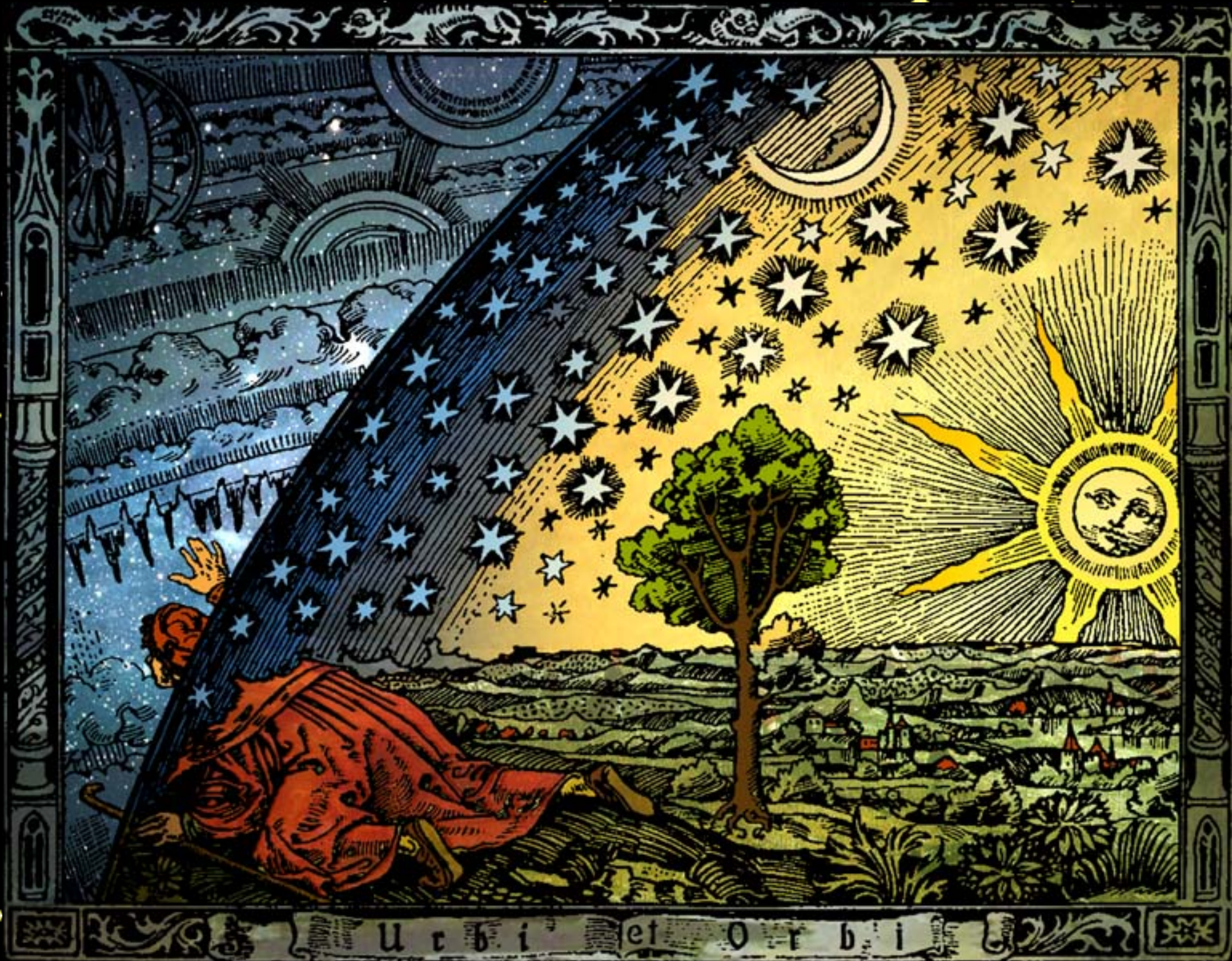
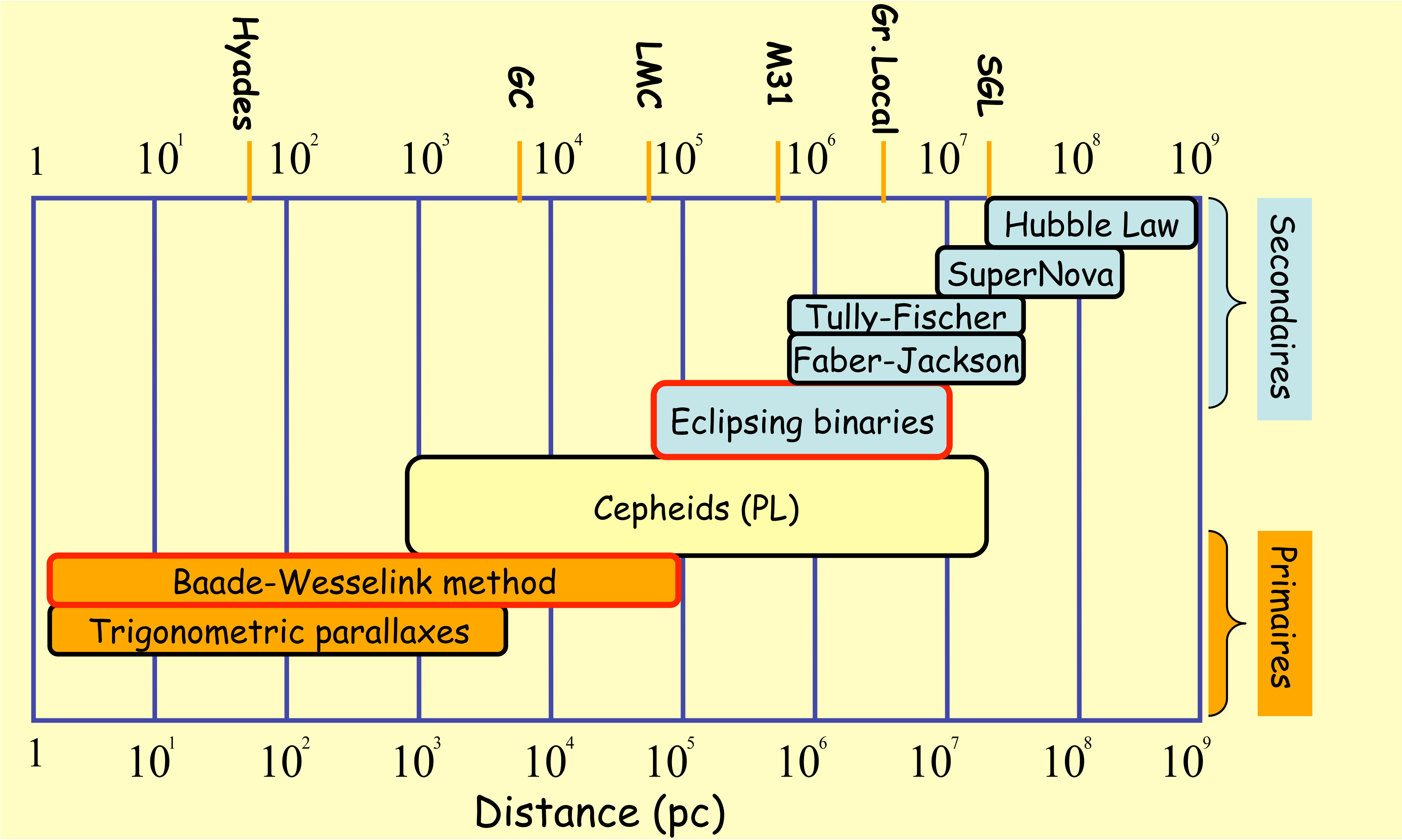
Interferometry in the visible: distance scale calibration using Cepheids (pulsating stars) and eclipsing binaries



N., Nardetto, D. Mourard, P. Kervella, A. Mérand, A. Gallenne, J. Breitfelder and colleagues from the Araucaria project

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

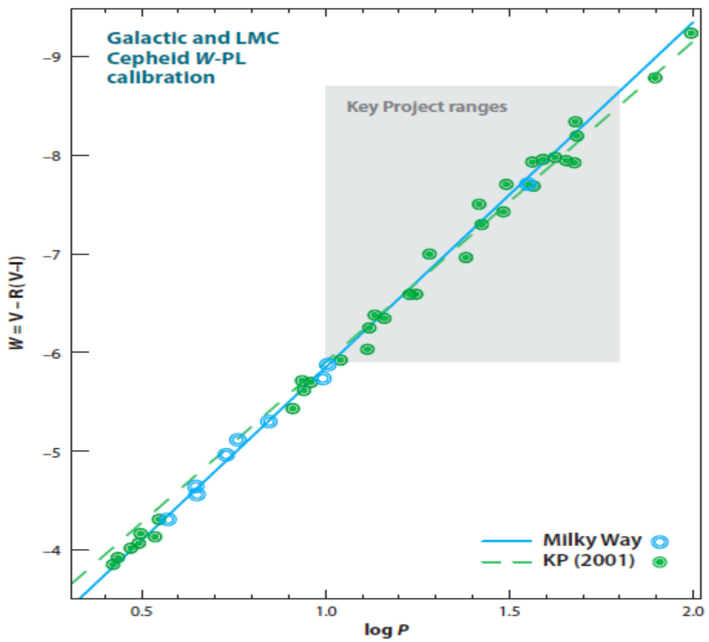
The distance scale in the universe

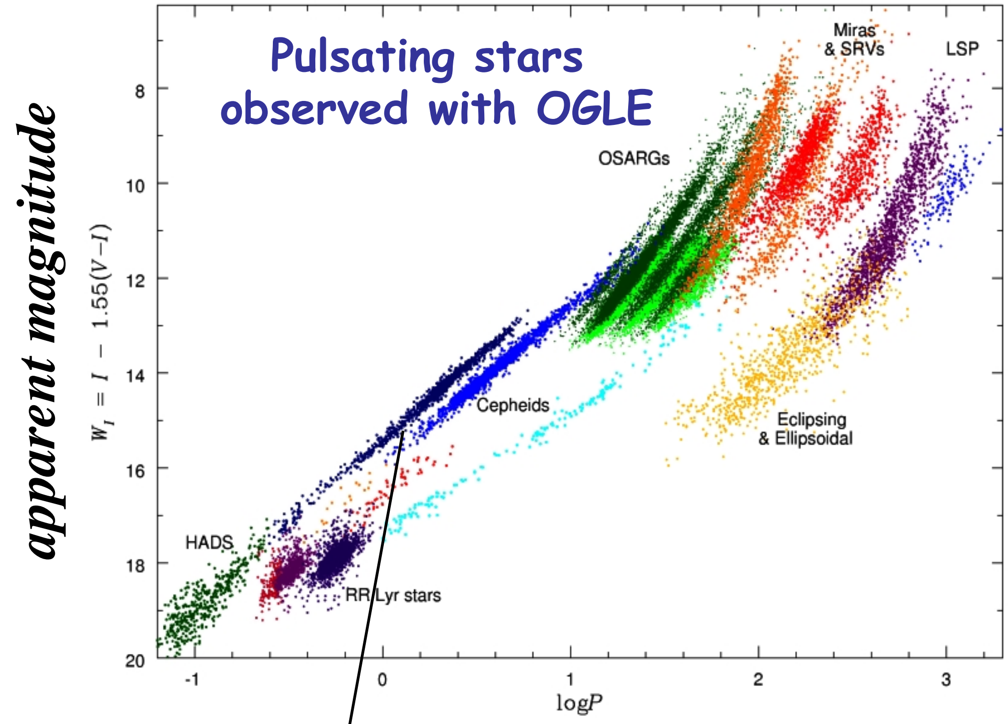


How do we use Cepheids to derive LMC distance ?

