Molecular line imaging of young planetary nebulae

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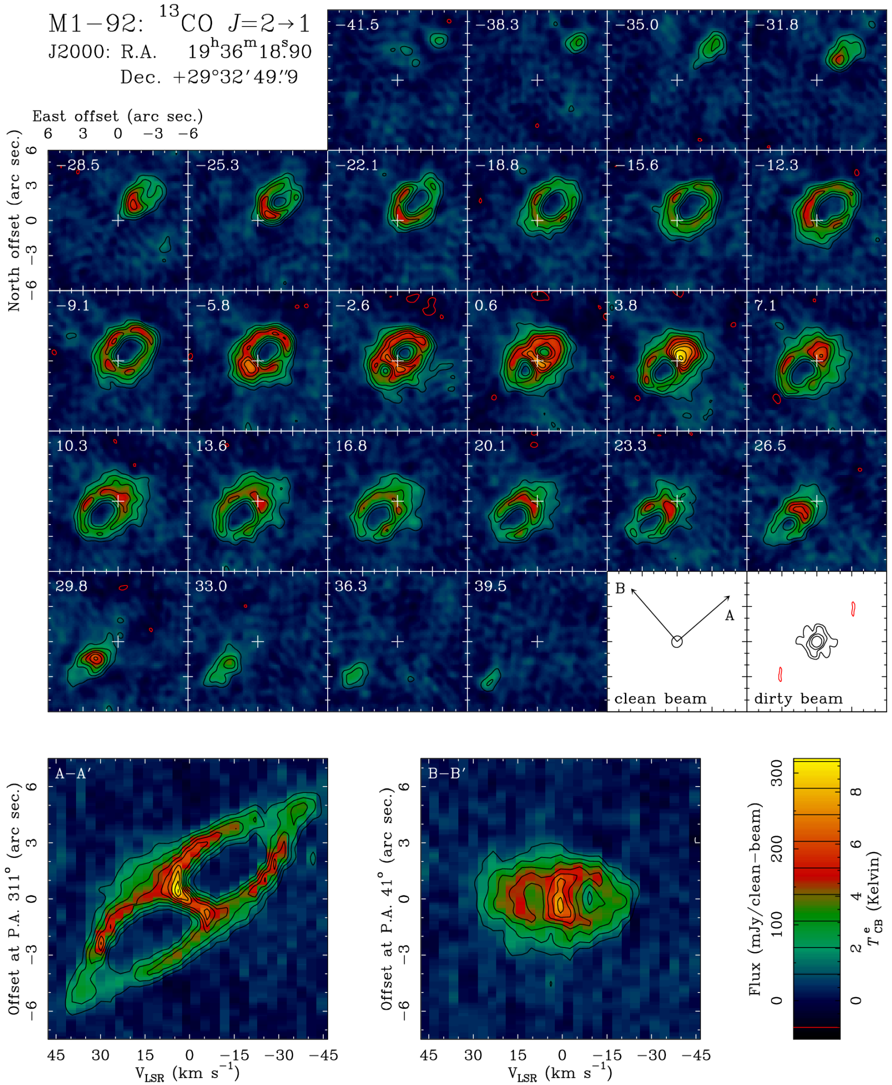
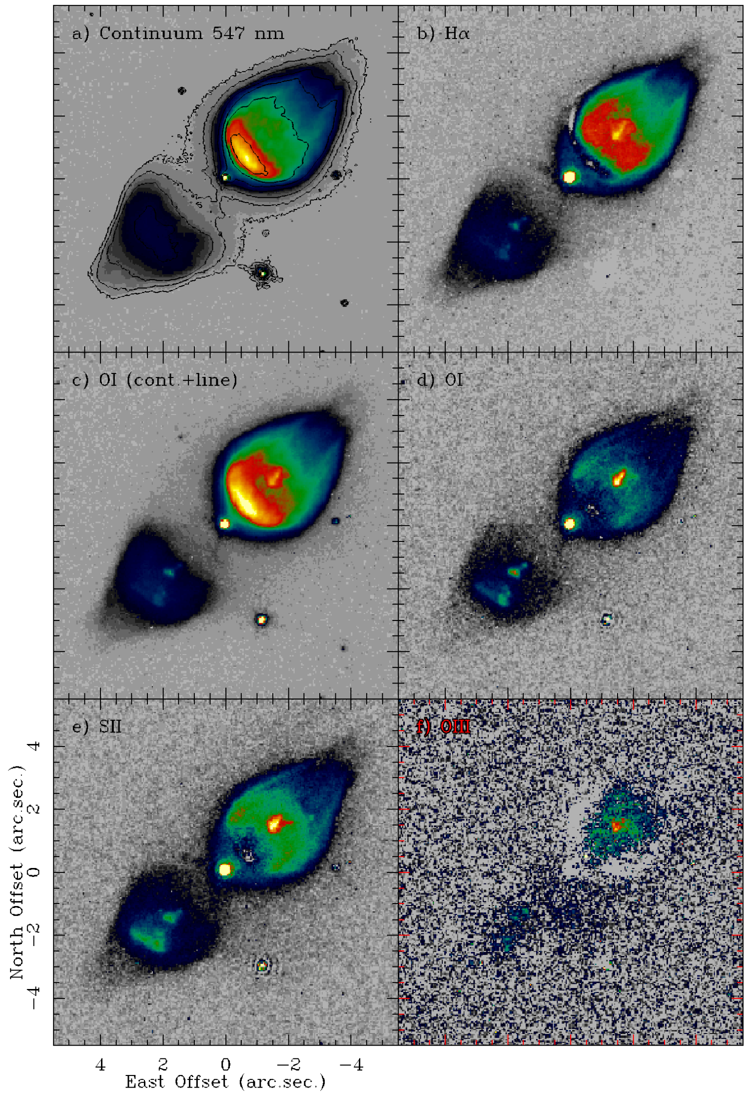
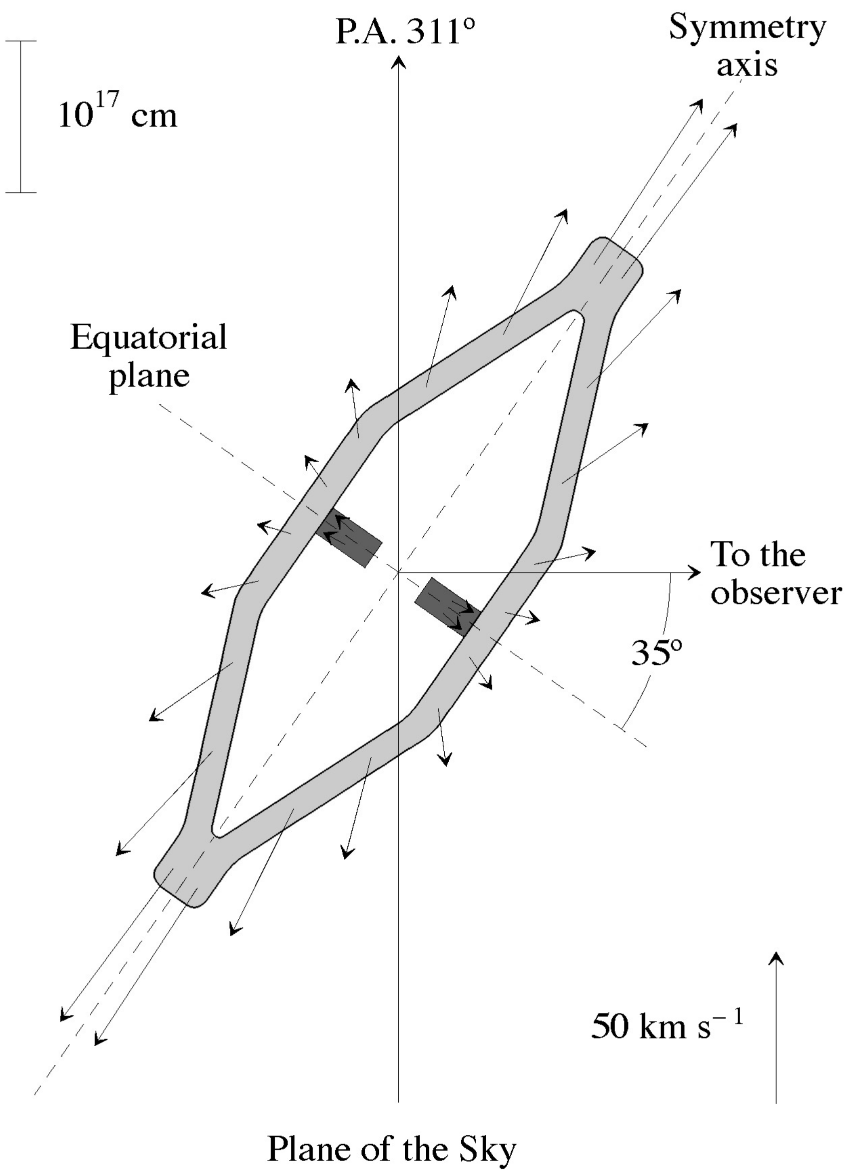
M 1–92: an example of the power of molecular lines in the study of young PNe





Bujarrabal et al., 1998, ApJ 504, 915; A&A 331, 361

M 1–92: a prototype of young PN with axial outflows



Densities between 5 10^4 and 3 10^5 cm^{-3}

$T_k \sim 15$ K

Radial, ballistic expansion => 900 yr old

Total mass $\sim 0.9\ M_\odot$, most nebular mass $\sim 0.5\ M_\odot$ in the fast bipolar outflow

strong momentum excess

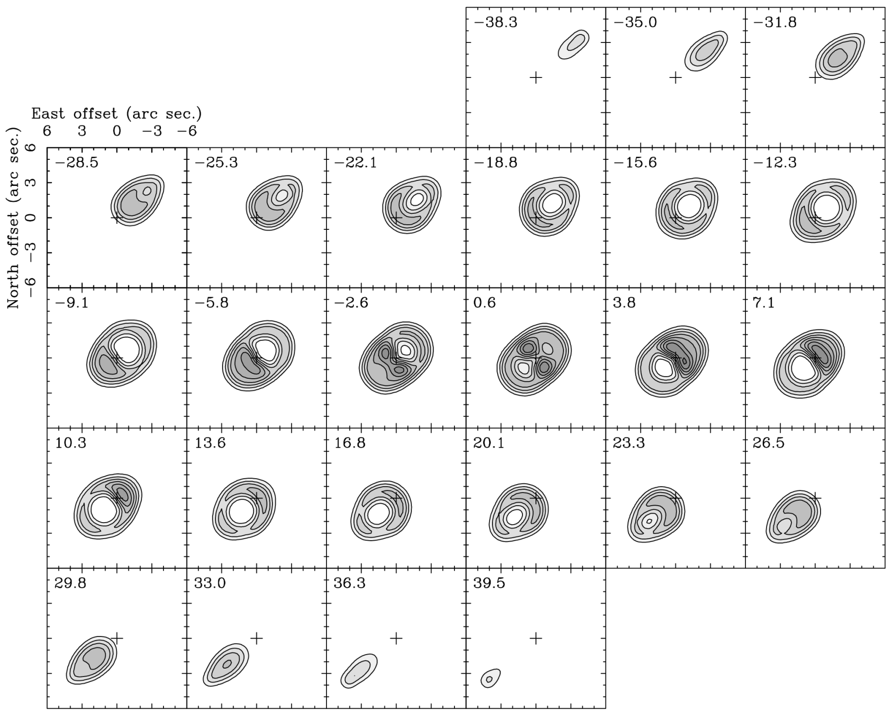
common phenomena !

VERY ACCURATE DESCRIPTION
OF DOMINANT COMPONENT

models kept quite simple (by the moment)

but low-J transitions do not probe warmer (less massive) components

M 1–92: a prototype of young PN with axial outflows



Simple, accurate analysis of data

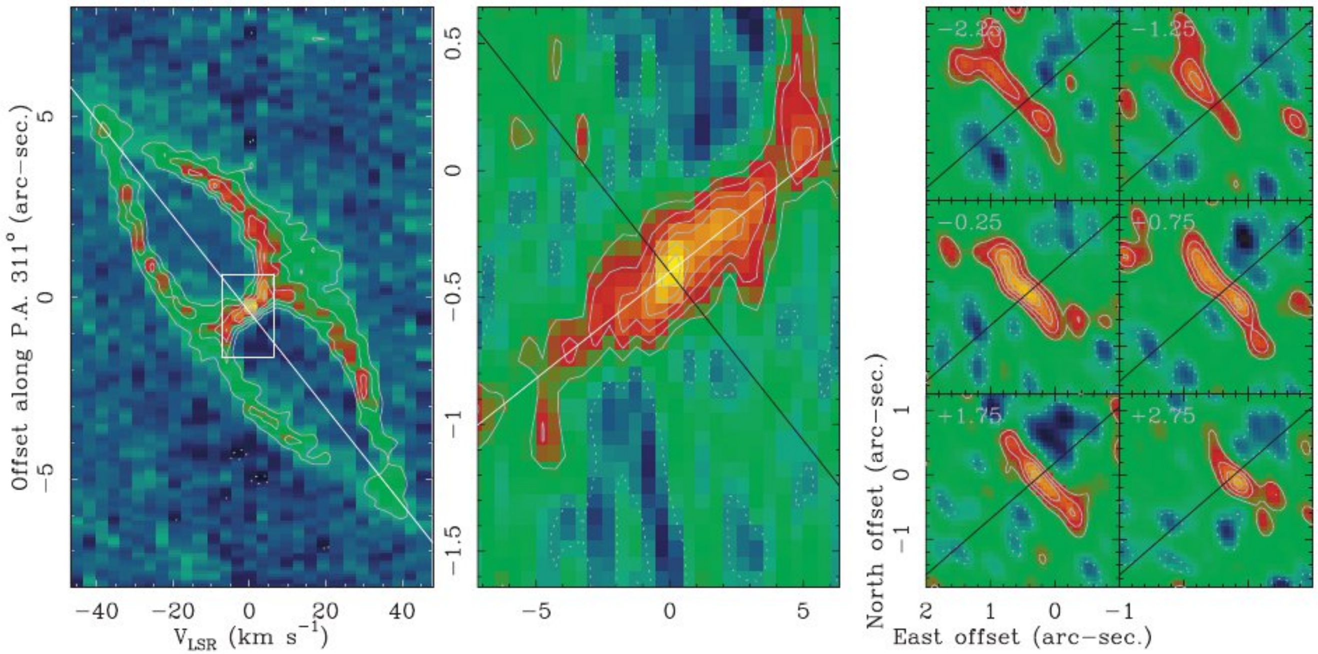
Easy collisional excitation (CO), low req.

