REVEALING NEW CHANNELS OF SINGLE AND BINARY EVOLUTION AND NUCLEOSYNTHESIS

WITH

POST- ASYMPTOTIC GIANT BRANCH (POST-AGB) STARS

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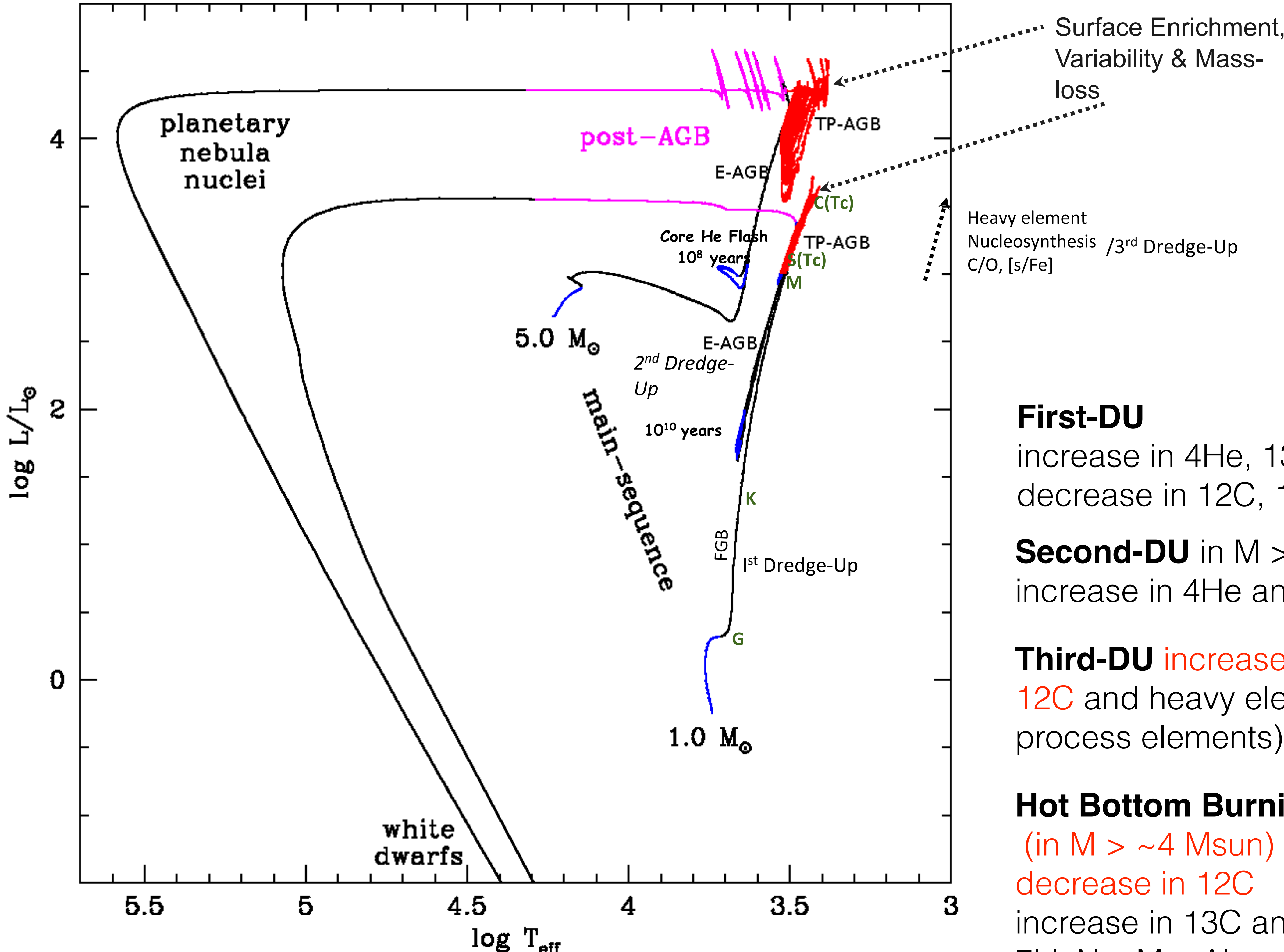
- The search for Post-AGB stars in the Magellanic Clouds
- Constraining AGB nucleosynthesis with observations from post-AGB stars
- A newly discovered phase in binary *evolution*: The *dusty* post-RGB phase
- Monitoring Post-AGB and Post-RGB binaries…
- Constraining dredge-up AGB stars with 13C/12C, C/O from post-AGB stars
- Resolving proto-planetary disc around post-AGB binaries
- The B[*e*] phenomenon in *evolved* stars

POST-AGB STARS - EVOLUTIONARY STATUS

Nuclear burning lives are terminated on the AGB with a *'Superwind'* mass-loss (mass-loss rates up to $10^{-4}\,M_\odot\,yr^{-1}$)



First-DU
increase in 4He, 13C, 14N, 17O
decrease in 12C, 16O and 18O

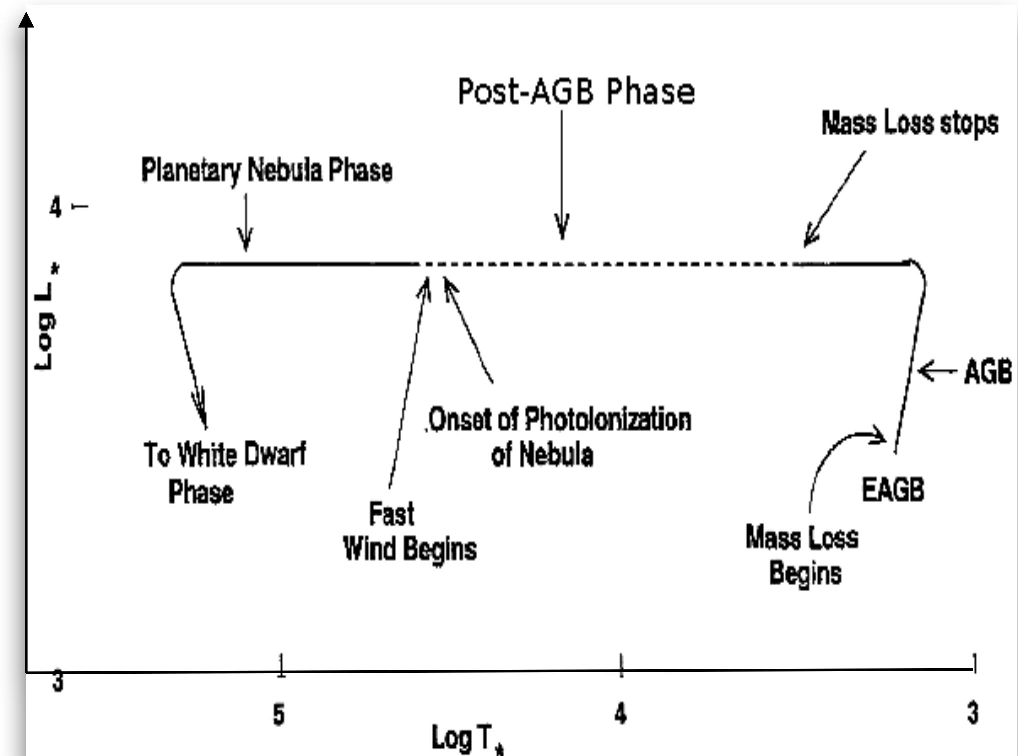
Second-DU in M > ~4 Msun
increase in 4He and 14N

Third-DU increase in 4He and 12C and heavy elements (s-process elements)

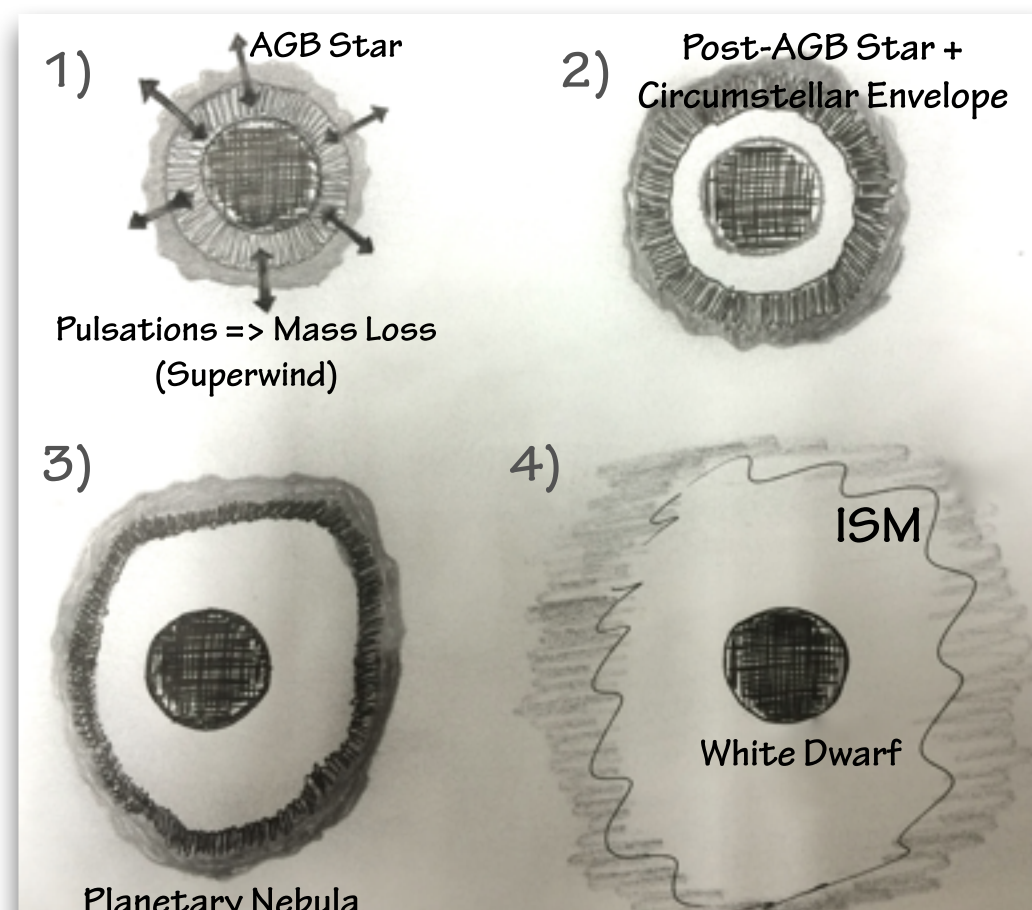
Hot Bottom Burning
(in M > ~4 Msun)
decrease in 12C
increase in 13C and 14N
7Li, Na, Mg, Al

SINGLE POST-AGB STARS

Super-wind mass loss resulting in a 'post-AGB' star with a dusty circumstellar shell



- Transient phase
- A - K Spectral types
- R* ~ 1 AU on the AGB to R_{WD}
- Variable
- Obscure to naked



AN ALTERNATIVE EVOLUTIONARY CHANNEL

Great majority of PNe are not spherical: axi-symmetry; point-symmetry

jet-like structures are common… NOAM :)

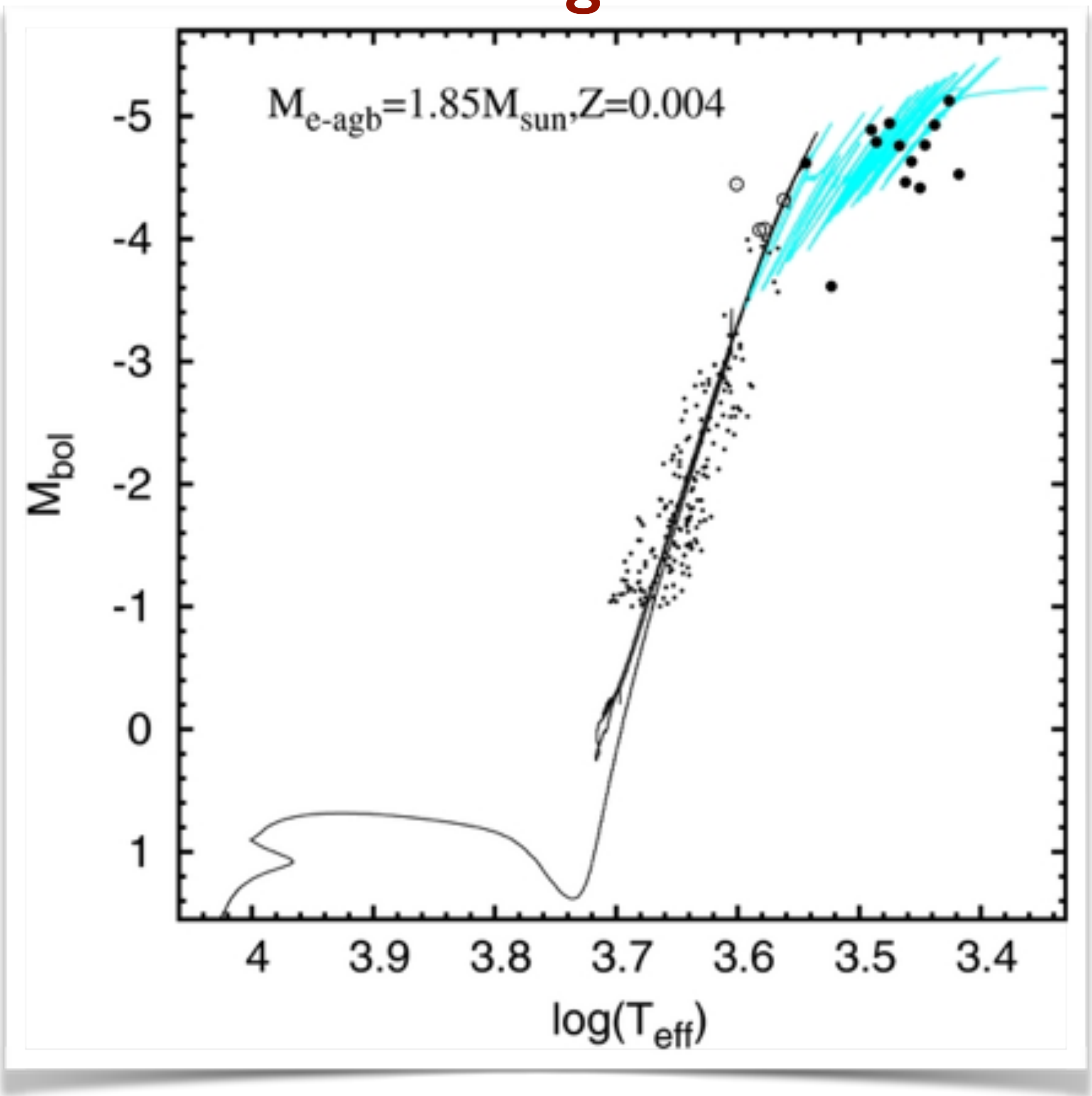
(Balick & Frank, 2002; De Marco 2008, Zijlstra 07)

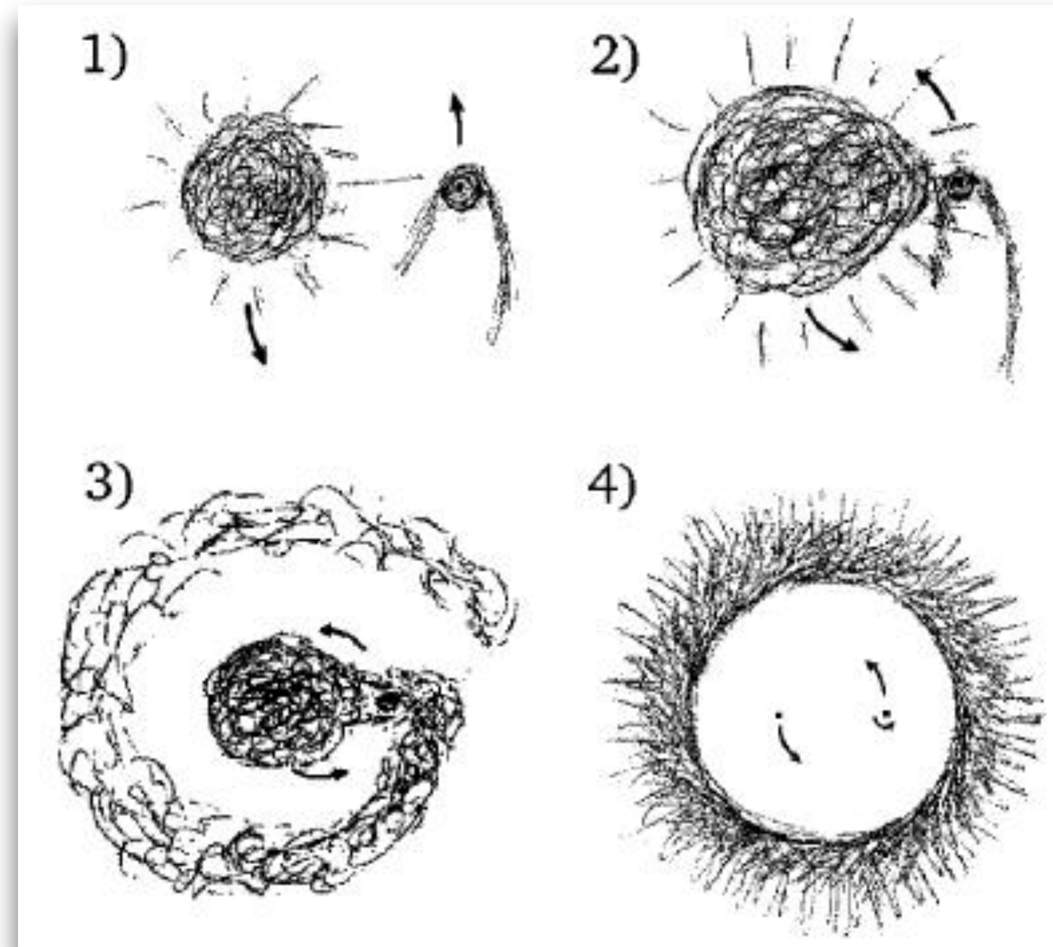
BINARITY!

Binary interaction can determine the ultimate of the star …

BINARY EVOLUTIONARY SCENARIOS

Roche lobe filling occurs **on the AGB but above the RGB-tip…**





Courtesy: Michel Hillen

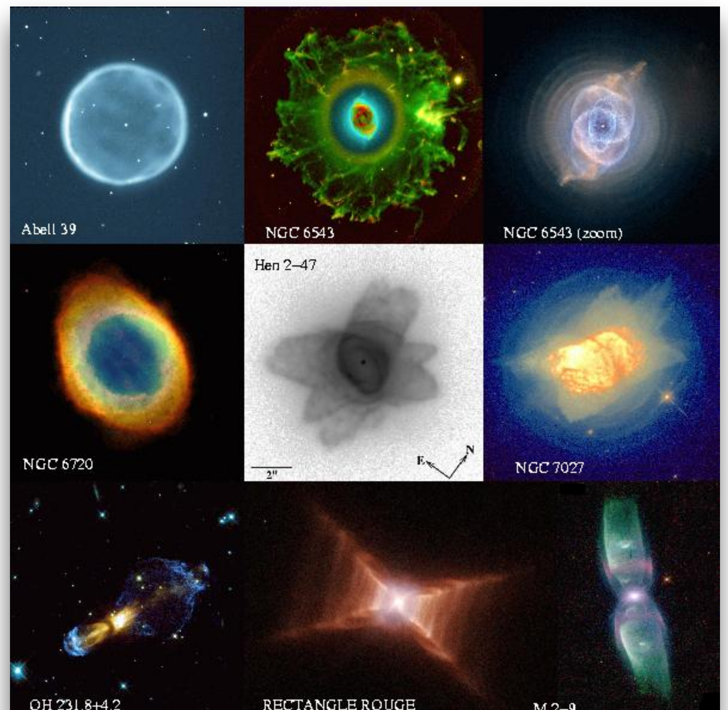
OUTCOME ~ some sort of a stable mass transfer

RESULT ~ Formation of an intermediate period binary

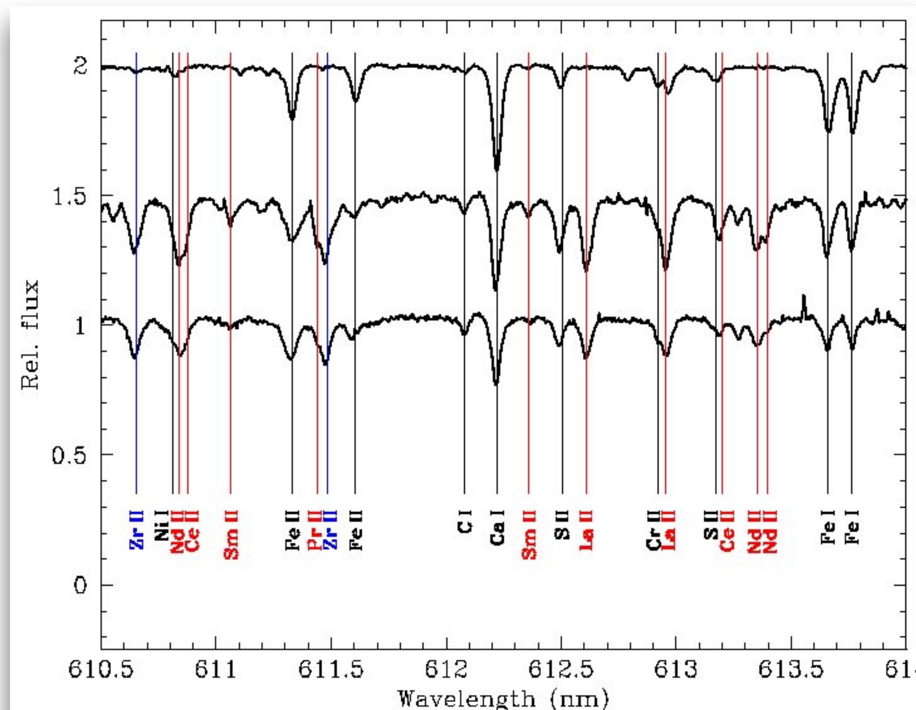
e.g.: Post-AGB binaries surrounded with DUSTY circumbinary discs (Van Winckel 2007)

Common envelope evolution via some sort of a stable mass transfer resulting in a circumbinary disc around the 'post-AGB' star

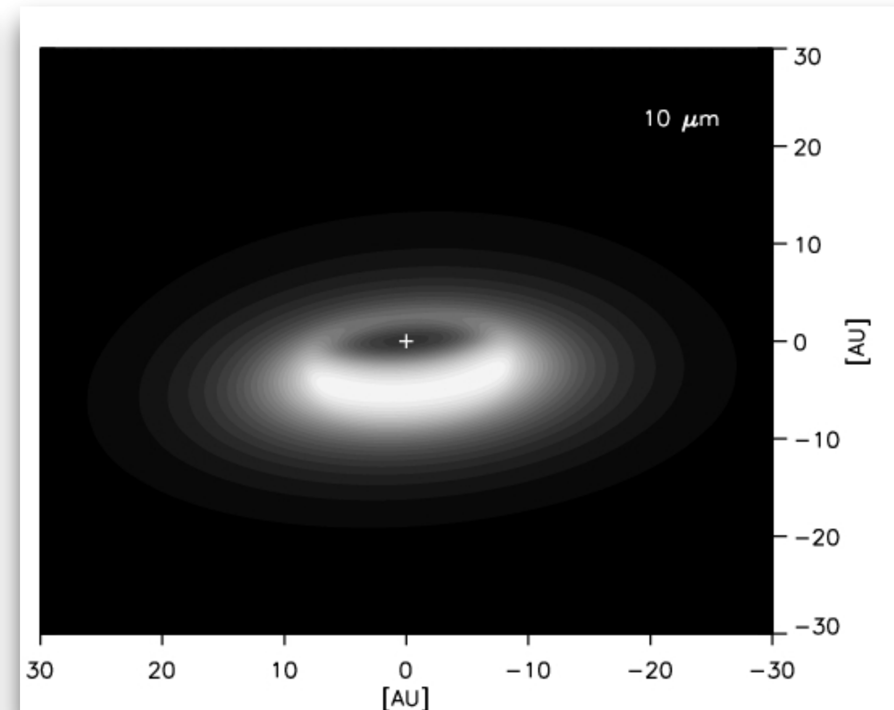
POST-AGB STARS: WHY DO WE CARE???



