# Molecular observations of Keplerian disks:
# A key element to understand the PN formation and structure

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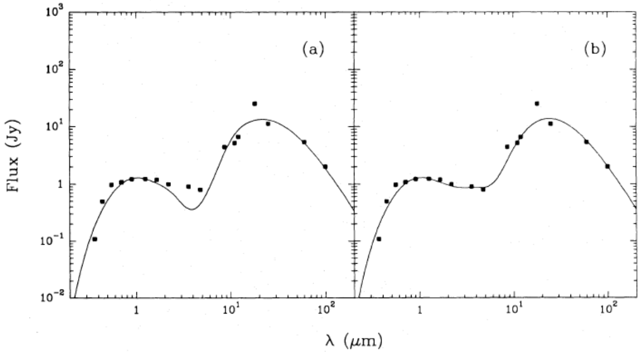
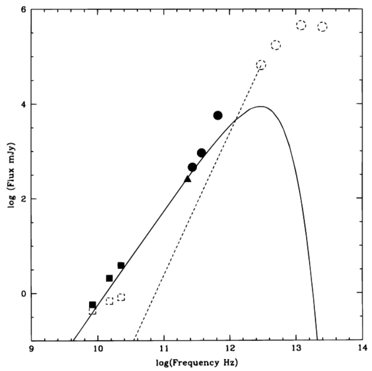
# Indications of stable (probably rotating) discs in some post-AGB nebulae

## Mainly around binary stars

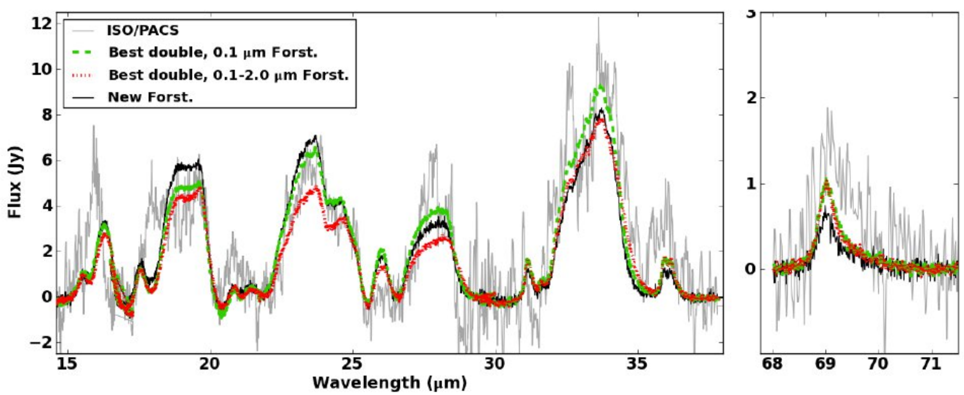



Remarkable NIR excess

Hot dust probably kept close to the star (a few $10^{14}$ cm)




Probable overabundance of large grains




Highly evolved (crystalline) grains

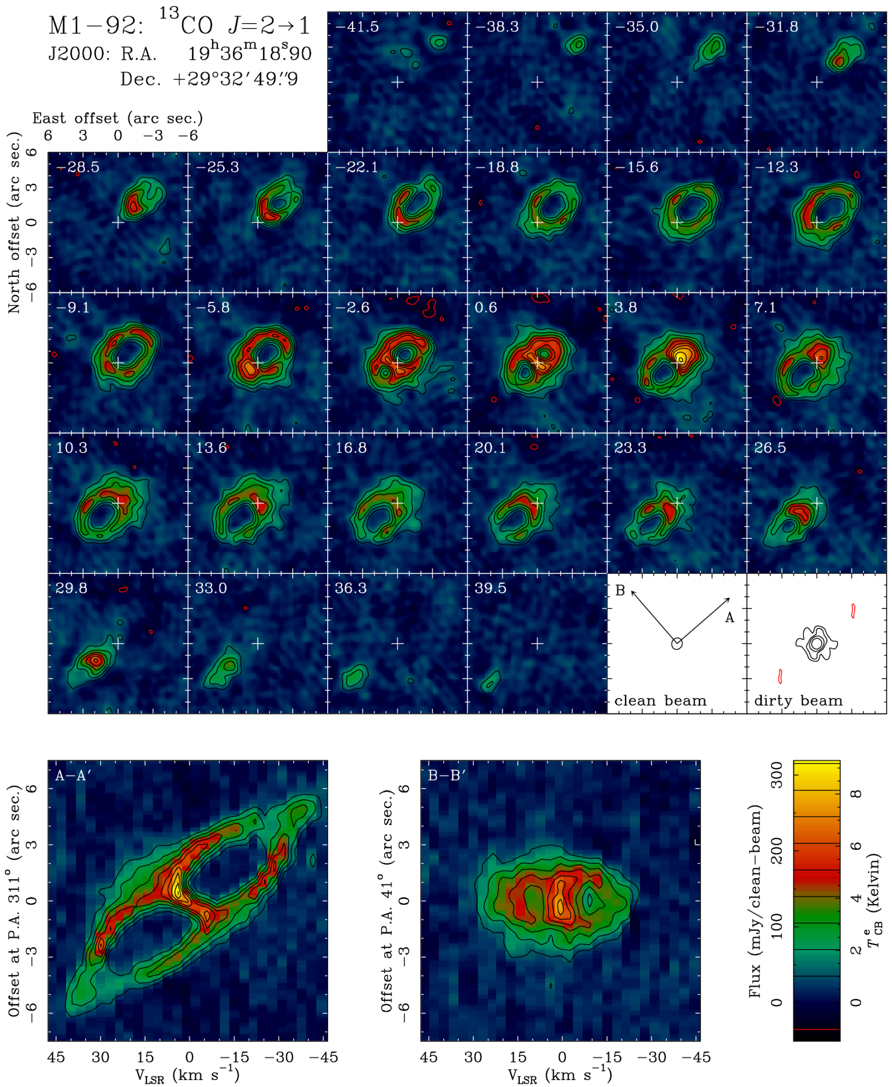
+ possible reaccretion by the star,

elongated central structures, etc

Alcolea & Bujarrabal, 1992, A&A 245, 499; Jura et al., 1997, ApJ 474, 741; Hillen et al., 2015, A&A 578, 40; Van Winckel 1998, ARA&A 41, 391

## Which is the dynamics of the very inner regions of PPNe ?

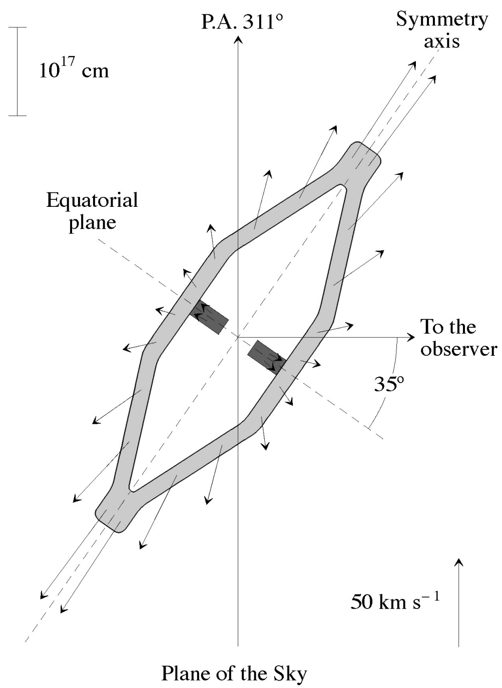
Ballistic expansion (Hubble-like law) is observed at large scale in almost all PPNe !!




CO maps indicate radial expansion with V $\propto$ r

No rotation observed (in most nebulae)

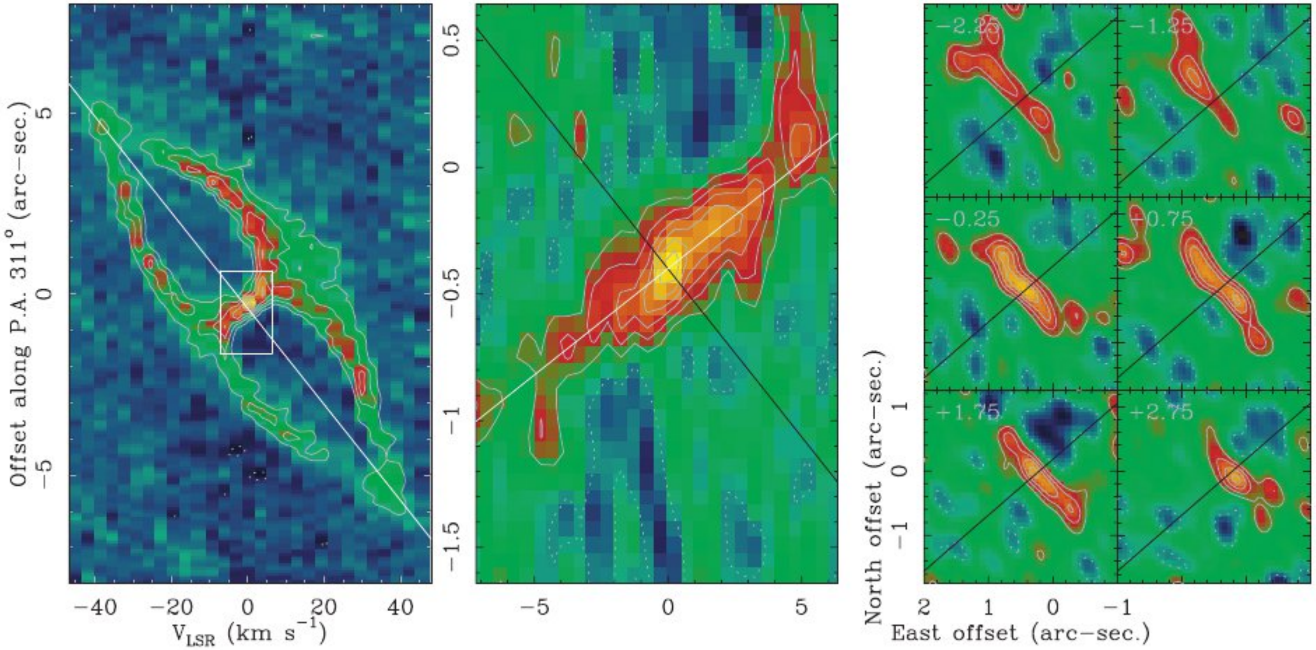
Well described by simple models (down to $\sim 1''$)




Bujarrabal et al., 1998, ApJ 504, 915

# Which is the dynamics of the very inner regions of PPNe ?

M 1–92: higher resolution :




Linear velocity field holds down to 1 km s$^{-1}$ and $0\farcs1$ ($\sim 5\ 10^{15}$ cm) !!

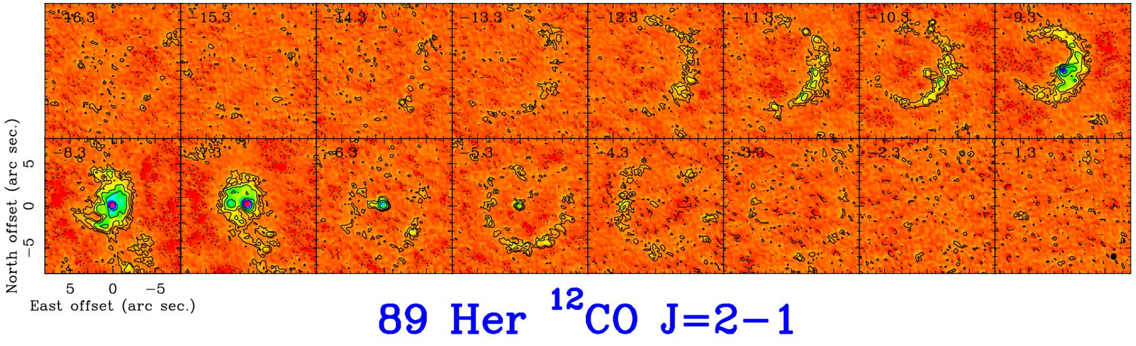
Due to expansion starting from a relat. wide Keplerian disc ? ($V_{exp} \approx$ escape velocity)

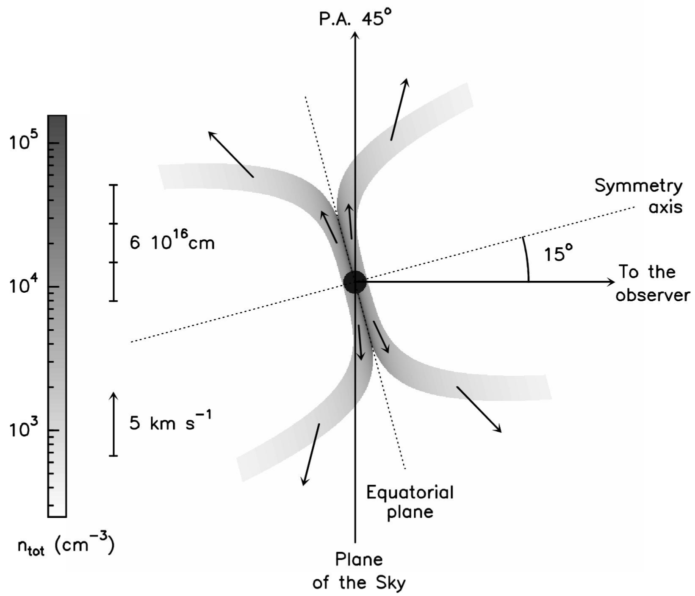
Can we just extrapolate the velocity law down to a few $10^{14}$ cm (the hot-grain region) ?
=> very low expansion velocities ($\lesssim$ 0.1 km s$^{-1}$ !), almost stable

