Mass loss of AGB stars and RSG in the Magellanic Clouds

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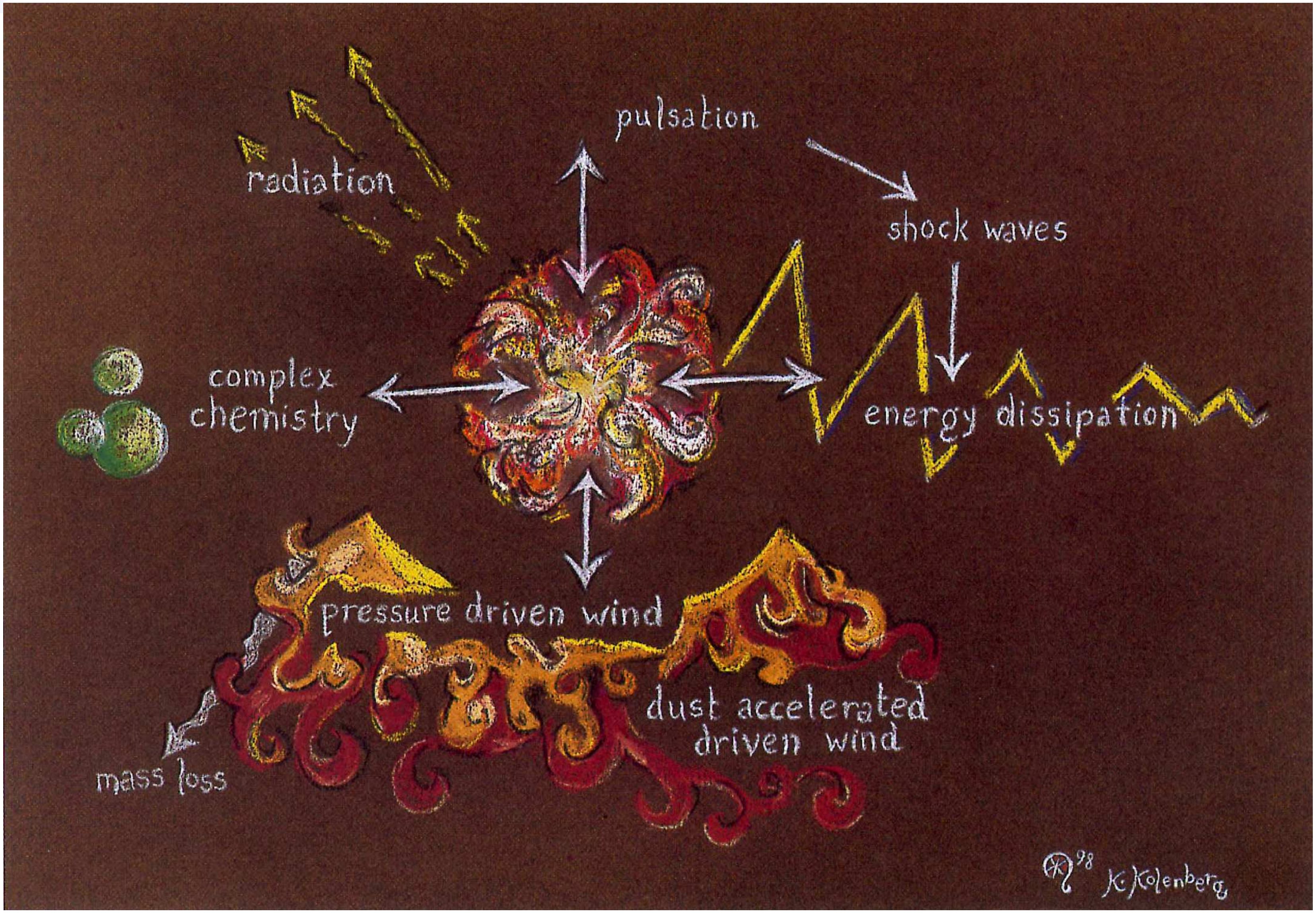
Overview Talk

- Introduction
- Luminosities and mass-loss rates of AGB & RSG with *Spitzer* IRS spectra in MCs
- ALMA: Expansion velocities of AGB stars in the MCs
- Future/ongoing work:

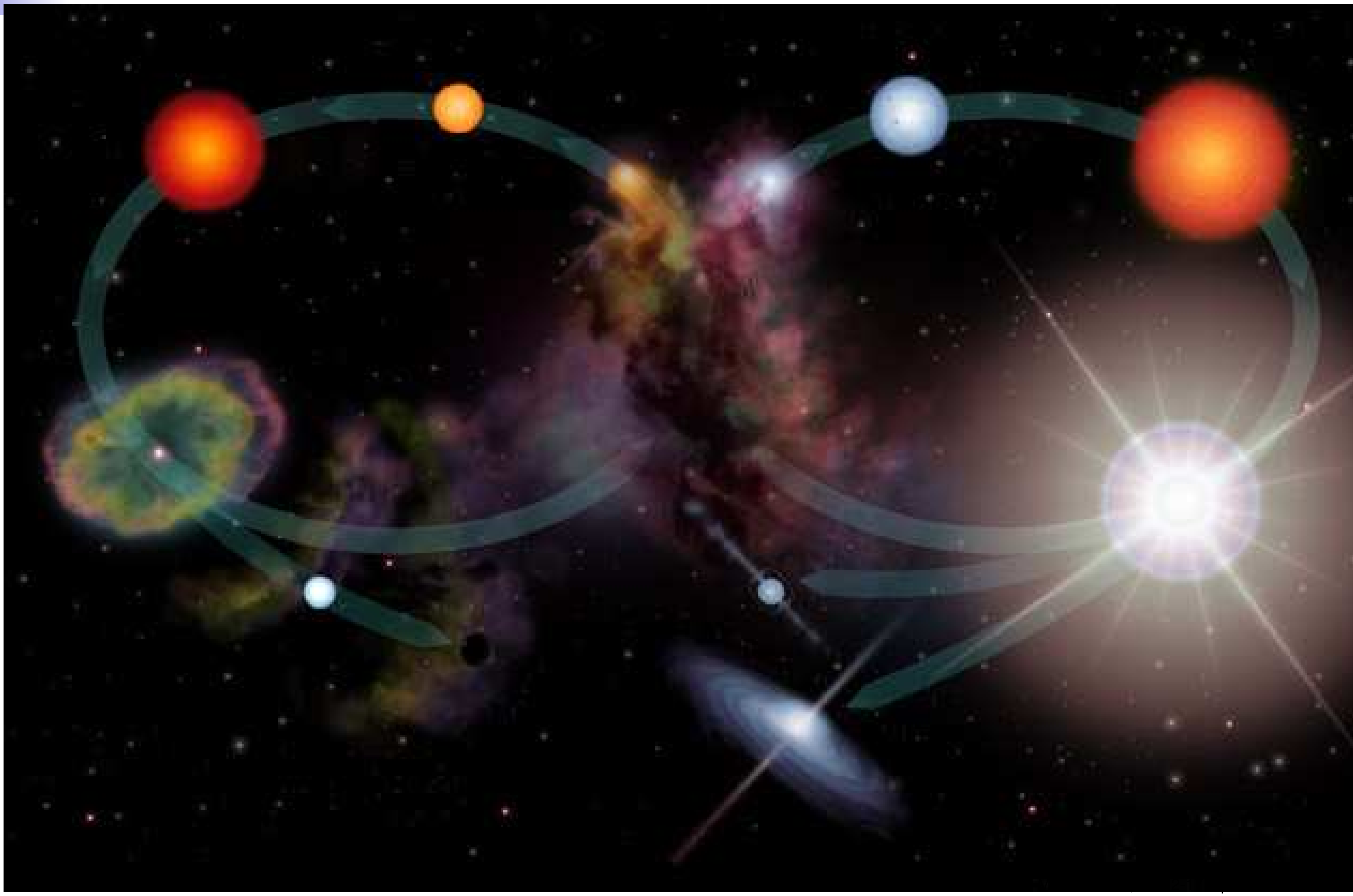
  -Fluffy grains
  -Dust budget MCs

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

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

Ψ = 1/200

Magellanic Clouds

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

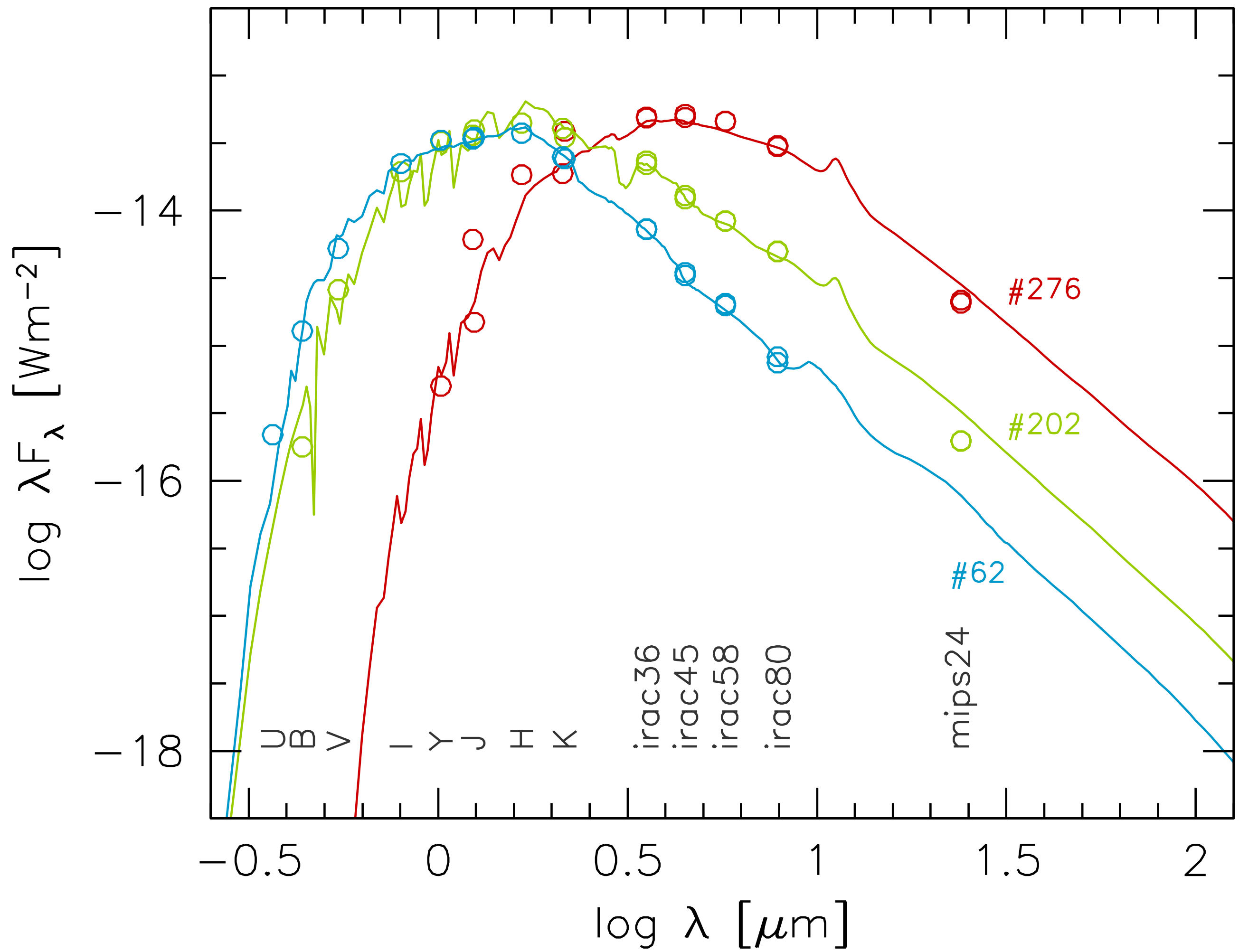
- Fit pre-computed model grid.
  Groenewegen (2006), used in Padua isochrones.

  'Grid of Red supergiant and Asymptotic giant branch star ModelS' (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

Gullieuszik et al.

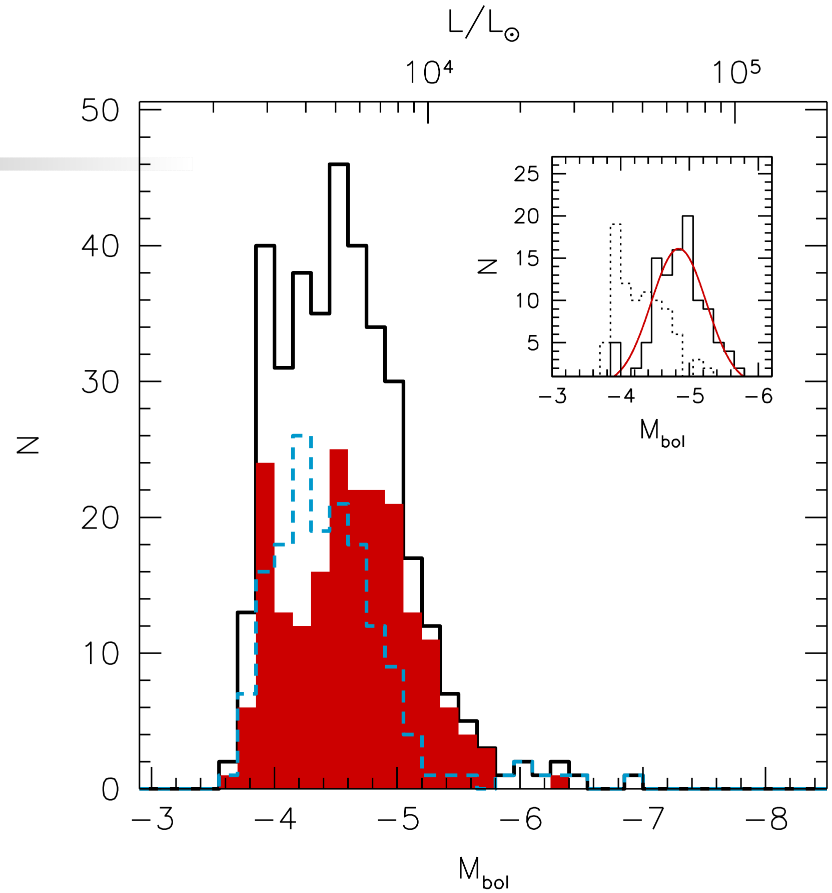


blue: O-rich with $J - K \sim 1.2$,

green: C-rich $J - K \sim 1.5$, red: C-rich $J - K \sim 4$

LF: total (solid), red filled (C-stars), dashed (O-rich). Inset: dust-free (dotted), and dusty (solid) C-stars

(Gullieuszik et al. 2012)



- C- and O-star LF.
- Distribution in mass-loss rate.
- Period Distribution.

