Sub-mm observations of AGB stars

Hans Olofsson
Onsala Space Observatory & Stockholm Observatory

- The central stars
- The circumstellar envelopes
- The circumstellar molecules
- The termination of the AGB, early post-AGB

The importance of AGB stars

- The final stellar evolutionary stage for stars in the mass range ≈0.8-8 M_{sun}
  => the majority of all stars that have died in our universe have done this as AGB stars

- They have a large mass return and so are important for the cosmic gas/dust cycle:
  - they produce heavy elements (3α, s-process)
  - they produce dust particles
  - they produce complex molecules (PAHs, ...)

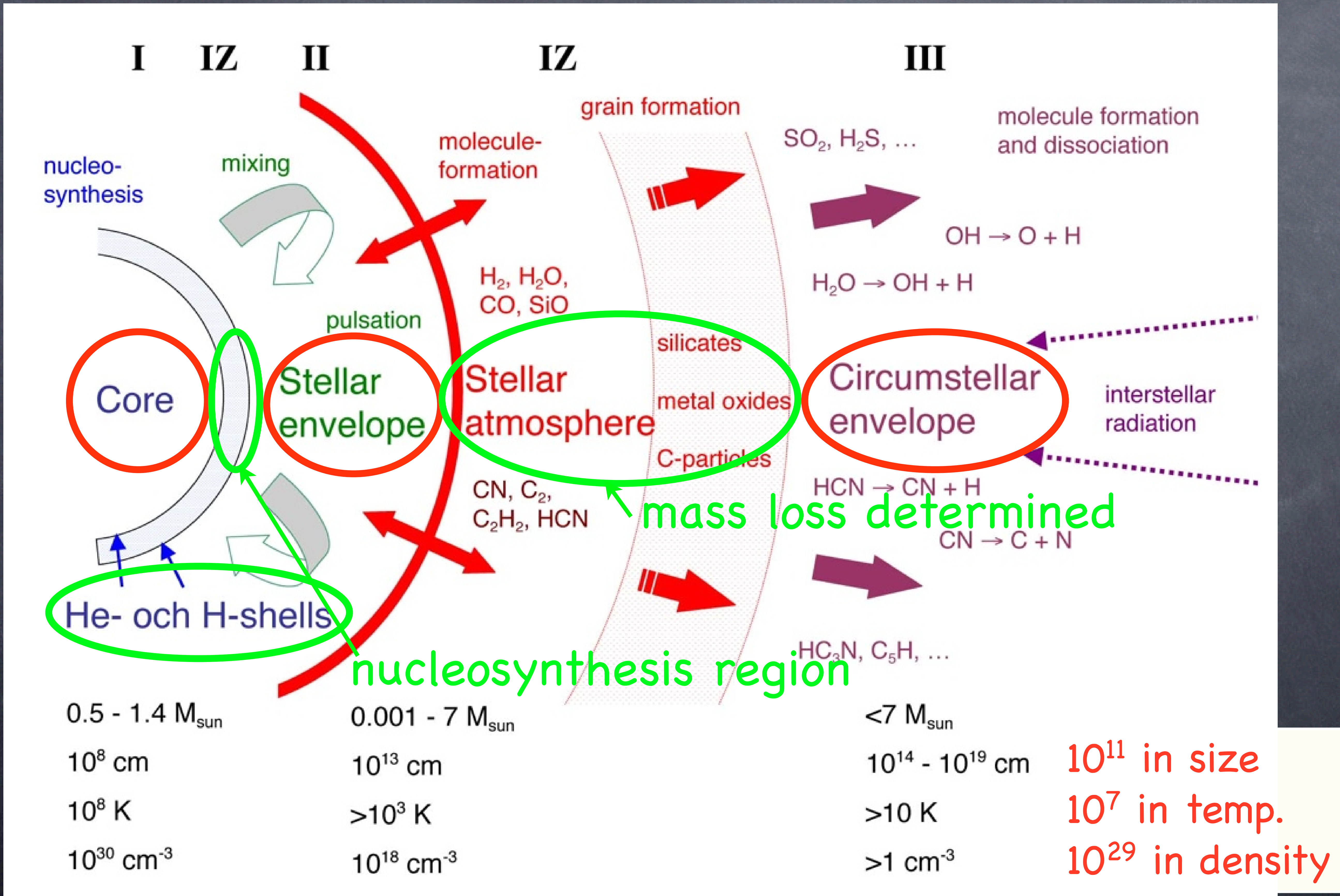
The importance of AGB stars

- They are very luminous and old
  => probes of galaxy structure, kinematics, and SF history

- Their CSEs provide excellent astrophysical and astrochemical laboratories
  => $C/O<1$, $C/O\approx1$, $C/O>1$

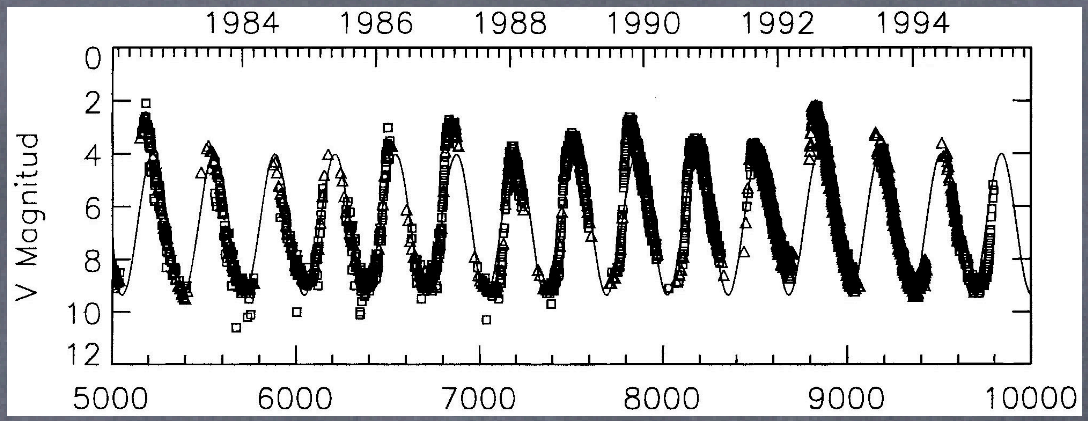
- They are intricate objects
  => a full description requires a complex interplay between different physical/chemical processes with different time scales

The structure of an AGB-object



AGB stars are dynamical objects

o Ceti visual lightcurve

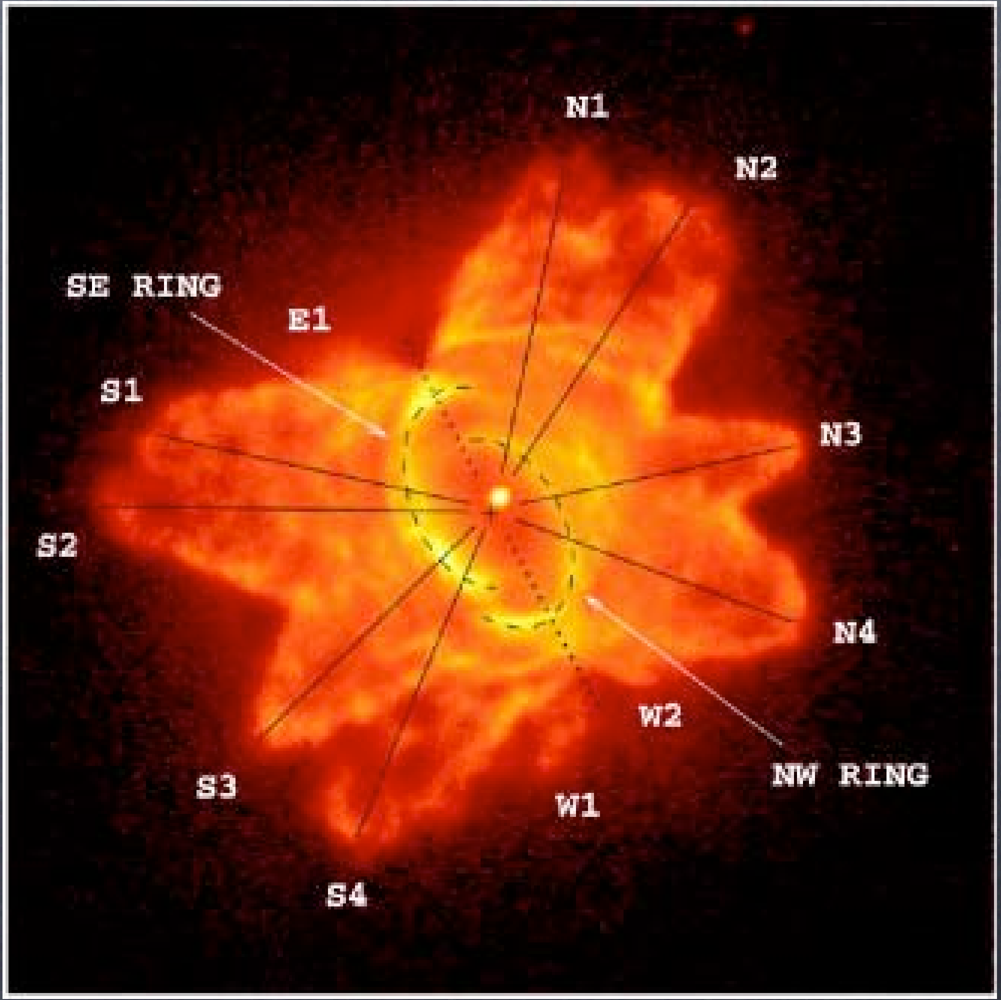


- stellar pulsation 1 yr
- super-period effects 5 yr
- clump ejection 1 yr
- gas-dust interaction < 100 yr
- thermal pulsing 10^{2-3} yr and 10^{4-5} yr
- termination of AGB < 100 yr

AGB stars are dynamical objects

This applies even more to post-AGB objects:

- fast winds
- bipolar outflows
- jets
- shocks
- ionization fronts
- dissociation fronts



The central stars

Flux density of an AGB star:

$$S_{*,\mathrm{lowL}} \approx 20 \left[\frac{\nu}{200\,\mu m}\right]^2 \left[\frac{1\,\mathrm{kpc}}{D}\right]^2 \ \mathrm{mJy}$$ L=4000 L_{sun}, T_e=2800K

$$S_{*,\mathrm{highL}} \approx 150 \left[\frac{\nu}{200\,\mu m}\right]^2 \left[\frac{1\,\mathrm{kpc}}{D}\right]^2 \ \mathrm{mJy}$$ L=15000 L_{sun}, T_e=2200K

