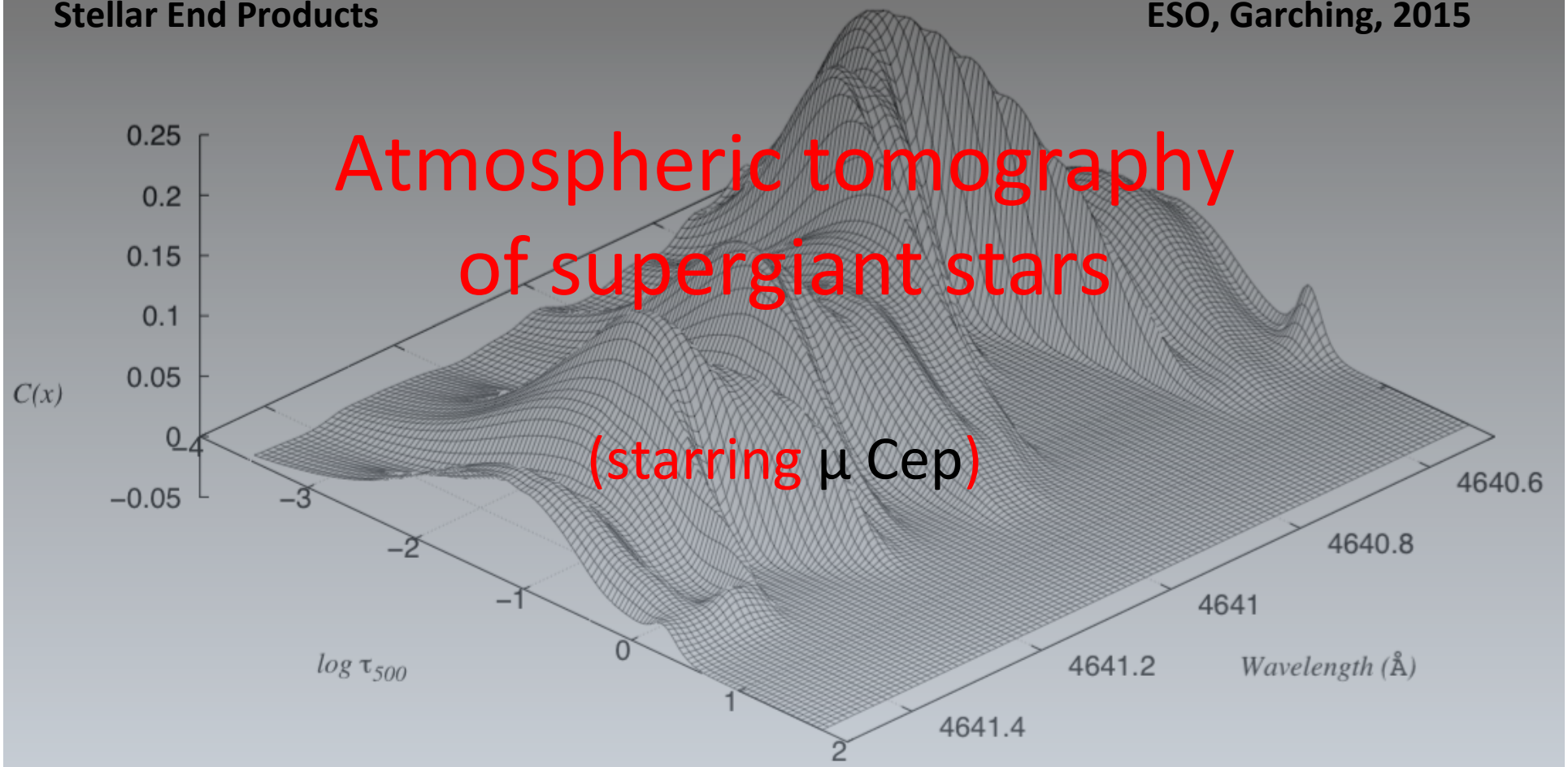
# Atmospheric tomography of supergiant stars

## (starring μ Cep)

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(Université de Montpellier II)

Based on observations carried out with the HERMES spectrograph on the Mercator 1.2m telescope

# Tomography: I.1 technique

- Aim is to probe velocity fields in stellar atmospheres

Alvarez et al. (2000, A&A 362,655; 2001 A&A379, 288; 2001, A&A 379, 305)

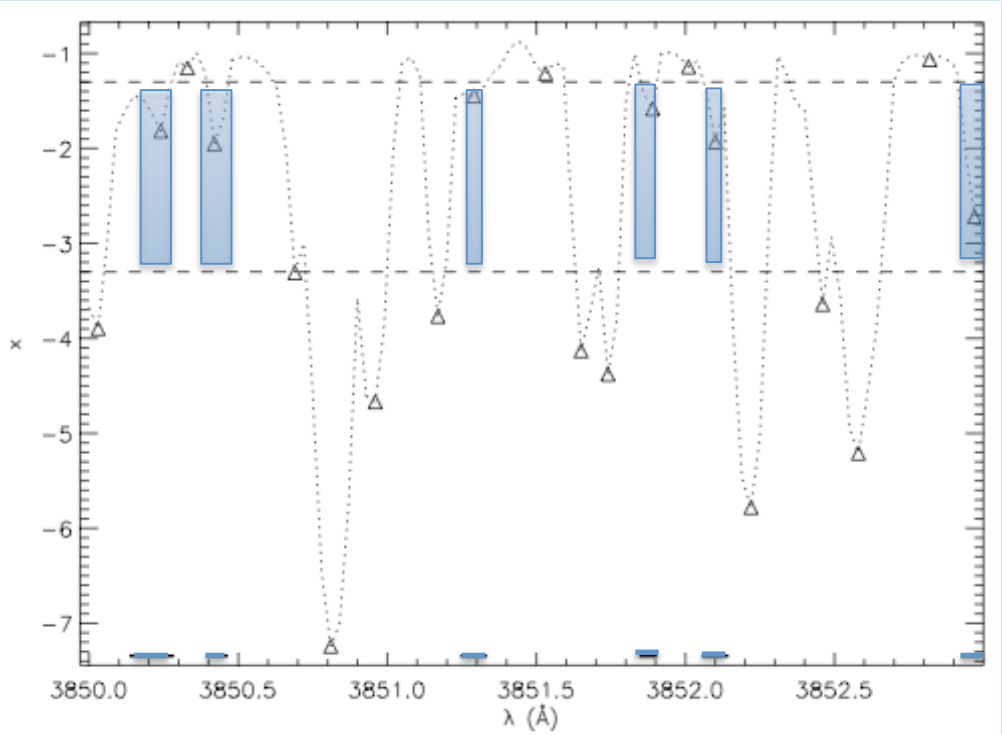
➔ cross-correlate the observed spectrum with numerical masks

probing layers of increasing depth

- Construction of the numerical masks :

Computation of the depth function: $\tau_{500nm} = C(\lambda;$ where $\tau_\lambda = 2/3)$

$X = \log(\tau_{500})$




Region I (innermost)

Region II (middle)

Region III (outermost)

➔Holes in mask II probing middle layer

# Tomography: I.2 technique (improved)

Instead of imposing $\tau_\lambda = 2/3$ for defining the mask holes,

computation of « *contribution function* » expressing the depth of formation of spectral lines :

Albrow & Cottrell (1996, MNRAS 278, 337):

contribution function to the spectral-line flux depression:

$$C_U(\tau_0) = \int_0^1 \frac{\kappa_l}{\kappa_c + \kappa_l}(I_c - S_l)e^{-\tau/\mu}d\mu$$

with $S_l$, $I_c$, $\mu$, $\tau$, $\kappa_l$, $\kappa_c$ taken from TURBOSPECTRUM (Alvarez & Plez 1998) using MARCS (1D) model atmospheres.

# Tomography: I.3 technique (improved)

$S_l$, $I_c$, $\mu$, $\tau$, $\kappa_l$, $\kappa_c$ taken from TURBOSPECTRUM (Alvarez & Plez 1998)
using MARCS (1D) model atmosphere:

Contribution function C(λ,τ) for the Fe I λ6546.245 line:

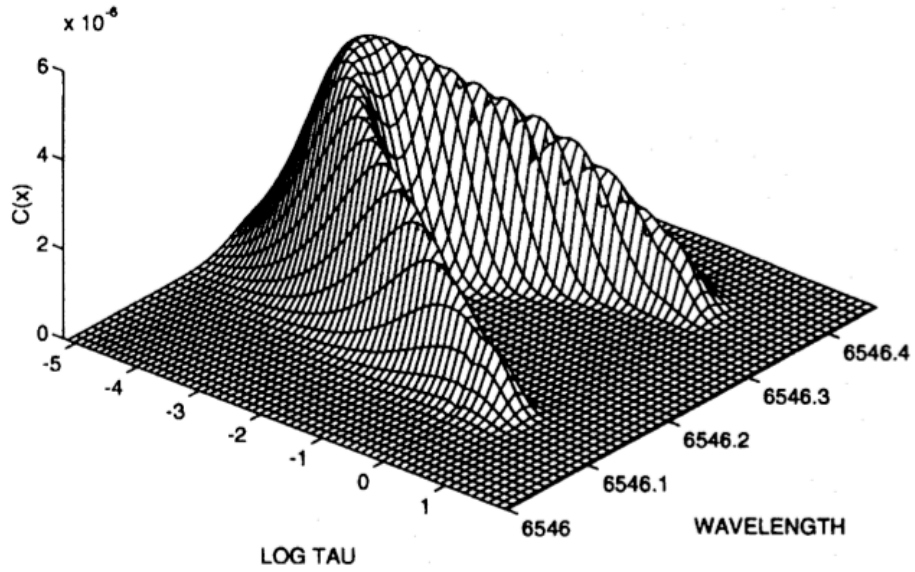
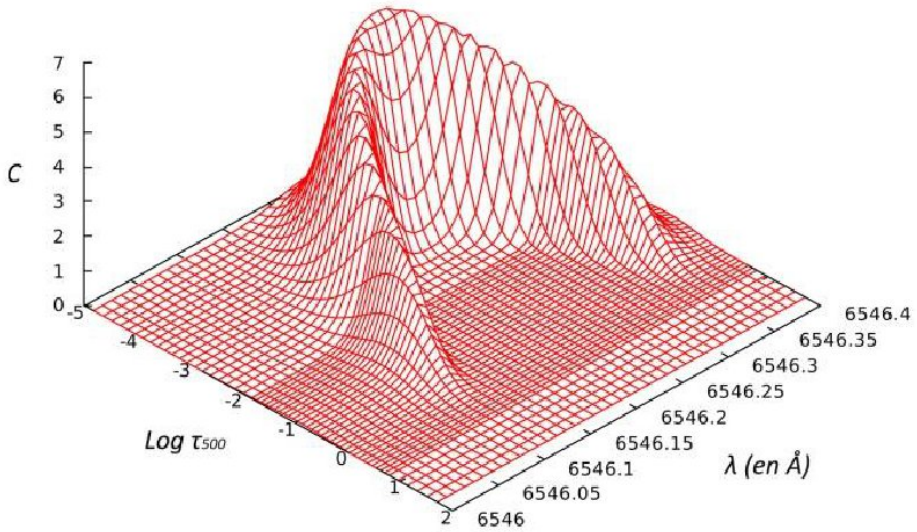



**Figure 1.** Flux contribution function for the Fe I 6546.245-Å line, with $\log gf = -2$ and for a standard static solar abundance Kurucz model atmosphere with $T_{\rm eff} = 5000$ K, $\log g = 1.0$ and $\xi = 2$ km s$^{-1}$.

