

MESS - Mass loss of Evolved StarS

An overview

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on behalf of the MESS consortium



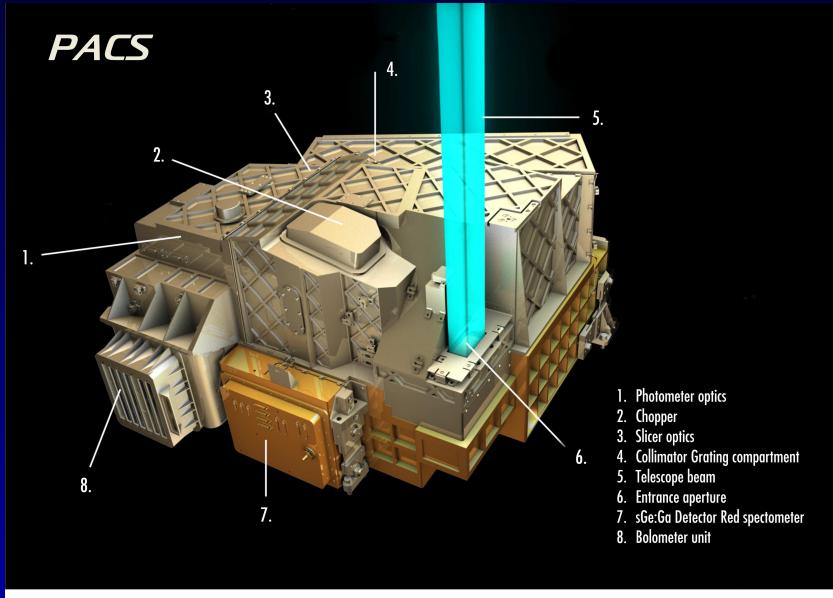
©2009 ESA/CNES/ARIANE SPACE / Optique Vidéo du CNES - P. BAUDON

Herschel - Planck launch 14 May 2009



3.3m effective diameter
3 year of Routine Phase starting Dec. 2009
EoHe: 29 April 2013

Herschel instruments



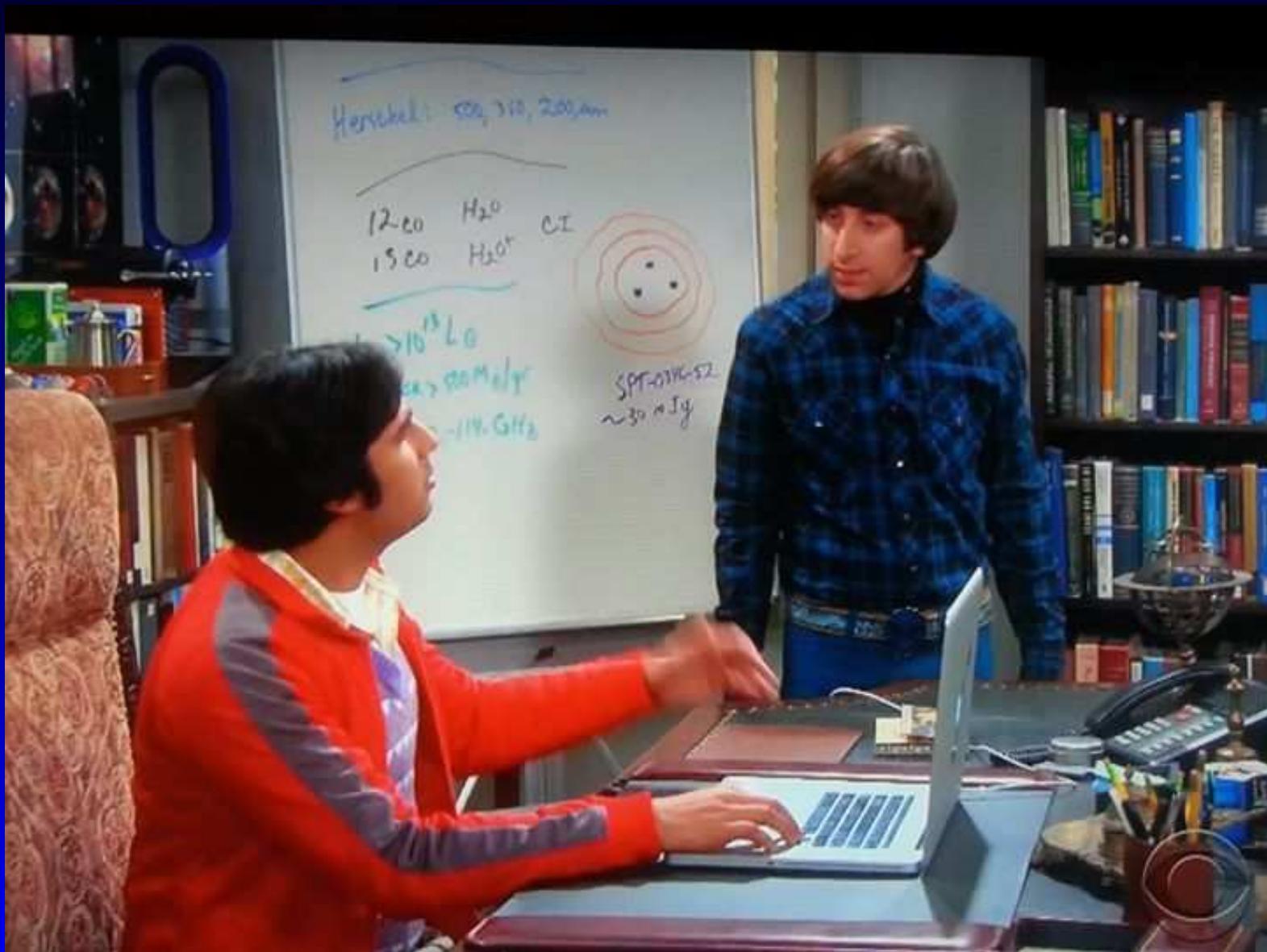
PACS - SPIRE - HIFI

FWHM:

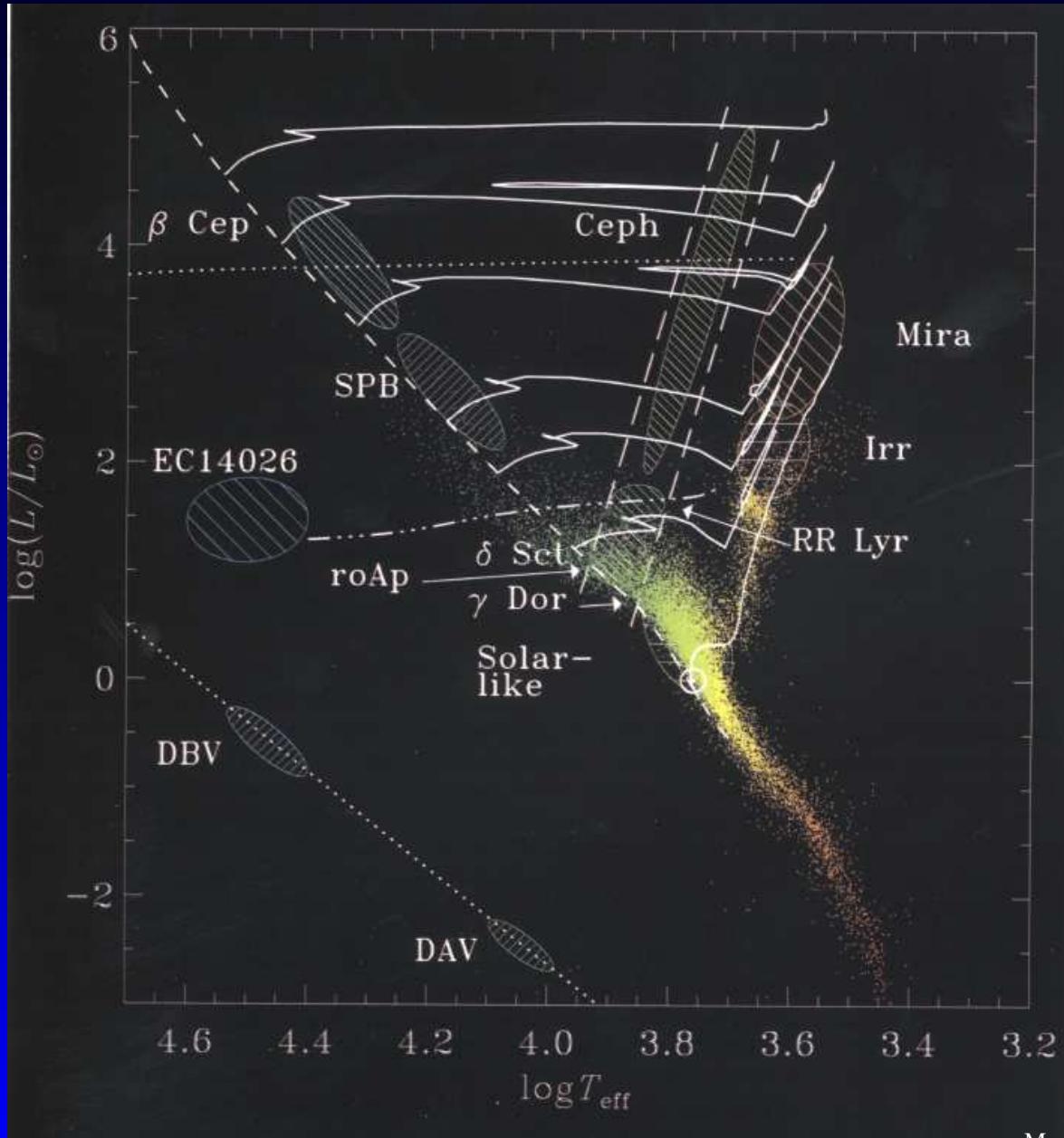
5.6, 6.8, 11.4'' (PACS)
(70, 100, 160 μ m)

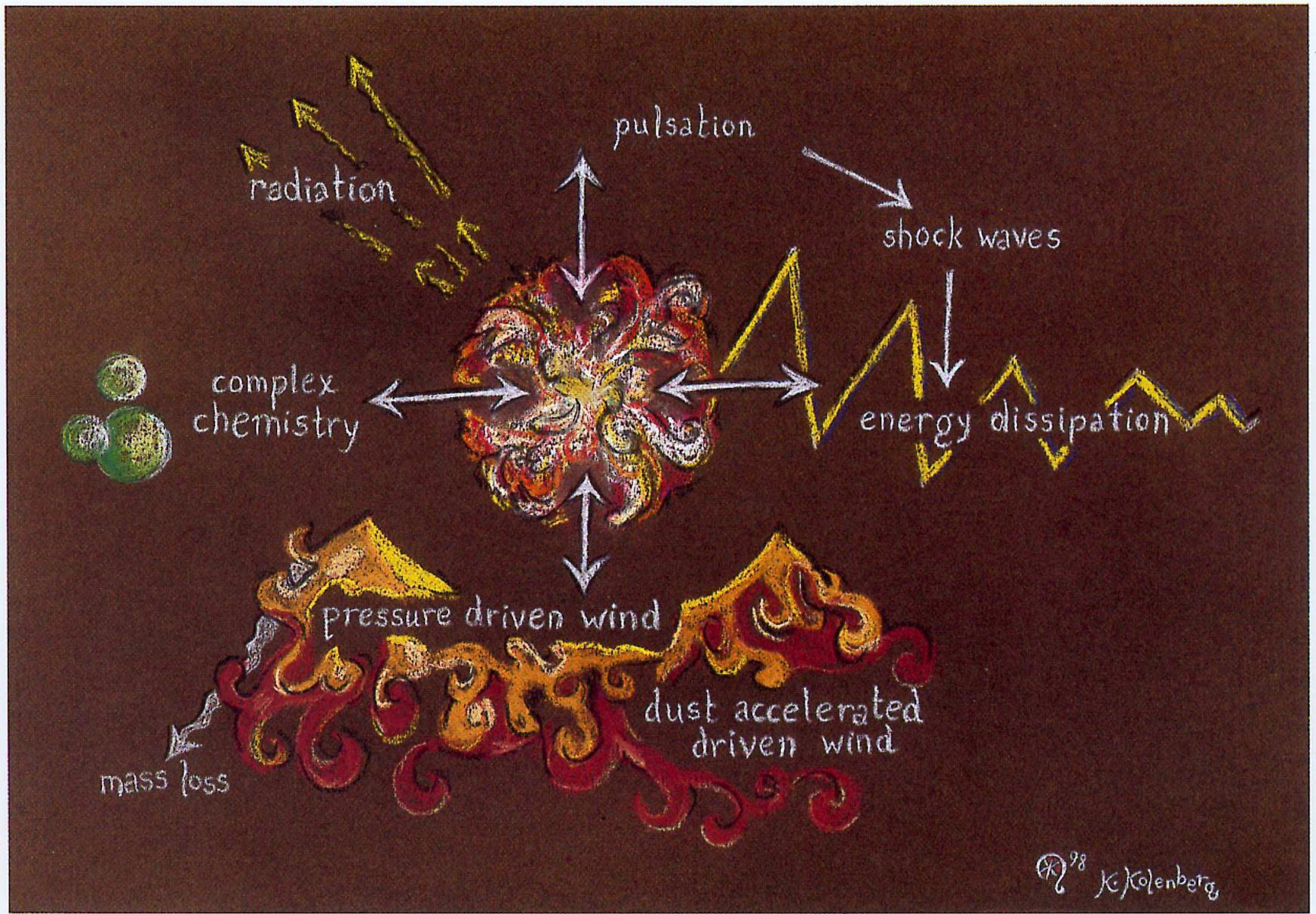
18.1, 25.2, 36.6'' (SPIRE)
(250, 350, 500 μ m)

Big Bang Theory

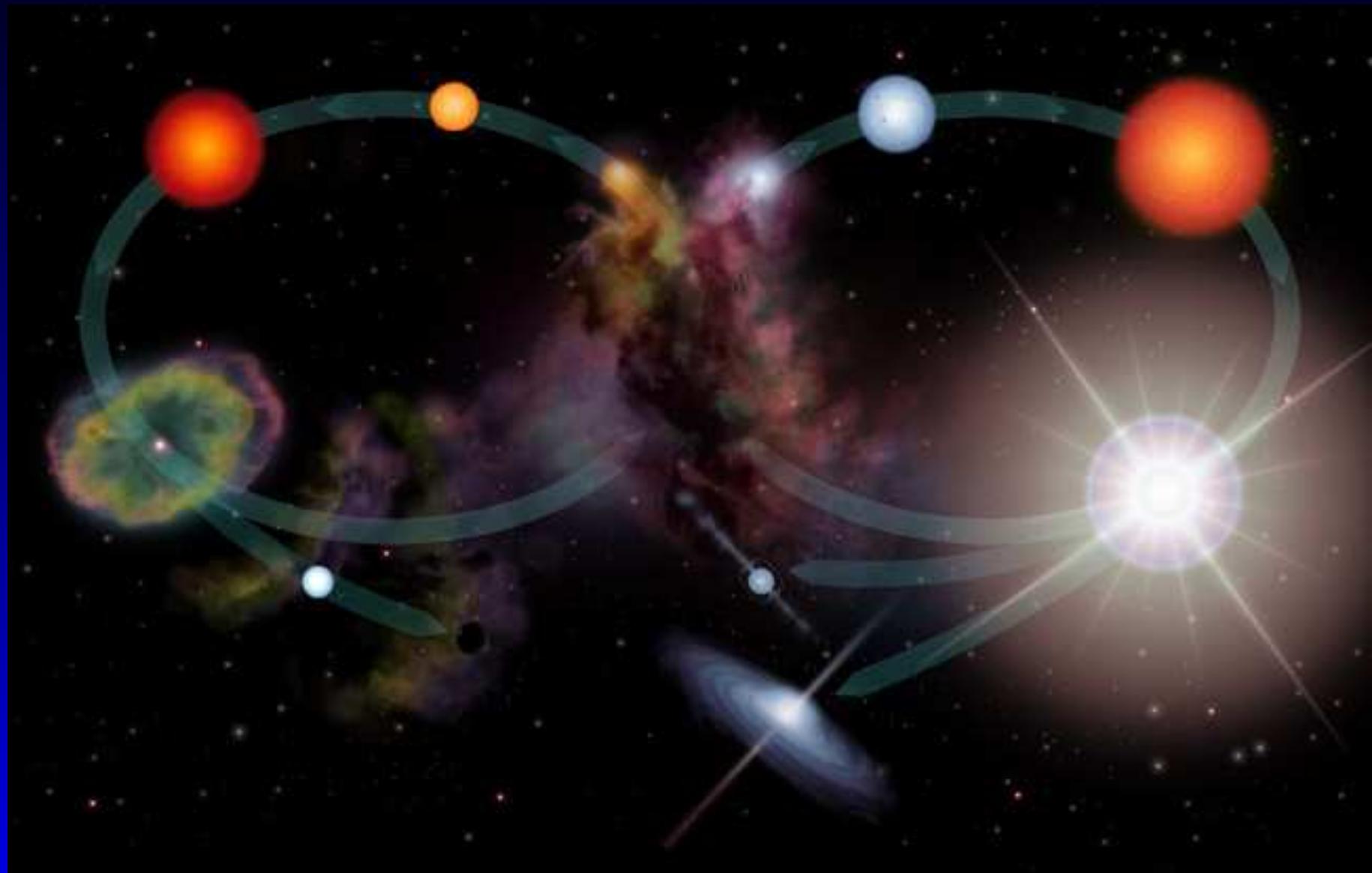


Evolved stars





Lifecycle of dust and gas



Evolved stars GT Key Programs

- **MESS** (Mass loss of Evolved StarS)

PACS + SPIRE

(PI: Martin Groenewegen

PACS Co-PI: Christoffel Waelkens, KUL, IMEC, CSL)

PACS (50-200 μ m)

SPIRE (200-650 μ m)

both have a bolometer array (FOV of a few arcmin)

both have a spectrometer (R= 1000-2000)

- **HIFISTARS** - HIFI (PI: Valentin Bujarrabal)

- Other smaller programs in GT2, OT1, OT2

MESS

This GT KP aims at studying the circumstellar matter in evolved objects

- AGB, Post-AGB, PNe, RSG, WR, LBV, SN
 - Photometric mapping of nearby objects
 - Spectroscopy of nearby objects
 - SPIRE and PACS
- Mass-loss dominates the evolution
How? How much? Time evolution? Spherical?
Production of dust
- $\dot{M}(Z)$
AGB vs. SN gas & dust return at high- z

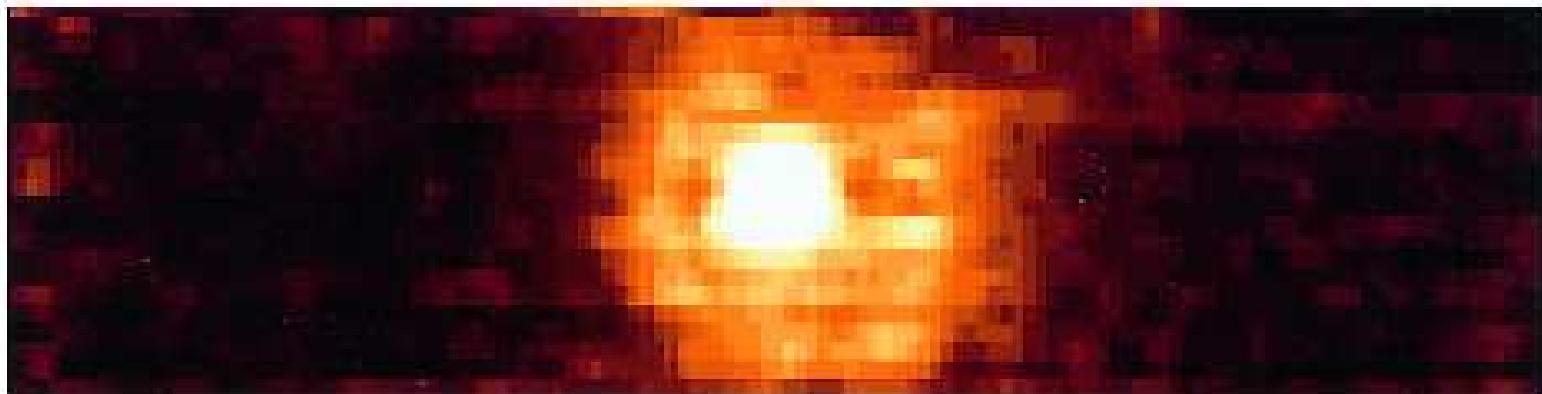


Fig. 1. 90 μm image of Y CVn taken with PHT-C100 array detector and C90 filter displayed in linear brightness scale.

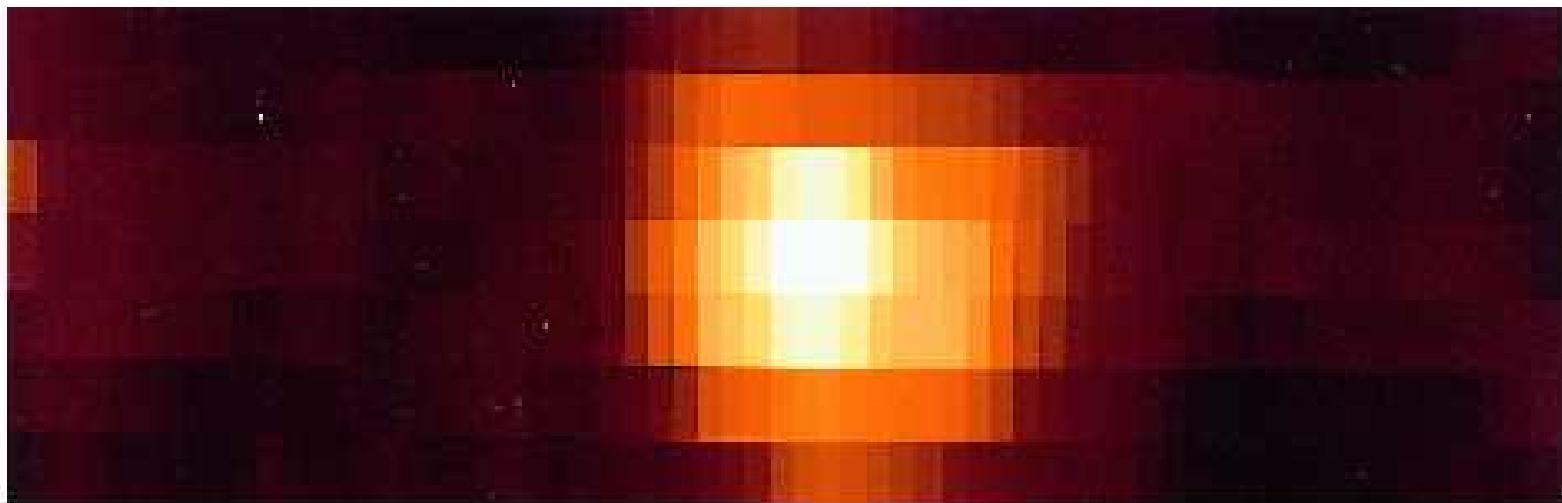
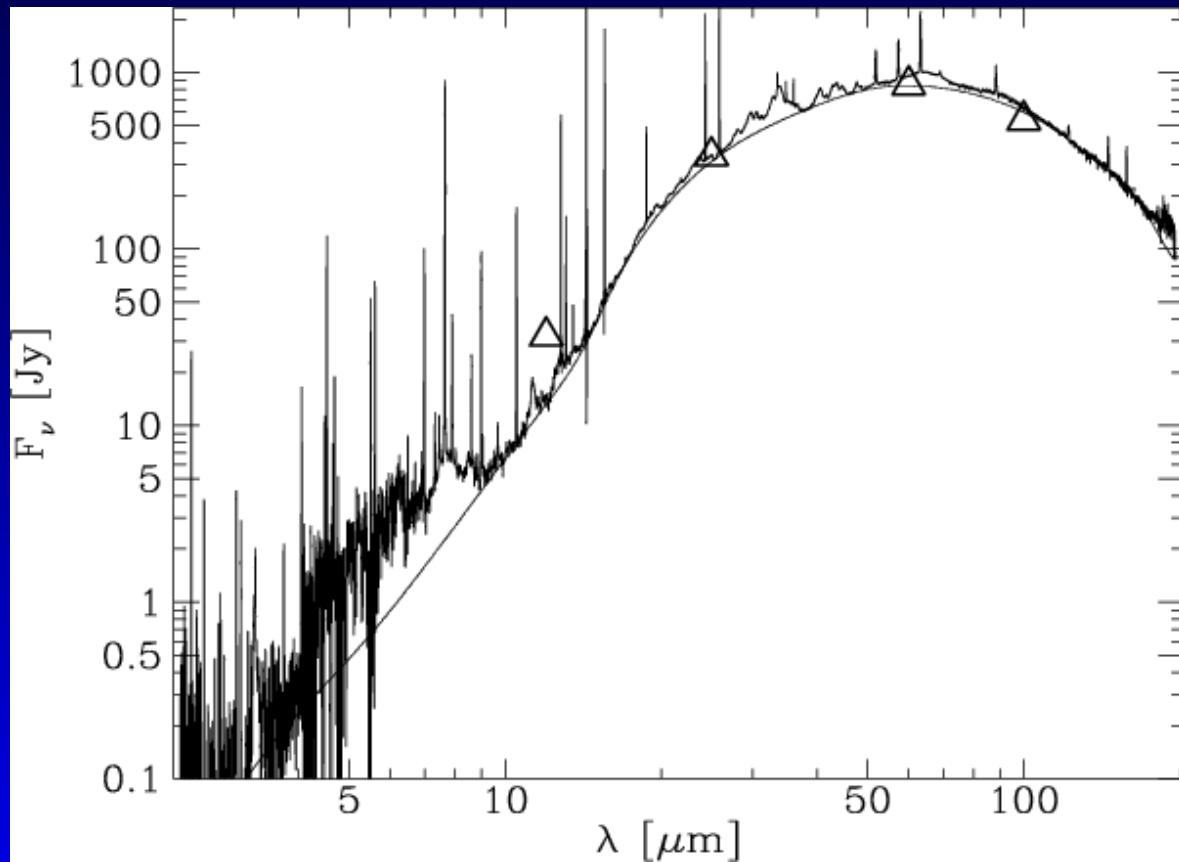


Fig. 2. 160 μm image of Y CVn taken with PHT-C200 array detector and C160 filter displayed in linear brightness scale.

