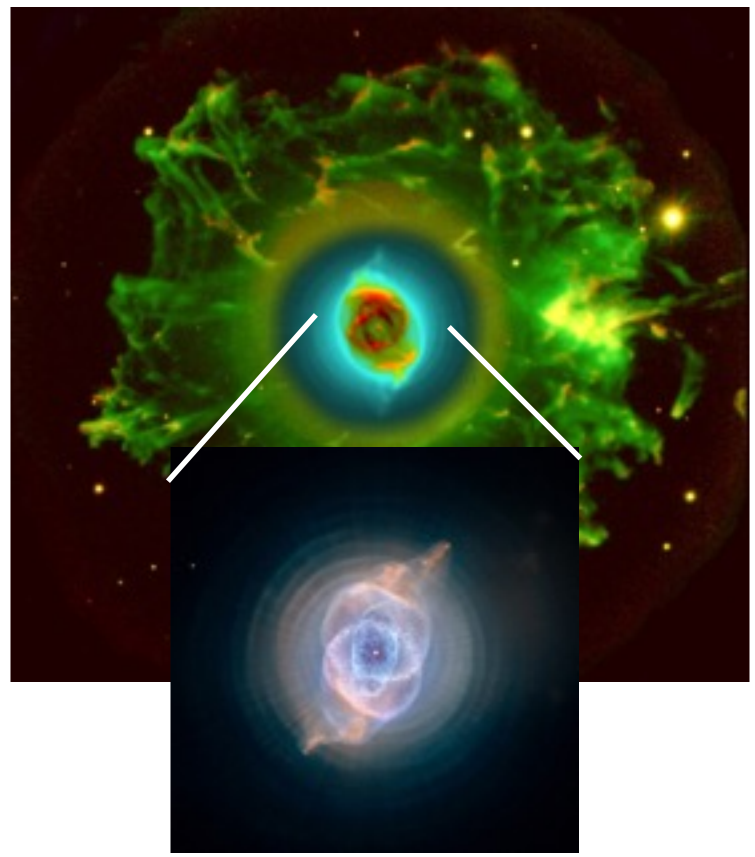
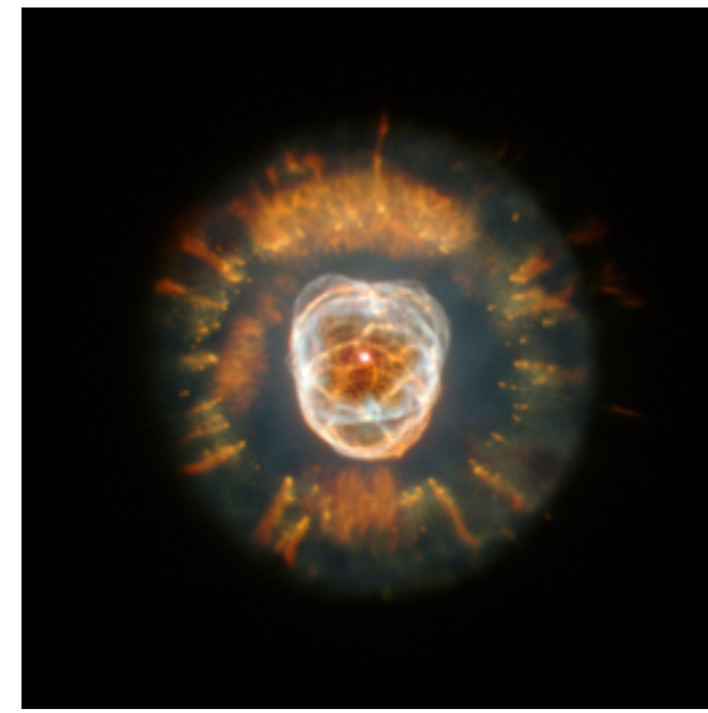
An ALMA view of the (post-common-envelope-evolution) post-AGB object HD101584

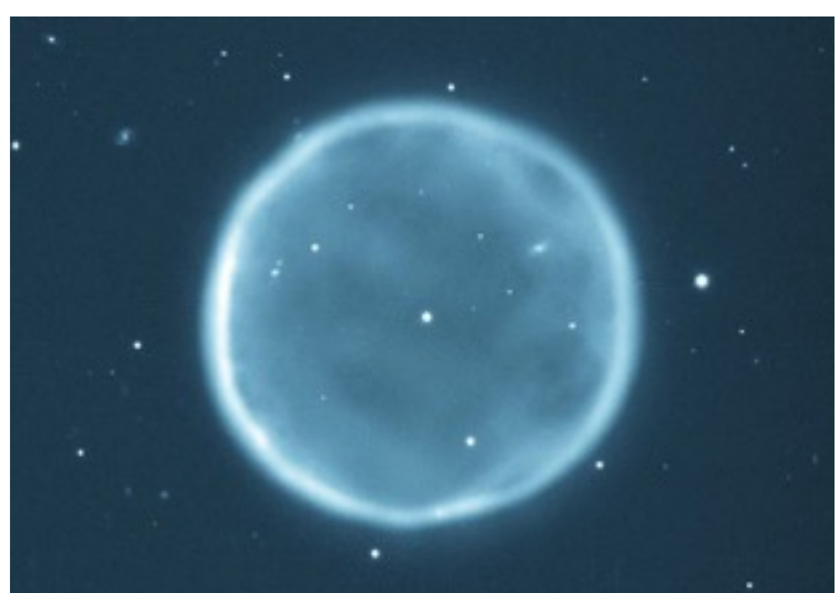
Hans Olofsson
Dept. of Earth and Space Sciences, Chalmers

Co-Is: Lars Nyman, Elizabeth Humphreys, Michael Lindqvist, Matthias Maercker, Sofia Ramstedt, Wouter Vlemmings

“The extra-ordinary deaths of ordinary stars”: The remarkable morphological transformation from spherical AGB stars, and largely spherical circumstellar envelopes, to the complex geometries of most PNe.

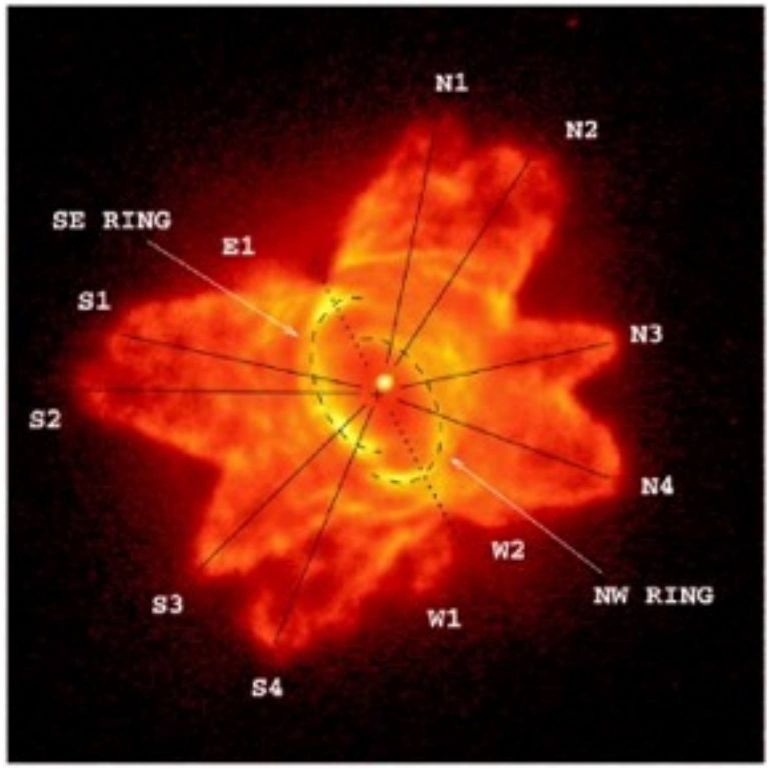






Non-sphericity particularly prominent among the young PNe.

The most commonly accepted interpretation is the effects induced by a (nearby) companion (star or planet).



Photometry & Spectrometry of HD101584

Photometry:

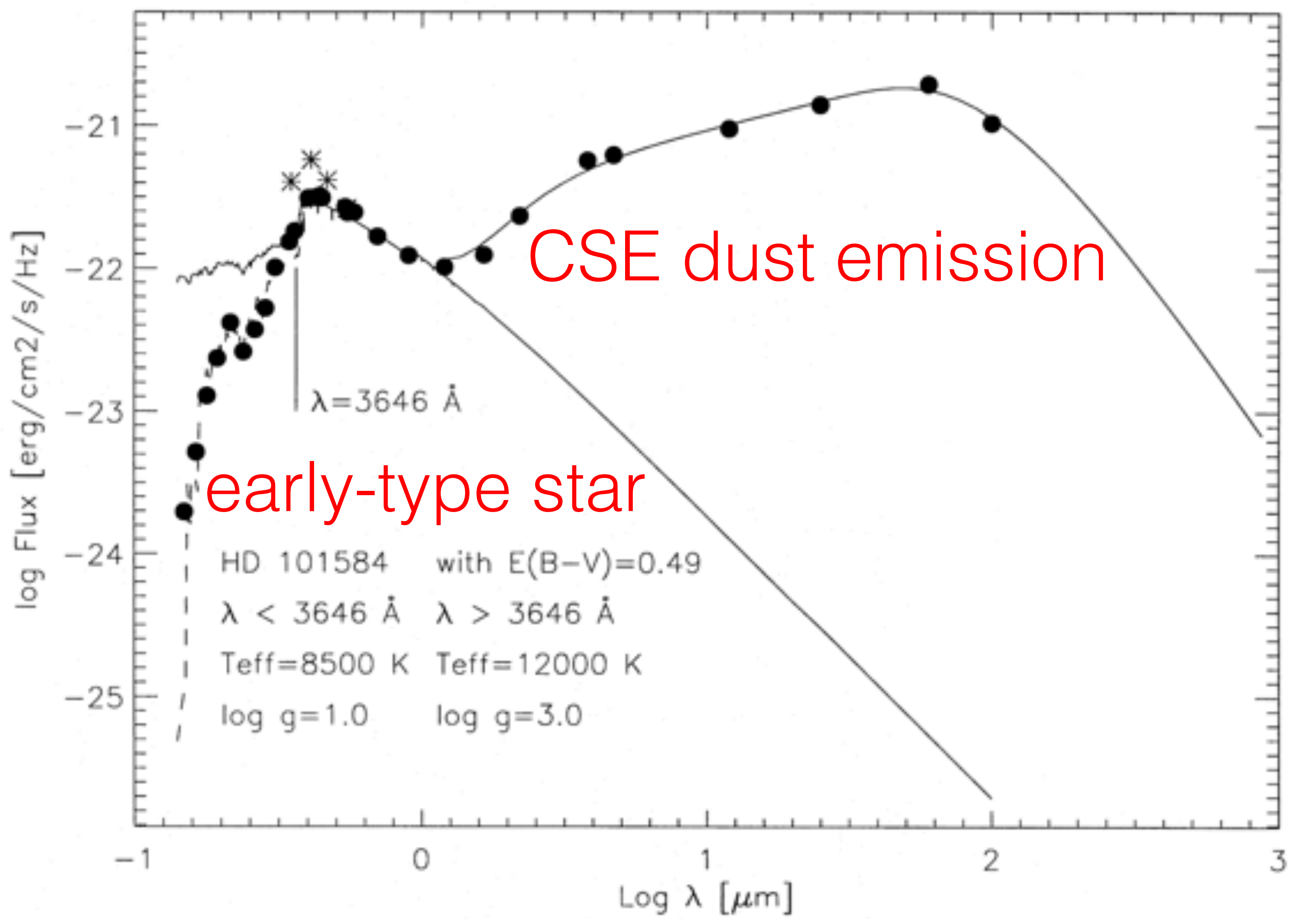


Fig. 7. A B9II (solid line) and a A5I (dashed line, only for $\lambda \leq 3646$ Å) Kurucz models are fitted to the dereddened energy distribution ($E(B-V) = 0.49$) of HD 101584. Due to the many wind lines in the blue and UV part of the spectrum, we observe an iron curtain in front of the B-star and the UV SED mimics an A to F-type star blue-wards of the Balmer jump ($\lambda = 3646$ Å)

Spectroscopy: A wealth of lines of different excitation and with different line profiles.

from Bakker et al. (1996)

From optical data

- A 7:th magnitude A6Ia central star (Sivarani et al. 1999, Kipper 2005).
- Most likely a post-AGB object (Bakker et al. 1996).
- Mass is estimated to be $\approx 0.6\ M_\odot$.
- A binary; period 140 days (Diaz et al. 2007) to 220 days (Bakker et al.1996).
- The system has most likely gone through an evolution (possibly common envelope) where the companion spiralled in towards the primary, yet survived.

Optical HST images

The optical appearance is not spectacular!

