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

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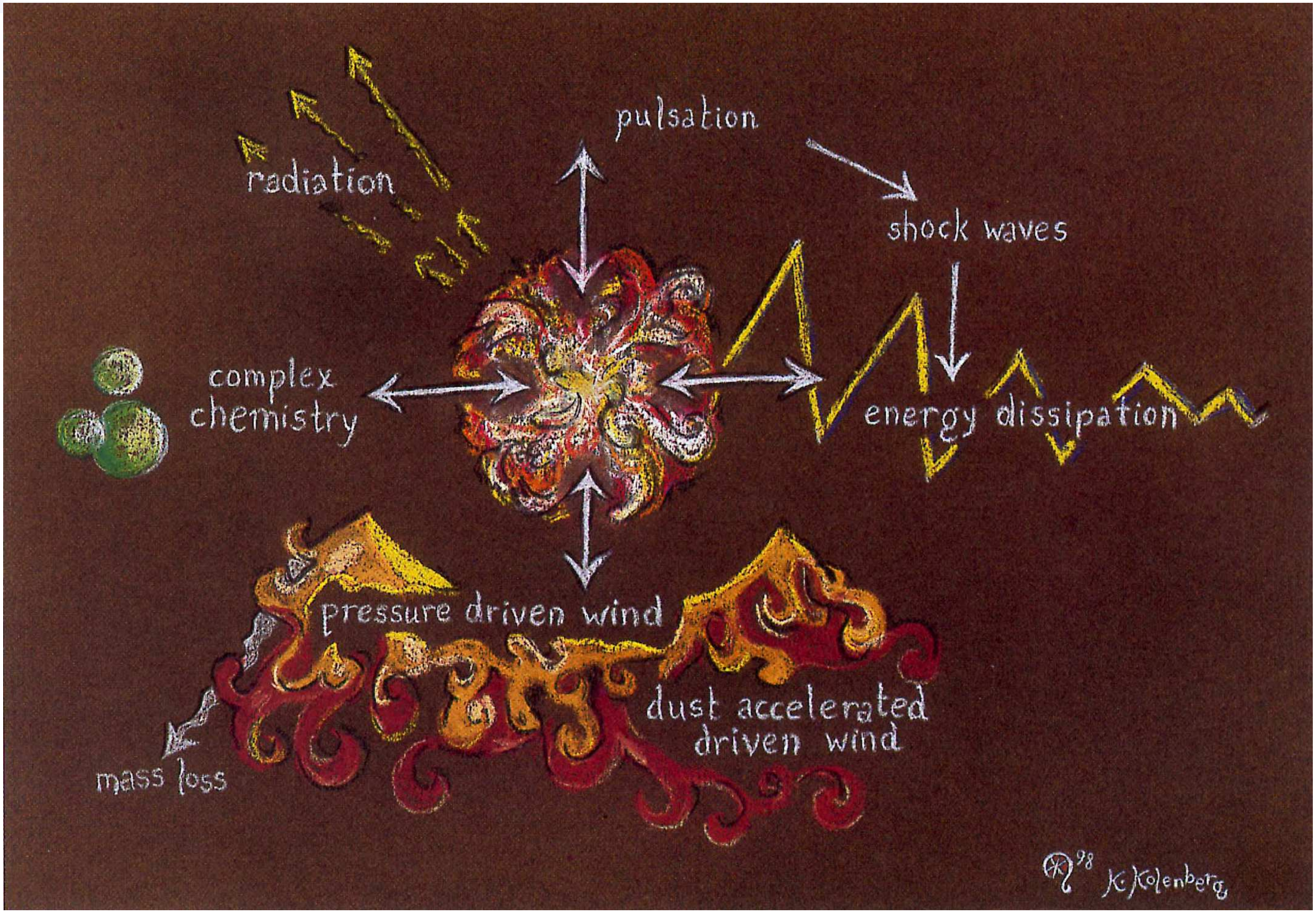
A complicated problem



(Katrien Kolenberg)

Overview Talk

- Introduction
  - Effect of Dust size, type, shape
- AGB & RSG with *Spitzer* IRS spectra in MCs

  Groenewegen & Sloan (2015)

RT models

- Balance between detail, and practicality
- 1D DUSTY (Ivezić et al. 1999)
  More of DUSTY (MoD) (Groenewegen 2012)
- 2-Dust (Ueta & Meixner 2003)
- 2D MCMax (Min et al. 2009)
- 3D Hyperion (Robitaille 2011)

Some Basics

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

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

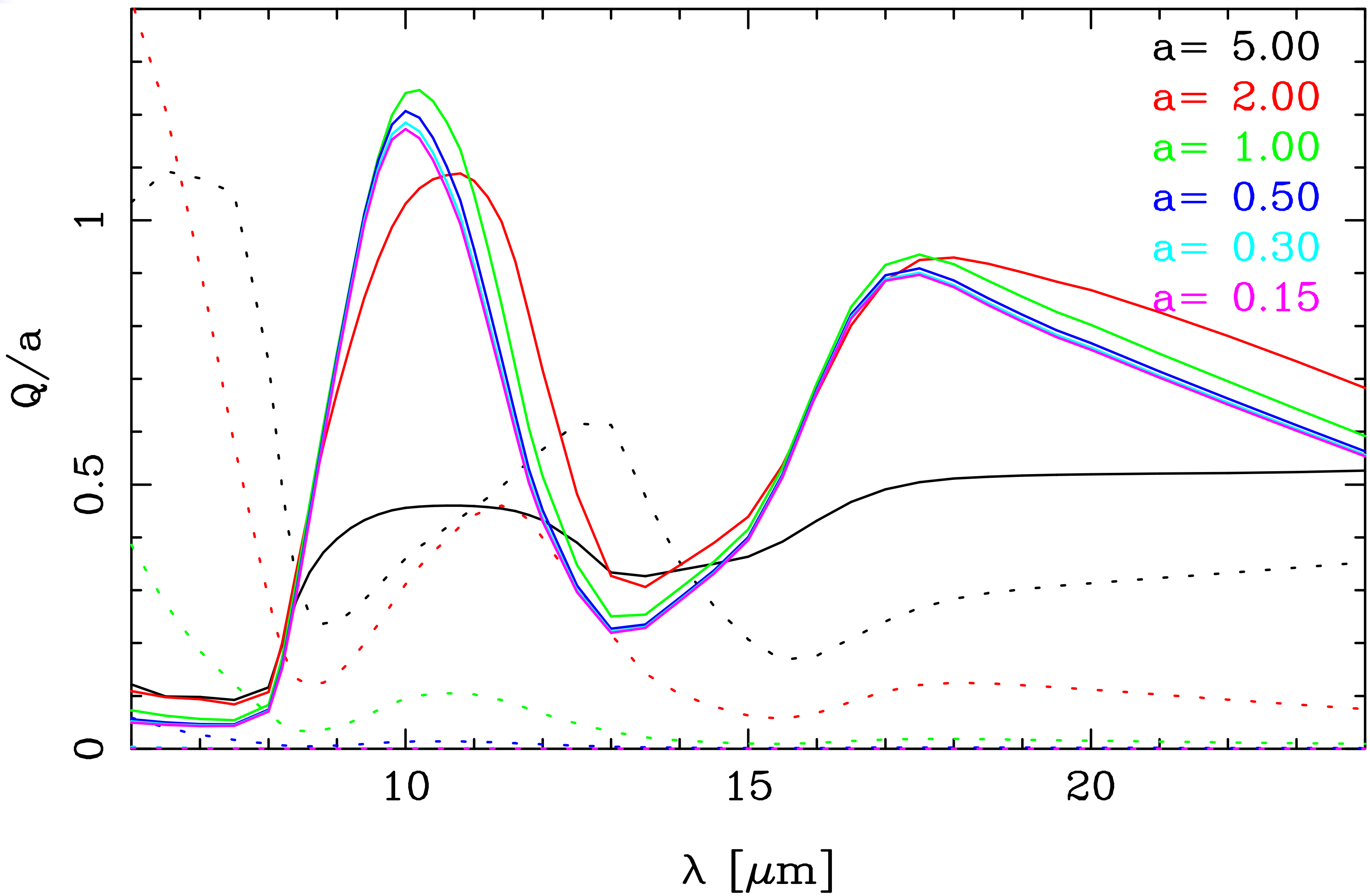
$$m = \frac{4}{3} \, \pi a^3 \rho_{\rm dust}$$

