Inner regions of young stellar objects revealed by optical long baseline interferometry

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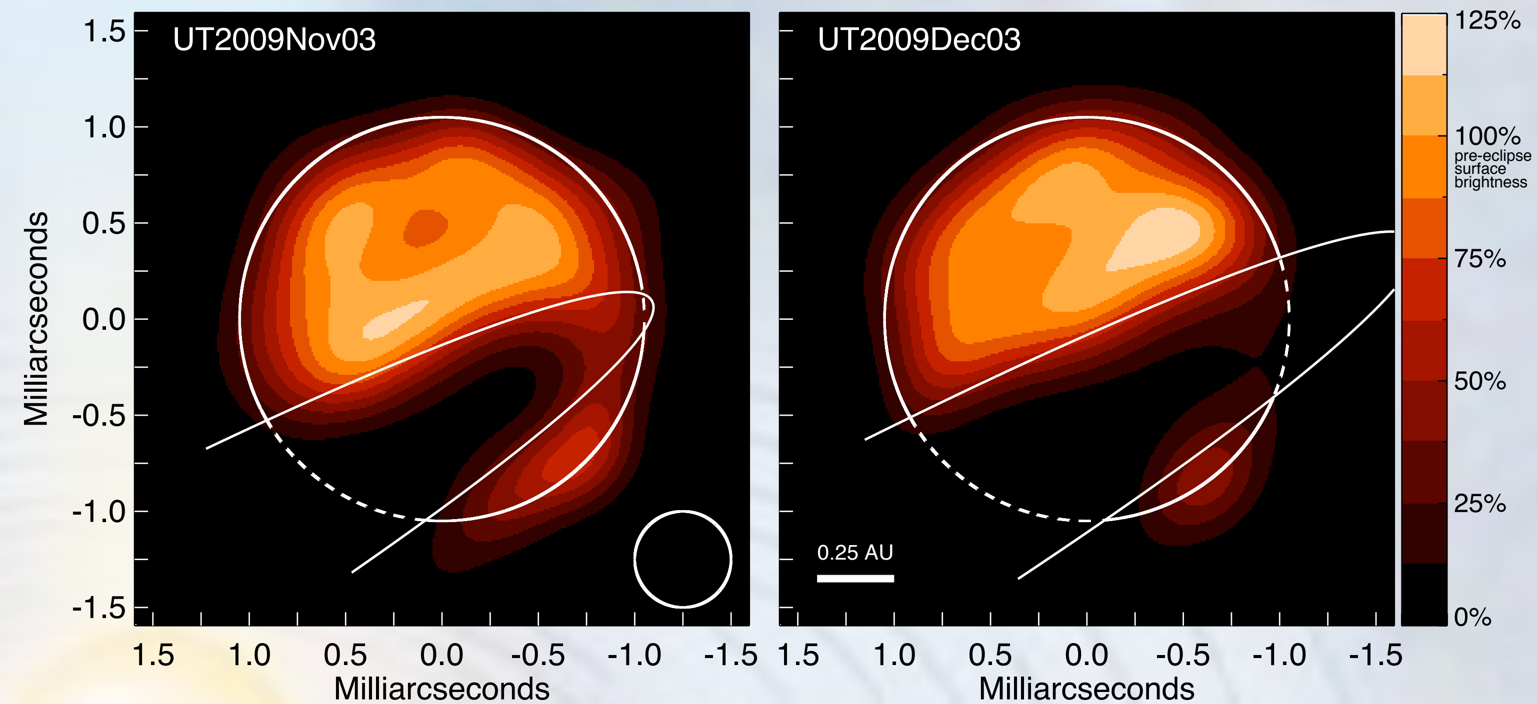
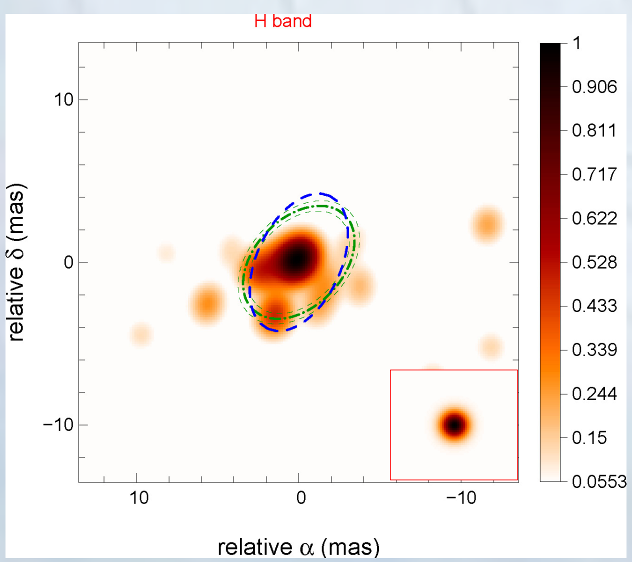
VLTI Summer School - Porquerolles
21 April 2010

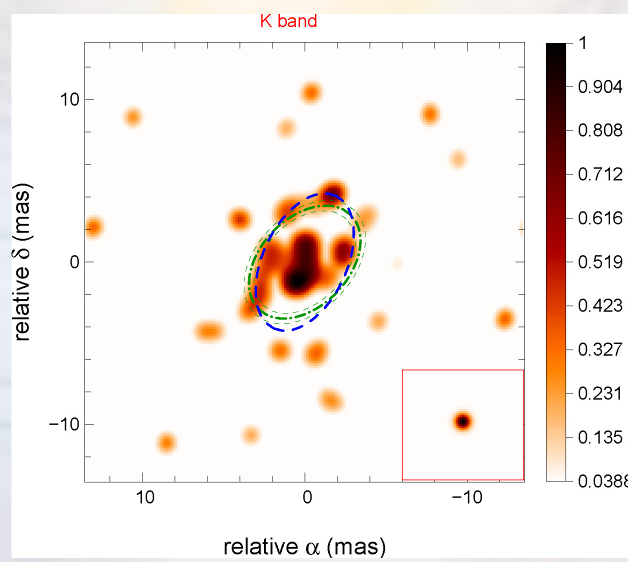
We start «seeing» disks with milli-arcsec resolution !!

Epsilon Aurigae Eclipse (CHARA-MIRC)



Kloppendorf et al. (2010)





Renard et al. (2010)

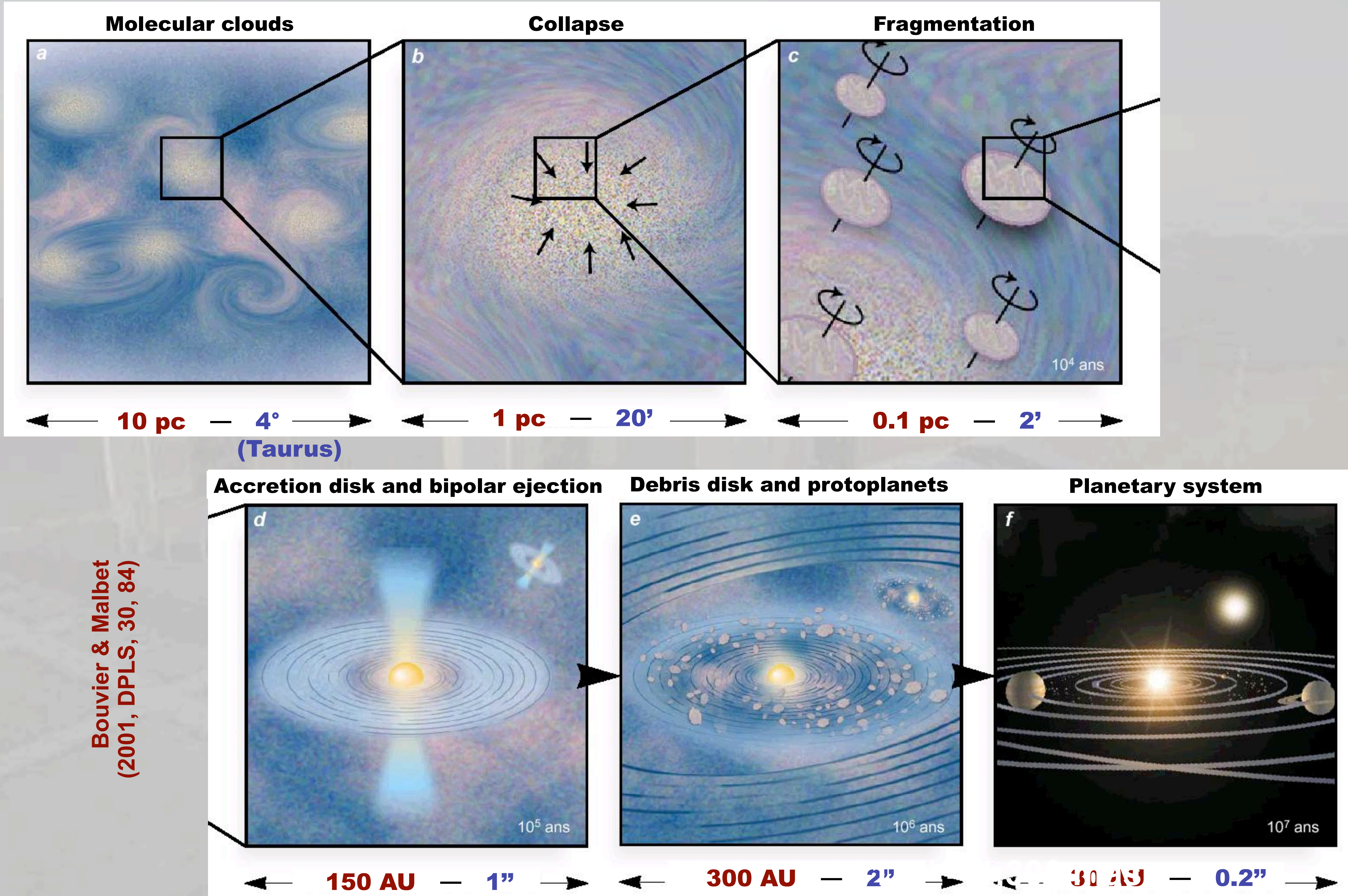
Outline

- **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**
  - Sizes of circumstellar structures
  - Constraints on disk structure (T, z,…)
  - Dust mineralogy
  - Gas/dust connection
  - Debris disks
- **Other AU-scale phenomena**
  - Outflows and winds
  - Magnetosphere
  - Binaries and multiple systems
- **Future prospects**

INTRODUCTION

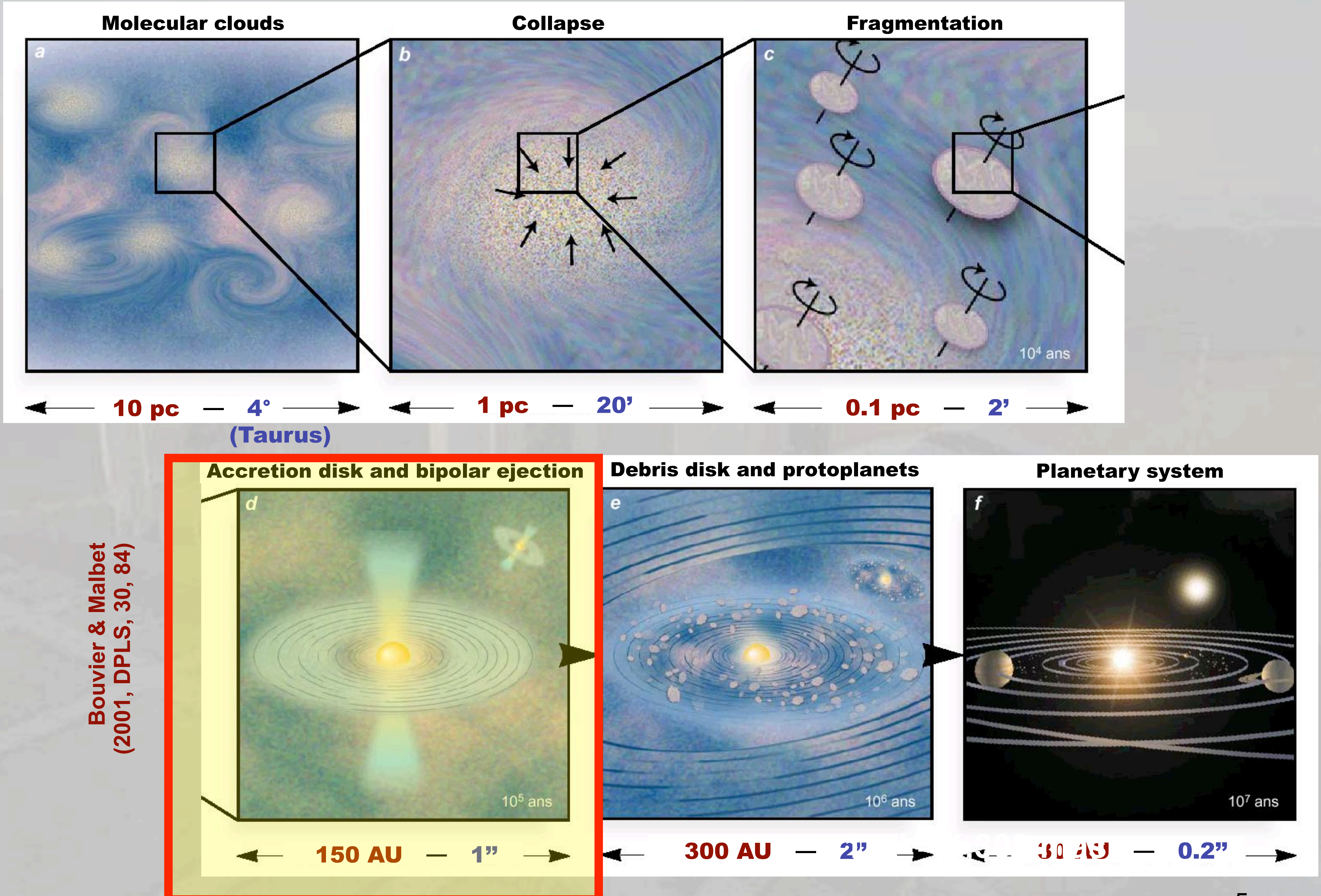
- Formation of stars, disks and planets
- Physical conditions in the inner regions of YSOs
- Need for very high angular resolution
- Physical processes

Formation of stars, disks and planets



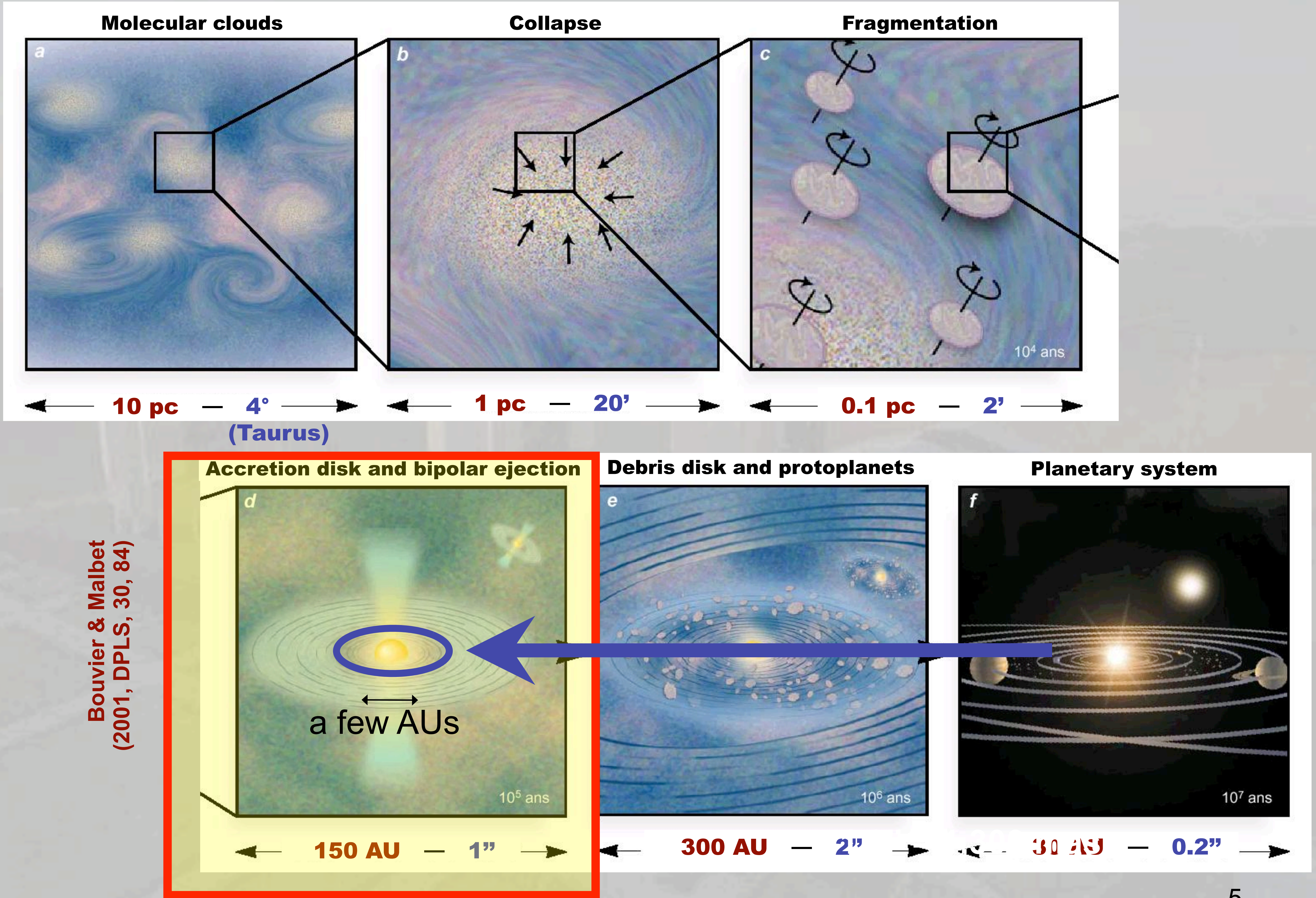
Bouvier & Malbet
(2001, DPLS, 30, 84)

Formation of stars, disks and planets



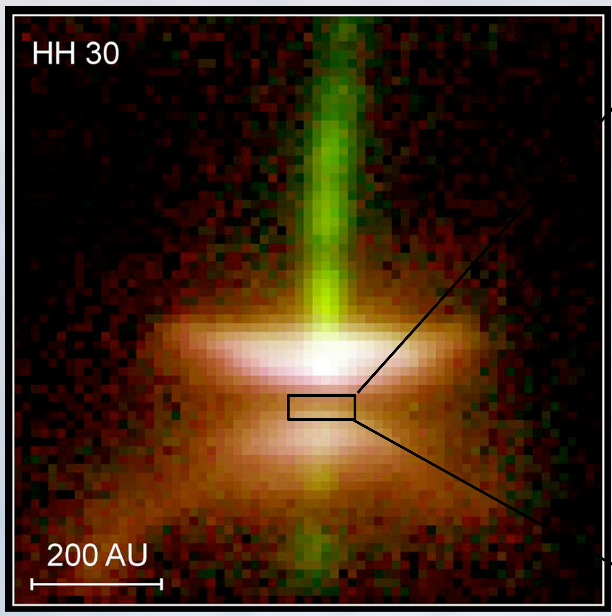
Bouvier & Malbet
(2001, DPLS, 30, 84)

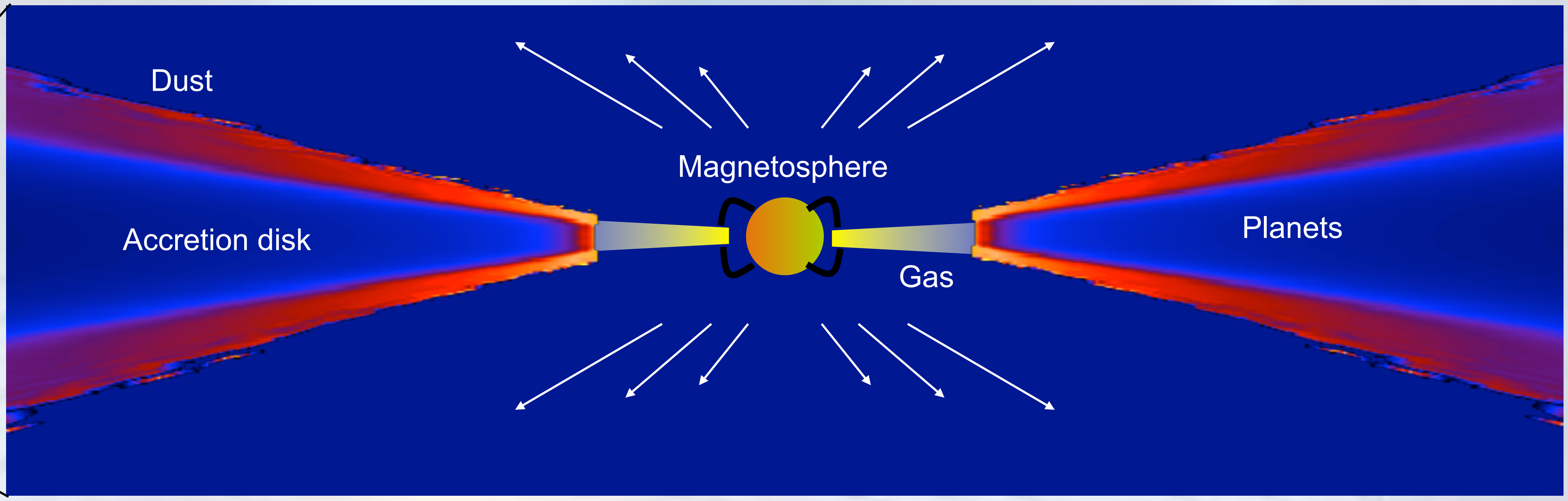
Formation of stars, disks and planets



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 :
1µm ≤ λ ≤ 20µm and spatial scales between **0.5 et 70 mas**

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

Instrumental requirements

- **Wavelength domain**

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

- **Angular resolution**

  Spatial scales

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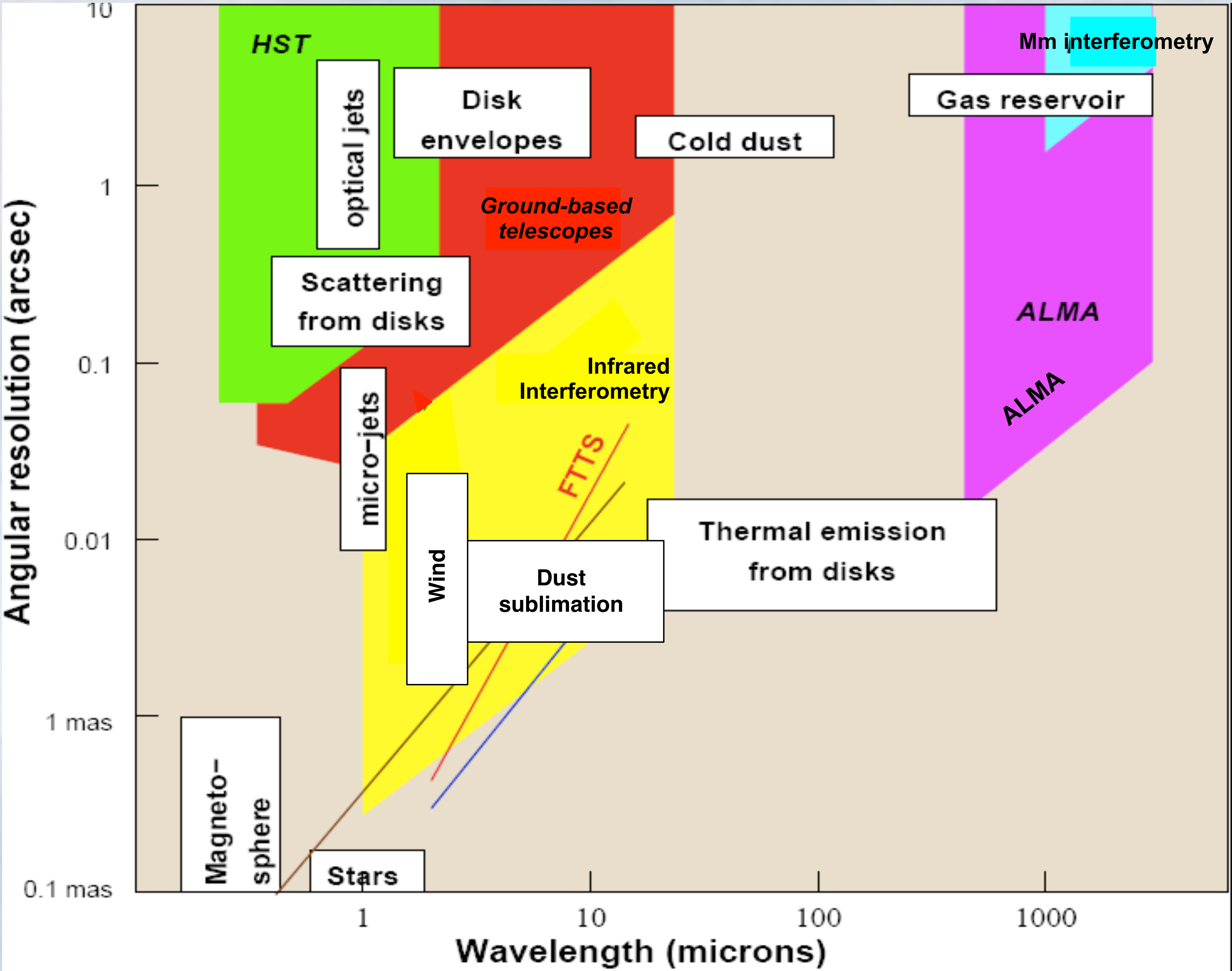
450pc	0.2mas	2mas	10mas	20mas

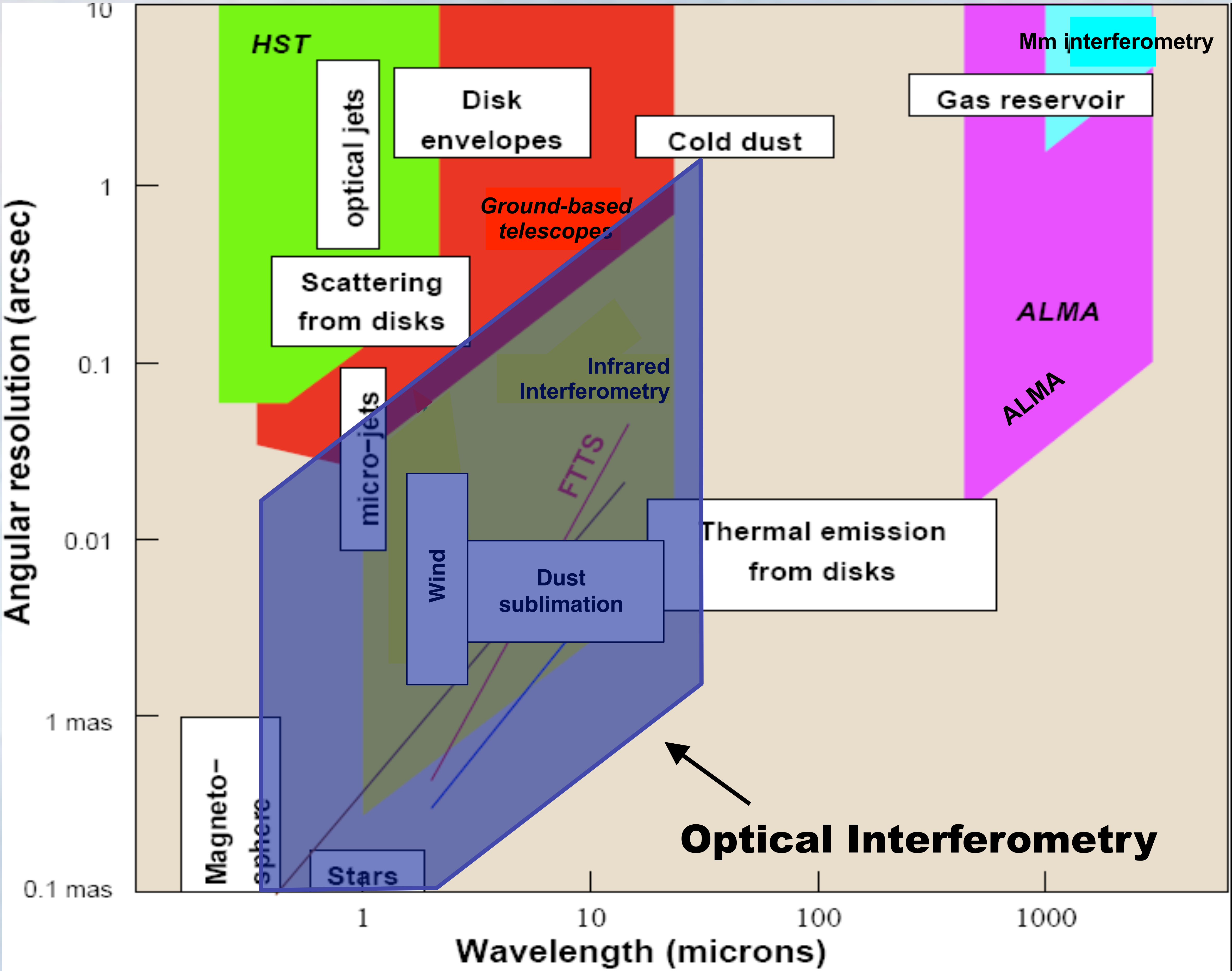
Spatial telescope

Adaptive optics

Interferometry



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


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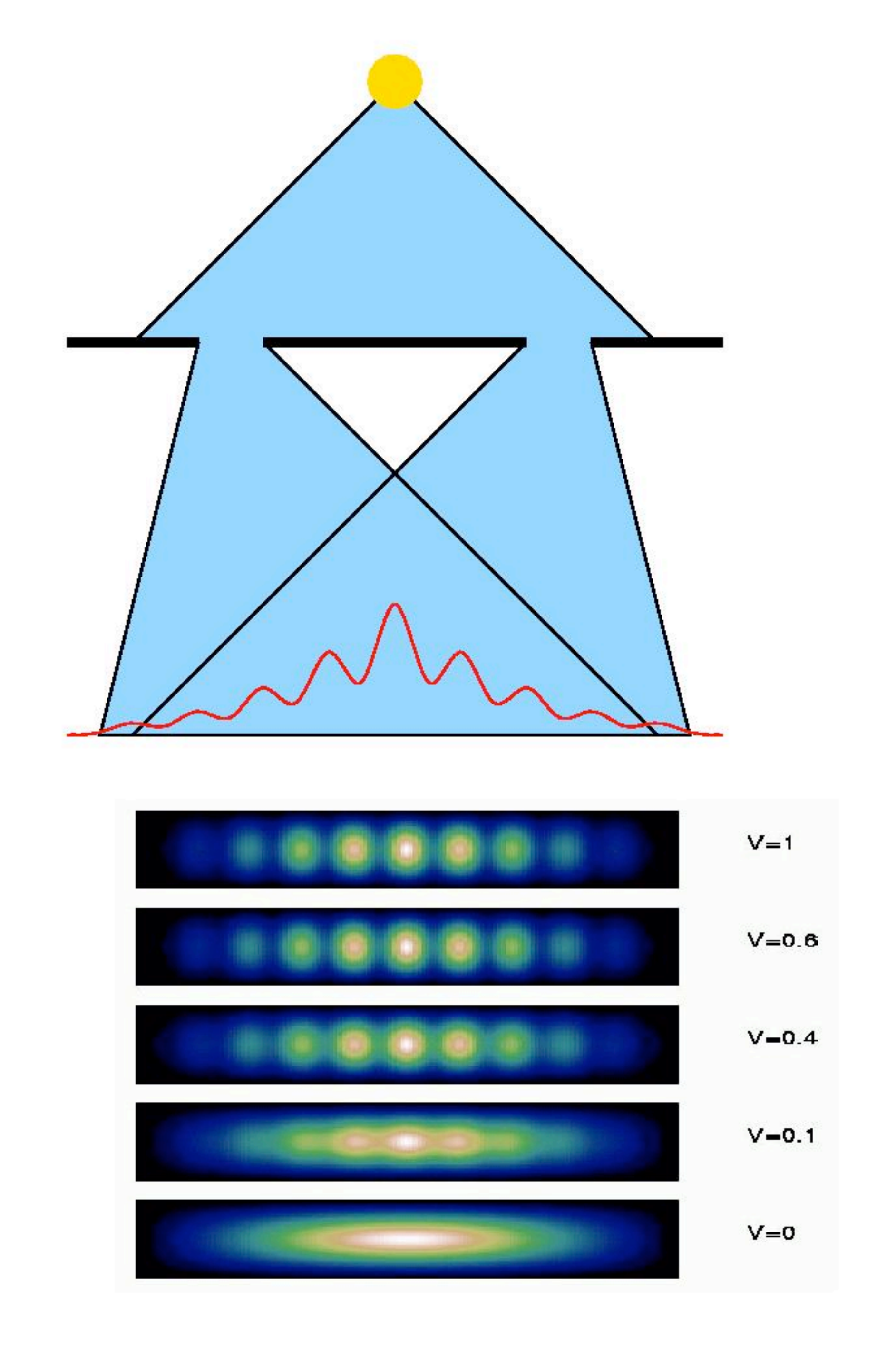
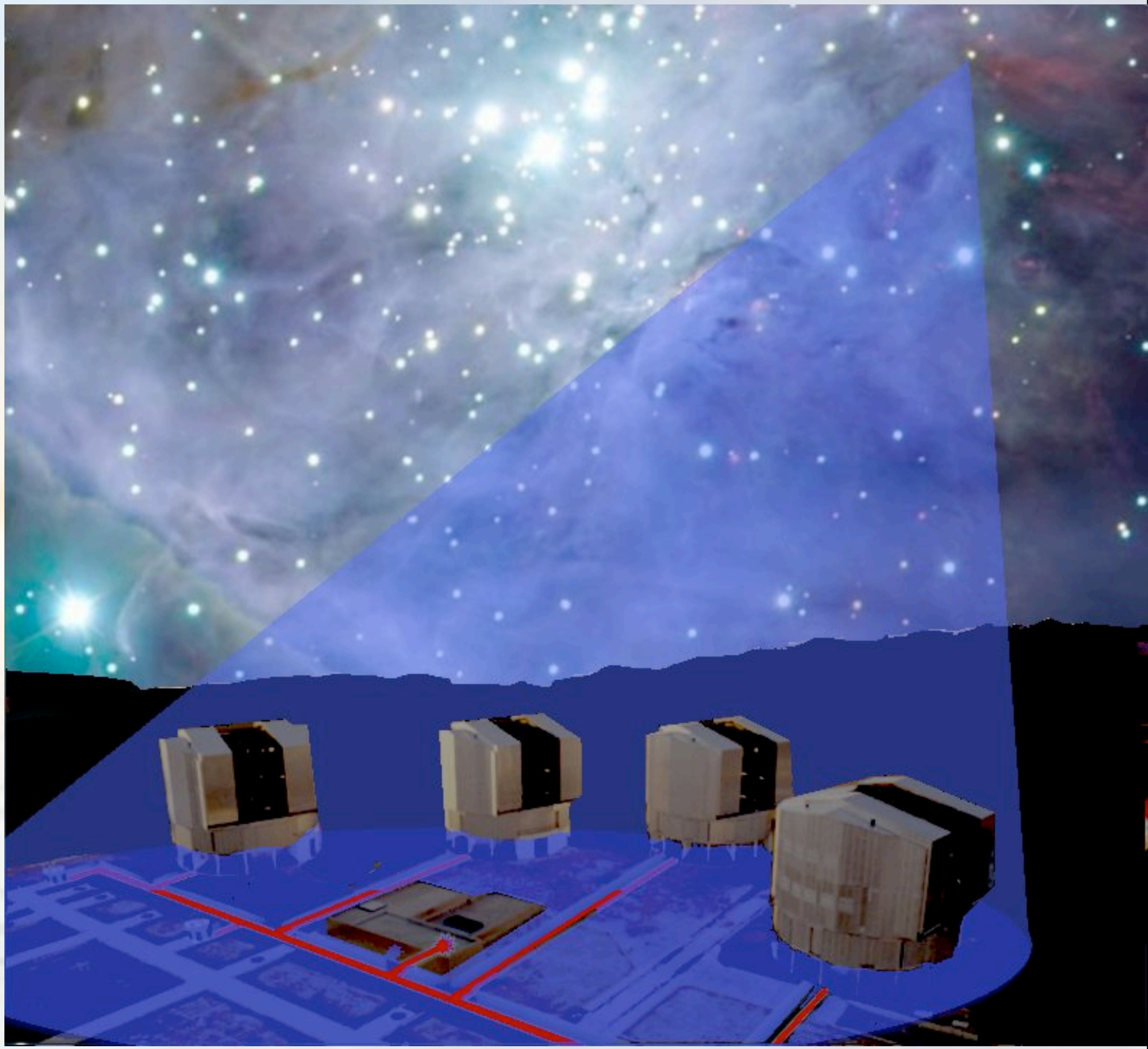
micro-jets
FTTS
Thermal emission from disks
Wind
Dust sublimation
Magneto-sphere
Stars
Optical Interferometry
Angular resolution (arcsec)
10
1
0.1
0.01
1 mas
0.1 mas
1
10
100
1000
Wavelength (microns)

Infrared and visible Interferometry

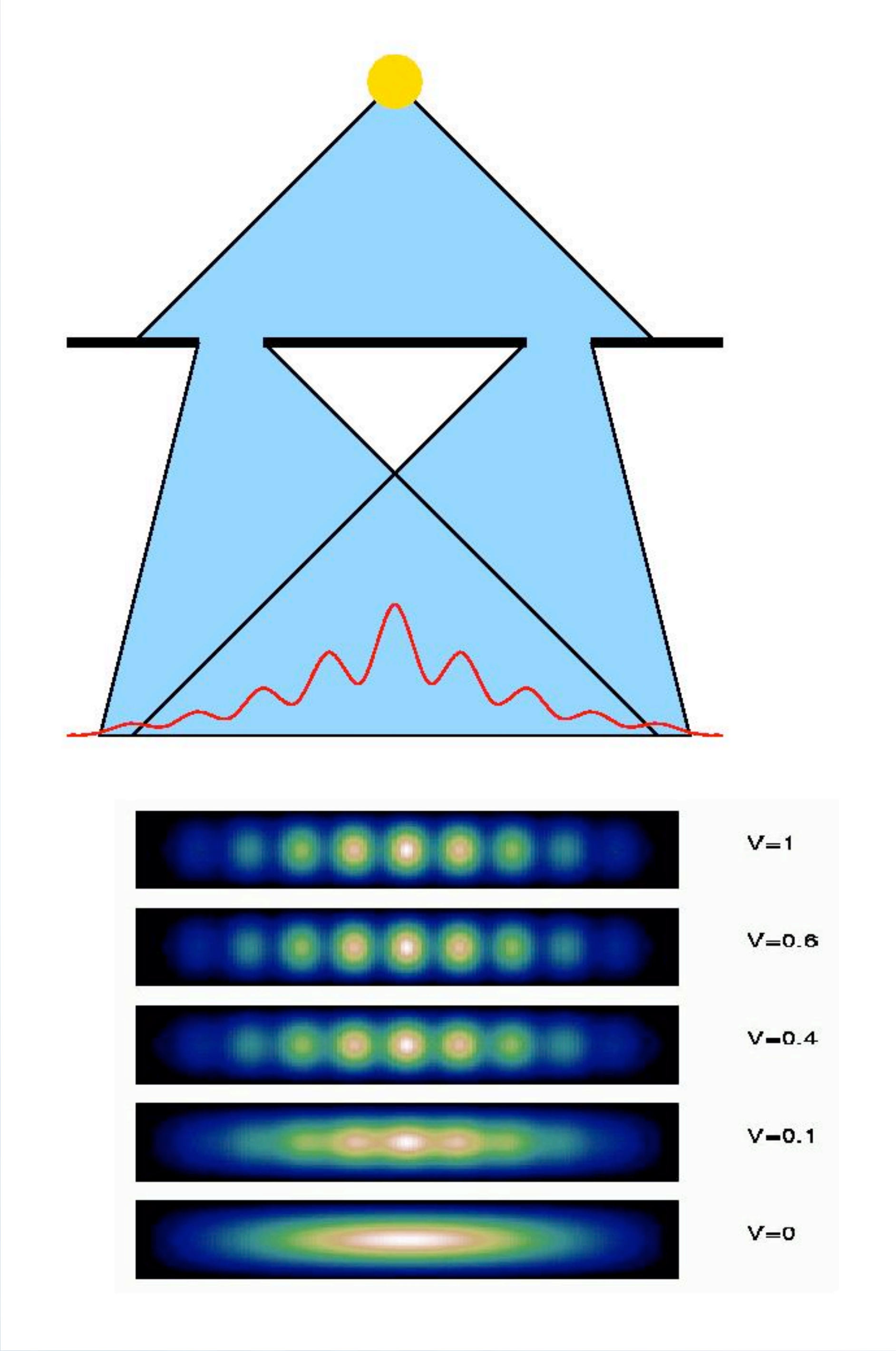
– Principles and observables
– Instruments available for YSO studies
– Elements of bibliography on YSO science results

