Fast and furious: Modeling the cometary structure of the planetary nebula HFG1

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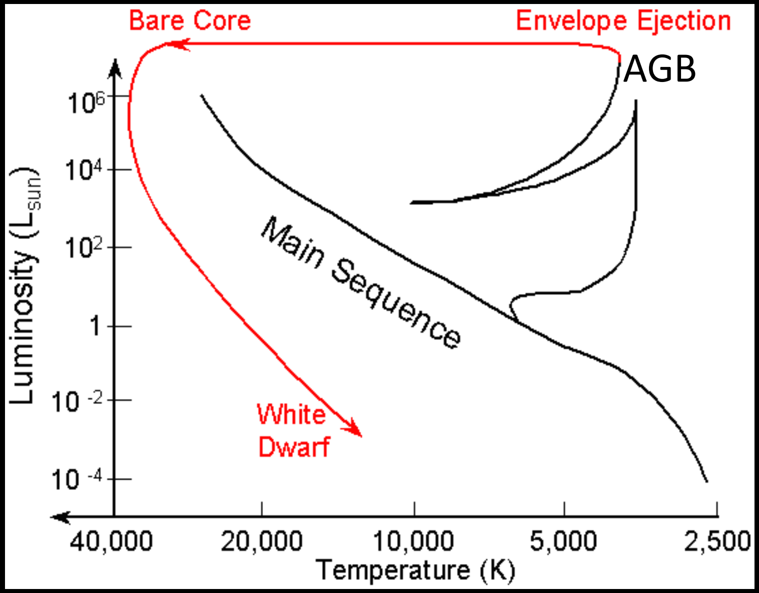
Planetary Nebulae (PNe)

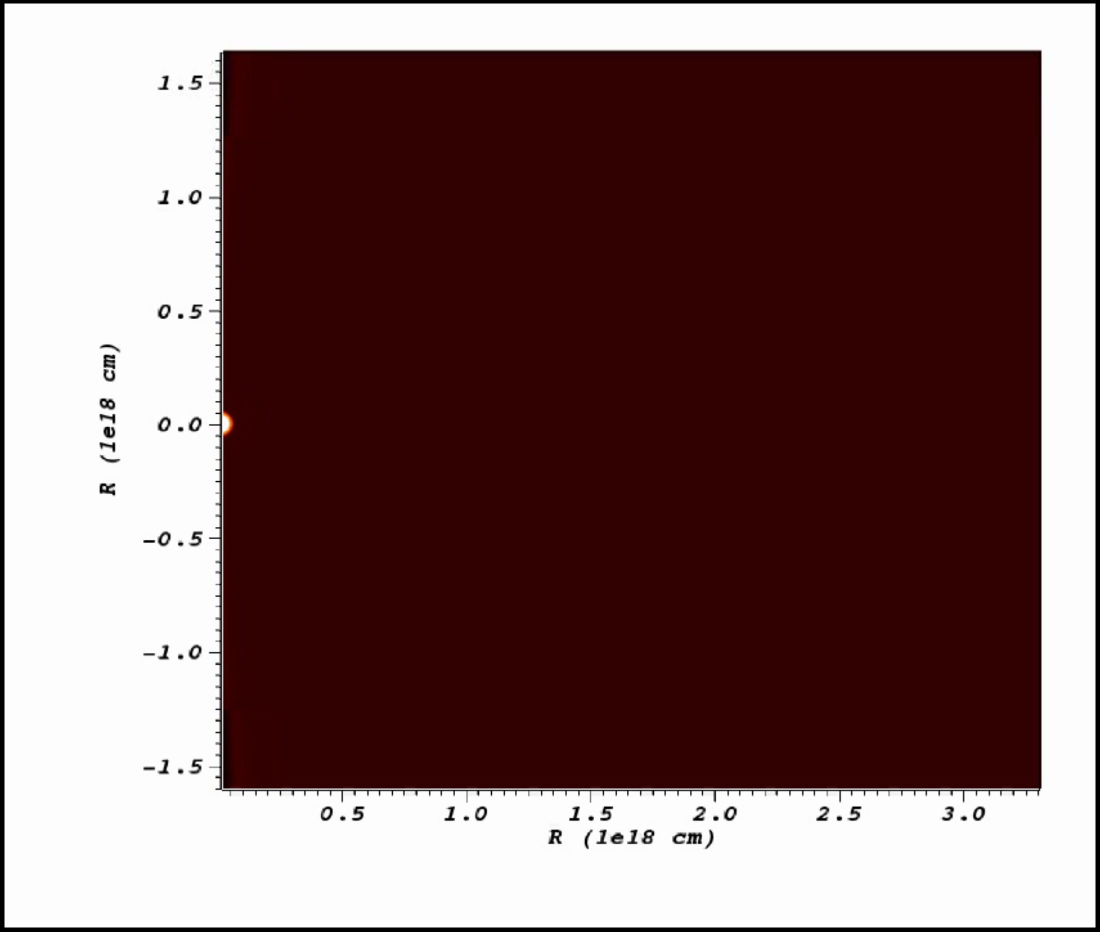
- Large expanding shells of ionized gas
- Their nature is connected with last stage of low/intermediate mass stars (~ 1- 8 $M_\odot$)
- Formed by the mass outflows that accompany the death of the star and the formation of a white dwarf

Planetary Nebulae (PNe)

<u>Interactive Stellar Wind theory</u> (Kwok et al. 1978)



