La dynamique atmosphérique des Céphéides, la rotation de la Voie Lactée et l'étalonnage des échelles de distance dans l'Univers

Sommaire:

1/ Les Céphéides : petit historique

2/ Etalonnage des échelles de distance dans l'Univers

3/ Structure Vélocimétrique de la Voie Lactée

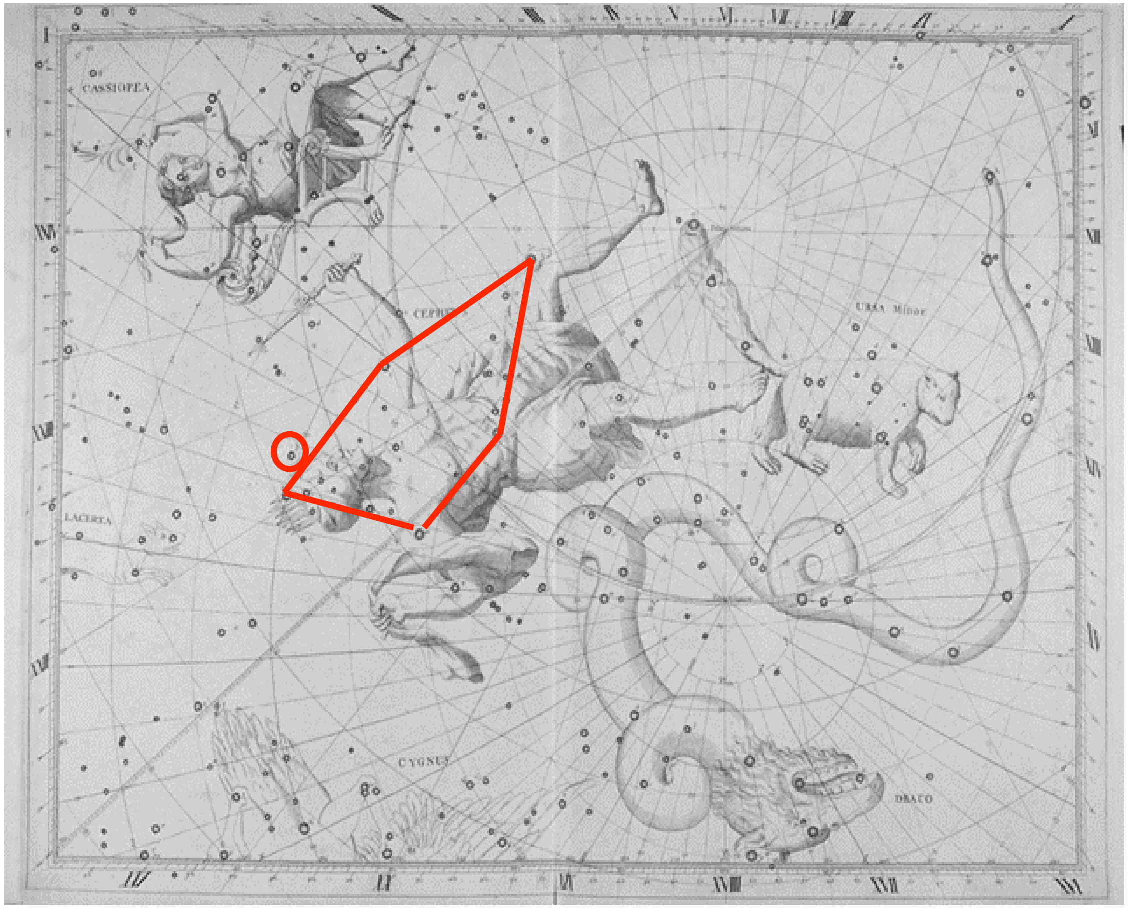
4/ Enveloppe circumstellaire

5/ Perspectives : la spectro-interférométrie

Nicolas Nardetto

Post-Doc à l'Université de Concepcion, Chili

Découverte de la première Céphéide : δ Cephei



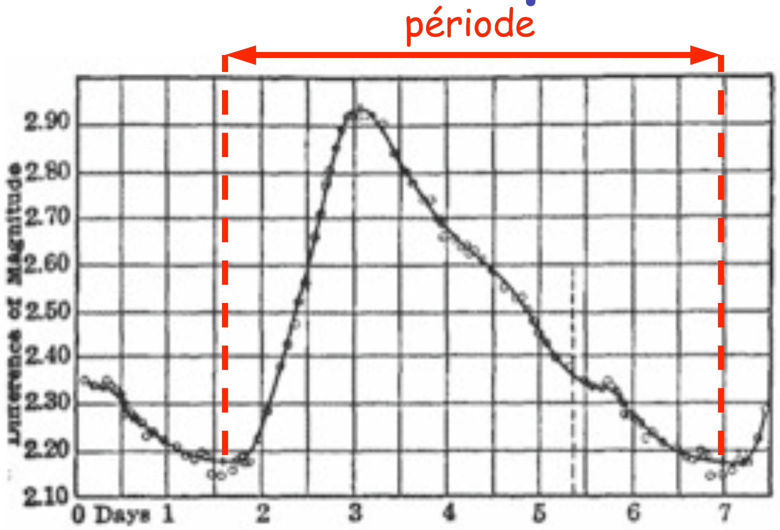
John Goodrick (1764-1786)

M=5 Ms
R=41.6 Rs
L=2000 Ls
Teff=5500-6800 K

P=5.36 jours
ΔR/R=10%

Découverte de la relation période-luminosité (PL)

16 Céphéides dans les Nuages de Magellan



H. Leavitt (1908)

magnitude

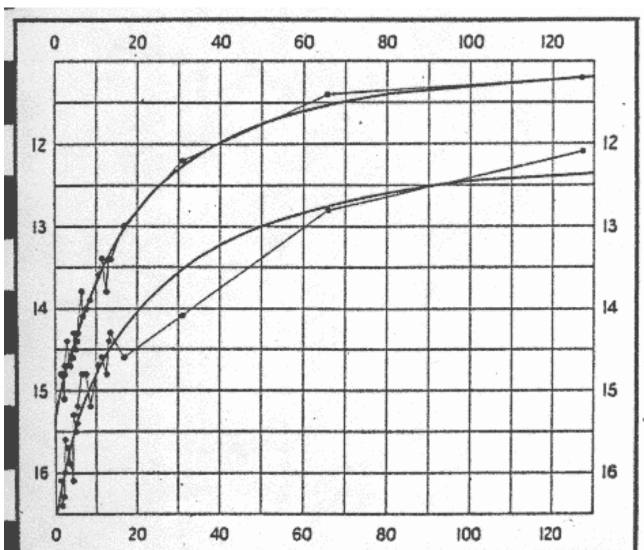


FIG. 1.

Période (jours)

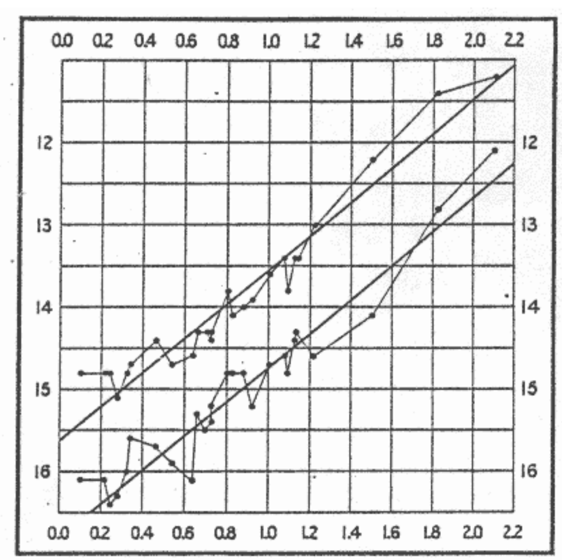


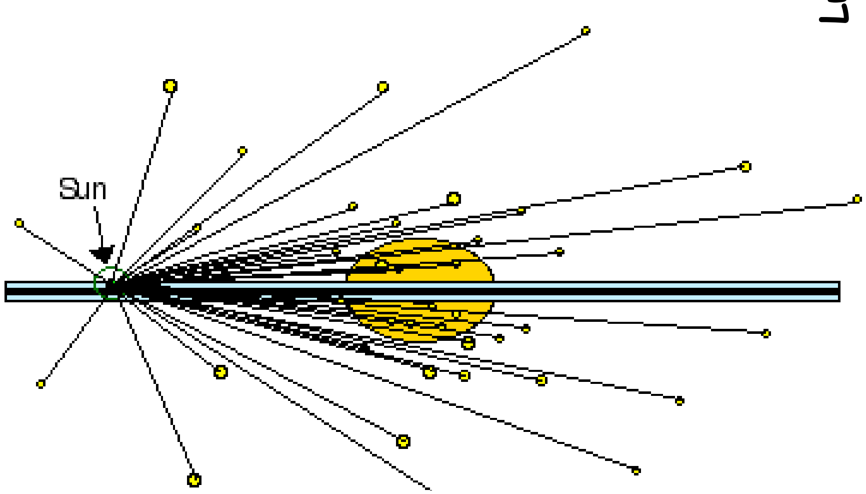
FIG. 2.

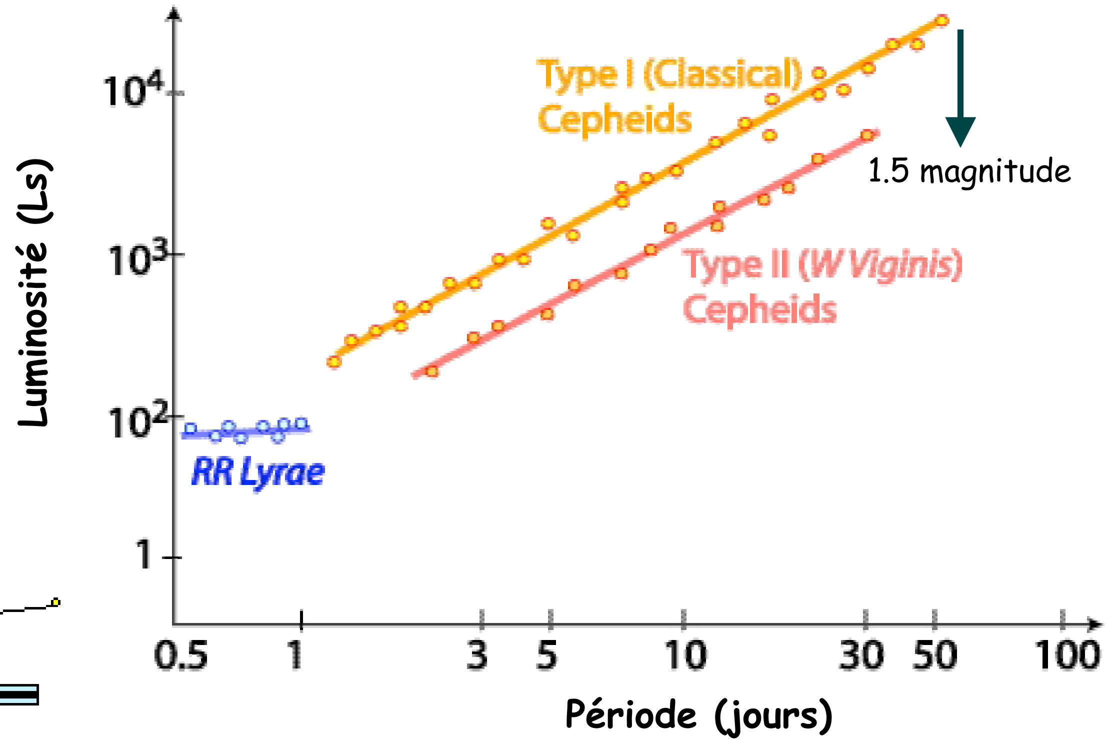
log P (jours)

Premiers étalonnages de la relation PL

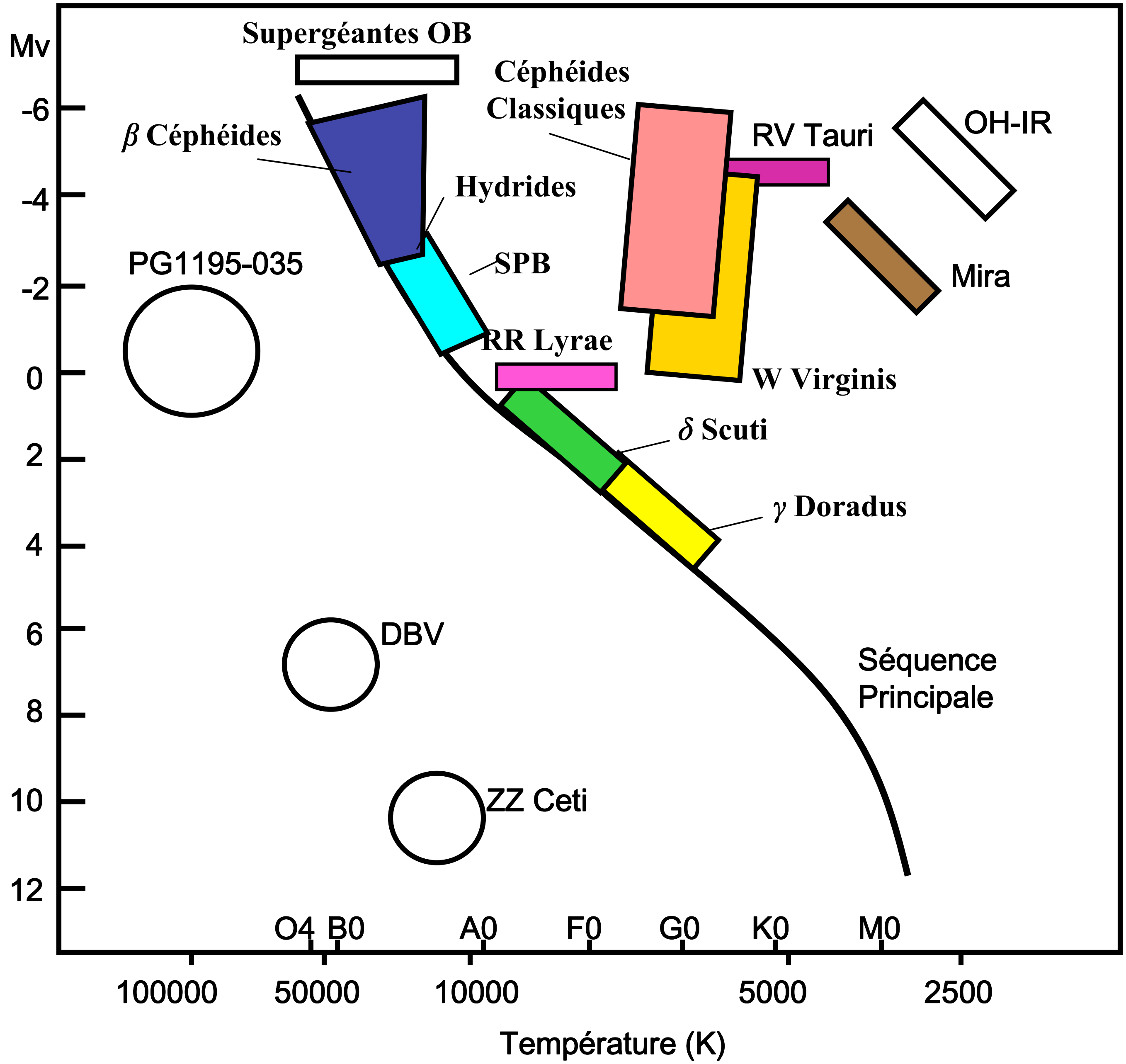
Hertzsprung (1913) : <M> = $a + b\log_{10}P$ (3000 a.l. pour le SMC au lieu de 210000!)

Shapley (1920) : il confond les Céphéides de type I et de type II (ou W Virginis)



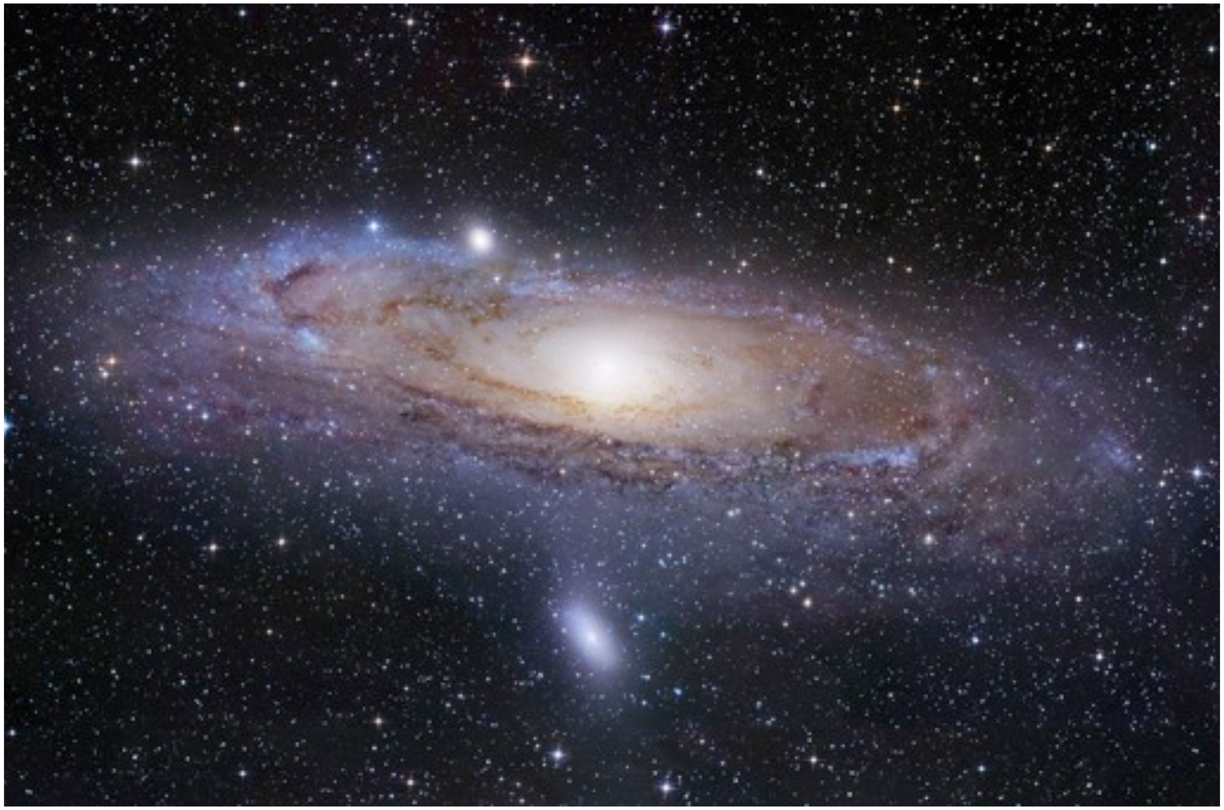


Les différents type d'étoiles pulsantes



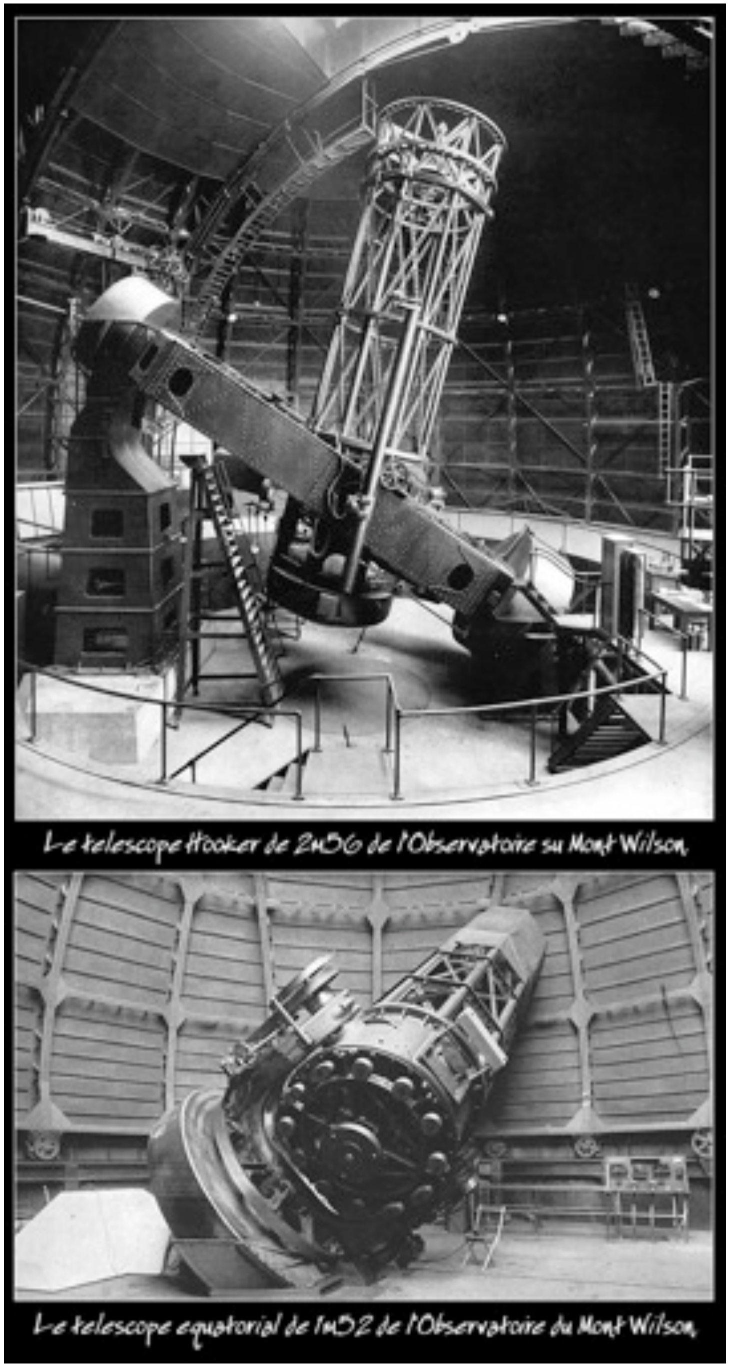
La distance à la Galaxie d'Andromède (M31)

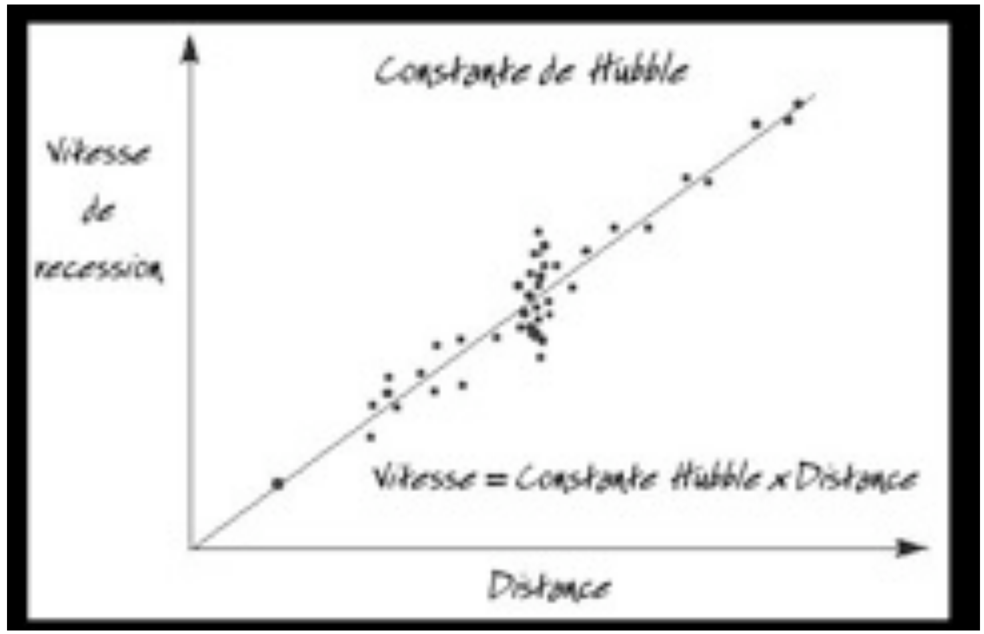
Hubble (1925) : distance de M31, 2 fois trop prés! Il observe les Céphéides de type I et utilise la relation de Shapley (valable pour les W Virginis).



Baade (1944) : distinction entre les Céphéides et les W Virginis

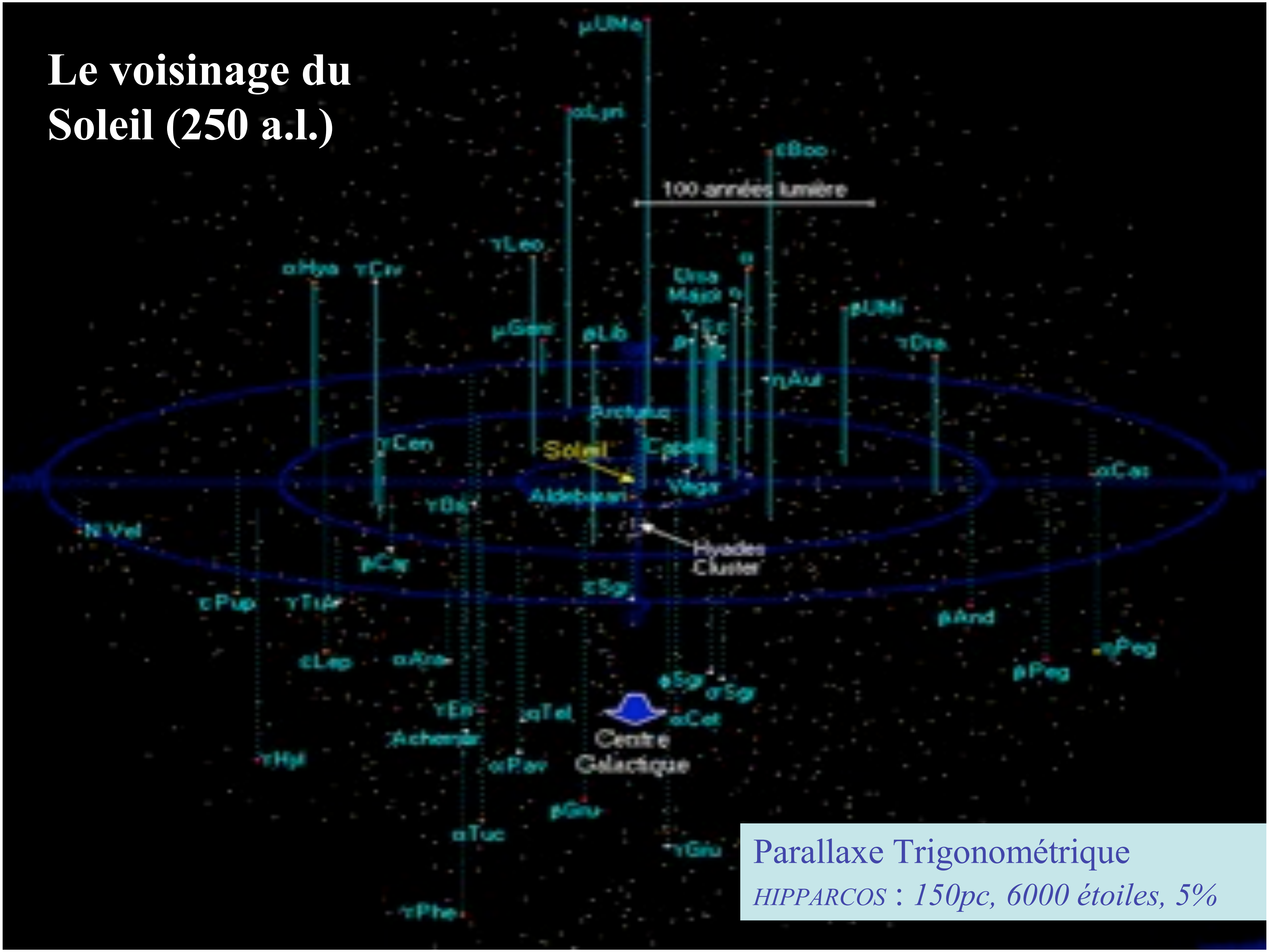
La constante de Hubble





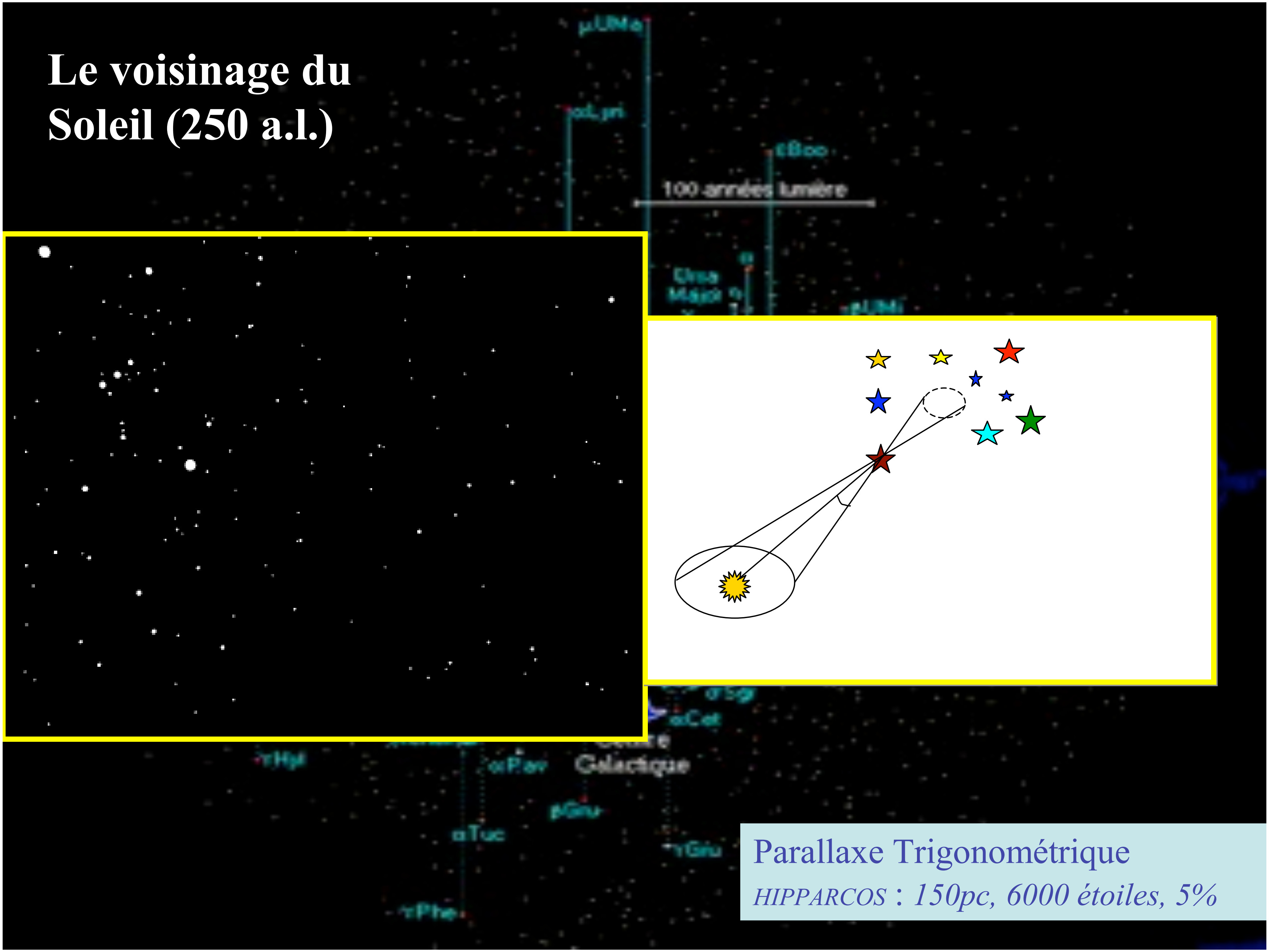
Hubble, 1929

Le voisinage du Soleil (250 a.l.)

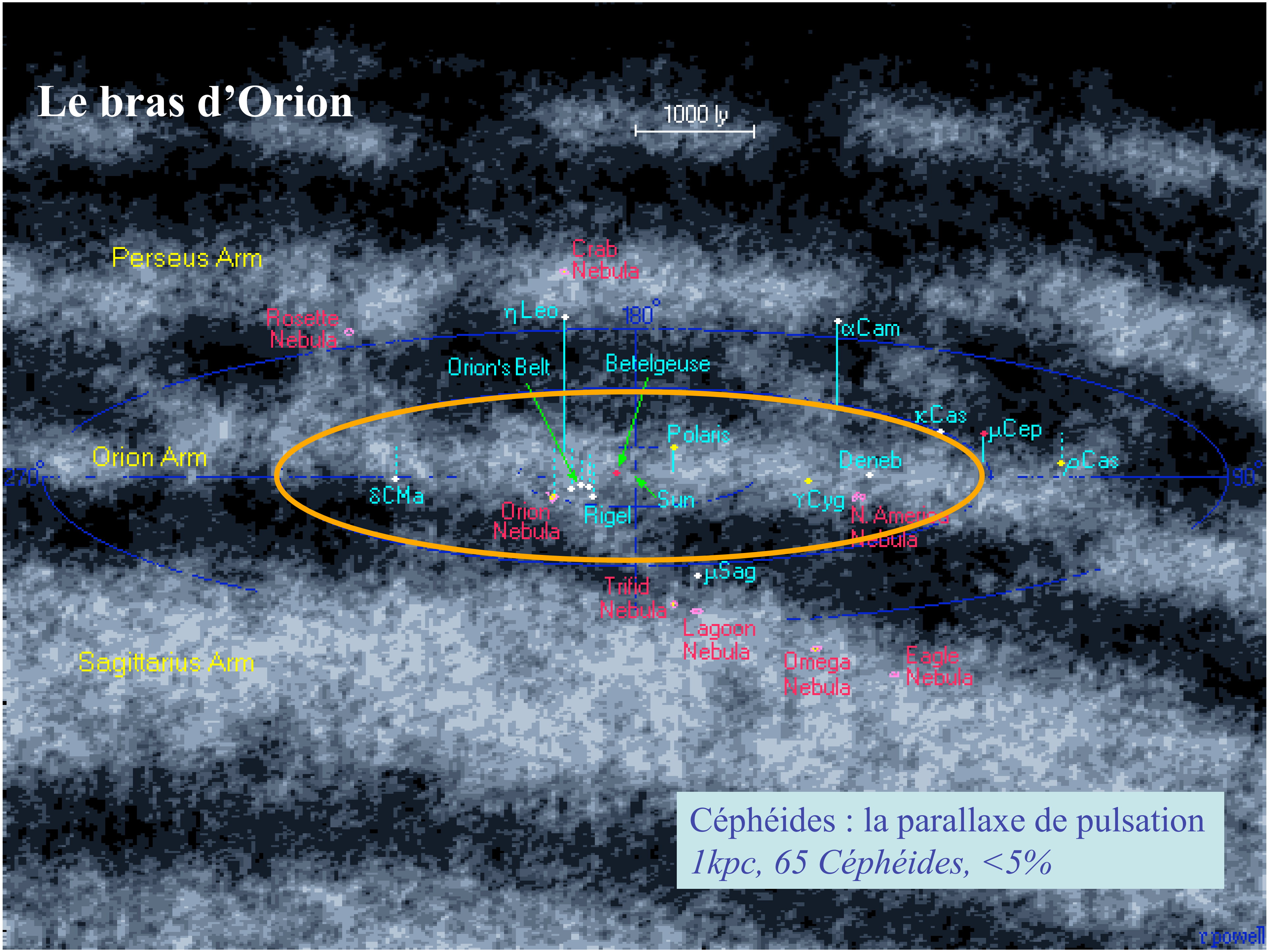


Parallaxe Trigonométrique

HIPPARCOS : *150pc, 6000 étoiles, 5%*


Le voisinage du Soleil (250 a.l.)
100 années lumière
Parallaxe Trigonométrique
HIPPARCOS : 150pc, 6000 étoiles, 5%

