Modeling the 3D morphology and proper motions of the Butterfly Nebula - NGC 6302

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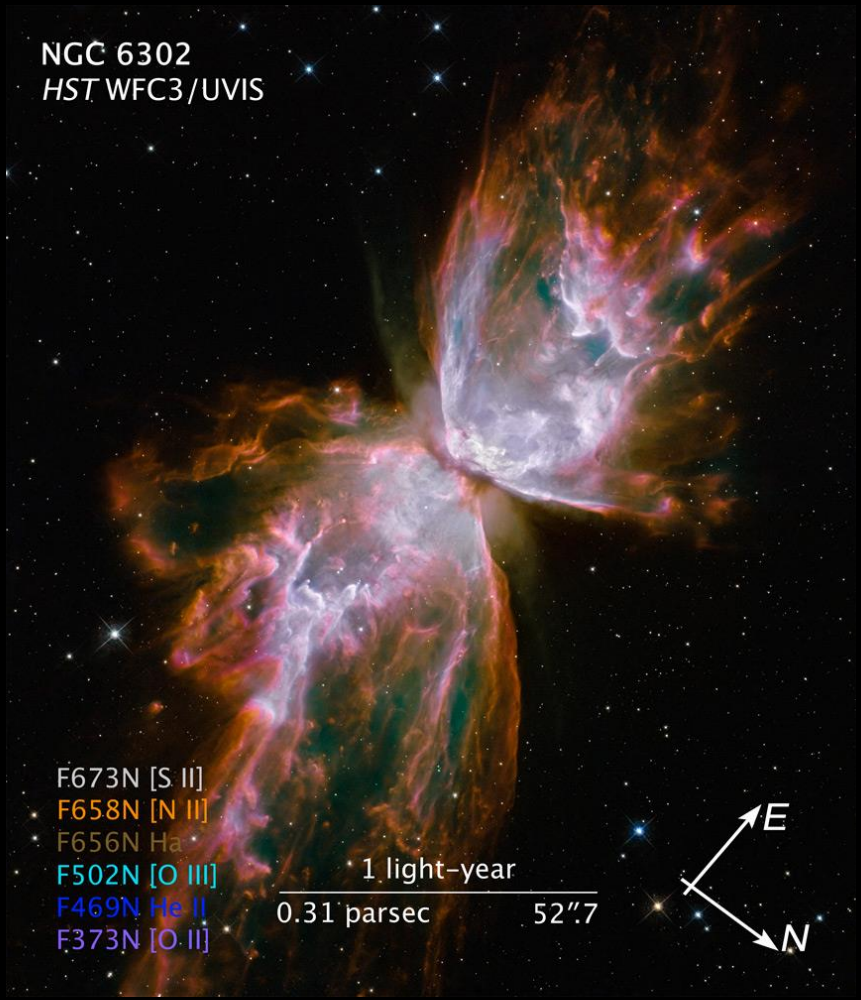
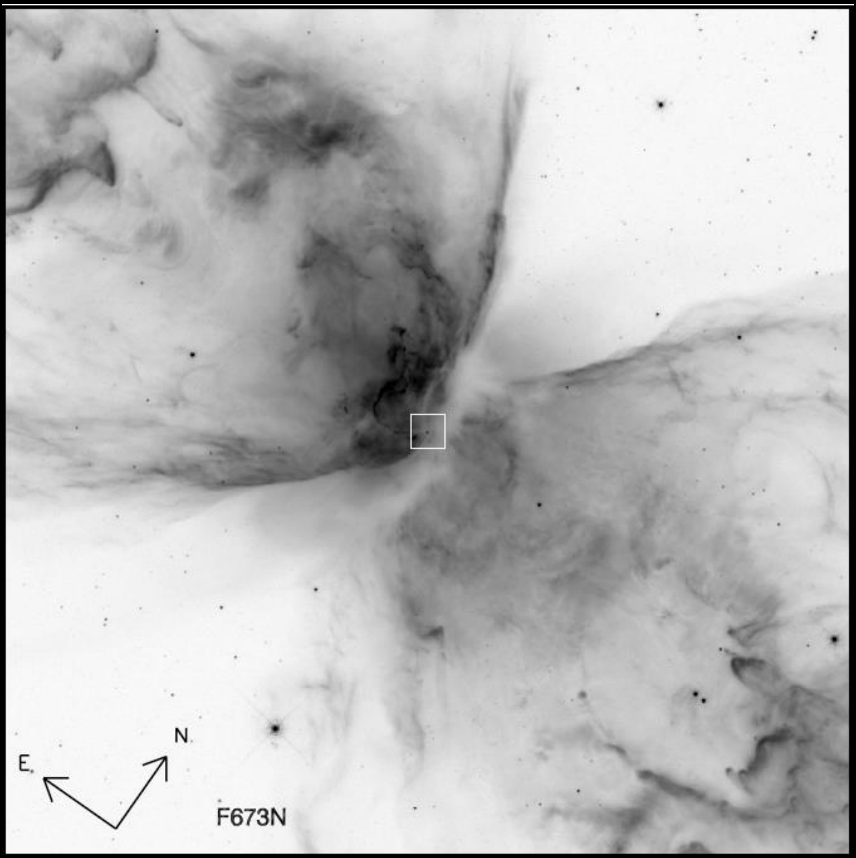
Roque de
Los Muchachos
Altitud 2426 m

