Stellar Winds & interferometry
Hot (massive) Stars

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(help from A. Meilland, P. Crowther, O. Delaa)

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Outline

- Physics of massive hot stars
- Application to active hot stars (NLTE physics)
- The SIMECA code
- Interferometry
- Results from Be stars, B[e] stars, HAe/Be
- Conclusions

Diagnostics of mass-loss

- Hot star winds can be observed through a variety of observations
  - UV resonance lines
  - Optical or IR emission lines
  - Continuum excess in IR or radio
- A theory of radiatively driven has been developed for hot stars which is broadly in agreement with observations.

Spectral lines from winds

- Spectral lines from winds can easily be distinguished from photospheric lines because of their large width or wavelength shift due to the outflowing motion of the gas in the wind.
- Wind lines can appear in absorption, emission or a combination of the two (P Cygni profile). For hot stars, two line formation processes tend to dominate.

Formation of Spectral lines

- Line scattering – If a photon emitted by the photosphere is absorbed by an atom, it causes an electron of the atom to be excited. Very quickly the photon is re-emitted by spontaneous emission. So it appears the photon was only scattered in another direction. If the line transition is from the ground state, the line is a resonance line and the scattering is called *resonance scattering.* Most P Cygni profiles are formed from resonance scattering.
- Line emission by recombination – If an ion in a stellar wind collides with an electron it can recombine. The most likely recombination is directly to the ground state, however it may recombine to an excited state. The resulting excited ion may then cascade downwards by photo-deexcitation. Each de-excitation results in the emision of a line photon. This process is responsible for Hα emission in hot stars.

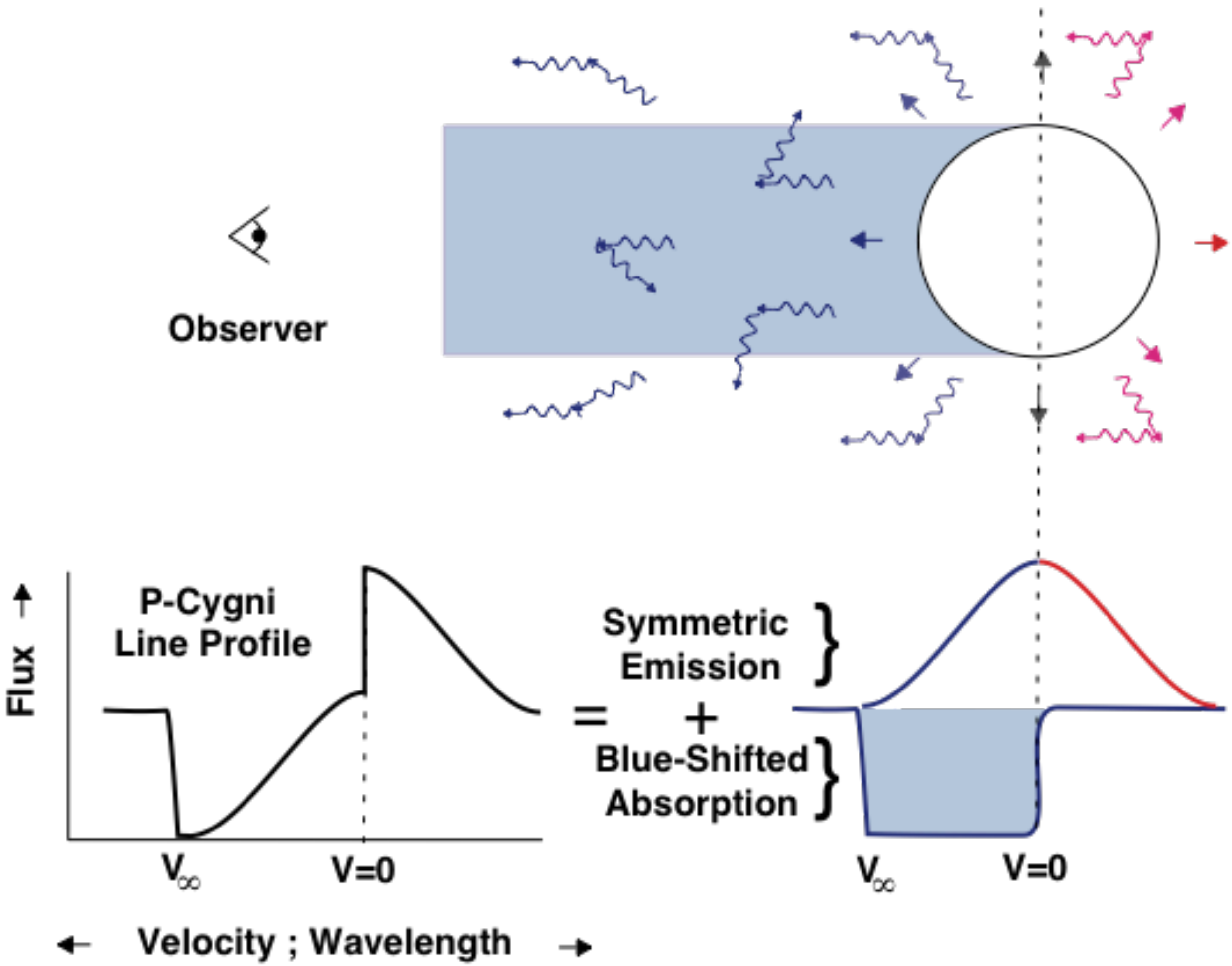
P Cygni profiles

The most sensitive indicators of mass loss from hot stars are resonance lines from abundant ions, such as CIV 1550A in O stars, which generally have large oscillator strengths.

If the column density of the absorbing ions in the wind is relatively small, they can produce an absorption line that shows the Doppler shift (blue shifted since material is moving towards the observer)

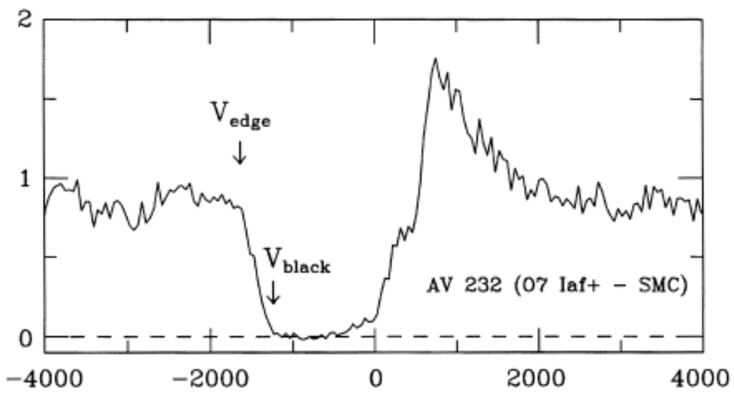
If the column density of the absorbing ion is large, the blueshifted absorption is combined with emission that is symmetric about the line centre (from a halo of gas surrounding the stellar disk), producing a blue-shifted absorption component plus a red-shifted emission component .

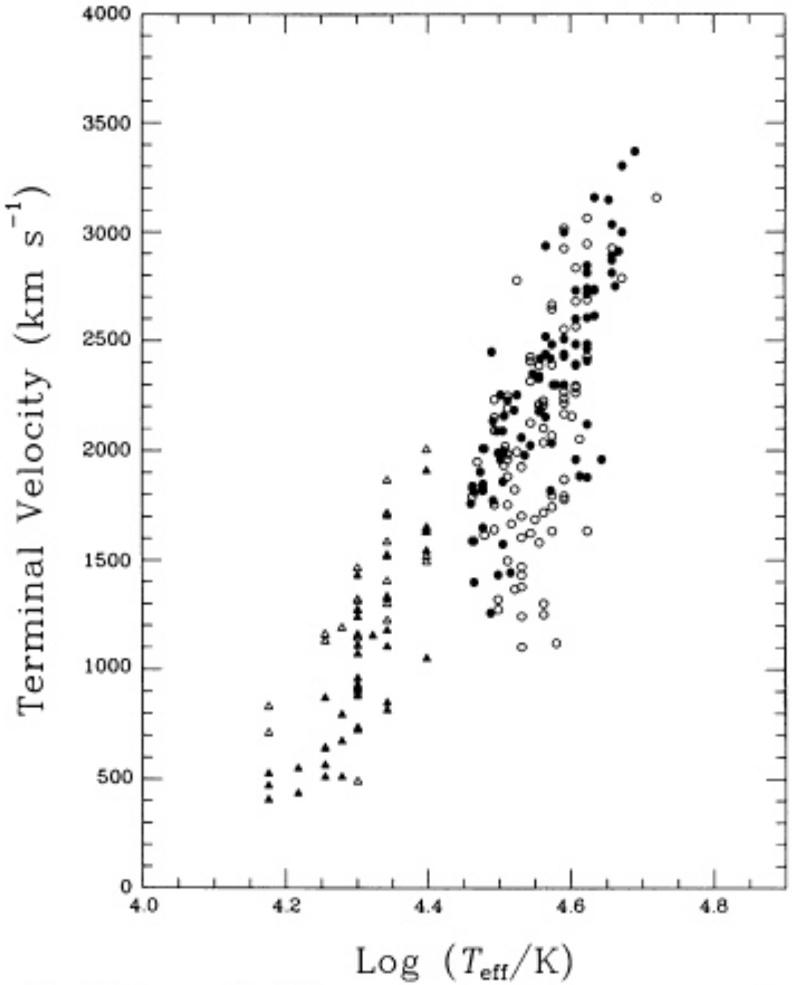
Formation of P Cygni profile



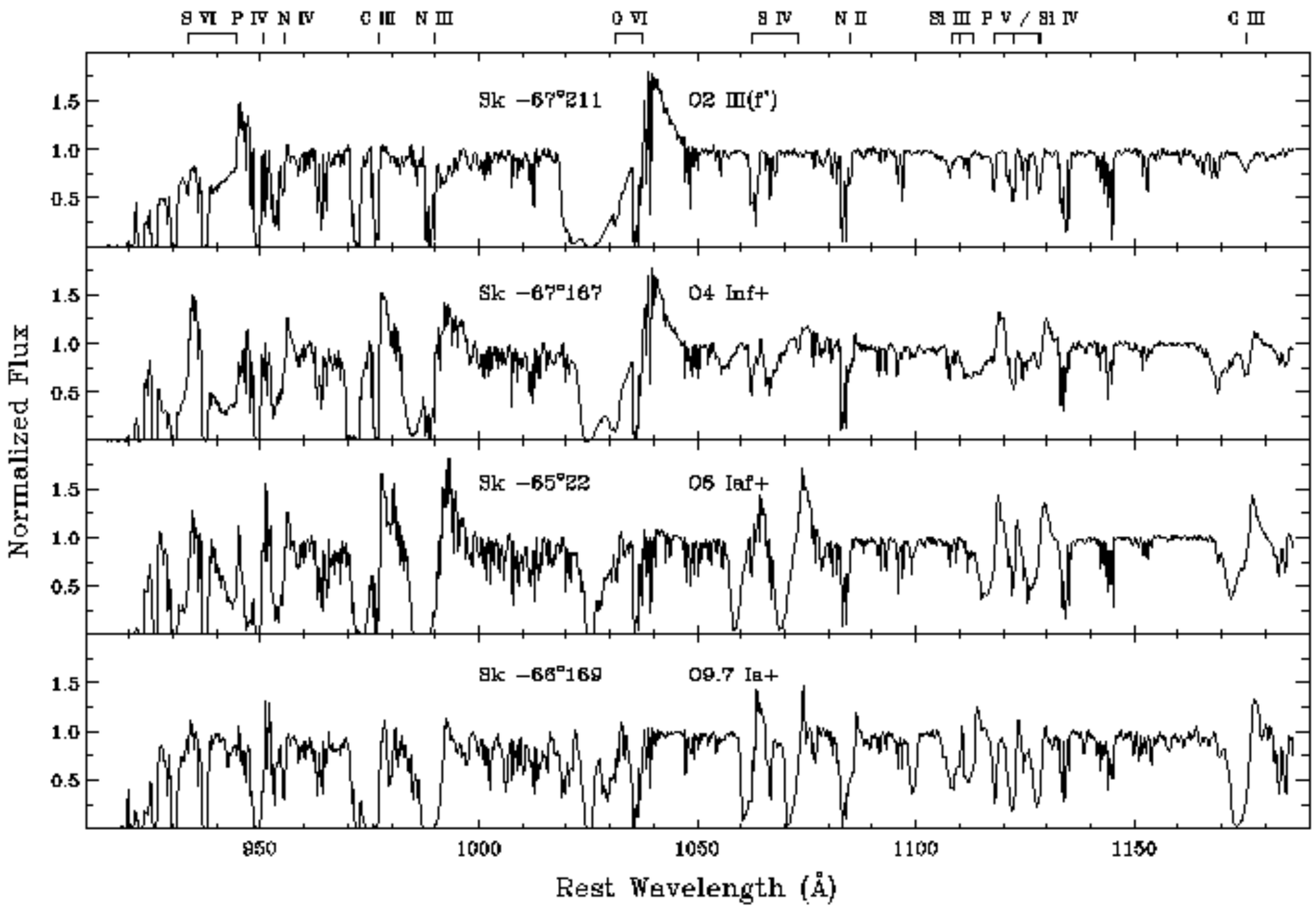
Wind velocities

Wind velocities of early-type stars are directly measured from so-called `black' troughs of blue-shifted saturated P Cygni profiles – observed to range from several hundred to several thousand km/s





Far-UV spectroscopy



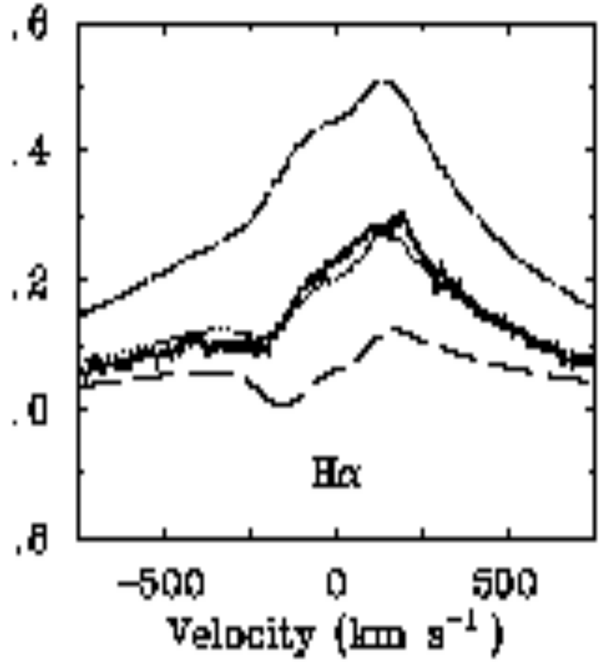
Far-UV FUSE atlas of OB stars in Magellanic Clouds

Emission lines

Optical lines appear in emission for only very extreme winds – generally exclusively Hα at 6562A may be used for OB supergiants.

Strength provides information on dM/dt since Hα is a recombination line (since proportional to ρ^2)

Lines are narrower than UV resonance lines since Hα formed very close to star where density is high.



Hα fit to LMC O4If star – dM/dt=6, 8.5, 11x10^{-6} Mo/yr

IR and radio excess

Stars with an ionized stellar wind emit an excess of continuum emission at long wavelengths, due to free-free `thermal' emission from the wind with $f_\nu \propto \lambda^{-0.6}$ which falls off much slower than the photosphere ($f_\nu \propto \lambda^{-2}$). The f-f emission depends on the density and temperature structure of the winds. If the wind velocity is known, the radio flux provides information on the mass-loss rates via

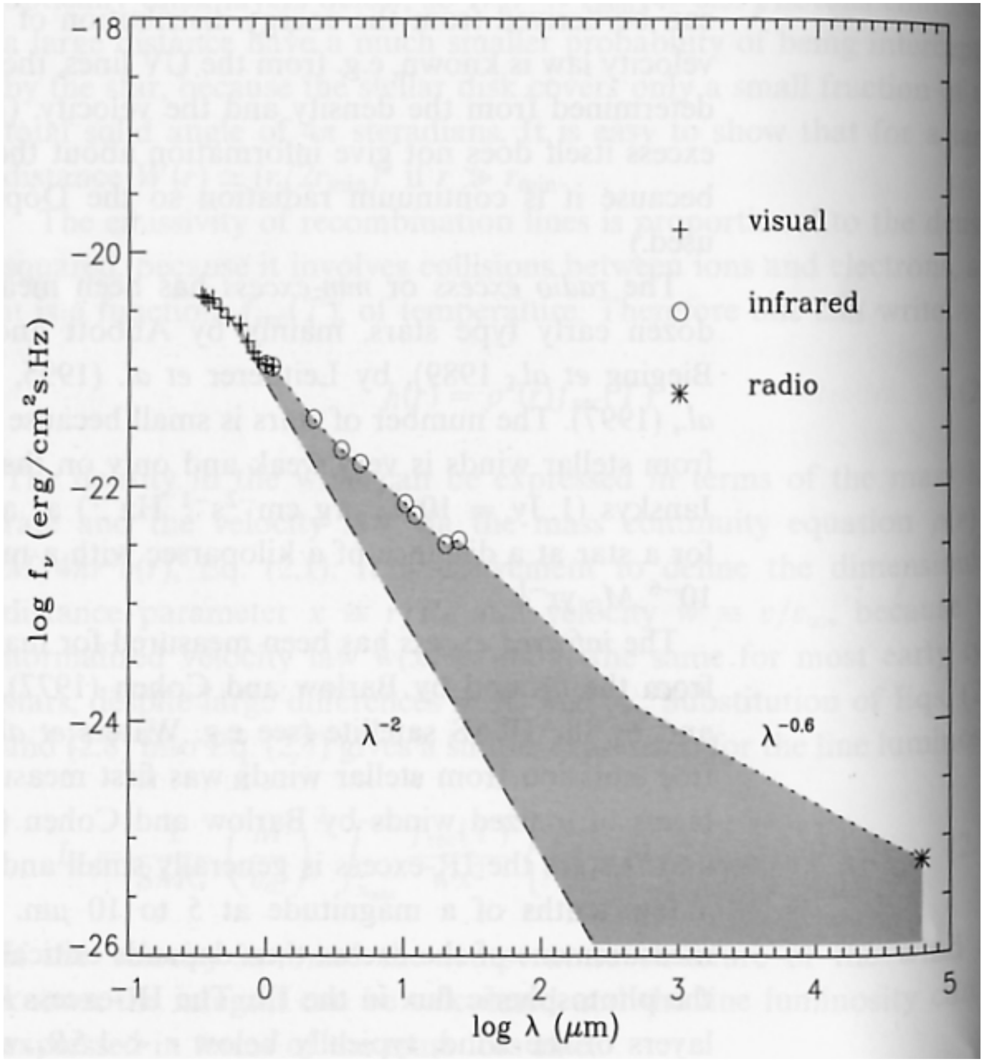
$$dM/dt \propto v_\infty f_\nu^{0.75} \, d^{1.5} \, \lambda^{-0.25}$$

This technique is limited to relatively nearby (few kpc) stars with strong winds due to poor radio sensitivity since the free-free emission is very weak.

