Molecular lines from PPNe and young PNe :
Recent studies of their structure and dynamics

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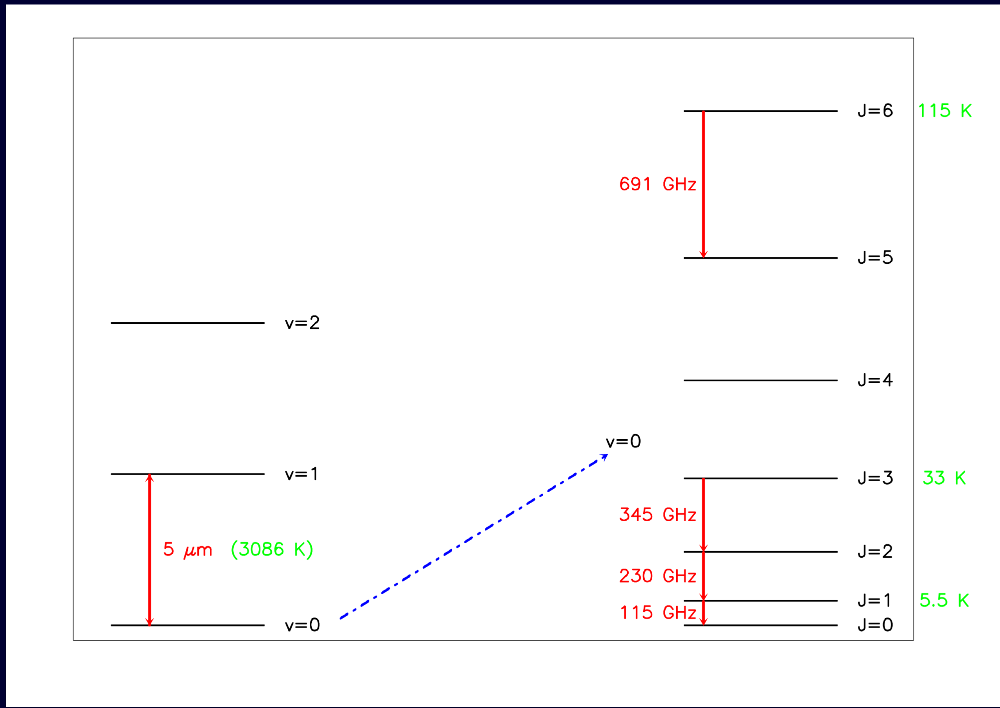
Quantitative, accurate results on structure, kinematics, temperature, density, ...

Example: ^{12}CO, ^{13}CO : Simple rotational ladder, simple excitation

Easily populated by collisions (low A-coeff.)



low-Js (e.g. J=2-1, J=1-0; mm-waves) :

Easy excitation, depends slightly on $T_{rot} \sim T_k$

We see most gas (in PPNe and young PNe)

and can measure densities and total mass

higher-Js (e.g. J=6-5; sub-mm-waves) :

more difficult to excite

probe warm gas and line ratios give temperatures

POWERFUL INSTRUMENTS (ALMA) –> very high spectral and spatial resolutions

Very accurate description of structure and kinematics over the whole nebula

Powerful instruments

1: Very high spectral resolution, limited in fact by sensitivity   heterodyne technology

2: Very high spatial resolution

$0\farcs3$ at present, soon better than $0\farcs1$

3: High sensitivity

enough in ALMOST ALL our cases   (at least in the Galaxy)

each line tends to select regions not much hotter or cooler than E_J(K) !!

low T: we do not populate the levels;   high T: many other levels populated

Intense lines ($\tau \gtrsim 1$) : $T_B(J \rightarrow J{-}1, K) \sim E_J(K)$!!   very general result, widely satisfied

state-of-the-art (well designed) instruments can map such a brightness !!

Systematic high-resolution observations of young PNe are feasible !!

$$\sigma(K) \sim 10^2 \frac{T_{sys}(K)\ \lambda(mm)^{2.5}}{A(m^2)\ \theta(arcsec)^2\ \sqrt{N(N-1)}\ \sqrt{\Delta V(km/s)\ t(sec)}\ \sqrt{N_{pol}}}$$

A : antenna surface ; N: number of antennas

(assuming: app. efficiency = 0.5 ; efficiency of correlator + atm. decorrelation = 0.8)

Plateau de Bure (clever design with big antennas)

(230 GHz, CO J=2-1; t = 8 h, $\theta = 0''\!.5$, T_{sys} = 200 K, ΔV = 1 km/s)

$\sigma(K) \sim 0.6$ K (0.15 K for 1″)

E(CO,J=2) = 16 K => T_{mb}(J=2–1) $\sim$ 10 – 20 K

=> S/N $\sim$ 25 at $0''\!.5$ res. (100 at 1″) !!

Good maps, even for rare species or weaker sources, even with subexcited lines.

NOEMA (extended PdBI) : higher resolution with higher surface: will also work

Systematic high-resolution observations of young PNe are feasible !!

ALMA : High-resolution (as high as $0\farcs01$), high-sensitivity mapping

6 times more surface; higher frequency; better system; much better atmosphere

higher brightness because of higher Js and more compact clumps

=> $\sim$ S/N and efficiency as PdB, but HIGHER ν and MUCH HIGHER RESOLUTION

CO J = 3–2 : σ(K) $\sim$ 1 K, for $\theta = 0\farcs1$ to map $T_{mb} \sim 30$ K

CO J = 6–5 : σ(K) $\sim$ 3 K, for $\theta = 0\farcs05$ to map $T_{mb} \sim 100$ K

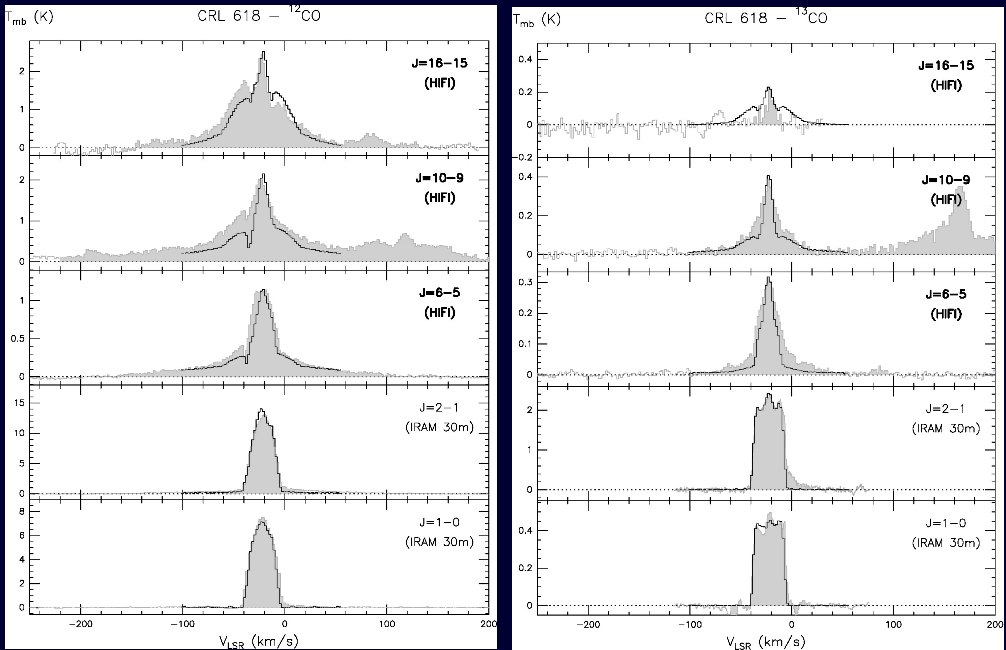
CO J = 6–5 : σ(K) $\sim$ 20 K, for $\theta = 0\farcs02$ to map $T_{mb} \gtrsim 300$ K

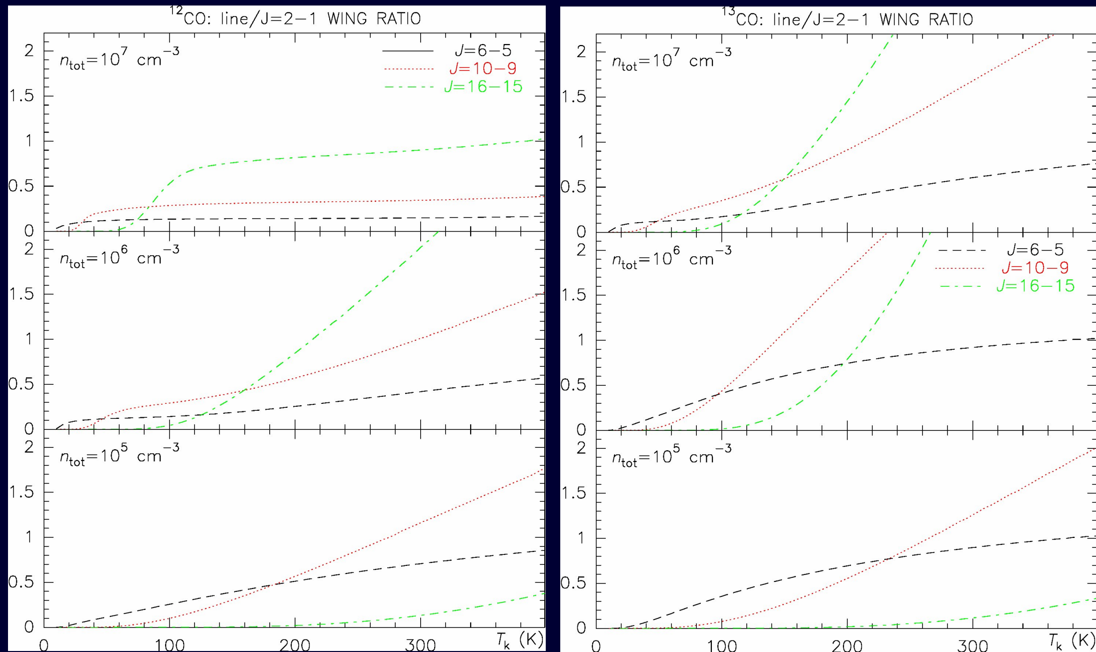
not optimistic estimates, very probably they will do better

