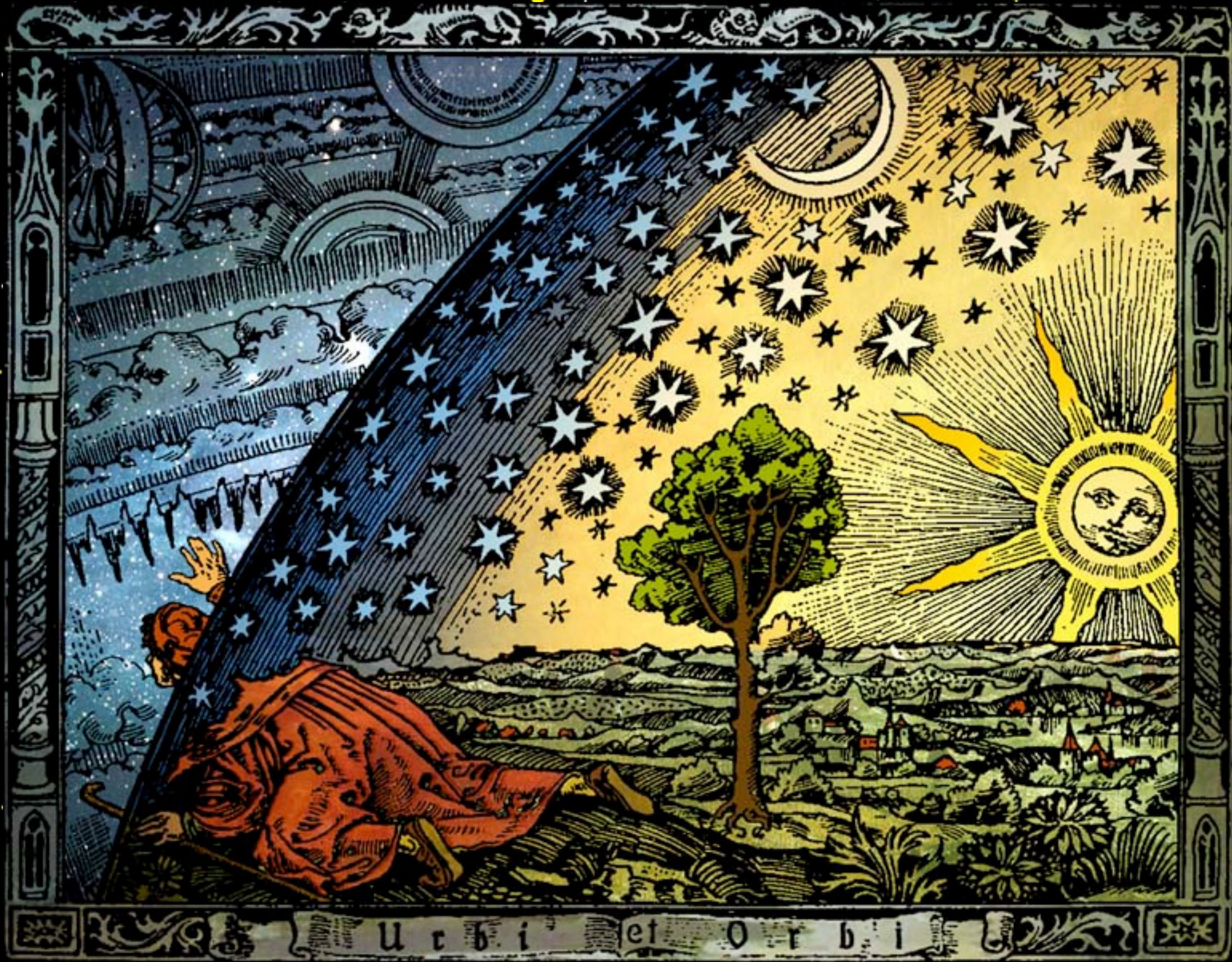
Calibration of the distance scale in the universe

(and interferometry ...)



N. NARDETTO - école VLTI (Barcelonnette, Sept. 2013)


www.picturalissime.com
Vincent Van Gogh la Nuit étoilée

The sky is 'like a painting' i.e. without third dimension

Outlines

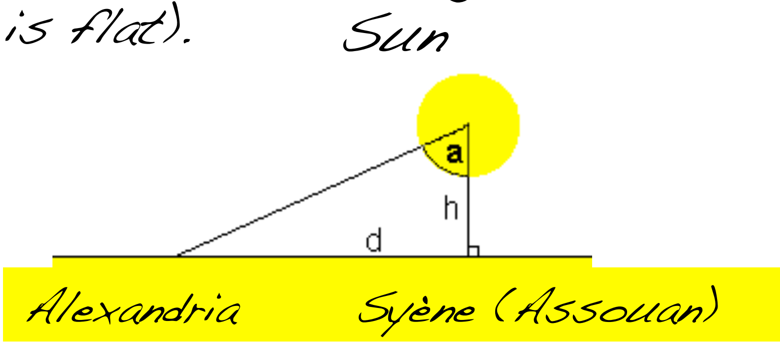
1/ The distances in the Universe (overview)

2/ The interferometric and photometric version of the Baade-Wesselink method of the distance determination of Cepheids

3/ What can bring interferometry to the Eclipsing Binary method of distance determination ?

Brief history of measuring distances...

1/ In 420-430 before JC, the Greek Philosopher Anaxagore tried to measure the distance to the Sun (but made the wrong assumption that the earth is flat).

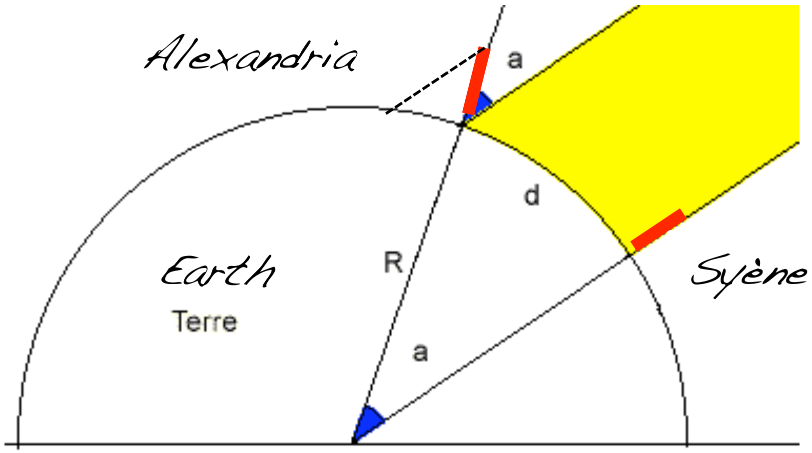


$$\tan(a) = d/h$$

$$h = 800/(\tan 7°) = 6515km$$

$$\theta_{sun} = 6515 * \tan(0.5°) = 57km$$

2/ Using the same method (but considering the curvature of the earth), Erathosthène (-276, -194) found the radius of the earth with an error of 2.5% only!

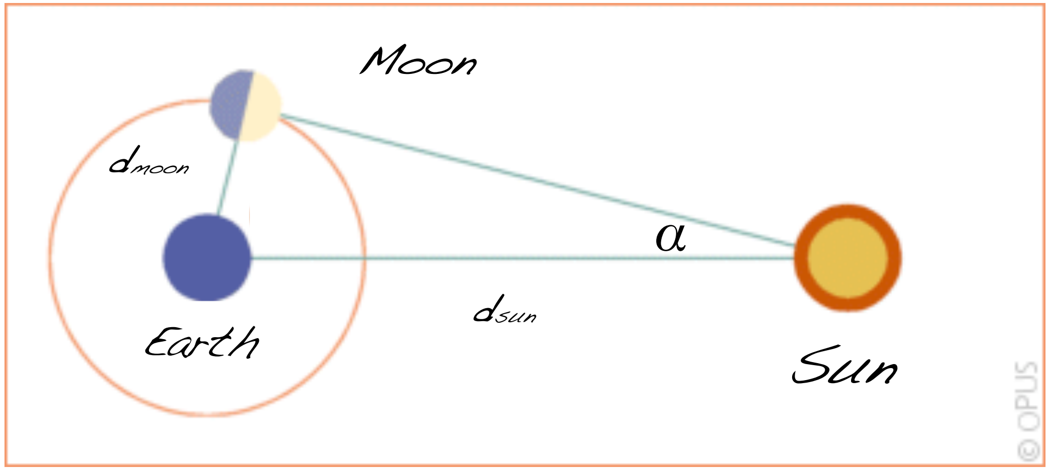


$$R = d/2 * \tan(a/2) = 400/\tan(3.5°)$$
$$= 6540km$$

The story continues slowly...

3/ Hipparque derived the distance Sun-Moon in 150 before JC using a solar eclipse

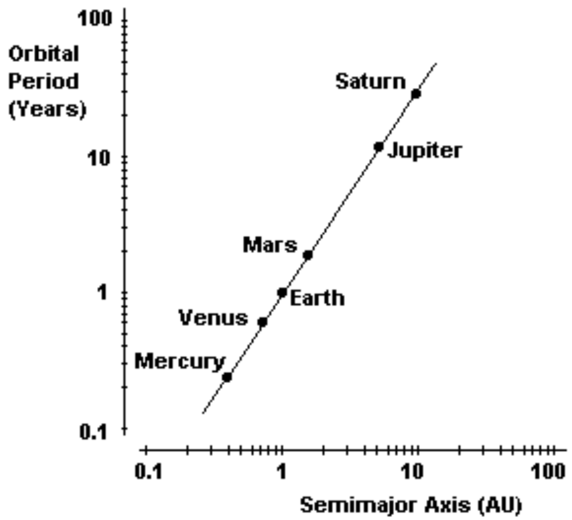
4/ IIIe century before JC, Aristarchus of Samos (-310, -230) found the distance between the Earth and the Sun using the half-moon.



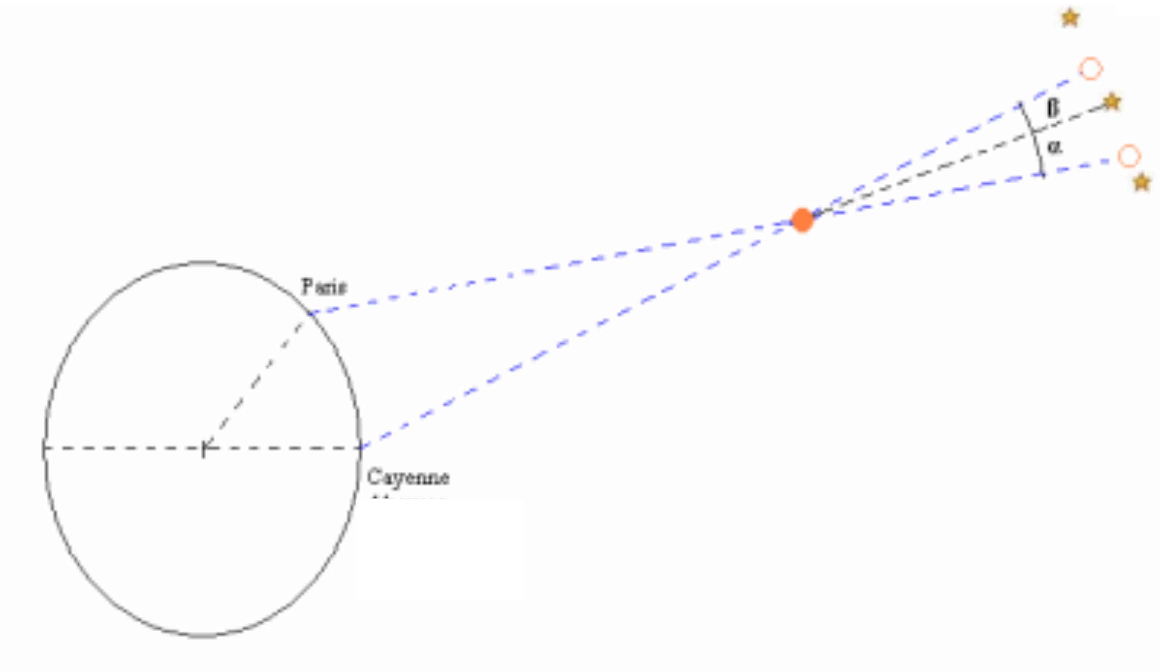
$$\sin(\alpha) = \frac{d_{moon}}{d_{sun}} \approx 19$$

Instead of 400

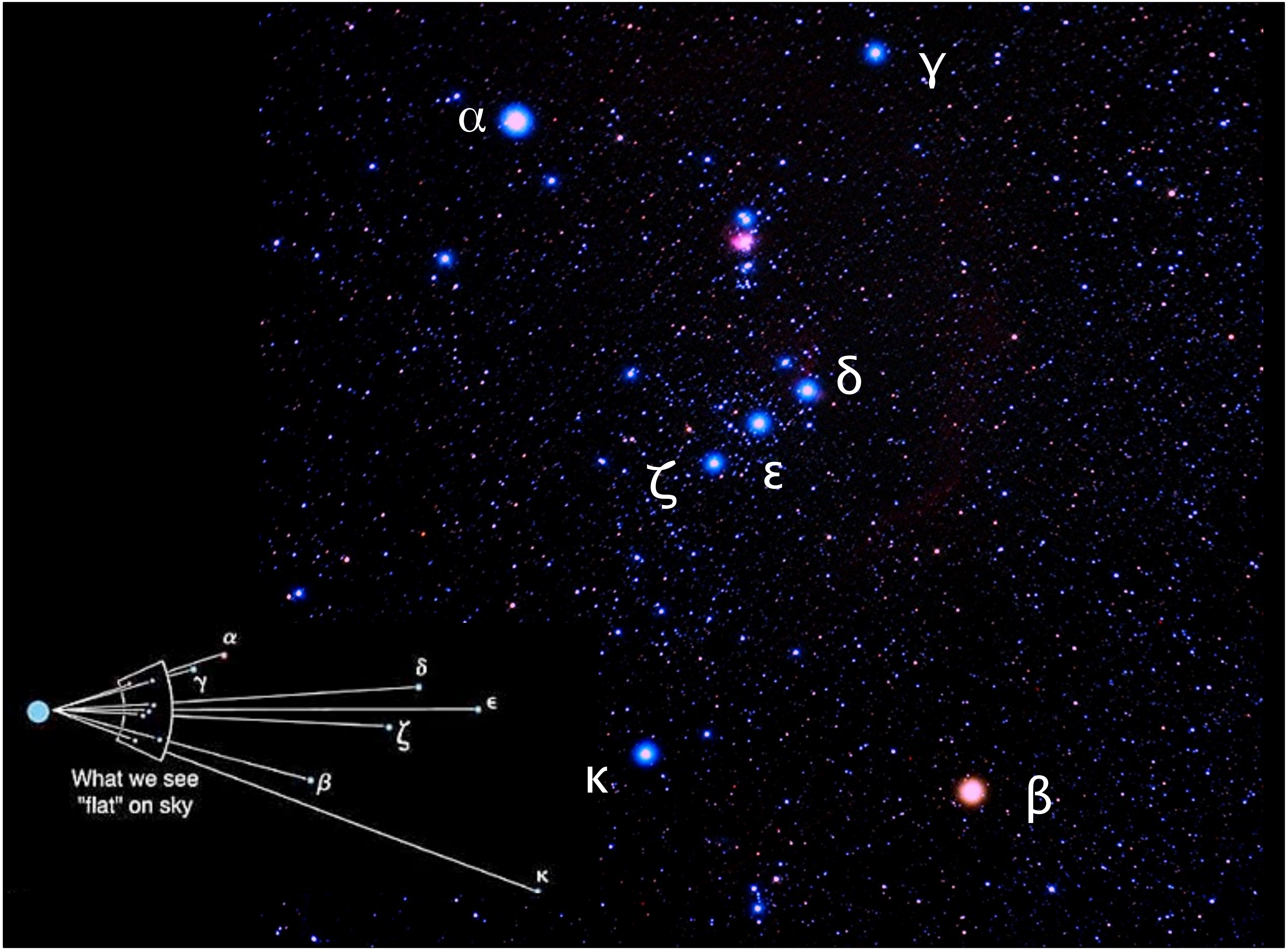
5/ Then in 17th century, the third law of Kepler (T^2/a^3=cste) was used to derive the relative distance to the planets.



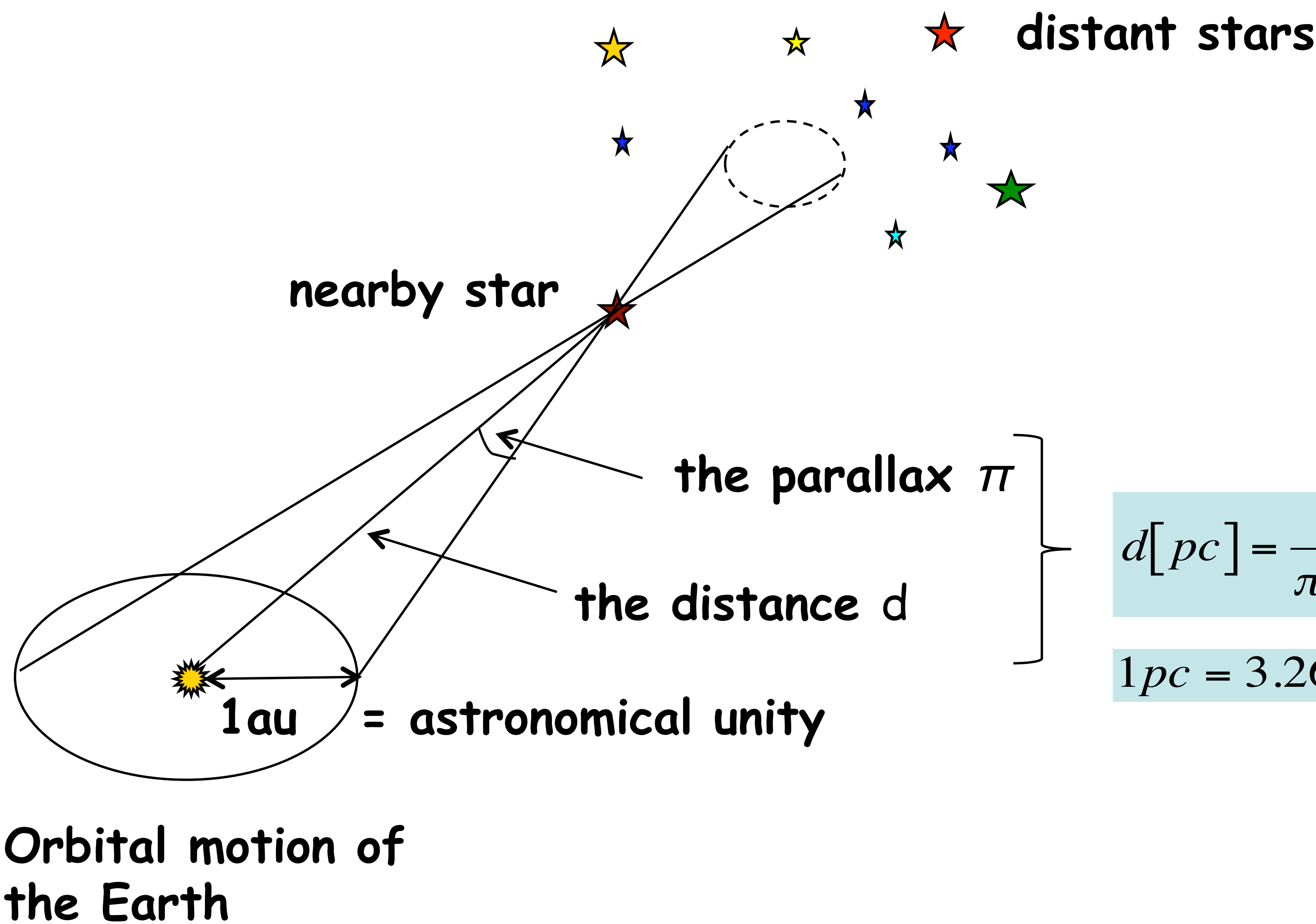
6/ The Earth-Mars distance is derive by Cassini and Richer in 1672 by measuring the parallax of Mars. Then, all the distances of planets follows with the Third Kepler law.



7/ Friedrich Wilhelm Bessel (22 July 1784 – 17 March 1846) was a German mathematician, astronomer, who first measured the parallax of a star (61 Cyg) in 1838. He found π=0.314 (!) which corresponds to a distance of 3.18 parsecs. The actual value is 0.286 (or 3.50pc).


α
γ
δ
ζ
ε
κ
β
What we see
"flat" on sky
α
γ
δ
ε
ζ
β
κ

The trigonometric parallax



$$d[pc] = \frac{1}{\pi['']}$$

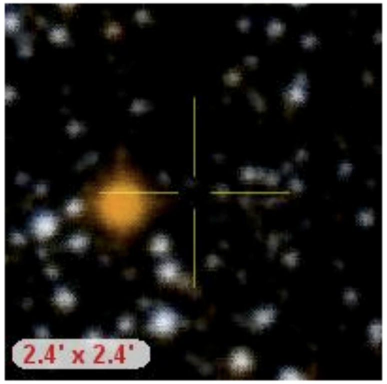
$$1pc = 3.26al.$$

Example : proxima Centauri on SIMBAD

http://simbad.u-strasbg.fr/simbad/sim-fid

V* V645 Cen -- Flare Star

query around with radius 2 arcmin



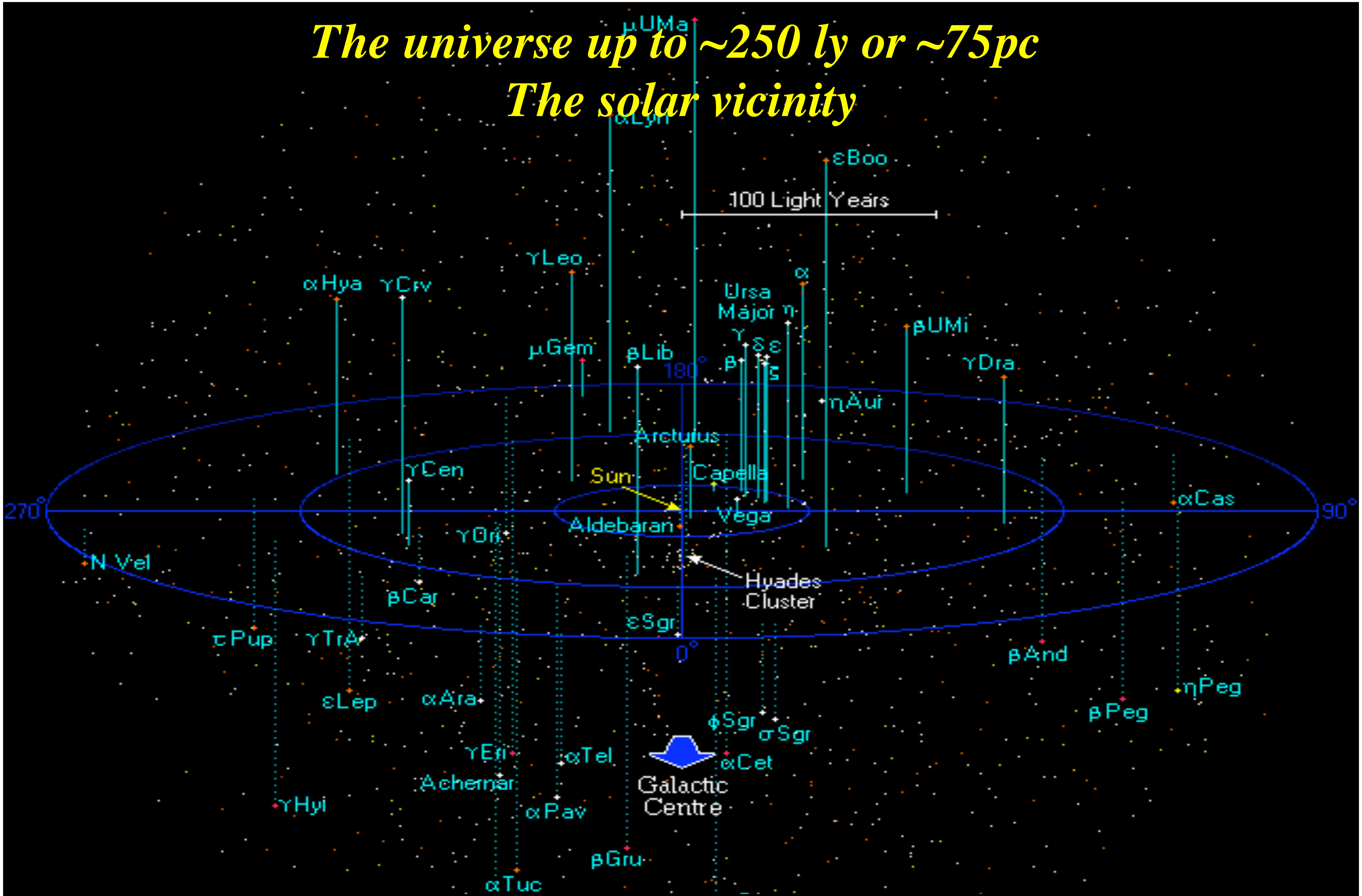
Other object types:	EB* () ,* (*,CSI,GEN#,GJ,HIC,HIP,JP11,LPM,PLX,PMSC,Zkh,[AOP94],[RHG95]) , X (1E,2E,1ES,RE,RX,1RXS,[FS2003]) ,PM* (Ci,LFT,LHS,LTT,NLTT,PM) ,UV (2EUVE,EUVE,2RE) ,** (CCDM,WDS) ,V* (V*,CSV) ,IR (IRAS,2MASS) ,Fl* ([GKL99])
ICRS coord. (ep=J2000) :	14 29 42.94853 -62 40 46.1631 (Optical) [17.66 14.33 90] A 2007A&A...474..653V
FK5 coord. (ep=J2000 eq=2000) :	14 29 42.949 -62 40 46.16 (Optical) [17.66 14.33 0] A 2007A&A...474..653V
FK4 coord. (ep=B1950 eq=1950) :	14 26 18.98 -62 28 04.2 (Optical) [102.04 82.75 0] A 2007A&A...474..653V
Gal coord. (ep=J2000) :	313.9399 -01.9271 (Optical) [17.66 14.33 0] A 2007A&A...474..653V
Proper motions *mas/yr* [error ellipse]:	-3775.75 765.54 [1.63 2.01 0] A 2007A&A...474..653V
Radial velocity / Redshift / cz :	V(km/s) -22.4 [0.5] / z(~) -0.000075 [0.000002] / cz -22.40 [0.50] (~) C 2006A&A...460..695T
Parallaxes *mas*:	771.64 [2.60] A 2007A&A...474..653V
Spectral type:	M6Ve C 2006A&A...460..695T
Fluxes (5) :	B 13.02 [~] C ~ V 11.05 [~] C ~ J 5.357 [0.023] C 2003yCat.2246....0C H 4.835 [0.057] C 2003yCat.2246....0C K 4.384 [0.033] C 2003yCat.2246....0C

Proxima Centauri has a parallax of 0.77164'' which corresponds to a distance of ~1.29pc or ~4.22 a.l.

The Hipparcos Satellite (Perryman et al. 1997, A&A, 323, 49 ; van Leeuwen 2007, A&A, 474, 653) has measured the parallax of about 100000 nearby stars with a precision of 0.001'' (V<9).

- *Proxima Centauri has a precision on the Hipparcos parallax measurement of 0.3%*
- *A star at **300pc** has a precision on the Hipparcos parallax measurement 0.001''/(1''/300) = ~**30%***
- *A star at **1000pc** has a precision of **100%***
- *A star at **150pc** has a precision of ~**15%***

The universe up to ~250 ly or ~75pc
The solar vicinity



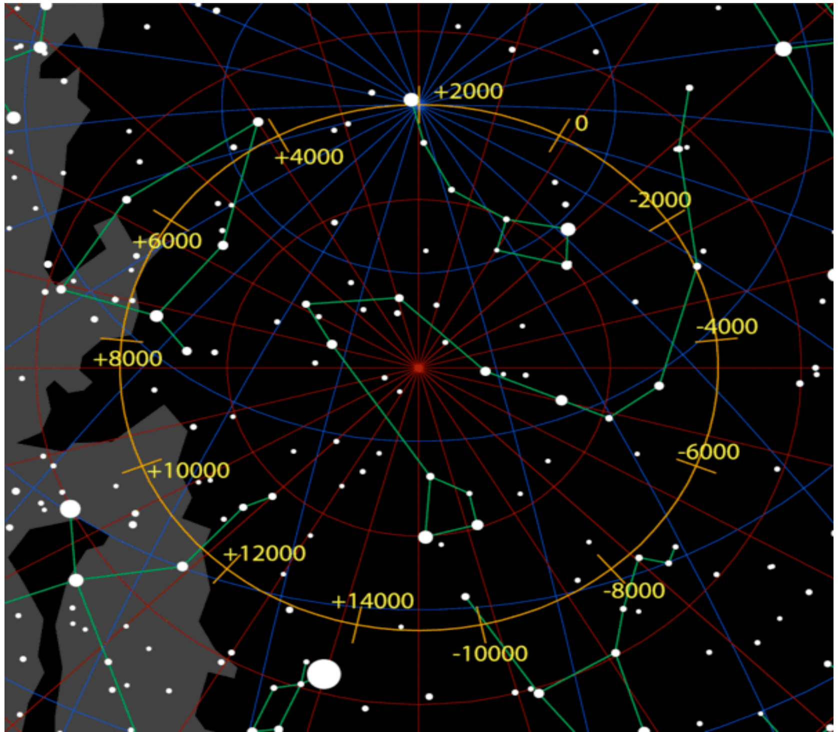
Trigonometric parallax

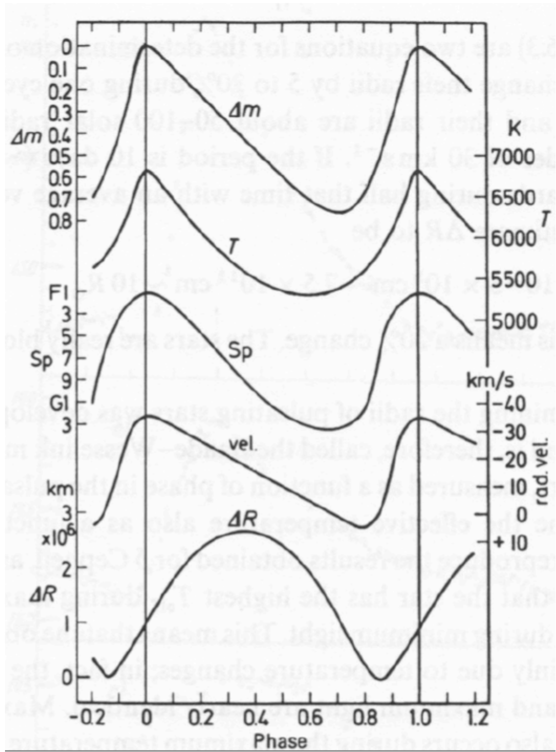
HIPPARCOS Satellite - d<150pc, 6000 stars (seen by eye), precision of ~15%

r powell

1784 : Discovery of the first Cepheid δ Cephei

John Goodrick (1764-1786)

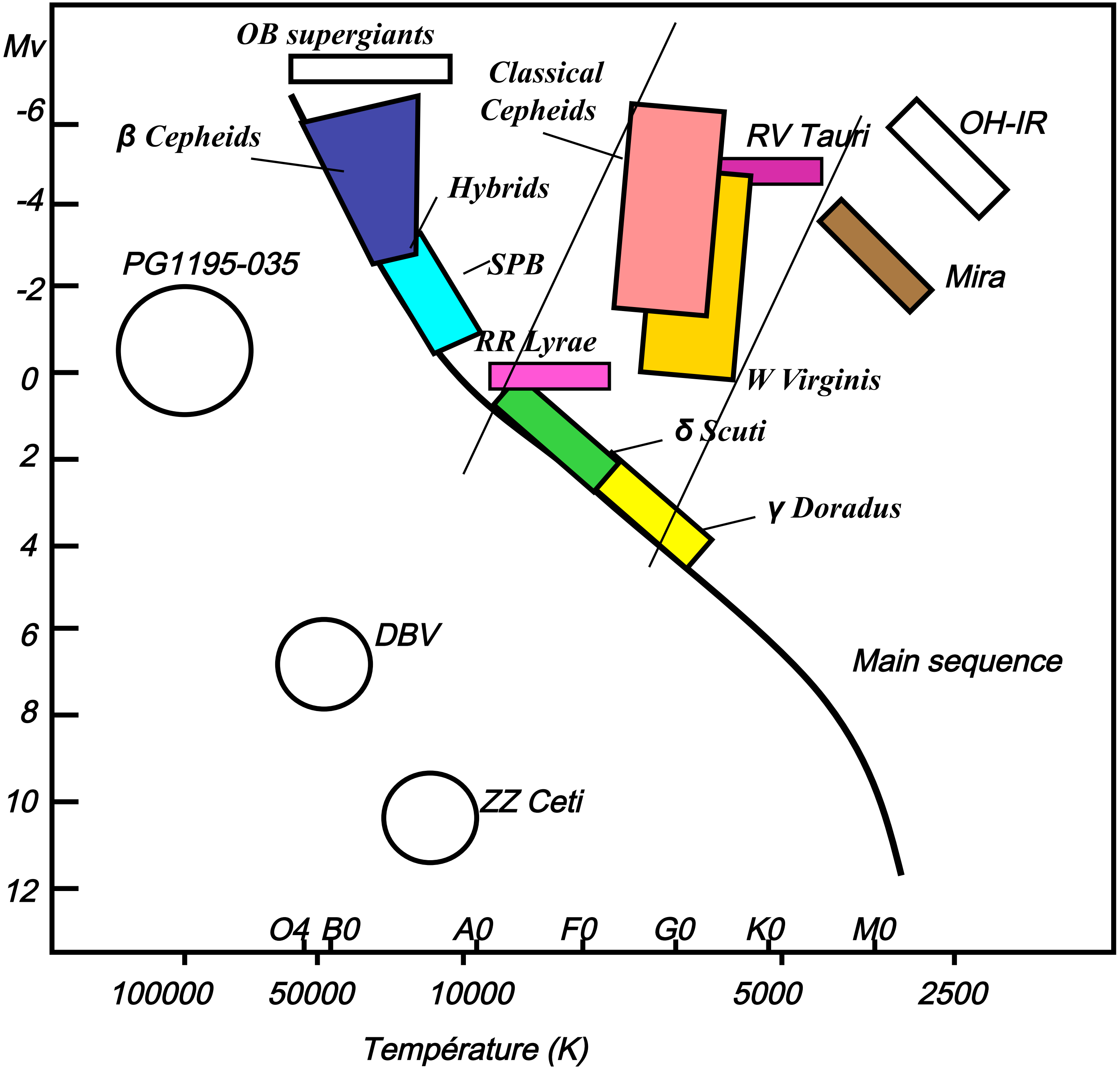




M=5 Ms	(4 to 15Ms)
R=41.6 Rs	(10 to 300Rs)
L=2000 Ls	(100 to 100000Ls)
Teff=5500-6800 K	(5000-8000K)
Spectral Type=F51ab	(F5 to K2)
P=5.36 days	(1 to 135 days)
DR/R=10%	

Pulsation: kappa-mechanism (opacity effect)

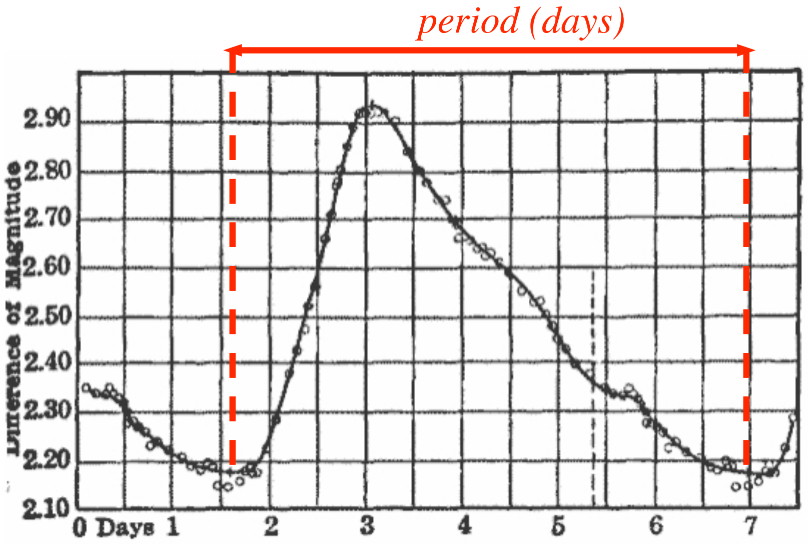
Pulsating stars in HR diagram



Cepheids ar evolved stars (thus bright) but rare: 500 identified Cepheids in the WM (probably 9000 in total).

