^{12}CO emission from the Red Rectangle

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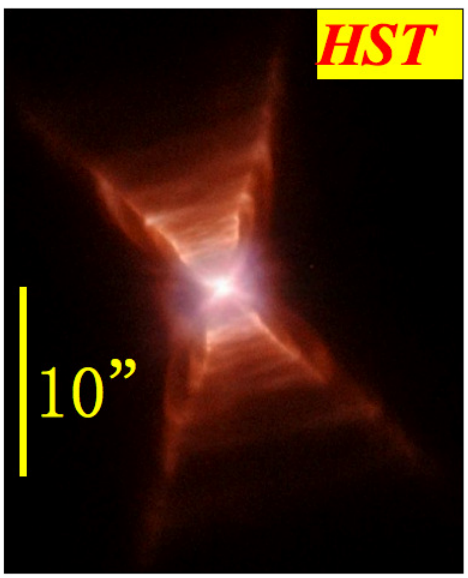
1. Generalities on the Red Rectangle

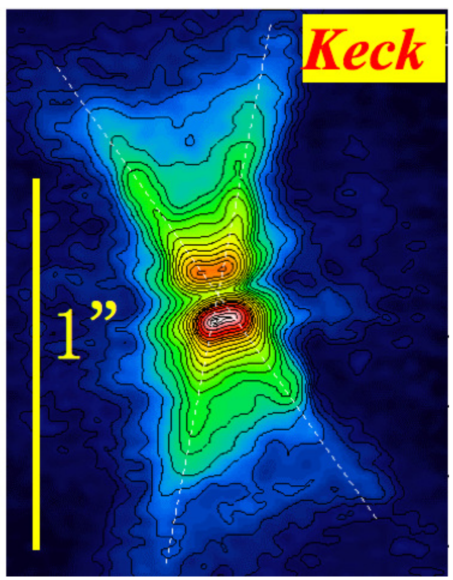
The Red Rectangle: d=710 pc, Proto-Planetary Nebula, Constellation: Monoceros, biconical structure; axis perpendicular to the line of sight; The star in the centre: (spectroscopically unresolved) a binary = post AGB star + MS star or White Dwarf accreting its wind.

Fast jet parallel to the line of sight having dug a conical cavity in the slow wind of the post AGB star.

Visible/NIR light obscured by a dense dust torus

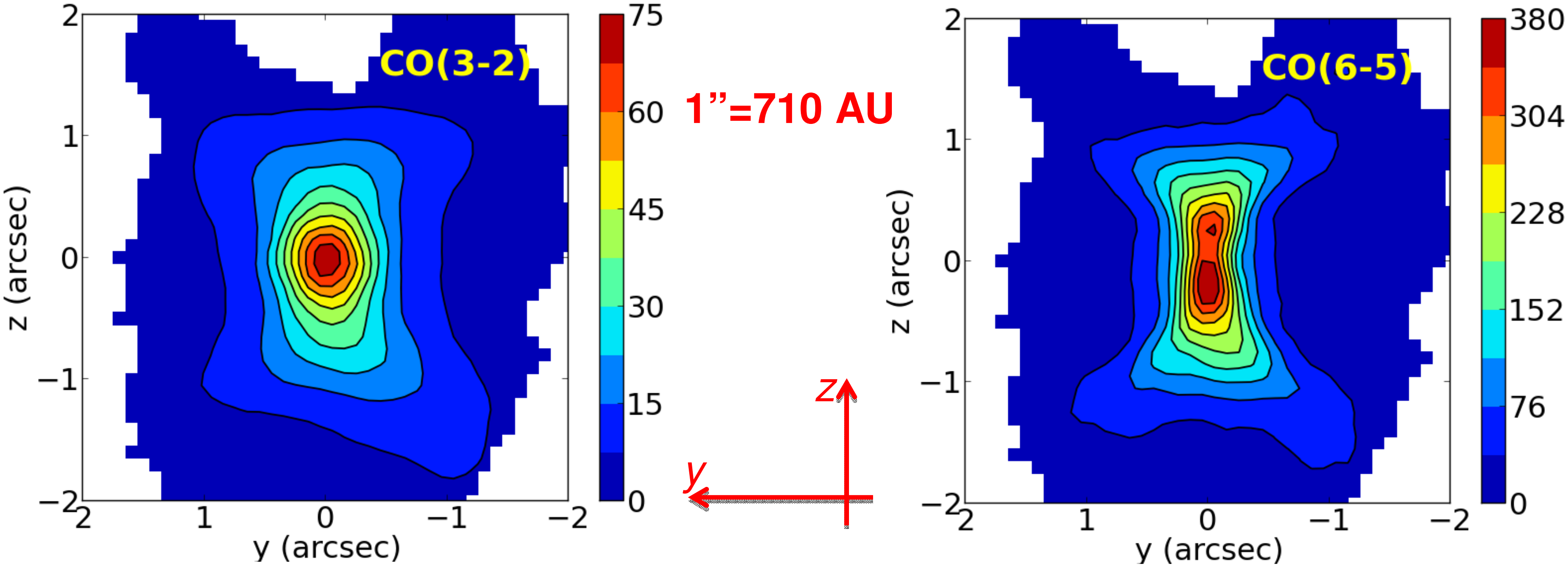


Cohen *et al.* 2004



Tuthill *et al.* 2002

- 2005, PdBI IRAM, CO(1-0), CO(2-1), resolution ~1”: revealed the presence of a disk of gas.
- Recently, ALMA, CO(3-2), CO(6-5) resolution: an **order of magnitude better** have been made available.

