3-D Structures of Planetary Nebulae

Palaeontology in space

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Blog and 3D Astrophysics Newsletter
3dastrophysics.wordpress.com

Outline

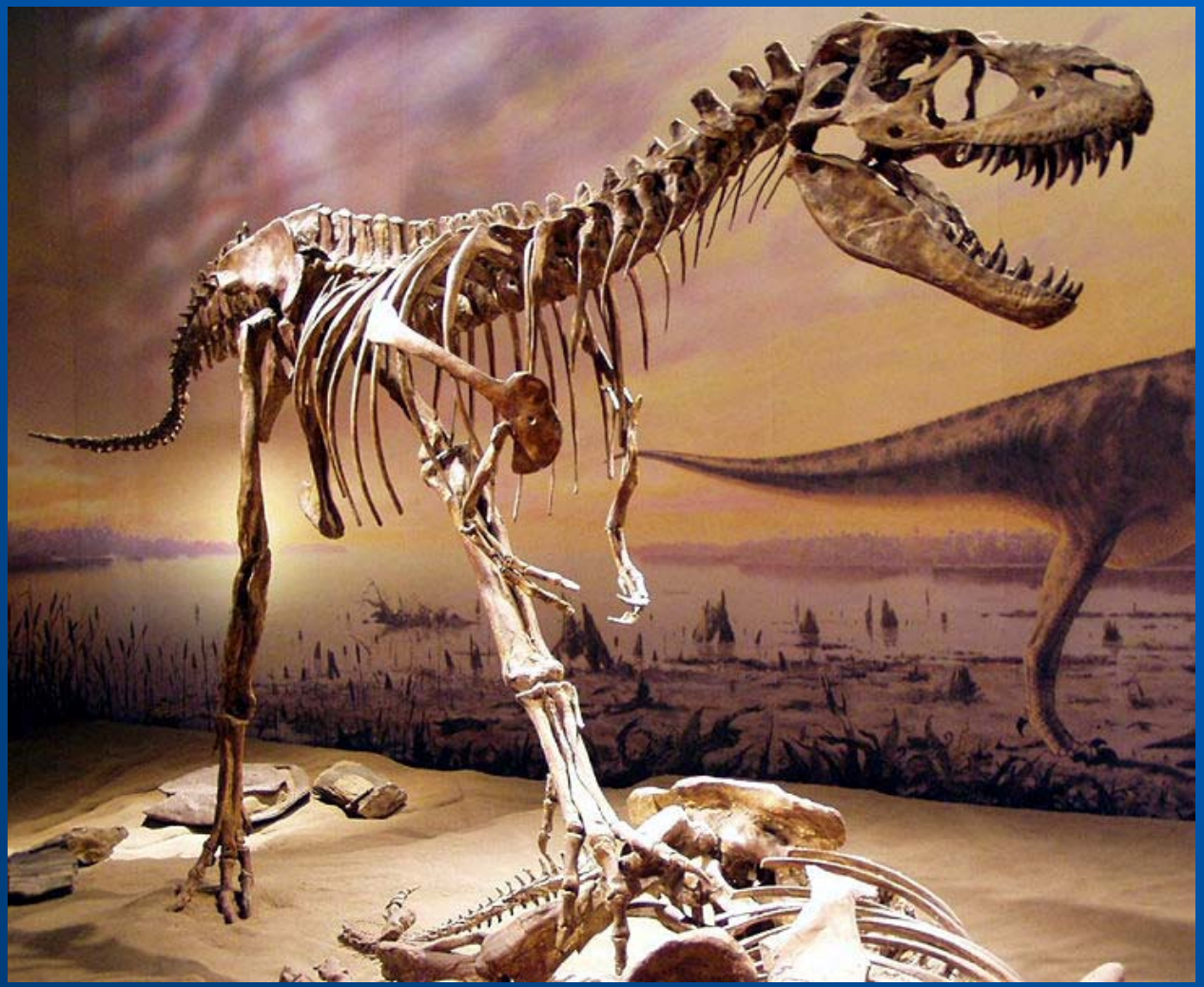
- 3-D structural research
- Methods: instrumentation and software
- Current results
- Second order accuracy: beyond homologous expansion
- Research needed to improve result reliability
- Software development needed

Palaeontology/Archaeology

Observation

Palaeontology/Archaeology

3D reconstruction



Palaeontology/Archaeology

Theory

Observation

3D Reconstruction

Theory

Key Problem in 3D Astronomy:
Ambiguities

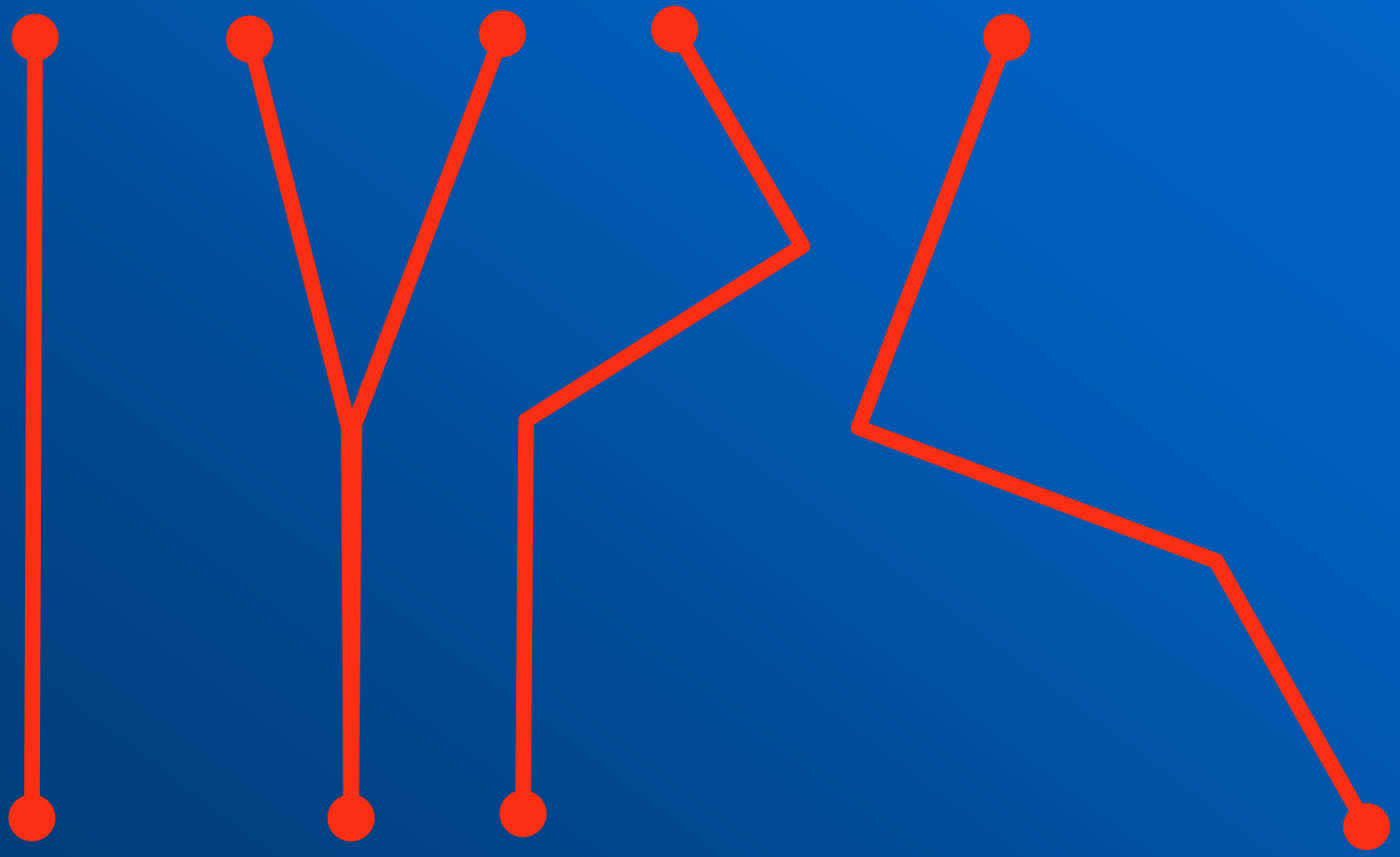
Projection effects on structure and multi-polarity

What´s this?

Key Problem in 3D Astronomy:
Ambiguities

Projection effects on structure and multi-polarity

How to distinguish?



Software: ARTIST/LIME

Adaptive Radiative Transfer Innovations for *Submillimeter Telescopes*

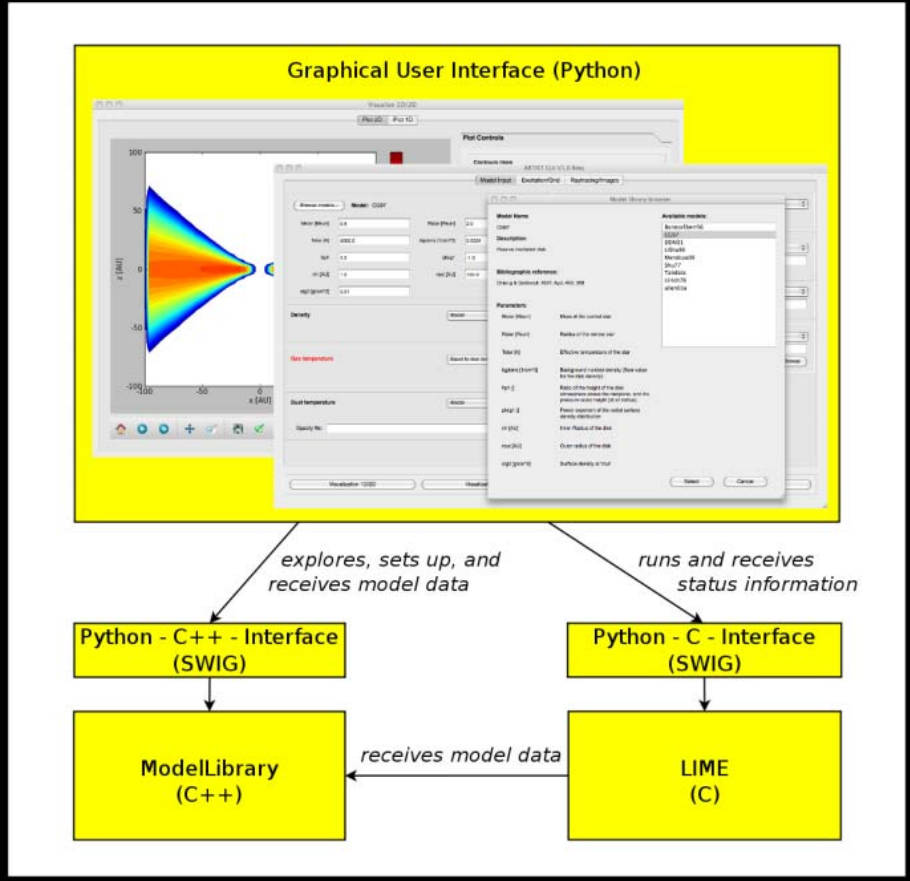
Components: Graphical User Interface

ARTIST's **GUI** allows users to select and set up physical models from the ModelLibrary and to run LIME for the selected model.

Import of physical quantities from RATRAN, RADMC, and RADMC-3D files is possible.

1D/2D visual inspection of models is supported; 3D visualization requires freely available external software (Paraview).

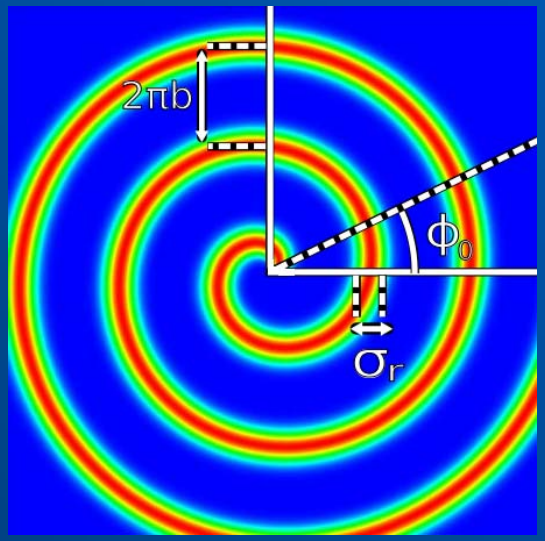
Resulting images and datacubes can be visualized.



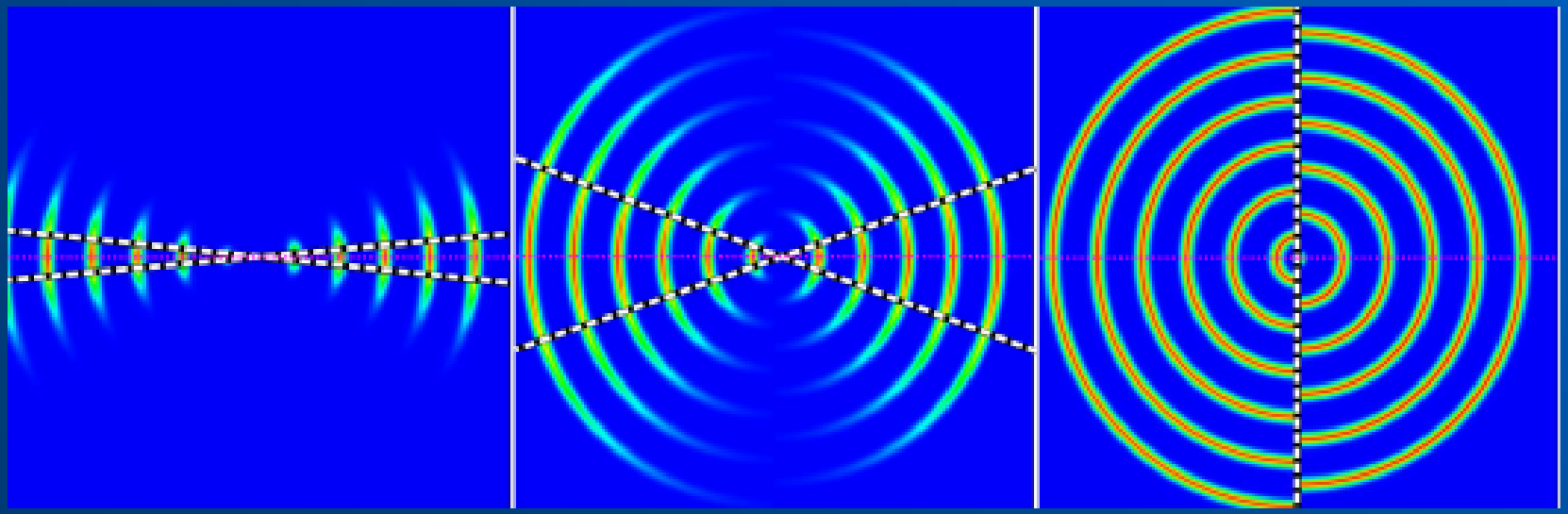
Jes Jørgensen, Frank Bertoldi, Christian Brinch, Pau Frau, Josep Miquel Girart, Michiel Hogerheijde, Attila Juhasz, Rolf Kuiper, Marco Padovani, Reinhold Schaaf, Wouter Vlemmings

Software: ARTIST/LIME

Adaptive Radiative Transfer Innovations for *Submillimeter Telescopes*

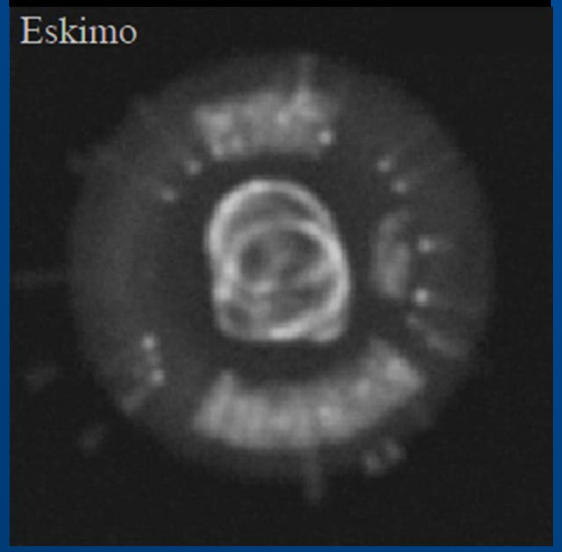


Homan et al., 2015



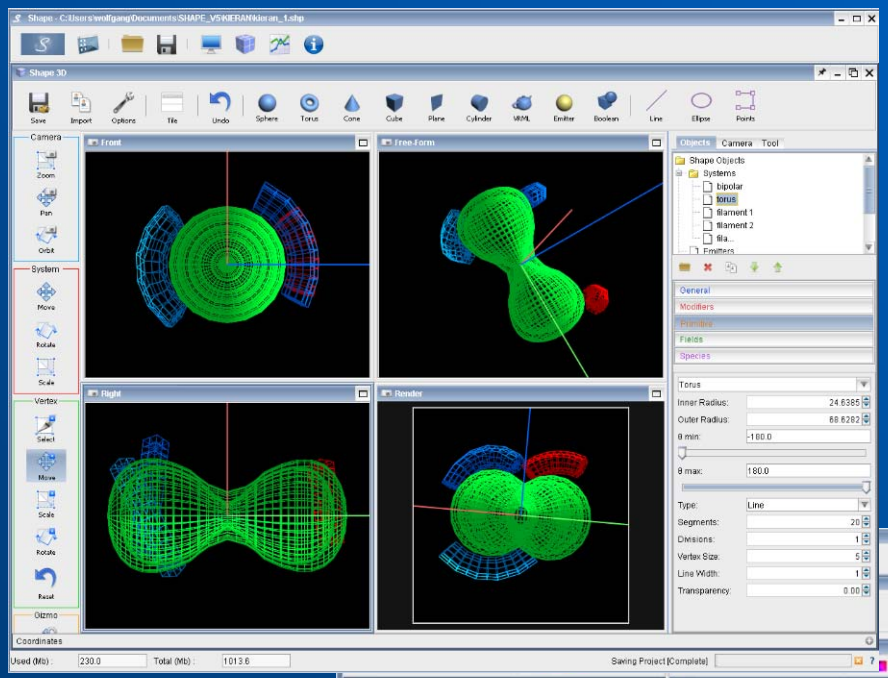
Software: ARTIST/LIME

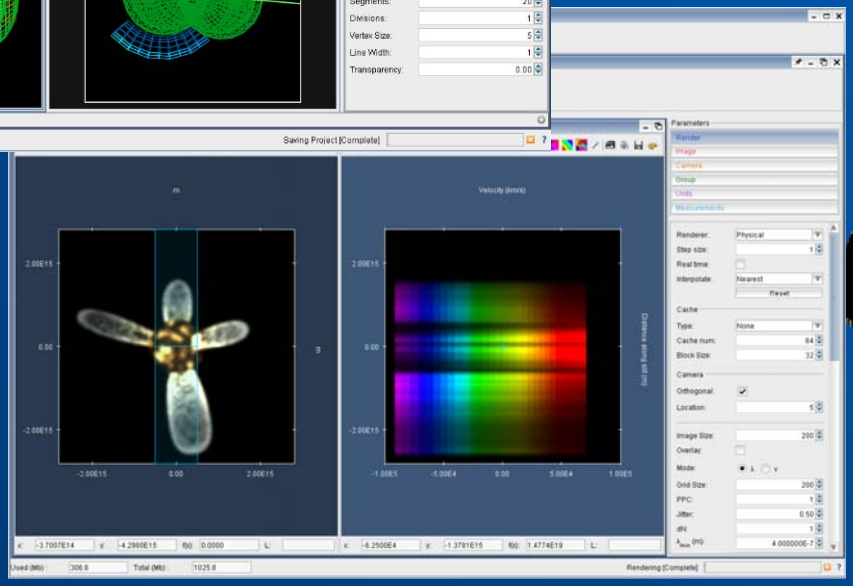
Adaptive Radiative Transfer Innovations for *Submillimeter Telescopes*



