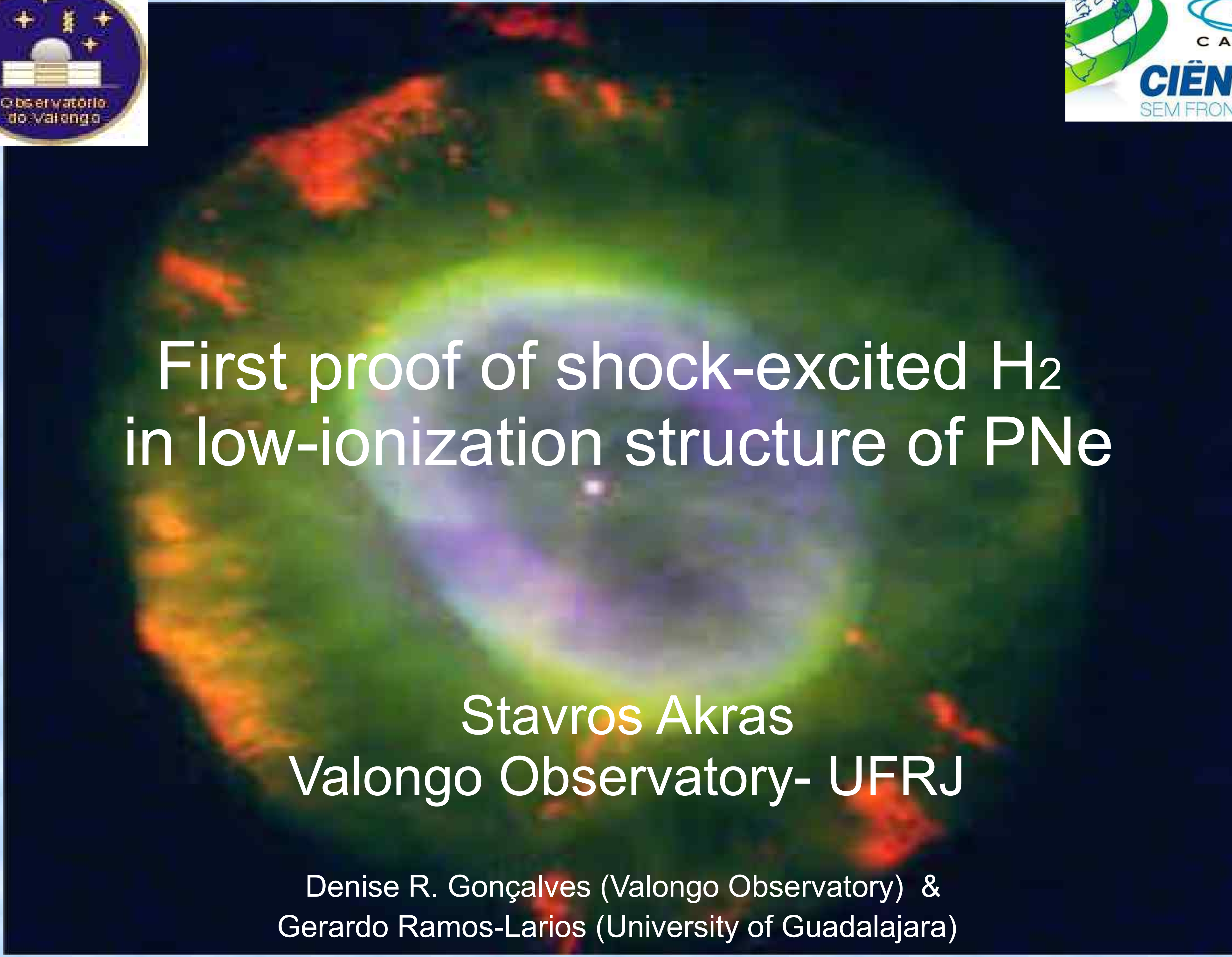


First proof of shock-excited H_2 in low-ionization structure of PNe

Stavros Akras
Valongo Observatory- UFRJ

Denise R. Gonçalves (Valongo Observatory) &
Gerardo Ramos-Larios (University of Guadalajara)

What do we know about the low-ionization structures?

I. They are bright in the [N II], [O II], [S II], [O I] emission lines. Moreover, they are found in variety of morphological types: knots, jets, filaments, etc. either in pairs or isolated (e.g. Gonçalves et al. 2001)

II. T_e and chemical abundances are the same in the main nebular components (rims, shells, halos) and LISs (Balick et al. 1993, Gonçalves et al. 2003, 2009, Akras & Gonçalves 2016)

III. A large range of expansion velocities from a few tens of km/s up to a few hundreds of km/s → shock interaction has to been taken into account

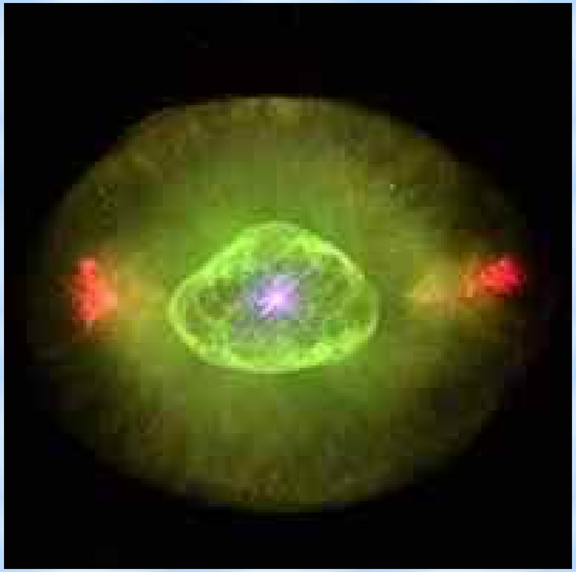
- FLIERs (Fast Low Ionization emission regions, Balick et al. 1993)
- BRETS (Bipolar rotating episodic jets, Lopez et al. 1995)
- SLOWERs (Slow moving Low Ionization Emitting Regions; Perinotto 2000)

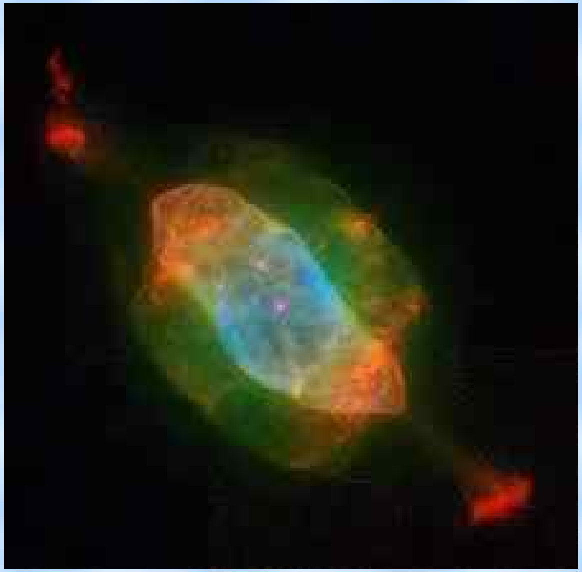
IV. LISs are the result of photo-ionization and shock-excitation mechanisms depending on the stellar (T_{eff} and $L_\odot$) and LISs' parameters (V_{exp}, Ne, distance to the CS)(Akras & Gonçalves 2016)

V. Ne is usually lower in the LISs compared to the main nebular components (Balick et al. 1993, Gonçalves et al. 2003, 2009, Akras & Gonçalves 2016).

Are LISs made of molecular gas?

Low – Ionization Structures (LISs)





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Molecular Hydrogen emission

I. Deep, high angular resolution H_2 images of K 4-47 and NGC 7662 were obtained with the 8-m Gemini-North telescope on September 6 and October 13, 2014

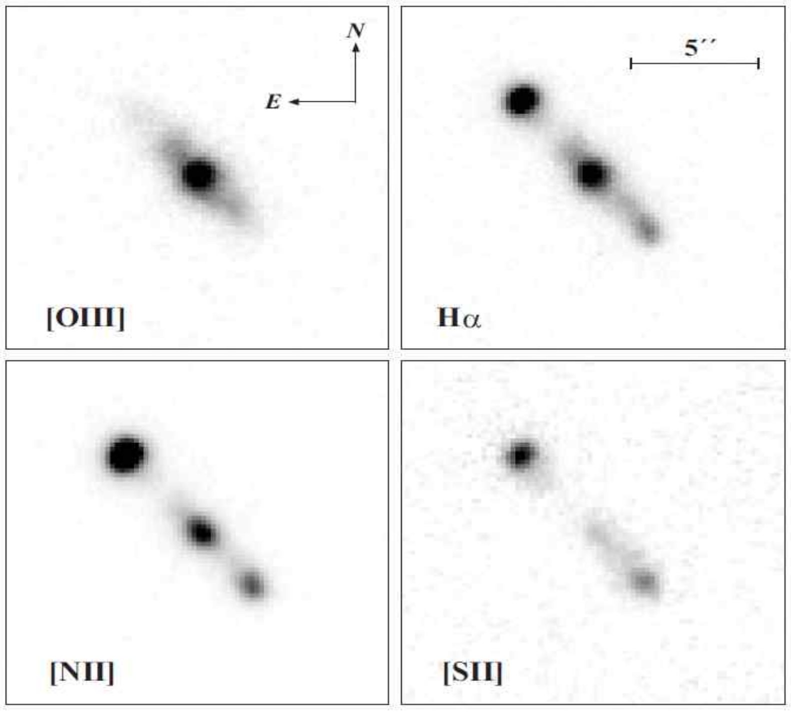
- H_2 v=1-0 S(1) at 2.122 μm (90s x 9 frames / 115s x 9 frames)
- H_2 v=2-1 S(1) at 2.248 μm (155s x 21 frames / 190s x 14 frames)