$\Downarrow$

- compare to TRILEGAL
  (we *know* the SFH for each VMC field!)
  Could now be done for all fields (future work...)

AGB/RSG with IRS spectra

Groenewegen & Sloan (2018; arXiv 1711.07803)

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

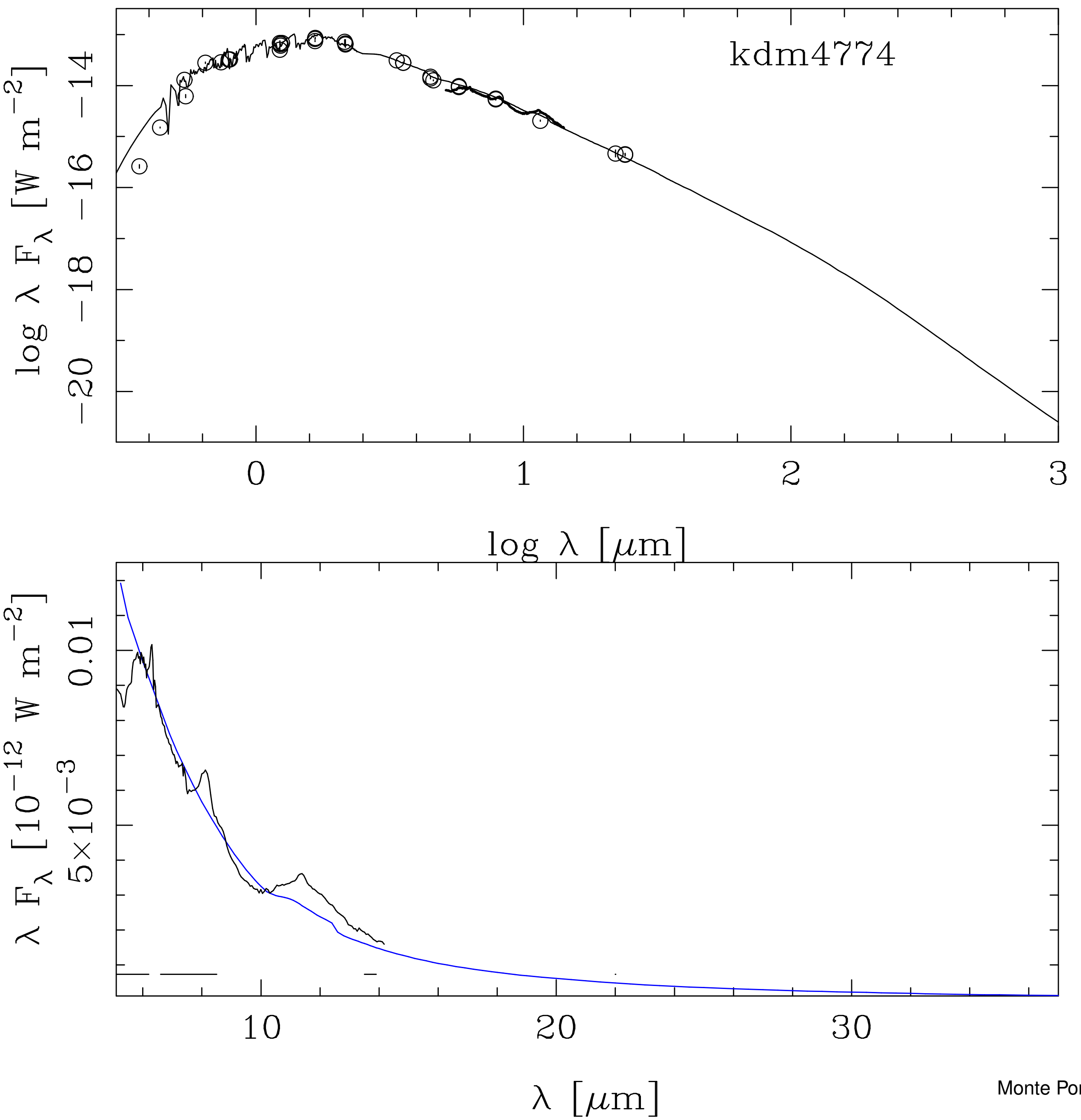
Presently:
225 (46 SMC, 19 dSphs) C- and
171 (40 SMC) O-rich stars (11 FG, 81 RSG, 79 O-AGB)

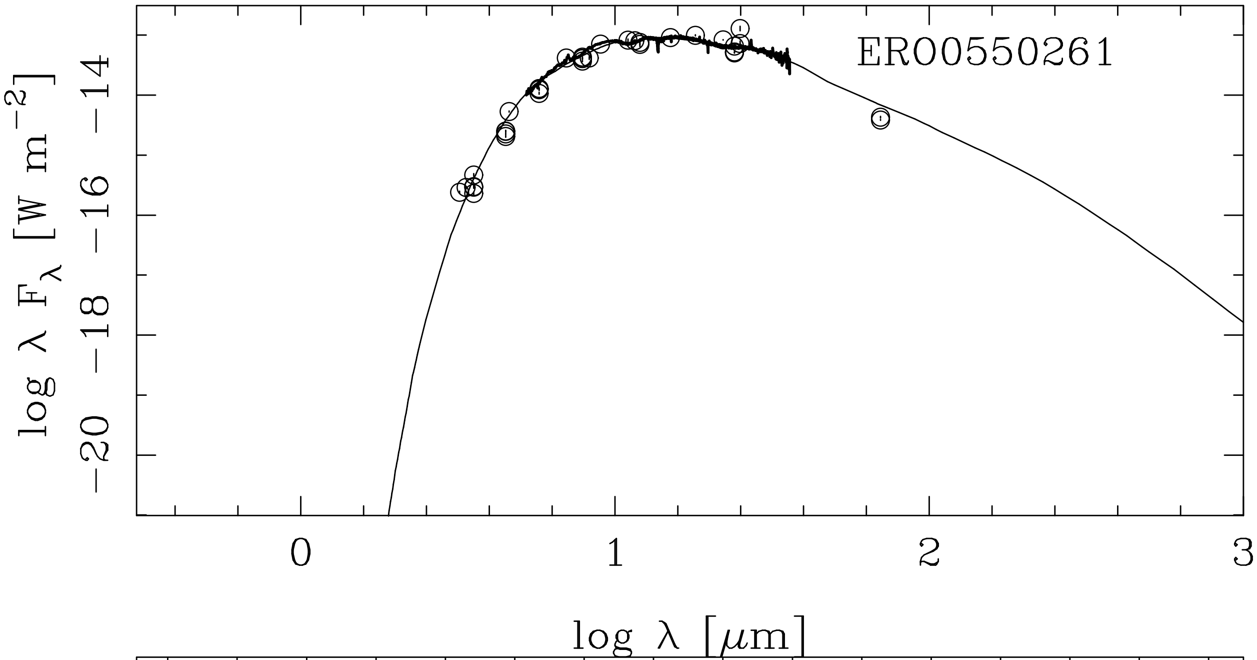
Improvements:

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

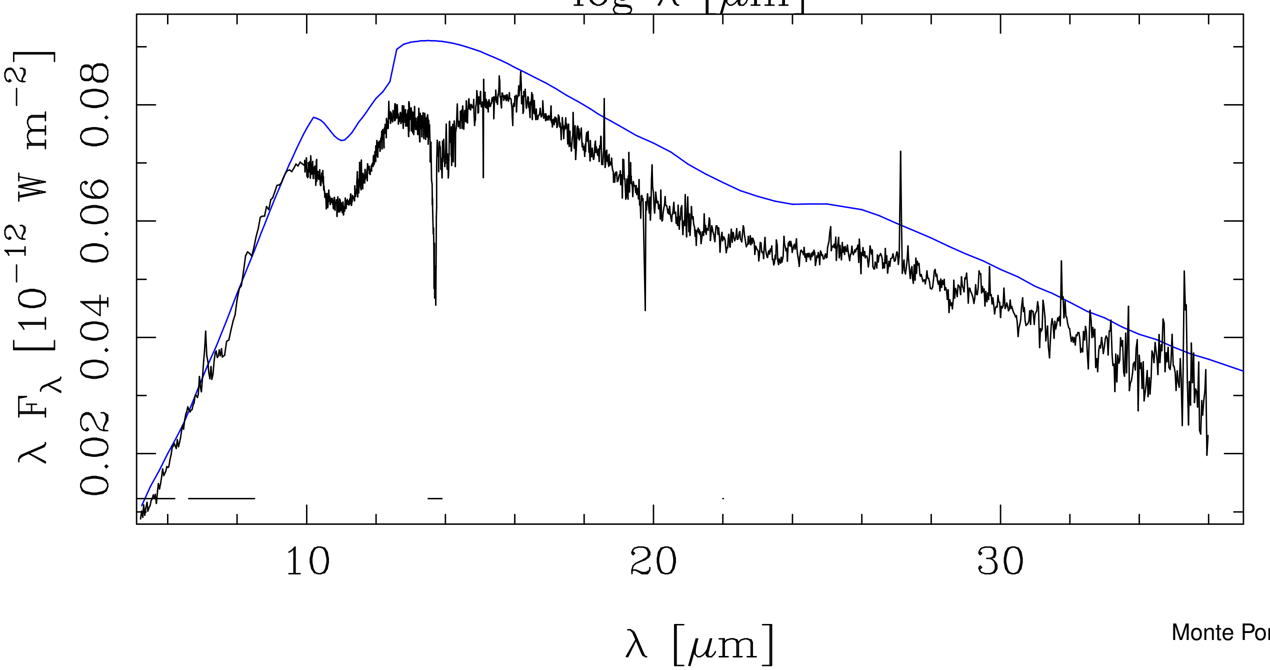
More of DUSTY - MoD

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

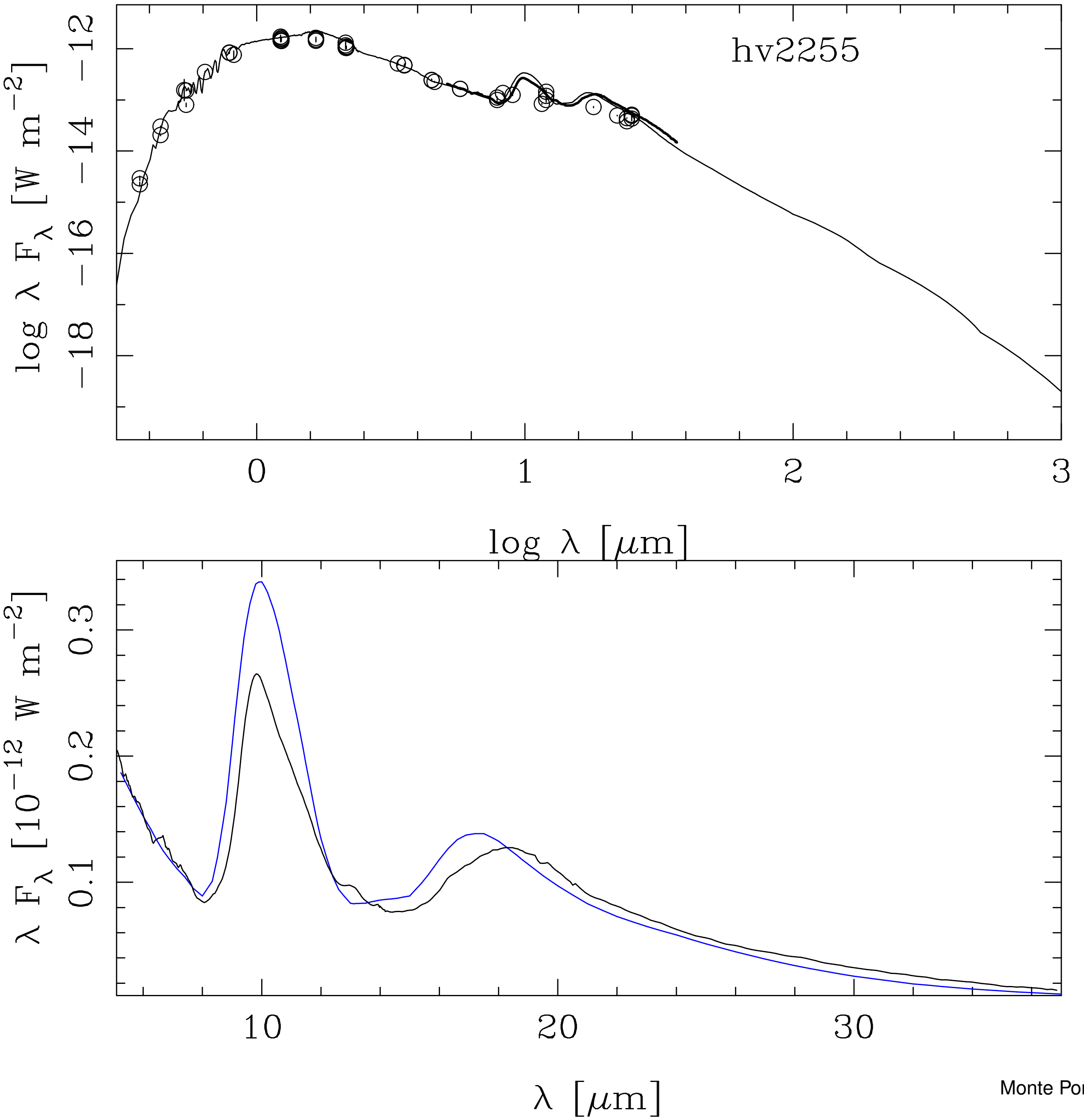

kdm4774
log λ F$_\lambda$ [W m^{-2}]
−14
−16
−18
−20
0
1
2
3
log λ [μm]
λ F$_\lambda$ [10^{-12} W m^{-2}]
0.01
5×10^{-3}
10
20
30
λ [μm]

