Mass-Loss Rates and Luminosities of Evolved Stars in the Magellanic Clouds

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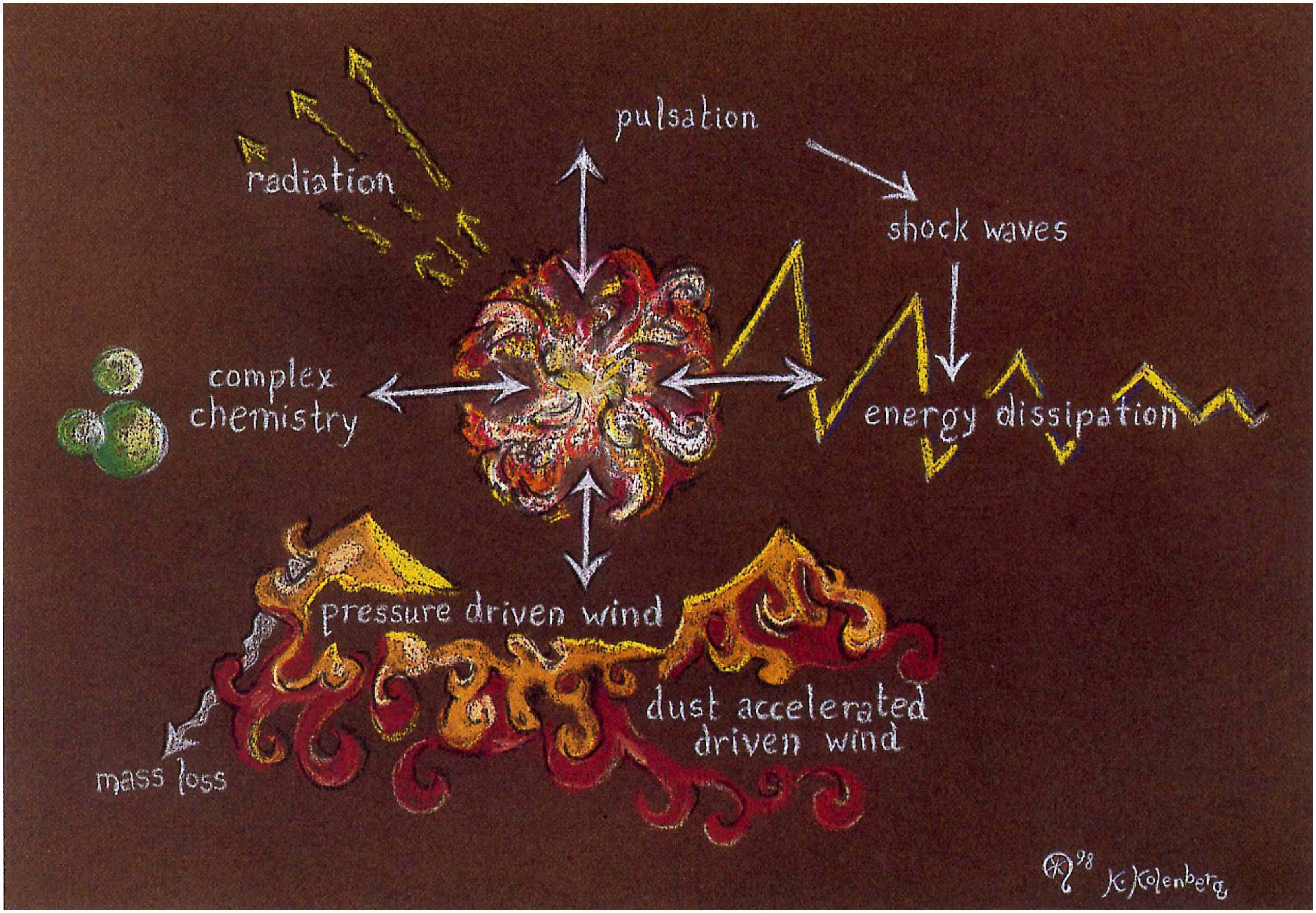
Overview Talk

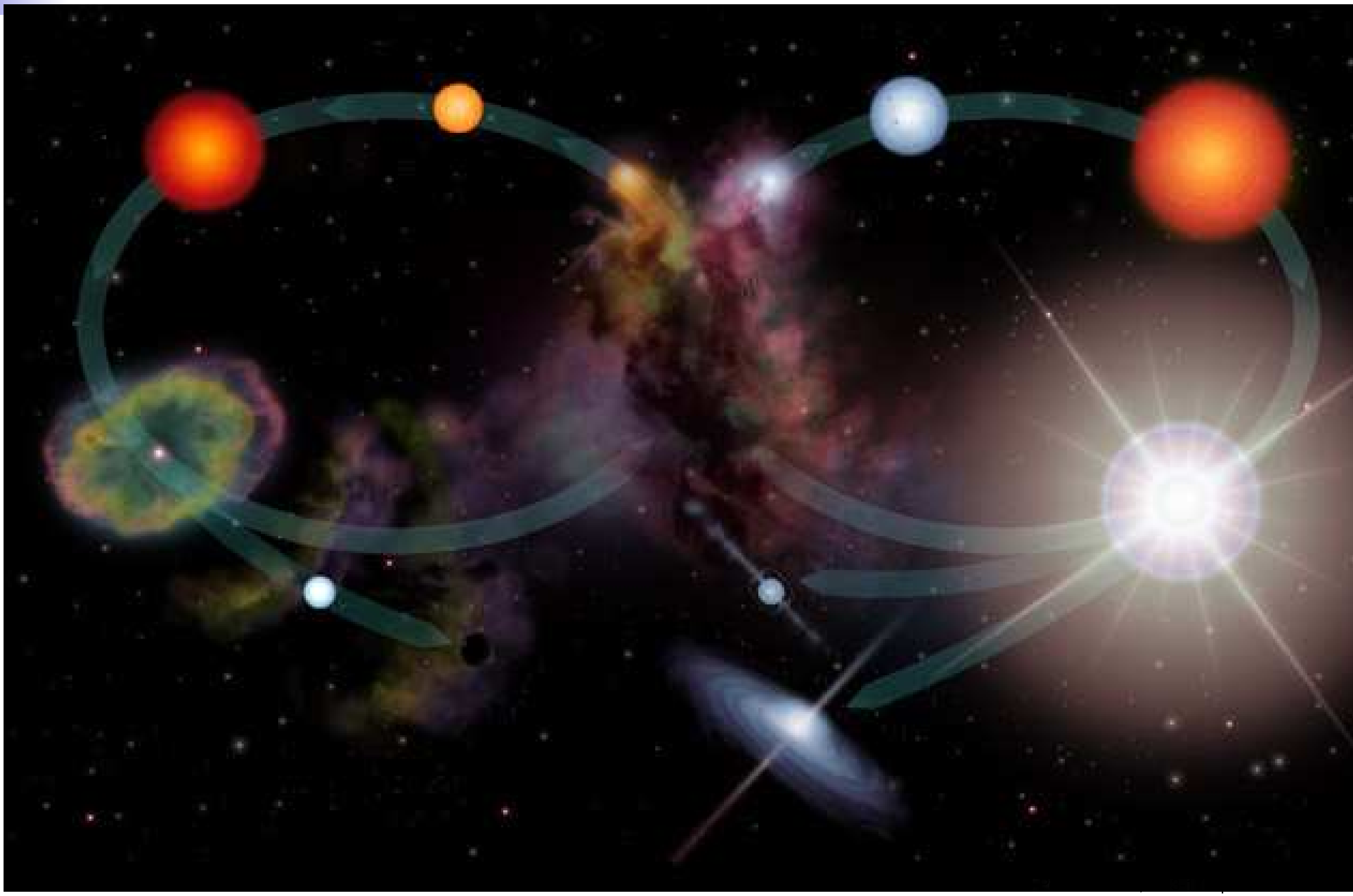
- Introduction
  - Radiative transfer
- MLRs in AGB & RSG in MCs
  - Sample of stars with *Spitzer* IRS spectra
  - Results
- Prospects - JWST

A complicated problem



(Katrien Kolenberg)

