The VLTI view of compact dusty environments around evolved stars

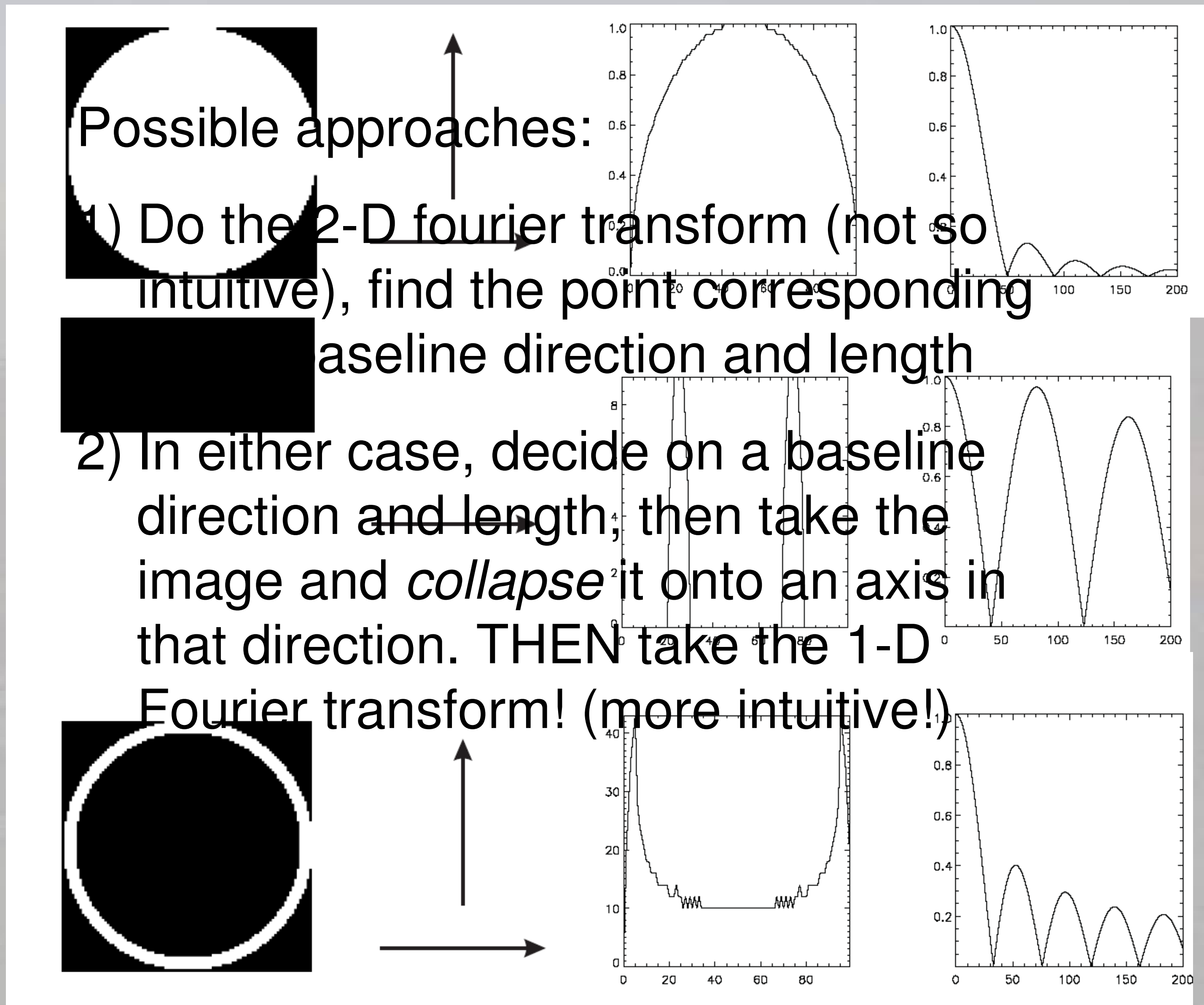
Olivier CHESNEAU
Observatoire de la Côte d’Azur (OCA)

The VLTI is at the moment in a ‘discovery’ stage, in the sense that many of the current studies have never been carried out by any optical interferometer. As a consequence, the current studies presented in this talk represent more an investigation of the possibilities of the VLTI than a focused research. The evolved stars cover a zoo of phenomena that are interesting as they provide some information of the interior and environments of stars. Due to the multiplicity of the phenomena, there is also a zoo of spectral type…

The outline of the talk is the following:

- Disk ‘hunting’ in the core of Planetary Nebulae (PNs)
    - Searching whether disks can have helped to shape PNs,
    - Searching, through the disks, the shaping agents,
- The dust formation in evolved stars,
    - Searching how dust can form efficiently in these stars
    - Searching the origin of the asymetries suspected,
- The Novae
    - Trying to detect asymetries close in space and time to the outburst,
    - Searching how dust form efficiently in dust forming event,
- The Massive stars: disks around B supergiants, wind-wind collision in evolved massive systems, study of massive Wolf-Rayet stars…

Thinking in Fourier space: 1 baseline = 1 visibility measurement per λ

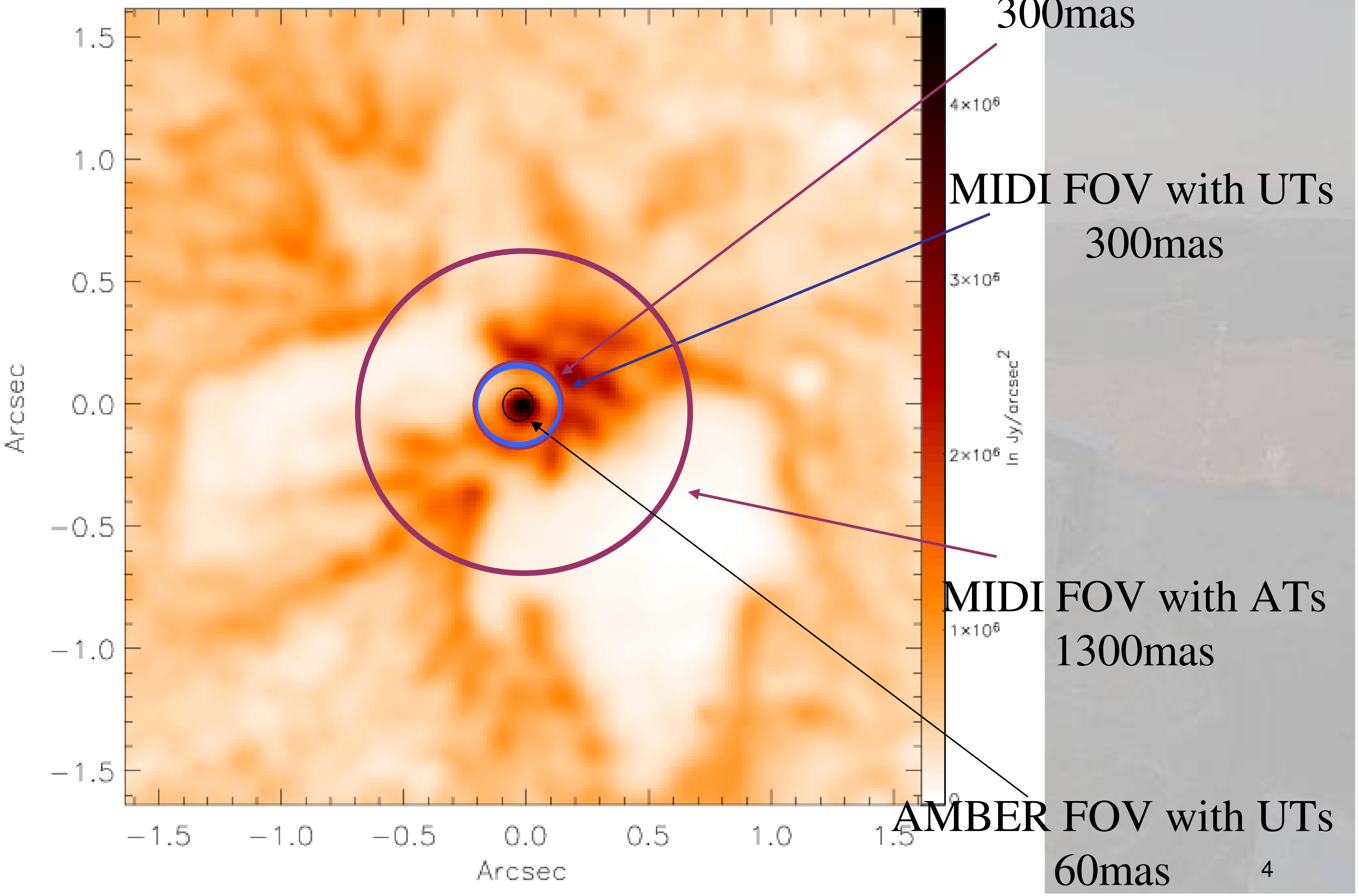


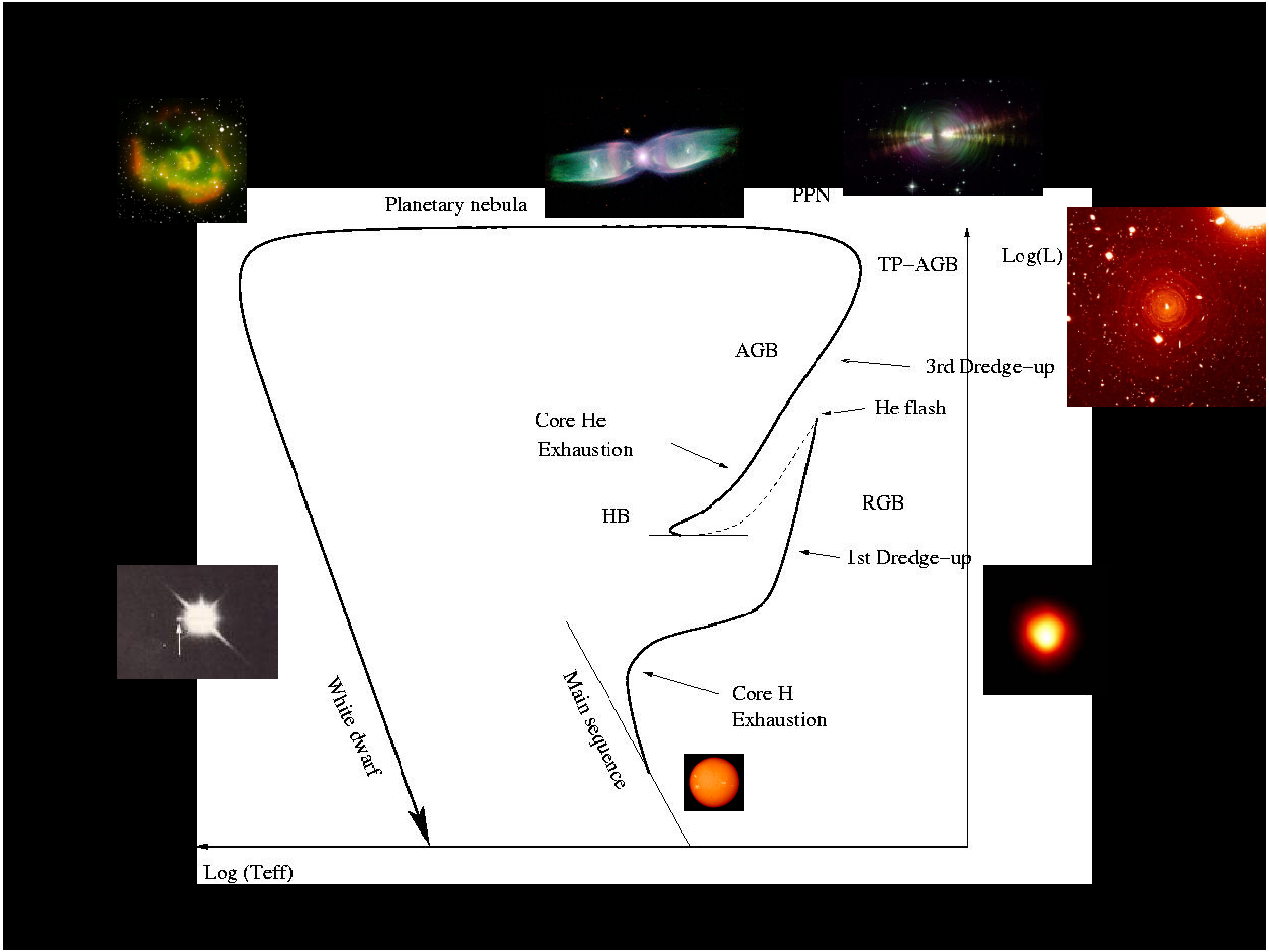
Possible approaches:

1) Do the 2-D fourier transform (not so intuitive), find the point corresponding … aseline direction and length

2) In either case, decide on a baseline direction and length, then take the image and *collapse* it onto an axis in that direction. THEN take the 1-D Fourier transform! (more intuitive!)

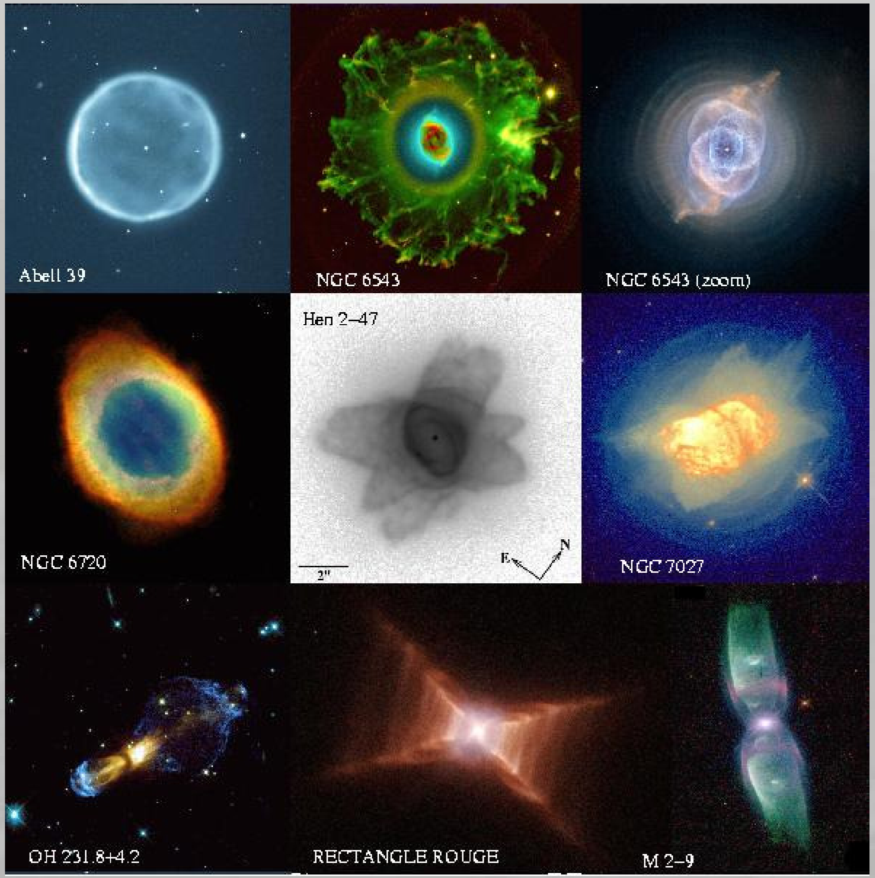
Interferometric Field-Of-View



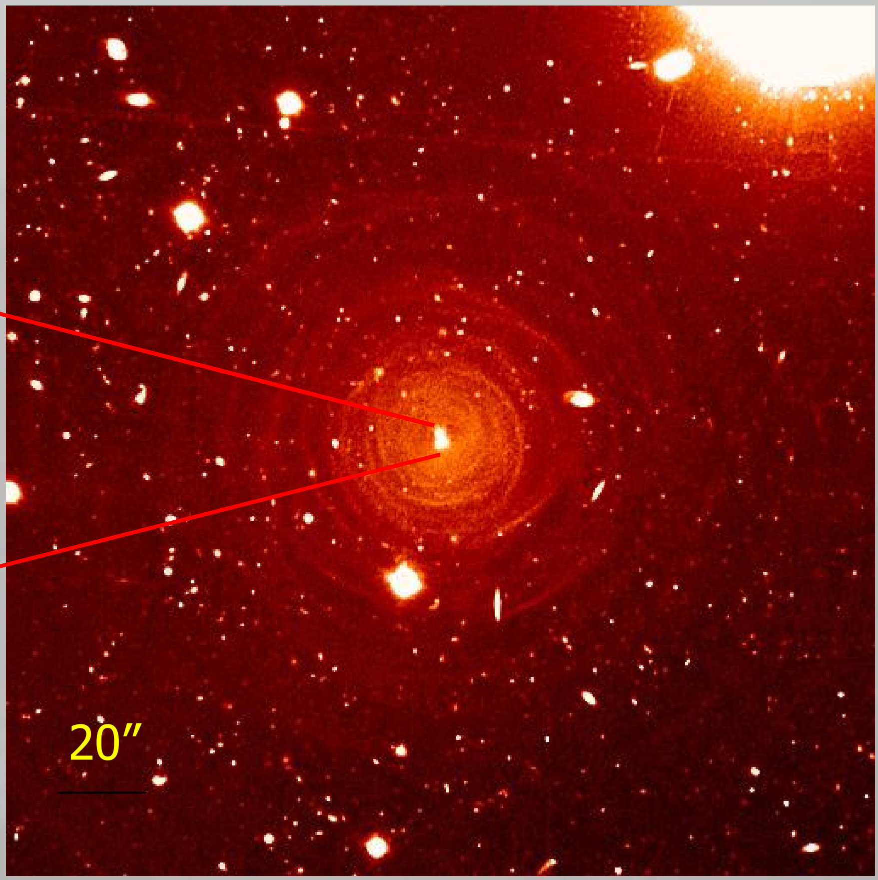


Planetary nebula
PPN
TP−AGB
Log(L)
AGB
3rd Dredge−up
He flash
Core He
Exhaustion
HB
RGB
1st Dredge−up
White dwarf
Main sequence
Core H
Exhaustion
Log (Teff)

Study of the envelopes of AGB and post-AGB stars



Different PNe

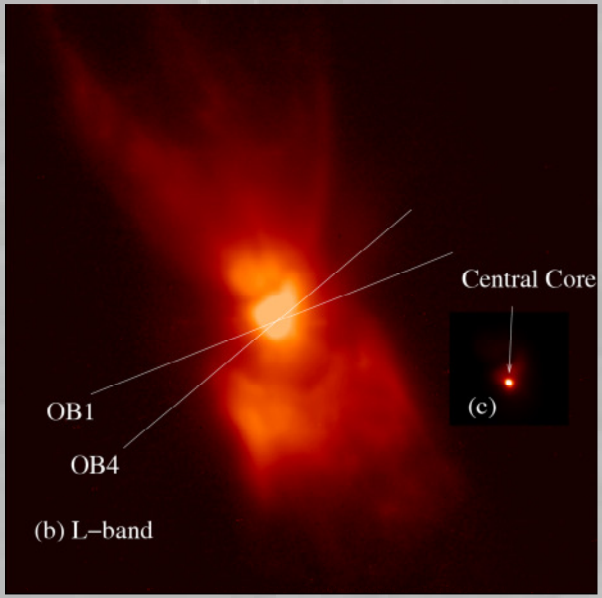


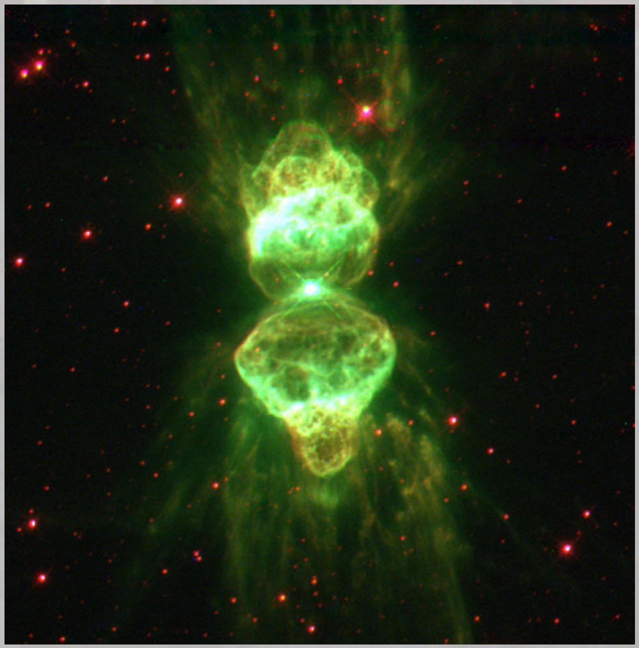
AGB star

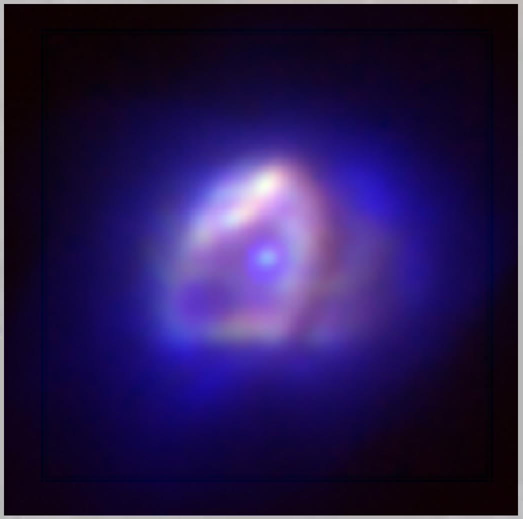
The hunting of disks in the center of Planetary Nebulae

Context: the complexity of the shapes of Planetary Nebulae witness the many physical processes that can affect the outer regions of evolved giant stars as they follow the AGB/post-AGB/PN track. Emerging magnetic fields? Binarity (taking into account Jovian-size planets)?
Nearly all models have now in common the need of a compact disk: The disk(s) are either circum-stellar or –binary.

