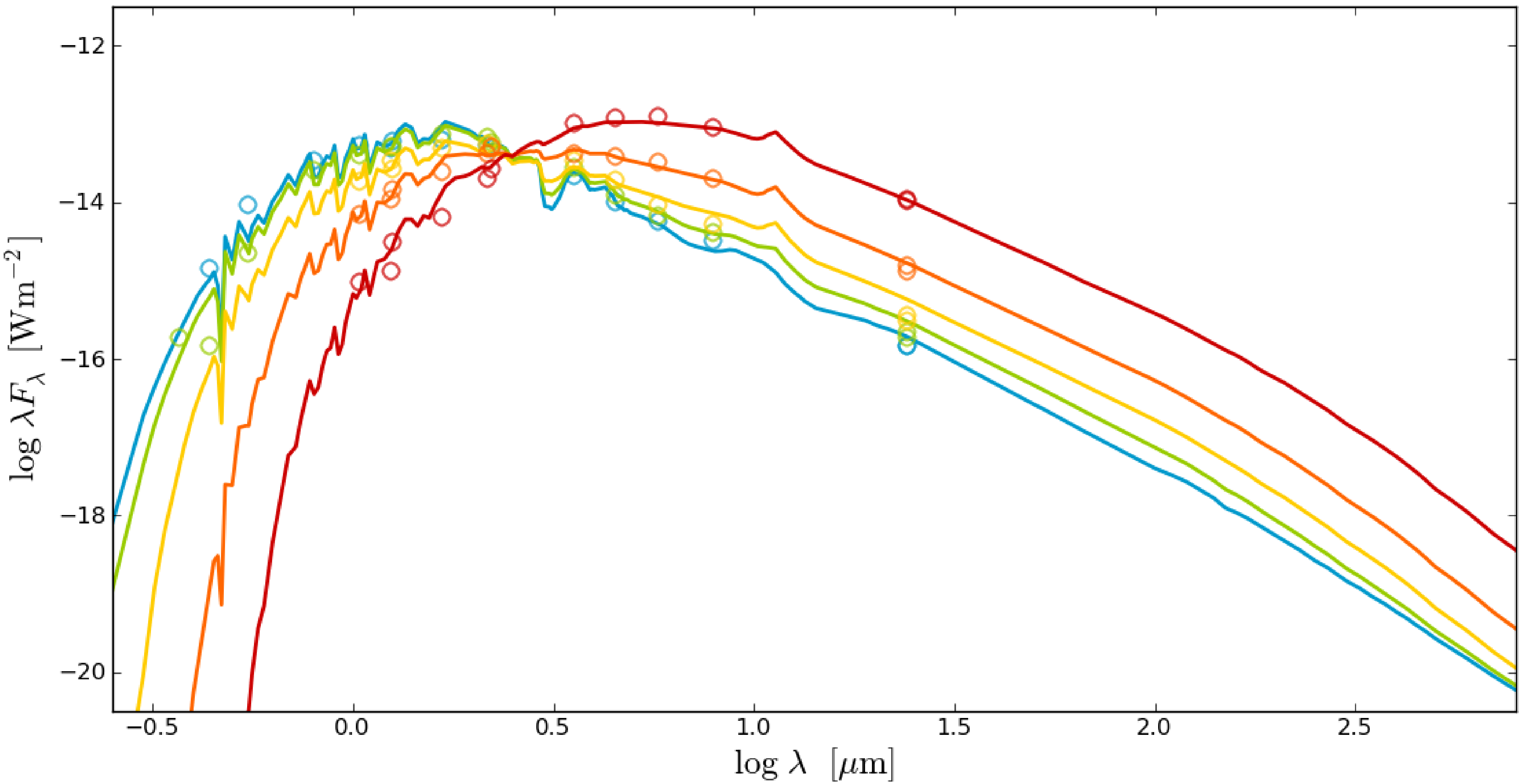
Mass-loss rates and luminosities of LMC AGB stars



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The VMC survey

I. Strategy and first data

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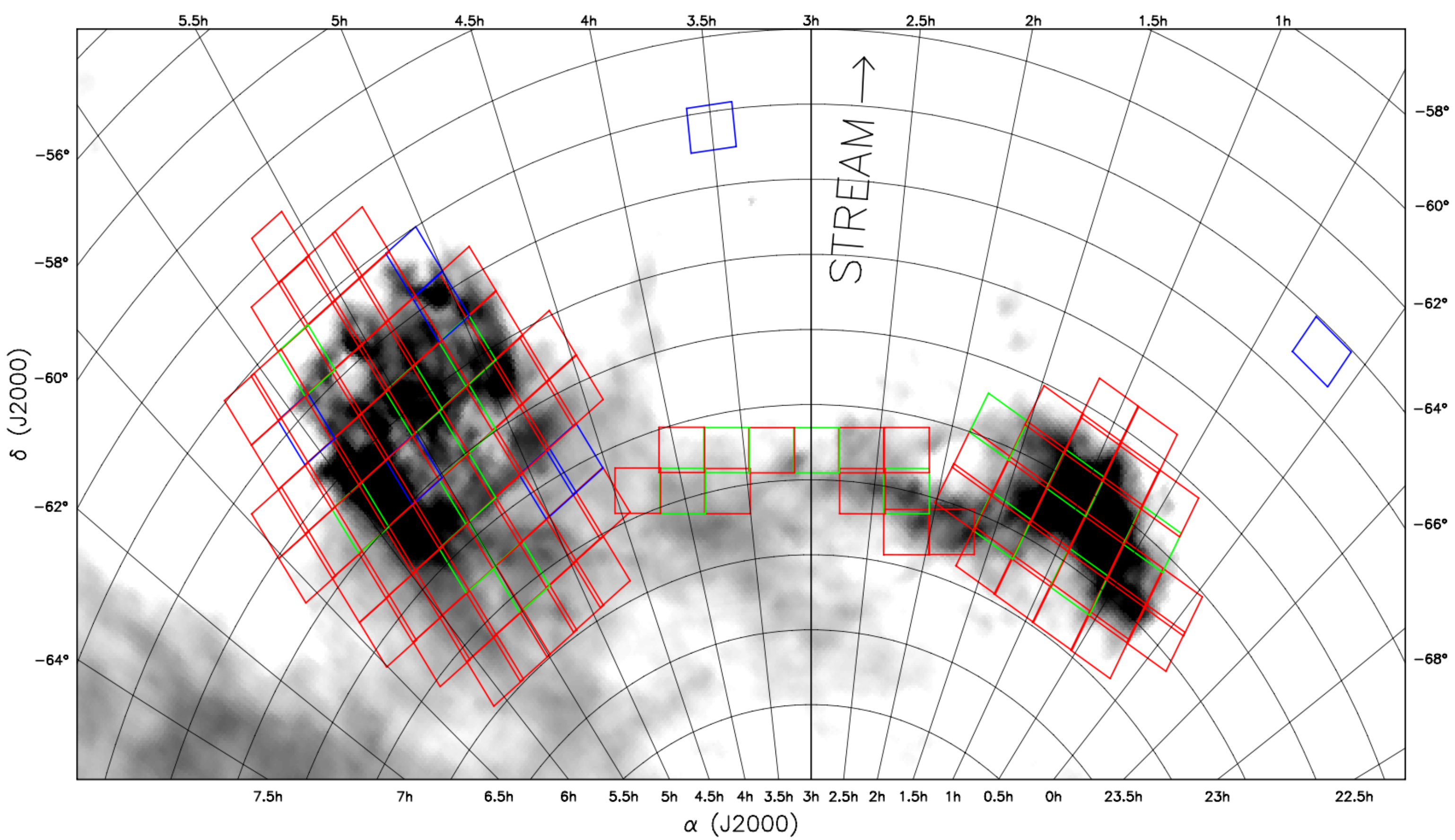
The VMC

- The VISTA Magellanic Cloud ESO public survey (Cioni et al. 2011, A&A, 527, 116)
- Deepest survey of the Magellanic Cloud system in the near-IR (Ks~21.5 i.e. old MS turn-off)
- Total surveyed area ~ 180 deg^2 (LMC = 116 deg^2; SMC = 45 deg^2 ; Bridge = 20 deg^2)
- Started on October 2009 (completion ~ 11%)
- Main Science Goals: spatially resolved SFH; 3D structure of the MCs; stellar clusters; variable stars; evolved stellar populations.



AGB stars

AGB stars are major polluters of the interstellar medium

Dust

Gas: He, C, N, Na, Li

→ fundamental role to understand galaxy chemical evolution

→ AGB yields are the most reliable candidate to explain the chemical “anomalies” and/or multiple populations in Globular Cluster (Ventura & d'Antona 2009, Carretta et al. 2009, d'Ercole et al 2010)

AGB stars are major contributors to the integrated light of a stellar population.

→ up to 40% of bolometric luminosity and 80% in the near-IR for intermediate-age stellar population

→ TP-AGBs are fundamental to understand the properties of distant (=unresolved) galaxies

→ extremely important for high-z systems.

z=2 : age of the Universe ~ 3 Gyr

z=3 : age of the Universe ~ 2 Gyr

The light emitted by high z galaxies is dominated by AGB stars

AGB: models

Complex aspects of the evolution:

• Dredge-up & convection

• Mass-loss rates ↔ dust formation & stellar winds

Synthetic models (e.g. Marigo et al 2008)

The AGB evolution is described using analytical relations. Parameters calibrated on observations

+ basic observed properties (red tail of C-stars)

– difficulties in reproducing star counts and luminosities of O- and C-rich populations in metal-poor galaxies (e.g. Gullieusik+2008; Girardi+2010)

Parameters that need a more detailed calibration:

• 3^{rd} dredge-up efficiency

• Parameters related to mass-loss process

Data required:

• Complete/unbiased database of O- and C-rich stellar populations

• Direct measure of mass-loss rates

Our project

>> Context

Direct measure of mass-loss rates available for 100s stars in the Magellanic Cluods (e.g. Groenewegen+2009)

Estimates on larges samples of stars are based on empirical relations between IR colours or mid-IR excess and mass-loss rates (Matsuura+2009; Snrinivasan+2009)

>> Aims

To obtain direct measures of mass-loss rates and bolometric magnitudes for all AGB stars in the MCs

Disentangle O-rich and C-rich stellar populations

To constrain the TP-AGB models

>> Method

To select a complete sample of AGB stars in the Magellanic Clouds

To build SEDs combining optical to mid-IR photometry

To derive mass-loss rates, bolometric magnitudes and chemical properties of the dusty shells (C/O classification) fitting the SEDs with dust radiative transfer models.