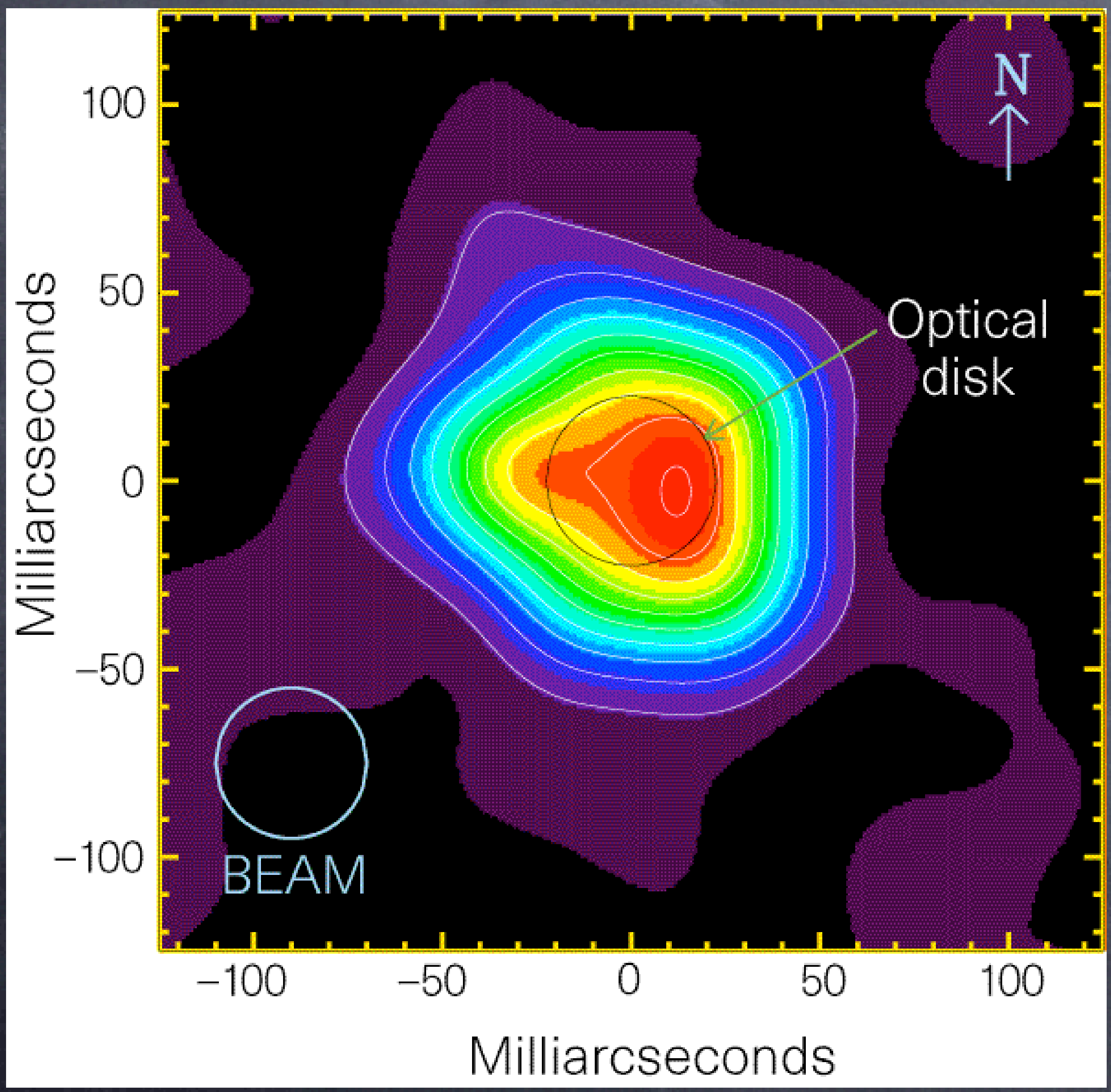
Observational space (1 hour, $5\sigma = 50$mJy, 200 μm):

$$D_{*,\mathrm{lowL}} \approx 0.6\ \mathrm{kpc}$$

$$D_{*,\mathrm{highL}} \approx 3\ \mathrm{kpc}$$

The central stars

A "radio photosphere" appears to exist, and it is larger than R_* ($\approx 2R_*$; Reid & Menten)



Lim et al. Nature 392, 575

α Ori, VLA, 7 mm

size ≈ 0.1″

S ≈ 28 mJy

$T_b \approx 3500$ K

Radio emission is an excellent probe of the complicated, inhomogeneous stellar atmosphere

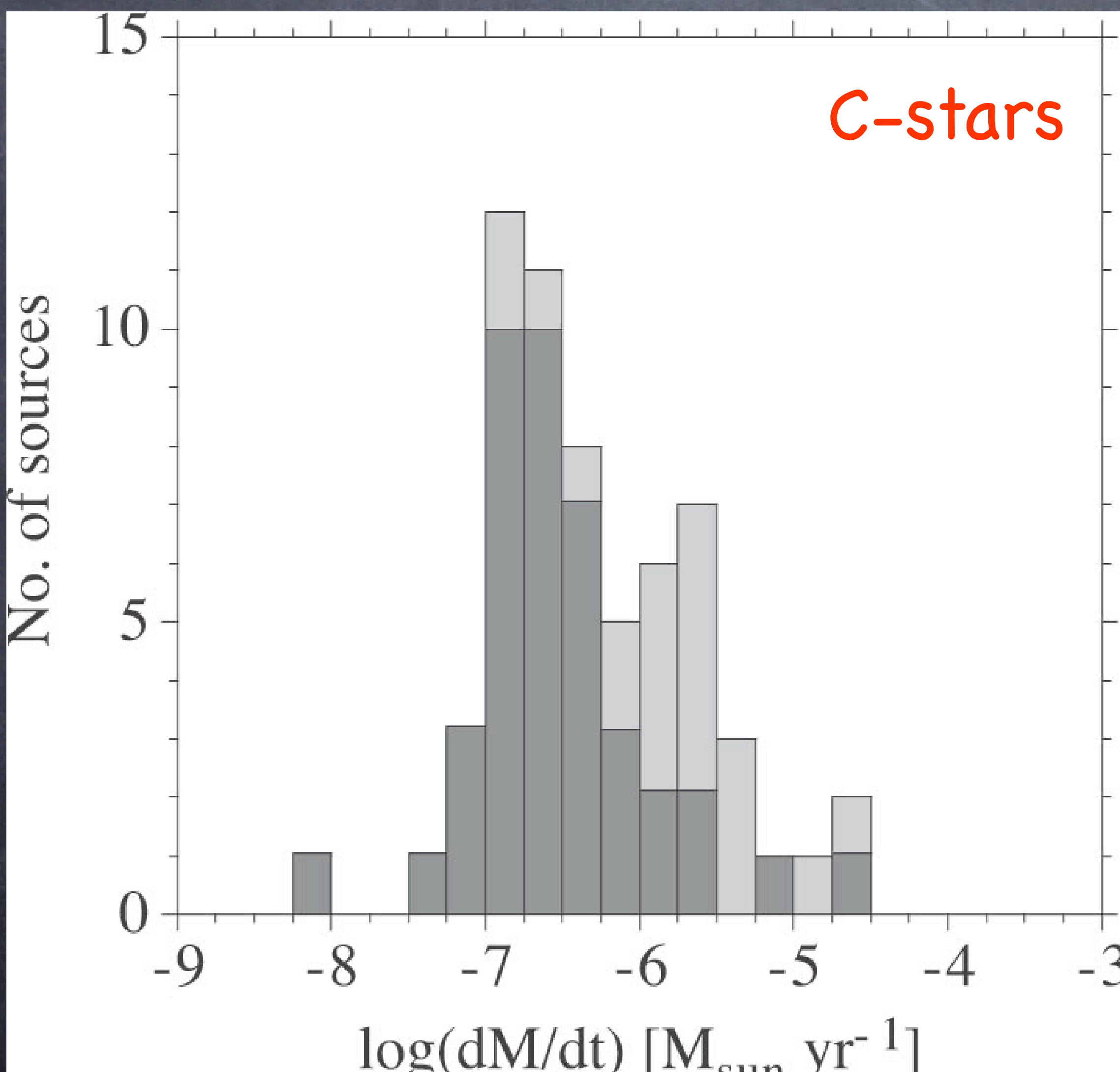
The stellar mass loss

The mass loss is the process that determines it all:

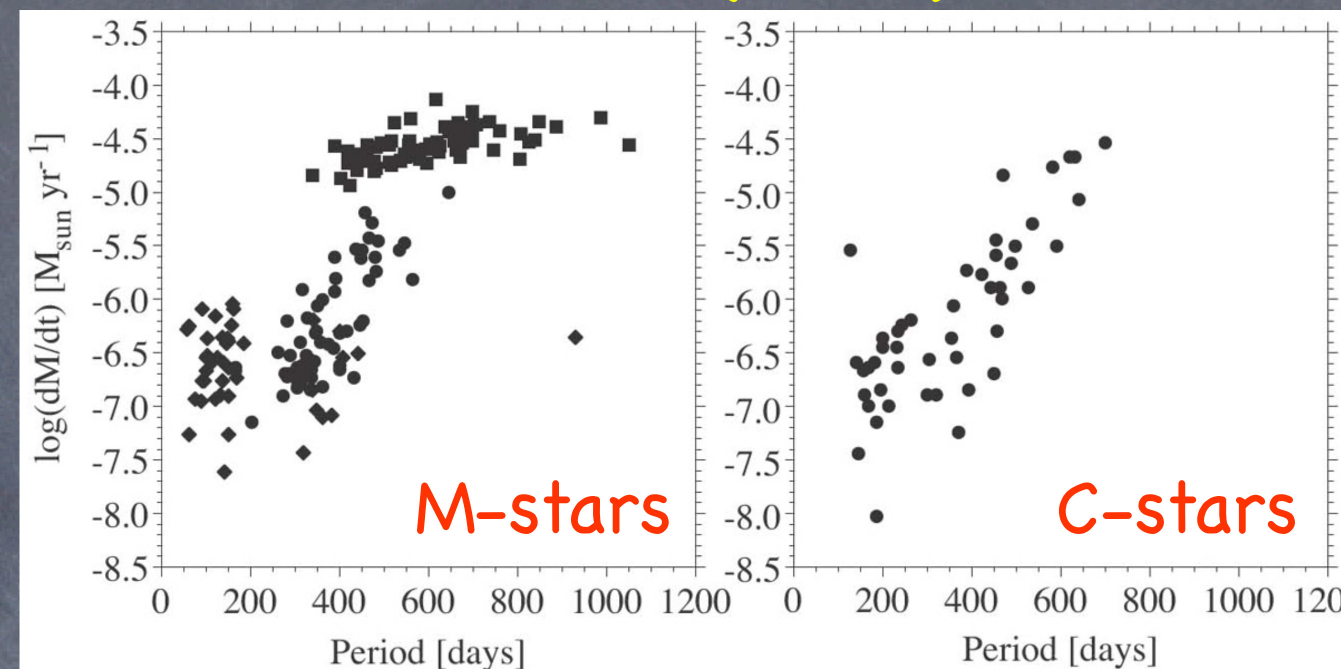
- the lifetime on the AGB
- the luminosity reached
- the gas/dust return
- the chemical composition of the returned gas

