Expanding molecular bubble surrounding Tycho's SNR — evidence for a single-degenerate progenitor

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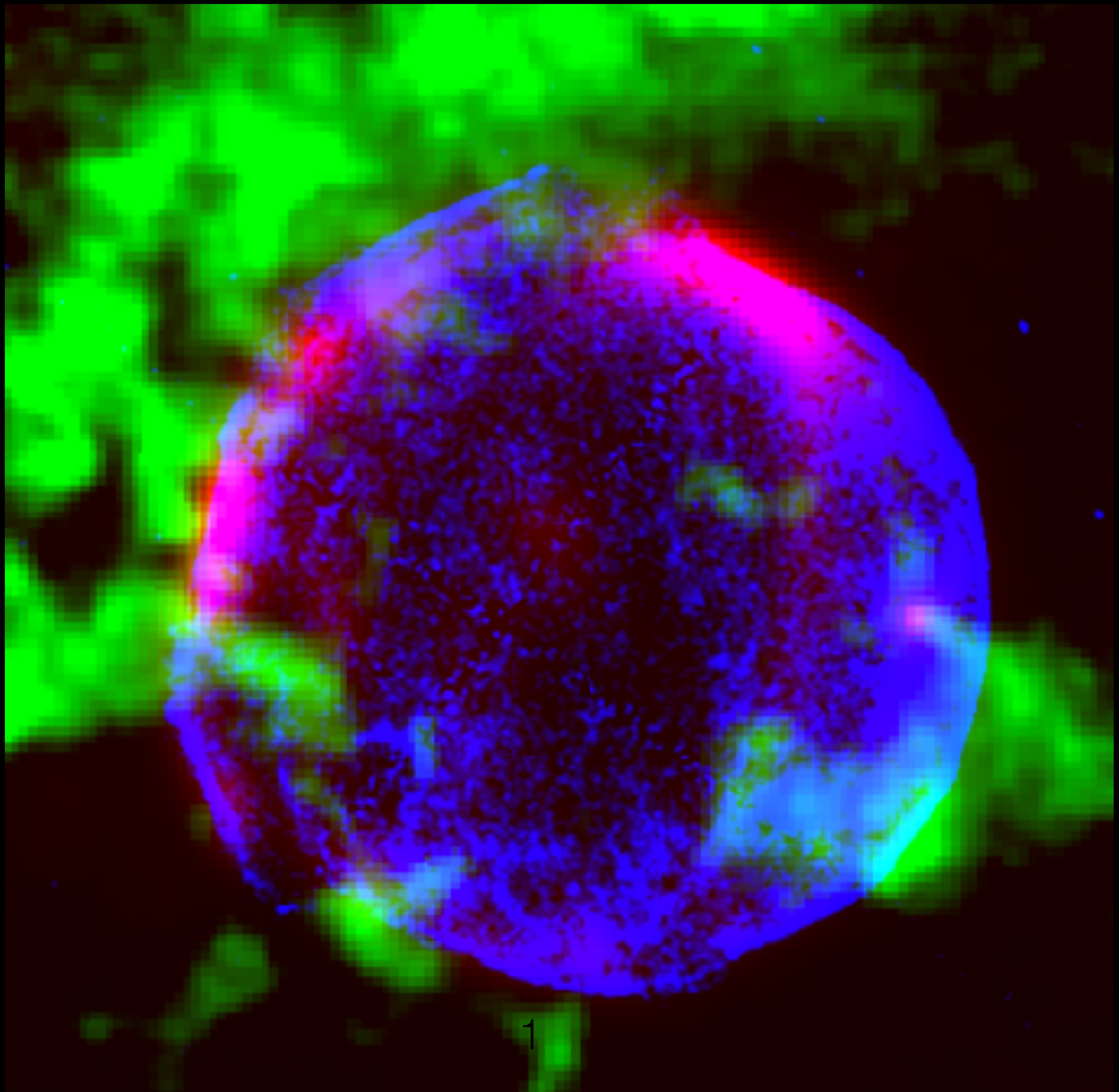


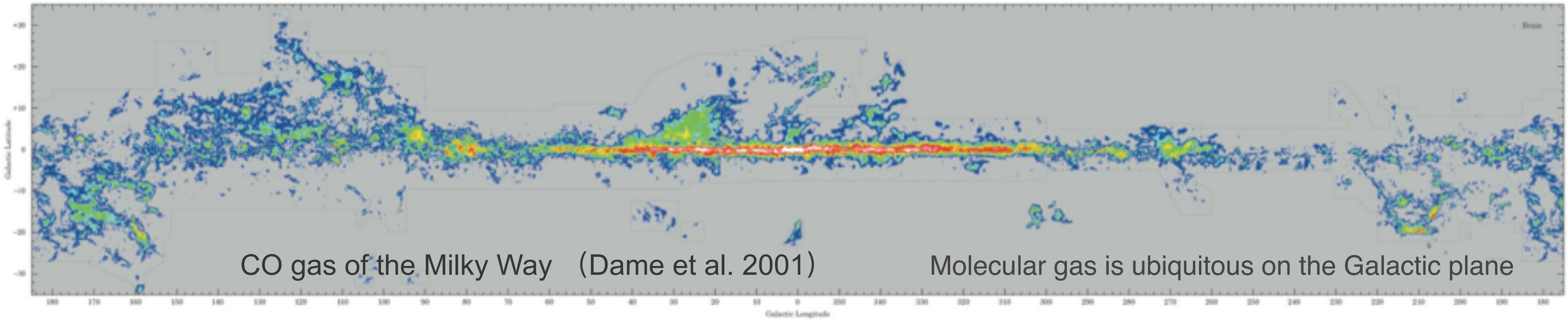
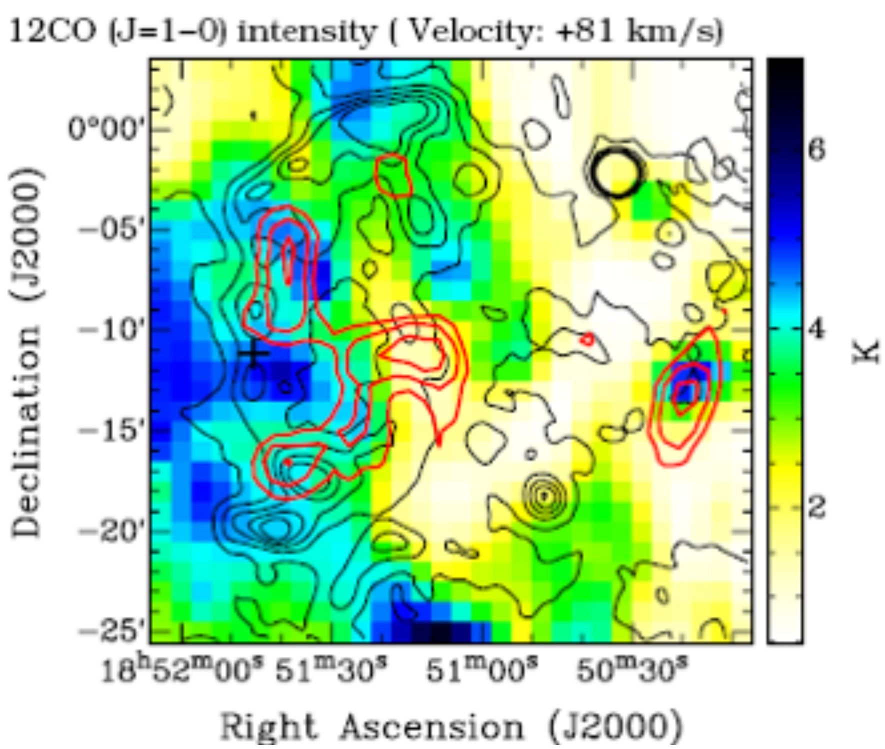


Table 12.3 The principal phases of the interstellar gas. (Courtesy of Dr. John Richer.)

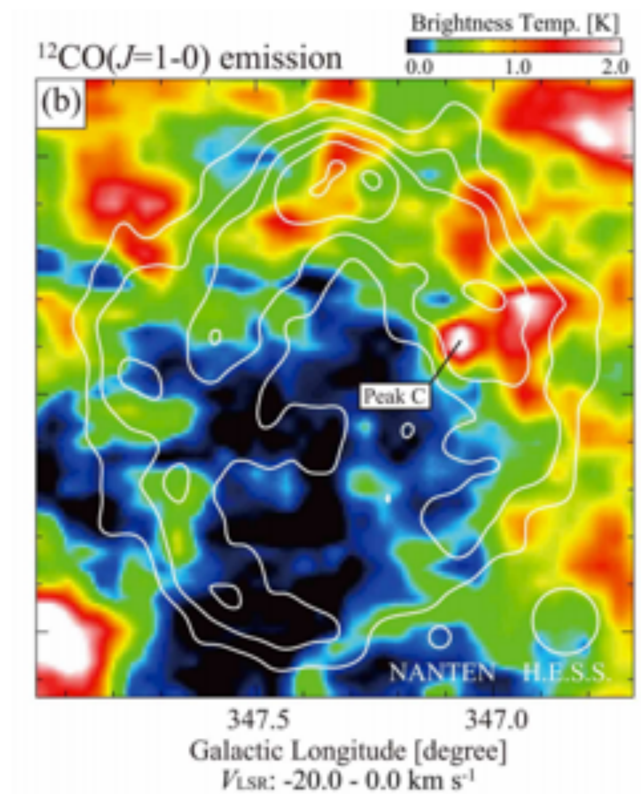
Names	Main constituent	Detected by	Volume of interstellar medium	Fraction by mass	N (cm^{-3})	Temperature (K)
'Molecular clouds'	H_2, CO CS, etc	Molecular lines. Dust emission	$\sim$0.5%	40%	$\geq 10^3$	10–30
'Diffuse clouds' 'H I clouds' 'Cold neutral medium'	H, C, O with some ions, C^+, Ca^+	21-cm emission & absorption	5%	40%	1–10^2	80
'Intercloud medium'	H, H^+, e^- Ionisation fraction 10–20%	21-cm emission & absorption Hα emission	40%	20%	10^{-1}–1	8000
'Coronal gas'	H^+, e^- Highly ionised species, O^{5+}, C^{+3}, etc	O VI Soft X-rays 0.1-2 keV	$\sim$50%	0.1%	$\sim 10^{-3}$	$\sim 10^6$