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

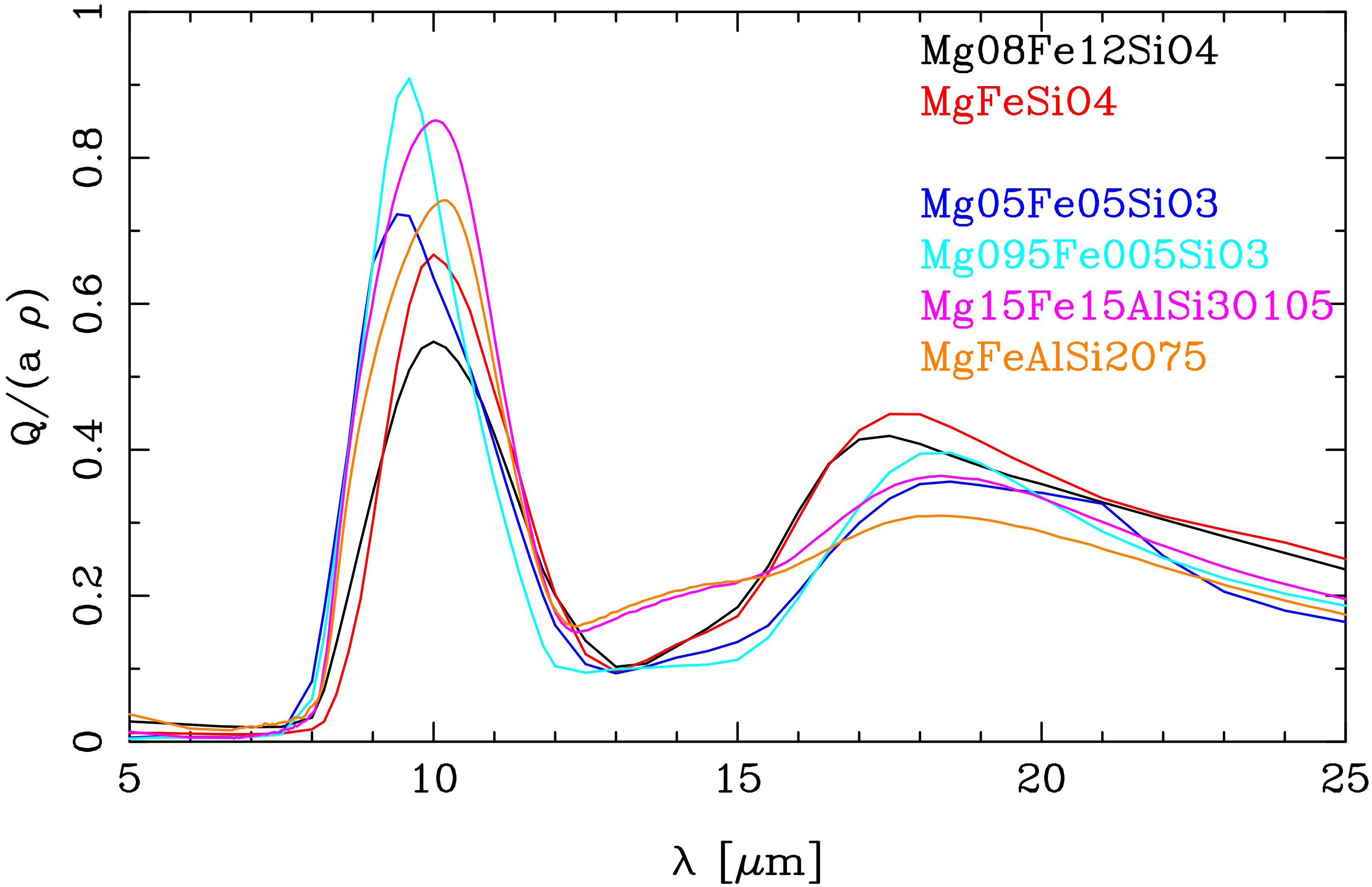
$$\tau_\lambda \sim \kappa_\lambda \, \dot{M} \, \Psi / (R_\star \, R_{\rm c} \, v_{\rm exp})$$

Opacities - κ

- Laboratory: optical constants $(n, k) \Rightarrow Q_{\mathrm{abs}}, Q_{\mathrm{sca}}$
- grain size (distribution)
  $a \ll \lambda$ (small particle limit)
- spheres, ellipsoidal, irregular
  (T-matrix codes, Discrete Dipole Approximation)
- separate species, core-mantle grains,
  effective medium theory

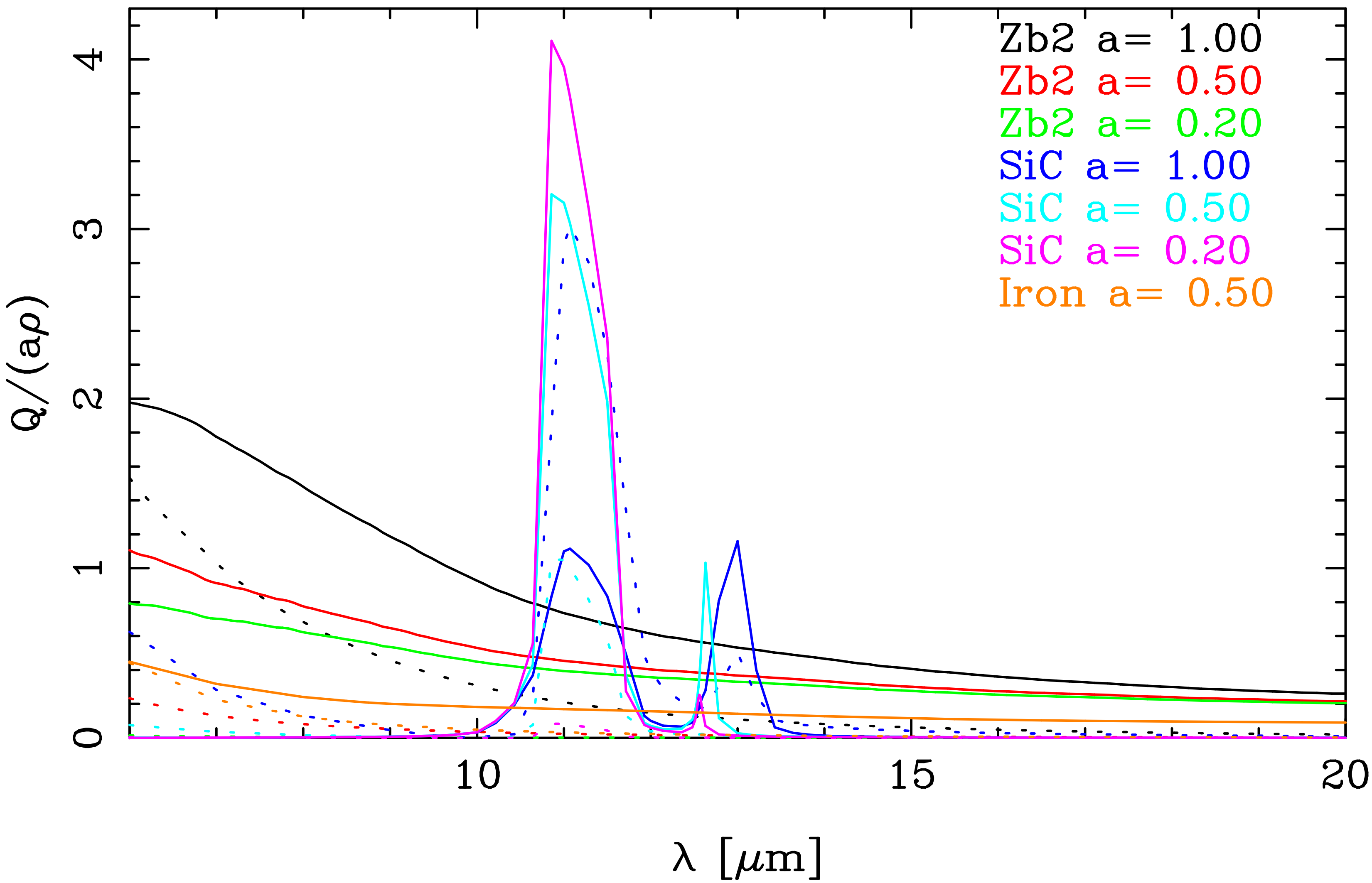


DHS $Mg_{0.8}Fe_{1.2}SiO_4$: effect of grain size.