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)

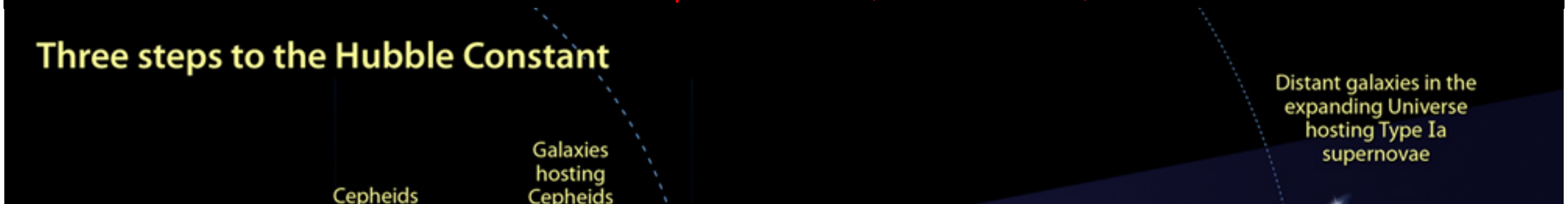




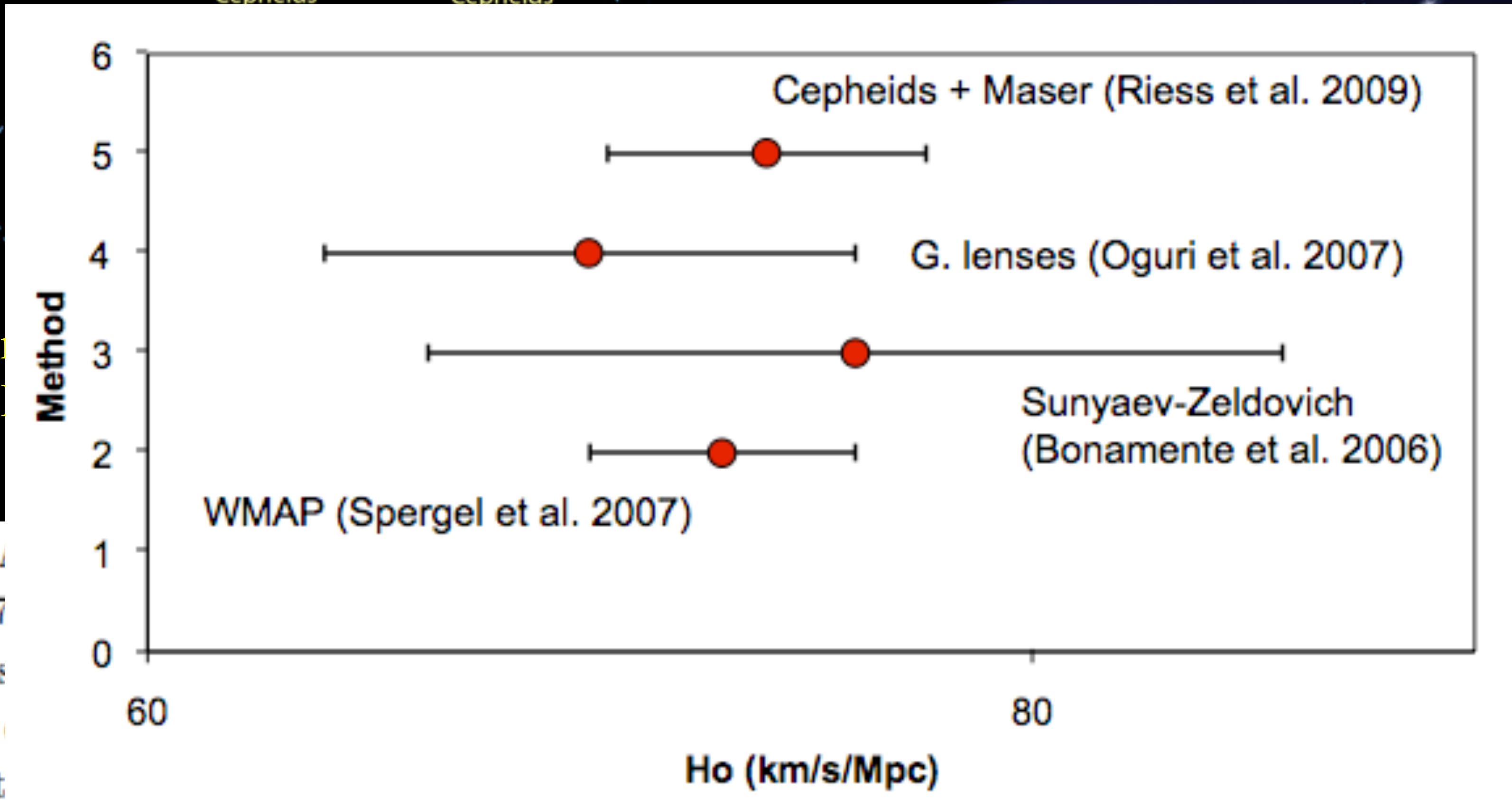
$$M = a(\log P - 1) + b$$

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

Riess et al. 2009, ApJ, 699, 539 (~550 citations)



Maser
MW(
LMC



... et al. (2007 ... ard" of dis ... reci- 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%)

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

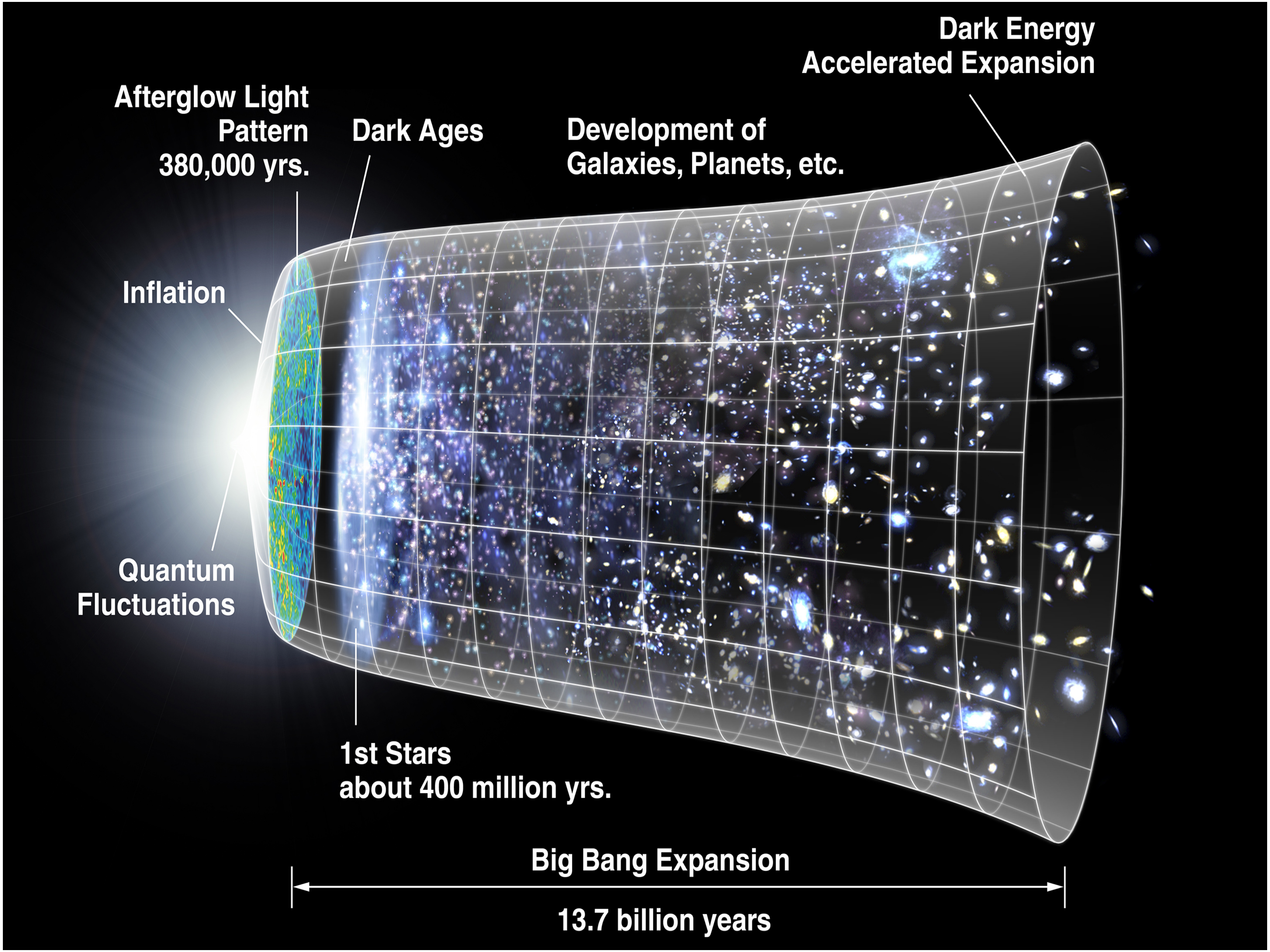
Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

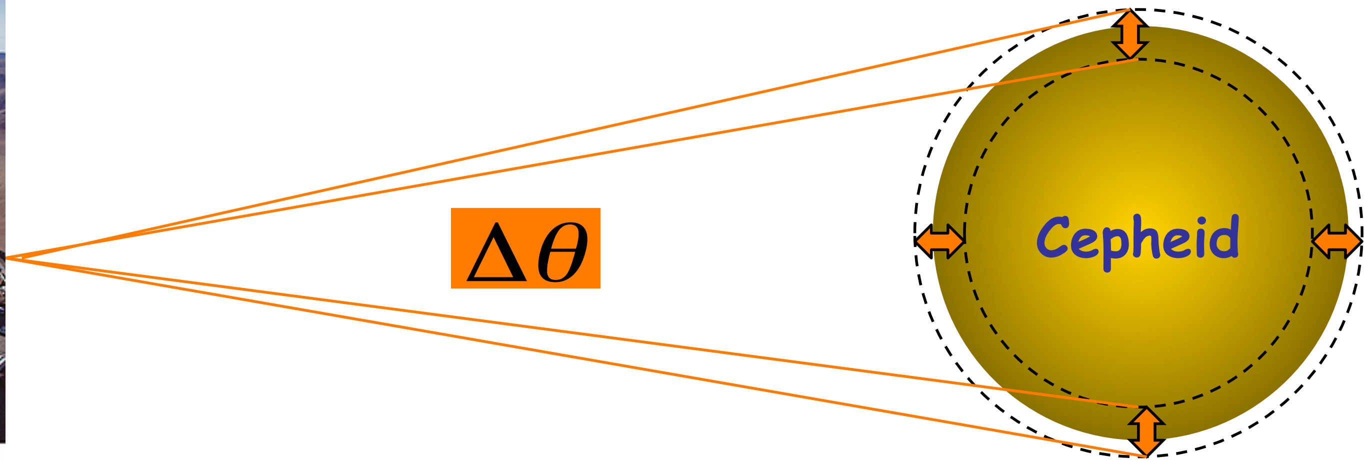
Photo: U. Montan

Adam G. Riess


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

The Baade-Wesselink Method or parallax of pulsation

1 – Interferometry

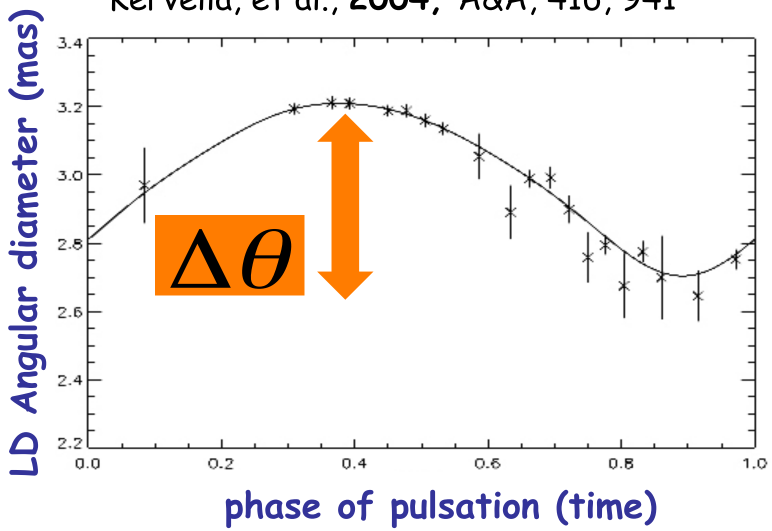


Interferometry

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

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

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



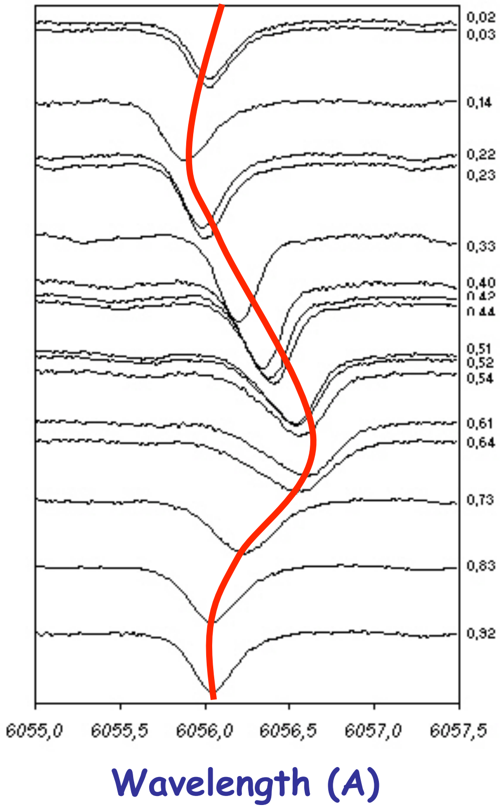
Interferometry provides the angular size variation of the star