Y CVn
Izumiura et al. (1996), 8' \times 35' ISOPHOT map

Spectroscopy of nearby objects

Goal: Study of
dust properties, molecular lines, emission lines



NGC 6302; Molster et al., SWS + LWS spectrum

Dust and Ices

mineral	chemical formula	‘60+’ band positions [μm]
fosterite	Mg_2SiO_4	69–70
fayalite	Fe_2SiO_4	93–94, 110
diopside	$\text{CaMgSi}_2\text{O}_6$	65-66
calcite	CaCO_3	92
dolomite	$\text{CaMg}(\text{CO}_3)_2$	62
water ice	H_2O	62
methanol ice	$\alpha\text{-CH}_3\text{OH}$	68, 88.5
dry ice	CO_2	85
PAHs “flopping modes”		(far-IR)

Partners involved

Partner	“origin”	hours	special interest
Belgium	PACS GT	145	KUL (AGB, post-AGB, PN, WR, LBV) ROB (AGB, PN) ULB (binary AGB) IAGL (WR, LBV)
Vienna	PACS GT	47	AGB
Heidelberg	PACS GT	10	SN remnants
SAG 6	SPIRE GT	80	SN, AGB, post-AGB, PN
HSC	HSC	26	special type of post-AGB
MS	MS	5	Molecules in specific stars

Implementation (Photo)

PACS:

“Scan Maps” at 70 + 160 μm

78 AGB/RSG, 16 post-AGB/PN, 8 WR/LBV, 5 SN

SPIRE:

“Large maps” at 250, 350, 500 μm

26 AGB/RSG, 8 post-AGB/PN, 5 SN

Implementation (Spectro)

PACS:

Concatenation of two AORs to cover entire
60-210 μm region

Spatial information: 5×5 pixels = $47'' \times 47''$

27 AGB/RSG, 26 post-AGB/PN, 2 WR/LBV, 4 SN

SPIRE:

Complete FTS scan in a single AOR

9 AGB/RSG, 10 post-AGB/PN, 2 WR/LBV, 5 SN

Results

8 papers in the A&A Volume 518 Special Issue (2010)

+ 1 *Nature* paper (2010)

+ Overview paper

(Groenewegen et al. 2011, A&A 526, A162)

+ 17 other refereed papers

-*Not covered*: Massive stars

-*Not covered*: SNe

-*Almost Not covered*: PNe

In more detail:

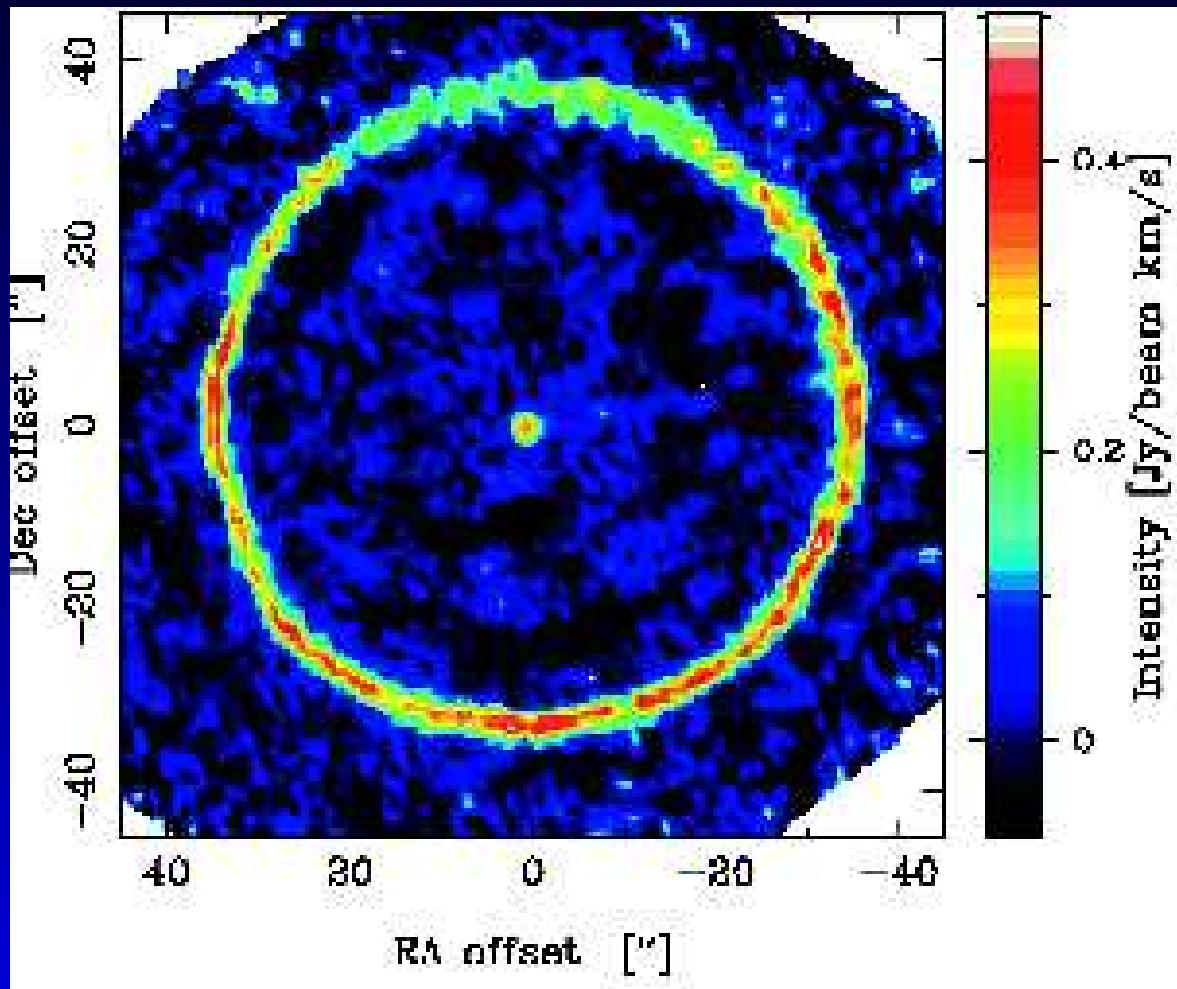
-AGB imaging

-AGB spectroscopy

AGB star imaging

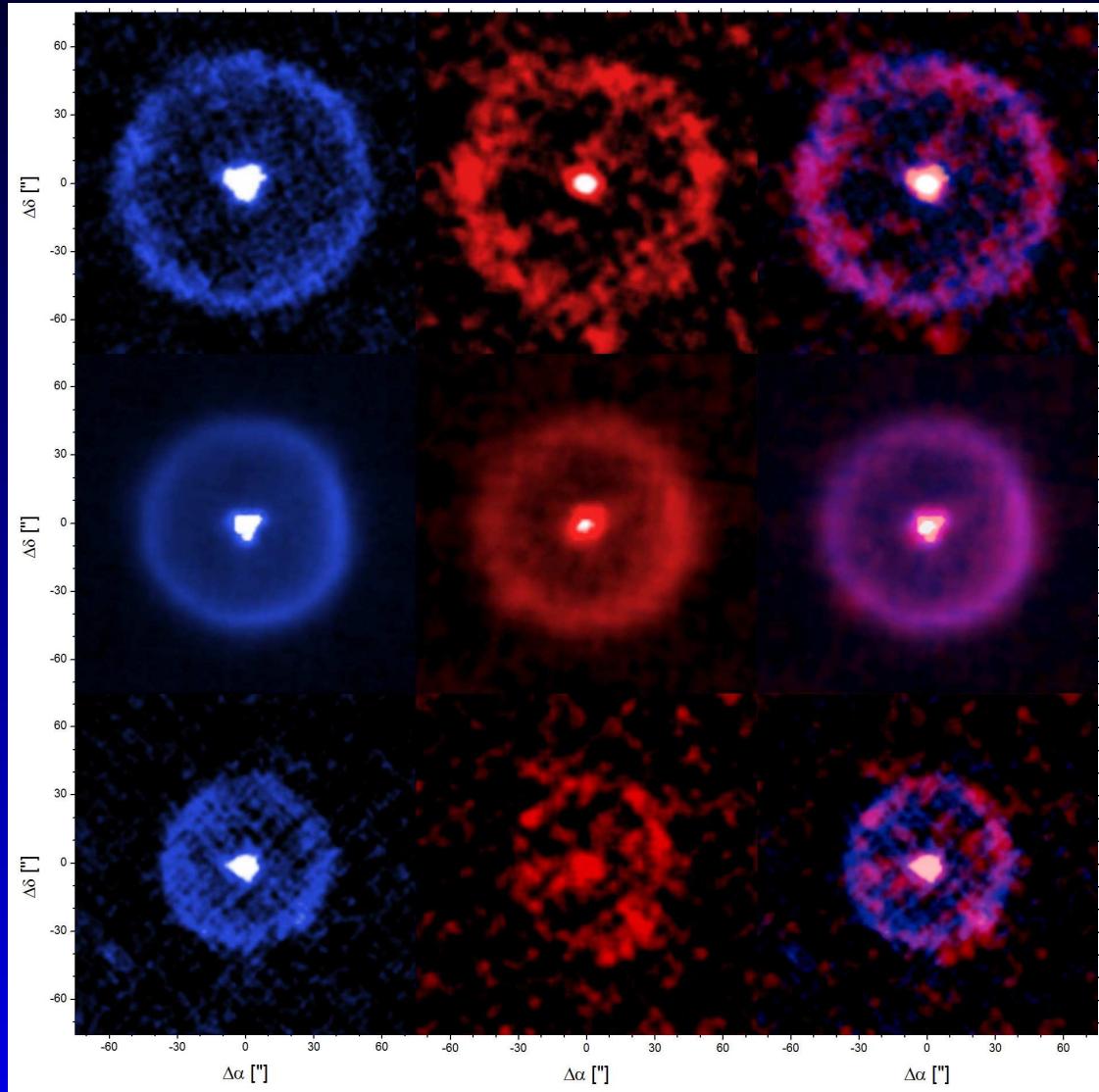
- "detached shell" objects
- CW Leo
 - bow shock
 - inner parts
 - phase-lag distance
- Betelgeuze and its environment
- interaction CSE with the ISM

Detached shells



TT Cyg; Olofsson et al. (2000). PdB CO (1-0)
Short-duration large mass-loss rate event

Detached shells

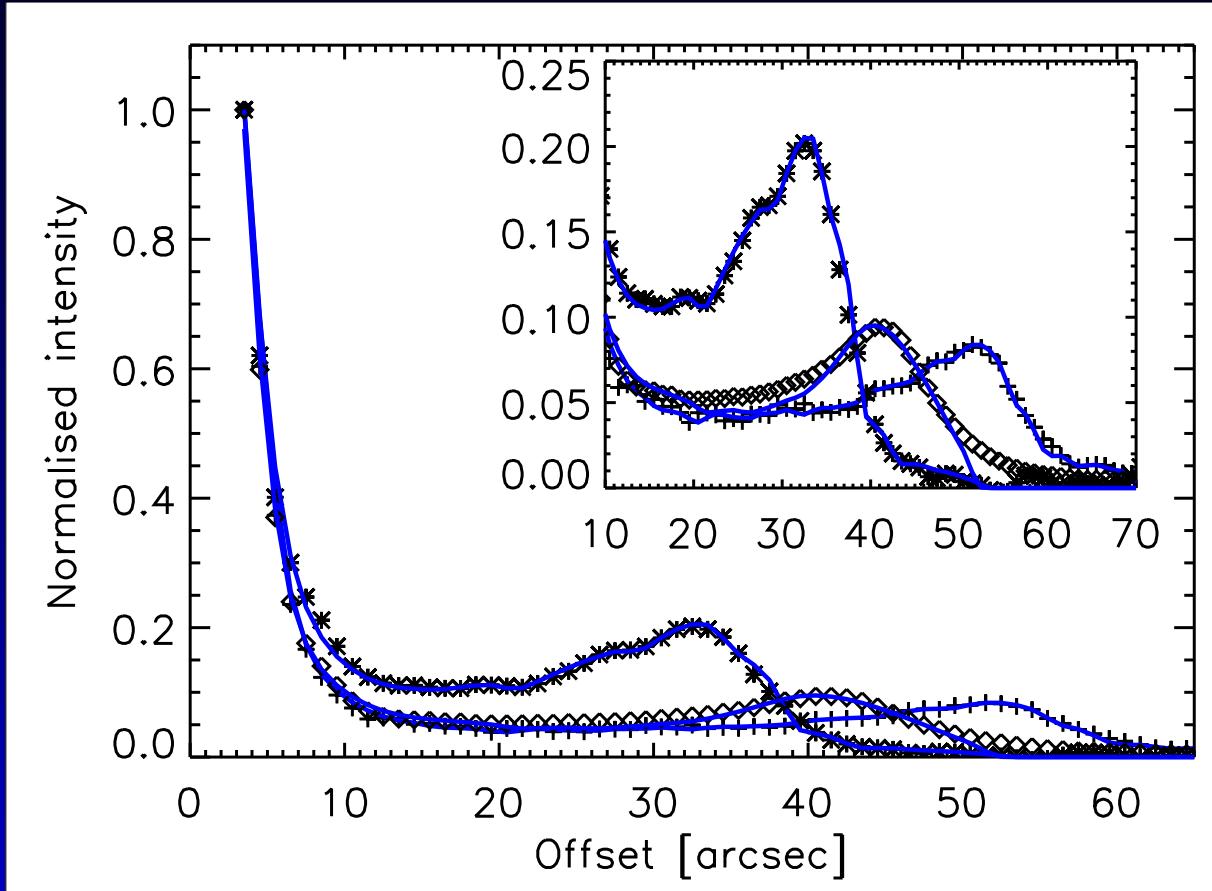


Kerschbaum
et al. (2010)

PACS:
blue / red /
combined

AQ And,
U Ant,
TT Cyg

Detached shells



AQ And=+
U Ant=◊
TT Cyg=×

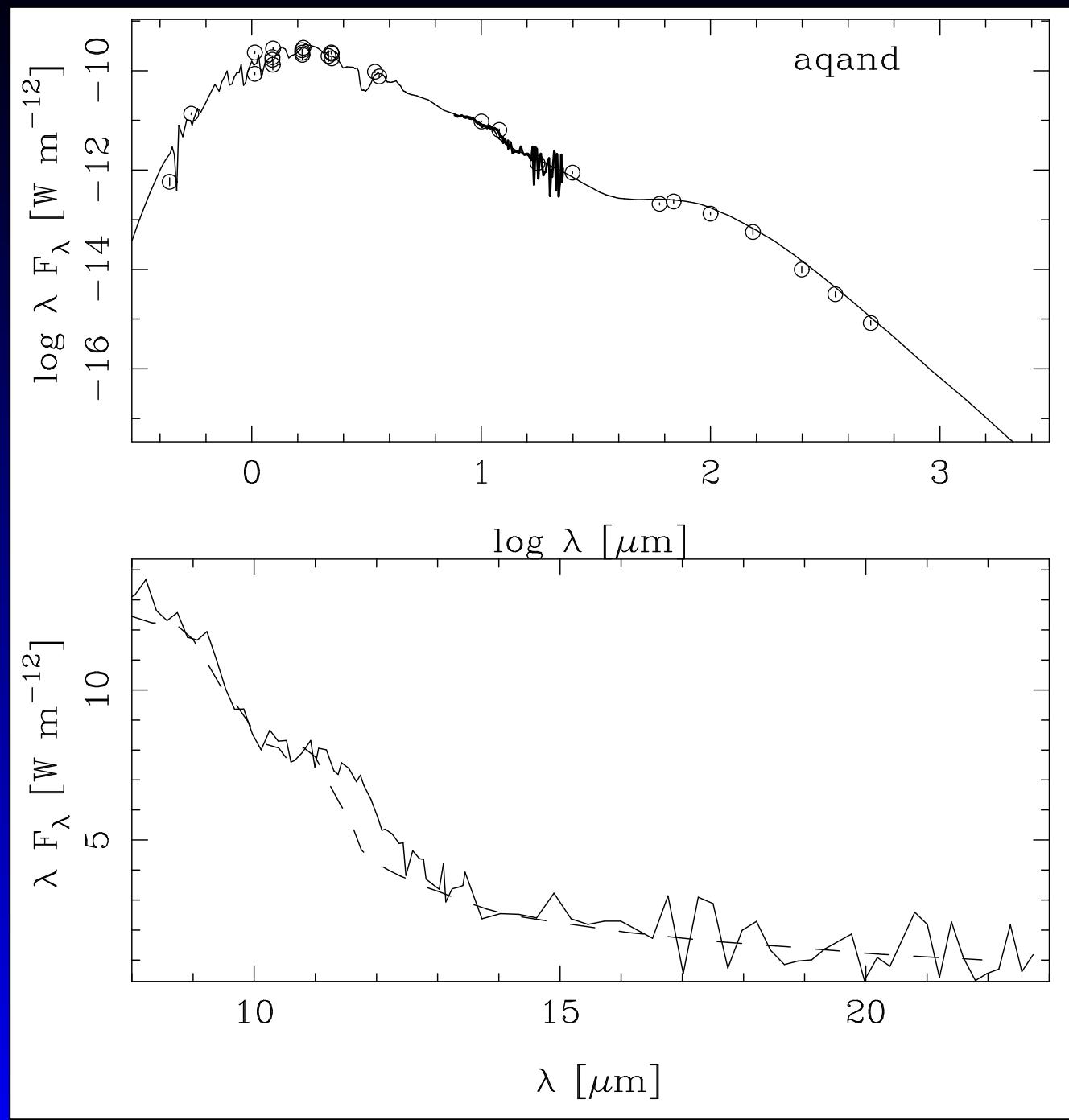
DUSTY
multiple-
shells

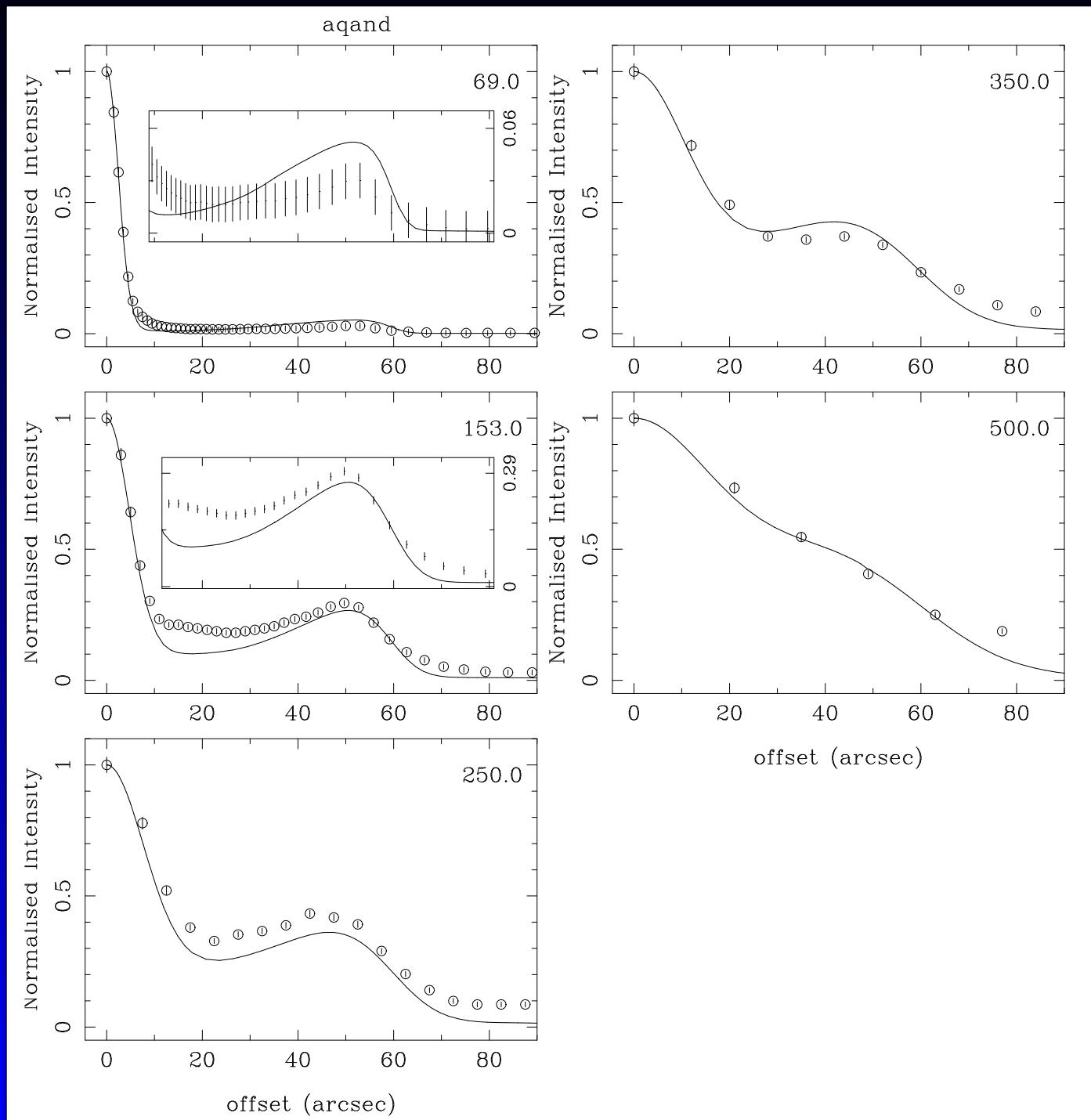
T_{dust} =
25-50 K

Kerschbaum et al. (2010, A&A Special Issue)

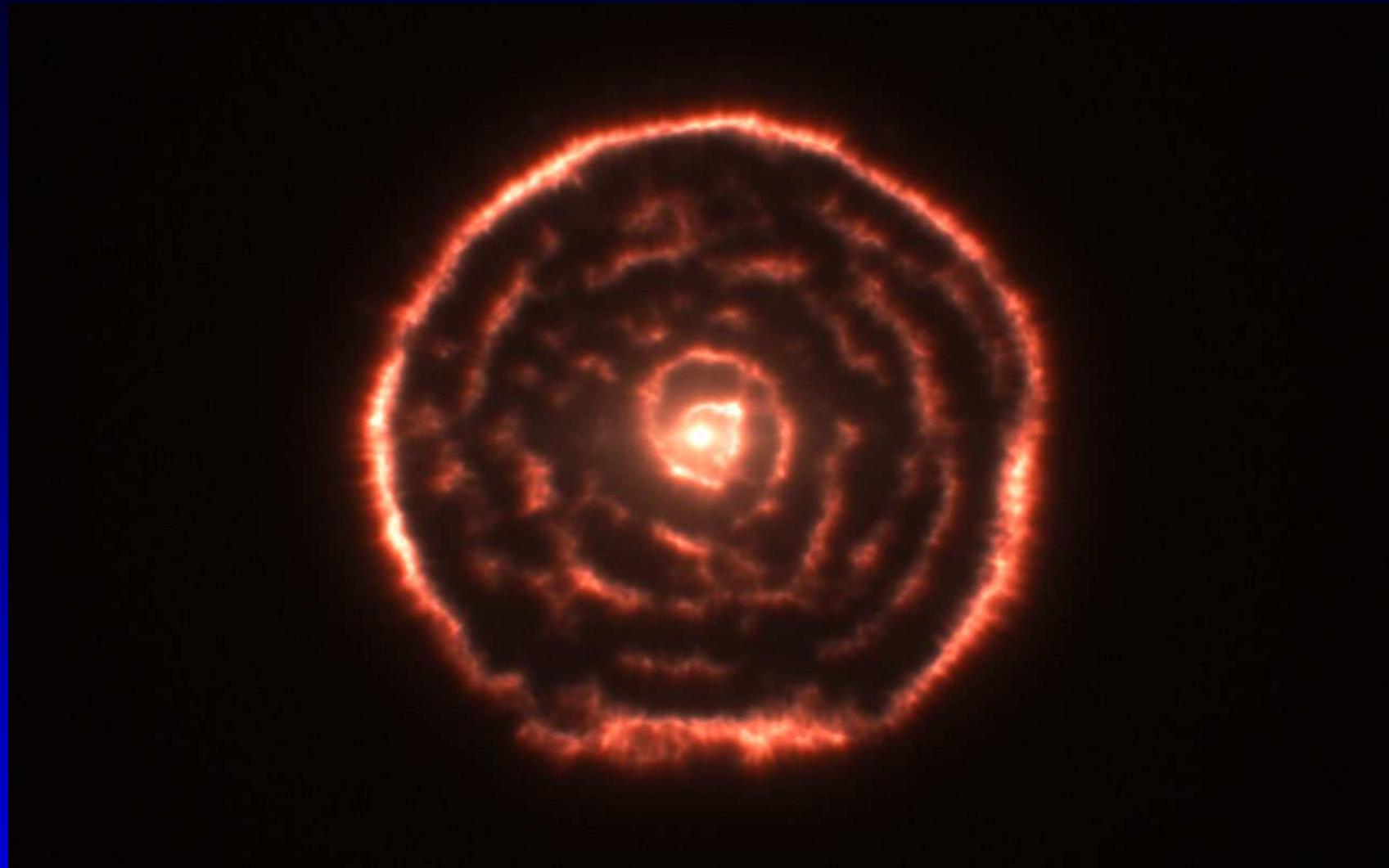
MoD - More of DUSTY

- Improved DUSTY
(discontinuous density distribution, $\sim r^{-p}$)
- embedded DUSTY code into a minimisation routine
- Can fit photometry, spectra, intensity distributions and visibility data
- Groenewegen 2012, A&A 543, A36
- AQ And: 7 parameters
 L , τ_V , $R_{\text{in,shell}}$, ΔR_{shell} , p_o , p_{shell} , “density jump”