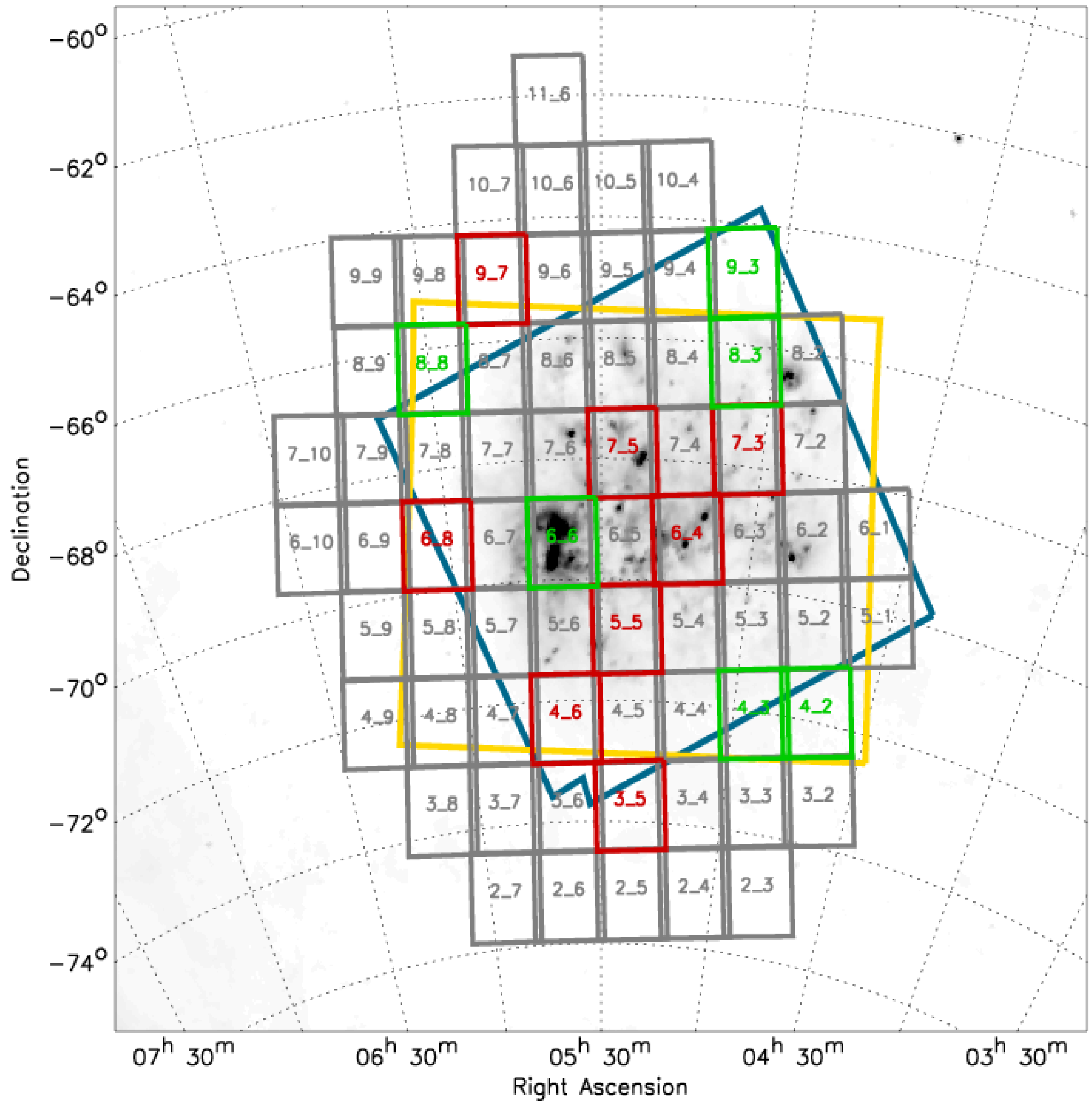
Data

- VMC 1.0 (near-IR)
- MCPS (optical)
- 2MASS + 2MASS 6x (near-IR)
- SAGE-LMC DR3 (mid-IR)
- Akari (mid-IR) all sky survey

Only 8_3 has SAGE and MCPS photometry (and 6_6, i.e. 30 Dor)

Multi-colour catalogue generation:
→ all stars with 2MASS or VMC or SAGE (epoch merged)

We use both SAGE epochs and both 2MASS and 2MASS 6x data to take into account long period variability of AGB stars



AGB Selection

The selection should:

Include all AGB stars (above the TRGB)
→ stars not detected by 2MASS
→ stars saturated in VMC

Exclude as much non AGB stars as possible
→ MW foreground
→ spurious detections

Selection based on 2MASS CMD

→ Redder than the line defined by Cioni+2006

→ brighter than Ks~12.0 (only if J-K<1.5)

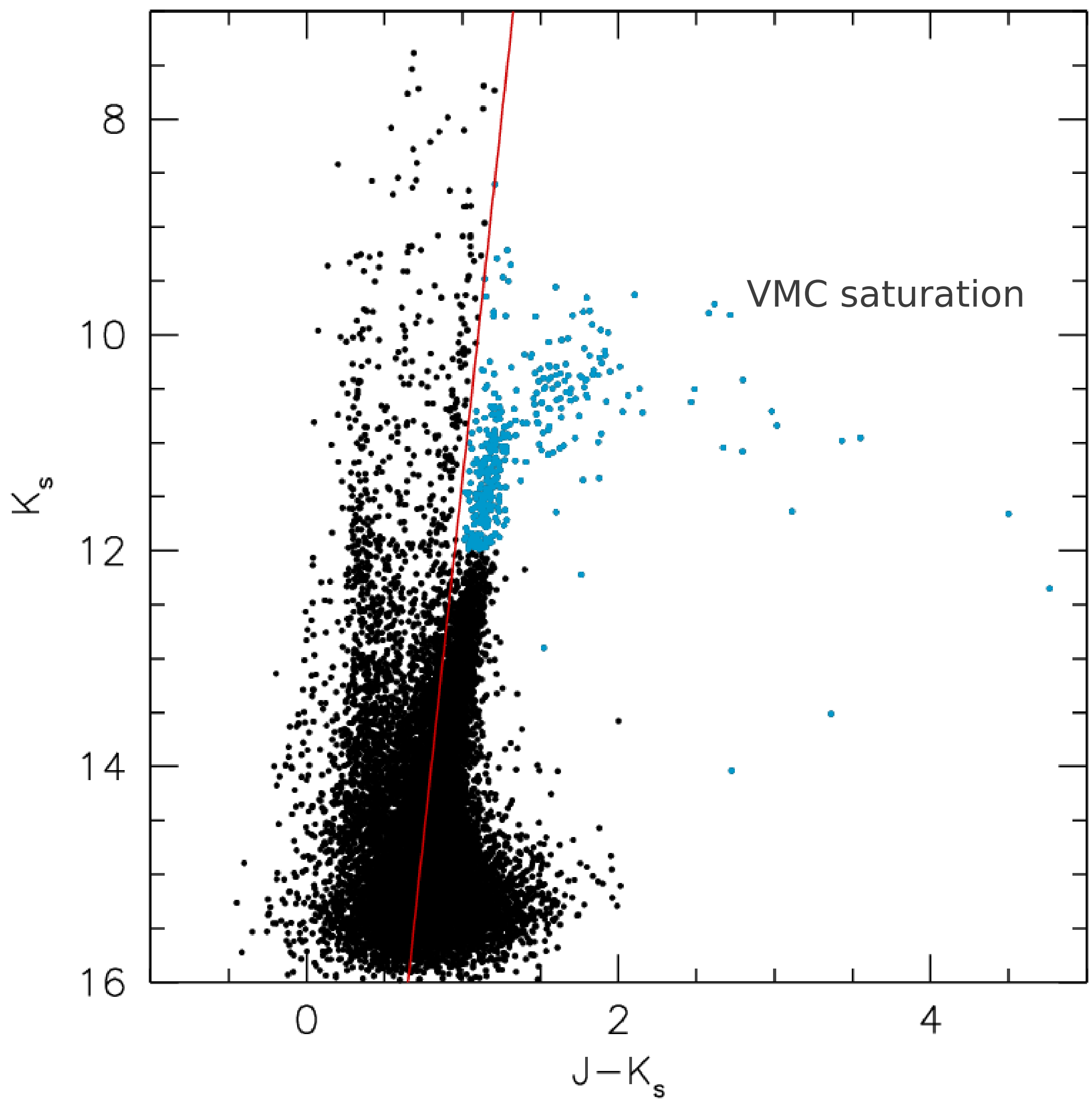
→ Emission in the mid-IR

→ include also stars not in 2MASS, but with VMC and mid-IR magnitudes compatible with AGB stars*.

→ 371 selected sources

* None in field 8_3

2MASS photometry



Fitting the SED

Model photosphere

→ C-rich : Aringer et al. (2009)

→ O-rich : MARCS models

Dust grain properties (results of Groenewegen+2009)

→ C-rich : 6% SiC 94% AMC

→ O-rich : “astronomical” silicates Volk & Kwok (1988)

Grain condensation temperature: 800, 900, 1000 1200 K

Radiative transfer equation solved using the Dusty code (Ivezic et al. 1999)

Free Parameters:

- Optical depth
- Luminosity

Minimization routine

Normalised χ^2 taking into accout photometric errors

Best-fitting solution:

- Optical depth
- Luminosity
- C/O classification

The mass-loss rate is derived from the optical depth using the relation from Groenewegen et al. (1998)

→ shell expansion velocity = 10 Km/s

→ dust-to-gas ratio =0.005

These are standard values for Galactic AGB stars. They may not be applied to the most metal-poor AGB stars.

