SPECTROSCOPIC SURVEYS OF MASSIVE AGB AND SUPER-AGB STARS

'The AGB-Supernovae Mass Transition'

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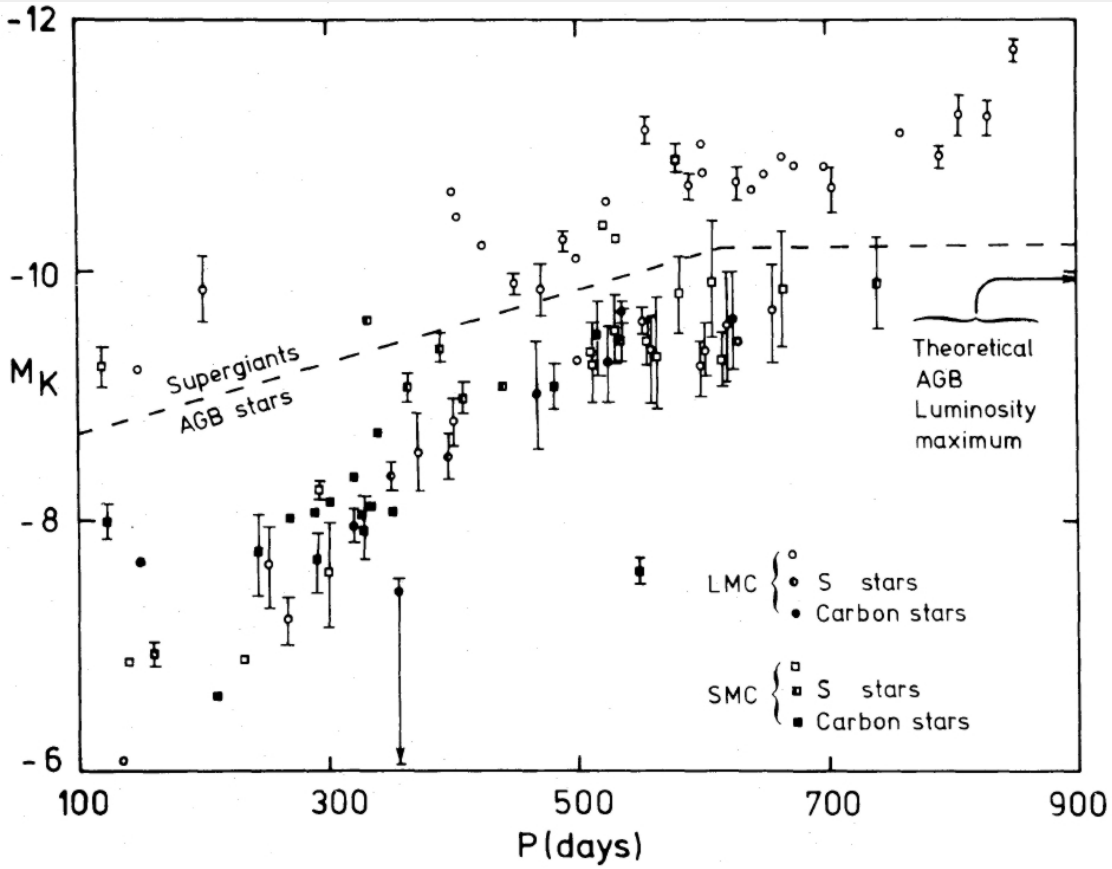
Rome, March 29th 2017

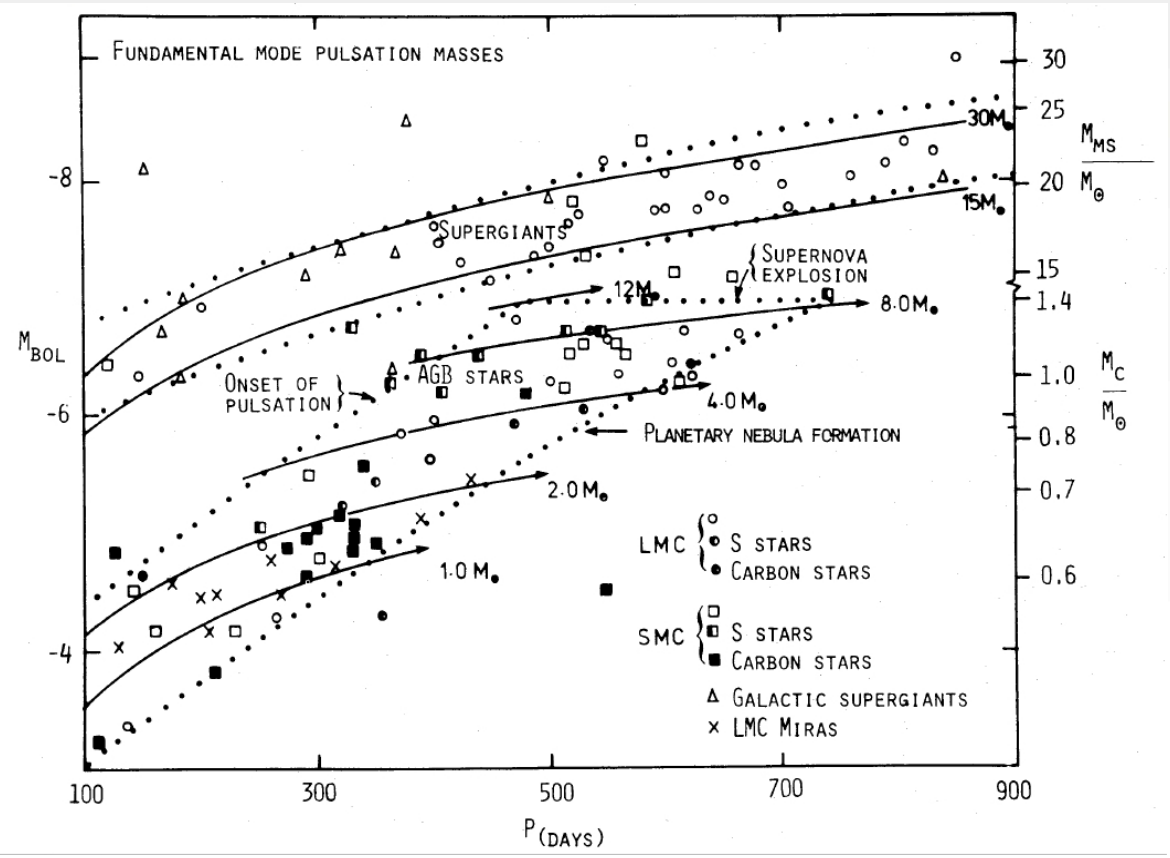
Discovery of massive AGB stars



Wood, Bessel & Fox (1983)

- **First identification dates back to about 30 yrs ago**
- **Photometric surveys in the Magellanic Clouds**
- **No C-rich AGBs brighter than $M_{bol} \sim -6$**

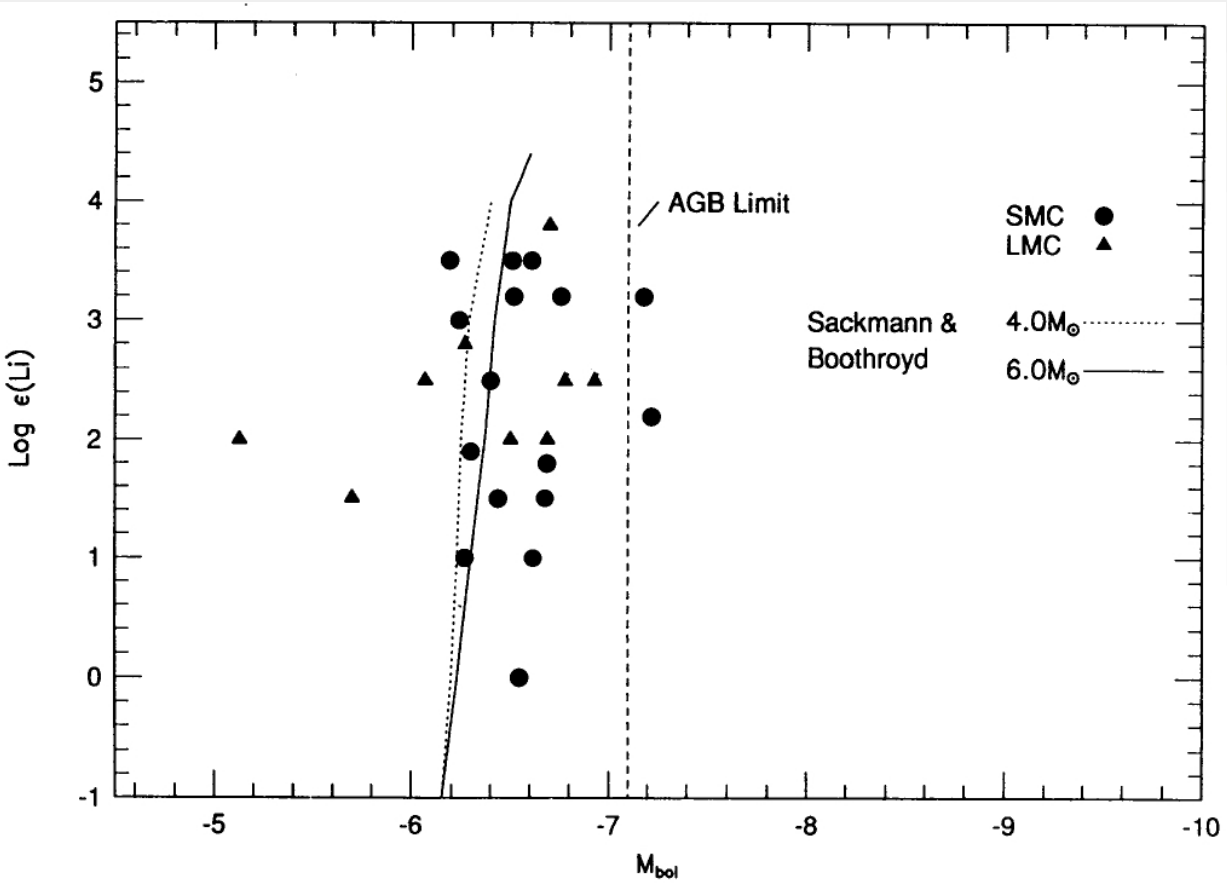
Discovery of massive AGB stars



Wood, Bessel & Fox (1983)

- **Long-period variables (~500-800 days)**
- **S-process enriched**
- **Concentrated in a narrow luminosity range $-7 \leq M_{bol} \leq -6$**
- **Consistent with relatively high-mass progenitors**

Confirmation of HBB in MC AGBs



Smith et al. (1995)

- Li-rich stars just confined at

  $-7 \leq M_{bol} \leq -6$

- Both LMC & SMC
- Log ε(Li) ~ 1.0–4.0
- HBB activation in the more luminous and massive AGB stars

The s-process in SMC AGBs

TABLE 5

SUMMARY OF MEASURED ABUNDANCES

Star	[z/H][a]	[Zr/z]	[Nd/z]	[s/z][b]	log ϵ(Li)[c]	$^{12}C/^{13}C$	[Rb/z][d]
HV 11223	−0.44	+0.21	+0.62	+0.42	+2.85	9	−0.5??
HV 1963	−0.48	−0.17	+0.68	+0.26	+2.75	7	≤ −1.0
HV 11366	−0.47	+0.17	+0.92	+0.55	+1.90	...	−1.0
HV 12179	−0.50	+0.15	+1.01	+0.58	+2.75	5	−0.5??
HV 11329	−0.37	−0.26	+0.40	+0.07	+3.50	...	−0.9
HV 1375	−0.69	+0.34	+0.66	+0.50	+3.00	...	≤ −1.0
HV 11452	−0.70	+0.40	+0.60	+0.50	+3.0	5	≤ −1.2
Average	−0.52	+0.12	+0.70	+0.41	+2.82	6.5	≤ −0.9
σ	0.13	0.25	0.21	0.18	0.48	1.9	≥0.25
N371:C12	−0.37	−0.23?	+0.02	−0.11	−0.8	25	−1.3[e]
Average −C12	−0.15	+0.35	+0.70	+0.52	+3.62		≤0.4?