Mass loss rates of O supergiants are of order 10^{-6} Mo/yr (compare with 10^{-14} Mo/yr for Solar Wind), rather lower for O dwarfs.

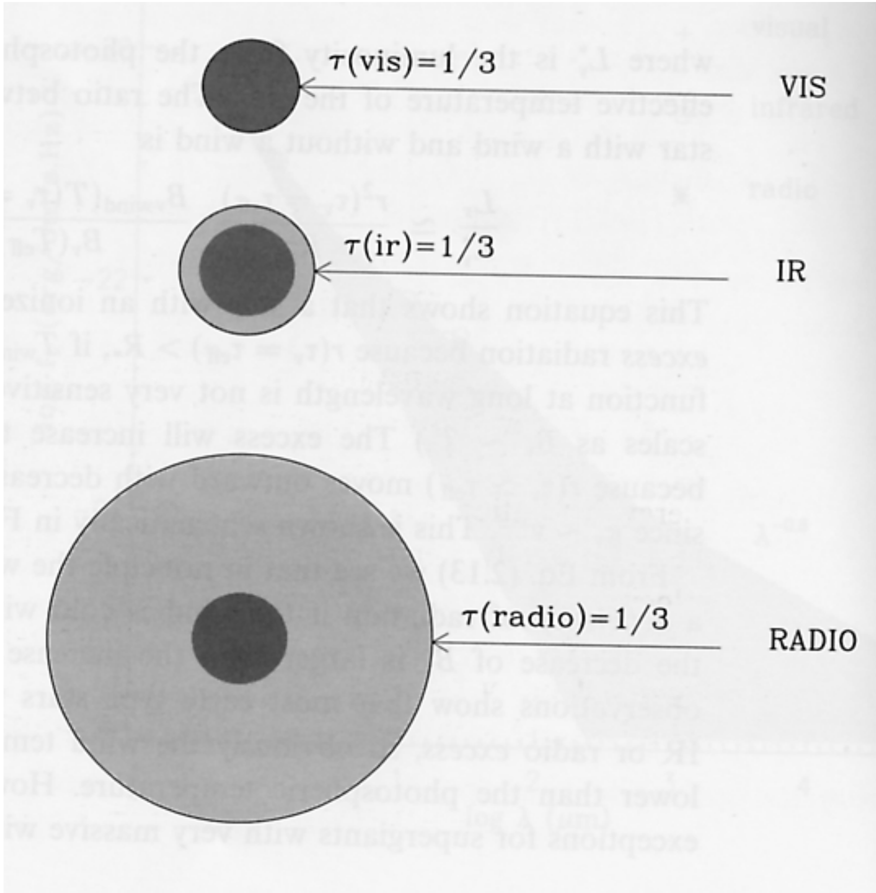
Excess emission from wind

Here we show the spectral energy distribution of a hot star with a *strong* wind. The dashed line is that expected for a hydrostatic photosphere without a wind – the grey region is the IR and radio free-free excess from the wind. The excess is much weaker for most hot stars.



Radius ($\tau \approx 2/3$) increases with λ

Since the free-free opacity increases as λ^2, the optical depth along a line-of-sight into the hot star wind also increases with λ^2 as does the effective radius of the star, so the `radio photosphere' corresponds to $\approx 10^2\ R_*$



What drives hot star winds?

- How are hot star winds driven? The dominant continuum opacity source in O stars is electron scattering. Does this drive the wind? If the force from electron scattering were to exceed gravity (known as the Eddington limit) the surface of a star could not remain bound and the star would blow itself apart.
- Instead, stellar winds are rather stable, using electrons bound in atoms to absorb the radiation: Radiation pressure is transferred to the wind material via **spectral lines**, which are plentiful in the UV. Bound e- provide much more opacity than free e- (e.g. opacity from CIV 1550 exceeds e.s. by 10^6!)
- Hot stars, unlike the Solar Wind, have plenty of line opacity in the ultraviolet where most of the photospheric radiation is. This combination allows for efficient driving of winds in hot stars by radiation pressure.

Doppler shift

- The large radiation force on ions due to their spectral lines would not be efficient in driving a wind if it were not for the Doppler effect.
- In a static atmosphere with strong line-absorption, the radiation from the photosphere will be absorbed or scattered in the lower layers of the atmosphere. The outer layers will *not* receive direct radiation from the photosphere, so the radiative acceleration in the outer layers is strongly diminished.
- However, if the outer layers are moving outwards, there is a velocity gradient, allowing the atoms in the atmosphere to see the radiation from the photosphere as redshifted (it appears to be receeding as viewed from gas in the expanding atmosphere). The Doppler shift allows the atoms to absorb *undiminished* continuum photons in their line transitions.

Line-driving

- Radiative acceleration due to spectral lines in the atmospheres of hot stars (main sequence OB stars, OBA supergiants, central stars of Planetary Nebulae, WDs) is very efficient for driving a stellar wind.
- This radiative acceleration in hot star winds is provided by the absorption and re-emission of UV photons in ions of abundant elements (CNO, Fe-peak) in the Lyman continuum (λ<912A).

Example

- The resonance line of NIV is at 765A, so an ion that absorbs such a photon will increase its velocity by $h\nu/mc$=37 cm/s. To accelerate a single N^{3+} ion to 2000km/s requires $5x10^6$ absorptions. In fact, since the wind is a plasma, the momentum gained by the N^{3+} ion is *shared* with all constituents in the wind (via interactions with surrounding protons, ions, e-, due to the electric charge of the ion).
- Ions which provide the radiative acceleration constitute about only 10^{-5} of all ions by number (since H and He contribute negligibly to the acceleration since fully ionized) so if a typical ion increases its velocity by 20cm/s, the effective increase per absorption is $2x10^{-3}$ cm/s. To accelerate the wind to 2000km/s requires 10^{11} absorptions!
- The terminal velocity is reached in a few stellar radii, so the time to accelerate the gas is $3R^*/v_\infty=10^4$s if $R^*=10R_{sun}$ so ions that provide the acceleration have to (and do!) absorb 10^7 ph/s (typical of strong lines with large oscillator strengths)

CAK theory

The theory of radiatively driven winds was developed by Castor et al. (1975, CAK), with the radiative acceleration dependent on the fraction of optically thick lines (parameter α), the number of strong lines (parameter *k*) and ionization (δ). Using these parameters, it was found that

$$\frac{dM}{dt} \propto k^{1/(\alpha-\delta)}$$

and

$$v_\infty \propto \left(\frac{\alpha}{1-\alpha}\right) v_{escape} \qquad v_{escape} = \sqrt{2 g_{eff} R}$$

$$g_{eff} = \frac{GM}{R^2}(1-\Gamma)$$

i.e. the mass-loss rate is predicted to scale with the number of strong lines, and the wind velocity is predicted to scale with escape velocity,

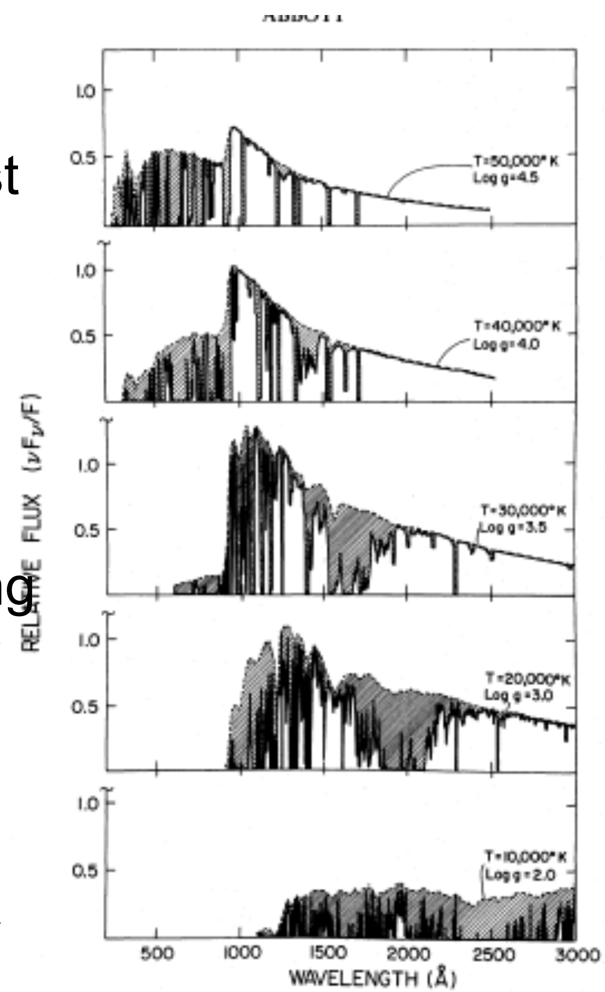
where the effective gravity is the stellar gravity corrected for the reducing effect of radiative pressure via Γ (related to M and R)

Sum of line driving

The total radiative acceleration (and hence α,k,δ) can be calculated by summing the contributions of all possible lines for all elements. This is rather difficult, but was first carried out by Abbott (1982). There are wavelength regions where few lines contribute to the acceleration and others which are crowded with lines (e.g. $300<\lambda<600$A in O stars).

Typically k>0.1, α=0.65, δ=0.1 from summing all ions of all elements in O stars, *predicting* wind properties that are in reasonable agreement with observed wind properties.

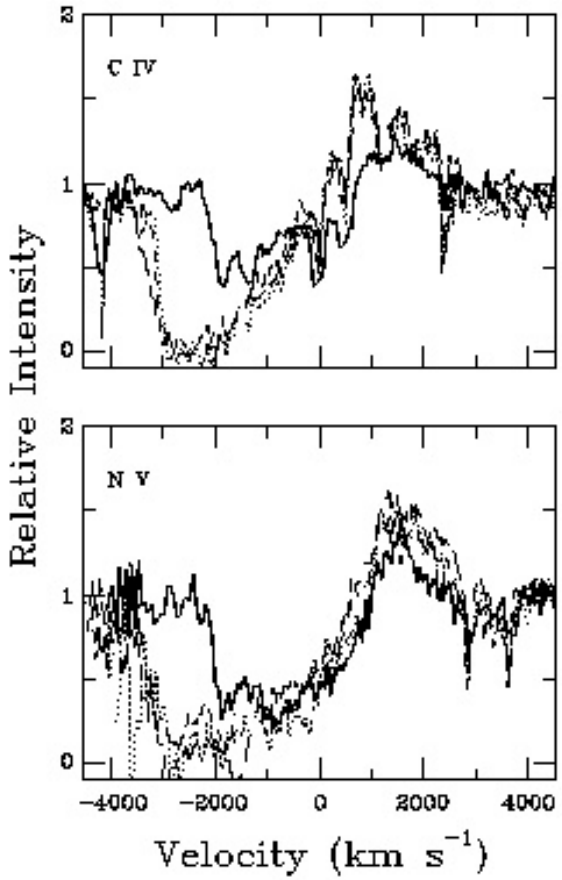
It has recently been found that CNO elements dictate the line driving in the outer wind (hence v_∞) whilst Fe-peak elements control the inner wind (hence dM/dt)



Metallicity influence of winds

For O and early B stars

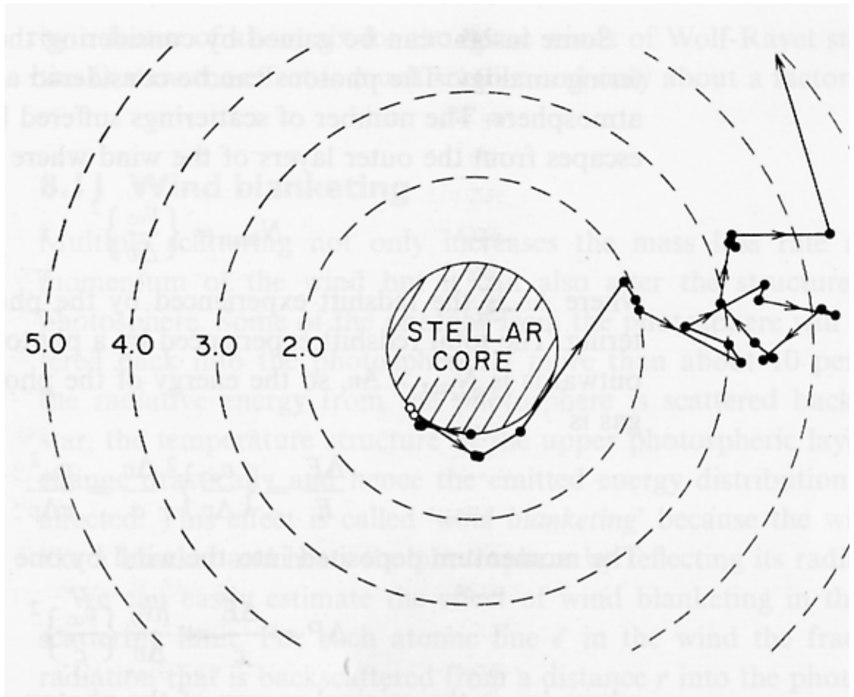
- $dM/dt \propto (Z/Z_o)^{0.85}$ *predicted* from radiatively driven wind. Observationally, stars in metal poor SMC galaxy do possess weaker winds than Galactic counterparts.
- $v_\infty \propto (Z/Z_o)^{0.1}$ predicted from theory, whilst observations show slower winds in SMC O dwarfs (thick lines) than Galactic stars (thin lines) from CIV 1550A & NV 1240A ultraviolet resonance lines.



Multiple scattering

The standard theory of line driving assumes that photons can be scattered only once in the wind which is a reasonable assumption for normal O stars.

Line driving in WR stars is still controversial, since the strength of their winds appears to exceed the single scattering limit. The absorption by photons in different spectral lines is called *multiple scattering.* The process of multiple scattering is shown schematically here.Each scattering occurs in a different specral line, successive scatterings occur at lower energy (longer wavelength).



Applications to active hot stars
Be stars and other friends

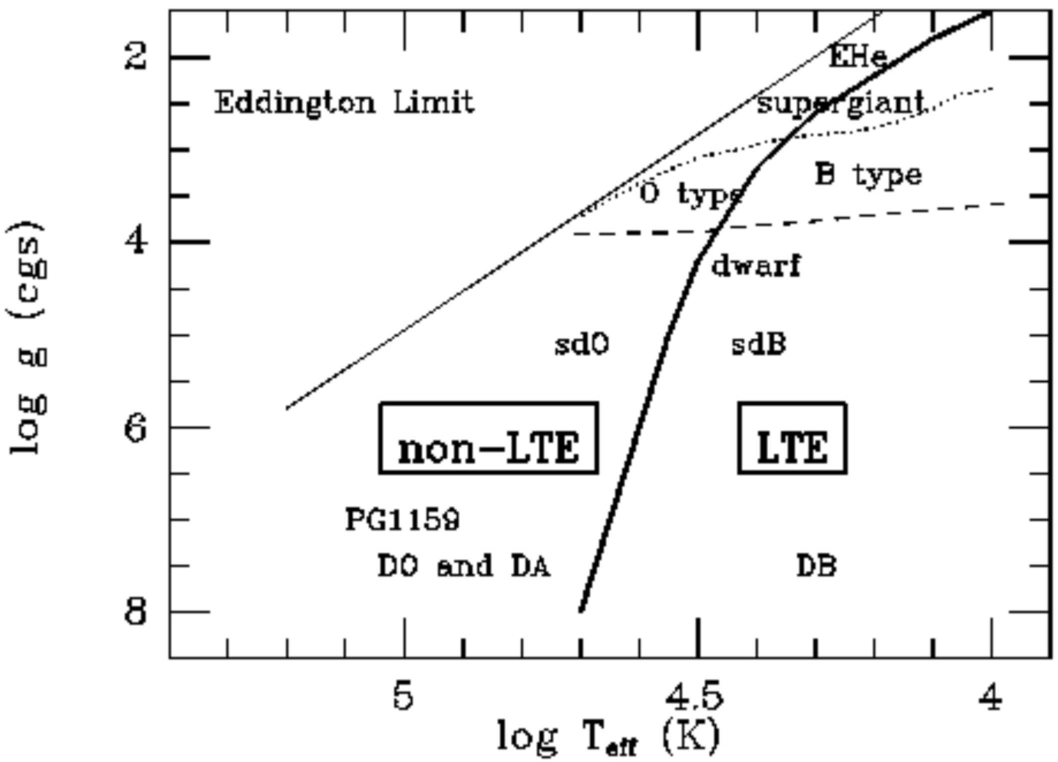
Open questions

- Origin of the Be phenomenon:
  - Why some hot stars are forming disks and some others not ?
  - What is the effect of the rotation ?
  - What is the effect of the magnetic field ?
  - What is the influence of stellar winds ?
  - What is the importance of these disks on the stellar evolution ?
  - What is the impact on the ISM ?

Active hot stars = NLTE physics

Non-LTE for hot stars

Radiation field is so intense in hot stars (O-type, OBA supergiants, WDs) that their popluations are only weakly dependent on local (Te,Ne), consequently LTE represents a poor assumption.