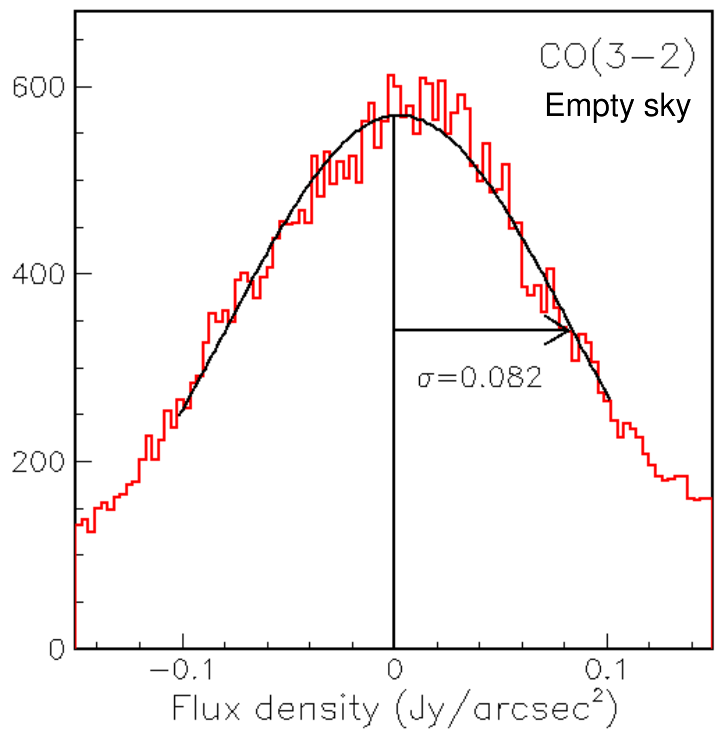


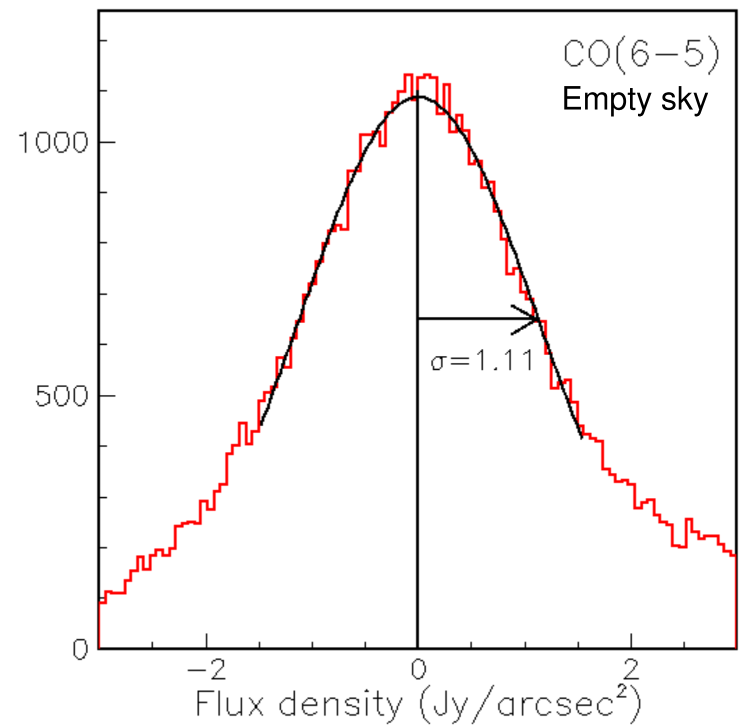
Use CO(3-2) and CO(6-5) public access data:

Rearranged: 50×50 pixels, centred on continuum emission, solid angle 5"×5", $V_{Doppler}$=[–7.2, 7.2 kms^{-1}] in 36 bins of 0.40 kms^{-1}

New array: rotated by 13^{o} counter clockwise in order to have it aligned with the star axis. Both sky maps and velocity spectra associated with the new arrays are centred on the star.

Beam sizes: 0.50"×0.49" [CO(3-2)], 0.27"×0.24" [CO(6-5)].