MIDI is an ideal tool for that (with complementary observations from HST, NACO adaptive optics, VISIR mid-IR images et VLTI/AMBER near-IR interferometry)
Core Team: O. Chesneau, E. Lagadec, F. Lykou, M. Matsuura, A. Zijlstra, S. Wolf
5 systems already studied: 4 resolved with MIDI, 1 over-resolved (direct UT imaging)
Lagadec, Chesneau et al. 2006, Matsuura, Chesneau et al. 2006, Chesneau, Collioud et al. 2006, Chesneau, Lykou et al. 2007

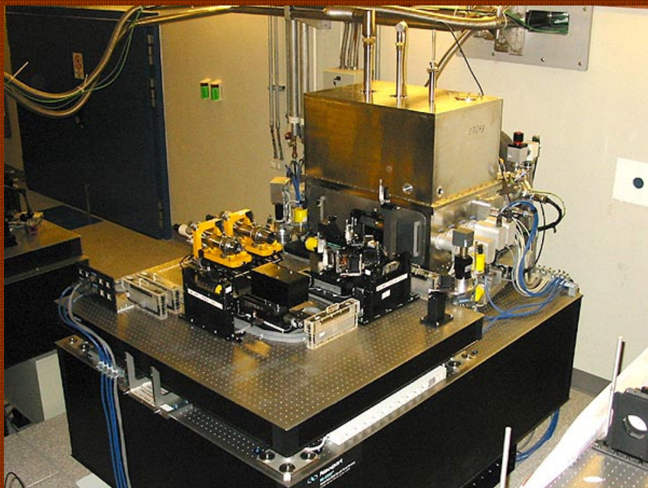






The AMBER and MIDI instruments

MIDI

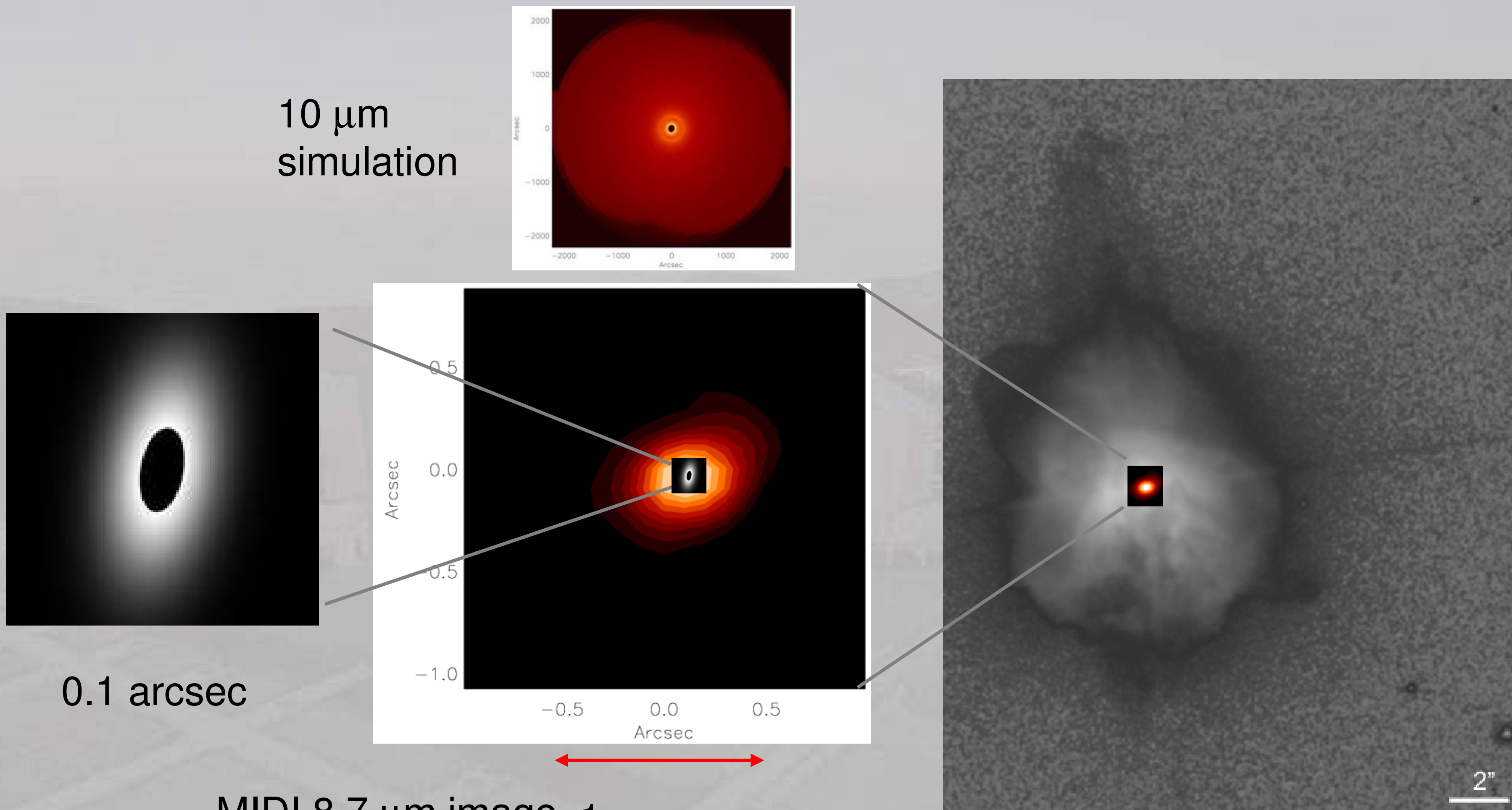


Mid-IR (8-13µm)
2 telescopes
Visibility and differential phase
R=30, 230
θ_{min}=10mas, beam=300mas

AMBER

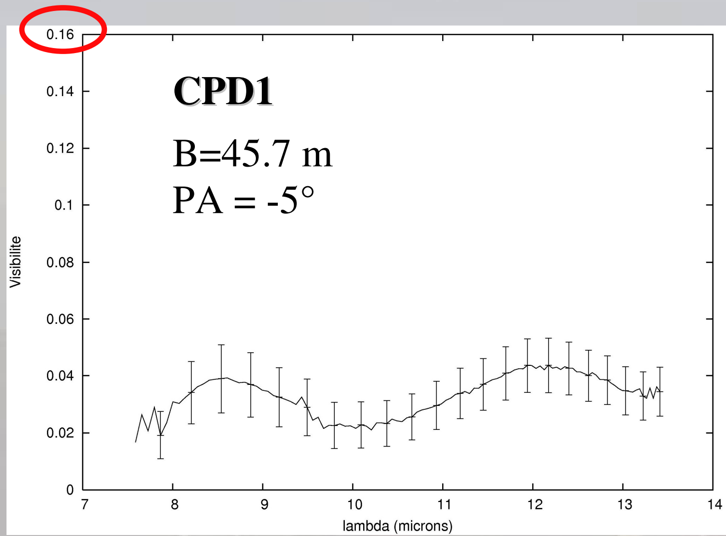
Near-IR (JHK)
3 telescopes
Visibility, differential phase and phase closure
R=30, 1500, 12000
θ_{min}=2mas, beam=60mas

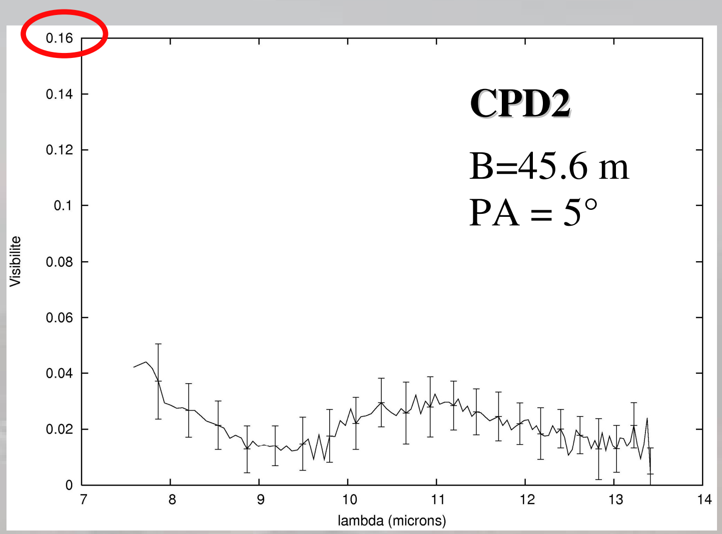
CPD –568032 seen at different spatial scales

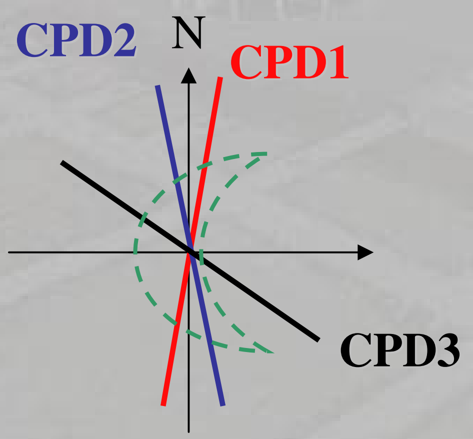


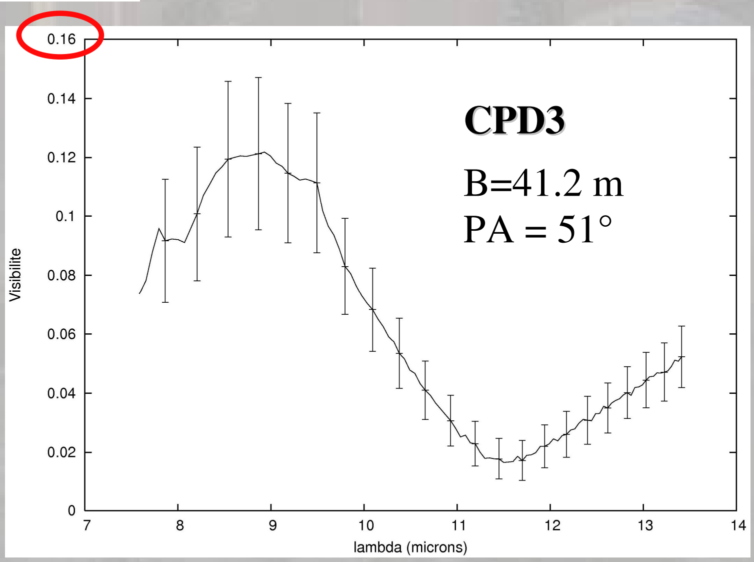
Chesneau, O., Collioud, A., De Marco O. et al., 2006, A&A

MIDI data on CPD-56°8032



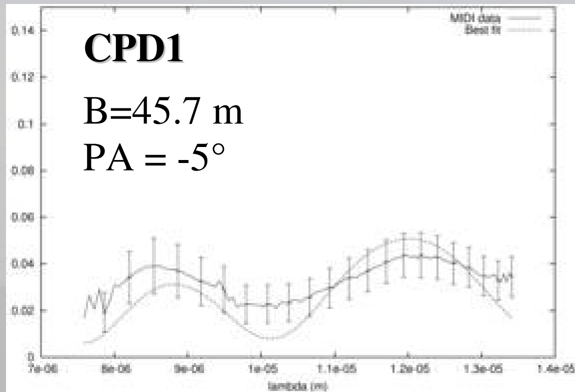


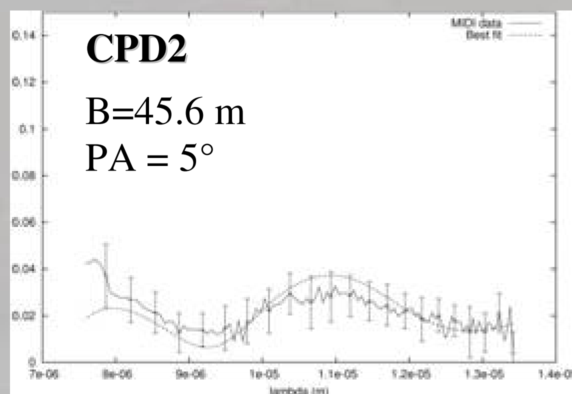


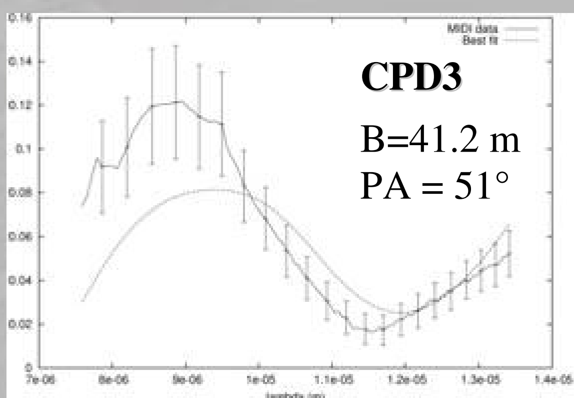


<u>Résolution</u>
36 mas à 8 μm
60 mas à 13.5 μm

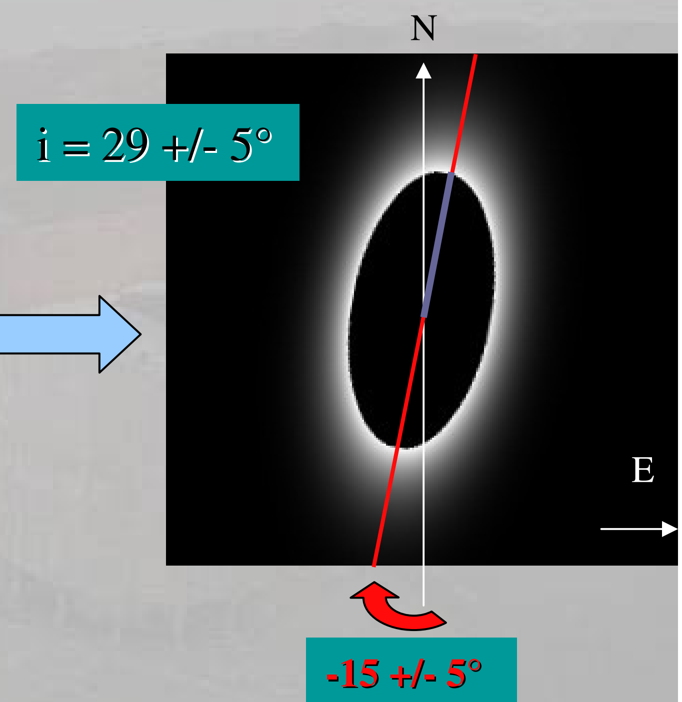
Best geometrical model for CPD-56°8032 ?







R = 72 +/- 3 mas
(110 +/- 5 UA)



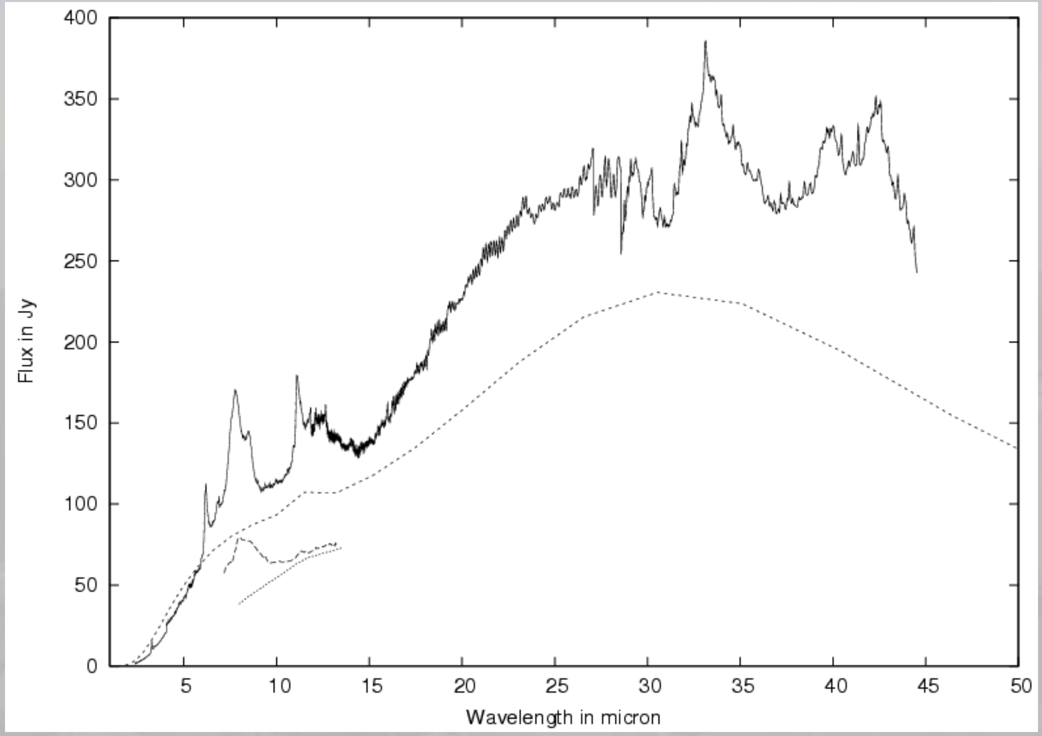
Good model ???

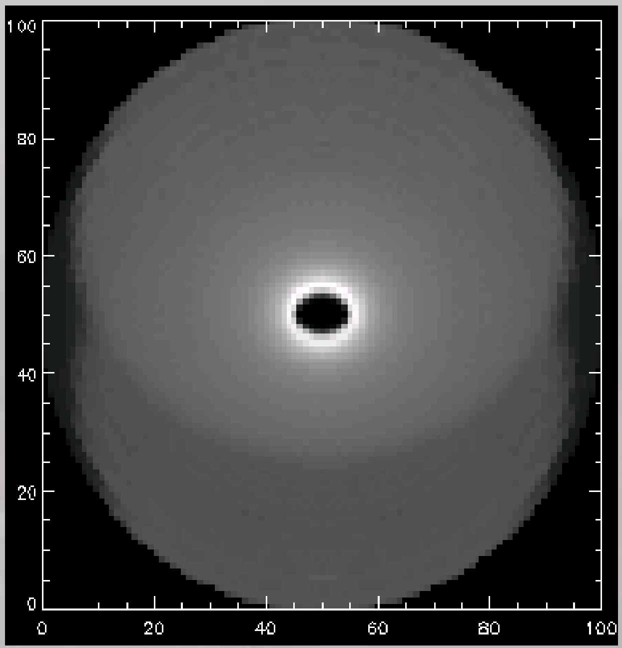
Best model

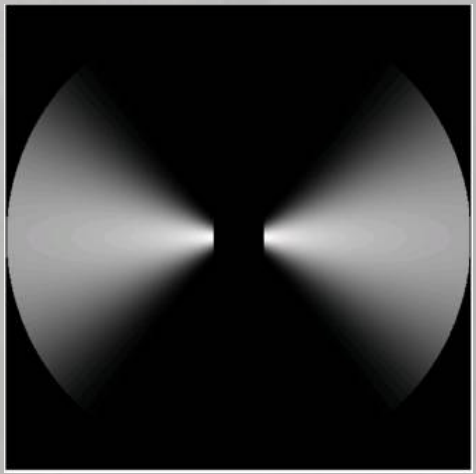
10 micron image

Résolution : 13 mas
par pixel

SED fit based on carbon chemistry only







$$\rho(r,z) = \rho_o \left(\frac{R_*}{r}\right)^{\alpha} \exp\left[-\frac{1}{2}\left(\frac{z}{h(r)}\right)^2\right]$$

Passive disk model

$$h(r) = h_o \left(\frac{z}{R_*}\right)^{\beta}$$

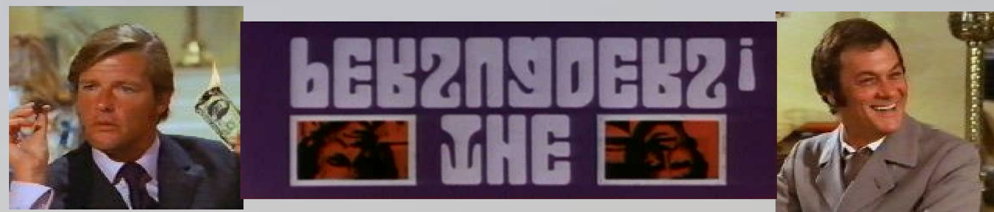
Difficulties encountered

- Dusty structure optically thin: projection effects, and inclination not constrained much→Complex geometry, an *image* is required, not only visibilities
- Extended object→link for low frequencies mandatory→ NACO/deep VISIR high spatial resolution (50-100mas) imaging required!

Lessons learned

- These sources are close to be resolved at 50-300mas scale,
- High spatial resolution complementary techniques are absolutely required, to encompass the complexity of the source: NACO, VISIR (and HST), and avoid to over-resolve the source by the VLTI
- We have to concentrate on 'simpler targets' for which the inclination (at least) is better constrained: i=0° PNs, or i=90° strongly asymmetric bipolar nebulae
- Based on the work from Smith et al. 2003, 2005, we have chosen two well known targets:

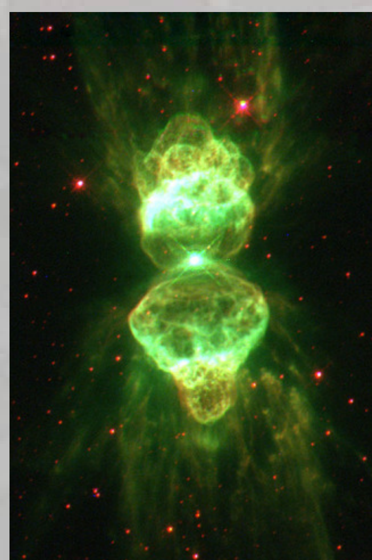
The bipolar PNs Mz3 and M2-9



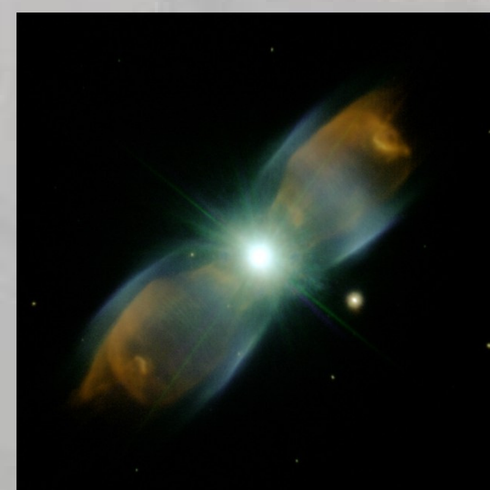
- Central Stars
  - Not observable,
  - Bright core, many emission lines, unresolved at 0.1” scale

- Nebula [Santander-Garcia et al. 2004, Guerrero et al. 2007, Schwartz et al.]
  - Bipolar with very narrow waist,
  - Strong IR emission → dust, in core and in lobes
  - SED similar in flux and shape,
  - Distance: ~1.5 kpc (but large range…)