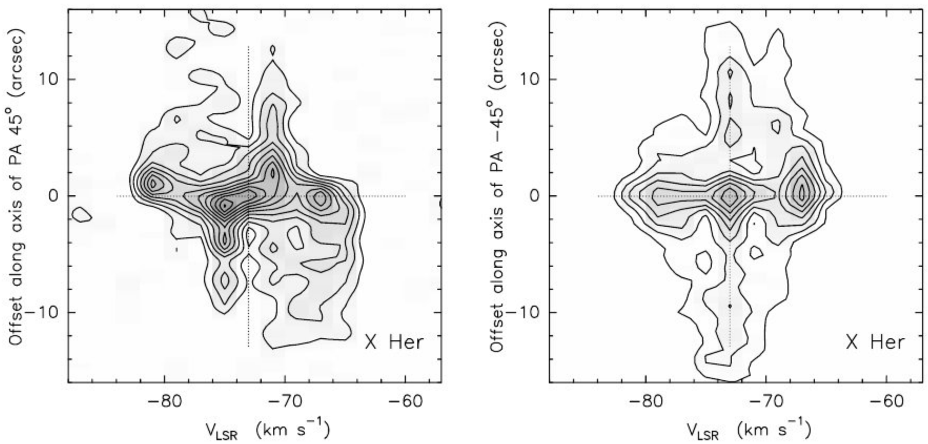
Alcolea et al., 2007, A&A 468, L41

# Which is the dynamics of the very inner regions of PPNe ?

Also appears in NIR-excess post-AGBs and some AGBs




X Her, AGB semiregular-variable star:

bipolar geometry, low-velocity expansion

## Observations of Keplerian discs with high spatial and spectral resolution

Keplerian disks in PPNe are basic to understand post-AGB evolution

– launching of post-AGB jets and PN shaping

– coherent description of nebular structure and dynamics

High spatial and spectral resolution are necessary to demonstrate their existence

– indirect indications are not concluding

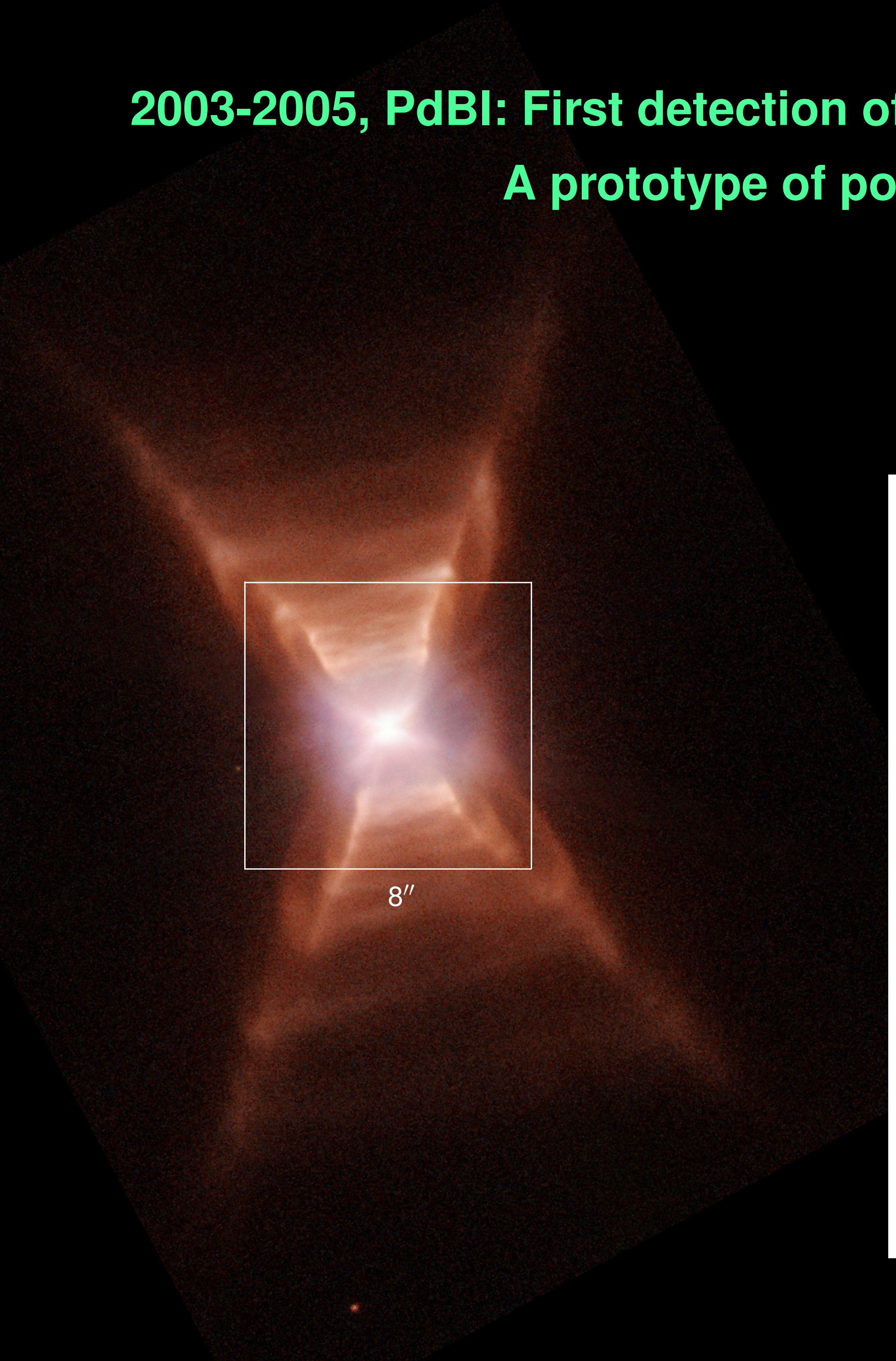
– distinguishing possible dynamics requires accurate information on the gas velocity

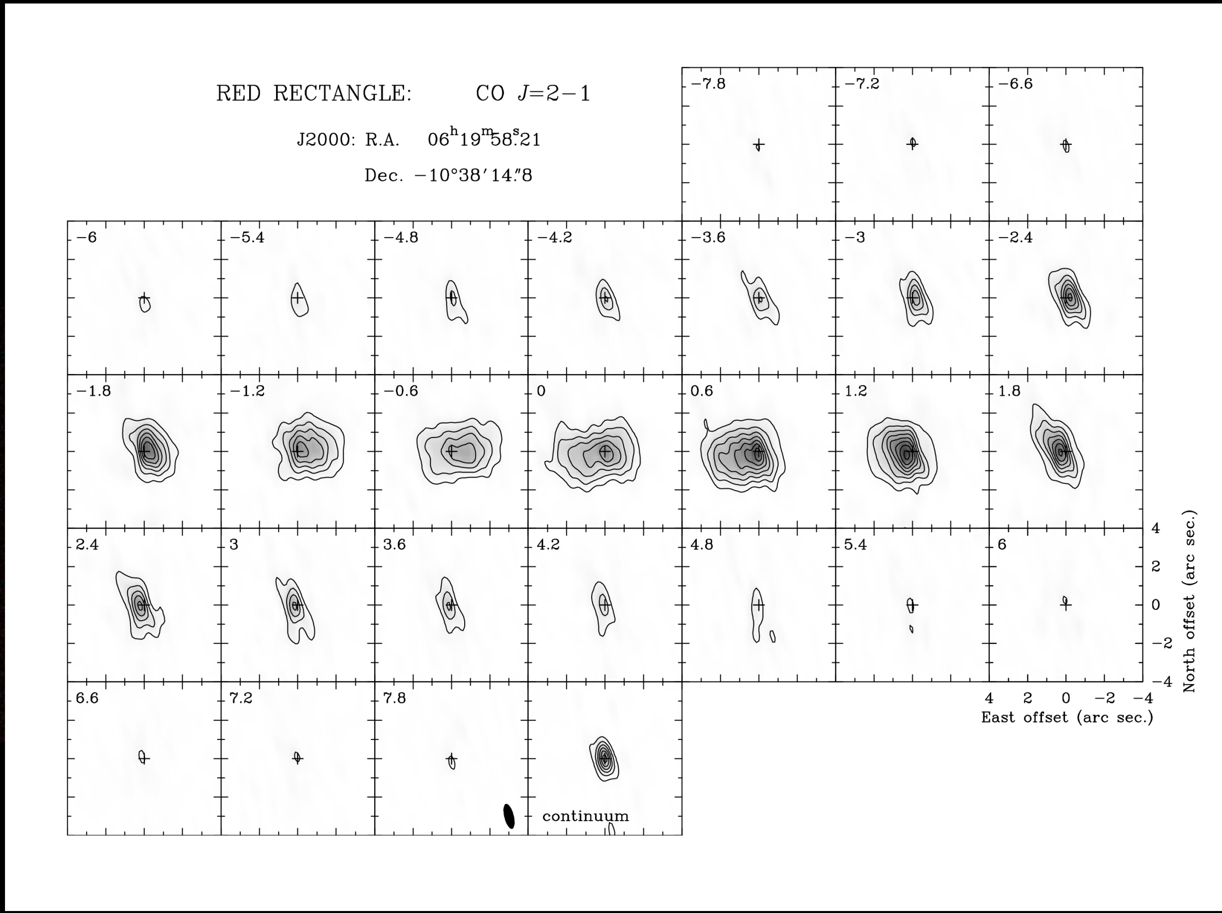
Their properties (mass, extent, dynamics) are still poorly known

– a lot of information has been obtained in the last years

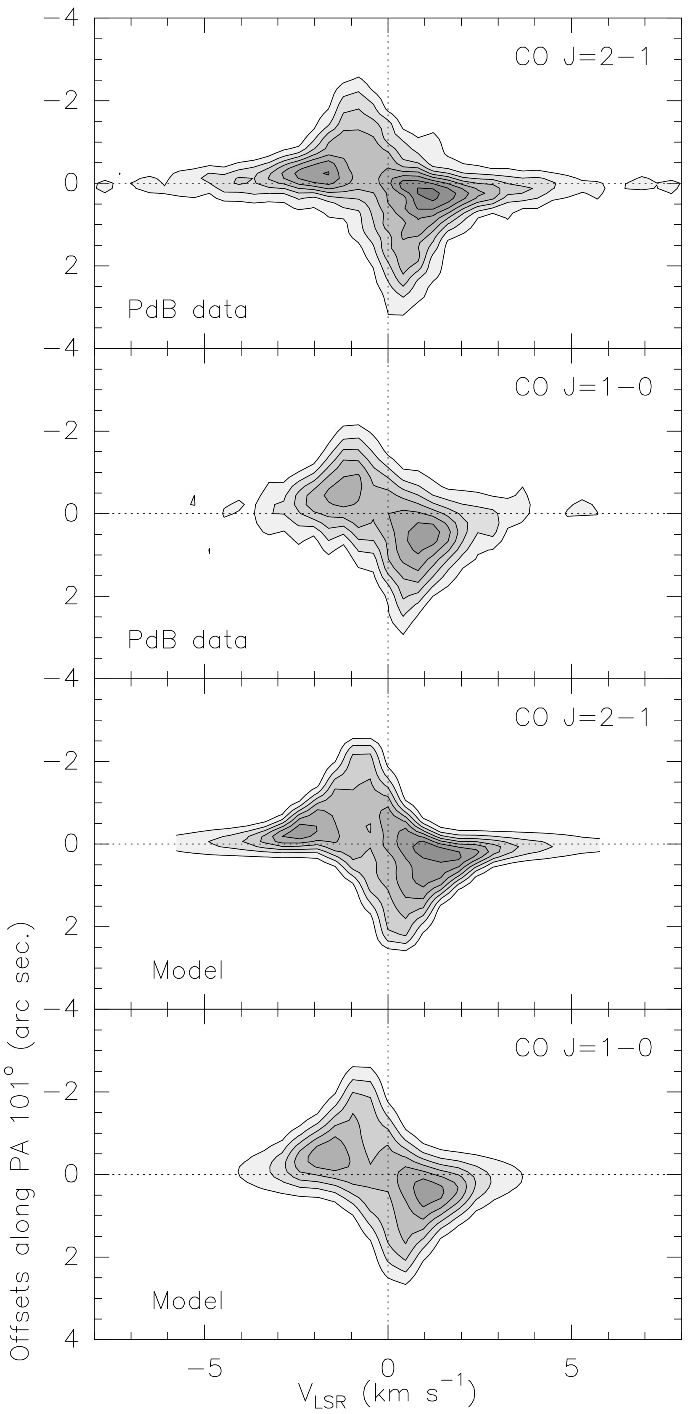
– but a lot is still to be done

# 2003-2005, PdBI: First detection of Keplerian dynamics in the Red Rectangle. A prototype of post-AGB NIR-excess nebula




Bujarrabal et al., 2003, A&A 409, 573; 2005, A&A 441, 103




Disk in rotation

keplerian rotation, up to $r \sim 10^{16}$ cm

central mass (binary star) $\sim 1.5\ M_\odot$

For $r > 10^{16}$ cm :

rotation + a slow equatorial expansion ($\sim 0.8$ km $s^{-1}$)