Sahai 1998, Ballick 2002, Lagadec 2011



Reyniers et al, 2003, 2004, 2007 etc



Hillen et al, 2013

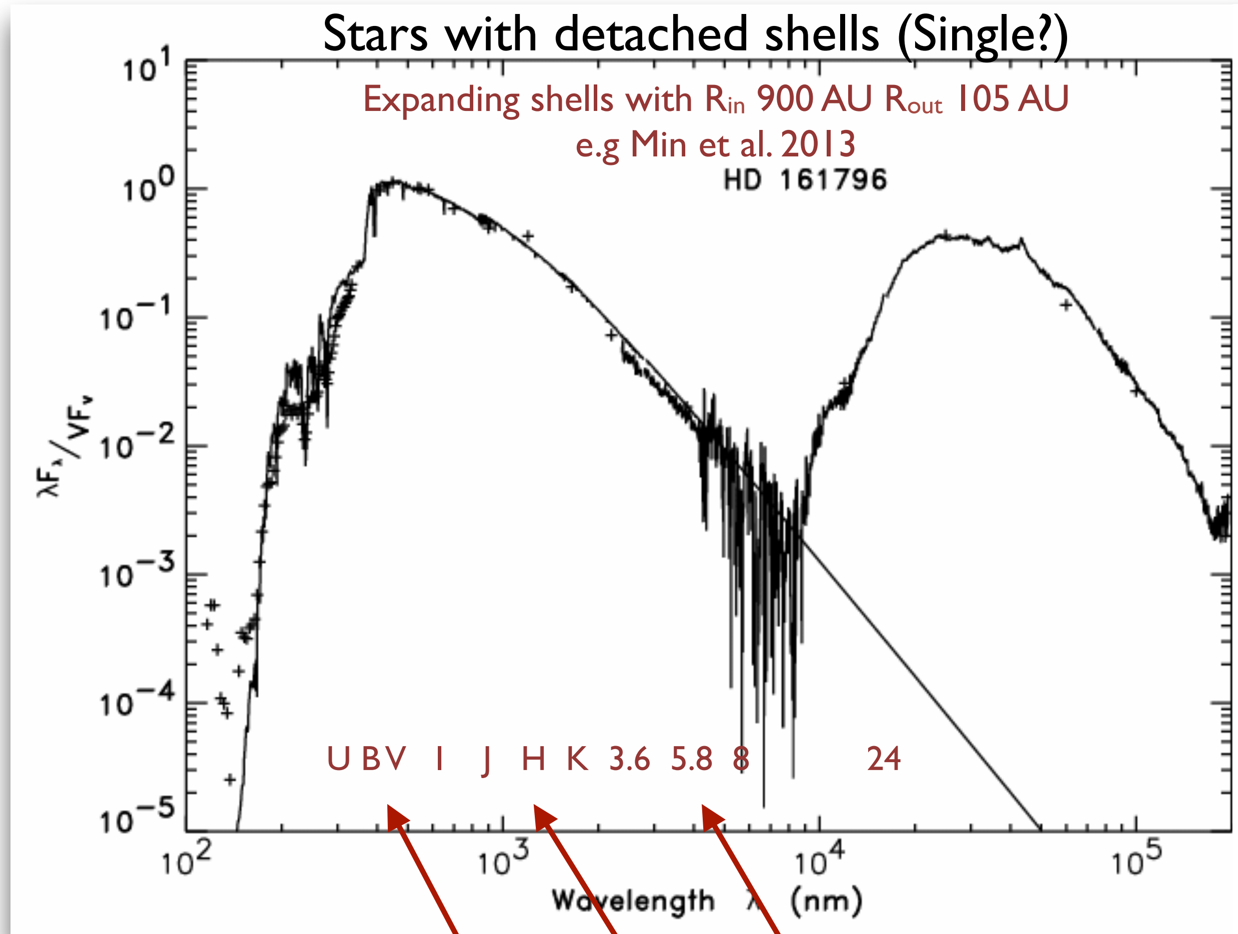
Late stages of (single and binary) stellar evolution

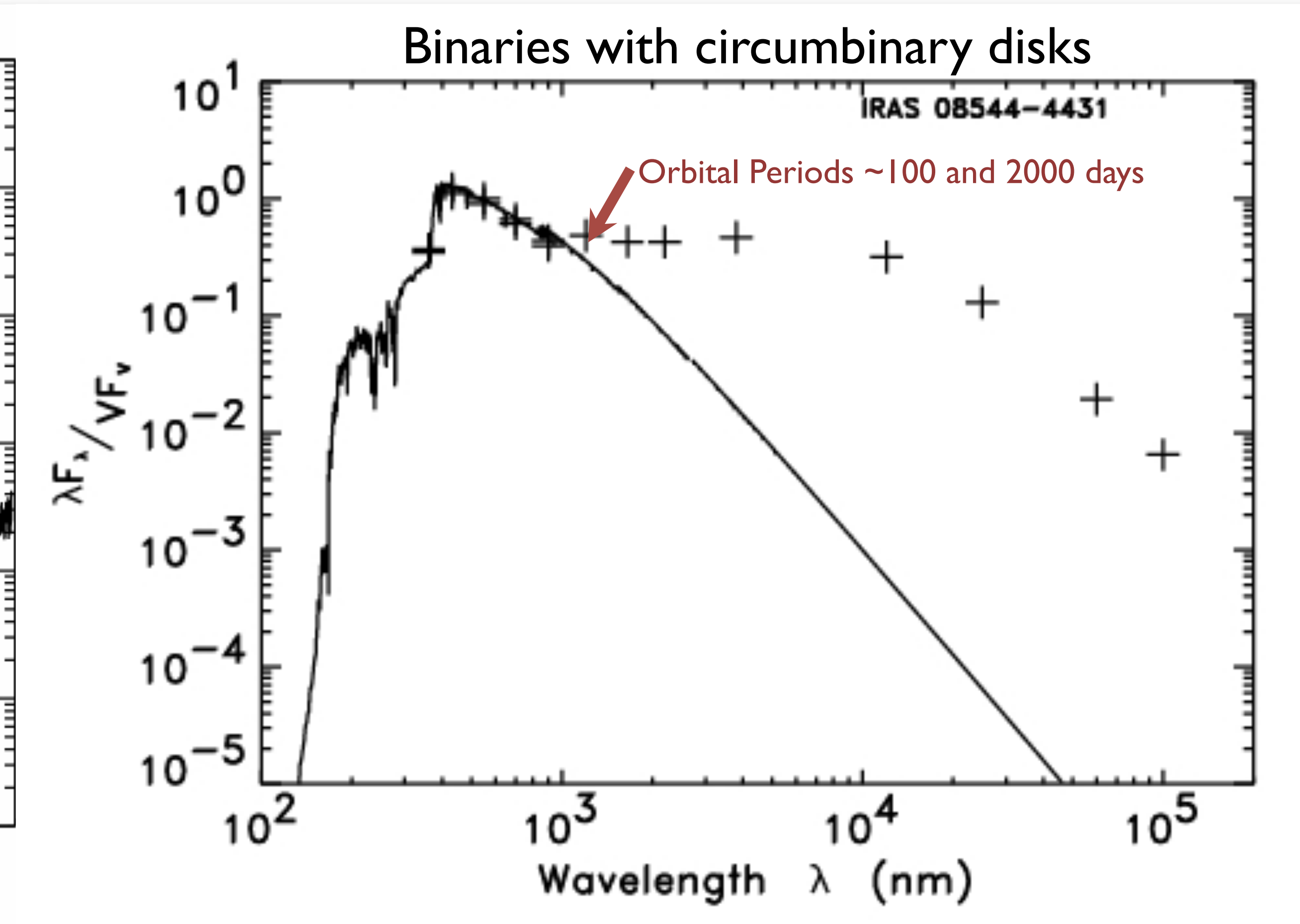
AGB nucleosynthesis in single and binary systems

Disc formation in binary systems and relation to other systems with discs - like YSOs

OPTICALLY VISIBLE GALACTIC POST-AGB STARS

(Toruń Catalog - Szczerba et al. 2007)





Studies by: Van Winckel 2003,2007, 2009; De Ruyter et al. 2006; Gielen et al. 2009

Optical + 2MASS + Spitzer bands allow us to distinguish between the two types - not always...

Mid-IR dust emission is characteristic of Post-AGB stars!

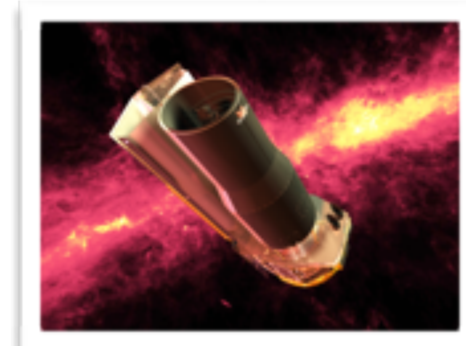
LIMITATION: LACK OF DISTANCES!!!

THE SEARCH FOR POST-AGB STARS IN THE MAGELLANIC CLOUDS…

OPTICALLY VISIBLE POST-AGB STARS IN THE SMC AND LMC

**Kamath et al. 2014*
***Kamath et al. 2015*

Mid-IR Spitzer Space Telescope Surveys

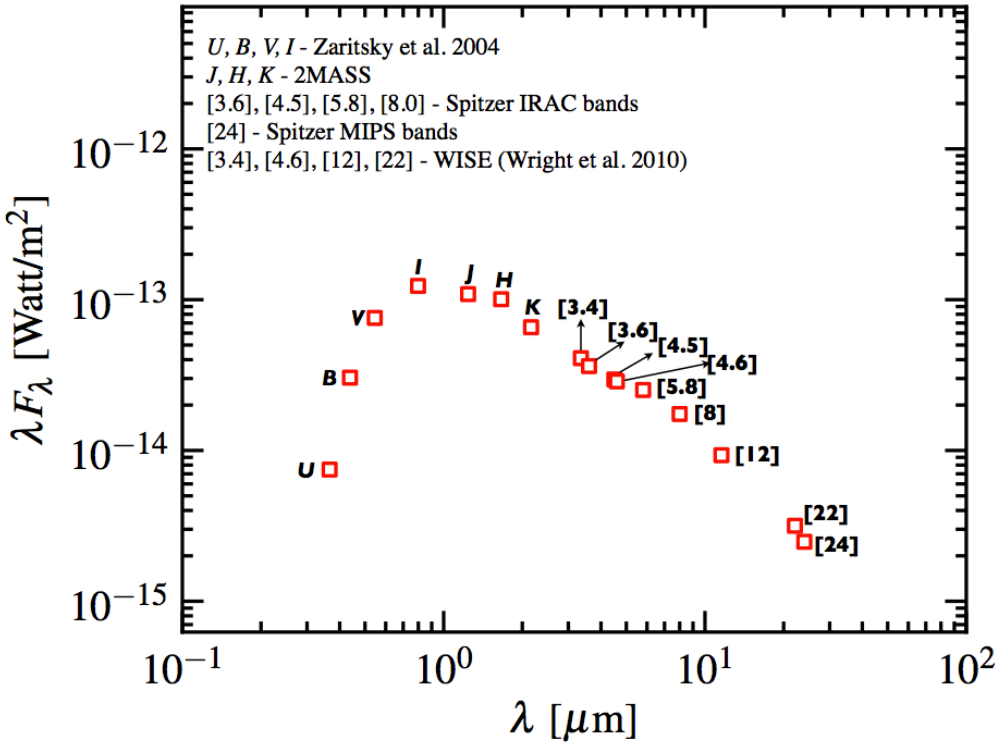


Candidates with Mid-IR excess selected from the Mid-IR SST survey

SMC: **S^{3}MC** (Bolatto et al. 2007) & **SAGE-SMC** (Gordon et al. 2010)

LMC: **SAGE** (Meixner et al. 2006) & (Blum et al. 2006)

✓ Mid-IR Candidate Selection
✓ Spectroscopic Examination
✓ SED Analysis
✓ Variability Analysis
✓ Spectroscopically verified Catalogues of Post-AGB, “Post-RGBs* and other interesting objects

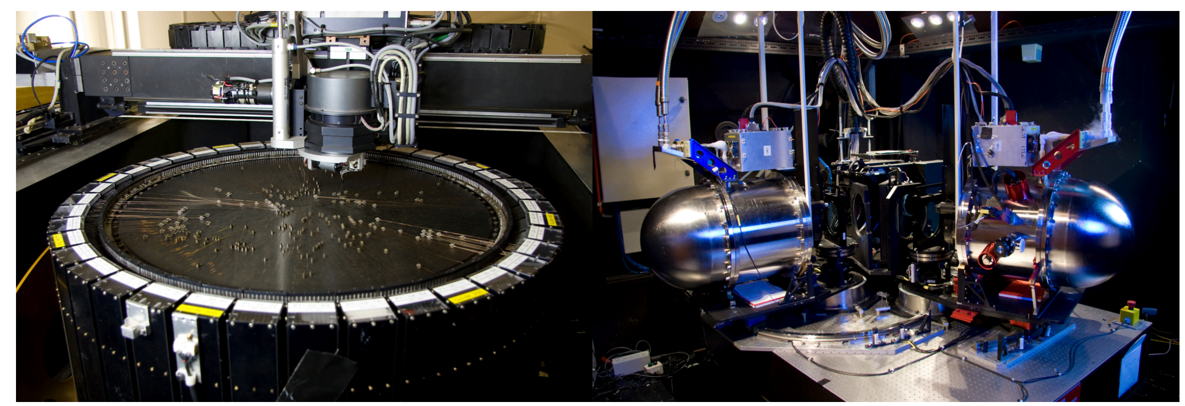


1) CANDIDATE SELECTION:

Mid-IR excess

Optical colour

Suitable luminosity

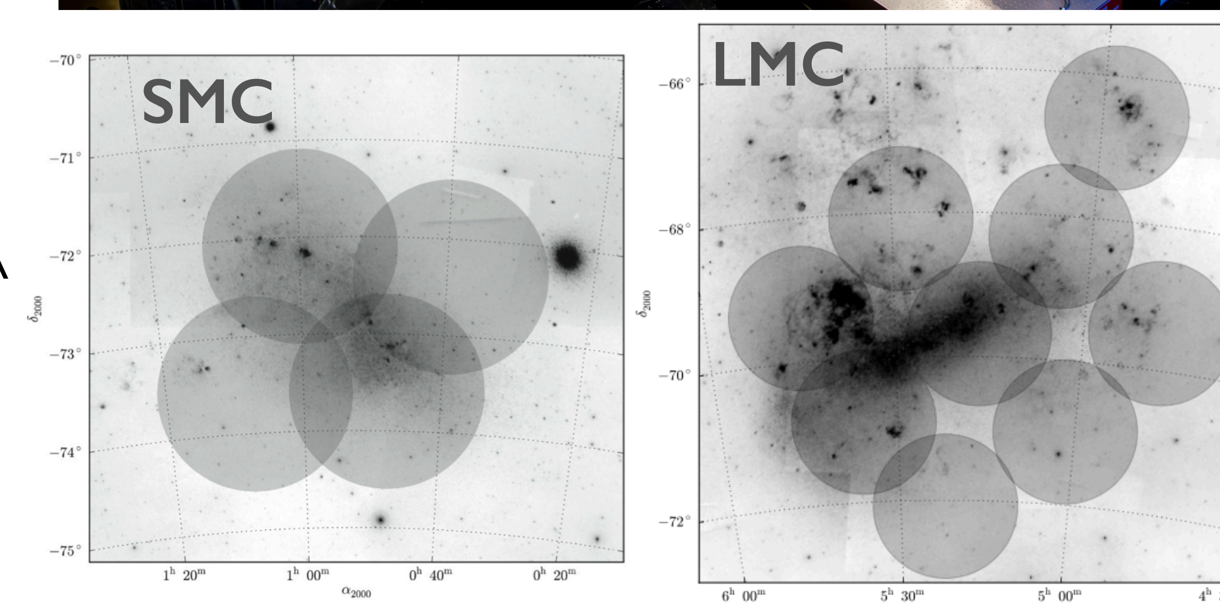


2) OPTICAL SPECTROSCOPY

AAOmega on the 3.9m AAT

Optical Low Resolution Spectra R~1300

Wavelength Coverage = 3700 Å - 8700 Å

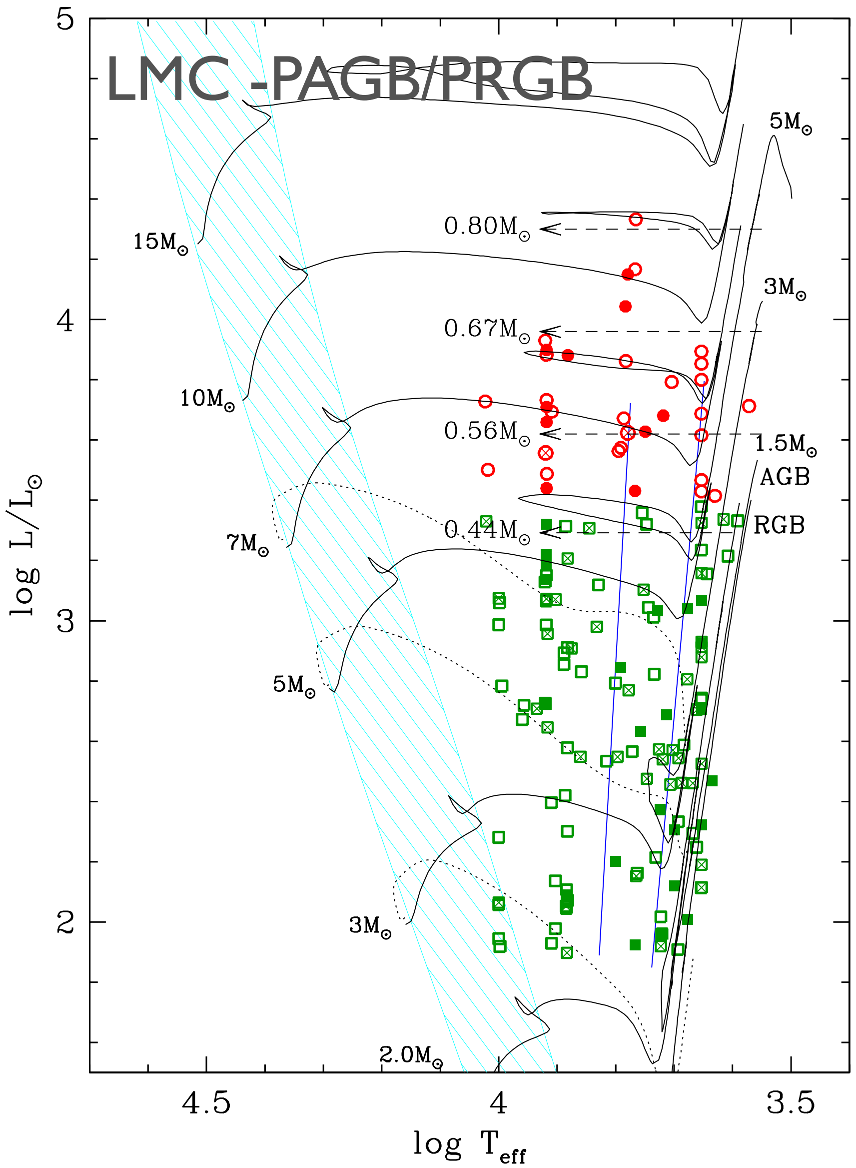


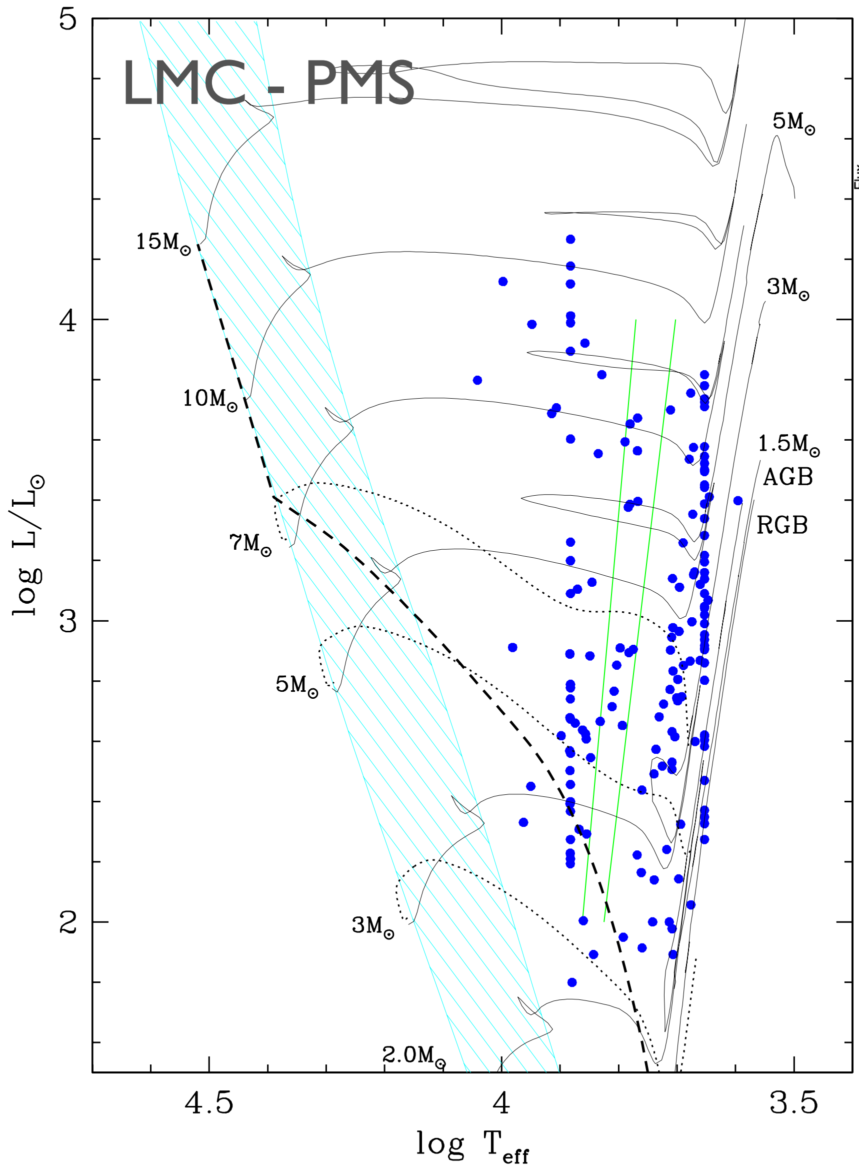
OUTCOMES…

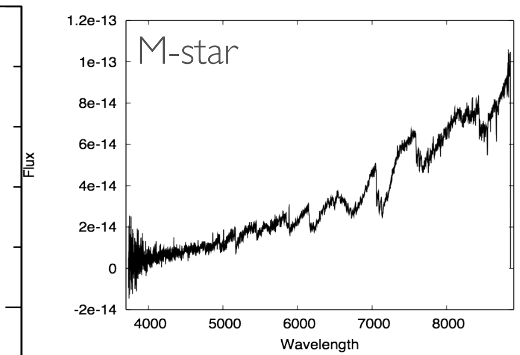
- **Spectroscopically verified post-AGB (and post-RGB) stars in the Magellanic Clouds**
- 42 post-AGBs and 42 post-RGBs in the SMC
- 35 pos-AGBs and 119 post-RGBs in the LMC

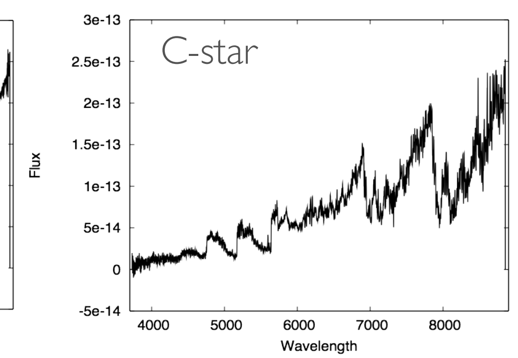
- **A robust surface-gravity criterion to disentangle post-AGB stars from the pre-main sequence stars.**
- Spectroscopically verified pre-main sequence stars
- 40 in the SMC and 162 in the LMC

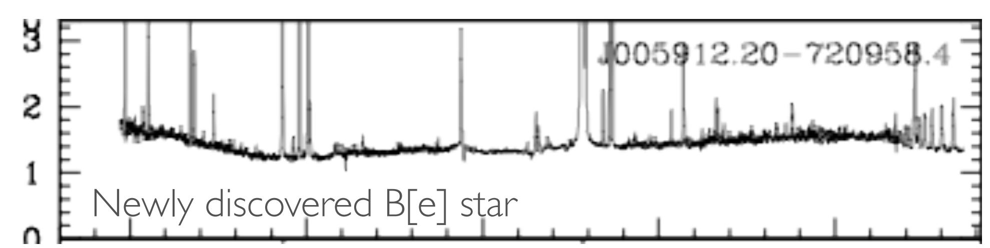
- **Other Interesting contaminants with mid-IR excesses**

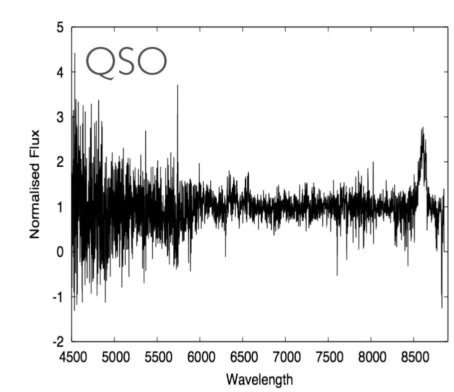


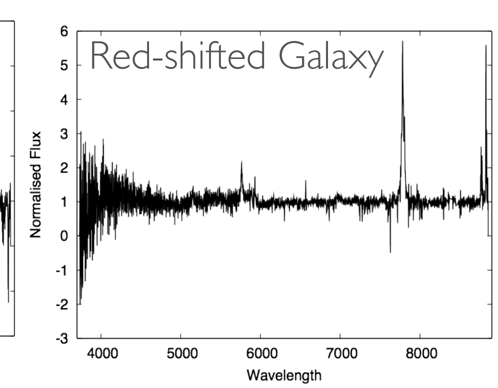










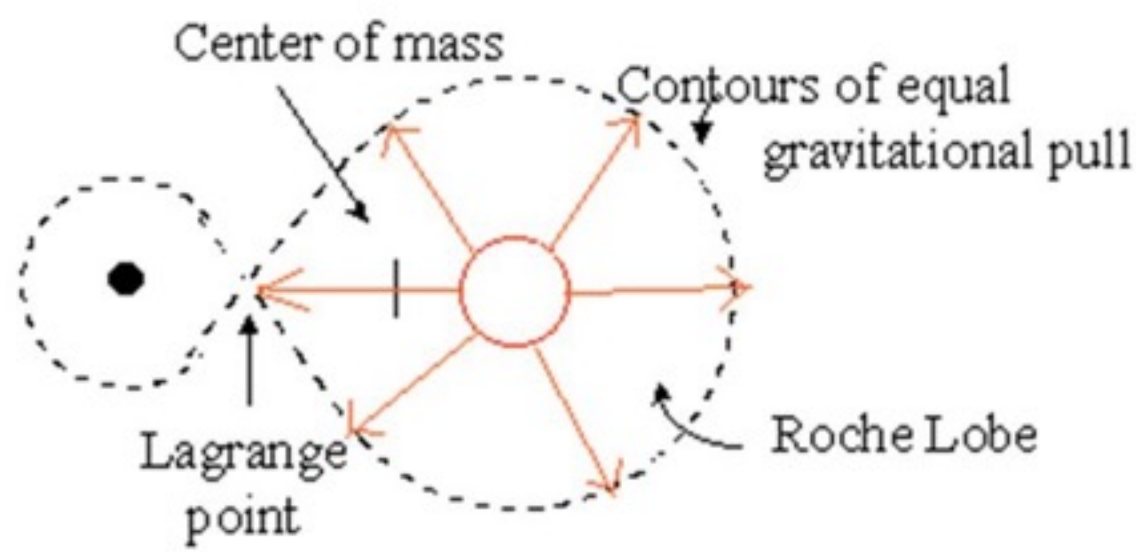


A NEWLY DISCOVERED PHASE IN BINARY EVOLUTION OF LOW- TO INTERMEDIATE- MASS STARS:

THE DUSTY POST-RGB PHASE

WHEN DOES THE STAR FILL ITS ROCHE-LOBE???