F435W F606W F435W-F606W colour

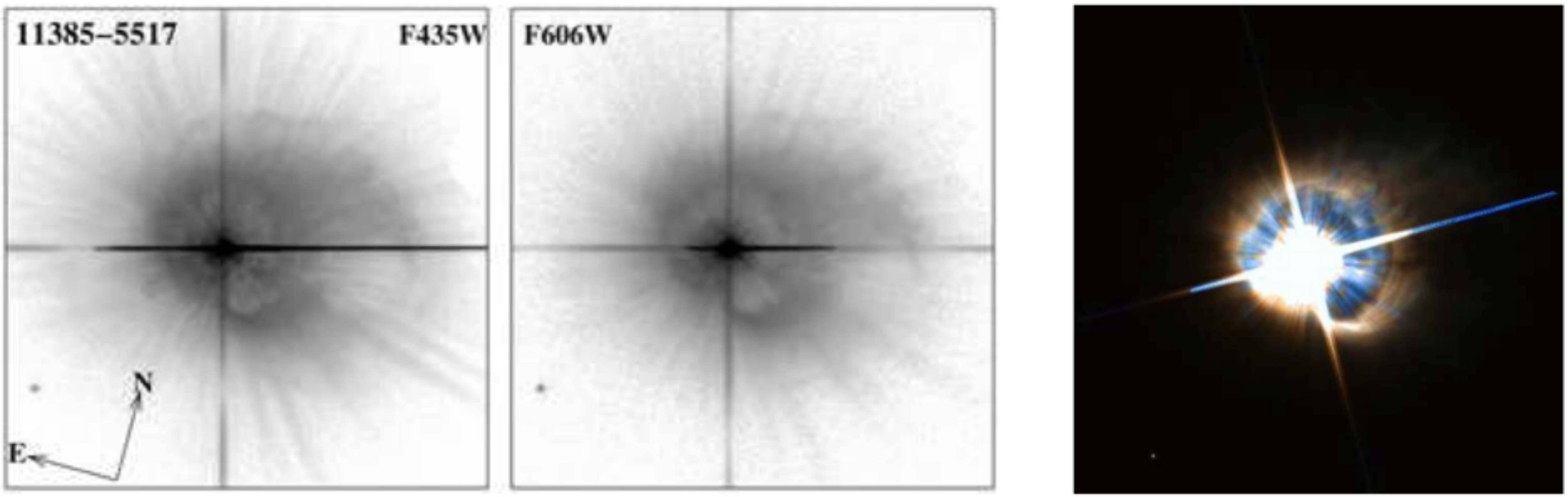
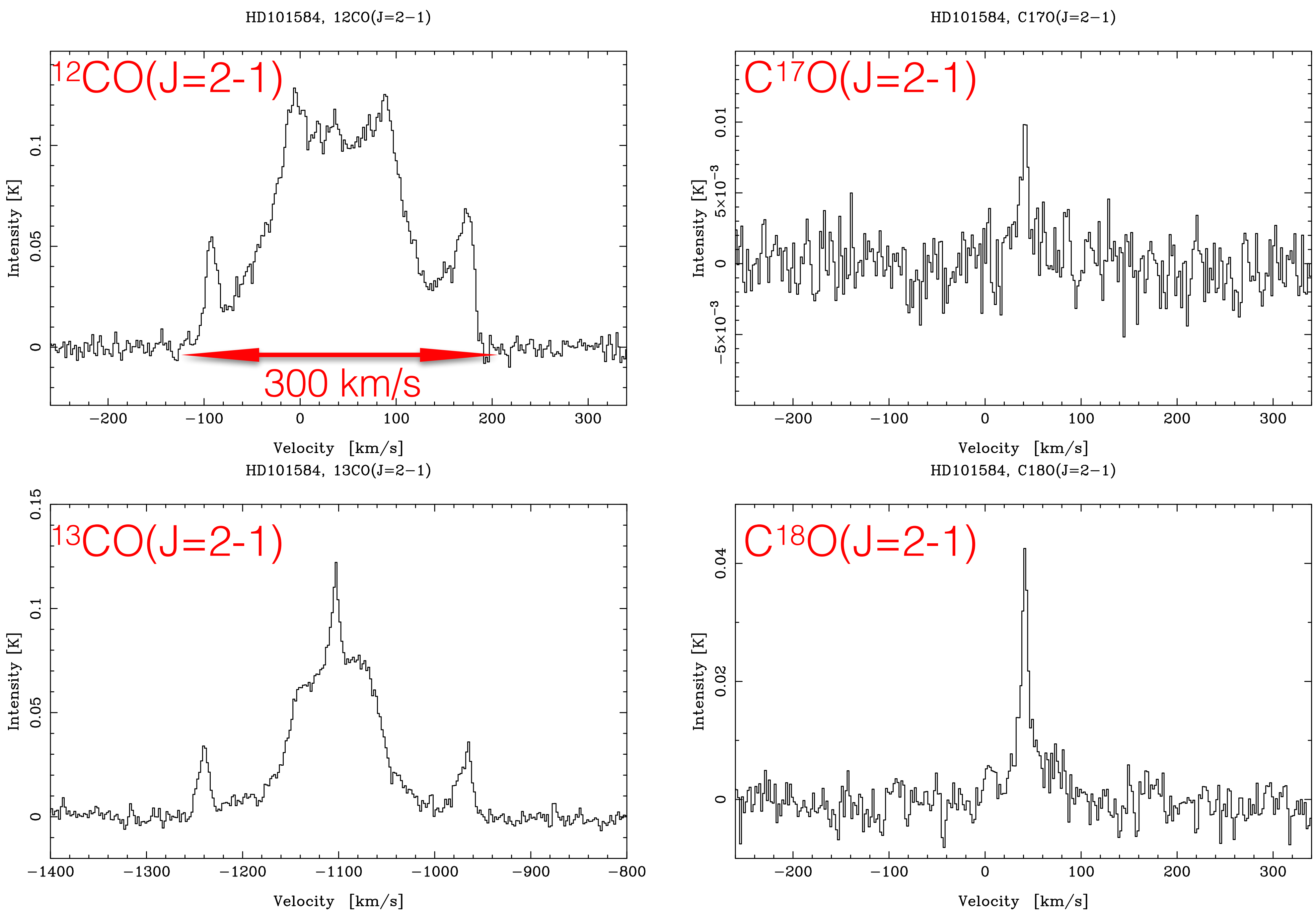


Figure 1: **Left:** HST images (logarithmic intensity scale) of HD 101584 in blue (F435W) and red (F606W) filters (12.5" × 12.5"). **Right:** Colour image formed from the F435W and F606W images; east to the left, north is up).

from Sahai et al. (2007)

CO single-dish spectra

The radio appearance is much more promising!



A spectacular line profile that varies significantly between the CO isotopologues.

See Olofsson & Nyman A&A 347, 194 (1999)

ALMA observations

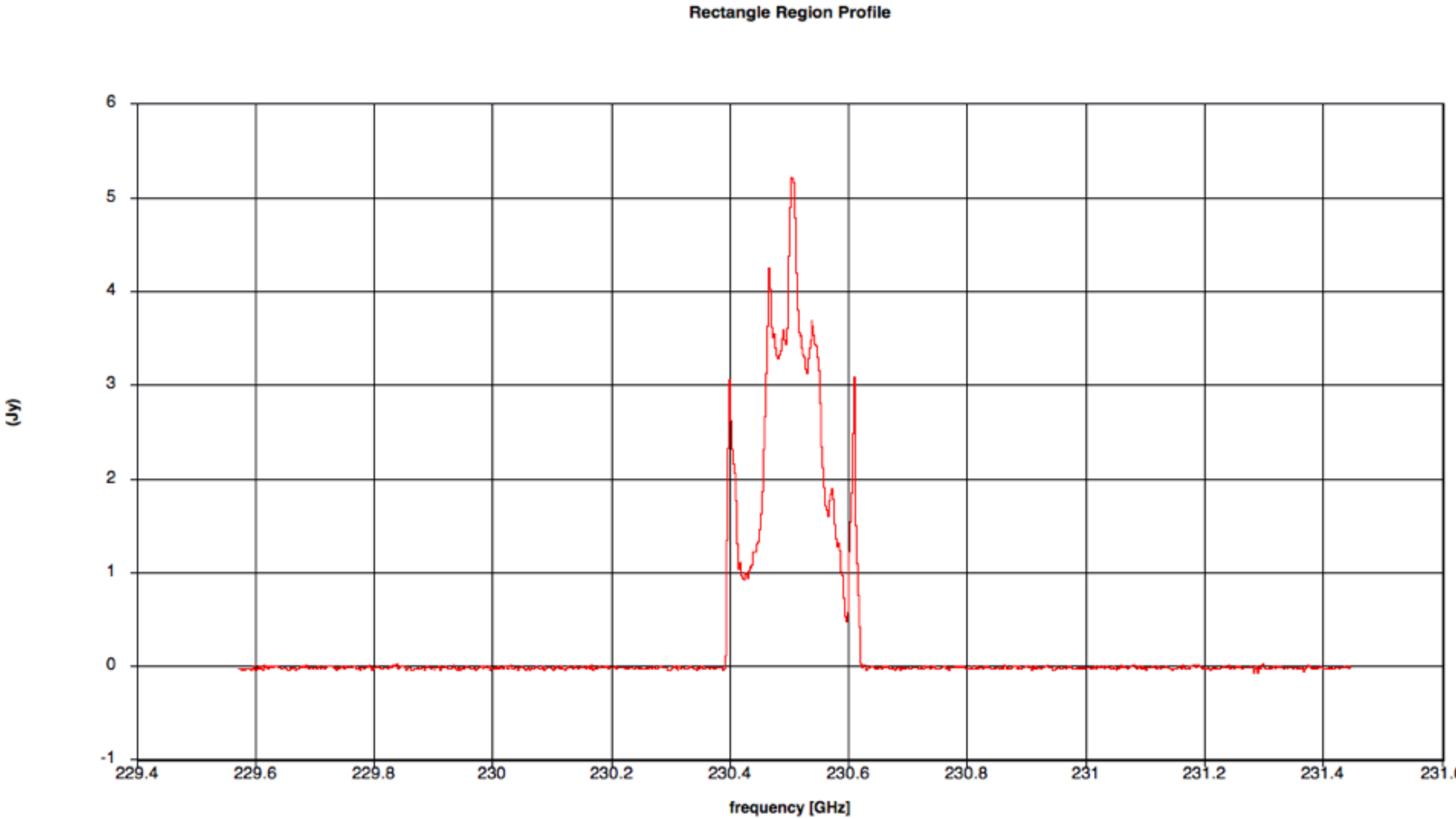
- Cycle 1, ≈30 telescopes
  Cycle 3, ≈40 telescopes

- Two settings covering:
  $^{12}CO(2\text{-}1)$
  $^{13}CO(2\text{-}1)$ & $C^{18}O(2\text{-}1)$ (not in Cycle 3)

- "Lots" of other molecular lines detected
  SiO, SO, SO_2, H_2S, CS, OCS, H_2CO,
  and isotopologues.

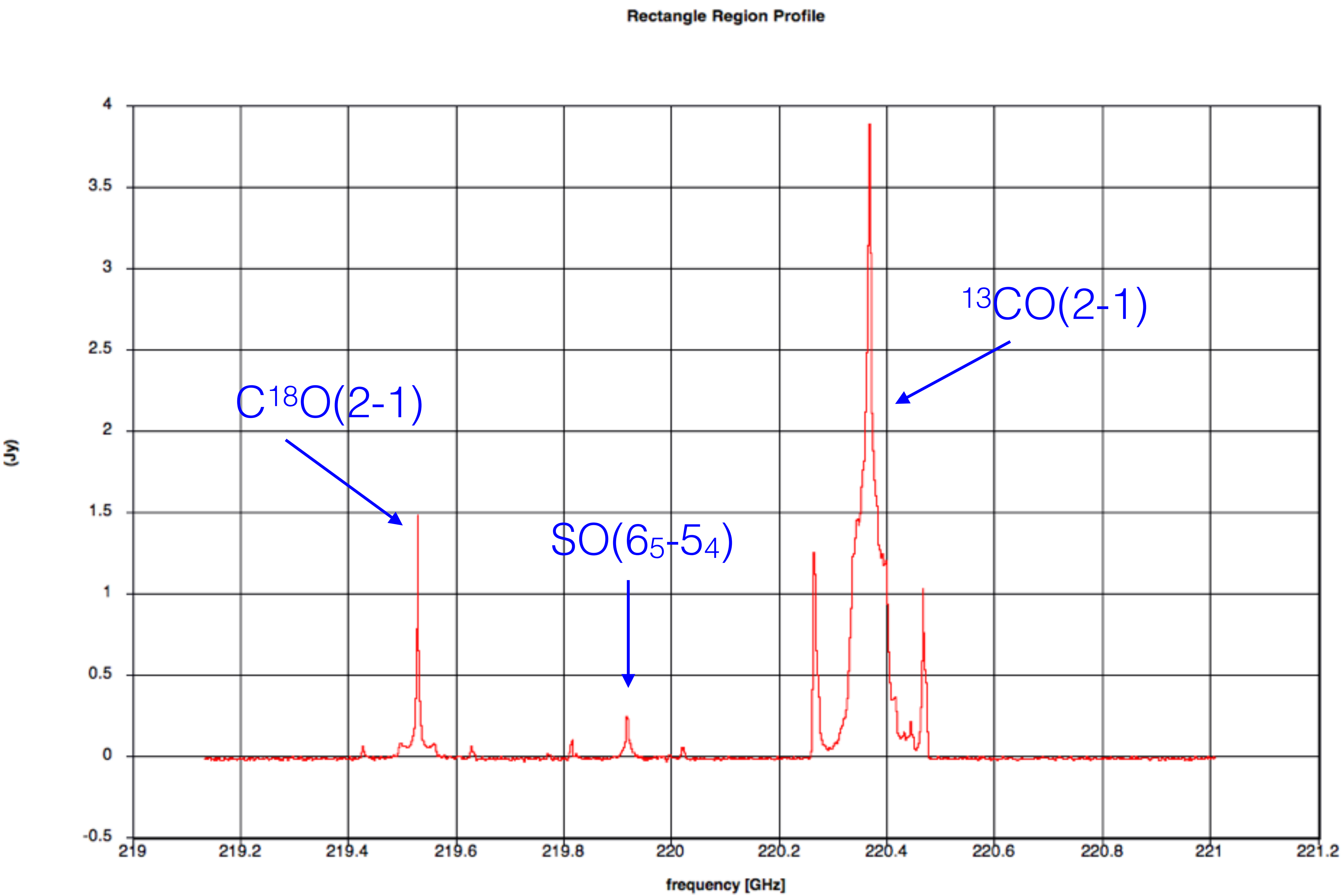
- Beam ≈0.5" (Cycle 1), ≈0.3" (Cycle 3, just observed), and ≈0.05" (Cycle 3).

Global $^{12}CO(2-1)$ line profile, Cycle 1



Comparison with SEST data suggests that *only little flux* is lost by ALMA.