SNRs associated with MCs

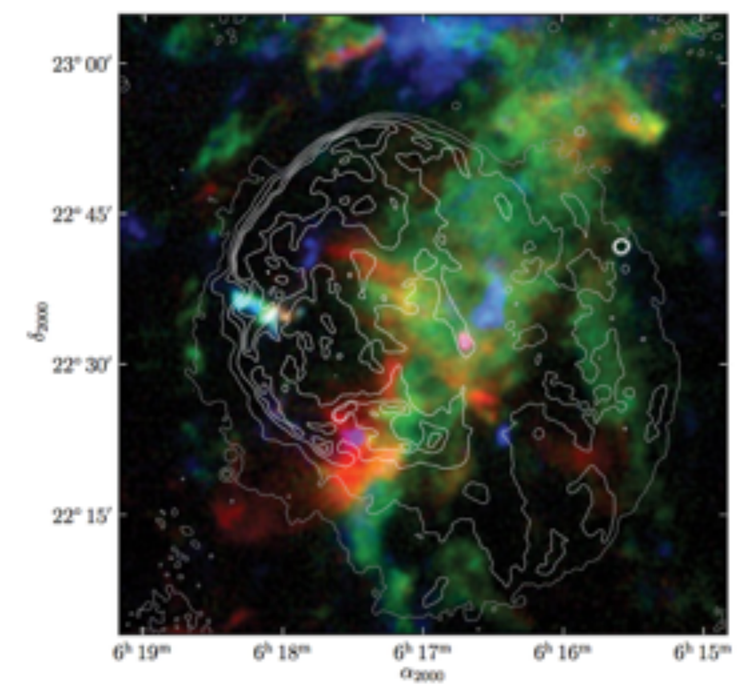
- Among the over 300 Galactic SNRs, over 70 are confirmed to be/ possibly associated with molecular clouds (MCs; Jiang et al. 2010; Jeong et al. 2012; Chen et al 2013). http://astronomy.nju.edu.cn/~ygchen/others/bjiang/interSNR6.htm



Kes 78
(Zhou & Chen 2011)



RX J1713.7-3946
(Fukui+ 2011)



IC443
(Lee+, 2012; Su+2015)

- The tool of MCs: distance, a probe of SNR acceleration of cosmic-ray protons, feedback to dense ISM, **progenitor**,…

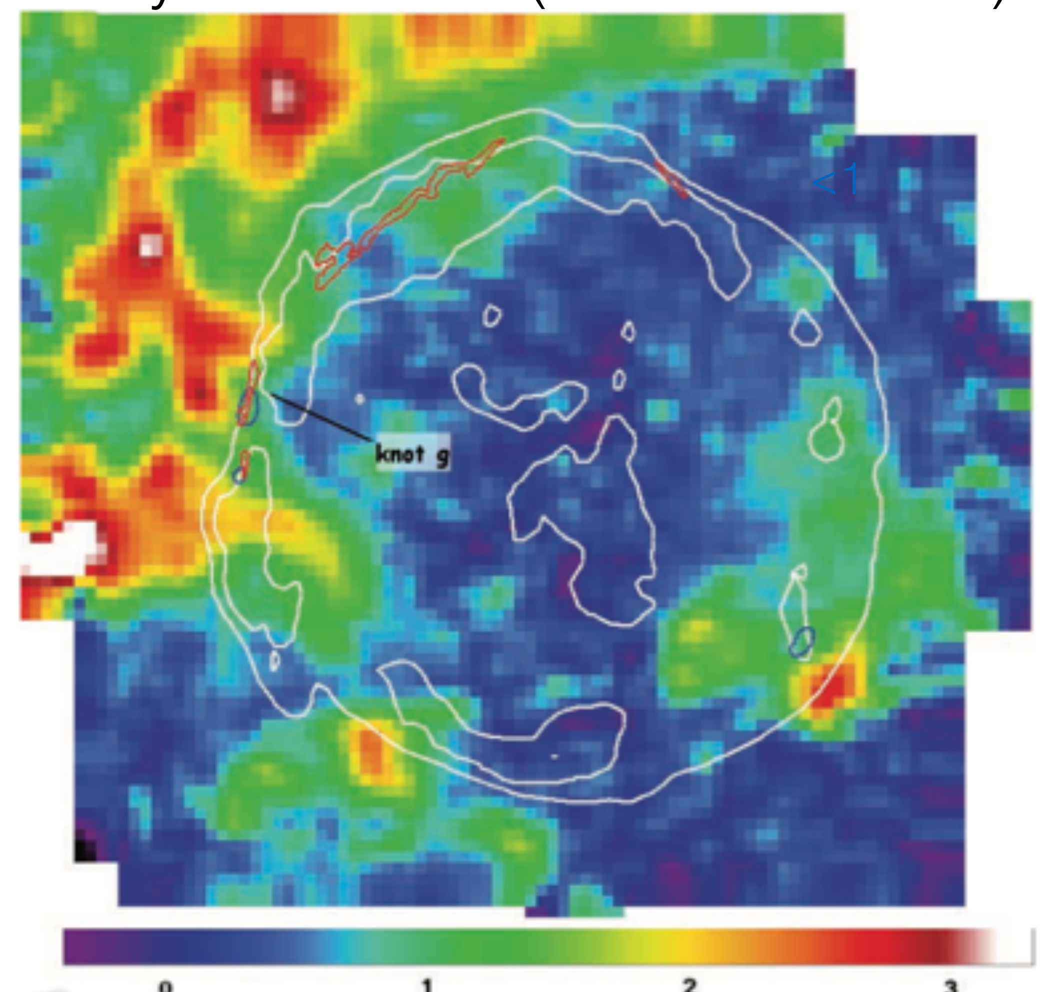
Tycho— the only Type-Ia SNR **may** interact with MC

- Observational evidence of SNR-MC interaction (Jiang+2010)

kinematic/physical evidence

1. 1720 MHz OH maser (n~10^5 cm^{-3}, T=50—125K)
2. Broad molecular line profiles
3. large high-to-low excitation line ratio (e.g. T(^{12}CO 2-1)/T(^{12}CO 1-0)>1)
4. IR emission lines such as [FeII] and H_2
5. IR colors
6. Morphological agreement

density of the shocked gas from X-ray <~0.2 cm^{-3} (Katsuda +2010)



^{12}CO 1-0
Nobeyama, resolution~16”
(Lee, Koo & Tatematsu 2004)

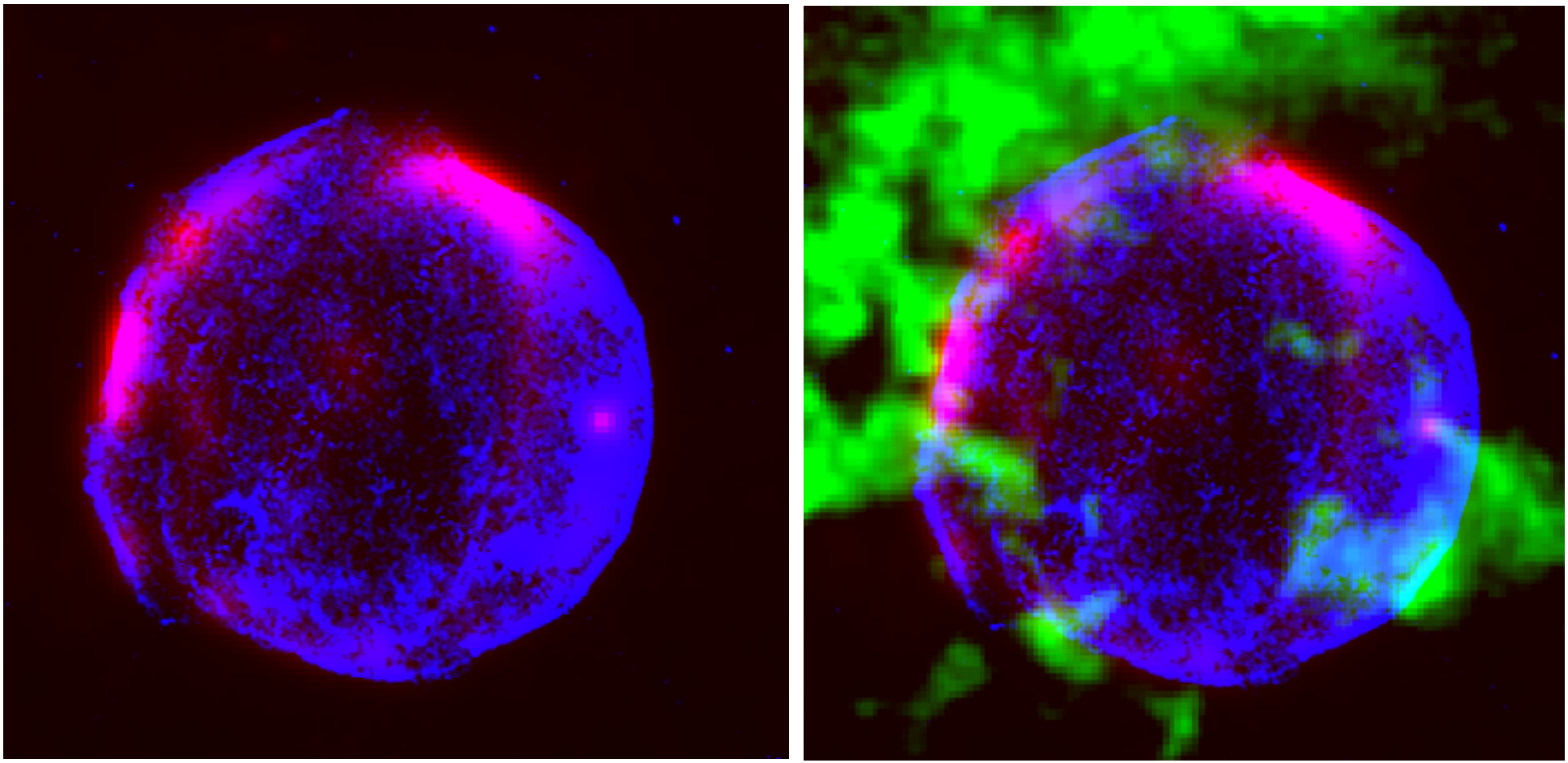
1 kinematic/physical evidence + morphological agreement—> SNR-MC interaction