Menzel 3 (Mz3)
The Ant

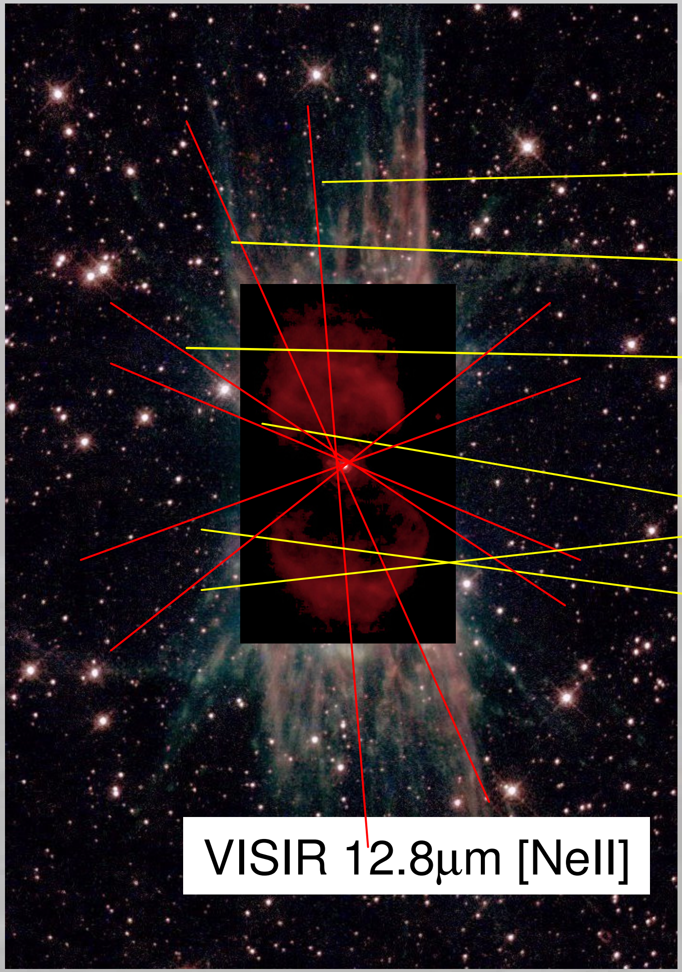


M2-9
The Butterfly

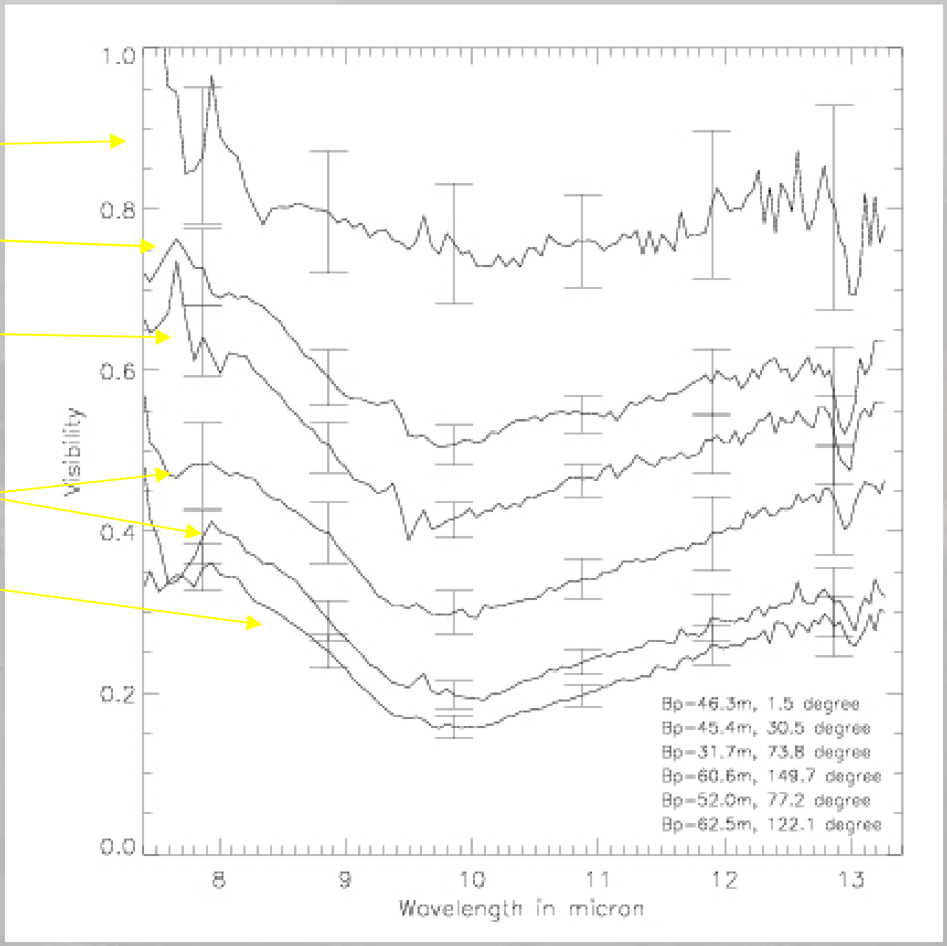


An amorphous silicate disc in the Ant nebula, Mz 3

Chesneau, O., Lykou, F. et al., 2007, A&A



HST observations



MIDI visibilities for different baselines orientations

Density (2d disk)

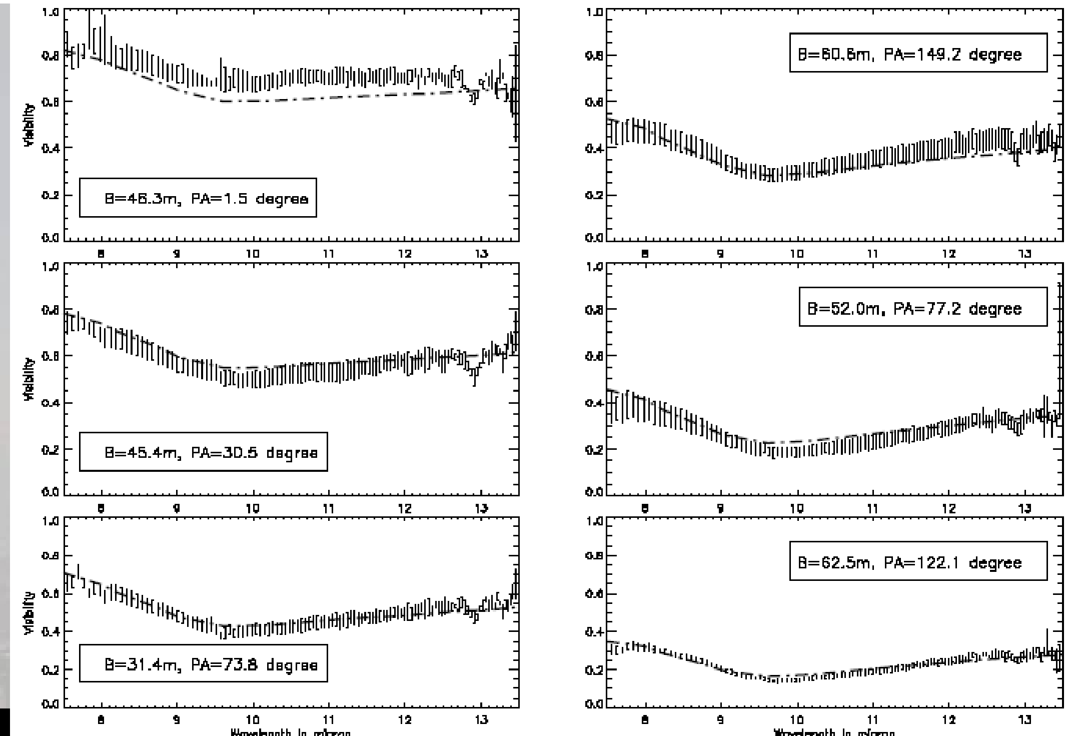
$$\rho(r,z) = \rho_o \left(\frac{R_*}{r}\right)^{\alpha} \exp\left[-\frac{1}{2}\left(\frac{z}{h(r)}\right)^2\right]$$

with

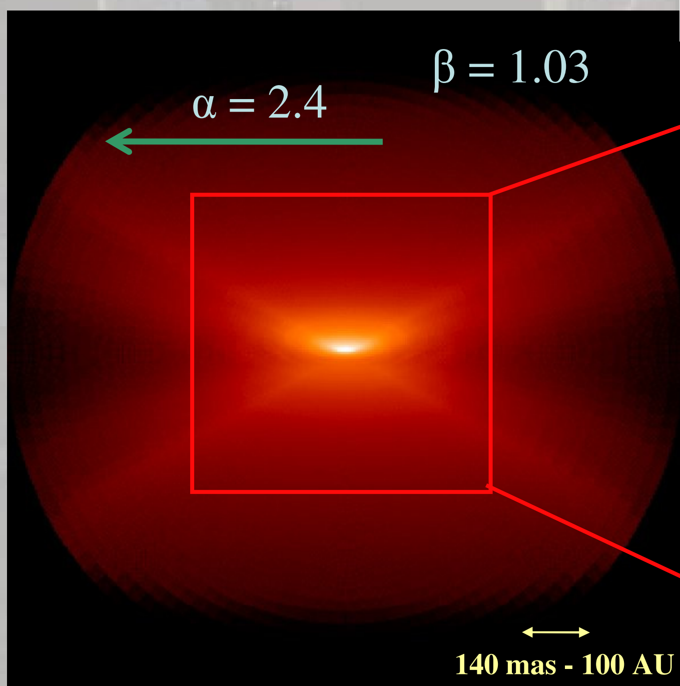
$$h(r) = h_o \left(\frac{z}{R_*}\right)^{\beta}$$

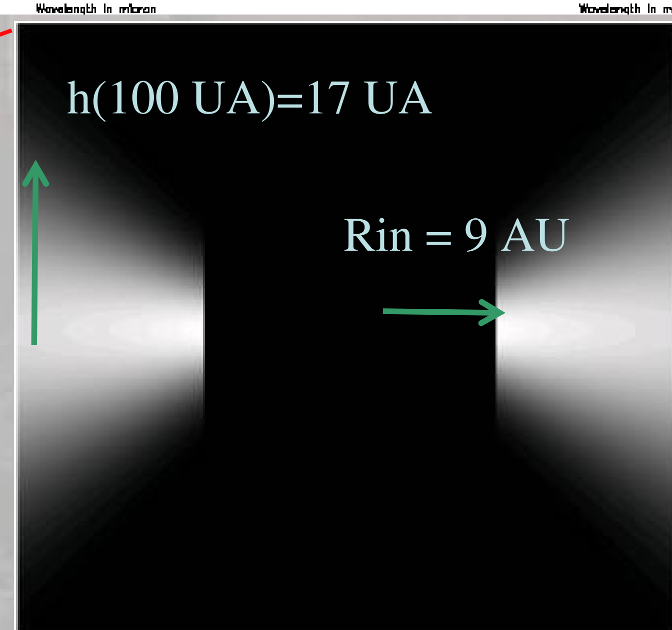
$\alpha = 2.4 \quad \beta = 1.03 \quad h_{100AU} = 17$ AU

VERY GOOD FIT, VISIBILITY+SED

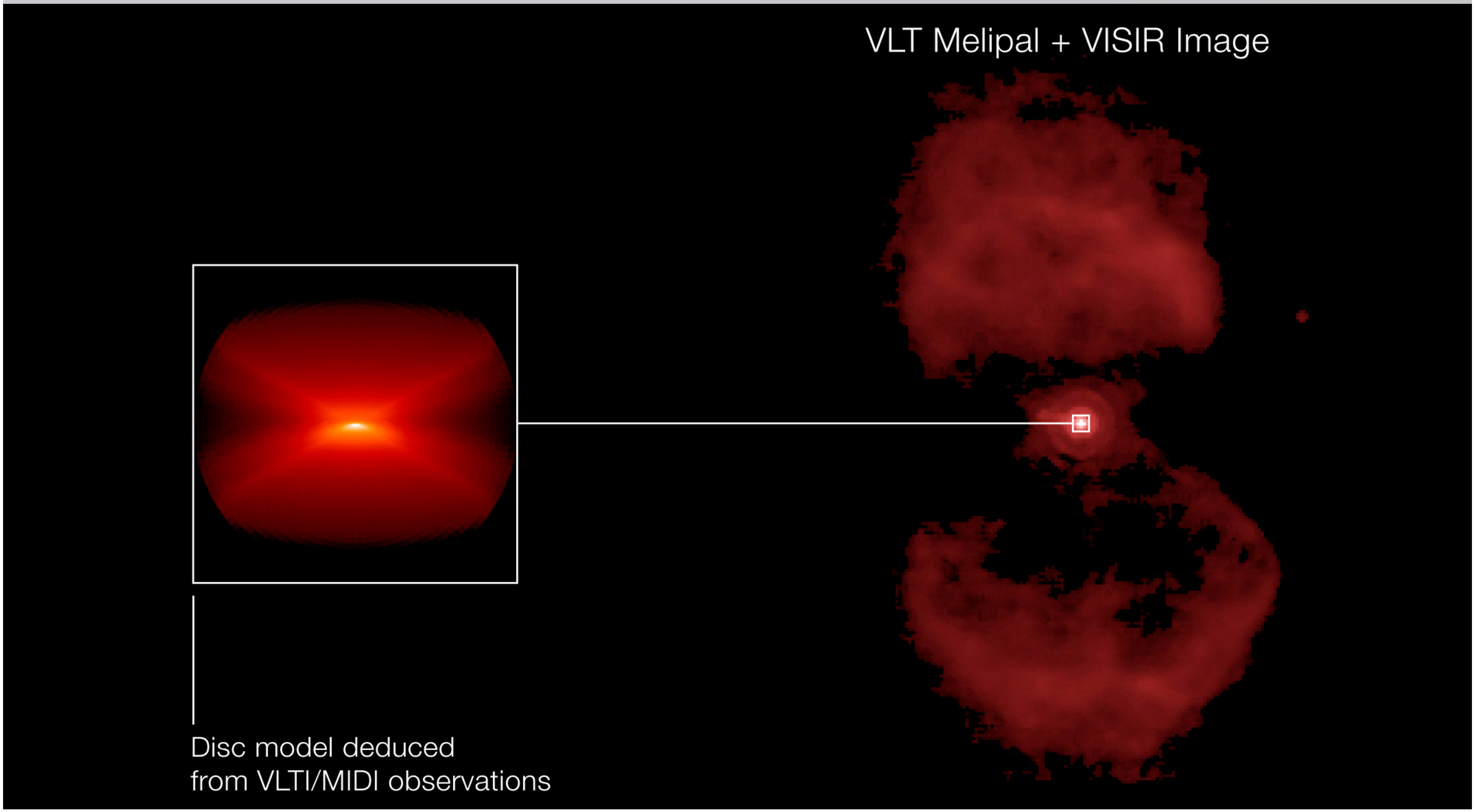


500 AU



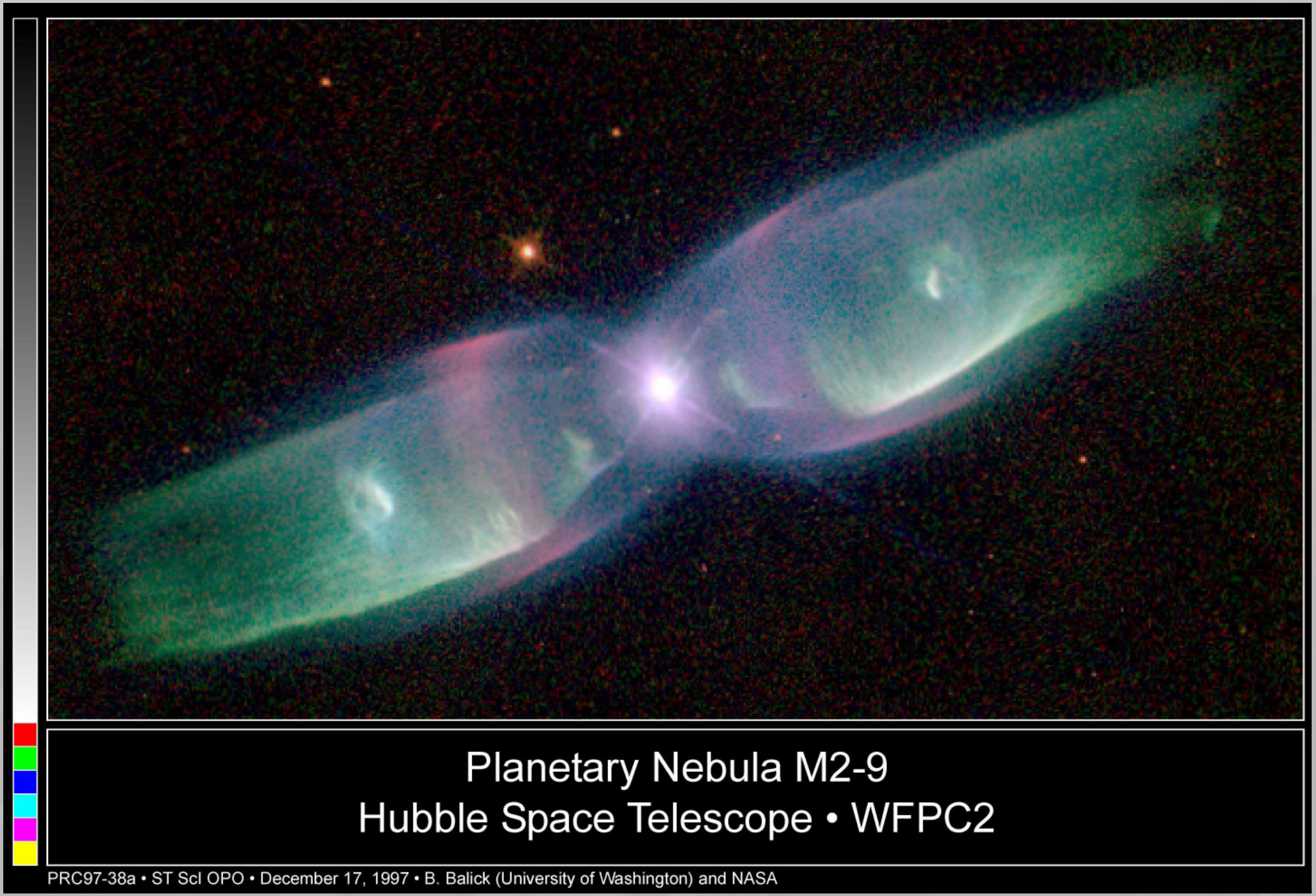


Which scenario for the formation of Menzel 3?

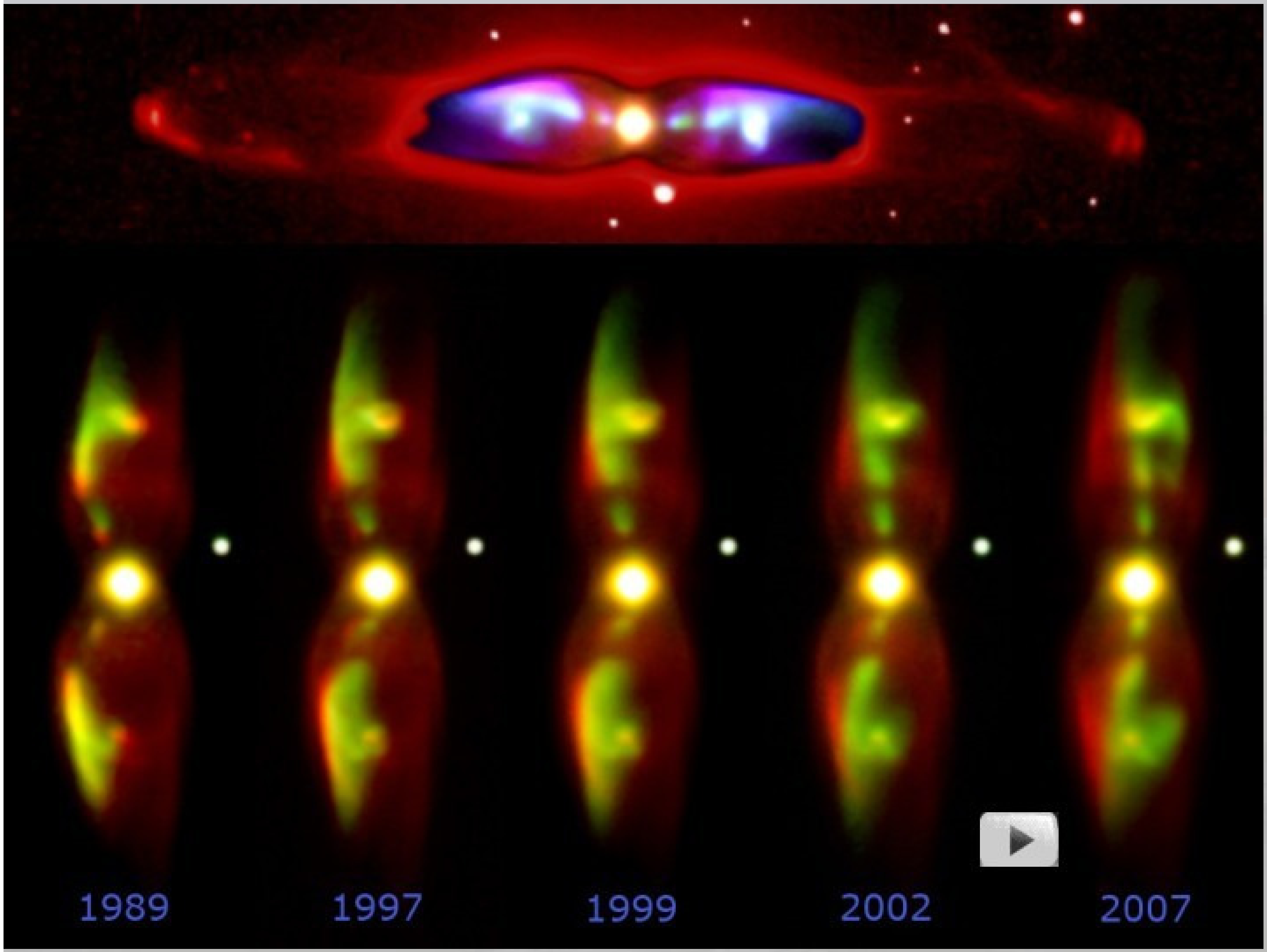


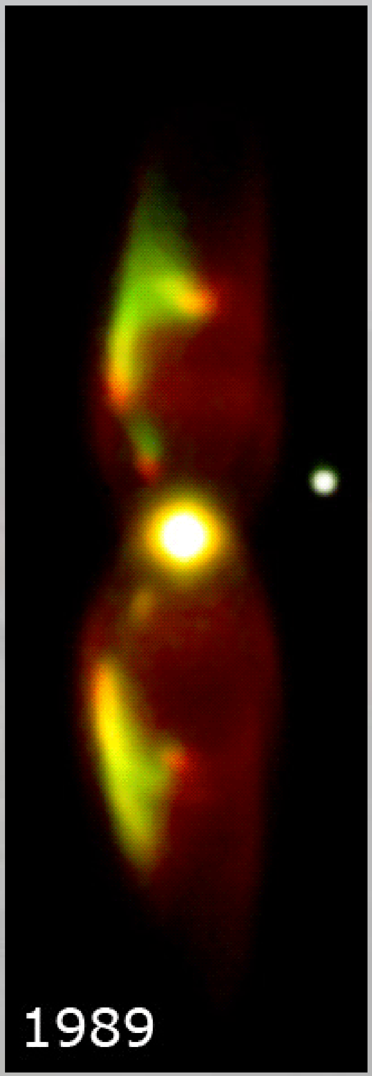
A Disc in the Ant Nebula

ESO Press Photo 42/07 (27 September 2007)


Planetary Nebula M2-9
Hubble Space Telescope • WFPC2
PRC97-38a • ST ScI OPO • December 17, 1997 • B. Balick (University of Washington) and NASA

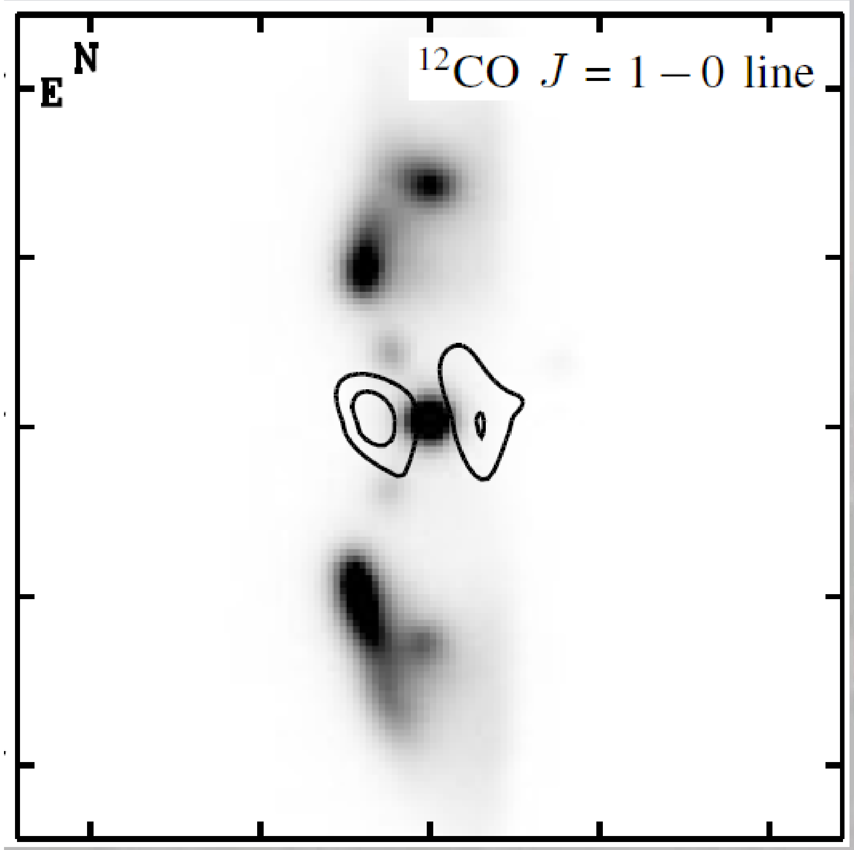
The light-house effect of M2-9, the Butterfly