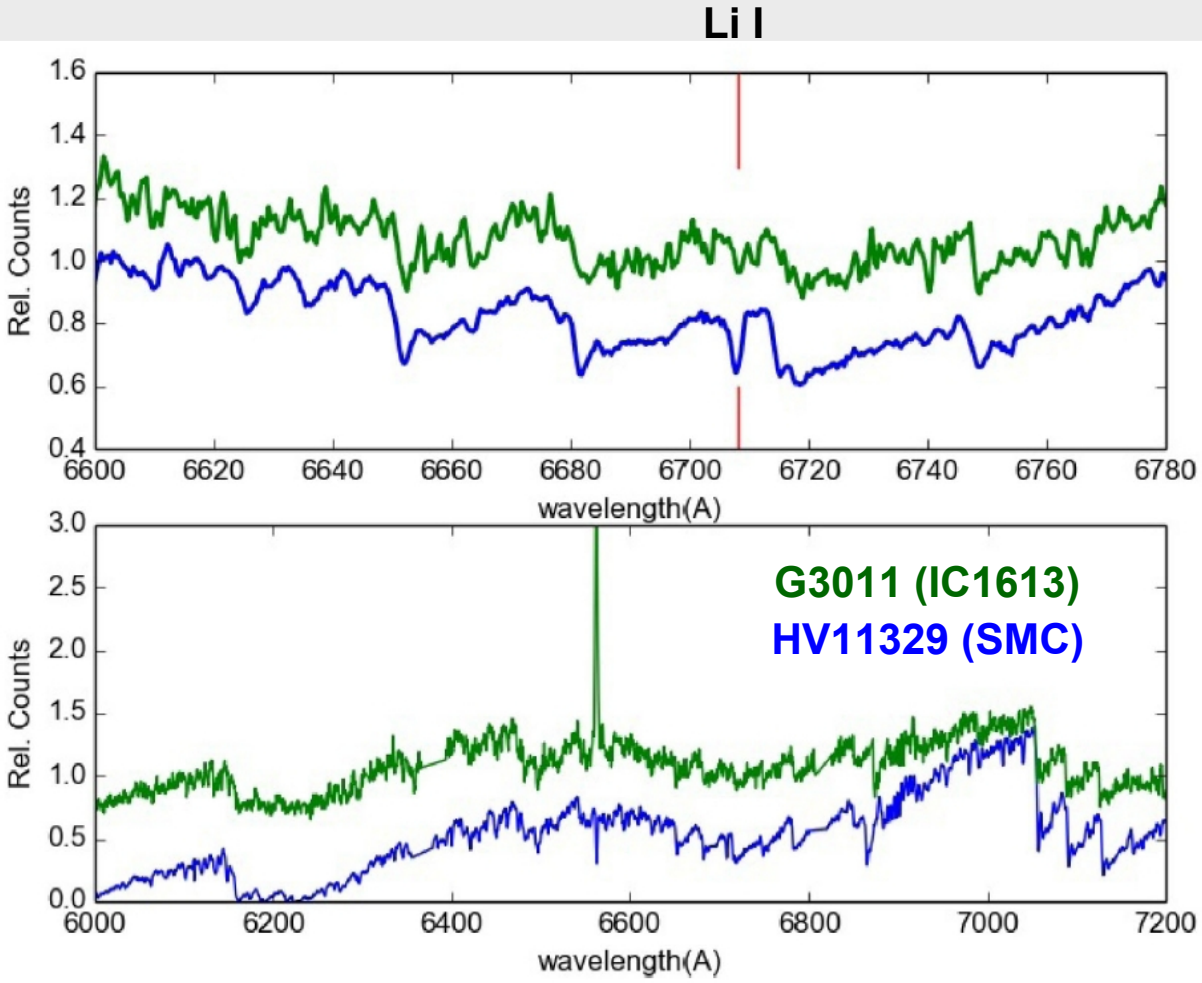
[a] z is the average of the Fe and Ni abundances.
[b] s is the average of the Nd and Zr abundances.
[c] Straight average of the 6707 Å and 8126 Å abundances.
[d] Relative to solar photospheric value: log ϵ(Rb) = 2.60.
[e] From AAT spectrum.

No Rb-rich stars!

^{13}C drives the s-process?

Plez et al. (1993)

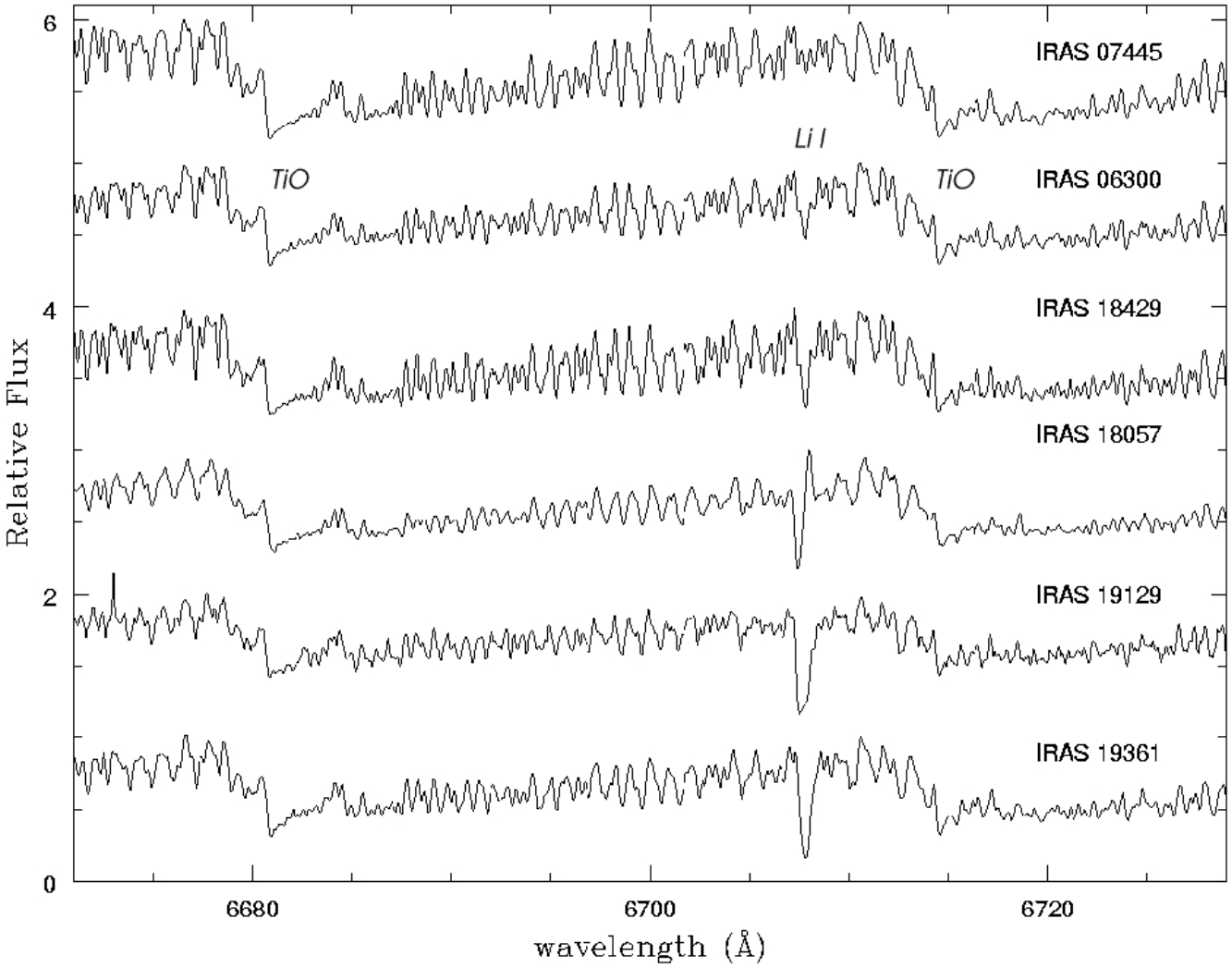
HBB stars in IC 1613



- **Recently identified in the dwarf galaxy IC 1613**
- **A Li-rich massive HBB AGB (G3011)**
- **HBB activation down to [Fe/H]=-1.60 ?**

Menzies et al. (2015)

Massive Galactic HBB AGBs



García-Hernández et al. (2007)