C/O classification

C-rich O-rich
Difficult classification Bad fit

	Blue		Red		All	
	C	O	C	O	C	O
Total	113	161	93	4	206	165
OK	54	93	78	0	132	94
uncertain	58	67	10	0	68	67
bad fit	1	1	5	4	6	4

4 “bad O” have SED not compatible with AGB stars:

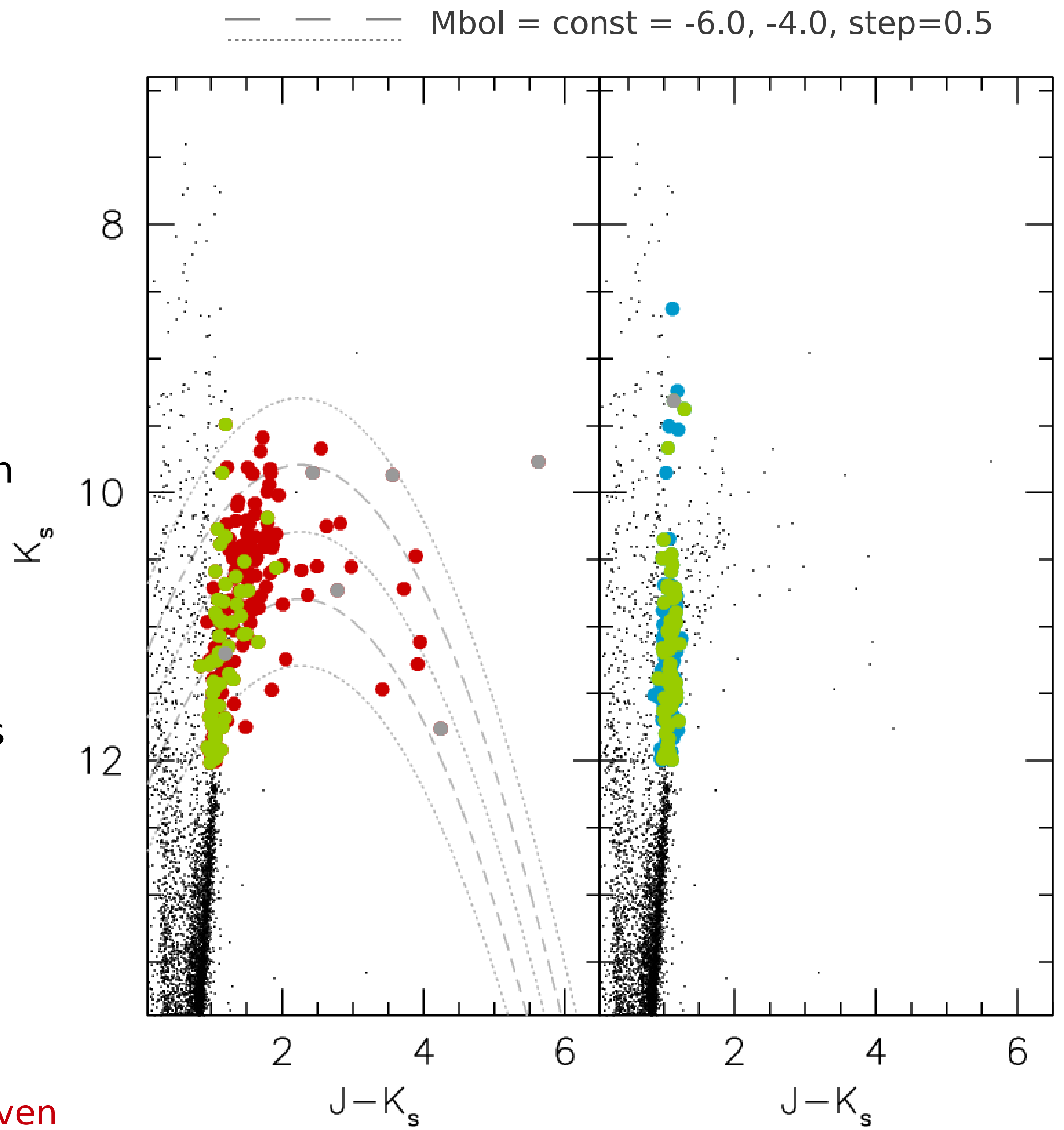
3 YSO

1 Seyfert galaxy

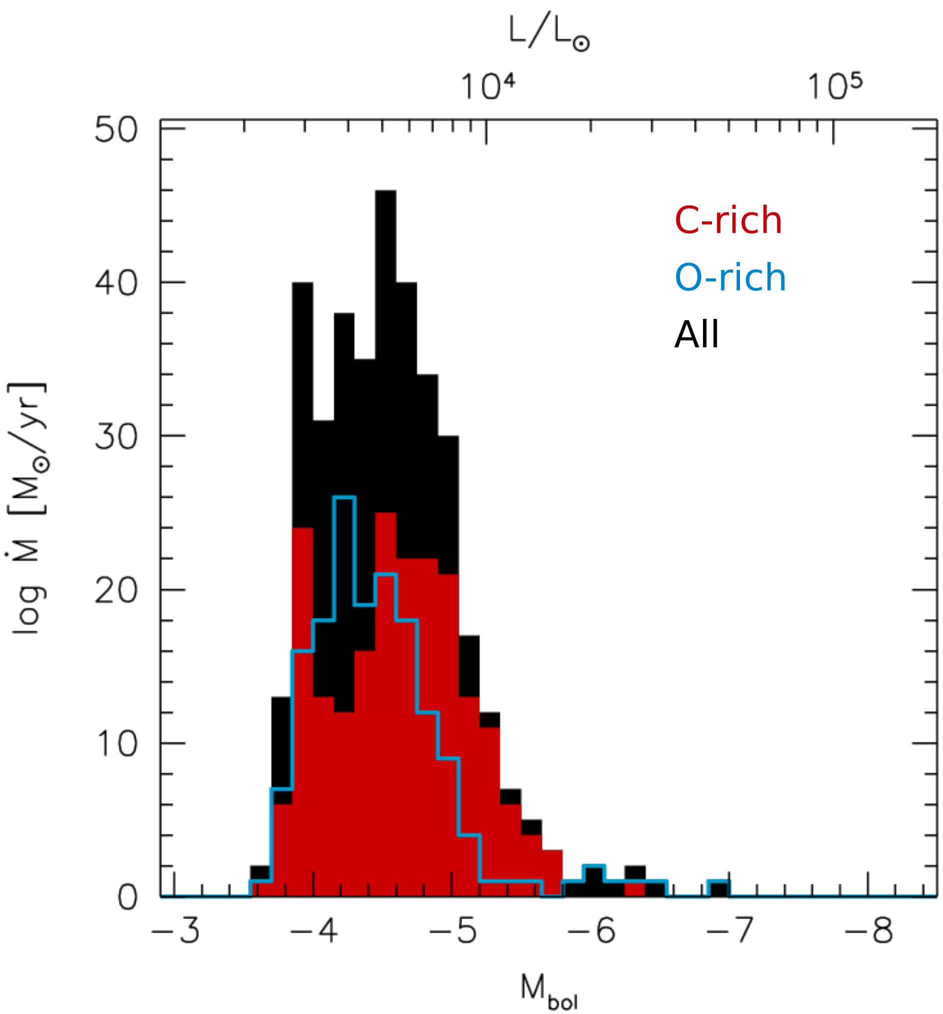
All other stars with bad fit are AGB stars (variability)

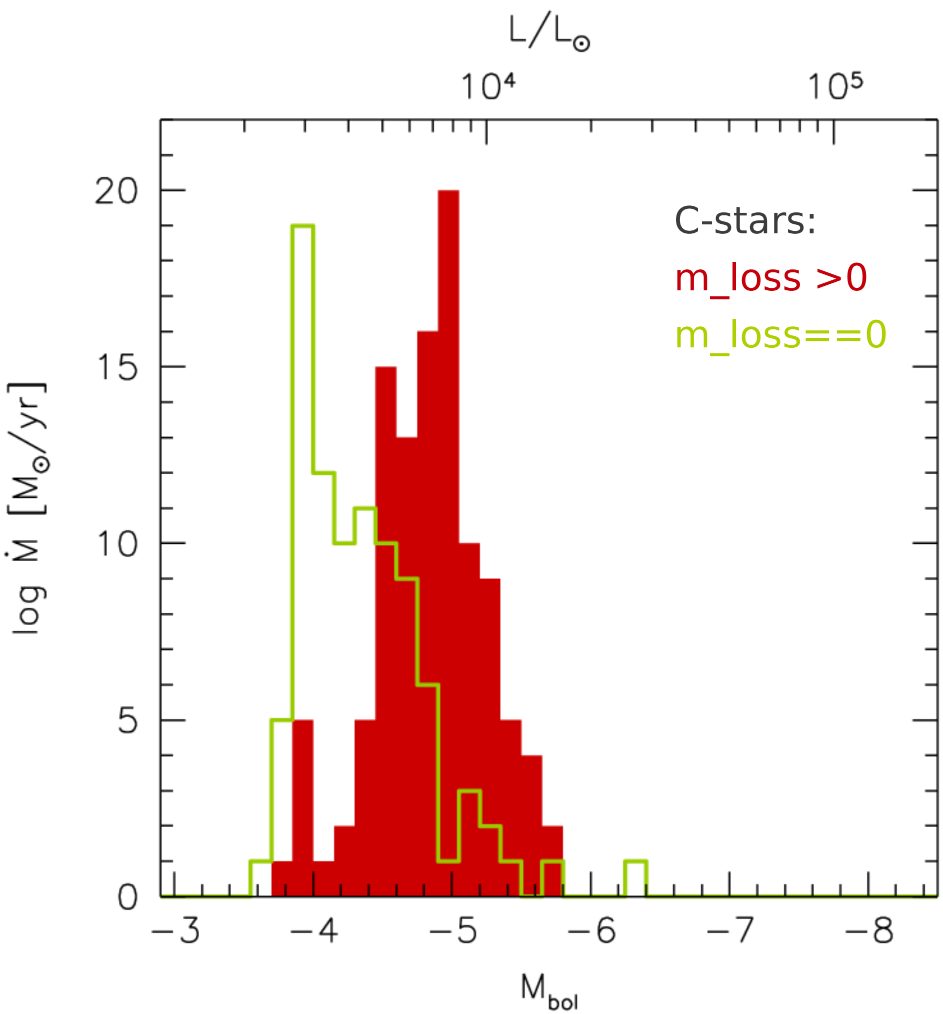
No O-rich dusty stars !!

Comparison with spectroscopic surveys (Kontzias+2001; Groenewegen+2009; Groenewegen in prep.) showed that our classification is reliable at a >75% level. Even better for reddest, dusty, stars.