1912 : Discovery of the period-luminosity relation (PL)

16 Cepheids in Large Magellanic Cloud



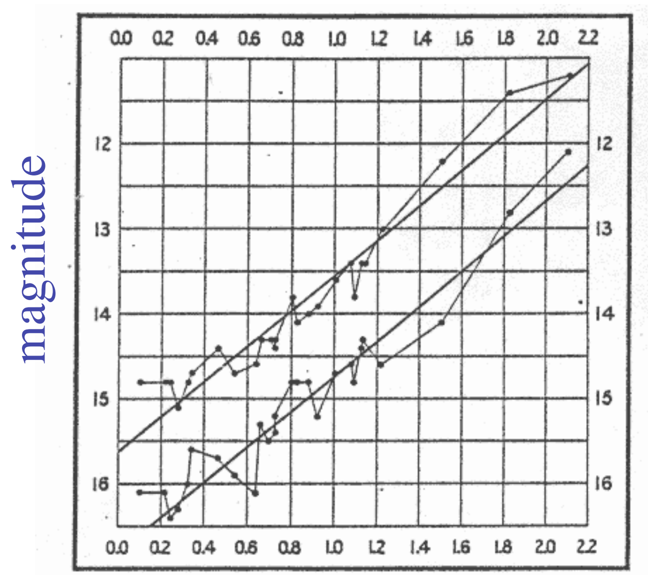
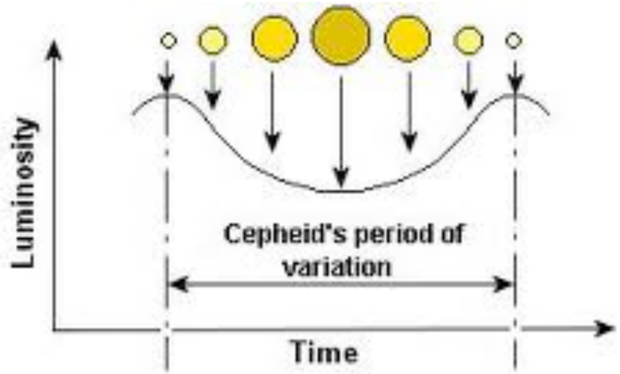


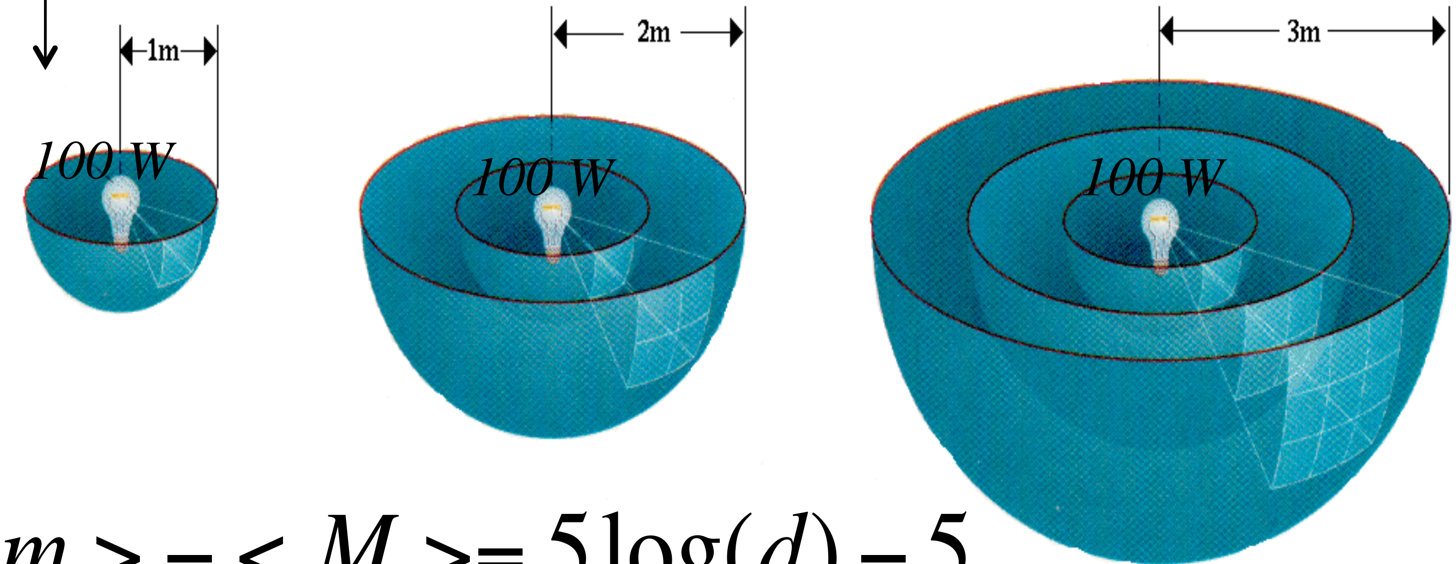
Fig. 2.

H. Leavitt *(1868-1921)*

How do we use the Period-luminosity relation ?

$$< M >= a(\log(P) - 1) + b$$





$$< m > - < M >= 5\log(d) - 5$$

The calibration of the Period-Luminosity relation

$$m - M = 5\log d - 5$$

$$M = a(\log P - 1) + b$$

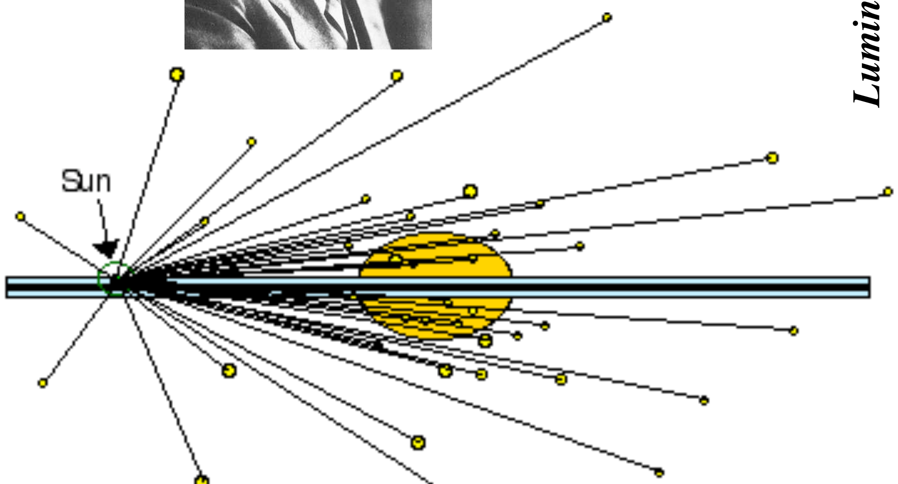
the slope and the zero-point are fitted
This is an empirical relation

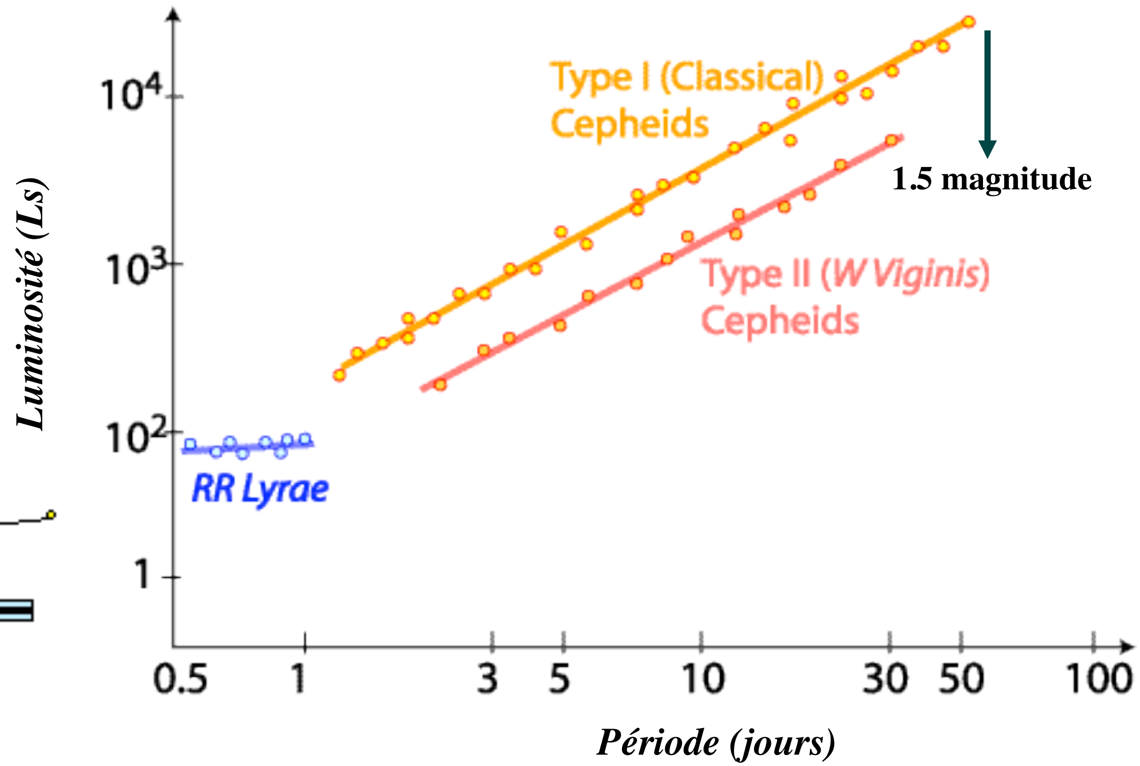
In summary, in order to calibrate we need to derive
the distance of nearby Cepheids using independent methods

Calibration of the period-luminosity relation

Hertzsprung (1913) : secular parallax (motion of the Sun within the Milky Way) for 13 nearby Cepheids. He calibrated the relation, but put the distance of the stars 10 times closer (typo !?). He derive the distance to SMC using this relation.

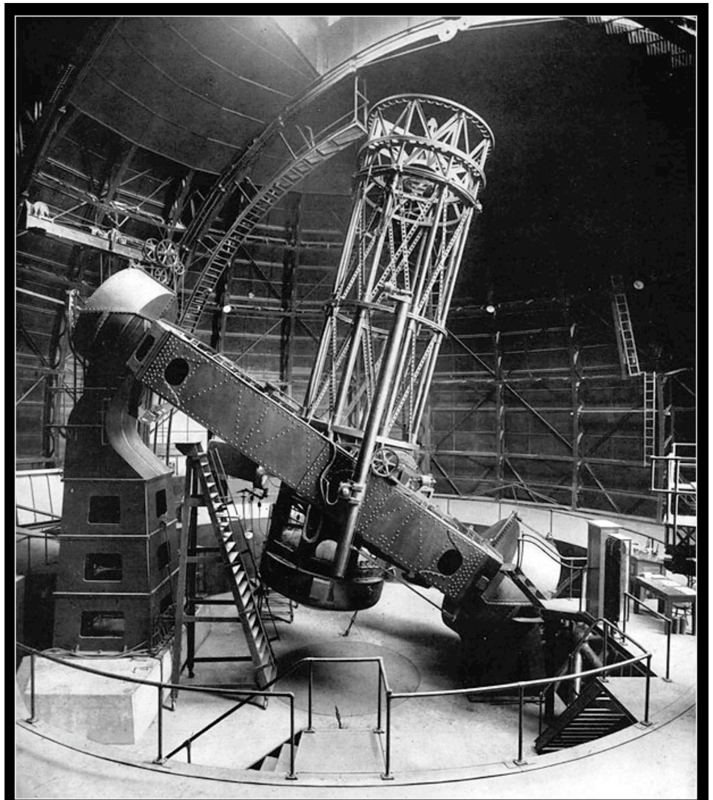
Shapley (1920) : he calibrated of the Period-Luminosity for type 1 Cepheids but made a mistake of 1.5 magnitude because of the extinction. By an extraordinary coincidence he provides a calibrated PL relation consistent for type 2 Cepheids (or W Virginis) !!



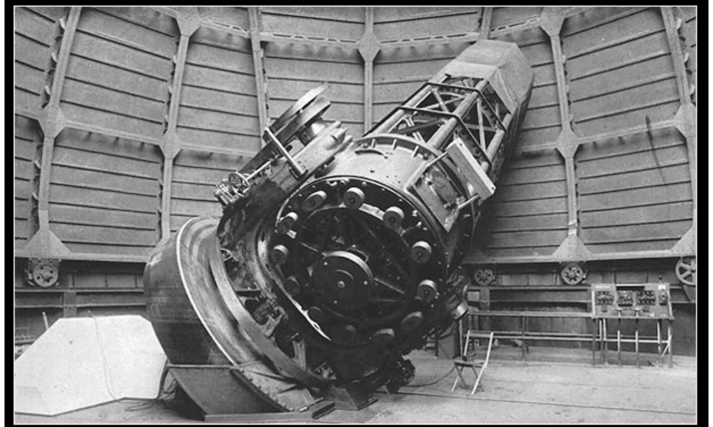


However, using (W Virginis+RR Lyrae) in globular clusters, Shapley shows that the sun is NOT in the center of the Milky Way !

The distance to the Andromeda galaxy



Le telescope Hooker de 2m56 de l'Observatoire su Mont Wilson.

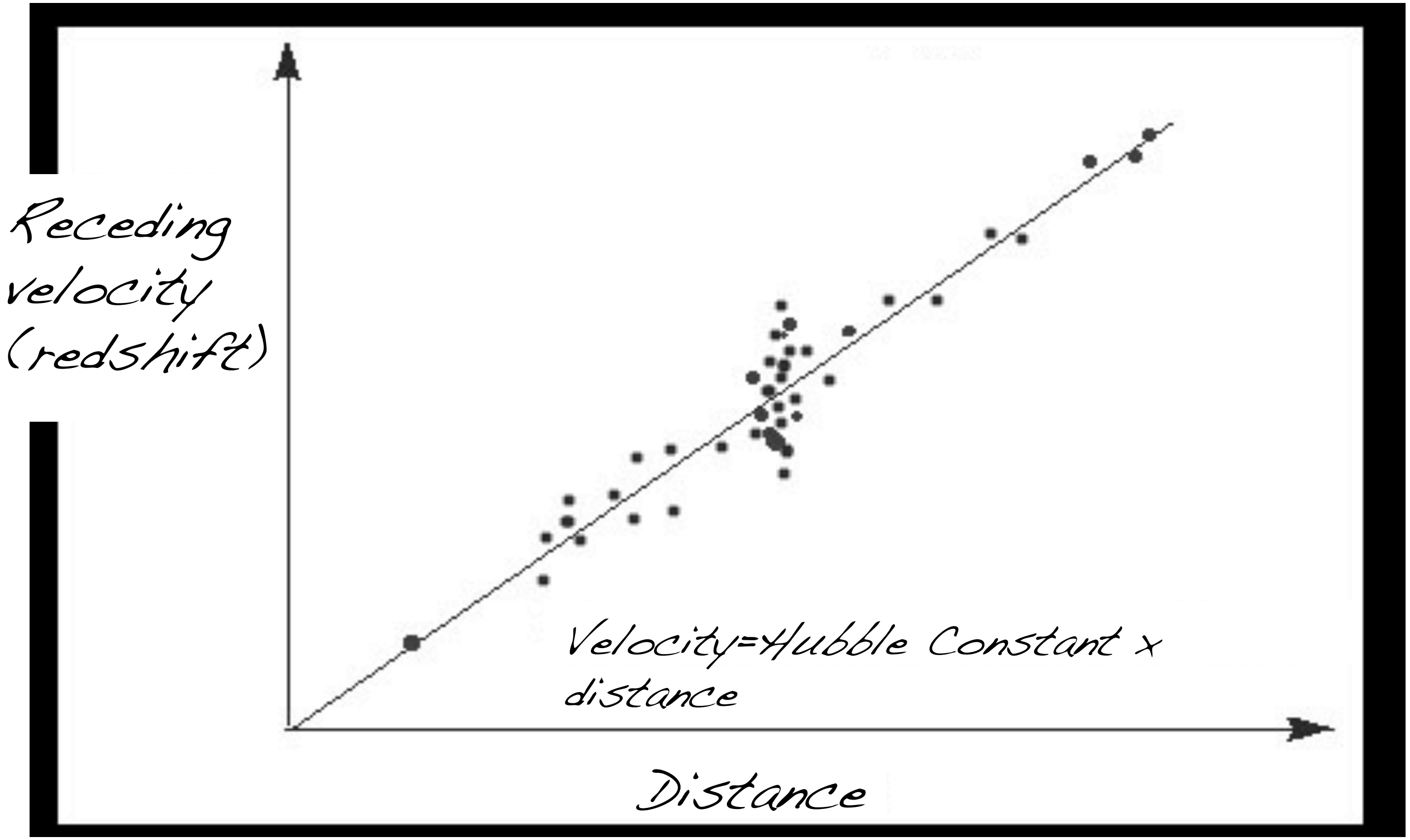


Le telescope equatorial de 1m52 de l'Observatoire du Mont Wilson.

Hubble (1925) : distance to M31, 2 times too close ! He observed type 1 Cepheids but used the Shapley's PL relation (relevant for W Virginis). Great conclusion however, the Milky Way is a Galaxy (as guess already by Kant) !

The CHARA interferometer

The Hubble Law using Cepheids (1929)

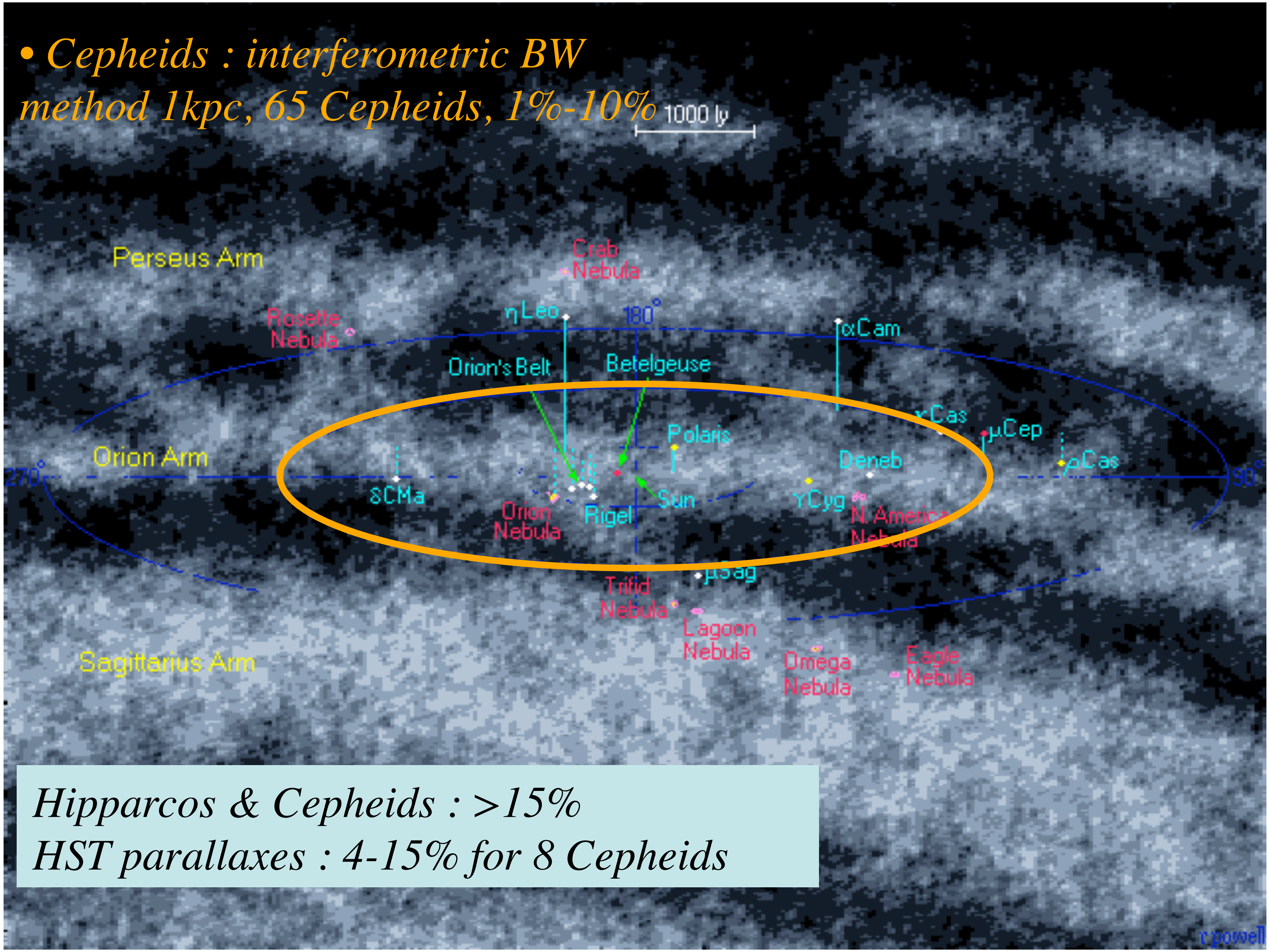


Actually, already mentioned by G. Lemaître in 1927, but published in English only in 1931...

Baade (1944) : first distinction between type 1 and 2 Cepheids (during the black out of 2nd world war)

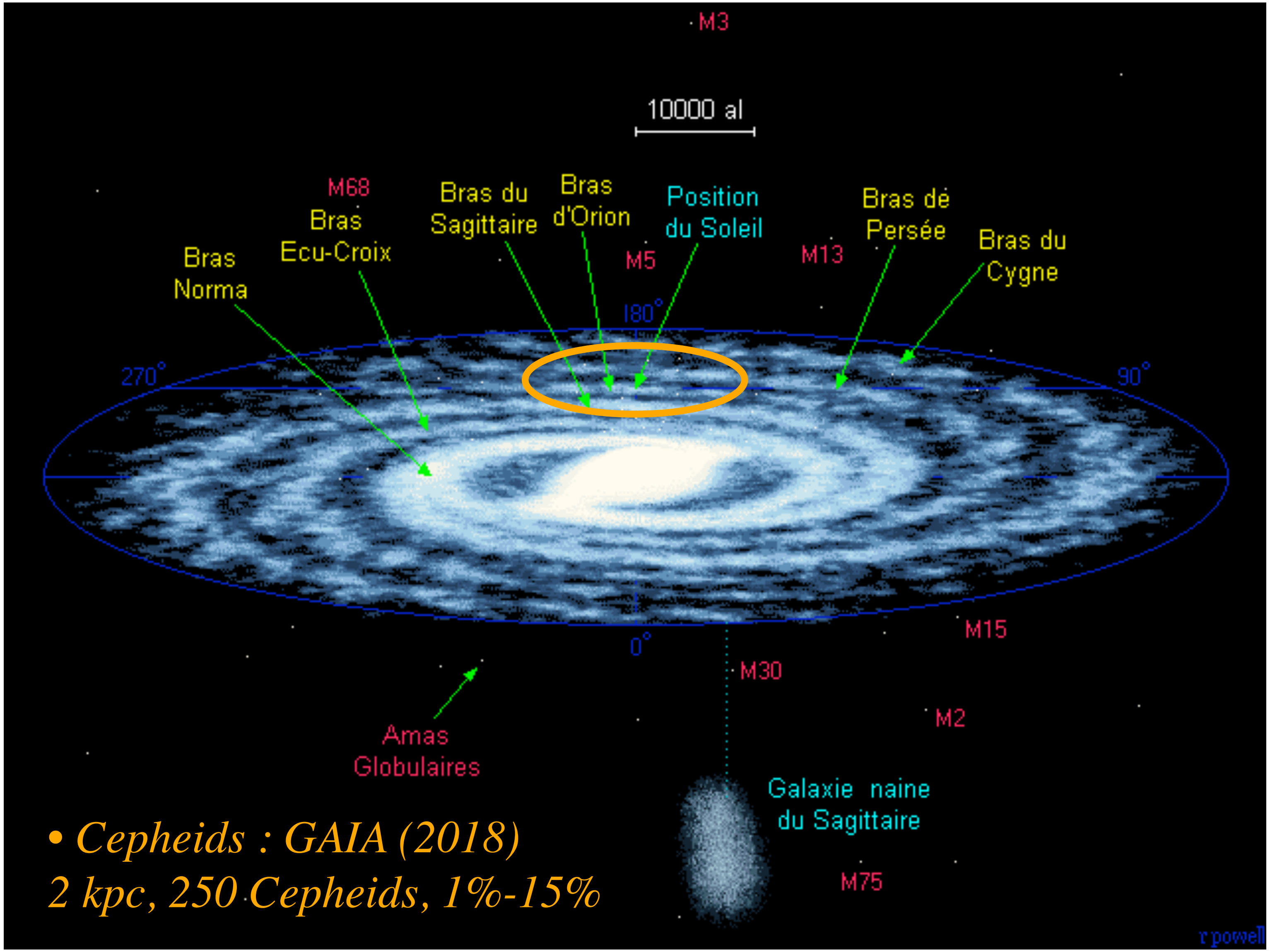
The universe up to 5000ly (or 1.5kpc): The Orion Arms

• Cepheids : interferometric BW method 1kpc, 65 Cepheids, 1%-10%



Hipparcos & Cepheids : >15%
HST parallaxes : 4-15% for 8 Cepheids

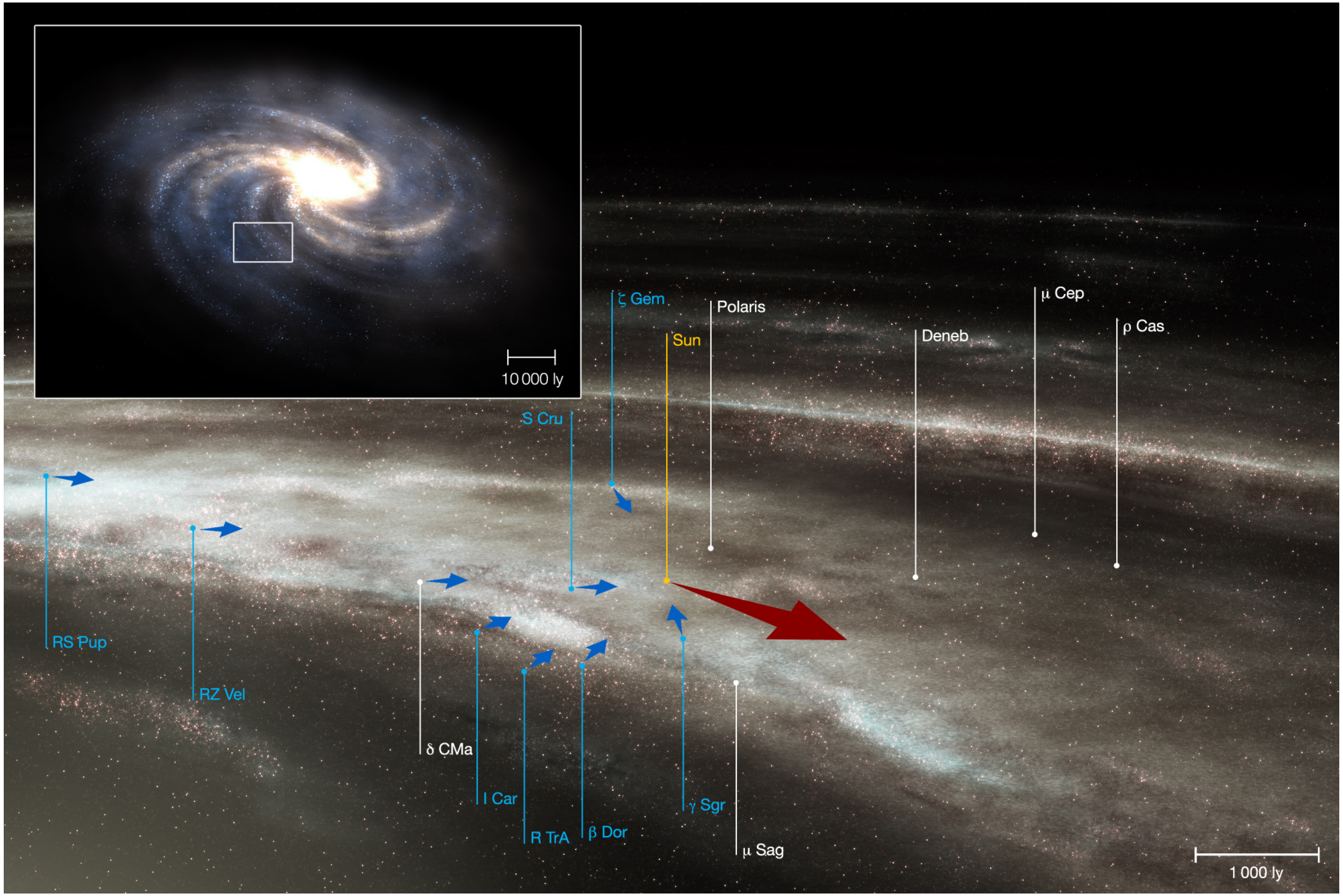
The Milky Way (100000ly or 30kpc)



The GAIA mission : 1 billion of stars (V<20)
Accuracy of 7 µas at V<12, 20 µas at V =15 and 300 µas at V=20 (reminder Hipparcos 1mas at V=9)

The rotation of the Milky Way

The K-term of Cepheids: Joy (1939)



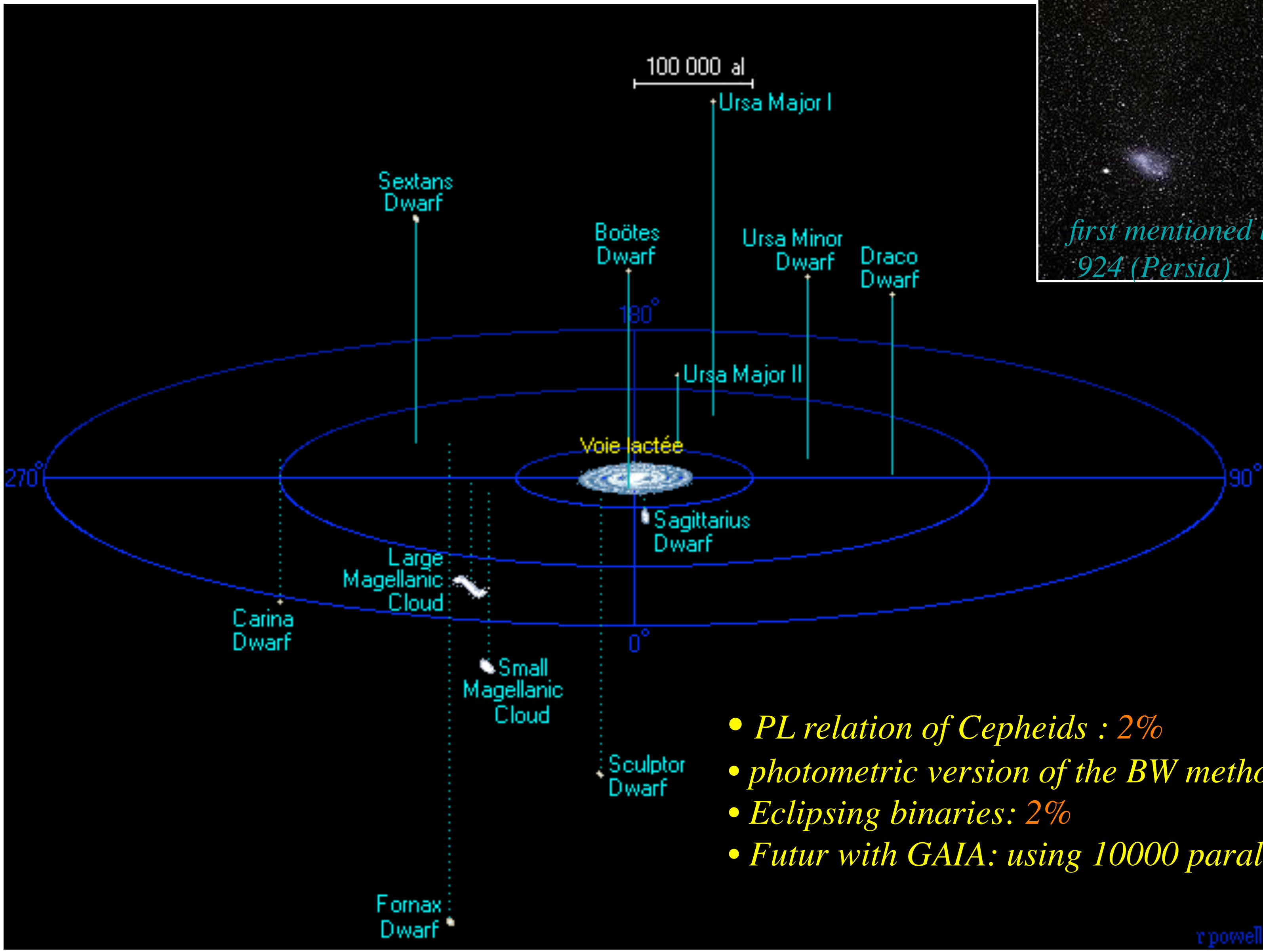
A debate of 70 years: ***Parenego (1947), Stibbs (1956), Wielen (1974), Caldwell & Coulson (1987), Moffett & Barnes (1987), Wilson et al. (1991), Pont, Mayor & Burki (1994)***

Atmoshere dynamics or kinematical structure of the Milky Way?

The Magellanic Clouds

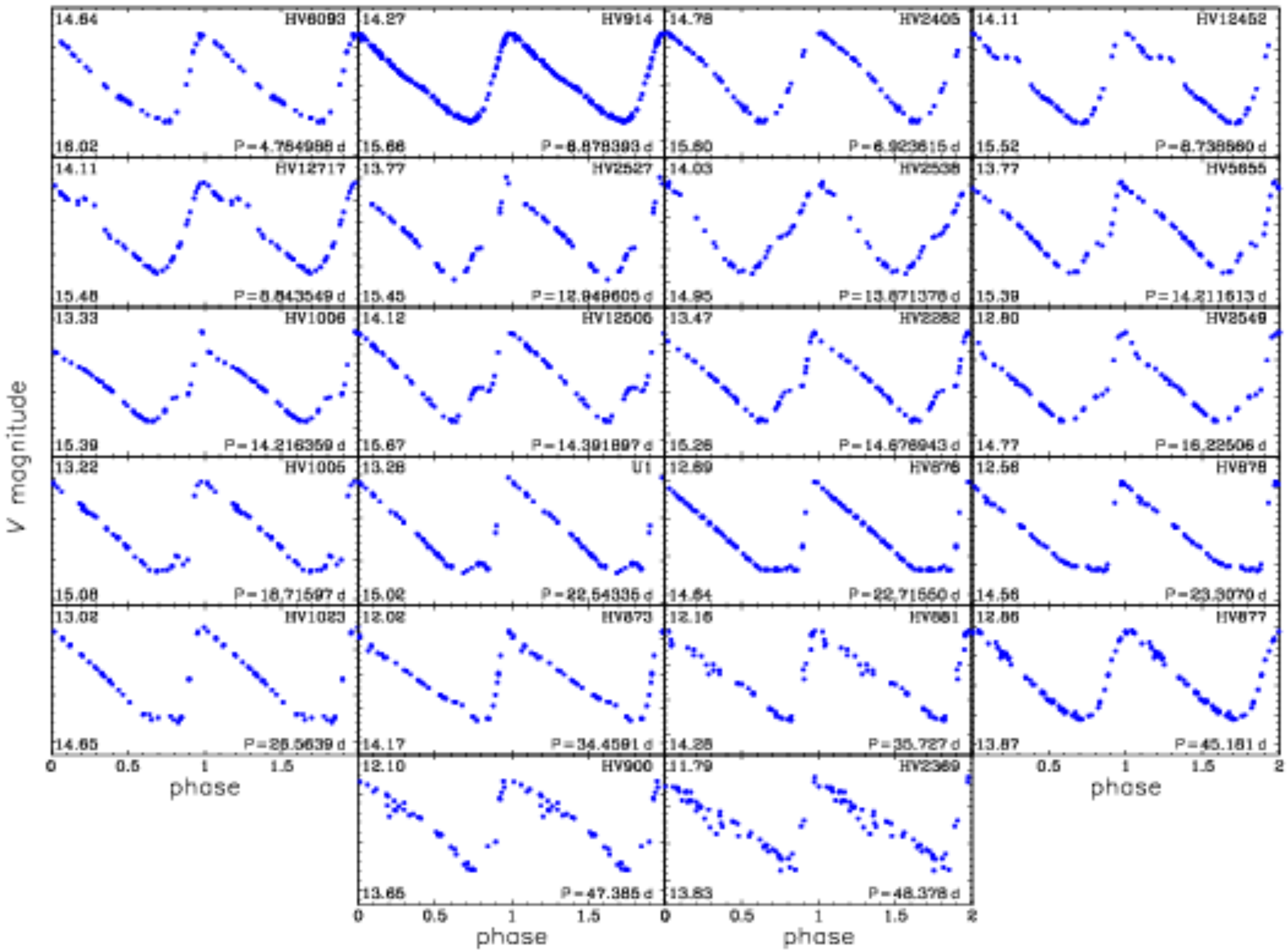
LMC distance ~ 50 kpc (or 160000 ly) – size 5kpc and i=35° (i=0=pole-on)

SMC distance ~ 60 kpc (or 195000 ly)



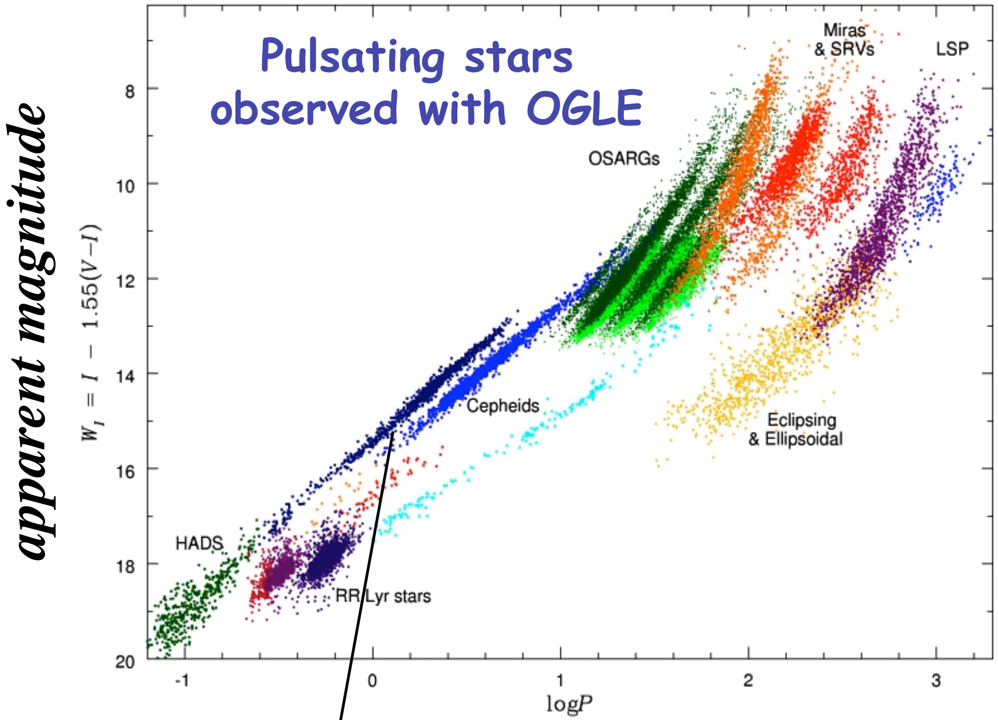
- *PL relation of Cepheids : 2%*
- *photometric version of the BW method : 2% (but p)*
- *Eclipsing binaries: 2%*
- *Futur with GAIA: using 10000 parallaxes : 2%*

V light curves of LMC Cepheids from OGLE 3

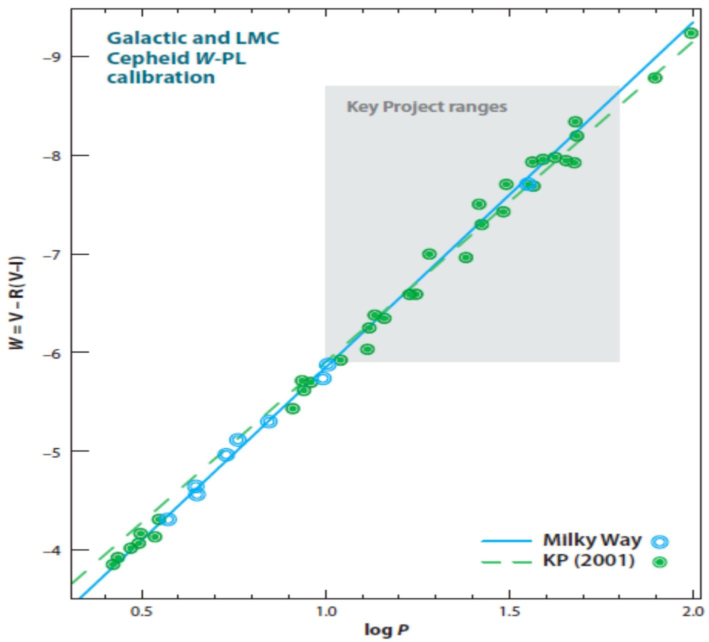


How do we use Cepheids to derive LMC distance ?

