Tracing the mass loss history and dust formation in the winds of massive stars

Michaela Kraus

Astronomical Institute, Ondrejov, Czech Republic

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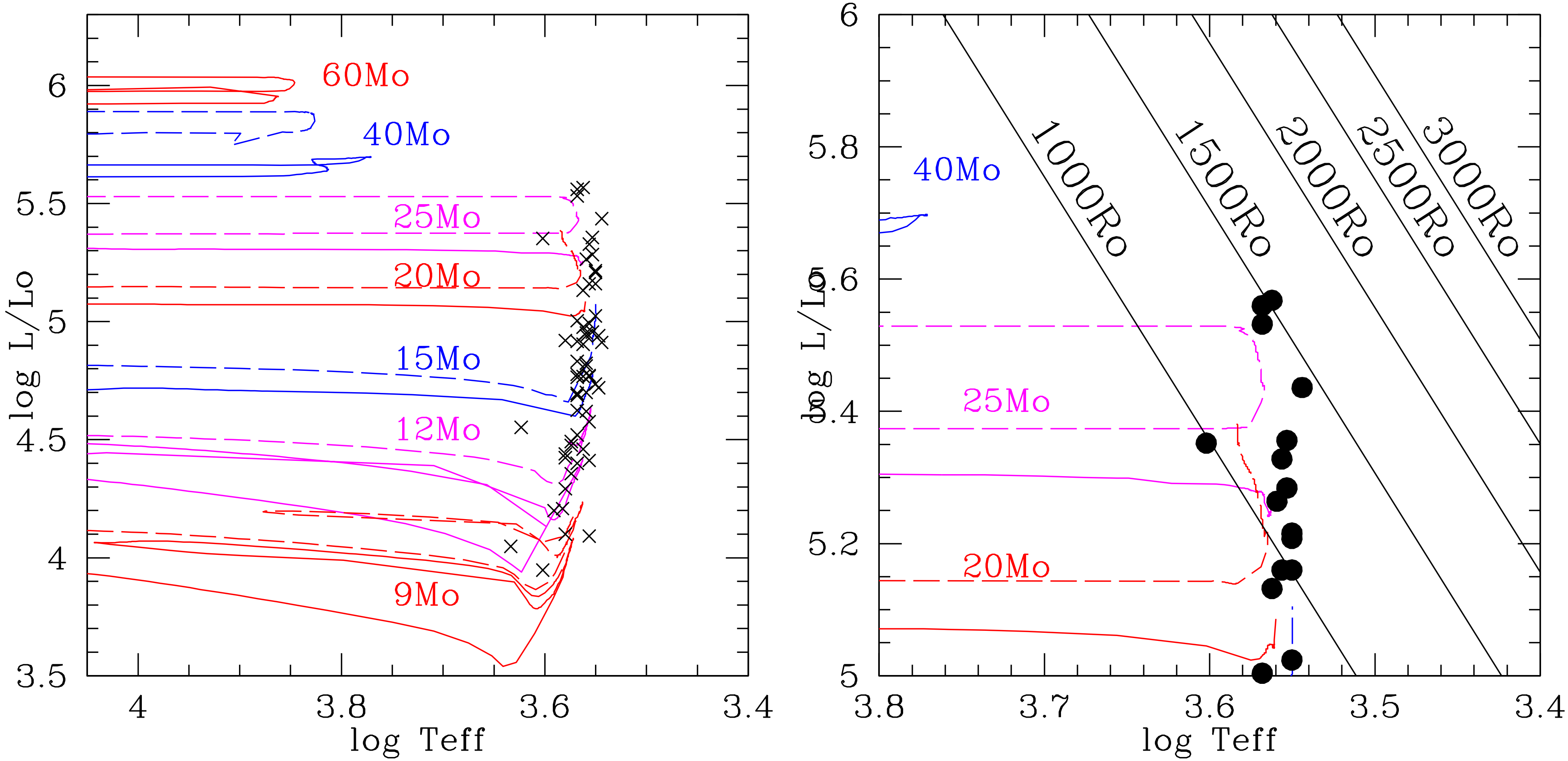
(First) dust must have formed from different progenitors !

Alternatives (at low Z)

- Type II Supernovae, Wolf-Rayet stars
- Red Supergiants (RSG)

RSGs in the Milky Way (Massey et al. 2008)



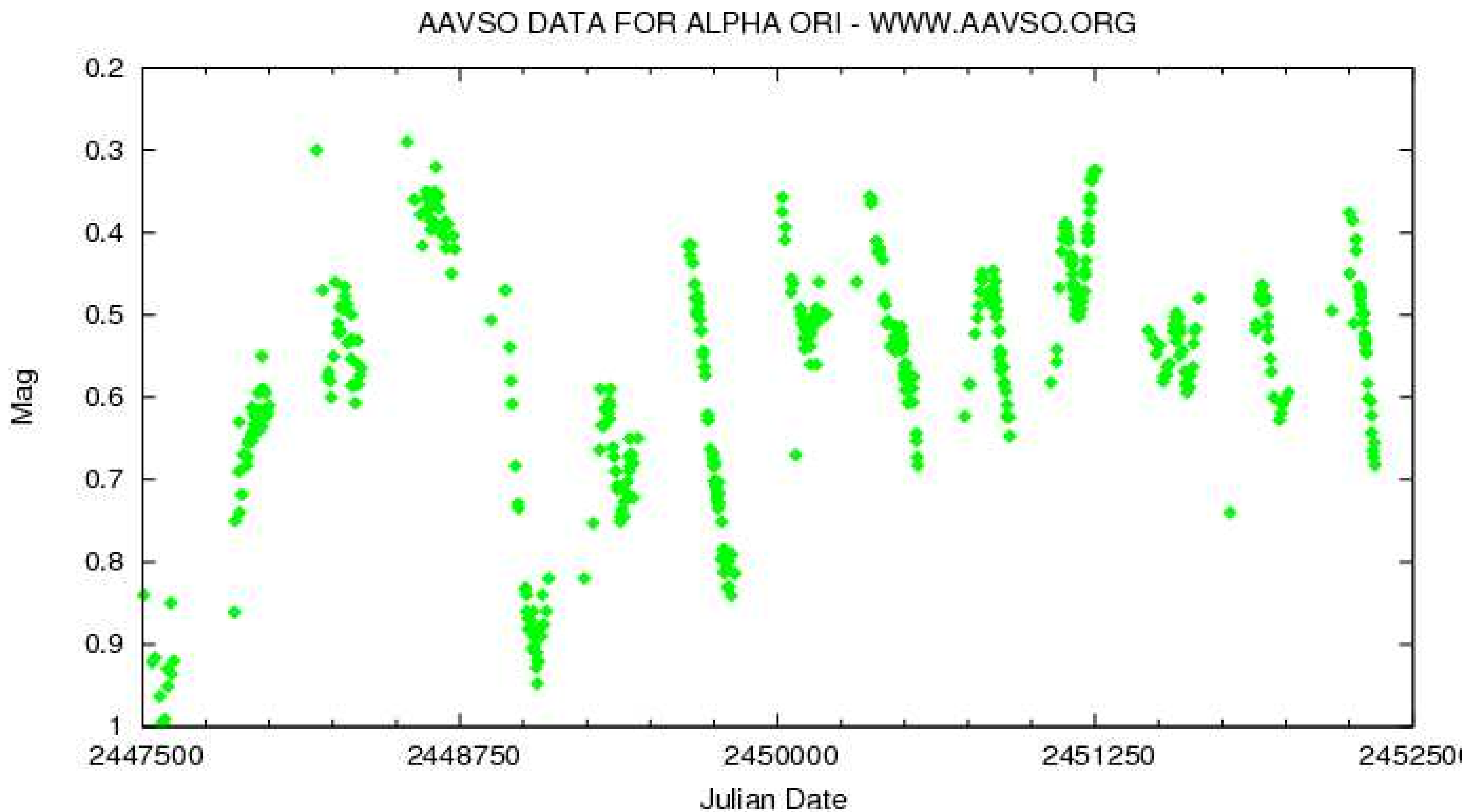
No dredge−ups => O−rich composition of the RSG atmospheres