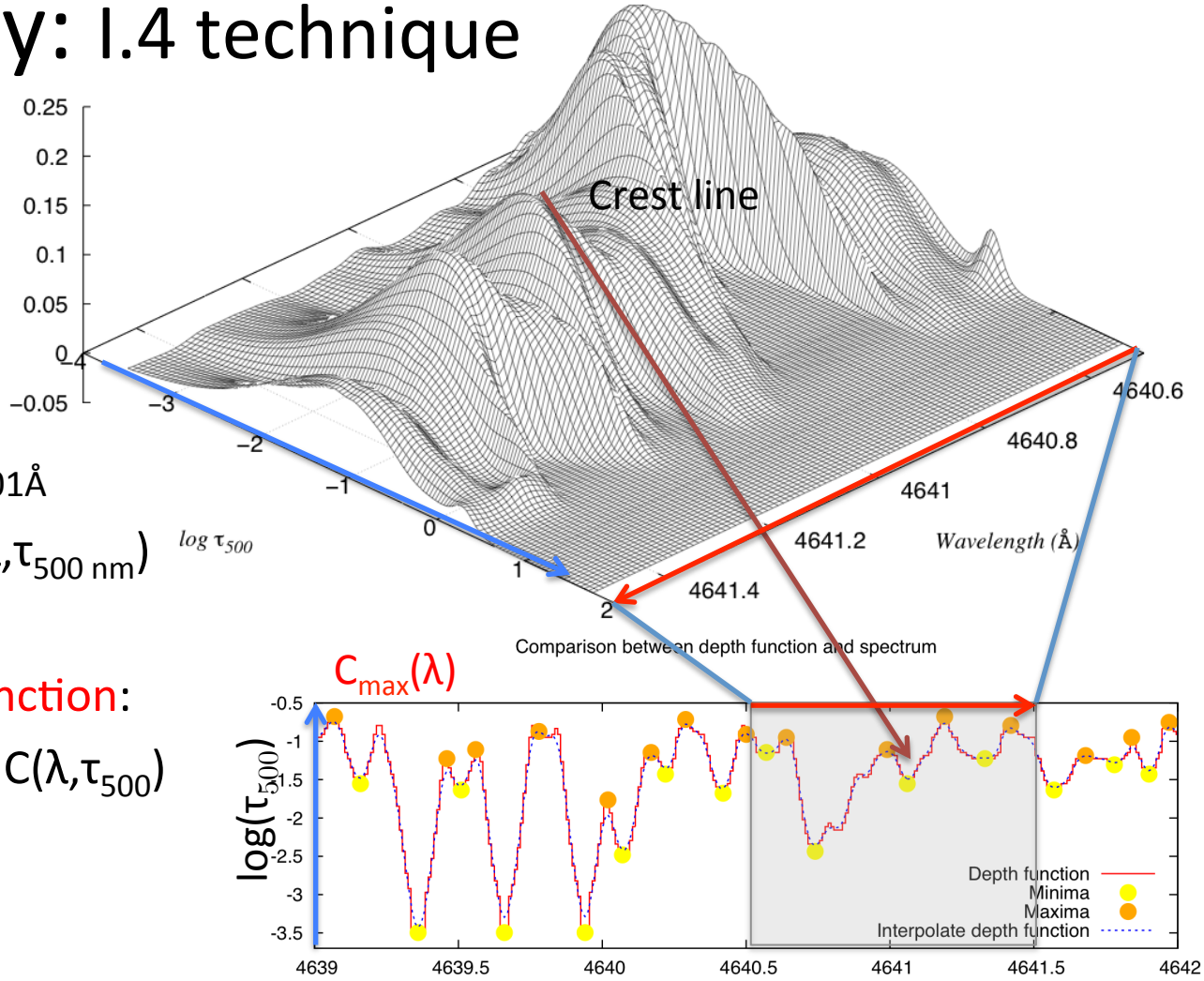



Albrow & Cottrell 1996

Same spectral line, this work

# Tomography: I.4 technique

- For RSG:
  - Teff = 3490 K
  - log g = -0.6
  - M = 12 $M_{\odot}$
  - Solar composition
  - Microturbulence 2 km/s
  - Spectral resolution: Δλ = 0.01Å
- Contribution function $C(\lambda,\tau_{500\ nm})$




- Computation of depth function:

$C_{max}(\lambda) = \tau_{500}$ of max $C(\lambda,\tau_{500})$

**on all τ**

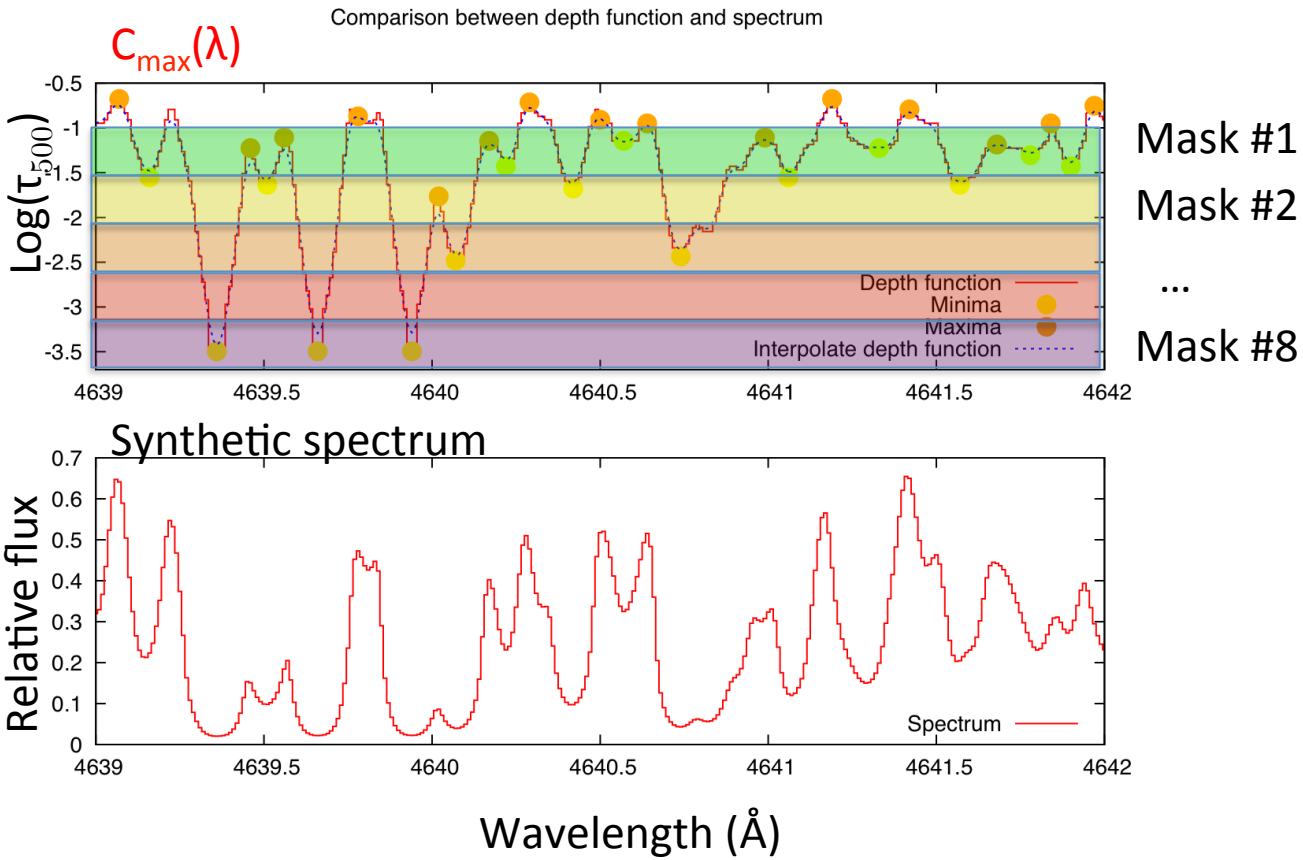
Wavelength (A)

# Tomography: I.5 technique (improved)

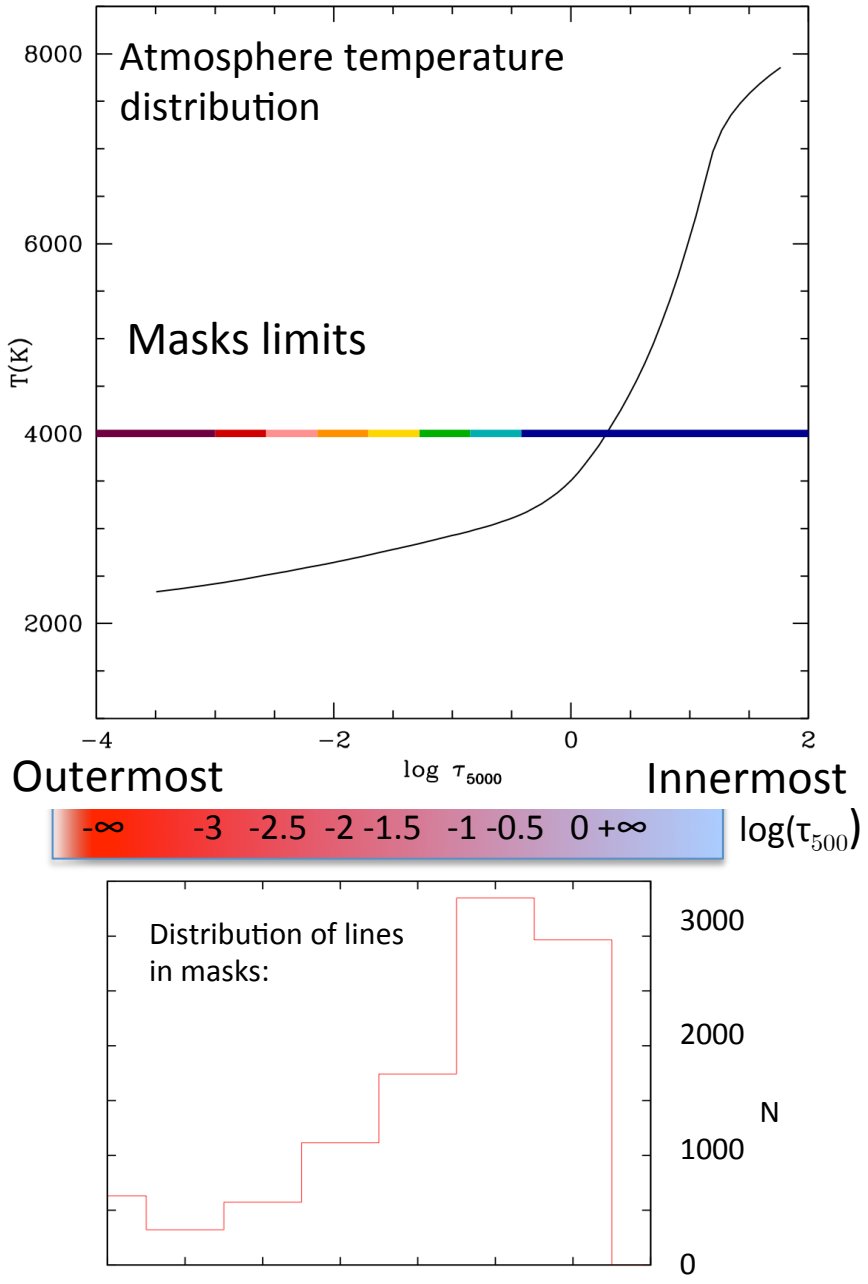
- Computation of depth function:

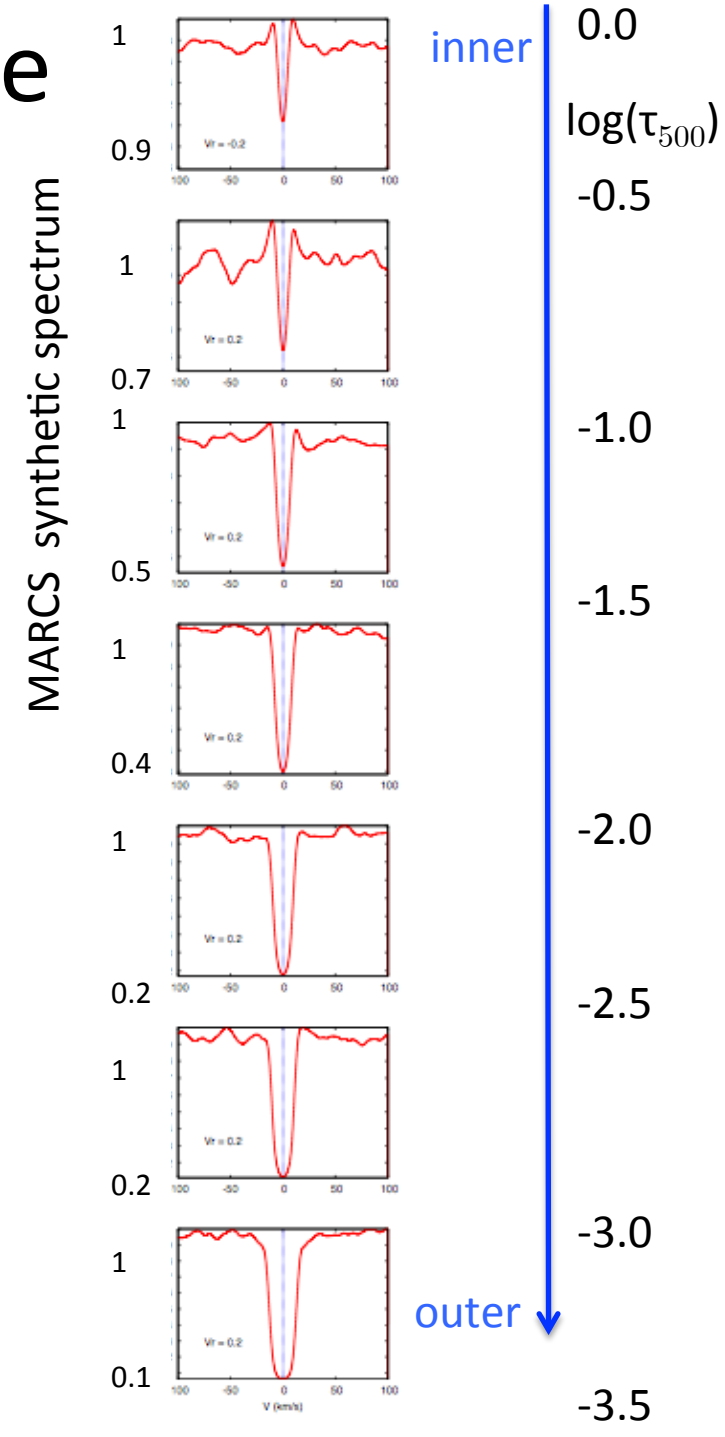
$C_{max}(\lambda) = \max_{\text{for all } \tau} C(\lambda,\tau)$ $\quad (370 < \lambda\,(nm) < 910)$

- Atmosphere split in 8 vertical layers
- In each layer, mask hole when $C_{max}(\lambda)$ is minimum (in $\tau_{500}$)



# Tomography: I.6 technique



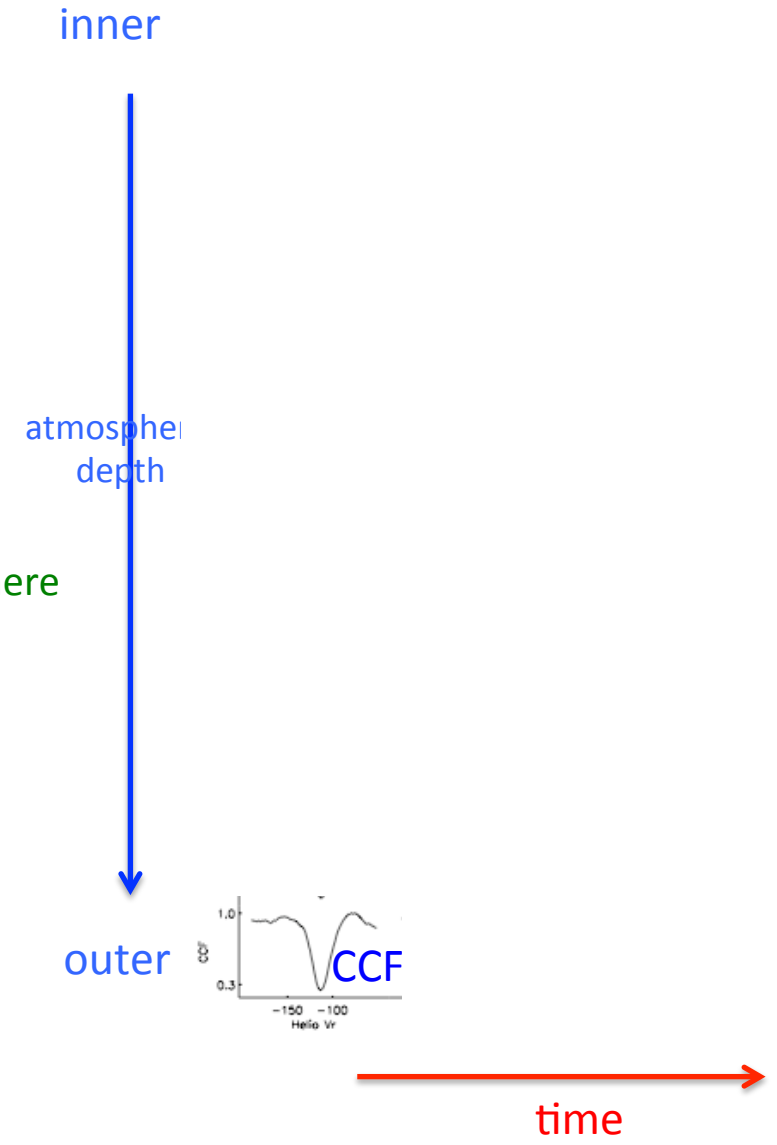



# Tomography: II. Application to Miras

Alvarez et al. 2000, A&A 362,655

- Cross-correlation of observed spectrum with mask function
  = CCF (Cross Correlation Function)

- Follow the progression of a shock wave in the atmosphere
  - Spatially
  - temporally



# Tomography: III. Interpretation

Alvarez et al. 2000, A&A 362,655

The Schwarzschild mechanism

Lagrangian description
of the pulsating atmosphere

Evolution of
Mira star CCF
with depth

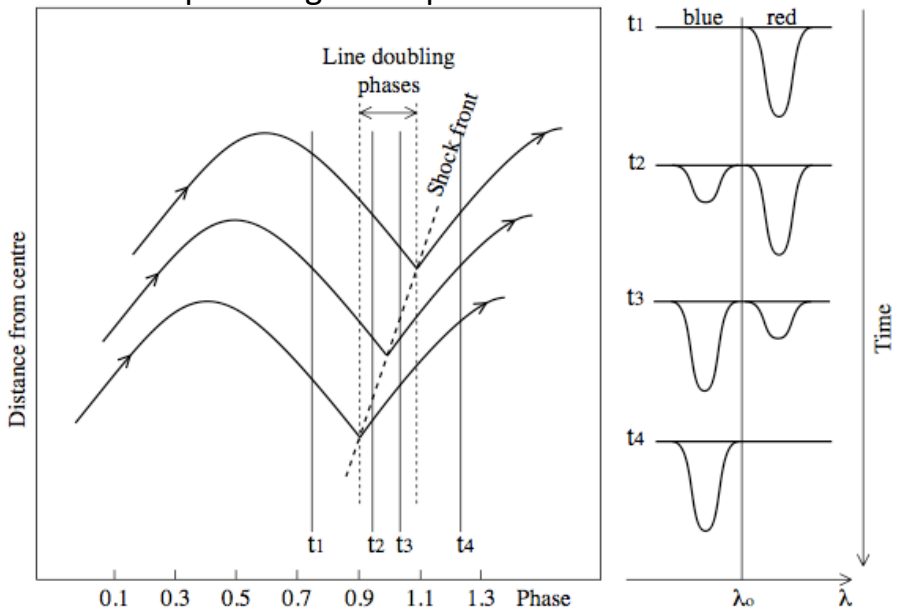



**Fig. 1.** The Schwarzschild scenario: temporal sequence followed by the intensity of the red and blue components of absorption lines close to light maximum, when the shock wave propagates through the photosphere, in the absence of any complication due to radiative processes associated with the shock wave