Mass transfer by Roche Lobe Overflow



Star expands on main sequence.
when it fills its Roche Lobe mass transfer happens through the L1 Lagrangian point

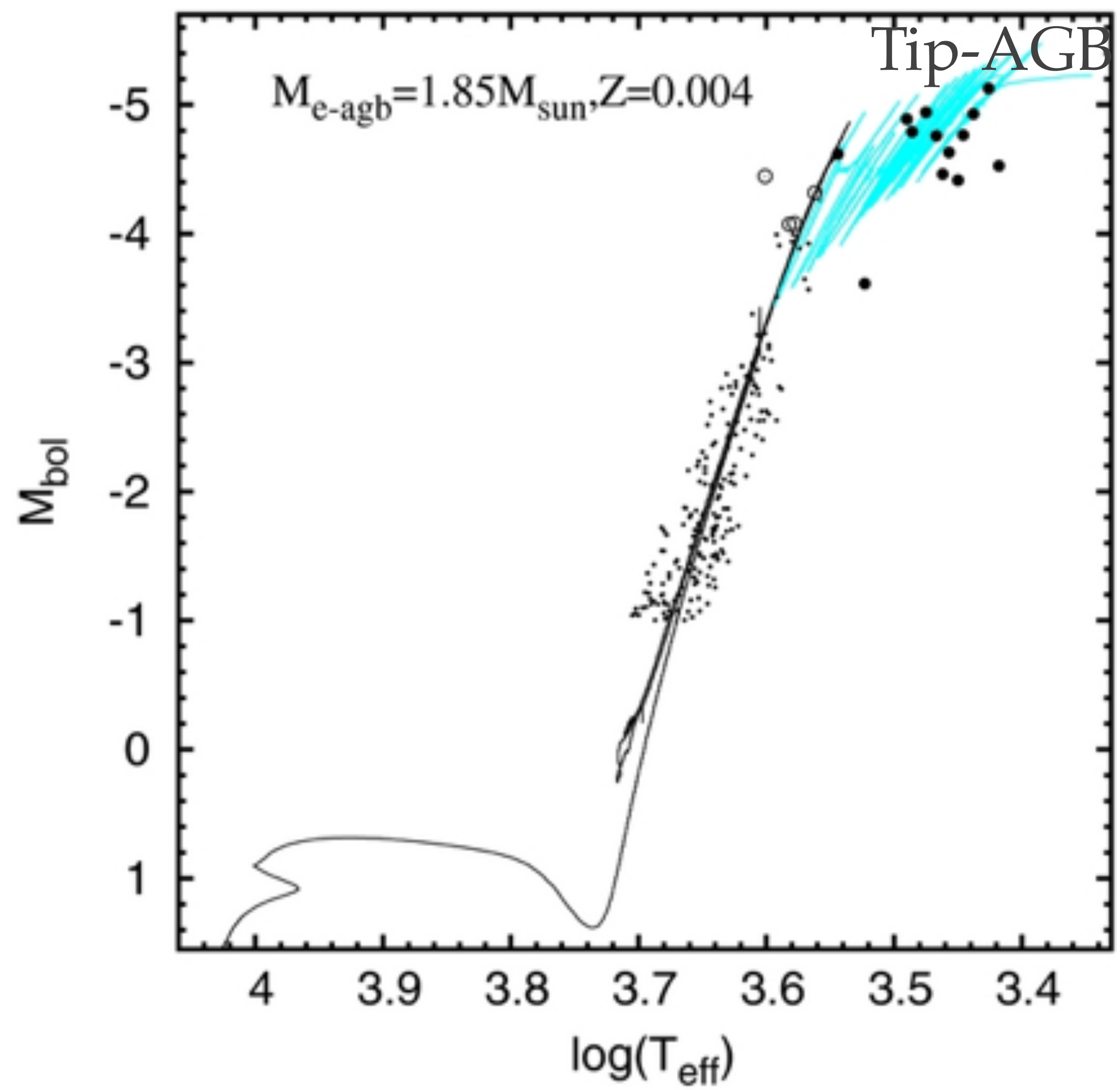
DISCLAIMER: THE PHYSICS OF THE POST-ROCHE LOBE FILLING EVOLUTION ARE VERY UNCERTAIN…

Stars reach the tip of the AGB (TAGB) <u>**without**</u> filling its Roche lobe…

OUTCOME ~ they likely evolve as single stars do

RESULT ~ formation of a PN central star on a wide orbit

(Moe & De Marco 2006)

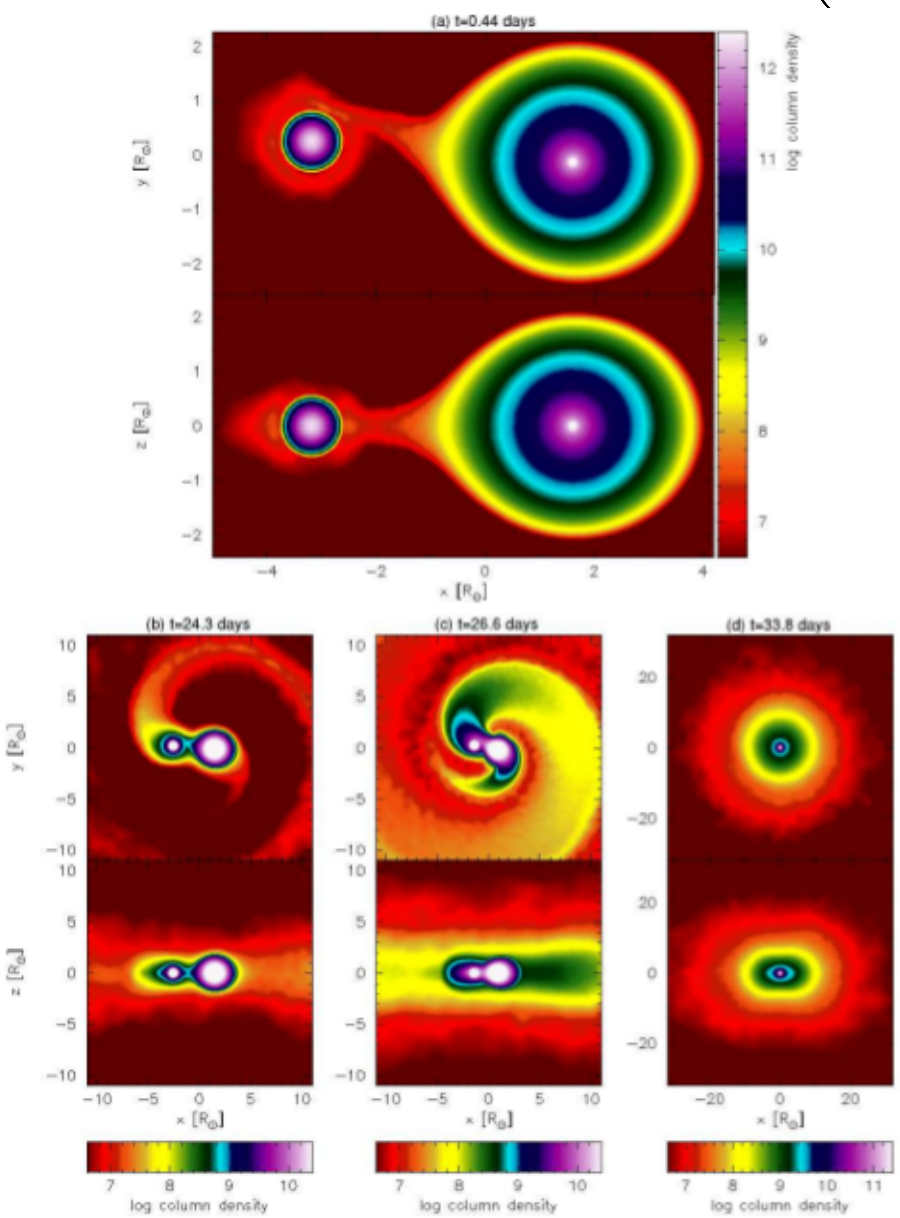


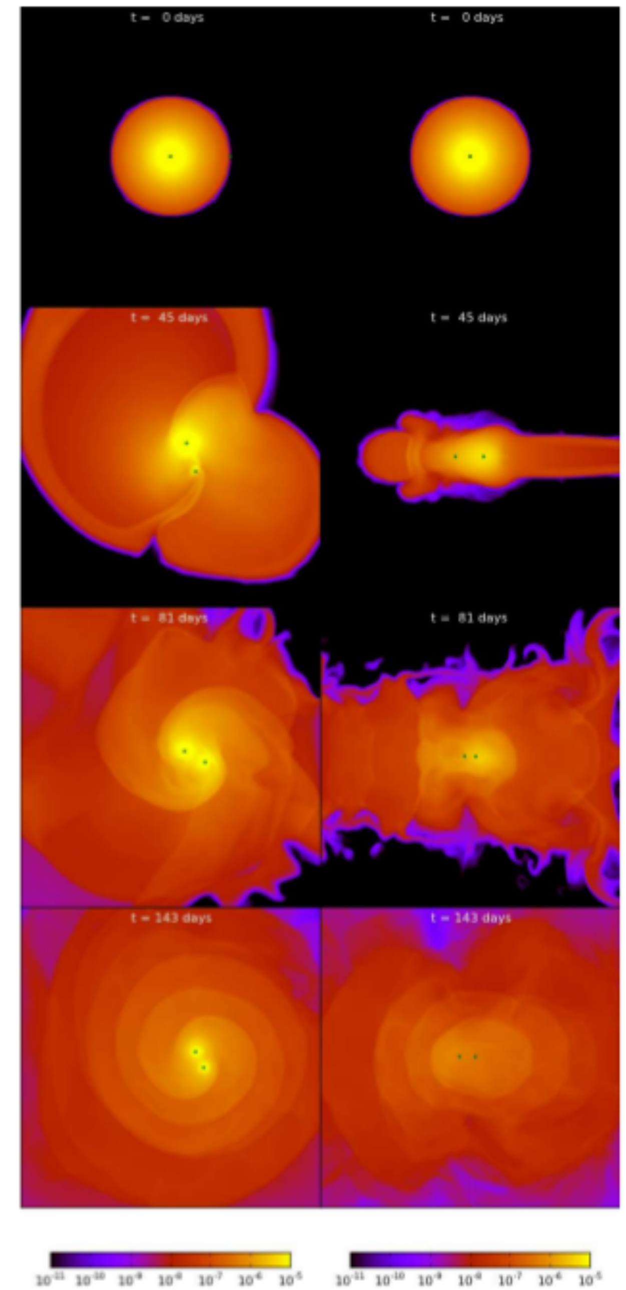
Roche lobe filling occurs:

on the AGB but above the RGB-tip...

OUTCOME 1 ~ **common envelope** (CE) event

(Ivanova et al. 2013)





RESULT = Close binaries

with a 1.2M⊙ early giant and 0.6M⊙ MS star

RESULT = Stellar mergers

0.88M⊙ giant and 0.6M⊙ MS star

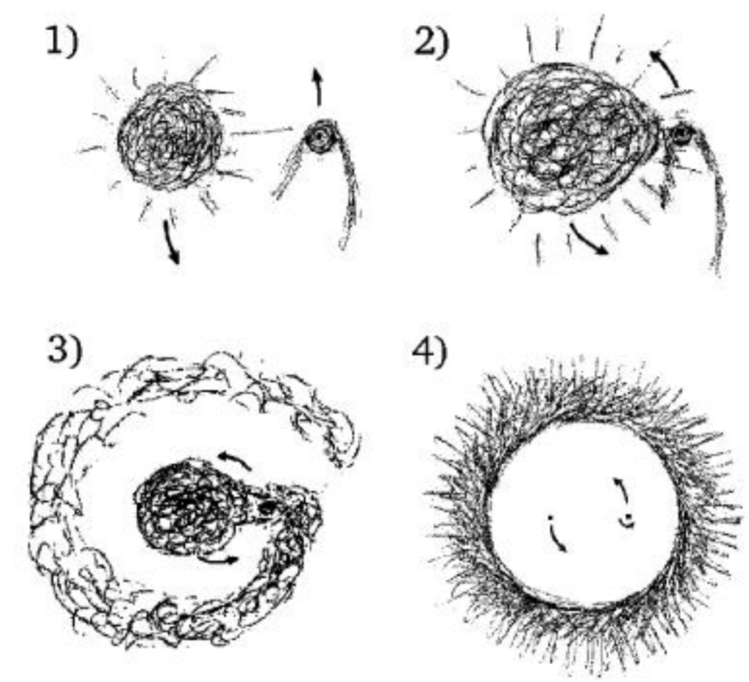
Roche lobe filling occurs:

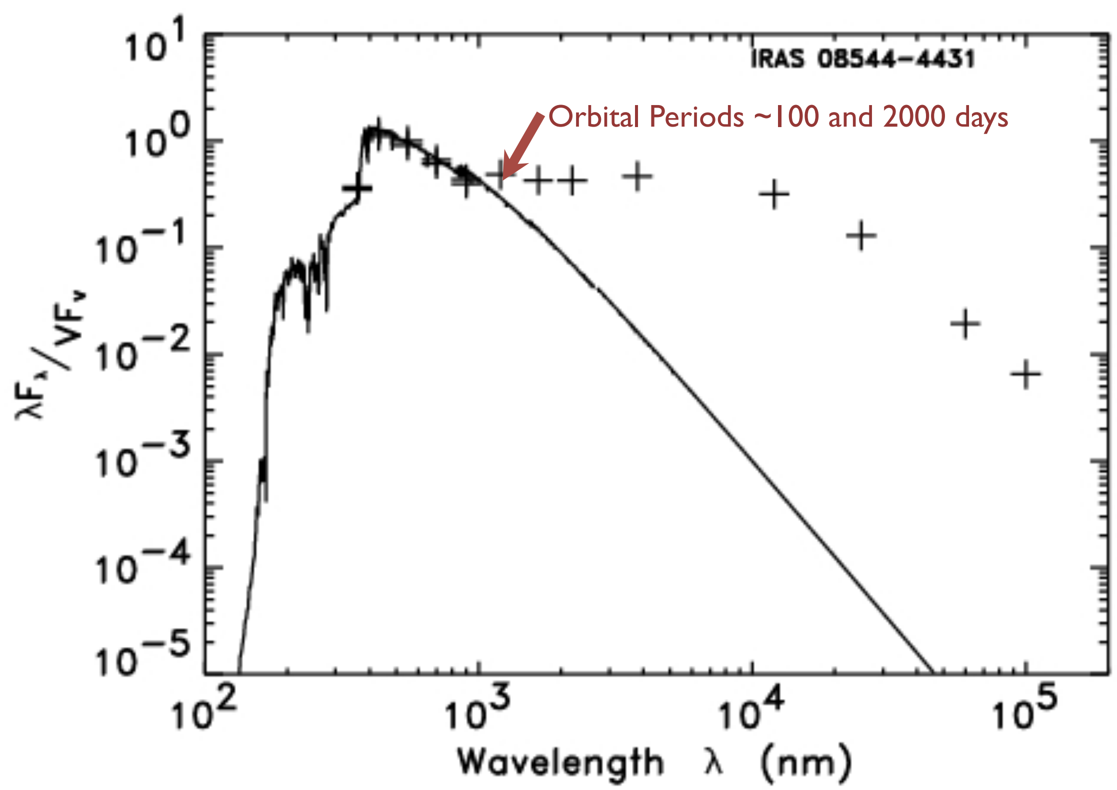
<u>on the AGB but above the RGB-tip...</u>

OUTCOME2 ~ some sort of a **stable mass transfer**

RESULT 2~ Formation of an intermediate period binary

e.g.: Post-AGB binaries surrounded with DUSTY circumbinary discs (Van Winckel 2007)





Roche lobe filling occurs:

below the RGB-tip…

(e.g., Han et al. 1995; Heber 2009; Nie et al. 2012)

OUTCOME 1 ~ **common envelope** (CE) event

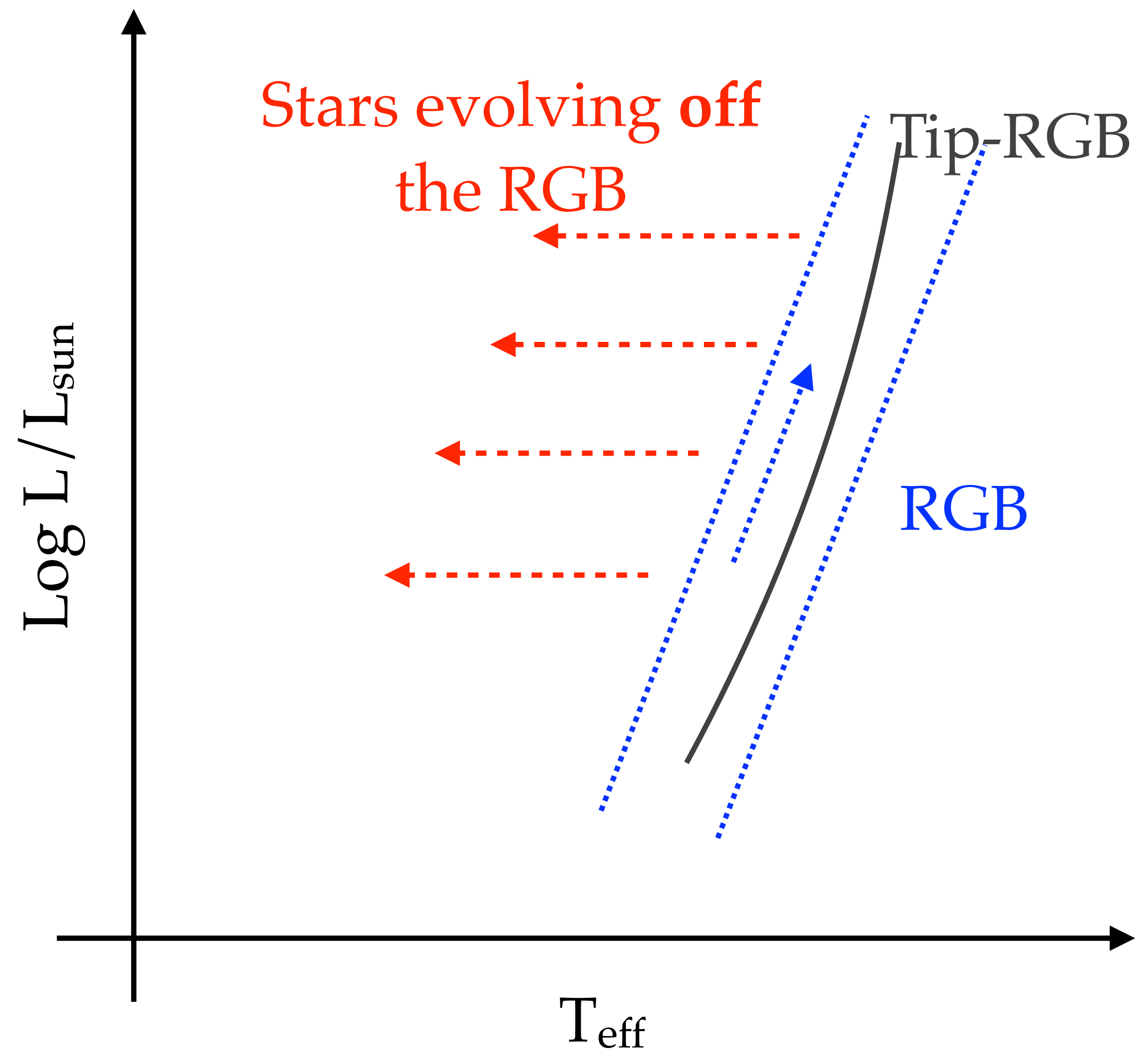
RESULT ~ close binary or stellar merger

(Paczynski 1976; Webbink 1984)

OUTCOME2 ~ some sort of **stable mass transfer**

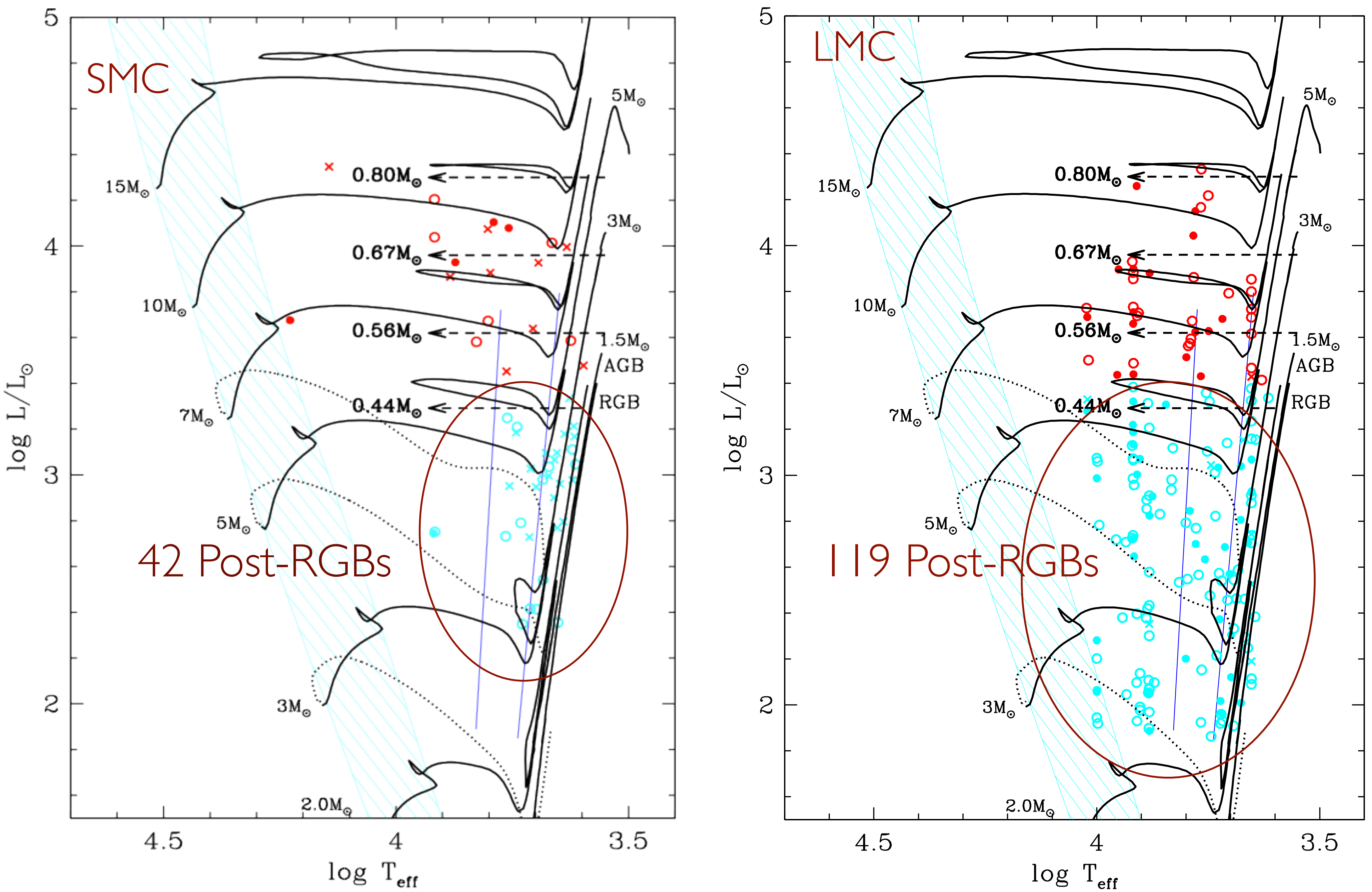
RESULT 2 ~ Formation of an intermediate period binary

An expected e.g., "Post-RGB" binaries surrounded with DUSTY circumbinary discs!!!