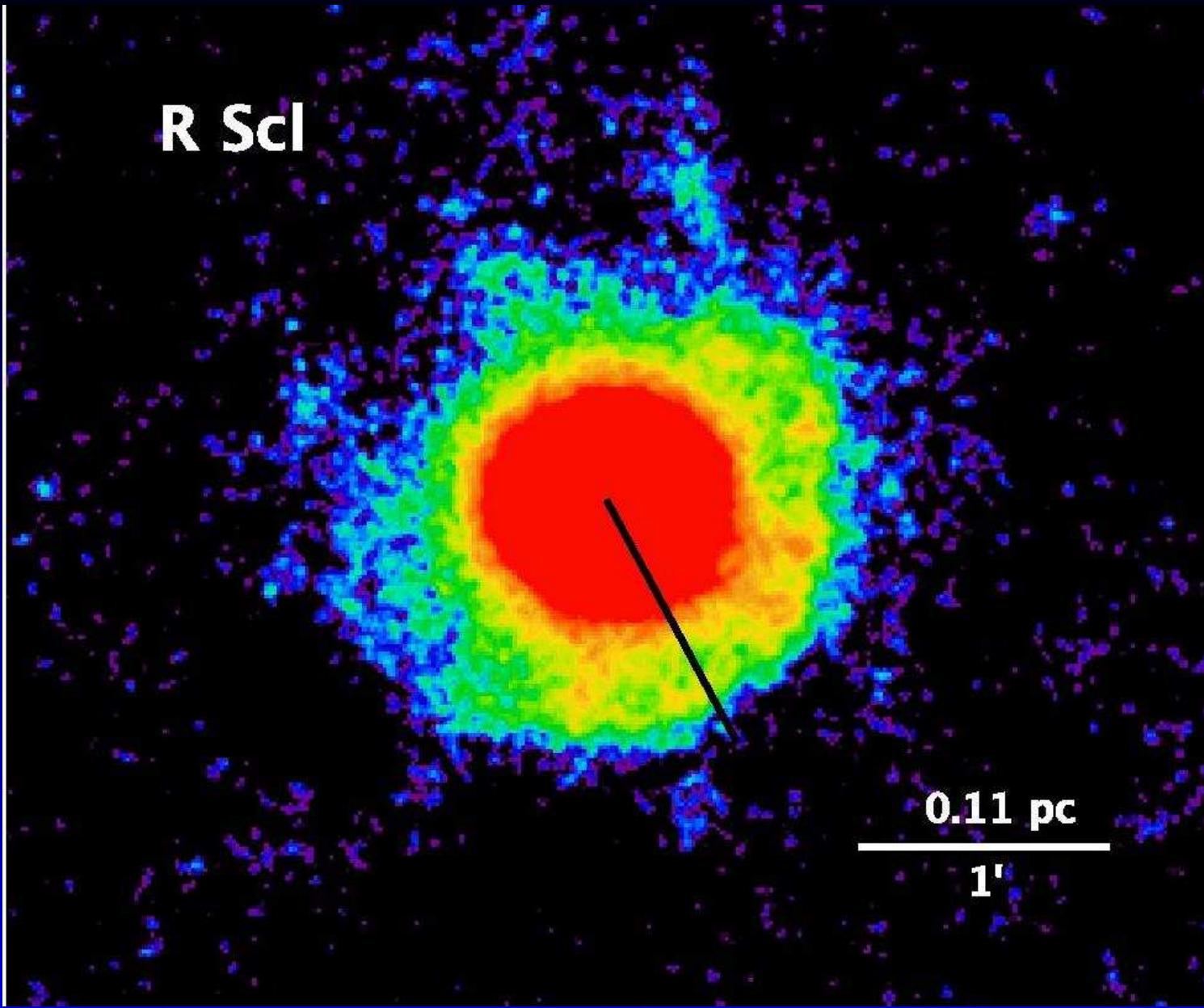




ALMA - Synergy

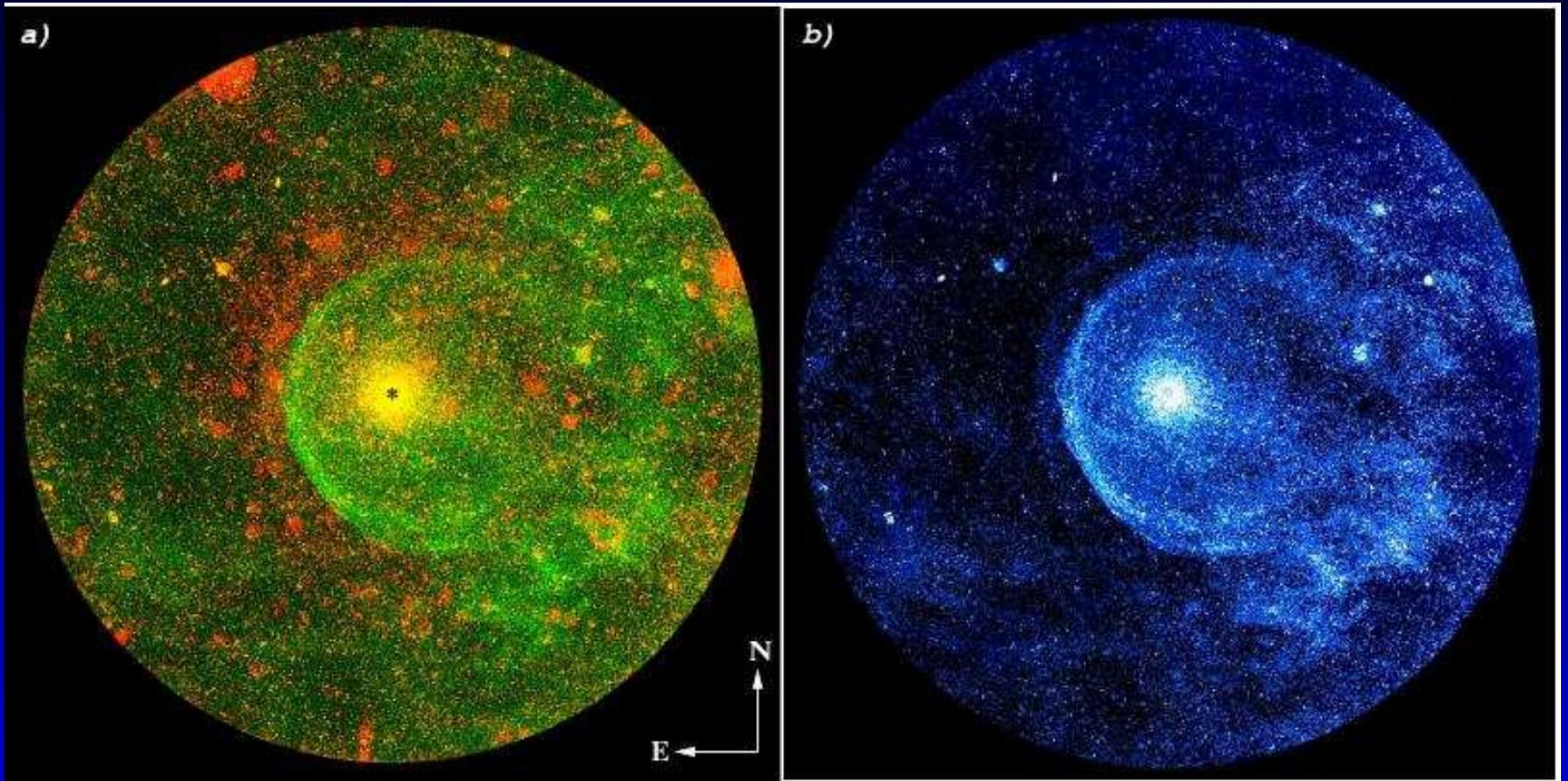


Maercker et al. (2012, Nature 490, 232)
R Scl CO(3-2) $40'' \times 40''$



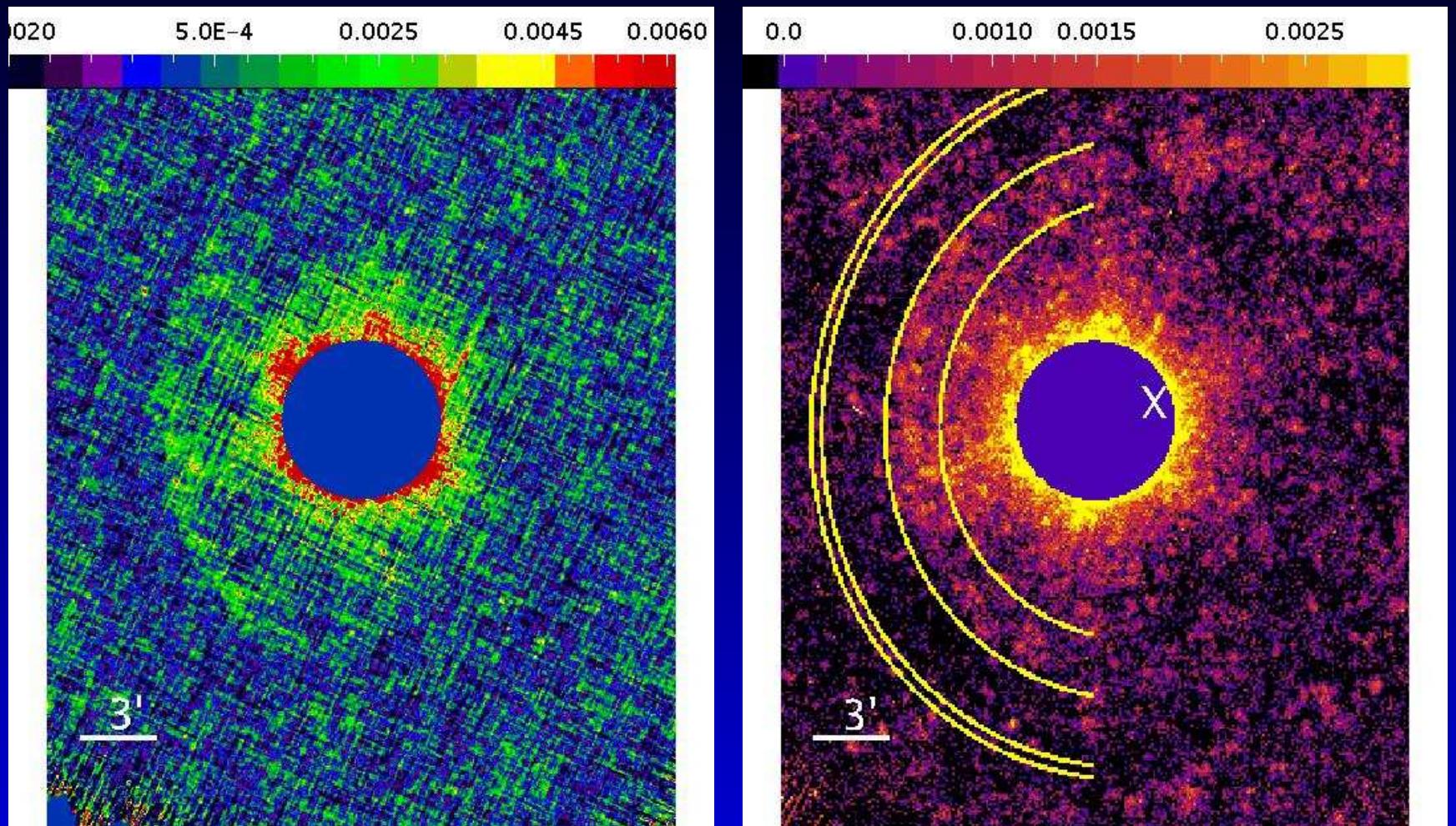
Herschel view at $70 \mu\text{m}$. Note different spatial scale !!

CW Leo - bowshock



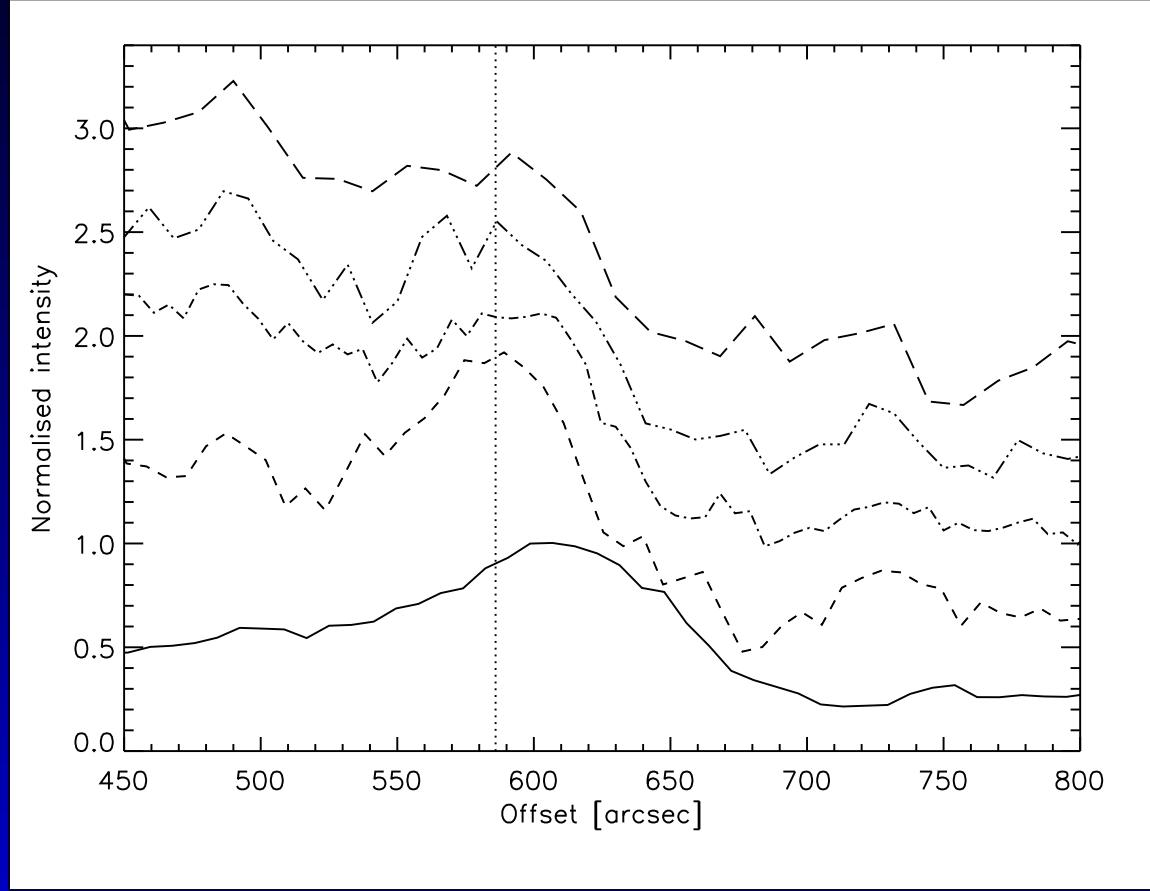
GALEX NUV/FUV composite (left), FUV (right).
Sahai & Chronopoulos (2010)

CW Leo - bowshock



PACS 160 and SPIRE 250 micron
23' \times 27' (Ladjal et al. 2010)

CW Leo - bowshock

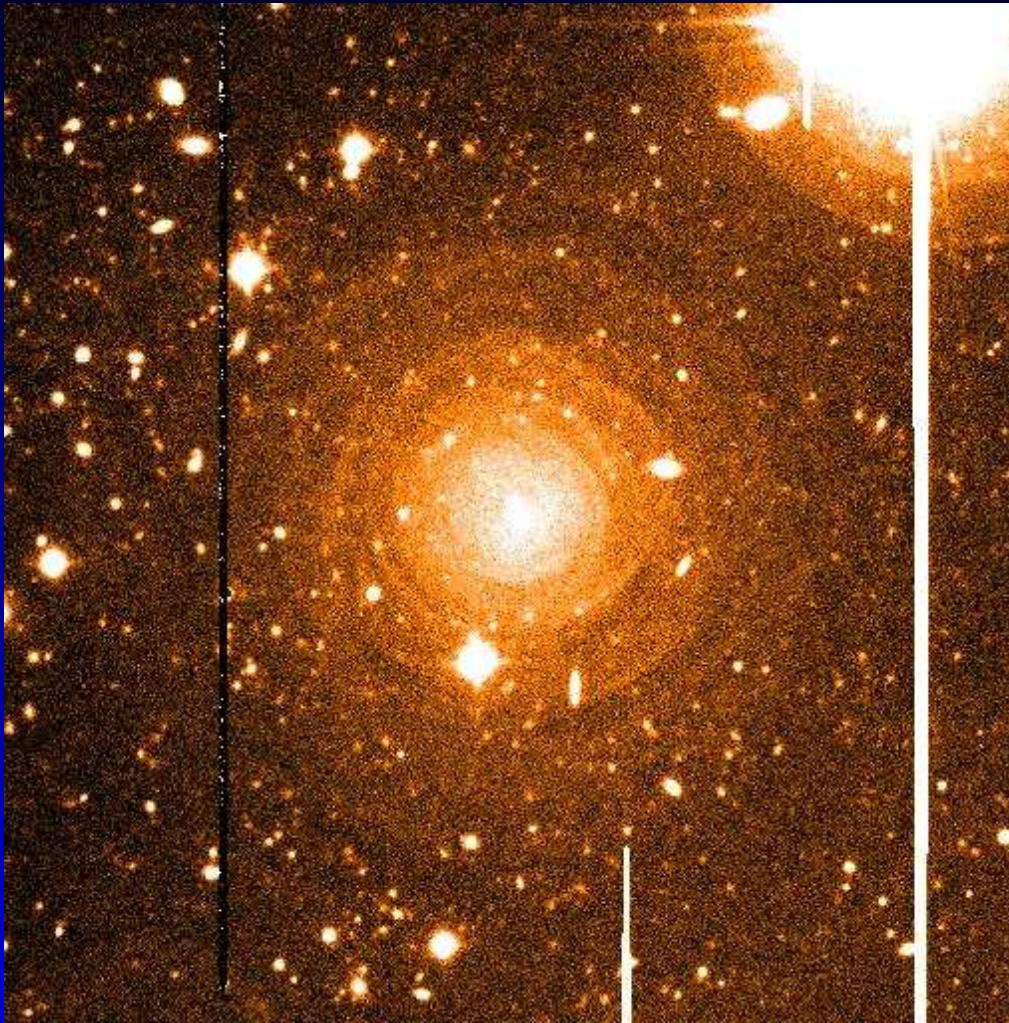


Intensity profiles FUV, 160, 250, 350, 550 micron

$$T_{\text{dust}} = 25 \text{ K}$$

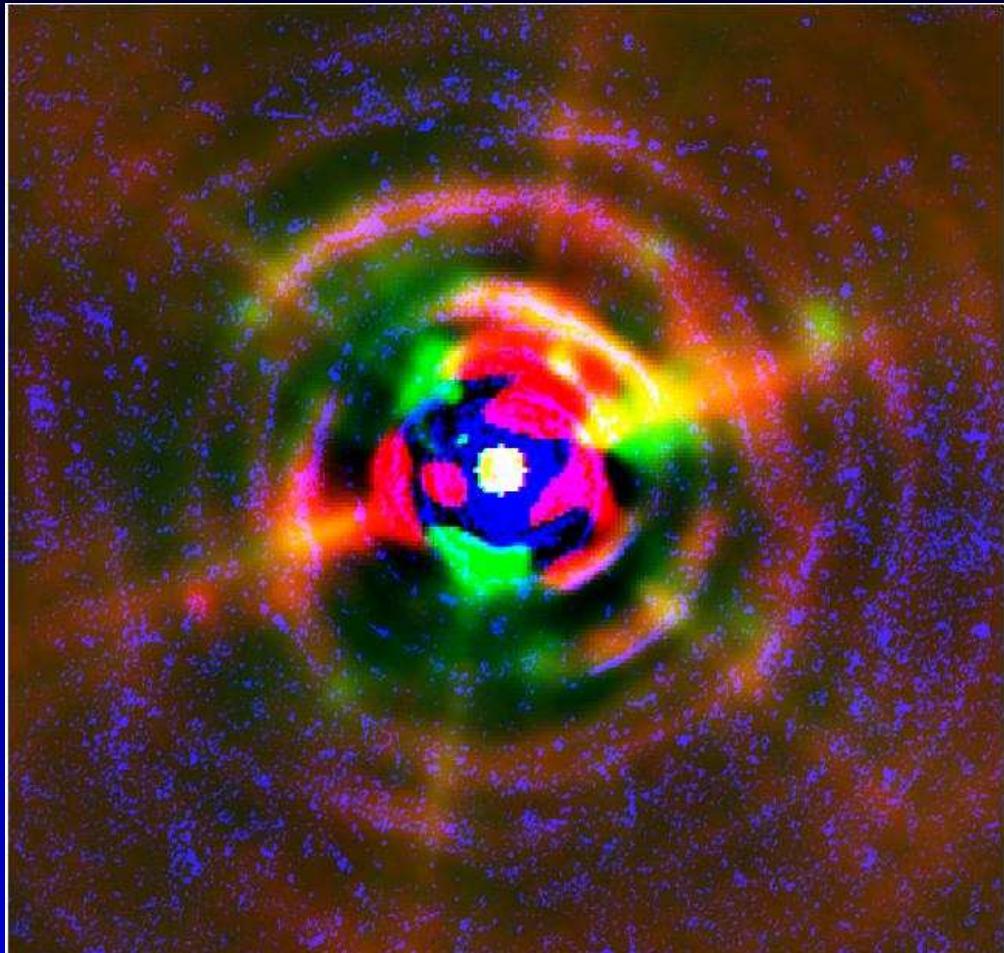
$$V_{\star\text{relativeISM}} = 107 / \sqrt{n_{\text{ISM}}} \text{ km s}^{-1}$$

CW Leo - inner part



(Mauron & Huggins 1999) V -band, FoV= 223 x 223''

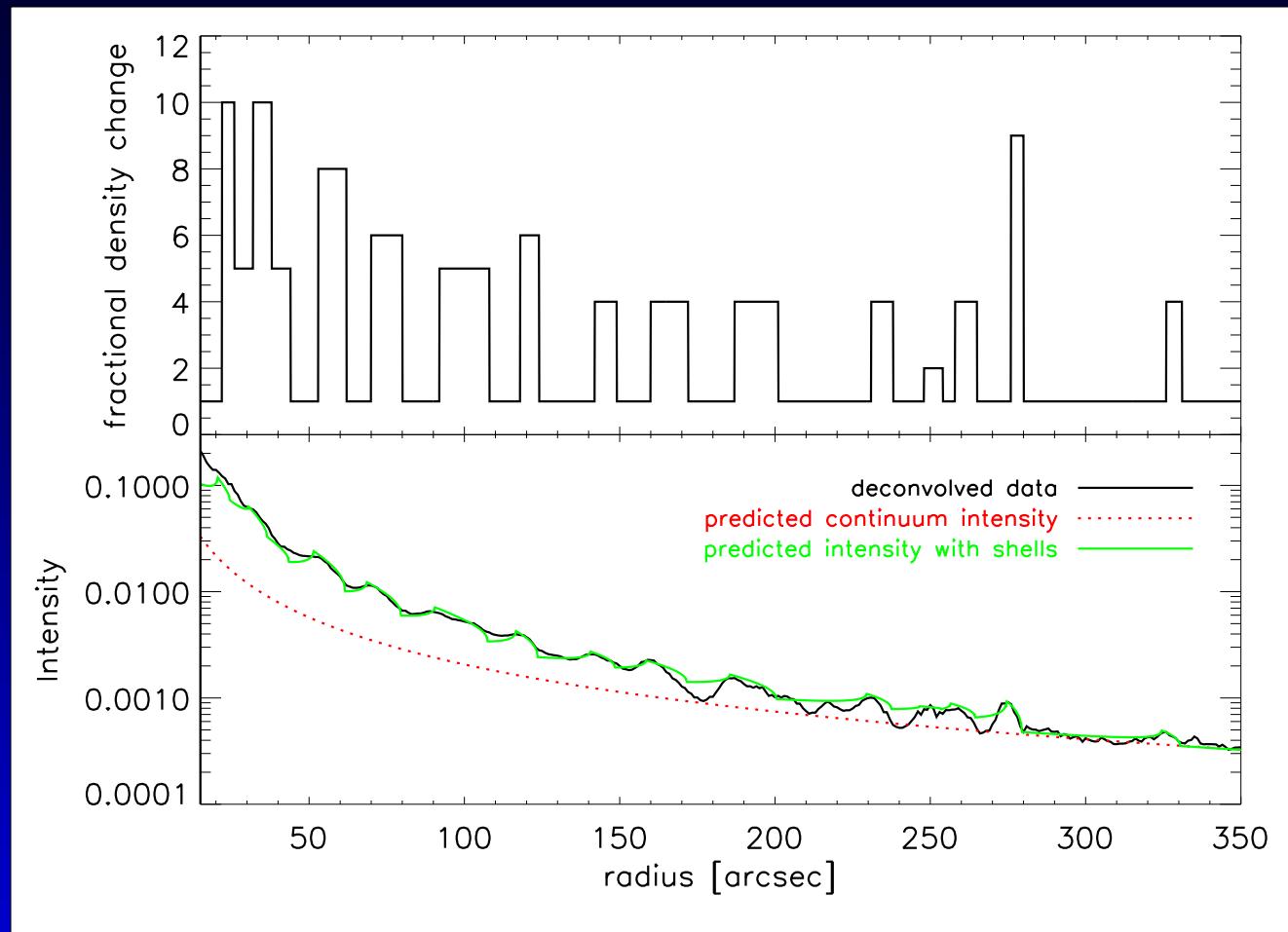
CW Leo - inner part



Combined image of
the PACS 70 μm
(green), PACS 100
 μm (red) and *V*-band
(blue).
FoV= 204 x 204"

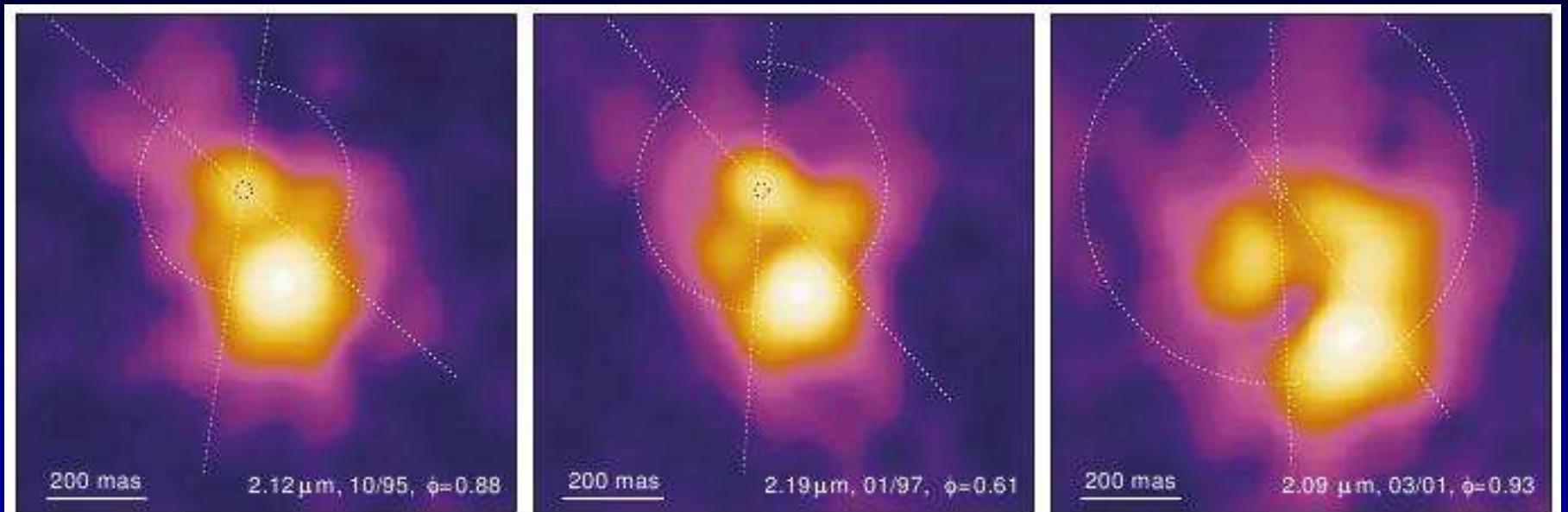
Decin et al. (2011)
non-isotropic mass-loss events and clumpy dust
formation

