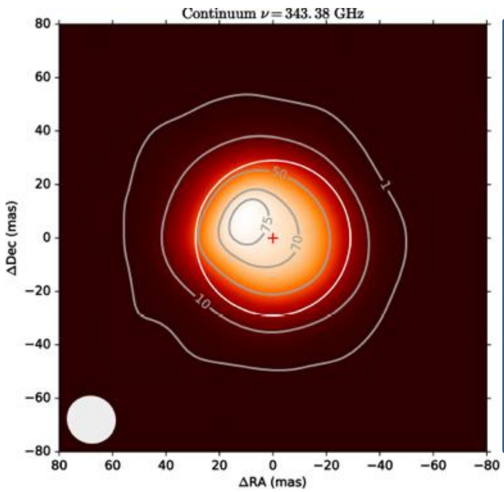
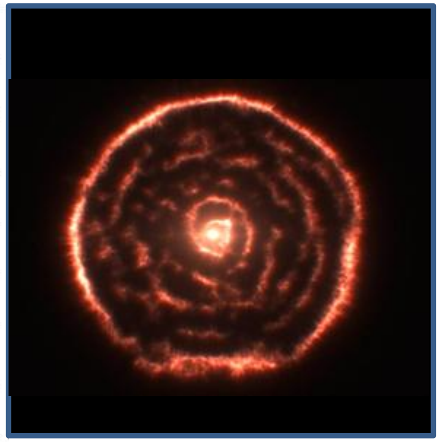
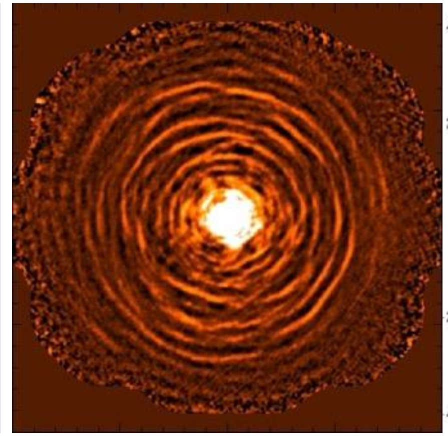
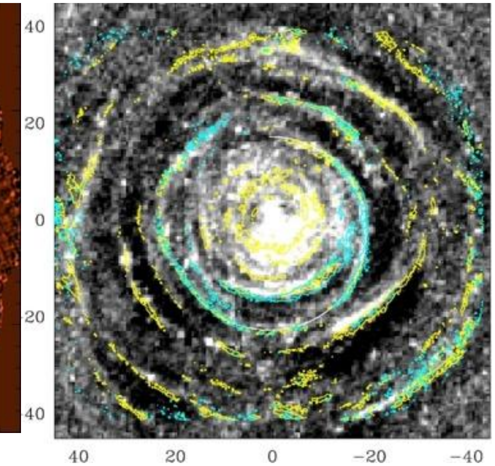


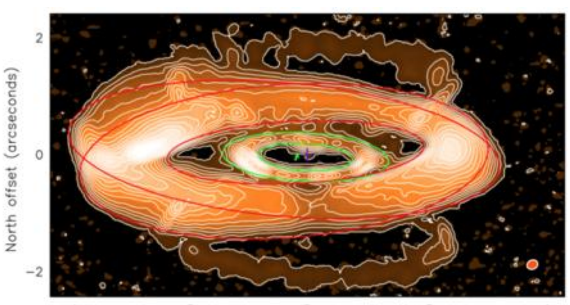




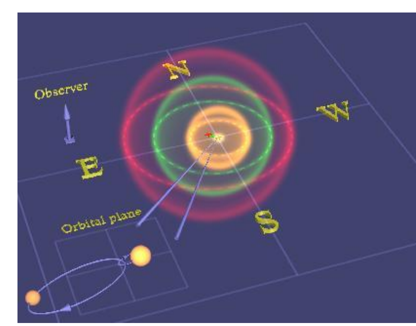
AGB stars and their environment

Michel Guélin
(Presenter: Ka Tat Wong)

Institut de Radioastronomie Millimétrique (IRAM)

Grenoble, France



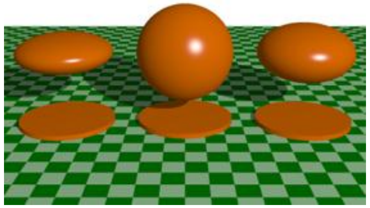


OUTLINE

1. **AGB stars and their winds: why, how?**

2. **New interferometric observations**
   ⇨ *Physical conditions + Keys to the mass loss mechanism*

3. **Reconstruction of the envelopes in 3-D**
   - 3-D modeling based on velocity fields
   - Test cases
   - Application to the observed X,Y,V cube
     ⇨ ***IRC +10 216 3-D model***

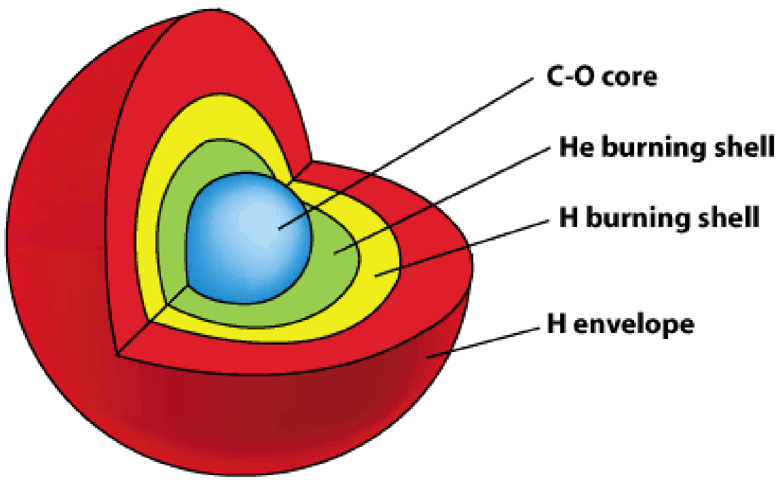


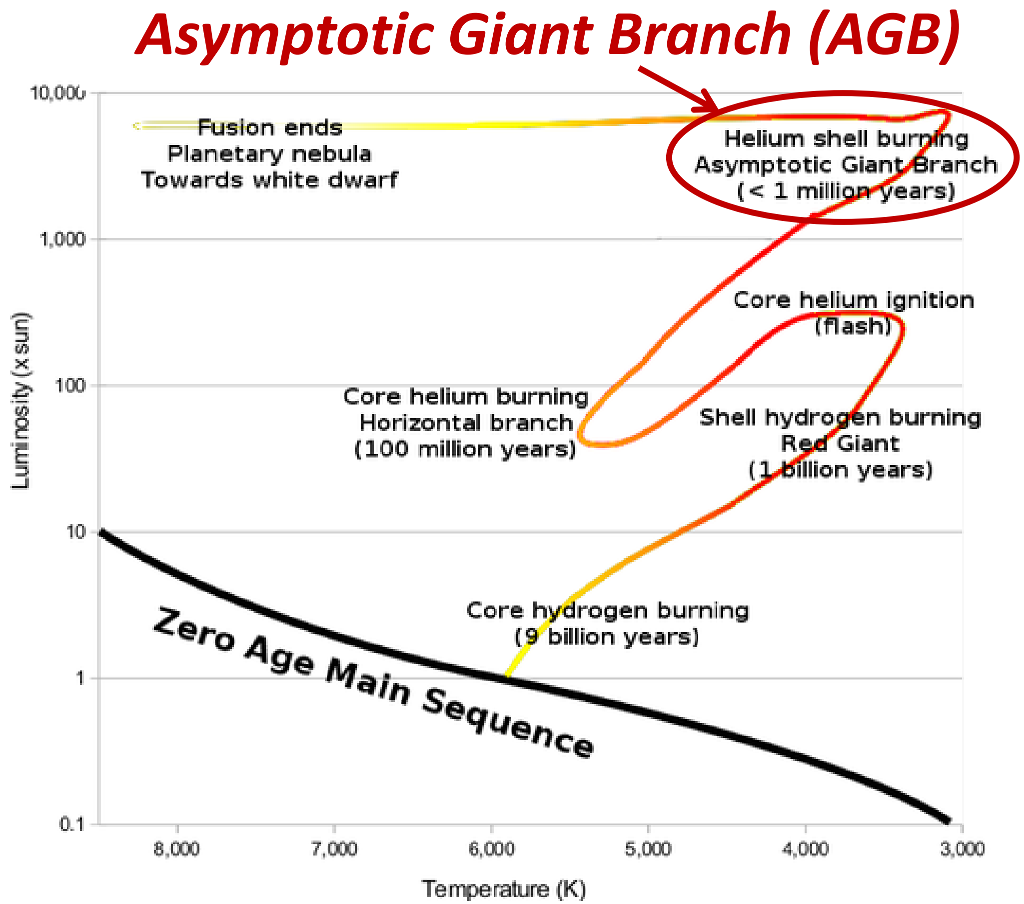
4. **The case of multiple stars**

5. **A rich circumstellar chemistry**

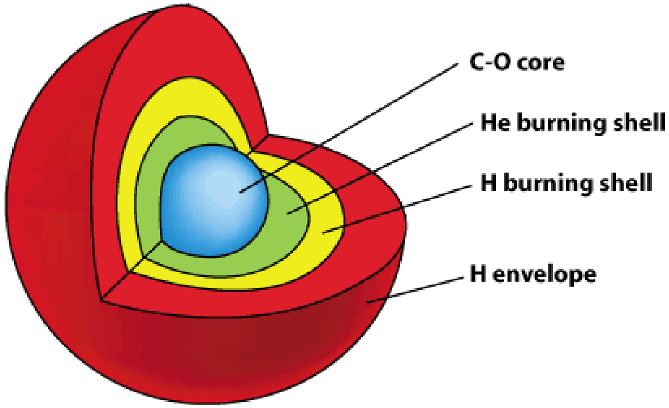
1.1 Asymptotic Giant Branch stars

- They are ***Red Giant stars*** with a degenerated ***Carbon-Oxygen*** *core* surrounded by ***burning Helium*** *and* ***Hydrogen*** *shells.*





1.2 Asymptotic Giant Branch stars



- **Critical stellar masses**:

  M > 0.8 $M_\odot$ → **He core burning**

  M > 8 $M_\odot$ → **C-O core burning**

  Initial mass of an AGB star ≈ 0.8 – 8 $M_\odot$

- **Chemical types**: ***M-type/oxygen-rich stars*** (**C/O≈0.5**);

  S-type stars (**C/O≈0.5–1**);

  C-type/carbon-rich stars (**C/O>1**).

  Carbon star masses are in the range 1.5 $M_\odot$ < M < 4 $M_\odot$.

M-type star EP Aqr ➜ *see D. T. Hoai's talk*

see A. Zijlstra's talk

- **Luminosity Pulsations:** Short period irregular,

  Long-period (>100 d) regular (Mira-type).

- **Thermal Pulses**: every few × 10^4 years

1.3 Asymptotic Giant Branch stars

- At the end of the AGB phase (‘*Thermally Pulsing*’ or TP) the stars experience **strong stellar winds**:

$$\dot{M} = \text{few} \times 10^{-8} \text{ to few} \times 10^{-4}\ M_{\odot}/\text{yr}$$

I. C. Leão et al.: The CSE of IRC+10216

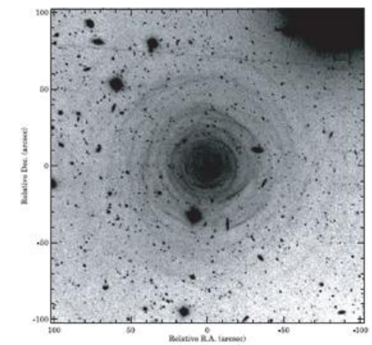


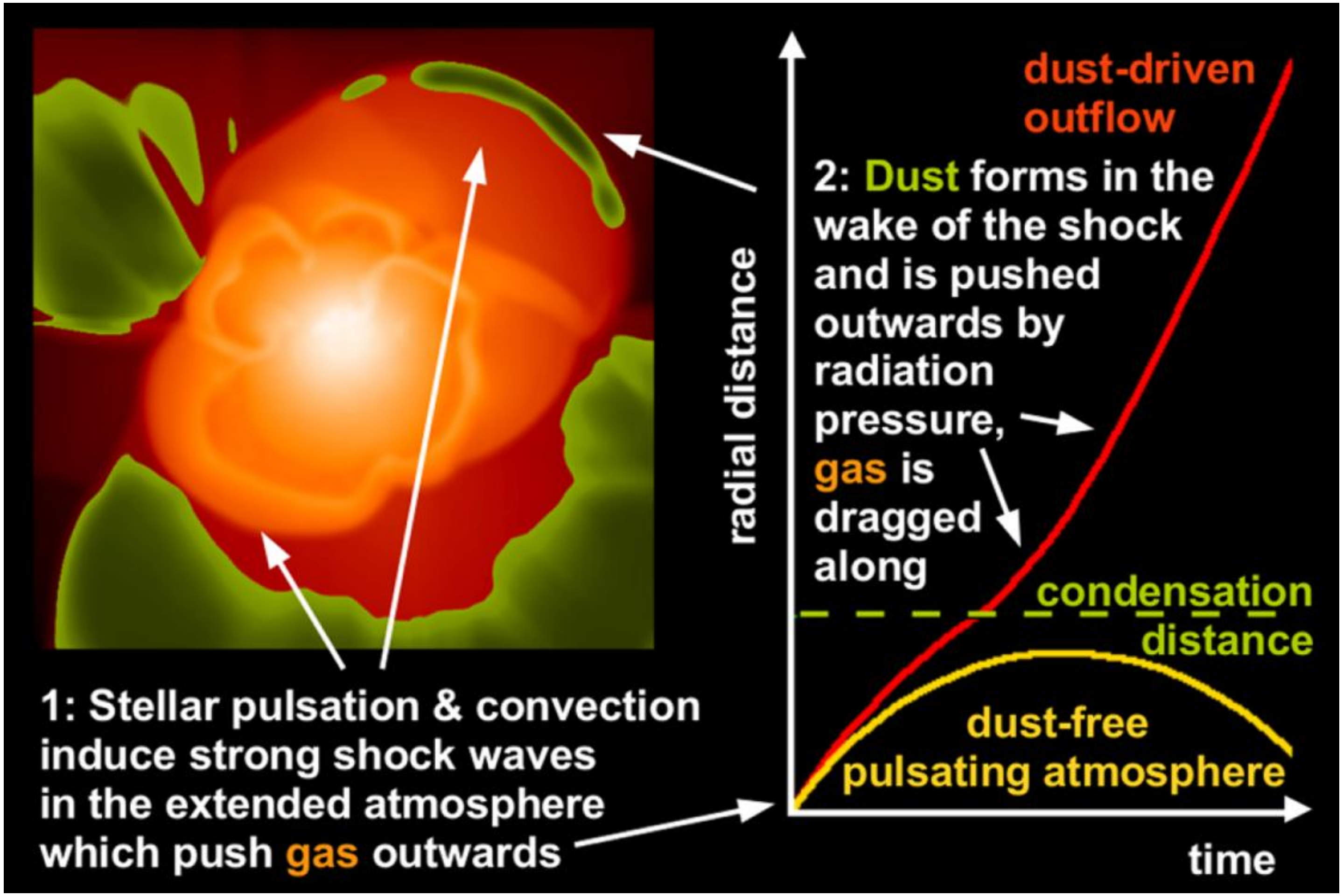
Fig. 3. FORS1 deconvolved *V*-band image of IRC+10216. North is up and East is left.

- They are surrounded by **thick expanding envelopes** opaque to visible light.
- AGB star envelopes contribute to the **regeneration of the ISM** providing 80% of newly synthetized elements.
- They are also the **main providers of interstellar dust grains**.

1.4 Strong AGB stellar winds

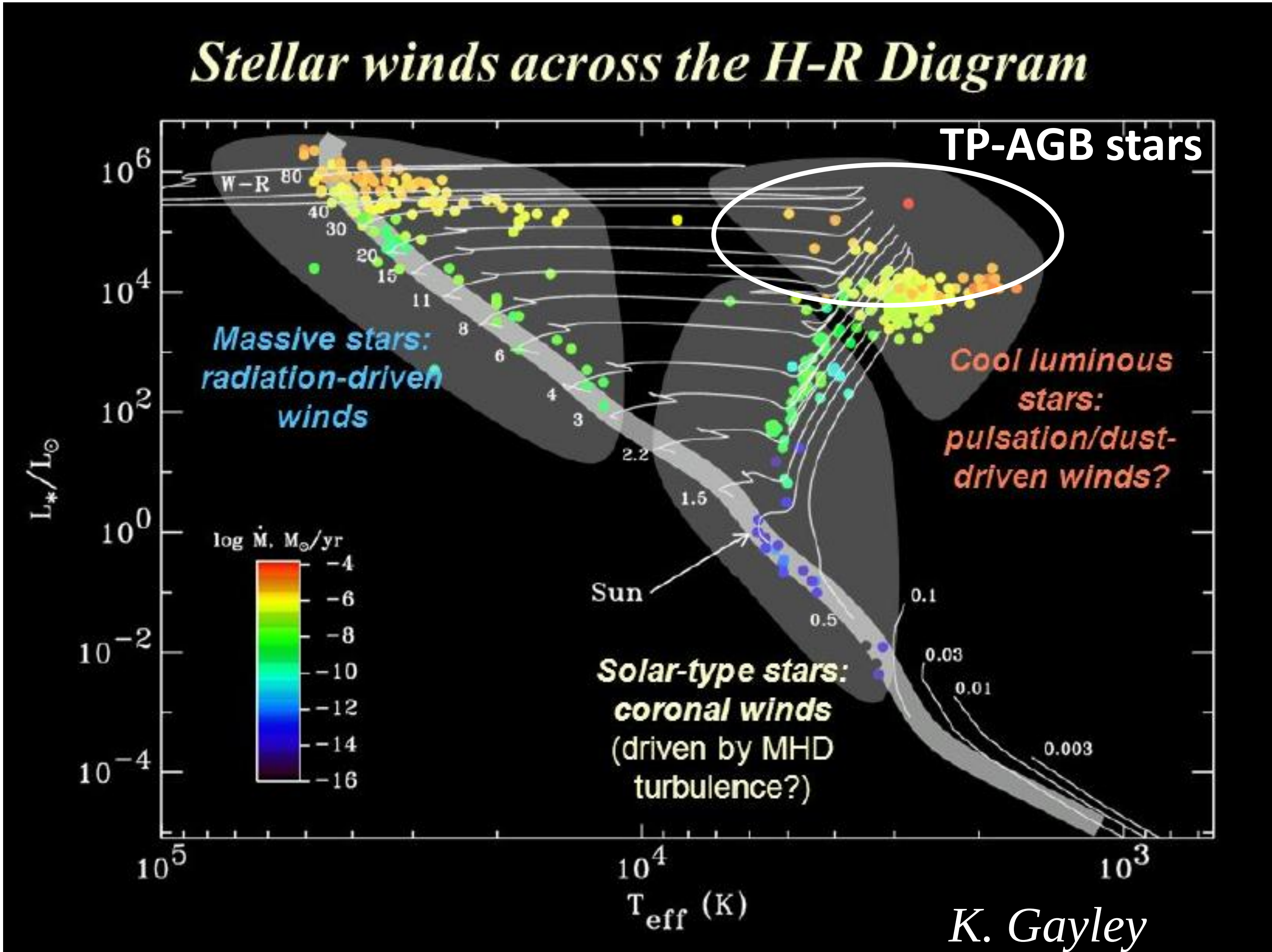
- **Why do they arise?** *Not fully clear as*:
  - Photosphere **temperature is not high enough** for gas particles to reach the escape velocity. Also, AGB stars do **not shine enough UV radiation** to accelerate the gas through UV line absorption.
  - Needs **cooling** of the upper atmospheric layers **to form dust grains** that will be accelerated by radiation pressure and drag the gas.