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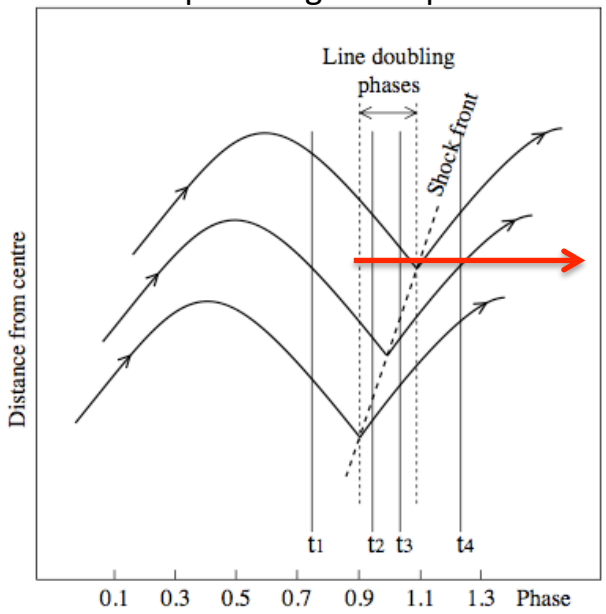


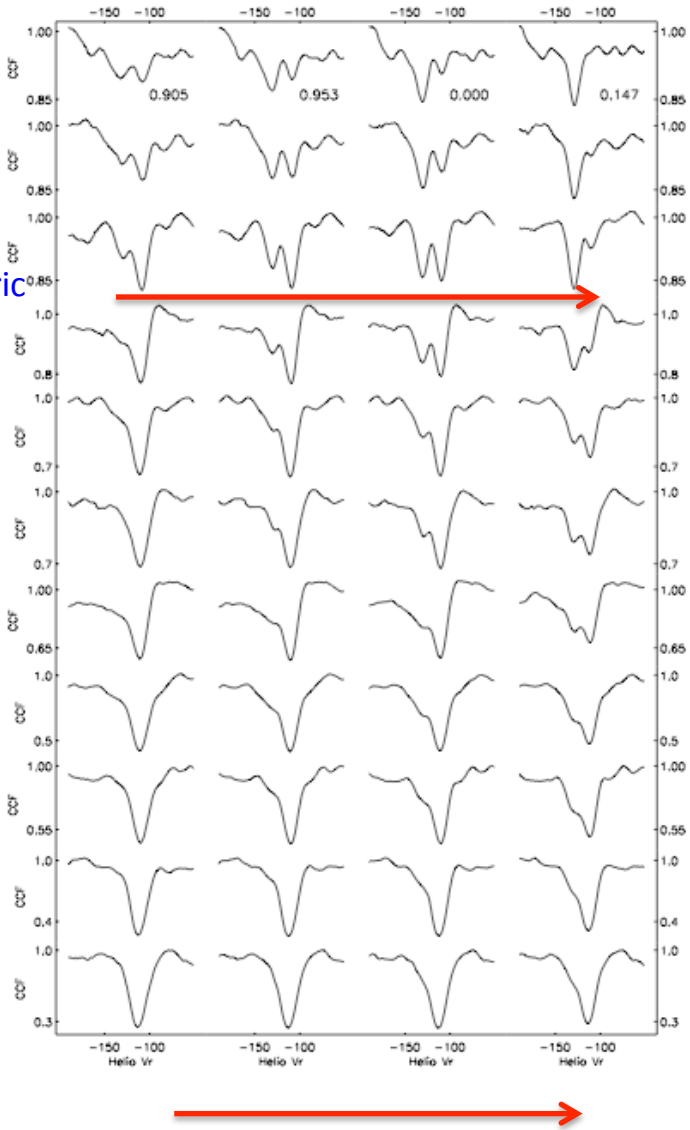

**Fig. 1.** The Schwarzschild scenario: temporal sequence followed by the intensity of the red and blue components of absorption lines close to light maximum, when the shock wave propagates through the photosphere, in the absence of any complication due to radiative processes associated with the shock wave

Evolution of
Mira star CCF
with time at
given depth

inner

atmospheric
depth

outer




time

# Tomography: IV. Application to sg

Josselin & Plez 2007, A&A 469, 671

- Same technique and masks, applied to supergiant stars
- No cyclic behaviour
- Steep velocity gradients are observed on time scales of ~ 150 days

inner

outer

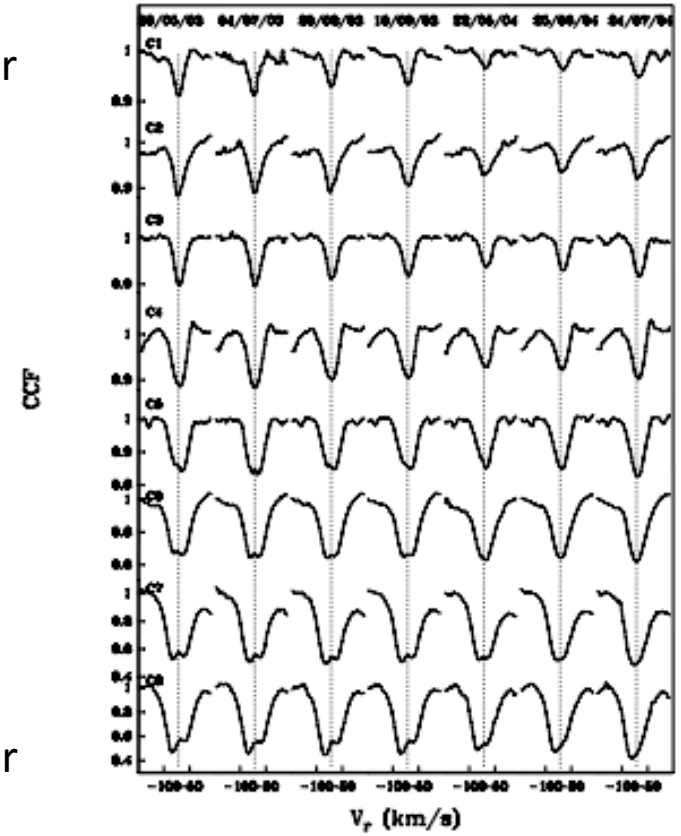



**Fig. 4.** CCF profiles for SW Cep. The dashed vertical lines indicate the central velocity measured in mask C1 at first epoch (upper left profile).

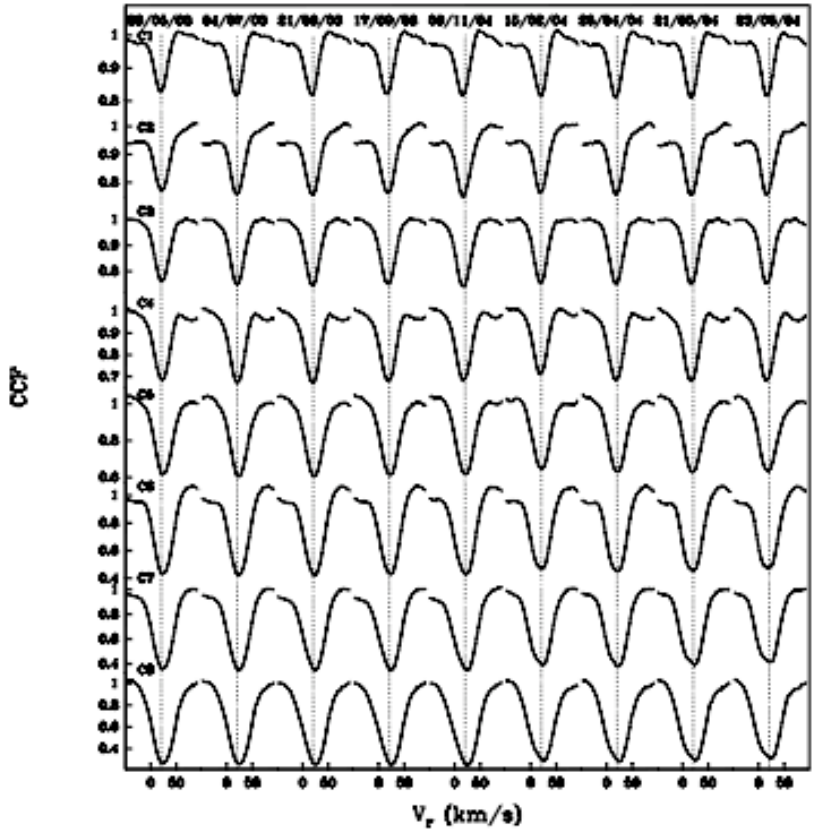



**Fig. 5.** Correlation profiles for $\mu$ Cep. The vertical dashed lines indicate the central velocity measured in mask C1 at first epoch (upper left profile).