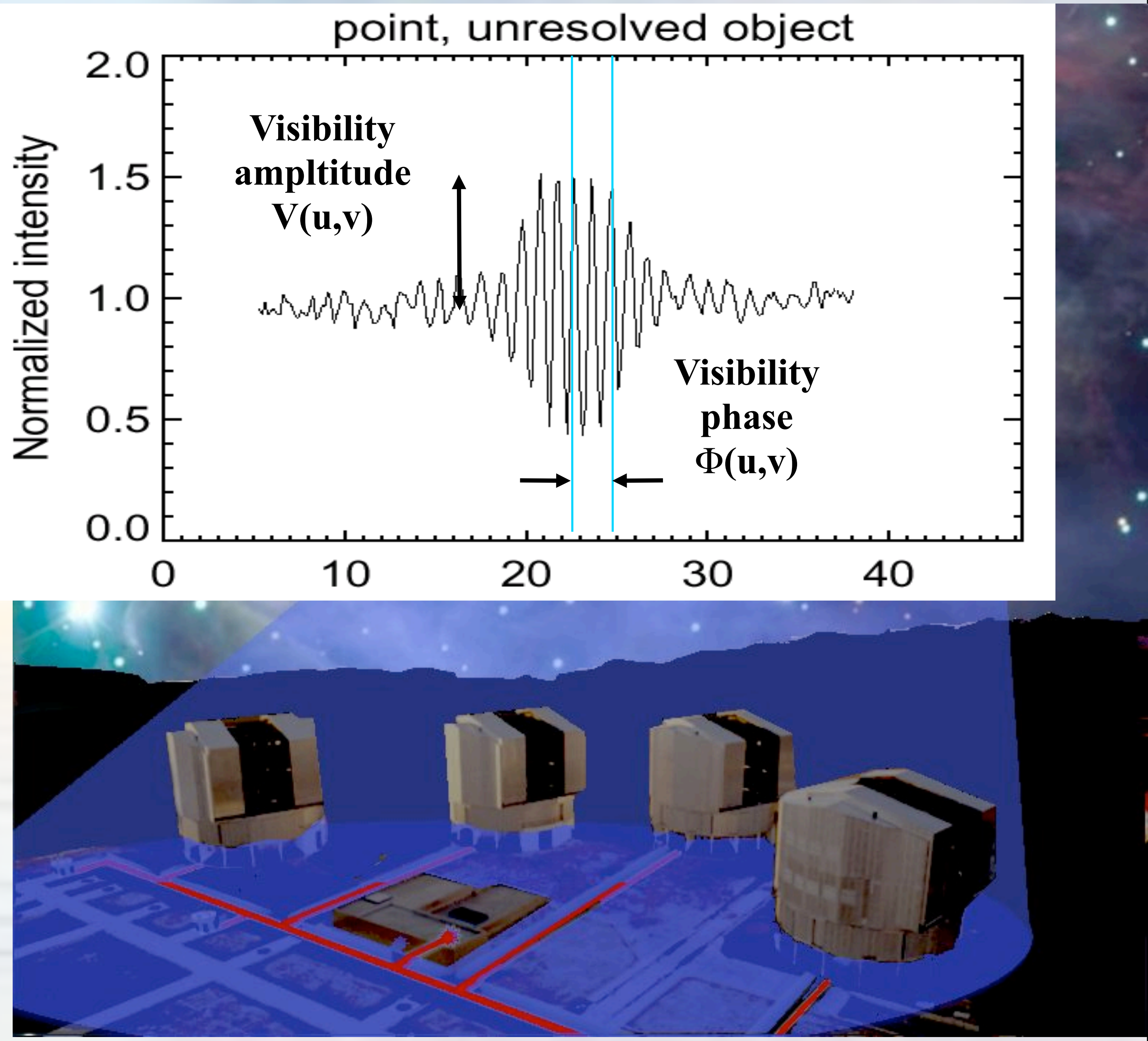
Basics of optical interferometry



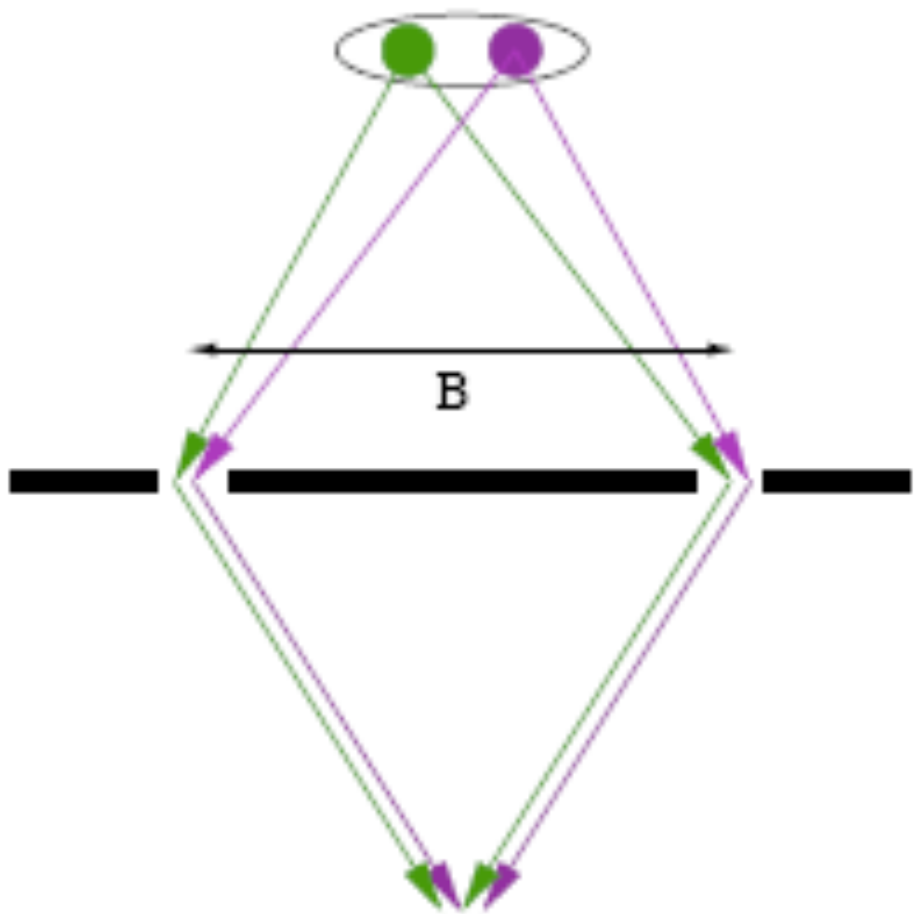


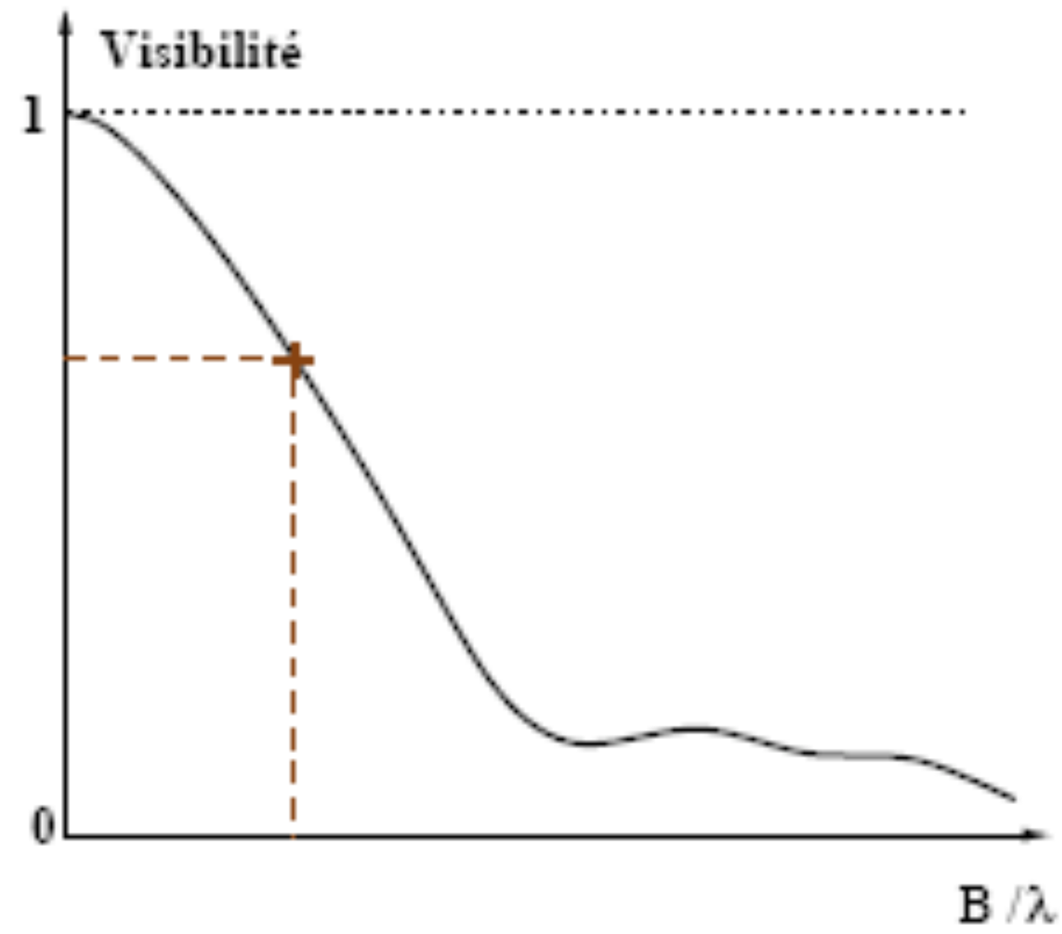
Basics of optical interferometry





Spatial coherence



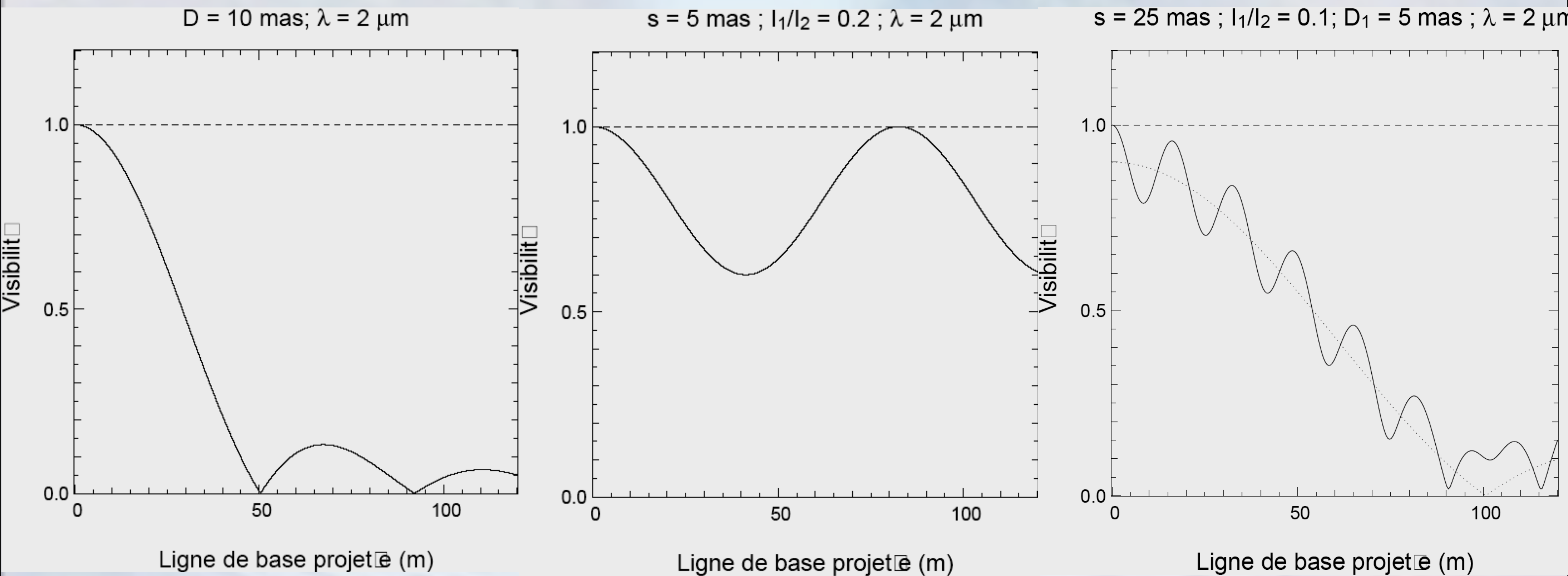


Interferogram 1 + Interferogram 2 = Reduced contrast / Shifted phase

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

<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>PTI</td><td>V^2</td><td>H, K</td><td colspan="2">3</td><td>0.4</td><td>80-110</td></tr>
<tr><td>IOTA</td><td>V^2, CP</td><td>H, K</td><td colspan="2">3</td><td>0.4</td><td>5-38</td></tr>
<tr><td>ISI</td><td>Heterodyne</td><td>11</td><td colspan="2">2/3</td><td>1.65</td><td>4-70</td></tr>
<tr><td rowspan="2">KI</td><td>V^2</td><td>K, L / spectral</td><td colspan="2" rowspan="2">2</td><td rowspan="2">10</td><td rowspan="2">80</td></tr>
<tr><td>nulling</td><td>N</td></tr>
<tr><td rowspan="2">VLTI</td><td>AMBER: V^2, CP</td><td>1-2.5 / spectral</td><td>3</td><td rowspan="2">4 (8)</td><td>8.2</td><td>40-130</td></tr>
<tr><td>MIDI: V^2, V</td><td>8-13 / spectral</td><td>2</td><td>1.8</td><td>8-200</td></tr>
<tr><td>CHARA</td><td>V^2, CP, Imaging</td><td>1-2.5 (spectral)</td><td colspan="2">2/4 (6)</td><td>1</td><td>50-350</td></tr>
<tr><td colspan="7">Future facilities</td></tr>
<tr><td>LBT</td><td>V^2, nulling</td><td>1-12 μm</td><td colspan="2">2</td><td>8.4</td><td>6-23</td></tr>
<tr><td>MROI</td><td>V^2, CP, imaging</td><td>V, NIR</td><td colspan="2">3/6 (10)</td><td>1.4</td><td>7.5-340</td></tr>
</table>

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~~
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Interferometers involved in YSO research

Small apertures

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Large apertures

Interferometers involved in YSO research

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Spectral resolution

Interferometers involved in YSO research

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~~PTI~~	~~V^2~~	~~H, K~~	~~3~~	~~0.4~~	~~80-110~~
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	MIDI: V^2, V	8-13 / spectral	2	1.8	8-200
CHARA	V^2, CP, Imaging	1-2.5 (spectral)	2/4 (6)	1	50-350
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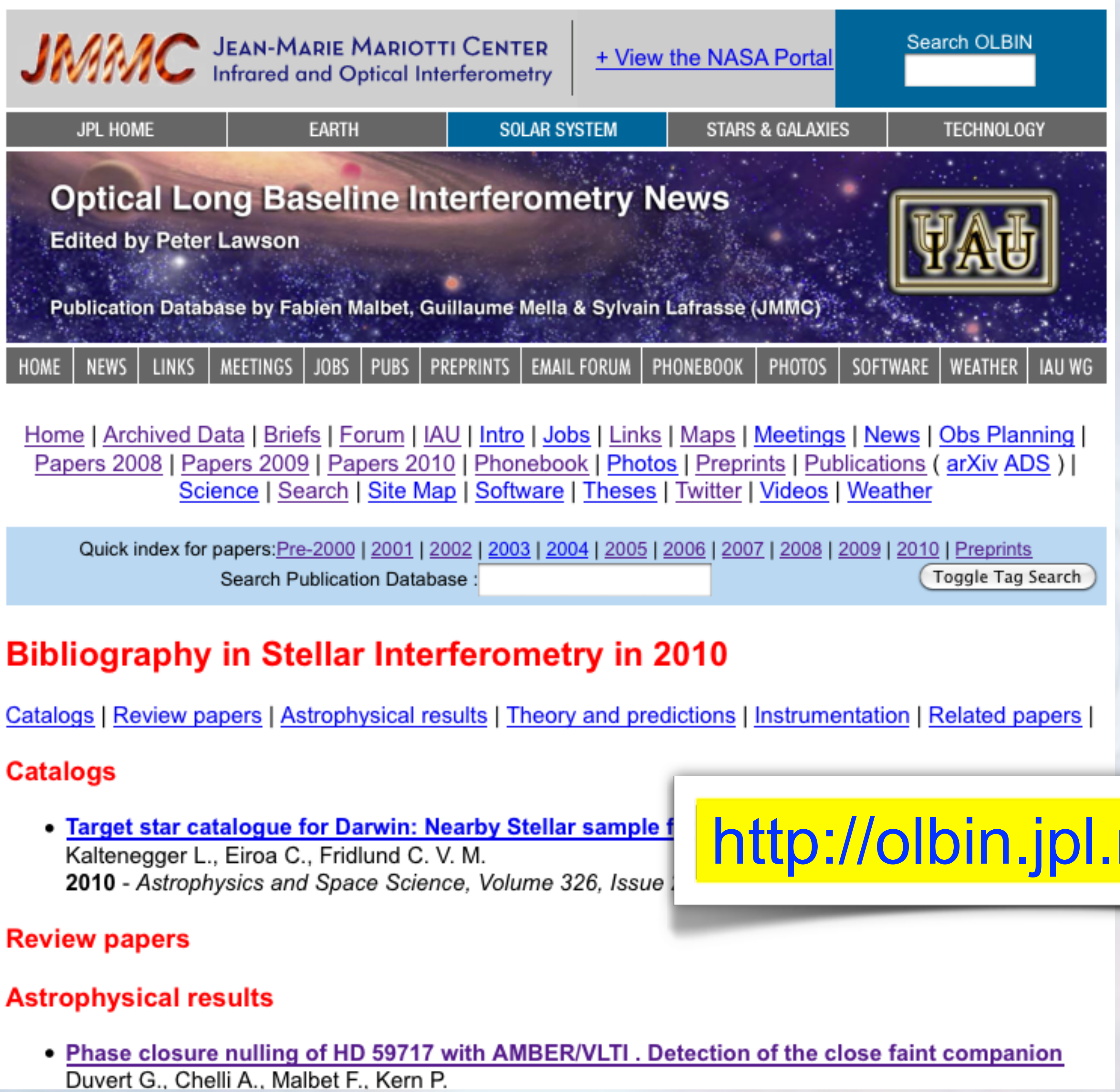
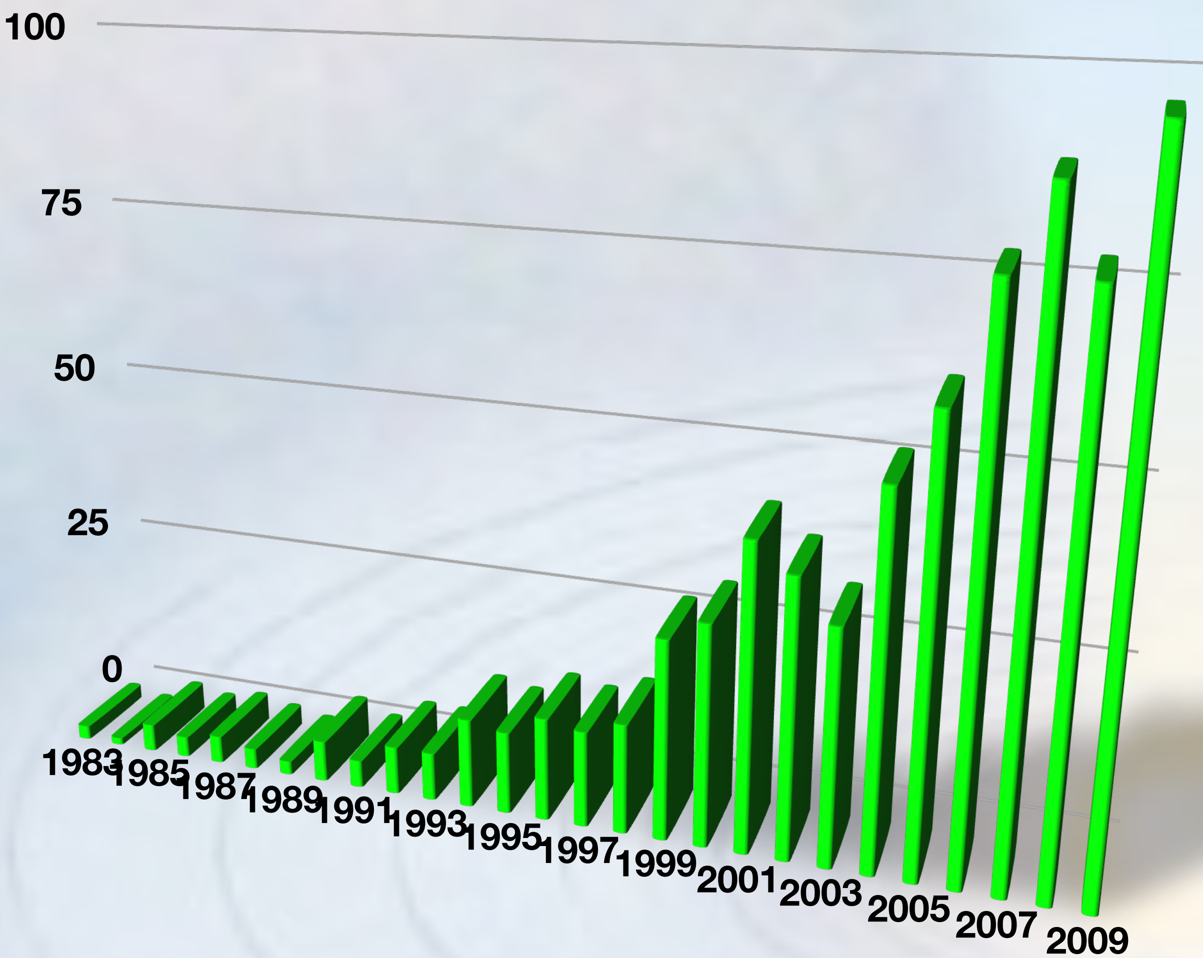
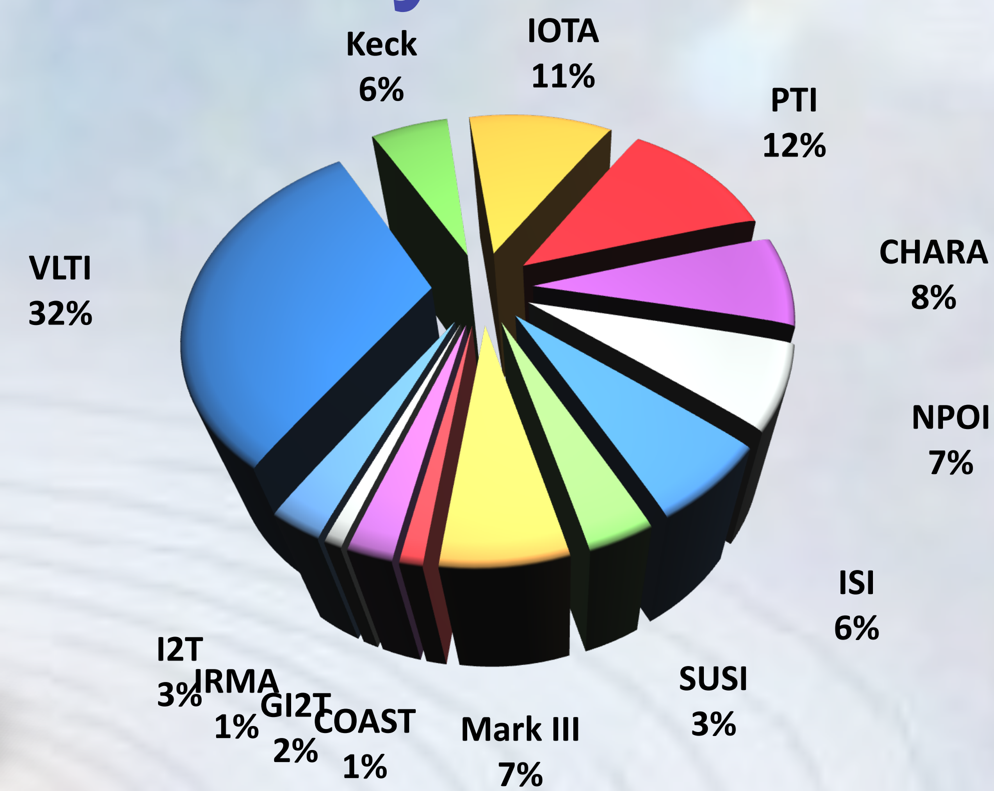
Interferometry publication OLBIN database

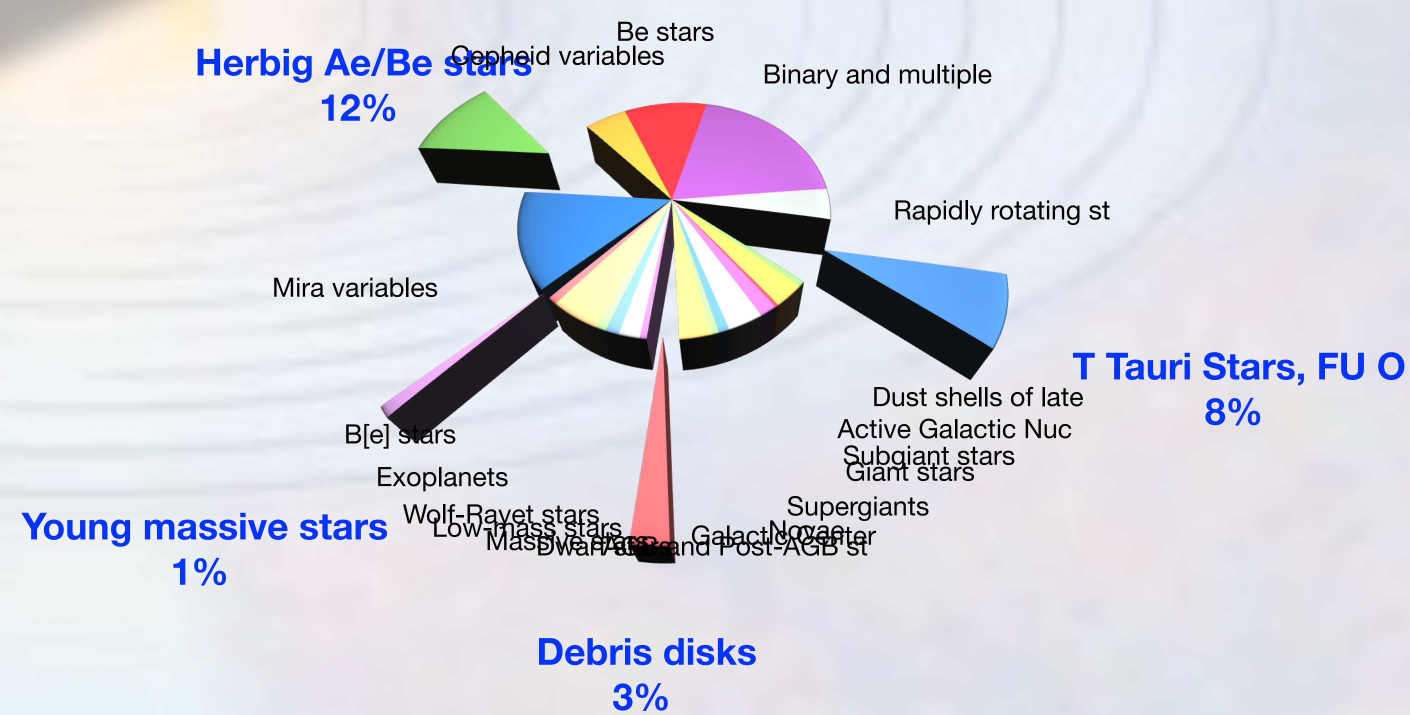


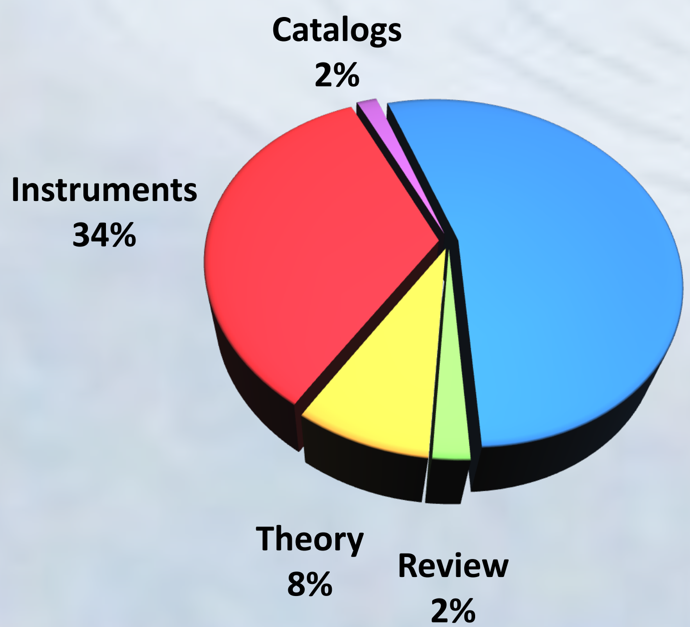
http://olbin.jpl.nasa.gov

Young stellar objects and debris disks in general interferometry









Total publications

Census of results

#	Name	Type	Instrument	Band	Spect. Resol.	Observables	References
1	FU Ori	FUOr	PTI, IOTA, MIDI	H, K, N	BB, LR	V^2	01, 15, 23
2	AB Aur	HAeBe	IOTA, PTI, CHARA, MIDI	H, K, N	BB, LR	V^2, CP	02, 04, 06, 10, 21, 22, 27, 39, 46, 49
3	T Tau N	TTS	PTI, MIDI	K, N	BB, LR	V^2	03, 51
4	SU Aur	TTS	PTI	K	BB	V^2	03
5	MWC 147	HAeBe	IOTA, PTI, AMBER, MIDI	H, K, N	BB, LR	V^2	03, 04, 08, 38
6	V380 Ori	HAeBe	IOTA	H	BB	V^2	04
7	MWC 166	HAeBe	IOTA	H	BB	V^2, CP	04, 22
8	Omega Ori	HAeBe	IOTA	H, K	BB	V^2	04
9	MWC 863	HAeBe	IOTA, KI	H, K	BB, LR	V^2, CP	04, 22, 47
10	MWC 361	HAeBe	IOTA	H, K	BB	V^2, CP	04, 22
11	V1685 Cyg	HAeBe	IOTA, PTI, KI	H, K	BB, LR	V^2	04, 06, 10, 14, 27
12	MWC 1080	HAeBe	IOTA, PTI, KI	H, K	BB, LR	V^2, CP	04, 06, 10, 22, 27, 47
13	MWC 297	HAeBe	IOTA, PTI, AMBER, MIDI	H, K, N	BB, MR, LR	V^2, CP	04, 08, 10, 22, 25, 42, 44
14	V1295 Aql	HAeBe	IOTA, PTI, KI	H, K	BB, LR	V^2, CP	04, 08, 10, 22, 27, 47
15	MWC 614	HAeBe	IOTA, PTI, MIDI	H, K, N	BB, LR	V^2, CP	04, 08, 09, 22
16	V594 Cas, M	HAeBe	IOTA, PTI, KI	H, K, L	BB, LR	V^2	04, 08, 52
17	MWC 275, H	HAeBe	IOTA, MIDI, KI, CHARA, AMBER	H, K, N	BB, LR, MR	V^2, CP	04, 09, 11, 14, 22, 39, 44, 46, 47, 56
18	T Ori	HAeBe	IOTA, PTI	H, K	BB, LR	V^2	04, 10, 27
19	LkHa 101	HAeBe	ISI	N	BB	V^2	05
20	VV Ser	HAeBe	PTI, KI	K	BB, LR	V^2	06, 10, 27, 47
21	AS 442	HAeBe	PTI, KI	K	BB, LR	V^2	06, 10, 14, 27, 47
22	DG Tau	TTS	KI	K	BB, LR	V^2	07, 17, 47
23	V1057 Cyg	FUOr	PTI, KI	K	BB	V^2	08, 20
24	HD 142527	HAeBe	MIDI	N	LR	V^2	09, 11
25	HD 144432	HAeBe	MIDI, KI, IOTA	N, K, H	BB, LR	V^2, CP	09, 11, 14, 22, 47
26	HD 100546	HAeBe	MIDI, AMBER	K, N	LR	V^2	09, 57
27	HD 179218	HAeBe	MIDI	N	LR	V^2	09, 45
28	KK OPh	HAeBe	MIDI	N	LR	V^2	09
29	51 Oph	HAeBe	MIDI, AMBER, KI	K, N	LR, MR	V^2, nuller	09, 43, 54
30	CQ Tau	HAeBe	PTI	K	BB, LR	V^2	10, 27
31	MWC 120	HAeBe	PTI	K	BB, LR	V^2	10, 27
32	HD 158352	HAeBe	PTI	K	BB	V^2	10
33	MWC 480	HAeBe	PTI, KI, IOTA	K, H	BB, LR, MR	V^2, CP	10, 22, 27, 29, 47
34	MWC 758	HAeBe	PTI, AMBER, KI	K, H	BB, LR	V^2, CP	10, 14, 27, 40, 47
35	HD 141569	HAeBe	PTI, KI	K	BB, LR	V^2	10, 14, 47
36	RY Tau	TTS	PTI, MIDI, KI	K, N	BB, LR	V^2, CP	12, 22, 36, 47, 58
37	DR Tau	TTS	PTI, MIDI	K, N	BB, LR	V^2	12, 50
38	AS 207A	TTS	KI	K	BB	V^2	13
39	V2508 Oph	TTS	KI	K	BB	V^2	13
40	AS 205A	TTS	KI	K	BB, LR	V^2	13, 47
41	PX Vul	TTS	KI	K	BB	V^2	13
42	UX Ori	HAeBe	KI	K	BB	V^2	14
43	ZCMa-NW	HAeBe	KI, AMBER	K	BB, LR	V^2	14, 37
44	HD 58647	HAeBe	KI	K	BB	V^2	14
45	HD 146666	HAeBe	KI	K	BB	V^2	14
46	HD 143006	HAeBe	KI	K	BB	V^2	14
47	HD 150193	HAeBe	KI	K	BB	V^2	14
48	WW Vul	HAeBe	KI	K	BB	V^2	14
49	AS 477	HAeBe	KI	K	BB	V^2	14
50	HD 98800B	TTS	KI	K	BB	V^2	16, 34
51	BP Tau	TTS	KI	K	BB	V^2	17
52	DI Tau	TTS	KI	K	BB	V^2	17
53	GM Aur	TTS	KI	K	BB	V^2	17, 58
54	LkCa15	TTS	KI	K	BB	V^2	17, 58
55	RW Aur A	TTS	KI	K	BB, LR	V^2	17, 32, 47

#	Name	Type	Instrument	Band	Spect. Resol.	Observables	References
56	V830 Tau	TTS	KI	K	BB	V^2	17
57	TW Hya	TTS	KI, MIDI	K, N	BB, LR	V^2	18, 31
58	V1515 Cyg	FUOr	KI	K	BB	V^2	20
59	ZCMa-SE	FUOr	KI	K	BB	V^2	20
60	V1647 Ori	FUOr	MIDI	N	LR	V^2	19
61	HR 5999	HAeBe	MIDI	N	LR	V^2	24
62	HD 45677	HAeBe	IOTA	H	BB	V^2, CP	22
63	MWC 342	HAeBe	IOTA	H	BB	V^2, CP	22
64	HD 104237	HAeBe	AMBER	K	MR	V^2	26, 44
65	Theta1 Ori C	HMS	IOTA	H	BB	V^2, CP	28
66	Hen 3-1191	HAeBe	MIDI	N	LR	V^2	30
67	CI Tau	TTS	KI	K	BB	V^2	32
68	DK Tau A	TTS	KI	K	BB	V^2	32
69	DK Tau B	TTS	KI	K	BB	V^2	32
70	AA Tau	TTS	KI	K	BB	V^2	32
71	RW Aur B	TTS	KI	K	BB	V^2	32
72	V1002 Sco	TTS	KI	K	BB	V^2	32
73	V1331 Cyg	TTS	KI	K	BB	V^2	32
74	DI Cep	TTS	KI	K	BB	V^2	32
75	BM And	TTS	KI	K	BB	V^2	32
76	V773 Tau A	TTS	KI	K	BB	V^2	33
77	W33A	HMS	MIDI	N	LR	V^2	35
78	Harro 1-14c	TTS	KI	K	BB	V^2	41
79	HD 98922	HAeBe	AMBER	K	MR	V^2	44
80	V921 Sco	HAeBe	AMBER	K	MR	V^2	44
81	HD 101412	HAeBe	MIDI	N	LR	V^2	45
82	HD 135344	HAeBe	MIDI	N	LR	V^2	45
83	HD 142666	HAeBe	KI	K	LR	V^2	47
84	DQ Tau	TTS	KI	K	BB	V^2	48
85	GW Ori	TTS	MIDI	N	LR	V^2	50
86	HD 72106B	TTS	MIDI	N	LR	V^2	50
87	RU Lup	TTS	MIDI	N	LR	V^2	50
88	HBC 639	TTS	MIDI	N	LR	V^2	50
89	S CrA N	TTS	MIDI	N	LR	V^2	50
90	S CrA S	TTS	MIDI	N	LR	V^2	50
91	T Tau S	TTS	MIDI	N	LR	V^2	51
92	M8E-IR	HMS	MIDI	N	LR	V^2	53
93	R CrA	HAeBe	AMBER	K, H	LR	V^2, CP	55
94	DM Tau	TTS	KI	K	BB	V^2	58
95	UX Tau A	TTS	KI	K	BB	V^2	58
1	Vega	Debris	CHARA/FLU	K	BB	V^2	d01
2	τ Ceti	Debris	CHARA/FLU	K	BB	V^2	d02
3	ε Eri	Debris	CHARA/FLU	K	BB	V^2	d02
4	β UMa	Debris	CHARA/FLU	K	BB	V^2	d03
5	η Crv	Debris	CHARA/FLU	K	BB	V^2	d03
6	σ Boo	Debris	CHARA/FLU	K	BB	V^2	d03
7	α CrB	Debris	CHARA/FLU	K	BB	V^2	d03
8	γ Oph	Debris	CHARA/FLU	K	BB	V^2	d03
9	ζ Aql	Debris	CHARA/FLU	K	BB	V^2	d03
10	α PsA, Fomalha	Debris	VLTI/AMBEF	K	BB, MR	DP, V^2	d04, d06
11	e Corvi	Debris	VLTI/MIDI	N	LR	V^2	d05
12	HD 69830	Debris	VLTI/MIDI	N	LR	V^2	d05
13	ε Aur	Debris	CHARA/MIR	H	LR	image	d07

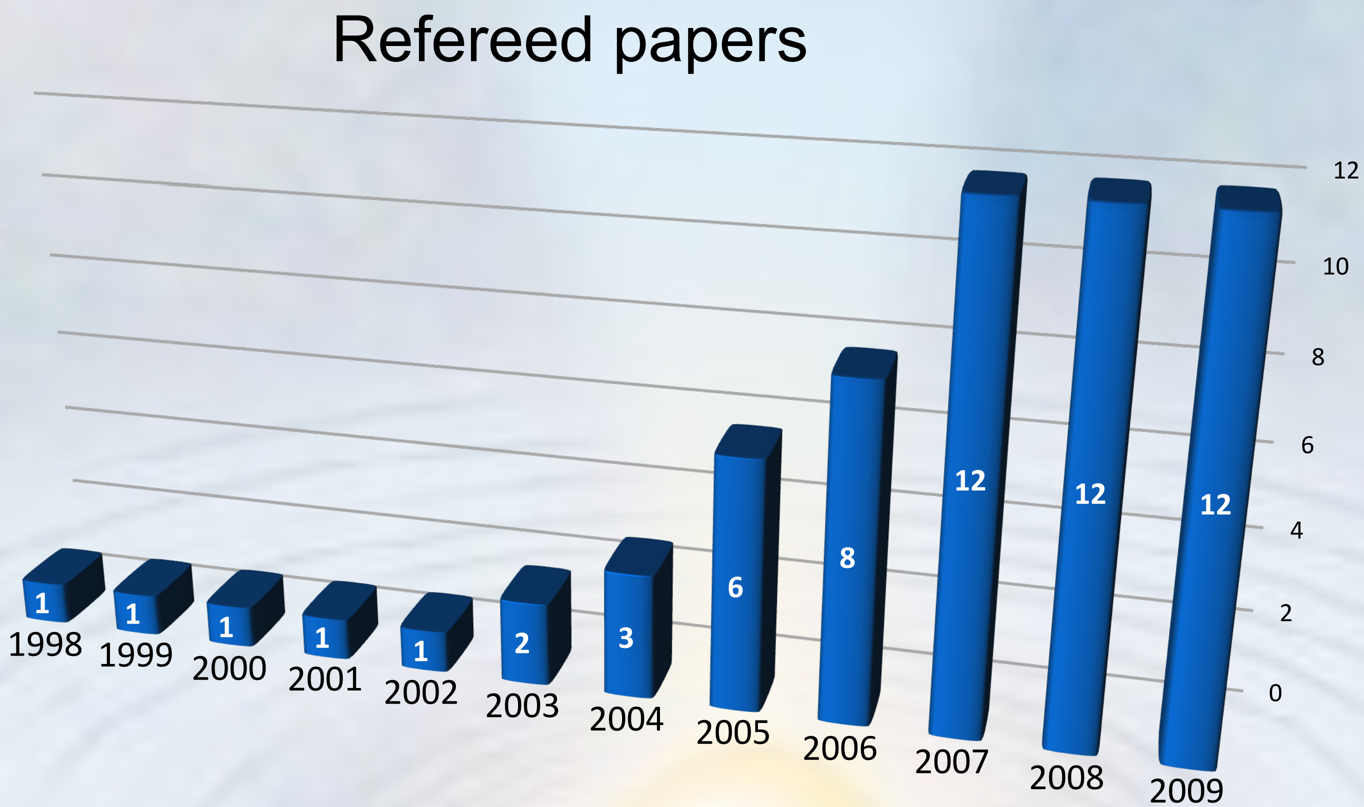
→ **95 young stellar objects** observed and published to date,

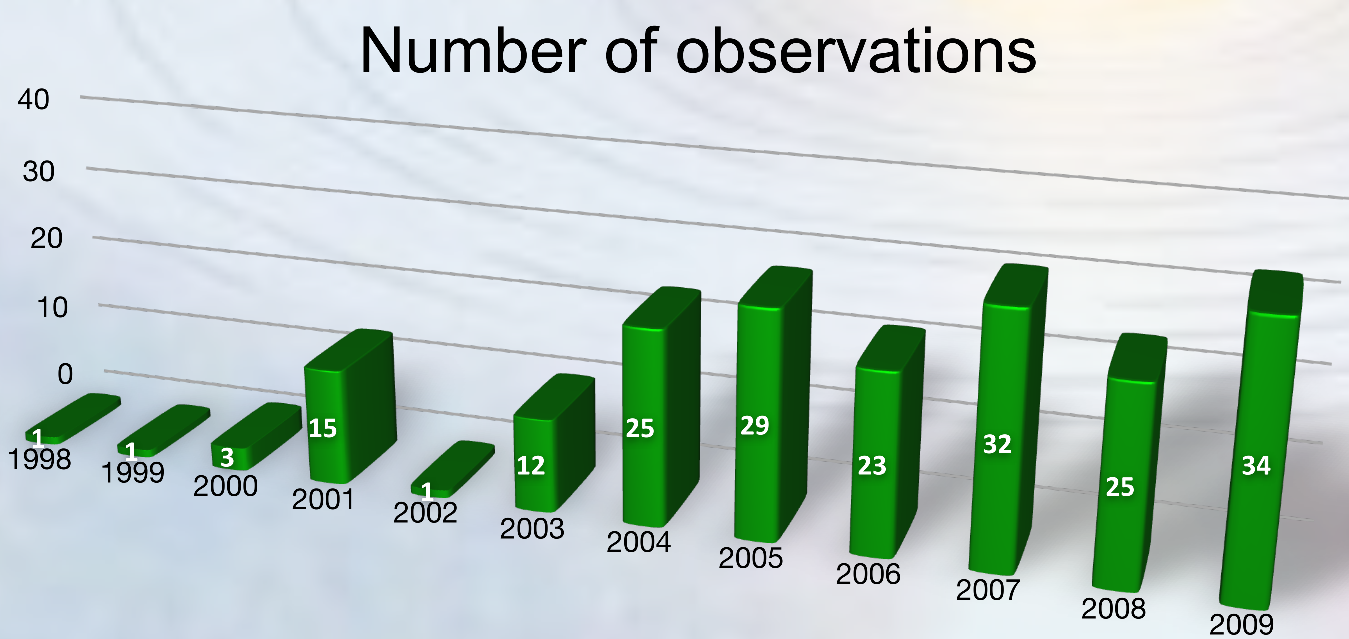
→ **13 debris disks** observed and published to date,

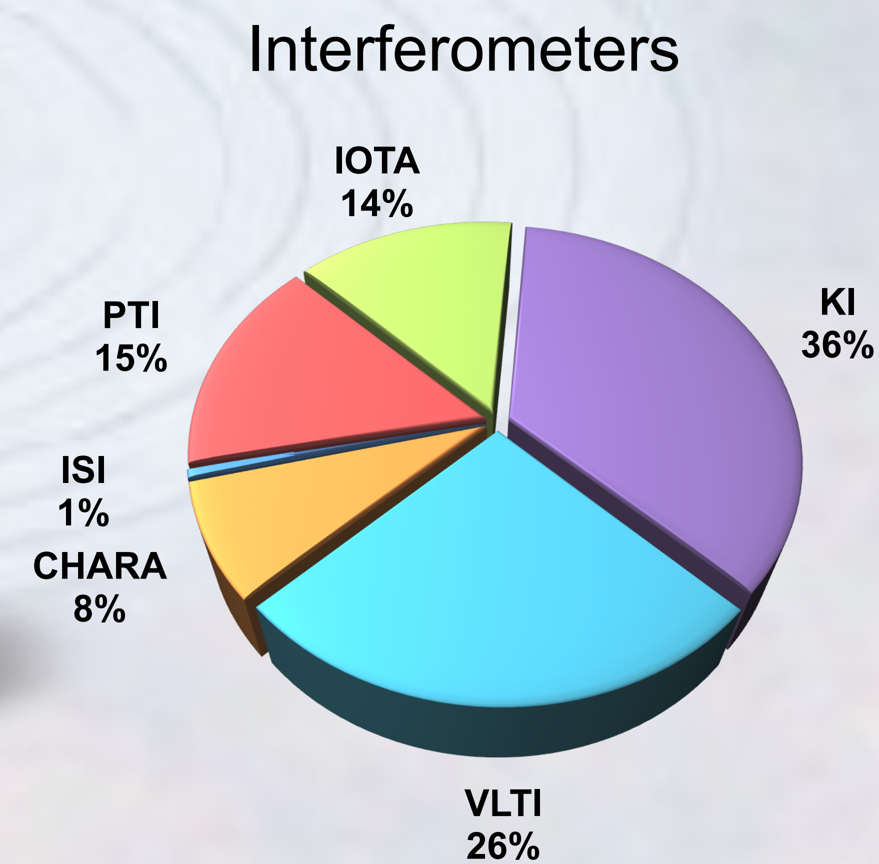
→ **58+7 refereed articles** (65 total) in a decade

01	**Malbet, Berger, Colavita** et al.	**1998**	ApJ, 507, L149	*FU Orionis Resolved by Infrared Long-Baseline Interferometry at a 2 AU Scale*	1
02	**Millan-Gabet, Schloerb, Traub** et al.	**1999**	ApJ, 513, L131	*Sub-Astronomical Unit Structure of the Near-Infrared Emission from AB Aurigae*	1
03	**Akeson, Ciardi, van Belle** et al.	**2000**	ApJ, 543, 313	*Infrared Interferometric Observations of Young Stellar Objects*	3
04	**Millan-Gabet, Schloerb & Traub**	**2001**	ApJ, 546, 358	*Spatially Resolved Circumstellar Structure of Herbig AE/BE Stars in the Near-Infrared*	15
05	**Tuthill, Monnier, Danchi** et al.	**2002**	ApJ, 577, 826	*Imaging the Disk around the Luminous Young Star LkHa 101 with Infrared Interferometry*	1
06	**Eisner, Lane, Akeson** et al.	**2003**	ApJ, 588, 360	*Near-Infrared Interferometric Measurements of Herbig Ae/Be Stars*	5
07	**Colavita, Akeson, Wizinowich** et al.	**2003**	ApJ, 592, L83	*Observations of DG Tauri with the Keck Interferometer*	1
09	**Leinert, van Boekel, Waters** et al.	**2004**	A&A, 423, 537	*Mid-infrared sizes of circumstellar disks around Herbig Ae/Be stars measured with MIDI on the VLTI*	8
10	**Eisner, Lane, Hillenbrand** et al.	**2004**	ApJ, 613, 1049	*Resolved Inner Disks around Herbig Ae/Be Stars*	14
11	**van Boekel, Min, Leinert** et al.	**2004**	Nature, 432, 479	*The building blocks of planets within the 'terrestrial' region of protoplanetary disks*	3
12	**Akeson, Walker, Wood** et al.	**2005**	ApJ, 622, 440	*Observations and Modeling of the Inner Disk Region of T Tauri Stars*	2
13	**Eisner, Hillenbrand, White** et al.	**2005**	ApJ, 623, 952	*Observations of T Tauri Disks at Sub-AU Radii: Implications for Magnetospheric Accretion and Planet Formation*	4
14	**Monnier, Millan-Gabet, Billmeier** et al.	**2005**	ApJ, 624, 832	*The Near-Infrared Size-Luminosity Relations for Herbig Ae/Be Disks*	14
15	**Malbet, Lachaume, Berger** et al.	**2005**	A&A, 437, 627	*New insights on the AU-scale circumstellar structure of FU Orionis*	1
16	**Boden, Sargent, Akeson** et al.	**2005**	ApJ 635, 442	*Dynamical Masses for Low-Mass Pre-Main Sequence Stars: A Preliminary Physical Orbit for HD 98800 B*	1
17	**Akeson, Boden, Monnier** et al.	**2005**	ApJ 635, 1173	*Keck Interferometer observations of classical and weak line T Tauri stars*	7
18	**Eisner, Chiang & Hillenbrand**	**2006**	ApJ 637, L133	*Spatially Resolving the Inner Disk of TW Hydrae*	1
19	**Ábrahám, Mosoni, Henning** et al.	**2006**	A&A 449, L13	*First AU-scale observations of V1647 Orionis with VLTI/MIDI*	1
20	**Millan-Gabet, Monnier, Akeson** et al.	**2006**	ApJ 641, 547	*Keck Interferometer Observations of FU Orionis Objects*	3
21	**Millan-Gabet, Monnier, Berger**, et al.	**2006**	ApJ 645, L77	*Bright Localized Near-Infrared Emission at 1-4 AU in the AB Aurigae Disk Revealed by IOTA Closure Phases*	1
22	**Monnier, Berger, Millan-Gabet**, et al.	**2006**	ApJ 647, 444	*Few Skewed Disks Found in First Closure-Phase Survey of Herbig Ae/Be Stars*	14
23	**Quanz, Henning, Bouwman**, et al.	**2006**	ApJ 648, 472	*FU Orionis: The MIDI VLTI Perspective*	1
24	**Preibisch, Kraus, Driebe** et al.	**2006**	A&A 458, 235	*A compact dusty disk around the Herbig Ae star HR 5999 resolved with VLTI / MIDI*	1
25	**Malbet, Benisty, de Wit** et al.	**2007**	A&A 464, 43	*Disk and wind interaction in the young stellar object MWC 297 spatially resolved with VLTI/AMBER*	1
26	**Tatulli, Isella, Natta**, et al.	**2007**	A&A 464, 43	*Constraining the wind launching region in Herbig Ae stars: AMBER/VLTI spectroscopy of HD 104237*	1
27	**Eisner, Chiang, Lane**, et al.	**2007**	ApJ 657, 347	*Spectrally Dispersed K-Band Interferometric Observations of Herbig Ae/Be Sources: Inner Disk Temperature Profiles*	11
28	**Kraus, Balega, Berger**, et al.	**2007**	A&A 466, 649	*Visual/infrared interferometry of Orion Trapezium stars: Preliminary dynamical orbit and aperture synthesis imaging of the Theta 1 Orionis C syste*	1
29	**Eisner**	**2007**	Nature, 447, 562	*Water vapour and hydrogen in the terrestrial-planet-forming region of a protoplanetary disk*	1
30	**Lachaume, Preibisch, Driebe**, et al.	**2007**	A&A 469, 587	*Resolving the B[e] star Hen 3-1191 at 10 microns with VLTI/MIDI*	1
31	**Ratzka, Leinert, Henning**, et al.	**2007**	A&A 471, 173	*High Spatial Resolution Mid-Infrared Observations of the Low-Mass Young Star TW Hya*	1
32	**Eisner, Hillebrand, White**, et al.	**2007**	ApJ 669, 1072	*Near-Infrared Interferometric, Spectroscopic, and Photometric Monitoring of T Tauri Inner Disks*	10
33	**Boden, Torres, Sargent**, et al.	**2007**	ApJ 670, 1214	*Dynamical Masses for Pre-Main Sequence Stars: A Preliminary Physical Orbit for V773 Tau A*	1
34	**Akeson, Rice, Boden, A.** et al.	**2007**	ApJ, 670, 1240	*The Circumbinary Disk of HD 98800B: Evidence for Disk Warping*	1
35	**de Wit, Hoare, Oudmaijer** et al.	**2007**	ApJ 671, L169	*VLTI/MIDI 10µm Interferometry of the Forming Massive Star W33A*	1
36	**Schegerer, Wolf, Ratzka** et al.	**2008**	A&A 478, 779	*The T Tauri star RY Tauri as a case study of the inner regions of circumstellar dust disks*	1
37	**Li Causi, Antoniucci & Tatulli**	**2008**	A&A 479, 589	*De-biasing interferometric visibilities in VLTI-AMBER data of low SNR observations*	1
38	**Kraus, Preibisch & Ohnaka**	**2008**	ApJ 676, 490	*Detection of an inner gaseous component in a Herbig Be star accretion disk: Near- and mid-infrared spectro-interferometry and radiative transfer*	1
39	**Tannirkulam, Monnier, Millan-Gabet** et a	**2008**	ApJ 677, L51	*Strong Near-Infrared Emission Interior to the Dust Sublimation Radius of Young Stellar Objects MWC 275 and AB Aur*	2
40	**Isella, Tatulli, Natta** et al.	**2008**	A&A 483, L13	*Gas and dust in the inner disk of the Herbig Ae star MWC 758*	1
41	**Schaefer, Simon, Prato**, et al.	**2008**	AJ, 135, 1659	*Preliminary Orbit of the Young Binary Haro 1-14c*	1
42	**Acke, Verhoelst, van den Ancker** et al.	**2008**	A&A 485, 209	*MWC 297: a young high-mass star rotating at critical velocity*	1
43	**Tatulli, Malbet, Ménard**, et al.	**2008**	A&A 489, 1151	*Spatially resolving the hot CO around the young Be star 51 Ophiuchi*	1
44	**Kraus, Hofmann, Benisty**, et al.	**2008**	A&A 489, 1157	*The origin of hydrogen line emission for five Herbig Ae/Be stars spatially resolved by VLTI/AMBER spectro-interferometry*	5
45	**Fedele, van den Ancker, Acke**, et al.	**2008**	A&A, 491, 809	*The structure of the protoplanetary disk surrounding three young intermediate mass stars. II. Spatially resolved dust and gas distribution*	3
46	**Tannirkulam, Monnier, Harries**, et al.	**2008**	ApJ, 689, 513	*A Tale of Two Herbig Ae Stars, MWC 275 and AB Aurigae: Comprehensive Models for Spectral Energy Distribution and Interferometry*	2
47	**Eisner, Graham, Akeson**, et al.	**2009**	ApJ, 692, 309	*Spatially Resolved Spectroscopy of Sub-AU-Sized Regions of T Tauri and Herbig Ae/Be Disks*	15
48	**Boden, Akeson, Sargent**, et al.	**2009**	ApJ, 696, L111	*Interferometric Evidence for Resolved Warm Dust in the DQ Tau System*	1
49	**di Folco, Dutrey, Chesneau**, et al.	**2009**	A&A, 500, 1065	*The flared inner disk of the Herbig Ae star AB Aurigae revealed by VLTI/MIDI in the N-band*	1
50	**Schegerer, Wolf, Hummel**, et al.	**2009**	A&A, 502, 367	*Tracing the potential planet-forming regions around seven pre-main-sequence stars*	7
51	**Ratzka, Schegerer, Leinert**, et al.	**2009**	A&A, 502, 623	*Spatially resolved mid-infrared observations of the triple system T Tauri*	2
52	**Ragland, Akeson, R. Armandroff**, et al.	**2009**	ApJ, 703, 22	*First L-Band Interferometric Observations of a Young Stellar Object: Probing the Circumstellar Environment of MWC 419*	1
53	**Linz, Henning, Feldt**, et al.	**2009**	A&A, 505, 655	*Mid-infrared interferometry of massive young stellar objects. I. VLTI and Subaru observations of the enigmatic object M8E-IR*	1
54	**Stark, Kuchner, Traub**, et al.	**2009**	ApJ, 703, 1188	*51 Ophiuchus: A Possible Beta Pictoris Analog Measured with the Keck Interferometer Nuller*	1
55	**Kraus, Hofmann, Malbet**, et al.	**2009**	A&A, 508, 787	*Revealing the sub-AU asymmetries of the inner dust rim in the disk around the Herbig Ae star R Coronae Austrinae*	1
56	**Benisty, Natta, Isella**, et al.	**2010**	A&A, 511, A74	*Strong near-infrared emission in the sub-AU disk of the Herbig Ae star HD 163296: evidence of refractory dust?*	1
57	**Benisty, Tatulli, Ménard**, et al.	**2010**	A&A, 511, A75	*The complex structure of the disk around HD 100546. The inner few astronomical units*	1
58	**Pott, Perrin, Furlan**, et al.	**2010**	ApJ, 710, 265	*Ruling Out Stellar Companions and Resolving the Innermost Regions of Transitional Disks with the Keck Interferometer*	5
d01	**Absil, di Folco, Mérand** et al.	**2006**	A&A, 452, 237	*Circumstellar material in the Vega inner system revealed by CHARA/FLUOR*	1
d02	**di Folco, Absil, Augereau** et al.	**2007**	A&A, 475, 243	*A near-infrared interferometric survey of debris disk stars. I. Probing the hot dust content around É› Eridani and Ï„ Ceti with CHARA/FLUOR*	2
d03	**Absil, di Folco, Mérand** et al.	**2008**	A&A, 487,1041	*A near-infrared interferometric survey of debris disc stars. II. CHARA/FLUOR observations of six early-type dwarfs*	6
d04	**Le Bouquin, Absil, Benisty** et al.	**2008**	A&A, 498, L41	*The spin-orbit alignment of the Fomalhaut planetary system probed by optical long baseline interferometry*	1
d05	**Smith, Wyatt, & Haniff**	**2009**	A&A, 503, 265	*Resolving the hot dust around HD69830 and η Corvi with MIDI and VISIR*	2
d06	**Absil, Mennesson, Le Bouquin** et al.	**2009**	ApJ, 704, 150	*An Interferometric Study of the Fomalhaut Inner Debris Disk. I. Near-Infrared Detection of Hot Dust with VLTI/VINCI*	1
d07	**Kloppenborg, Stencel, Monnier** et al.	**2010**	Nature, 464, 870	*Infrared images of the transiting disk in the ε Aurigae system*	1