1.5 Strong AGB stellar winds



S. Höfner

Dust formation ➜ *see J. M. Winters' talk*



Stellar winds across the H-R Diagram
TP-AGB stars
W-R
80
40
30
20
15
11
8
6
4
3
2.2
1.5
0.5
0.1
0.03
0.01
0.003
Massive stars: radiation-driven winds
Cool luminous stars: pulsation/dust-driven winds?
Solar-type stars: coronal winds (driven by MHD turbulence?)
Sun
log Ṁ, M⊙/yr
−4
−6
−8
−10
−12
−14
−16
L*/L⊙
Teff (K)
K. Gayley

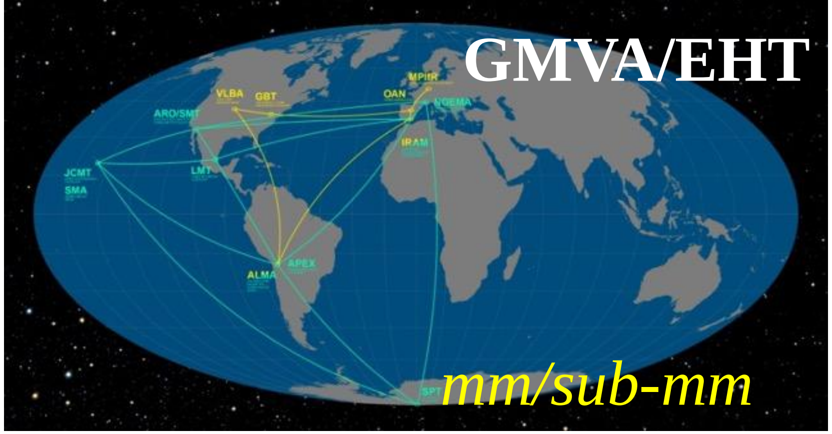
1.6 Strong AGB stellar winds

– **How to lift and cool those layers?** Through stellar pulsations? Shocks? Magnetic pressure? Gravitational pull by companion star or planet?

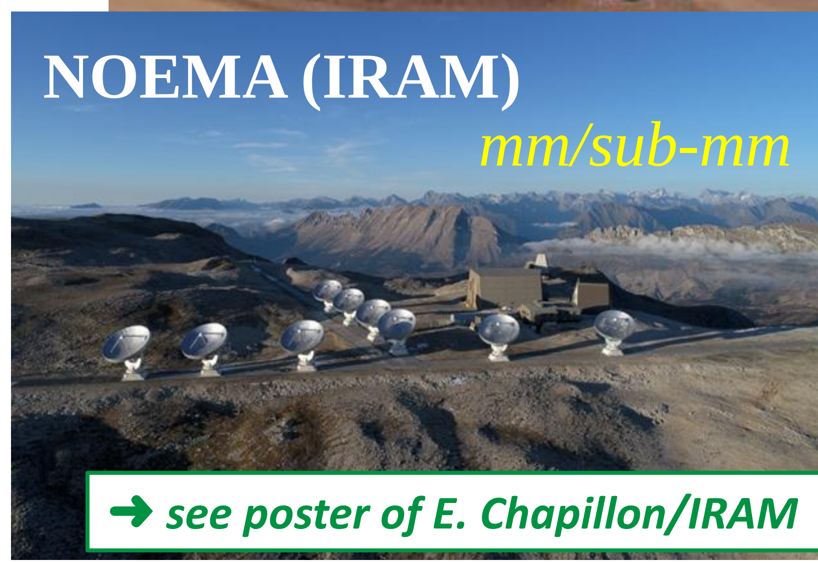
- **How may we find out?**
  – Stars have **very small angular sizes** and their envelopes are **opaque to visible radiation**

→ IR and mm/sub-mm interferometry

Fortunately, we have new, powerful instruments!



2.1 Powerful interferometers operating in the IR, sub-mm and mm domains



2.2 What do we learn from first interferometric observations?

A. Photospheres: **blobs, plumes & hot spots**: *magnetic pressure?*
B. Envelopes: **3-D morphology may be reconstructed**
   1. **Detached expanding shells**: *sporadic mass loss*
   2. **Filled expanding spheres:** *continuous mass loss*
      a. Spirals (+ detached shells)
      b. Over-dense shells
   3. **Bipolar outflows collimated by disks:** *transition to PPNs*
C. Frequent presence of **binary stars**
D. **Time dependence** of **chemistry**

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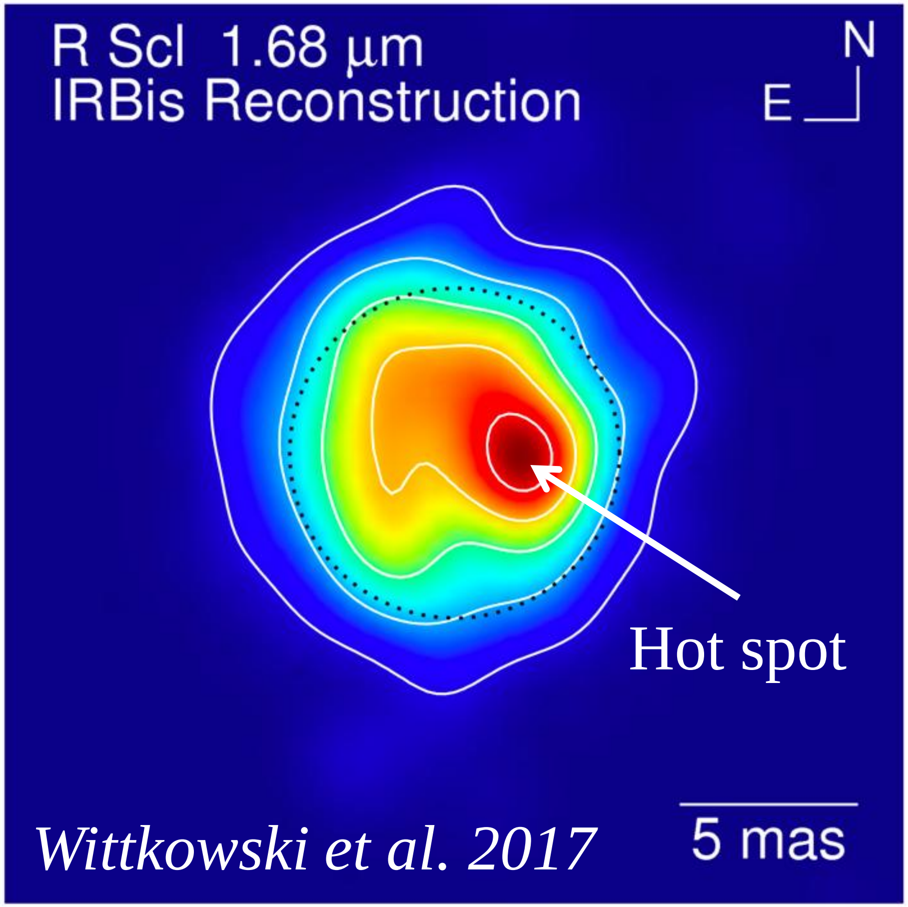
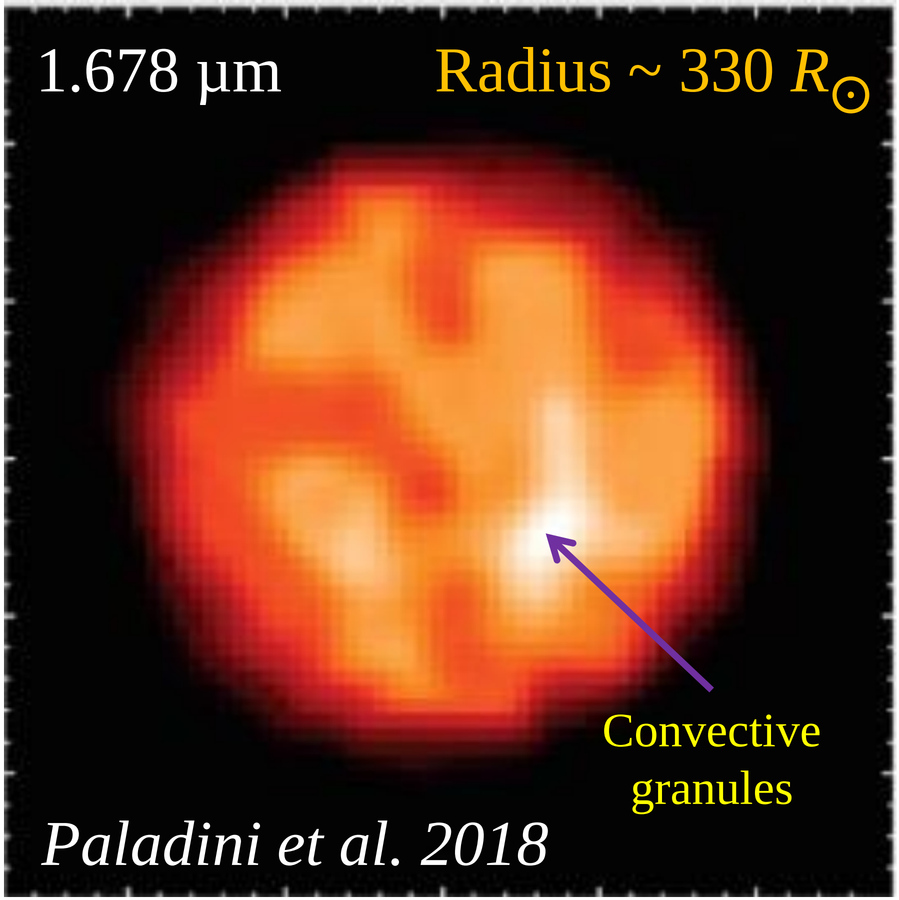
(A.1) We can now resolve stellar photospheres!

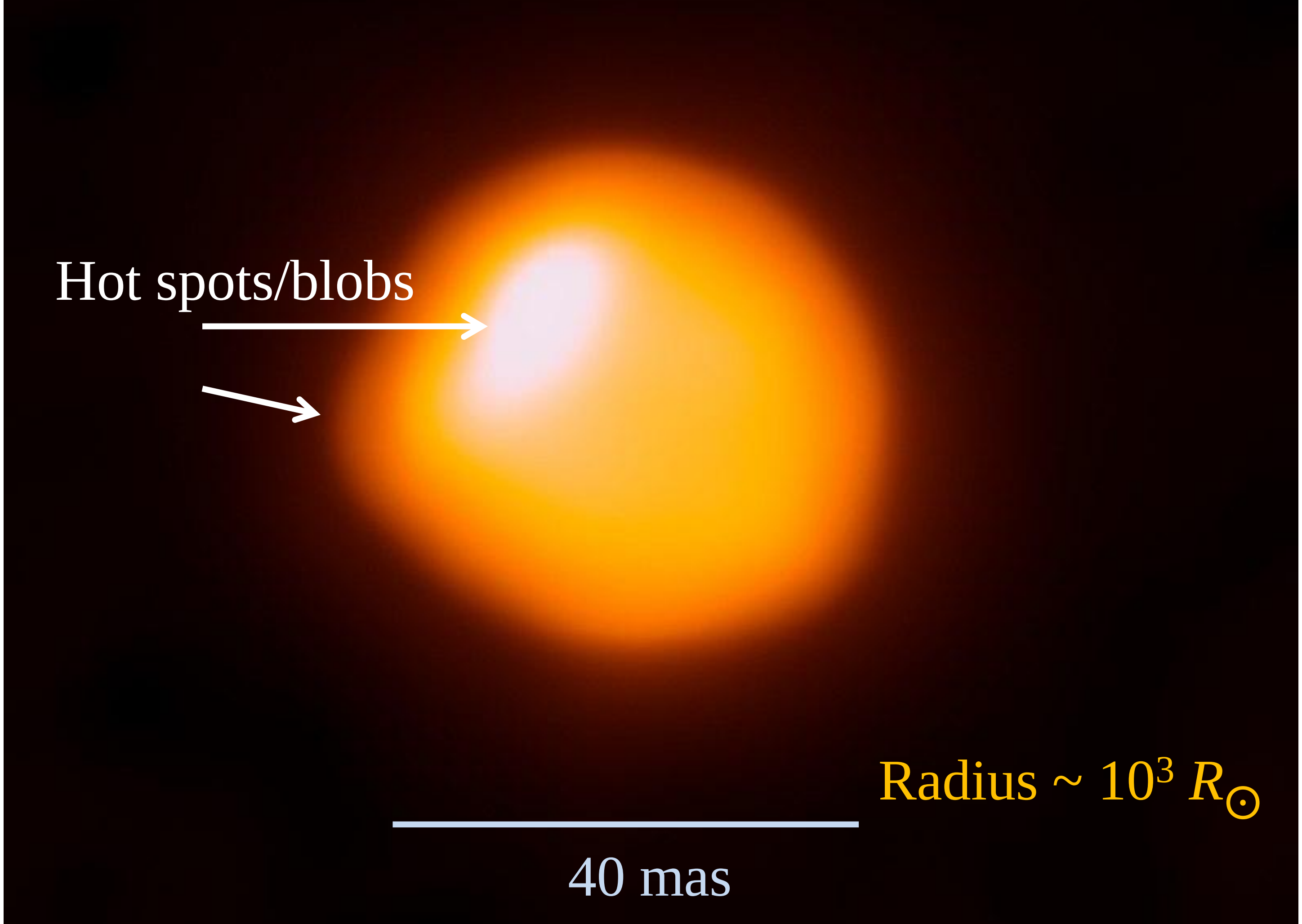
C-star R Sculptoris (VLTI/PIONIER)



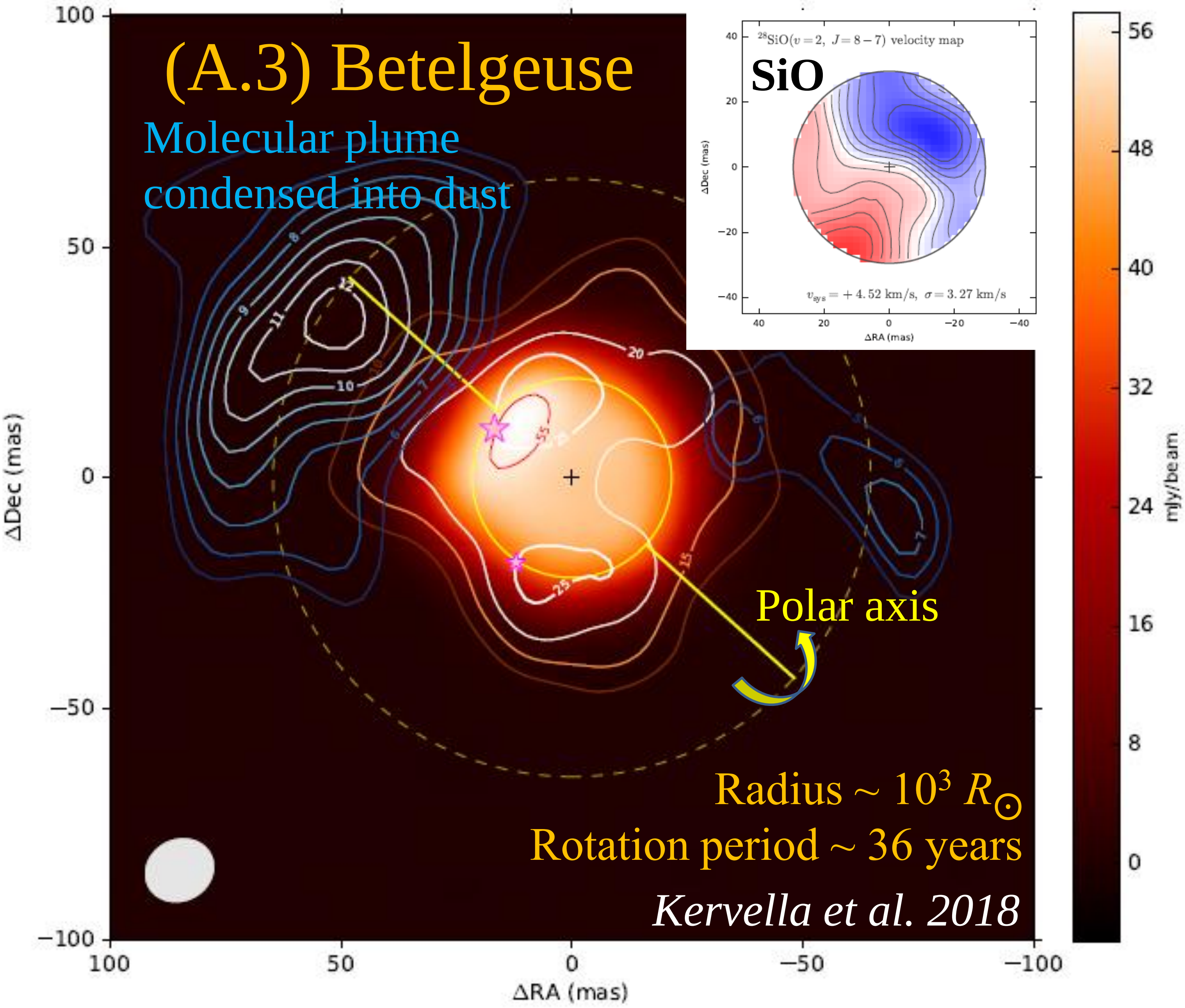
S-star π^1 Gruis (VLTI/PIONIER)



(A.2): Photosphere of the Red supergiant ***Betelgeuse*** in the 338 GHz continuum (*ALMA*)



O'Gorman et al. 2017; Kervella et al. 2018



(A.3) Betelgeuse
Molecular plume
condensed into dust
SiO
^{28}SiO($v=2$, $J=8-7$) velocity map
$v_{sys} = +4.52$ km/s, $\sigma = 3.27$ km/s
ΔRA (mas)
ΔDec (mas)
Polar axis
Radius ~ $10^3\ R_\odot$
Rotation period ~ 36 years
Kervella et al. 2018
mJy/beam