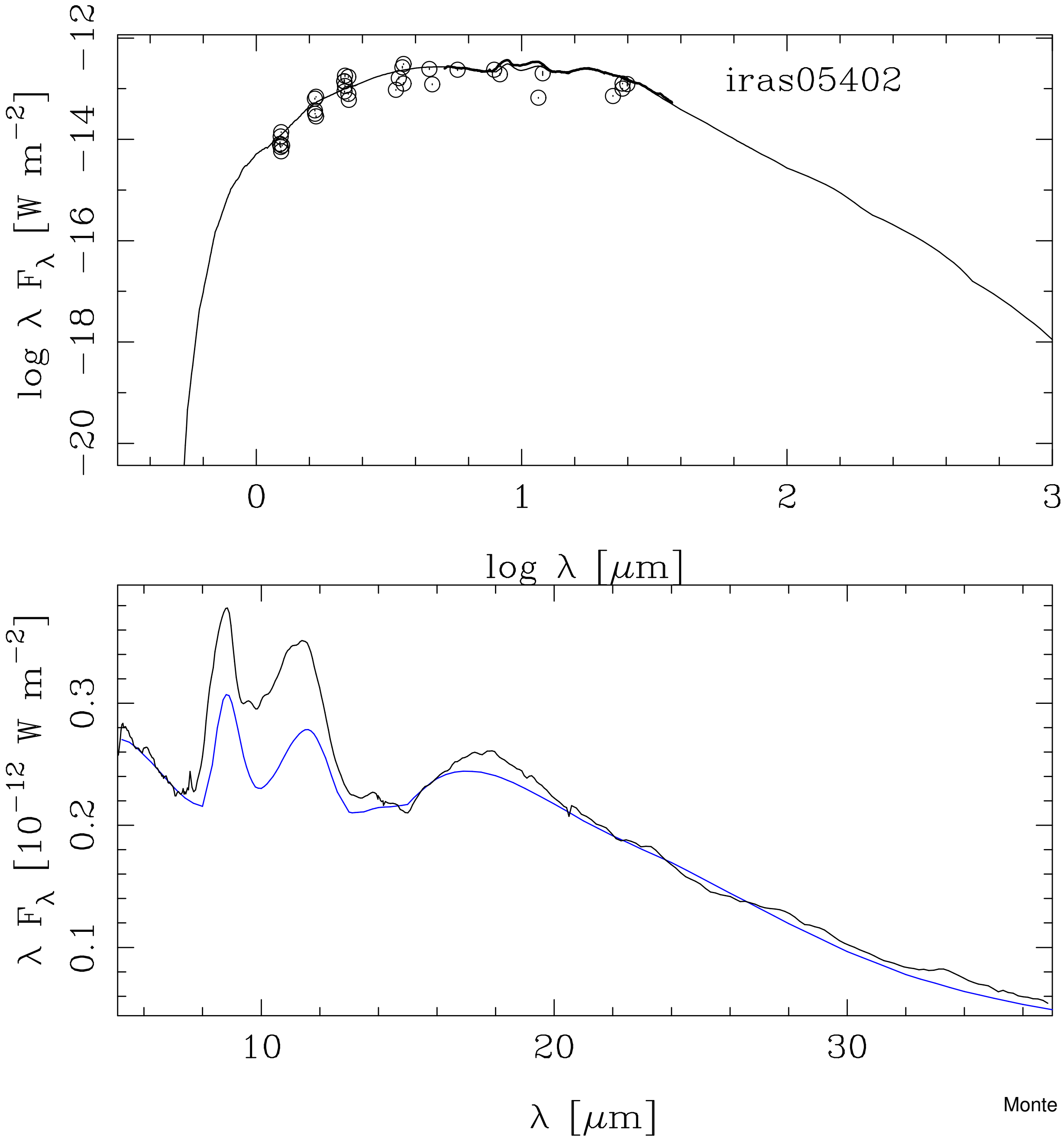


ER00550261
log λ F$_\lambda$ [W m^{-2}]
−14
−16
−18
−20
0
1
2
3
log λ [μm]

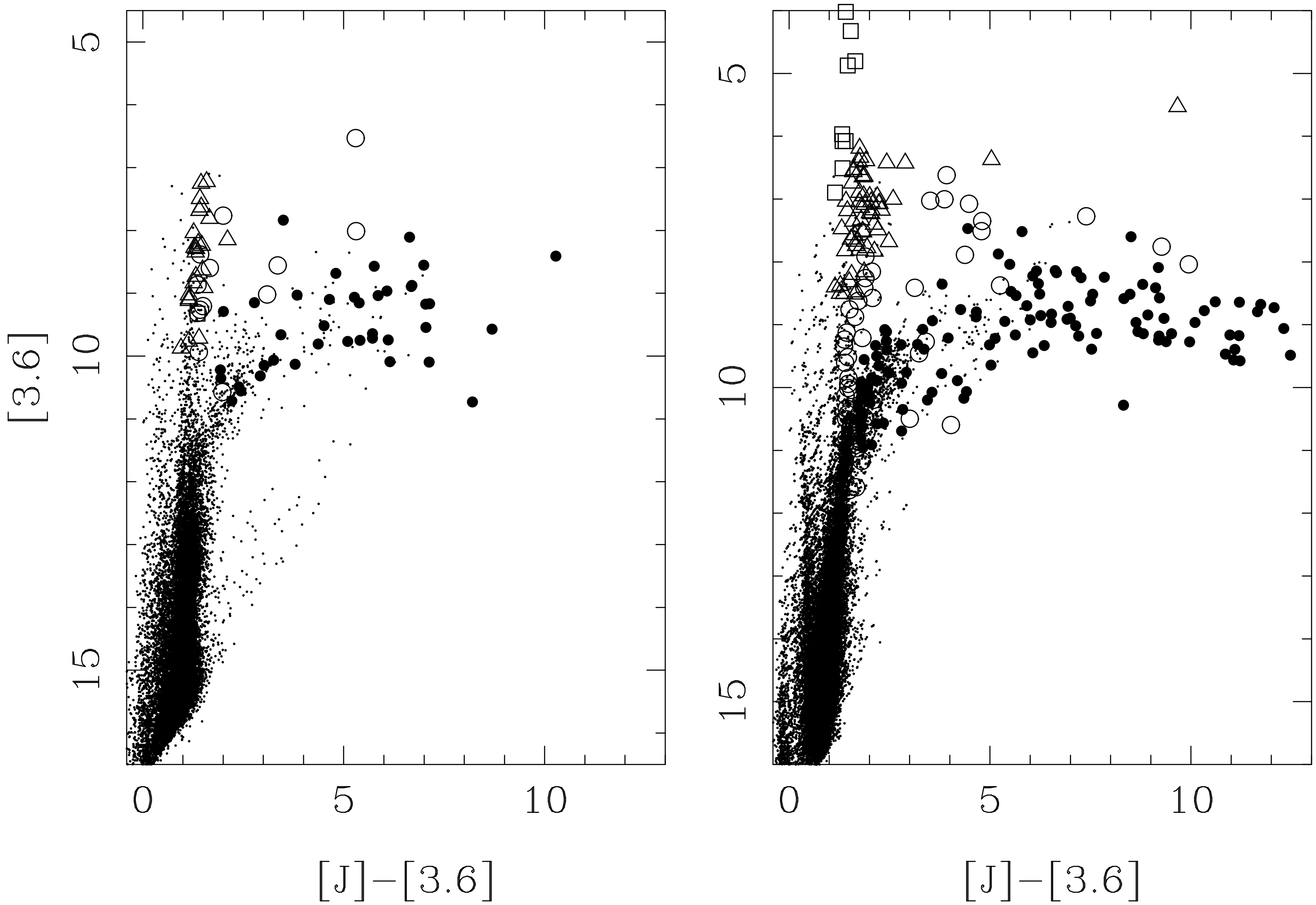


λ F$_\lambda$ [10^{-12} W m^{-2}]
0.02
0.04
0.06
0.08
10
20
30
λ [μm]

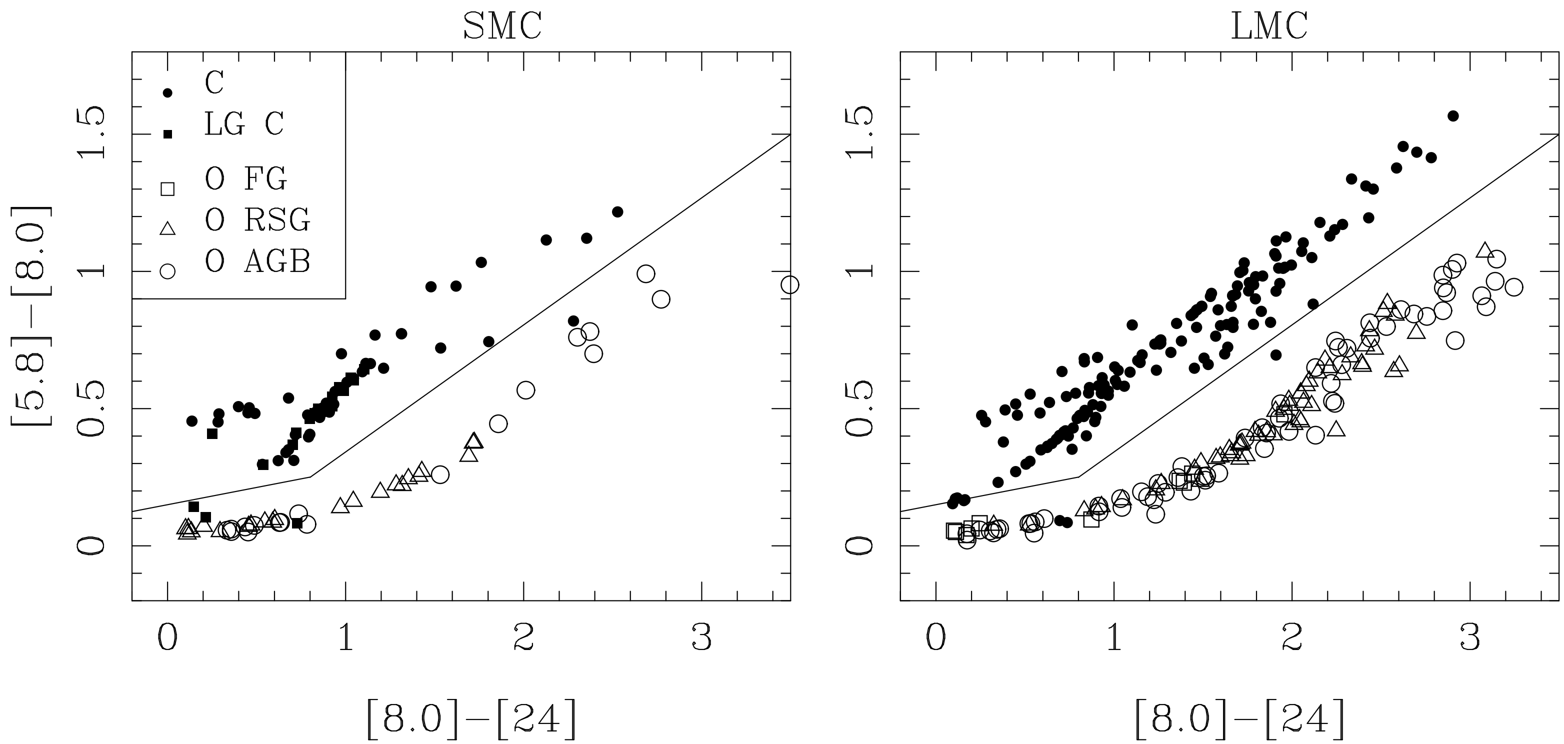

hv2255
log λ F_λ [W m^{-2}]
−18
−16
−14
−12
0
1
2
3
log λ [μm]
λ F_λ [10^{-12} W m^{-2}]
0.1
0.2
0.3
10
20
30
λ [μm]


iras05402
log λ F_λ [W m^{-2}]
−12
−14
−16
−18
−20
0
1
2
3
log λ [μm]
λ F_λ [10^{-12} W m^{-2}]
0.1
0.2
0.3
10
20
30
λ [μm]