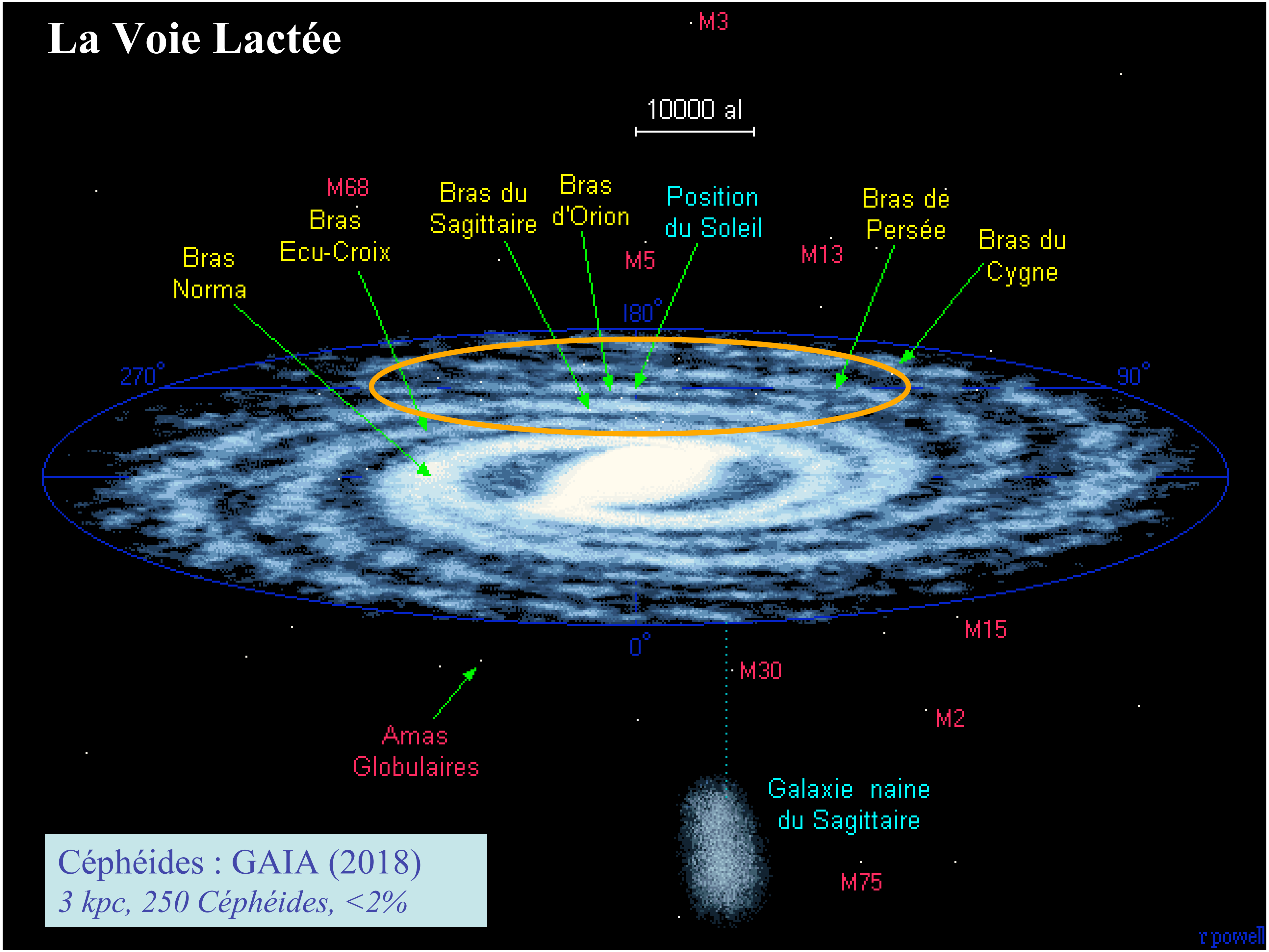
Le bras d'Orion



Céphéides : la parallaxe de pulsation

1kpc, 65 Céphéides, <5%

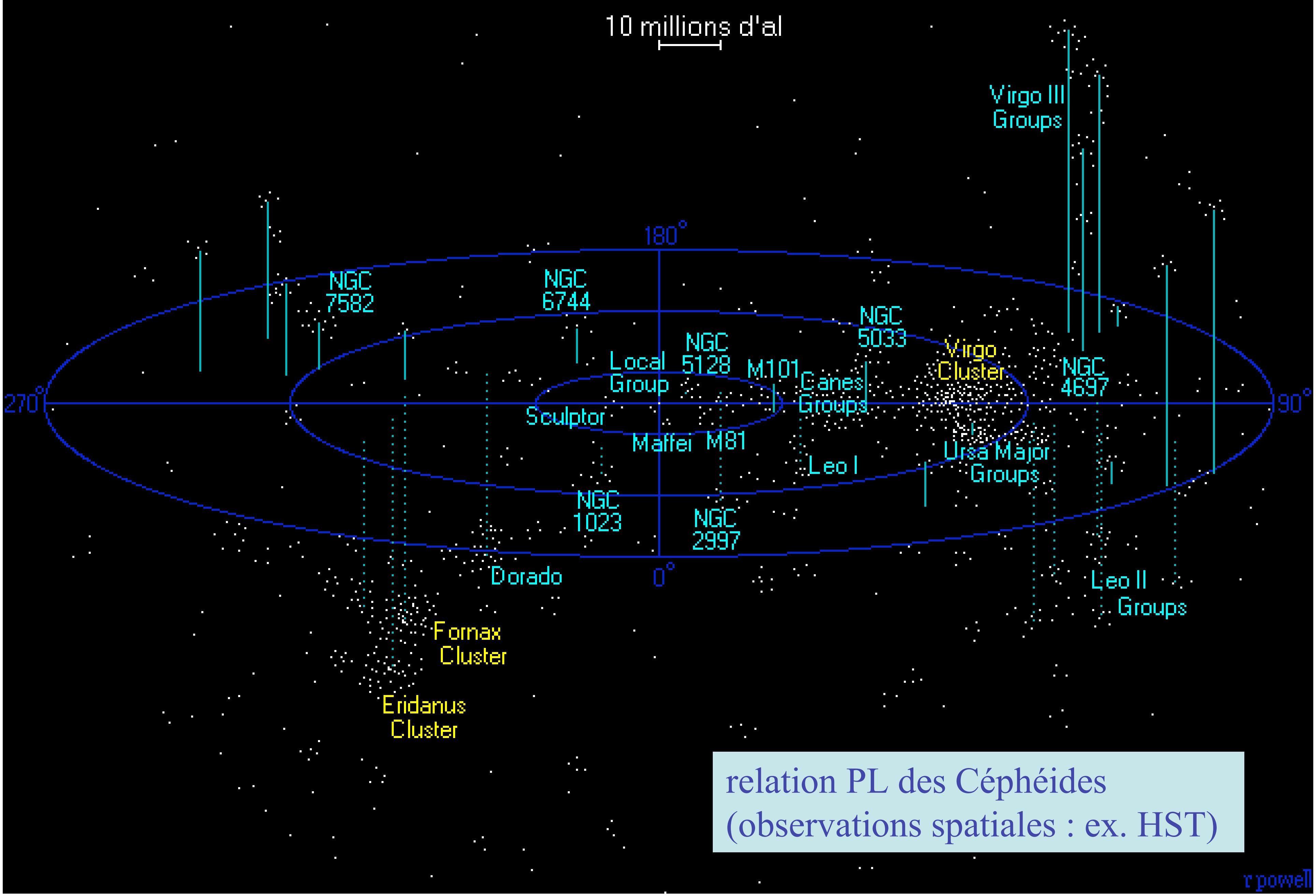
La Voie Lactée



Céphéides : GAIA (2018)

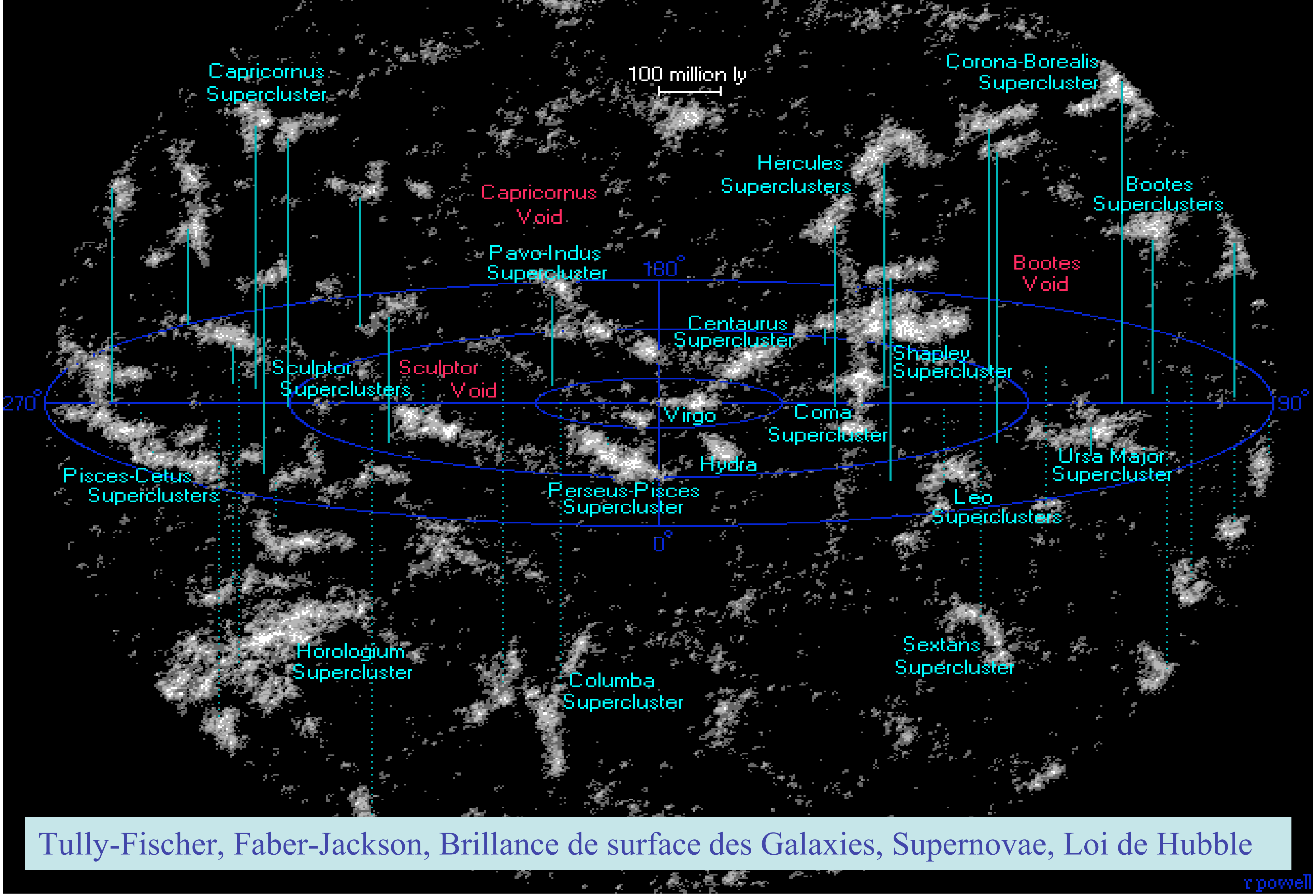
3 kpc, 250 Céphéides, <2%

Le Superamas de la Vierge



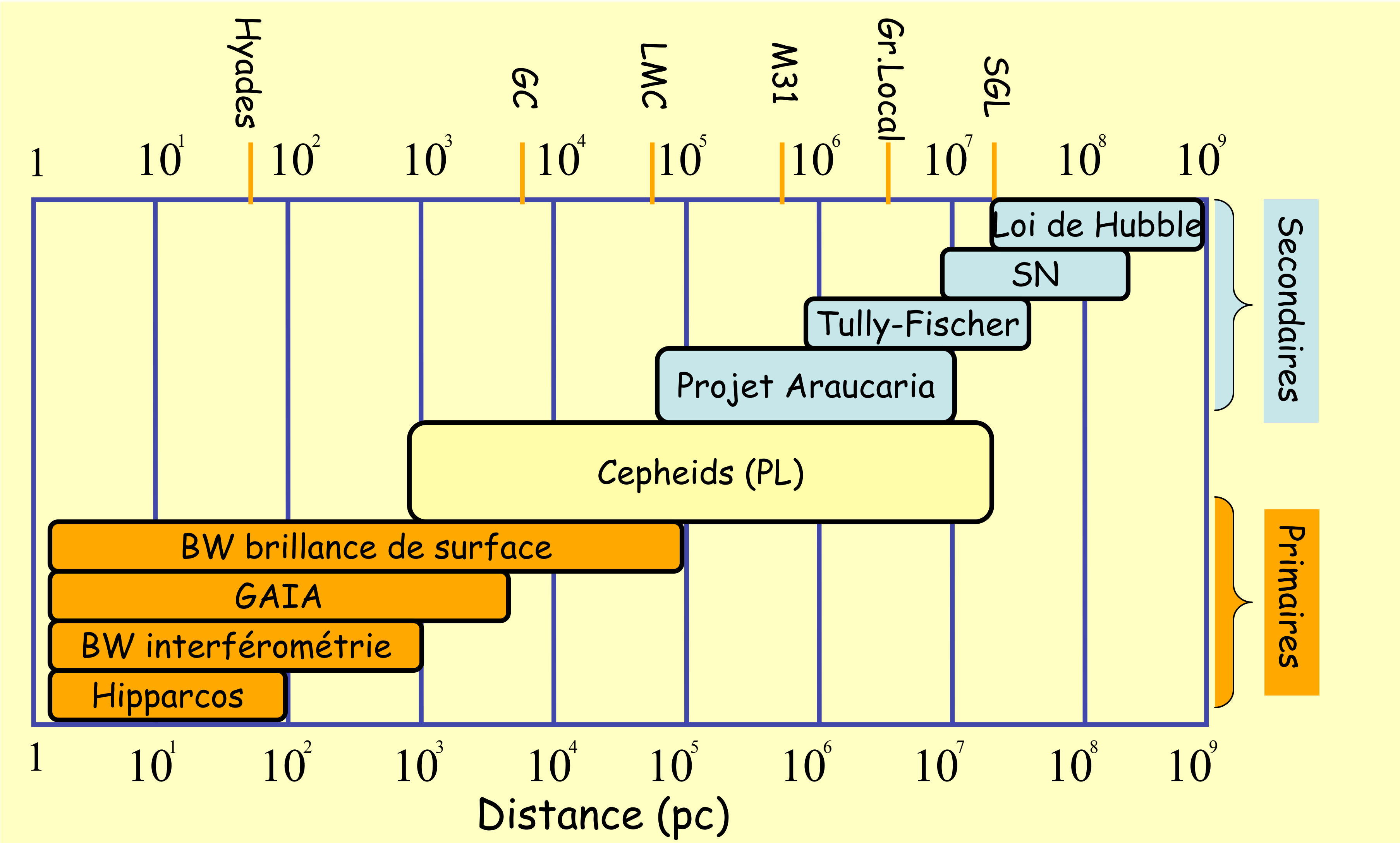
relation PL des Céphéides
(observations spatiales : ex. HST)

Les Superamas voisins



Tully-Fischer, Faber-Jackson, Brillance de surface des Galaxies, Supernovae, Loi de Hubble

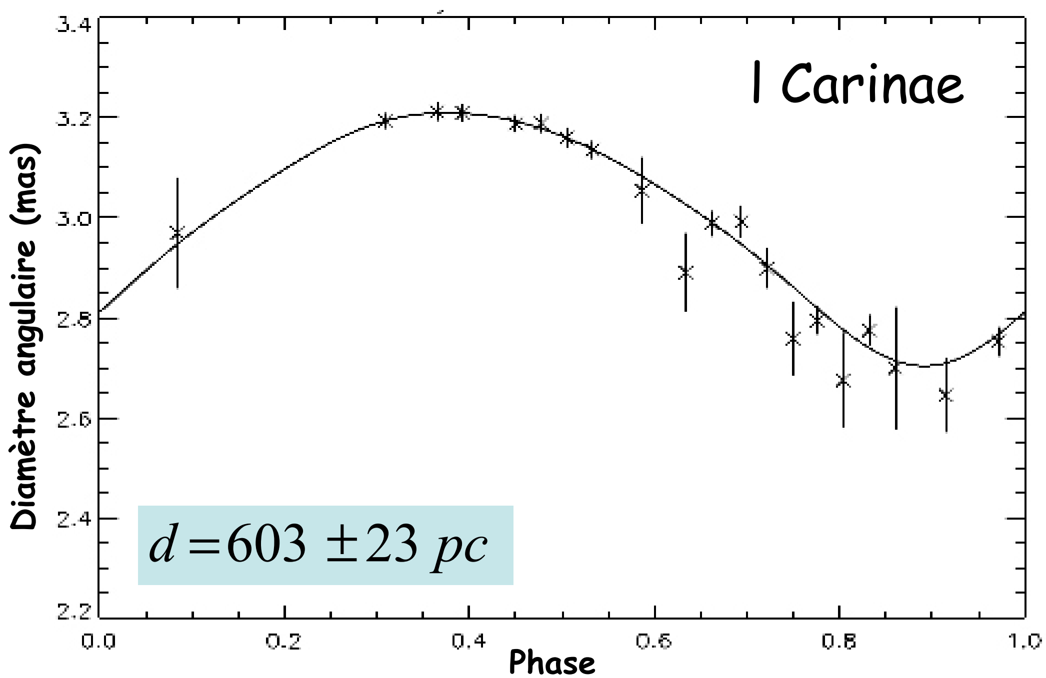
L'étalonnage des échelles de distance

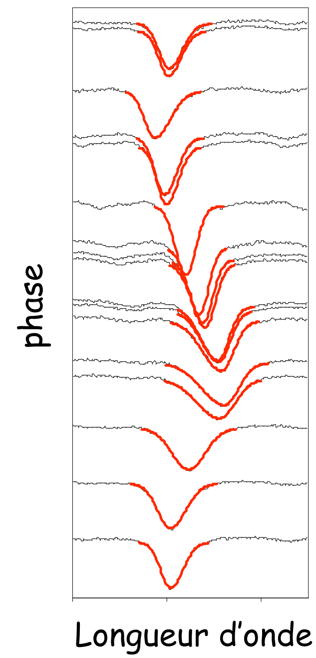


Les méthodes de type Baade-Wesselink

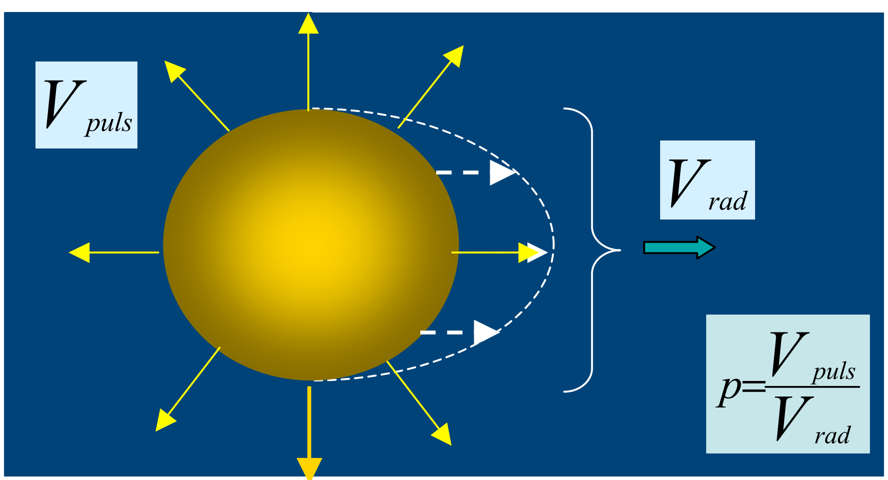
Cepheid distances from infrared long-baseline interferometry I. VINCI/VLTI observations of seven Galactic Cepheids

P. Kervella, N. Nardetto, D. Bersier, D. Mourard and V. Coudé du Foresto, **2004**, A&A, **416**, **941K**





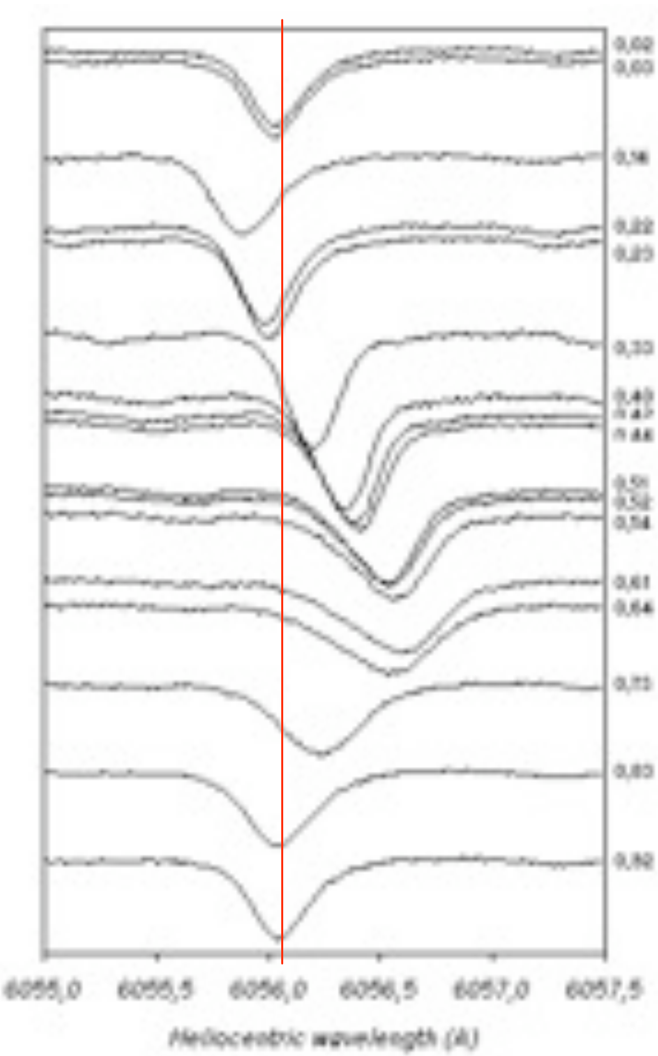
V_{rad} → p → V_{puls}



$$\theta(\phi) = \overline{\theta_{LD}} + 9.305 \left(\frac{\int_0^P V_{puls}\, dt}{d} \right)$$

$\Delta R \Leftrightarrow \Delta \theta$

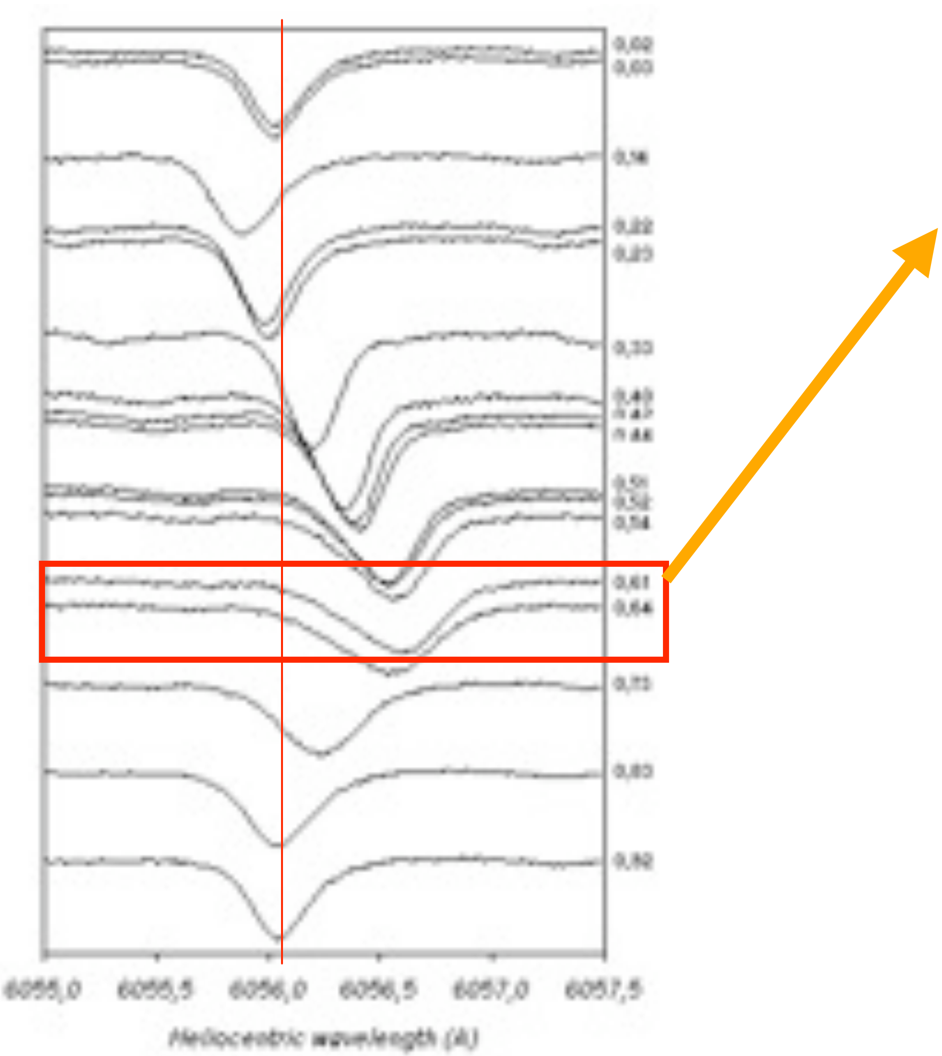
La définition de la vitesse radiale V_{rad} et de p_{o} (1/3)



β Dor – FeI line

Observations HARPS

La définition de la vitesse radiale V_{rad} et de p_{o} (1/3)



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Observations HARPS

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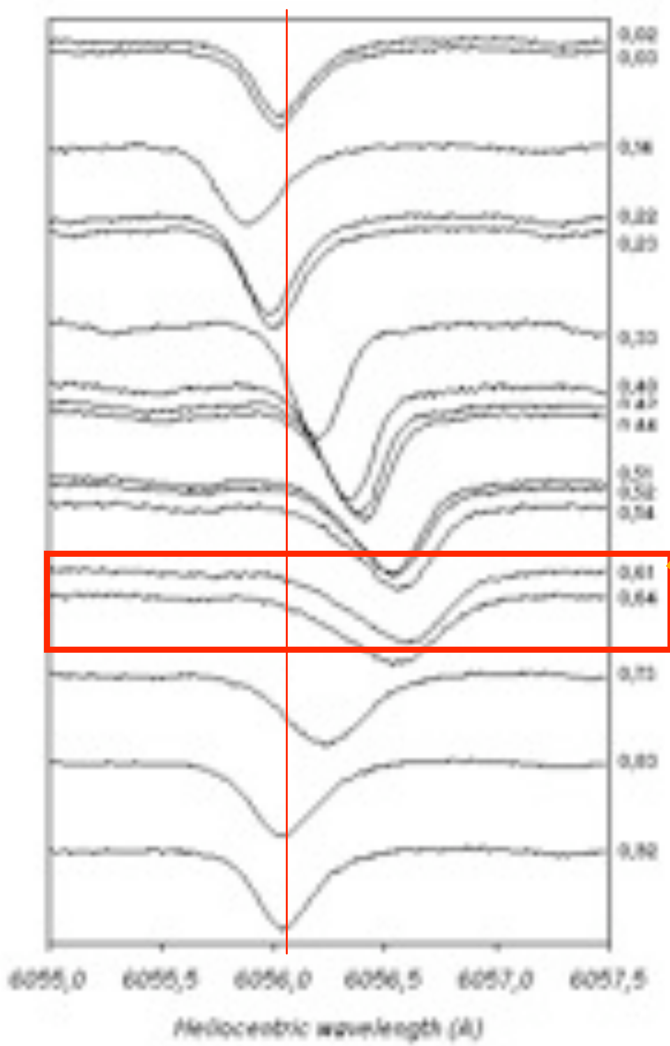
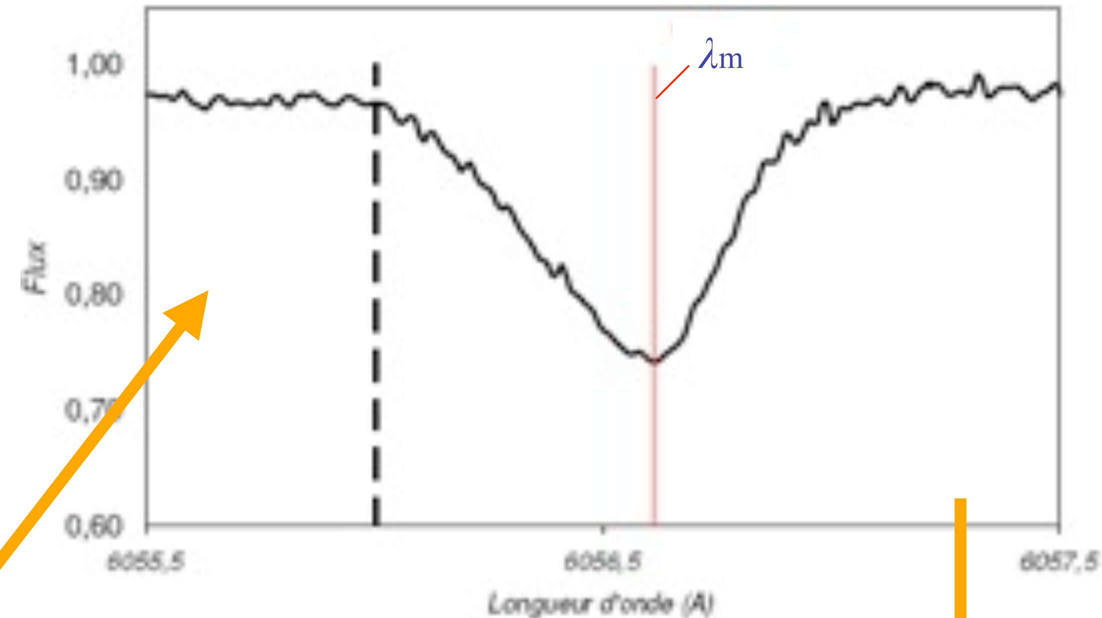
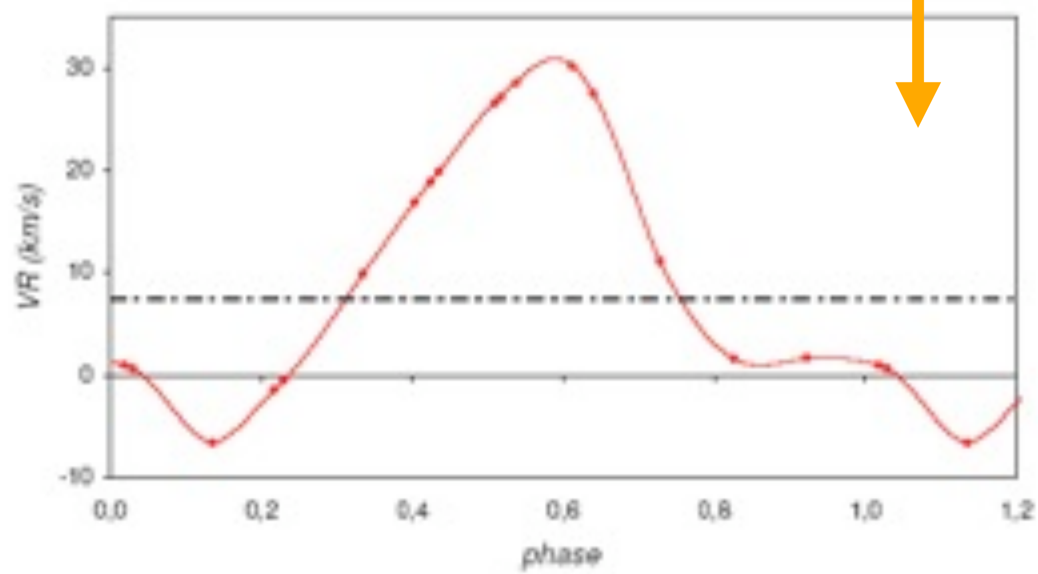


βDor – FeI line

Observations HARPS





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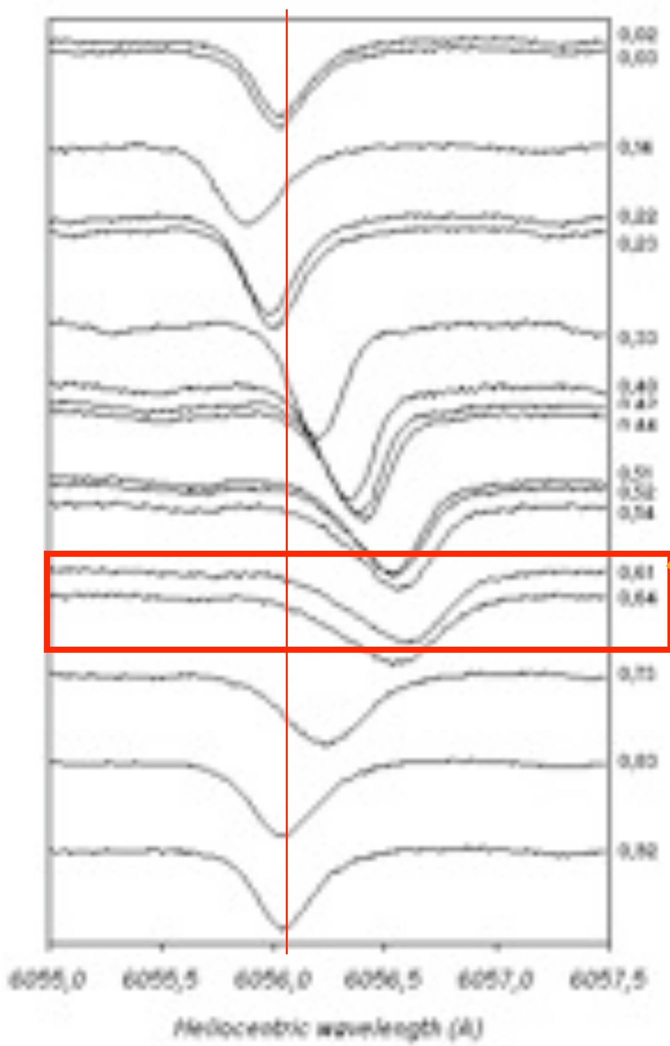

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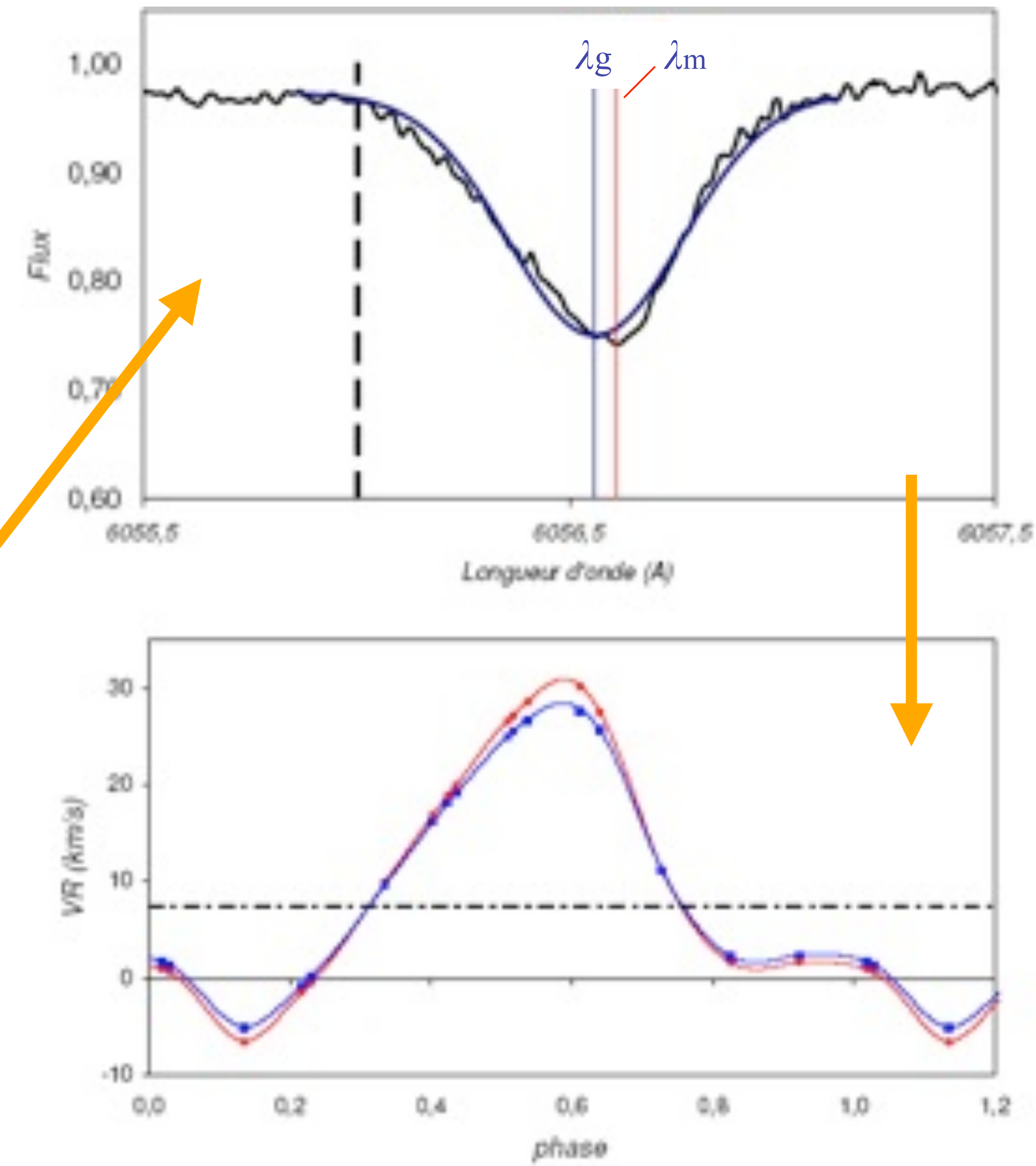

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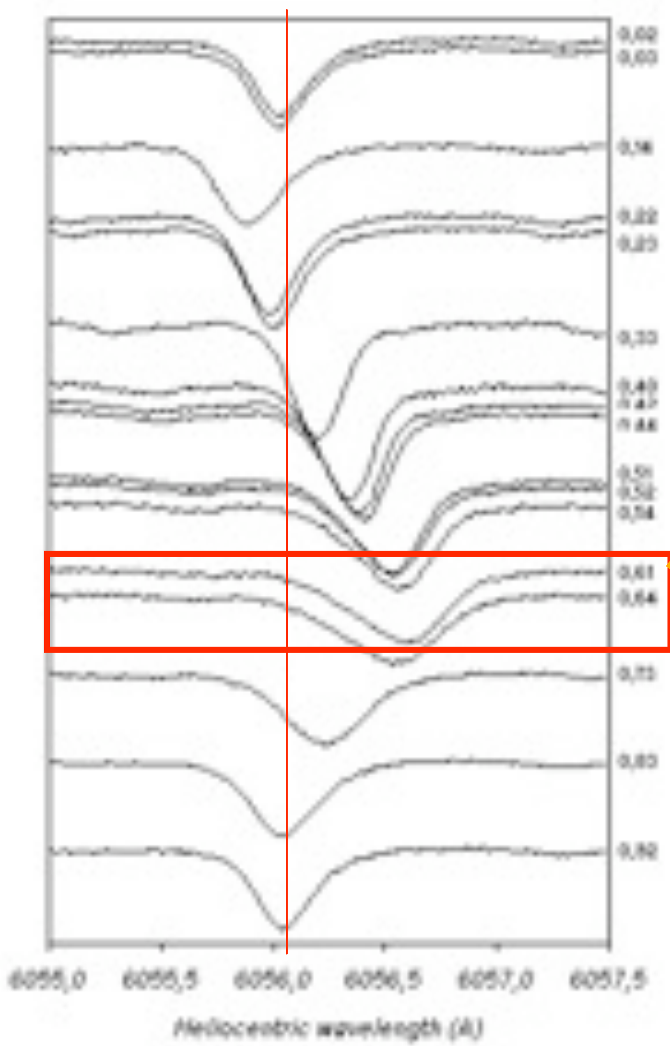