CW Leo - inner part



A model (Decin et al. 2011)

CW Leo - inner part



(Menshchikov et al. 2002) *K*-band speckle
FoV= $1 \times 1''$

CW Leo - Distance

CW Leo (= IRC +10 216 = AFGL 1381)

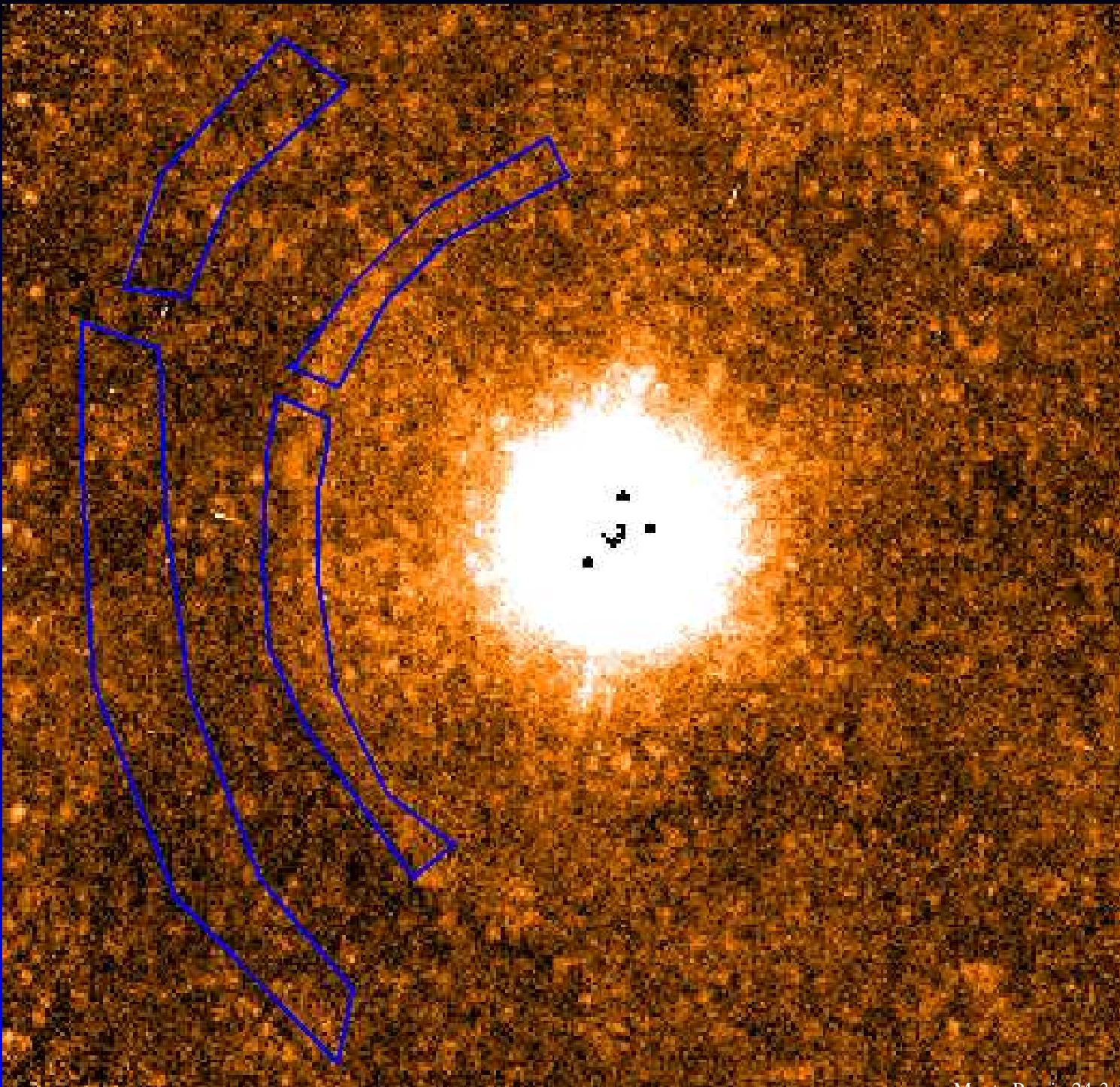
Two-micron Sky Survey (Becklin et al. 1969)

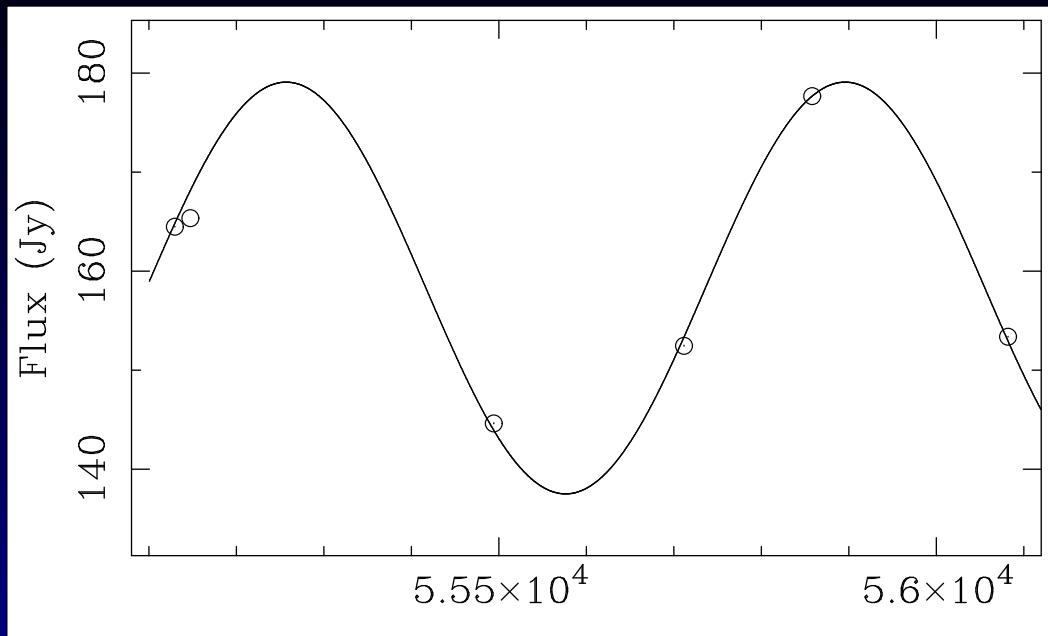
$d = 110\text{-}135 \text{ pc}$ (Groenewegen et al. 1998)

Dust and molecular radiative-transfer models were used to fit simultaneously the available photometric data, the *IRAS* LRS spectrum, near- and mid-IR interferometric observations, and CO J= 1-0 up to 6-5 molecular line emission data.

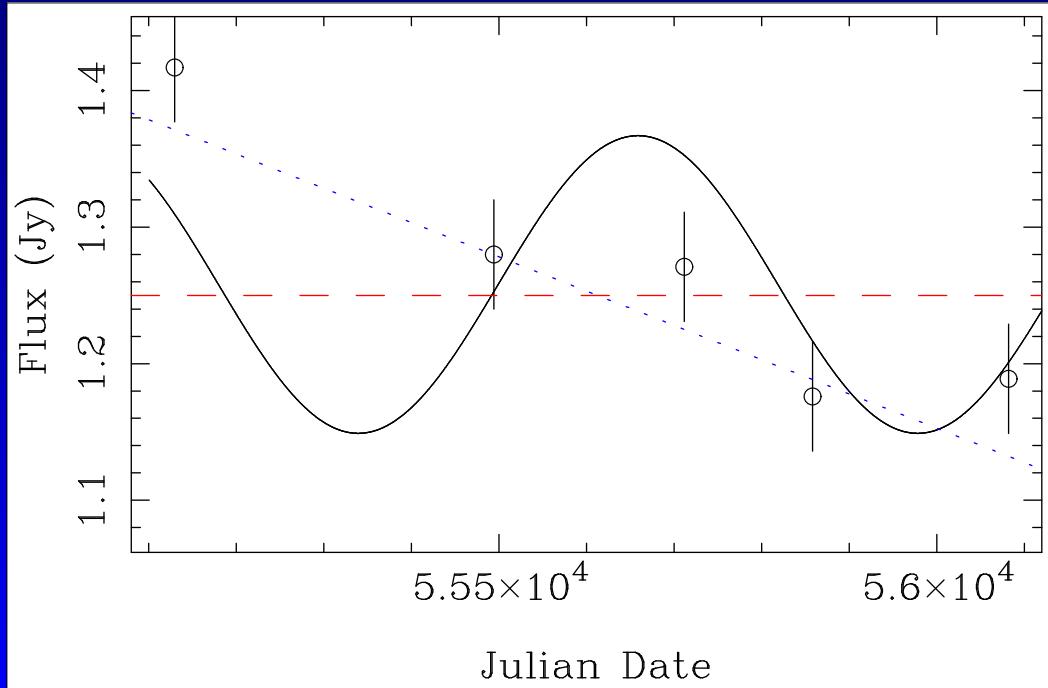
Pulsation Period: 644 ± 17 days (Witteborn et al. 1980), 636 ± 3 days (Ridgway & Keady 1988), 638 days (Dyck et al. 1991)

5 epochs (2 MESS + 3 DDT (PI. Groenewegen))





Julian Date



Julian Date

Groenewegen et al. (2011)

The phase lag of (402 ± 37) days

CW Leo - Distance

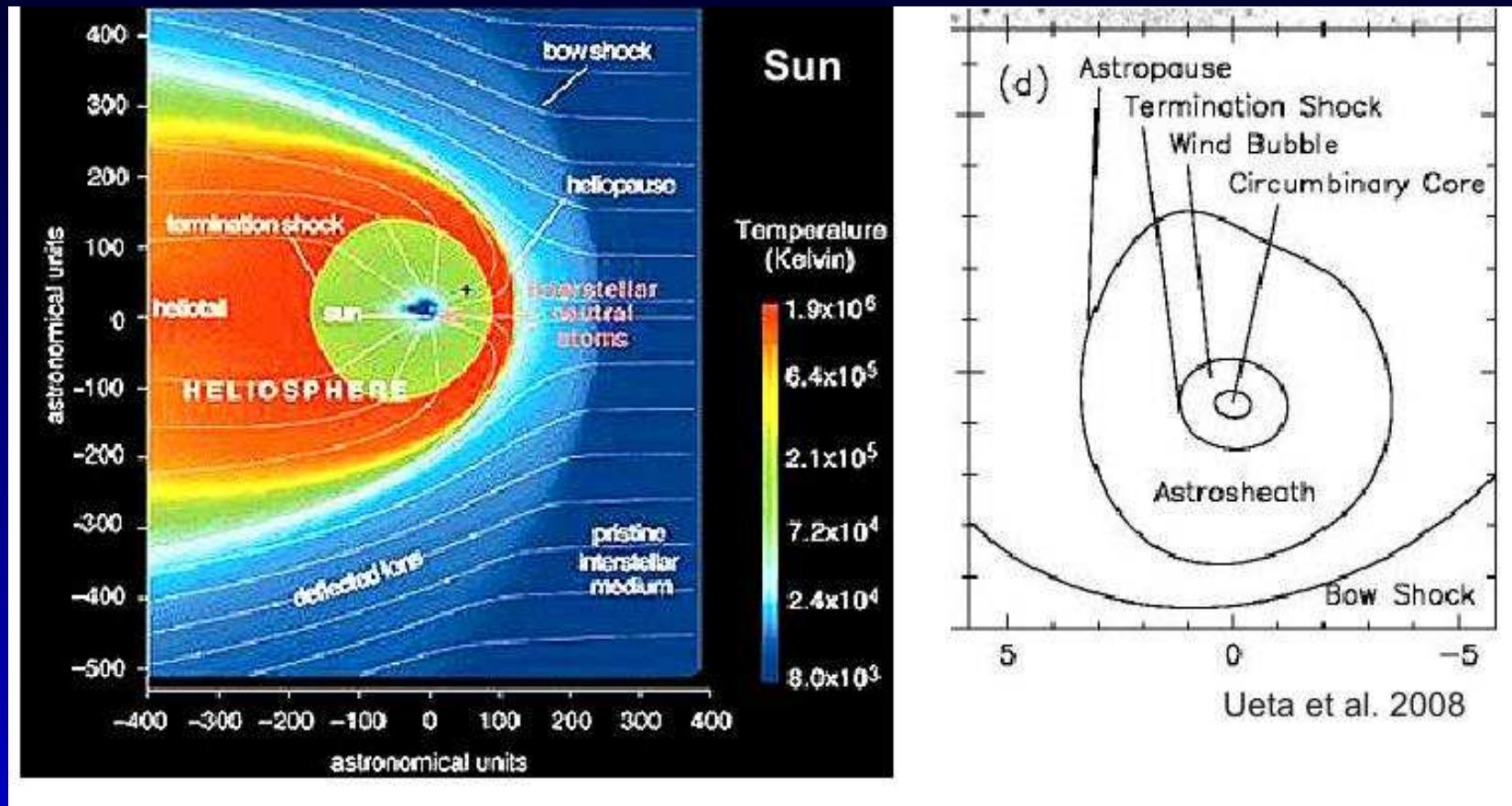
Angular separation between the emission of the central star and the bow shock is $(534 \pm 16)''$.

If the bow shock were located in the plane-of-the-sky, the distance to CW Leo would follow immediately as $d = 130 \pm 13$ pc. And this is a strict upperlimit.

Can one do better?

INTERMEZZO !

Interaction ISM

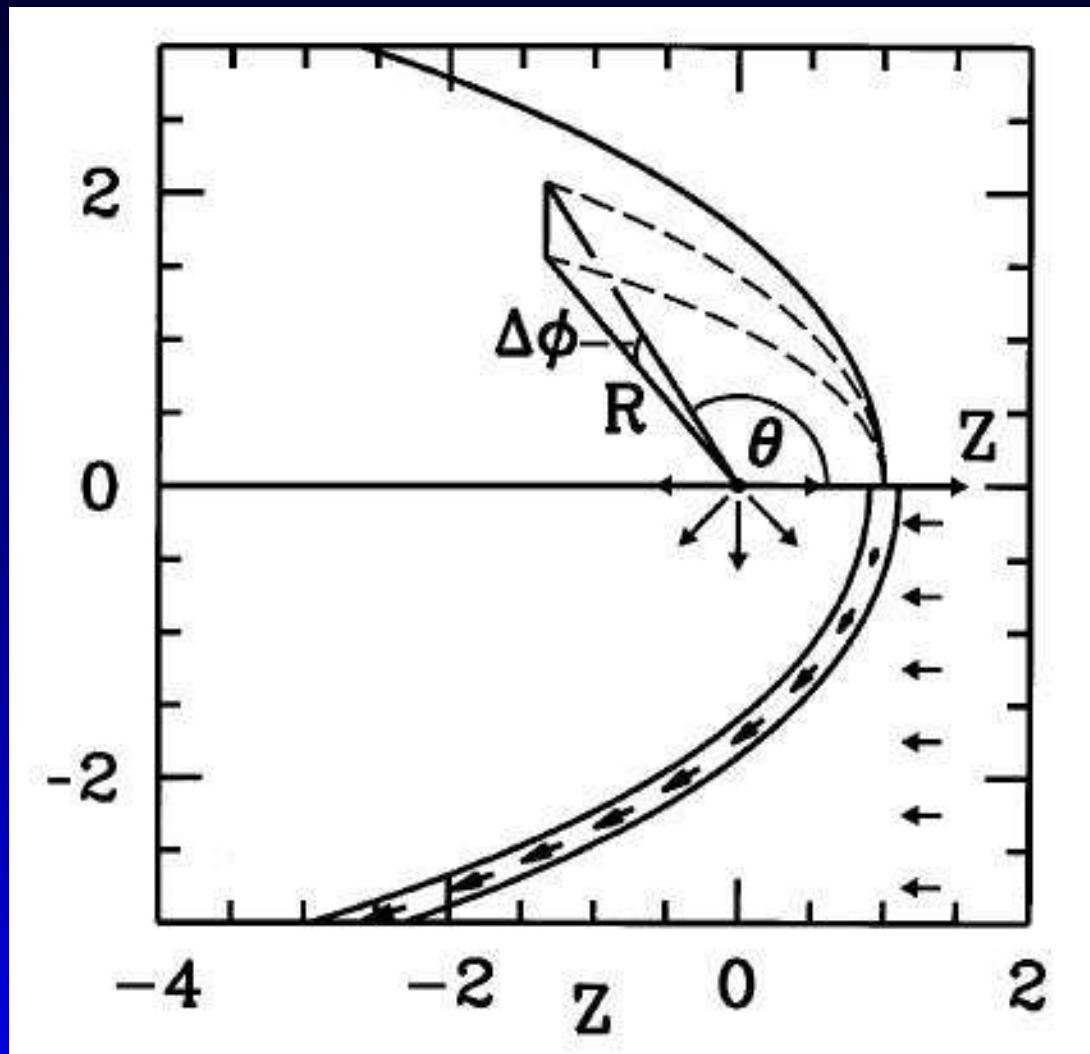


bow shock: where V_{ISM} goes from super- to subsonic

astropause: where $P_{ISM} = P_{CSE}$

termination shock: where V_{CSE} goes from super- to subsonic

Wilkin model



Thin-shell shock model (Wilkin 1996)

Wilkin model

$$R(\theta) = R_0 \sqrt{3 \cdot (1 - \theta / \tan(\theta))} / \sin(\theta)$$

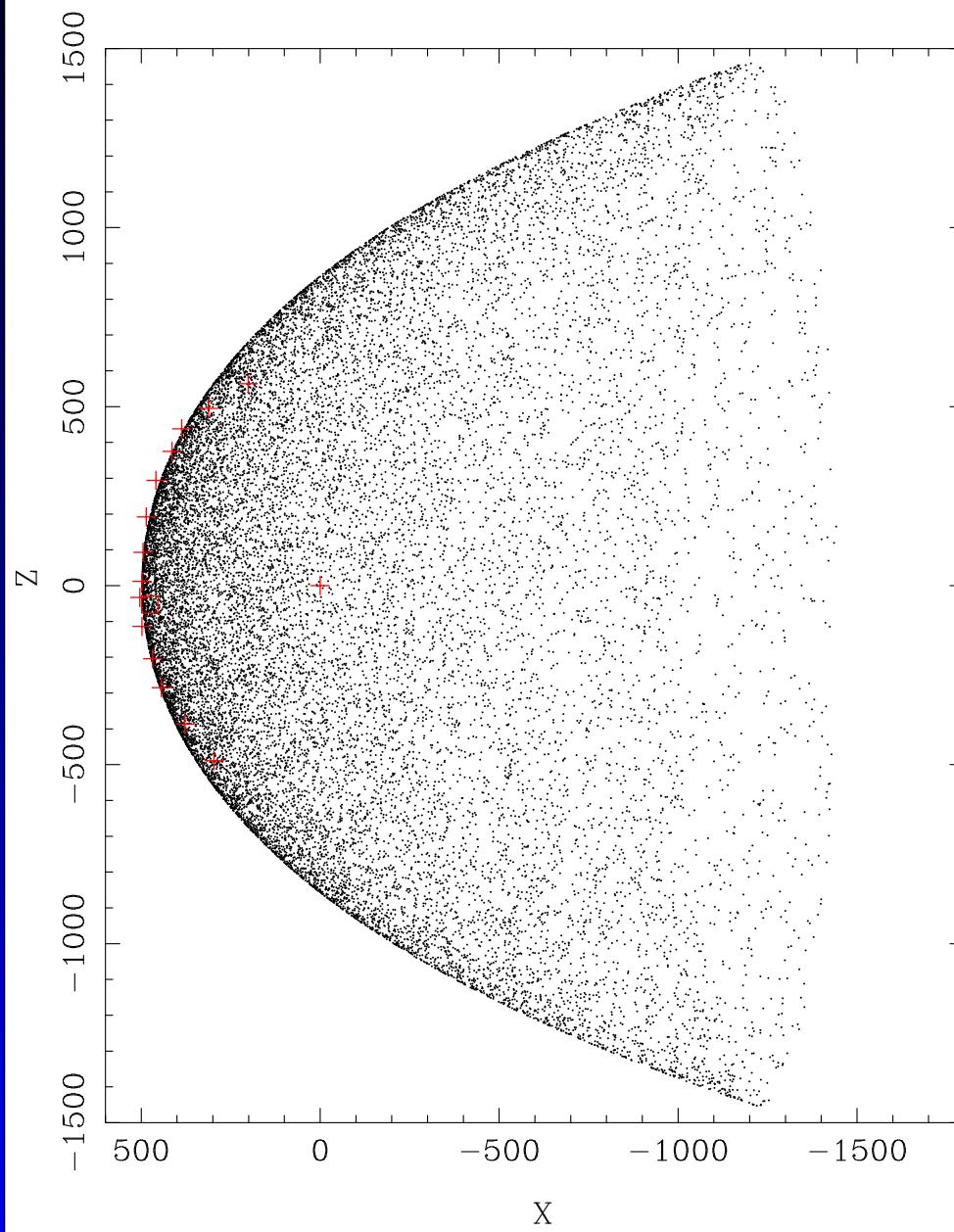
standoff distance:

$$R_0 = \sqrt{(\dot{M} V_{\text{exp}}) / (4\pi \rho_0 V_w^2)}$$

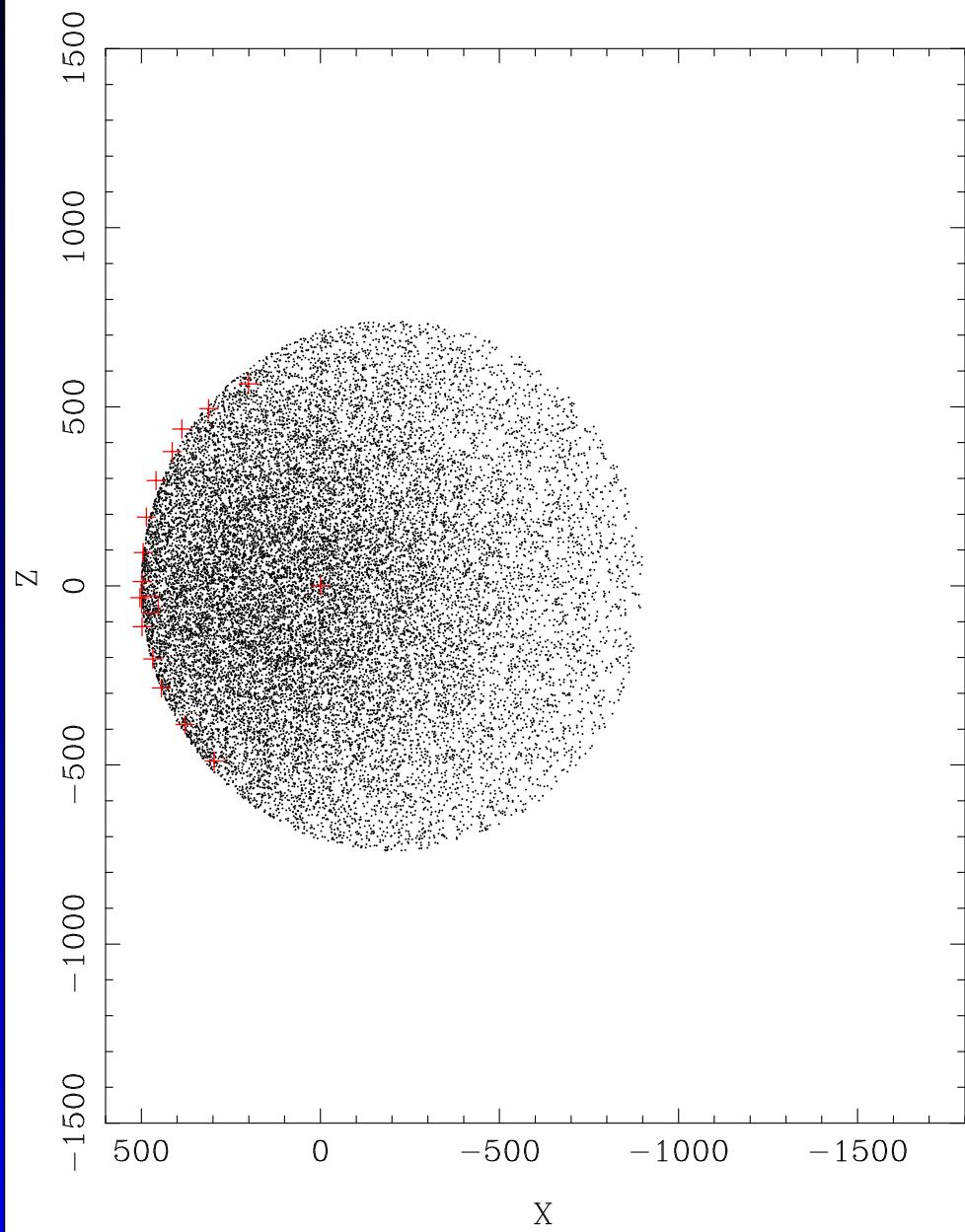
3D Wilkinoid

- Monte Carlo simulation
- Fit the outline to an observed profile

493.2 -9.0 0.3 130.



250.2 -71.2 0.1 130.