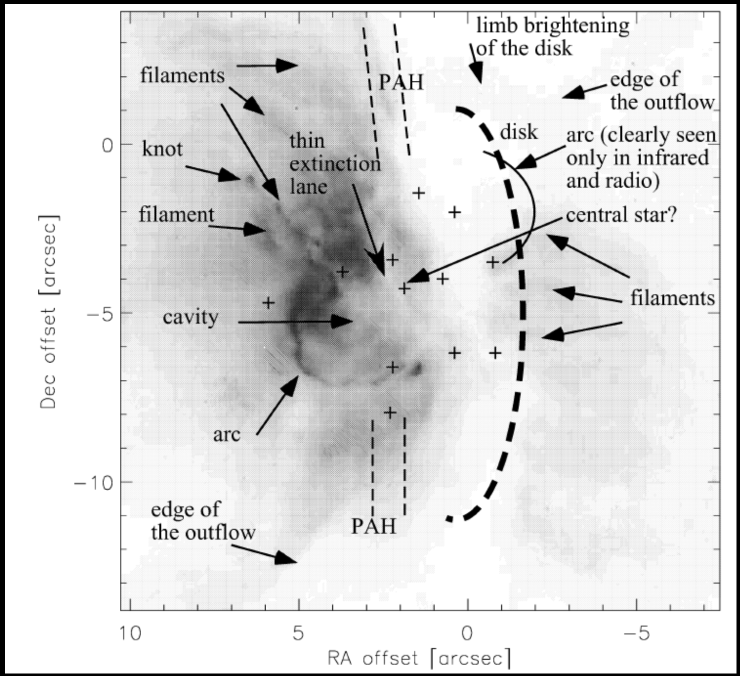


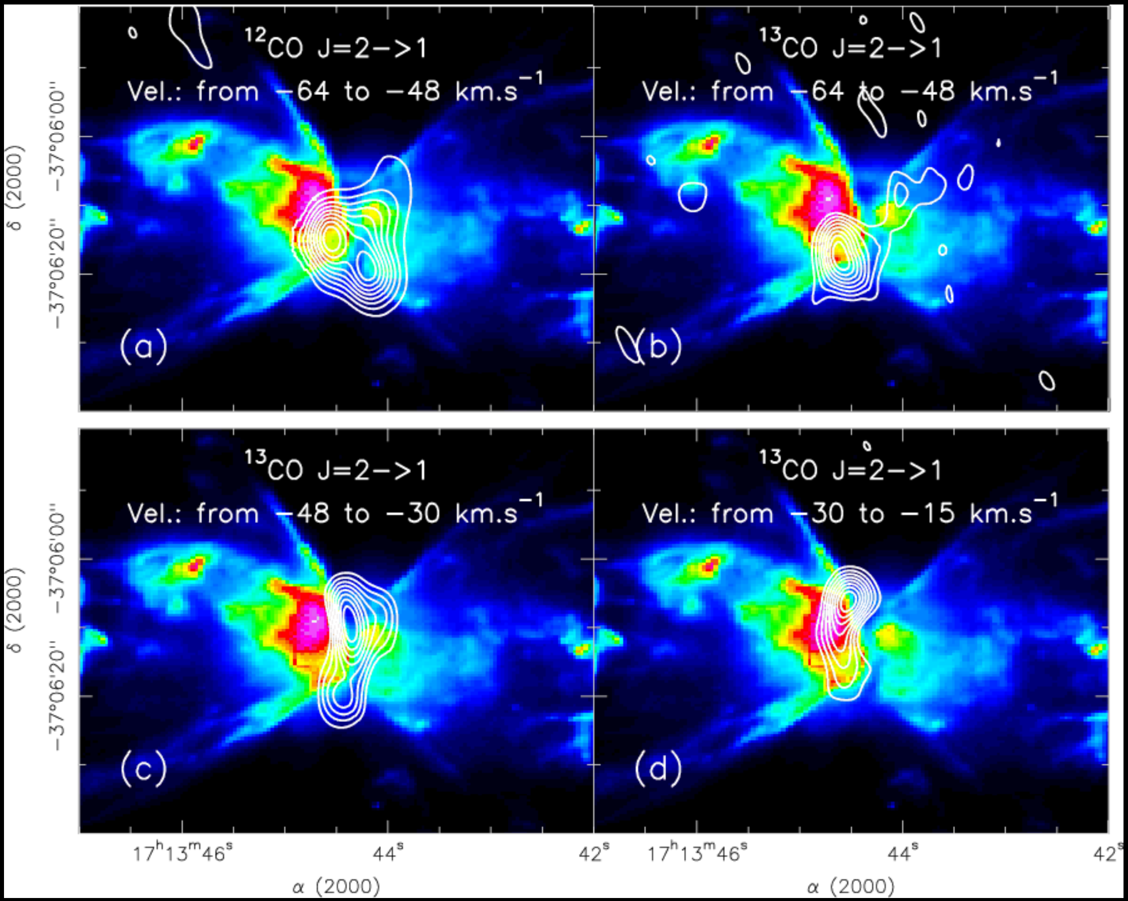


Szyszka et al. 2009
T > 200 000 K, M = 0.64 M⊙
Meaburn et al. 2008
D=1.17+/- 0.14 kpc