Morphological agreement

Red: WISE 22 μm

green: ^{12}CO 2-1 -64 — -60 km/s, IRAM 30m, 11” resolution

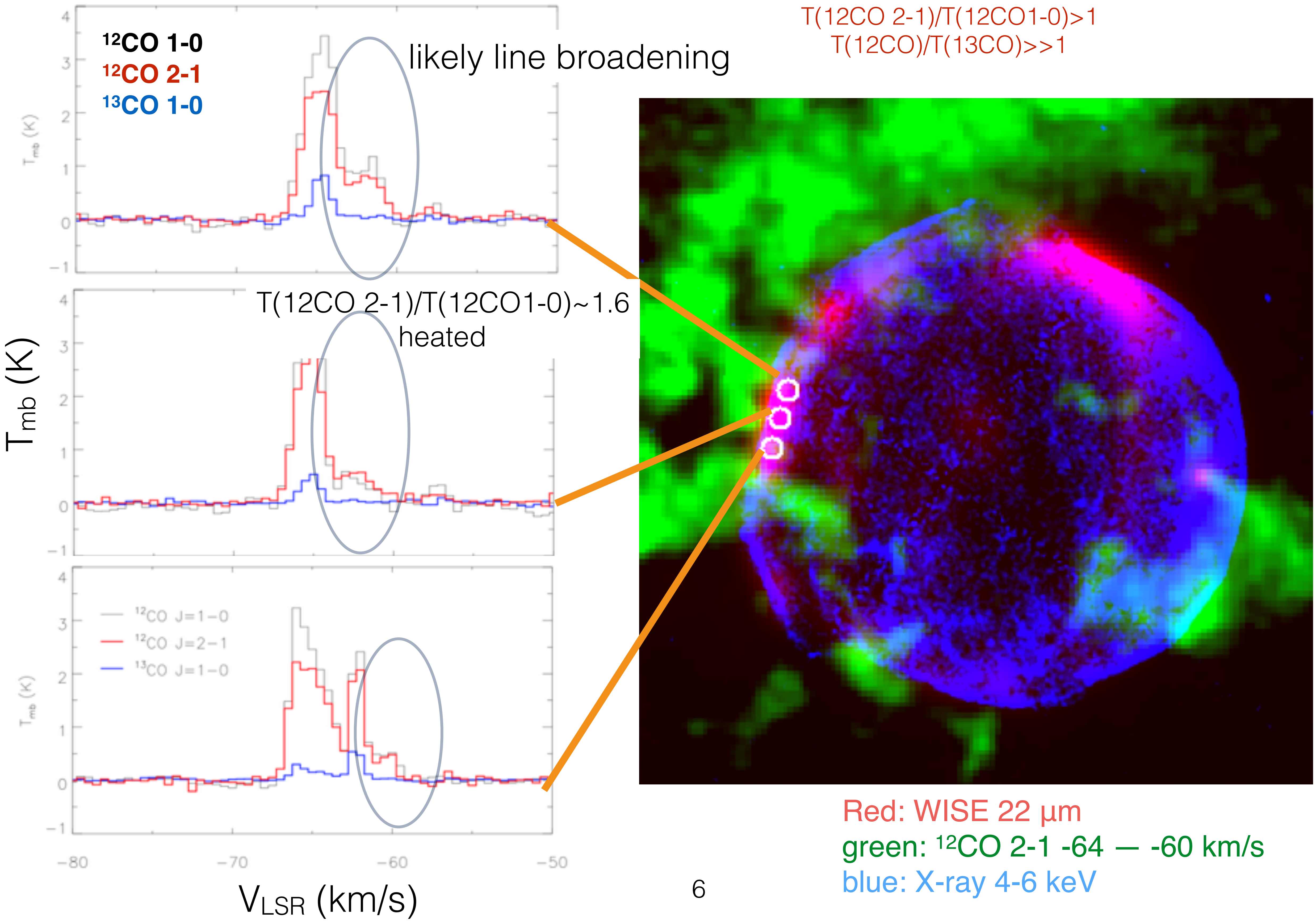
blue: X-ray 4-6 keV



clumpy, molecular clump size<0.14 pc

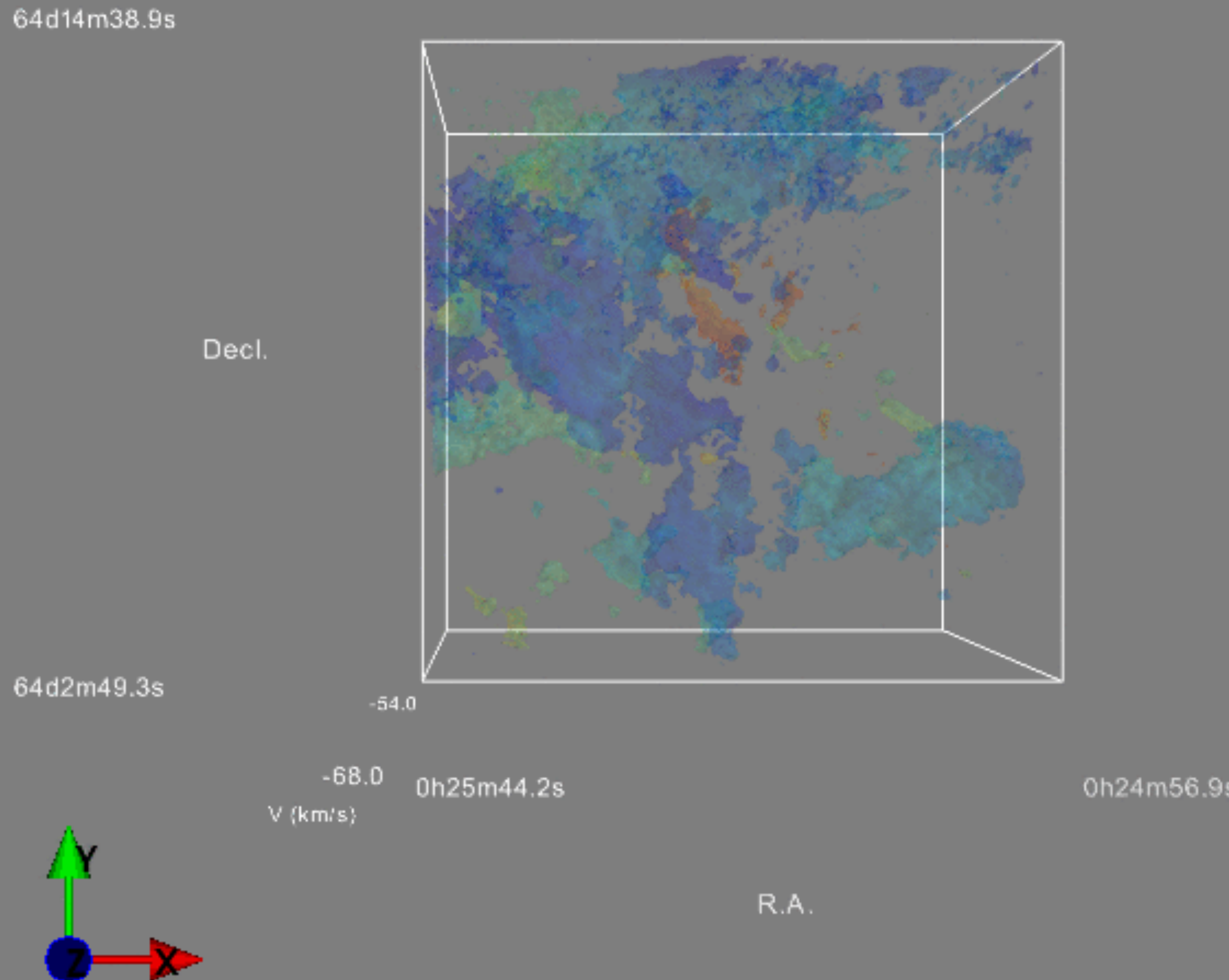
Shocked and heated gas

T(12CO 2-1)/T(12CO1-0)>1
T(12CO)/T(13CO)>>1