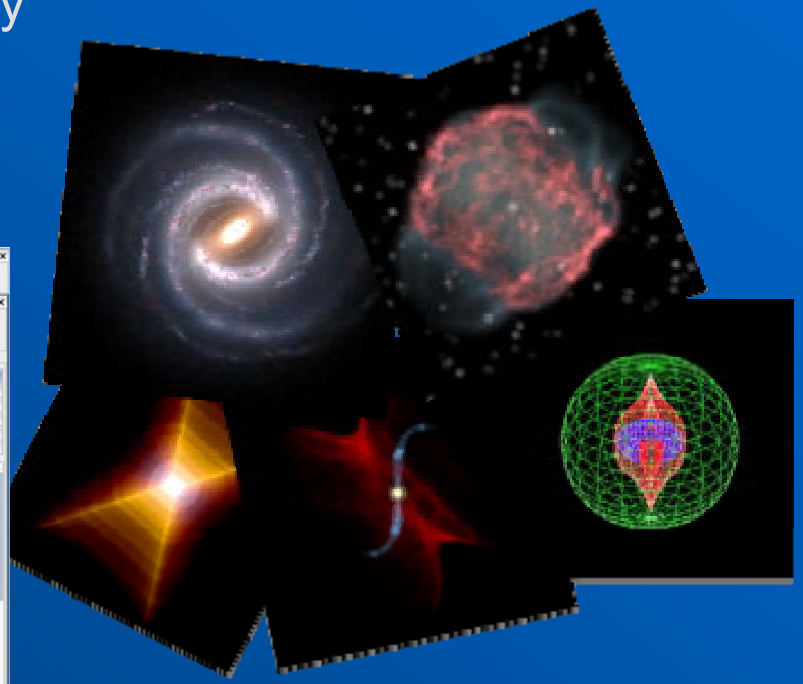

```
void
temperature(double x, double y, double z, double *temperature){
 int i,k,x0;
 double r;
 double temp[2][10] = {
 {2.0e13, 5.0e13, 8.0e13, 1.1e14, 1.4e14, 1.7e14, 2.0e14, 2.3e14, 2.6e14, 2.9e14},
 {44.777, 31.037, 25.718, 22.642, 20.560, 19.023, 17.826, 16.857, 16.050, 15.364}
 };
 r=sqrt(x*x+y*y+z*z);
if(r > temp[0][0] && r<temp[0][9]){
 for(i=0;i<9;i++){
 if(r>temp[0][i] && r<temp[0][i+1]) x0=i;
 }
 }
 if(r<temp[0][0]) temperature[0]=temp[1][0];
 else if (r>temp[0][9]) temperature[0]=temp[1][9];
else temperature[0]=temp[1][x0]+(r-temp[0][x0])*(temp[1][x0+1]-temp[1][x0])/(temp[0]
 [x0+1]-temp[0][x0]);
}
void
abundance(double x, double y, double z, double *abundance){
 abundance[0] = 1.e-9;
}
void
doppler(double x, double y, double z, double *doppler){
 *doppler = 200.;
}
void
velocity(double x, double y, double z, double *vel){
 double R, phi,r,theta;
 R=sqrt(x*x+y*y+z*z);
 theta=atan2(sqrt(x*x+y*y),z);
 phi=atan2(y,x);
 r=-sqrt(2*6.67e-11*1.989e30/R);
 vel[0]=r*sin(theta)*cos(phi);
 vel[1]=r*sin(theta)*sin(phi);
 vel[2]=r*cos(theta);
```

Software: *Shape*



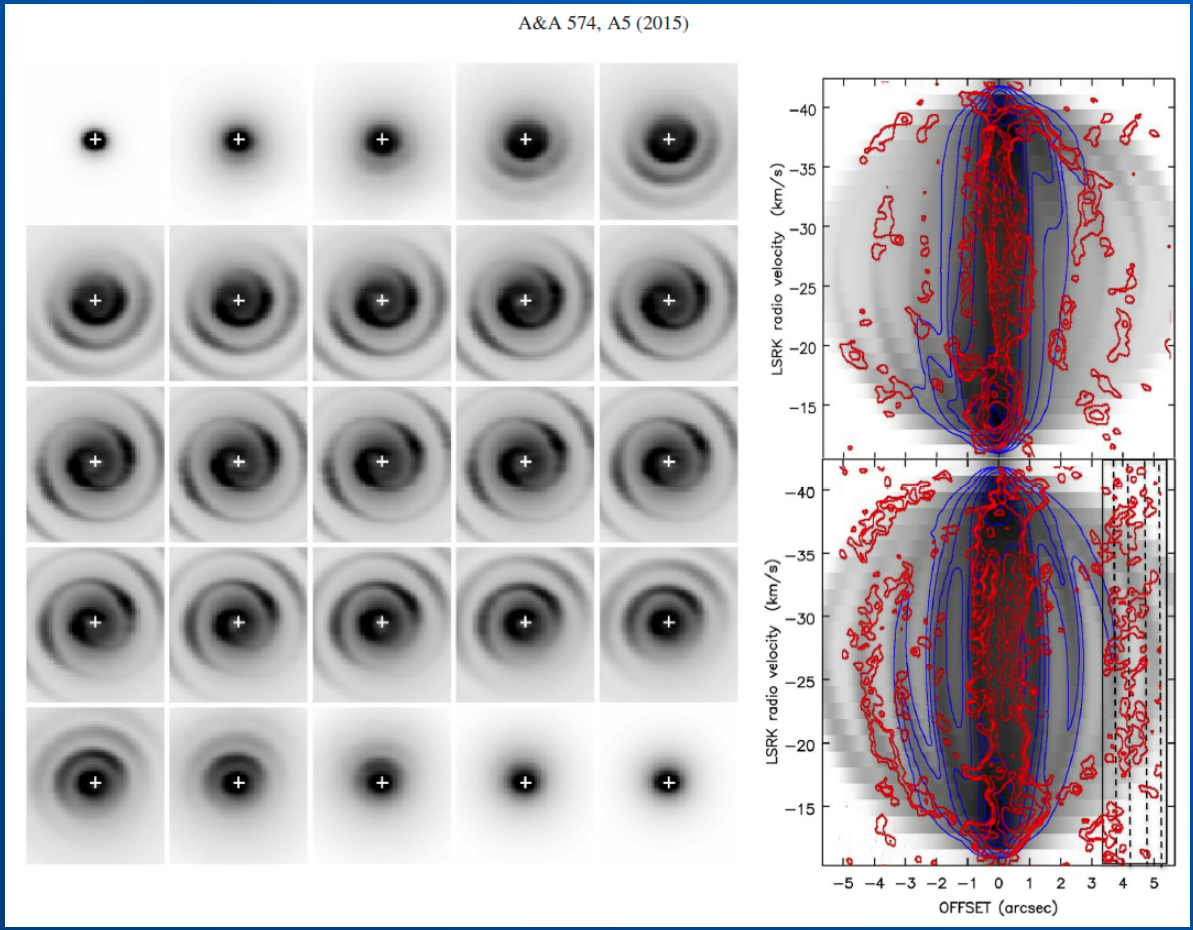


Shape:
Interactive
Virtual
Astrophysical
Laboratory



Steffen, Koning, et al., 2011

Instrumentation and data types: ALMA



Reconstructed channel maps

P-V diagrams

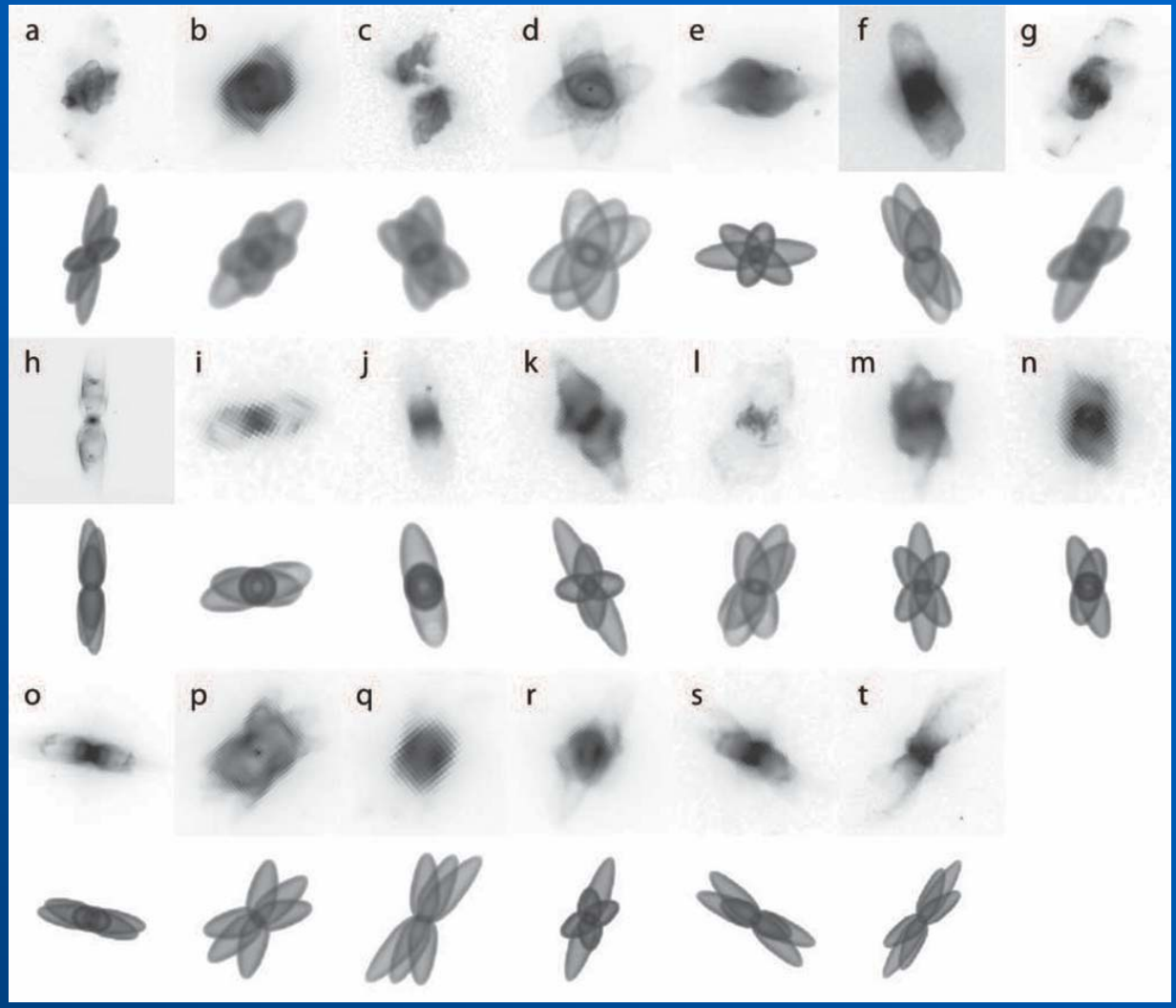
CW Leonis
CO observations

reconstructed as
3D spiral
with
Shape-Mol

Decin et al., 2015

Recent results: some Unification

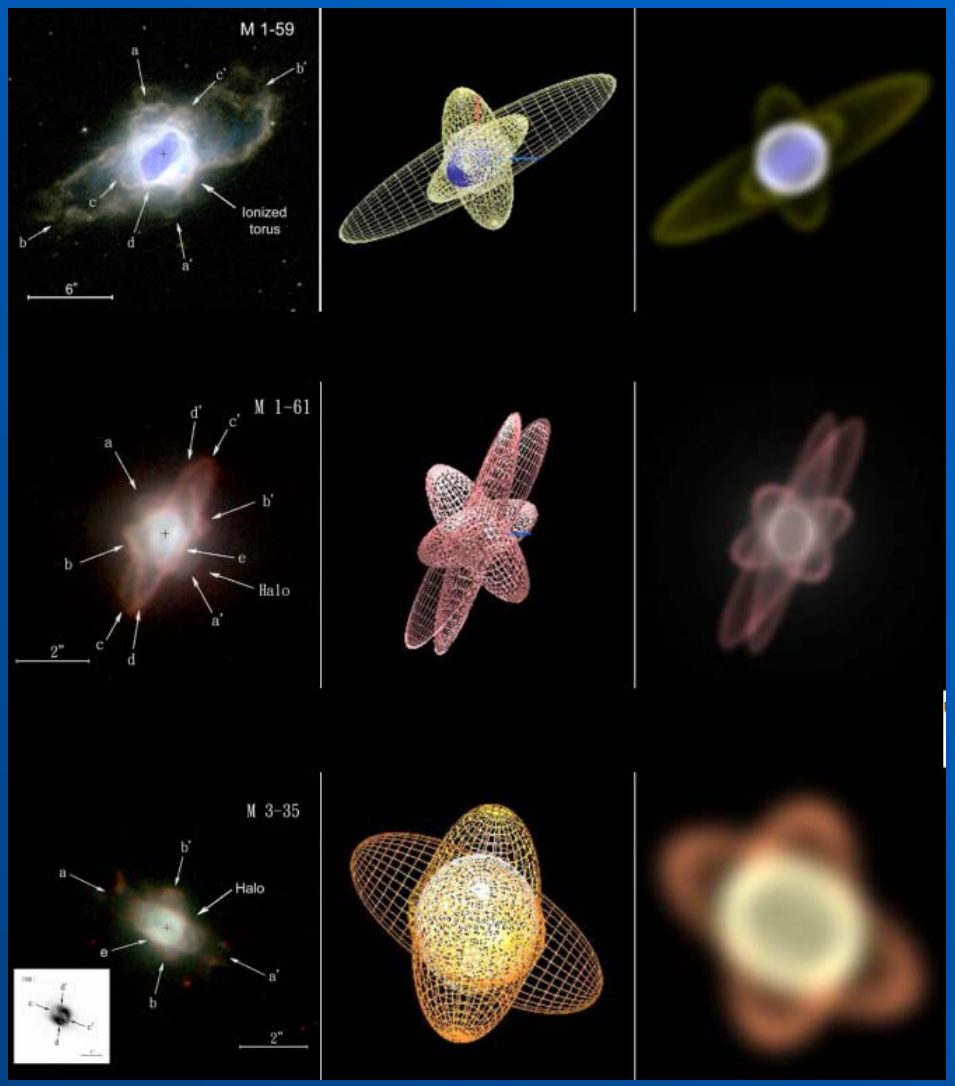
Projection effects on structure and multi-polarity



Hsia et al. (2014): Hubble Space Telescope observations and geometric models of compact multipolar planetary nebulae

Image based reconstructions

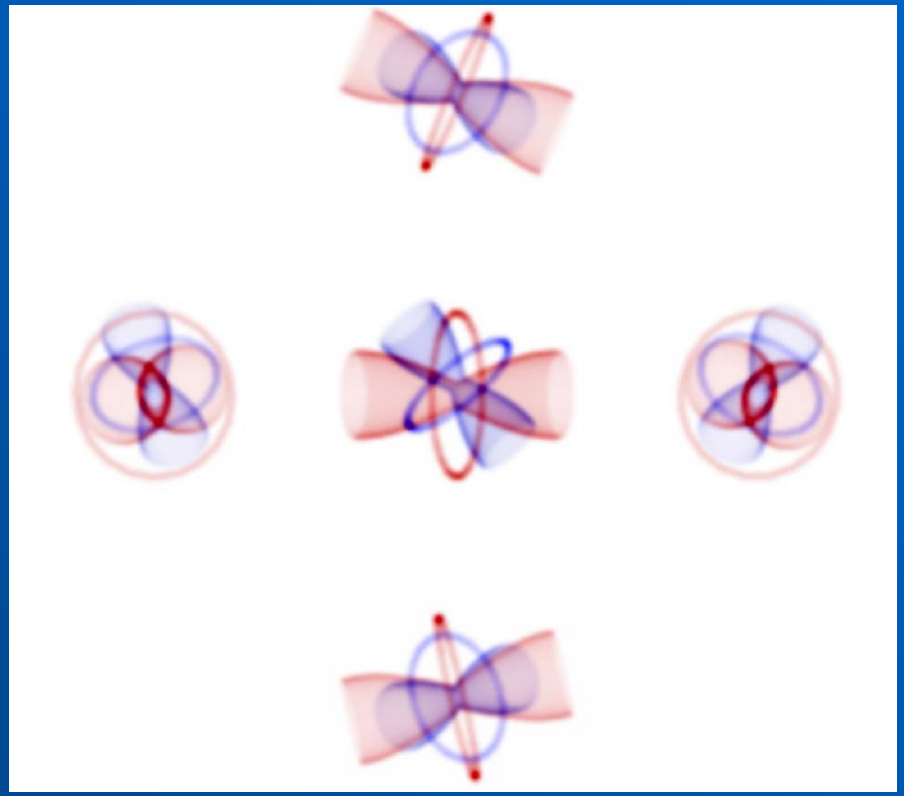
Projection effects on structure and multi-polarity



Hsia et al. (2014)