Herschel/HIFI observations of high-excitation molecular lines

High-spectral (but low-spatial) resolution in the FIR and sub-mm, up to CO J=17–16

–> study of warm components and measurement of temperature





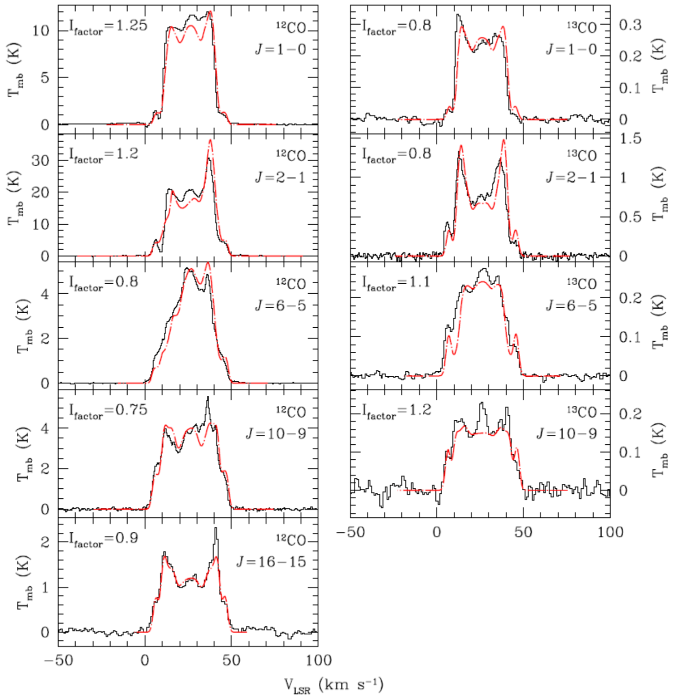
general and detailed results derived : e.g. CRL 618 shows a particularly warm fast outflow: $T_k \gtrsim 200$ K

see also atomic fine-structure (low-excitation) lines in poster by Santander-García et al.

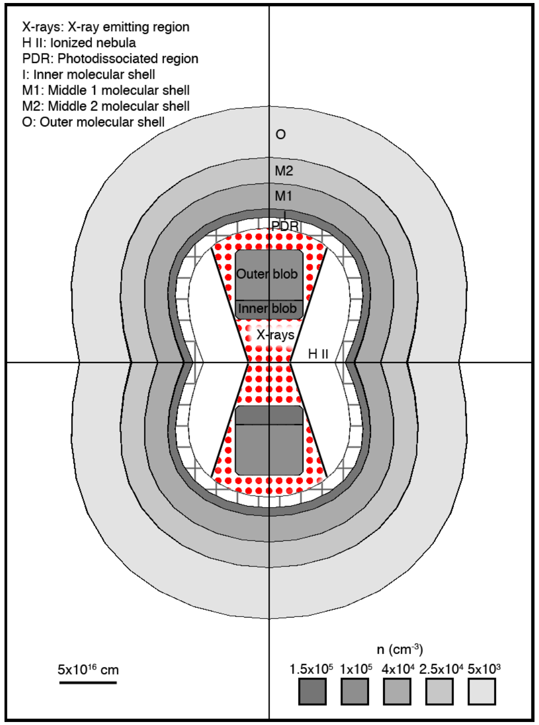
Bujarrabal et al. (2010, A&A 521, L3; 2012, A&A, 537, A8), Soria-Ruiz et al. (2013, A&A 559, A45), etc

High-excitation molecular lines: Example of detailed analysis: NGC 7027

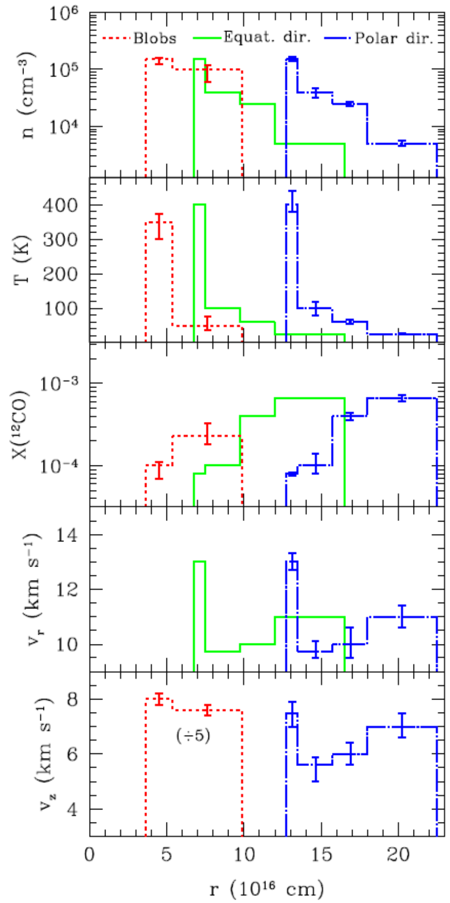
Model fitting



General structure of the nebula



Derived physical conditions



nebular components identified from profile components

Model fitting gives a very detailed and quantitative description of the nebula

Shock effects (higher velocity and temp.) in the inner shell and axial blobs

Santander-García et al. (2012, A&A, 545, 114)

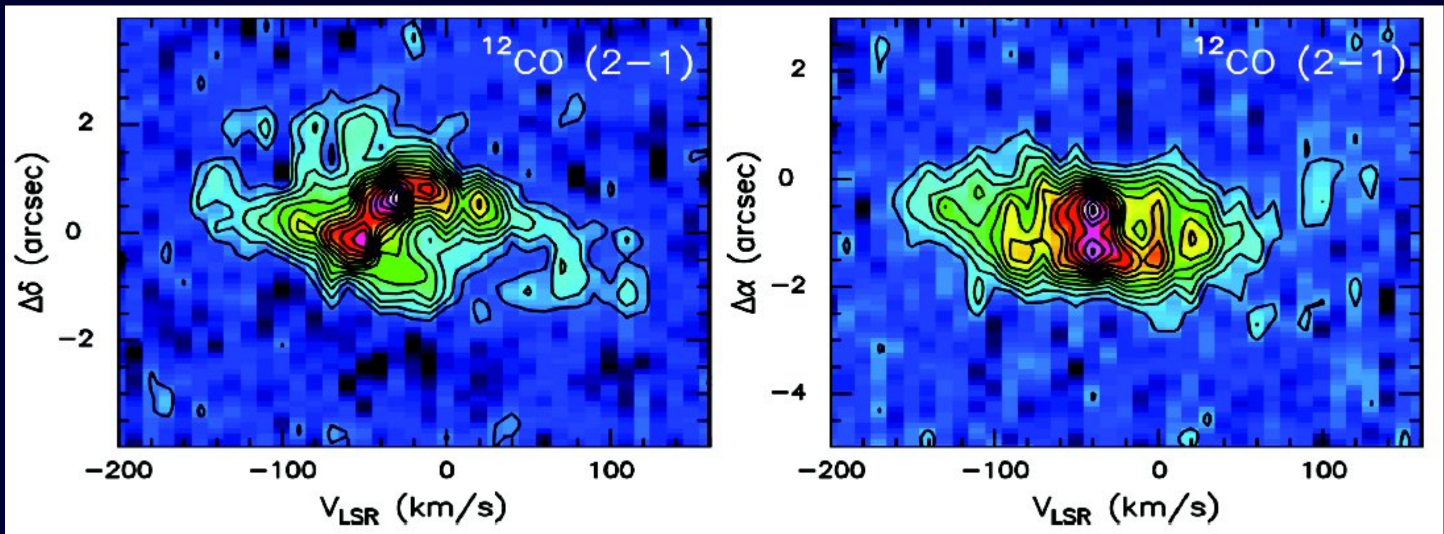
OVRO systematic observations of post-AGB nebulae: OPACOS

wide OVRO survey of post-AGBs/PPNe in ^{12}CO, ^{13}CO, and $C^{18}O$ J=1–0

Moderate resolution: 2$''$.2 - 10$''$.7   mostly detections and statistical

27 objects, almost 90% detection, selected mostly from FIR colors

An outstanding case : IRAS 19374+2359



Enormous velocities and linear momentum (the largest known)

$P \sim 45\,M_\odot$ km s^{-1} / sin(i)   equivalent to $\sim 0.5\,M_\odot$ at 130 km s^{-1} !!