1/ all Cepheids in LMC are at the same distance: it gives the slope (a) of the PL relation.



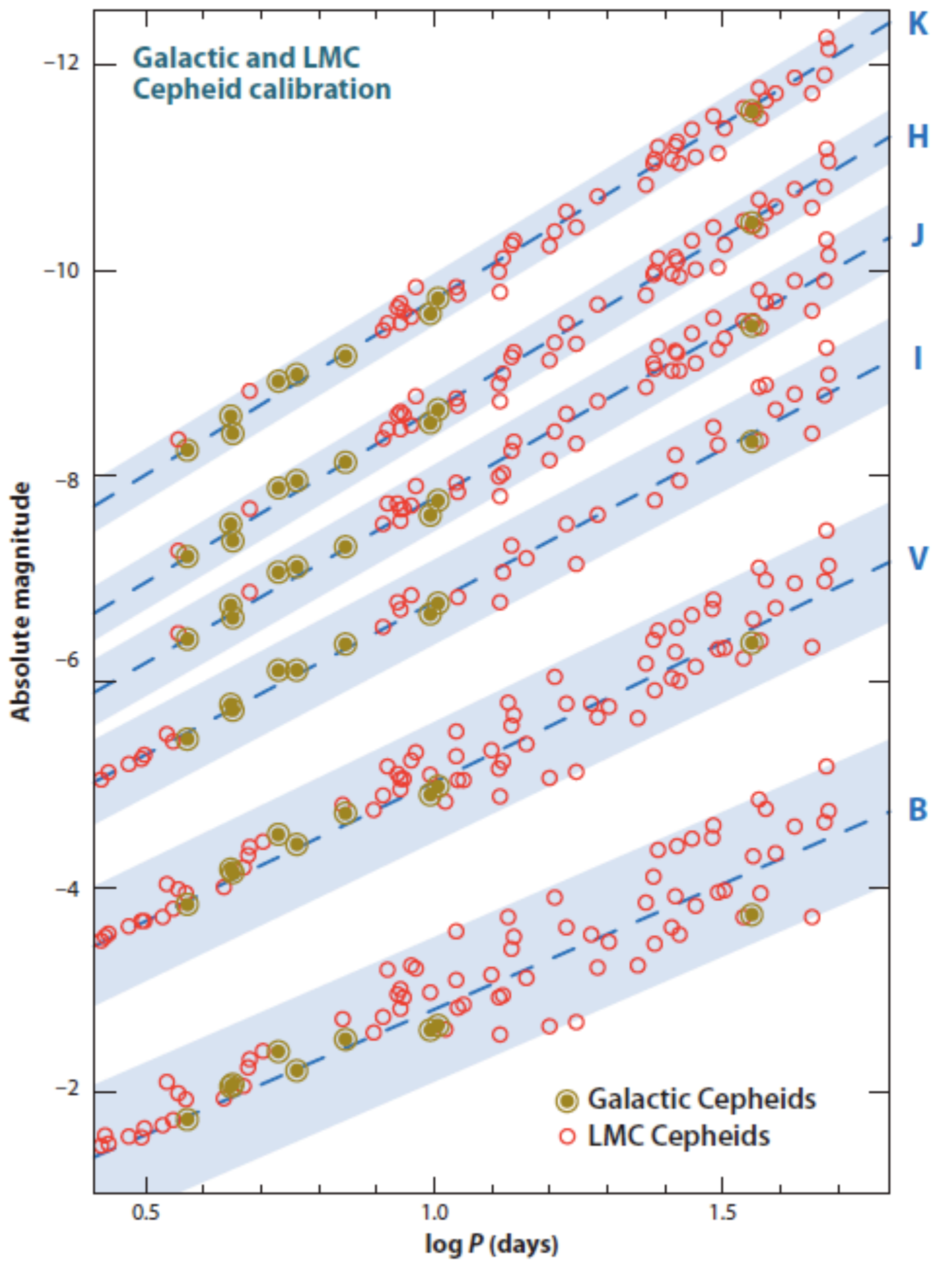
2/ verify that the slope in MW and LMC is the same (no metallicity effect)



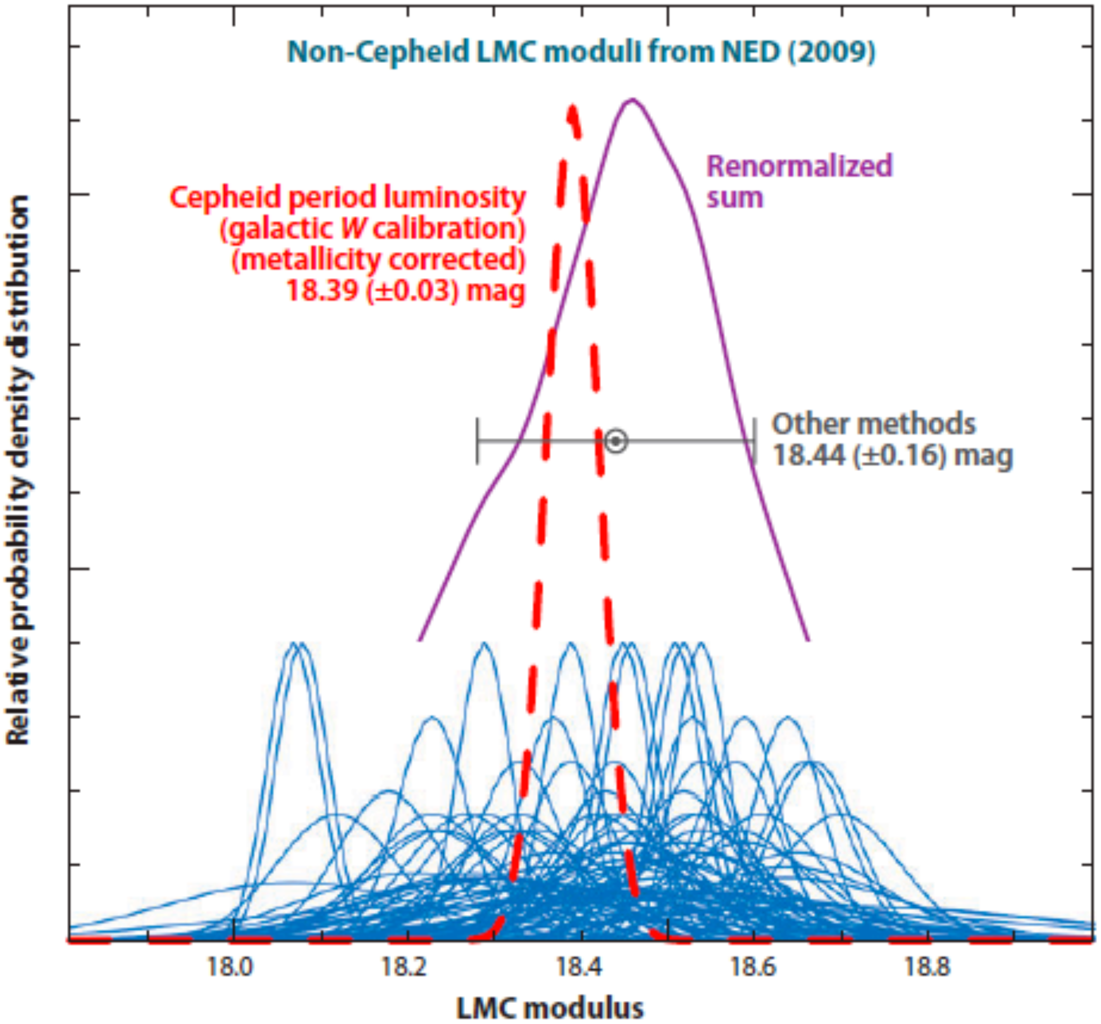
$$M = a(\log P - 1) + b$$

3/ Derive the distance to nearby Galactic Cepheids provides the zero-point (b). For instance, HST parallax, BW method (interferometric and photometric)...

Observing in K band is better !

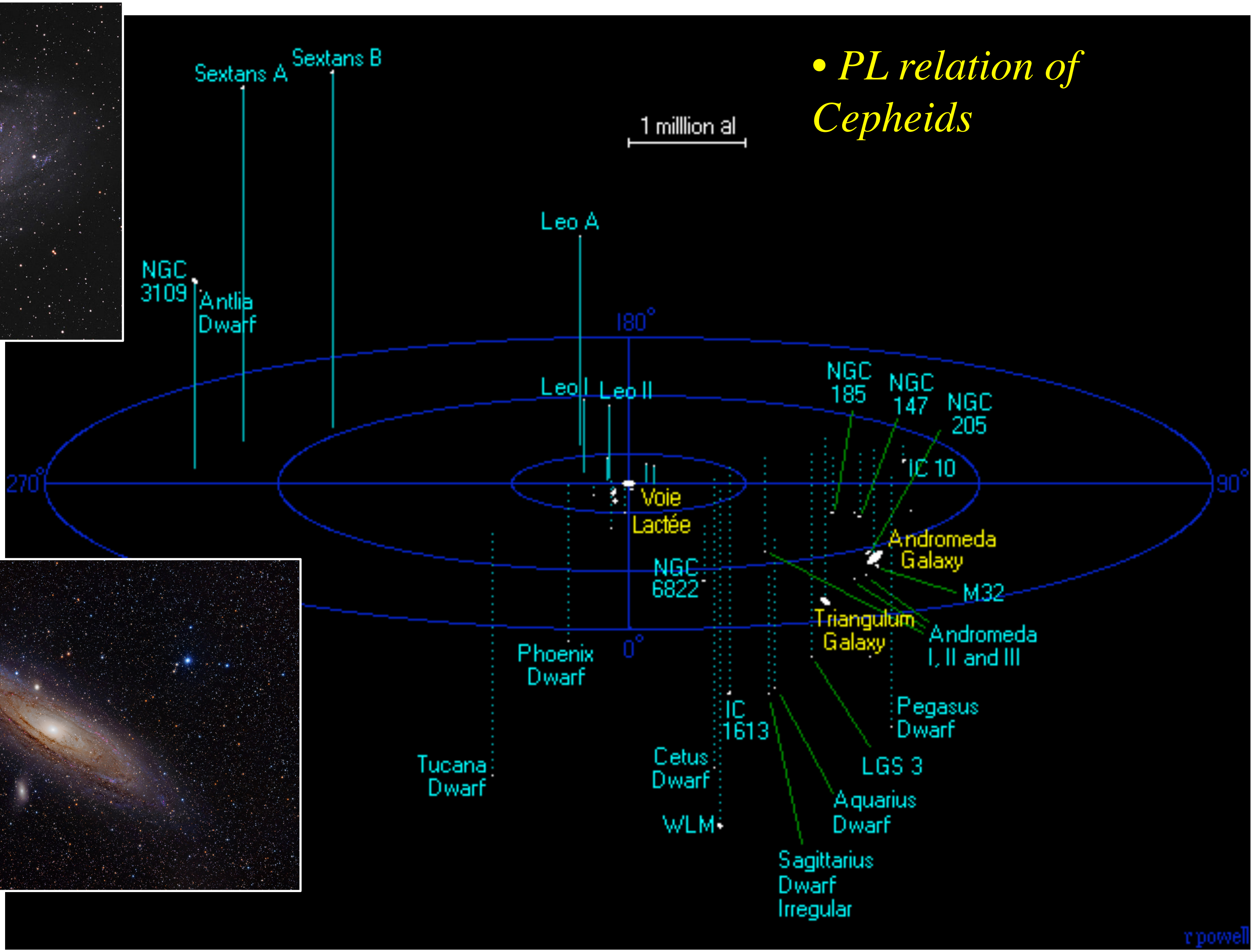


The distance to LMC (an fundamental anchor for the distance scale)



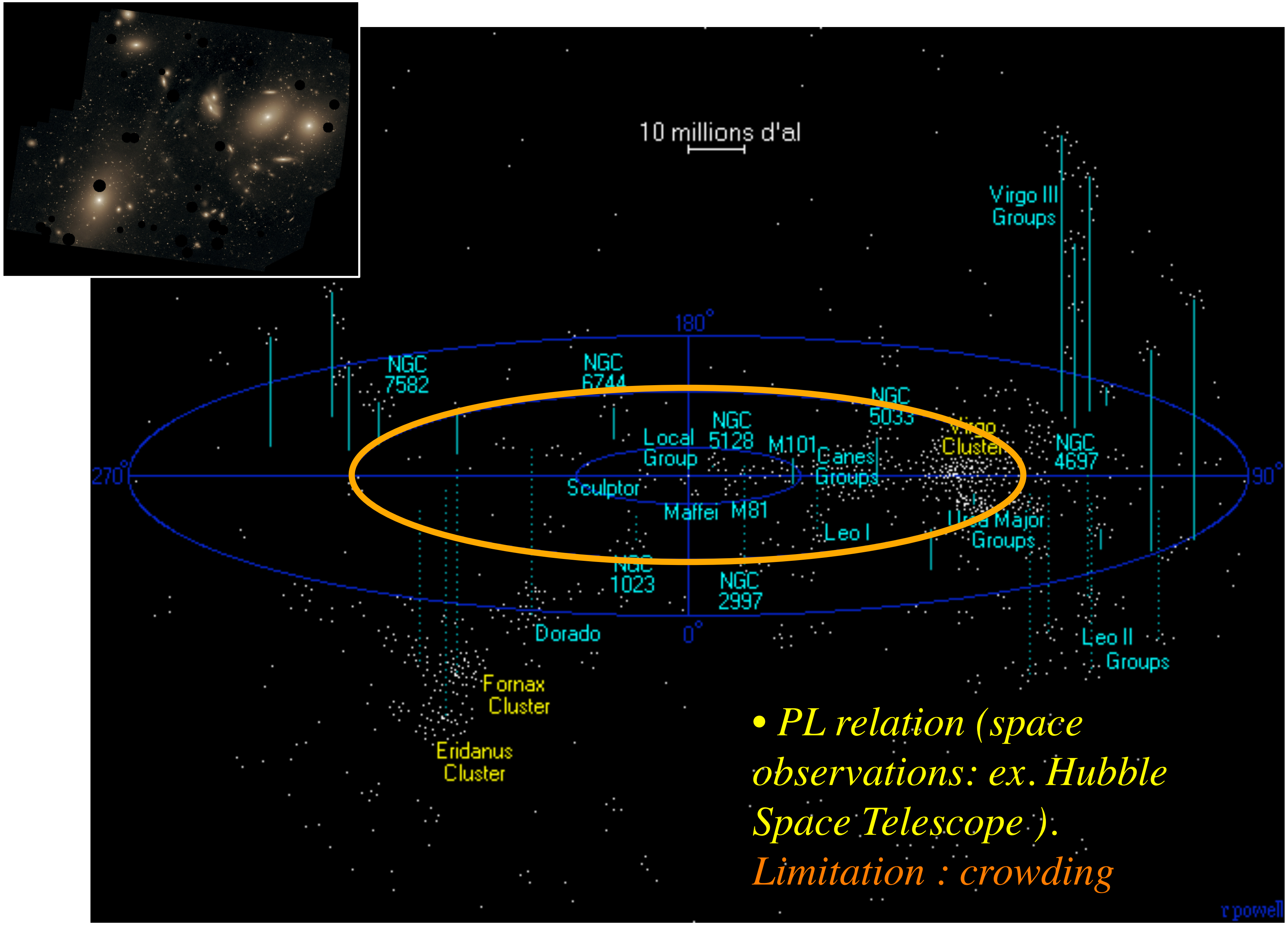
$$\mu = m - M = 5\log d - 5$$

The Local Group (5 millions ly or 1.5Mpc)



- *PL relation of Cepheids*

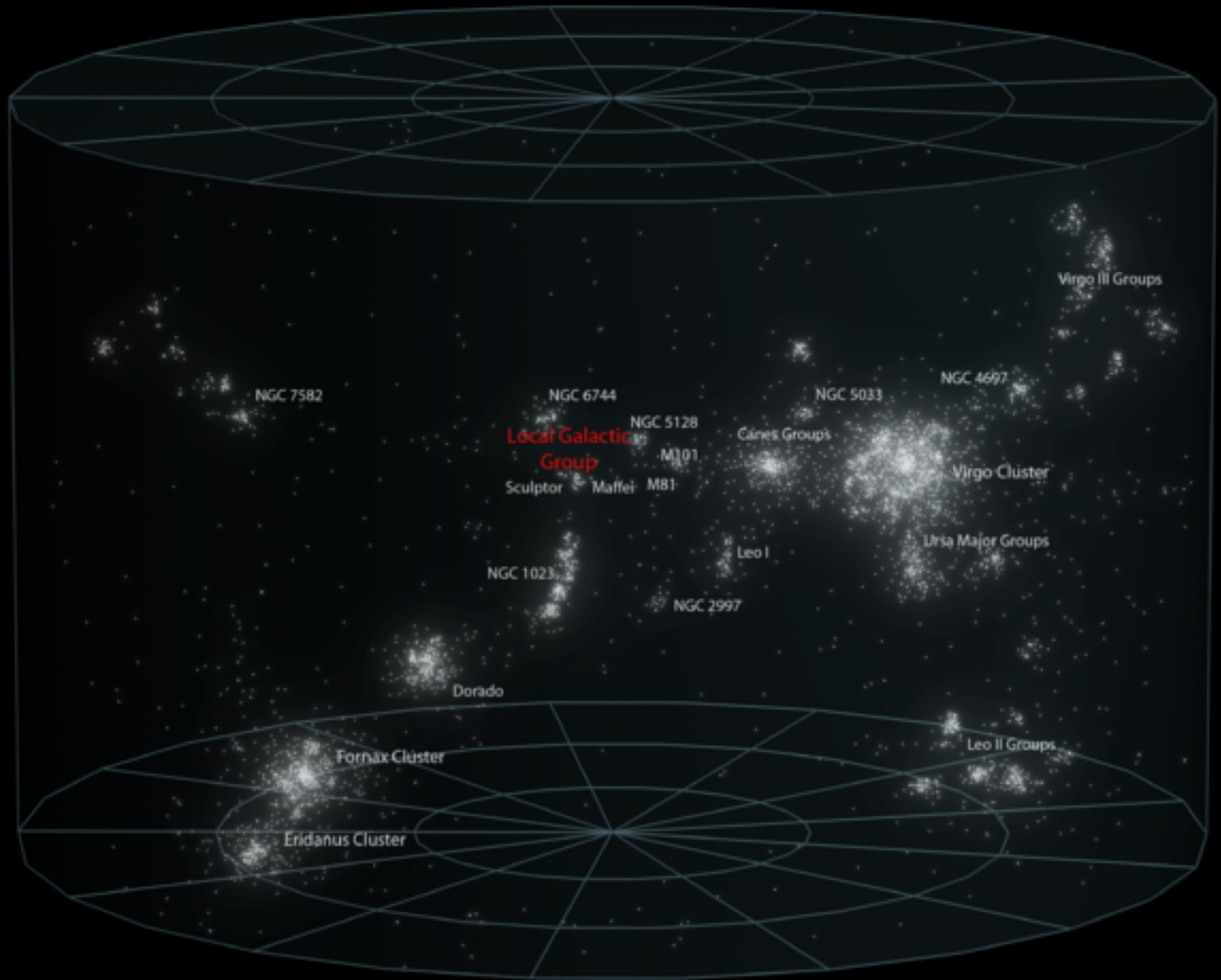
The Virgo Cluster (54 Mly or 16.5Mpc)



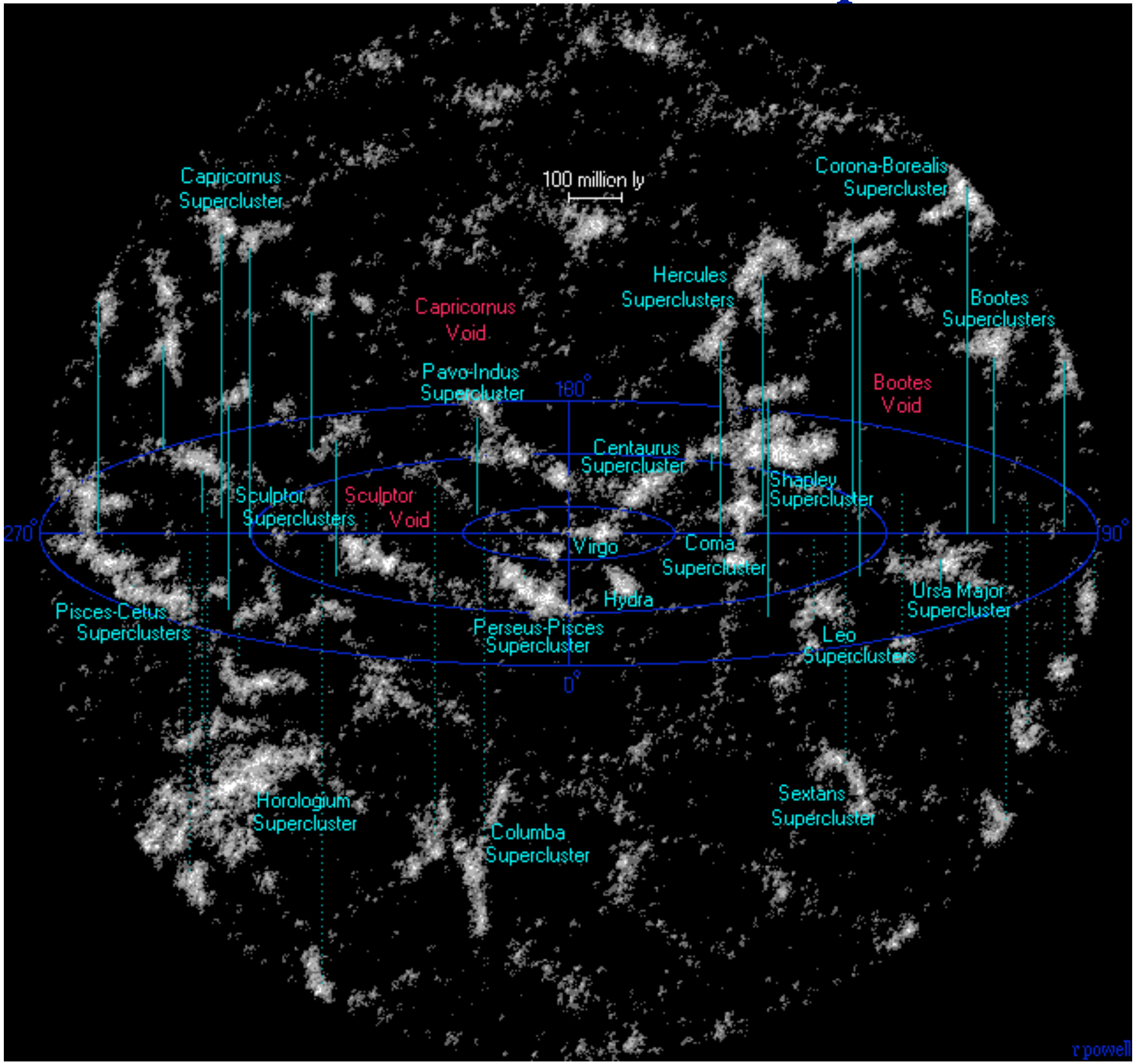
- *PL relation (space observations: ex. Hubble Space Telescope).*

Limitation : crowding

Virgo Supercluster



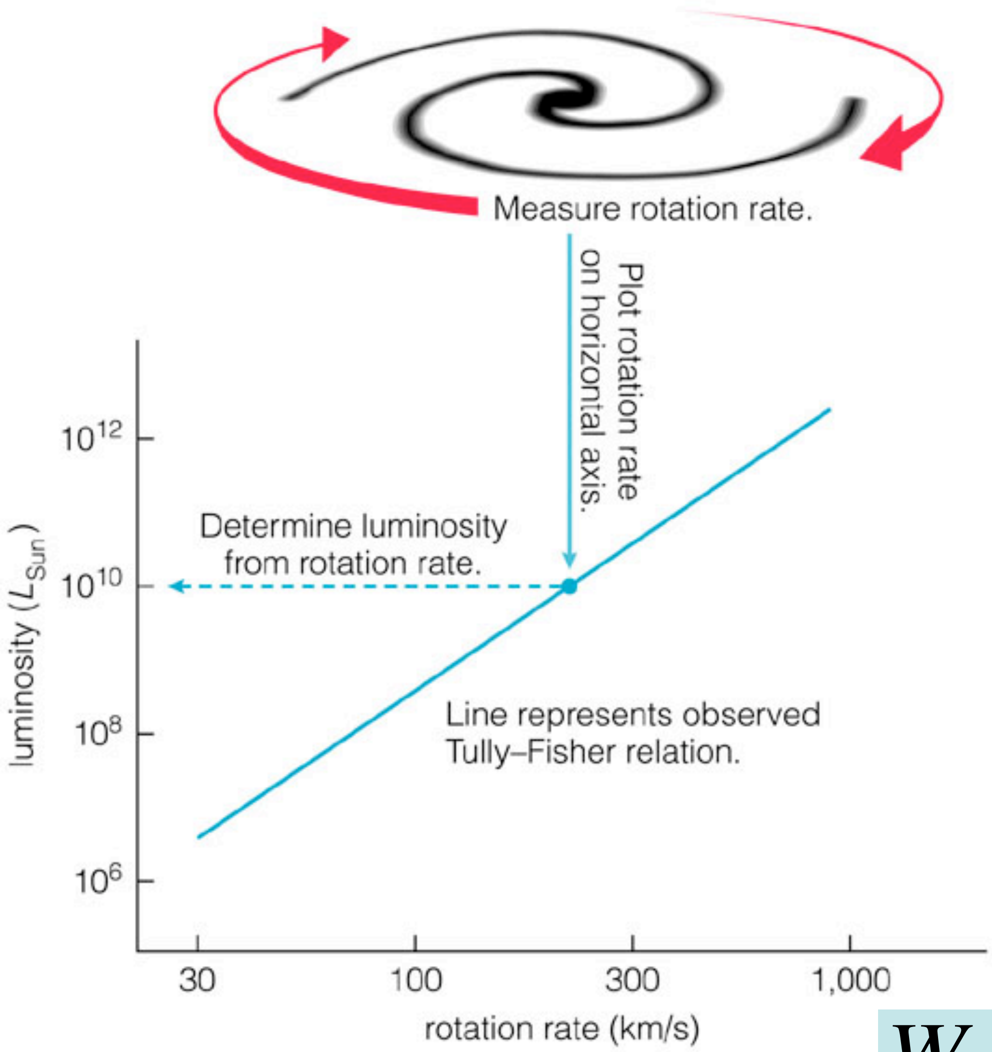
The universe up to 1 billion ly (1/15 of the visible universe) or 0.306Gpc

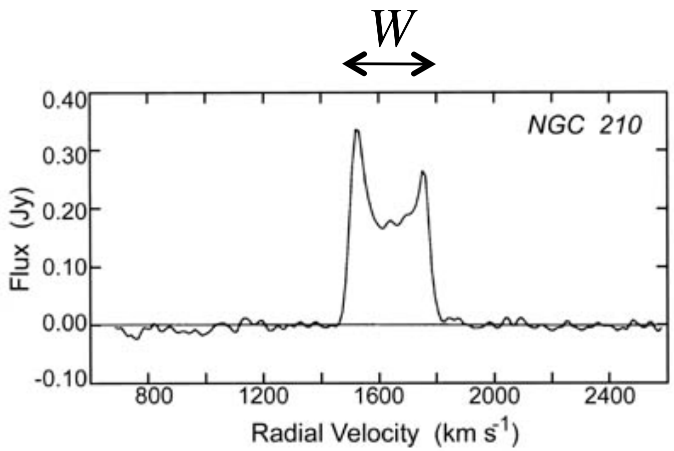


- *secondary methods of distance determination (Tully-Fischer, Faber-Jackson)*
- *and beyond : supernova 1a type*

The Tully-Fischer relation (spiral galaxies)

relation between the mass, the rotation velocity and the luminosity of a spiral galaxy



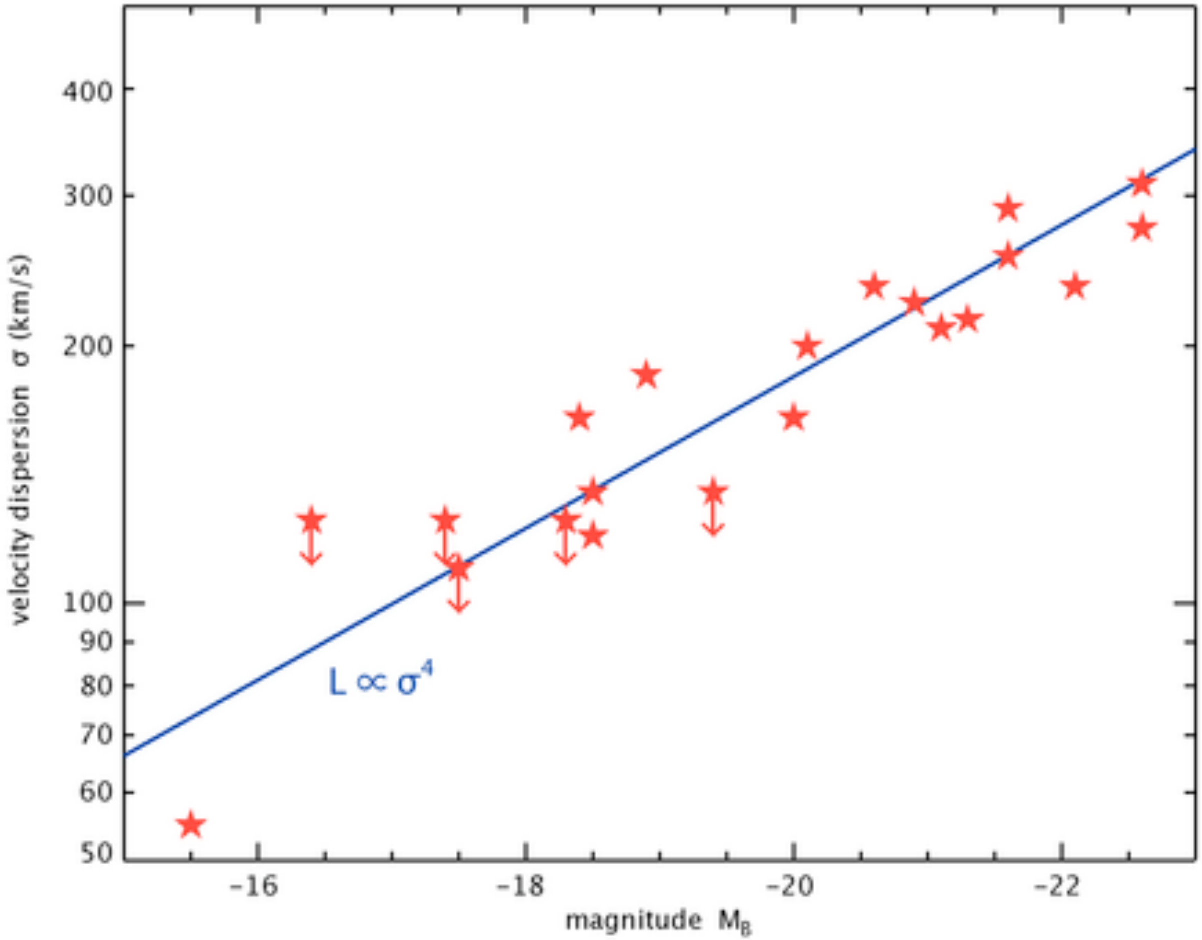


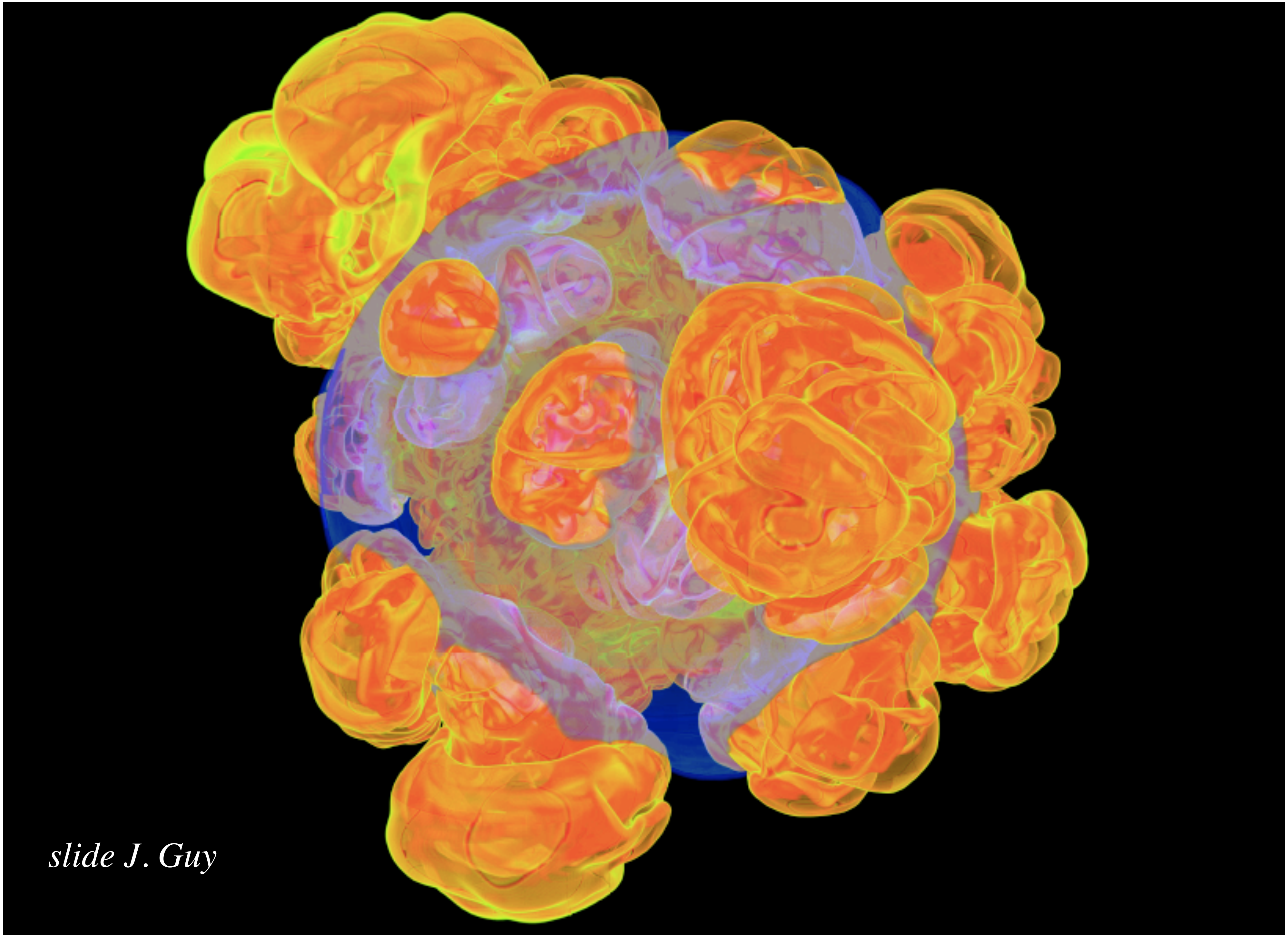
21cm (or 1420Mhz)
Neutral Hydrogen clouds
(hyperfin emission)

$$W = 2V_m \sin i \propto L$$

The Faber-Jackson relation (elliptic galaxies)

relation between the mass, the dispersion velocity and the luminosity of a elliptic galaxy




slide J. Guy

Prix Nobel de physique 2011

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess ”for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”.