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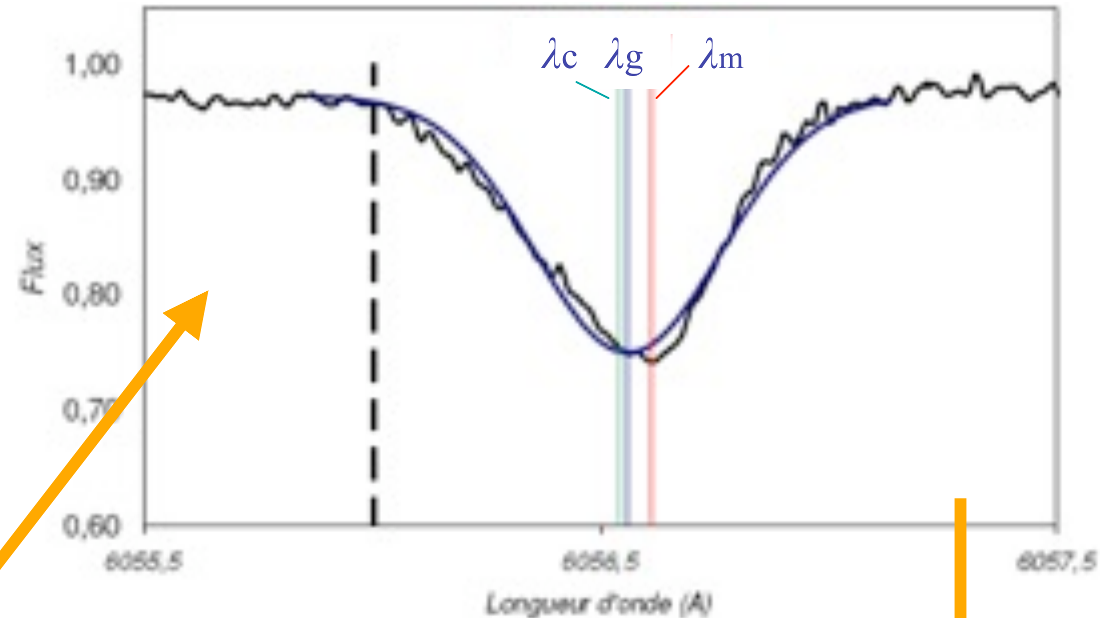
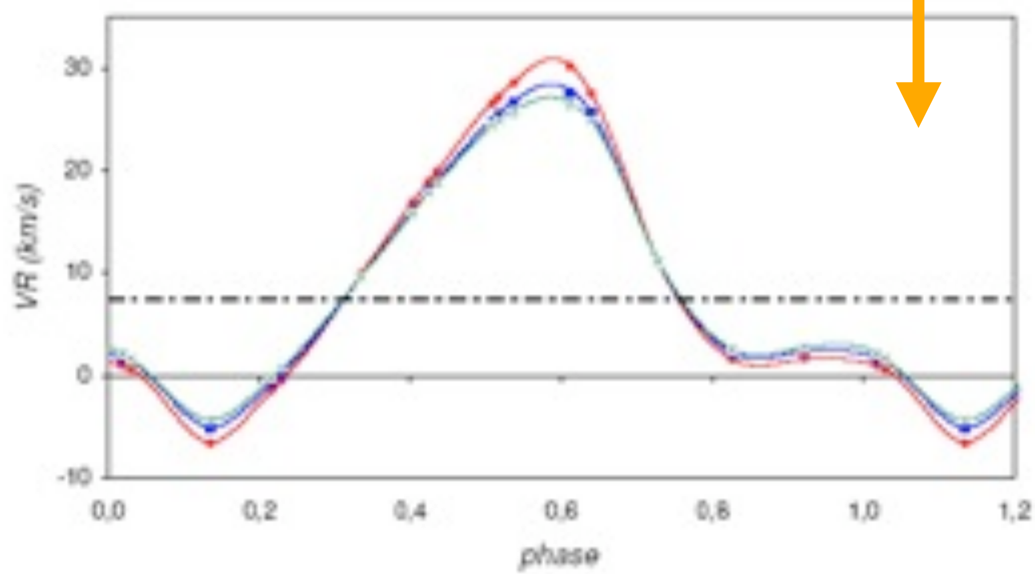
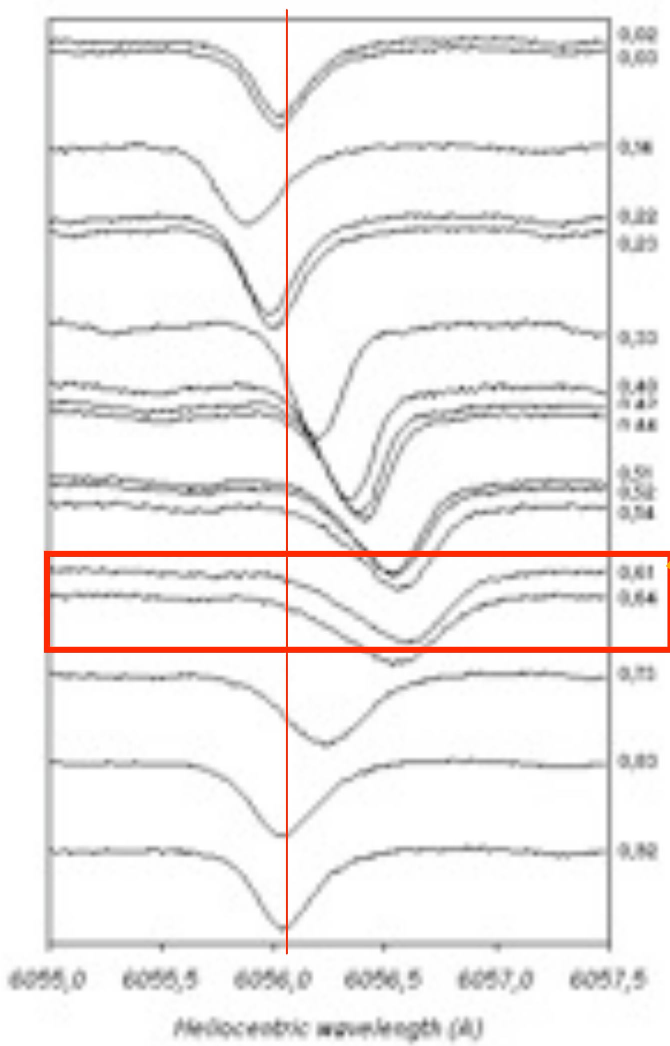




La définition de la vitesse radiale V_{rad} et de p_{o} (1/3)



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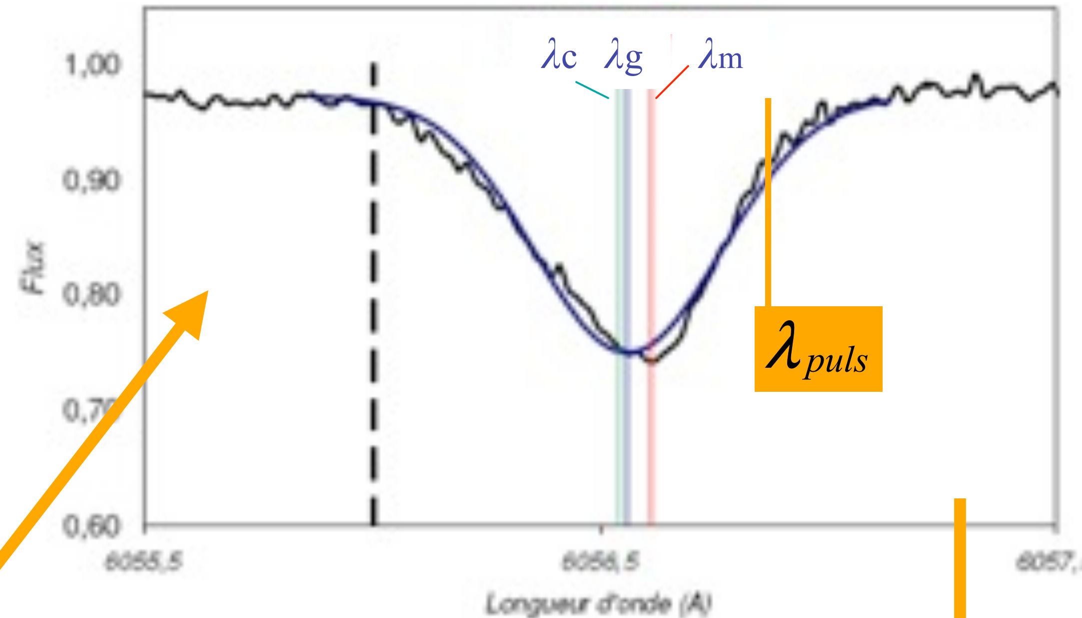
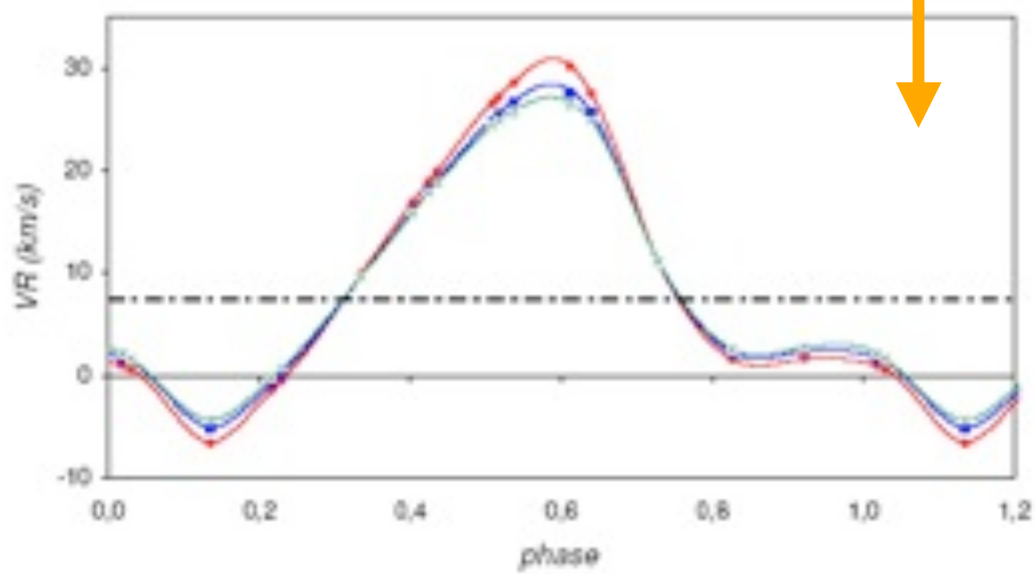
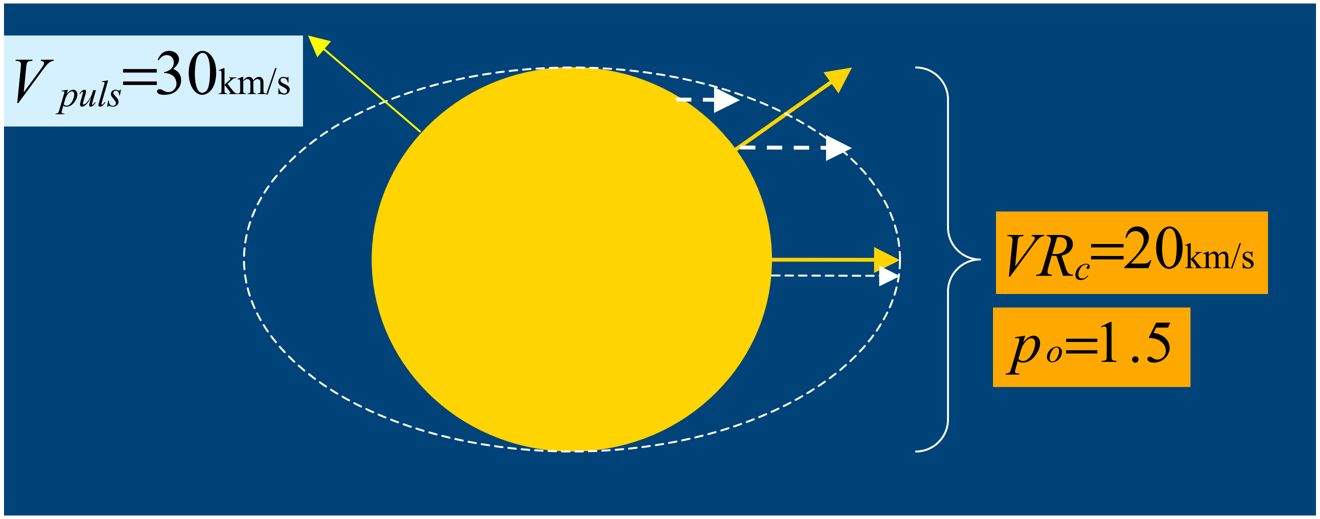




La définition de la vitesse radiale V_{rad} et de p_o (2/3)

- Effet de projection géométrique



ACB

$uV=0$

Dispersion Doppler

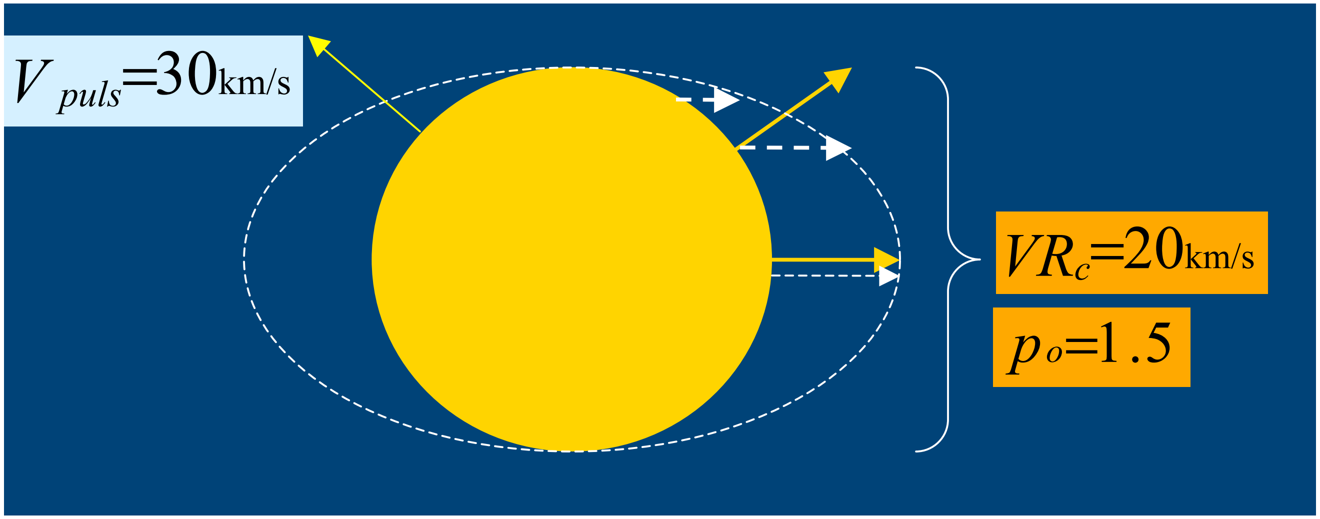
$\sigma_c = 0A$

Rotation

$V_{rot}\sin(i)=0$km/s

La définition de la vitesse radiale V_{rad} et de p_{o} (2/3)

- Effet de projection géométrique



ACB

$uV=0$

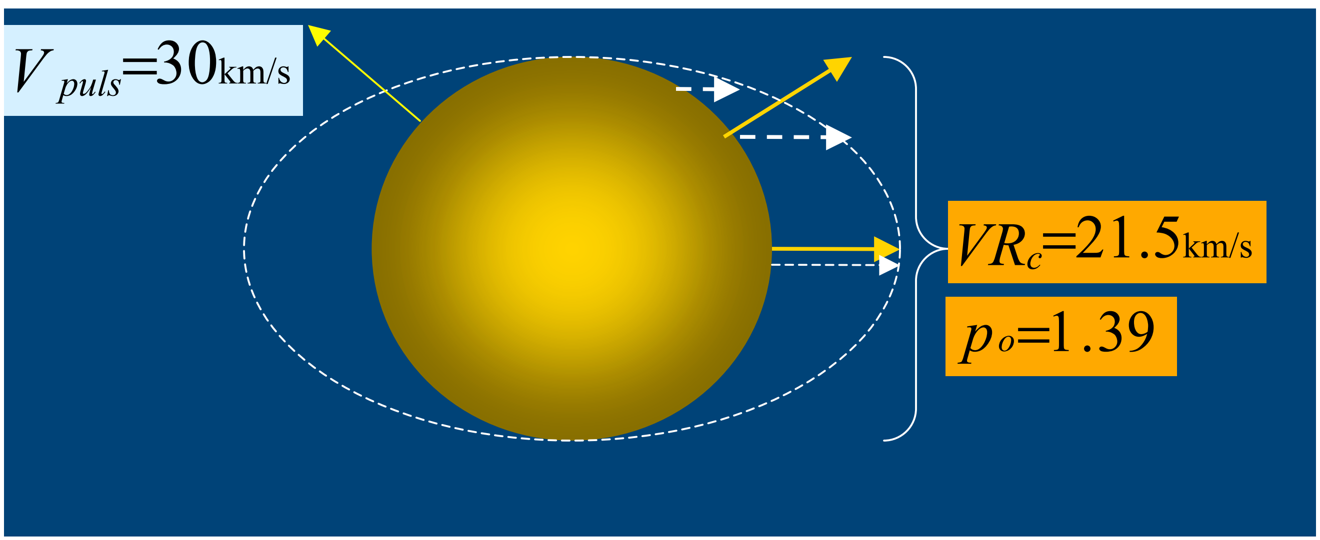
Dispersion Doppler

$\sigma_c = 0$ A

Rotation

$V_{rot}\sin(i)=0$ km/s

- Effet de l'assombrissement centre-bord



ACB

$uV=0.7$

Dispersion Doppler

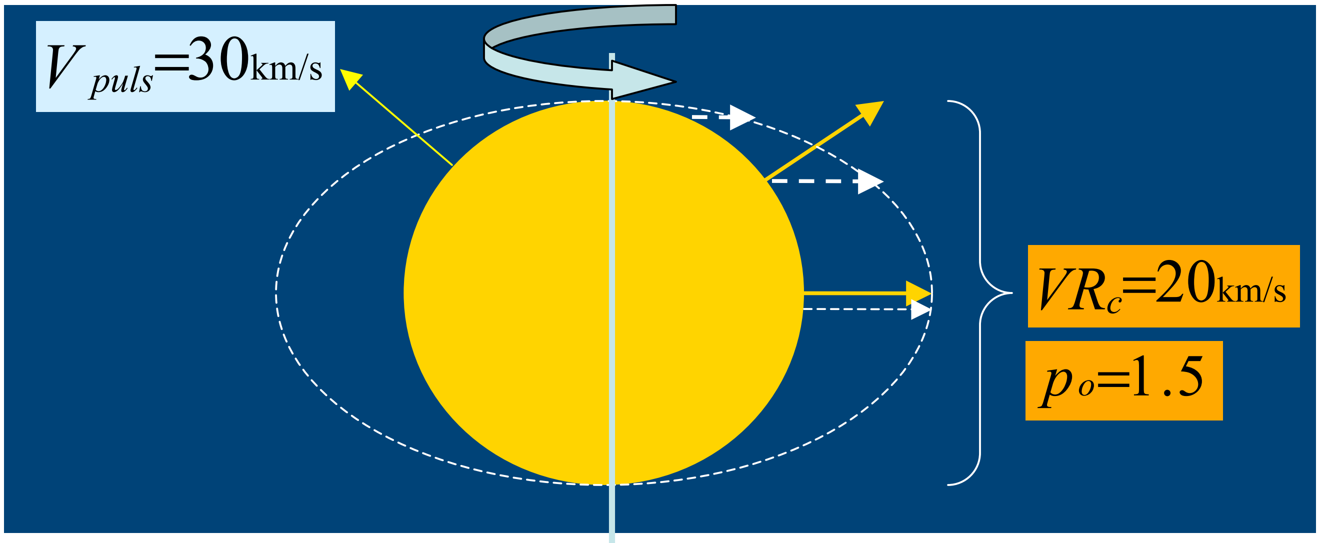
$\sigma_c = 0$ A

Rotation

$V_{rot}\sin(i)=0$ km/s

La définition de la vitesse radiale V_{rad} et de p_o (3/3)

- **Effet de la rotation**



ACB

$u=0$

Dispersion Doppler

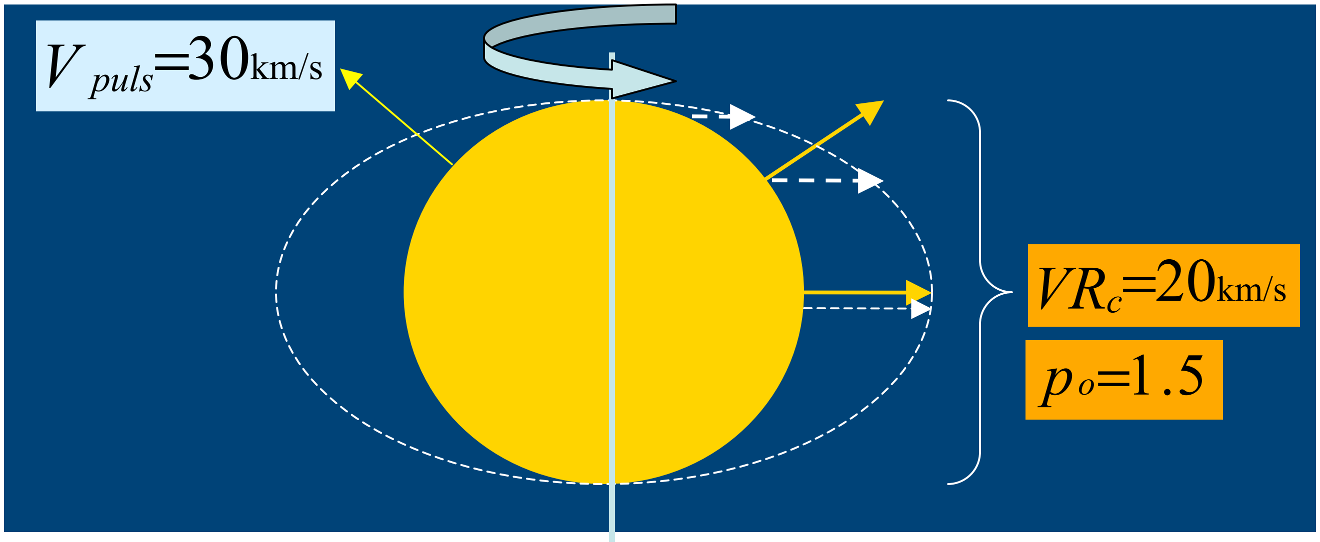
$\sigma_c = 0$ A

Rotation

$V_{rot}\sin(i)=10$ km/s

La définition de la vitesse radiale V_{rad} et de p_o (3/3)

- **Effet de la rotation**



ACB

$u=0$

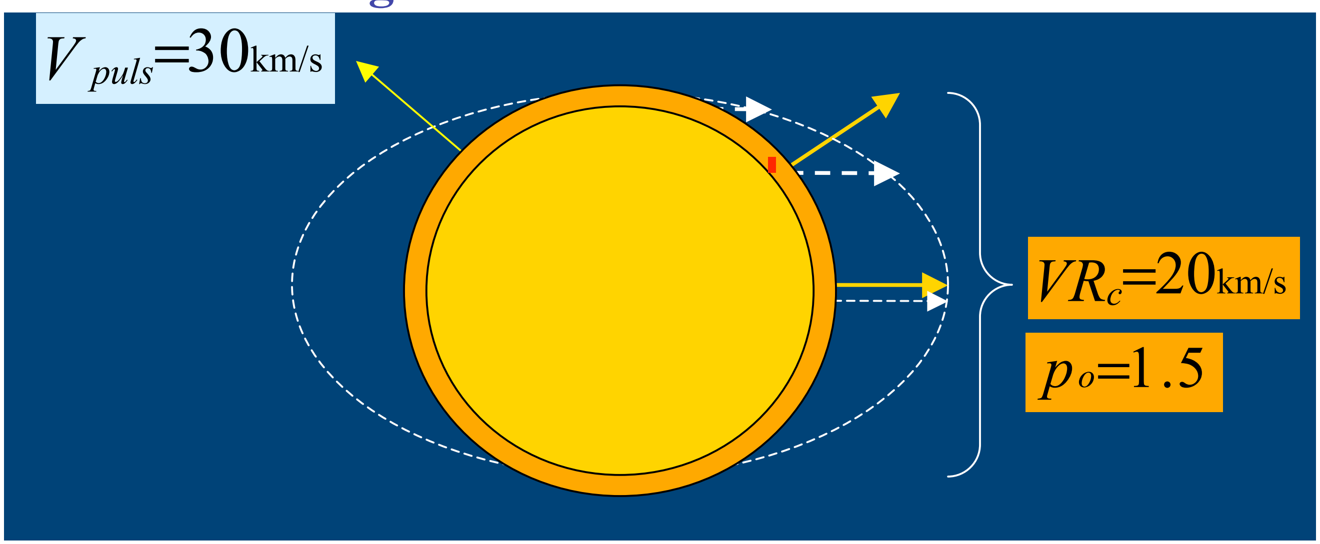
Dispersion Doppler

$\sigma_c = 0$A

Rotation

$V_{rot}\sin(i)=10$km/s

- **Effet de la largeur de la raie σc**



ACB

$u=0$

Dispersion Doppler

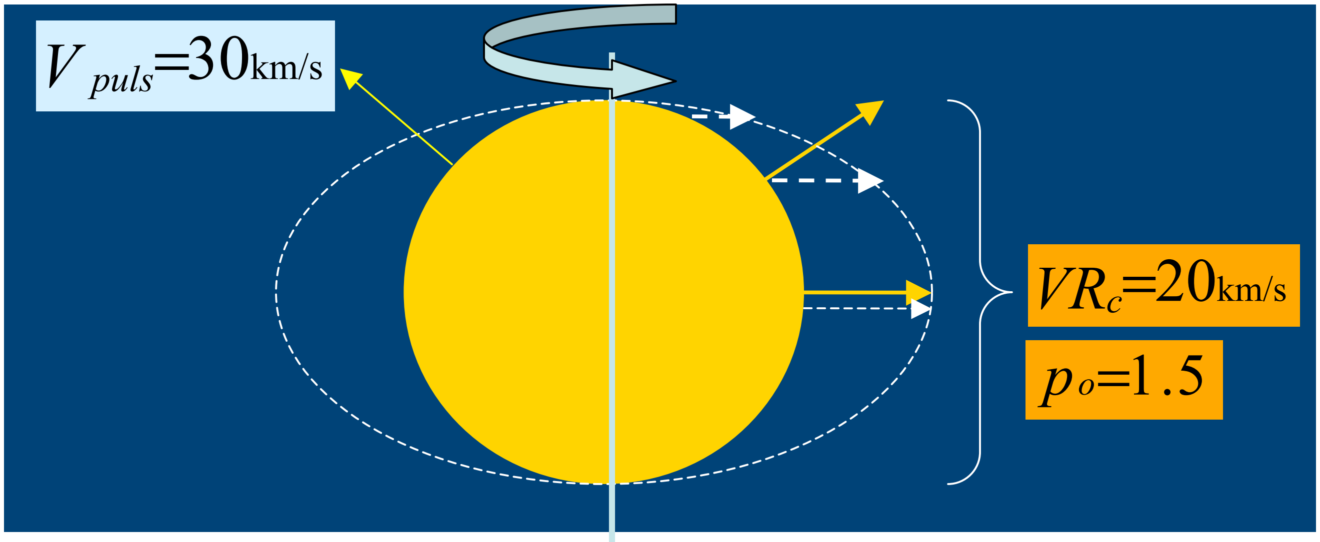
$\sigma_c = 0.30$A

Rotation

$V_{rot}\sin(i)=0$km/s

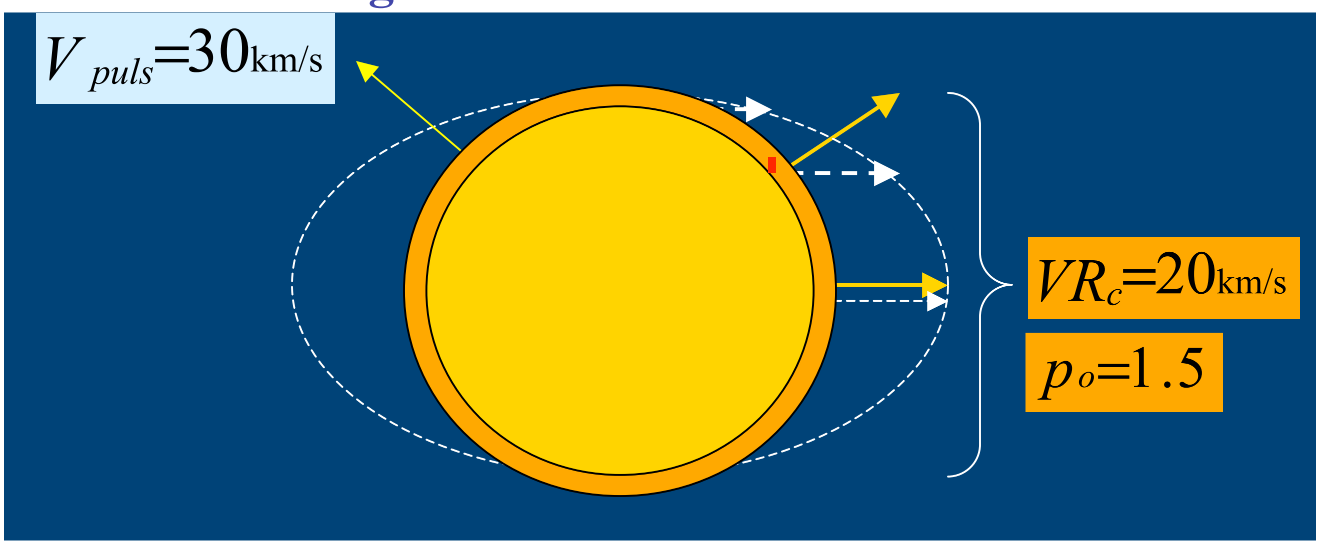
La définition de la vitesse radiale V_{rad} et de p_o (3/3)

- **Effet de la rotation**



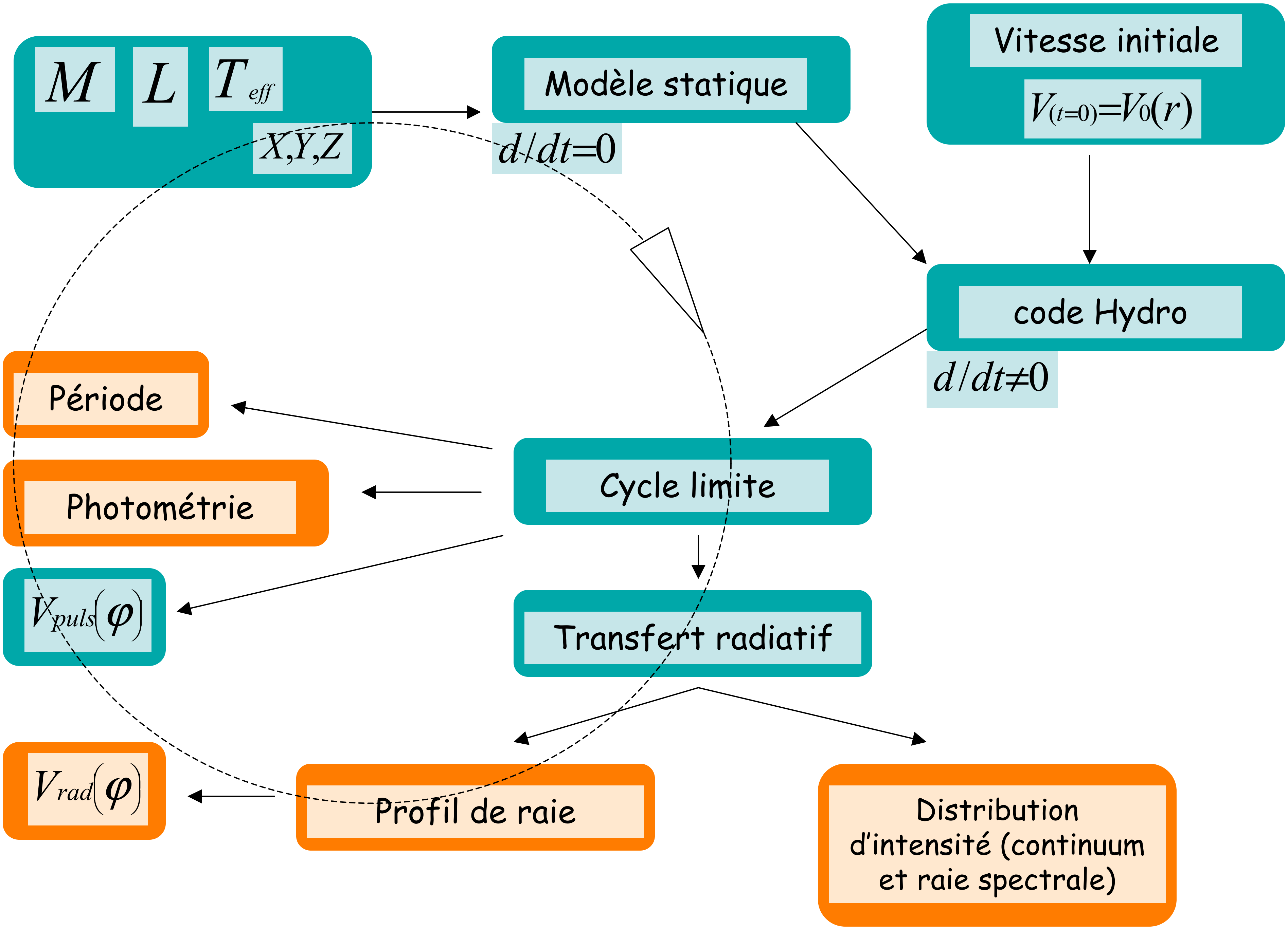
ACB
u=0
Dispersion Doppler
σ_c= 0A
Rotation
$V_{rot}\sin(i)$=10km/s

- **Effet de la largeur de la raie σc**



ACB
u=0
Dispersion Doppler
σ_c= 0.30A
Rotation
$V_{rot}\sin(i)$=0km/s

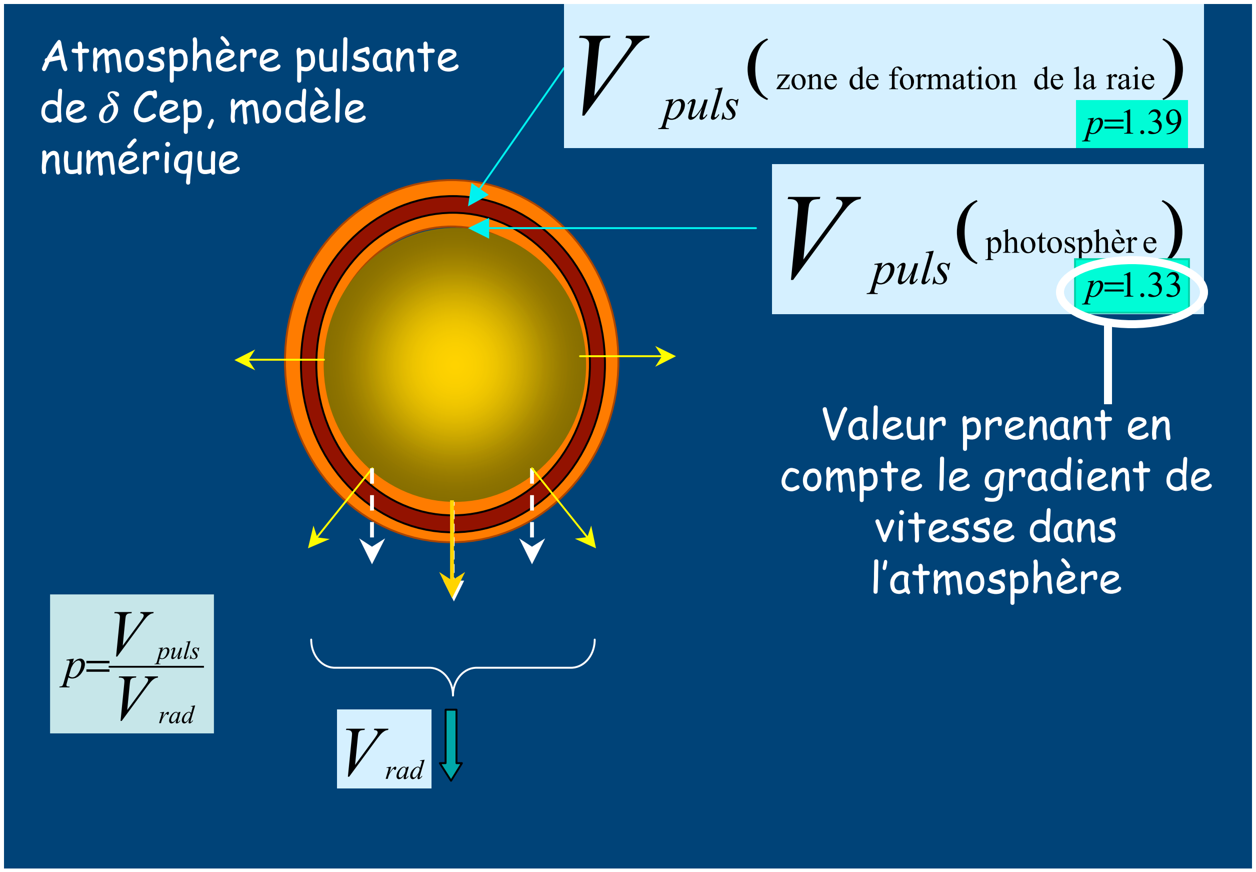
La Vitesse Radiale déduite de la méthode du premier moment est indépendante de la largeur de la raie et de la rotation