Image based reconstructions

Reveal multipolarity



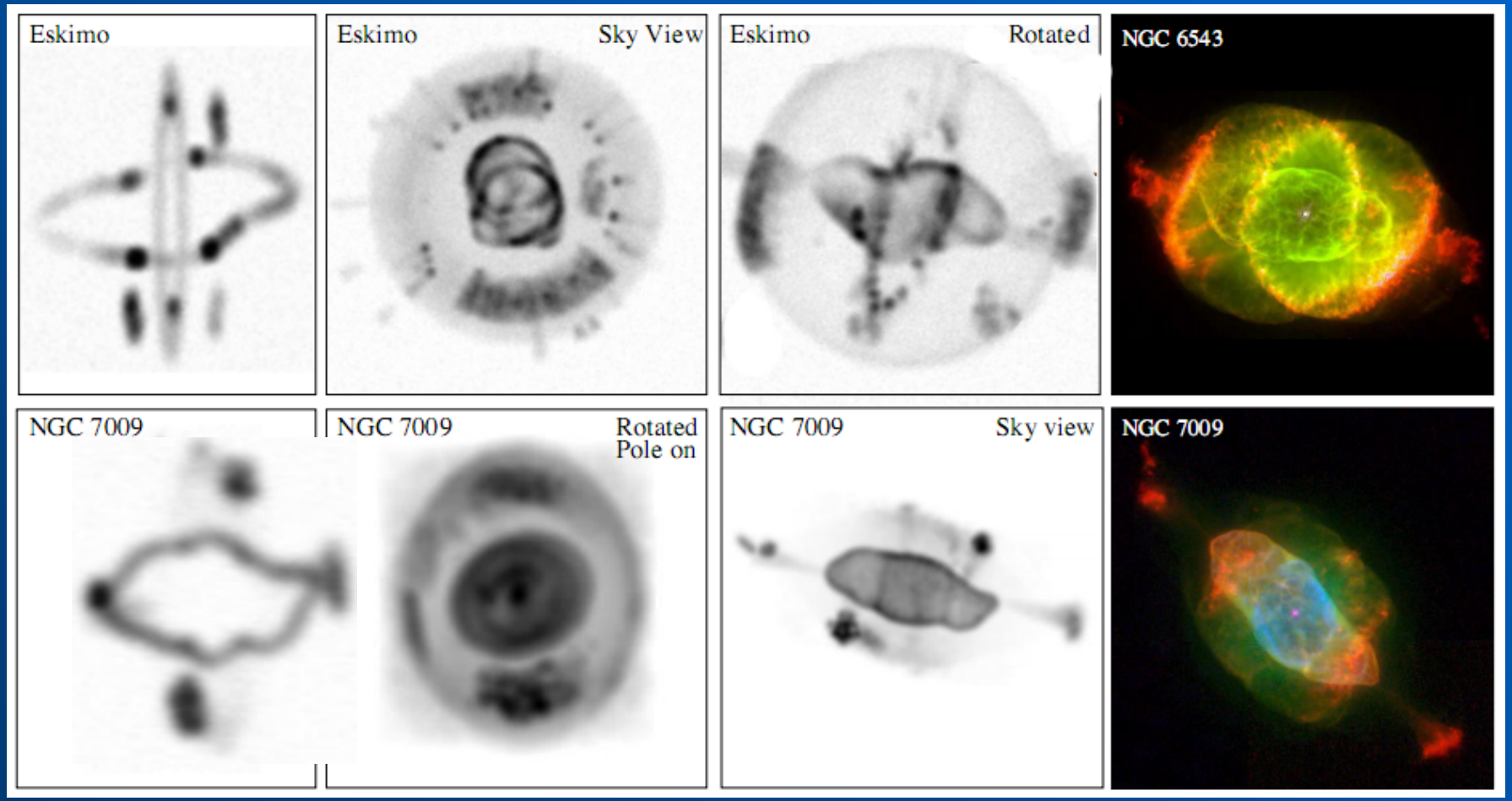
NGC 6072, Spitzer IRAC, Kwok et al. (2010)

Instrumentation and data types

Manchester Echelle Spectrograph (MES)
at the San Pedro Mártir Observatory, México

Results: Unify$_{\text{Some}}$

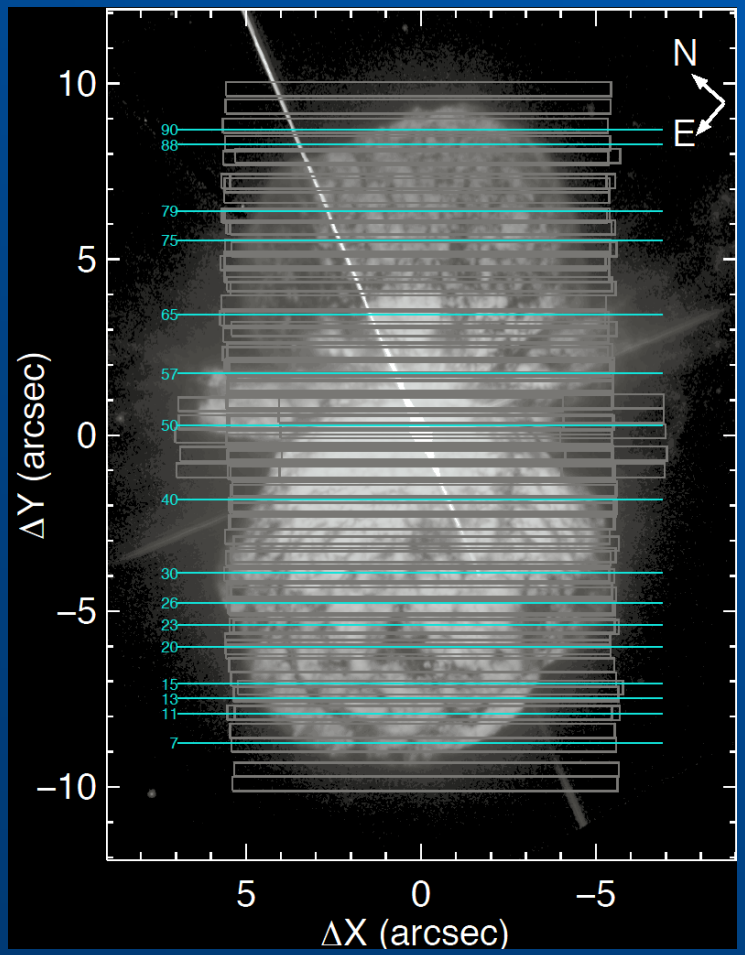
Projection effects and "unification" of some PNe

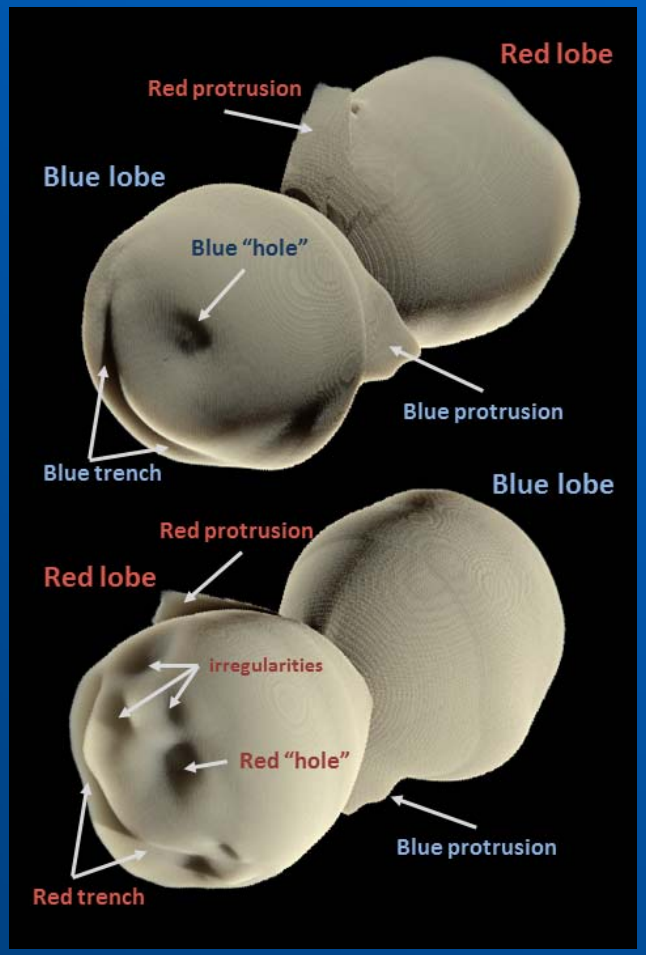


García-Díaz et al. (2012)

Results: Connect core and nebula

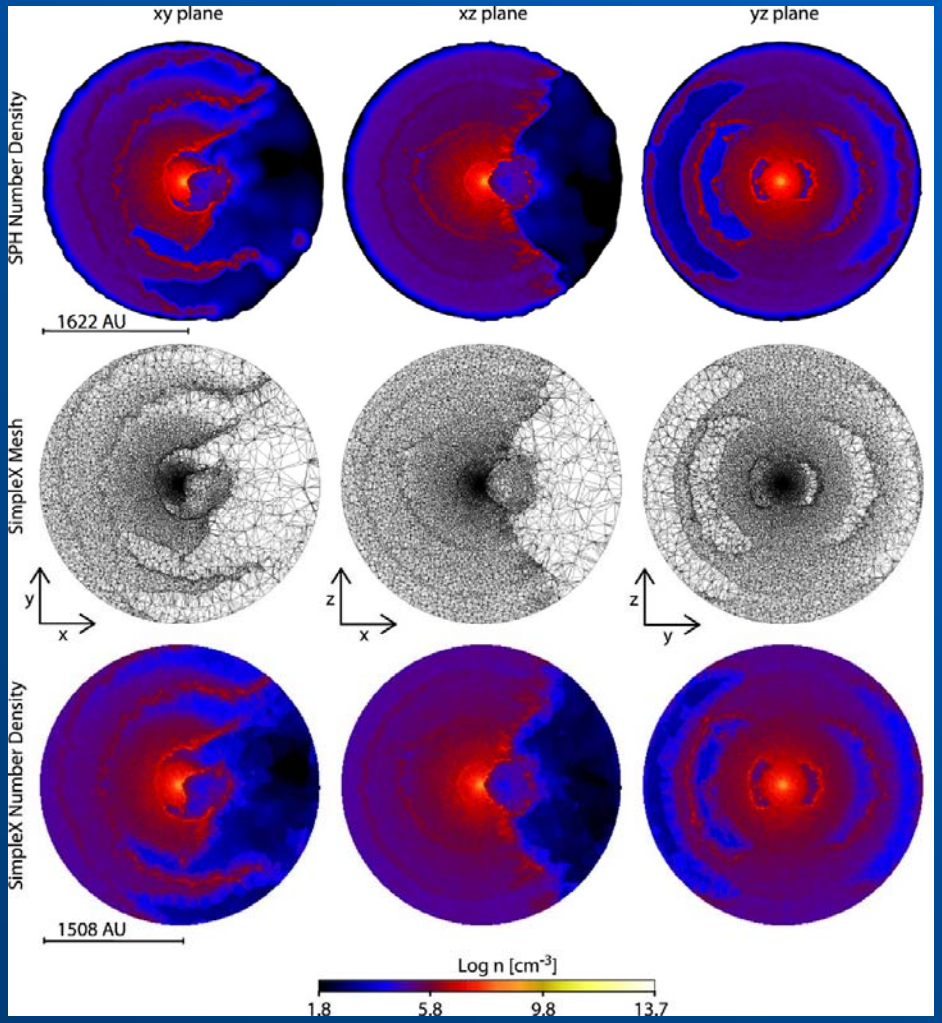
Eta Carinae: Connection Central Stars and Nebula



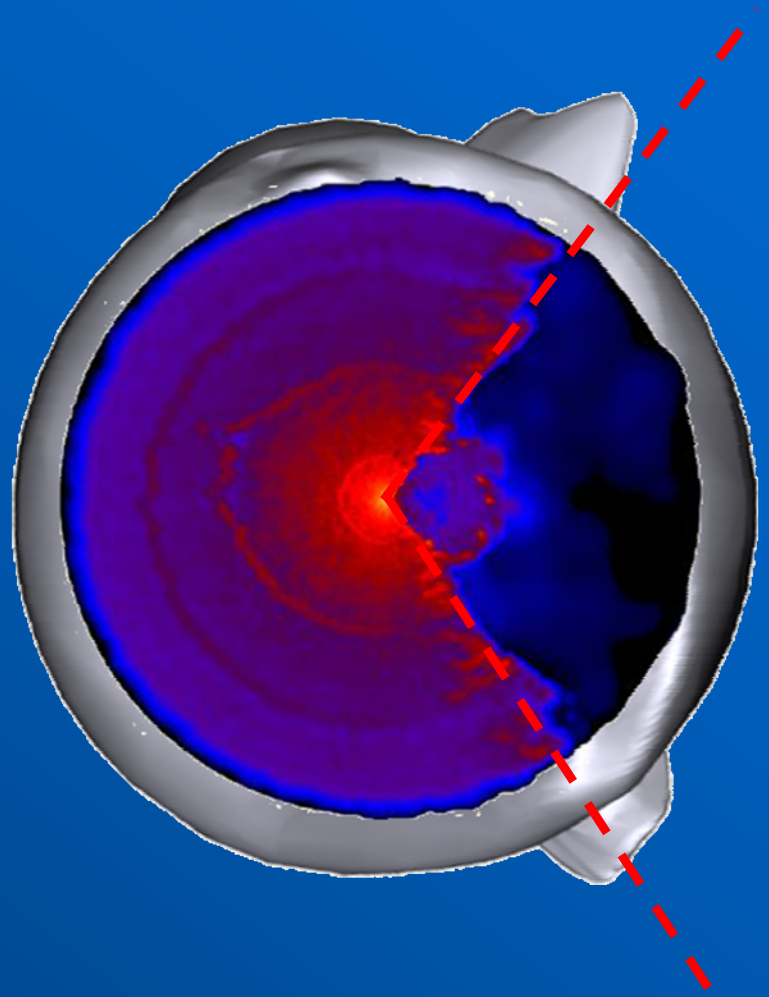


VLT XShooter H_2 molecular observations, Steffen et al. (2014)

Results: Connect core and nebula



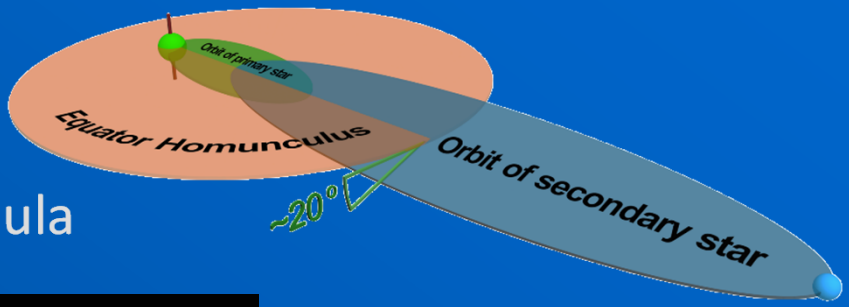
Clementel N et al., 2014

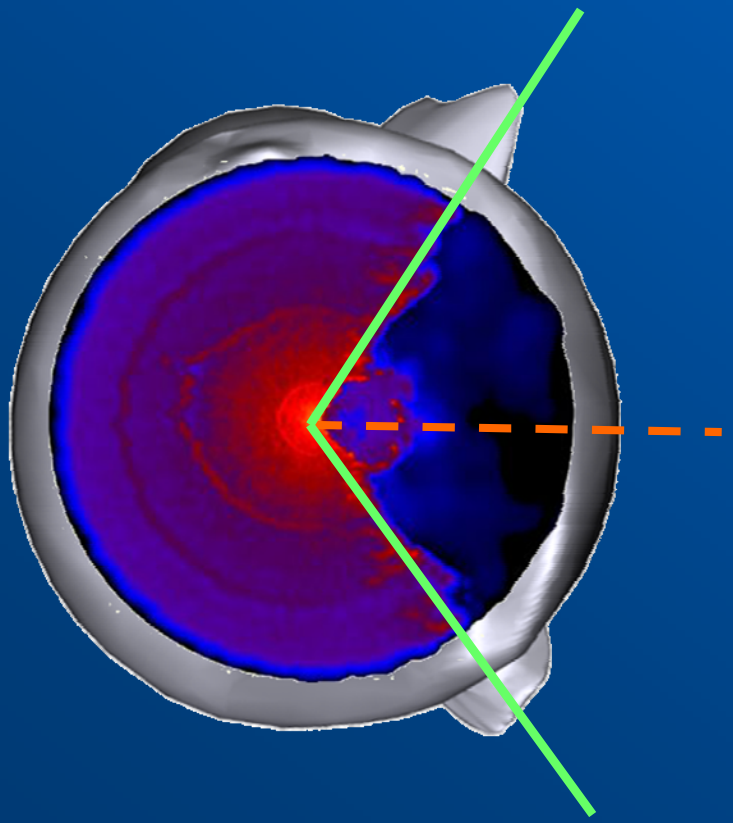


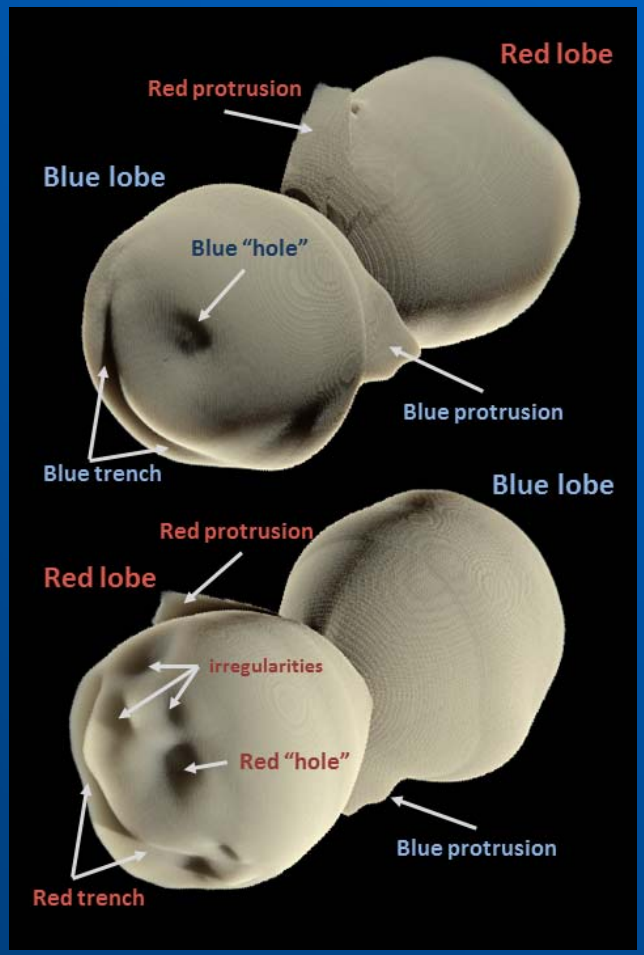
Grey: Shape 3D Model (along axis)

