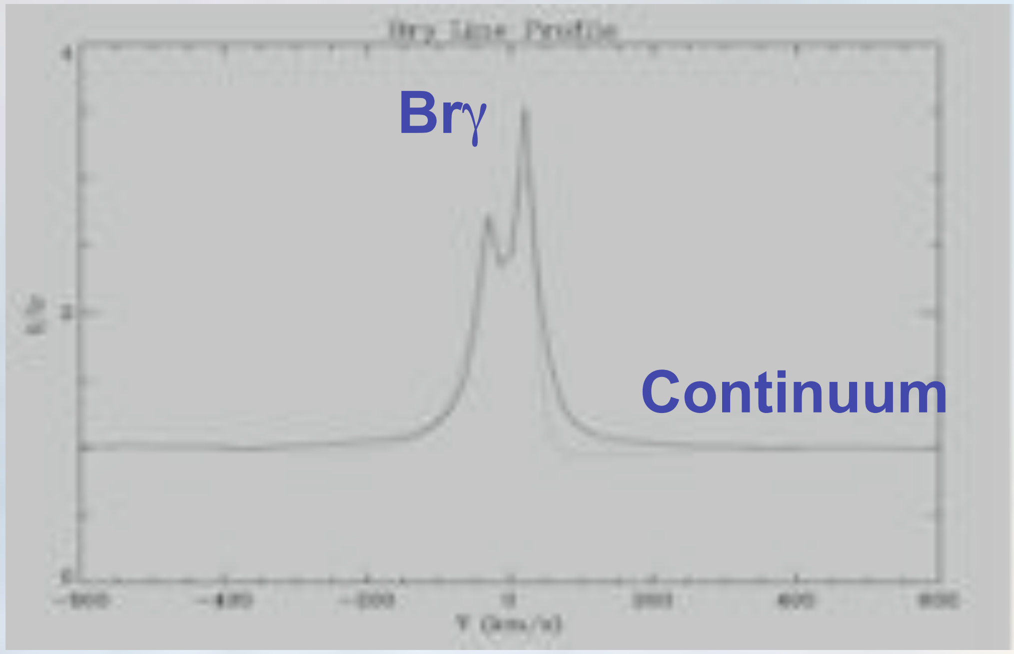


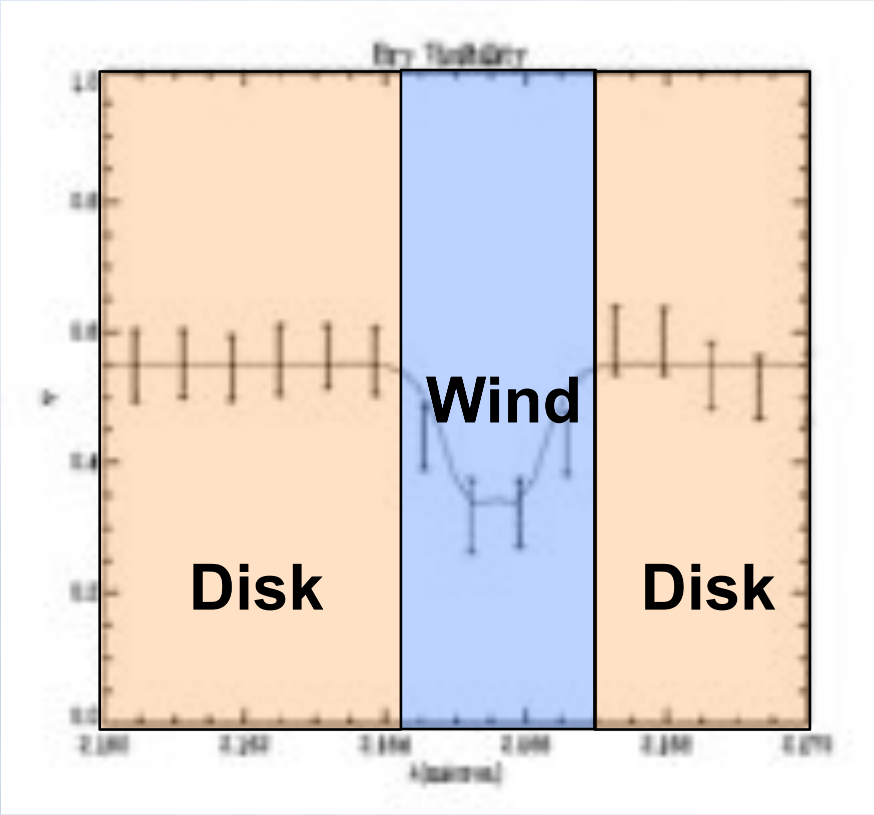


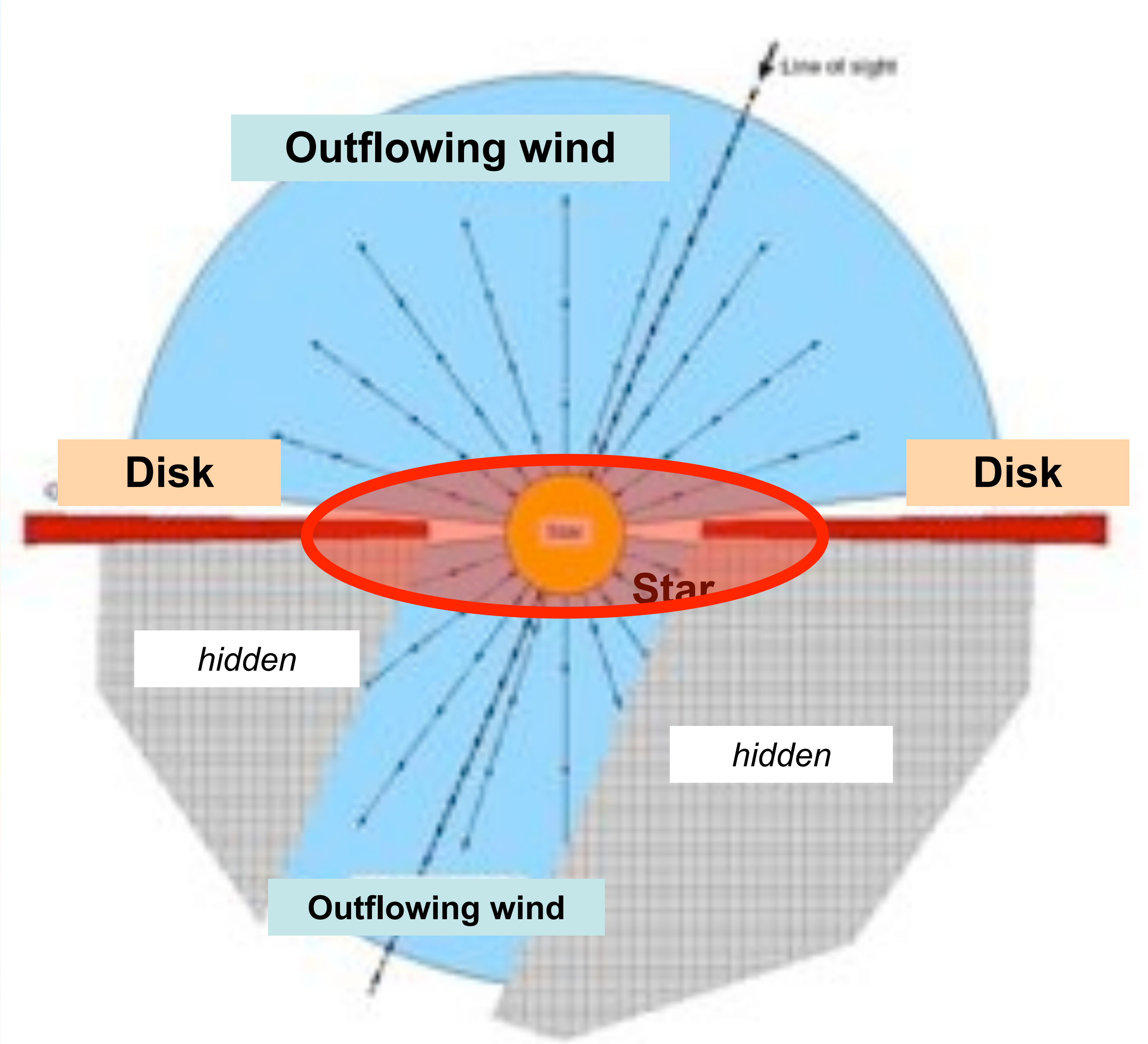


Malbet et al. (2007, A&A 464, 43)

Disk and wind spatially are spectrally resolved in MWC 297



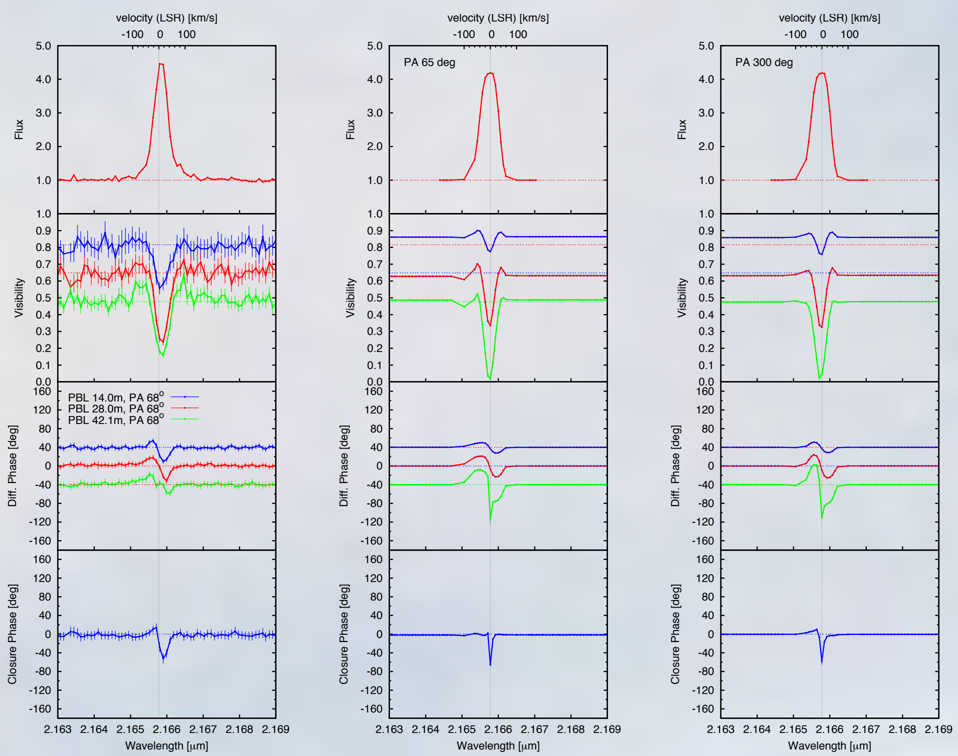




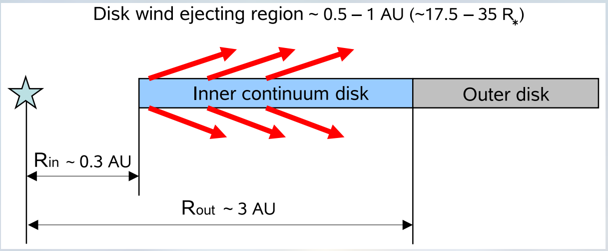
Malbet et al. (2007, A&A 464, 43)

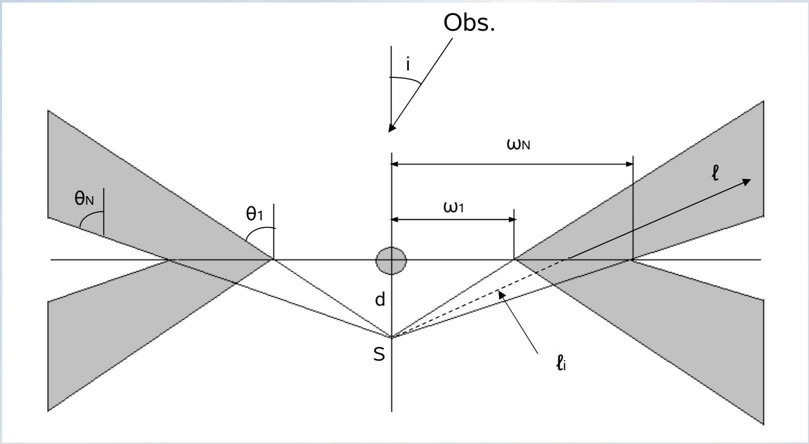
→ Investigate the link between disk, star and wind

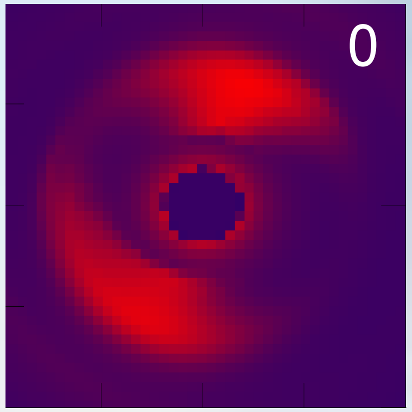
Magneto-centrifugally driven disk wind

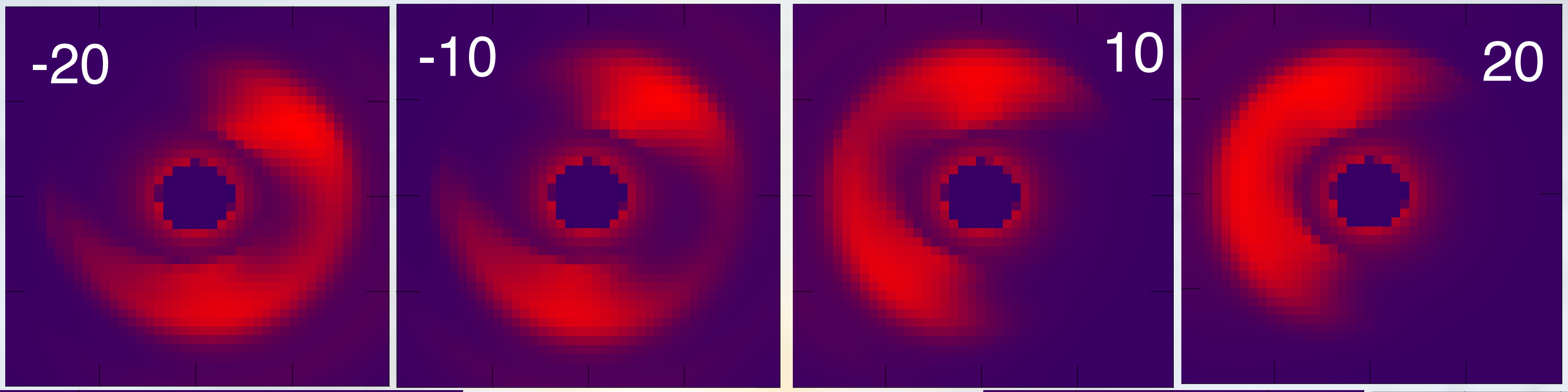


Weigelt et al. (2011, A&A 527, A103)