Dense equatorial lane

Massive expanding torus observed in CO





Matsuura et al. 2005

Peretto et al. 2007

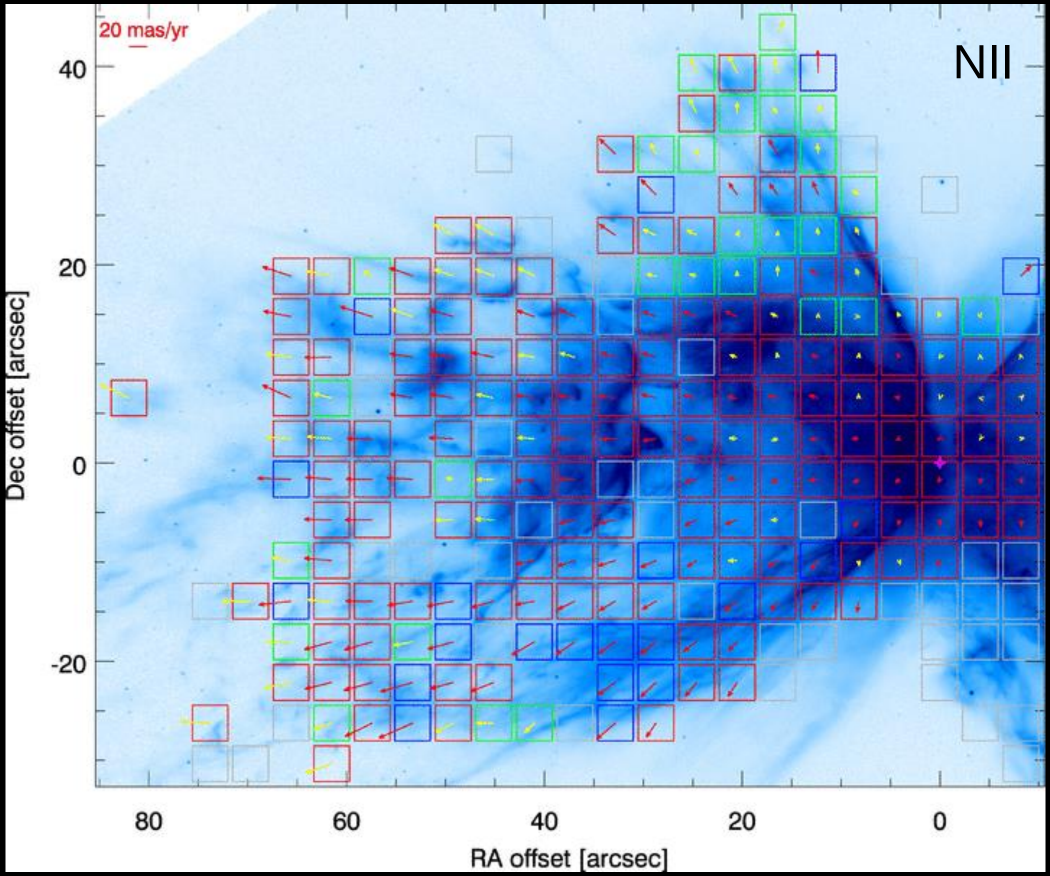
Dinh-V-Trung et al. 2008

expansion velocity ~10-15 km/s

Observed Proper Motions (PMs)

Wide field Hα image of NGC 6302 (162 X 162 arcsecs²)

The velocity field follows a Hubble law in agreement with the previous results of Meaburn et al. 2008



Szyszka et al. 2011

We present 3D hydrodynamical simulations of an isotropic fast wind interacting with a previously ejected toroidally-shaped slow wind in order to model both observed morphology and kinematics of the PN NGC 6302

We assume that the slow wind presents a density distribution with high contrast between the equator and pole densities (Mellema 1995),

$$\rho(r,\theta) = \rho_0 f(\theta)(r_0/r)^2$$

with,

$$f(\theta) = 1 - \alpha\left[\frac{1-\exp(-2\beta cos^2\theta)}{1-\exp(-2\beta)}\right]$$

r: *distance from the central star*
θ: *polar angle*
α: *ratio between the density at the equator and the pole*
β: *density variation from the equator to the pole*

$$\rho_0 = \dot{M}_s/(4\pi {r_0}^2 v_s)$$

v_s: *expansion velocity of the AGB remnant*
r_0: *radius of the region where the stellar wind is imposed*