Results: Connect core and nebula

Eta Carinae: Connection Central Stars and Nebula

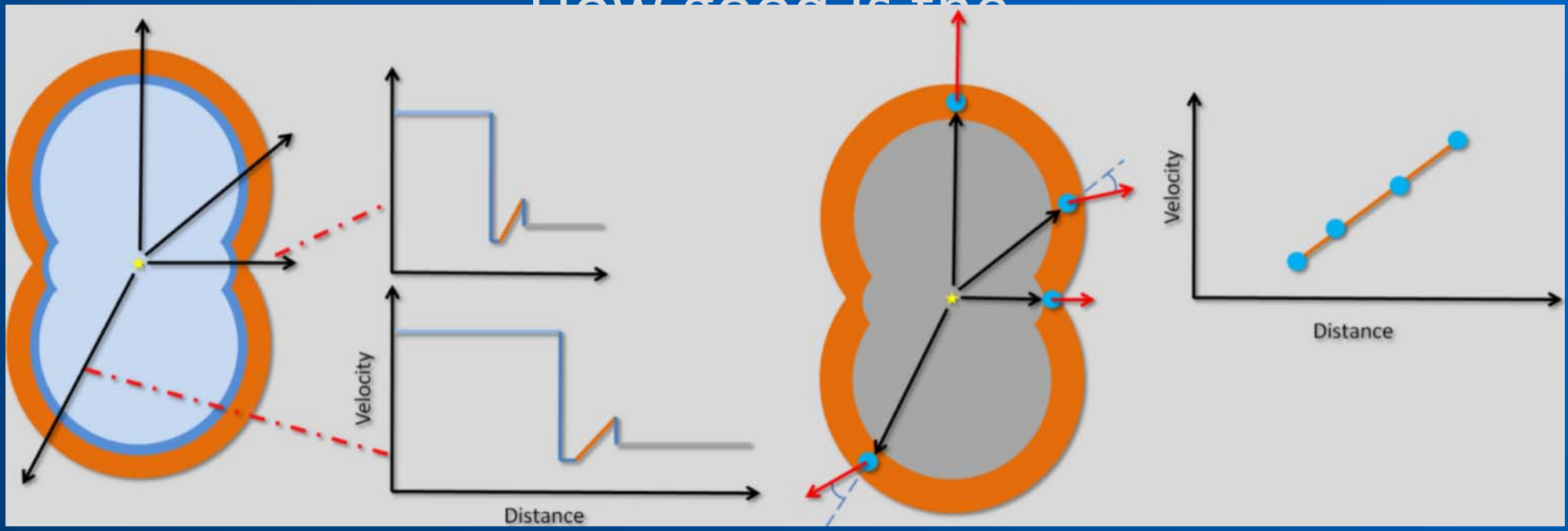




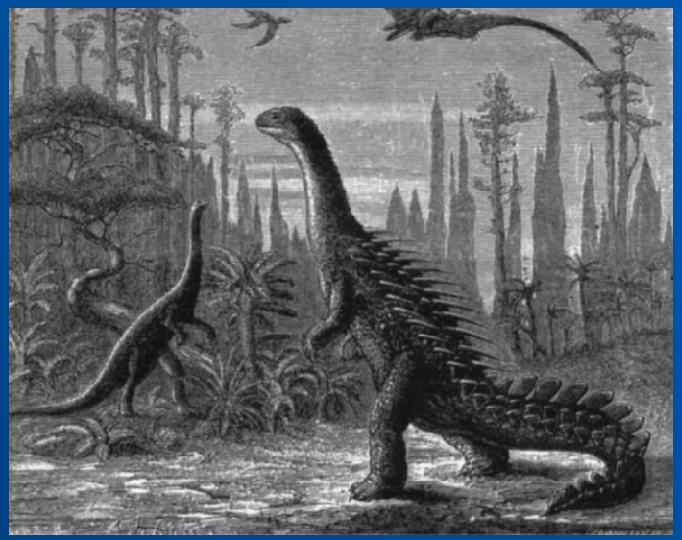


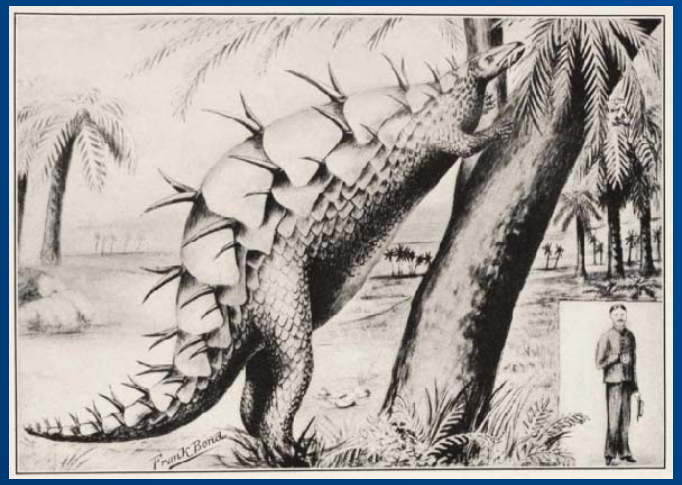
VLT H_2 molecular observations, Steffen et al. (2014)

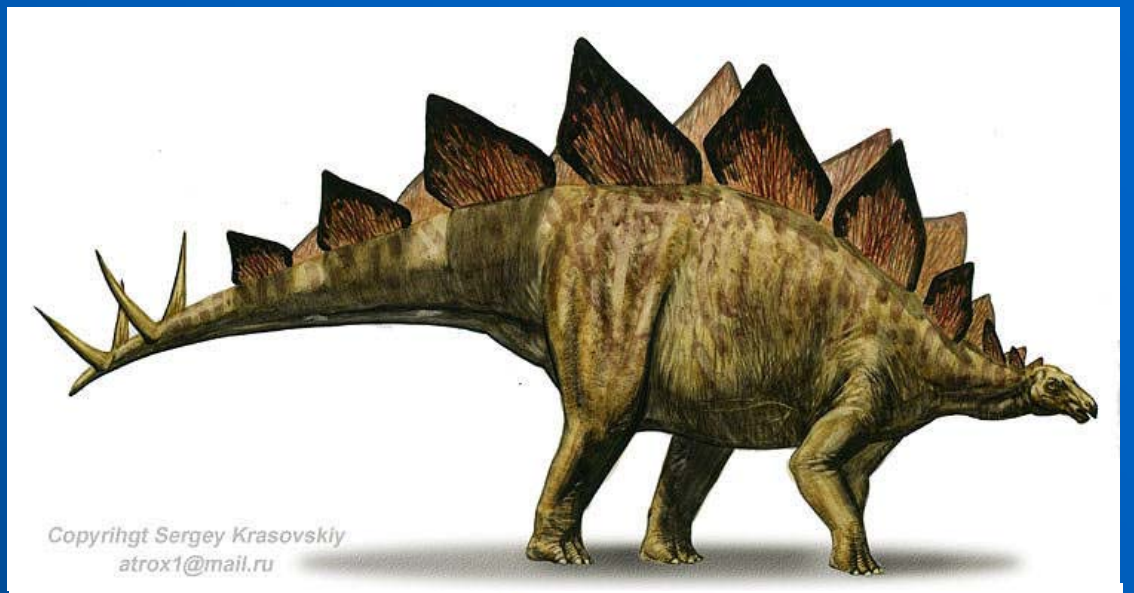
How good is the



The need for second order precision







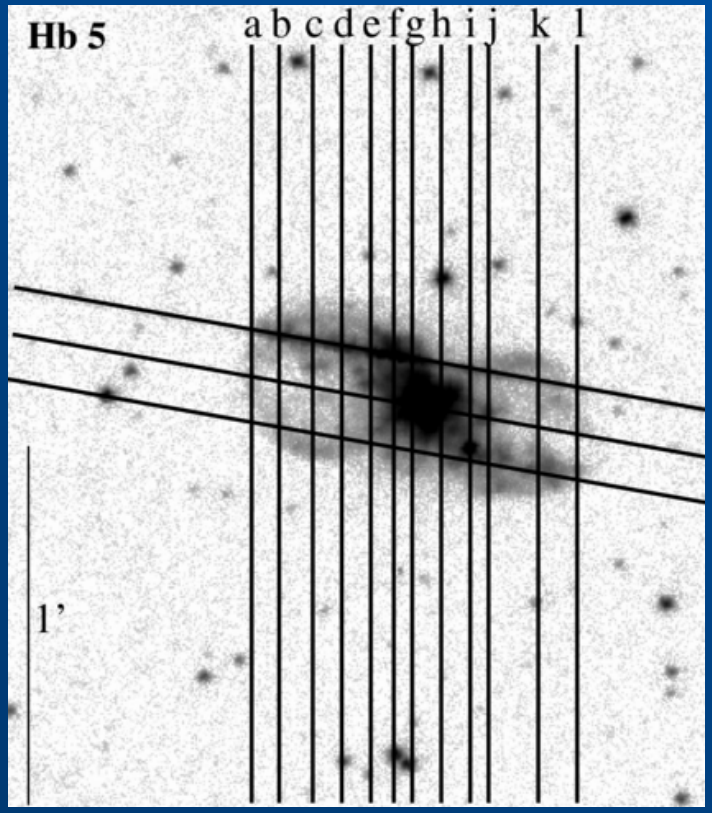
Current reconstruction and "theory" for stegosaurus

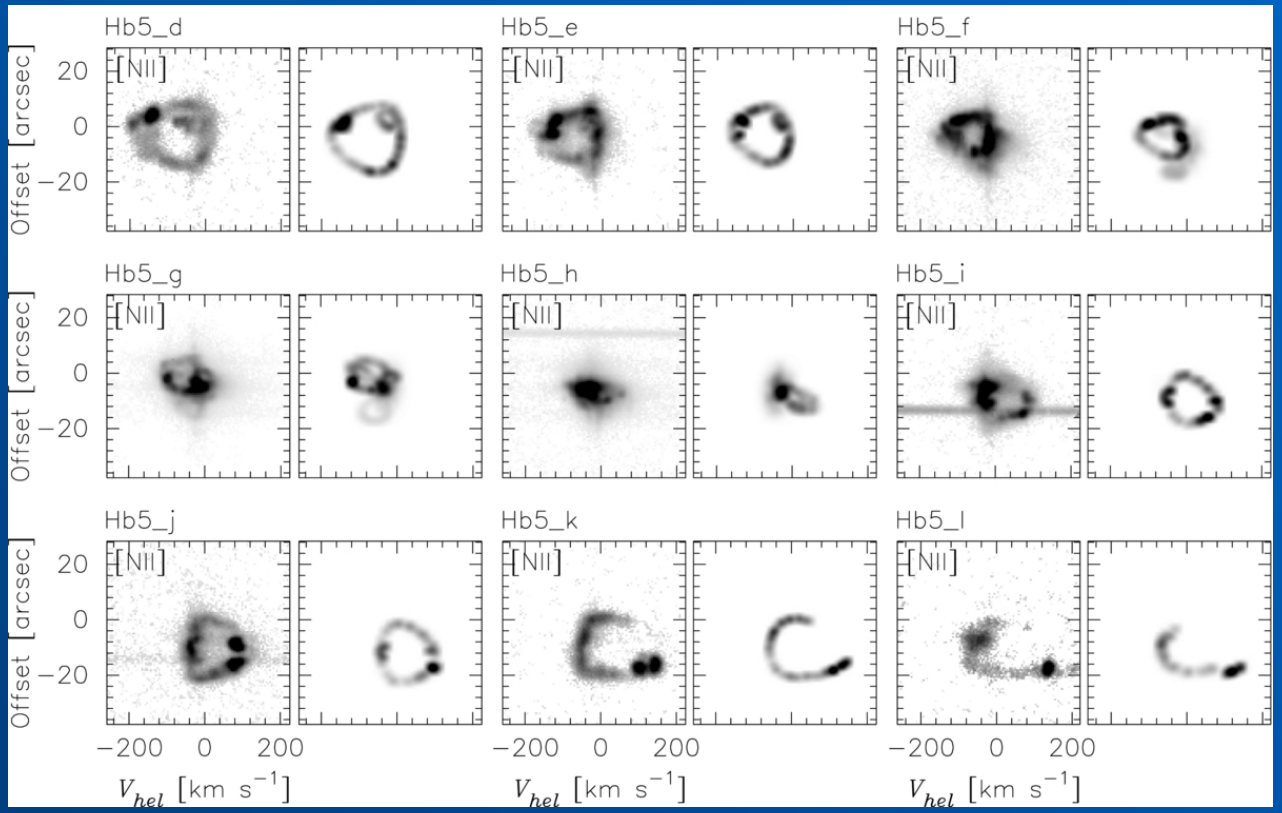
Doppler-Method
to find structure along Line of Sight

Problem to solve:
Find the distribution of emission as a function of x,y,z based on imaging and spatially resolved Doppler-velocity

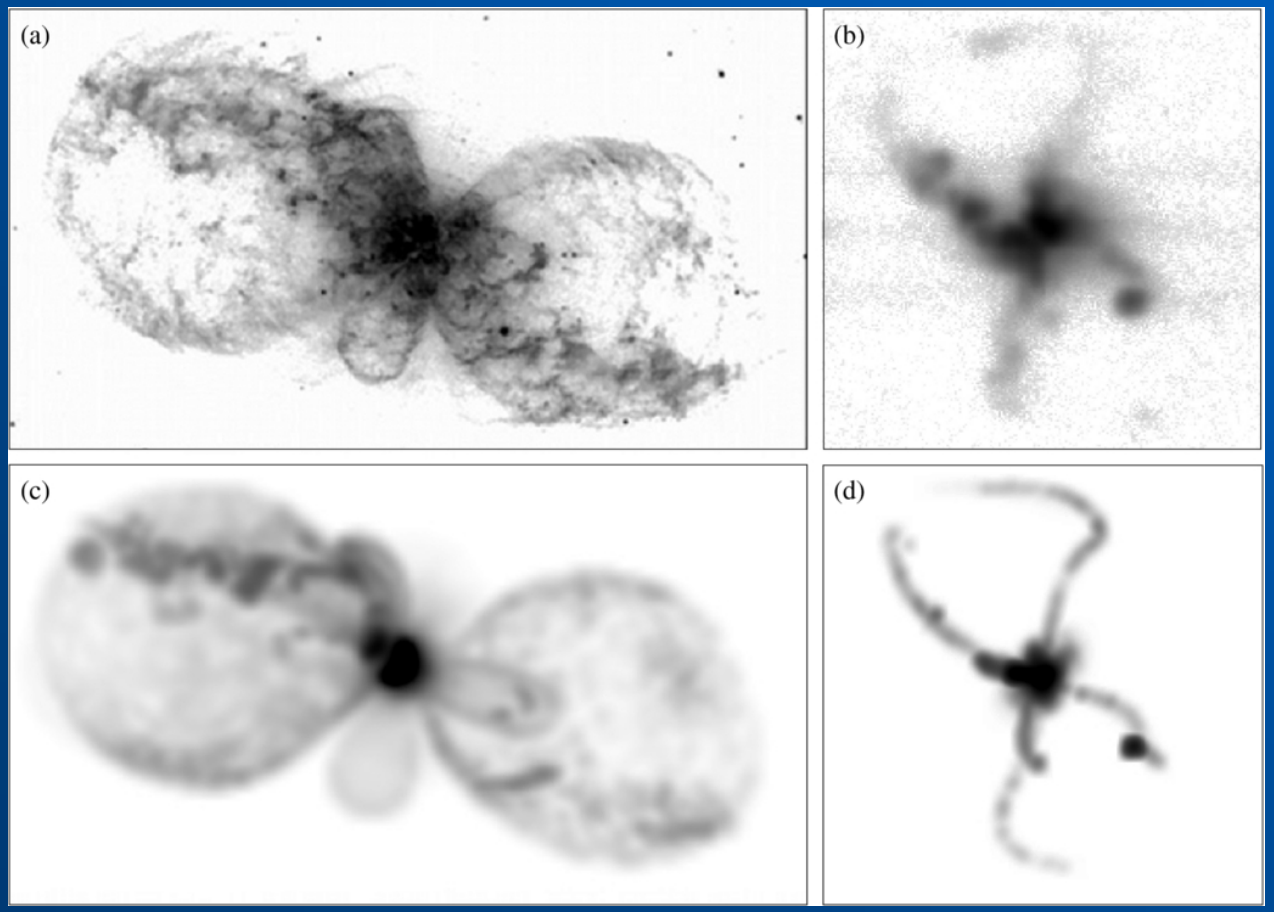
Velocity to position mapping for homologous expansion: $v_z = k\ z$

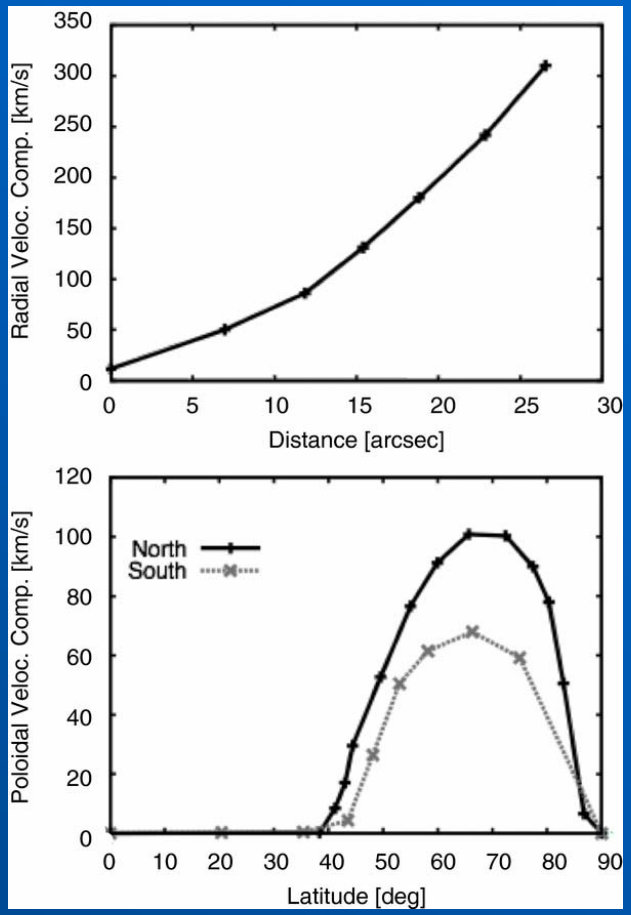
López et al., 2012





How good is the homologous expansion law?