Optically thick (^{12}CO) and thin (^{13}CO)

accurate, quantitative modeling is possible !

M 1–92: Which is the dynamics of the very inner regions of PPNe ?

higher resolution CO maps :



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

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

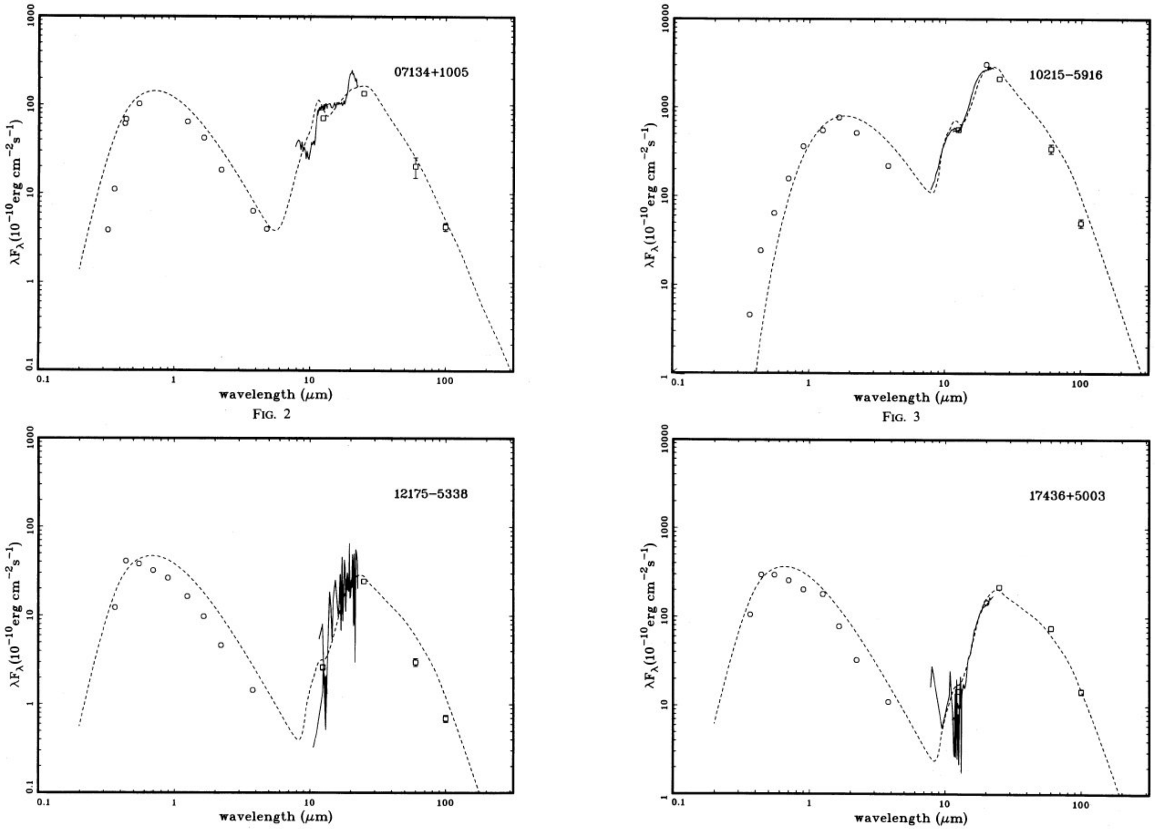
Can we just extrapolate the velocity law down to a few 10^{14} cm ?

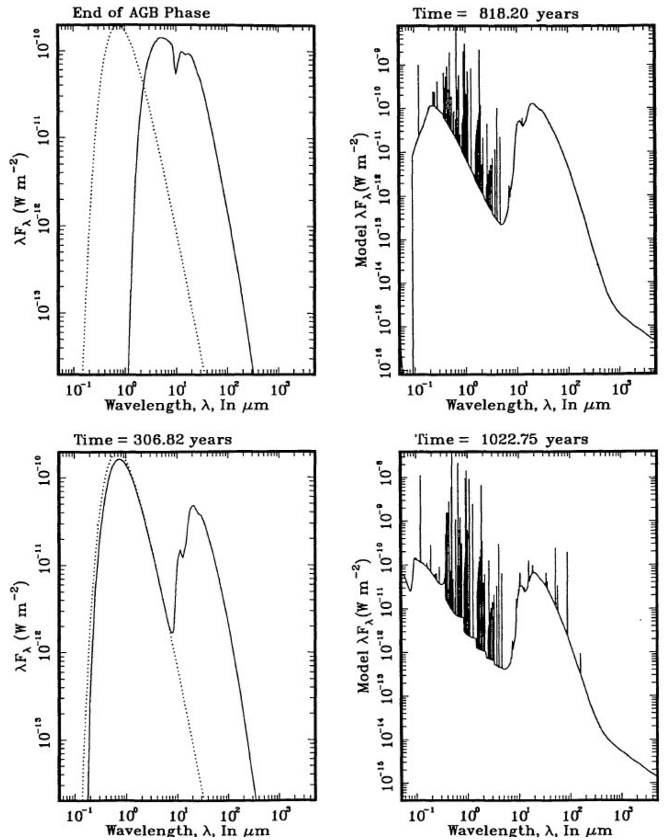
=> very low expansion velocities ($\lesssim$ 0.1 km s^{-1} !), almost stable

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

Definition and identification of protoPNe / very young PNe

nebulae around post-AGB stars with very low mass loss and not yet ionized





TWO-COMPONENT SEDs corresponding to the (reddened) star and a detached shell

A good deal of commonly studied protoPNe were identified from two-component SEDs

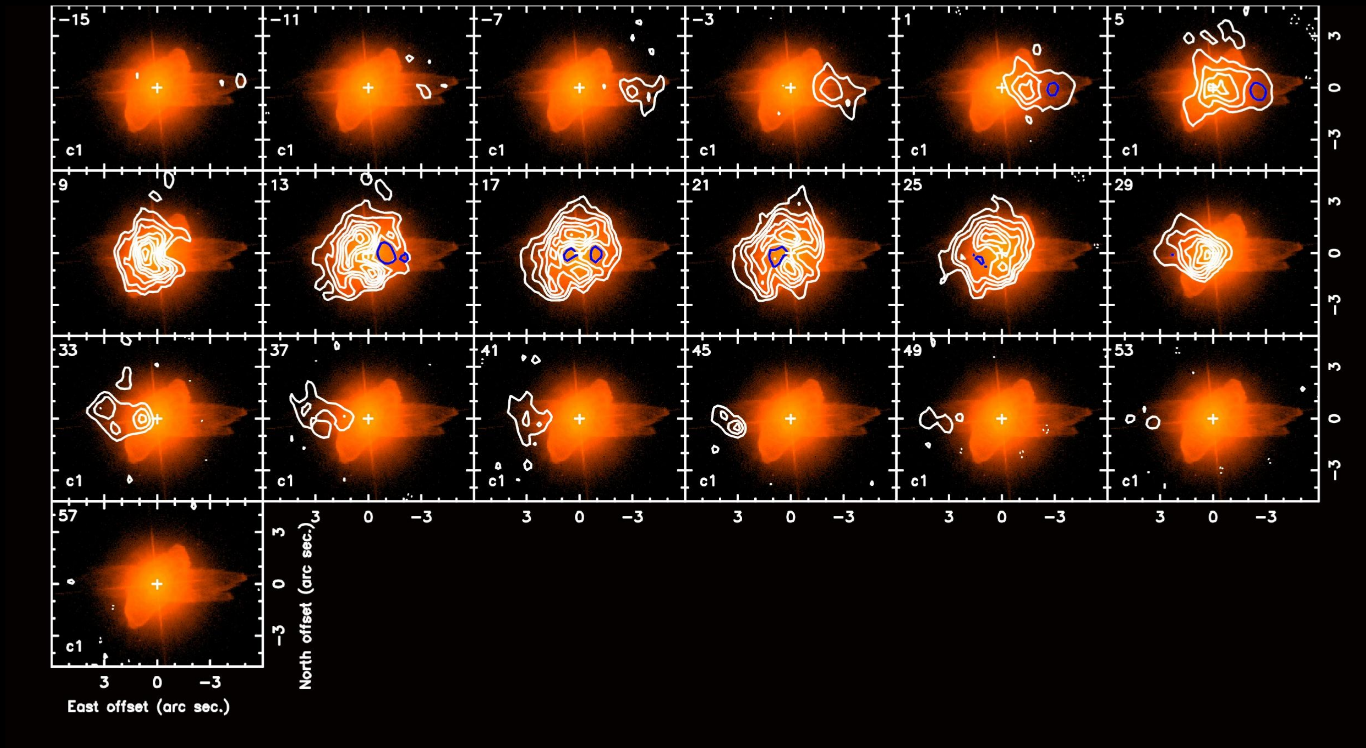
Hrivnak et al. 1989, ApJ 346, 265; Volk 1992, ApJS 80, 347; Kwok, 1993, ARA&A 31,63

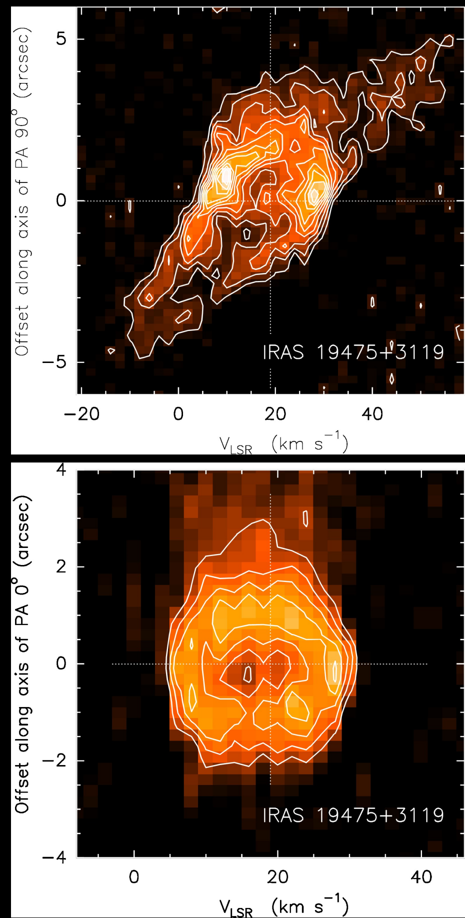
IRAS 19475+3119: a protoPN identified from IR properties

stellar + detached shell emission   Molecular line maps confirmed their nature

bipolar shape, ballistic expansion, momentum excess, ...