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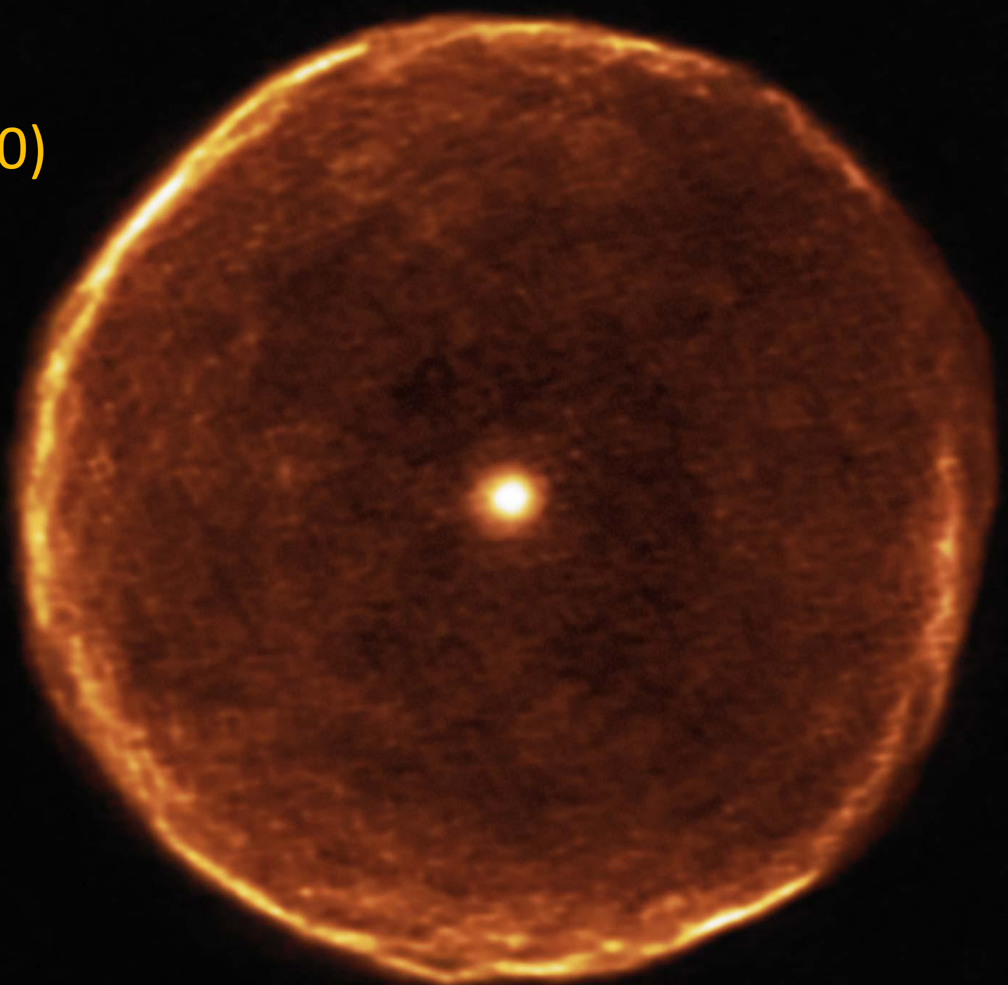
(B.1) Sporadic mass loss: detached envelope

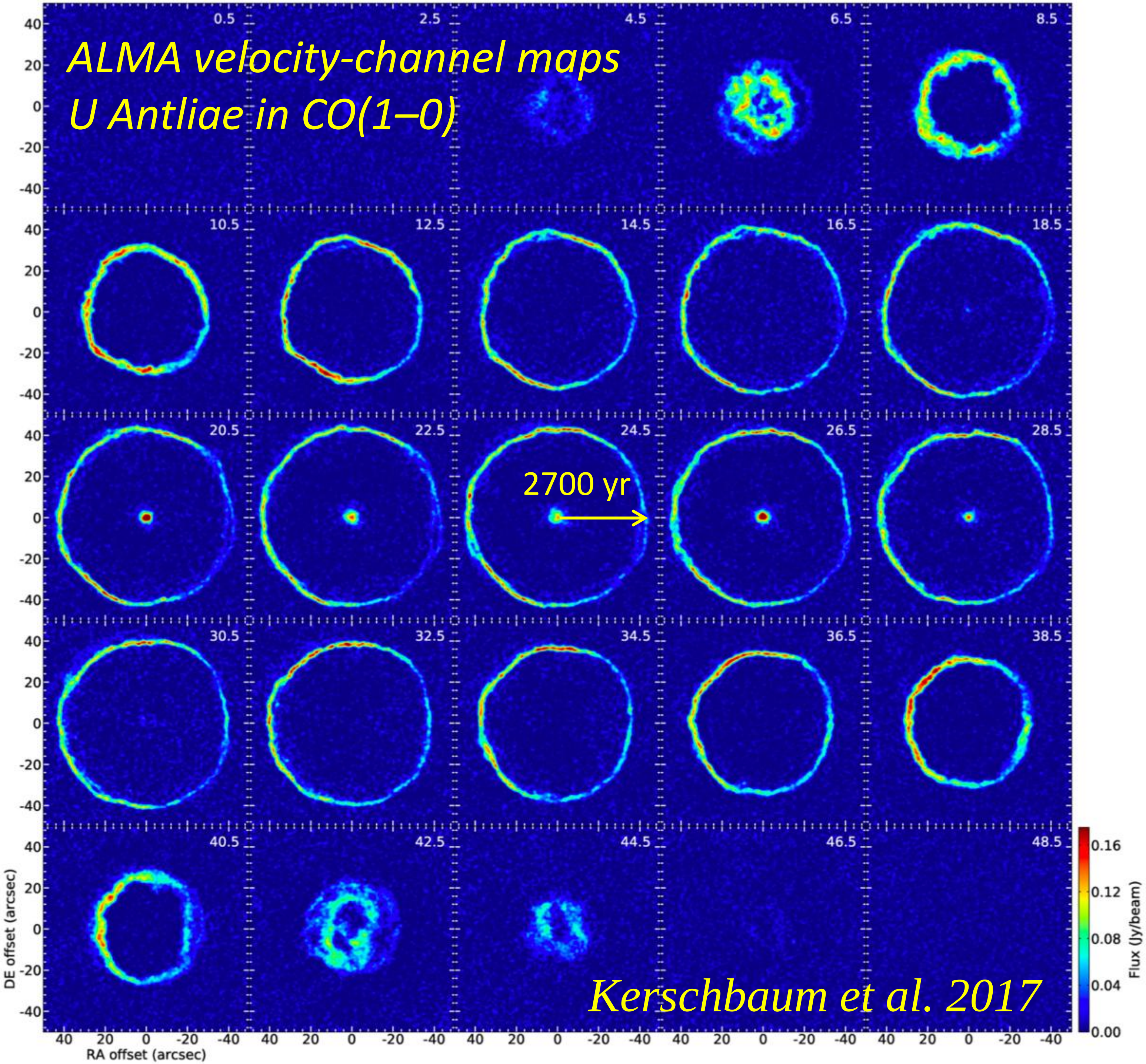
U Antliae

ALMA CO(1–0)

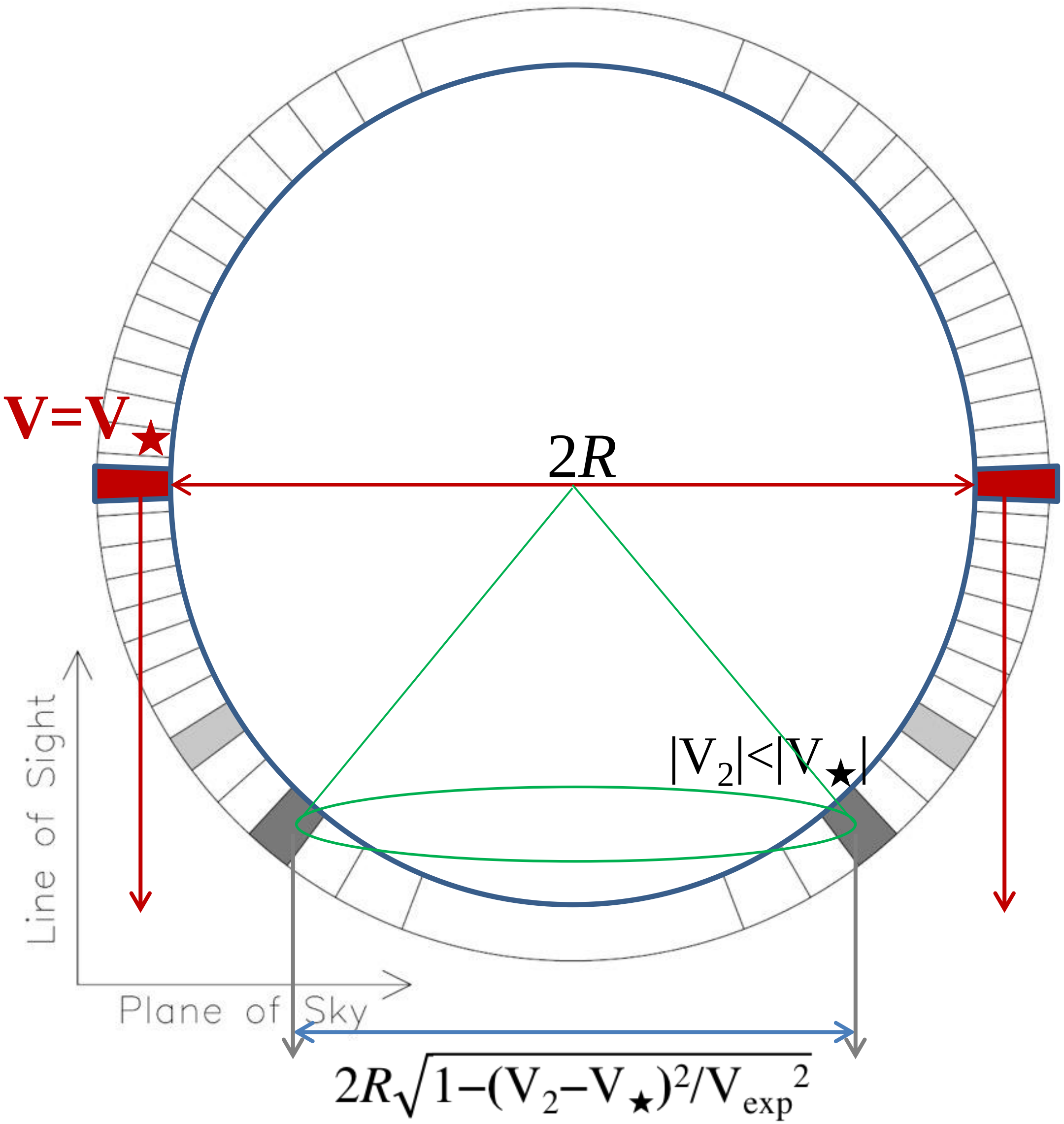


Simple geometry → reconstruct the 3-D morphology from velocity-channel maps

Credit: F. Kerschbaum
ALMA (ESO/NAOJ/NRAO)


ALMA velocity-channel maps
U Antliae in CO(1–0)
2700 yr
Kerschbaum et al. 2017
0.5
2.5
4.5
6.5
8.5
10.5
12.5
14.5
16.5
18.5
20.5
22.5
24.5
26.5
28.5
30.5
32.5
34.5
36.5
38.5
40.5
42.5
44.5
46.5
48.5
DE offset (arcsec)
RA offset (arcsec)
Flux (Jy/beam)
0.16
0.12
0.08
0.04
0.00

Velocity-channel maps for a uniformly expanding circumstellar shell

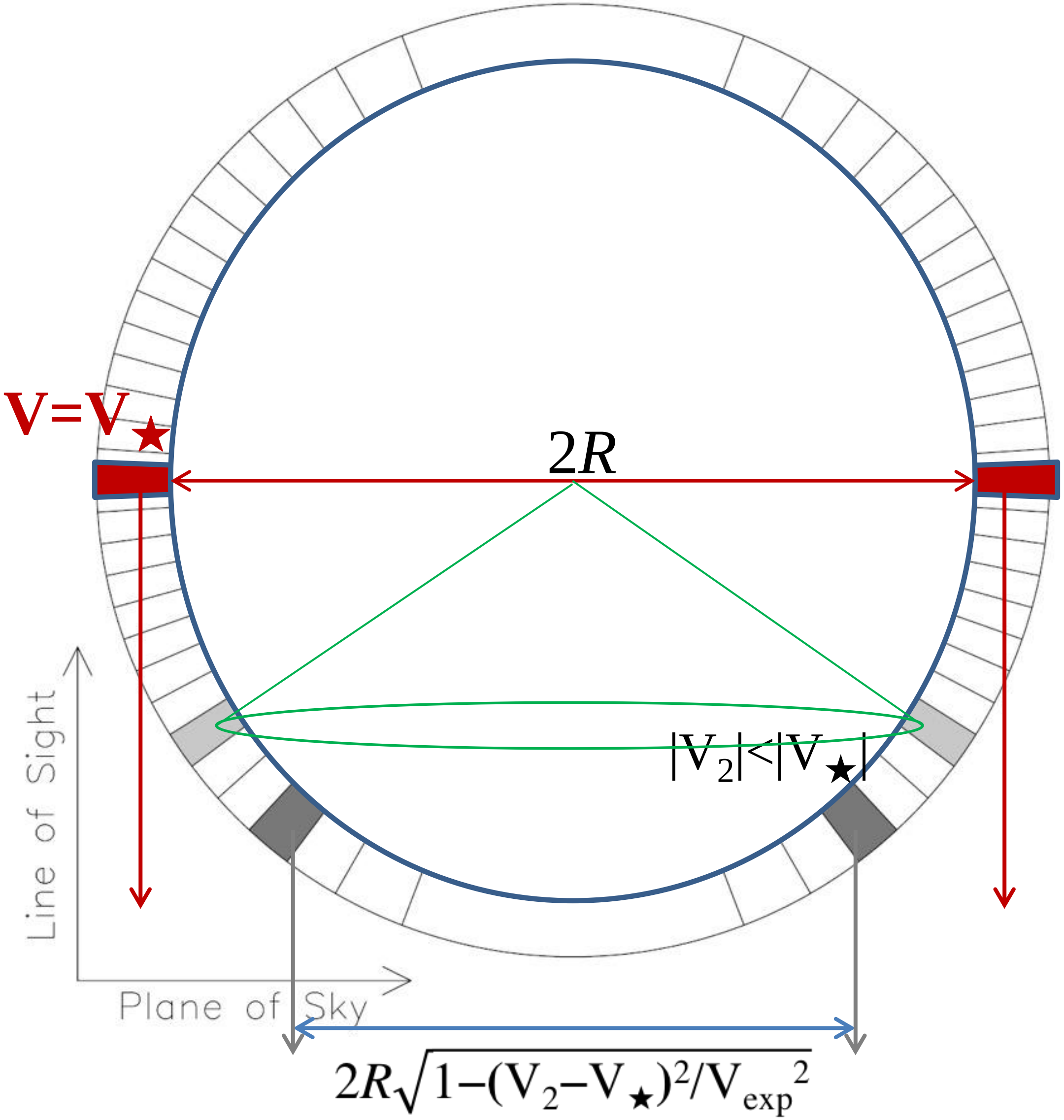


Velocity-channels close to the systemic velocity V★ (X,Y,V★) trace the gas in the ***meridional plane*** parallel to the plane of the sky

Velocity-channel maps (X,Y,V) trace the emissivity distribution from ***conical shells***