Lithium

- High-resolution optical surveys of luminous OH/IR stars

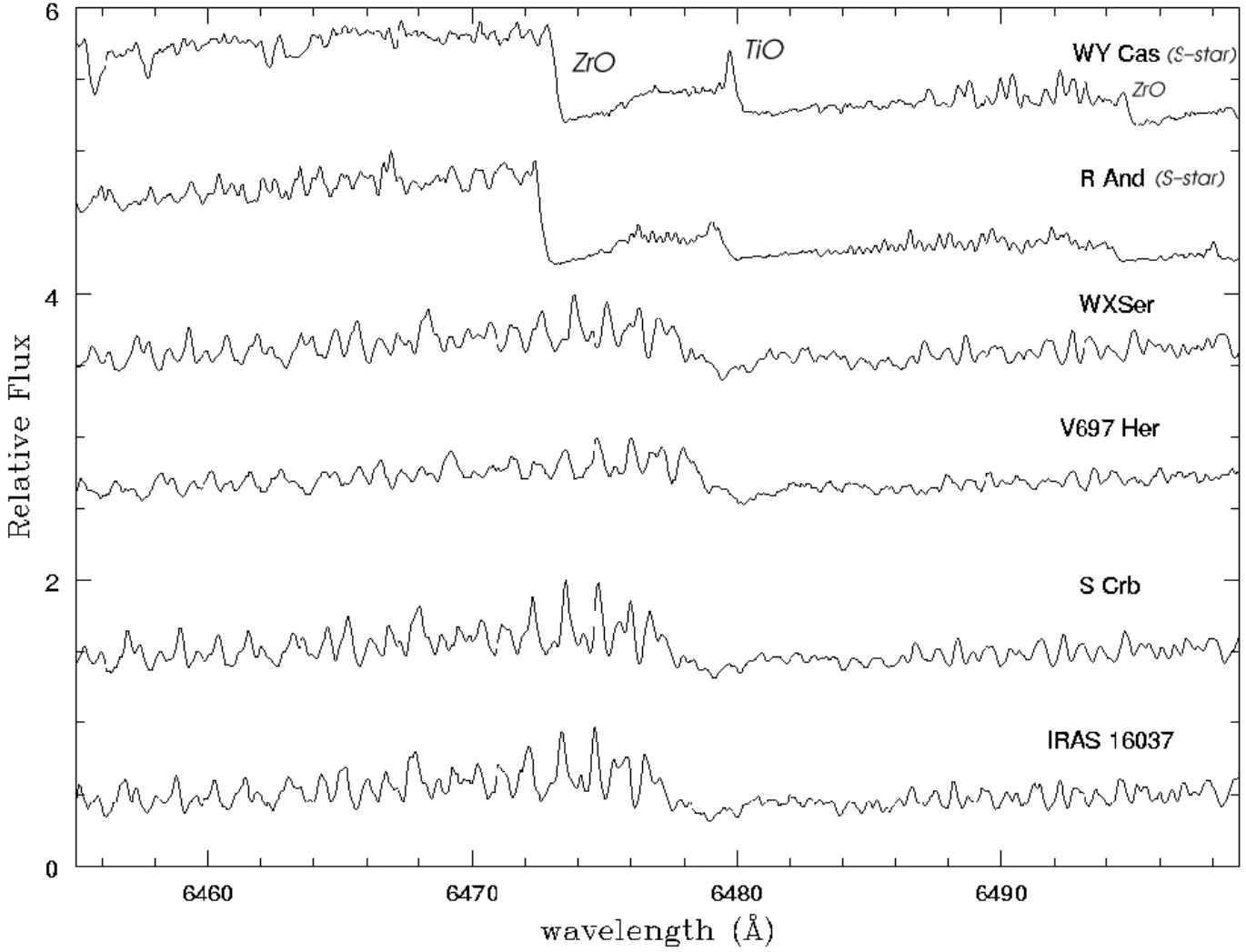
- Li-rich stars

Log ε(Li) ~ 1.0–3.0

P > 400 days

V_{exp}(OH) > 6 km/s

Massive Galactic HBB AGBs



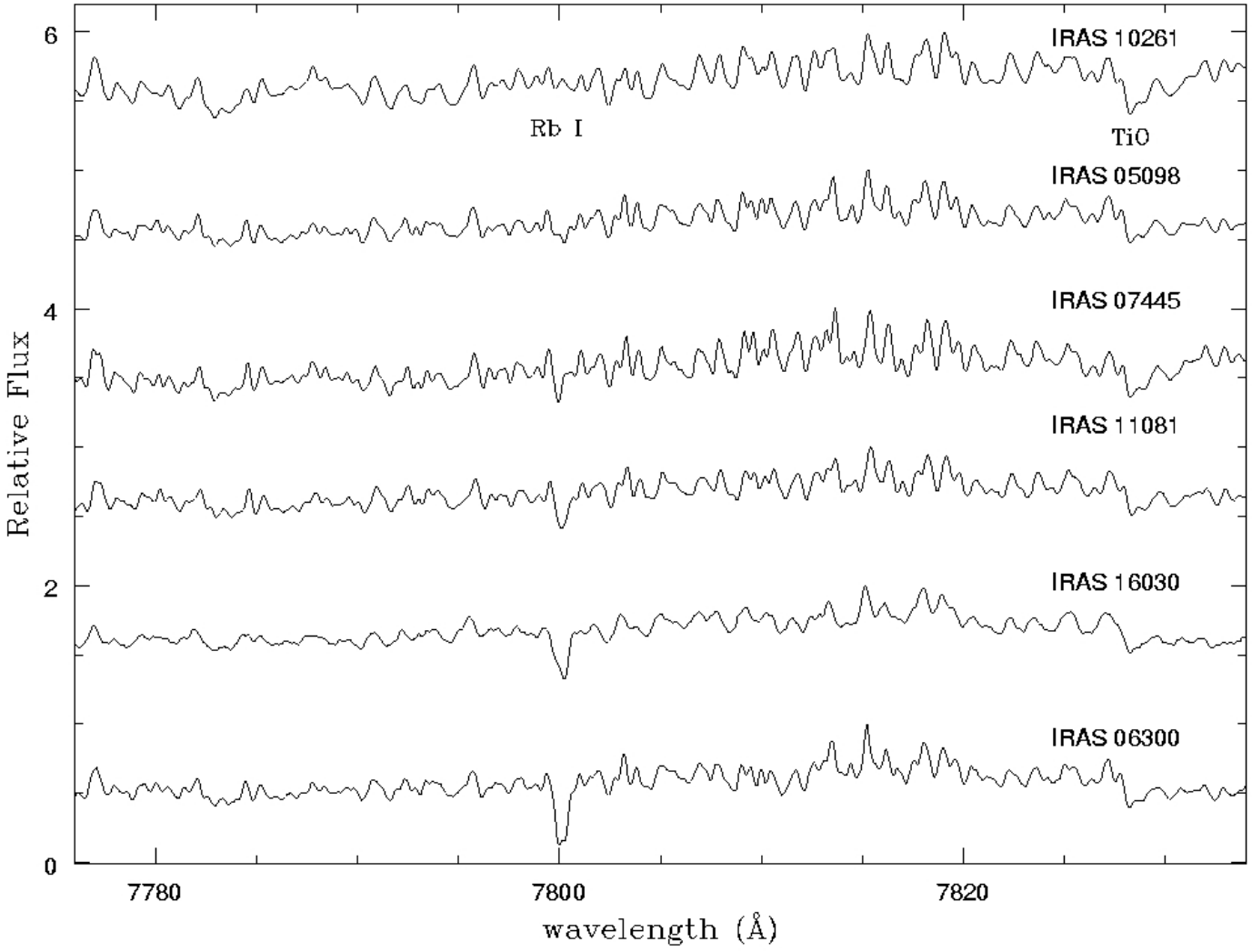
García-Hernández et al. (2007)

Zirconium

- High-resolution optical surveys of luminous OH/IR stars
- No Zr-enriched stars

[Zr/Fe] ≤ 0.25 dex

Massive Galactic HBB AGBs



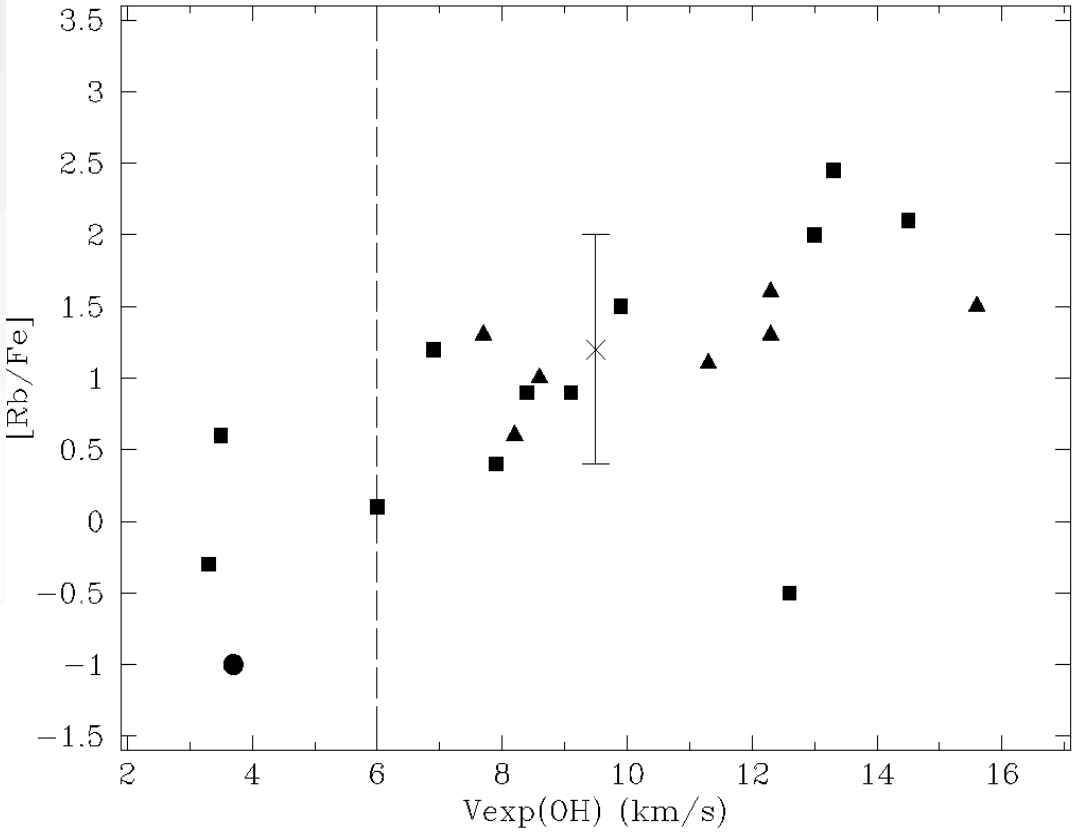
García-Hernández et al. (2006)

Rubidium

- High-resolution optical surveys of luminous OH/IR stars
- Strongly Rb-rich stars

[Rb/Fe] ~ 0.0–2.6

^{22}Ne nucleosynthesis confirmation



García-Hernández et al. (2006)

V_{exp}(OH) is a mass indicator in OH/IRs

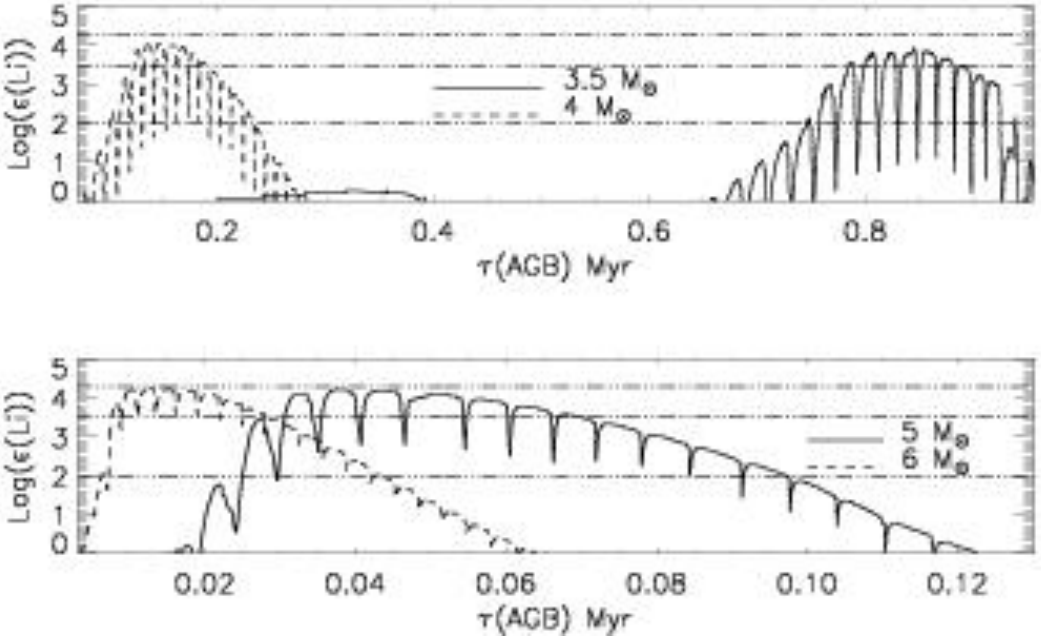
(e.g., Jiménez-Esteban et al 05)

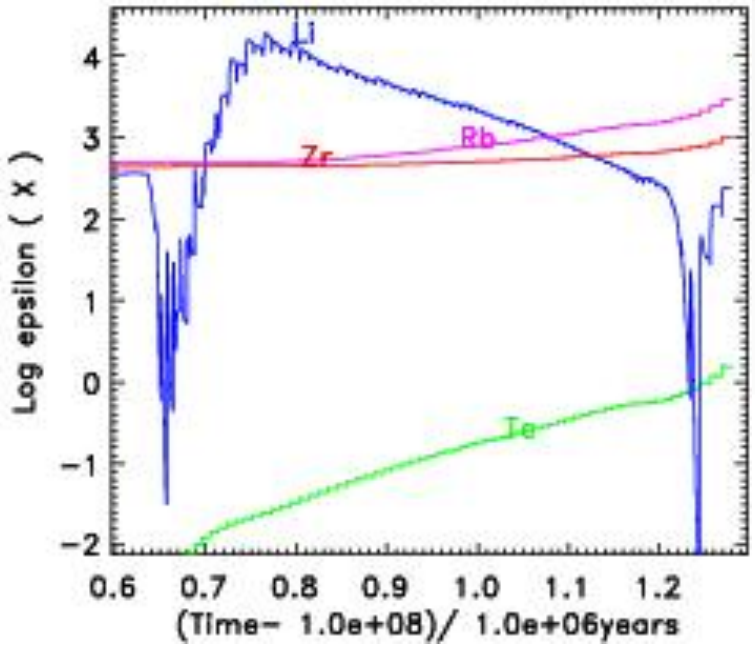
Theoretical models reproduce the observed correlation but cannot explain the high Rb

(e.g., van Raai et al. 2012)

Early massive HBB AGBs

- **Super Li-rich massive AGBs at the beginning of the TP phase**
- **Nucleosynthesis at the early AGB stages**
- **Strong Li coupled with no s-process elements as predicted**





García-Hernández et al. (2013)

Metallicity effects: summary

	Galaxy	Magellanic Clouds
Dust production	efficient	no efficient
Dredge-up	no efficient	efficient
AGB lifetime	small run of TPs	large run of TPs
HBB	for M > 4 $M_\odot$	for M > 3 $M_\odot$
s-process	[s/Fe] < 0.5 dex	[s/Fe] > 0.5 dex
Neutron density	high [Rb/Zr] ↑	low [Rb/Zr] ↓
Neutron source	^{22}Ne	^{13}C

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Where are the low-metallicity Rb-rich AGB counterparts?