THE DISCOVERY OF DUSTY POST-RGB STARS…

A NEW STELLAR TYPE: DUSTY POST-RGB STARS



- ✓Mid-IR excess
- ✓A- K spectral types
- ✓Low log g
- ✓low [Fe/H]
- ✓**low -luminosity (< 2500 L⊙)**

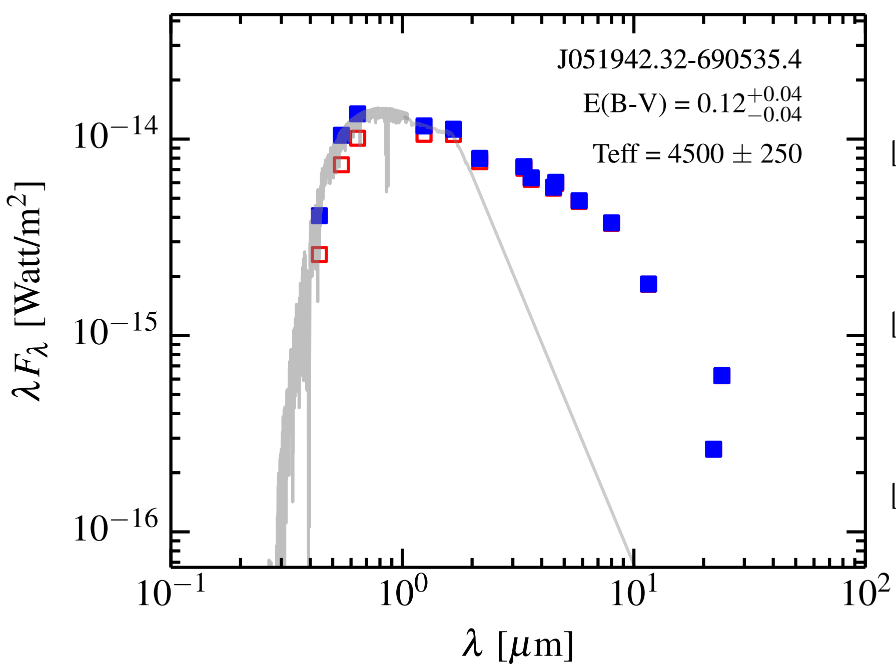
Post-AGB:Post-RGB ~ 1:2.5

Note: These numbers are not complete due to incompleteness of the survey…

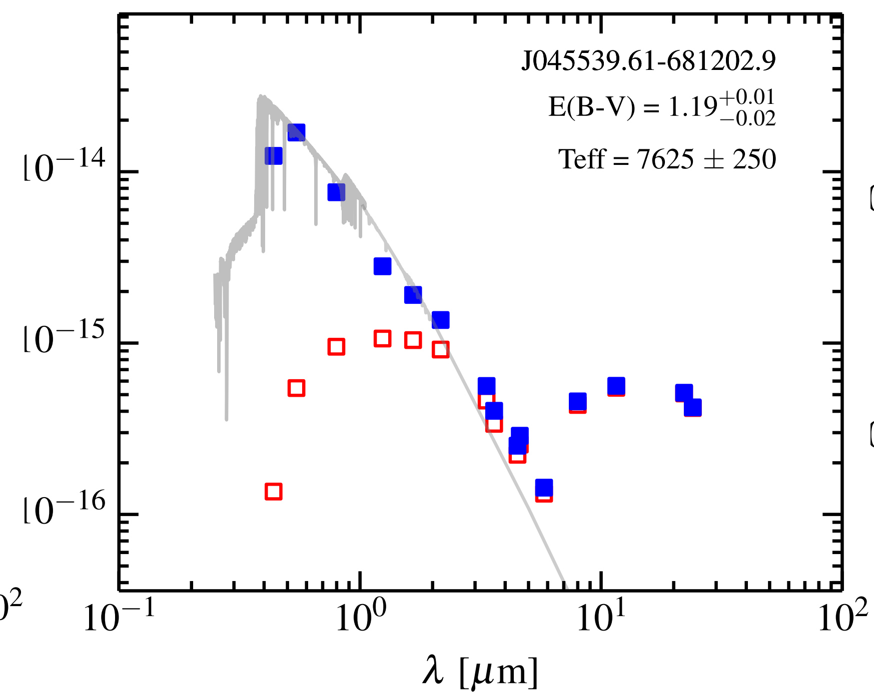
MINIMUM Expected numbers: SMC ~ 30 more, LMC ~ 750 more

ESTABLISHING THE BINARY NATURE OF THESE POST-RGB SYSTEMS

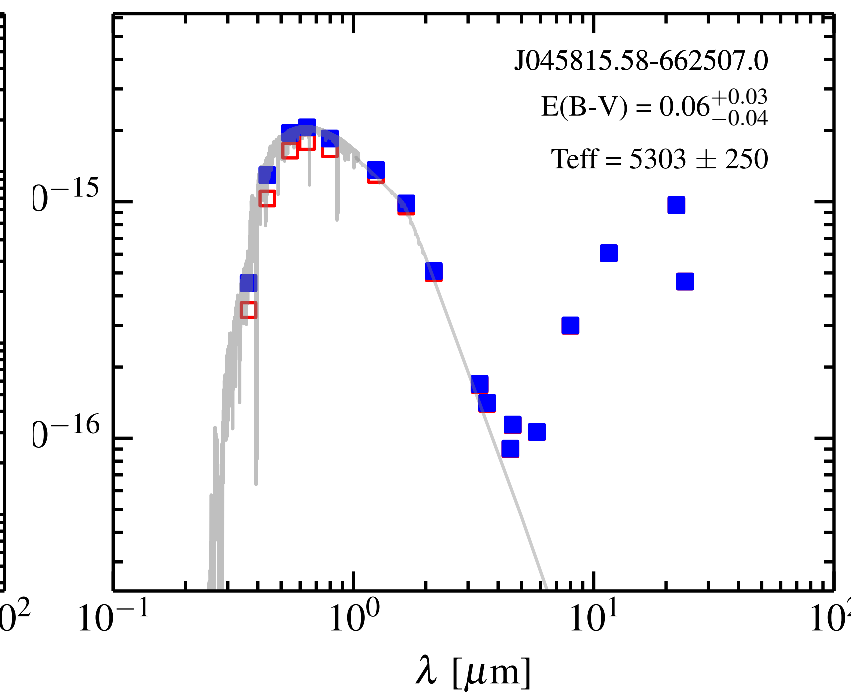
Post-RGB SEDs



Disc-type SED with hot dust

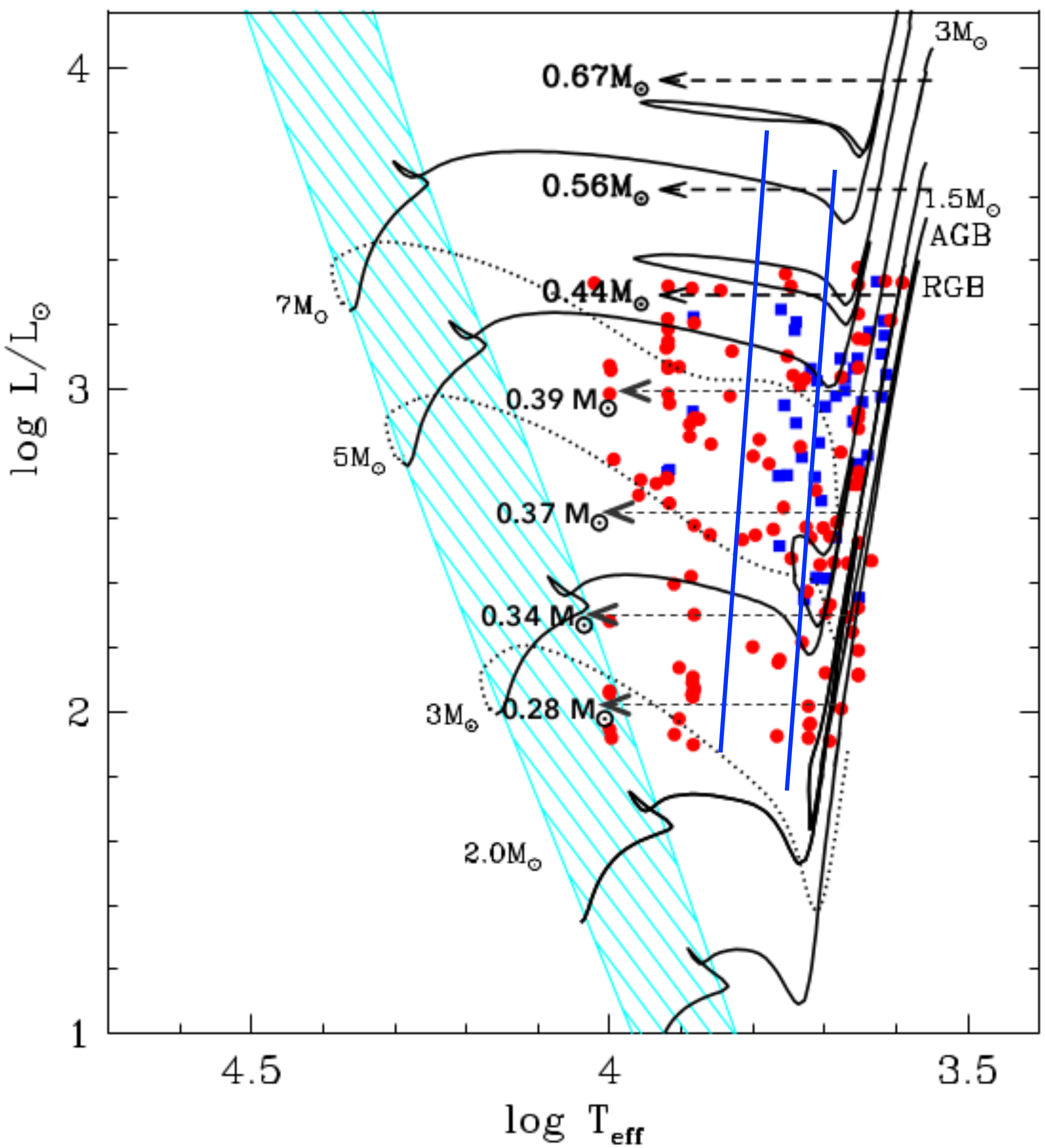


Disc-type SEDs (evolved discs)



Shell-type SED?

HOW DO THESE STARS EVOLVE?



- Pre-mature evolution off the RGB via mass-loss
- RGB to $T_{eff} \approx 10^4$ K
- Single star mass loss
  - too weak
- Mass loss induced via binary
- Evolution beyond the RGB is to higher T_{eff} values at near-constant luminosity (Driebe et al. 1998)

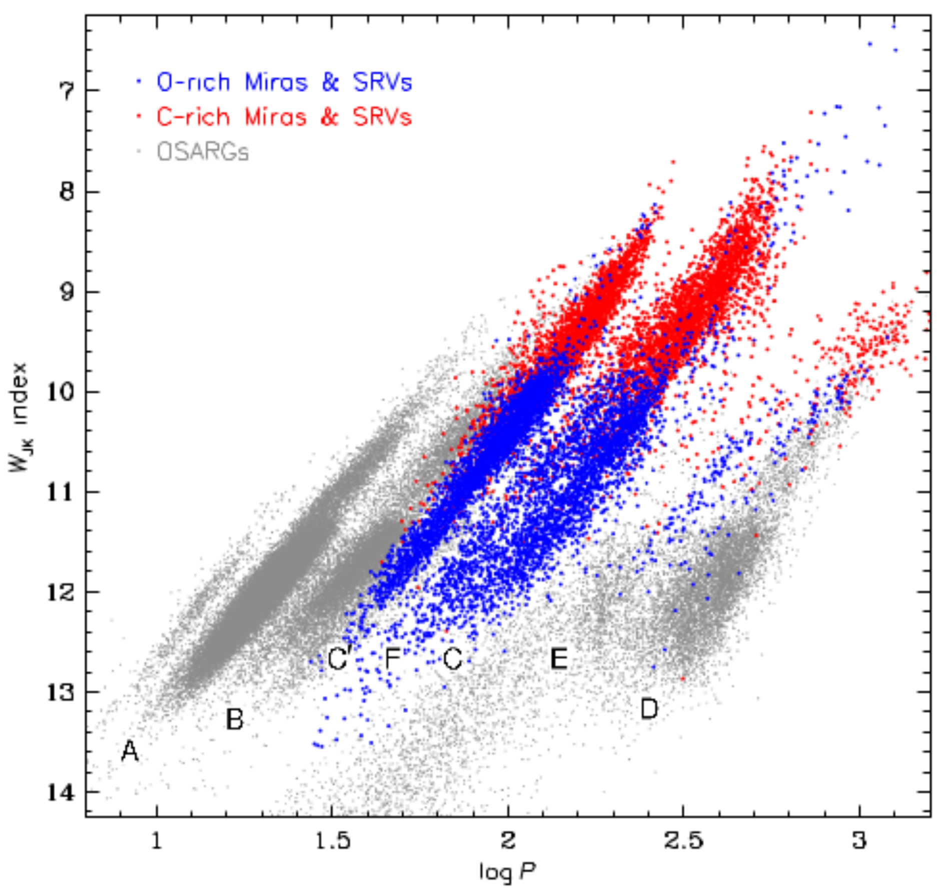
Establish connections to possible precursors and progeny….

ESTABLISHING THEIR EVOLUTIONARY STATUS - PRECURSORS

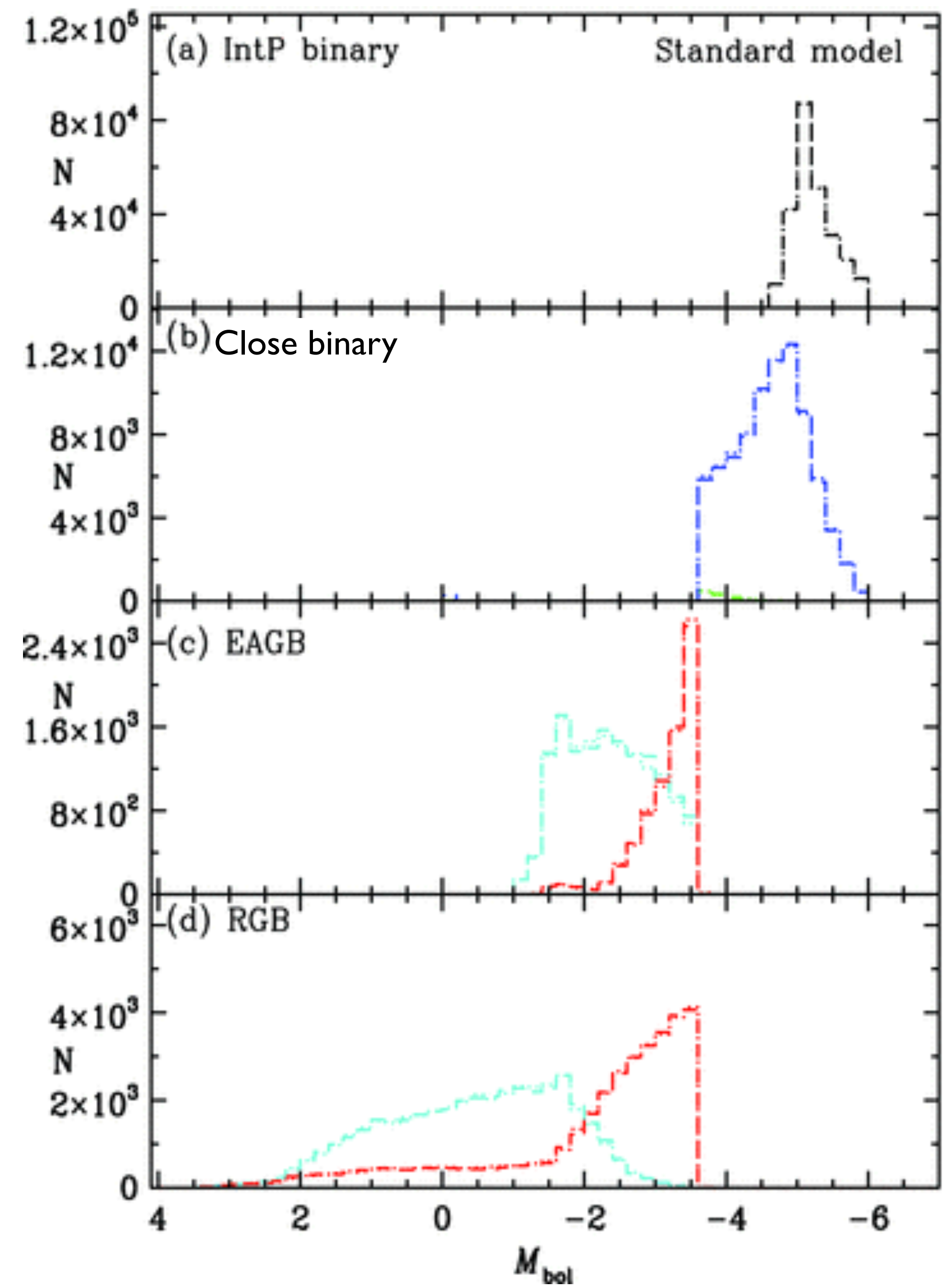
SEQUENCE-E Variables

Close binary red giants that show ellipsoidal light variations

Nicholls et al. 2010



Soszynski & Wood 2012



Nie et al., 2012

Luminosities of the TAGB

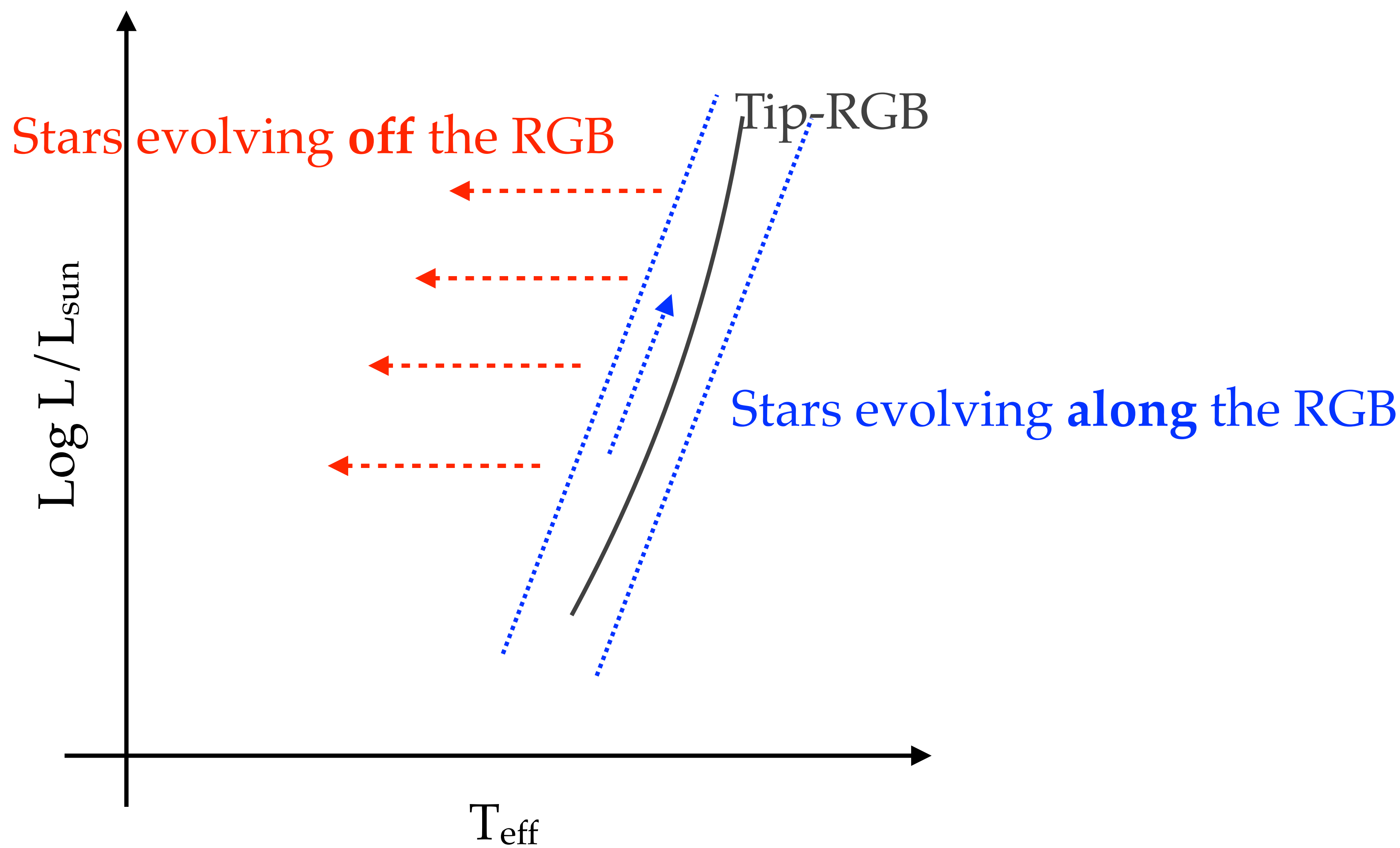
Close binary PNNe have AGB luminosities above the TRGB,

EAGB and RGB binaries undergoing a CE event but not merging have luminosities below the TRGB