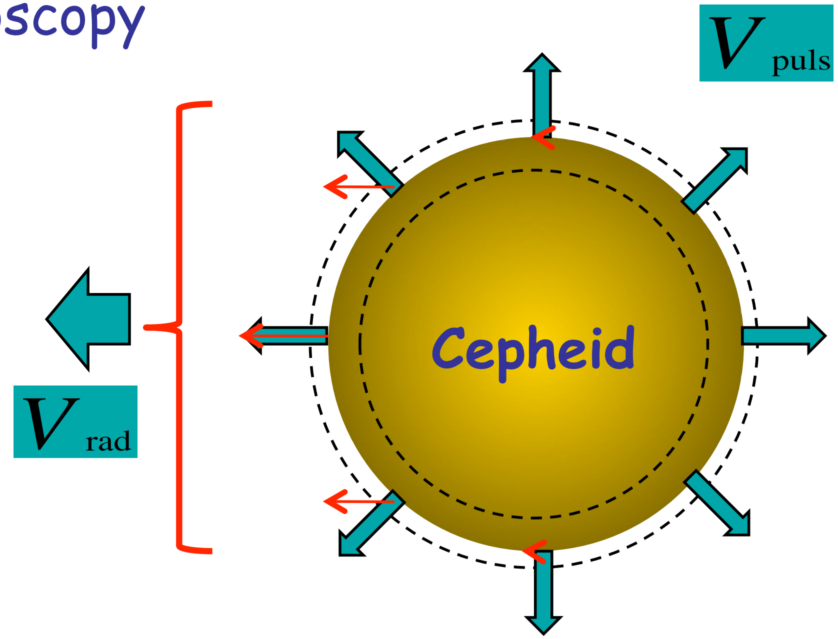
The Baade-Wesselink Method or parallax of pulsation

2 - spectroscopy

spectroscopy

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

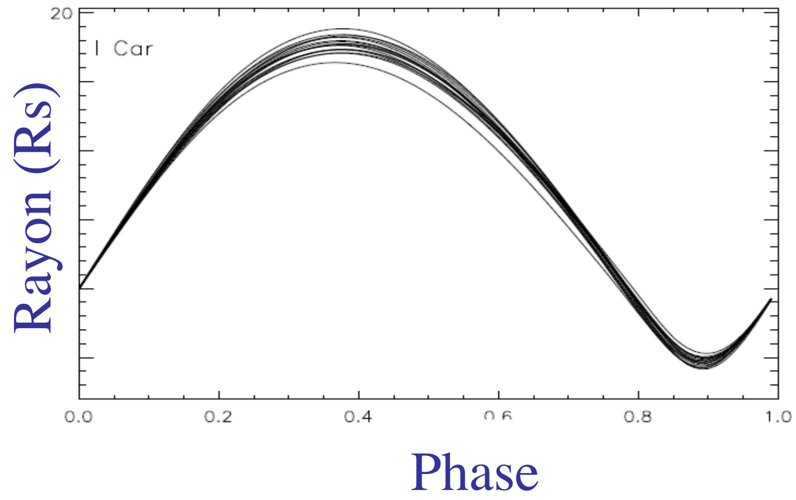




$$p = \frac{V_{puls}}{V_{rad}}$$

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

p is assumed to be constant with phase

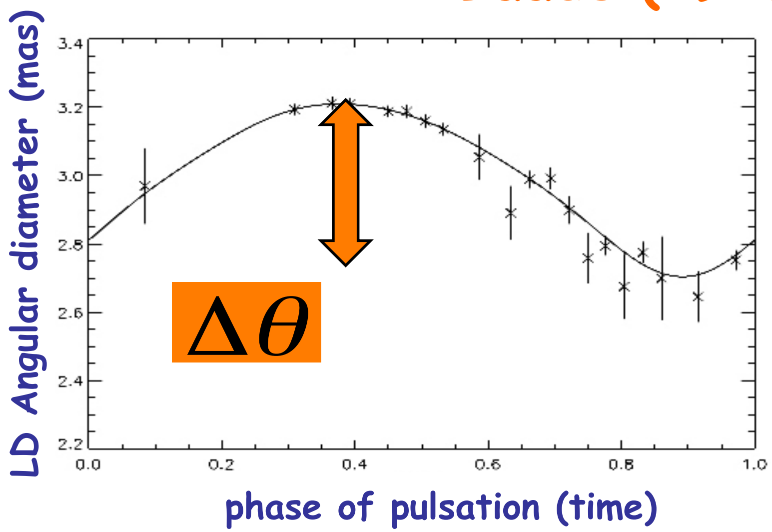


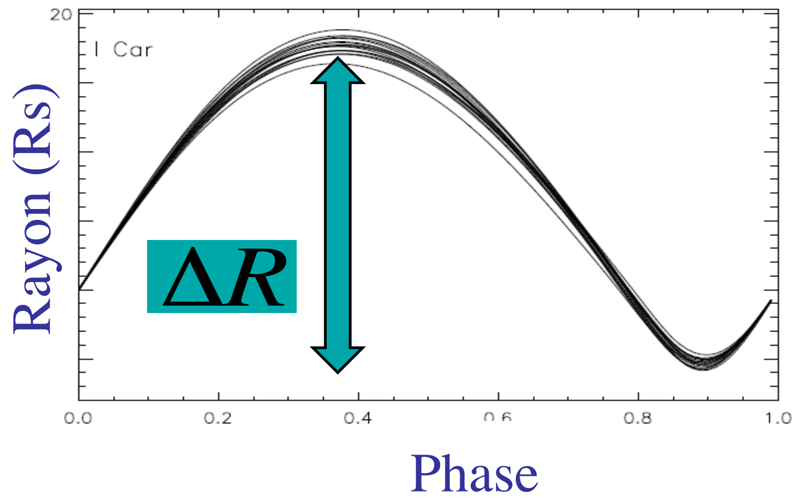
Spectroscopy provides the radius variation of the star

The Baade-Wesselink Method or parallax of pulsation

3-combining interferometry and spectroscopy

Baade (1926) – Wesselink (1946)





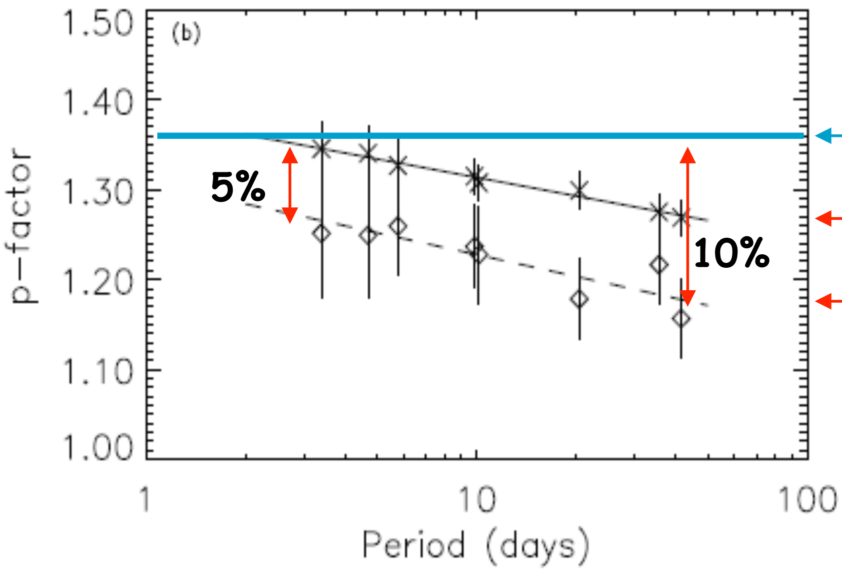
$$d \propto \frac{\Delta R}{\Delta \theta}$$

$\Delta R \Leftrightarrow \Delta \theta$

This two quantities have to correspond to the same layer in the star (atmospheric velocity gradient, dynamical affects)

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 gamma-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

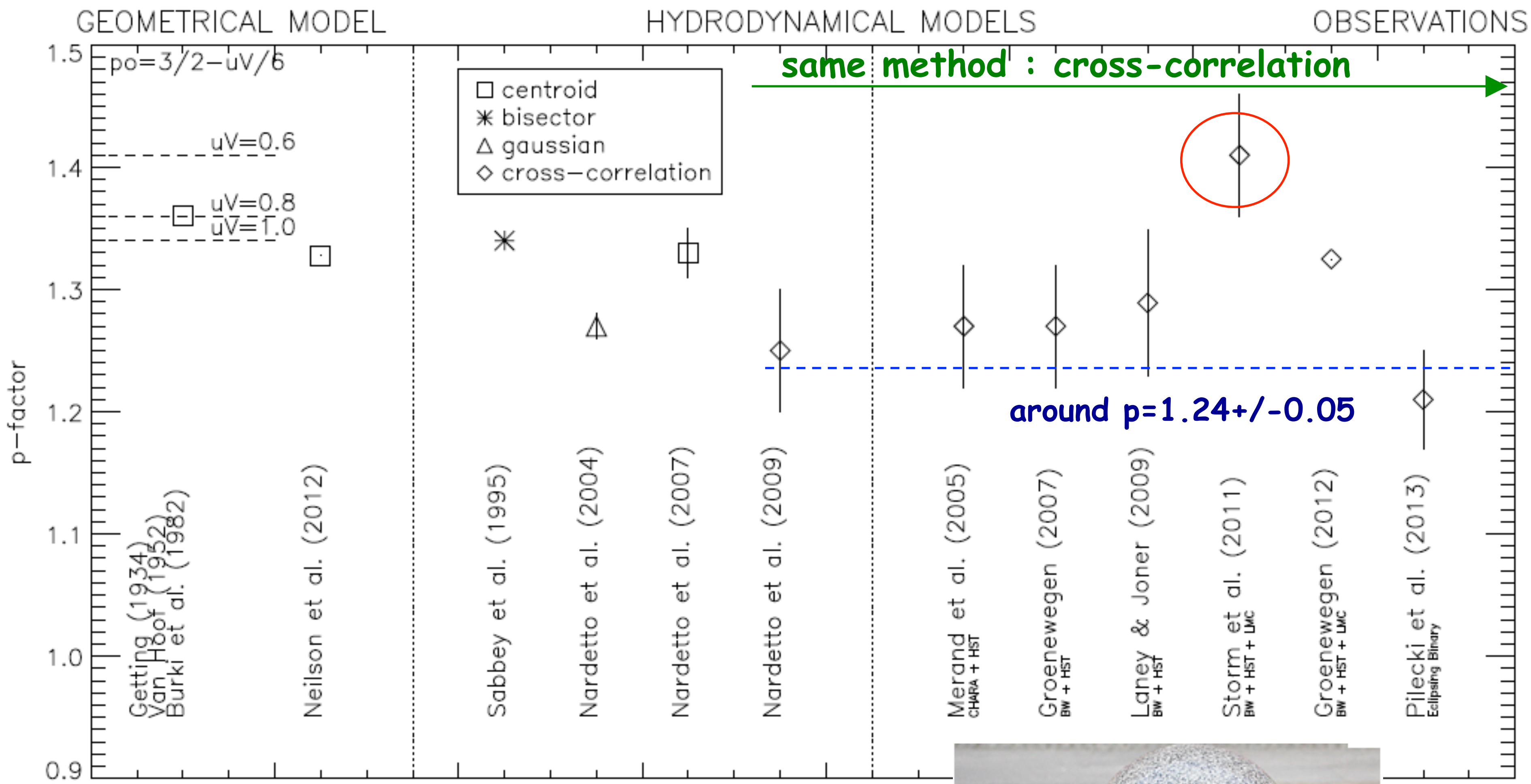
cross-correlation

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

➡ **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

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...