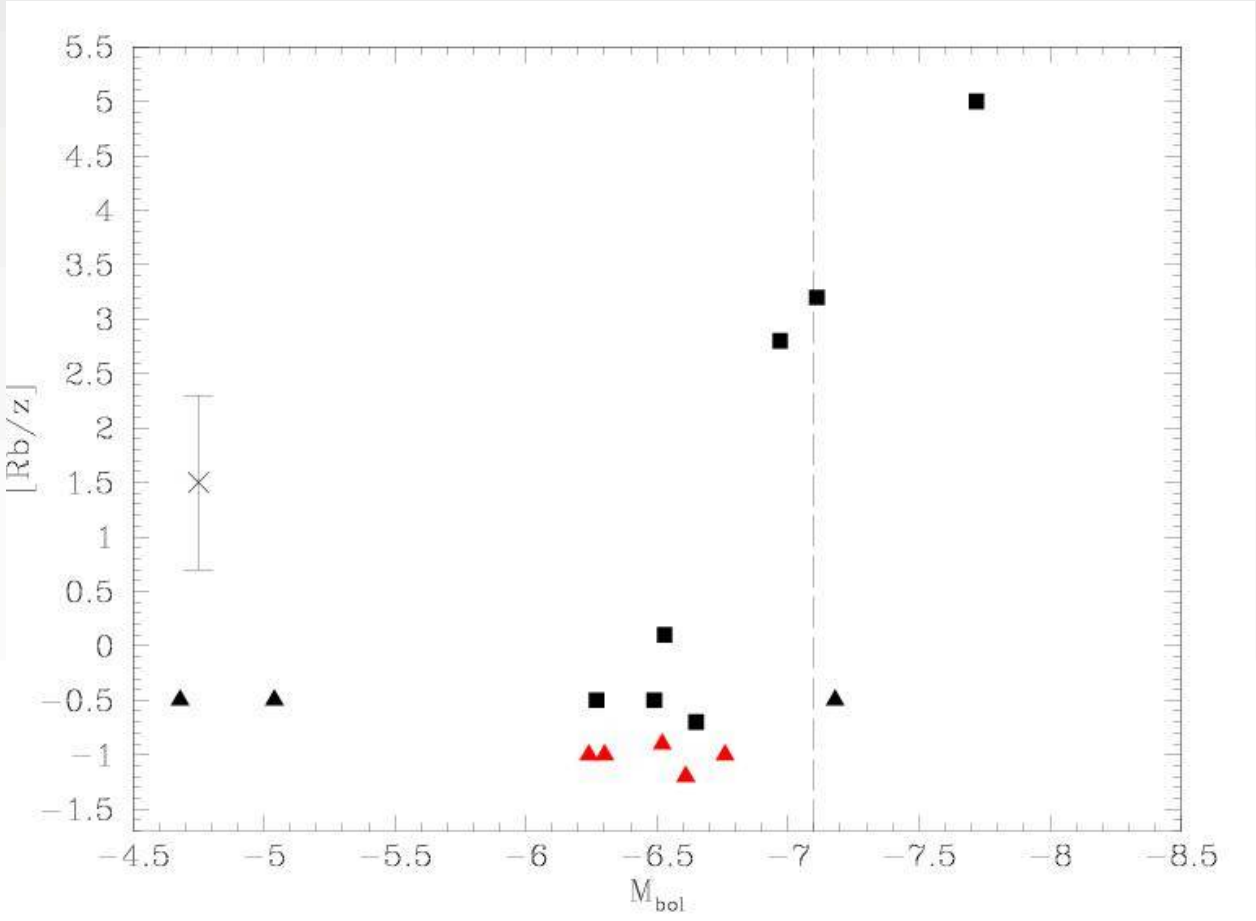
Rb-rich massive AGBs in the MCs

High-resolution optical surveys of luminous OH/IR stars in the MCs

- **Extremely high Rb overabundances (~10^3-10^5 times solar)**

- **Rb jumps at M_{bol}~-7.1 (the theoretical AGB limit;** Paczynski 1971**)**

- Useful to identify massive AGBs in LG galaxies



García-Hernández et al. (2009)

Progenitor masses

Massive AGBs or super-AGBs?

AGB evolutionary models for the LMC predicted the presence of very luminous massive AGBs
(Ventura et al. 2000)

A luminosity contribution from HBB explains the presence of very luminous Rb-rich AGBs

Rb-rich LMC AGBs (M_{bol} < -7) might have ~6-7 $M_{\odot}$

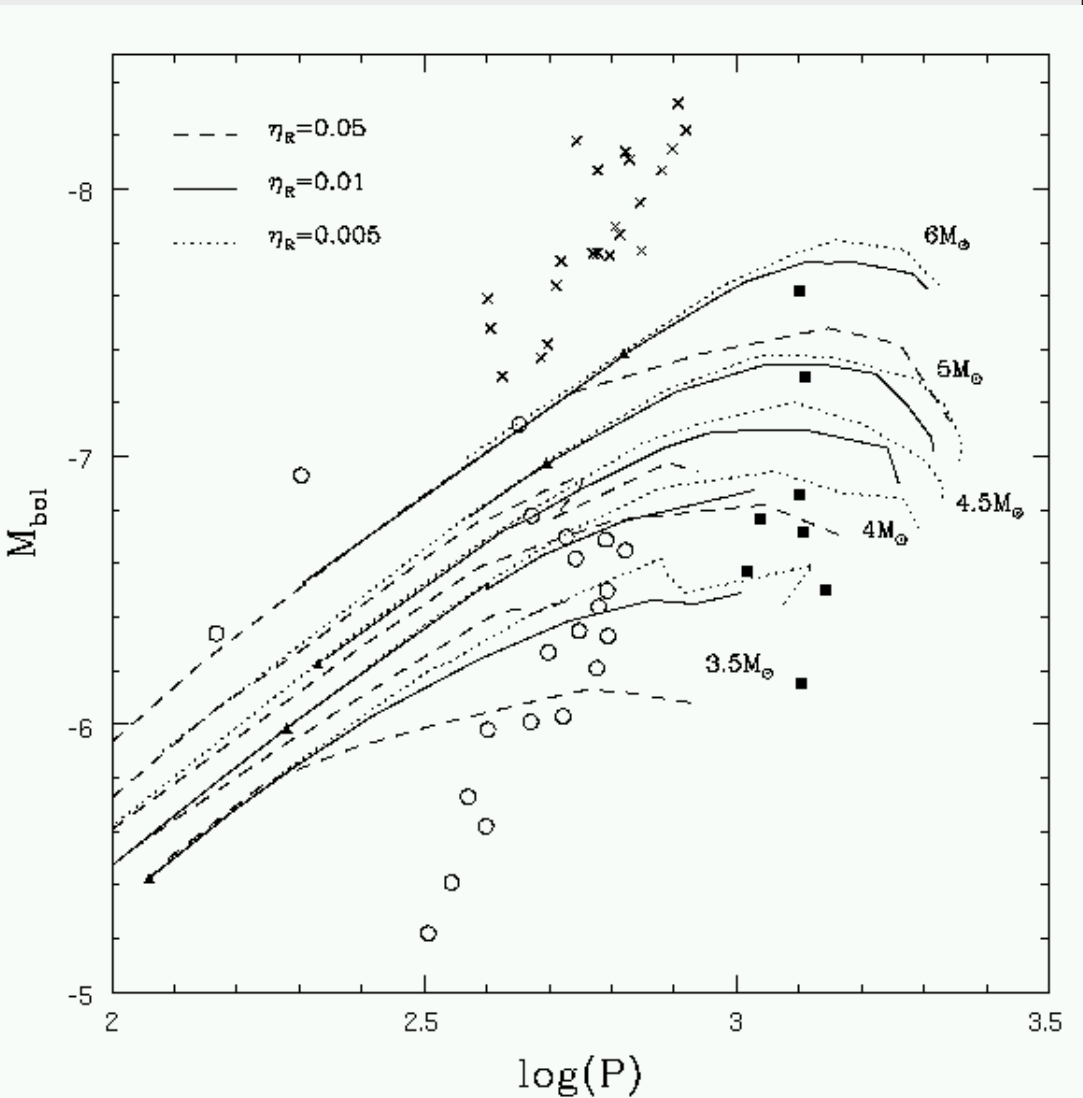


Fig. 7 from Ventura et al. (2000)

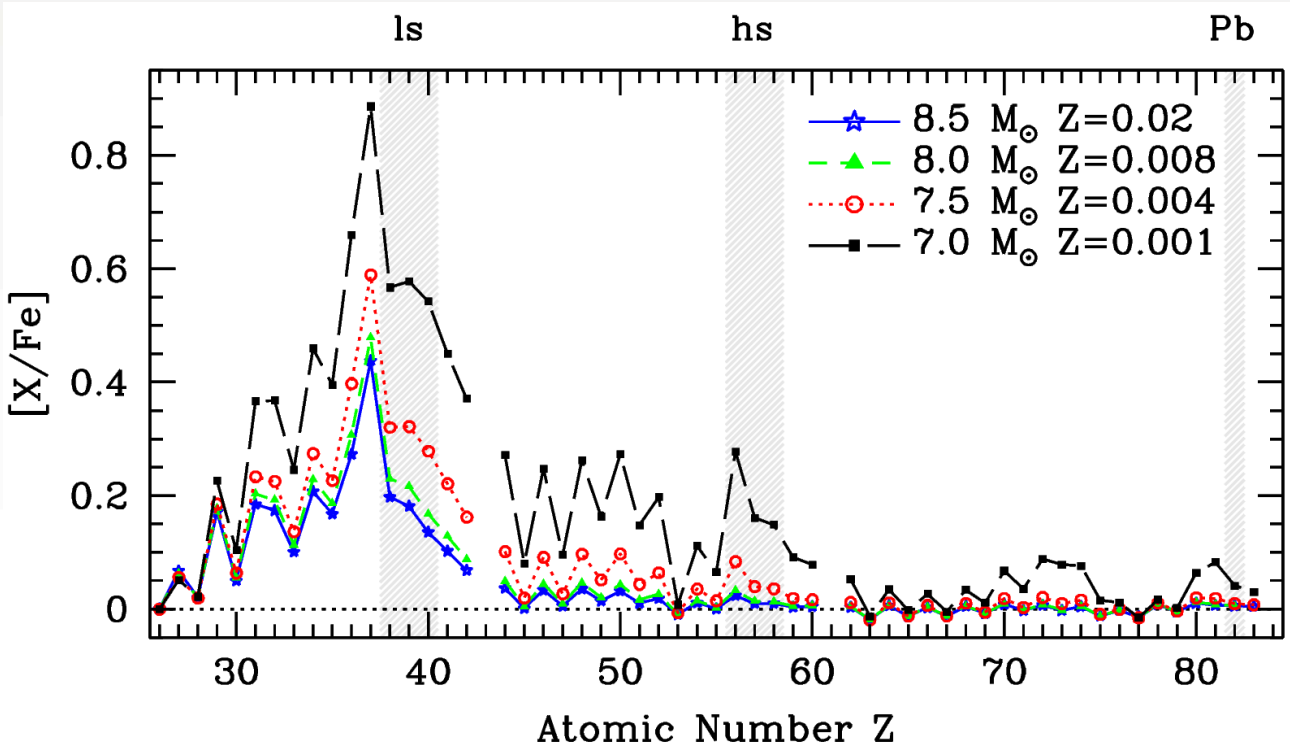
Massive AGB or super-AGB stars?

Both easily separared from RSGs:

- **Photometric variability**
- **Chemical composition (high-resolution spectra)**

But models predict them to be chemically identical:

- **HBB dominates**
- **^{22}Ne s-process nucleosynthesis**



Doherty et al. (2017) and references therein
See Talk by C. Doherty

“The rubidium problem”

1) The high Rb overabundance (~10^3 – 10^5 times solar)

2) The extraordinary [Rb/Zr] ratios (≥ 3 – 4)

Even if ^{22}Ne is the dominant neutron source, it is not possible to strongly produce Rb without co-producing Zr

The models qualitatively describe the observations
(van Raai et al. 2012)

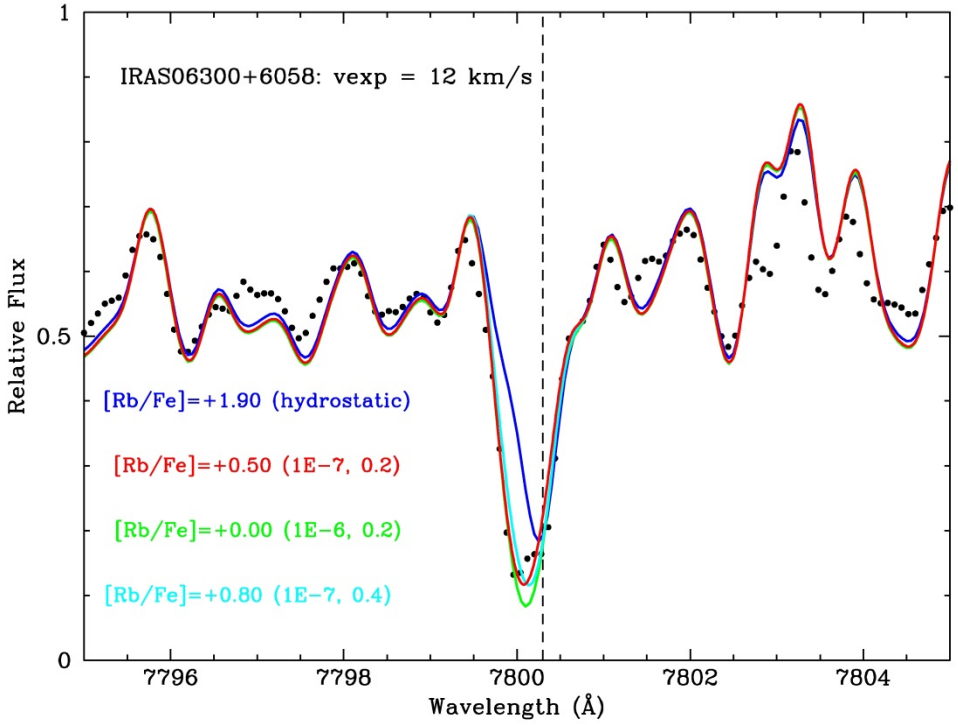
Mass	z	[Zr/Fe]	[Rb/Fe]
5 $M_\odot$	Solar	+0.01	+0.05
6 $M_\odot$	Solar	+0.07	+0.21
5 $M_\odot$	LMC	+0.21	+0.56
6 $M_\odot$	LMC	+0.41	+0.79
5 $M_\odot$	SMC	+1.07	+1.11