CW Leo - Distance

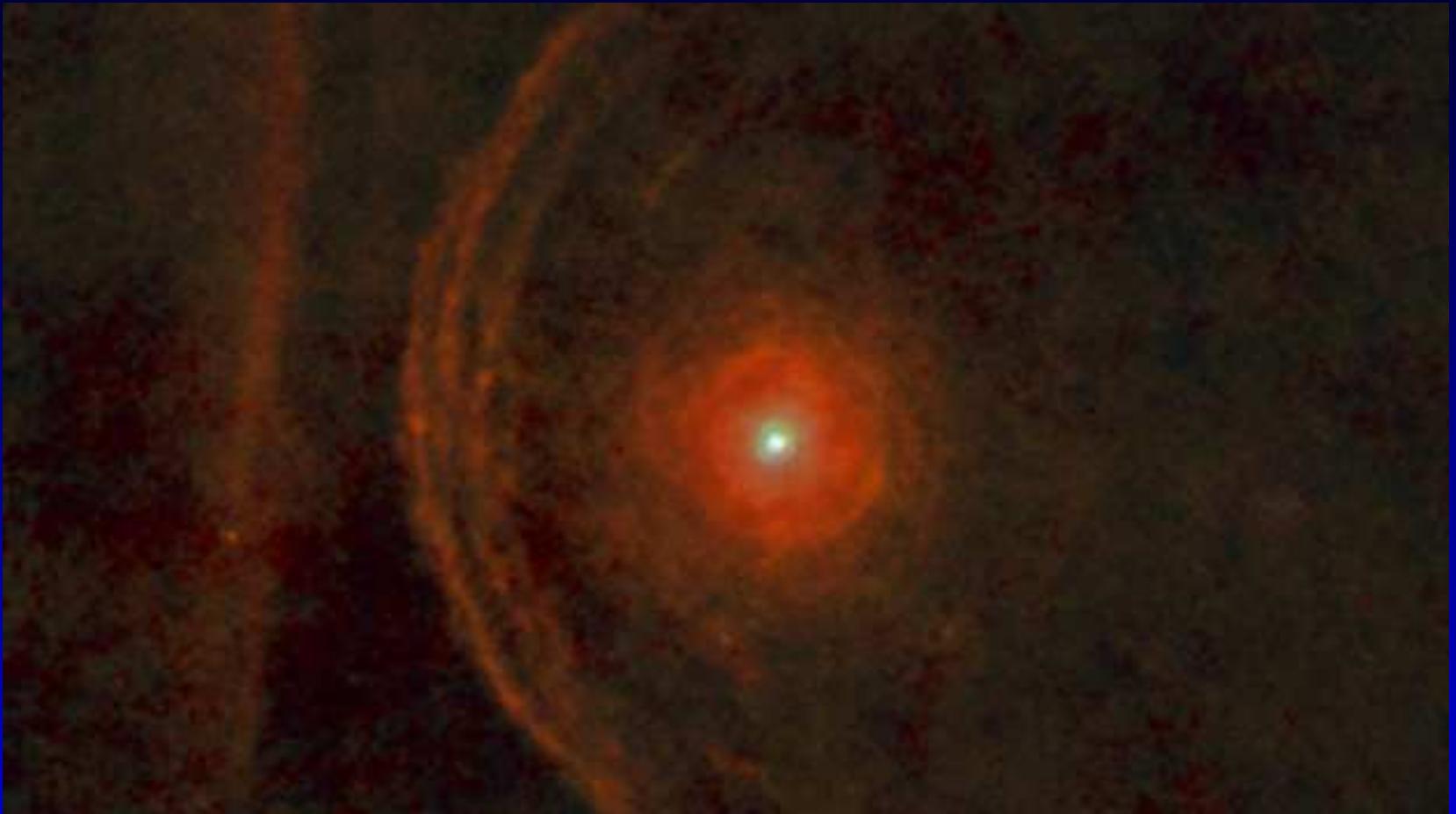
For any i , predict true distance between bowshock and central star

Radial velocity + proper motions $\Rightarrow i = -33.3 \pm 0.8^\circ$

We assume that the relative peculiar velocity between the ISM and the star is determined entirely by the stars space velocity with respect to the local standard of rest (LSR) In other words, we assume that there is no flow of the ISM itself.

Current best estimate of the distance to CW Leo
 $d = 123 \pm 14$ pc; mean $L = 7790 \pm 150 L_\odot$

α Ori / Betelgeuse



Decin et al. (2012, A&A 548). ESA press release.

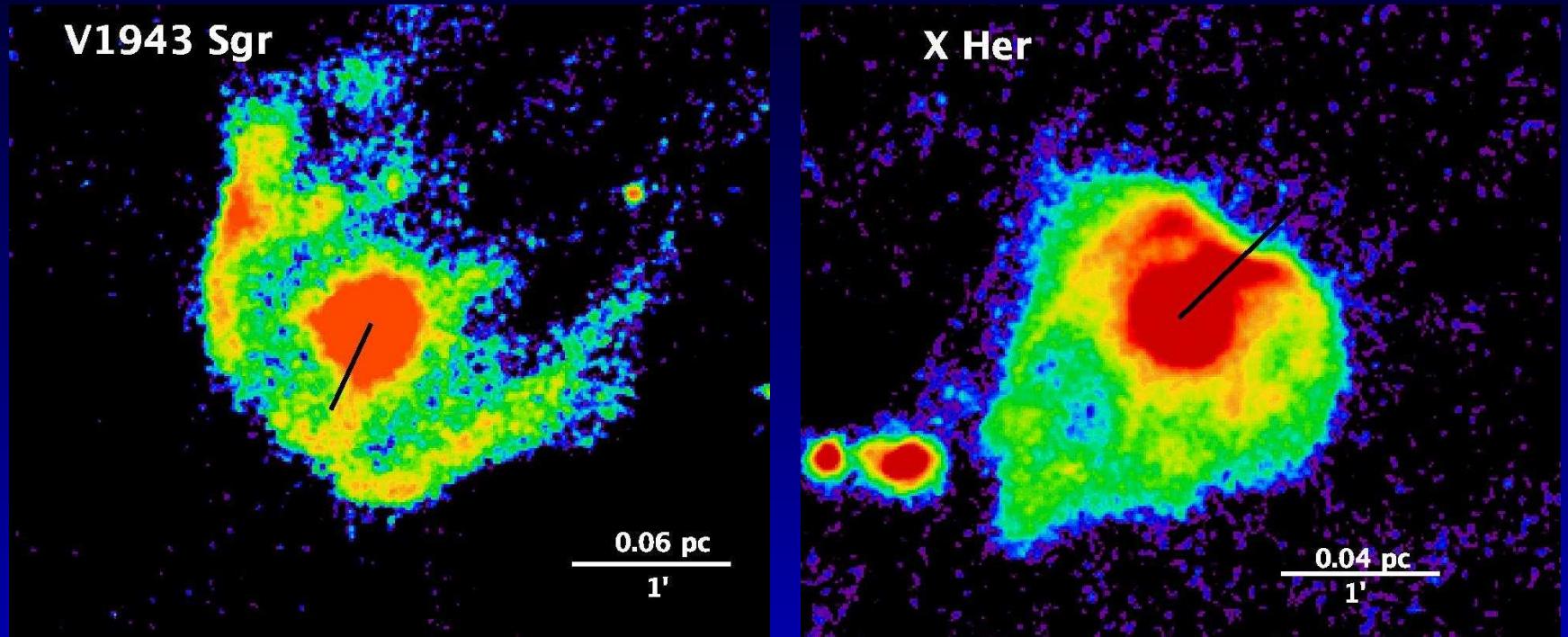
α Ori / Betelgeuse

Only object imaged with multiple arcs

Combines *WISE*, 21 cm GALFA-HI, UV *GALEX*

"Based on the observations and on hydrodynamical simulations, different hypotheses are formulated to explain the origin of the multiple arcs and to understand why no large-scale instabilities are seen in the bow shock region. In our opinion, the two main ingredients to explain both features are (1) a clumpy mass-loss process and (2) the influence of the Galactic magnetic field."

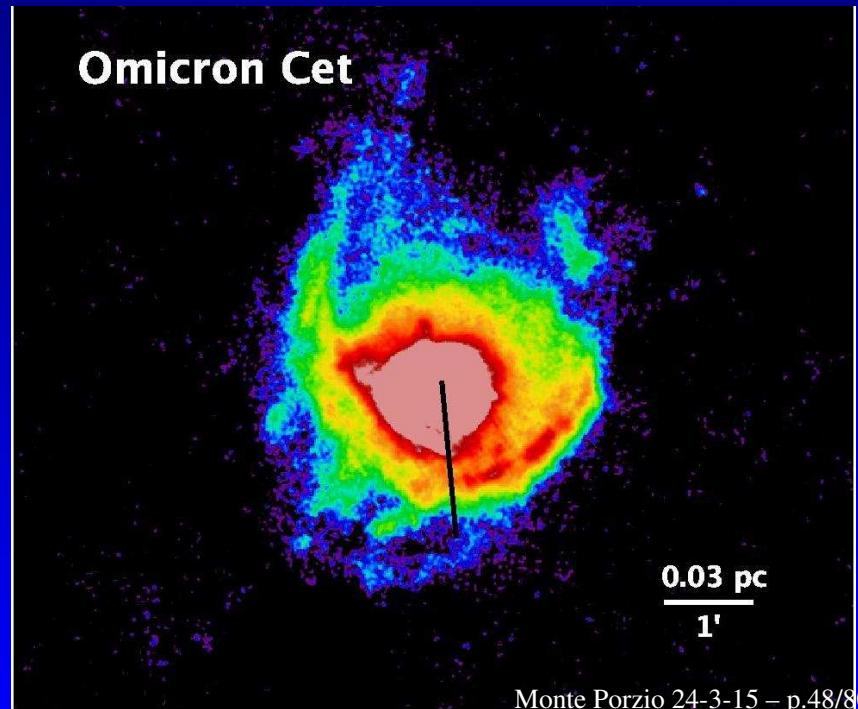
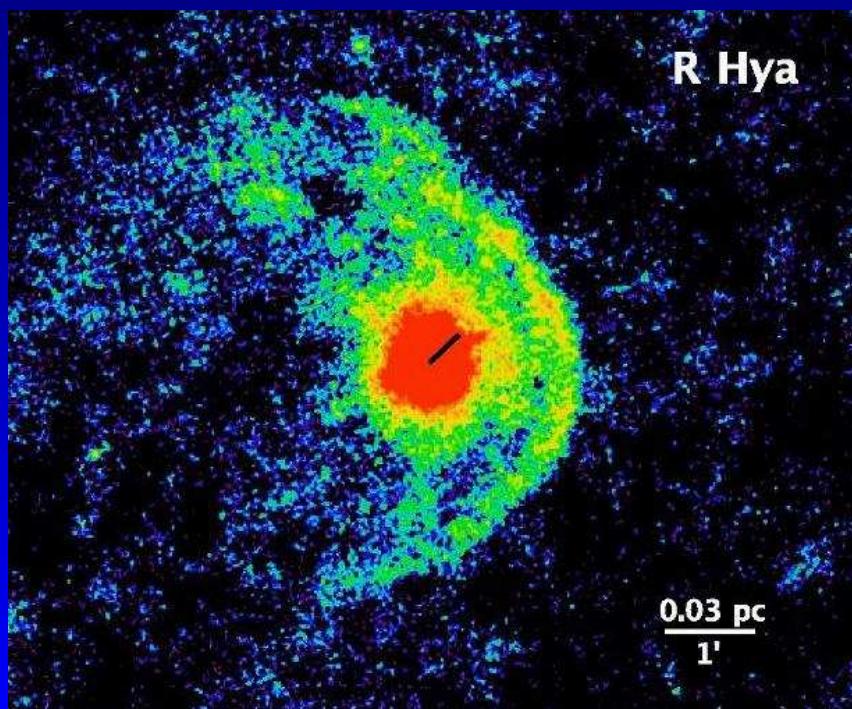
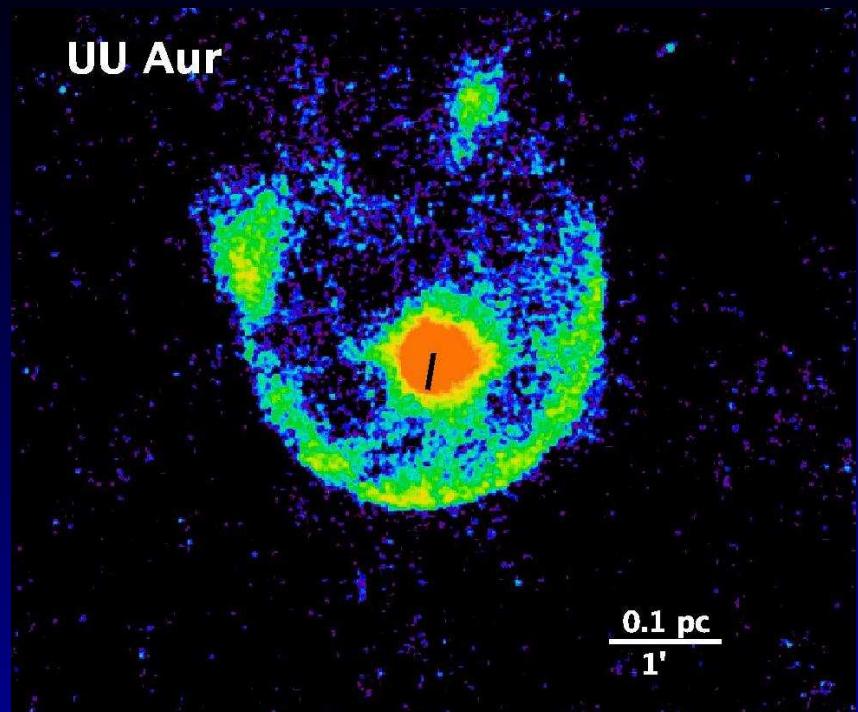
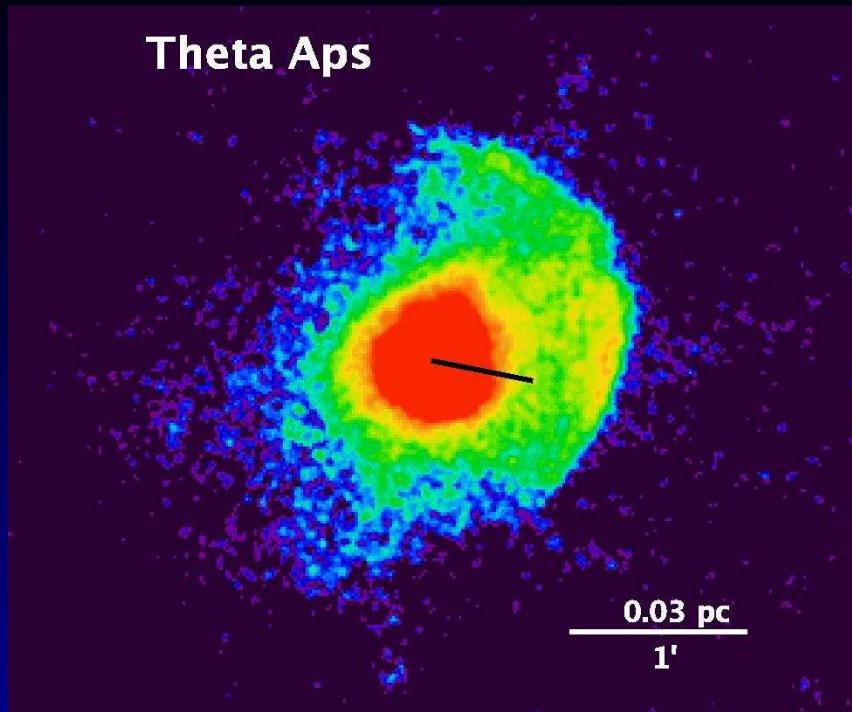
The Zoo

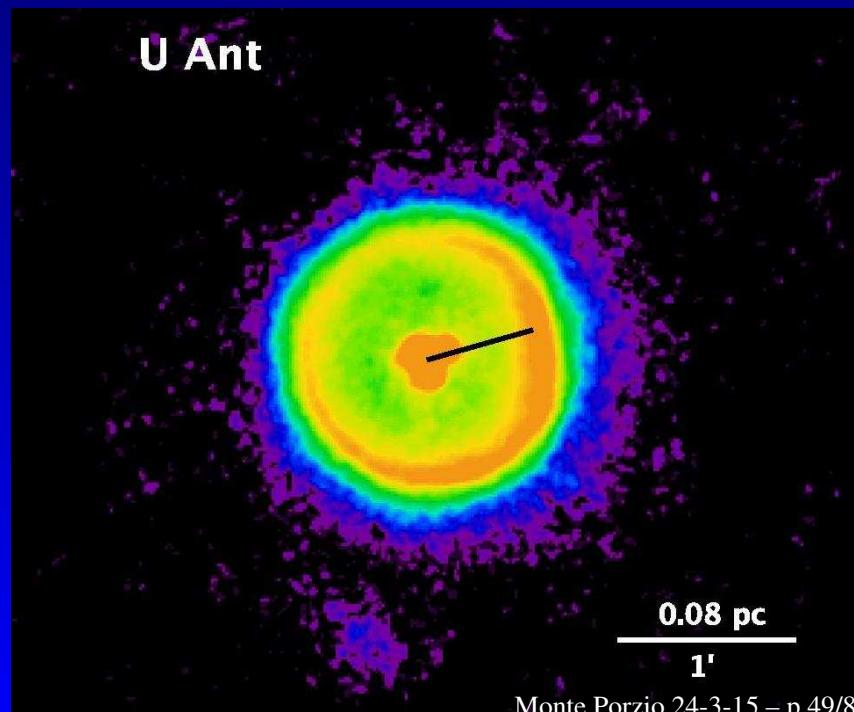
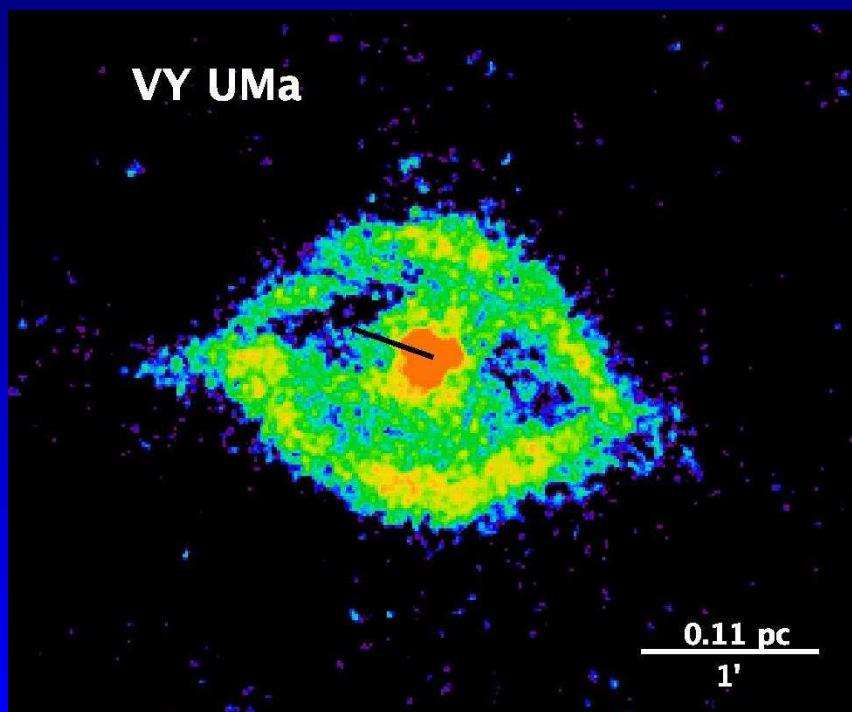
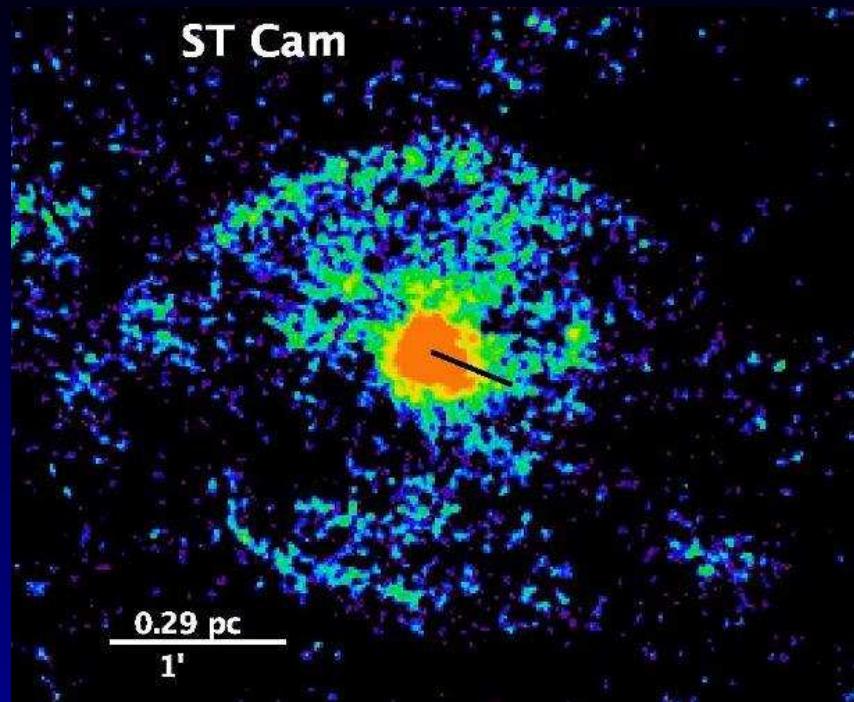
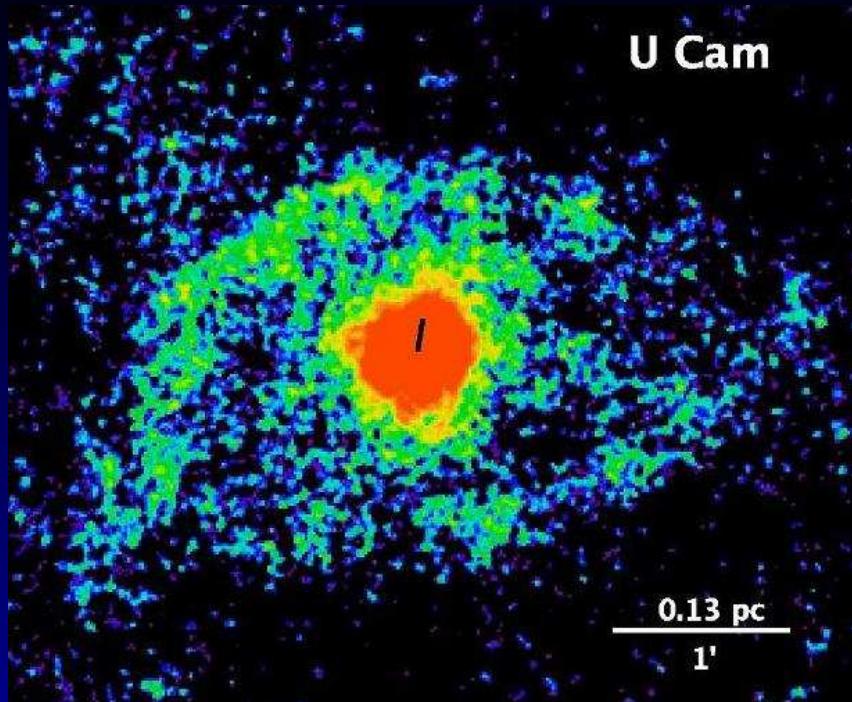


Cox et al. (2012 A&A 537)