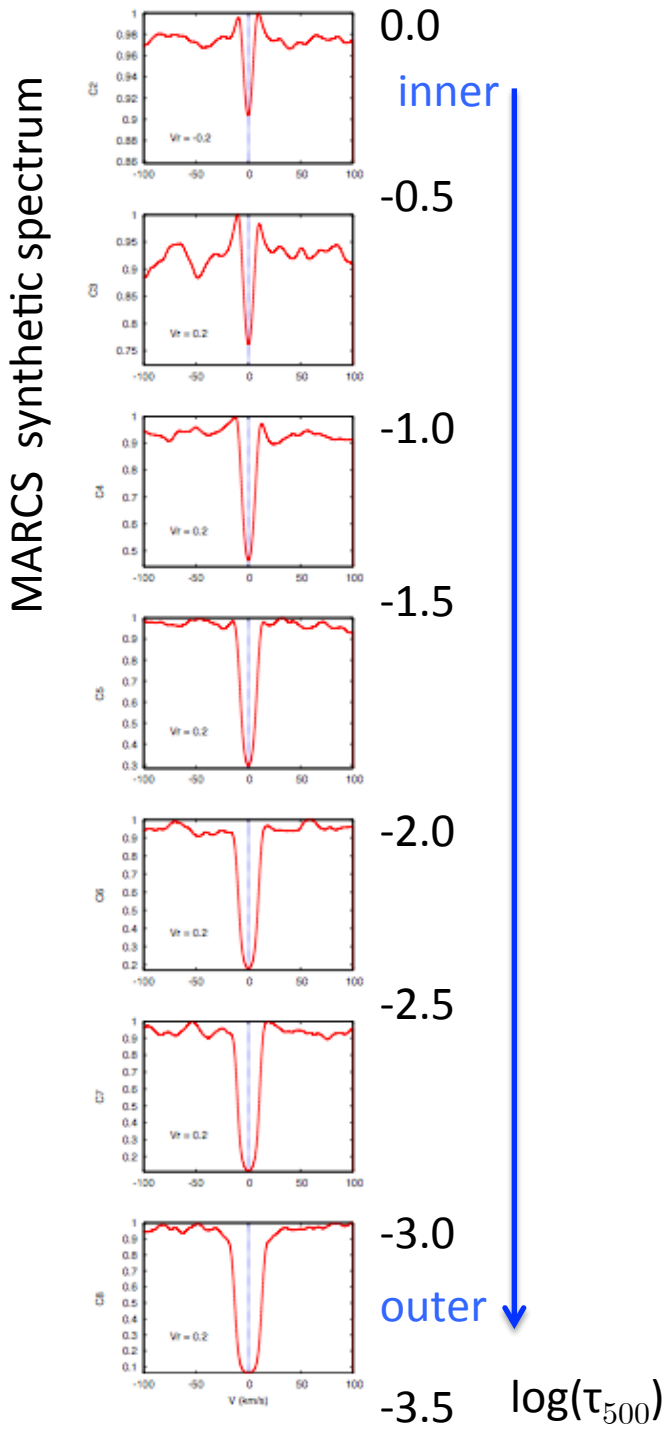
# V. Application to μ Cep

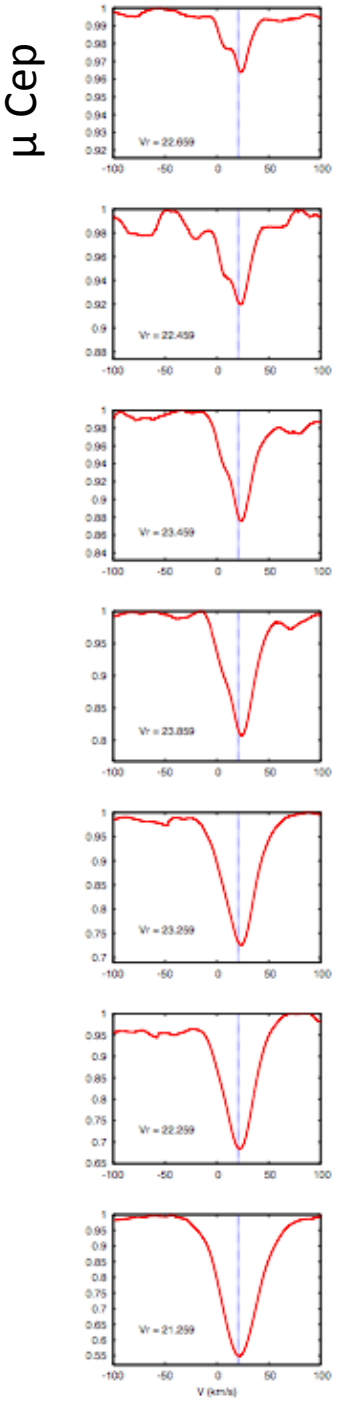
66 high-resolution
(R = 86 000) spectra of μ Cep

obtained on the HERMES spectrograph (Raskin et al. 2011) on MERCATOR telescope (La Palma)

Δt = 1505 d

Compute CCF (Radial Velocity)



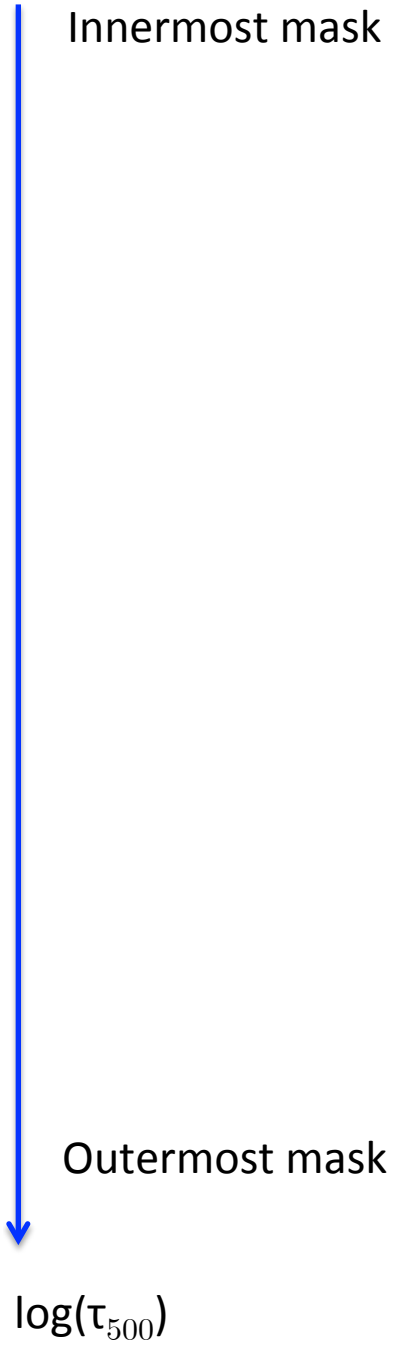



The dance of the supergiant:

Time lapse μ Cep

April 2011 – Jan 2015

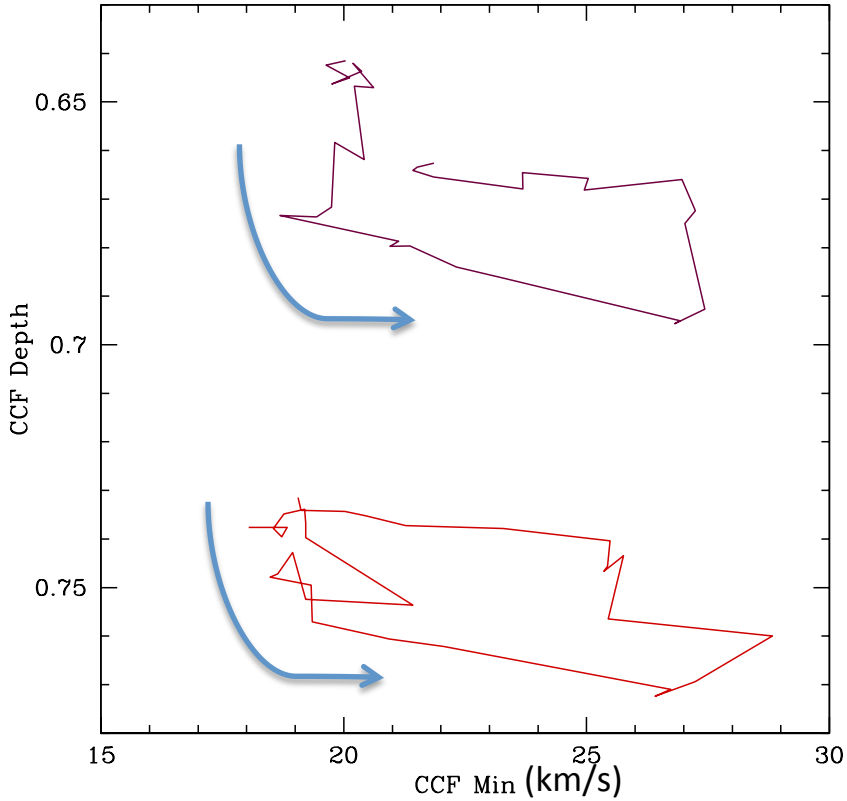
(see the attached file
tomo.mov)



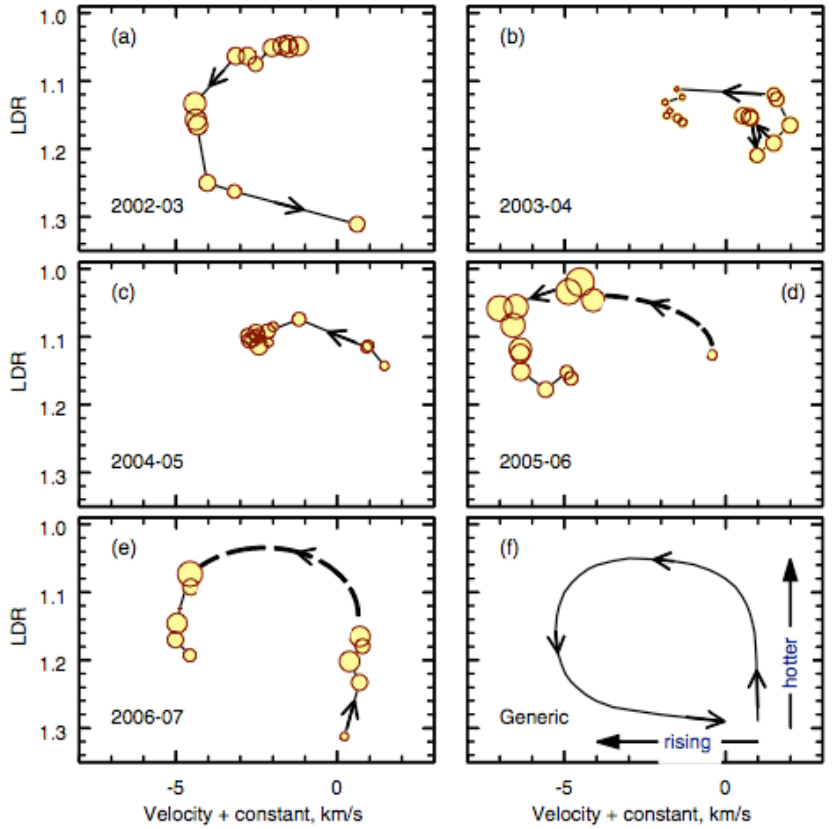
# Phase relation between velocities and line depth (ratio)

## Hysteresis (caused by convective cells?)

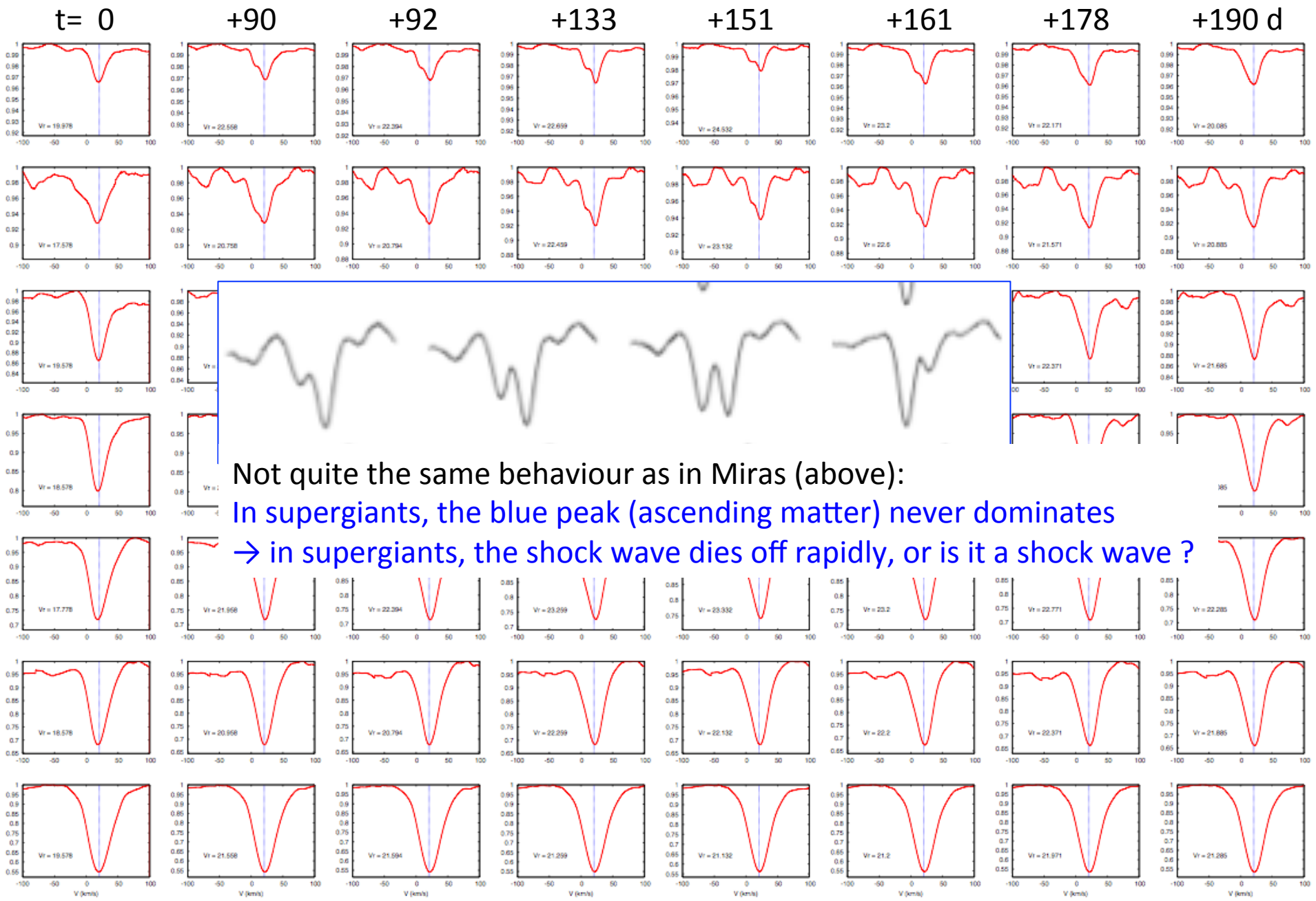
LDR = Line Depth(VI)/Line Depth(FeI)