Alternatives (at low Z)

- Type II Supernovae, Wolf-Rayet stars
- Red Supergiants (RSG)
  - * Several magnitudes of excess visual extinction (Massey et al. 2005) $\Longrightarrow$ large amount of CS dust
  - * In MW: return-rate in form of dust $R_{\rm AGB} \simeq 100 R_{\rm RSG}$
  - * At low Z: in principal: smaller mass-loss rates, but:
    - Stars at low Z need to rotate faster to evolve into RSGs
      $\Longrightarrow$ The higher the rotation speed, the longer the star remains in the RSG phase **the more mass is lost !** (Meynet et al. 2006)

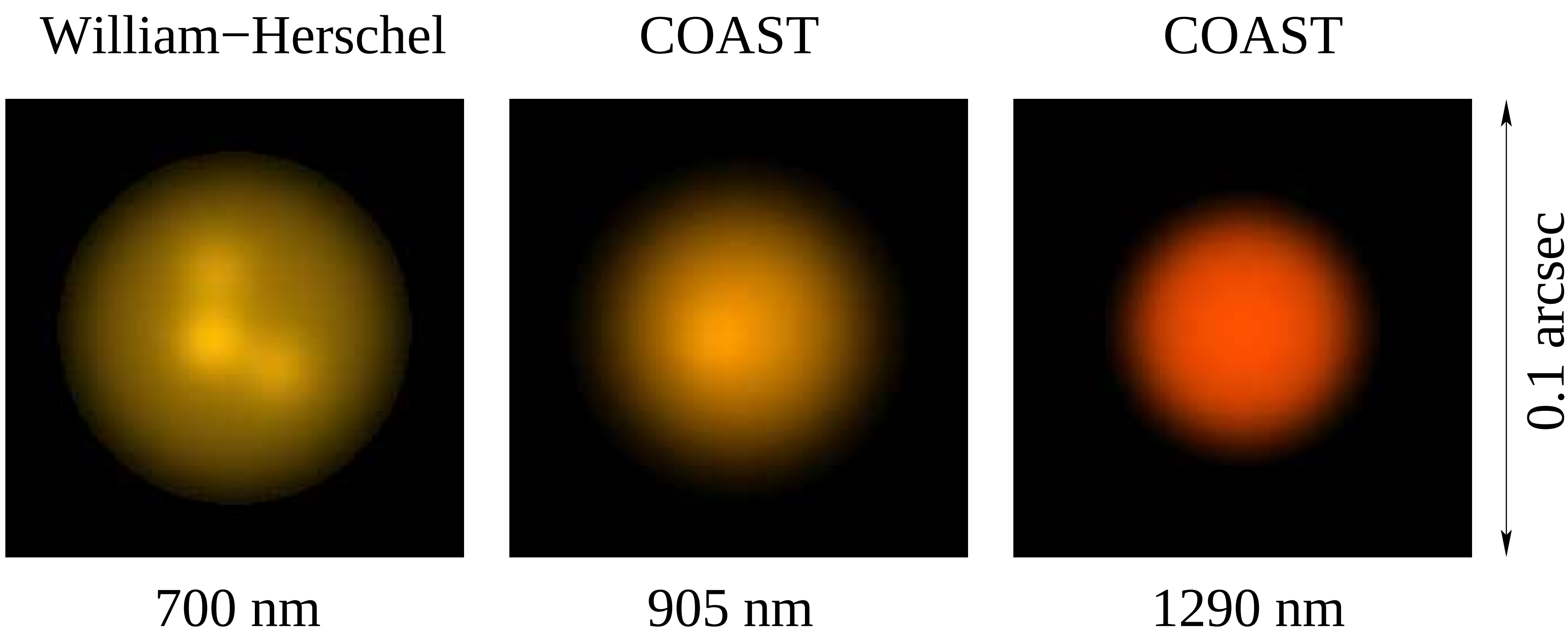
Especially at low Z, RSGs seem to be ideal candidates for dust production

Best studied galactic RSG : Betelgeuse



Irregular lightcurve : no regular pulsational mass−loss as in AGB stars !