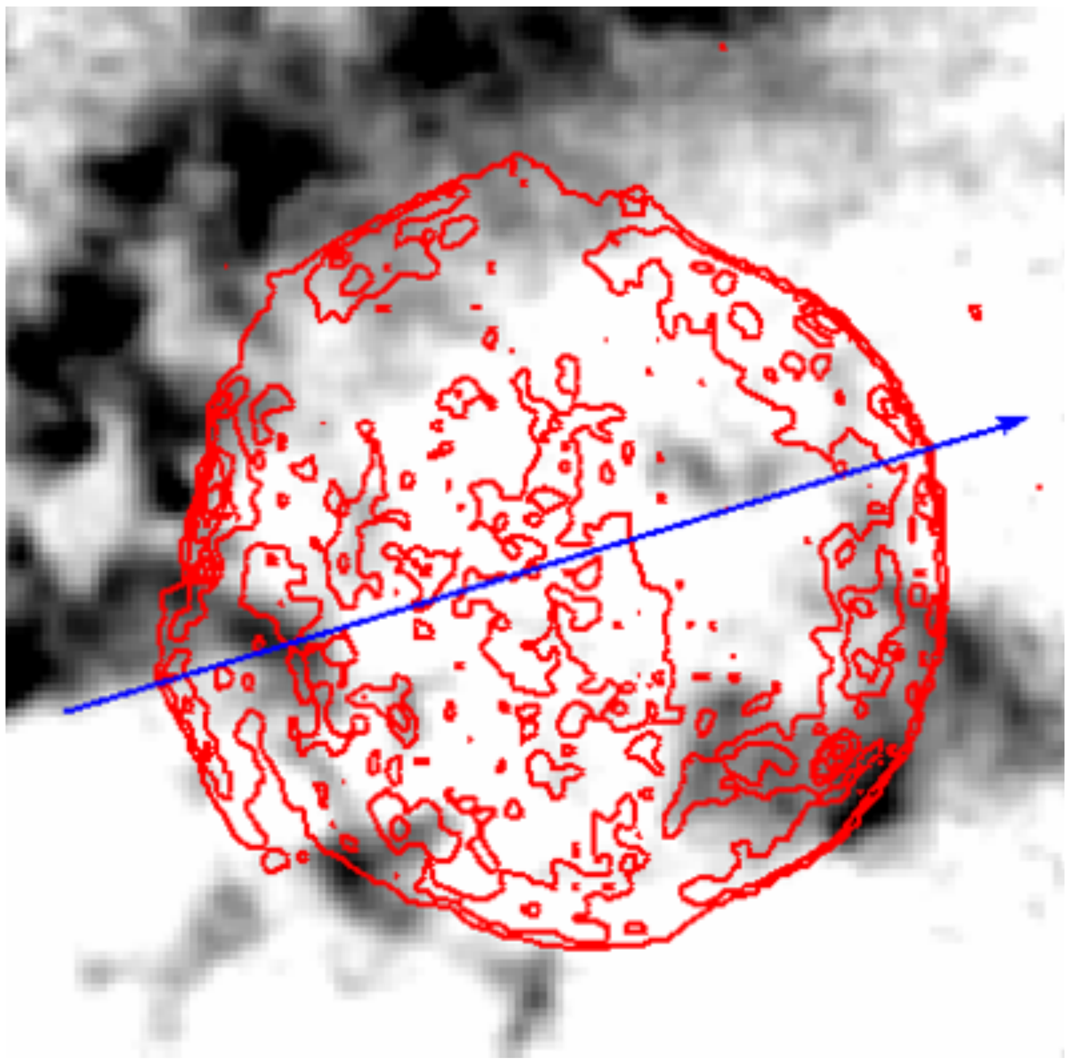


Red: WISE 22 µm
green: ^{12}CO 2-1 -64 — -60 km/s
blue: X-ray 4-6 keV

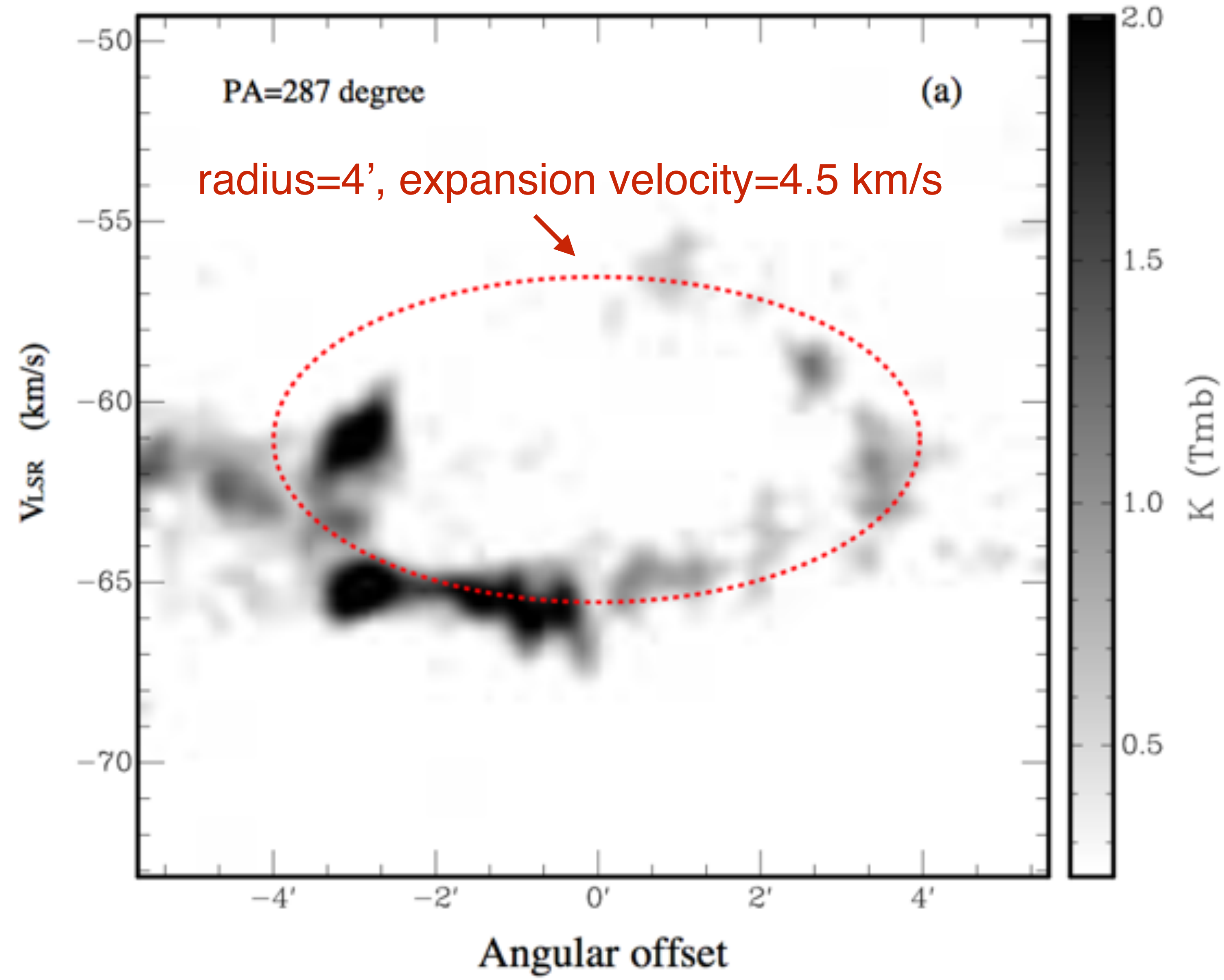
- systemic velocity: **V_{LSR}~ -61 km/s**
- distance: ~**2.5 kpc**
- expanding velocity: ~**4.5 km/s**
- mean radius: ~**3 pc**
- Molecular gas mass: ~**220 M_{sun}**