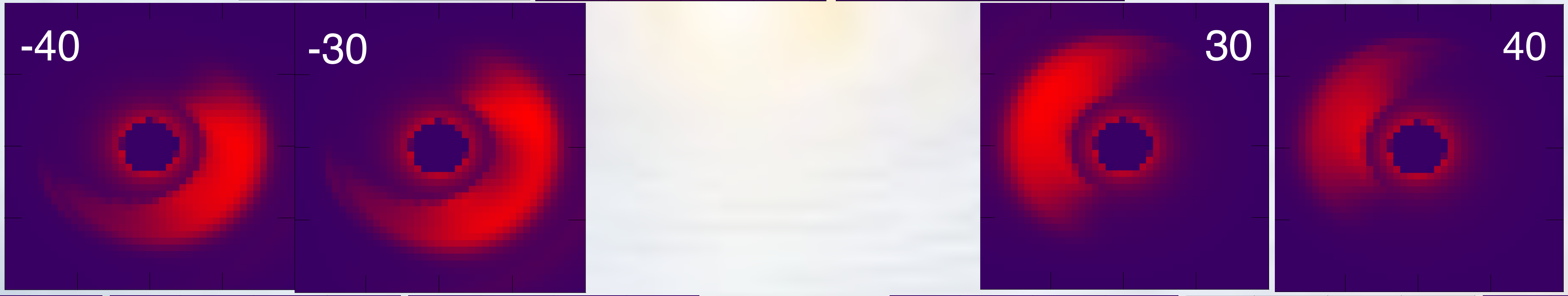


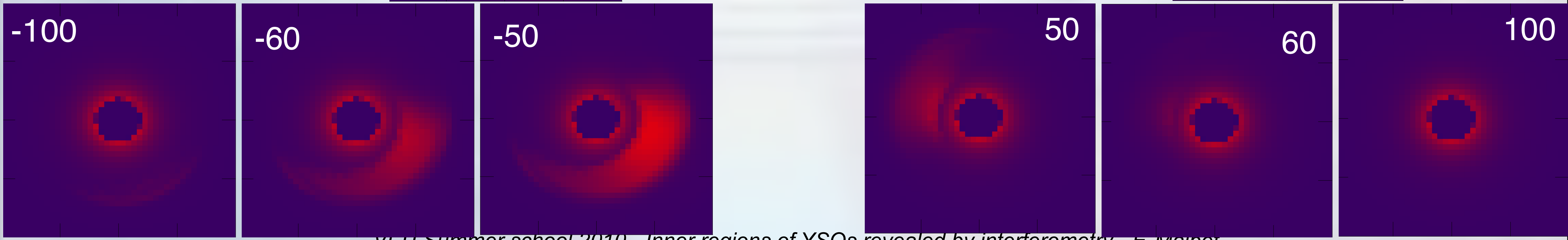




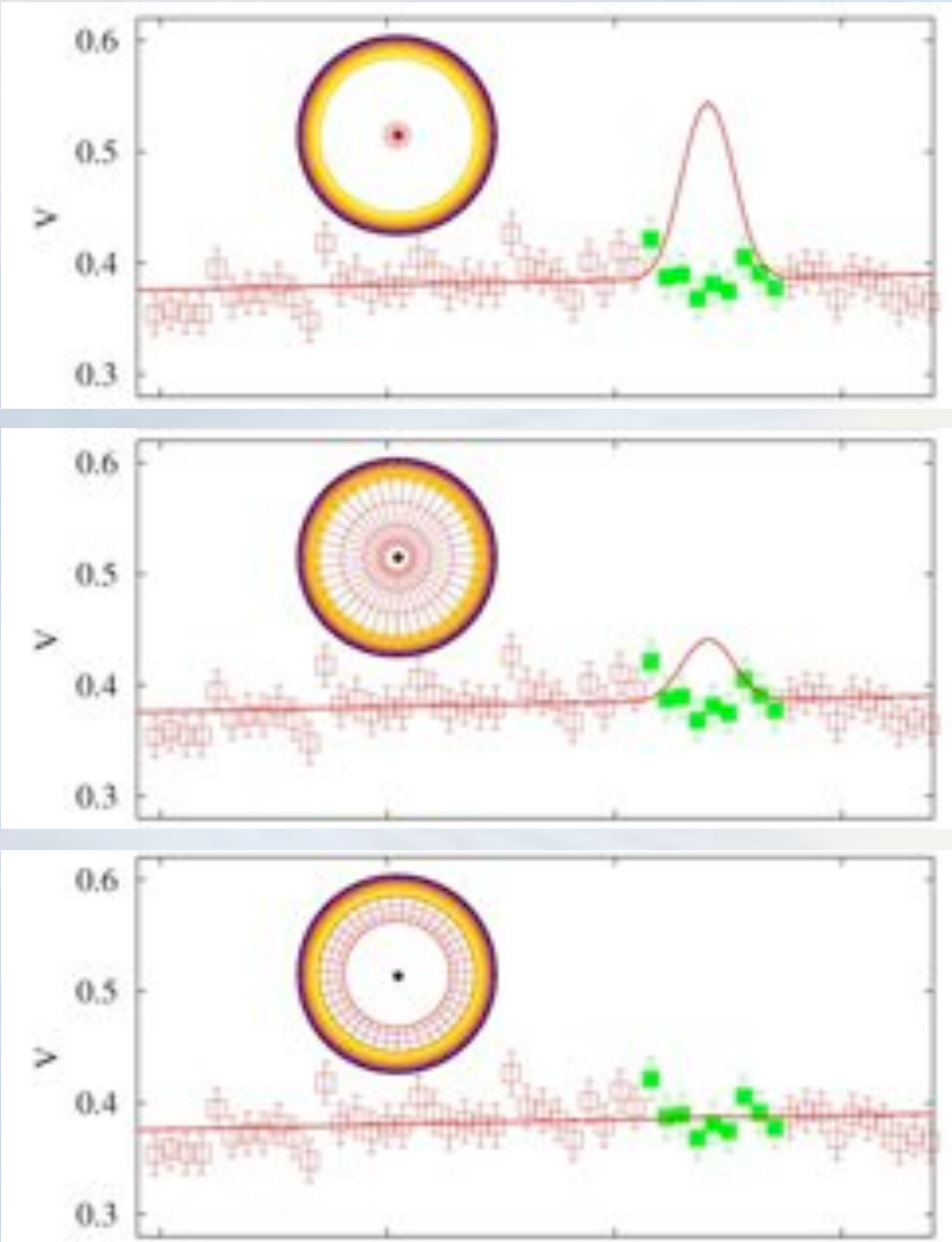


MWC 297 at R~120000





Nature of Brγ in the HAe star HD104237



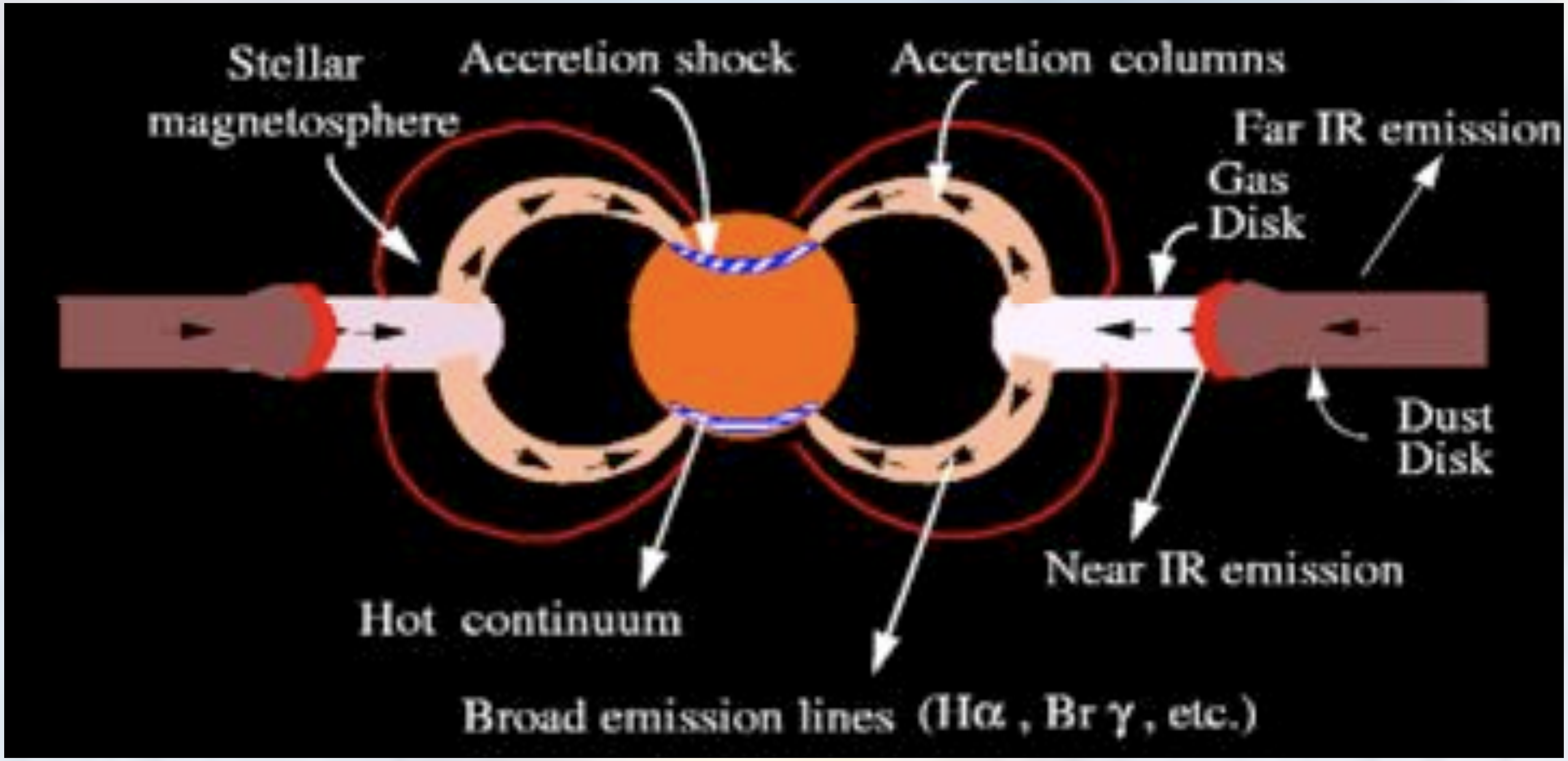
Disk truncated by magnetosphere

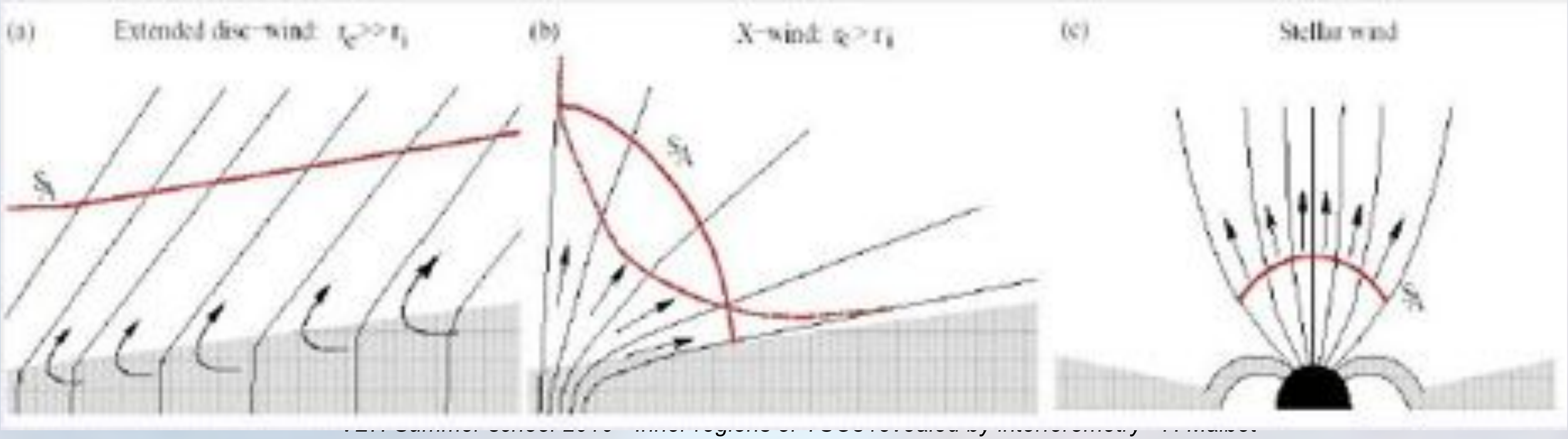
Gas within the disk

Outflowing wind

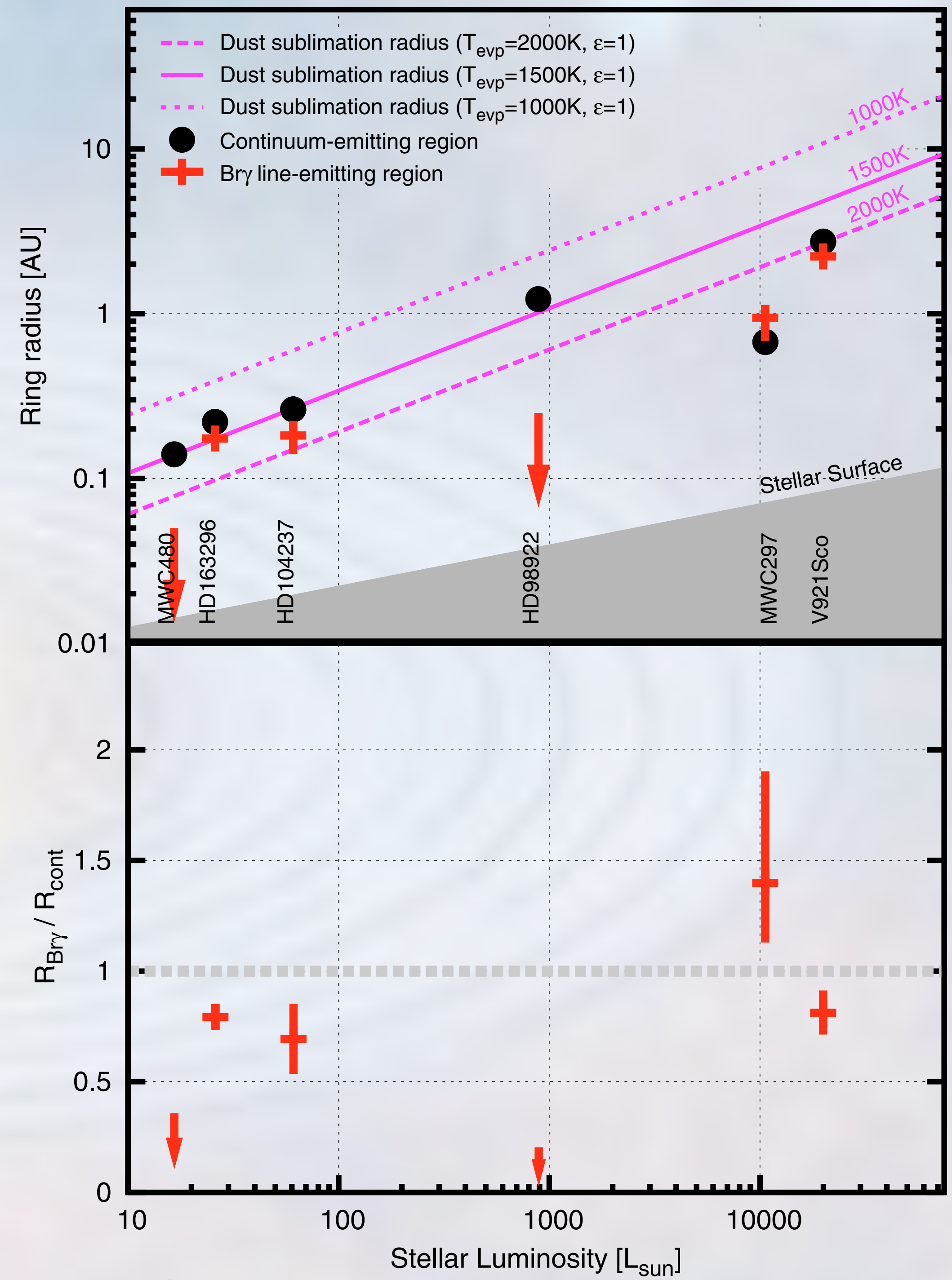
Tatulli et al. (2007, A&A 464, 55)

Disk/star interaction ?