Exploratory AGB wind models

The effect of the circumstellar envelope is dramatic

The new Rb abundances are much lower (sometimes by orders of magnitude)

Strong dependence with the mass-loss (and V_{exp}(OH))



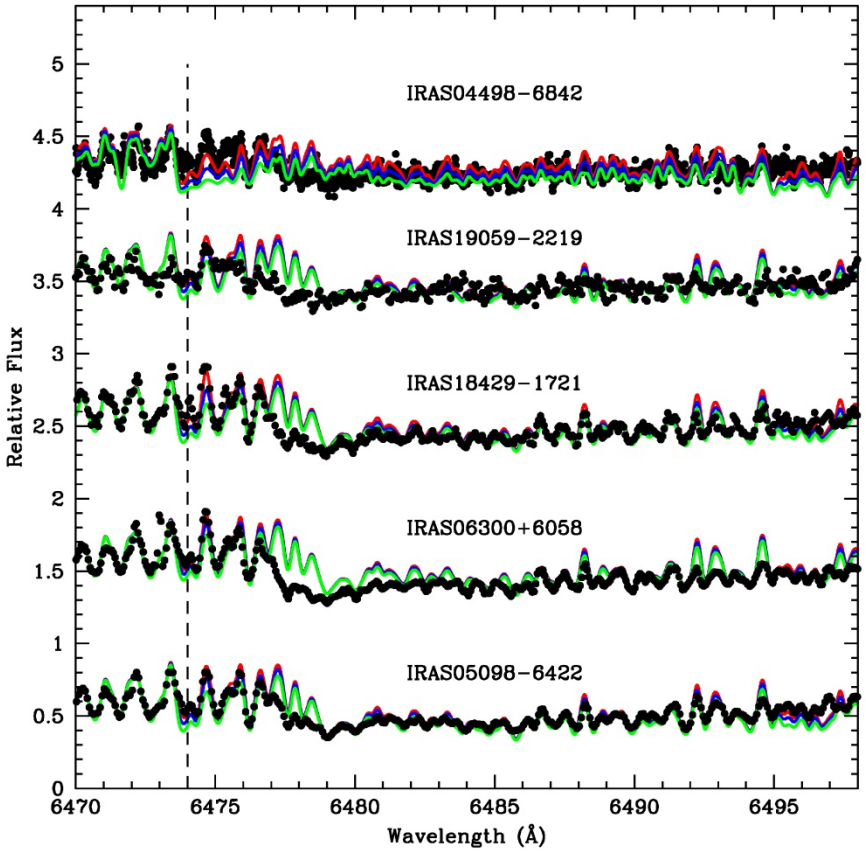
Zamora et al. (2014); Pérez-Mesa et al. (2017)

Zr with dynamical models

Zr is practically unaffected by the circumstellar envelope

Dynamical Zr abundances are similar to the hydrostatic ones (Zr nearly solar)

The 6474 Å ZrO bandhead is formed deeper in the atmosphere and less affected

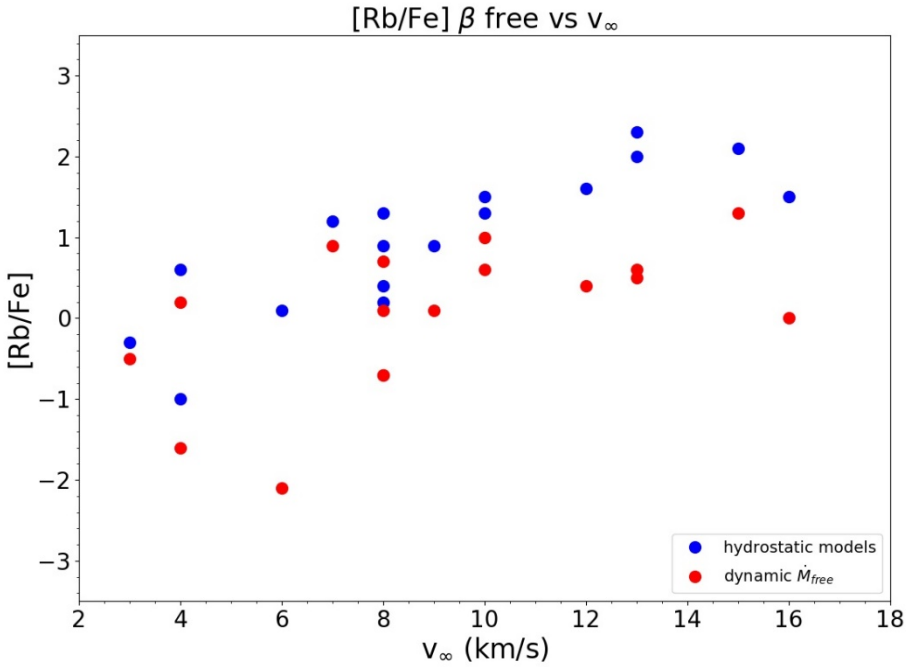


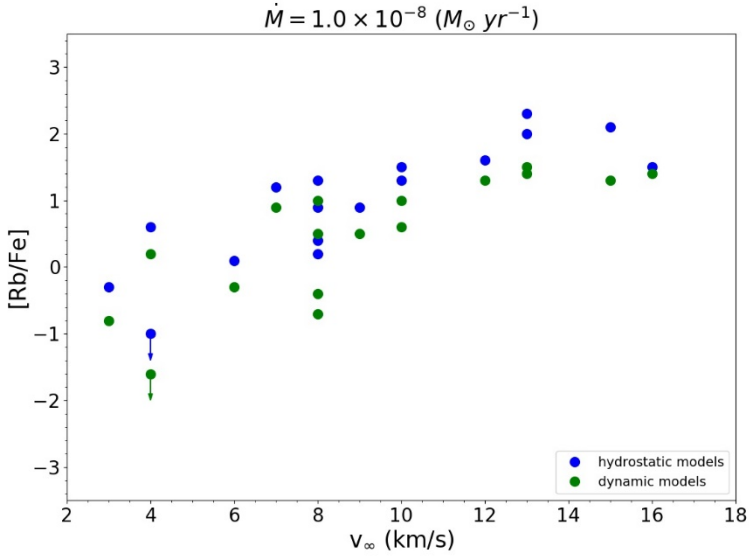
Zamora et al. (2014); Pérez-Mesa et al. (2017)

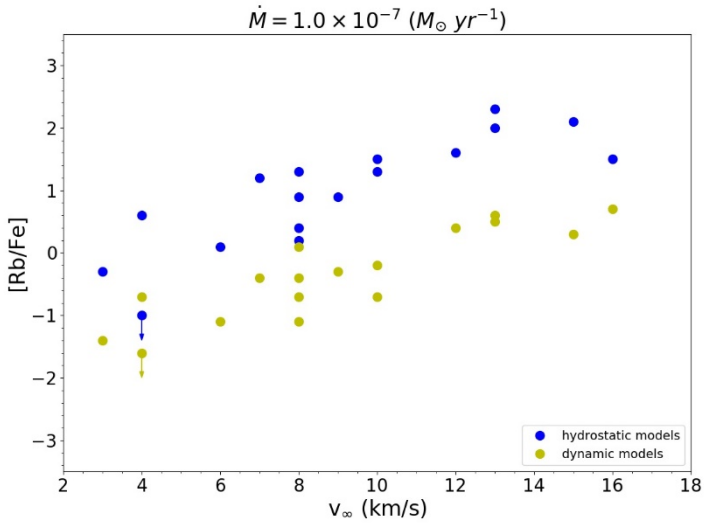
Rb revisited

Observations:
[Rb/Fe] ~ 0.0 – 1.3

Strong dependence with mass-loss



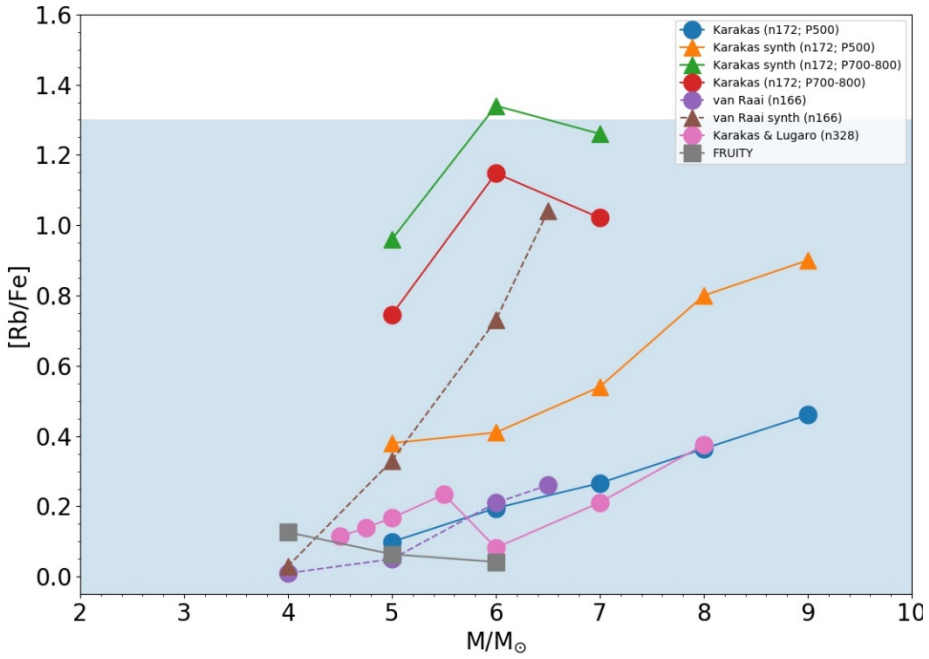


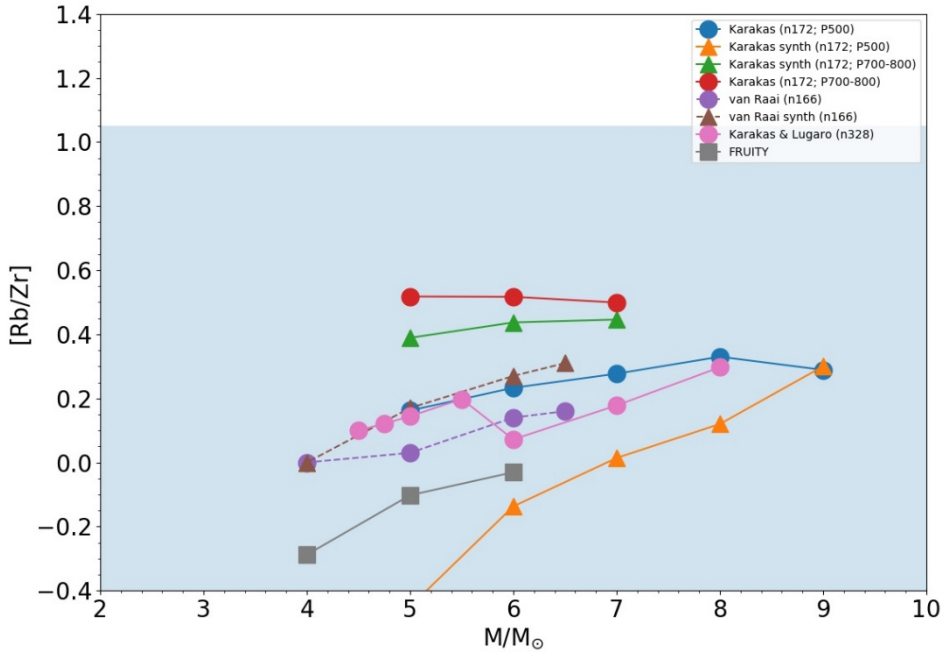


Pérez-Mesa et al. (2017)