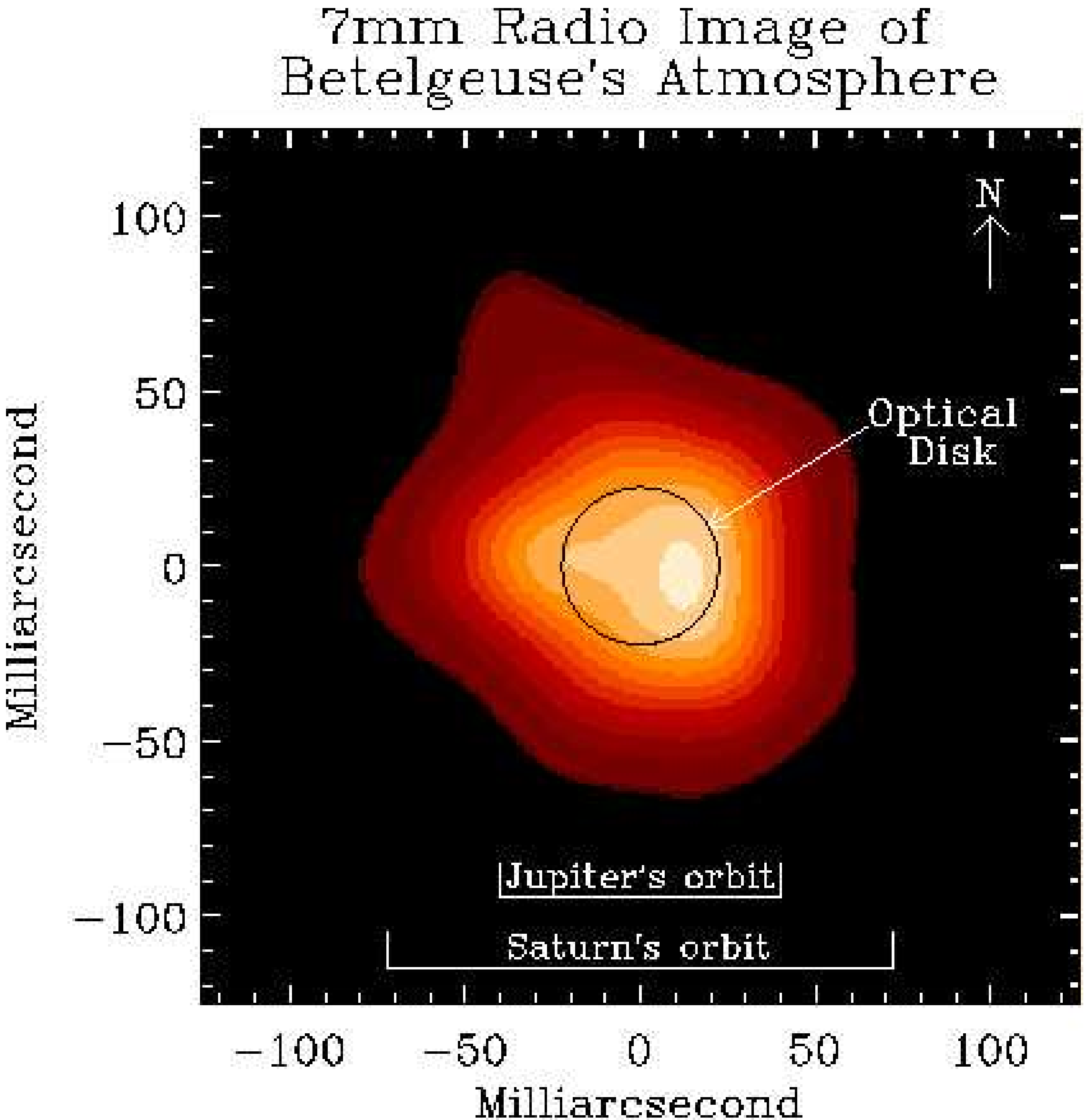
Young et al. (2000)



3 bright features ("hotspots") visible on the surface at 700 nm.

Only 1 feature at 905 nm; featureless, smaller surface in IR !

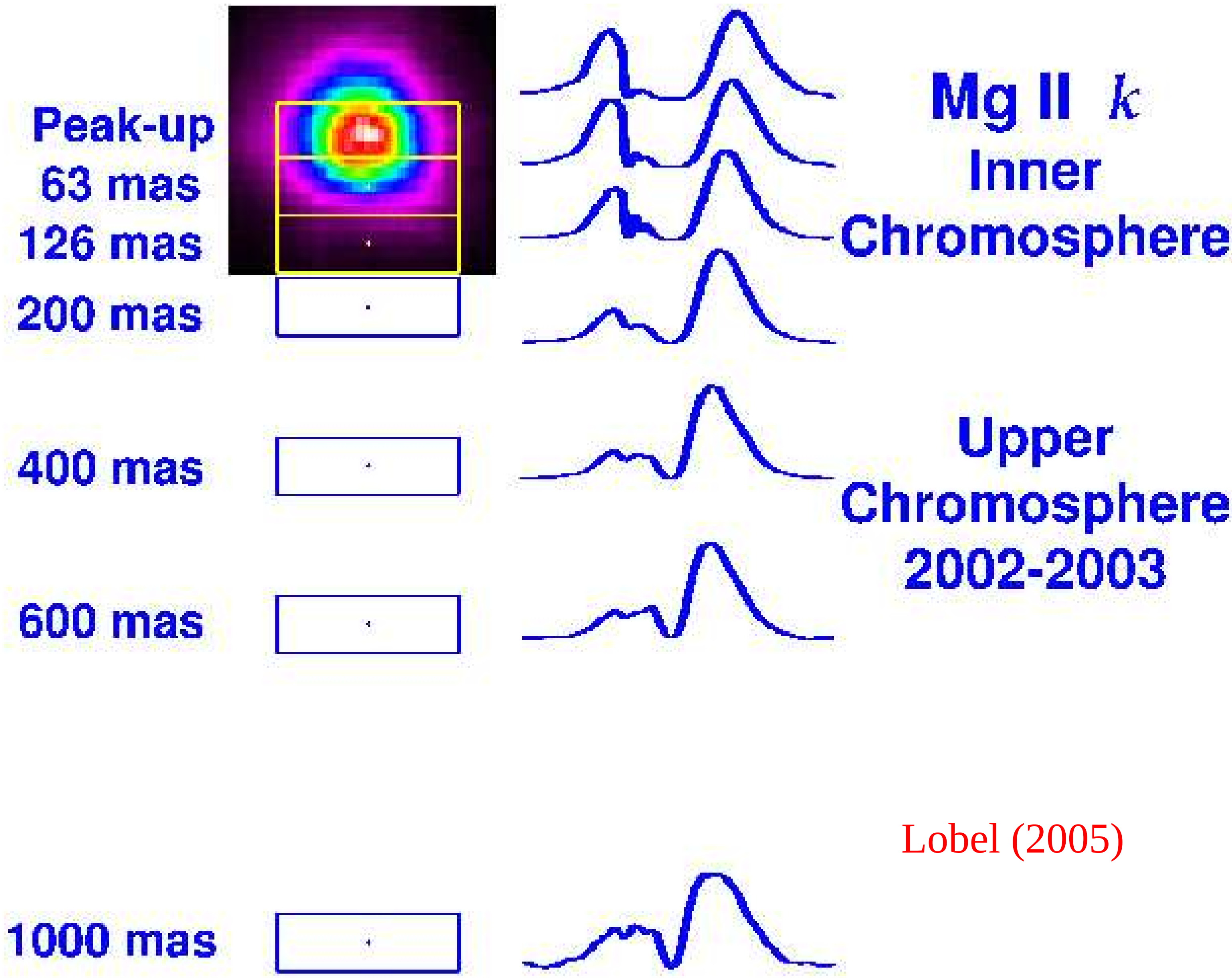
(resolution: 20−30 mas)