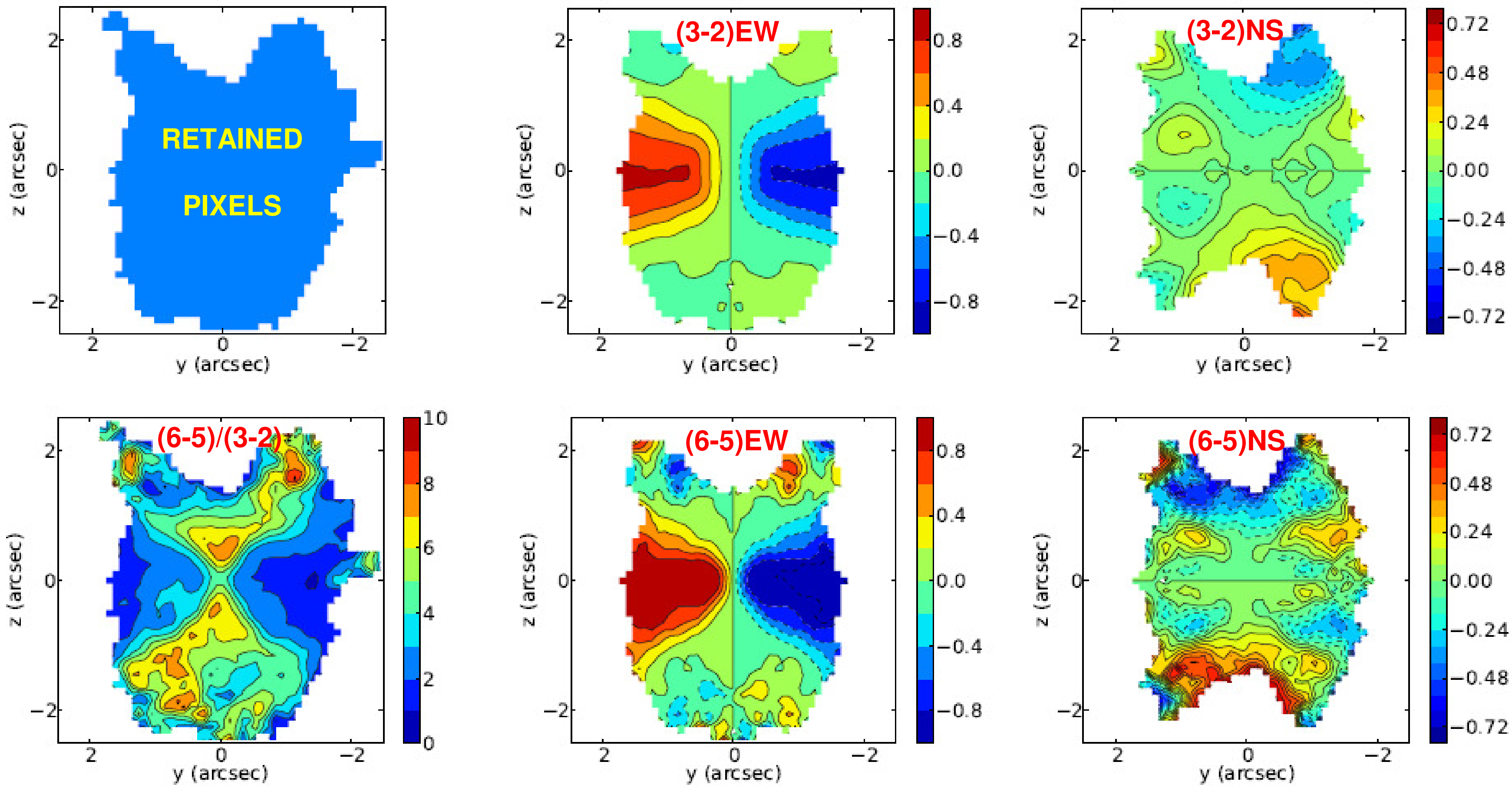




We conservatively restrict the present study to pixels containing:

> 0.75 Jy×arcsec^{-2}×kms^{-1} CO(3-2)

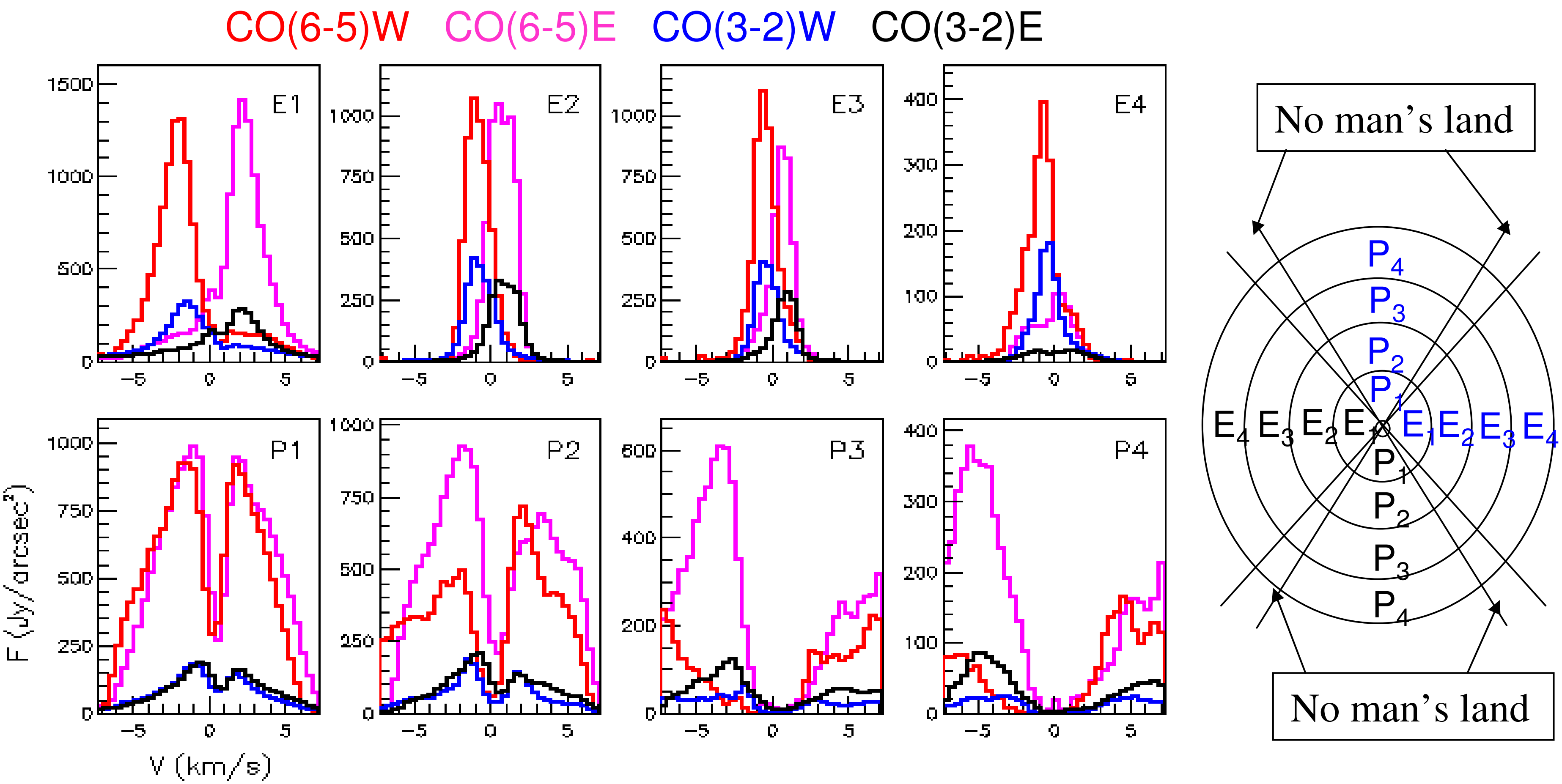
> 3.00 Jy×arcsec^{-2}×kms^{-1} CO(6-5)



CO(6-5)/CO(3-2) map: evidence for a **temperature distribution** dominated by the biconical structure down to low distances from the star.

The East-West (y axis) asymmetry reveals a very clear **rotation of the equatorial region** around the star axis;

A significant **North-South asymmetry** (z axis) is also present.