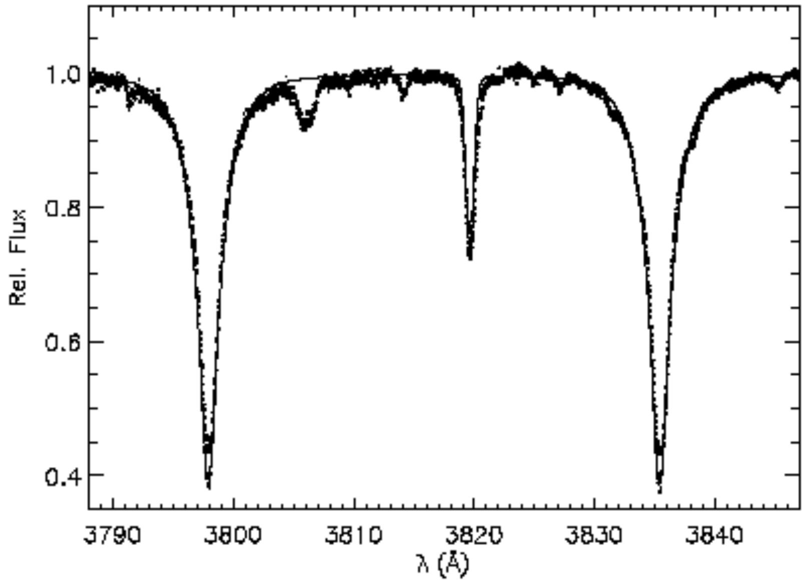


Eddington limit: Radiation pressure equals gravity

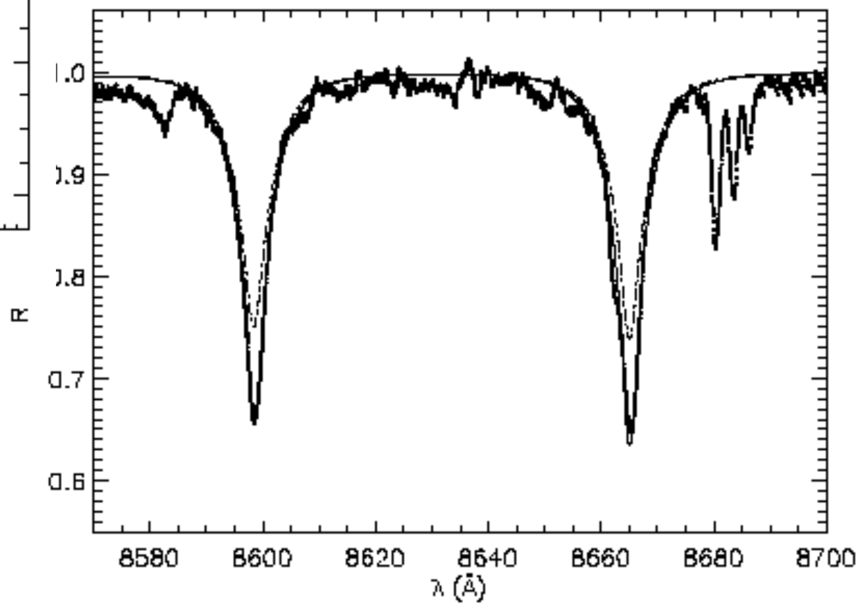
Non-LTE in OB stars

- O and early B dwarfs possess intense radiation fields in which LTE is invalid. Hydrostatic equilibrium is invalid in OBA supergiants – their tenuous atmospheres lead to a drop in the line source function below Planckian value.
- In O stars, LTE profiles are much too small. Departures from LTE make He I and He II lines *much* stronger.
- For B stars, in the blue-violet spectra of B stars, some He I lines are formed in LTE, however red and IR lines are not collision dominated, instead photoionization-recombination processes dominate, so non-LTE is necessary.
- In A supergiants, reliable metal abundance determinations require non-LTE treatment – lines become stronger in non-LTE with corrections of up to factor of 10 for strong lines.

Hydrogen lines in βOri (B8Ia)

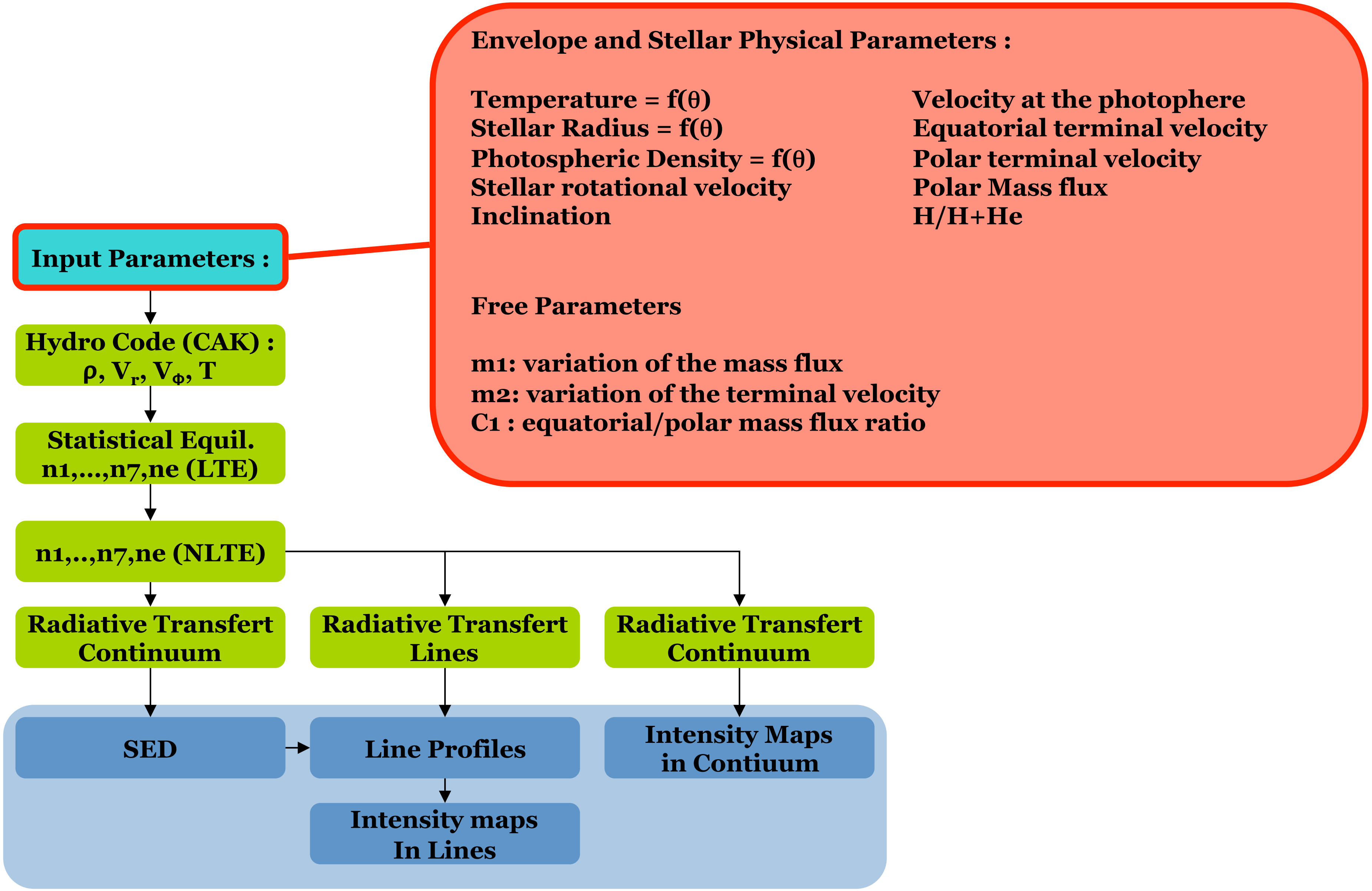


LTE (dash) and non-LTE (solid) lines agree for Balmer lines (left), but LTE lines too weak for Paschen lines (below) in β Ori



The SIMECA code
SIMulation Etoiles Chaudes Actives
(NLTE code)

SIMECA : Basic Scheme

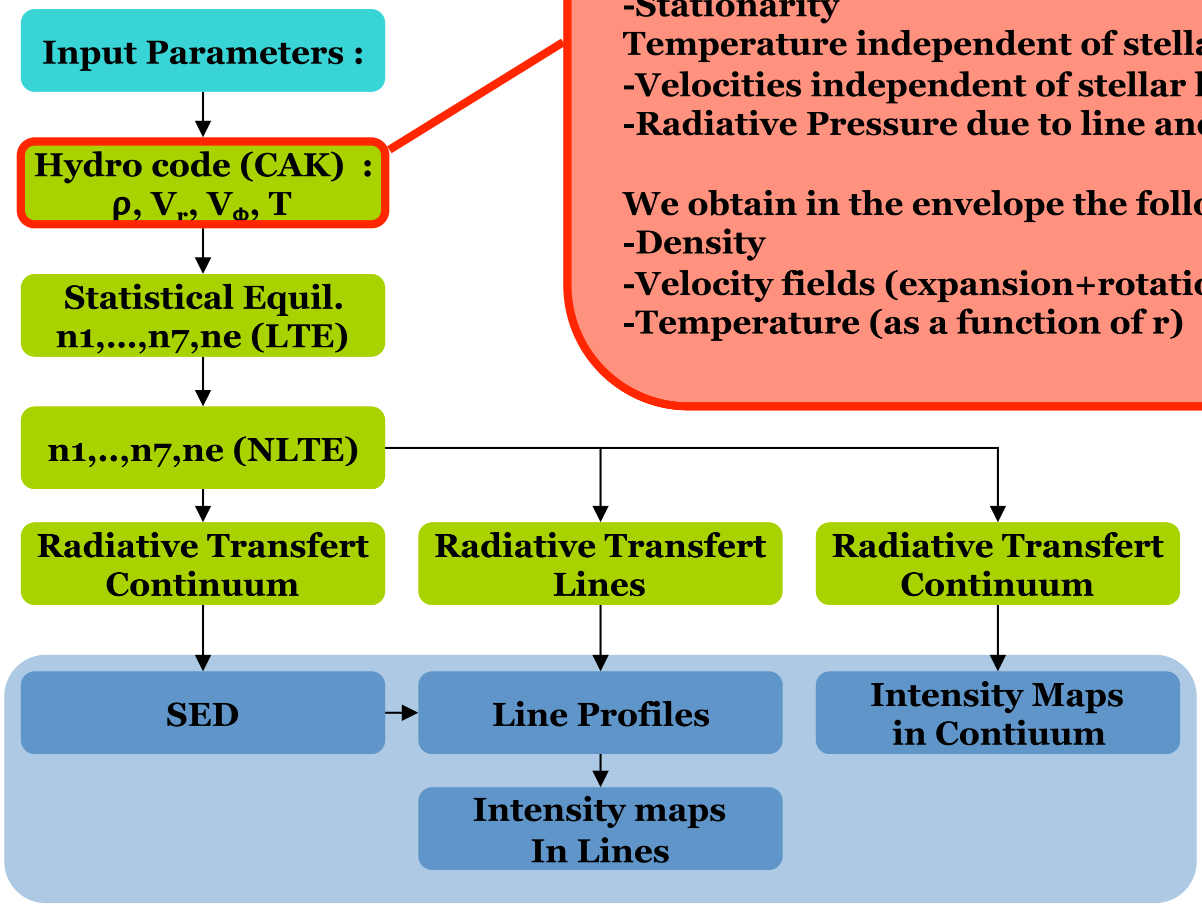


SIMECA : Basic Scheme

Based on hydrodynamical equations (CAK)
-Continuity Equation
-Mass flux conservation
-Perfect gas state equation

Hypothesis:
-Axial Symmetry (can be overcome)
-Stationarity
Temperature independent of stellar latitude
-Velocities independent of stellar latitude
-Radiative Pressure due to line and continuum

We obtain in the envelope the following distributions:
-Density
-Velocity fields (expansion+rotation)
-Temperature (as a function of r)



SIMECA : Basic Scheme

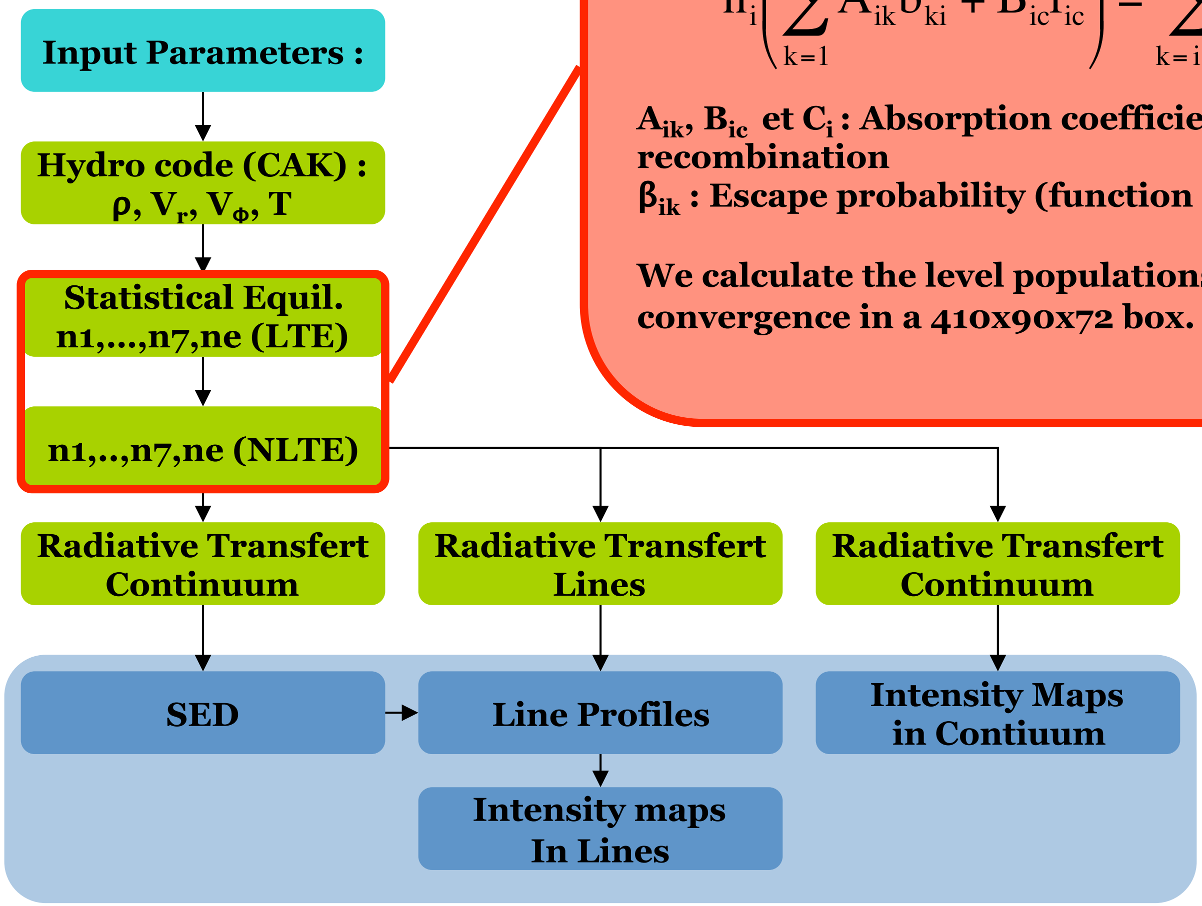
We start with the LTE population levels (1 to 7 levels + continuum)

We solve the statistical population equations in the Sobolev approximation :

$$n_i\left(\sum_{k=1}^{i-1} A_{ik} b_{ki} + B_{ic} r_{ic}\right) = \sum_{k=i+1}^{\infty} n_k A_{ki} b_{ik} + n_e^2 C_i(T_e)$$

A_{ik}, B_{ic} et C_i : Absorption coefficients, spontaneous emission and recombination
β_{ik} : Escape probability (function of the velocity gradient)

We calculate the level populations by iterations until we reach convergence in a 410x90x72 box.



SIMECA : Basic Scheme

Transfert Equation : $$\frac{dI_\upsilon}{dz} = -\kappa_\upsilon I_\upsilon + \varepsilon_\upsilon$$

We calculate τ by integration: dτ =-κ . dz (along the line of sight)

In the continuum :
-Envelope Opacity : free-free emission and electronic diffusion
-Envelope Emission : free-free and free-bound emission

In the lines :
-Calculate κ et ε for the given transition
- Sobolev Approximation

➡ Intensity as a function of spatial coordinates:
(in a plane perpendicular to the line of sight)
For a given transition (line) or as a function of the wavelength (continuum)

Input Parameters :
↓
Hydro Code (CAK) : ρ, V_r, V_Φ, T
↓
Statistical Equil. n1,…,n7,ne (LTE)
↓
n1,..,n7,ne (NLTE)
↓
Radiative Transfert Continuum	Radiative Transfert Lines	Radiative Transfert Continuum
SED →	Line Profiles	Intensity Maps in Contiuum
	Intensity maps In Lines	

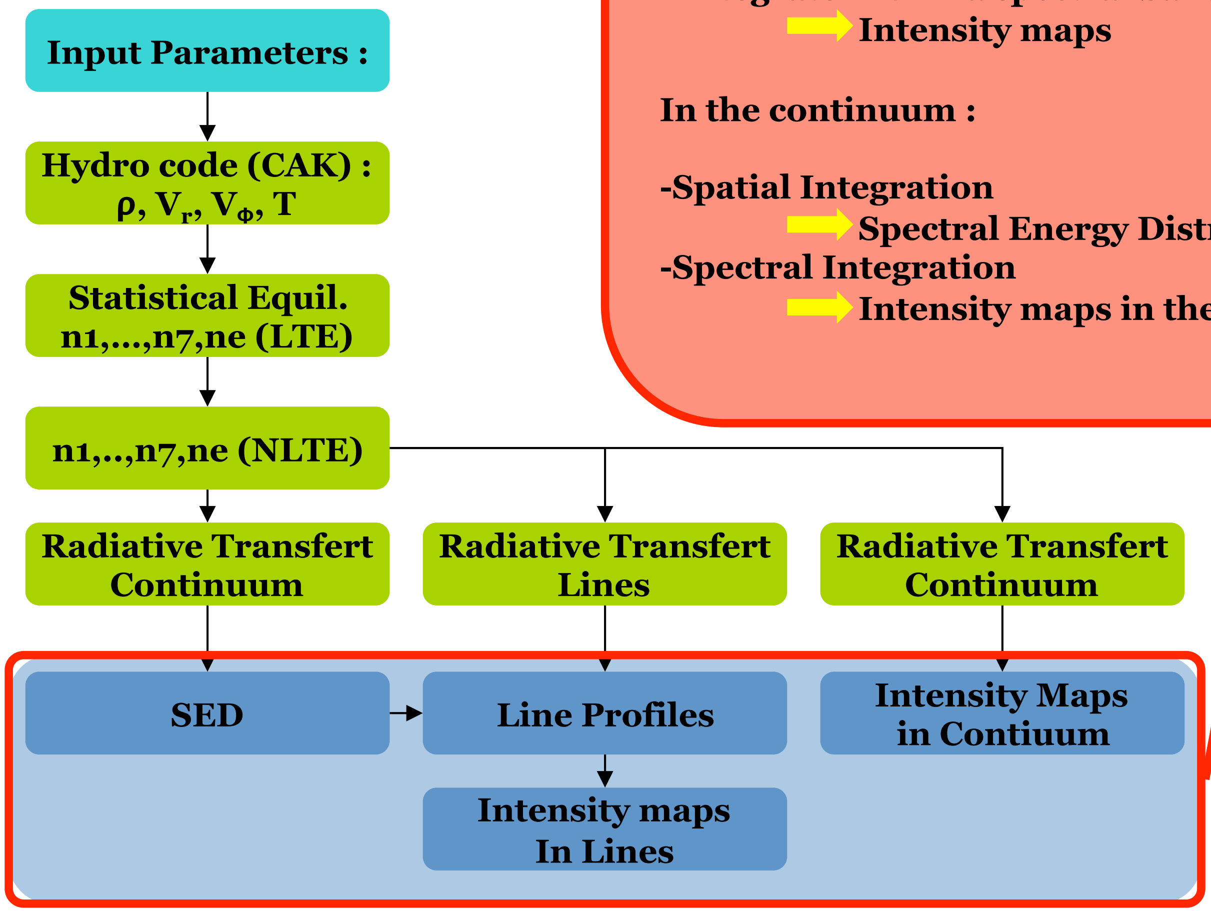
SIMECA : Basic Scheme

In a spectral line :