molecular bubble in expansion

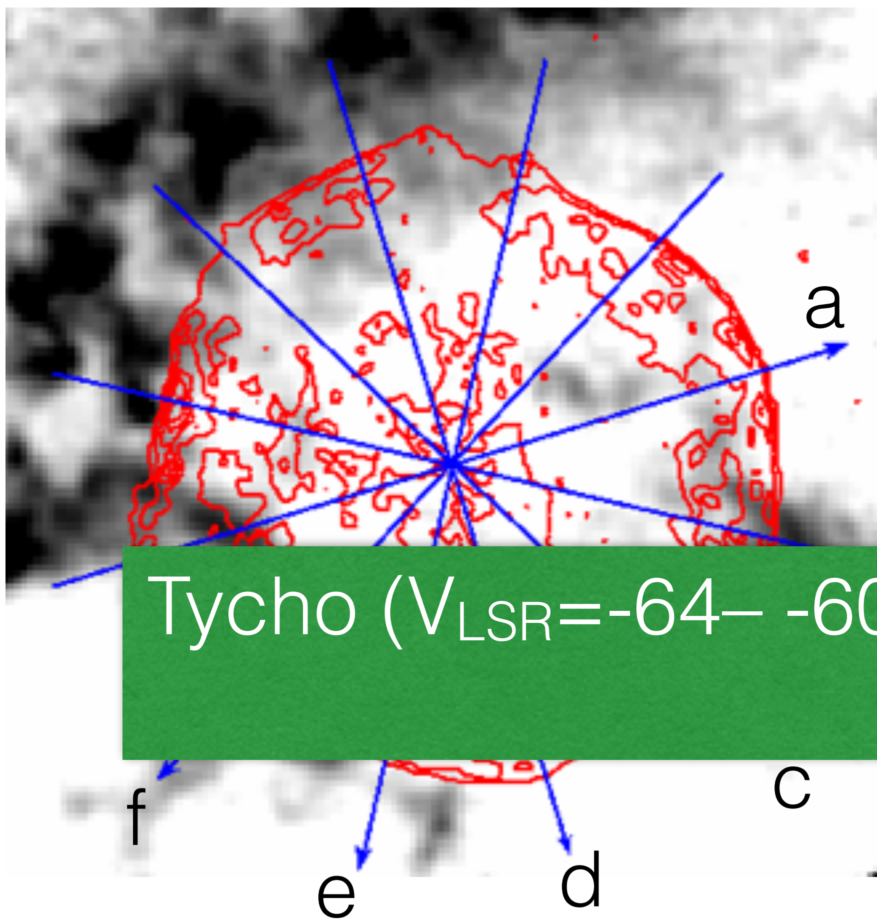


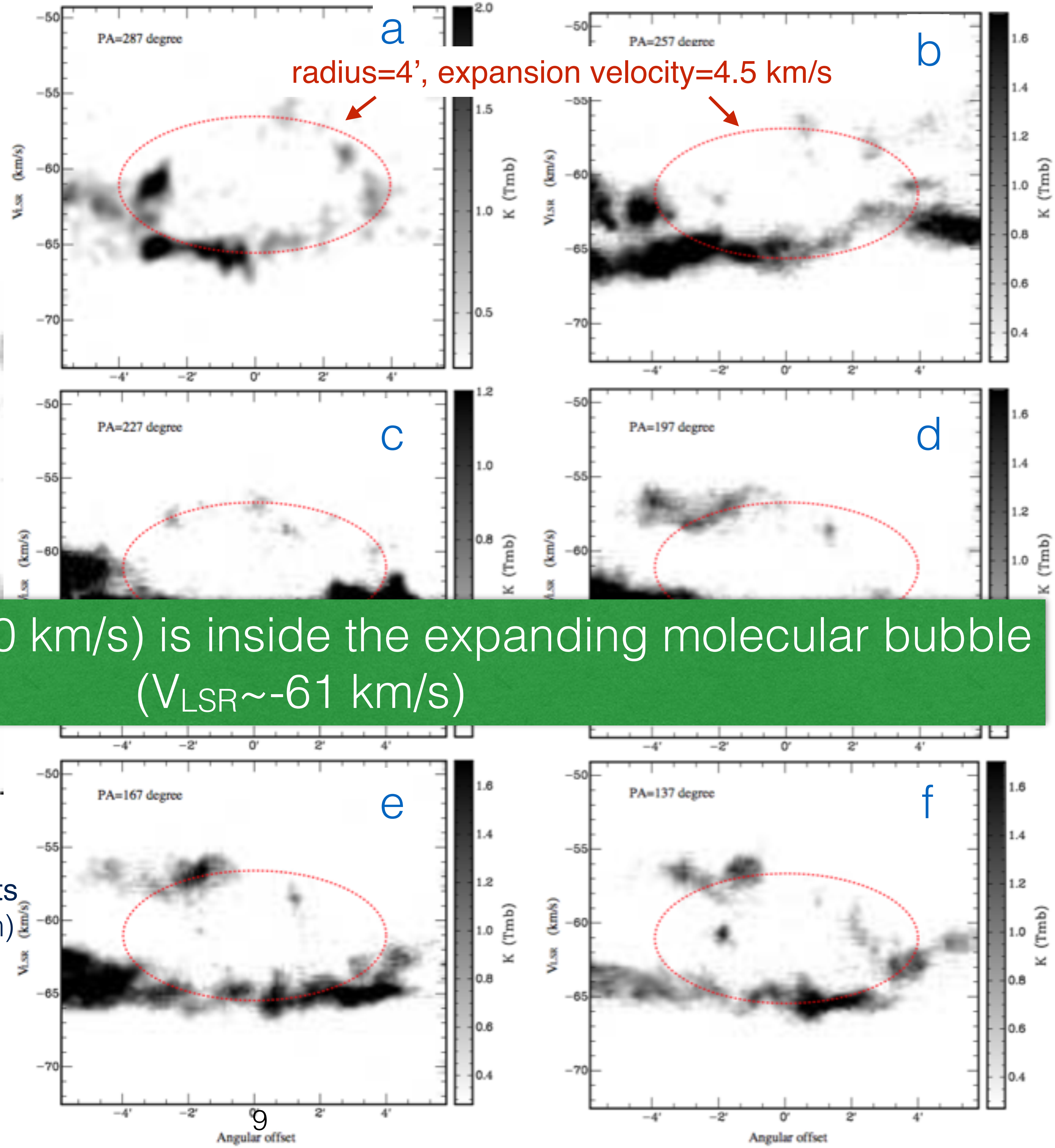
grey: 12CO J=2-1
contour: X-ray 4-6 keV



position-velocity (PV) diagram of CO 2-1
along the cut with PA=287degree
(equivalent to optical long-slit spectrum)

Position-velocity diagrams





Tycho (V_{LSR}=-64– -60 km/s) is inside the expanding molecular bubble (V_{LSR}~-61 km/s)

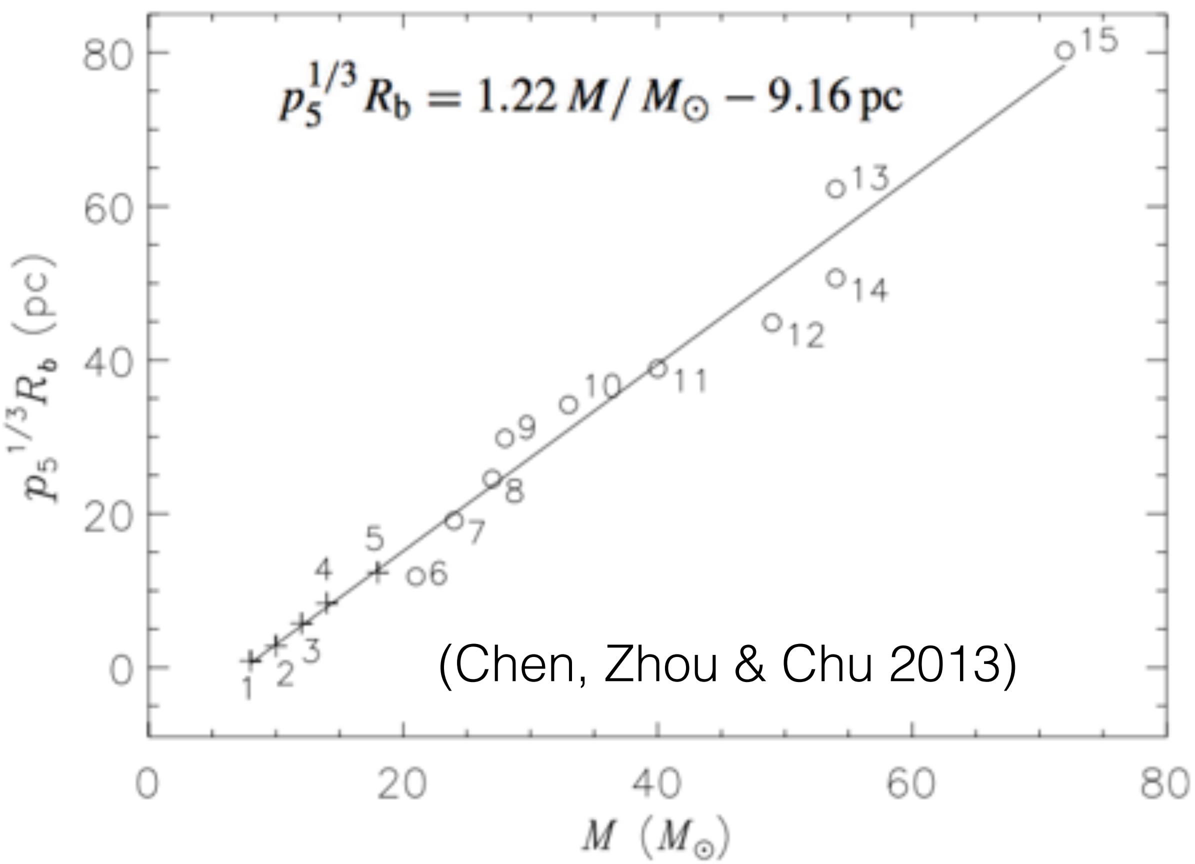
blue lines: directions for CO spectral cuts
(equivalent to optical long-slit spectrum)

Origin of the expanding molecular bubble

- ~~swept-up by SNR~~ Because the SNR-MC interaction is not extensively
- wind blown bubble
  - ~~possibility 1 (unrelated to Tycho): by the wind of a massive star on the line-of-sight~~
  - possibility 2 (related to Tycho): by the progenitor system of Tycho

The maximum size of a wind bubble by a massive star in the main-sequence stage (Chevalier 1999)

$$R_{\rm m} = 15.8 \left(\frac{\dot{M}}{10^{-7}\, M_\odot\, {\rm yr}^{-1}}\right)^{1/3} \left(\frac{\tau_{\rm ms}}{10^7\, {\rm yr}}\right)^{1/3} \left(\frac{v_{\rm w}}{10^3\, {\rm km\, s}^{-1}}\right)^{2/3} \times \left(\frac{p/k}{10^5\, {\rm cm}^{-3}\, {\rm K}}\right)^{-1/3} {\rm pc}$$



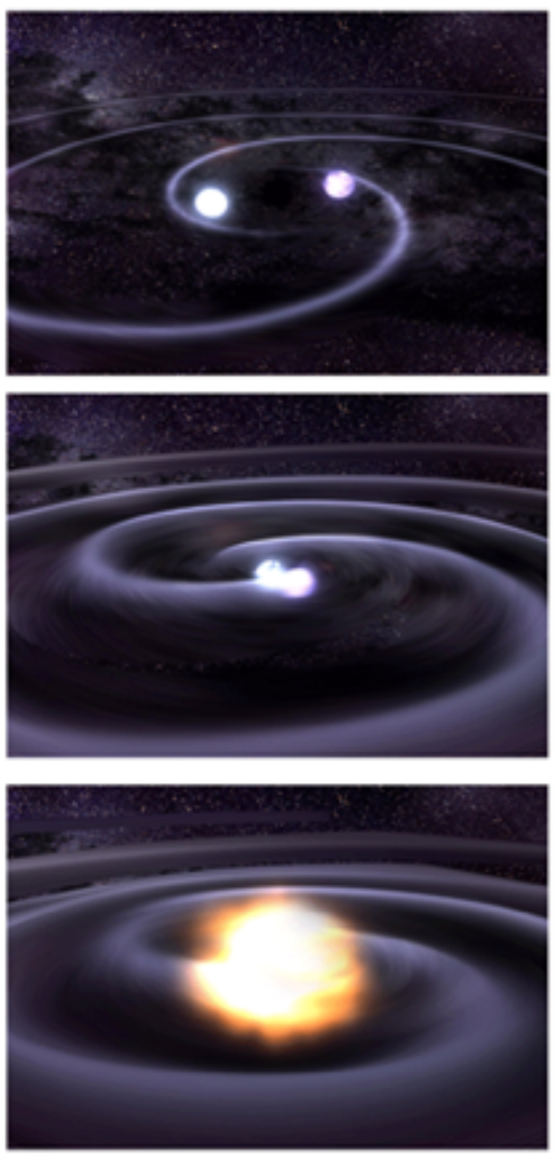
Need a massive star with M>10 Msun (B2 type or earlier) to create the 3 pc molecular bubble. Such a massive star is not seen in the field of Tycho!

