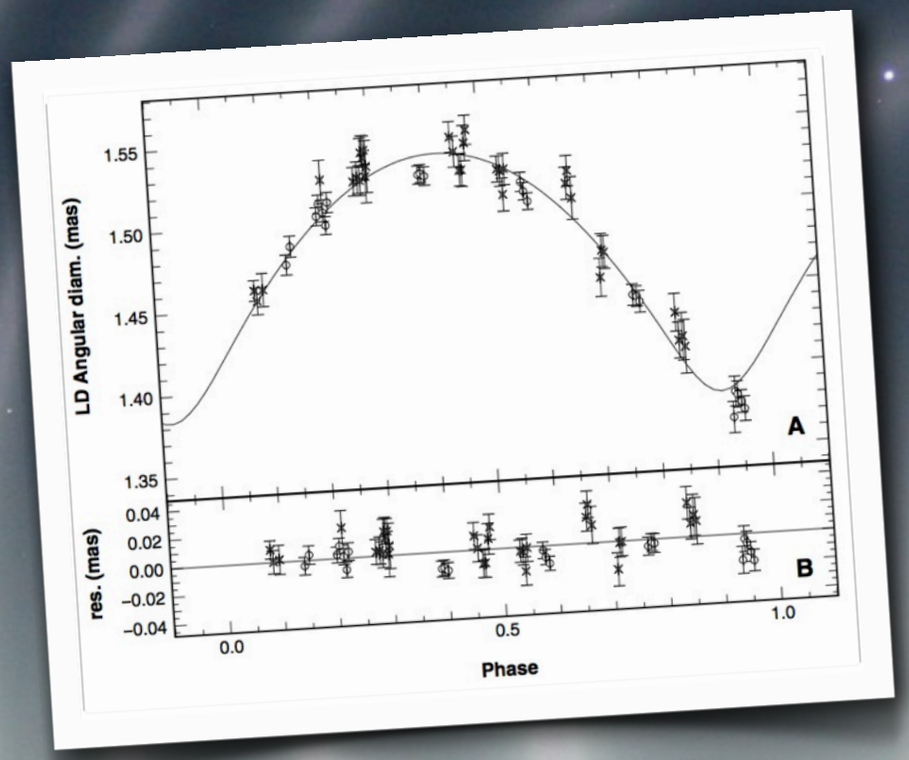
INTERFEROMETRY AND THE DISTANCE SCALE



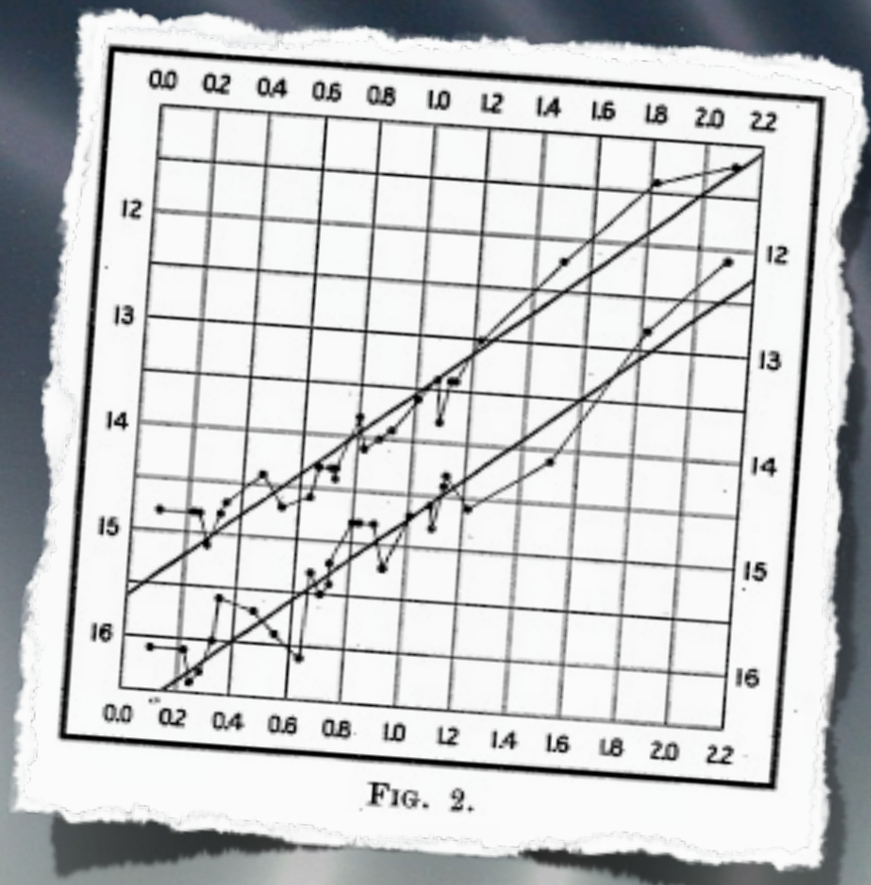


FIG. 2.