Global line profiles, Cycle 1



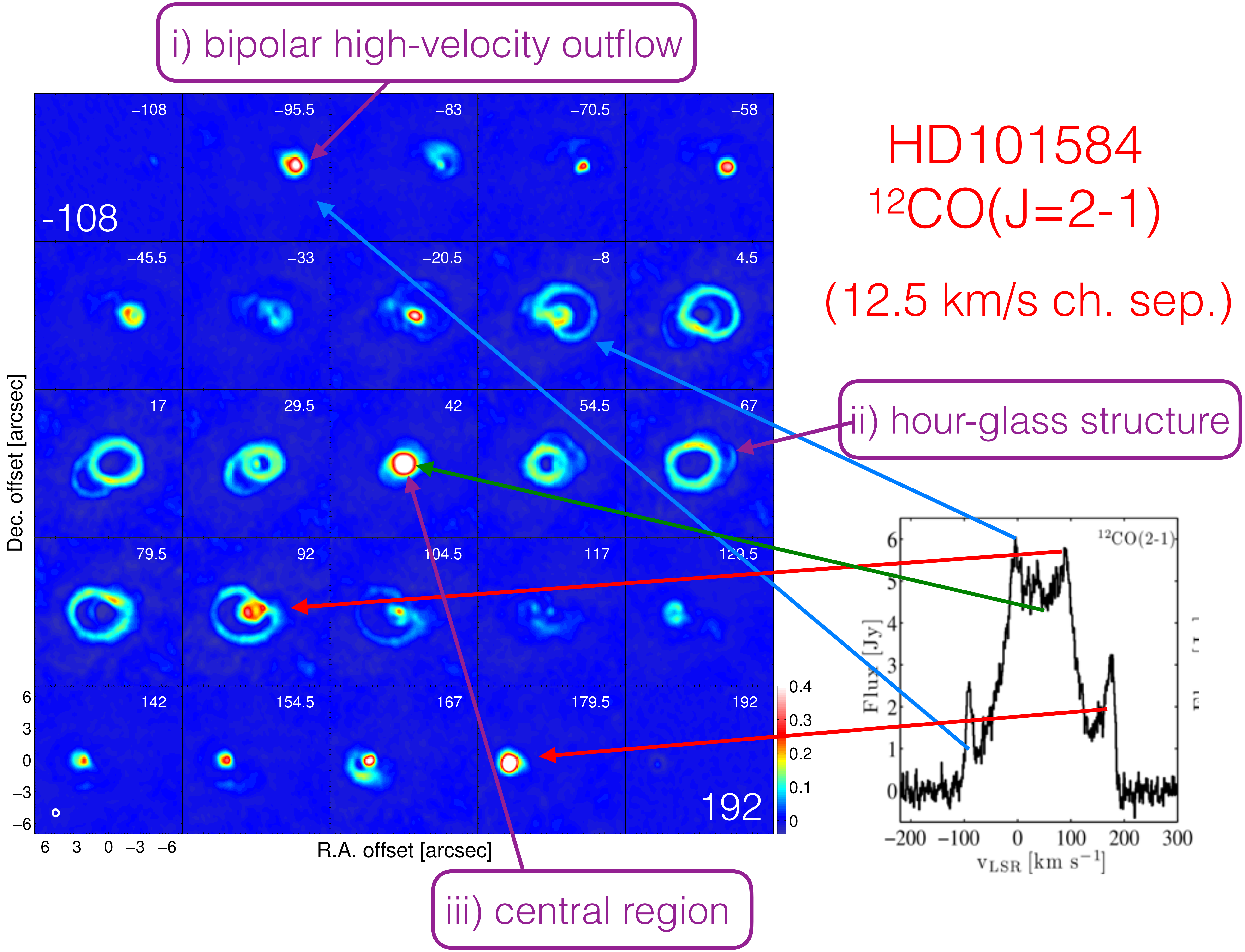
Three kinematical components

We can easily identify three kinematical components:

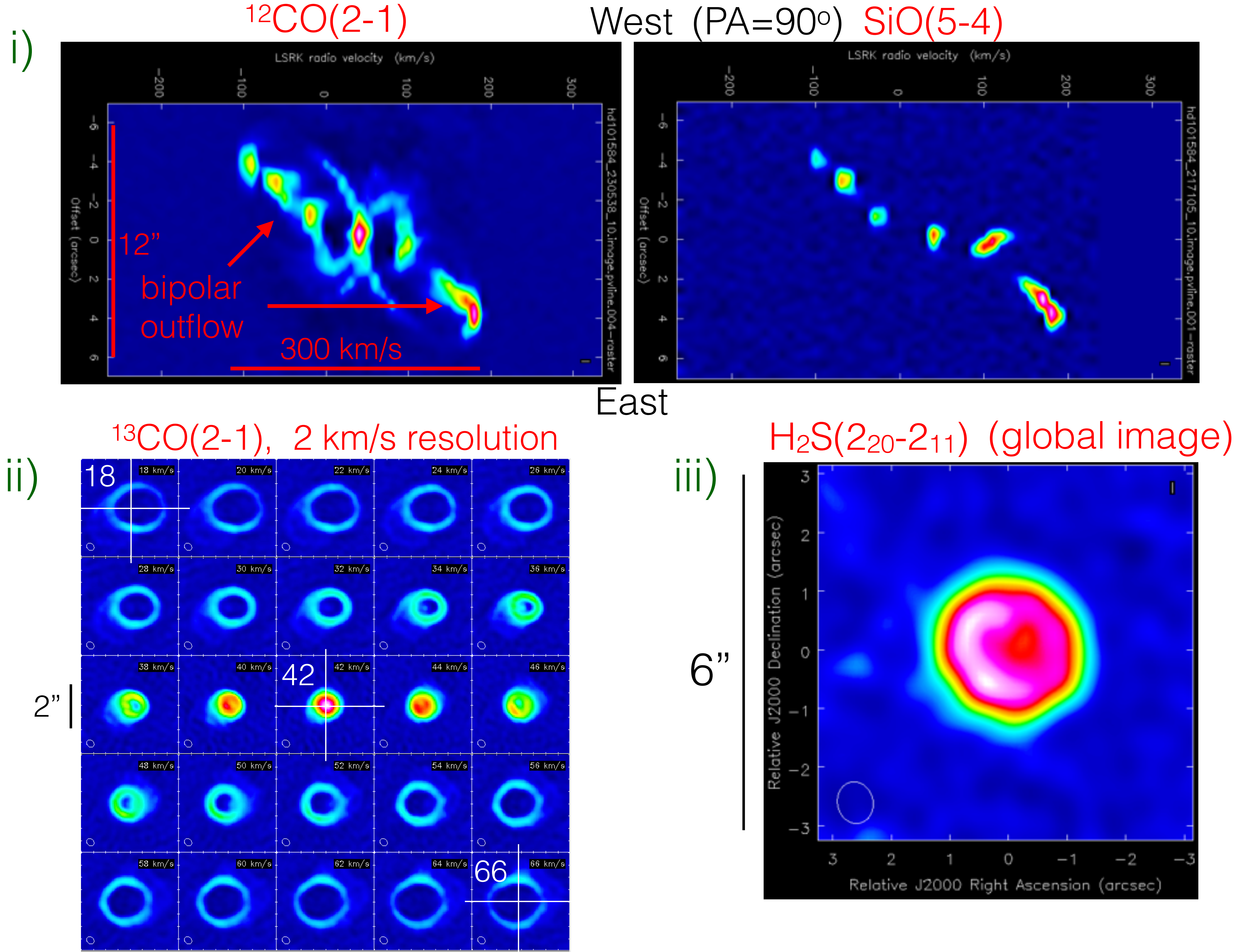
- A narrow bipolar high-velocity outflow, $\Delta v \approx 300$ km/s
- An hour-glass structure surrounding the high-velocity outflow, $\Delta v \approx 100$ km/s
- A central region, $\Delta v \approx 20$ km/s

The system is seen almost pole-on.

These results are discussed in Olofsson et al. A&A 576, L15 (2015).

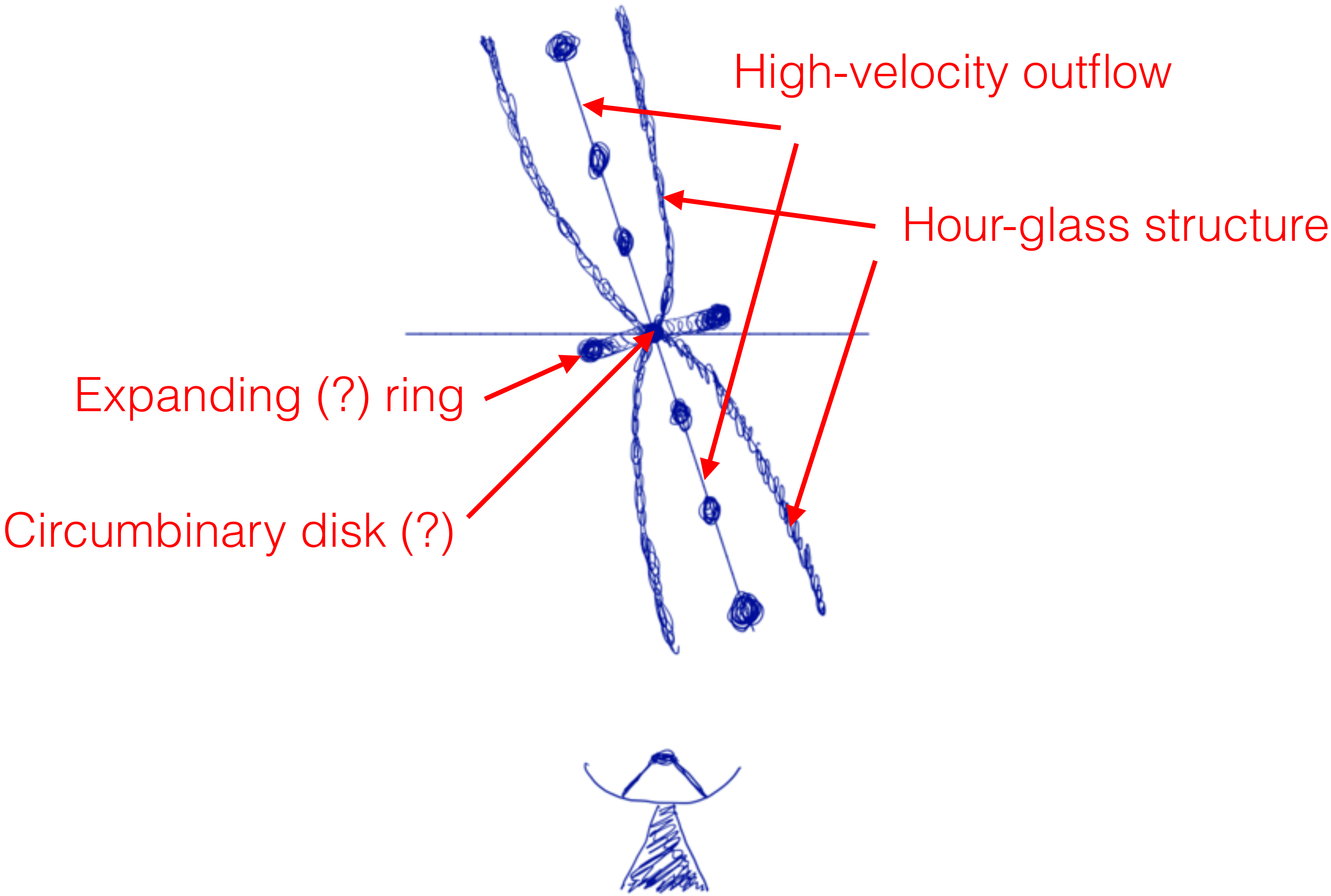


i) bipolar high-velocity outflow
HD101584
12CO(J=2-1)
(12.5 km/s ch. sep.)
ii) hour-glass structure
iii) central region
−108
−95.5
−83
−70.5
−58
-108
−45.5
−33
−20.5
−8
4.5
17
29.5
42
54.5
67
79.5
92
104.5
117
129.5
142
154.5
167
179.5
192
192
Dec. offset [arcsec]
R.A. offset [arcsec]
12CO(2-1)
Flux [Jy]
vLSR [km s−1]



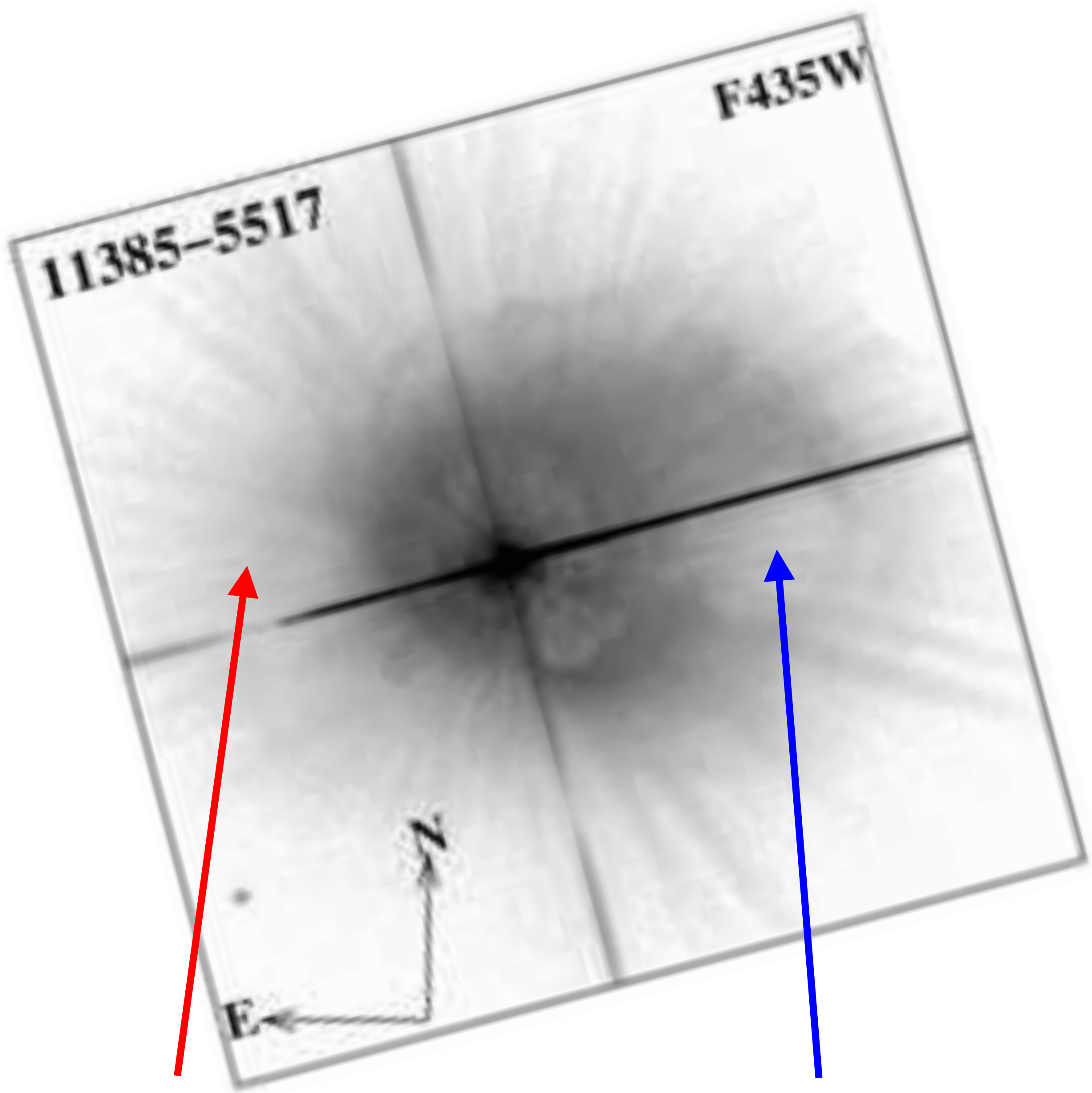
i)
$^{12}CO(2-1)$
West (PA=90°)
SiO(5-4)
LSRK radio velocity (km/s)
Offset (arcsec)
12"
bipolar outflow
300 km/s
East
ii)
$^{13}CO(2-1)$, 2 km/s resolution
18
42
66
2"
iii)
$H_2S(2_{20}-2_{11})$ (global image)
6"
Relative J2000 Declination (arcsec)
Relative J2000 Right Ascension (arcsec)

The geometry



Continuum at 1.3 mm

Most of the continuum comes from the central region (inside 1" radius); faint structures outside this region.