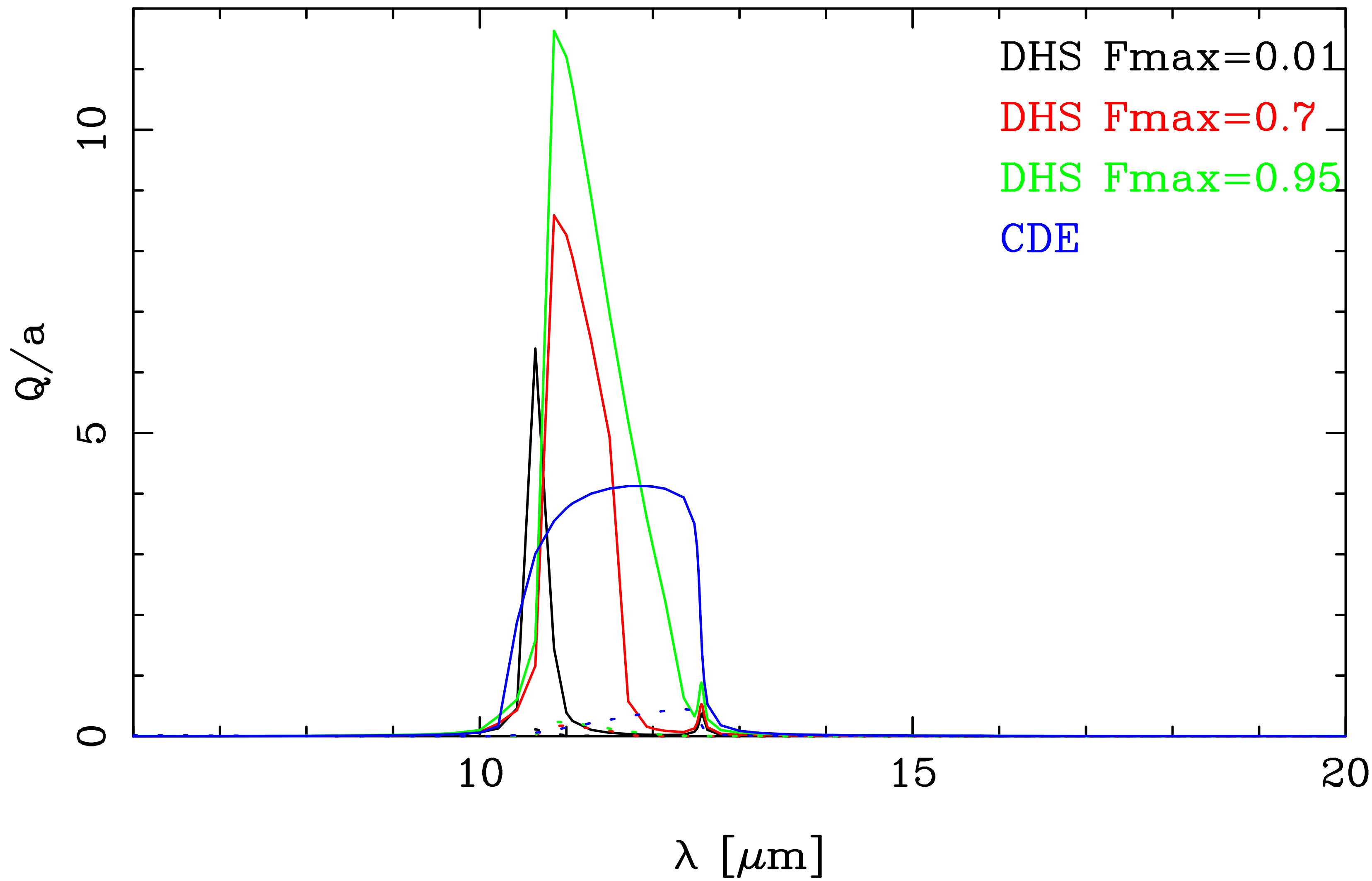


(DHS a= 0.15 μm)

Different olivines, role Aluminum



DHS AmC-Zubko2; SiC - Pitman et al.



SiC a= 0.20: Different shapes

Shapes

- DHS: Distribution of Hollow Spheres
  $f_{\rm max}$ (maximum fraction of vacuum)
- CDE: Continuous Distribution of Ellipsoids
  (small particle limit !)

$$Q_{\rm abs} \sim {\rm Im} \left(\frac{2\, m^2}{m^2 - 1} \ln(m^2) \right)$$

$m = n + i\, k$

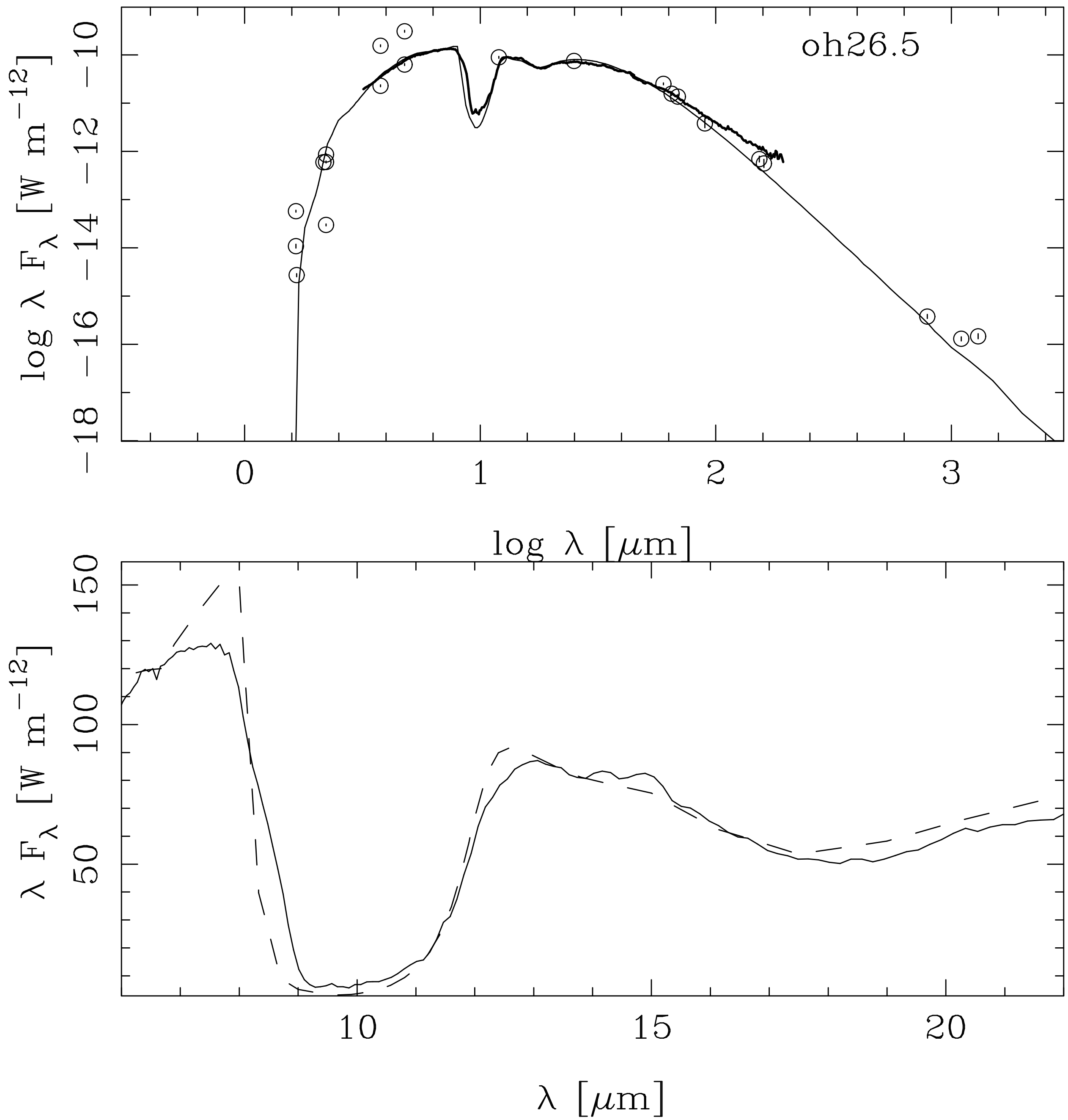
- EMT: Effective Medium Theory

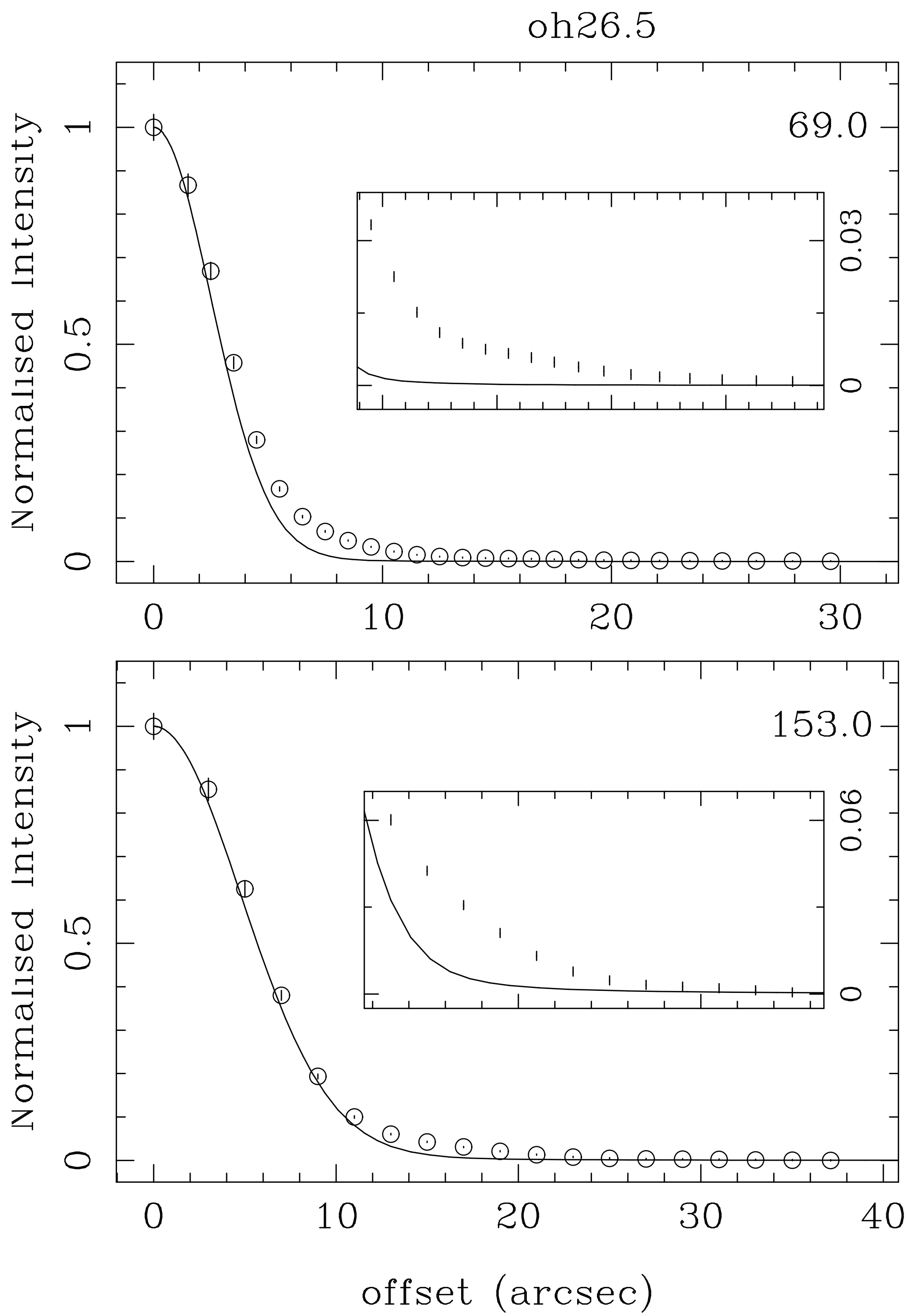
$$\sum_i {\rm vol}_i \; (m_i^2 - m^2)/(m_i^2 + 2\, m^2) = 0$$