Total CO detection radius $\sim 2.5\ 10^{16}$ cm

$n \propto r^{-2}$, $n(10^{15}\text{cm}) \sim 10^{8}\ \text{cm}^{-3}$

$T \propto r^{-0.7}$, $T(10^{15}\text{cm}) \gtrsim 100$ K

warm and dense central region

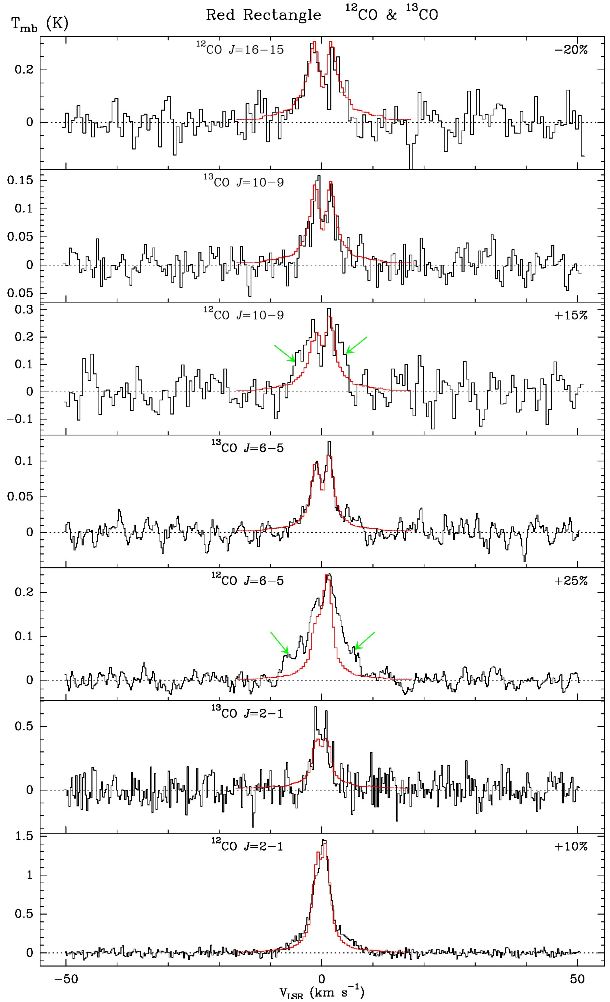
Disk angular momentum $\gtrsim$ stellar companion

=> efficient angular momentum transfer

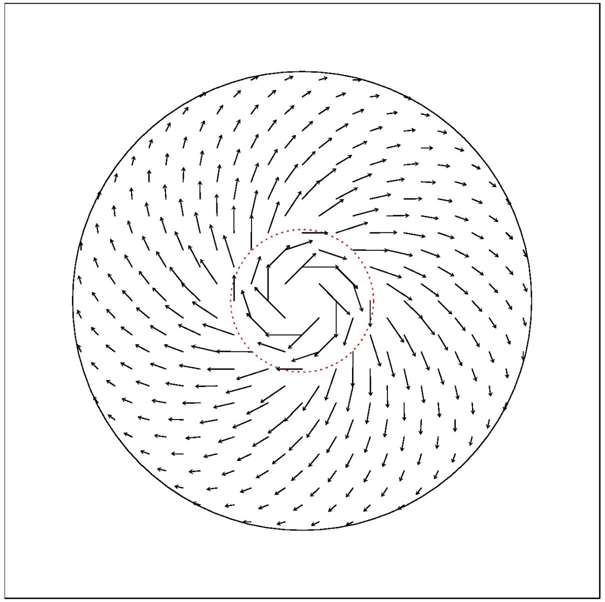
refined using FIR (Herschel/HIFI) spectroscopy

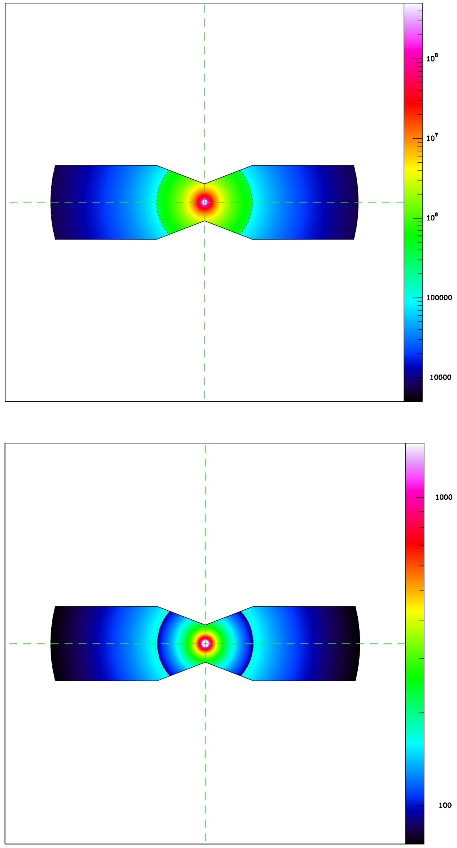
# High-J CO single-dish data in the Red Rectangle and further modeling

Model fitting




Derived velocity, density (cm$^{-3}$), and temperature (K)





Molecular lines come from a rotating equatorial disk

**Sophisticated 2-D non-local treatment required !**

Line-wing excess => bipolar outflow at 3–10 km s$^{-1}$ later confirmed by ALMA maps

Bujarrabal & Alcolea, 2013, A&A, 552, 116

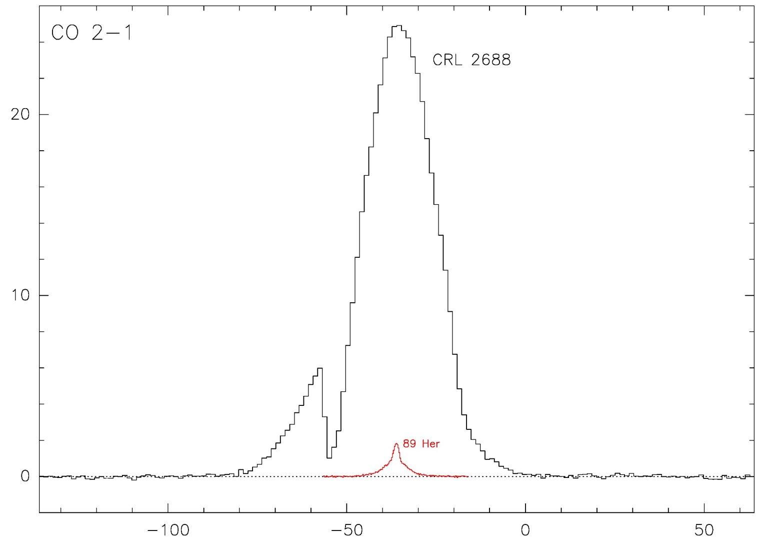
# CO lines from NIR-excess post-AGB objects

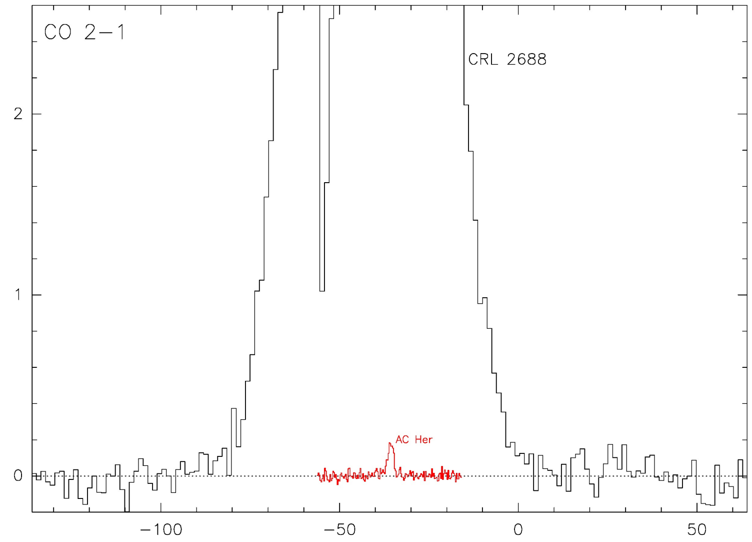
NIR-excess post-AGBs are known to show low nebular mass and velocities

$\sim 0.01\ M_{\odot}$ (including dust shells, molecule-rich shell, PDRs, and ionized gas)

Examples: the Red Rectangle, 89 Her, AC Her, HR 4049, RV Tau variables, ...

Represent $\sim$ 1/2 of low-mass PPNe and are (close) binaries



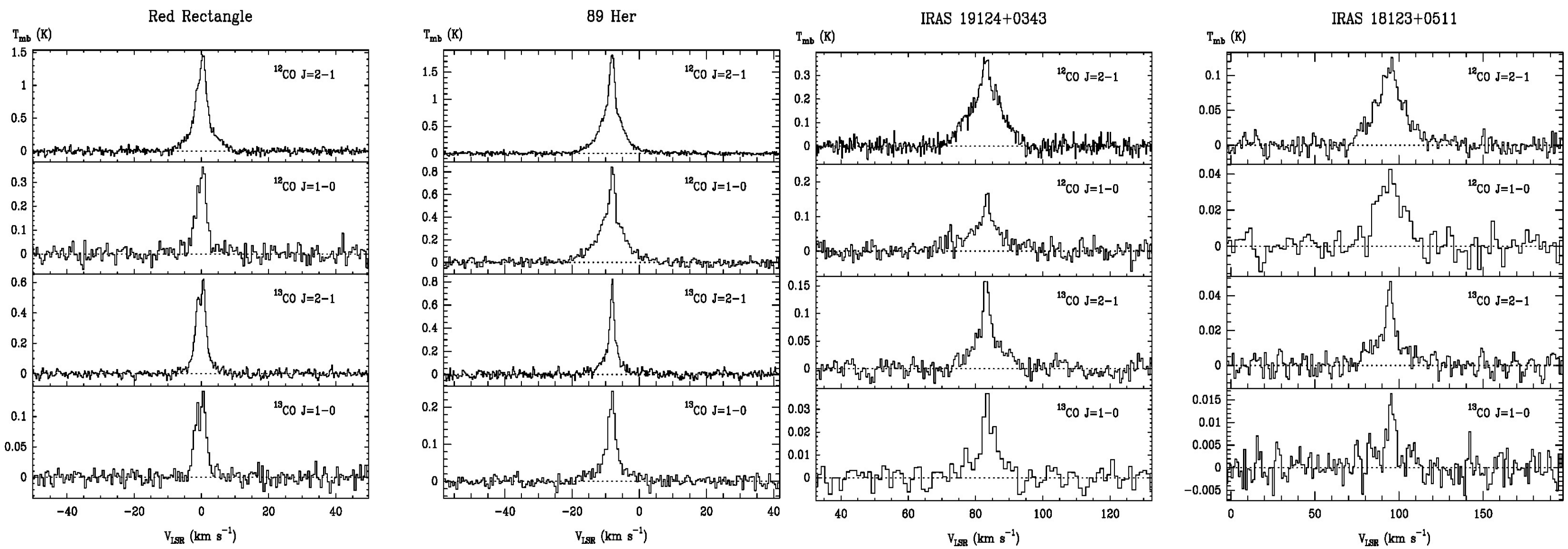

**89 Her:** NIR-excess post-AGB (1 kpc)
strongest NIR-excess source in CO emission

**AC Her:** NIR-excess post-AGB (1.1 kpc)
a good example of CO in a NIR-excess source

**CRL 2688:** *standard* PPN (D = 1.2 kpc) with high mass, velocity, and momentum

# Rotating and expanding gas in NIR-excess post-AGB nebulae: systematic CO single-dish observations

Practically al them (15/19 detected) show narrow profiles indicating a disk in rotation !!




Expansion probably present in most of them (too wide line wings)

Rotation well confirmed by maps in only one object, the Red Rectangle

Expansion confirmed by maps of 89 Her and IRAS 19125+0343

Bujarrabal et al., 2013, A&A 557, 104; A&A 557, L11

# Rotating and expanding gas in low-mass post-AGB nebulae

## Results from CO single-dish data

| Source | disk mass $M_\odot$ | typical size $''$ | cm | outflow mass $M_\odot$ | velocity km $s^{-1}$ | comments |
|---|---|---|---|---|---|---|
| RV Tau | $< 8\ 10^{-3}$ | $<$0.5 | $<1.3\ 10^{16}$ | | | |
| DY Ori | $2\ 10^{-3}$ | 0.37 | $1.1\ 10^{16}$ | | | |
| Red Rectangle | $10^{-2}$ | 2 | $2.3\ 10^{16}$ | $10^{-3}$ | 3 – 13 | PdB & ALMA maps |
| U Mon | $< 9\ 10^{-4}$ | $<$0.4 | $< 5\ 10^{15}$ | | | |
| AI CMi | $10^{-2}$ | 1.2 | $2.7\ 10^{16}$ | $\sim 10^{-2}$ | $\sim$ 4 | difficult est. |
| HR 4049 | $6.3\ 10^{-4}$ | 0.6 | $6\ 10^{15}$ | | | |
| 89 Her | $1.4\ 10^{-2}$ | 1.5 | $2.3\ 10^{16}$ | $10^{-2}$ | 3 – 7 | good PdB maps |
| IRAS 18123+0511 | $4.7\ 10^{-2}$ | 0.6 | $3\ 10^{16}$ | $\sim 10^{-2}$ | $\sim$ 15 | difficult estimates |
| AC Her | $8.4\ 10^{-4}$ | 0.7 | $1.1\ 10^{16}$ | | | |
| R Sct | $\sim 7\ 10^{-3}$ | $\sim$ 1 | $\sim 1.5\ 10^{16}$ | $4\ 10^{-2}$ | 10 | complex profile |
| IRAS 19125+0343 | $10^{-2}$ | 1 | $2.3\ 10^{16}$ | $4\ 10^{-3}$ | 5 – 12 | PdB maps |
| IRAS 19157–0247 | $1.4\ 10^{-2}$ | 0.7 | $3\ 10^{16}$ | | | |
| IRAS 20056+1834 | $\sim 2.5\ 10^{-2}$ | $\sim$0.6 | $\sim 1.7\ 10^{16}$ | $\sim 7\ 10^{-2}$ | $\sim$ 10 | complex profiles |
| R Sge | $< 9\ 10^{-3}$ | $<$0.3 | $<7\ 10^{15}$ | | | |
| IRAS 08544–4431 | $\sim 7.7\ 10^{-3}$ | 2.2 | $1.8\ 10^{16}$ | $\sim 2\ 10^{-3}$ | $\sim$ 5 | from $^{12}$CO data |
| IW Car | $\sim 5.3\ 10^{-3}$ | 1.3 | $2\ 10^{16}$ | | | from $^{12}$CO data |
| HD 95767 | $\sim 1.2\ 10^{-3}$ | 0.6 | $1.3\ 10^{16}$ | | | from $^{12}$CO data |
| HD 108015 | $\sim 2.3\ 10^{-2}$ | 1.2 | $3\ 10^{16}$ | | | from $^{12}$CO data |