Sánchez Contreras & Sahai, 2012, ApJS, 203, 16

OVRO systematic observations of post-AGB nebulae: OPACOS

Statistical results: not all PPNe are so spectacular

Many PPNe are very massive and show very fast outflows

but in most sampled objects $V_{outfl} \sim 20 - 70$ km s^{-1}

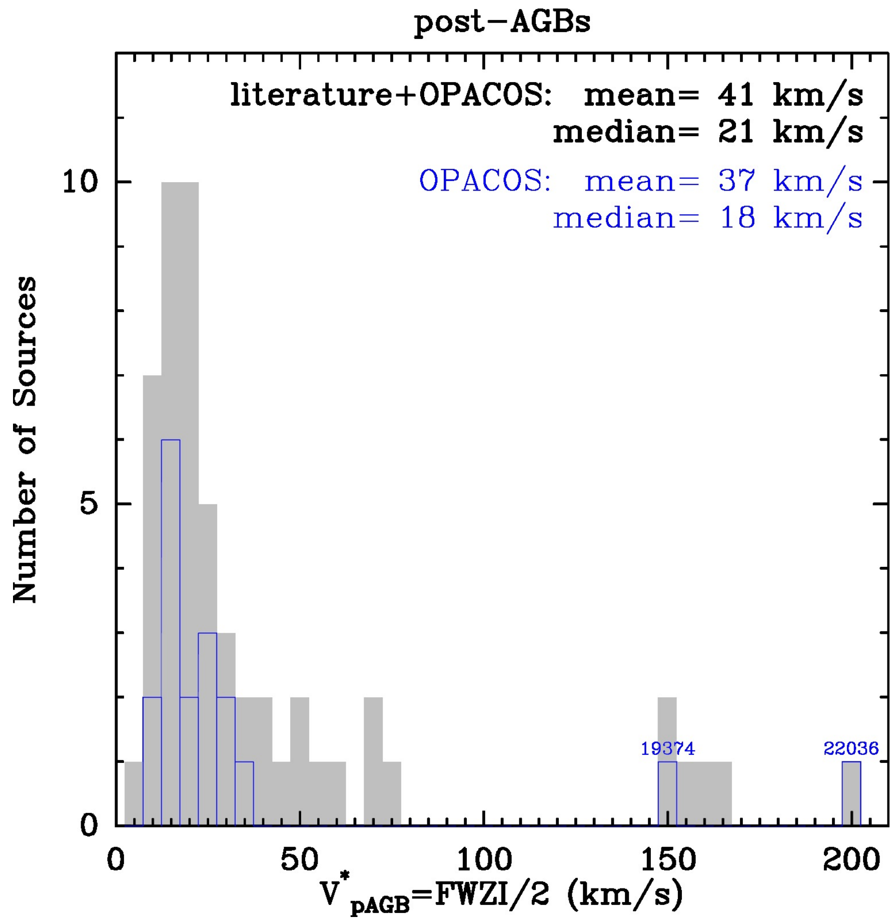
(after correcting for random inclination)

and $M_{tot} \sim 0.05 - 0.5\ M_{\odot}$

(after correcting for ^{12}CO opacities)

we will see more extreme cases later

pay attention to observational biases

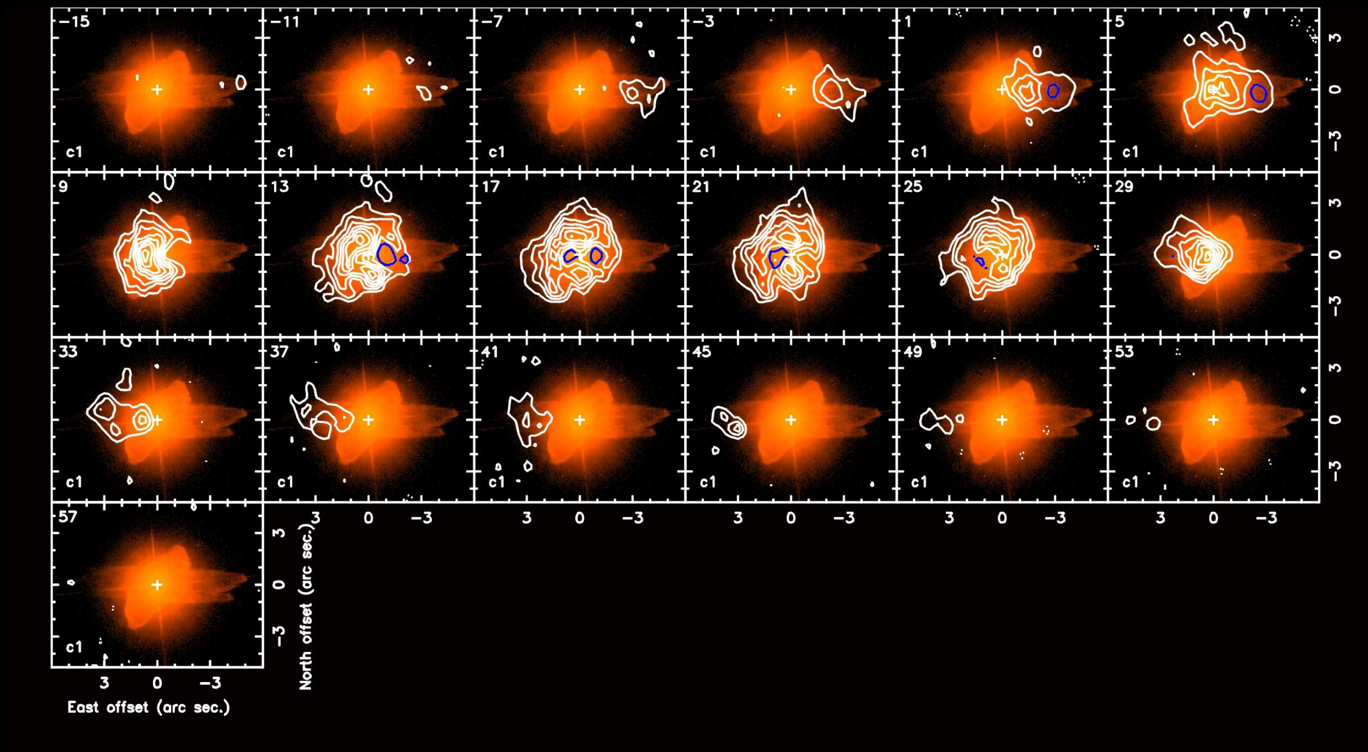


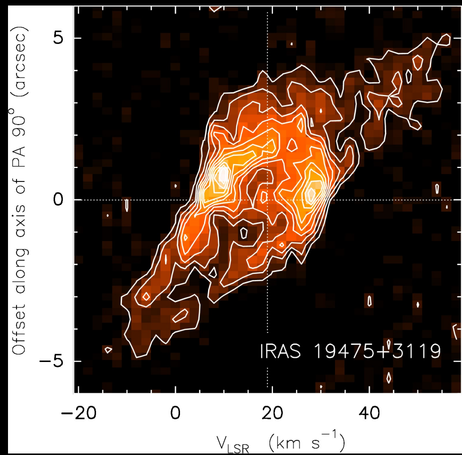
COSAS: Systematic PdB observations of AGB and post-AGB objects

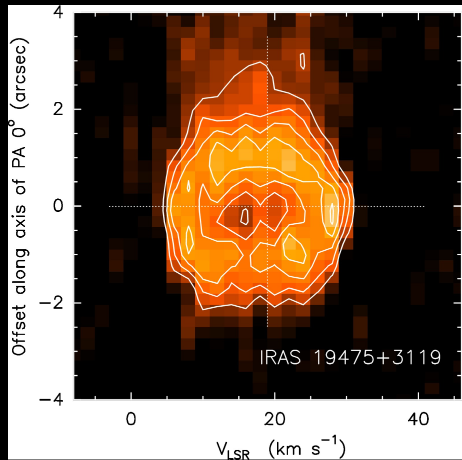
wide PdB survey of AGB and post-AGB nebulae J=1–0 and J=2–1

45 objects observed and reduced, 18 already published

high quality maps, res. < 2″ (in J=2–1)





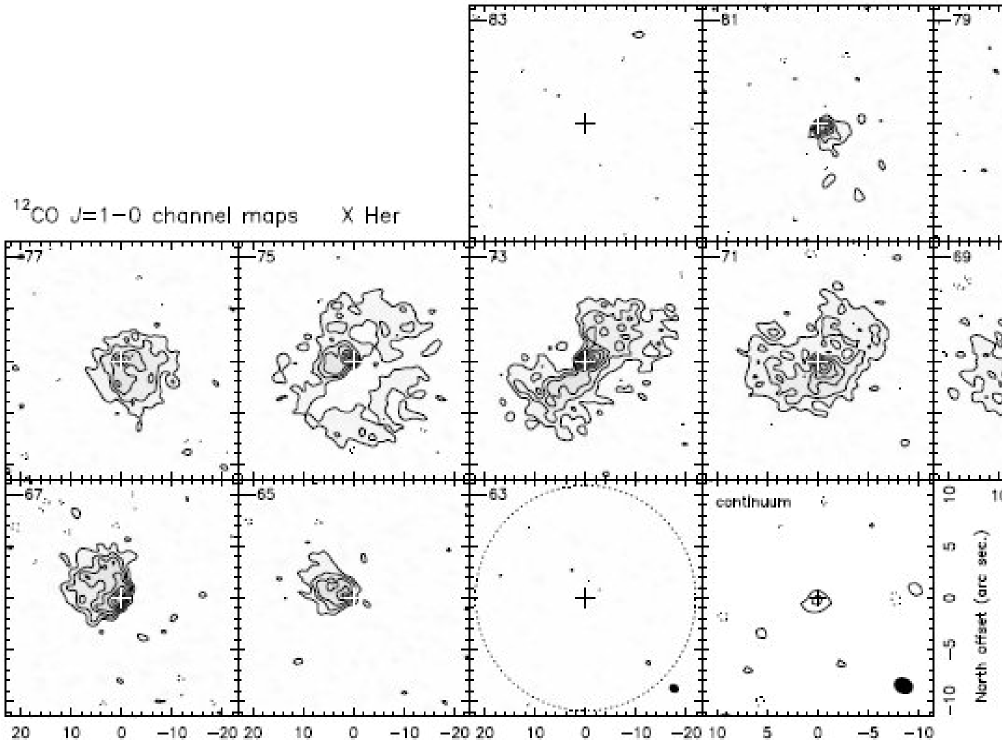


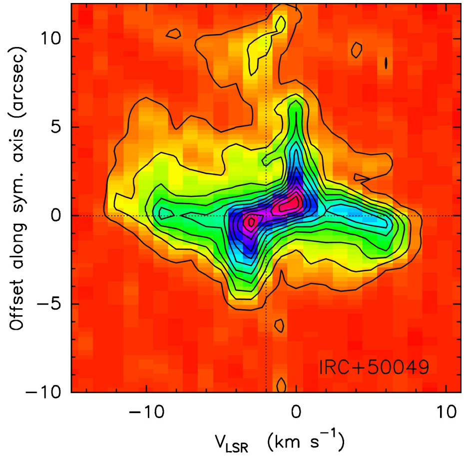
IRAS 19475+3119, bipolar PPNe, first group of data from COSAS