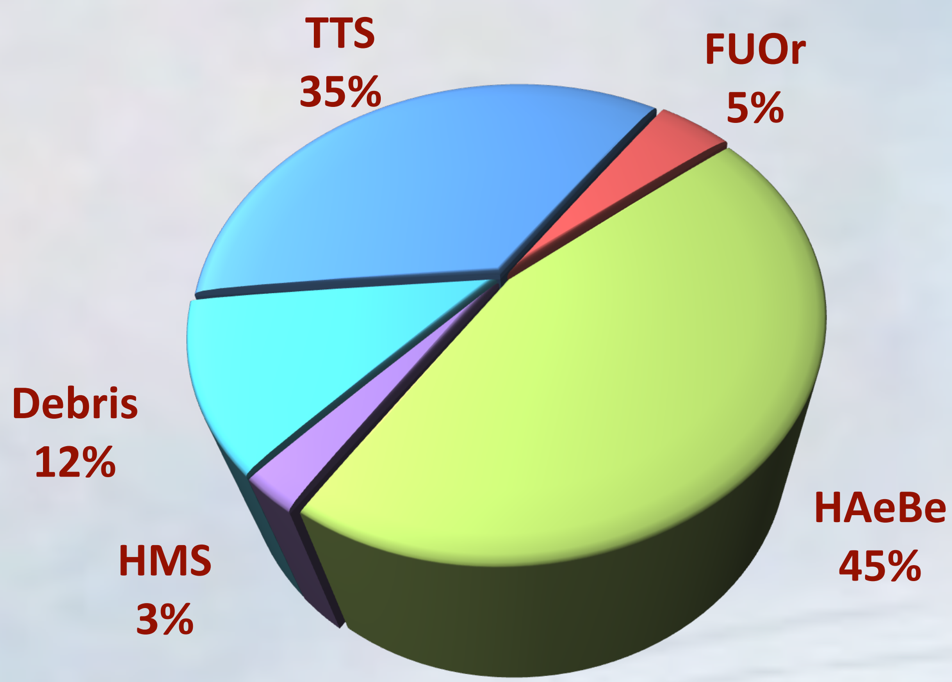
YSOs + Debris disks observed (1998-2010)



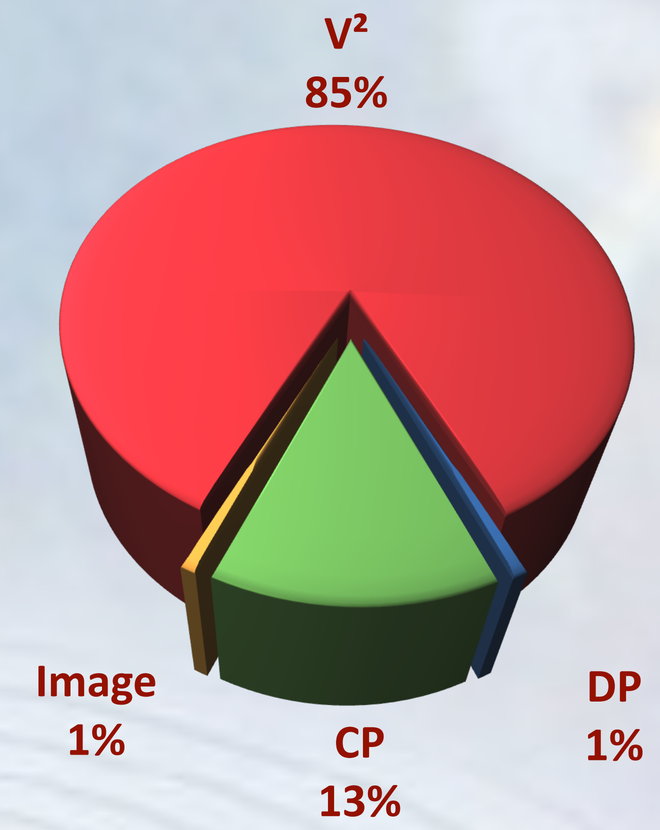




Type of objects

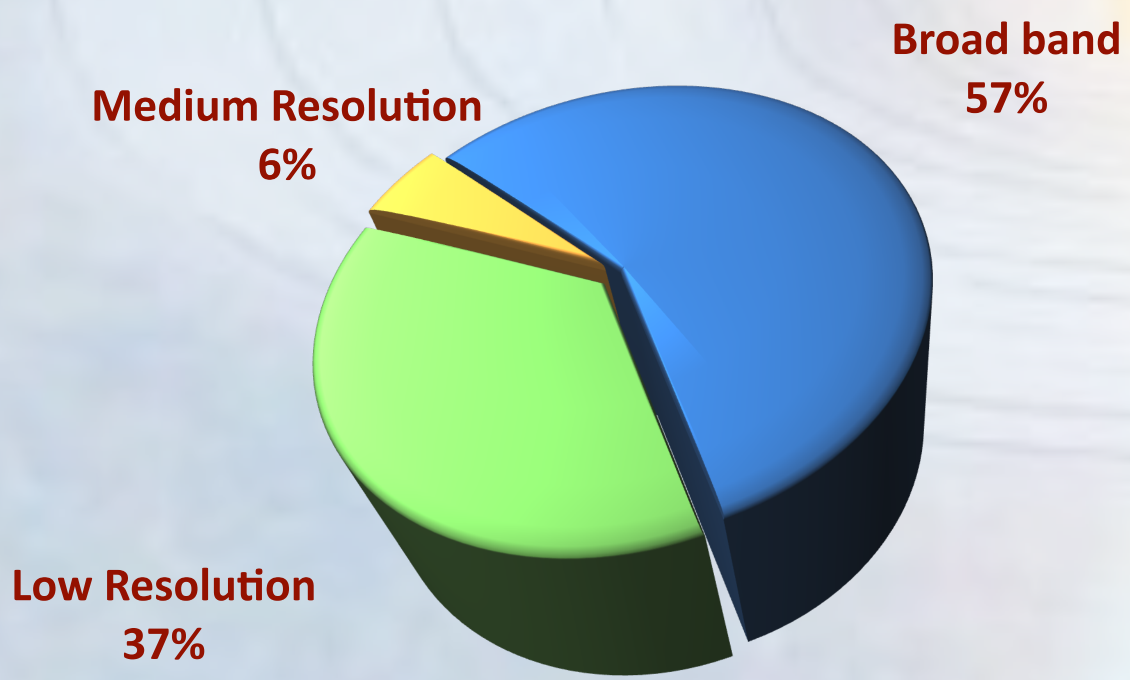


Observables

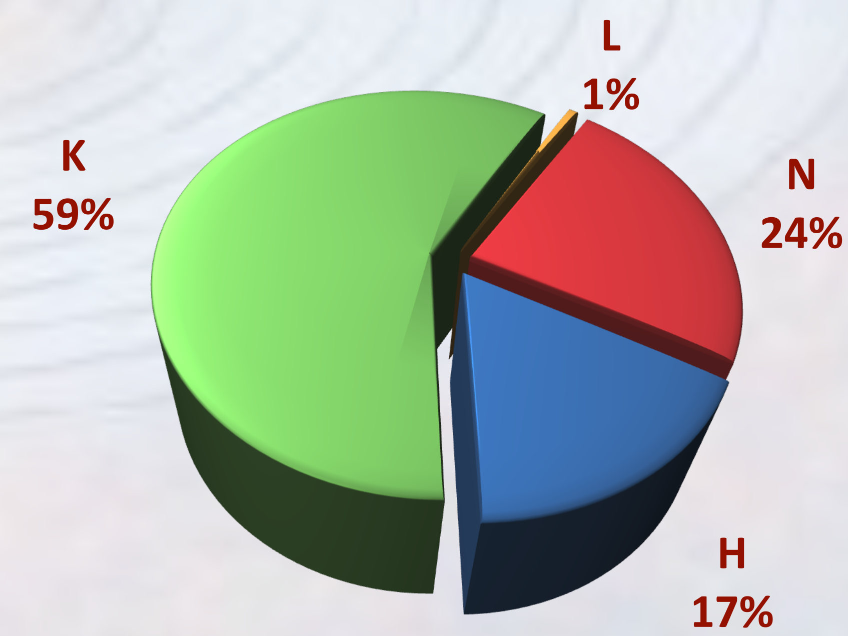


1998-2010

Spectral resolution



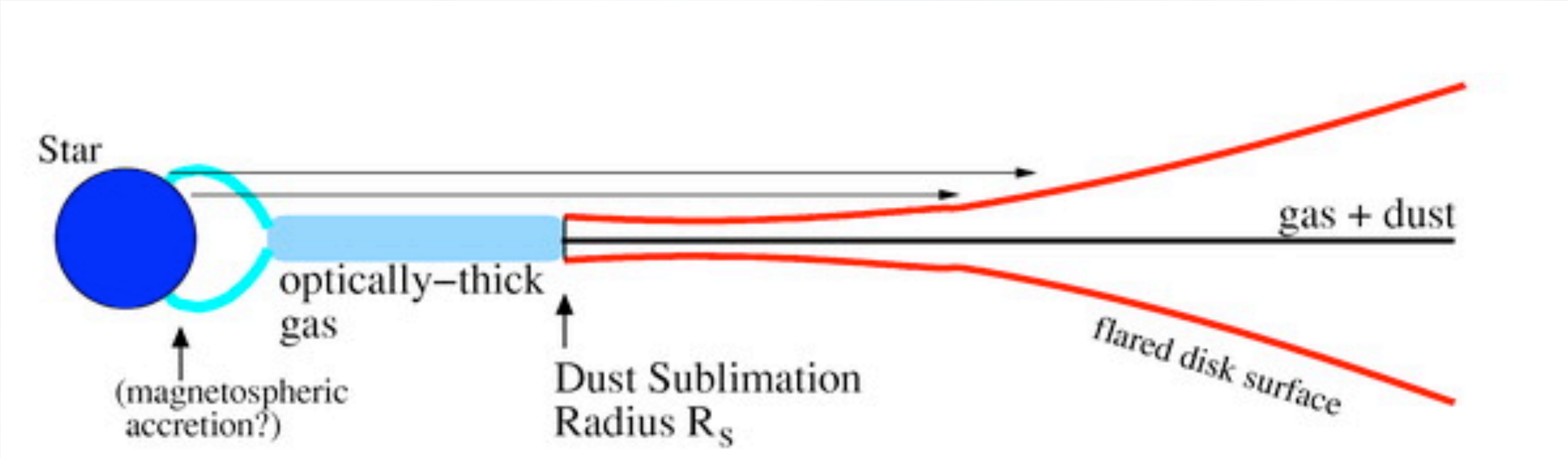
Spectral bands



INNER DISK PHYSICS

- Sizes of circumstellar structures
- Constraints on disk structure (T, z,…)
- Dust mineralogy
- Gas/dust connection
- Debris disks

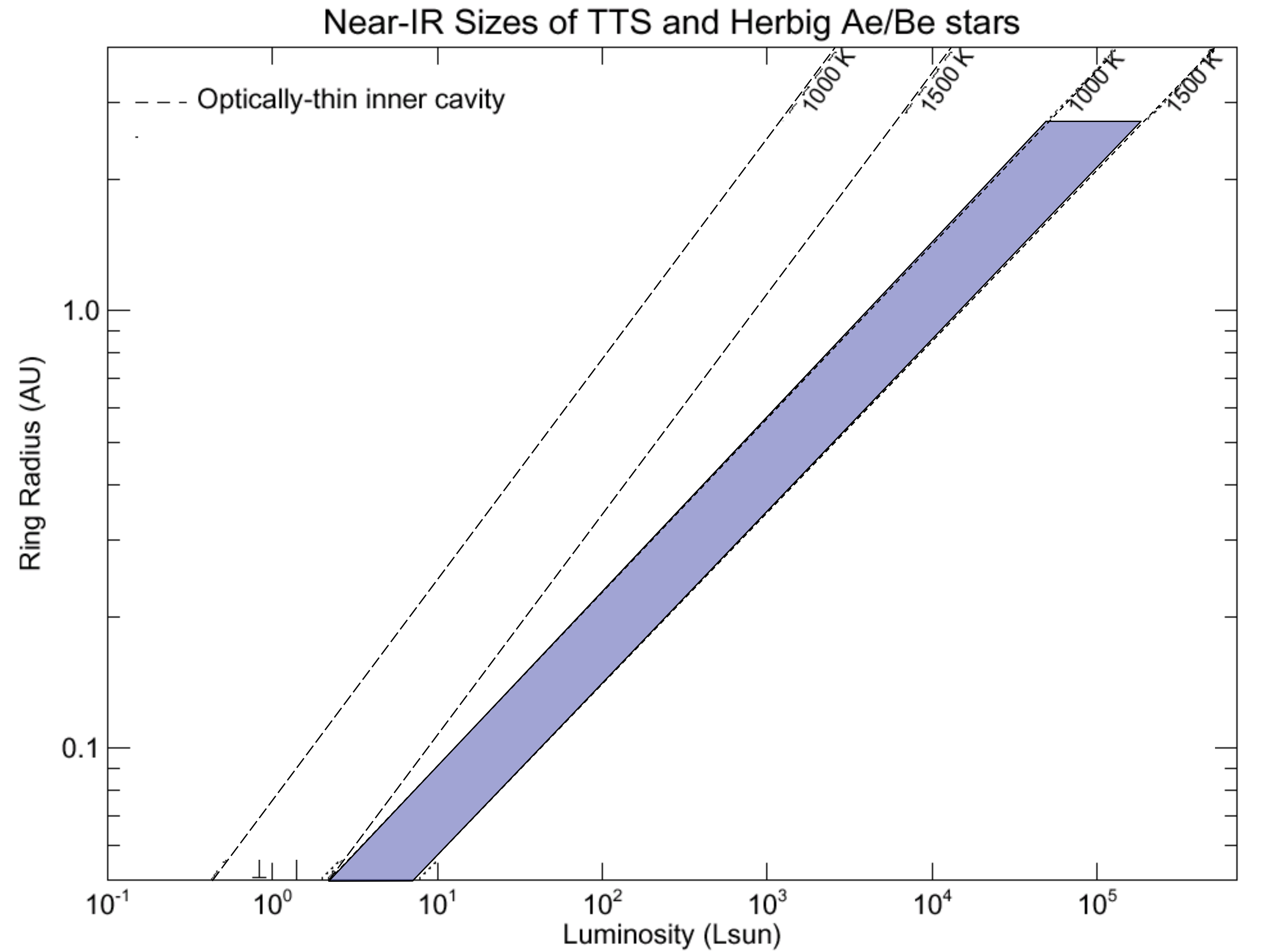
Original disk concept



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

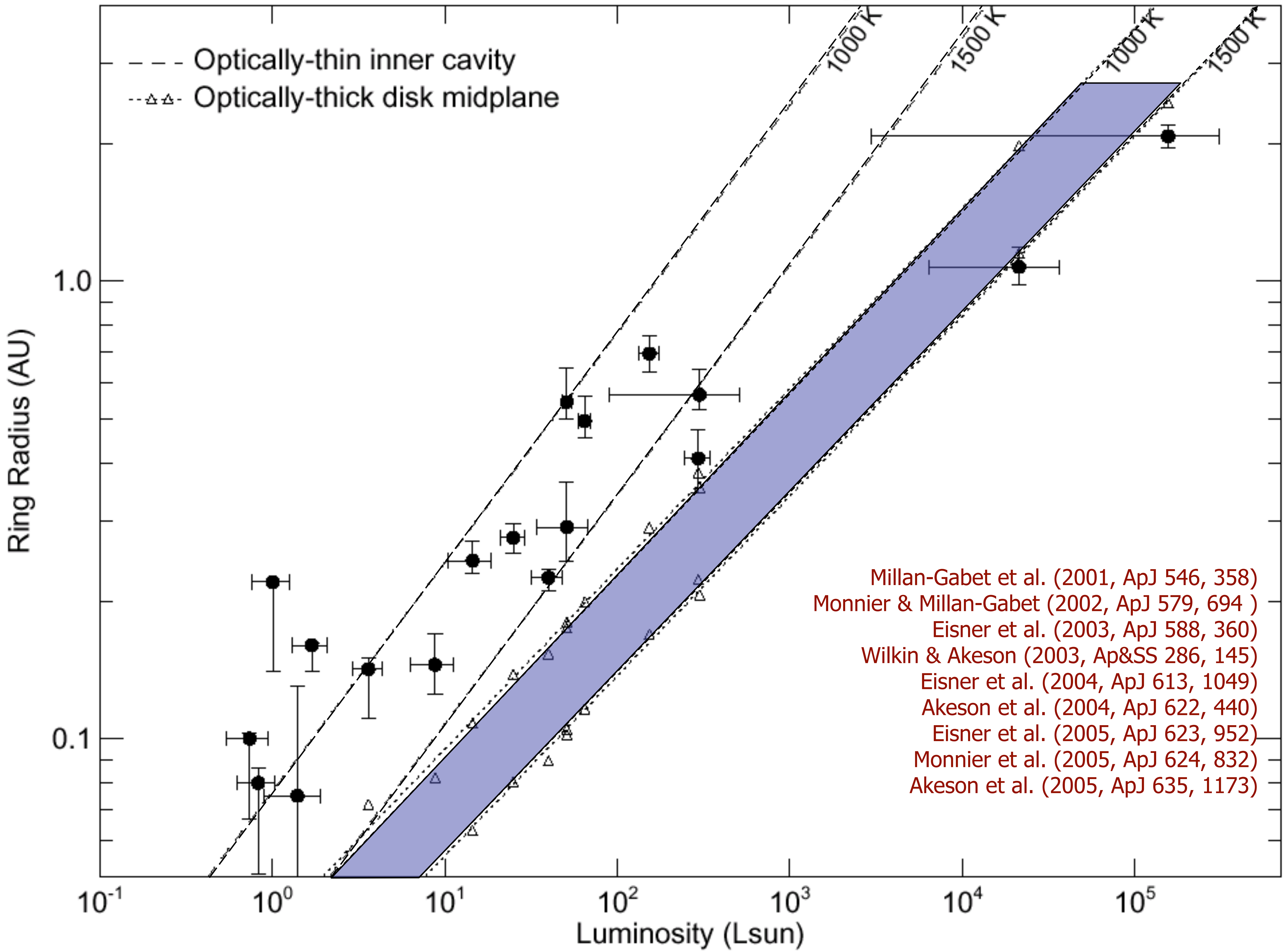
- **Optically thick disk both for inner gas and outer dust**
- **Simple power-law temperature distribution ($T \propto r^{-0.75}$, $T \propto r^{-0.5}$)**
- **Oblique disk heating**

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



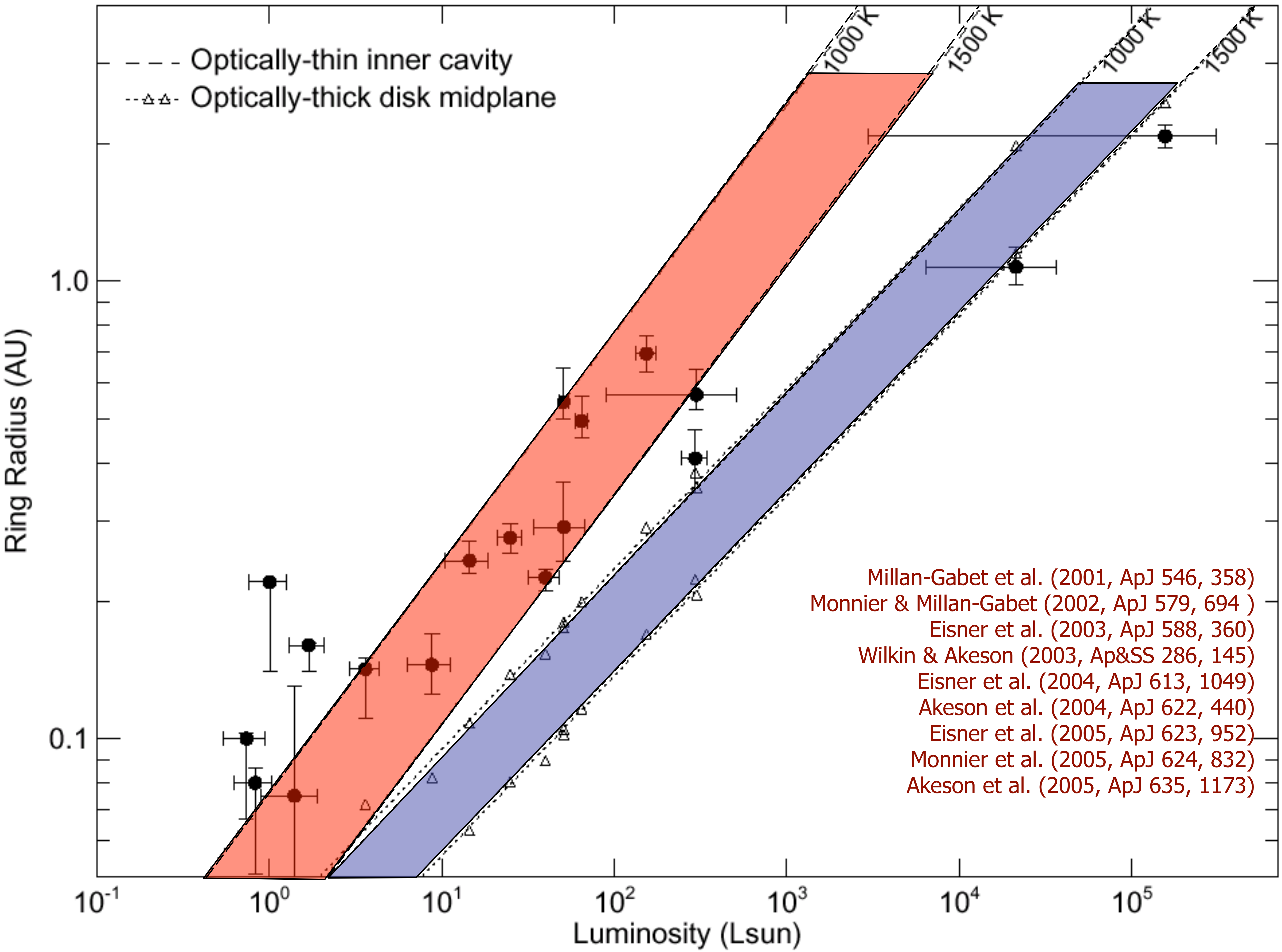
Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
1000 K
1500 K
1000 K
1500 K
1.0
0.1
Ring Radius (AU)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Luminosity (Lsun)

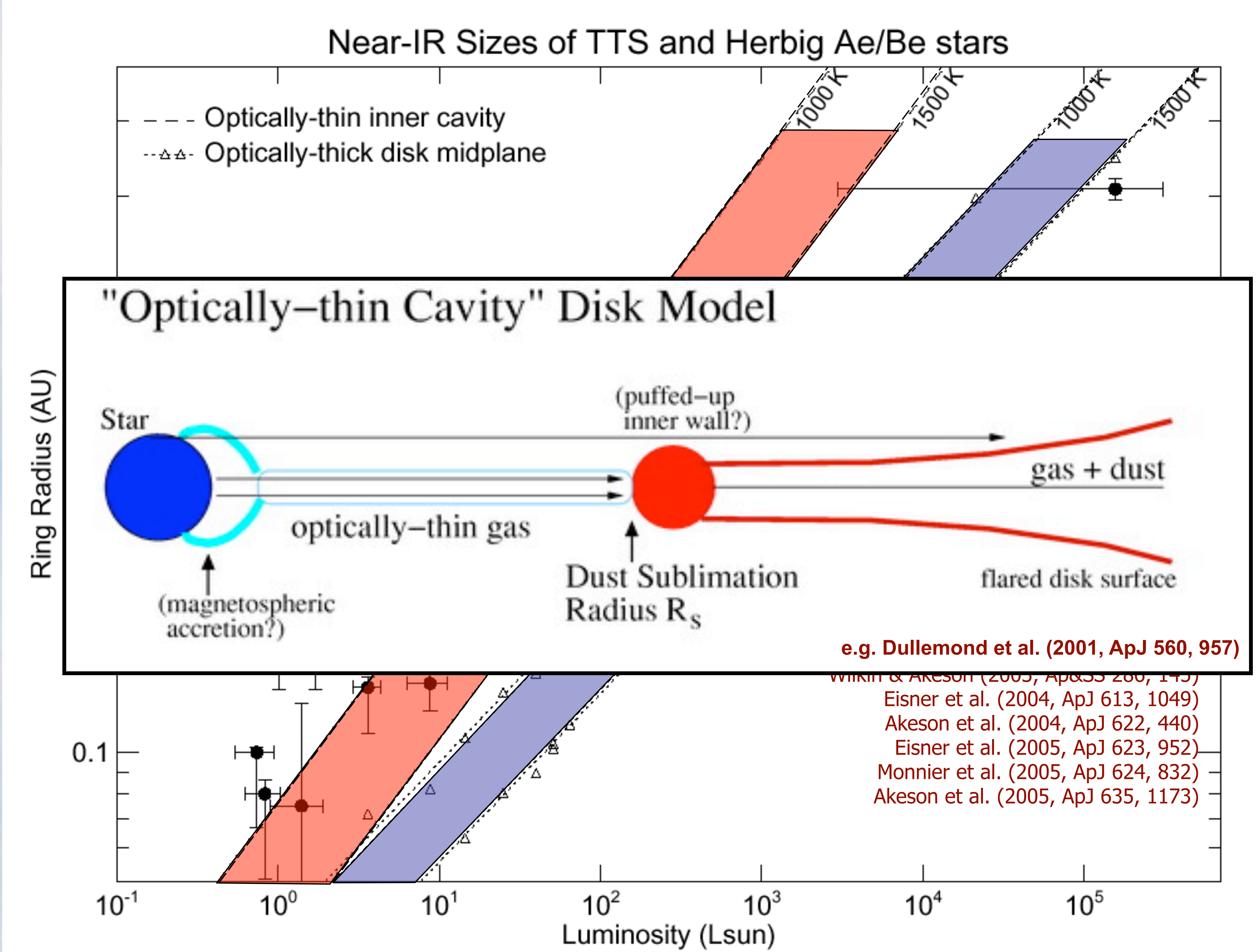
Near-IR Sizes of TTS and Herbig Ae/Be stars

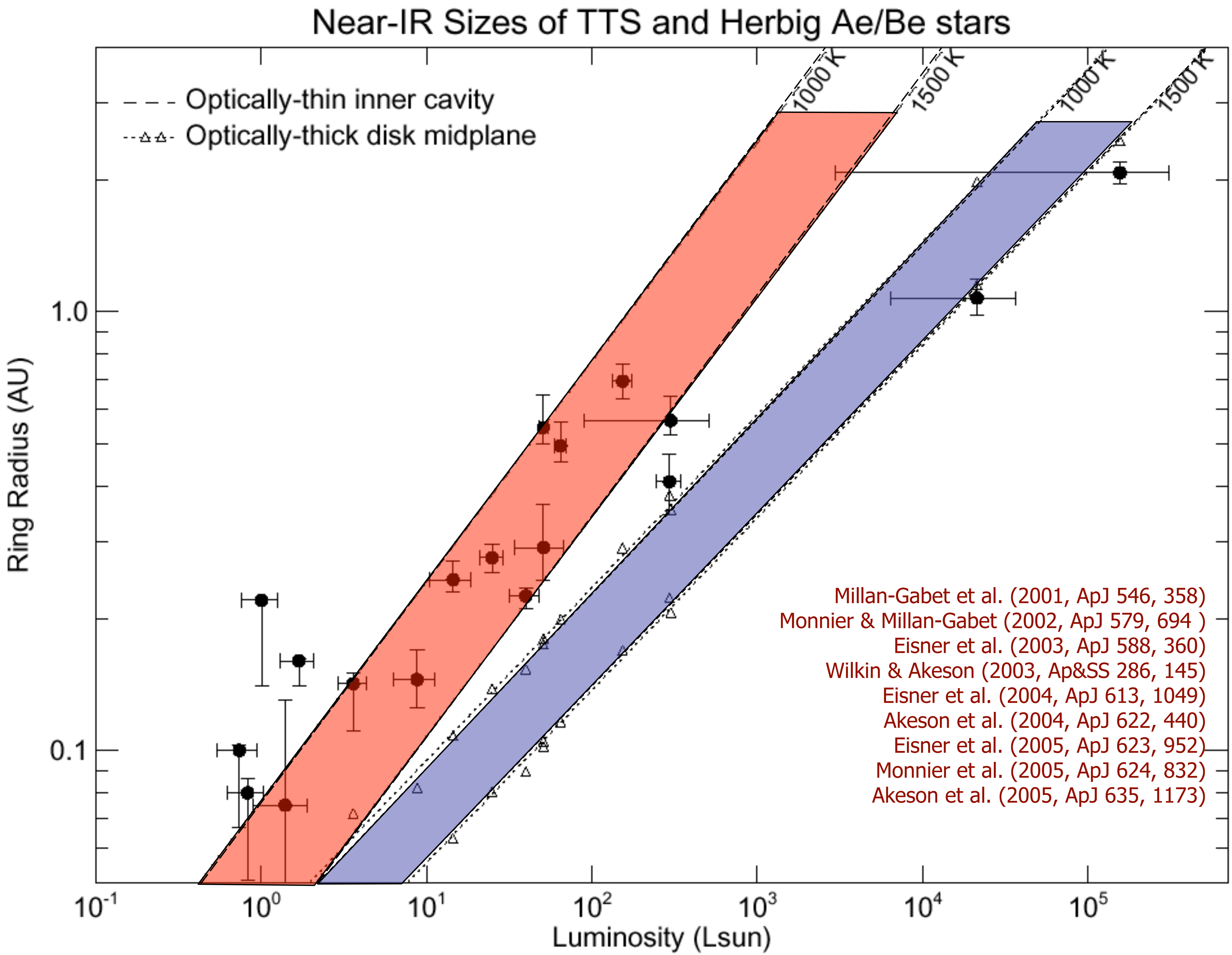


Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
Eisner et al. (2003, ApJ 588, 360)
Wilkin & Akeson (2003, Ap&SS 286, 145)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
Akeson et al. (2005, ApJ 635, 1173)

Near-IR Sizes of TTS and Herbig Ae/Be stars

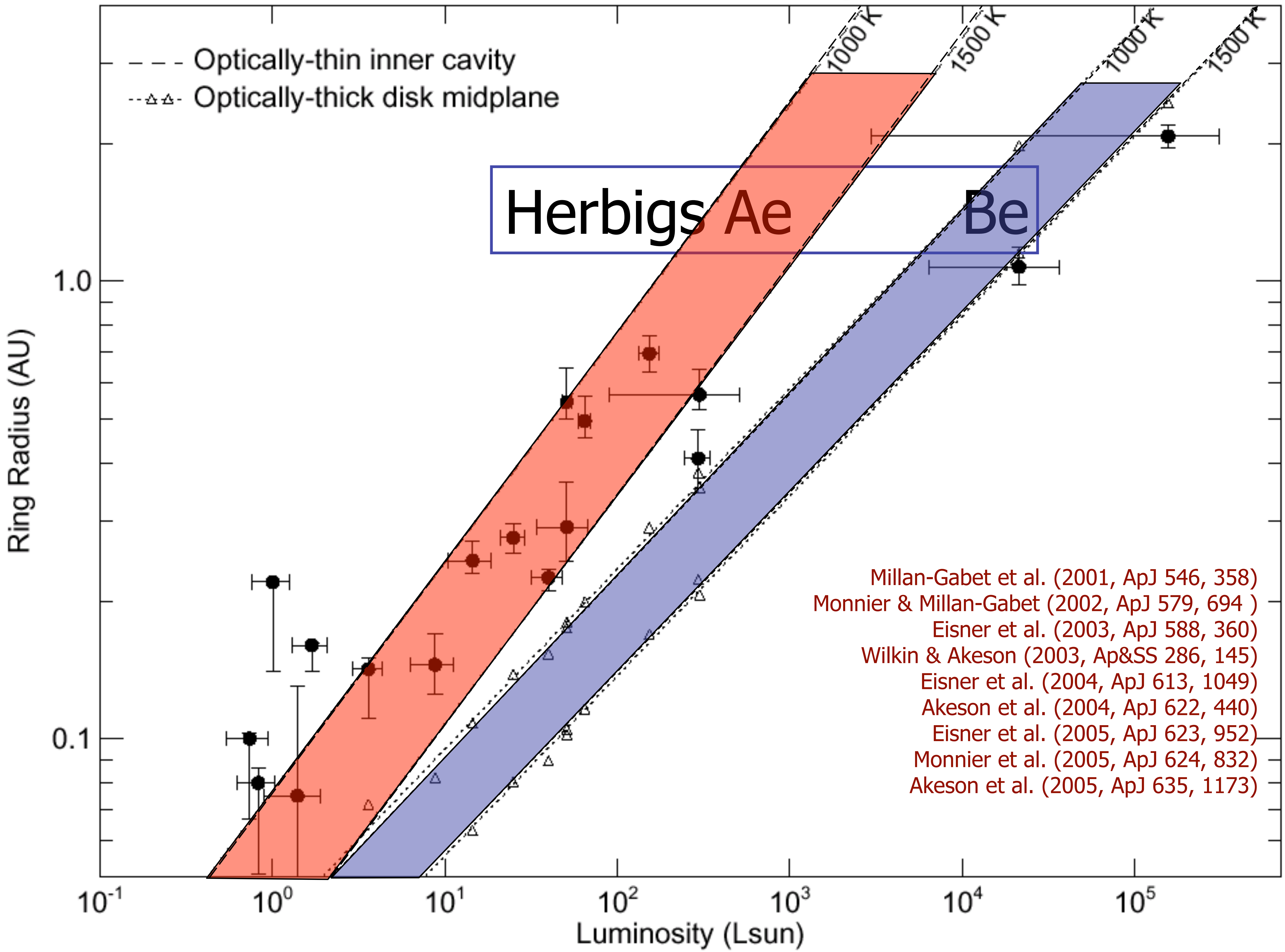


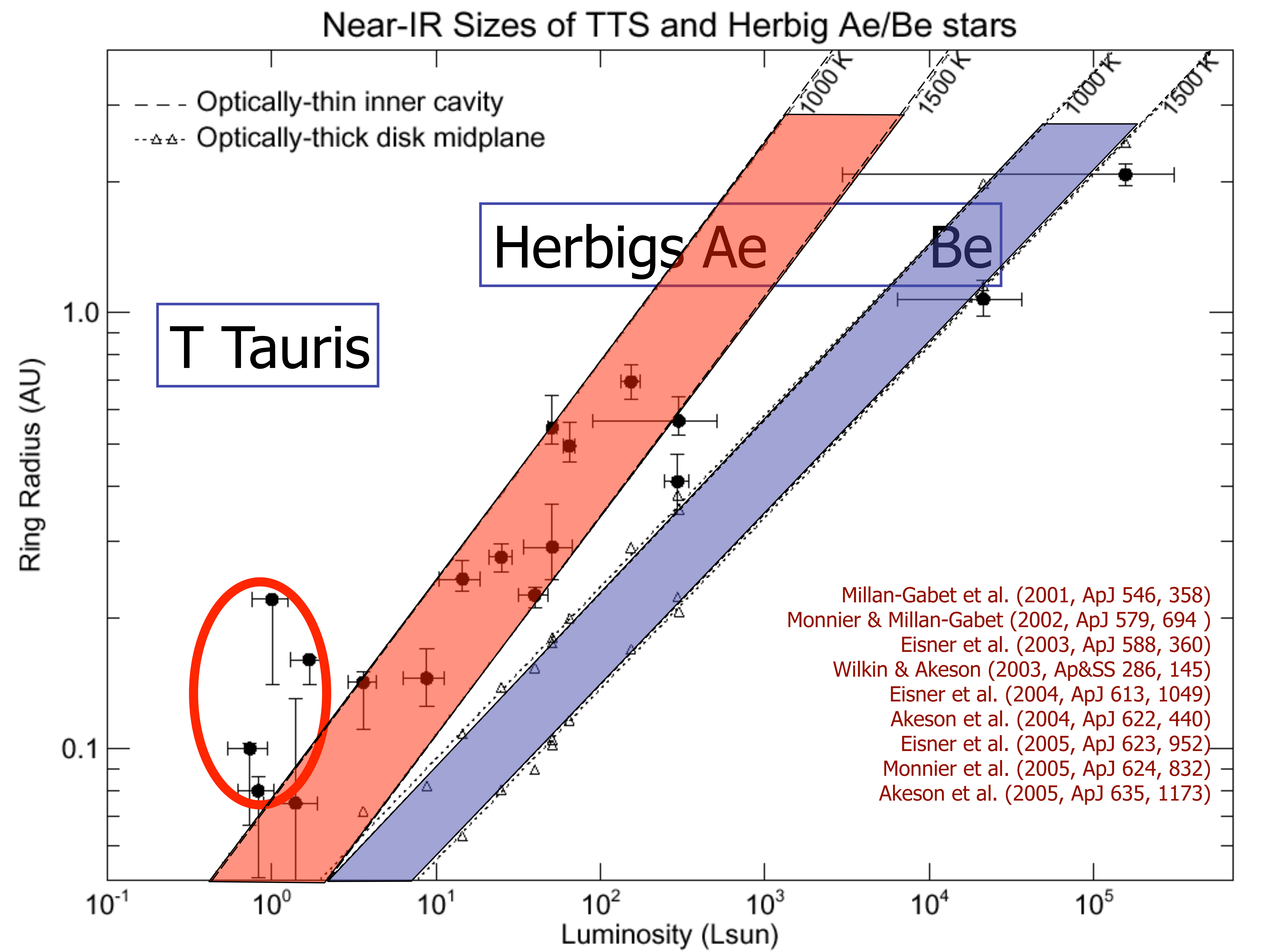

Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
Optically-thick disk midplane
1000 K
1500 K
1000 K
1500 K
Ring Radius (AU)
0.1
Luminosity (Lsun)
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
"Optically–thin Cavity" Disk Model
Star
(puffed–up inner wall?)
gas + dust
optically–thin 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)
Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
Akeson et al. (2005, ApJ 635, 1173)



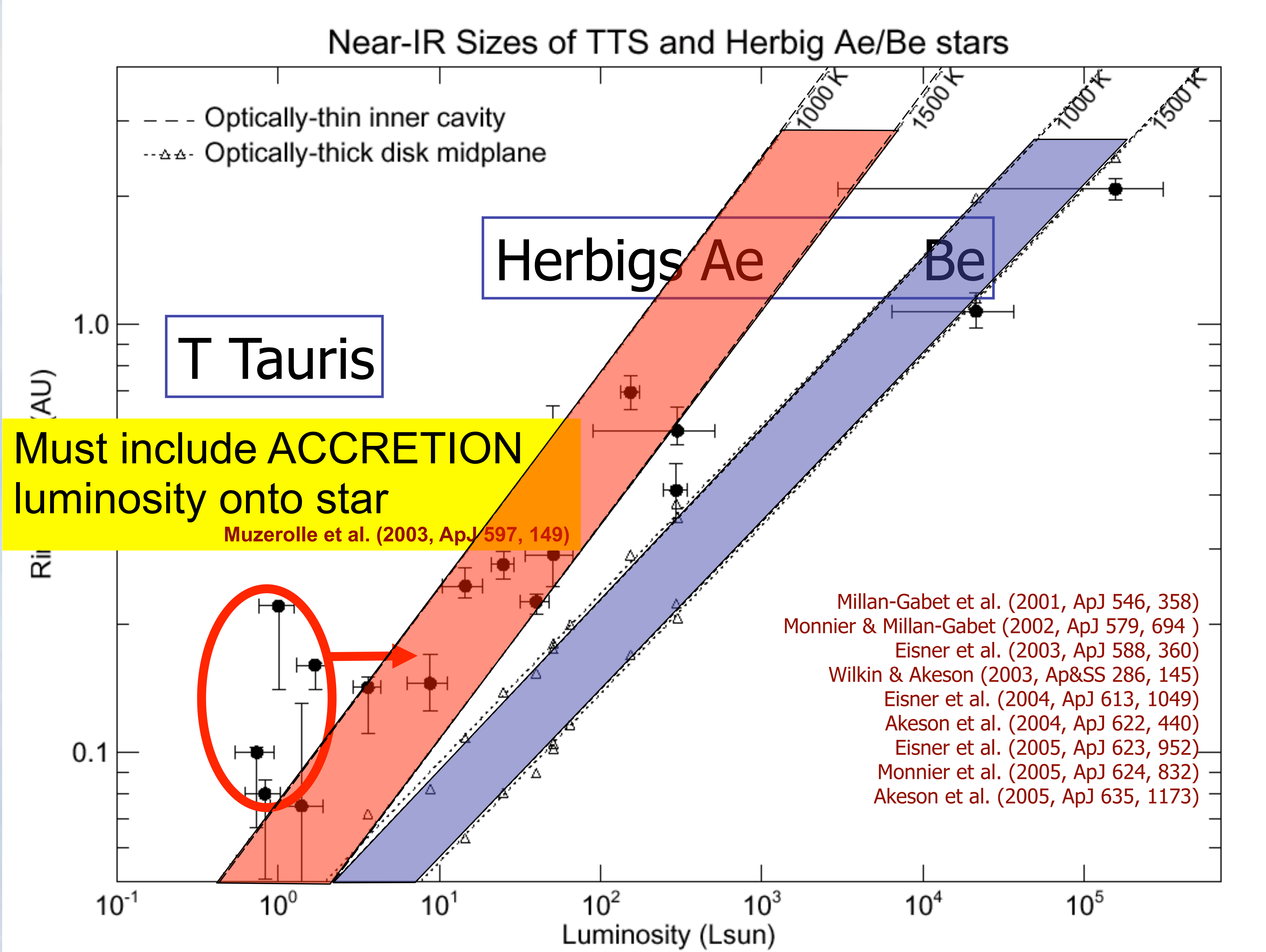
Near-IR Sizes of TTS and Herbig Ae/Be stars
Optically-thin inner cavity
Optically-thick disk midplane
1000 K
1500 K
1000 K
1500 K
Ring Radius (AU)
1.0
0.1
Luminosity (Lsun)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
Eisner et al. (2003, ApJ 588, 360)
Wilkin & Akeson (2003, Ap&SS 286, 145)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
Akeson et al. (2005, ApJ 635, 1173)

Near-IR Sizes of TTS and Herbig Ae/Be stars





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
1.0
0.1
Ring Radius (AU)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Luminosity (Lsun)
Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
Eisner et al. (2003, ApJ 588, 360)
Wilkin & Akeson (2003, Ap&SS 286, 145)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
Akeson et al. (2005, ApJ 635, 1173)



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
Luminosity (Lsun)
Millan-Gabet et al. (2001, ApJ 546, 358)
Monnier & Millan-Gabet (2002, ApJ 579, 694)
Eisner et al. (2003, ApJ 588, 360)
Wilkin & Akeson (2003, Ap&SS 286, 145)
Eisner et al. (2004, ApJ 613, 1049)
Akeson et al. (2004, ApJ 622, 440)
Eisner et al. (2005, ApJ 623, 952)
Monnier et al. (2005, ApJ 624, 832)
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

Inner region discussion

- Inner rim shapes: how sharp is it?