Photo: U. Montan

Saul Perlmutter

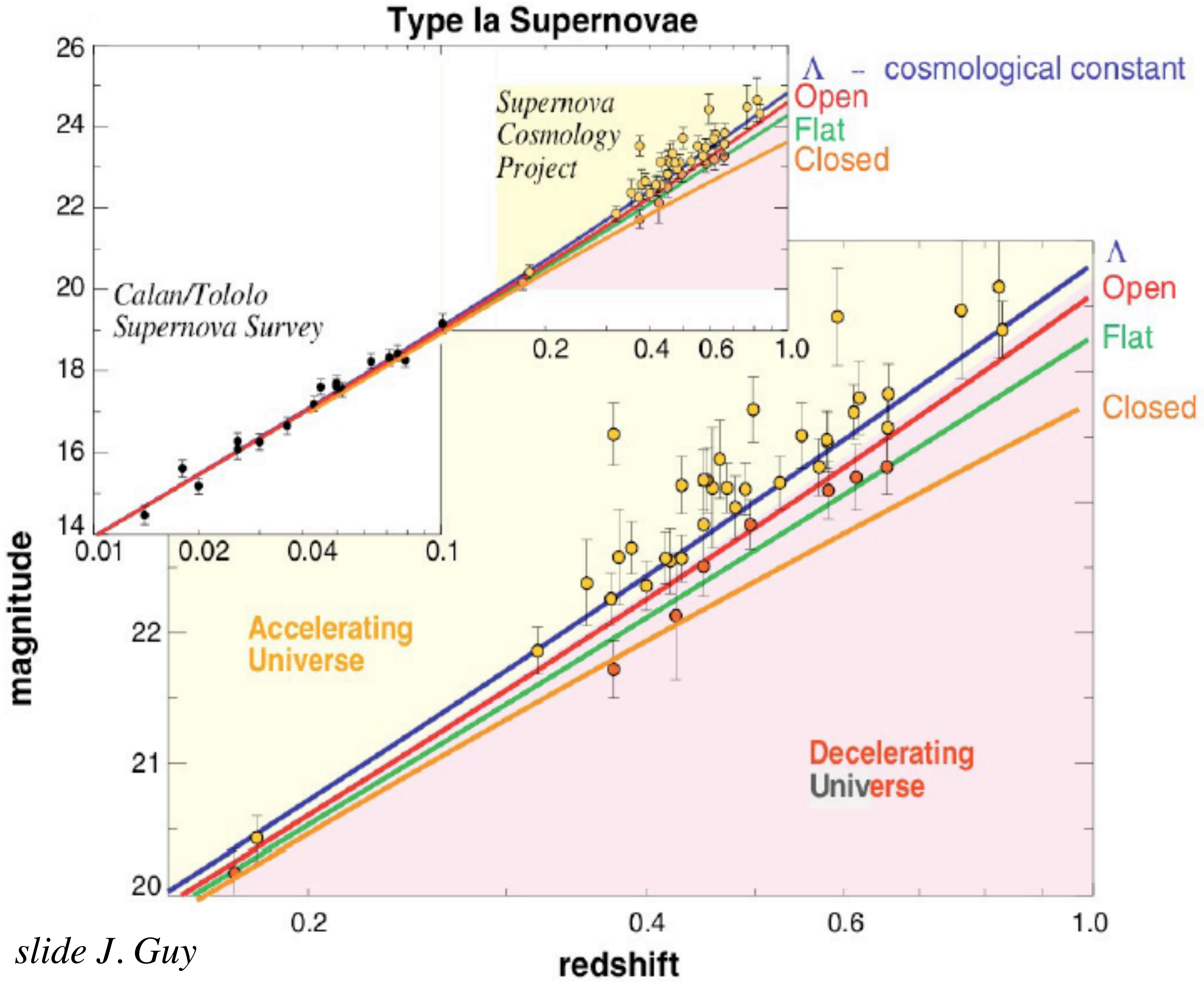
Photo: U. Montan

Brian P. Schmidt

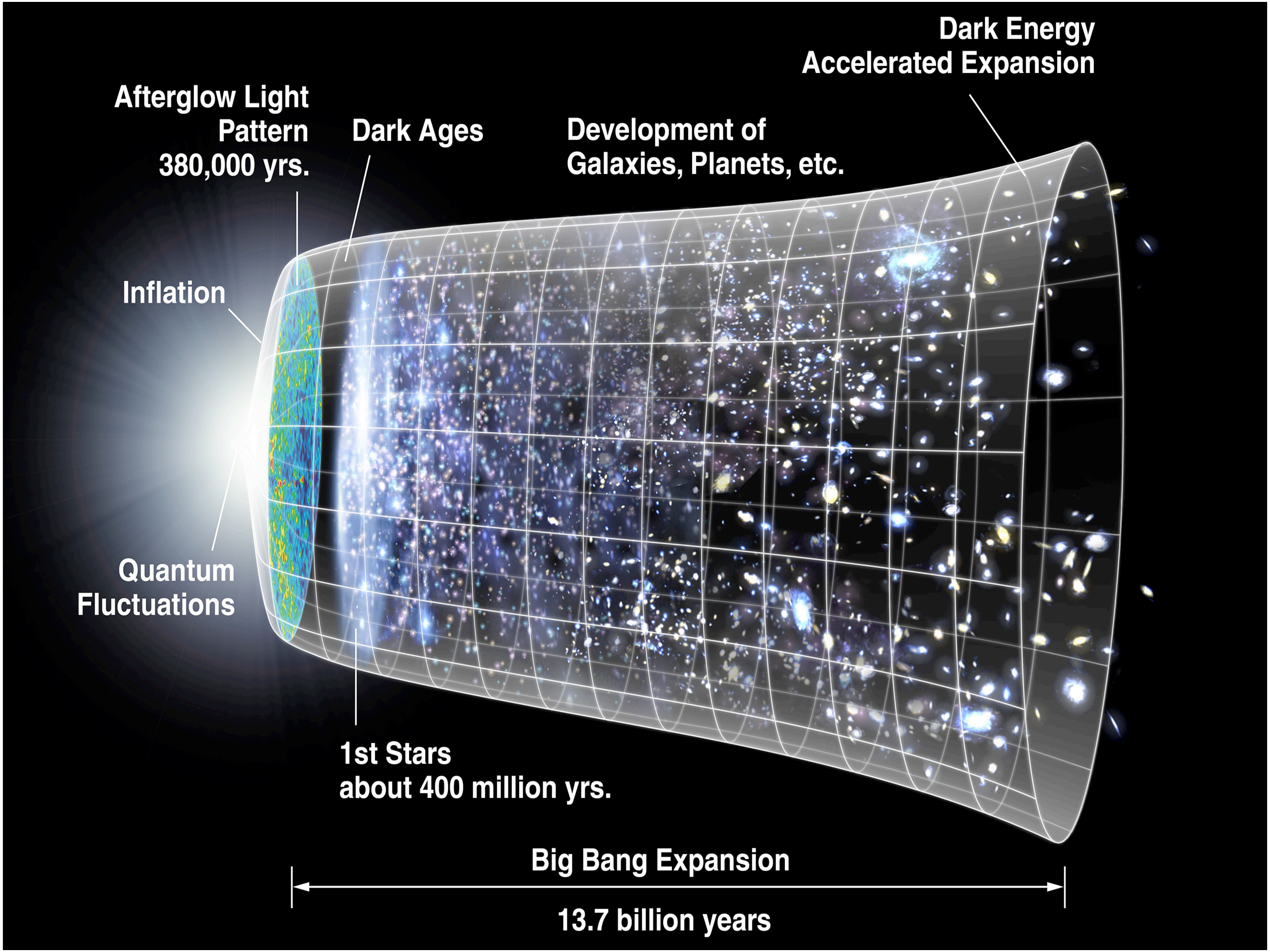
Photo: U. Montan

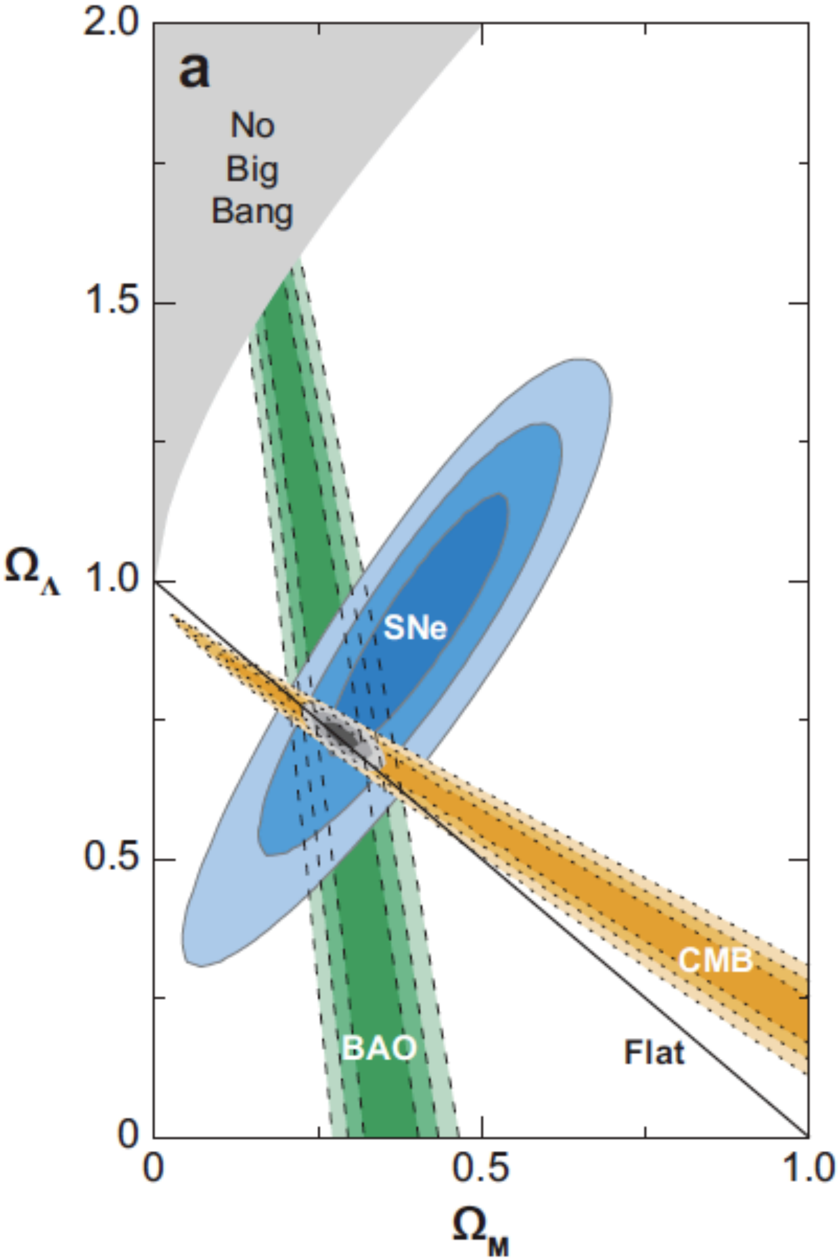
Adam G. Riess

$mag = -2.5 \log_{10}(flux) = 5 \log_{10}(distance)$



slide J. Guy


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


2.0
a
No
Big
Bang
1.5
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CMB
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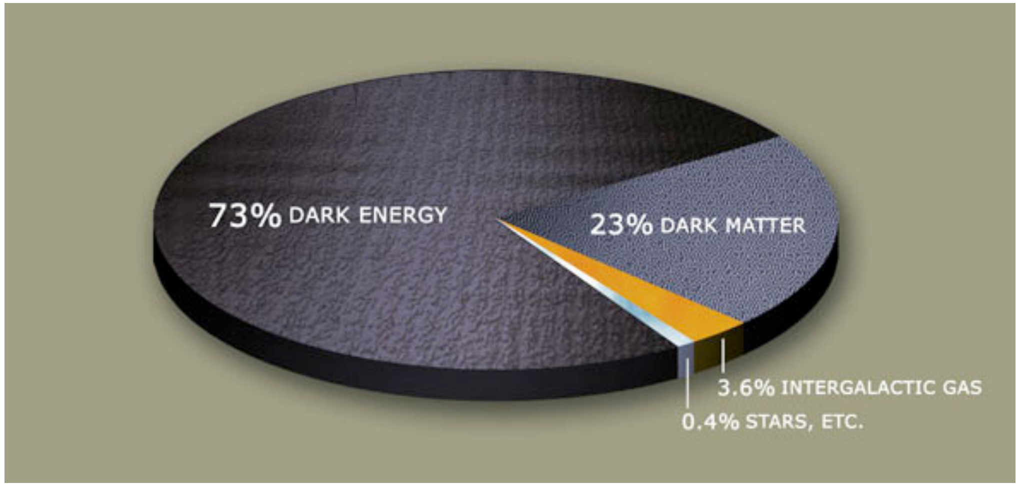
Ω_Λ
Ω_M


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

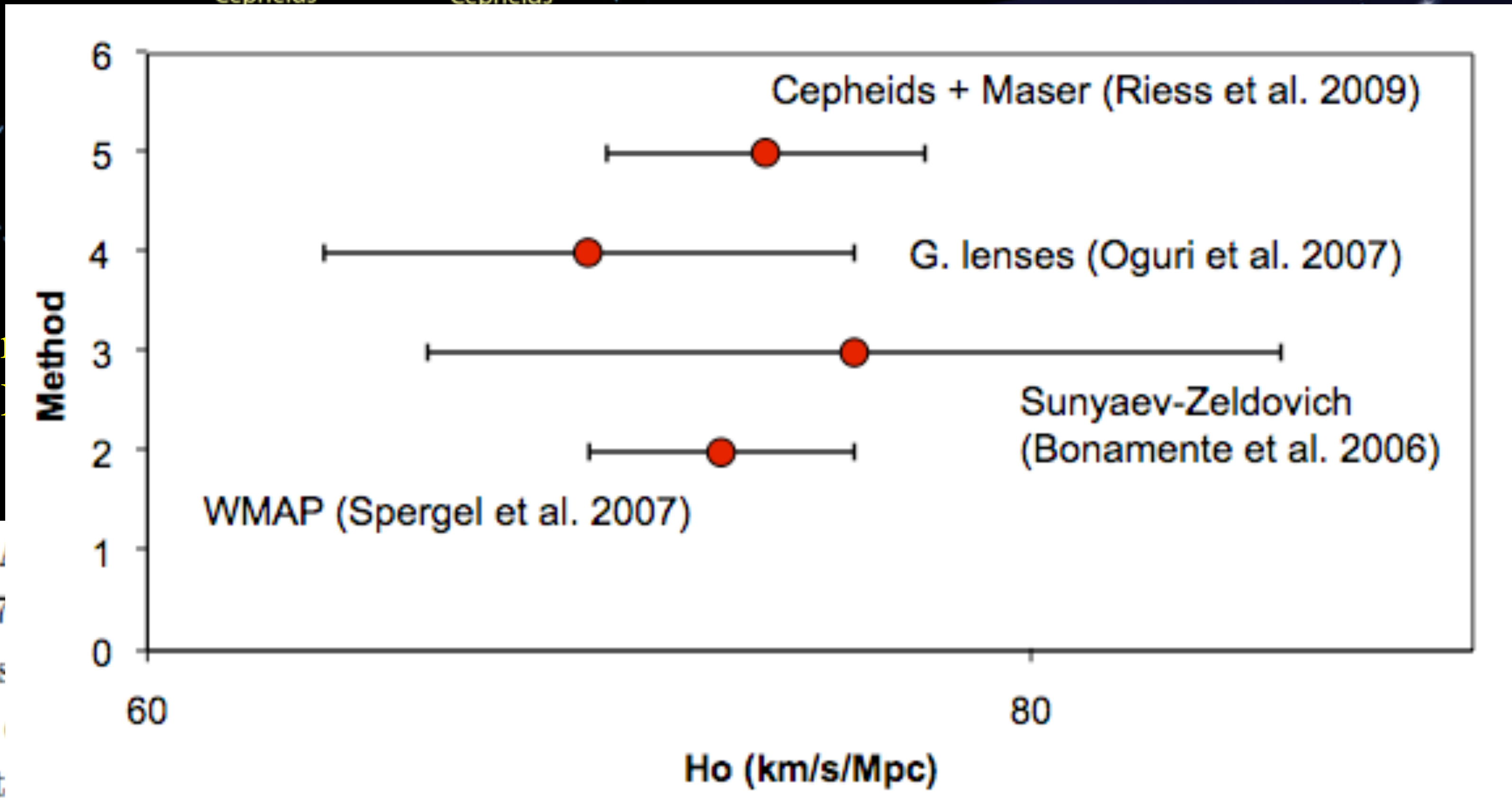
Riess et al. 2009, ApJ, 699, 539 (485 citations)

Three steps to the Hubble Constant

Cepheids

Galaxies hosting Cepheids

Distant galaxies in the expanding Universe hosting Type Ia supernovae

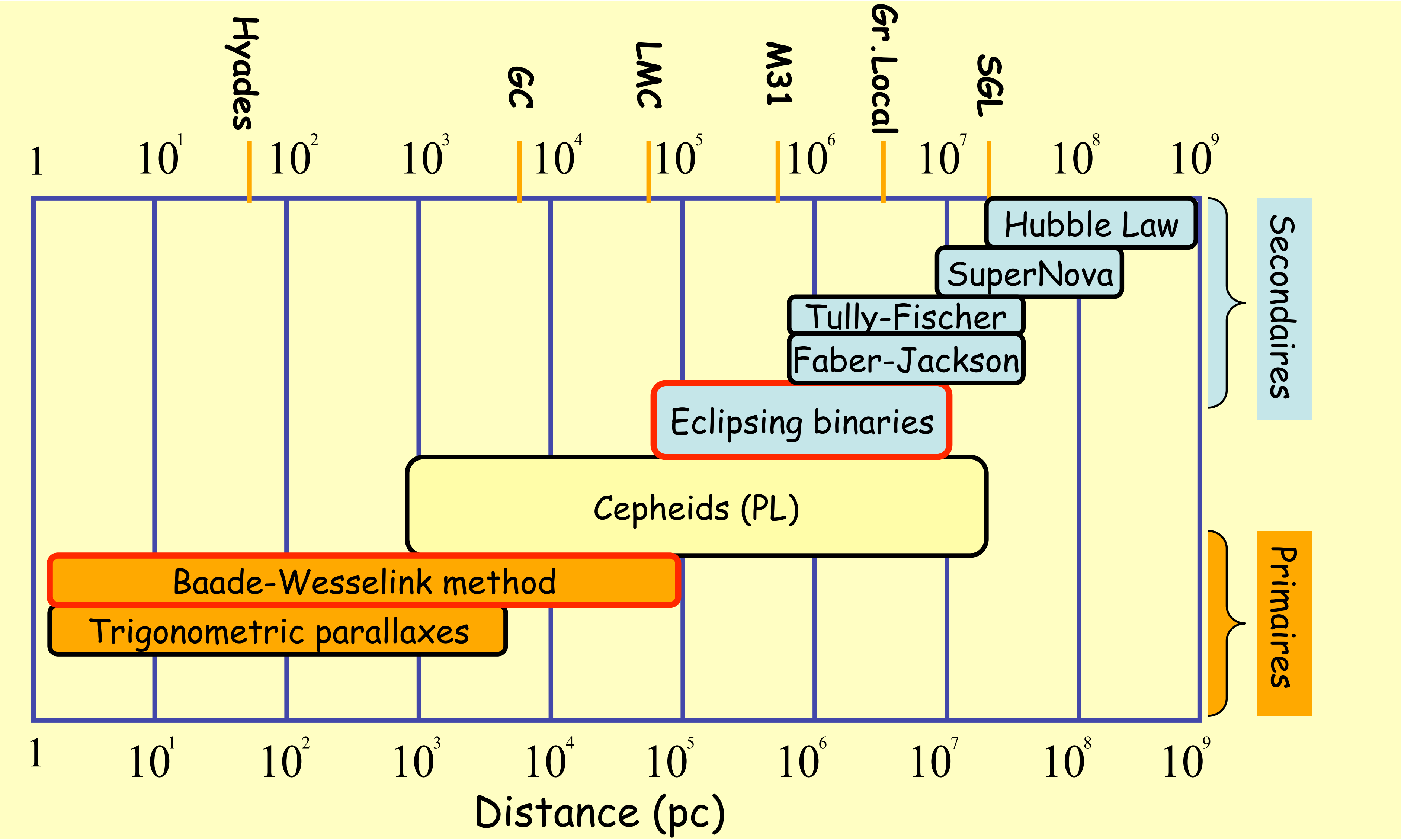


Maser
MW(
LMC

(2007 … et al.
… ard"
of dis … preci-
sion … se of
addit … ellar
associations as they are much more uncertain than well-measured parallaxes, and the former appear to be under refinement due to uncertainties in their projection factors, as discussed by Fouqué et al. (2007) and van Leeuwen et al. (2007).

MW (HST+IBW) : H0 = 73.7 ± 2.0 km/s/mpc (2.7%)

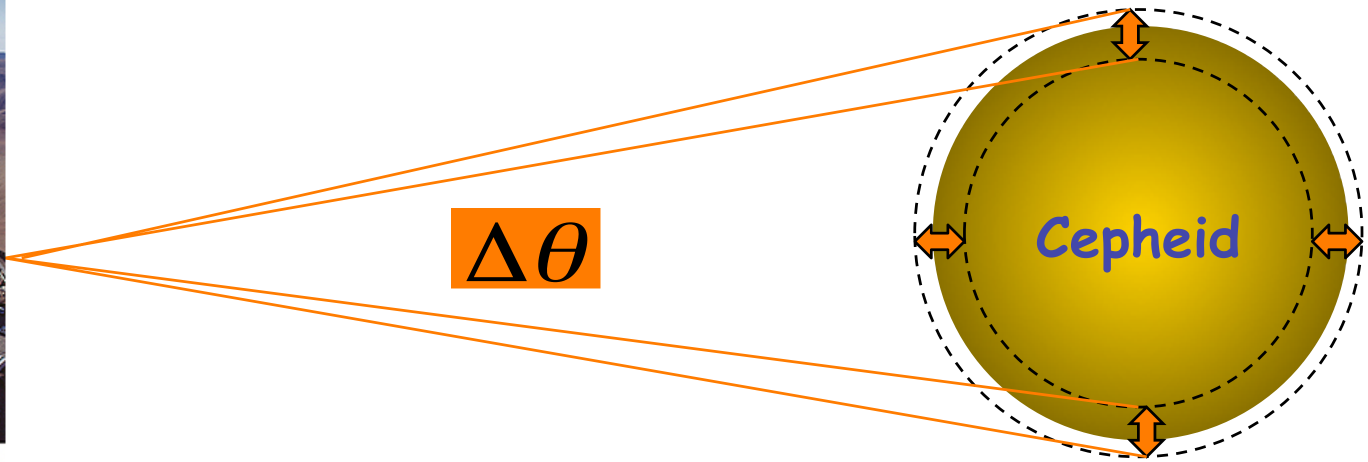
The distance scale in the universe



The Baade-Wesselink Method or parallax of pulsation

1 - Interferometry

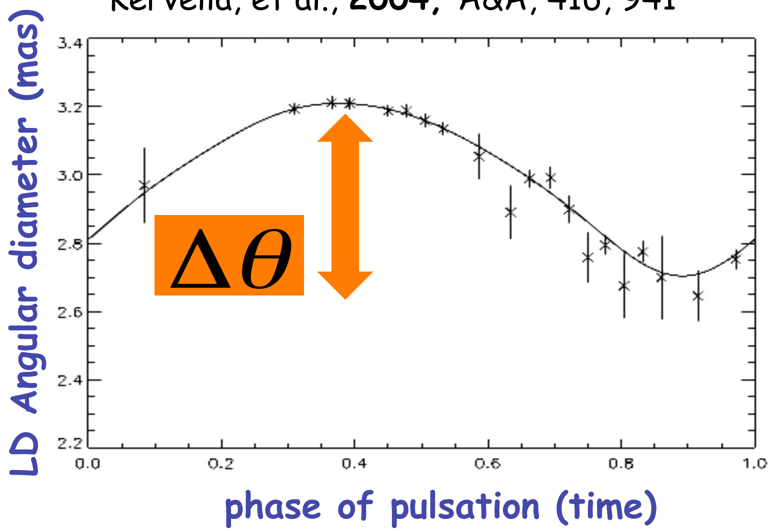
Interferometry



$$k = \frac{\theta_{UD}}{\theta_{LD}}$$

~0.94 in optical
~0.98 in IR
k is assumed to be constant with phase

Kervella, et al., **2004**, A&A, 416, 941



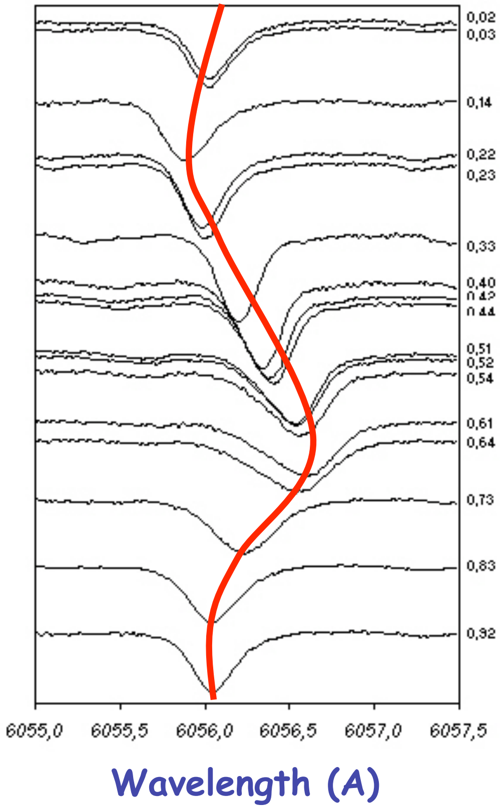
Interferometry provides the angular size variation of the star

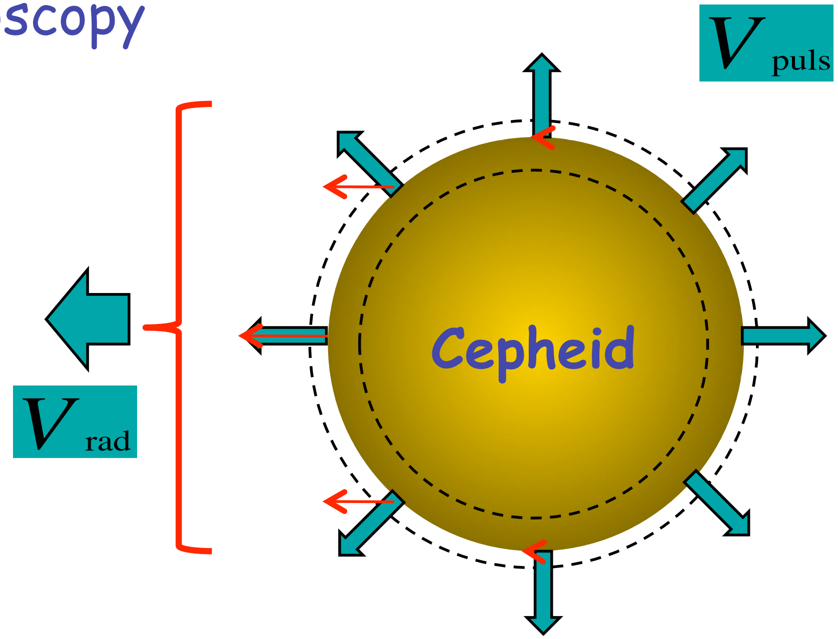
The Baade-Wesselink Method or parallax of pulsation

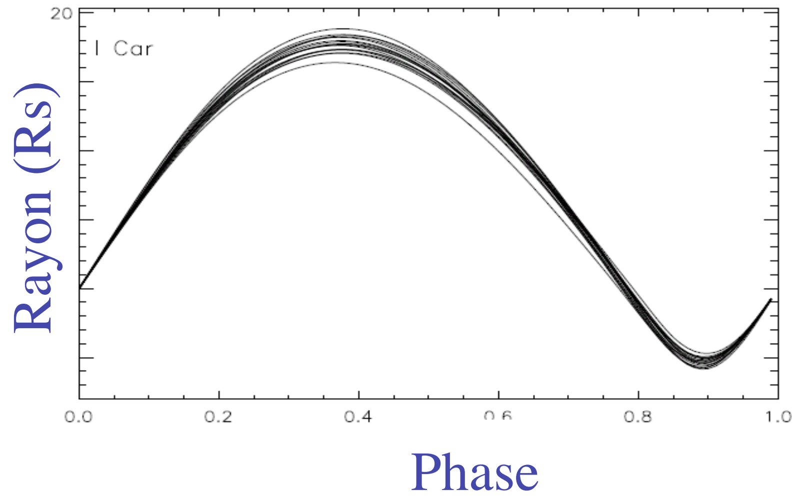
2 - spectroscopy

spectroscopy

Nardetto et al., **2006**
A&A, 453, 309







$$p = \frac{V_{puls}}{V_{rad}}$$

$$R(t) = p\int V_{rad}\,dt$$

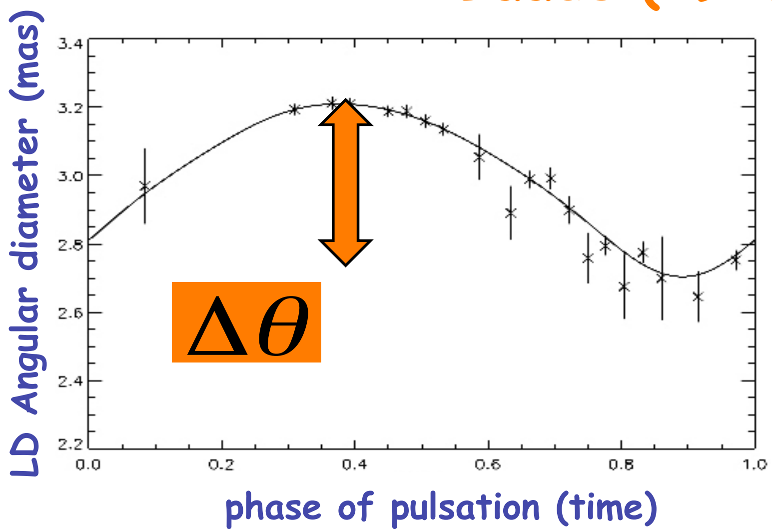
p is assumed to be constant with phase

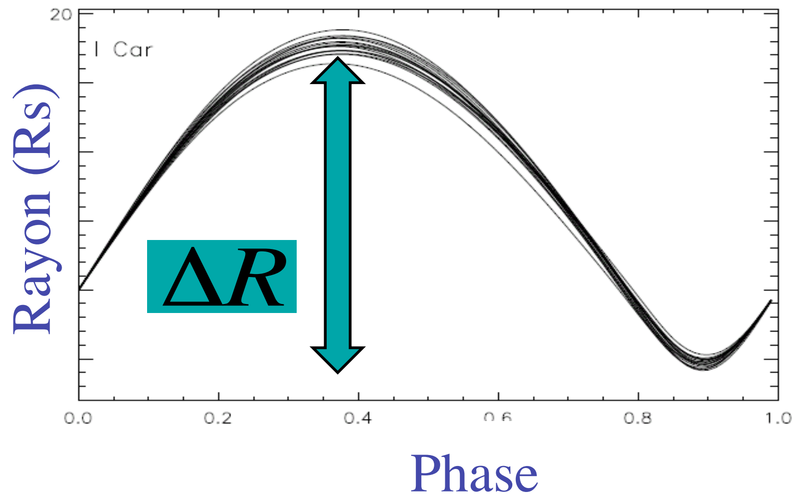
Spectroscopy provides the radius variation of the star

The Baade-Wesselink Method or parallax of pulsation

3-combining interferometry and spectroscopy

Baade (1926) – Wesselink (1946)



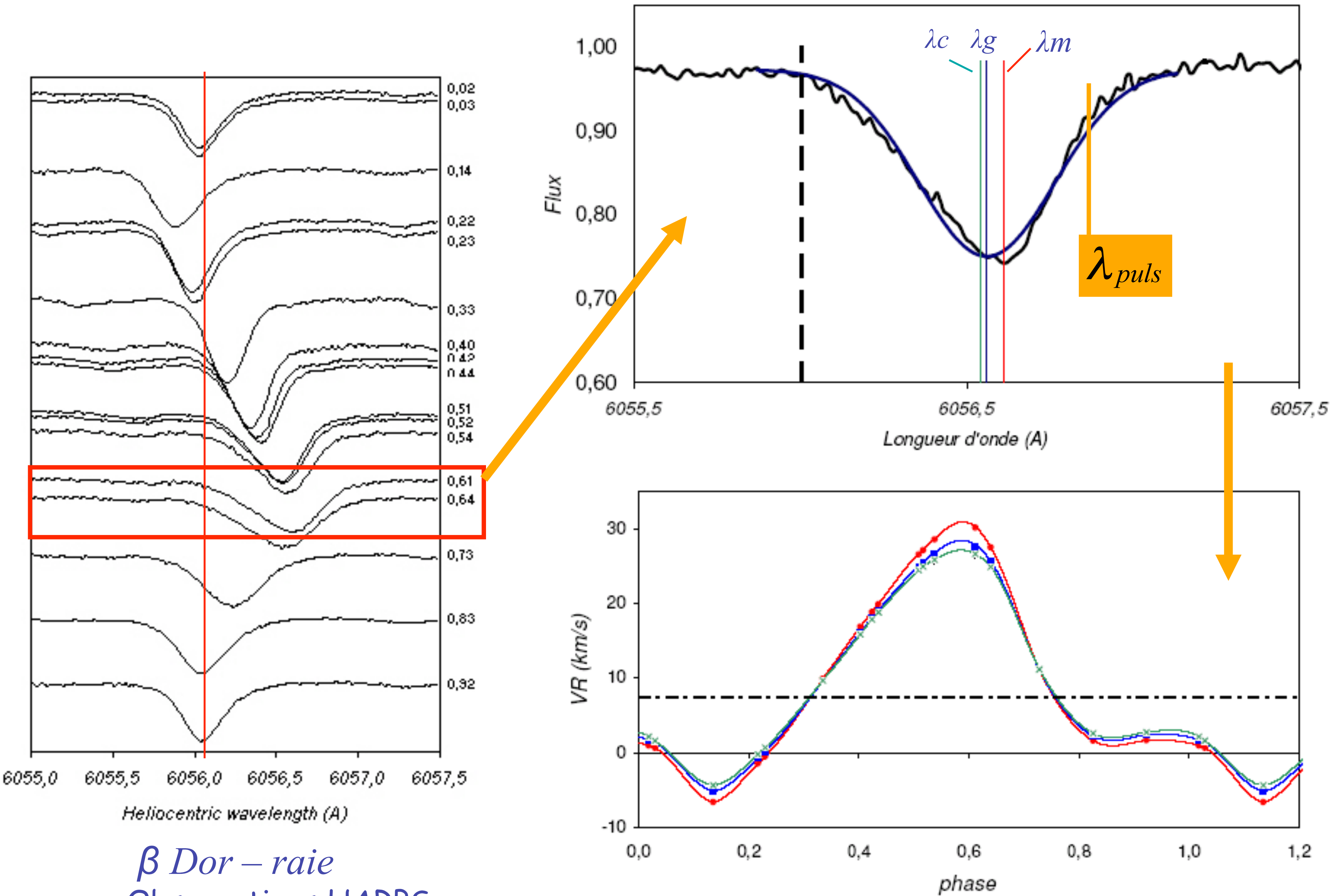


$$d \propto \frac{\Delta R}{\Delta \theta}$$

$\Delta R \Leftrightarrow \Delta \theta$

This two quantities have to correspond to the same layer in the star (related to the problem of the projection factor)

The radial velocity definition

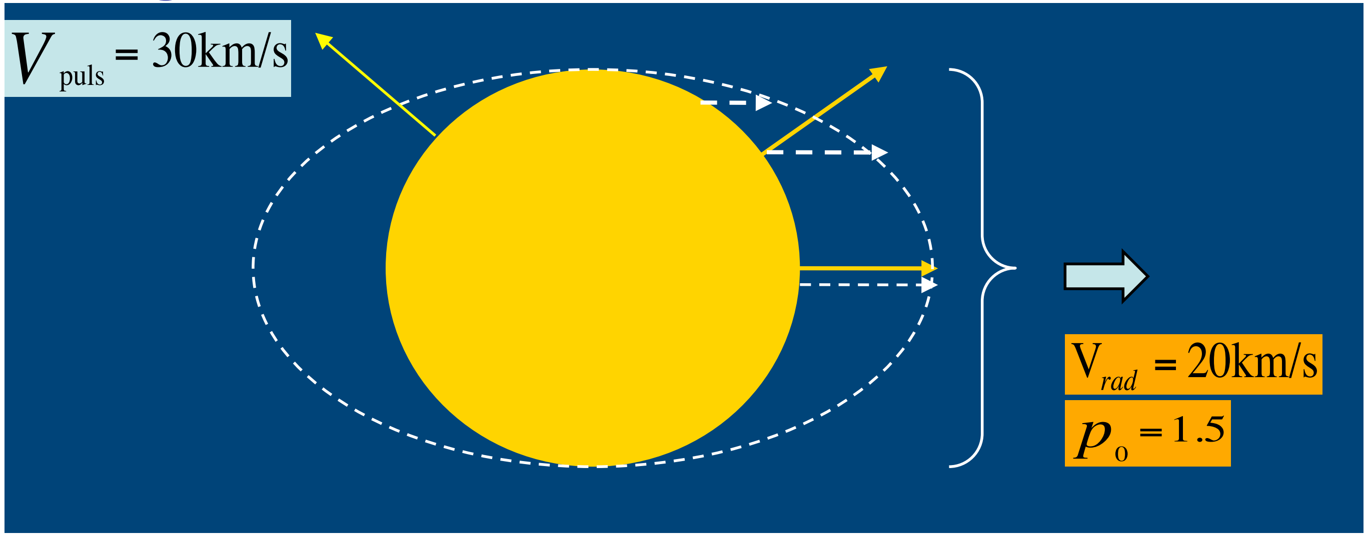


β *Dor – raie*

Observations HARPS

The Baade-Wesselink projection factor

- A geometric effect (uniform disk)



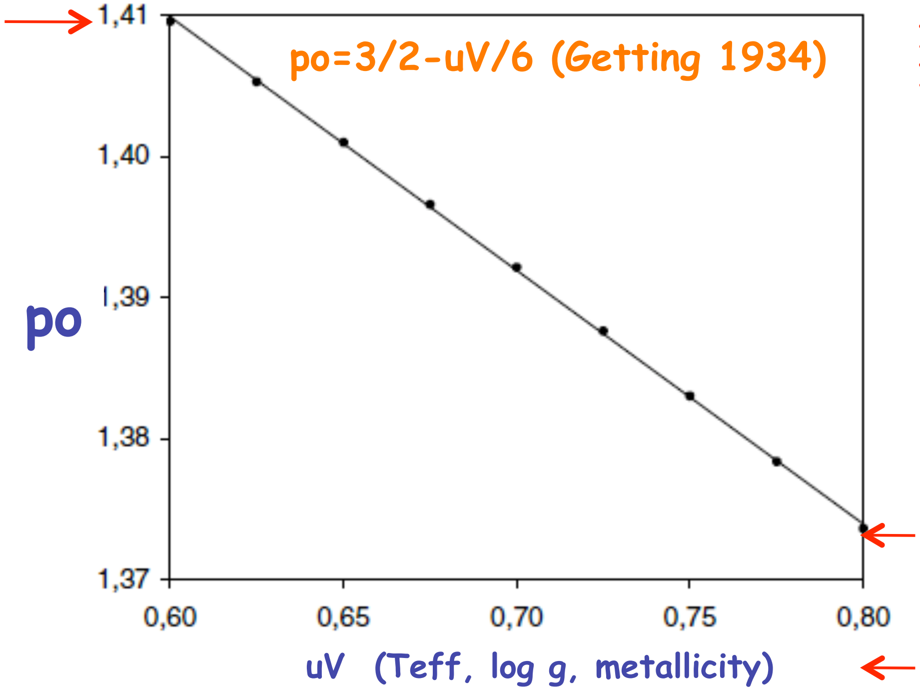
$$
\begin{aligned}
V_{rad} &= \frac{1}{\pi R^2} \int_{\rho=0}^{\rho=R} \left[V_{puls} \sqrt{1 - \frac{\rho^2}{R^2}} \right] * 2\pi\rho d\rho \\
&= \int_{\theta=0}^{\theta=\frac{\pi}{2}} [V_{puls} cos(\theta)] * 2cos(\theta)sin(\theta)d\theta \\
&= \int_{\mu=0}^{\mu=1} [V_{puls}\mu] * 2\mu d\mu
\end{aligned}
$$

Assumption: no LD time variation

p-factor value relevant ONLY with the first moment method !