Visible interferometry: science case for Cepheids (and pulsating stars)

Low/Medium Spectral resolution mode (high sensitivity)

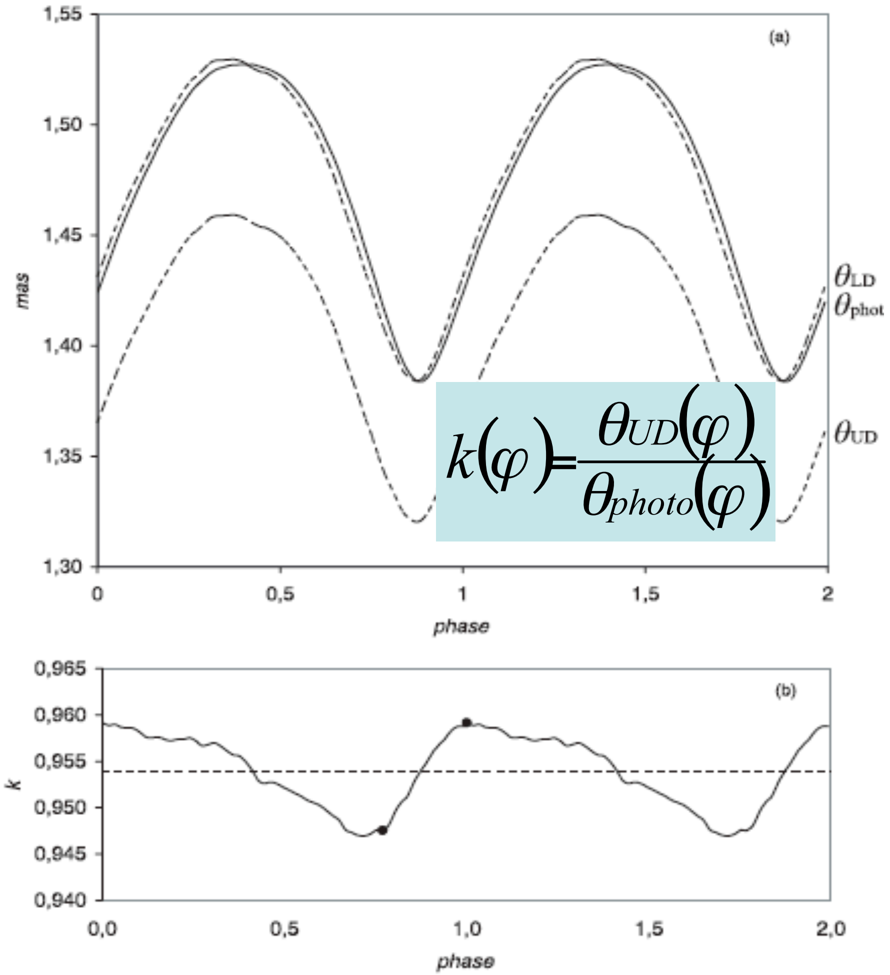
- Science Case 1: LD of Cepheids (p-factor)
- Science Case 2: p-factor from Cepheids in binaries
- Science Case 3: CSE of Cepheids in visible
- Science Case 4: Gaia + inverse BW = p-factor

High spectral resolution mode

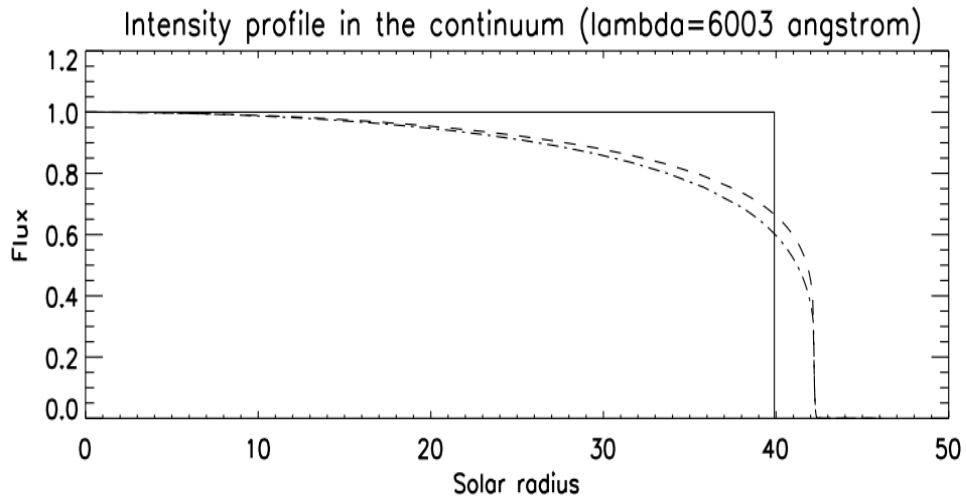
- Science case 5: the dynamical structure of Cepheid' atmosphere

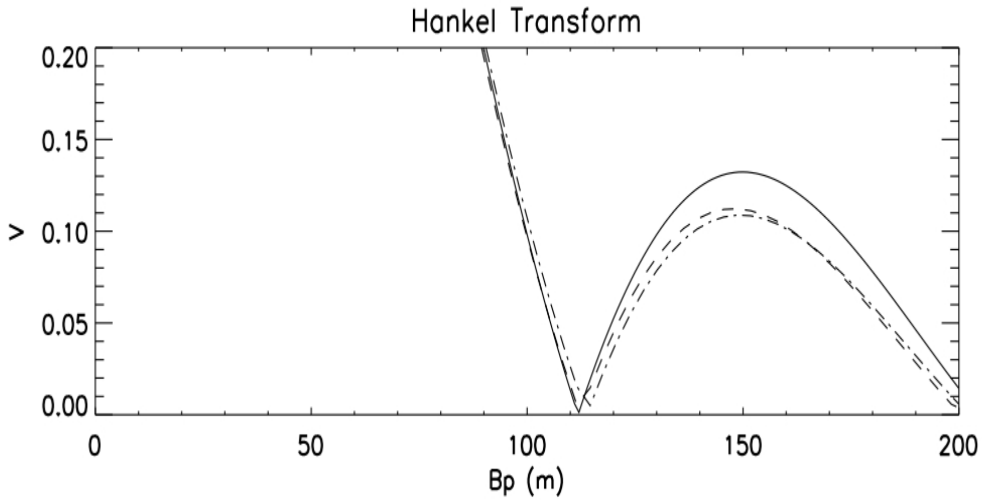
- Science Case 6: Do the same things but for RR Lyrae, δ Scuti stars, ...

Science Case 1: the limb-darkening of Cepheids (p-factor)



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



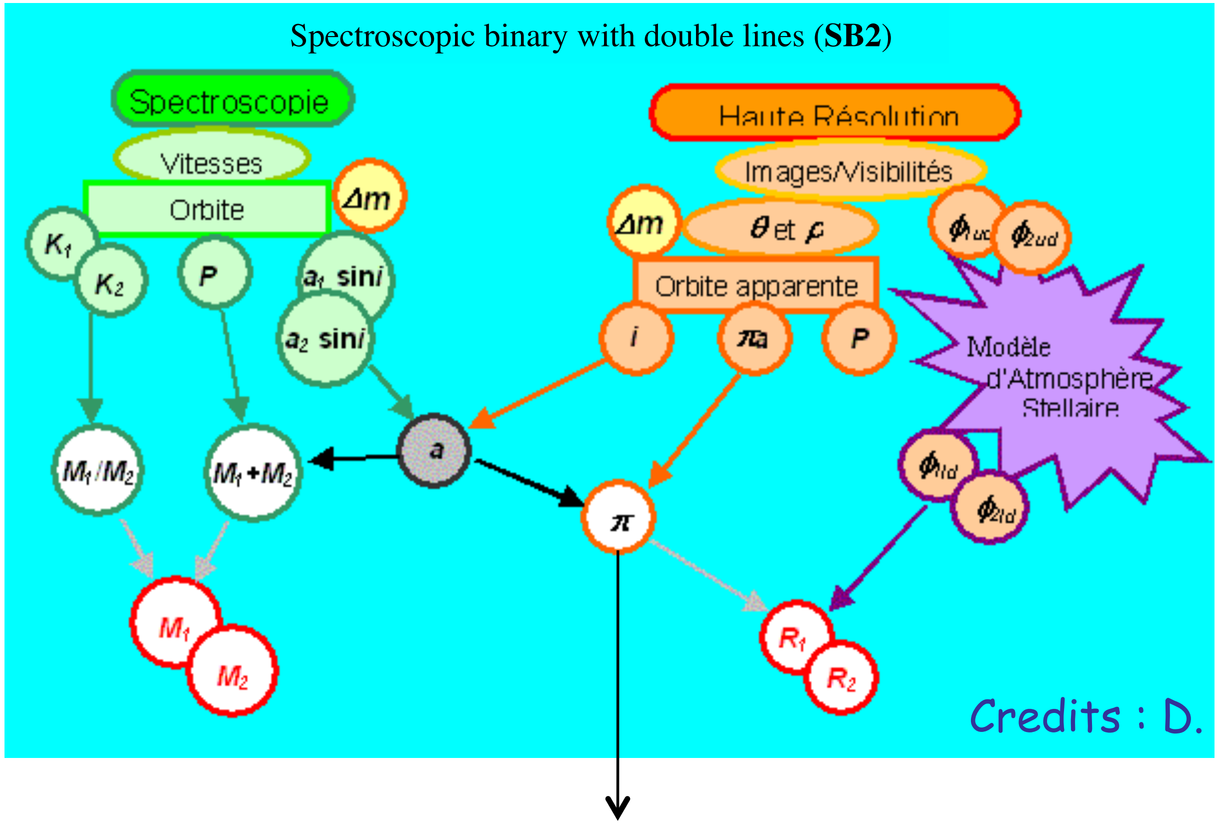


From models (Nardetto et al. 2006), assuming k=cste is acceptable in the BW approach (impact of 0.1% on the distance) but this is the first contribution to the p-factor (never measured) !