Fokin (1990, 1991)

Effet de la dynamique atmosphérique

Self consistent modelling of the projection factor for interferometric distance determination
N. Nardetto, A. Fokin, D. Mourard, Ph. Mathias, P. Kervella, D. Bersier, **2004**, A&A, **428, 131**



Surestimation des distances de 6% avec VINCI :
résultat confirmé par le HST + CHARA (Mérand et al. 2005)

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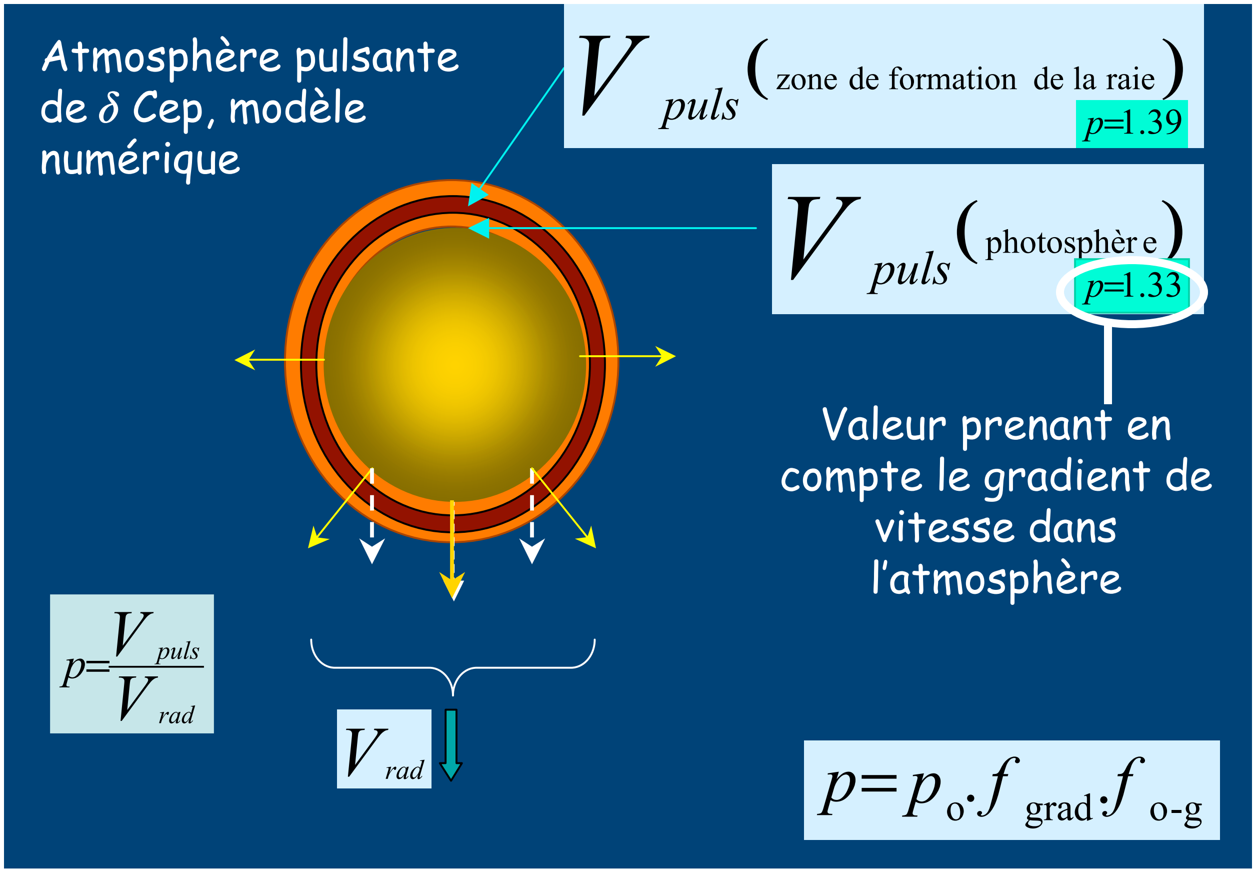


Surestimation des distances de 6% avec VINCI :
résultat confirmé par le HST + CHARA (Mérand et al. 2005)

Observations HARPS de 10 Céphéides (P=3j à P=42j)

300 spectres

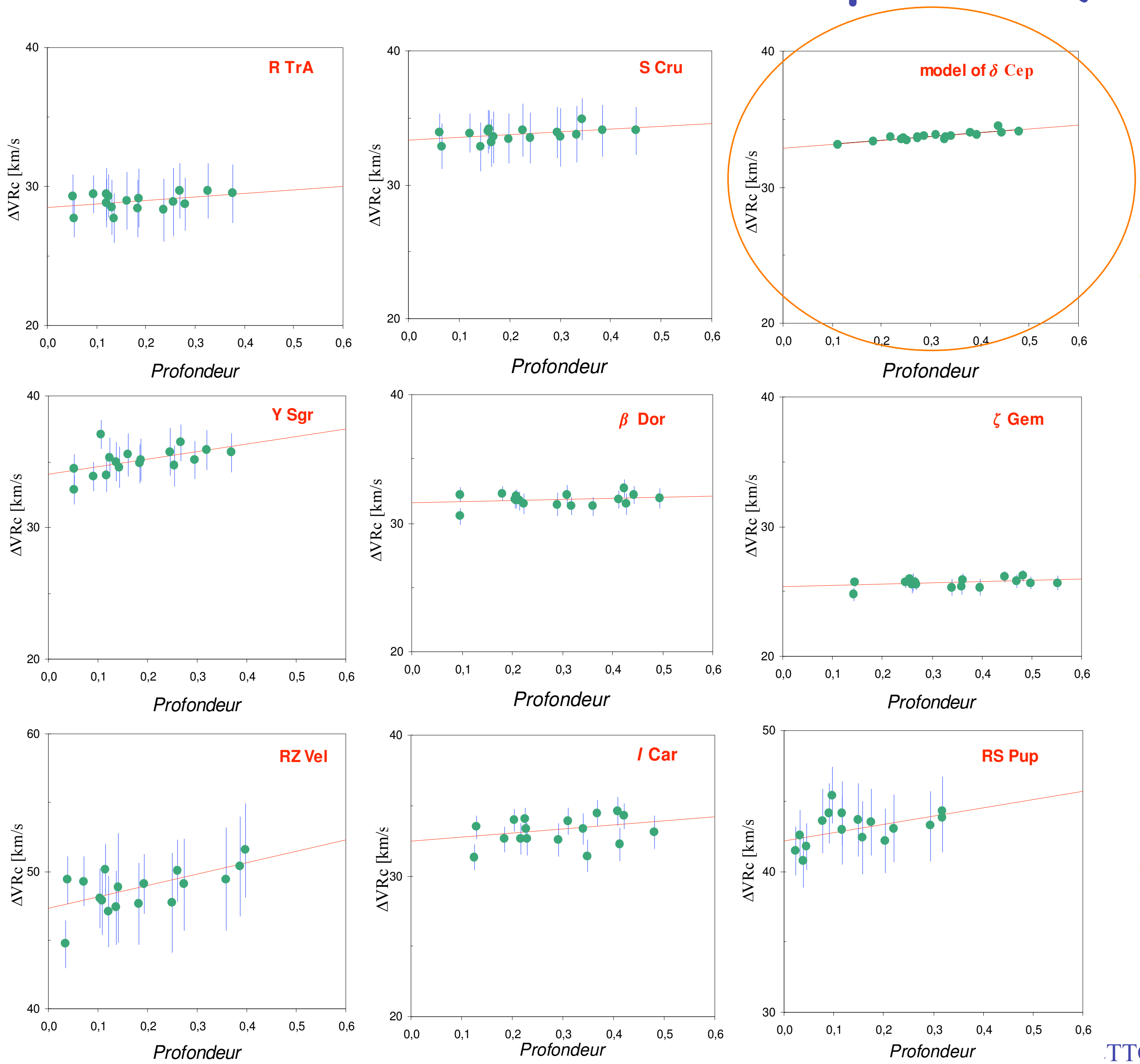
Des milliers de raies

17 retenues

Name	Wavelength (Å)
Fe I	4683.560
Fe I	4896.439
Fe I	5054.643
Ni I	5082.339
Fe I	5367.467
Fe I	5373.709
Fe I	5383.369
Ti II	5418.751
Fe I	5576.089
Fe I	5862.353
Fe I	6024.058
Fe I	6027.051
Fe I	6056.005
Si I	6155.134
Fe I	6252.555
Fe I	6265.134
Fe I	6336.824

$$\Delta VR_c = a_o D + b_o$$

Observations HARPS de 10 Céphéides (P=3j à P=42j)



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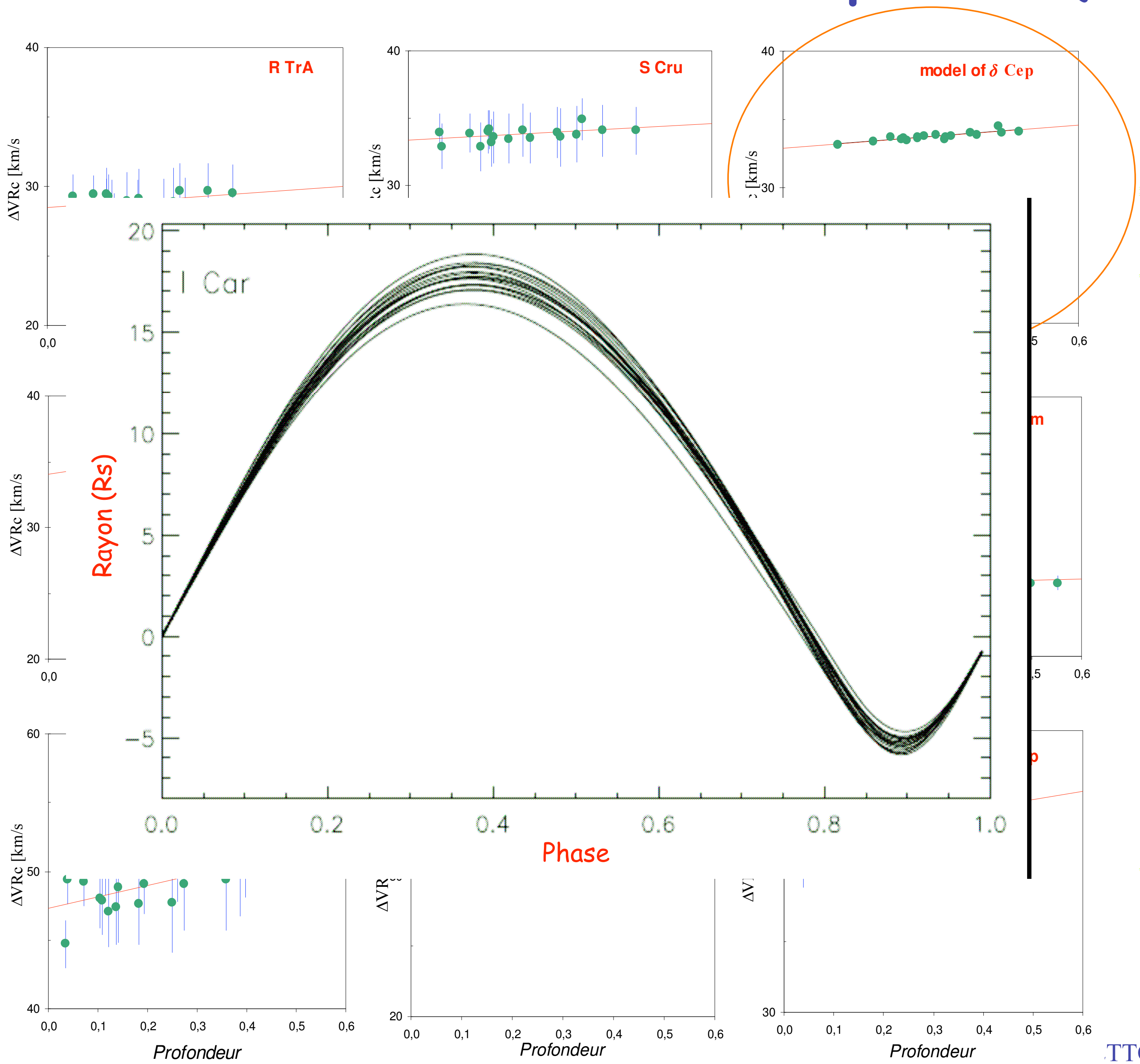

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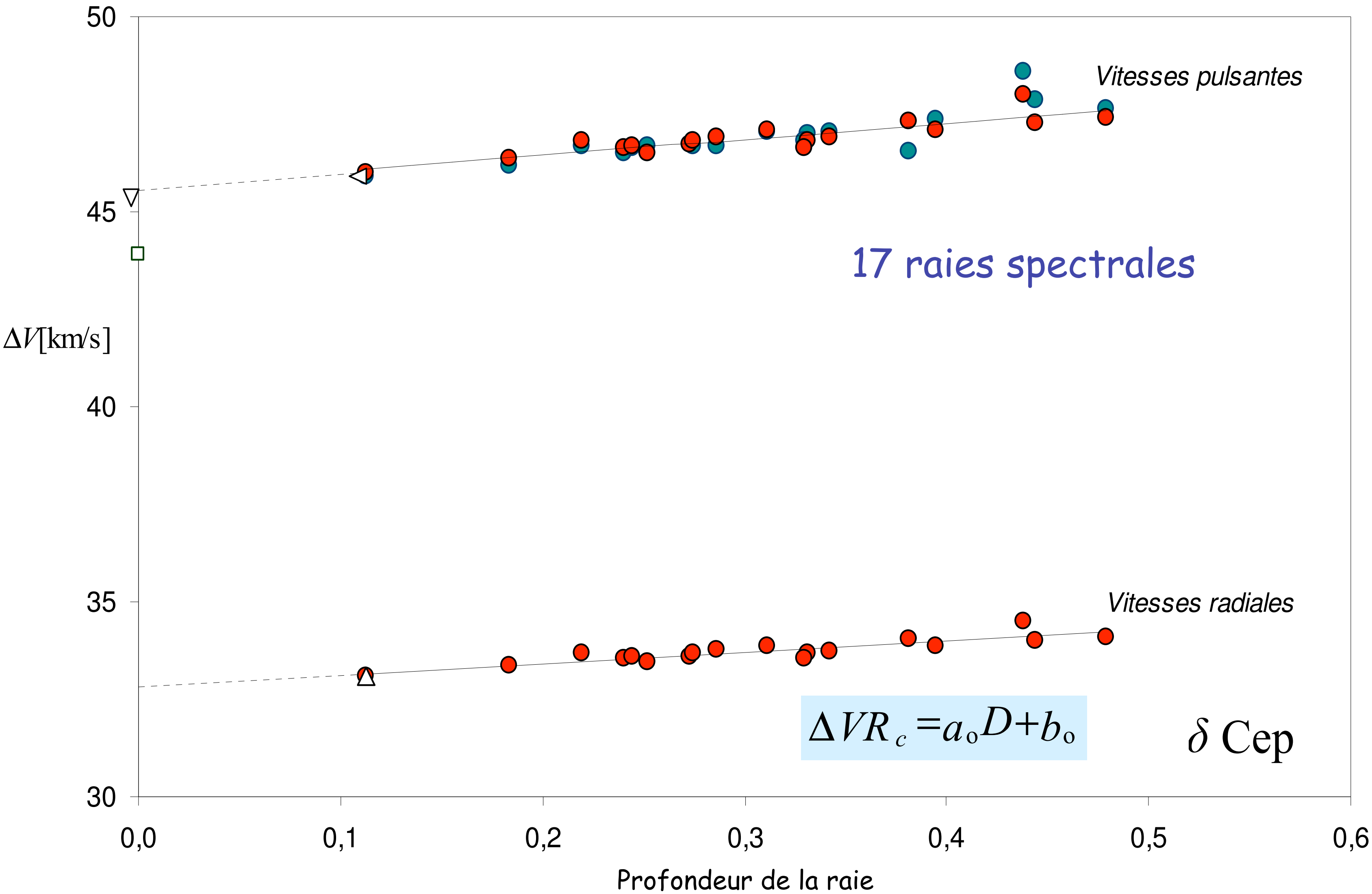
$$\Delta VR_c = a_0 D + b_0$$

Décomposition du facteur de projection

$p = p_o . f_{grad} . f_{o\text{-}g}$



Décomposition du facteur de projection

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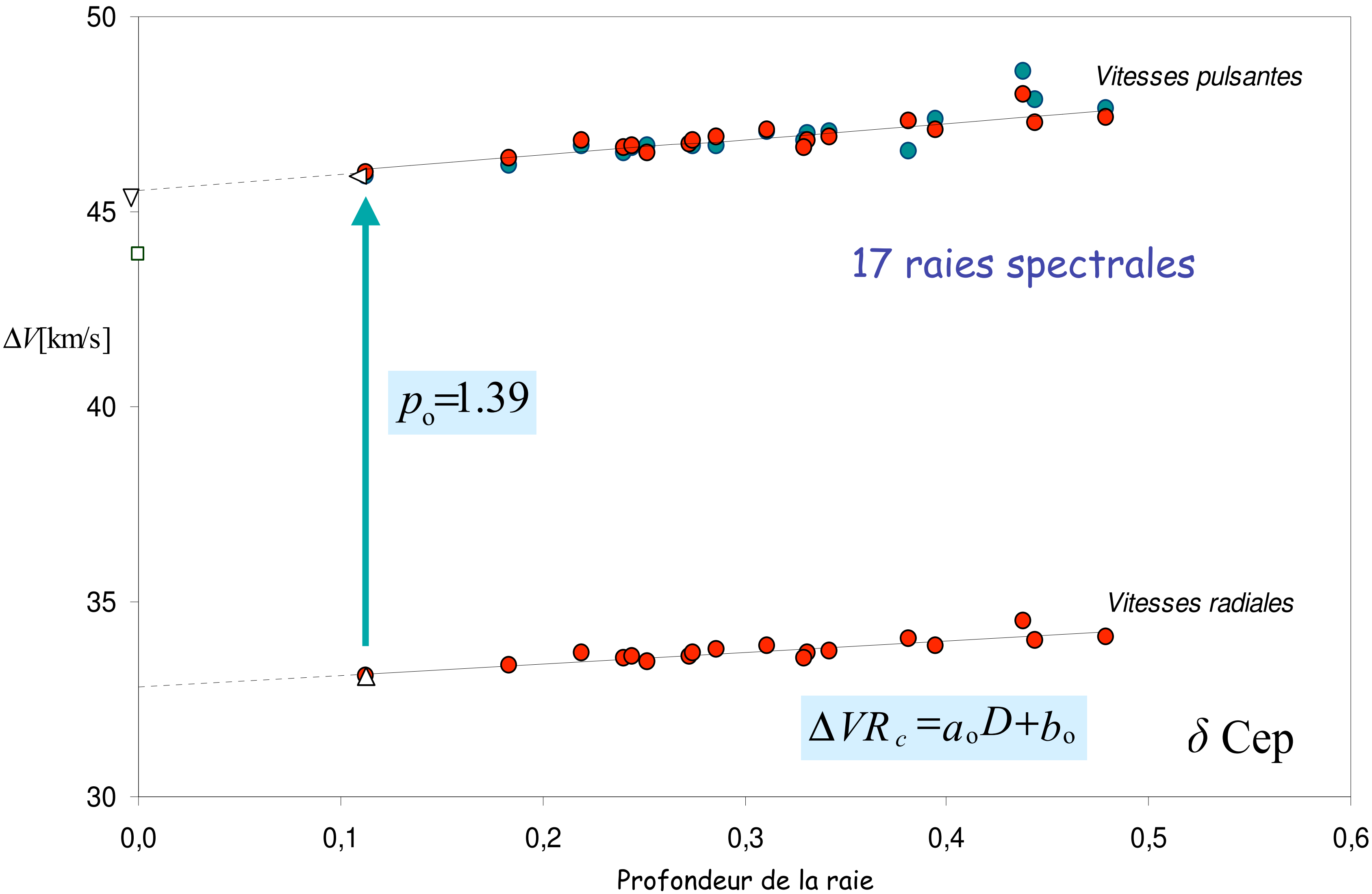
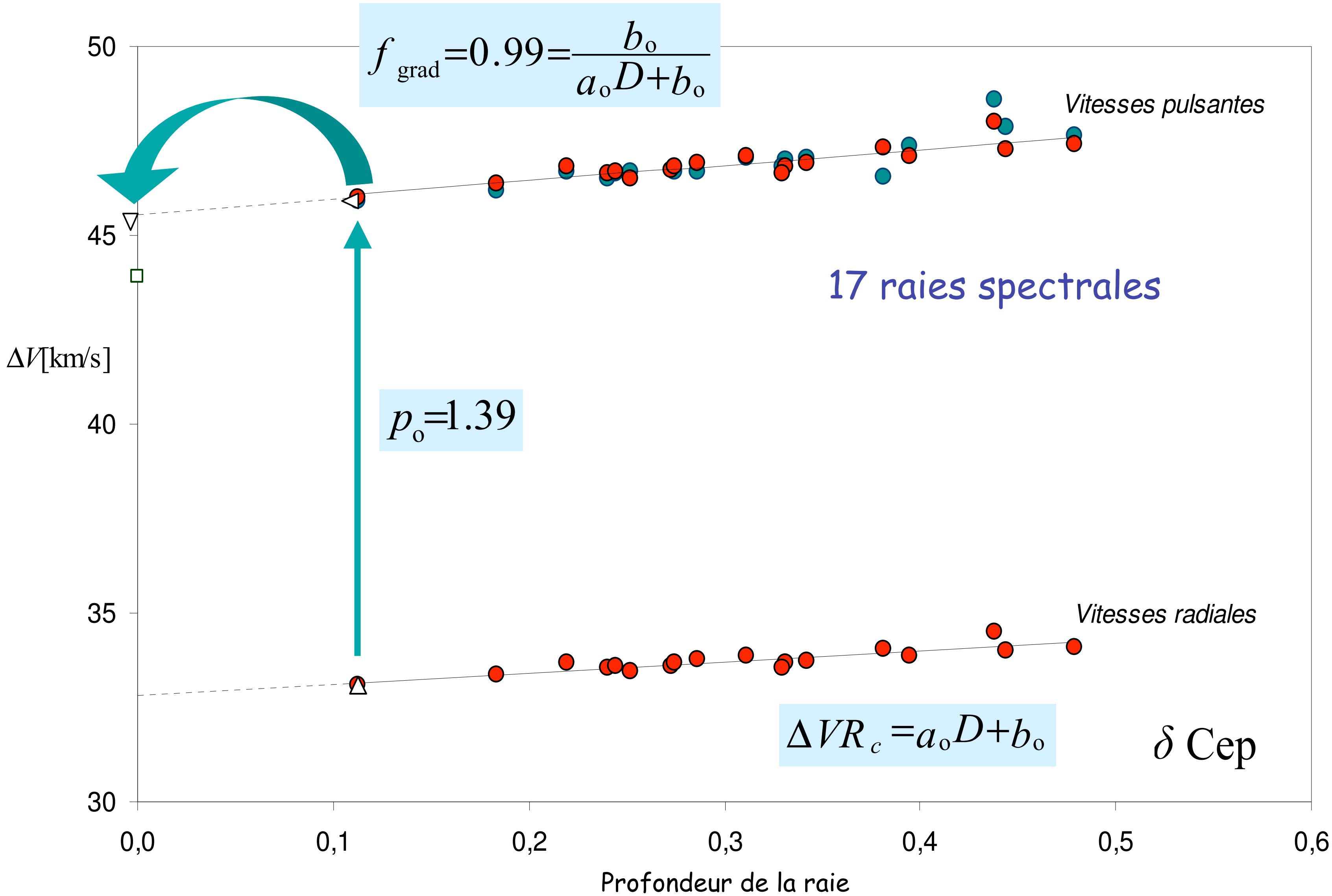


Décomposition du facteur de projection

$p = p_o . f_{grad} . f_{o-g}$



Décomposition du facteur de projection

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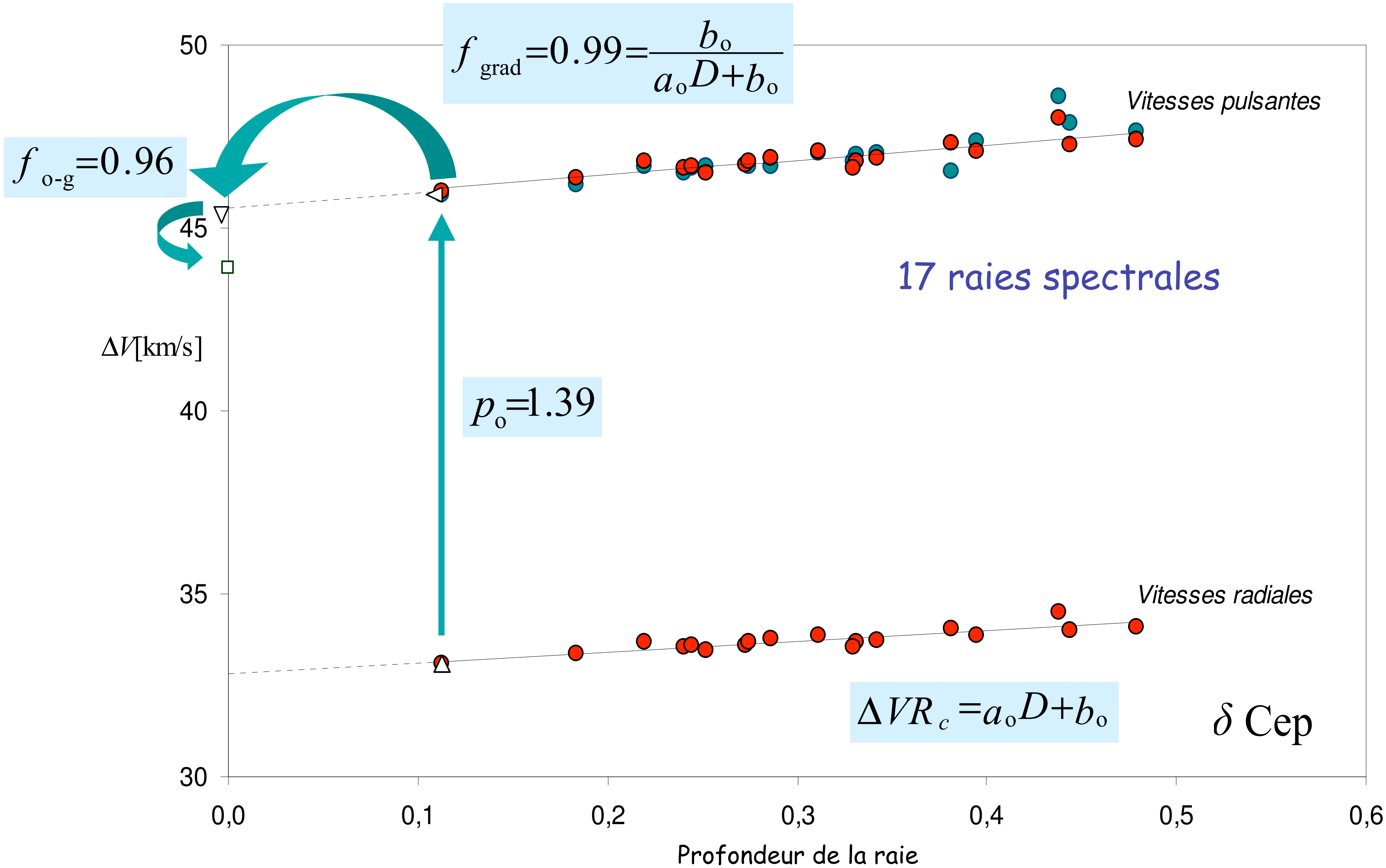
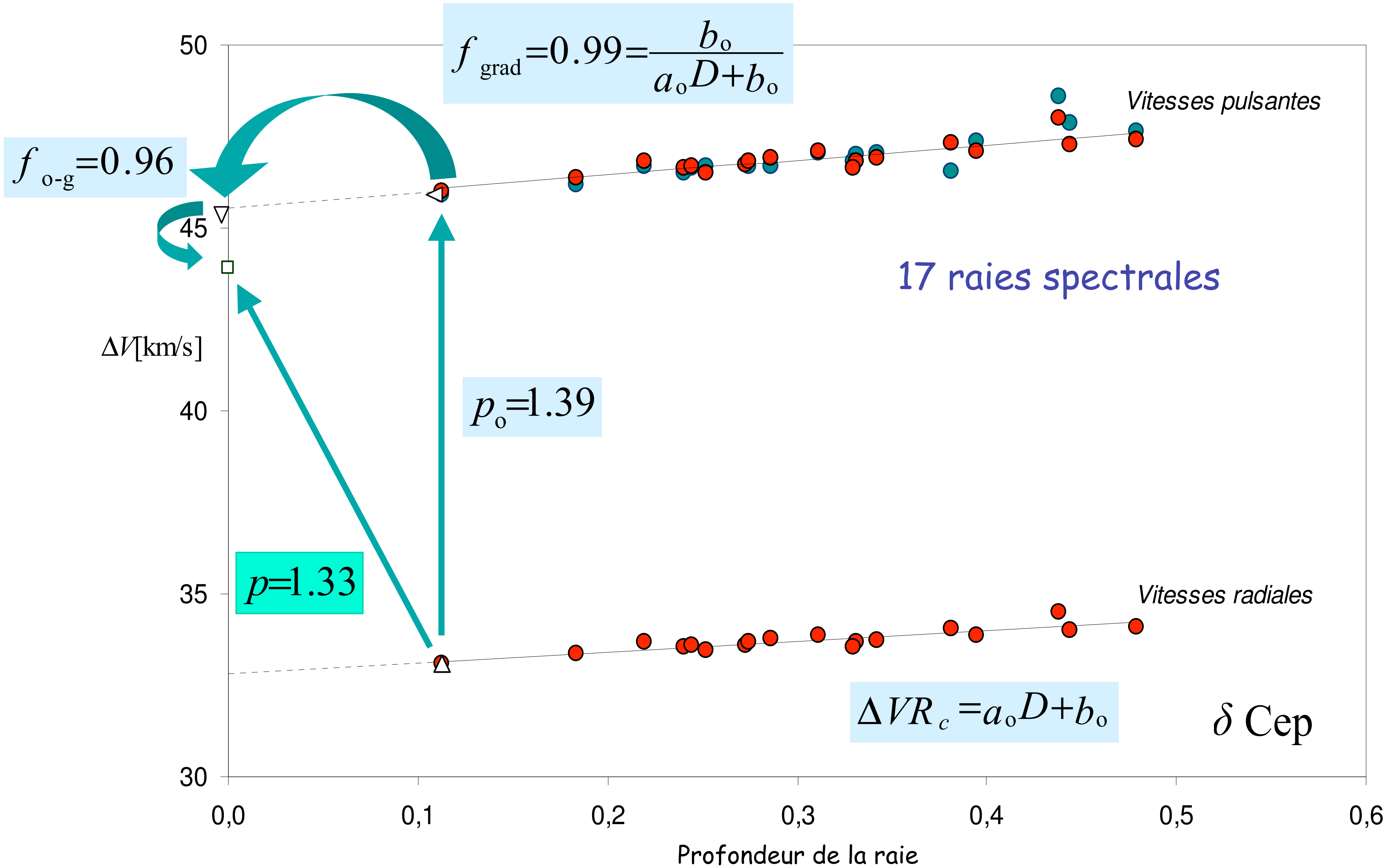


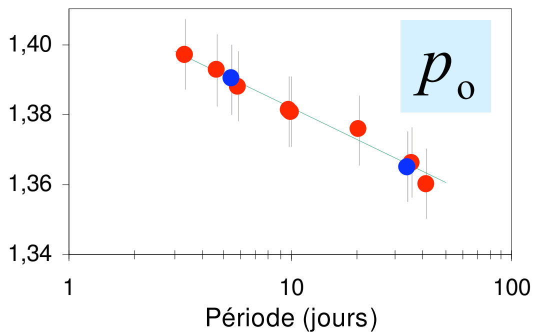
Décomposition du facteur de projection

$p = p_o . f_{grad} . f_{o\text{-}g}$

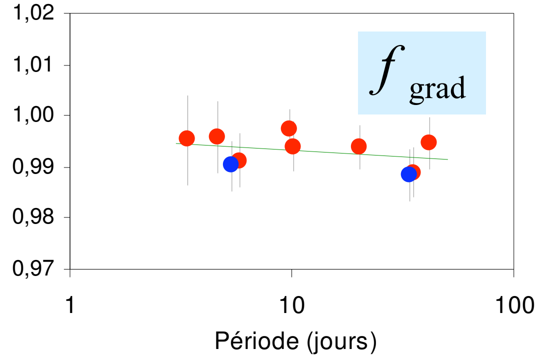


La relation Pp

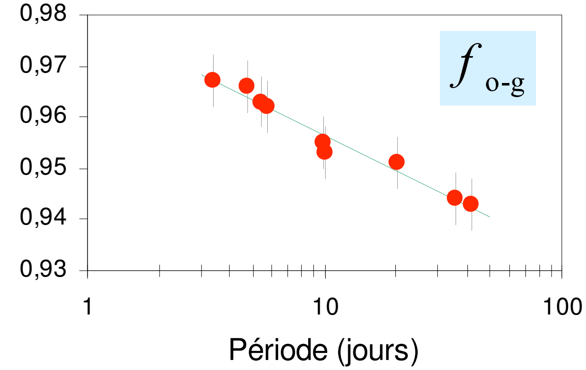
High resolution spectroscopy for Cepheids distance determination II. A period-projection factor relation
N. Nardetto, D. Mourard, Ph. Mathias, A. Fokin, D. Gillet, **2007**, A&A, **471**, **661**



Modélisation Géométrique



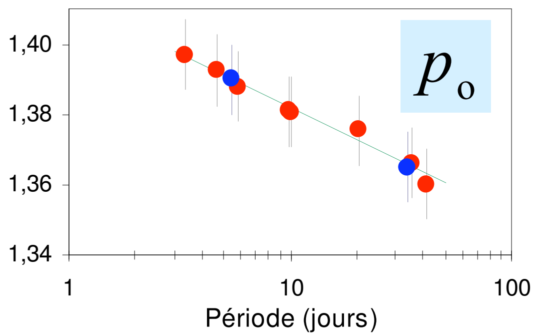
Observations HARPS



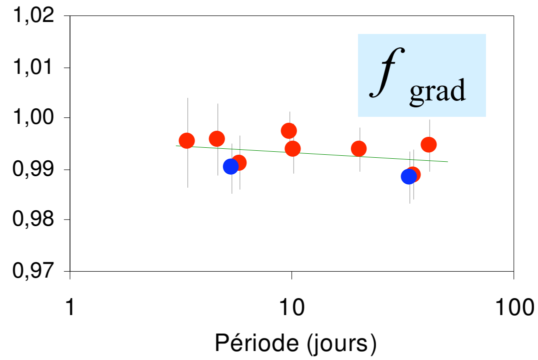
Modélisation Hydrodynamique

La relation Pp

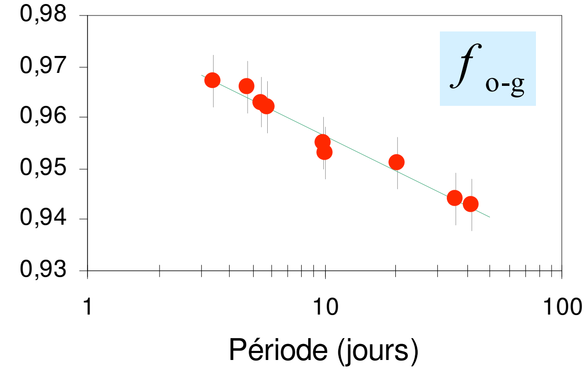
High resolution spectroscopy for Cepheids distance determination II. A period-projection factor relation
N. Nardetto, D. Mourard, Ph. Mathias, A. Fokin, D. Gillet, **2007**, A&A, **471**, **661**