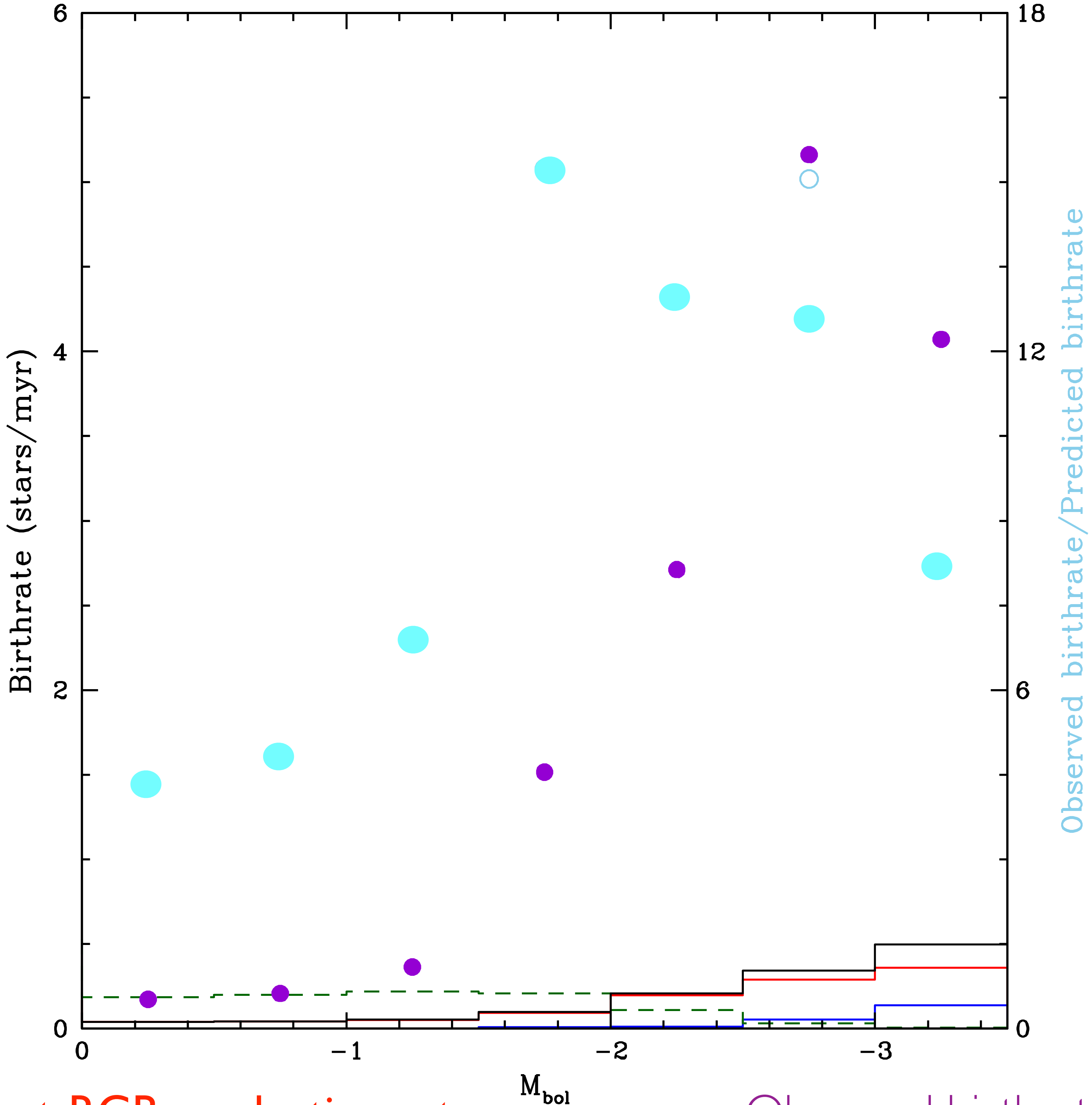
Mbol(TRGB) = −3.6

EVOLUTIONARY CONNECTION BETWEEN THE SEQUENCE- E STARS AND POST-RGB STARS

Method: Comparing theoretically predicted birthrates Nie et al. (2012) with the observationally determined birthrates of our new sample of dusty post-RGB stars



CONNECTION TO POPULATION MODELS OF RGB BINARIES



Post-RGB production rates

Post-EAGB production rates

Birthrates of mergers on the RGB

Total predicted rate of production

Observed birthrates

Observed BR/Predicted BR

Observationally estimated post-RGB birthrate is within an order of magnitude agreement the theoretically predicted birthrate

The average ratio of observed to predicted birthrate is 6.0

At lower luminosities, mergers dominate

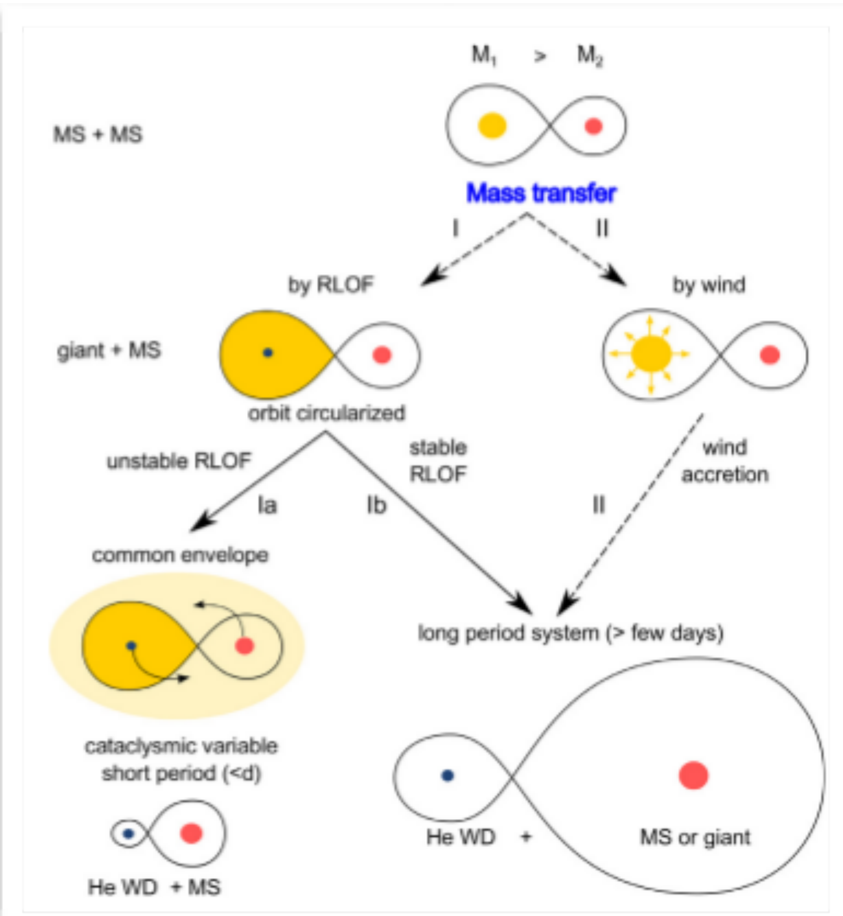
Post-EAGB birthrates increases to about 25% of the total birthrate at the highest luminosities

UNCERTAINTIES

- An over-estimation of the incompleteness factor
- An underestimate of the post-RGB evolution time
- Interlopers in the post-RGB sample
- Uncertainties in the model post-RGB birthrate

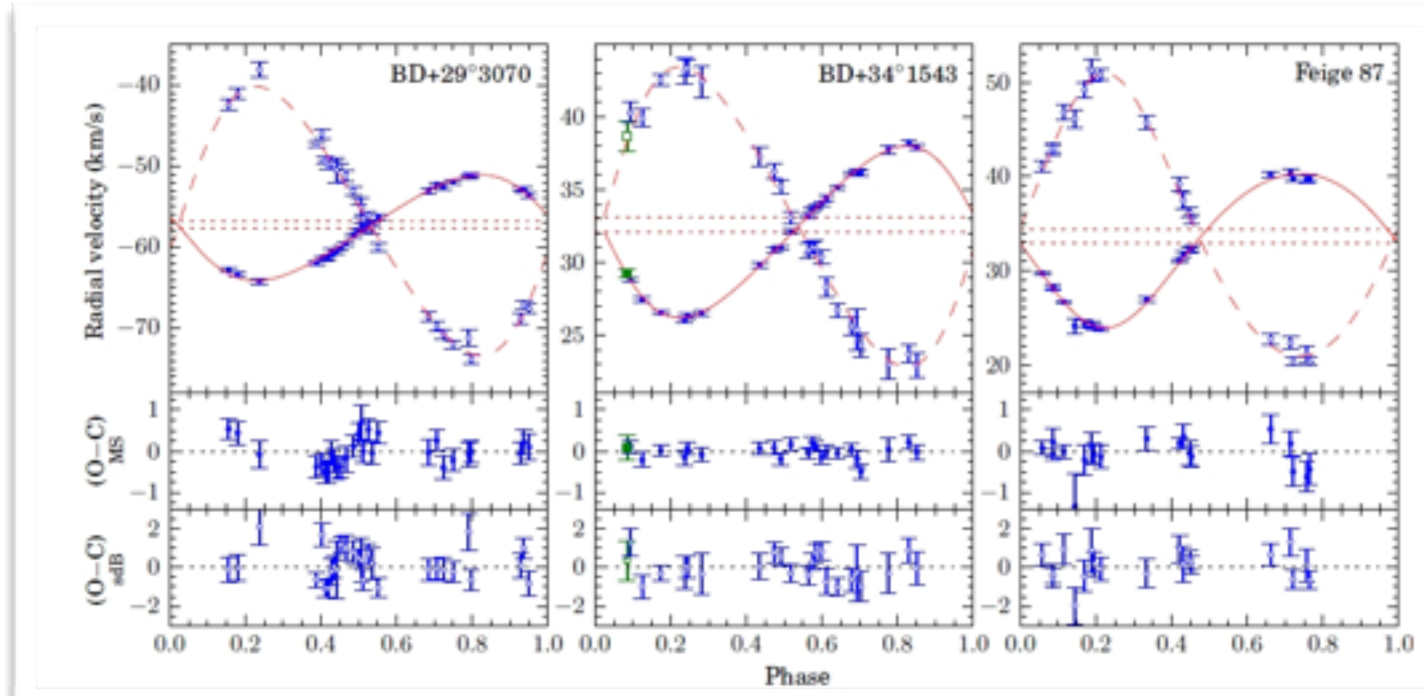
EVOLUTIONARY STATUS -PROGENY

Binary He WDs/ Cataclysmic Variables



Merle.T et al., 2014

Sub-dwarf B stars

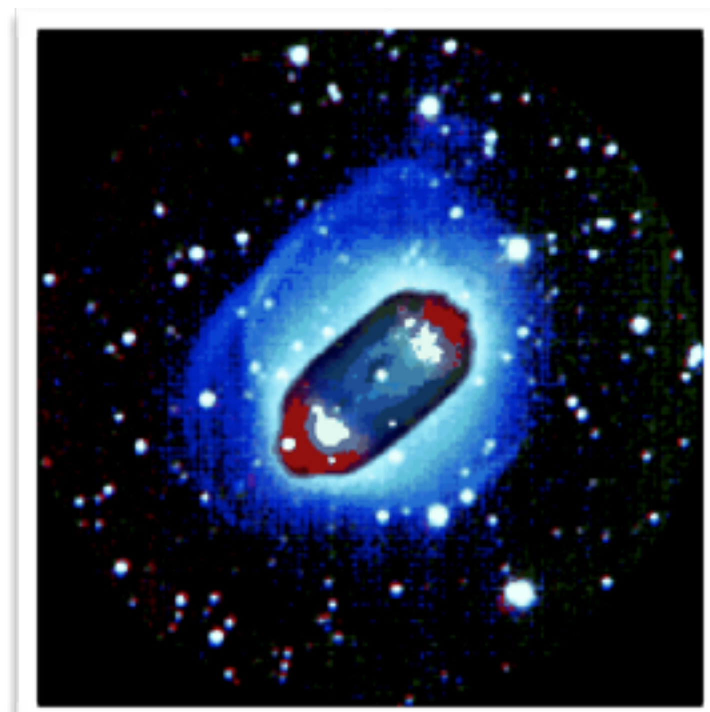


Vos et al., 2013; **see poster of Joris Vos**

Low-luminosity Planetary Nebulae

(Bond & Livio 1990; Yungelson et al. 1993; Soker 1997; Bond 2000; Zijlstra 2007; de Marco 2009)

(Bond 1994, 2000; Miszalski et al. 2009)



SUMMARY

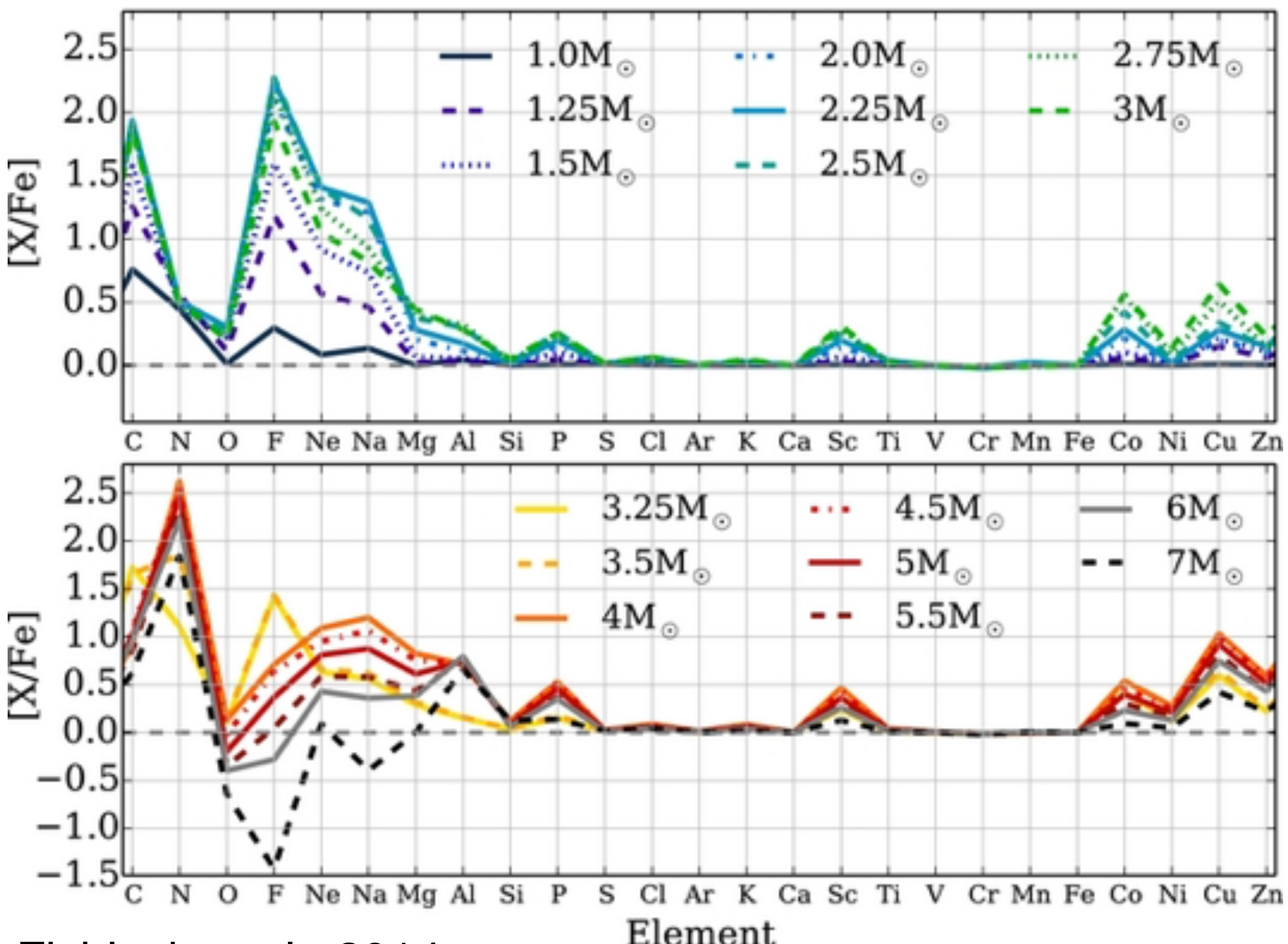
- **Newly discovered low-luminosity, dusty post-RGB stars**
  - An unexplored phase of binary stellar evolution : termination of RGB evolution via binary interaction
  - What kind of **CE? some sort of mass transfer? Jets?**
- **<u>Precursors - Sequence-E stars</u>**
  - The observationally estimated post-RGB birthrate is higher than the theoretically predicted birthrate
  - Some of these objects are likely to be products of mergers. Models predict that mergers dominate at lower luminosities
- **<u>Progeny - Binary He WDs, SdBs, Low-luminsoity PNe</u>**

CURRENT AND FUTURE RESEARCH…

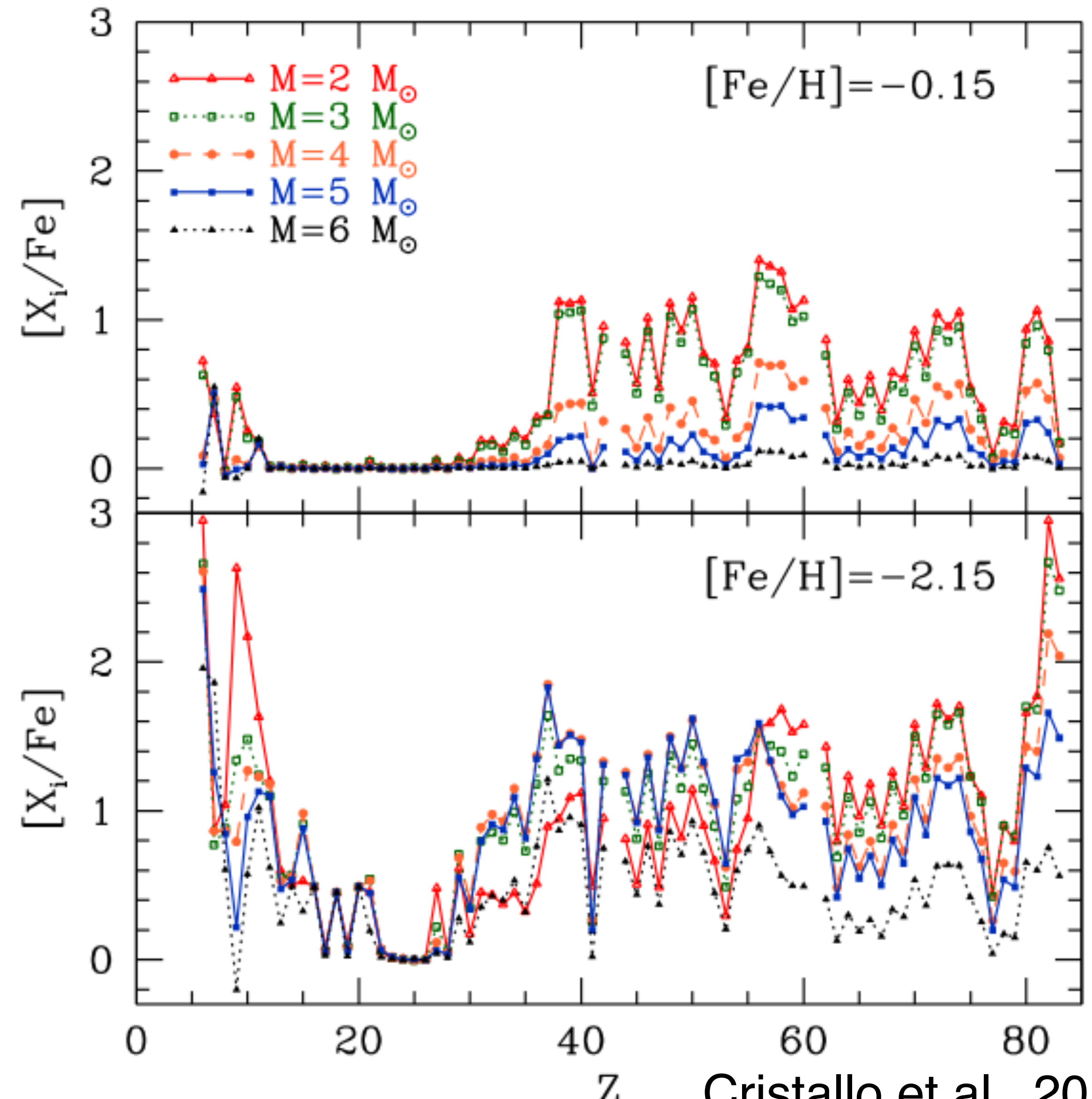
- **Magellanic Cloud Post-RGB stars:**
  - Radial velocity monitorting to detect bianrity and obtain orbital parameters…
  - Detailed chemical abundance analysis
- **Galactic Analogues:**
  - Possible with GAIA…
  - PopII cepheids with dust excesses
- **Disc Morphology - Are Post-RGB discs are similar to Post-AGB discs? PMS discs? …**
- **Potential planet hosts???**

WHAT DO POST-AGB STARS TELL US ABOUT (AGB) NUCLEOSYNTHESIS?

CONSTRAINING AGB EVOLUTION AND NUCLEOSYNTHESIS MODELS…



Fishlock et al., 2014



Cristallo et al., 2016

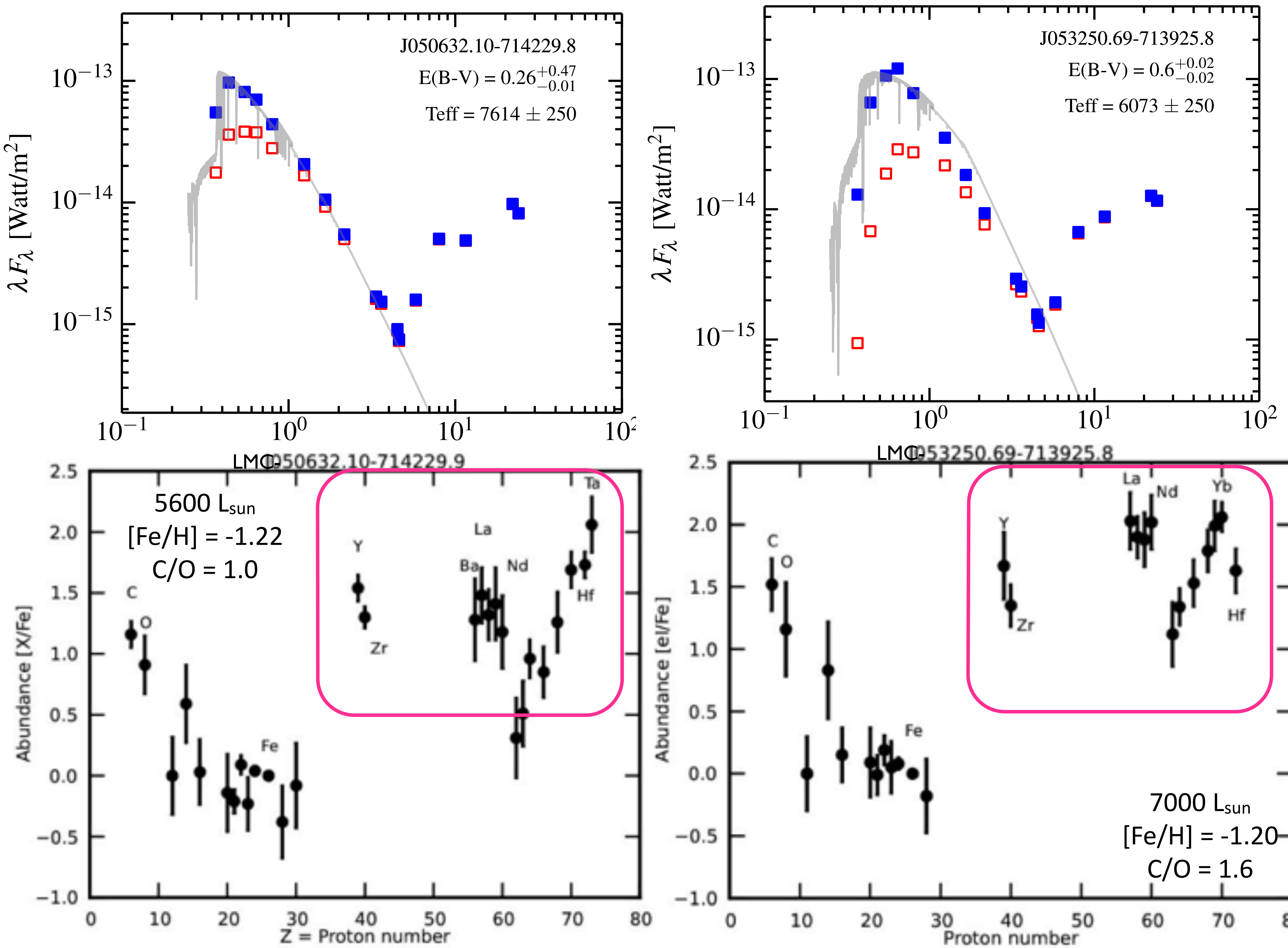
- Yields are very initial-mass (and hence luminosity) and metallicity dependant
- Yields of atomic elements up to Pb…

Answers: Post-AGB stars in the Magellanic Clouds and soon in the Galaxy (with GAIA)!