-> sigV=5% around V=0.1 (2nd lobe) would give 1% on <k>

-> sigV=1% around V=0.1 (2nd lobe) would give k variation at 5 sigmas

Science Case 2: p-factor from Cepheids in binaries

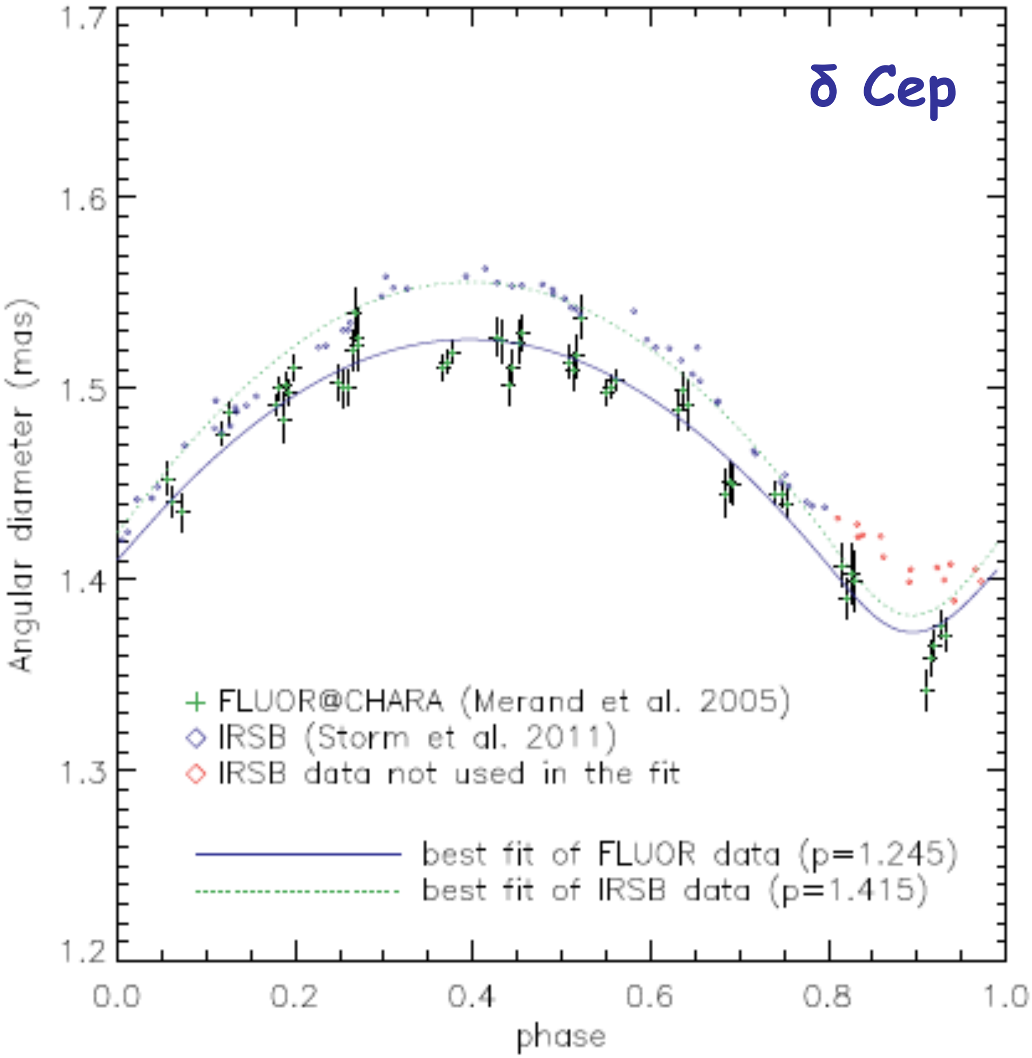


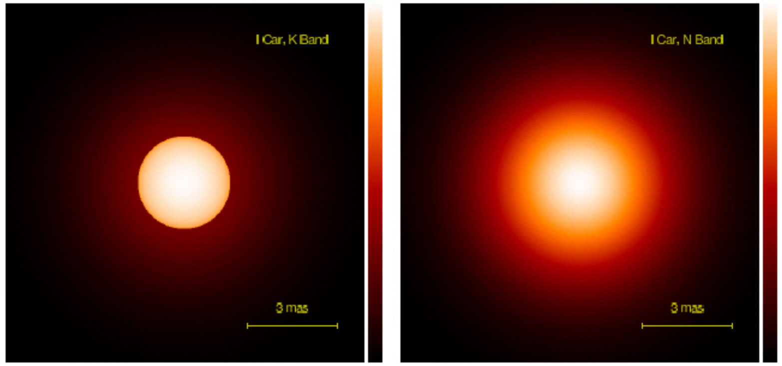
Credits : D. Bonneau

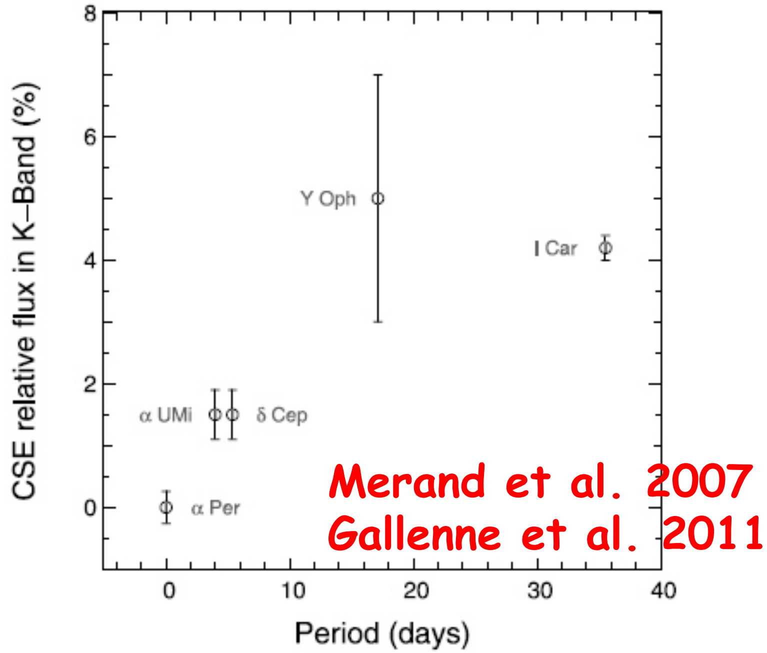
If we have the distance, we can inverse the BW method applied to the Cepheid in the binary and derive its p-factor and also its mass

See papers by Gallenne et al.2013, 2014a, 2014b
See also a LMC Cepheid into an eclipsing binary (Pilecki et al. 2013)

Science Case 3: CSE of Cepheids in visible







The IRSB method is using V and K band photometry. Imagine we have a significant contamination from a visible circumstellar environment (δ Cep, Nardetto et al. in prep.)

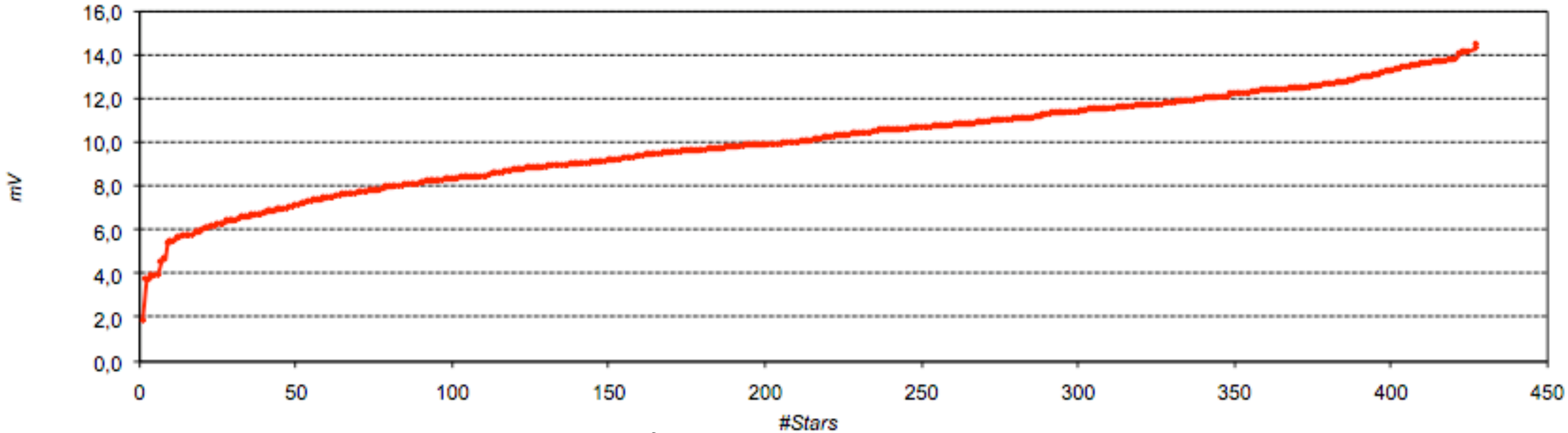
Science Case 4: Gaia + inverse BW = p-factor !

"Galactic Cepheids DataBase" *Fernie et al., S. 1995, IBVS No. 4148*

505 Cepheids (416 because 89 have no mV indicated)

272 observables with CHARA (δ >-25°)

256 observables with VLTI (δ < 25°)



105 observables with CHARA (δ >-25°) And magV < 10

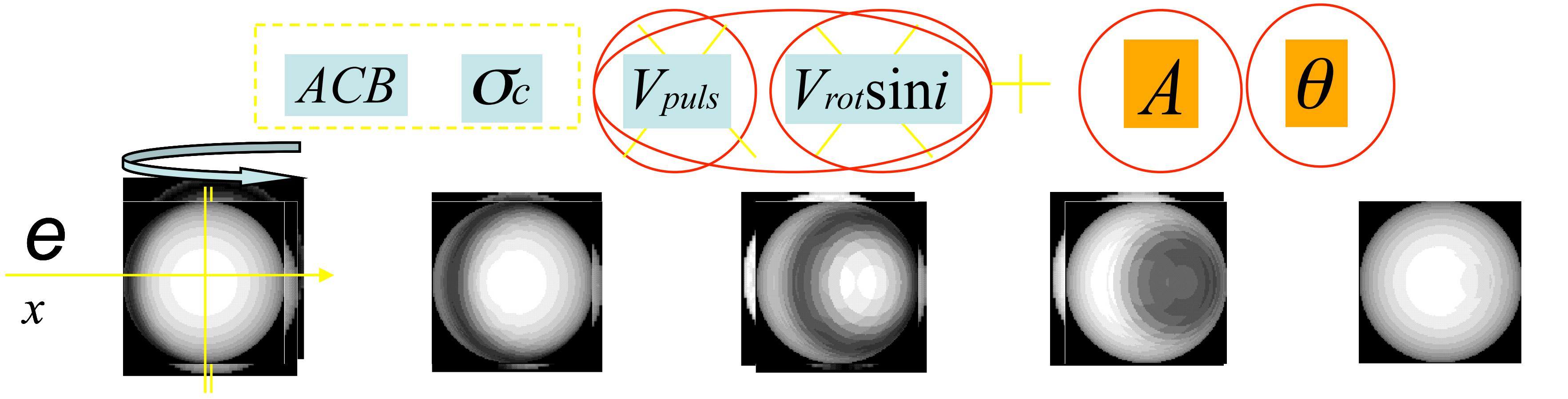
147 observables with VLTI (δ < 25°)) And magV < 10

We can show (see talk from previous « vegas » workshop in 2012):

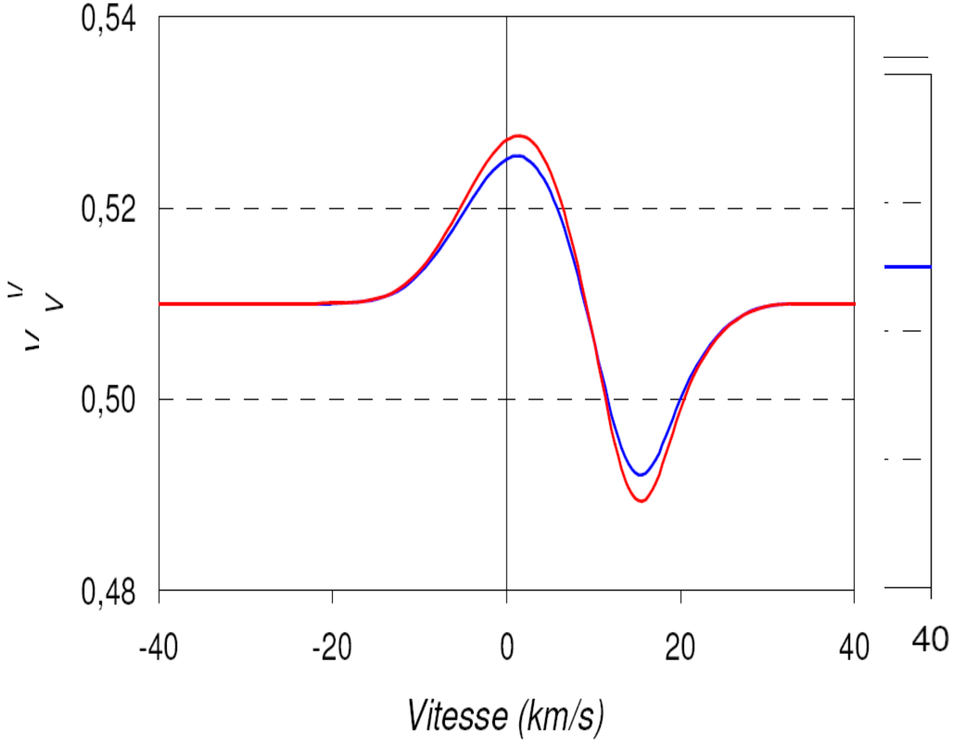
- *CHARA : 88 (+/- 20!) stars for which we can obtain 5% of precision on the p-factor*
- *VLTI : 52 (+/-10!) stars for which we can obtain 5% of precision on the p-factor*

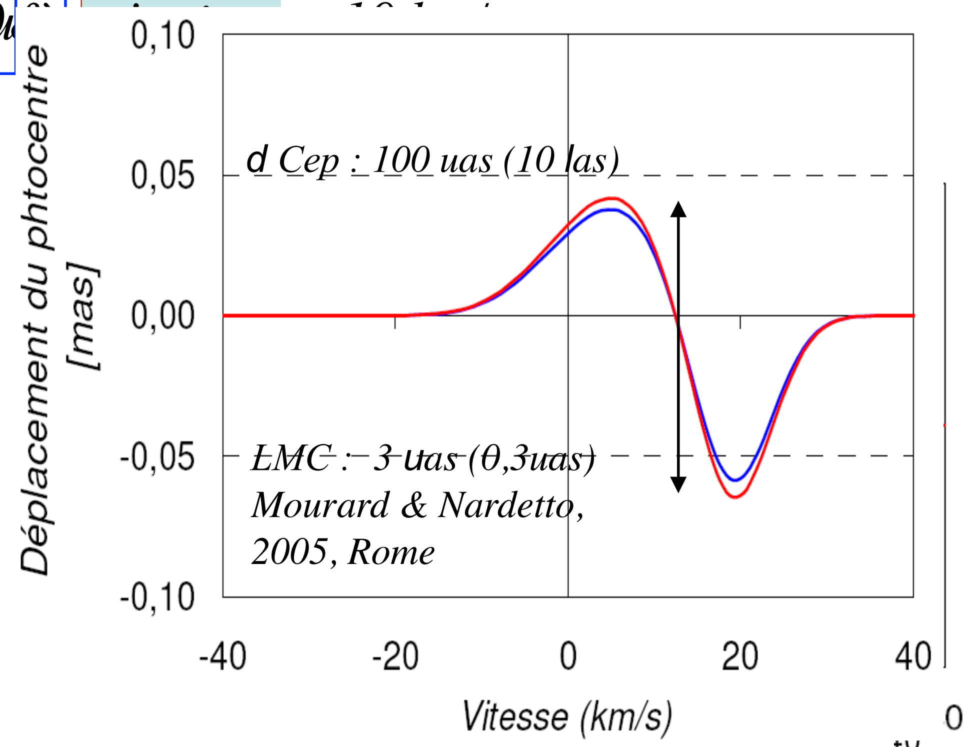
=> constrains on the period-projection factor relation