Life cycle of dust and gas in the Universe



Dust RT Basics

$$\tau_\lambda = \int_{r_{\rm inner}}^{r_{\rm outer}} \pi a^2 Q_\lambda \, n_d(r) \, dr$$

$$\dot{M} = 4\pi r^2 \, \rho v_{\rm gas}$$

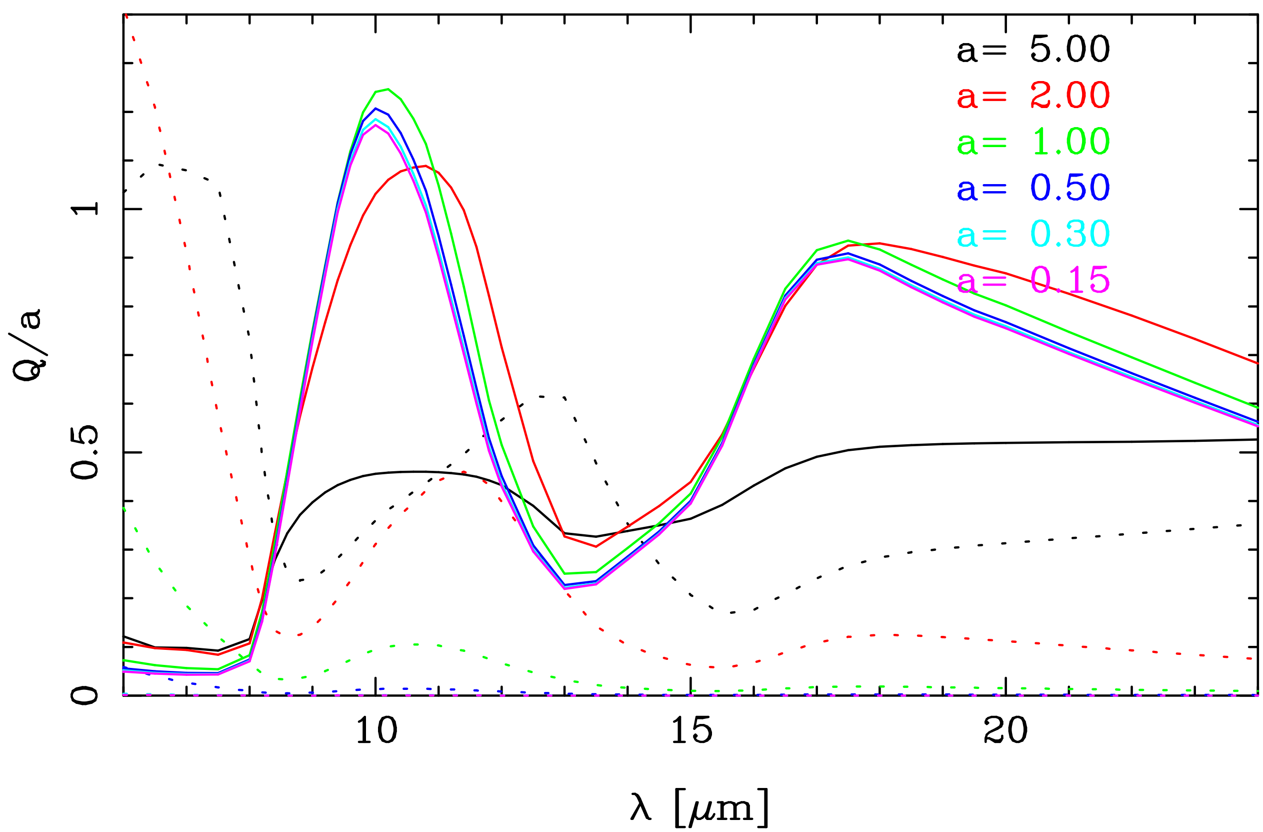
$$m = \frac{4}{3} \, \pi a^3 \rho_{\rm dust}$$

opacity: $\kappa_\lambda = \frac{3 \, Q_\lambda}{4 \, a \, \rho_{\rm dust}}$

$$\tau_\lambda \sim \kappa_\lambda \, \dot{M} \, \Psi / (R_\star \, R_{\rm c} \, v_{\rm exp})$$

Effect of Grain Size

Grains in the range 0.3-0.5 μm from interferometric and/or polarimetric observations.



DHS $Mg_{0.8}Fe_{1.2}SiO_4$: effect of grain size.

More of DUSTY - MoD

- MoD (Groenewegen 2012): DUSTY as subroutine in minimalisation routine $\Rightarrow$ fits L, τ, $T_{\rm c}$, $\rho \sim r^{-p}$
- Constraints:
  - photometry
  - spectra
  - visibilities
  - intensity profiles
- Input:
  - stellar model atmosphere
  - file with $Q{\rm abs}$ and $Q{\rm sca}$
  - distance, $A_{\rm V}$
  - $R_{\rm out}$

Magellanic Clouds

Fitting SEDs of THOUSANDs of sources
(typically photometry).
Issue: O-rich or C-rich ?

- Fit pre-computed model grid.
  Groenewegen (2006), used in Padua isochrones.

  SAGE (GRAMS)
  Sargent et al. (2011), Srinivasan et al. (2011, 2016),
  Riebel et al. (2012), Boyer et al. (2012),
  Jones et al. (2012)
- Alternative: model individual SEDs
  (Gullieuszik et al. 2012)
  VISTA Magellanic Cloud Survey (PI. M.-R. Cioni)

Gullieuszik et al.

- Selected 367 AGB star (candidates) in one VMC tile (1.5 deg^2), based on $(K, J-K)$, and ([8.0],[4.5-8.0]) CMD
- Collected photometry, and SEDs fitted
- Luminosity, and MLR, and chemical type
- Chemical classification tested:
  - Known C-stars in the field (Kontizas et al.) 76/87 (=87%); $(J-K) > 1.5$ even 54/54
  - IRS Spectroscopic sample (fitting only the photometry!) C-stars: 95%; O-stars: 75% correct

AGB/RSG with IRS spectra

Groenewegen & Sloan (2017)

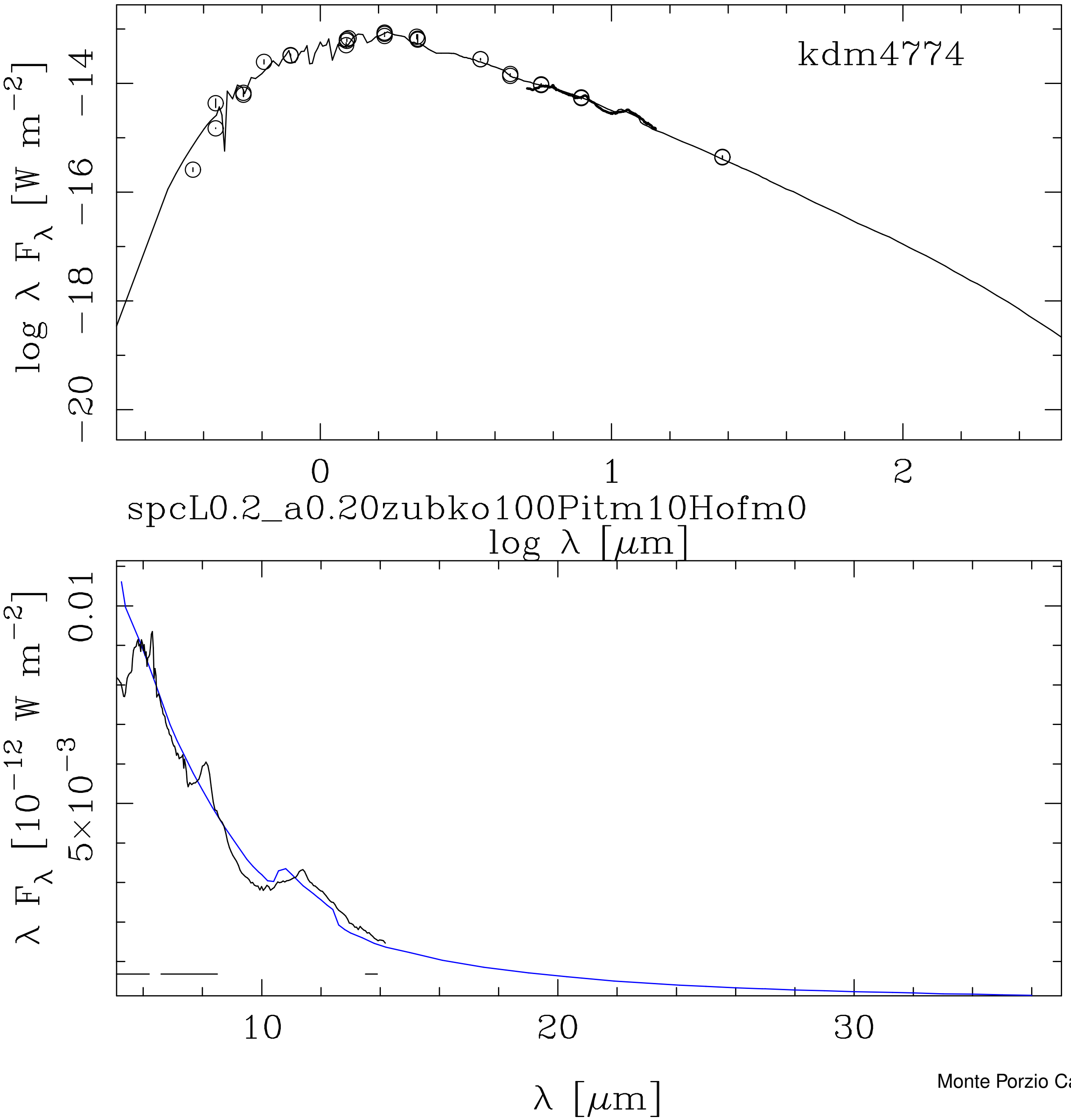
Update of:
Groenewegen M.A.T., Sloan G.C., Soszynski I., Petersen E.A. 2009, A&A 506, 1277