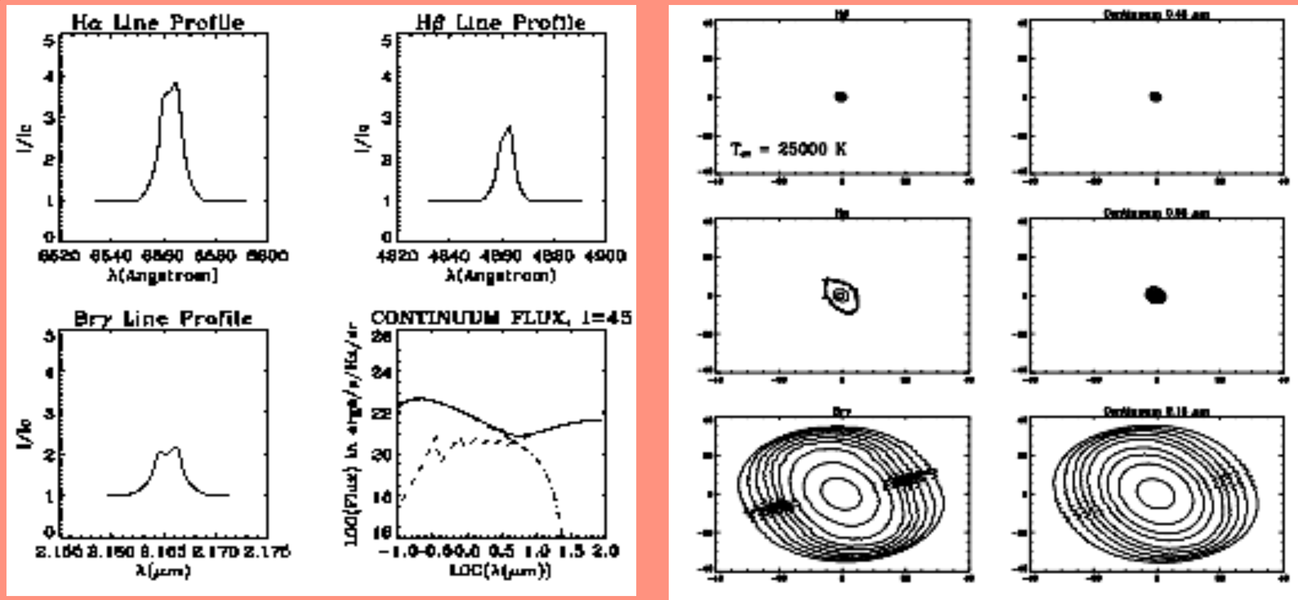
Compute the iso-velocity regions ⇔ Doppler Effect
- Integrate these regions
⇒ Line Profiles
- Integrate within a spectral bandwith
⇒ Intensity maps

In the continuum :

-Spatial Integration
⇒ Spectral Energy Distribution (SED)
-Spectral Integration
⇒ Intensity maps in the continuum



SIMECA : Basic Scheme



Input Parameters :

Hydro code (CAK) : **ρ, V_r, V_Φ, T**

Statistical Equil. **n1,…,n7,ne (LTE)**

n1,..,n7,ne (NLTE)

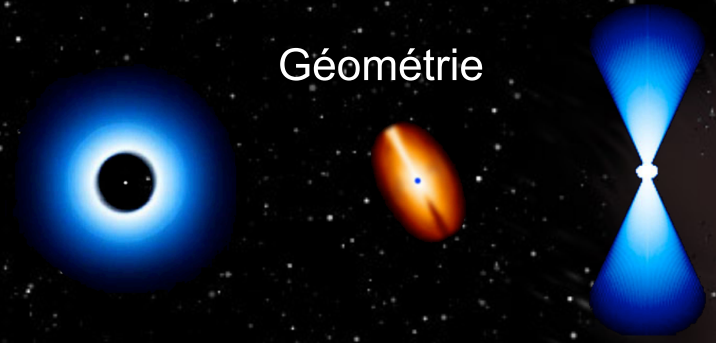
Radiative Transfert Continuum | **Radiative Transfert Lines** | **Radiative Transfert Continuum**

SED → **Line Profiles** | **Intensity Maps in Contiuum**

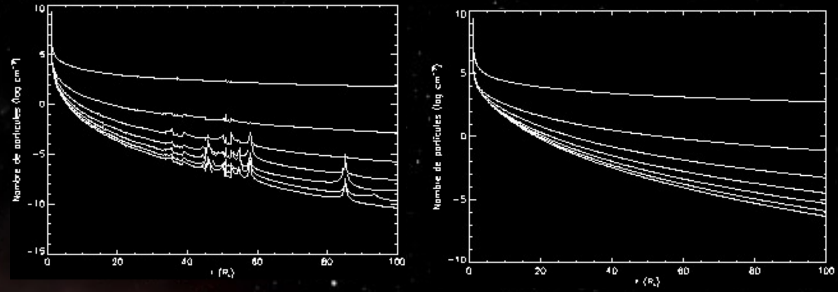
Intensity maps In Lines

Améliorations récentes de SIMECA

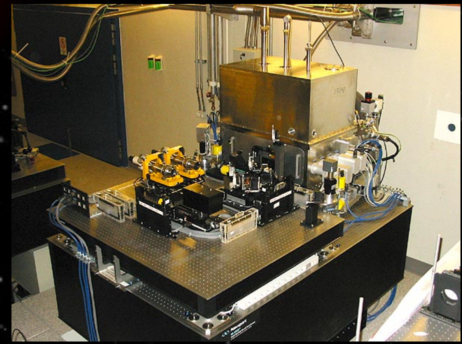
Géométrie



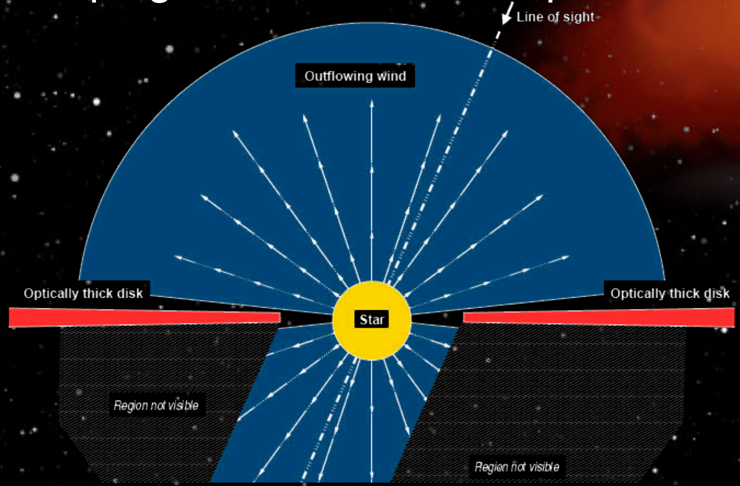
Peuplement des niveaux



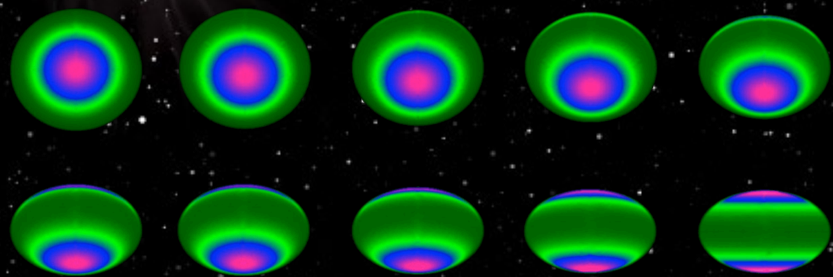
IR moyen et lointain



Couplage avec un code de poussière



Adaptation aux rotateurs rapides et critiques



Interferometry

Interferometry

Pb : How to obtain information on the brightness spatial distribution of an object ?

=>Direct observation limited by the spatial resolution of the telescope

•**Spatial resolution of a monolithic telescope :**

Image of a point source=> Airy disk (R=1.22λ\D)

Resolution limit:

Minimal angle to separate 2 points on the source (≈1,6λ\D)

θ (mas)= 250 λ (micron) / D (m)

• **In the visible:**

1.5'' **=> D≈10cm**

1.5 mas **=> D≈100m** (3 m on the Moon)

0.005 mas => D≈30000m (1 cm on the Moon)

•**Pb difficult to construct such large telescopes**

Interferometry

Interferometry with 2 telescopes

Two telescopes with a diameter D separated by a baseline B

Similar to the Young's fringes experiment:

Light interference from a single source

$\Rightarrow$Fringes in the Airy disk:

Diameter : $d = 2.44\,\lambda \backslash D$

Interfringe : $i = \lambda \backslash B$

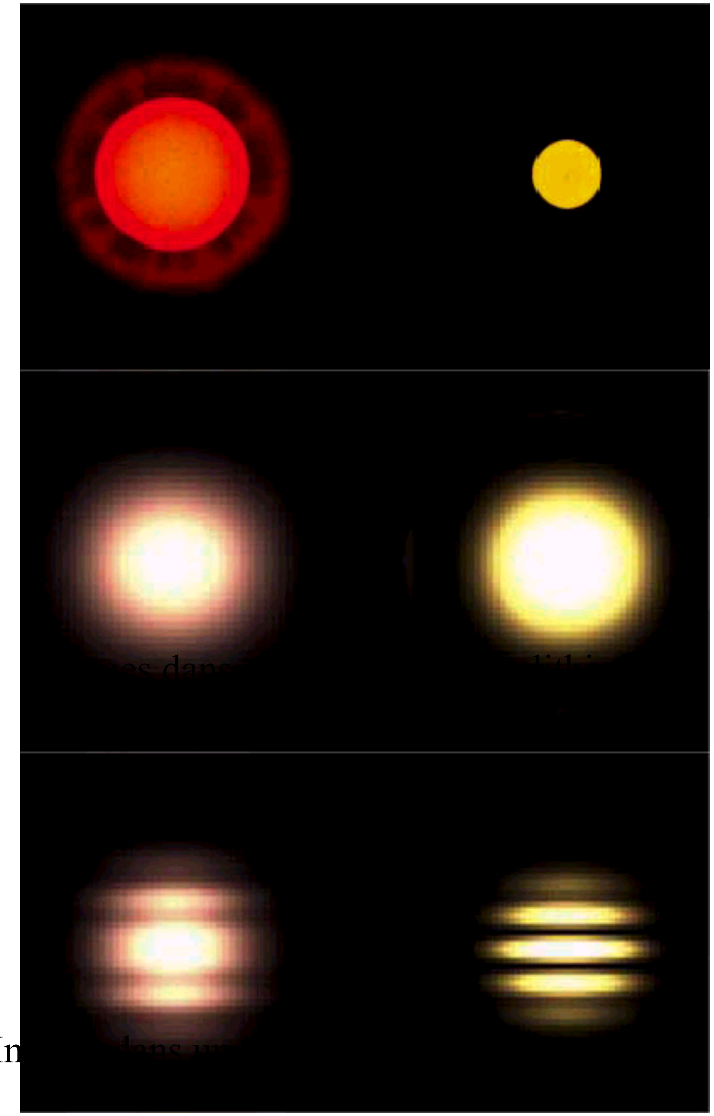
Interferometer $\Leftrightarrow$ Telescope with a diameter B + «mask with 2 holes with a diameter D»

$\Rightarrow$Spatial resolution equivalent to a monolitique telescope of diameter B.

Spatial resolution of an interferometer:

θ(mas)= 250.λ (micron) \ B (m)

How to use it ?



Interferometry

Visibility Function

Visibility (V) = Fringes contrast (between 0 and 1)

- Point source: V = 1   Fully resolved source: V=0 (no more finges !)
- Extended sources: Van-Cittert et Zernike theorem =>V equal to the modulus of the object FT at (u,v)= **B**\λ

Exemple : two stars with different diameters.

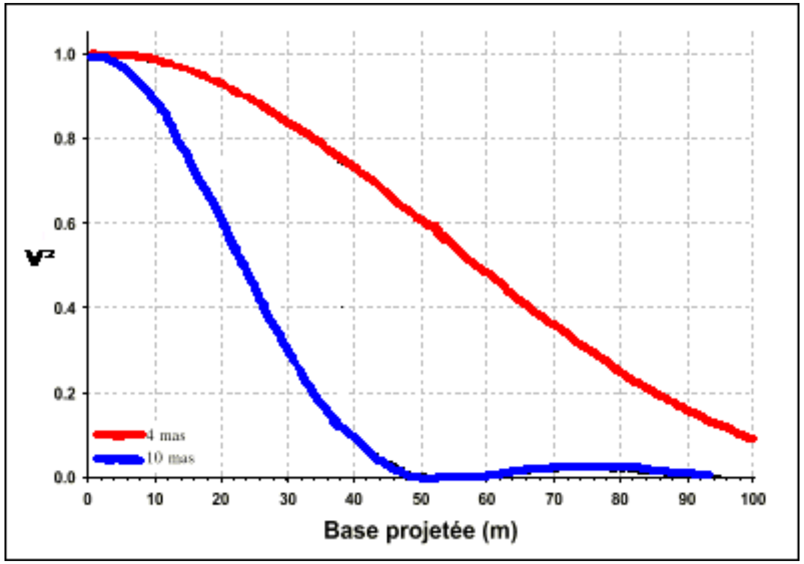
D1= 10 mas et D2 = 4 mas

Limb darkned disk

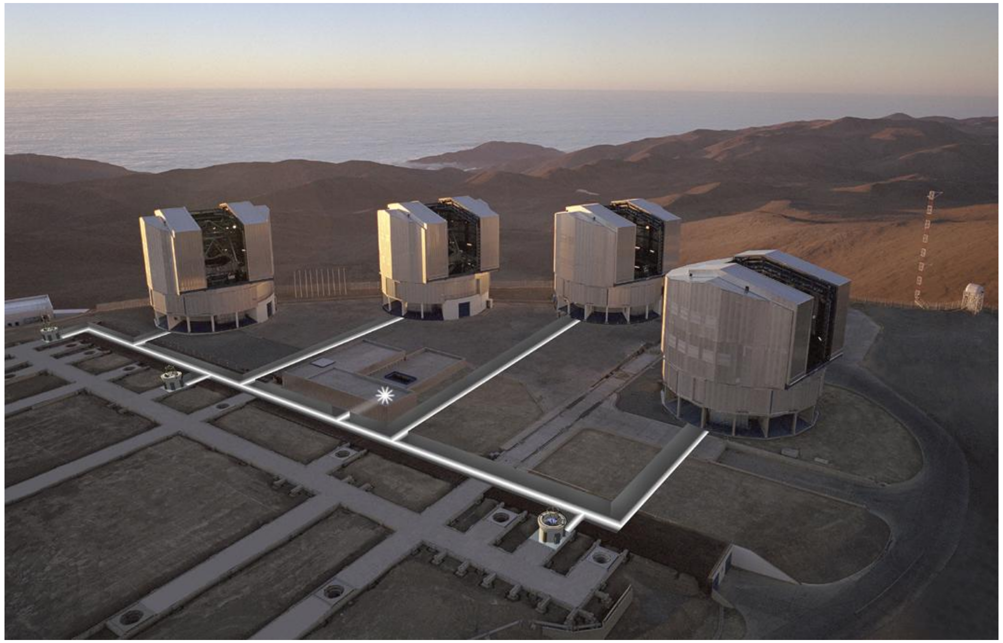
Visibility as a function of baseline between 0 and 100 meters

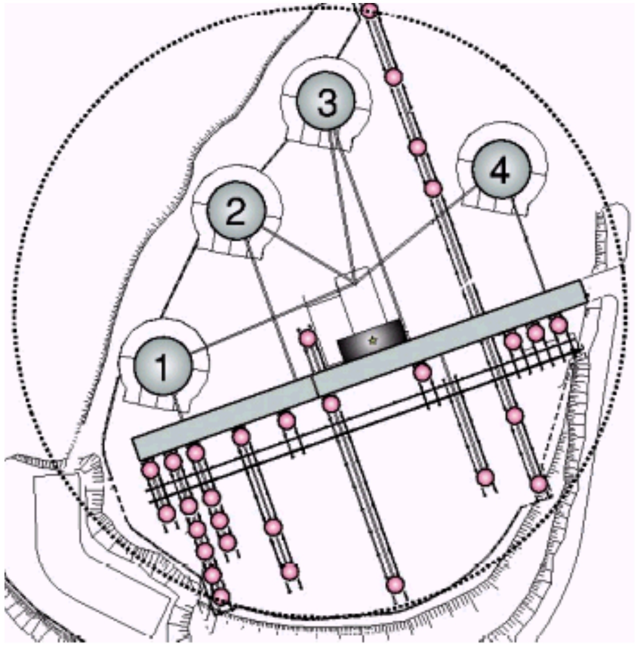
1 m : $V1^2 = 1$ et $V2^2 = 1$ (object not resolved

50 m : $V1^2 = 0$ et $V2^2 = 0.6$ (object 1 fully resolved)