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

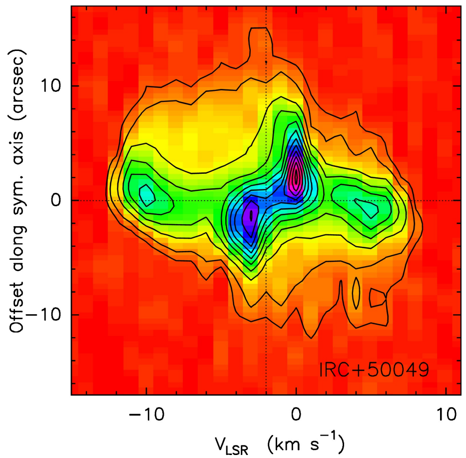
COSAS: AGB semirregular variables with axisymmetric CSEs: IRC+50049

A group of semiregular variables (X Her, RX Boo, IRC+50049, ...) show axial shells **expanding** at moderate velocity





CO J=2–1



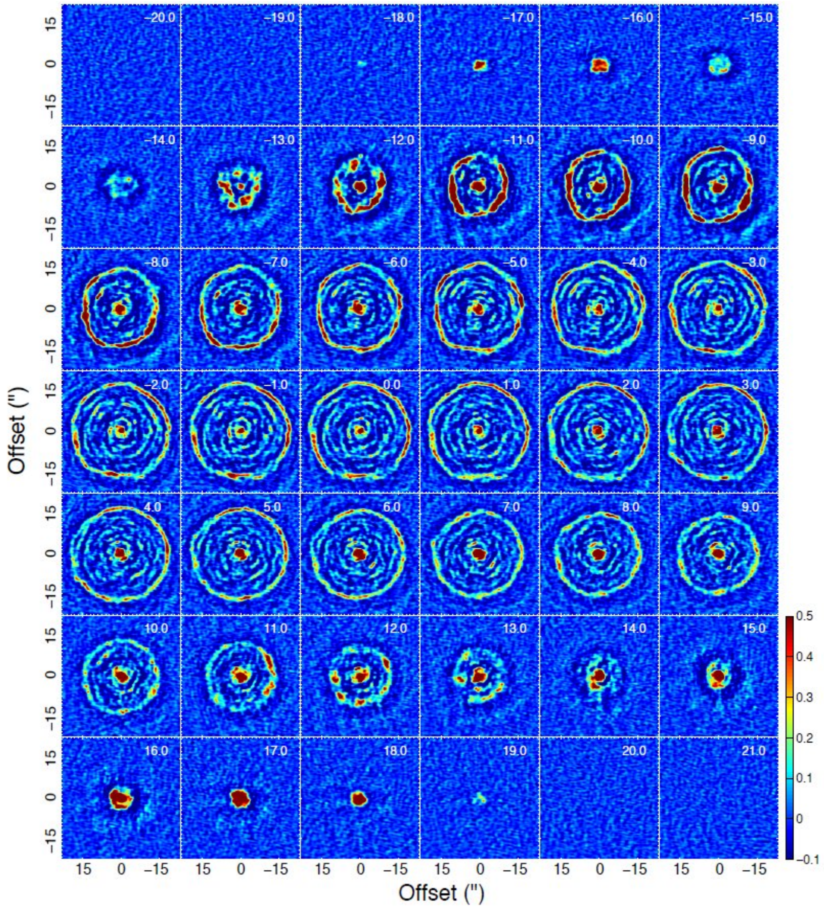
CO J=1–0

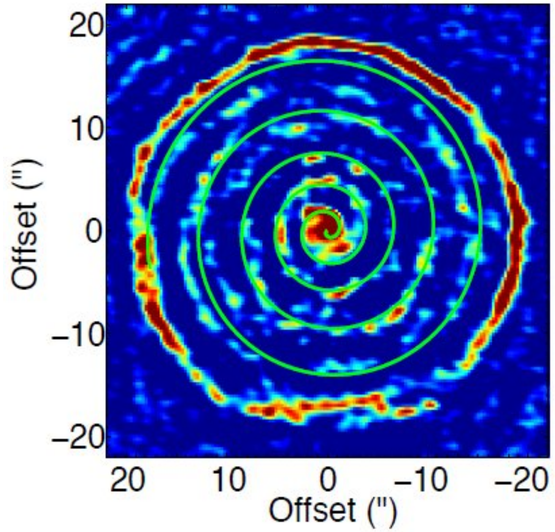
Origin of asymmetry ?? systematic studies in progress

Castro-Carrizo et al., in preparation (COSAS survey)

The detached envelope around the semiregular AGB star R Scl

ALMA high quality data show mass loss between periods of enhanced rates





Phases of increased mass loss were known

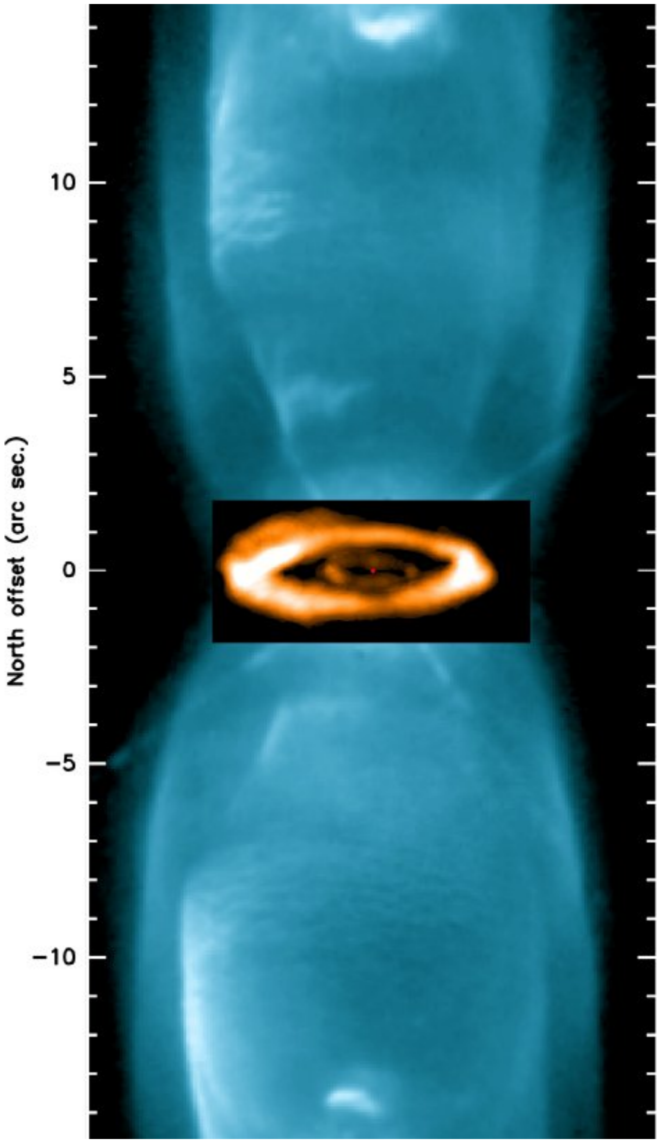
Moderate-resolution high-sensitivity ALMA maps show low-brightness spiral envelope probably due to binarity (also seen in scattered light images of AGBs and PNe)

see more details in poster by W. Vlemmings, including variations of isotopic ratios in the shell