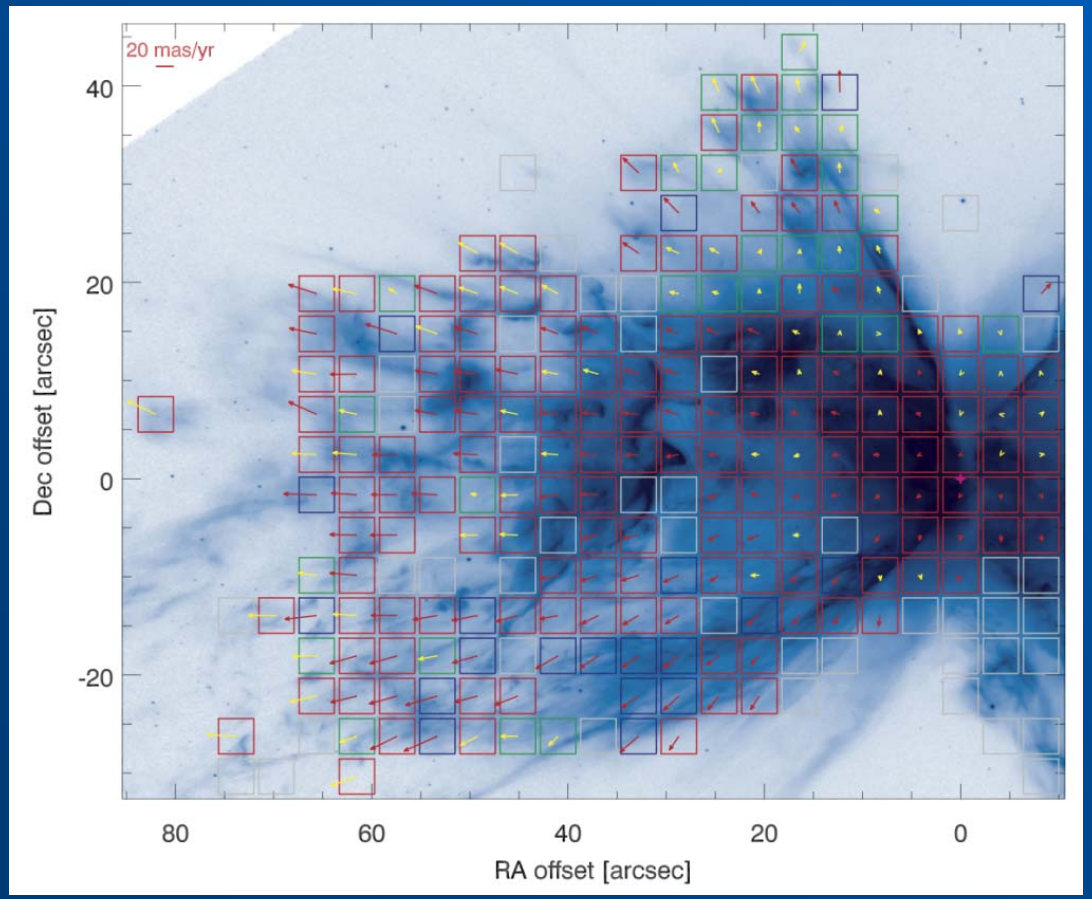


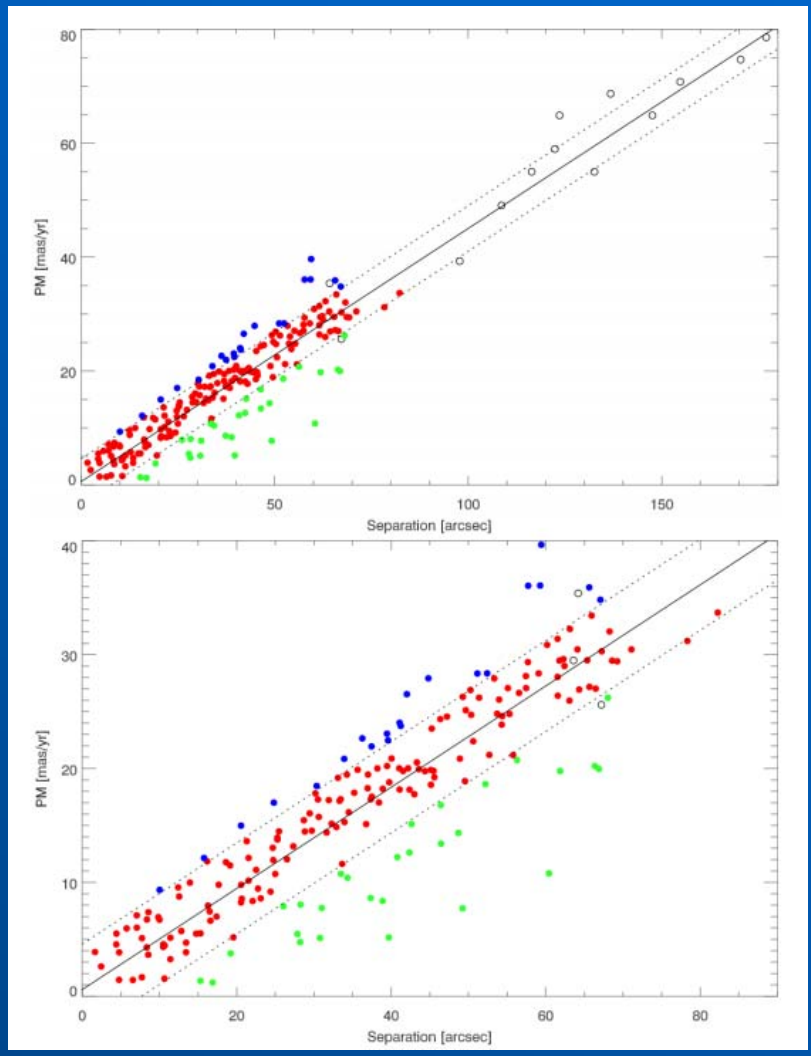


López et al. (2012)

How good is the homologous expansion law?

Observed kinematics in NGC 6302

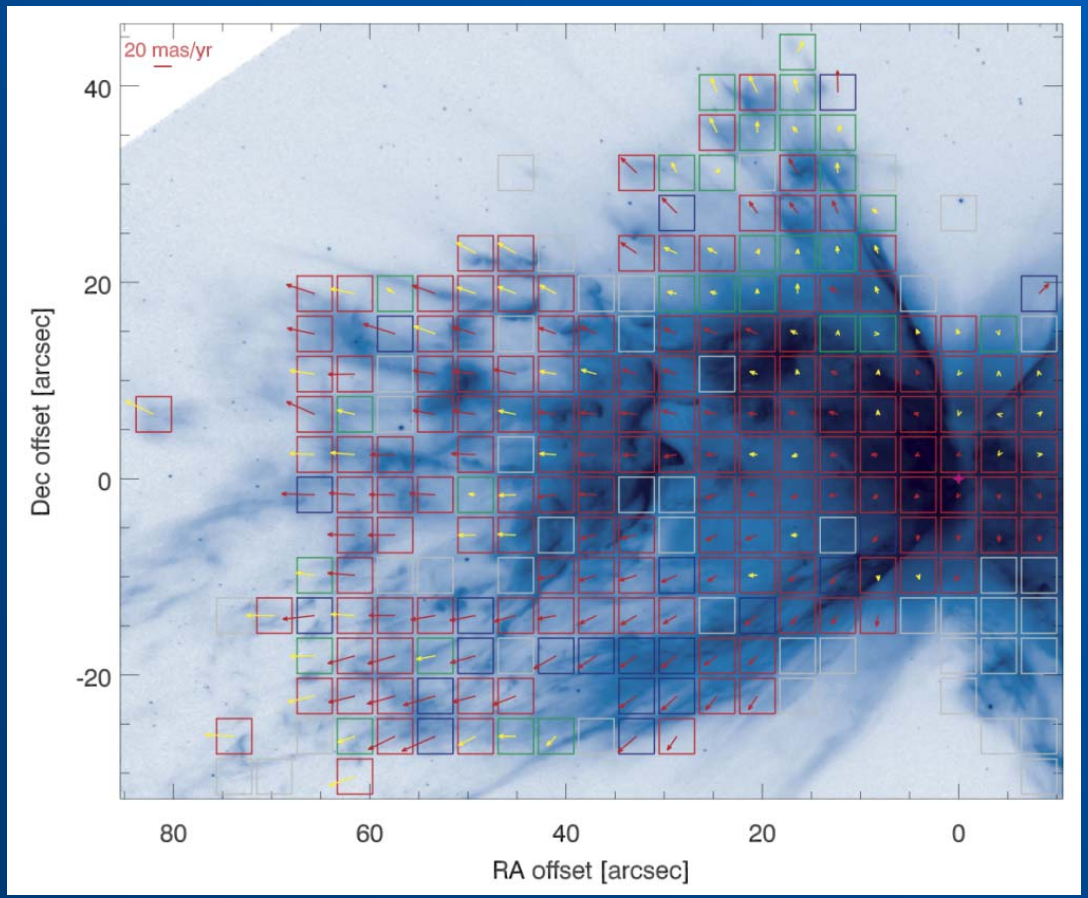


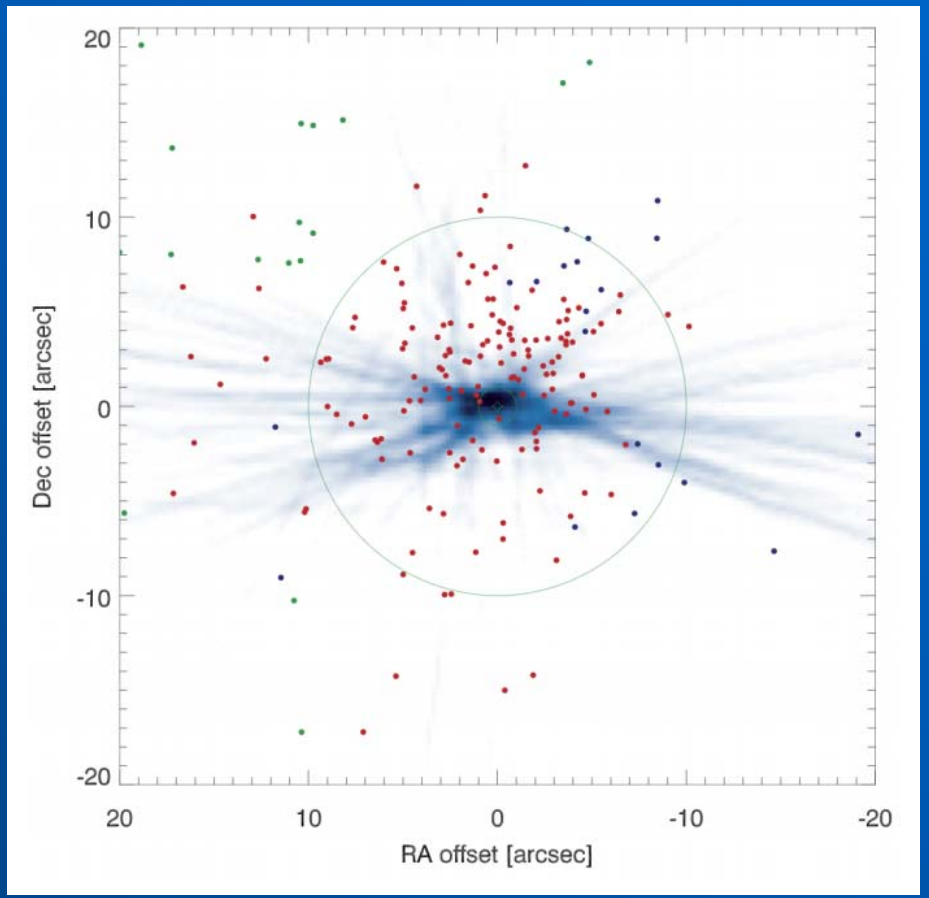


(Szyszka et al., 2011)

How good is the homologous expansion law?

Observed kinematics in NGC 6302

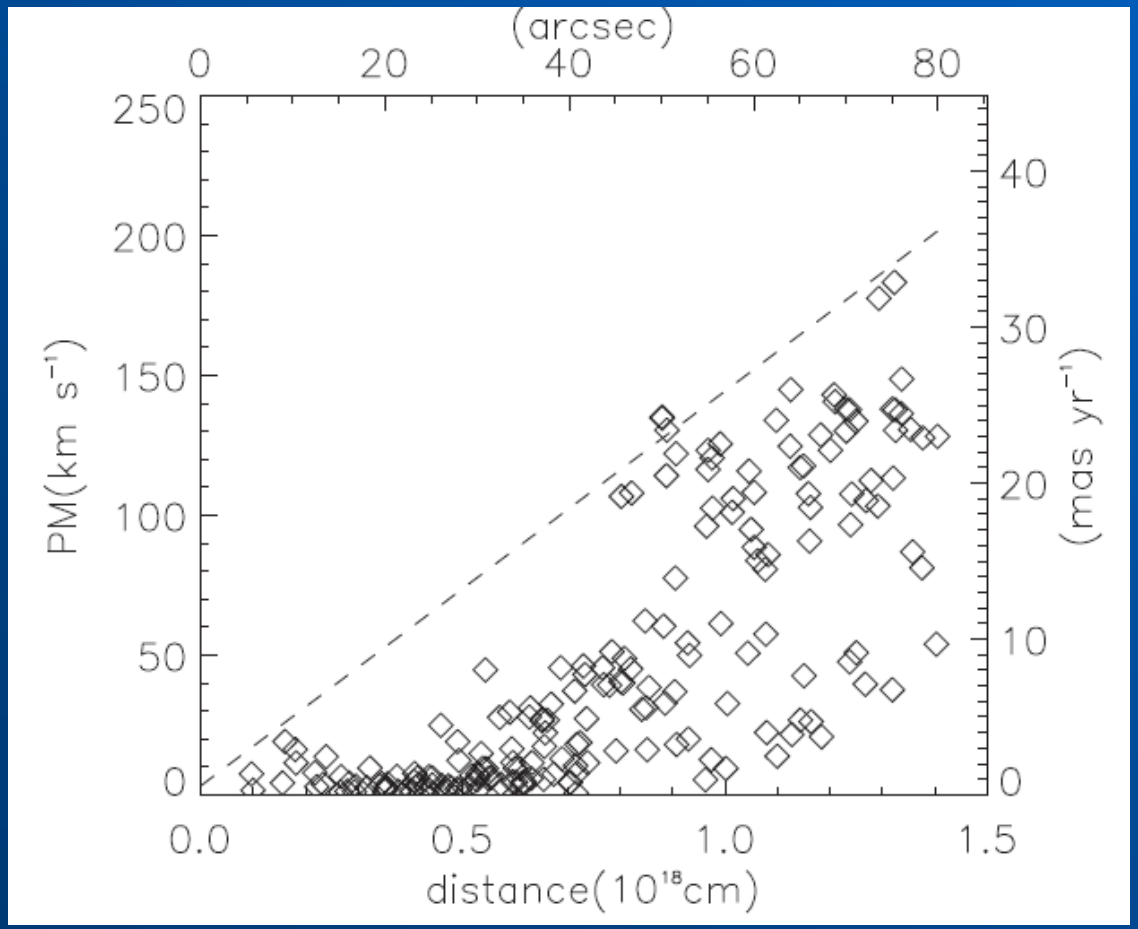


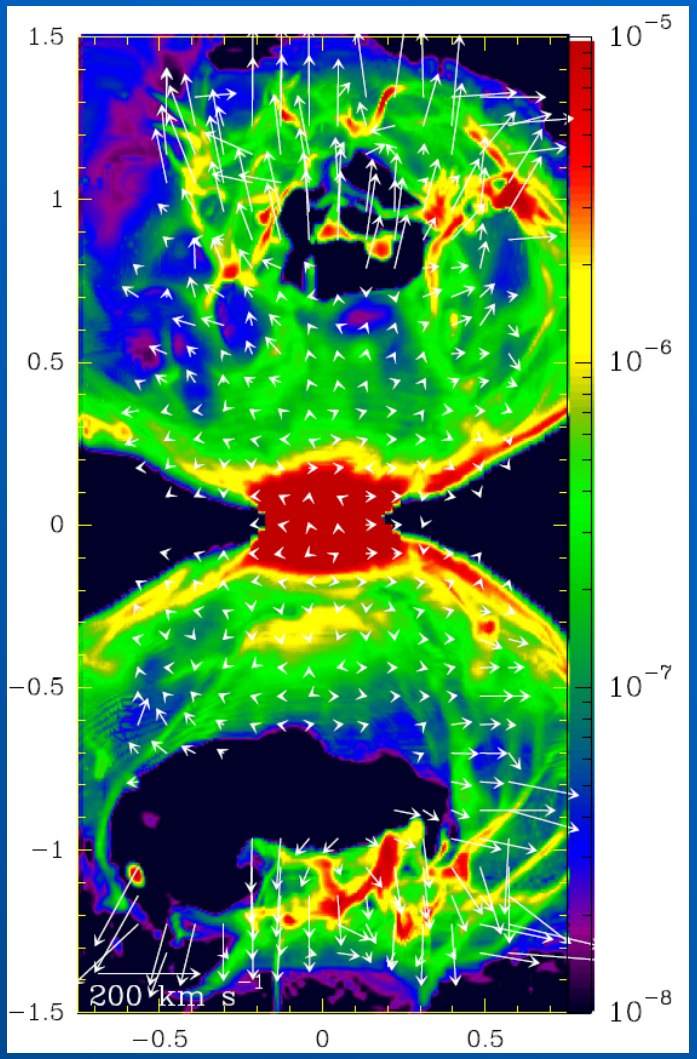


(Szyszka et al., 2011)

How good is the homologous expansion law?

Hydrodynamical simulation of NGC 6302

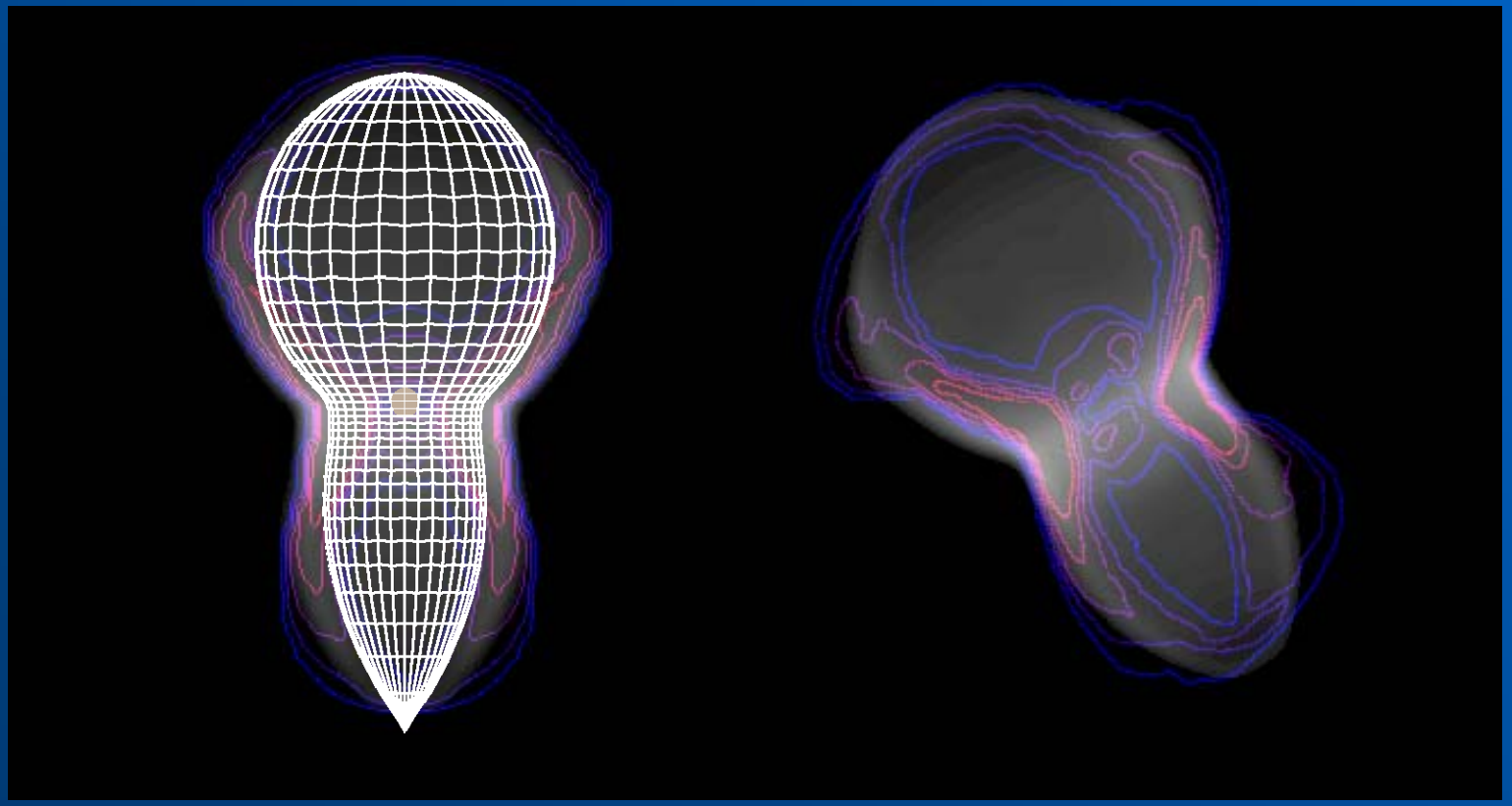




(Uscanga et al., 2014)

How good is the homologous expansion law?