Lim et al. (1998)

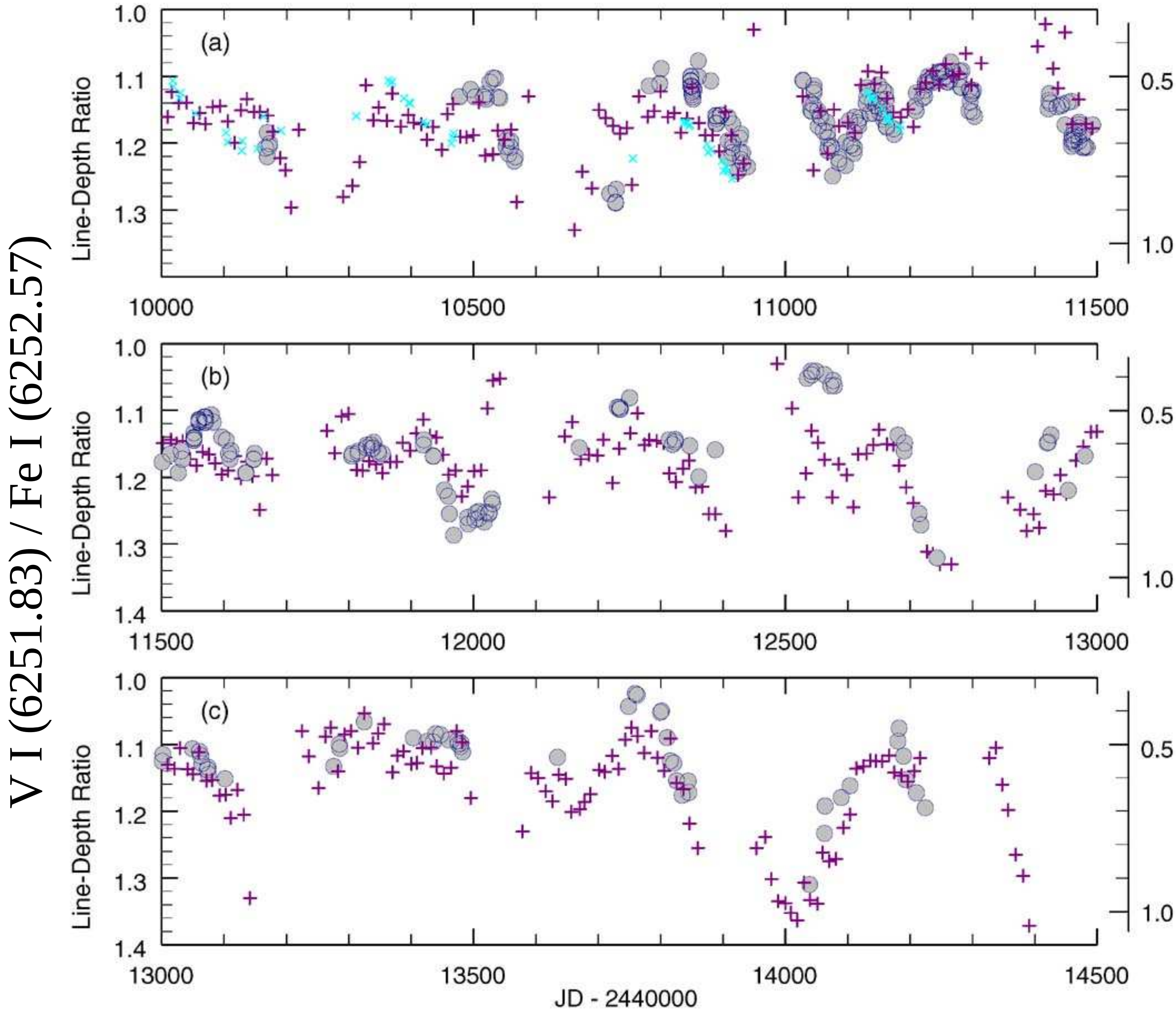
VLA detects

"Boiling" in the Atmosphere of Betelgeuse



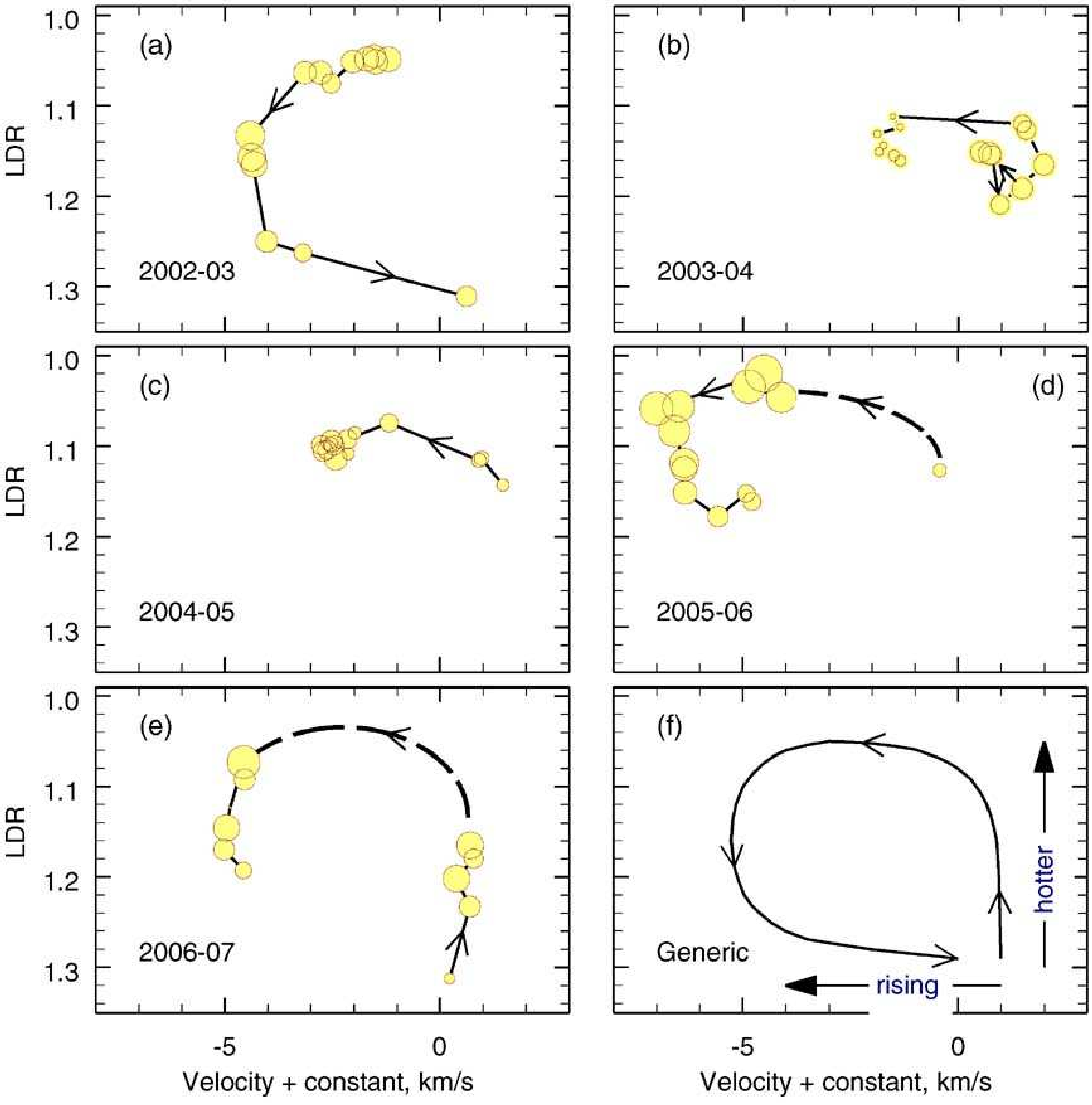
Lobel (2005)

Extended chromosphere seen in Mg II h & k lines (~ 120 R_star)



Line−depth ratio as temperature index (circles)

Overplotted: Visual Magnitudes from AAVSO (+) and photometric observations (x) from Krisciunas & Luedeke (1996)



Line−depth ratio as function of mean core velocity for individual observing seasons.

(Gray 2008)

Giant convection cells

Timescale: ~ 400 days

Major problems :

- What drives the mass-loss in RSGs ?
  - Must be linked to the strong convective motions in the atmosphere, resulting in temperature inhomogeneities and steep velocity gradients (Josselin & Plez 2007).

Latest (newest) numerical approaches :

MARCS (Model Atmospheres in Radiative and Convective Scheme, Gustafsson et al. 2008: http://marcs.astro.uu.se) :

- Limitations:
  - 1D, LTE, hydrostatic equilibrium, spherical symmetry
  - classical 1D models not capable to provide large and non-gaussian velocity fields in atmosphere
- Needed improvements (Gustafsson 2008):
  - A full non-LTE treatment of the electronic transition, taking into account optical depth effects.
  - Coupling with hydrodynamics.
  - Data needs: molecular opacities, absorption cross-sections of diatomic and polyatomic molecules, cross-sections for atomic and molecular collisions with electrons and hydrogen atoms

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CO^{5}BOLD (COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions, Freytag 2002: www.astro.uu.se/∼bf/co5bold_main.html) :