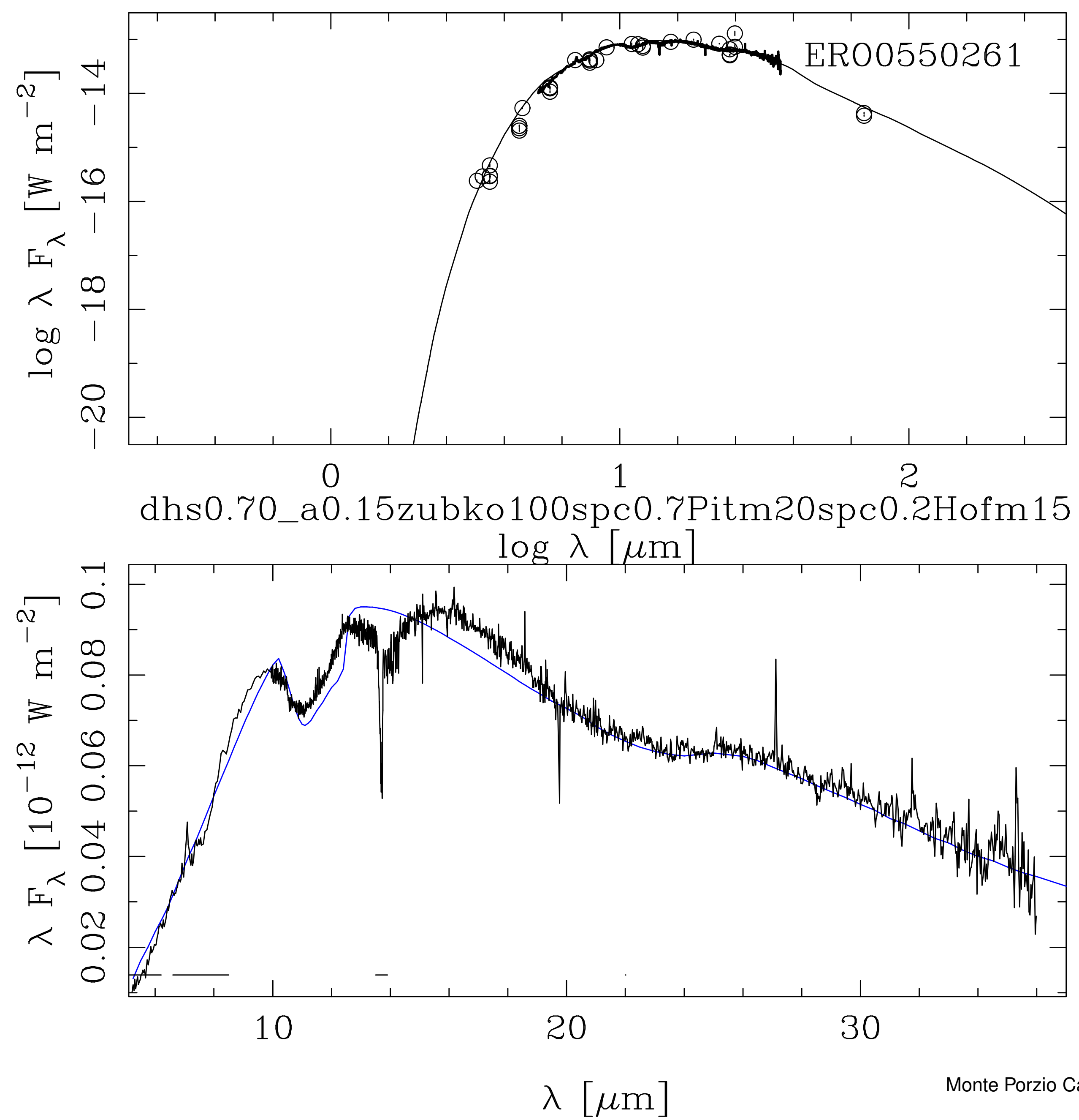
SED fitting of 101 C- and 86 O-rich stars in MCs with IRS spectra

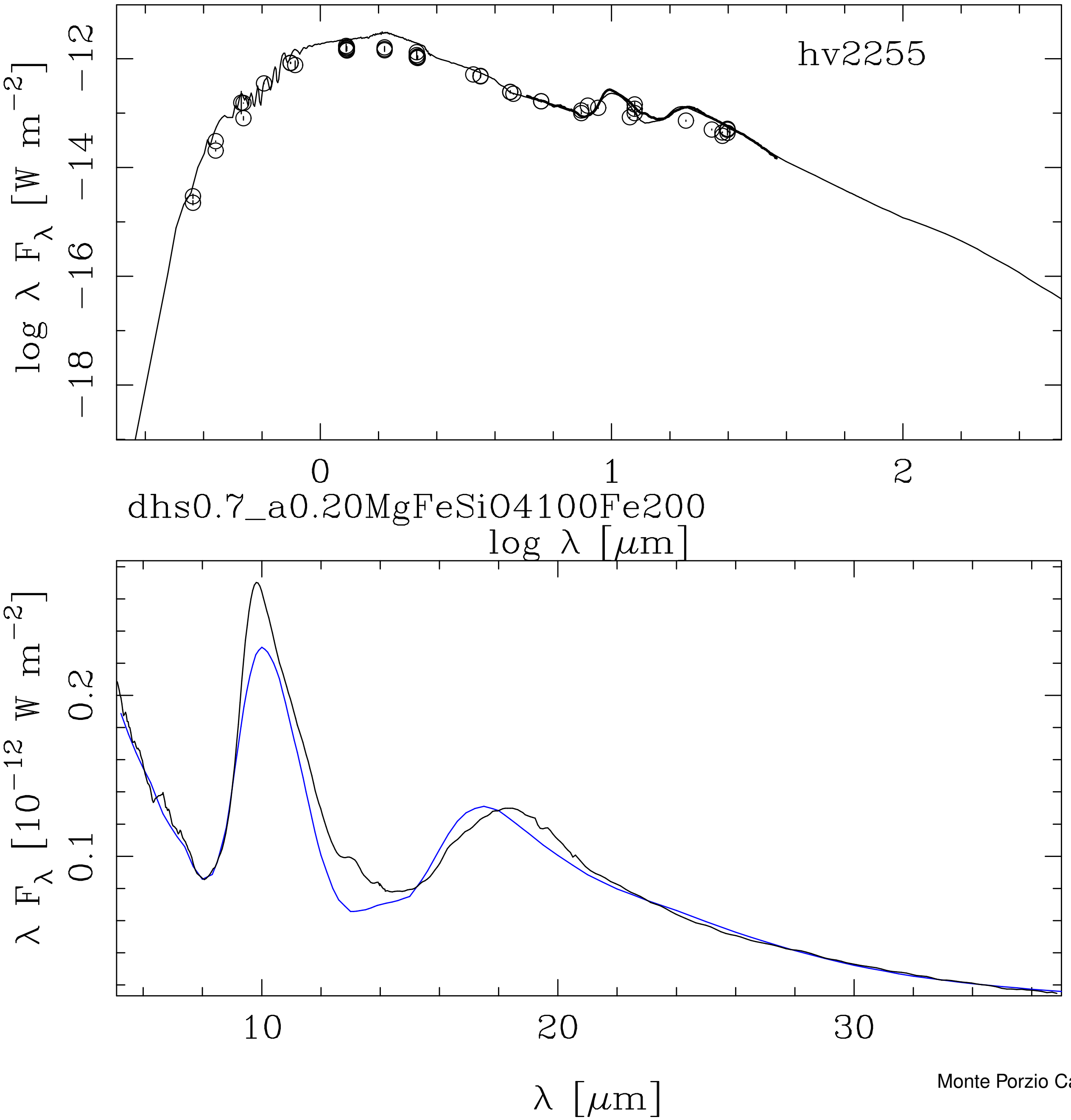
Presently:
225 (46 SMC, 19 dSphs) C- and
171 (40 SMC) O-rich stars (11 FG, 81 RSG, 79 O-AGB)