**low mass**, $10^{-3} - 5\ 10^{-2}\ M_\odot$

**low velocity**, $3 - 10$ km $s^{-1}$

small size

important group of post-AGBs

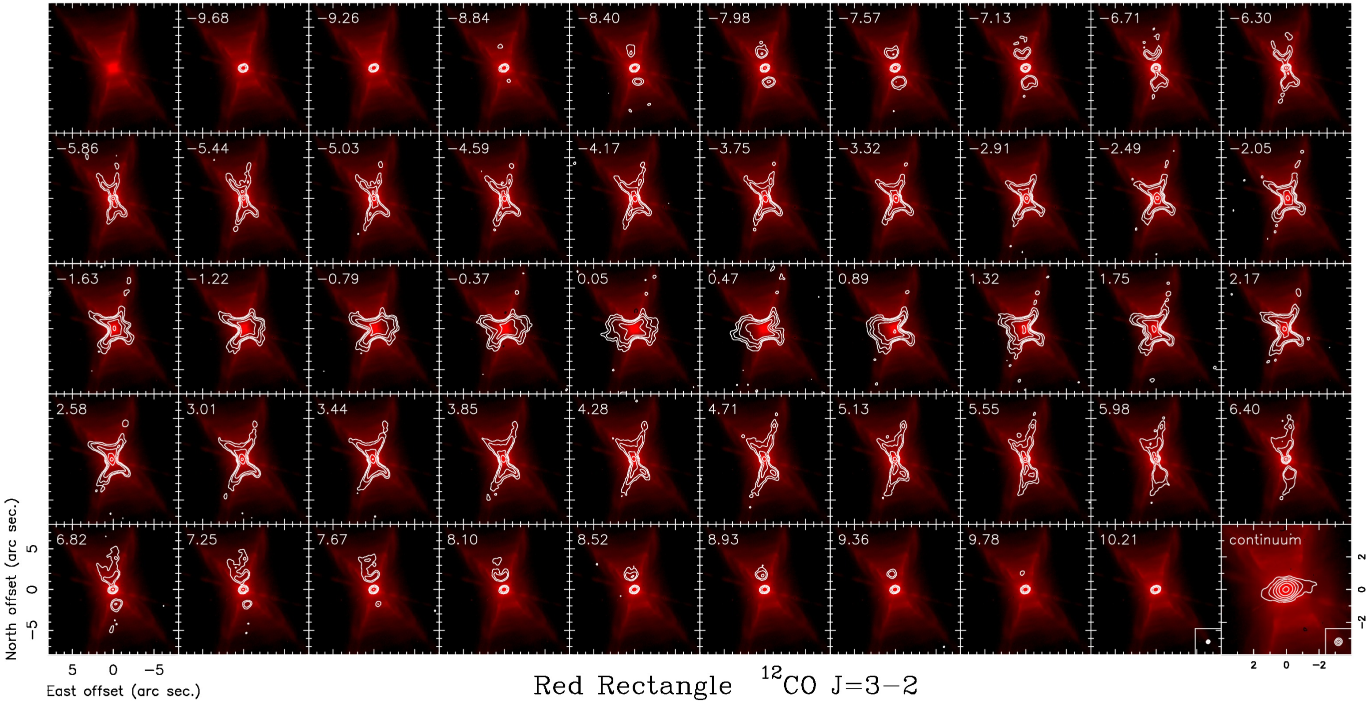
**which evolution ??**

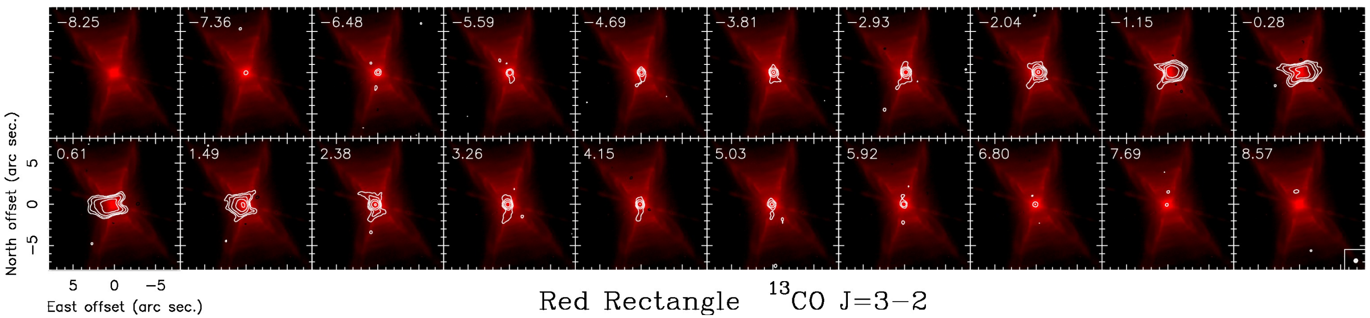
**resulting PNe ??**

maps only for 3 sources

# High-quality ALMA maps of the Red Rectangle

## $^{12}$CO and $^{13}$CO J=3–2 (0.8 mm)




both rotation and expansion !

rotational equatorial disk +

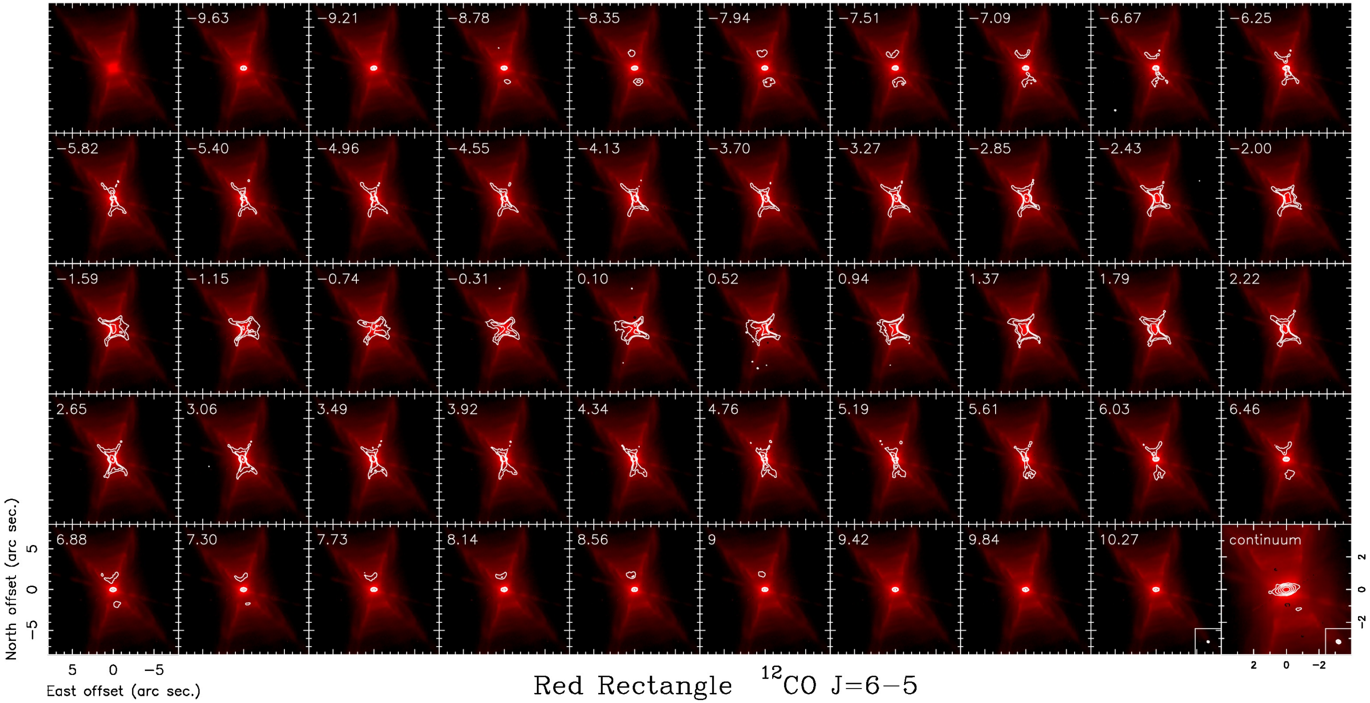
expanding gas between equator and X-shaped nebula

High resolution and sensitivity

outflow almost not det. in $^{13}$CO

Bujarrabal et al. 2013, A&A 557, L11

# High-quality ALMA maps of the Red Rectangle : particularly intense outflow in $^{12}$CO J=6–5 (0.4 mm)




0″.25 arcsec resolution !

high exc. line ($\gtrsim$ 100 K)

–> $T_k$

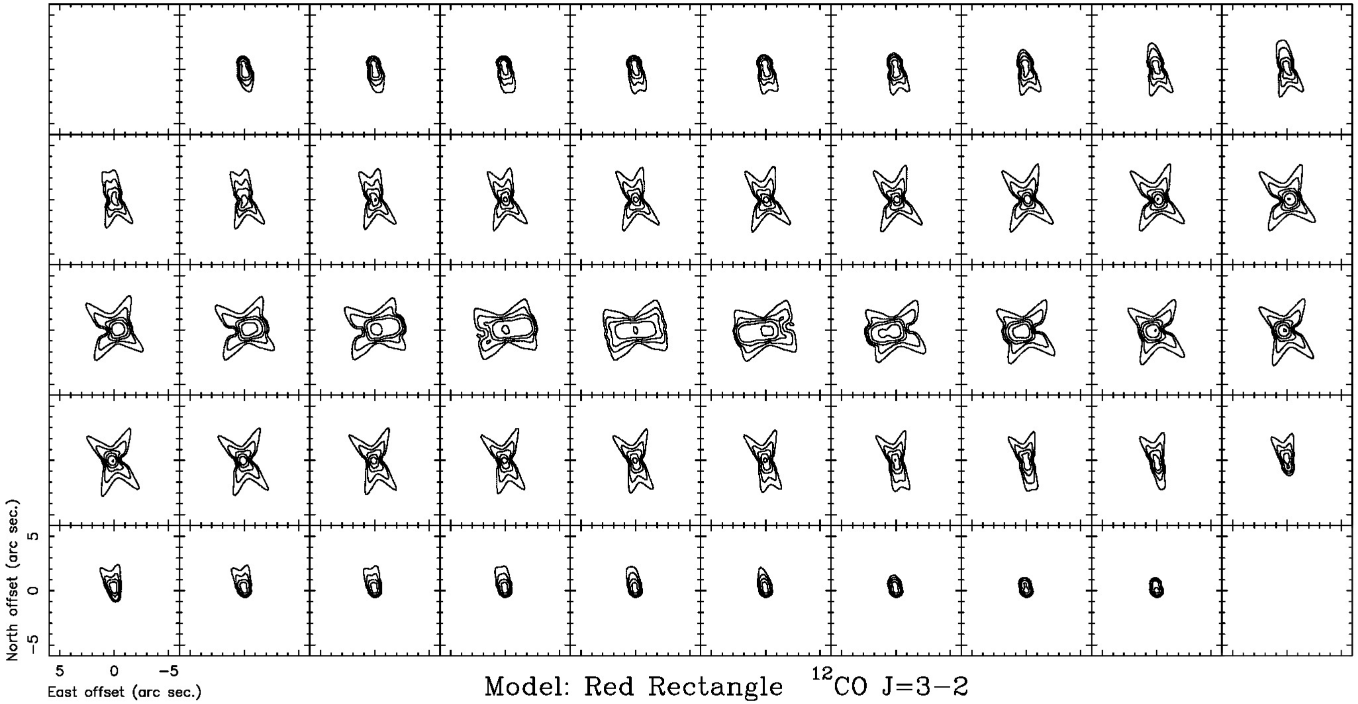
+ properties of the outflow

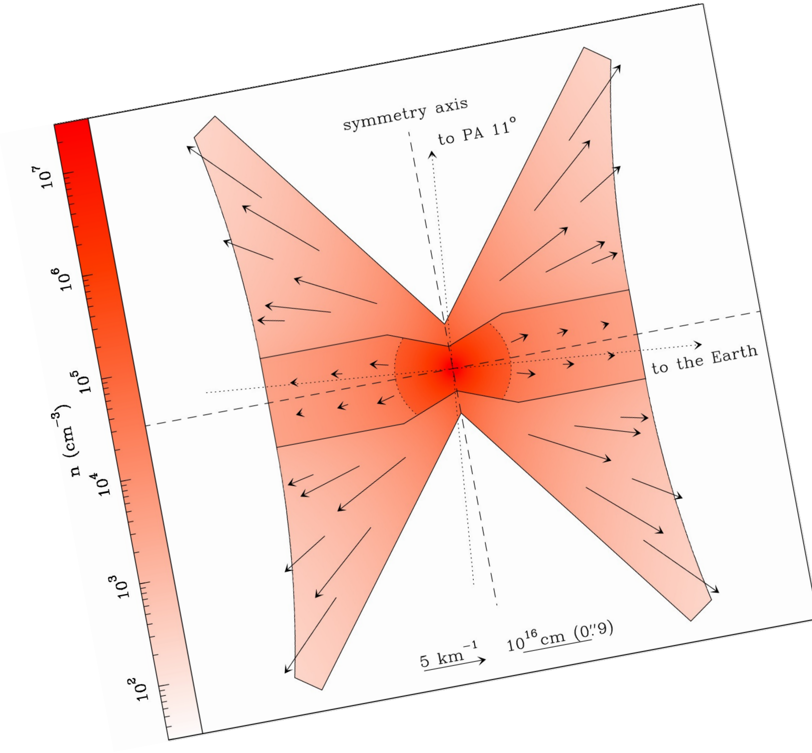
Challenging observations – excellent maps, high resolution and S/N