PIERRE KERVELLA (LESIA),
ANTOINE MÉRAND (ESO), ALEXANDRE GALLENNE (UDEC),
JOANNE BREITFELDER (ESO/LESIA), NICOLAS NARDETTO (OCA),
JOHN MONNIER (UMICH), AND MANY OTHERS

photo: S. Guisard

INTERFEROMETRY AND THE DISTANCE SCALE

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INTERFEROMETRY AND THE DISTANCE SCALE

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- Long-baseline interferometry can help in different ways:

    1. Baade-Wesselink distances of nearby Cepheids
    2. Surface-brightness-color relations
    3. Cepheids in binary stars

The variables appear to fall into three or four distinct groups. The majority of the light curves have a striking resemblance, in form, to those of cluster variables. As a rule, they are faint during the greater part of the time, the maxima being very brief, while the increase of light usually does not occupy more than from one-sixth to one-tenth of the entire period. It is worthy of notice that in Table VI the brighter variables have the longer periods. It is also noticeable that those having the longest periods appear to be as regular in their variations as those which pass through their changes in a day or two. This is especially striking in the case of No. 821, which has a period of 127 days, as 89 observations with 45 returns of maximum give an average deviation from the light curve of only six hundredths of a magnitude. Six of the sixteen variables are brighter at maximum than the fourteenth magnitude, and have periods longer than eight days. It will be noticed that this proportion is much greater here than in Table II. The number which have been measured up to the present time is 59, and of these the brighter stars were first selected for discussion, as the material for them was more abundant. A few of the fainter variables, selected at random, were then studied, but no attempt has yet been made to determine periods for the remainder. While, therefore, the light curves thus far obtained have characteristics to which the majority of the variables will probably be found to conform, no inference can be drawn with regard to the prevalence of any particular type, until many more of the periods have been de[illegible]mined.