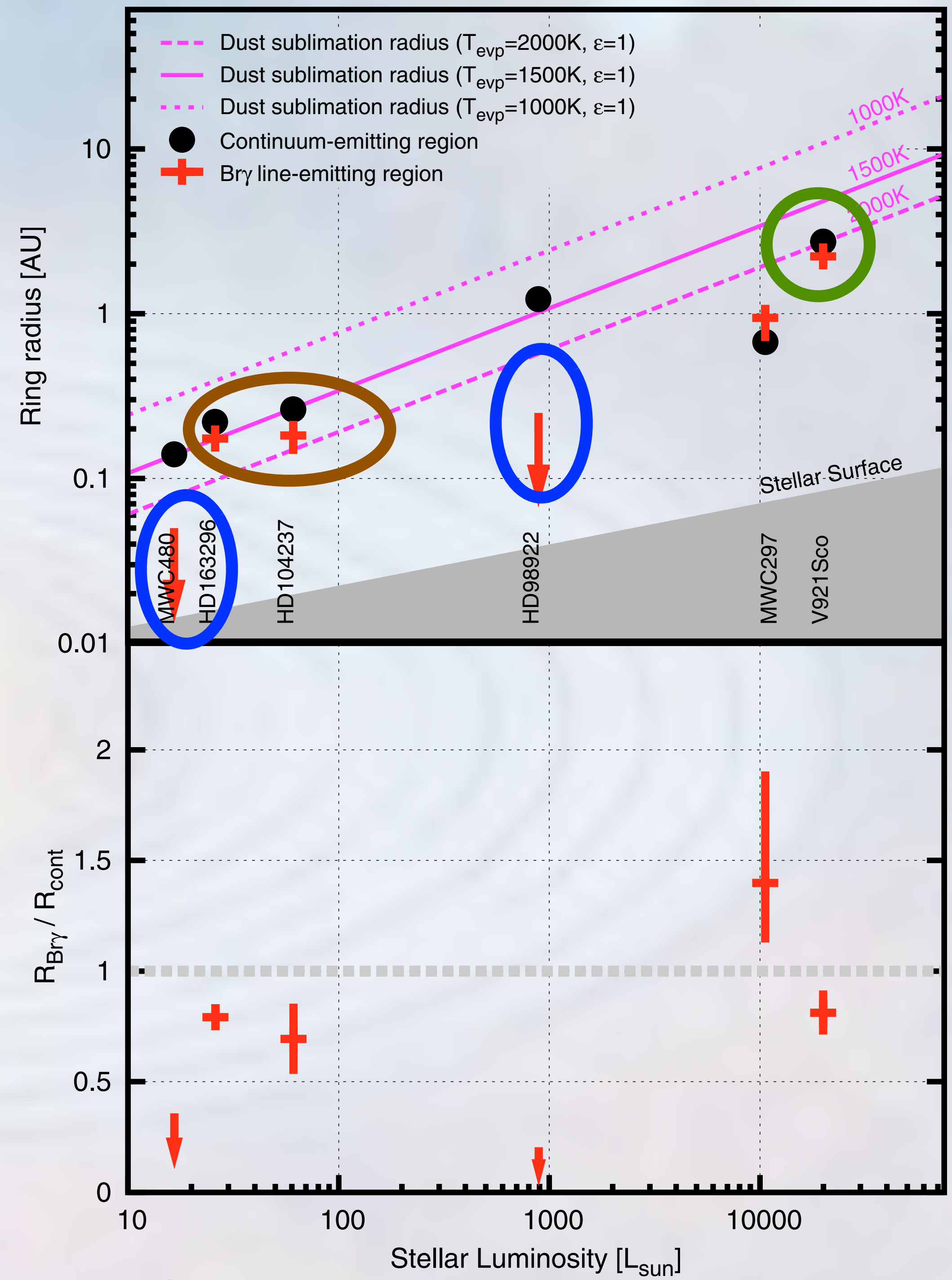
A systematic study of the origin of the BrΥ emission in Herbig Ae/Be stars



Kraus et al. (2008, A&A 489, 1157)

A systematic study of the origin of the BrY emission in Herbig Ae/Be stars

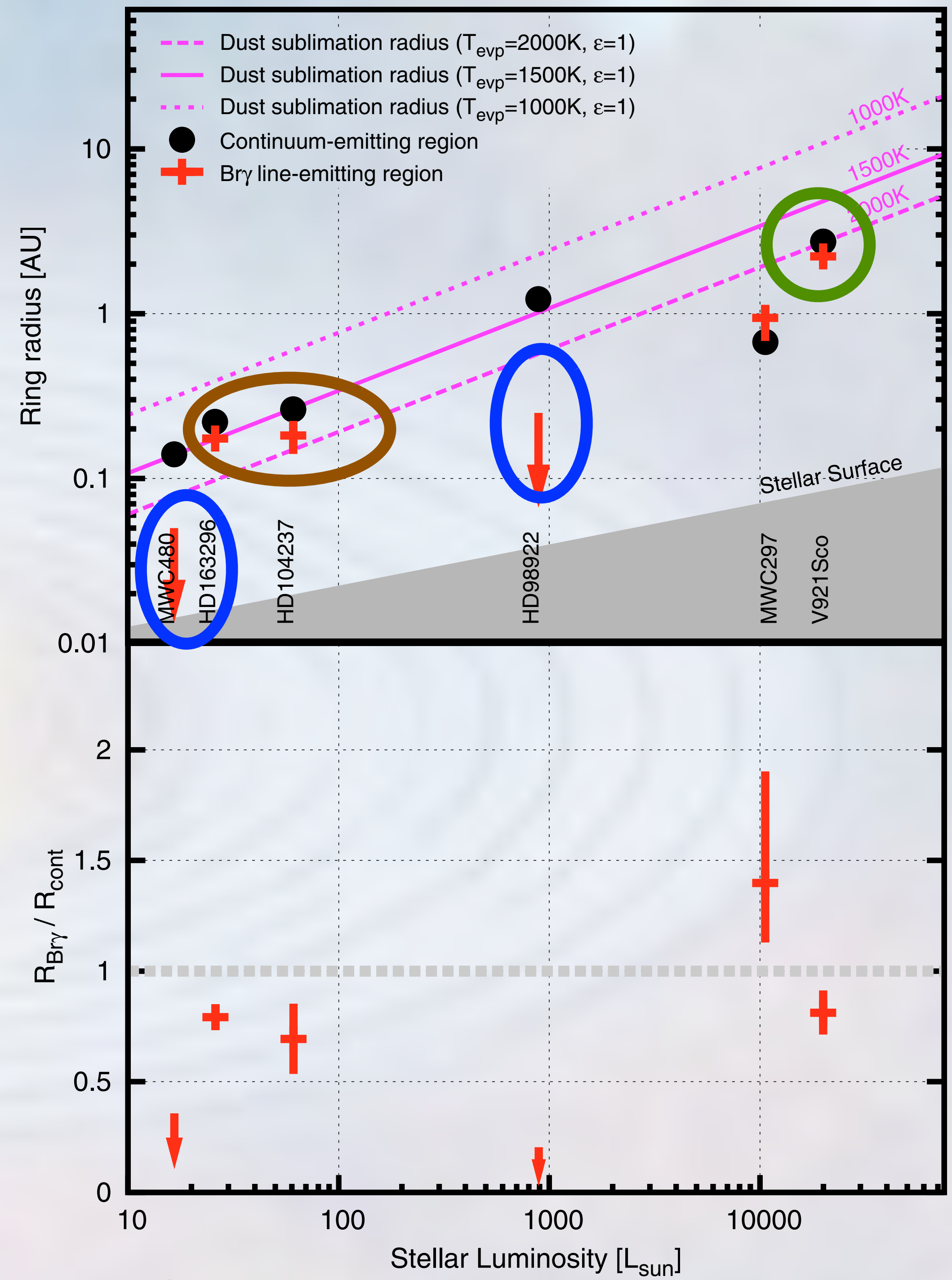
- magnetospheric accretion
- disk wind
- X-wind or disk wind ?



Kraus et al. (2008, A&A 489, 1157)

A systematic study of the origin of the Brϒ emission in Herbig Ae/Be stars

- **magnetospheric accretion**
- **disk wind**
- **X-wind or disk wind ?**

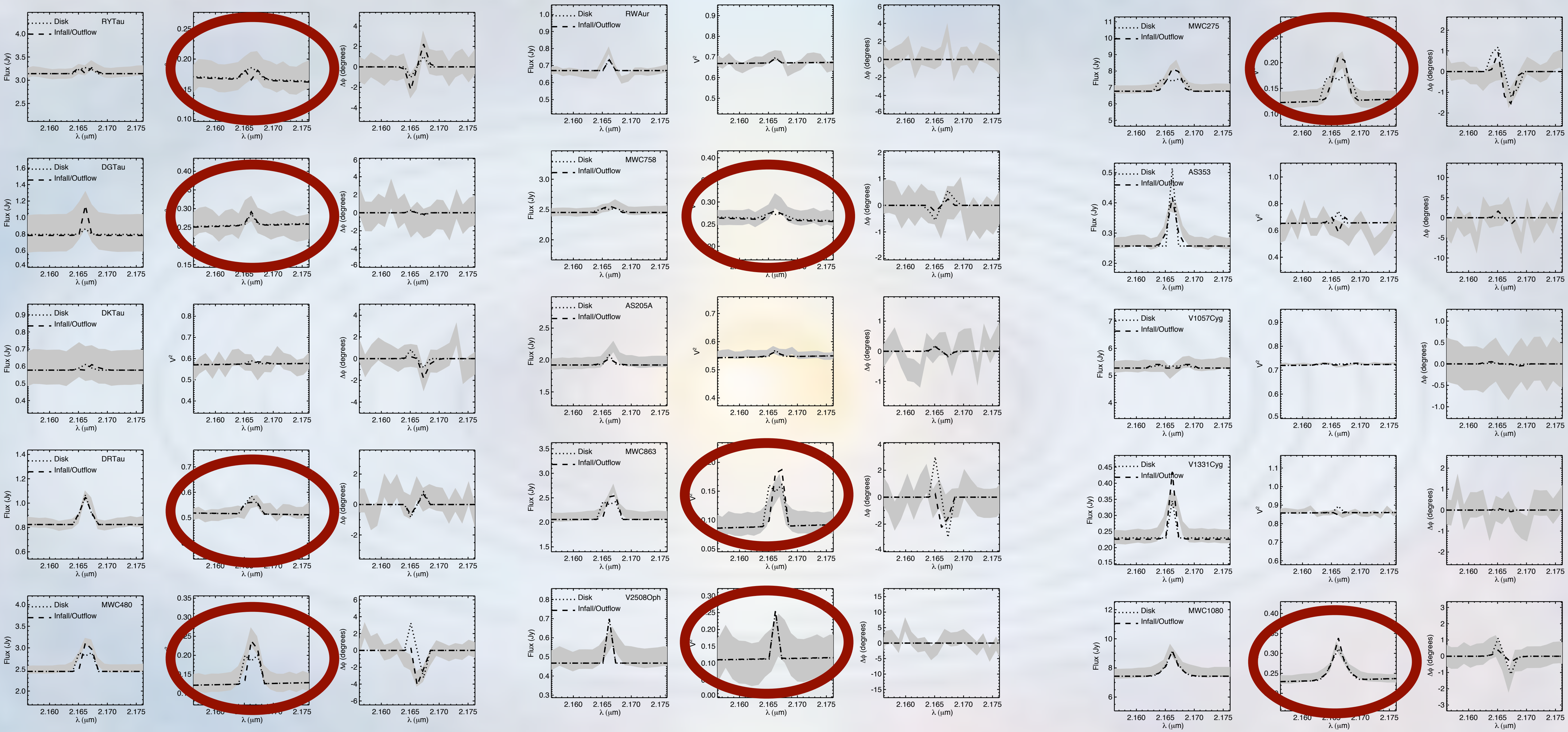


➡ No correlation with L_* as suggested by Eisner et al. 2007

➡ We are probing mostly outflows phenomena:
Brγ indirect accretion tracer through accretion-driven mass loss?