We have used this relation to derive the progenitor masses of a dozen of SNRs in molecular bubbles (See Chen, Zhou & Chu 2013, Zhang+2015, ApJ, 799, 103)

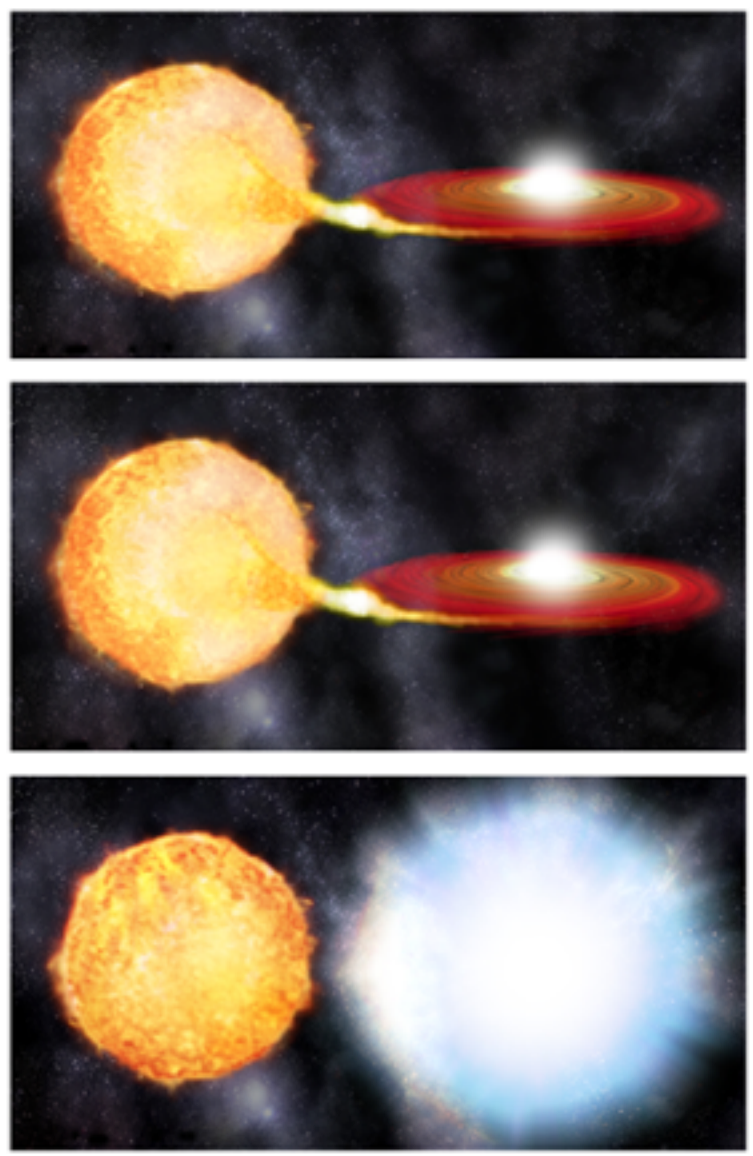
Origin of the expanding molecular bubble

- wind blown bubble created by the progenitor system of Tycho

double-degenerate
WD+WD



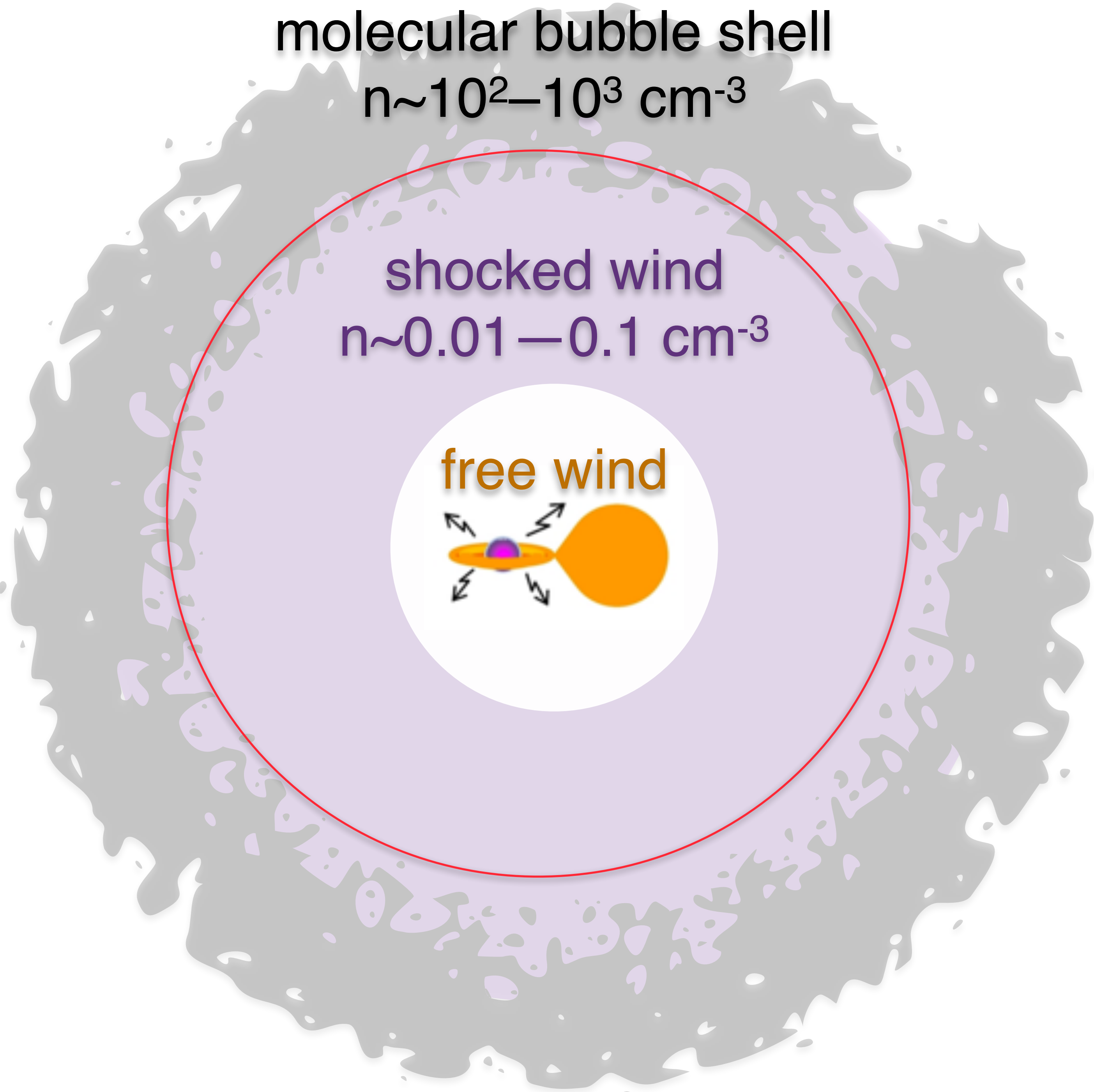
single-degenerate
star+WD (disk wind)