The mass loss properties

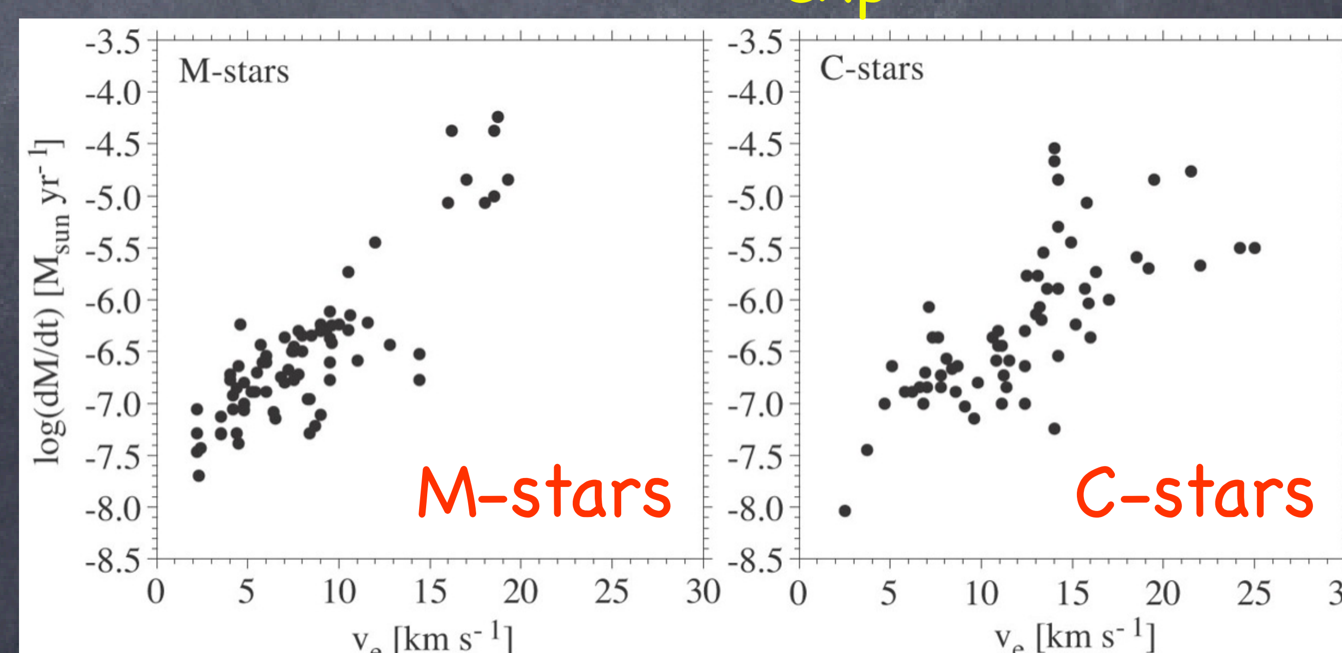
dN/d$\dot{M}$



$\dot{M}$ vs P(M_{MS})



$\dot{M}$ vs v_{exp}



The circumstellar envelopes

$$\dot{M} = -\frac{\mathrm{d}M_*}{\mathrm{d}t}$$

$$\dot{M} = \frac{\mathrm{d}M_{\mathrm{CSE}}}{\mathrm{d}t} \approx \frac{M_{\mathrm{CSE}} v_{\mathrm{exp}}}{R_{\mathrm{CSE}}}$$

$\dot{M}(t,\theta,\phi,M_{MS},Z,P, \ldots)$ & $dN/d\dot{M}$

The probes of this process are:

- circumstellar atomic/molecular line emission
- circumstellar dust continuum emission

AGB circumstellar environment

Well-defined conditions of the environment:

- spherical geometry
- constant expansion velocity
- densities follow r^{-2} law, temperatures follow $r^{-(0.4-1)}$ law
- radiation fields: central star and CS dust
- C/O<1 and C/O>1; two chemical environments
- expansion makes possible temporal evolution studies

High T => small spatial scales

- $T_{kin} = 500(r/10^{15}\ \mathrm{cm})^{-1}$ K

- $hBJ(J+1)/k = T_{kin}$ (linear rotor)

For CO where B=2.75 K the result is

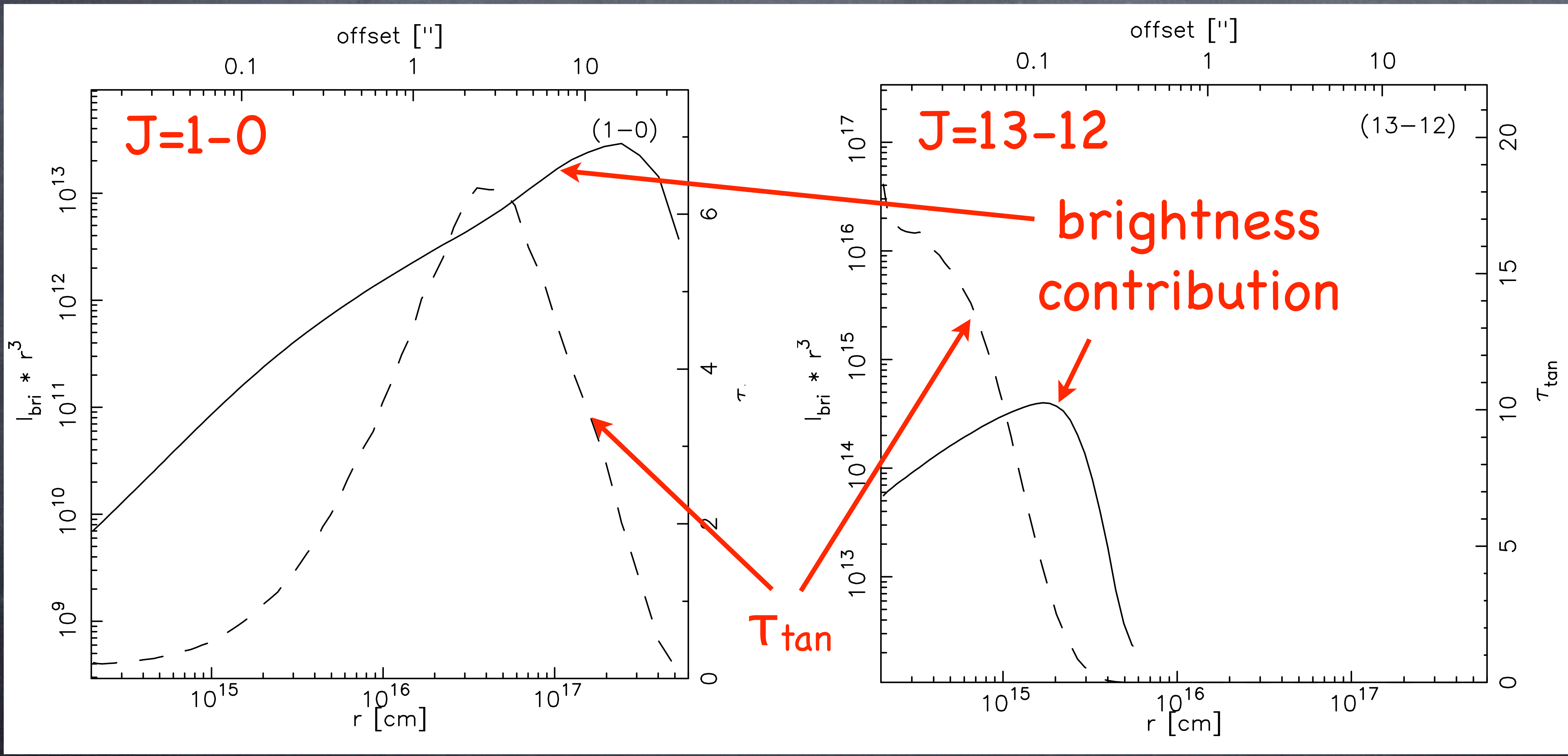
J=1, 115 GHz, $r=5\times10^{16}$ cm, $\theta=10''(500\ \mathrm{pc}/D)$

J=13, 1.5 THz, $r=5\times10^{14}$ cm, $\theta=0.1''(500\ \mathrm{pc}/D)$

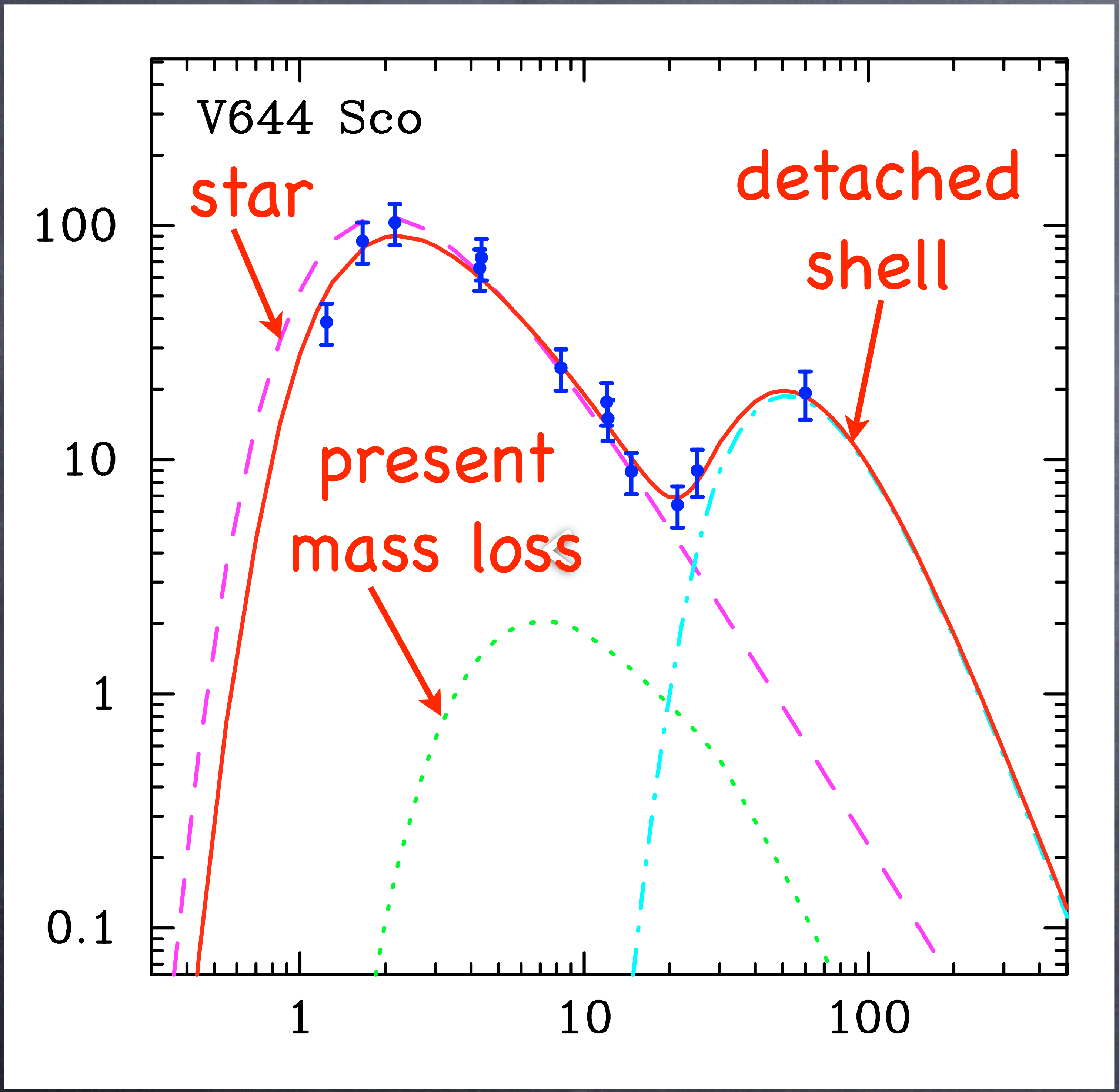
The same arguments apply to dust emission