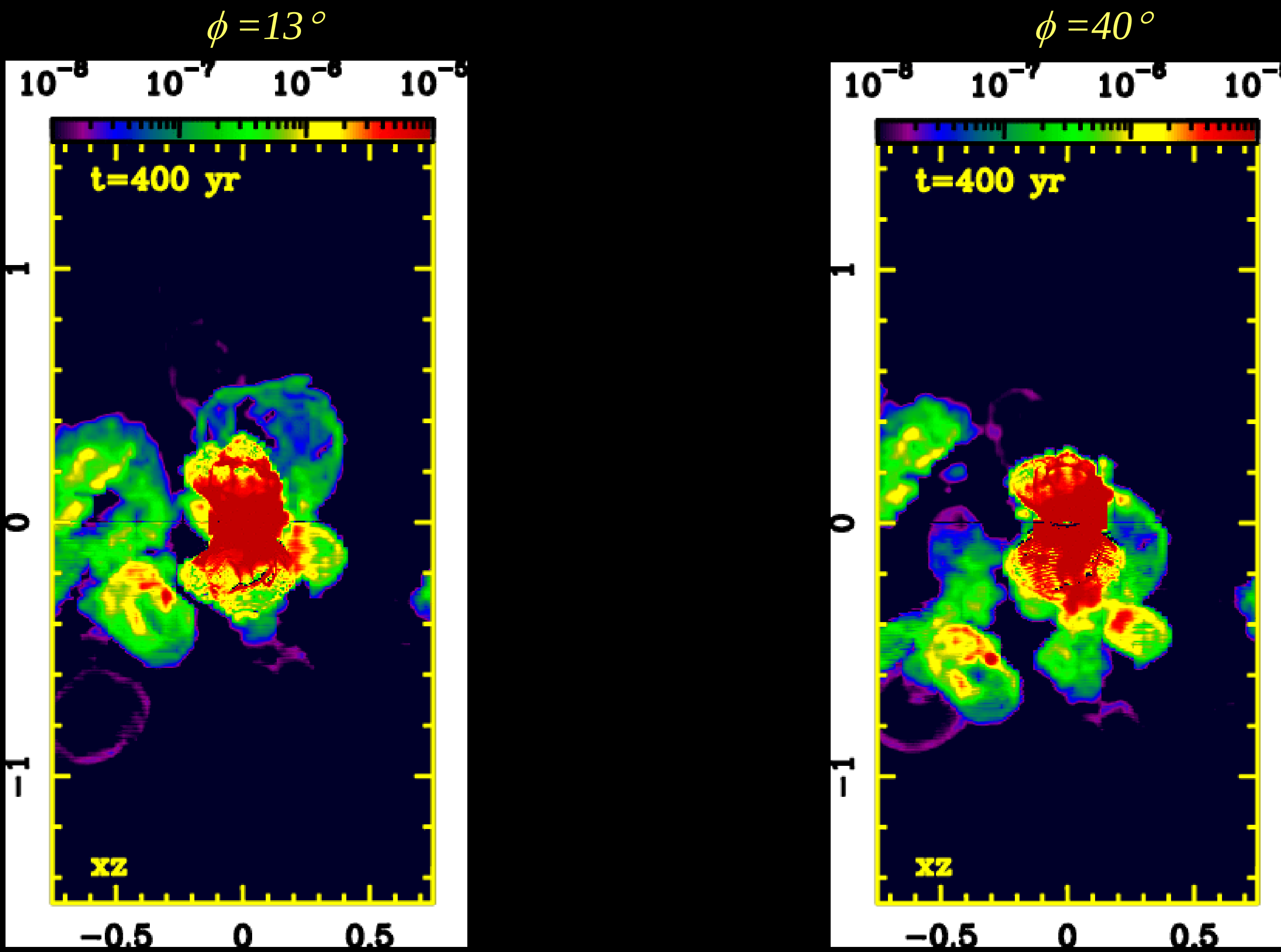
Initial conditions for the numerical simulations

Computational domain: (1.5,1.5, 3.0) X 10^{18} cm

$$\dot{M}_s = 5 \times 10^{-5}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$
$$v_s = 15\ \mathrm{km\ s}^{-1}$$
$$r_0 = 3.8 \times 10^{16}\ \mathrm{cm}$$
$$\alpha = 0.99$$
$$\beta = 5$$