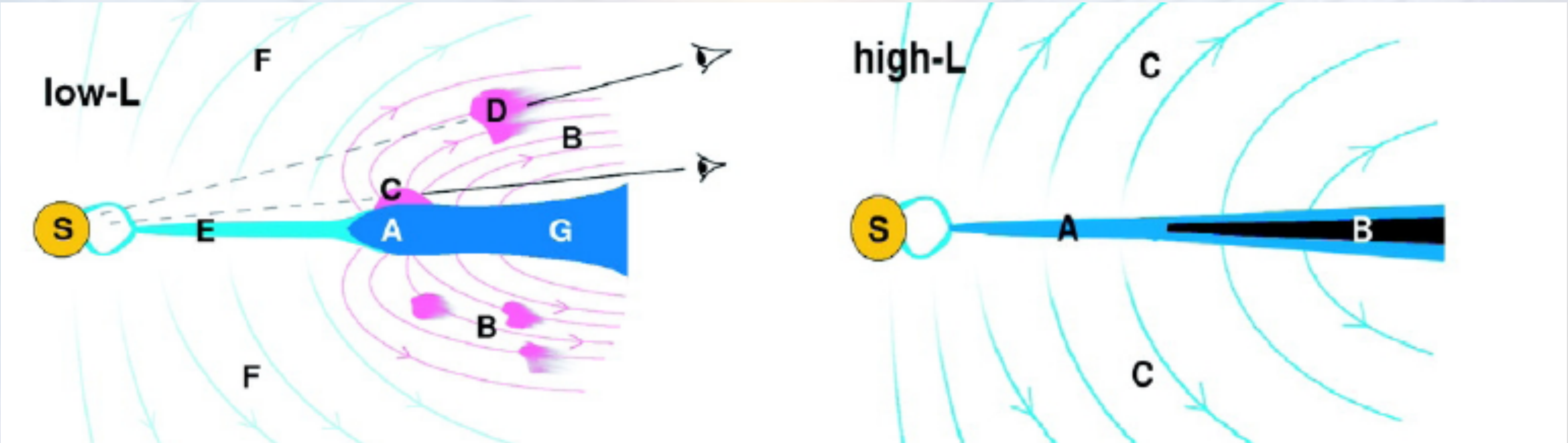
  Dust sublimation **Isella & Natta (2005, A&A 438, 899)**

  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

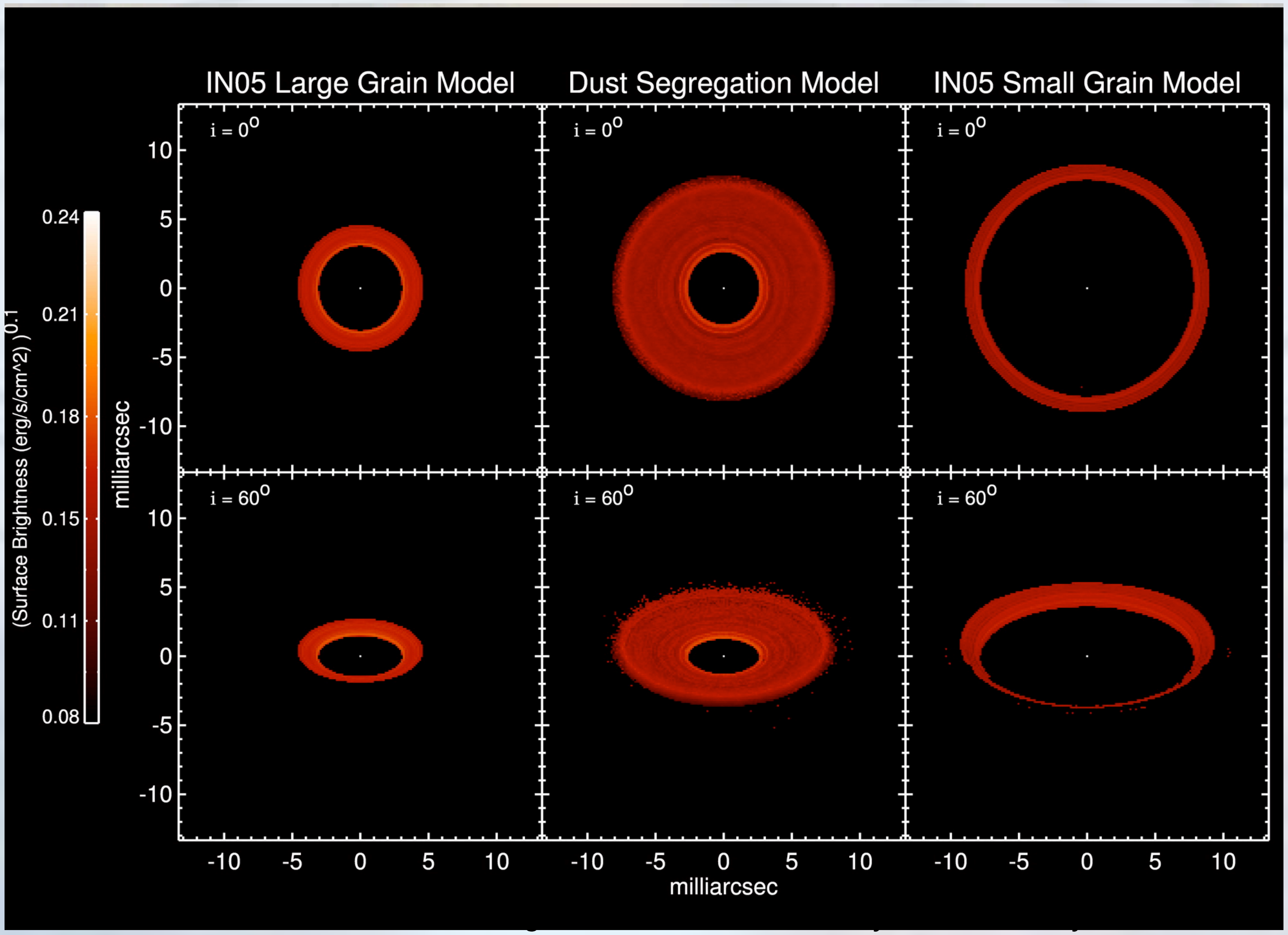
    Vinkovic & Jurkic (2007, ApJ 658..462)



The geometry of the inner rim

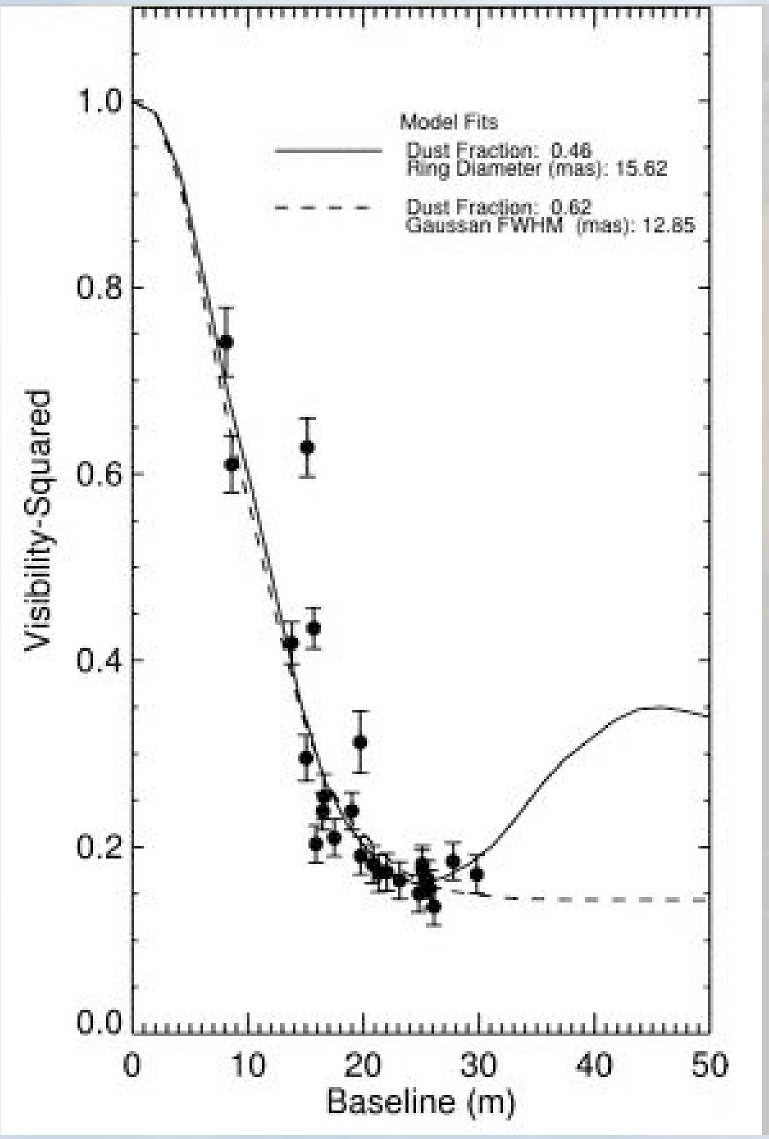
The geometry of the inner rim

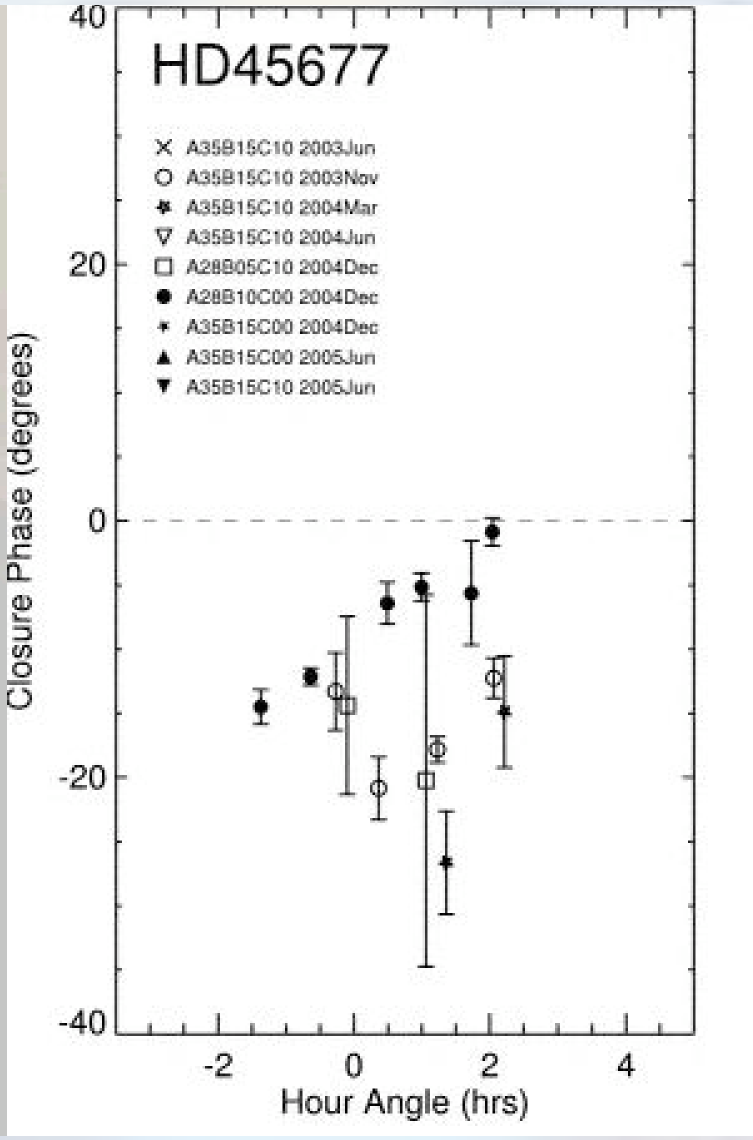
- If inclined disk: asymmetries (skewness) depending on dust characteristics **Tannirkulam et al. (2007, ApJ 661, 374)**

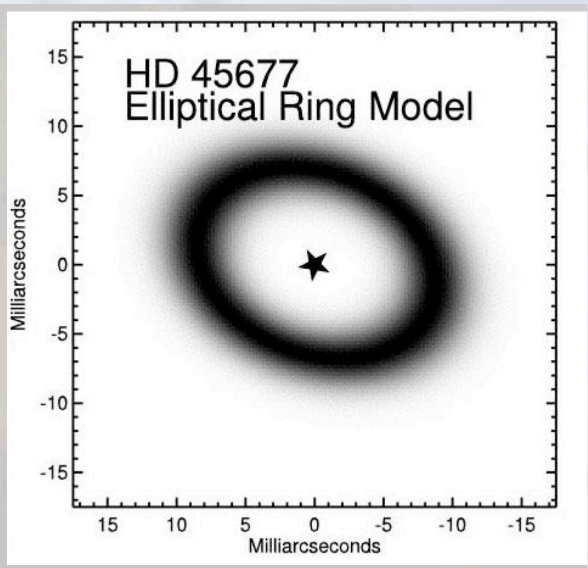


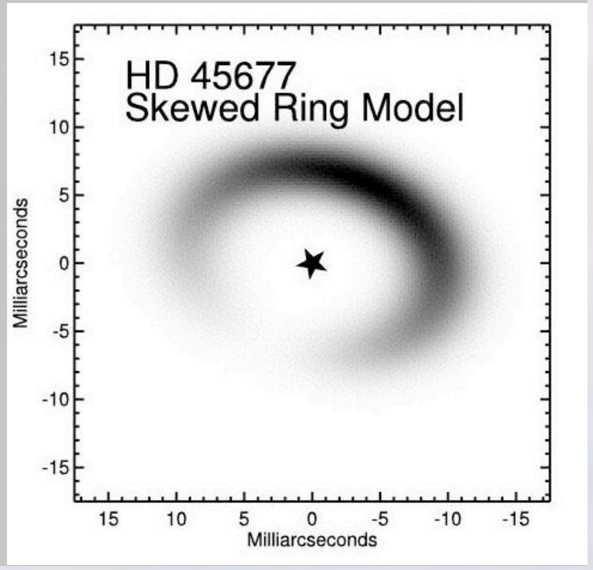
The geometry of the inner rim

- 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)

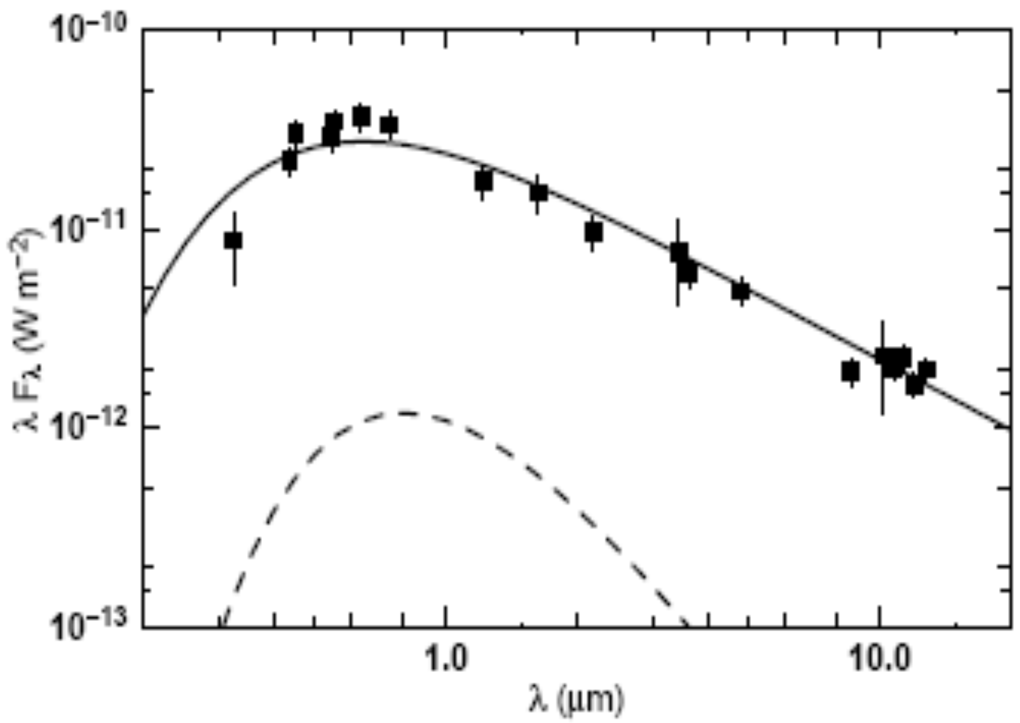


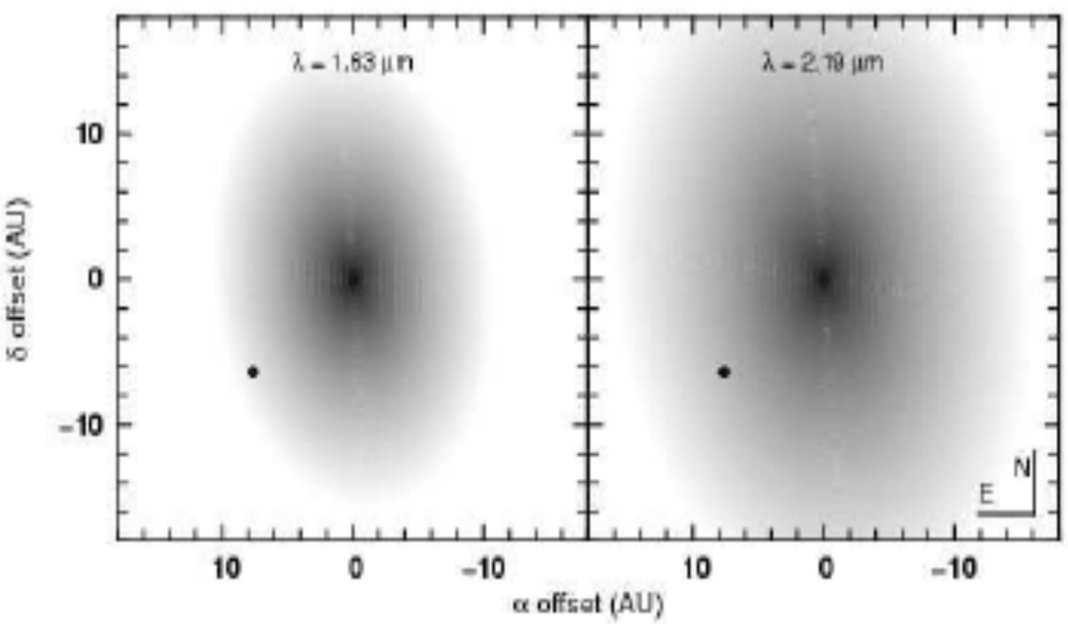


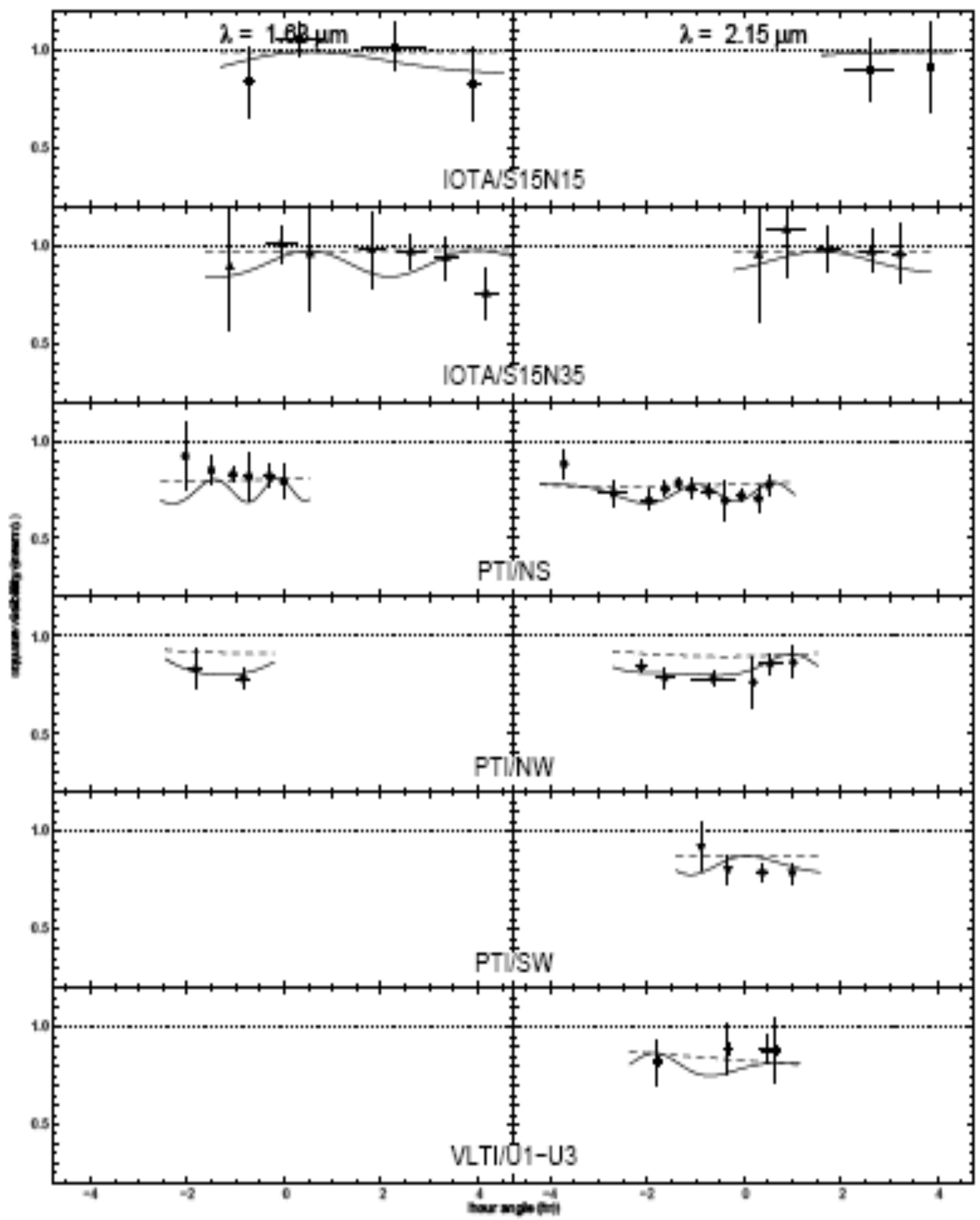




FU Orionis

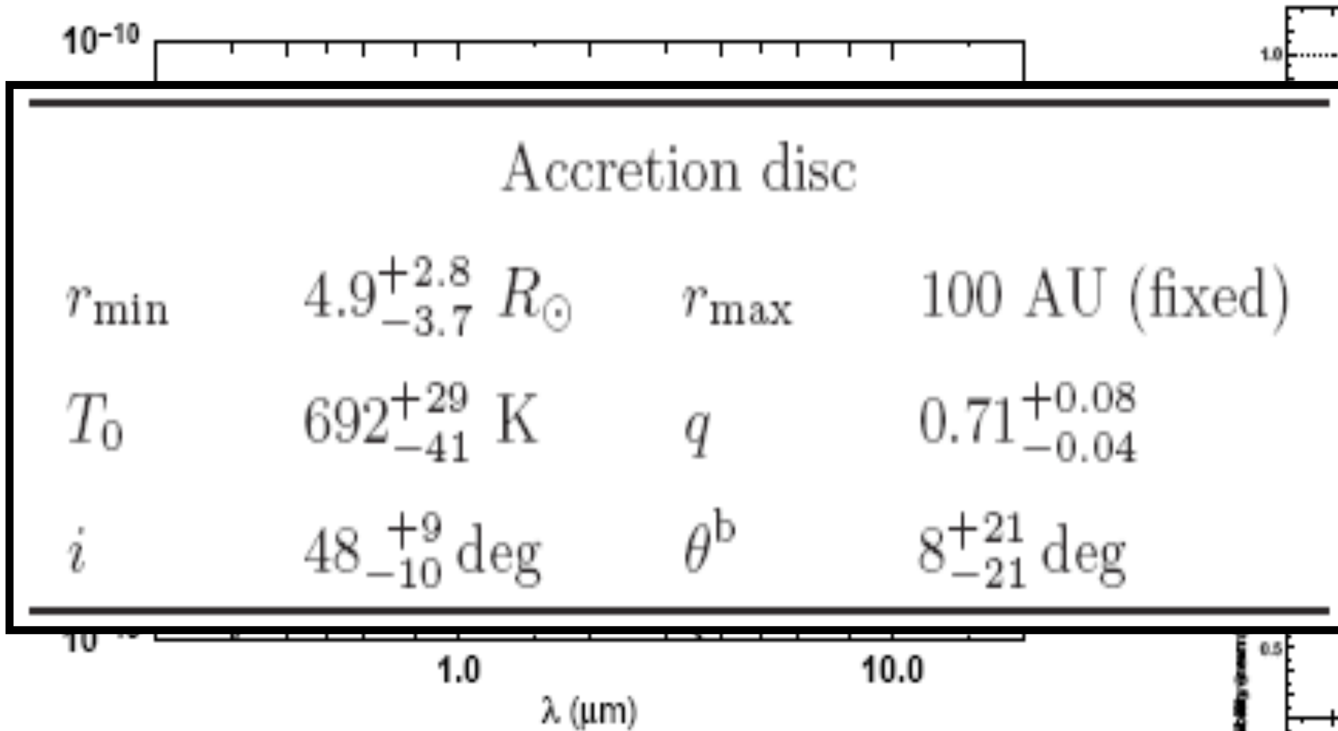




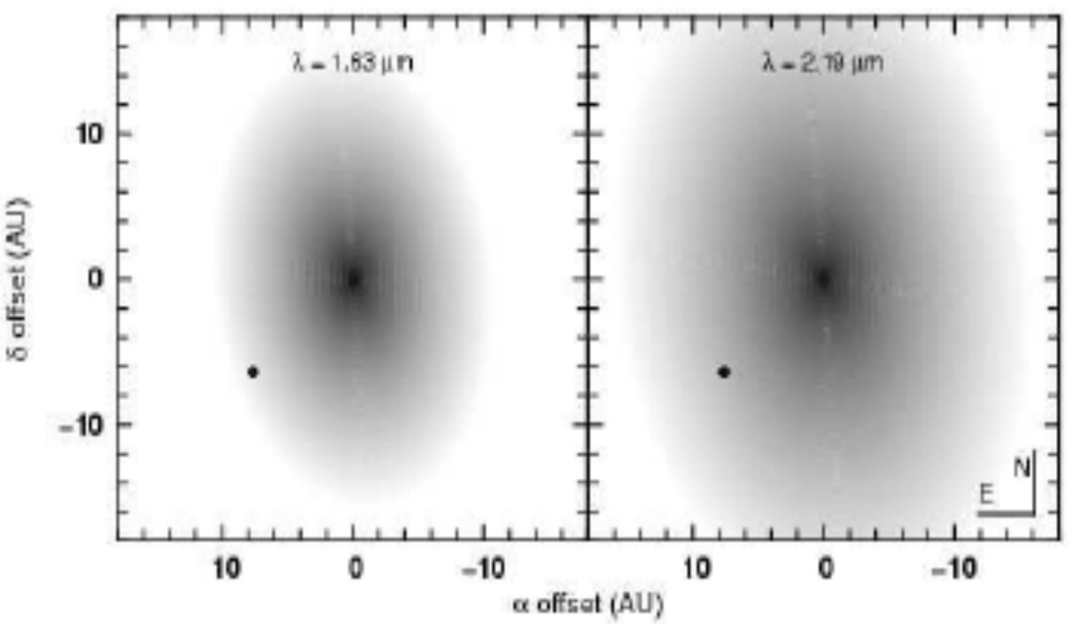


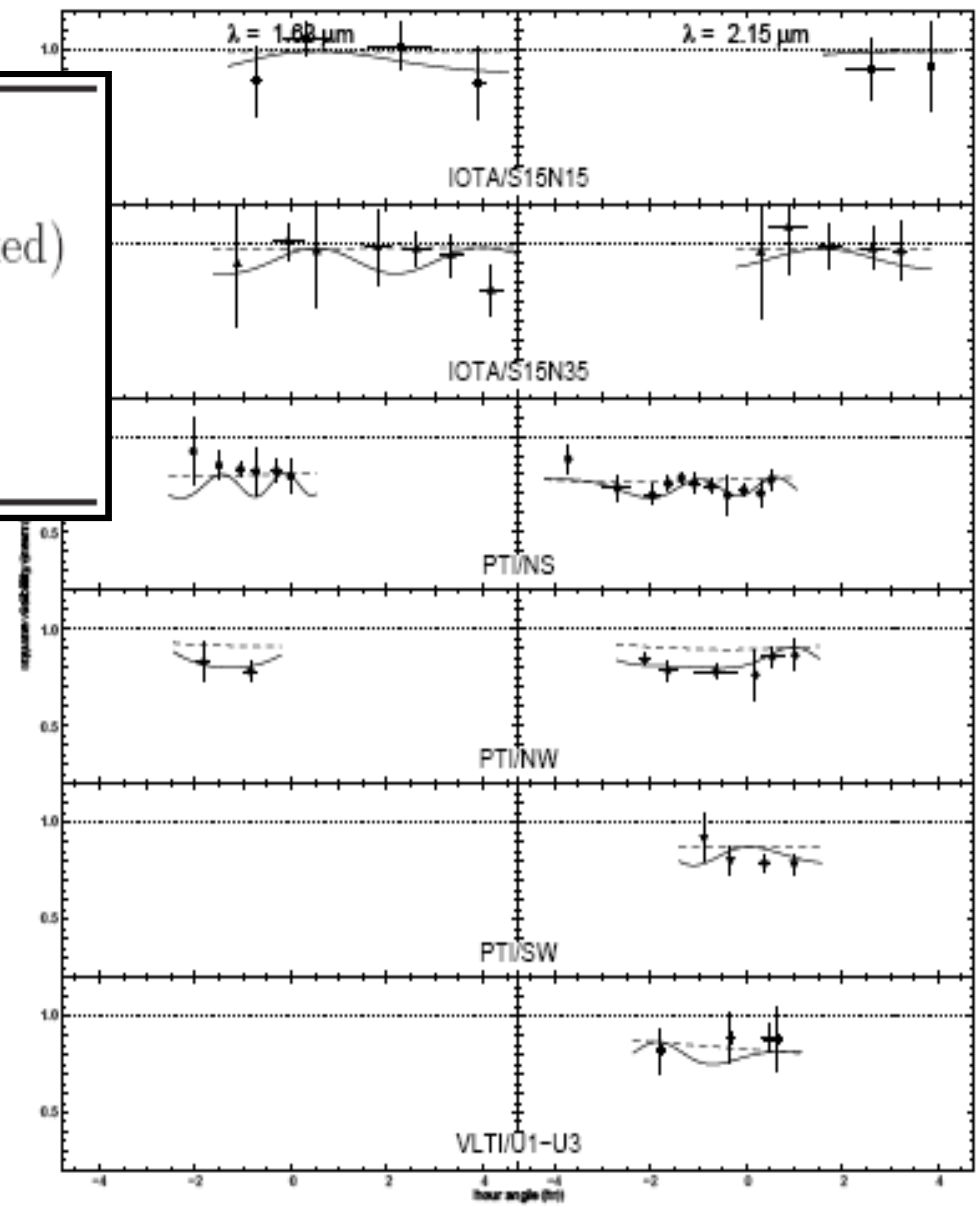
Malbet et al. (2005, A&A, 437, 627)

FU Orionis



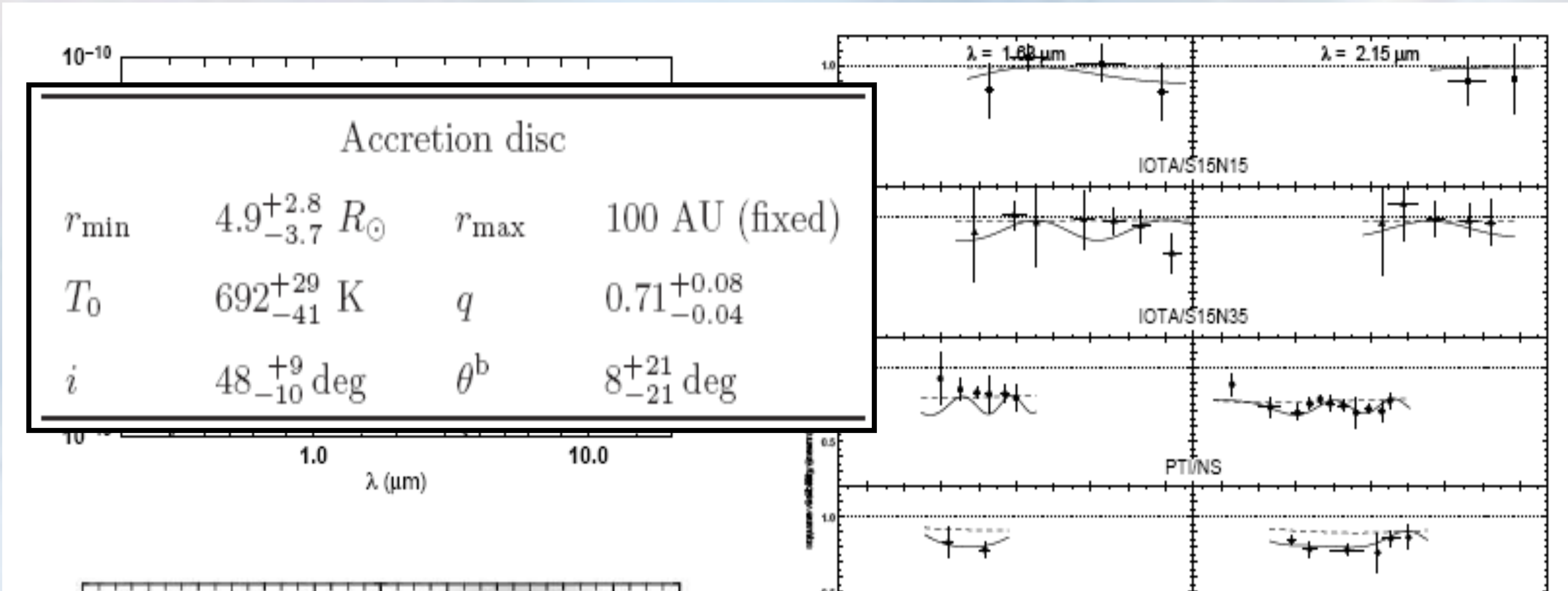
Accretion disc			
$r_{\min}$	$4.9^{+2.8}_{-3.7}\ R_\odot$	$r_{\max}$	100 AU (fixed)
T_0	692^{+29}_{-41} K	q	$0.71^{+0.08}_{-0.04}$
i	48^{+9}_{-10} deg	θ^{b}	8^{+21}_{-21} deg





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

FU Orionis



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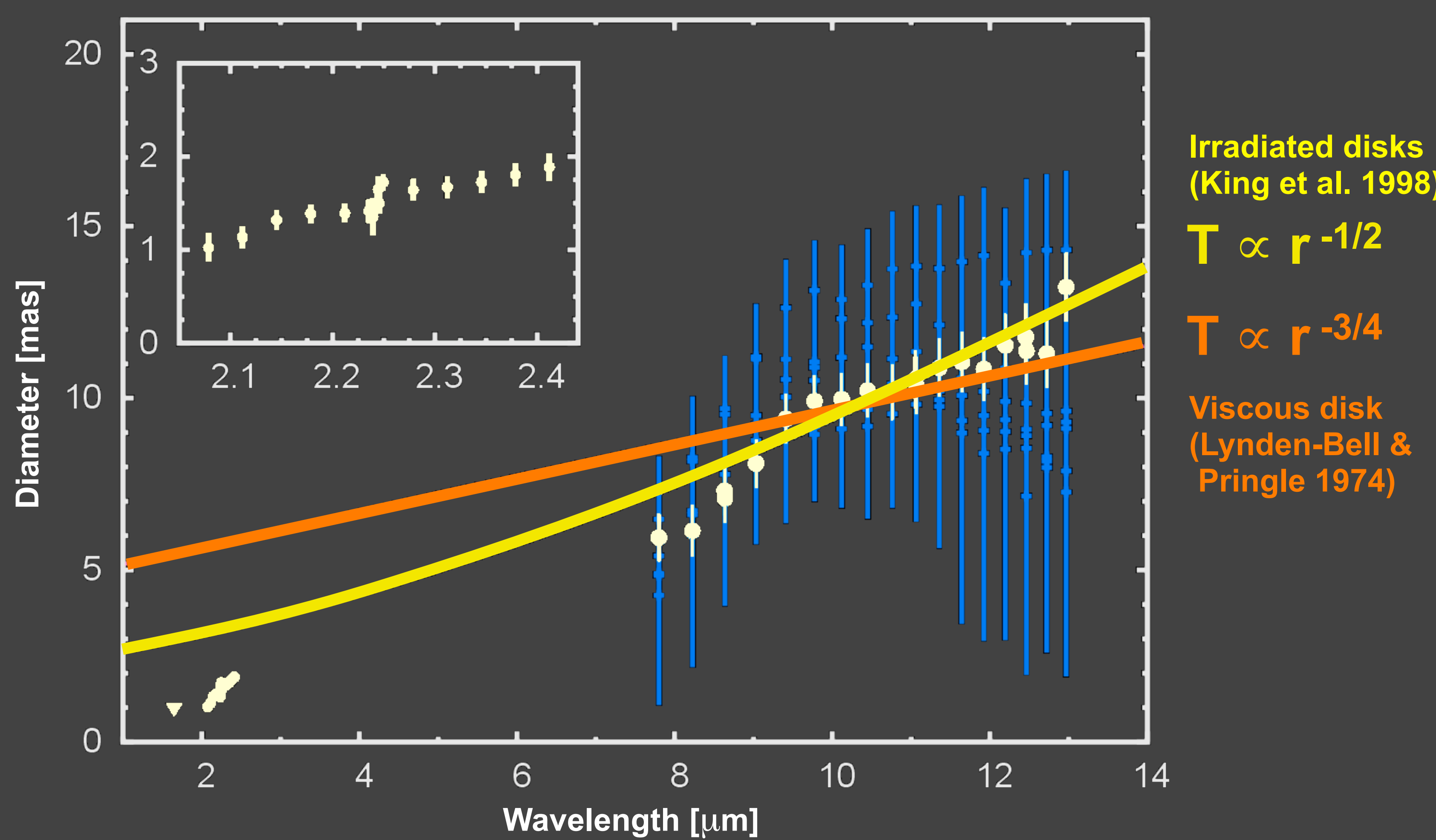
- **The 4 brightest FUors have been observed**
- **FU Ori well constrained** Quanz et al. (2006, ApJ 648, 472)
- **Others like Z CMa appear more extended: background emission or companion?** Millan-Gabet et al. (2006, ApJ 645, L77)
- **Recent FUOr: V1647 Ori** Ábrahám, Mosoni, Henning et al. (2006, A&A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

A tool to probe the radial temperature distribution of disks

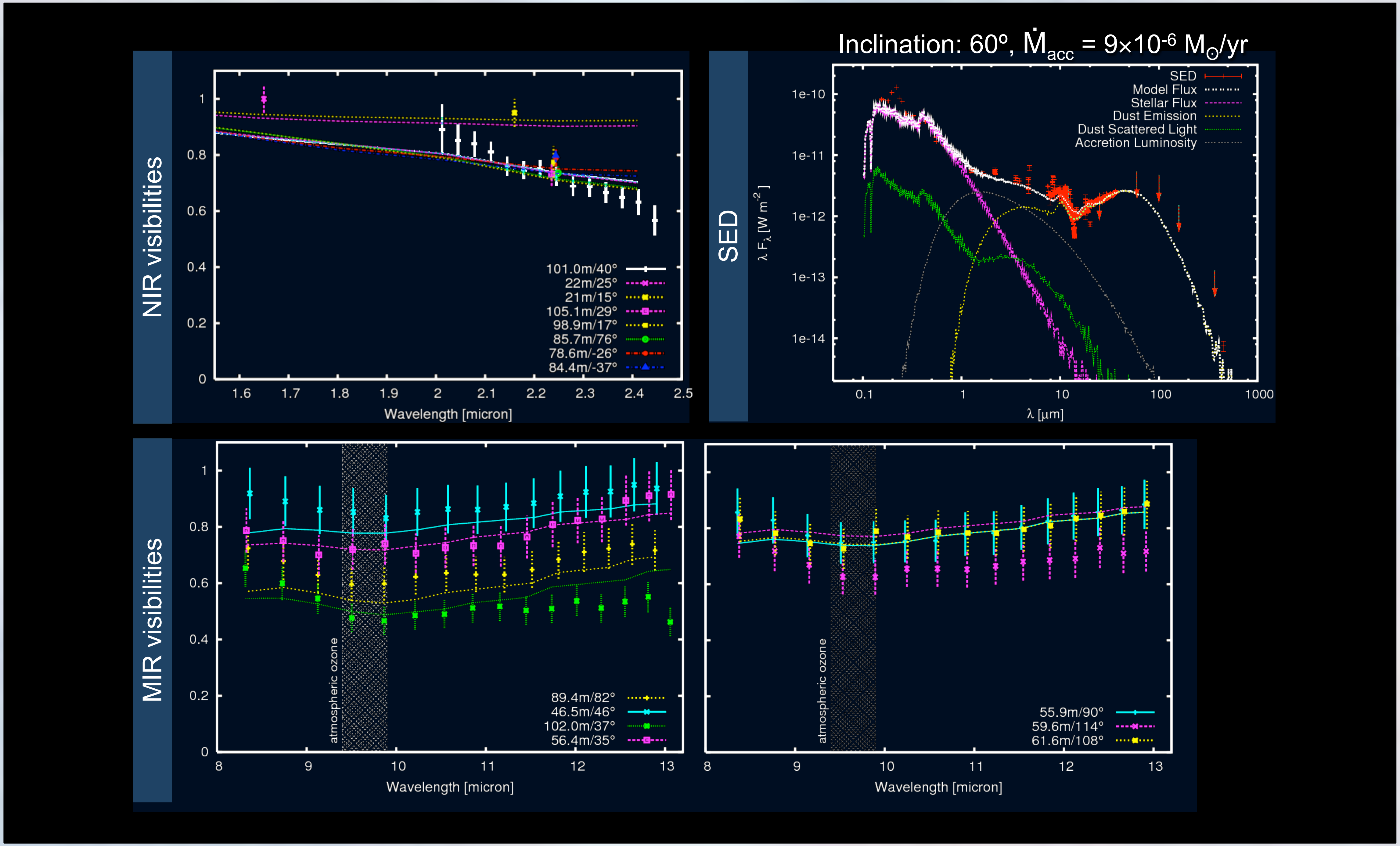


Commonly used analytic temperature-power-law disk models ($T \propto r^{-1/2}$ or $T \propto r^{-3/4}$) cannot describe the measured wavelength-dependence of the apparent size

→ Detailed physical modeling required

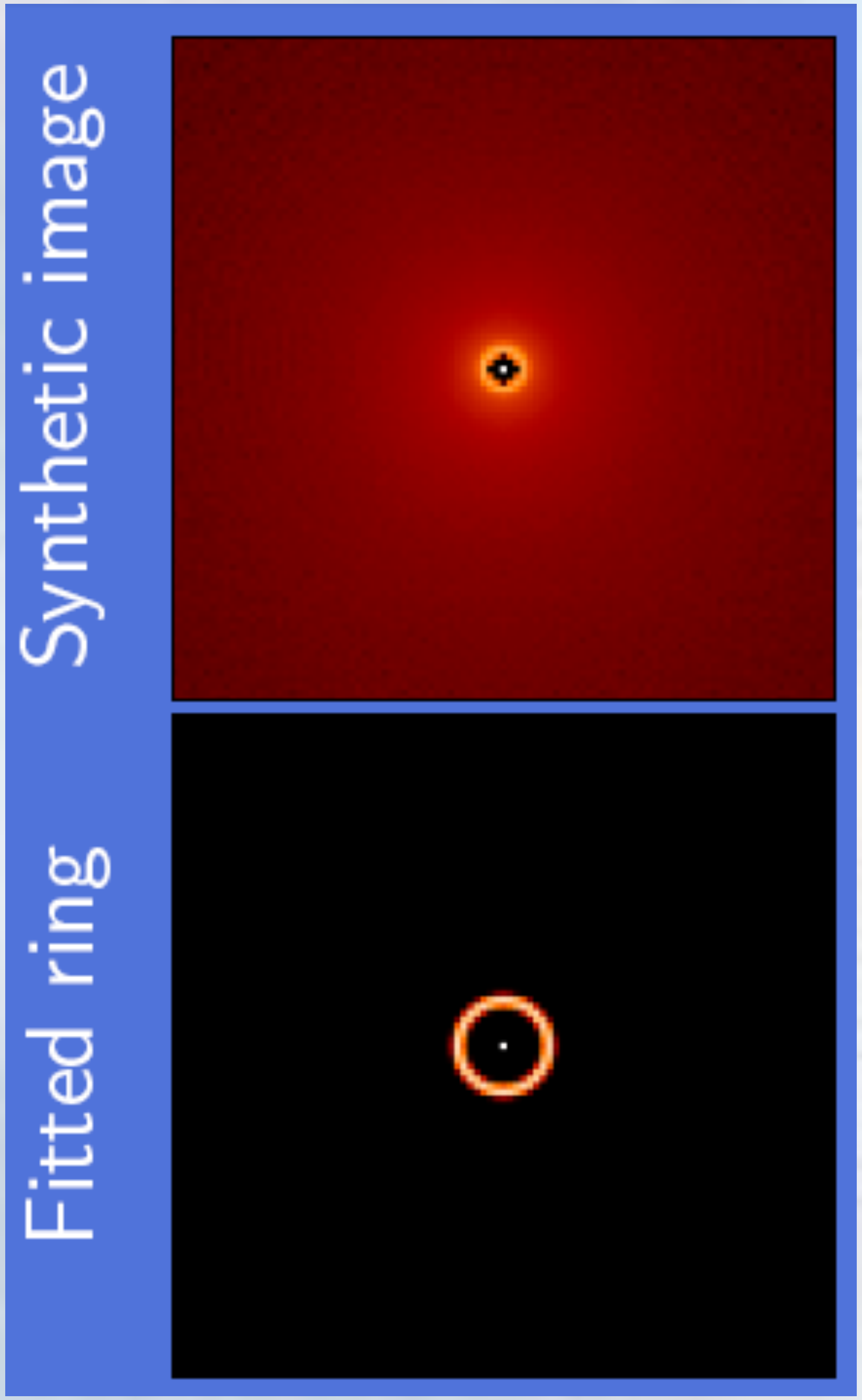
Kraus et al. (2007, ApJ 676, 490)