- AGB: slow dense stellar wind



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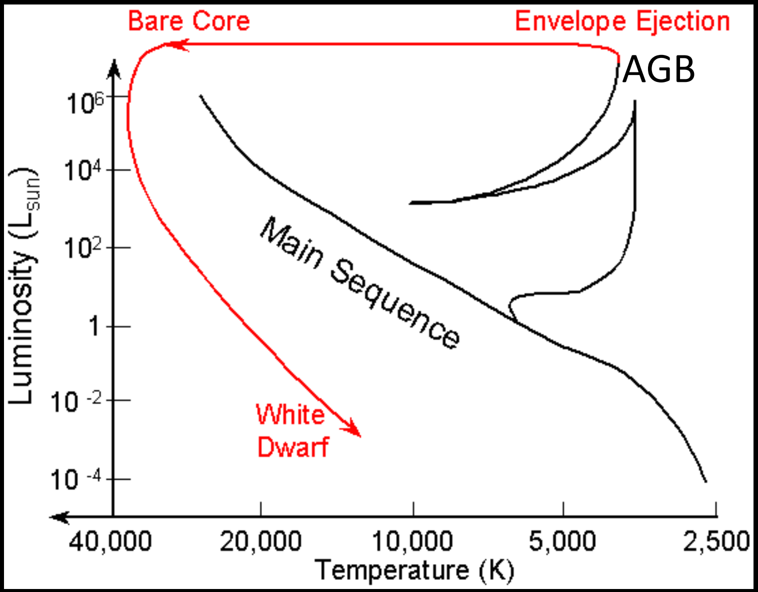
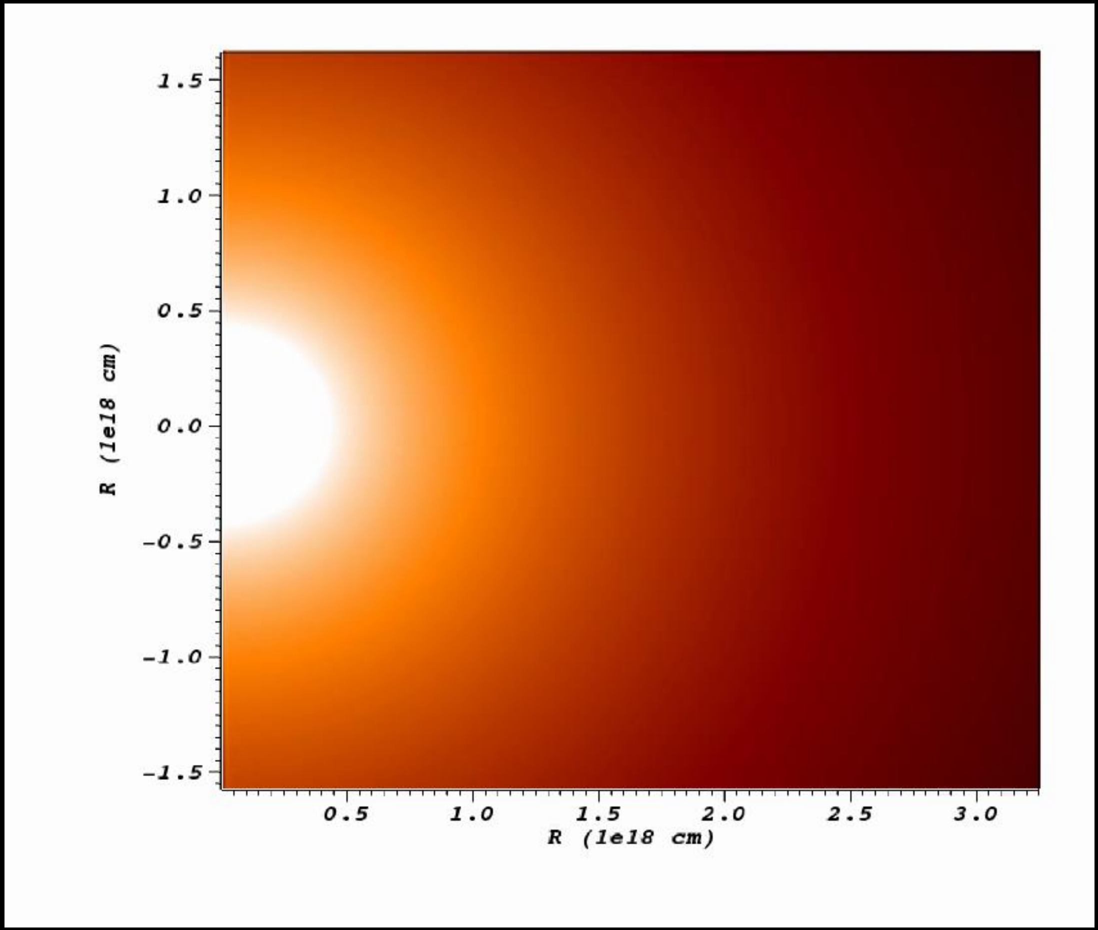