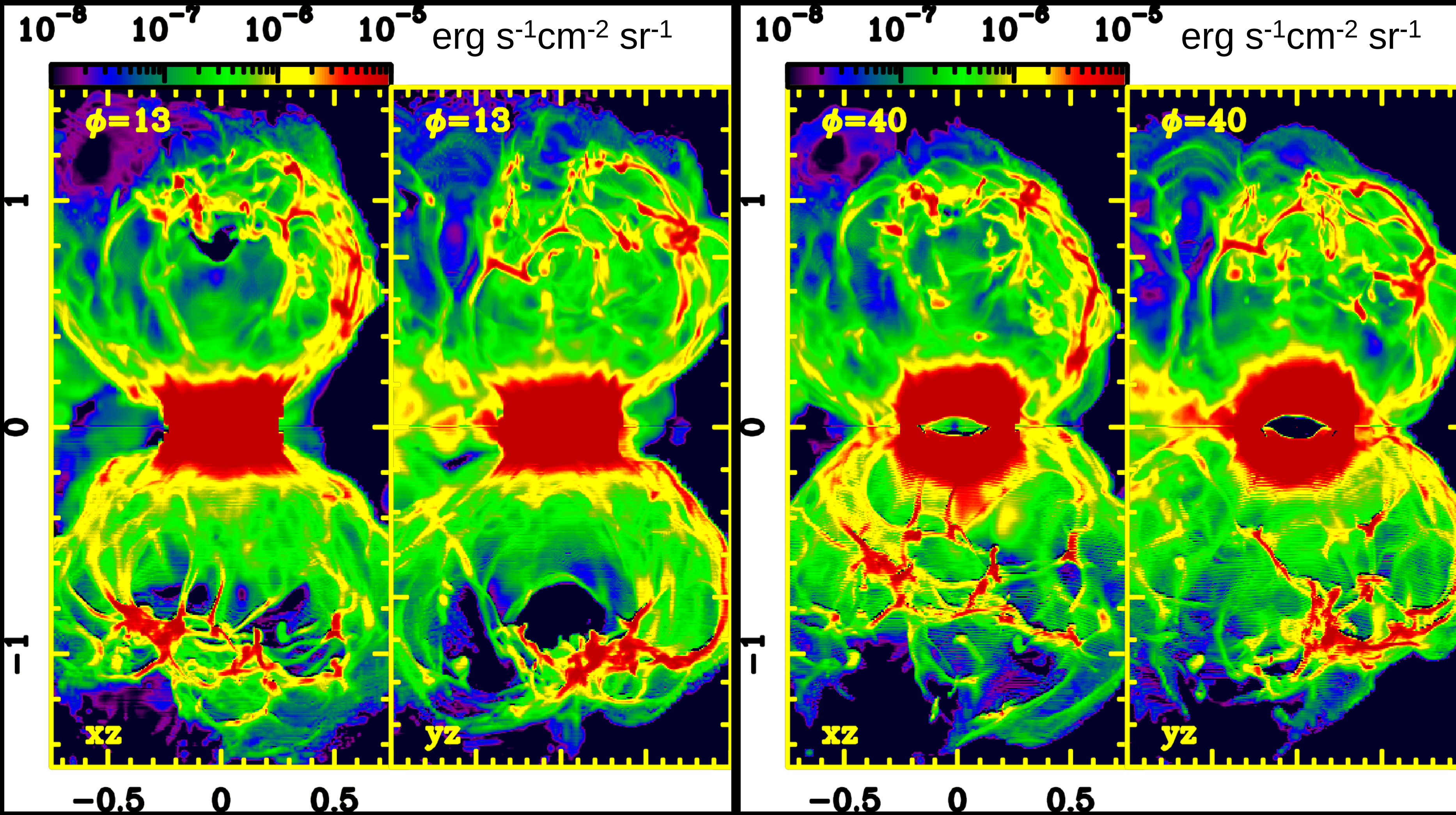
$$\dot{M}_f = 10^{-7}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$
$$v_f = 1500\ \mathrm{km\ s}^{-1}$$

To simulate a ‘clumpy’ CSM, we adopted a fractal density distribution with a spectral index of -11/3, which is consistent with a turbulent insterstellar medium (Esquivel & Lazarian 2005, Esquivel et al. 2003)



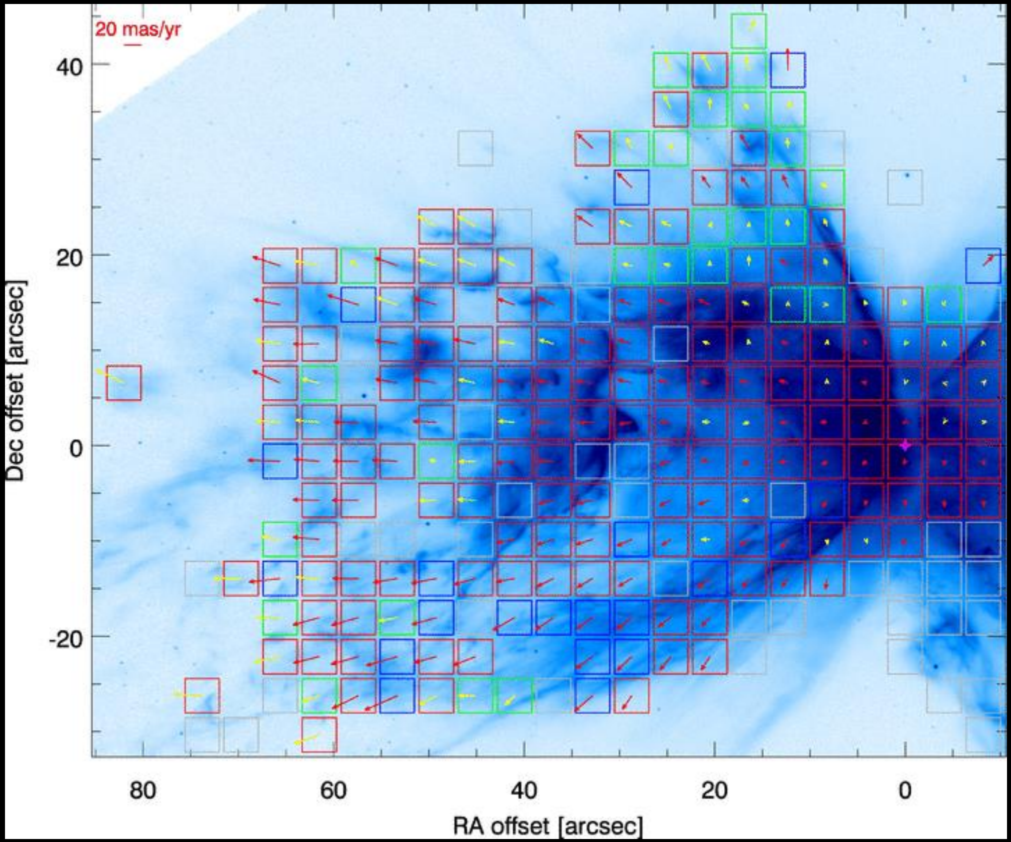
From the density and temperature distributions given by our 3D hydrodynamical simulations, we perform sythetic Hα emission maps. The angle ϕ is the angle between the nebula axis and the plane of the sky