Modélisation Géométrique

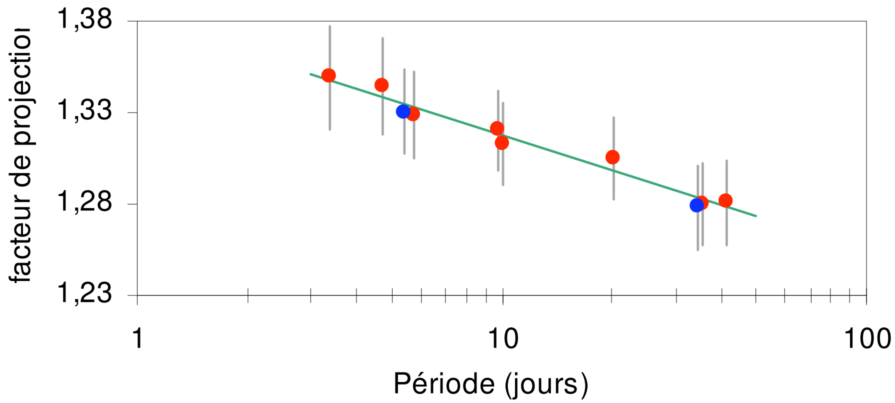


Observations HARPS



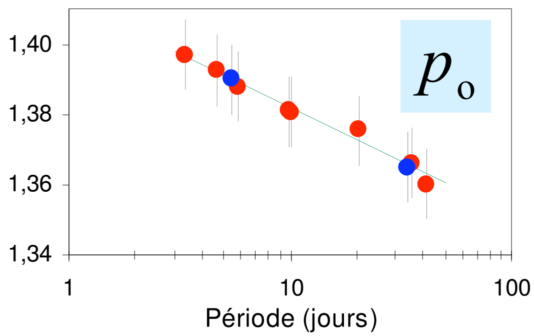
Modélisation Hydrodynamique

FeI 4896A

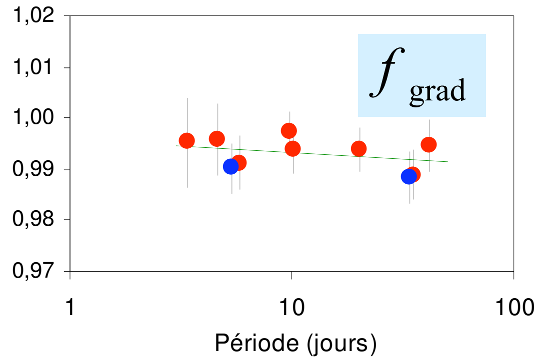


La relation Pp

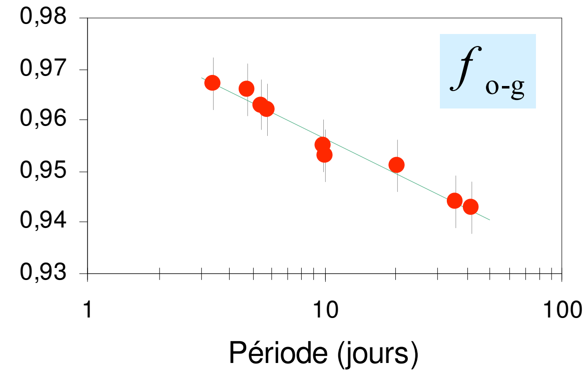
High resolution spectroscopy for Cepheids distance determination II. A period-projection factor relation
N. Nardetto, D. Mourard, Ph. Mathias, A. Fokin, D. Gillet, **2007**, A&A, **471**, **661**



Modélisation Géométrique

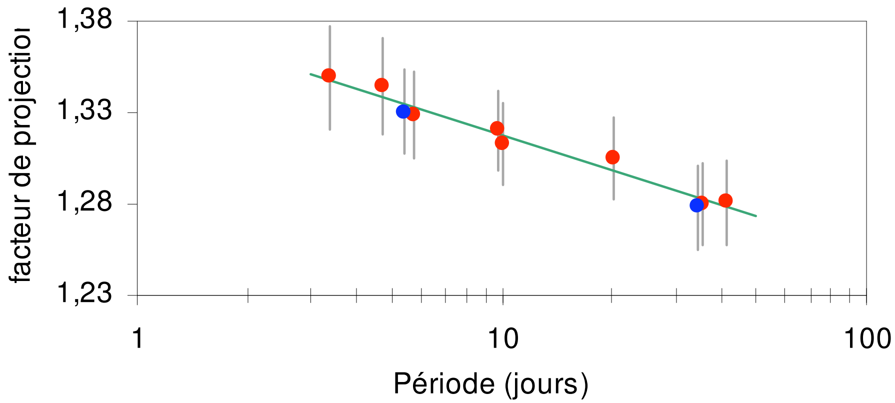


Observations HARPS



Modélisation Hydrodynamique

FeI 4896A



Découverte d'une relation Pp.
Résultats confirmés par le HST

↓

A new calibration of Galactic Cepheid Period-Luminosity relations based on four different methods
P. Fouqué, P. Arriagada, J. Storm , T.G. Barnes, N. Nardetto, A. Mérand, P. Kervella, W. Gieren, D. Bersier & G. F. Benedict & B. E. Mc Arthur **2007**, A&A, **476, 73**

Implications sur la CONSTANTE DE HUBBLE

Freedman (2001)
Programme clef du HST

PL du LMC → 5 estimateurs secondaires → Constante de Hubble

$H_o = 72 \pm 3 \pm 7$ km/s/Mpc

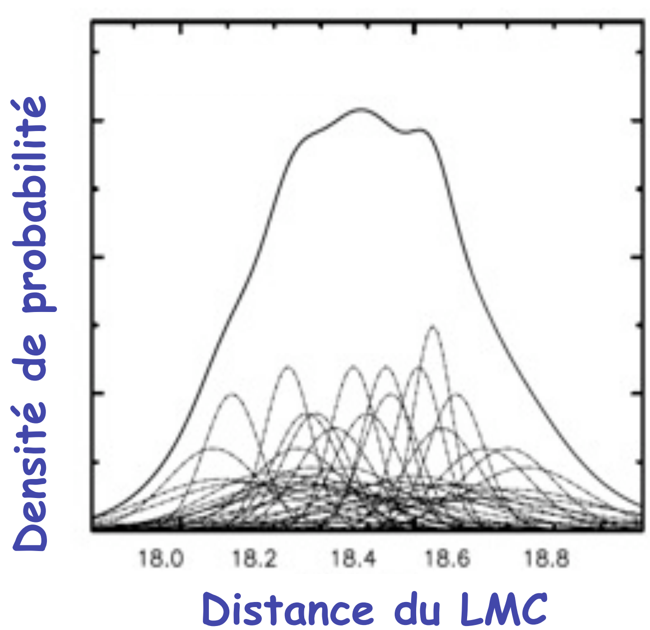
4% stat.
10% syst.

Métallicité (pente):
4% syst. sur Ho

→ pente (Voie Lactée) = pente (LMC)

Distance du LMC
(Point-zéro):
5% syst. sur Ho

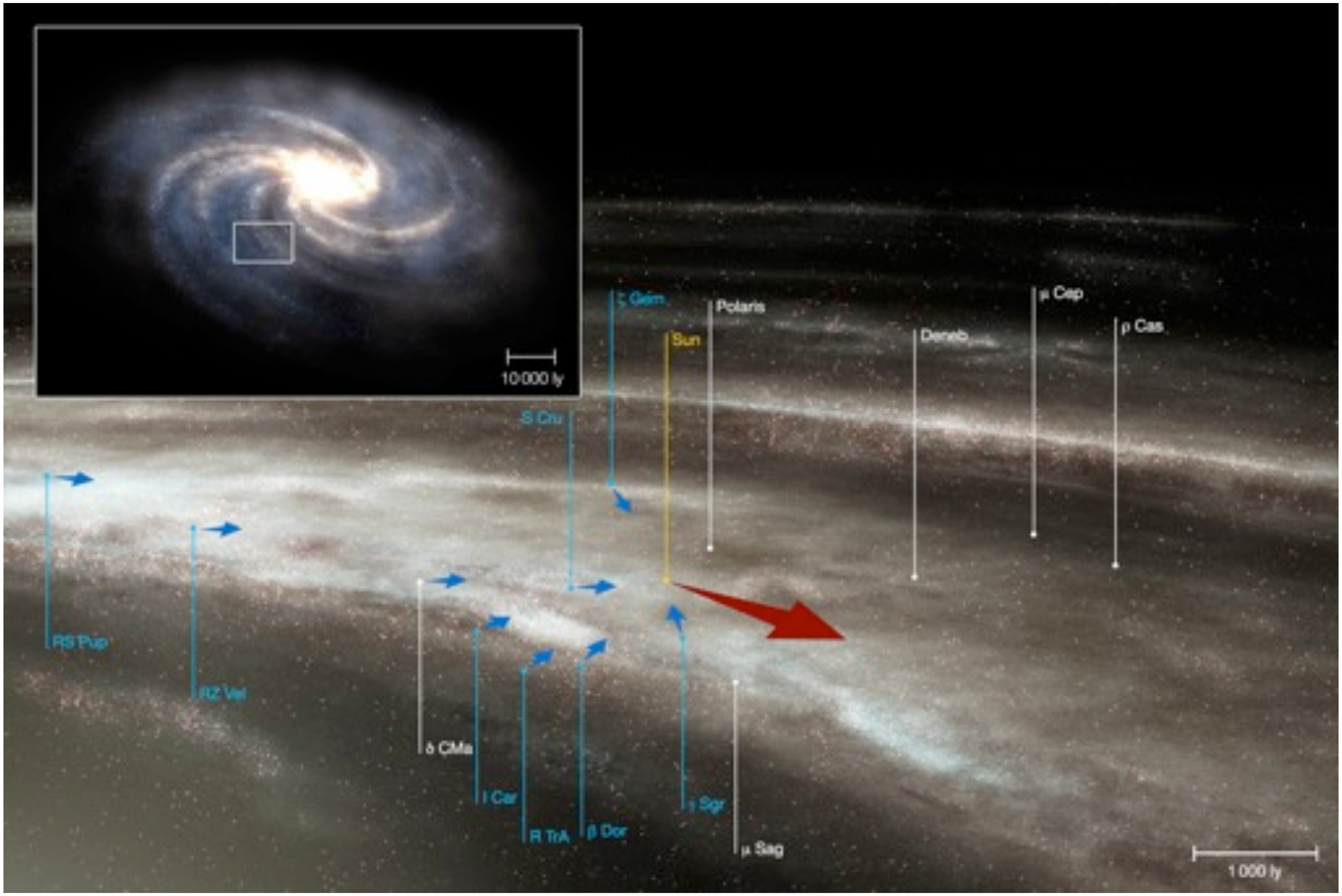
$_0$(LMC)=18.50±0.10mag



→ Objectif : précision et exactitude de 0.01 mag

La rotation de la Voie Lactée

Le problème du « K-term » des Céphéides : Joy (1939)



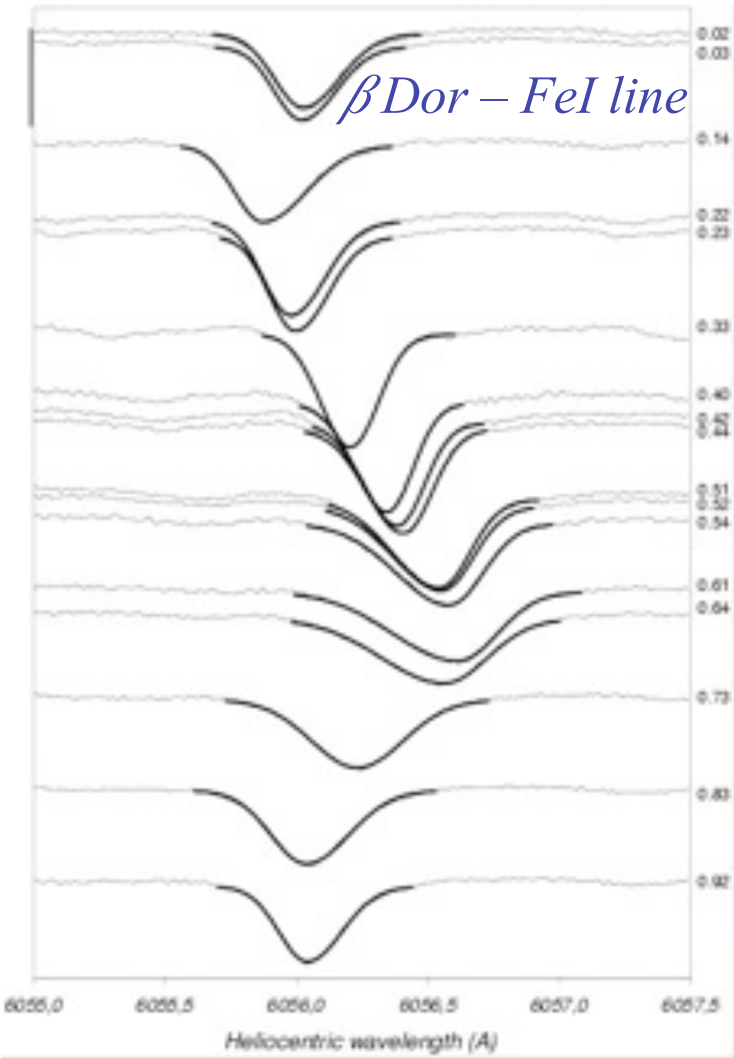
Un débat de 70 ans: Parenego (1947), Stibbs (1956), Wielen (1974), Caldwell & Coulson (1987), Moffett & Barnes (1987), Wilson et al. (1991), Pont, Mayor & Burki (1994)

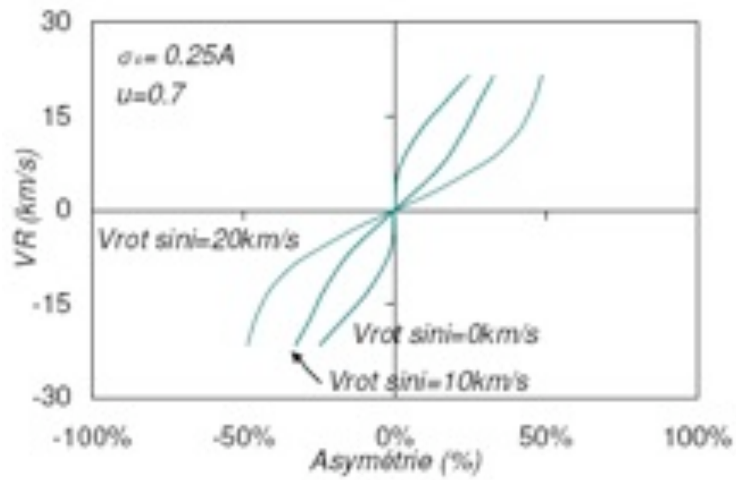
Dynamique atmosphérique ou structure cinématique de la Voie Lactée

Les "γ - asymétries" (1/2)

High resolution spectroscopy for Cepheids distance determination I. Line asymmetry

N. Nardetto, D. Mourard, P. Kervella, Ph. Mathias, A. Mérand, D. Bersier., **2005**, A&A, **453, 409**





Les “γ - asymétries” (1/2)

High resolution spectroscopy for Cepheids distance determination I. Line asymmetry

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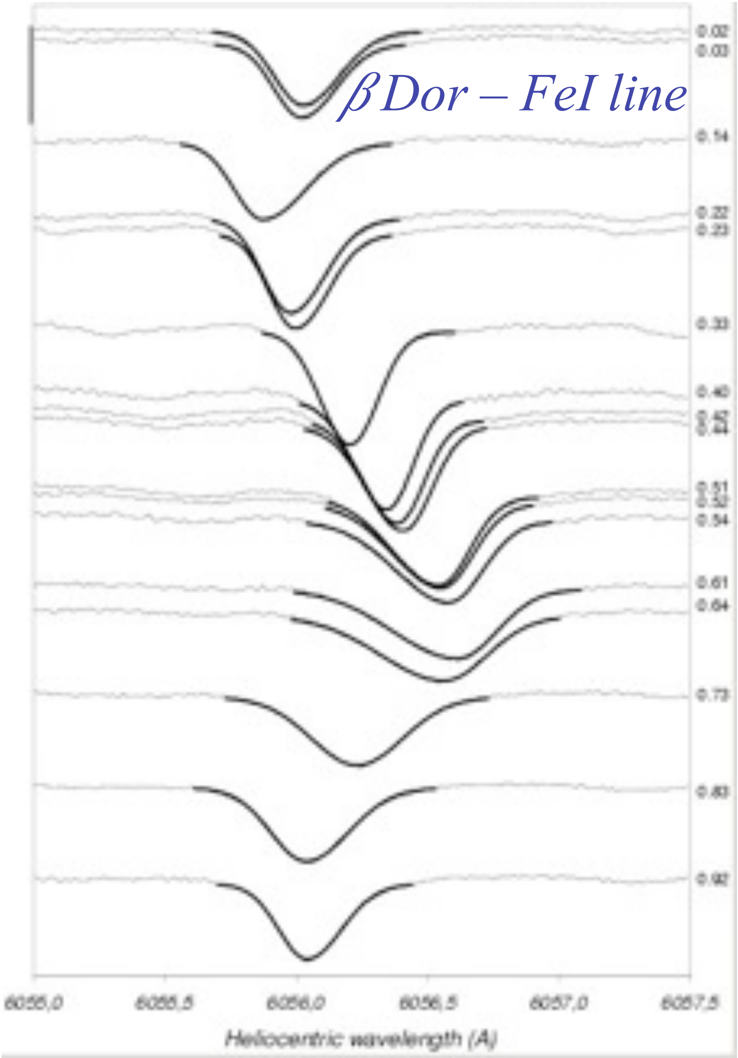
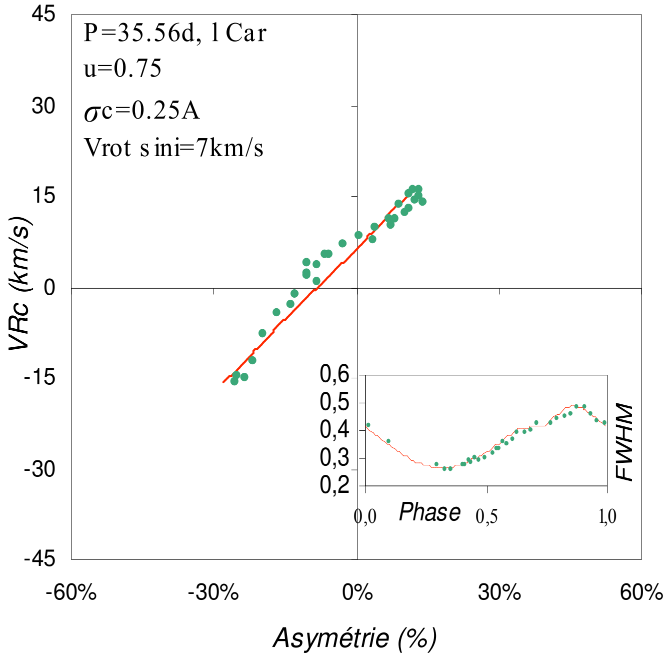
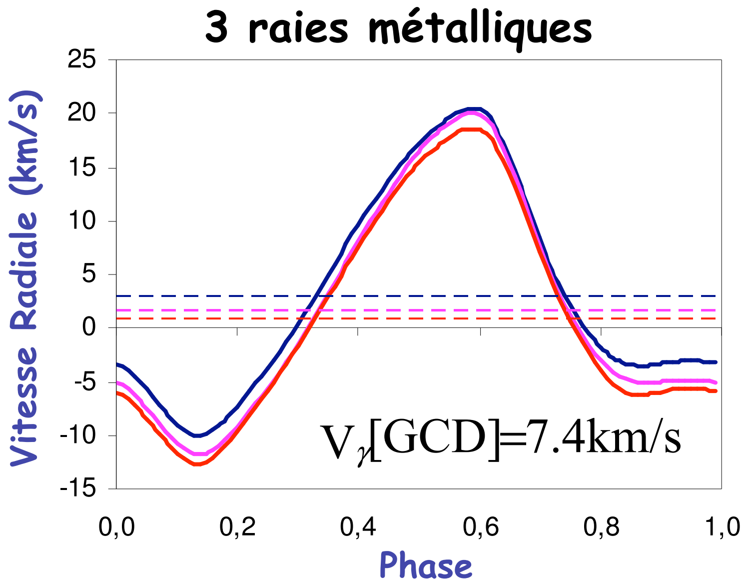
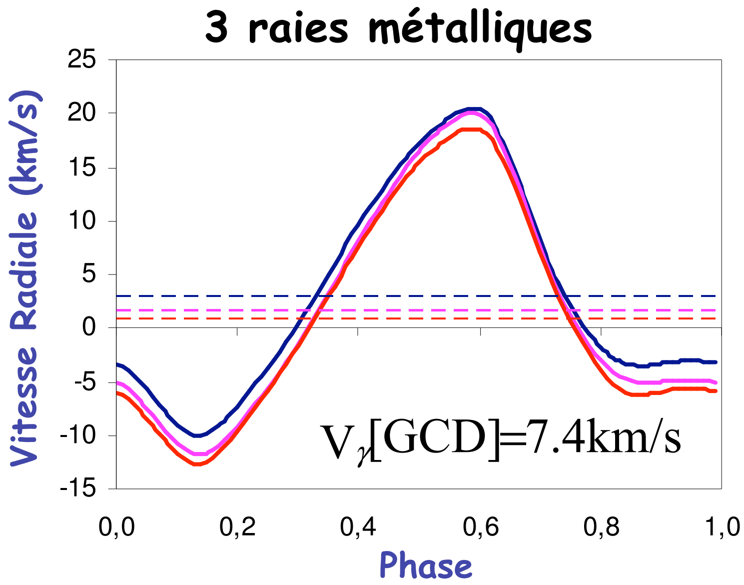


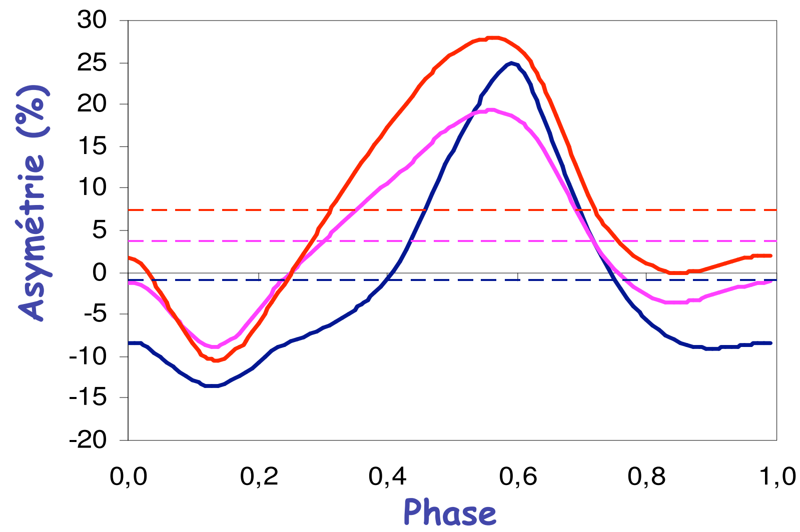


Les "γ - asymétries" (2/2)

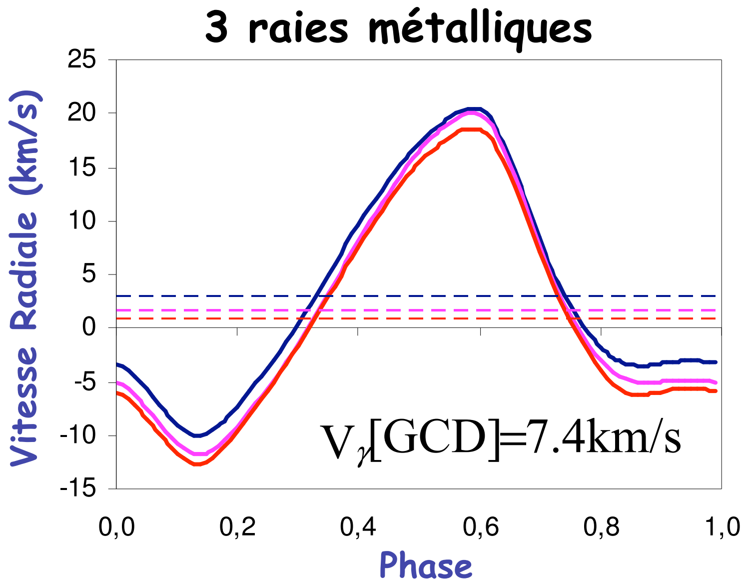


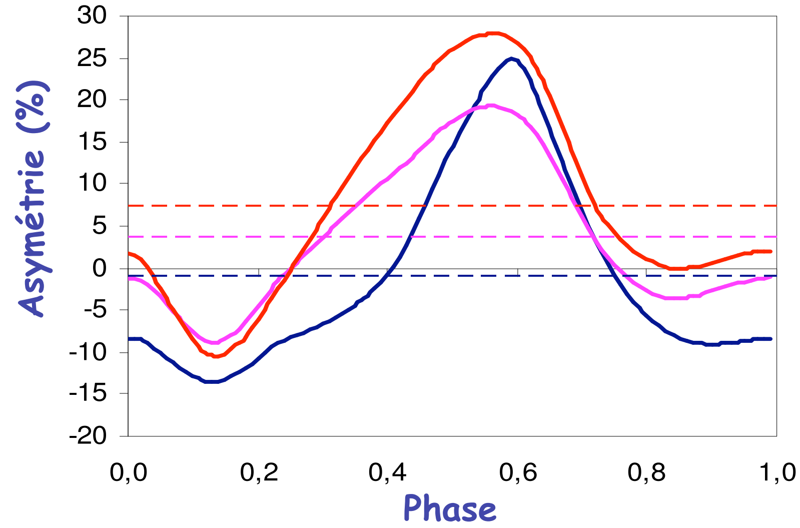
Les "γ - asymétries" (2/2)

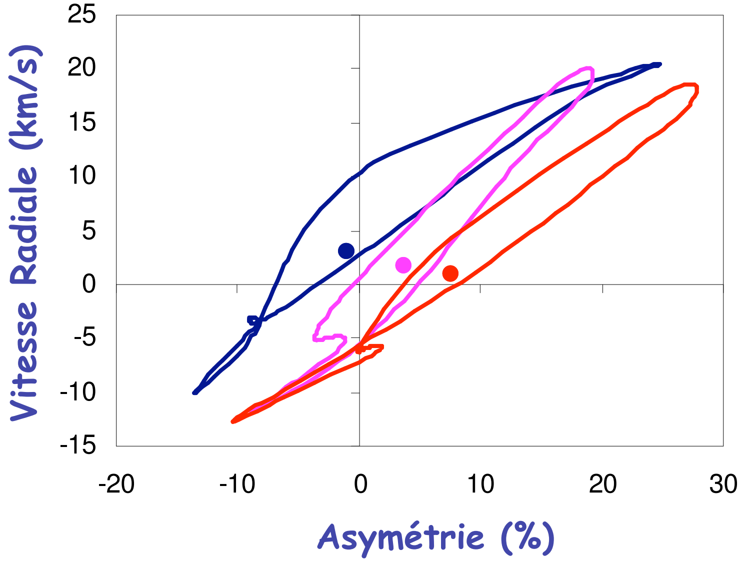




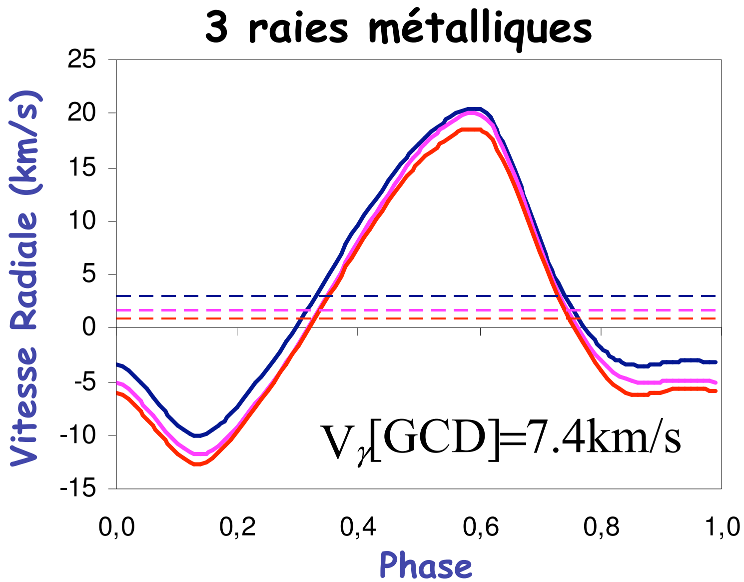
Les "γ - asymétries" (2/2)

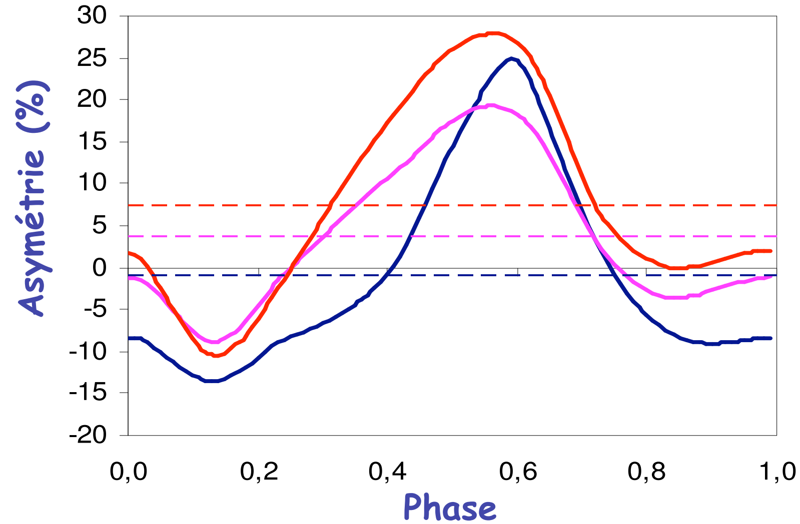


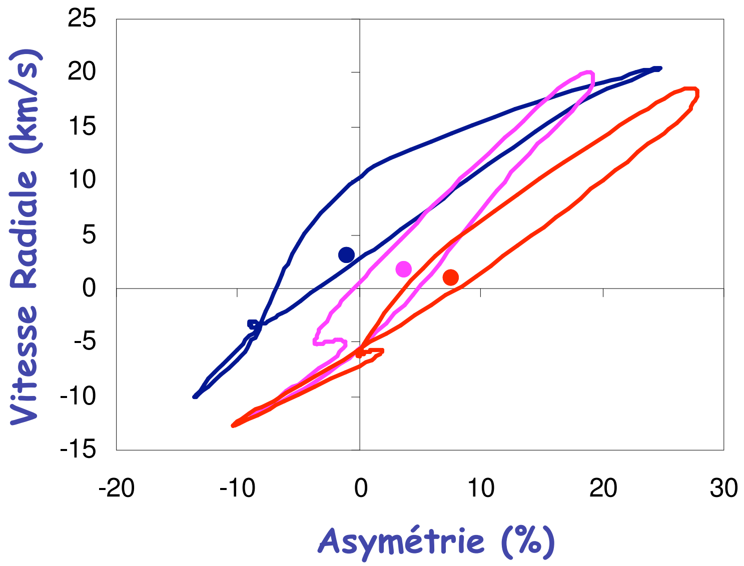


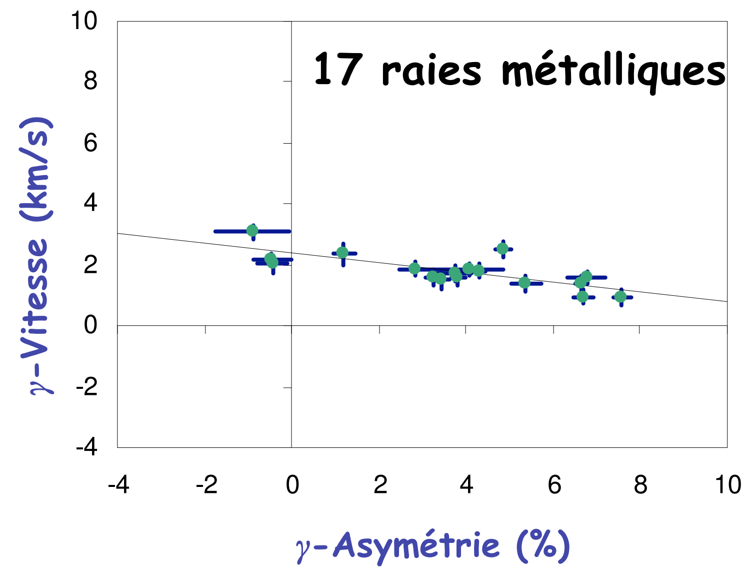


Les "γ - asymétries" (2/2)









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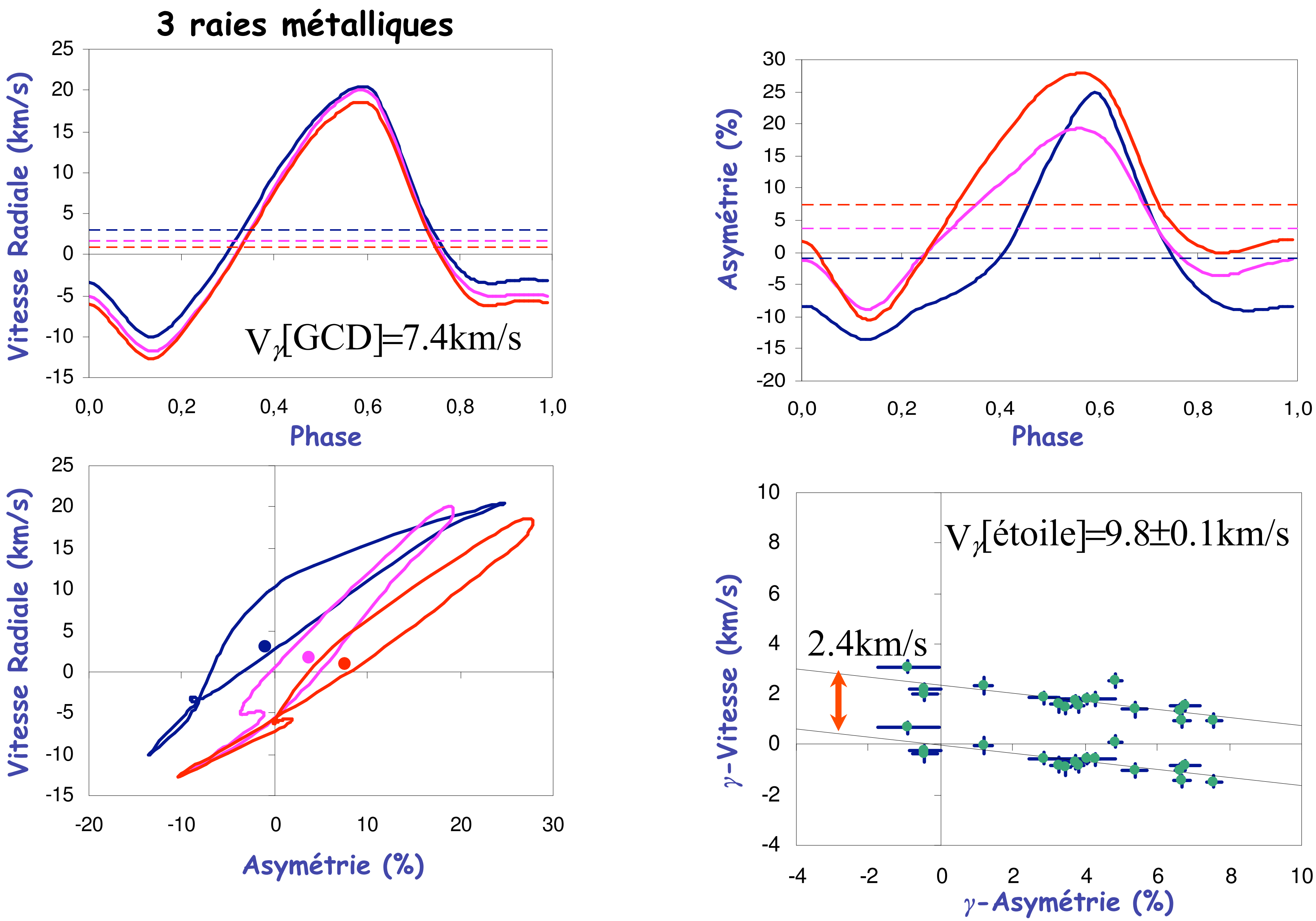
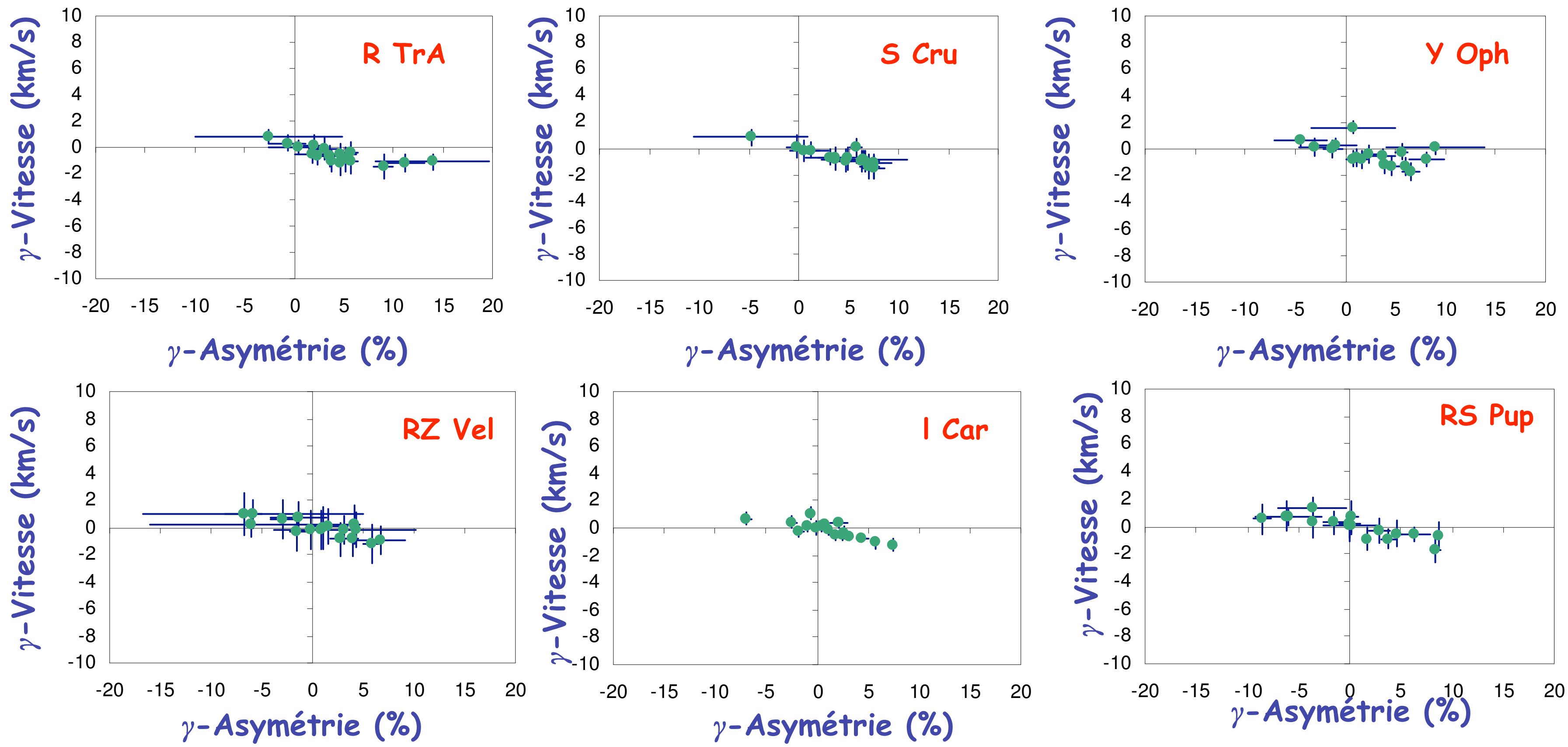