II. The H_2 v=1-0/v=2-1 ratio is an indicator of the excitation mechanism (Black & van Dishoeck 1987, Burton 1992)

- ~2 → photo-ionized regions
- ~10 → shocked-excited regions

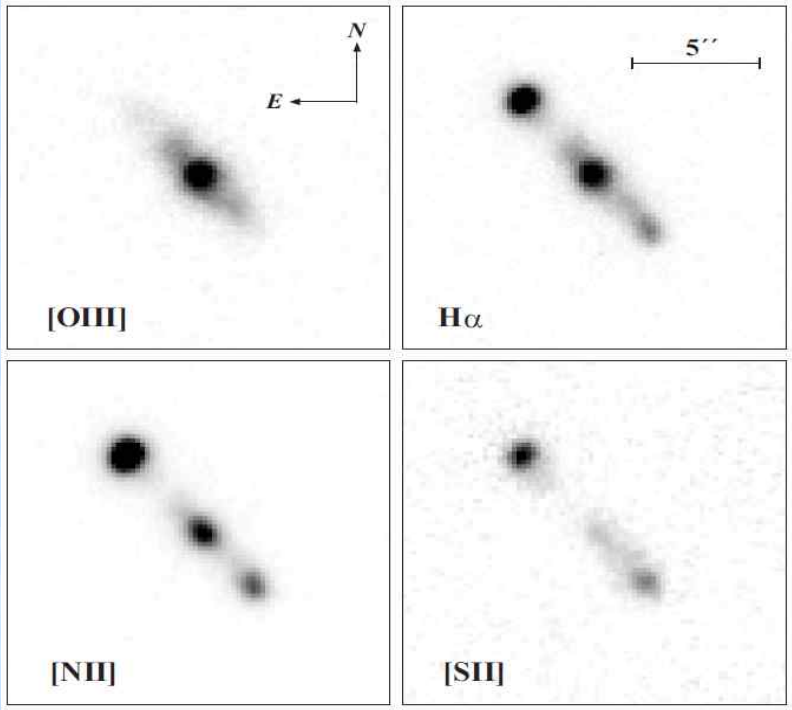
III. H_2 emission was recently detected in comentary knots and clumps at the equatorial region of the bipolar PN NGC 2346 (Manchado et al. 2015)

K 4-47



(Corradi et al. 2000)

K 4-47



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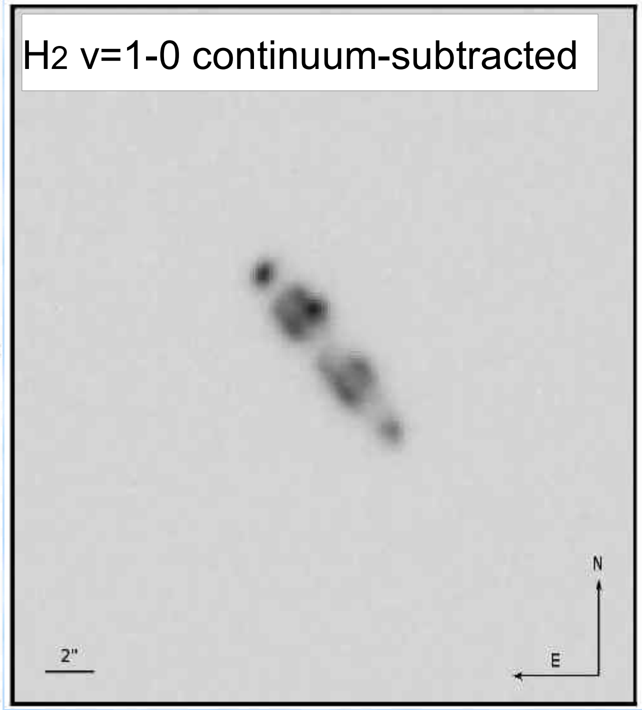
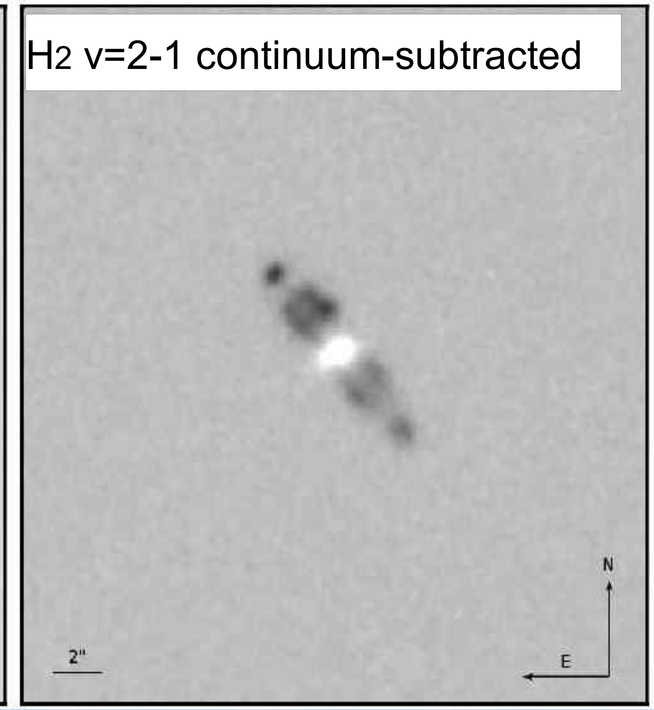


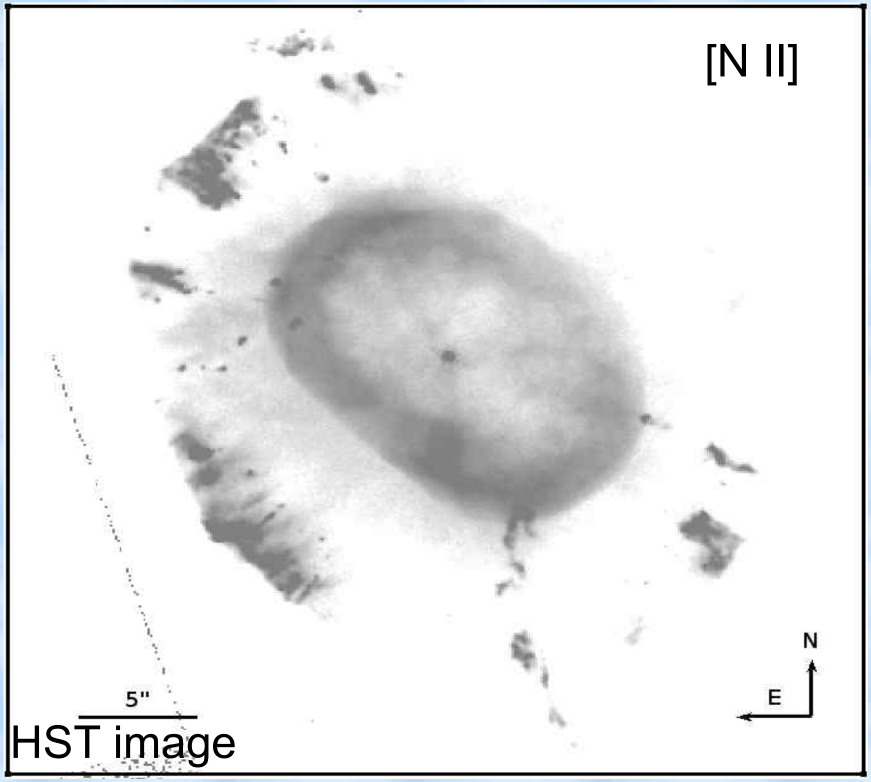
0.2-1 x 10^{-15} erg/cm^2/s/arc^2

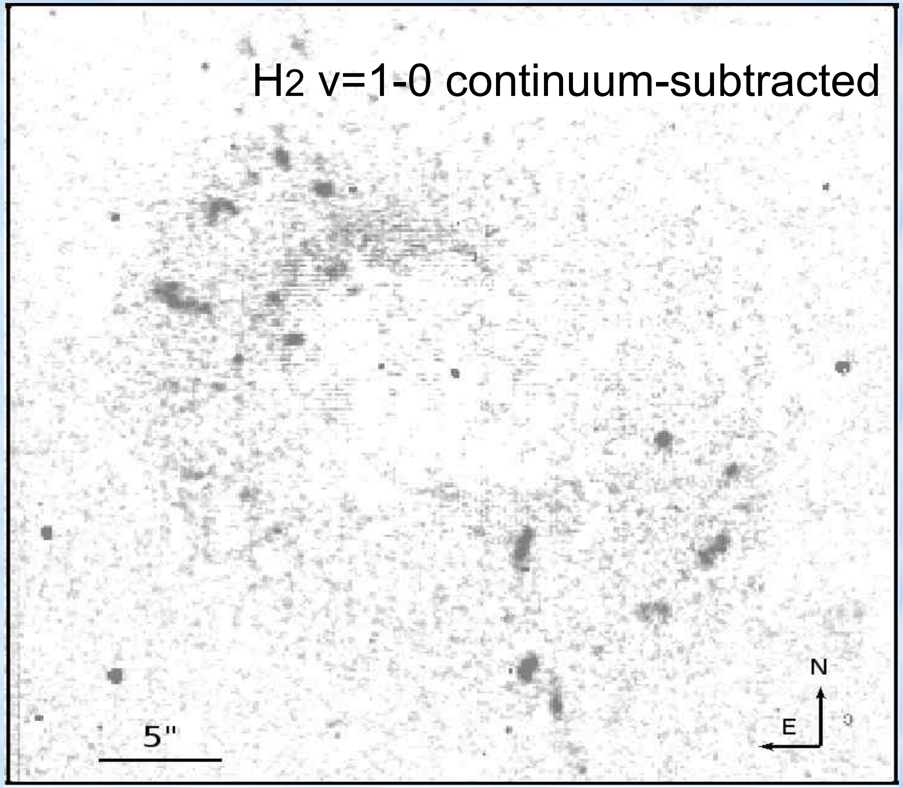


0.2-1 x10^{-16} erg/cm^2/s/arc^2

- H_2 emission shows a bipolar structure that is not seen in the optical emission lines→ is K 4-47 a very young PN?
- First detection of H2 emission from high velocity LISs (V_{knots}~100-300 km/s, Corradi et al. 2000; Goncalves et al. 2004)
- The H_2 v=1-0/ v=2-1 ratio is around 7-8 → shock excitation mechanism

NGC 7662





- Several small scale LISs are identified in H_2 v=1-0 S(1) line (2.12 μm)
- The H_2 v=1-0/v=2-1 ratio is between 3 and 5 → photo-ionized & shock excited regions.
- F_{H_2} (v=1-0): 1-4.8x10^{-16} erg/cm^2/s/arc^2, F_{H_2} (v=2-1):0.6-1x10^{-16} erg/cm^2/s/arc^2
- 3D morpho-kinematic model is required