Maercker et al. 2012, Nature, 490, 232; Vlemmings et al. A&A, 556, L1

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

Bipolar nebula 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

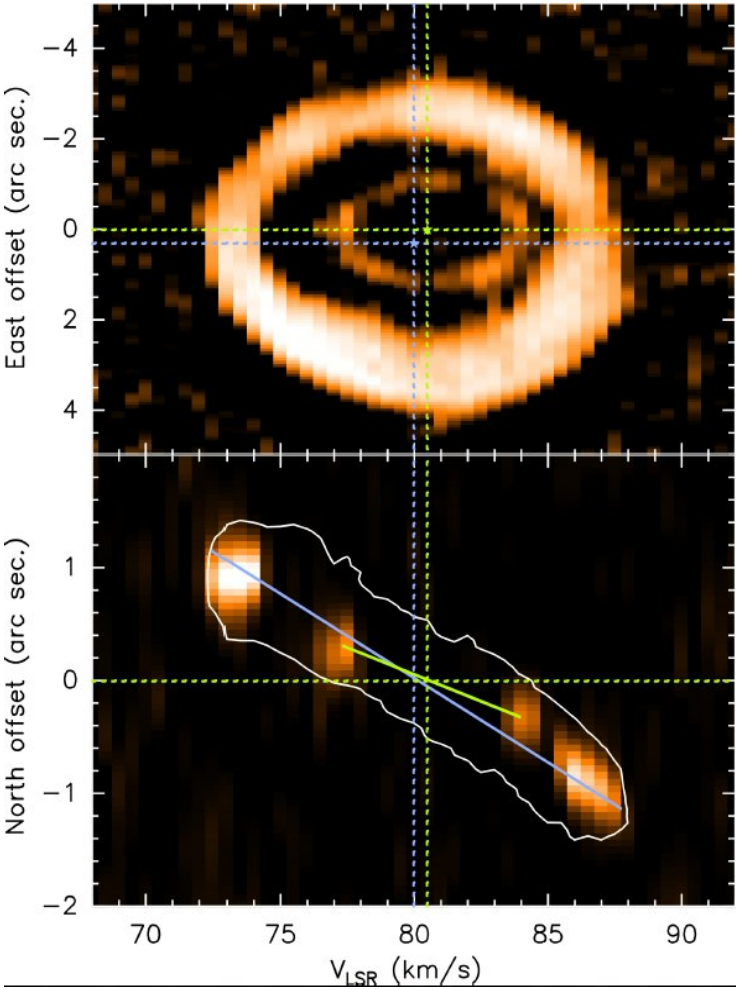
and with low velocities : 4 km s^{-1} and 8 km s^{-1}

High quality PdB maps, resolutions: 0.1 km s^{-1}, $0''.5$

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

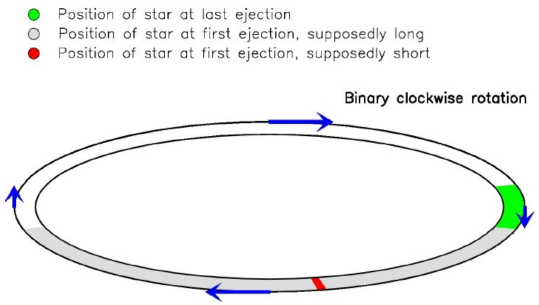
Expanding equatorial rings in M 2–9, the Butterfly Nebula

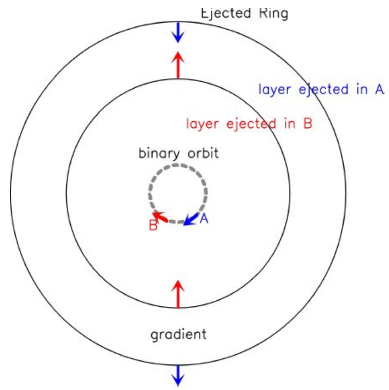
The spatial and velocity centroids of the rings are not the same !



Ejected in two different phases of the (primary) orbit

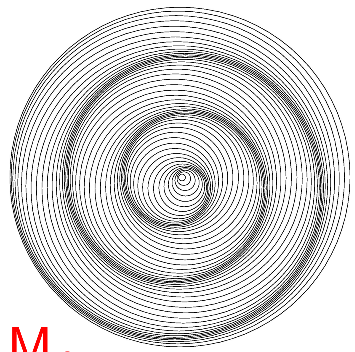
The stellar velocity affects the velocity of the rings, their central position, and the gradients within the rings





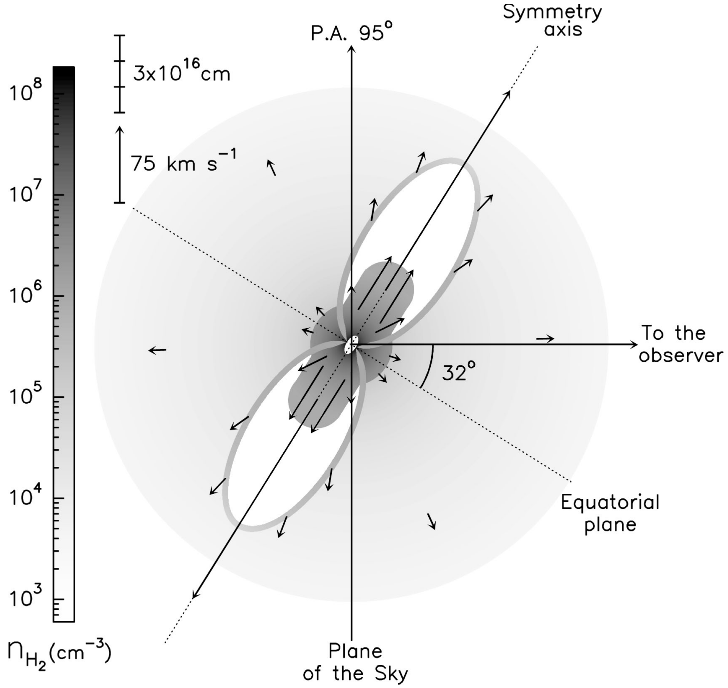
confirms binary origin of spirals !!

(seen in many objects)



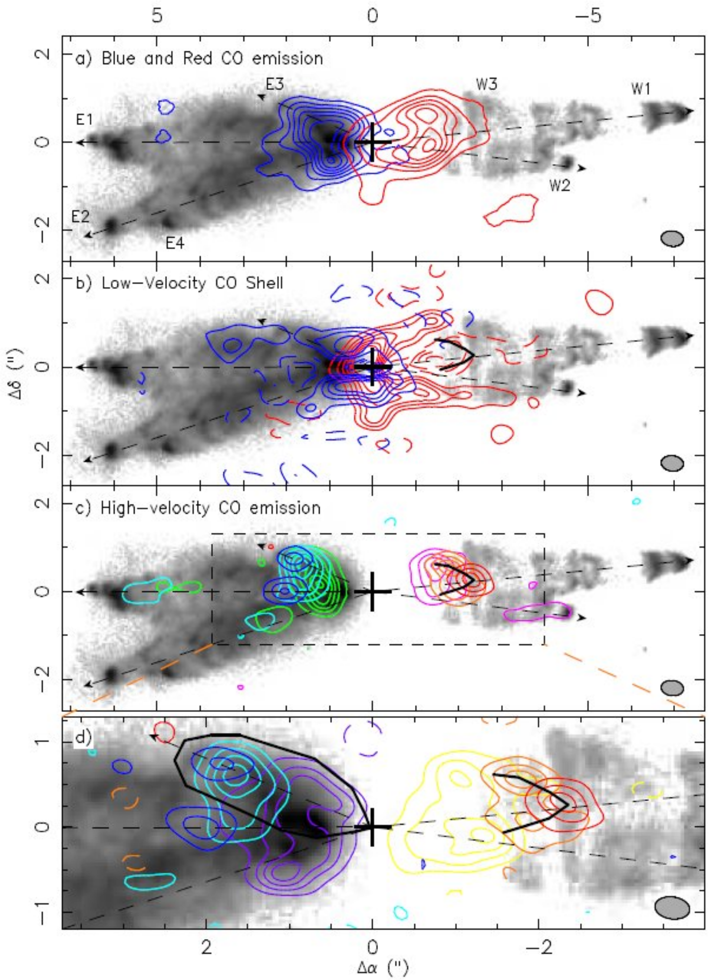
Orbital parameters derived. Mass of secondary in M 2–9 $\lesssim 0.2\ M_\odot$