Kraus et al. (2008, A&A 489, 1157)

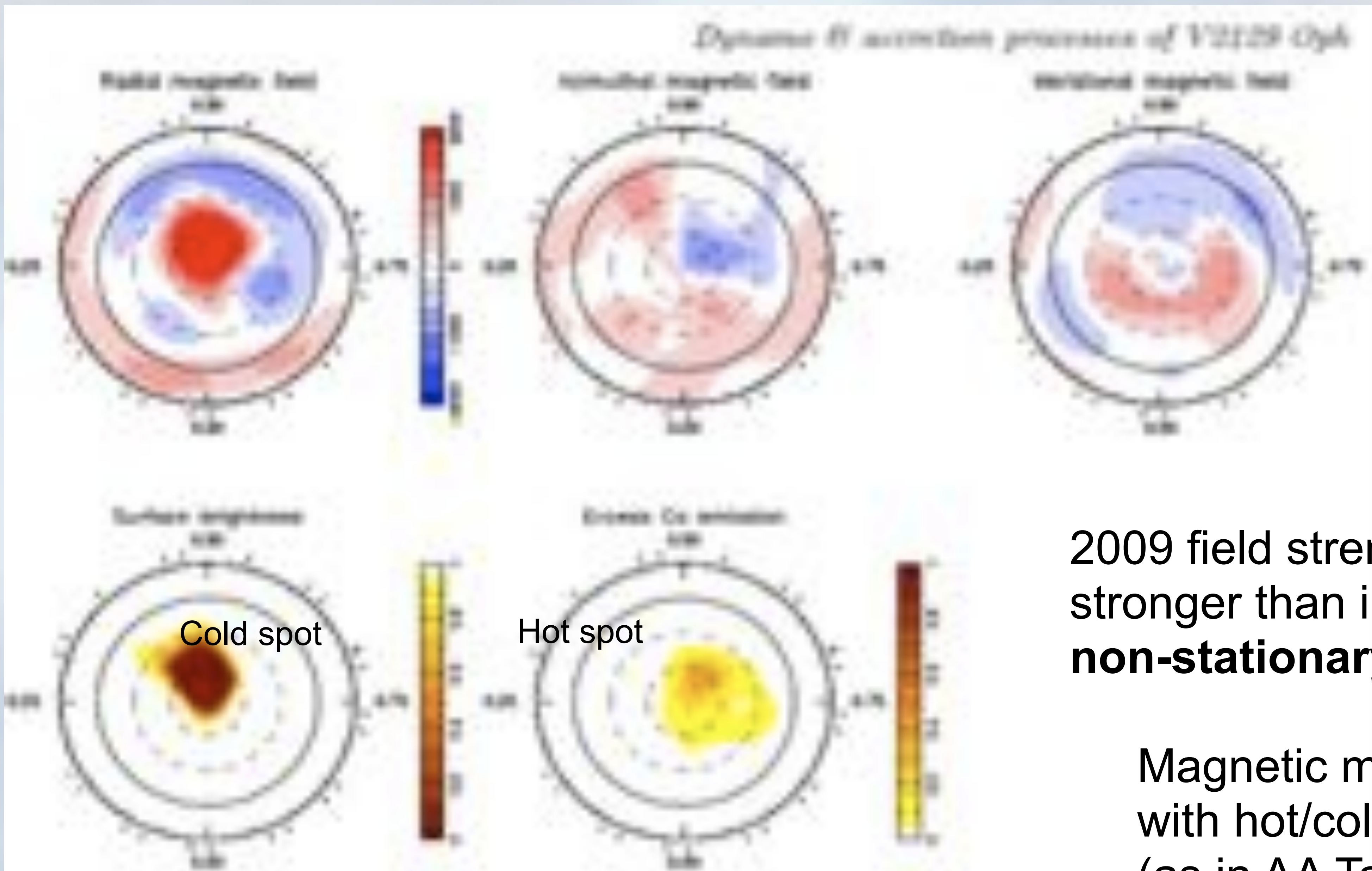
Spatially and Spectrally Resolved Hydrogen Gas within 0.1 AU of T Tauri and Herbig Ae/Be Stars



Eisner et al. (2010, ApJ 718, 774)

V2129 Oph magnetic field

2.1kG octupole + 0.9kG dipole, both tilted at ~20 deg onto the rot. axis



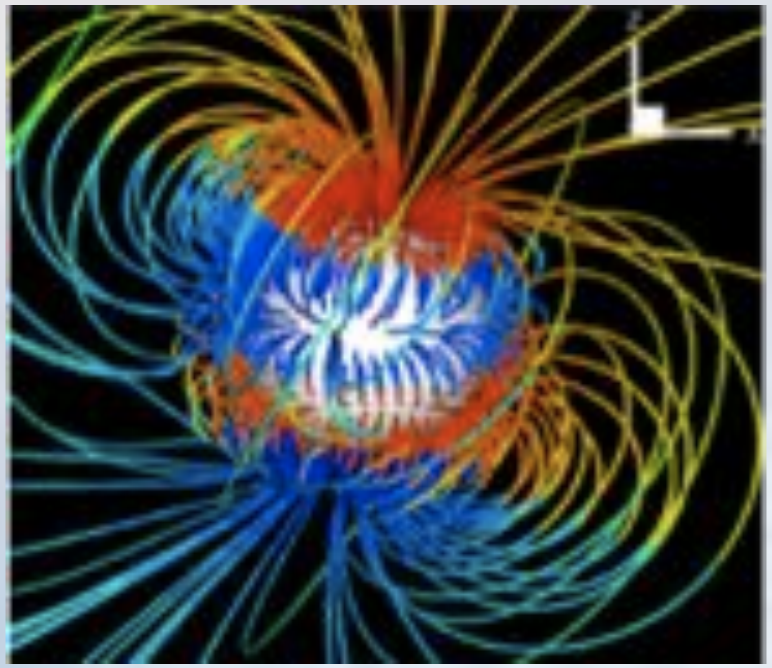
2009 field strength *1.5-3 stronger than in June 2005 : **non-stationary dynamo**

Magnetic map consistent with hot/cold spot location (as in AA Tau)

Donati et al. 2010

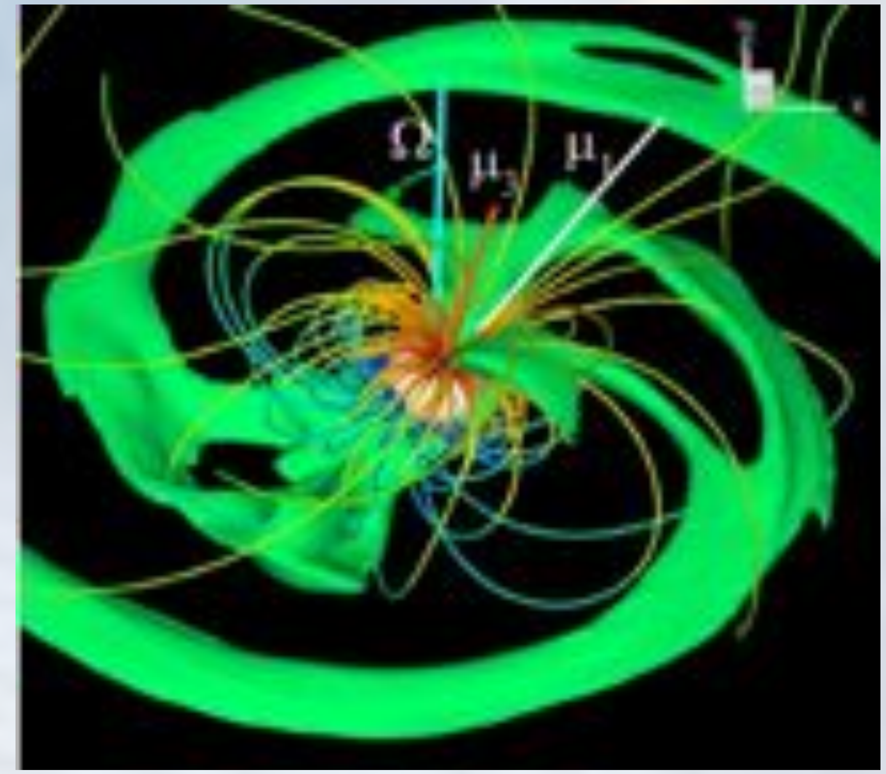
V2129 Oph MHD simulations

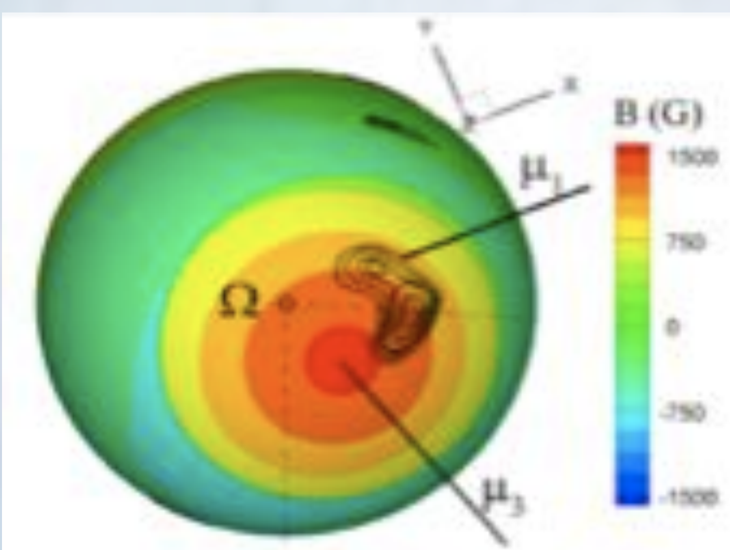
Tilted 1.2kG octupole + 0.35kG dipole



Disc truncation by the dipole (dominates at large distances) @ r_m=6.2R*

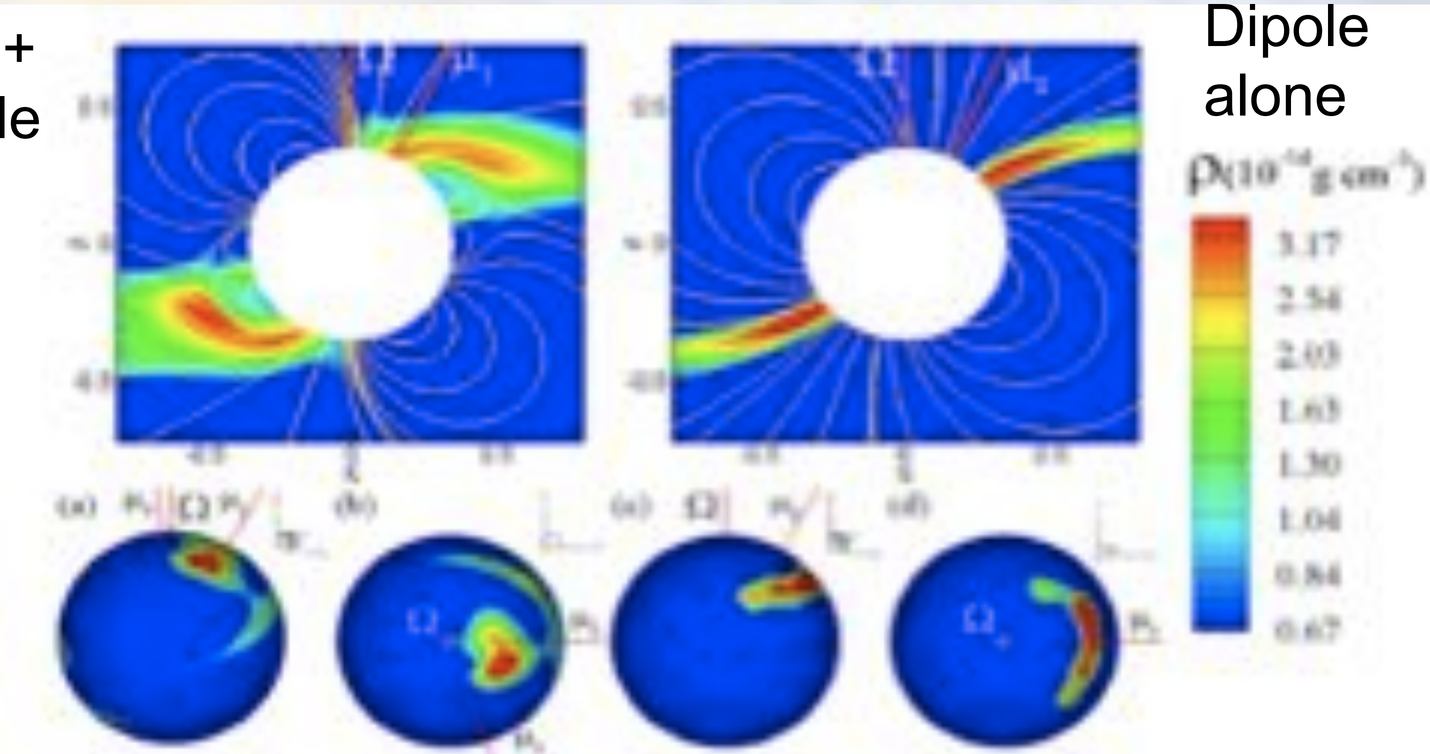
Accretion flow redistributed into the octupole close to the star