Bolometric magnitudes





LF of C-stars peaks around Mbol=-4.7 as expected

No stars brighter than expected AGB limit at Mbol=-7. No massive (> ~8Msun) AGB stars

Faint-end cut is due to our selection

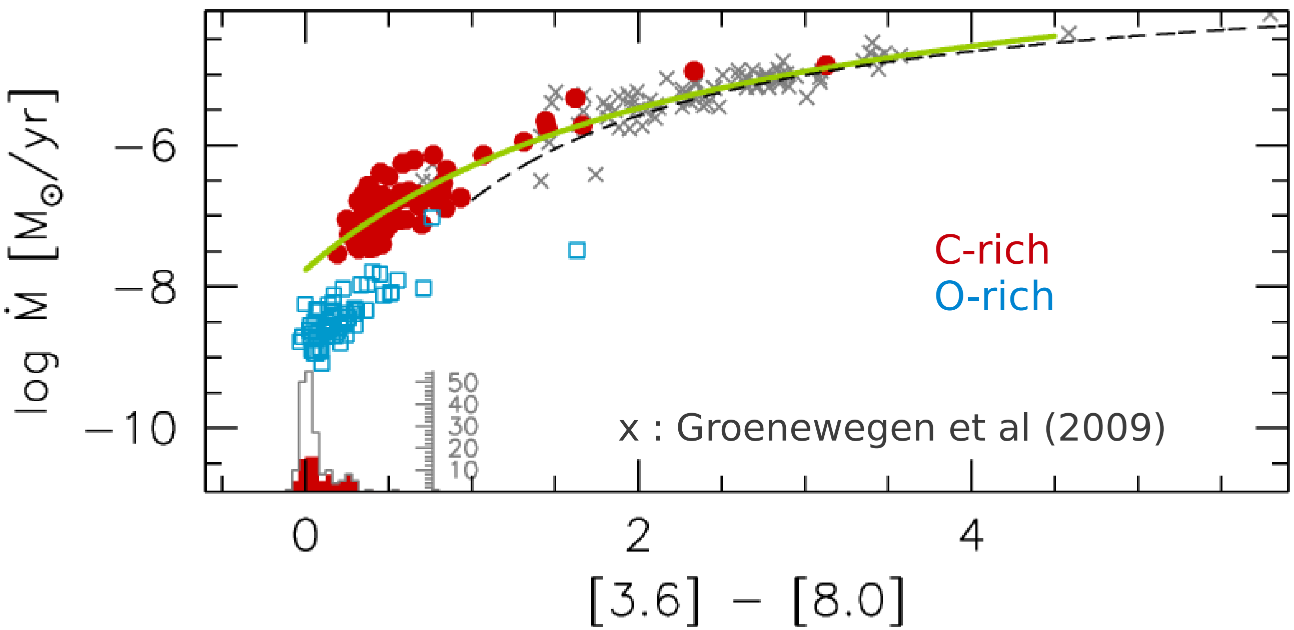
We expect high number of C-stars with no (low) mass loss below the TRGB.

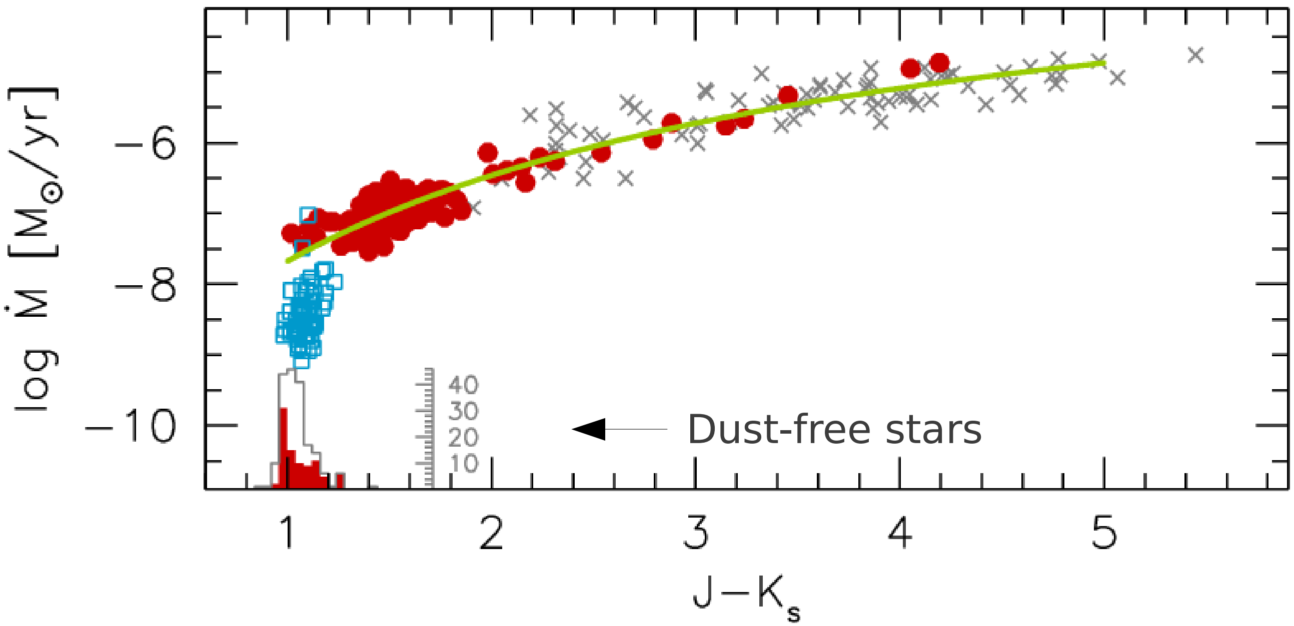
Mass loss rates

- ✔ Well defined colour vs. mass-loss rate relation
- ✔ Correct position for dust-free stars

$$\log \dot{M} = \frac{-15.42}{(J - K_s) + 2.10} - 2.70$$

$$\log \dot{M} = \frac{-12.78}{([3.6] - [8.0]) + 2.49} - 2.63$$





Mass loss rates

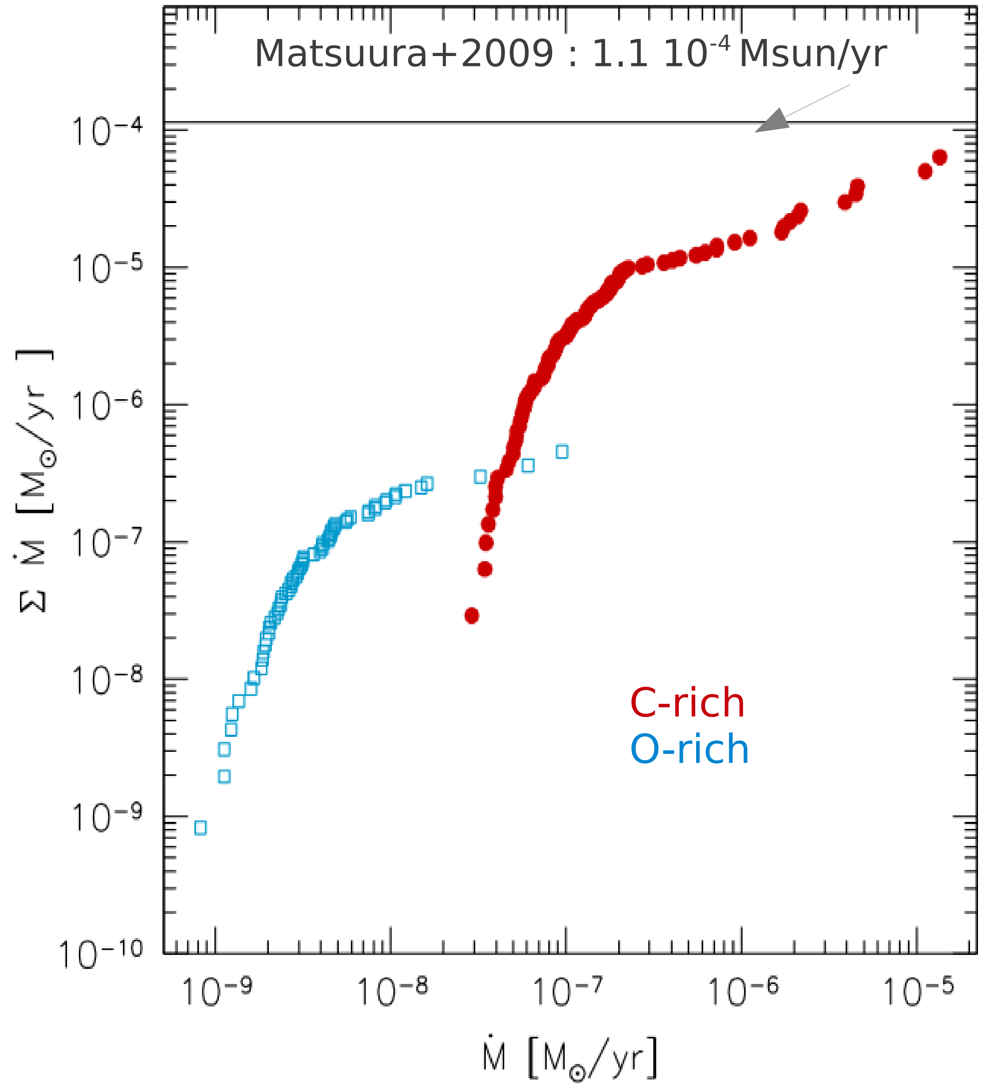
$\dot{M}$ range $M_\odot\ yr^{-1}$	N_{M09}	N	$\dot{M}_{TOT}$ $10^{-5} M_\odot\ yr^{-1}$
$< 1 \times 10^{-6}$	9.1	102	1.52
$[1 \times 10^{-6}, 3 \times 10^{-6}]$	8.1	6	1.07
$[3 \times 10^{-6}, 6 \times 10^{-6}]$	4.4	3	1.30
$[6 \times 10^{-6}, 1 \times 10^{-5}]$	1.8	0	0
$[1 \times 10^{-5}, 3 \times 10^{-5}]$	1.8	2	2.47
$[3 \times 10^{-5}, 6 \times 10^{-5}]$	0.5	0	0
$> 6 \times 10^{-5}$	0.2	0	0
Total:			6.37

O-rich stars : negligible contribution. 4.5 10^{-7} Msun/yr

102 stars with low mass-loss (<10^{-6} Msun/yr) → 24% of total

2 most extreme stars → 38% of total

Total mass-loss rate dominated by the few most massive stars



Much more data needed to study the overall mass-loss properties and dust life-cycle in the LMC. This is just 1 VMC field!