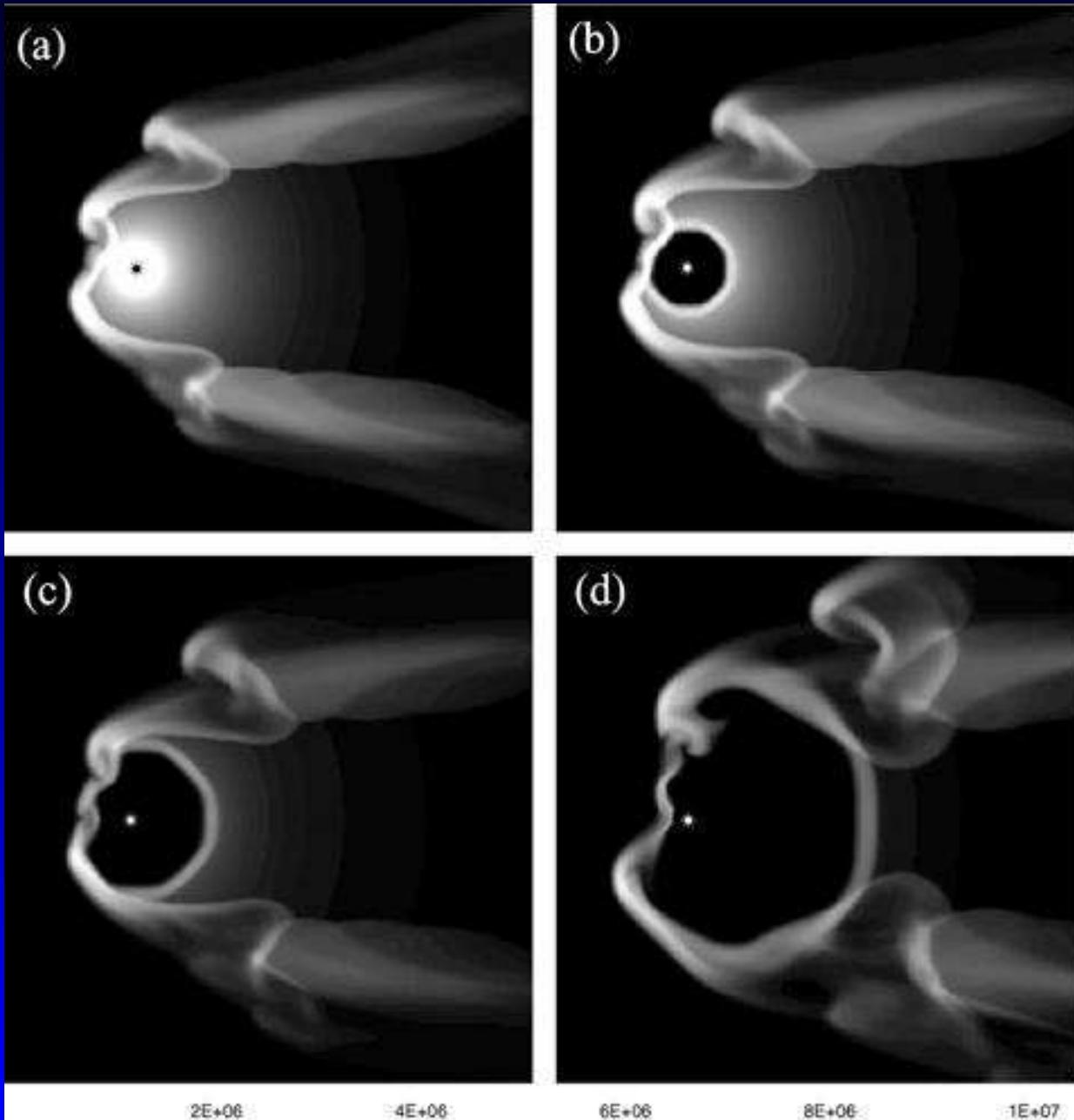
"fermata", "eyes", "irregular", and "rings"

stand-off distances, ISM densities



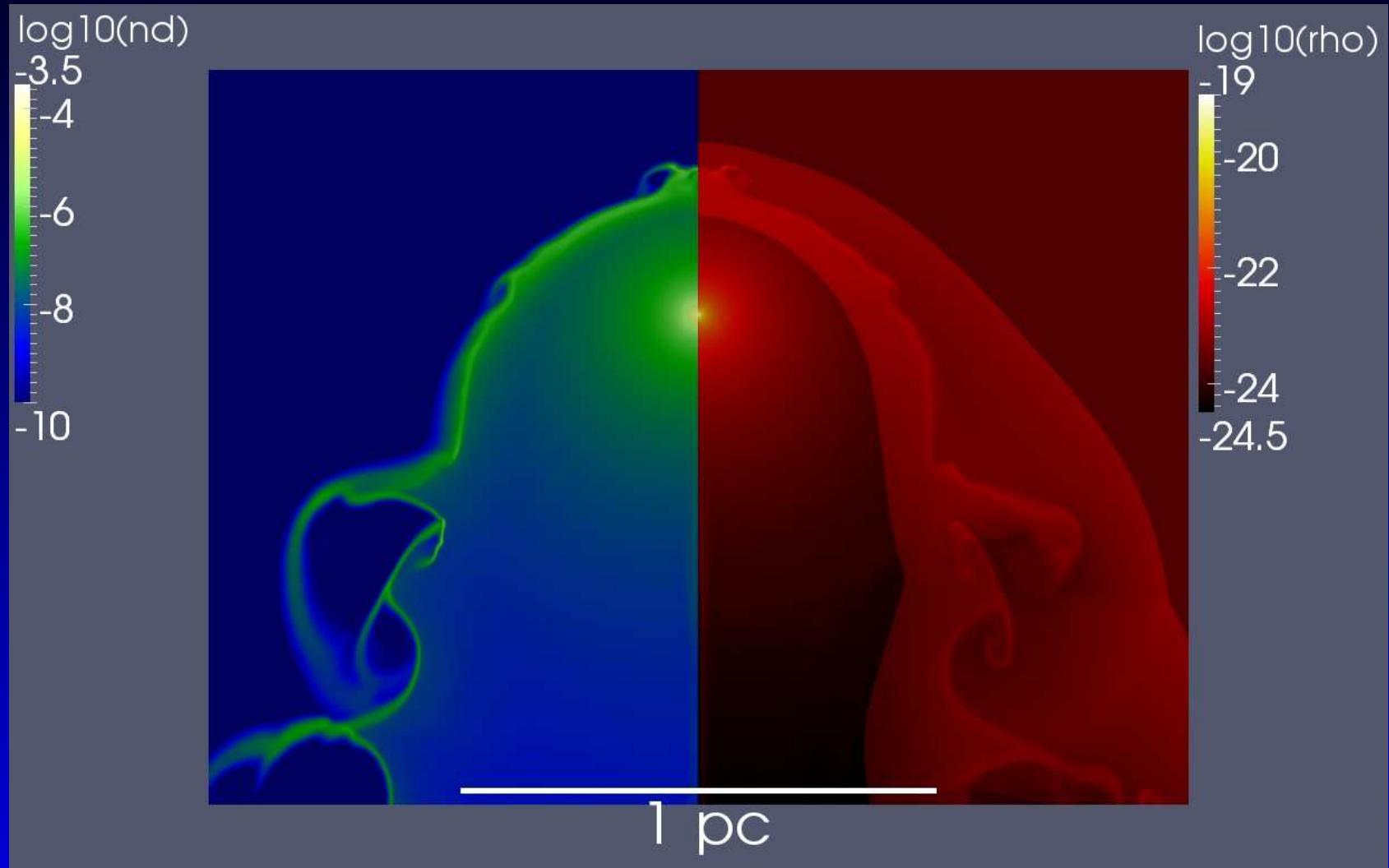


Hydro Models



Wareing et al.
(2007)

Models



van Arle et al. (2011)

AGB star - Spectroscopy

- CW Leo

- Water
(Decin et al. 2010, Nature)

- HCl lines from J=1-0 up to J=7-6 have been detected.
(Cernicharo et al. 2010, A&A Special Issue)

- Tens of lines from SiS and SiO, including lines from the v=1 vibrational level.
Both species trace the dust formation zone.
(Decin et al. 2010, A&A Special Issue)

AGB star - Spectroscopy

- AFGL 2688, AFGL 618 and NGC 7027

Wesson et al. 2010, A&A special issue

- VY CMa

Royer et al. 2010, A&A special issue

- OH⁺

Etxaluze et al. 2014

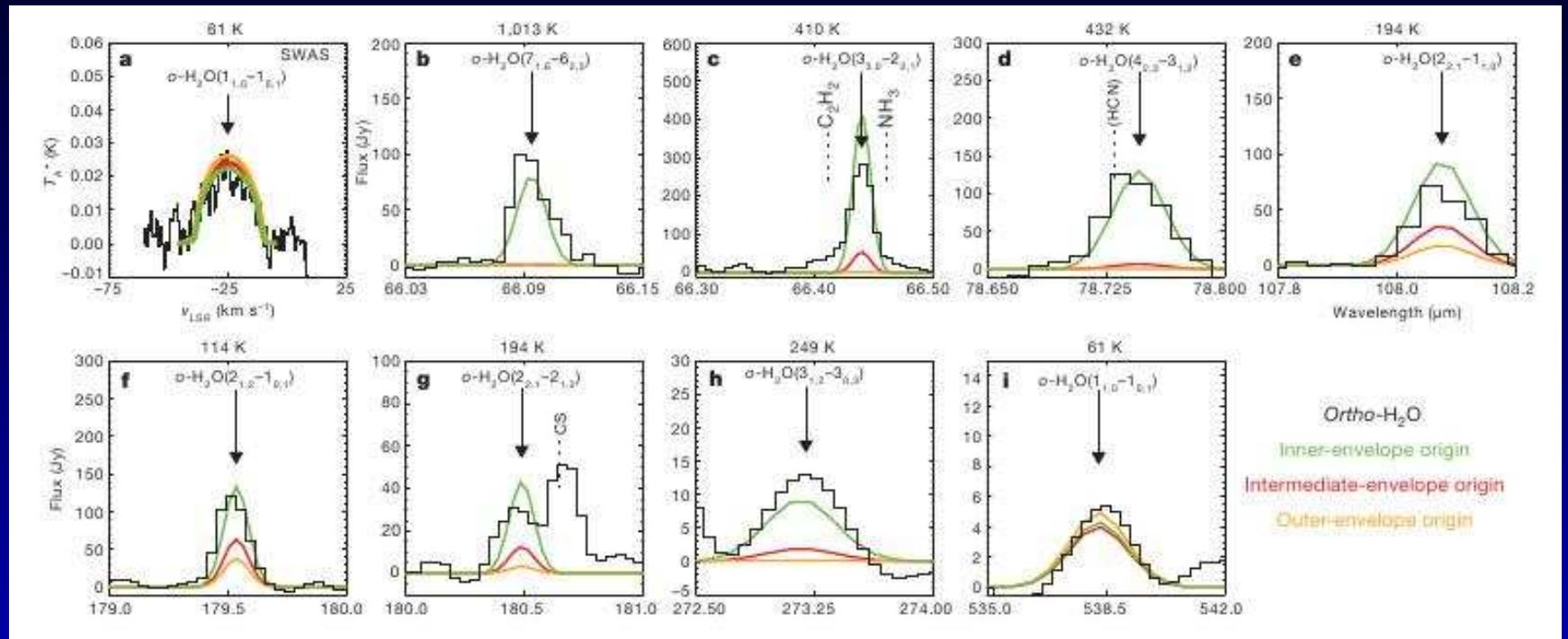
- Dust

CW Leo - Water



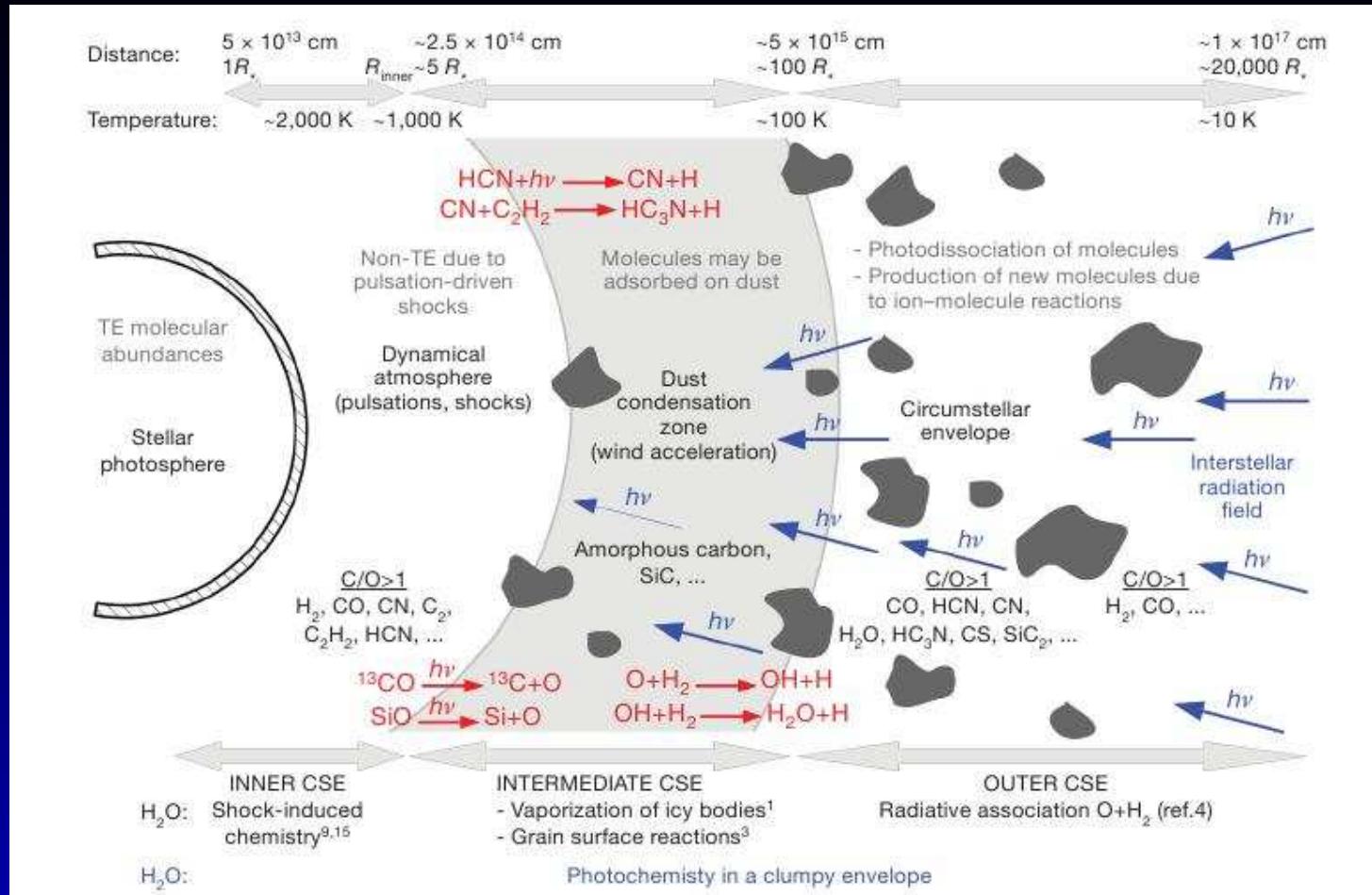
Decin et al. 2010, Nature 467, 64

CW Leo - Water



1 line with SWAS

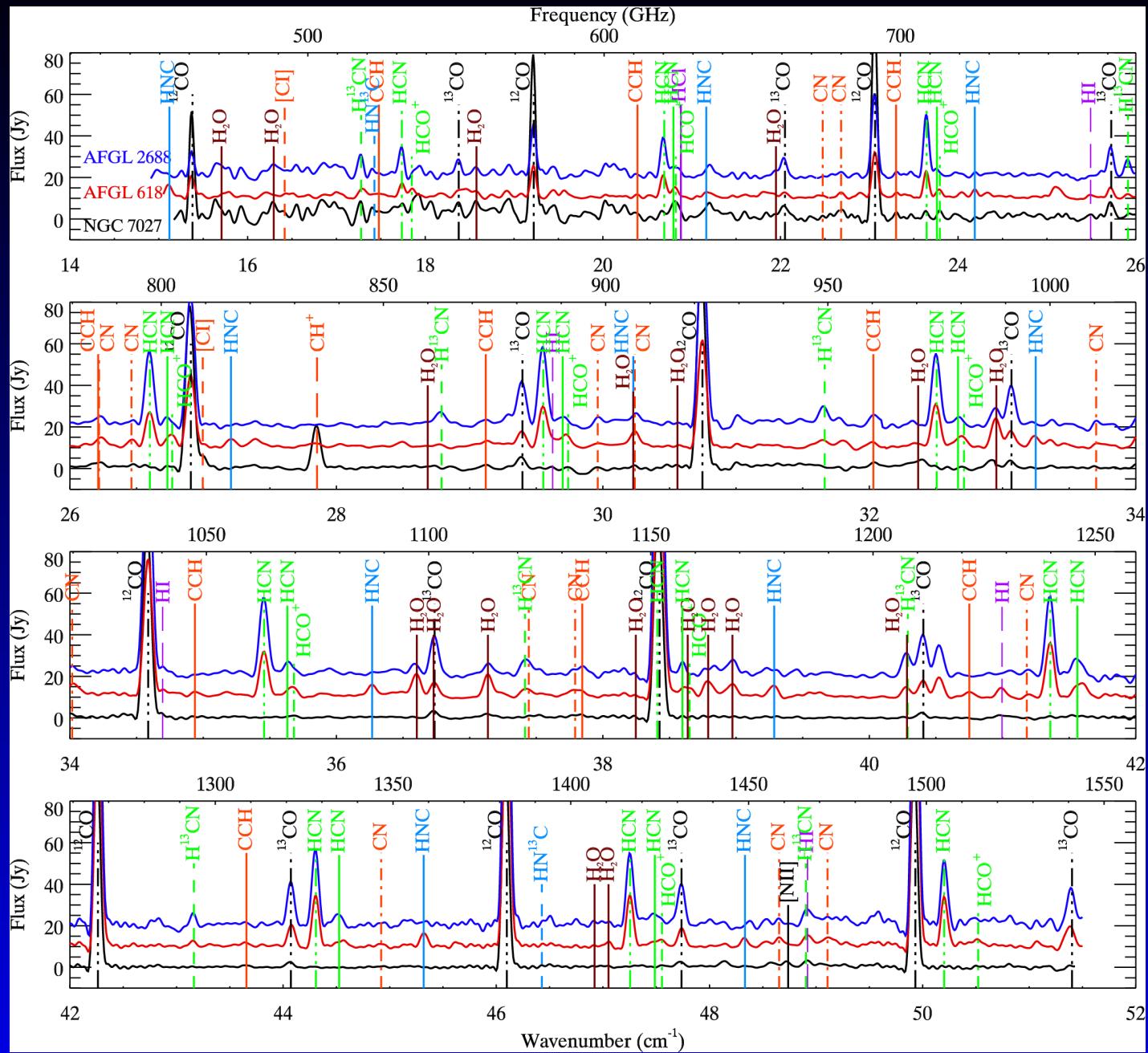
Melnick et al. 2001, Nature 412, 160
"Discovery of water vapour around IRC +10216 as evidence for comets orbiting another star"

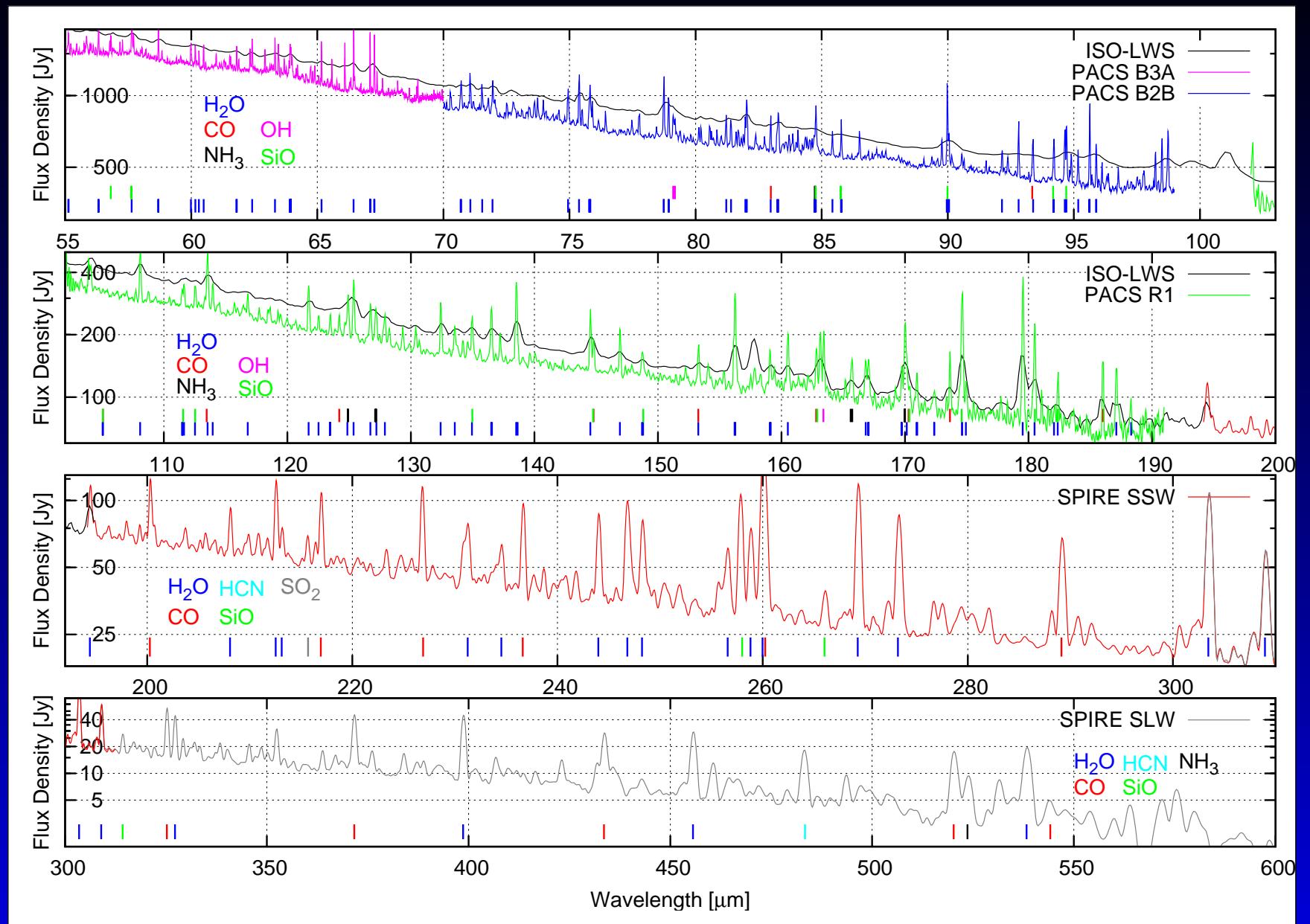


39 ortho- H_2O and 22 para- H_2O with T_{ex} up to 1000 K

"A plausible explanation for the warm water appears to be the penetration of ultraviolet photons deep into a clumpy circumstellar envelope. This mechanism also triggers the formation of other molecules, such as ammonia, whose observed abundances are much higher than hitherto predicted"

Wesson et al. (2010). Continuum-subtracted SPIRE FTS spectra of NGC 7027 (black), AFGL 618 (red) and AFGL 2688 (blue)





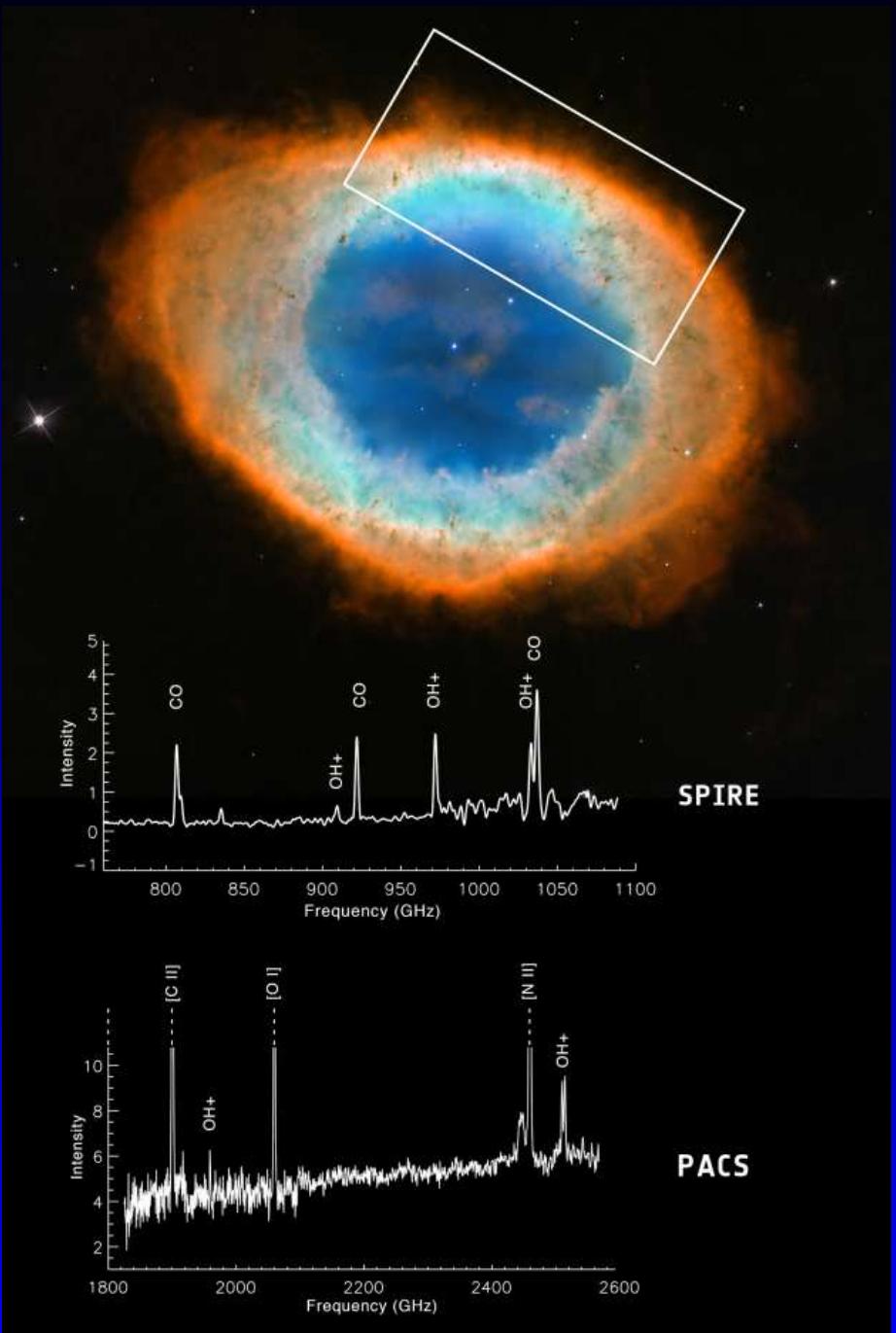
VY CMa, Royer et al. (2010)

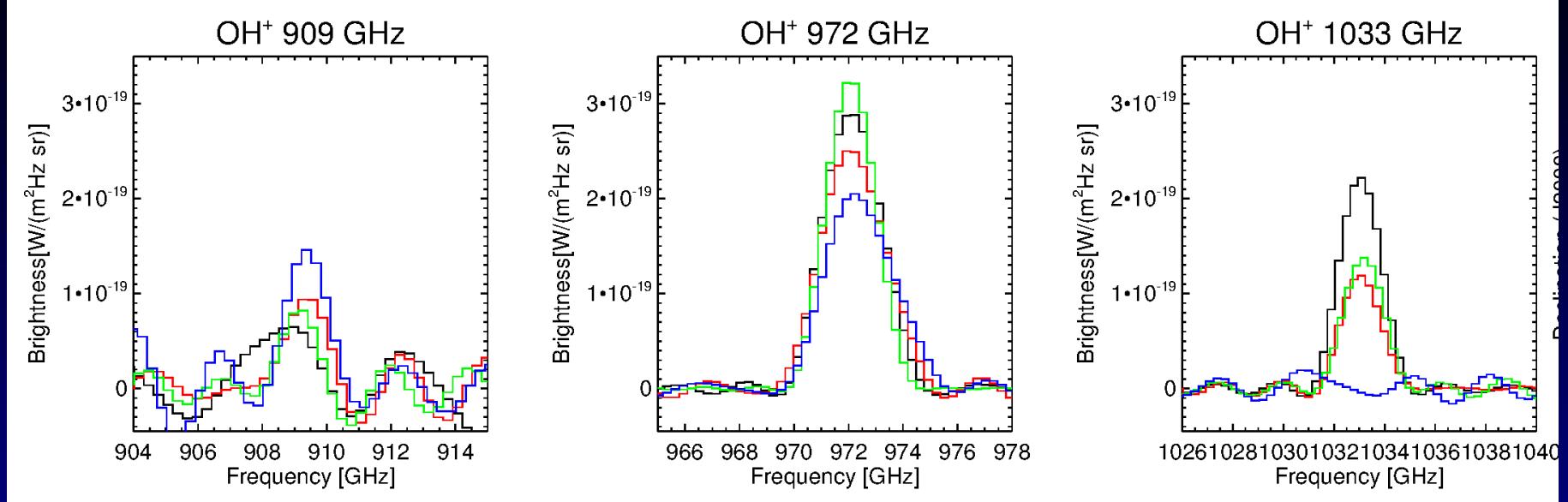
OH^+

First detection in PNe.