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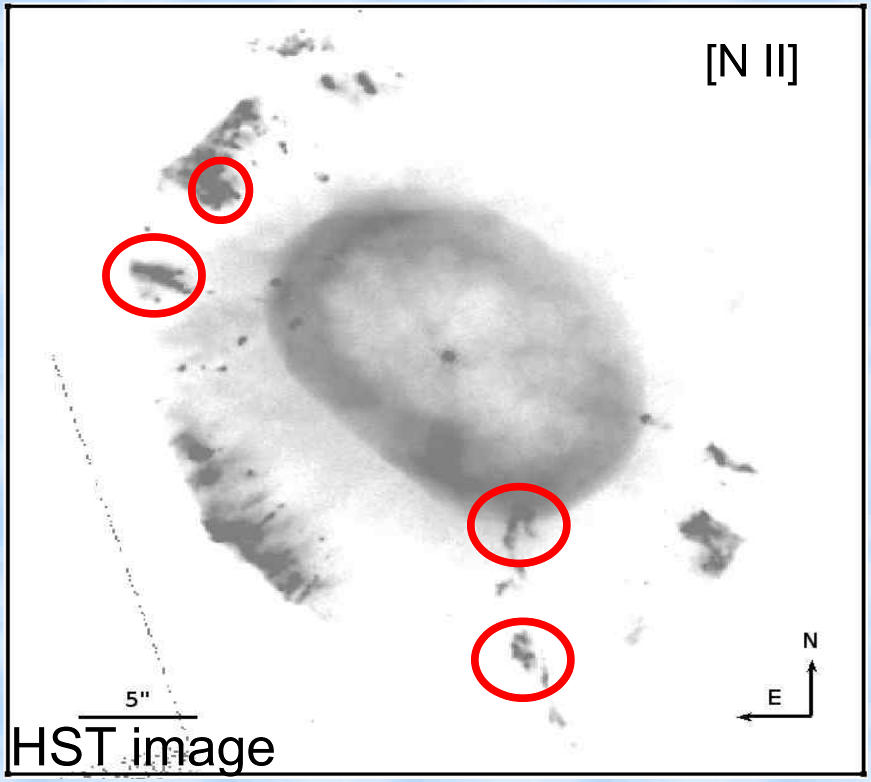

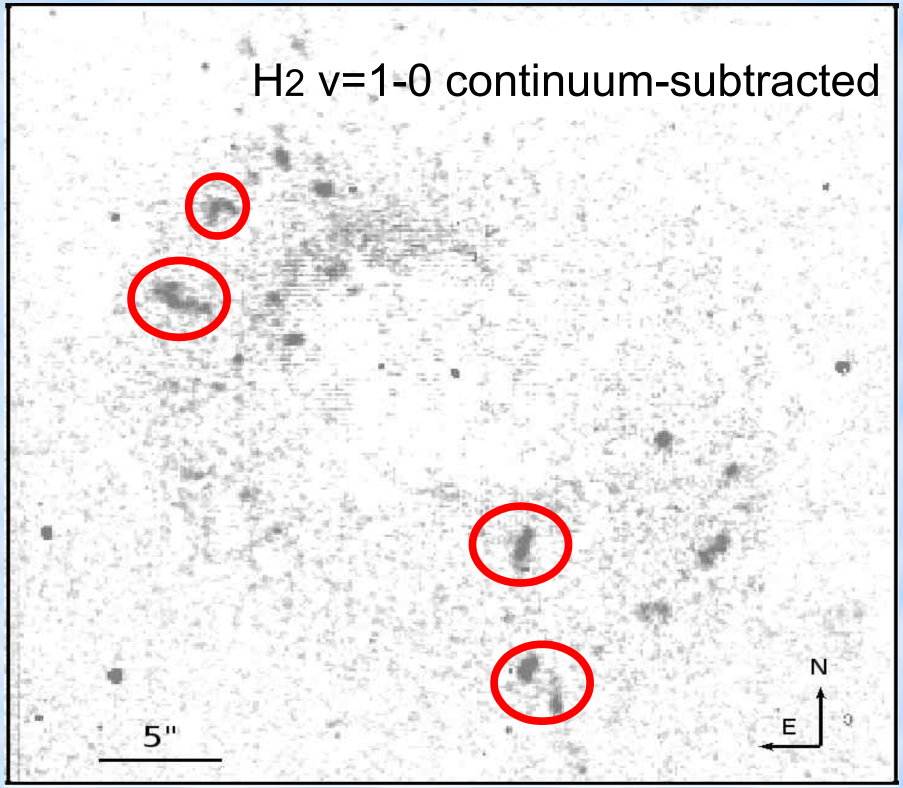

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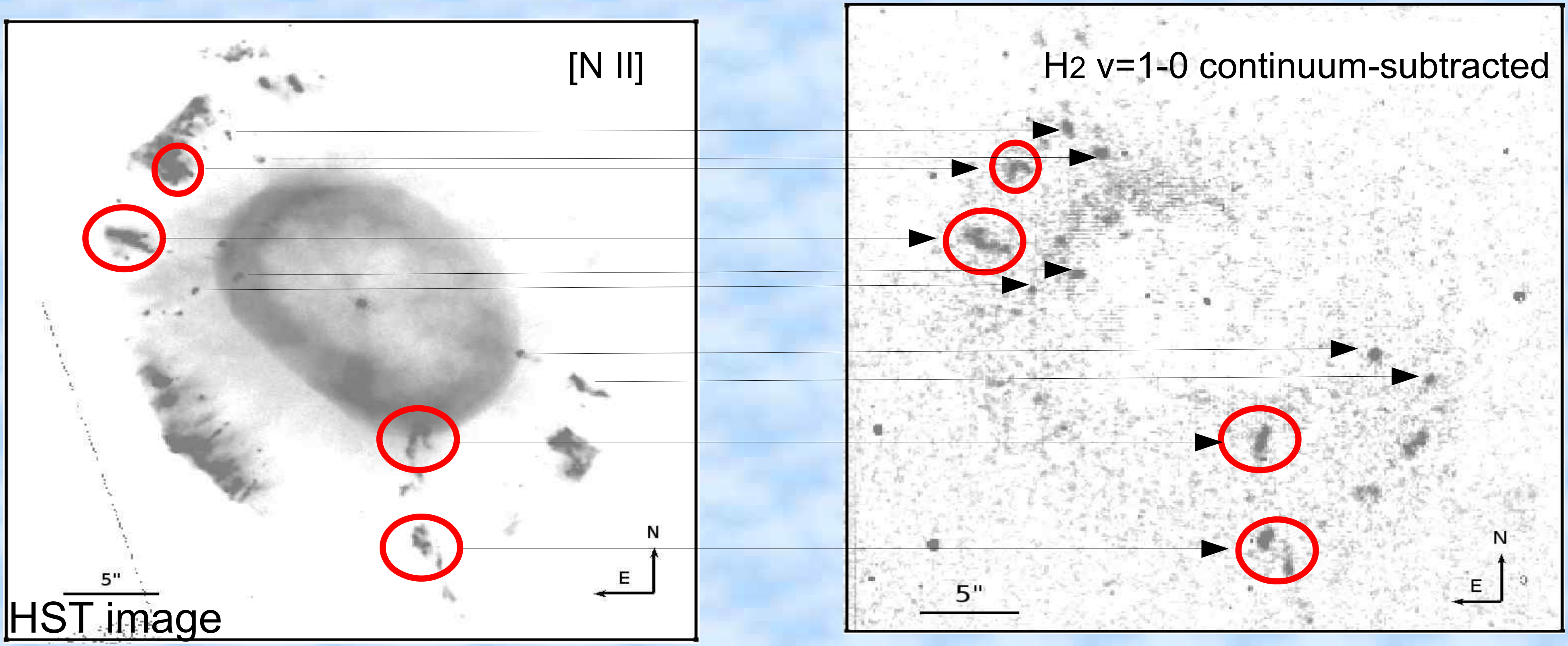