Total nebular mass $\sim$ 1 $M_\odot$, fast outflow mass $\sim$ 0.1 $M_\odot$

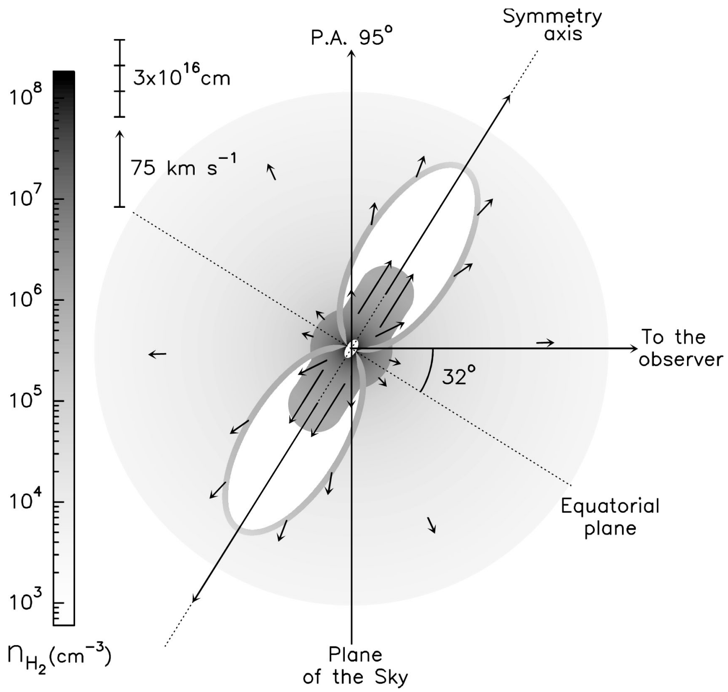




part of the first group of data from COSAS

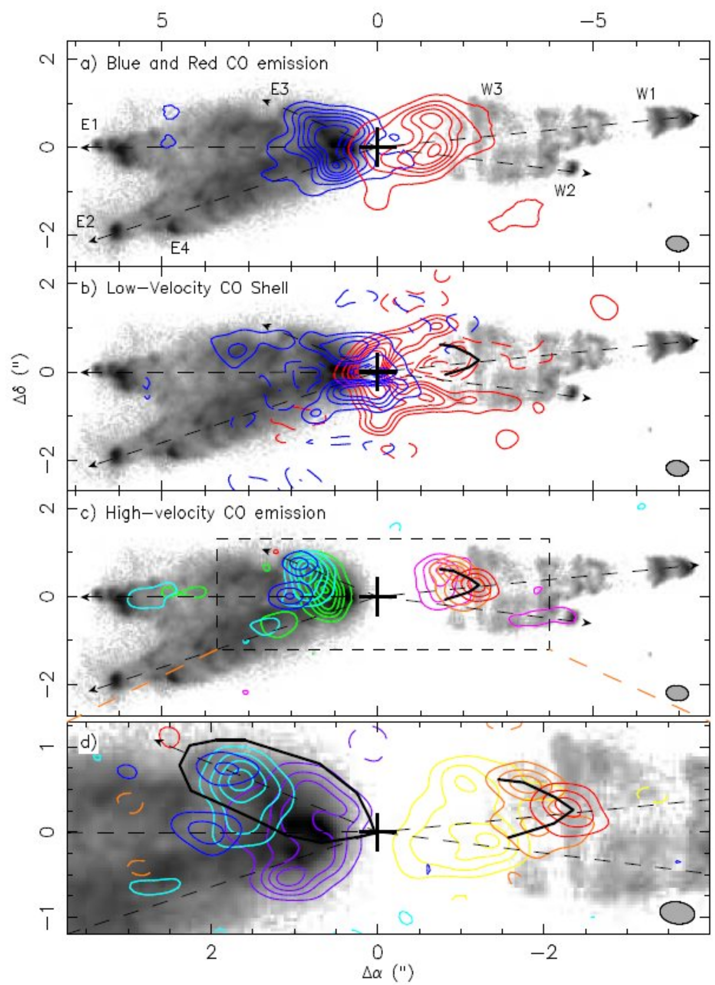
Castro-Carrizo et al. 2010, A&A, 523, 59

New high-resolution observations of CO in CRL 618



Old OVRO observations revealed the general structure

New SMA observations of ^{12}CO J=3–2, 0$\farcs$3 resolution

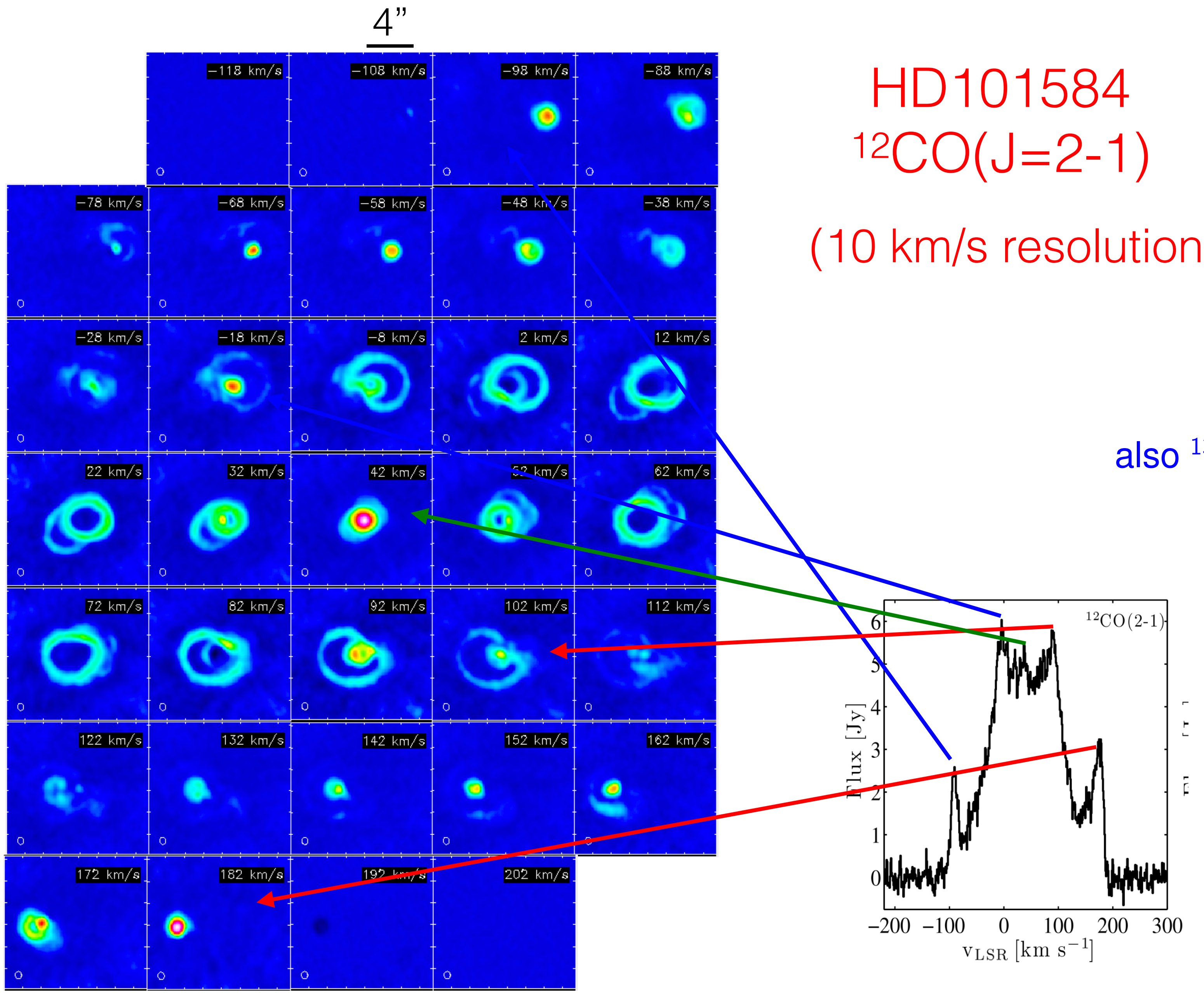


Very complex structure of the fast outflows

cavity probably converging to a bow shock

Sánchez Contreras et al., 2004, ApJ, 617, 1142; Lee et al., 2013, ApJ, 777, 37

HD 101584: ALMA maps of a young PN with a very fast bipolar jet



HD101584

^{12}CO(J=2-1)

(10 km/s resolution)

also ^{13}CO, SiO, SO, H_2S, etc

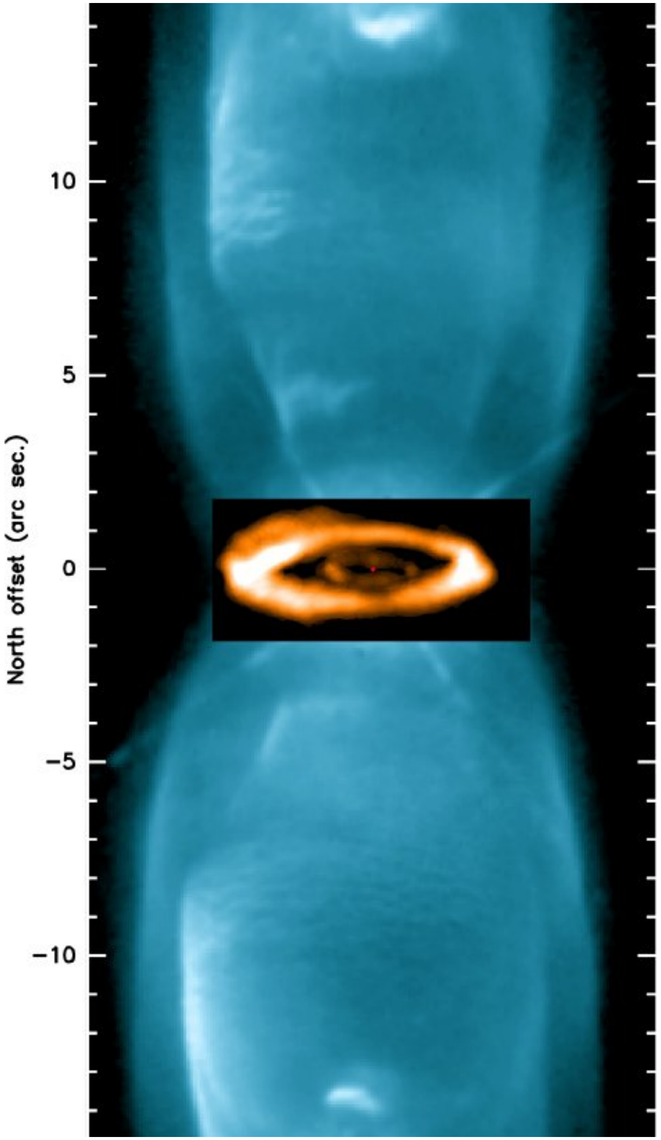
ang. resolution: 0$''$.5

peak $T_B \sim 50$ K

Olofsson et al. 2015, A&A 576, L15; see also talk

Expanding equatorial rings in M 2–9, the Butterfly Nebula

Young PN around a binary star. Molecular gas just occupies two equatorial rings



Molecule-rich gas is $\sim$ 20% of the total nebula

total mass just $\sim$ 0.05 $M_\odot$

dominated by the PDR (ionized gas represents < 10%)

Two short episodes of equatorial ejection

during $\sim$ 40 yr, separated by $\sim$ 500 yr

and with low velocities : 4 km s^{-1} and 8 km s^{-1}

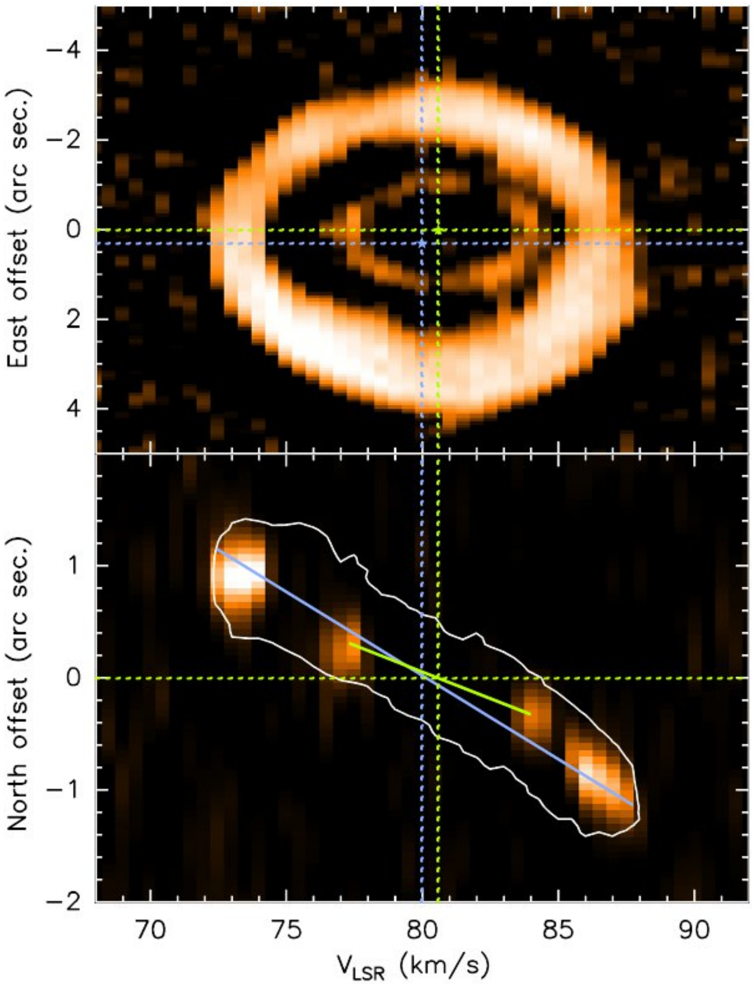
High quality PdB maps, resolutions: 0.1 km s^{-1}, $0\farcs5$

impressive recent ALMA data confirm results

Castro-Carrizo et al. 2012, A&A 545, 1

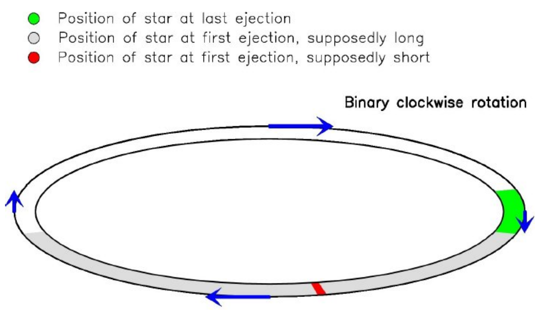
Expanding equatorial rings in M 2–9, the Butterfly Nebula

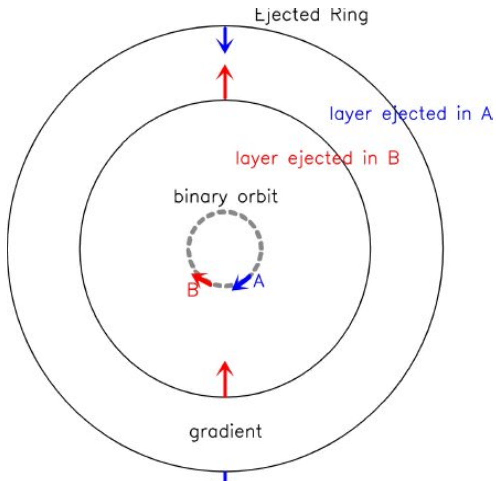
The spatial and velocity centroids of the rings are not the same !