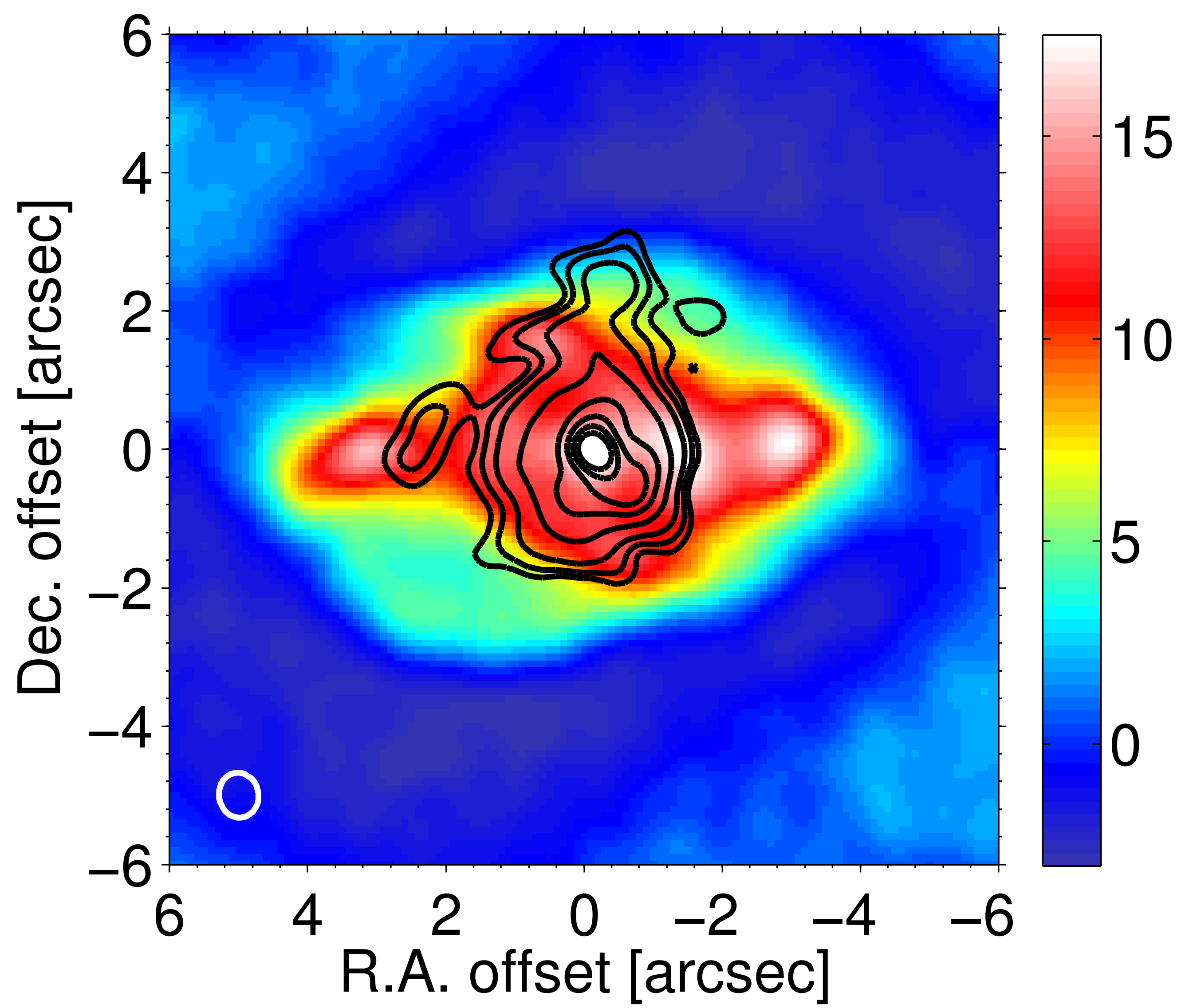


red outflow

blue outflow

Integrated $^{12}CO(2-1)$: colour

1.3 mm continuum: contours



The full SED

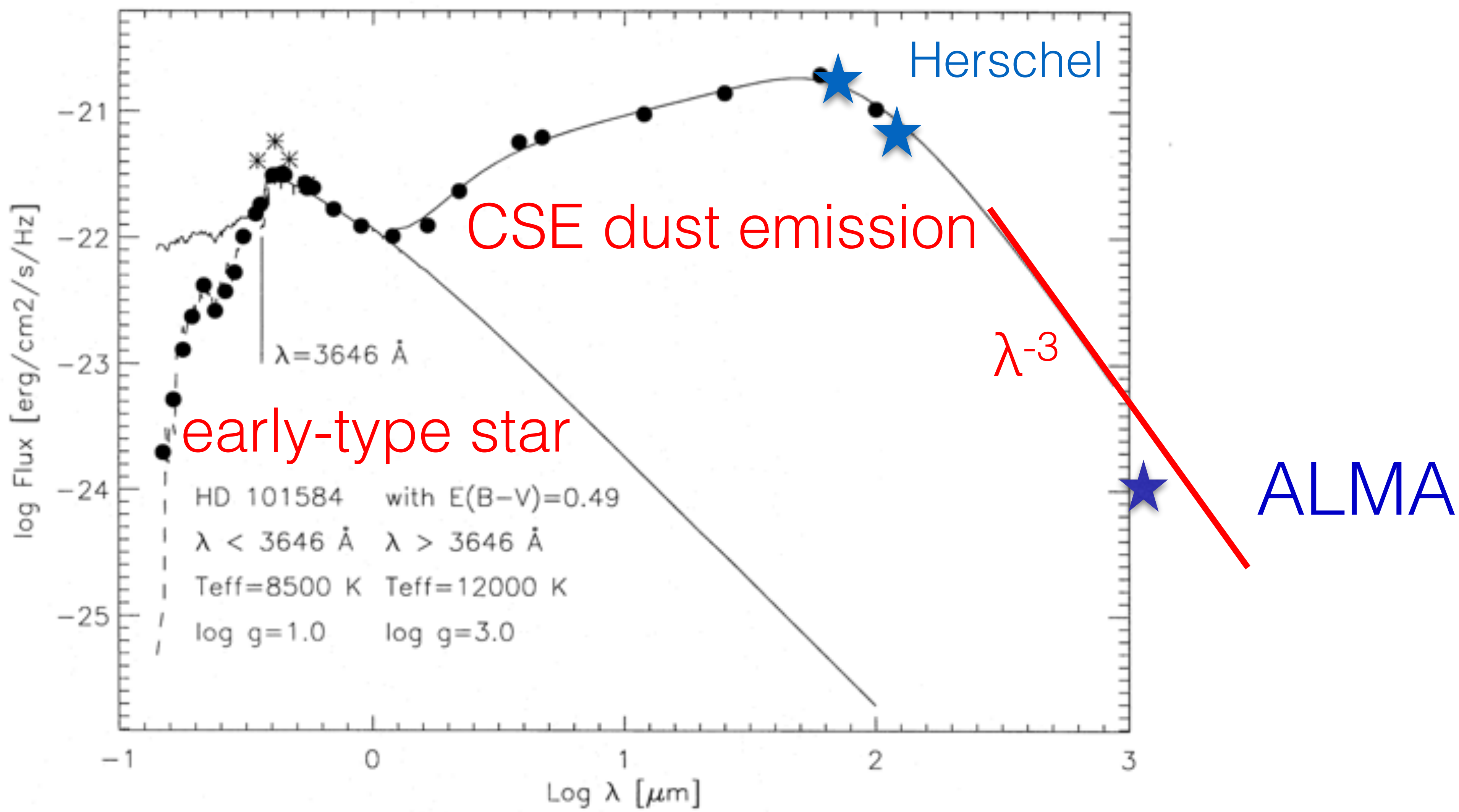


Fig. 7. A B9II (solid line) and a A5I (dashed line, only for $\lambda \leq 3646$ Å) Kurucz models are fitted to the dereddened energy distribution ($E(B-V) = 0.49$) of HD 101584. Due to the many wind lines in the blue and UV part of the spectrum, we observe an iron curtain in front of the B-star and the UV SED mimics an A to F-type star blue-wards of the Balmer jump ($\lambda = 3646$ Å)

We may recover only 25% of the 1.3mm flux.

Studies of other young post-AGB objects often show sub-mm excesses, suggesting the presence of large grains.

Mass estimates

Dust mass: $M_d \approx 0.02\ M_\odot$ from 1.3 mm ALMA data

Gas mass: $M_g > 0.3\ M_\odot$ from $C^{18}O$ ALMA data

Both are uncertain, but >50% of the mass lies in the central region.

About a solar mass of circumstellar material lies in the central region (radius < 1”).

This is consistent with the very strong H_2S (and $H_2{}^{33}S$ and $H_2{}^{34}S$) emission from the central region.

Time scales

Assuming that the bipolar outflow is driven by a jet that has its origin at the binary system and has been expanding with a velocity of 150 km/s, a tilt angle of 10^{o} (estimated from our data), and a projected distance of 4”,

the kinematic age of the jet is (jet is moving faster than molecular outflow):

< 500 yr

Momentum rate

Using the same assumptions as in the mass estimate we can estimate the momentum rate of the gas in the velocity range $|v - v_{sys}| > 10$ km/s assuming that the time scale is 500 yr:

$$dP/dt|_{gas} > 7 \times 10^{28} \text{ erg/cm}$$

The momentum rate of the radiation field (L/c) is:

$$dP/dt|_{rad} > 5 \times 10^{26} \text{ erg/cm}$$

Bujarrabal et al (2001) found very similar results for a sample of 28 PPNe and PNe.

That is , the radiation field cannot supply the momentum.

Energy

Using the same assumptions as in the mass estimate we can estimate the kinetic energy of the gas in the velocity range $|v - v_{sys}| > 10$ km/s:

$$E_{kin} > 4 \times 10^{45} \text{ erg}$$

The amount of potential energy released when the companion (*estimated mass 0.6 $M_{\odot}$* and *present distance 0.7 AU* using spectroscopic data and our inclination angle) spiralled in towards a 1.6 $M_{\odot}$ AGB star:

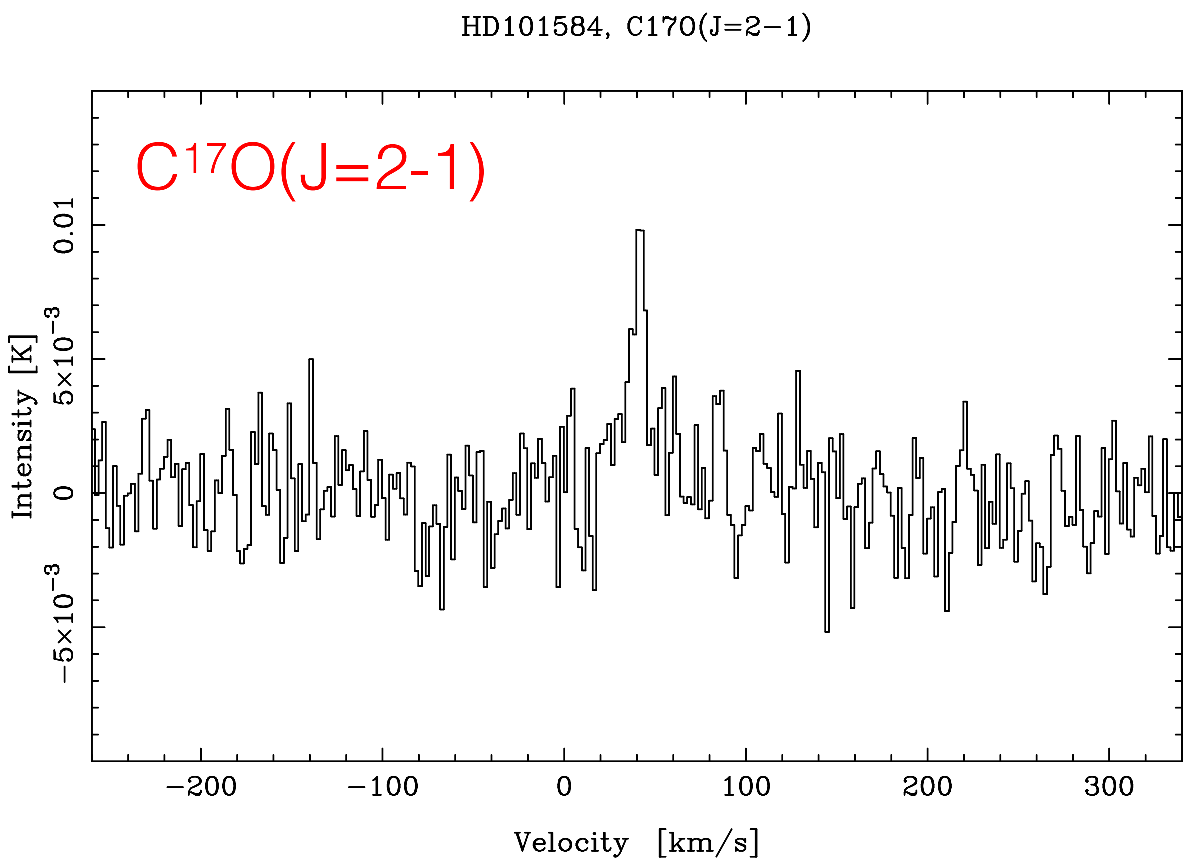
$$E_{rel} \approx 2 \times 10^{45} \text{ erg}$$

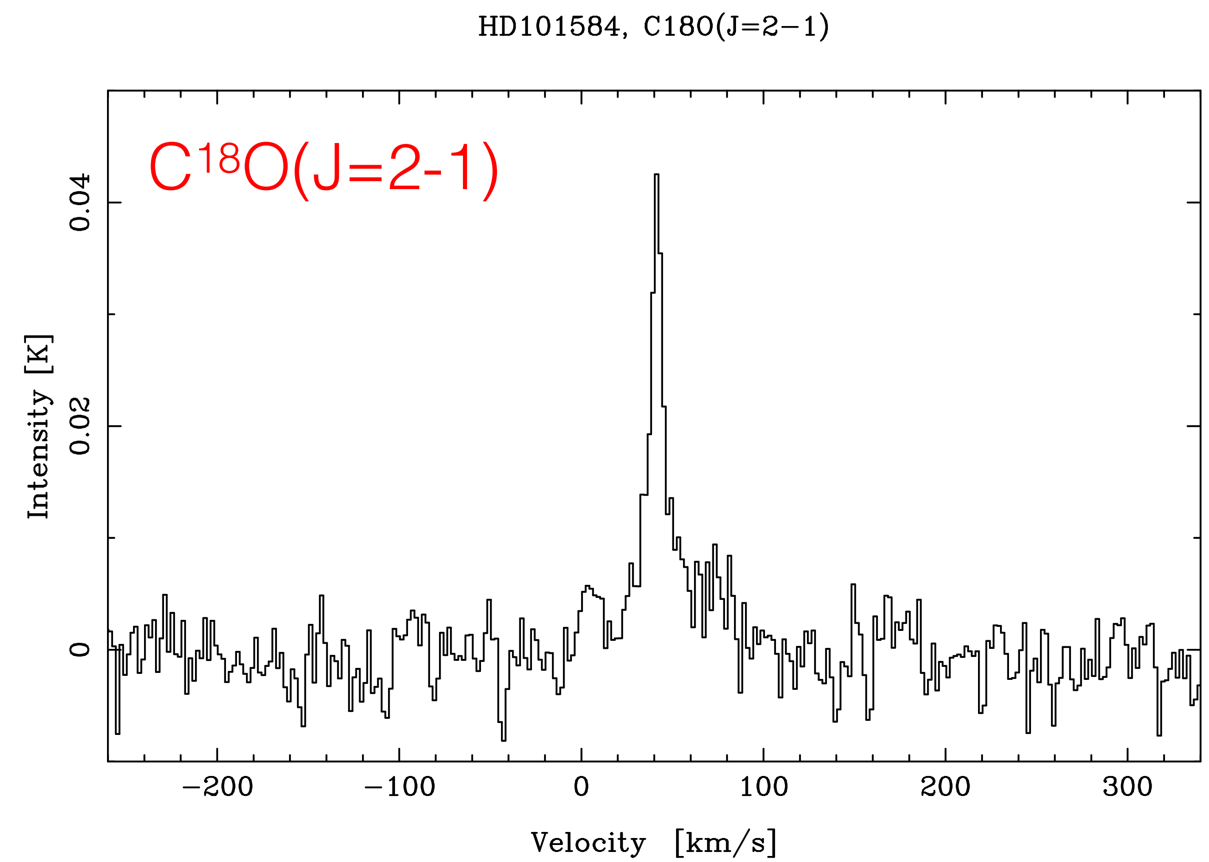
Taken at face values $E_{kin} > \eta E_{rel}$