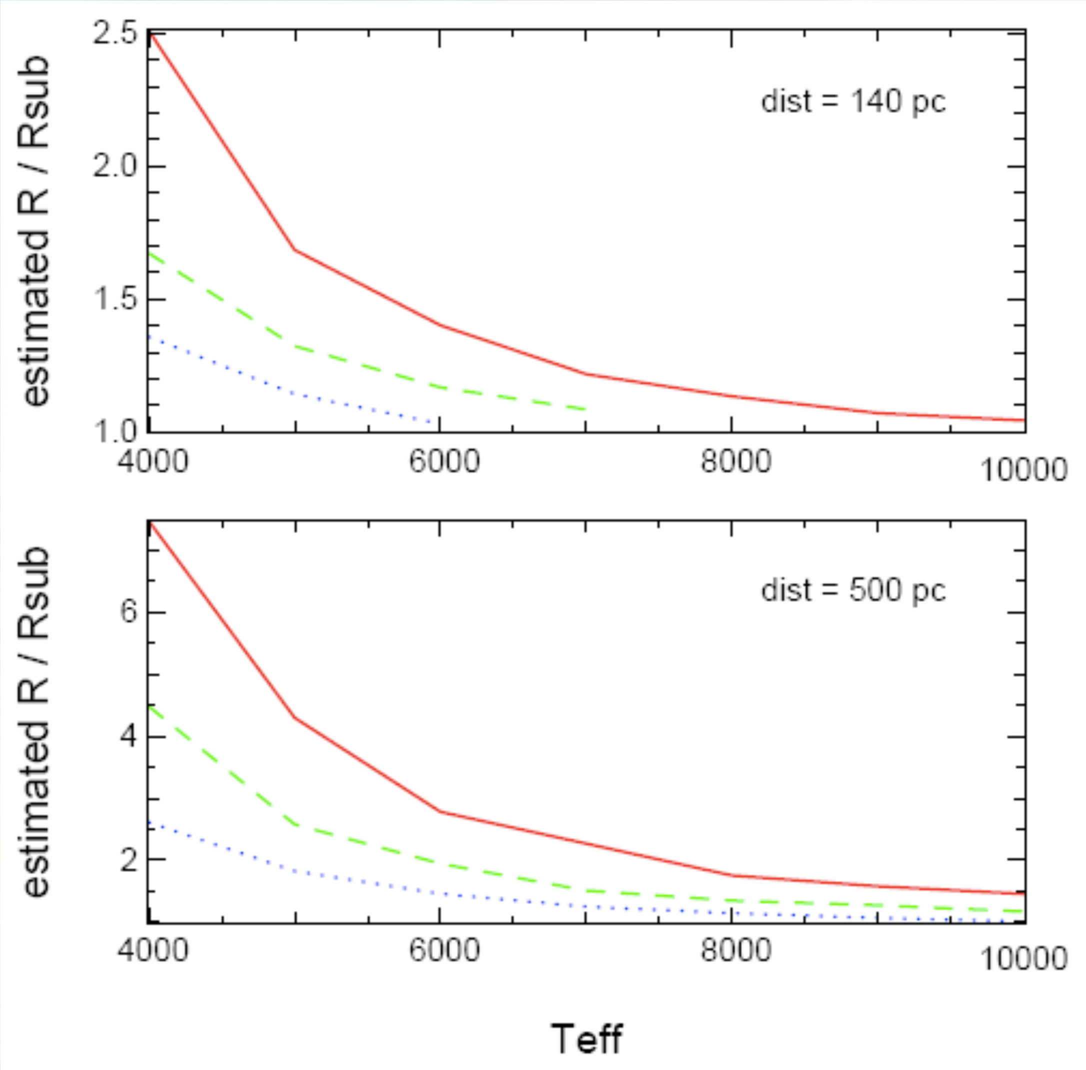
MWC 147: a full disk model to understand NIR and MIR measurements



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

Effect of extended scattered light

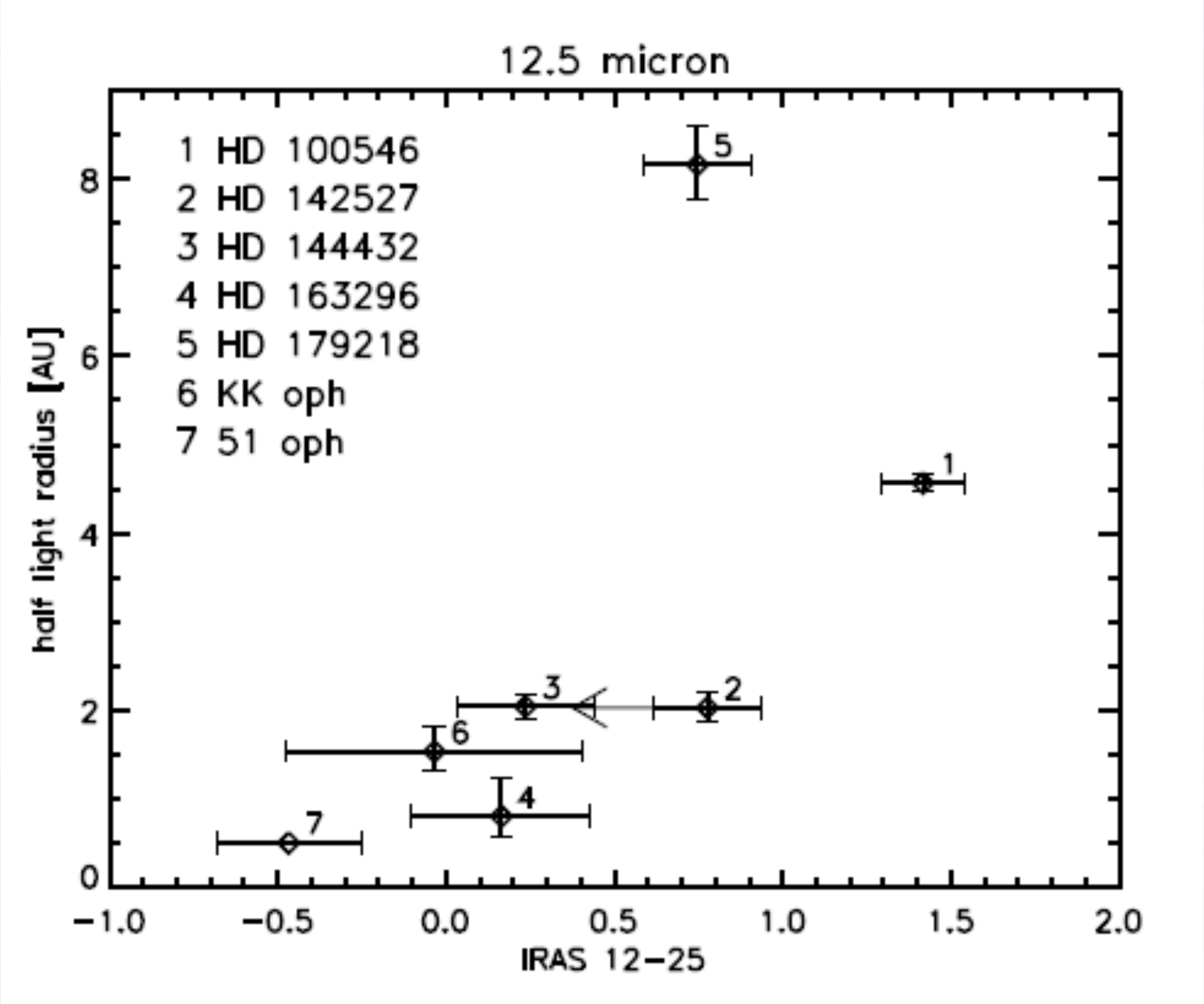




- Ring radius fitting can lead to overestimated sizes
- Careful modeling must be performed including all sources of radiation

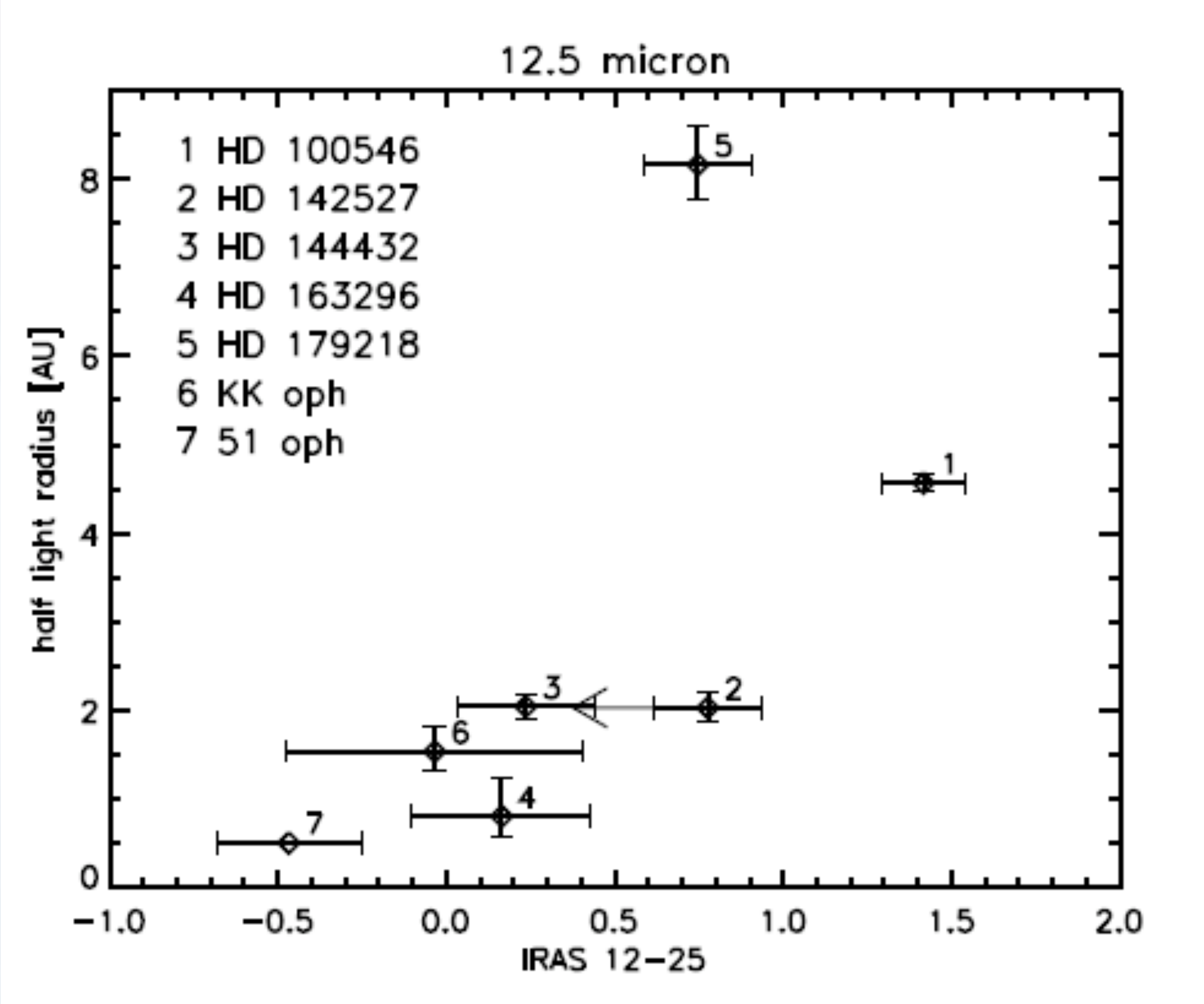
Pinte et al. (2007, ApJ 673, L63)

Vertical structure @ 10 microns



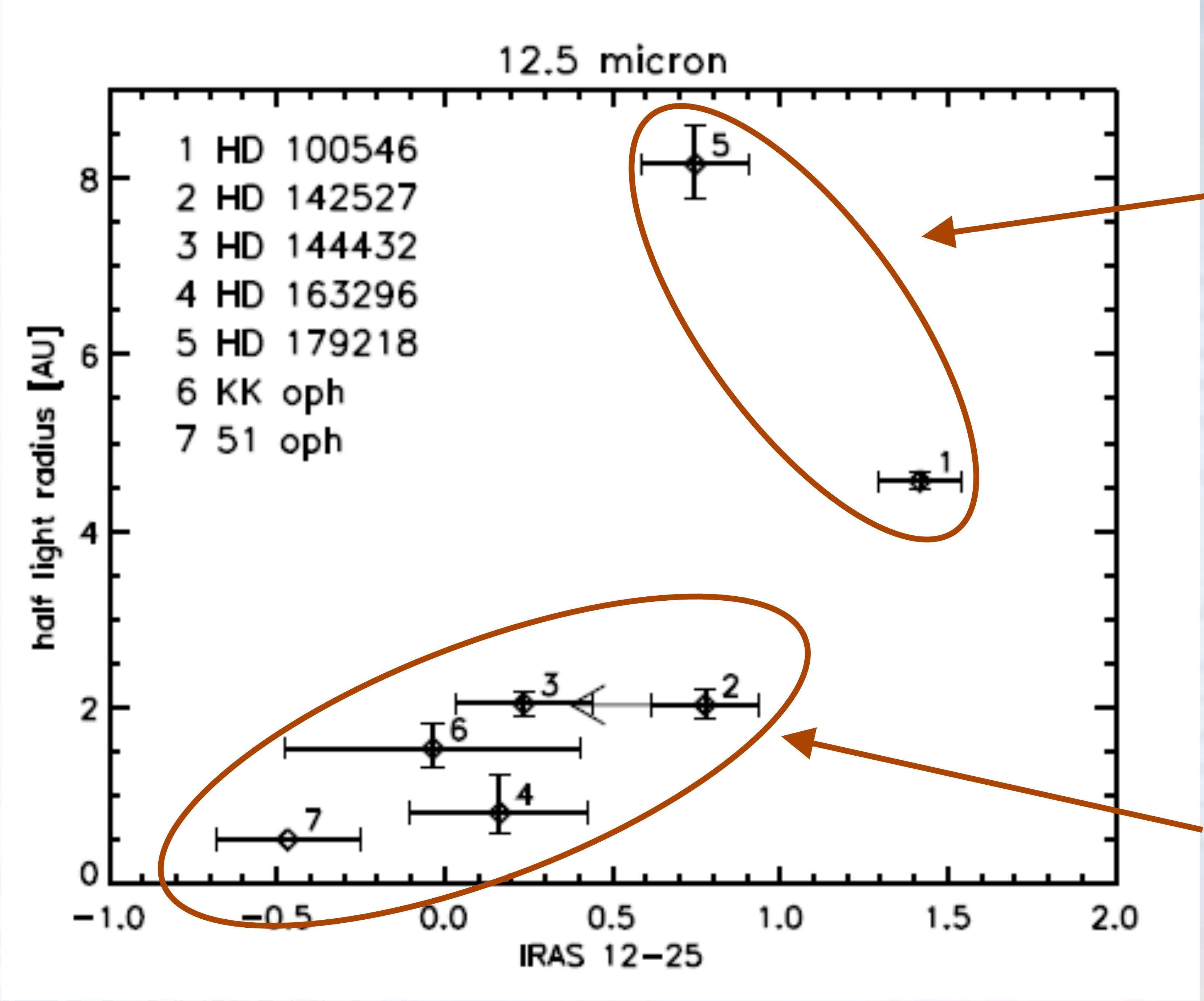
Leinert et al. (2004, A&A, 423, 537)

Vertical structure @ 10 microns

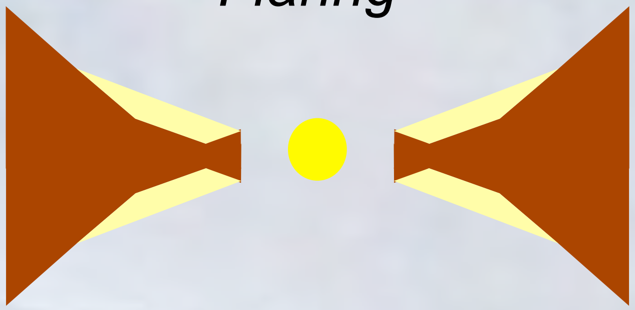


Leinert et al. (2004, A&A, 423, 537)

Vertical structure @ 10 microns



Flaring

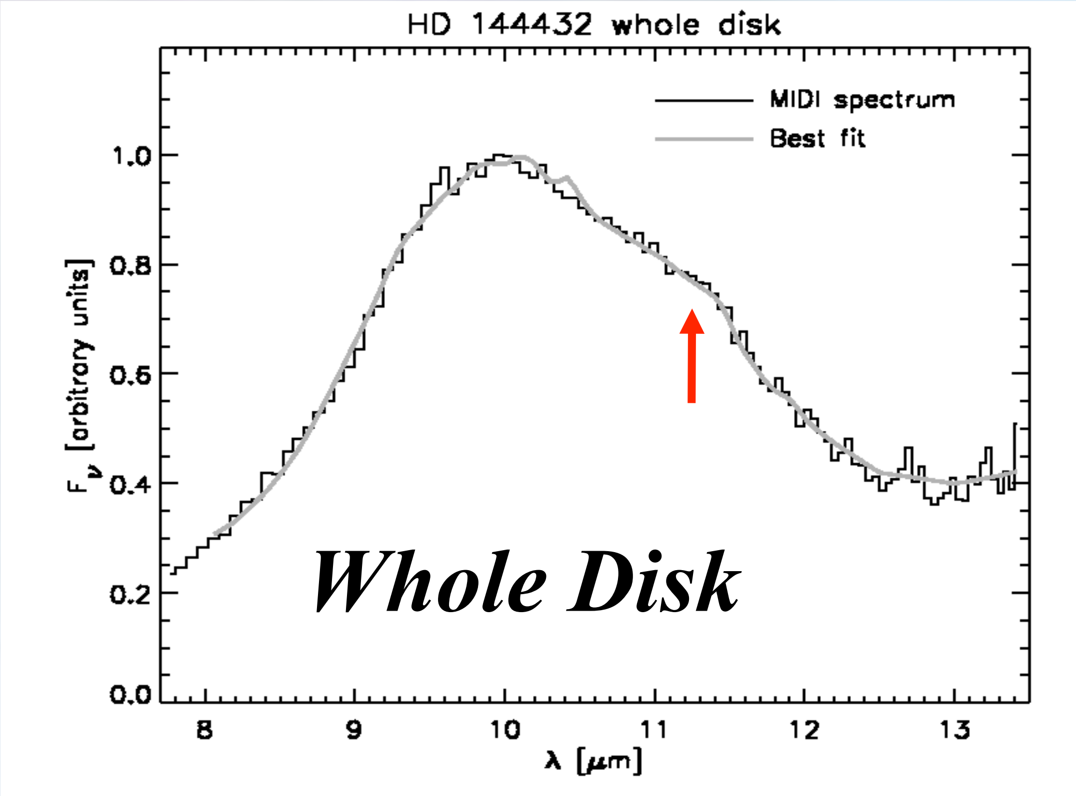


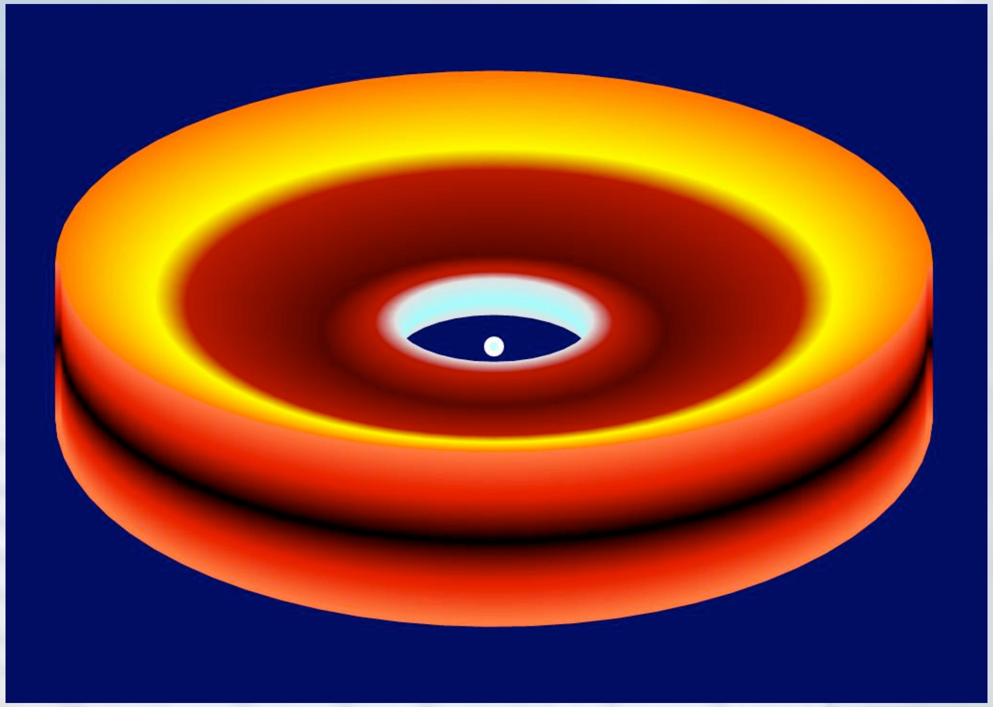
Sizes consistent with flat self-shadowed / flaring disk model SED classification

Self-shadowed

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

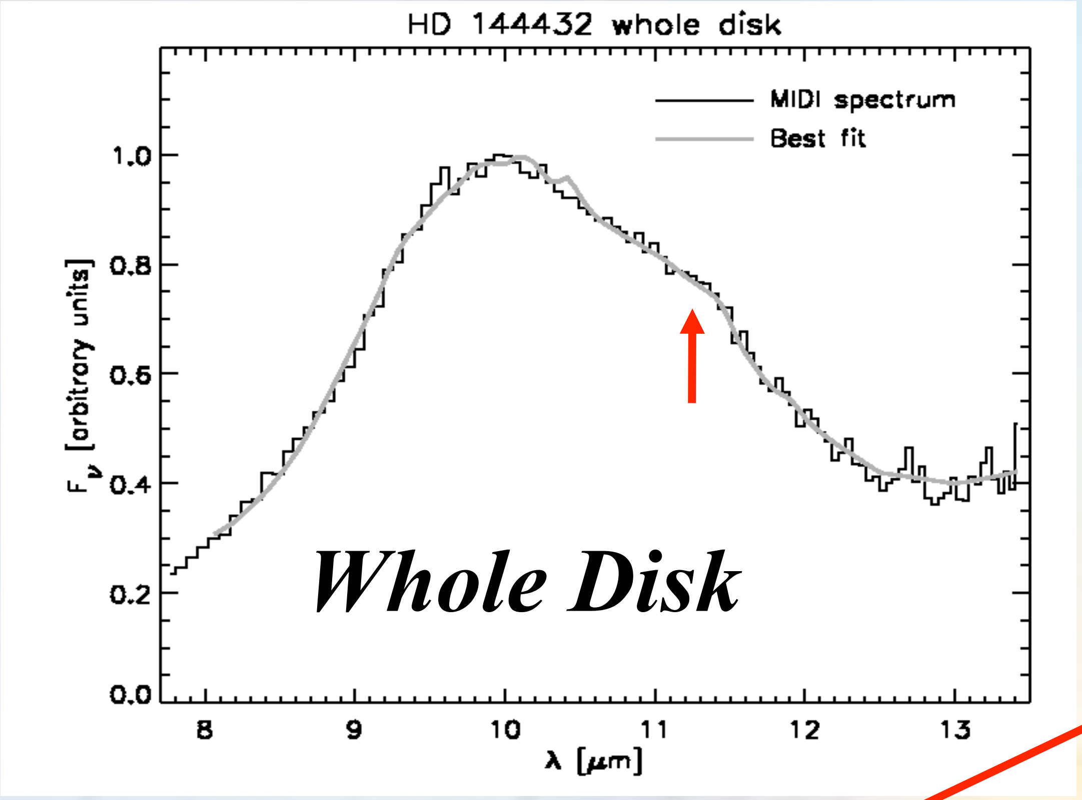
Dust mineralogy in HAeBe

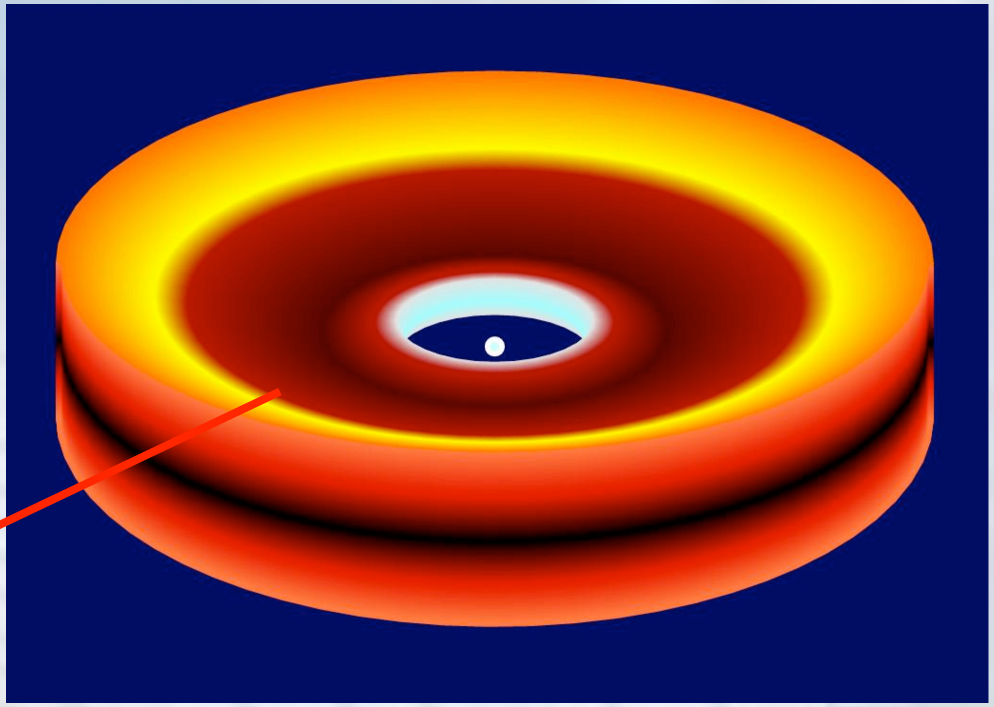


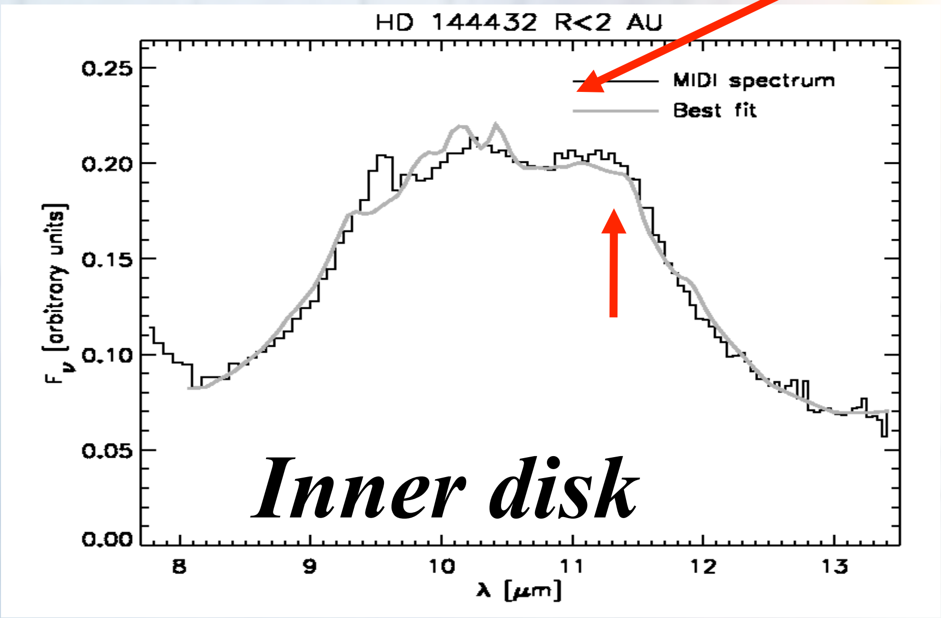


Van Boekel et al. (2004, Nature, 432, 479)

Dust mineralogy in HAeBe

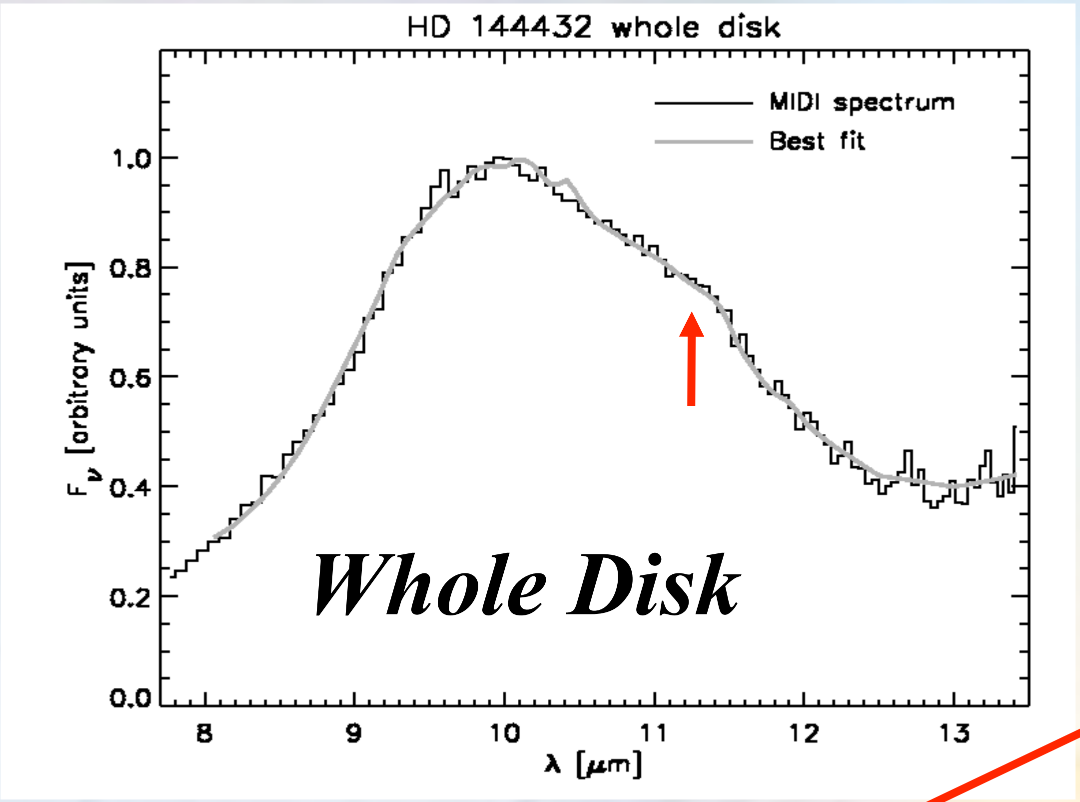


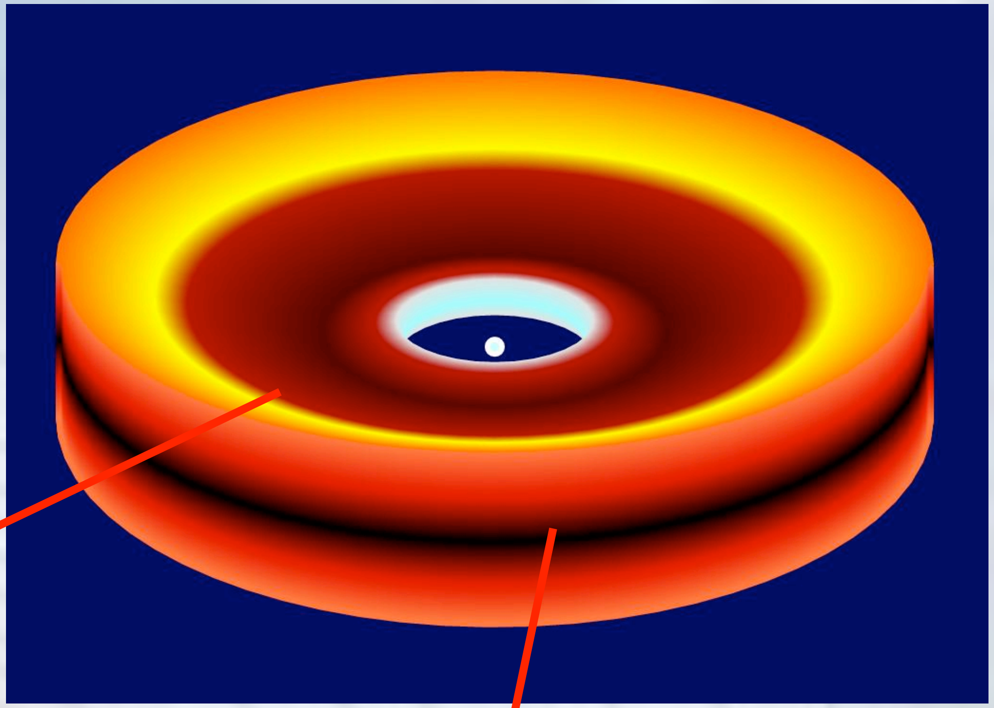


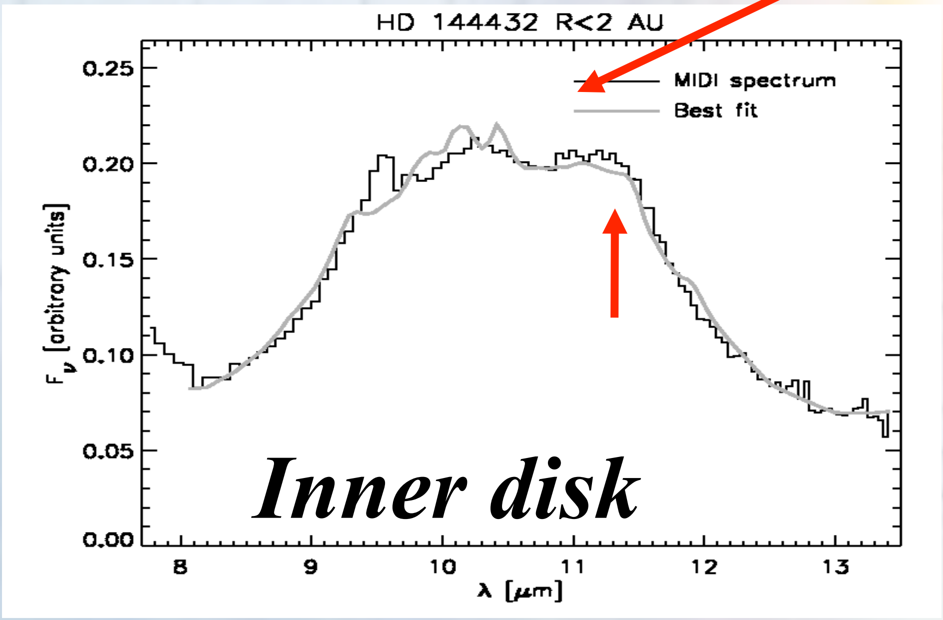


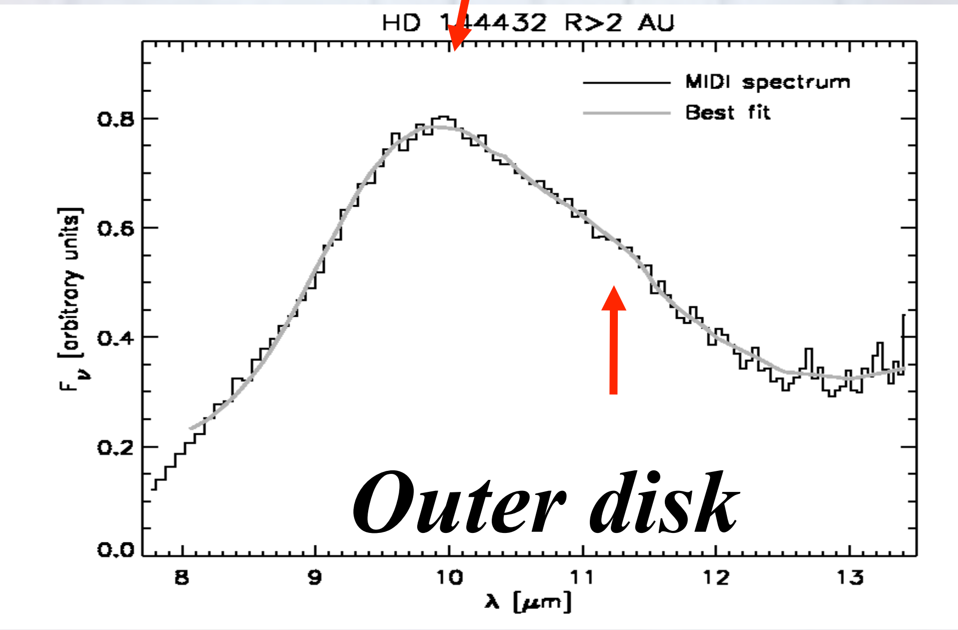
Van Boekel et al. (2004, Nature, 432, 479)

Dust mineralogy in HAeBe



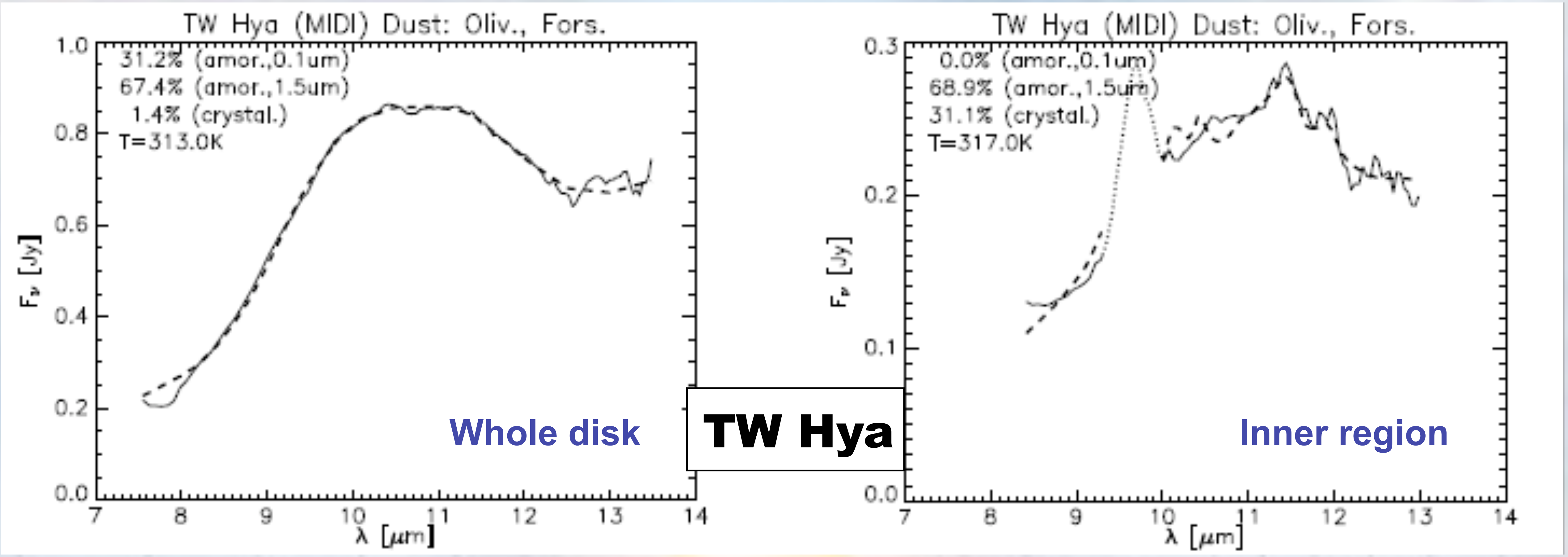






Van Boekel et al. (2004, Nature, 432, 479)

… also in T Tauri disks!

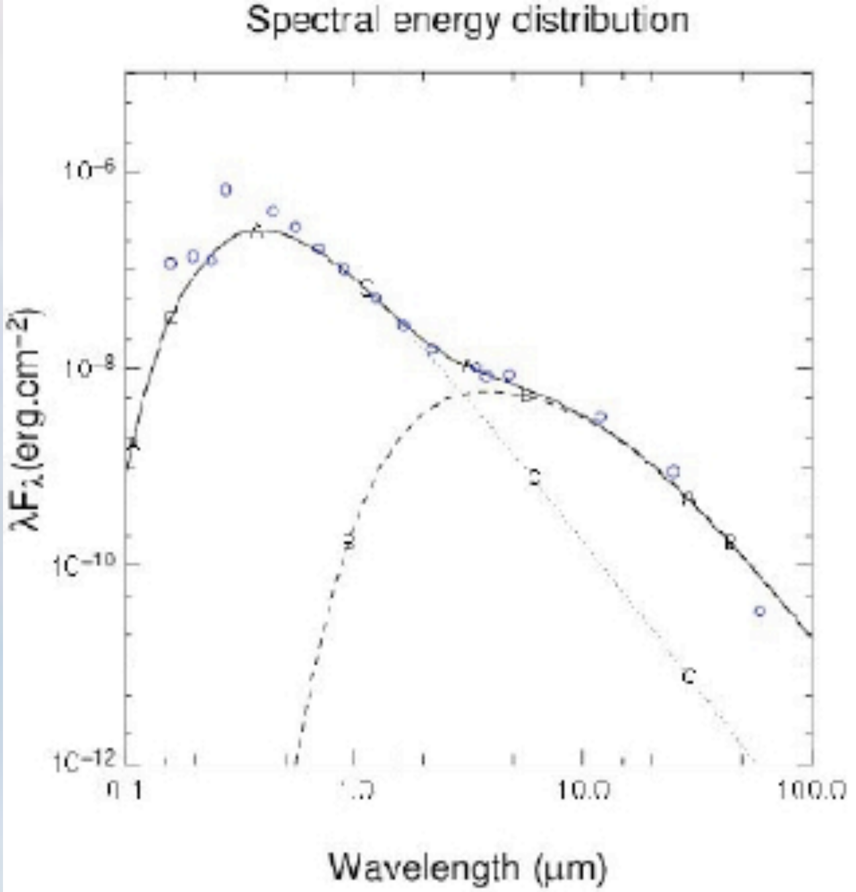


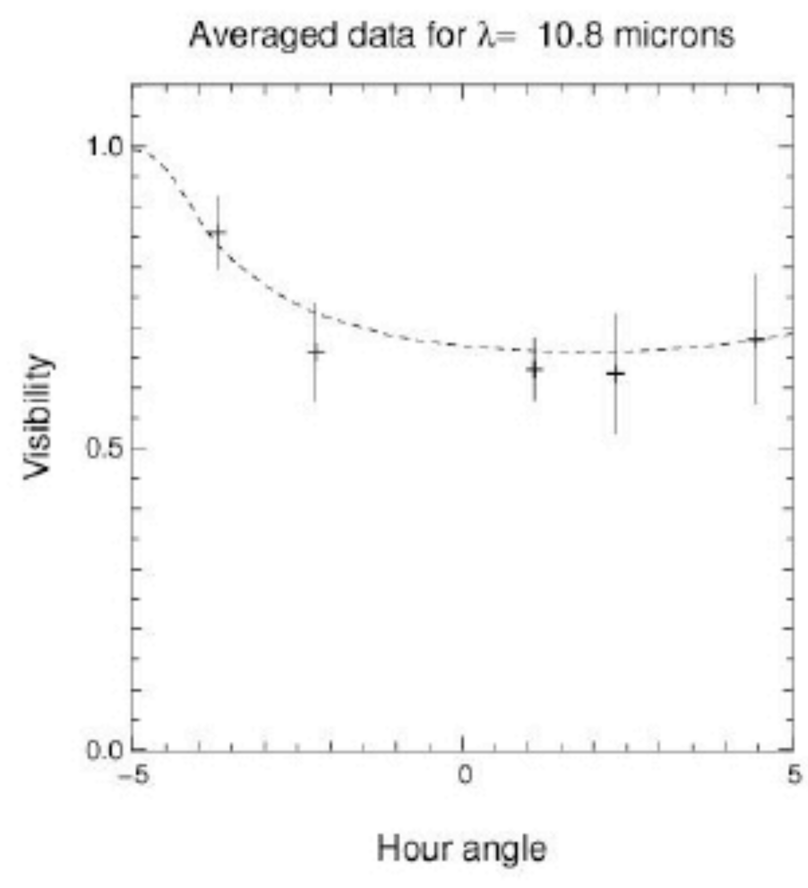
Ratzka et al. (2007, A&A 471, 173)

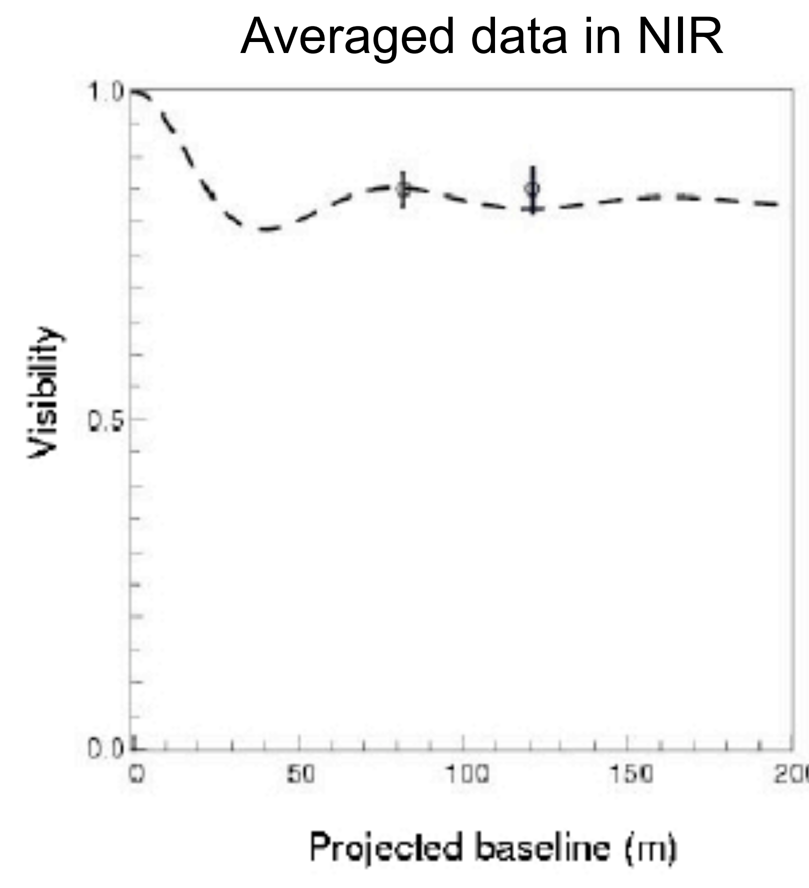
→ Inner disks (< 2 AU) have:

- larger silicate grains
- higher fraction of silicates is **crystalline** (40-100%)

51 Oph: NIR CO overtone emission



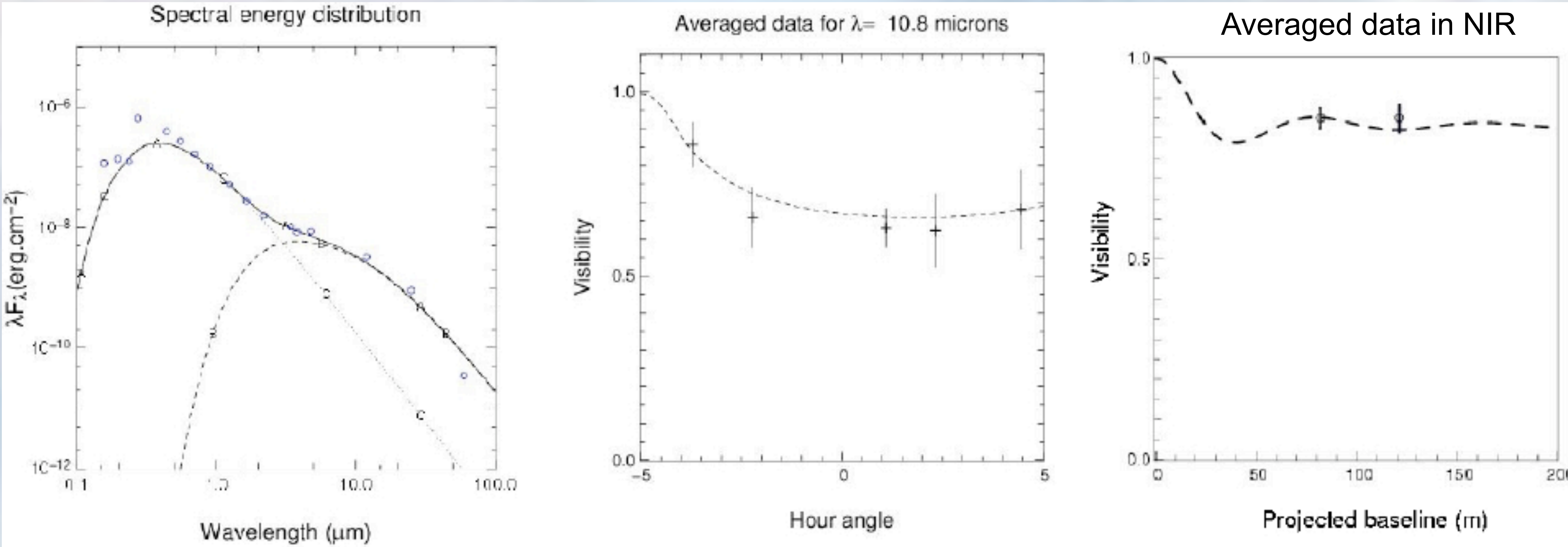




Parameter	Best fit Value
Distance	131 pc
$R_\star$	$7\ R_\odot$
$M_\star$	$3.8\ M_\odot$
$T_{\rm eff}$	10000 K
Av	0.15
Accretion rate	$7.10^{-5}\ M_\odot/{\rm yr}$
Disk outer radius	7 AU
Disk inner radius	0.55 AU
Inclination	88°
Position Angle	78°

Tatulli, et al. (2007, in prep.)