The relation between the geometric projection factor (po) and the limb-darkening

Van Hoof, 1952ApJ, 115, 166V
(u=0.6 -> p=24/17=1.41)

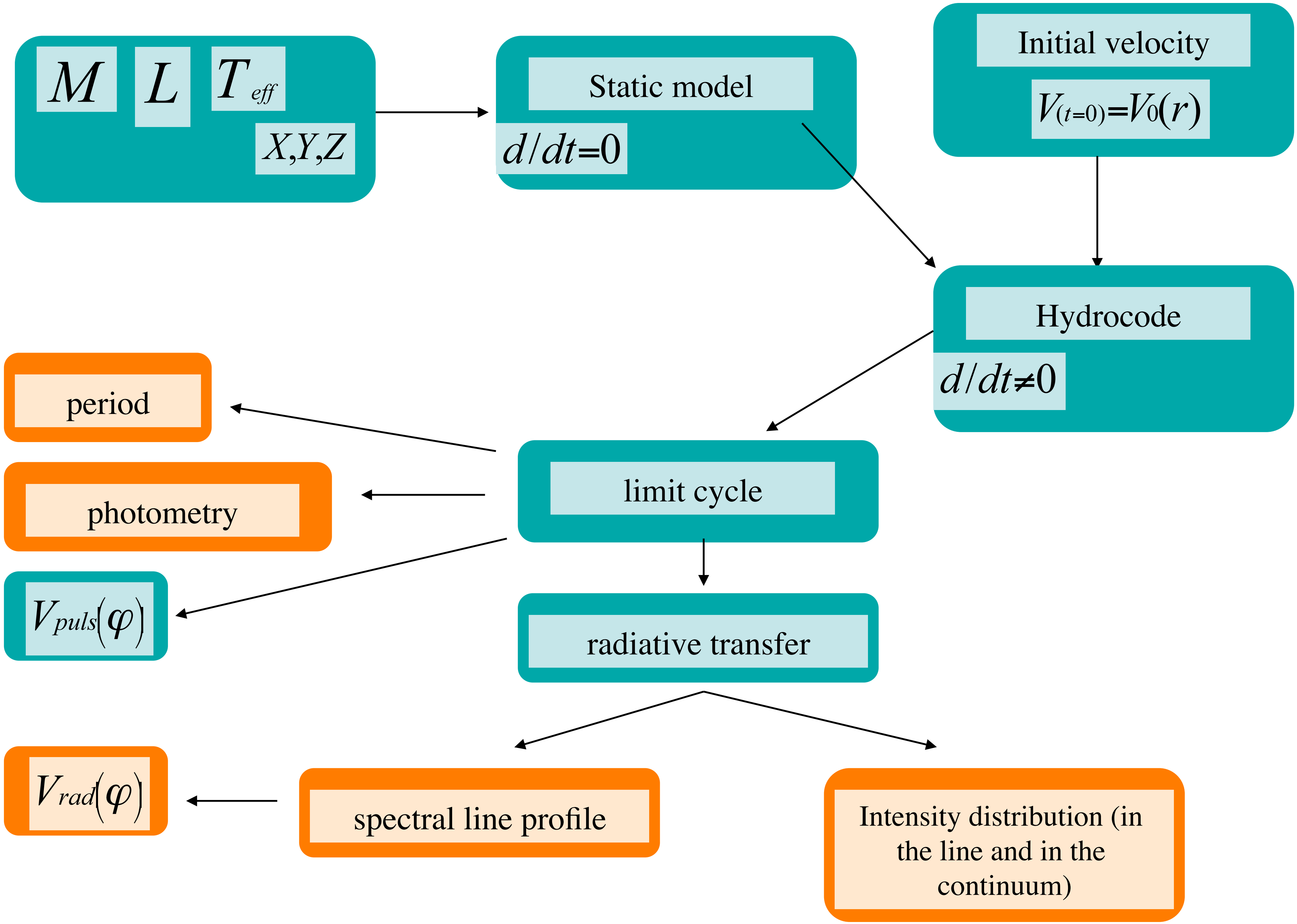


from Claret et al (2011)

If u=0 (uniform disk) then p=1.5
If u=1 then p=1.33

Getting, 1934, MNRAS, 95, 139
(u=0.8)

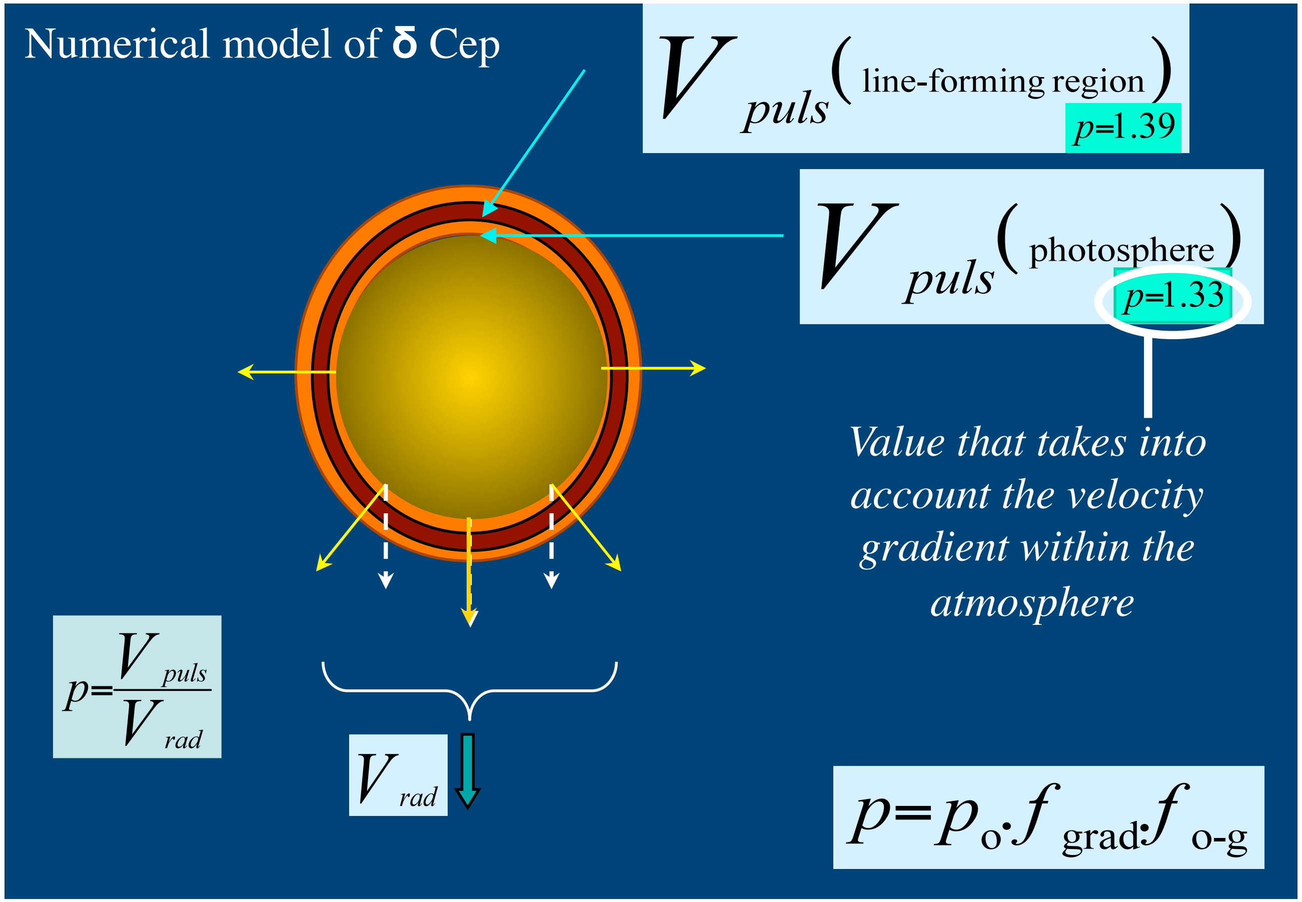
Burki et al. 1982, A&A, 109, 258
(u=0.85 ; p=1.36)



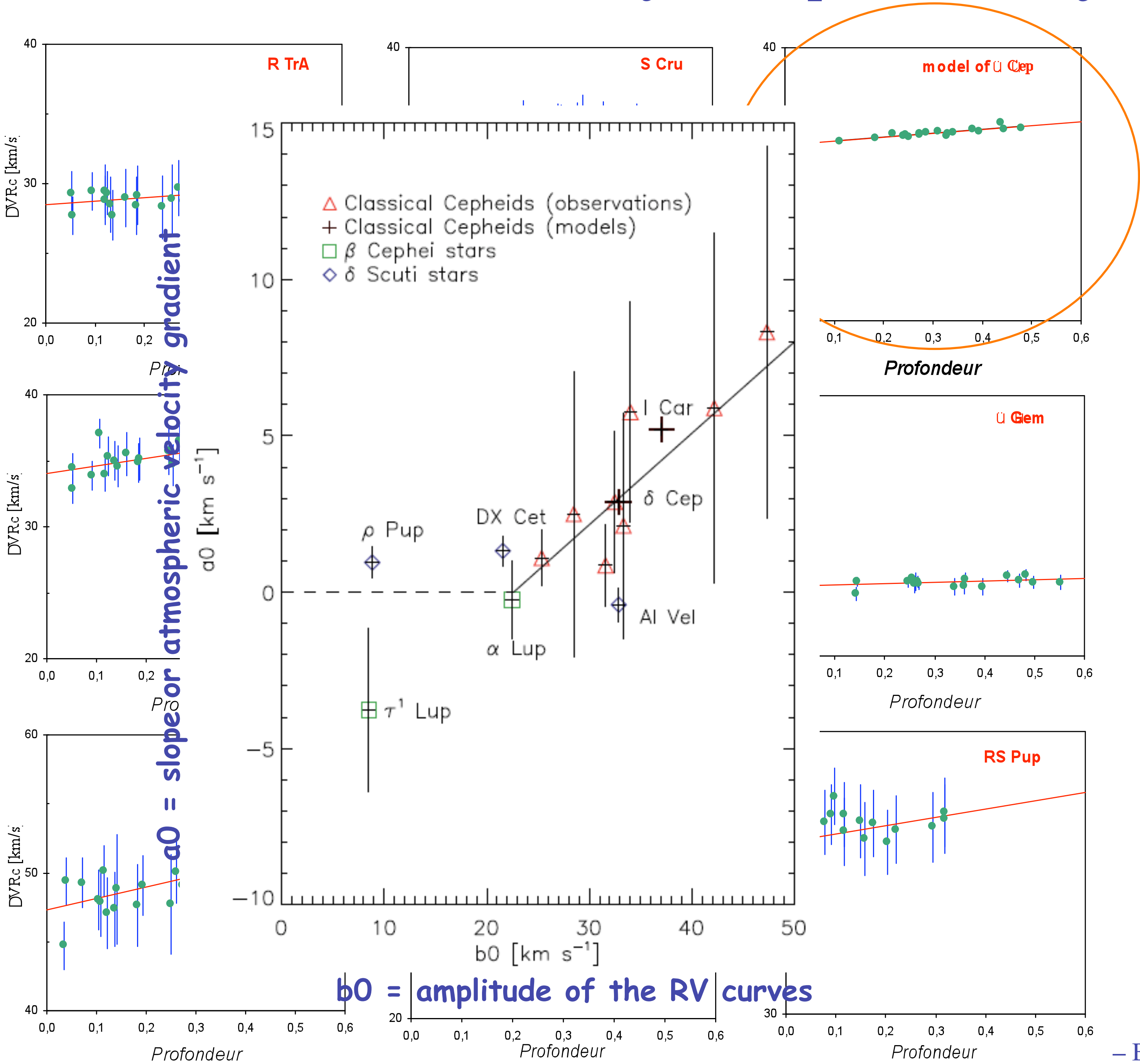
Fokin (1990, 1991)

The impact of the velocity gradient in the atmosphere

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**



HARPS observation of 10 Cepheids (P=3j à P=42j)

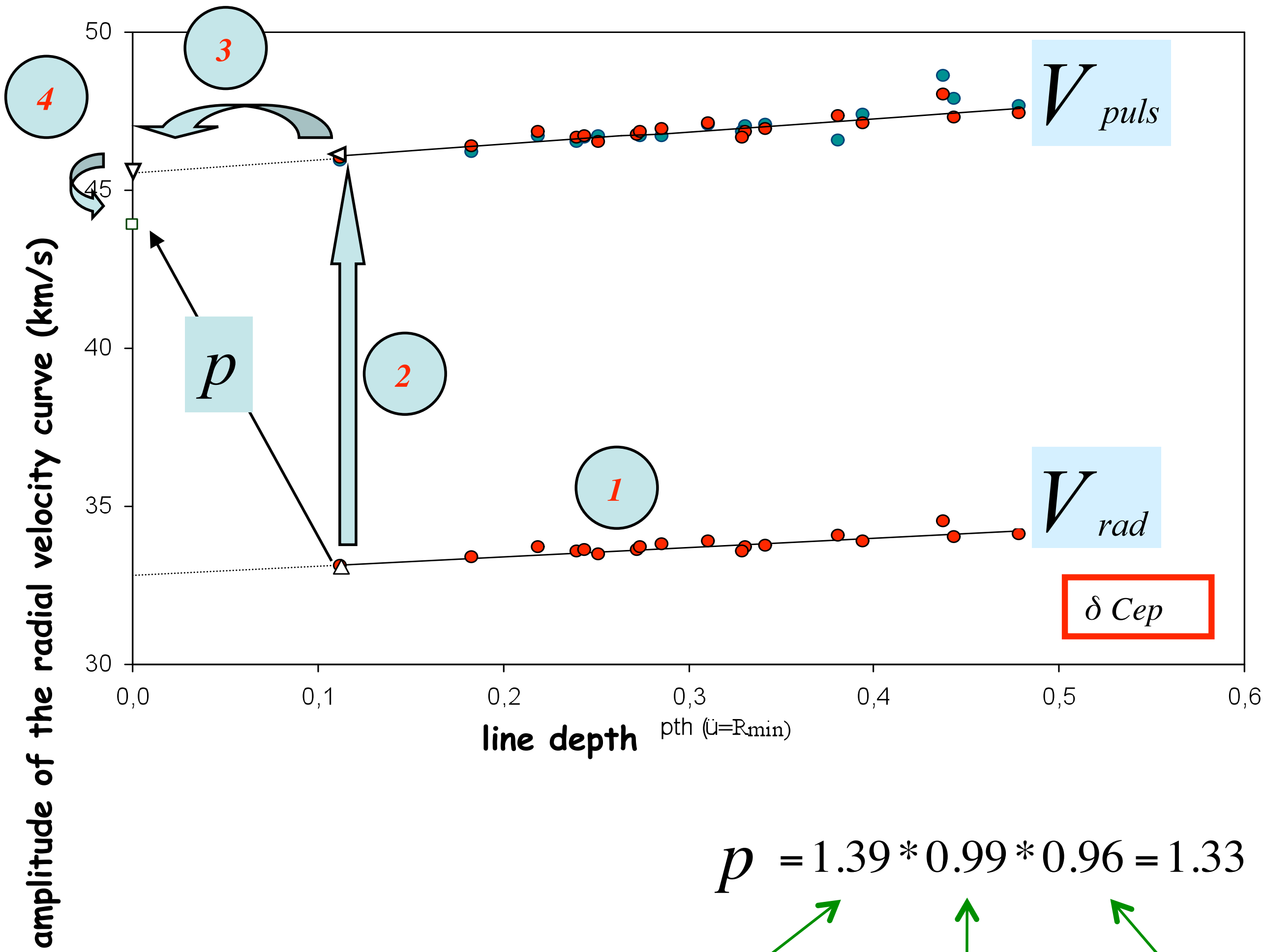


300 spectra
Thousand of lines
17 selected

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

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

Summary : decomposition of the projection factor



N. Nardetto et al., 2007, A&A, 471, 661

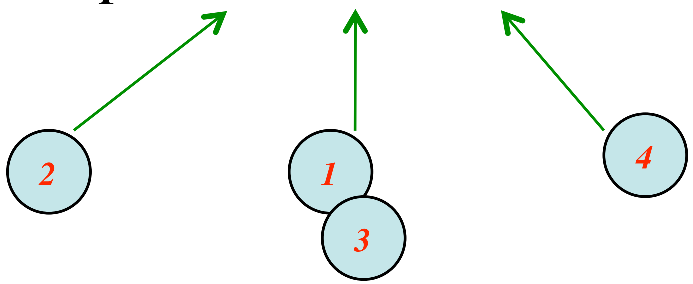
1 – Direct measurement of the velocity gradient (HARPS)

2 – geometric p-factor

3 – extrapolation to the photosphere

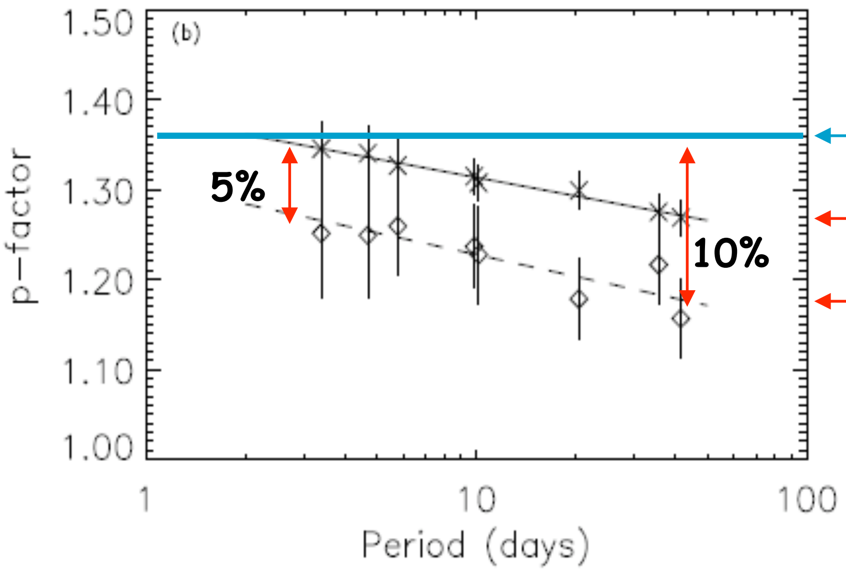
4 – correction optical versus gas layers: code hydro

$$p = 1.39 * 0.99 * 0.96 = 1.33$$



Impact of the projection factor on the distance

High resolution spectroscopy for Cepheids distance determination
V. Impact of the cross-correlation on the p-factor and the c-velocity
N. Nardetto, W. Gieren, P. Kervella, P. Fouqué, J. Storm, G. Pietrzynski, D. Mourard, D. Queloz, 2009, A&A, 502, 951



traditional static value (p=1.36 – Burki et al. 1982)

first moment of the spectral line

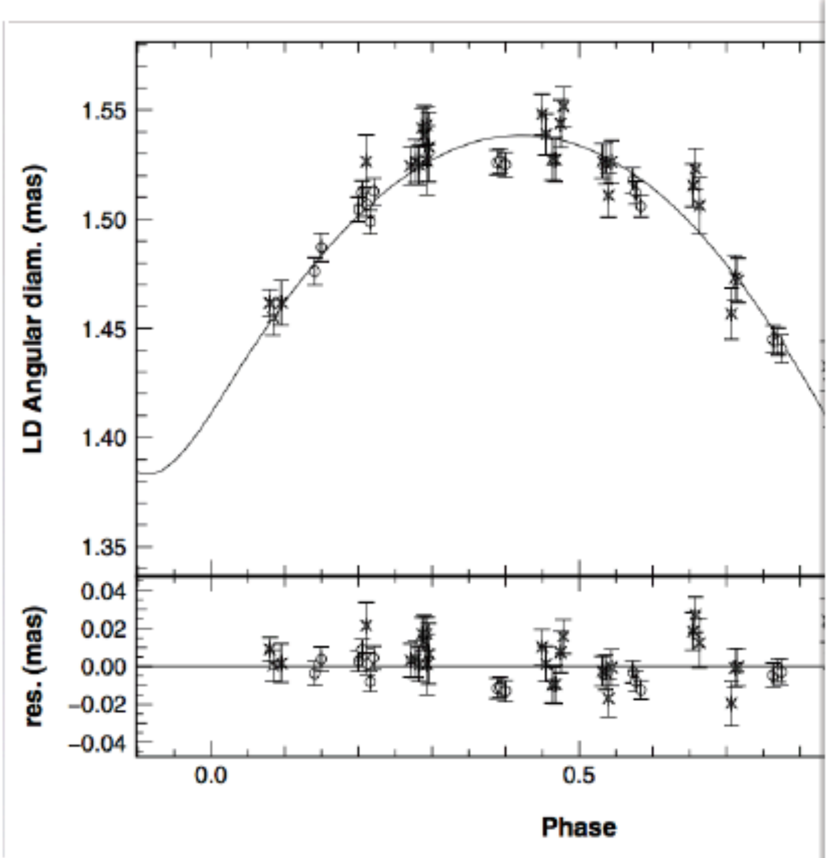
cross-correlation

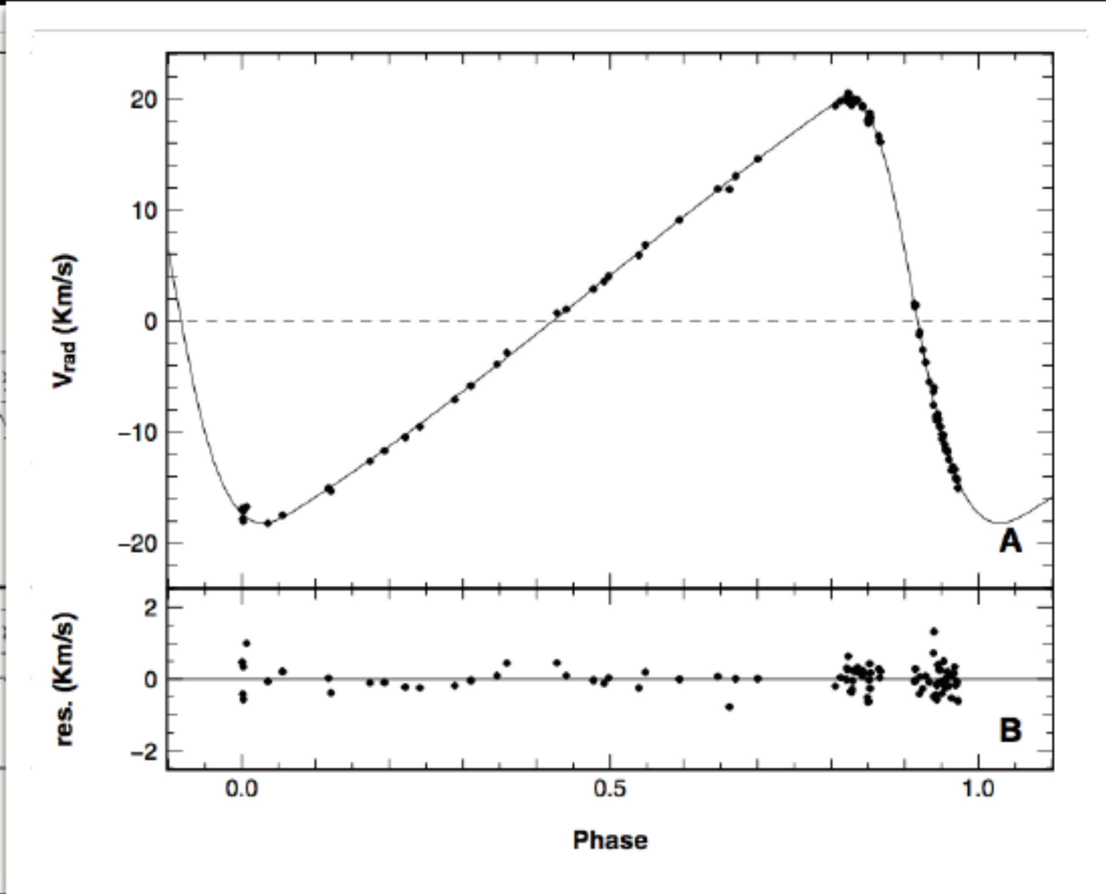
$$p = -[0.08 \pm 0.05]\log P + [1.31 \pm 0.06]$$

→ the static approach leads to an overestimation of the distances from 5% (for short-period Cepheid) up to 10% (for long period Cepheids).

for δ Cep (P=5.36 days) p=1.25+/-0.05

δ CEP : A MEASUREMENT OF *p*

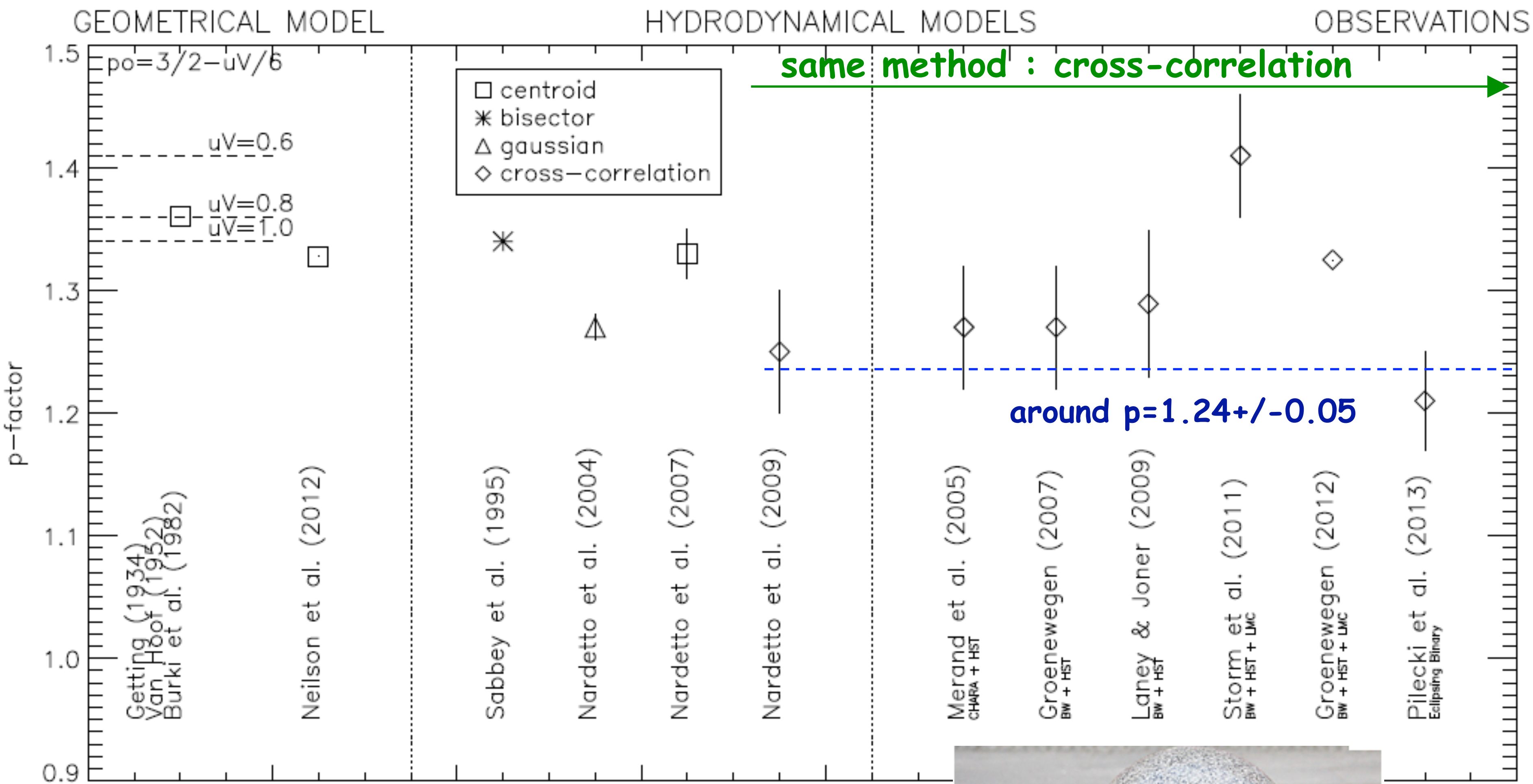




p-factor = 1.27 ± 0.06, with d=274 ± 11 pc from HST-FGS

Mérand et al. 2005, A&A 438, L9

History of the projection factor of δ Cep

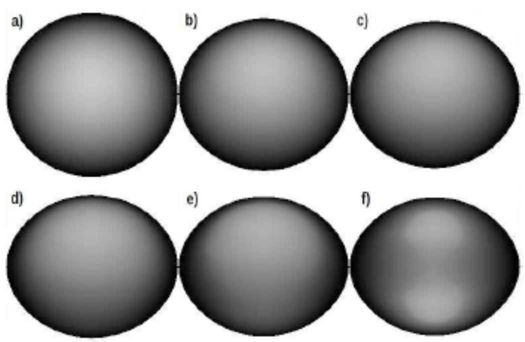


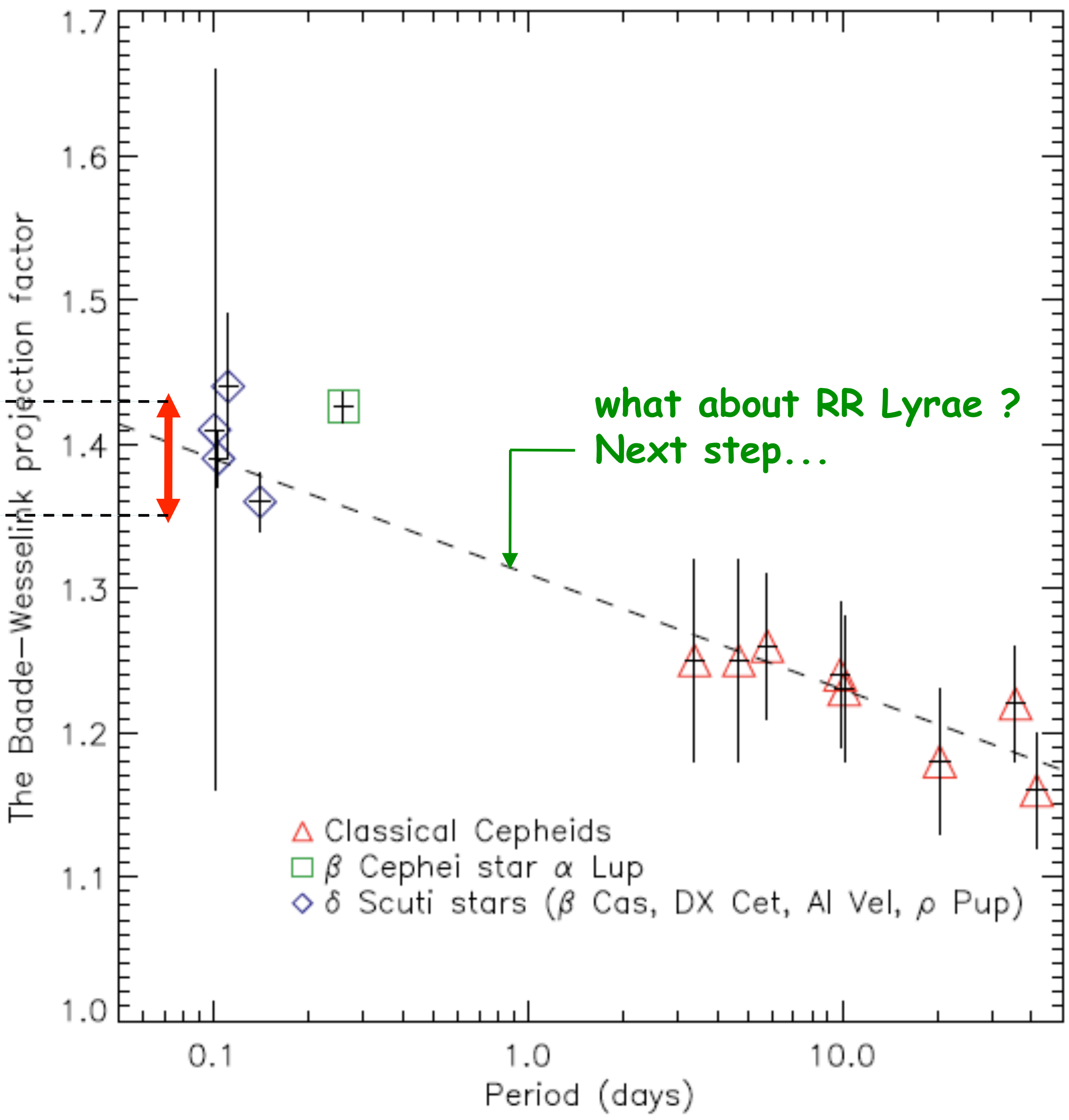
inconsistency of p for Storm et al. 2011ab but no impact on the distances (the method is self calibrated by HST + LMC Cepheids) – this is under investigation...