η is the efficiency of the energy transfer

Mass of primary

APEX data





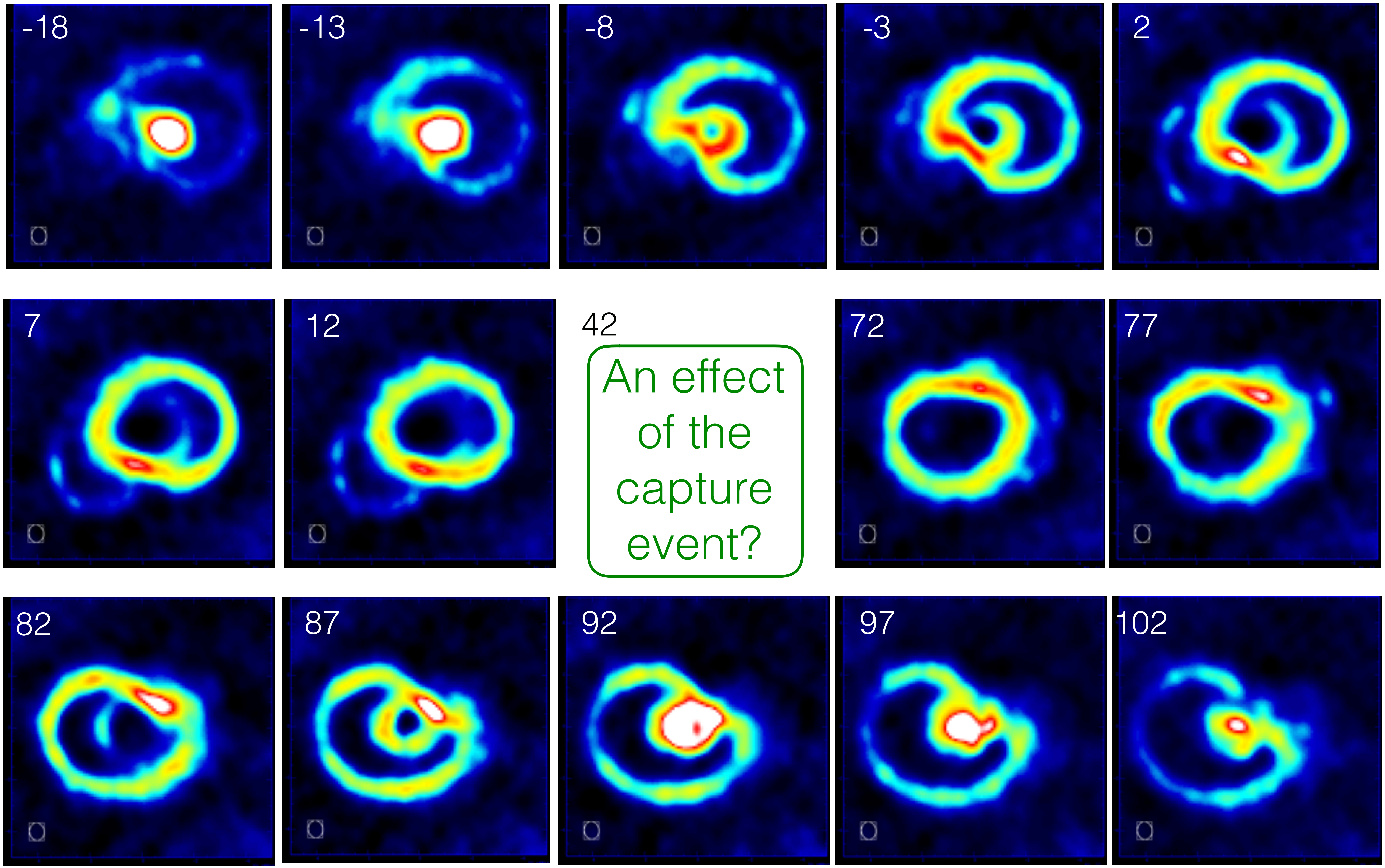
The $^{17}O/^{18}O$ ratio is strongly changed during the RGB (and it depends on M_{MS}) and not during the AGB (except for the HBB where ^{18}O is strongly destroyed).

I($C^{17}O$)/I($C^{18}O$) < 0.25 suggests $M_{\rm MS} \approx 1.2\, M_\odot$ (if post RGB).

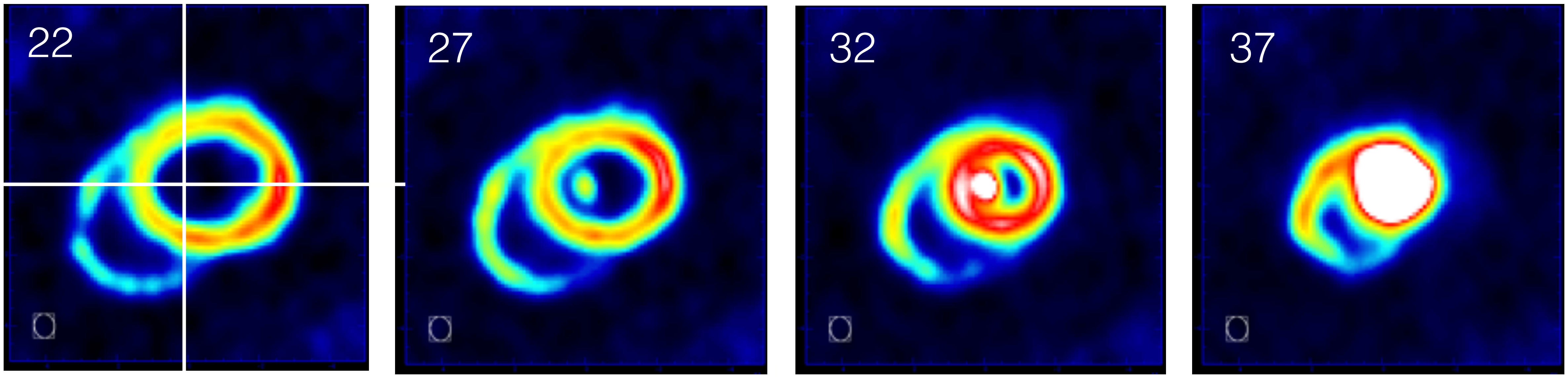
Some interesting question marks remain!

Complex morphology at the "edges" of the hour-glass structure!

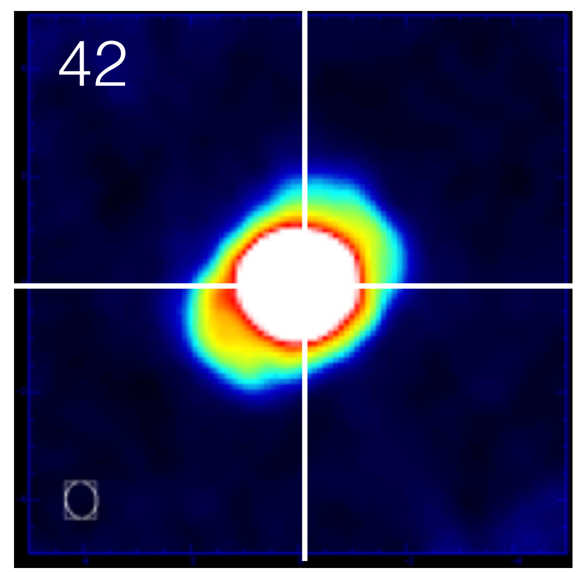
$^{12}CO(2-1)$



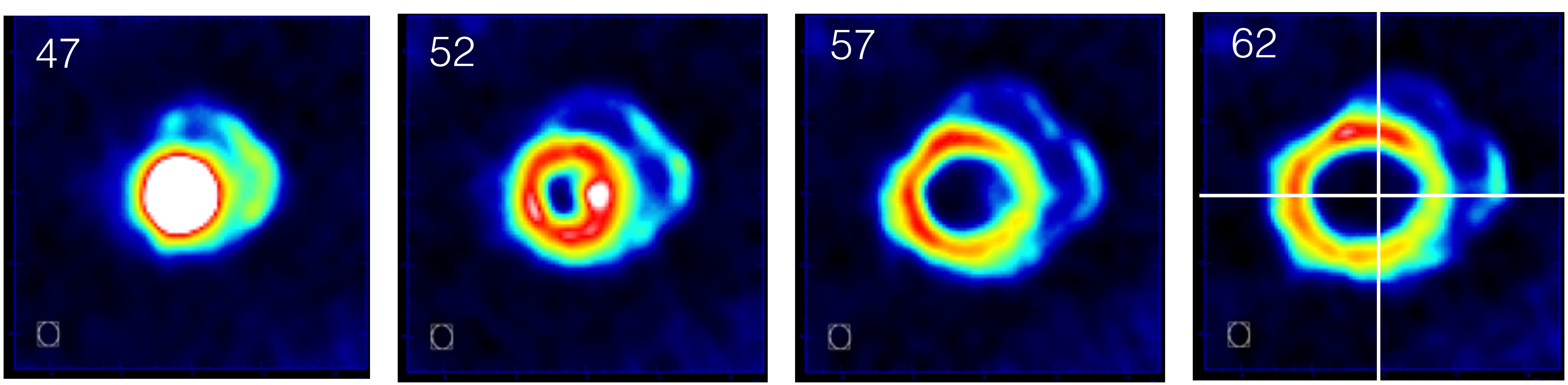
Another bipolar outflow?