The Very Large Telescope Interferometer

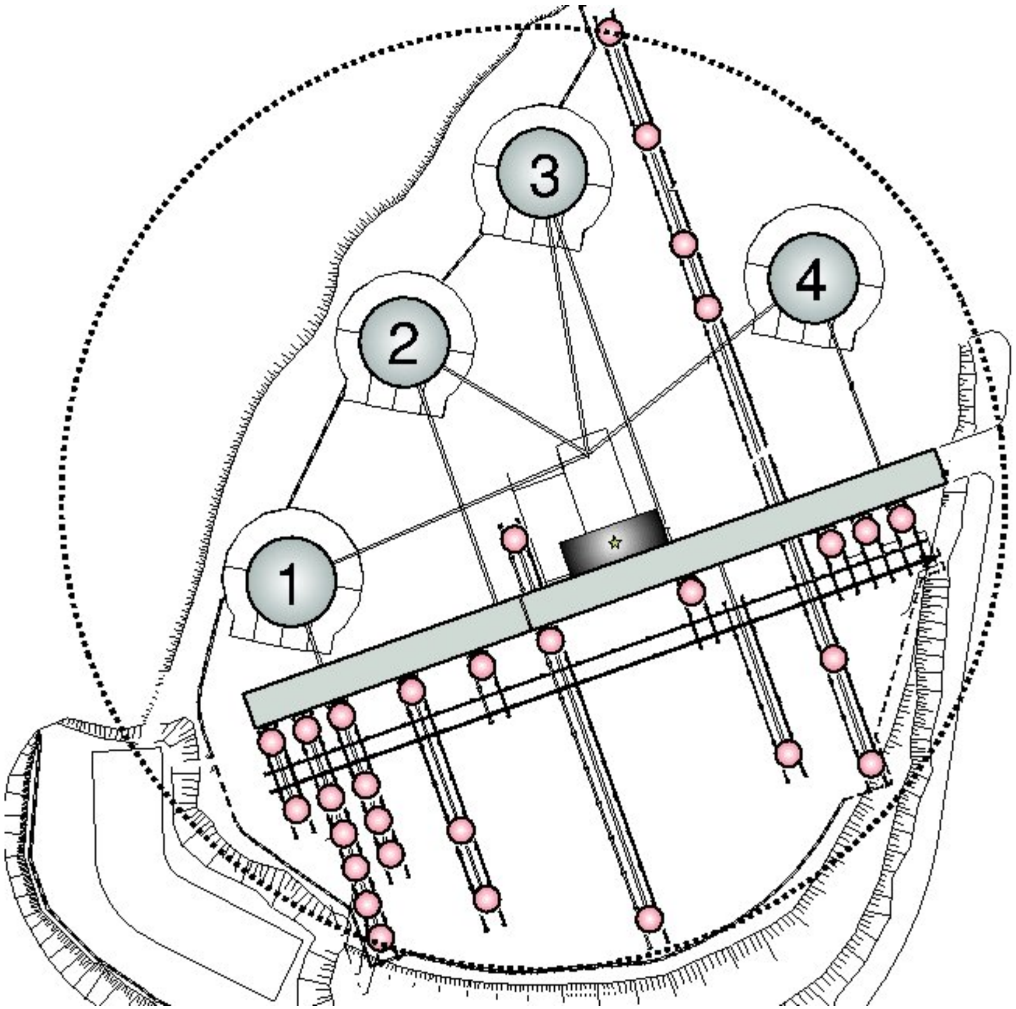


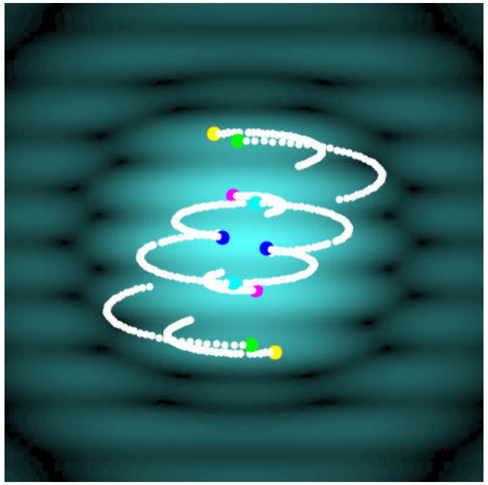


2 instruments available

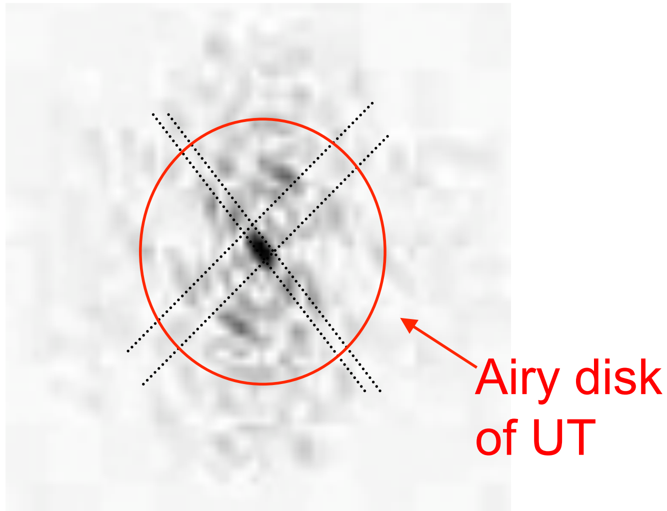
MIDI
8-13µm
2 telescopes
Modulus and Differential phase
R=200
θmin=10mas

AMBER
1.2-2.3µm (JHK)
3 telescopes
Modulus, Differential phase, and phase closure
R=35,1500,10000
θmin=2mas



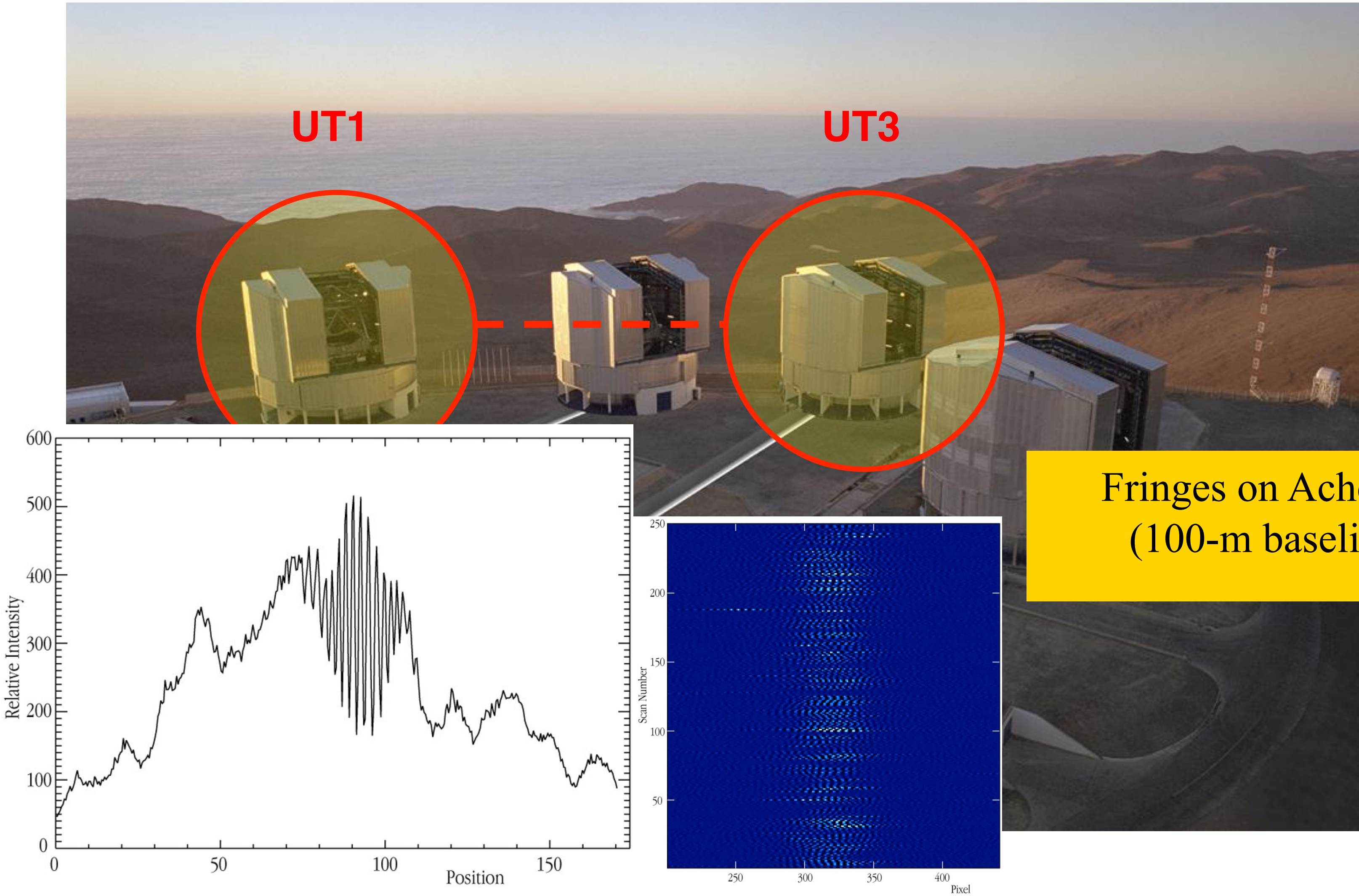


uv coverage after 8 hour observation with all UTs (object at -15°)



Resulting PSF is the Fourier transform of the visibilities at λ = 2.2μm (K-band)

First fringes with the UTs (Oct 2001)



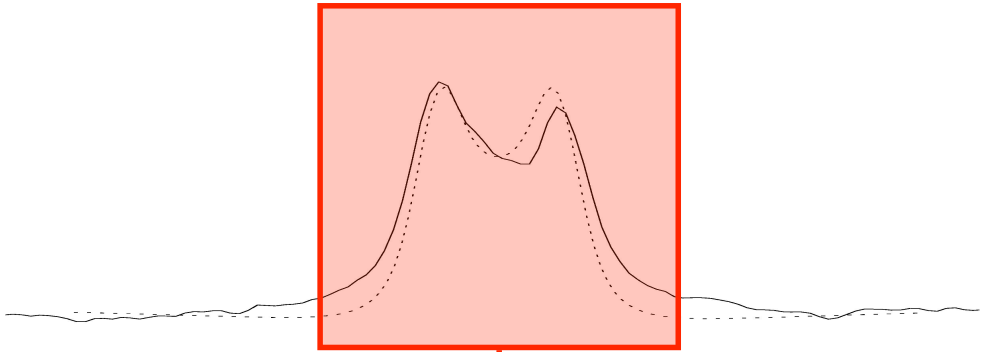
Fringes on Achernar
(100-m baseline)

AT1 and AT2 with Open Domes

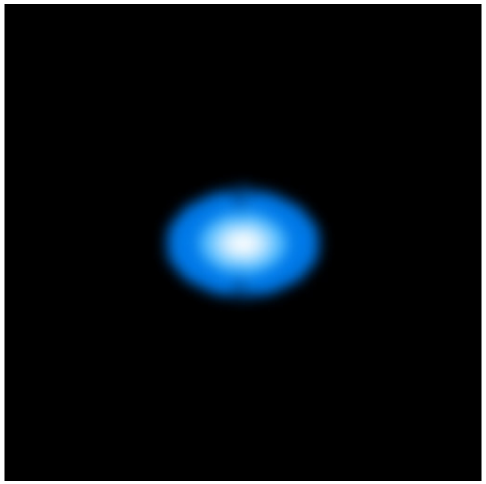
ESO PR Photo 07b/05 (14 March 2005)

Spectro-interferometry

(Doppler Effect)



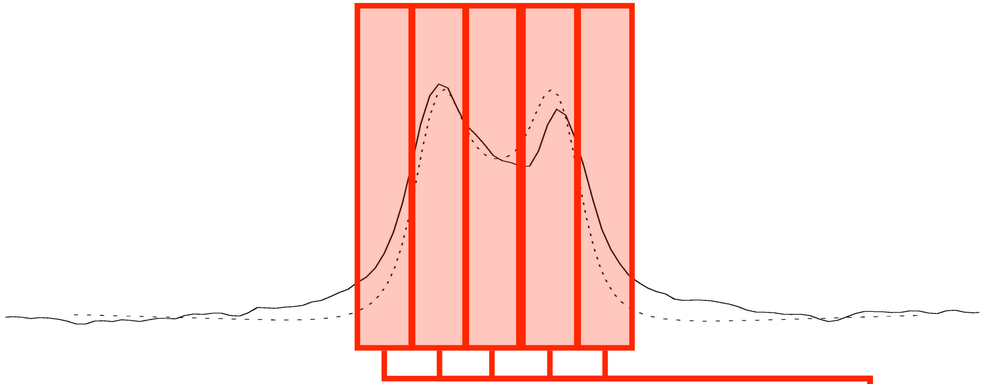
In the whole line



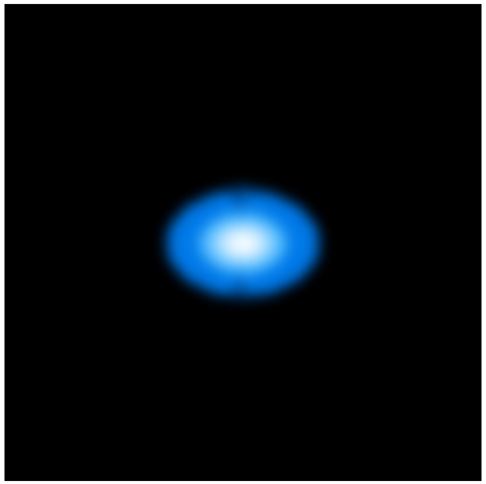
Geometry

Spectro-interferometry

(Doppler Effect)



In the whole line



Geometry

Narrow spectral bandwith within the line

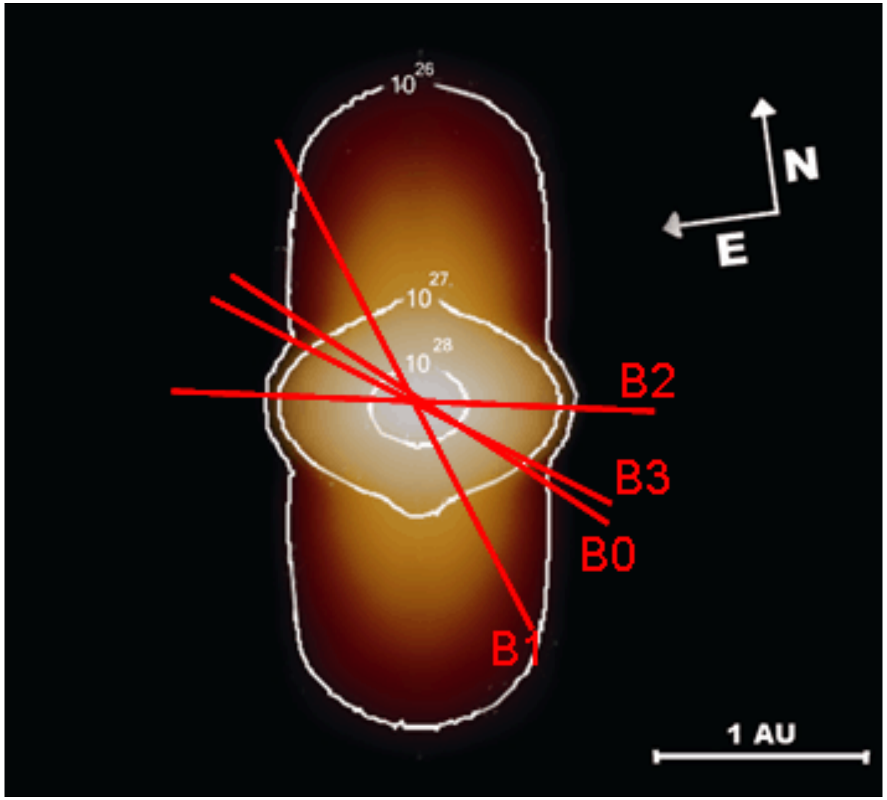
Variation of the visibility modulus and phase as a function of wavelength

Geometry + Kinematics

Expansion/rotation, rotational law, inhomogeneities…

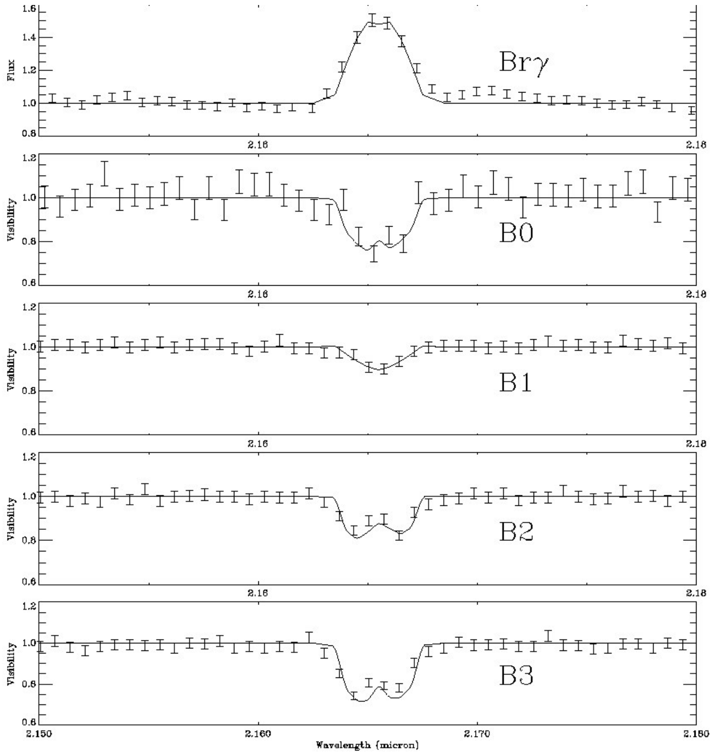
Be Stars:
α Arae

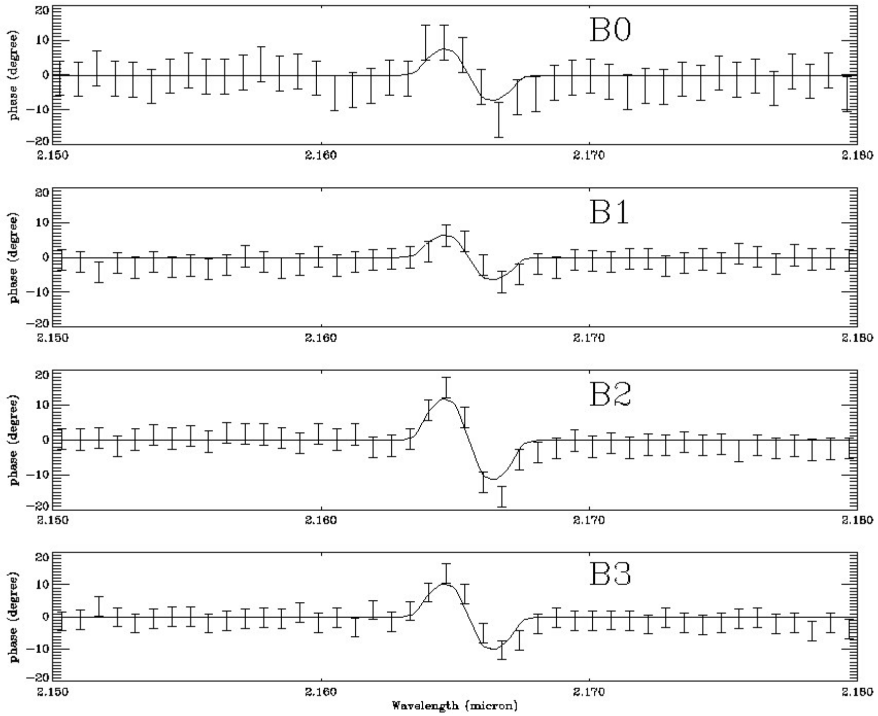
α Arae (VLTI/AMBER)



Intensity map computed with
SIMECA (continuum @ 2 μm)

What is the rotation law within the circumstellar disk ?