Ejected in two different phases of the (primary) orbit

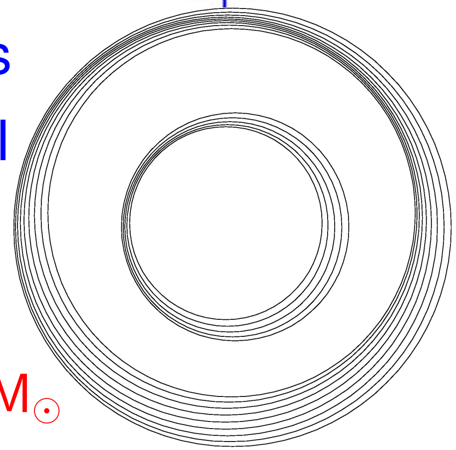
The stellar velocity affects the velocity and center of rings





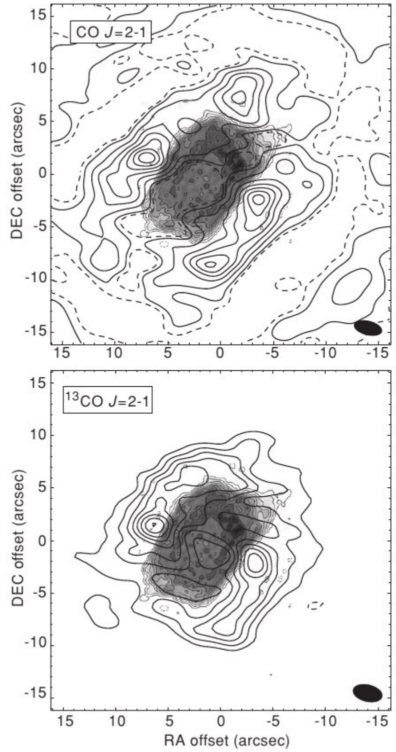
similar as for spirals in (post-)AGBs

each ejection forms a slice of spiral

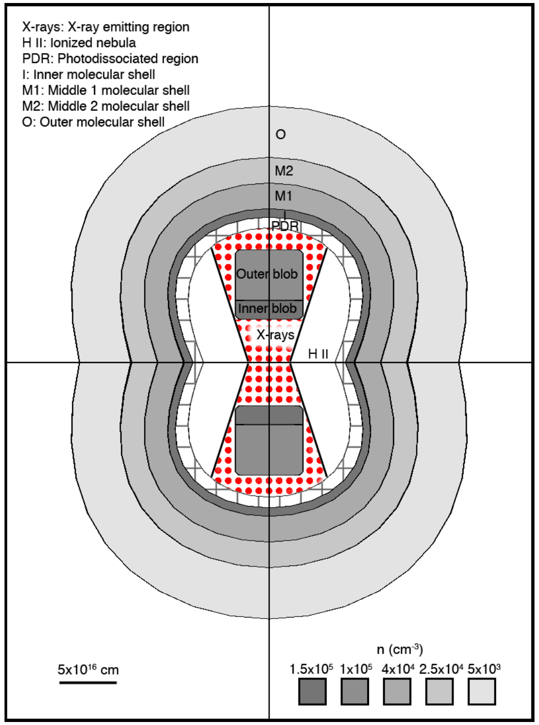


Orbital parameters derived: mass of secondary in M 2–9 $\lesssim 0.2\ M_{\odot}$

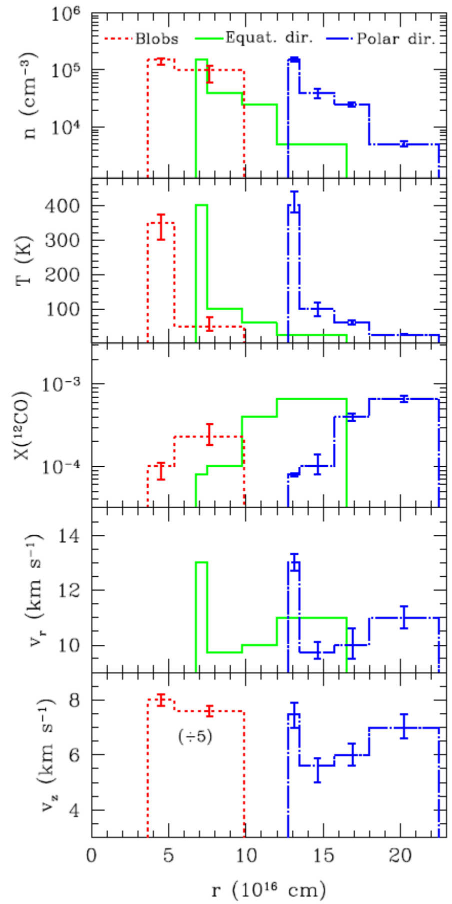
CO maps and high-excitation molecular lines: detailed analysis of NGC 7027

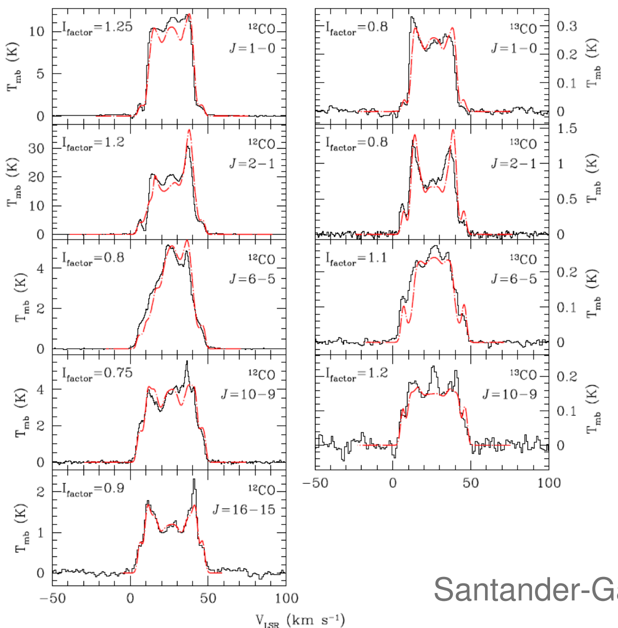


General structure of the nebula



Derived physical conditions



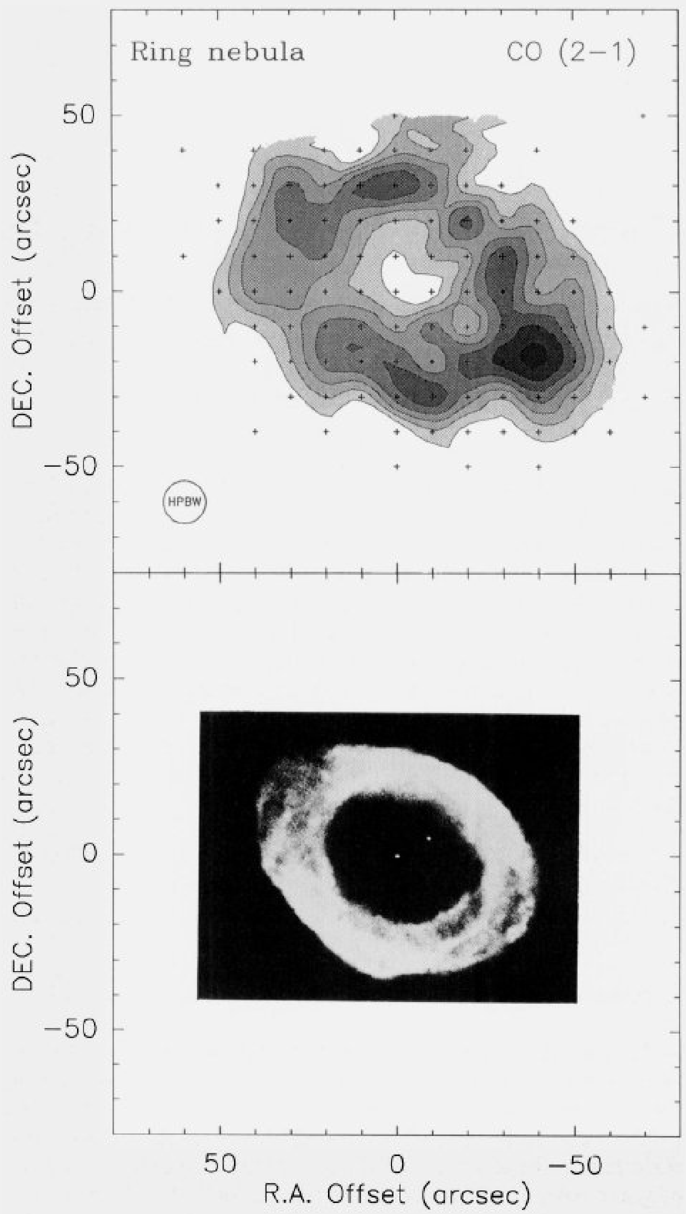


detailed and quantitative description, wind interaction

using SHAPEMOL   but unfortunately not so simple

Santander-García et al., 2012, A&A 545, 114; Nakashima et al., 2010, AJ 140, 490; Kwok et al., 1978, ApJ 219, L125

More evolved PNe: ring nebulae



photodissociation by stellar UV is crucial

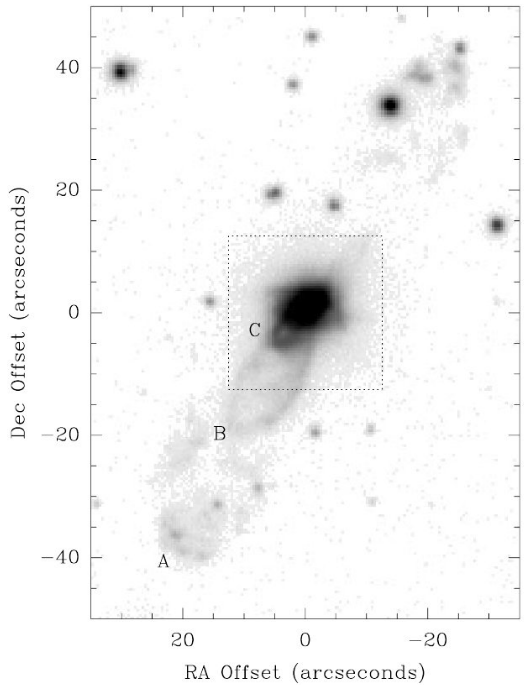
Often CO is mainly found in equatorial regions (always in expansion)

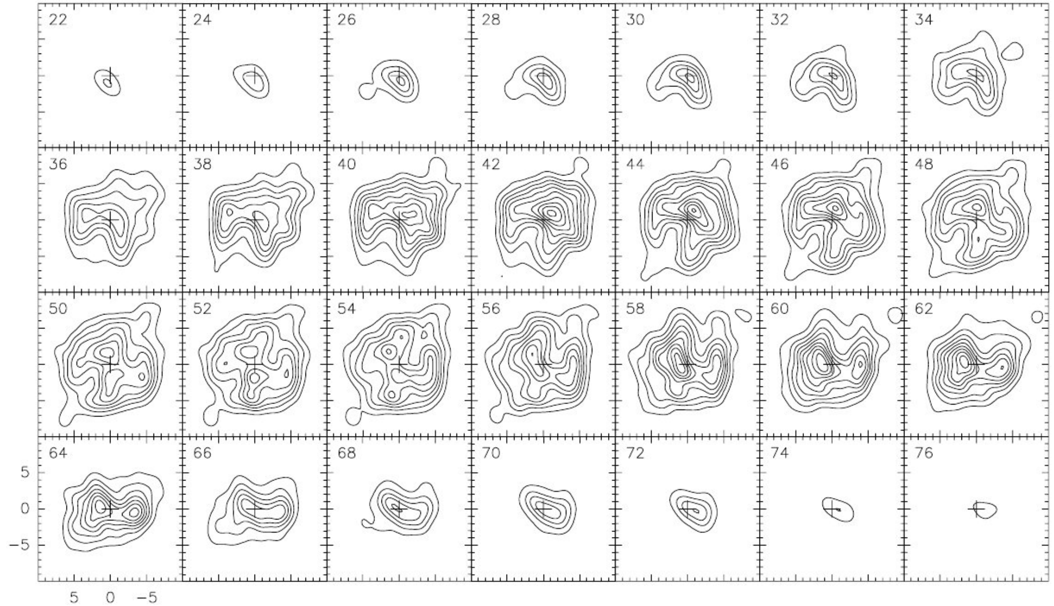
Similar rings found in NGC 2346, KjPn 8, the Helix, NGC 6781, NGC 6772, M1–16