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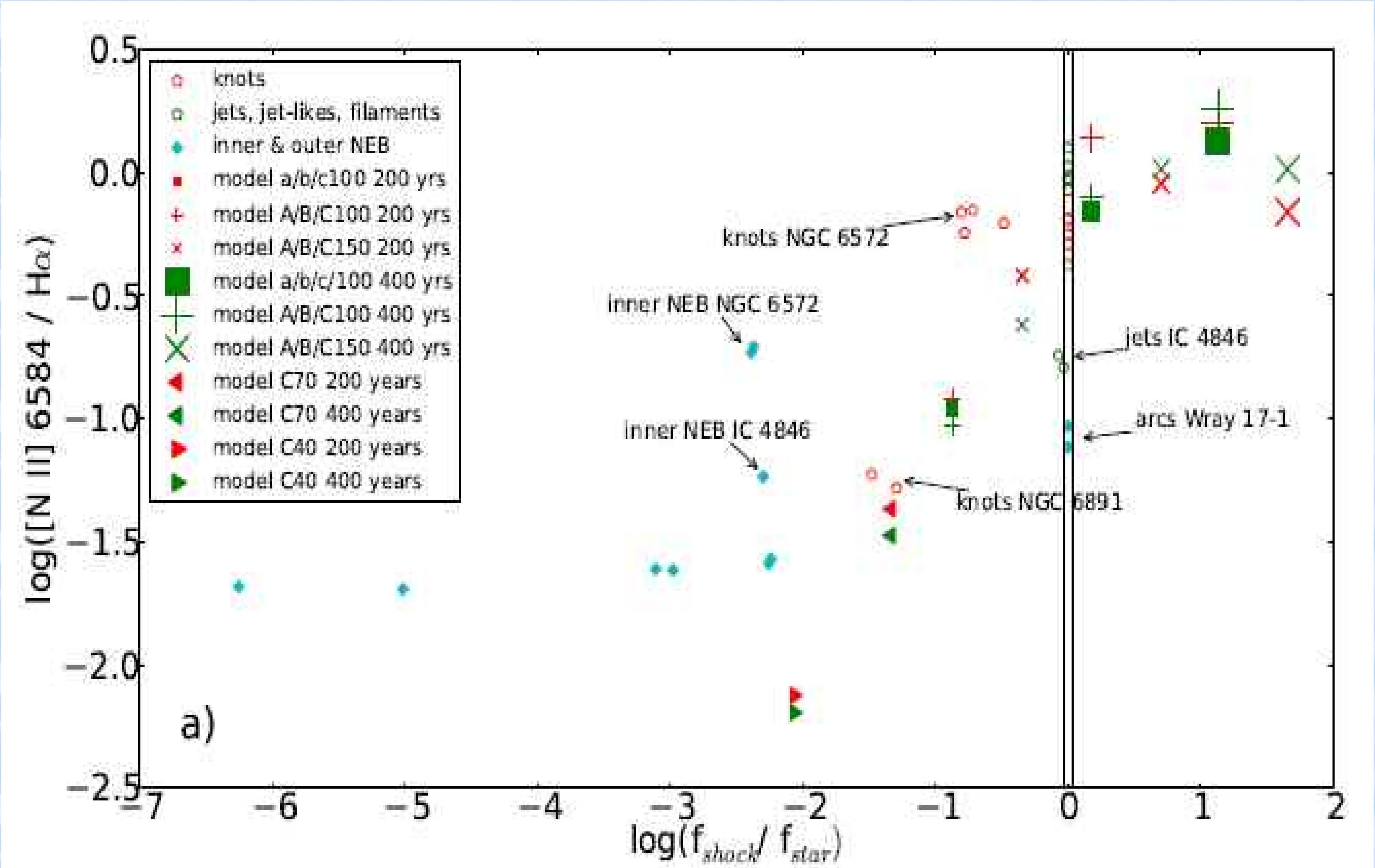
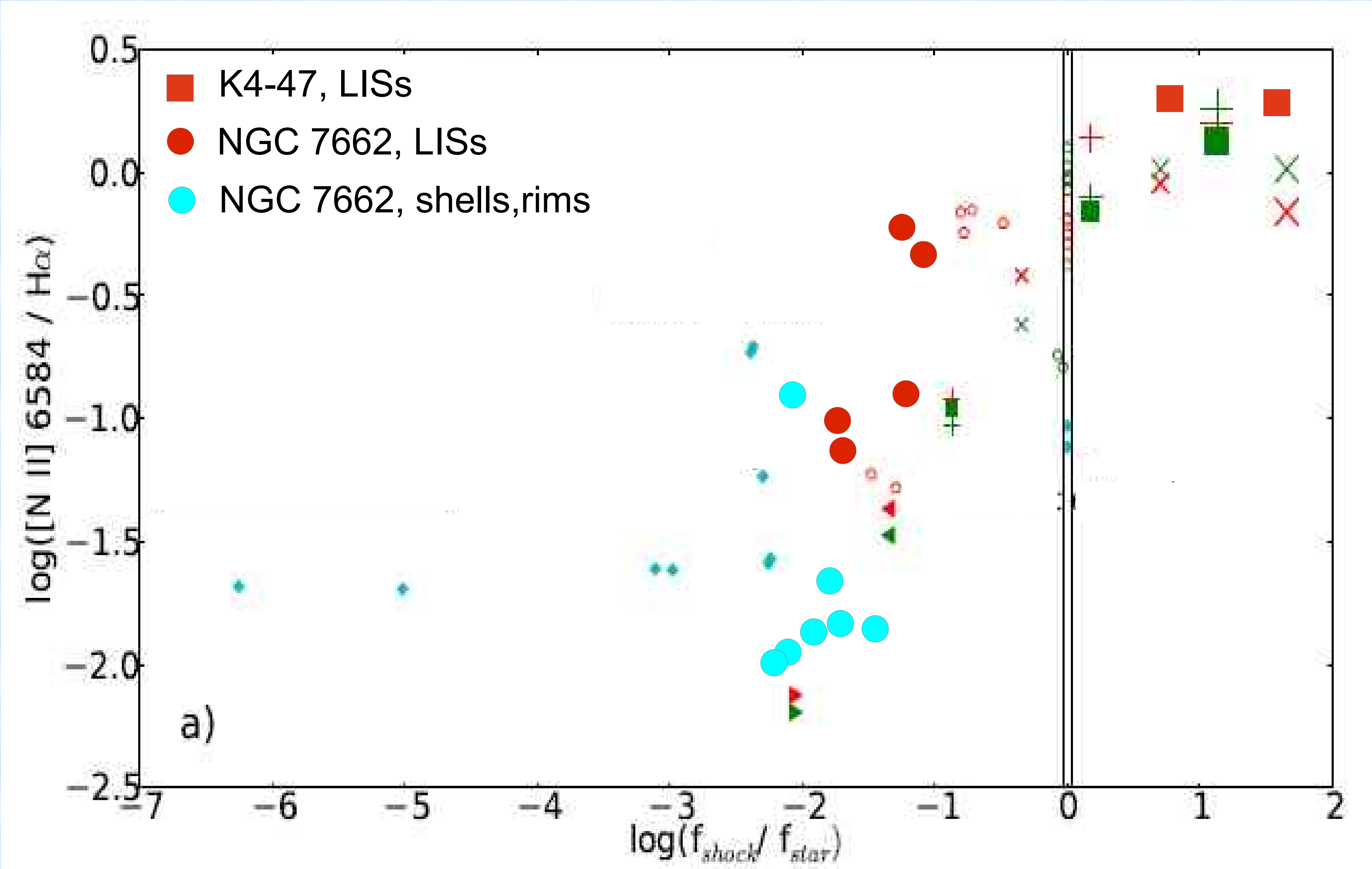
K 4-47 & NGC 7662



(Akras & Gonçalves 2016)

K 4-47 (Gonçalves et al. 2004) & NGC 7662 (Perinotto et al. 2004 & Gonçalves et al. 2009)



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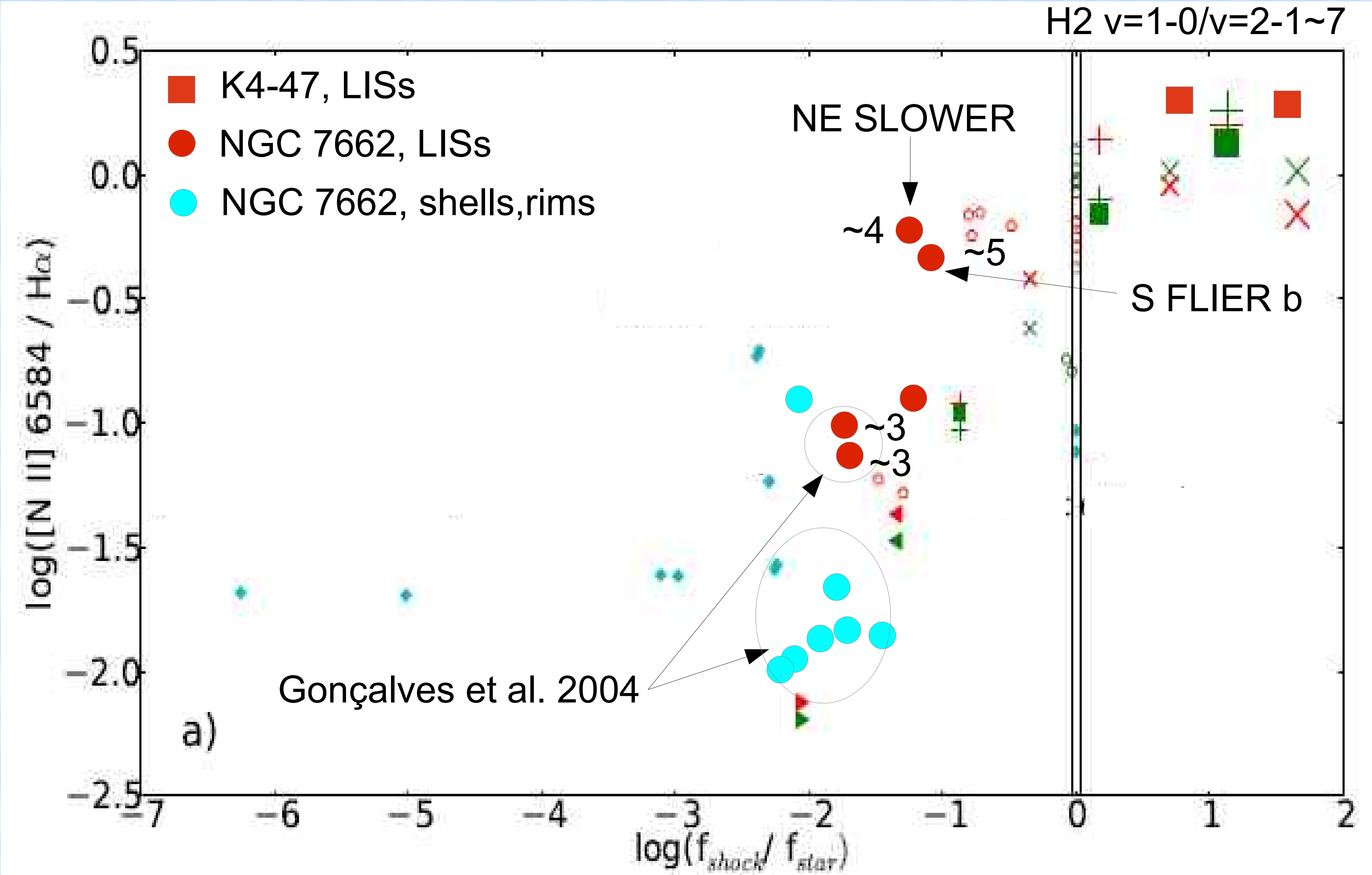