High resolution spectroscopy for Cepheids distance determination
III. A relation between γ-velocities and γ-asymetries

N. Nardetto, A. Stoekl, D. Bersier, T. Barnes, **2008**, A&A, 489, 1255



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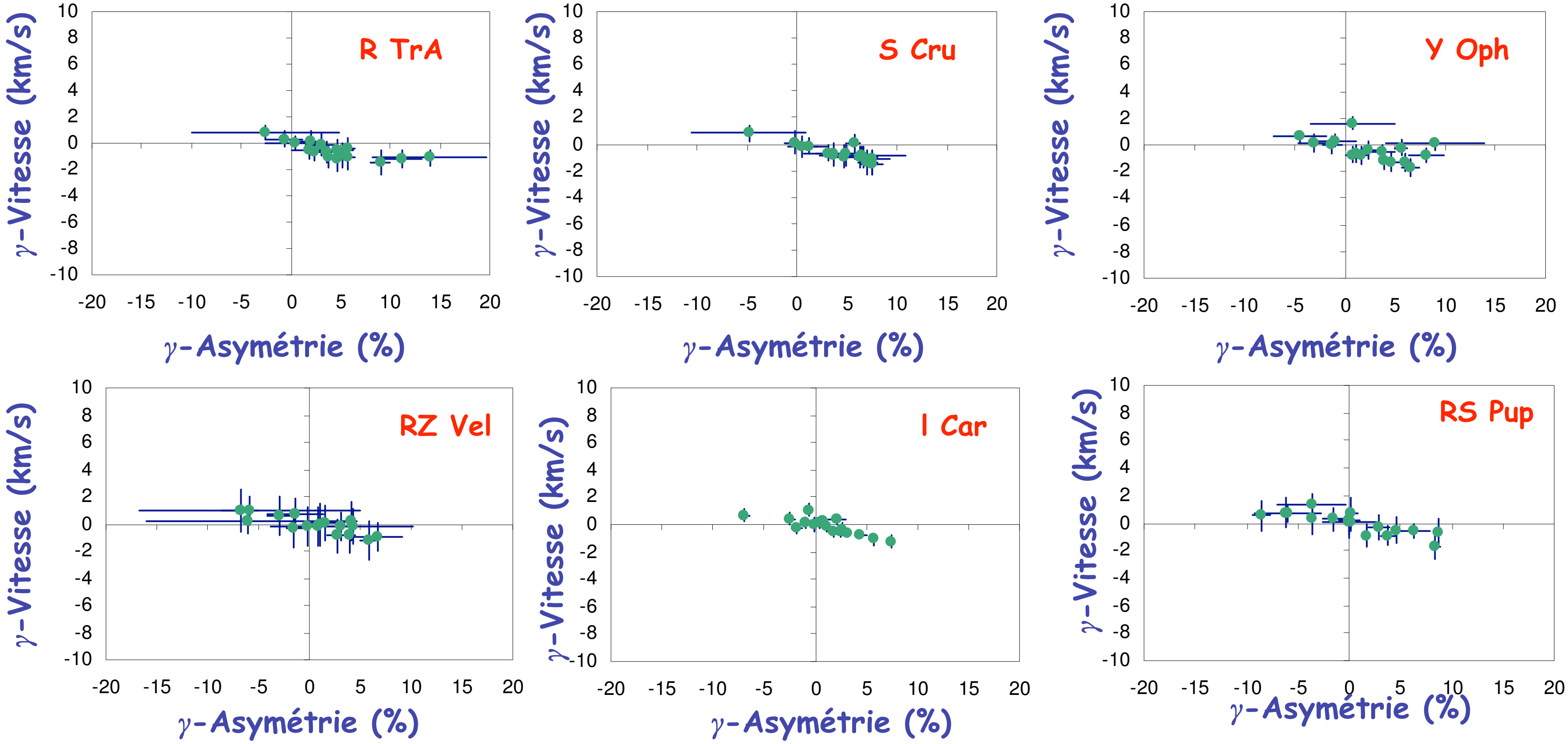

On trouve pour les 8 étoiles une correction moyenne (redshift) de 1.8+-0.2km/s!

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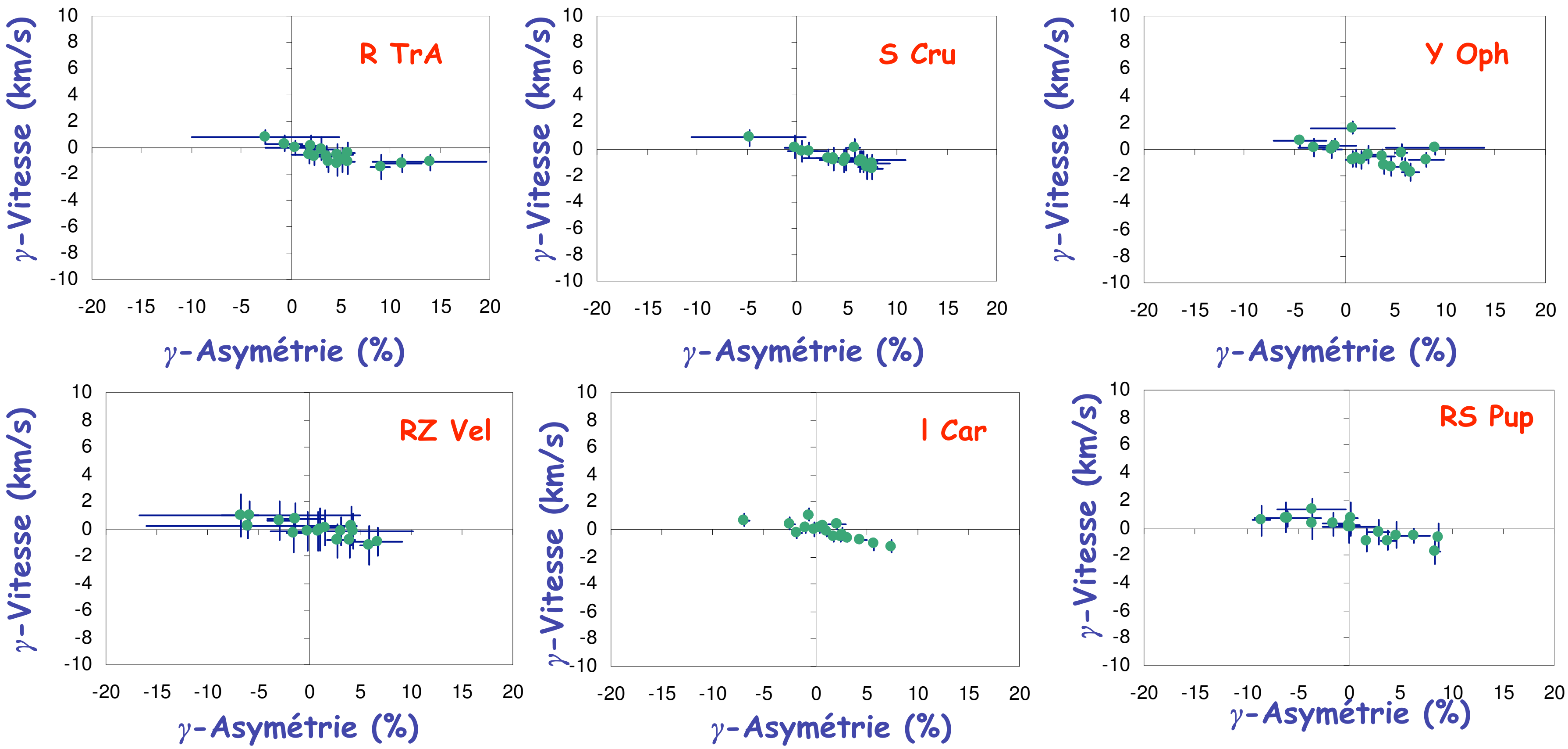

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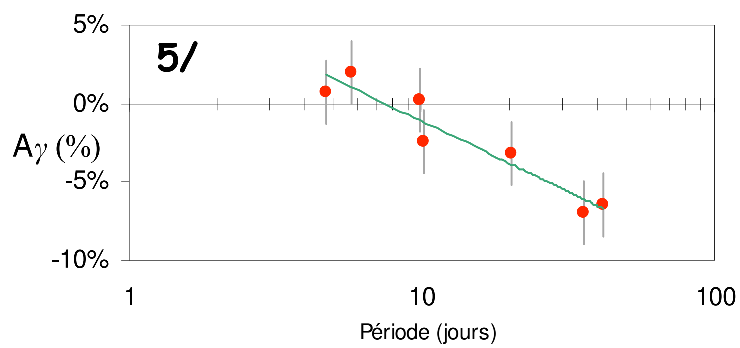
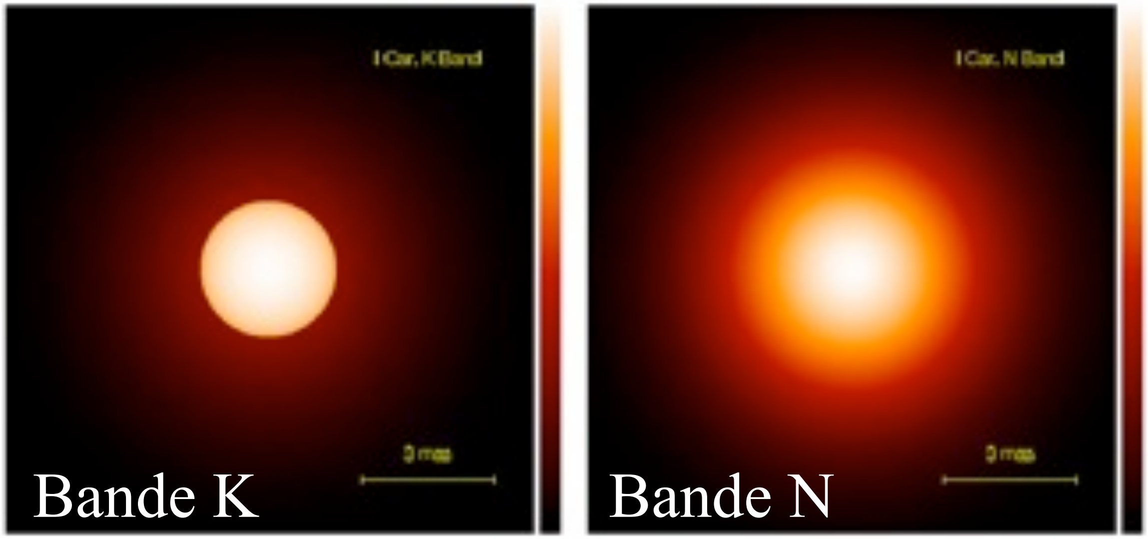


L'enveloppe circumstellaire des Céphéides (CHARA)

l Car



Kervella et al. 2006, A&A, 448, 623

L'enveloppe circumstellaire des Céphéides (CHARA)

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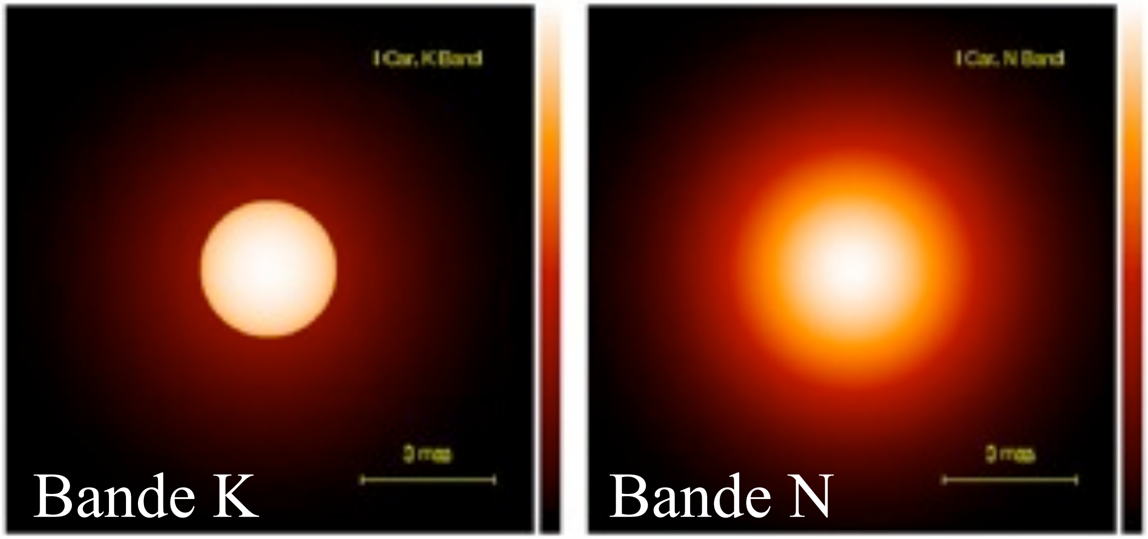
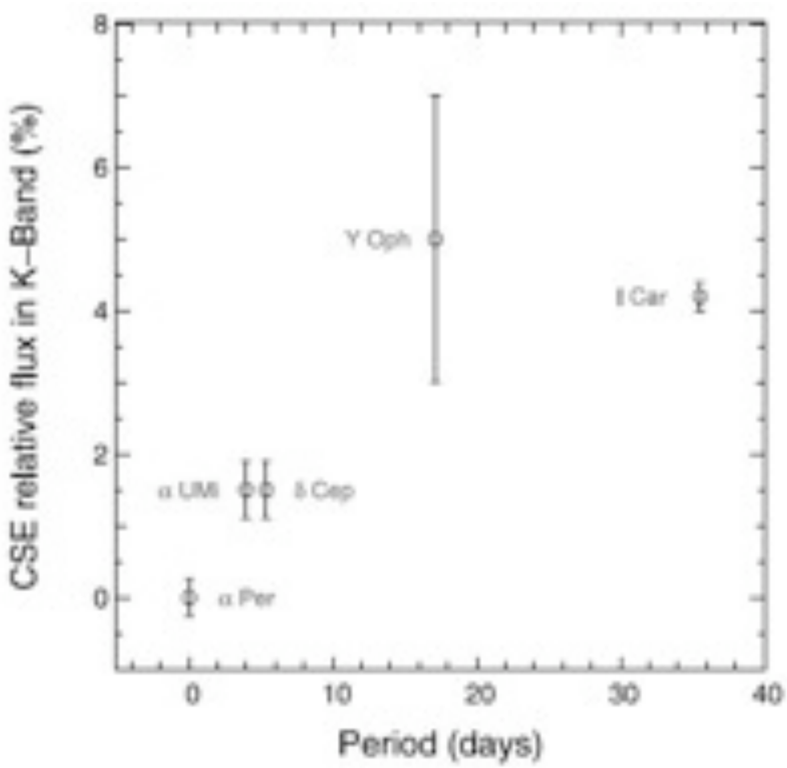
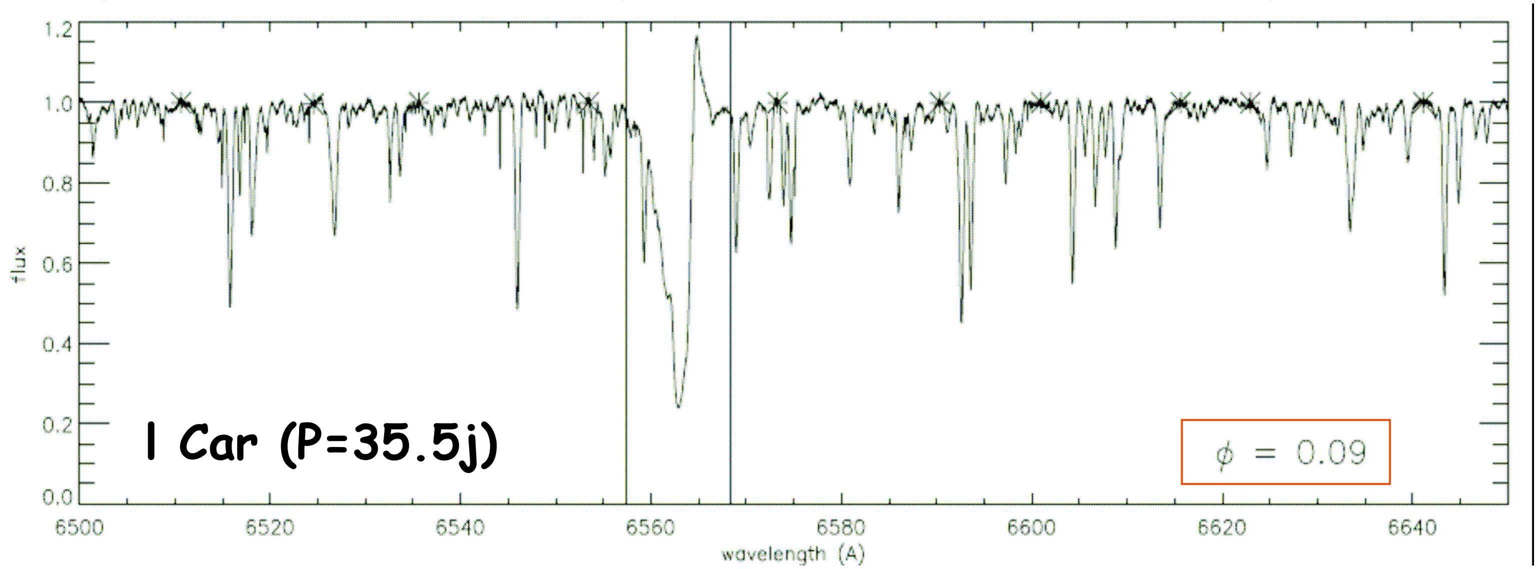


Kervella et al. 2006, A&A, 448, 623



Mérand et al. 2007, A&A, 453, 155

Les profiles Hα des Céphéides (1/3) : le cas particulier de *l* Car



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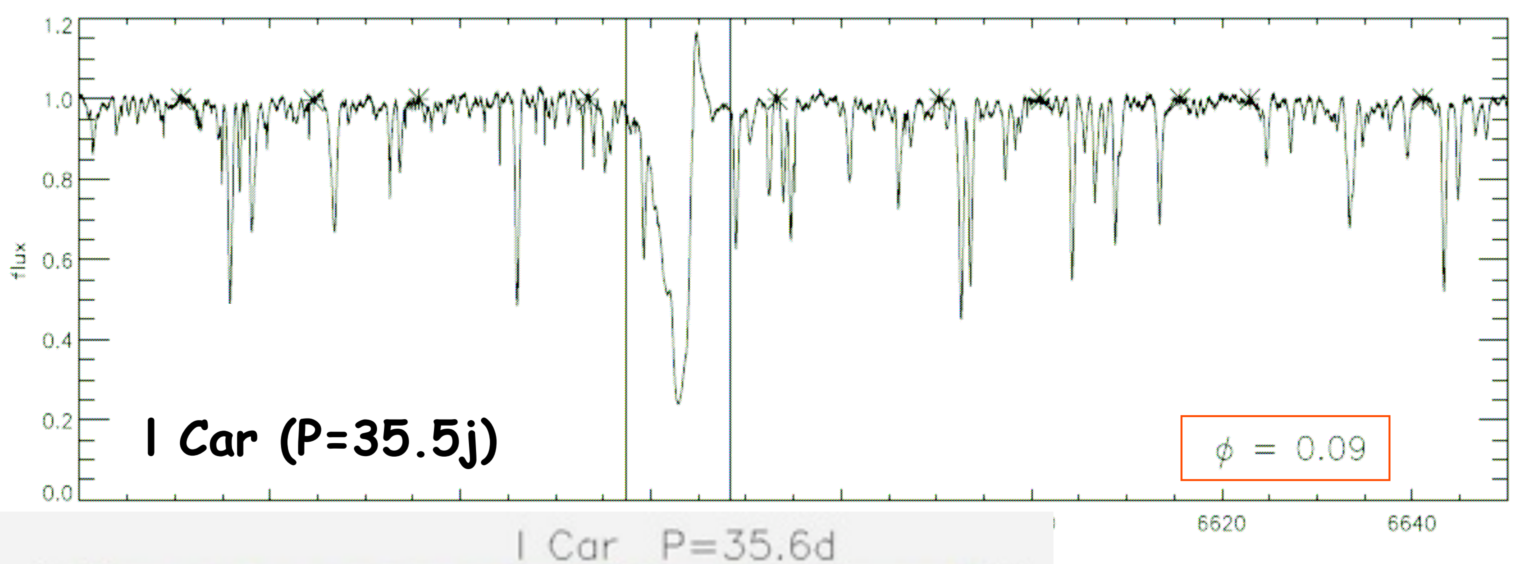
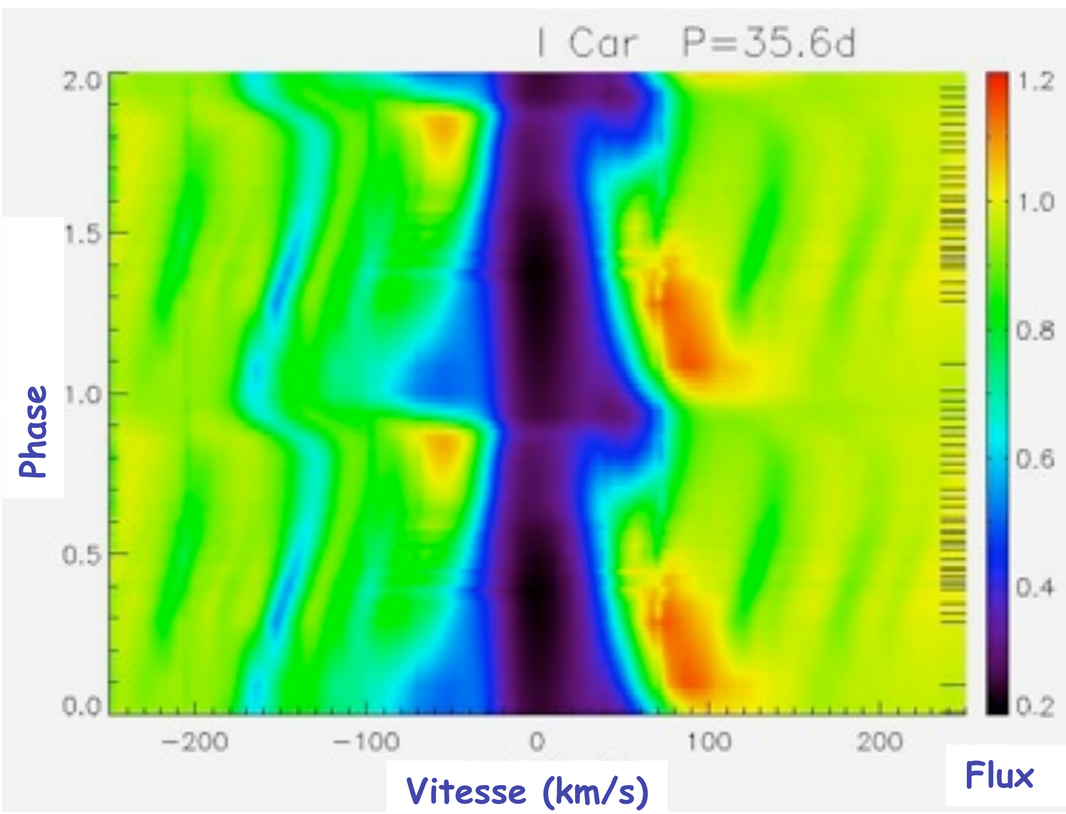
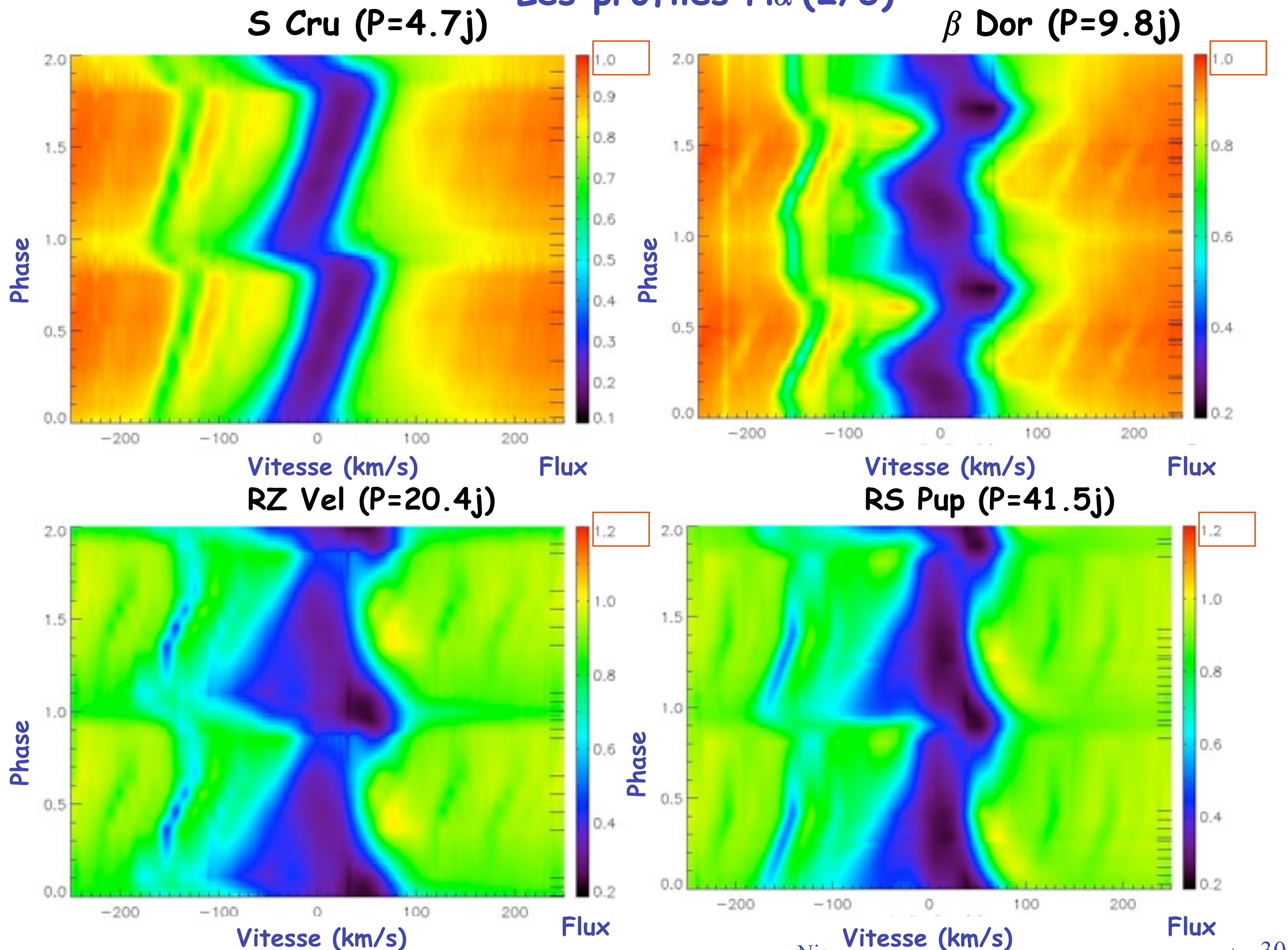




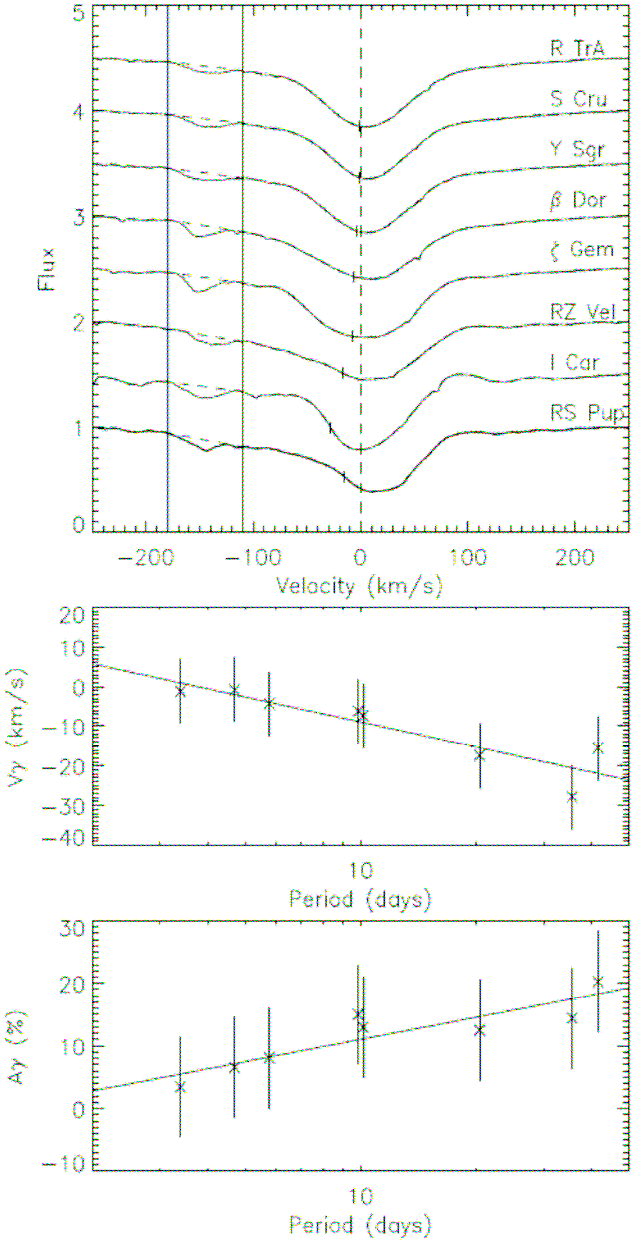
CONCLUSIONS concernant l Car:

- Une composante centrale en absorption
- Composantes en émission (du côté rouge et du côté bleu)
- Forte asymétrie

Les profiles Hα (2/3)



Les profiles Hα des Céphéides (3/3): une relation “Période-Aγ”



High resolution spectroscopy for Cepheids distance determination
IV. Times series of Hα line profiles
N. Nardetto, J. Groh, S. Kraus, F. Millour, D. Gillet,
2008, A&A, 489, 1263

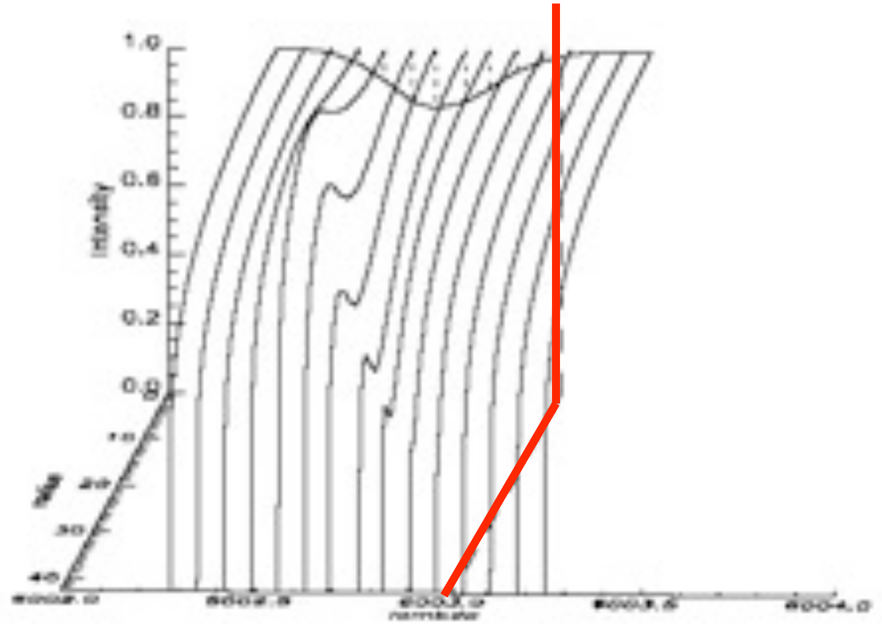
CONCLUSIONS générales:

1/ Une relation entre la période et la perte de masse?