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.″3 resolution

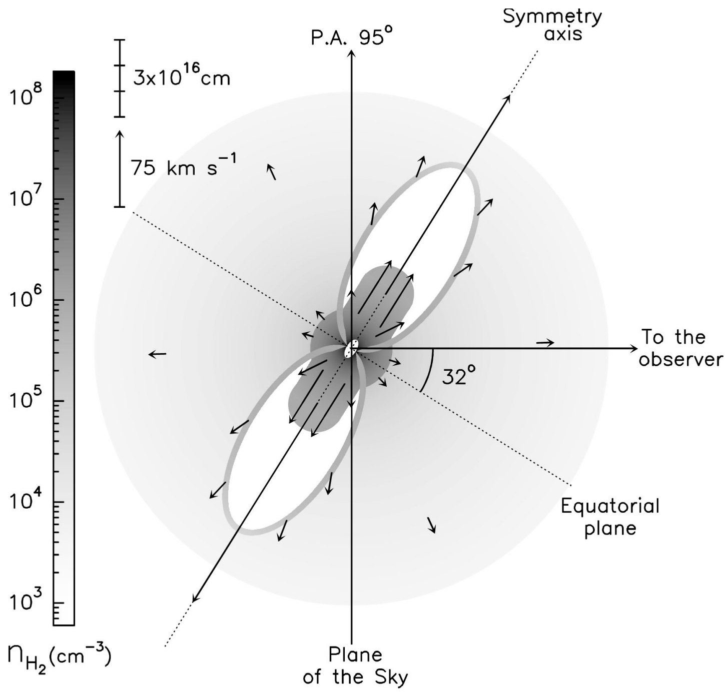


Very complex structure of the fast outflows

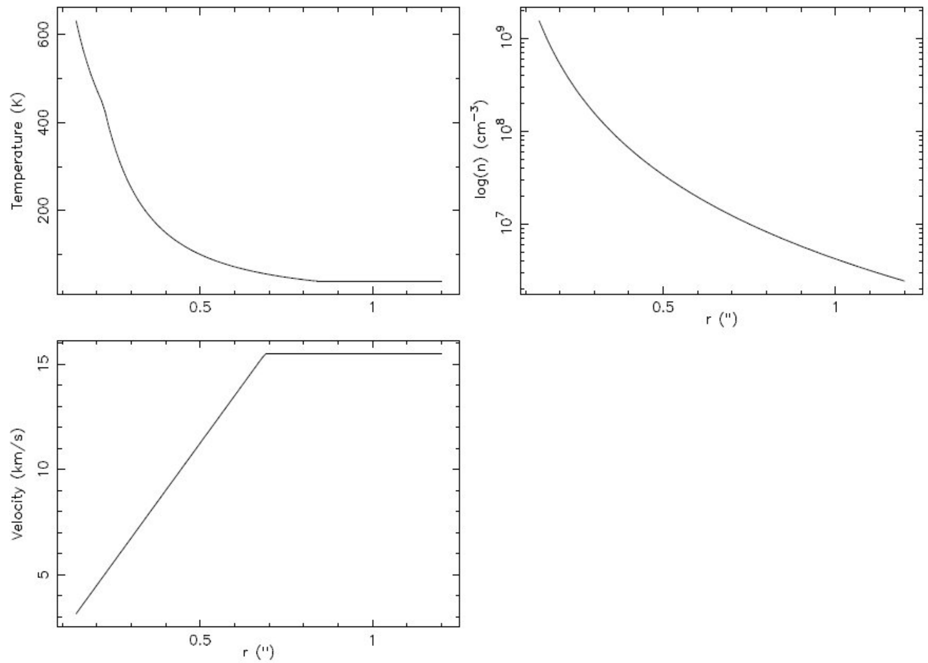
∼ cavity converging to ∼ bow shock

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

High-resolution observations of lines of HCN and HC_3N in CRL 618



SMA maps of HCN and HC_3N (+ isotopes + vibr. exc.)



select efficiciently the nebula center –>

accurate description of the phys. conditions

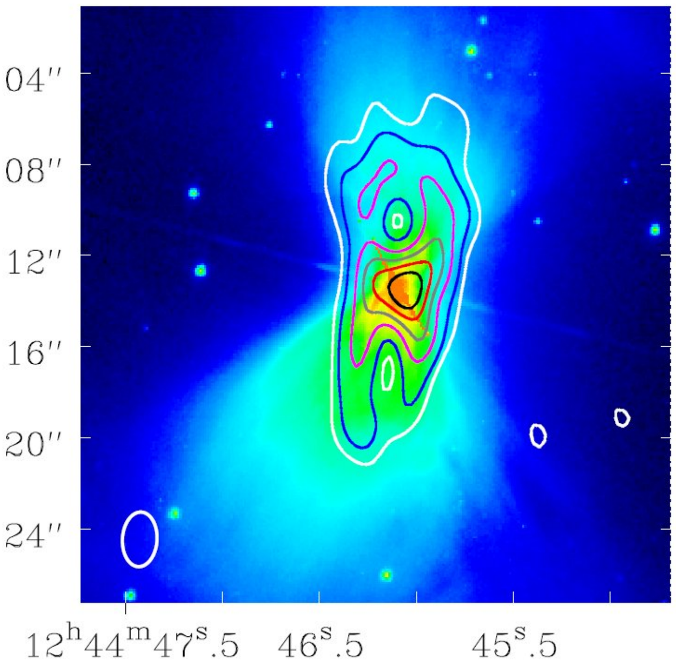
and dynamics of the slow and dense inner core

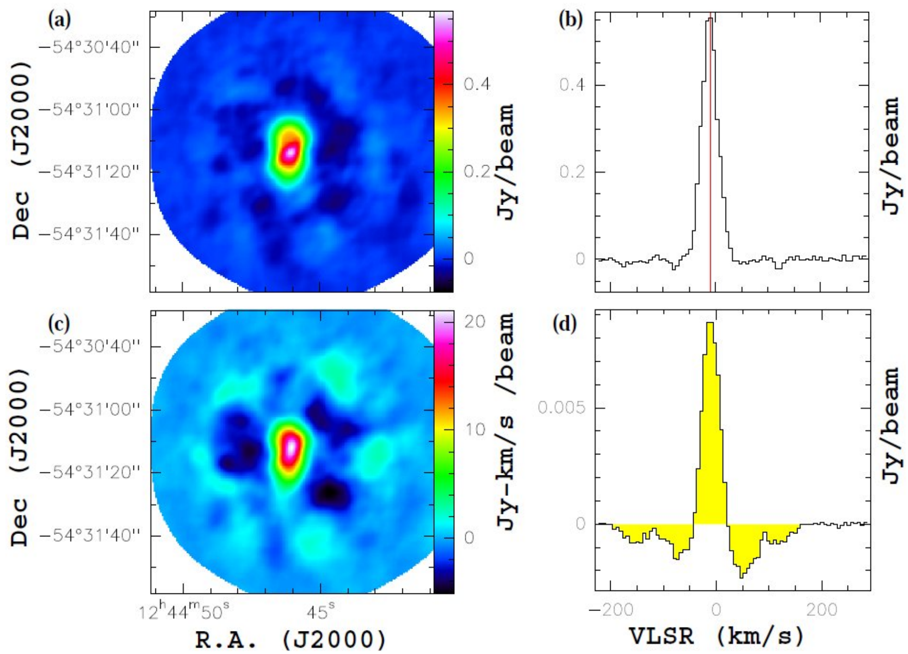
the expansion velocity decreases with time in very late AGB phases (or acceleration?)

(inner $0\rlap{.}''6 \cong 8\ 10^{15}$ cm $\cong$ 200 yr)

Lee et al. (2013, ApJ 770, 153)

The Boomerang Nebula:
The coldest region in the Universe? ALMA and SEST data





Double shell at moderate velocity

+ very extended and fast halo at very low temperature (< 2.7 K)

Sahai et al. (2013, ApJ, 777, 92)

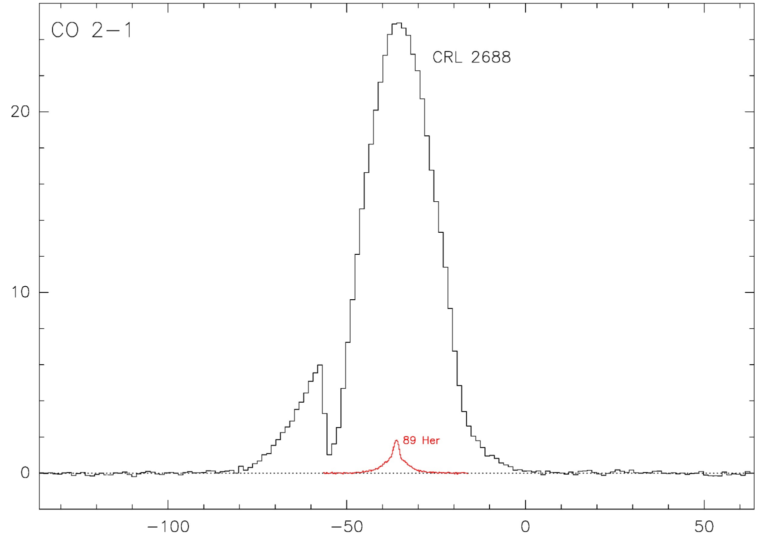
Rotating and expanding gas in low-mass post-AGB nebulae

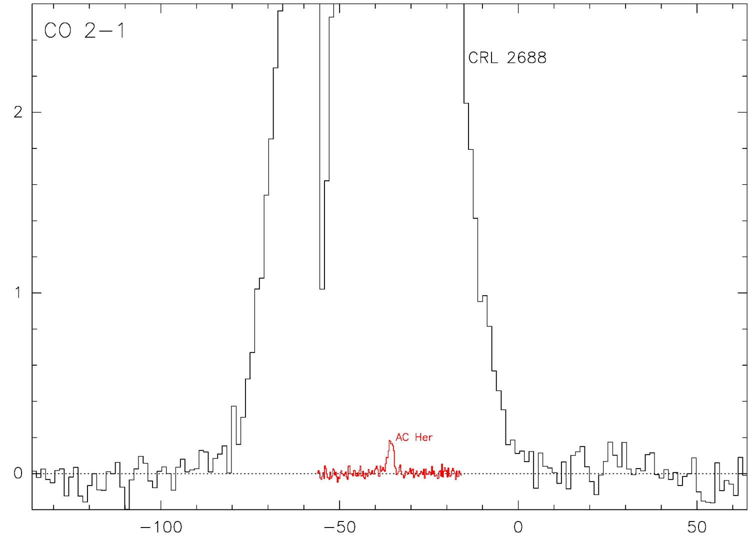
Some post-AGB objects are known to show very low nebular mass (and weak CO)

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

the Red Rectangle, 89 Her, HR 4049, RV Tau variables, IRAS 19500-1709, ... (M 2–9?)