CMD

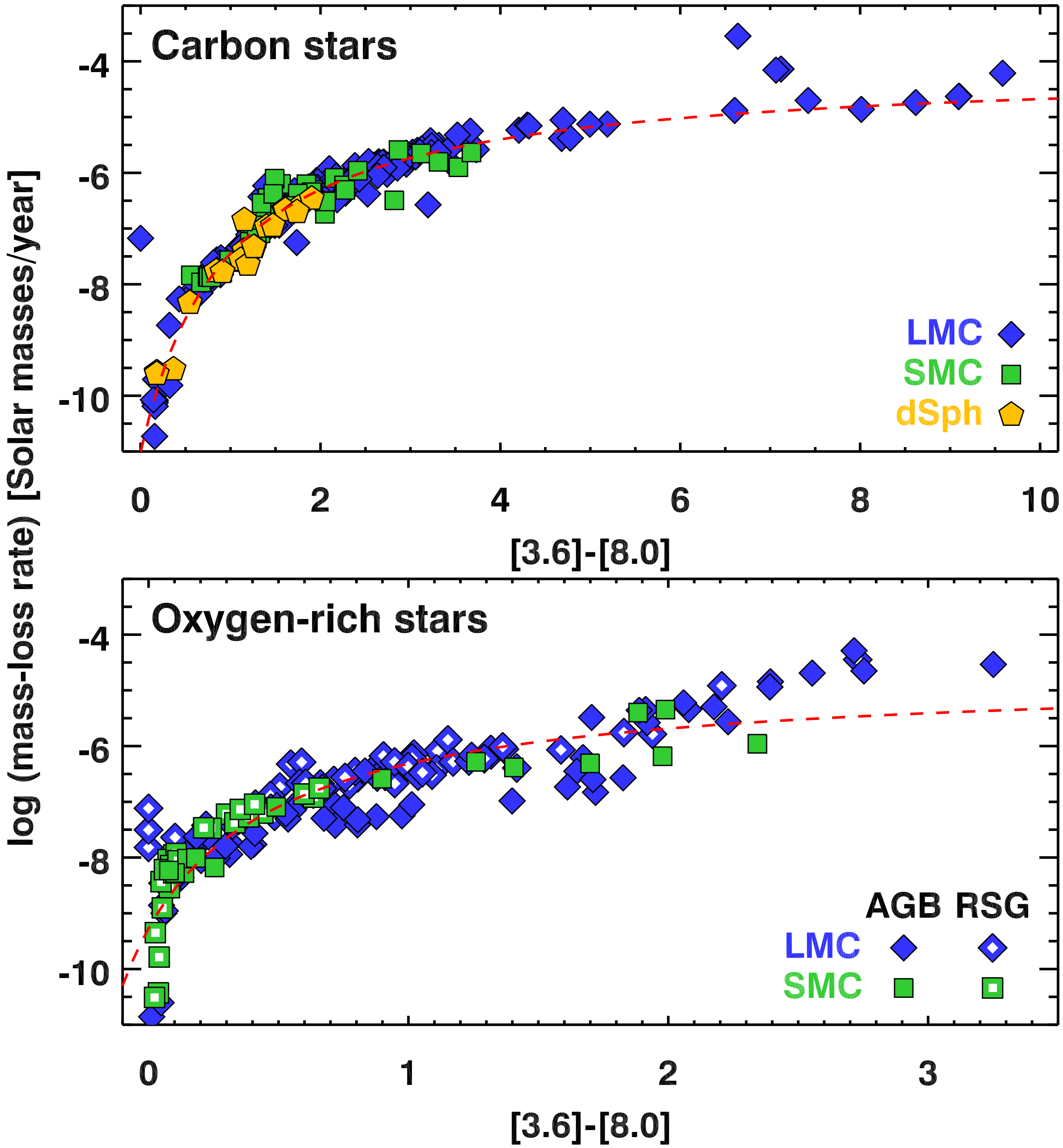


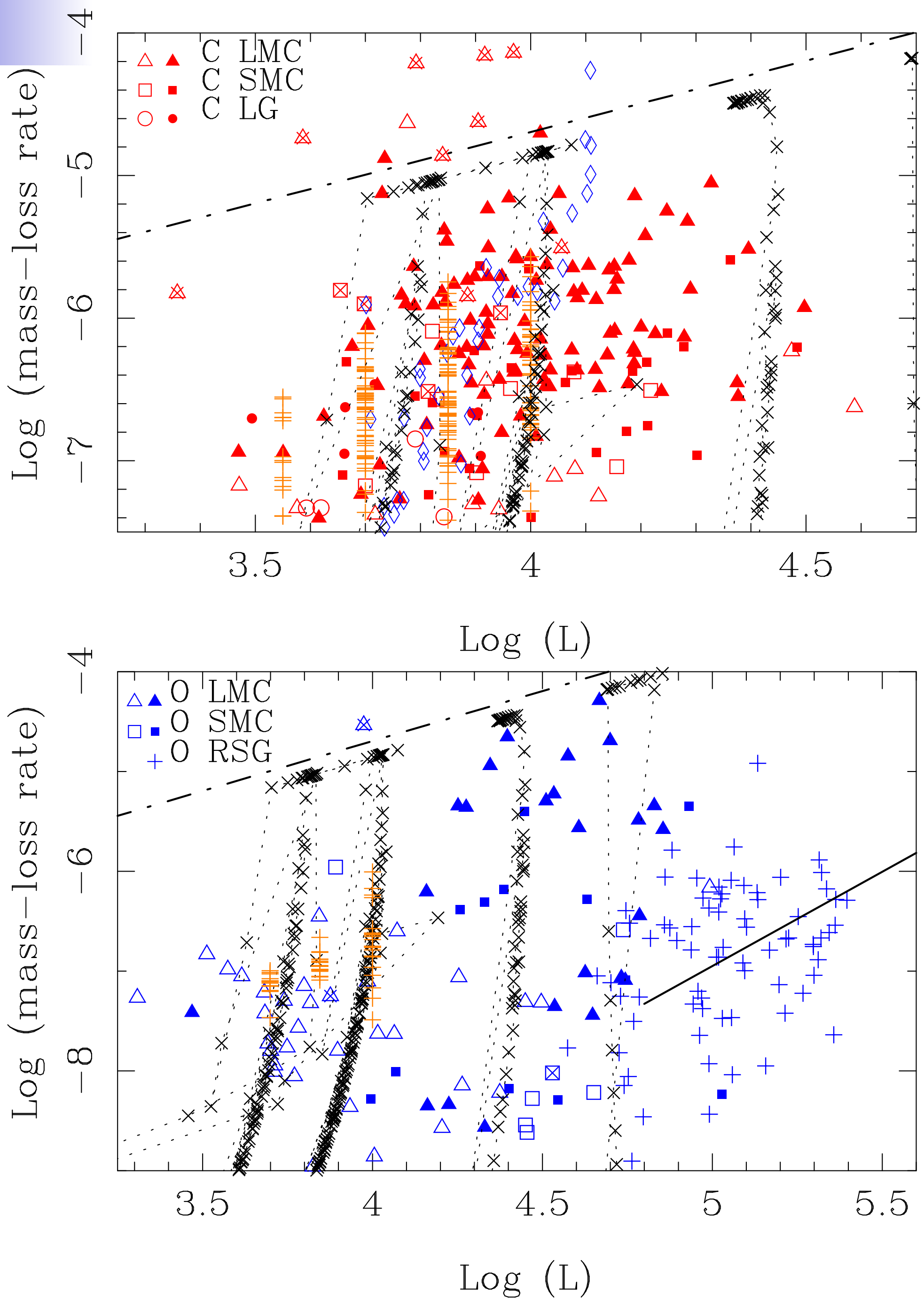
SMC: left ; LMC: right. Offset 0.5 mag.



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

Mass-loss rates





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.

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

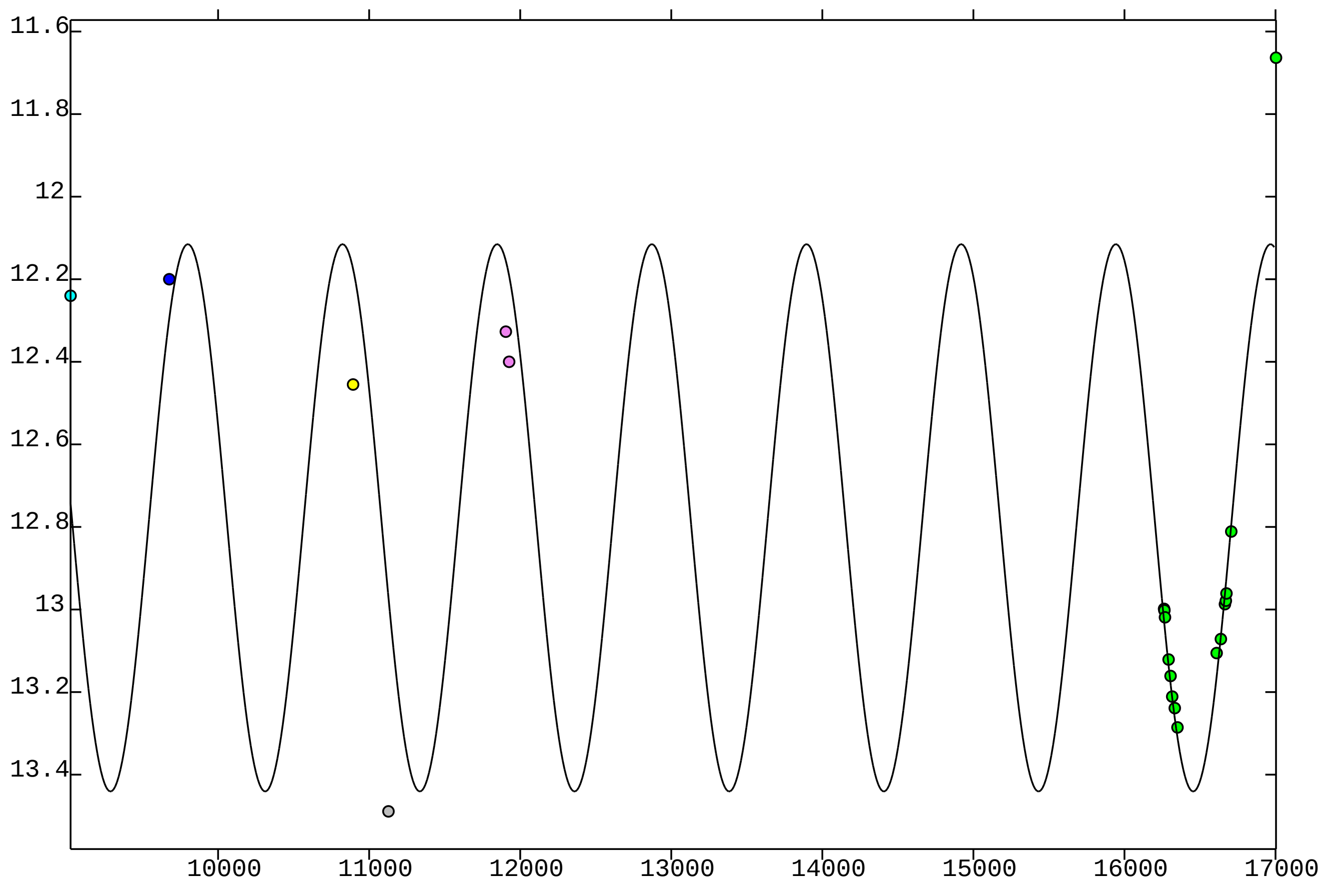
MLR comparison

- G09
  C-stars: G09/current factor of 5 lower.
  Rouleau & Martin (1991) vs. Zubko et al. (1996).

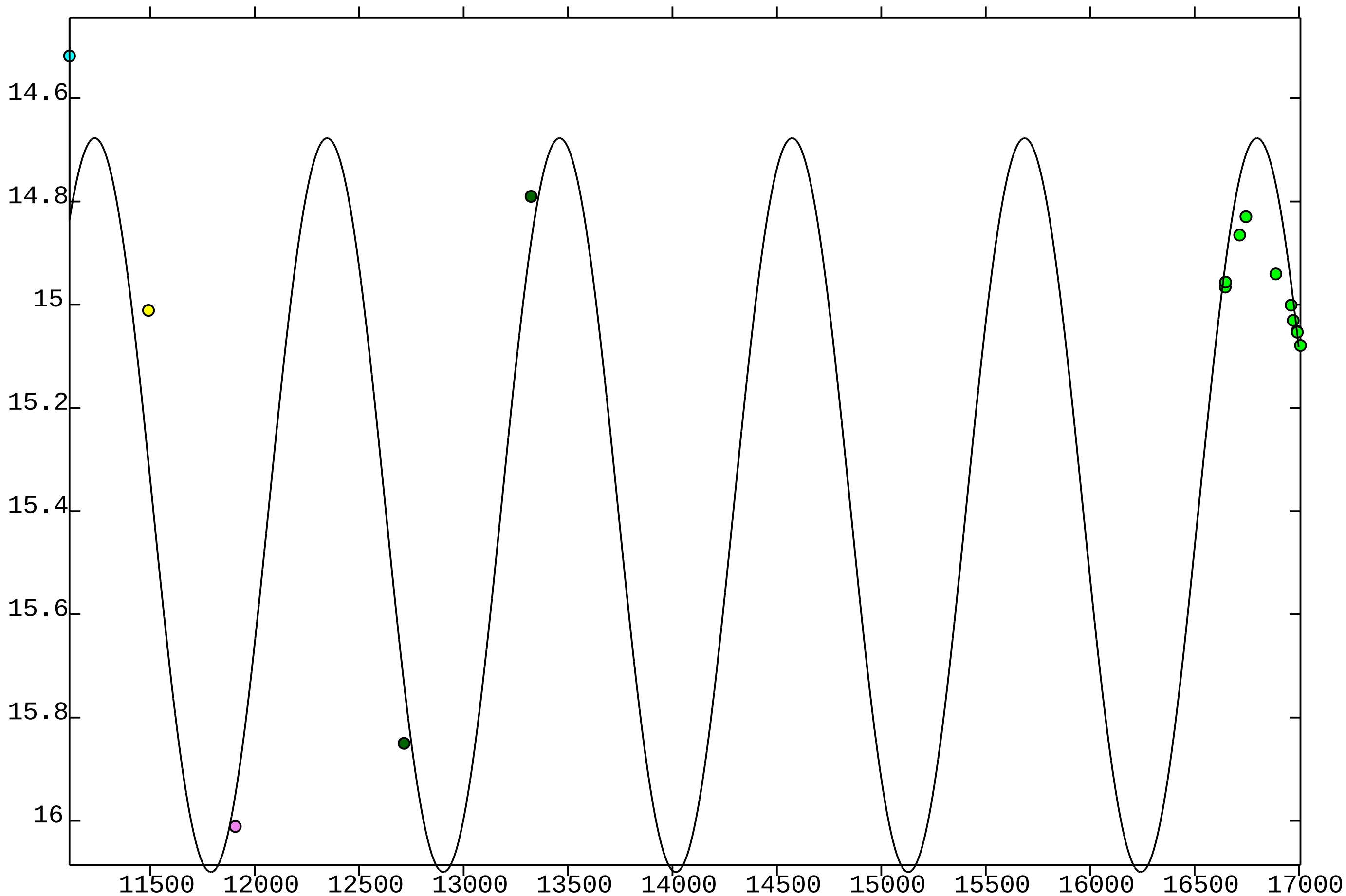
  M-stars: G09/current factor of 1.2.
  Dispersion indicates fitting error of factor of 2.
- Comparison to Riebel et al. (2012), Jones et al. (2012, 2014), Srinivasan et al. (2011)
  - modelling details, $T_{\rm cond}$
  - astronomical silicates vs. lab. constants
  - role of metallic iron