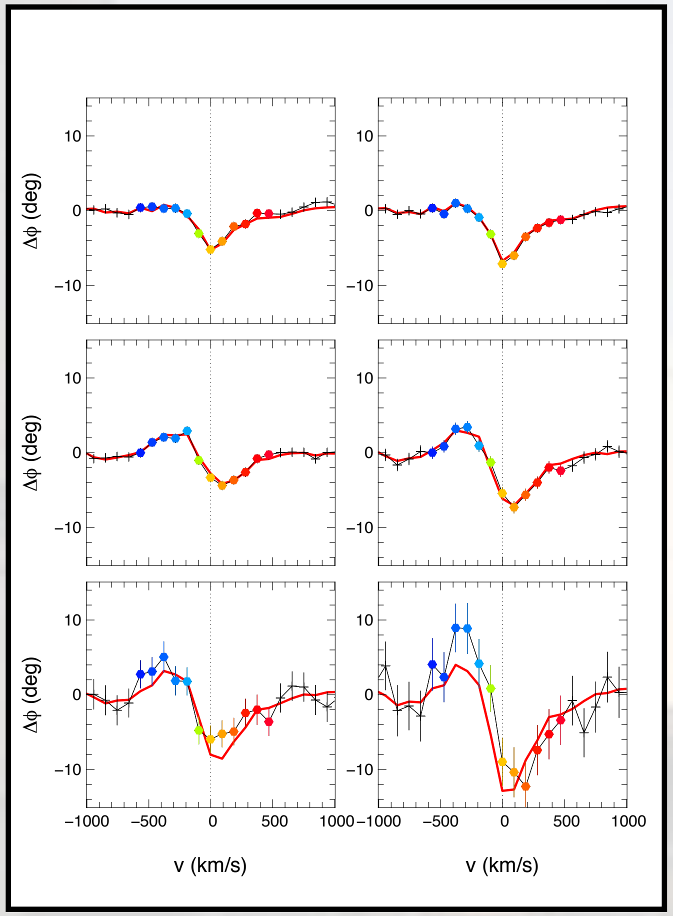
Dipole + octupole

Dipole alone

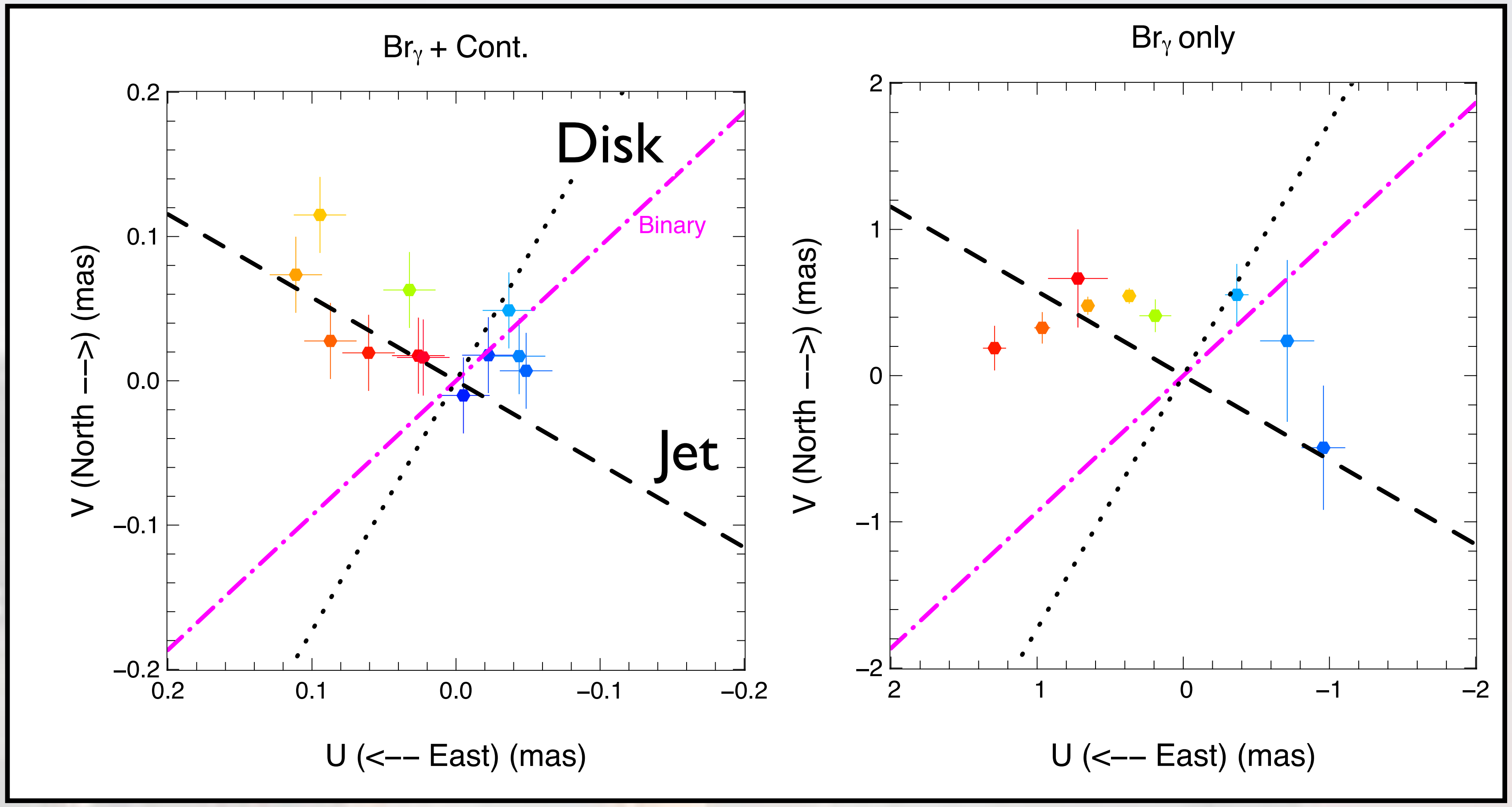


Romanova et al. 2010

Spectro-astrometry of Z CMa



6 differential-phase signals



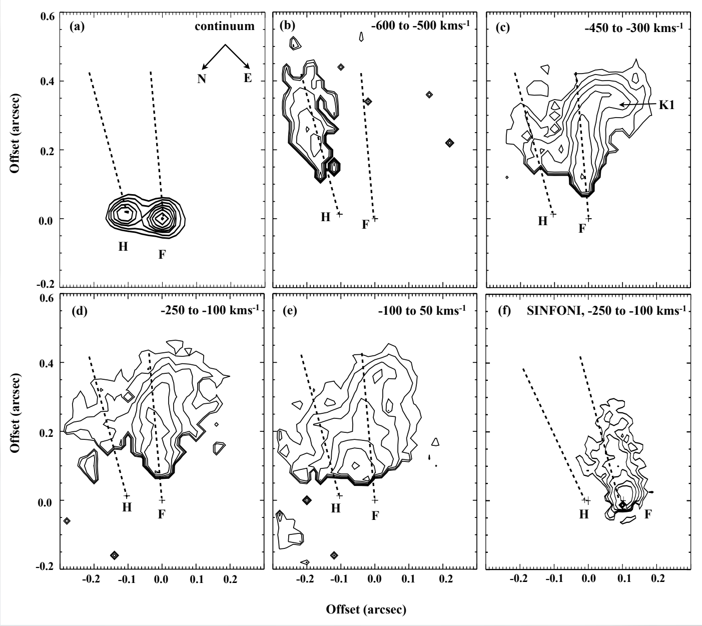
Brγ + continuum

Brγ only

Δφ ⇨ photocenter displacement ⇨ spectro-astrometry

Clear asymmetric displacements up to ~150 μas
at red- and blue-shifted velocities.

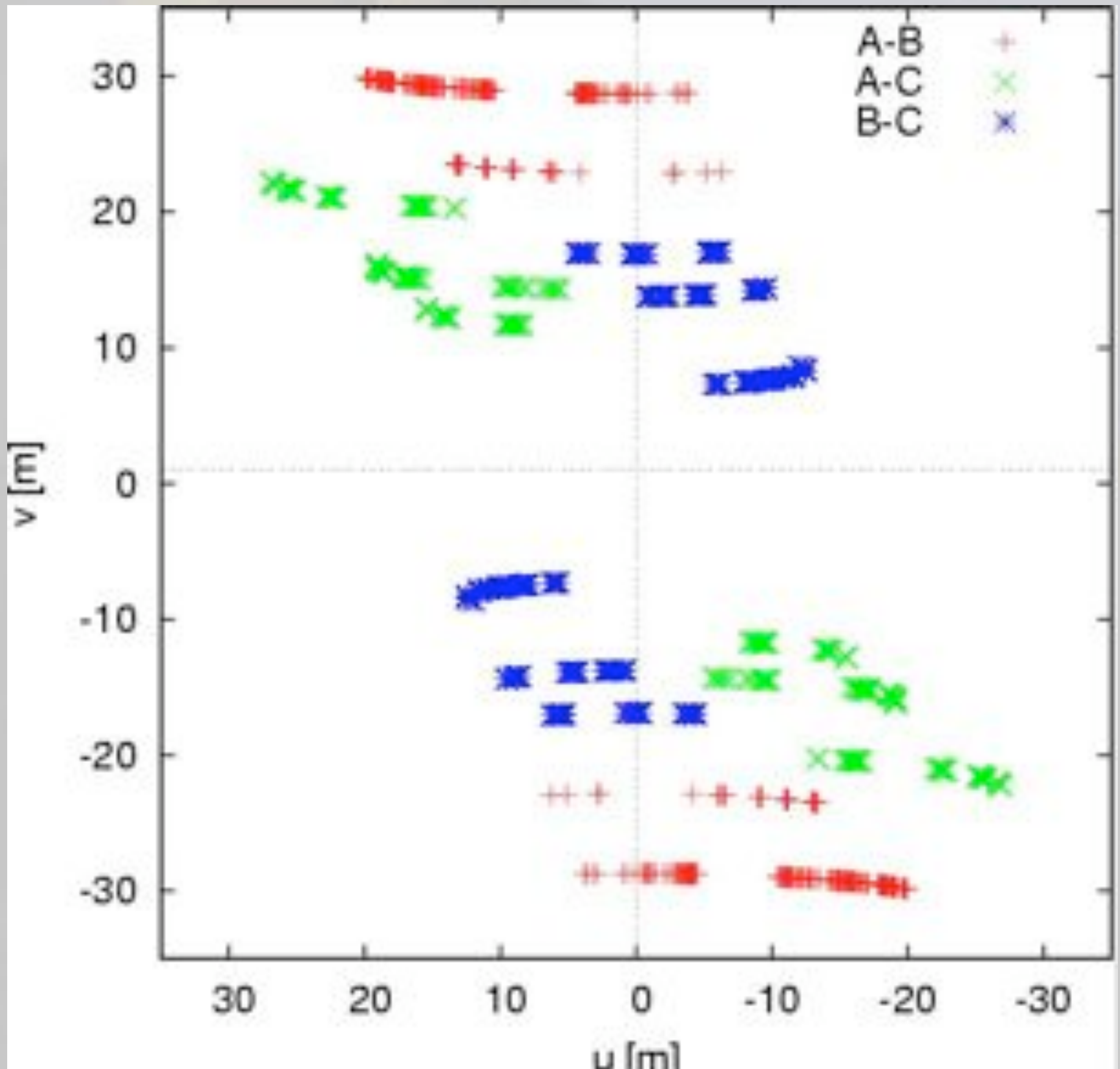
Benisty et al. (2010, A&A 517, L3)

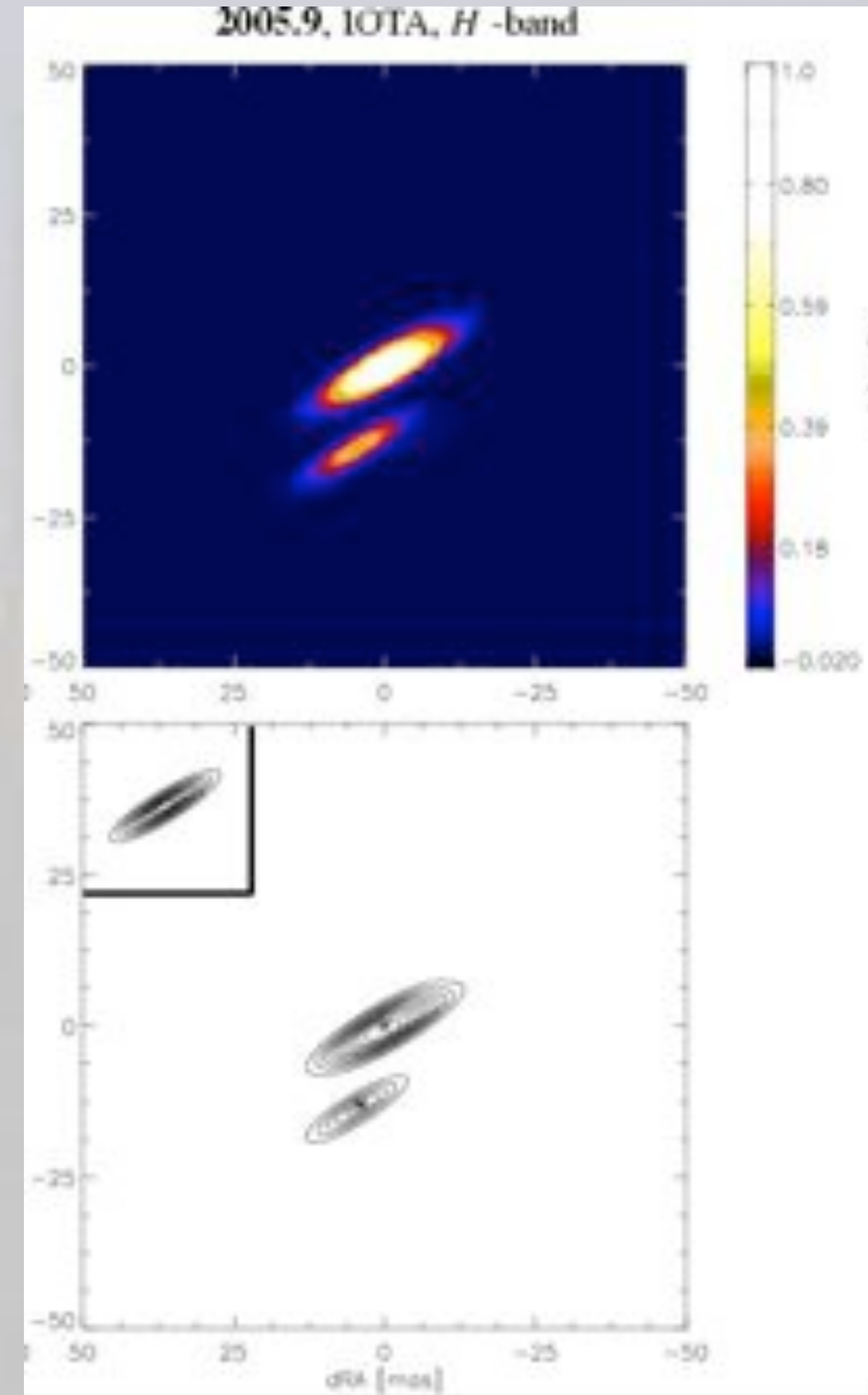


Whelan, Dougados et al. (2010)
OSIRIS @ Keck

MULTIPLE SYSTEMS

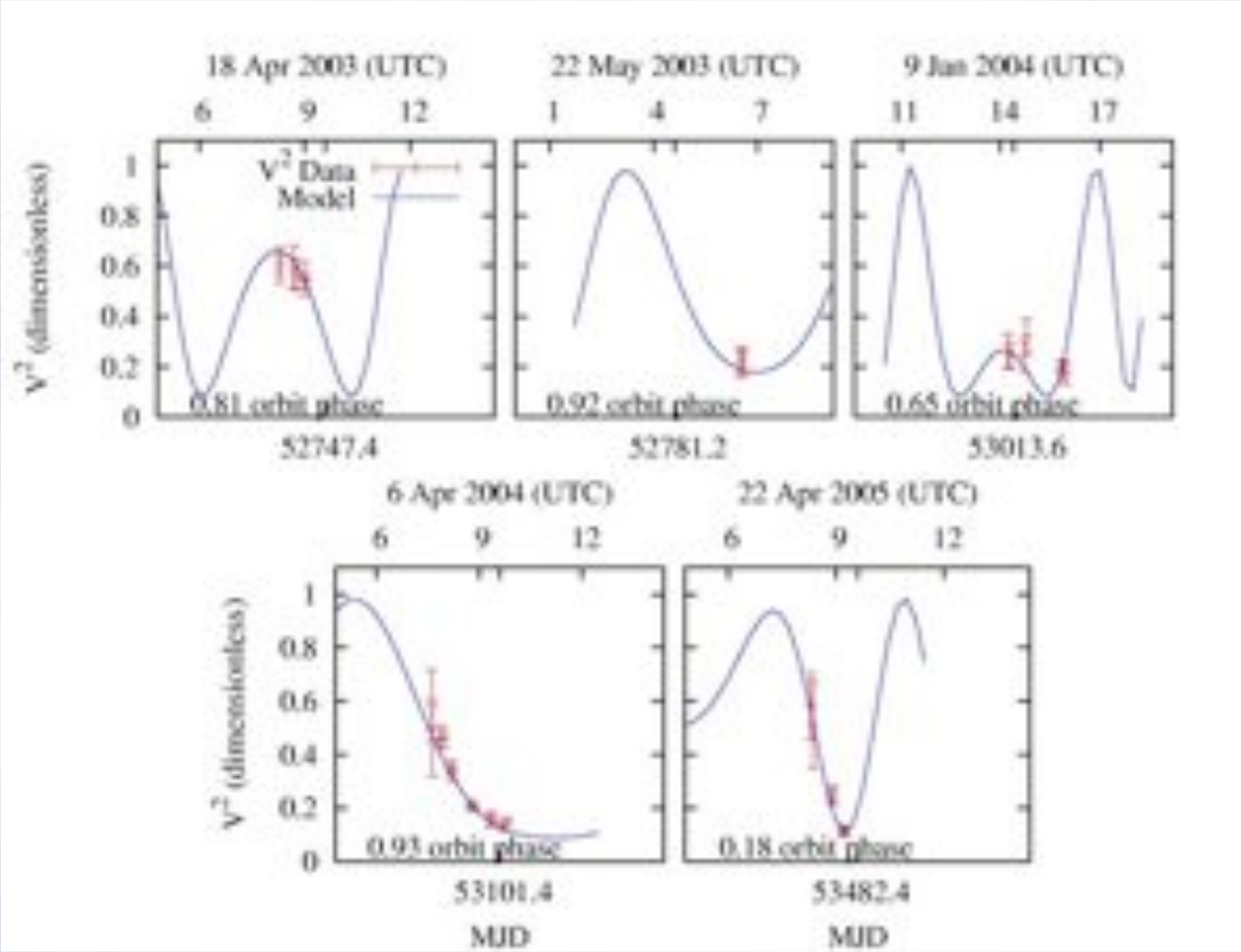
Aperture synthesis imaging of the θ¹ Orionis C system with IOTA