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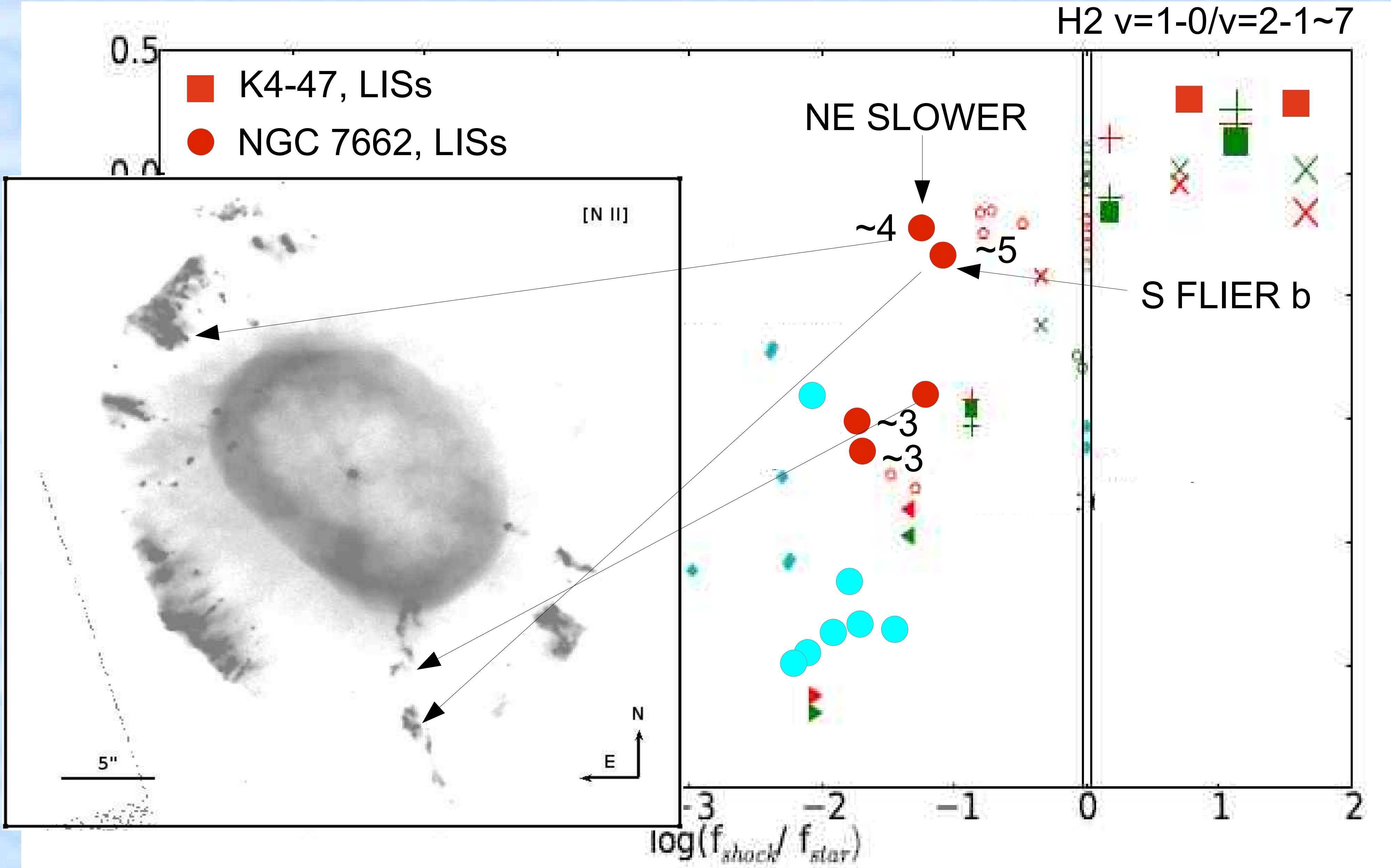

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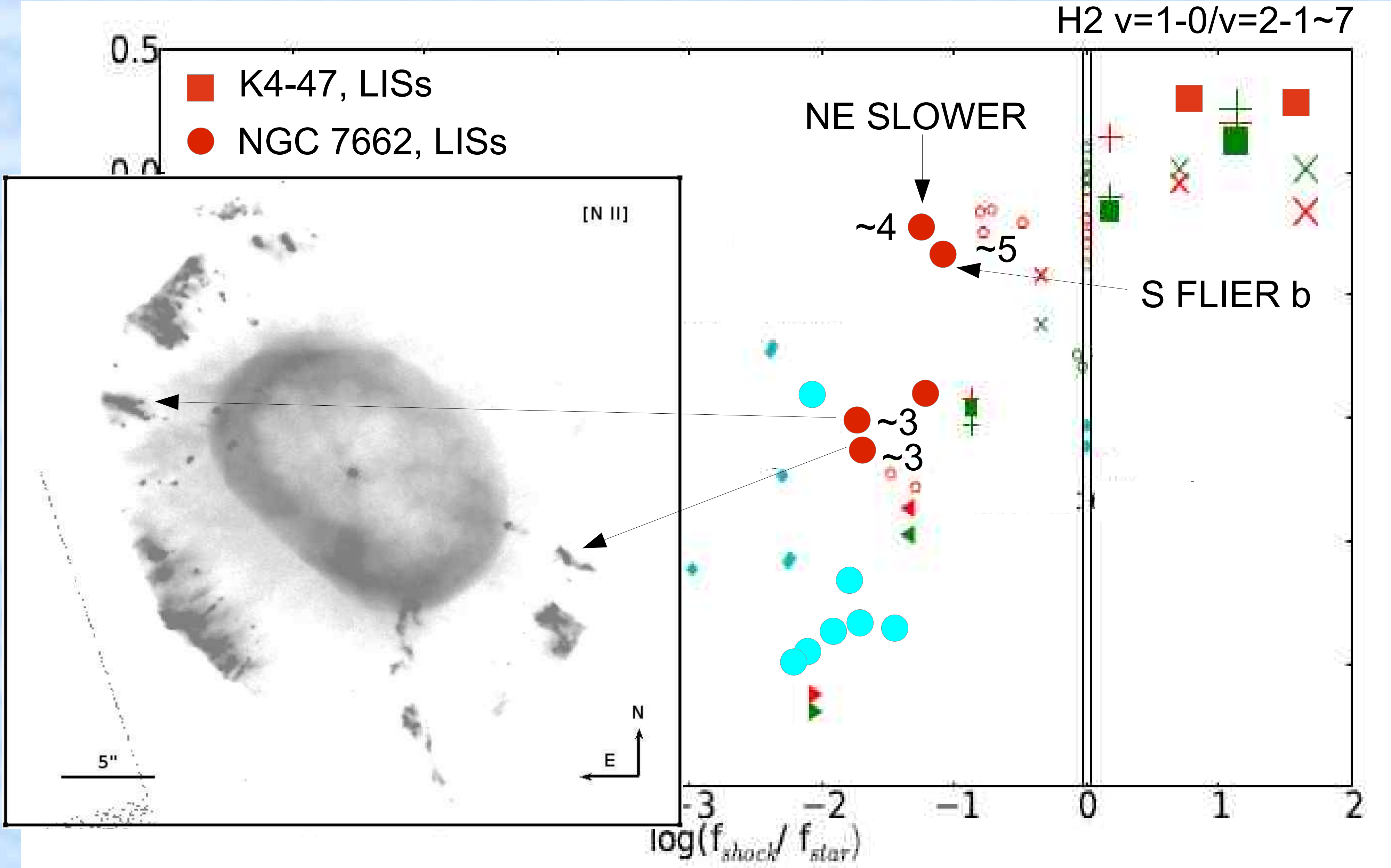


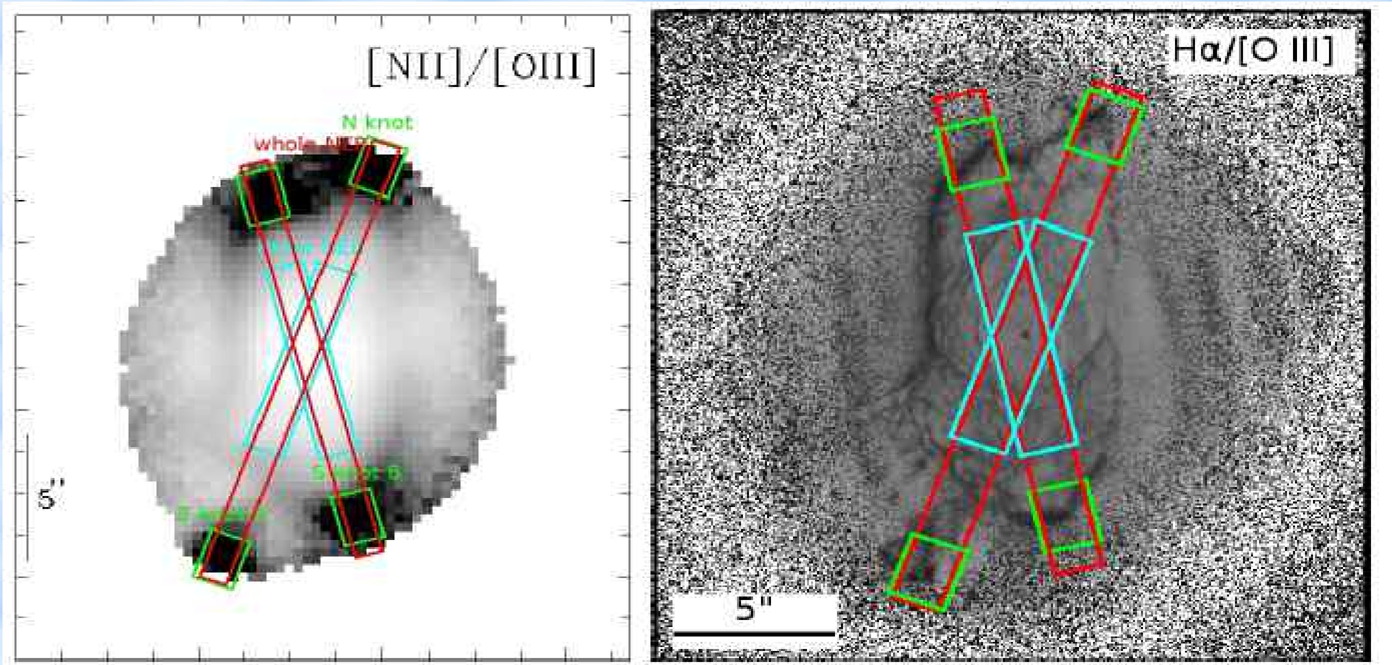
(Akras & Gonçalves 2016)