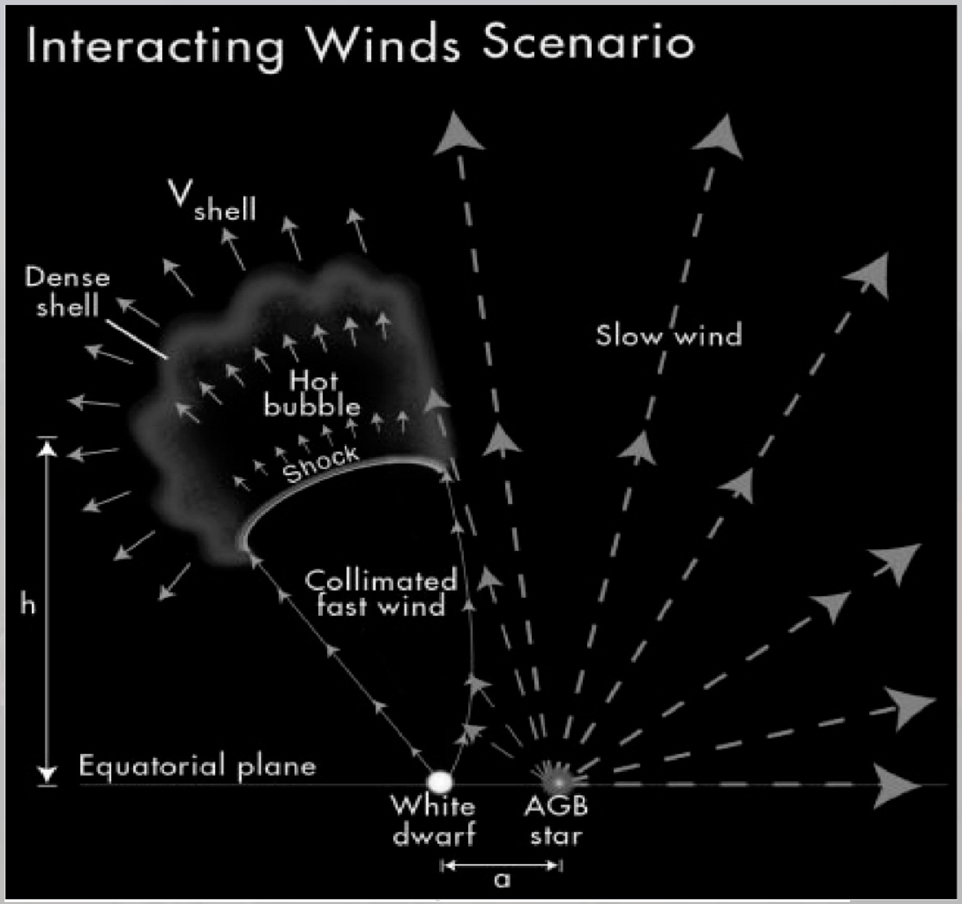




http://antwrp.gsfc.nasa.gov/apod/ap070618.html

A long-lived silicate disc in M2-9?





MIDI obs. to be continued…
PdB proposal submitted

Soker & Livio (2001)

WORK IN PROGRESS! (F. Lykou et al.)

The symbiotic system HM Sge

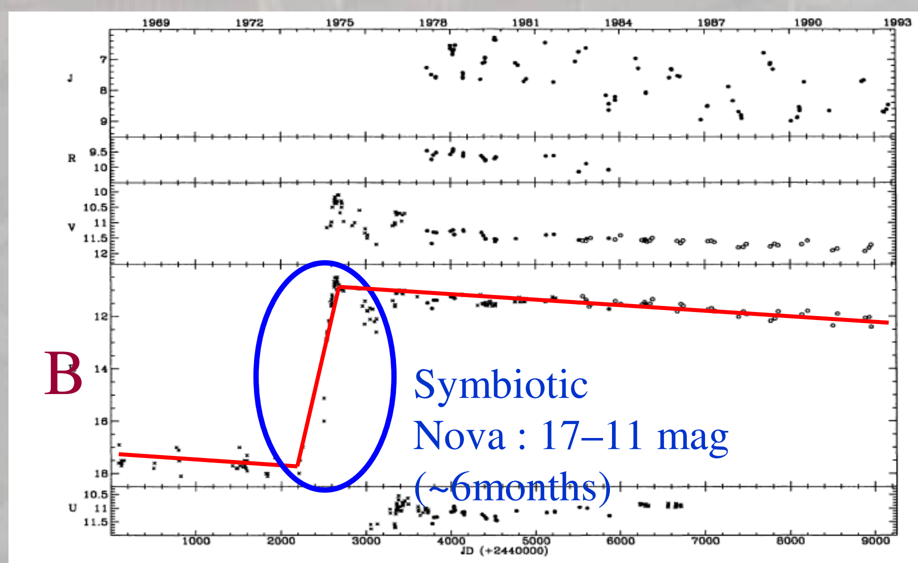
HM Sge :

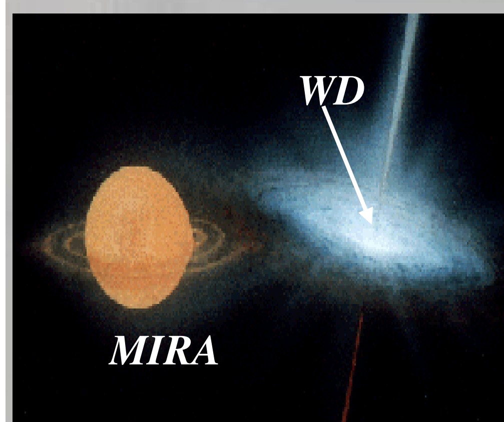
✓ **Dusty symbiotic system (d~1.5 kpc), large separation 40mas~60 AU (Sources isolated with HST, Eyres et al. 2001)**

✓ **Nova-like explosion (1975), unknown system before**

✓ **Cold component: pulsating Mira (3000 K) +**
Hot component: White Dwarf (2×10^5 K)

HST: Eyres et al.



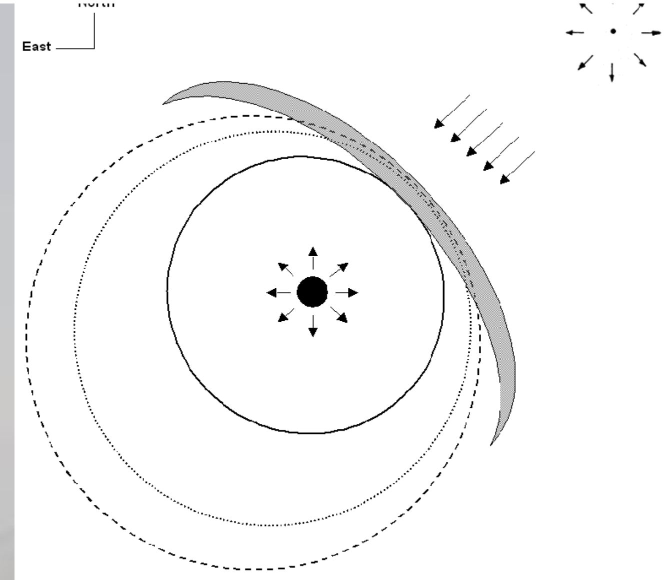


HWHM~8 mas at 8.5µm (~12AU), flattening 0.8,

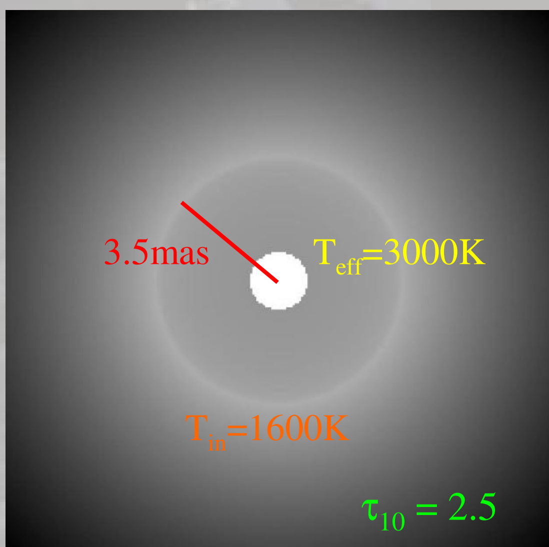
Major axis ***perpandicular*** to binary orientation

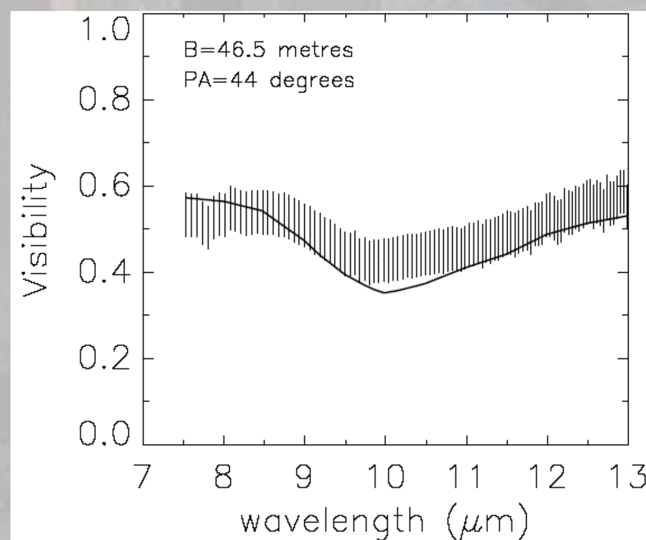
HWHM~13 mas at 13.5µm (~22AU), flattening ~1

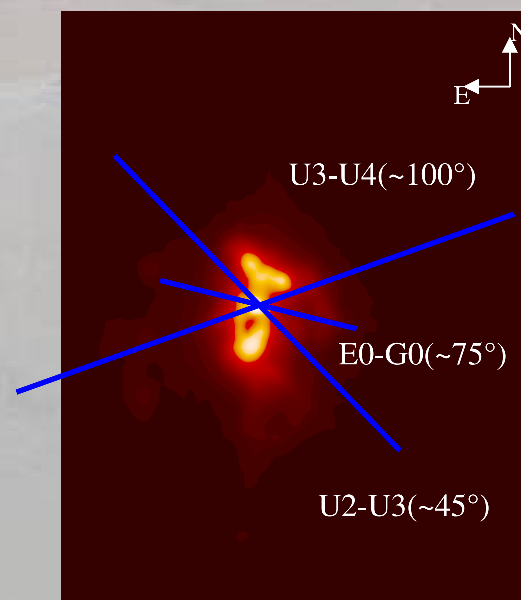
Mira distorted wind or wind-wind collision?
Imaging+high dynamical range needed (VLTI second generation+extreme AO)



MIDI Observations with UTs/ATs: 6 bases
Various DUSTY models from literature tested,
Double shell models discarded (Schild et al. 2000, Bogdanov & Taranova 2001)



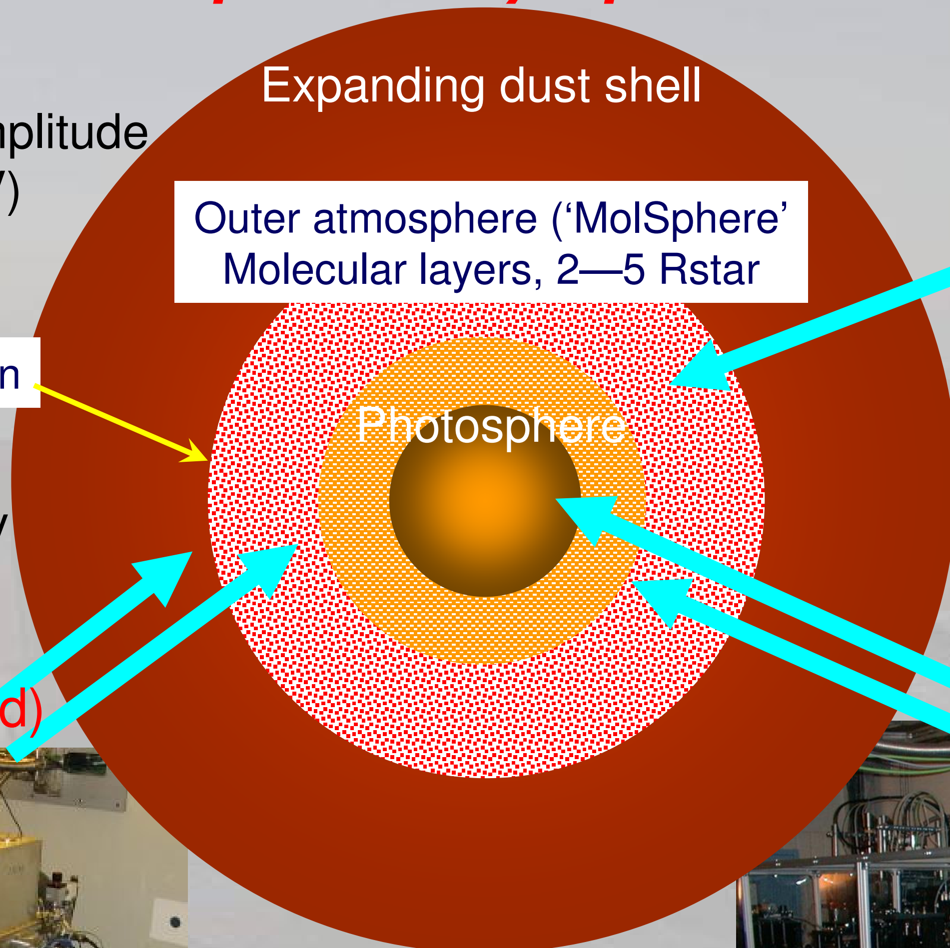




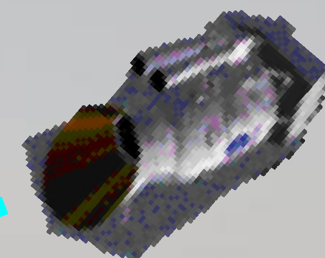
Sacuto, S., Chesneau, O., Vannier, M., et Crusalèbes, P. 2007, A&A, 465, 469

IR interferometry of Mira stars

Mira variables:
Large variability amplitude
~ 9 mag (in V)



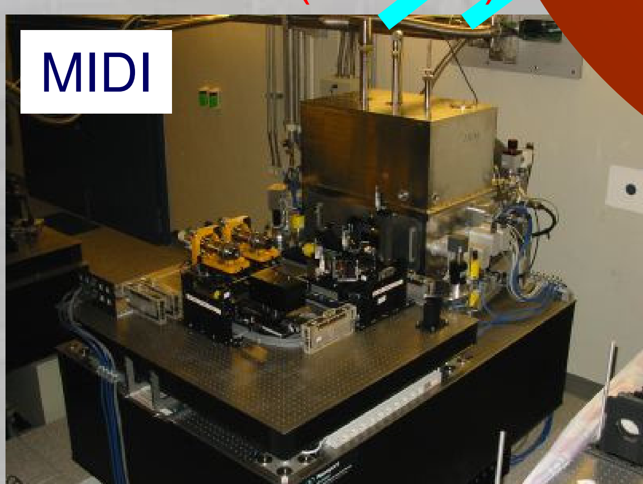
Dust formation



ISO & high-resolution spectroscopy,
Spatially unresolved

Spectro-interferometry
Spatial + Spectral resolution
Mid-infrared (*N* band)

Near-infrared (JHK)



MIDI

AMBER

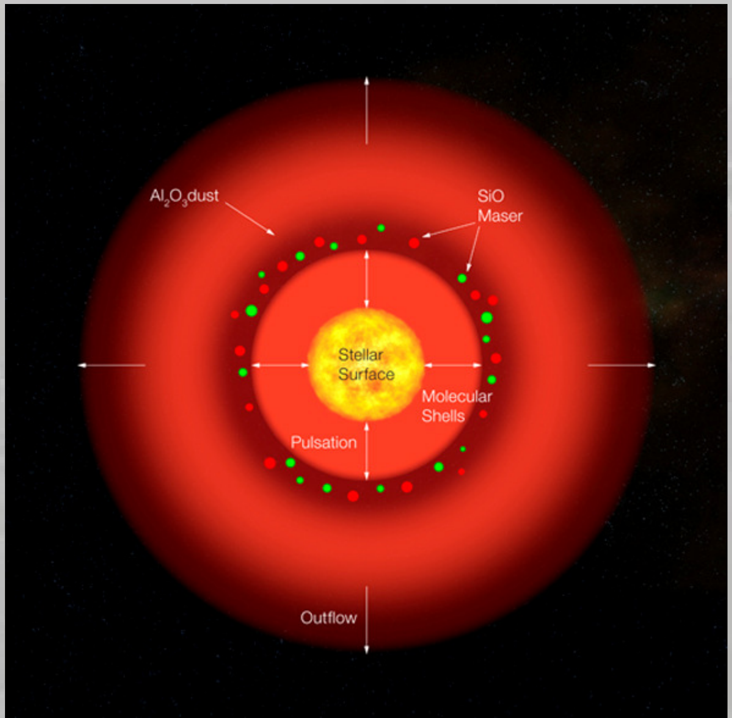
From K. Ohnaka

Numerous papers from K. Ohnaka, M. Wittkowski and collaborators.

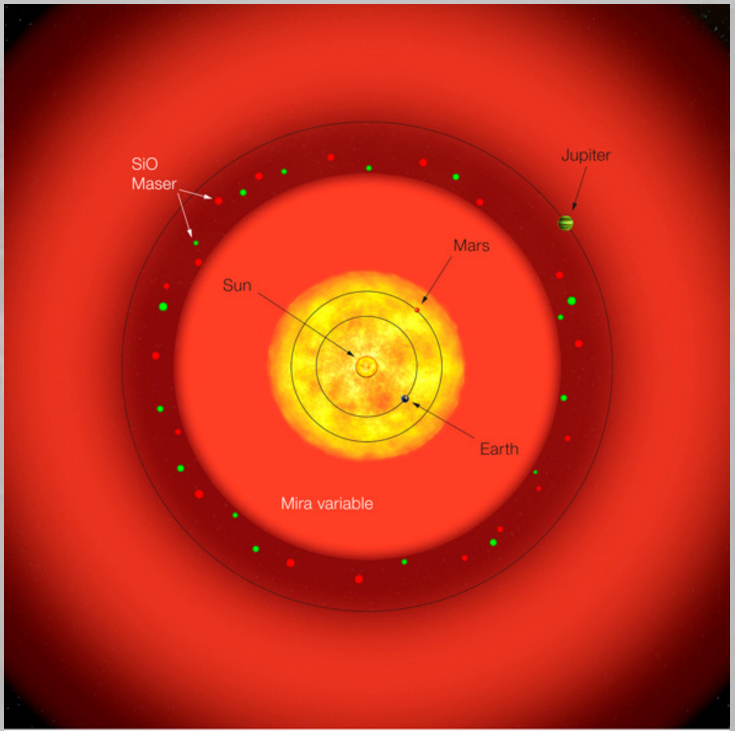
Ohnaka, K., Driebe, T., Weigelt, G., & Wittkowski, M. 2007, A&A, 466, 1099

Wittkowski, M., Boboltz, D.A., Ohnaka, K., et al. 2007, A&A, 470, 191

Sacuto, S., Jorissen, A., Crusalèbes, P. et al. 2008, A&A



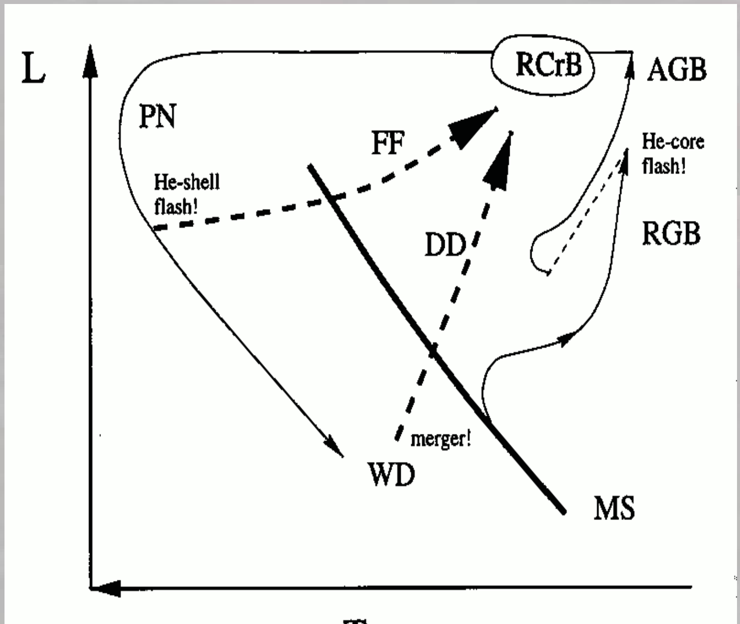
Structure of the Pulsating Red Giant S Ori
(Artist's Impression)
ESO Press Photo 25b/07 (31 May 2007)



S Ori to Scale
(Artist's Impression)
ESO Press Photo 25c/07 (31 May 2007)

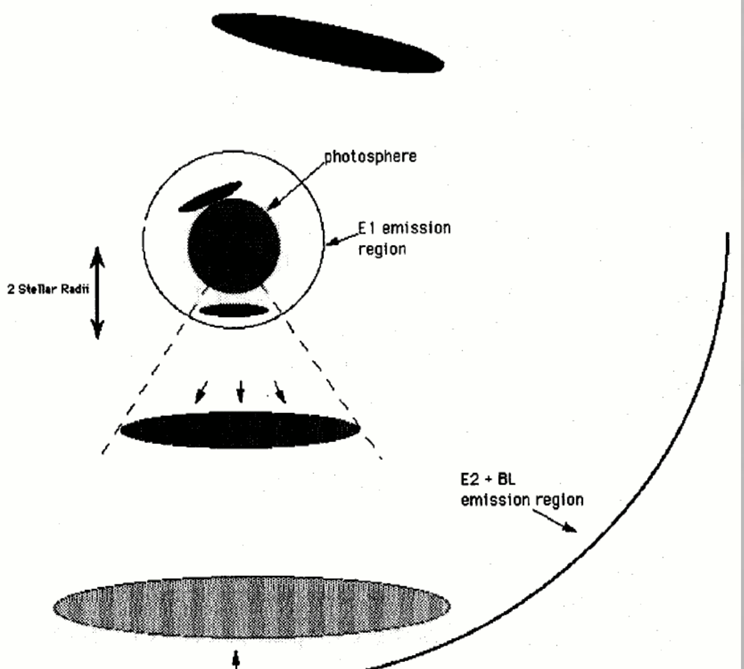
The R CrBs

- Very evolved objects :
  - No Hydrogene left,
  - Post-AGB at the end of the Helium burnig?
  - Resulting of the fusion of two White dwarves ?
  - Seem closely related to the born-again phenomenon (Clayton et al. 1996, 2001, 2007)