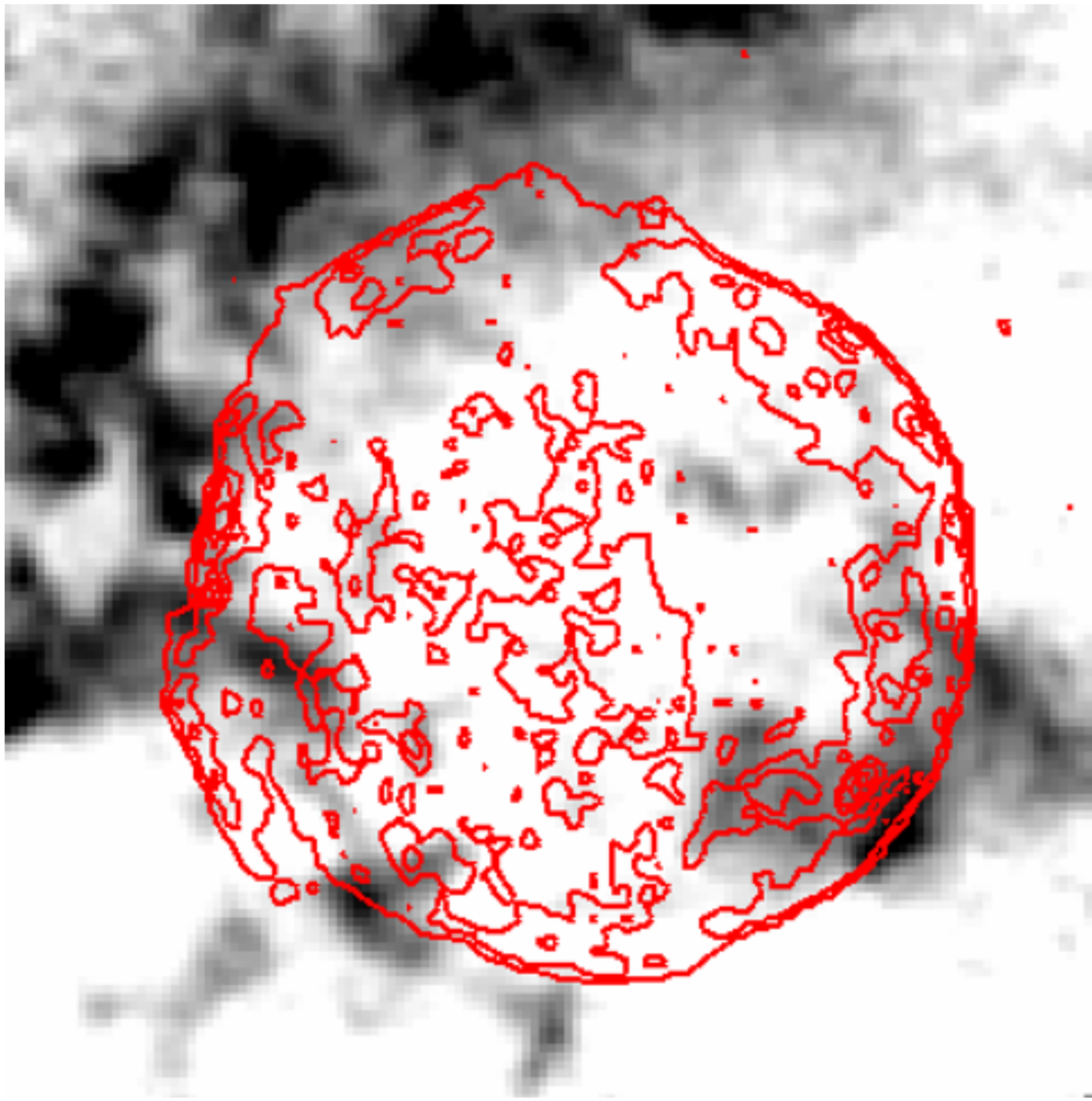


The key difference between the two scenarios is present or absence of outflows from the binary system during the pre-SN evolution (Badenes+ 2007)

If accretion exceeds a critical value ($\dot{M}_{cr}$ ~10^{-6} M_{sun}/yr),
the rest is blown off in the strong wind (>hundreds of km/s; Hachisu+ 1996).

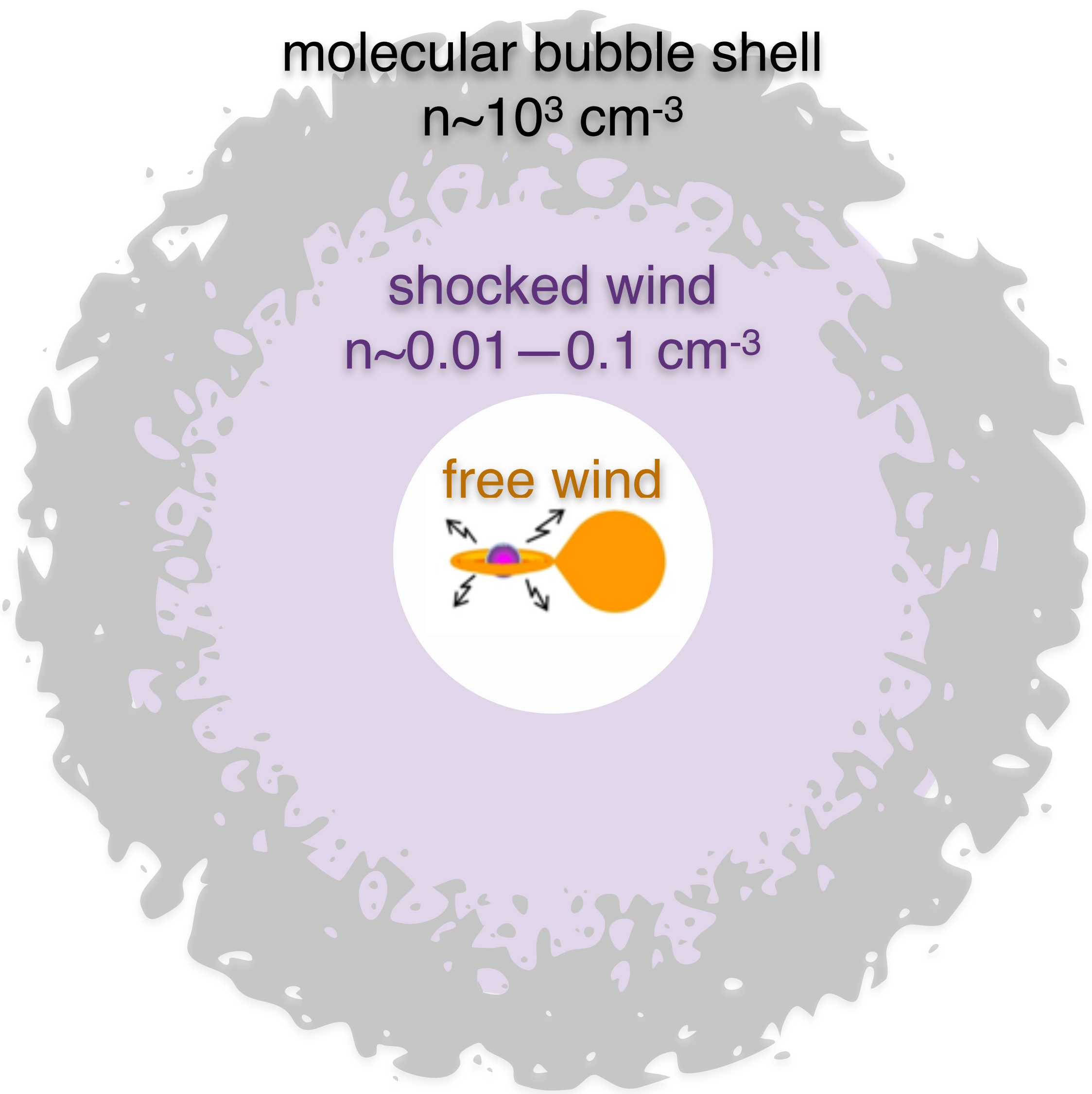
The strong wind of the WD can evacuate a low density cavity and sweep up an expanding molecular bubble shell





The shock wave has just reached the molecular cavity wall

The wind parameters can match those expected in SD scenario



Parameters for the exemplified evolutionary paths of the bubble.

Path	v_w (km s^{-1})	$\dot{M}$ ($10^{-6}M_\odot$)	t_t (10^5 yr)	t_{elapse} (10^5 yr)	$n_b(t_t)$ (cm^{-3})	$n_b(t_b)$ (cm^{-3})
P1	250	0.3	3.9	0	0.04	0.04
P2	250	1.0	1.3	1.6	0.09	0.02
P3	280	1.0	1.1	1.7	0.10	0.03
P4	350	1.0	0.8	1.8	0.13	0.02

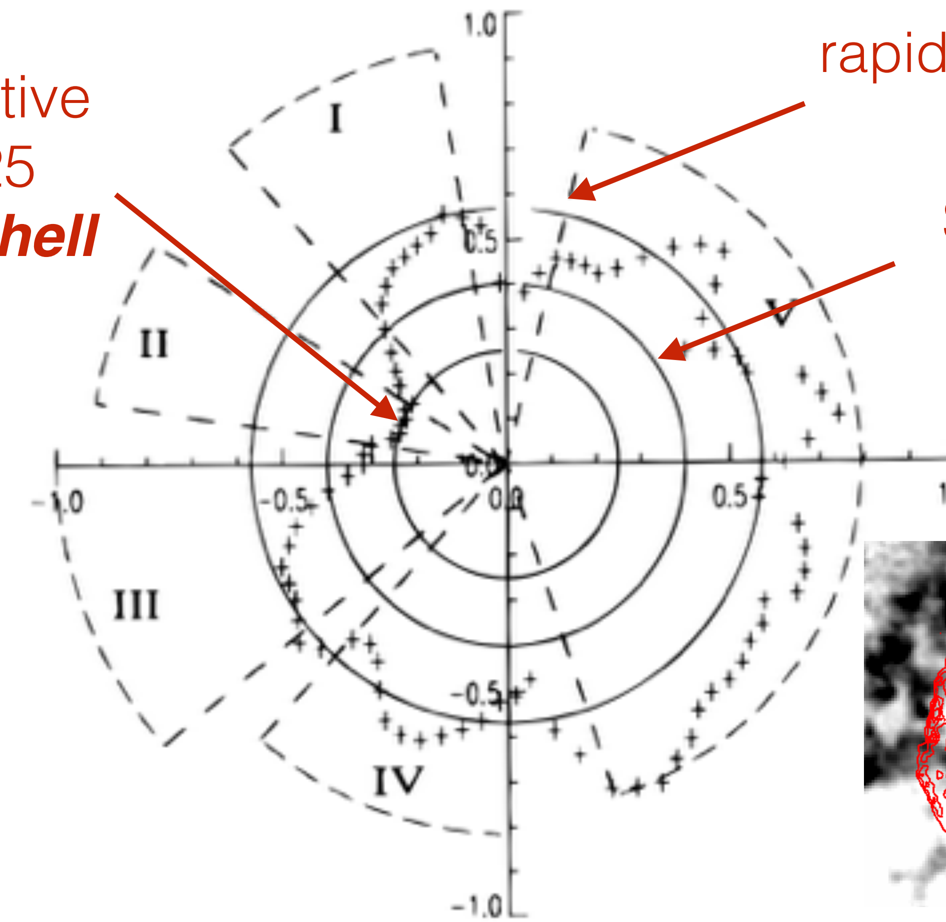
v_w—wind velocity
$\dot{M}$—mass-loss rate
t_t—duration of the wind
t_{elapse}—elapse time between the wind stop and SN explosion
n_b—density of the wind bubble