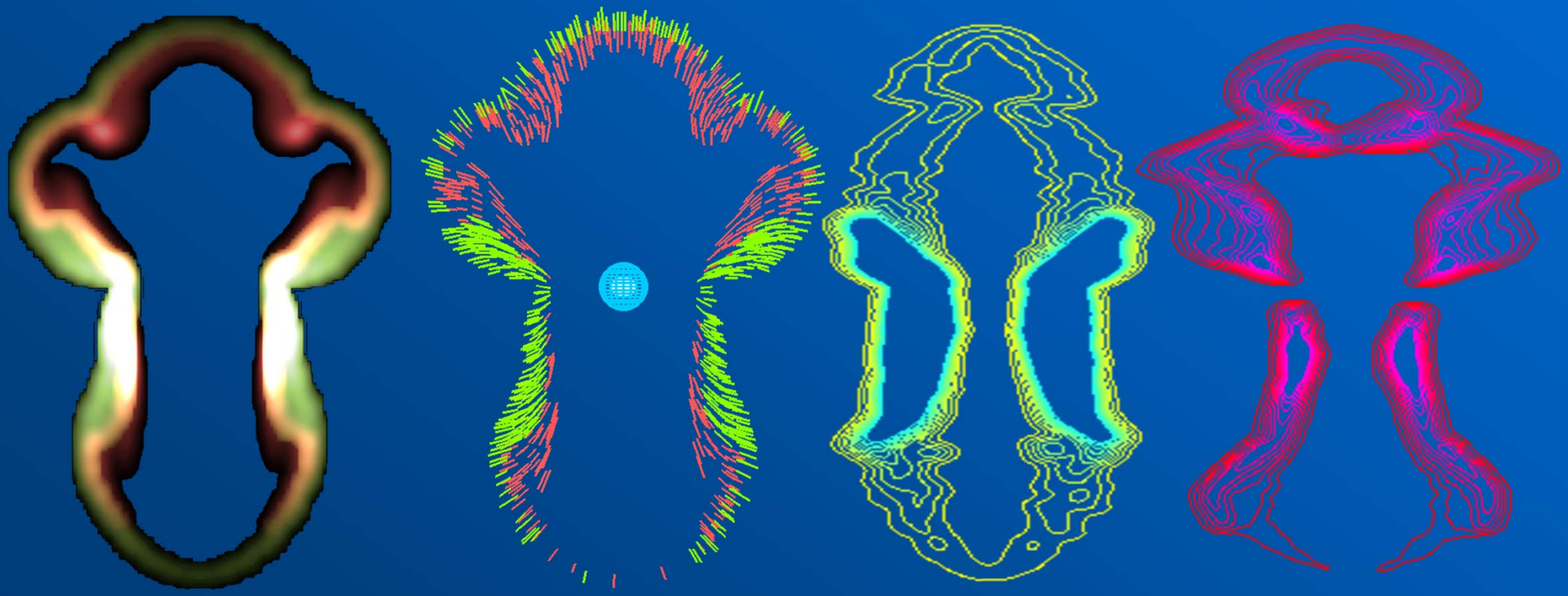
Quick massive shell ejection



Contour: position-velocity diagram

Greyscale: image

Recent results

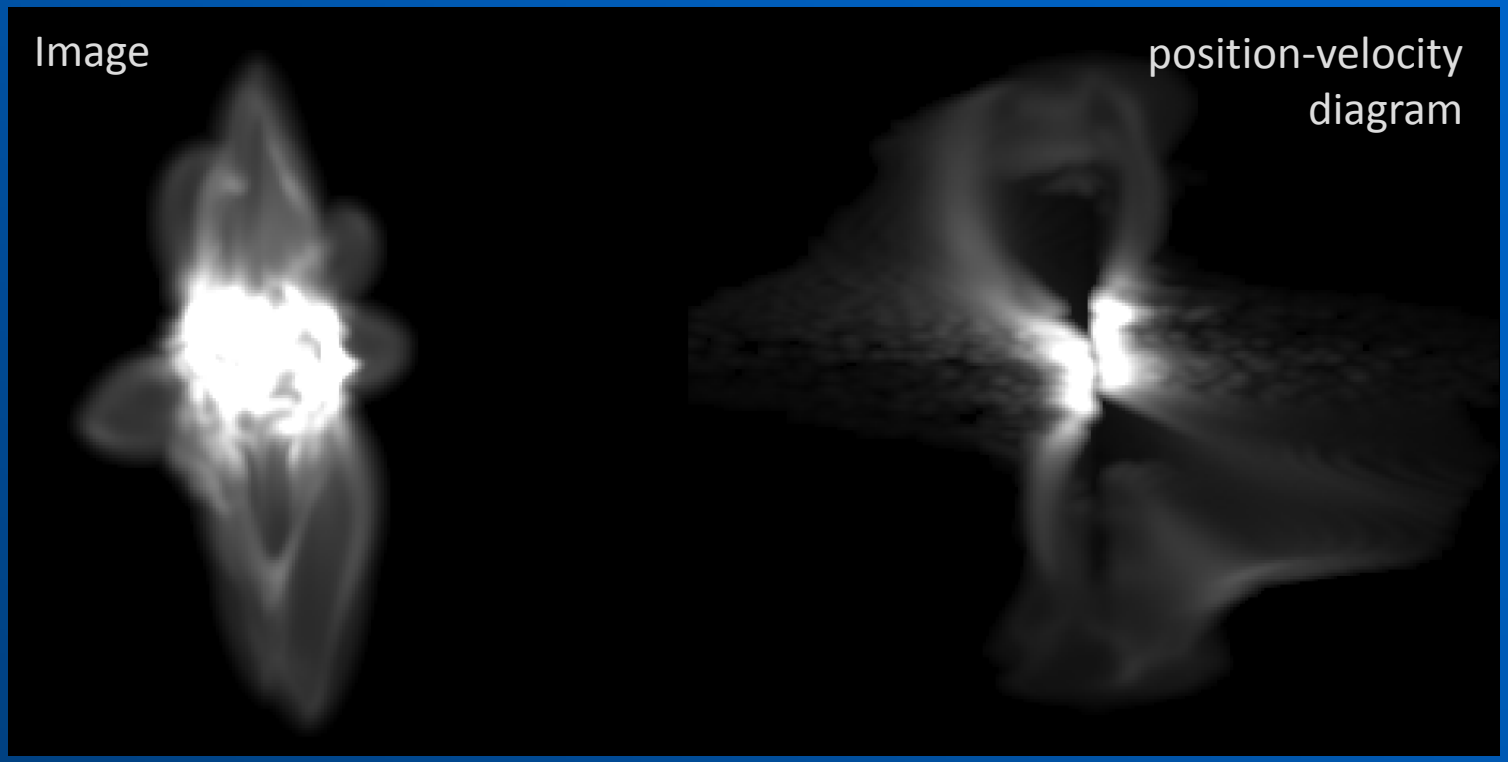


Images Velocity Vectors P-V diagrams

Space velocity (color coding): 10-20 km/s 20-50 km/s

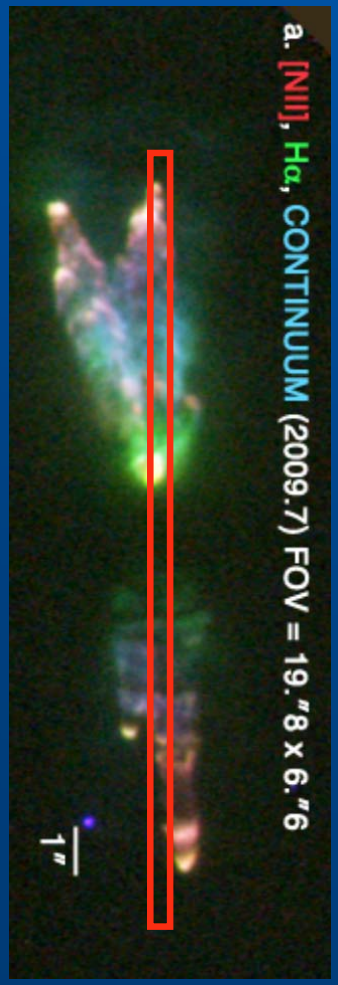
How good is the homologous expansion law?

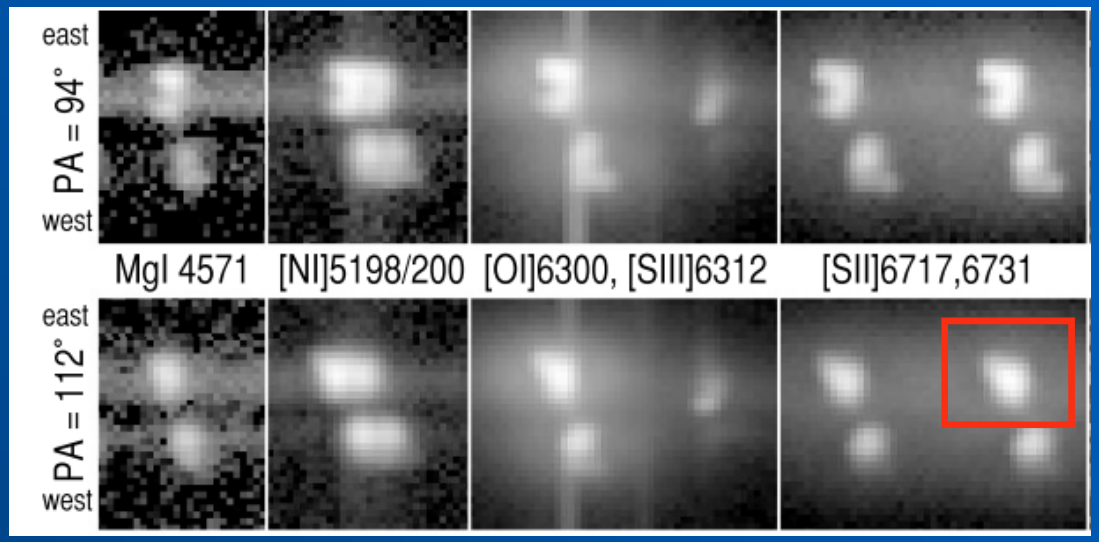
(Balick et al., 2011)



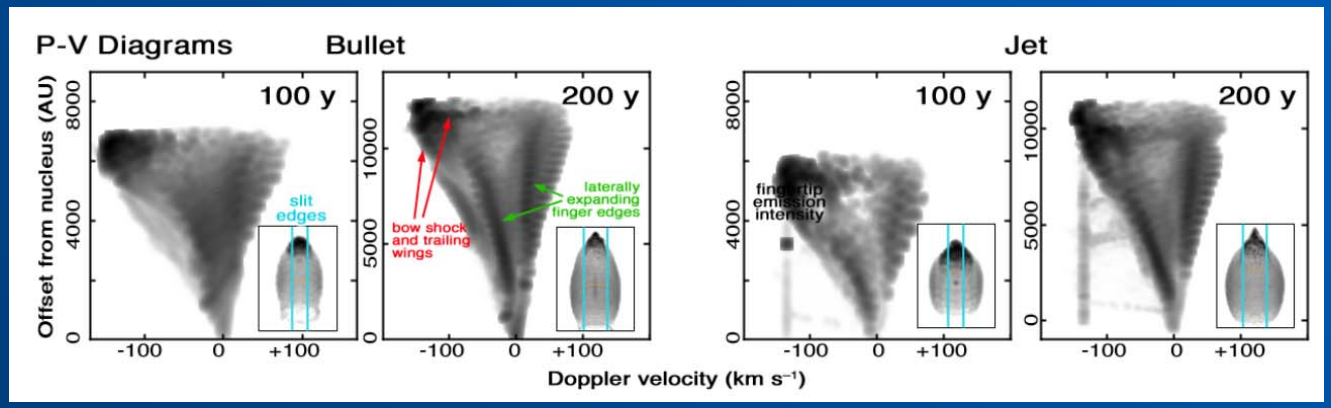
Hydrodynamical simulations wind in inhomogeneous environment (Steffen et al., 2013)

How good is the homologous expansion law?



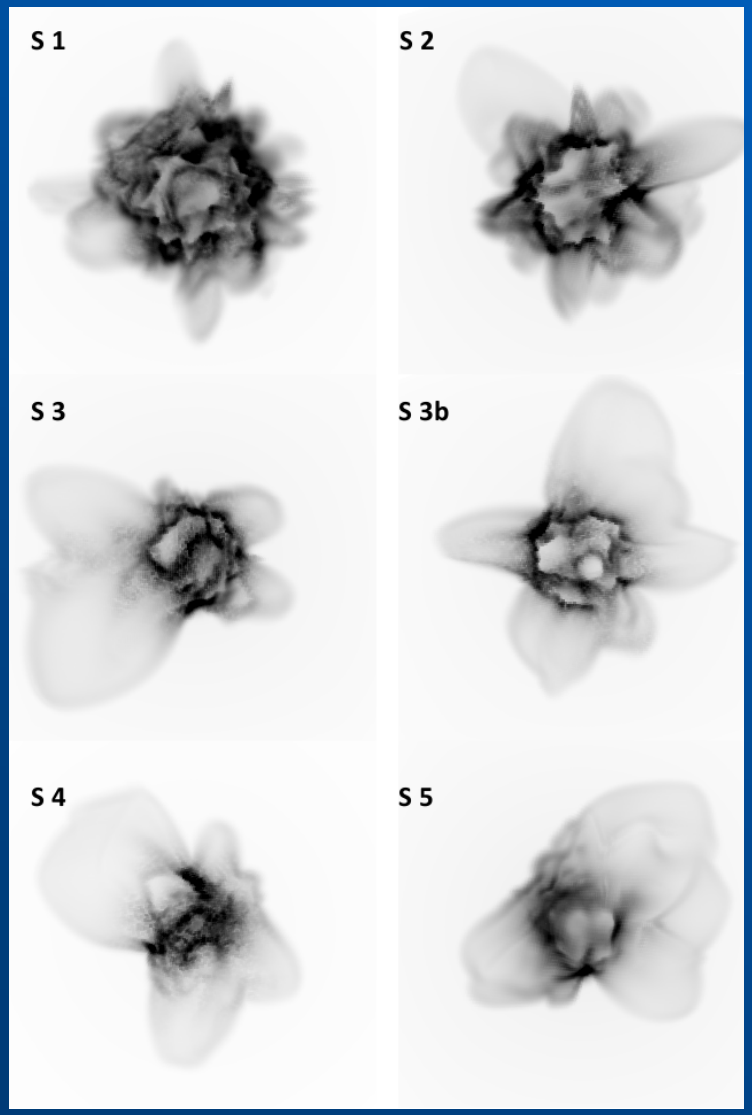


(Long-slit observations, Balick et al., 2014)

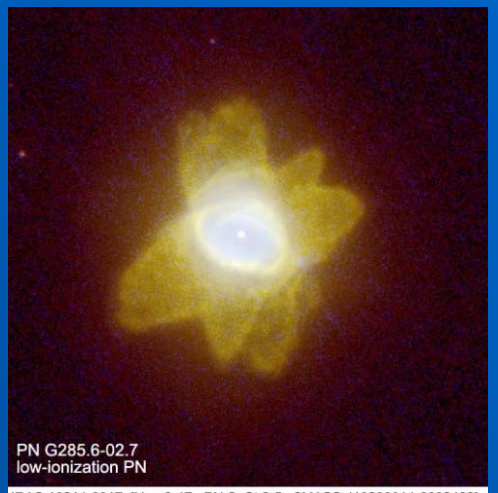


(Hydro Simulation, Balick et al., 2011)

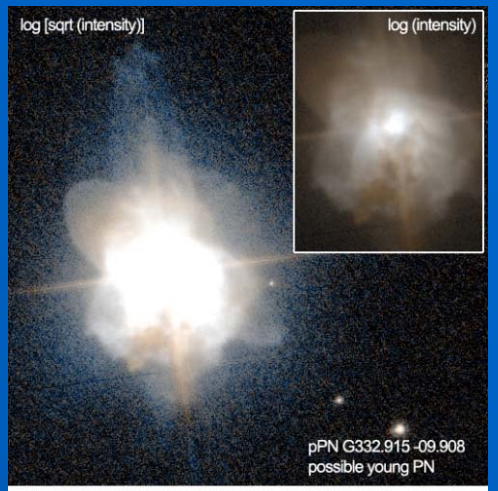
Extended Modified Interacting Stellar Wind Model



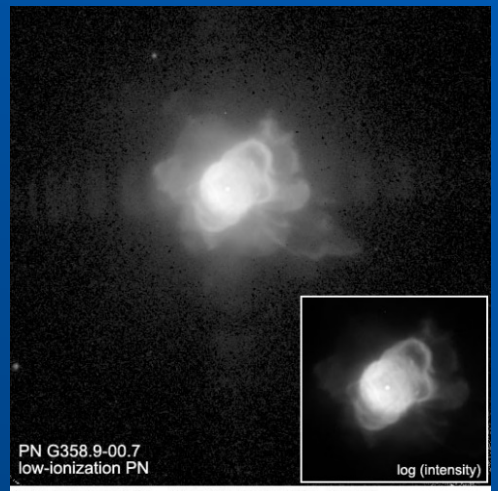
Changing size scale of density fluctuations
(Steffen et al., 2013)



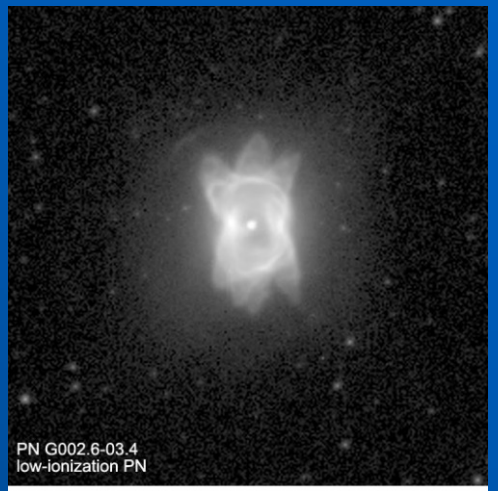
IRAS 10214-6017 [Hen 2-47, PN SaSt 2-5, 2MASS J10230914-6032422]
18 05 25.80 -28 22 04.2 (2000) FOV = 23.3" R:G:B = F658N:"F656N:F502N
WFPC2/PC Credit: PI: NOLL GO11090, NASA/ESA/STScI, Hubble Archives



IRAS 17047-5650 [Hen 3-1333, PK 332-09 1, PN G332.9-09.9]
17 09 00.87 -56 54 48.0 (2000), FOV=12.8", R:G:B = F435W:comb:F606W
ACS/HRC, credit PI:SAHAI GO9463 NASA/ESA/STScI, Hubble Archives