New Pulsation Periods

VMC: typically 15 epochs of data, spread over 6 months.
Combine with DENIS, 2MASS, 2MASS 6X, IRSF



P= 1026 days (Groenewegen et al. 2018, in prep;
Cioni et al. arXiv:1703.06769)


14.6
14.8
15
15.2
15.4
15.6
15.8
16
11500
12000
12500
13000
13500
14000
14500
15000
15500
16000
16500
17000

P= 1113 days

ALMA Observations

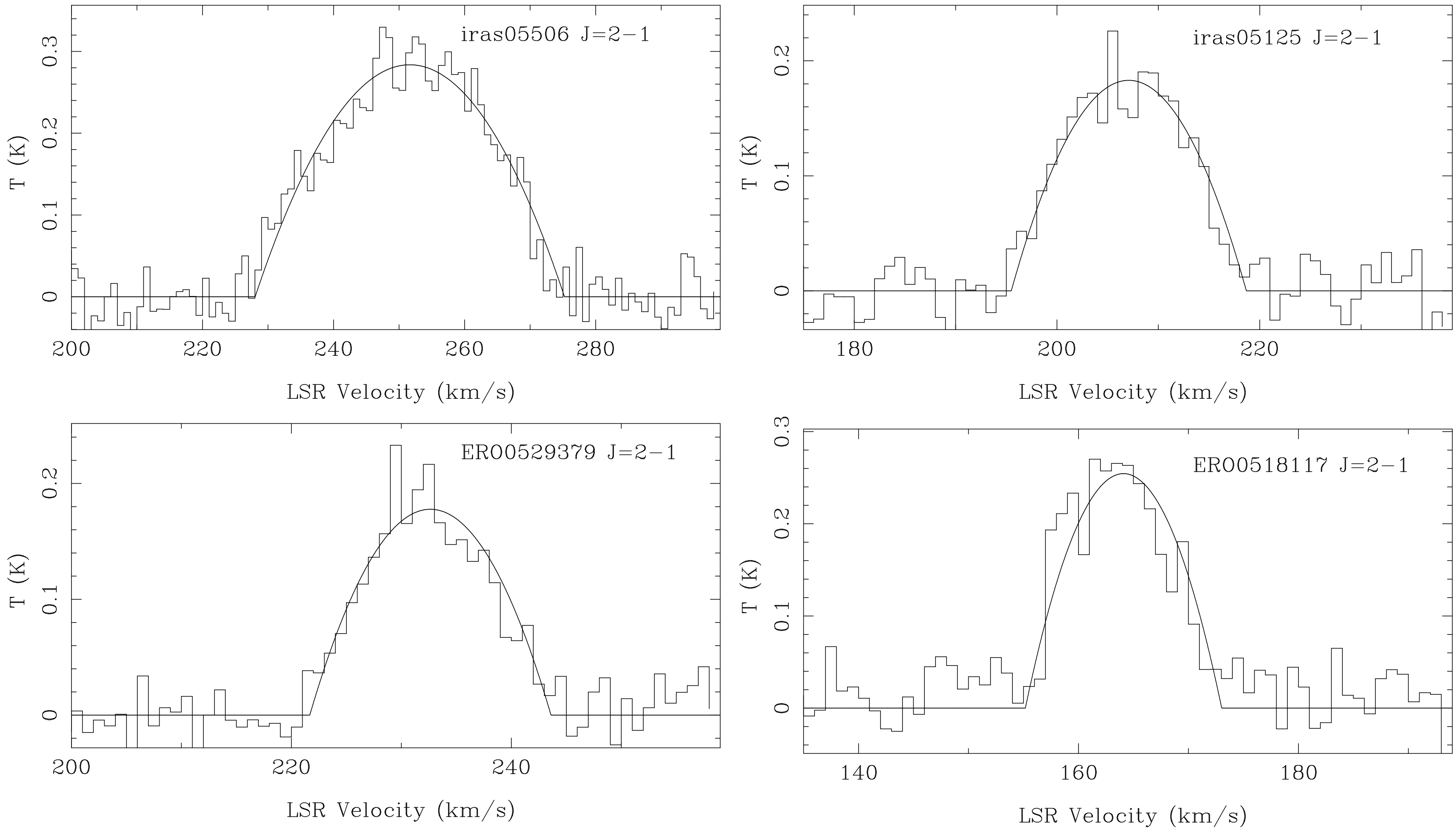
AIM:

- Get expansion velocity
  (one uncertainty in dust mass-loss rate)
- Test dust driven wind theory
- Determine mass-loss rates (and thus Ψ) from detailed modelling of CO lines

ALMA Cycle-2 proposal to observe 6 stars.
CO J= 2-1 was carried out at the end of Cycle-2
CO J= 3-2 was carried over to Cycle-3, but not observed

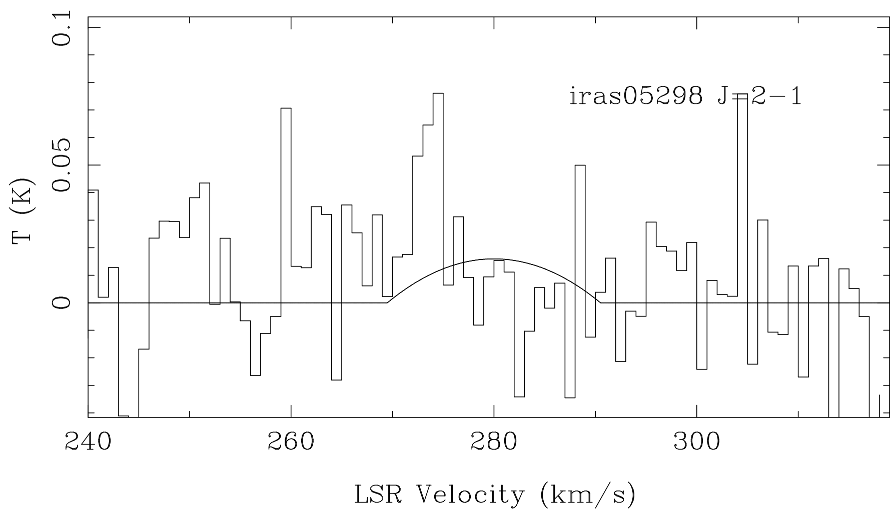
No time granted in Cycle-4 ☹

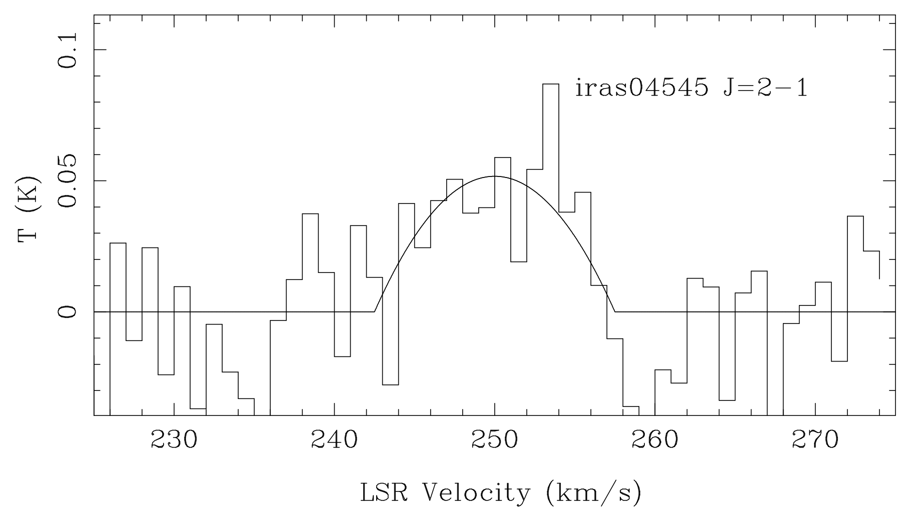
ALMA Observations



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

ALMA Observations





1 out of 2 OH/IR stars detected

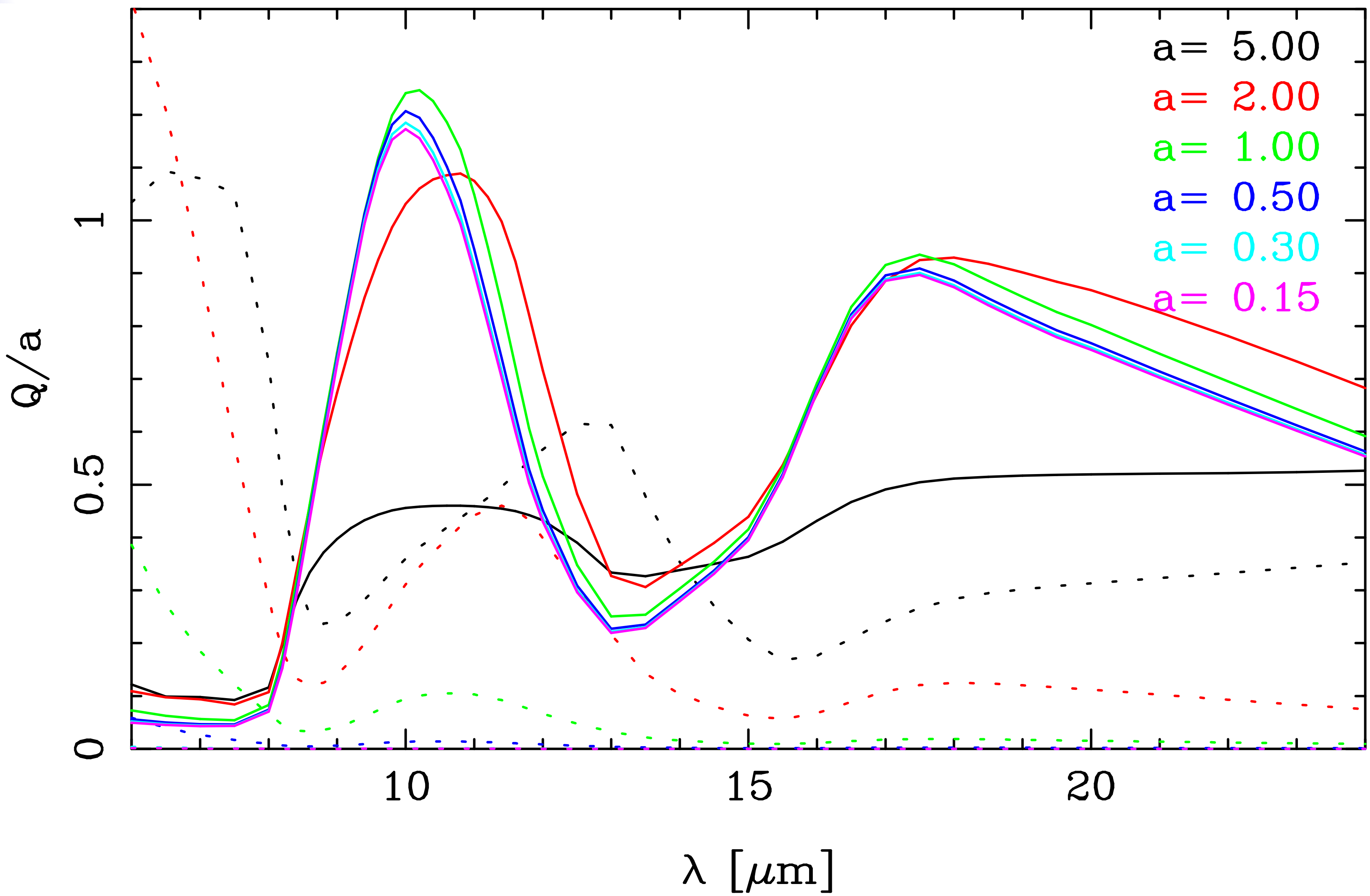
($V_\star$ and $V_{\rm exp}$ fixed from OH-maser observations, Goldman et al. 2017).