Chemical Diversity in post-AGB stars…

Observed nucleosynthesis in SINGLE stars

C-enhancement and *s*-process nucleosynthesis…



- Shell-type SEDs
- C, N and O follow expected AGB nucleosynthesis yields
- s-process enhancement
- Conforms to single star evolution

De Smedt et al., 2012; Van Aarle 2013, Kamath et al., 2014

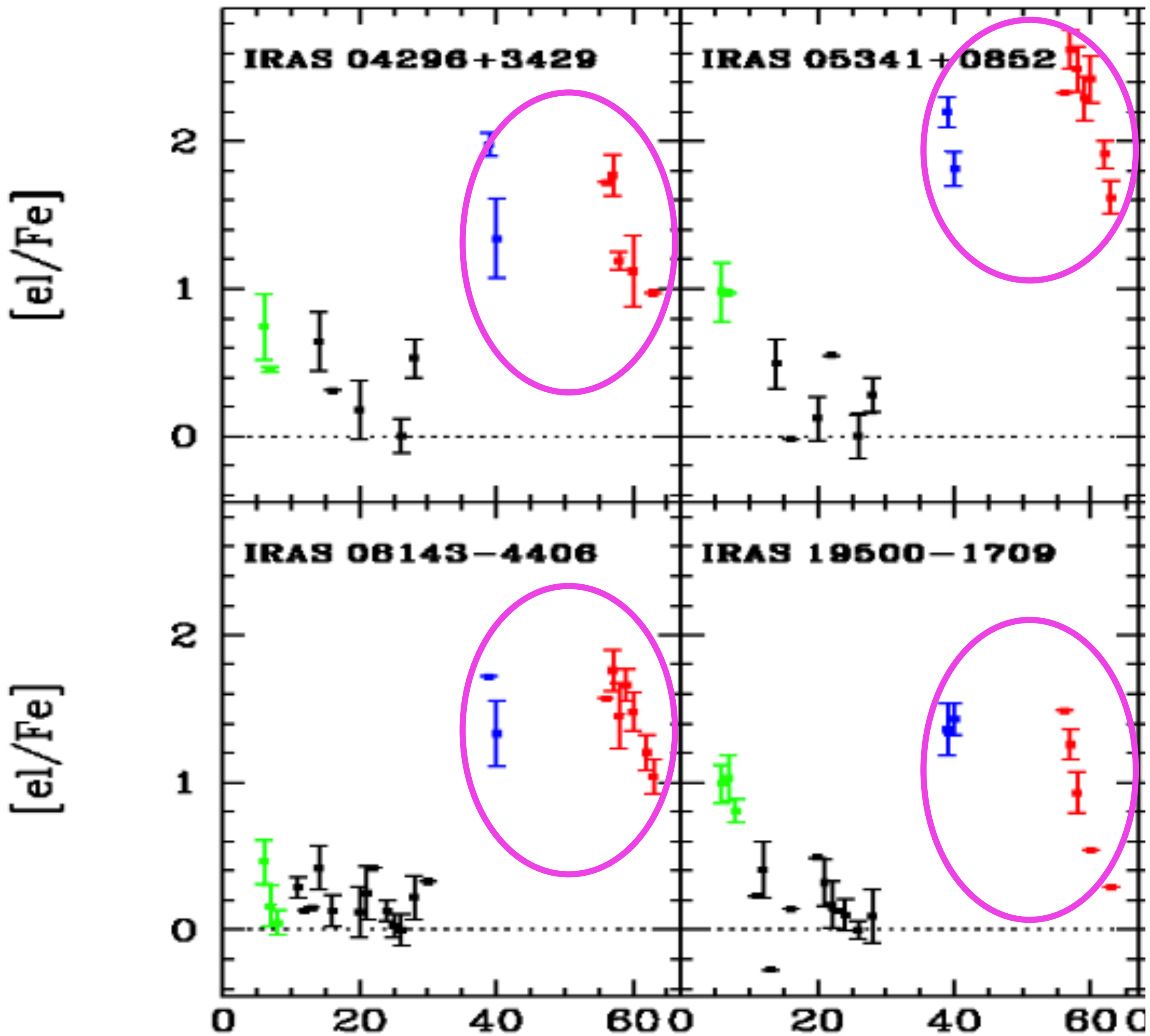
Chemical Diversity in post-AGB stars…

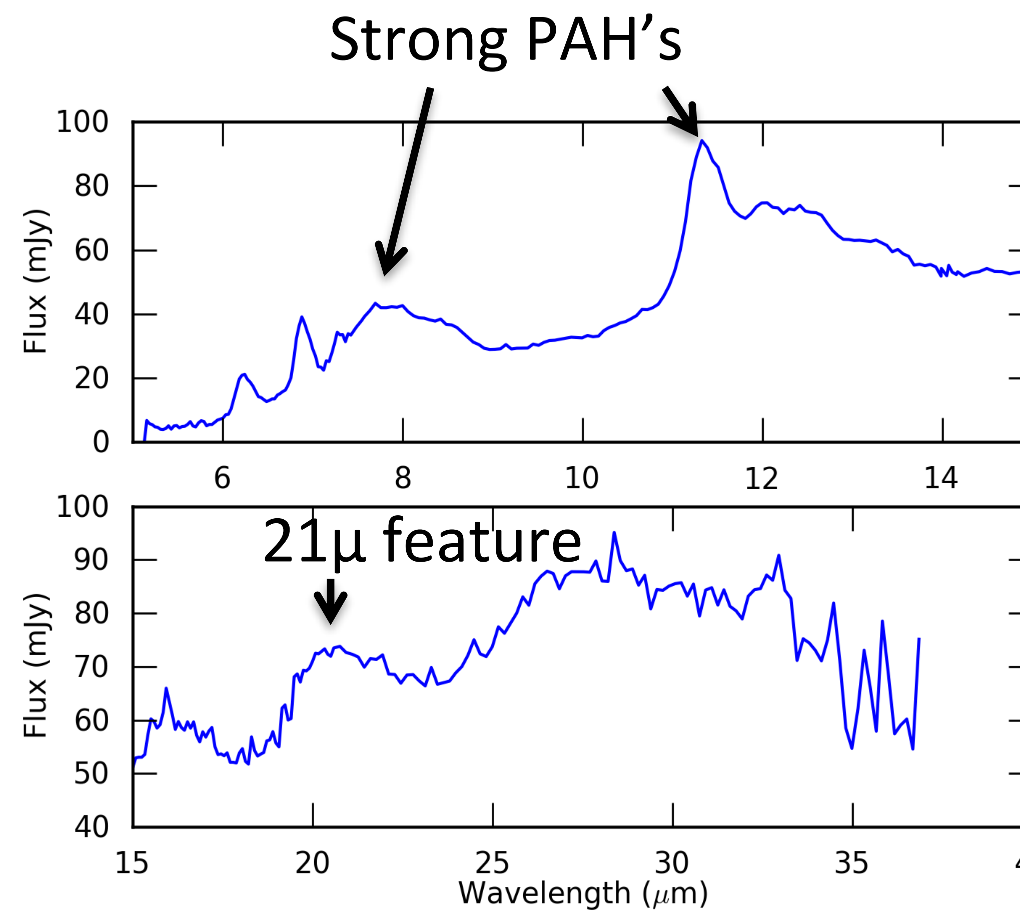
21 micron sources

Trend observed in Galactic/SMC/LMC binary stars

Post-AGB (post- carbon) single shell sources

s-process rich with 21 micron spectral feature



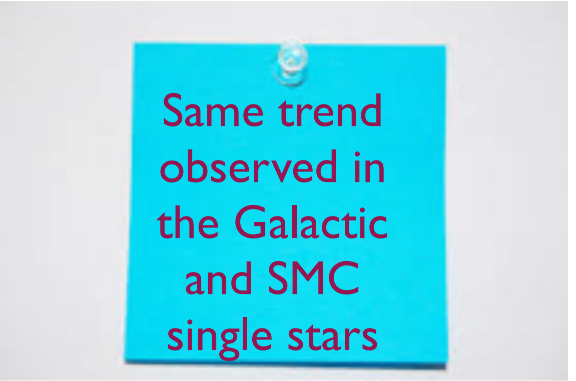


Van Winckel & Reyniers 2000

Volk et al. 2011

CHEMICAL DIVERSITY - II
DEPLETION PATTERNS OBSERVED IN BINARY (DISC) SOURCES

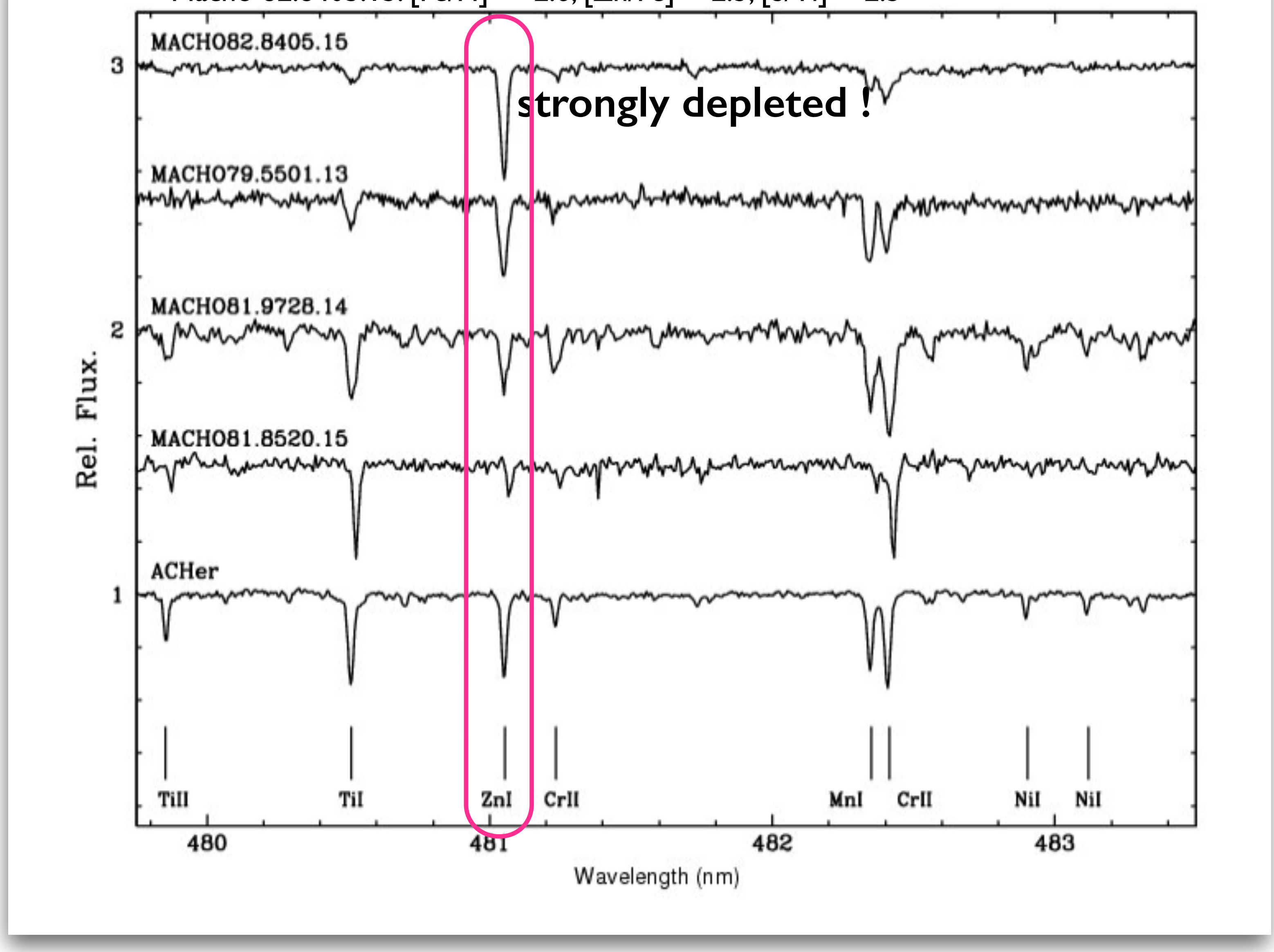
- Disc-type SEDs
- Depletion patterns
- Conforms to **binary** evolution

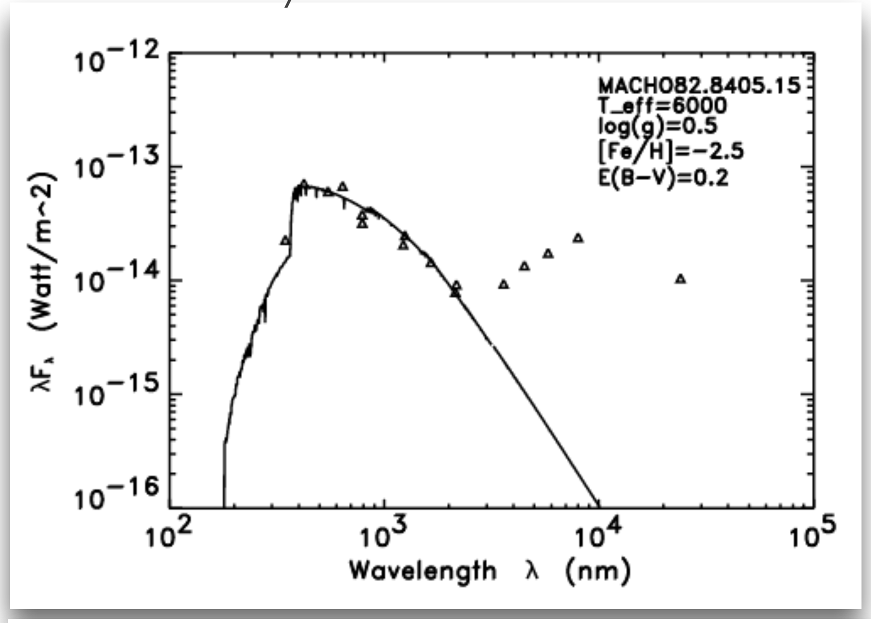


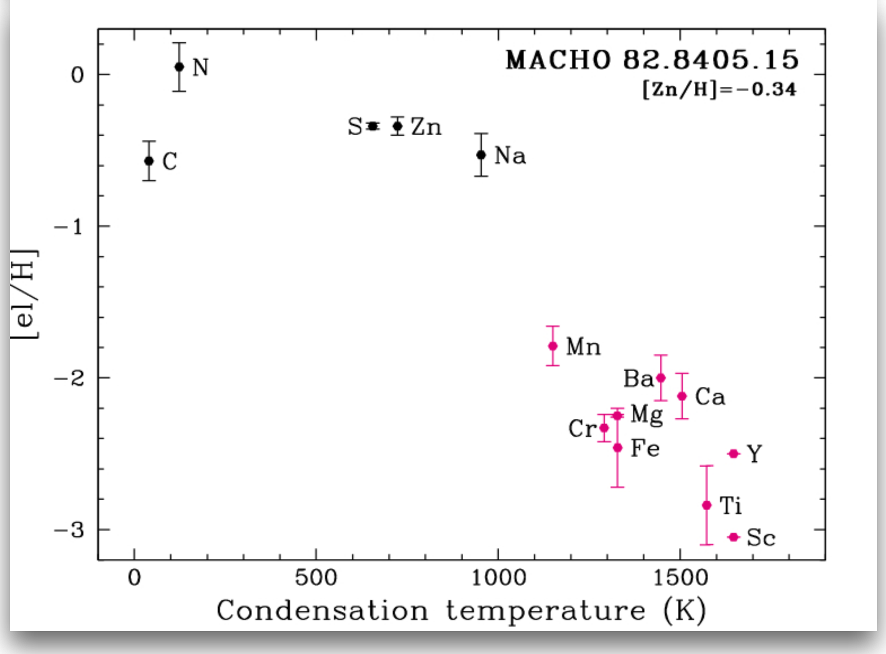
IR spectra are very rich and strongly crystalline !

Photospheric Depletion: Feedback from disc => Loss of nucleosynthetic history

Macho 82.8405.15: [Fe/H] = -2.6, [Zn/Fe]=+2.3, [S/Ti]=+2.5





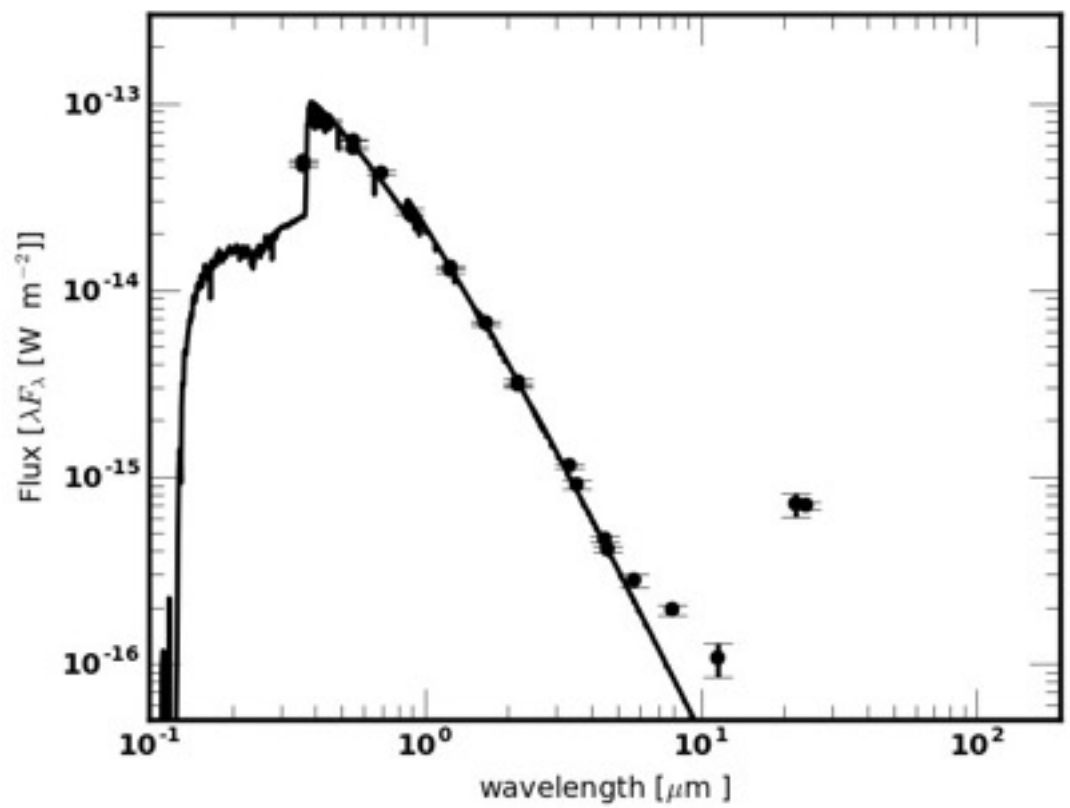


(Reyniers et al., 2007; Gielen et al., 2009, 2011)

What’s up with the third dredge-up?

J005252 - A peculiar Post-AGB star in the SMC

- L = 9000 Lsun
- Teff = 8500K
- Logg = 1.5
- [Fe/H] = -1.2
- E(*B*-*V*) = 0.55



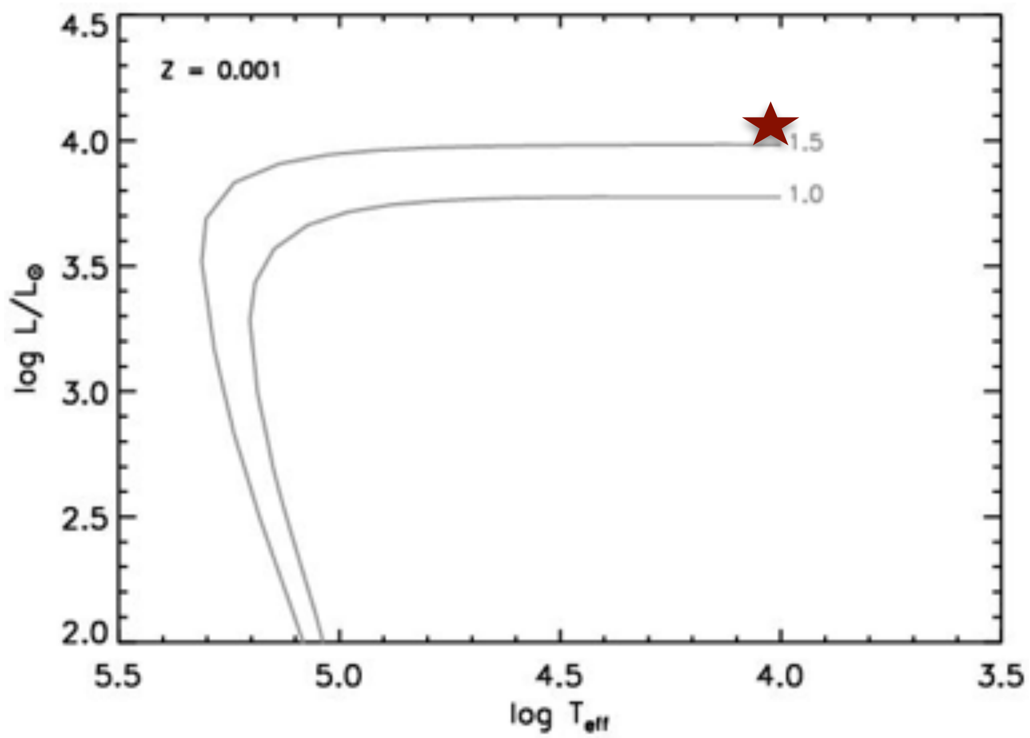
- *Has a shell-type SED => single star !?!*

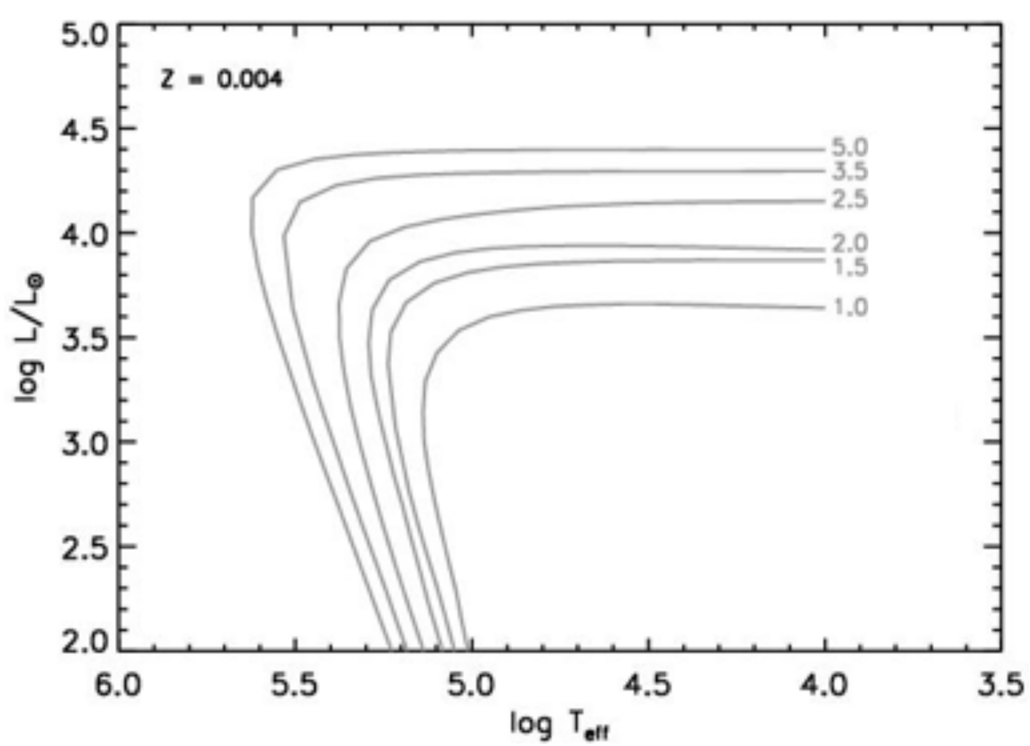
Kamath et al., to be submitted.

Deriving Initial Mass

The Luminosity-Core Mass Relation

Known luminosities to the LMC/SMC sources make them very valuable!