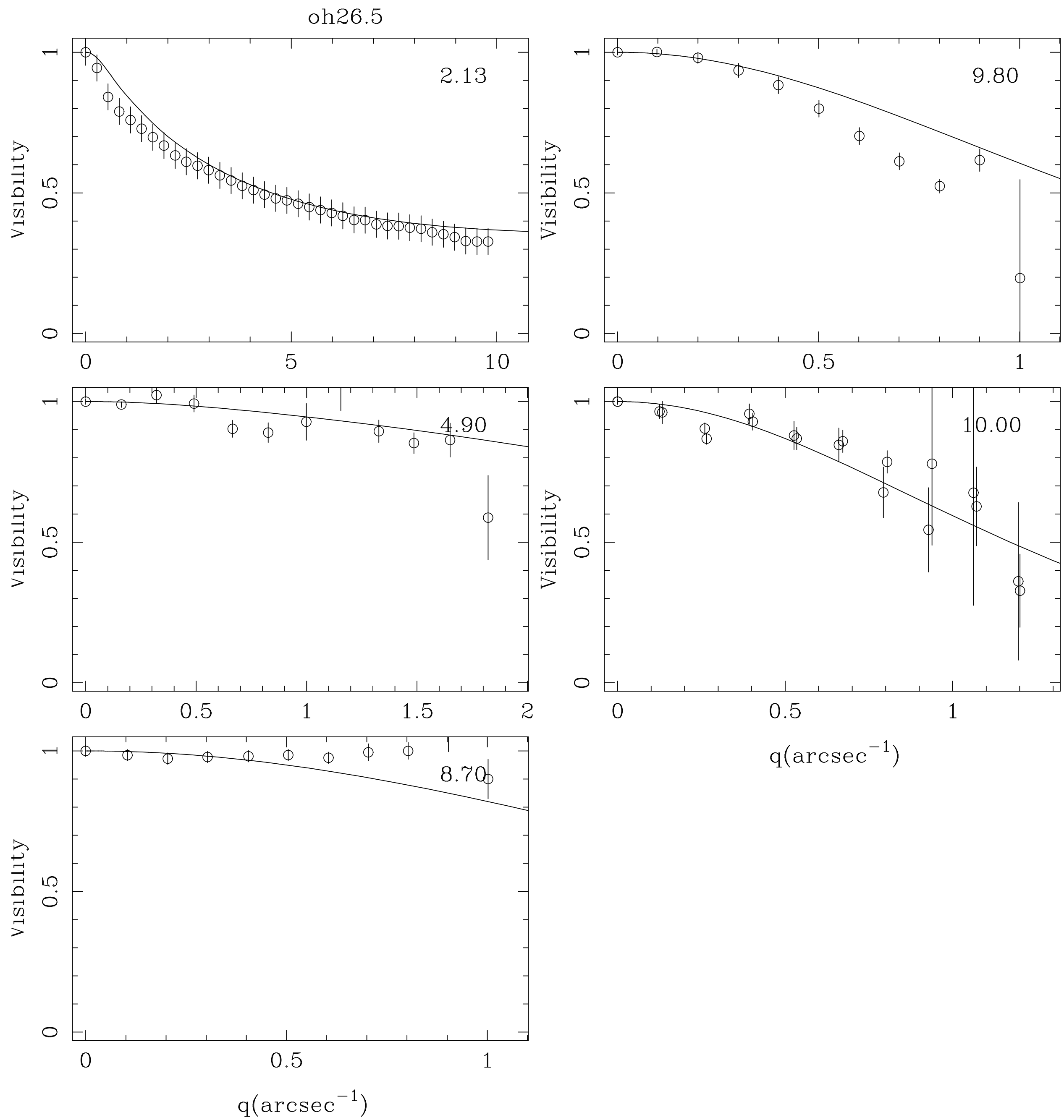
More of DUSTY - MoD

- 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, $A_{\rm V}$
  - $R_{\rm out}$

Example


oh26.5
log λ F_λ [W m^−12]
−18
−16
−14
−12
−10
0
1
2
3
log λ [μm]
λ F_λ [W m^−12]
50
100
150
10
15
20
λ [μm]


oh26.5
69.0
153.0
0.03
0.06
Normalised Intensity
offset (arcsec)


oh26.5
2.13
9.80
4.90
10.00
8.70
Visibility
q(arcsec^{-1})
0
0.5
1
5
10
1.5
2

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.

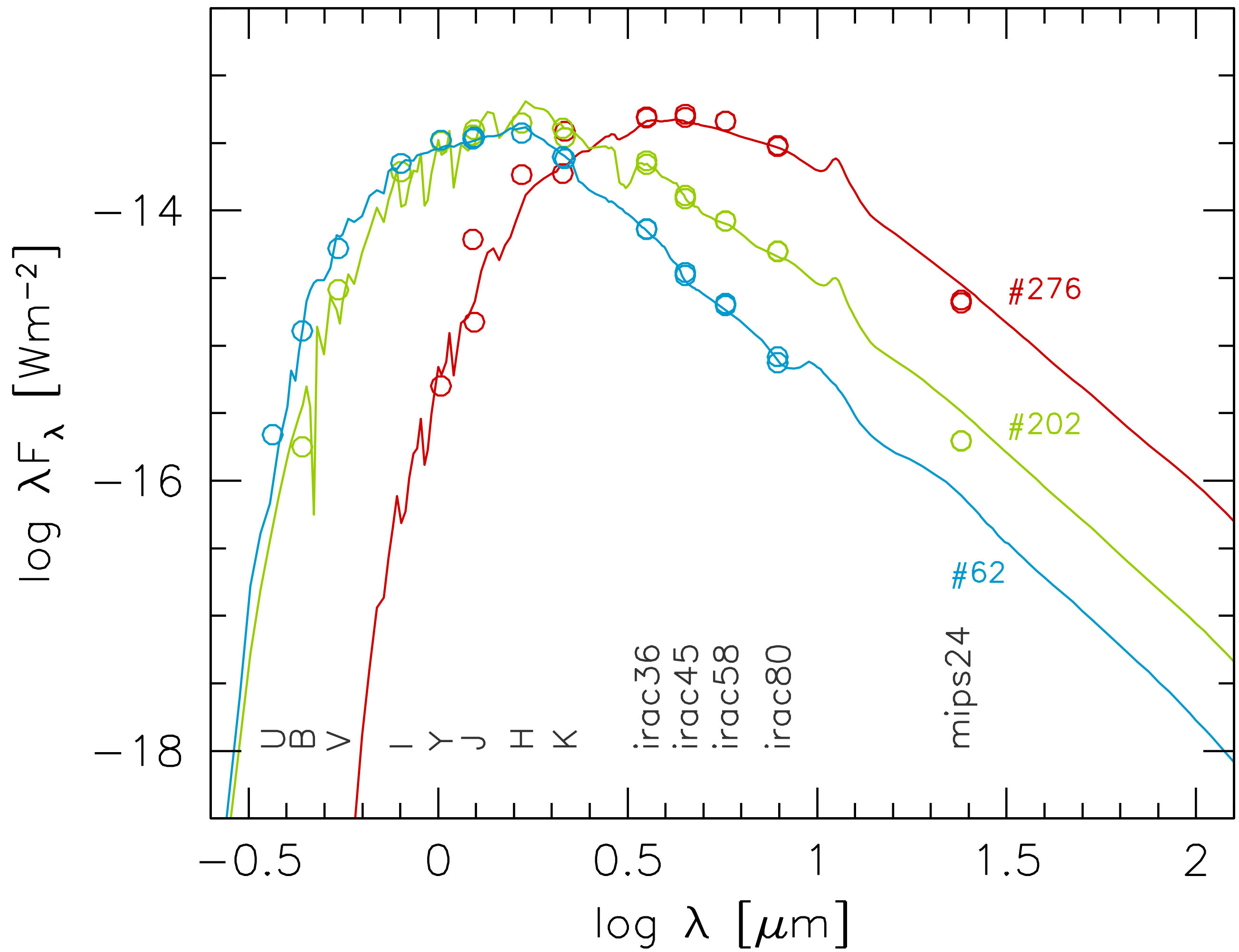
  SAGE (GRAMS)
  Sargent et al. (2011), Srinivasan et al. (2011), Riebel et al. (2012), Boyer et al. (2012)