- AGB: slow dense stellar wind
- Contraction of AGB core: Fast tenuous wind



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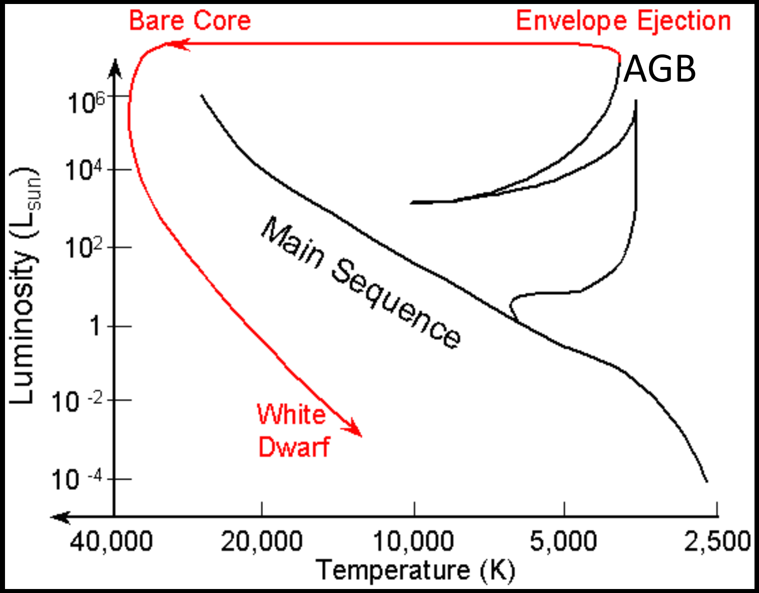
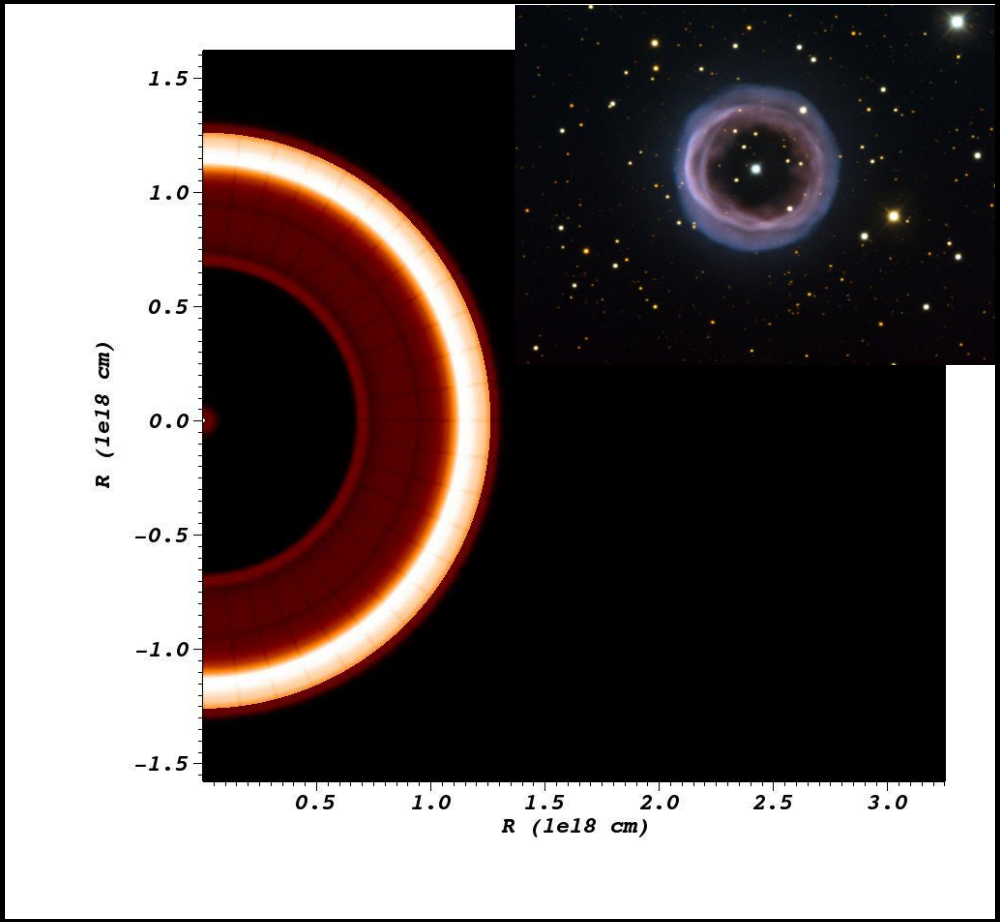




- AGB: slow dense stellar wind
- Contraction of AGB core: Fast tenuous wind
- Photoionization from the hot central star

Diversity of Planetary Nebulae

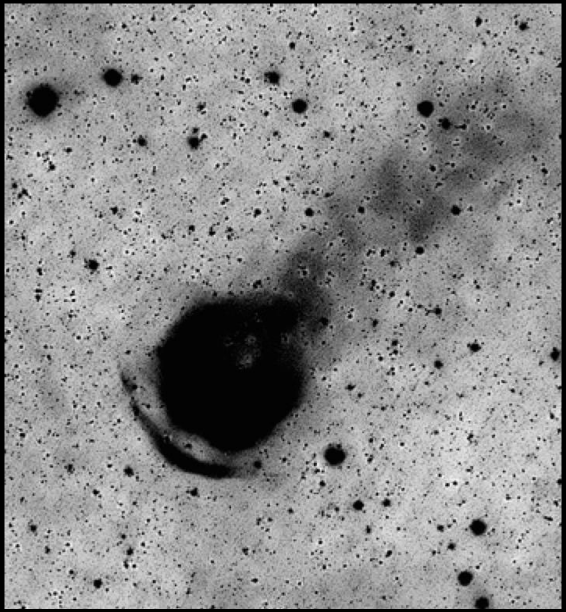



<u>For non-spherical PNe more ingredients are needed to be introduced:</u>

- Binary central star → Aspherical mass outflows
- Magnetic fields
- Inhomogeneous ambient medium

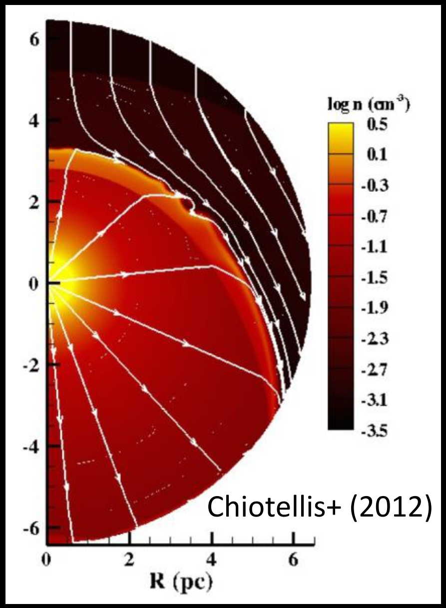
The intriguing case of HFG1

- 9 arcmin asymmetric nebula
- 15 arcmin bow-shaped outer shell (Heckathorn+ 1982)
- Long collimated tail:
  < 20 arcmin long;
  5 arcmin wide (Boumis+ 2009)
- Proper motion: PM = 13 ± 1.5 mas yr^{-1}



"HFG1 morphology is due to the interaction of the local ambient medium with the supersonically PN" (Boumis+ 2009)

Two rare PNe properties in HFG1



Chiotellis+ (2012)

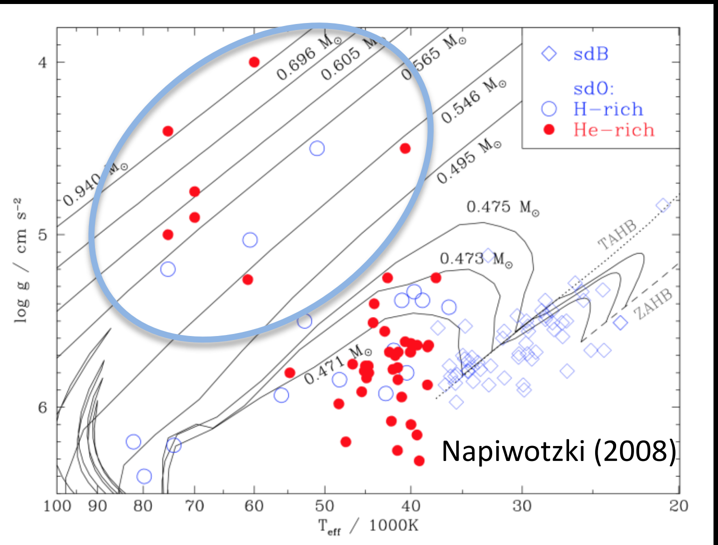
1. ***The first observed PN which reveals a bow – shaped shell***