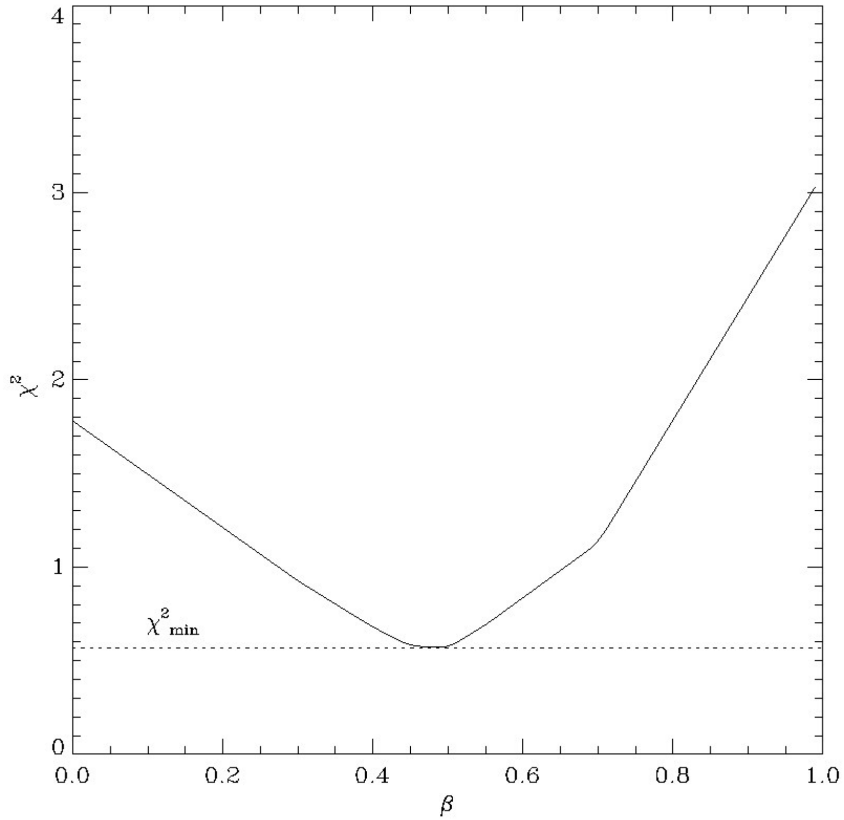




Line profile and modulus of the visibility

Differential phases

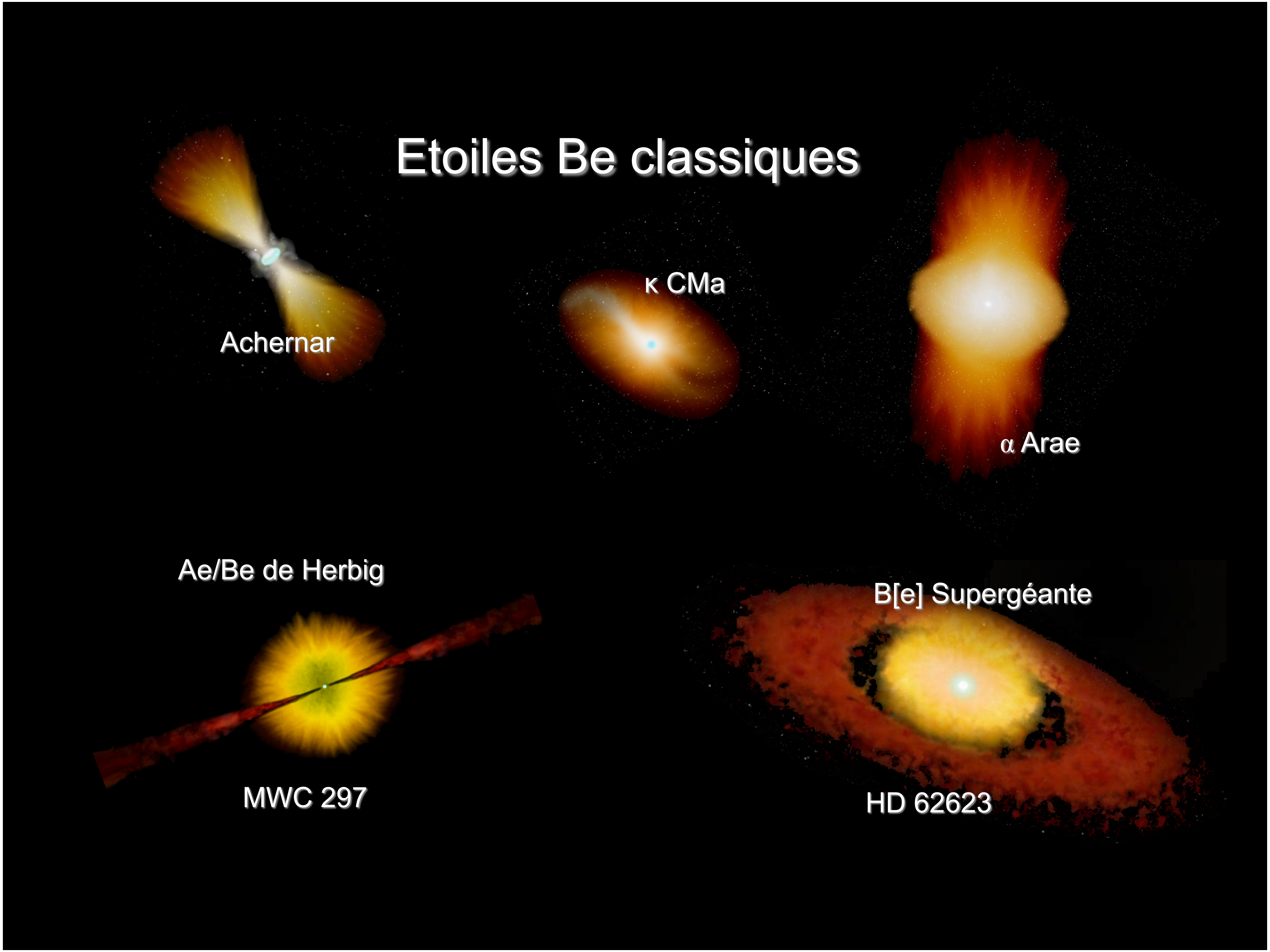
Keplerian ! (Q. depuis 1866…)



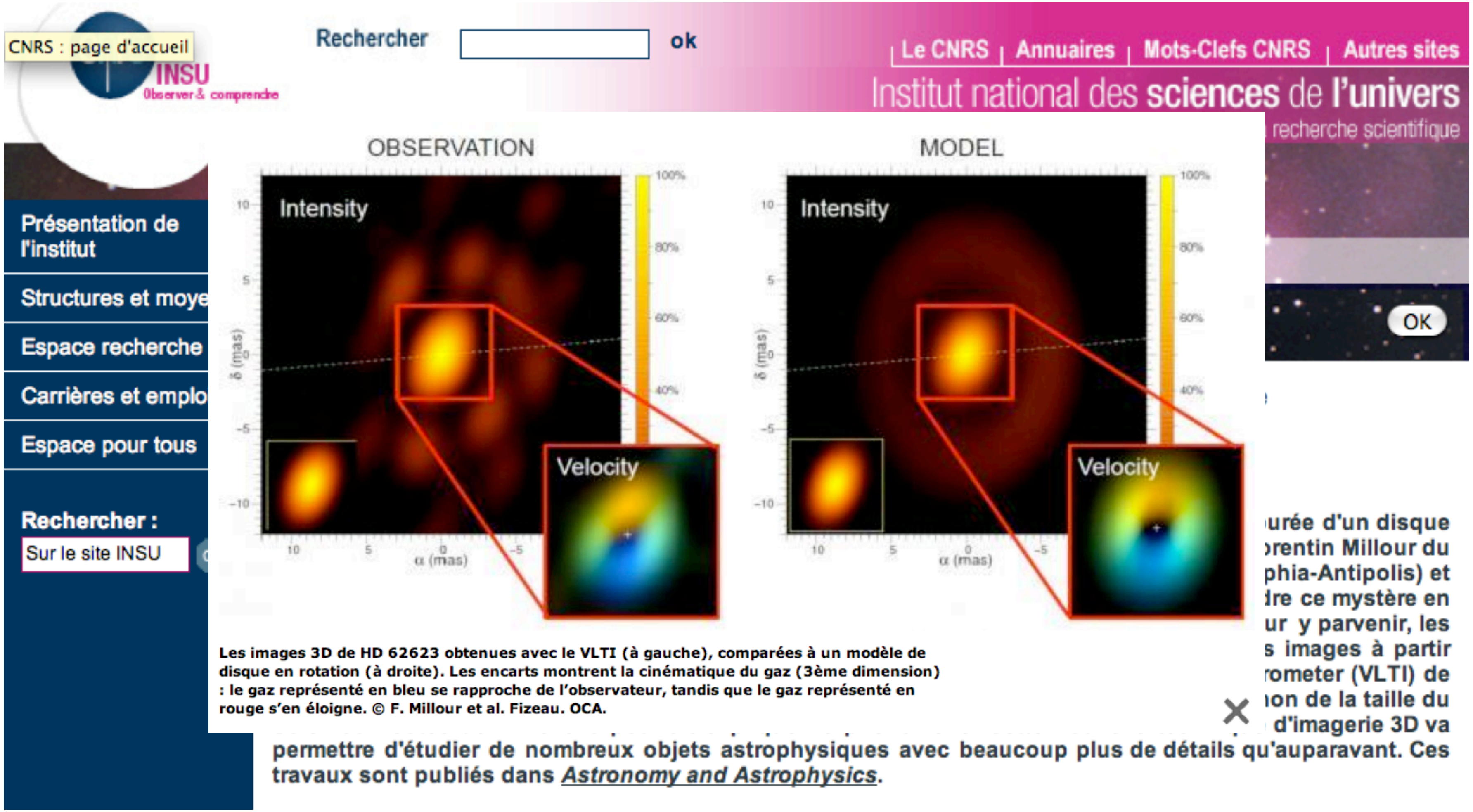
$$V_\theta \approx \frac{V_{rot}}{r^\beta}$$

Keplerian β = 0.5
Angular Cons. Mt β =1

"First direct detection of a Keplerian rotating disk around the Be star α Arae using the VLTI/AMBER instrument" Meilland, A., Stee, Ph. et al. 2006, A&A, astro-ph/0606404


Etoiles Be classiques
Achernar
κ CMa
α Arae
Ae/Be de Herbig
MWC 297
B[e] Supergéante
HD 62623

Première image 3D de l'environnement proche d'une étoile supergéante chaude



Disque de gaz compatible avec une loi de rotation képlérienne

Millour et al. 2011, A&A, 526, A107

Disk Formation and Dissipation

Be Stars : One Ring to rule them all?

Meilland et al. 2006, A&A, 455, 953

Ring
vs
Mass-Flux variation

Study the variation of observables during the
Disk dissipation

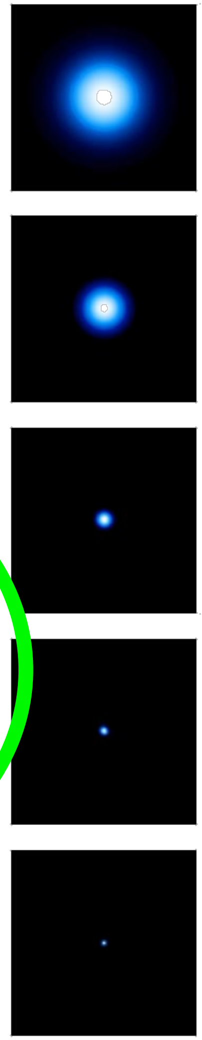
Visibilities

Amplitude and position
Of the visibility second lobe

~~SED~~

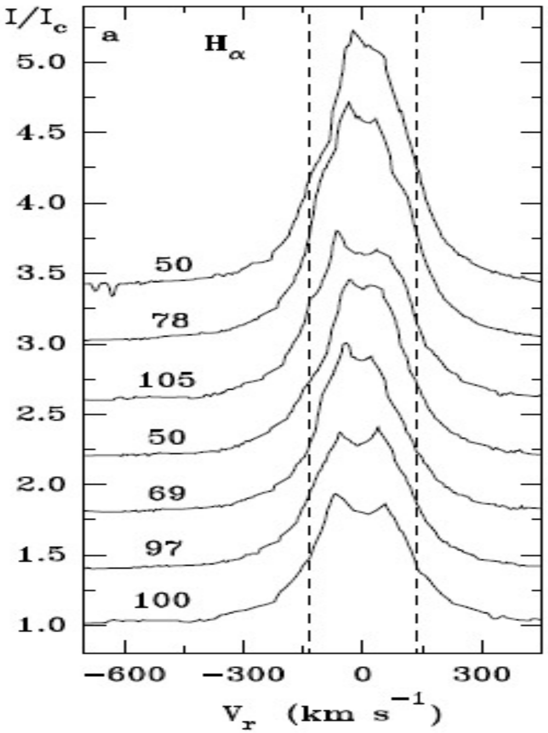
Line profiles

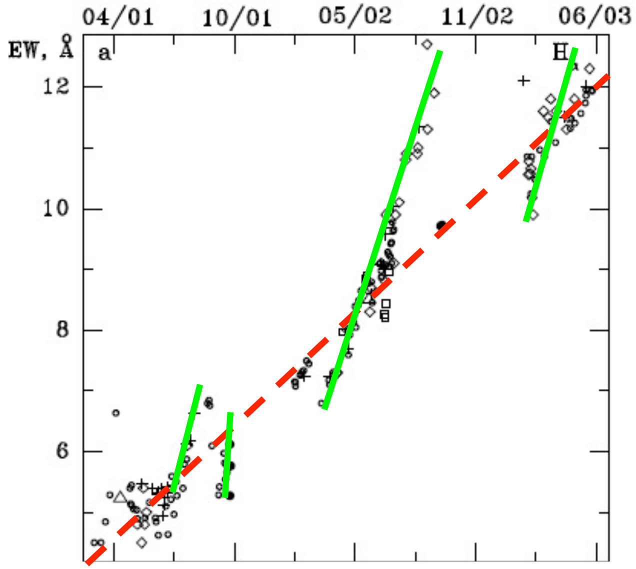
Double-pics separation
Time of the dissipation



DISK FORMATION AND DISSIPATION

δ Sco

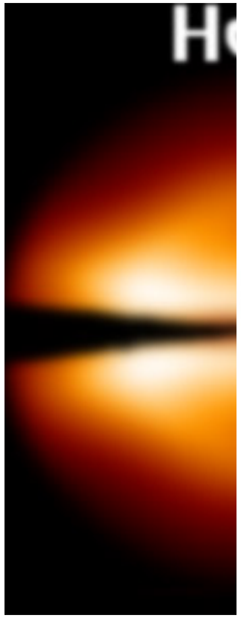


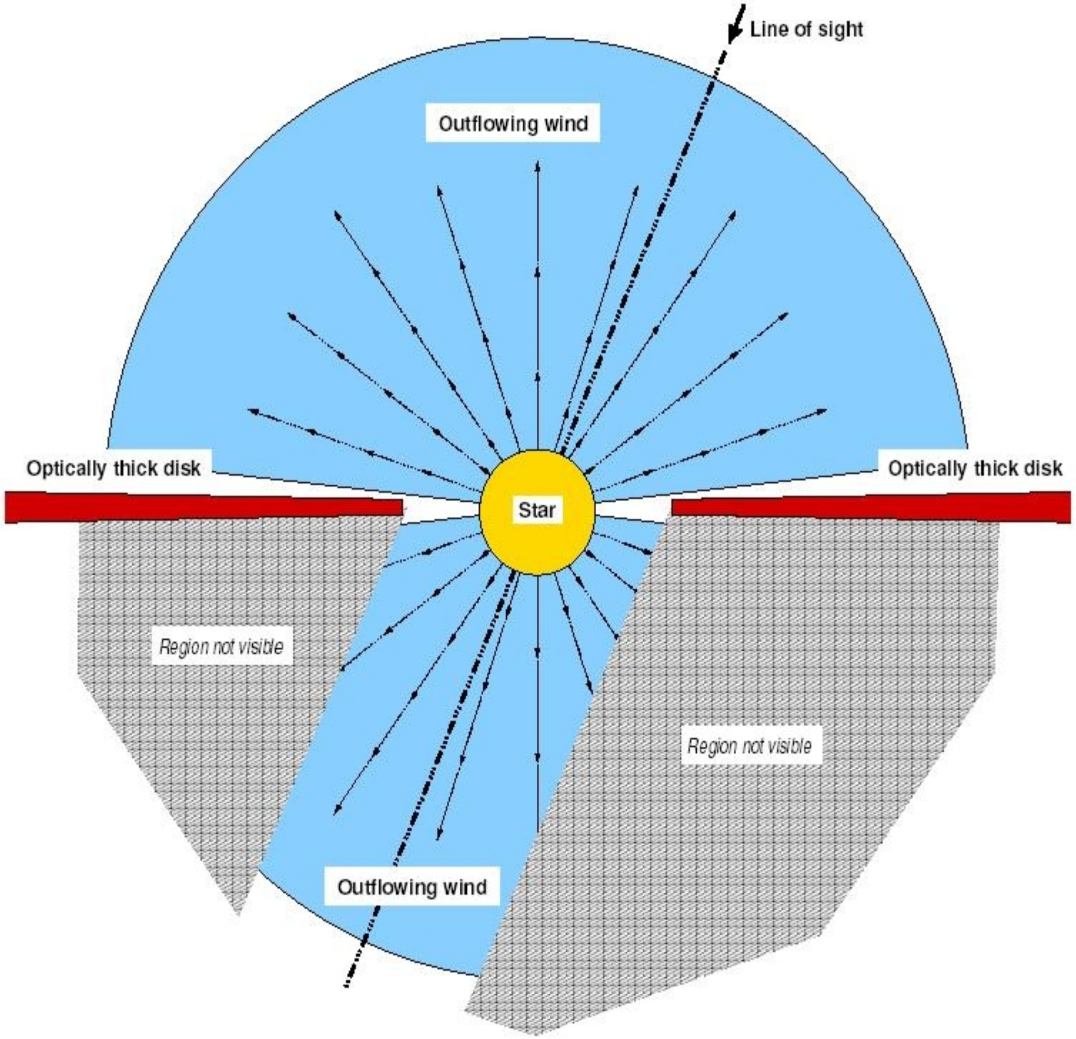


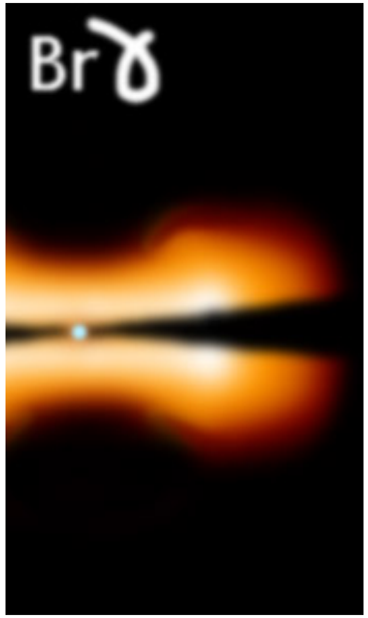
MIROSHNICHENKO ET AL. 2003 A&A 408,305

- GROWING DISK TILL 2000 (PERIASTRON)
- R_{DISK}(2003)~ 10R_*
- V_R~0.4kms^{-1}
- KEPLERIAN ?
- MULTIPLE OUTBURSTS?