Conclusion

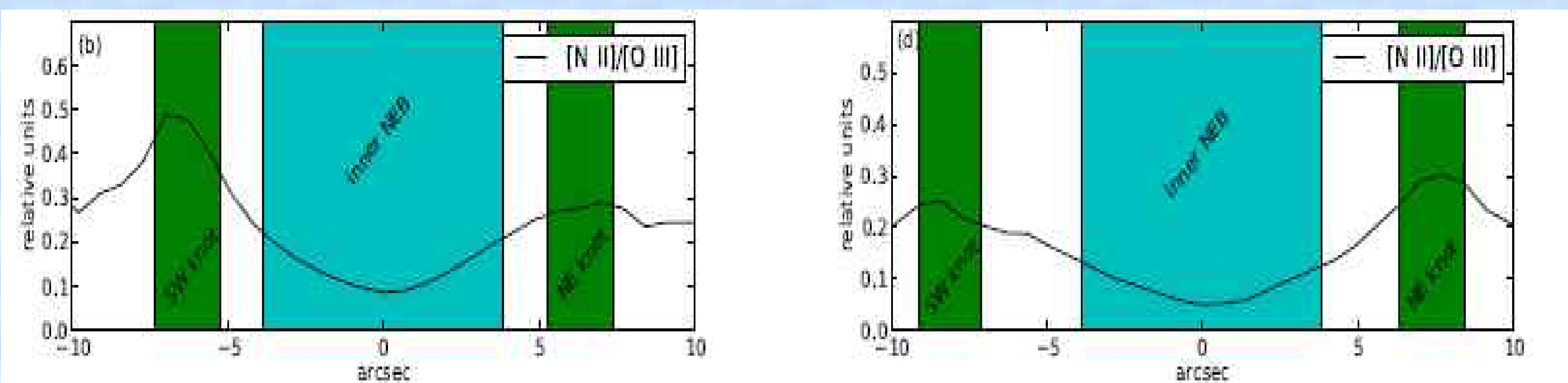
- The new Log(f_{shock}/f_{star}) vs I(N[II], [O I],etc) diagnostic diagrams provide a useful tool disentangle the photo-ionized and shock-excited regions
- The excitation mechanisms in LISs is a combination of shock and UV excitation mechanisms
- H_2 emission is detected for the first time in LISs of two Galactic PNe (K4-47 and NGC 7662)
- LISs are also made of H_2 gas
- The H_2 v=1-0/v=2-1 ratio increases with the intensity of low-ionization lines
- The H_2 v=1-0/v=2-1 ratio in K 4-47 indicates shock excitation
- The H_2 v=1-0/v=2-1 ratio in NGC 7662 indicates shock and UV excitation

Thank you

NGC 6572

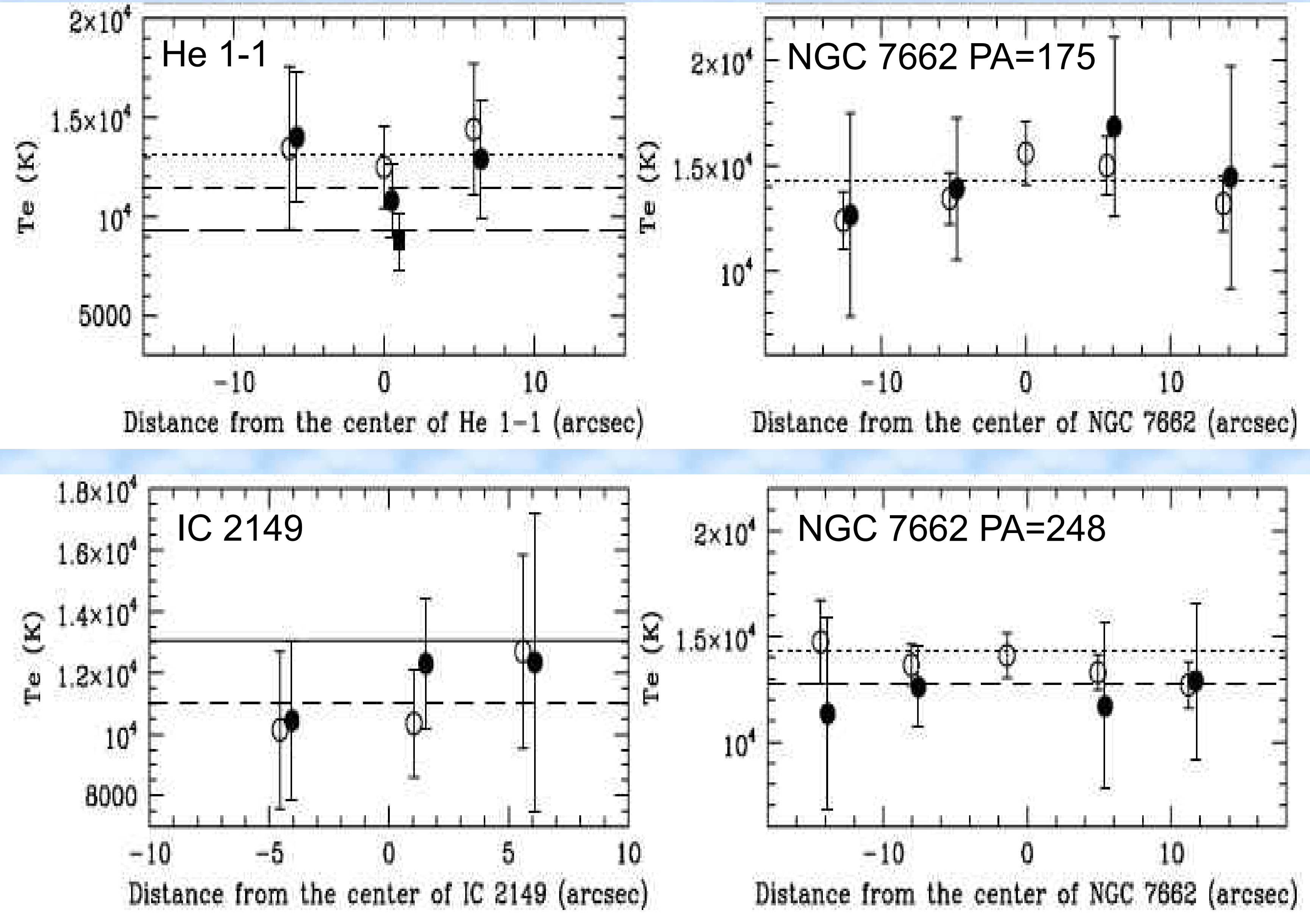


(Miranda et al. 1999)



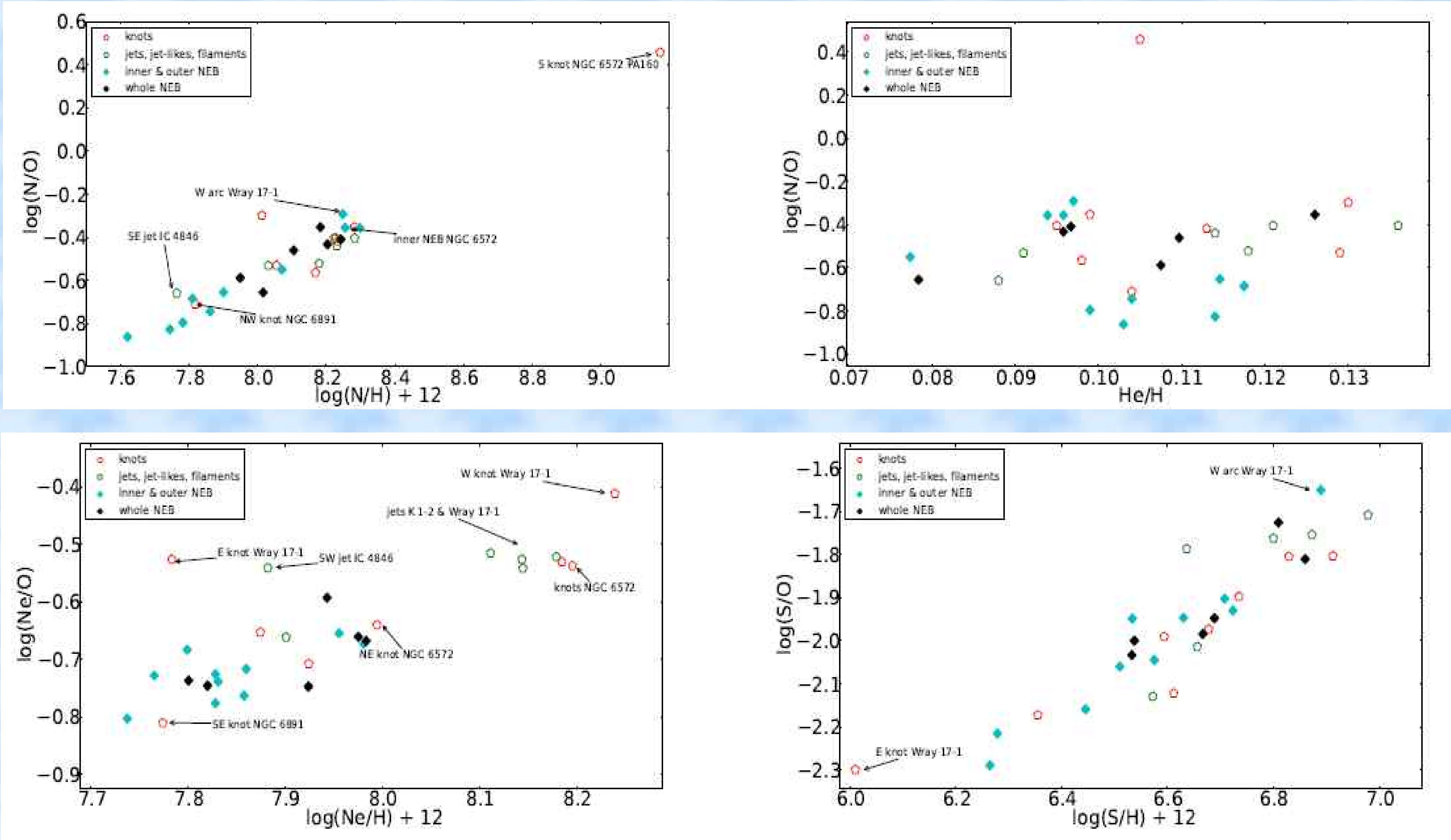
(Akras & Gonçalves 2016)