High J => small spatial scales

$\dot{M} = 10^{-5}\ M_{sun}/yr$ model (D=1 kpc)



The circumstellar envelopes



Long-λ dust emission is optically thin also at high mass loss rates (S scales as ν^3)

Long-λ dust emission is a very good tracer also of fossile dust shells, i.e. $\dot{M}(t)$

The circumstellar envelopes

Flux density of a dusty CSE (optically thin):

$$S_{\rm CSE,d} \approx 5 \left[\frac{\dot{M}}{10^{-6}}\right] \left[\frac{\nu}{200\,\mu m}\right]^3 \left[\frac{1\,{\rm kpc}}{D}\right]^2 \quad {\rm Jy}$$

Observational space, 1 hour (5σ = 50 mJy, 200 μm):

$$D_{\rm CSE,d} \approx 10 \left[\frac{\dot{M}}{10^{-6}}\right]^{0.5} \quad {\rm kpc}$$

- 10^{-7} M_{sun}/yr in GC in 5 hours
- 10^{-5} M_{sun}/yr in LMC in 4 hours

The circumstellar envelopes

Flux density of a gaseous CSE:

$$S_{\mathrm{CO}(13-12)} \approx 10 \left[\frac{\dot{M}}{10^{-6}}\right]^{0.5} \left[\frac{15\,\mathrm{km\,s^{-1}}}{v_{\mathrm{e}}}\right]^{1.5} \left[\frac{f_{\mathrm{CO}}}{10^{-3}}\right]^{0.7} \left[\frac{1\,\mathrm{kpc}}{D}\right]^{2} \;\mathrm{Jy}$$

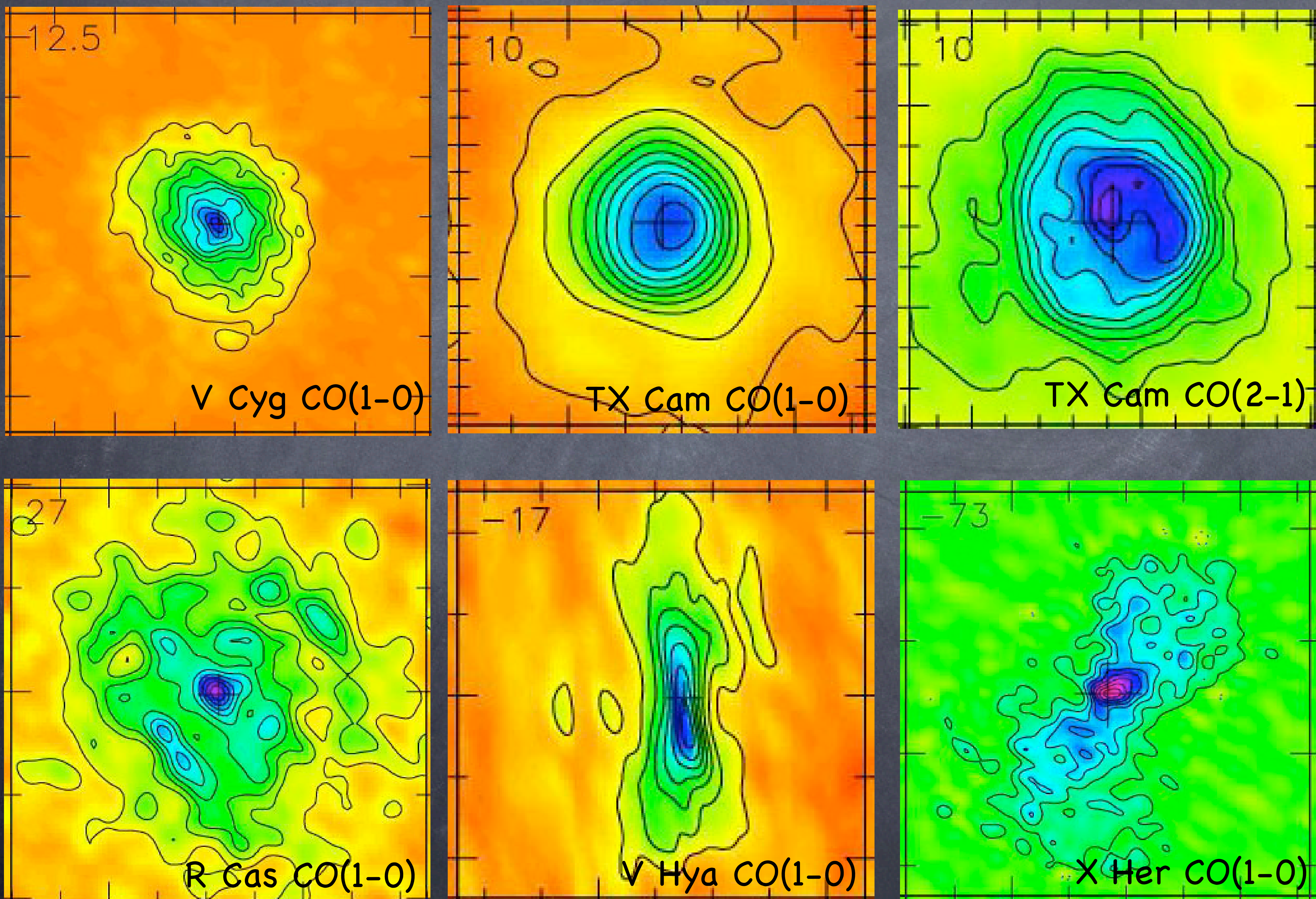
(based on detailed modelling)

The THz CO lines are relatively saturated.

- Probes of the present mass-loss rate
- Possible to detect stars with low mass-loss rates [S(13-12)/S(1-0) ≈ 100]

CO brightness distributions

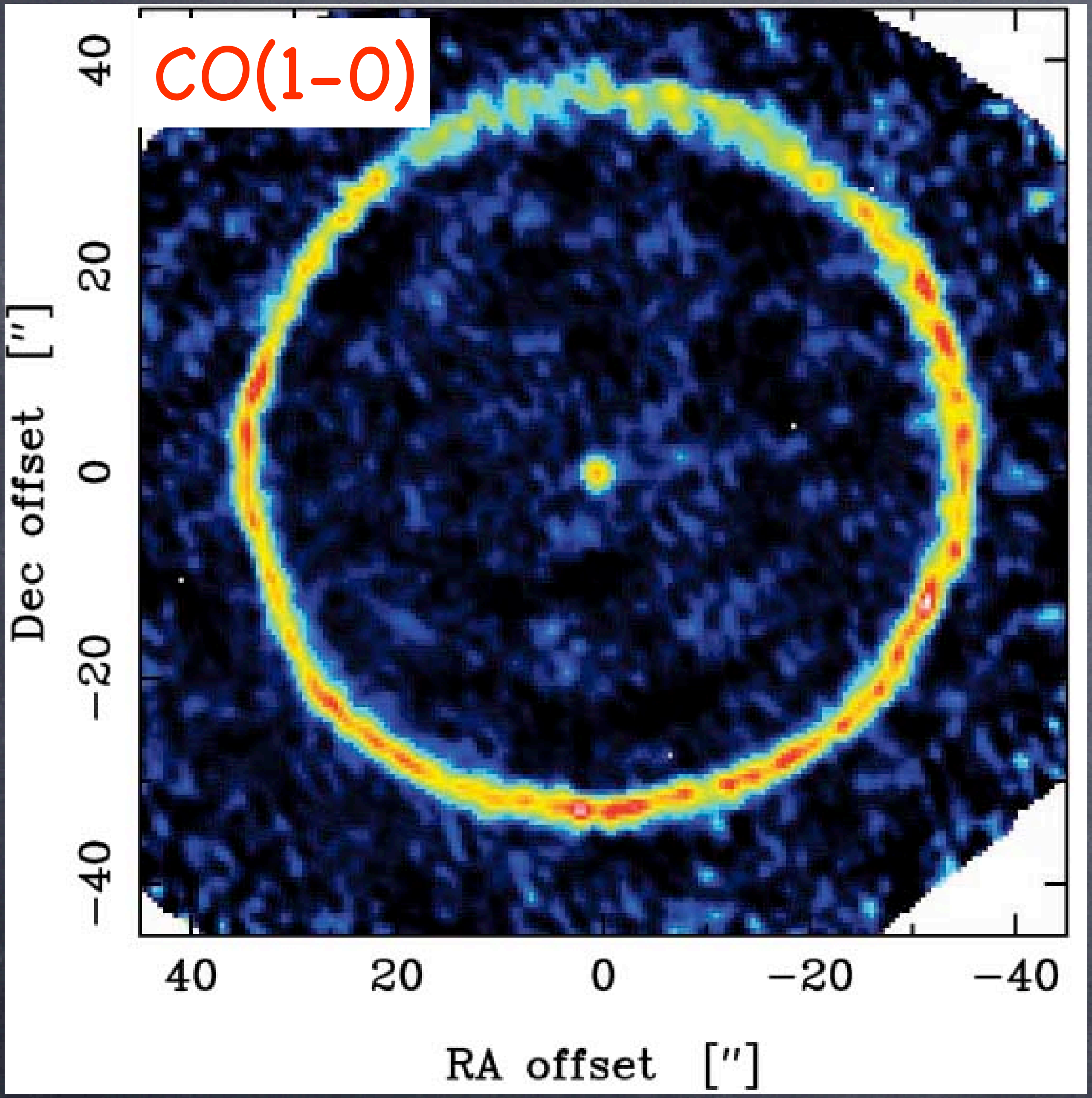
PdB large project, syst. vel. maps, Castro-Carrizo et al.