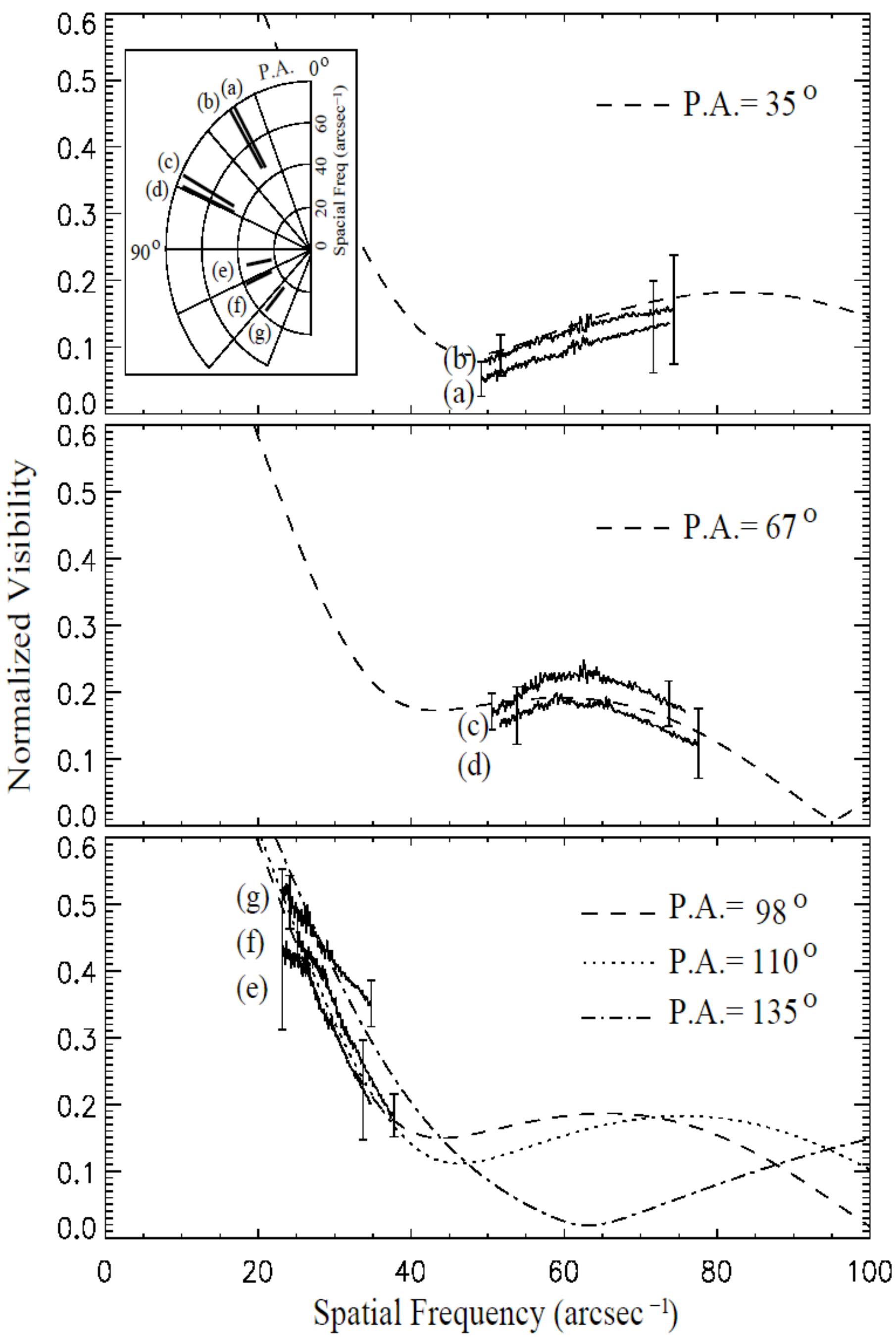


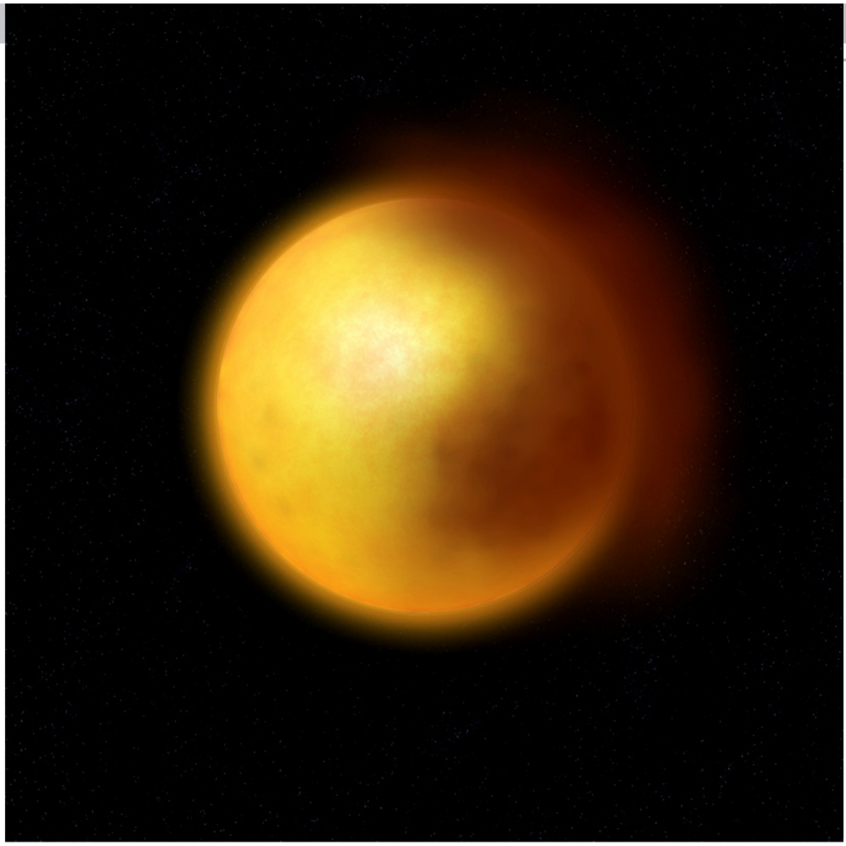
(Asplund 1997)

- Typical light curve resulting from the light absorbtion of dust clouds passing in the line-of-sight (Loreta 1934).



(Clayton 1996)





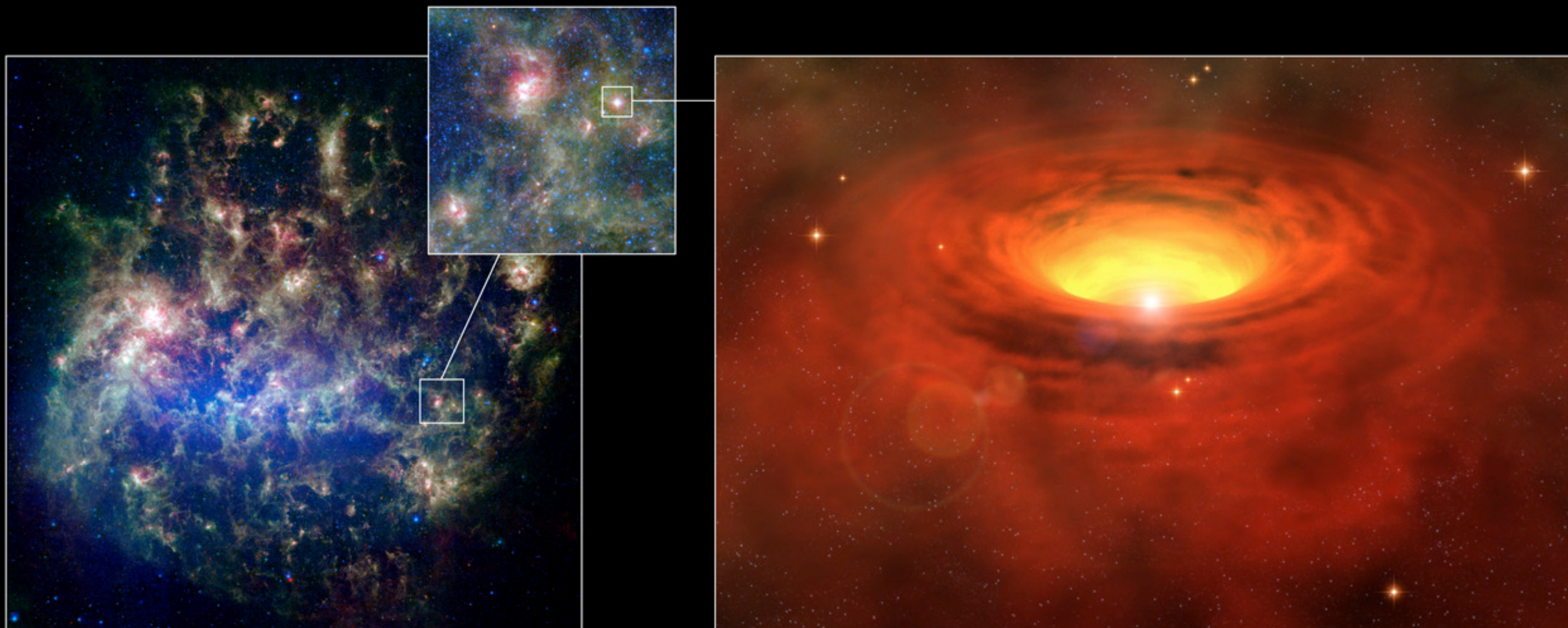
Dust Cloud around a R CrB Star
(Artist's Impression)

ESO Press Photo 34a/07 (3 August 2007)

Leao, I., De Laverny, P. et al. 2007, A&A

VLTI monitoring of clumps formation and evolution but the wind itself is highly variable!
Sphericity to be checked…

Red supergiants



The Large Magellanic Cloud (Spitzer Space Telescope)

Star WOH G64 - Artist Impression (ESO)

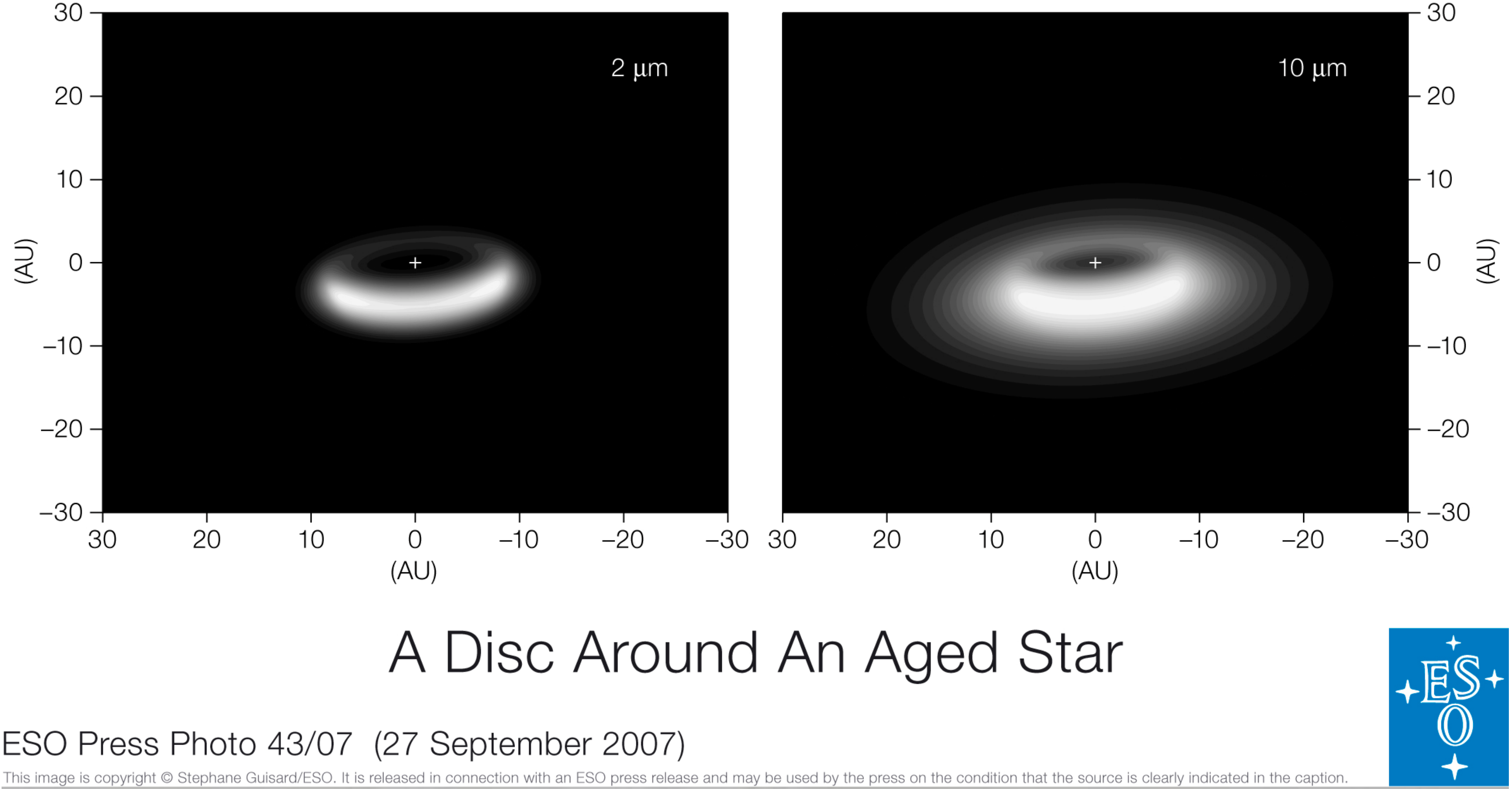
A Thick Belt around a Massive Star in another Galaxy

ESO Press Photo 15/08 (27 May 2008)

Origin of silicate carbon stars:

AGB star + main sequence star (or white dwarf)

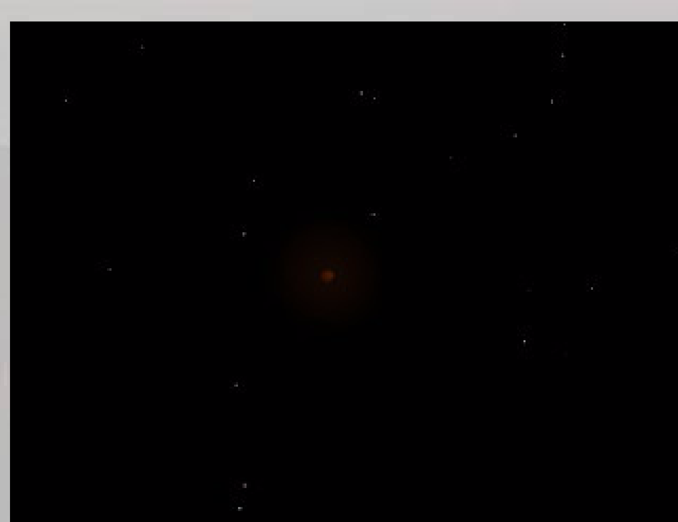
AGB, primary star: oxygen-rich, mass loss
→Circumbinary disk is formed



Numerous papers from K. Ohnaka, P. Deroo and collaborators.

What is the distance of the source?

Is the ejection spherical?



How a jet can form?

How dust can form?

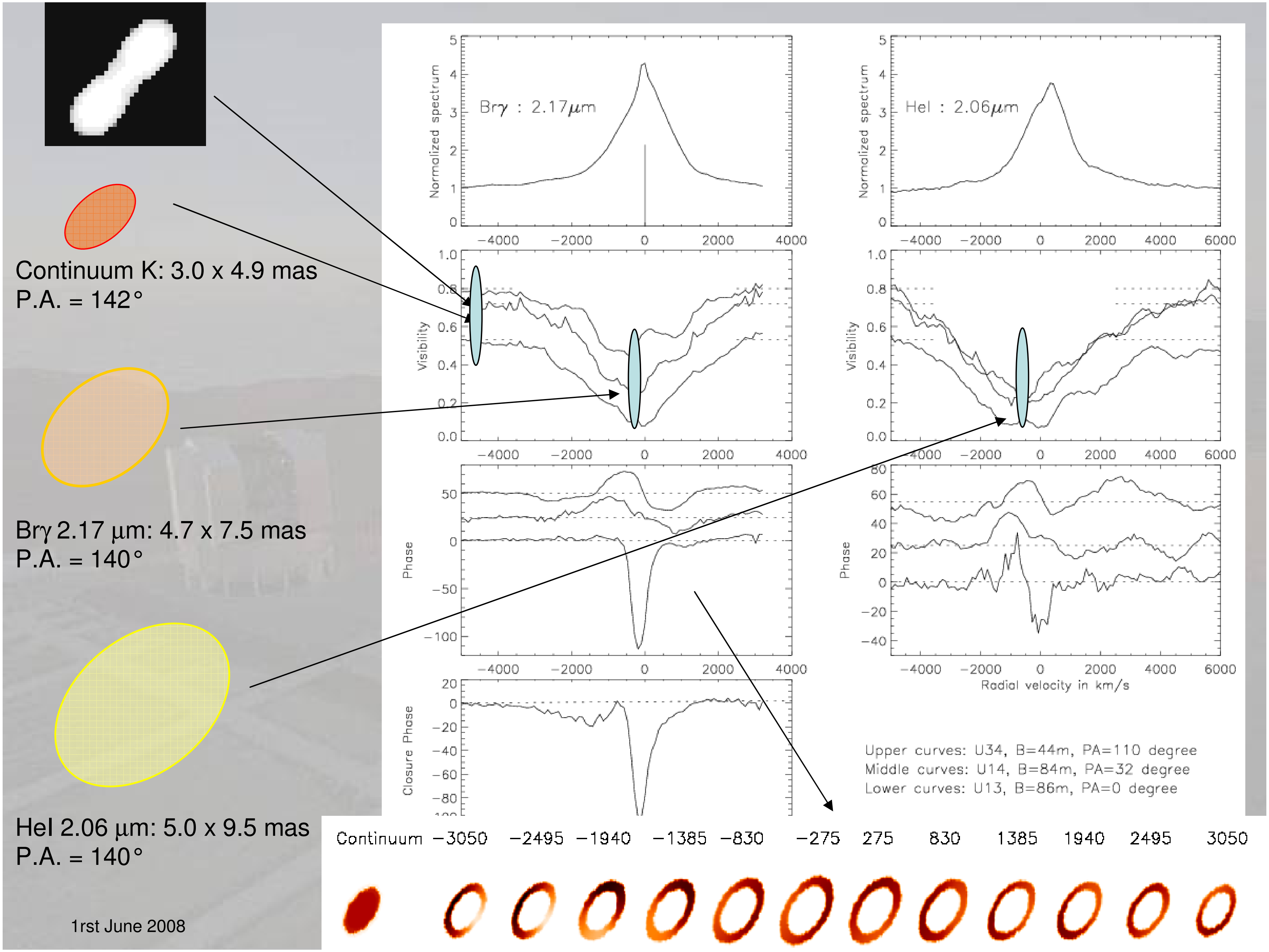
Is the nova wind spherical?

AMBER Observations of the recurrent nova RS Oph 5.5 days after discovery

•One of the best AMBER dataset ever obtained BUT lonely data (1 triplet of base, 3 visibility curves and phase, one closure phase,
•Competition: many optical interferometer observed it (PTI, Keck, IOTA)
•Difficulty to understand a complex, evolving object for which most of the information comes from radio and X-rays,
•We had to wait long, work hard to understand, with the pressure to publish fast (the ‘nova world’)
•It was a good and hard first try for the VLTI!

- Recurrent Nova: previous outbursts 1898, (1907), 1933, 1958, 1967, 1985
- Central system: high mass WD (1.2-1.4 $M_{\odot}$)+Red Giant (M2III); p = 455 d
- The WD is claimed to be future progenitor of a supernova Ia

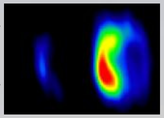
CHESNEAU, NARDETTO, MILLOUR ET AL. A&A 2007, SPECIAL ISSUE ON AMBER INSTRU


Continuum K: 3.0 x 4.9 mas
P.A. = 142°
Brγ 2.17 µm: 4.7 x 7.5 mas
P.A. = 140°
HeI 2.06 µm: 5.0 x 9.5 mas
P.A. = 140°
1rst June 2008
Brγ : 2.17µm
HeI : 2.06µm
Normalized spectrum
Visibility
Phase
Closure Phase
Radial velocity in km/s
Upper curves: U34, B=44m, PA=110 degree
Middle curves: U14, B=84m, PA=32 degree
Lower curves: U13, B=86m, PA=0 degree
Continuum −3050 −2495 −1940 −1385 −830 −275 275 830 1385 1940 2495 3050

The asymmetric outburst of the recurrent nova RS Oph

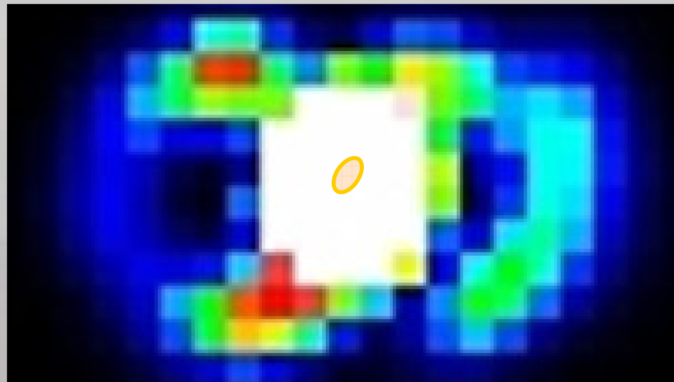
Chesneau, O., Nardetto, Millour et al., 2007, A&A

40 mas
65 AU

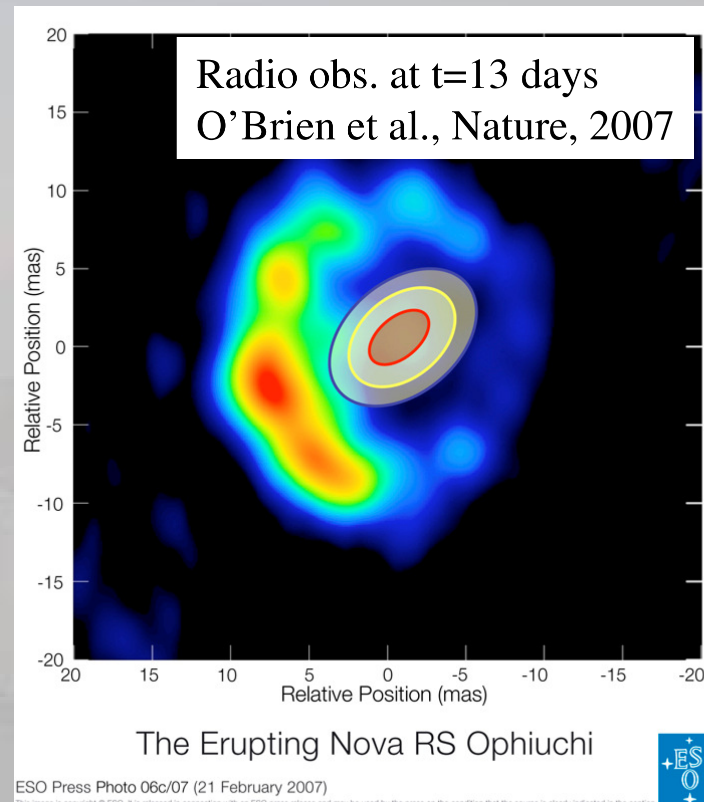


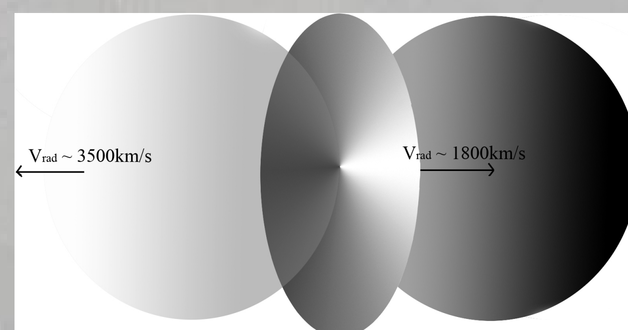
Radio obs. at t=22 days

240 mas
380 AU



HST visible image at t=150 days (Bode et al., ApJ, 2007)