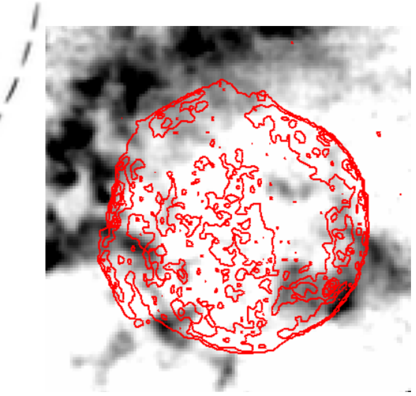
We constrain the wind velocity to be no less than 250 km/s so that the modelled bubble is in the energy conservation stage.
In this state, the density of shocked wind has a flat density profile, consistent with the observation.

These wind parameters are expected in the single-degenerate scenario.

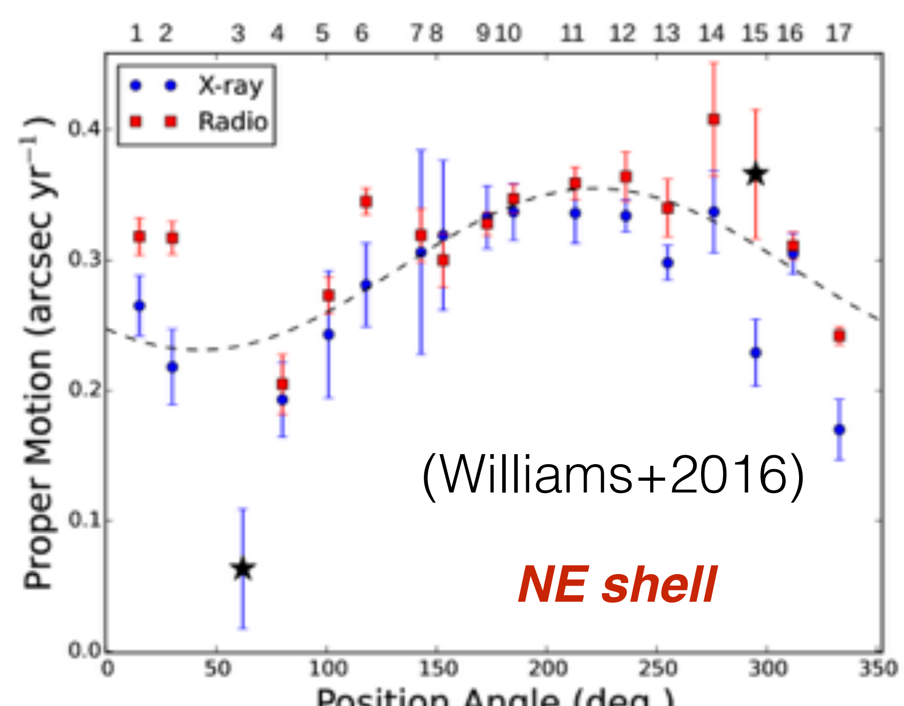
Importance of the MCs in the study of Tycho and its progenitor

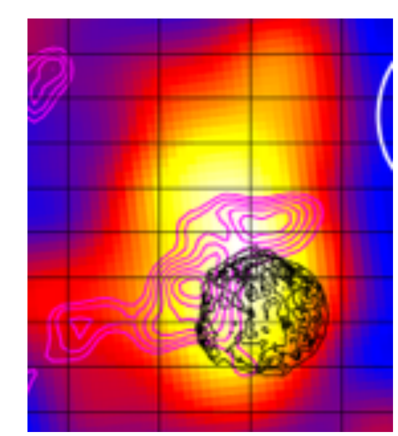
- constitutes evidence for a single-degenerate progenitor of Tycho
- explains the rapid deceleration and deformed morphology of the NE shell
- distance: ~2.5 kpc (see Lee+ 2004)
- consistent the GeV and TeV emission detected in the east and north of Tycho
- raise the target density of hadronic collision, allow a lower energy conversion fraction of CRs (Zhang, X.+ 2013; of order 1%)





Variation of the expansion rate (Reynoso+ 1997)

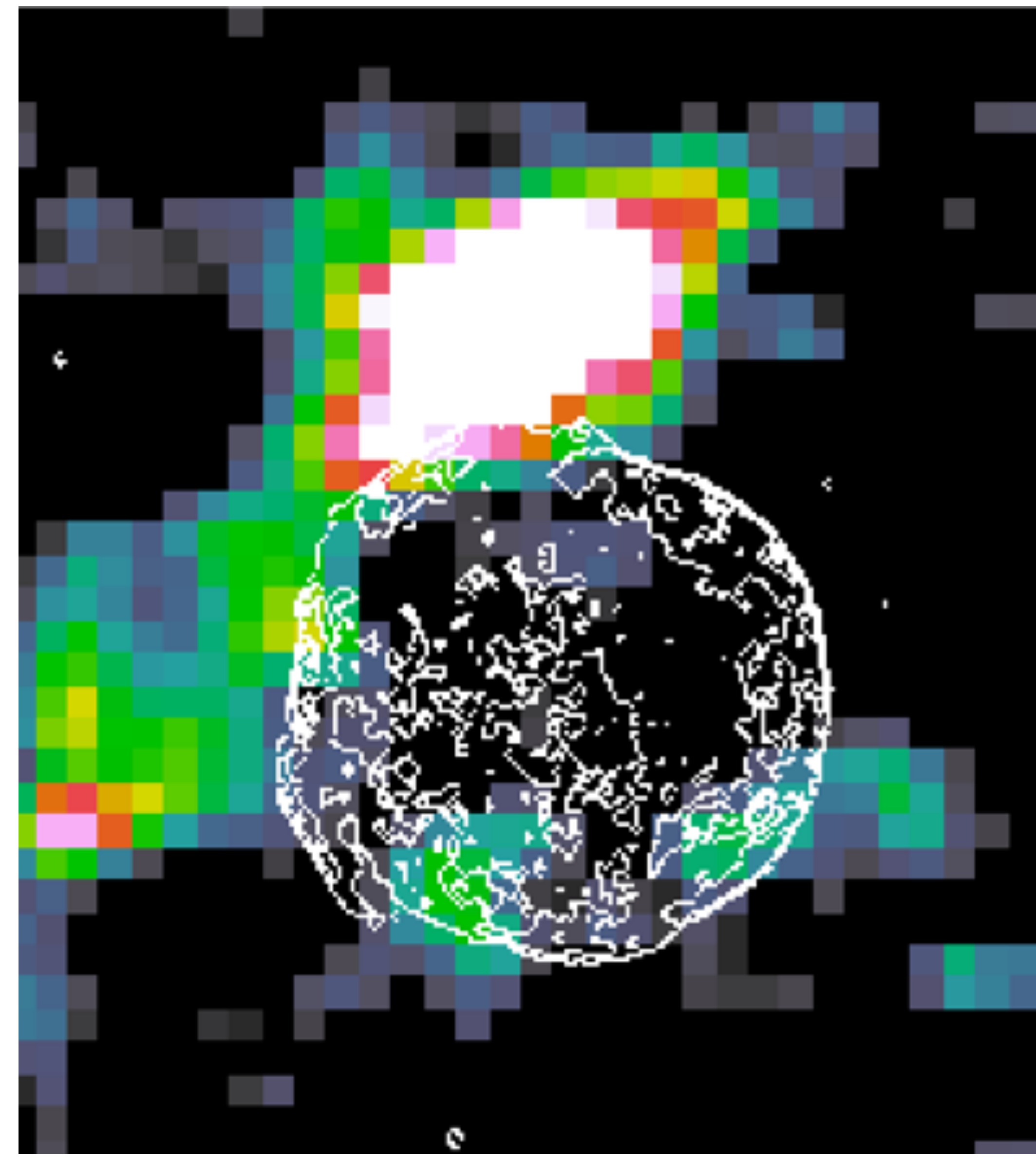




Tev
(Acciari+2011)

Future monitoring study of Tycho

- Tycho is expanding towards nonuniform dense medium. Tycho-MC interaction is expected to be more and more extensive and strong.
- Molecular/IR monitoring observation will be important to study the young SNR in the nonuniform medium



Distribution of H_2 column density

Summary

1. SNR Tycho is confined in the clumpy ($< 11''$) molecular gas at $V_{LSR} \sim -64 - -60$ kms^{-1}.
2. We discover the expanding motion ($\sim$ 4.5 km s^{-1}) of the molecular bubble at $V_{LSR} = -61$ kms^{-1}. The mass of the molecular bubble is $\sim 220\ M_\odot$.
3. The most plausible origin for the expanding bubble is the fast outflow (with velocity hundreds of km/s) driven from the vicinity of the progenitor WD.
4. This is the first unambiguous detection of the expanding bubble driven by the progenitor of the Type-Ia SNR, which provides important and independent evidence to support that the progenitor of Tycho was a single-degenerate system.

More details:
http://arxiv.org/abs/1605.01284