ALMA Observations

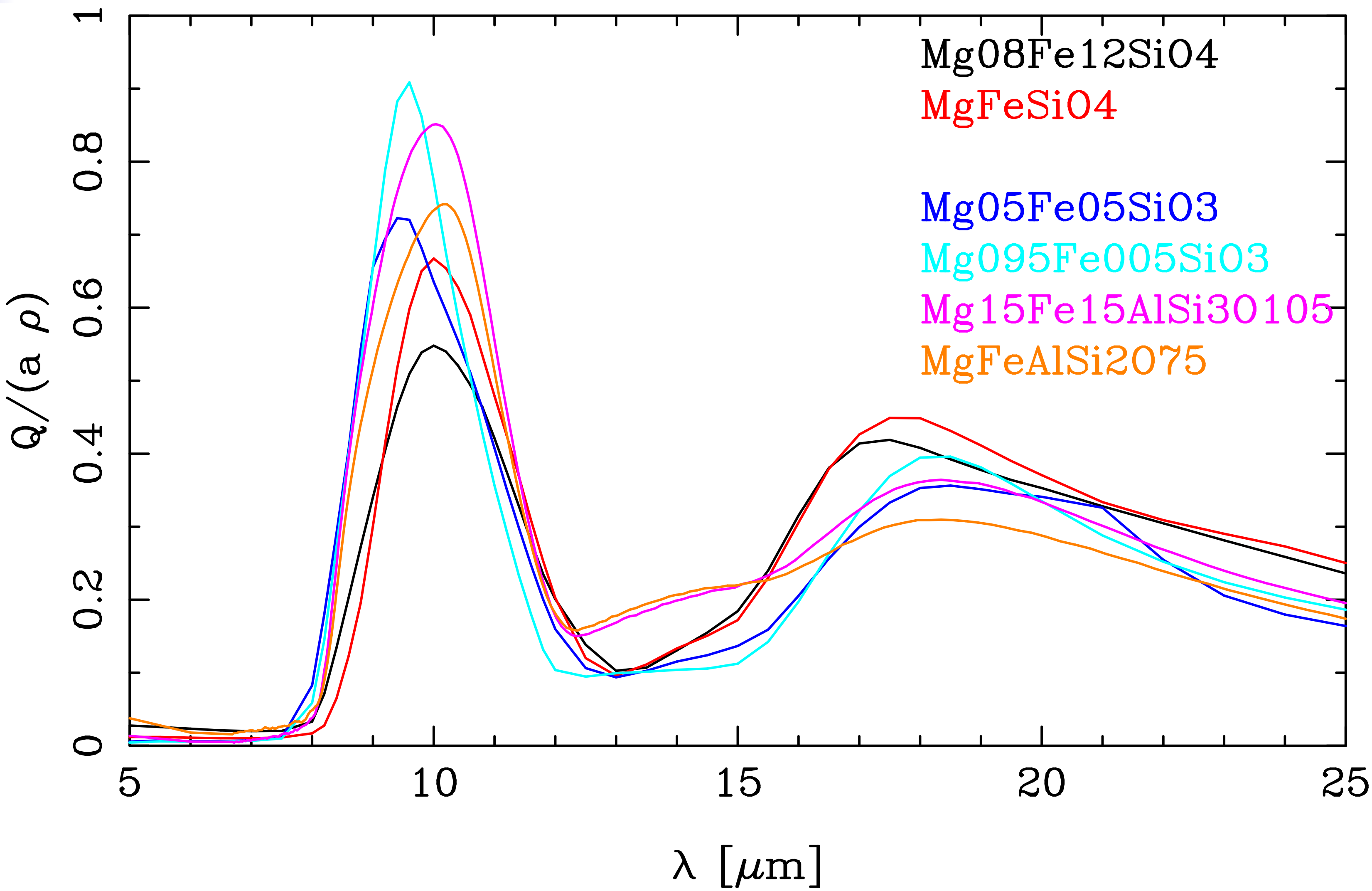
Identifier	dust MLR ($M_\odot$ yr^{-1})	Lum. ($L_\odot$)	$v_\star$ (km/s)	$v_{\rm exp}$ (km/s)	Colour
		OH/IR stars			
iras05298	0.72 $\times 10^{-8}$	37700	280	10.5	J-K= 3.5
iras04545	1.12 $\times 10^{-8}$	24900	250	7.5	J-K= 3.1
		carbon-rich stars			
iras05506	2.8 $\times 10^{-8}$	17800	251.6	23.6	J-K= 7.6
iras05125	3.6 $\times 10^{-8}$	15500	207.1	11.8	J-K= 12.5
ERO0529379	6.6 $\times 10^{-8}$	5400	232.7	11.0	J-K= (17)
ERO0518117	41. $\times 10^{-8}$	9300	164.0	8.9	J-K= (16)

Future Work: Opacities

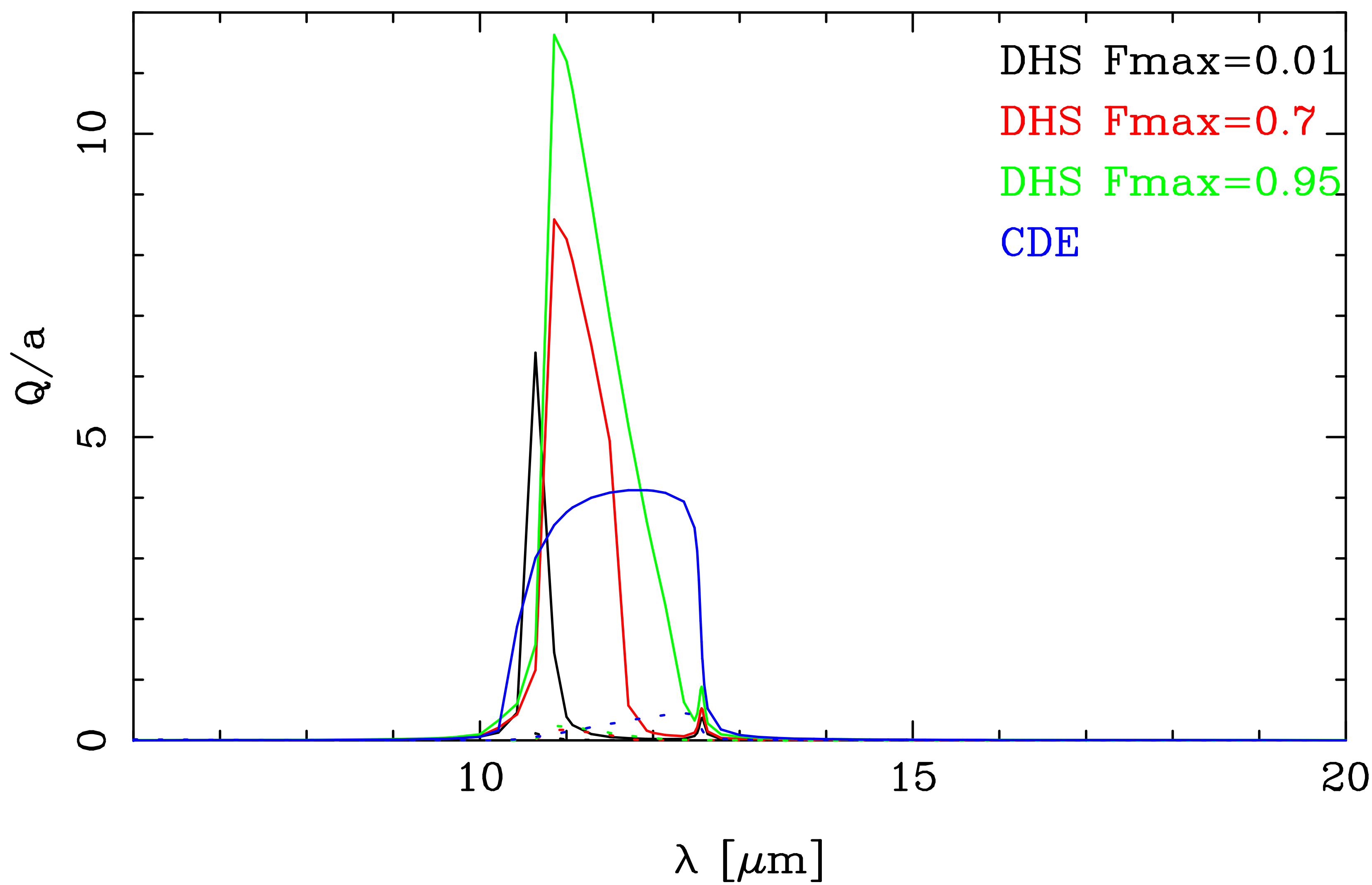
- Laboratory: optical constants $(n, k) \Rightarrow Q_{\rm abs}, Q_{\rm sca}$
- grain size (distribution)
  $a \ll \lambda$ (small particle limit)
- spheres (classical Mie theory), ellipsoidal, irregular
- separate species, core-mantle grains,
  effective medium theory



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



(DHS a= 0.15 μm)
Different olivines, role Aluminum



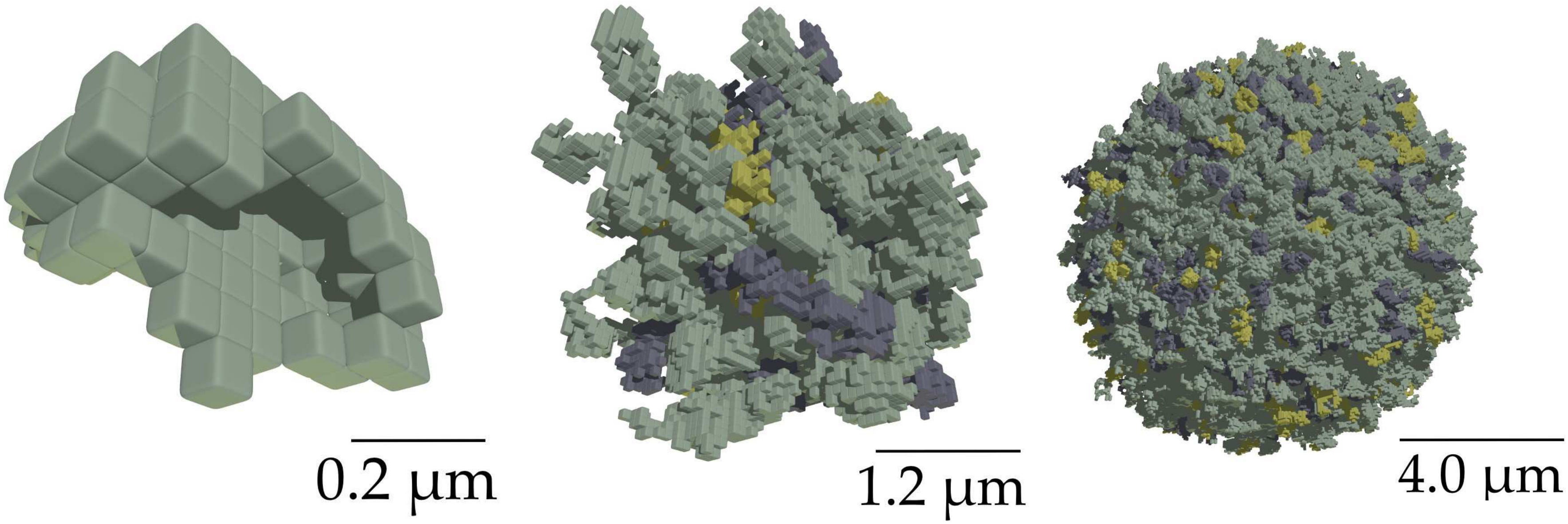
SiC a= 0.20 μm: Different shapes

Irregular shaped particles

Fluffy Grains: Ambra Nanni, Peter van Hoof

- DDA: Discrete Dipole Approximation
  - DDSCAT 7.3.2 (August 2016)
    Draine & Flatau
  - ADDA (Yurkin & Hoekstra 2011)
- T-matrix codes
  - MSTM 3.0 (multiple sphere T-matrix)
    Daniel W. Mackowski April 2013
  - GMM (generalised multi-particle Mie solution)
    Xu & Gustafson (2001)

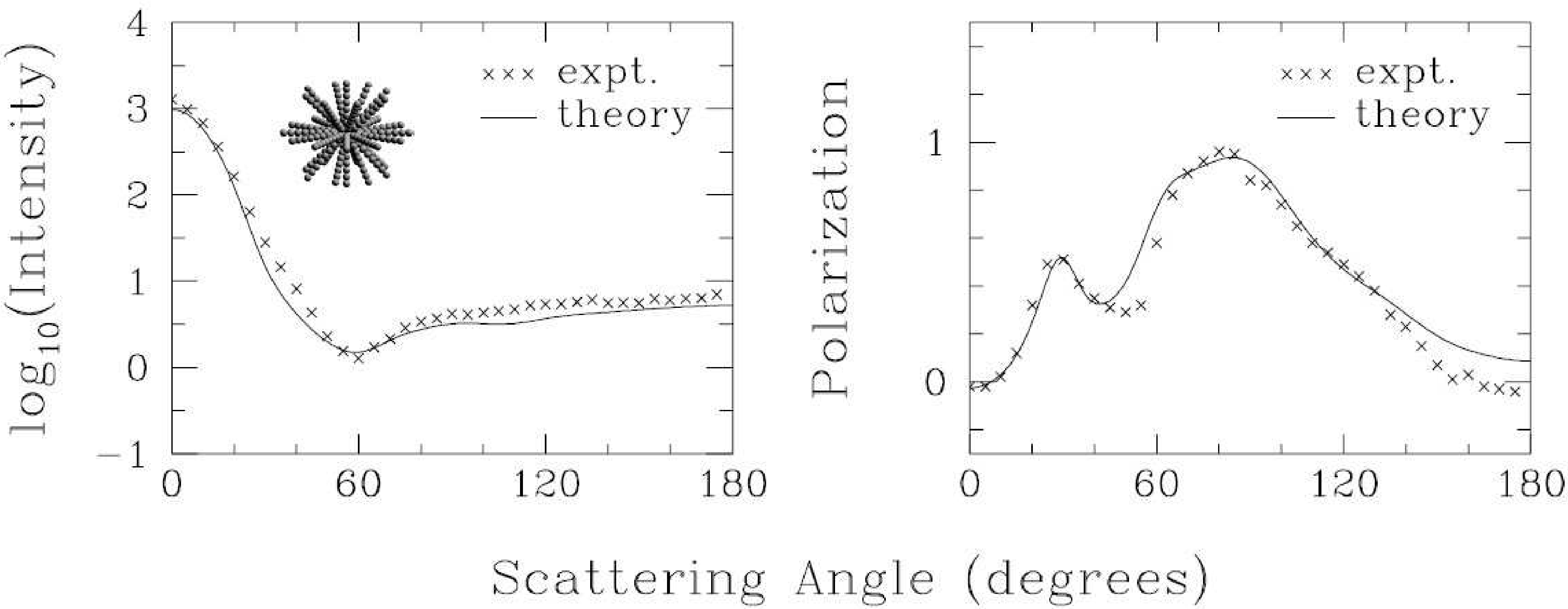
ADDA



Min et al (2016)
"$a_{\text{eff}} = 4\mu m$, composed of 8000 monomers with $a = 0.2\mu m$. Each built from 100 dipoles, total 800 000 dipoles."