The projection factor for other kind of pulsating stars

Nardetto, Poretti et al. **2013**, submitted

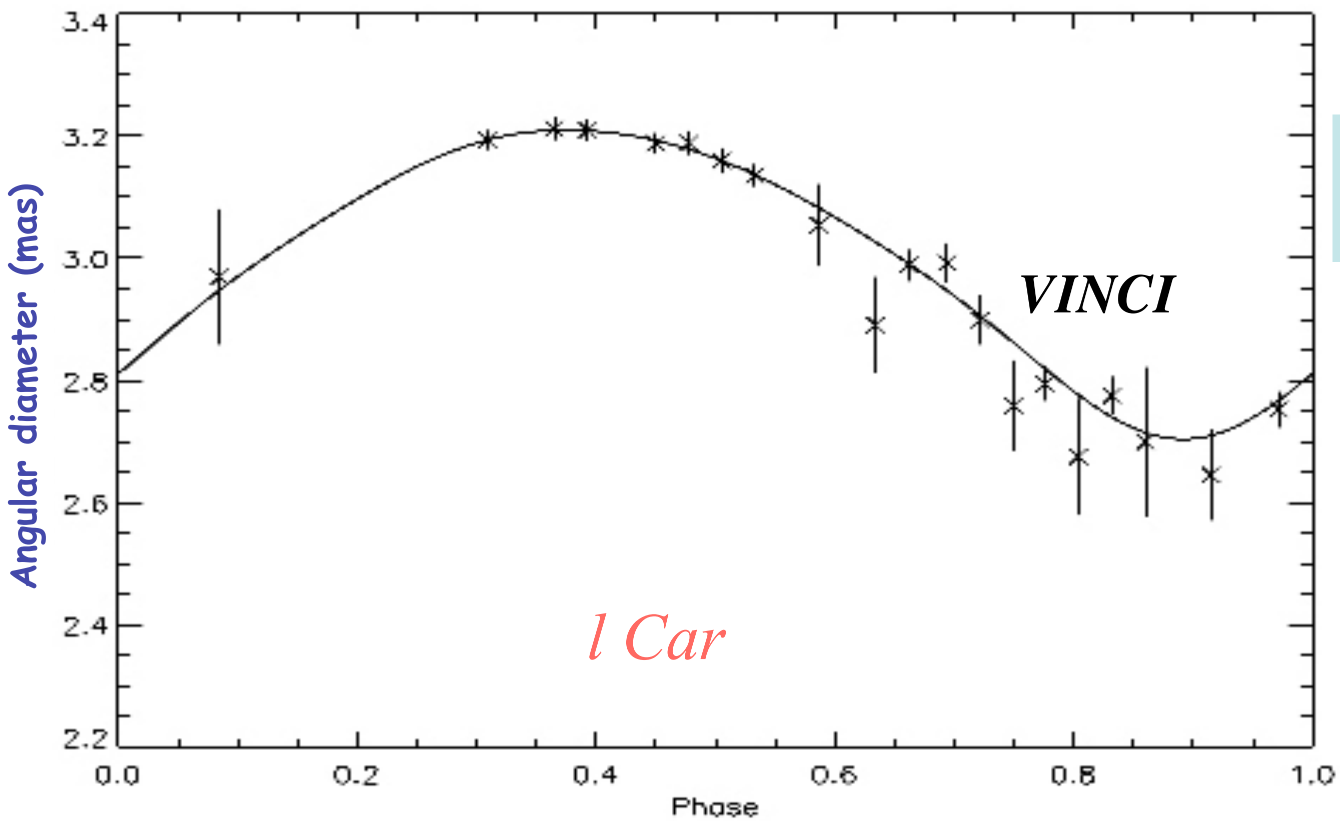
typical impact of the fast rotation and inclination on the projection factor





VINCI/VLTI observations of seven galactic cepheids

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



statistical uncertainty

$$d = 603^{+24}_{-19}\begin{bmatrix} 24 & 3 \\ 19 & 2 \end{bmatrix} pc$$

systematical uncertainty (due to the interferometric calibrator)

Relative precision of 5%

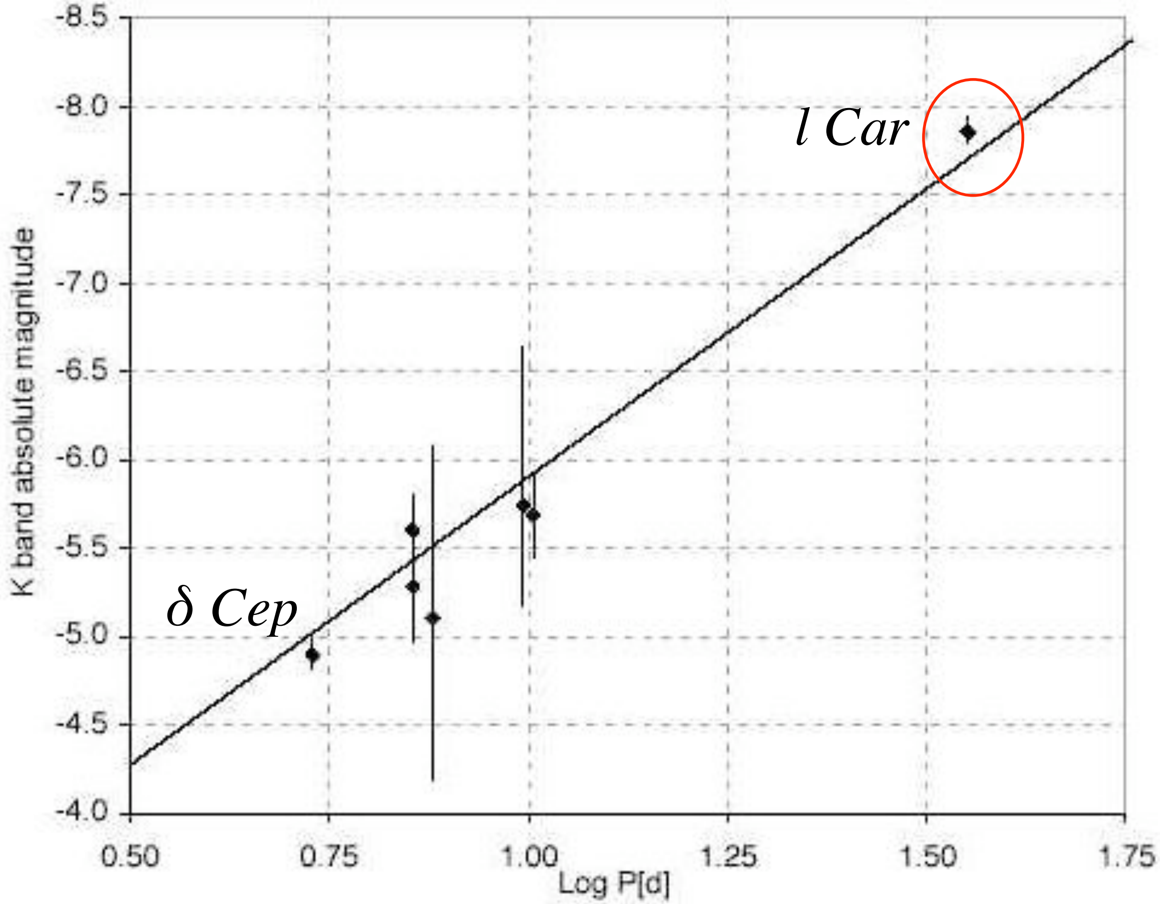
$$\theta_{LD-MODEL}(\phi_i) = \overline{\theta_{LD}} + 9.305\left(\frac{\Delta R(\phi_i)}{d}\right)$$

Fitted parameters

using p=1.36 !

Calibration of the Period-Luminosity relation

Cepheid distances from infrared long-baseline interferometry
II. Calibration of the period-radius and peiod-luminosity relations
P. Kervella, D. Bersier, D. Mourard, N. Nardetto, and V. Coudé du Foresto, **2004**, A&A, 423, 327



precision in magnitude on the zero-point of 0.06 in K band

$$M_K = \alpha_K(\log P - 1) + \beta_K$$

$\alpha_K = -3.267 \pm 0.042$

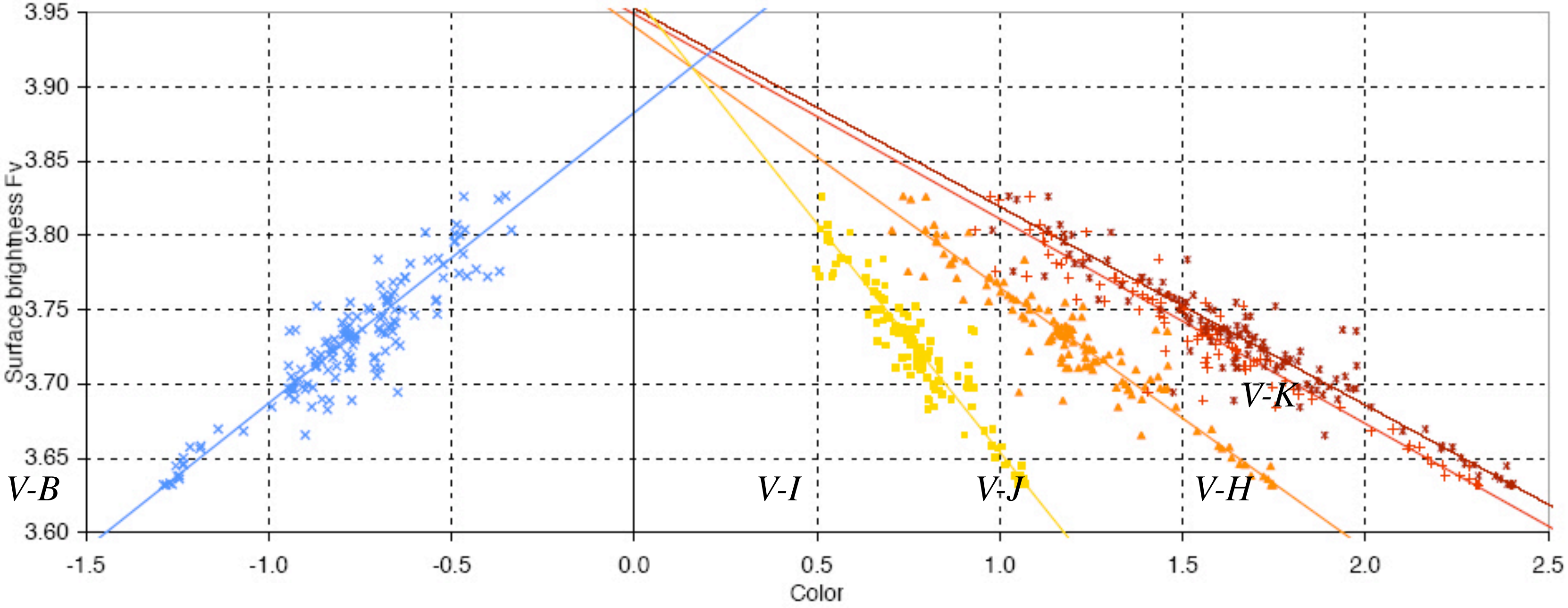
$\beta_K = 5.904 \pm 0.063$

Calibration of the surface brightness-color relation

Cepheid distances from infrared long-baseline interferometry
III. Calibration of the surface brightness-color relations

P. Kervella, D. Bersier, D. Mourard, N. Nardetto, P. Fouqué, and V. Coudé du Foresto, **2004**, A&A, 428, 587

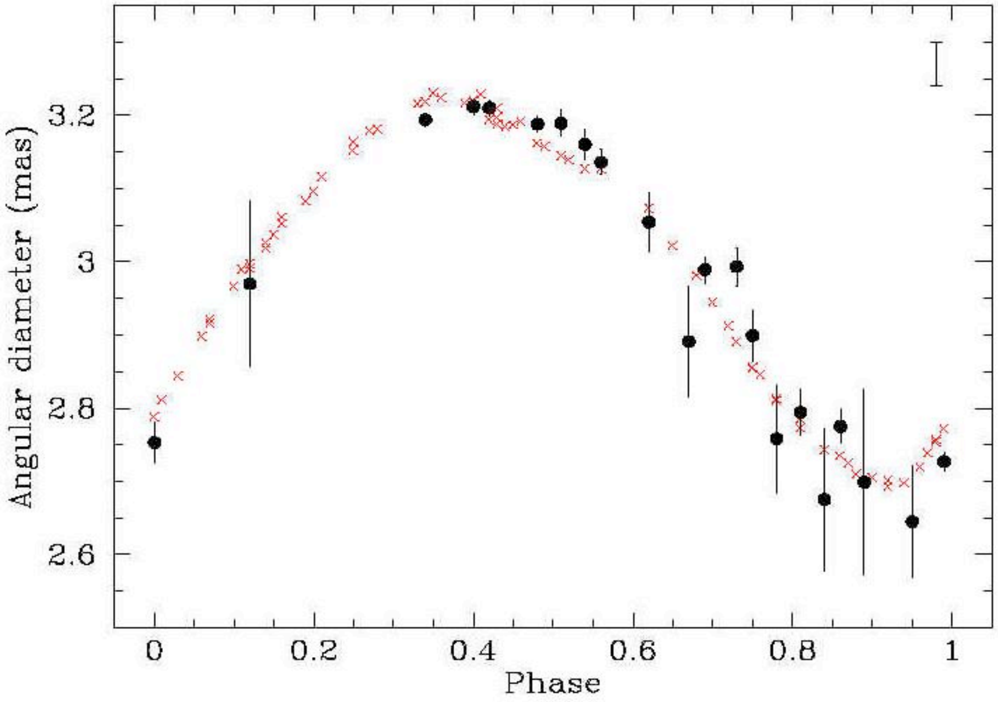
Relation between the surface brightness (F), the magnitude (V) and the interferometric limb-darkened angular diameter



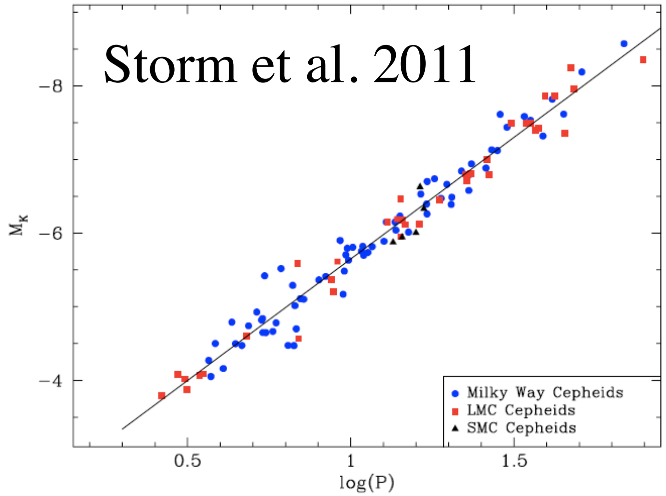
$$F_{V_0} = (3.9530 \pm 0.0006) - (0.1336 \pm 0.0008)(V - K)_0$$

A comparison of the interferometric and the photometric version of the Baade-Wesselink method

The angular size of the Cepheid l Car : a comparison of the interferometric and surface brightness techniques. P. Kervella, P. Fouqué, J. Storm, W. P. Gieren, D. Bersier, D. Mourard, N. Nardetto, V. Coudé Du Foresto. (ApJ)



Consistency of about 1.5%

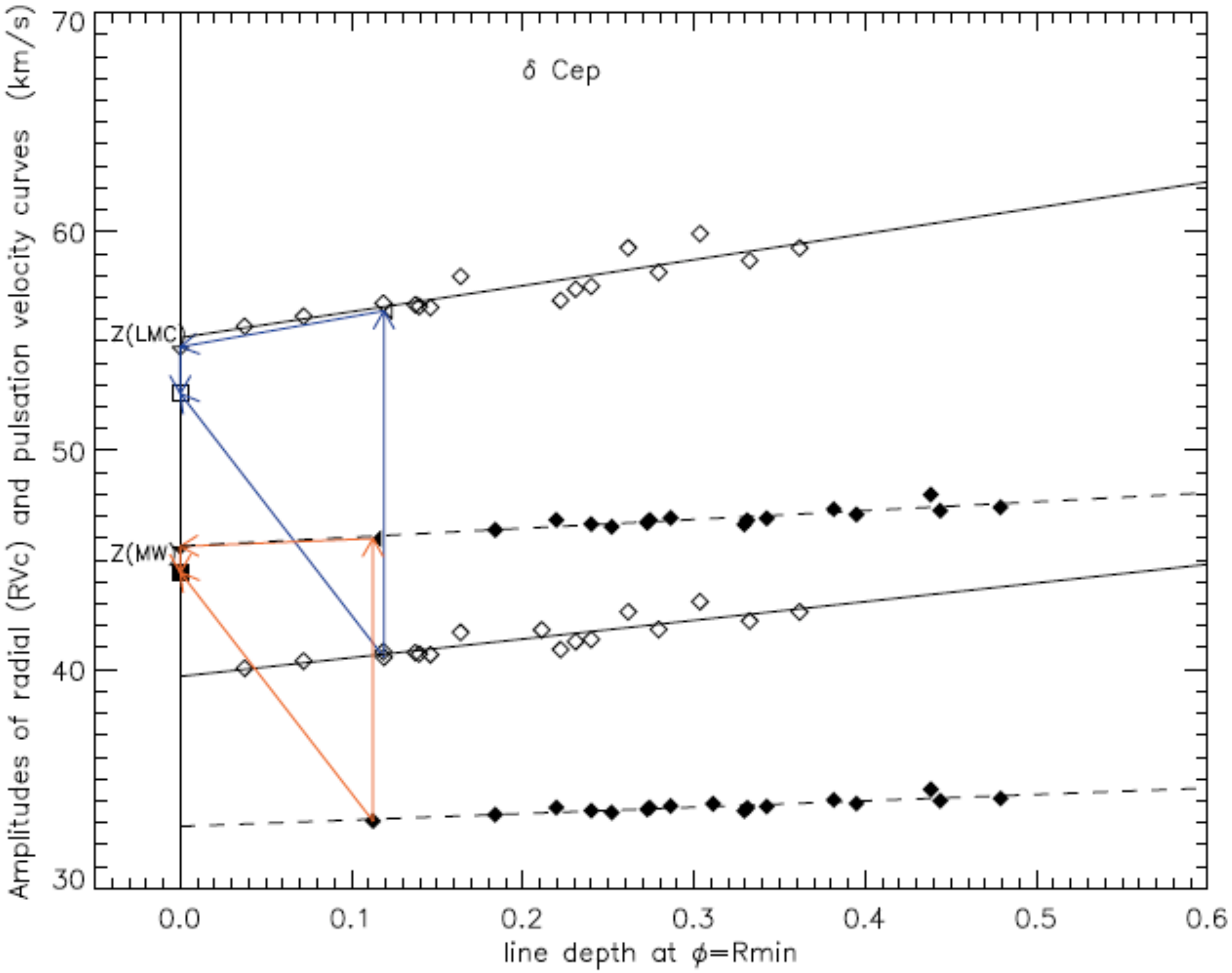


- The infrared surface-brightness relation can be used to derive the distance to Galactic and LMC Cepheids
- The surface brigthness relation is a tool which is used also for the eclipsing binary method

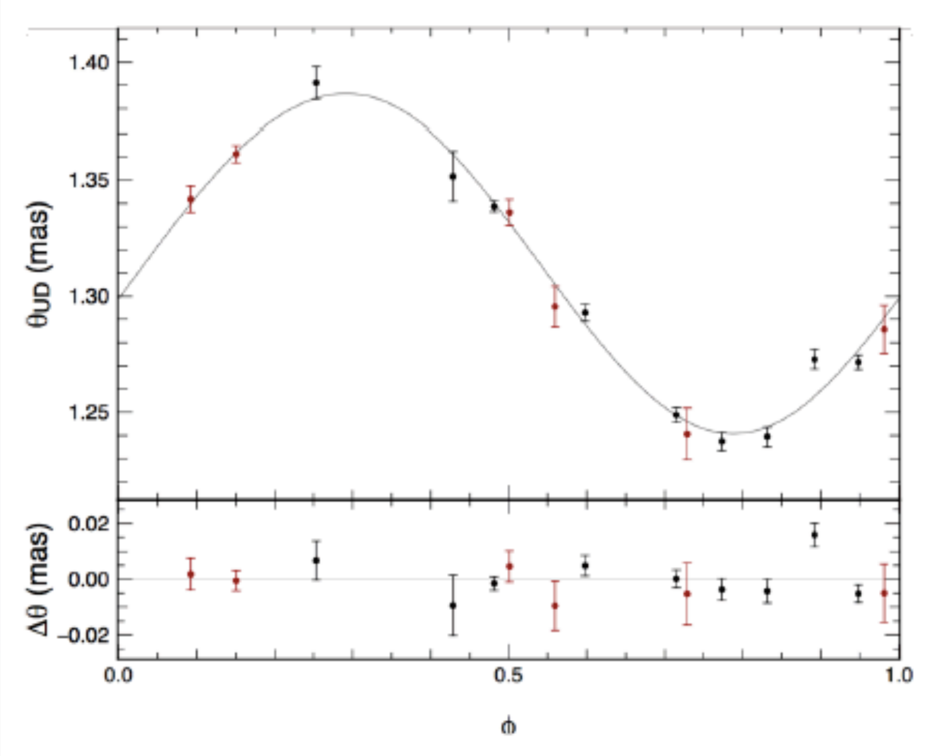
The p-factor applicable to LMC cepheids (from models)

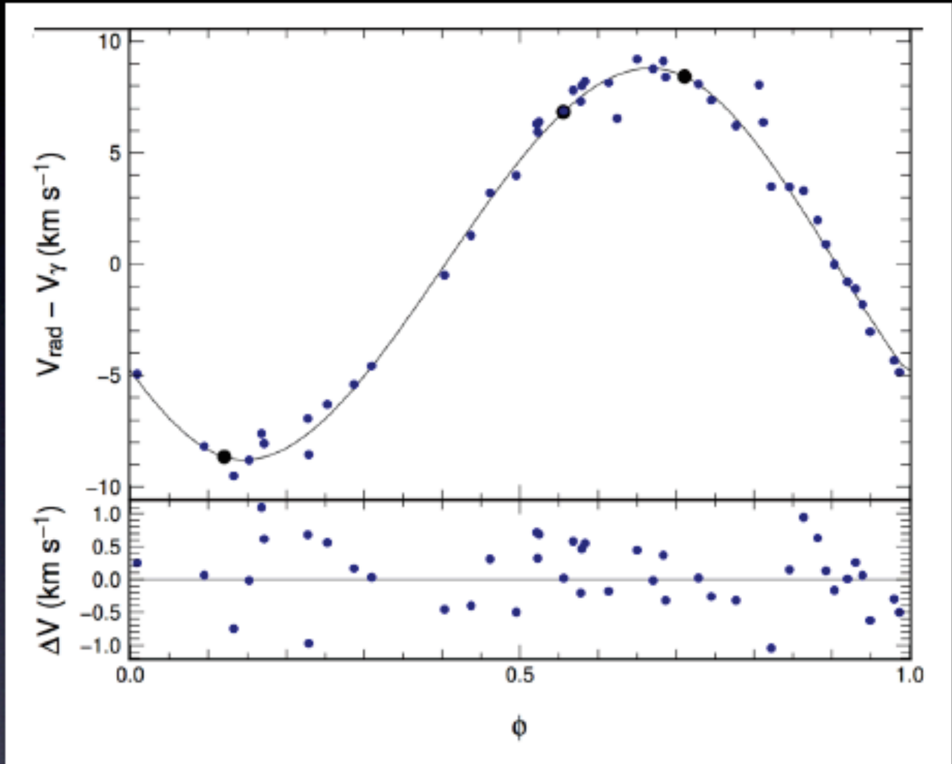
LMC:
M=4.8Ms
L=2290Ls
Teff=6100K
X=0.73
Y=0.262
Z=0.008
Period=5.38d.
p=1.325

MW:
M=4.8Ms
L=1995Ls
Teff=5877K
X=0.70
Y=0.28
Z=0.02
Period=5.41d.
p=1.305



Y Oph





Distance: 472 ± 18 pc (4%) for p = 1.27 and k = 0.983

Mérand et al. 2007, ApJ 664, 1087
Gallenne et al. 2011, in prep.

Slide by Pierre Kervella

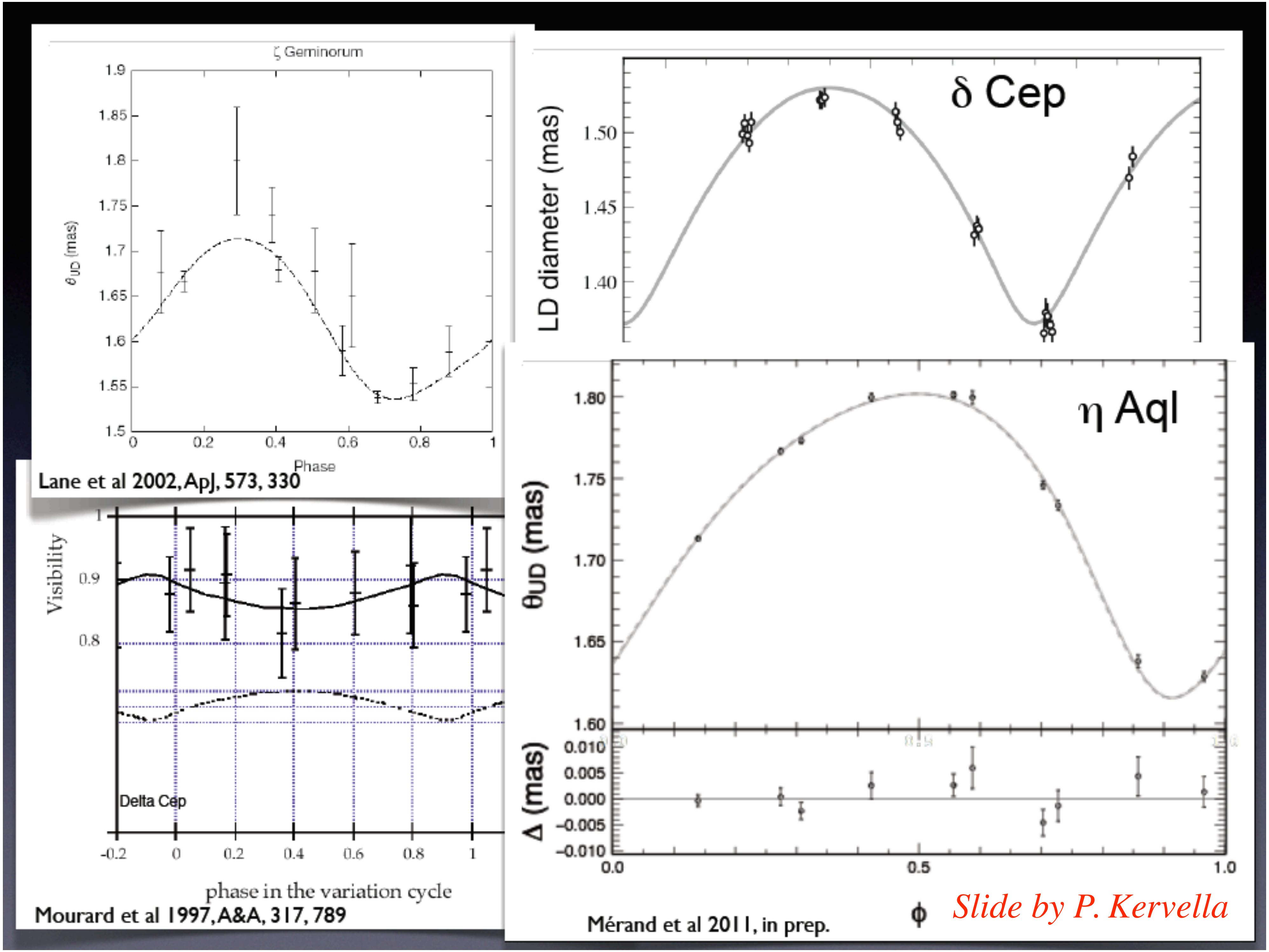
Cepheids Observed by Interferometry

SV Vul (45.0 d)
[RS Pup] (41.4 d)
L Car (35.6 d)
T Mon (27.0 d)
X Cyg (16.4 d)
TT Aql (13.8 d)
ζ Gem (10.2 d)
β Dor (9.84 d)
V636 Cas (8.38 d)
S Sge (8.38 d)
U Vul (7.99 d)
W Sgr (7.59 d)

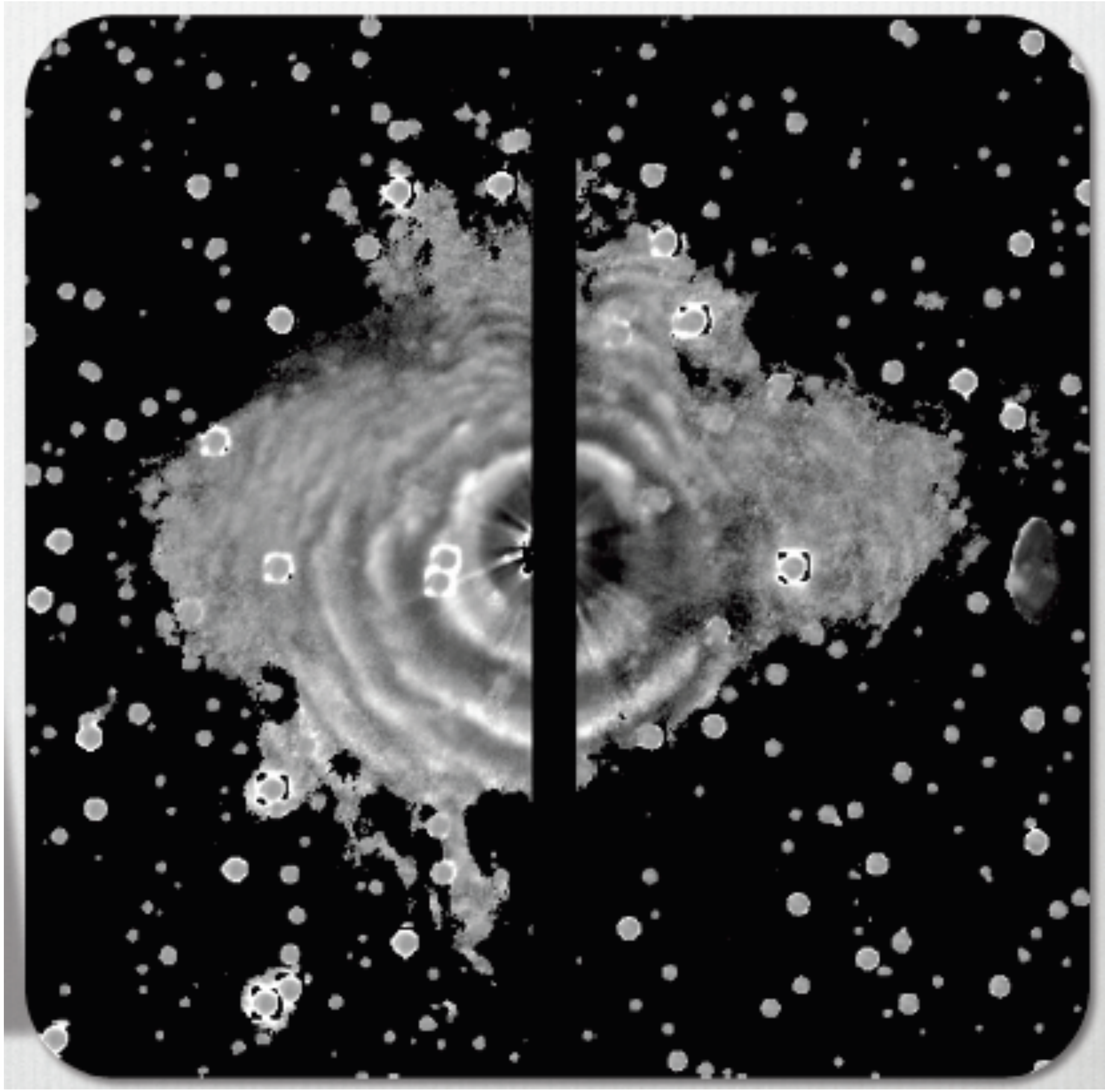
V440 Per (7.57 d)
η Aql (7.17 d)
U Aql (7.02 d)
X Sgr (7.01 d)
U Sgr (6.75 d)
Y Sgr (5.77 d)
δ Cep (5.36 d)
FF Aql (4.47 d)
T Vul (4.44 d)
[Polaris] (3.97 d)
SZ Tau (3.15 d)
SU Cas (1.95 d)

Slide by Pierre Kervella

24 stars total, 22 stars for IBW, 9 with FGS parallax

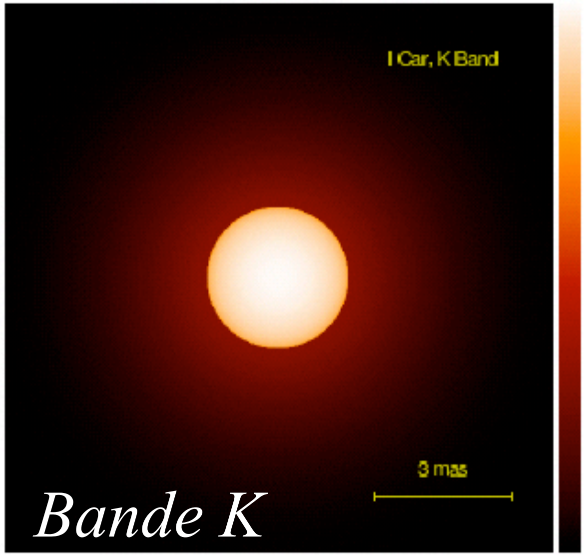

ζ Geminorum
θUD (mas)
1.9
1.85
1.8
1.75
1.7
1.65
1.6
1.55
1.5
0
0.2
0.4
0.6
0.8
1
Phase
Lane et al 2002, ApJ, 573, 330
δ Cep
LD diameter (mas)
1.50
1.45
1.40
η Aql
θUD (mas)
1.80
1.75
1.70
1.65
1.60
Δ (mas)
0.010
0.005
0.000
−0.005
−0.010
0.0
0.5
1.0
ϕ
Visibility
1
0.9
0.8
Delta Cep
-0.2
0
0.2
0.4
0.6
0.8
1
phase in the variation cycle
Mourard et al 1997, A&A, 317, 789
Mérand et al 2011, in prep.
Slide by P. Kervella

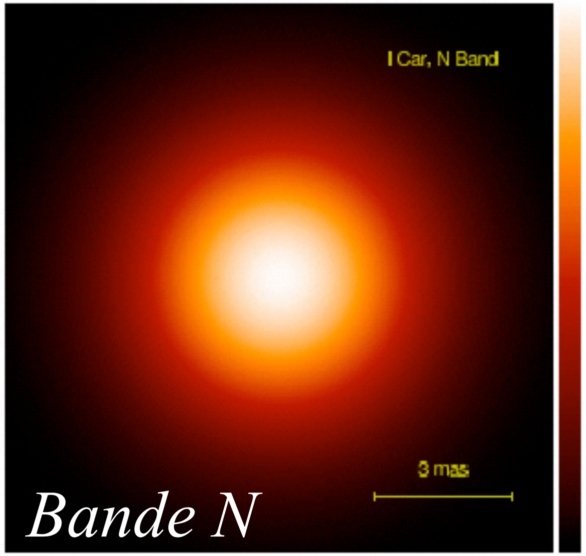
The circumstellar environment of Cepheids (RS Pup)