Note the continuum (dust) extent in the equatorial direction

## High-quality ALMA maps of the Red Rectangle

## **preliminary** LTE modeling of $^{12}$CO J=3–2




outflow structure, density & velocity

$T_k \gtrsim$ 200 K; rotation not displayed

Moderate mass, velocity, and linear momentum

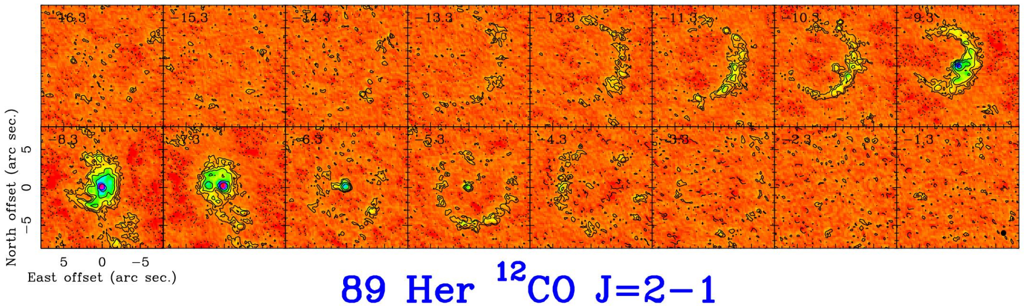
We interpret: material extracted from the disk –> limit to the disk lifetime

These results may apply to all sources of this kind

## But other similar objects only showed expansion in high-resolution maps ...

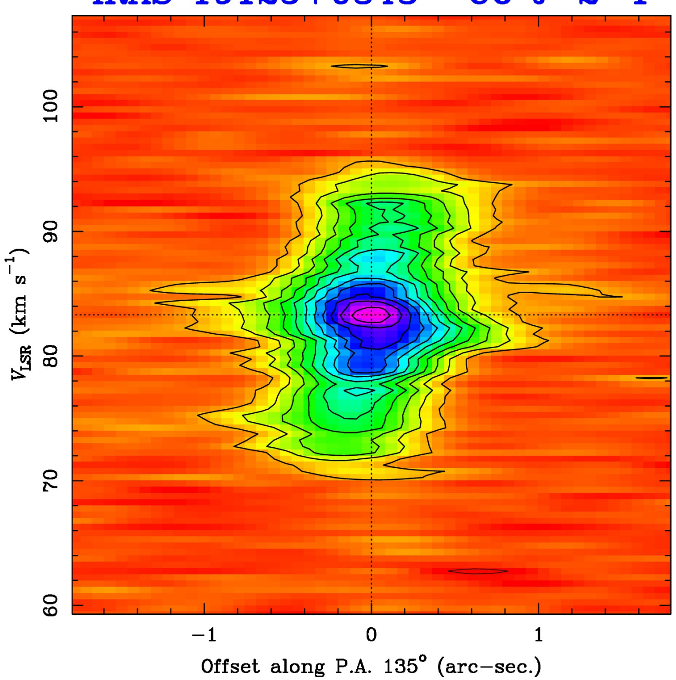
Two sources showing disk-like profiles had been mapped (other than the RR)

Even in them, expansion dominates




89 Her $^{12}$CO J=2−1

IRAS 19125+0343 $^{12}$CO J=2−1




indications of a central condensation

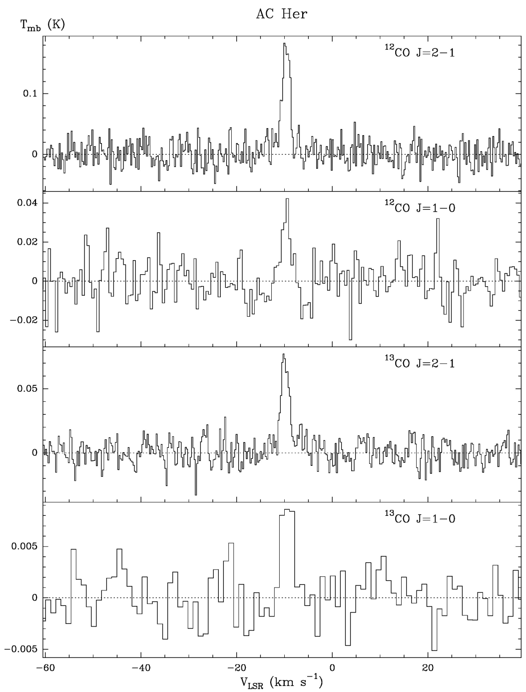
but only expansion was really detected

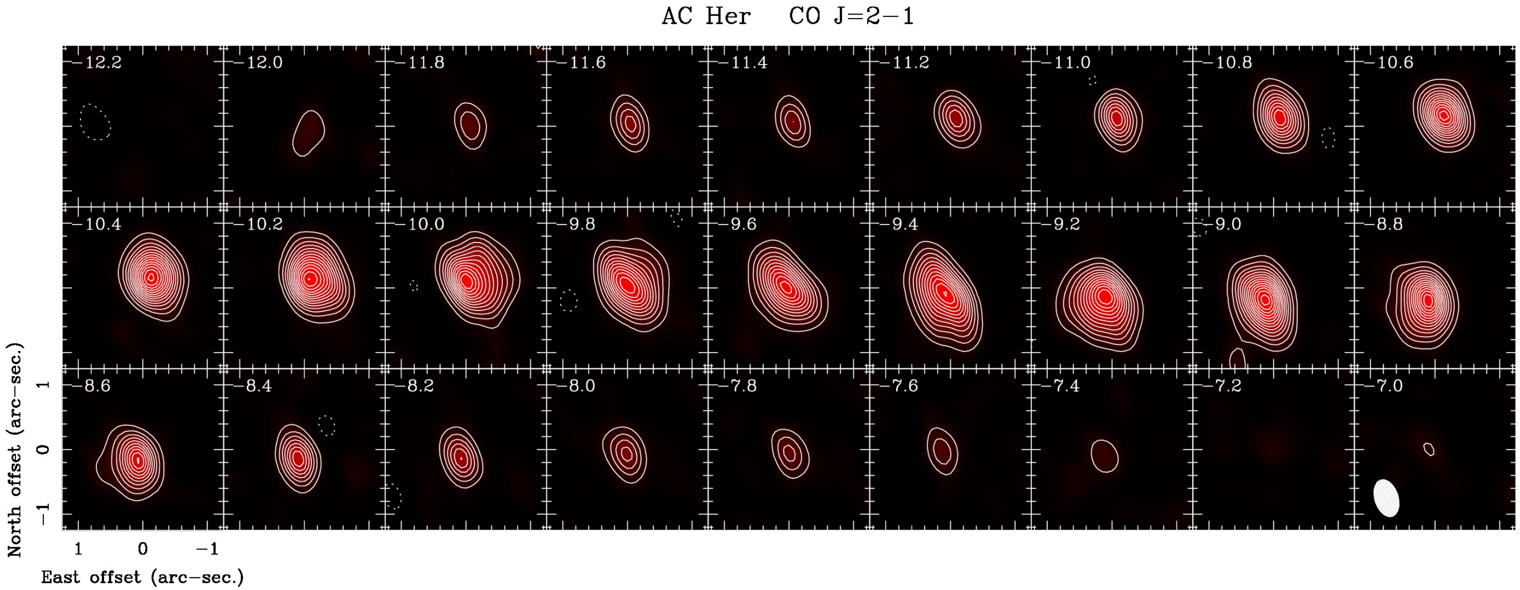
**evidence of Keplerian dynamics only in one object:**

**the Red Rectangle**

# Recent detection of a second Keplerian disk around a post-AGB star: AC Her (uff!)

Remarkable NIR-excess source with **narrow weak-wing** CO lines




PdB maps hardly resolved the disk

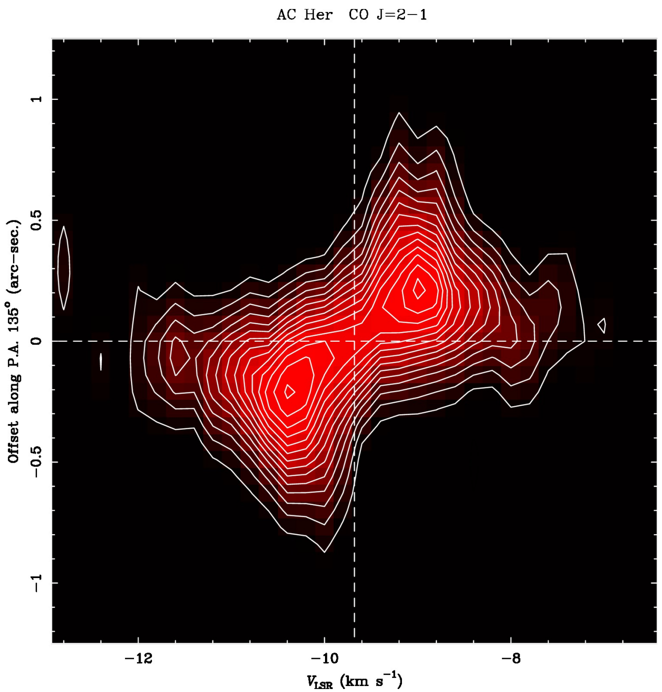
Peak $\sim$ 25 K ($\sigma \sim$ 0.45 K)

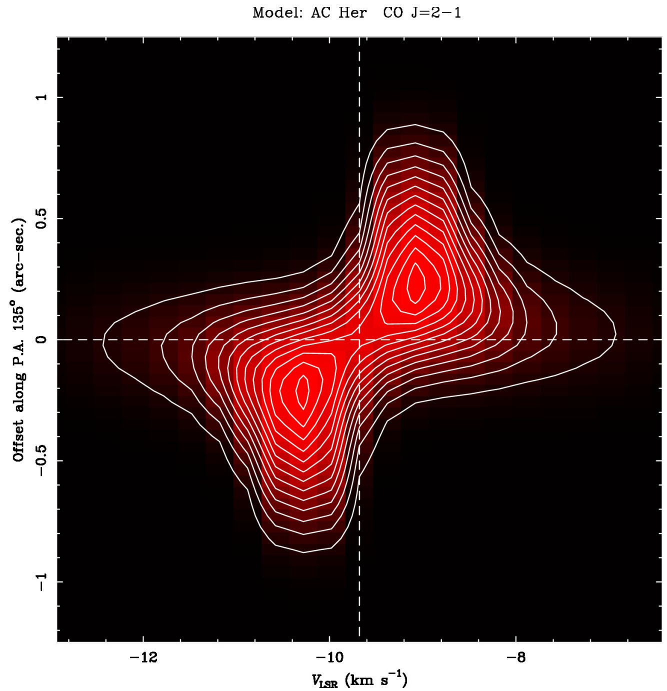
Low velocity dispersion $\Delta V \sim 4.5$ km s$^{-1}$

**Lack of expansion helped to detect the disk**

Bujarrabal et al. 2015, A&A 575, L7

# A Keplerian disk around the post-AGB star AC Her: models




Keplerian dynamics is well detected

No sign of expansion was found in those maps

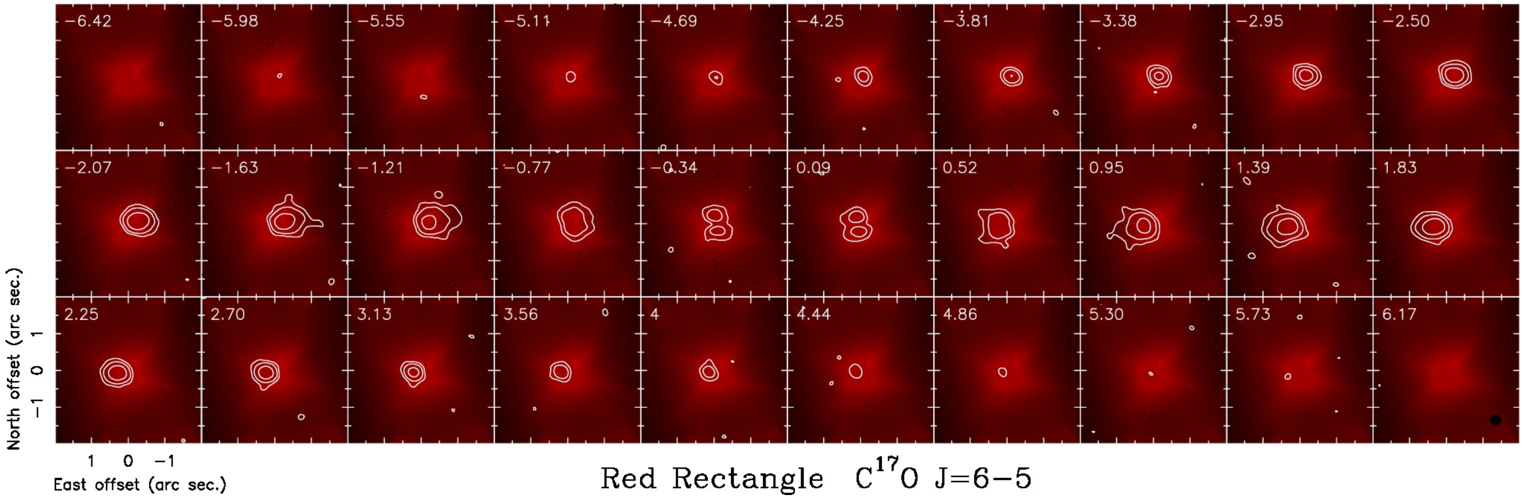
Similar central (stellar) mass than the Red Rectangle $\sim 1.5\ M_\odot$

But smaller disk extent ($3.5\ 10^{16}$ cm) and mass ($1.5\ 10^{-3}\ M_\odot$), lower temp. (80 – 20 K)

Less efficient transfer of angular mom. Wide variety of properties in post-AGB disks !!