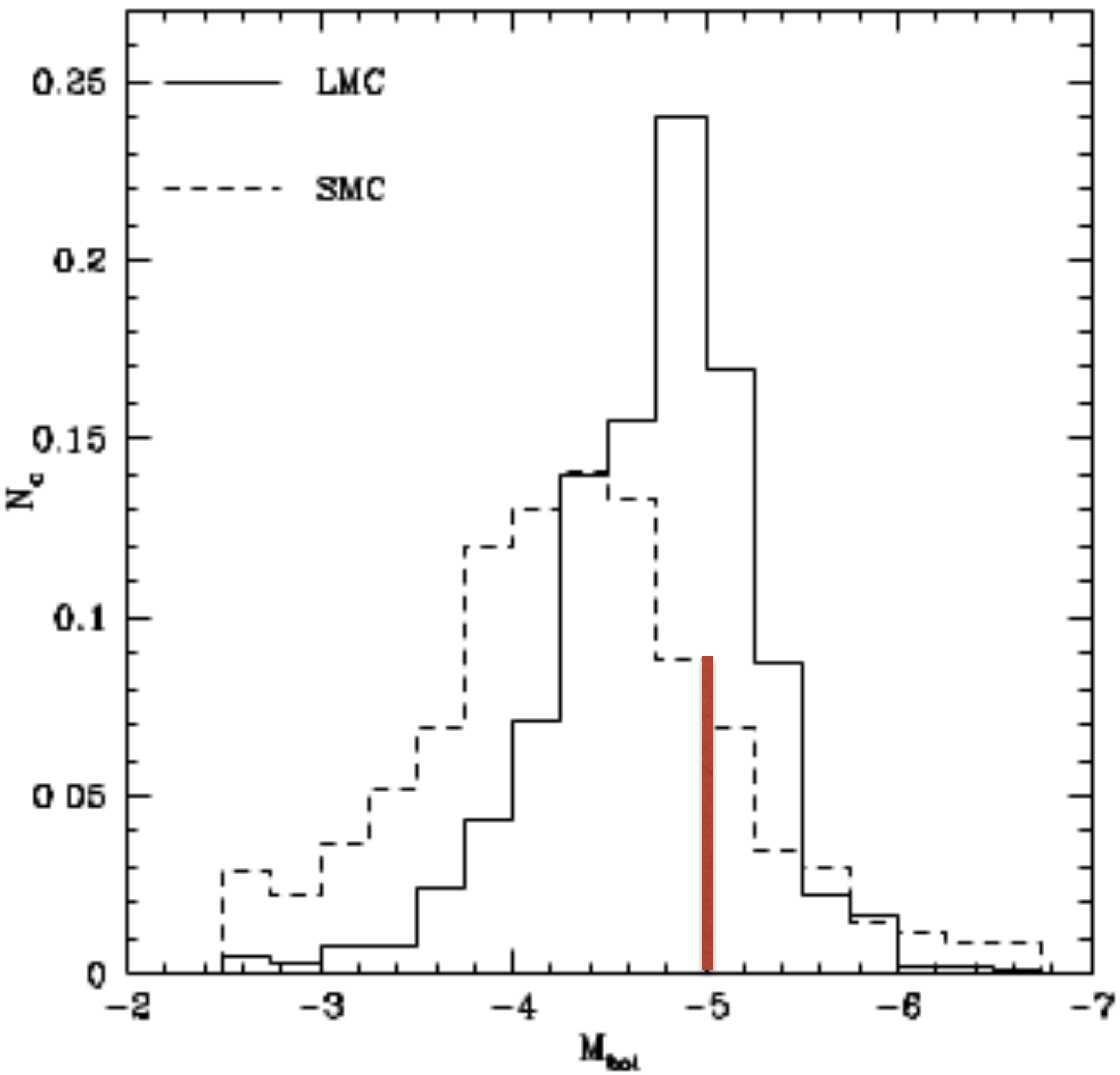
J005252

- L ~ 9000 $L_\odot$,
- Teff ~ 8500K
- Z = 0.001
- **$M_{initial}$ ~1.5 to 2 M_{sun}**

(Wood & Zarro 1981)
(Vassiliadis & Wood 1994)

Based on the observed C-Star Luminosity Function of the SMC…

J005252 is likely to be a C-star at it's luminosity!



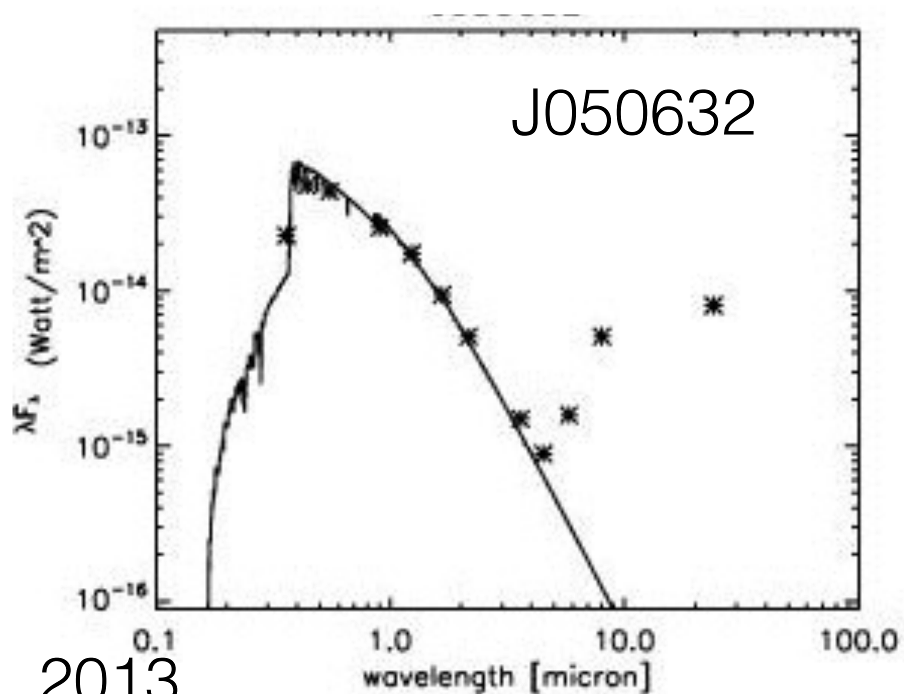
Note: We don't see C-stars at higher luminosities because of HBB

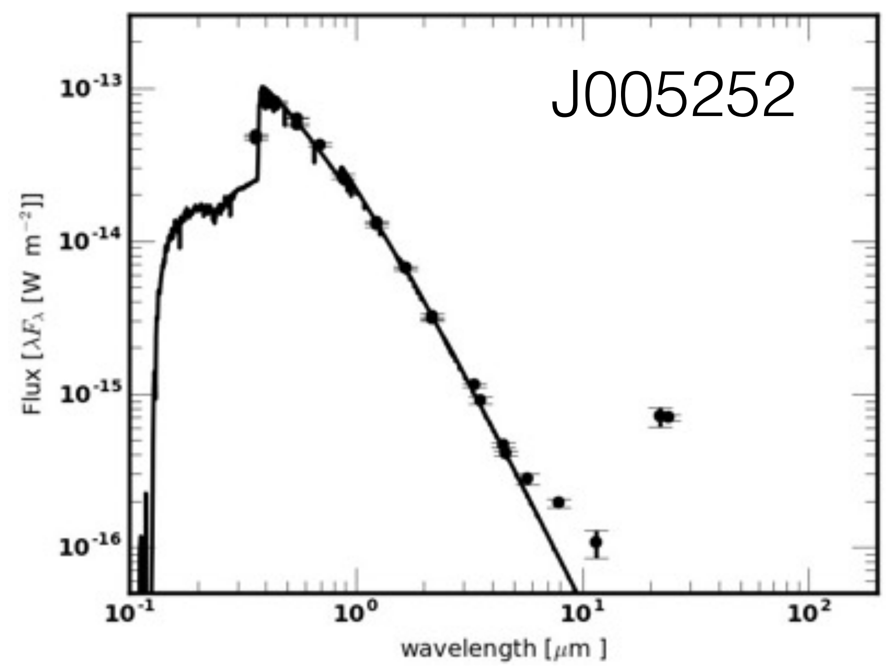
Costa & Frogel (1996); Groenewegen (1997); marigo et al., (1999)

NOT *s*-process enhanced!!!

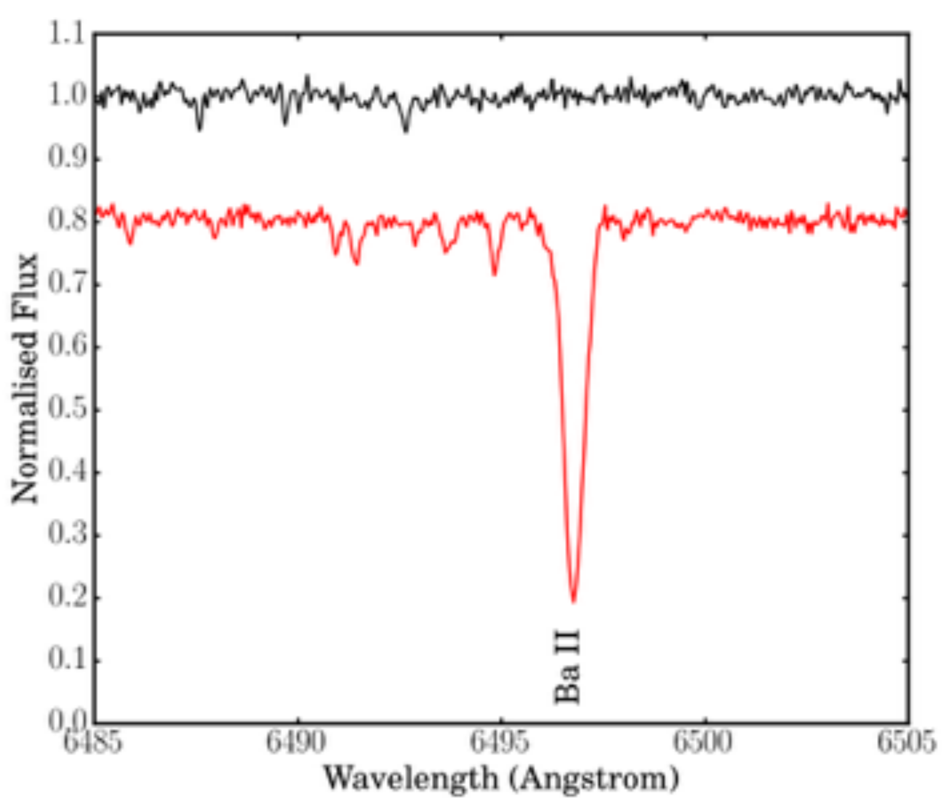
- L = 7000 Lsun
- Teff ~ 7000
- Logg ~ 0.5
- [Fe/H] ~ -1.0

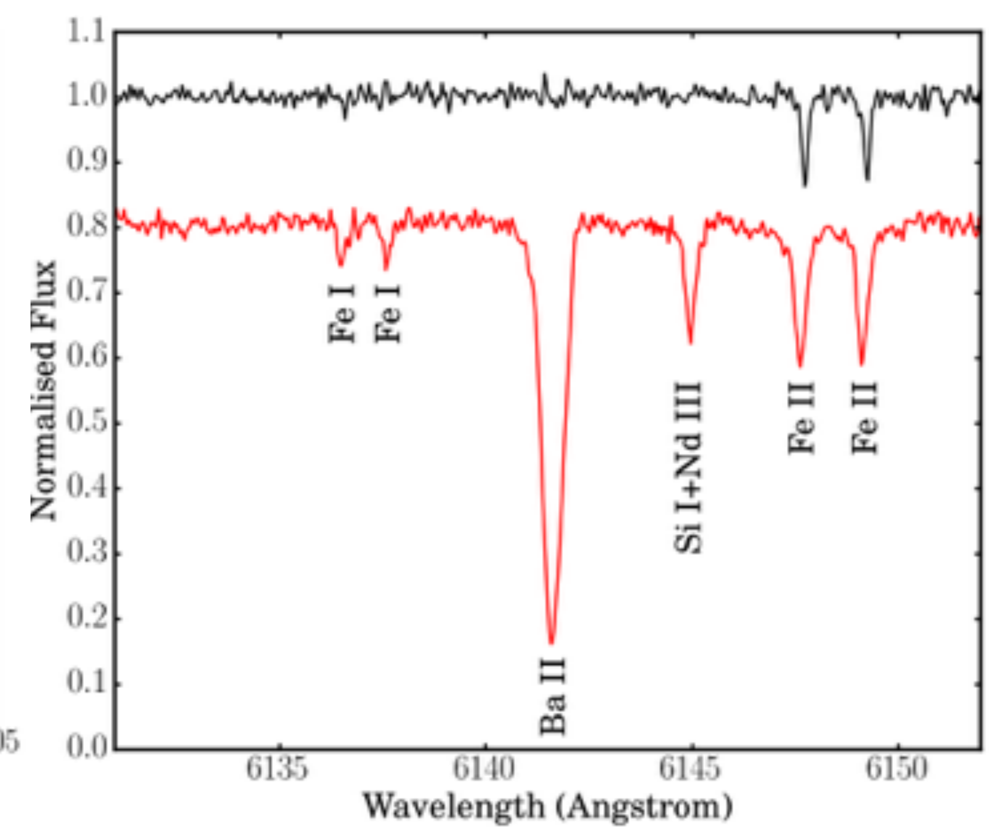
Van Aarle et al., 2013





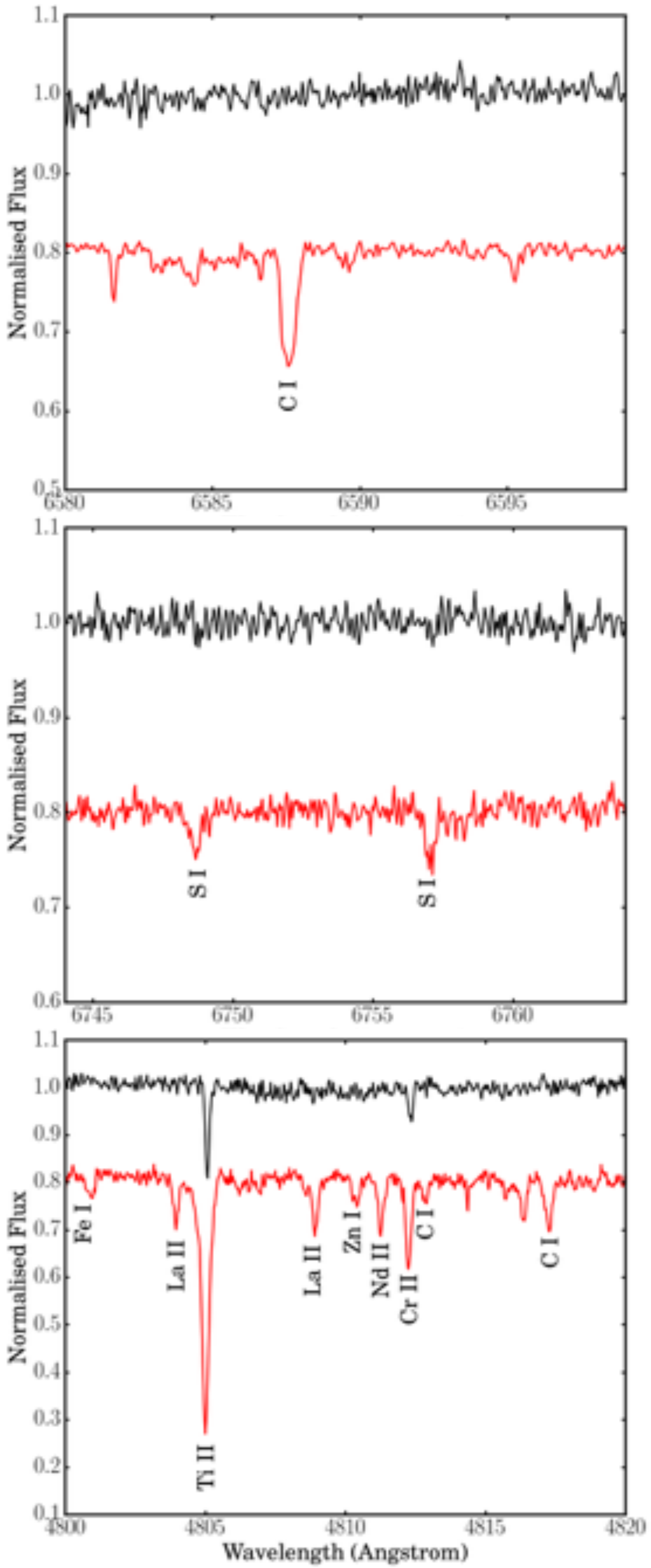
- L = 9000 Lsun
- Teff = 8500K
- Logg = 1.5
- [Fe/H] = -1.2
- E(*B*-*V*) = 0.55

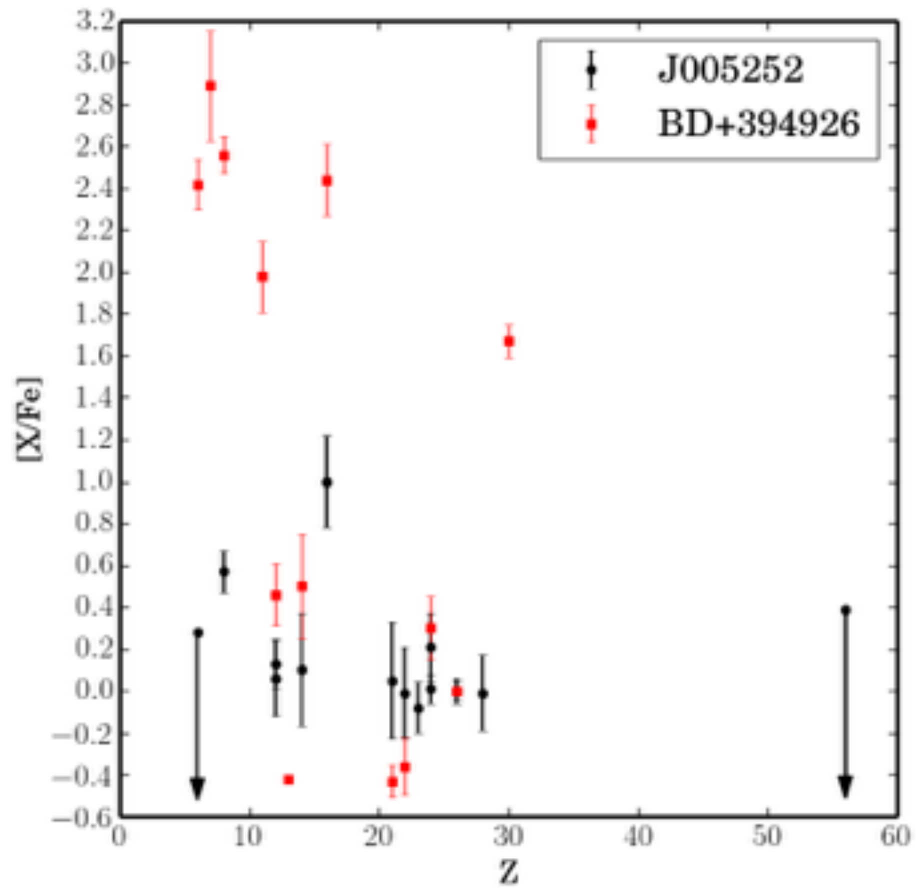




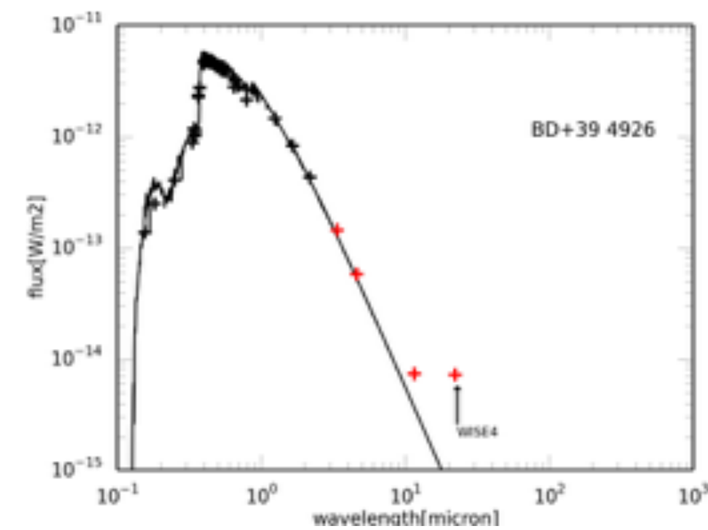
Kamath et al., to be submitted

NOT depleted!!!





Galactic-BD+39 4926



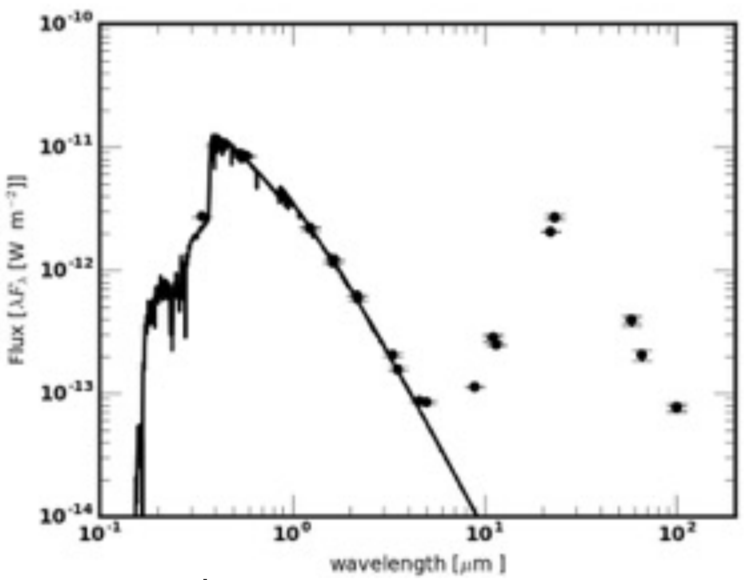
- L = … unknown
- Teff ~ 7500 K
- Log g ~ 1.0
- [Fe/H] ~ -2.9
- P = 874 days

Hrivnak, B et al., 2008; Rao, S. S., et al., 2011; Kamath et al., to be submitted

Other stars that are neither *s*-process enhanced NOR depleted

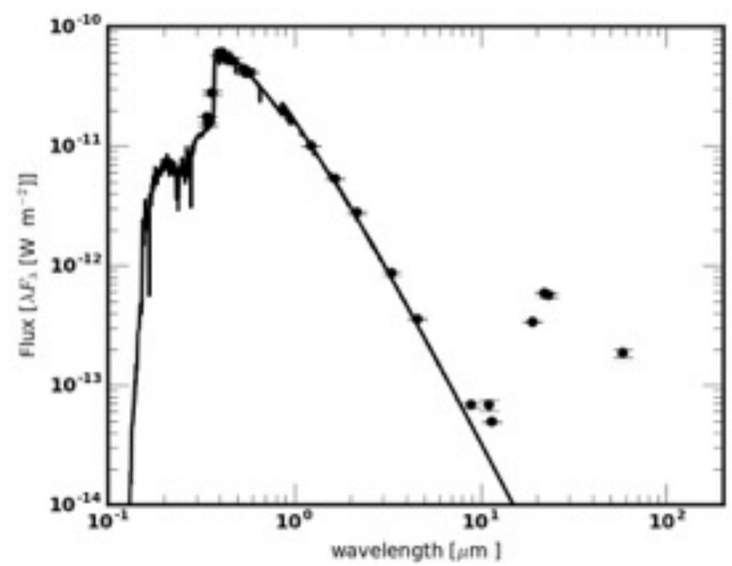
Galactic Objects: SAO 239853 and HD133656