- Geometry of a bow shock: function of dM/dt, n_{ISM}, u_{star}
- Detection of optical bow shocks could be used for determine the properties of the stellar wind

2. ***Central binary V664 Cas:***

main sequence + luminous O- Type subdwarf (SdO)

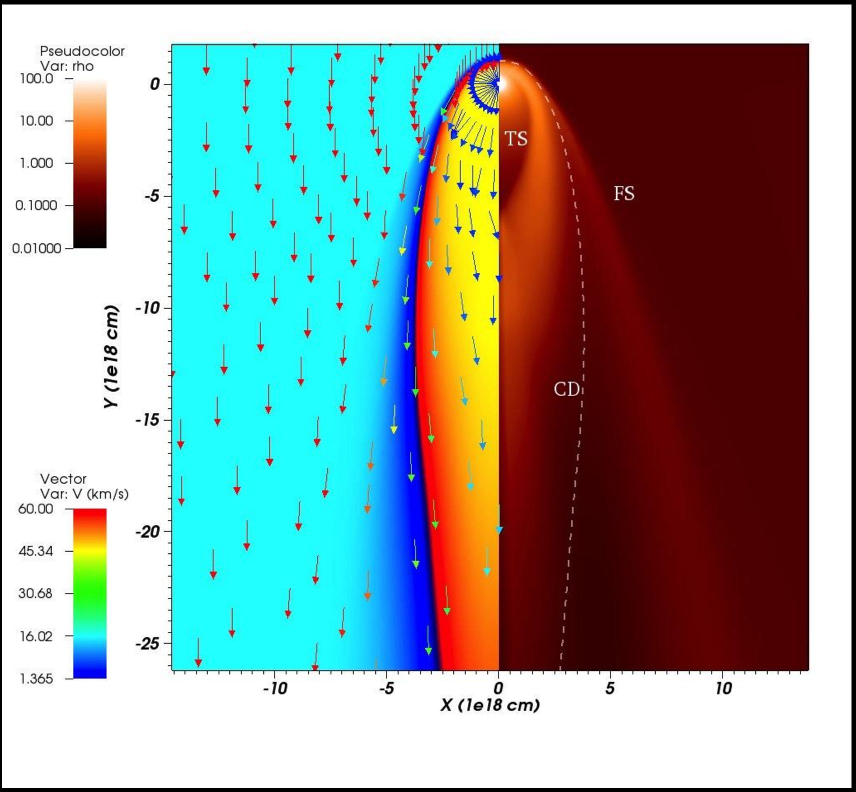
- SdO subdwarfs: remnant of a stellar evolution beyond the AGB phase ?
- If yes PNe associations are needed → only few PNe + SdOs systems have been observed (Aller+ 2014)



Napiwotzki (2008)

Hydrodynamic Modeling of HFG1

Code: AMRVAC (Keppens et al. 2003)



- Continuous spherically symmetric inflow in the form of a stellar wind
- ISM is entering the grid antiparallel to the y-axis

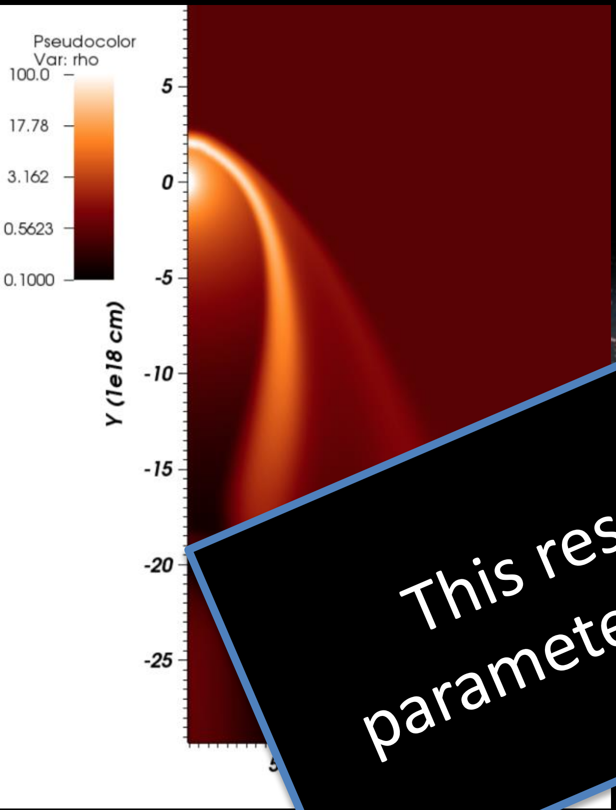
Input parameters:

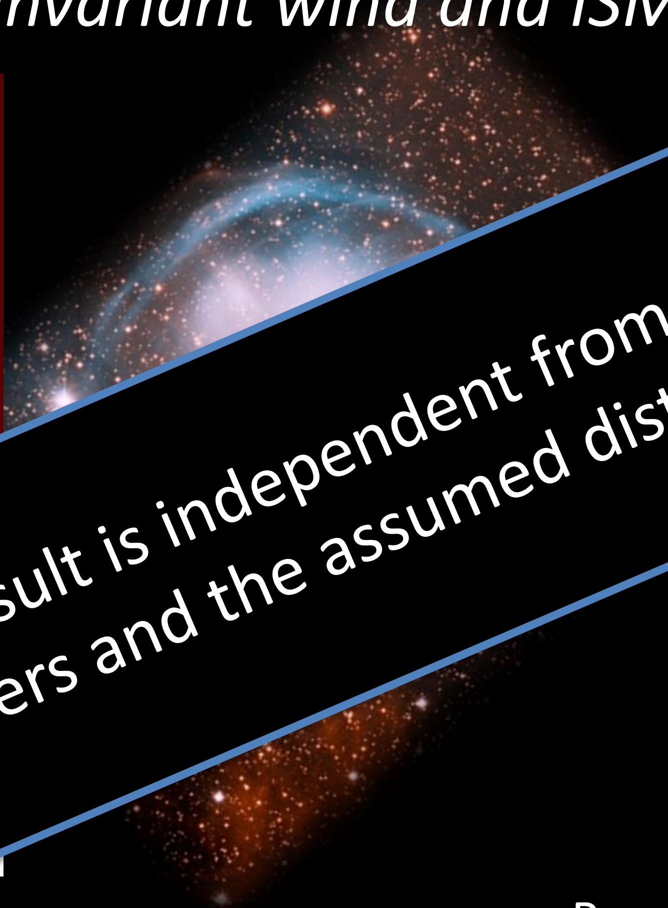
- $dM/dt = 10^{-7} - 10^{-5}\ M_\odot\ yr^{-1}$
- $u_w = 5 - 15\ km\ s^{-1}$
- $u_{star} \rightarrow PM = 13 \pm 1.5\ mas\ yr^{-1}$
- $n_{ISM} \rightarrow P_{wind} = P_{ISM}$

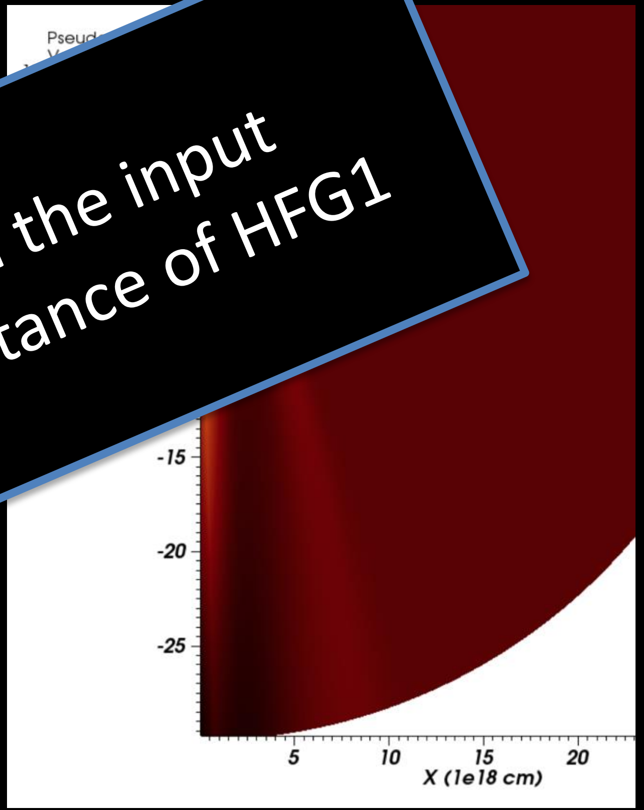
AGB winds

Results

Models with time invariant wind and ISM properties







This result is independent from the input parameters and the assumed distance of HFG1

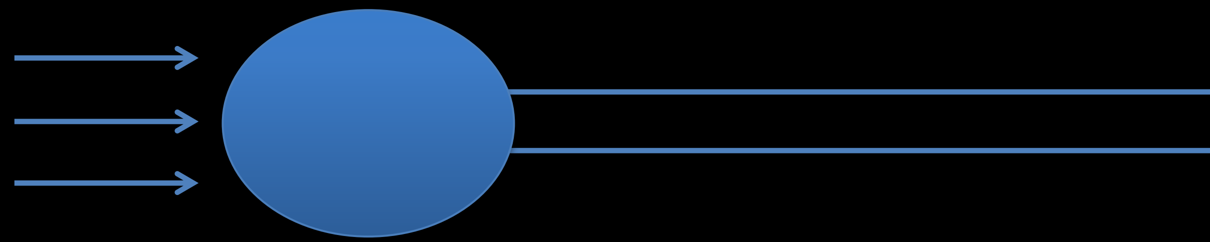
- Reproduces the stagnation point radius ✓
- More extended shell ✗
- The tail starts far away from the central star ✗

- Reproduces the width and length of the tail ✓
- Smaller stagnation point radius ✗
- The overall structure of the shell is much smaller ✗

Alternatives

- *Models with time invariable stellar wind/ ISM properties cannot reproduce HFG1*

- *Time variability?*



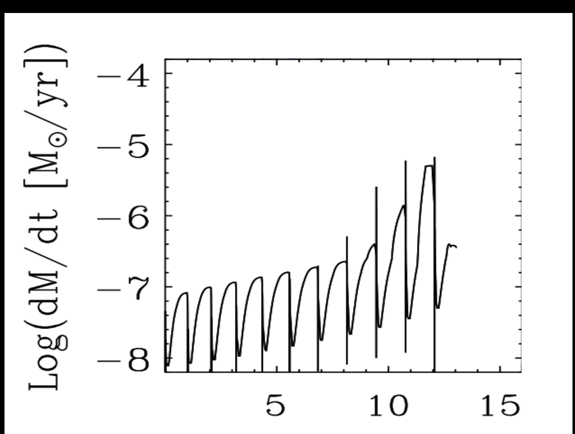
$t_1 : P_{wind} = P_{ISM}$

$t_2 : P_{wind} \uparrow$ or and $P_{ISM} \downarrow$

- *<u>What is changing with time</u> ?*
  - The ISM medium decreased
  - The systemic velocity decreased
  - The mass loss rate increased