Rb and Rb/Zr ratios in massive AGBs

Much better agreement with the theoretical predictions and the Rb/Zr mistmatch is significantly resolved



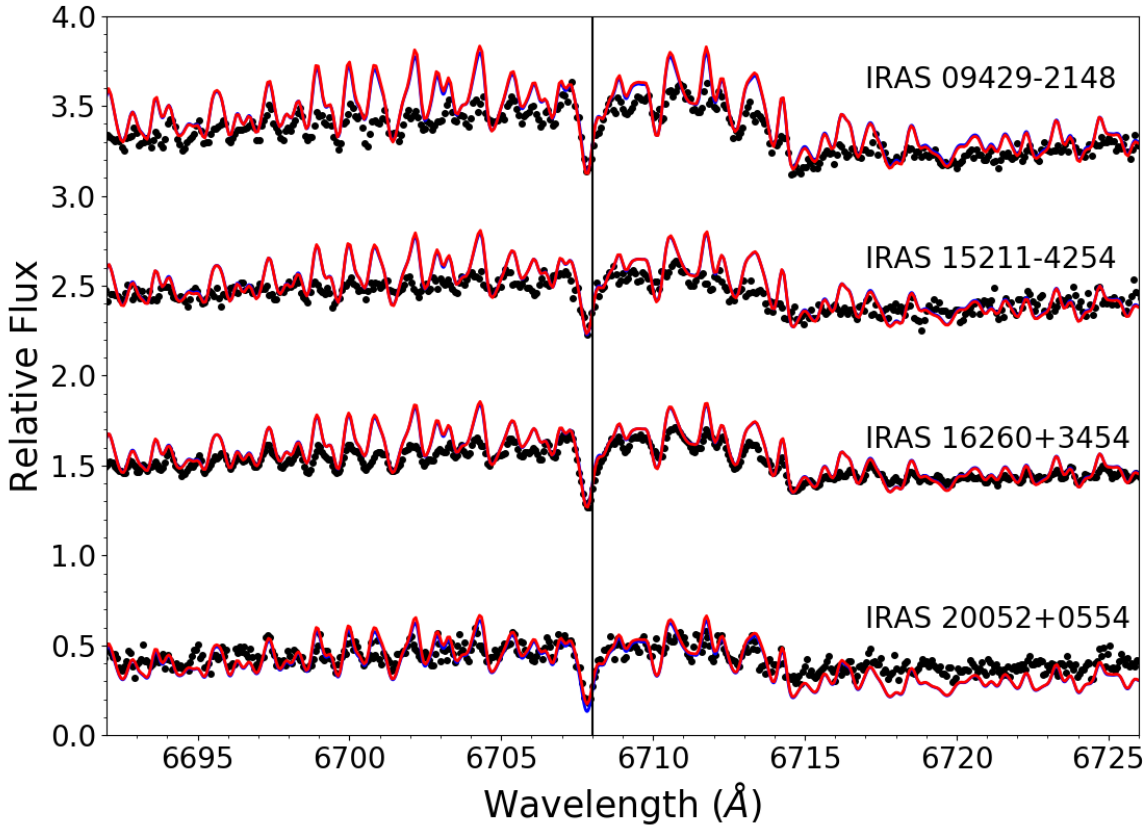


Pérez-Mesa et al. (2017)

Li with dynamical models

Li is only slightly affected by circumstellar effects

Further confirmation of the HBB activation in massive AGB stars



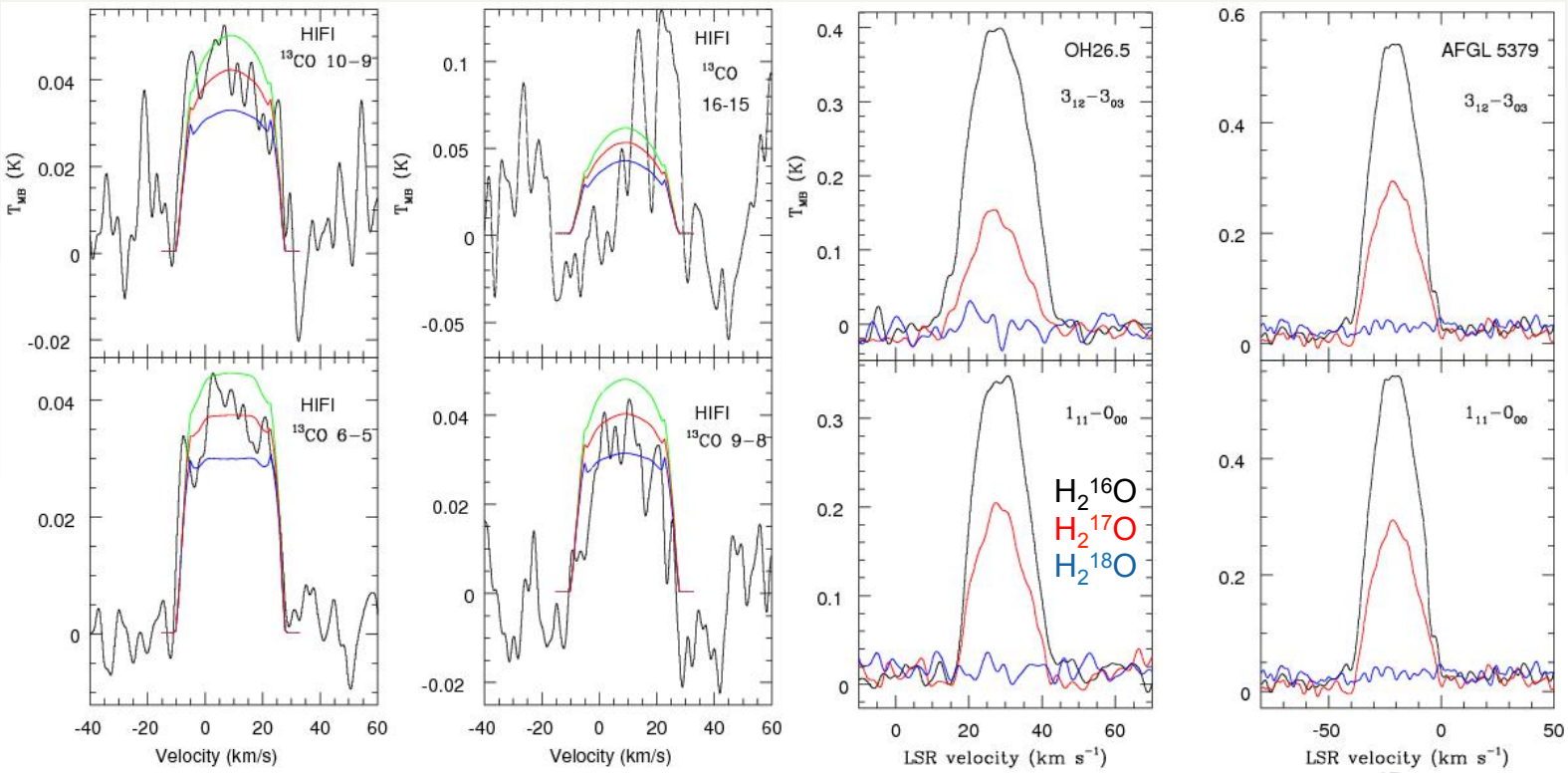
See Poster by Pérez-Mesa et al.

C and O isotopic ratios (far-IR)

Far-IR Herschel observations of extreme Galactic OH/IR stars confirm their HBB nature

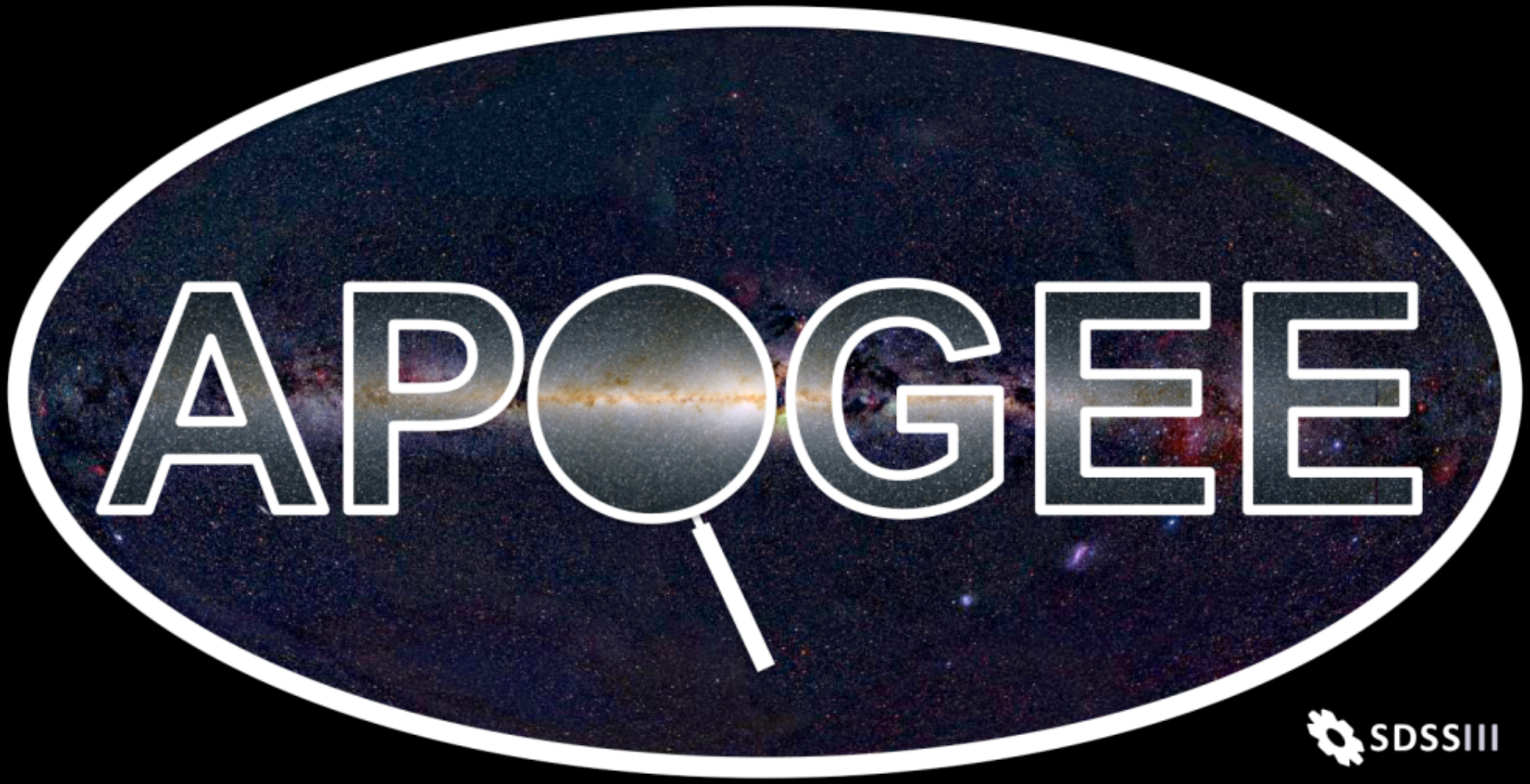
$^{18}O/^{17}O \leq 0.1$

$^{12}C/^{13}C \sim 2–30$



Justtanont et al. (2013, 2015)

See also Talk by C. Abia



Logo by Gail Zasowski.