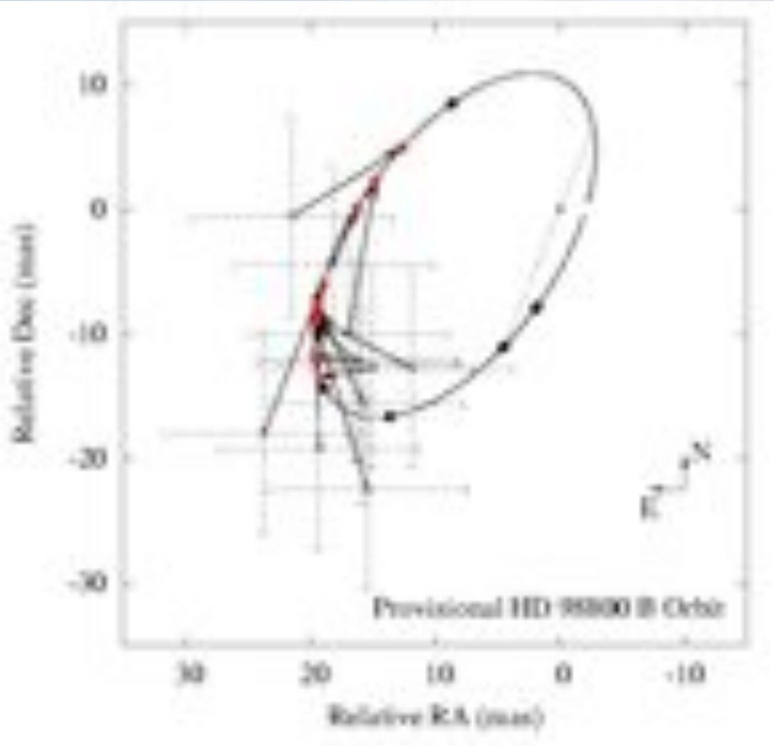


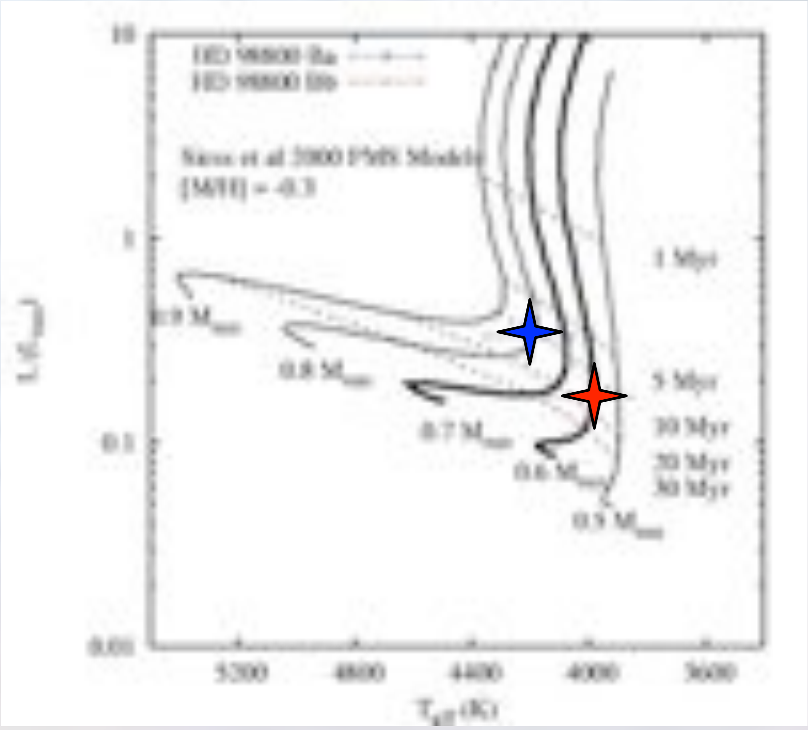


Kraus et al. (2007, A&A 466, 649)

HD 98800B: orbit and masses



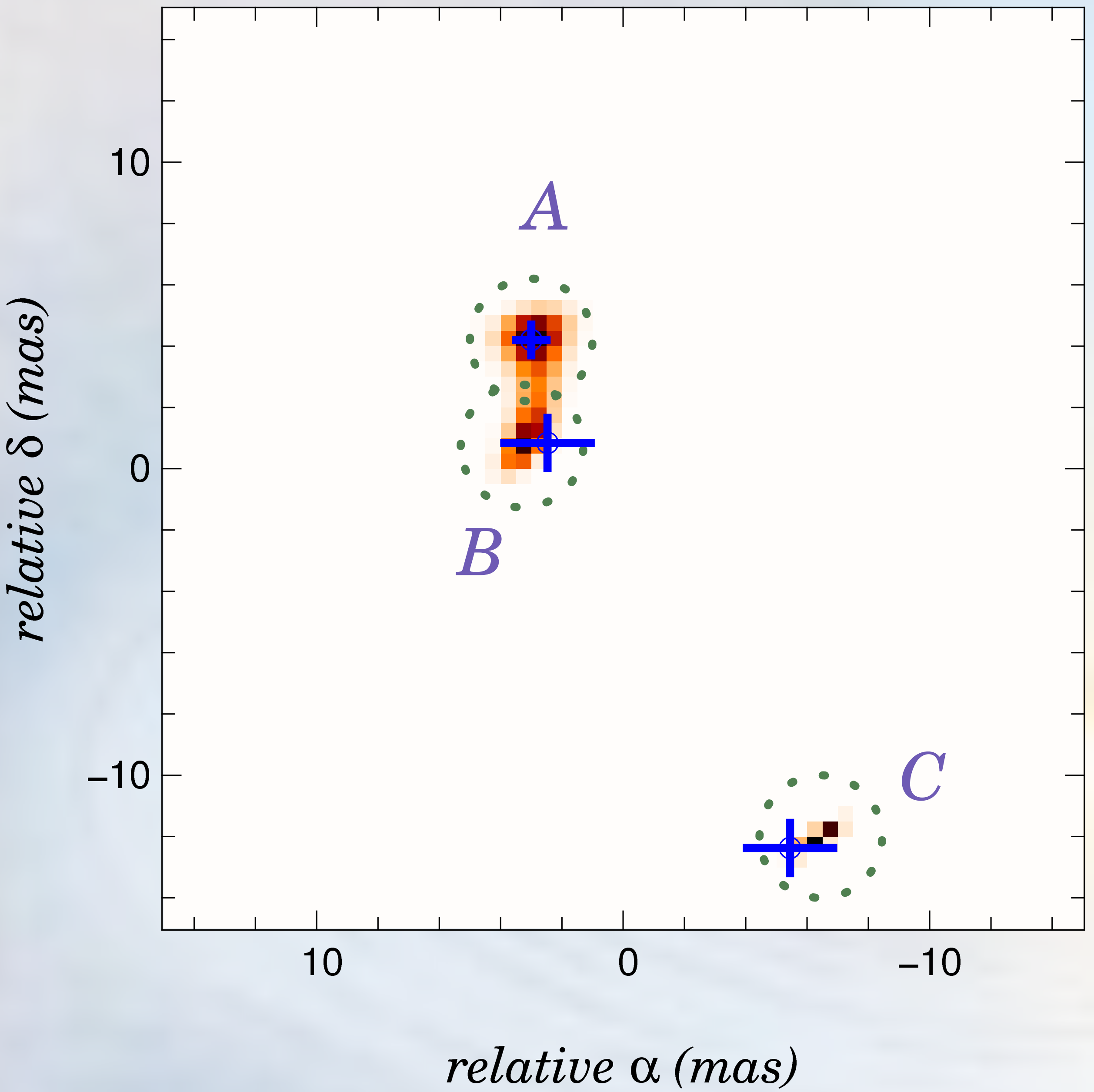


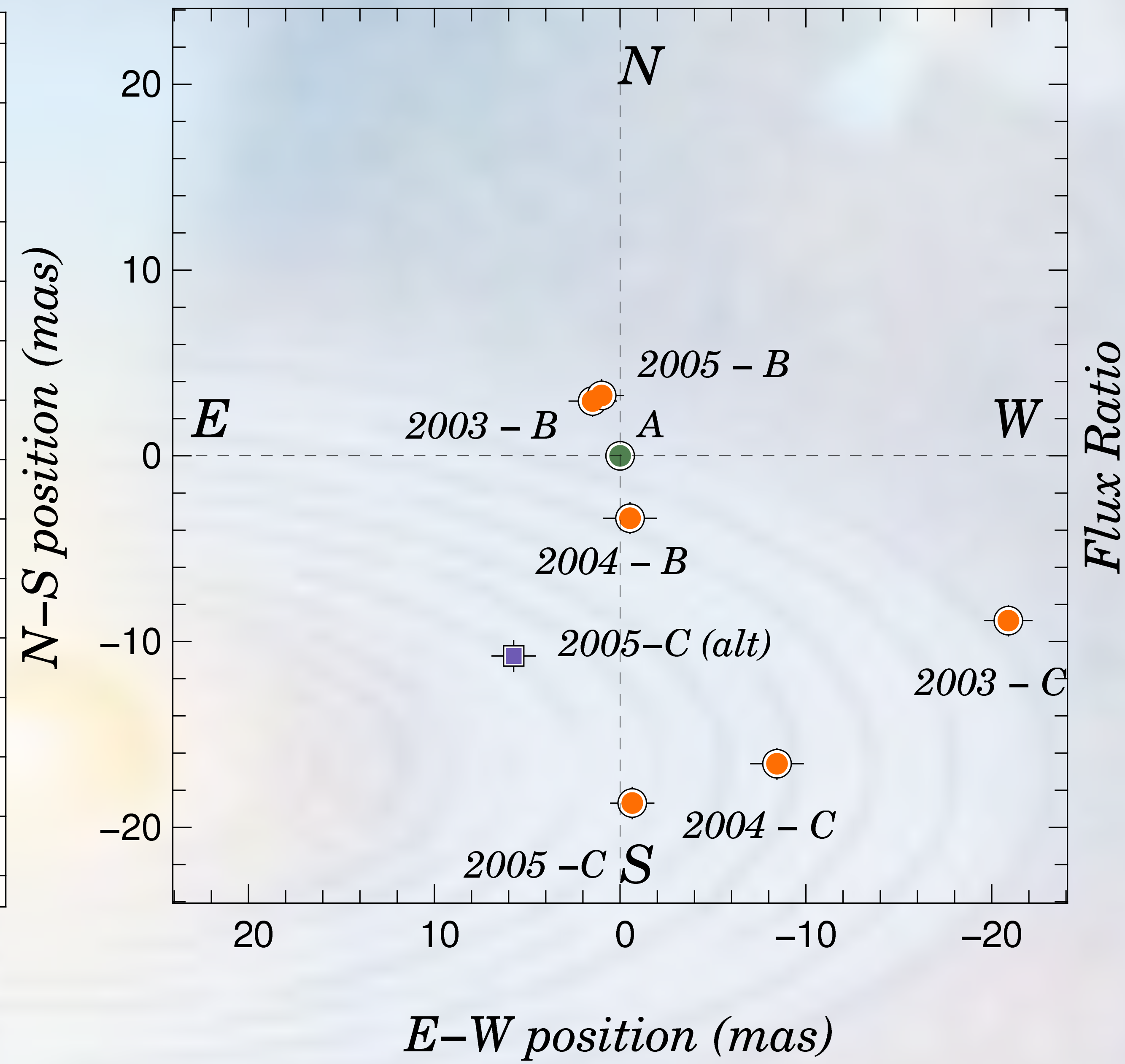


Boden et al. (2005, ApJ 635, 442)

+ radial velocities

GW Orionis triple system



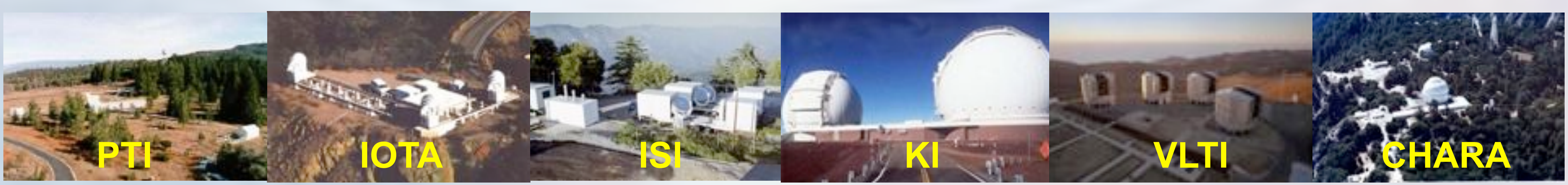


Berger et al. (2011, A&A 529, L1)

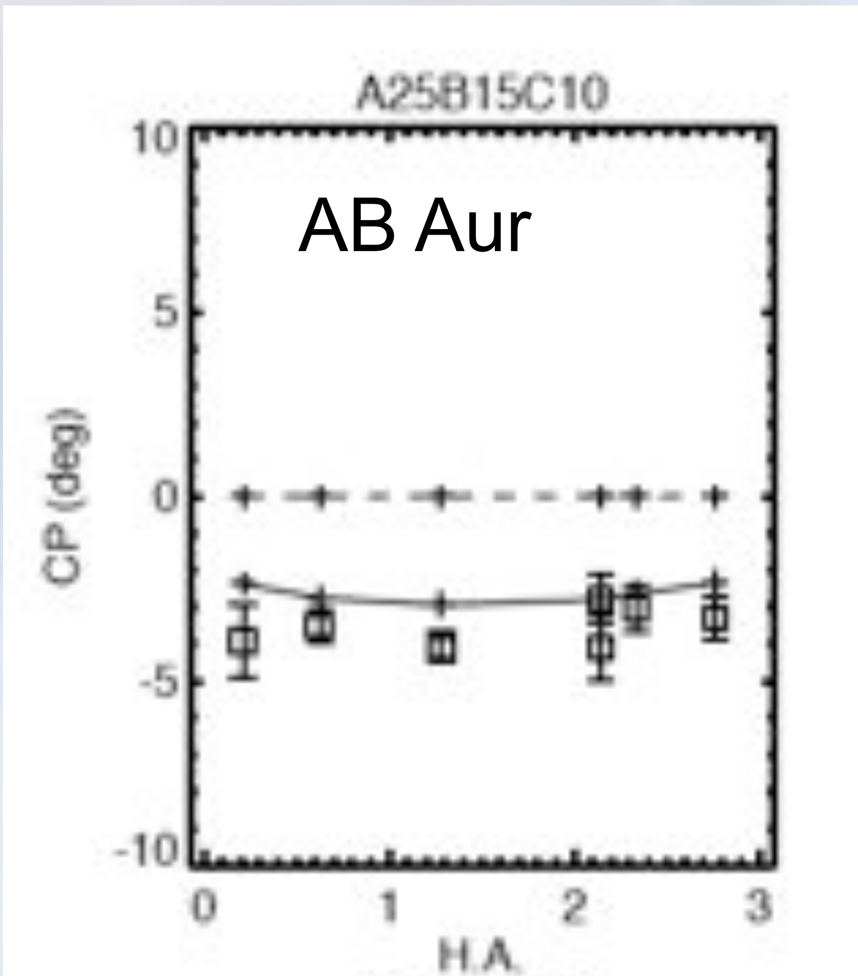
The nearly equal (2:1) H-band flux ratio of the inner components suggests that:

- either GW Ori B is undergoing a preferential accretion event that increases its disk luminosity
- or that the estimate of the masses has to be revisited in favour of a more equal mass-ratio system that is seen at lower inclination.