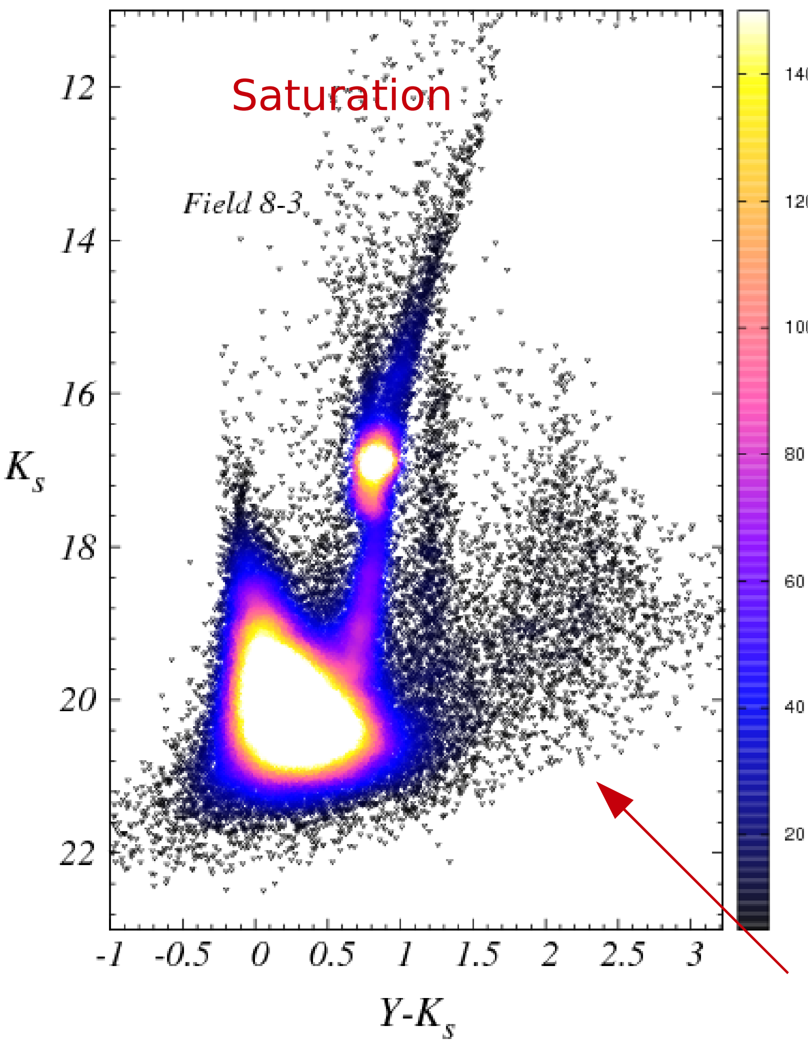
Comparison with stellar evolution models

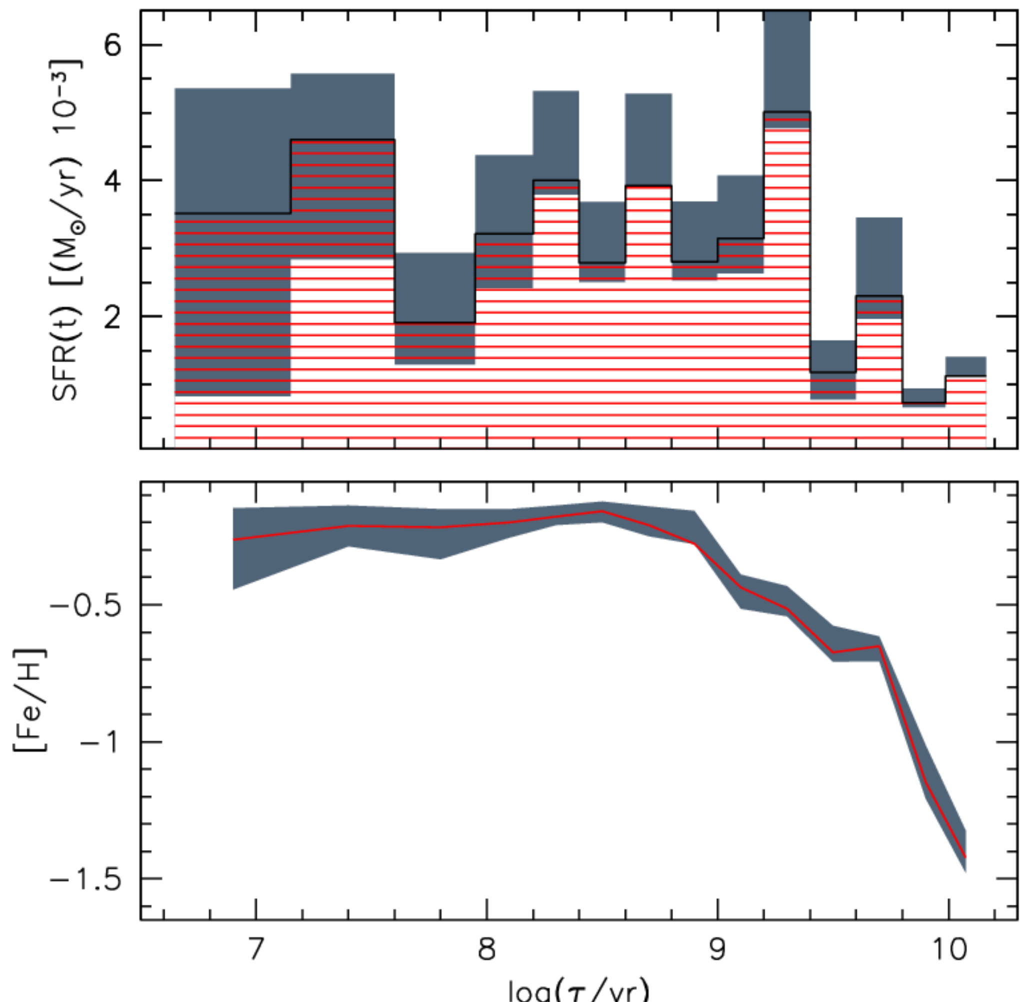
SFHs from Padova VMC team for different regions of each VMC tile.

TRILEGAL to generate CMDs using updated Padova isochrones

The SFH is well constrained at intermediate ages (few Gyr)

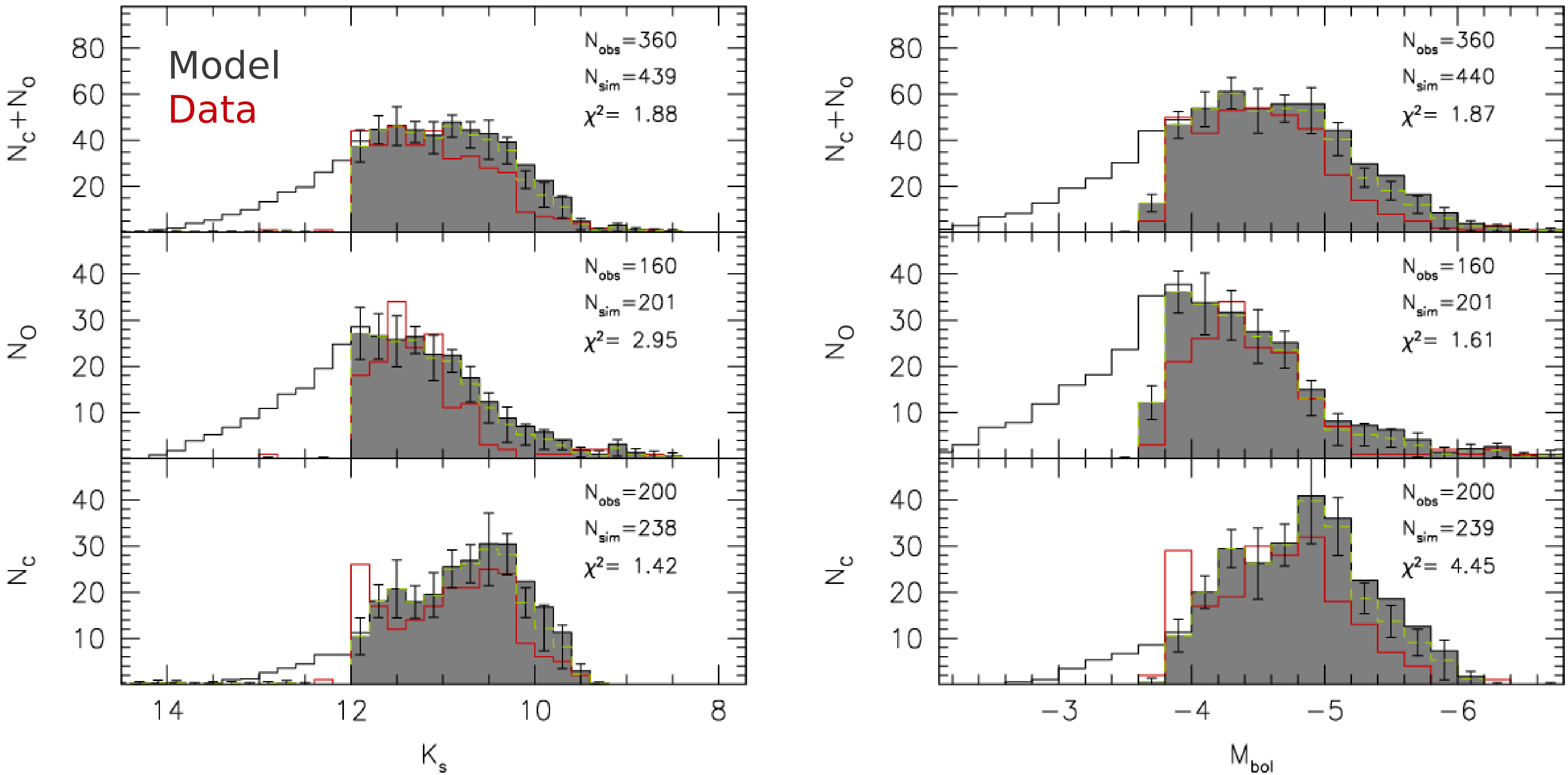
Rubele et al. In prep





Deep DAOPHOT photometry

Comparison with stellar evolution models



Good agreement (within 20%) of star counts and luminosity (in Mbol and in all photometric bands)

Overproduction of bright (C-rich) stars: uncertainties in the SFH at young ages (<0.8 Gyr)?