Electron temperature



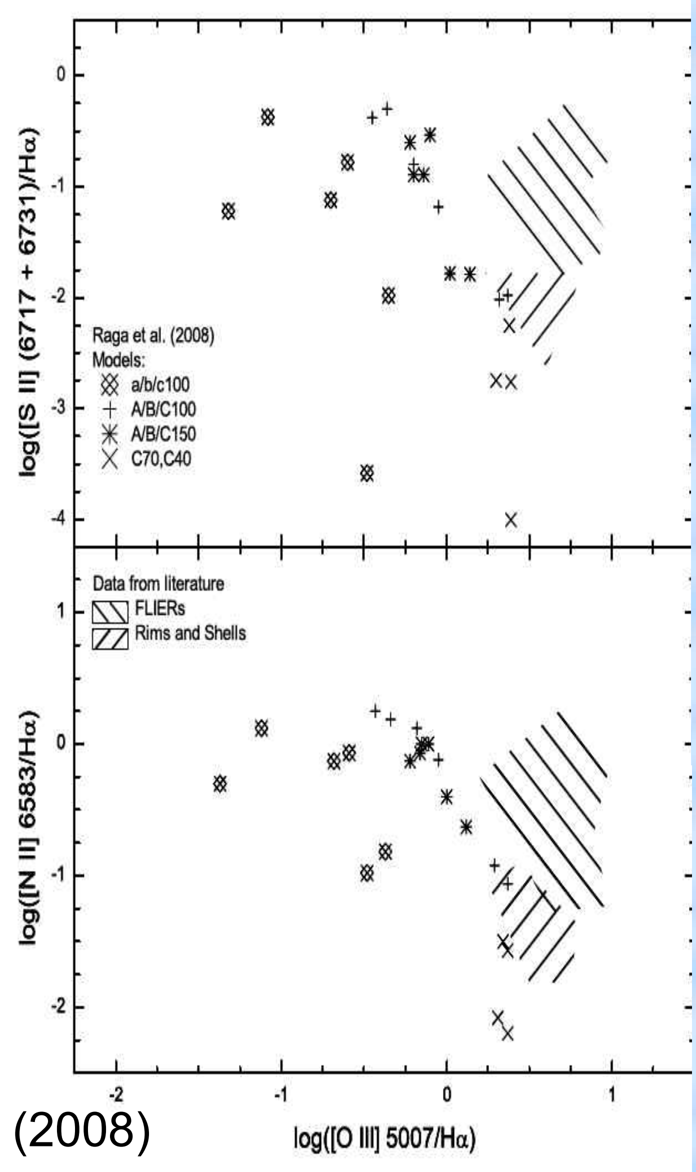
(Gonçalves et al. 2009)

Chemical abundances



(Akras & Gonçalves 2016)

Shock-excited vs. photo-ionized regions



Raga et al. (2008)

- a→b→c, the distance from the central source decreases from 3→1→0.3 (10^{18} cm)
- a→A, the T_{eff} increses (50000K→70000K); Raga et al. (2008)

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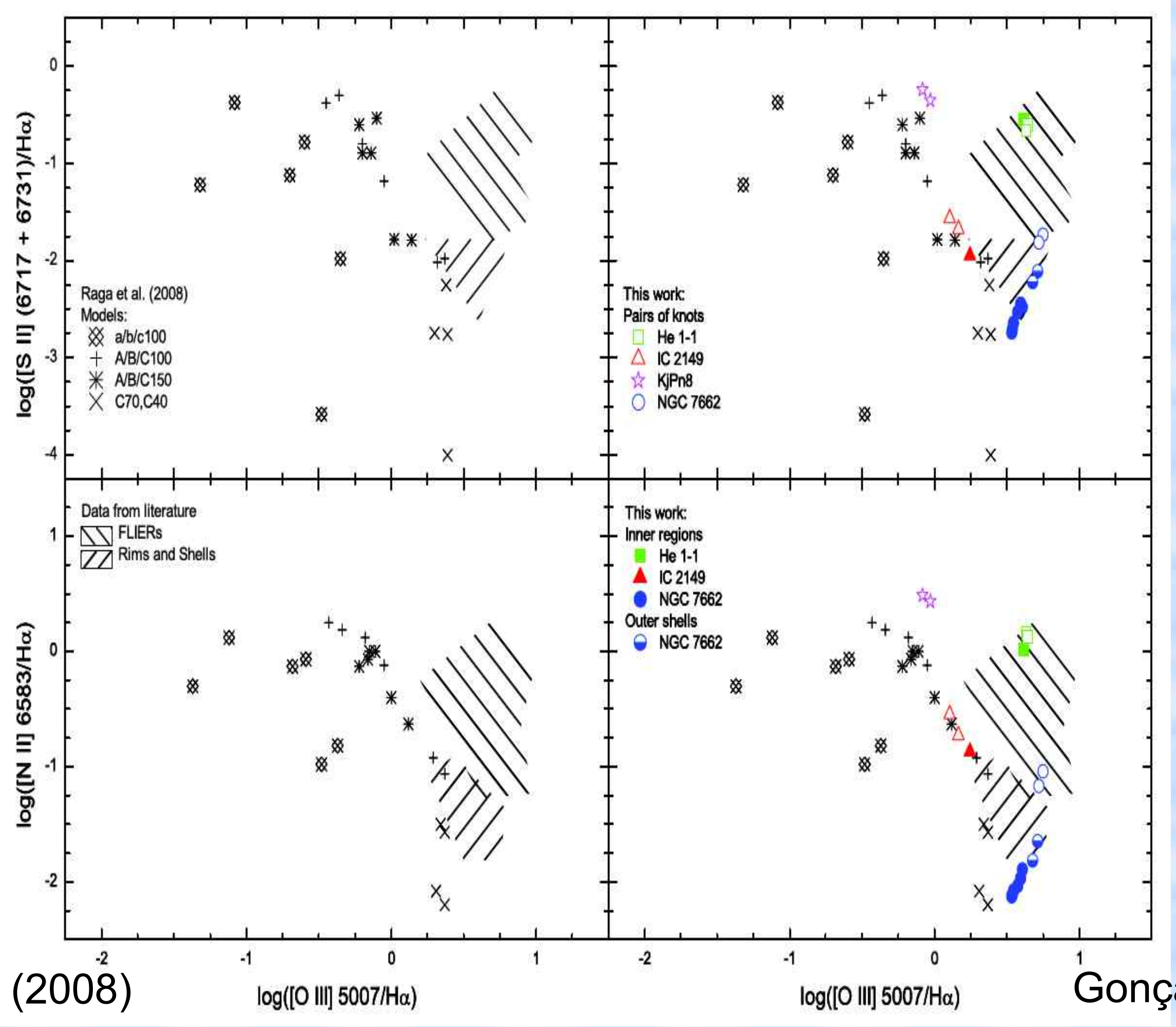

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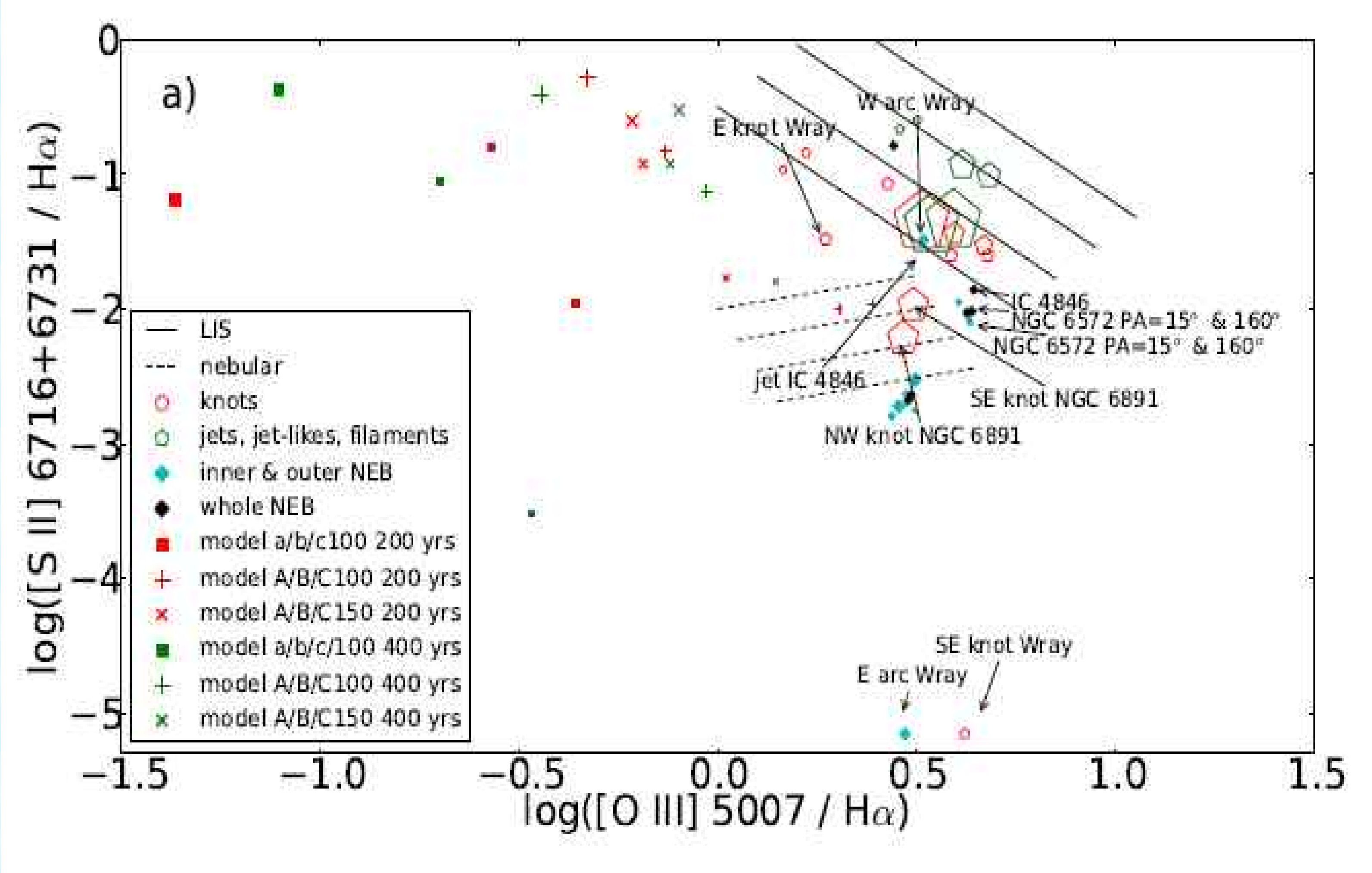
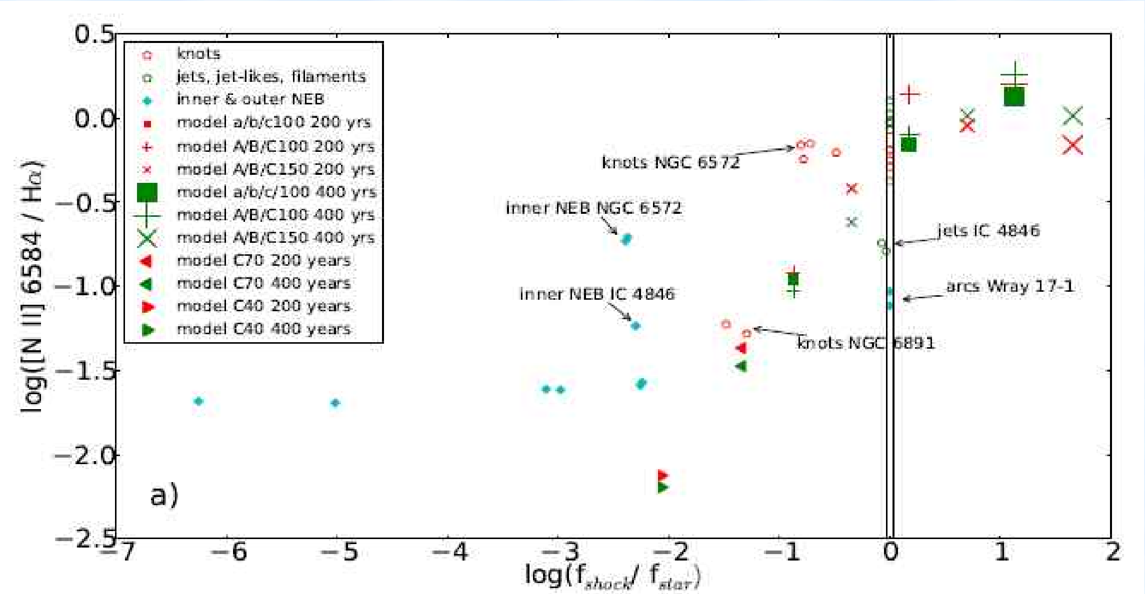