$\sim$ 1/2 show a significant NIR excess; all NIR-excess sources 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

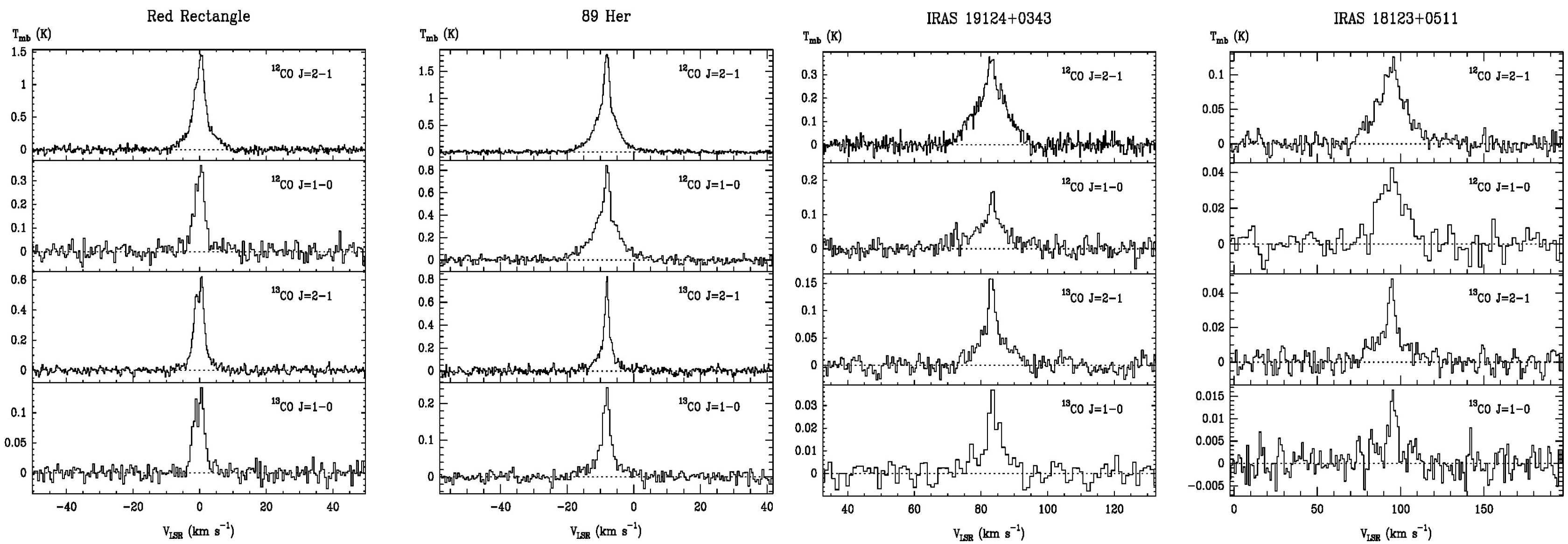
CRL 2688: *standard* PPNe (D = 1.2 kpc)

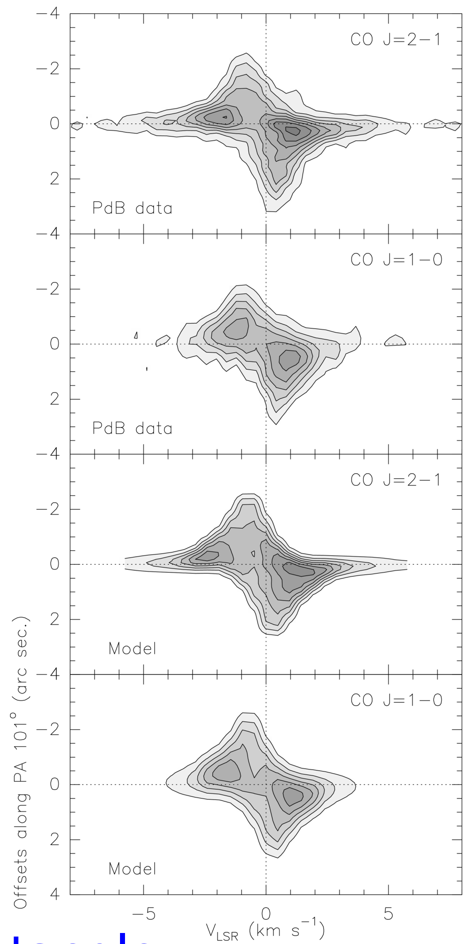
high mass, velocity, and momentum

why there is an observational biass !!

Rotating and expanding gas in low-mass post-AGB nebulae: systematic CO observations

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





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

(too wide and intense line wings)

confirmed by maps in a one or two objects, notably in the Red Rectangle

Bujarrabal et al. (2013, A&A 557, 104; A&A 557, L11), see also poster

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

Results from CO lines

Source	disk mass $M_\odot$	typical size $''$	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	$6\ 10^{-3}$	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	$2.7\ 10^{16}$	$\sim 10^{-2}$	~ 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	$3\ 10^{16}$	$\sim 10^{-2}$	~ 15	difficult estimates
AC Her	$8.4\ 10^{-4}$	0.7	$1.1\ 10^{16}$			
R Sct	$\sim 7\ 10^{-3}$	~ 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	$\sim 2.5\ 10^{-2}$	~ 0.6	$\sim 1.7\ 10^{16}$	$\sim 7\ 10^{-2}$	~ 10	complex profiles
R Sge	$< 9\ 10^{-3}$	<0.3	$<7\ 10^{15}$			
IRAS 08544–4431	$\sim 7.7\ 10^{-3}$	2.2	$1.8\ 10^{16}$	$\sim 2\ 10^{-3}$	~ 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}–10^{-2} $M_\odot$!!

low velocity, 5–10 km s^{-1}!!

small size

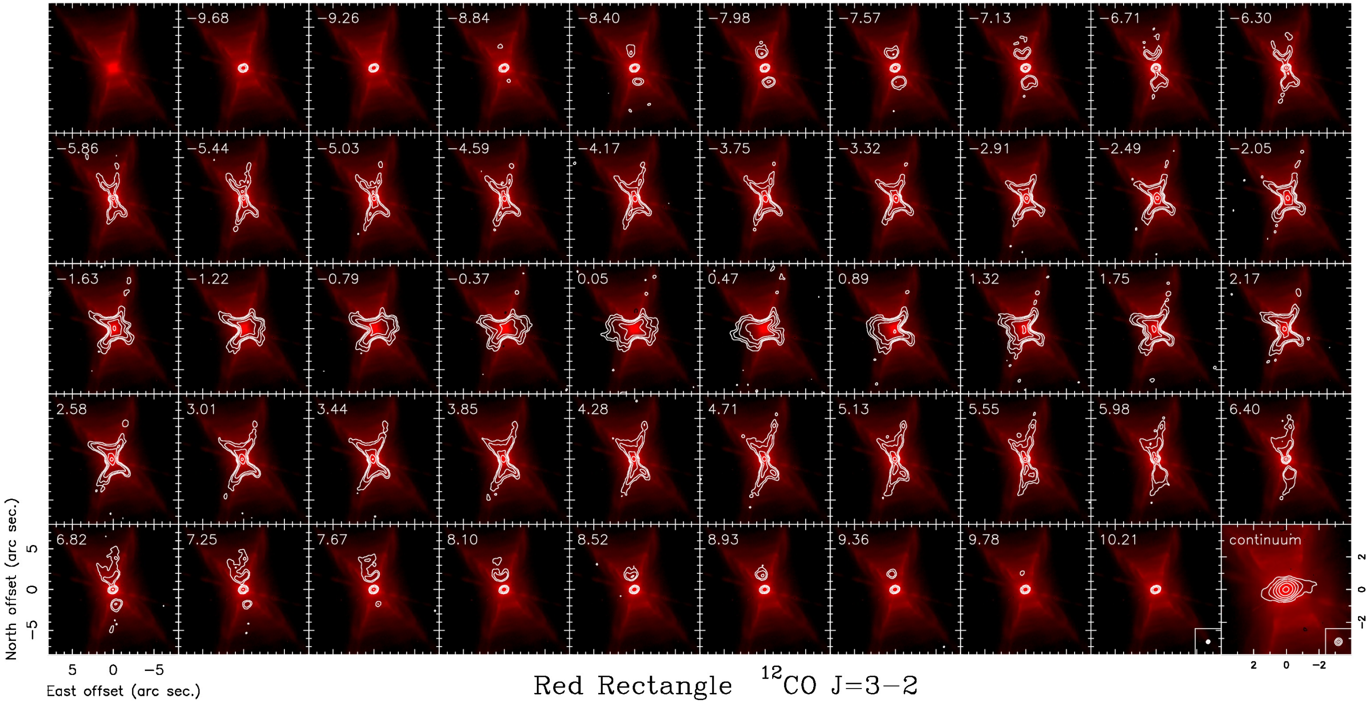
which evolution ??