- Alternative: model individual SEDs (Gullieuszik et al. 2012)
  VISTA Magellanic Cloud Survey (PI. M.-R. Cioni)
  YJK

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 (example)
- 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 (next slides) (fitting only the photometry!) C-stars: 95%; O-stars: 75% correct

Gullieuszik et al.



blue: O-rich with $J - K \sim 1.2$,
green: C-rich $J - K \sim 1.5$, red: C-rich $J - K \sim 4$

AGB/RSG with IRS spectra

Groenewegen & Sloan (2015, work in progress)

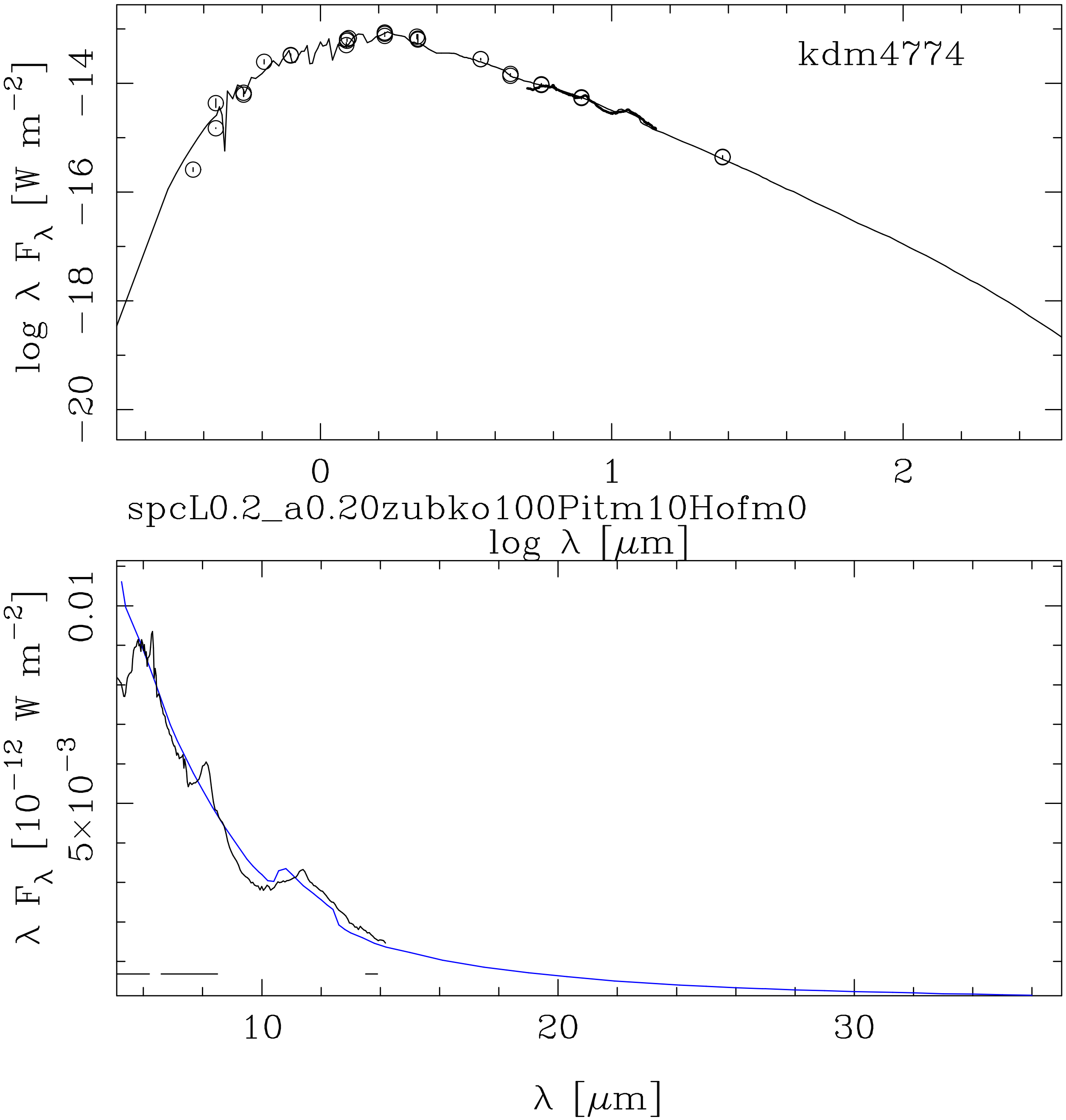
Update of:
Groenewegen M.A.T., Sloan G.C., Soszynski I., Petersen E.A. 2009, A&A 506, 1277

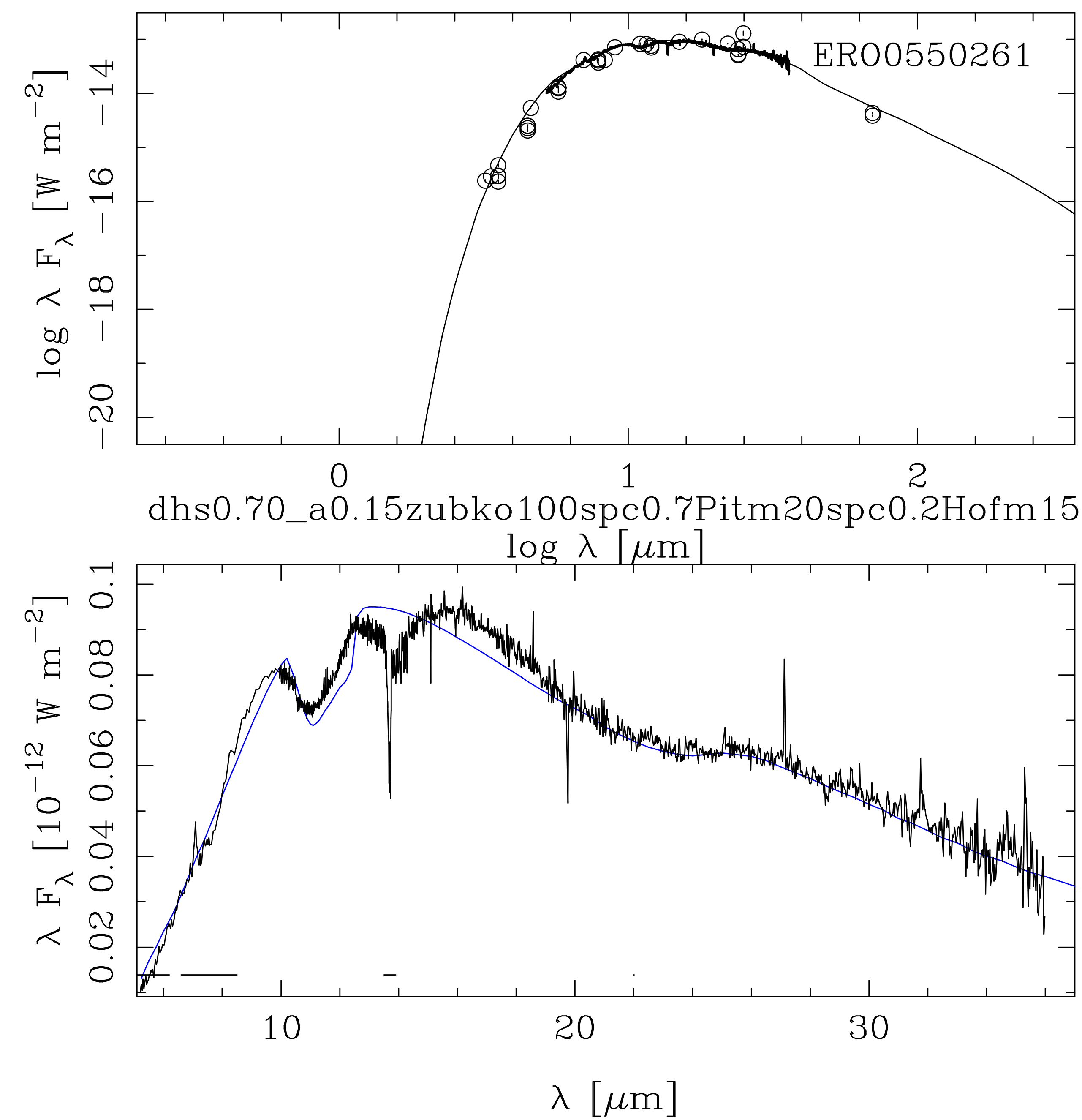
SED fitting of 101 C- and 86 O-rich stars in MCs with IRS spectra