We need to take into account systematic and random errors in the SFRs ...work in progress

Conclusions

371 candidate AGB stars in the LMC selected using near-IR photometry in VMC field 8_3. 3 YSOs 1 AGN

SEDs were built combining MCPS (optical) 2MASS (near-IR), VMC (near-IR) SAGE (mid-IR) and AKARI (mid-IR)

The C/O classification method was found to be reliable at >75% level

No O-rich dust enshrouded stars

Mbol LF in good agreement with classical prediction for AGB stars:

Peak of C-star distribution at Mbol ~-4.5 mag, No AGB stars brighter than classical limit Mbol=-7.1 (no over-luminous super-AGB stars)

We provided mass-loss rates vs, colour relations in near and mid-IR.

This is an important testbed for theoretical model (AGB lifetimes)

contribution of different stellar population to the integrated mass-loss rate:

→ 102 C-stars with low mass-loss ($<10^{-6}$ Msun/yr) → 24% of total

→ 2 most extreme C-stars → 38% of total

→ negligible contribution from O-rich stars

Good agreement between our observations and AGB stellar evolution models.

work in progress: compare measured mass-loss rate and outputs of theoretical models ↔ mass-loss rates / AGB lifetimes

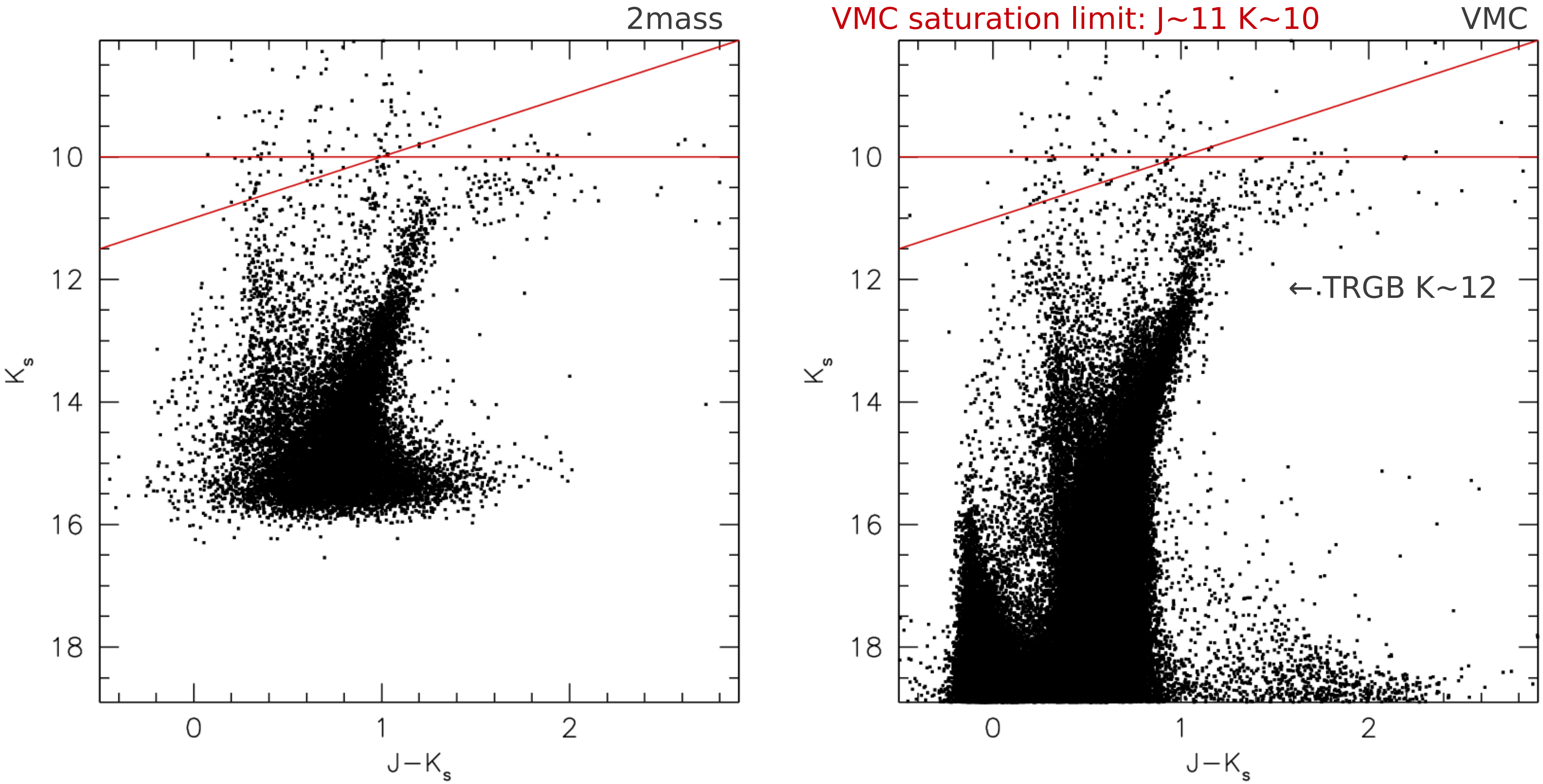
##################################

The main limitation of our results is related to the relatively low number of mass-losing AGB stars in our sample.

This is the first systematic study of ALL AGB stars in the MCs. We provided for the first time reliable mass-loss rates for the bluest AGB stars, which is the bulk of AGB population

VMC is scheduled to regularly carry out observations. At the end of the ~5 year survey we aspect to obtain data for two orders of magnitude more stars.

VMC and 2MASS



Why VMC?

The reddest AGB stars are at the detection limit of 2MASS

Most AGB stars are long-period high-amplitude variables. Photometric data at different epochs are required to take into account variability

AGB: mass loss

Mass loss rate is a crucial parameter for AGB evolutionary time-scale → number of AGB stars

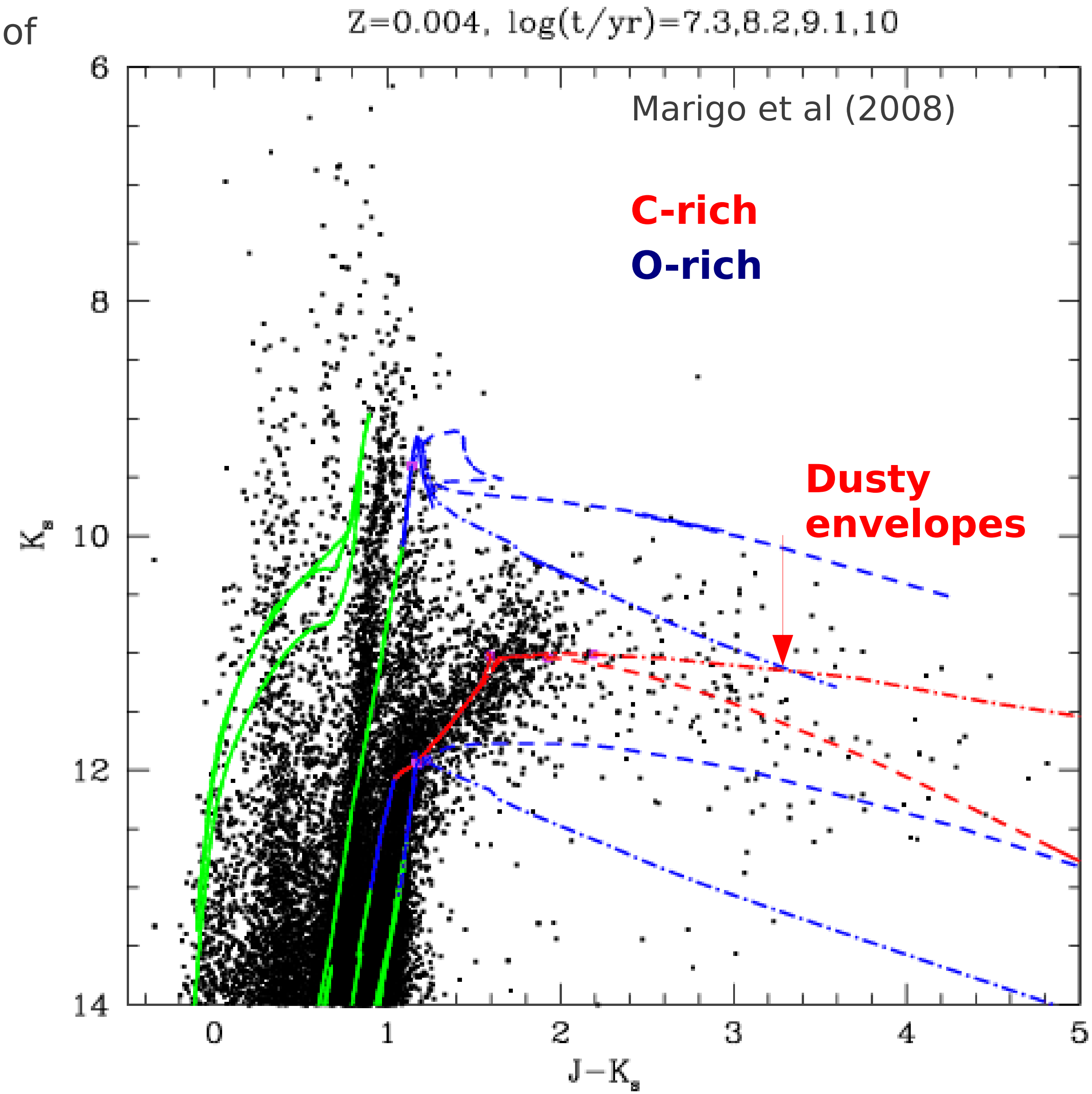
Dust properties and mass-loss rates strongly depends on C/O ratio