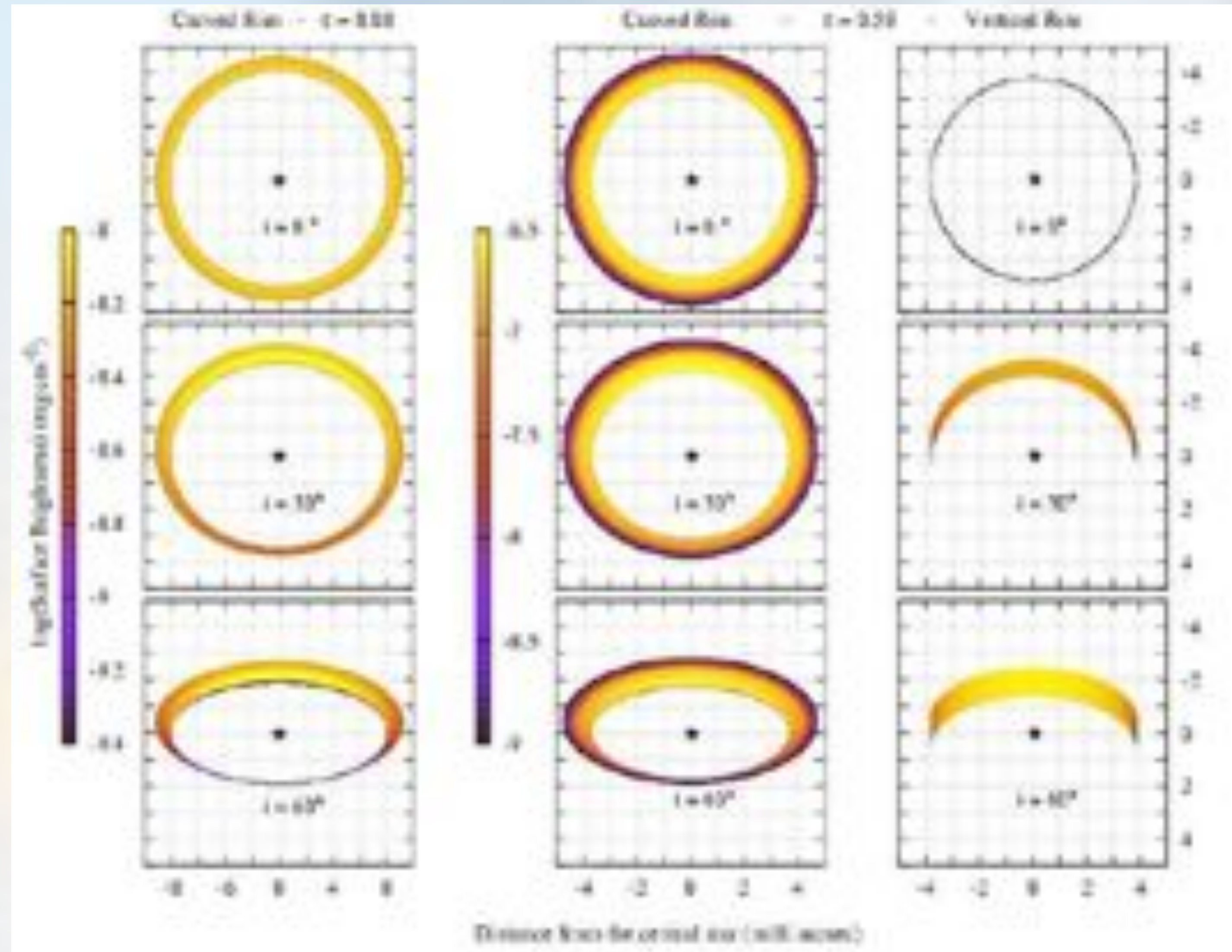
FUTURE PROSPECTS



First steps to imaging



Millan-Gabet et al. (2006, ApJ 645, L77)

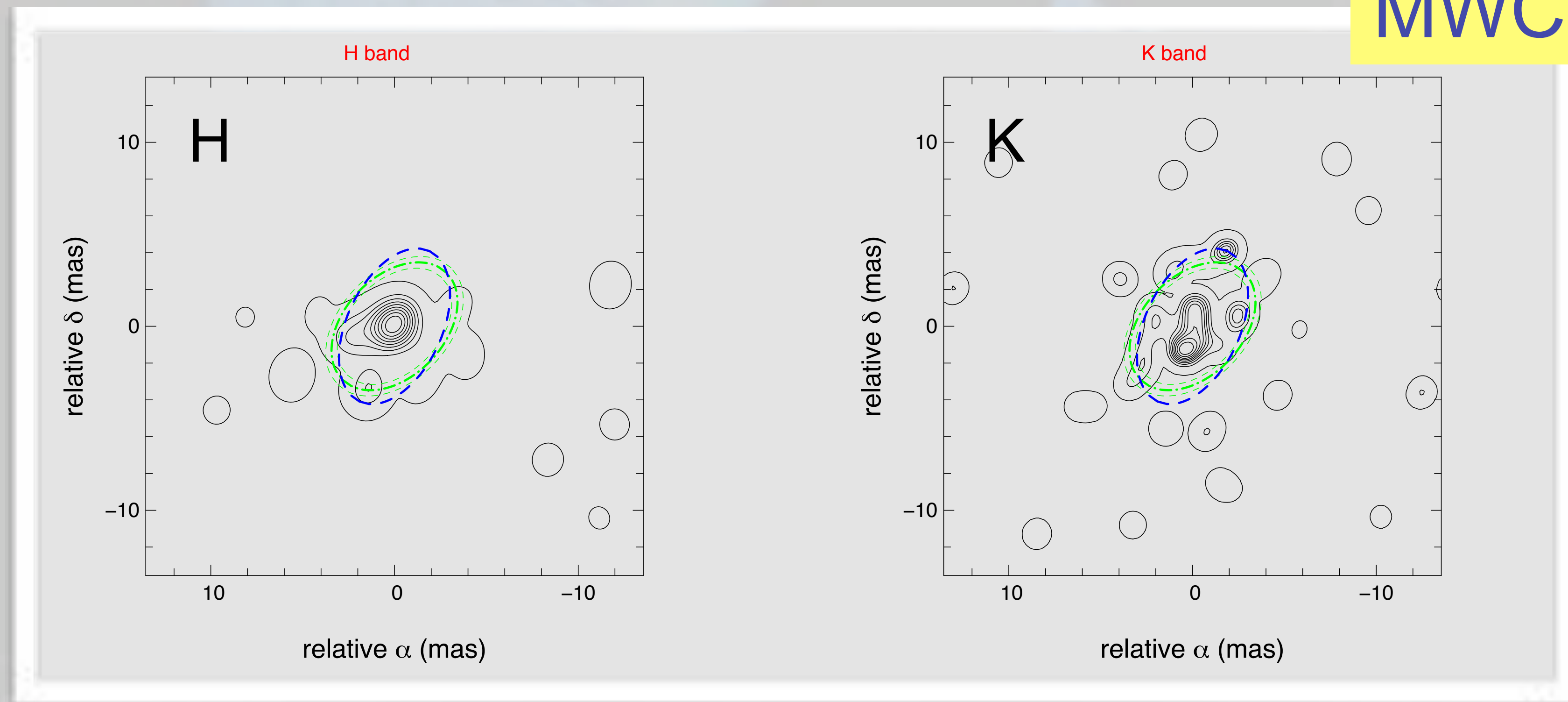


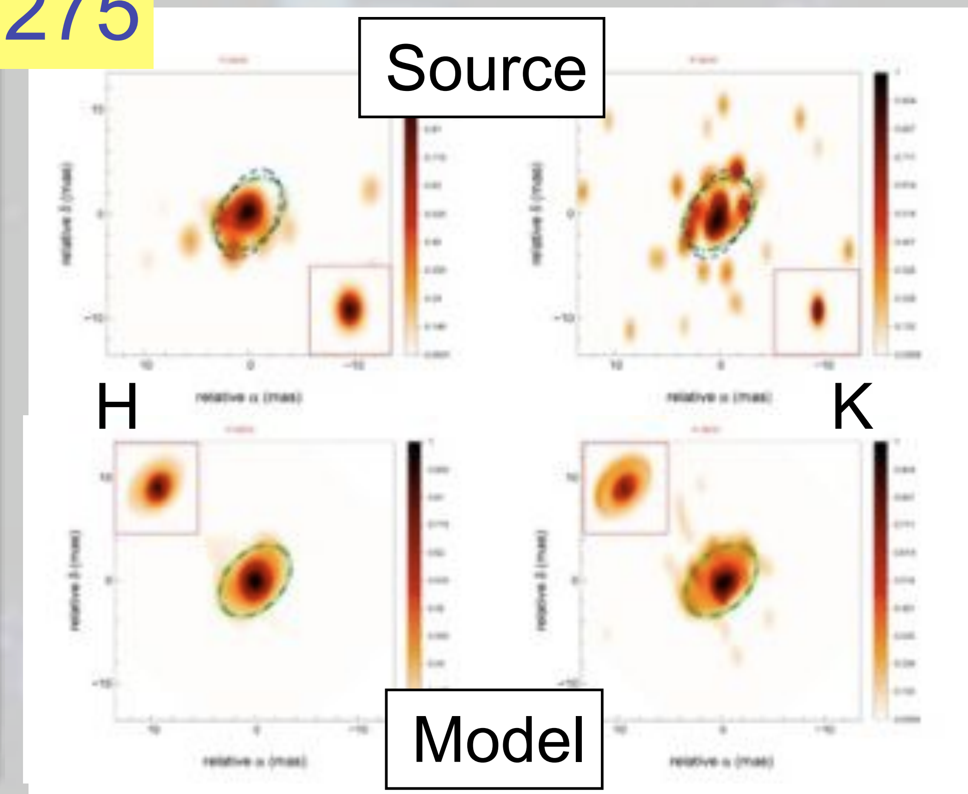
Isella & Natta (2005, A&A 438, 899)

Closure phase provides information on departure from centro-symmetry

First images of young disks

MWC 275





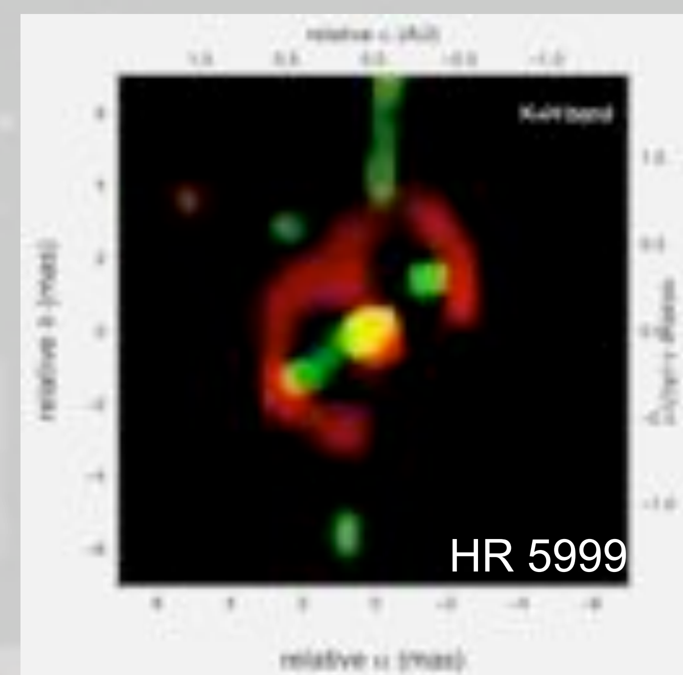
VLTI/AMBER

Renard, Malbet, Benisty et al. 2010

Image reconstruction is tricky:

- # measures ~1500 with VLTI/AMBER: 3 AT configs
- artefacts due to the (u,v) plane coverage
- disk + ring model consistent with Benisty 2009
- 1/1000 contrast compared with first VLA images

→ First indices on the morphology of disks around young stars



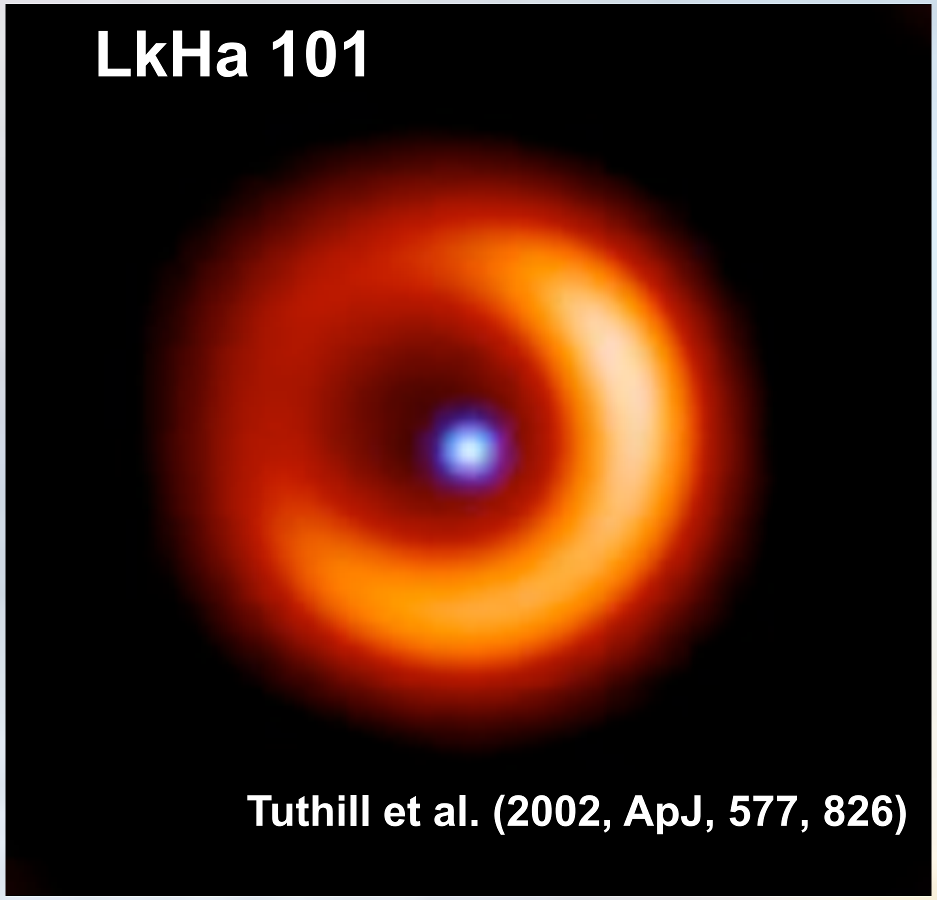
Benisty et al. (subm. A&A)

Conclusion

- A **major leap** in less than 10 years:
  - ~100 objects observed so far,
  - +70 refereed papers (mainly with **one baseline broad-band** observations, but it is changing).
  - new types of observations with **spectral resolution, closure phases, imaging**
- Observations are **mature enough** to allow **detailed modeling**.