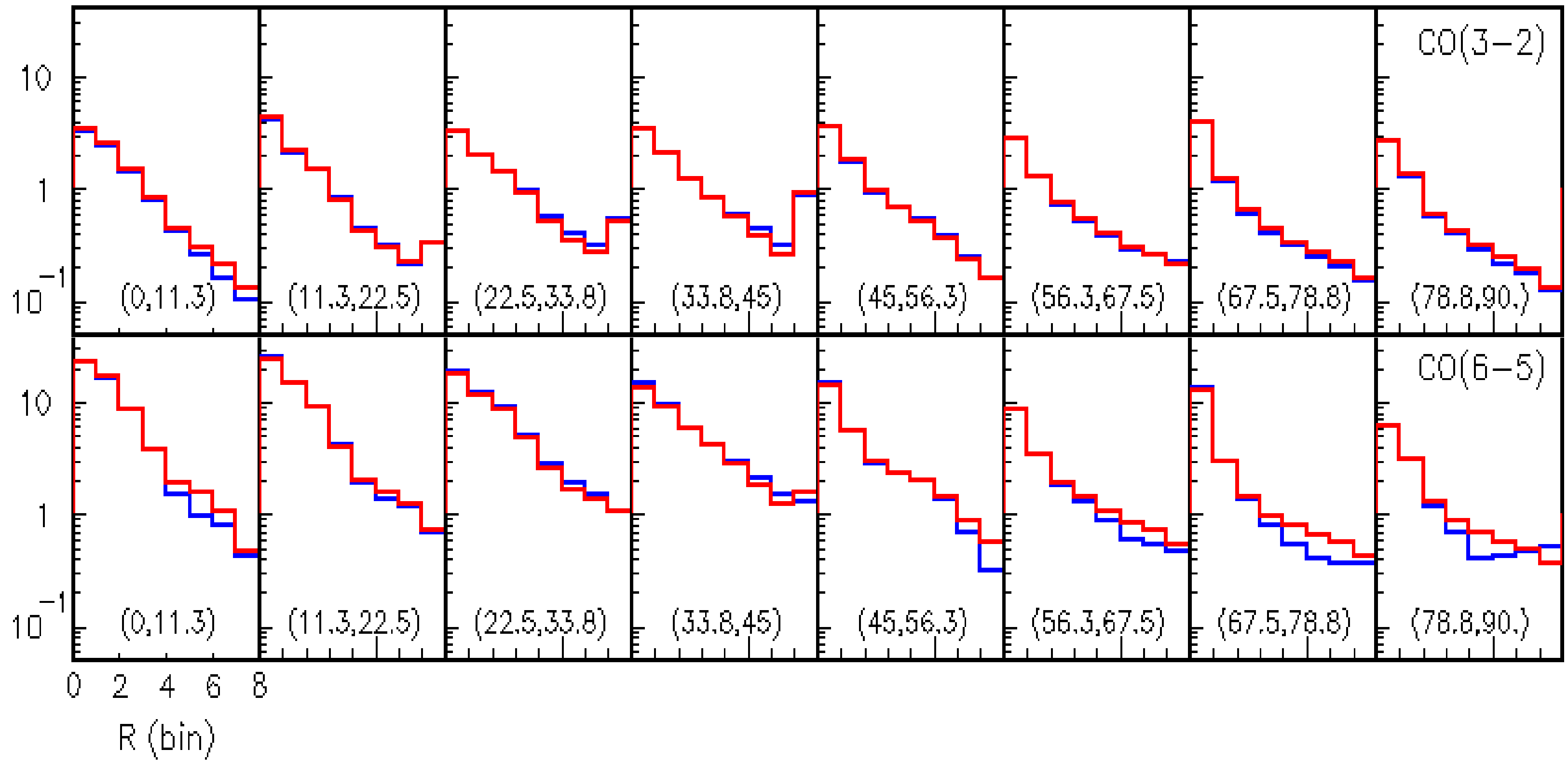


Equatorial region: dominated by rotation, **velocities decreasing with *R*,** V~2 km/s (*R*~0.5”) to V~0.7 km/s (*R*~1.5”).

Polar regions: dominated by an outflow, Doppler velocities **increasing significantly with *R*,** extending beyond the limits of the spectra.