Michel Guélin & Ka Tat Wong, Quy Nhơn 2018

Velocity-channel maps for a uniformly expanding circumstellar shell



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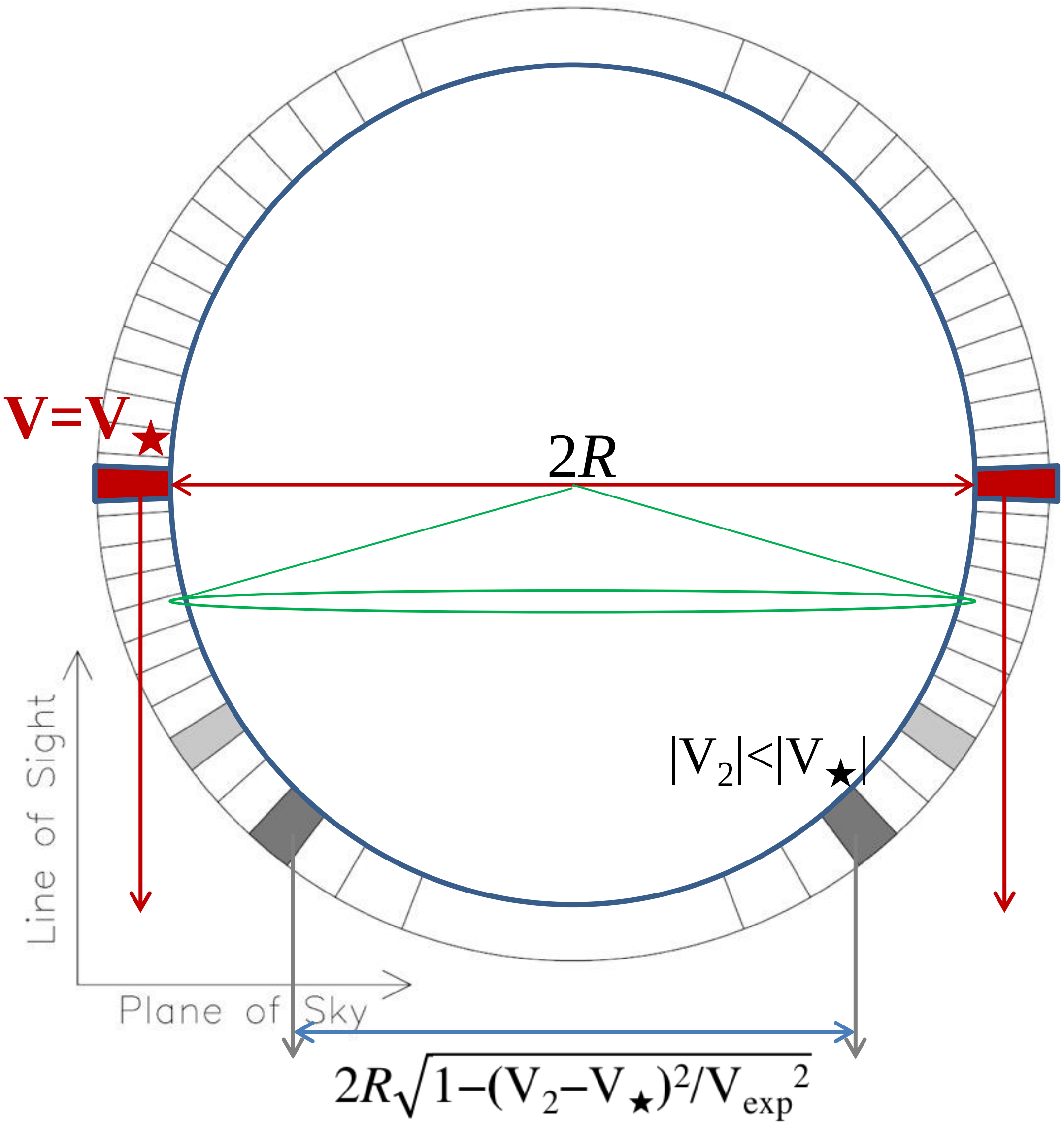
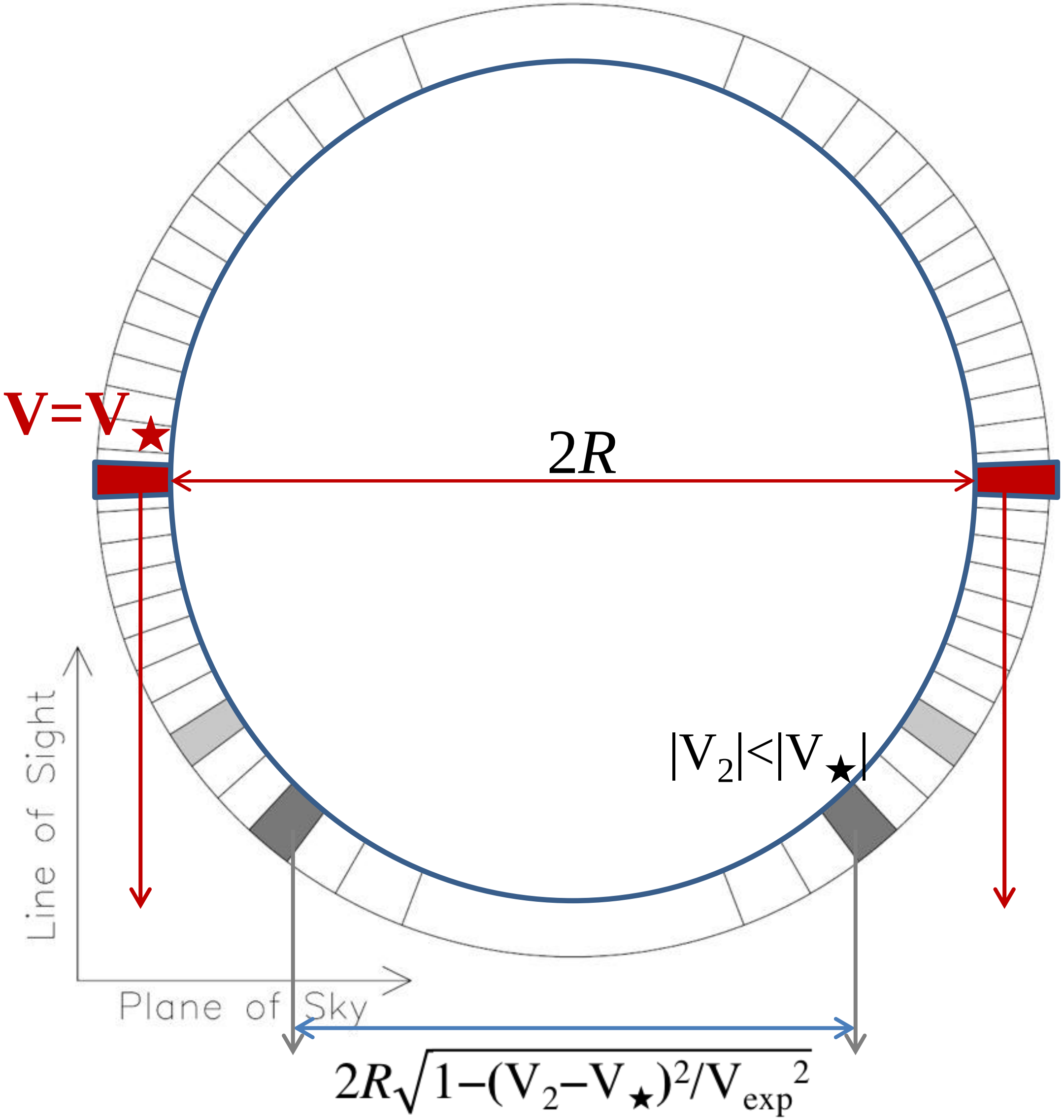
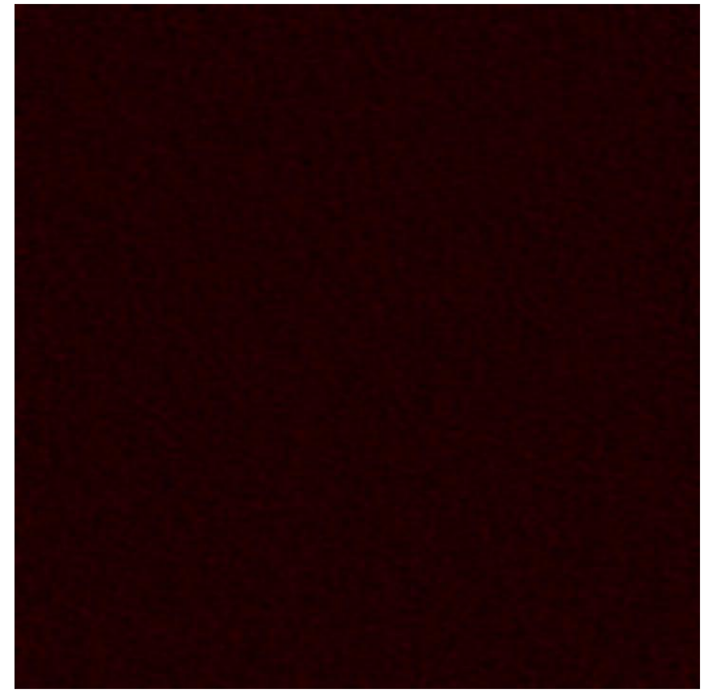


Velocity-channels close to the systemic velocity $V_\star$ $(X,Y,V_\star)$ trace the gas in the ***meridional plane*** parallel to the plane of the sky

Velocity-channel maps (X,Y,V) trace the emissivity distribution from ***conical shells***

Velocity-channel maps for a uniformly expanding circumstellar shell





*Imply a **thin** (200 yr-thick), almost **spherical, detached** shell of gas ejected 2700 yr ago, plus a recent one!*

Kerschbaum et al. 2017

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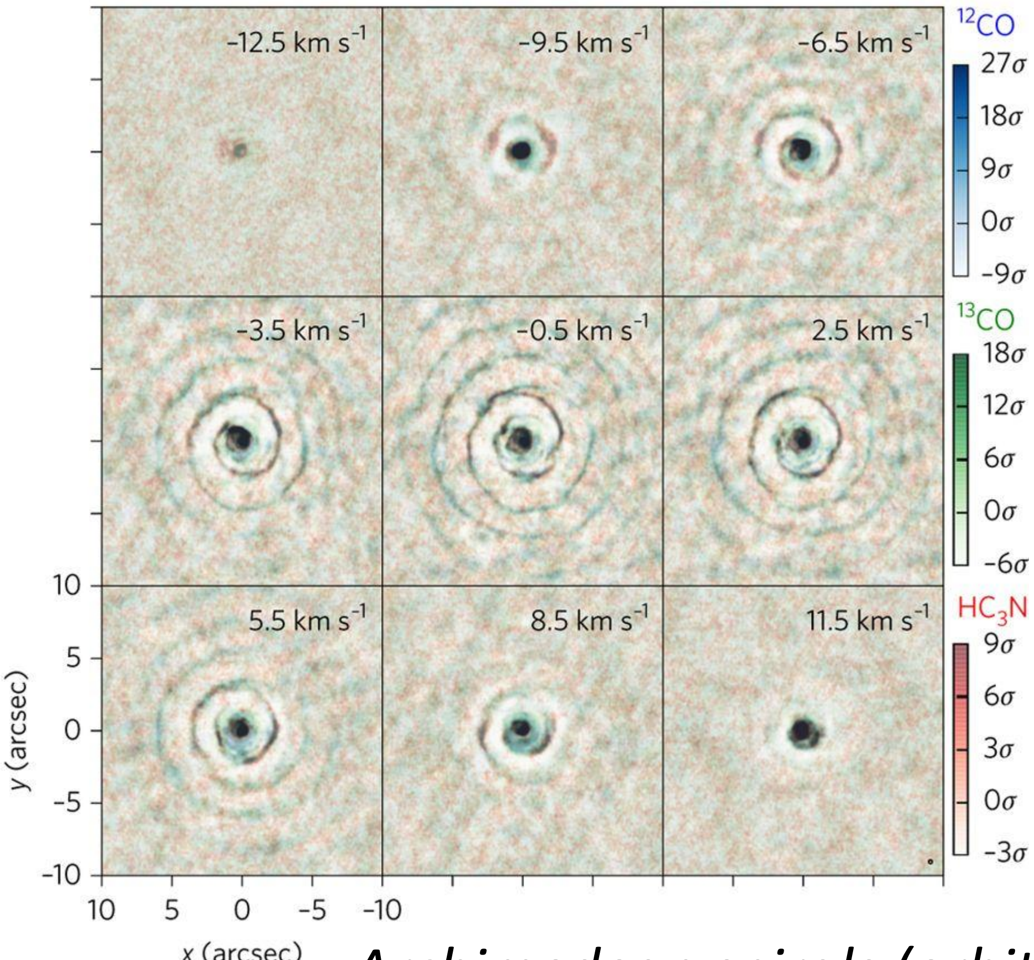
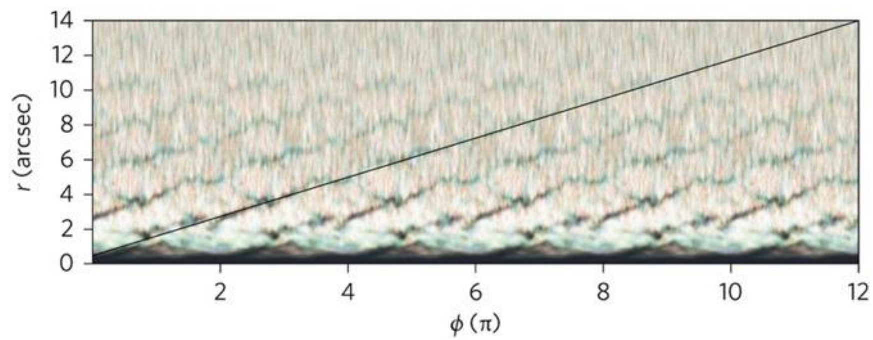
(B.2) Continuous mass-loss: spiral pattern

ALMA velocity-channel maps



AFGL 3068 (LL Pegasi)

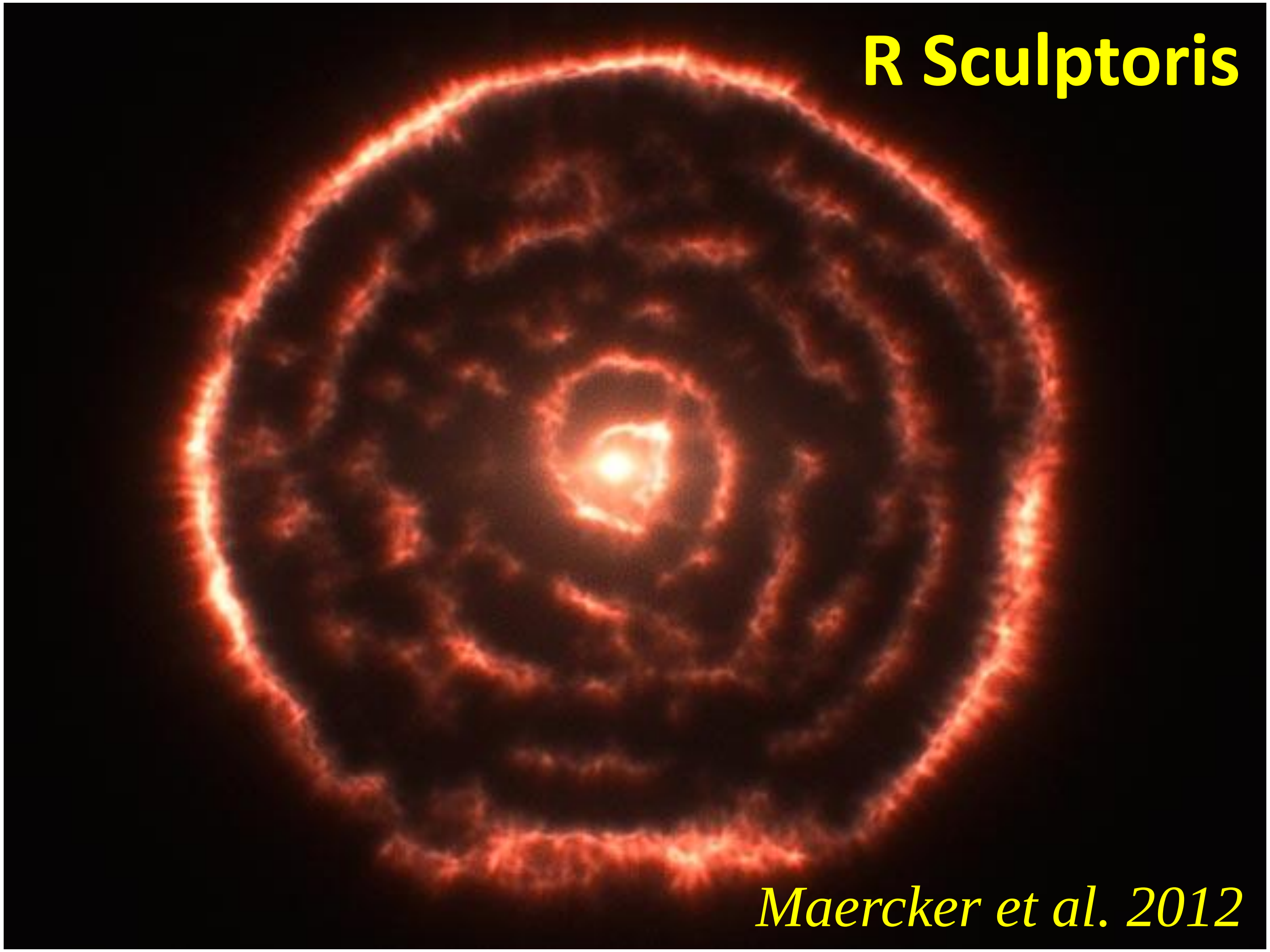
Central channel in polar coordinates



Kim et al. 2017

Archimedean spirals (orbital plane in the plane of the sky) + bifurcation (eccentric orbit)

(B.3) Continuous mass-loss after sporadic flare: inner spiral + outer detached shell



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D. **Time dependence** of **chemistry**

(B.4) Continuous mass-loss with periodic enhancements: FILLED ENVELOPE

IRC+10 216 (CW Leonis)

Archetype of (and among the closest) TP-AGB stars

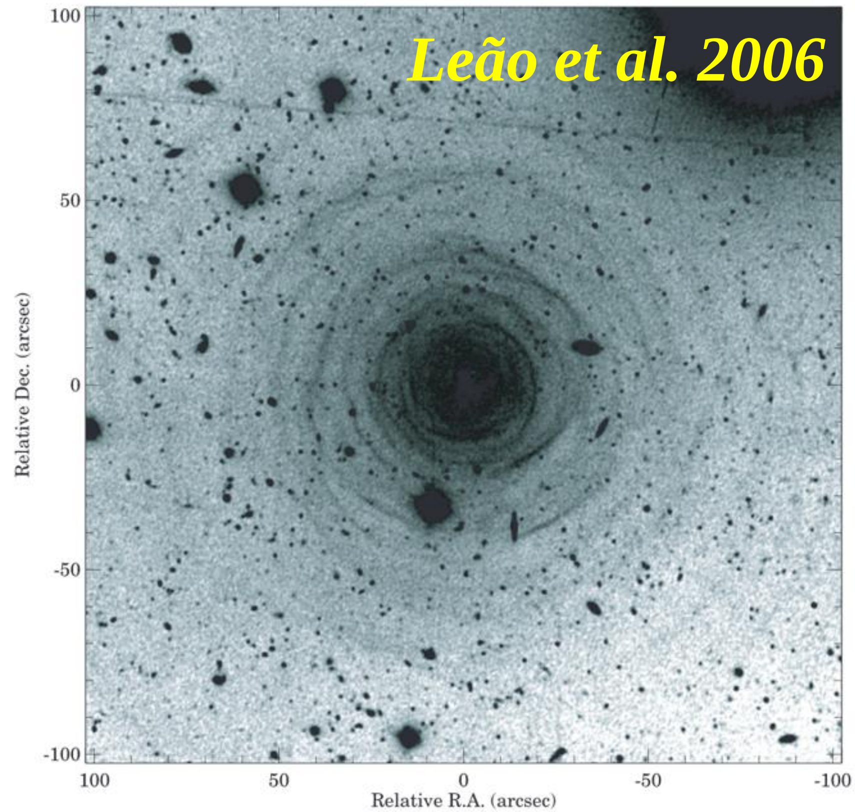


Fig. 3. FORS1 deconvolved *V*-band image of IRC+10216. North is up and East is left.

D ≈ 130 pc

Properties of IRC+10 216 (CW Leo)

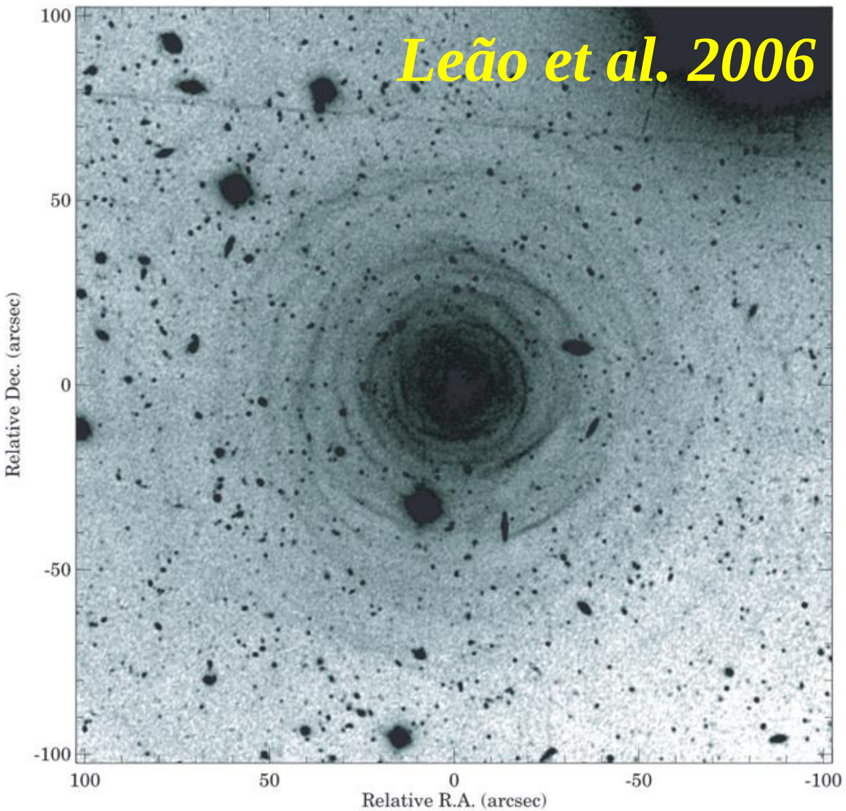
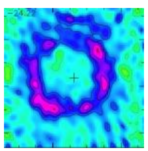


Fig. 3. FORS1 deconvolved *V*-band image of IRC+10216. North is up and East is left.