μ Cep
Observation: 550 d




Gray, 2008, AJ 135, 1450
Betelgeuse
Typical time 400 d

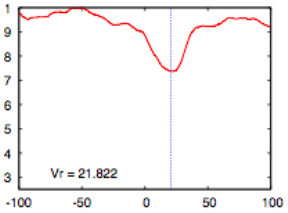
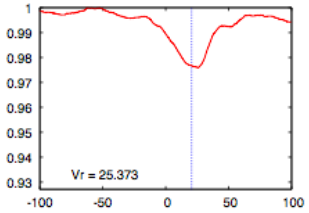
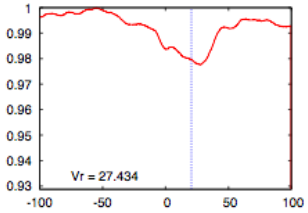
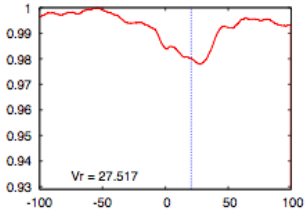
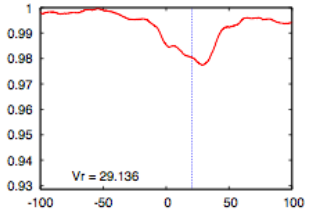
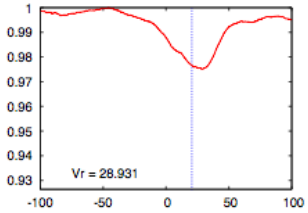
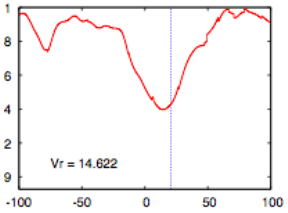
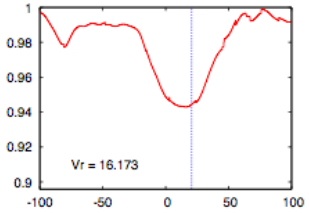
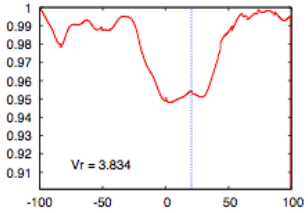
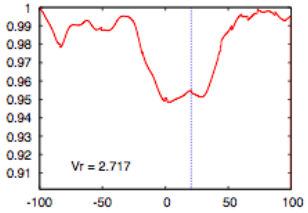
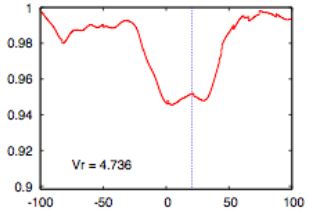
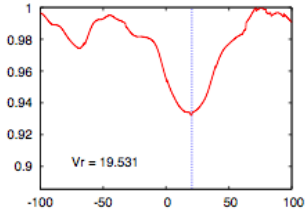
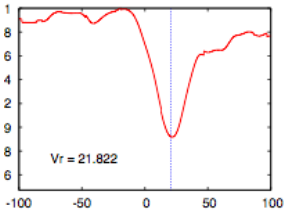
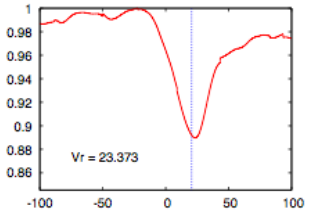
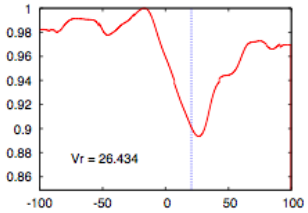
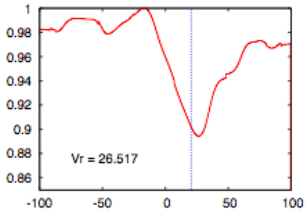
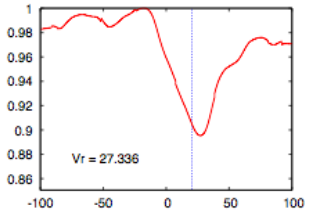
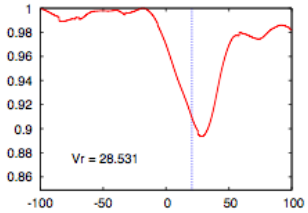
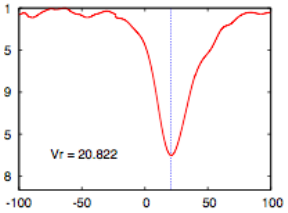
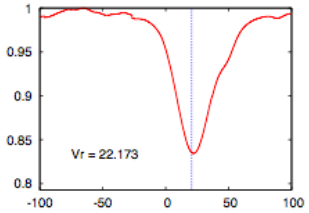
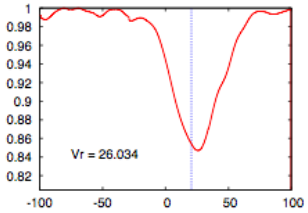
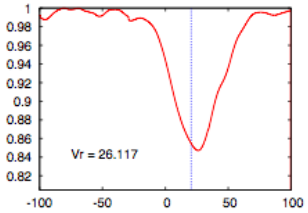
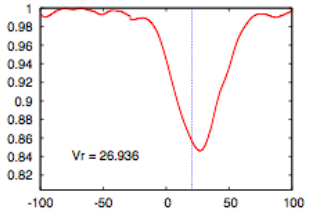
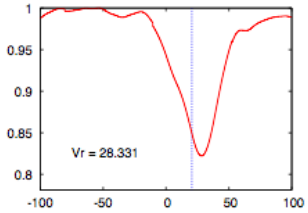



Not quite the same behaviour as in Miras (above):

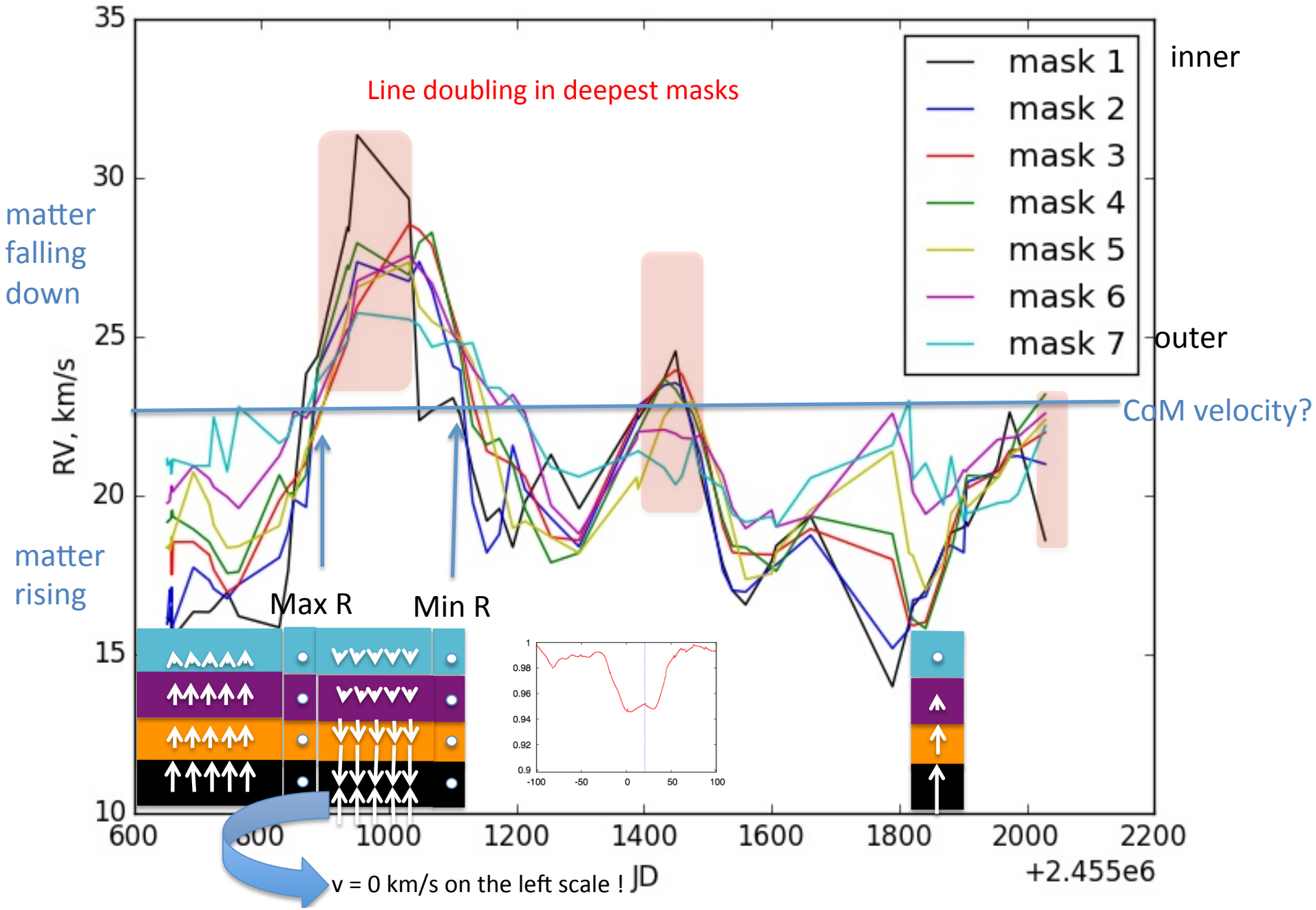
In supergiants, the blue peak (ascending matter) never dominates

→ in supergiants, the shock wave dies off rapidly, or is it a shock wave ?