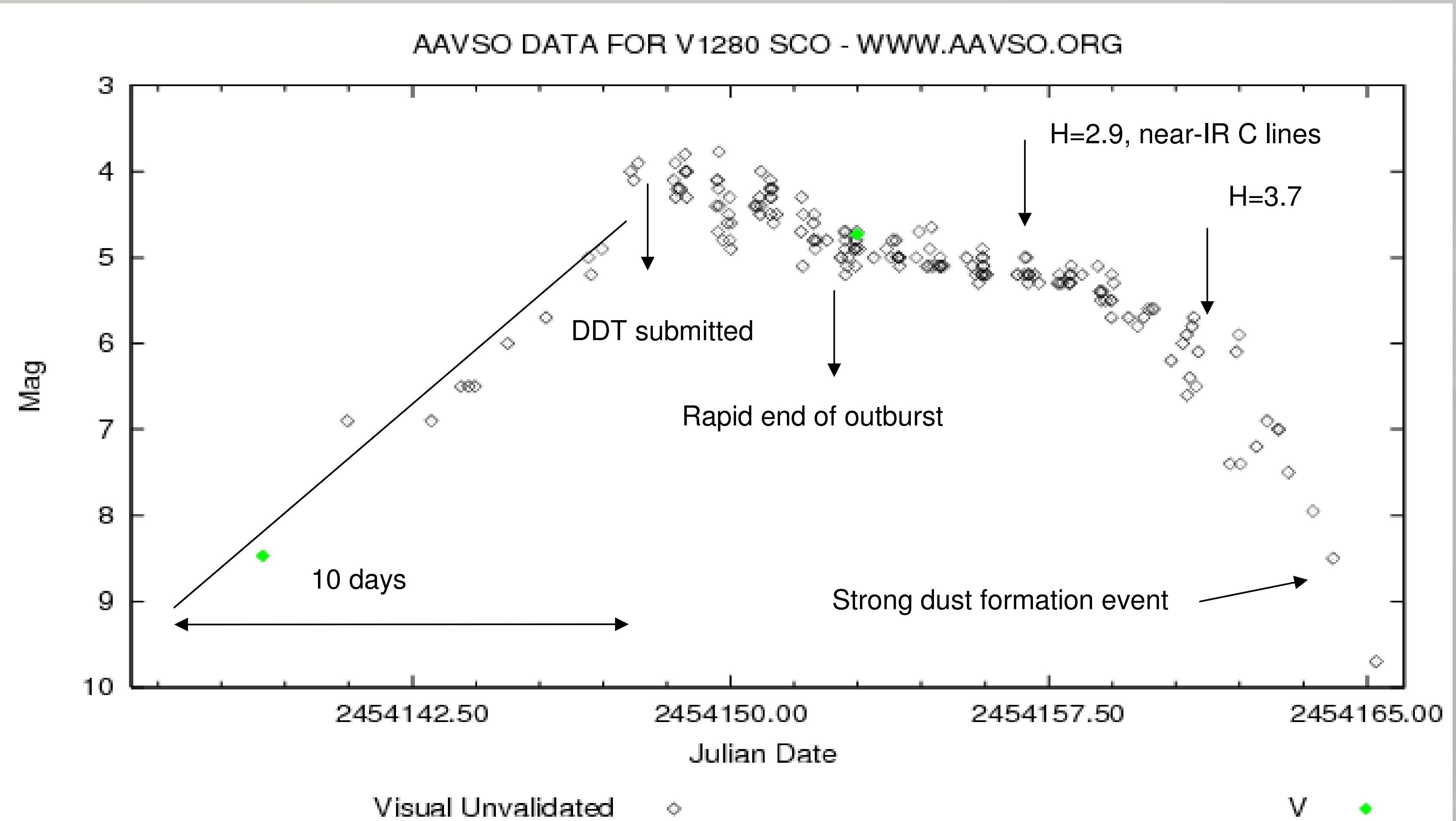


A very complex event! Main question:
What is the origin of the asymetry?
- An asymetrical outburst (fast rotation)?
- The influence of a preexisting disk,
- Small amount of dust detected with Spitzer

The dust formation event of V1280 Sco monitored by MIDI and AMBER

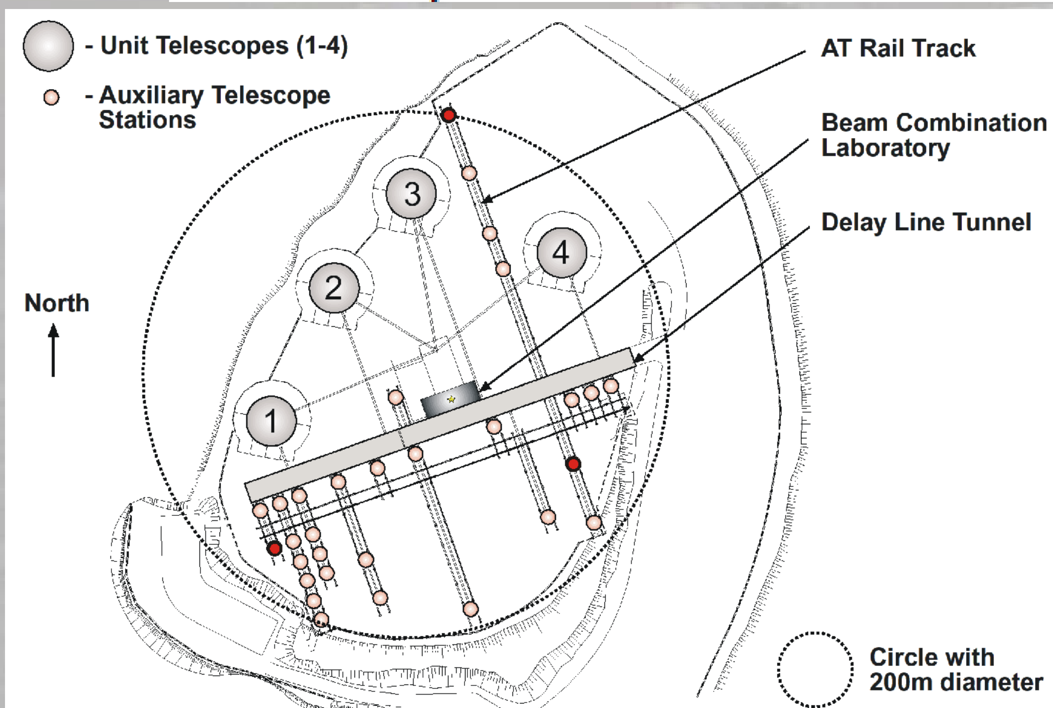
RS Oph was a reccurrent nova: this implies many earlier studies!

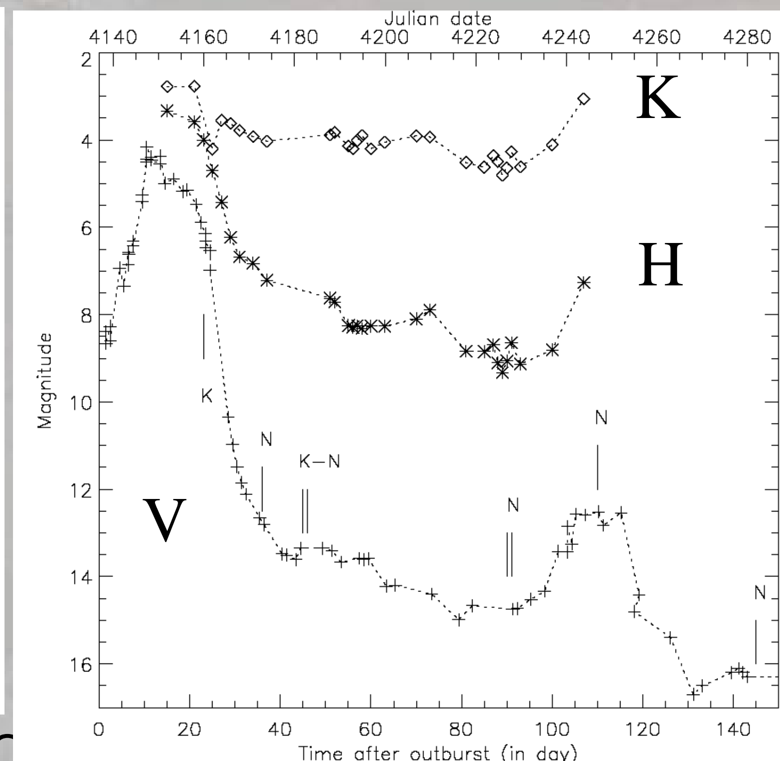
‘Simple’ light curve in visual and in K band…



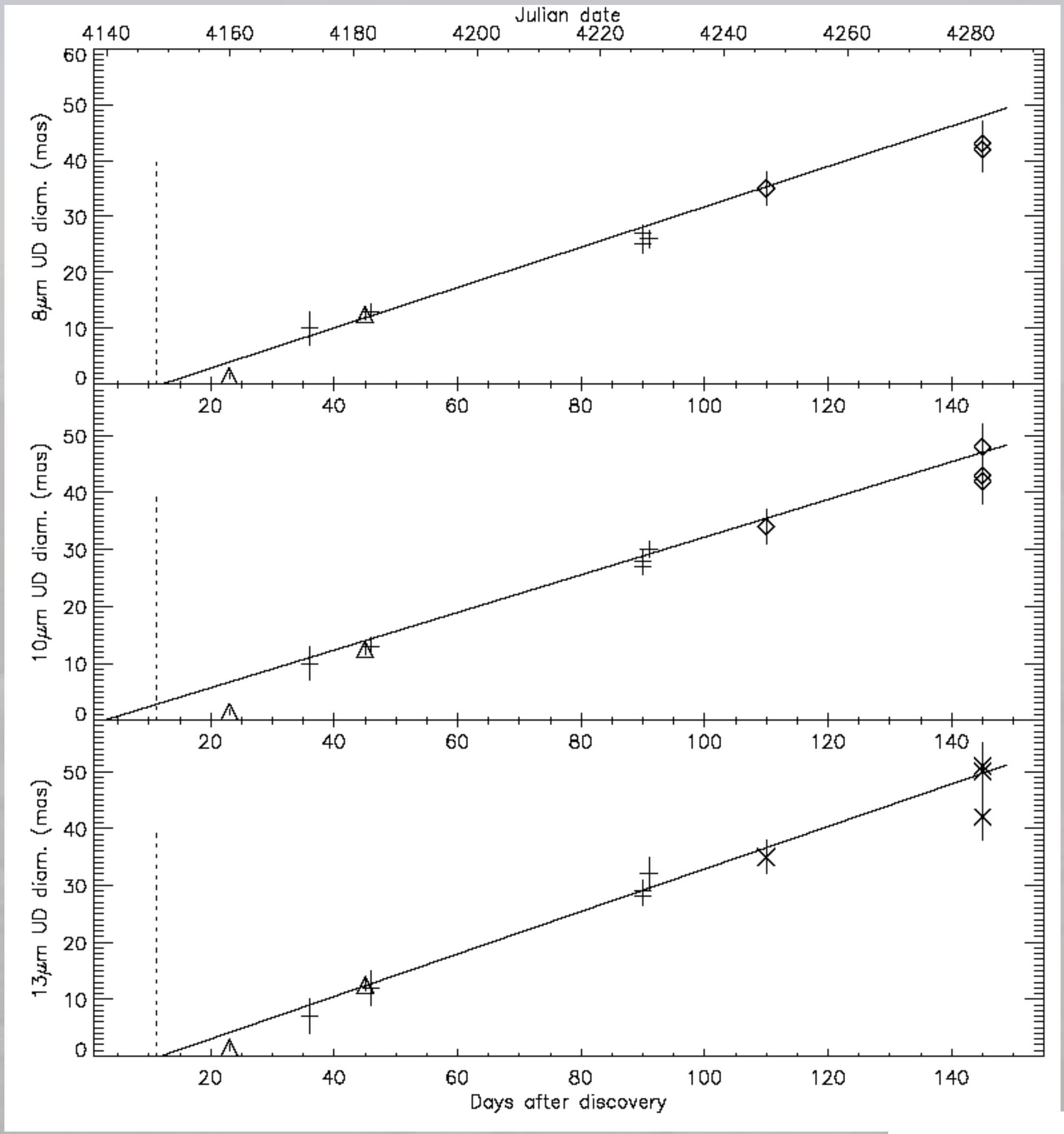
Julian Day	2007 UTC Date	Day[1]	Instrument	Magnitude	Telescope stations	Projected baseline Length [meter]	PA [degrees]
2454160.4	2007-02-28T09	23	AMBER (K)	3.8 (K)	G1 - H0	71	175
2454173.3	2007-03-13T08	36	MIDI (N)	1 (N)	G0 - K0	60.2	53
2454181.3	2007-03-22T07	45	AMBER (K)	4.2 (K)	G0 - H0	29.0	46
2454182.4	2007-03-23T08	46	MIDI (N)	0.3 (N)	A0 - G0	62.7	61
2454182.4	2007-03-23T09	46	MIDI (N)	0.3 (N)	A0 - G0	63.9	67
2454226.7	2007-05-06T05	90	MIDI (N)	-0.8 (N)	U3 - U4	60.1	102
2454226.9	2007-05-06T09	90	MIDI (N)	-0.8 (N)	U3 - U4	57.9	132
2454227.8	2007-05-07T08	91	MIDI (N)	-0.8 (N)	U3 - U4	59.3	128
2454246.5	2007-05-26T01	110	MIDI (N)	-1.5 (N)	U3 - U4	35.0	75
2454281.5	2007-06-30T00	145	MIDI (N)	-1.1 (N)	U3 - U4	52.8	93
2454281.7	2007-06-30T05	145	MIDI (N)	-1.1 (N)	U3 - U4	58.7	129
2454281.8	2007-06-30T07	145	MIDI (N)	-1.1 (N)	U3 - U4	49.5	166

[1] From discovery, Feb. 4.85 UT. JD=2454136.85





Classical result: a distance estimate…



A 'dusty' distance estimation

….BUT….

- Based on the expansion of a dust shell…~0.35mas/d
- Taking into account a radial velocity from IAU notices…
- 500km/s (relatively slow…)
- and a crude error estimate +/- 100km/s

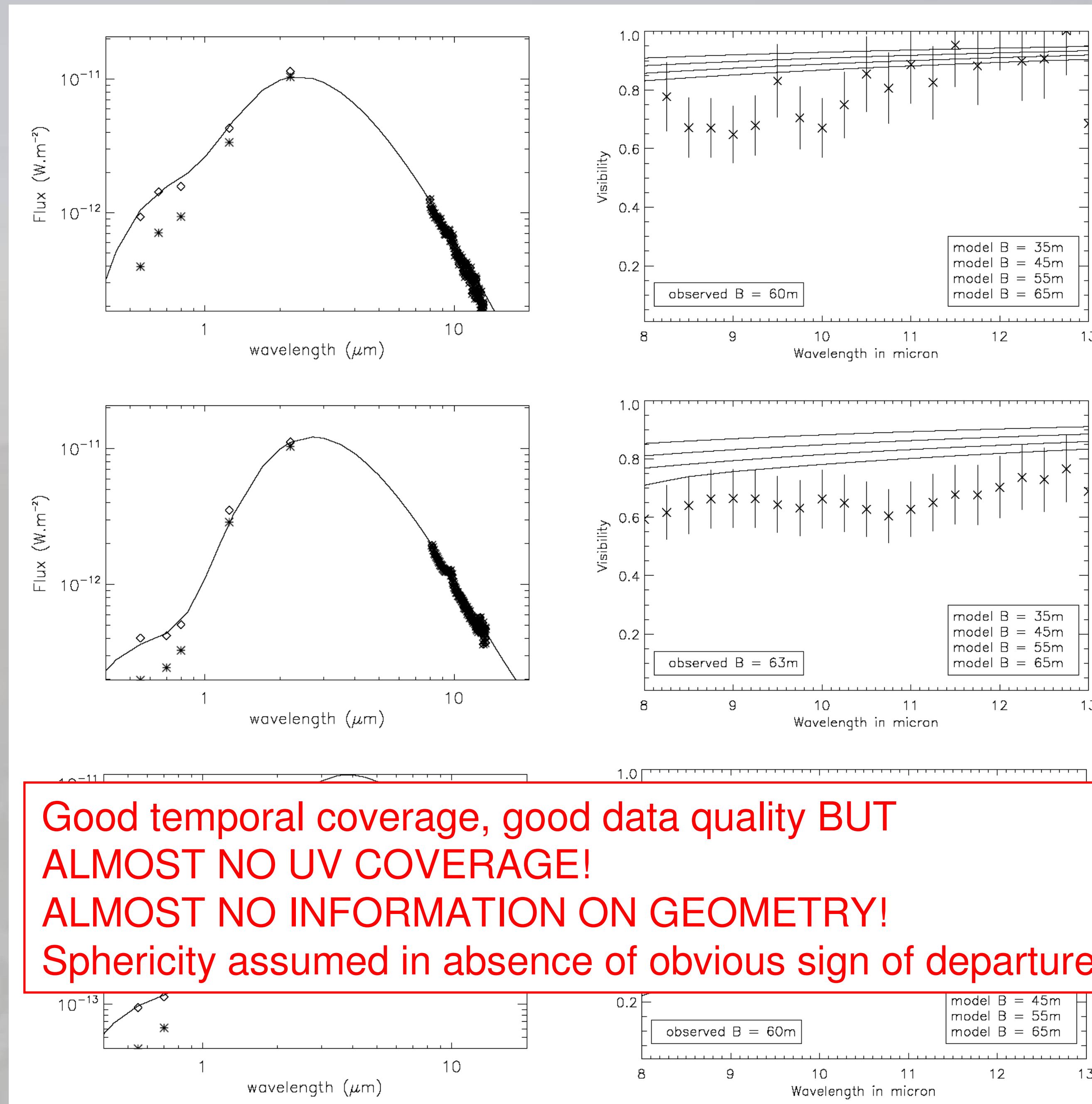
- D~ 1.6+/-0.4kpc…
- The nova was not so close…but the outburst was MASSIVE.

Chesneau, O. et al., 2008, A&A, in preparation

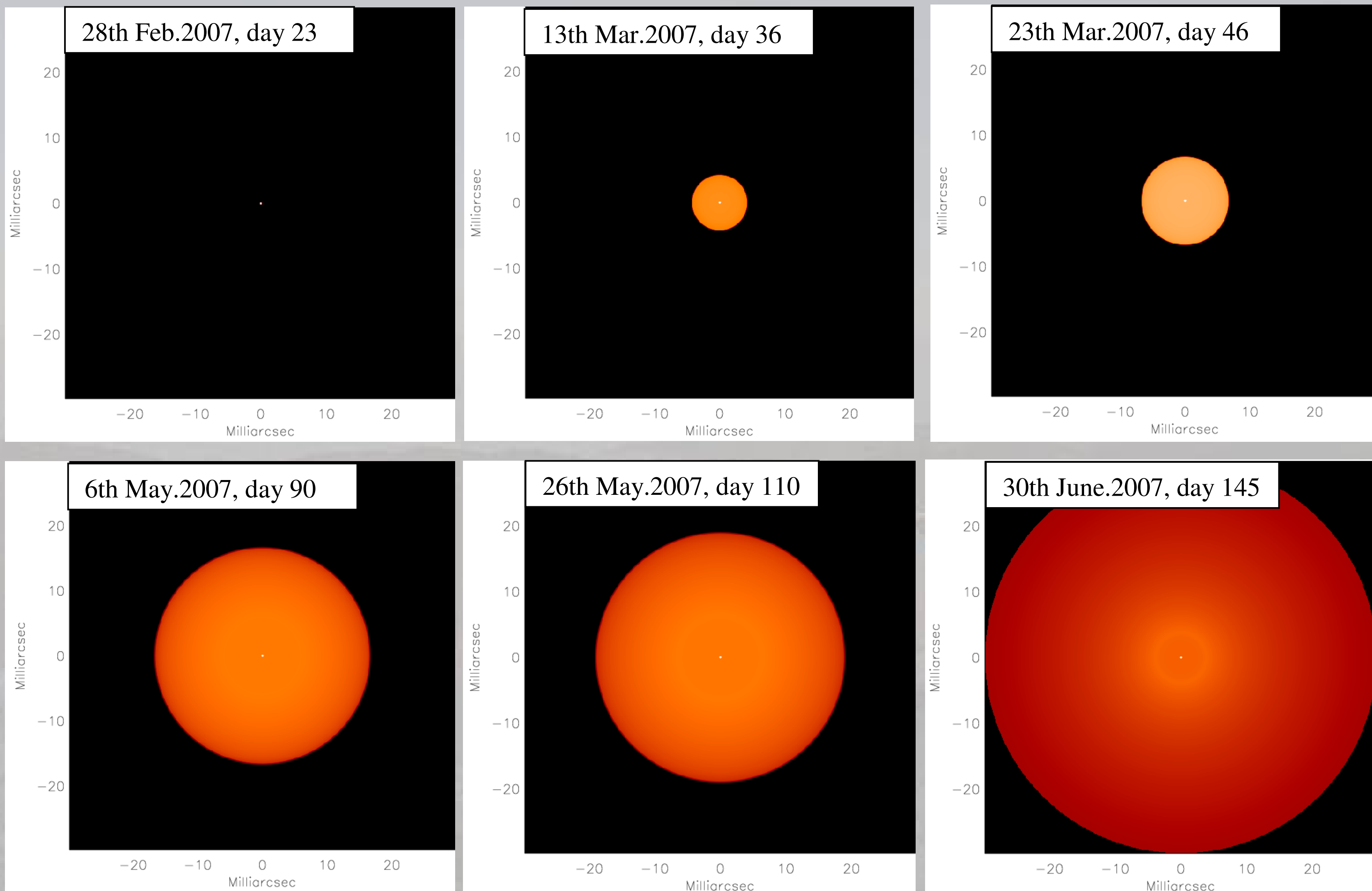
13th March,
t=36d, 13mas

23rd March,
t=46d, 16mas

6th May,
t=90d, 26mas



Good temporal coverage, good data quality BUT
ALMOST NO UV COVERAGE!
ALMOST NO INFORMATION ON GEOMETRY!
Sphericity assumed in absence of obvious sign of departure



Chesneau, O., Banerjee, D., Millour F., Nardetto N. et al., 2008, A&A, in press

A full set of models for each date of observation

Table 3. Models parameters for V1280 Sco for the different epochs, using a single dust shell. The parameters (and in particular the luminosity) are scaled for a distance of 1.6kpc. A chronology of dust formation based on an approximate date of dust (t=23d) formation estimated from the light curve is also shown. For t=145, an alternative model is proposed (see text for discussion).