A "coincidence" is needed

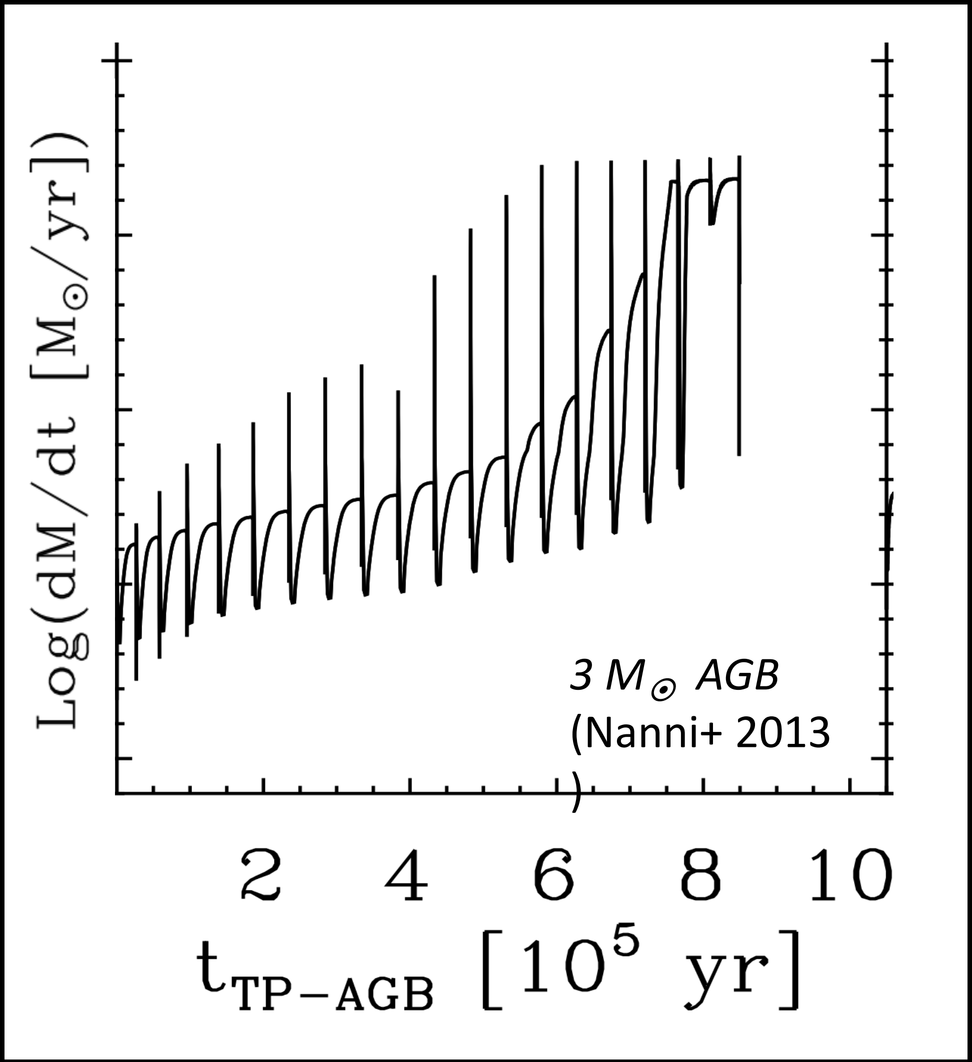
-> Motivation: stellar evolution

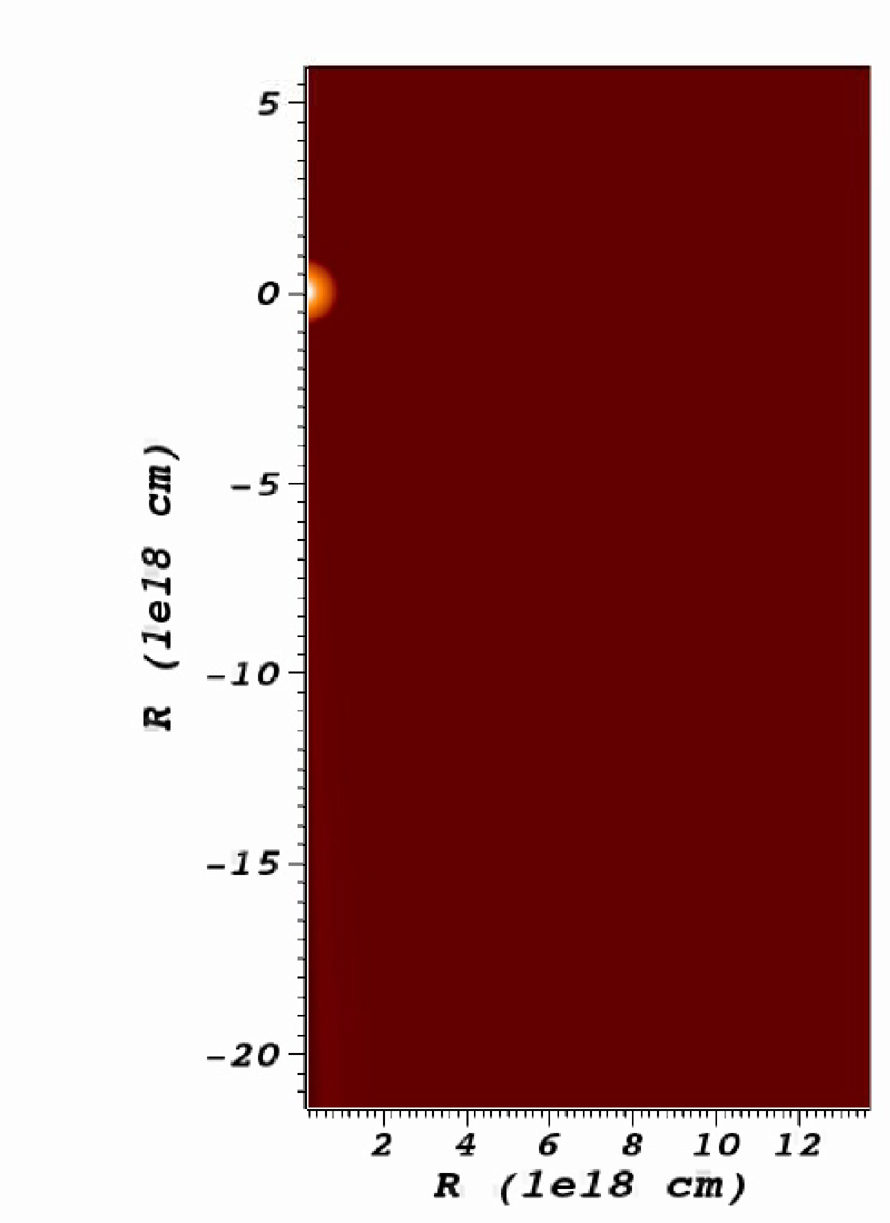


AGB winds are time variable !