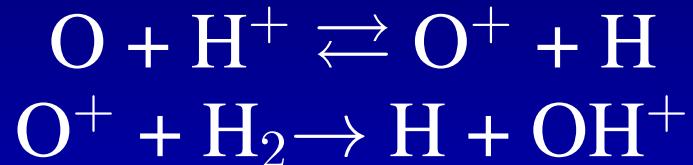
Etxaluze et al. (2014)
NGC 7293 (Helix Nebula)

Aleman et al. (2014)
NGC 6445, NGC 6720,
NGC 6781





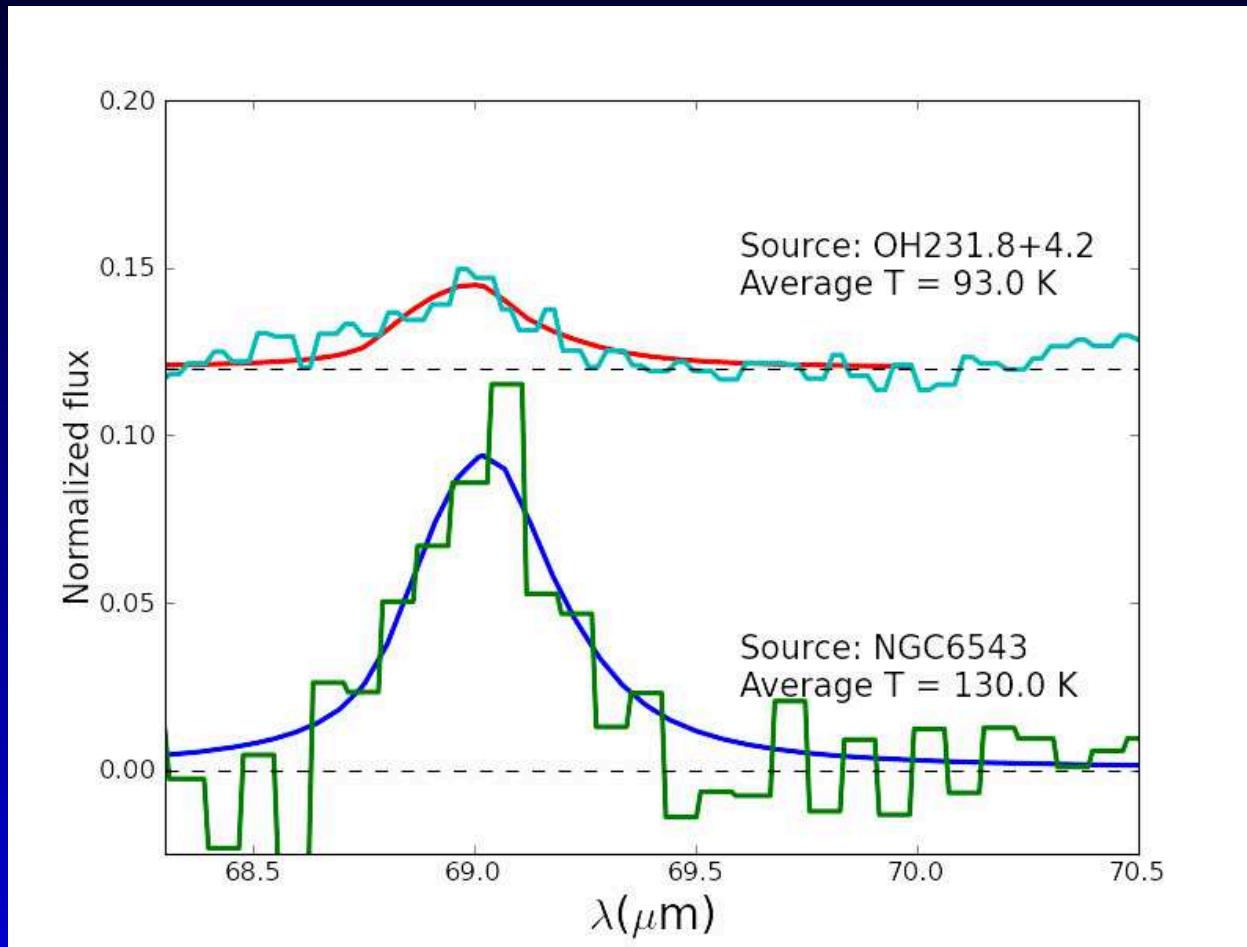
When CO is photodissociated



In PNe, the OH⁺ rotational line emission appears to be produced in the PDR.

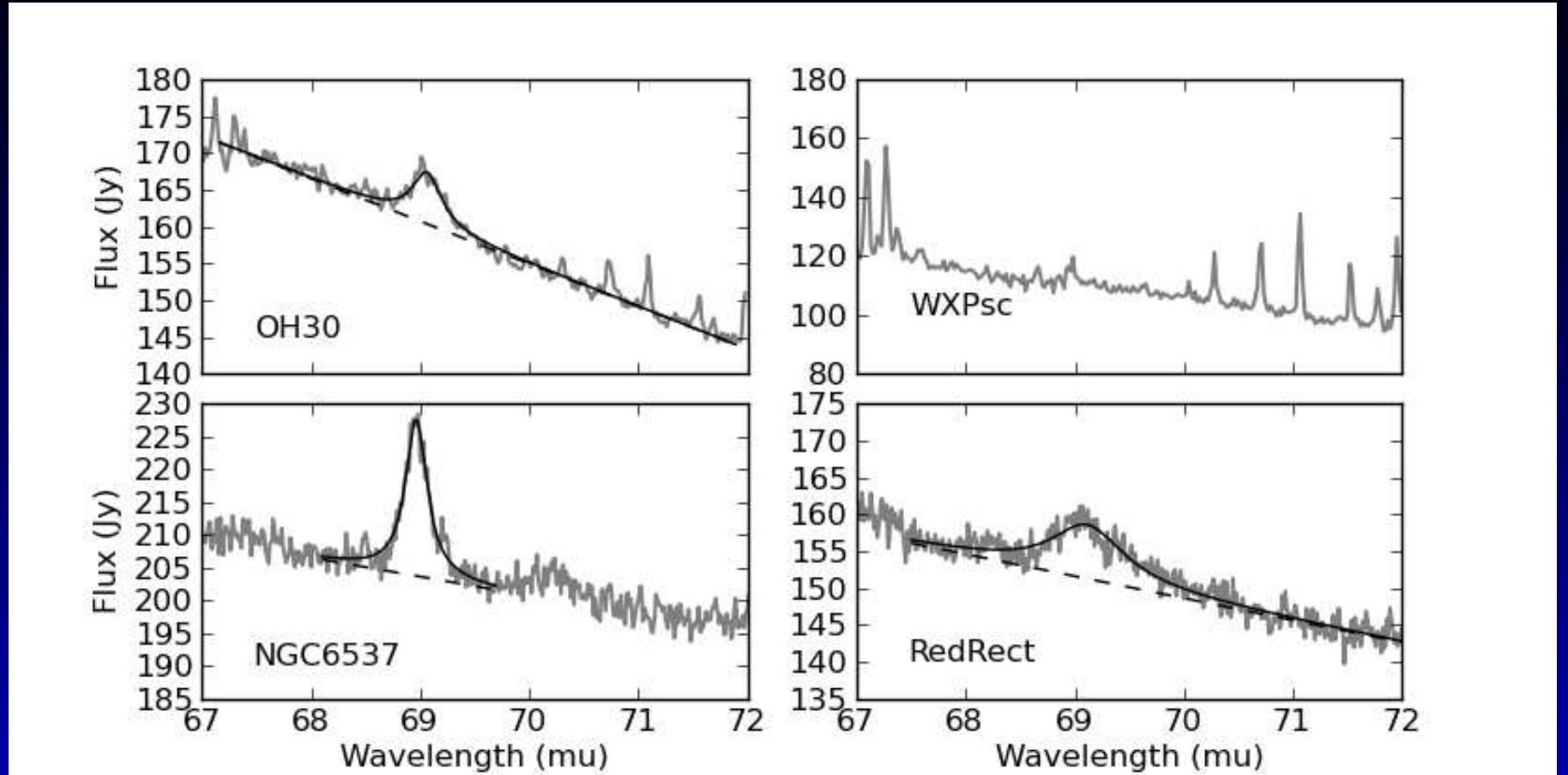
The emission of OH⁺ is observed only in PNe with hot central stars ($T_{\text{eff}} > 100\,000$ K).

Dust spectroscopy



de Vries et al. (2014)

Fosterite at $69\mu\text{m}$



Joris Blommaert et al. (2014); MESS + GT1 + OT1
 (both JB)
 14 OH/IR, 14 post-AGB, 10 PNe, 8 massive stars.
 Pure Mg-rich for both disk and outflow sources,
 <200 K.

Conclusions

- Detected "old" dust mass loss in AGB stars !
- Interaction with the ISM is common
- Influence of binary companion
-and this can happen all at the same time....!
- Line spectroscopy succesfull, and high potential
 - Ongoing improvements in data reduction in spectroscopy ; RSRF; pointing jitter
- Up to the modellers
 - Dust + molecules RT modelling ...!!
 - Hydrodynamical simulations ...!!

This MESS is produced by

A. Baier, M. Barlow, B. Baumann, J. Blommaert, J. Bouwman,
P. Cernicharo, L. Decin, L. Dunne, K. Exter,
P. Garcia-Lario, H. Gomez, M.A.T. Groenewegen, P. Hargrave,
Th. Henning, D. Hutsemékers, R. Ivison, A. Jorissen,
F. Kerschbaum, O. Krause, D. Ladjal, T. Lim, M. Mecina,
W. Novotny-Schipper, G. Olofsson, R. Ottensamer,
E. Polehampton, Th. Posch, G. Rauw, P. Royer, B. Sibthorpe,
B. Swinyard, T. Ueta, C. Vamvatira-Nakou, B. Vandenbussche,
G. Van de Steene, S. van Eck, P. van Hoof, H. Van Winckel,
E. Verdugo, C. Waelkens, R. Wesson

FWF-projects: P18939-N16 & I163, P21988

FWO

STFC

ASAP-CO-016/03

PRODEX C90371

THE END

ADVERTISEMENT

STARLAB: “Evolved stars and their shells:
Laboratories for stellar physics“

Hiring 3 Ph.D. students (starting September):

-ROB-KUL: Mass-loss rates and evolution.
Herschel & ALMA data.

-KUL-ULB: Nucleosynthesis. Abundances of
(P-)AGB stars in the Galaxy, the MCs and the GB.

-KUL-ULB: Binary evolution. BINSTAR will be used
to compute evolutionary sequences and do population
synthesis studies; compare to observations.

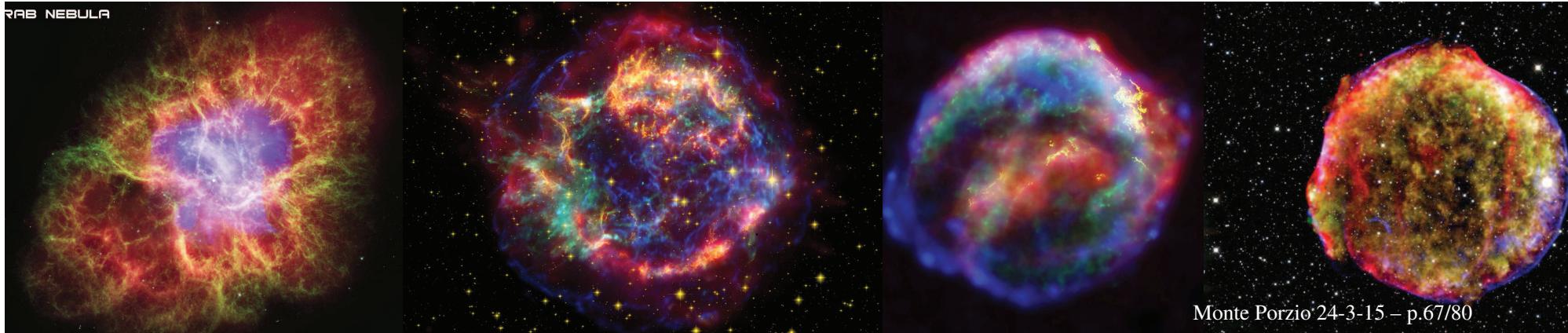
www.astro.ulb.ac.be/pmwiki/BRAIN/HomePage

The Herschel MESS Supernova Programme

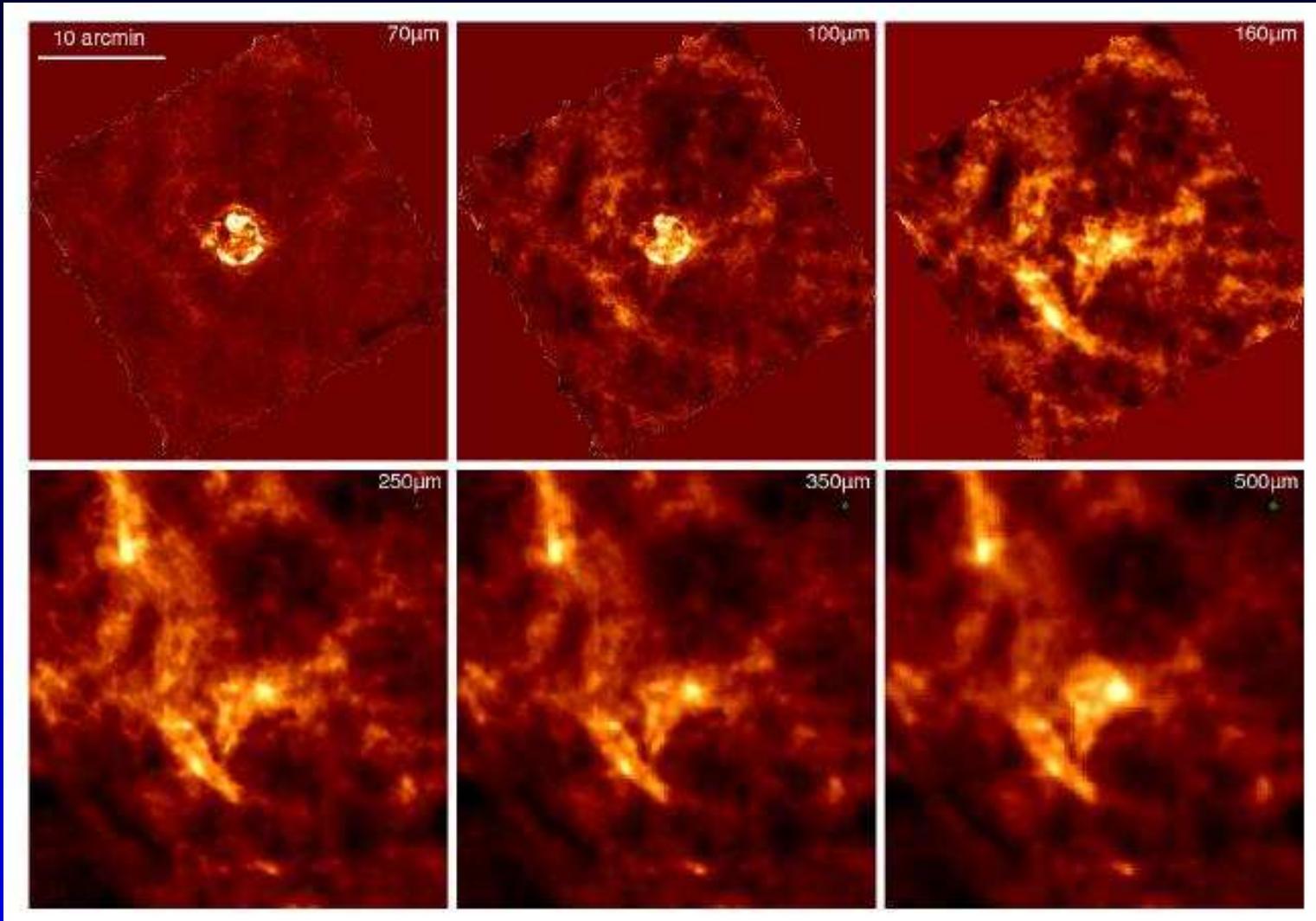
Targets: 4 historical supernova remnants in the Milky Way

M(dust) ($T_d < 50K$)				
1680	IIb	Cas A	0.10 Msun	Barlow et al (2010)
1604	Ia	Kepler	0.003 Msun	Gomez et al (2012a)
1572	Ia	Tycho	0.009 Msun	Gomez et al (2012a)
1054	II	Crab	0.10-0.24 Msun	Gomez et al (2012b)

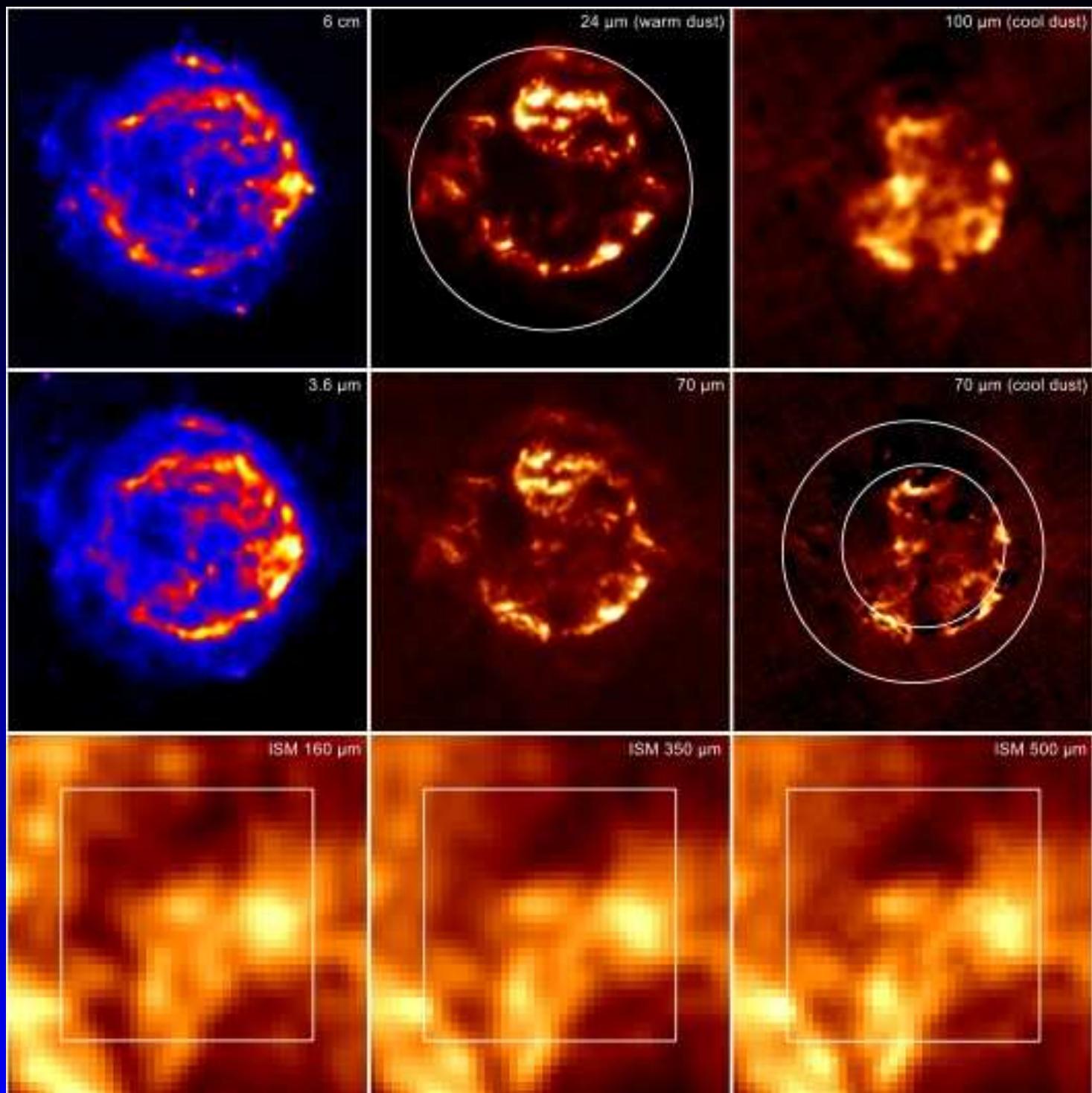
All young: so swept-up interstellar gas mass is low



SN remnant: Cas A



Barlow et al. (2010)



SN remnants

- non-thermal component: based on 6-cm VLA and 3.6- μ m IRAC image (*Planck, WISE*)
- line contributions: dedicated PACS/SPIRE spectroscopy & archival LWS spectrum
(Cas A: $\sim 5\%$, $\sim 10\%$ neglegible at 70,100,160 μ m)

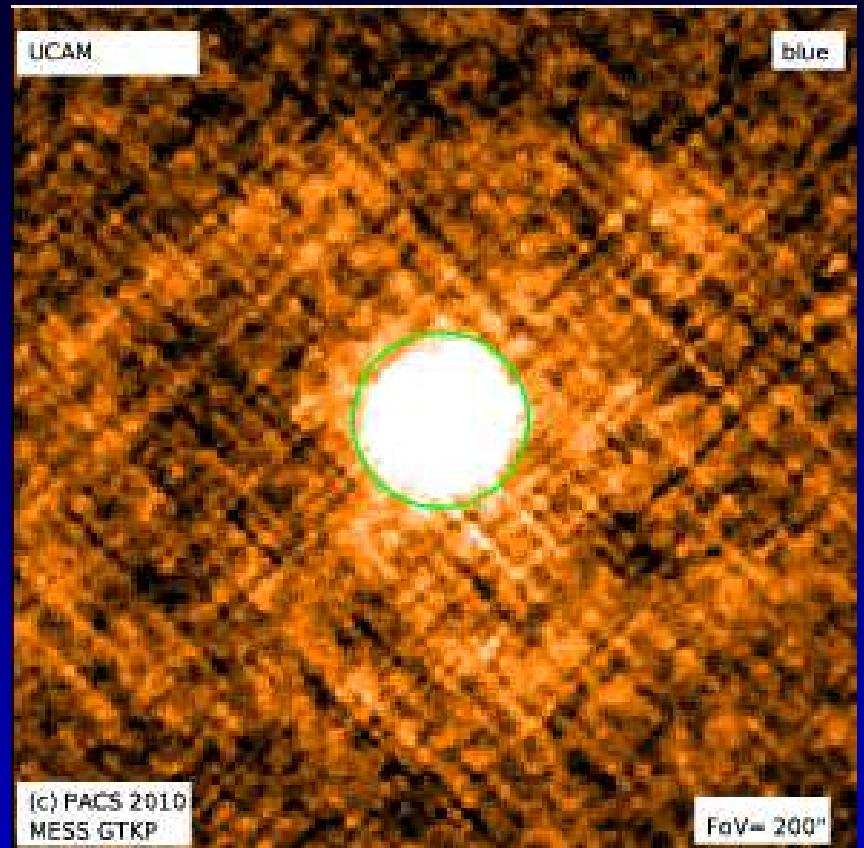
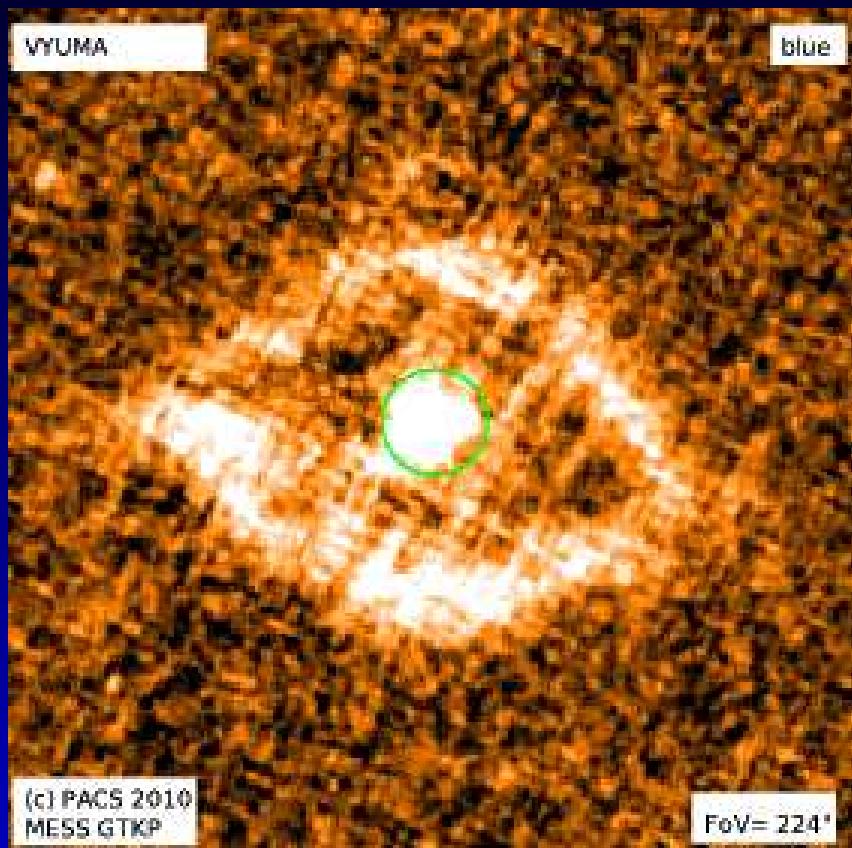
Crab A: T= 56 K, M= 0.008 M_{\odot} ; T= 28 K, M= 0.24 M_{\odot}
(silicates)