	Day after outburst					
Days after discovery	36	45/46	90	110	145	145^b
Since dust detection	13	22/23	67	87	122	122
T_* (K)	8500±1000	10000±1000	10000±1000	10000±1000	10000±1000	10000±1000
T_d (K)	1450±150	1550±150	1300±100	1450±100	1550±100	1700±100
L ($L_\odot$)	3500	4400	6600	16000	8400	8400
q	2.1±0.4	2.1±0.4	2.9±0.3	2.9±0.3	3.0±0.2	3.0±0.2
$Y=1+\Delta R/R$	1.3±0.3	1.5±0.3	2.8±0.4	3.0±0.5	5.0^{+5}_{-1}.	17^{+3}_{-6}
r_{in} (mas)	3.4	5	6.	6.4	3.8	2.2
r_{in} (AU)	5.4	8	9.6	10.2	6.1	3.5
r_{out} (mas)	4.2	6.8	16.7	19.3	29.1	37
τ_V	3.±0.3	4.5±0.3	6.5±0.3	5.4±0.3	6.2±1.	5.5±0.4
$\tau_{10\mu m}$	2.3	4.1	2.8	2.3	2.1	1.5
$\tau_{100\mu m}$	$4.43\ 10^{-2}$	$6.42\ 10^{-2}$	$4.05\ 10^{-2}$	$3.27\ 10^{-2}$	$2.47\ 10^{-2}$	$1.9\ 10^{-2}$
$M_{dust}(M_\odot)$	$4\ 10^{-8}$	$1.4\ 10^{-7}$	$2.2\ 10^{-7}$	$2.2\ 10^{-7}$	$1.1\ 10^{-7}$	$1\ 10^{-7}$

T pseudo-photosphere

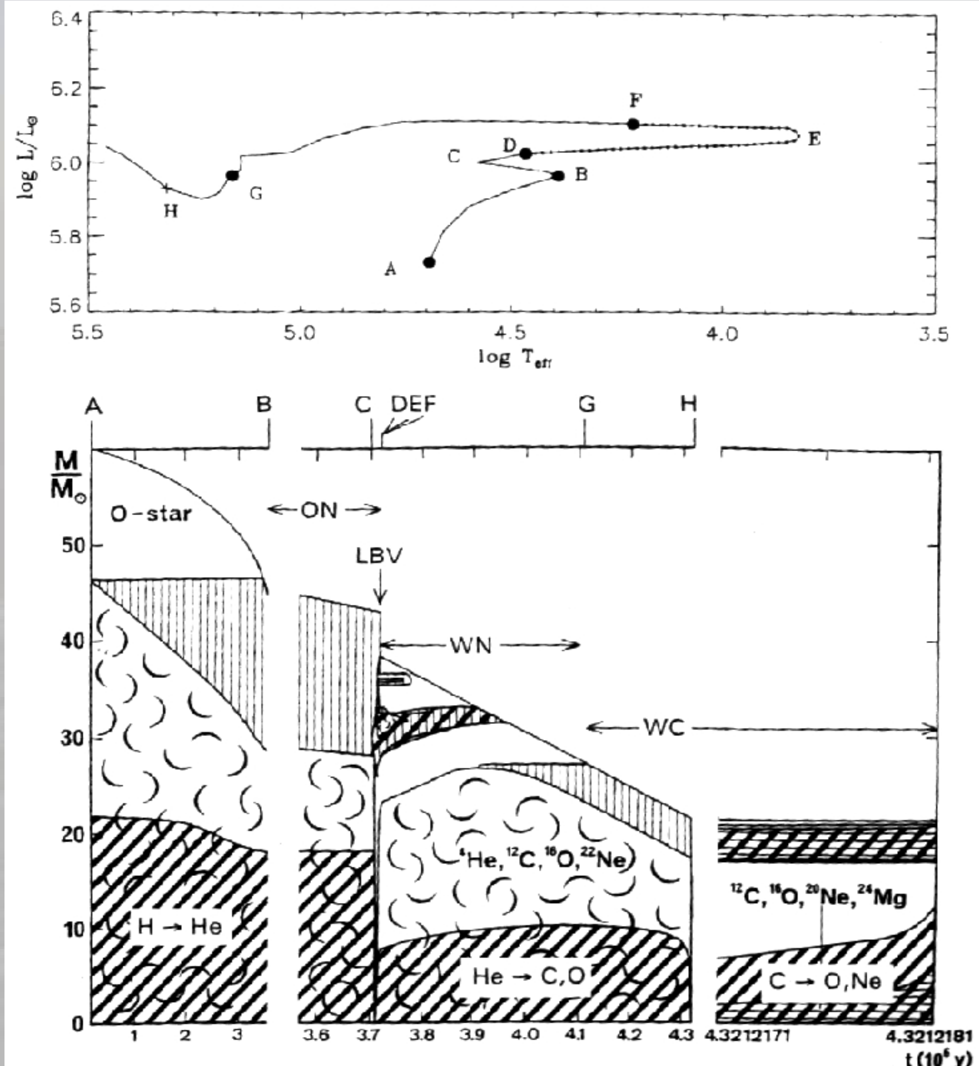
T inner radius

Dust mass estimate

Knowing that the nova emerged from its dusty cocoon in November 2007 only (~250d after discovery), we easily can estimate the ejected mass to 10^{-4} solar mass: one of the heaviest event ever recorded

Care! This does not imply that the WD was massive!
The hydrogene stolen from the companion slowly stratified. If the WD is ‘small’ (0.6 solar mass), a large mass is needed to reach the temperature and pressure level for the ignition of the nuclear reactions!.

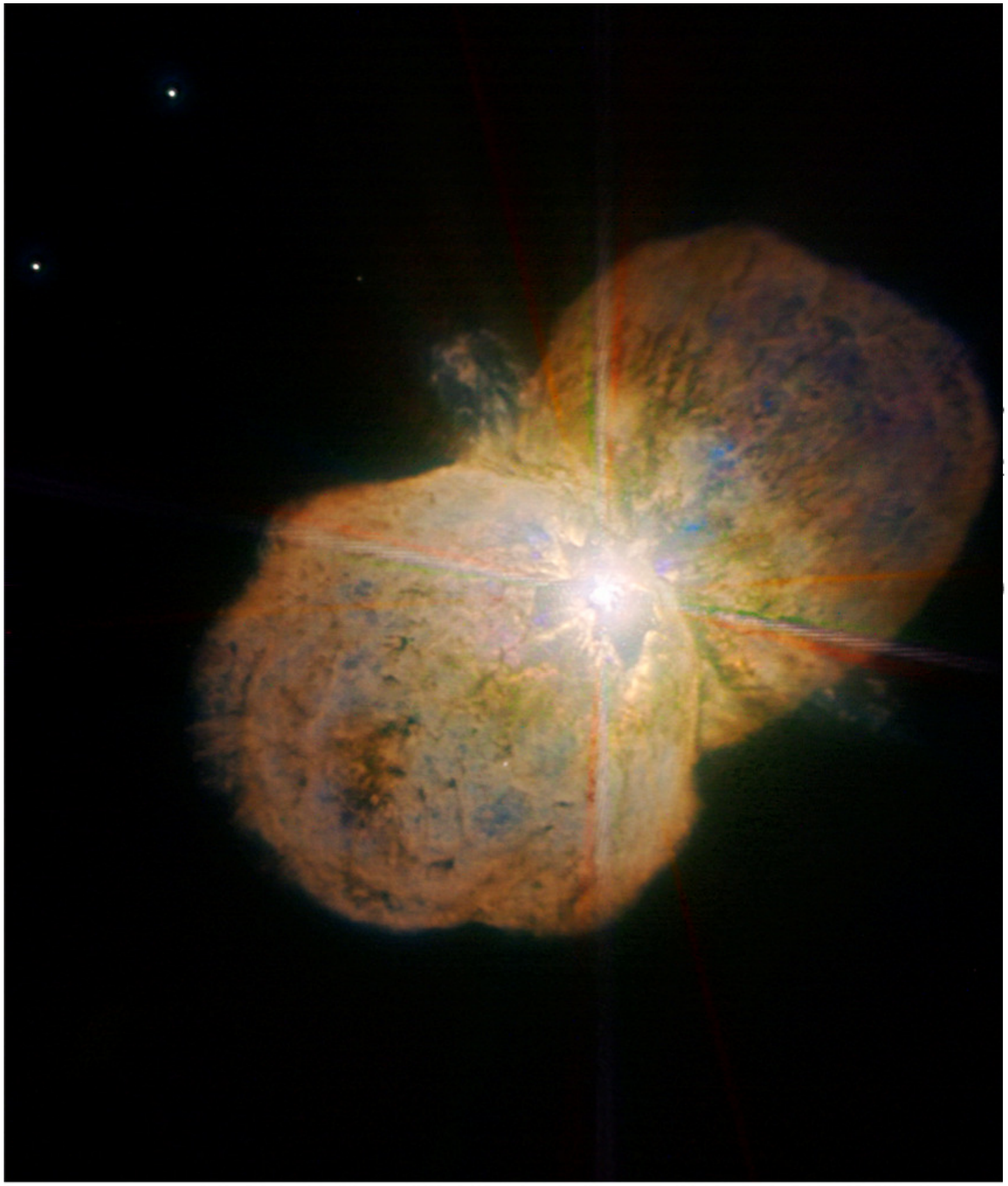
Mass loss from evolved stars: loss of spherical sphericity
Massive stars ('Hot')

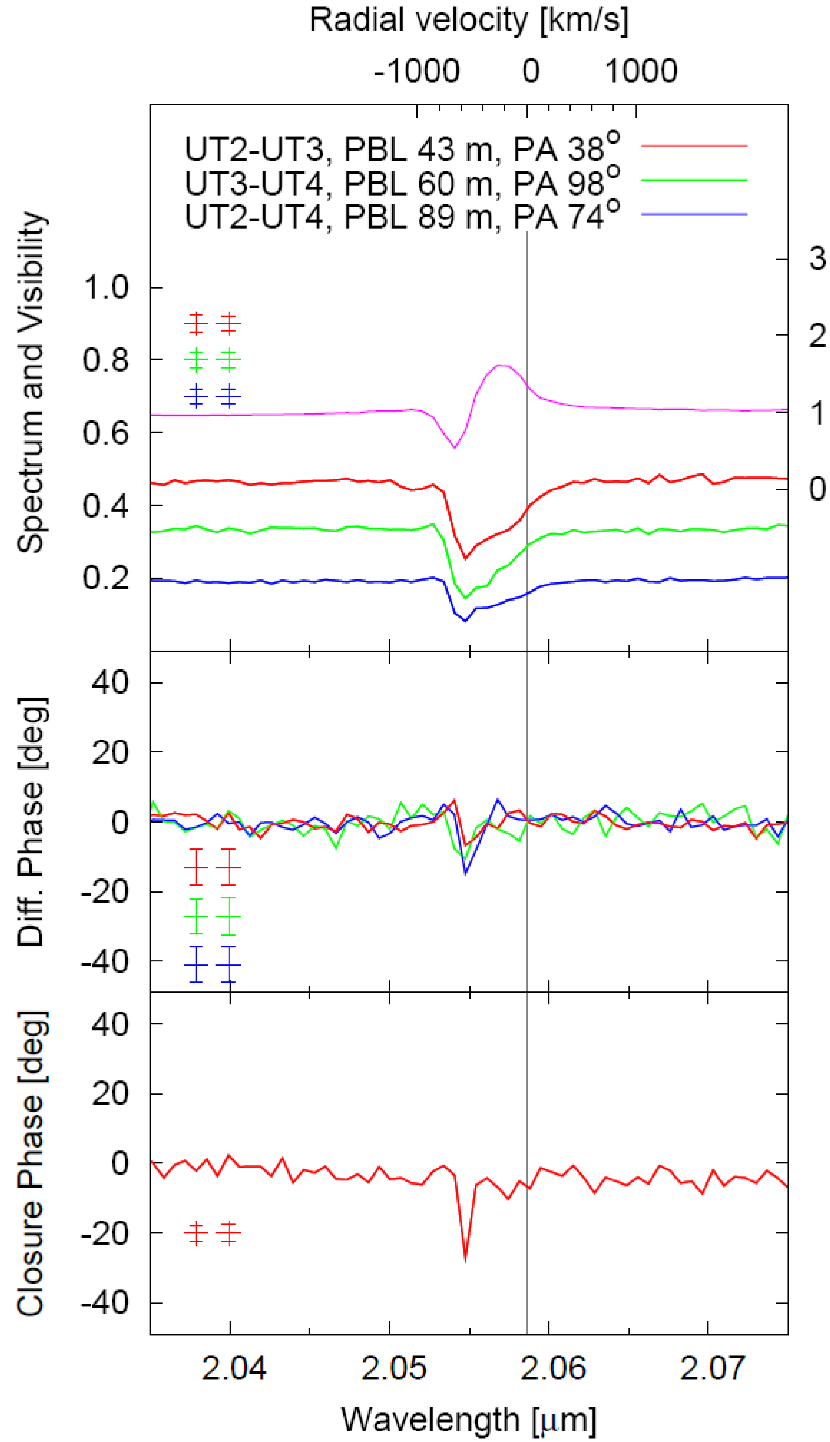


Lamers et Cassinelli, 1999

Associated issues:

. Binarity,
. Rotation,
. X ray generation in radiative winds,
. Supergiant eruptions and instabilities,
. Supernovae Ib,c, II remanent geometry
. Dust production from hot stars
  . LBVs,
  . B[e],
  . WR of carbon type,

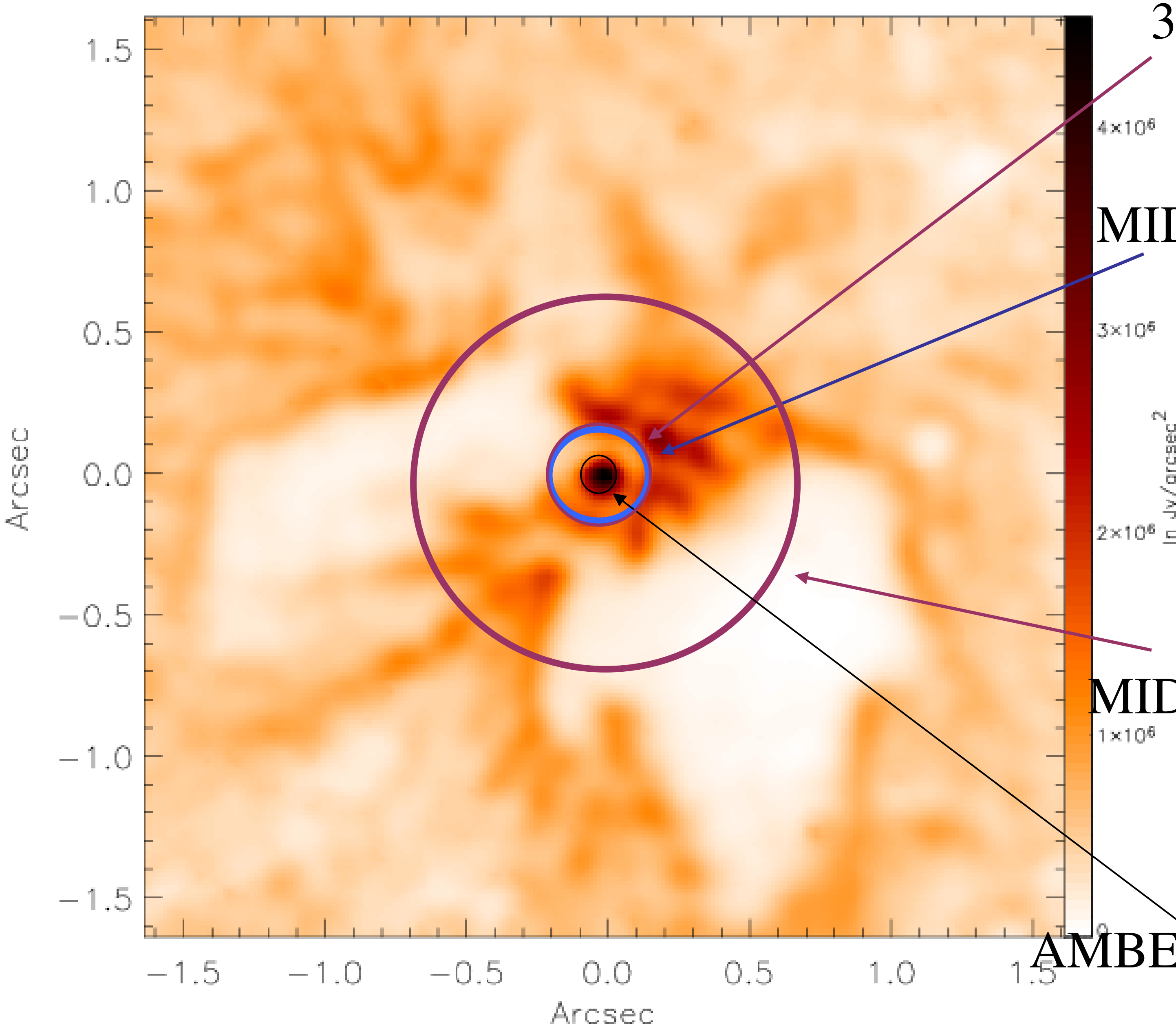




Eta Carinae (NACO/VLT)

ESO Press Photo 17a/08 (27 May 2008)

Interferometric Field-Of-View



AMBER FOV with ATs
300mas

MIDI FOV with UTs
300mas

MIDI FOV with ATs
1300mas

AMBER FOV with UTs
60mas

The B[e] phenomenon

(Lamers et al. 1998)

Supergiants B[e] ➔ $L_{*}/L_{sun} > 10^4$

Observations point towards asymmetrical stellar environments

Rotation?

Binarity?

Complex evolution?

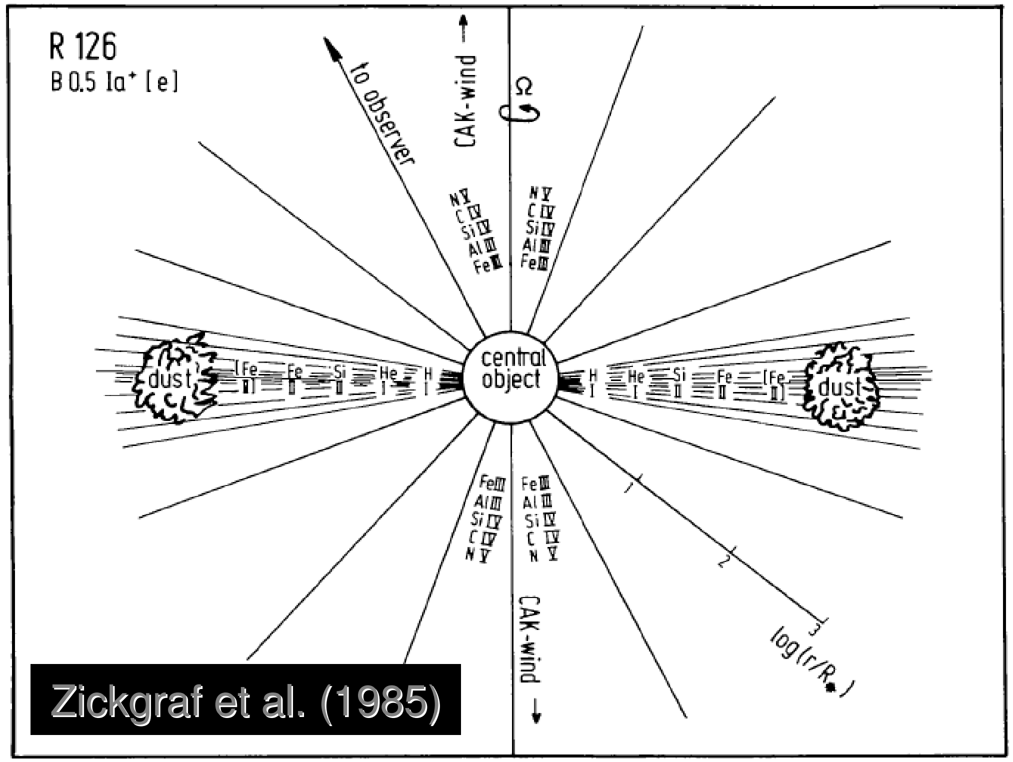
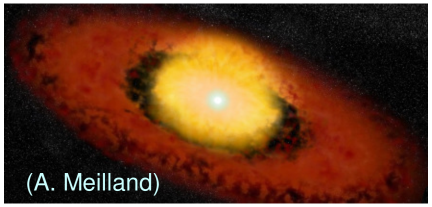
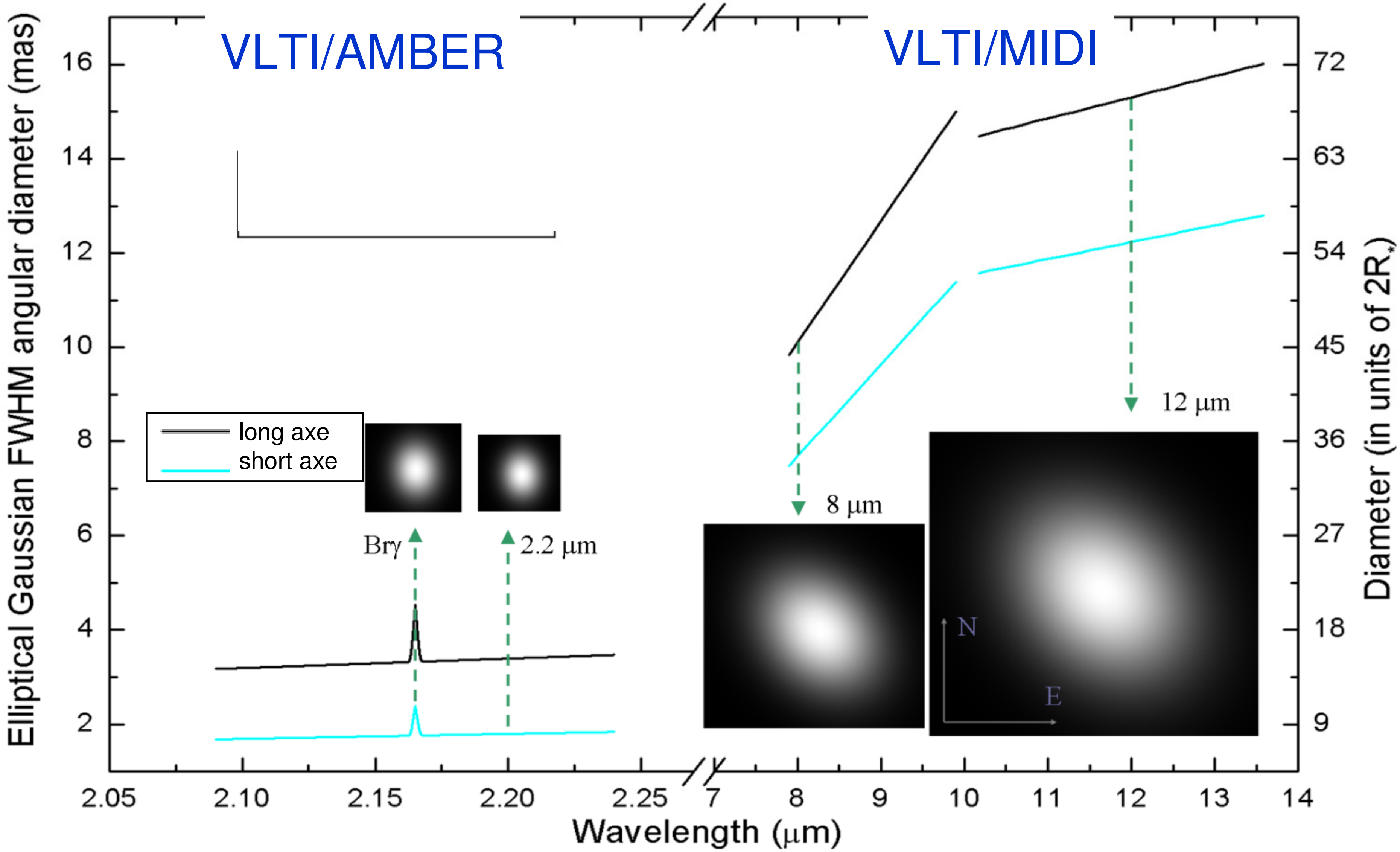