In less evolved objects $M_{mol} \gtrsim 0.1\ M_{\odot} \gg M_{ionized}$ but undetected in very wide, evolved nebula

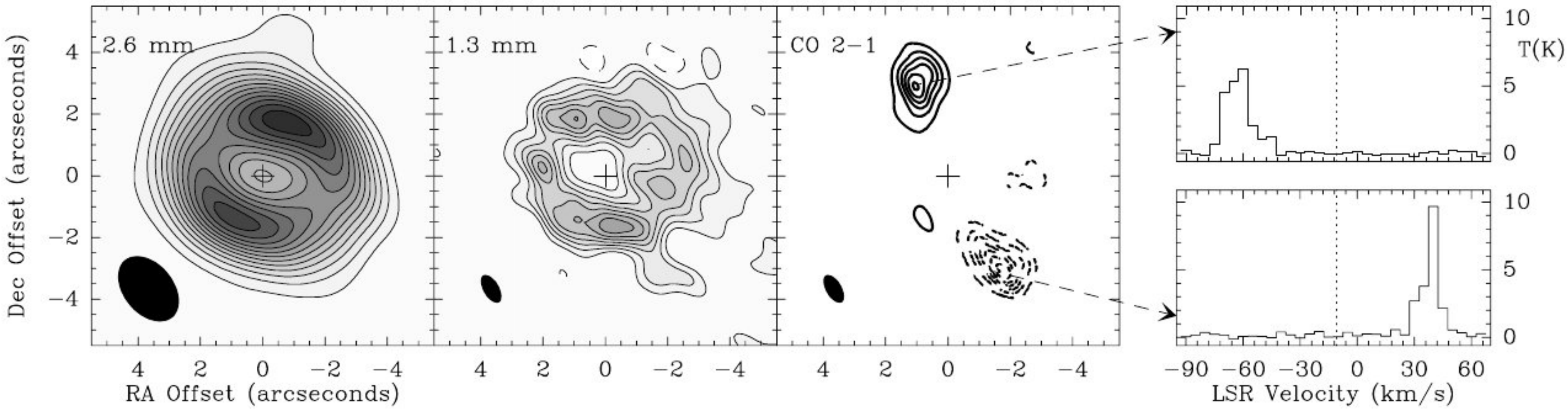
Bachiller et al., 1989, A&A 218, 252; 1993, A&A 267, 177; Forveille et al., 1998, ApJ 495 L111; Huggins et al., 2000, ApJ 544, 889

More evolved PNe: rings and bullets





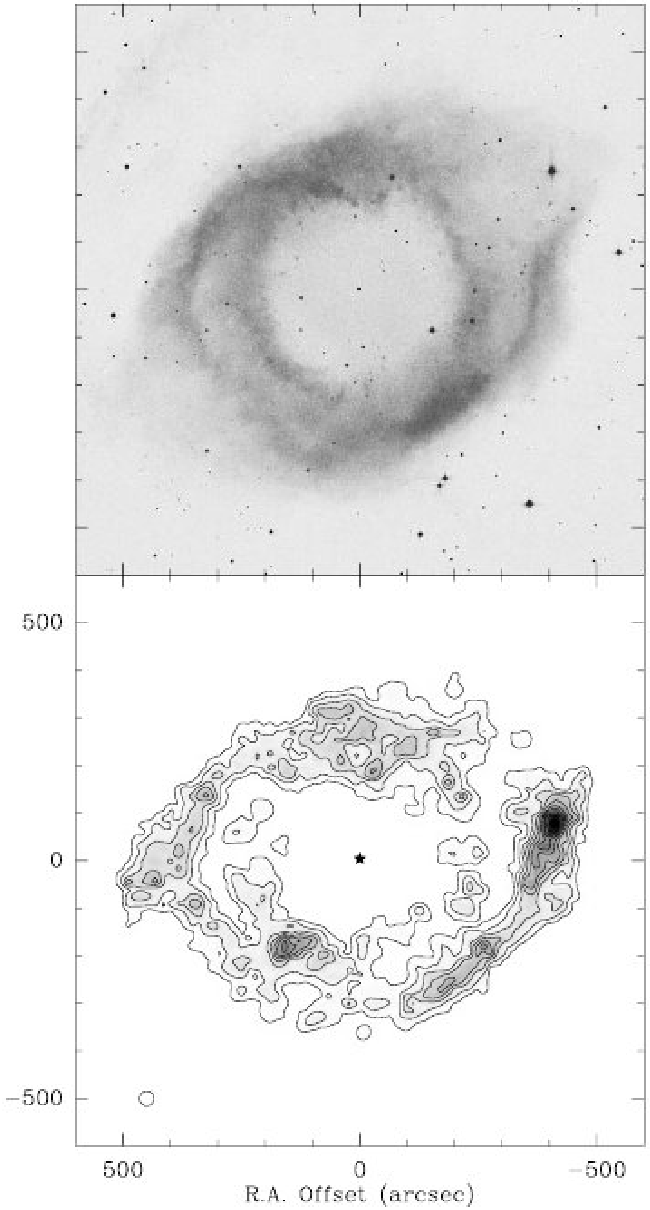
M 1-16

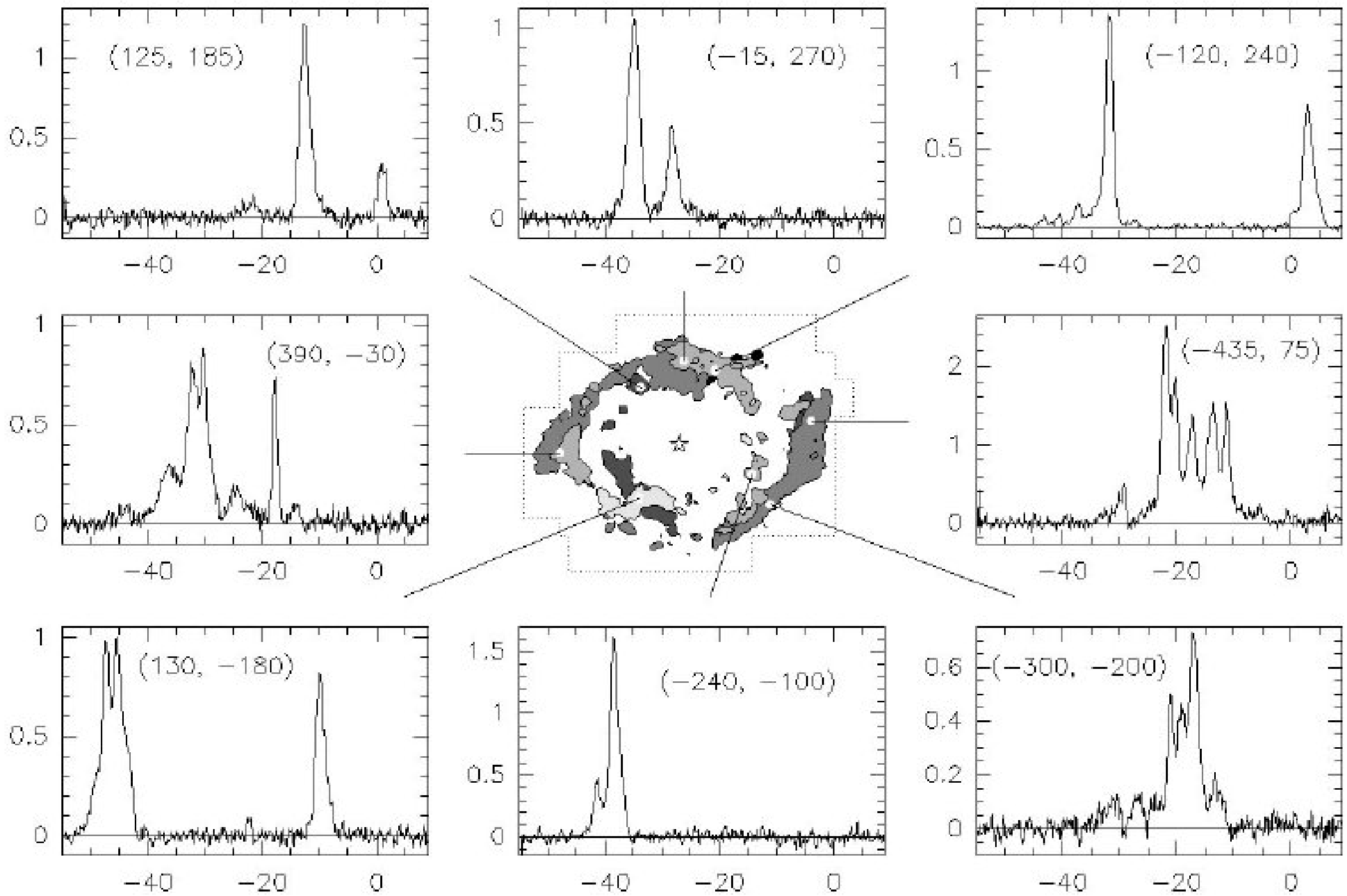


BD +30 3639

Huggins et al., 2000, ApJ 544, 889; Bachiller et al., 2000, 353, L5

More evolved PNe, detailed structure: the Helix

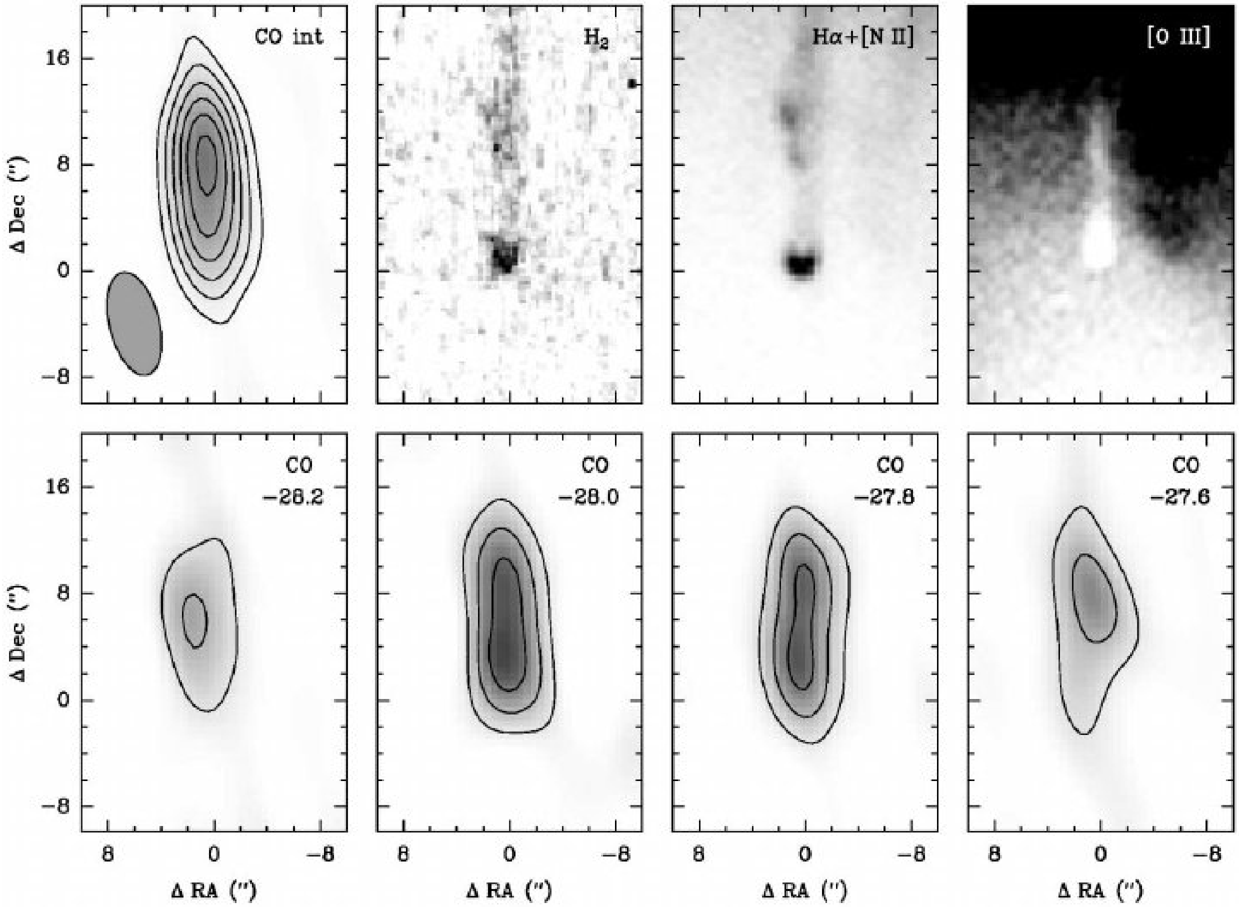




high equat. velocities (“interacting stellar wings” paradigm)

Young et al., 1999, ApJ 522, 387; Kwok et al., 1978, ApJ 219, L125

More evolved PNe, detailed structure: the Helix: globules



Again a quantitative description !