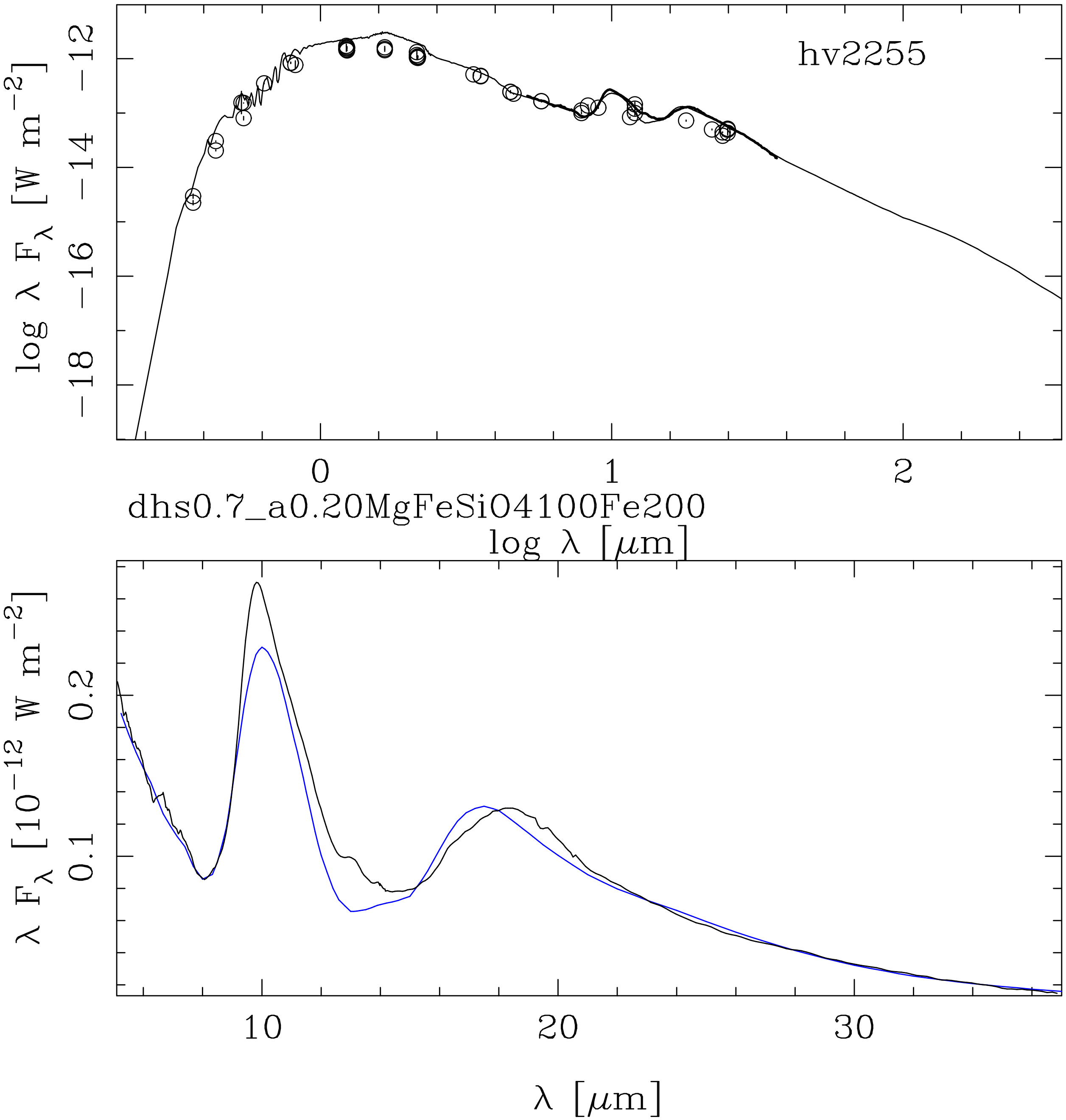
Presently:
191 (43 SMC) C- and
166 (38 SMC) O-rich stars
(11 FG, 78 RSG, 77 O-AGB)

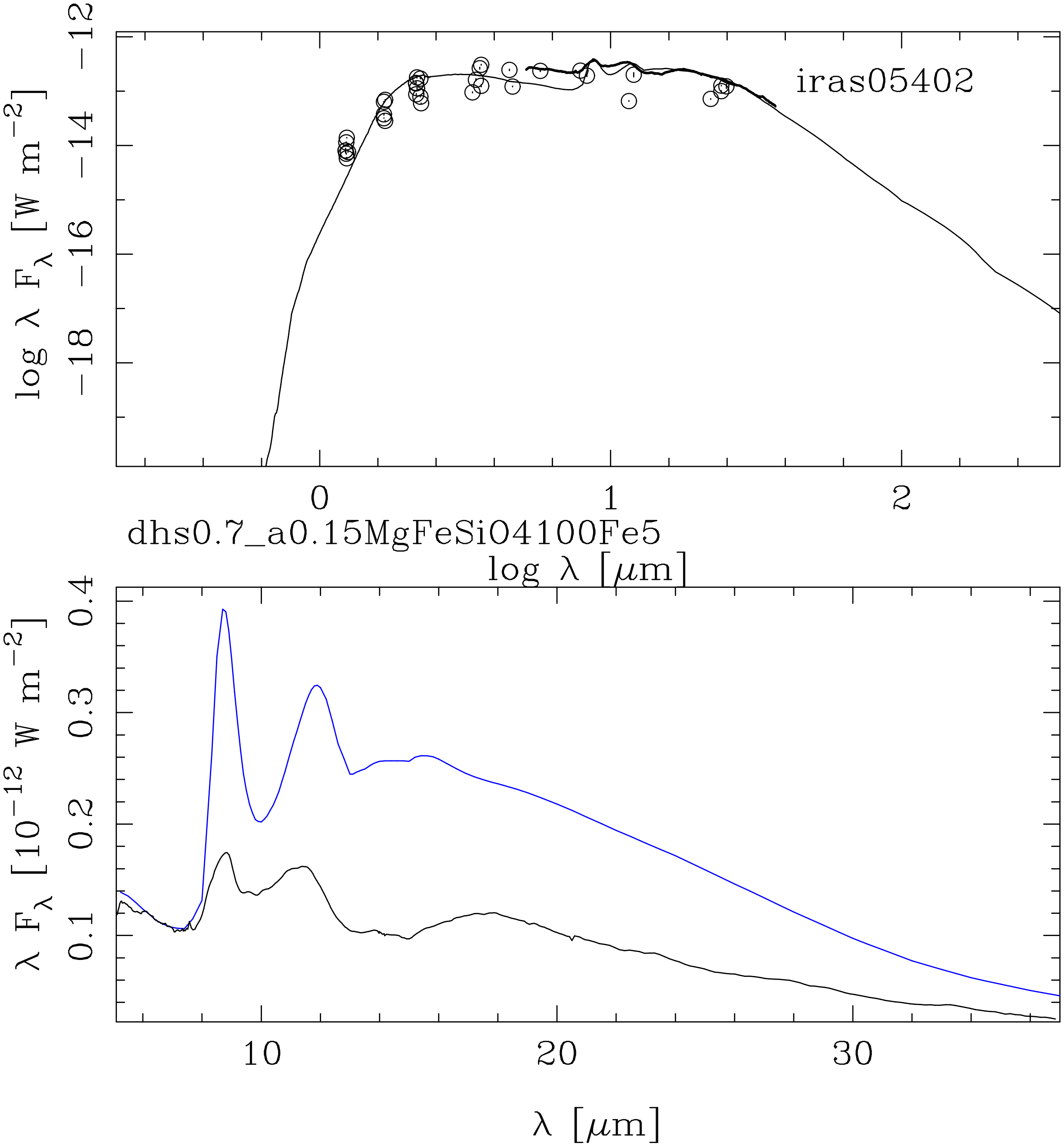
Improvements:

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

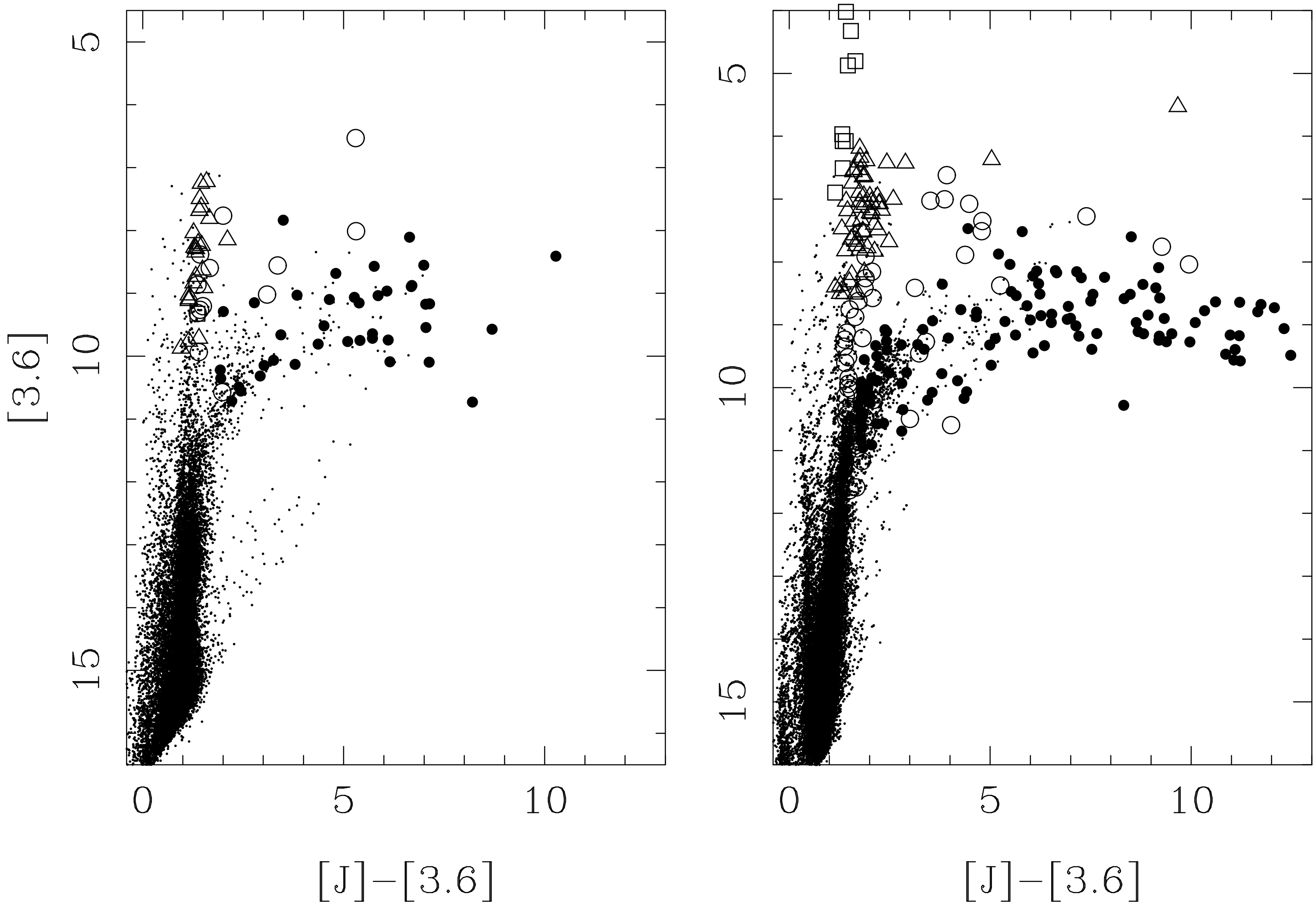

kdm4774
log λ F_λ [W m^-2]
−20
−18
−16
−14
0
1
2
spcL0.2_a0.20zubko100Pitm10Hofm0
log λ [μm]
λ F_λ [10^-12 W m^-2]
5×10^-3
0.01
10
20
30
λ [μm]


ERO0550261
log λ F_λ [W m^-2]
−20
−18
−16
−14
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_λ [W m^−2]
−12
−14
−16
−18
0
1
2
dhs0.7_a0.20MgFeSiO4100Fe200
log λ [μm]
λ F_λ [10^−12 W m^−2]
0.2
0.1
10
20
30
λ [μm]

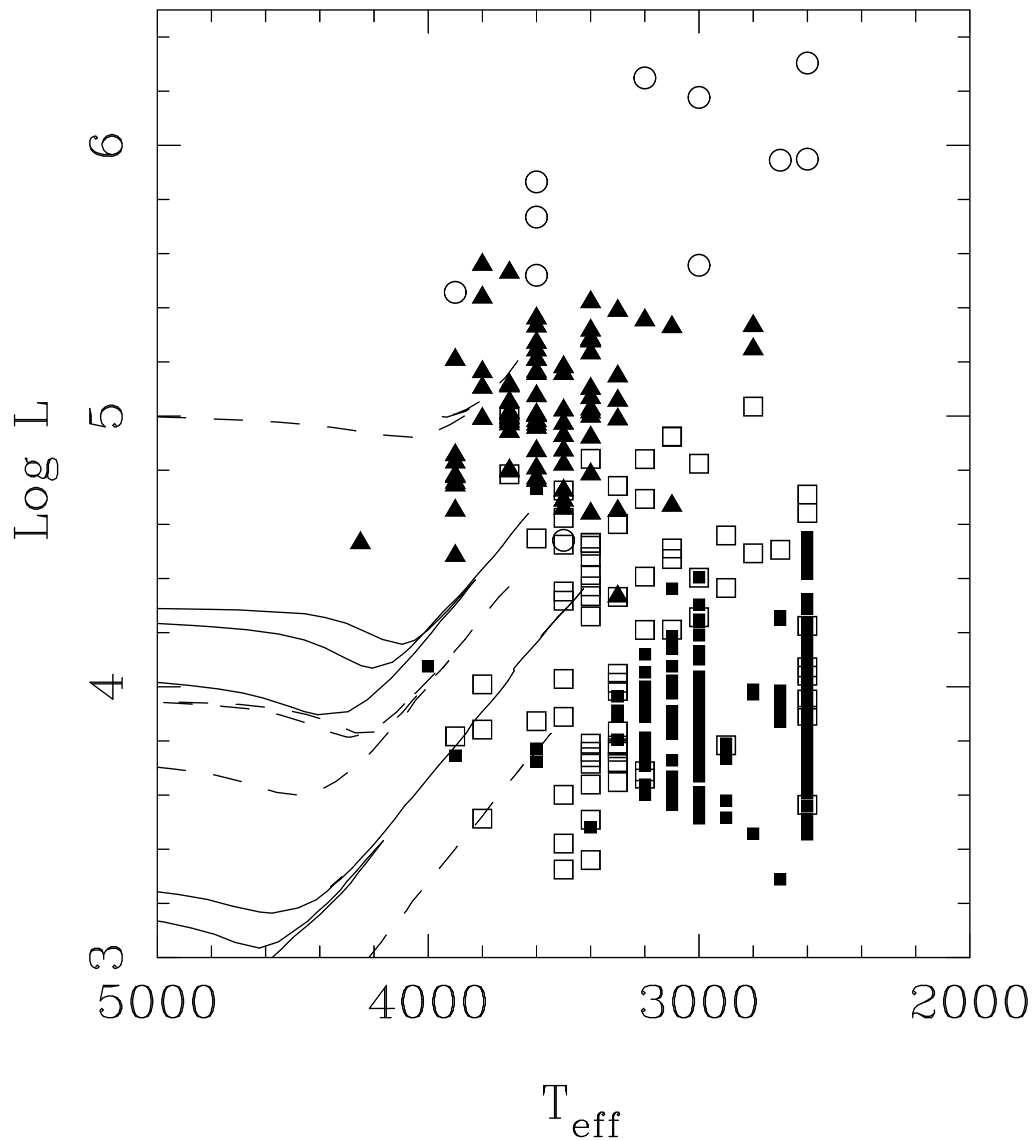

iras05402
log λ F_λ [W m^-2]
−12
−14
−16
−18
0
1
2
log λ [μm]
dhs0.7_a0.15MgFeSiO4100Fe5
λ F_λ [10^-12 W m^-2]
0.1
0.2
0.3
0.4
10
20
30
λ [μm]