Preliminar Results: Synthetic Hα emission maps

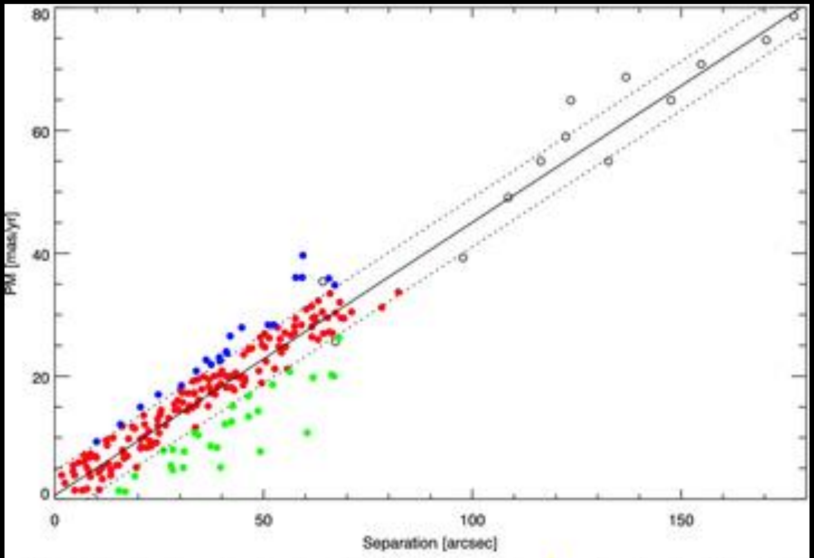


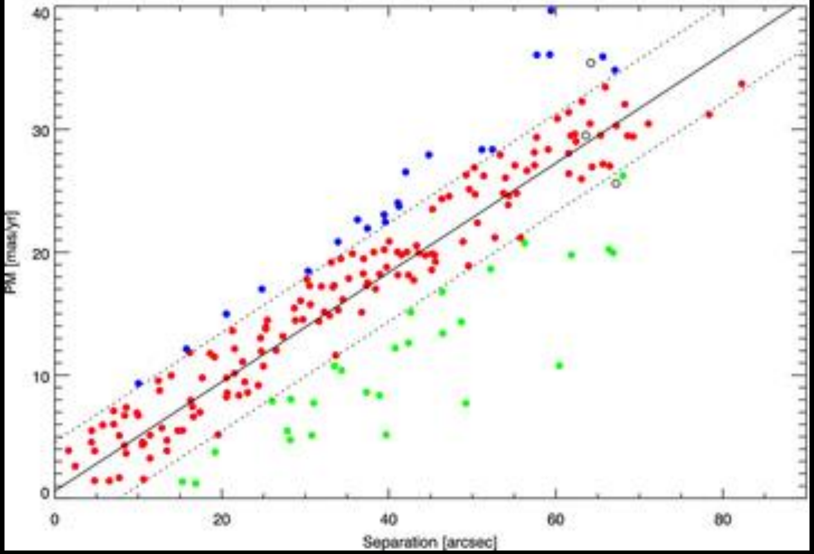
t = 2000 years

Observed PMs measurements



Szyszka et al. 2011



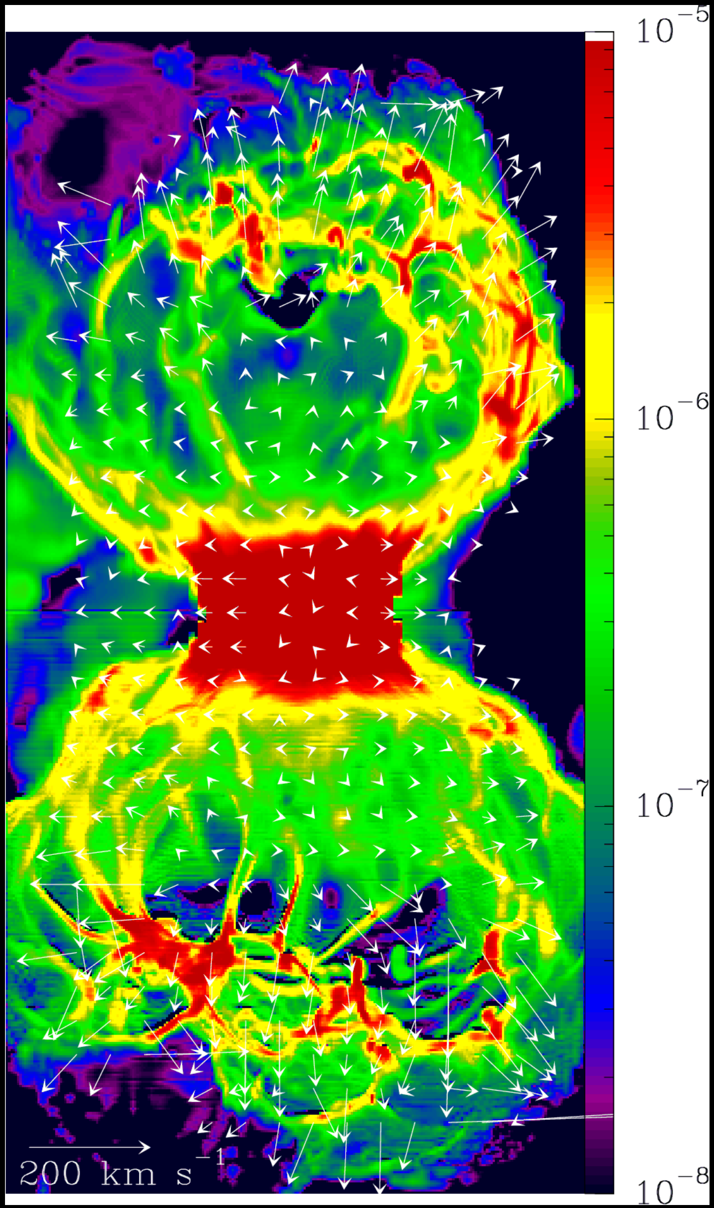


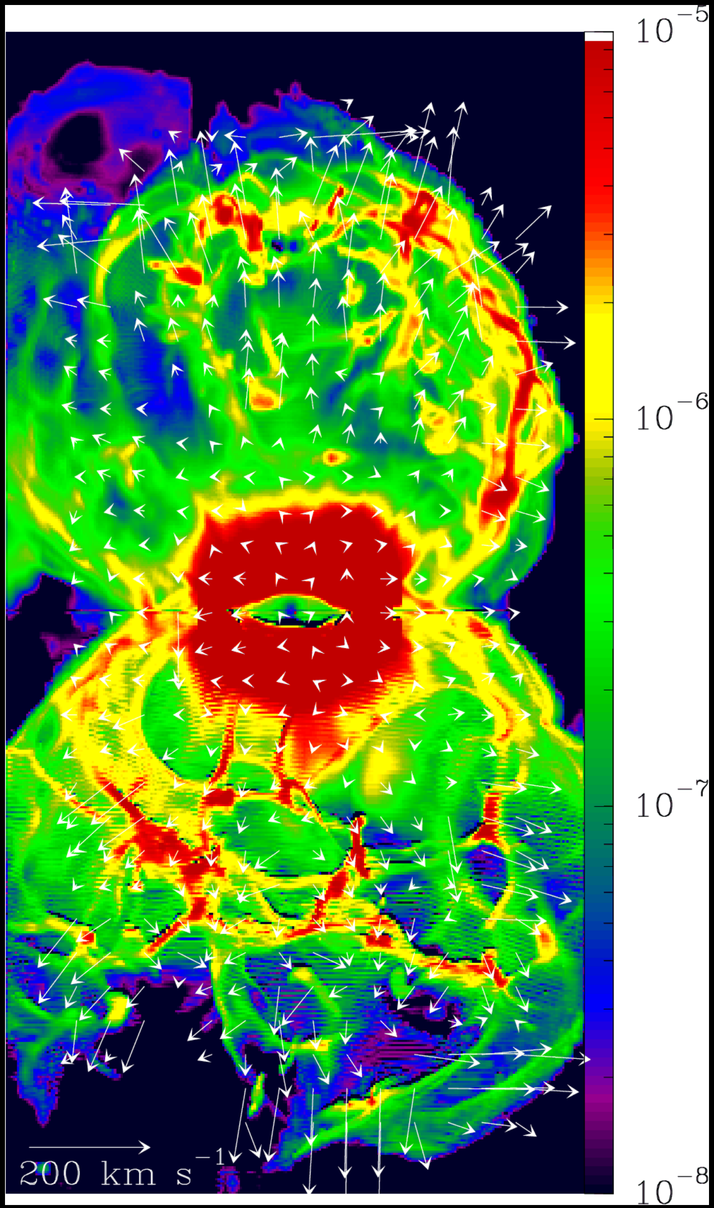
For calculating the proper motions of the nebular knots, we have restarted our simulation at an integration time of 2000 yr, and leave it to evolve by 10 yr more. Then we proceed to perform the cross correlation function method to obtain the PMs of the knots observed in both lobes of the nebula.