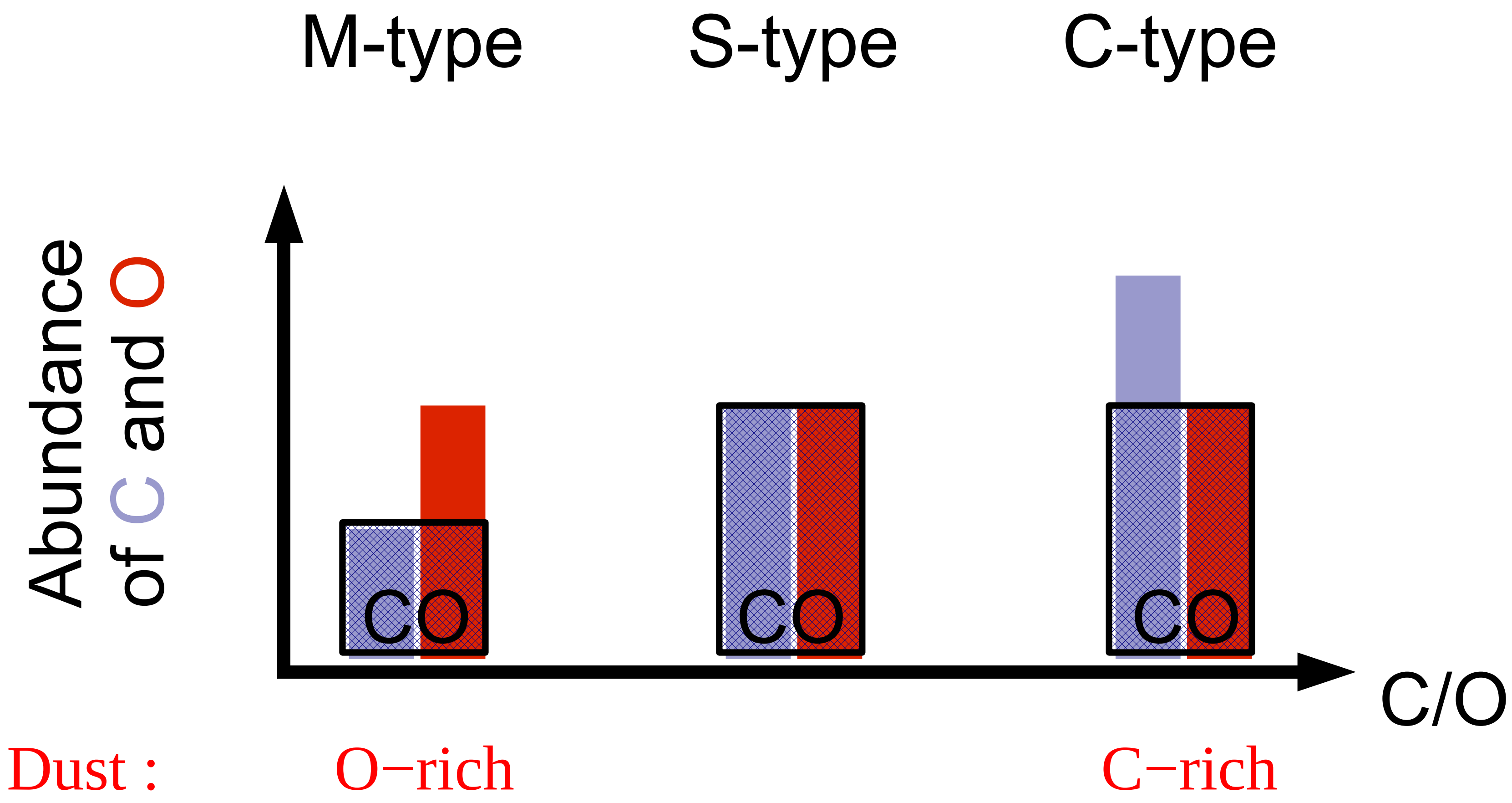
- 3D radiative HD simulations
- star-in-a-box calculations
- Limitation:
  - simplified grey radiation transfer
  - Simulation snapshot has to be used to compute detailed RT (e.g. Chiavassa 2008)

Major problems :

- What drives the mass-loss in RSGs ?
  - Must be linked to the strong convective motions in the atmosphere, resulting in temperature inhomogeneities and steep velocity gradients (Josselin & Plez 2007).

- How is dust formed in an O-rich environment ?
  (and especially at low Z where initial abundance in Si is reduced)