51 Oph: NIR CO overtone emission



All observations fitted by the standard disk model!

but it seems not to be physically possible

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Distance	131 pc
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$M_\star$	3.8 $M_\odot$
$T_{\rm eff}$	10000 K
Av	0.15
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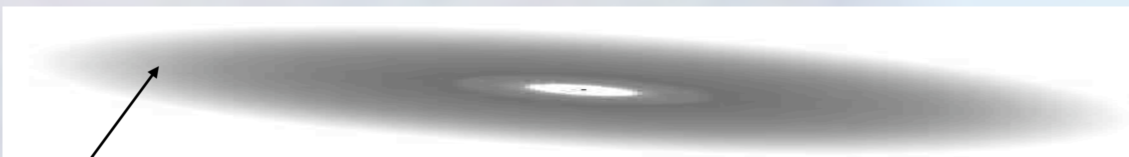
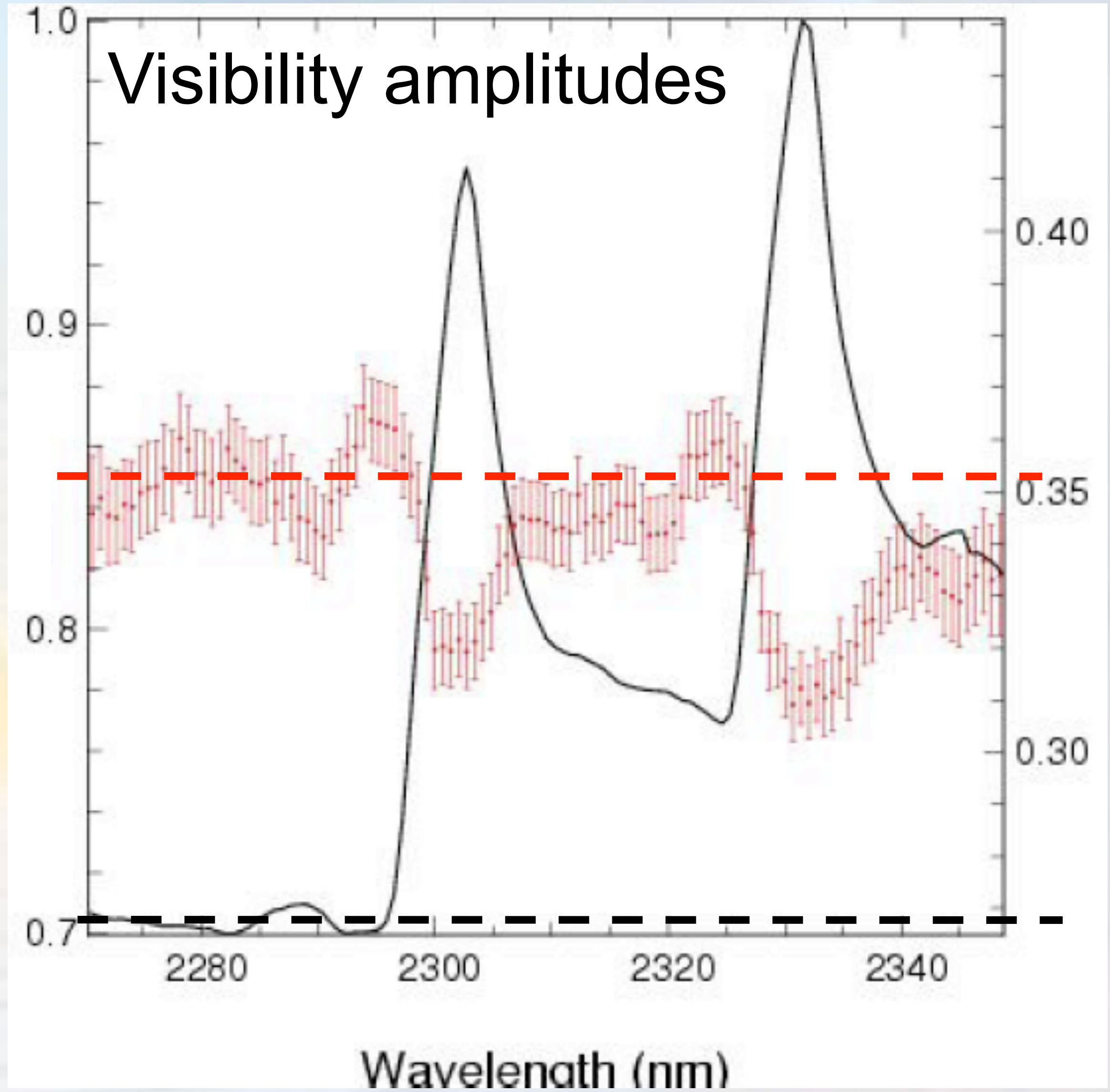
Tatulli, et al. (2007, in prep.)

Region of CO emission in 51 Oph

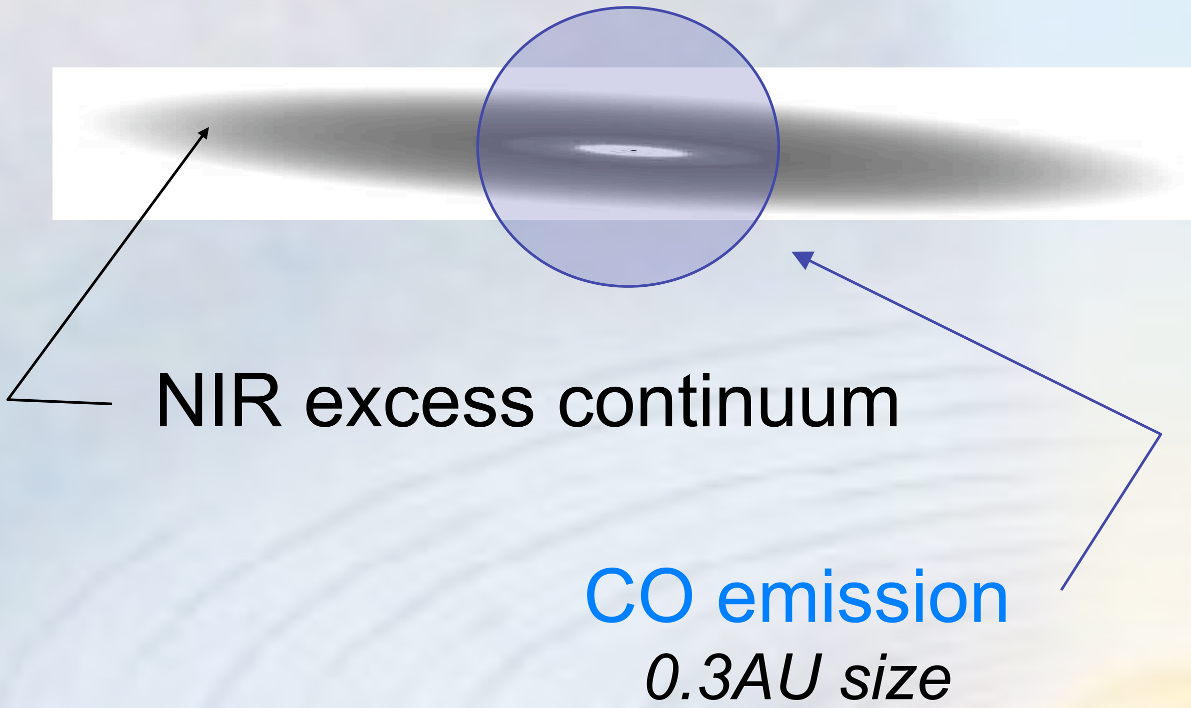


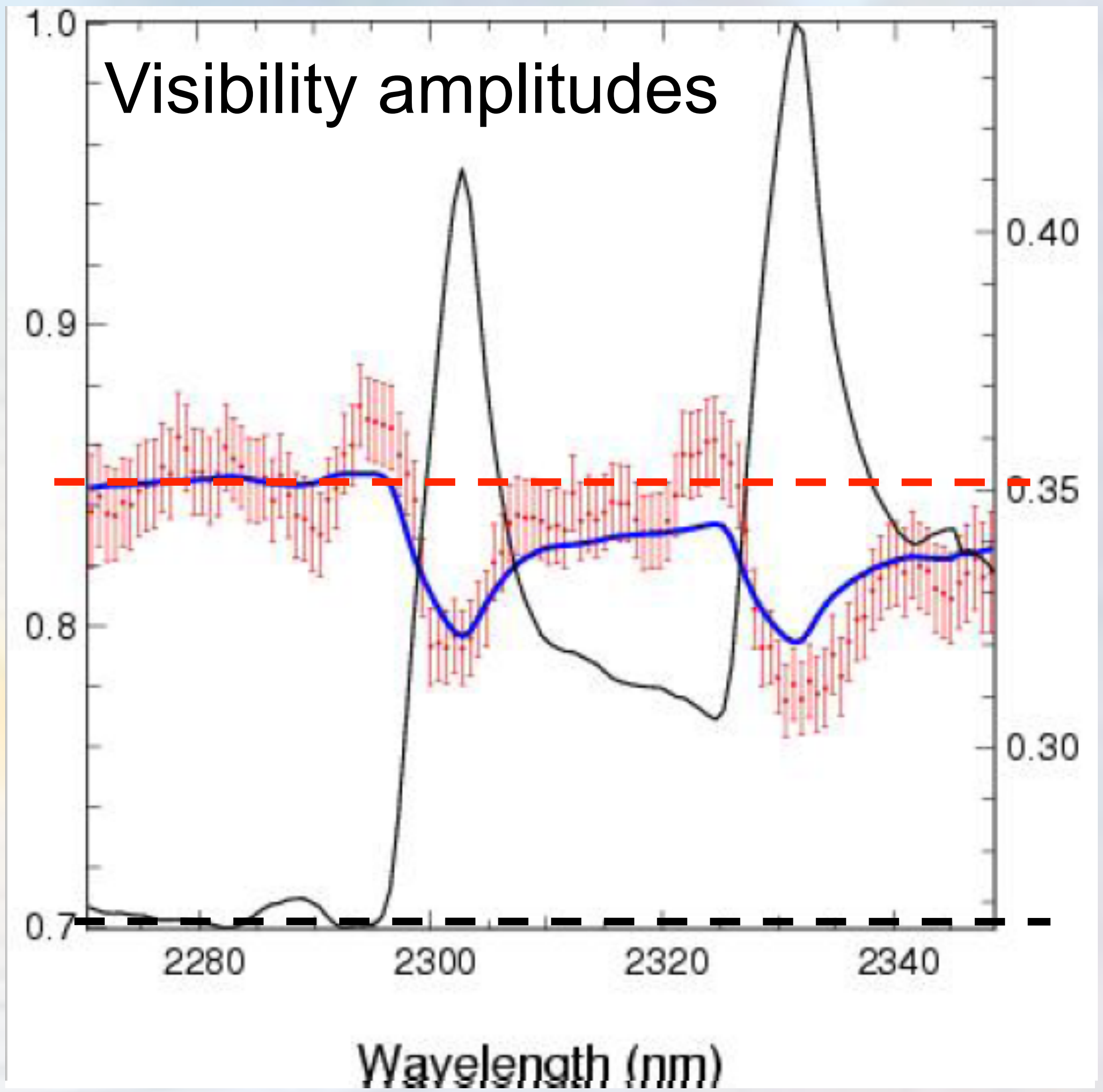
NIR excess continuum



Tatulli, et al. (2007, in prep.)

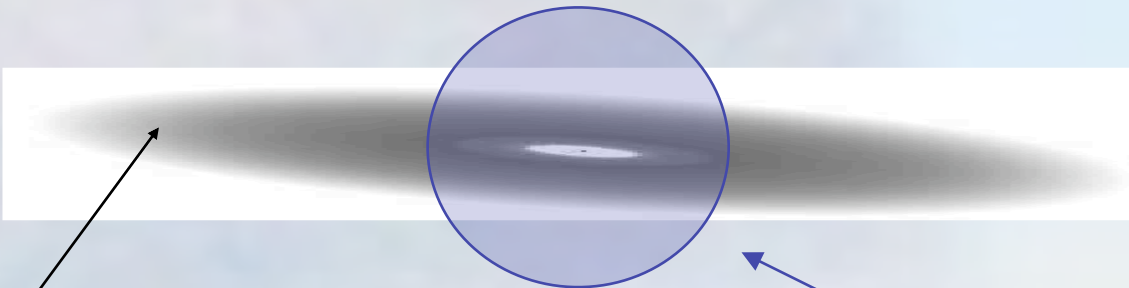
Region of CO emission in 51 Oph





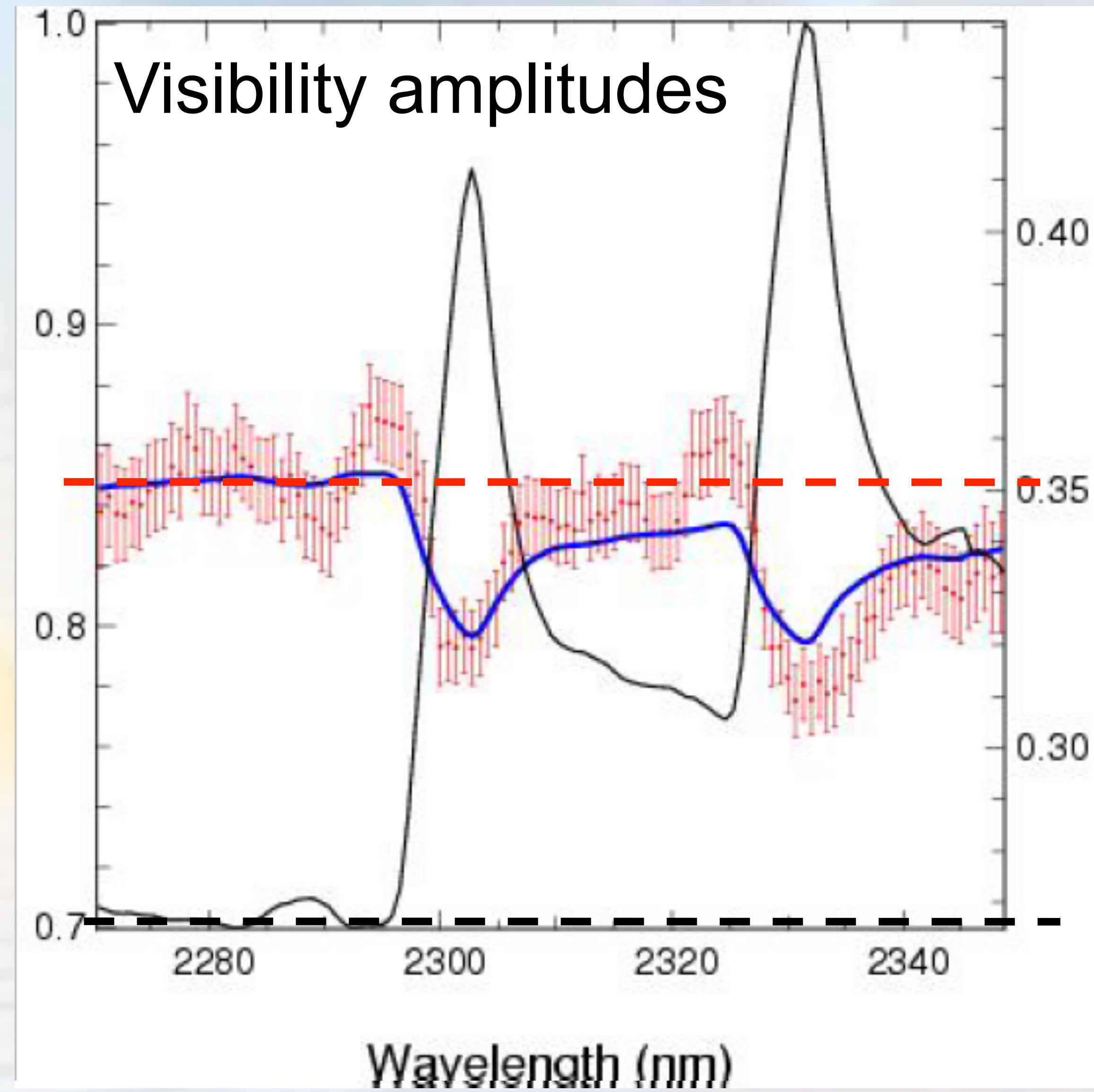
Tatulli, et al. (2007, in prep.)

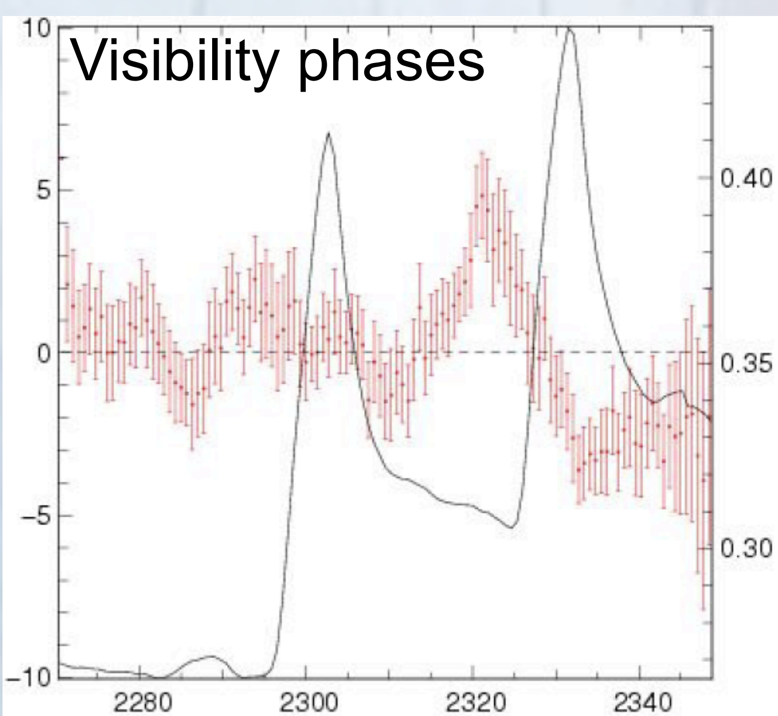
Region of CO emission in 51 Oph



NIR excess continuum

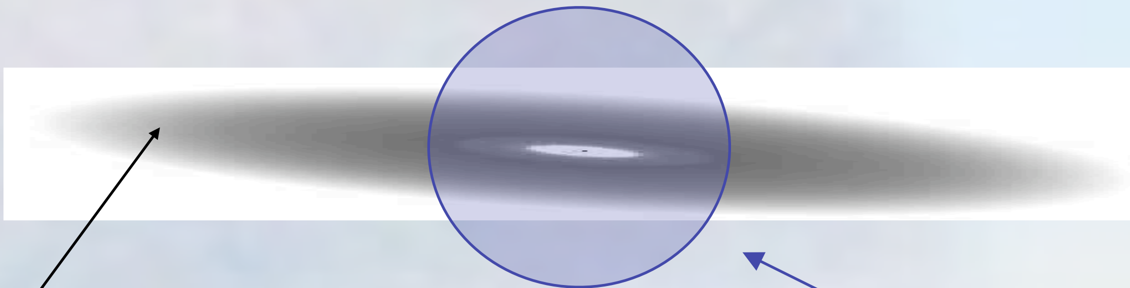
CO emission
0.3AU size





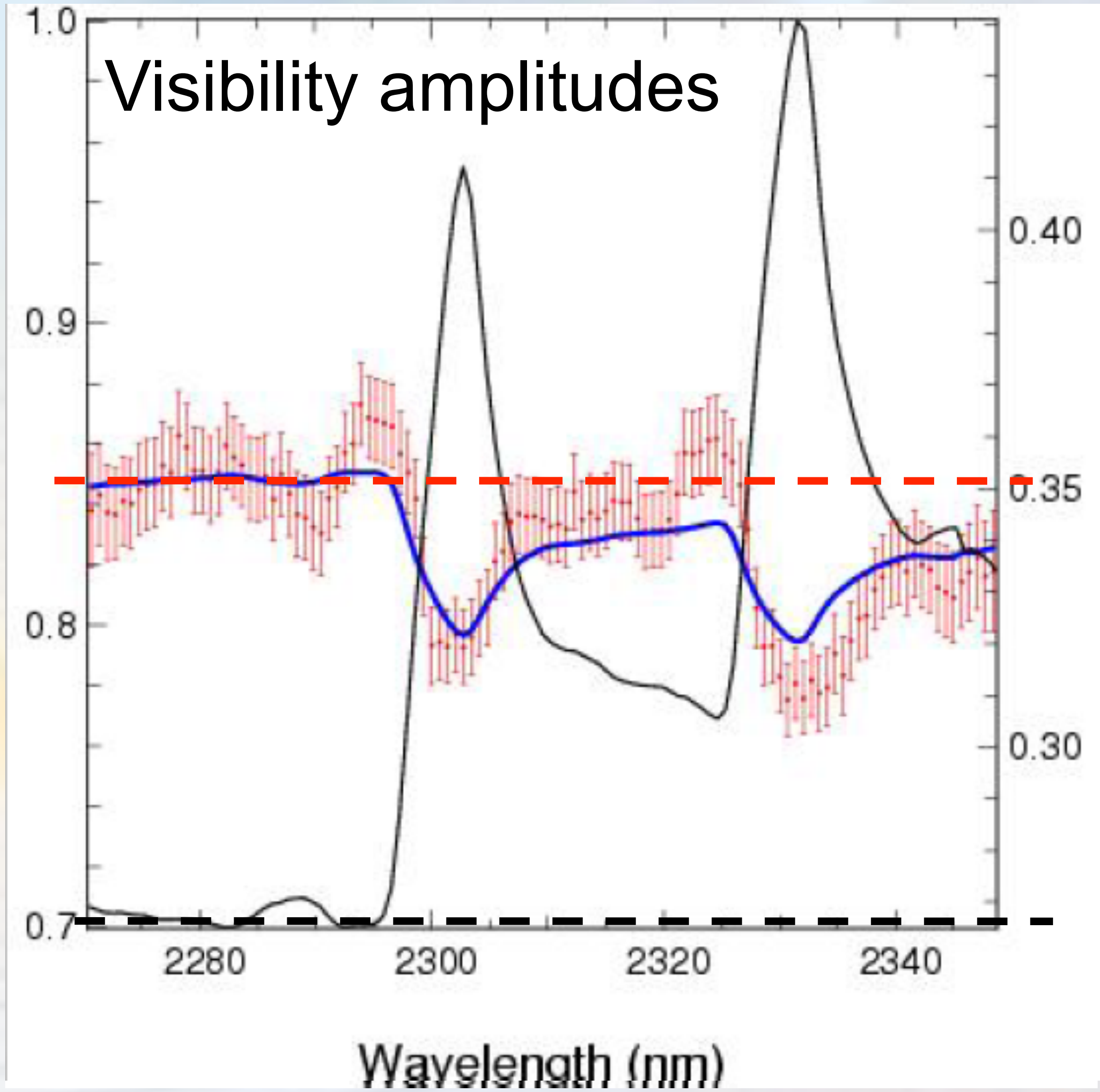
Tatulli, et al. (2007, in prep.)

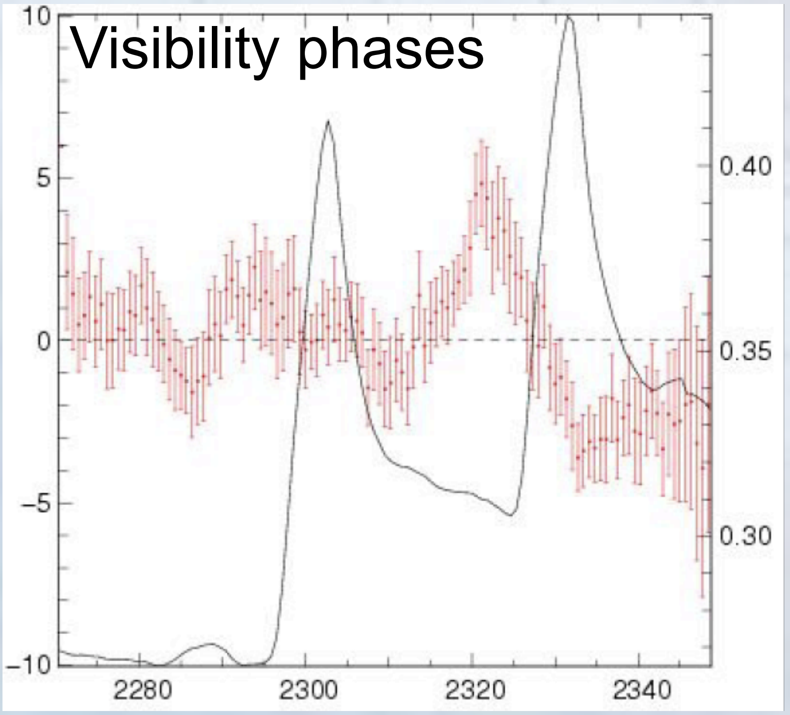
Region of CO emission in 51 Oph



NIR excess continuum

CO emission
0.3AU size

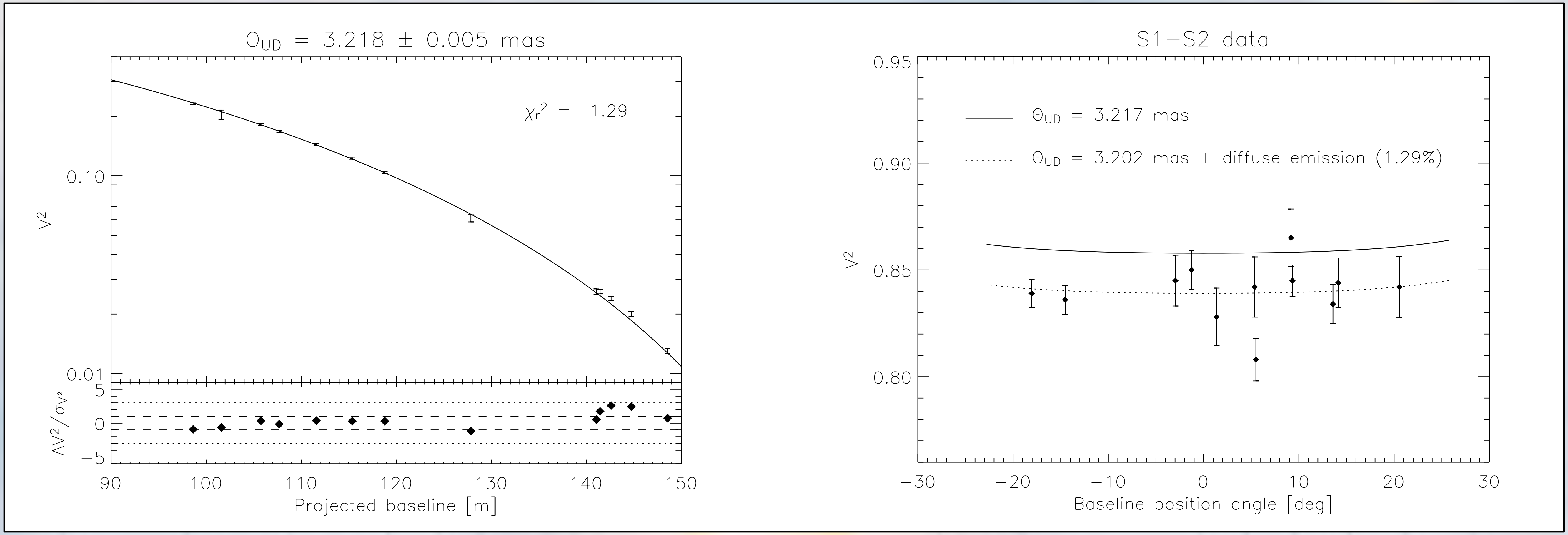




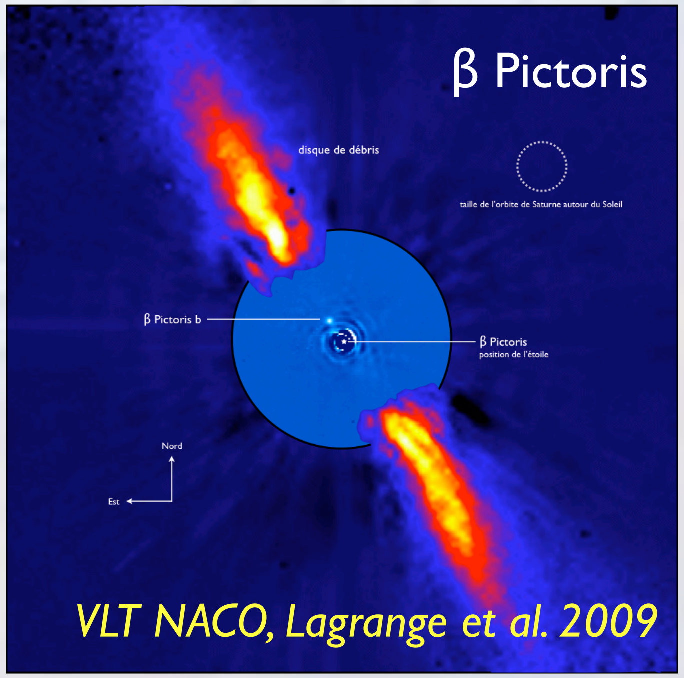
Comprehension of the dust vs gas morphology will increase with better coverture.

Tatulli, et al. (2007, in prep.)

Debris disks



Absil et al. (2006)



- Debris disks are difficult because of the contrast (<2%)
- Need for short baselines
- accurate interferometry

Differential phases on Fomalhaut

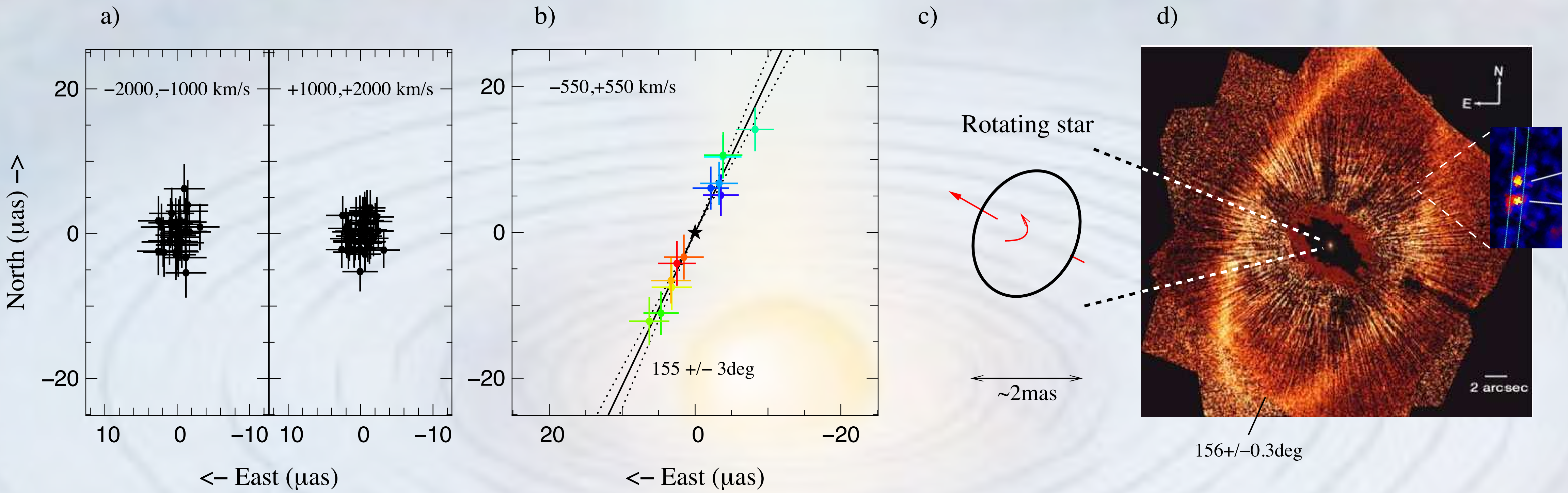
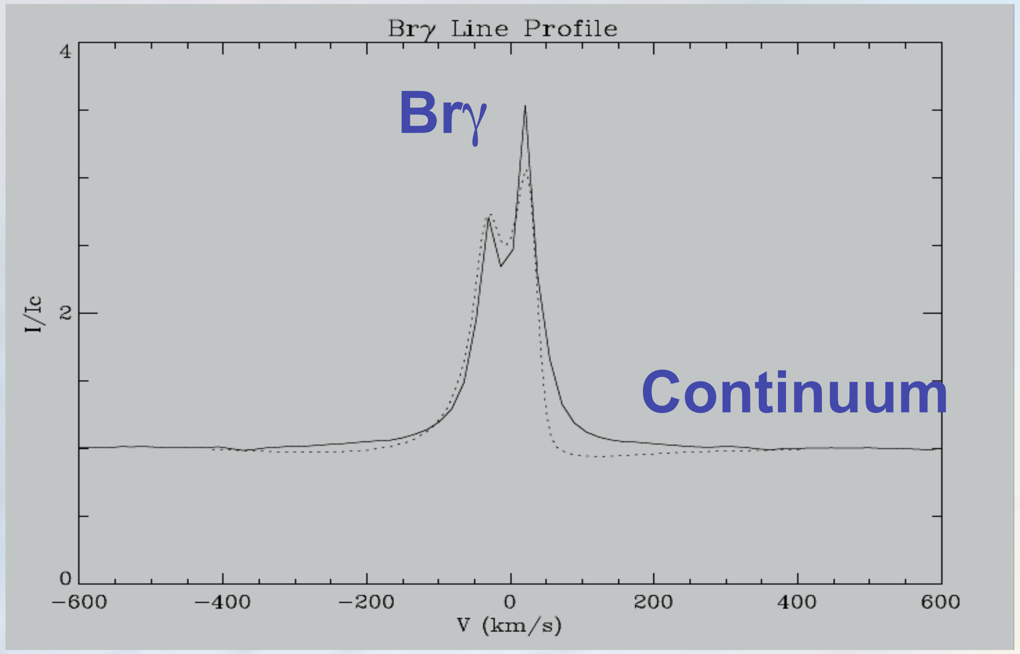


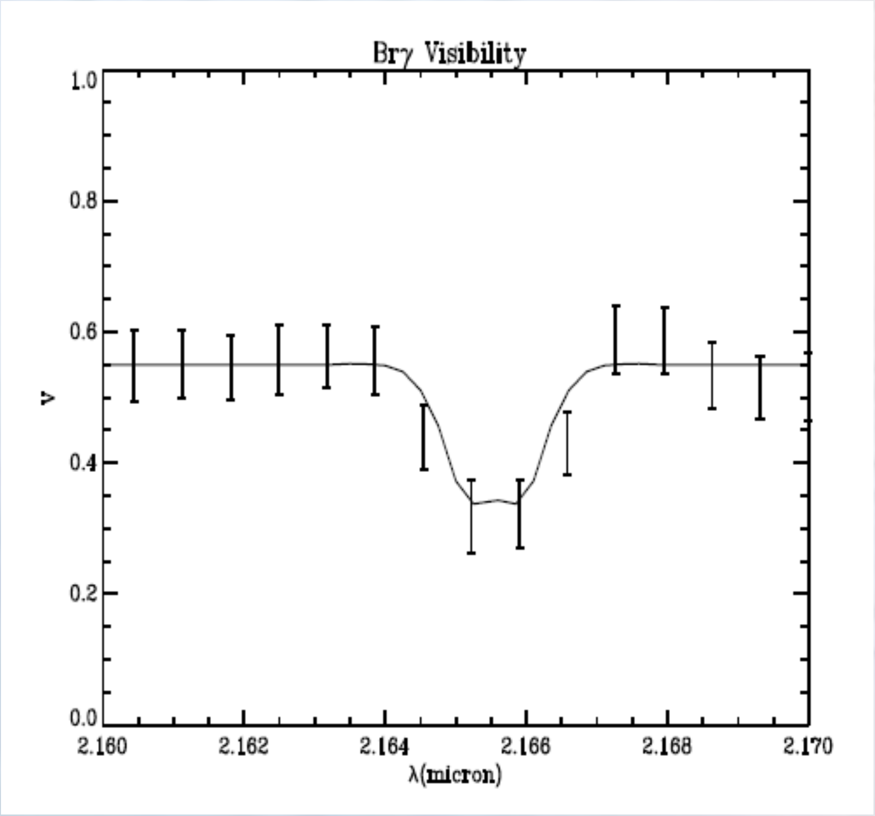
Fig. 3. AMBER spectro-astrometric positions $\boldsymbol{p}(\lambda)$ in the continuum (a) and across the Br-γ absorption line (b). Colors refer to the wavelength bin, as shown in Fig. 2. The signature of the rotating photosphere (c) is clearly detected and is compared to the debris disk and the planetary companion (d) imaged in the visible by Kalas et al. (2008). For the sake of clarity, the astrometric error ellipses are represented by their projection into the North and East directions.

OTHER AU-SCALE PHENOMENA

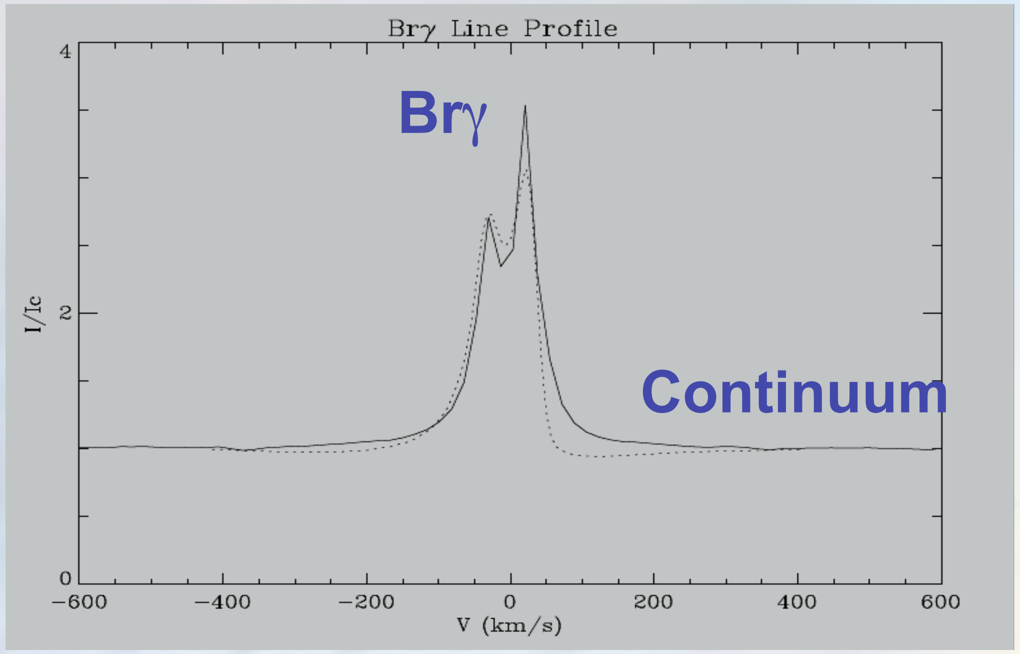
- Outflowing winds
- Magnetospheres
- Binaries and multiple systems

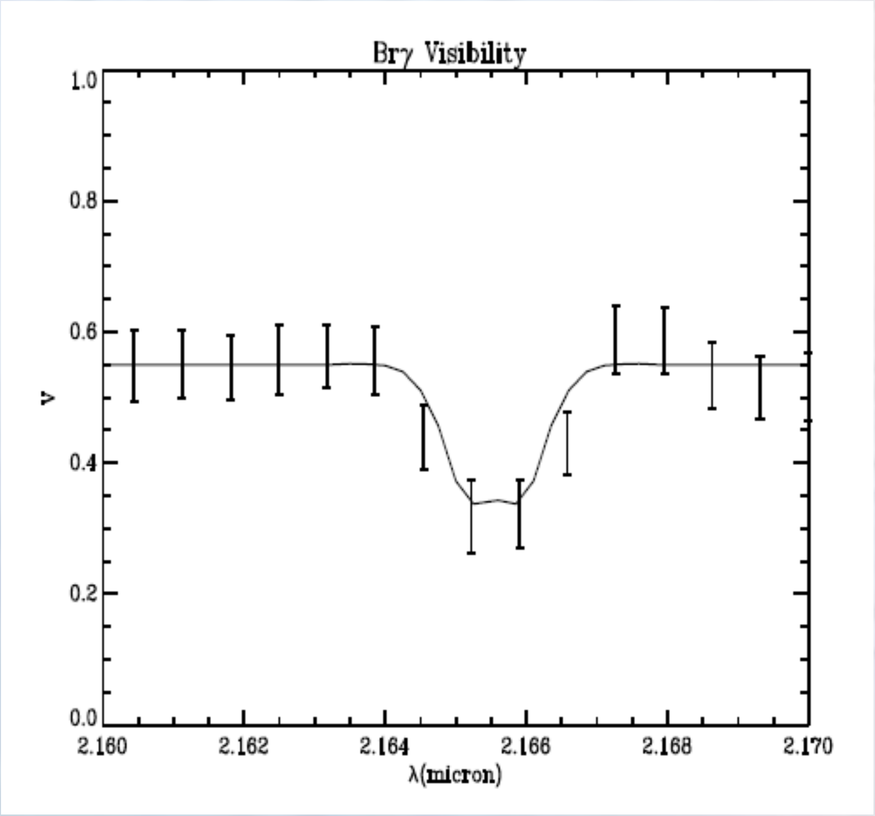
Disk and wind spatially are spectrally resolved in MWC 297