2/ Modélisation de l’enveloppe circumstellaire

3/ Observations spectro-interférométriques (AMBER & VEGA)

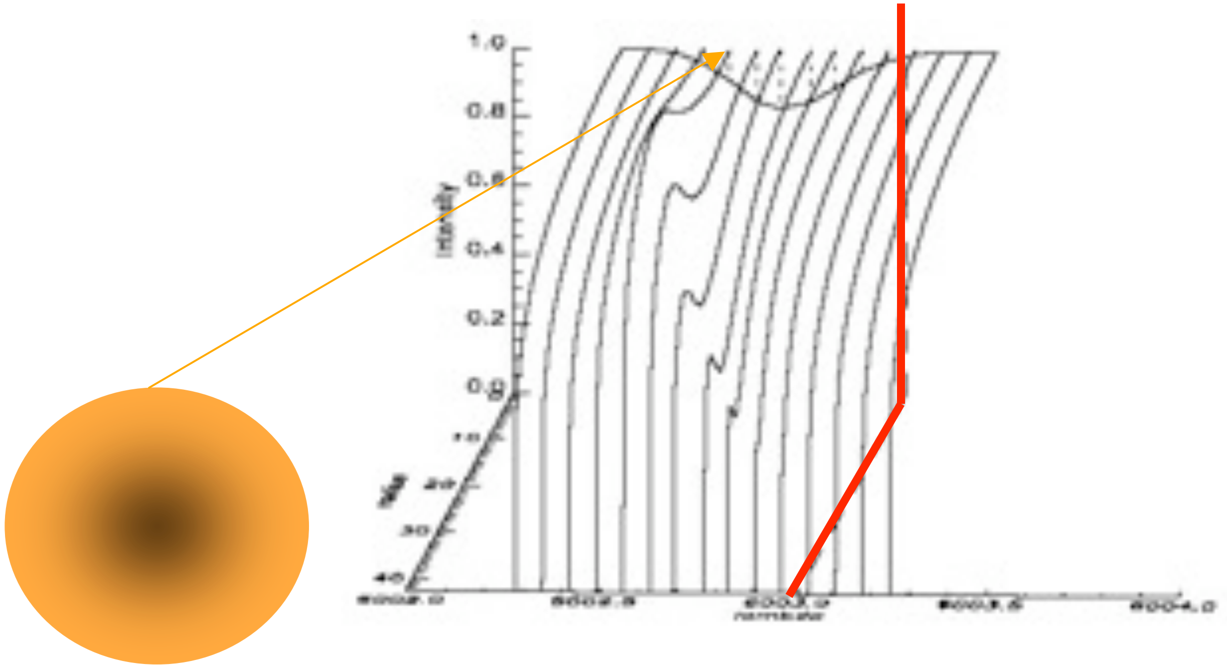
Perspectives : spectro-interférométrie



$\varphi=0$ $V_{puls}=20km/s$

$V_{rot}*\sin i=0km/s$

Perspectives : spectro-interférométrie



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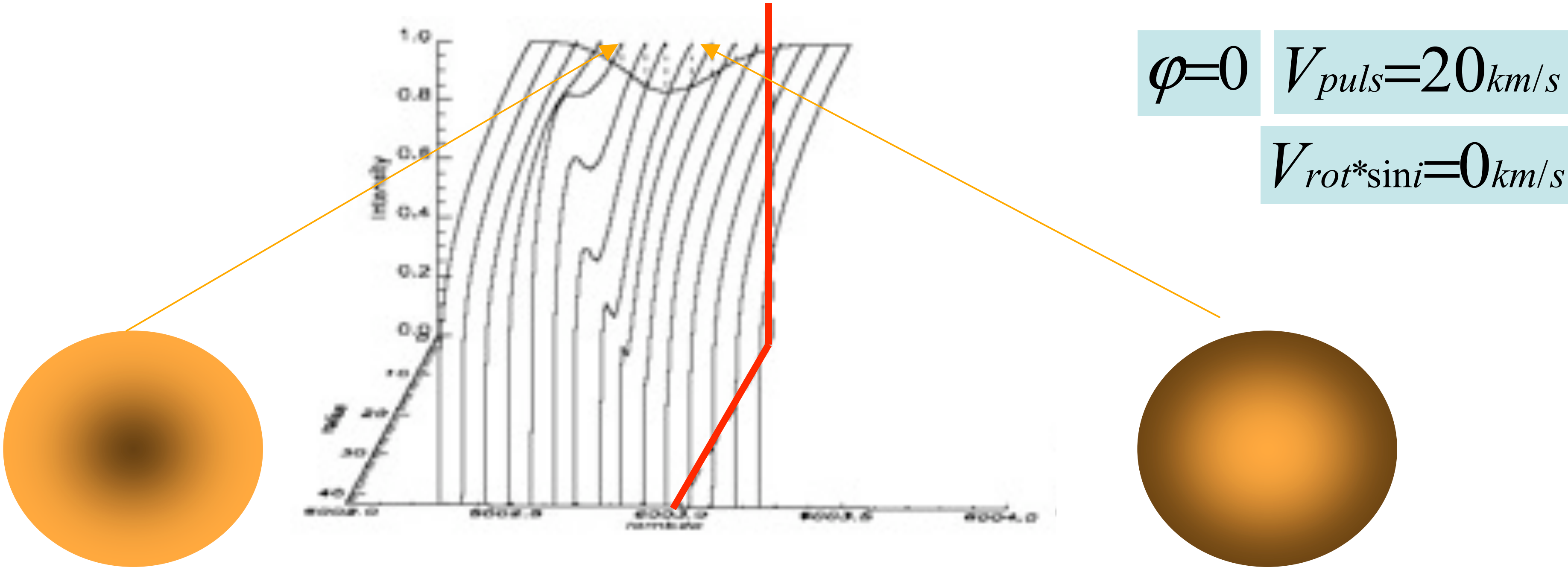
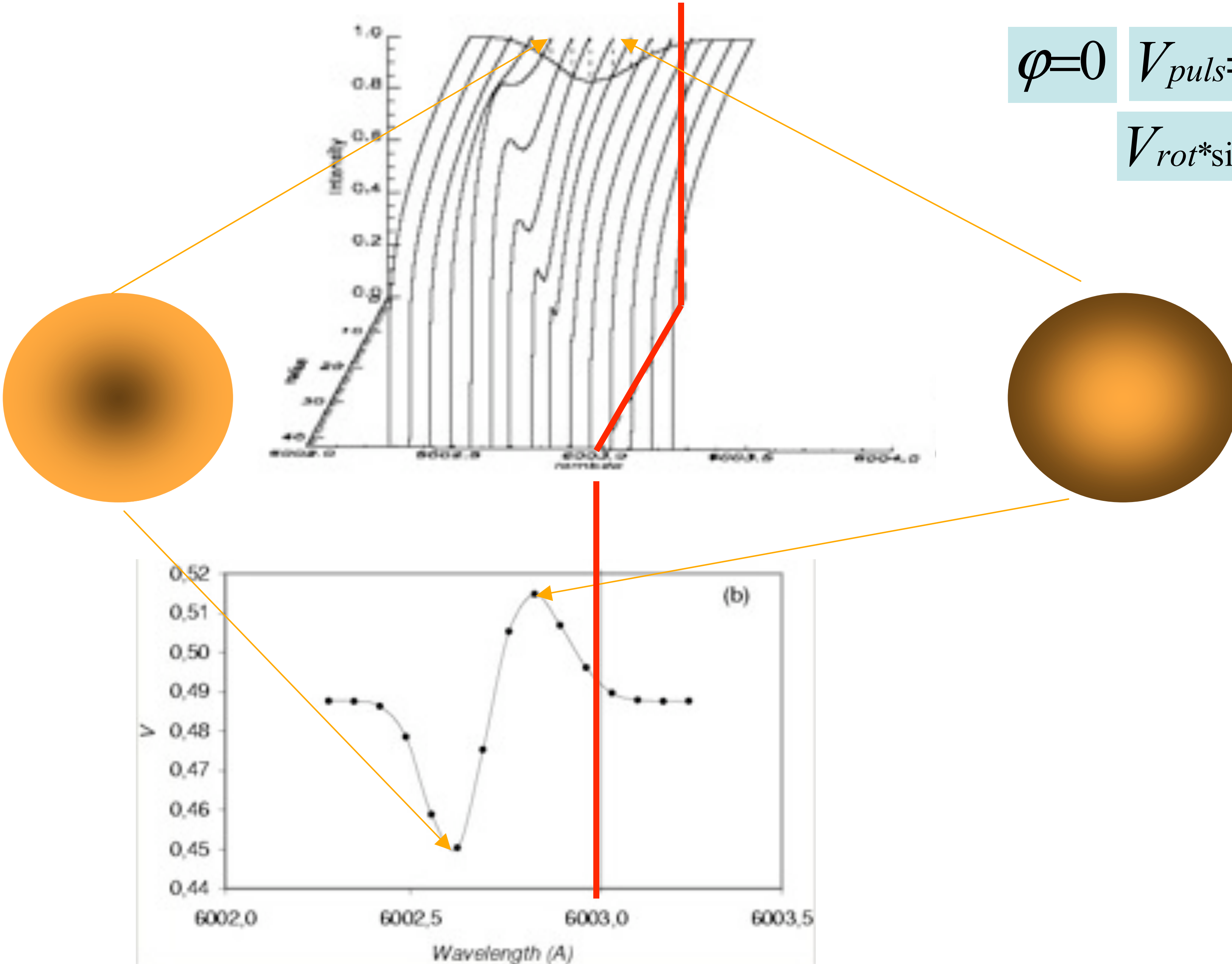


Perspectives : spectro-interférométrie

$\varphi=0$ $V_{puls}=20_{km/s}$

$V_{rot}{*}\sin i=0_{km/s}$



Perspectives : spectro-interférométrie

$\varphi = 0$ $V_{puls} = 20\,km/s$

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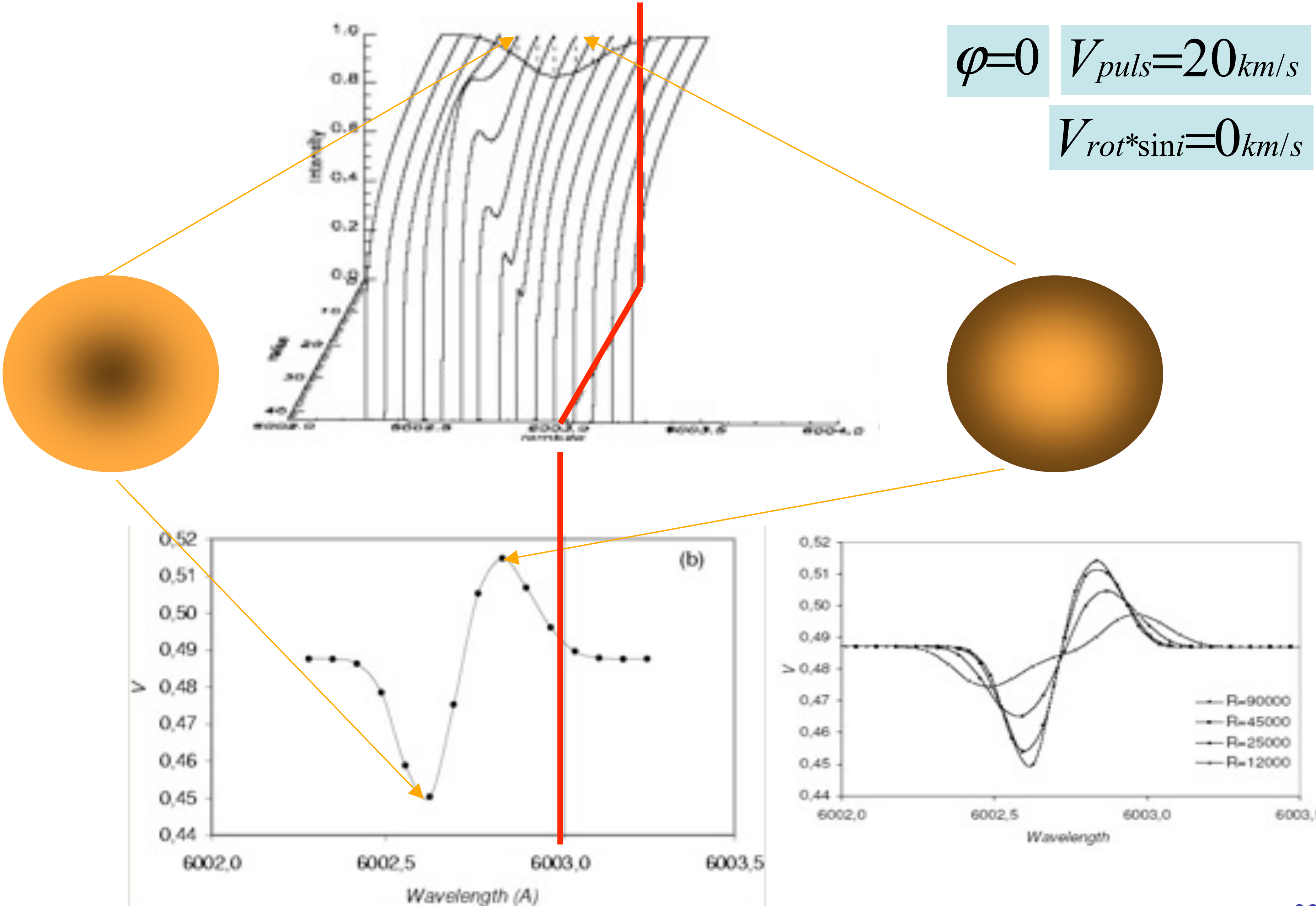
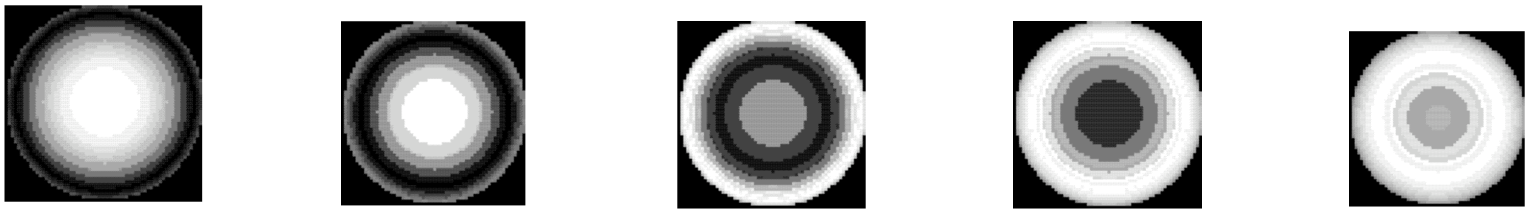


Perspectives : spectro-interférométrie

ACB σ_c V_{puls} ~~$V_{rot} \sin i$~~ $+$ D θ



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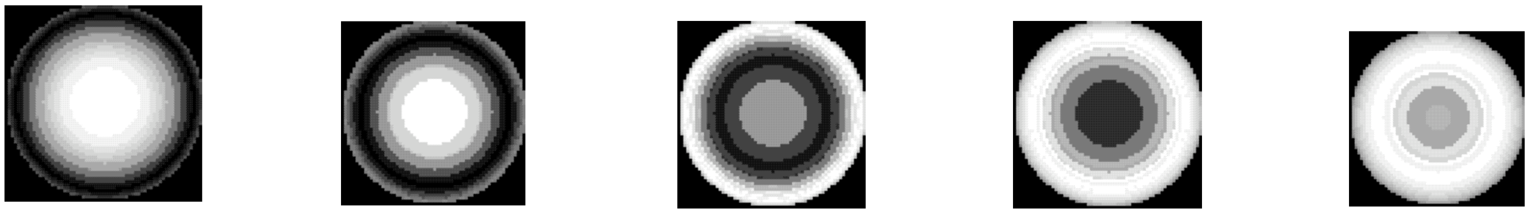
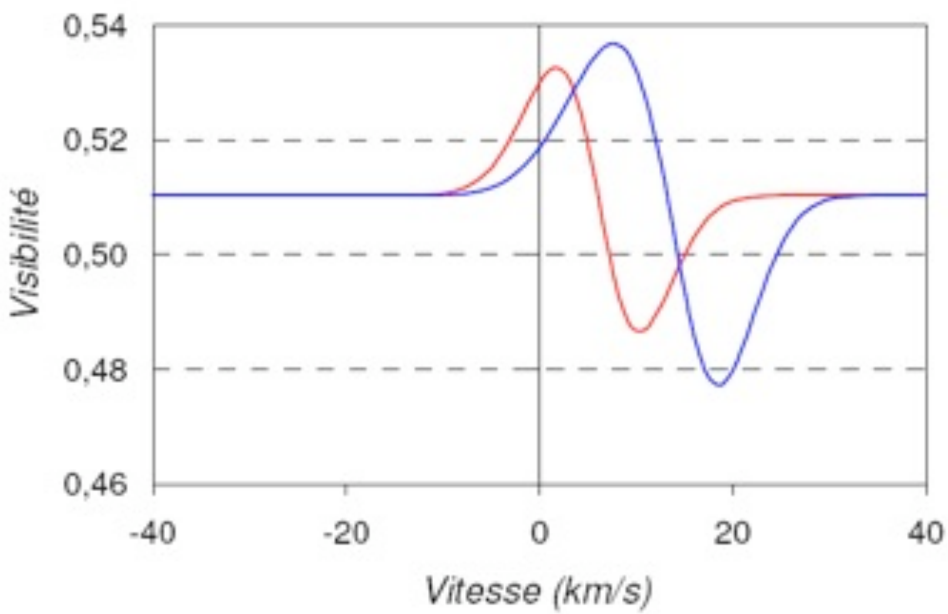
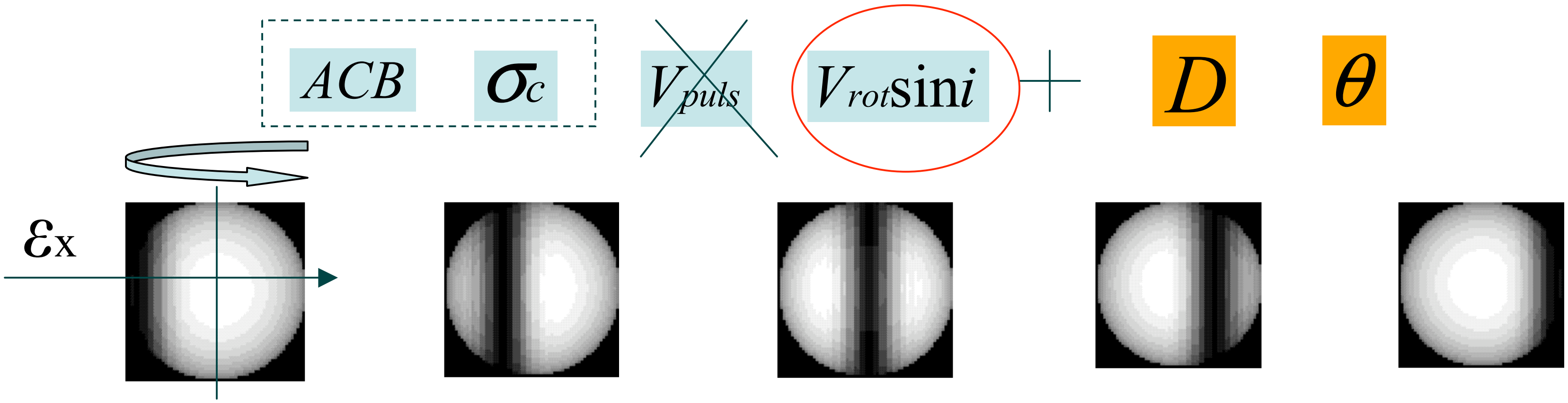