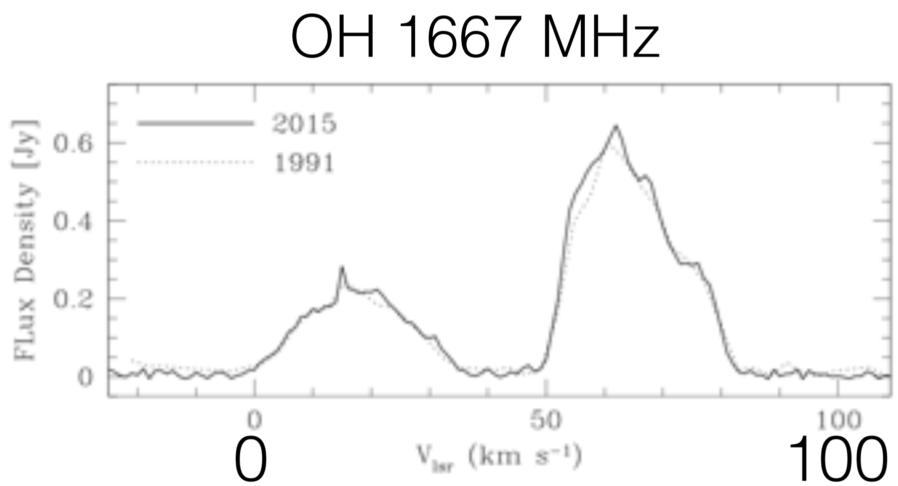
Enhanced to see low surface brightness

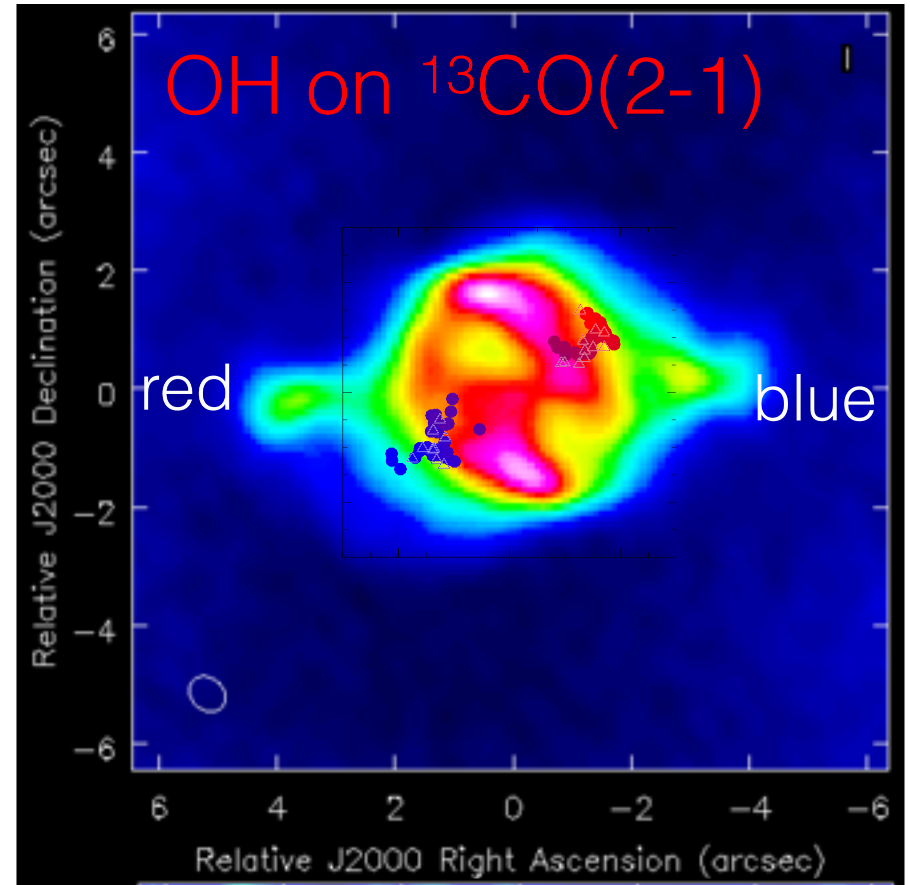


Ring-like structure system at PA ≈ -60^{o}, with an opposite velocity gradient

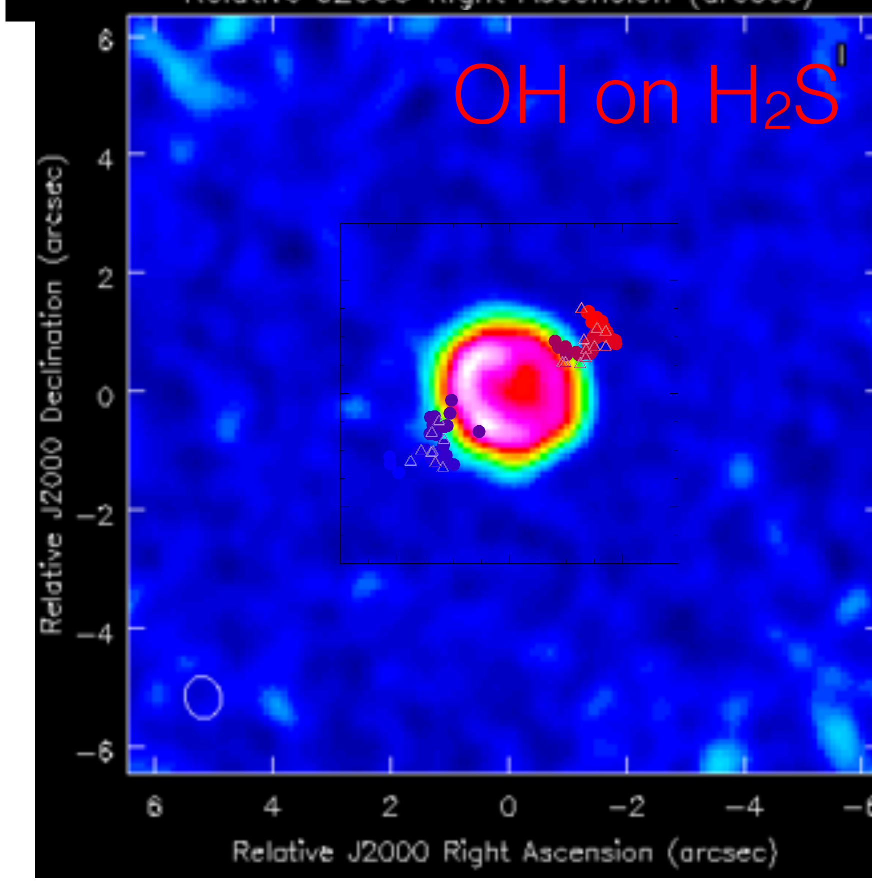


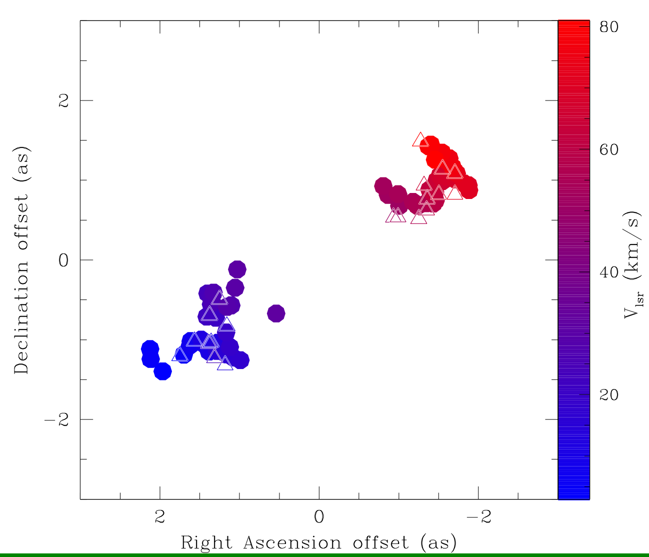
OH ATCA data





- No time variability (25 year)
- No polarisation
- No 1612, 1665, or 1720 MHz emission





- PA ≈ -60°, opposite velocity gradient

Constraints on n_{H2}, T_g, T_d, sp. index, B, …

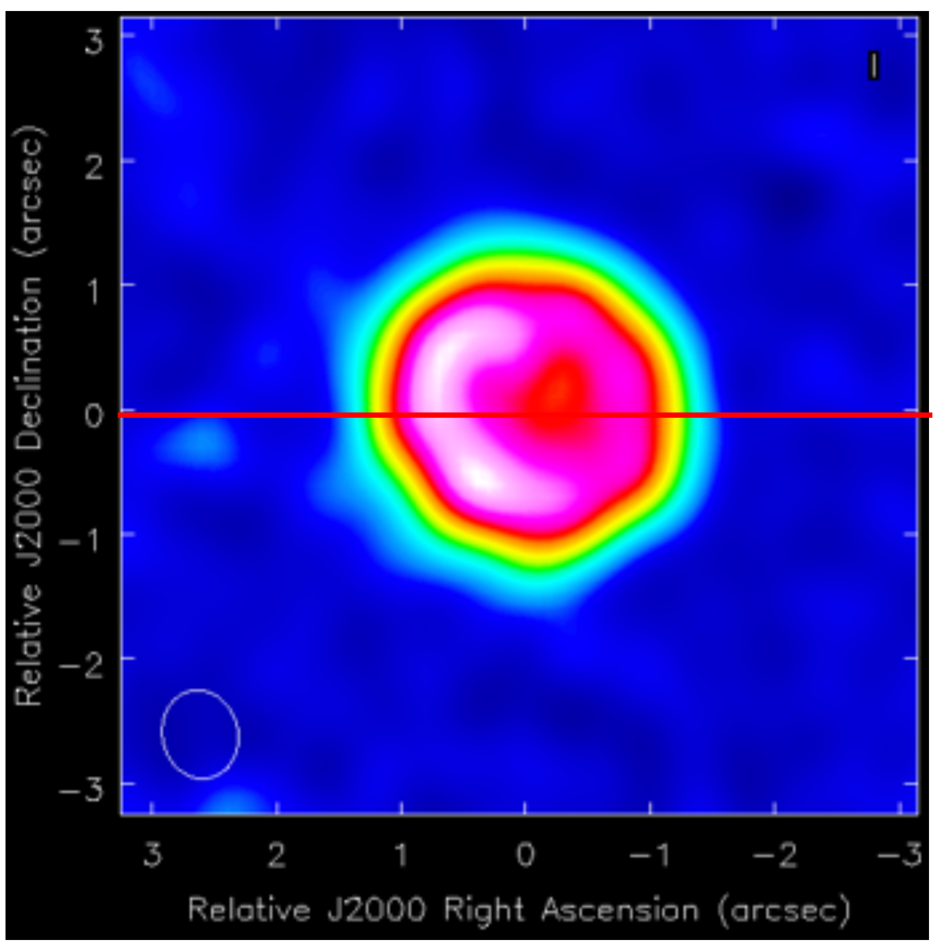
The central region

An expanding (?) ring and
a circumbinary disk (?)

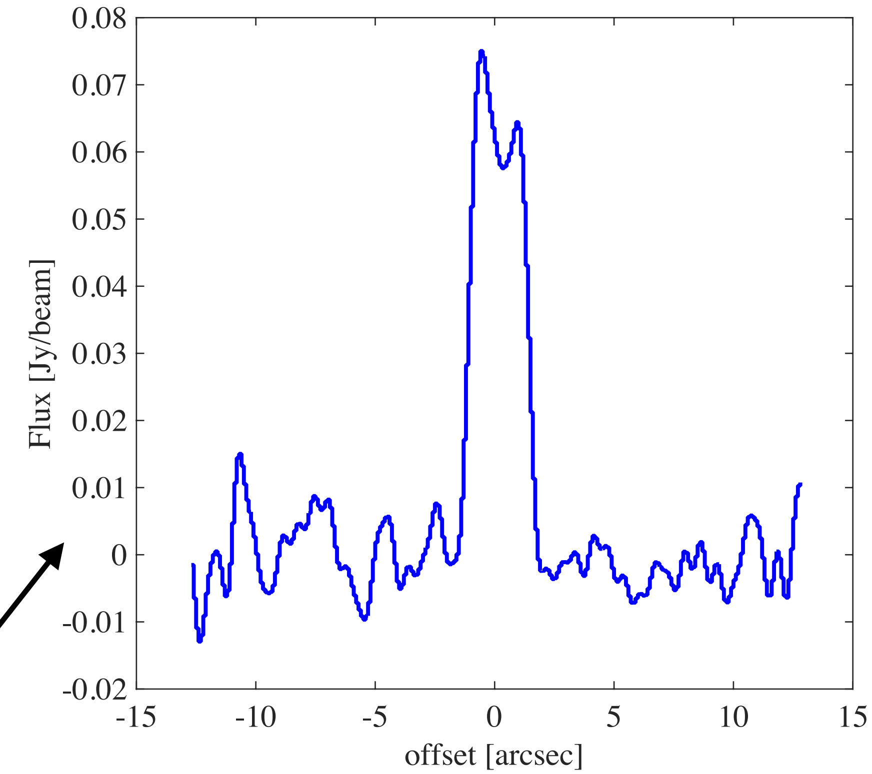
Sharply truncated emission

$H_2S(2_{20}$-$2_{11})$ emission comes only from this region.

$H_2S(2_{20}$-$2_{11})$ (global image)

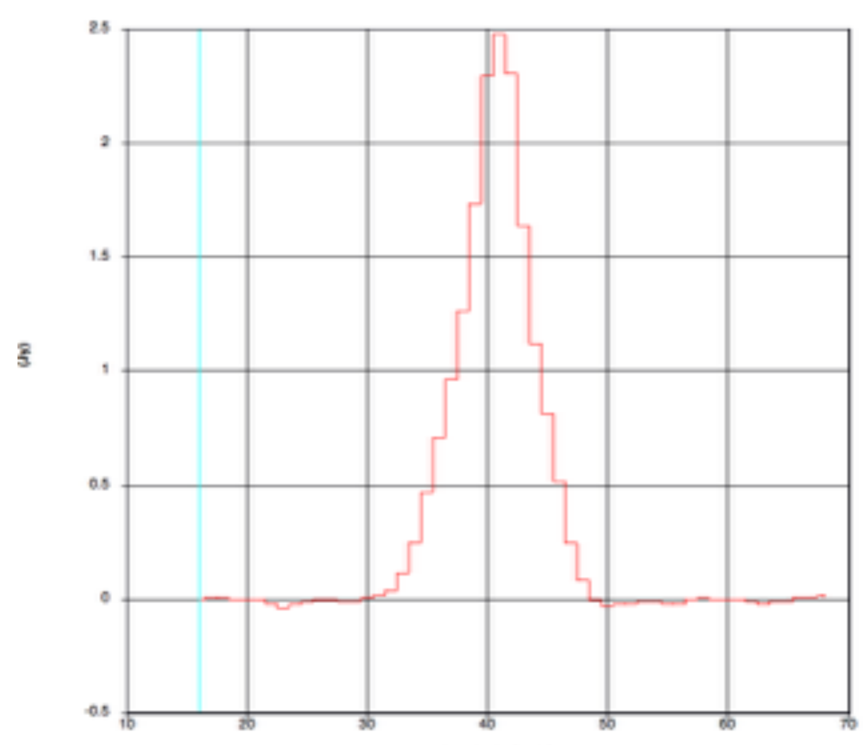


6”