HAe/Be star: MWC 297



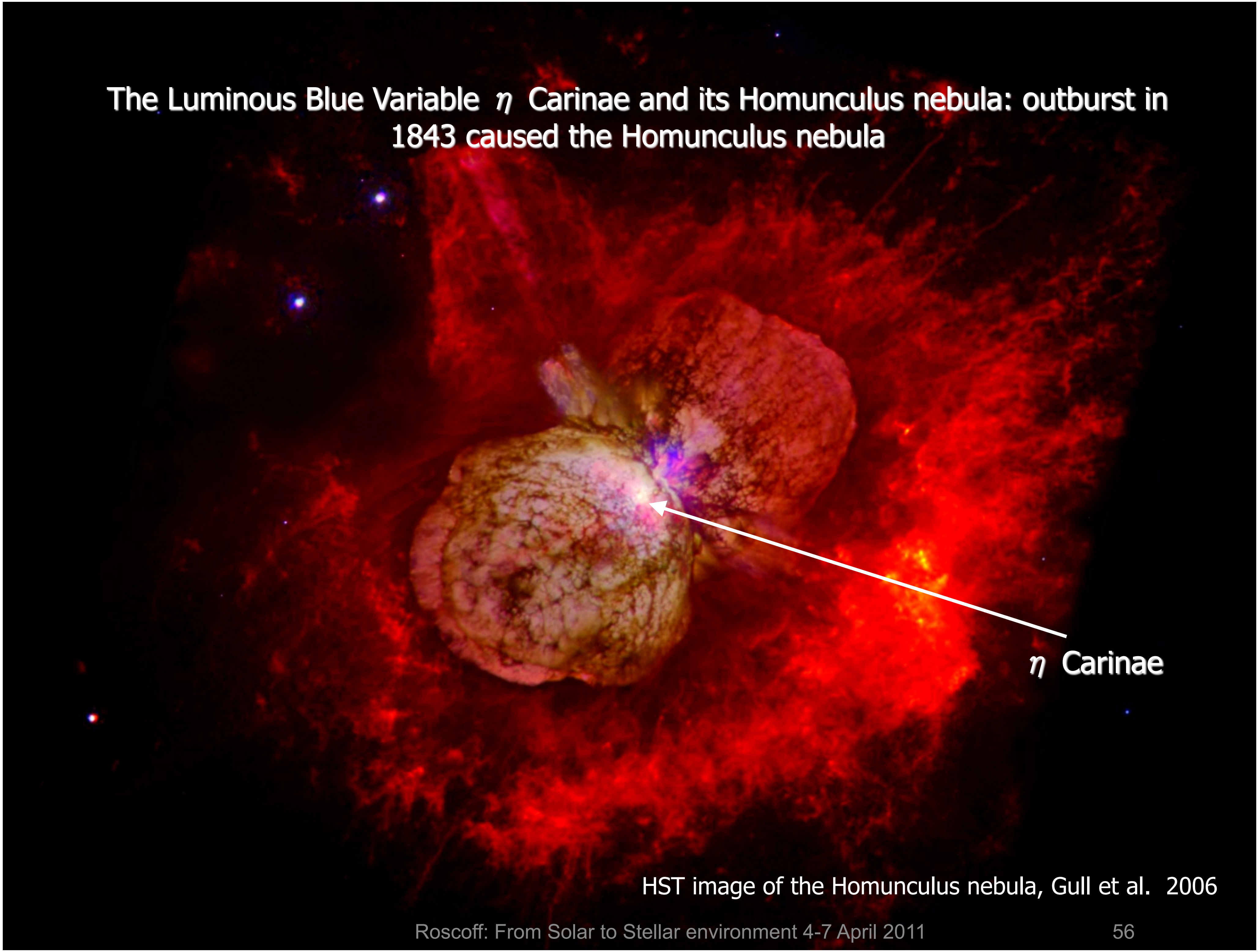




"Disk and wind interactions in the young stellar object MWC 297 spatially resolved with AMBER/VLTI" Malbet F., Benisty, M. et al. 2006, A&A, astro-ph/0510350

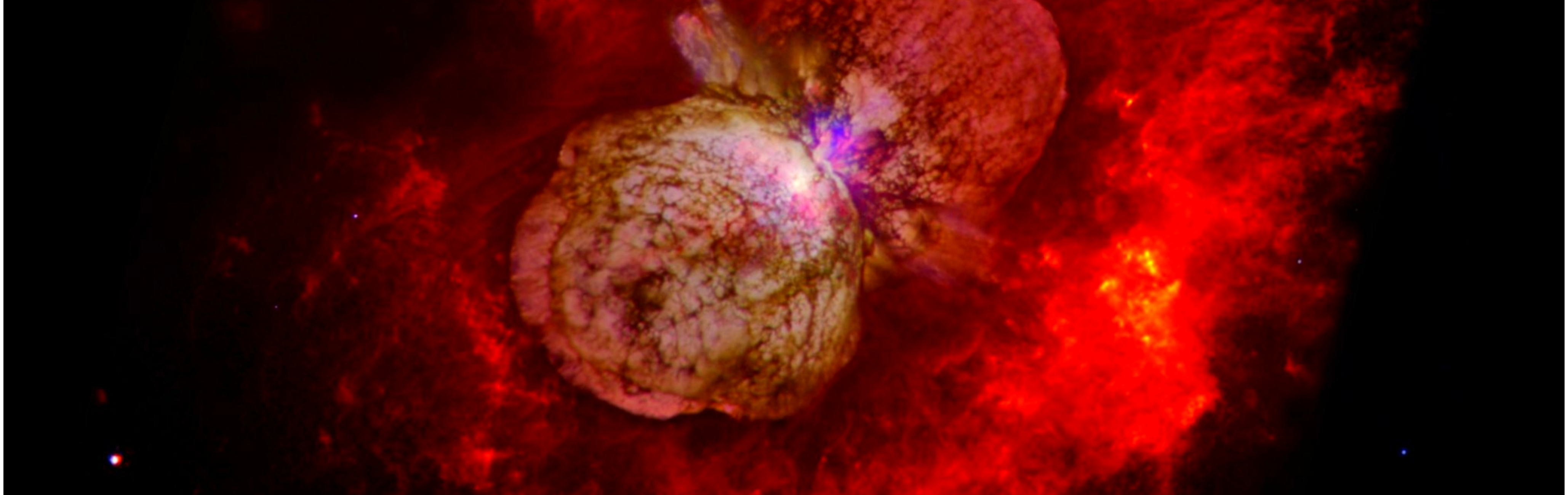
Eta Car (LBV)

The Luminous Blue Variable η Carinae and its Homunculus nebula: outburst in 1843 caused the Homunculus nebula

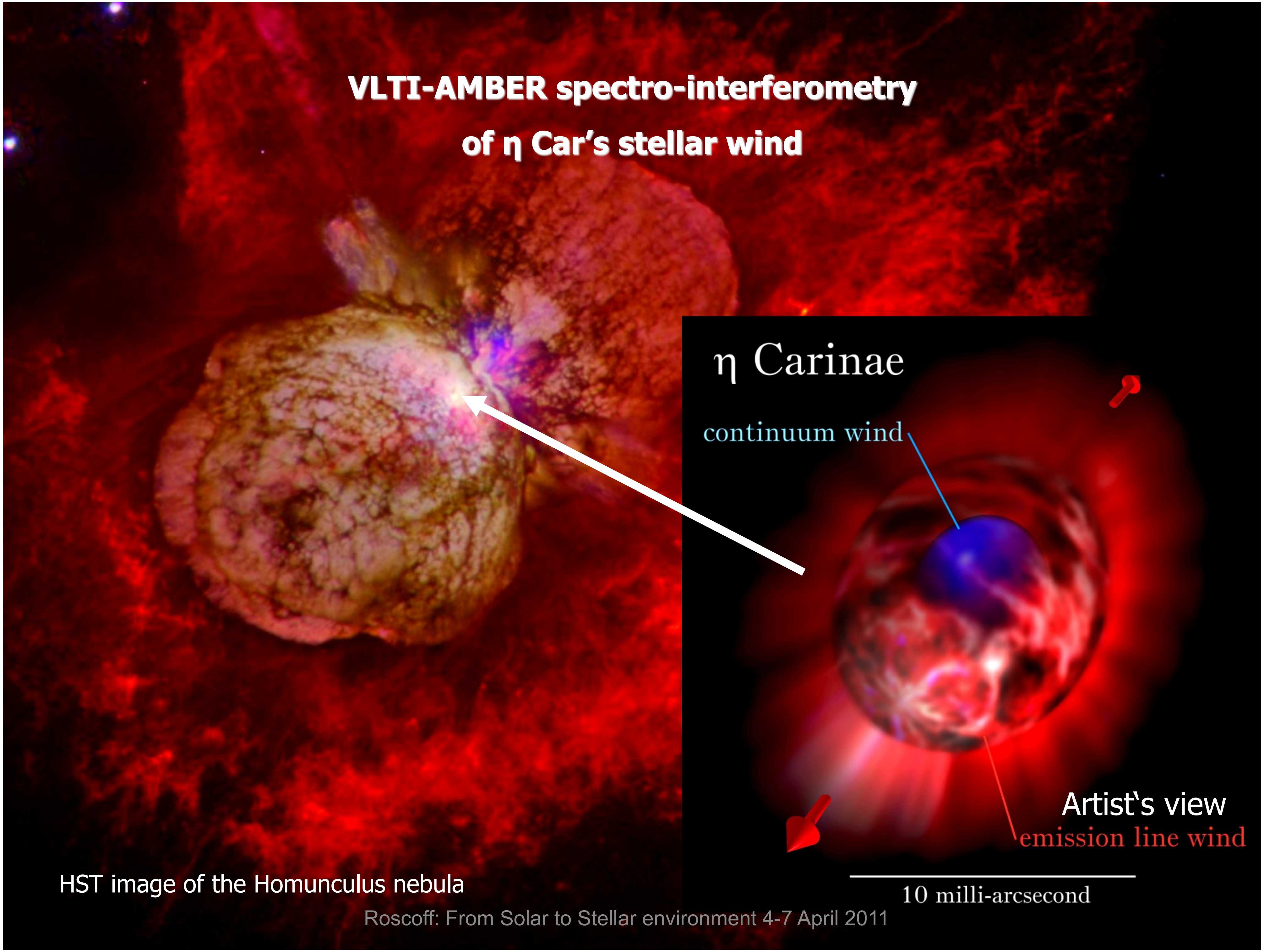


HST image of the Homunculus nebula, Gull et al. 2006

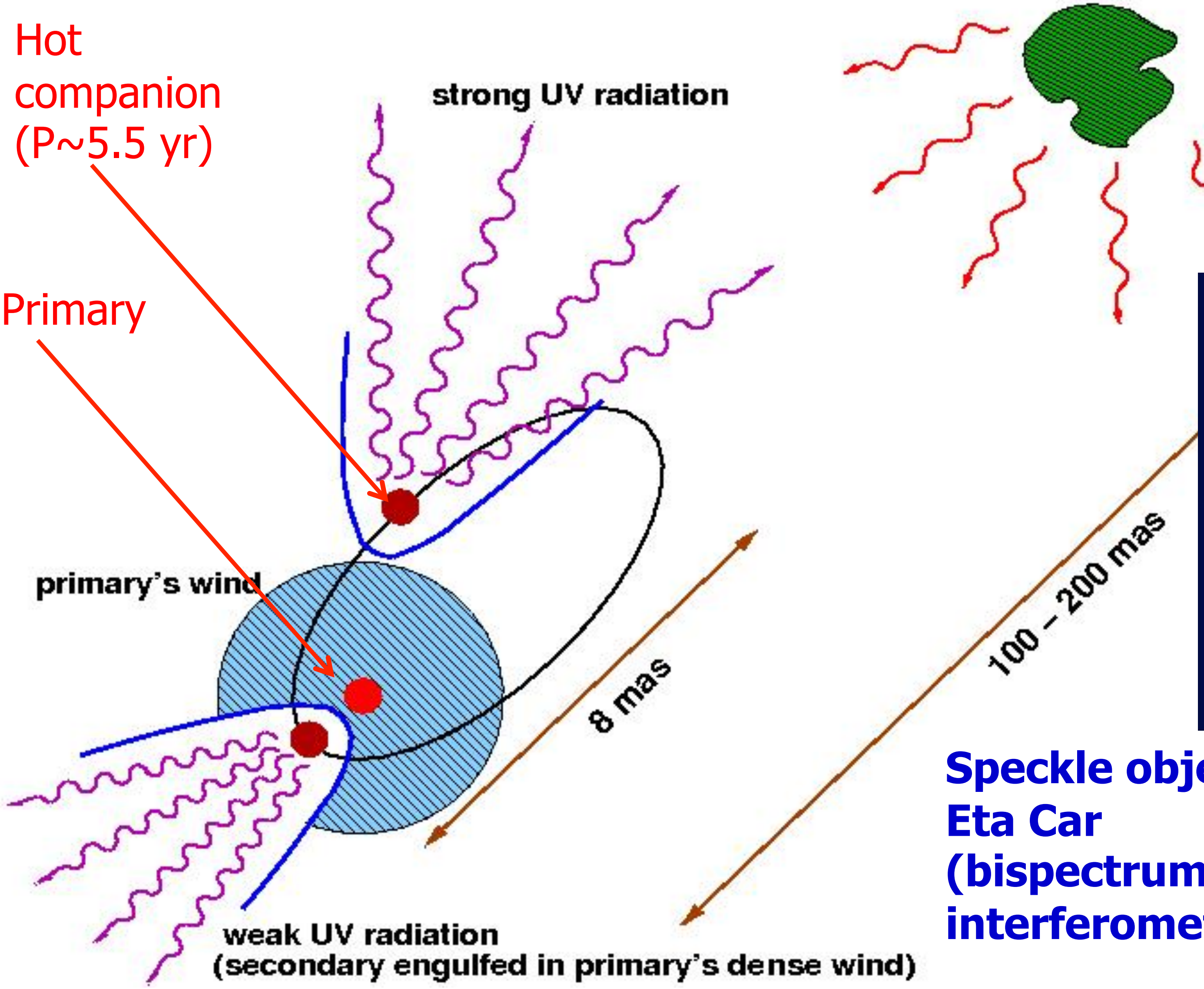
- Extreme Luminous Blue Variable with spectacular outbursts
- Eta Carinae's mass: 70 to 100 solar masses
- Dense aspherical stellar wind: diameter ~4 mas ~ 9 AU diameter
- High density of the stellar wind → star is not visible
- WR binary companion (P~5.5 yr), spectroscopic events …

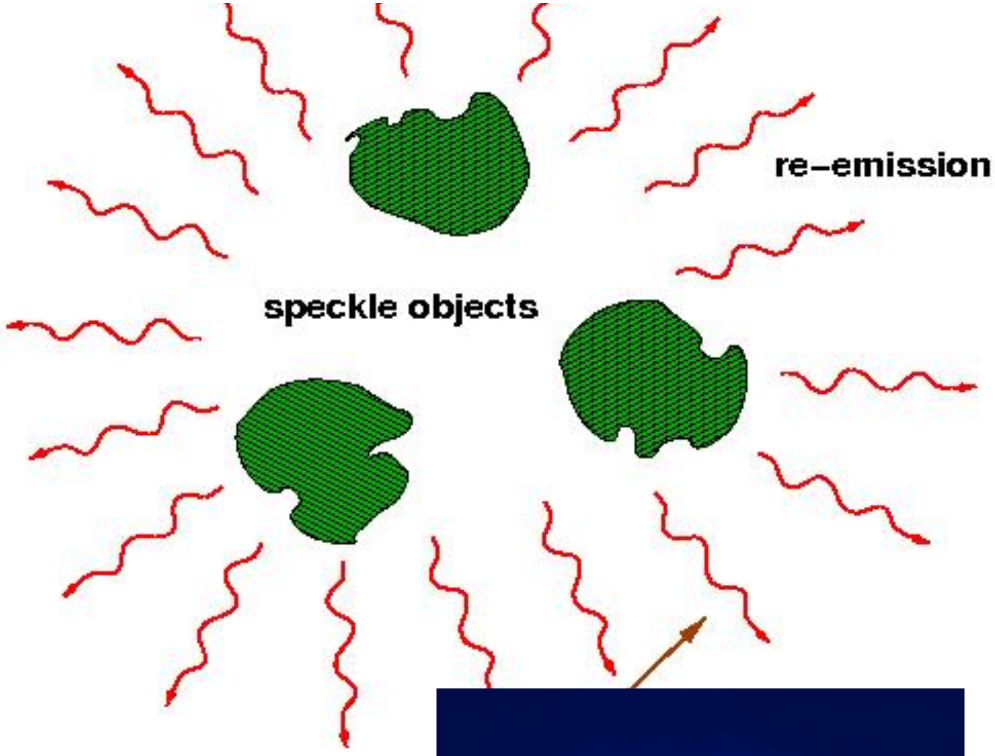


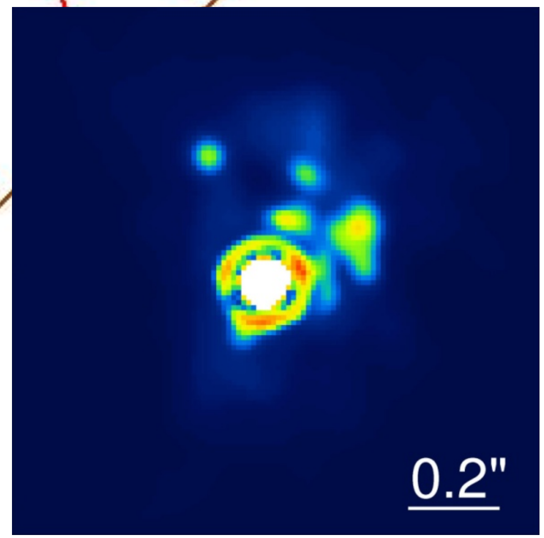
- Observations: visibilities, differential & closure phases
- Resolution of η Car's aspheric wind region: continuum, Br γ & He I; interpretation
- see Weigelt et al., A&A 464, 87 (2007)