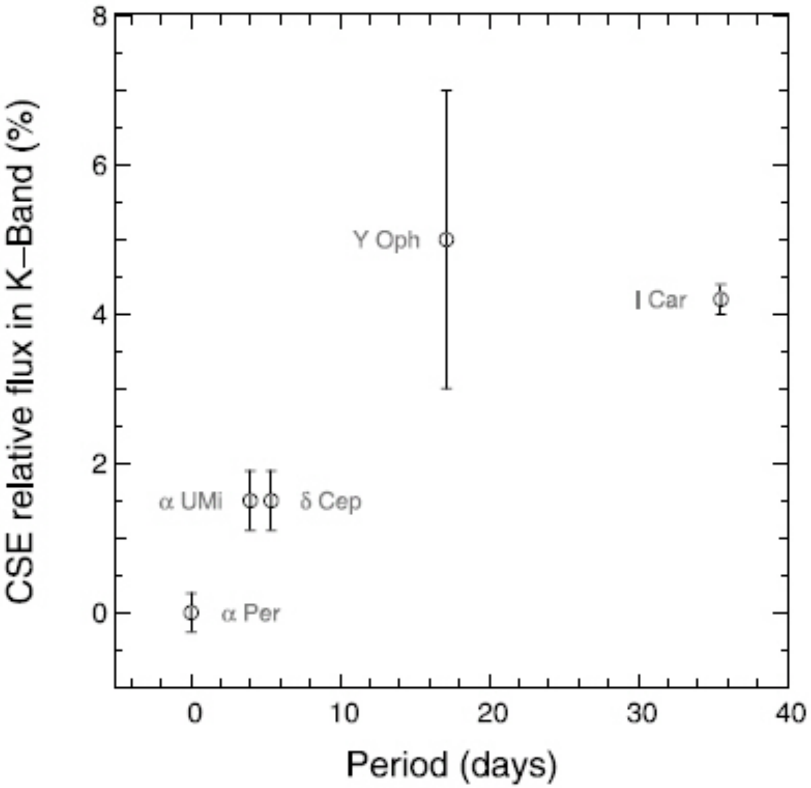
Circumstellar Envelope (CSE) of Cepheids (FLUOR/CHARA)

l Car



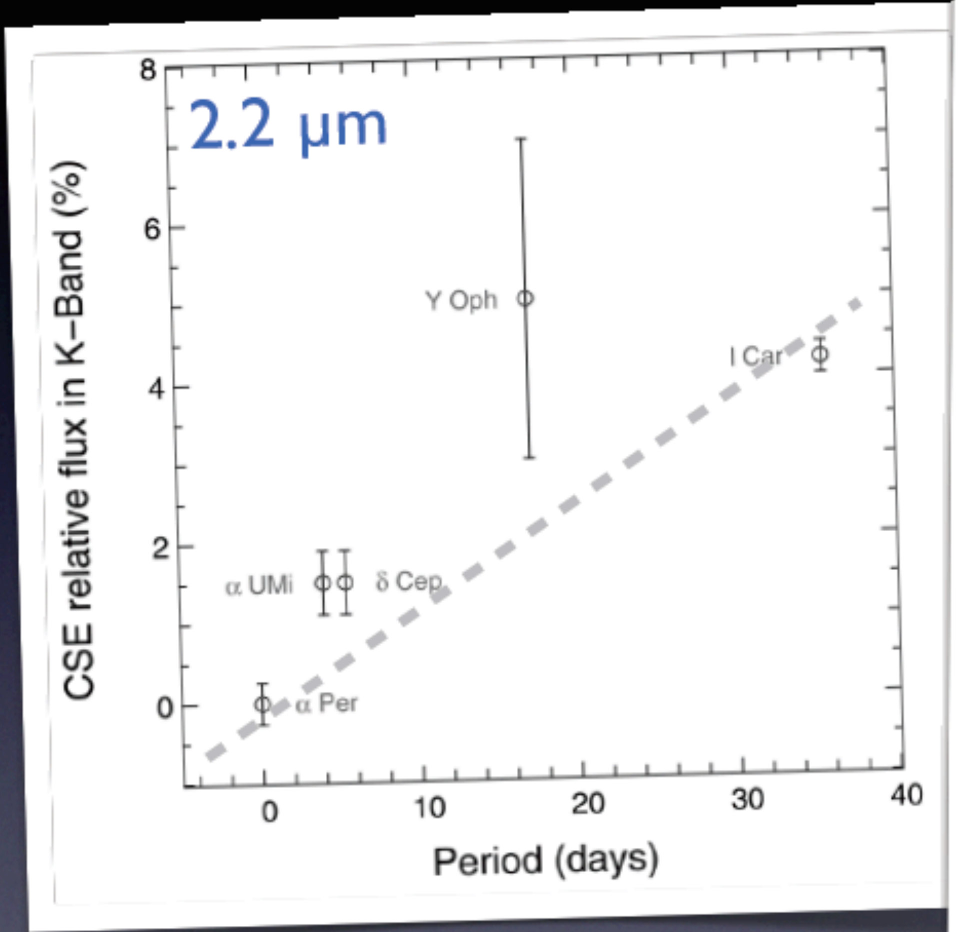


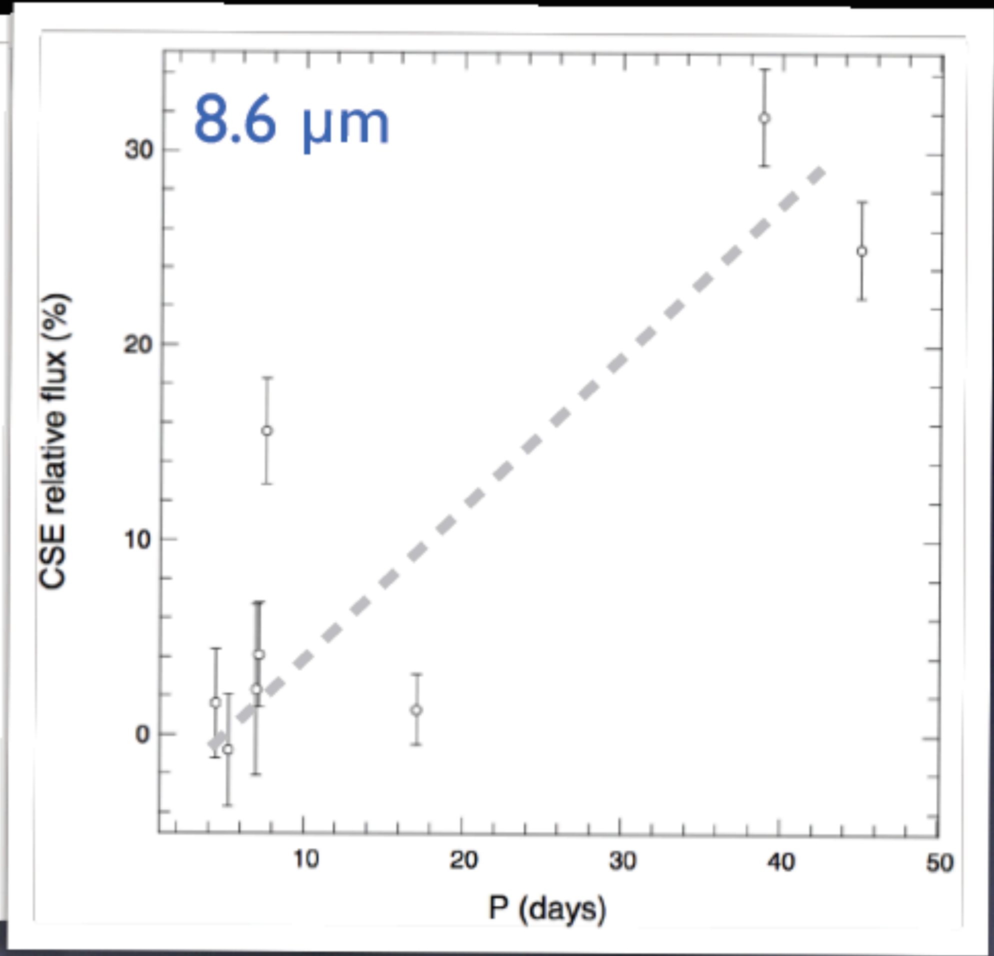
Kervella et al. 2006, A&A, 448, 623



Mérand et al. 2007, A&A, 453, 155

Cepheid envelope contributions

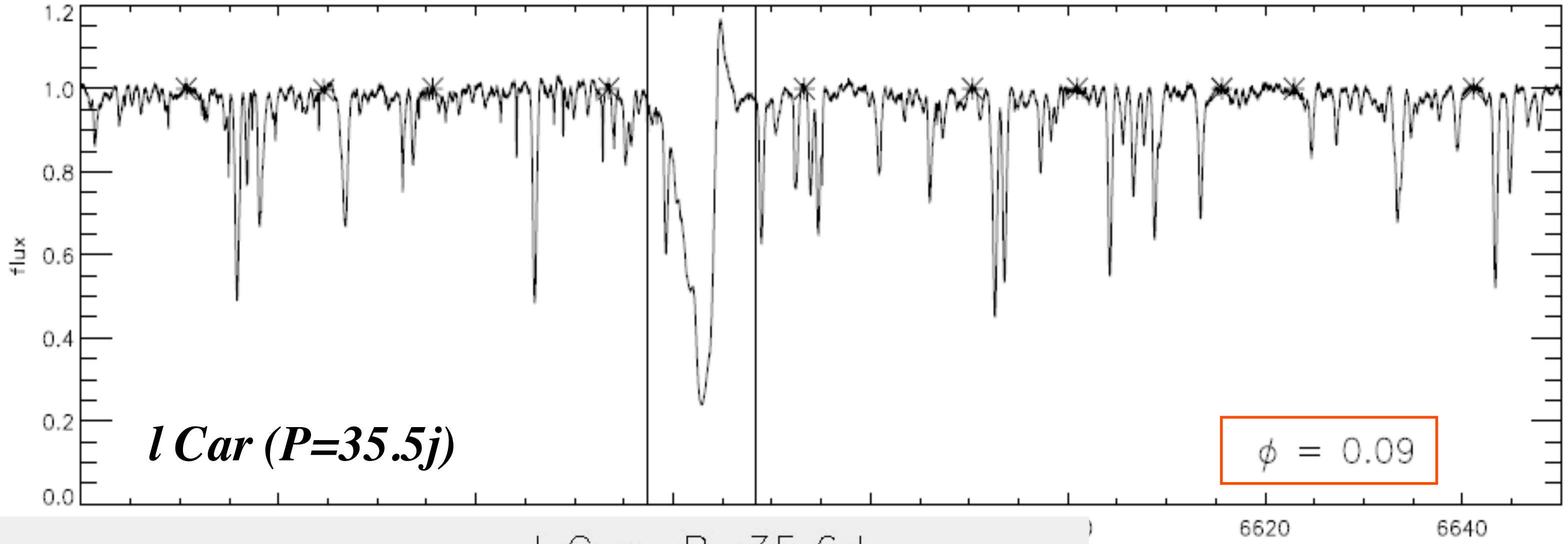


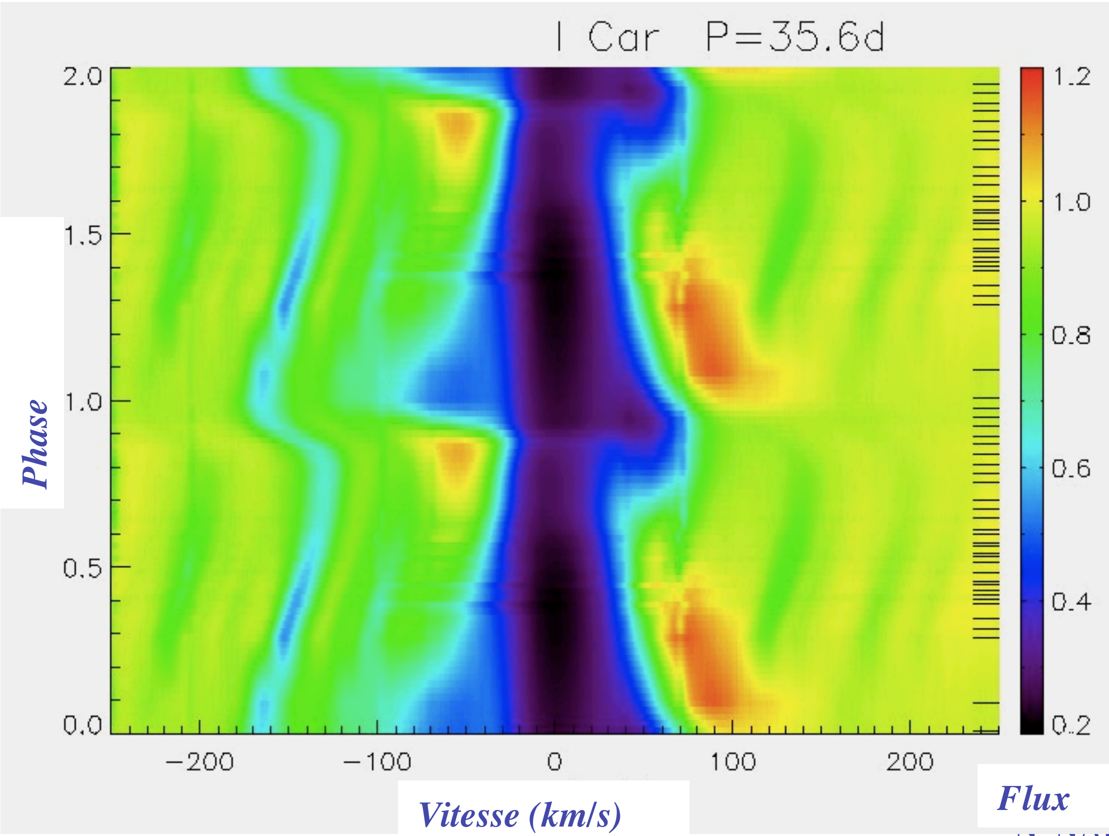


Slide by P. Kervella

Mérand et al. 2007, ApJ 664, 1087
Gallenne et al. 2011, A&A, submitted

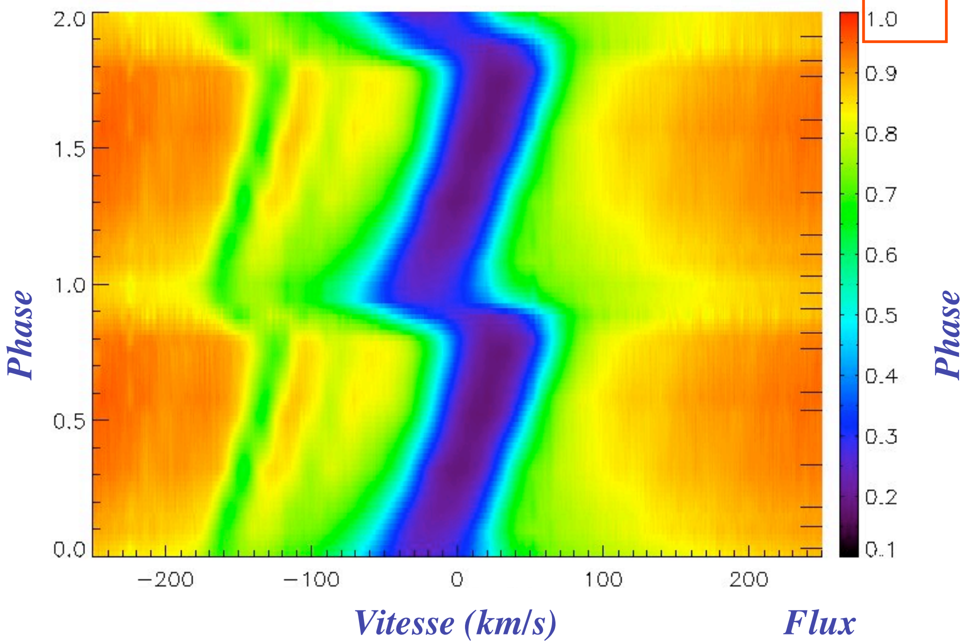
Hα spectral line profile of *l* Car



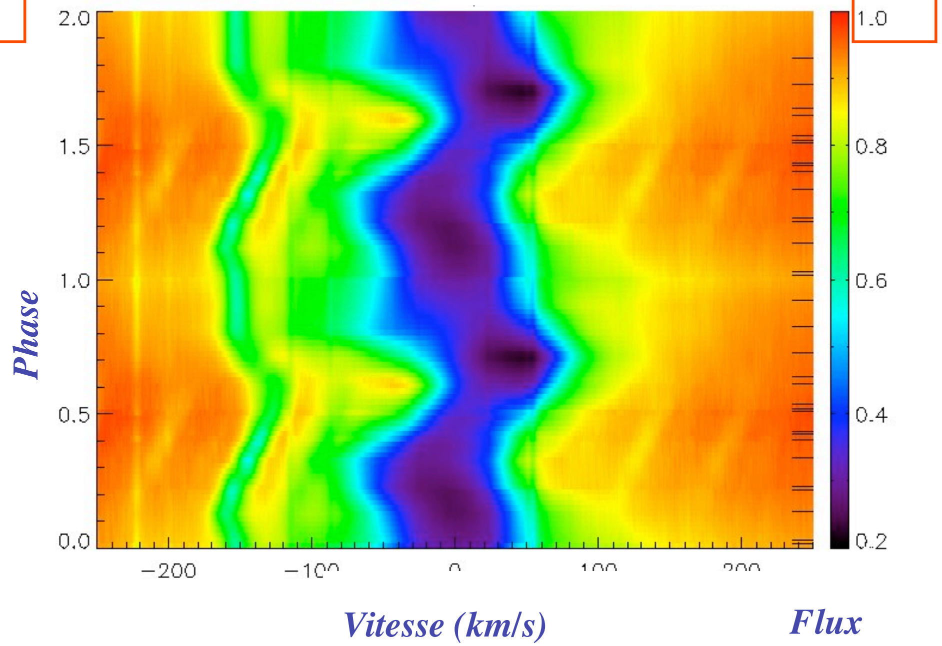


Hα spectral line profile

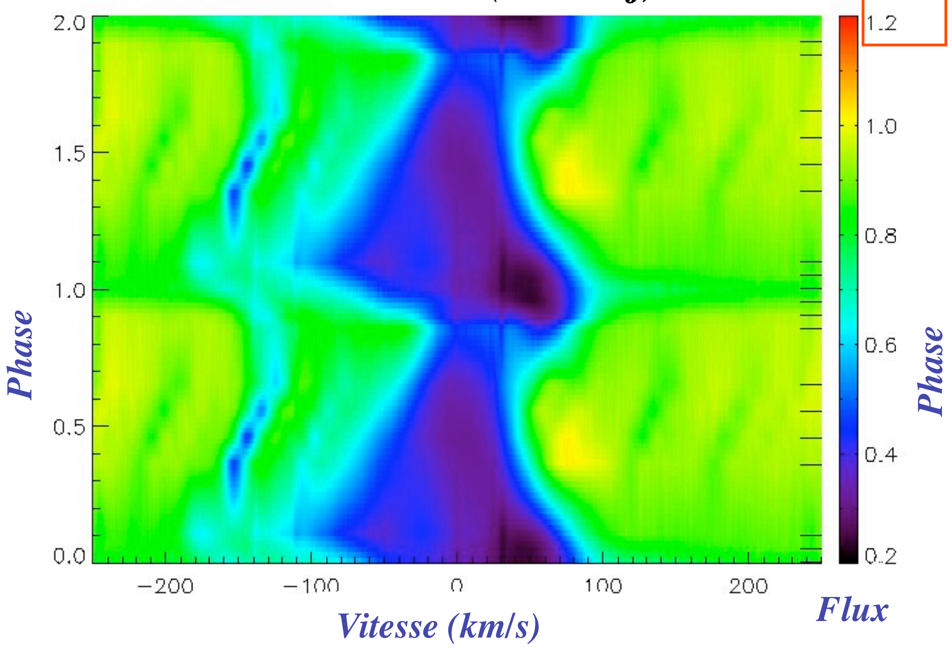
S Cru (P=4.7j)



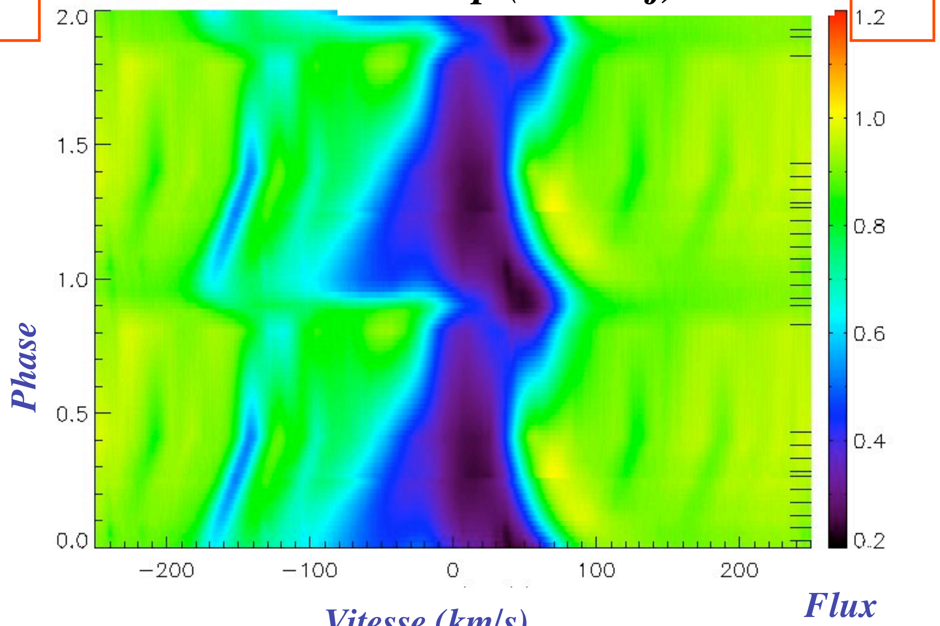
β Dor (P=9.8j)



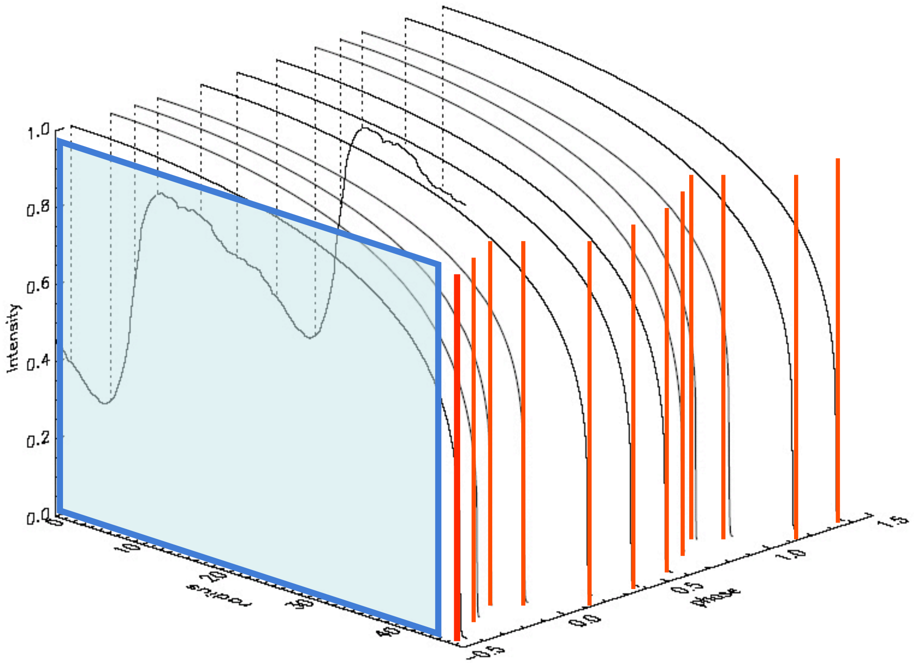
RZ Vel (P=20.4j)

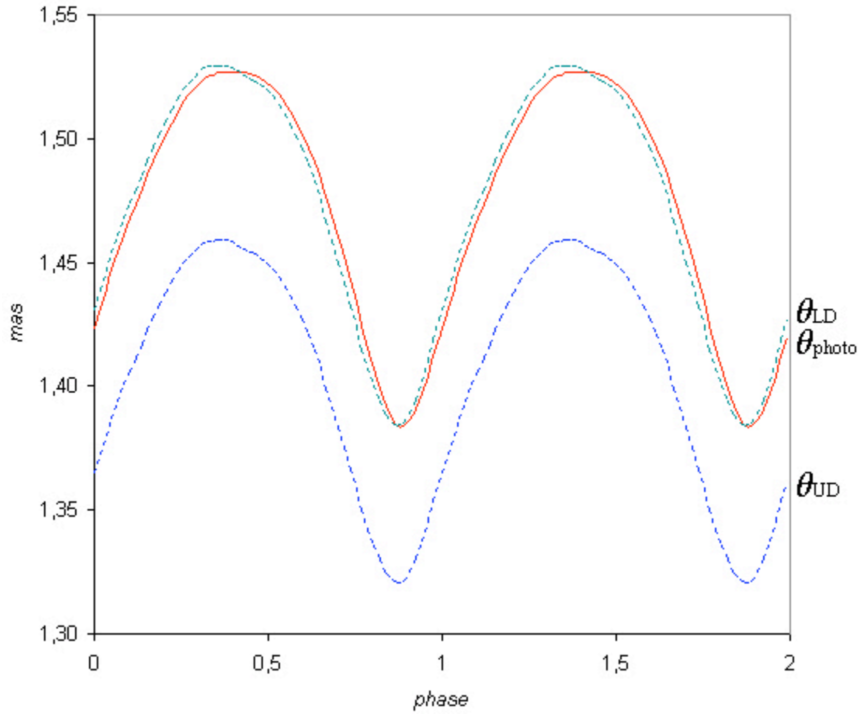


RS Pup (P=41.5j)

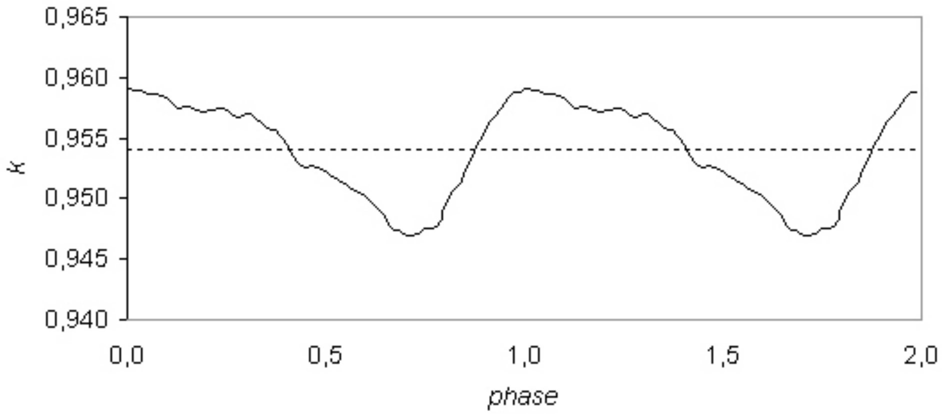


Limb-darkening time variation (model)



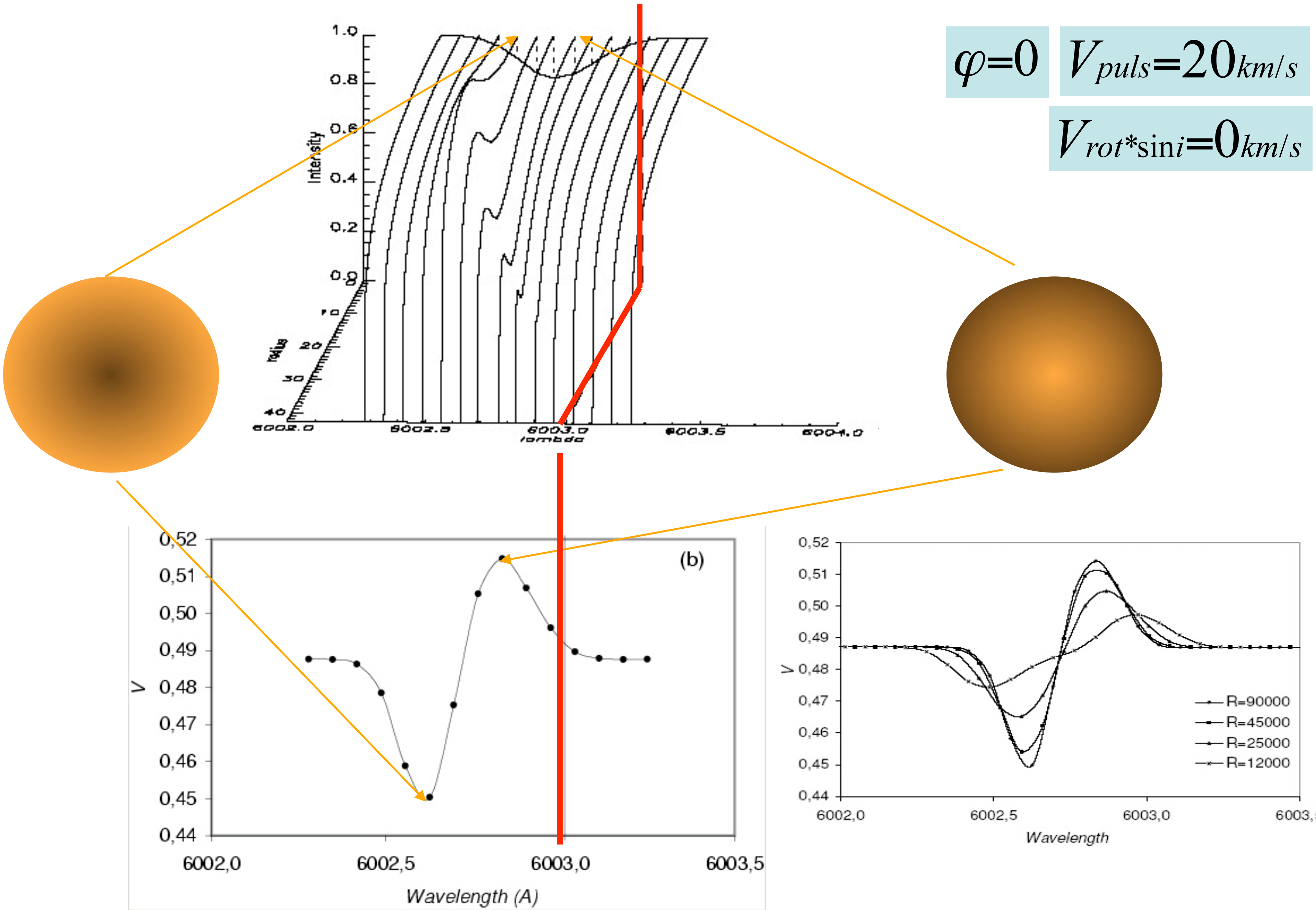


$$k(\varphi) = \frac{\theta_{UD}(\varphi)}{\theta_{photo}(\varphi)}$$



From models, assuming k=cste is acceptable (impact of 0.1% on the distance)

Cepheids and spectro-interferometry (1/3)

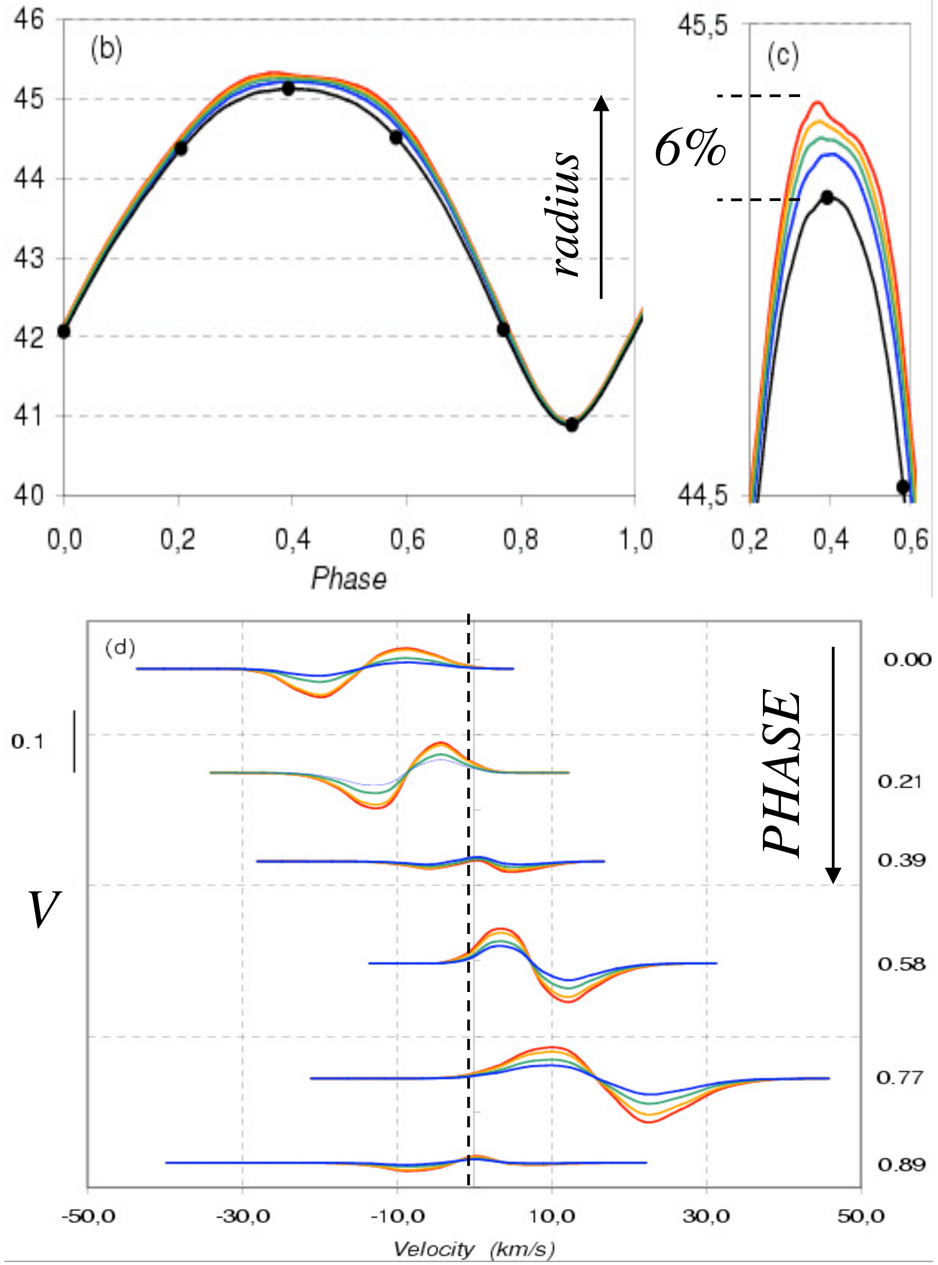


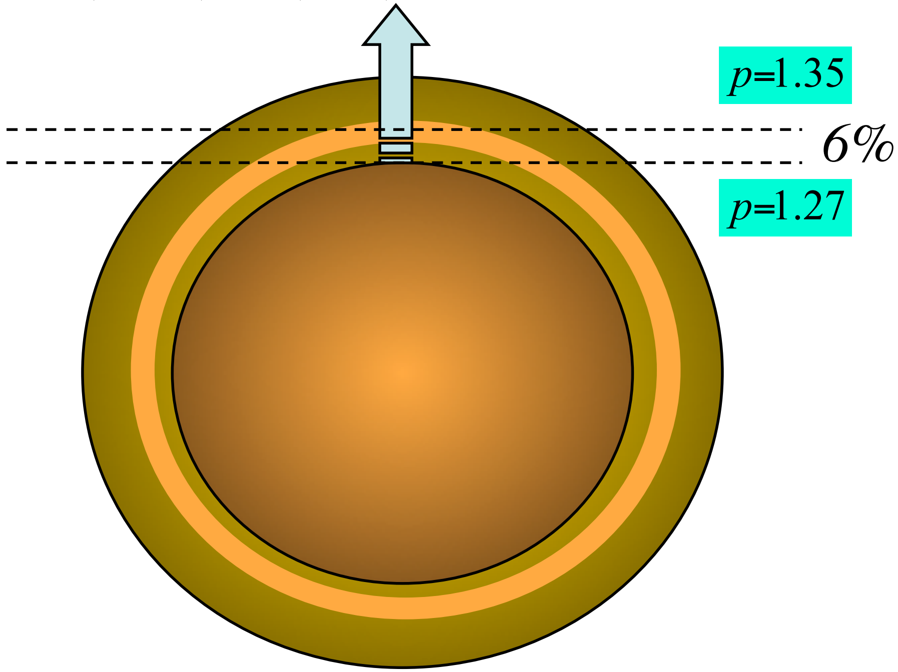
Nicolas NARDETTO – Chili, 2009

Cepheids and spectro-interferometry (2/3)

« Probing the dynamical structure of Cepheid's atmosphere »

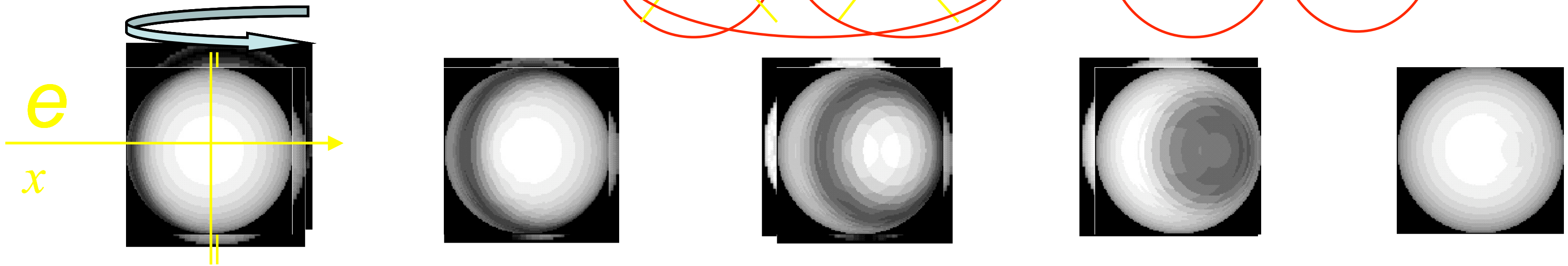
N. Nardetto, F. Fokin, D. Mourard, Ph. Mathias, 2005, A&A, 454, 327



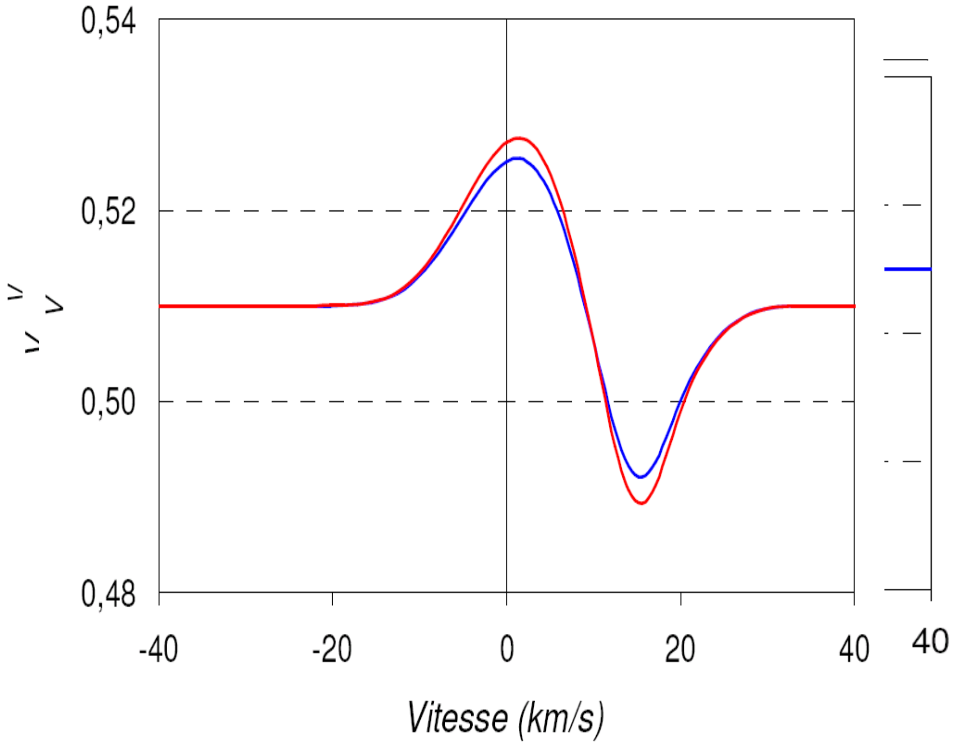


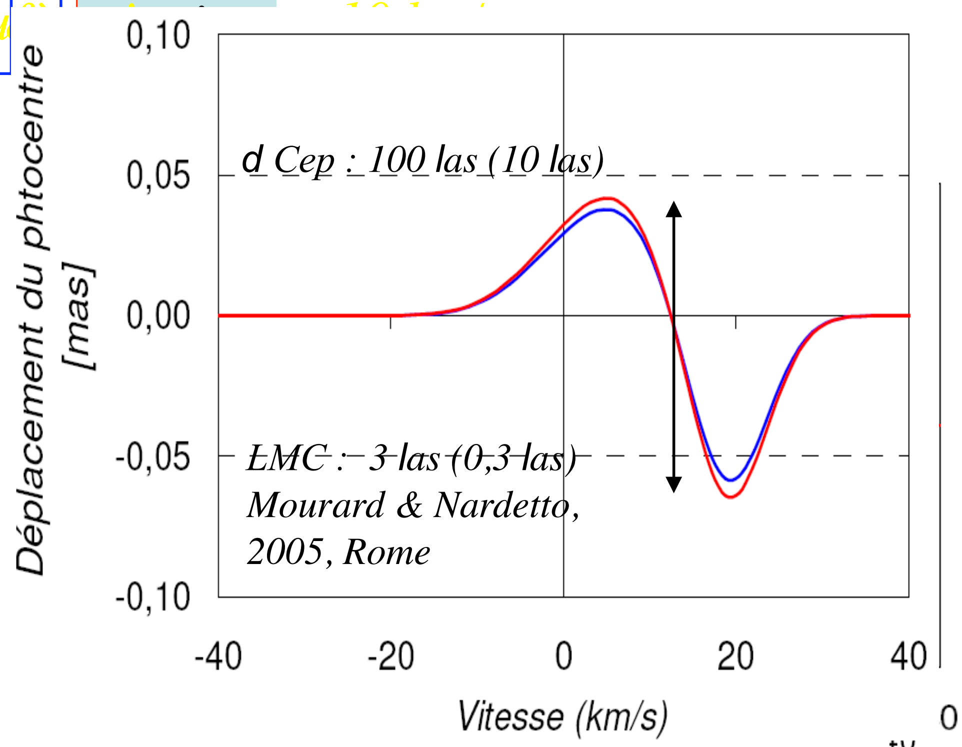
Cepheids and spectro-interferometry (3/3)