Atmospheric Chemistry of AGB stars: The Simple Picture



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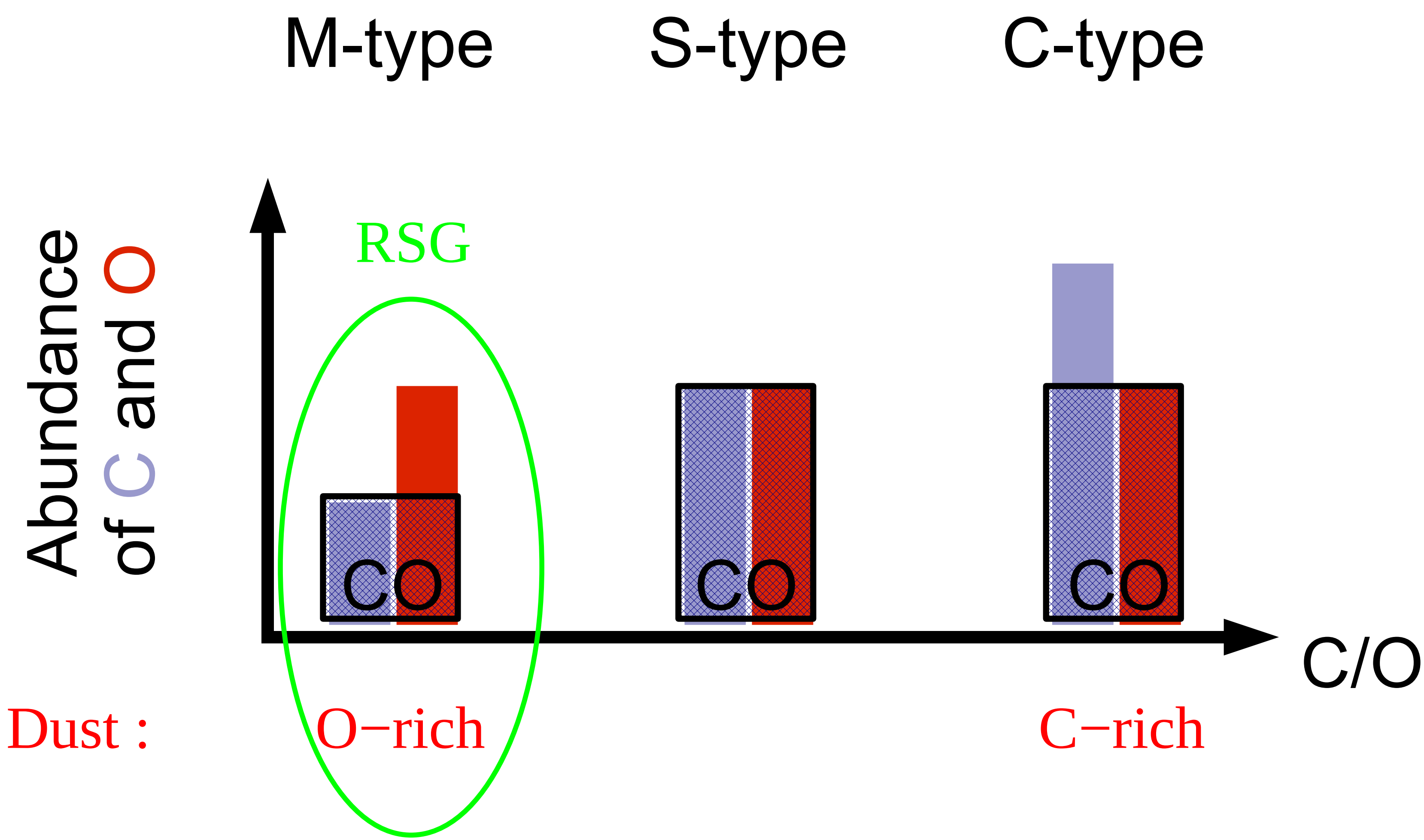
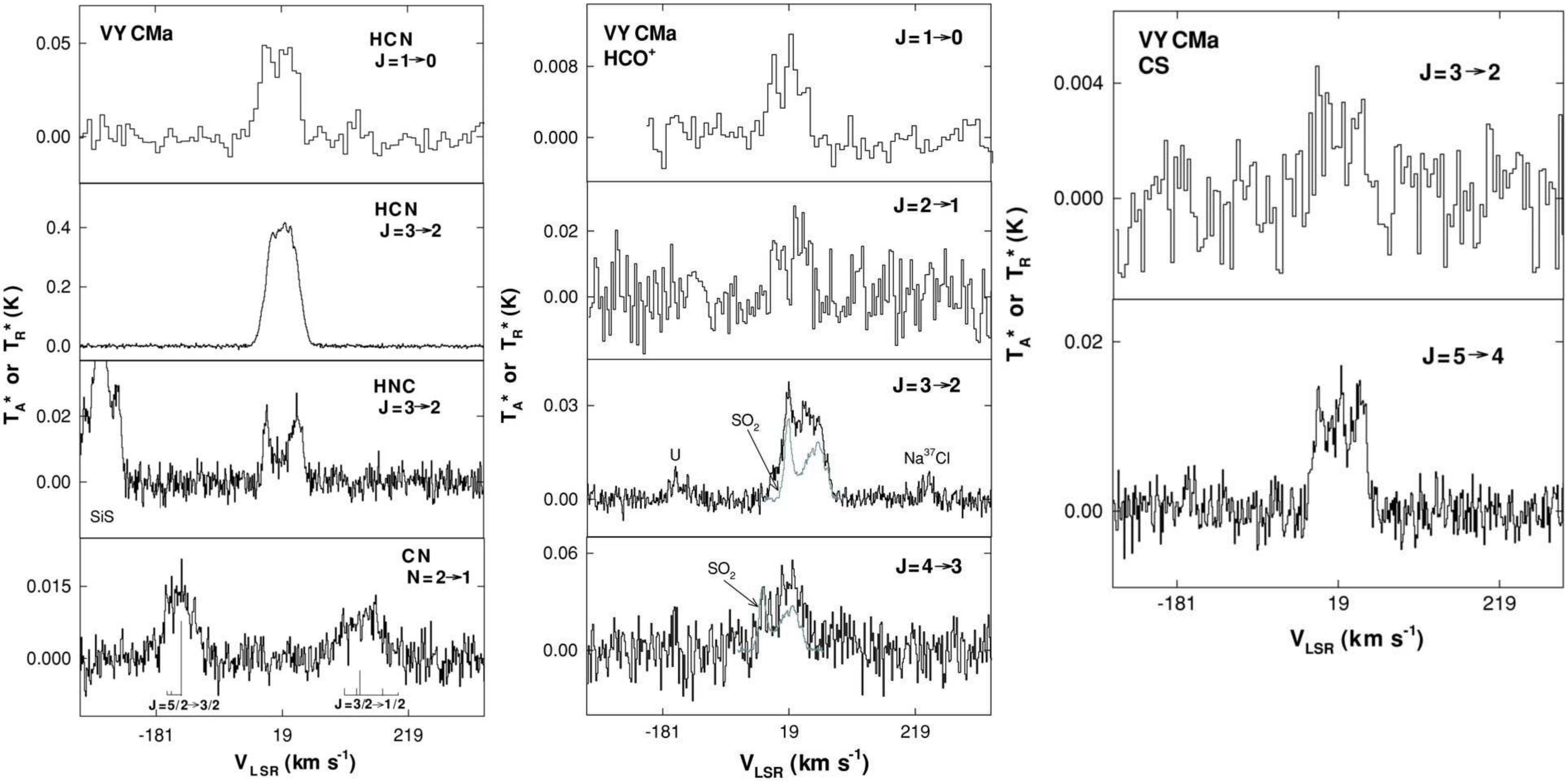
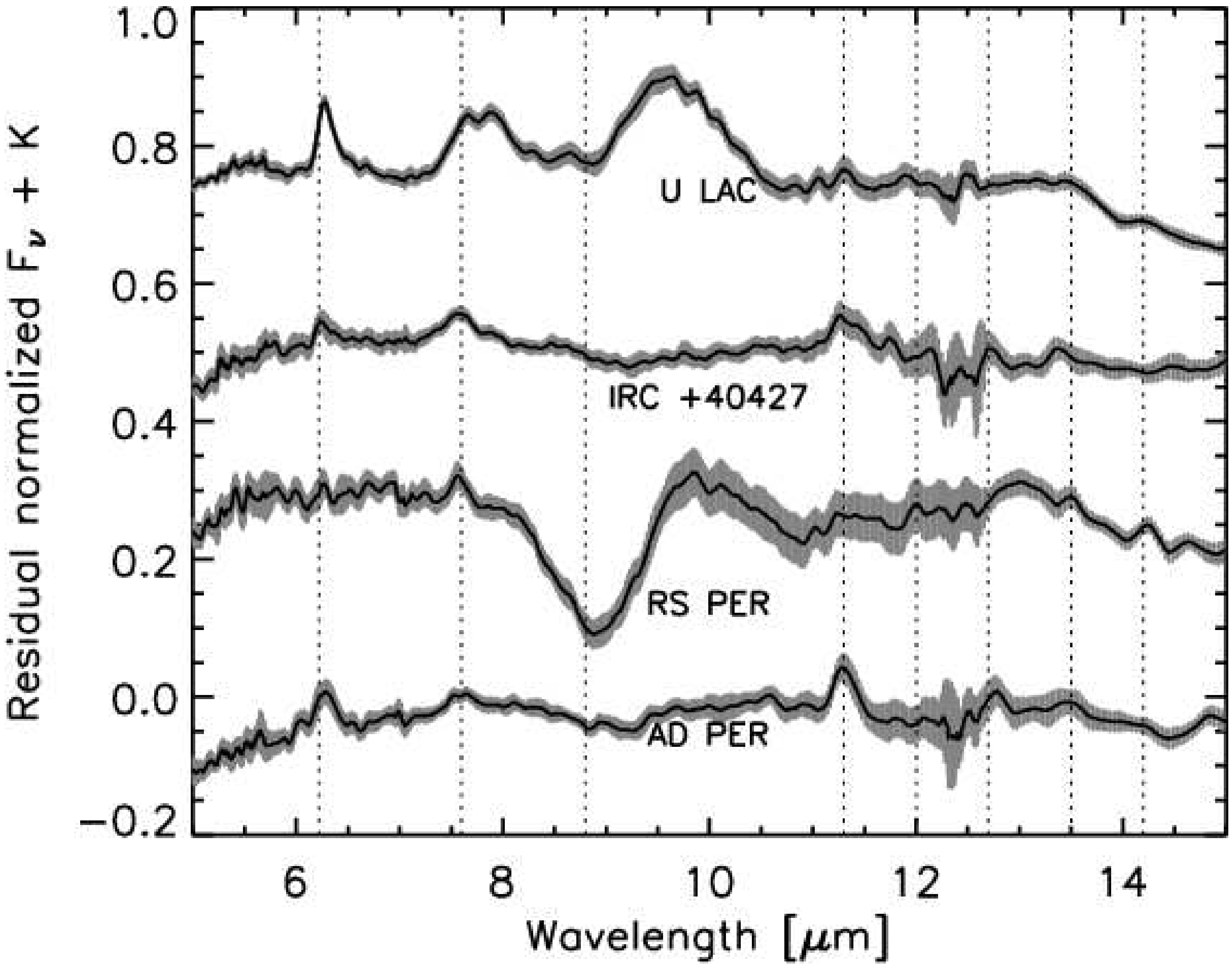