VLTI-AMBER spectro-interferometry
of η Car's stellar wind
η Carinae
continuum wind
Artist's view
emission line wind
10 milli-arcsecond
HST image of the Homunculus nebula

The inner 1 arcsec: speckle objects, primary wind, binary, & wind-wind interaction zone





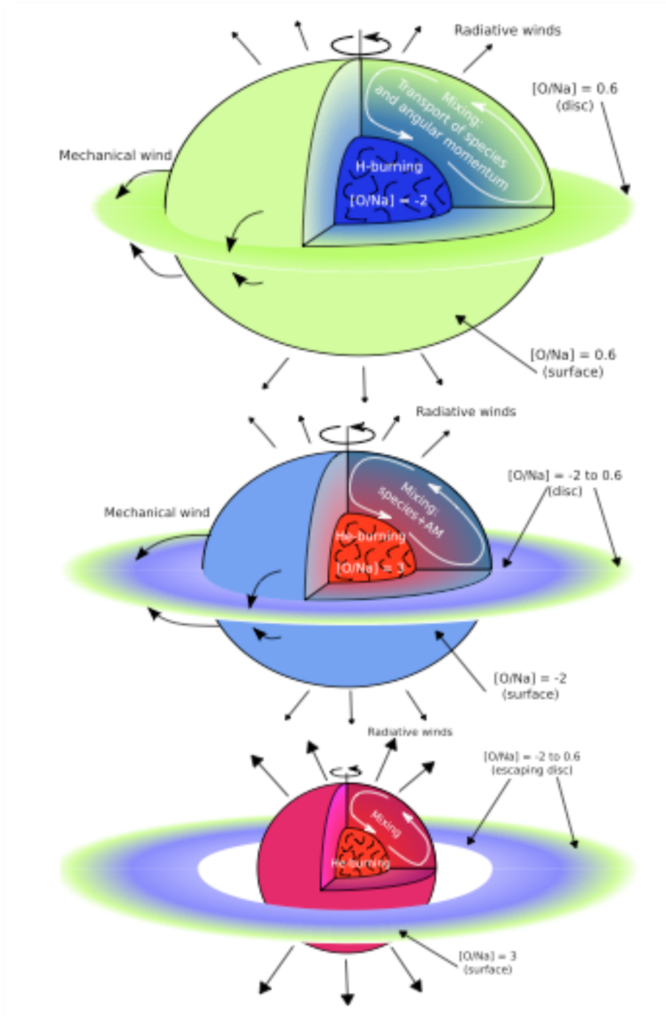


Speckle objects: ejecta excited by Eta Car (bispectrum speckle interferometry, ESO 3.6 m, 2008)

Intérêt de l'étude des étoiles chaudes massives ?

✧ Influence sur les modèles d'évolution stellaire: contraintes sur la perte de masse.
(Decressin, Charbonnel, Meynet 2007, A&A, 475, 859)

✧ Modèles 2D d'étoile en rotation (ESTER, Rieutord et al.)



Intérêt de l'étude des étoiles chaudes massives ?

✧ Diagramme HR évolutif:

effet des vents non-isotropes

sur l'évolution

(Georgy, Meynet & Maeder 2011,

A&A, 527, A52)

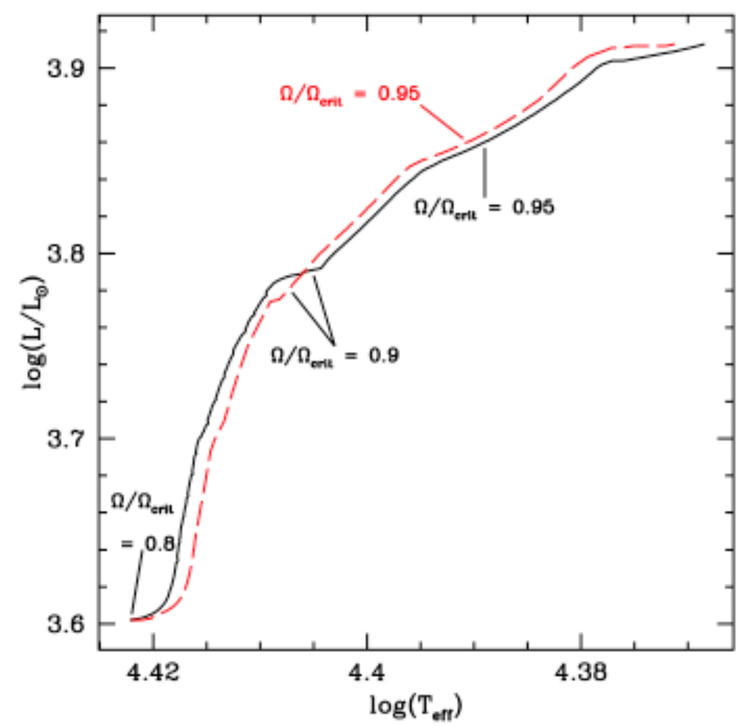
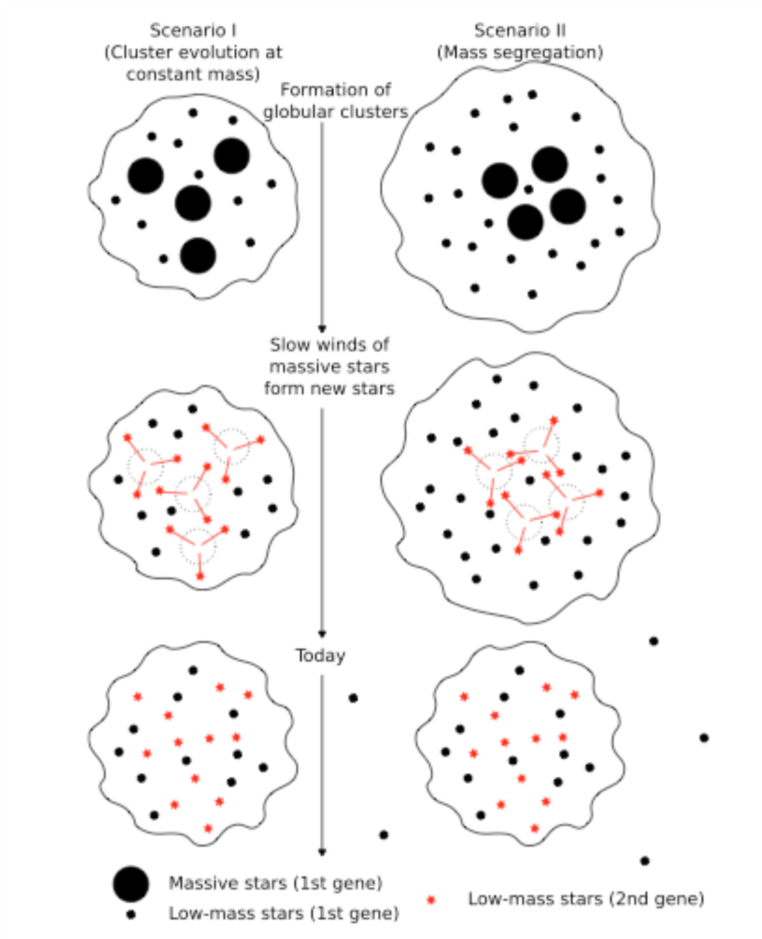


Fig. 9. HR diagram for the isotropic model (black solid line) and anisotropic model (red dashed line) with realistic mass-loss rates. The rotation rate is indicated for some points along the tracks.

Intérêt de l'étude des étoiles chaudes massives ?

✧ Effet sur l'enrichissement des amas globulaire et leur évolution chimique.

(Decressin et al. 2007, A&A, 475, 859)

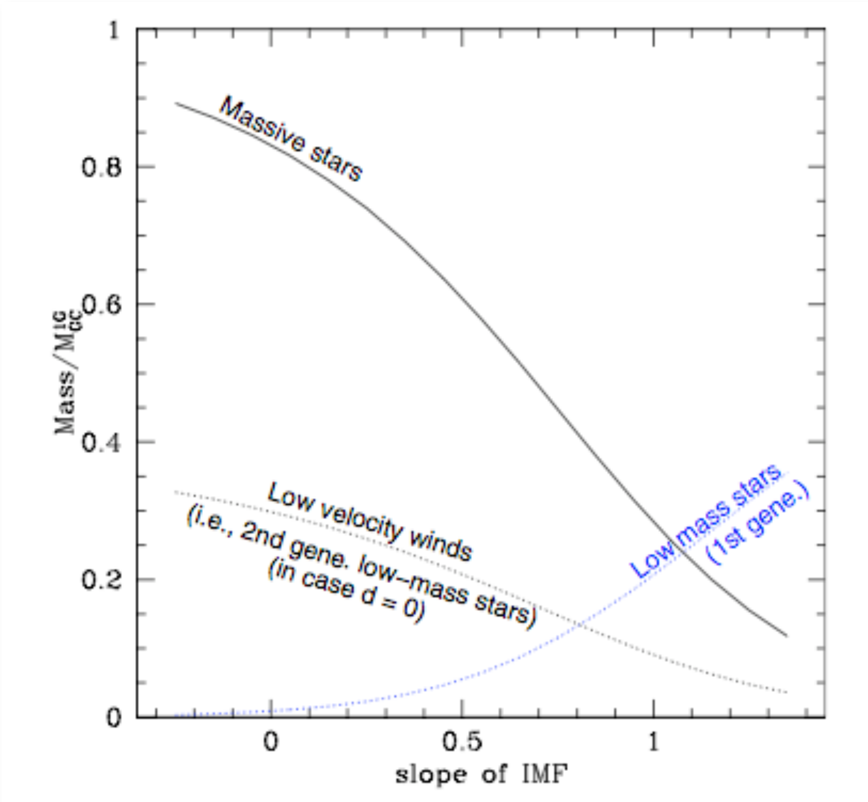


Intérêt de l'étude des étoiles chaudes massives ?

✧ Contrainte sur l'IMF

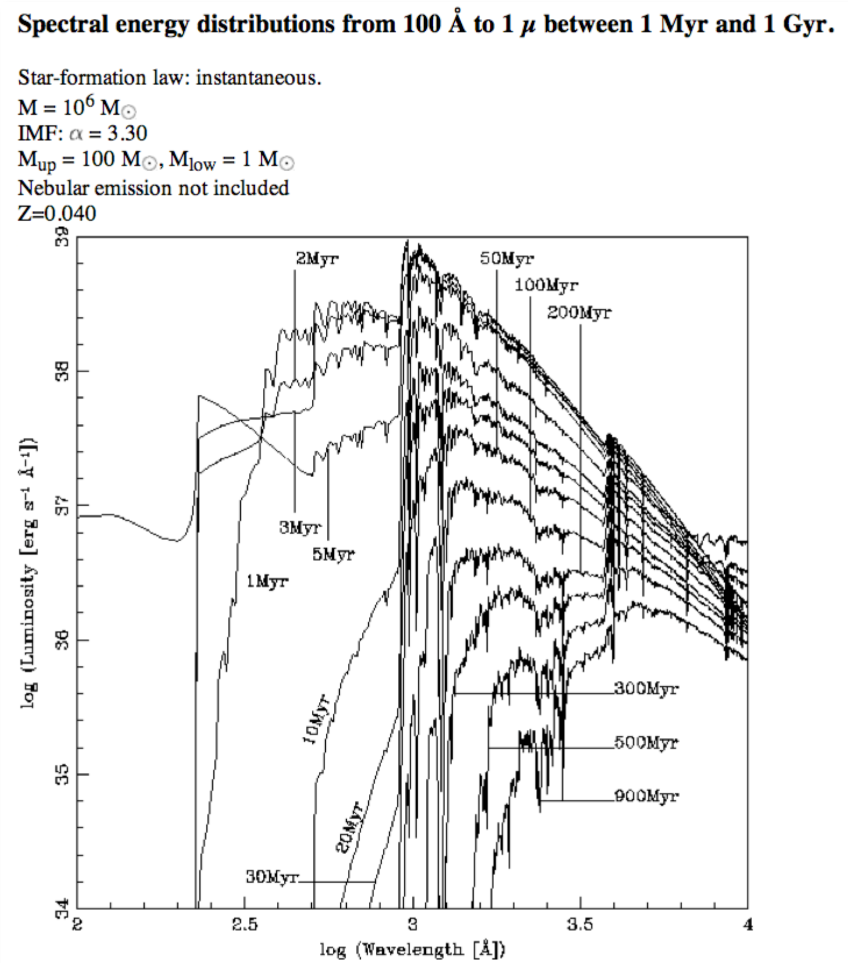
(Decressin, Charbonnel,

Meynet 2007, A&A, 475, 859)



Intérêt de l'étude des étoiles chaudes massives ?

✧ Spectres synthétiques
de « star-forming » galaxies.
(Voir travaux de Schaerer
et al. et le code Starburst 99)



Intérêt de l'étude des étoiles chaudes massives ?

✧ Contraintes sur les paramètres fondamentaux et la structure interne des modèles d'évolution.

(Maeder, Georgy, Meynet, 2008, A&A, 479, L37)

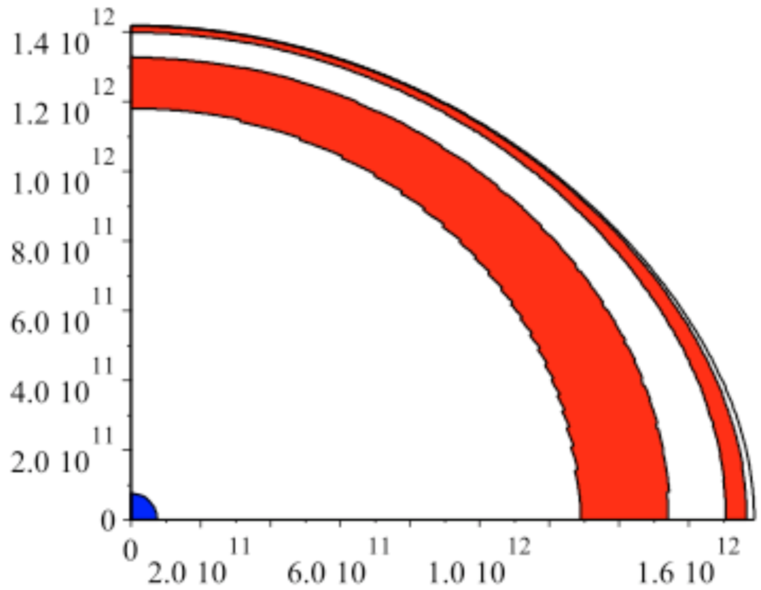


Fig. 2. 2D model of the external convective zones and of the convective core (dark areas) in a model of 20 $M_\odot$ with $X = 0.70$ and $Z = 0.020$ at the end of MS evolution with fast rotation ($\omega = \Omega/\Omega_{crit} = 0.94$). The axes are in units of cm.

Intérêt de l'étude des étoiles chaudes massives ?

✧Etoiles Be/Oe possibles progéniteurs de « long-γ ray bursts »

(Martayan et al. 2010, A&A, 516, A103)

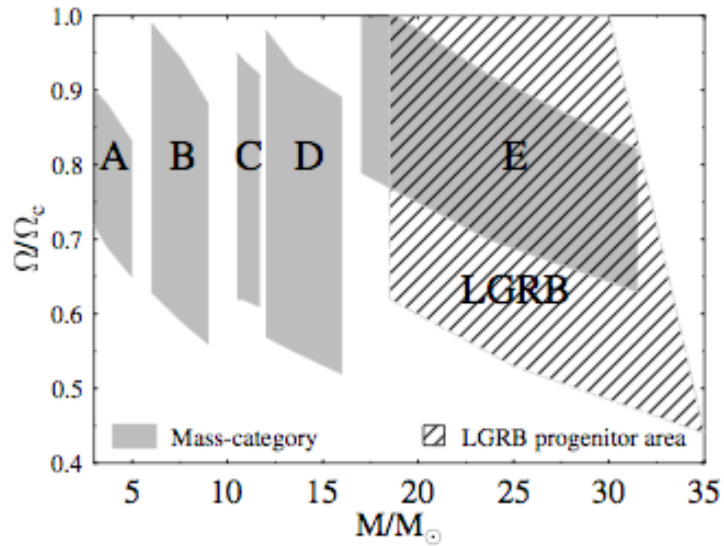


Fig. 3. Comparison of the (Ω/Ω_c, $M/M_\odot$) parameters in the ZAMS per mass category for SMC Oe/Be stars with the area of long gamma ray bursts progenitors at SMC metallicity predicted by Yoon et al. (2006).

Conclusions:

✓ Active hot stars: very nice laboratory to test NLTE physics

✓ Interferometry: powerful tool to study this physics with sub-mas spatial resolution.

✓ We need NLTE & 3D models to constrain the data

✓ Spectrally-resolved interferometry, i.e. with both spatial & spectral resolution is a key to constrain these models

✓ Multi-wavelengths studies are mendatory (physics = f(λ))

✓ Laboratory astrophysics can strongly help us since same processes can be studied in a « box », i.e. NLTE physics, radiative transfer, 3D hydro, coupling hydro-rad…and development of codes also useful for the astrophysical community…