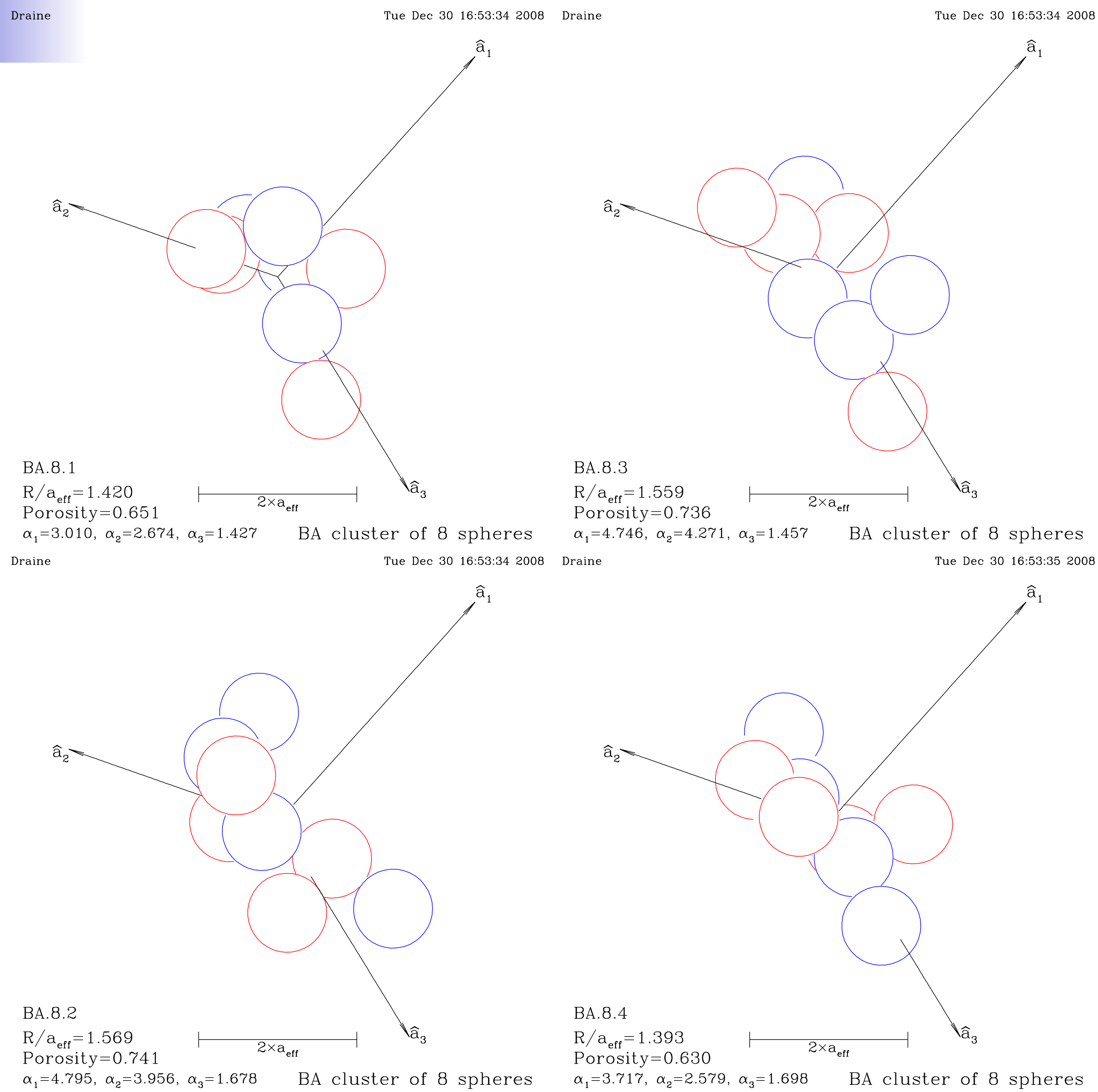
"The computation of the largest aggregate took four days of CPU time using 64 cores for 44 wavelength points."

GMM

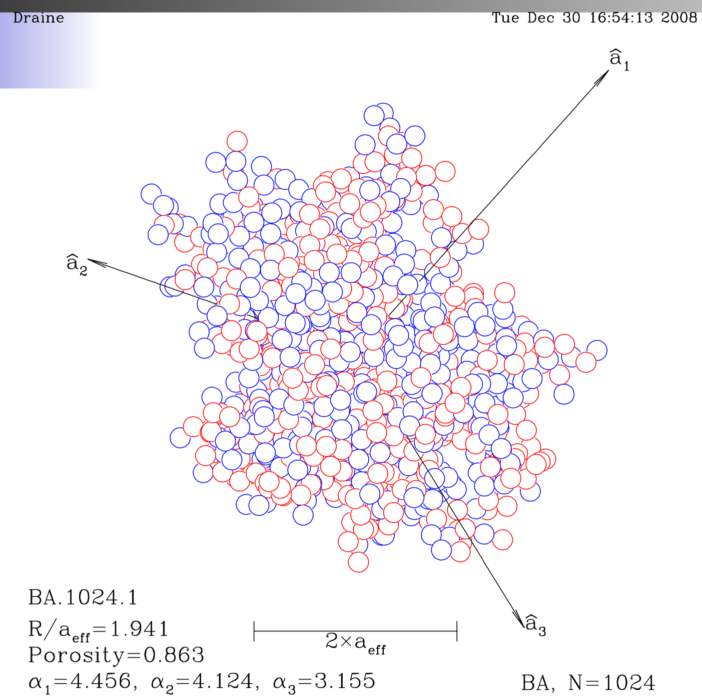


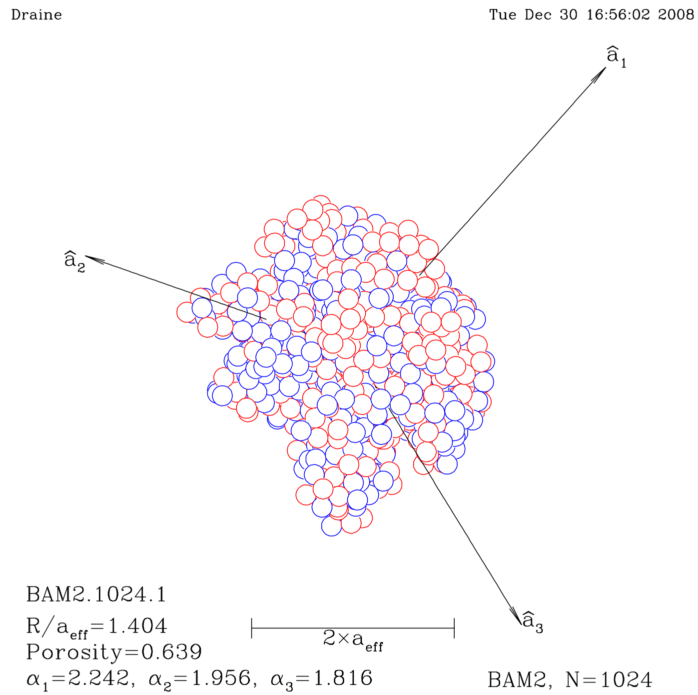
240 Nylon spheres: $m = 1.735 + 0.007i$

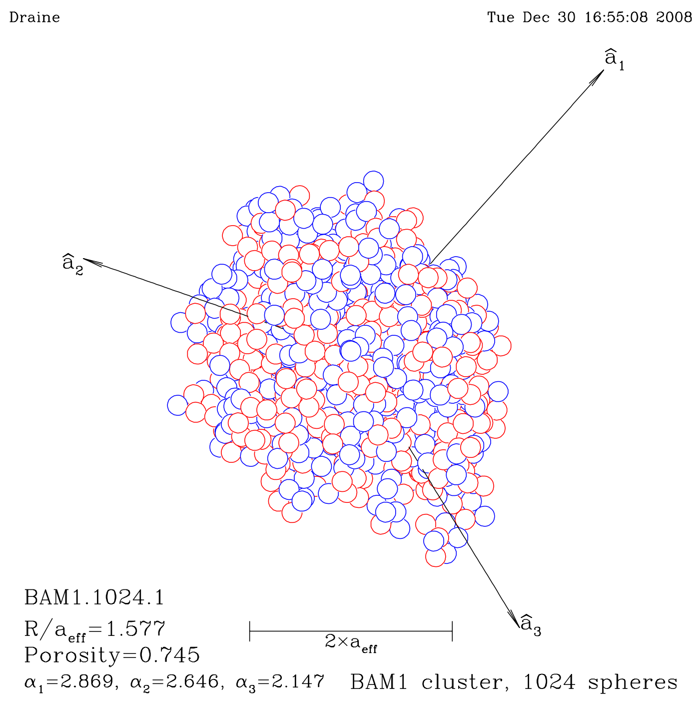
Targets


Draine
Tue Dec 30 16:53:34 2008
$\hat{a}_1$
$\hat{a}_2$
$\hat{a}_3$
BA.8.1
R/a_{eff}=1.420
Porosity=0.651
$2\times a_{eff}$
α_1=3.010, α_2=2.674, α_3=1.427
BA cluster of 8 spheres
Draine
Tue Dec 30 16:53:34 2008
$\hat{a}_1$
$\hat{a}_2$
$\hat{a}_3$
BA.8.3
R/a_{eff}=1.559
Porosity=0.736
$2\times a_{eff}$
α_1=4.746, α_2=4.271, α_3=1.457
BA cluster of 8 spheres
Draine
Tue Dec 30 16:53:34 2008
$\hat{a}_1$
$\hat{a}_2$
$\hat{a}_3$
BA.8.2
R/a_{eff}=1.569
Porosity=0.741
$2\times a_{eff}$
α_1=4.795, α_2=3.956, α_3=1.678
BA cluster of 8 spheres
Draine
Tue Dec 30 16:53:35 2008
$\hat{a}_1$
$\hat{a}_2$
$\hat{a}_3$
BA.8.4
R/a_{eff}=1.393
Porosity=0.630
$2\times a_{eff}$
α_1=3.717, α_2=2.579, α_3=1.698
BA cluster of 8 spheres

Targets

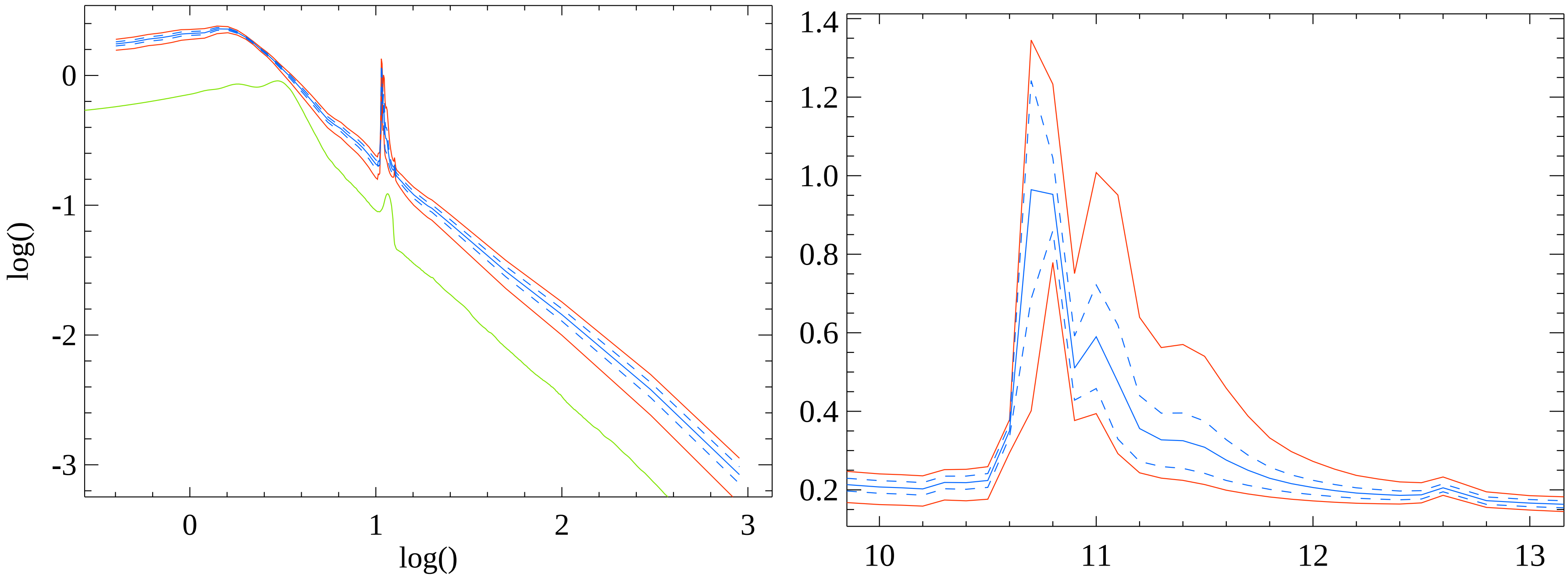






Target files:
Shen, Draine, and Johnson (2008).
16 realisations for N= 8, 16, 32, 64, 128, 256, 512, 1024
BA, BAM1, BAM2