HFG1 based on the properties of V664 Cas

Stellar evolution models: *Progenitor of the 0.57 $M_\odot$ sdO was a 3 $M_\odot$ AGB star*



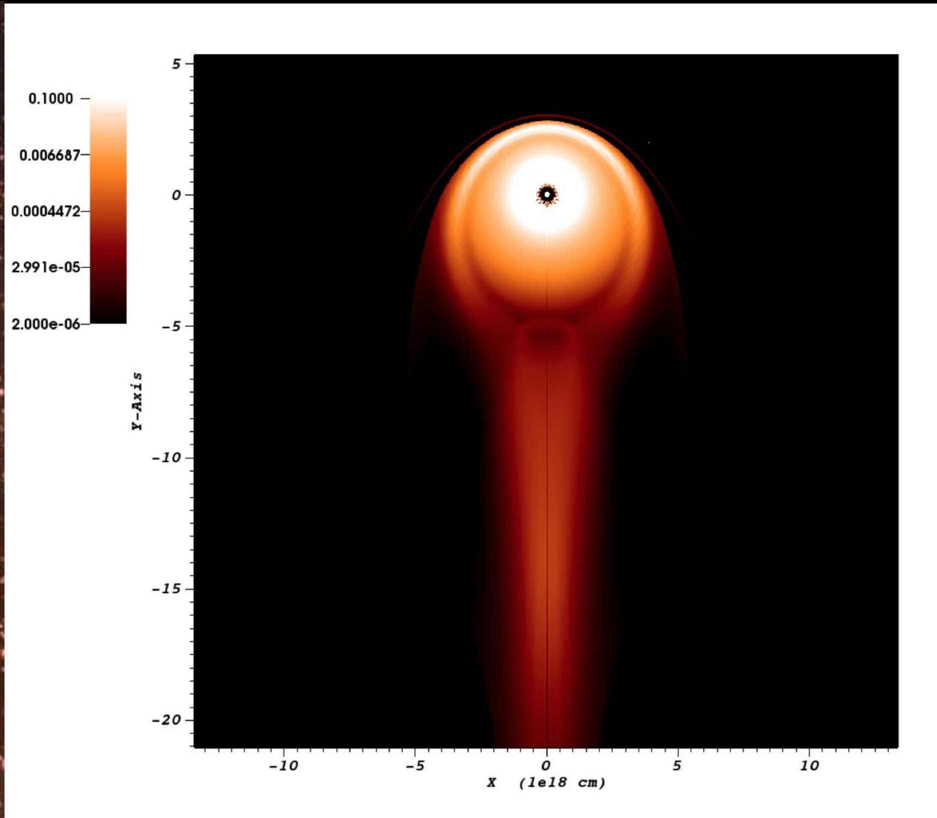


Results

- *Introduce fast wind based on the post-AGB evolution models*
- *Photoionization: T → 10^4 K for regions with gold plasma (T< 1000 K)*

HFG1

Luminosity



Conclusions

- The cometary structure of HFG1 results form the supersonic motion of the PN in respect to the local ISM

- The morphological properties of HFG1 can be explained by the AGB and post-AGB evolution models for a 3 $M_\odot$ star

- This results is aligned with the current observed properties of SdO primary of V664 Cas

  → bridges the PN properties with the evolution of its central star

What has been shown from HFG1 modeling:

- AGB winds *must* be variable to explain its morphology

- Verifies the predictions AGB and post- AGB evolution theory towards the formation of sdO stars

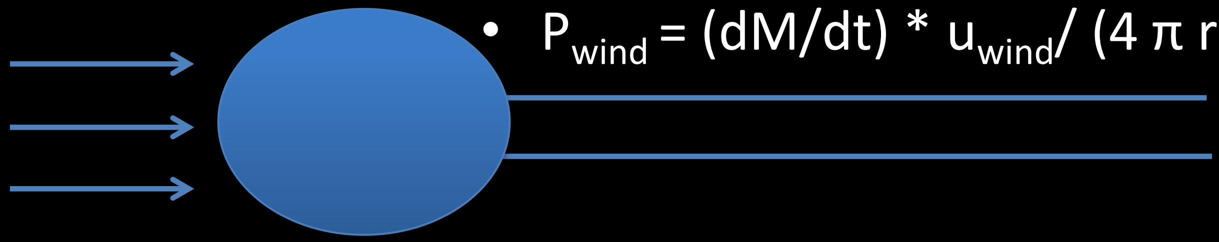
Alternatives

- *Models with time invariable stellar wind ISM properties cannot reproduce HFG1*

- *Time variability?*

t_1 : $P_{wind} = P_{ISM}$

t_2 : P_{wind} ↑ or and P_{ISM} ↓



- $P_{ISM} = n_{ISM} * u^2_{star}$
- $P_{wind} = (dM/dt) * u_{wind} / (4 \pi r^2)$

- *What is changing with time ?*
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A "coincidence" is needed

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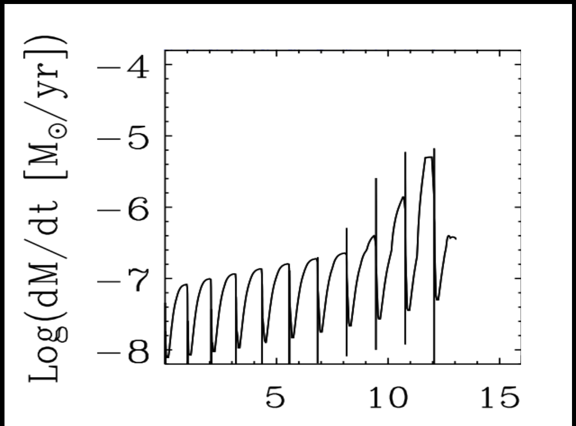
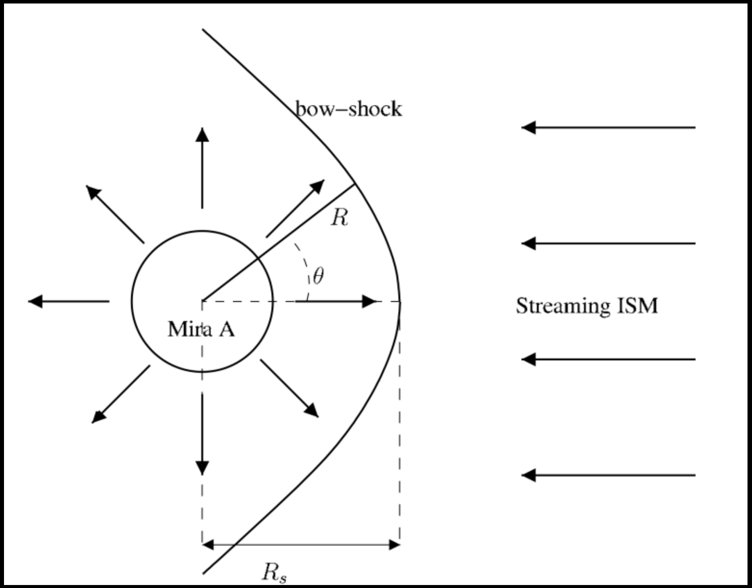