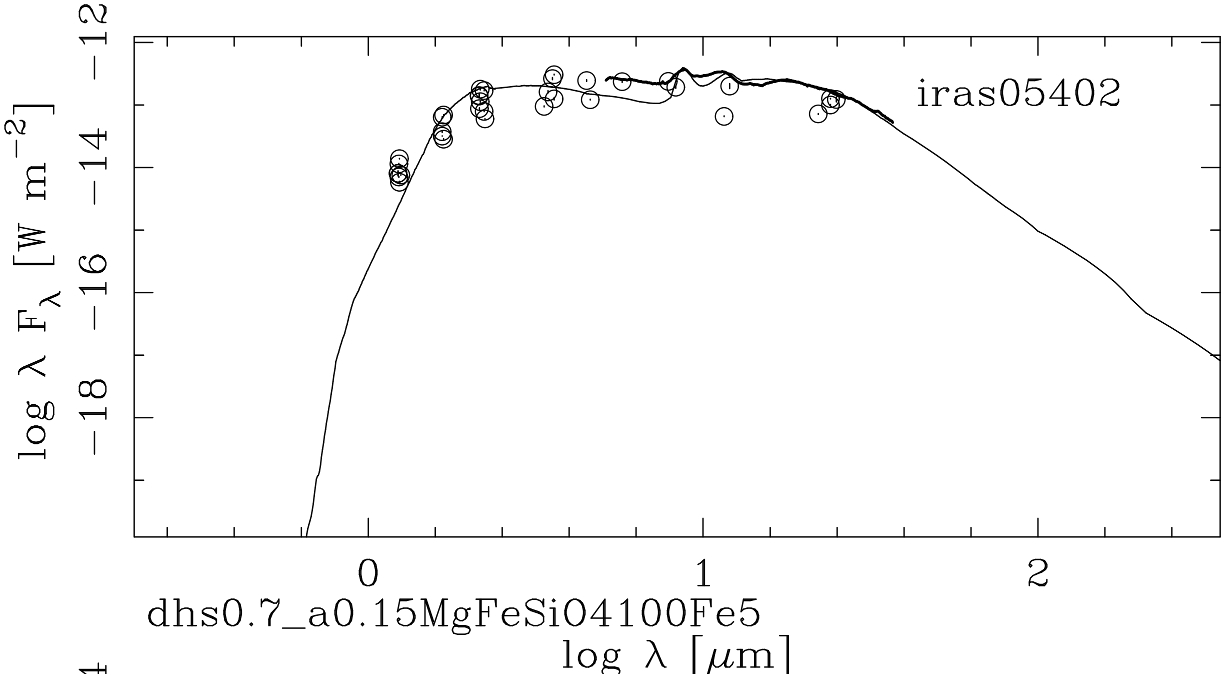
Improvements:

- MoD
- Improved stellar model atmospheres: MARCS (M), Aringer et al. (C)
- Photometry (SAGE, WISE, Akari)
- Dust properties from optical constants

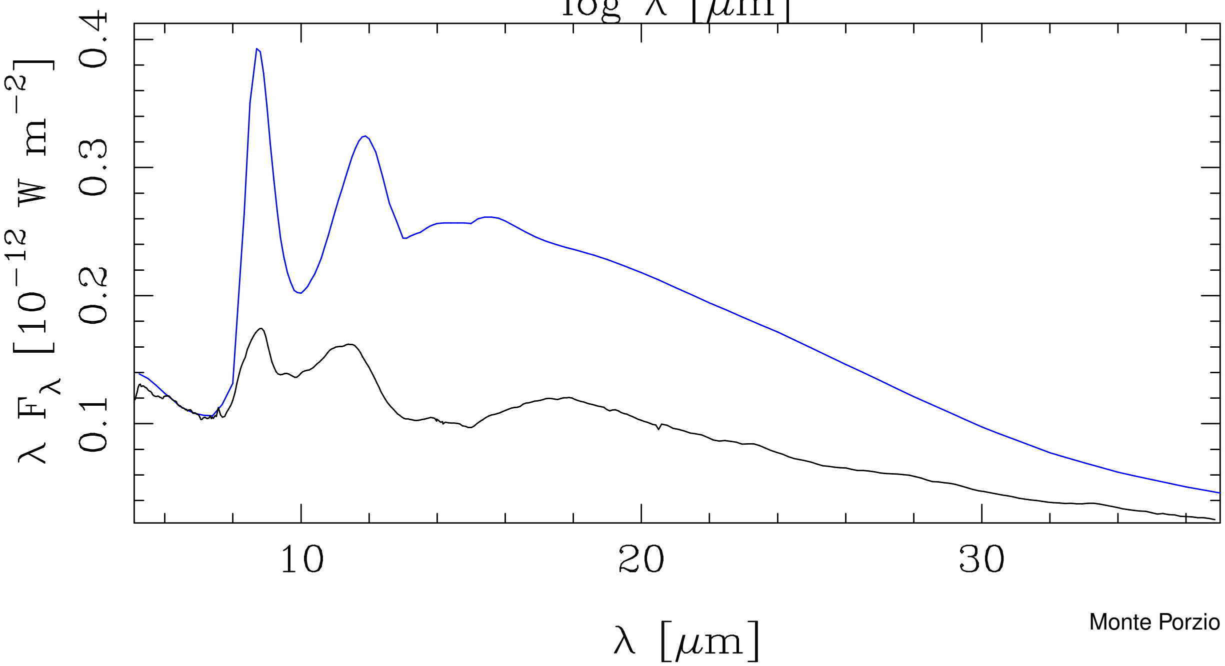

kdm4774
log λ F$_λ$ [W m^{-2}]
−14
−16
−18
−20
0
1
2
spcL0.2_a0.20zubko100Pitm10Hofm0
log λ [μm]
λ F$_λ$ [10^{-12} W m^{-2}]
0.01
5×10^{-3}
10
20
30
λ [μm]


ERO0550261
log λ F_λ [W m^-2]
−14
−16
−18
−20
0
1
2
dhs0.70_a0.15zubko100spc0.7Pitm20spc0.2Hofm15
log λ [μm]
λ F_λ [10^-12 W m^-2]
0.02
0.04
0.06
0.08
0.1
10
20
30
λ [μm]