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



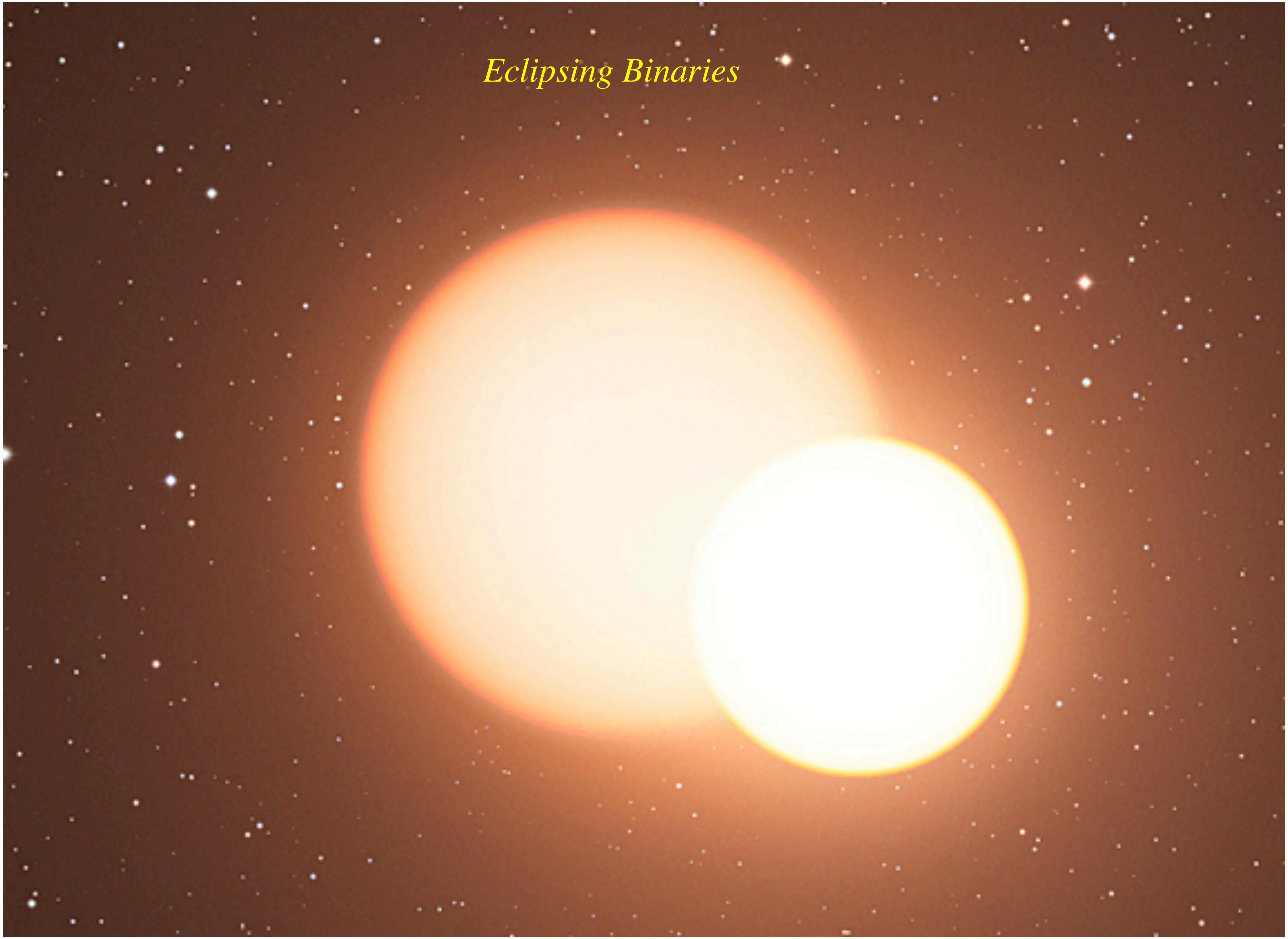
θ de 1.38 mas à 1.53 mas



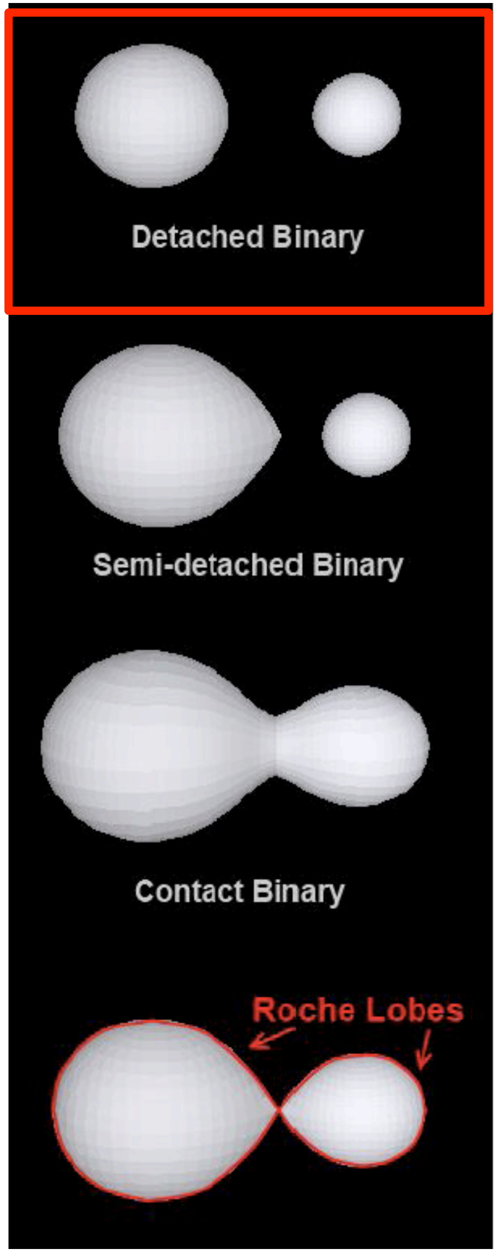


Précision à 1 lm &, B=200m : 1 las (AMBER/VLTI)

Précision à 0.6 lm &, B=300m : 0.5 las (VEGA/CHARA)

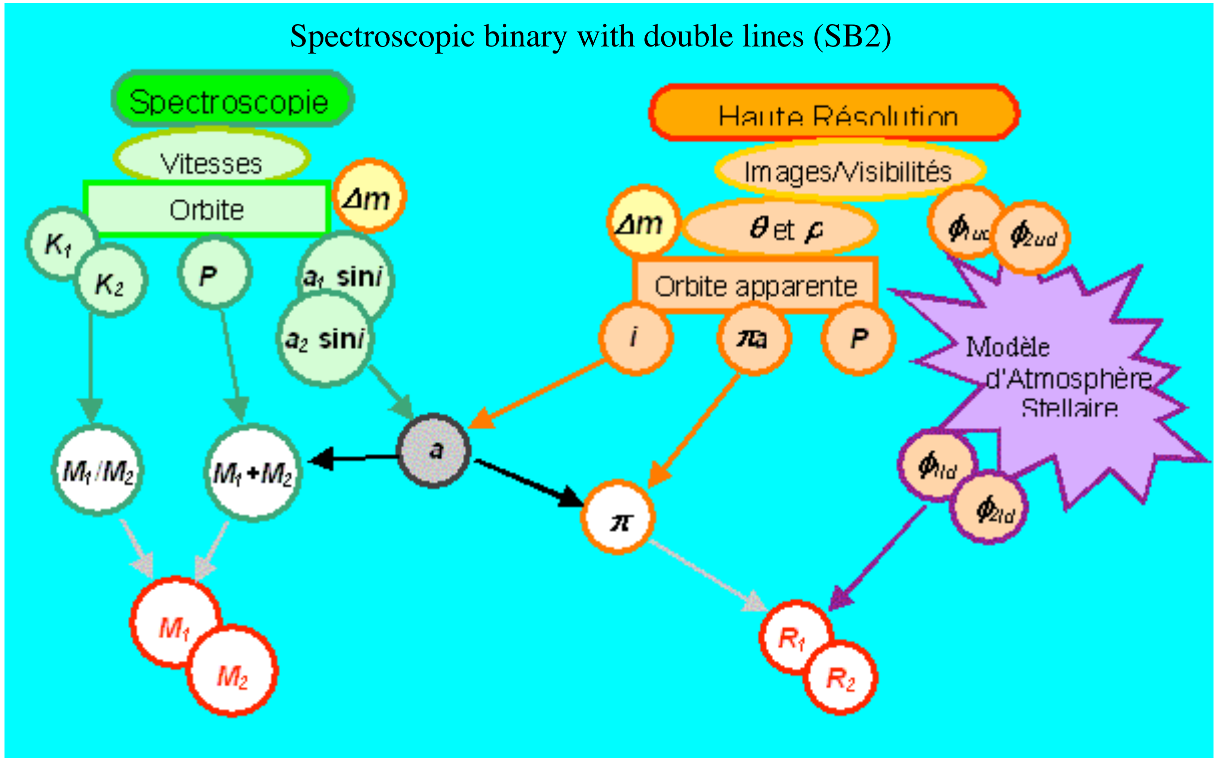

Eclipsing Binaries

Binaries (SB2)



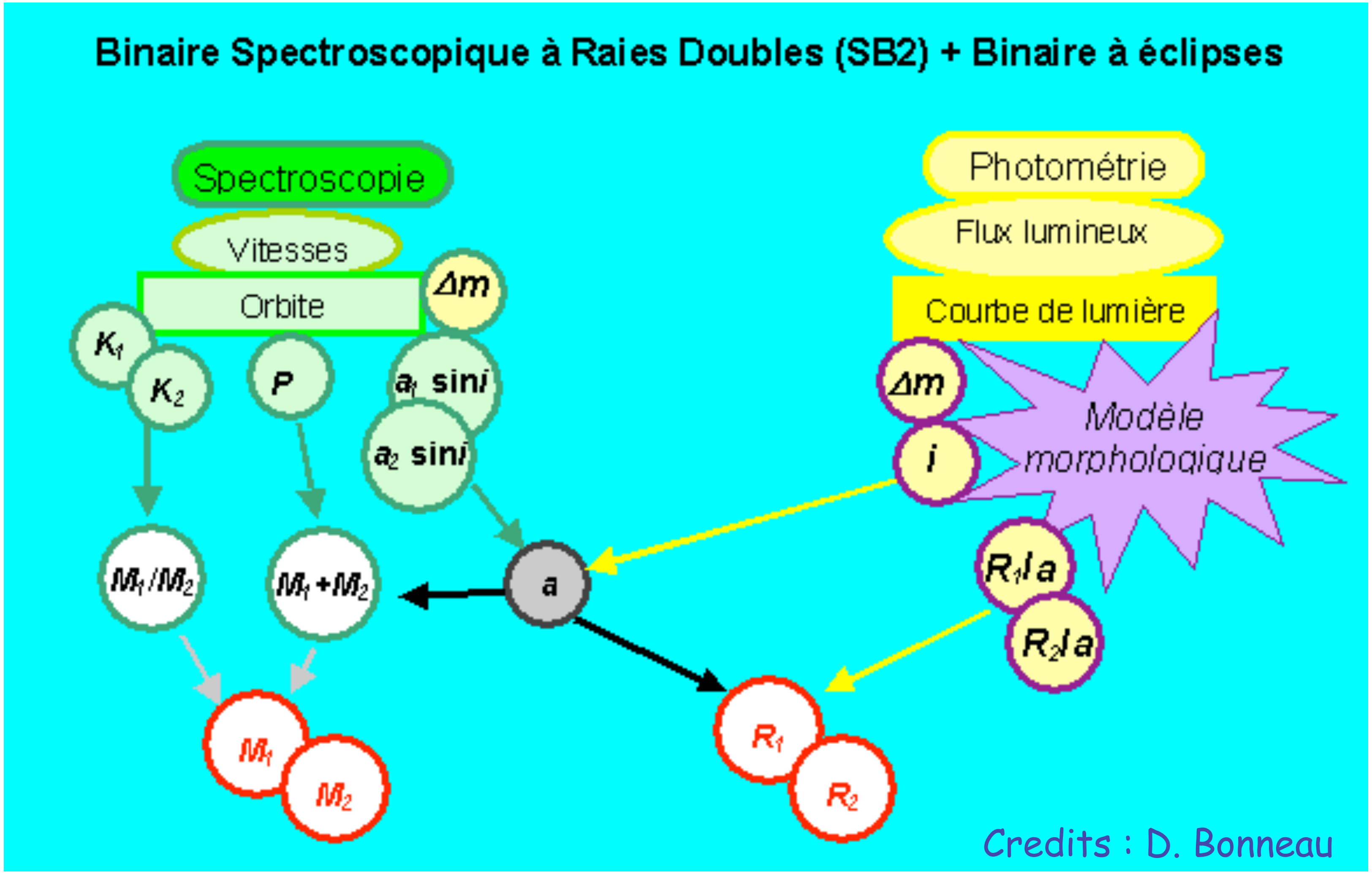
detached is easier for distances
Also, is SB2 is the best...

velocities



Credits : D. Bonneau

Eclipsing binaries



LETTER

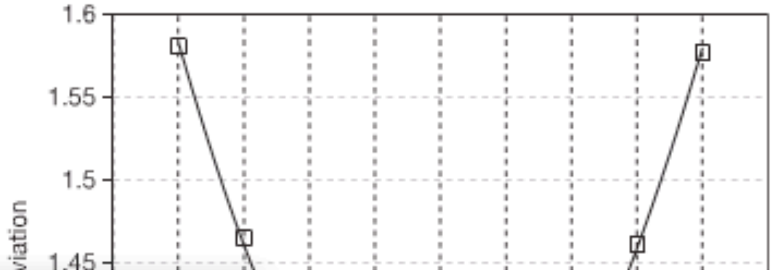
doi:10.1038/nature09598

The dynamical mass of a classical Cepheid variable star in an eclipsing binary system

G. Pietrzyński[1,2], I. B. Thompson[3], W. Gieren[1], D. Graczyk[1], G. Bono[4,5], A. Udalski[2], I. Soszyński[2], D. Minniti[6] & B. Pilecki[1,2]

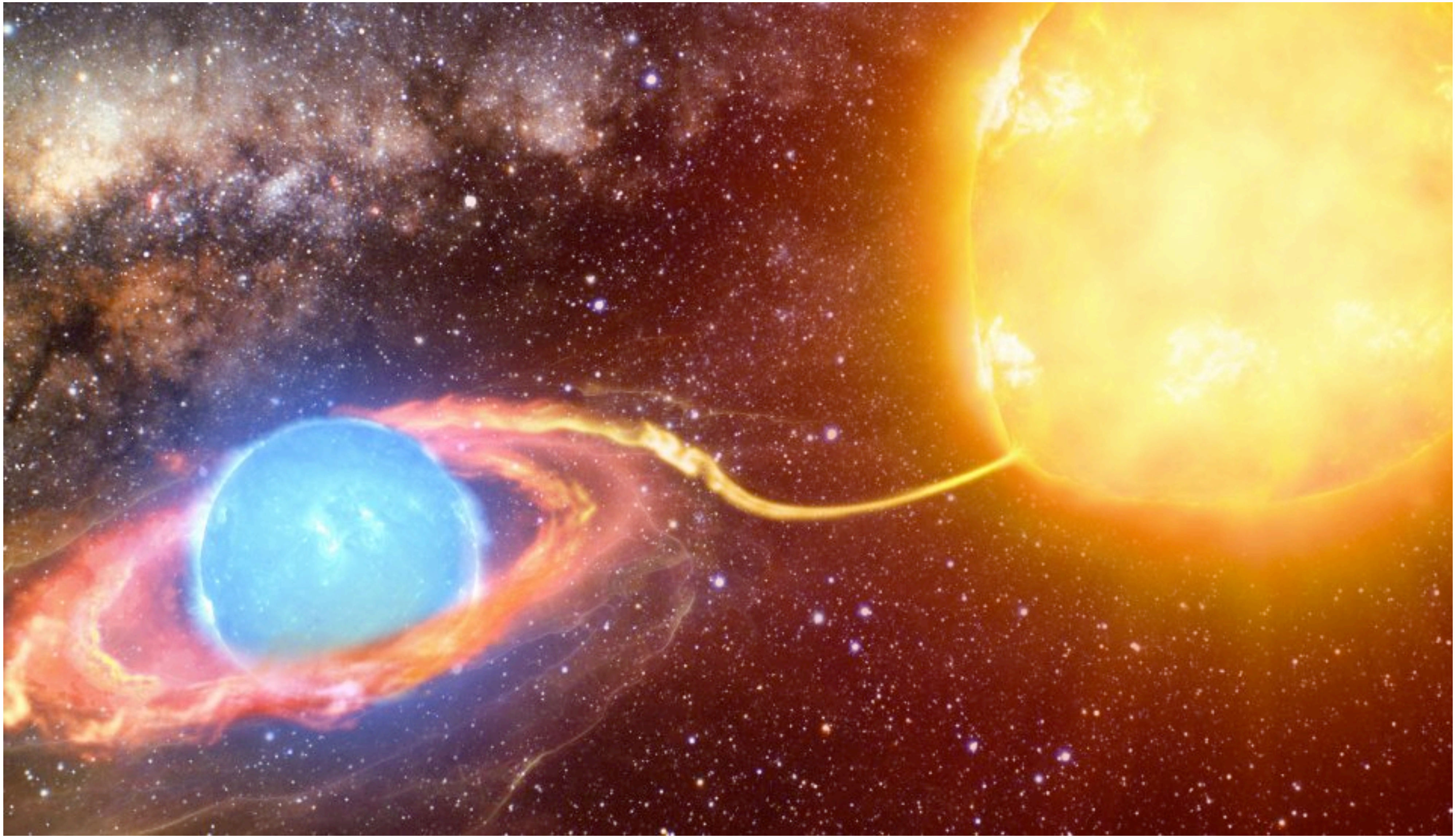
Stellar pulsation theory provides a means of determining the masses of pulsating classical Cepheid supergiants—it is the pulsation that causes their luminosity to vary. Such pulsational masses are found to be smaller than the masses derived from stellar evolution theory: this is the Cepheid mass discrepancy problem[1,2], for which a solution is missing[3–5]. An independent, accurate dynamical mass determination for a classical Cepheid variable star (as opposed to type-II Cepheids, low-mass stars with a very different evolutionary history) in a binary system is needed in order to determine which is correct. The accuracy of previous efforts to establish a dynamical Cepheid mass from Galactic single-lined non-eclipsing binaries was typically about 15–30% (refs 6, 7), which is not good enough to resolve the mass discrepancy problem. In spite of many observational efforts[8,9], no firm detection of a classical Cepheid in an eclipsing double-lined binary has hitherto been reported. Here we report the discovery of a classical Cepheid in a well detached, double-lined eclipsing binary in the Large Magellanic Cloud. We determine the mass to a precision of 1% and show that it

The mean radius of the primary (Cepheid) component that we obtained from our binary analysis shows excellent agreement with the radius predicted for its period from the Cepheid period–radius relation of ref. 13 (32.3 $R_\odot$, where $R_\odot$ is the solar radius), strengthening our confidence in our results. In order to assign realistic errors to the derived parameters of our system, we performed Monte Carlo simulations. Our analysis of the very accurate existing data sets for OGLE-LMC-CEP0227 has resulted in a purely empirical determination of the dynamical mass of a classical Cepheid variable, with an unprecedented accuracy of 1%. We note that an end-to-end simultaneous solution for all parameters might reveal slightly different



LETTER

doi:10.1038/nature10966



Late-type eclipsing binaries

ϕ is derived from the surface brightness - color relation, very well established for late-type stars based on interferometric data (di Benedetto 1998, 2005; Kervella et al. 2004)

$$\phi\ [\mathrm{mas}] = 10^{0.2\cdot(S-m_0)} \qquad S_V = 2.656 + 1.483 \times (V-K)_0 - 0.044 \times (V-K)_0^2$$

$$d\ [\mathrm{pc}] = 9.2984 \cdot \frac{R\ [R_\odot]}{\phi\ [\mathrm{mas}]} \qquad S_V \Leftrightarrow (V-K)_0$$

Currently rms on this relation is 0.03 mag (2 % !)

=> very weakly depends on metallicity !

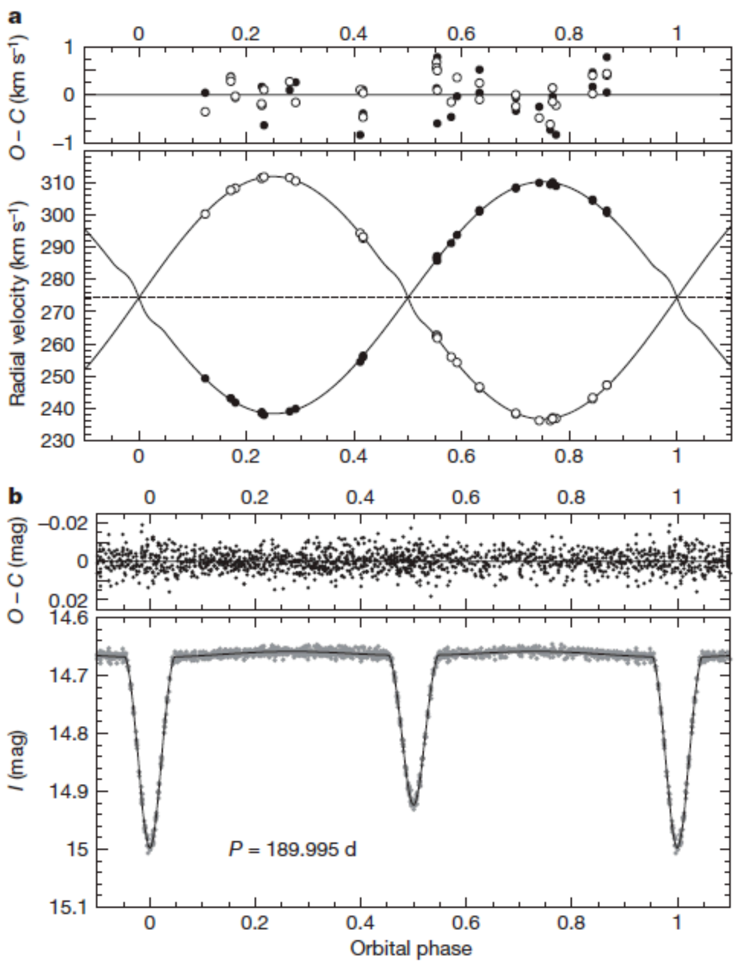
=> is almost parallel to the reddening line !

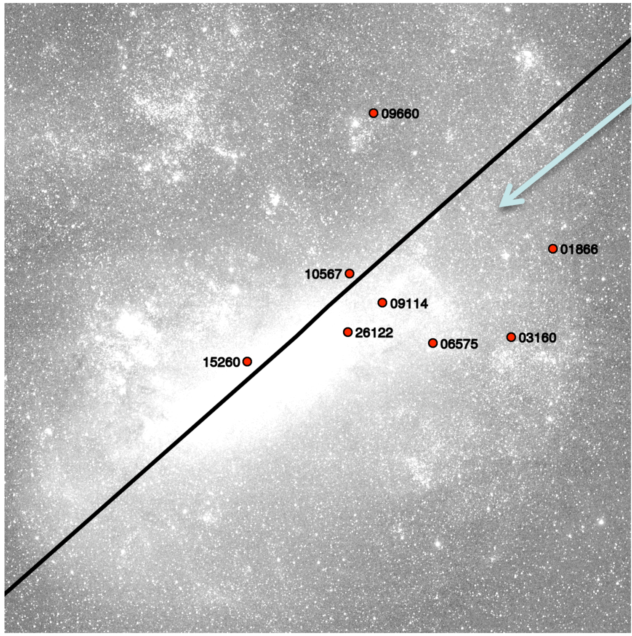
The distance of eclipsing binaries in the local Group

R + θ (from surface brigthness relation)

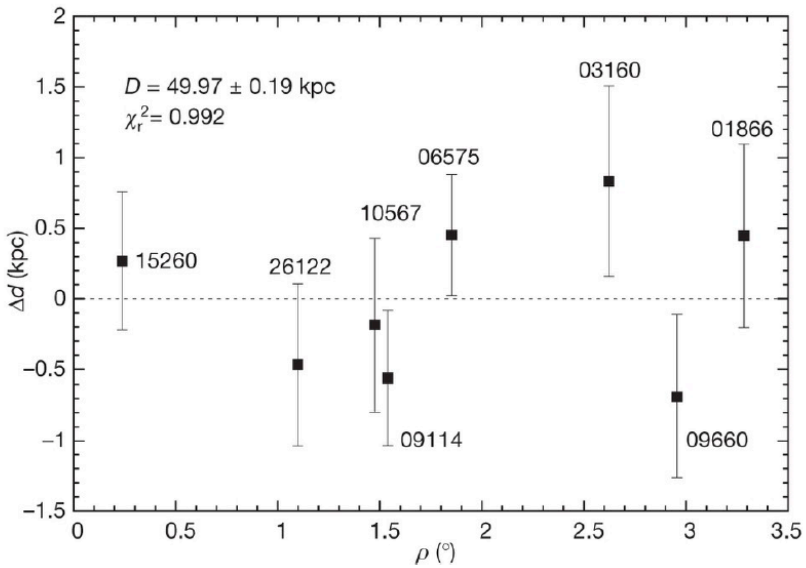
=

distance at few percents





8 eclipsing binaries in LMC



LETTER

doi:10.1038/nature11878

2 1 An eclipsing-binary distance to the Large Magellanic Cloud accurate to two per cent

G. Pietrzyński[1,2], D. Graczyk[1], W. Gieren[1], I. B. Thompson[3], B. Pilecki[1,2], A. Udalski[2], I. Soszyński[2], S. Koz½owski[2], P. Konorski[2], K. Suchomska[2], G. Bono[4,5], P. G. Prada Moroni[6,7], S. Villanova[1], N. Nardetto[8], F. Bresolin[9], R. P. Kudritzki[9], J. Storm[10], A. Gallenne[1], R. Smolec[11], D. Minniti[12,13], M. Kubiak[2], M. Szymański[2], R. Poleski[2], Ł. Wyrzykowski[2], K. Ulaczyk[2], P. Pietrukowicz[2], M. Górski[2] & P. Karczmarek[2]

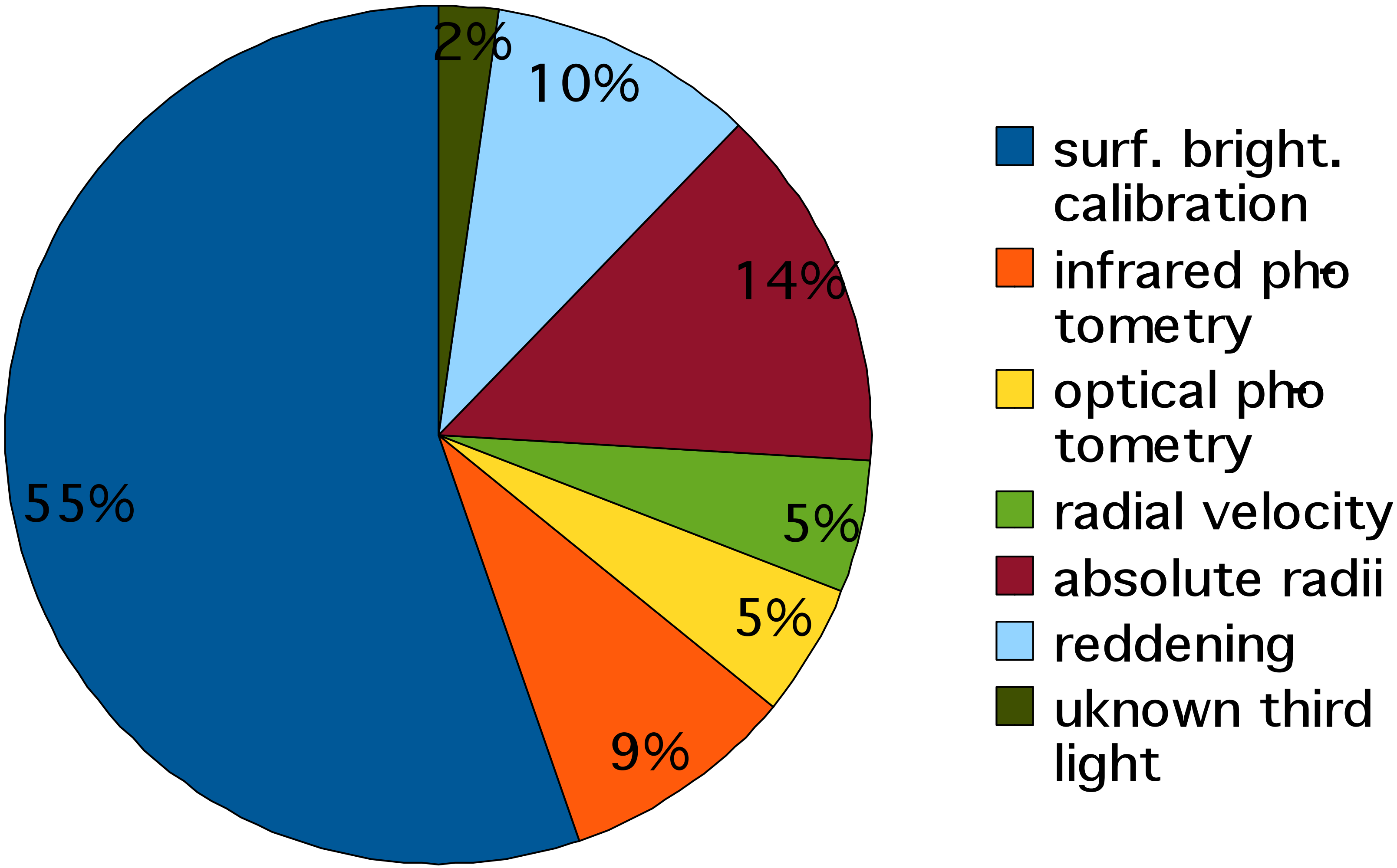
In the era of precision cosmology, it is essential to determine the Hubble constant to an accuracy of three per cent or better[1,2]. At present, its uncertainty is dominated by the uncertainty in the distance to the Large Magellanic Cloud (LMC), which, being our nearest galaxy, serves as the best anchor point for the cosmic distance scale[2,3]. Observations of eclipsing binaries offer a unique opportunity to measure stellar parameters and distances precisely and accurately[4,5]. The eclipsing-binary method was previously applied to the LMC[6,7], but the accuracy of the distance results was lessened by the need to model the bright, early-type systems used in those studies. Here we report determinations of the distances to eight long-period, late-type eclipsing systems in the LMC, composed of cool, giant stars. For these systems, we can accurately measure both the linear and the angular sizes of their components and avoid the most important problems related to the hot, early-type systems. The LMC distance that we derive from these systems (49.97 ± 0.19 (statistical) ± 1.11 (systematic) kiloparsecs) is accurate to 2.2 per cent and provides a firm base for a 3-per-cent determination of the Hubble constant, with prospects for improvement to 2 per cent in the future.

Silla, together with near-infrared photometry obtained with the 3.5-m New Technology Telescope located on La Silla.

The spectroscopic and OGLE V- and I-band photometric observations of the binary systems were then analysed using the 2007 version of the standard Wilson–Devinney code[14,15], in the same way as in our recent work on a similar system in the Small Magellanic Cloud[9]. Realistic errors in the derived parameters of our systems were obtained from extensive Monte Carlo simulations (Fig. 2). The astrophysical parameters all the observed eclipsing binaries were determined with an accuracy of a few per cent (Supplementary Tables 2–9).

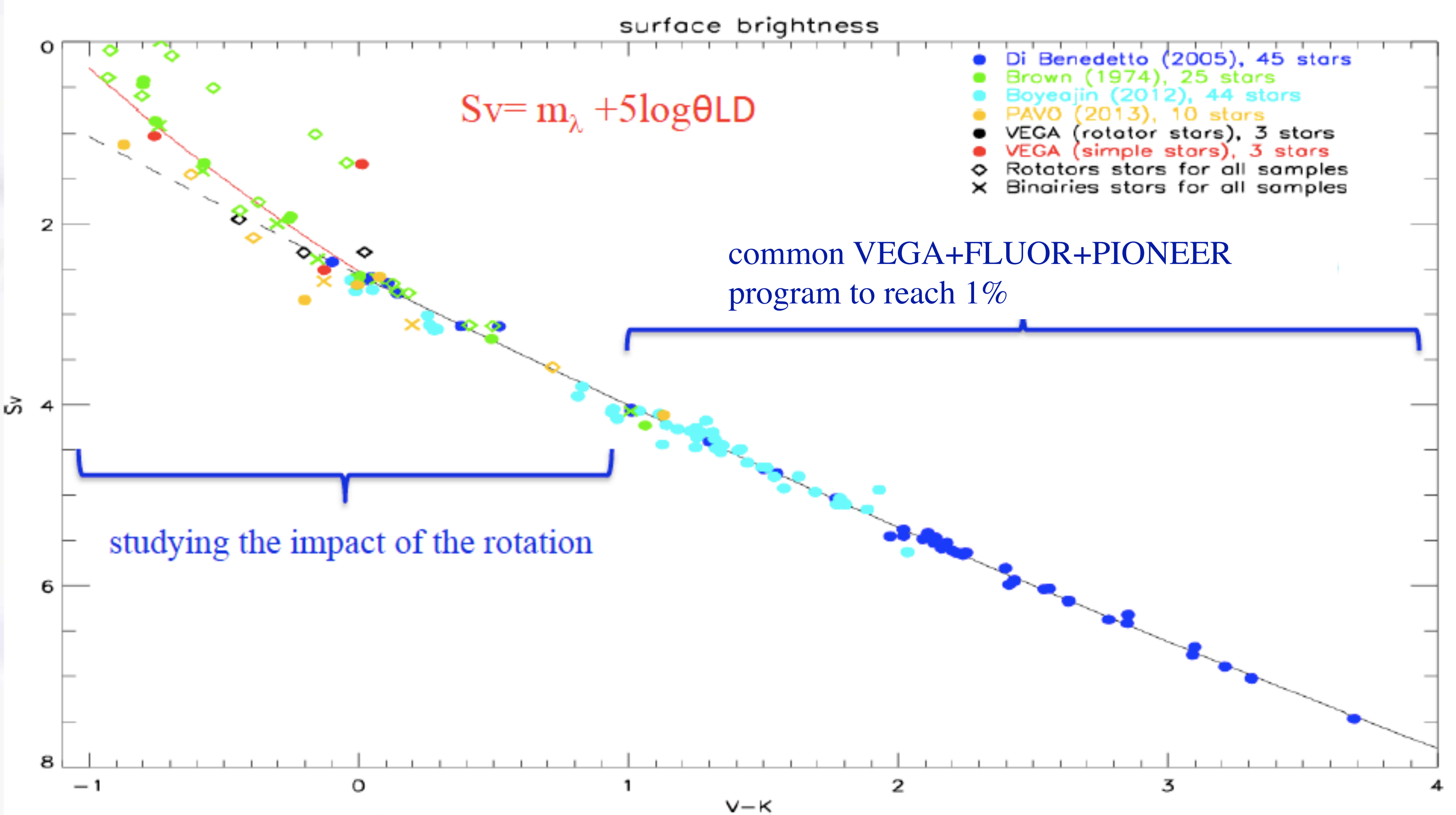
For late-type stars, we can use the very accurately calibrated (2%) relation between their surface brightness and $V-K$ colour to determine their angular sizes from optical (V) and near-infrared (K) photometry[16]. From this surface-brightness/colour relation (SBCR), we can derive angular sizes of the components of our binary systems directly from the definition of the surface brightness. Therefore, the distance can be measured by combining the angular diameters of the binary components derived in this way with their corresponding linear dimensions obtained from the analysis of the spectroscopic and photometric data. The distances measured with this very simple but accur-

The distance error budget (2.5 % total error)



Improving the surface-brigthness relation using CHARA array)

PhD by Mounir Challouf (preliminary results, see poster)



Bright early-type stars (O-A-B) for distances in Local Group

Late-type stars (F-G) for LMC distance

Conclusion/objectives (Araucaria Project)

Stellar Pulsation : period-projection factor relation

⇩

Interf. and photo. Baade-Wesselink method (Galactique and LMC Cepheids)
No metallicity dependency in K band (Storm et al. 2011ab)

⇩

Distance to LMC at 2% using EBs (Pietrzynski et al. 2013)
Distances in Local Group to 5% (early-type eclipsing binaries, etc...)

⇩

SHOES Project (Riess et al. 2009)
Objective : Hubble Constant to the 2% precision