RECENT PdBI DATA UNDER ANALYSIS

# Further ALMA observations and models of the disk in the Red Rectangle




$C^{17}O$ J=6–5 is well detected in the disk (not from the outflow)

Peak $\gtrsim$ 50 K, logarithmic contours starting at 2.54 K and varying by a factor 3 (!!)

**again, high quality maps:** high S/N $\sim$ 100 and resolution $0''.31 \times 0''.26$

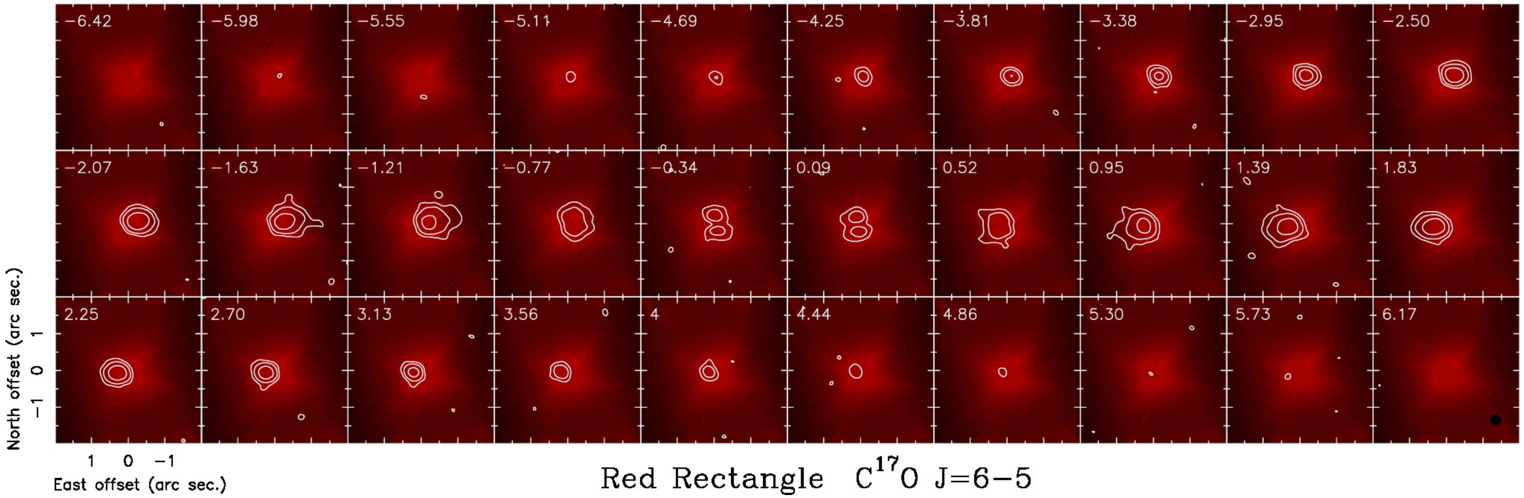
Optically thin emission (but not very optically thin), coming from the inner disk

Careful 2D treatment of radiative transfer and excitation required

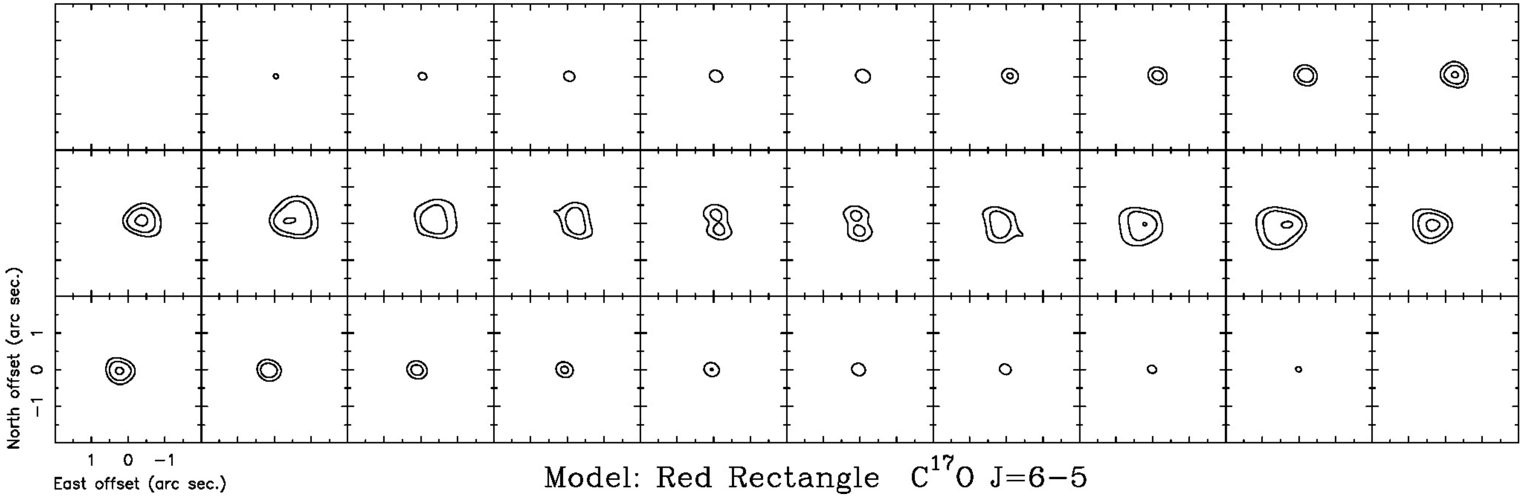
but important information on the inner disk properties are expected

Bujarrabal et al. 2015, in preparation

# Further ALMA observations and models of the disk in the Red Rectangle

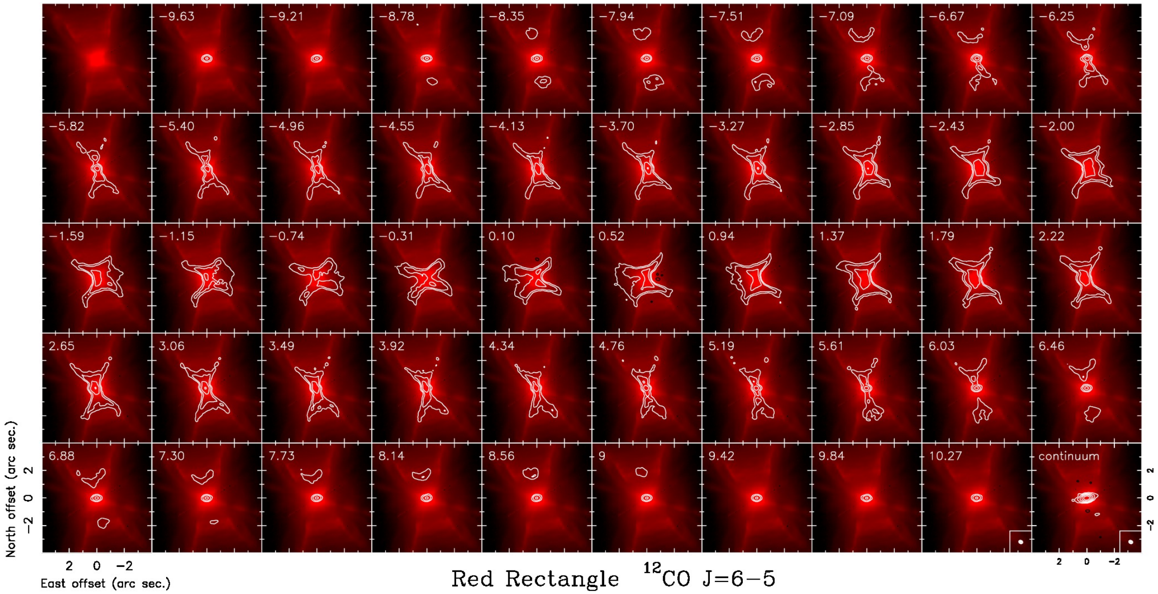


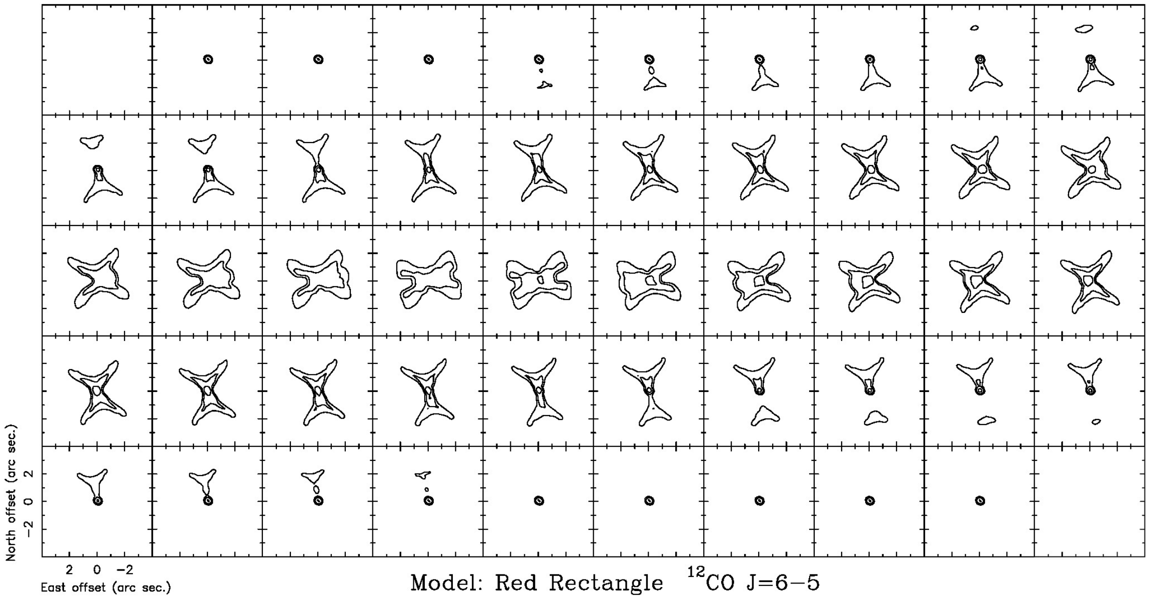

Red Rectangle $C^{17}O$ J=6−5




Model: Red Rectangle $C^{17}O$ J=6−5

# Improved modeling of the disk in the Red Rectangle



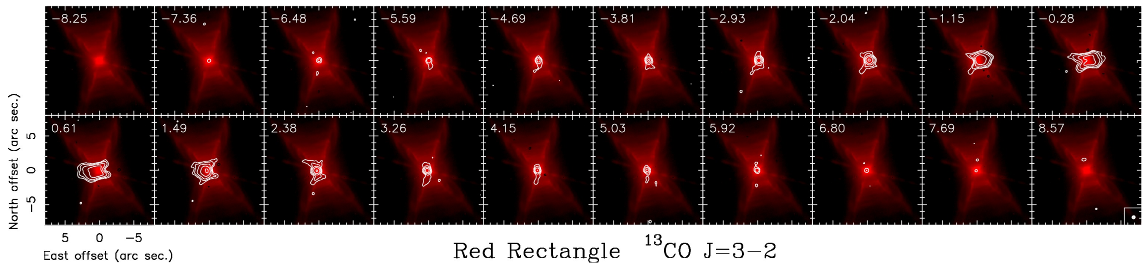

Models also of more intense lines

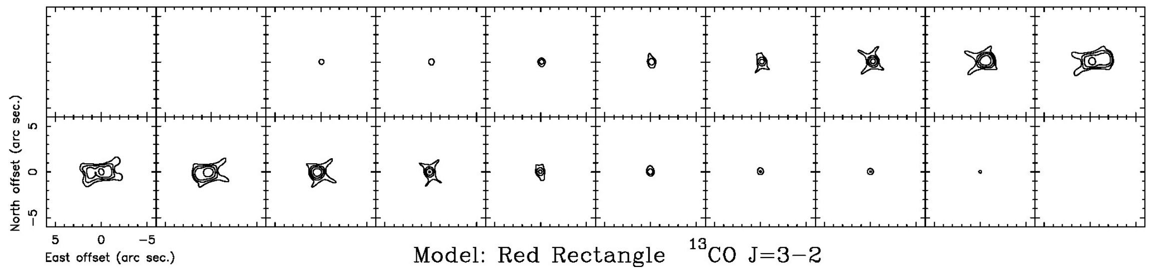
- outflow physical conditions
- very inner regions
- outer disk
- effects of n, T and X(mol)

But it's a lot of work !