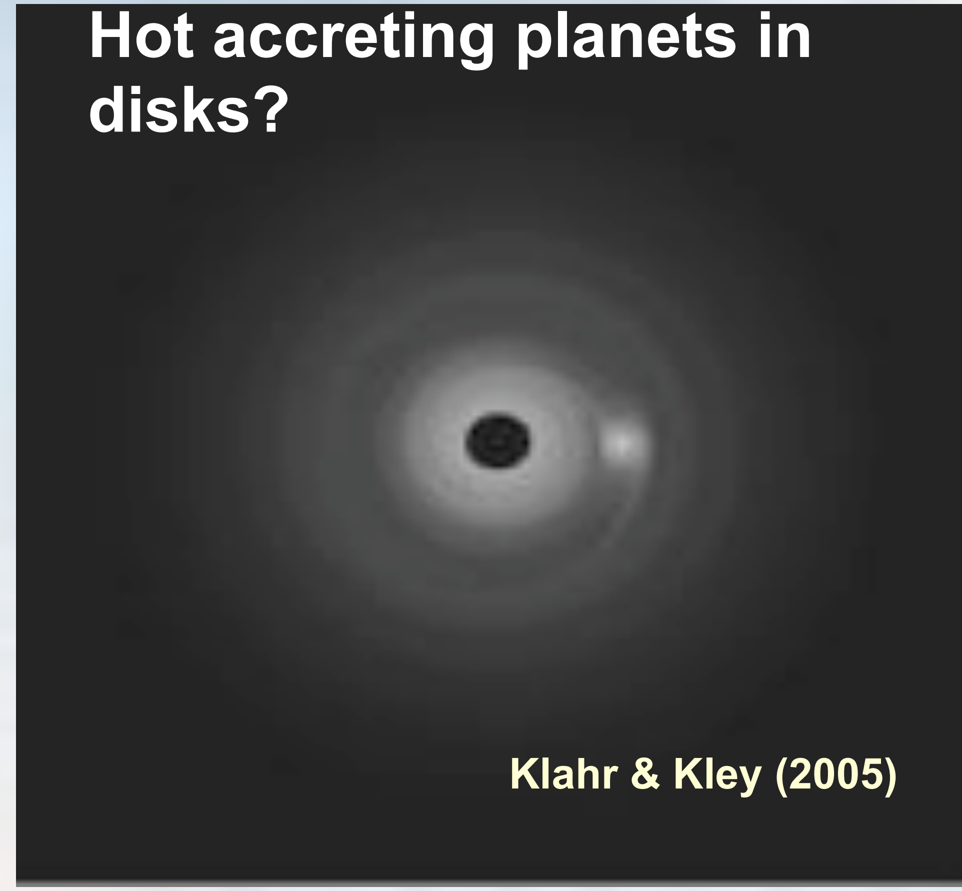
More images?

Actual Imaging Data

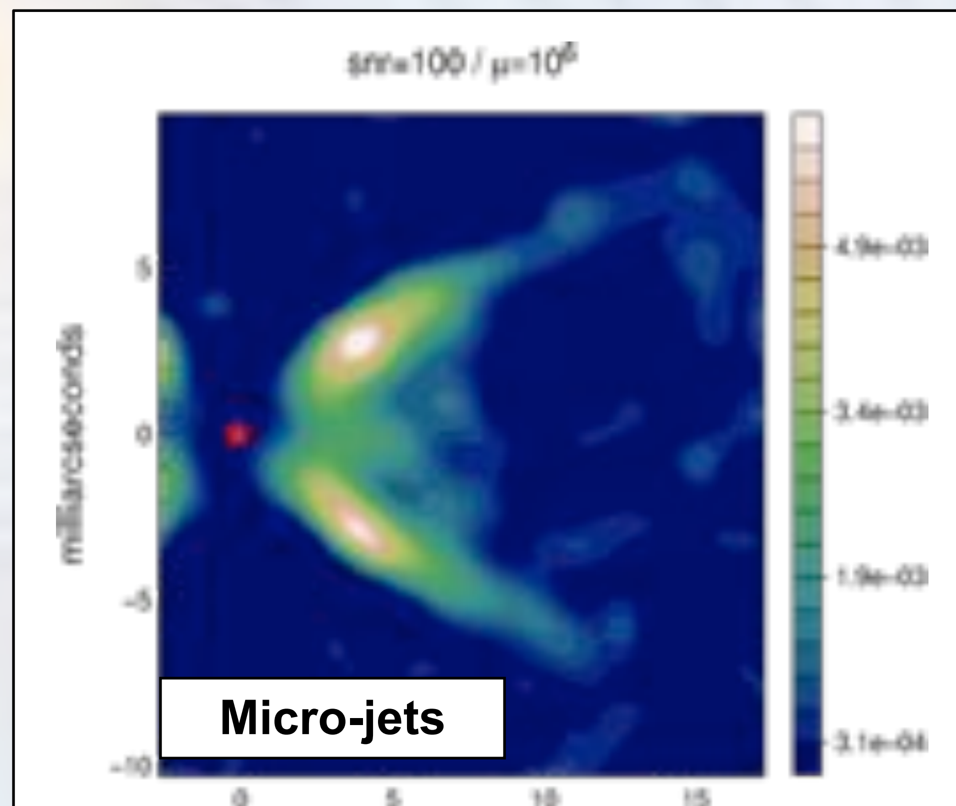


Tuthill et al. (2002, ApJ, 577, 826)

Image simulations



Klahr & Kley (2005)

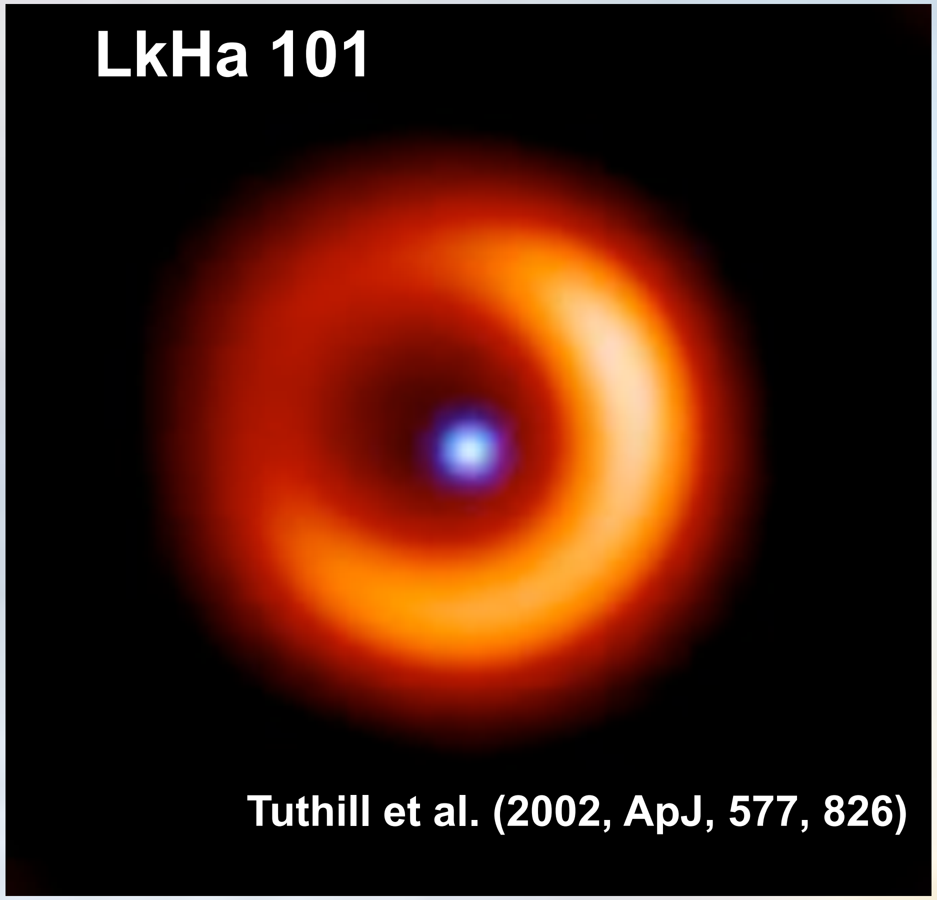


Thiébaut et al. (2005, Ap&SS, 286, 171)

Kloppendorf et al. (2010)

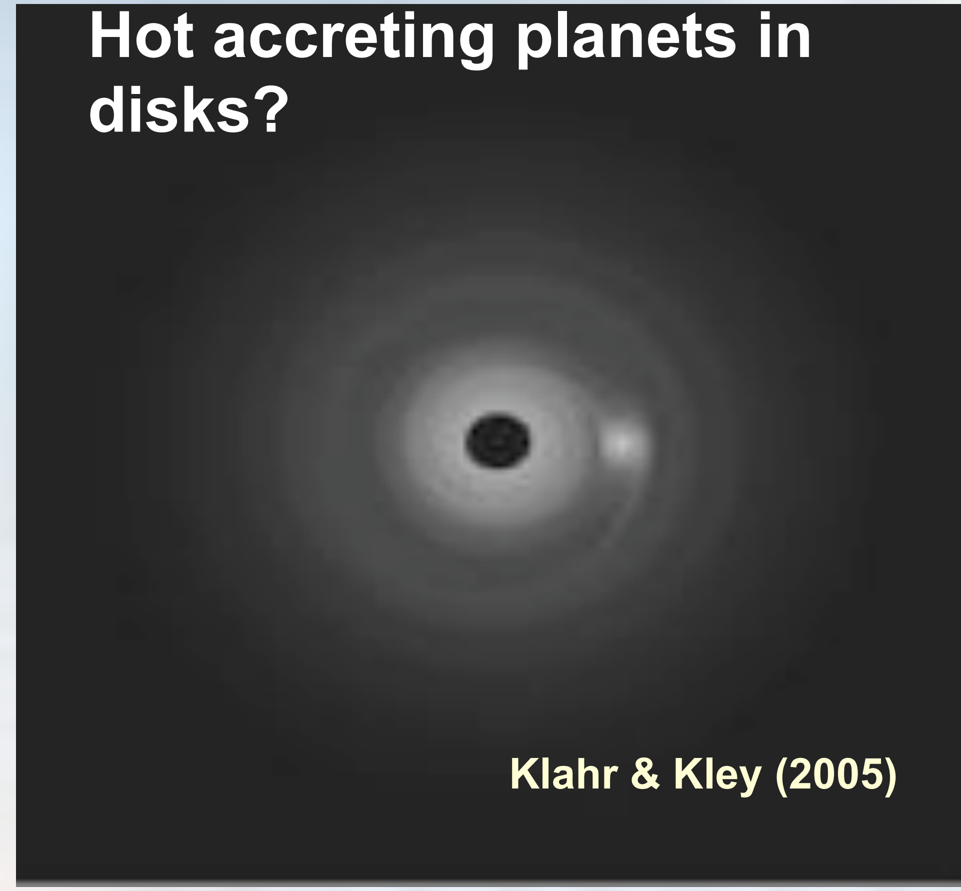
More images?

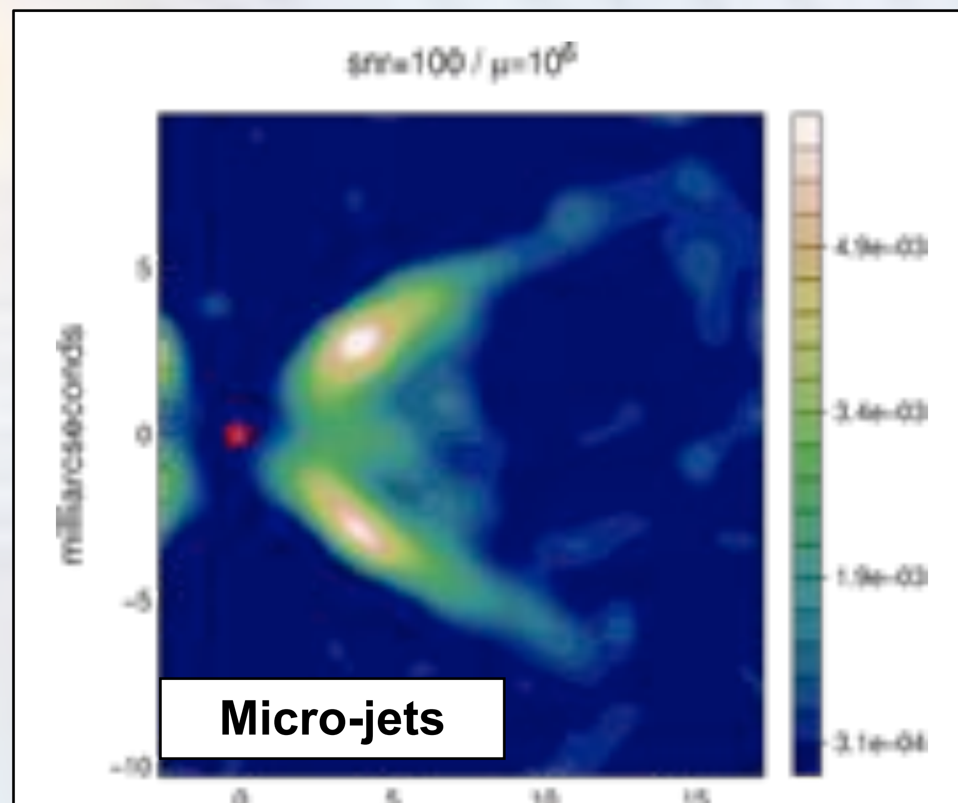
Actual Imaging Data



Kloppendorf et al. (2010)

Image simulations





Thiébaut et al. (2005, Ap&SS, 286, 171)

Open issues

- Disks starts to be imaged: shifts from axial symmetry?
- NIR emitting zone larger than corotation / magnetospheric radii .

  What implications for disk/star connection?

- Which implications do these measurements have for the **initial conditions of planetary formation?**
- Need to combine **NIR+MIR** to secure the disk structure.
- Origin of the **Brγ emission** ?
- Companions, formation of planets