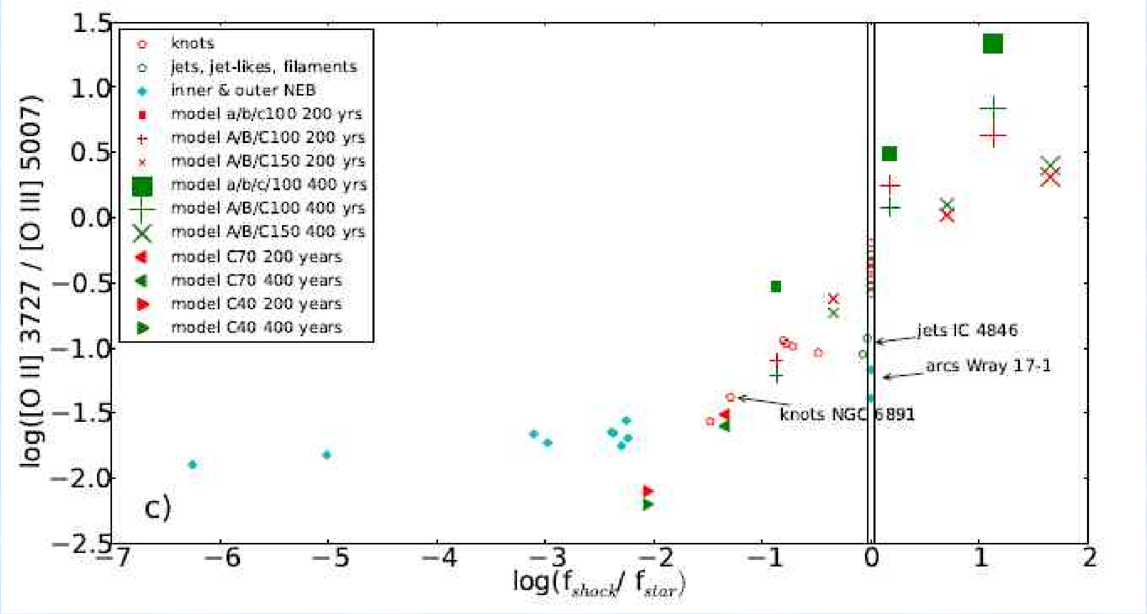
(Akras & Gonçalves 2016)

Log(f_{shock}/f_{star}) vs I(λ)



- ➔ ***f_{star}***
  - T_{eff} and L☉
  - Distance of the PN
  - Knot's distance from the central star

(Akras & Gonçalves 2016)



- ➔ ***f_{shock}***
  - Expansion velocity
  - Density

$$f_{\rm shocks} = 2.28 \times 10^{-3} (V_s/100\ {\rm km\,s^{-1}})^3 \times (n/cm^{-3})$$

(Dopita & Sutherland 1996)

Formation mechanisms

- GISW model with an equatorial enhancement (e.g. torus/disk)

  → a close binary system in a common-envelope phase (Soker & Livio 1994)

  → magnetic fields (Garcia-Segura et al. 1999, Blackman et al. 2000)

- Interaction with the ISM (Soker & Zucker 1997, Cliff et al. 1995)
- Dynamical and radiation instabilities during the evolution of PNe (Garcia-Segura et al. 1999)
- Stagnation models (Steffen & Lopez 2000)
- Fossil AGB condensations

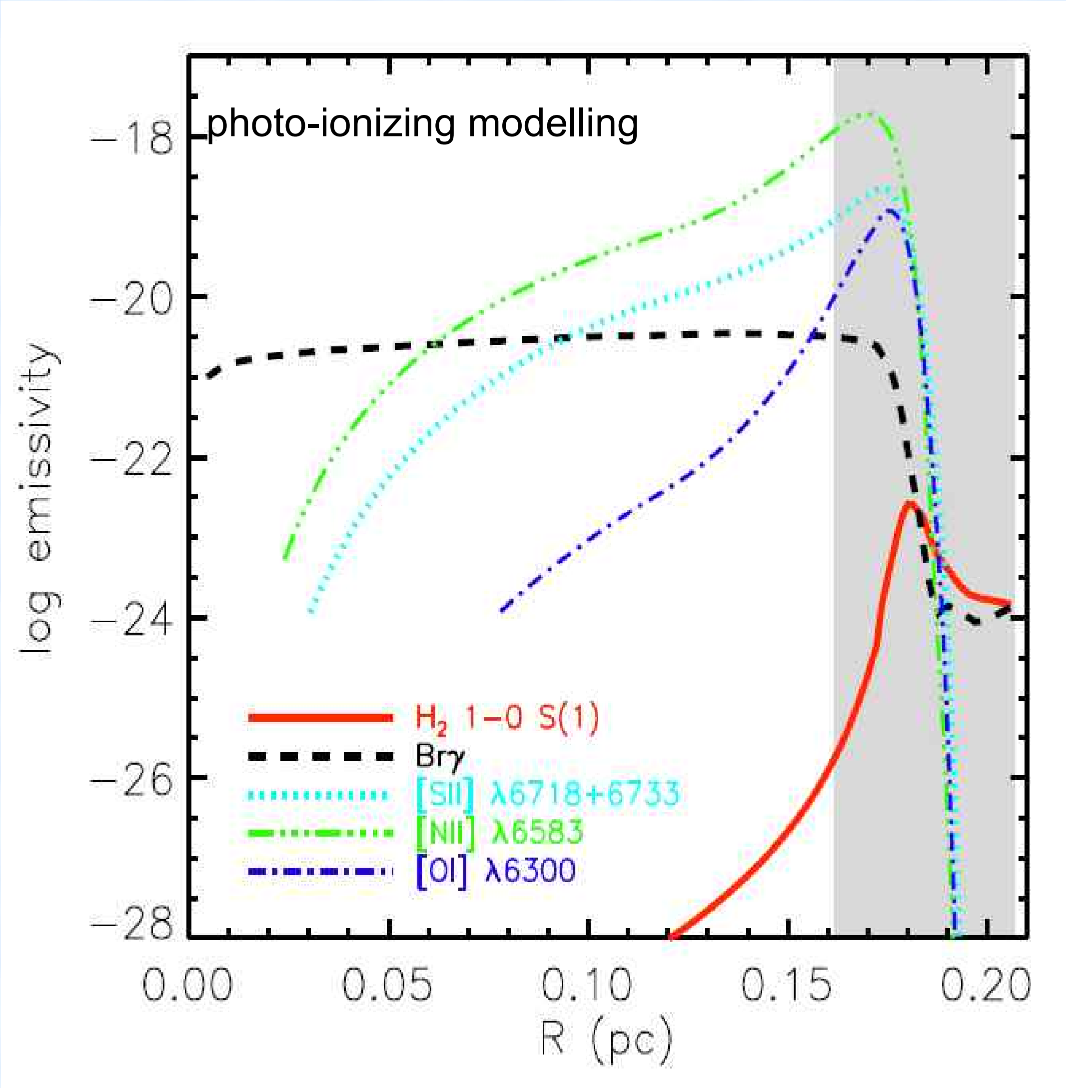
Excitation mechanisms?

I. Absorptions of UV photons emitted from the central star (photo-ionized or fluorescence regions)

II. Shock interactions

III. A combination of both

Low-ionization lines and H_2 emission



(Aleman et al. 2011)

- H_2 molecule coexists with N^+, S^+ and O^O
- H_2 flux increases with T_{eff}
- A linear relation between the H_2 and [O I] fluxes in PNe has been reported (Reay et al. 1988)