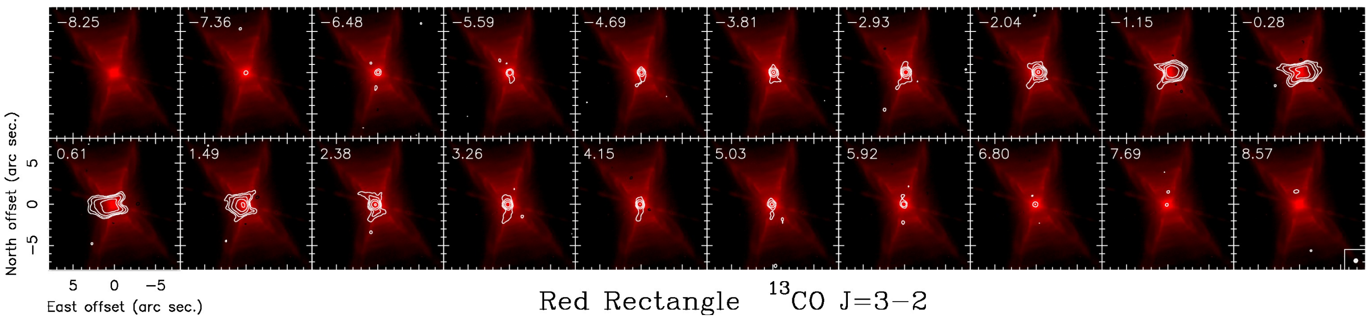
resulting PNe ??

maps exist 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

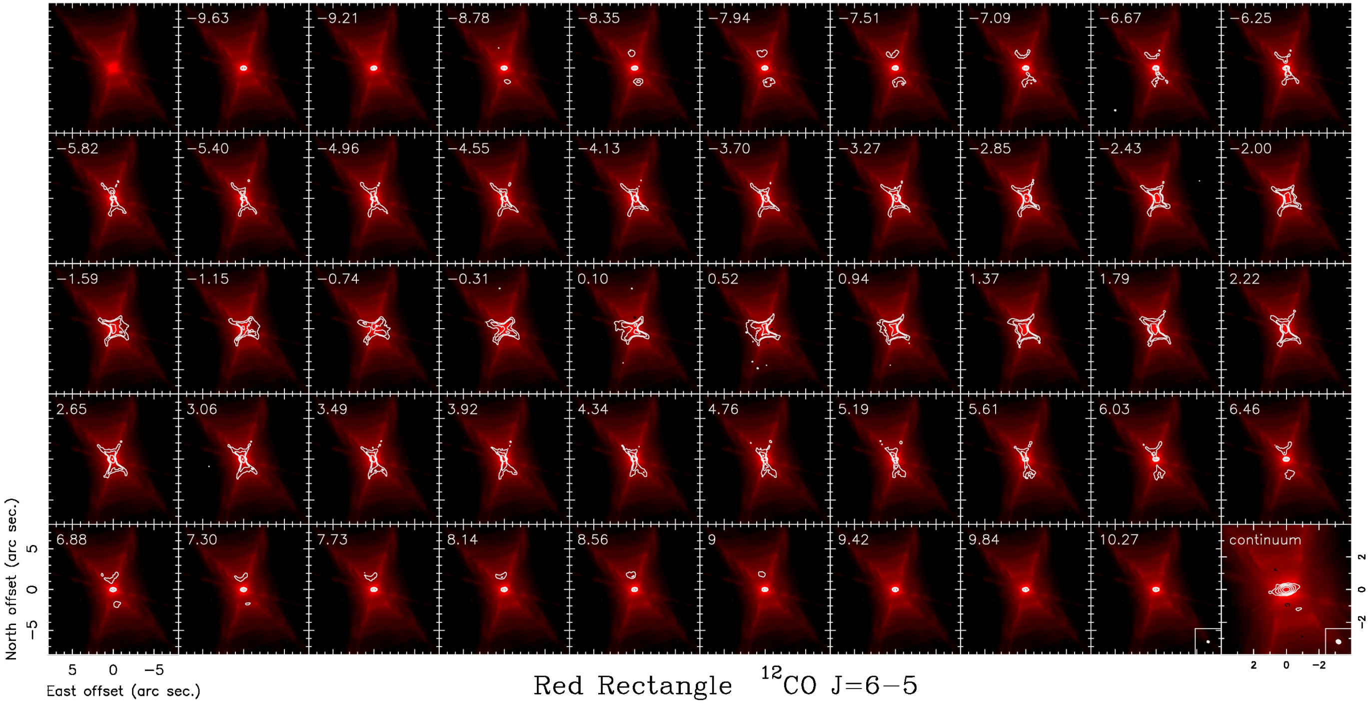
High resolution and sensitivity

outflow almost not det. in ^{13}CO

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

High-quality ALMA maps of the Red Rectangle

^{12}CO J=6–5 (0.4 mm)



0.″25 arcsec resolution !

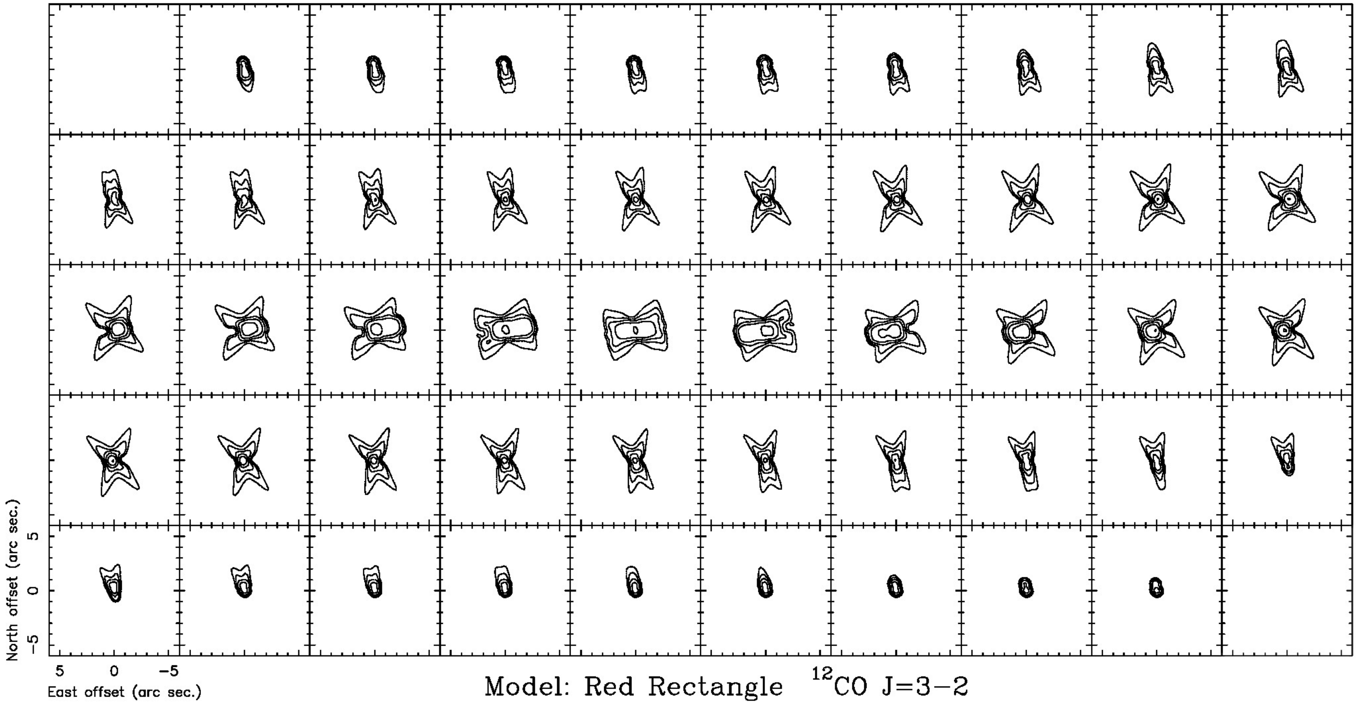
high exc. line ($\gtrsim$ 100 K)

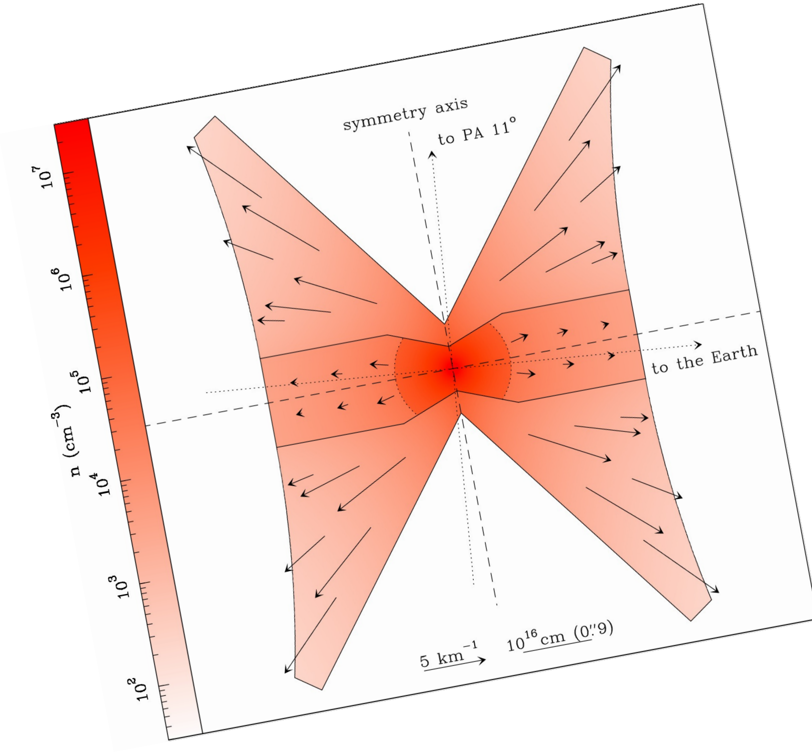
–> T_k

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

High-quality ALMA maps of the Red Rectangle

preliminary modeling of ^{12}CO J=3–2





structure, density, & velocity

$T_k \sim$ 200 K; rotation not displayed

Moderate mass, velocity, and momentum

We interpret: material from the disk entrained by interaction with the axial fast jets

=> short disk lifetime, 1000 - 3000 years (for RedRect, 89 Her, and IRAS 19125)

We speculate: these results basically apply to all sources of this kind