AGB winds are time variable !

A model for HFG1

"HFG1 morphology is due to the interaction of the local ambient medium with the supersonically PN" (Boumis+ 2009)



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- $u_w = 5 - 15\ km\ s^{-1}$

AGB wind

- $u_{star} \rightarrow PM = 13 \pm 1.5\ mas\ yr^{-1}$ (observed)
- $n_{ISM} \rightarrow$ stagnation point:

$$P_{wind} = P_{ISM} \Rightarrow$$

$$n_{ISM} = 1.78 \times 10^3\ (dM/dt\ .\ u_w) / (Rs\ .u_{star})$$

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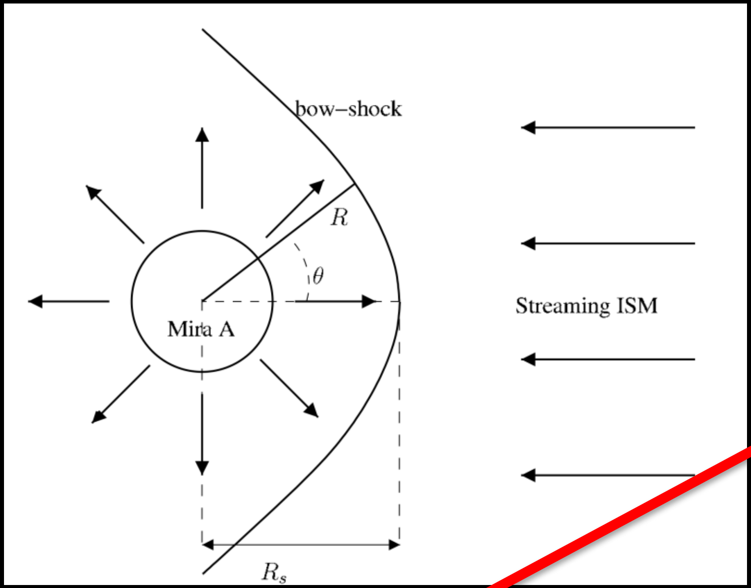

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} AGB wind

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- n_{ISM} → stagnation point:

$$P_{wind} = P_{ISM} \Rightarrow$$

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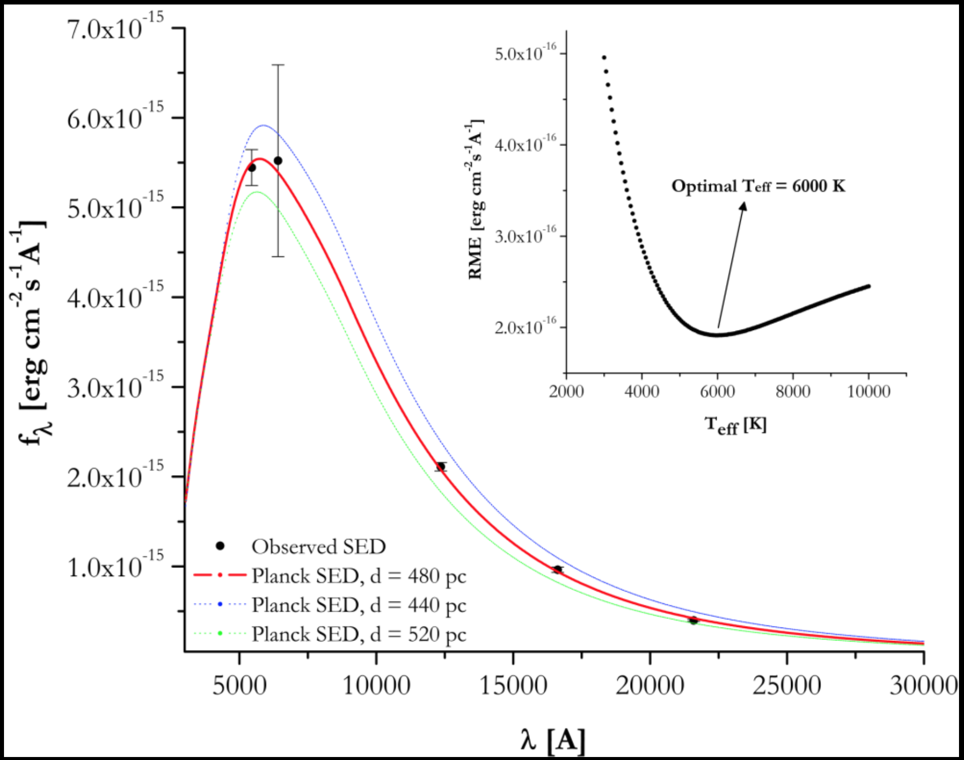
Distance dependent: D_{HFG1} = 310 – 950 pc (Exter+ 2005)

→ Large uncertainties are introduced to the model

Re-estimation of HFG1 distance



- Model the spectral energy distribution of the secondary star of V664 Cas (following Bonanos 2006):

$$f_\lambda = \frac{1}{D^2} R^2 F_\lambda 10^{-0.4A(\lambda)}$$

Re-estimated distance: **D_{HFG1}= 480 ± 40 pc**