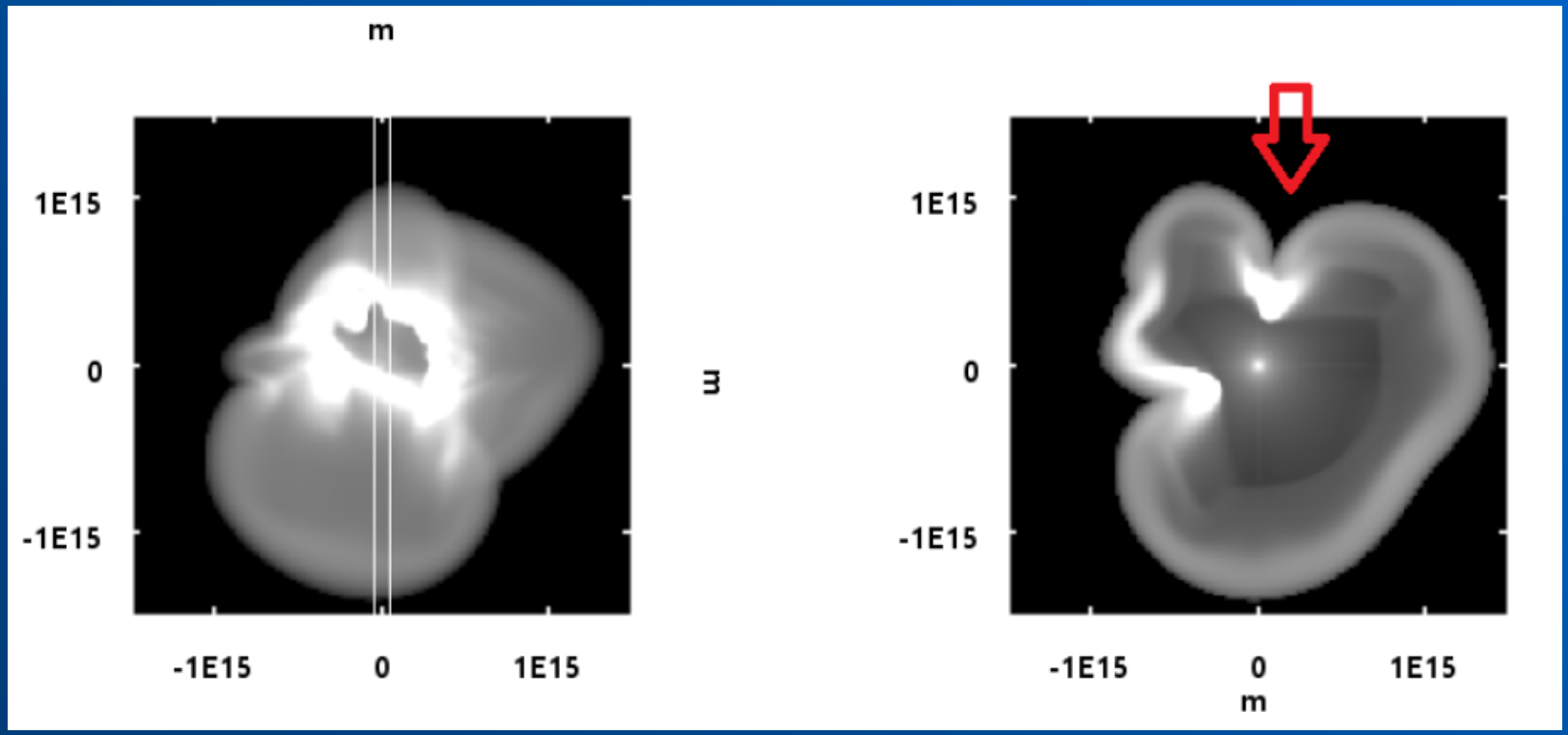
IRAS 17427-3010 [Hen 2-277, PN M 1-26, PN SaSt 2-17]
17 45 57.65 -30 12 00.6 (2000) FOV = 23.3" filter = F656N
WFPC2/PC Credit: PI: SAHAI GO6563, NASA/ESA/STScI, Hubble Archives



IRAS 18022-2822 [Hen 2-339, PN M 1-37, 2MASS J18052581-2822043]
18 05 25.80 -28 22 04.2 (2000) FOV = 11.6" (North not up) filter = F656N
WFPC2/PC Credit: PI: SAHAI GO6563, NASA/ESA/STScI, Hubble Archives

How good is the homologous expansion law?

Hydrodynamical simulation of multipolar planetary nebula



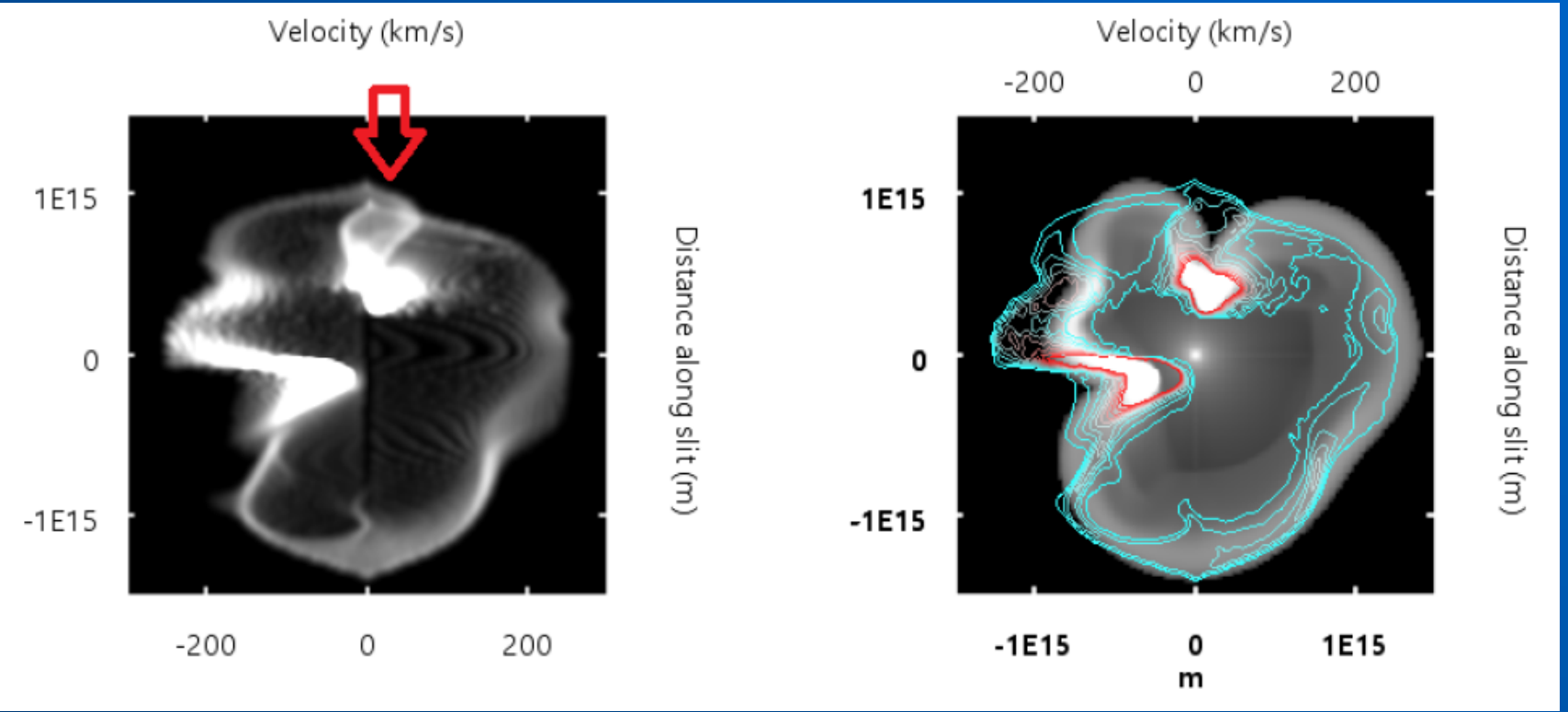
Image

Cut along the line of sight

(Bermudez 2015,MSc Thesis)

How good is the homologous expansion law?

Hydrodynamical simulation of multipolar planetary nebula



Position-velocity diagram

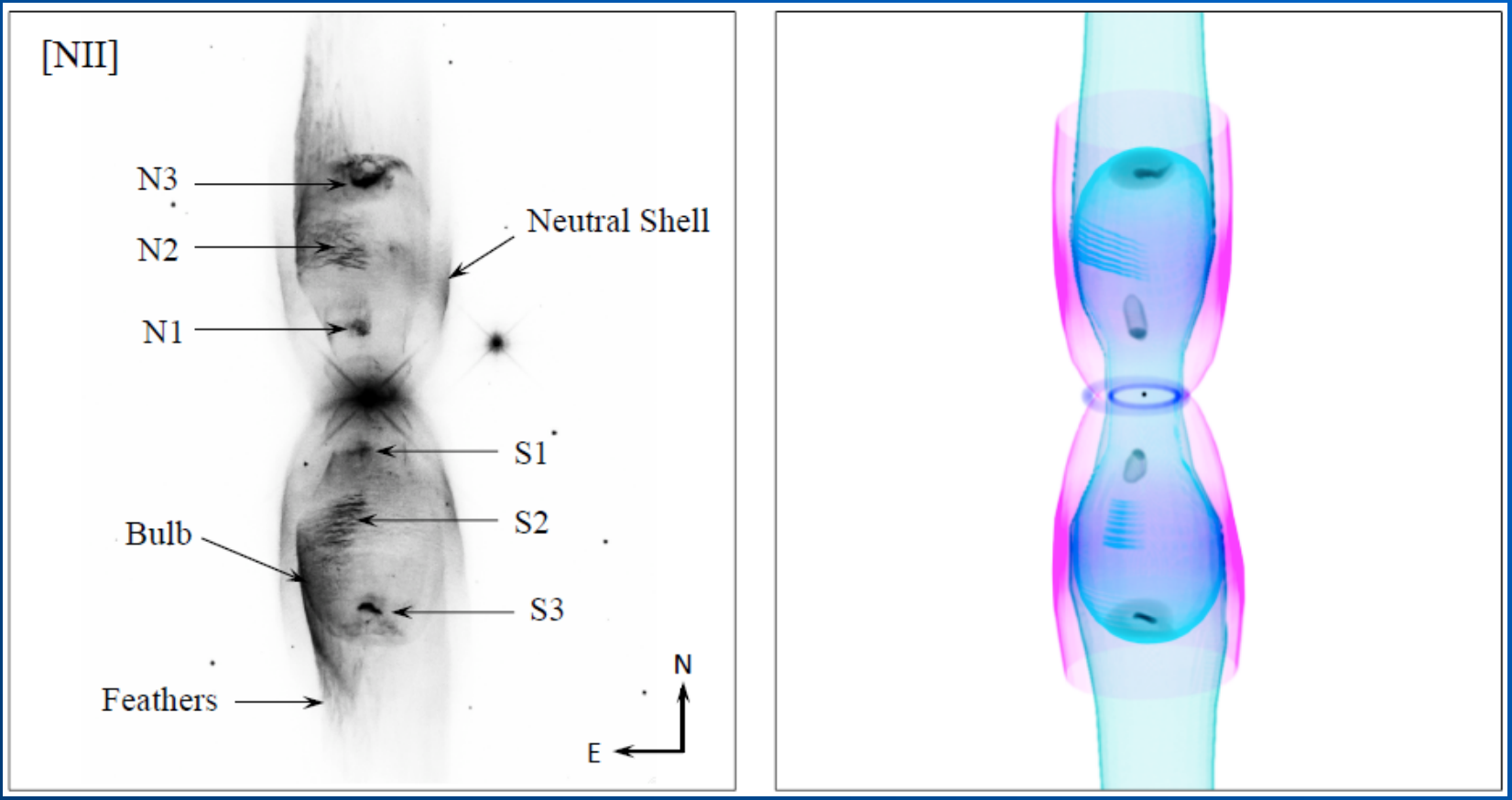
Superposition PV over cut

(Bermudez 2015,MSc Thesis)

Recent results

Complexity

M2-9

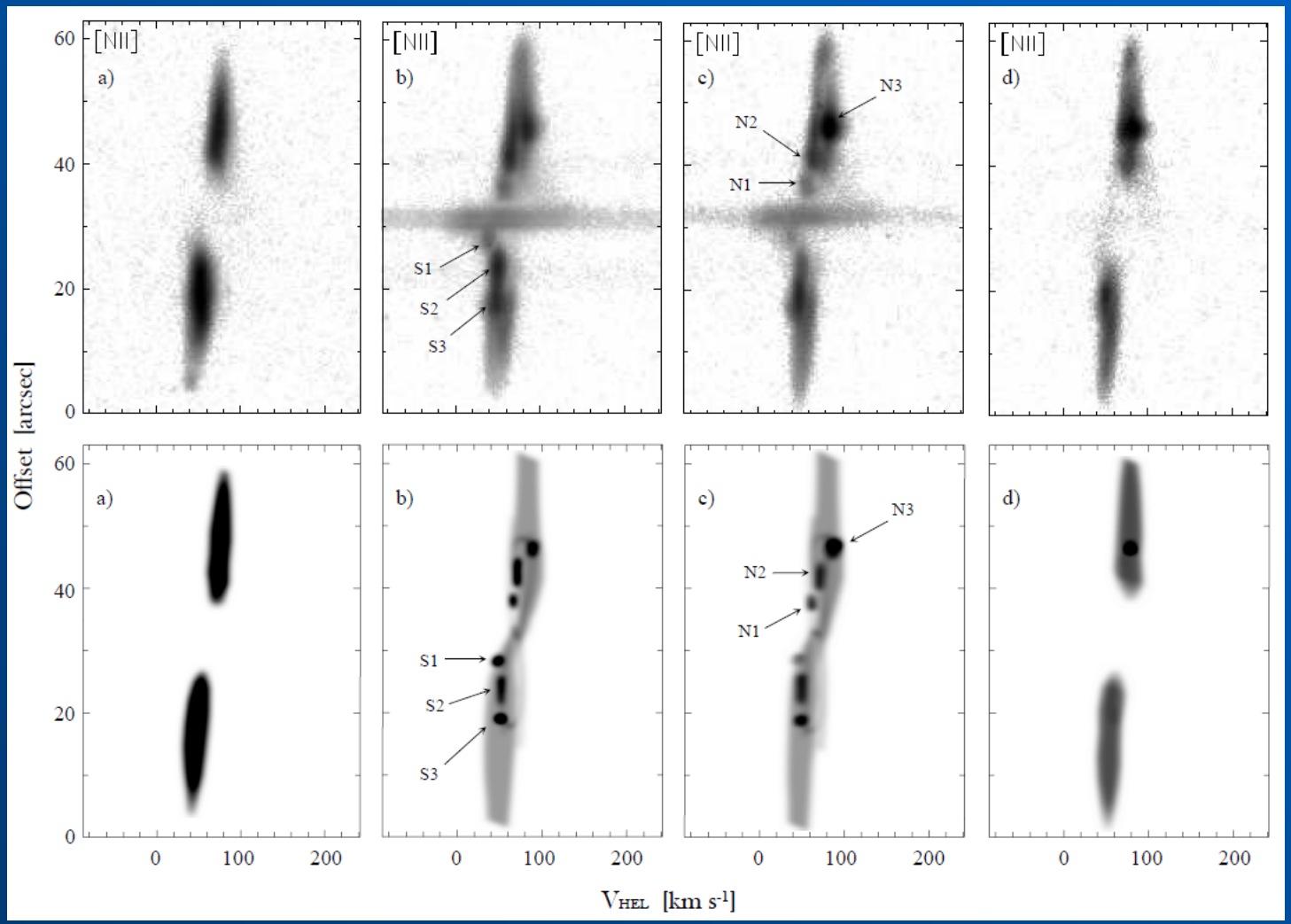


Clyne et al. (2015)

Recent results

M2-9

P-V diagrams



Observation

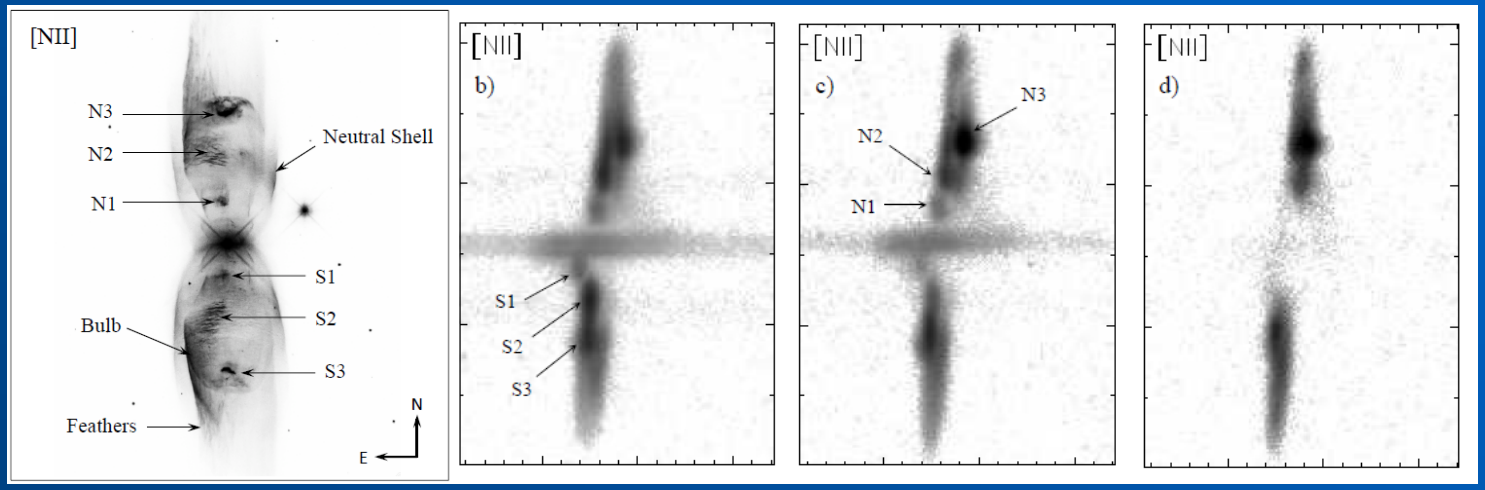
Reconstruction

Clyne et al. (2015)

Recent results

M2-9

P-V diagrams



Observation
Clyne et al. (2015)

Central density cut

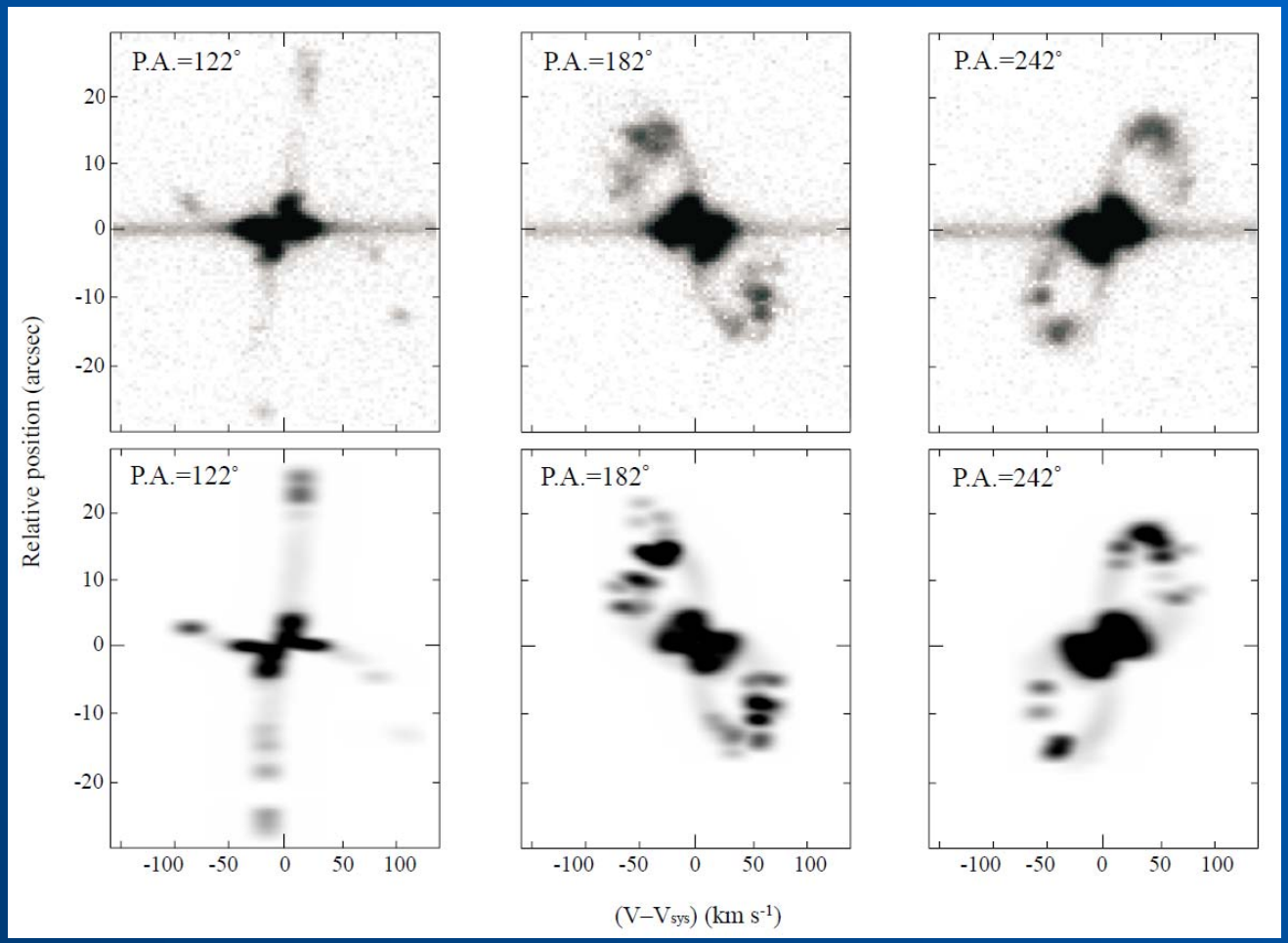
Density image (incl=70°)

P-V diagram

Hydro Simulation
Steffen etal., in prep.