C/O > 1 → carbonaceus grains

+ opacity, + mass-loss rates

C/O < 1 → silicates

– opacity, – mass-loss rates

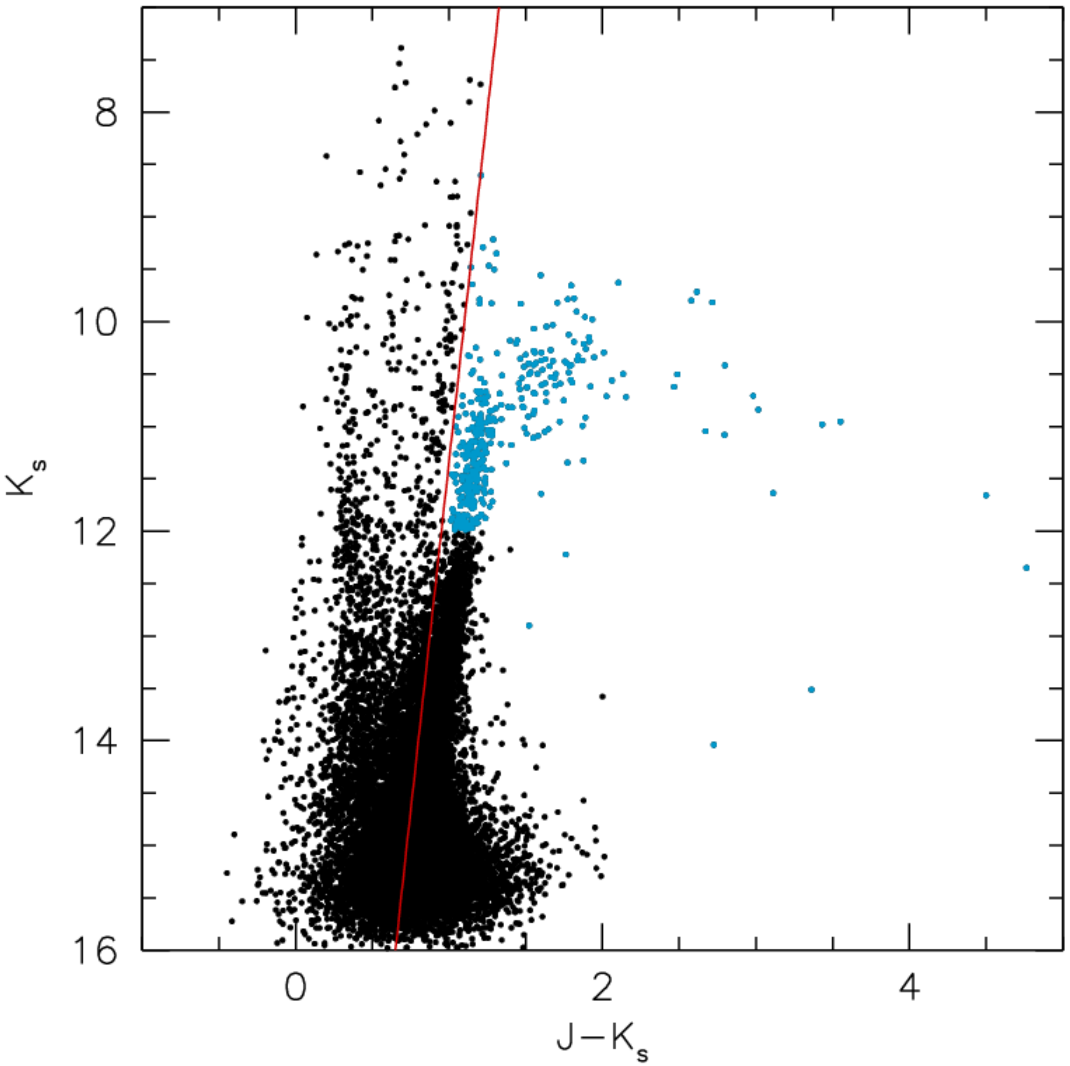


Photospheric models

The sample was divided in two groups:

Red stars (J-K>1.5):
- → low temperature
- → high mass-loss rates
- → thick dusty envelope
- → SED dominated by the dust

Blue stars (J-K<1.5):
- → higher temperatures
- → low mass-loss rates, if any
- → thin dusty envelope
- → SED dominated by the photosphere



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→ SED dominated by the photosphere

$T_{\rm eff}$	Blue		Red	
[°K]	C-rich	O-rich	C-rich	O-rich
2600	0 F		F	
2800			F	F
3000	0 F		F	
3200	0	0 F		F
3600	0	0 F		F
4000	0	0		

0: dust-free models
F: models with mass loss set as a free parameter

Red stars:
6 dusty models (x4 condensation Temperatures)
→ 24 runs

Blue stars:
4 dusty models (x4 Tcond) + 8 dust-free models
→ 24 runs

C/O classification: testbeds

Kontzias+2001: a catalogue of C-stars spectroscopically classified in the LMC.

87 stars in common. All relatively blue, J-K<2

54 red stars: J-K>1.5. → all correctly classified as C-rich

33 blue stars: J-K<1.5 → 84% C-stars

Groenewegen+2009: a selection of bright mid-IR sources in the MCs with Spitzer spectra. They applied a procedure similar to our one but with IRS spectra (5-40 microns) and much more photometric points, in particular in the mid-IR. Very robust C/O classification.

Groenewegen (in prep.) included other sources. 260 stars in LMC and SMC.

None in field 8_3,

we used their photometric data, considering only the photometric systems we are using (optical, JHK, Spitzer) and applied our procedure.

100% success rate for red C-stars

reliable classification for red O-stars

	Blue		Red	
	C	O	C	O
total	46	72	113	29
	(38)	(44)	(93)	(22)
correct	93%	72%	97%	76%
	(95%)	(82%)	(100%)	(73%)

Excluding stars with uncertain classification → (values in parentheses)

Fitting the SED

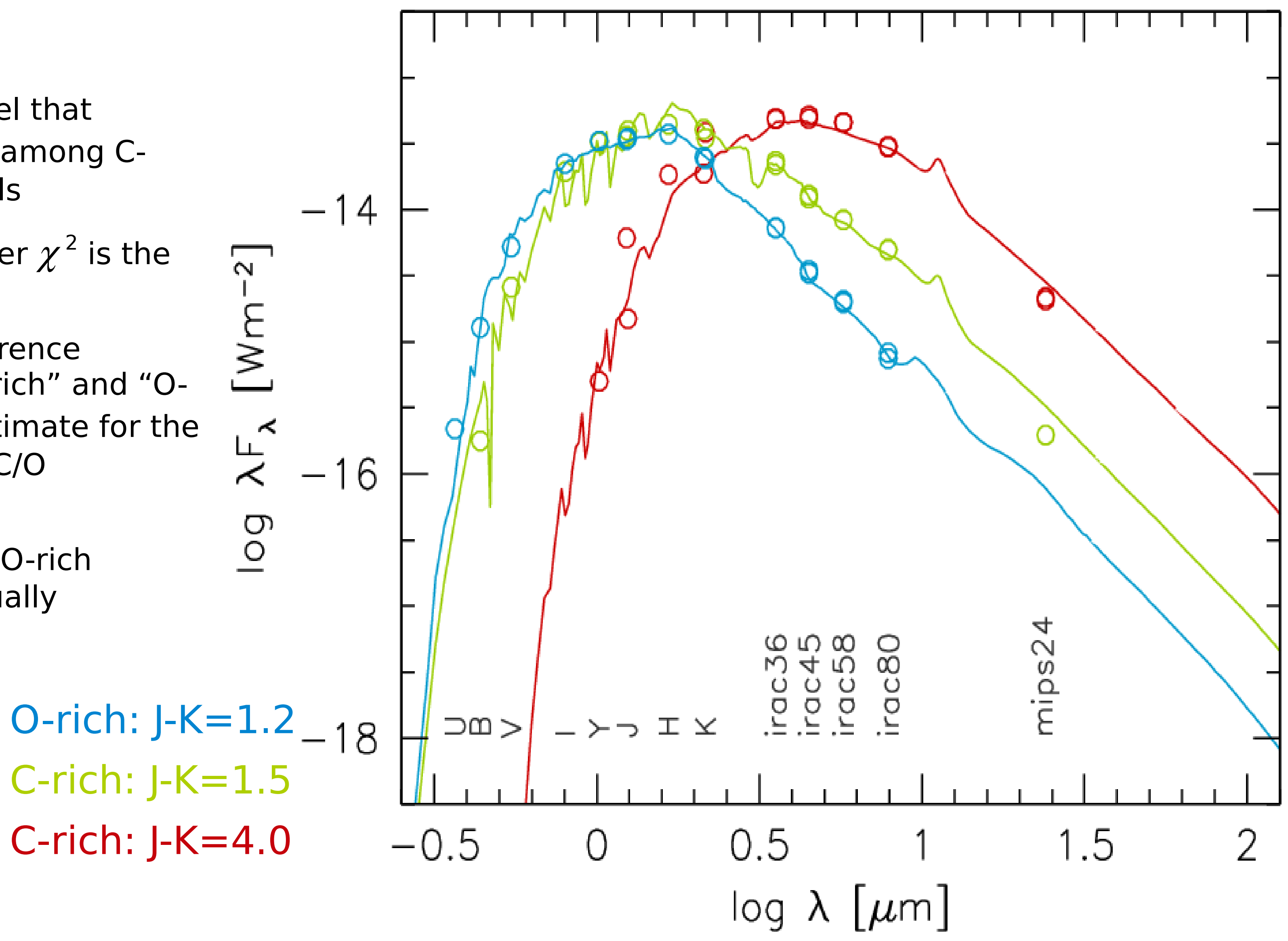
Best fit models and C/O classification

→ Choose the model that minimise the χ^2 among C- and O-rich models

→ the one with lower χ^2 is the best fit model

→ the relative difference between the “C-rich” and “O-rich” χ^2 is an estimate for the reliability of the C/O classification.