- **Massive** envelope of **large** apparent size (several arcmin)
- Simple symmetric shape
- Uniform expansion velocity (14.5 km/s)
  1 arcsec ≈ 130 a.u. ≈ 50 yr
- **Rich molecular content** (>80 molecular species, including all known **interstellar anions**)

IRC+10 216: *V*-band, C_6H, and CO emission in the plane of the sky at the same scale

C_6H/PdBI



Guelin et al. 1999

16” radius empty shell

VLT *V*-band image

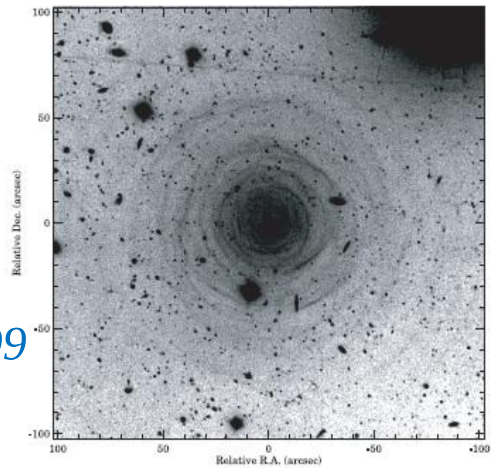
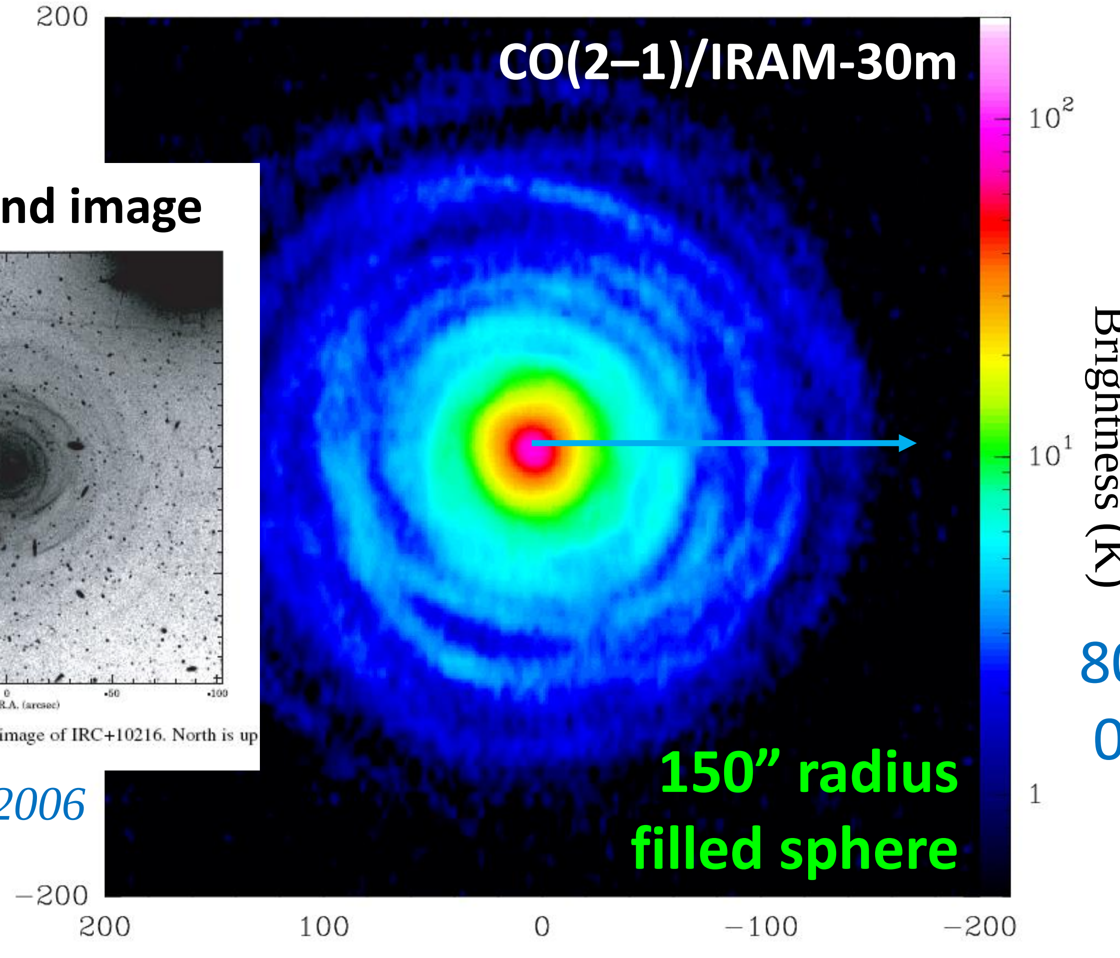


Fig. 3. FORS1 deconvolved *V*-band image of IRC+10216. North is up and East is left.

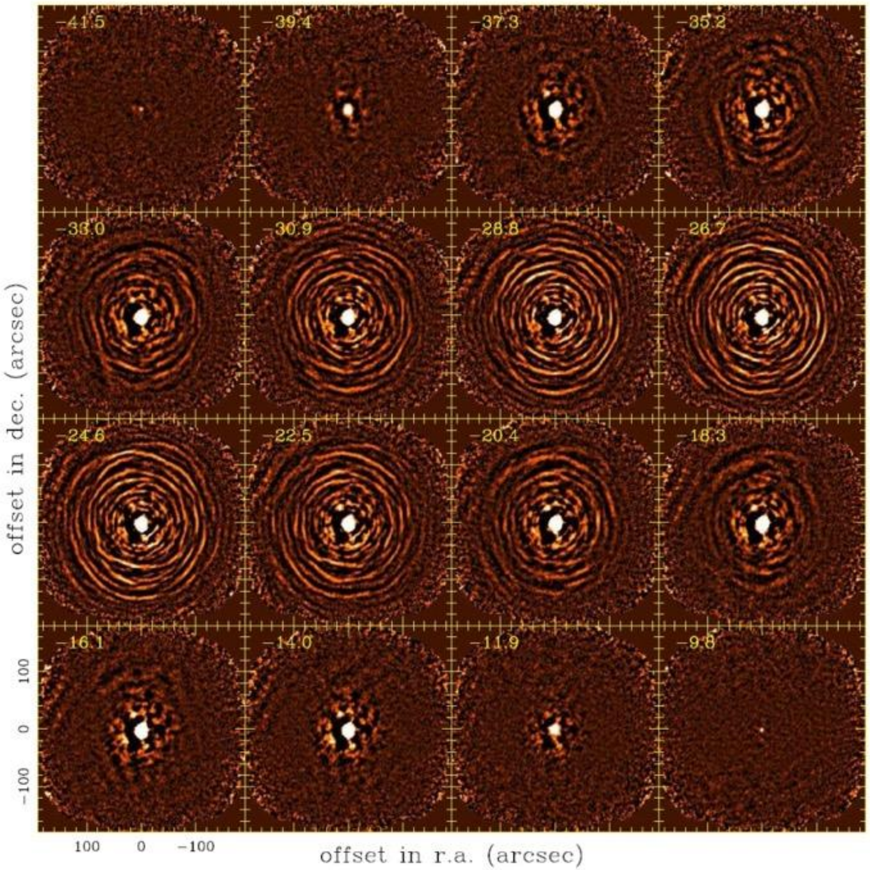
Leão et al. 2006

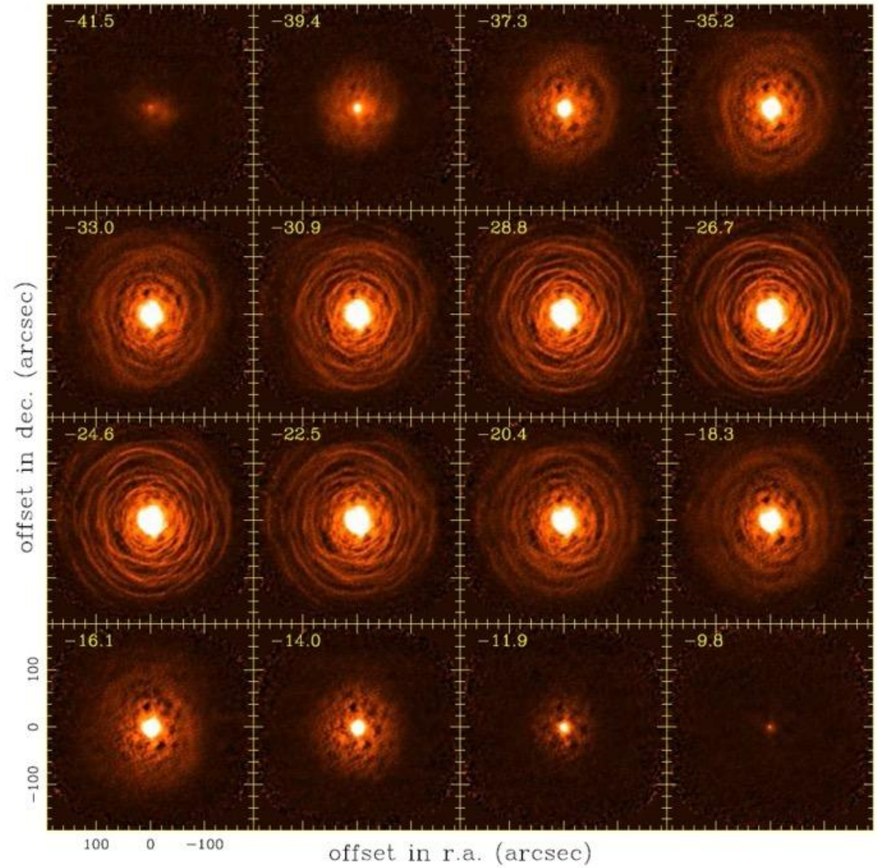


8000 yr
0.1 pc

Cernicharo et al. 2014

CO(2–1) X,Y,V cube: whole envelope (6 arcmin) at 3’’ resolution





+

=

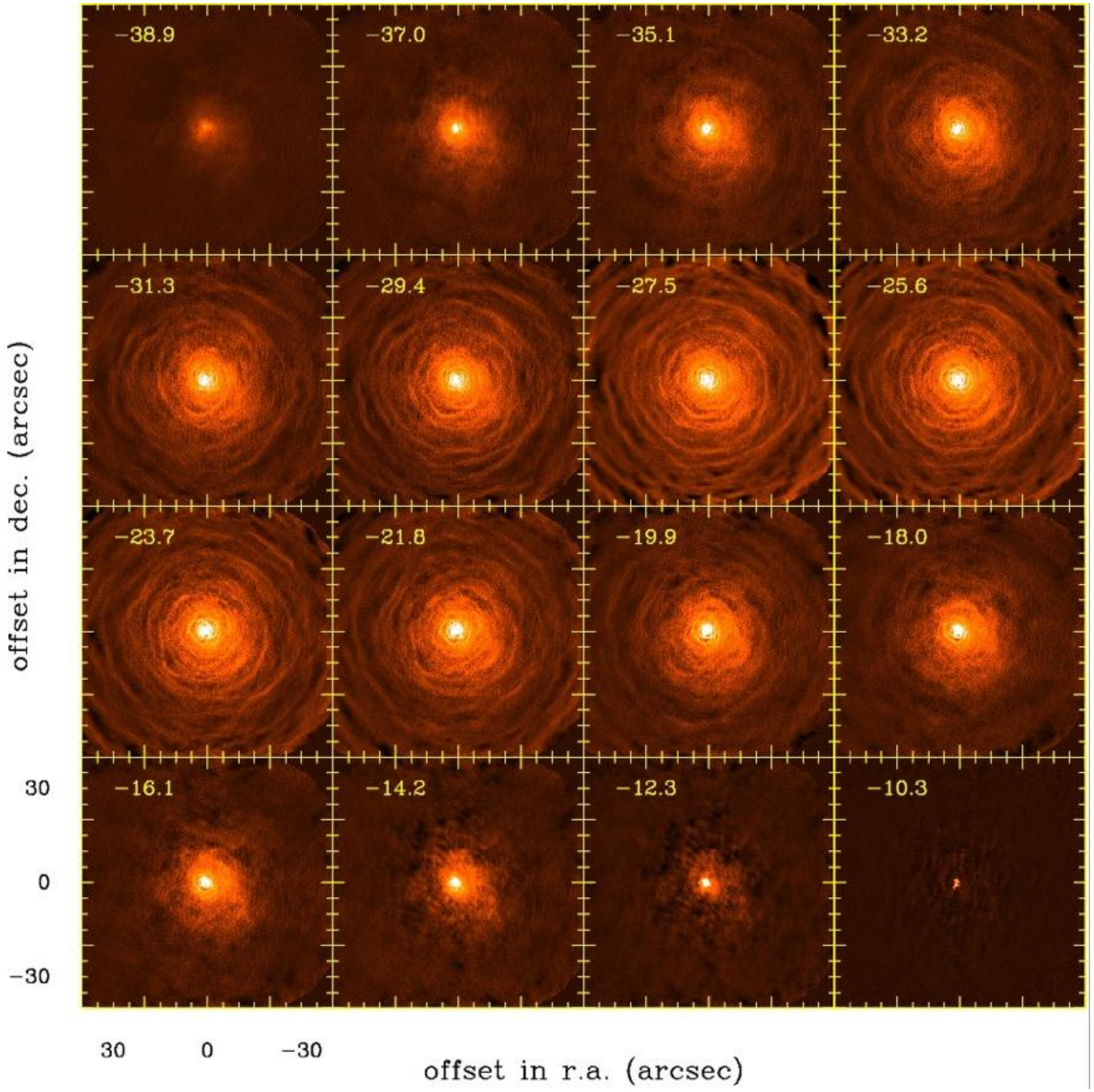
CO emission:

Filled sphere

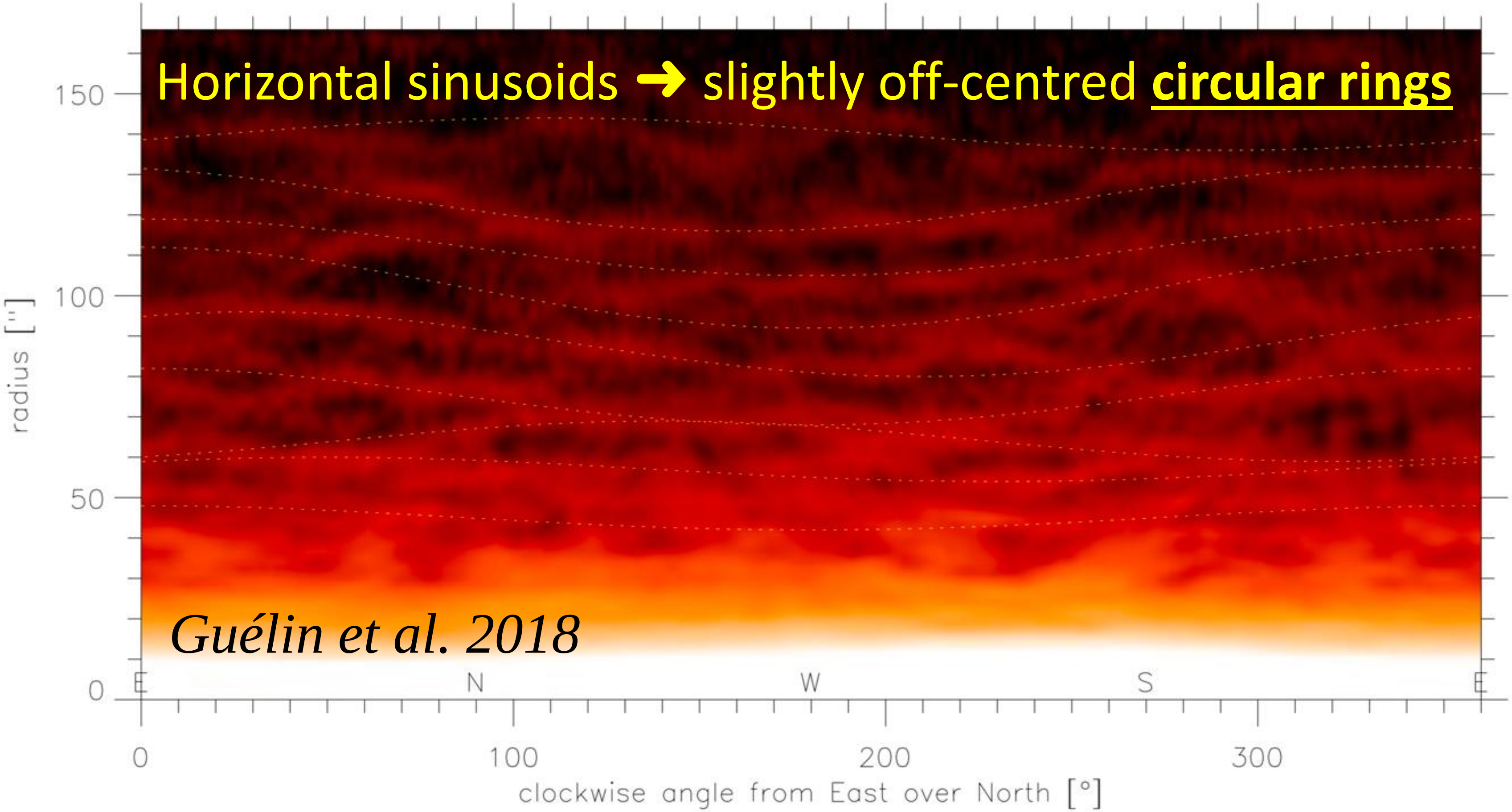
Michel Guélin & Ka Tat Wo

CO(2–1) X,Y,V cube: central 1.5 arcmin at 0.3'' resolution

+

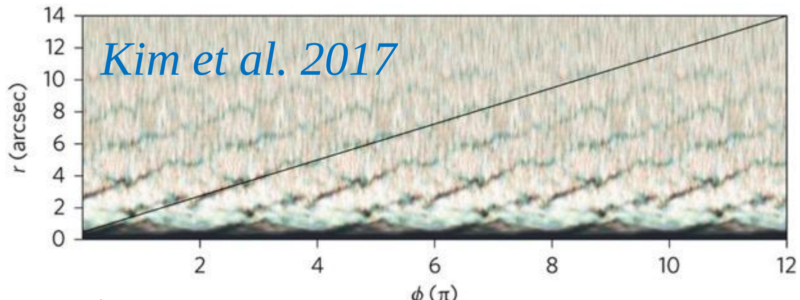


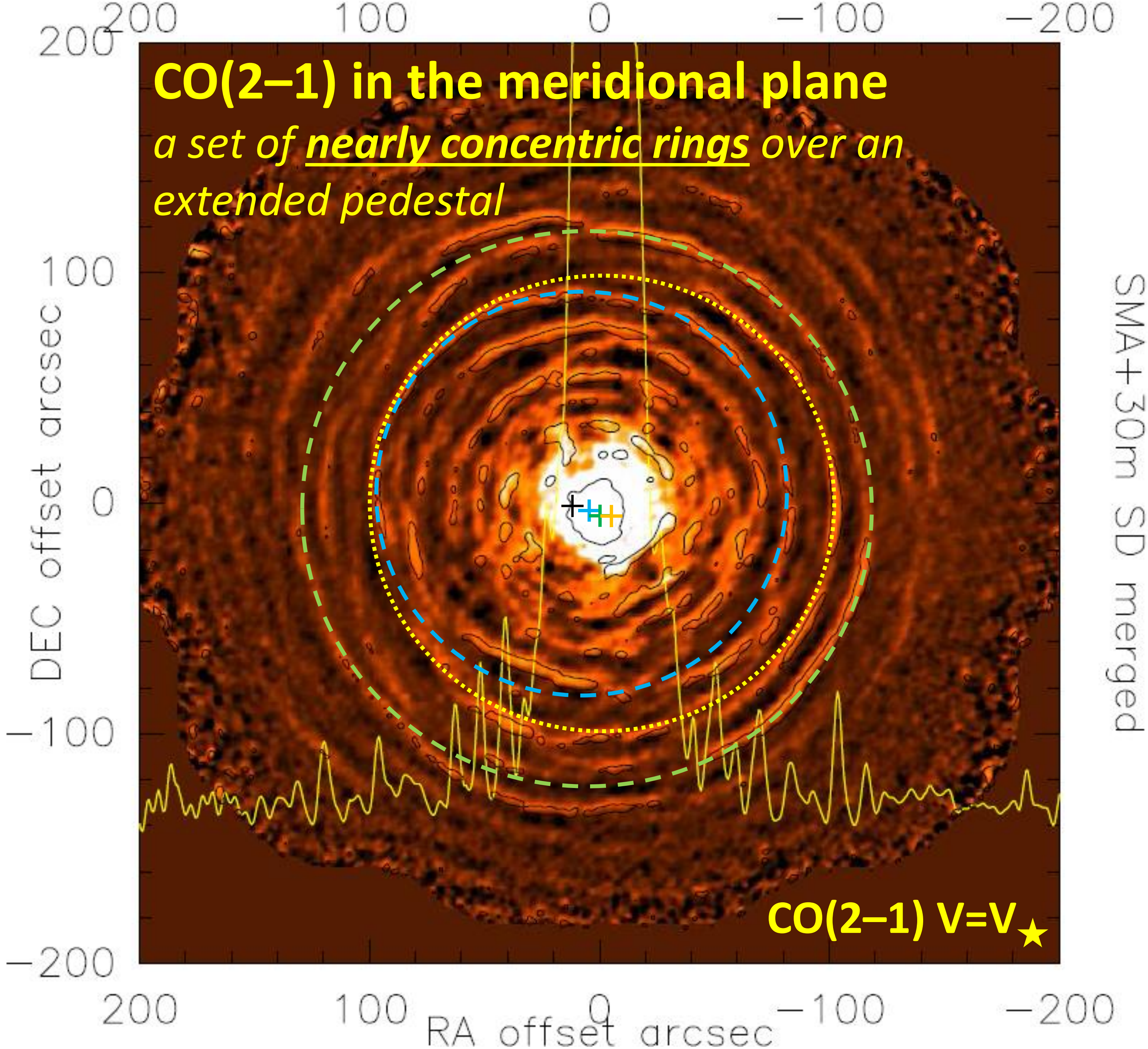
Same image (CO(2–1)) in polar coordinates



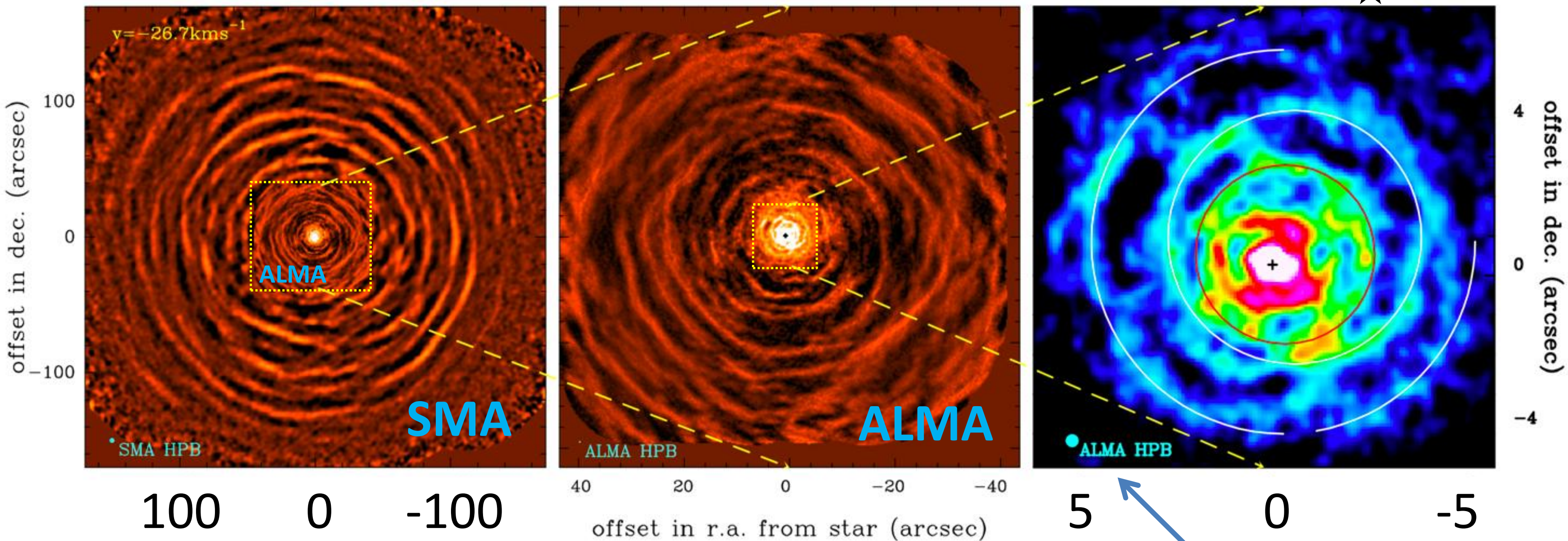
No spirals in IRC+10 216!

Spirals in AFGL 3068

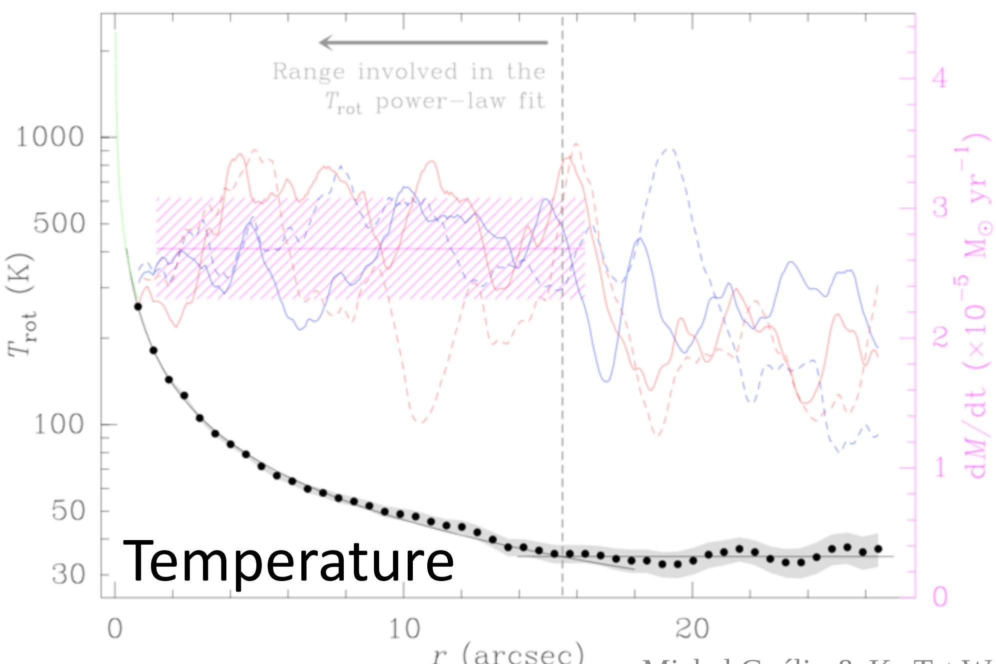



CO(2–1) in the meridional plane
a set of nearly concentric rings over an extended pedestal
CO(2–1) V=V★
SMA+30m SD merged
DEC offset arcsec
RA offset arcsec
200
100
0
−100
−200

ZOOM on the CO(2-1) emission in the meridional plane(V=V$_\bigstar$)



ALMA beam 0.3" (≈16 yr)

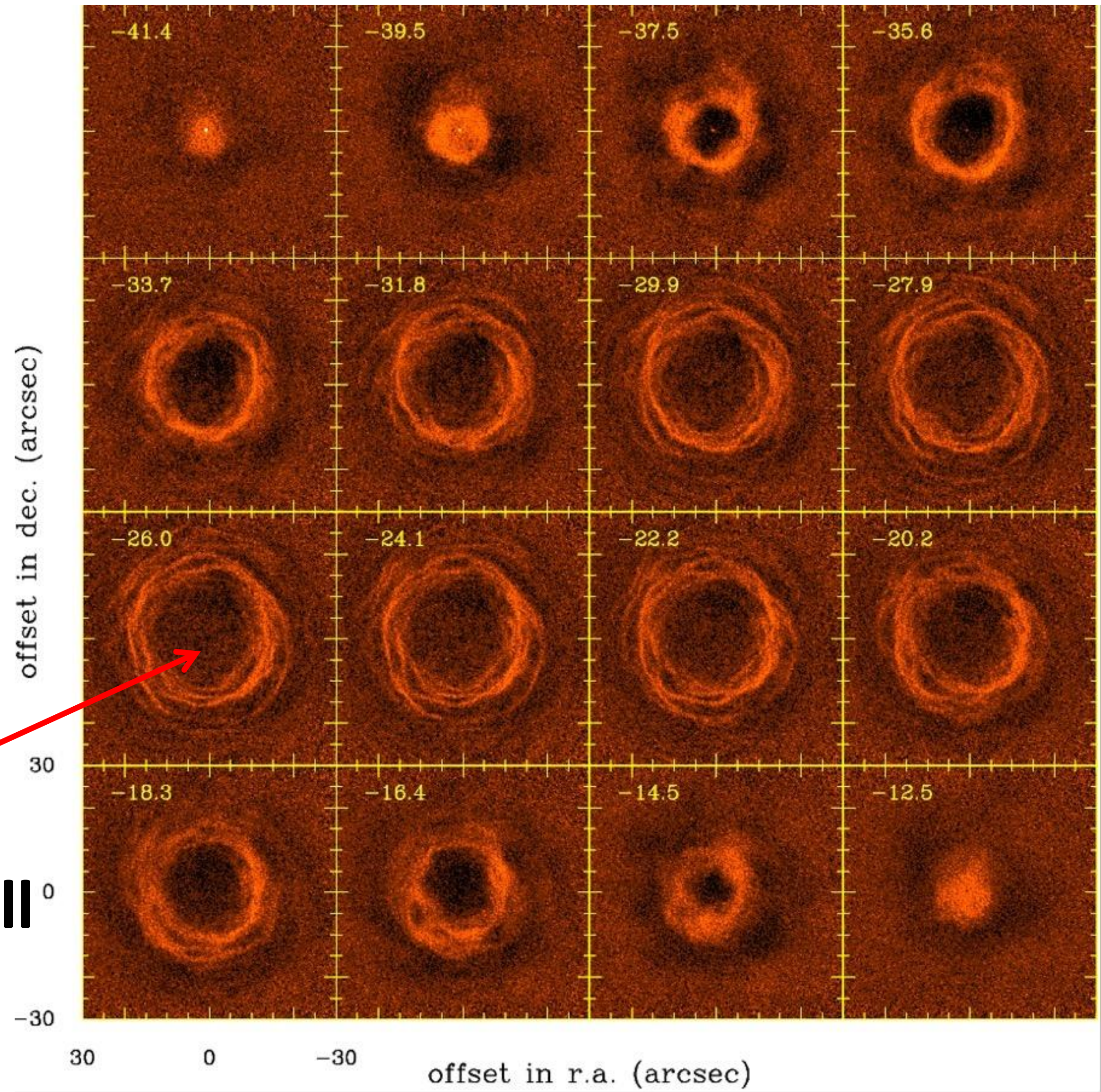


Mass-loss rate

- derived from ^{12}CO and ^{13}CO (2–1) and (1–0) lines
- roughly constant over the last 7000 yr with a 3× periodic modulation

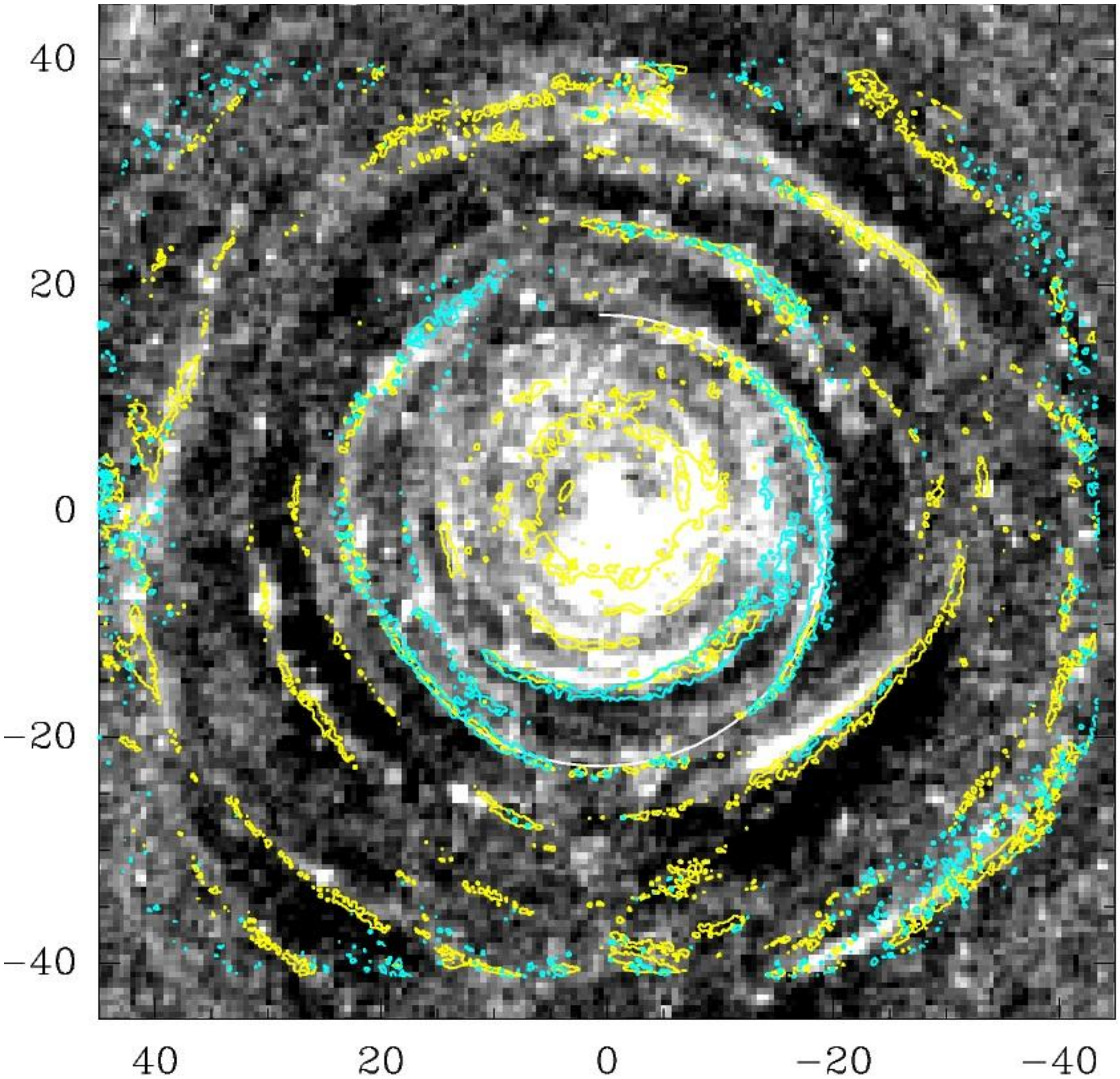
Michel Guélin & Ka Tat Wong, Quy Nhơn 2018

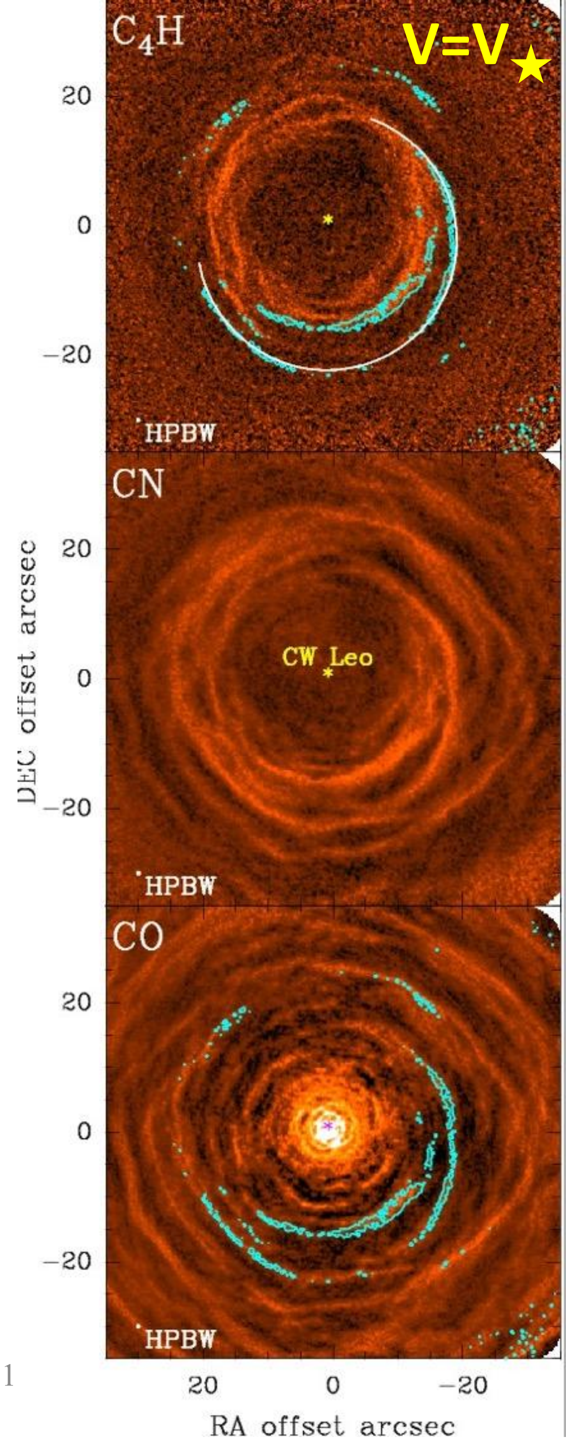
C_4H(24–23) X,Y,V cube: <u>central 1 arcmin</u> at 0.3'' resolution



CN, C_2H, C_4H, C_6H:
an empty spherical shell

CO (yellow) and CN (cyan) emission contours on VLT optical image

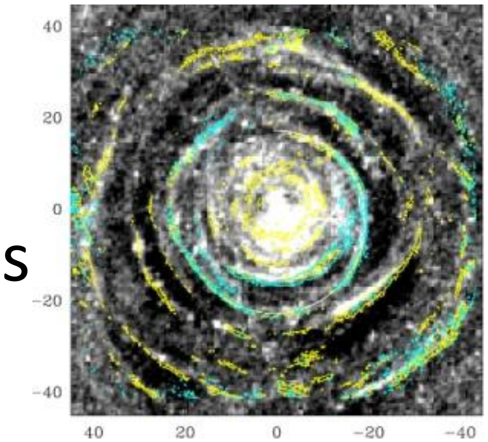




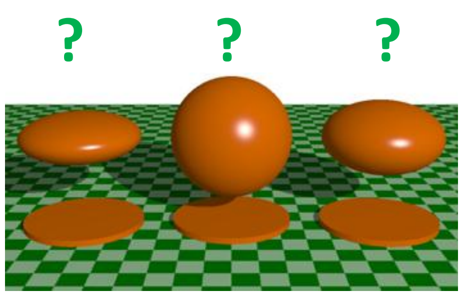
Michel Guélin & Ka Tat Wong, Quy Nhơn 201

CONCLUSIONS from meridional plane images of IRC+10 216

- **Quasi-regular** pattern of CO-bright shells
  - Typical shell spacing in the outer envelope is **~16" or 700 yr**
  - Pattern is **tighter** inside 40"
- Very good spatial correlation between CO, C_4H, CN and dust (optical) ⇒ **density pattern**
- Shell/intershell density contrast of ~3
- Pattern may be explained with mass loss modulation by a **low-mass companion** with an orbit in the plane of the sky.