Recent results

Southern Crab (Hen 2-104)

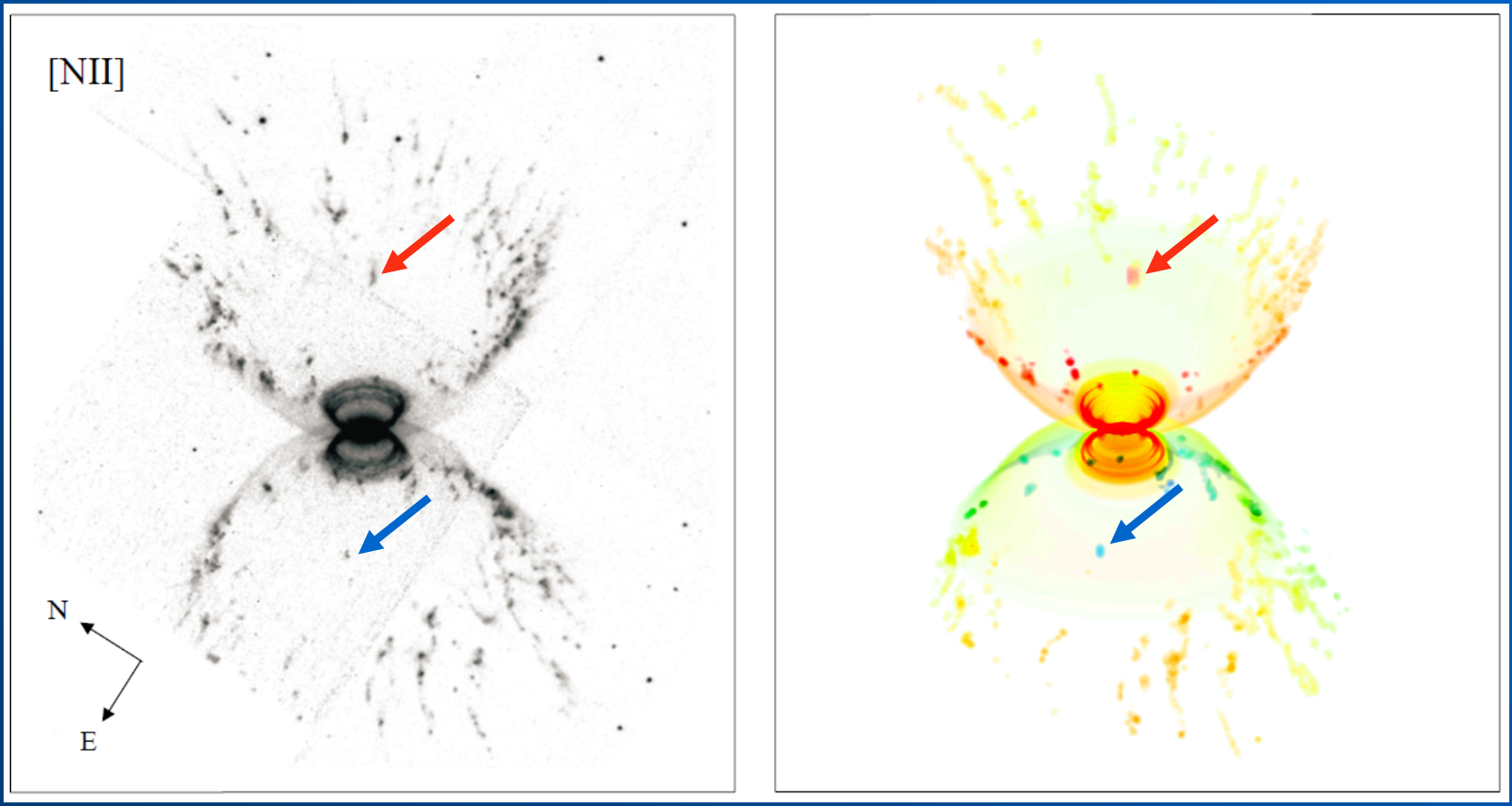


Clyne et al. (2015)

Recent results

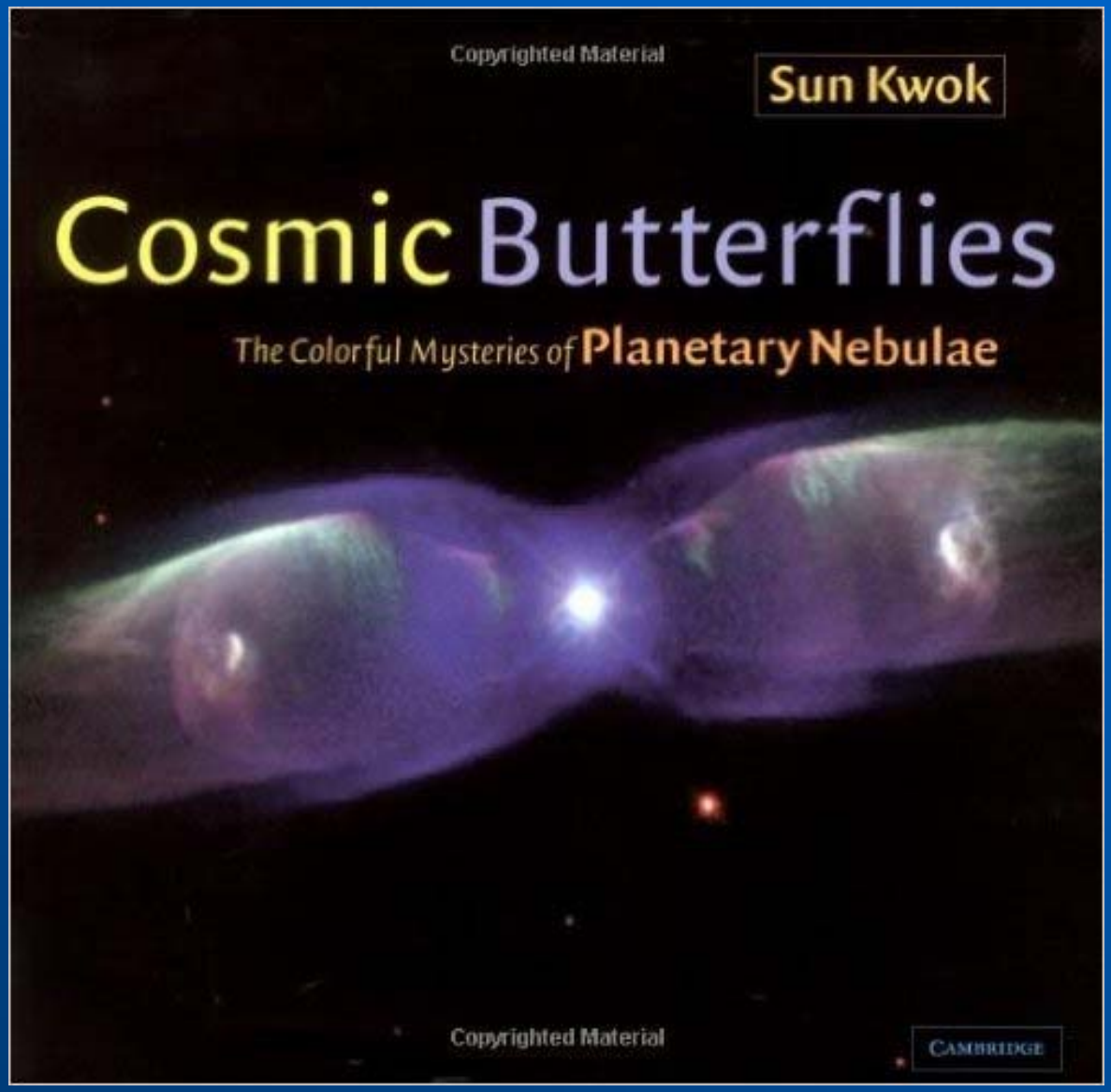
Southern Crab (Hen 2-104)

Click here !

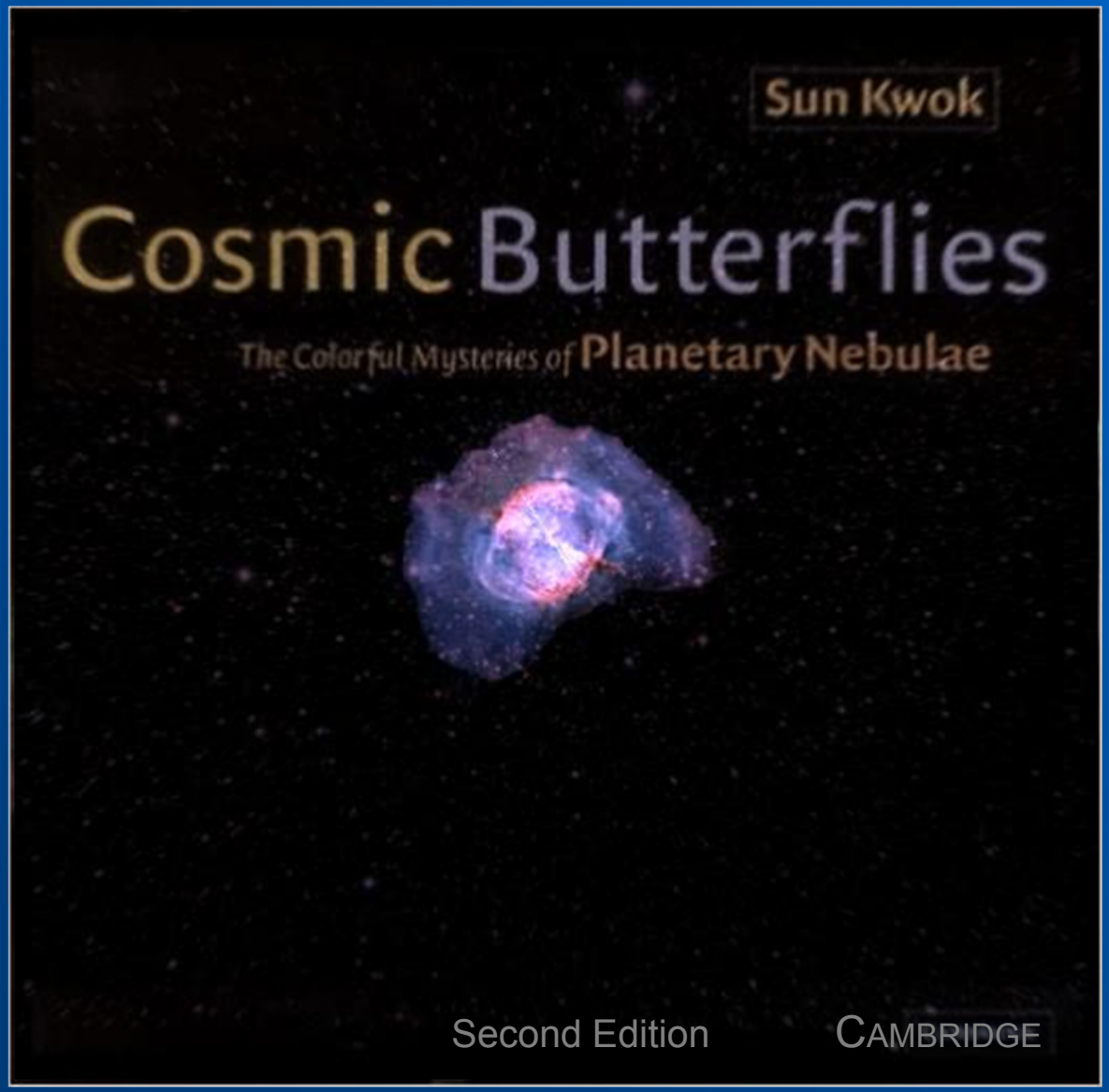


Clyne et al. (2015)

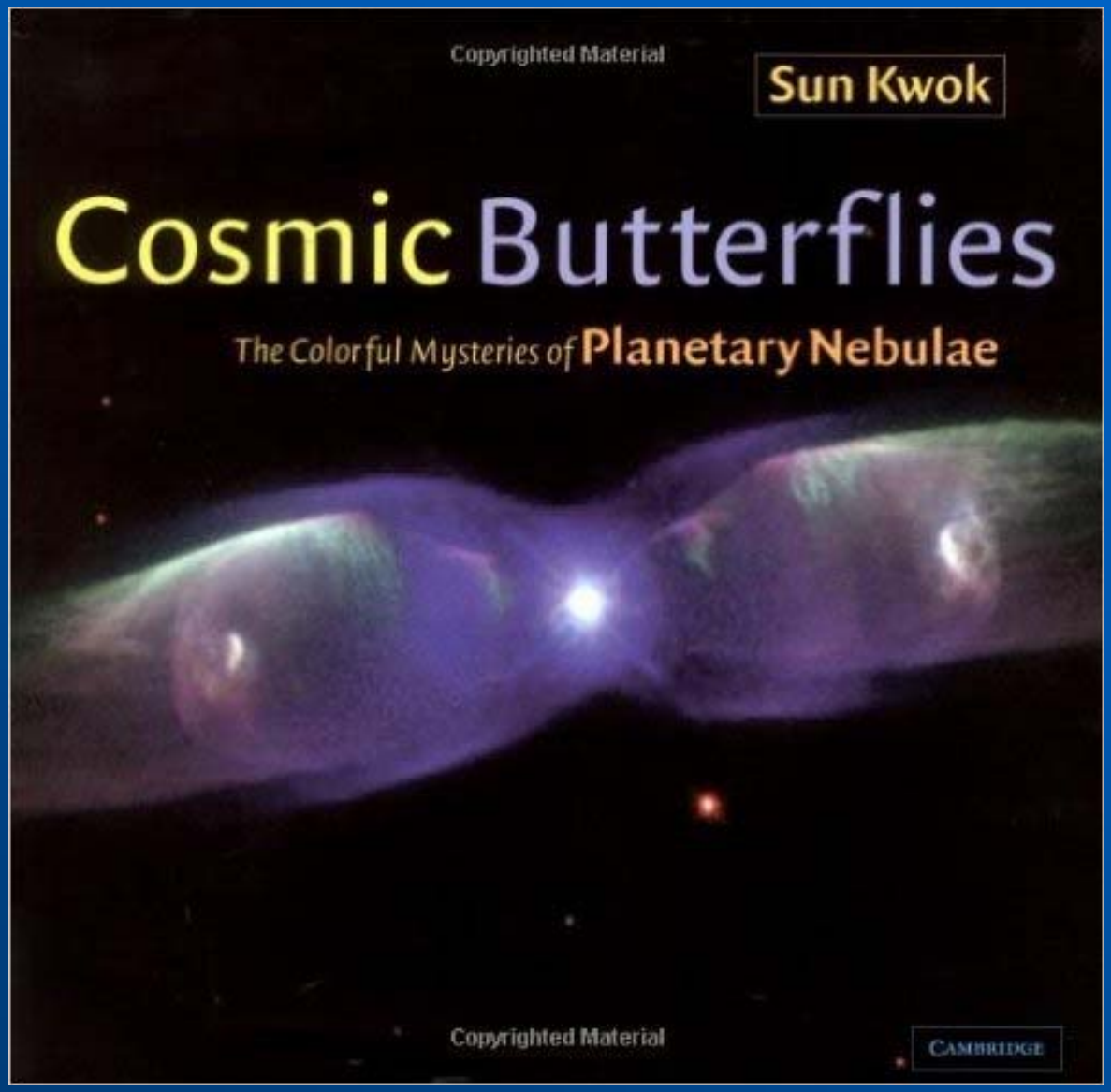
Interstellar Motion



Interstellar Motion

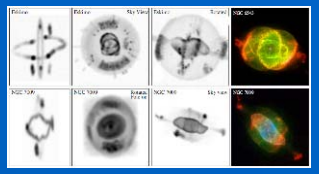
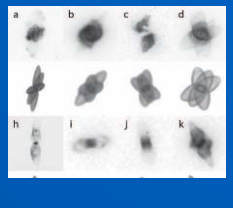


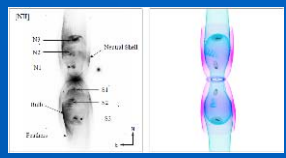
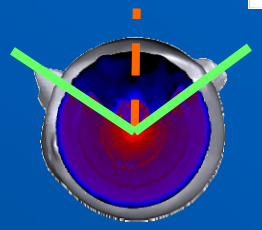
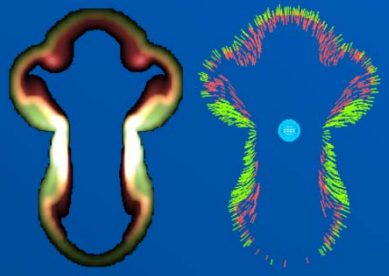
Interstellar Motion



Summary

- 3D reconstruction: intermediate step between observation & theory
- Can lead to reclassification & unification of PNe
- Diversity of PNe may not be as large as thought
- The assumption of homologous expansion for reconstruction must be carefully evaluated in every case
- Solution with spatial & velocity constraints can lead to improved reconstructions and information on the velocity field
- Detailed analysis of 3D reconstructions can lead to key constraints for the central stars and the formation mechanism
- Hydro-simulations with photo-ionization postprocessing (MOCASSIN) to study velocity field as a function of spectral lines should help!

Summary

Observation

3D Reconstruction

Theory