Molecules survive shielded by condensations

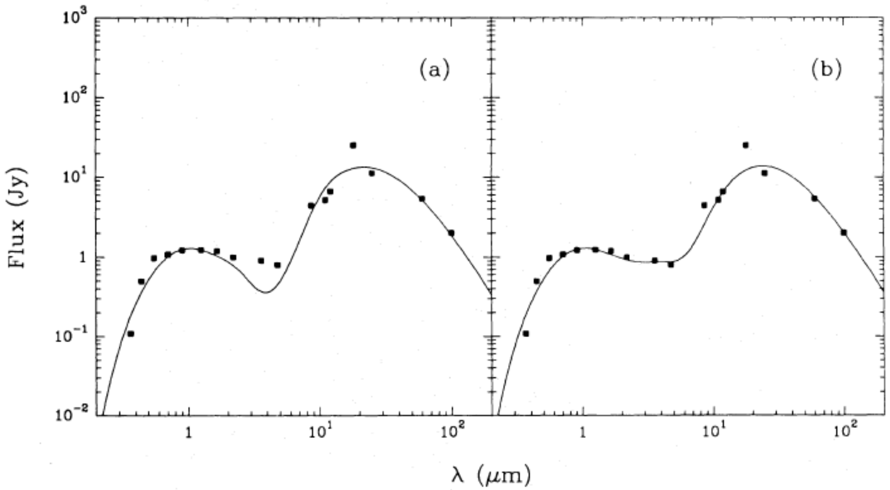
Low velocity and velocity dispersion

Cold ($\sim$ 25 K) and massive CO-rich clump ($\gtrsim 10^{-5}$ $M_\odot$)

Huggins et al., 2002, ApJ 573, L55

Keplerian disks in post-AGBs – to explain reaccretion and jet launching

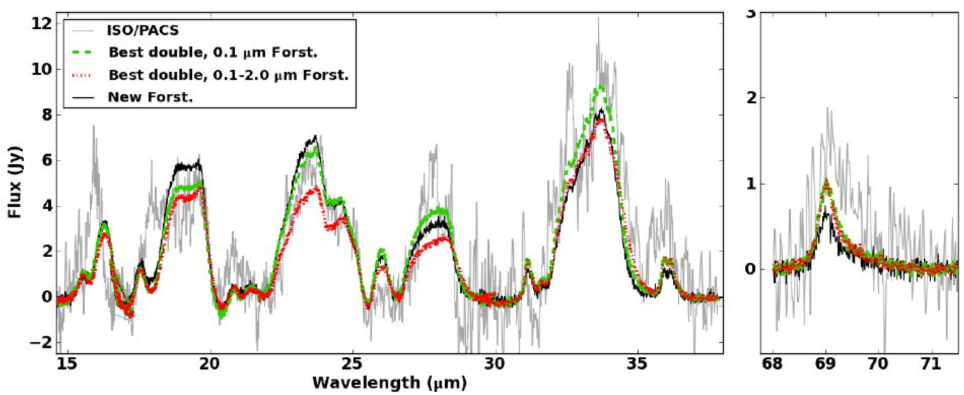
There is a class of binary post-AGB stars showing indications of stable structures



Remarkable NIR excess

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

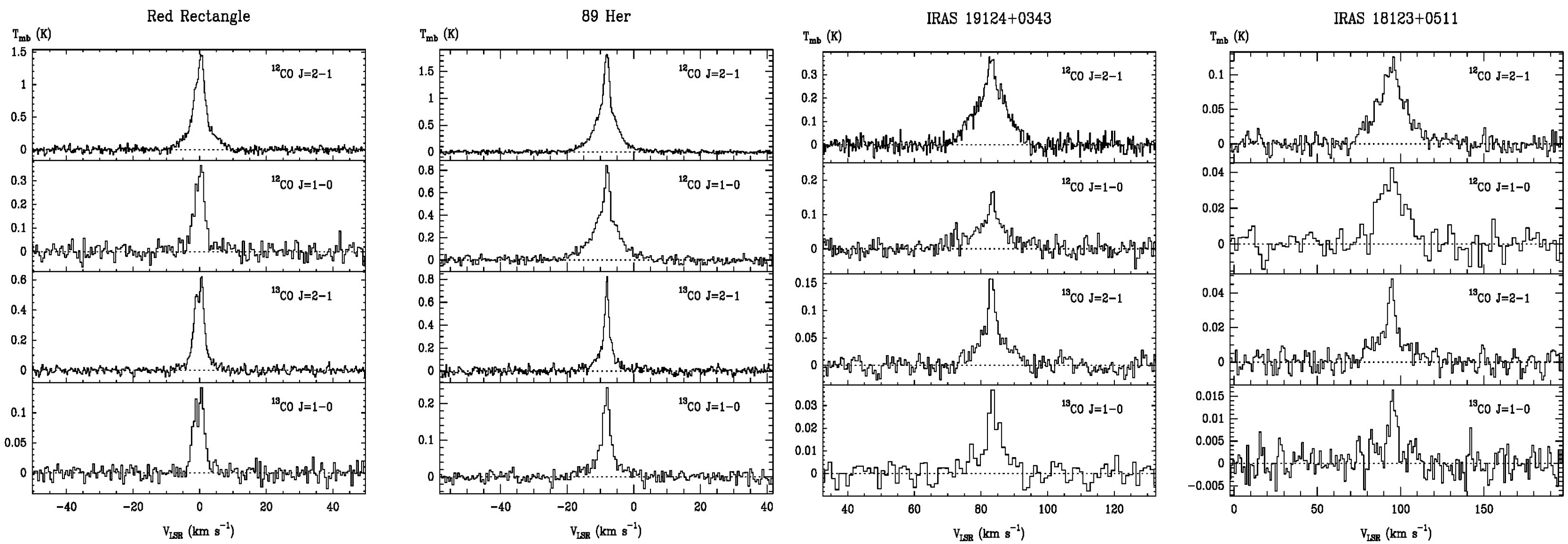
+ probable overabundance of large grains + highly evolved (crystalline) grains, etc

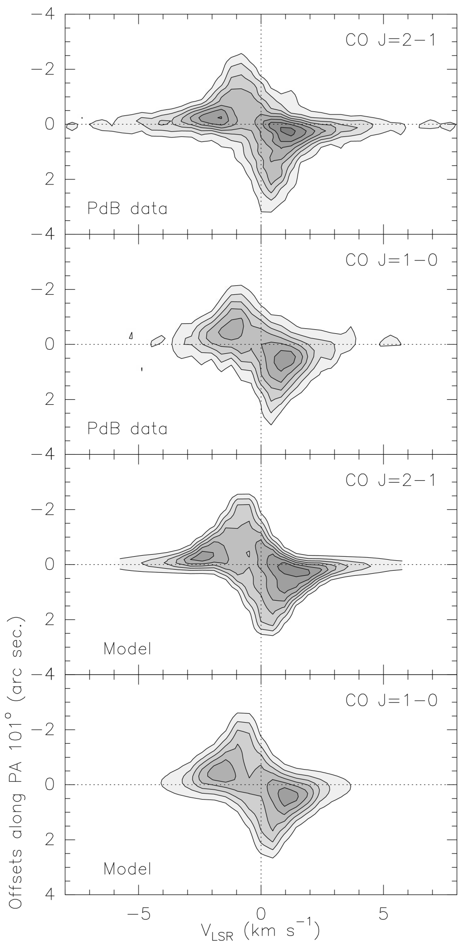


Alcolea & Bujarrabal, 1992, A&A 245, 499; Jura et al., 1997, ApJ 474, 741; Hillen et al., 2015, A&A 578, 40; Van Winckel 1998, ARA&A 41, 391

Search for rotating disks in NIR-excess post-AGB nebulae

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





confirmed by maps in a few objects, notably in the Red Rectangle

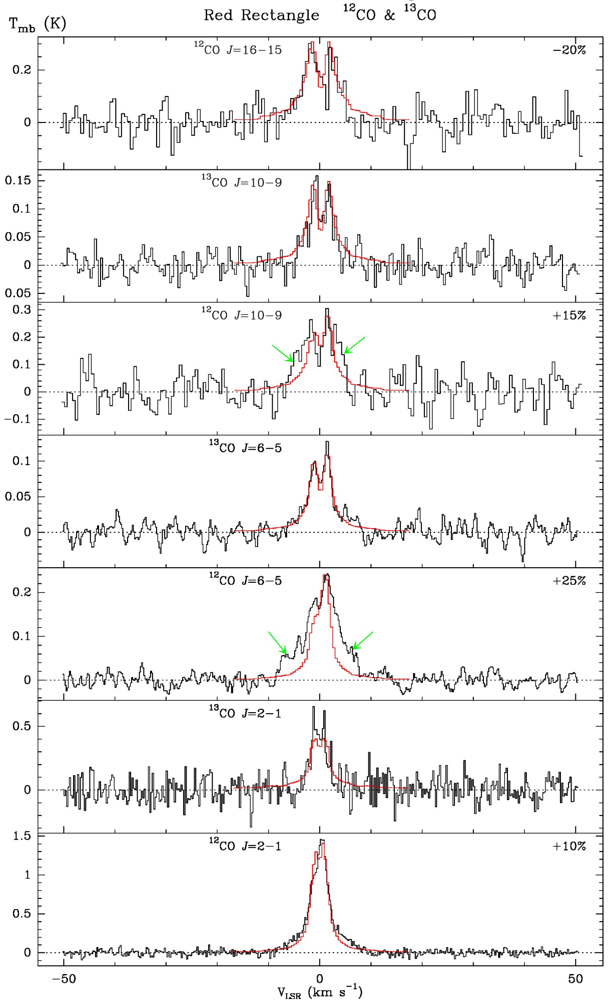
a good deal (8 in total) also show signs of expansion

(too wide and intense line wings)

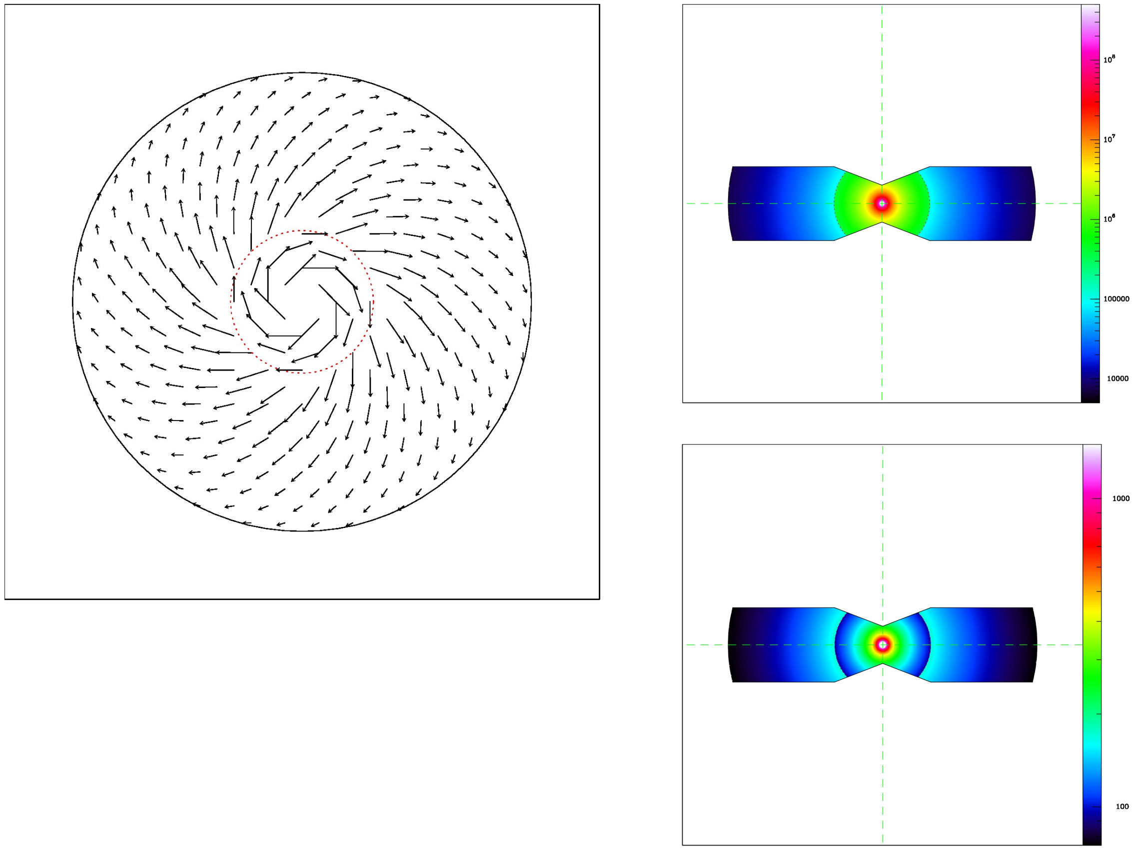
Bujarrabal et al. 2013, A&A 557, 104; A&A 557, L11; 2005, A&A 441, 1031