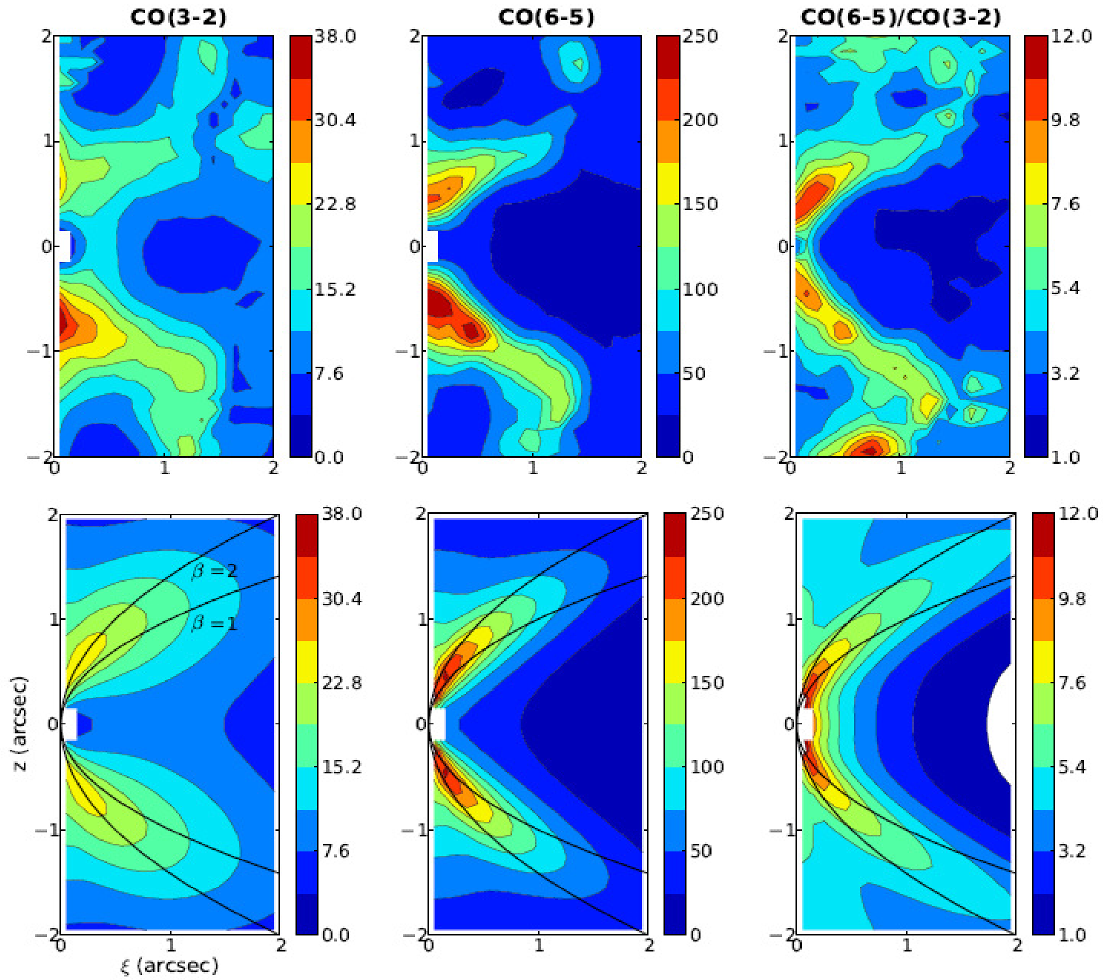
2. Effective density

Define effective density $\rho(x,y,z)$= **gas density×population of emitting state×probability of emission** such that: its integral over the line of sight (x axis) equals the measured flux in pixel (y,z) (integrated over Doppler velocity V_x): $\boldsymbol{F(y,z)=\int F(y,z,V_x)dV_x=\int \rho(x,y,z)dx}$

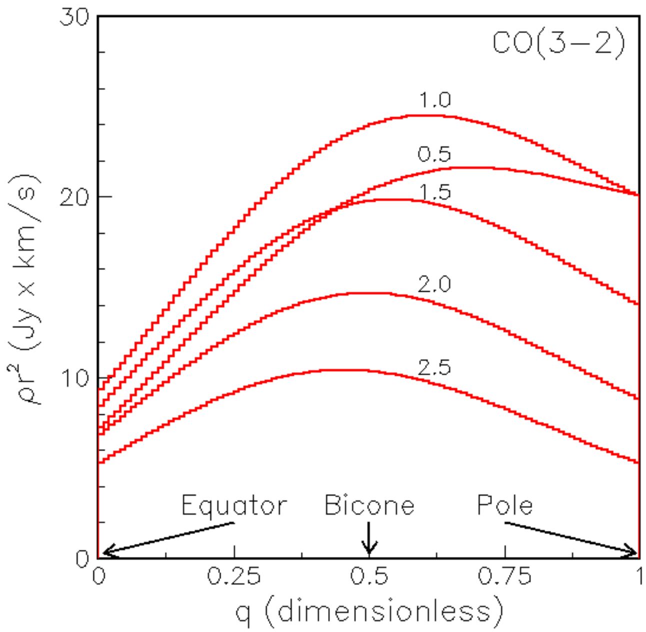


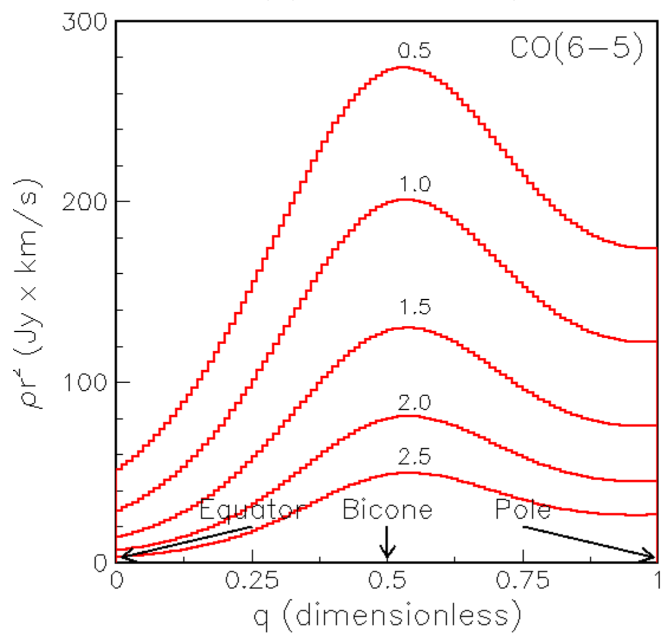
Parameterization of the effective density

Assuming **rotational invariance** about the star axis, we integrate the integral equation and obtain ***ρ(x,y,z)= ρ(ξ,z)*** in a meridian half-plane of the star, **(ξ,z).**