Science case 5: the dynamical structure of Cepheid'atmosphere



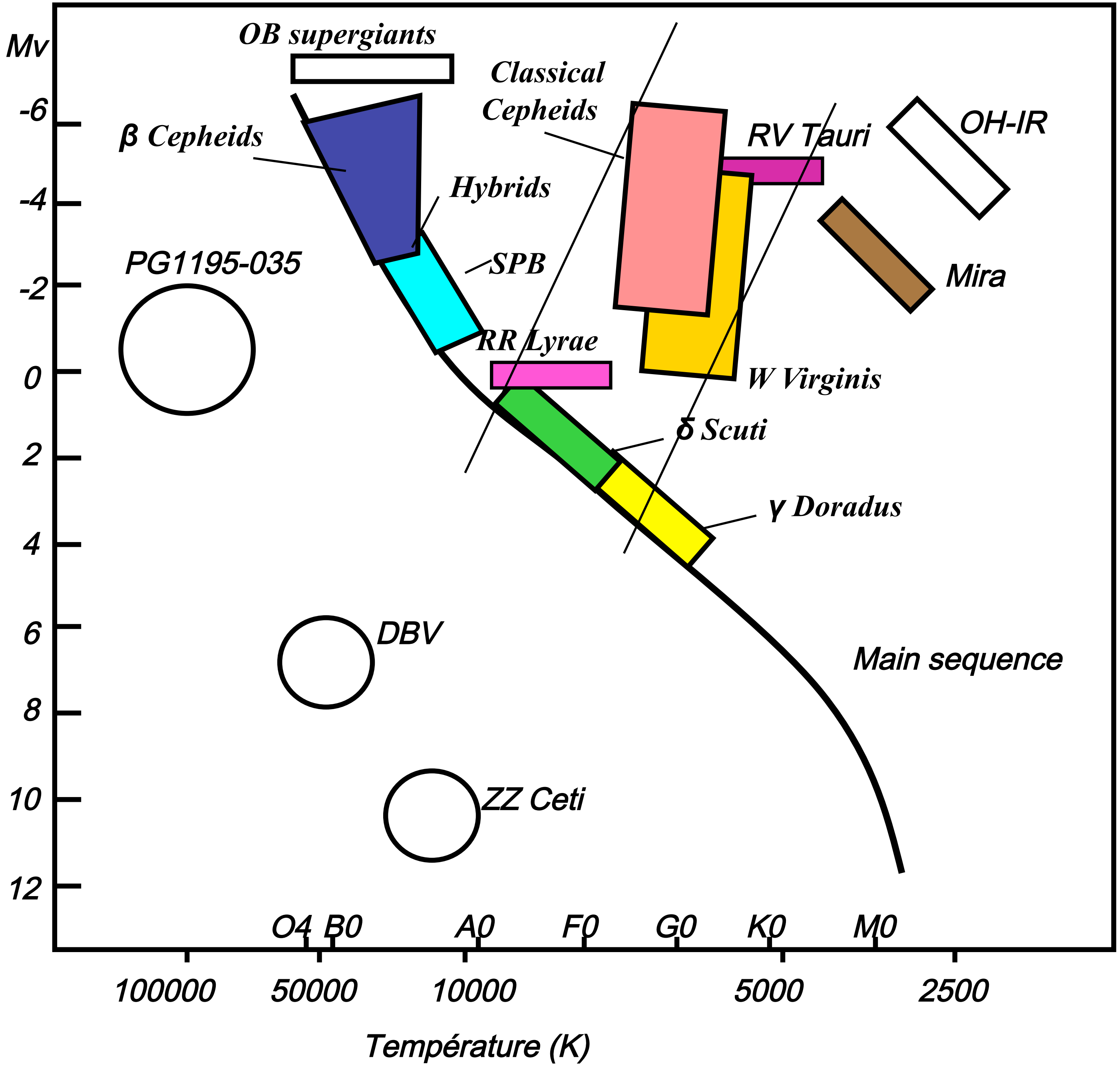
θ de 1.38 mas à 1.53 mas





Precision à 1 um &, B=200m : 1 uas (AMBER/VLTI)
Precision à 0.6 um &, B=300m : 0.5 uas (VEGA/CHARA)

Science Case 6: Do the same things but for RR Lyrae, δ Scuti stars, ...



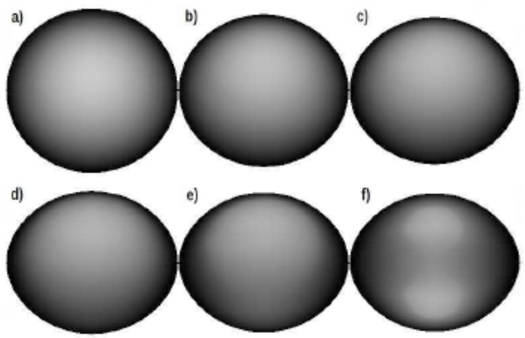
Cepheids are evolved stars (thus bright) but rare: ~500 identified Cepheids in the MW (probably 9000 in total).

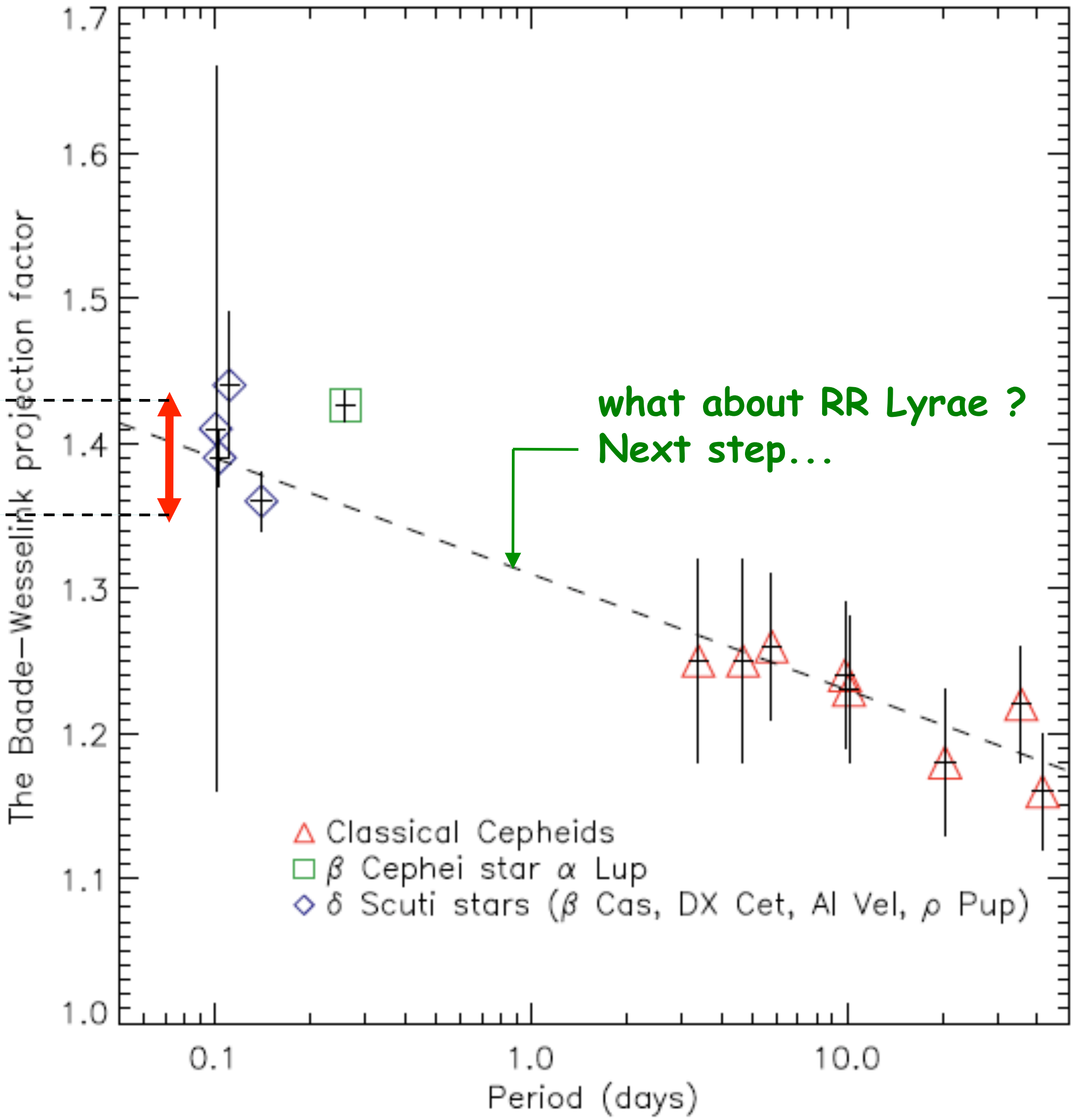
The BW could be in principle apply to other pulsating stars in the instability strip (radial mode dominant)

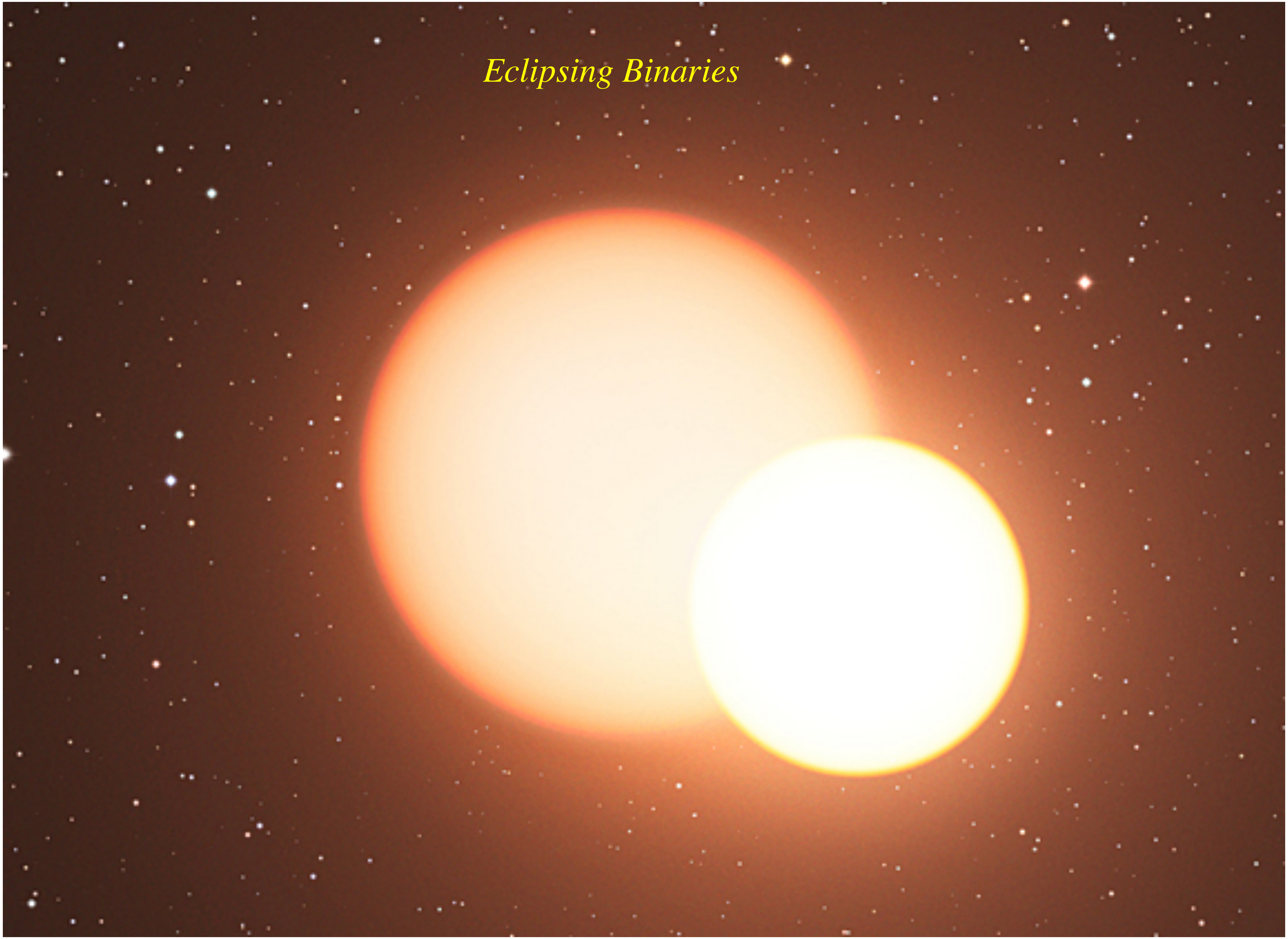
Science Case 6: Do the same things but for RR Lyrae, δ Scuti stars, ...