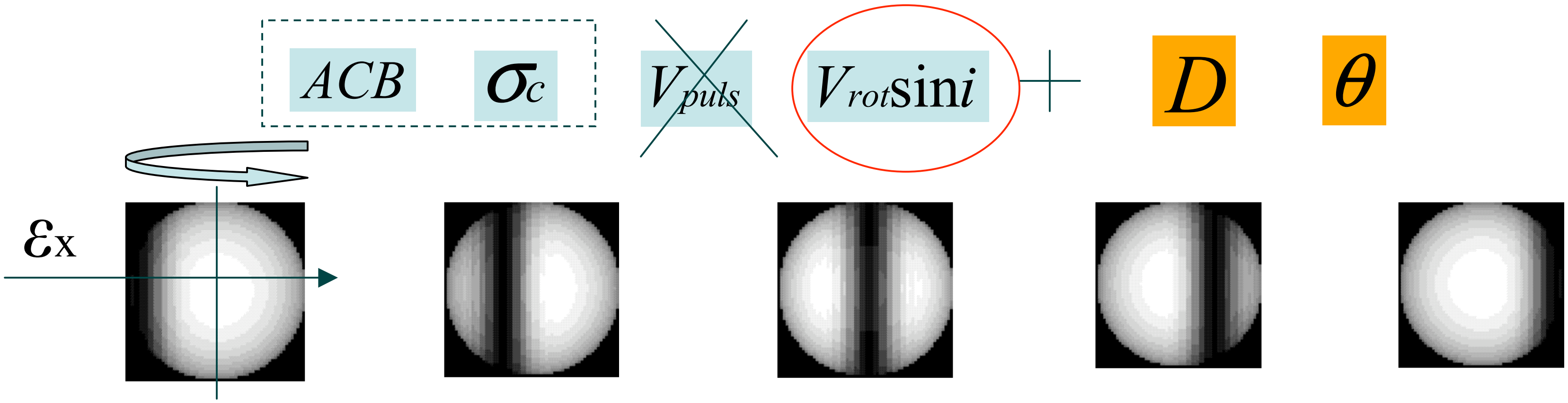
V_{puls} : 10 & 20 km/s



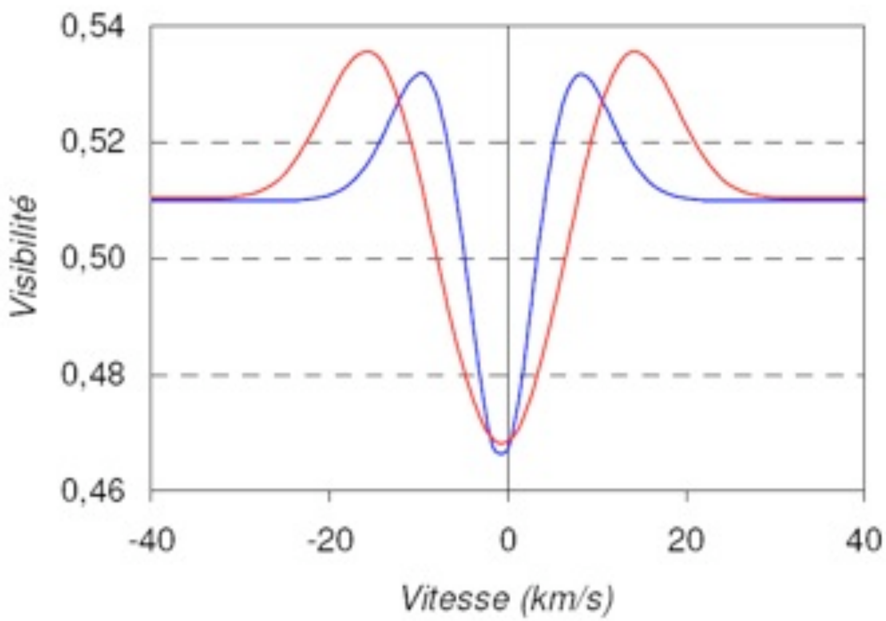
Pas de déplacement du photocentre

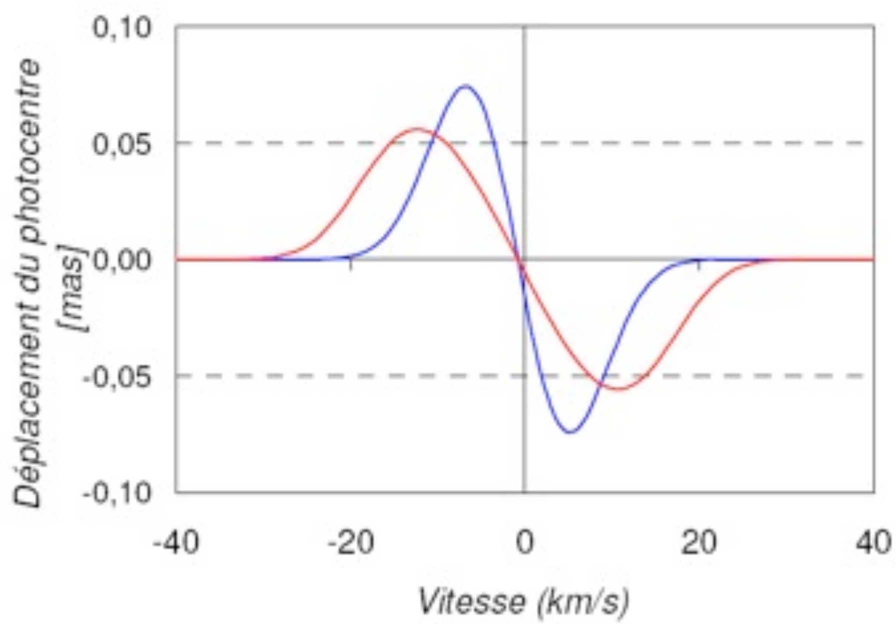


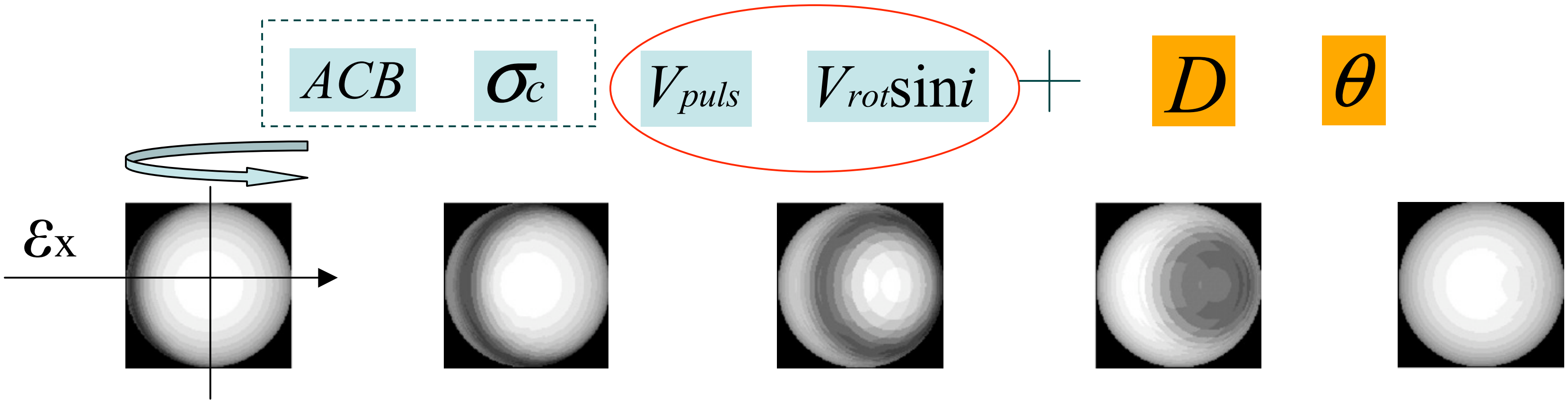
ACB
σ_c
V_{puls}
$V_{rot}\sin i$
D
θ
εx



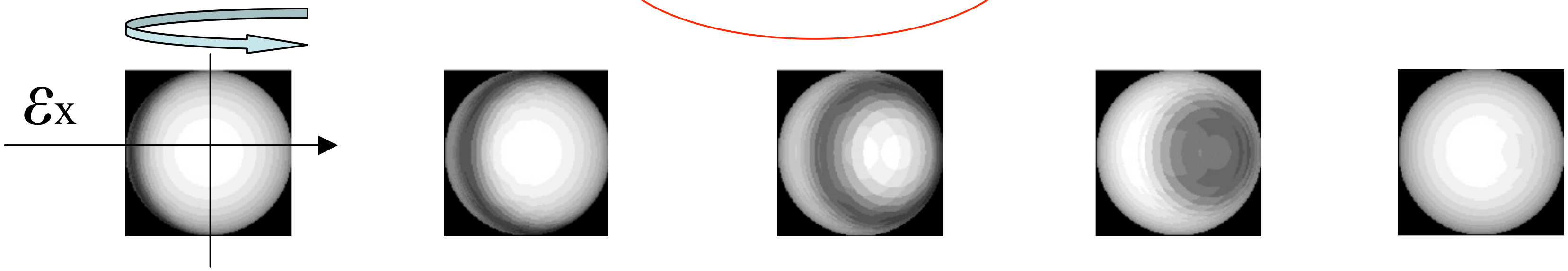
$V_{rot}\sin i$: 10 à 20 km/s



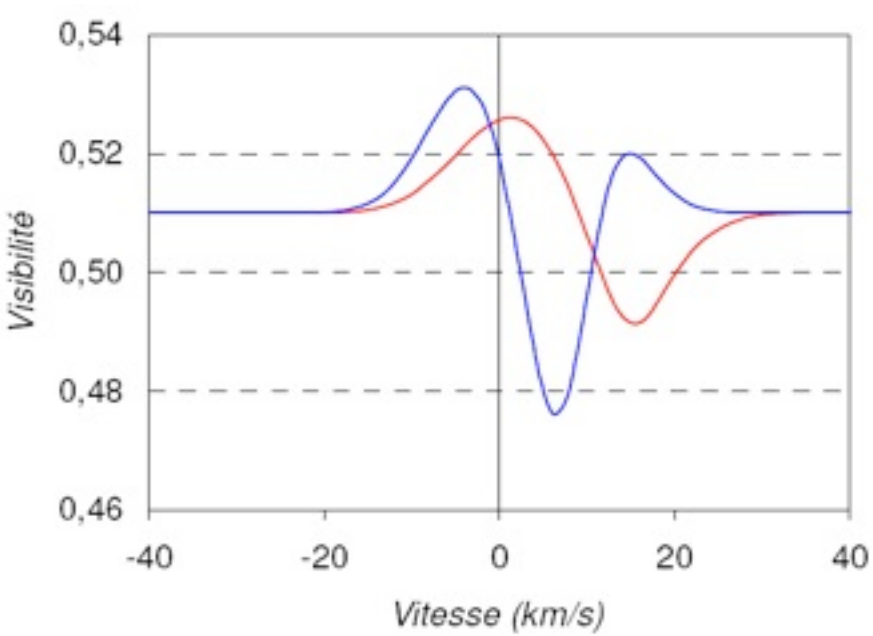


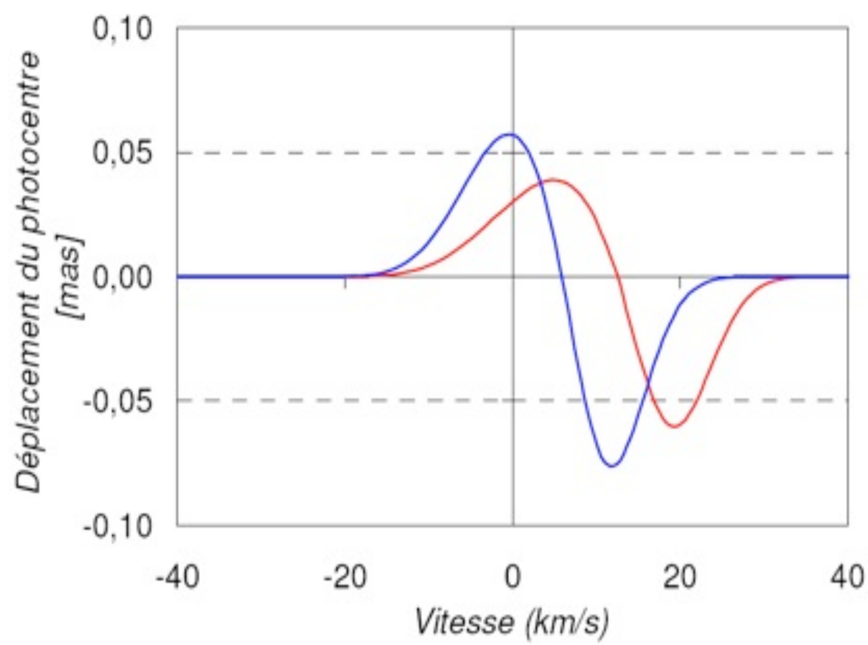

ACB
σc
Vpuls
Vrot sini
+
D
θ
εx

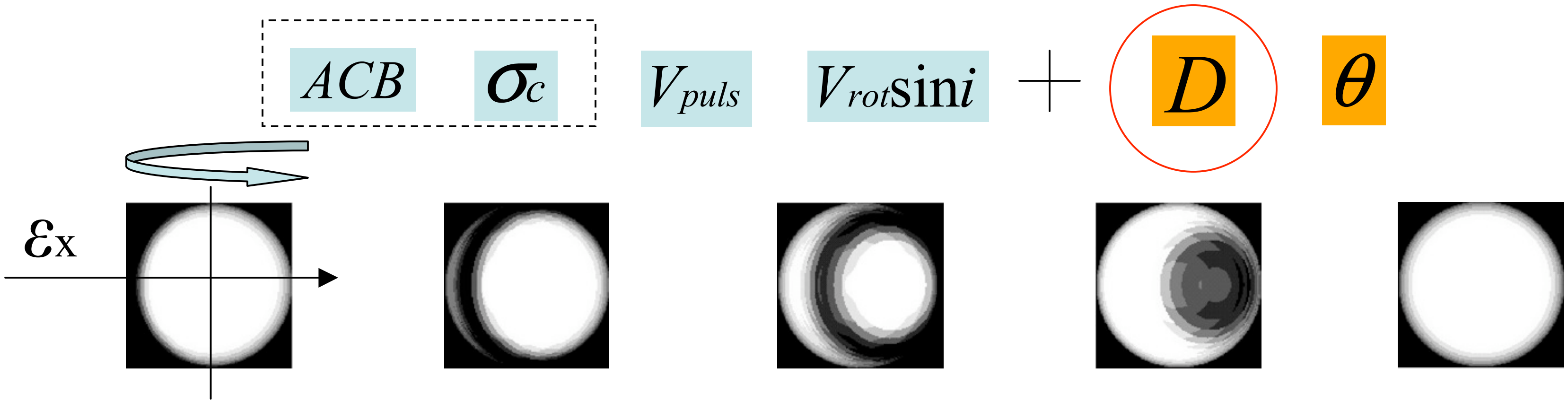
ACB σ_c V_{puls} $V_{rot}\sin i$ + D θ

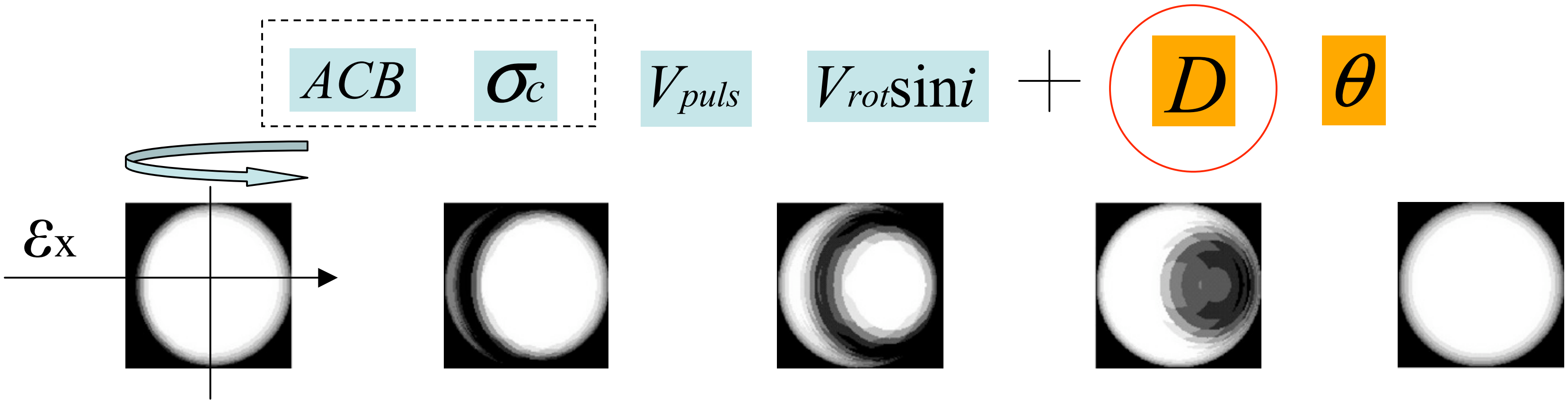


V_{puls} : 10 & 20 km/s + $V_{rot}\sin i$: 10 km/s

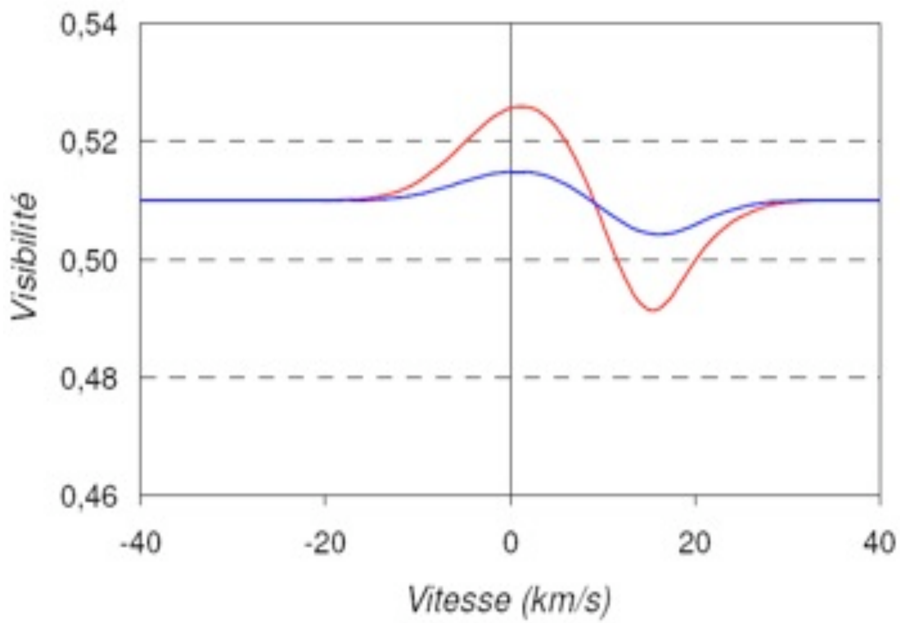


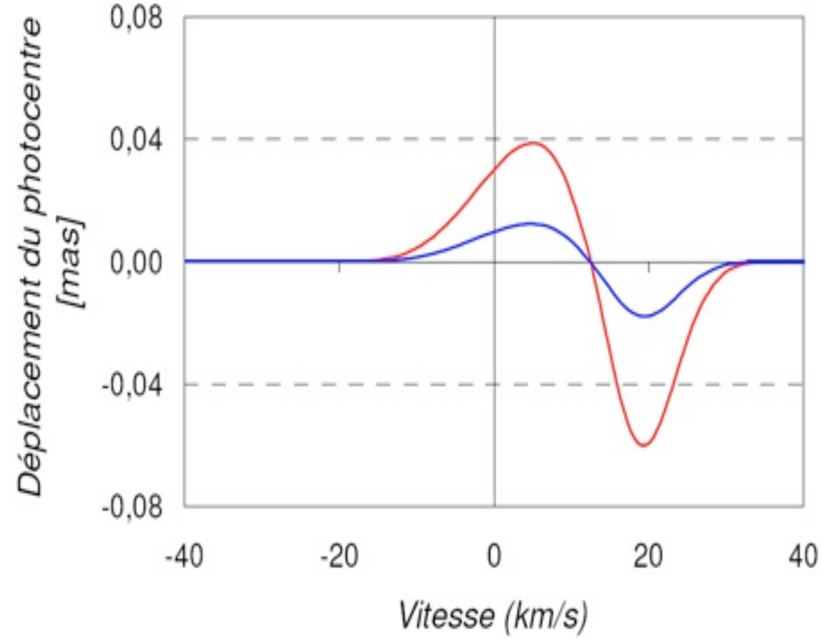


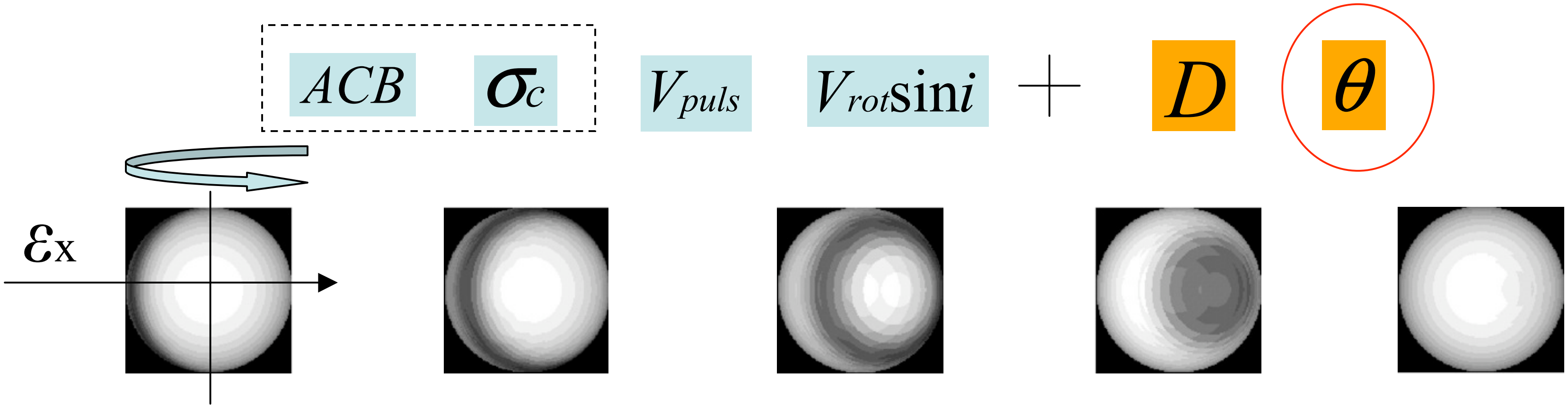

ACB
σ_c
V_{puls}
$V_{rot}\sin i$
$+$
D
θ
εx



A : 0.05 à 0.15 of continuum

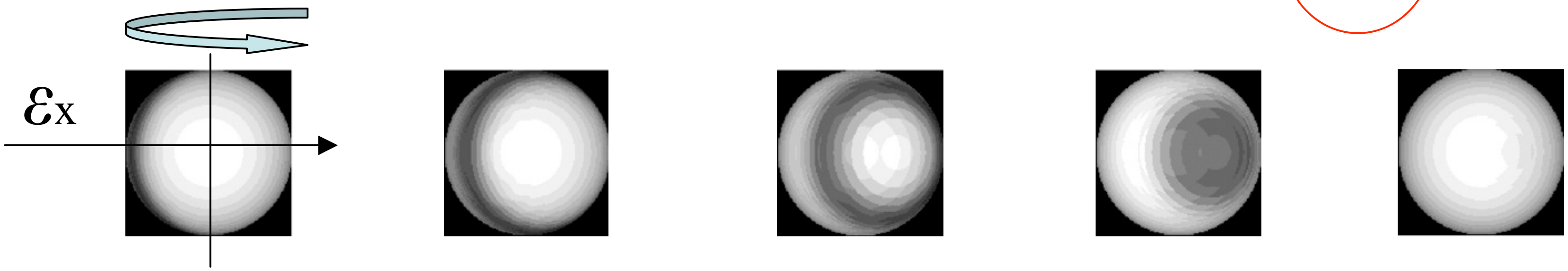




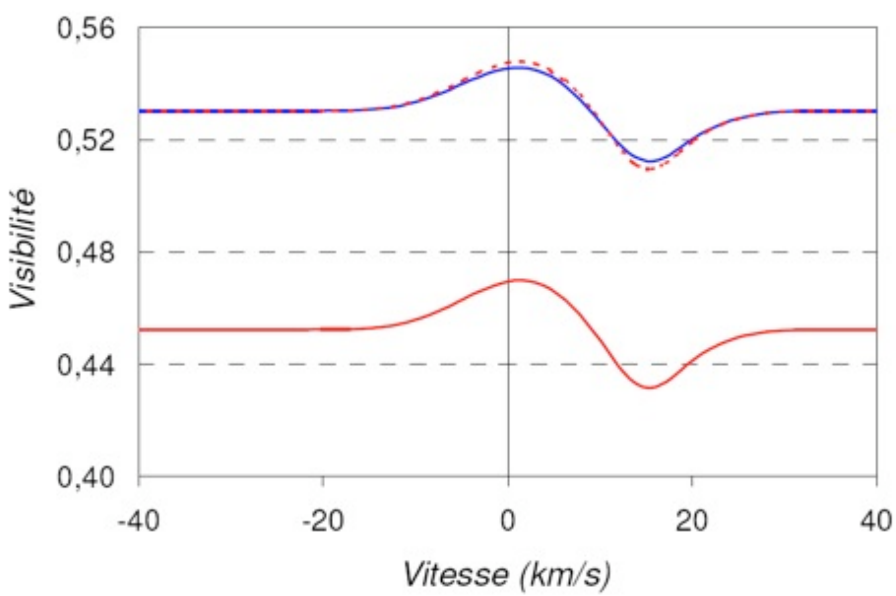


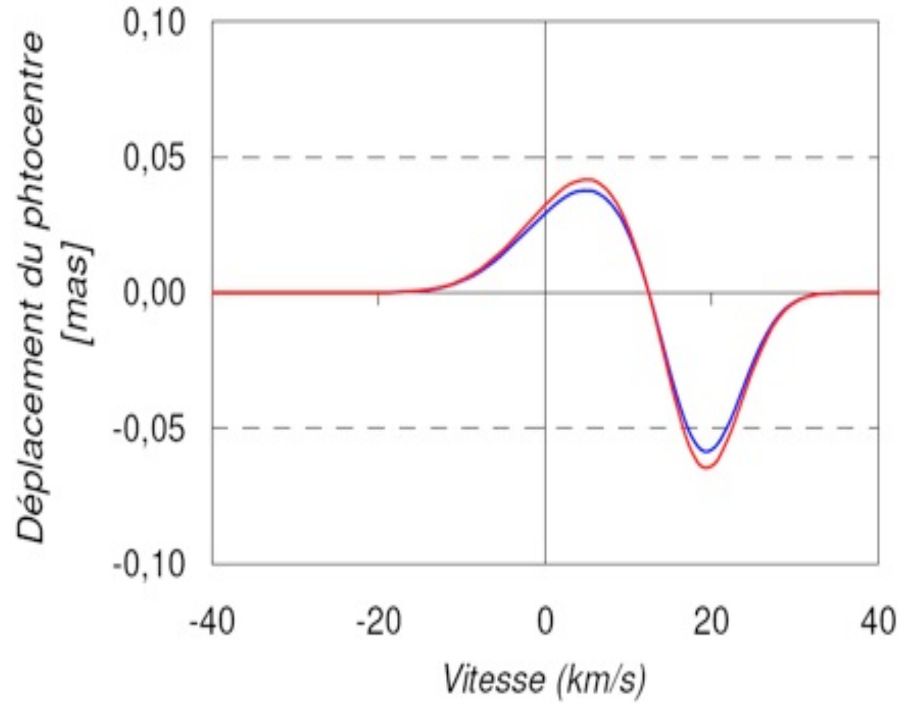
ACB
σc
Vpuls
Vrot sini
+
D
θ
εx

ACB σ_c V_{puls} $V_{rot}\sin i$ + D θ



θ 1.38 mas & 1.53 mas (10%)





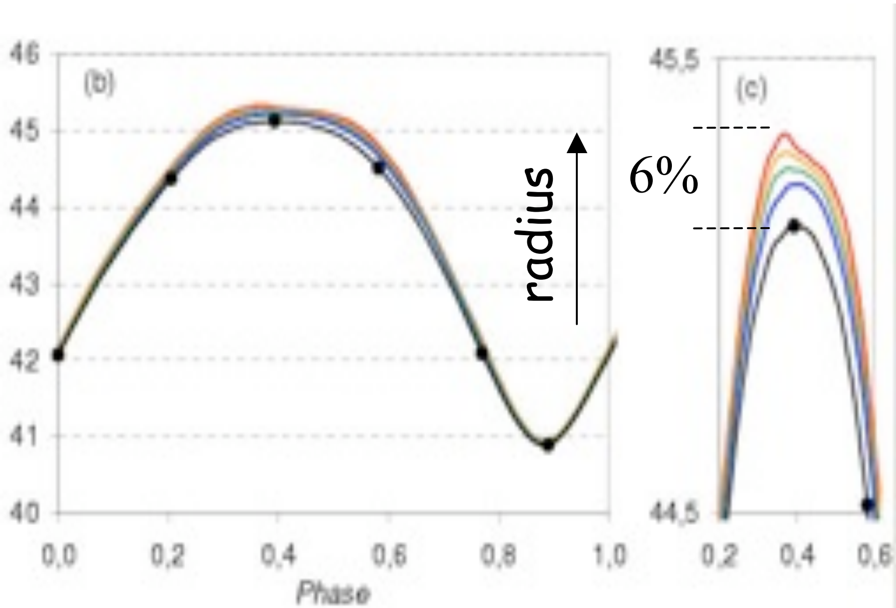
Precision at 1 μm &, B=200m : 1 μas (AMBER/VLTI)

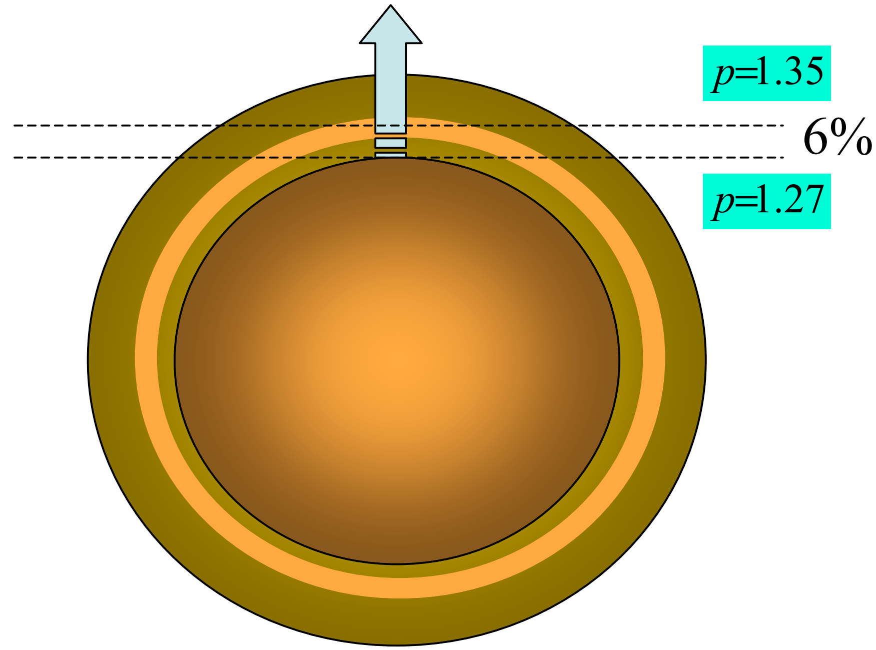
Precision at 0.6 μm &, B=300m : 0.5 μas (VEGA/CHARA)

Perspectives : spectro-interférométrie

« Probing the dynamical structure of Cepheid's atmosphere »

N. Nardetto, F. Fokin, D. Mourard, Ph. Mathias, 2005, A&A, 454, 327





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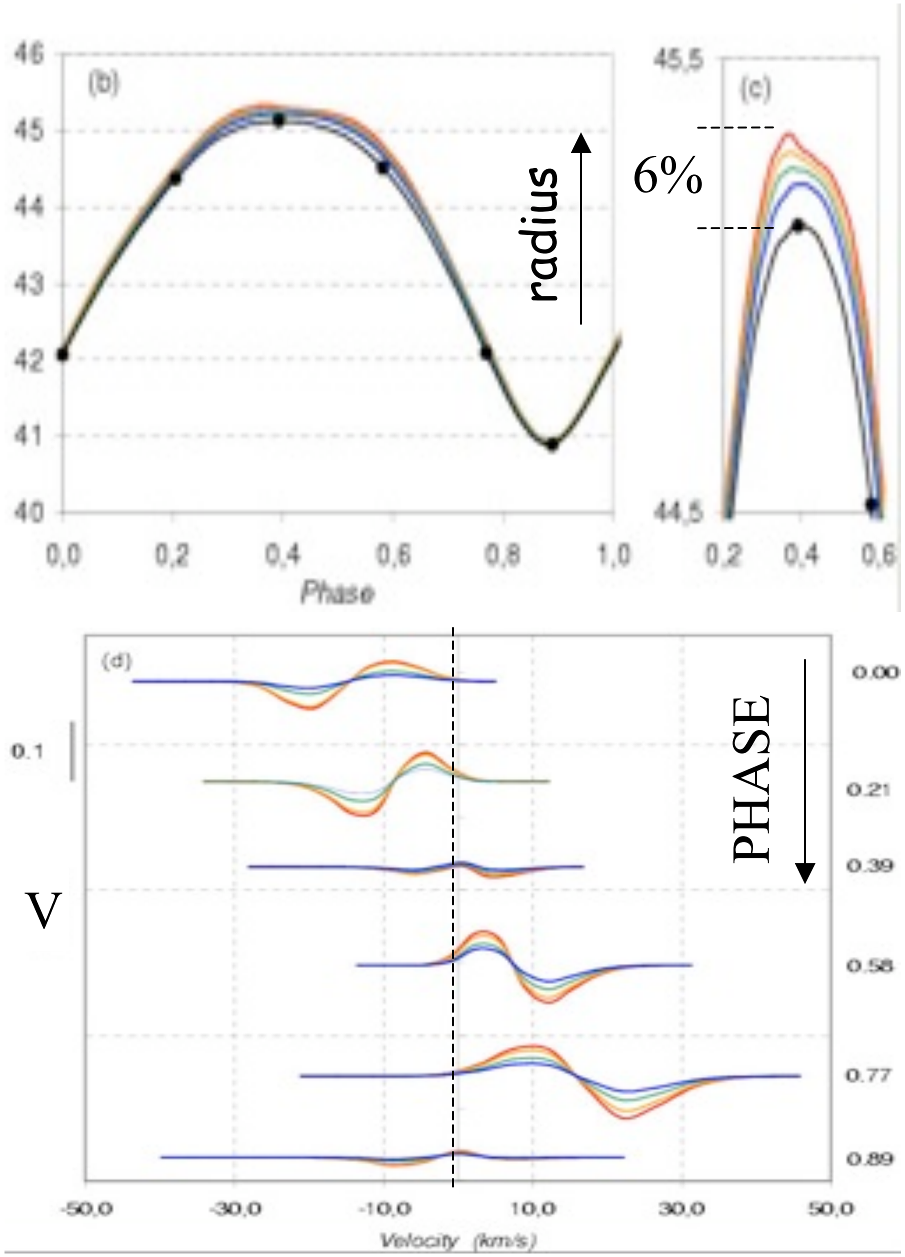
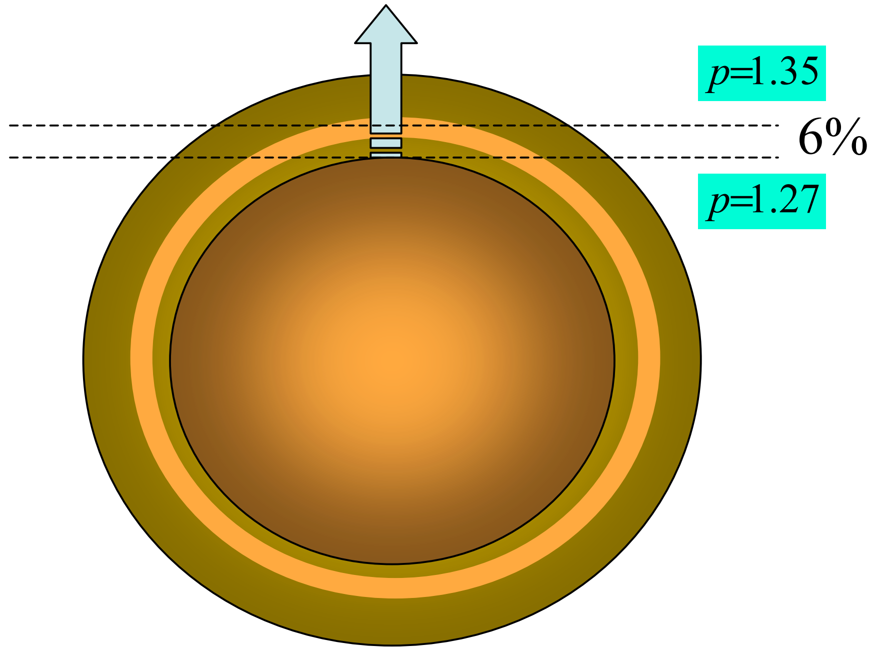




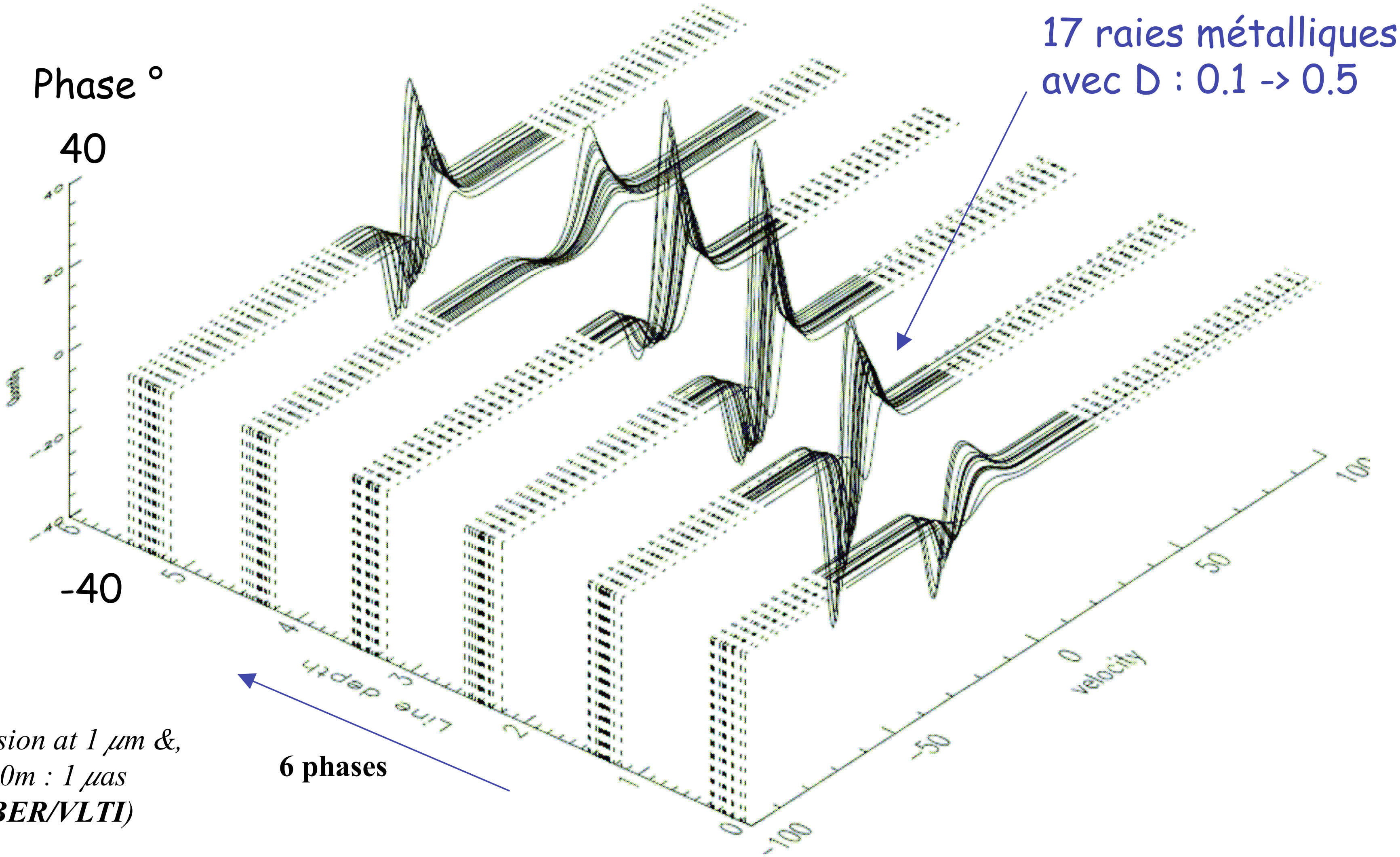
Conclusion:

PHYSIQUE DES CEPHEIDES

↓

DISTANCES GALACTIQUES & EXTRAGALACTIQUES
CONSTANTE DE HUBBLE

p-facteur & spectro-interférométrie(3/3)



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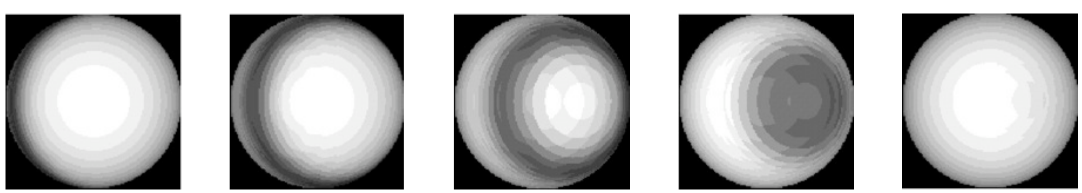
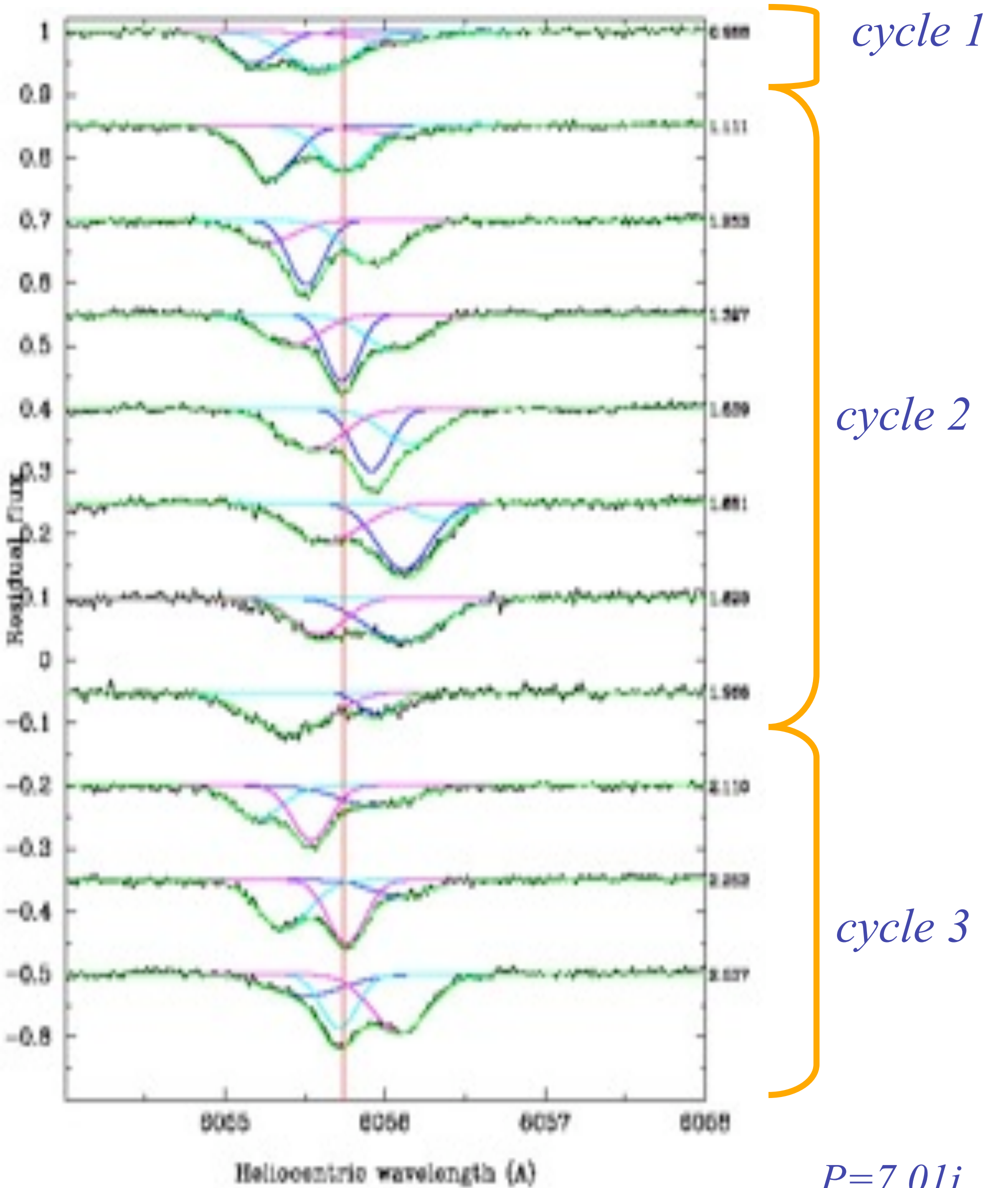
Precision at 0.6 µm &, B=300m : 0.5 µas ***(VEGA/CHARA)***



Le cas atypique de X Sgr

Multiple shock waves in the atmosphere of the Cepheid X Sagittarii?

Mathias, P.; Gillet, D.; Fokin, A. B.; Nardetto, N.; Kervella, P.; Mourard, D., A&A, 2006, 457, 575



P=7.01j

Le cas atypique de X Sgr

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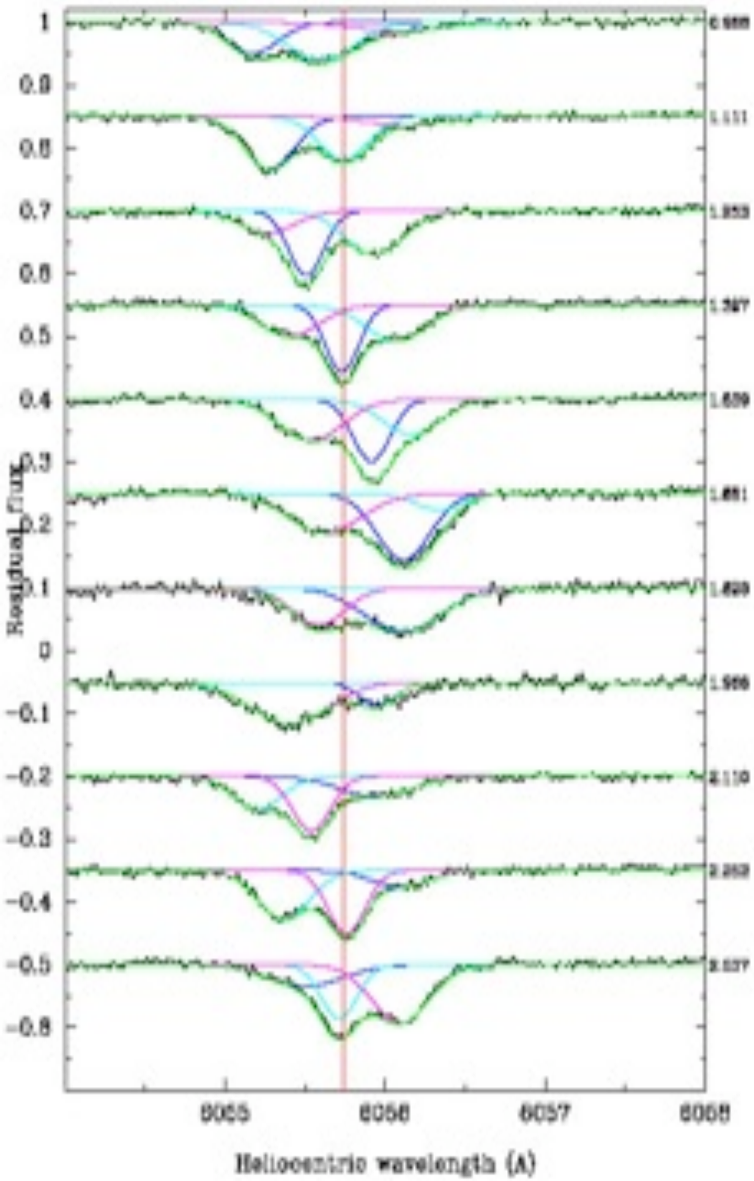
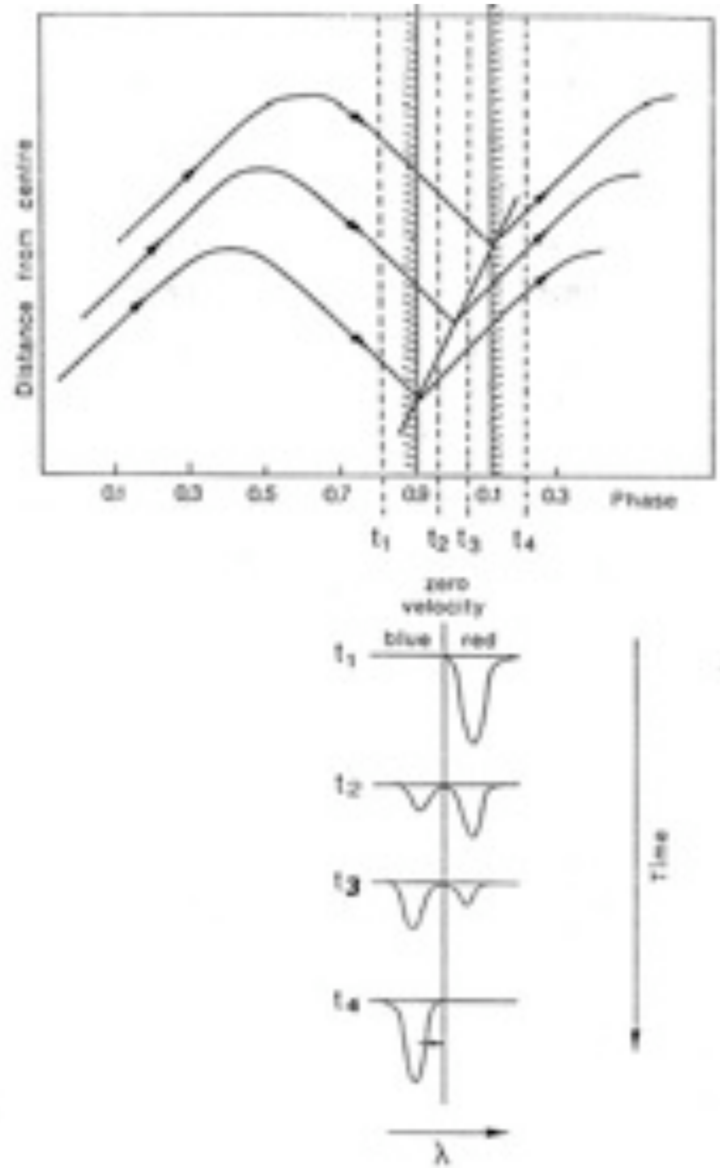


cycle 1

cycle 2

cycle 3

P=7.01j



OBERVATIONS versus MODELISATION : perspectives

2. Asymétrie des raies métalliques non expliquée

P-«dynamique atmosphérique»

- **Grille adaptative**: Vienne
- **Convection**: Lyon, Vienne

1. Profils d'hydrogène non expliqués

P- «perte de masse»
P-«env. circumstellaire»

- **Modélisation de l'enveloppe circumstellaire**

Physique des Céphéides

Extension aux **étoiles pulsantes** du diag. HR

- **Transfert radiatif hors-ETL…**
Boston, Moscou, …

P-«assombrissement centre-bord»

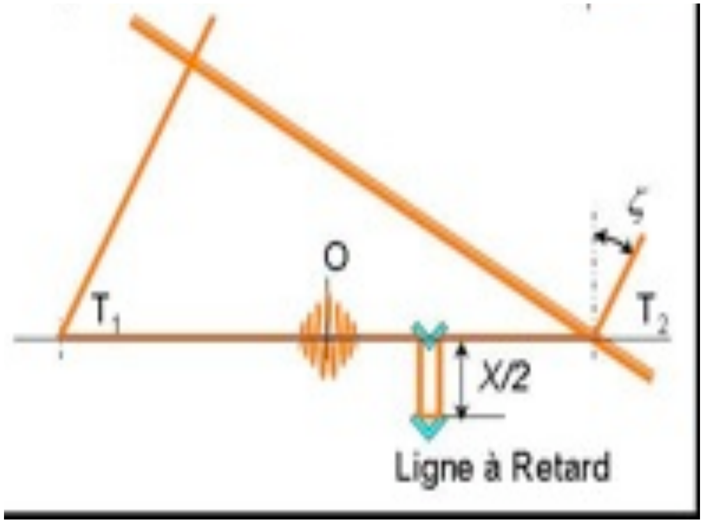
3. Lois d'ACB incompatibles (moyenne et variation)

- **Evolution/pulsation**:
Lyon, Rome, Budapest, Nice (CESAM)

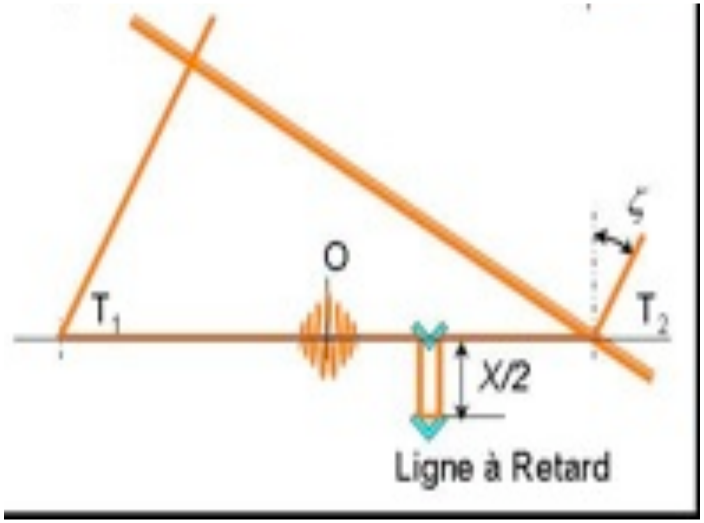
P-«masse»
paramètres fondamentaux

4. Masses incompatibles (10%)

Principe de l'interférométrie



Principe de l'interférométrie

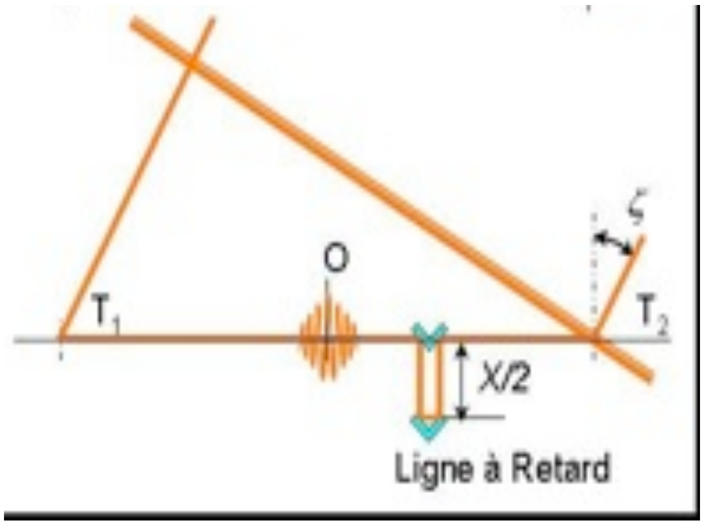


$$I = \left|\Psi_1 + \Psi_2 e^{i\theta}\right|^2$$

$$I = \left|\Psi_1\right|^2 + \left|\Psi_2\right|^2 + 2\Psi_1\Psi_2^* \cos(\theta)$$

$$I = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{\Psi_1\Psi_2^*}{\sqrt{\left|\Psi_1\right|^2\left|\Psi_2\right|^2}} * \cos(\theta)\right)$$

Principe de l'interférométrie



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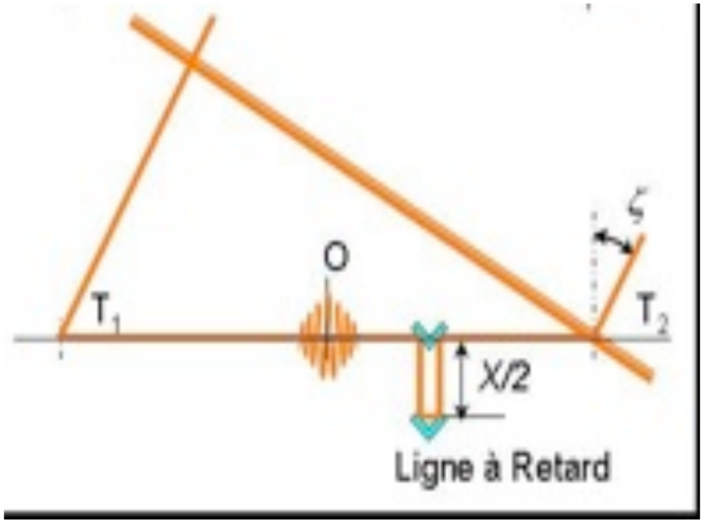
$$\gamma_{12} = \frac{\Psi_1\Psi_2^*}{\sqrt{\left|\Psi_1\right|^2\left|\Psi_2\right|^2}} = \frac{\left|\tilde{O}\left(\frac{B}{\lambda}\right)\right|}{\left|\tilde{O}(0)\right|}$$

Principe de l'interférométrie



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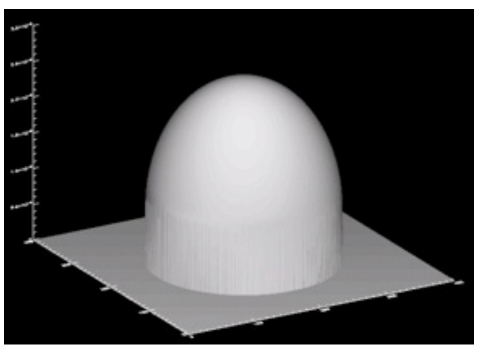
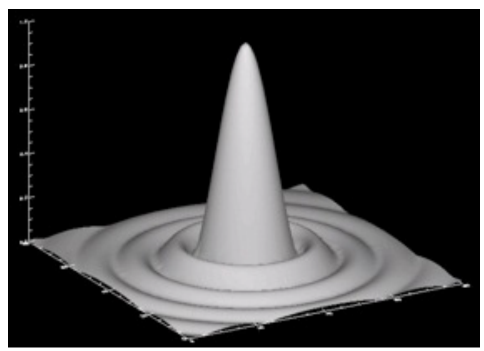


|TF|



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θ PHOTOSPHERE

ACB