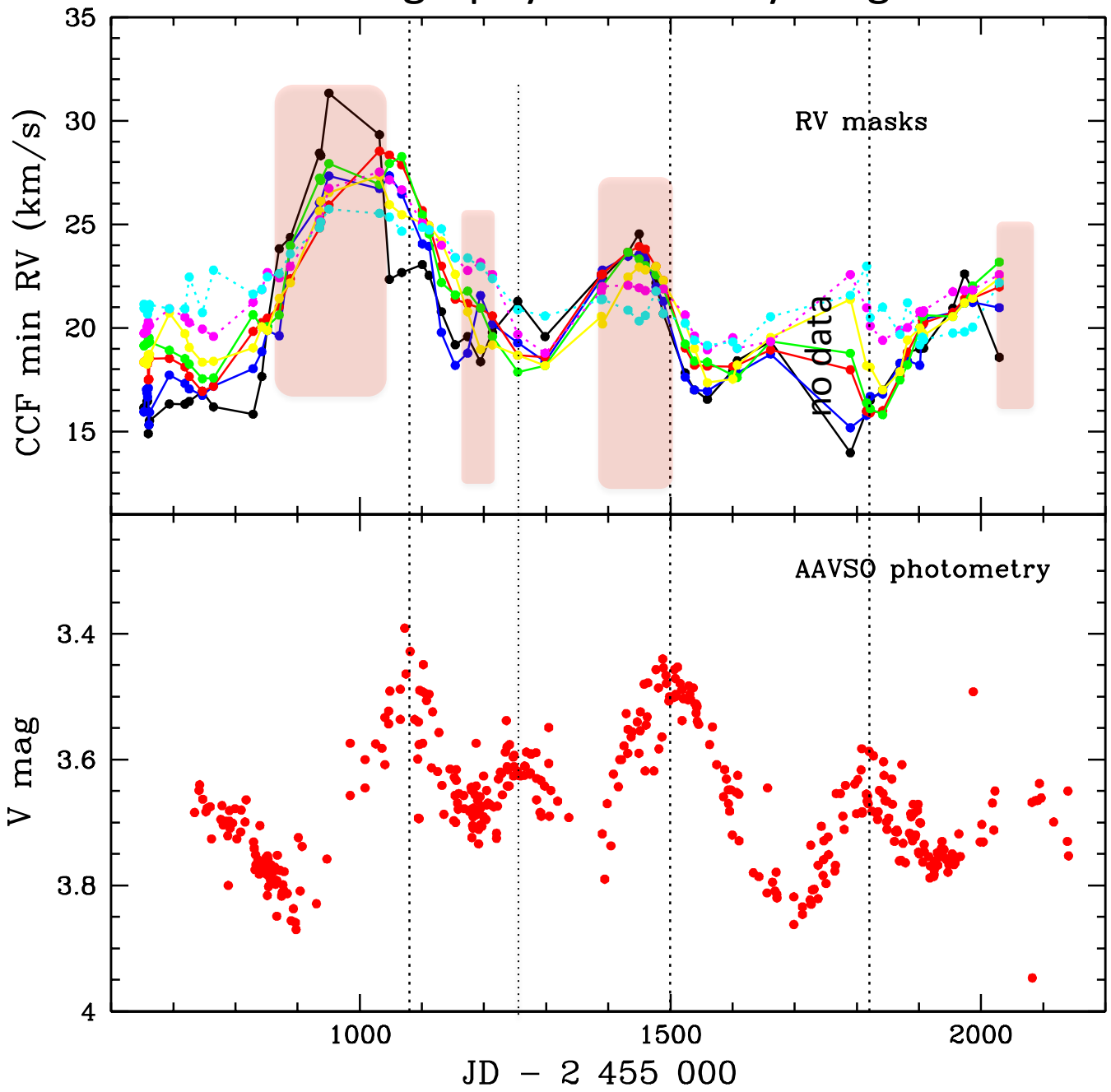
# Another example, 450 d later

| t= 0 | +18 | +65 | +67 | +80 | +161 d |
|---|---|---|---|---|---|
|   |   |   |   |   |   |
|   |   |   |   |   |   |
|   |   |   |   |   |   |
|   |   |   |   |   |   |

# Tomography: V. Velocity curve of μ Cep



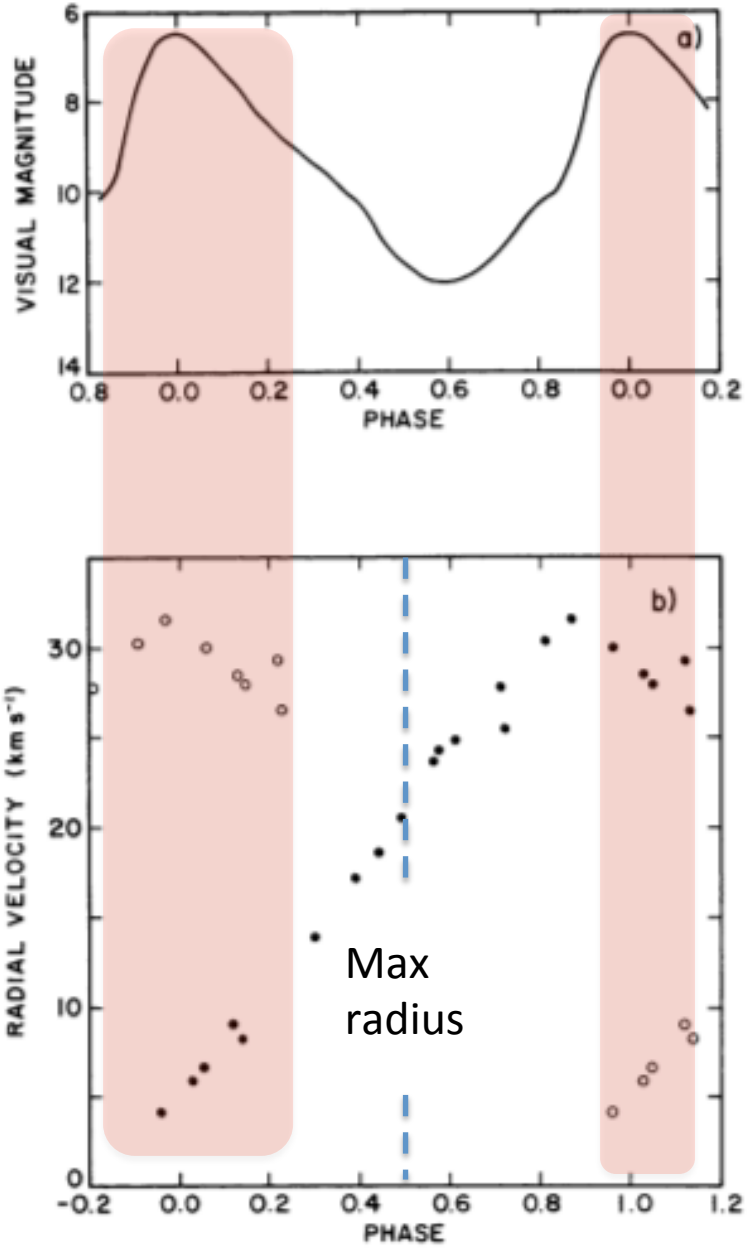
# Tomography: V. Velocity & light curves of μ Cep