APOGEE HIGH-RESOLUTION SPECTROSCOPY

- H-band contains useful lines from ~15 elements (C,N,O,Mg,Si,S,Ca,Ti,V,Mn,Fe,Ni,Na,K,Al) → goal: 0.1 dex precision

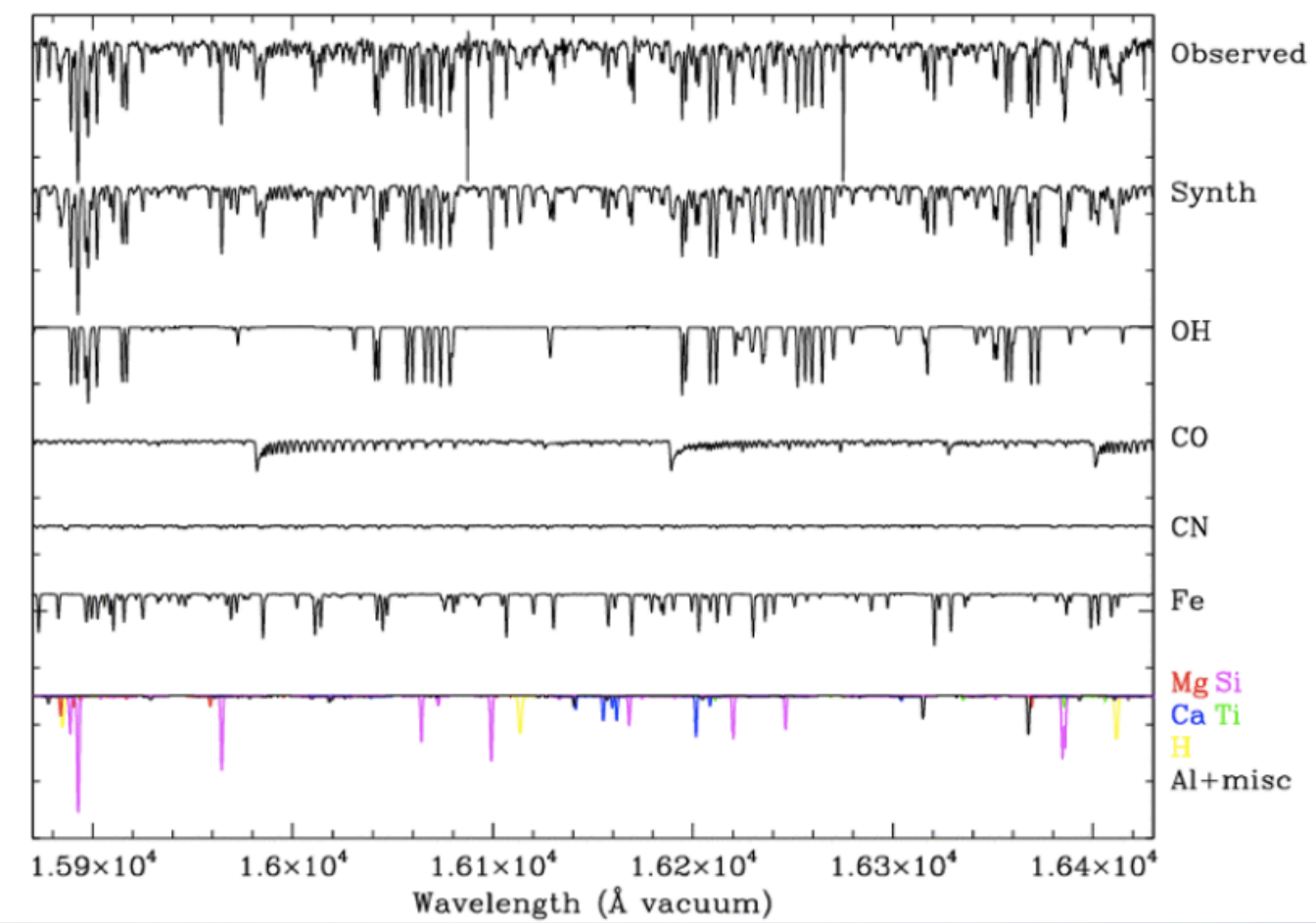
s-elements (Nd, Ce, and Yb)

&

$^{12}C/^{13}C$ ratios

in an important fraction of stars

R~22,500



SDSS-IV (2014-2020)

SDSS

APOGEE-2: A stellar survey of the Milky Way, with two major components:

- *A northern survey using the bright time at APO*
- *A southern survey using the 2.5m du Pont Telescope at Las Campanas*

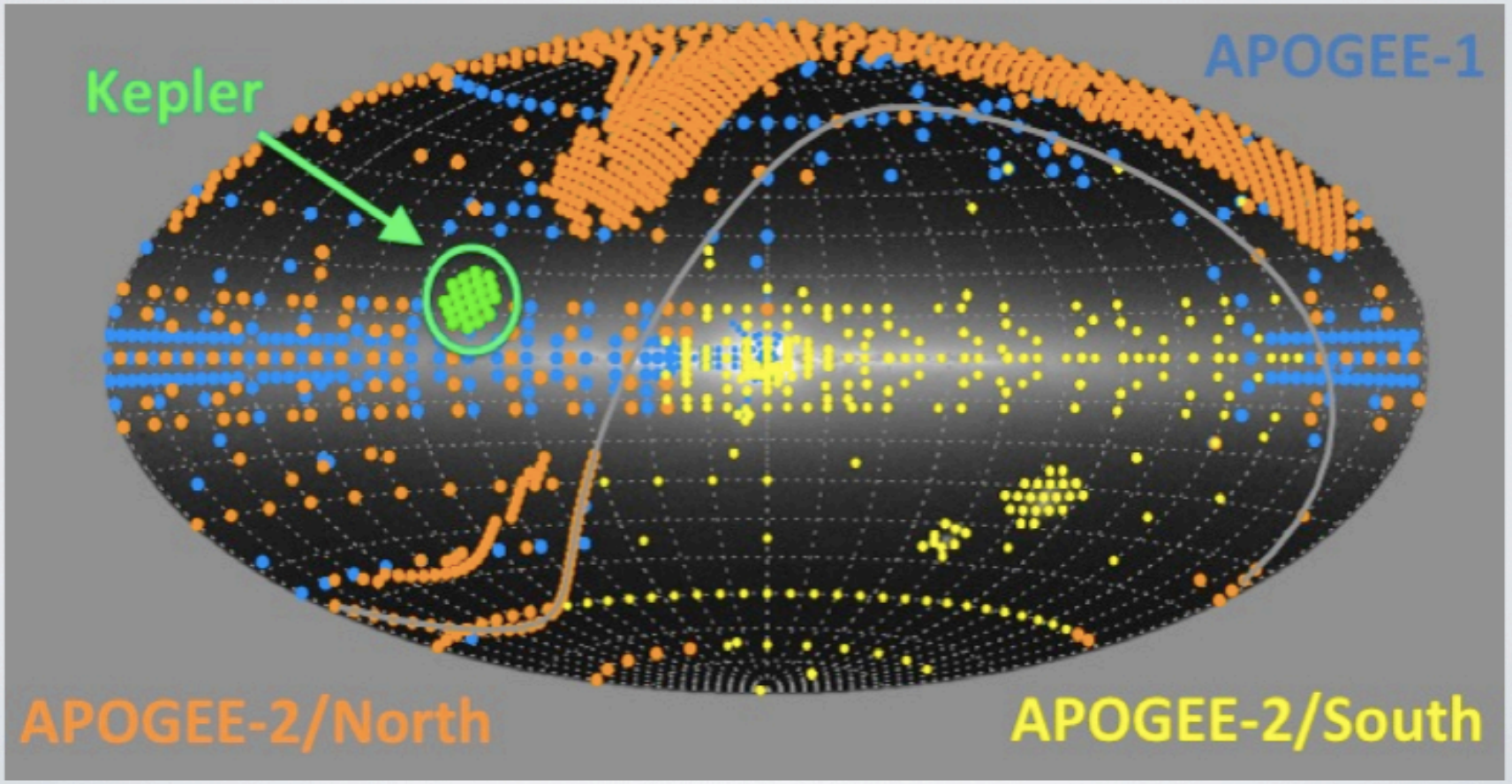
APOGEE-2 will observe:

- *more than 300,000 stars (RGB and AGB) in the inner parts of the Galaxy (bulge, disk)*
- *the Magellanic Clouds*
- *more globular and open clusters*
- *planet-hosting stars discovered by Kepler*
- *etc.*

APOGEE-2 COVERAGE

SDSS

- Much finer sampling of all major components

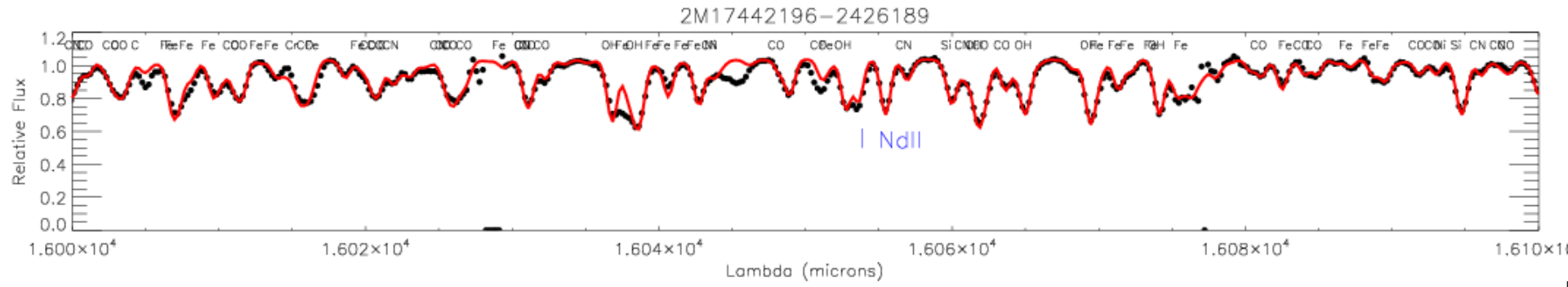


AGB nucleosynthesis with APOGEE

HBB, TDUP, and s-process in massive AGB stars

- **large numbers of stars**
- **inner Galaxy (high-Z) and the Magellanic Clouds**

New discoveries (e.g., very low-Z HBB AGB bulge stars)



See Talk by O. Zamora

The Gaia era

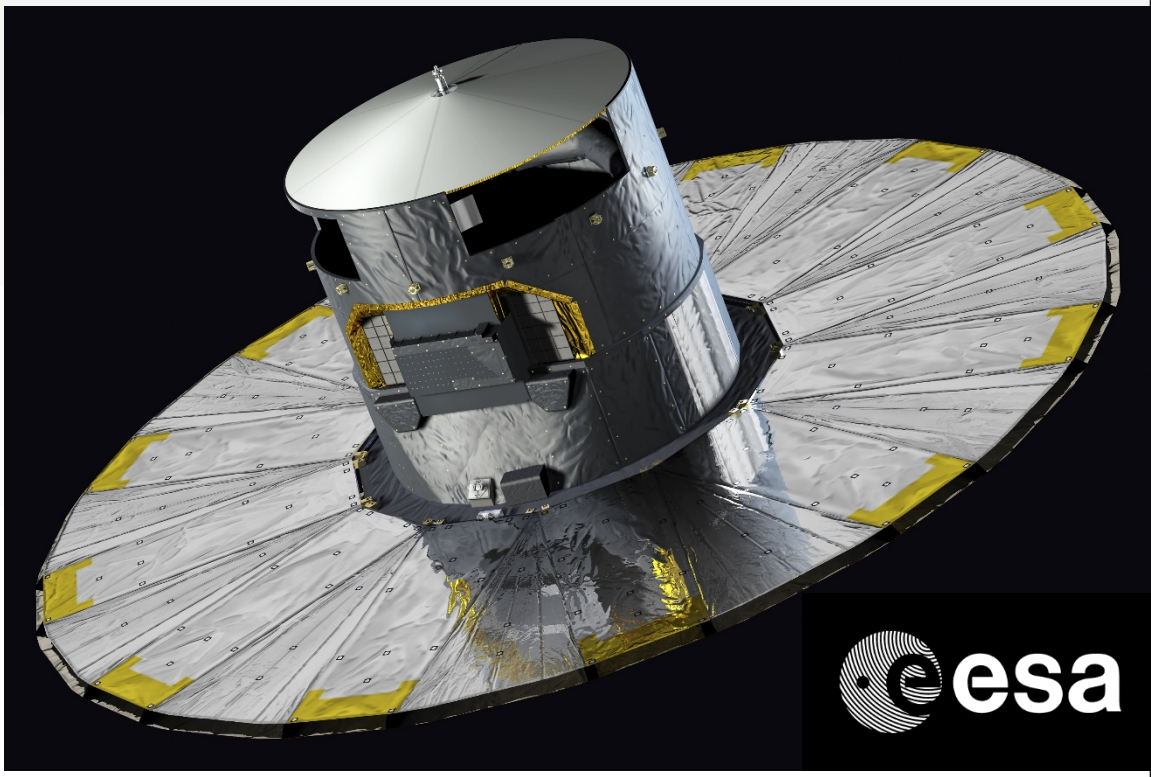
Distances (luminosities) for all types of Galactic AGBs

Strong constraints to the AGB nucleosynthesis models

This would help to distinguish massive AGBs from the more luminous super-AGBs

But..