Intensity along PA=90°

Sharply truncated brightness distribution

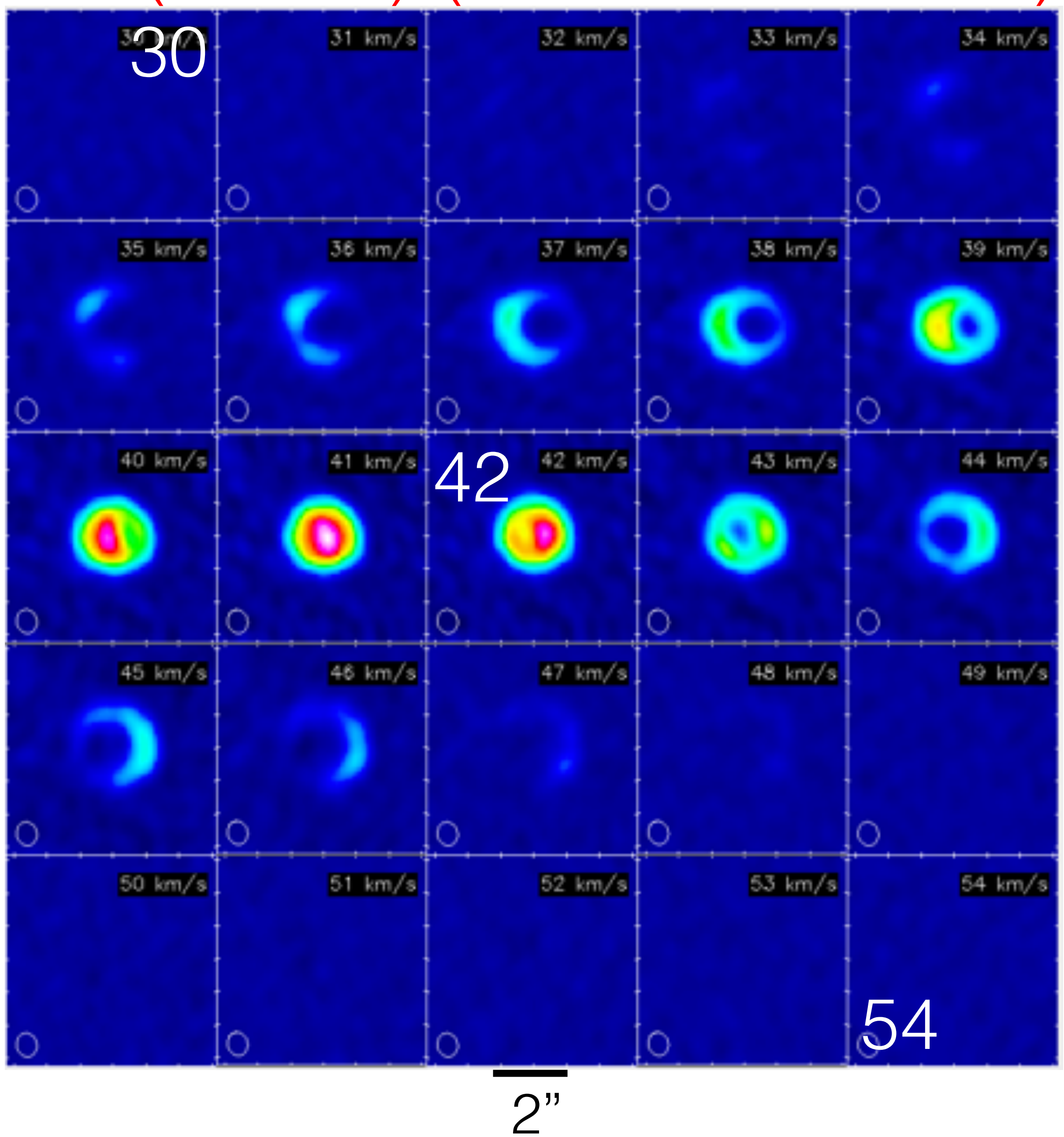


30 40 50 km/s

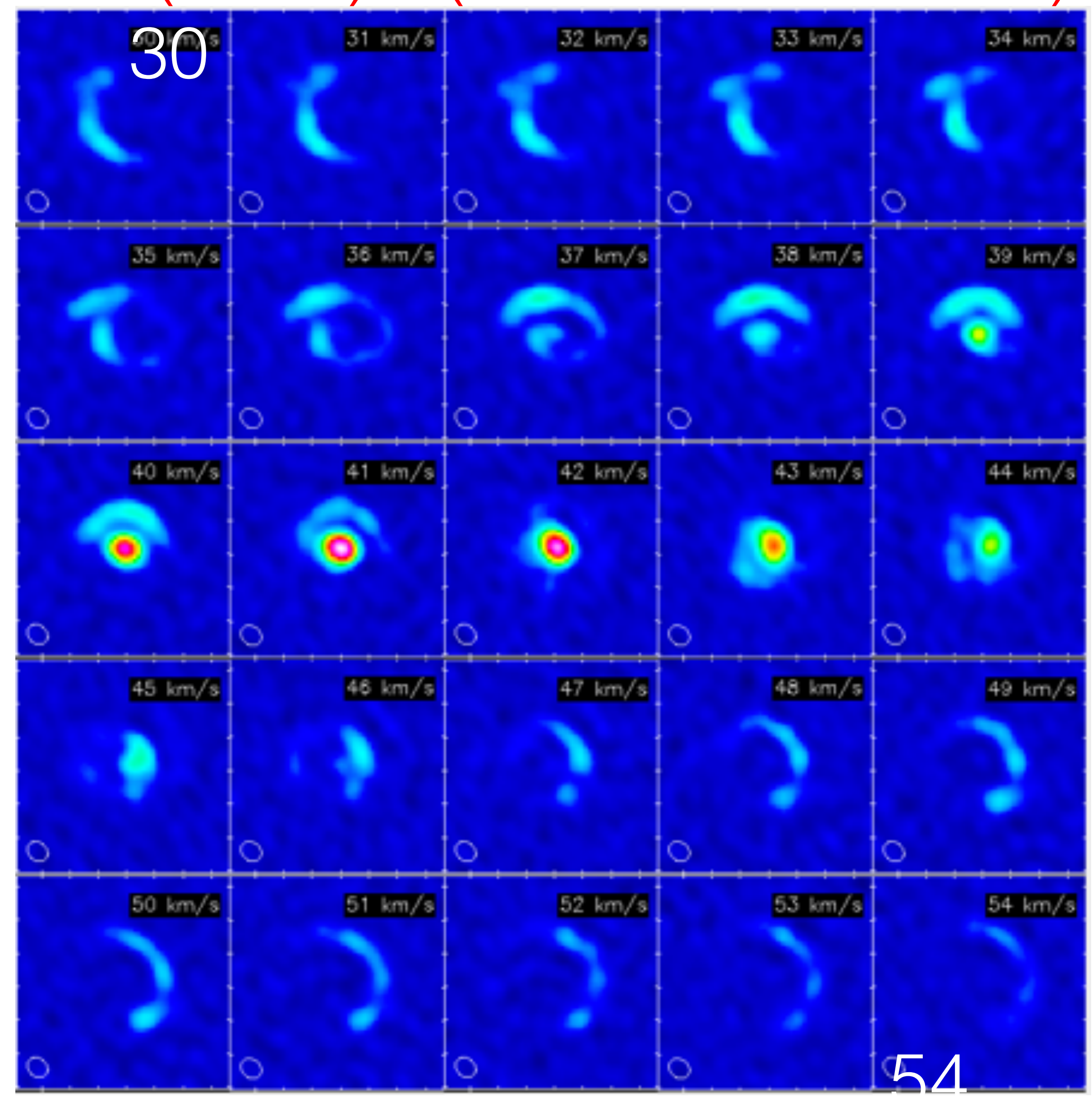
Emission covers ≈16 km/s

Expanding (?) ring

$H_2S(2_{20}-2_{11})$ (1 km/s resolution)



$SO(6_5-5_4)$ (1 km/s resolution)

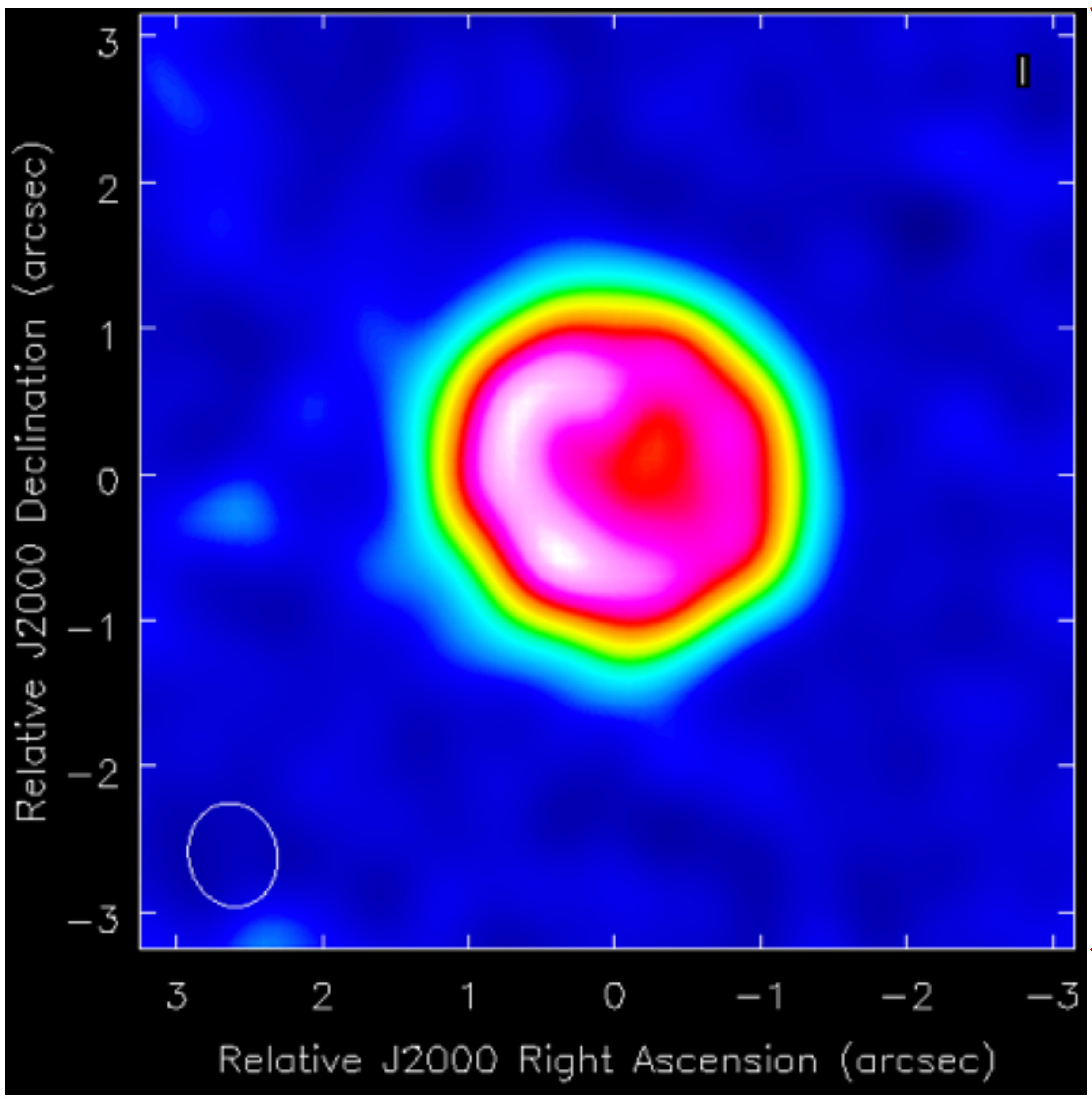


Velocity gradient opposite to that of the outflow => most likely an equatorial ring.

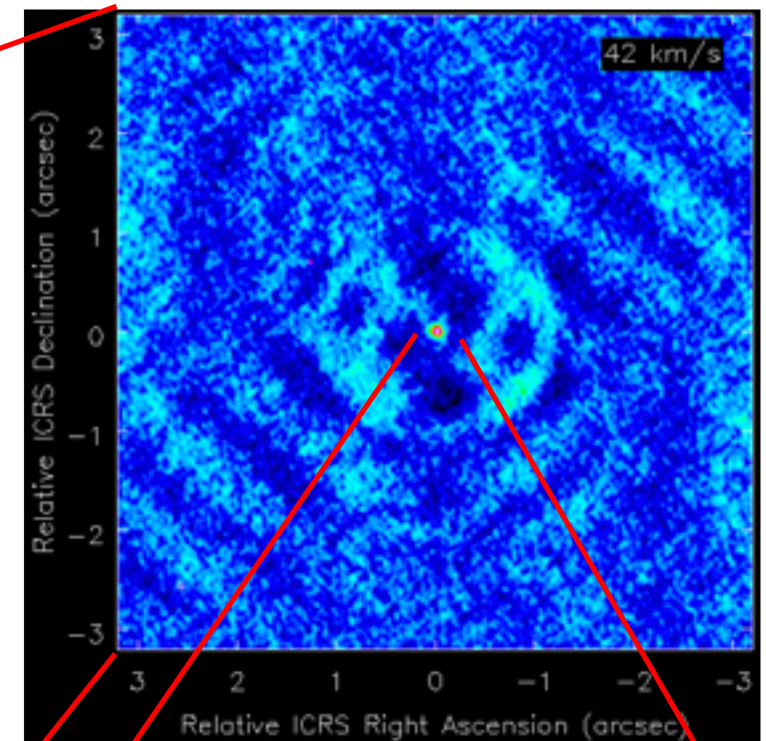
But, expansion velocity is uncomfortably high, ≈50 km/s.

A circumbinary disk?