low $\delta\chi^2$ → C- and O-rich solutions are equally acceptable



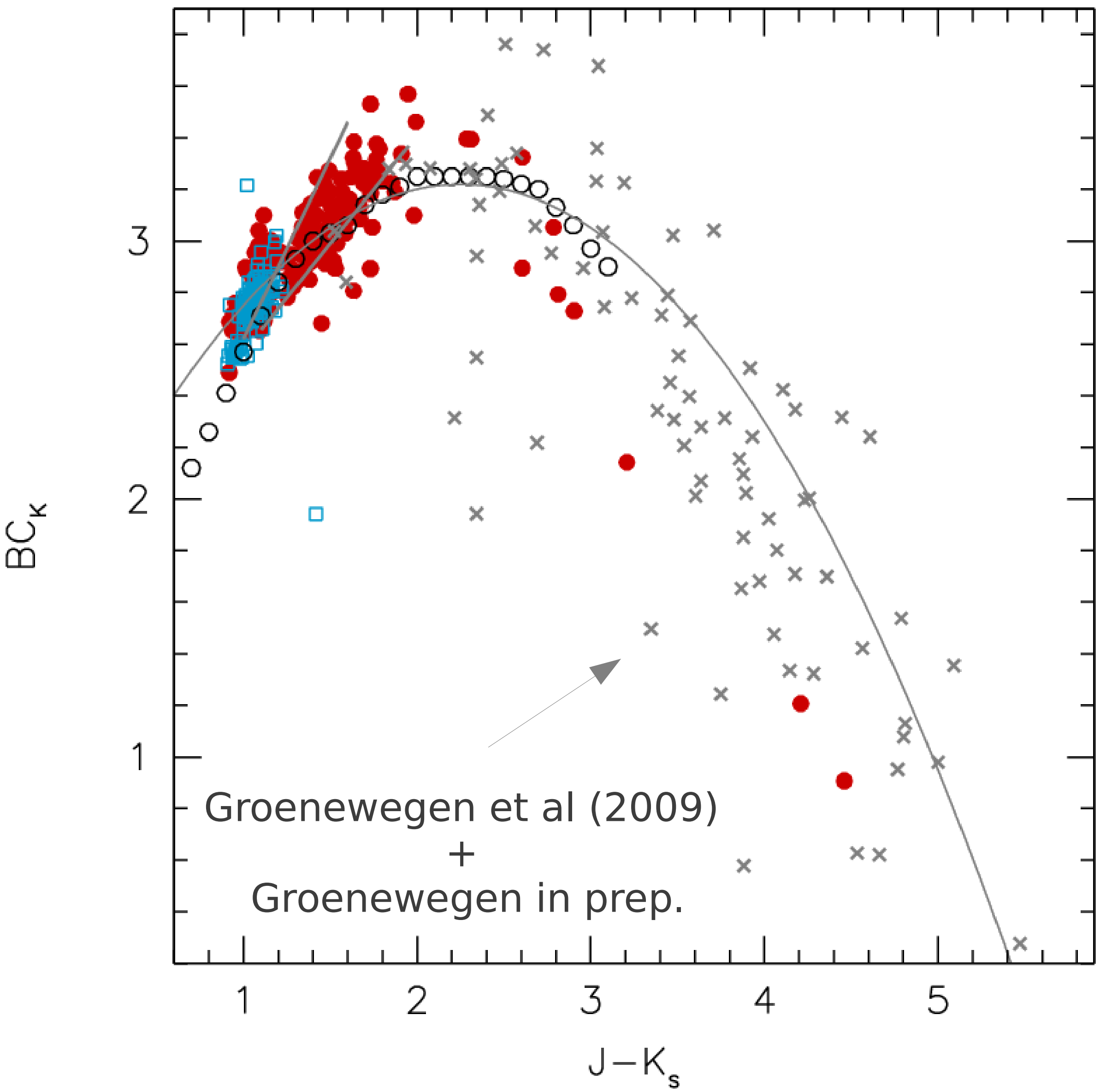
Bolometric magnitudes

K-band bolometric correction obtained from total luminosity and Ks magnitude

Good agreement with the empirical bolometric correction

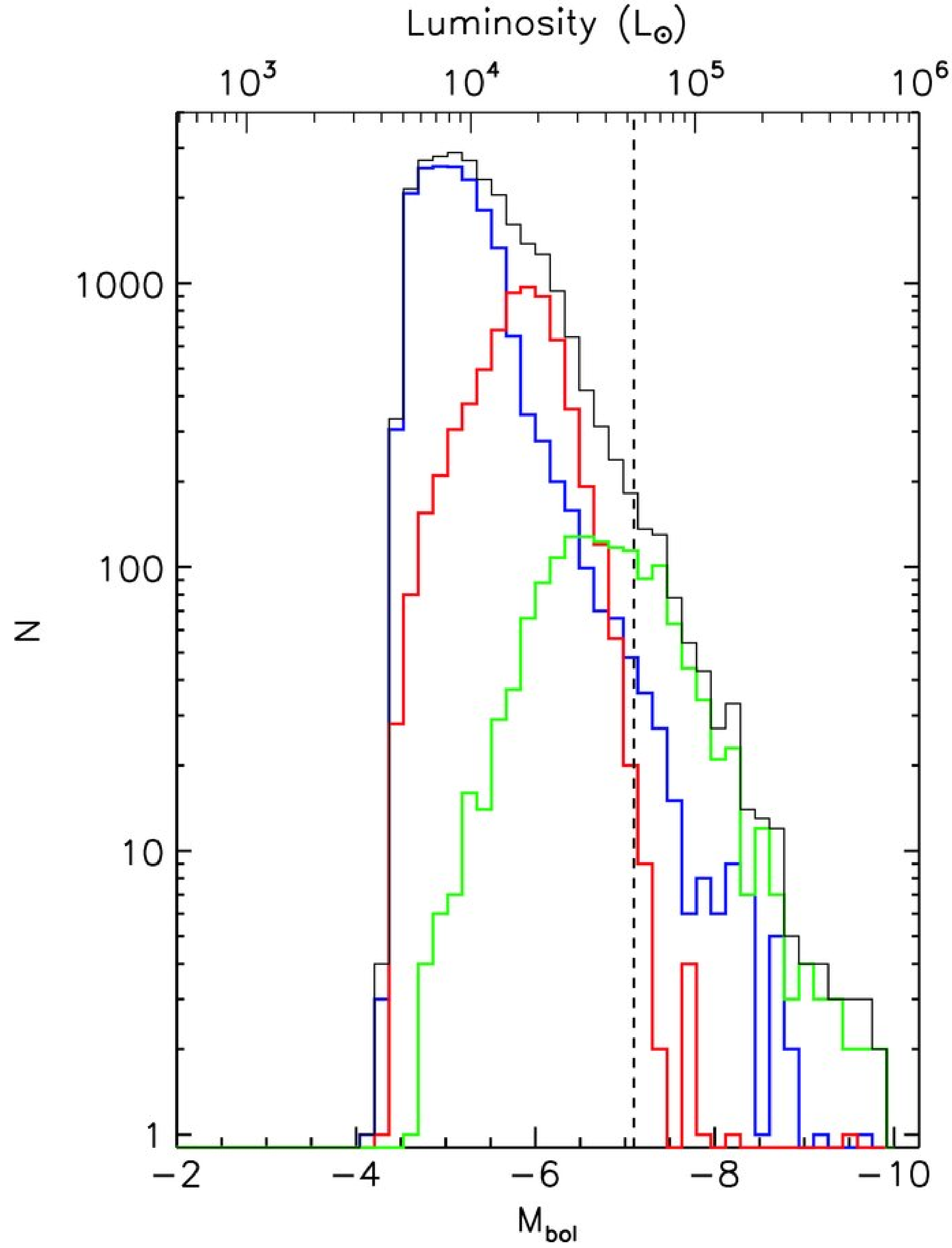
Bergeat+2002: C-rich

Kerschbaum+2010 C-rich and O-rich

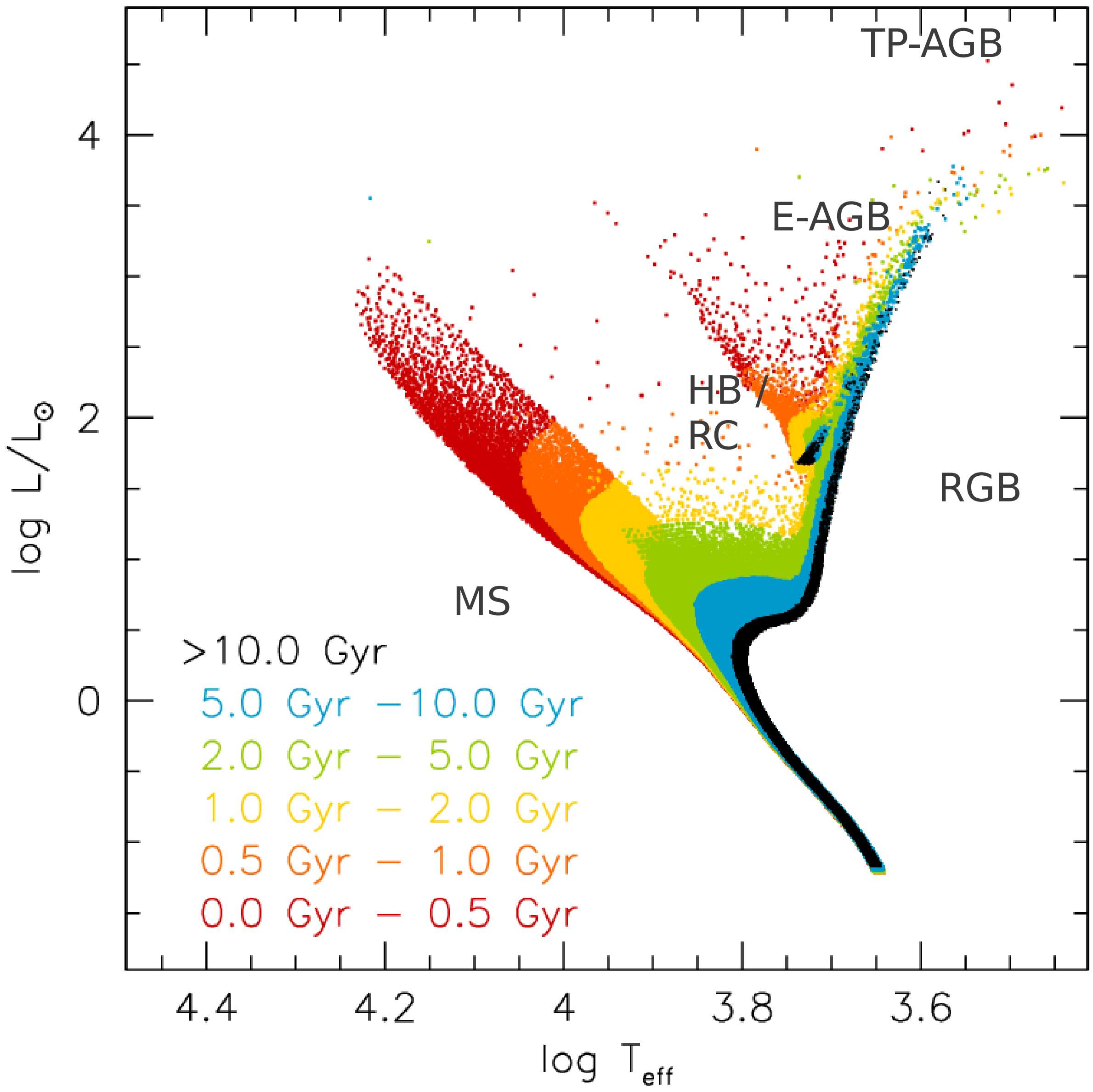


Srinivasan et al (2009)

O-rich
C-rich
Extreme AGB



AGB stars



Intermediate- and low- mass stars

>> low Teff: 2500-4000 K

>> bright : Mbol ~ -4/-5 mag

>> SEDs peak in the near- IR

>> mass-loss (up to 50% of initial mass)

>> dust enshrouded stars emit most of the light in mid-IR