These stars are intrinsically faint (and strongly variable) in the optical Gaia bands



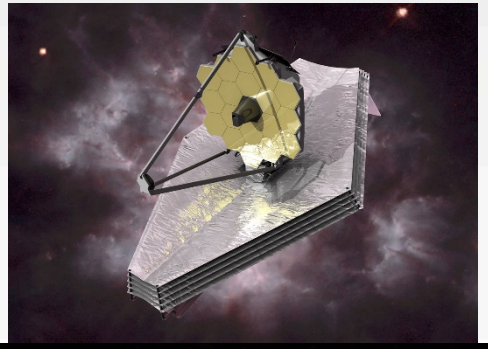
See e.g., Di Criscienzo et al (2016)

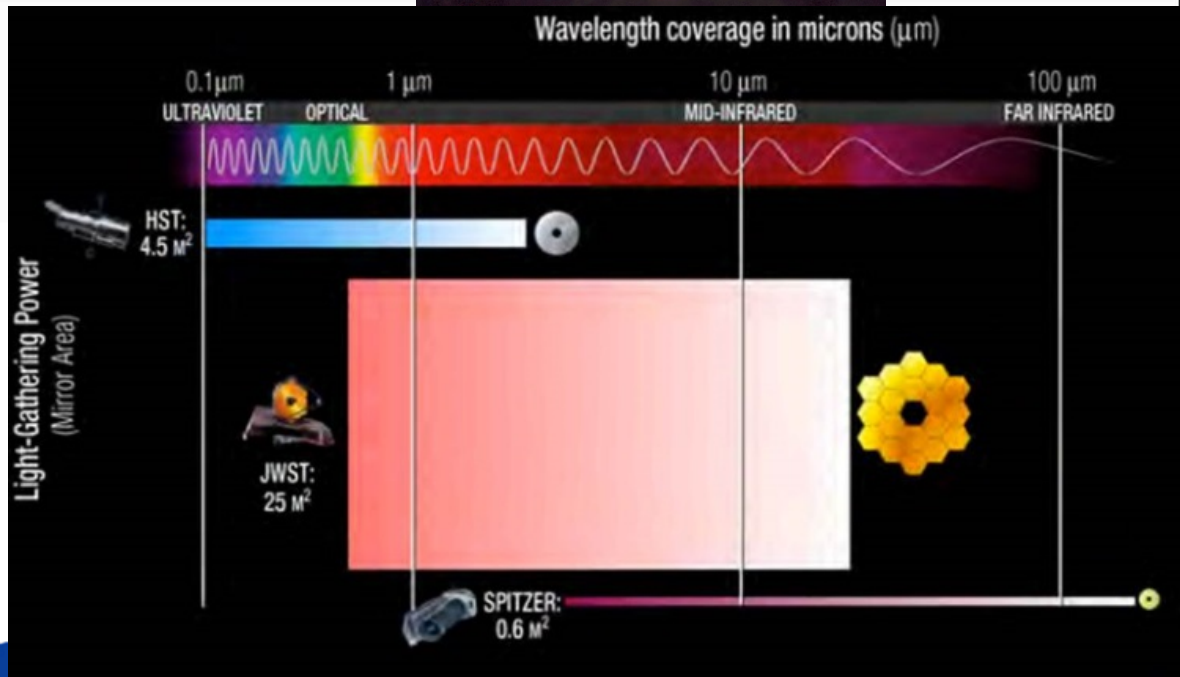
The James Webb Space Telescope

IR studies of massive AGBs and super-AGBs in LG galaxies

Near- and mi-IR spectroscopic studies of individual sources in LG galaxies

- **dust chemical composition**
- **mass-loss rates**
- **dust production**
- **T_{eff}**
- **abundances**





See Reviews by J. van Loon & M. Boyer

Summary

- Multiwavelength (from the optical to the far-IR) observations confirm the HBB and ^{22}Ne activation in massive AGBs (and super-AGB stars)

  *Accurate mass-loss rates can break the degeneracy of the wind AGB models → more reliable Rb abundances

- Efficient separation between massive AGBs and RSGs but …

  *Massive AGBs chemically identical to super-AGBs

  *Present observational samples may contain super-AGBs

On-going and future surveys
- APOGEE
- Gaia
- JWST

Rb and Rb/Zr ratios in massive AGBs

Much better agreement with the theoretical predictions and the Rb/Zr mistmatch is significantly resolved

IRAS name	$T_{\rm eff}$ (K)	log g	β	$\dot{M}$ ($M_\odot$ yr^{-1})	v (km s^{-1})	$[{\rm Rb/M}]^{\rm ref}_{\rm static}$ [a]	$[{\rm Rb/M}]_{\rm static}$ [b]	$[{\rm Rb/M}]_{\rm dyn}$ [b]	$[{\rm Zr/M}]_{\rm dyn}$ [b]
Galactic stars									
05098−6422	3000	−0.5	1.0	1.0×10^{-8}	6	0.1	0.0 ± 0.4	0.0 ± 0.4	≤0.3 ± 0.3
06300+6058	3000	−0.5	0.2	1.0×10^{-7}	12	1.6	1.9 ± 0.4	0.5 ± 0.7	≤0.1 ± 0.3
18429−1721	3000	−0.5	1.0	1.0×10^{-8}	7	1.2	1.2 ± 0.4	1.0 ± 0.4	≤0.3 ± 0.3
19059−2219	3000	−0.5	0.4	1.0×10^{-7}	13	2.3/2.6	2.4 ± 0.4	0.8 ± 0.7	≤0.3 ± 0.3
LMC star									
04498−6842	3400	0.0	1.0	1.0×10^{-7}	13	3.9[c]	3.3 ± 0.4	1.5 ± 0.7	≤0.3 ± 0.3

Observations

[Rb/M] ~ 0.0 – 1.0

[Rb/Zr] = -0.3, 0.4, 0.5, 0.7

Still the LMC star displays [Rb/Zr] = 1.2

Theoretical models

[Rb/M] ~ 0.0 – 1.04 (van Raai et al. 2012)

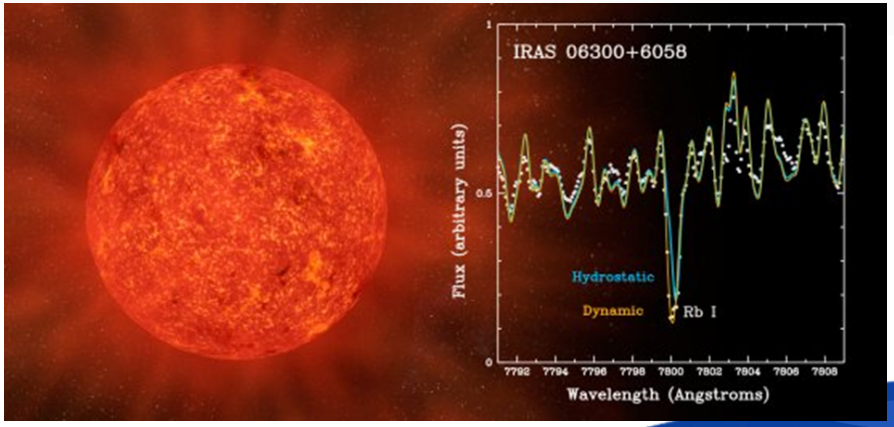
[Rb/M] ~ 0.0 – 1.34 (Karakas et al. 2012)

-0.2 < [Rb/Zr] < 0.6

Realistic AGB model atmospheres

Development of more realistic AGB model atmospheres

- Circumstellar effects
- Dust inclusion (IR range)
- Extension to 3D hydrodynamical models



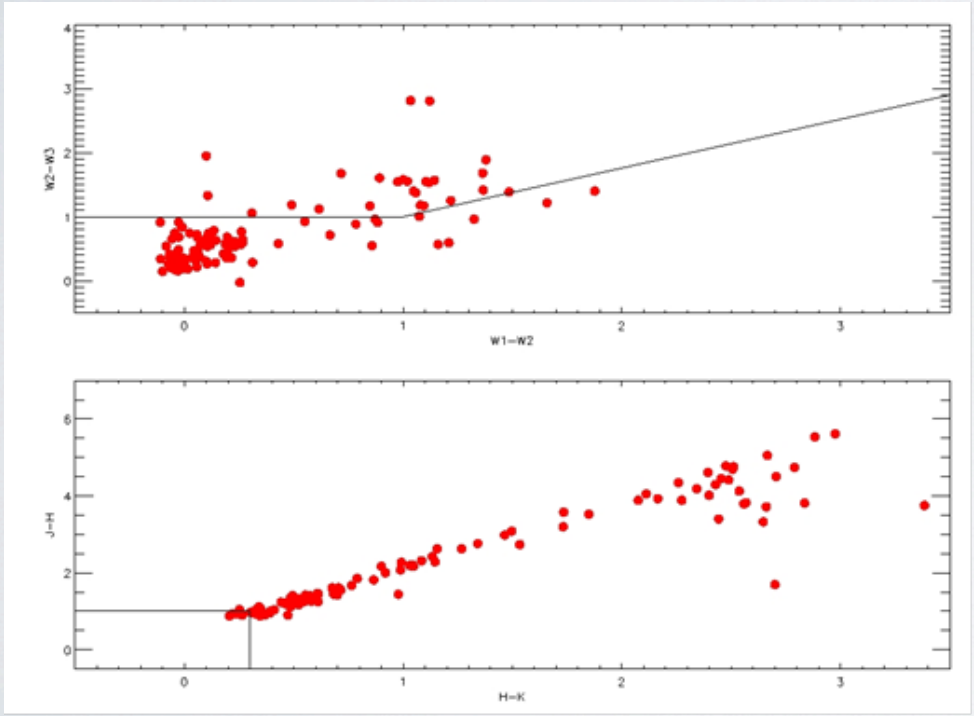
Extended and complex dynamical atmospheres

WORK IN PROGRESS: AGBs

SDSS

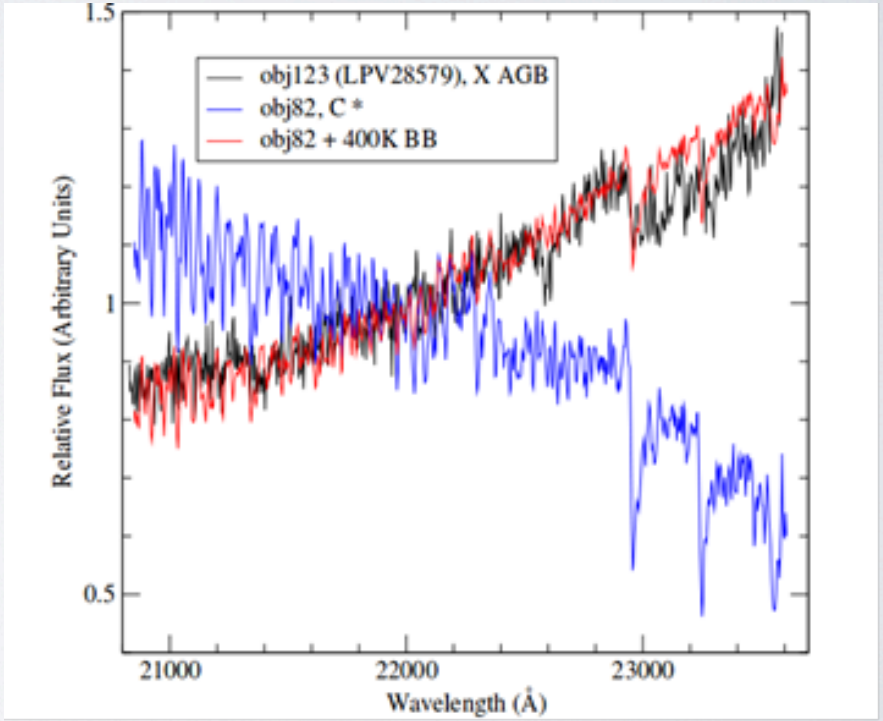
AGB candidates in SDSS/APOGEE

'AGB canditates in APOGEE'



WISE & 2MASS Color-Color Diagrams
(First year data + DR10)

'Extreme AGB stars'



Blum et al. (2014)