CMD

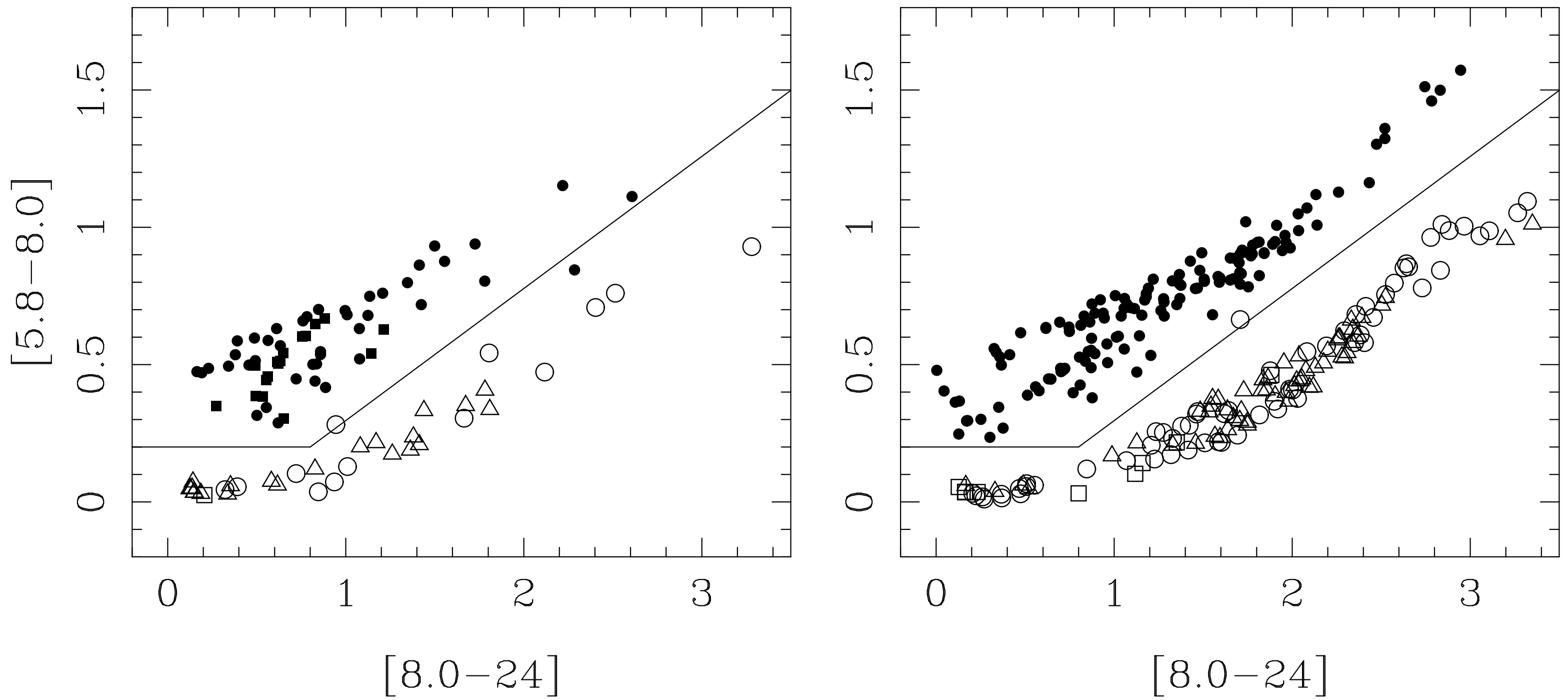


SMC: left ; LMC: right. Offset 0.5 mag

HRD



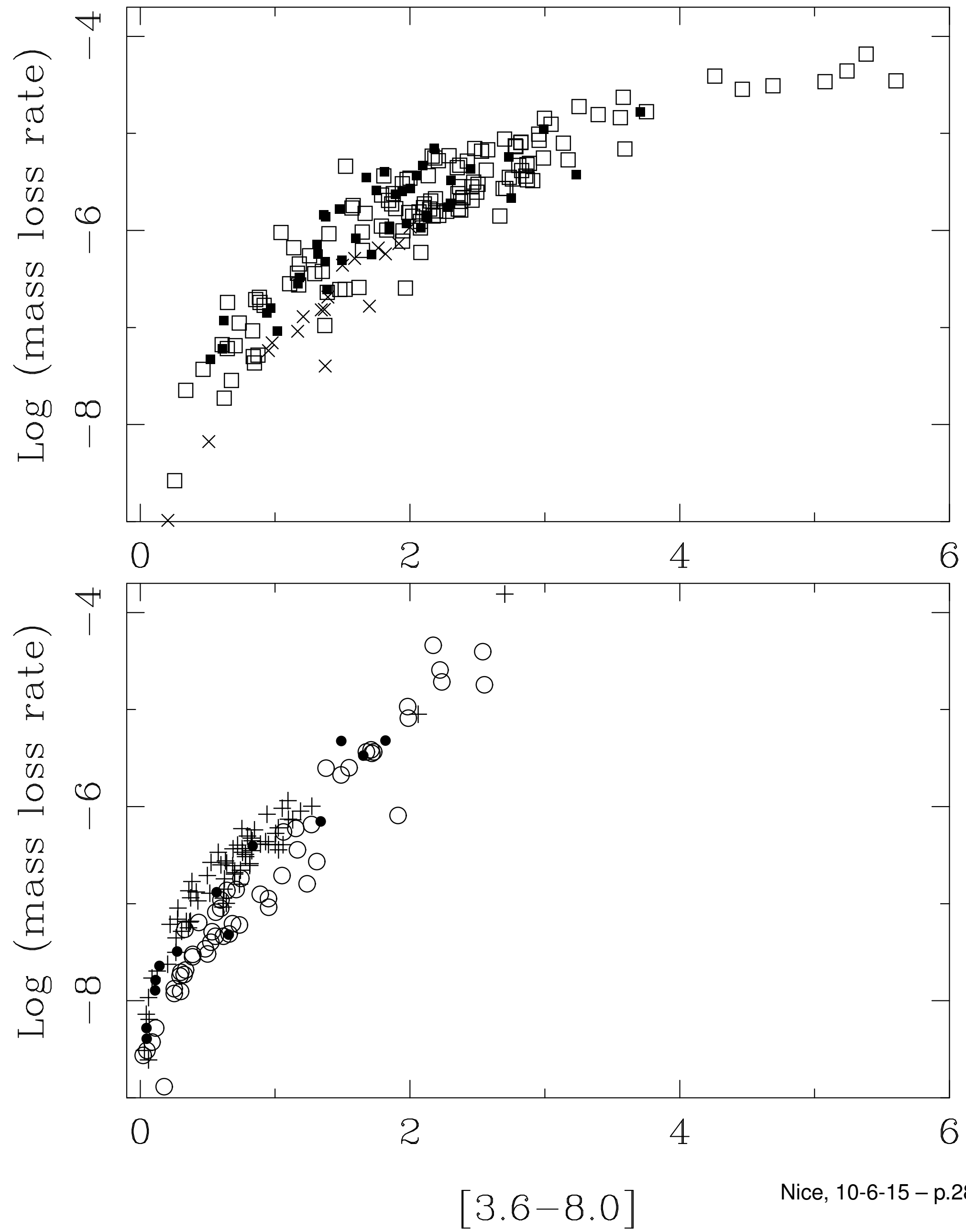
(Groenewegen et al. 2009)

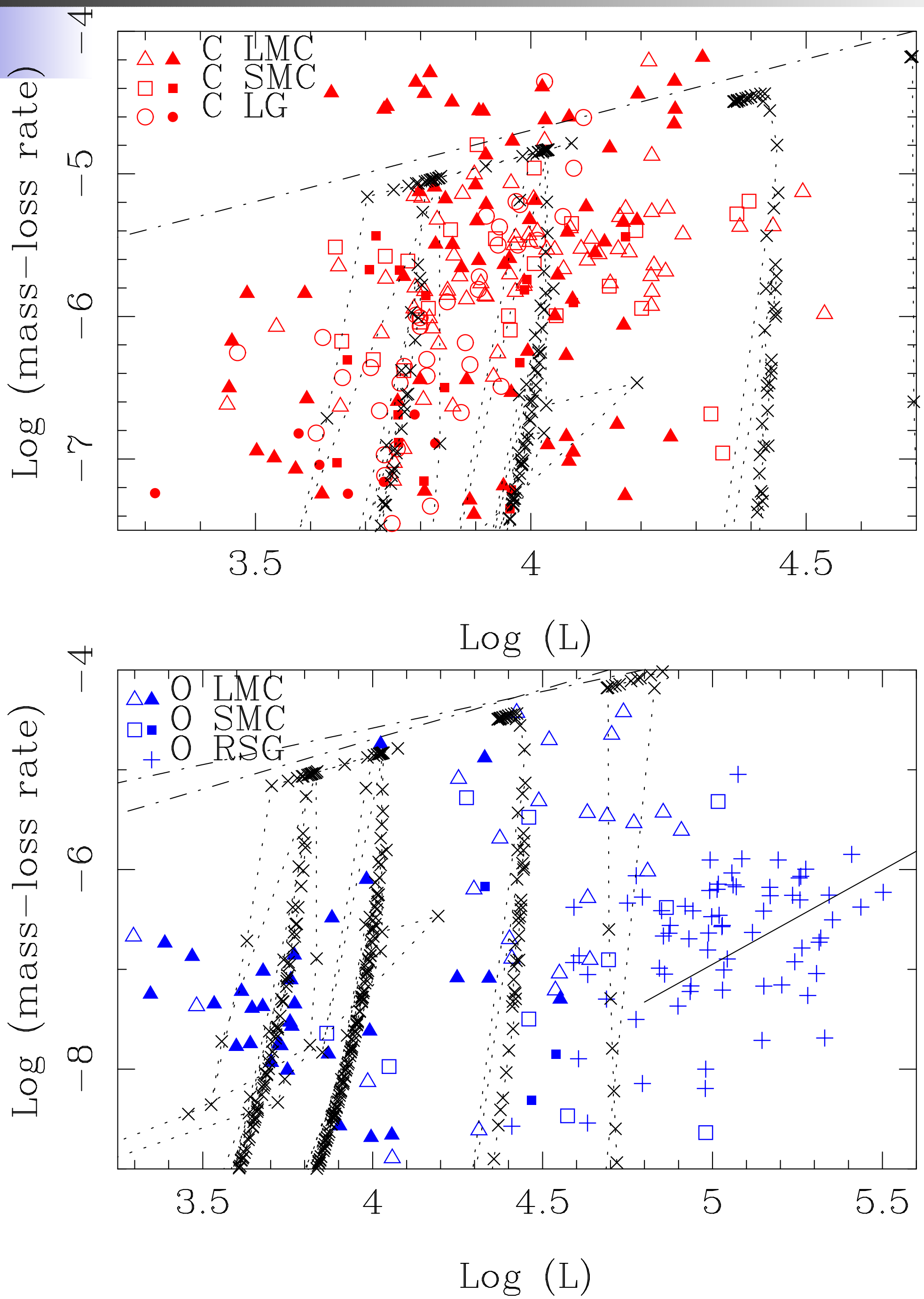


Good separation between C- and O-rich using IRAC/MIPS !
C-stars (filled symbols), O-stars (open symbols)
SMC: left ; LMC: right.

C-stars (upper panel),
O-stars (lower panel)

(Groenewegen et al. 2009)





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.

(Groenewegen & Sloan 2015)

Summary and Prospects

- Fitting SEDs (w. or w/o spectroscopy) is a relatively simple way to have an estimate of the (dust) mass-loss rate.
  With current data its possible to do this out to IC 10 (715 kpc, LeBouteiller et al.)
- $\dot{M}$ - colour, some C-C, and BC relations, can be used to estimate chemical type, L, and MLR
- Lots of data is available (e.g. VMC, AllWISE, Akari)
- 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).

Summary and Prospects

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

  V_∞ from ALMA

  Test dust driven wind theory

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

  ALMA continuum for free

THE END