Fig. 7. Proposed schematic model for R126. The ions in the equator disk region (see text) are ordered corresponding to their line widths and in the polar region according to the expansion velocity (cf. Table 3b and c)



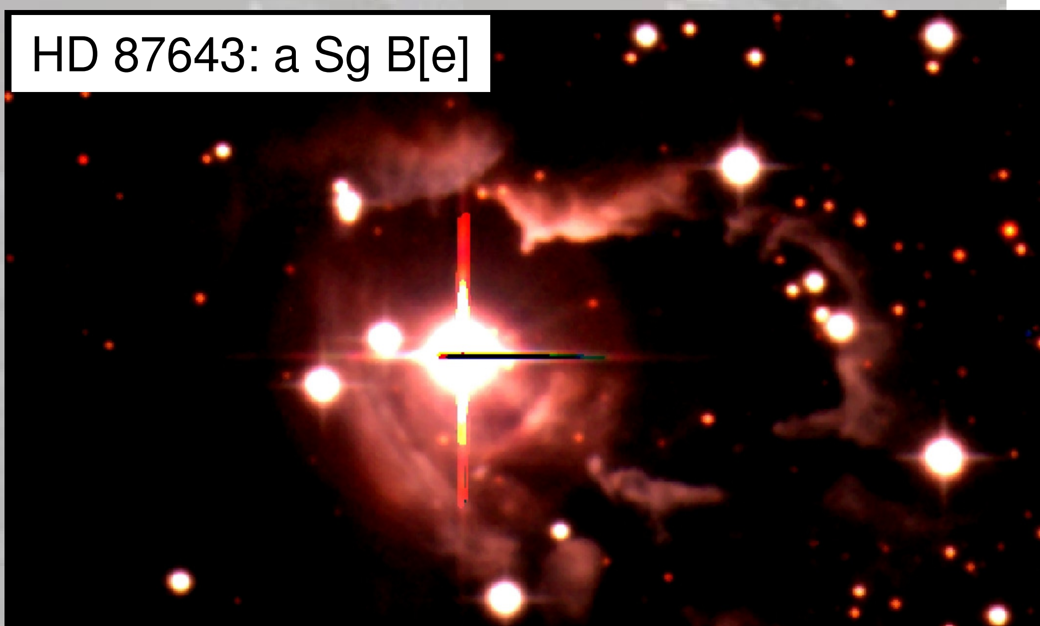
Domiciano de Souza et al. (2007 A&A ; ESO Press Release 2005)

CPD-57 2874



Adopted Stellar Parameters

Star	E_{B-V}	Distance (kpc)	log T_e	log $L/L_\odot$	
AG Car	0.8	2.5	4.4	5.5	LBV MIDI 2pts
HR Car	1.3	2.5	4.3	5.9	LBV MIDI 1pt
HD 87643	1.0	2.5	4.2	4.9	B[e] MIDI/AMBER
HD 316285	2.1	>2.	4.3	>6.1	LBV MIDI/1pt, non rés.
CPD −52°9243	1.7	3.1	4.2	5.4	CPD MIDI?
CPD −57°2874	>0.8	2.5	4.2	>4.8	CPD B[e] MIDI/AMBER
GG Car	0.9	2.5	4.2	4.7	GG B[e] MIDI/AMBER
CD −42°11721	1.6	>2.	4.2	>4.5	CD B[e] à observer
HD 326823	1.1	>2.	4.3	>5.0	HD LBV à observer?
BI Cru	1.4	4.4	4.4	5.5	BI Cru?
HD 45677	0.3	0.5	4.3	3.1	B[e] HaBe
η Car	1.2	2.5	4.5	6.9	Eta Car…



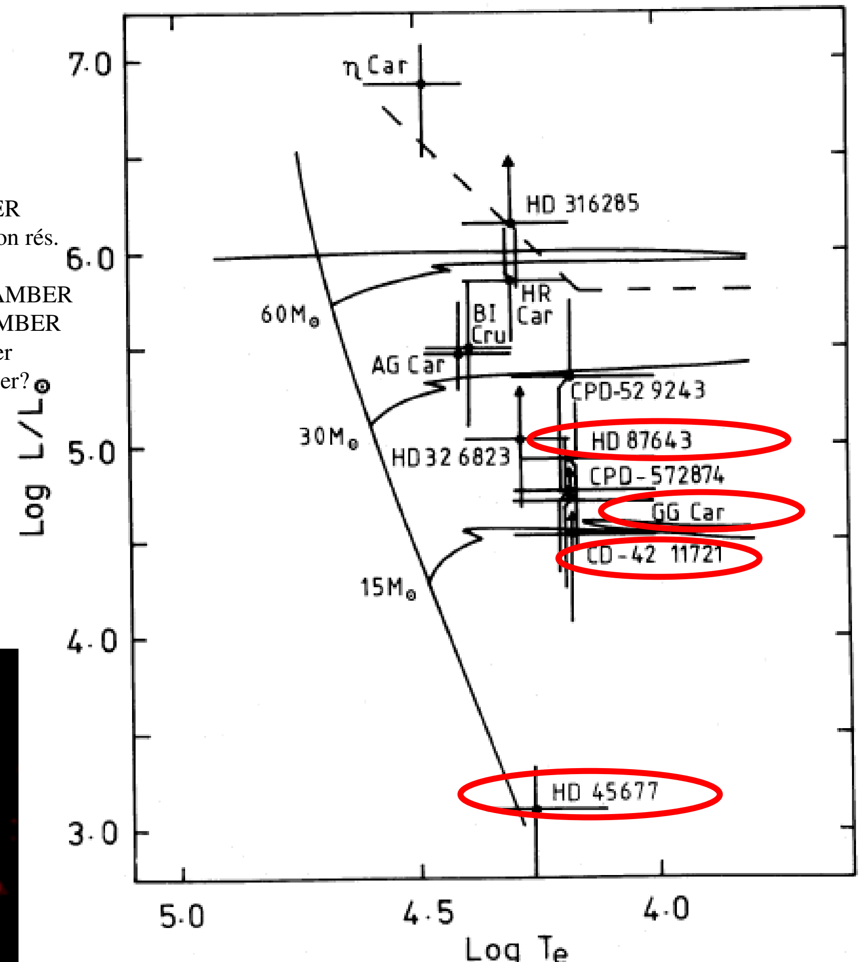
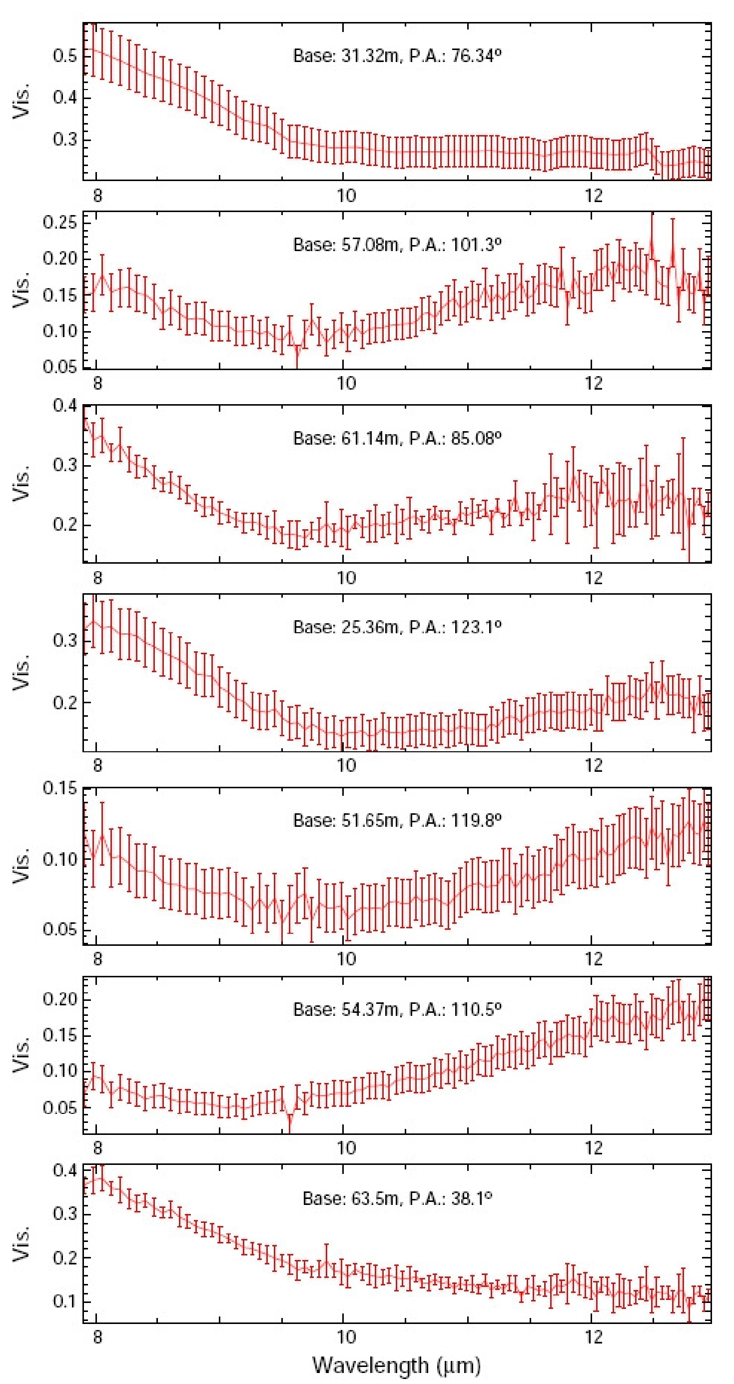
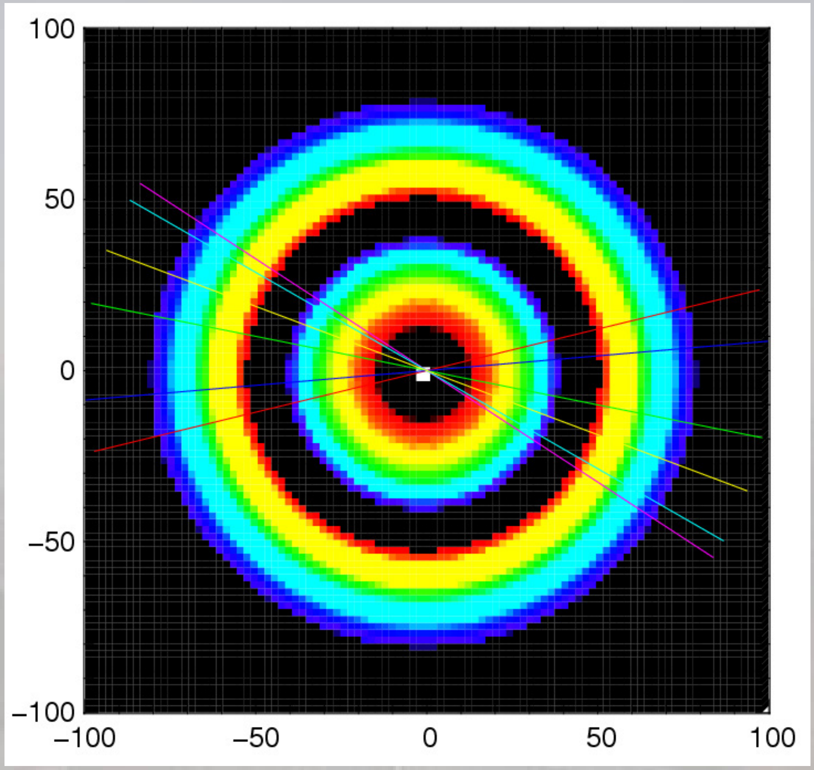


FIG. 5.—log $L/L_\odot$ vs. log T_e diagram for the emission line stars with measured photometry. The derived parameters are obtained as described in the text. Error bars for each point indicate estimated 1 σ uncertainties in these parameters. Systematic effects may produce errors in excess of those indicated. The upper stellar luminosity limit (Humphreys and Davidson 1979) is schematically represented by dashed lines. Evolutionary tracks for 15, 30, and 60 $M_\odot$ stars (Maeder 1981*a*, *b*) are shown as solid lines.

McGregor et al. 1988





MIDI GTO data: a mess…

Is the image of the source achromatic?

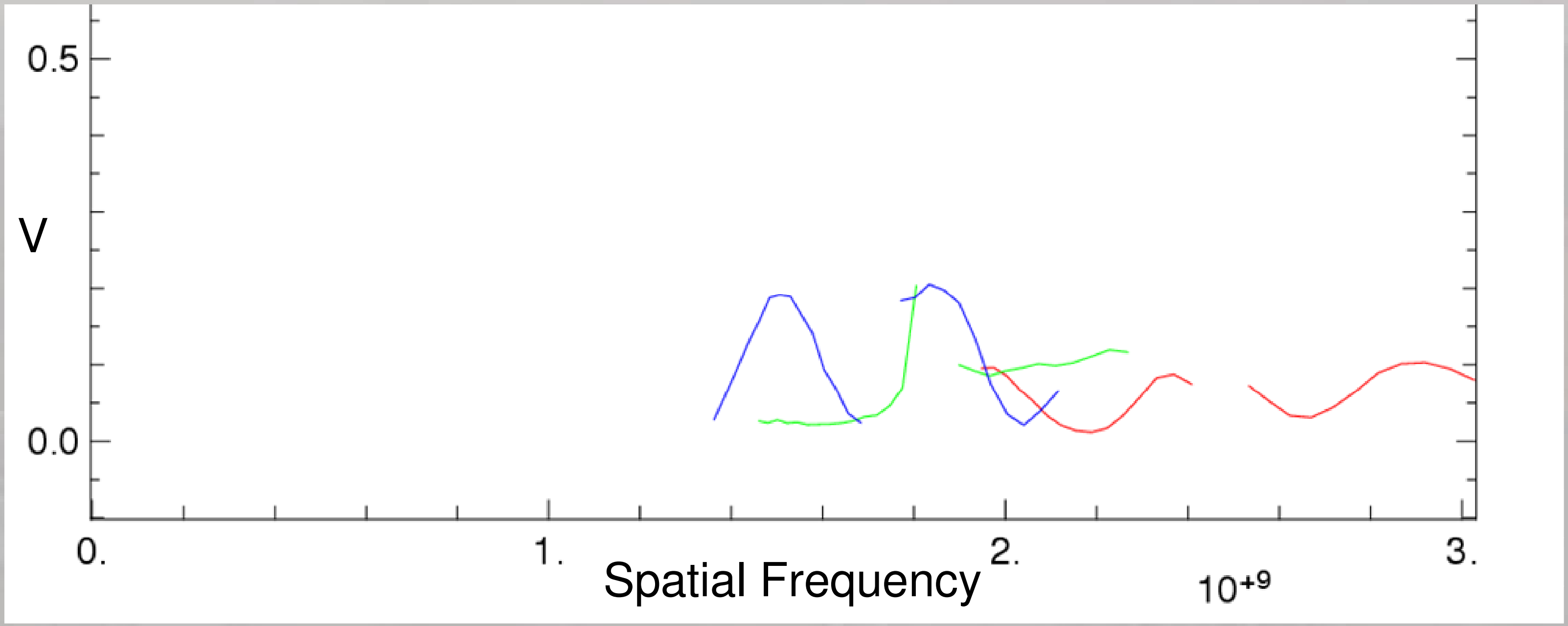
A disk model does not work…

Surprisingly, a double ring model fits in…

New AMBER data requested…

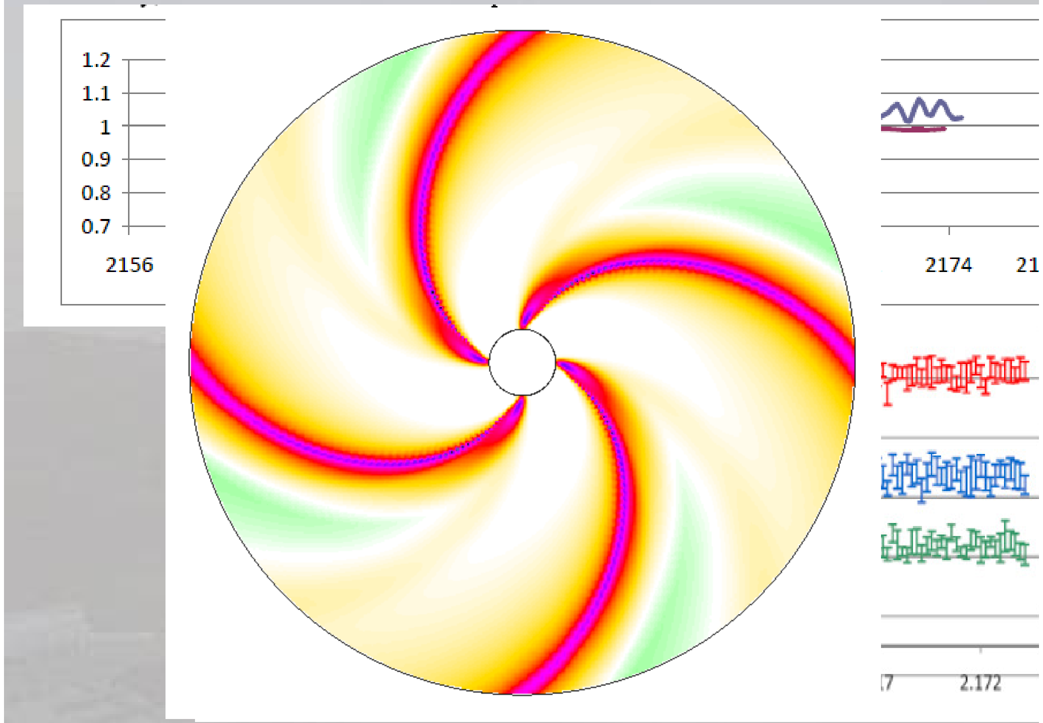
Run ID	Telescope	Instrument	Hours	
380.D-0340(A)	VLTI	AMBER	4.5	B
380.D-0340(B)	VLTI	AMBER	4.5	C

NACO DDT observations accepted (and performed, waiting for the data)

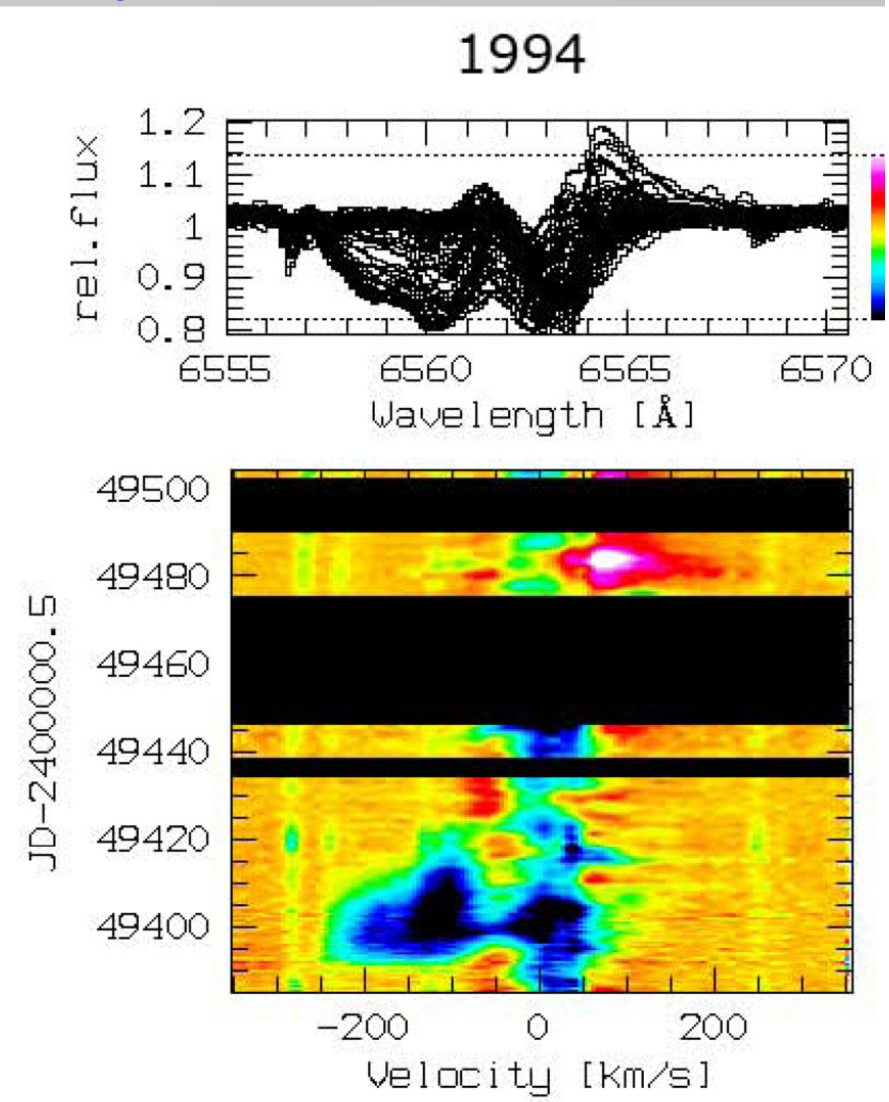


HD 87643 is a binary!!! Probably B+B system! +disk,+jet+????
Paper in preparation: Millour, Chesneau et al. 2009

Rigel (β Orionis): B8Ia



Radiation hydrodynamics
simulation of CIRs in a hot-star wind



◎**These may stem from large-scale surface structure that induces spiral wind variation analogous to solar Corotating Interaction Regions.**

The asymmetric environment of evolved stars

So far, the study of asymetric environments is very rich, we discover the potential:
- The core of PPN/PNs (a team is formed, currently limited to ~10 sources),
- Nova observations (an international collaboration is under way, 2 novae per yr),
- Study of large dust clumps, (many sources, a team is slowly forming)
- Study of 'mol-spheres' and pulsating stars (many sources, a well-identified team)
- Symbiotic systems with dust: complex geometries suspected, high dynamics needed (Almost no dedicated study to date, except for binary post-AGBs)
-Evolved B supergiants with dust (a growing team is formed),
-Wind activities in OB stars, wind-wind collision zones (no organized team yet, but some focused collaborations)

My strategy with the VLTI: reassess famous, 'prototypal' targets, demonstrate the possibilities of the instrument. The VLTI observations and interpretation of evolved stars are to date manpower limited, not instrument limited. A number of 10-20 papers in the field of evolved stars could be published from the observations per year, in an 'industrial' sense. In depth, more systematical studies must come later.

These studies are an exploration of the possibilities offered by the VLTI
A great VLTI2/ALMA synergy expected in a few years,
Large scale studies will become possible (manpower needed!)