30" to 60" in size

Highly episodic mass loss

TT Cyg PdB map



shell diameter = 68"
shell age ≈ 8000 yr

High-J lines are important probes of the region where the mass loss is initiated

The circumstellar envelopes

Observational space (1 hour, 2 km/s, $5\sigma = 20$ Jy, $T_{sys} = 5000$ K):

$$D_{\mathrm{CO}(13-12)} \approx 0.7 \left[\frac{\dot{M}}{10^{-6}}\right]^{0.25} \left[\frac{15\,\mathrm{km\,s^{-1}}}{v_{\mathrm{e}}}\right]^{0.8} \left[\frac{f_{\mathrm{CO}}}{10^{-3}}\right]^{0.4} \mathrm{kpc}$$

- 10^{-7} M_{sun}/yr to 1 kpc in 5 hours
- 10^{-6} M_{sun}/yr to 1 kpc in 2 hours
- 10^{-5} M_{sun}/yr to 1 kpc in 1 hour

Circumstellar molecules

2-atoms:	● AlCl	CN	● NaCl	● SiN
	● AlF	● CP	OH	SiO
	● C_2	CS	● PN	SiS
	CO	● KCl	SiC	SO
3-atoms:	● AlNC	CO_2	HNC	SiC_2
	● C_3	HCN	● MgCN	● SiCN
	C_2H	H_2O	● MgNC	● SiNC
	C_2S	H_2S	● NaCN	SO_2
4-atoms:	ℓ-C_3H	● C_3S	H_2CO	NH_3
	C_3N	C_2H_2	H_2CS	● SiC_3
	● C_3O	● HC_2N		
5-atoms:	● C_5	c-C_3H_2	HC_3N	● HNC_3
	C_4H	● CH_2CN	● HC_2NC	● SiH_4
	● C_4Si	● CH_4	● H_2C_3	
6-atoms:	● C_5H	● C_2H_4	● HC_4N	● H_2C_4
	● C_5N	CH_3CN		
$\geq$7-atoms:	● C_6H	● C_8H	HC_5N	● HC_9N
	● C_7H	● CH_2CHCN	HC_7N	● H_2C_6
Ions:	HCO^+	● C_6H^-	● C_4H^-	

Σ = 70 circ. species

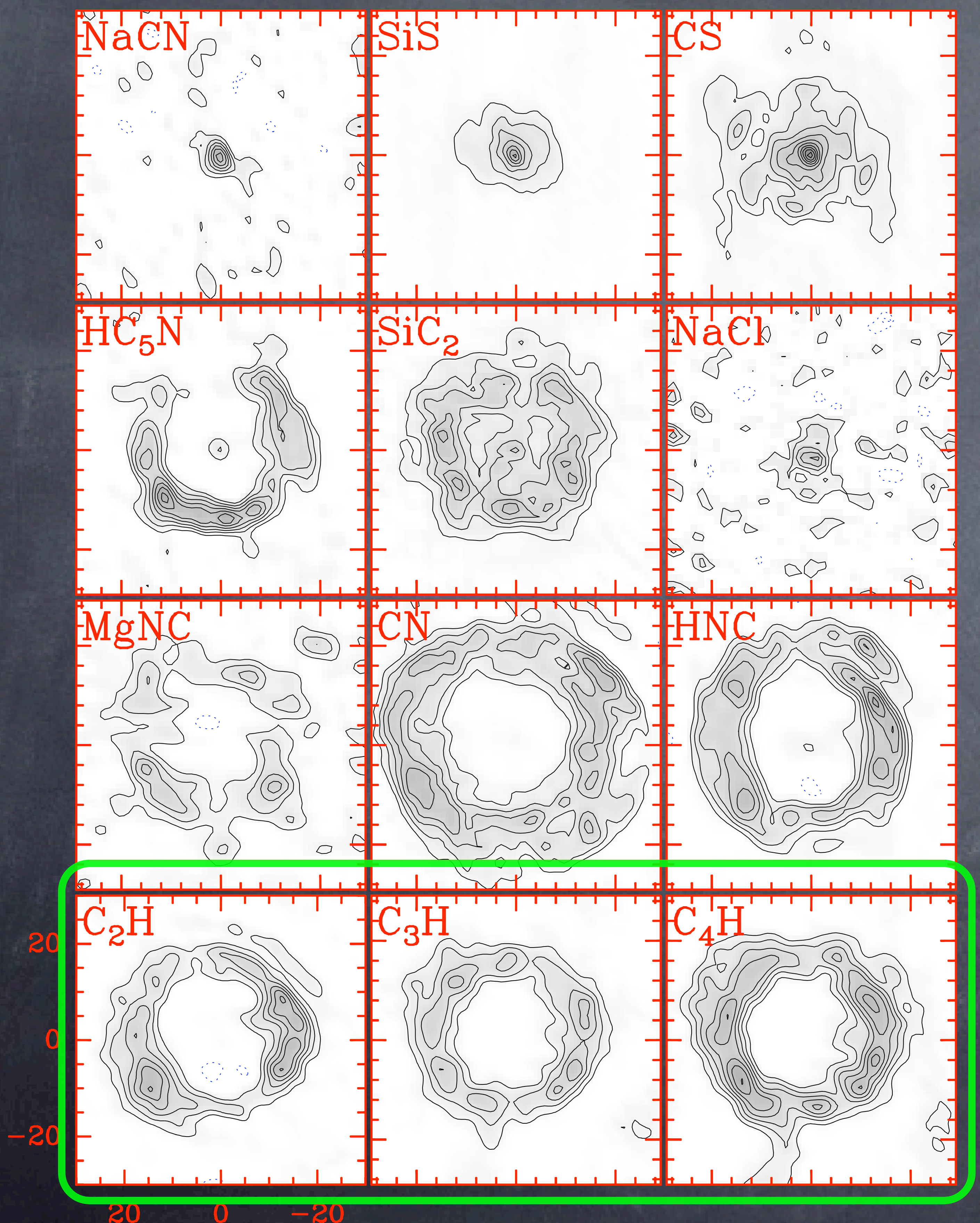
unique to post-AGB, Σ = 11

CH, CH^+, CO^+, H_2, N_2H^+, OCS, HC_4H, HC_6H, CH_3C_2H, CH_3C_4H, C_6H_6

● = only IRC+10216* !!!!

*IRC+10216: the most nearby C-star, and it has a high mass-loss rate

Circumstellar molecules, brightness distributions



IRAM PdB data towards IRC+10216 (Guelin et al. 1996)

Some molecules are of photospheric origin (e.g., SiS), some are photodissociation products (e.g., CN), and some are due to circumstellar chemistry (e.g., HNC)

For chemical reasons, these emissions should not coincide (Guelin et al. 1993).

Circumstellar molecules

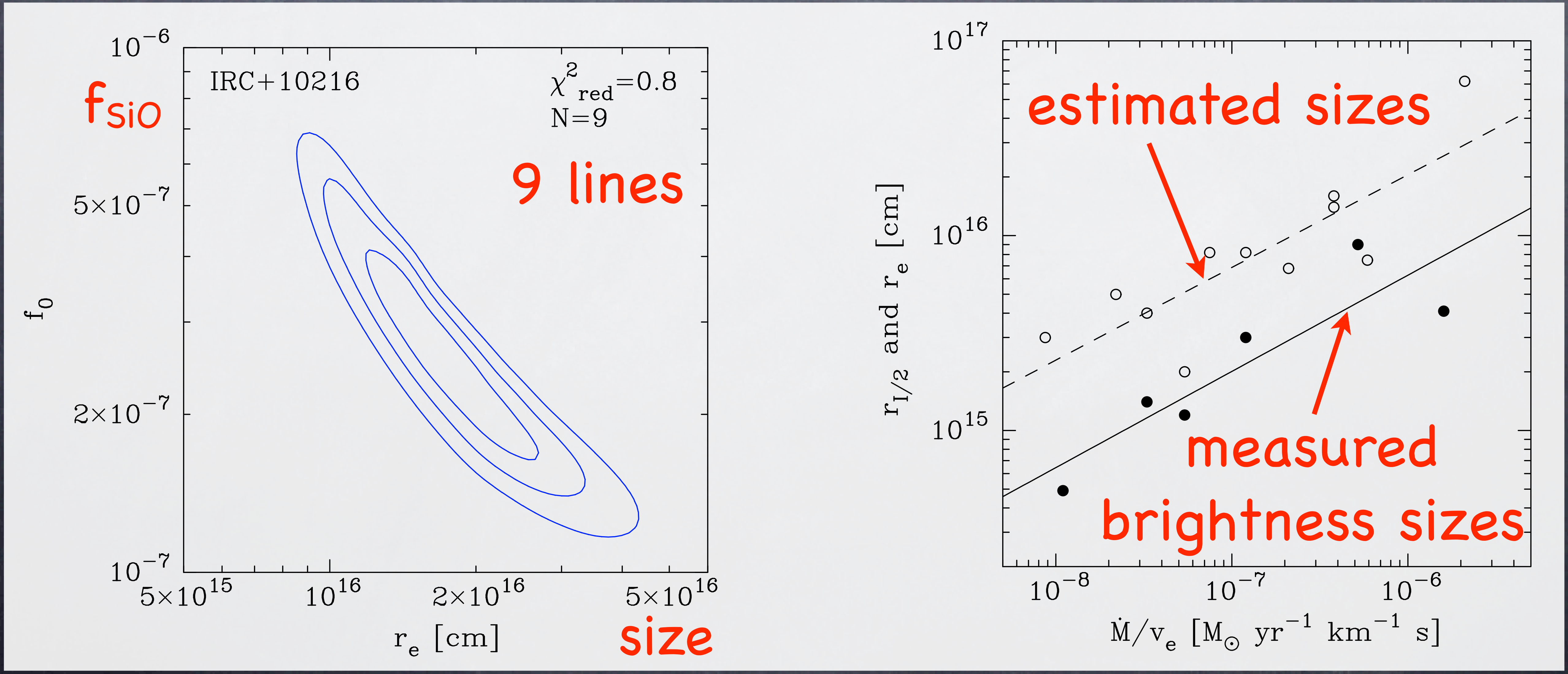
Search for new molecules at high frequencies:

- Hydrides, e.g., CH, OH, CH^+, OH^+, NH_3
- Bending mode transitions of large molecules, e.g., C_7 and C_8 at 200 μm
- Flopping mode transitions of e.g. PAHs

Circumstellar SiO abundance estimates

Accurate abundance estimates requires a knowledge of the size of the molecular envelope:

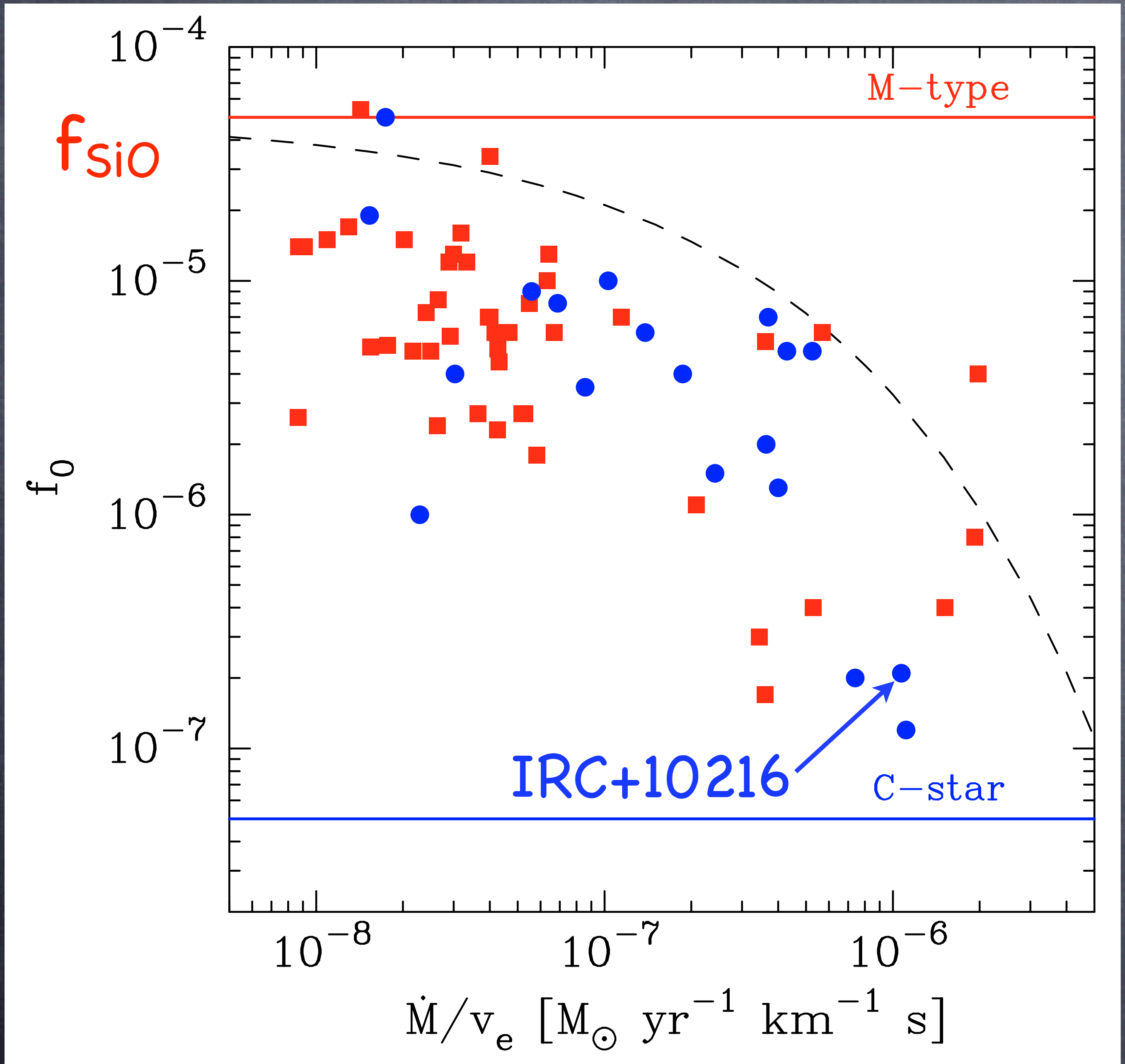
Low-J lines sensitive to the envelope size and the abundance, while high-J lines sensitive only to the abundance



Circumstellar SiO abundance estimates

Circumst. SiO abund. of 43 M- and 17 C-type stars

Only detailed study of a species in a large sample of stars



3 orders of magnitude spread in abundance

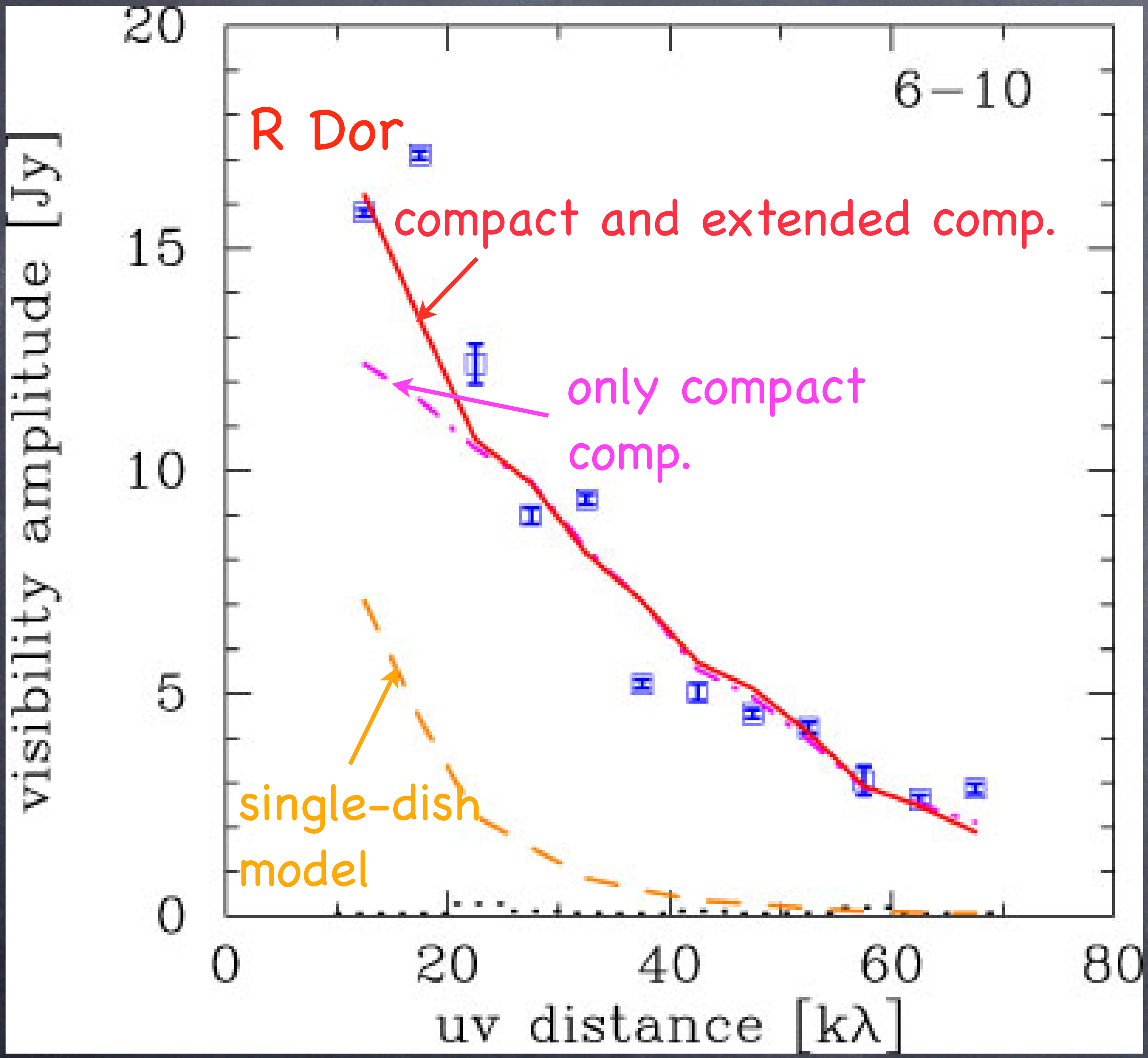
abundance in C-stars >> eq. value, while in M-stars it is << eq. value, abundance decline with $\dot{M}$

IRC+10216 is not representative of C-stars

Schöier et al. , A&A 454, 247

Circumstellar SiO abundance estimates

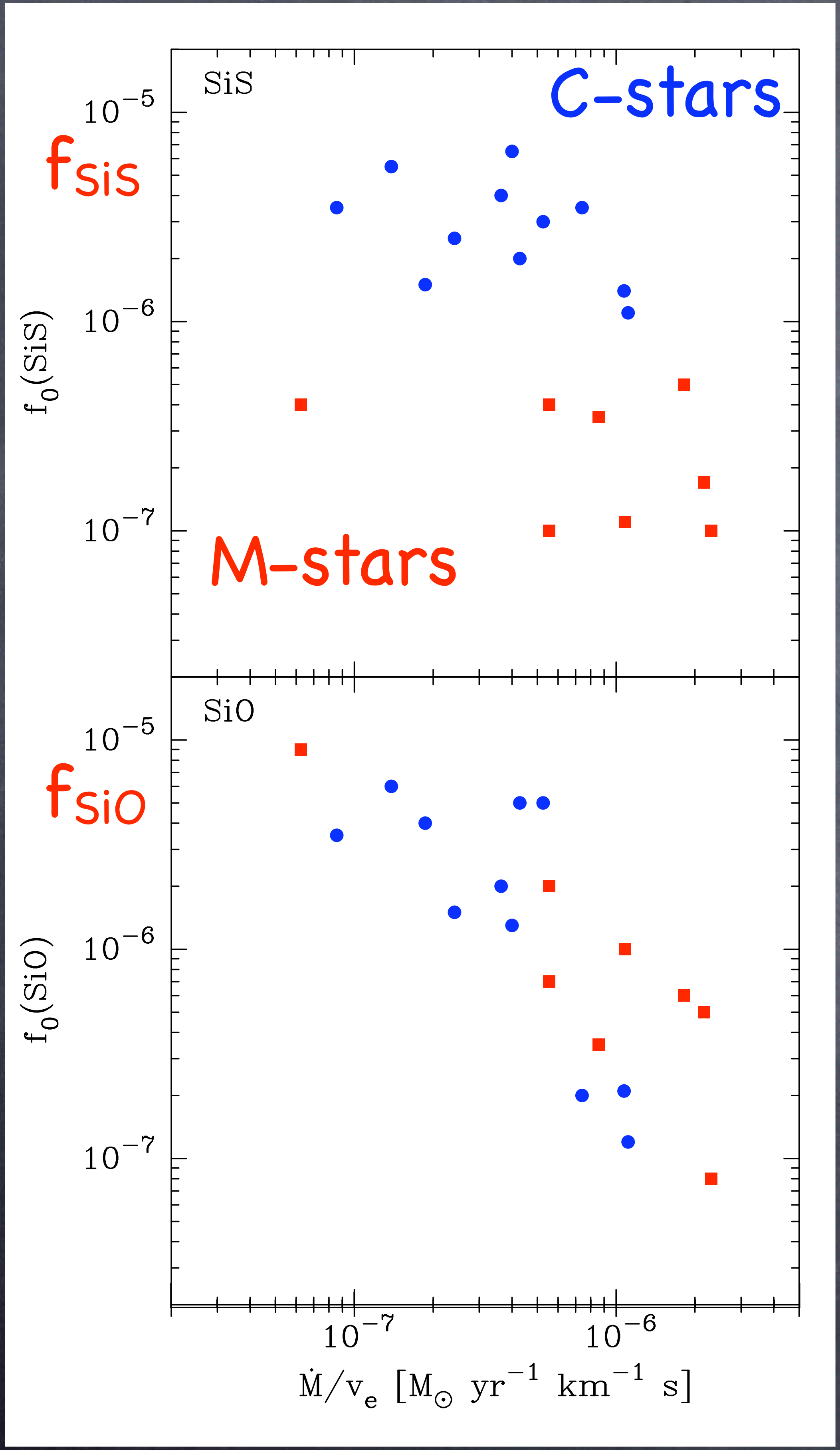
Rad. transf. modelling of interferometric SiO data



red line is the best-fit model using:
i) a compact high-abundance ($4x10^{-5}$) region (eq. value)
ii) an extended low-abundance ($3x10^{-6}$) region (SiO depleted)

Schöier et al. A&A 422, 651, 2004

Circumstellar SiS abundance estimates



High-J lines are important probes of the region where non-equilibrium chemistry and dust condensation takes place

Termination of the AGB phase

$M_{st.env}/\dot{M}$ < 10-100 yr at the end

$\dot{M}(\theta,\phi,t)$
$v_e(t)$; drastic changes?