BA



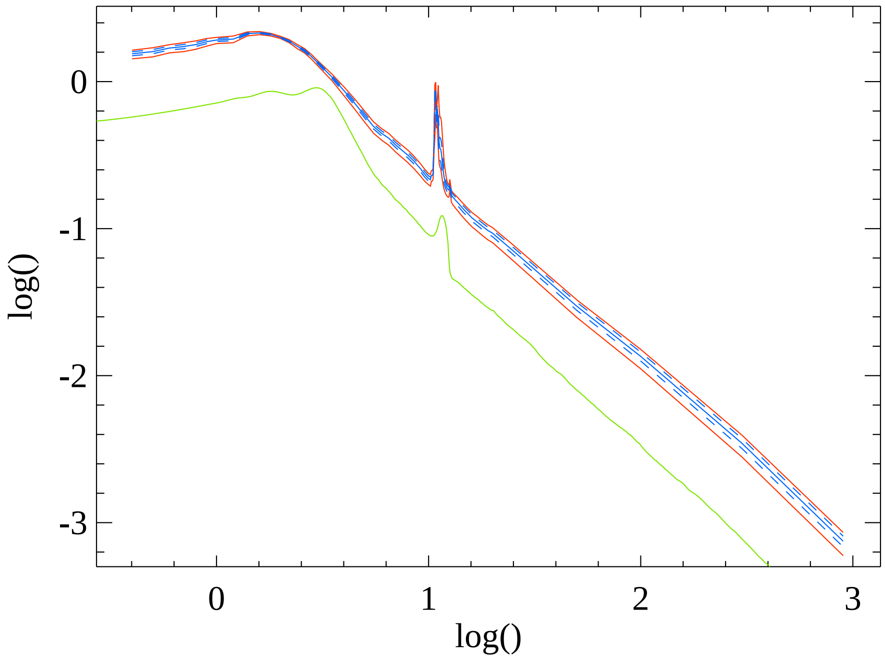
BA.8

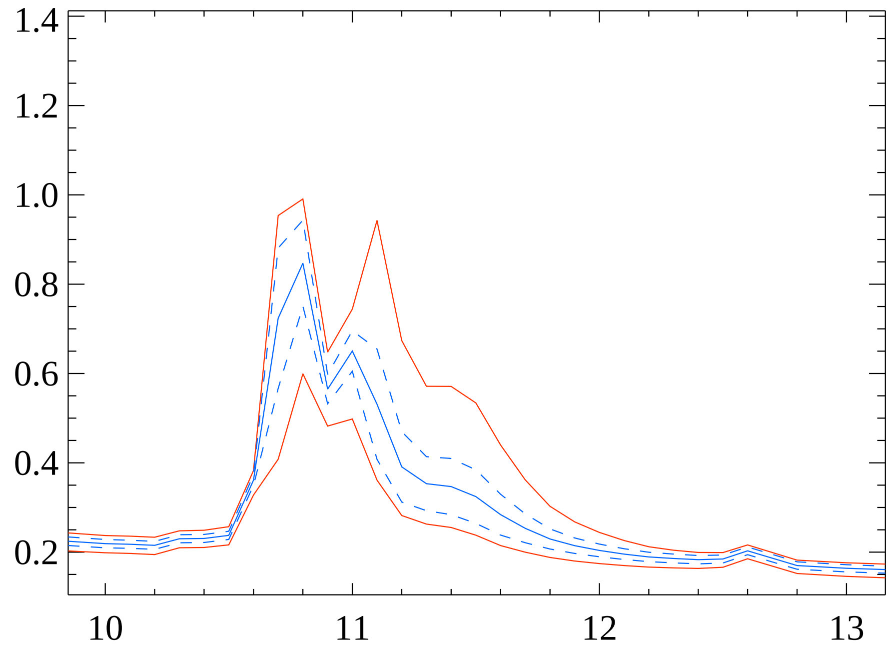
8 * 16 realisation

mean, min, max, $\pm 1\sigma$

green: sphere r= 0.5 μm (n,k)= EMT w. $\frac{1}{8}$ SiC & $\frac{7}{8}$ amC

BAM1



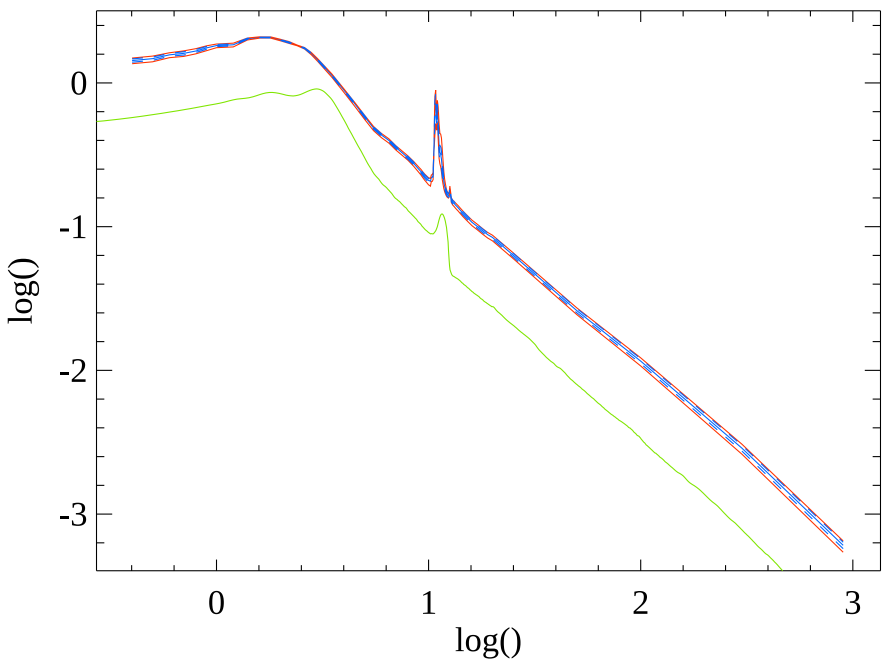


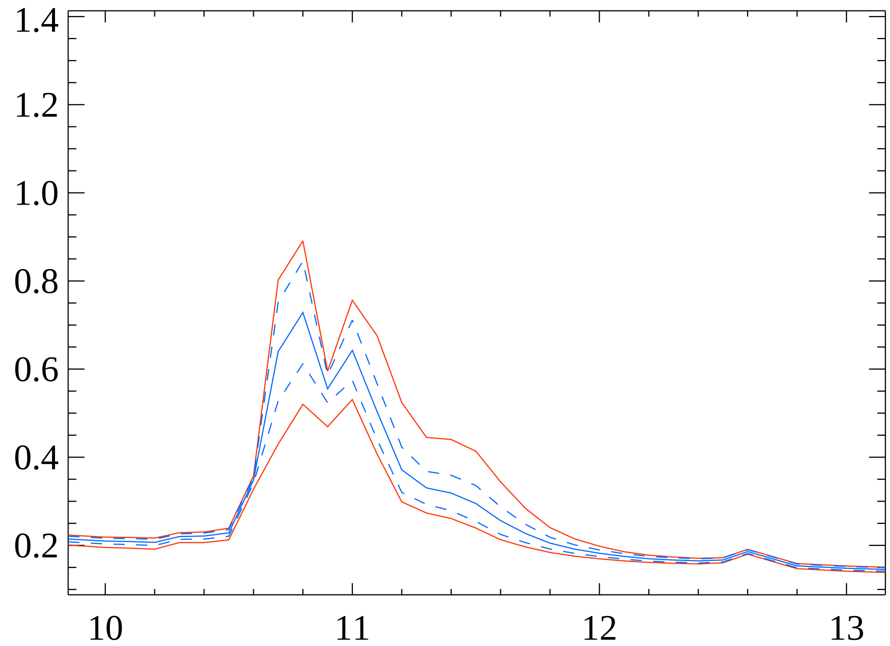
BAM1.8

8 * 16 realisation

mean, min, max, $\pm 1\sigma$

BAM2

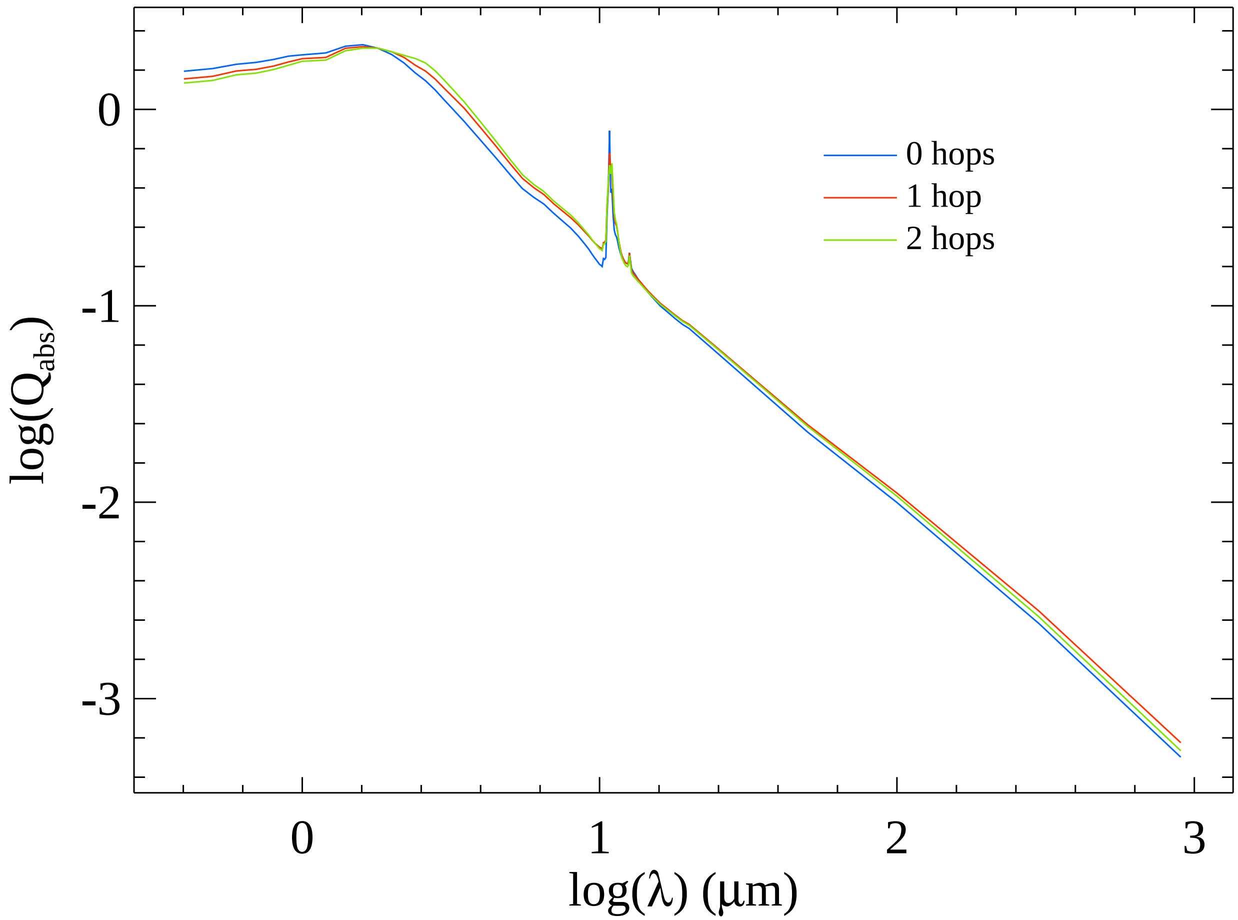




BAM2.8

8 * 16 realisation

mean, min, max, $\pm 1\sigma$



Comparison

Prospects

- Potentially interesting ☺
- ☹ Computationally expensive:
  non-touching spheres, number of Mie terms,
  optical constants

Future Work: Dust return

Lessons learned:

- GRAMS: 68 600 models (O-grid), 12 000 (C-grid)
  $T_{\rm eff}$, $R_{\rm in}$, τ, Luminosity (?), (C/O ratio)
  Combination of parameters that are physically improbable; limits by the grid; computationally fast
- Individual fitting: better determined parameters (but some are fitted, some are fixed), computationally expensive

Future Work: Dust return

- Now: grid of 400 REAL AGB/RSGs (add some YSOs, PAGB)
- Combine approaches:
  -minimise χ^2 over 400+ stars, keep the best
  -individual fitting for those.
- more realistic Ψ (O-, C-stars, models); $V_{\rm exp}$; Fluffy grains
- Link results to SFH and pulsational properties on a scale of a few square degrees

Summary and Prospects

- Detailed results (L, $\dot{M}$) for ~ 400 AGB/RSGs in SMC/LMC
- Could serve as templates for future research
- ALMA multi-line CO data is crucial:
  - $V_{\rm exp}$
  - Combine dust with CO line modelling $\Rightarrow$ constrain Ψ
- Choice of optical constants !
  Factor of a few uncertainty
- Work on dust opacities is needed

THE END