BUT, IS THE MASS LOSS ISOTROPIC?



From the XYV cube to 3-D XYZ envelope

Two Algorithms were developed for the envelope reconstruction:

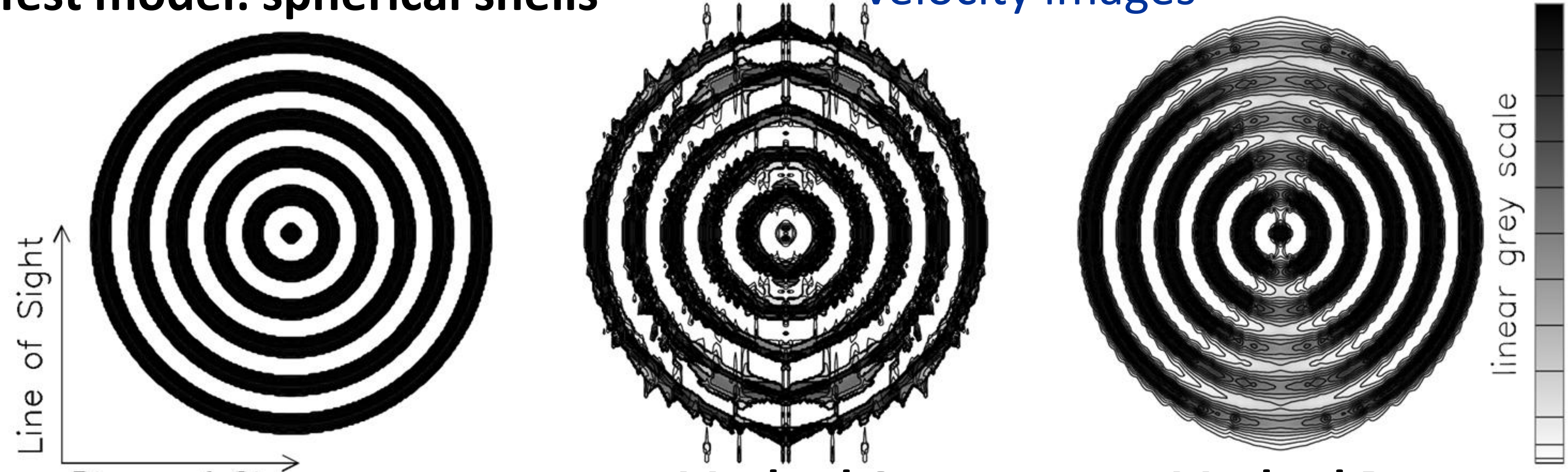
Non-iterative: (A)

Starts from the central ($V_\star$) velocity bin and moves alternatingly to neighboring velocity bins. Tries to match velocity images.

Iterative: (B)

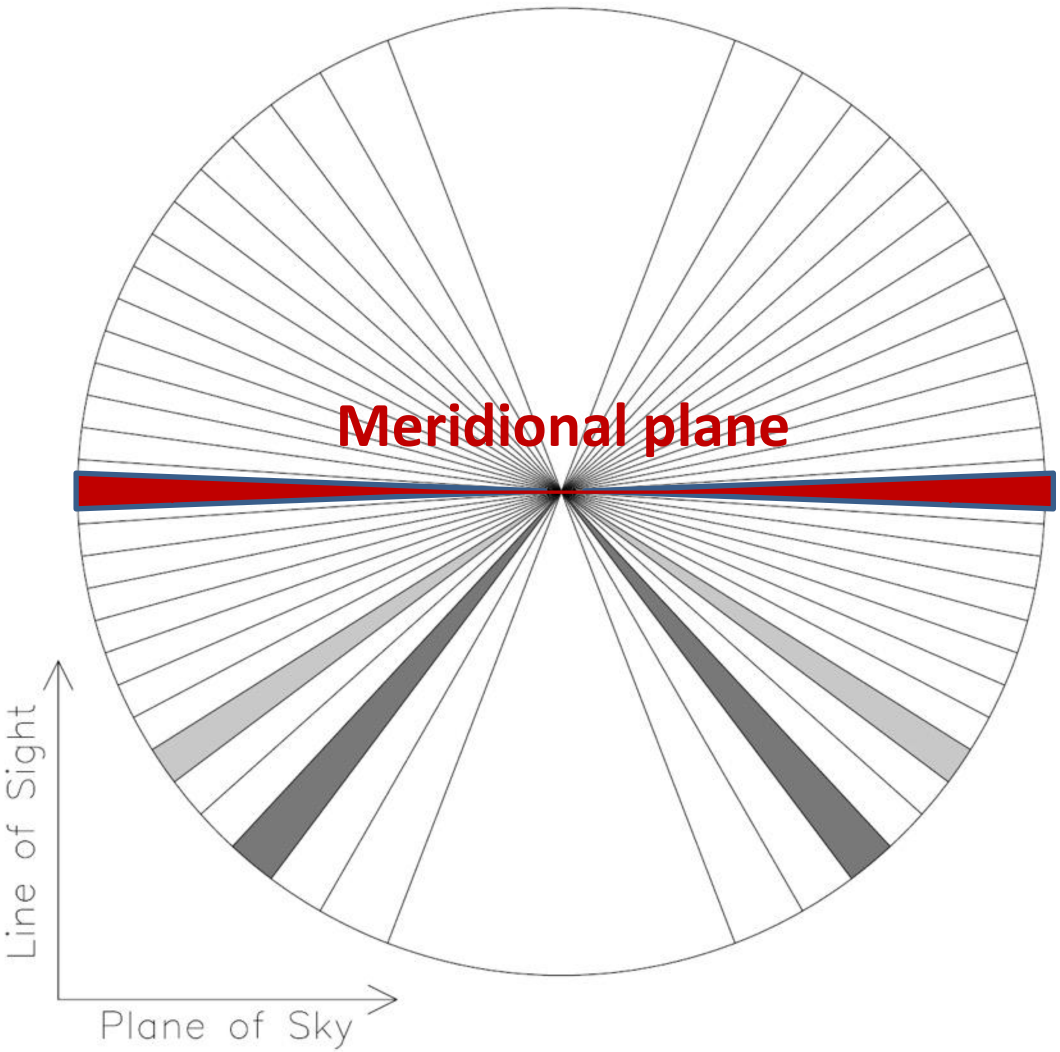
- Converts initial model to spherical coordinates.
- Smooths the spherical grid in polar (θ) direction.
- Converts back into Cartesian and normalises to match velocity images

Test model: spherical shells



Method A **Method B**

Results: the reconstructed envelope in 3-D

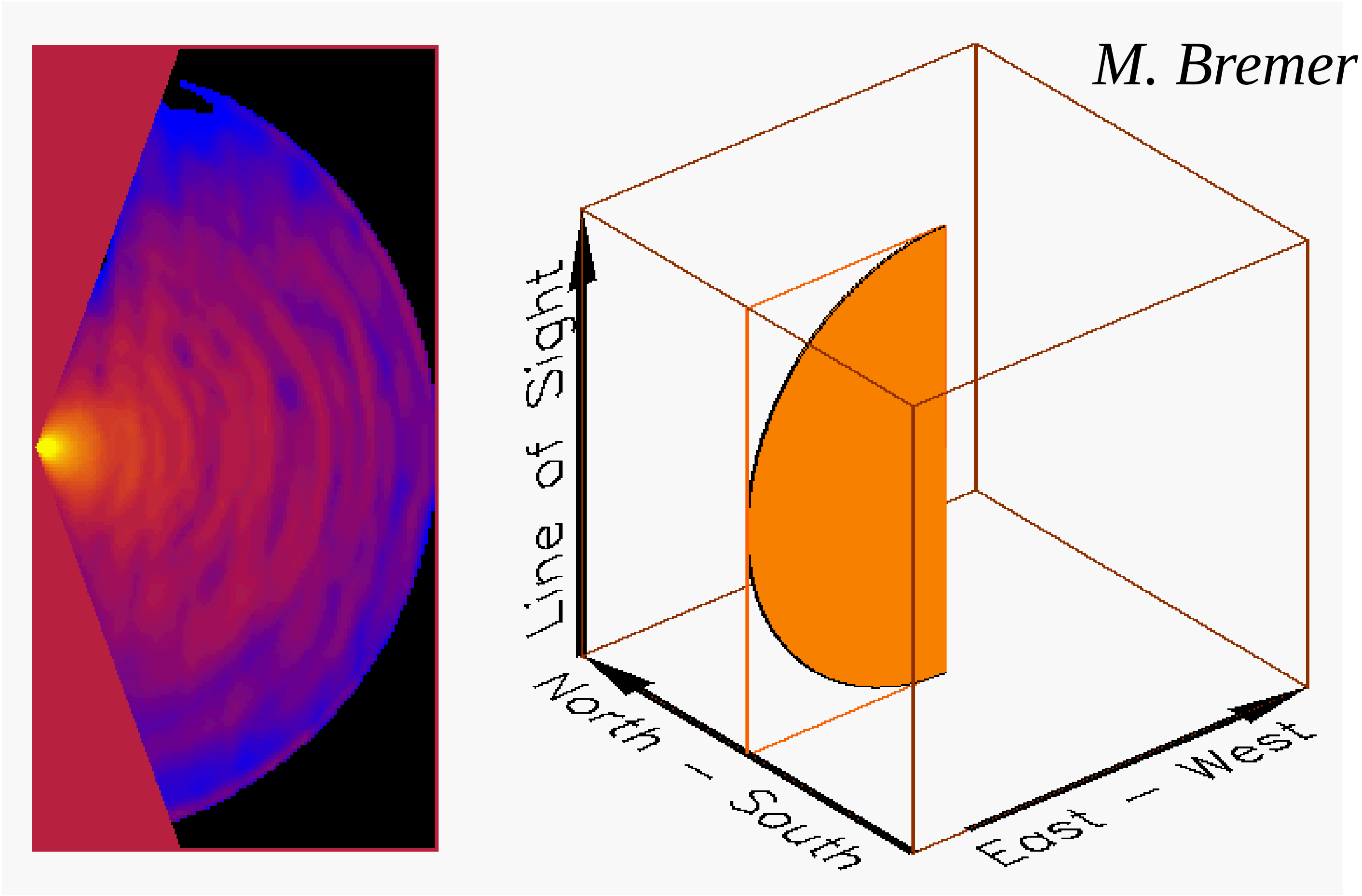


Method A and B yield very similar results!

So far, with the X,Y,V=V★ velocity-channel maps, we have considered the trace of the dense CO-bright shells in ***one single Meridional Plane****.*

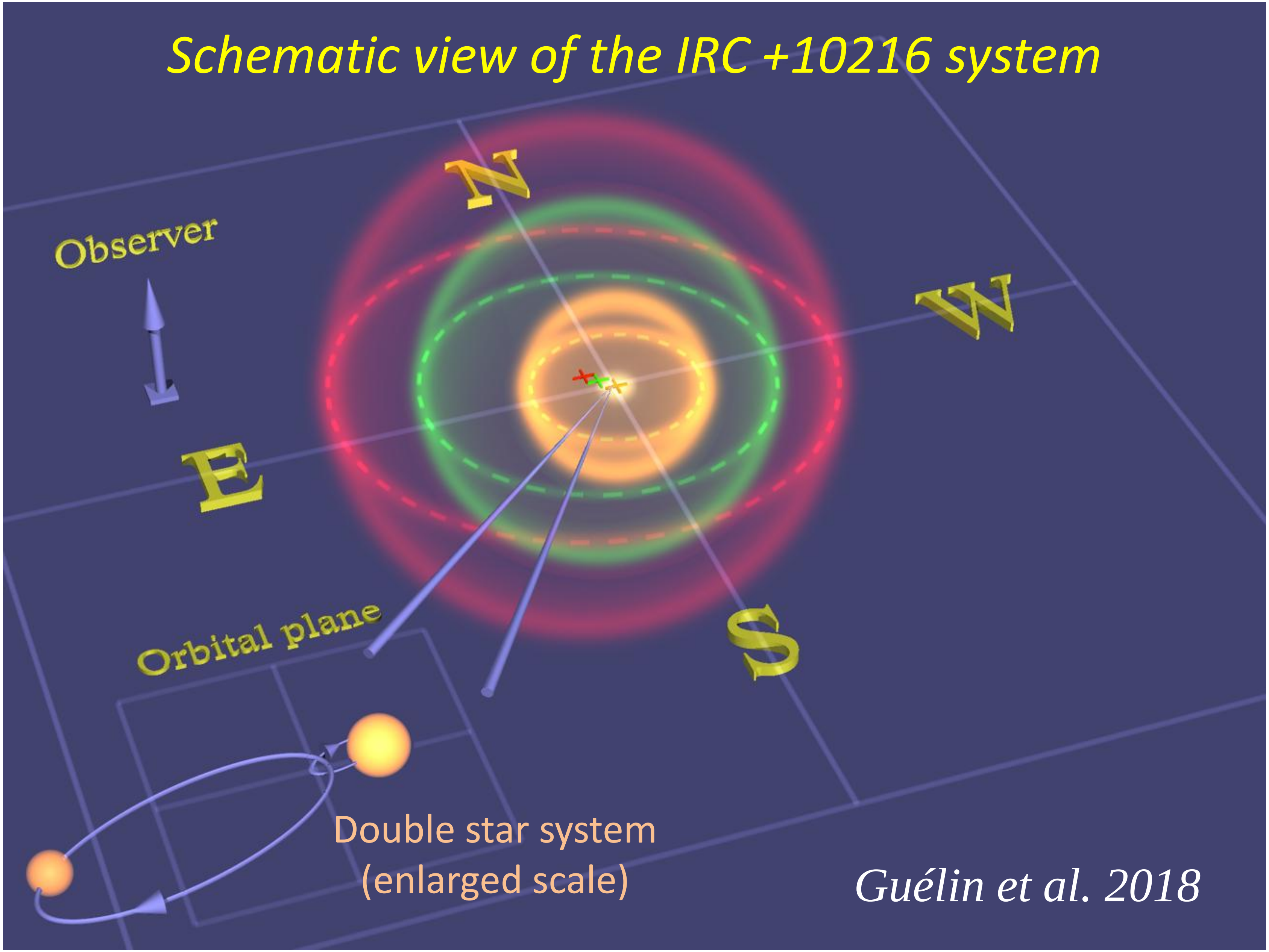
Now, using the reconstructed 3-D XYZ cube, we can follow the shells throughout the ***whole envelope****, e.g. following a set of inclined meridional planes.*

IRC +10 216 in 3-D



Animation of the IRC +10 216 morphology in 3-D through **a set of meridional planes**. The two extreme velocity channels with high opacity have been masked. **The shells have <u>spherical shapes</u> and <u>can be followed over large angular ranges (>3 steradian)</u>.**

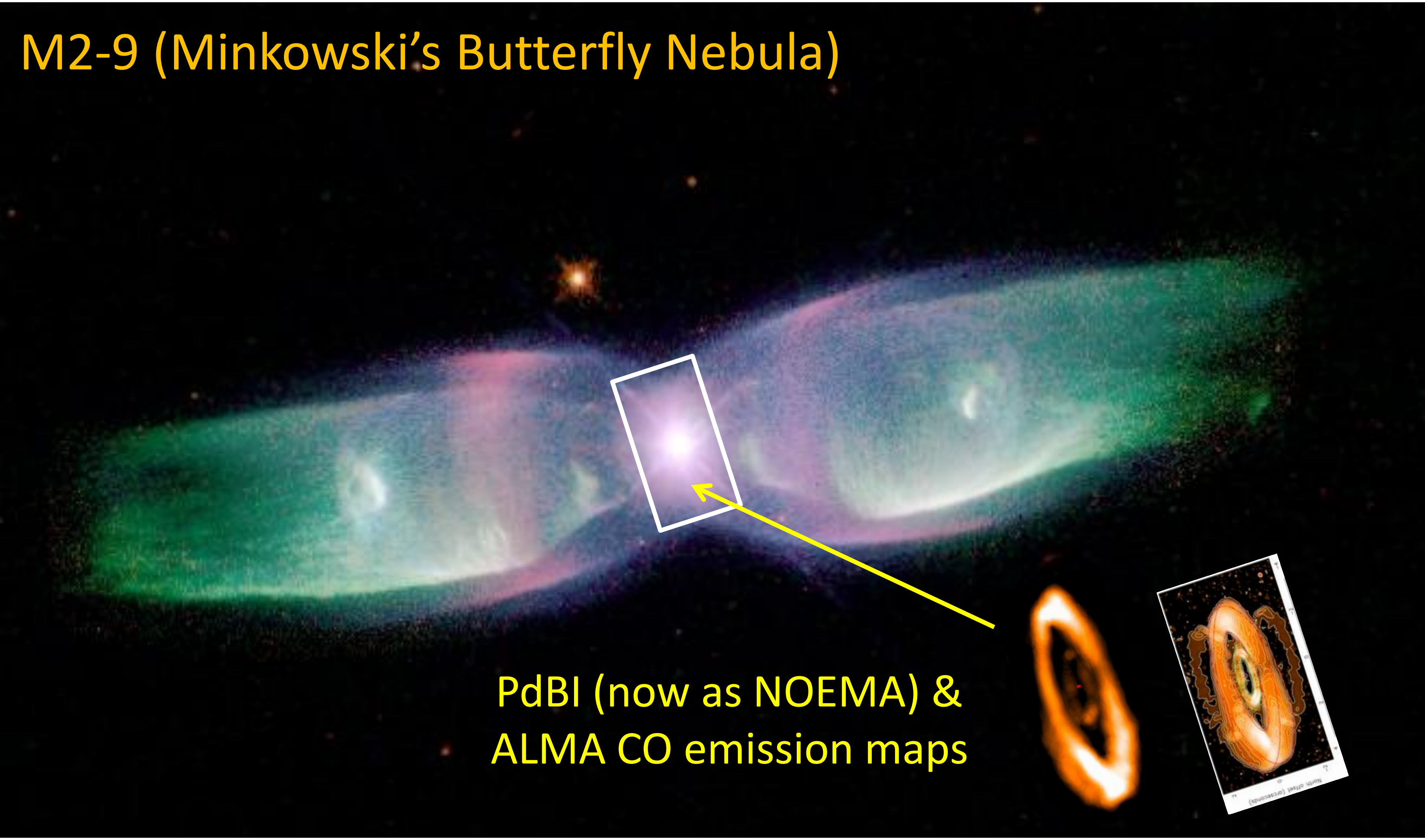
Conclusion: the mass loss is (nearly) isotropic!