Nardetto, Poretti et al. **2014, *A&A*, 561, 151**

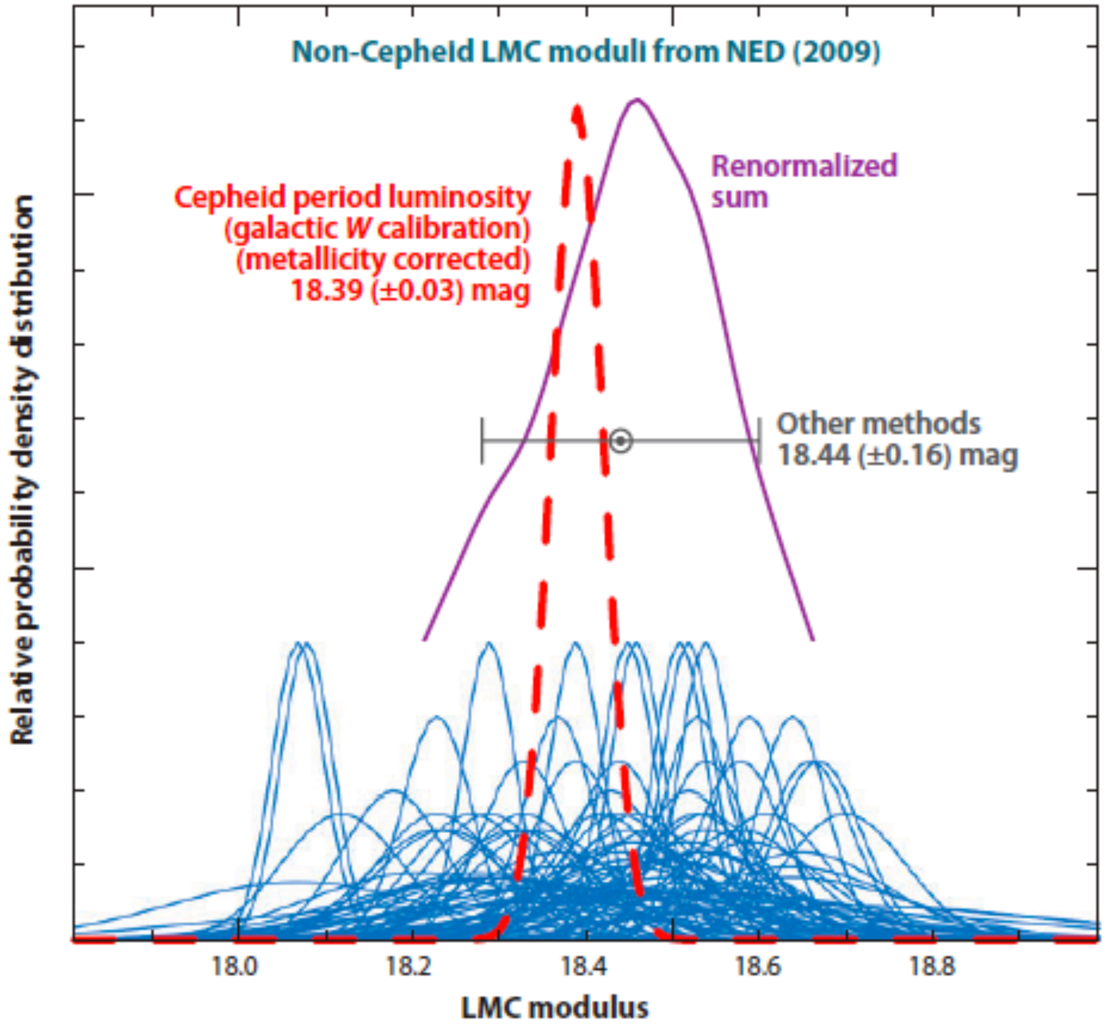
typical impact of the fast rotation and inclination on the projection factor






Eclipsing Binaries

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



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

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 !

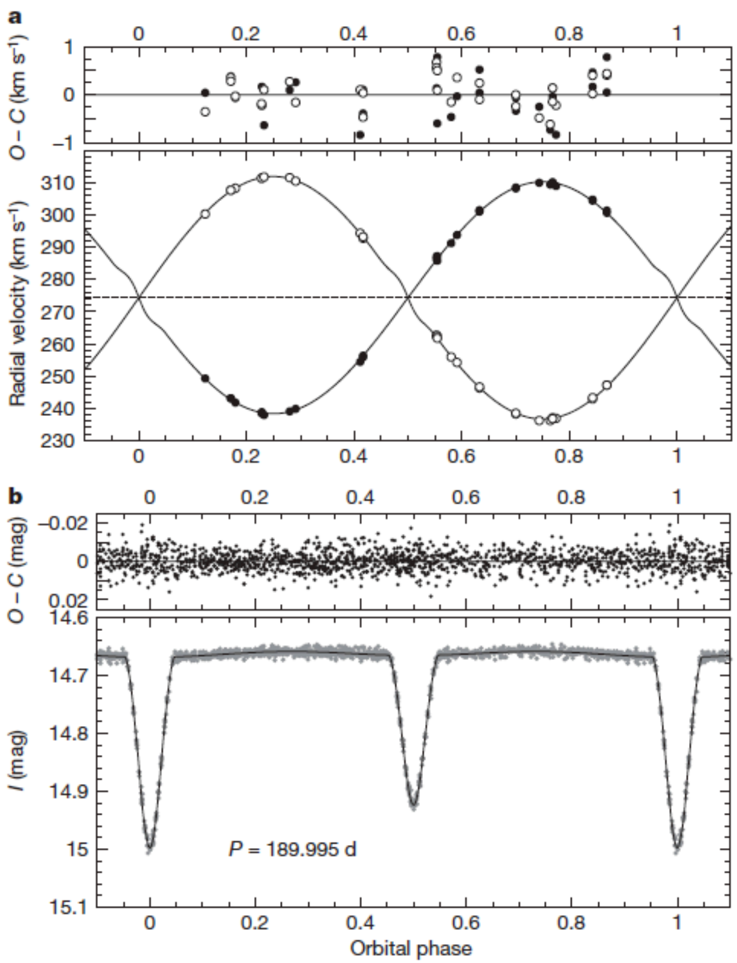
=> is almost parallel to the reddening line !

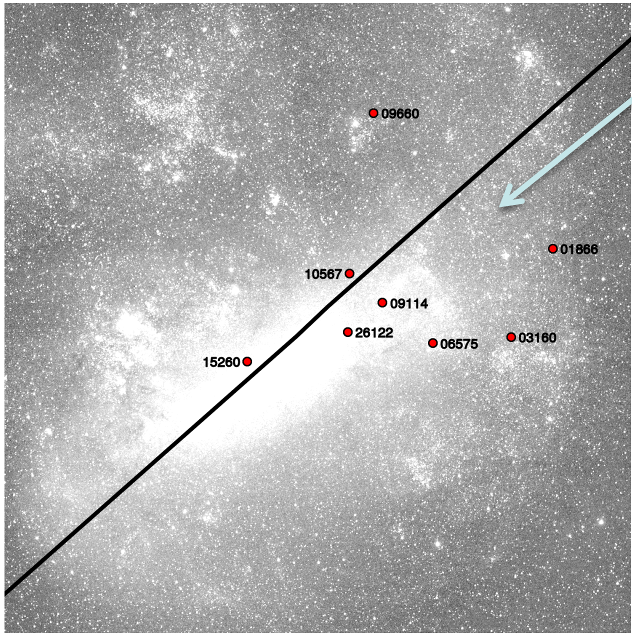
The distance of eclipsing binaries in the local Group

***R* + *θ* (from surface brigthness relation)**

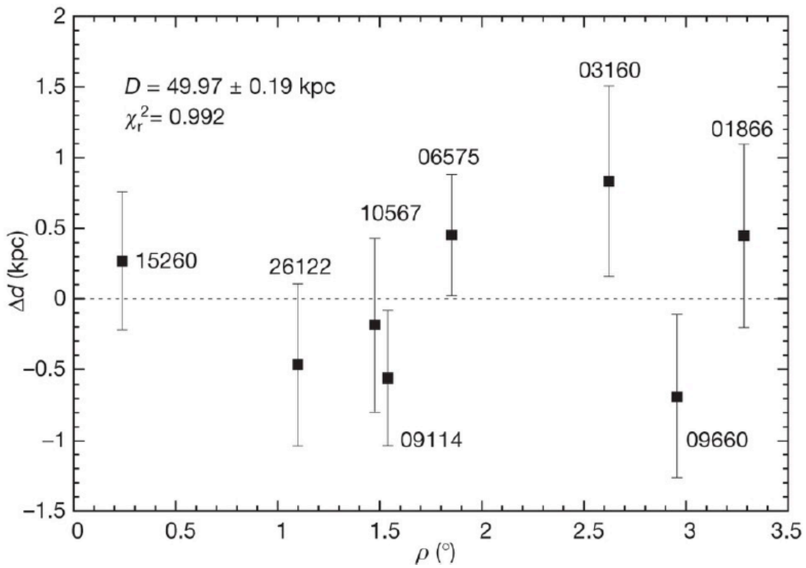
=

***distance* at few percents**





8 eclipsing binaries in LMC



LETTER

doi:10.1038/nature11878

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]

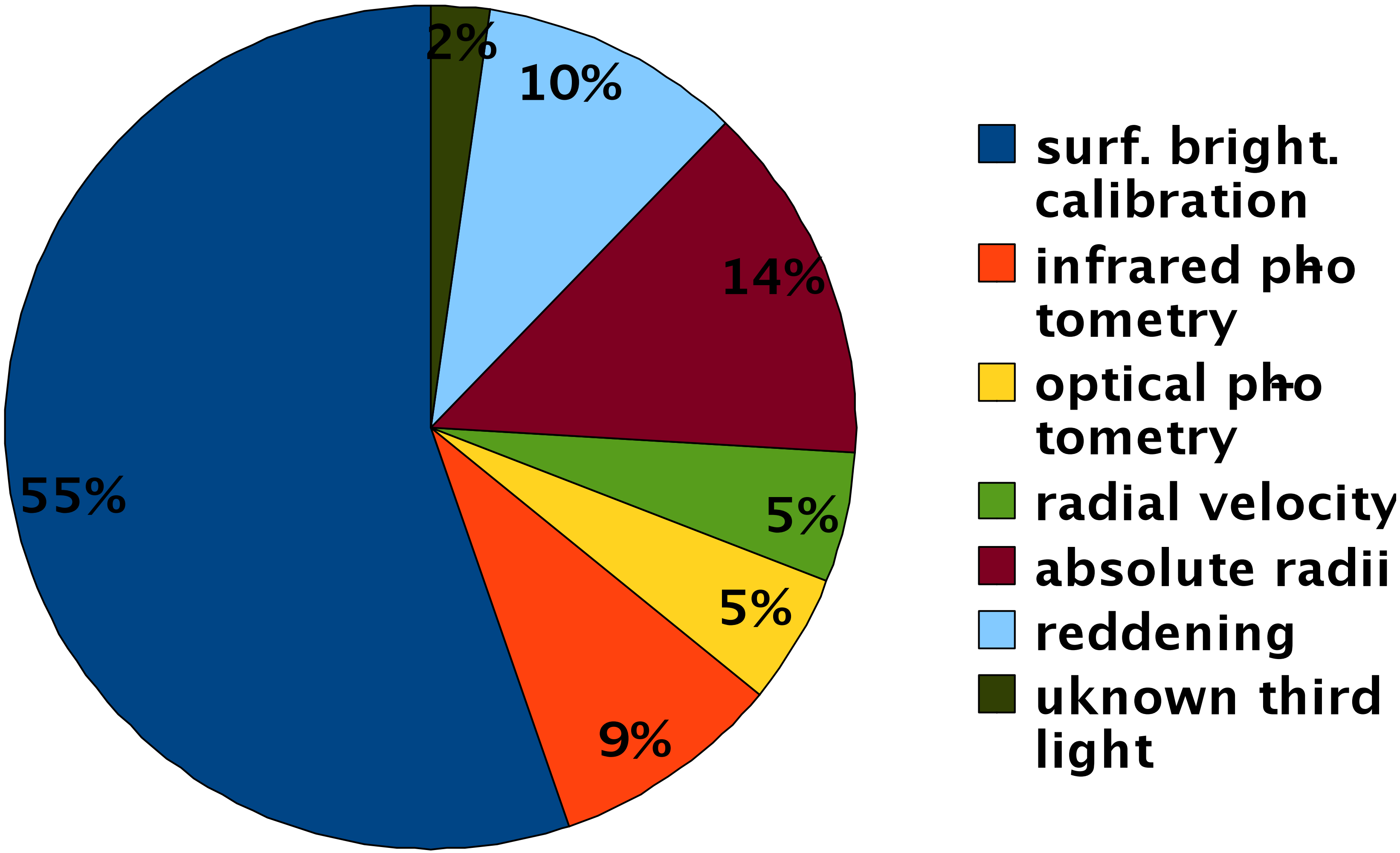
In the era of precision cosmology, it is essential to determine the Hubble constant to an accuracy of three per cent or better[1,2]. At present, its uncertainty is dominated by the uncertainty in the distance to the Large Magellanic Cloud (LMC), which, being our nearest galaxy, serves as the best anchor 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)