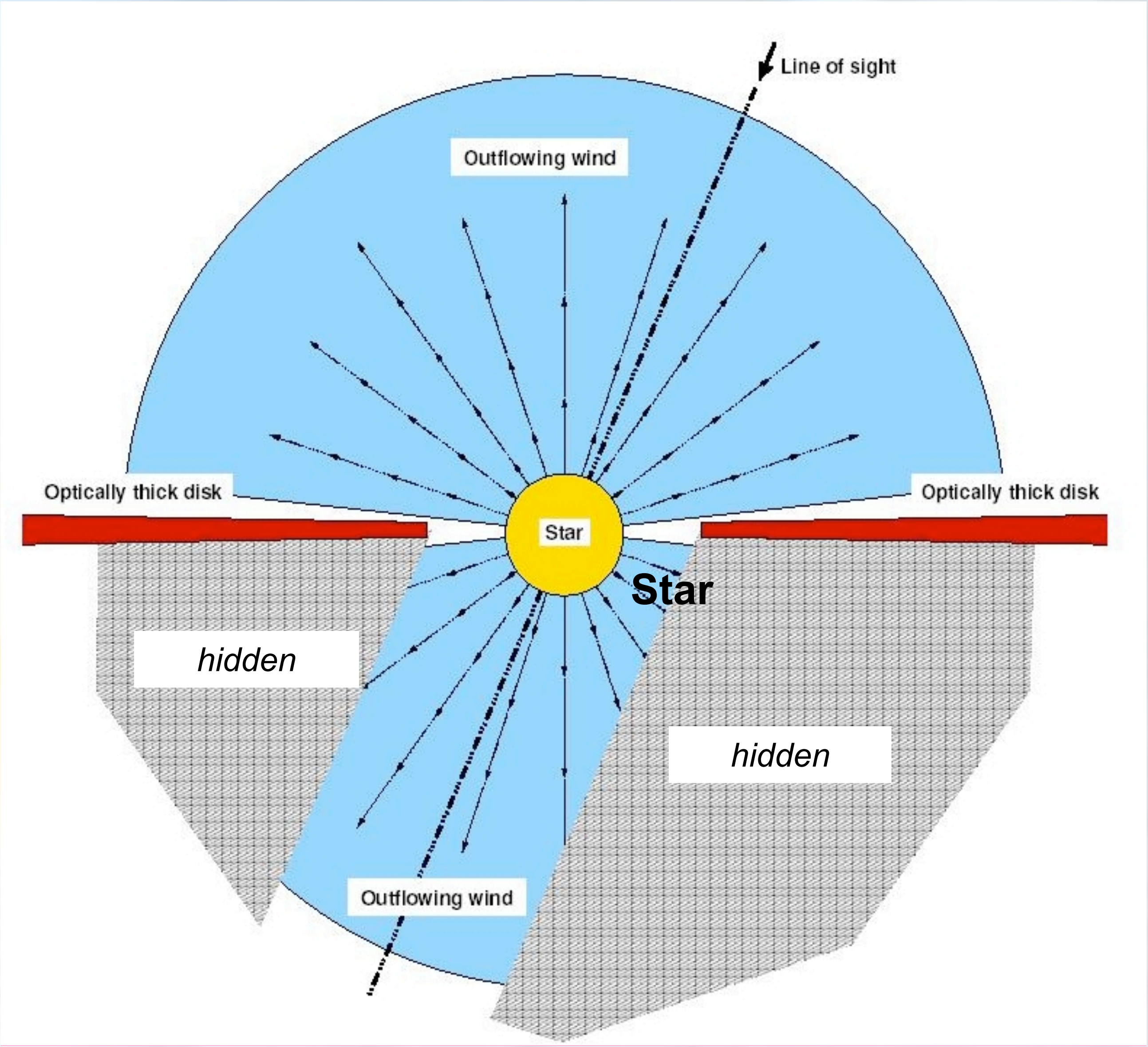




Disk and wind spatially are spectrally resolved in MWC 297

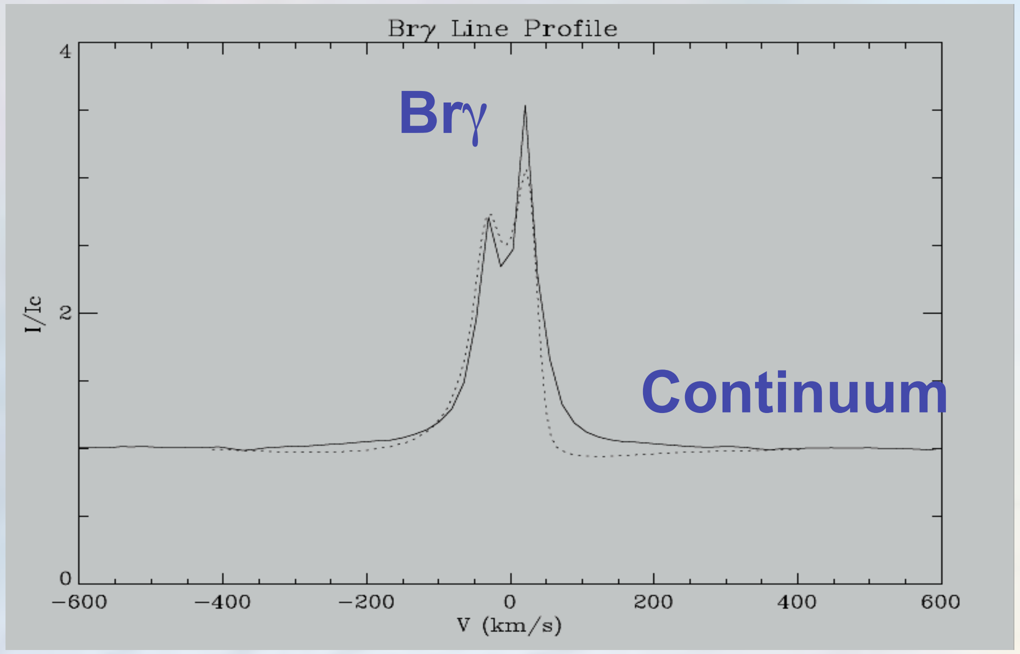


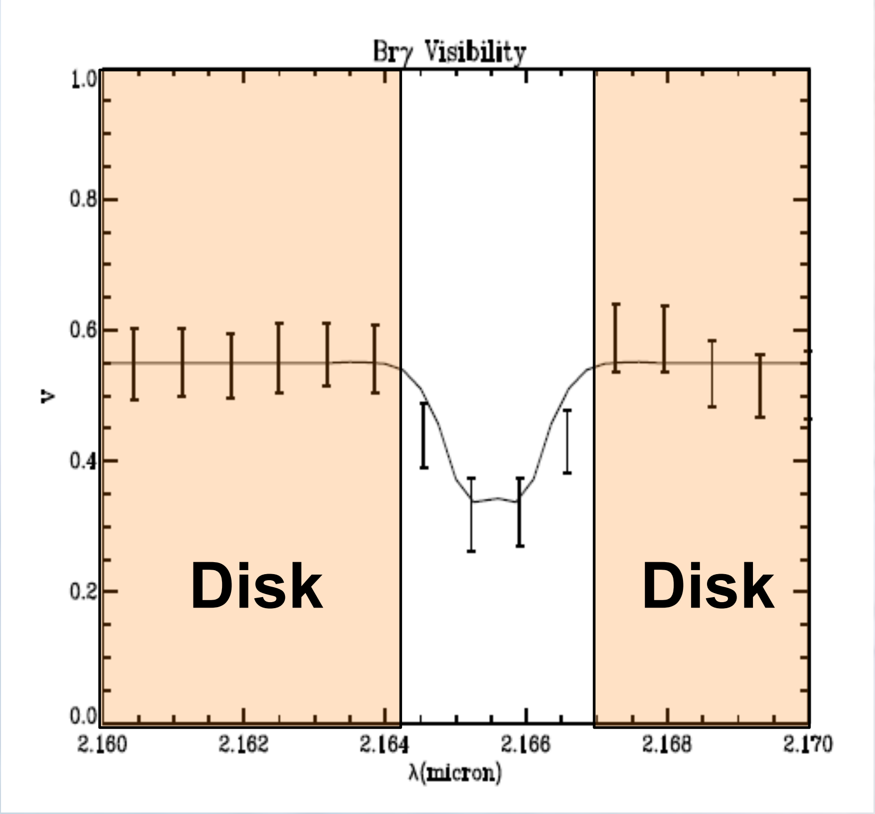


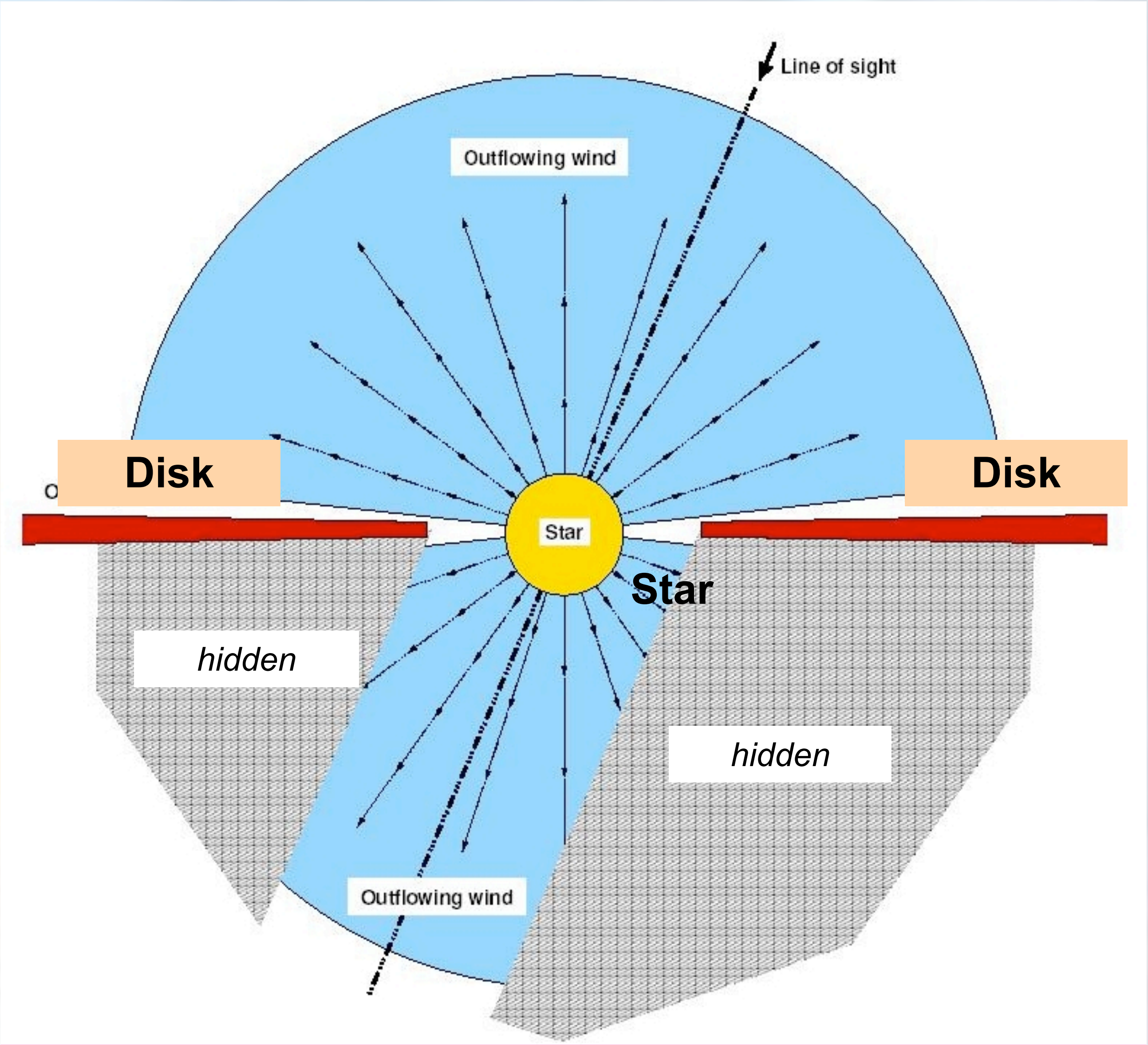


Malbet et al. (2007, A&A 464, 43)

Disk and wind spatially are spectrally resolved in MWC 297







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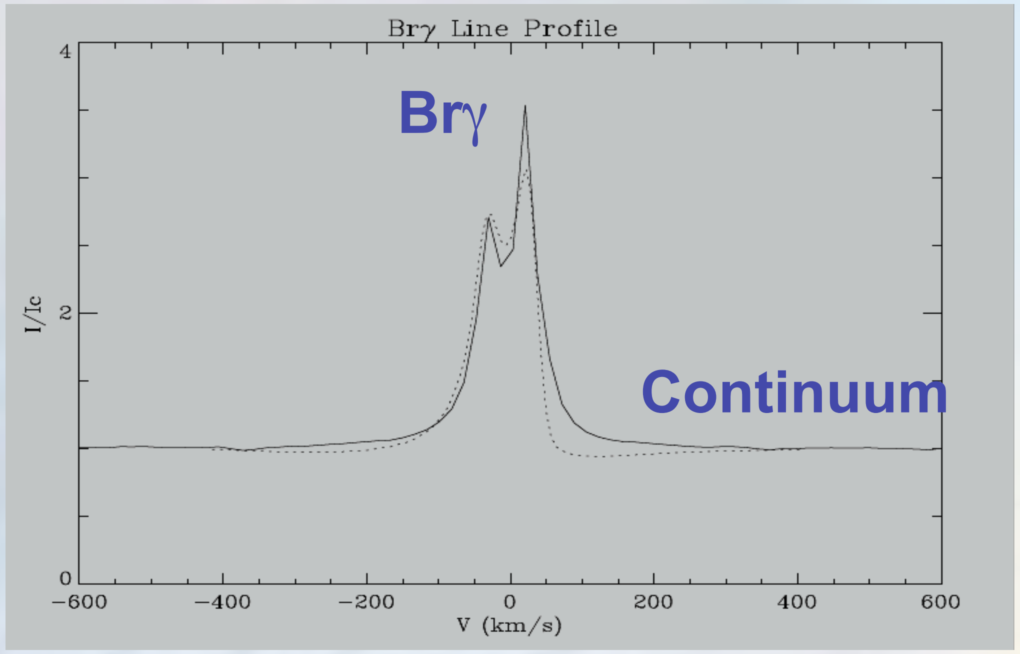
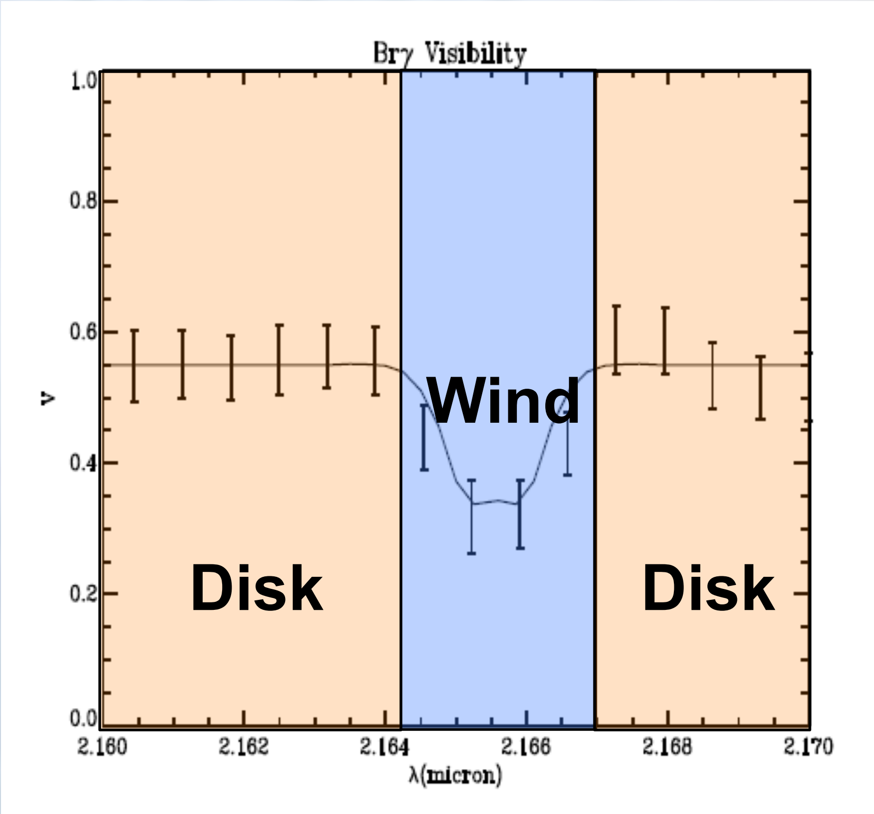
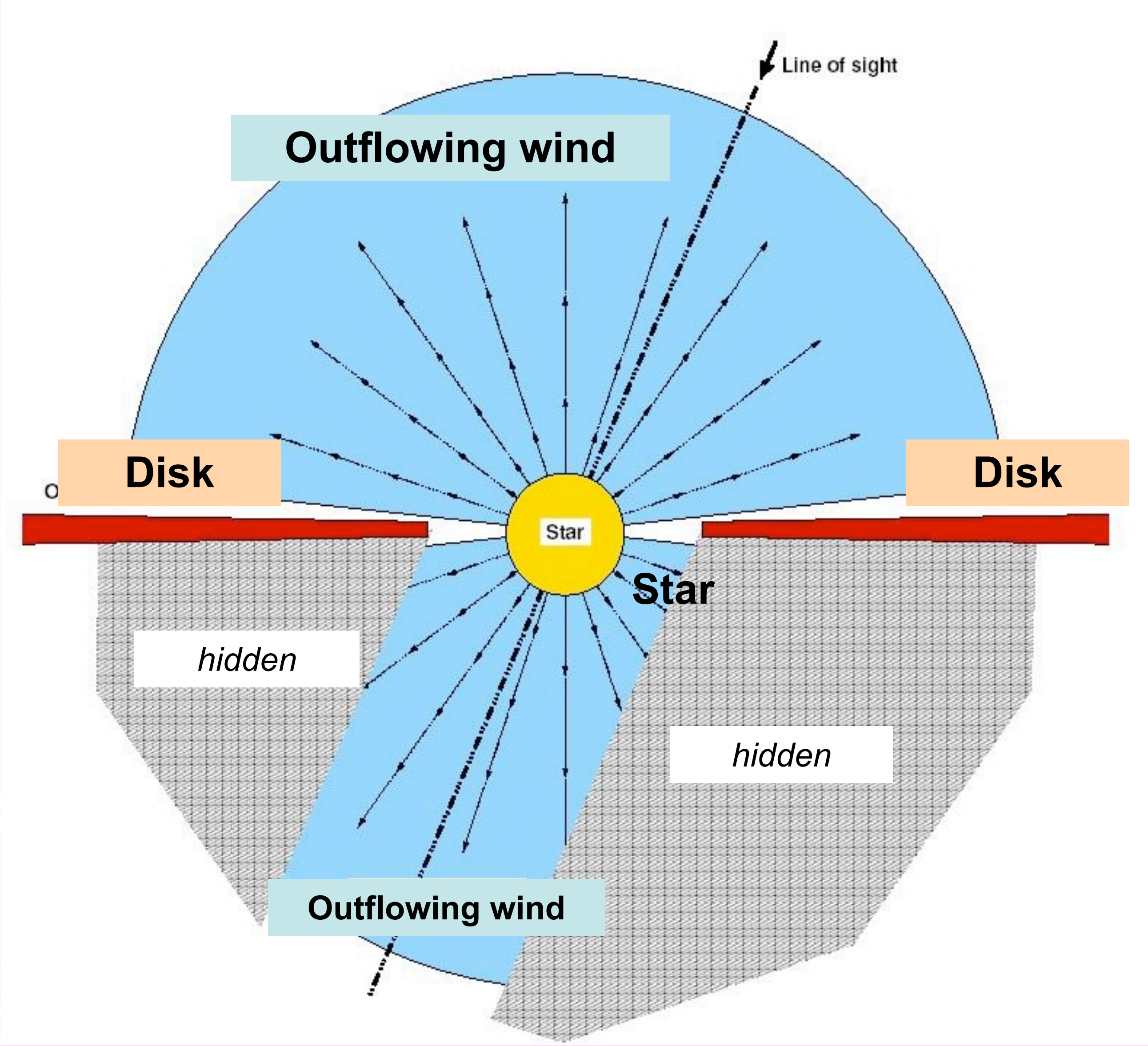
Disk and wind spatially are spectrally resolved in MWC 297







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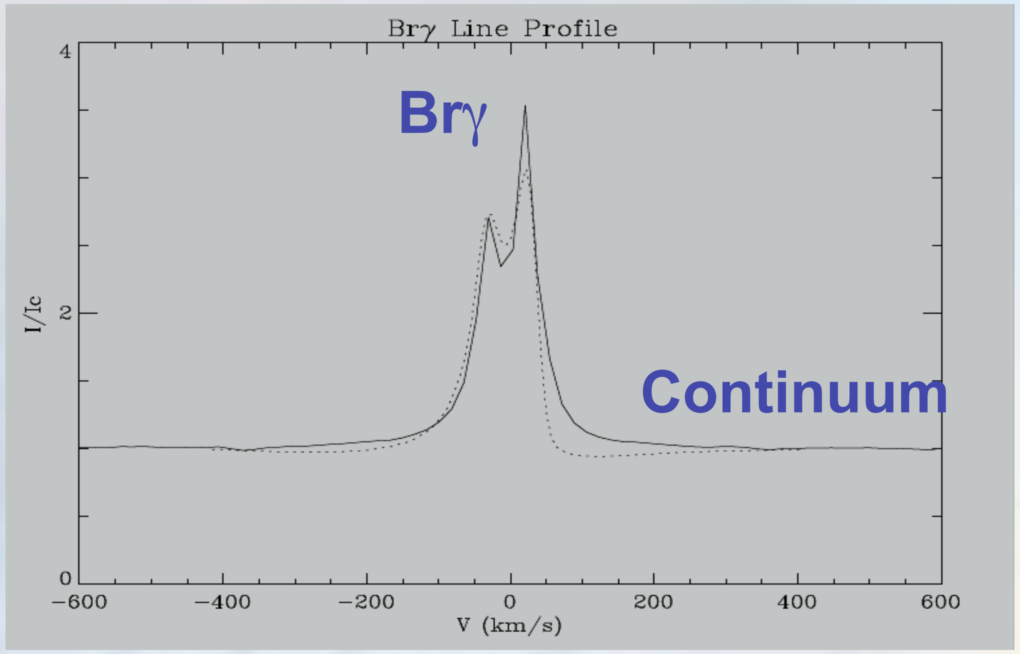
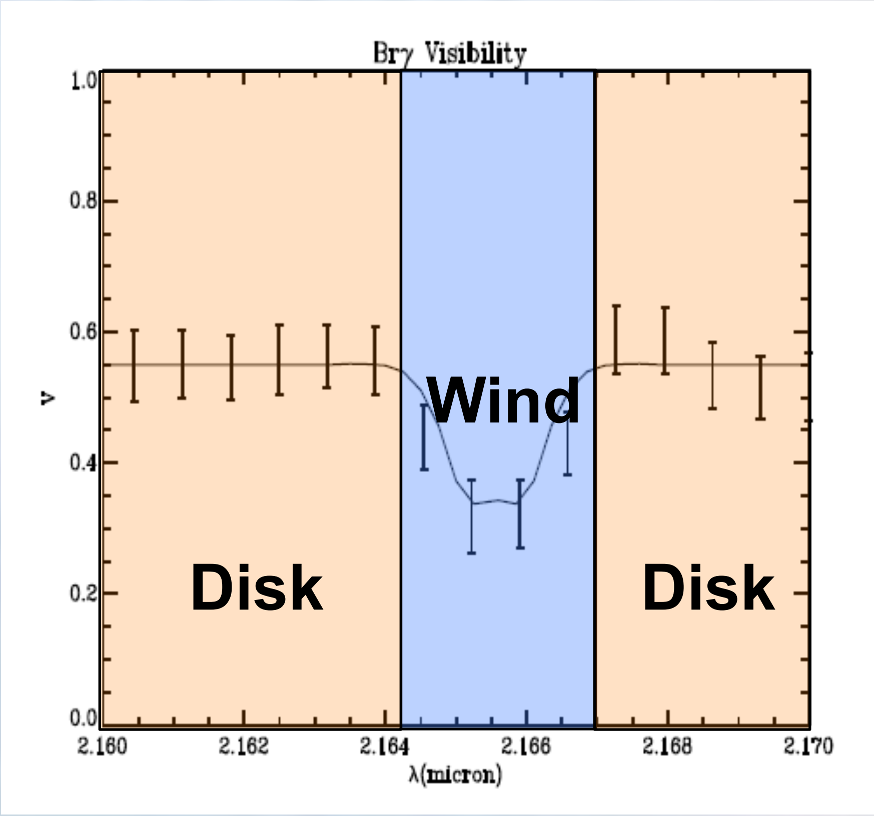
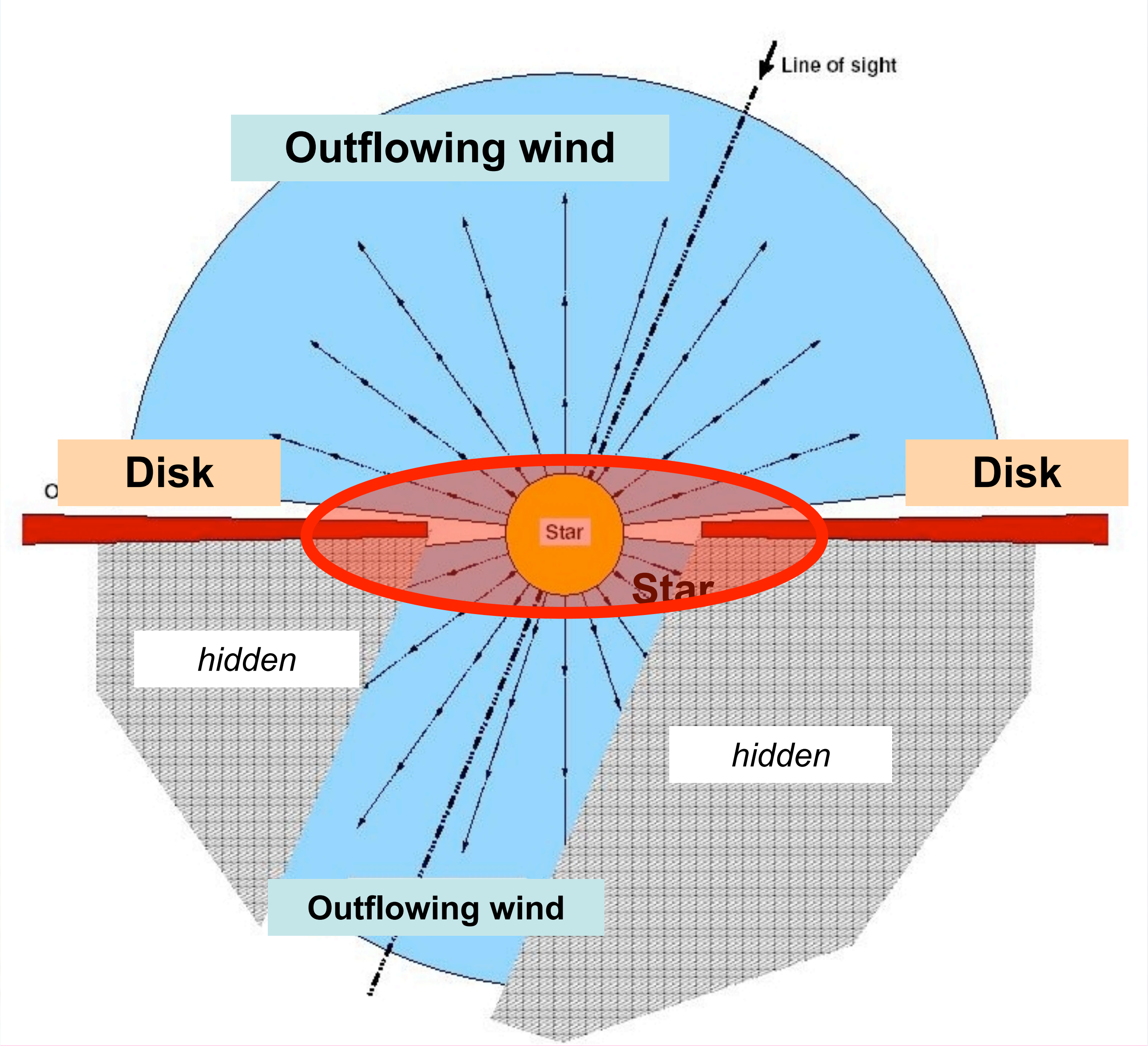
Disk and wind spatially are spectrally resolved in MWC 297



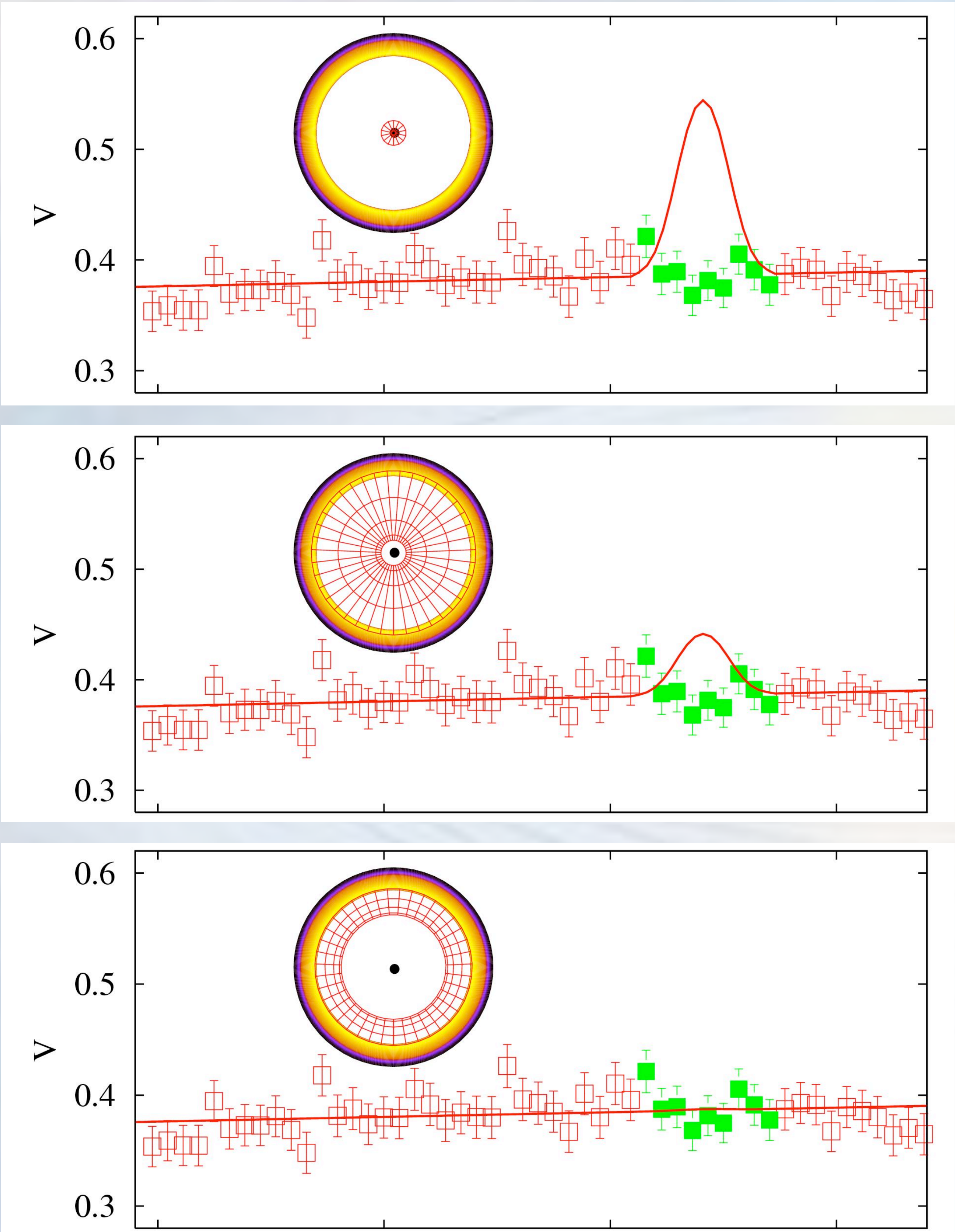




Malbet et al. (2007, A&A 464, 43)

→ Investigate the link between disk, star and wind

Nature of Brγ in the HAe star HD104237



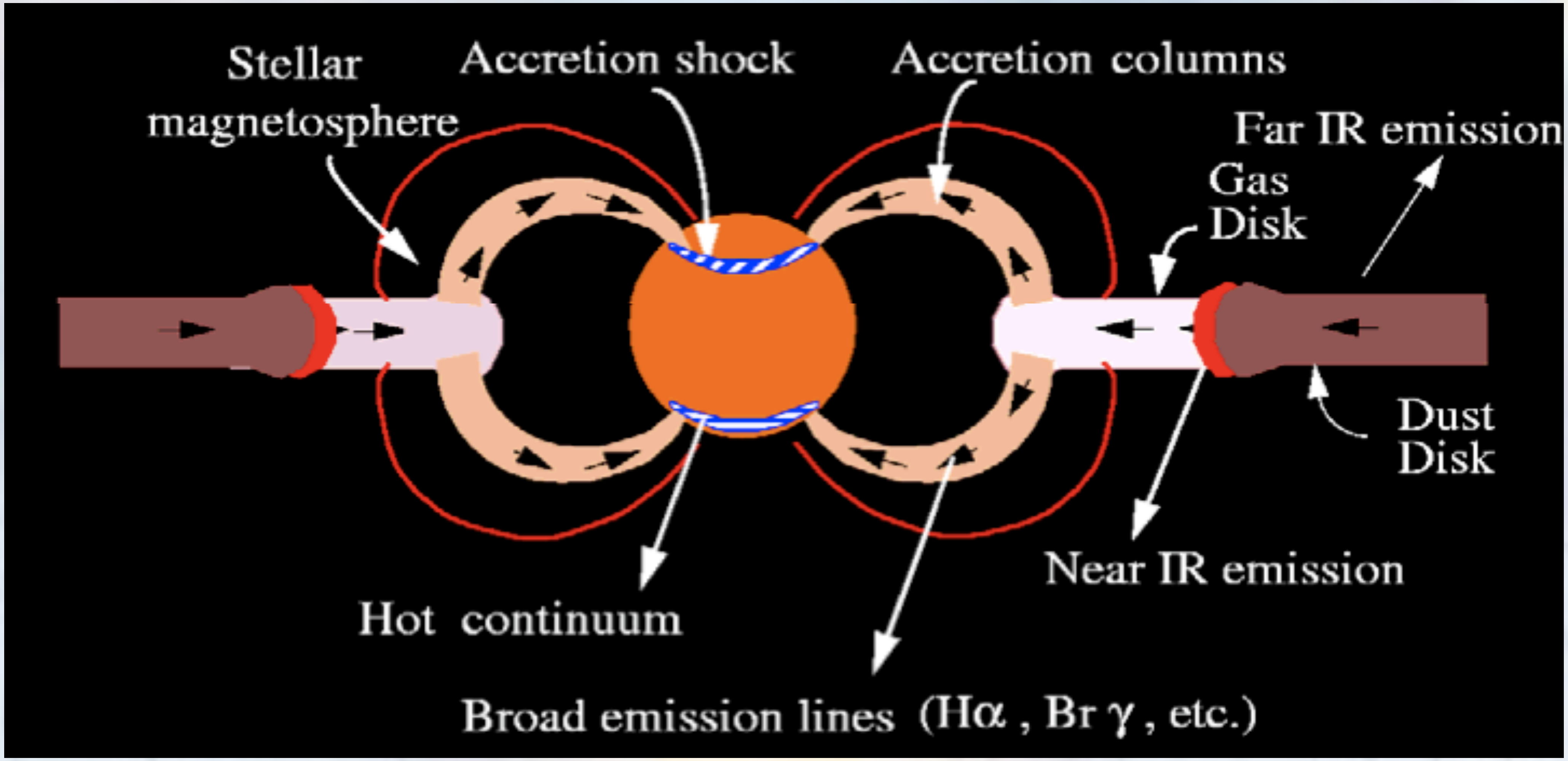
Disk truncated by magnetosphere

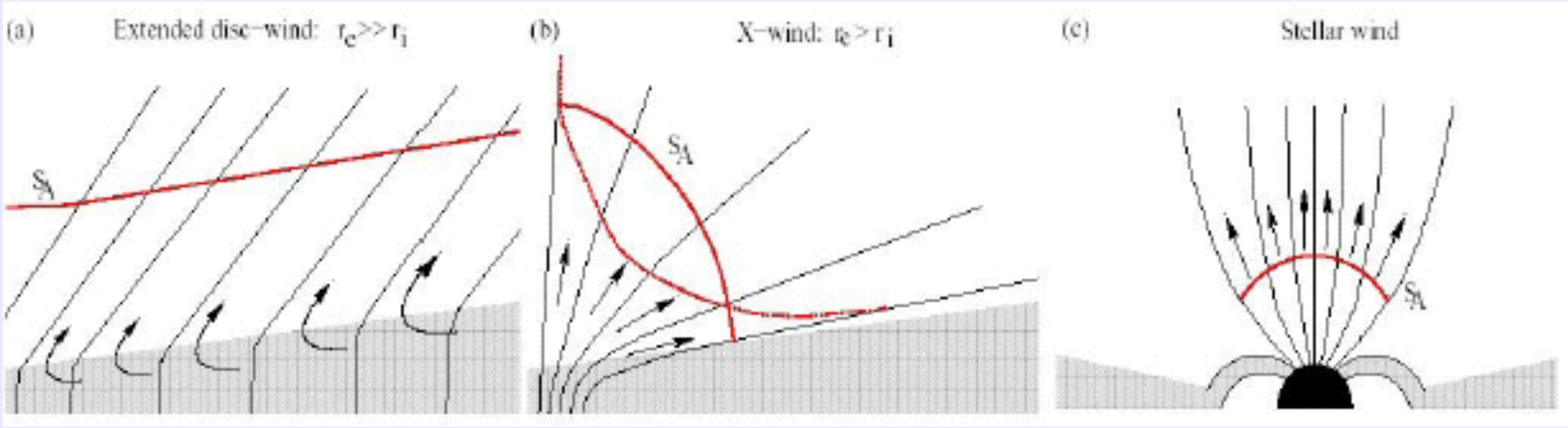
Gas within the disk

Outflowing wind

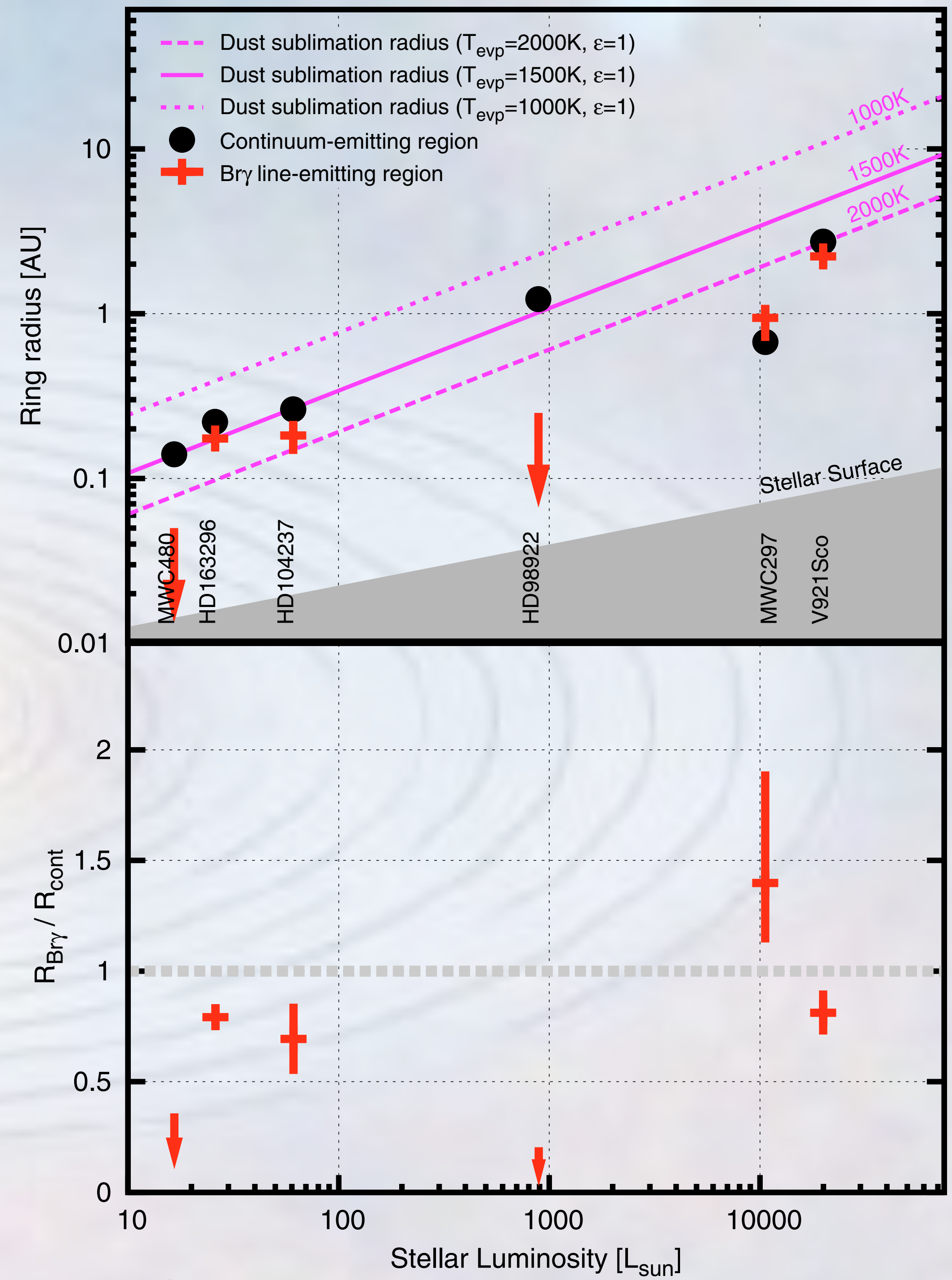
Tatulli et al. (2007, A&A 464, 55)

Disk/star interaction ?





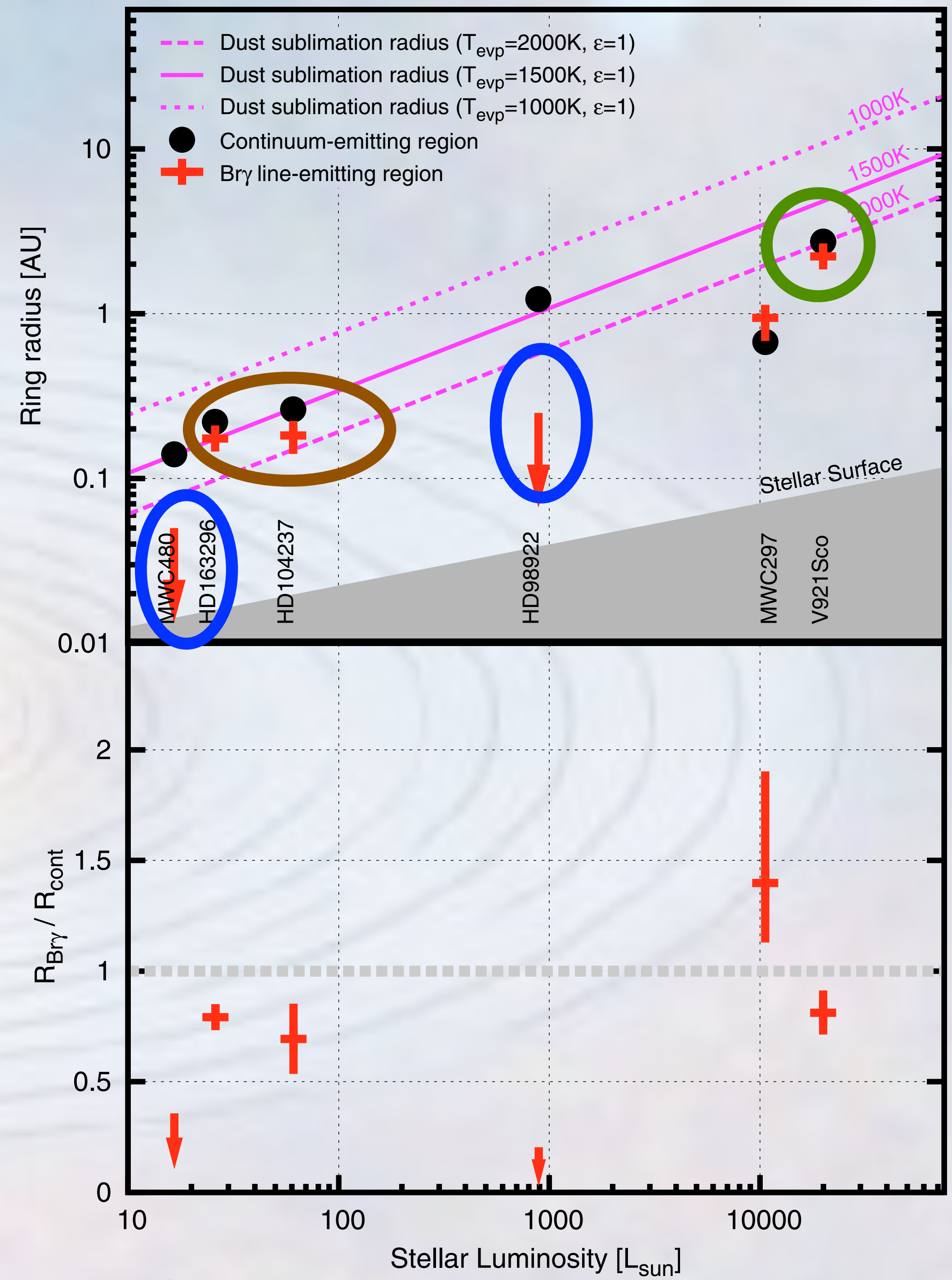
A systematic study of the origin of the BrY emission in Herbig Ae/Be stars



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 ?**



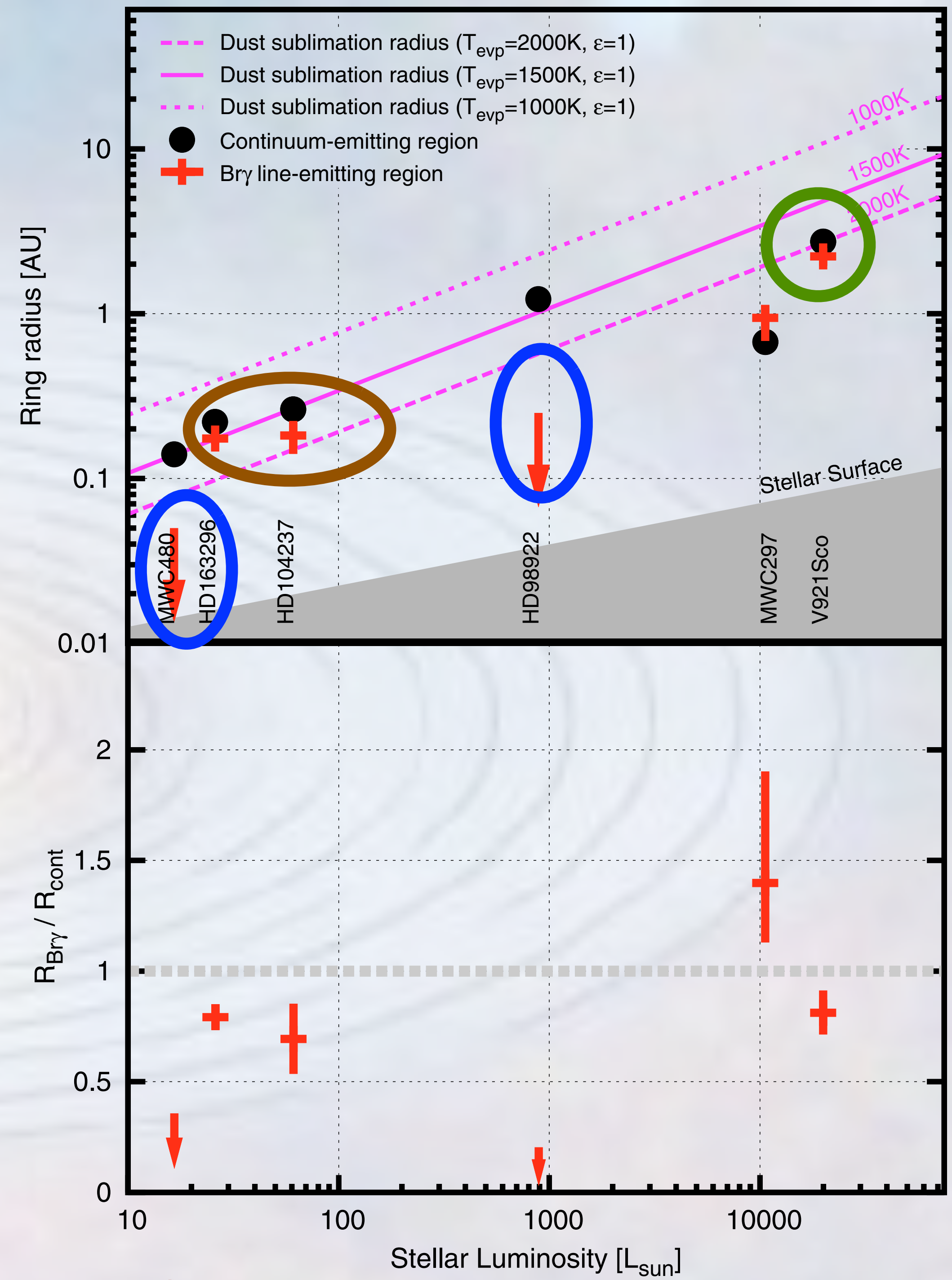
Kraus et al. (2008, A&A 489, 1157)

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

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

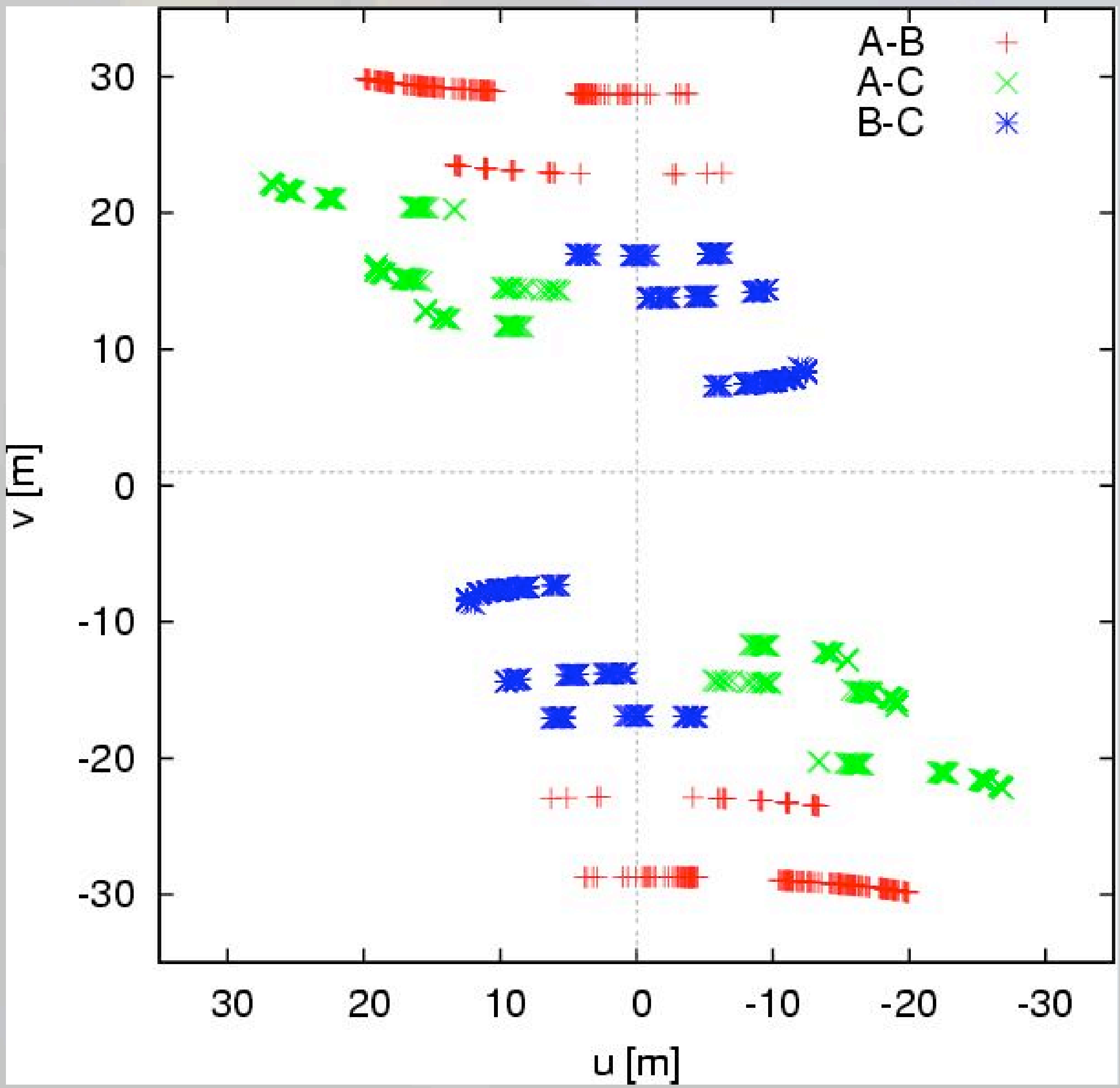
➡ No correlation with L_* as suggested by Eisner et al. 2007

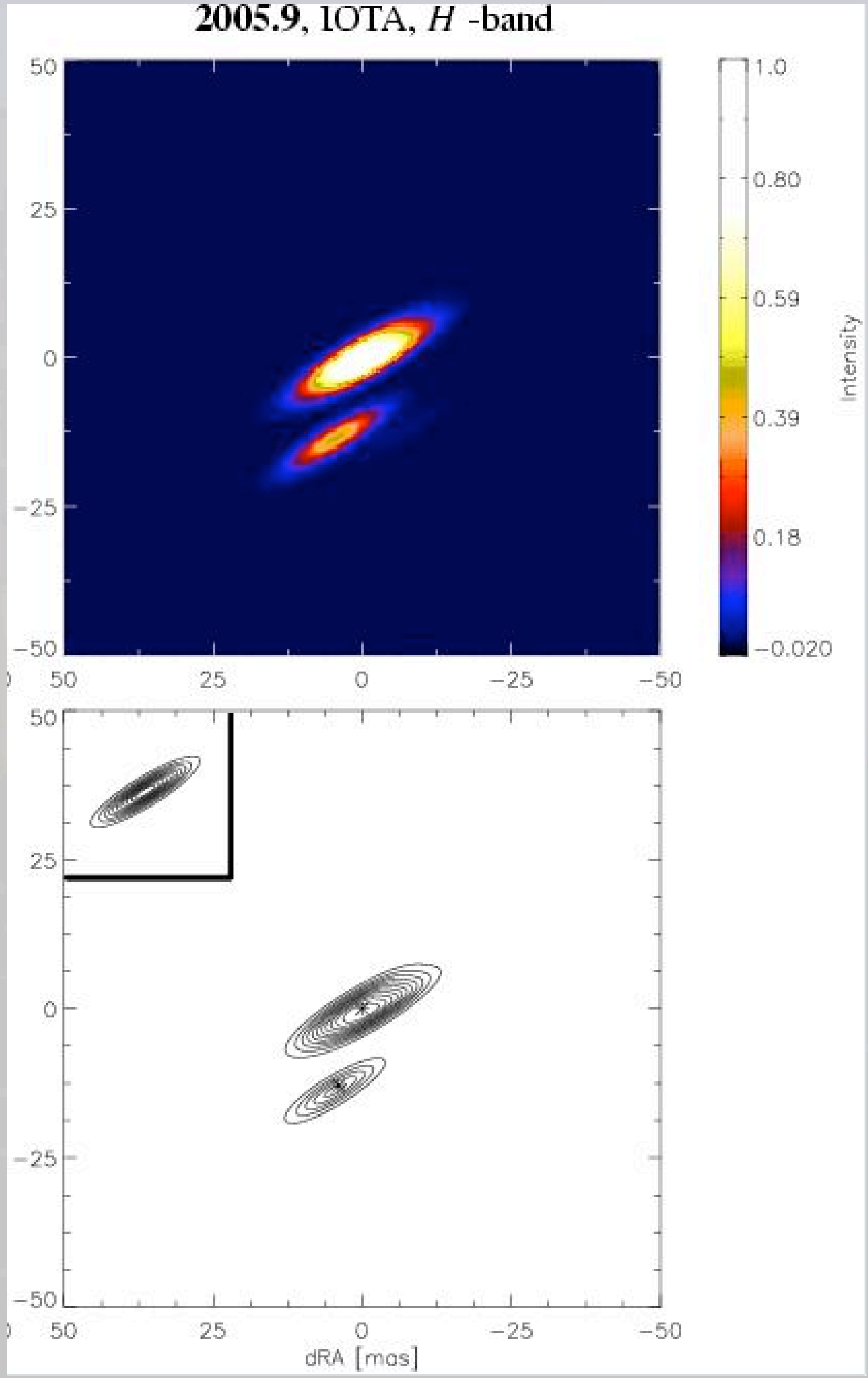
➡ We are probing mostly outflows phenomena:
Brγ indirect accretion tracer through accretion-driven mass loss?