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

Model fitting



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



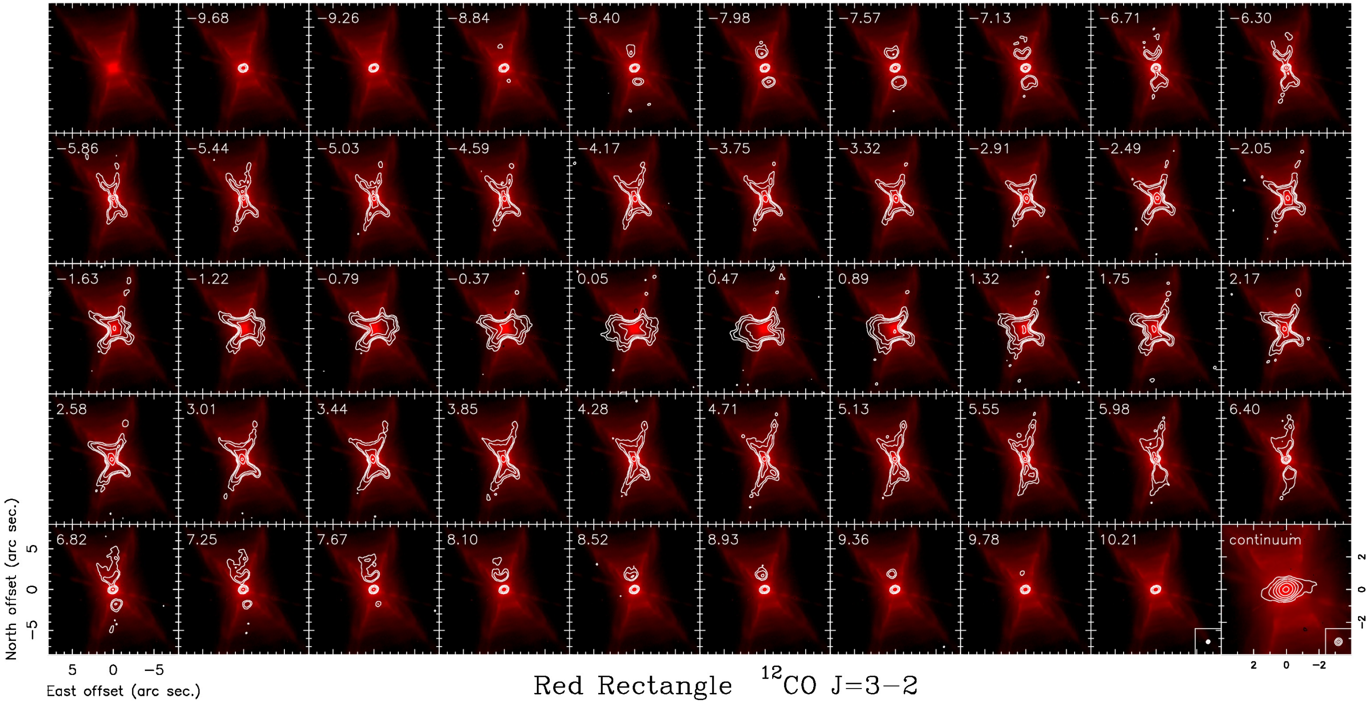
Molecular lines come from a rotating equatorial disk

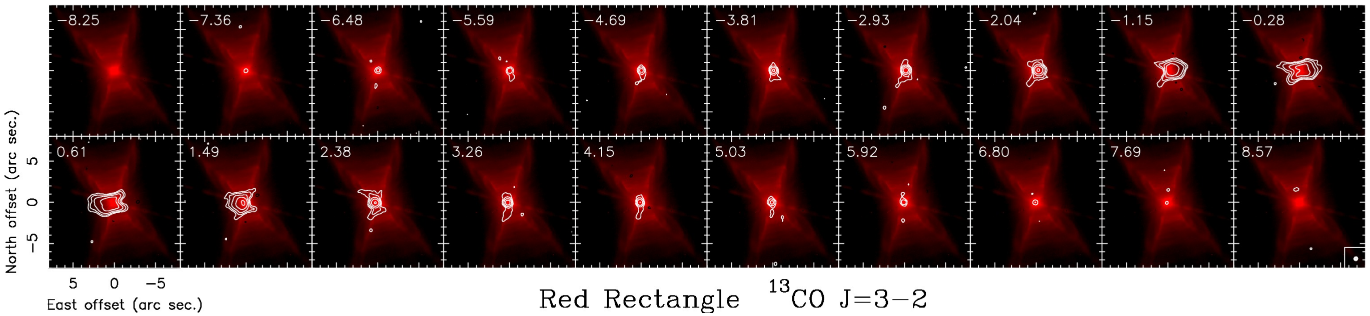
Sophisticated 2-D non-local treatment required !

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

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

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

probably extracted from the disk

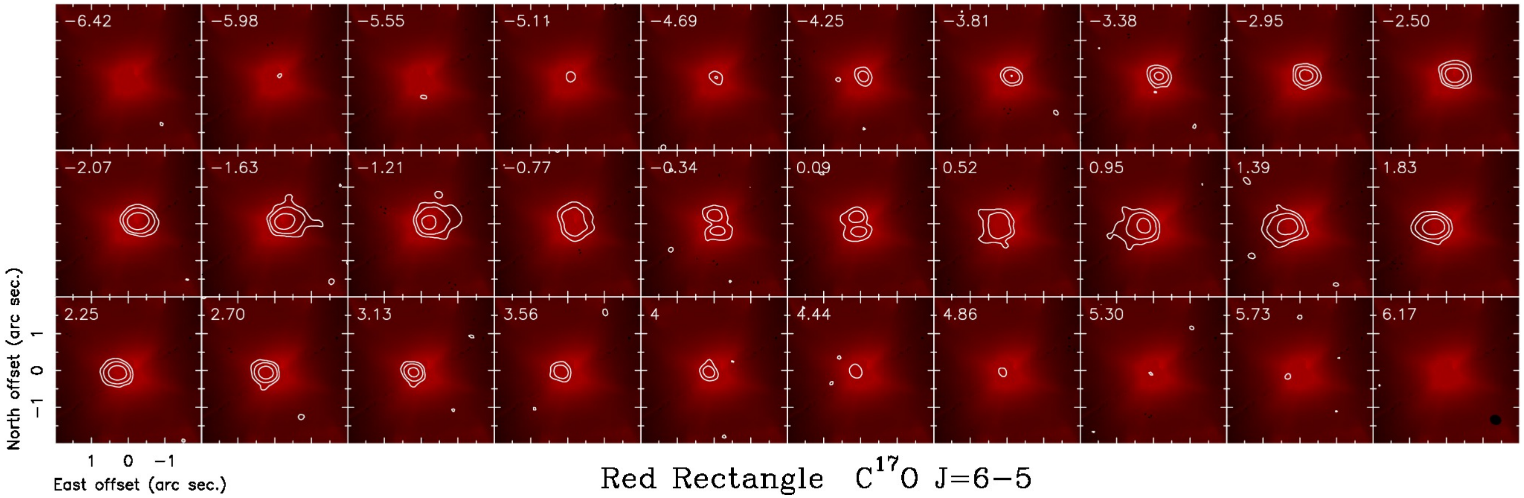
High resolution and sensitivity

S/N $\gtrsim$ 700

outflow almost not det. in ^{13}CO

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

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 $0\farcs31 \times 0\farcs26$

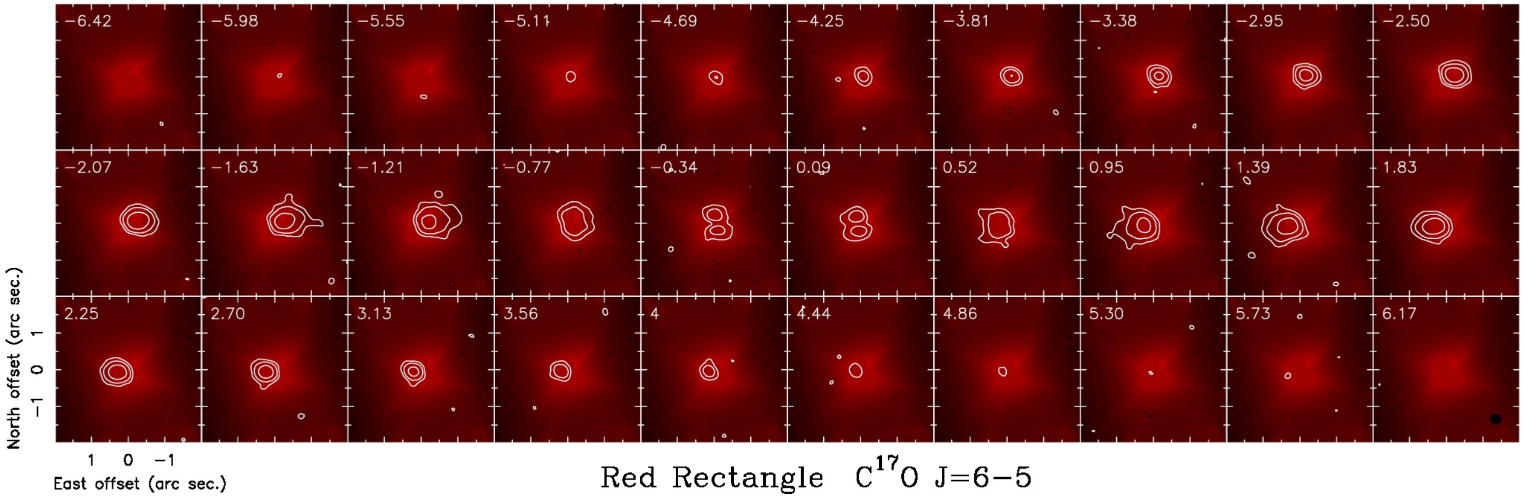
Optically thin emission (but not very optically thin), coming from the inner disk

Careful 2D treatment of radiative transfer and excitation required

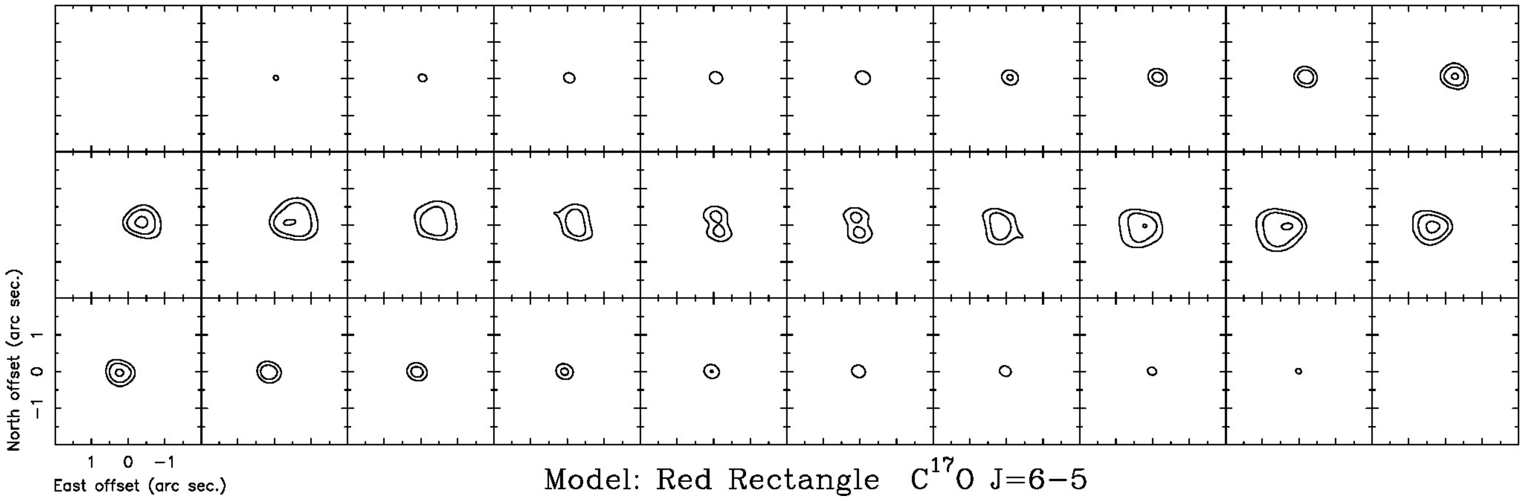
but important information on the inner disk properties are expected