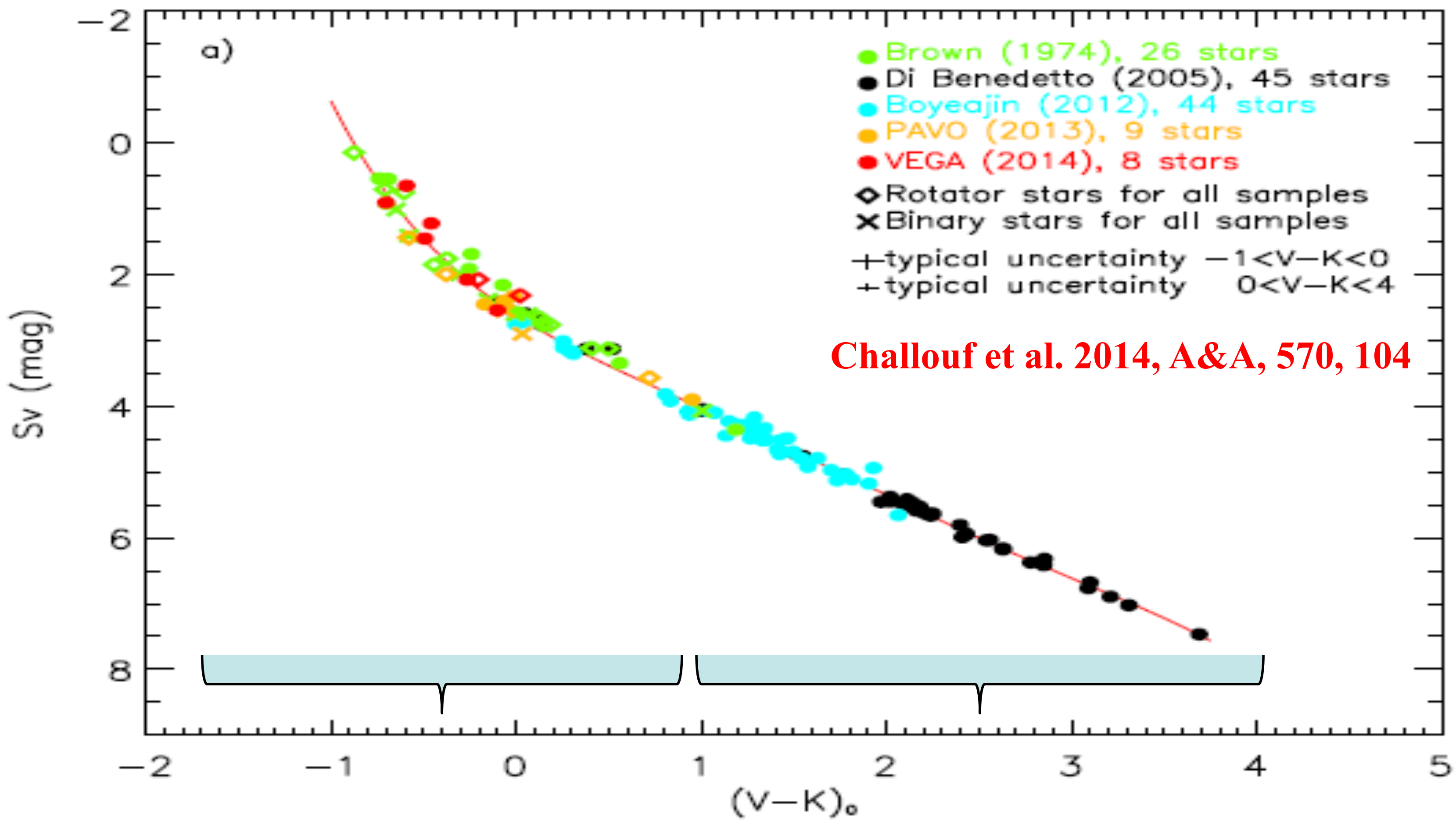


Visible interferometry: science case for Eclipsing binaries

Low/Medium Spectral resolution mode (high sensitivity)

- Science Case 7: surface-brightness relation of late-type and early-type stars
- Science Case 8: characterize closeby eclipsing binaries using visible interferometry (with Gaia we can inverse the eclipsing binary technique and check for systematics)

Science Case 7: surface-brightness relations



Bright early-type stars (O-A-B) for distances in Local Group
Objective= reach 5% and evaluate the impact of rotation, winds, environment

Late-type stars (F-G) for LMC distance
Objective= reach 1% and even better

Summary:

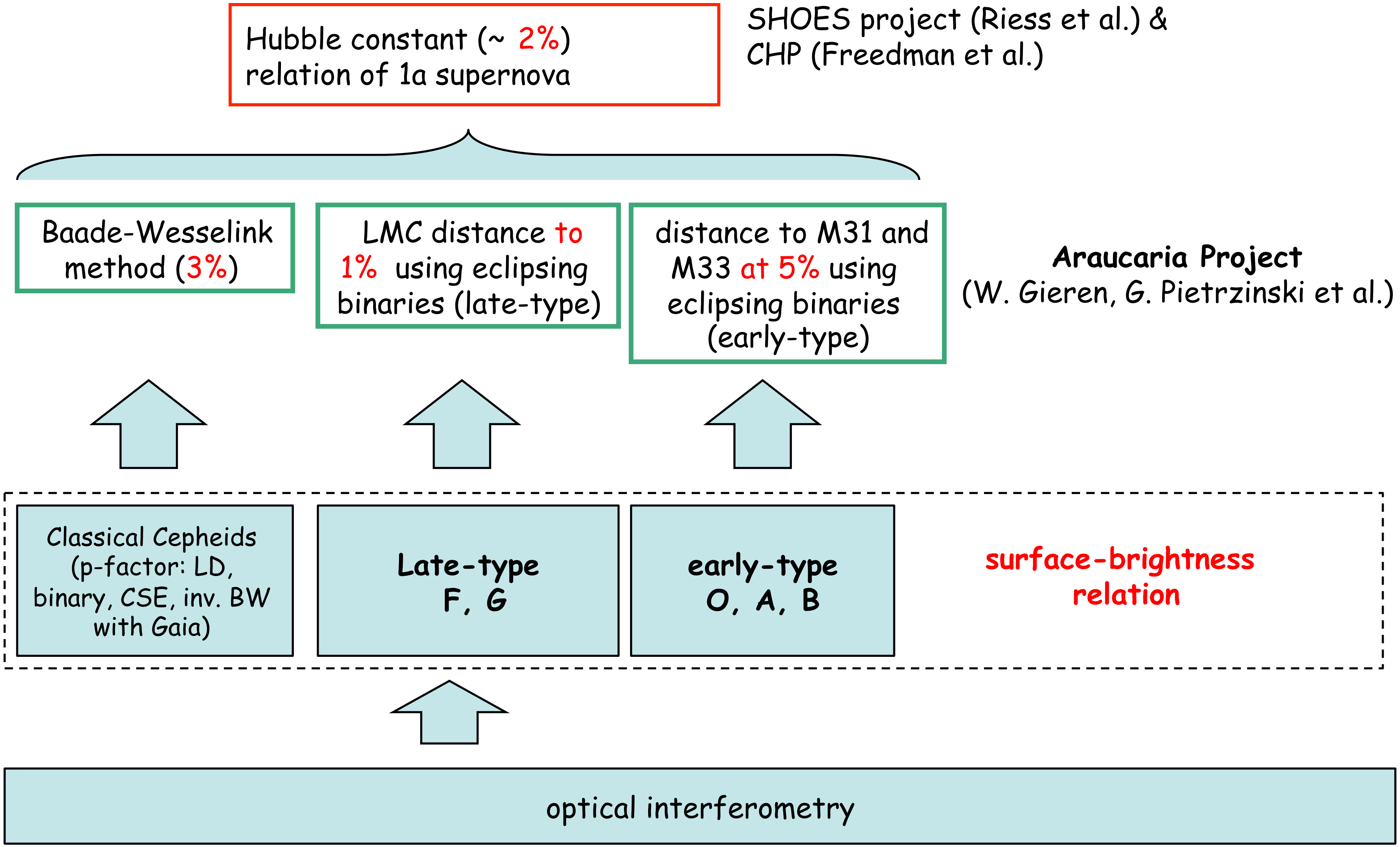

Hubble constant (~ 2%)
relation of 1a supernova
SHOES project (Riess et al.) &
CHP (Freedman et al.)
Baade-Wesselink method (3%)
LMC distance to 1% using eclipsing binaries (late-type)
distance to M31 and M33 at 5% using eclipsing binaries (early-type)
Araucaria Project
(W. Gieren, G. Pietrzinski et al.)
Classical Cepheids (p-factor: LD, binary, CSE, inv. BW with Gaia)
Late-type F, G
early-type O, A, B
surface-brightness relation
optical interferometry

Table 2. The limb-darkening of δ Cep and ℓ Car

$N_\star$	δ Cep and ℓ Car
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	$P = 5.36$d (δ Cep), $P = 35.5$d (ℓ Car
precision	1% in the second lobe (V$\simeq$ 10%)
imaging	3T is fine

Table 1. Cepheids in binaries

$N_\star$	10-15
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	2-40 years
precision	1% even at low visibilities
imaging	6T is best

Table 3. The CSE of Cepheids

$N_\star$	about 20
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	several obs. per star is enough
precision	1% in the first lobe (V$\simeq$ 50%)
imaging	3T is fine, but 6T better

Table 4. The inverse BW method using Gaia

$N_\star$	105
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	periods from 2 to 50 days
precision	5% on the visibility (V$\simeq$ 50%)
imaging	3T is fine, but 6T better

Table 5. A new distance indicator using specto-interferometry of Cepheids

$N_\star$	40 in MW ; 40 in LMC
spatial resolution	0.3 mas
spectral resolution	$R = 60000$
temporal resolution	periods from 2 to 50 days
precision	1μas for MW; 0.2μas for LMC
imaging	3T is fine, but 6T better

Table 1. HADS and RR Lyrae

$N_\star$	$\simeq 10$
spatial resolution	θ from 0.1 to 0.25 mas
spectral resolution	$R = 3000$
temporal resolution	10 minutes (high sensitivity required)
precision	1% at low visibilities
imaging	3T is fine, 6T is best

Table 6. The SBCR of late-type stars: distance to LMC

$N_\star$	$\simeq 200$
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	no particular constrain
precision	1% or better on θ
imaging	3T is fine, but 6T better

Table 7. The distance of Galactic EBs: a cross-check for the method

$N_\star$	50 eclipsing binary systems
spatial resolution	0.3 mas
spectral resolution	$R = 3000$
temporal resolution	to be defined
precision	1% on the visibilities
imaging	6T better

The sky is 'like a painting' i.e. with a third dimension