... still in progress

# Improved modeling of the disk in the Red Rectangle



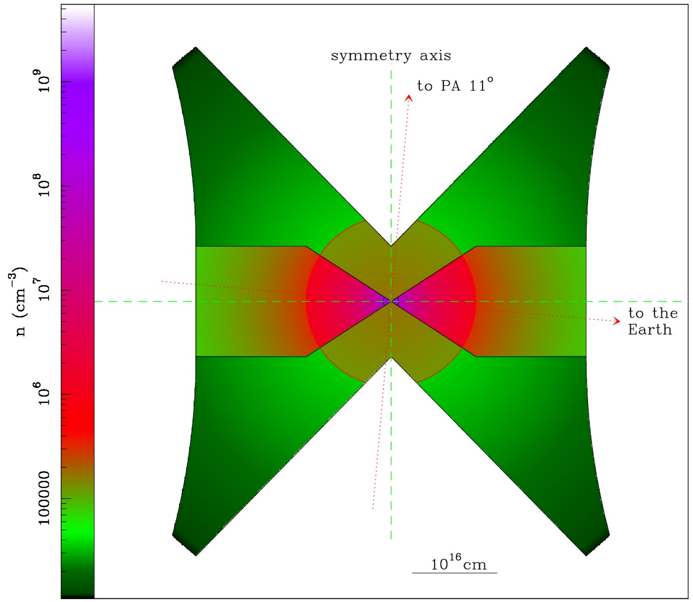

we detect CO emission at $\pm$ 7 km s$^{-1}$ => no inner hole larger than 40 AU

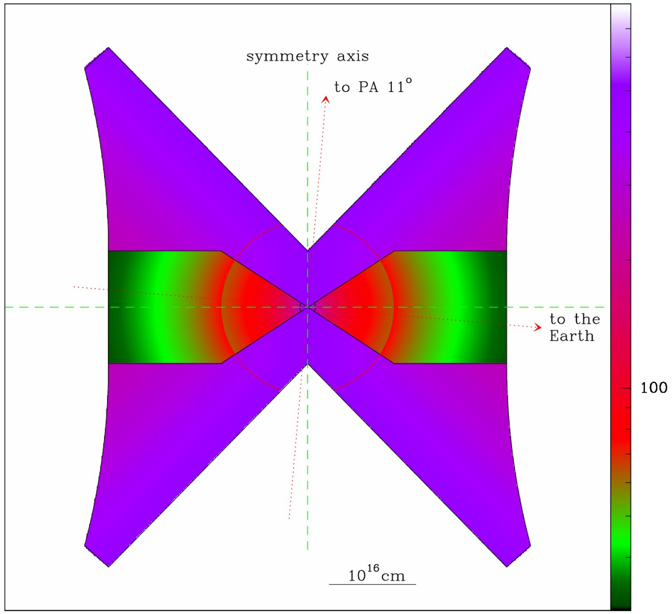
compatible with dust emission models

But not compatible with strong increase of the density proposed by some authors within $\sim$ 100 – 200 AU (by orders of magnitude): emission at $\pm$ 4 – 5 km s$^{-1}$ is weak

dust models: Men'shchikov et al., 2002, A&A 393, 867; Meixner et al. 2002, ApJ 571, 936; Hillen et al., 2015, A&A 578, 40; Speck et al., 2015, ApJ in press, arXiv:1506.03110; etc

# New model of the Red Rectangle disk and outflow: density and temperature



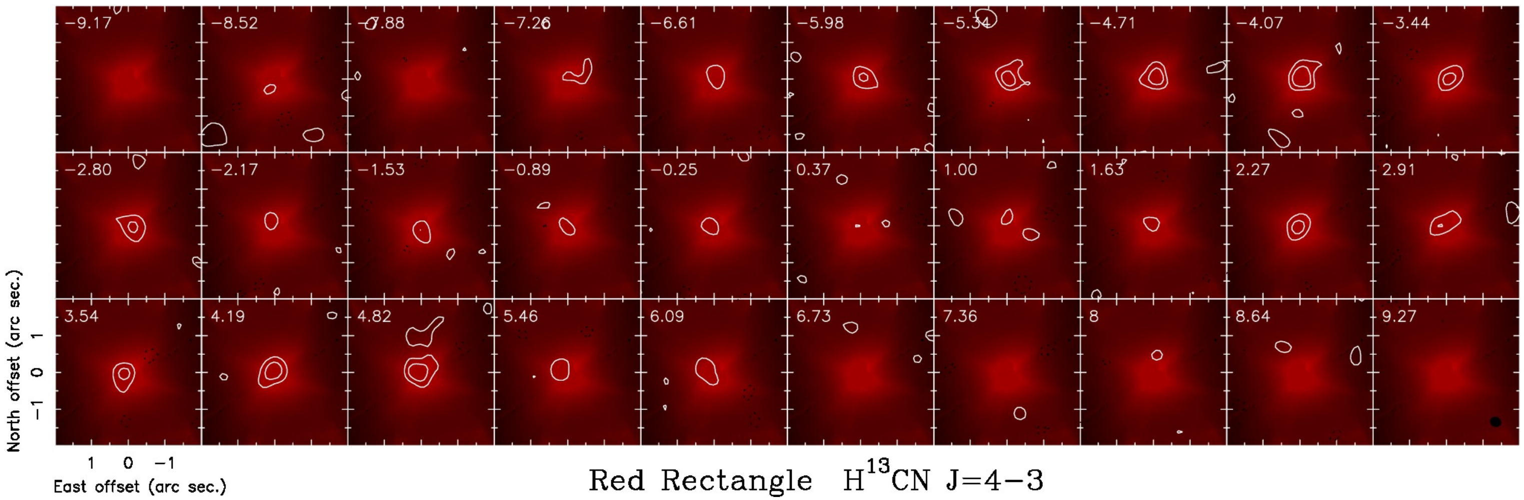

Better description of the central regions:

- Strong increase of the density but smaller size
- Temperature also increases
- No sign of collapse
- No sign of large increase of the density
- Central empty region ($\gtrsim$ 40 AU) not discarded

Model is kept very simple

(velocity is not represented)

## ALMA maps of $H^{13}CN$ J=4–3 in the Red Rectangle




The Red Rectangle and similar objects are poor in molecular lines

ALMA maps of $H^{13}CN$ J=4–3: first detection besides lines of CO and isotopes

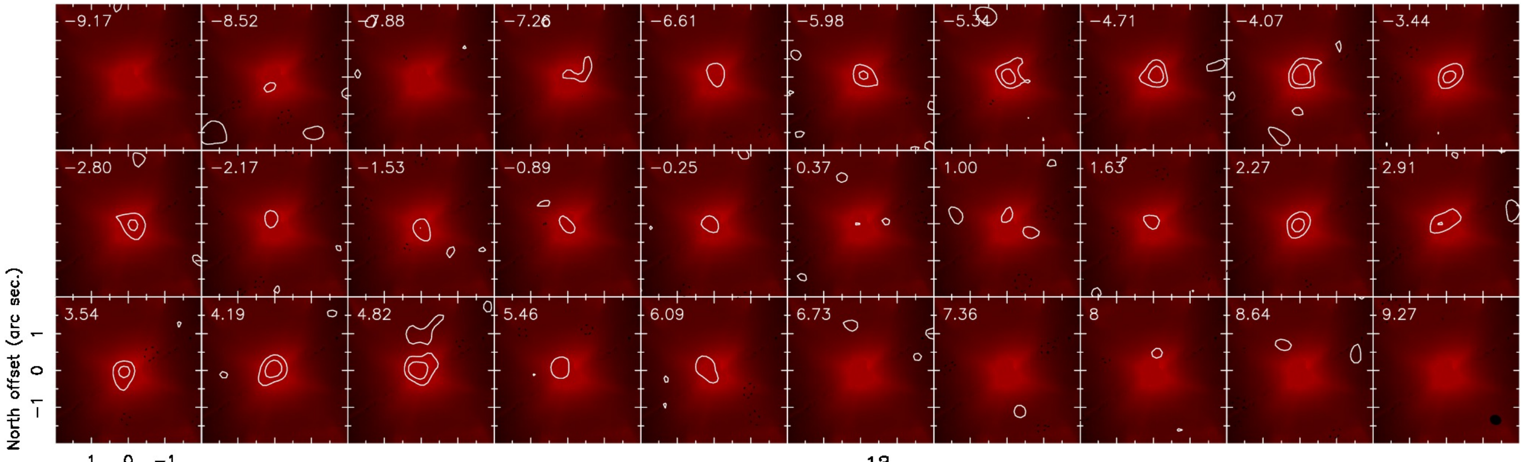
Weak emission, noisy data: first contour: 0.34 K, jumps by a factor two

Include new important information

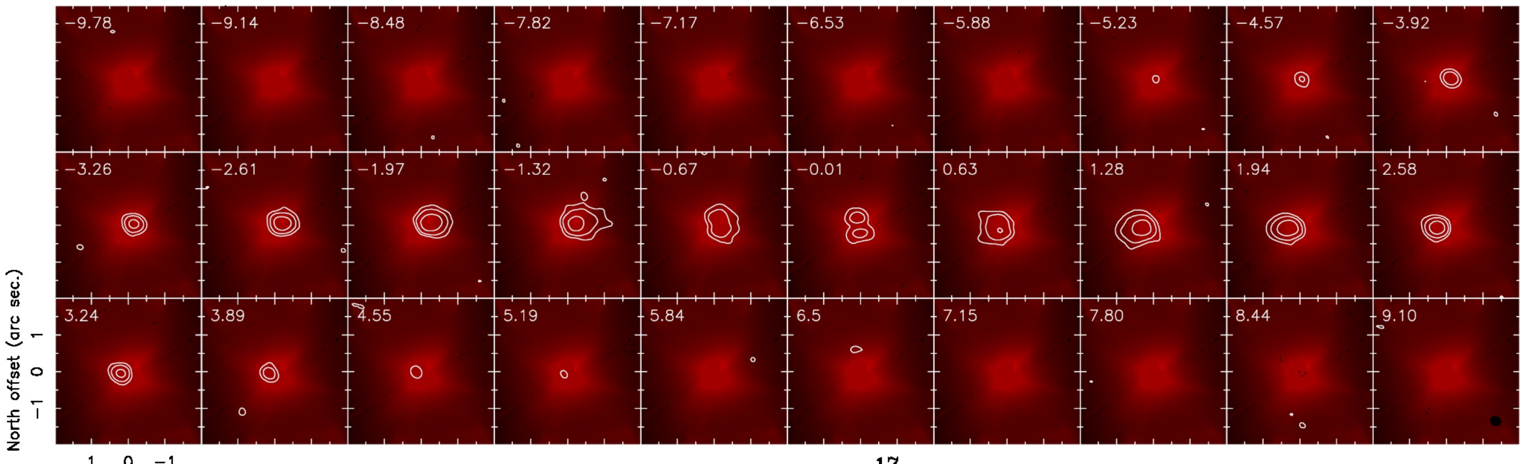
Note the high velocity dispersion: maximum at $\pm$ 4–5 km $s^{-1}$

despite the small region emitting at high velocity

# ALMA maps of $H^{13}CN$ J=4–3 in the Red Rectangle

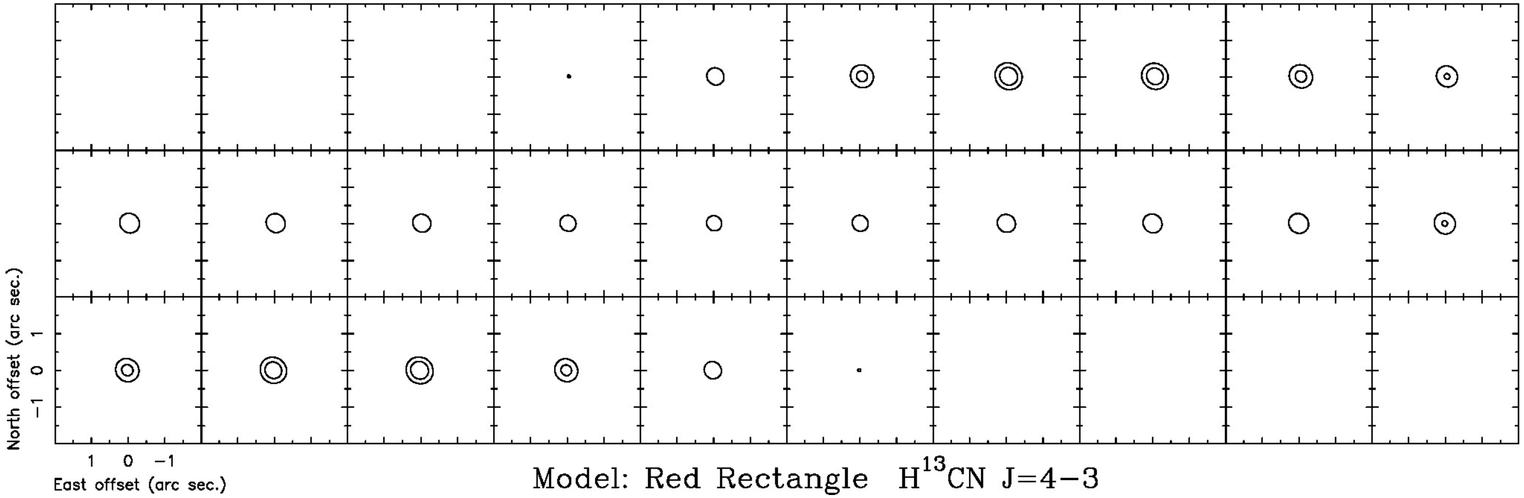



Red Rectangle $H^{13}CN$ J=4−3




Red Rectangle $C^{17}O$ J=6−5

# Models of $H^{13}CN$ J=4–3 emission in the Red Rectangle



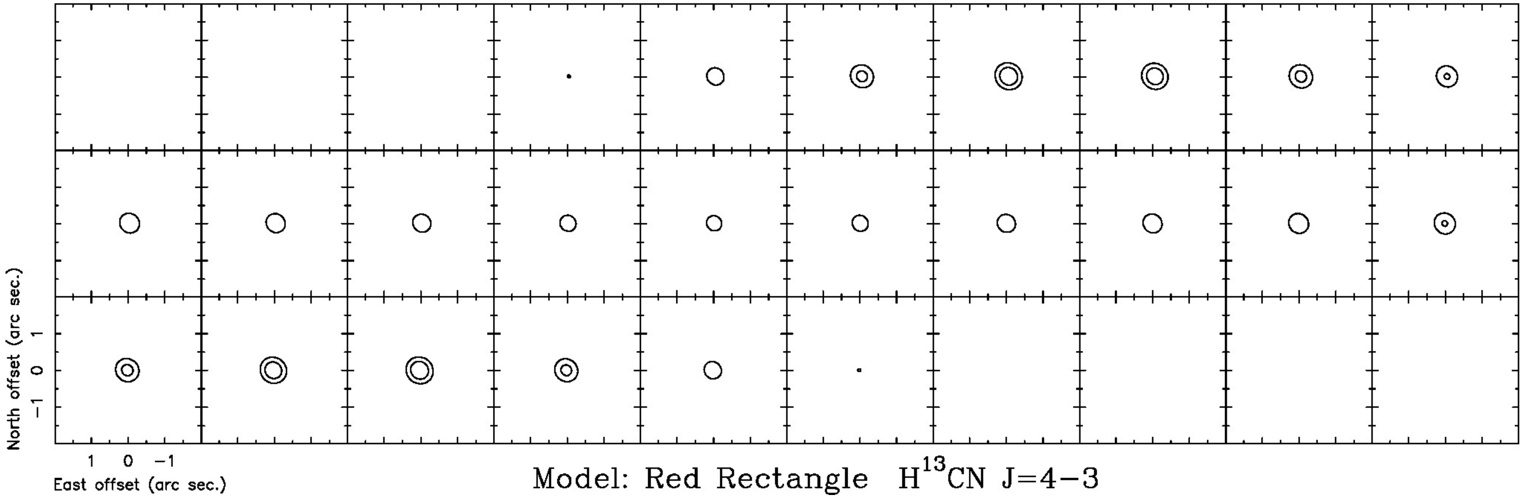

We must assume a very peculiar chemistry (and grains?) in a tiny central region:

- D $\sim$ 120 AU, where some models invoke large grains and chemistry seems C-rich
- $H^{13}CN$ is abundant only in it (with a *normal* X($H^{13}CN$) $\sim 10^{-9}$)
- But density cannot increase a lot, unless X(CO) decreases simultaneously
- Astrochemical models predict a large formation of HCN (and PAHs) in dense PDRs

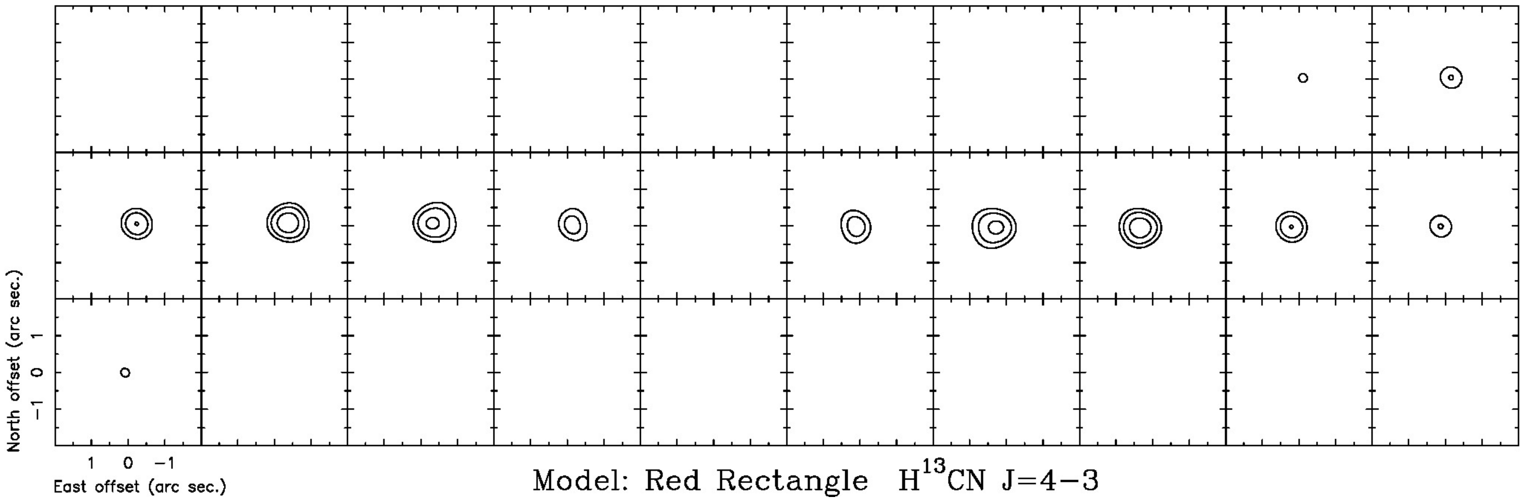
PAHs are very abundant in the RR: the X is due to their bands and the ERE

We speculate: a small central PDR would be the *PAHs factory* of the Red Rectangle

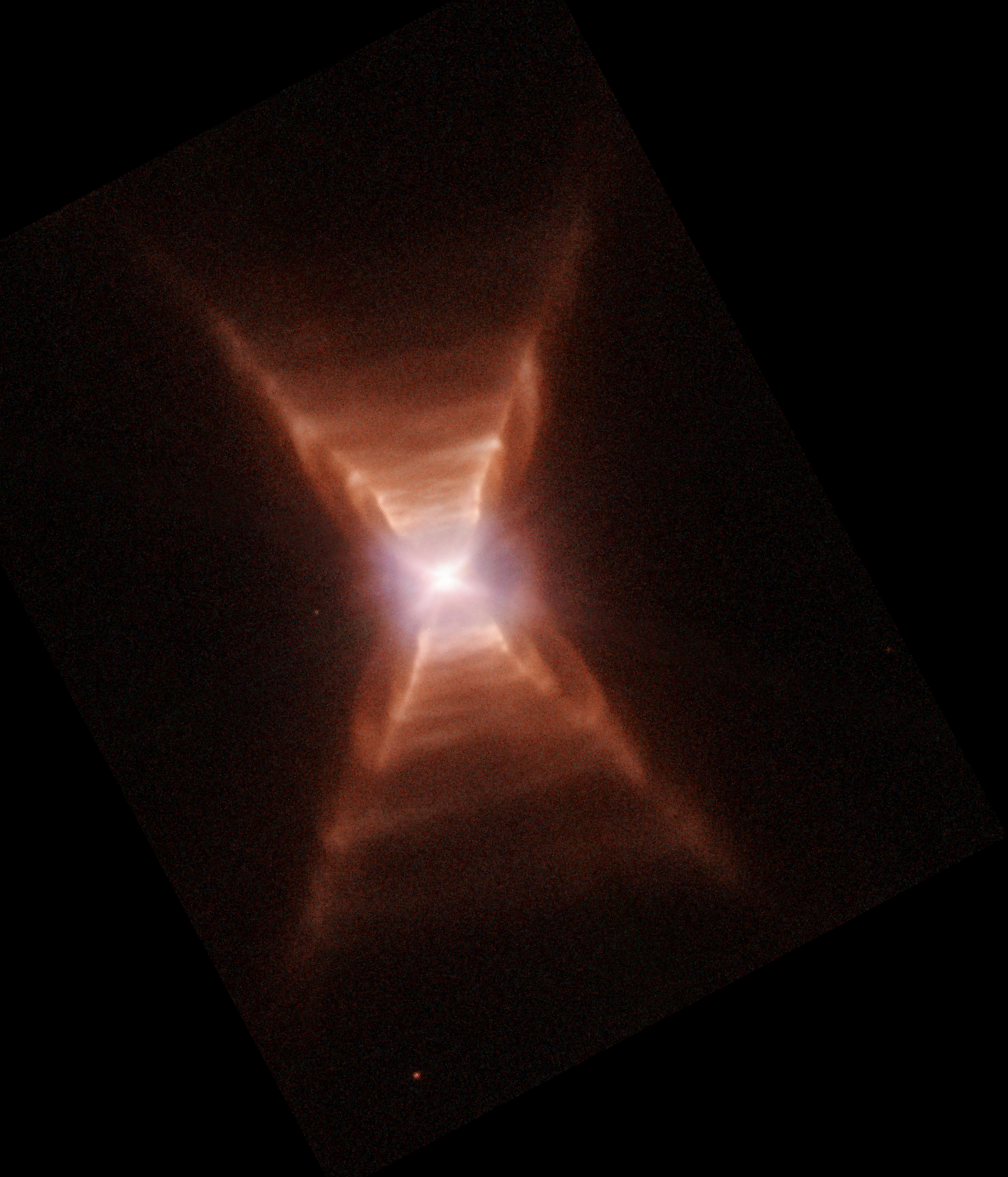
# Models of $H^{13}CN$ J=4–3 emission in the Red Rectangle

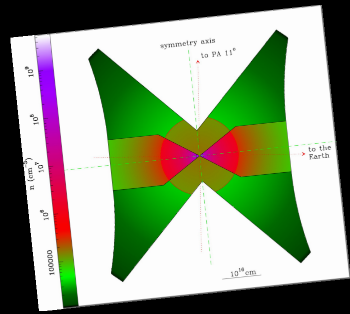



with PAHs factory




without PAHs factory





symmetry axis
to PA 11°
to the Earth
$10^{16}$ cm
n ($cm^{-3}$)
$10^9$
$10^8$
$10^7$
$10^6$
100000

## Conclusions (... after 12 years studying these objects)

A wide group of (binary) post-AGB stars are surrounded by extended Keplerian disks

Diameters between $10^{16}$ and 5 $10^{16}$ cm (central regions detected in dust emission)

Moderate total nebular mass: between $\sim 10^{-3}$ and 5 $10^{-2}$ $M_\odot$

Disk angular momentum also moderate, probably coming from the stellar system

In most of them, gas in slow expansion is also detected (outside the disk)

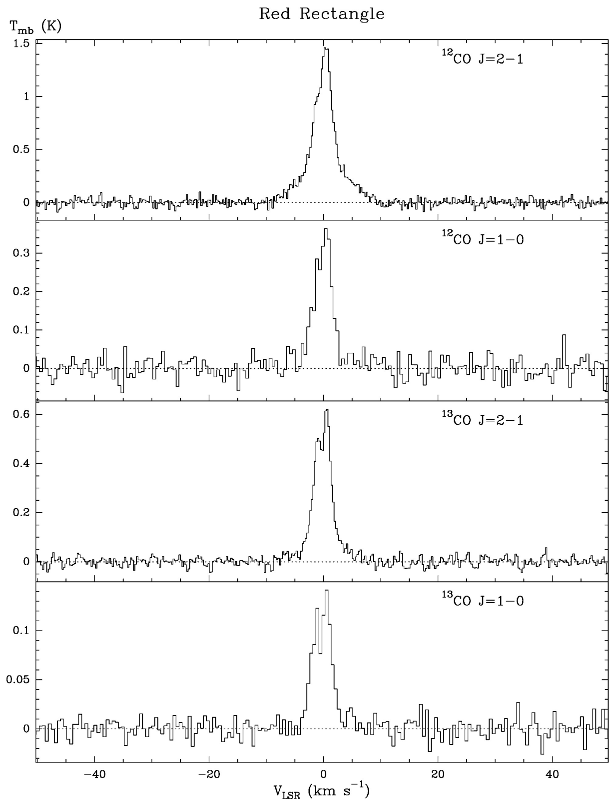
Probably extracted from the disk => disk's lifetime $\approx$ 1000 and 5000 yr

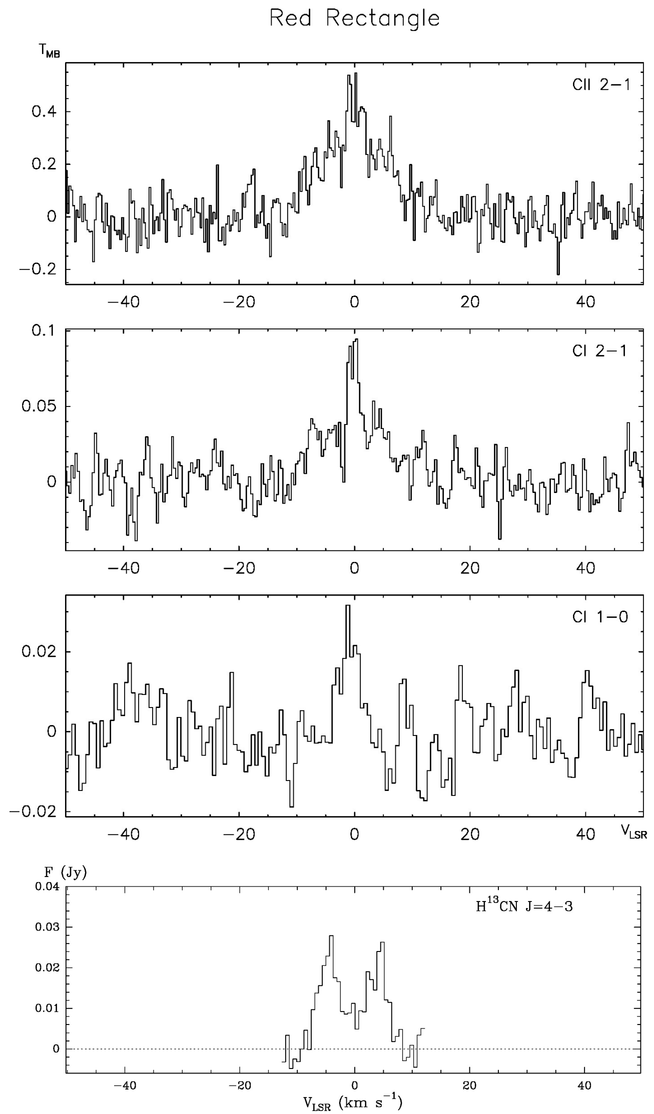
Disk temperatures between 200 and 20 K; probably higher in winds

Poor molecular content only CO and HCN detected

we suggest very strong PDR chemistry in inner $\sim$ 100 AU

# CI and CII Herschel/HIFI data in the Red Rectangle




PDR detected in CII and CI emission (as well as OI and NII)

Wide profiles: narrow (CO) + wide (H$^{13}$CN +outflow?)