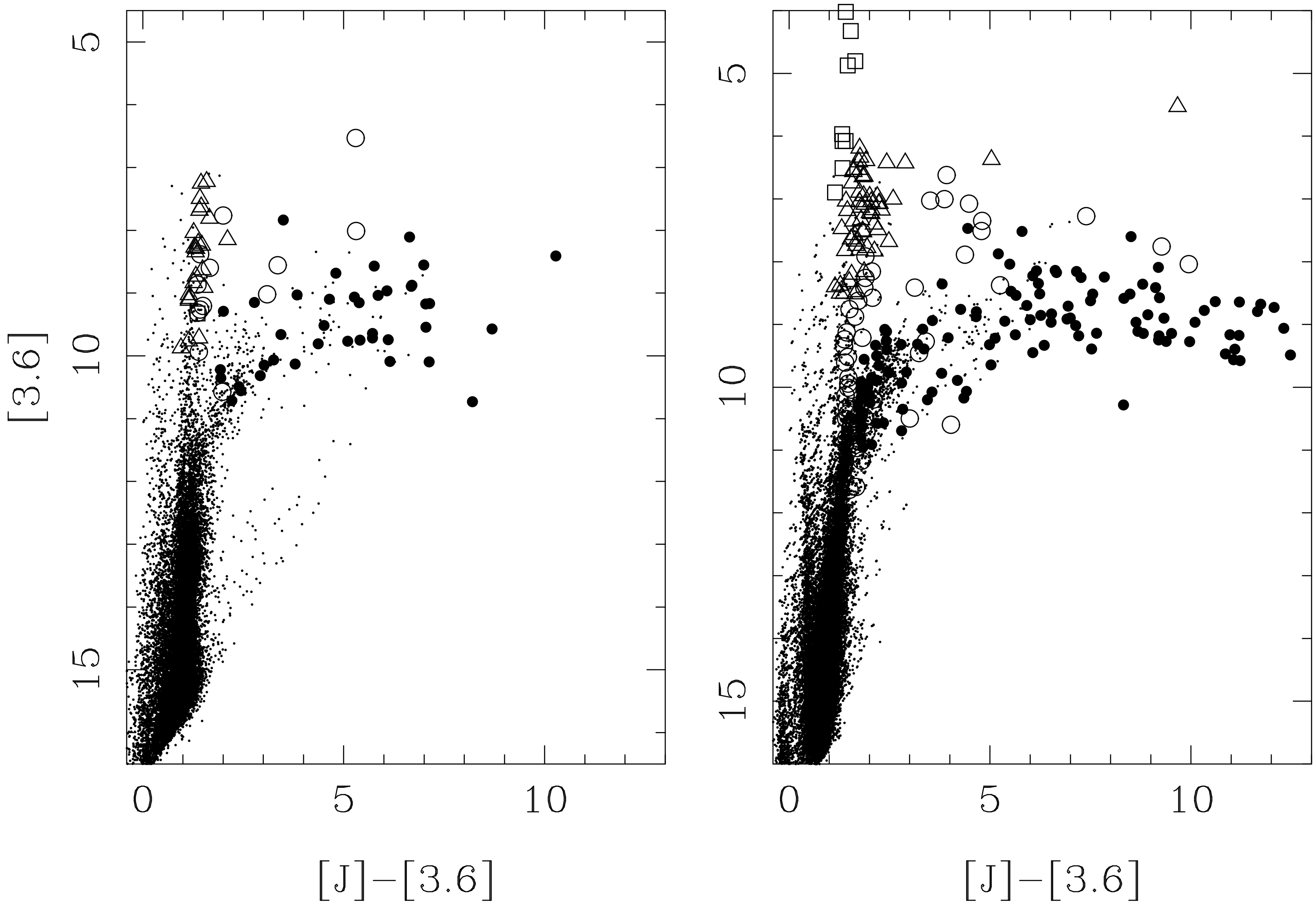

hv2255
log λ F$_\lambda$ [W m^{-2}]
−12
−14
−16
−18
0
1
2
dhs0.7_a0.20MgFeSiO4100Fe200
log λ [μm]
λ F$_\lambda$ [10^{-12} W m^{-2}]
0.2
0.1
10
20
30
λ [μm]