SAO 239853



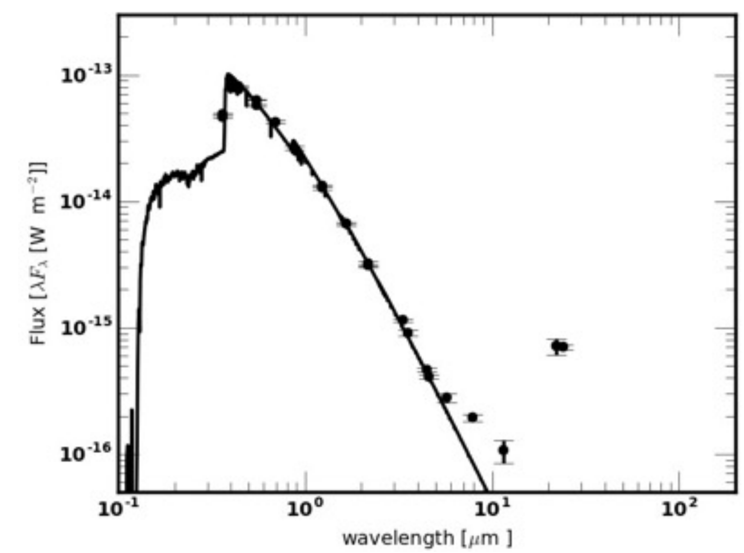
L = …
Teff ~ 7000K
Logg ~ 1.5
[Fe/H] ~ -1.0

HD 133656



L = …
Teff ~ 7500
Logg ~ 2.0
[Fe/H] ~ -1.0

J005252

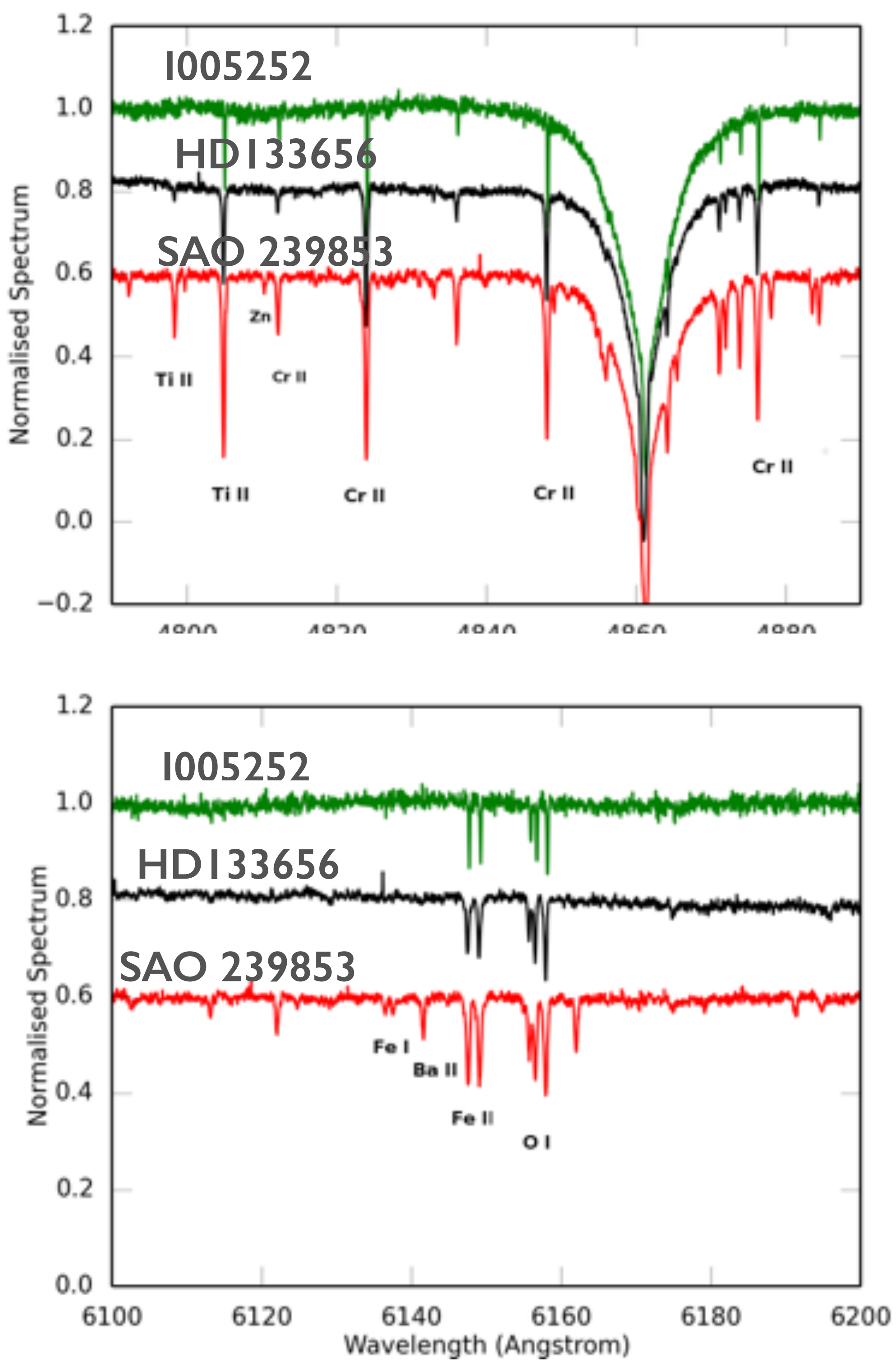


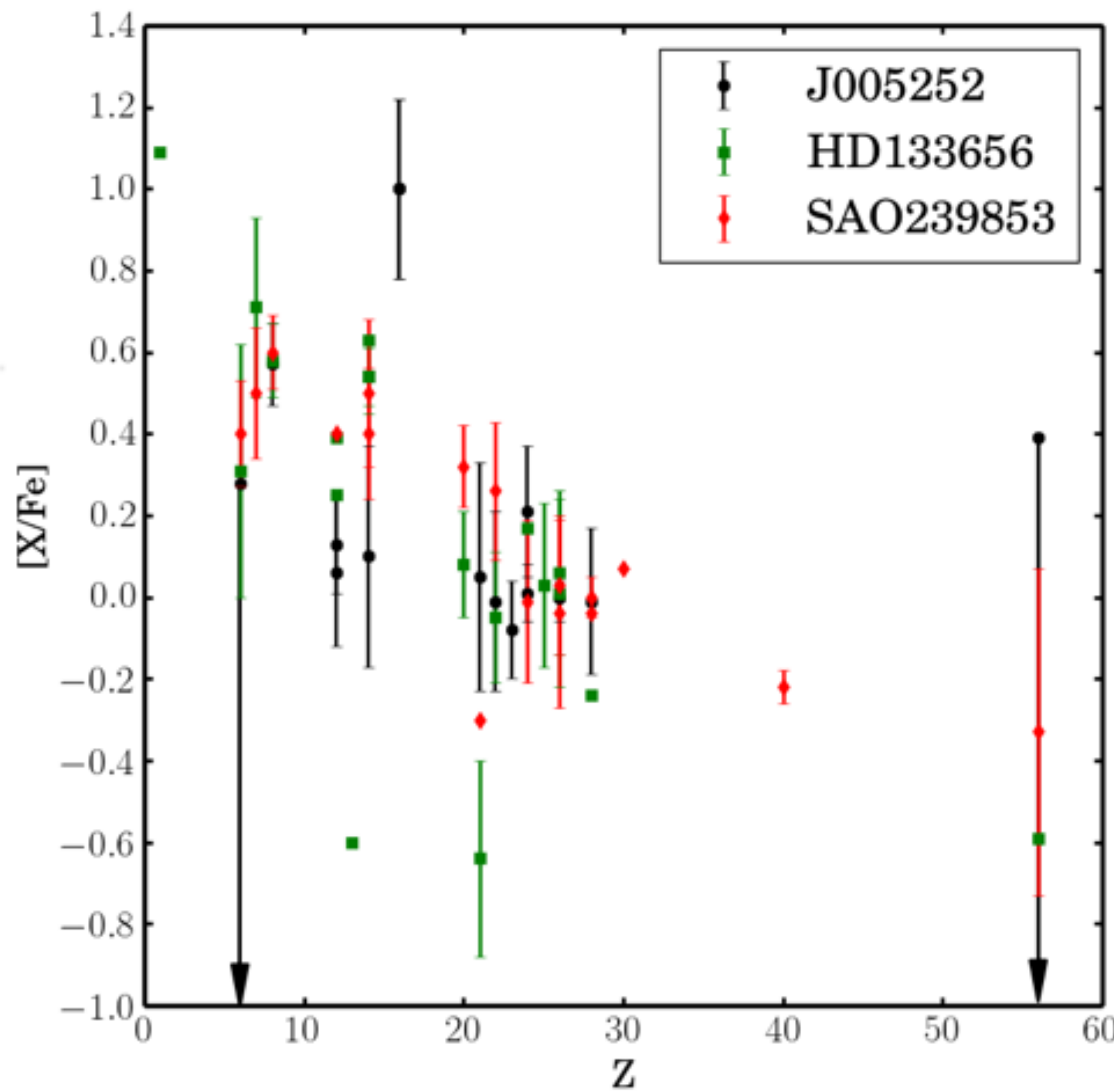
L = 9000 Lsun
Teff ~ 8500K
Logg ~ 1.5
[Fe/H] ~ -1.2

No Luminosity estimates to these objects!
Unlike for the SMC/LMC objects…

Van Winckel 1996; Kamath et al., to be submitted

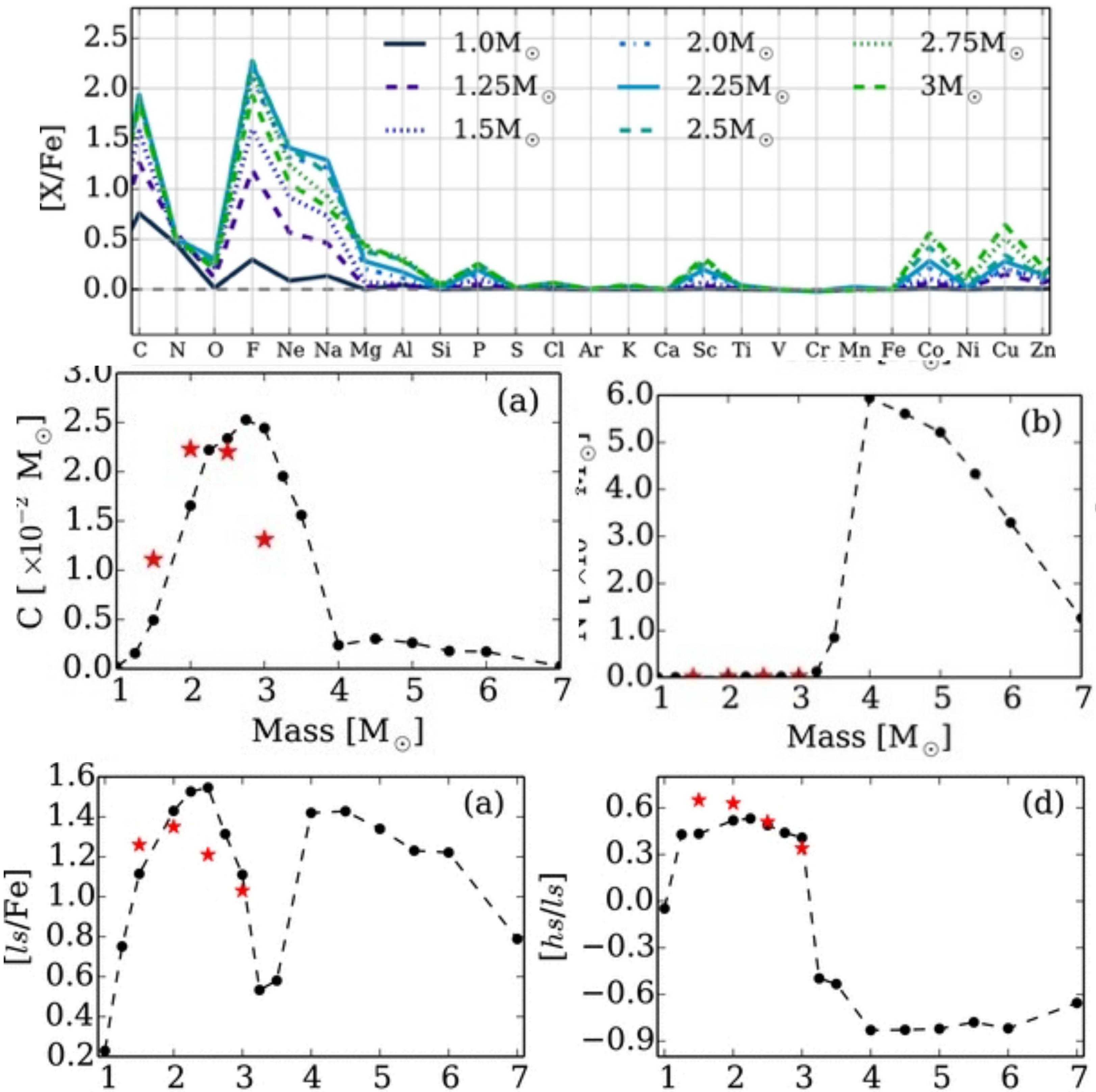
Galactic analogues:
HD 133656 and SAO 239853 ALSO likely fail the third dredge-up!?!





Van Winckel 1996; Kamath et al., in prep

Predicted nucleosynthesis in SINGLE stars…



Fishlock, Karakas et al., 2014

Dredge-up of Carbon and *s*-process elements

ALSO predicted by models by Cristallo, Marigo…

How can we get a low-metallicity (Z~0.001) and low-mass (M~1.5 to 2 Msun) AGB star to evolve without third-dredge Up???

Suggestion 1: **HOT BOTTOM BURNING?** 💀
Problem: J005252 is a low mass star!

Suggestion 2: Does this belong to the newly discovered class of **dusty-post-RGB** stars? 💀
Problem: Nope! We have well constrained luminosity for this object
[see, Kamath et al., 2016 for details on dusty post-RGB stars]

Suggestion 3: Are we looking at **born-again post-AGB stars, or post-AGB stars with a late flash**? 💀
Problem: These stars retain their s-process enrichment and they have high oxygen abundances. This is not observed in J005252

Suggestion 4: Is it **Merger**? 👽
Problem: Possibly, but how can we tell???

Suggestion 5**: Different mass-loss history - so an AGB life without dredge-up** 😱
Problem: Ground-control, can you hear me ?!?!

Suggestion 6: **Magnetic Fields** 😎
Problem: …

Summary…

Post-AGB stars are ideal tracers of AGB nucleosynthesis…

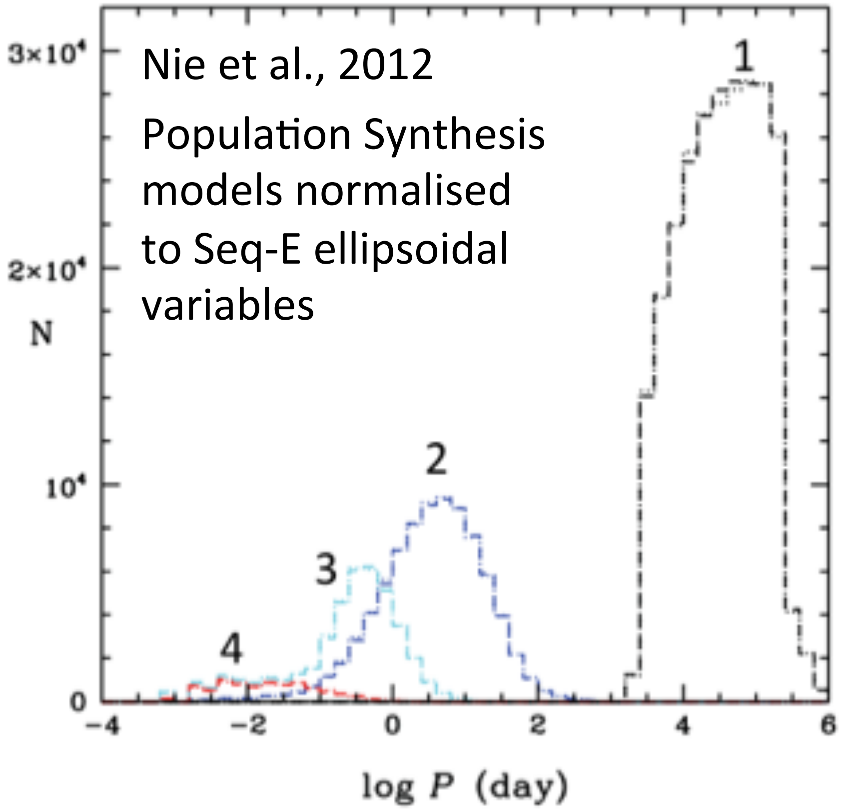
What do we get from post-AGB stars?

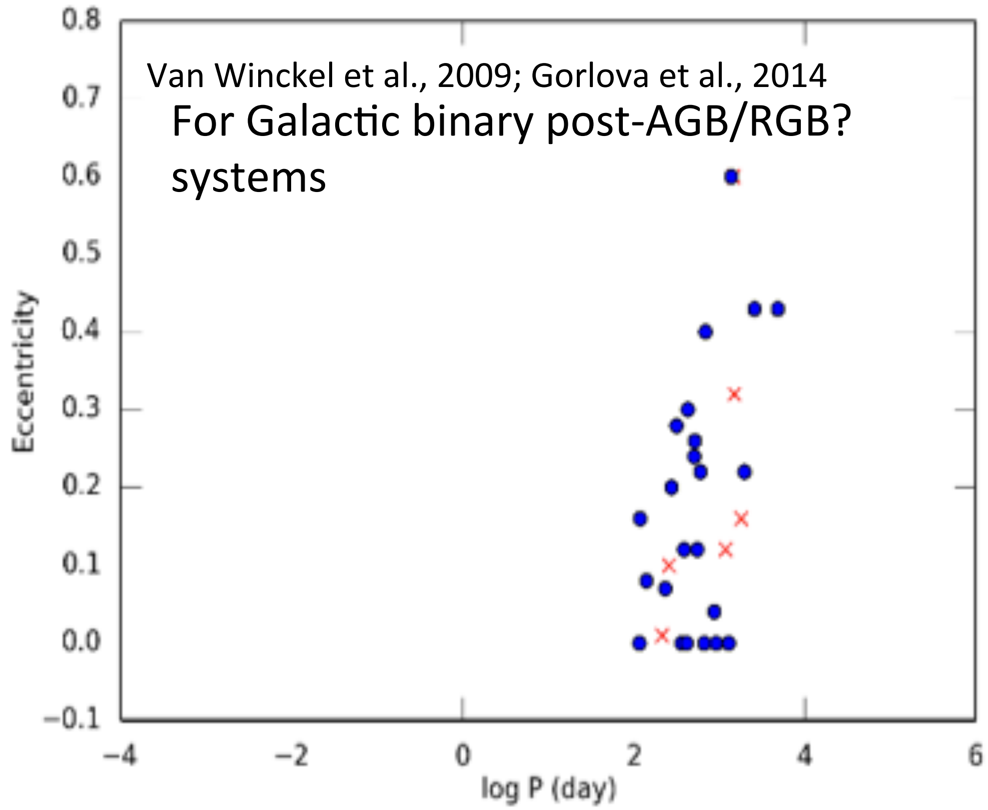
- Initial Luminosity (hence mass) + Stellar parameters (Teff, Log g, [Fe/H])
- Chemical Abundances of all CNO + s-process + elements upto Pb
- Isotopic ratios : $^{12}C/^{13}C$, $^{16}O/^{18}O$
- Chemical diversity -> reflects the evolutionary channel

What can we try to constrain?

- The relevance of extra mixing schemes along the different evolutionary tracks
- Mixing regimes and their influence on the photospheric abundances
- Overshoot parameters related to the creation of the ^{13}C pocket
- The integrated mass-loss on the AGB
- Luminosity and metallicity dependence of efficiency TDU, neutron irradiation, etc.

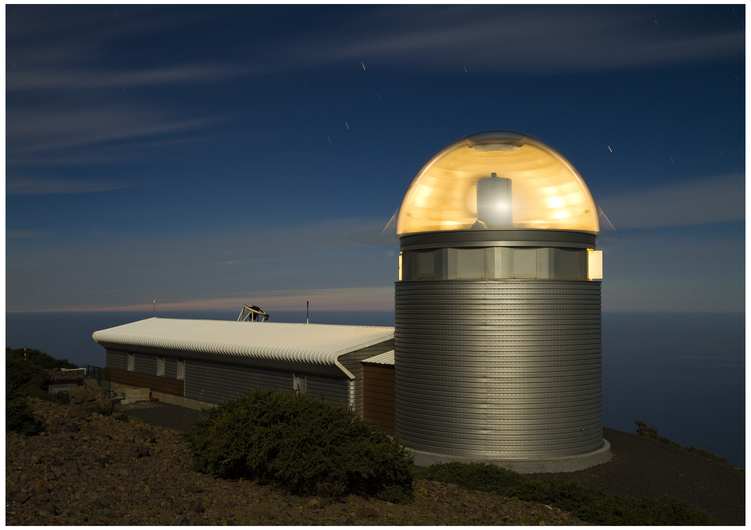
• Monitoring Post-AGB and Post-RGB binaries…





Discrepancy between observed period distribution and predicted ones!!!

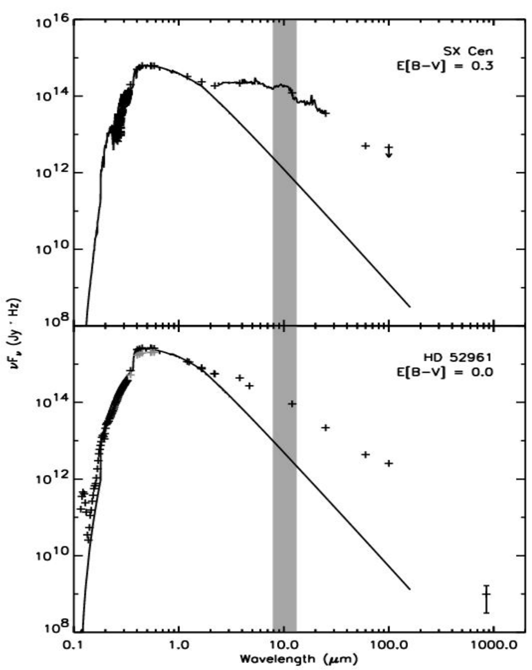
A radial velocity monitoring programme with the HERMES spectrograph mounted on the Mercator telescope



- # Resolving proto-planetary disc around post-AGB binaries

Probing the CSE of post-AGB binaries with Interferometry

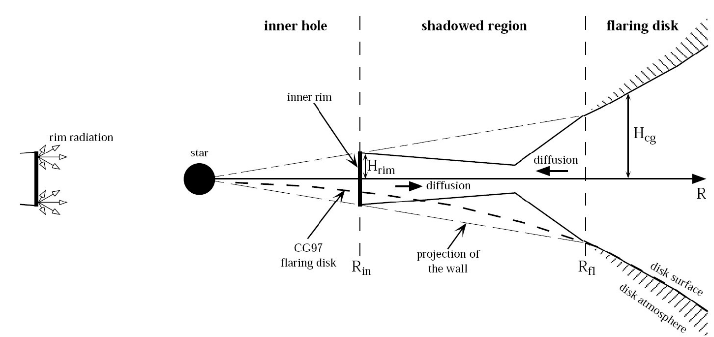
Michel Hillen et al.,2013 &2014

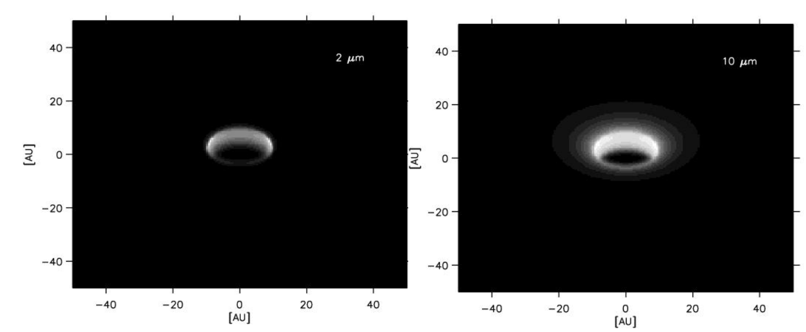


MIDI : N-band: near peak SED
AMBER: photosphere-hot dust region

Probing the CSE of post-AGB binaries with Interferometry

Basic Disc Structure





- Lstar = 2500 Lsun
- $M_* = 1$ Msun
- $T_* = 6000$ K
- R(in) = 10 AU
- Mdisk = 4 10^{-3} Msun
- R(out) = 200 AU
- silicates 0.1 micron

Deroo et al. 2007.; Hillen et al 2013

CONCLUDING REMARK(s)…

Post-AGB stars bear the signatures of the chemical and morphological changes that occur during and prior to the AGB phase of evolution…

They provide constraints for:

STELLAR EVOLUTION, NUCLEOSYNTHESIS, SHAPING OF PNe, DUST PRODUCTION and the CHEMICAL EVOLUTION OF THE HOST GALAXY