We have used the PM mapping technique described by Raga et al. 2013, in which, the PMs from pair of images are derived by defining boxes including the emitting knots and carrying out the cross-correlation funtion of the emission within the boxes.

Relative Hα Proper Motions (PMs) maps

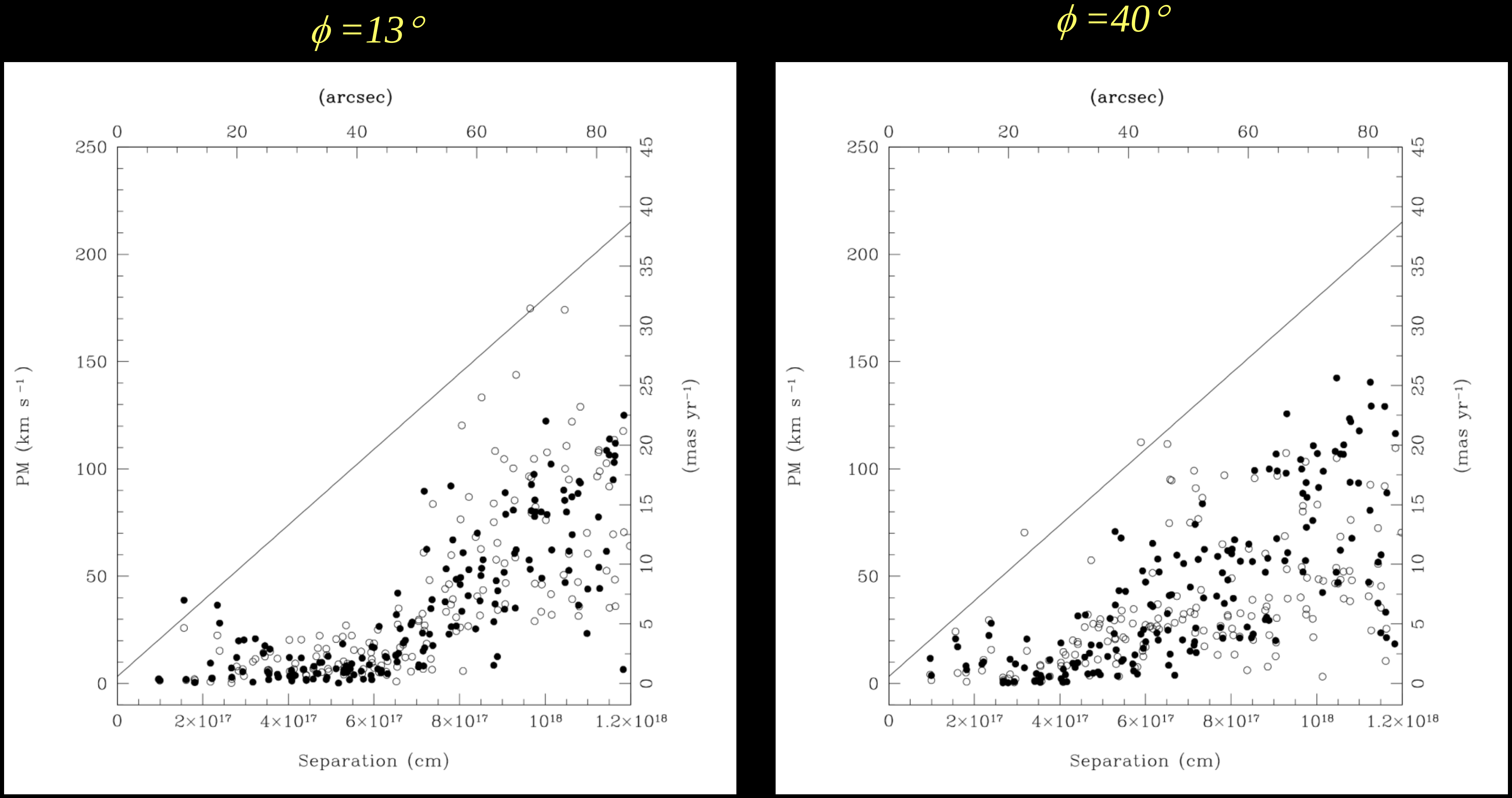
$\phi = 13°$





$\phi = 40°$

Derived PMs



PMs versus separation from the central source. Filled circles represent the PMs for z > 0 (northern lobe of the synthetic nebula) and the open circles represent the PMs for z < 0 (southern lobe of the synthetic nebula)

Summary

- We successfully reproduce the morphology and size of the nebula after an integration time of 2000 yr. The typical butterfly shape is better achieved when the angle between the main axis of the nebula and the plane of sky is higher ~40°. We note that we need to use a high density contrast $1/(1-\alpha)$ to reproduce the morphology

- We studied the proper motions (PMs) in the synthetic Hα images during a time span of 10 yr similar to the time span between the images where the observed PMs are measured. The magnitude of the PMs as well as the separation from the central star are quantitatively similar between the simulations and the observations.

- The derived PMs do not follow a Hubble-type expansion as the observations. The trend of PMs from the nebular knots behaves more similar to the observations when the inclination angle is higher.