dhs0.7_a0.15MgFeSiO4100Fe5

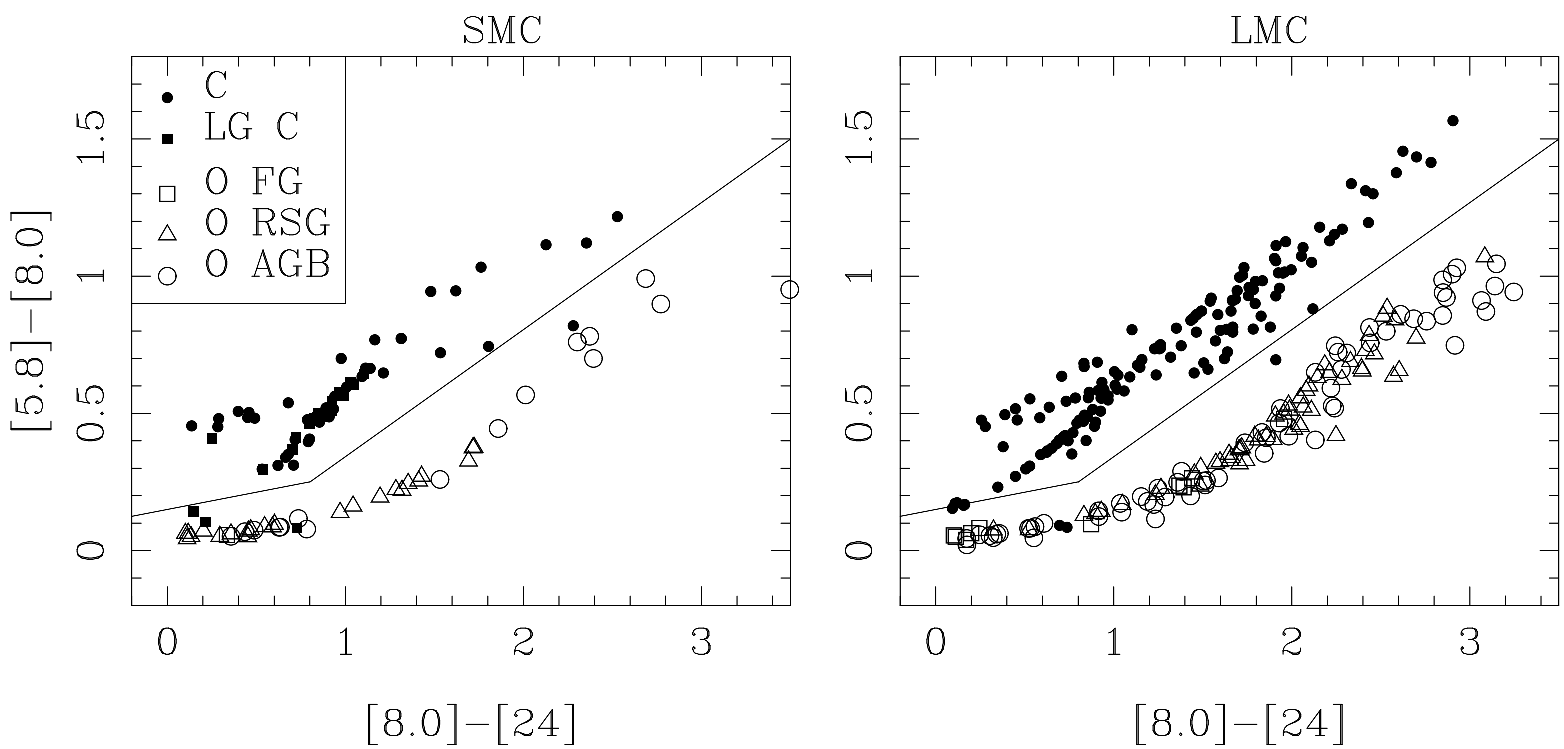


CMD

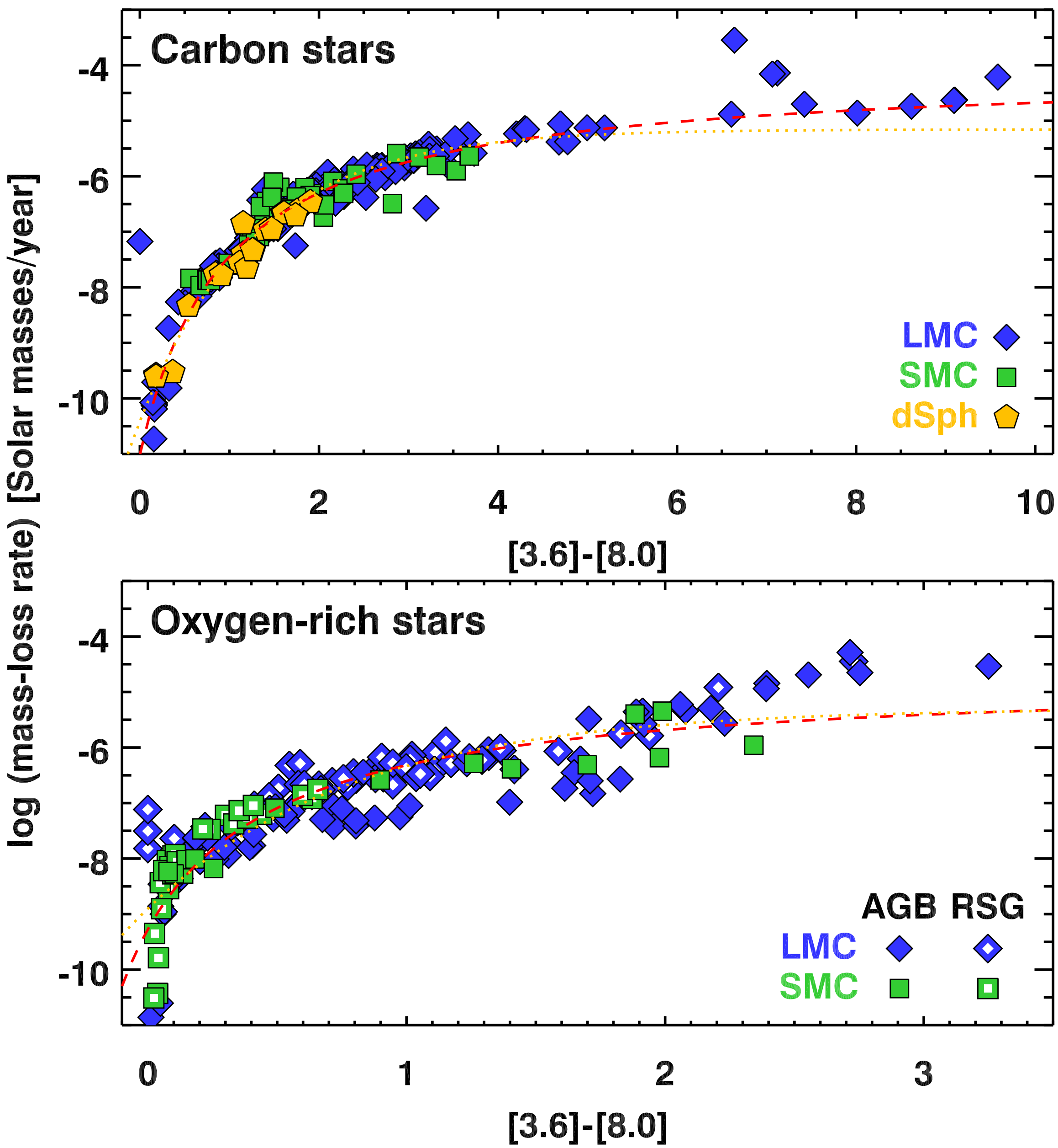


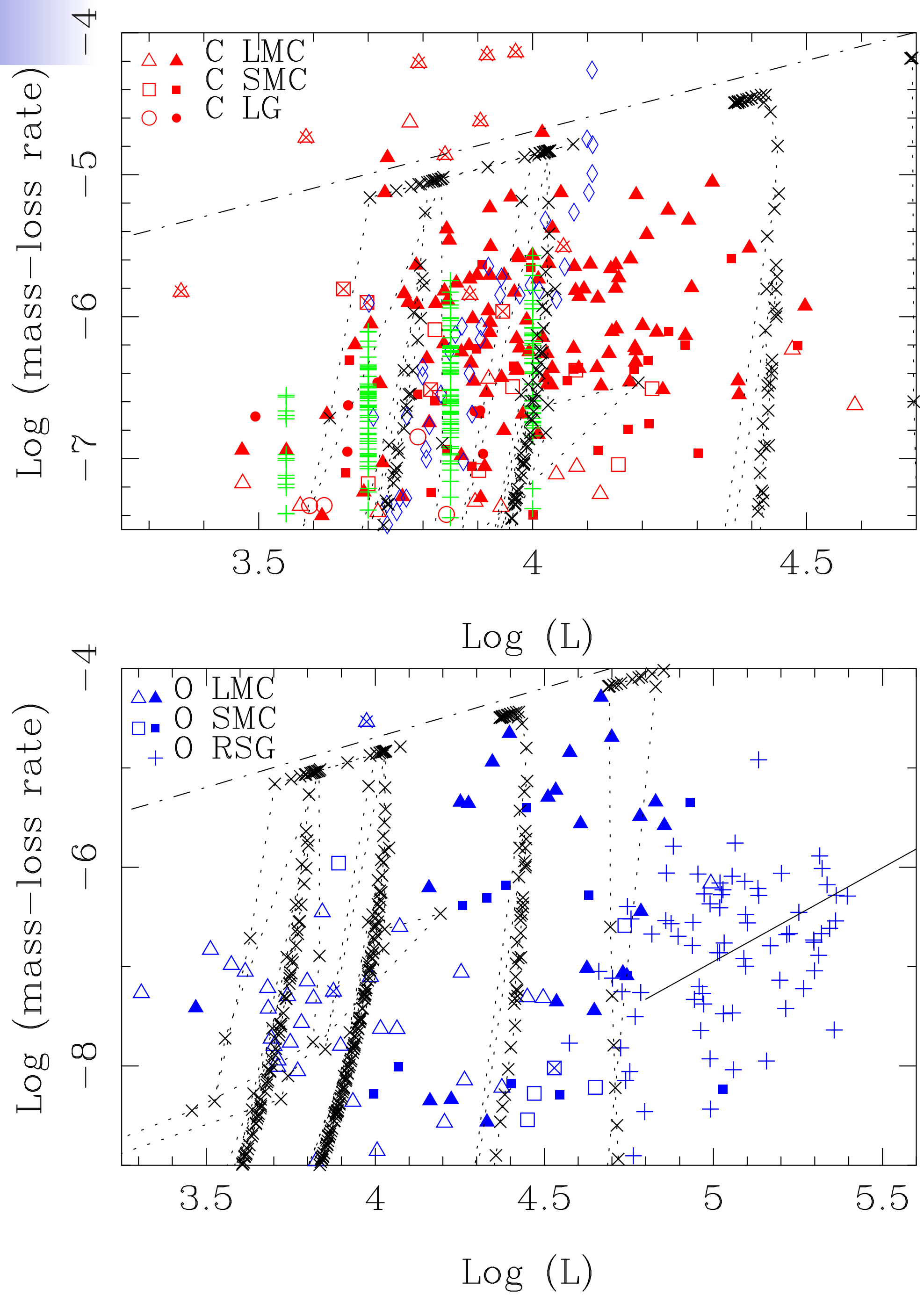
SMC: left ; LMC: right. Offset 0.5 mag

CCD



Good separation between C- and O-rich using IRAC/MIPS !
C-stars (filled symbols), O-stars (open symbols)
SMC: left ; LMC: right.


Carbon stars
-4
-6
-8
-10
0
2
4
6
8
10
[3.6]-[8.0]
LMC
SMC
dSph
Oxygen-rich stars
-4
-6
-8
-10
0
1
2
3
[3.6]-[8.0]
AGB RSG
LMC
SMC
log (mass-loss rate) [Solar masses/year]



x= Vassiliadis & Wood (1993) tracks.

$M_{\rm ini}$ = 1.5, 2.5, 5.0 and 7.9 $M_\odot$.

each cross represents a time interval of 5000 years.

dot-dashed line: single scattering limit for 10 km/s.

Green +: models by Eriksson et al. (2014) scaled to our adopted Ψ and $v_{\rm exp}$

Summary and Discussion

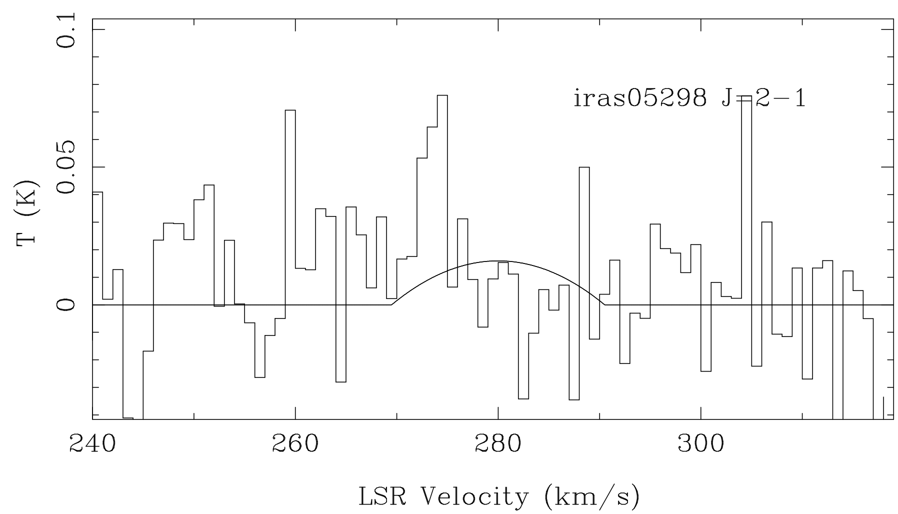
- Fitting SEDs (w. or w/o spectroscopy) is a relatively simple way to have an estimate of the (dust) mass-loss rate.
- $\dot{M}$ - colour, some C-C, and BC relations, can be used to estimate chemical type, L, and MLR
- The highest MLRs in C-stars exceed the single-scattering limit by a factor of a few. (cf. Dynamical models by Mattsson et al. 2010).
- MLR estimates in the literature can differ by factors of 5: R&M versus Zukbo+ (amC), Astronomical (Ossenkopf+ 1992) vs. Lab silicates, iron

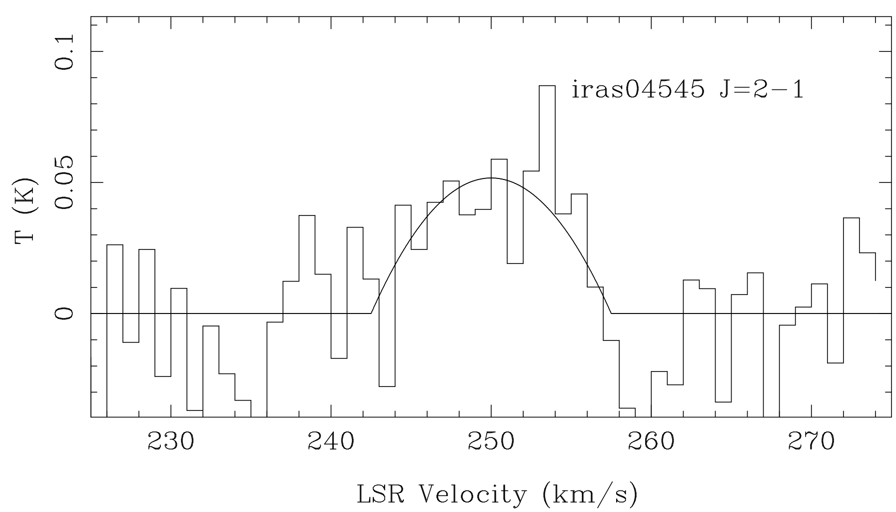
Summary and Discussion

- V_{∞}, dust-to-gas ratio, and dependence on Z, or L

  Gas mass-loss rates (and thus Ψ) from detailed modelling of CO lines

ALMA Cycle-3 in grade-A:



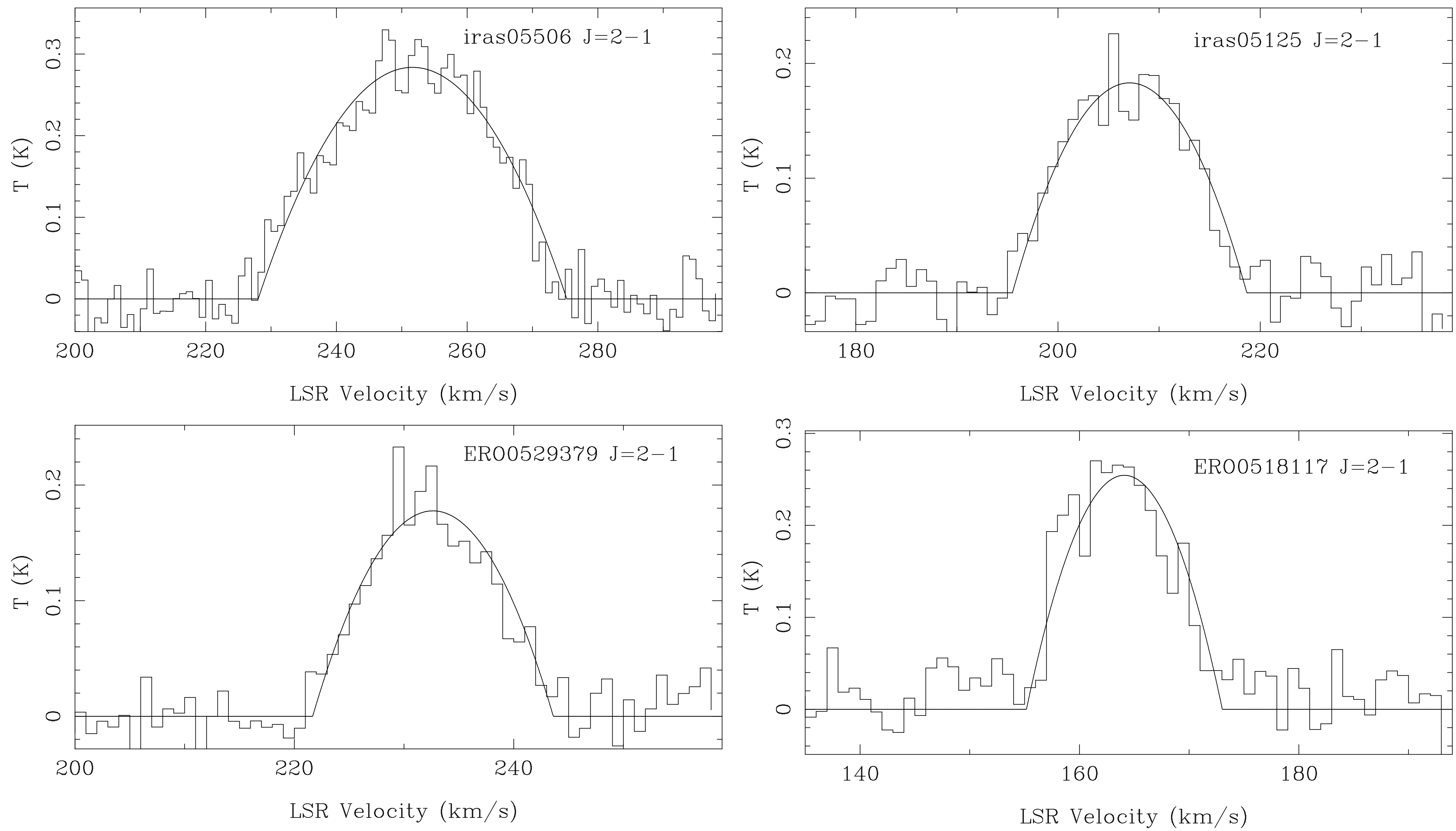


One non-detection

One marginal detection

($v_{\star}$ & $v_{\rm exp}$ from Goldman et al. 2016)

Carbon stars



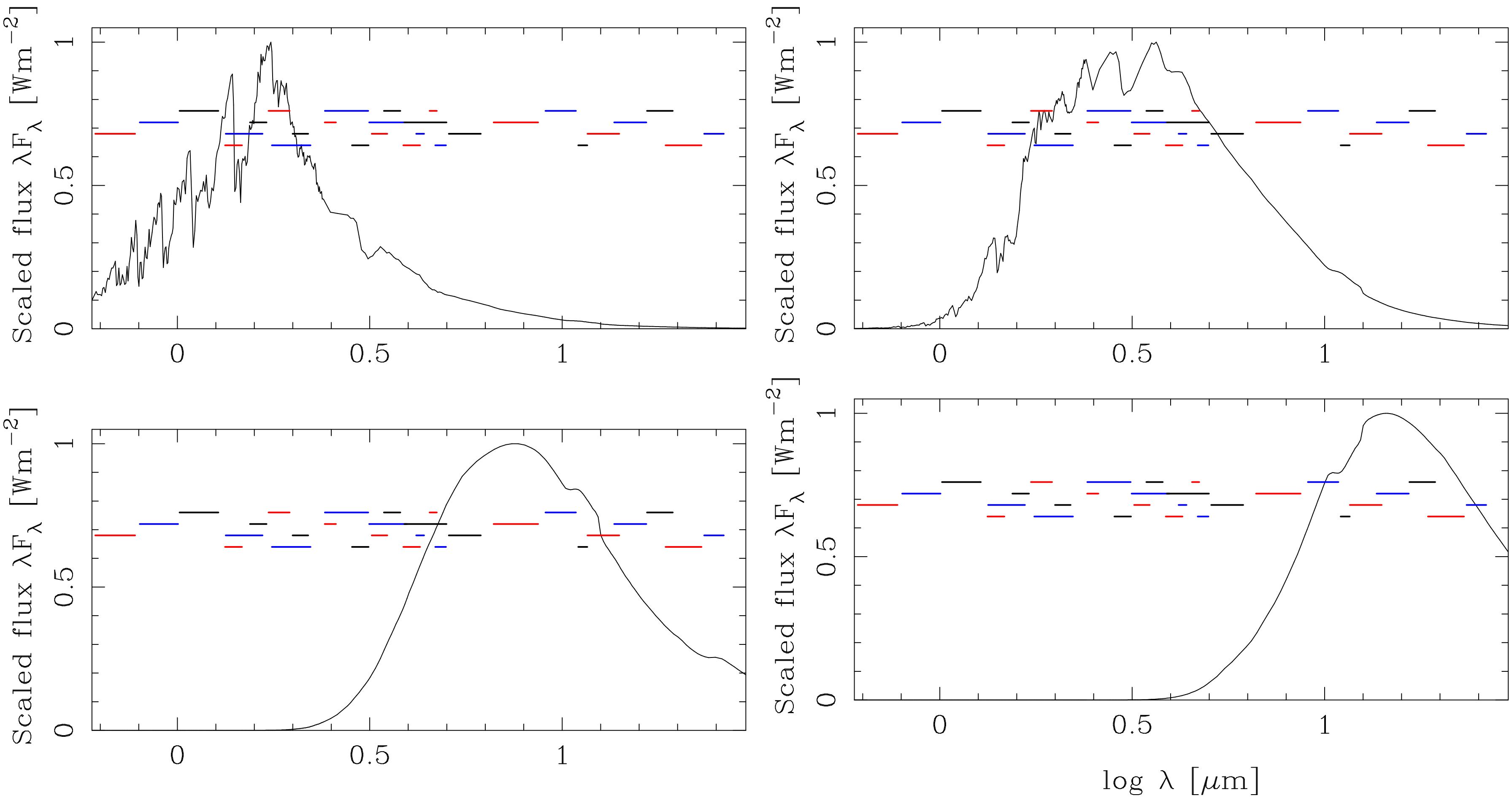
First spectrally resolved molecular lines in the MCs !
(Groenewegen, Vlemmings, Marigo, Sloan et al. 2016)