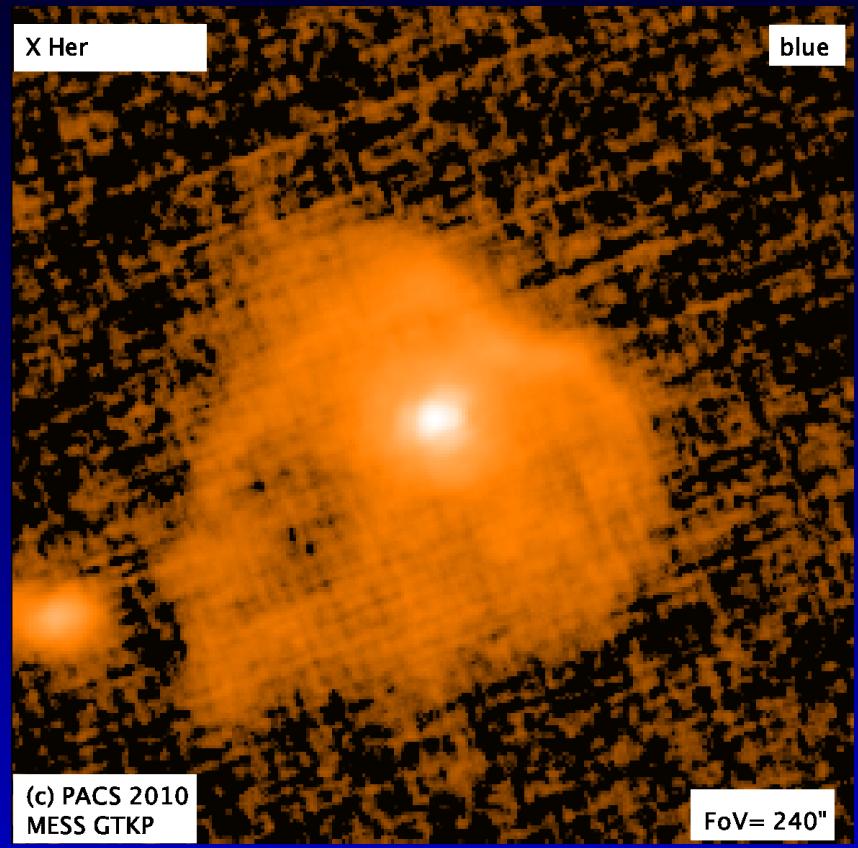
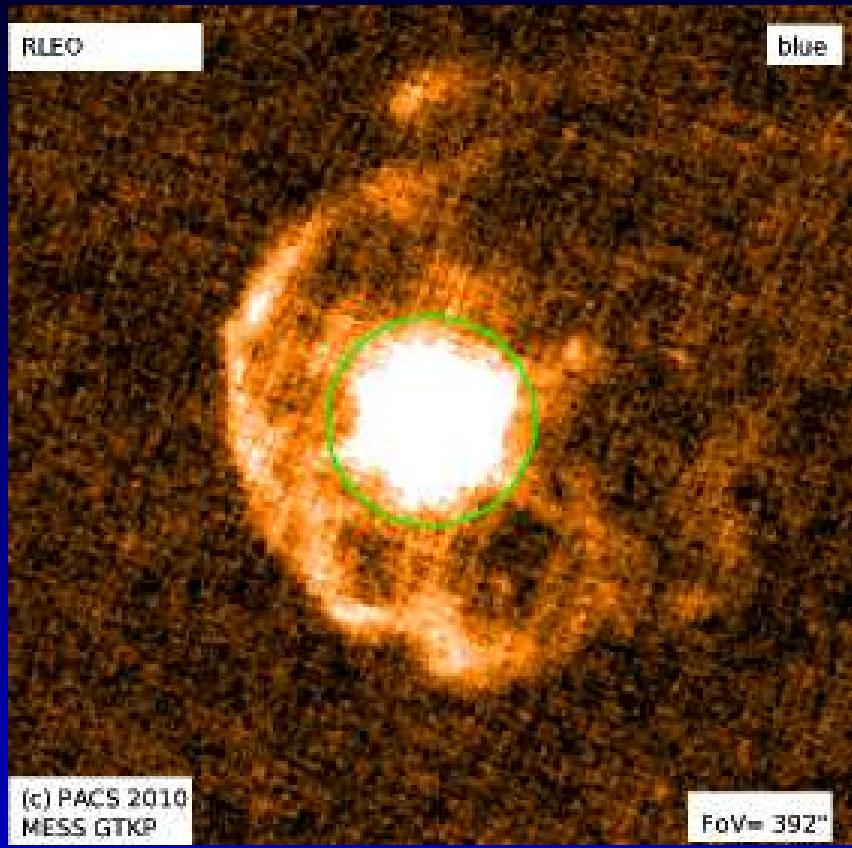
Cas A: T= 82 K, M= 0.003 M_{\odot} ; T= 35 K, M= 0.08 M_{\odot}

Kepler: T= 82 K, M= 0.003 M_{\odot} ; cool comp, M < 0.07 M_{\odot}

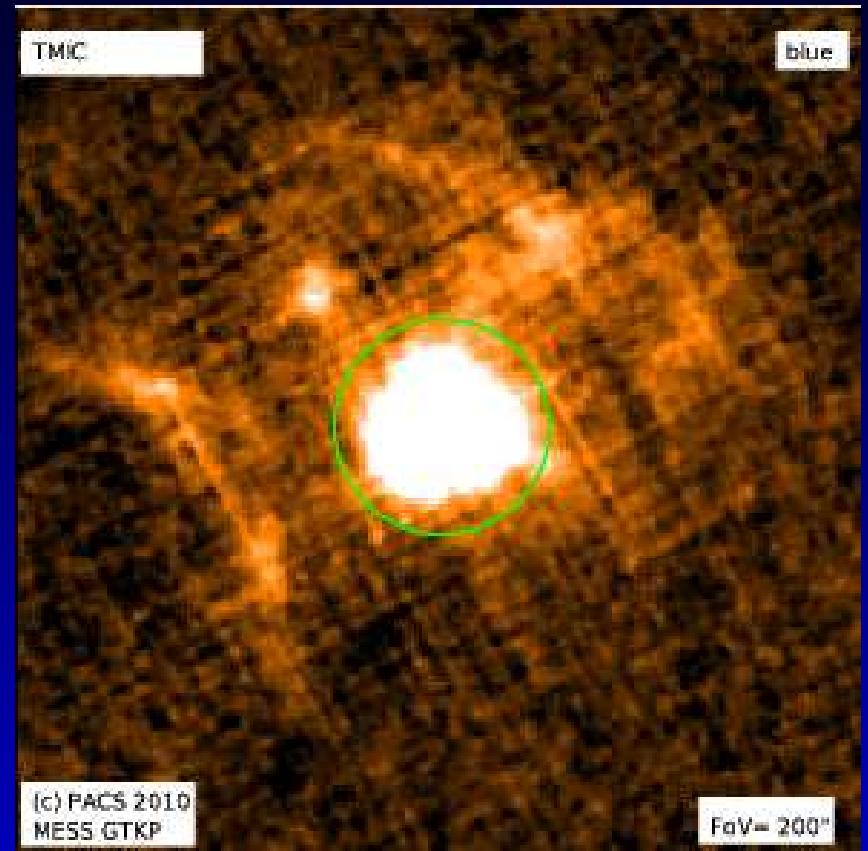
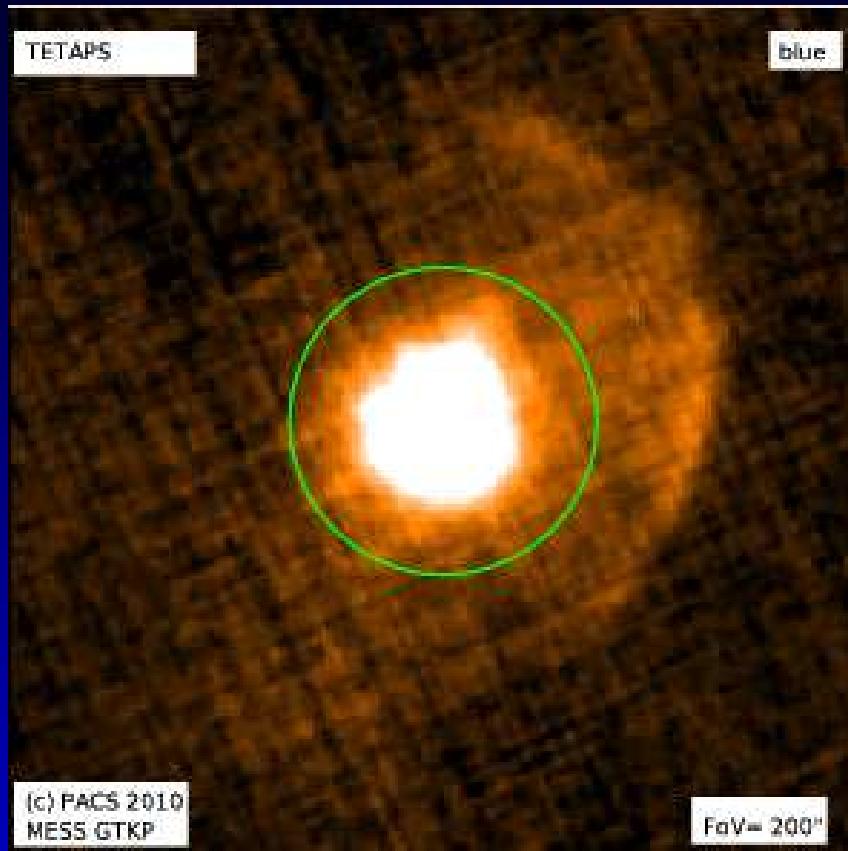
Tycho: T= 90 K, M= 0.009 M_{\odot} ; cool comp, M < 0.07 M_{\odot}

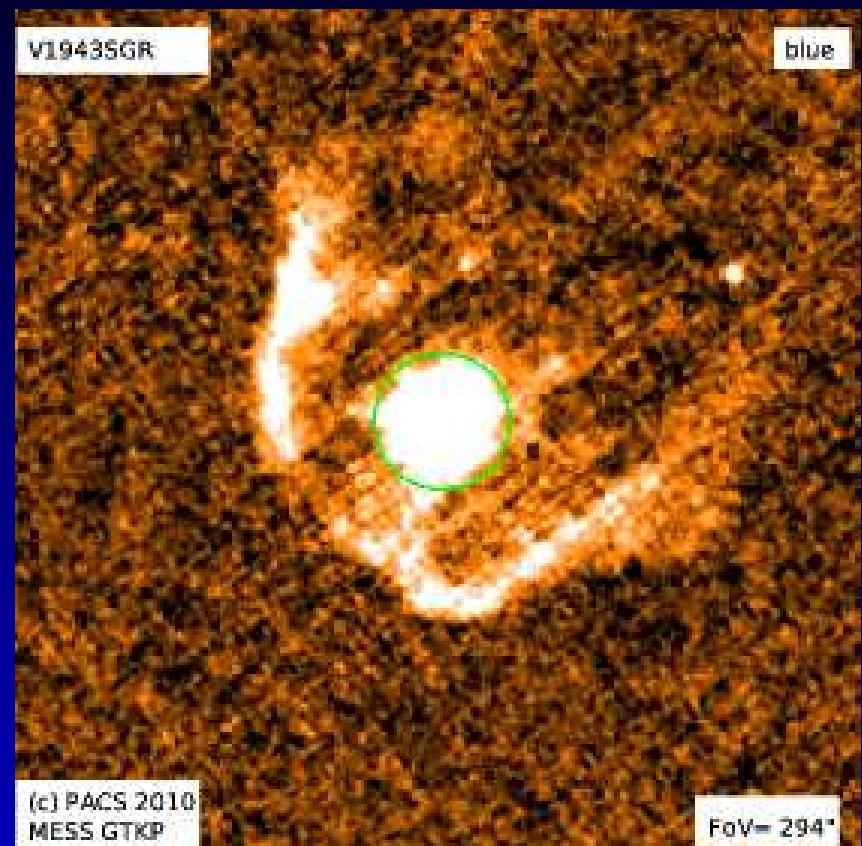
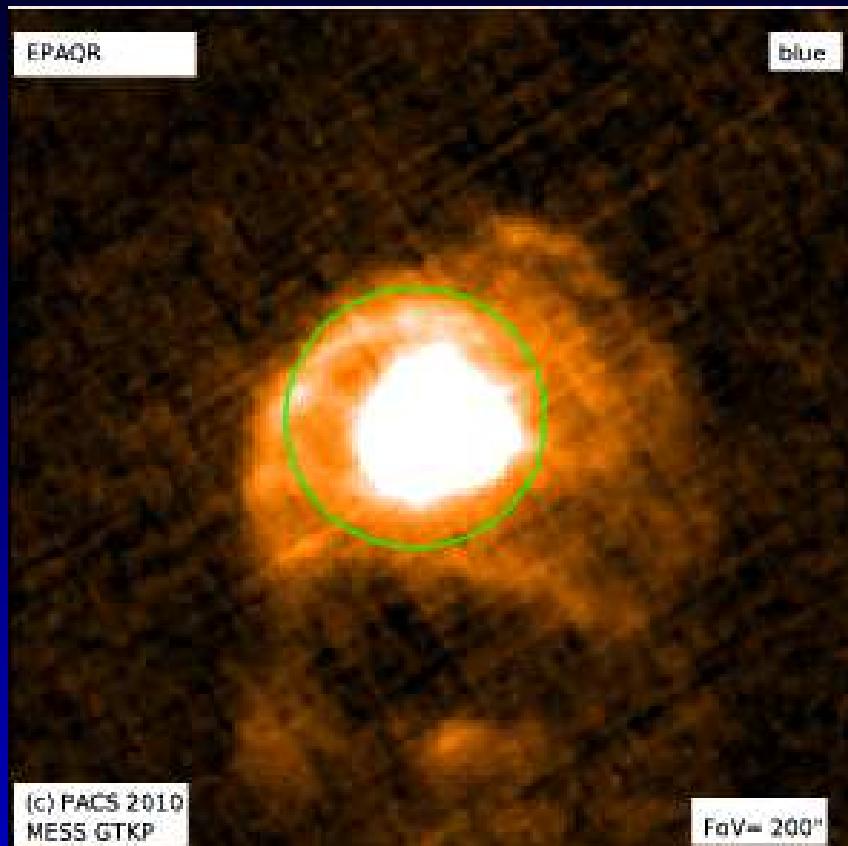
"...that significantly less dust forms in the ejecta of Type Ia supernovae than in the remnants of core-collapse explosions."





X Her & TX Psc (Jorissen et al. submitted)



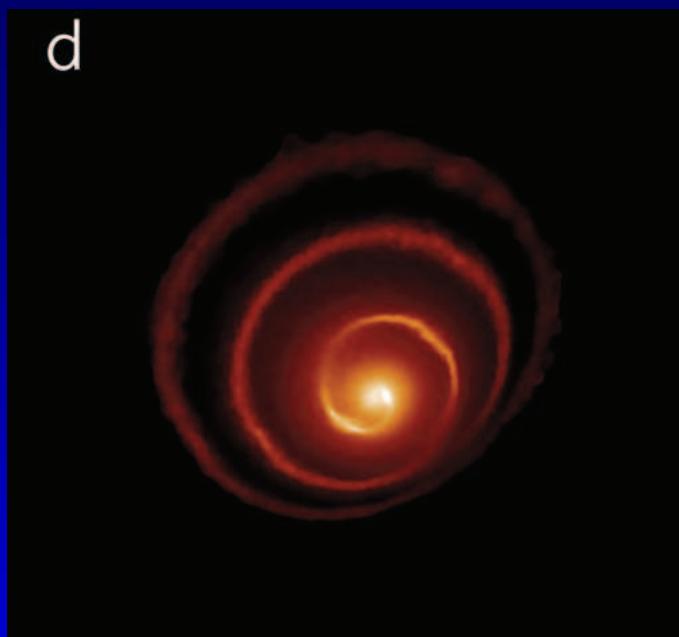
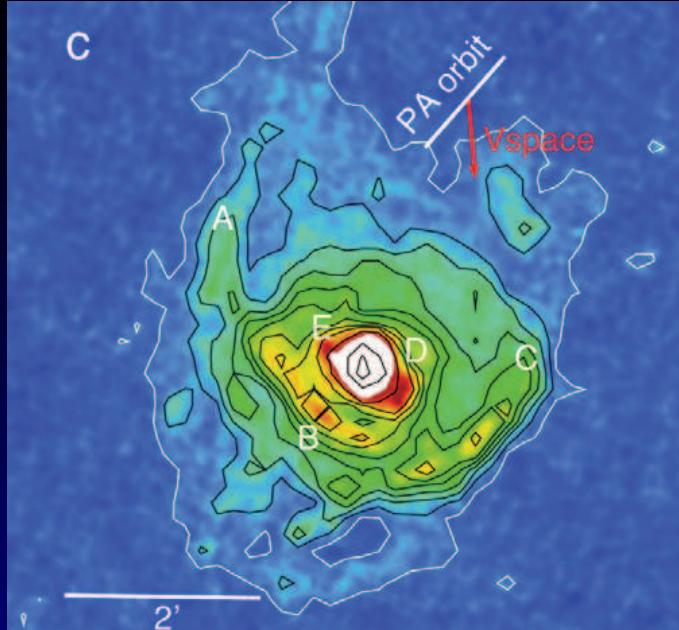
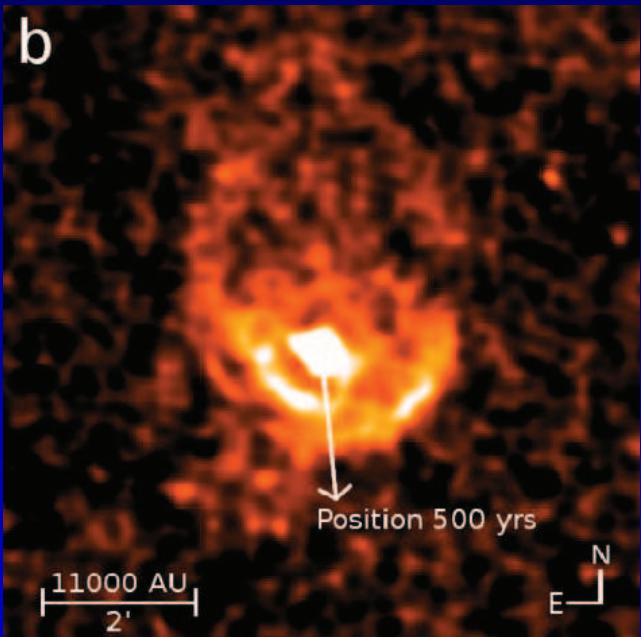
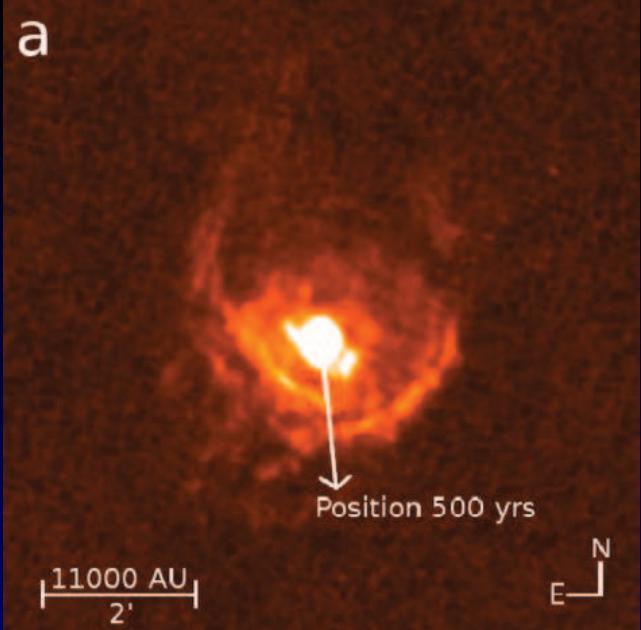


Binarity

"Herschel's view into Mira's head",
Mayer, Jorissen et al. (2011)

R Aql & W Aqr; Mayer, Jorissen et al. (2013)

Mira



(a) deconvolved $70 \mu\text{m}$ image,
(b) deconvolved $160 \mu\text{m}$ image, (c) deconvolved $70 \mu\text{m}$ image
with contours and arcs labelled, (d) toy model

Mira

"The overall shape of the IR emission around Mira deviates significantly from the expected alignment with Mira's exceptionally high space velocity.

...

By comparing Herschel and GALEX data, we found evidence for the disruption of the IR arcs by the fast outflow visible in both H α and the far UV.

...

Mira's IR environment appears to be shaped by the complex interaction of Mira's wind with its companion, the bipolar jet, and the ISM. "

Planetary Nebulae

Imaging:

NGC 650, 3587, 6543, 6720, 6853, 7027, 7293

Spectroscopy:

NGC 6302, 6537, 6543, 7027

NGC 6720 (van Hoof et al. 2010);

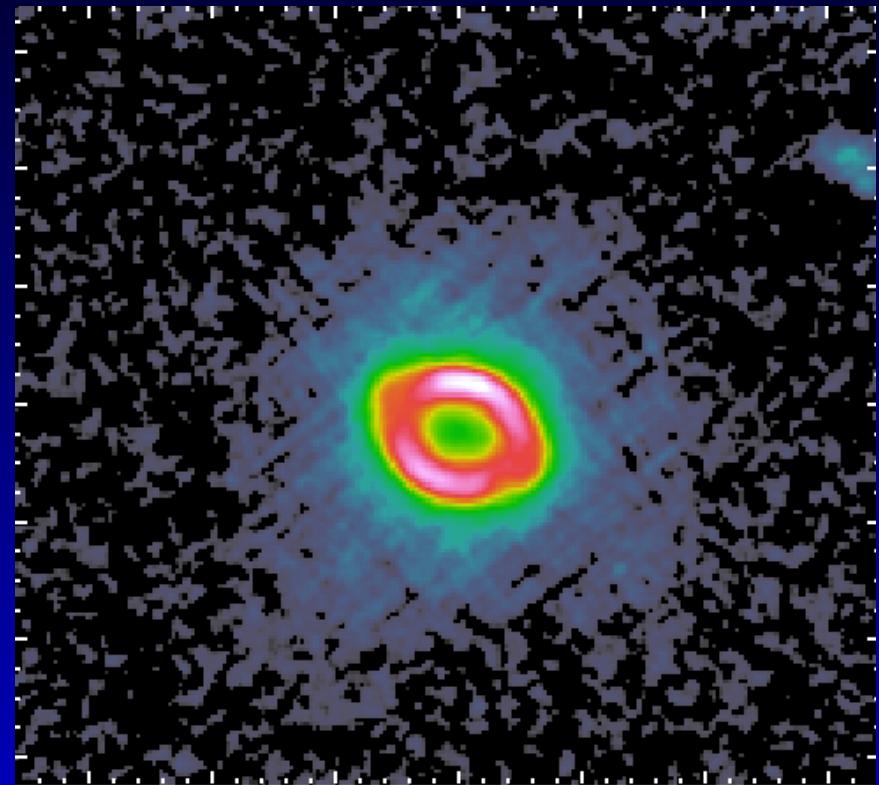
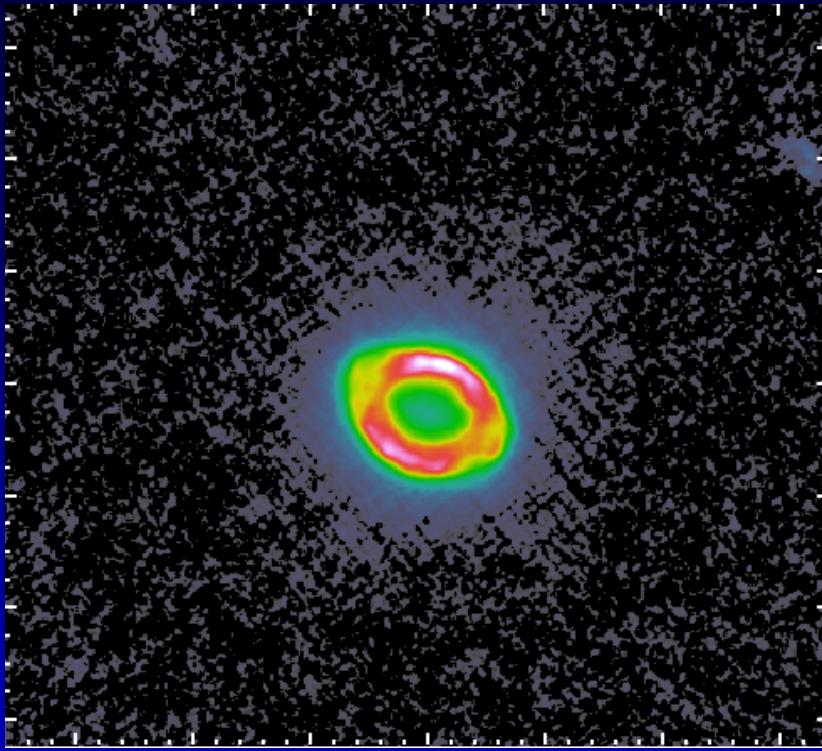
NGC 650 (van Hoof et al. 2013), NGC 7027 (in prep.)

Time consuming:

-Cloudy modelling

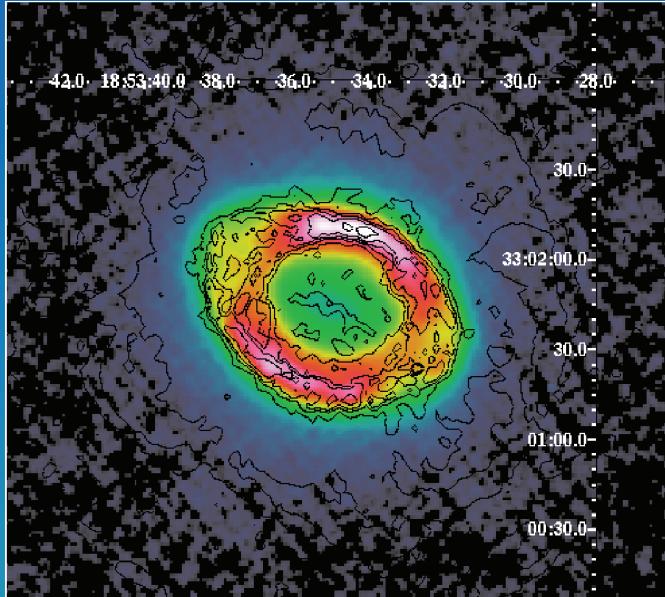
-Adding loads of literature data (different apertures...)

NGC 6720



van Hoof et al. (2010)
PACS 60 and 160 micron

NGC 6720: H₂ formation on dust grains



Overlay of the H₂ 2.12 μm emission (contours) on the PACS 70 μm image of NGC 6720 showing the dust emission. The detailed match between the H₂ and dust emission appears to be the first observational evidence that H₂ forms on oxygen-rich dust grains.

- We have developed a photoionization model of the nebula with the Cloudy code, which we used to investigate possible formation scenarios for H₂.
- We conclude that the most plausible scenario is that the H₂ resides in high density knots which were formed after the recombination of the gas started when the central star luminosity dropped steeply around 1000-2000 years ago.
- The models show that H₂ formation in the knots is expected to be substantial since then, and may well still be ongoing at this moment.
- van Hoof et al. 2010, A&A, 518, L137