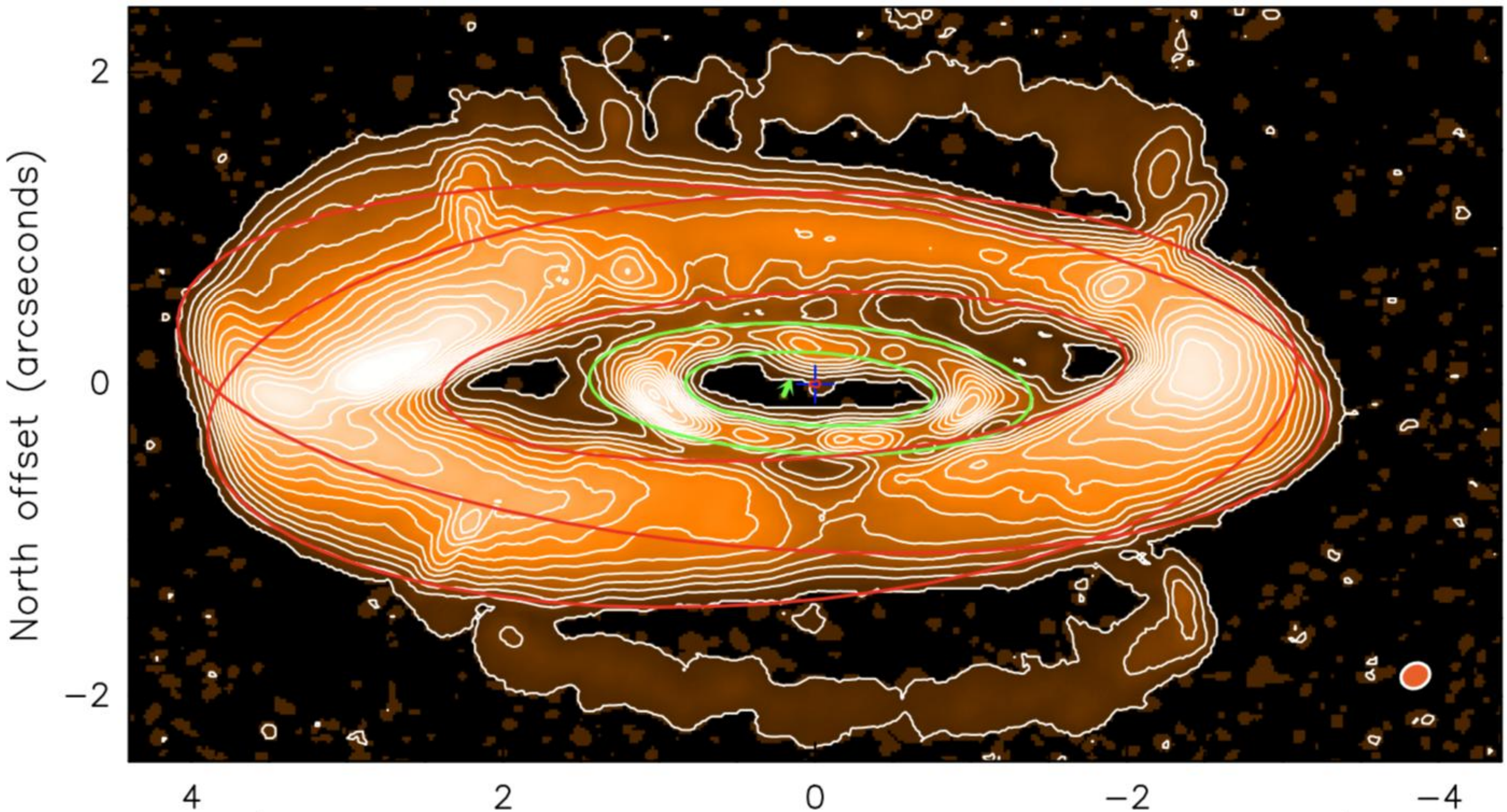
2.2 What do we learn from first interferometric observations?

A. Photospheres: **blobs, plumes & hot spots**: *magnetic pressure*?
B. Envelopes: **3-D morphology may be reconstructed**
   1. **Detached expanding shells**: *sporadic mass loss*
   2. **Filled expanding spheres:** *continuous mass loss*
      a. Spirals (+ detached shells)
      b. Over-dense shells
   3. **Bipolar outflows collimated by disks:** *transition to PPNs*
C. Frequent presence of **binary stars**
D. **Time dependence** of **chemistry**

(B.5) A more evolved case: bipolar winds collimated by a dense molecular disk



M2-9 in CO observed with NOEMA & ALMA



Castro-Carrizo et al. 2017

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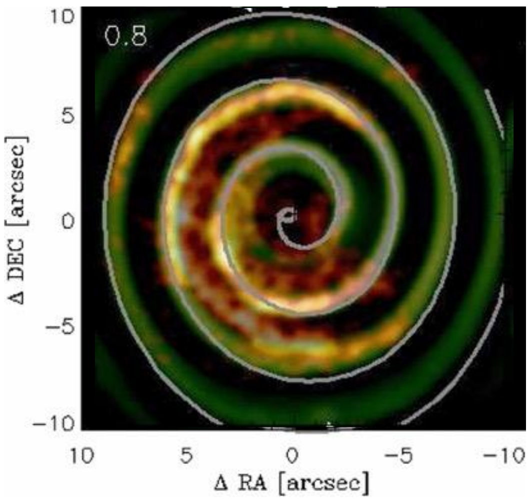
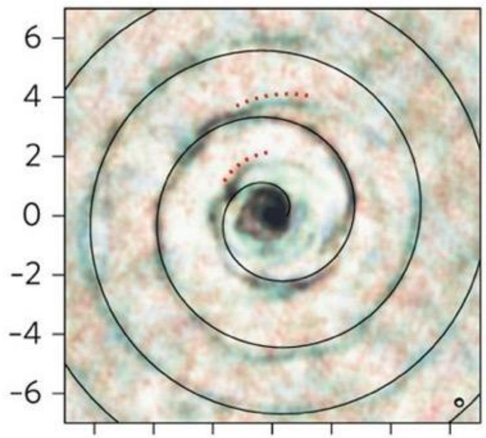
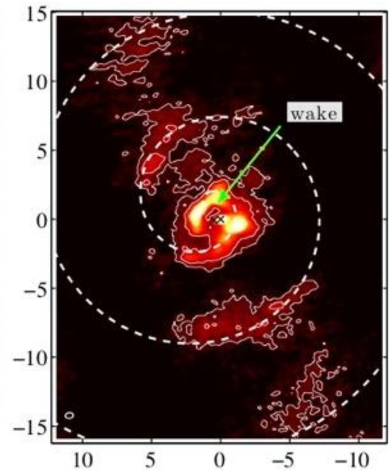
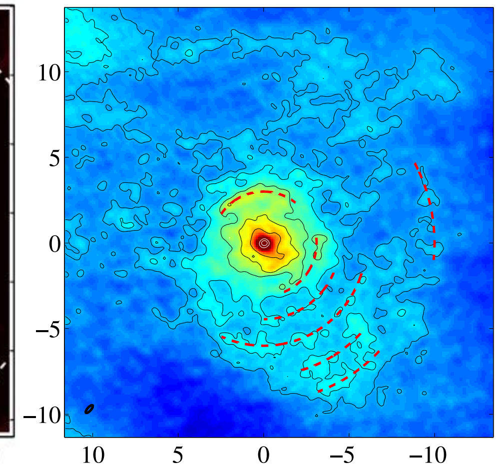
Binary effects on different AGB stars

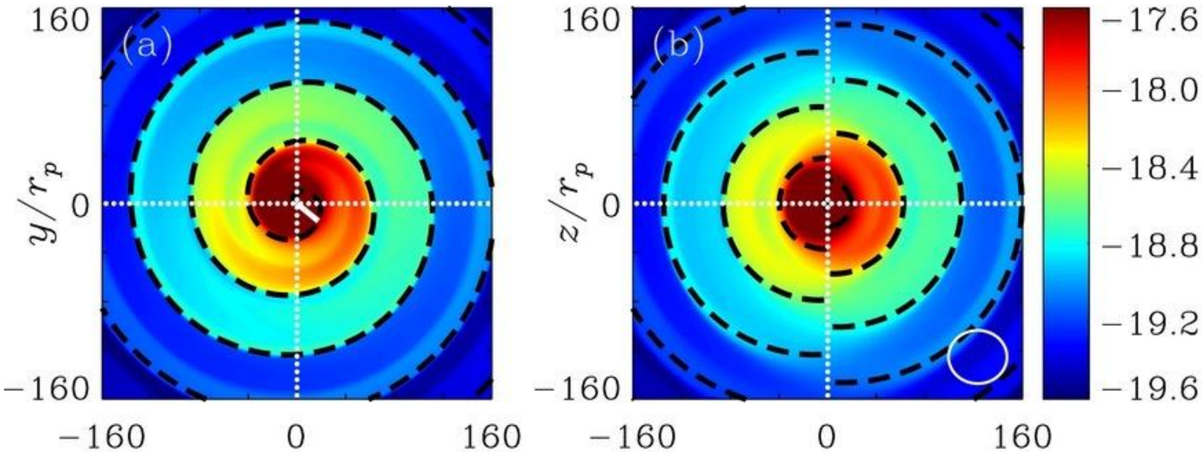
CIT 6	AFGL 3068	Mira	W Aquilae
			
VLA	***ALMA***	***ALMA***	***ALMA***
$HC_3N(4–3)$	^{12}CO, ^{13}CO, HC_3N	$^{12}CO(3–2)$	$^{12}CO(3–2)$

Kim et al. 2013   *Kim et al. 2017*   *Ramstedt et al. 2014; 2017*

Binary effects on different AGB stars

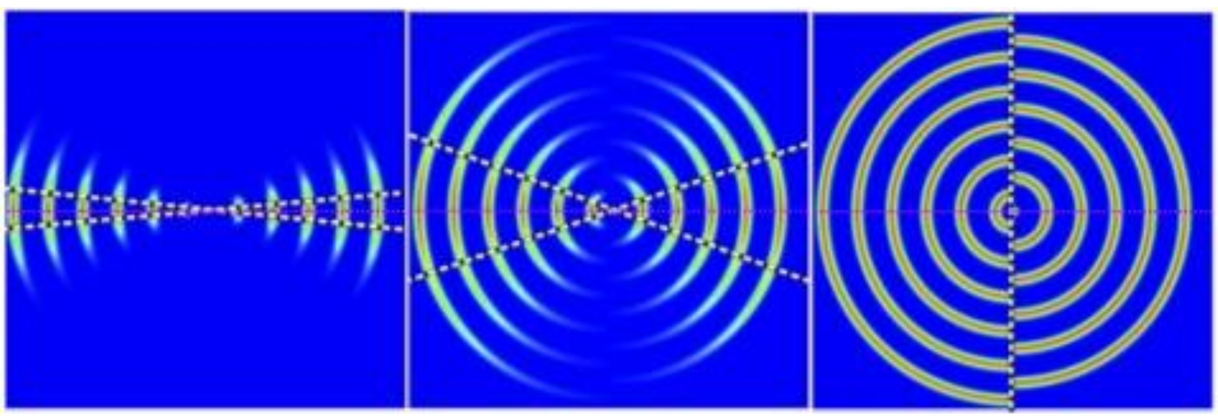
Mastrodemos & Morris 1999

Kim & Taam 2012a, b, c



Mohamed & Podsiadlowski 2012

Homan et al. 2015



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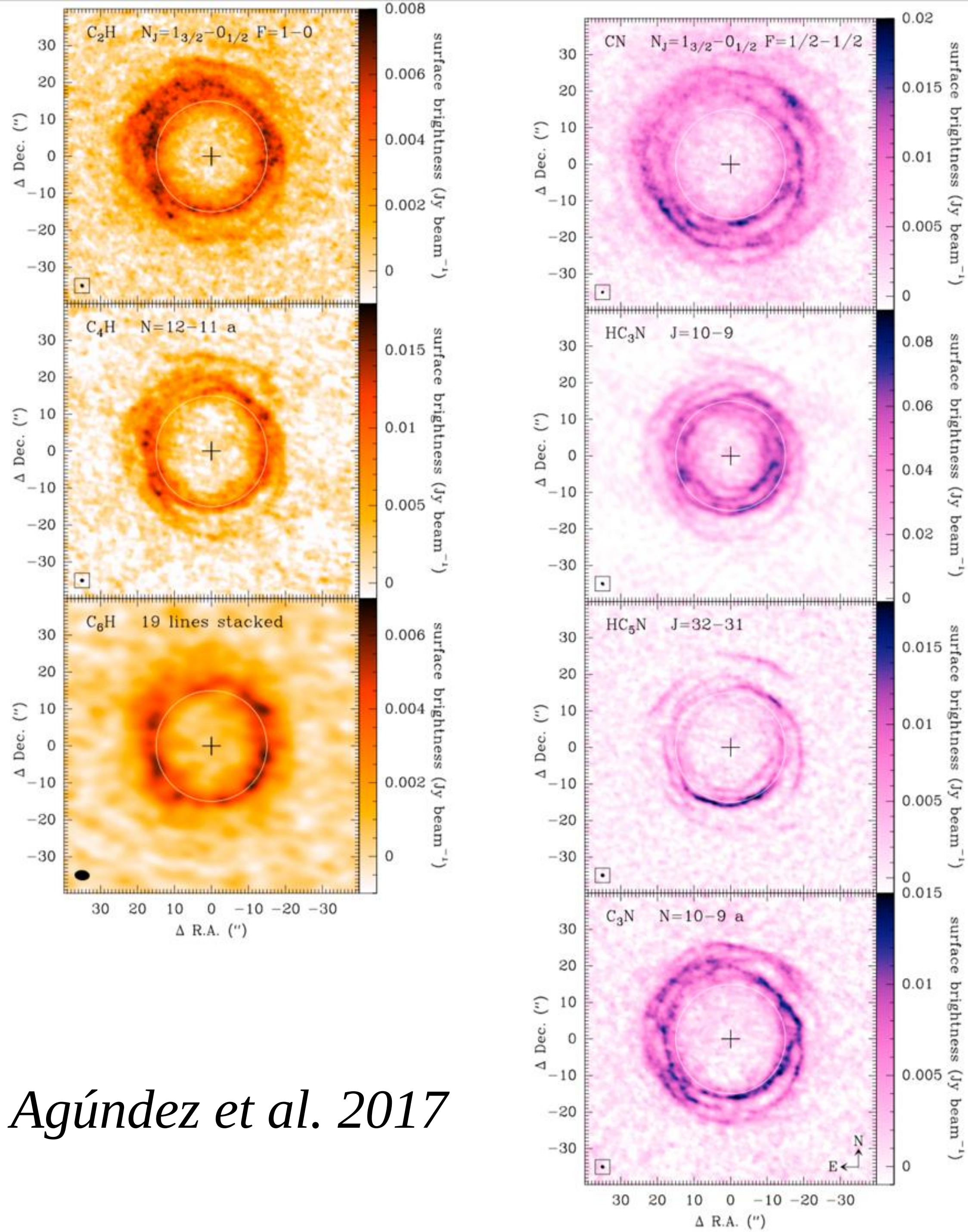
Growth of carbon chain species C_2H, C_4H, C_6H, CN, HC_3N, HC_5N, and C_3N

→ *see M. Agúndez' talk*



Agúndez et al. 2017

MOLECULES DETECTED IN AGB STARS

2-atoms:	AlCl	CN	KCl	SiC
	AlF	CP	NaCl	SiN
	AlO	CS	OH	SiO
	C_2	ClH	PN	SiS
	CO	FH	PO	SO
3-atoms:	AlNC	CO_2	HNC	SiC_2
	C_3	FeCN	KCN	SiCN
	C_2H	HCN	MgCN	SiCSi
	C_2N	HCP	MgNC	SiNC
	C_2P	H_2O	NaCN	SO_2
	C_2S	H_2S		
4-atoms:	c-C_3H	C_3S	H_2CS	NH_3
	ℓ-C_3H	C_2H_2	HMgNC	PH_3
	C_3N	HC_2N	MgC_2H (?)	SiC_3
	C_3O	H_2CO	NC_2P (?)	
5-atoms:	C_5	c-C_3H_2	CH_2NH	H_2C_3
	C_4H	CH_2CN	HC_3N	HNC_3
	C_4Si	CH_4	HC_2NC	SiH_4
6-atoms:	C_5H	C_5S	CH_3CN	H_2C_4
	C_5N	C_2H_4	HC_4N	SiH_3CN (?)
≥7-atoms:	C_6H	CH_2CHCN	HC_7N	
	C_7H	CH_3CCH	HC_9N	
	C_8H	HC_5N	H_2C_6	
Ions:	C_4H^-	C_6H^-	C_8H^-	HCO^+
	CN^-	C_3N^-	C_5N^-	

Only in O-rich stars

Conclusion and future prospects

- **New/upgraded interferometers**, operating in the **near-/mid-IR, (sub-)millimetre, and radio** domains, yield clues to the **mass-loss process** in AGB stars and the **morphology** and **chemical content** of their envelopes.
- Observations of a dozen of dusty envelopes show a variety of morphologies that can be related to:
  - the mechanisms expelling gas from the upper stellar atmosphere
  - the mass-loss history (sporadic or continuous)
  - its modulation by a companion star
- **High angular-/spectral-resolution observations** of more stars are needed to assess the effectiveness of those mechanisms.
- Positions of various molecules in the envelope allow us to test **time-dependent chemistry**.

Thank you!