Summary and Prospects

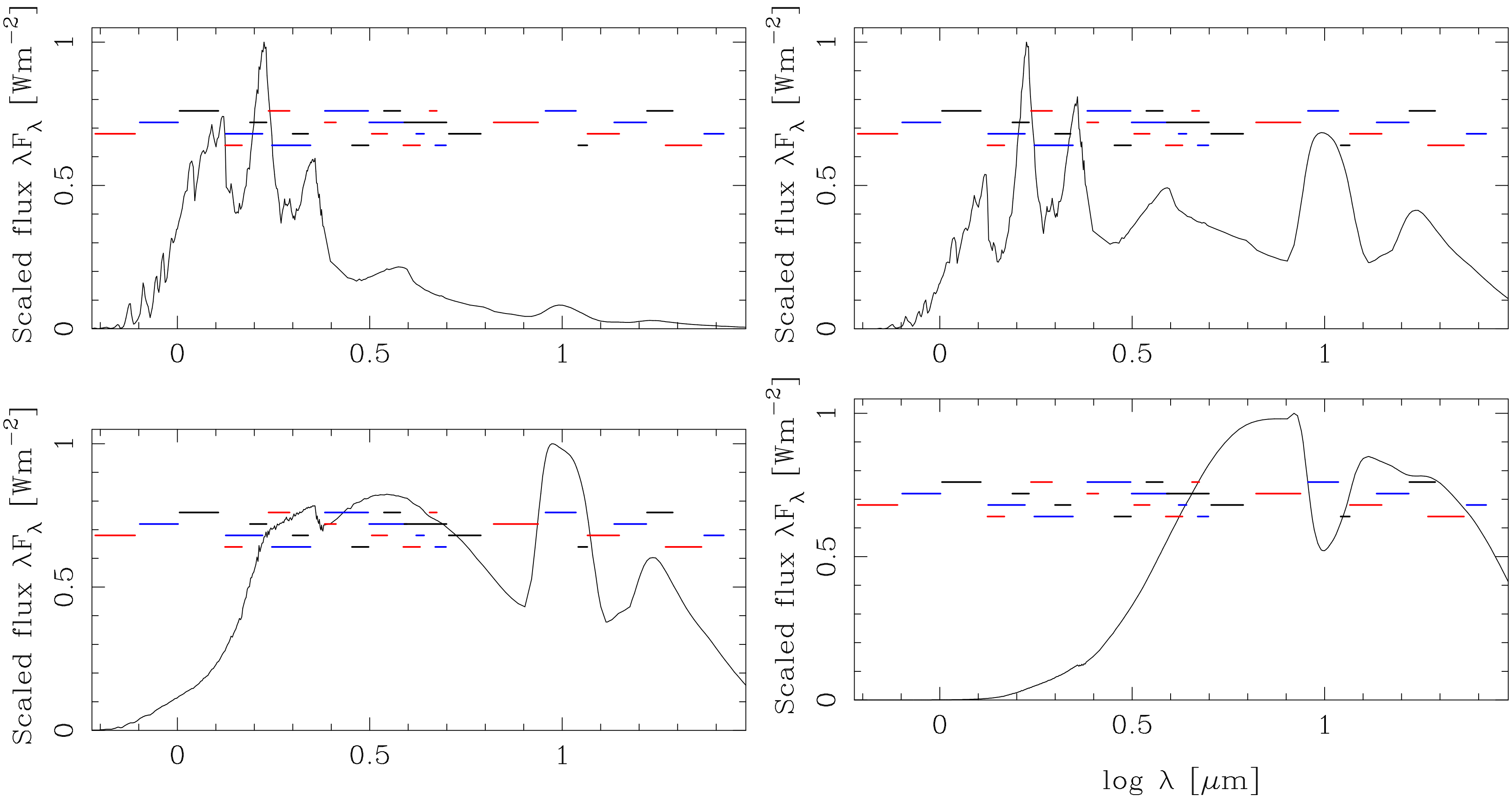
- Number of stars for which ALMA data could be obtained is limited... ☹
- One S-AGB candidate. "Super"-AGB.
  P= 1810 d, ΔI= 0.8 mag, L= 85000 $L_\odot$ ($M_{\rm bol} = -7.6$),
  $\dot{M}$= $4.5 \cdot 10^{-6}$ $M_\odot$ yr^{-1}
- Prospect: JWST

  MIRI & NIRCAM

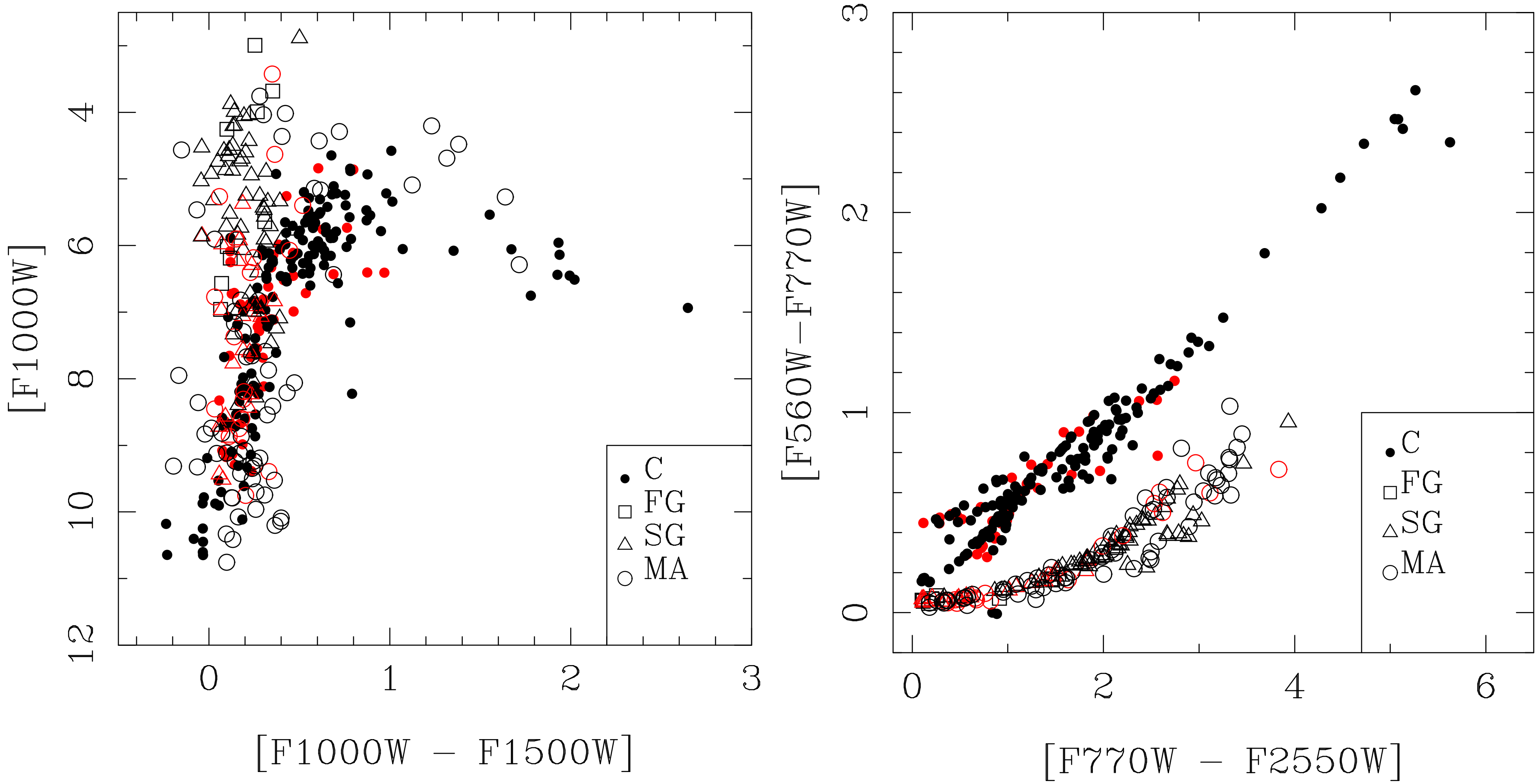
  (Kraemer, Sloan, Wood, Jones, Egan (2017), Jones, Meixner, Justtanont, Glasse focussed on MIRI)



29 NIRCAM & MIRI filters for C-stars with increasing MLR



29 NIRCAM & MIRI filters for O-stars with increasing MLR



Example of a CMD, and CCD (SMC stars in red)

THE END