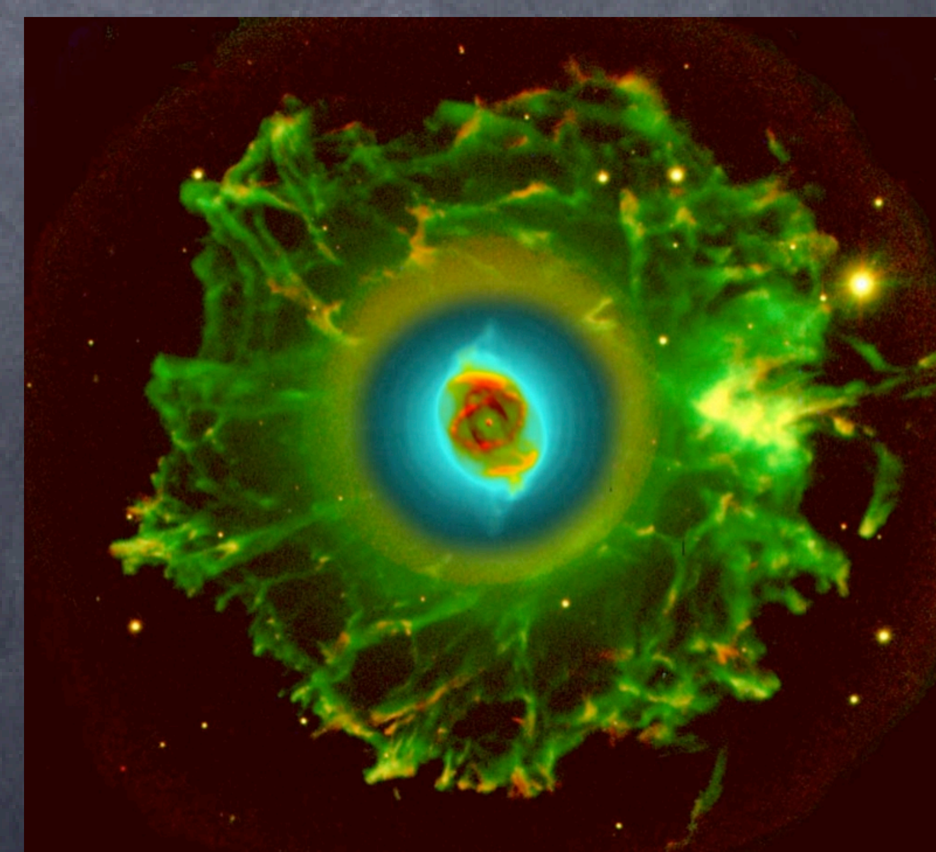
The emergence of jets

The shaping of planetary nebulae

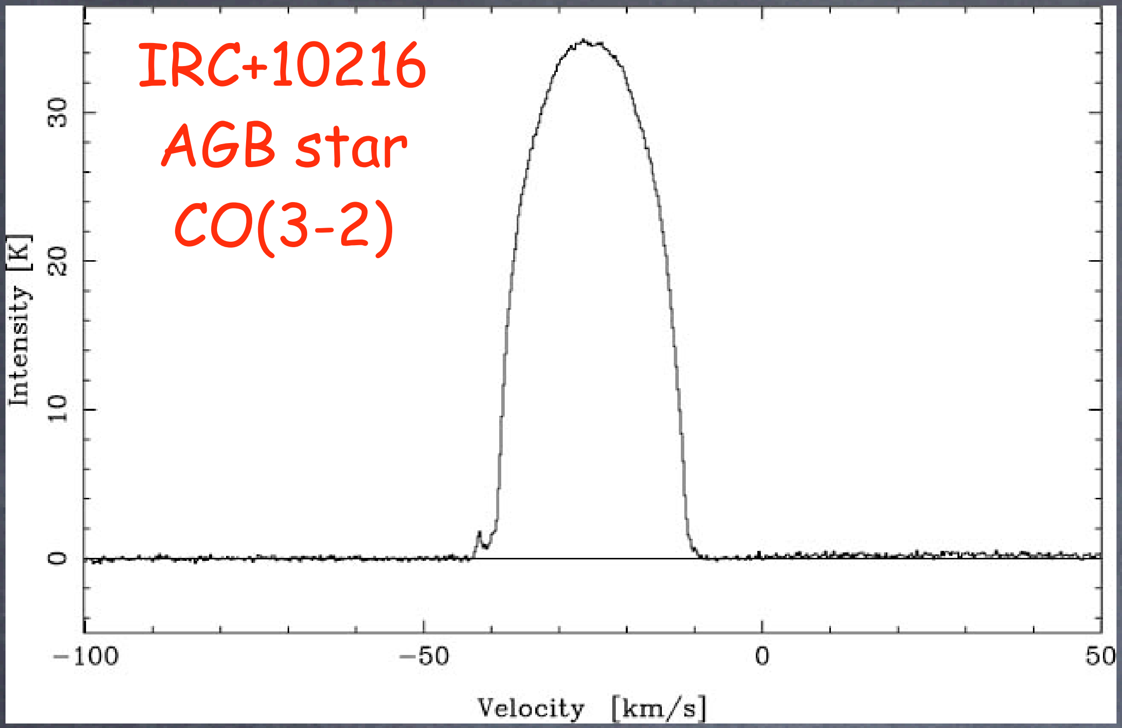
NGC6543

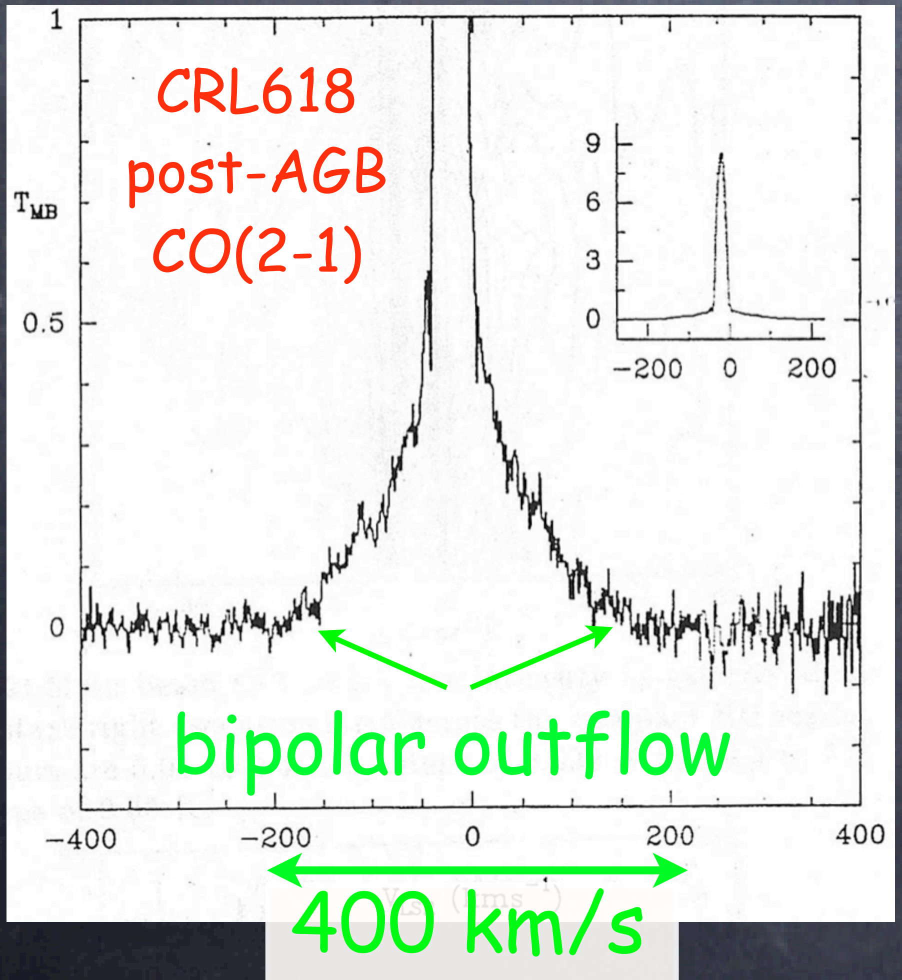
<- HST

NOT ->

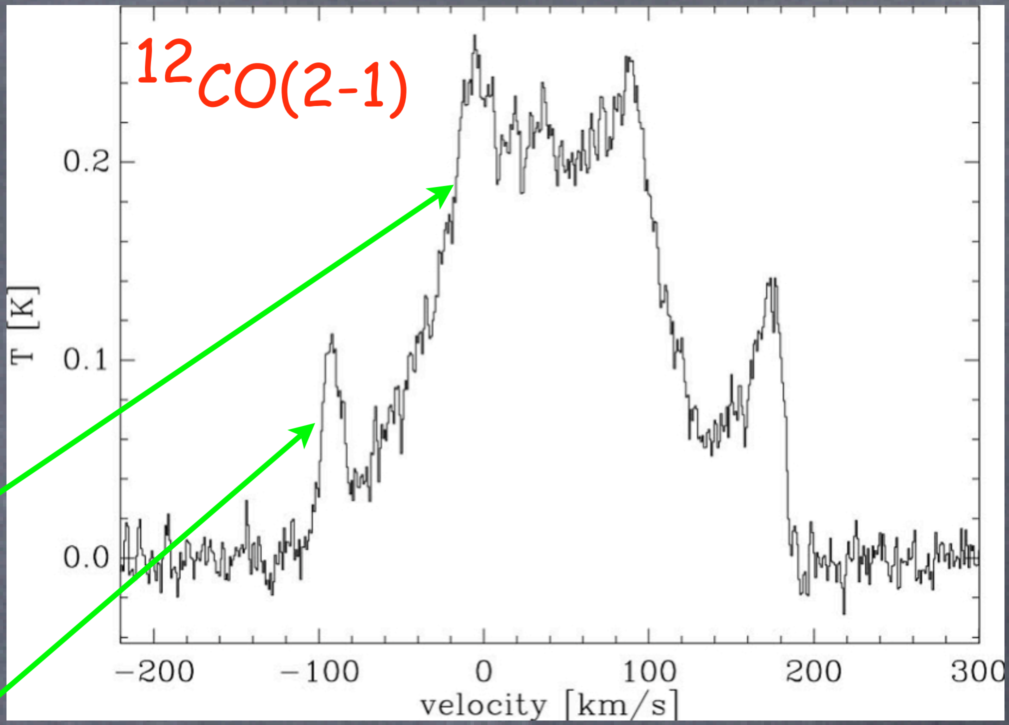


Termination of the AGB phase

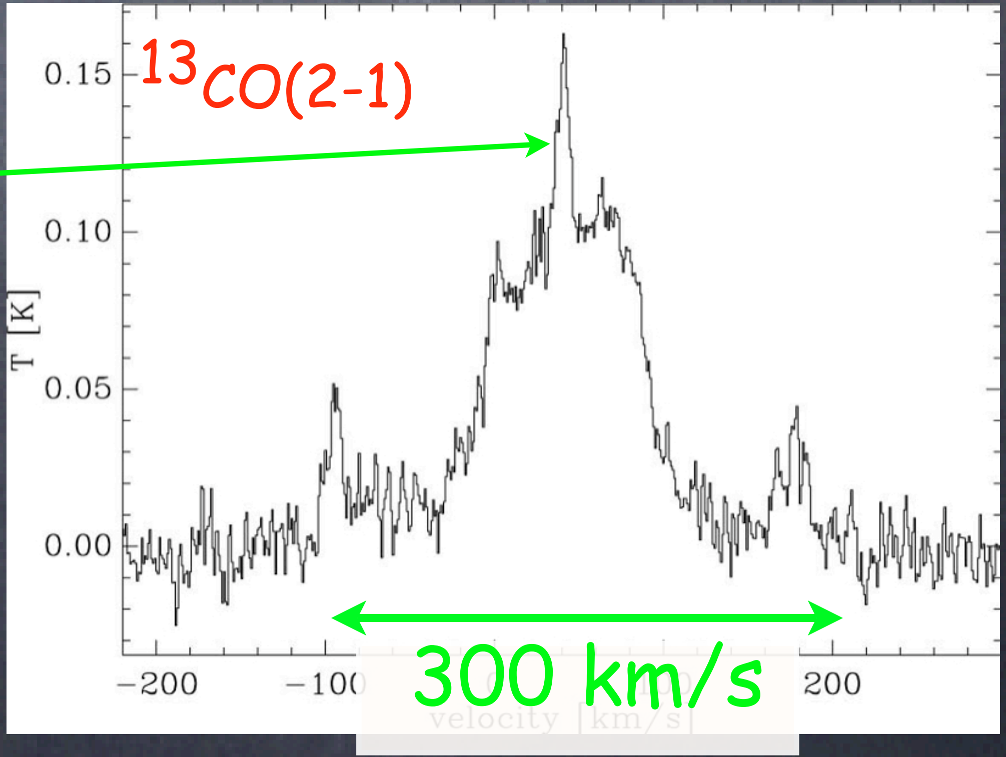




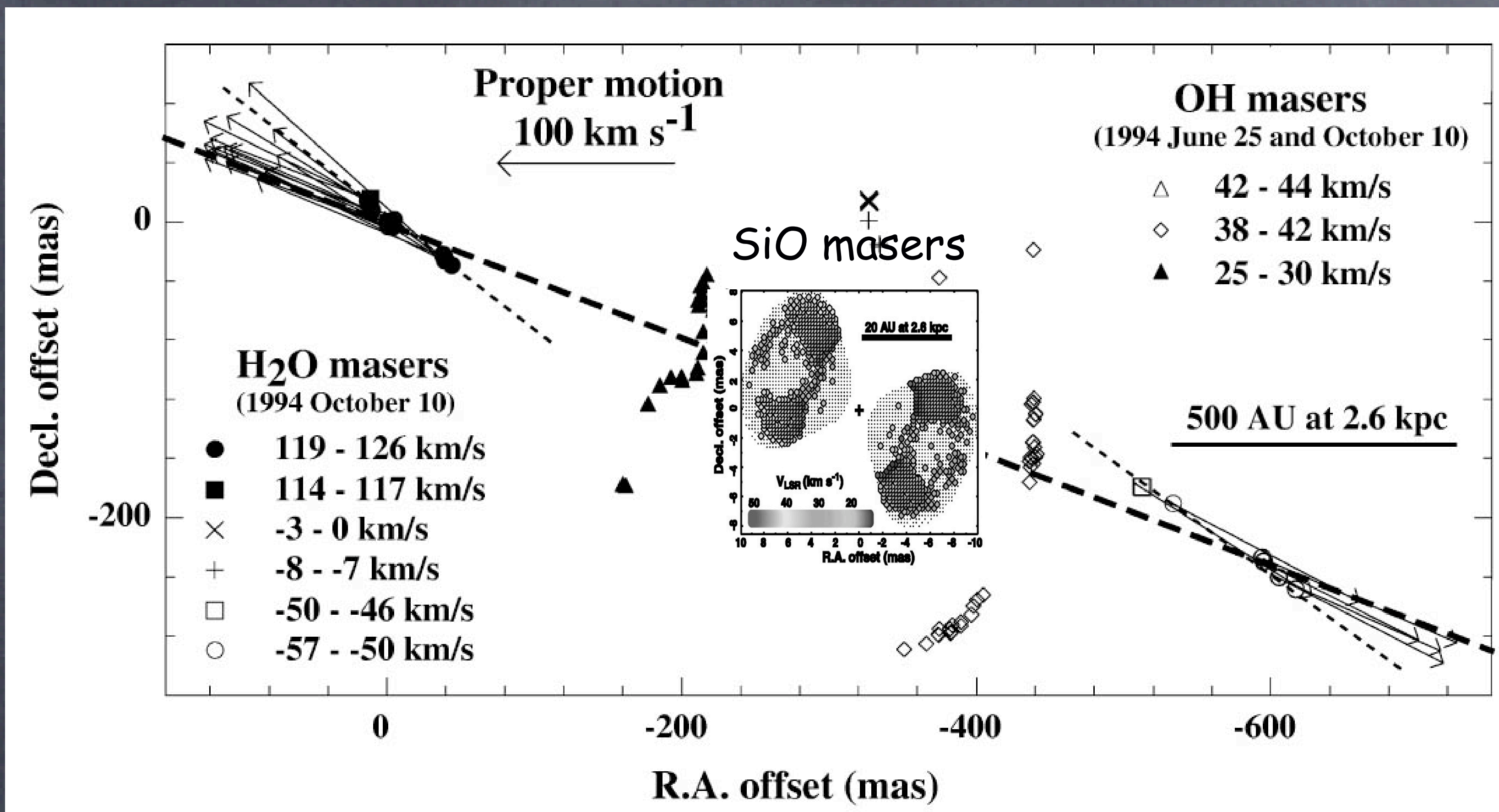