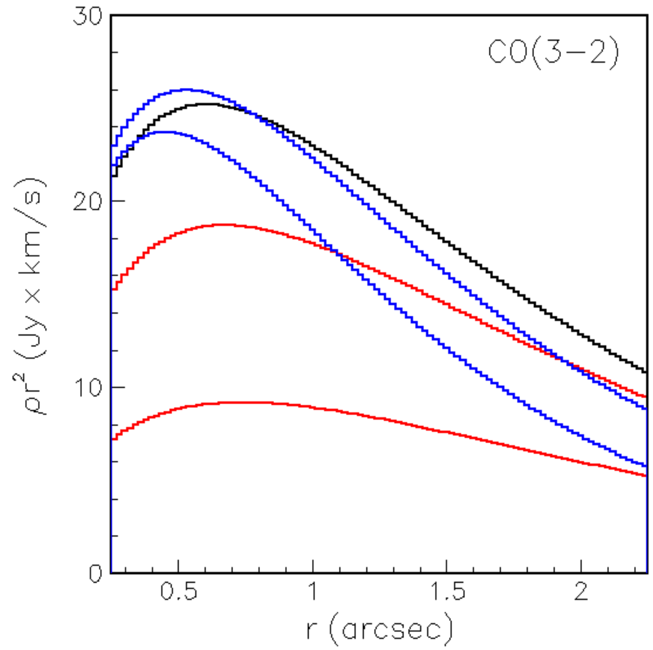


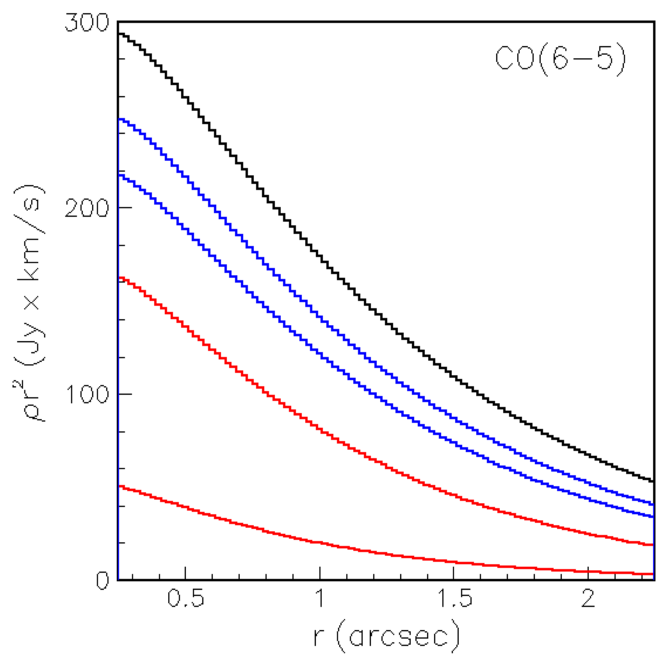
To illustrate the main features, we also seek a **simple parameterization** of the effective density as a product of a function of $r=\sqrt{(\xi^2+z^2)}$ and $\beta=z^2/\xi$.



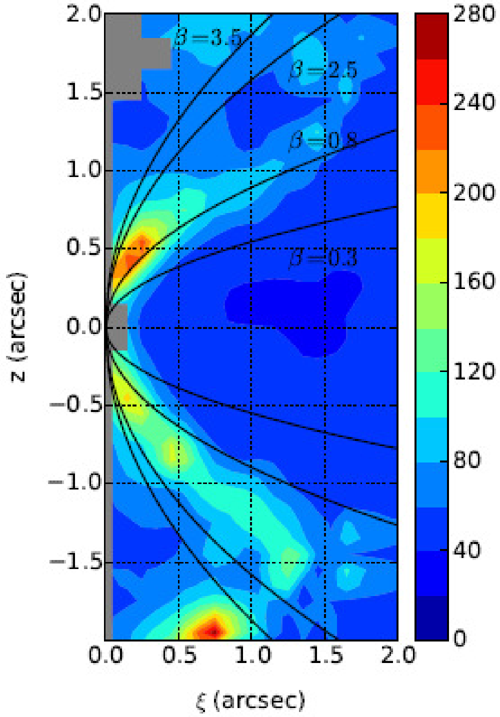


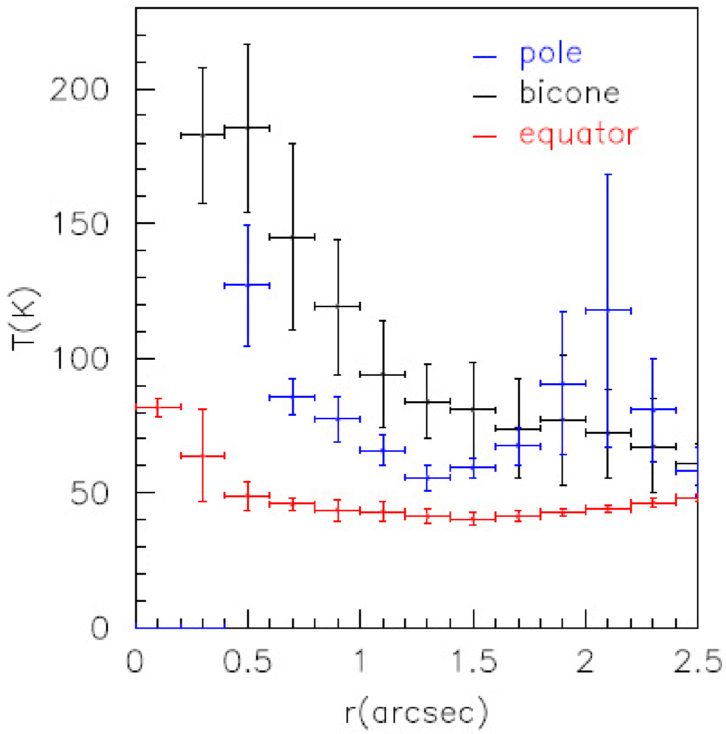
The parametrization shows: **broad latitudinal enhancements** around the bicone, broader for CO(3-2) than for CO(6-5) and **a steep decrease with radius**, faster than $1/r^2$ by an exponential factor of characteristic length ~1”.



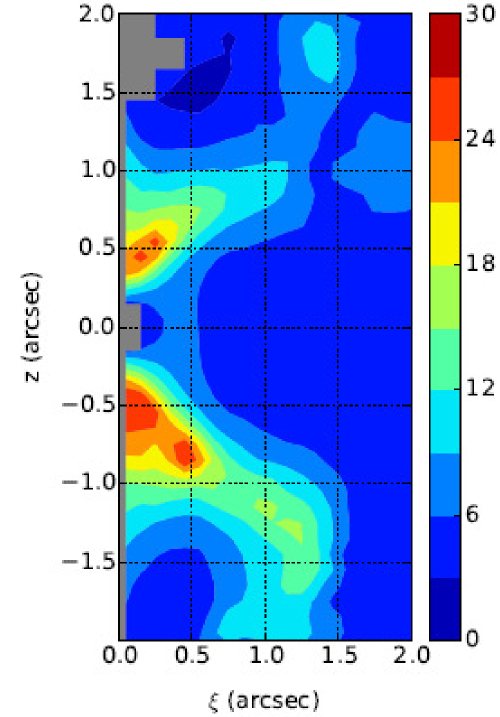


Temperature





Density×r^2



Under the assumption of LTE and neglecting absorption, $\boldsymbol{T=(E_6–E_3)/[k_B ln(C/R_T)]}$ where $(E_6–E_3)/k_B$=82.5 K and C=15.6.

Equatorial region: T decreases slowly from ~60 K (r=0.3") to ~50 K (r=2").