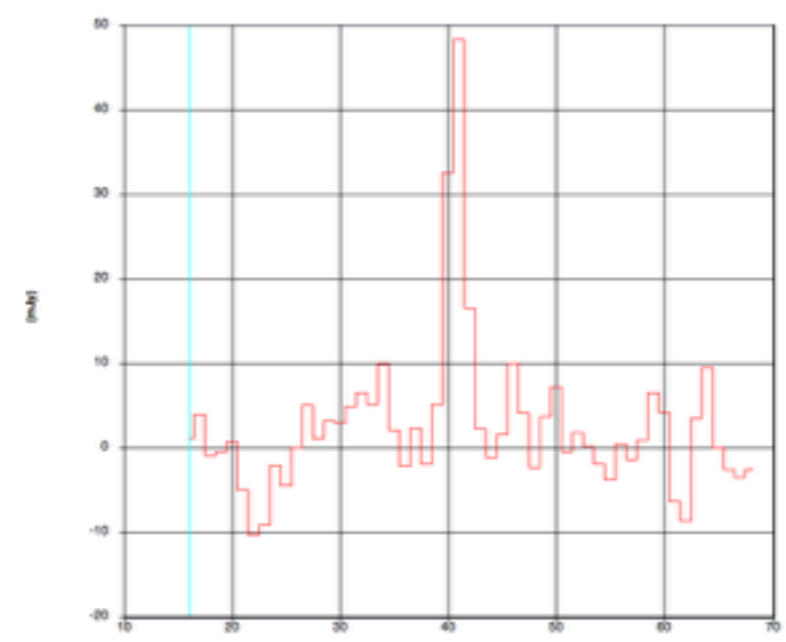
$H_2S(2_{20}-2_{11})$ 0.5” resolution



0.05” resolution <=> 35 AU



$SO_2(16_{1,15}-15_{2,14})$, 1 km/s



30 40 50 km/s

2 km/s in width

Central structure

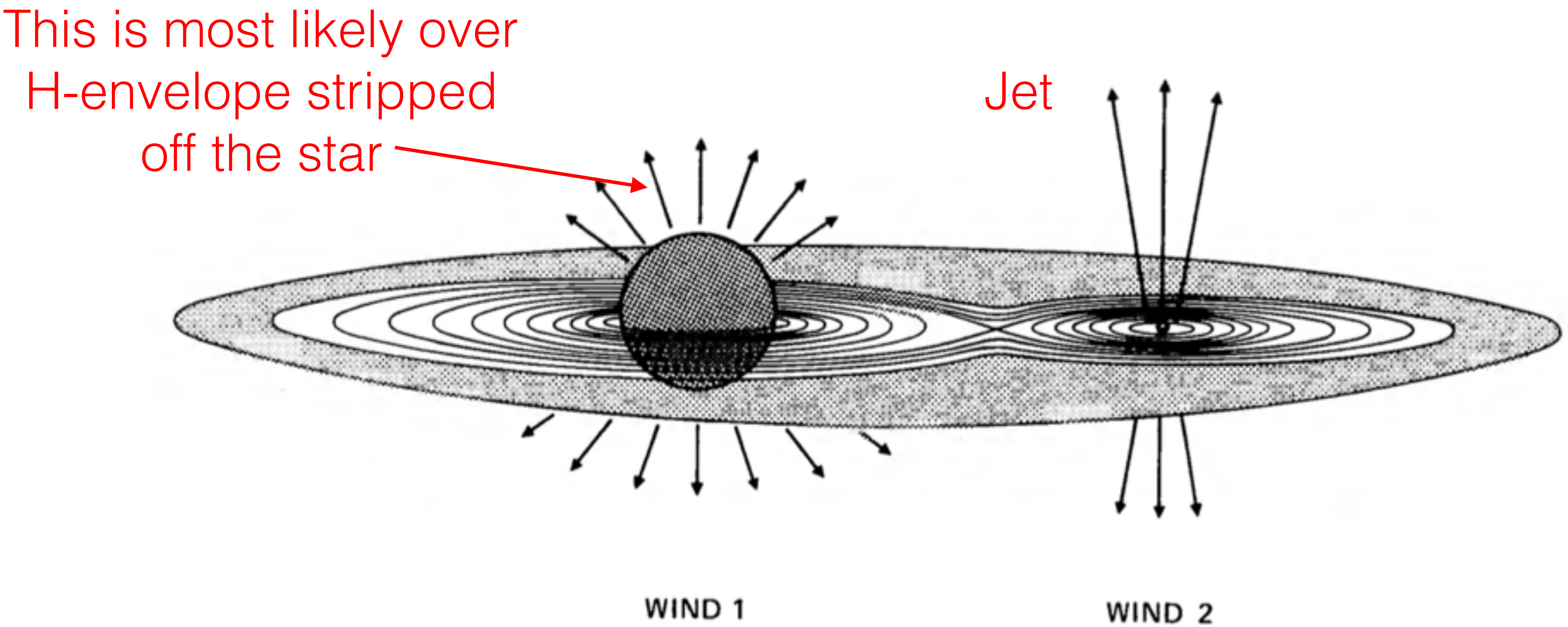


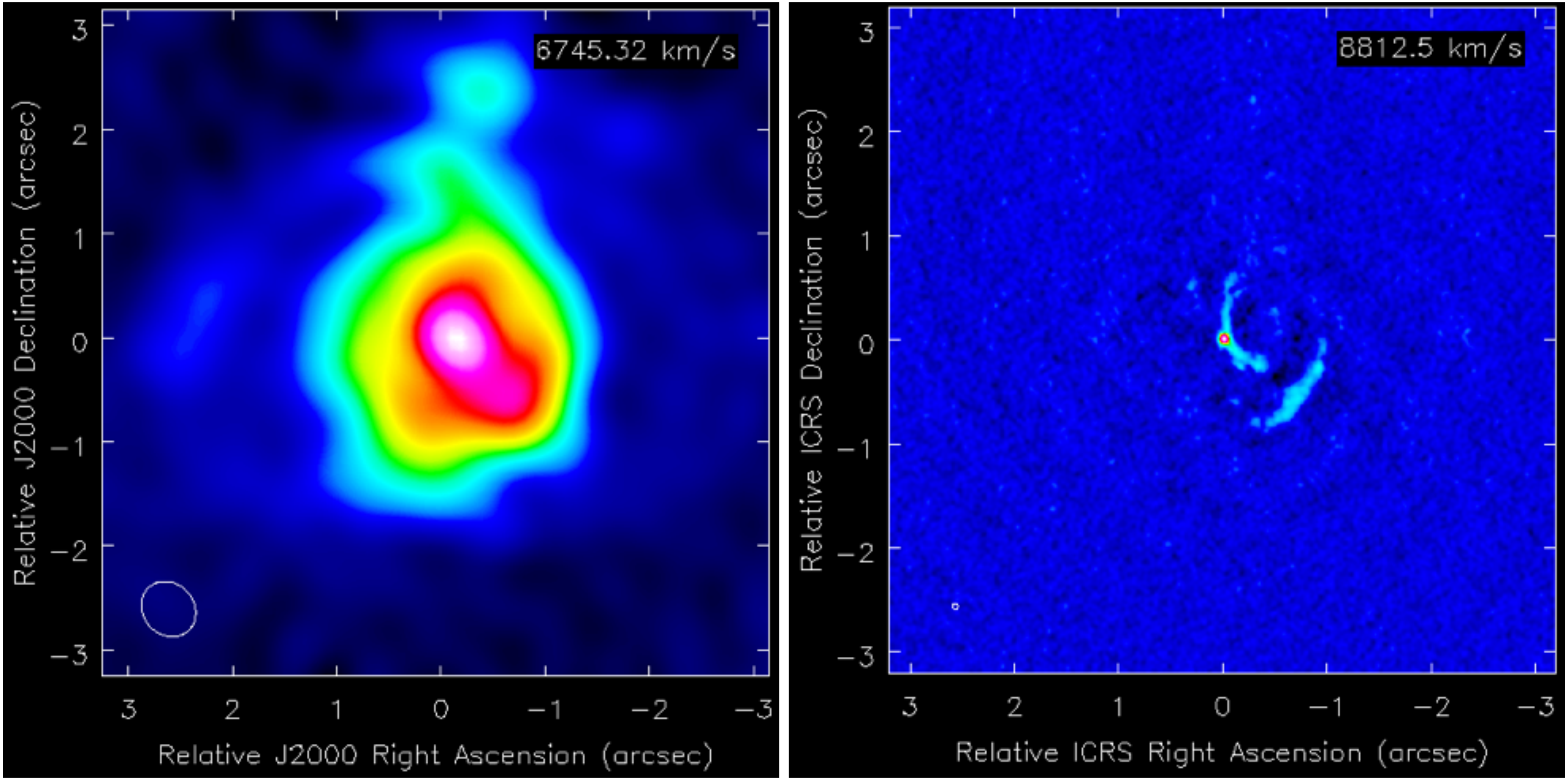
FIG. 2—Binary model for the creation of bipolar circumstellar outflows. The wind of the red giant (wind 1) is partially captured into an accretion disk around the much smaller secondary. This accretion disk grows with time to form an excretion disk, which encompasses the whole system. A second wind arises from the interior of the accretion disk about the secondary.

Morris 1987

1.3 mm continuum

0.5” resolution

0.05” resolution <=> 35 AU



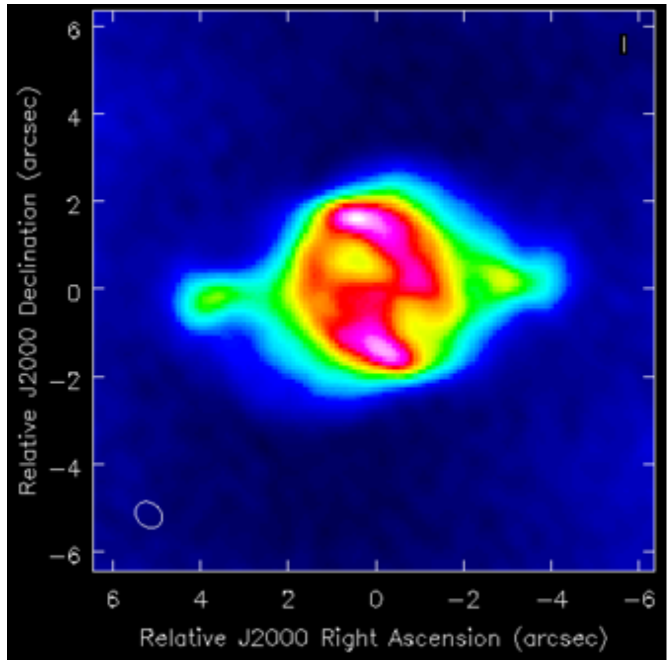
The central feature must be circumstellar dust emission.

Conclusions

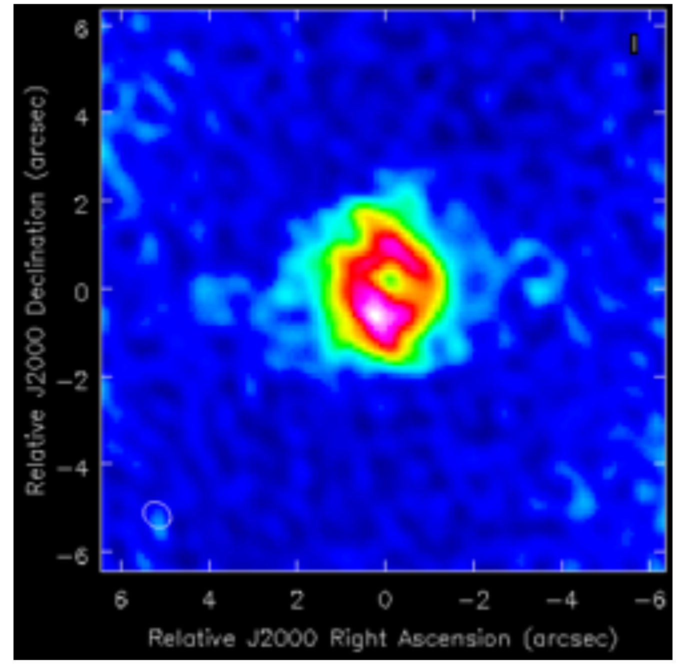
- HD101584 is most likely a very recent (O-rich) post-AGB object. The mass is estimated to be ≈ 0.6 $M_\odot$.
- It has a companion, estimated mass ≈ 0.6 $M_\odot$, at an estimated distance of ≈ 0.7 AU.
- The circumstellar medium has been severely affected by the evolution of the binary system. A high-velocity "jet" has excavated an hour-glass structure which is seen almost pole-on.
- It is possible that this was initiated as the companion spiralled in towards the primary less than 500 yr ago.
- The kinetic energy of the accelerated gas exceeds the potential energy liberated during the infall of the companion.
- There appears to be substantial amount of material, maybe as much as a solar mass, in a ring (?) and a circumbinary disk (?).
- Much structure remains to be explained.

Global maps

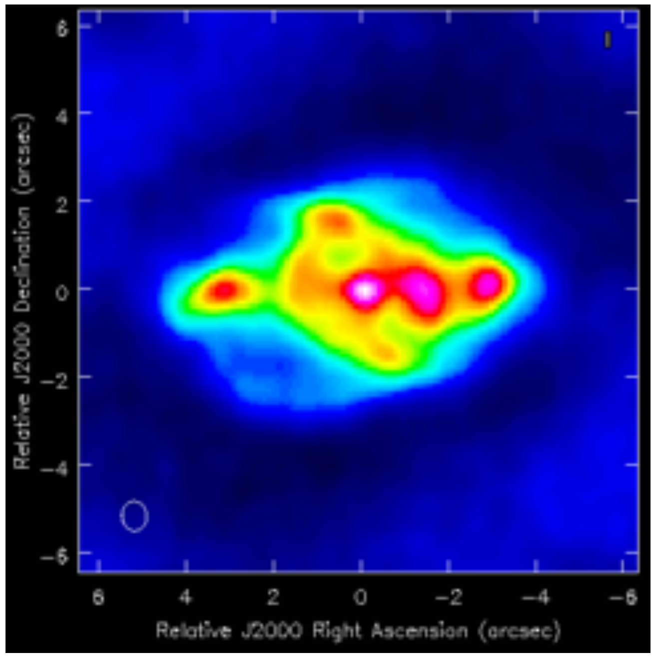
$^{13}CO(2-1)$



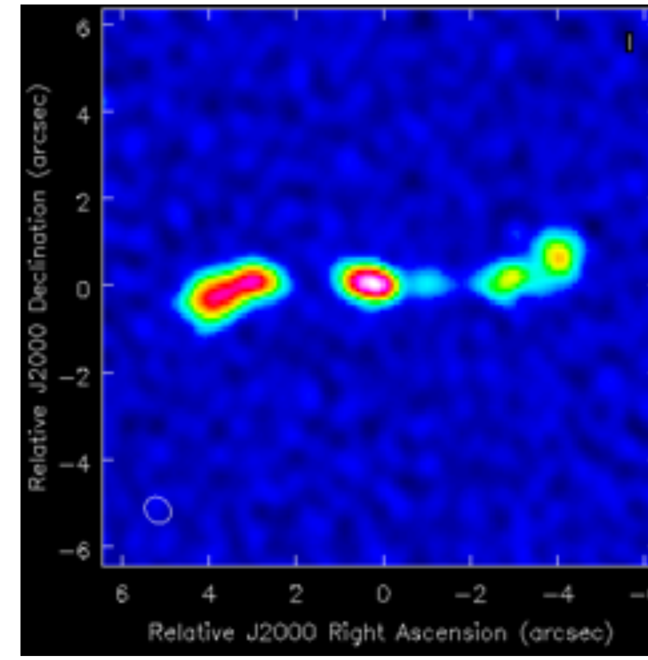
$C^{18}O(2-1)$



$^{12}CO(2-1)$

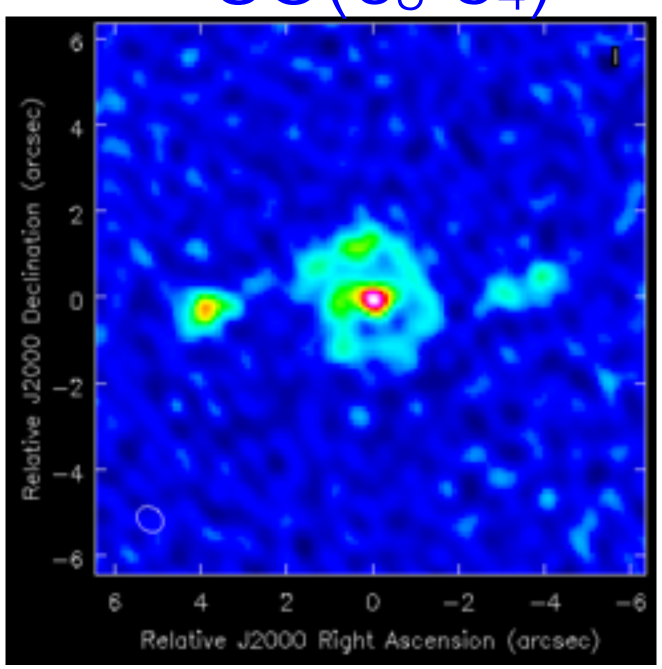


$SiO(5-4)$

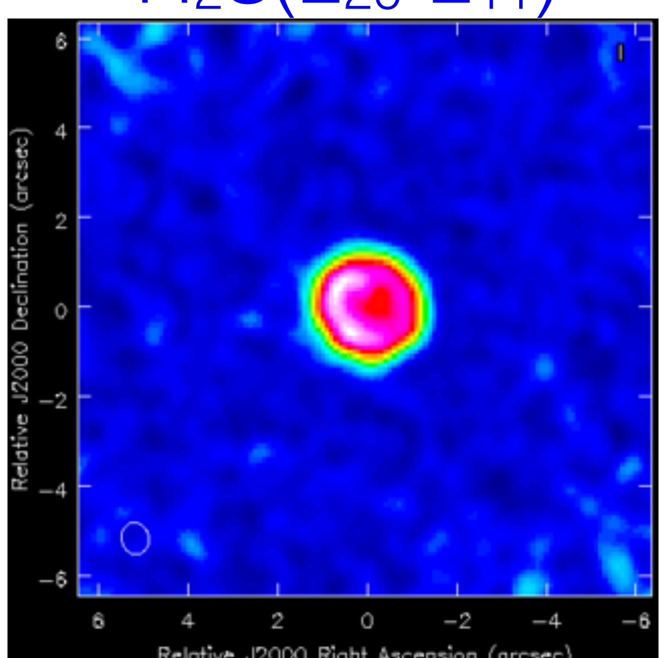


Thank you!

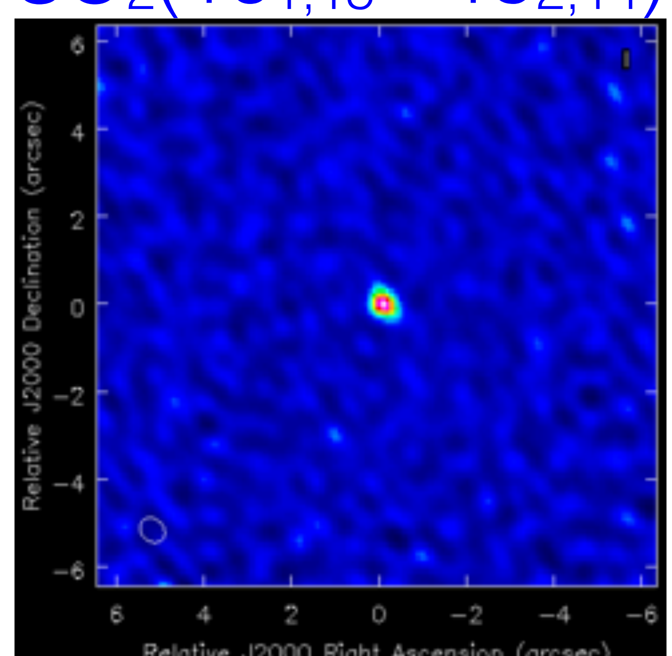
$SO(6_5-5_4)$



$H_2S(2_{20}-2_{11})$



$SO_2(16_{1,15} - 15_{2,14})$



$H_2CO(3_{03}-2_{02})$