HD101584, post-AGB(?)



at least three kinematical features



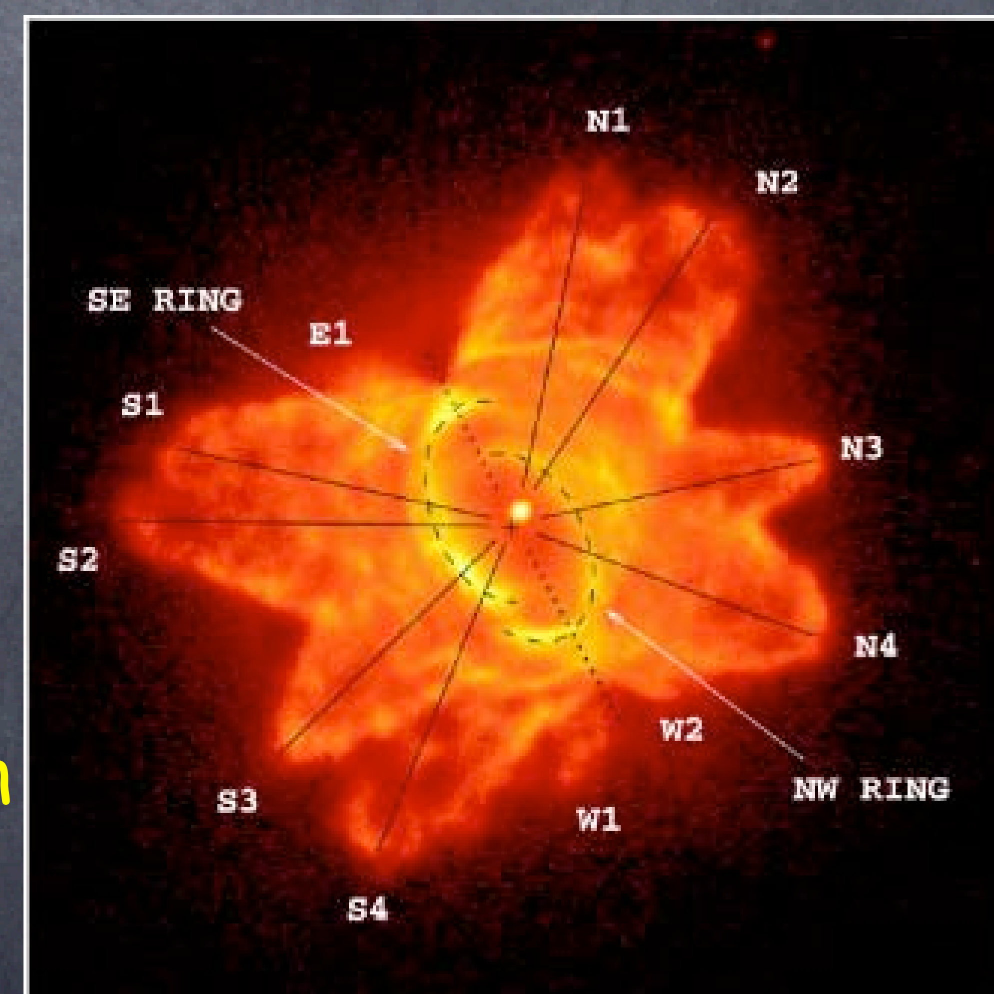
Termination of the AGB phase



He2-47, young PN

HST image

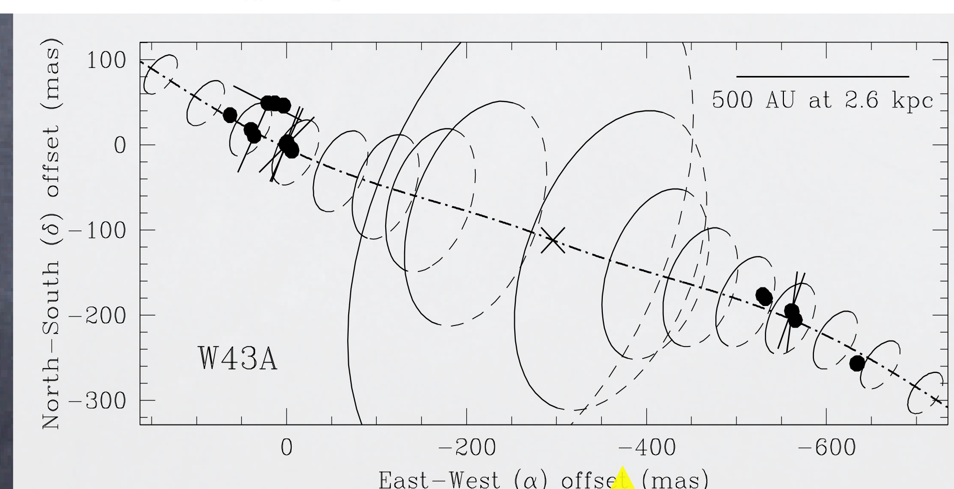
Sahai & Trauger



W43A, OH/IR star

VLBA image

Imai et al.



Magnetic collimation

(H_2O, 22 GHz, pol)

Vlemmings et al.