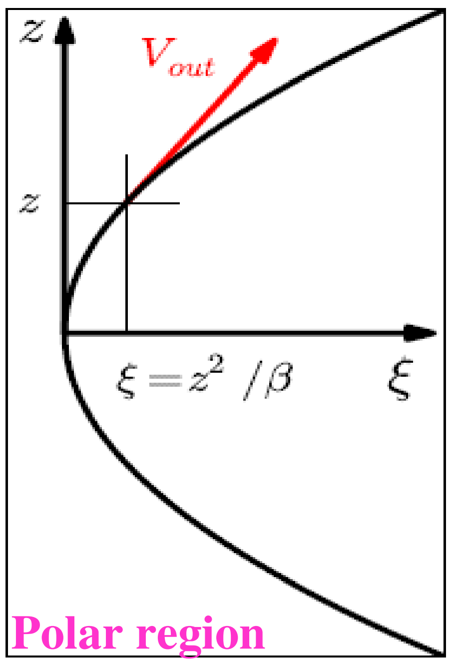
Outflow: T reaches 200 K (r=0.3") and decreases steeply with distance to 80 K (r=1.5").

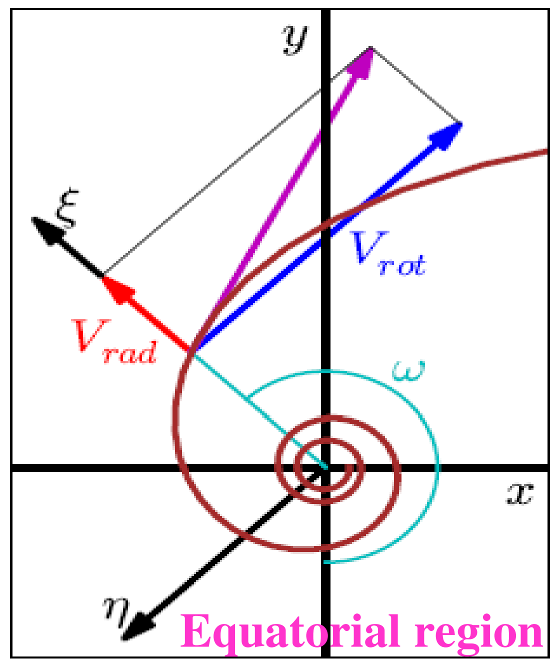
4. Gas kinematics

We model the velocities in **two distinct regions**: an **equatorial region**, $\beta<\beta_0$ and a **plar region**, $\beta>\beta_0$.

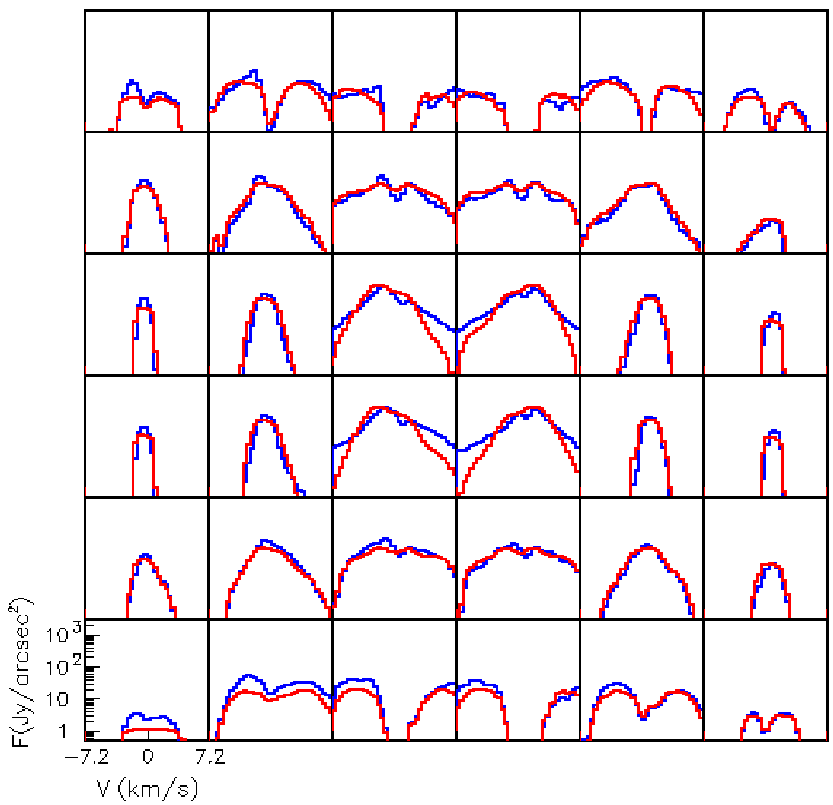
Equatorial region: a rotation velocity around the star axis, $\boldsymbol{V_{rot} r^{-k}}$ and a constant expansion velocity, $\boldsymbol{V_{rad}}$.

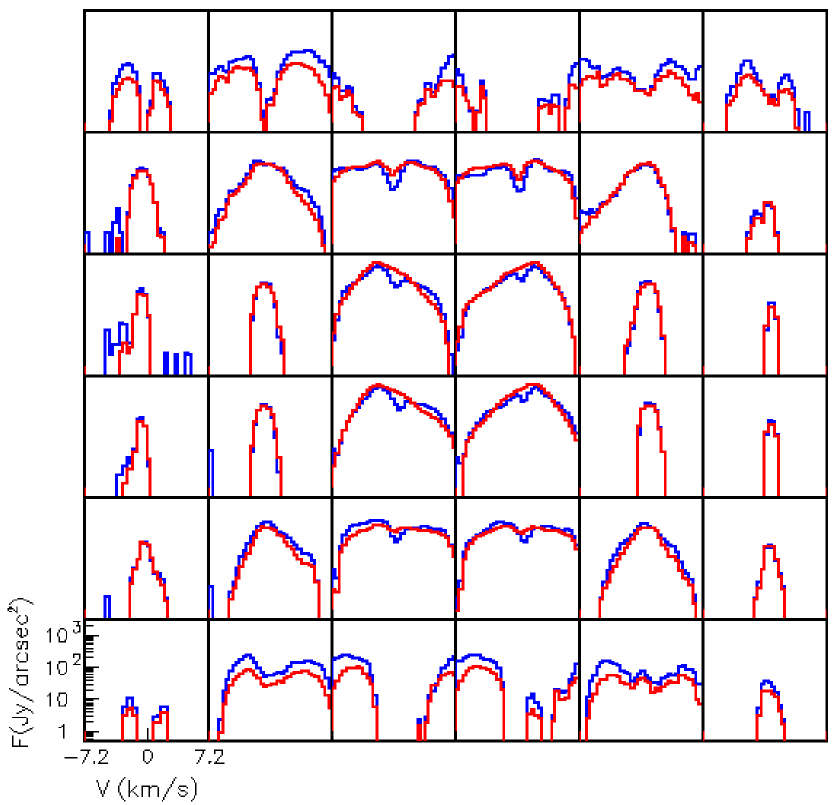
Polar regions: constatnt velocities, $\boldsymbol{V_{out}}$, tangent to parabola having a constant β.