Bujarrabal et al. 2015, in preparation

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

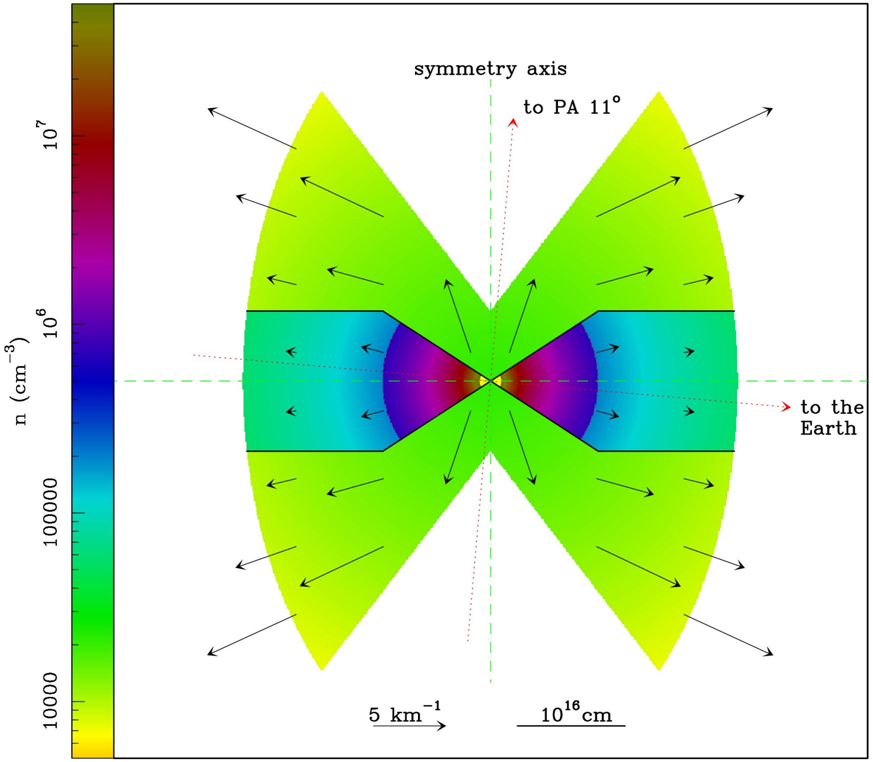


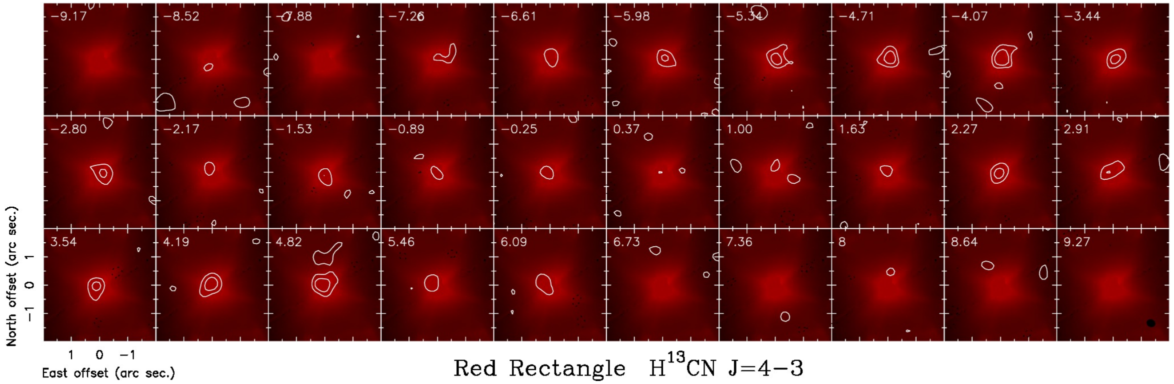
Red Rectangle $C^{17}O$ J=6−5

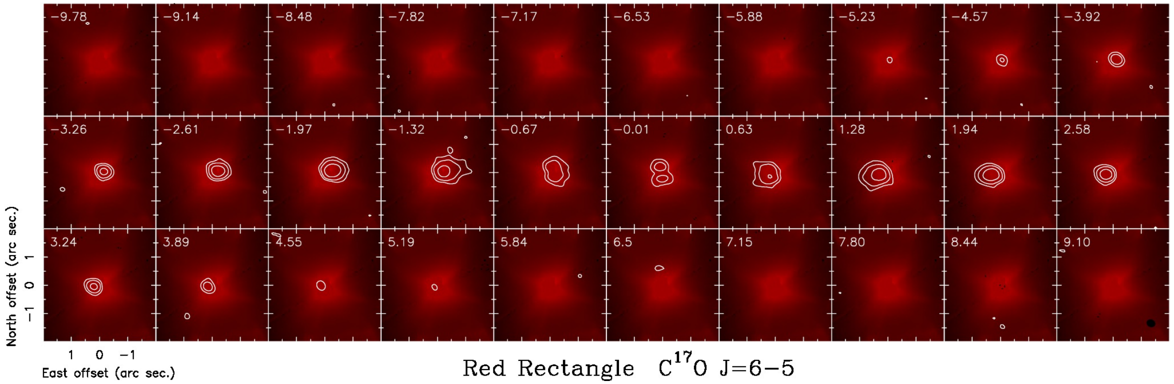


Model: Red Rectangle $C^{17}O$ J=6−5

ALMA maps of the Red Rectangle: last model and $H^{13}CN$ J=4–3







FINAL MODELING:

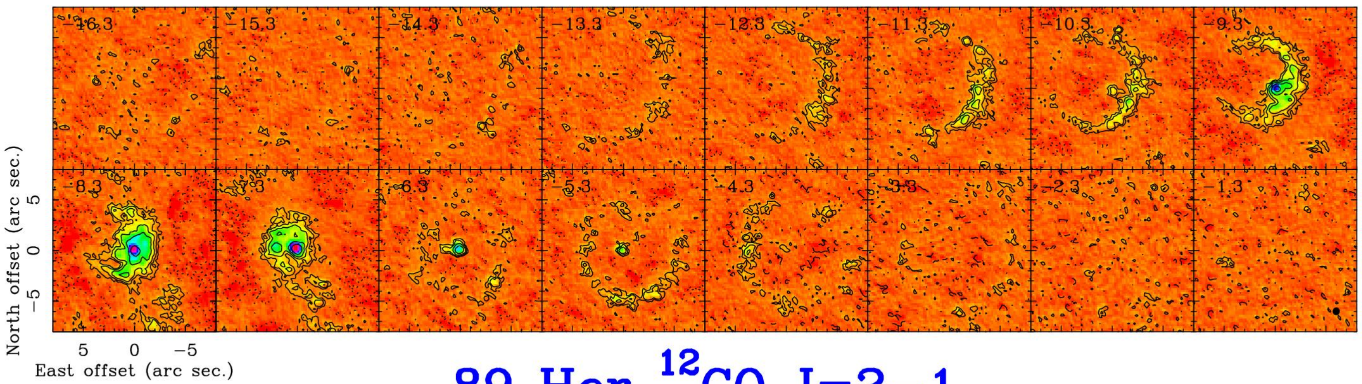
various lines allow distinguishing the effects of density, temp., and abundance

Total mass $\sim 0.01\ M_\odot$ Disk lifetime $\sim$ 8000 yr, not much smaller than the life of PNe

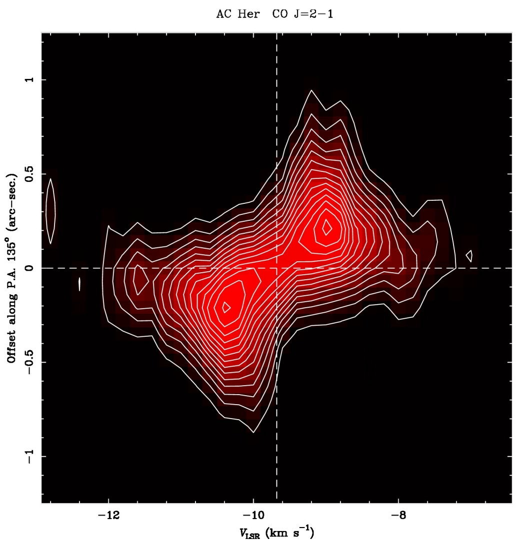
$H^{13}CN$ emission comes from a PDR in the very inner disk: the tiny bow tie

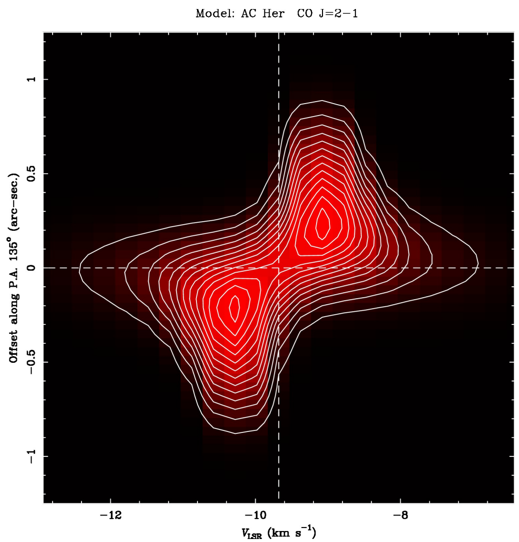
A few other similar objects also mapped with high angular resolution

89 Her and IRAS 19125+0343 show disk-like profiles but only expansion in the maps



89 Her ^{12}CO J=2−1



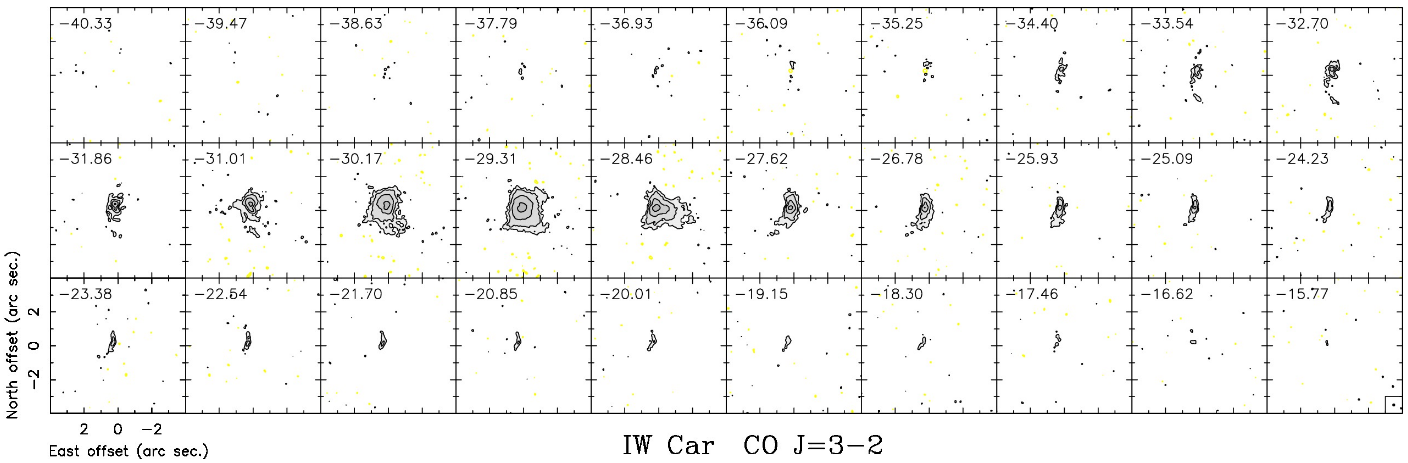


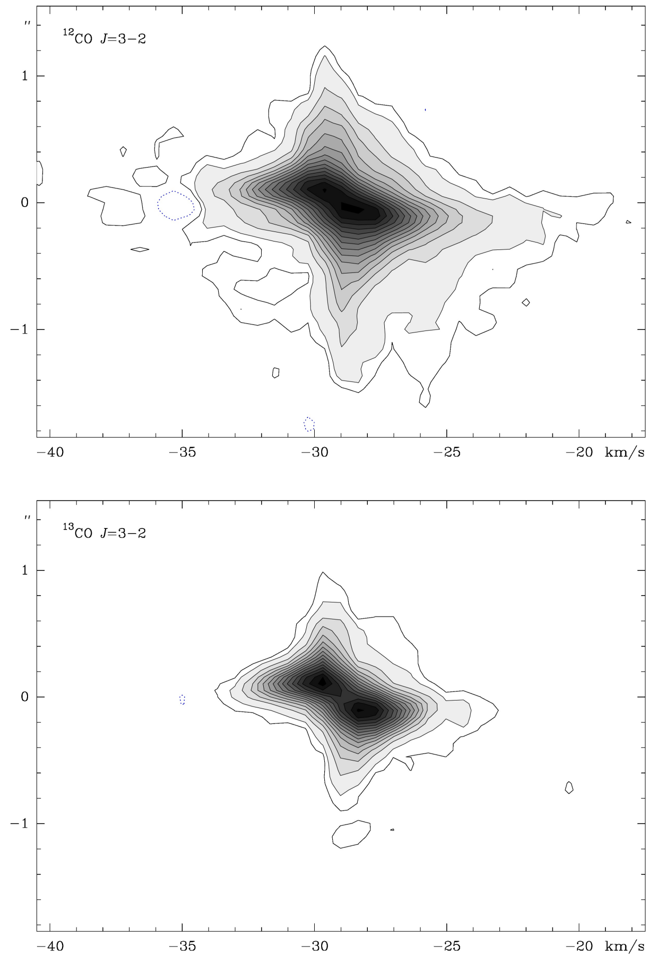
AC Her: Keplerian dynamics
but not expansion

shorter/longer lifetimes depending on outflow/disk mass ratio

Bujarrabal et al., 2007, AA, 468, L45; Bujarrabal et al., 2015, AA, 575, L7; recent PdBI data under analysis

IW Car: a Keplerian disk plus an outflow: fresh ALMA data





Again, very high dynamic range and resolution:

S/N $\sim$ 400, beam: $0\farcs15\times0\farcs15$

Again, bright emission $T_R \gtrsim 130$ K

expanding hourglass at PA $\sim 75^\circ$, Keplerian disk perp.

Similar disk/outflow ratio as the Red Rectangle

$=>$ similar disk lifetime

but disk $\sim$ 2 times smaller than for RR; outflow $\sim$ 4 times smaller than for 89 Her