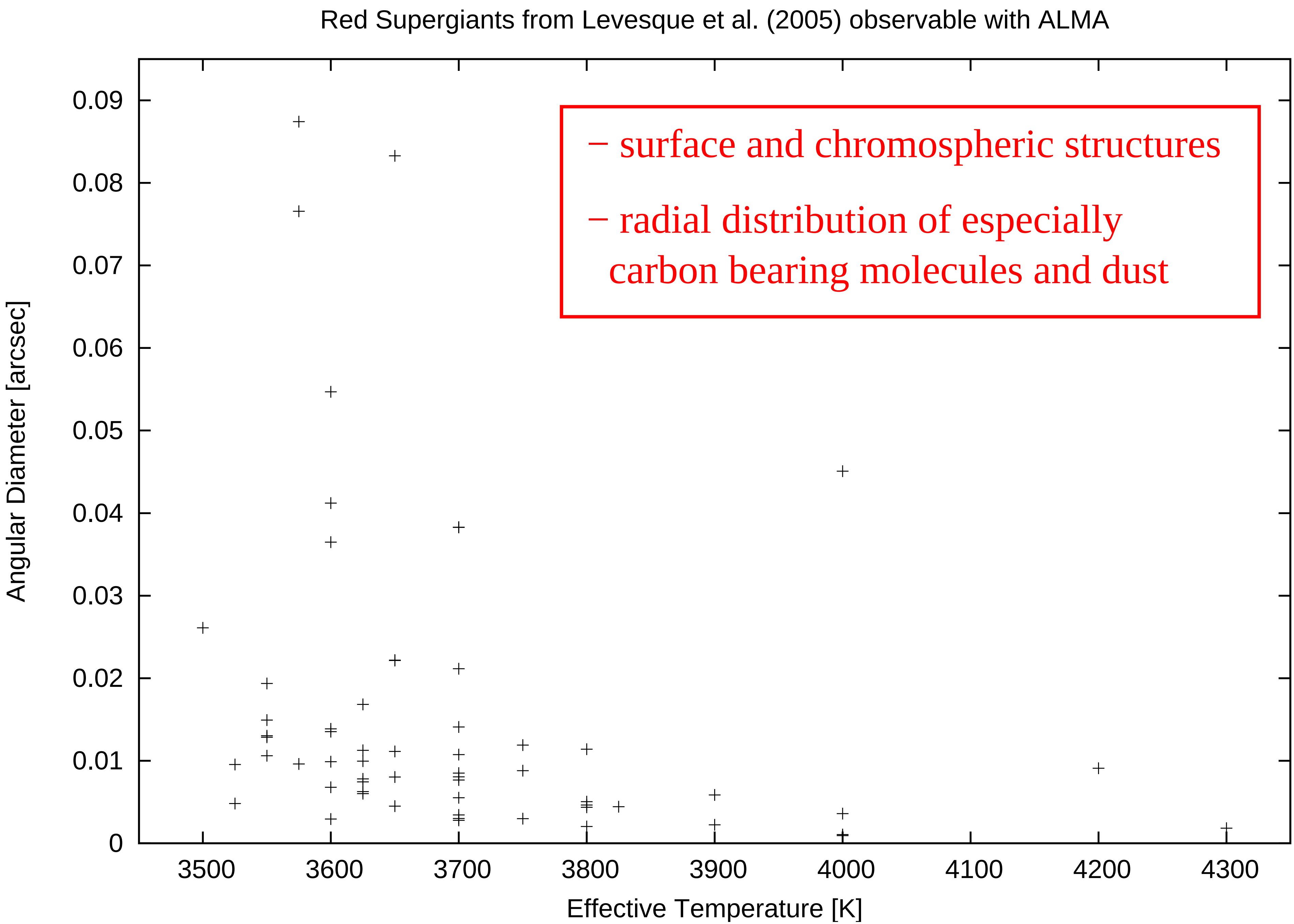


Carbon bearing molecules detected in O−rich environment of RSGs (Ziurys et al. 2009)

PAHs in ISO−SWS spectra of RSGs (Verhoelst et al. 2009)



Highly non−equilibrium chemistry in the winds of RSGs !!



Red Supergiants from Levesque et al. (2005) observable with ALMA
− surface and chromospheric structures
− radial distribution of especially carbon bearing molecules and dust
Angular Diameter [arcsec]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
3500
3600
3700
3800
3900
4000
4100
4200
4300
Effective Temperature [K]

Conclusions :

- Improved data (molecular opacities, absorption and collision cross sections) are needed for more realistic model atmosphere calculations

- Full non-LTE 3D hydro code definitely needed for simultaneous computation of the surface structure (large convection cells) and emerging lines

- Implementation of non-equilibrium processes (formation of carbon molecules/dust in O-rich environment) for better understanding of mass-loss processes and wind driving mechanisms