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

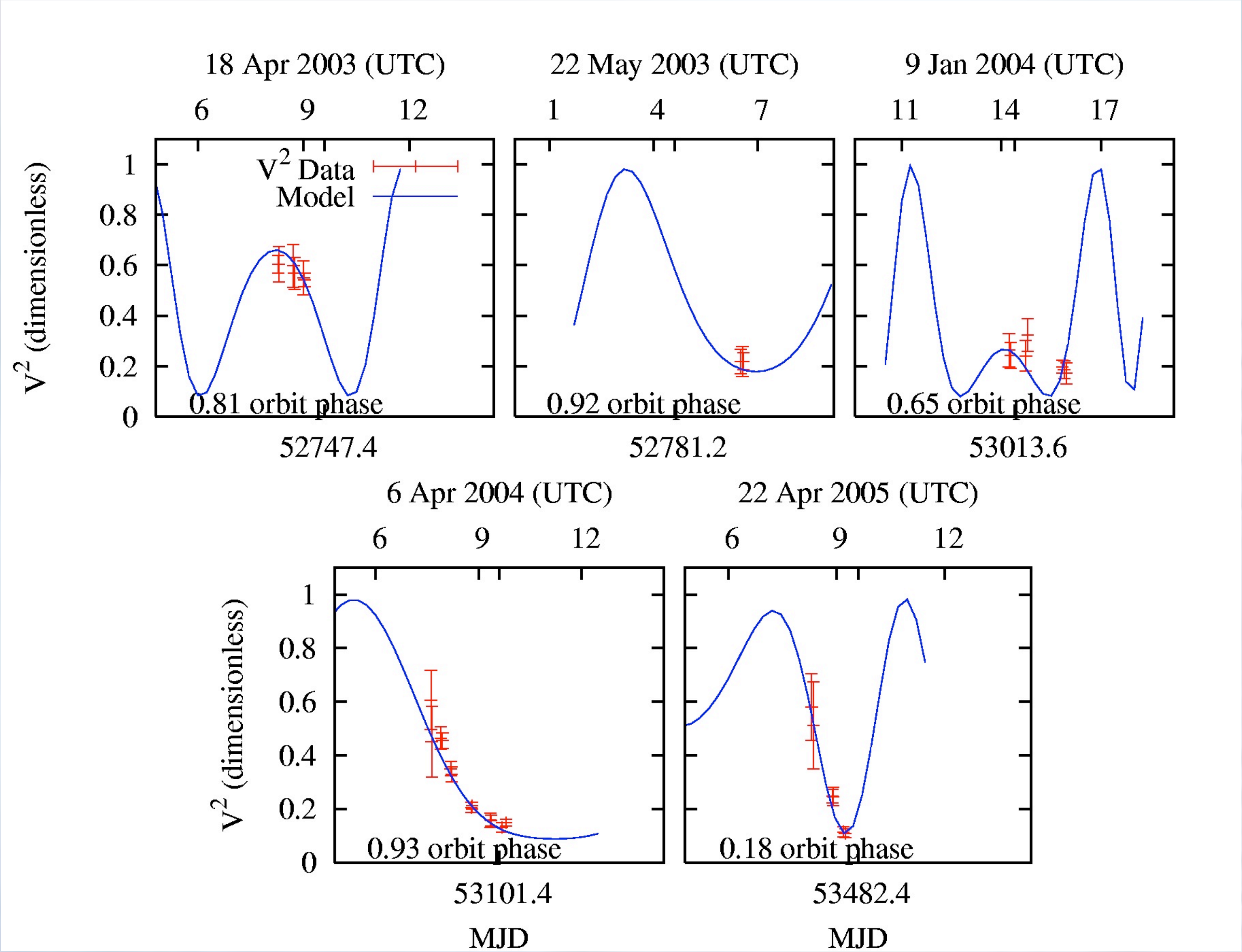
Aperture synthesis imaging of the θ¹ Orionis C system with IOTA

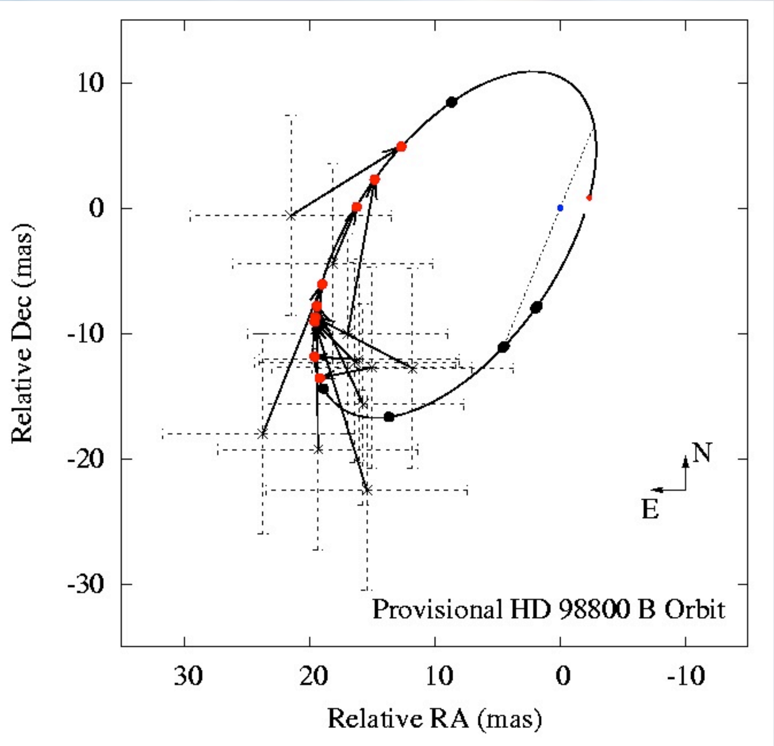


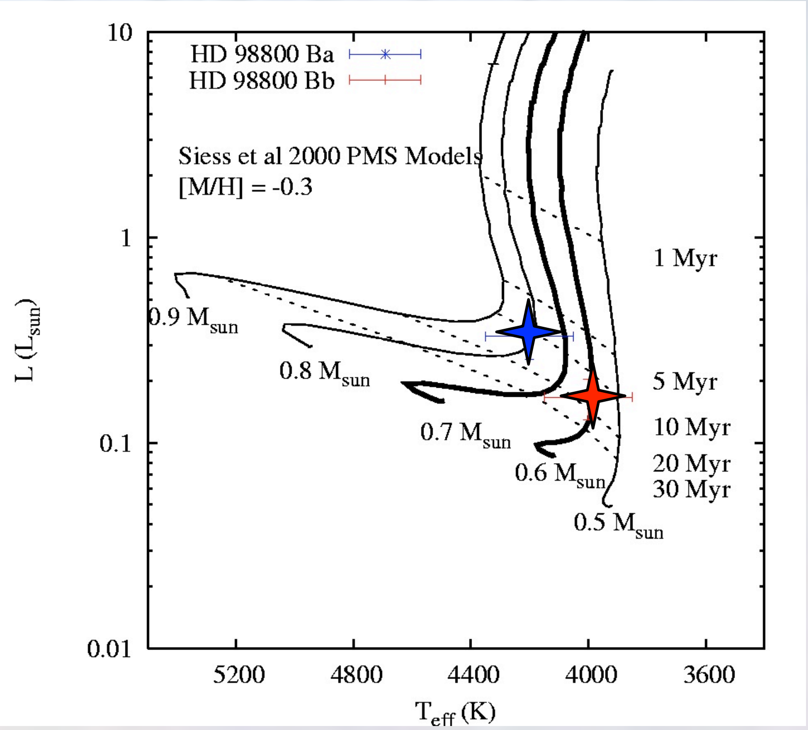


Kraus et al. (2007, A&A 466, 649)

HD 98800B: orbit and masses





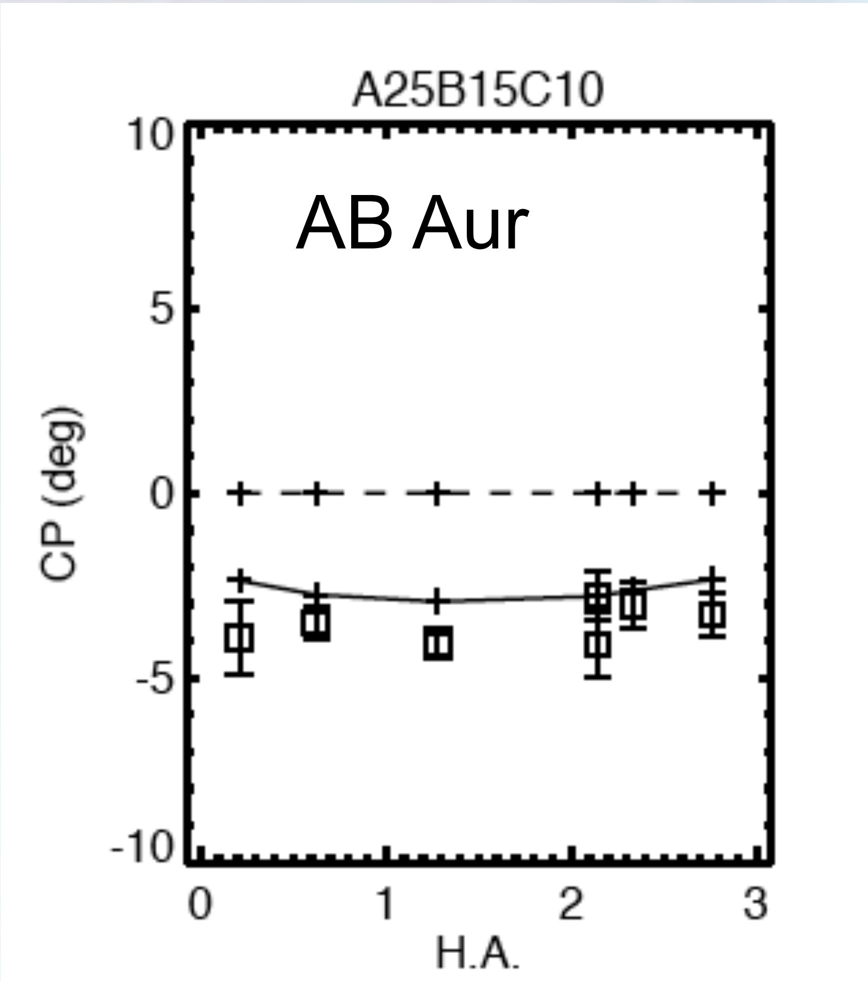


Boden et al. (2005, ApJ 635, 442)

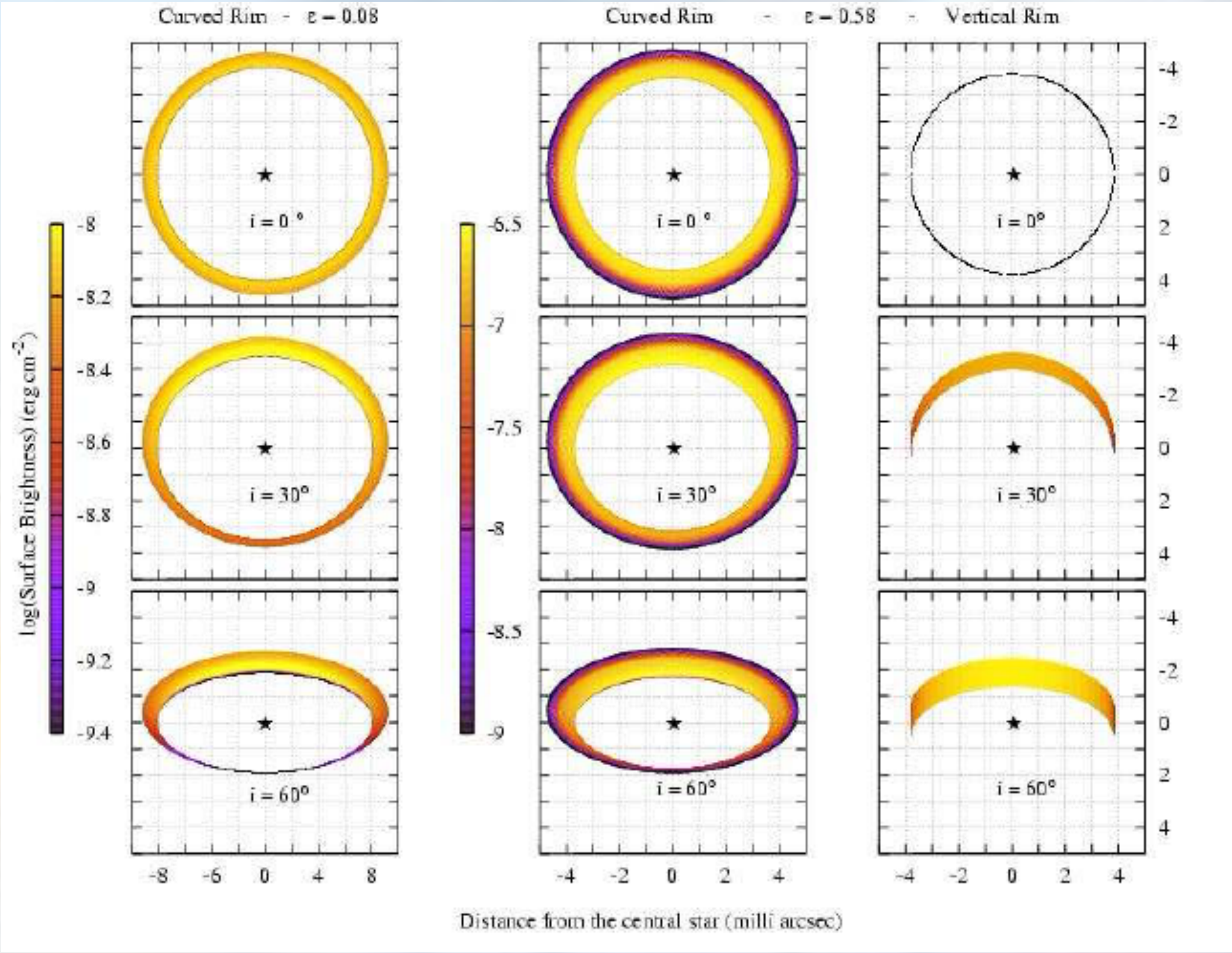
+ radial velocities

FUTURE PROSPECTS

First steps to imaging



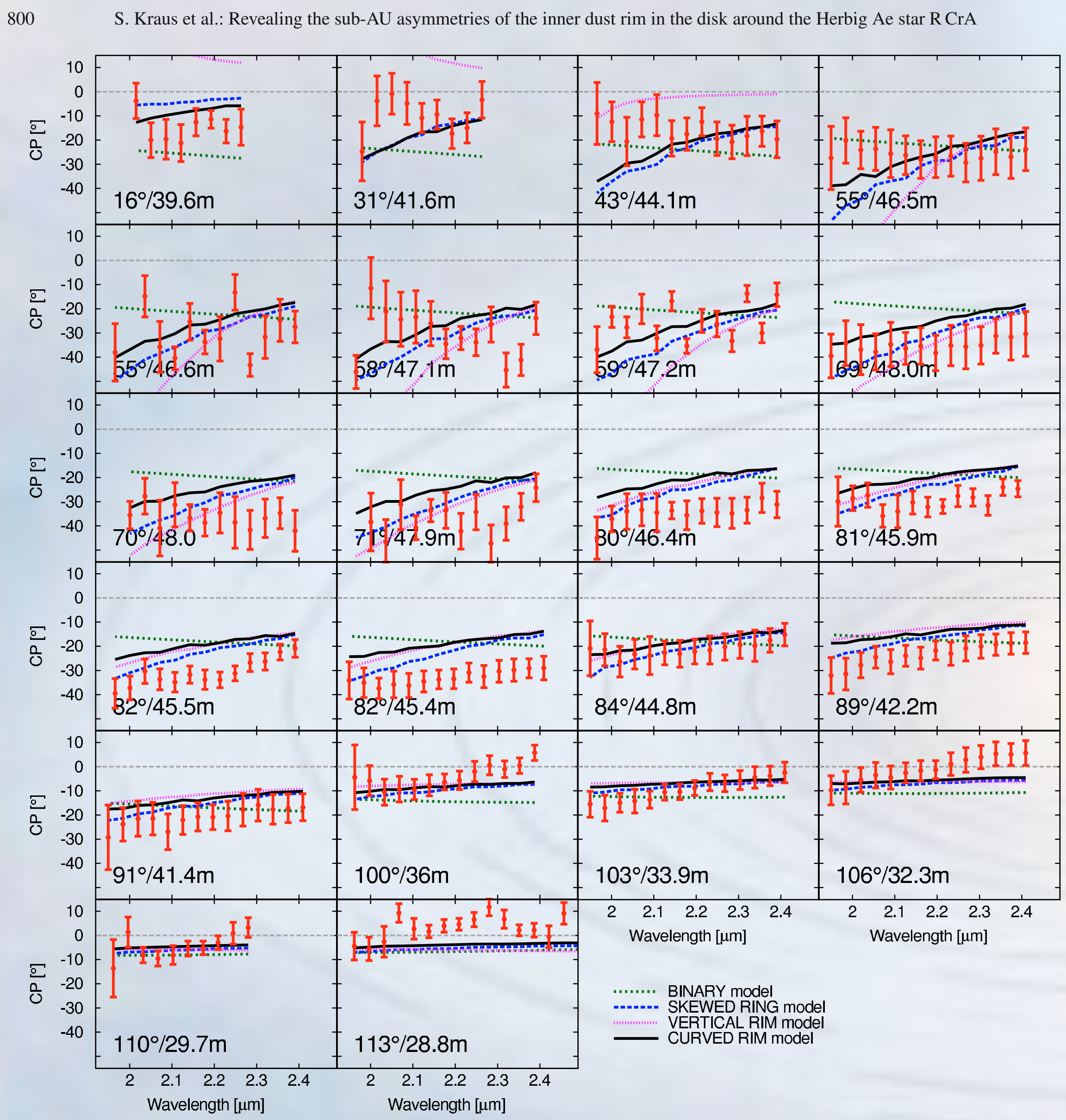
Millan-Gabet et al. (2006, ApJ 645, L77)



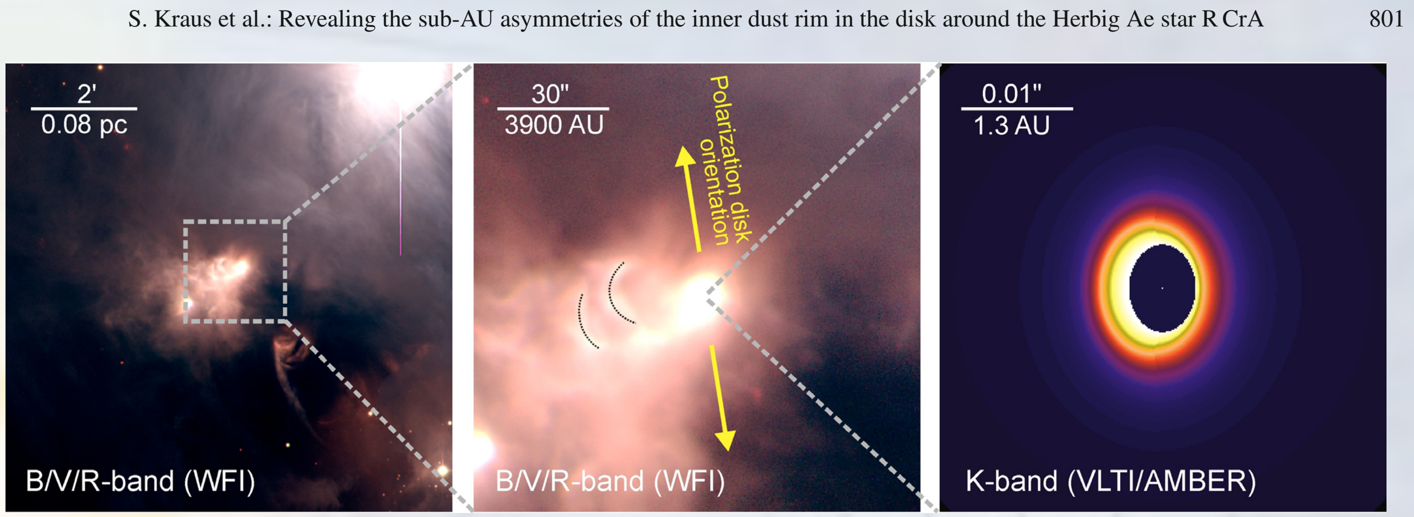
Isella & Natta (2005, A&A 438, 899)

Closure phase provides information on departure from centro-symmetry

Closure phases constrains disk geometry

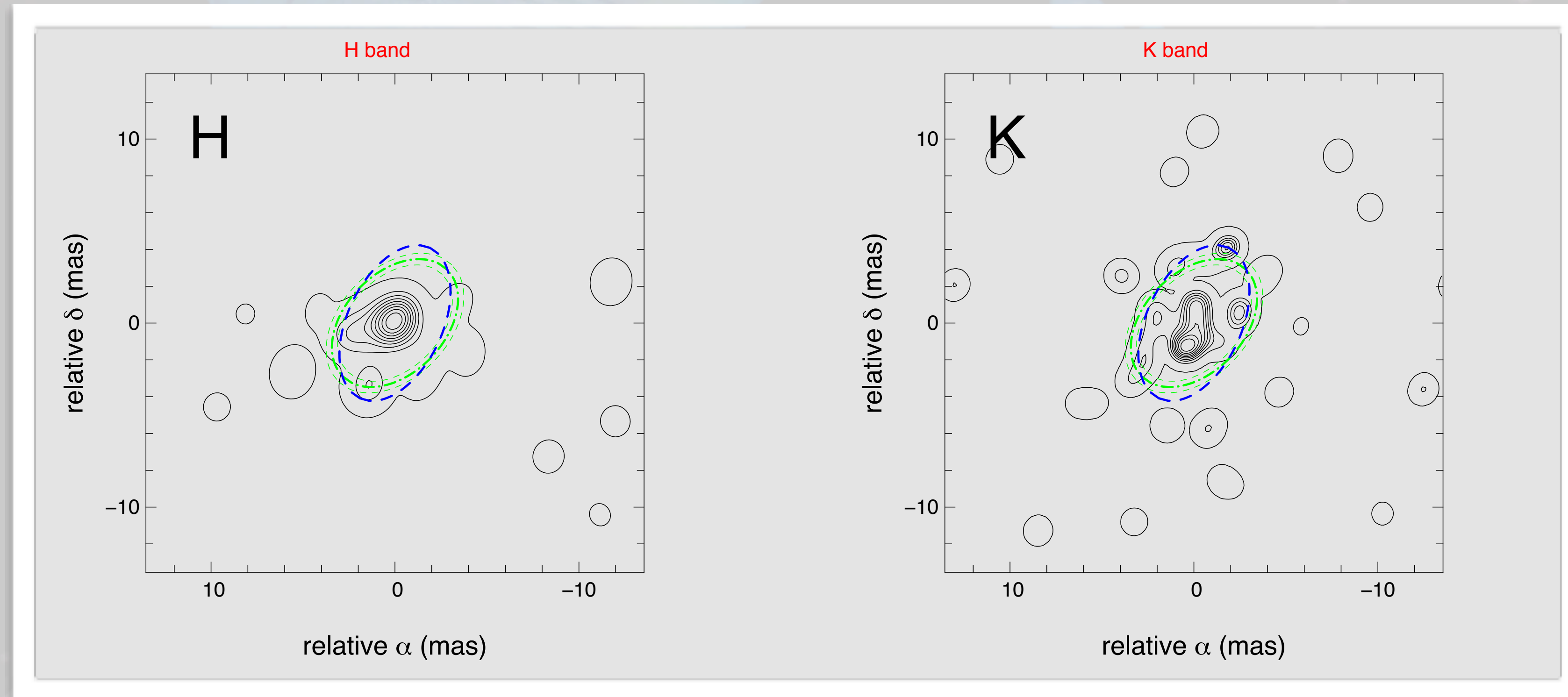


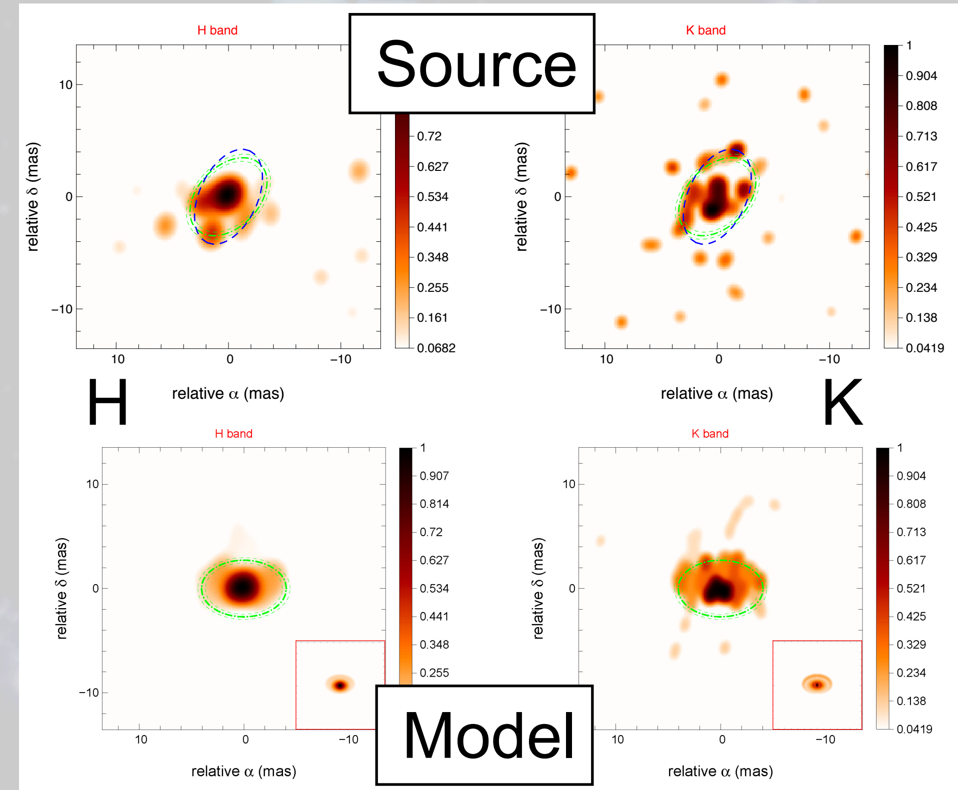
R CrA



Kraus et al. (2009)

First images of a young disk around 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

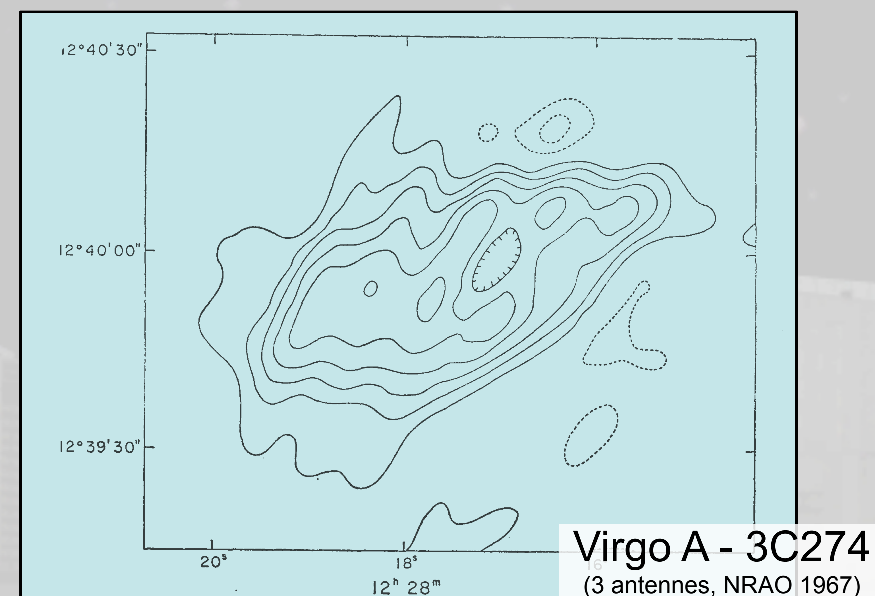


FIG. 5. The brightness distribution over the extended component of Vir A: This map was obtained from that of Plate XVII by removing two point sources, one at the nucleus and one in the jet.

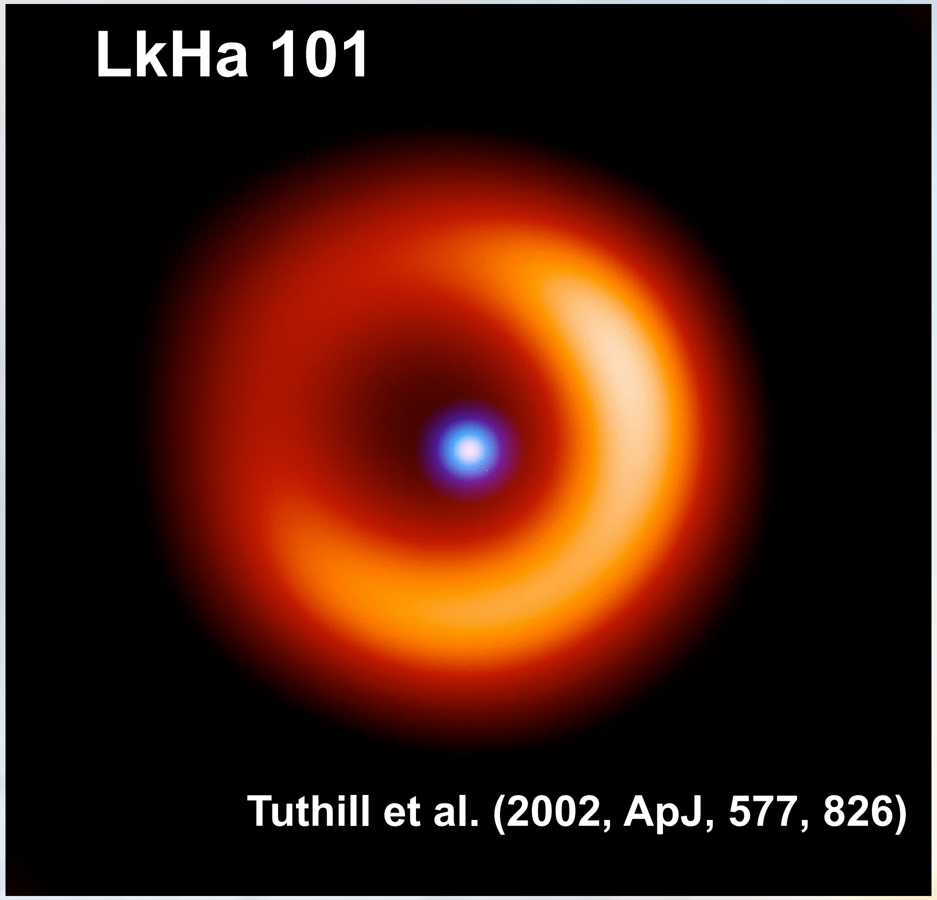
Hogg et al. (1969, AJ 74, 1206)

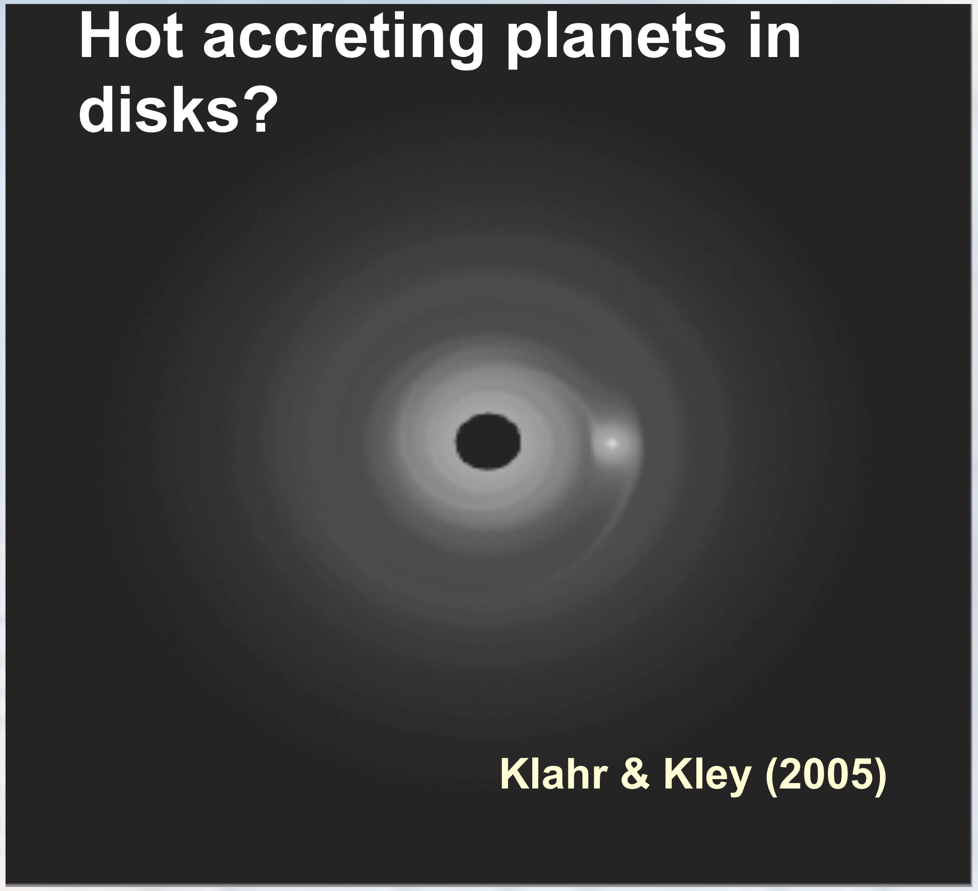
Conclusion

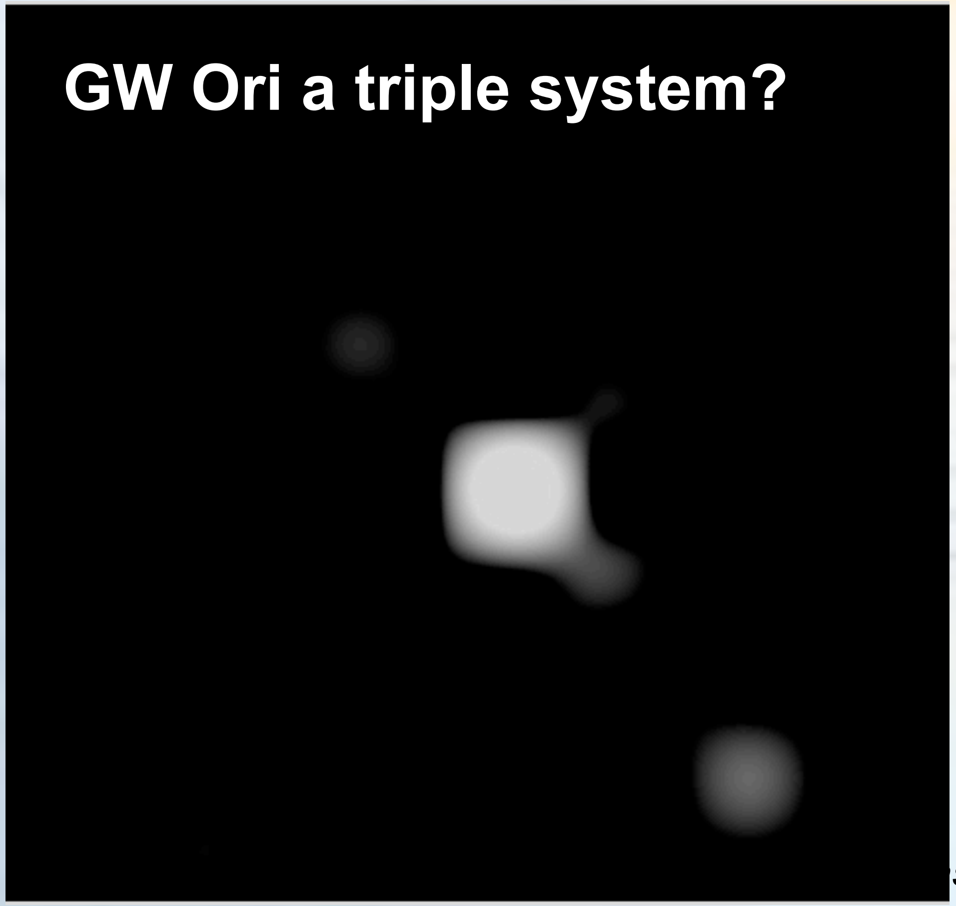
- A **major leap** in less than 10 years:
  - ~100 objects observed so far,
  - +60 refereed papers (mainly with **one baseline broad-band** observations, but it is changing).
  - new types of observations with **spectral resolution, closure phases, imaging**
- Observations are **mature enough** to allow **detailed modeling**.

More images?

Actual Imaging Data







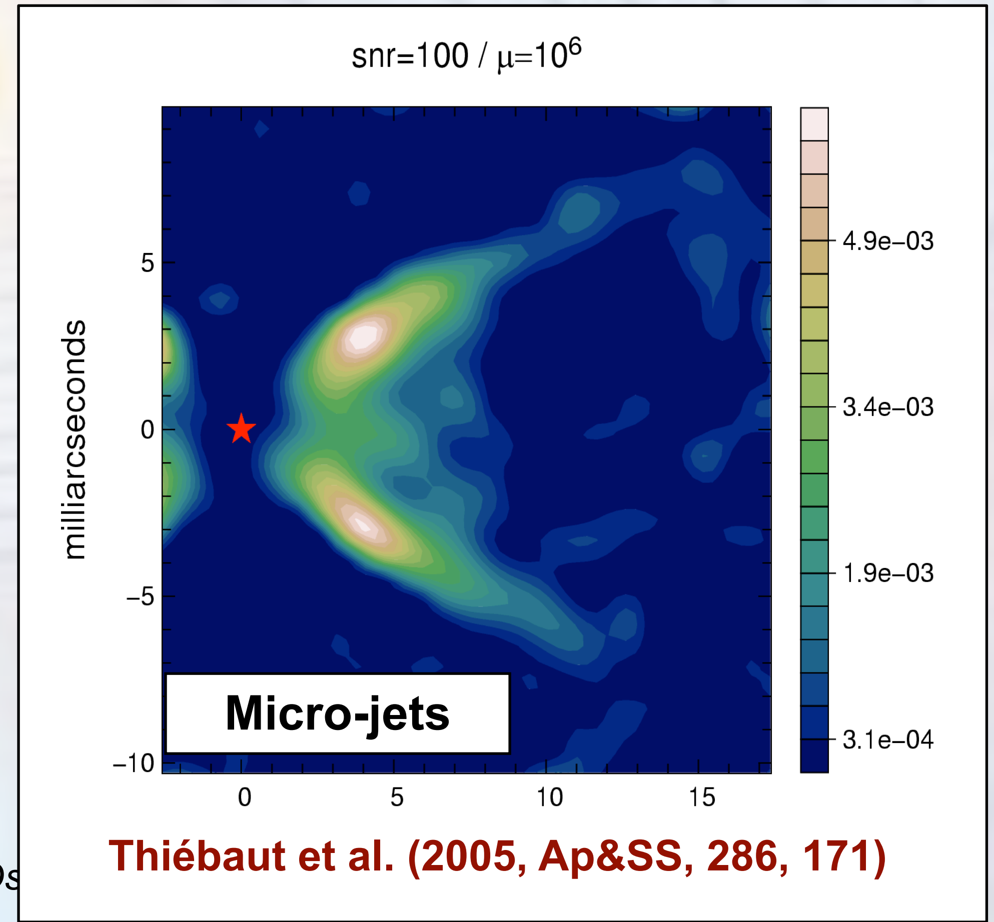
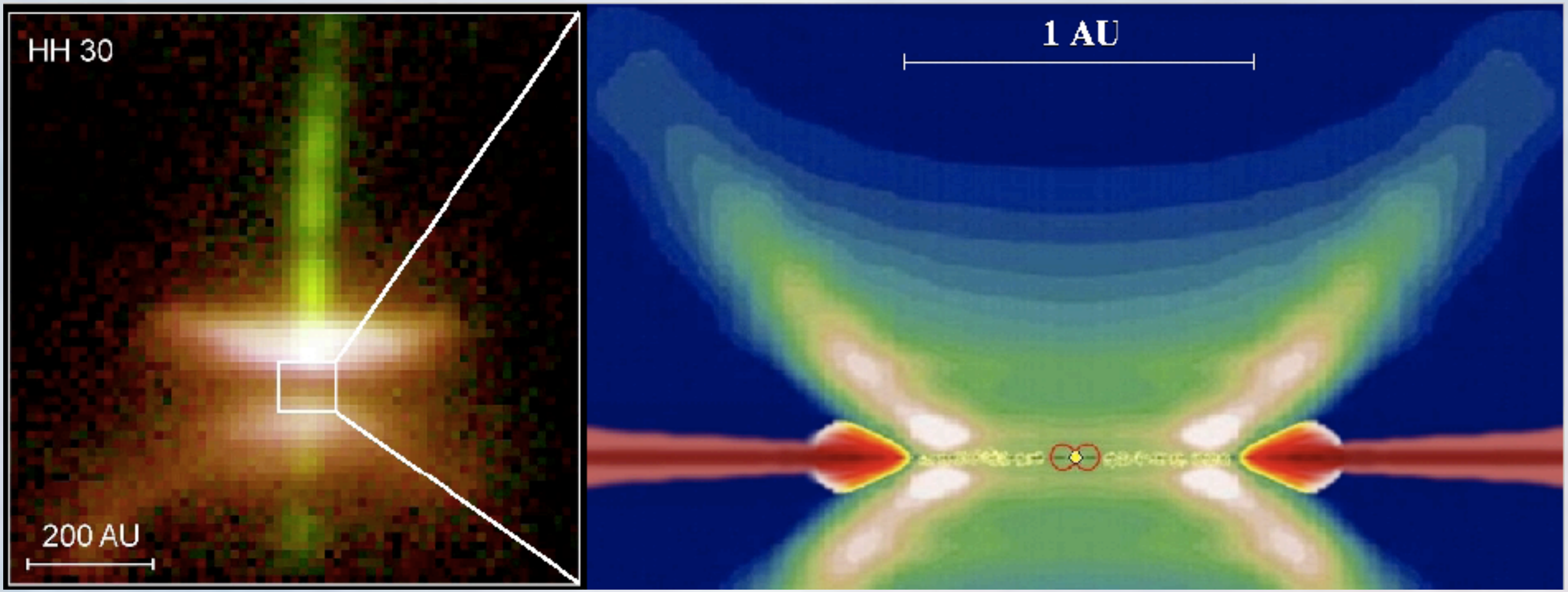


Image simulations

Open issues in YSO physics

- 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.
- Can we apply this technique to **gas disk** ?
- Origin of the **BrY emission** ?
- Companions, formation of planets

A tool to study the inner regions of Young Stellar Objects



From Isella et al. (2007)