Line doubling in deepest masks

**occurs during the rising part of the light curve**

# Tomography: VI. Situation in Mira variables (R Cas)




receding

approaching

Line doubling around max light

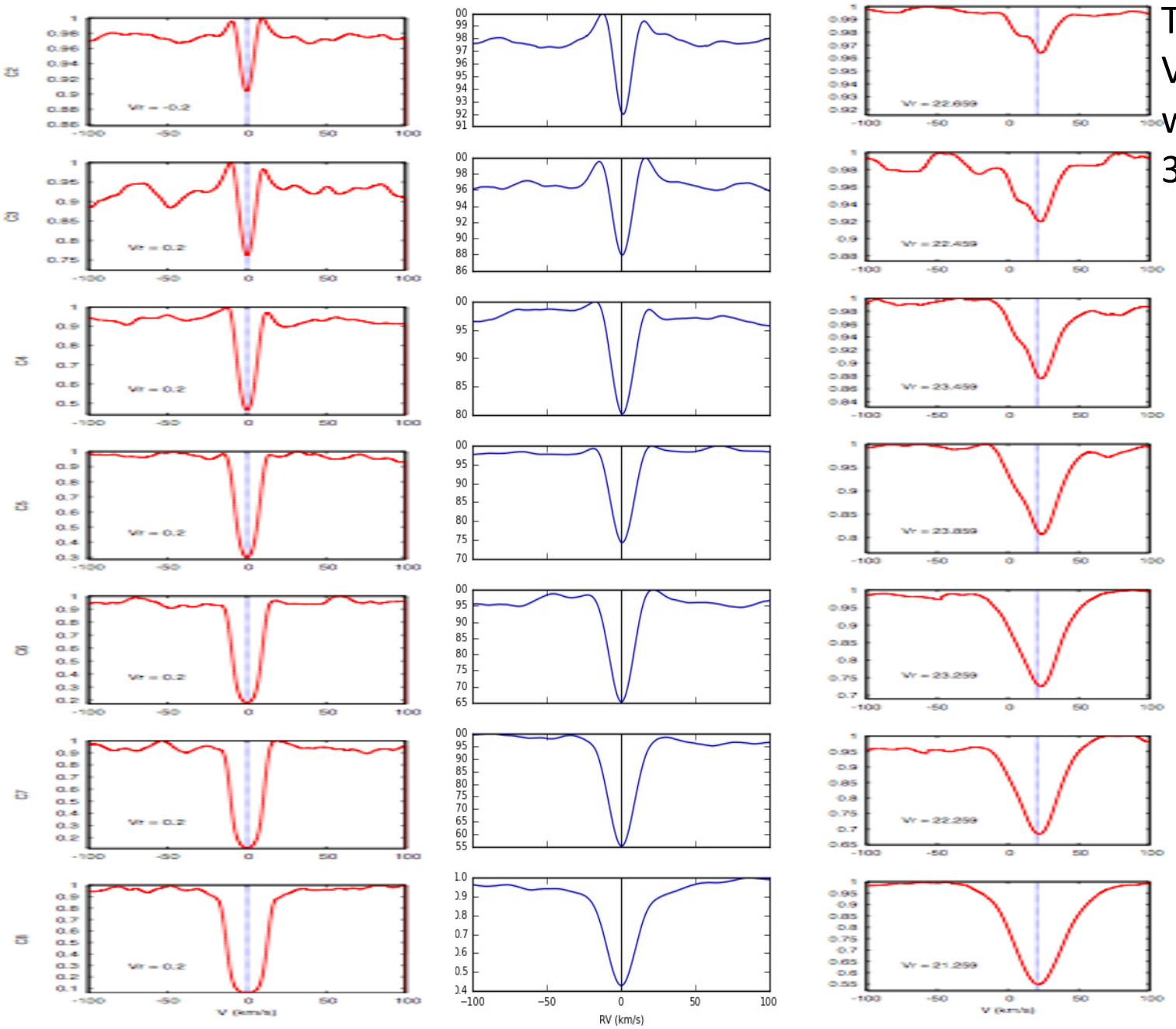
CO Δv = 3 lines

Hinkle, Scharlach & Hall, 1984, ApJS 56, 1

Synthetic MARCS 1D

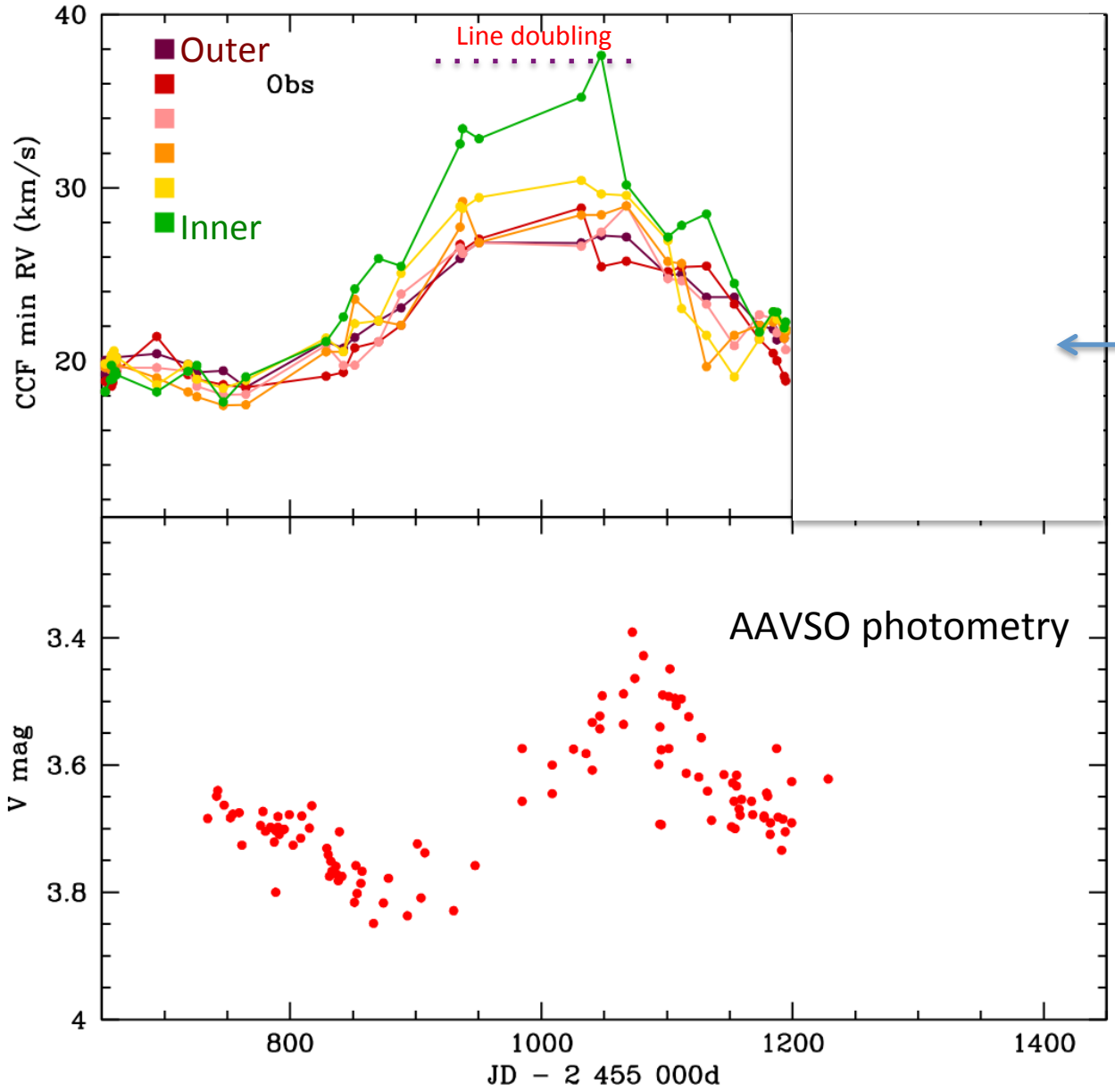
Synthetic CO$^5$BOLD 3D

Observed μ Cep




Tomography:
VII. Comparison with
3D models

# Tomography: VII. Comparison with 3D models

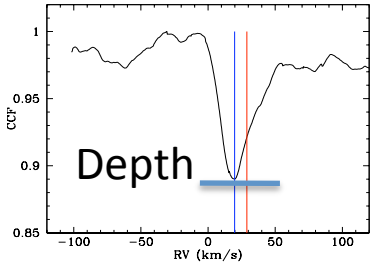


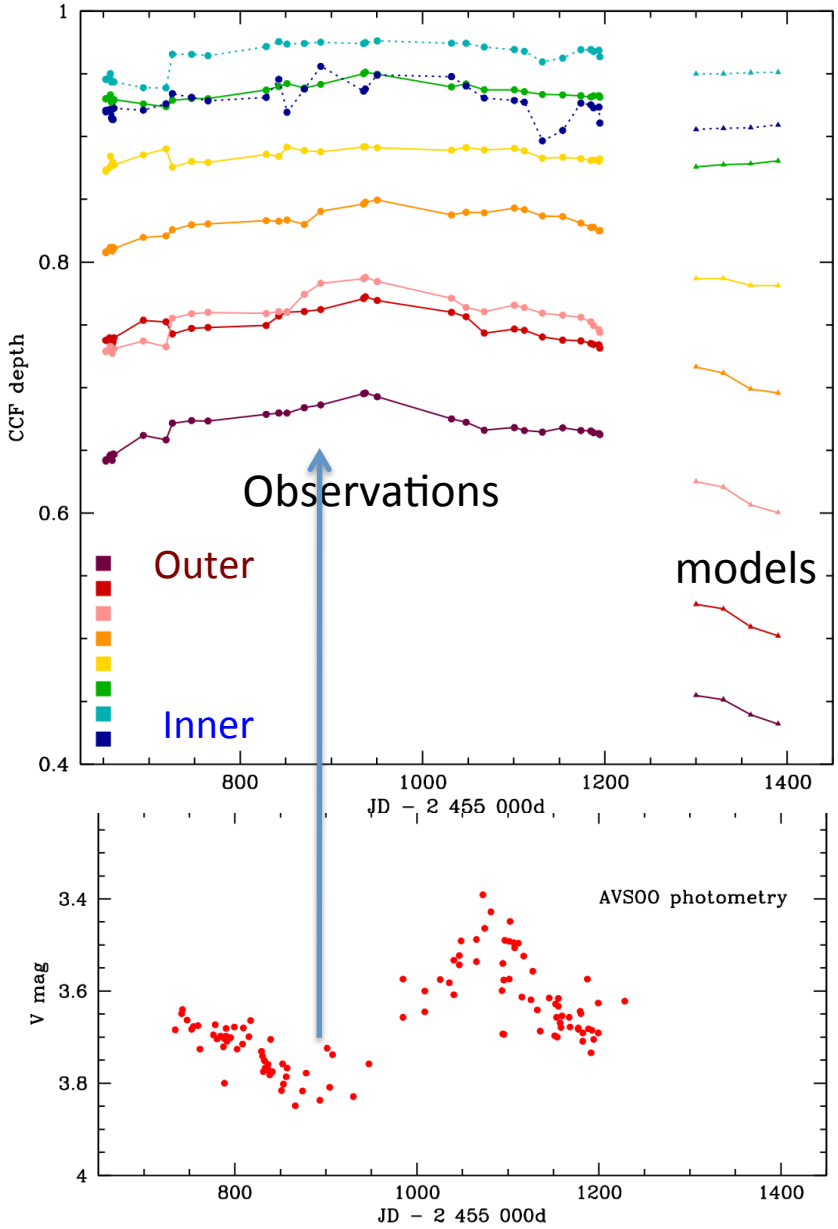

All masks show consistent variations following radial-velocity curve

**3D spectra**:
4 OPTIM3D snapshots from CO$^5$BOLD 3D models
(Chiavassa et al. 2011, A&A 535, A22)

$T_{eff}$ = 3430 K
M = 12 $M_\odot$
R = 846 $R_\odot$
log g = -0.35

# CCF depth




Inner masks sample weak lines
Outer masks sample strong lines

Comparison with 3D CO$^5$BOLD
(4 snapshots):
for outer masks especially:
3D CO$^5$BOLD lines are deeper
(factor ~1.5 to 2)

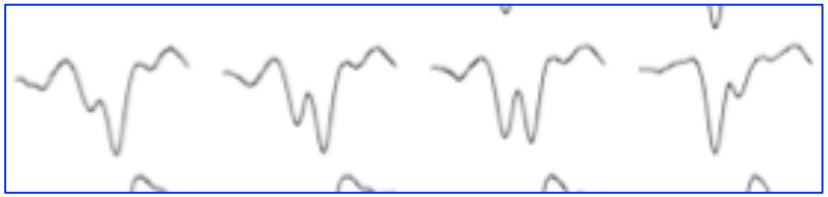
# Summary

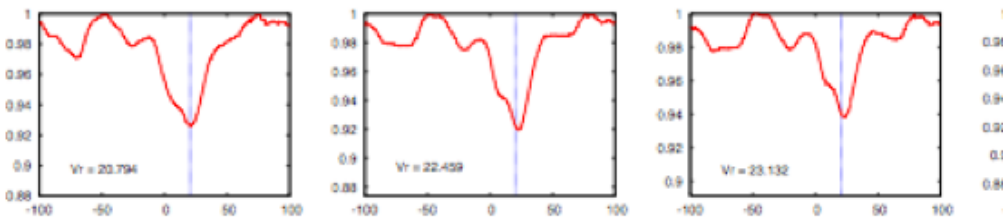
OBSERVED FEATURES:

- In the supergiant μ Cep, line doubling *systematically* occurs
  - on the rising part of the light curve;
  - in the innermost masks;
  - is never seen in the outermost masks;
  - with the red component stronger.

- Hysteresis between CCF/line depth and velocity

- The evolution of line doubling is different in Miras and supergiants





COMPARISON WITH 3D MODELS:

Some discrepancies for line depths, widths, & velocities (τ)

currently being investigated by increasing numerical resolutionof models (Chiavassa et al.)

A close collaboration with 3D-modellers is needed to make the models reproduce all these data