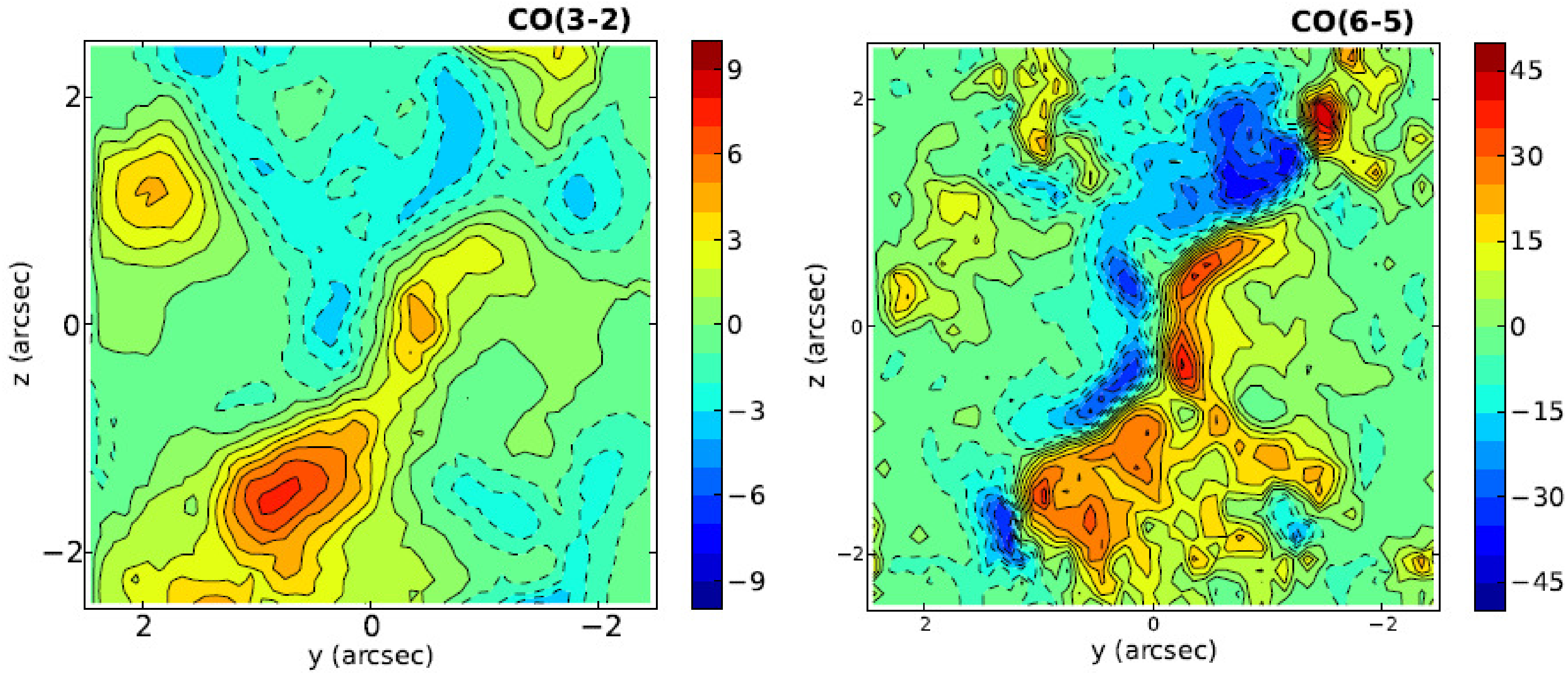


We find β_0~0.8", V_{rot}~−1.0 km/s, k~1, V_{rad}~1.6 km/s
The fit is surprisingly good in view of the crudeness of the model.
(improved when allowing for some Gaussian smearing of the velocity distributions, σ_{pole}=1.4 km/s and σ_{eq}=1.0 km/s).





5. Asymmetries



We map deviations $[F(y,z)-\langle F(y,z)\rangle]R$ from full North-South and East-West symmetry where $\langle F(y,z)\rangle=\frac{1}{4}[F(y,z)+F(-y,z)+F(y,-z)+F(-y,-z)]$. The factor R gives a proper balance between deviations at short distances and large distances from the star.

Important South-East excess, particularly enhanced in the region of the bicone where it reaches ~70%. A more detailed analysis than presented here would need to take such asymmetries into account.

6. Summary and conclusions

ALMA **unprecedented quality** observations of the CO emission of the Red Rectangle have been analysed.

The **effective density** was observed to decrease with distance faster than r^{-2}; The **gas temperature distribution** is evaluated; A **crude model of the calculated effective densities** has been presented.

The study of the **gas kinematics** has revealed a sharp separation between the equatorial and polar regions. The **rotation velocity** decreases with distance with a power index of order unity. The **expansion velocity** is constant across the torus. The **polar regions** are well described by parabolic meridian trajectories with a constant wind velocity on the order of 6 to 7 km/s.

Important **deviations** from a fully symmetric model have been revealed.

These observations are in qualitative **agreement** with the general picture proposed by Men'shchikov et al. (2002).

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