Leavitt, H. S. 1908, Annals of Harvard College Observatory, vol. 60, 87-108.3

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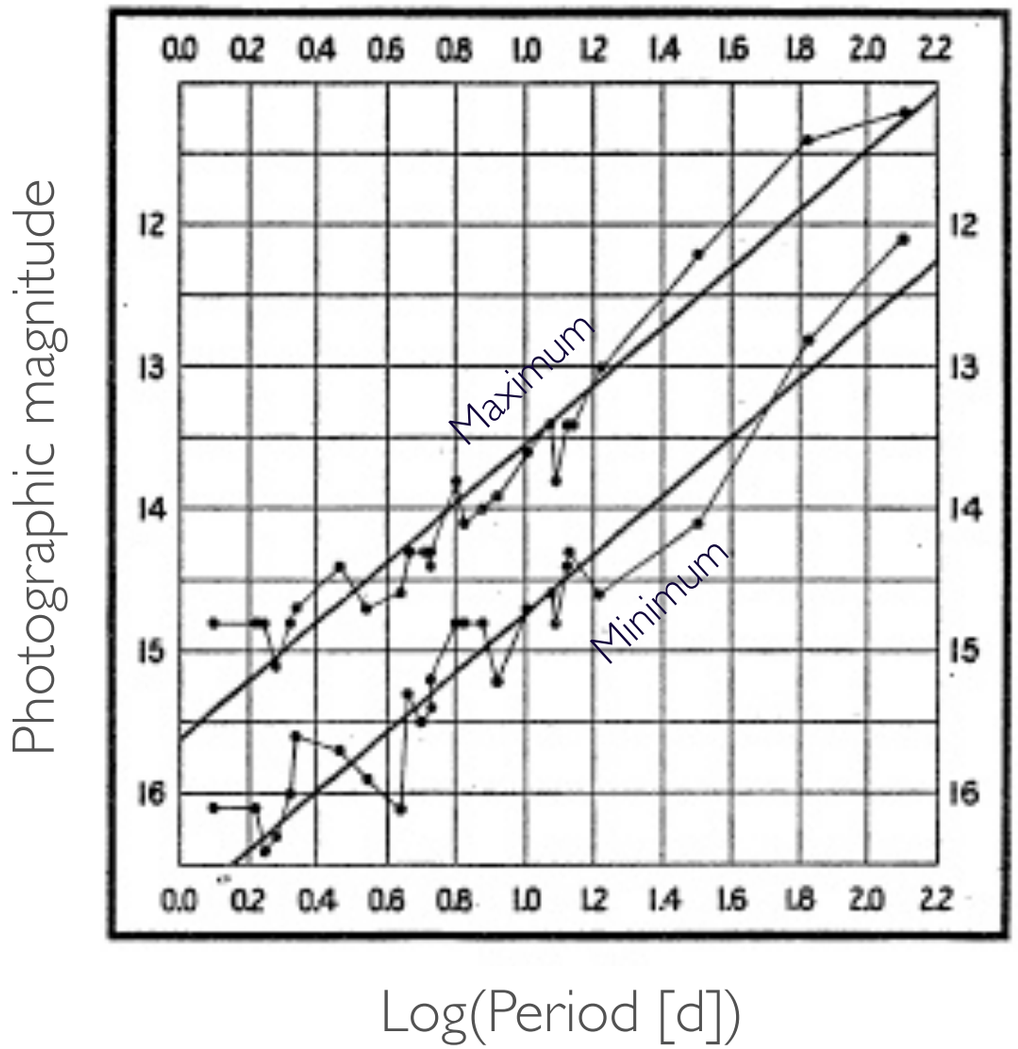
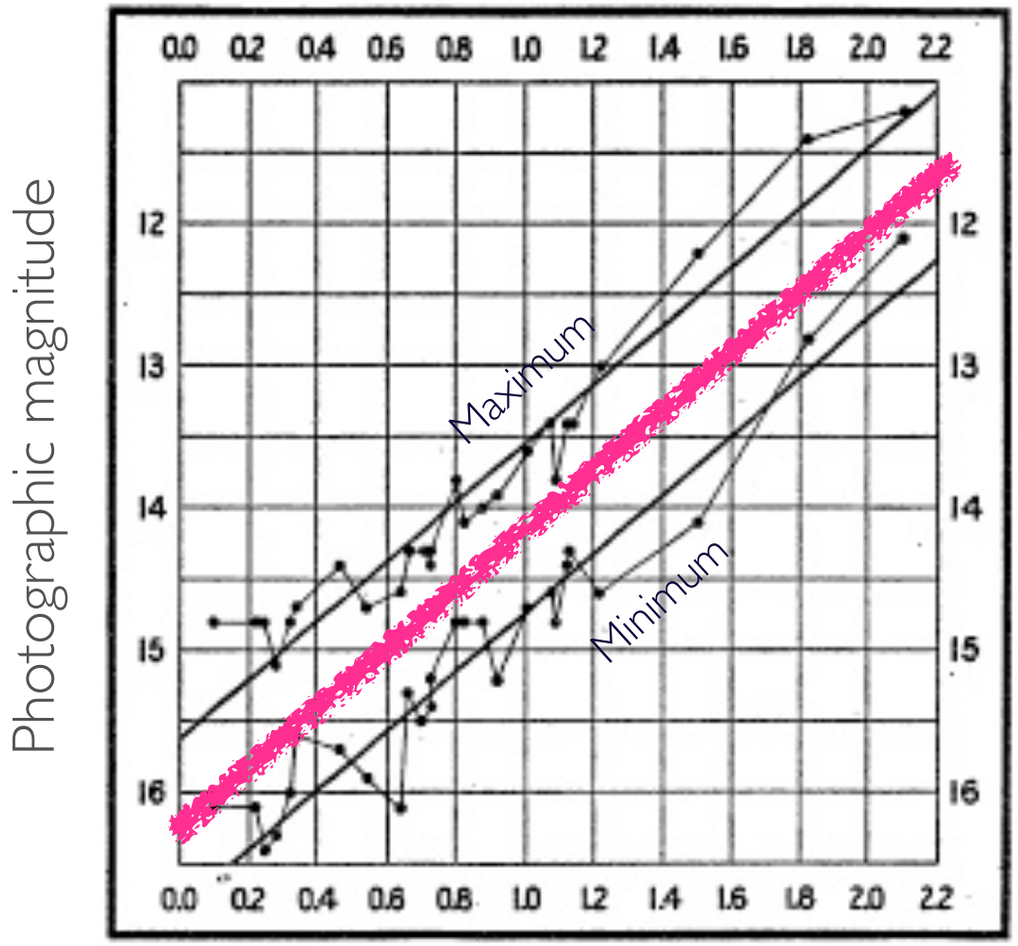


Leavitt, H. S. & Pickering E. C.1912, Harvard College Observatory Circular, vol. 173, pp.1-3

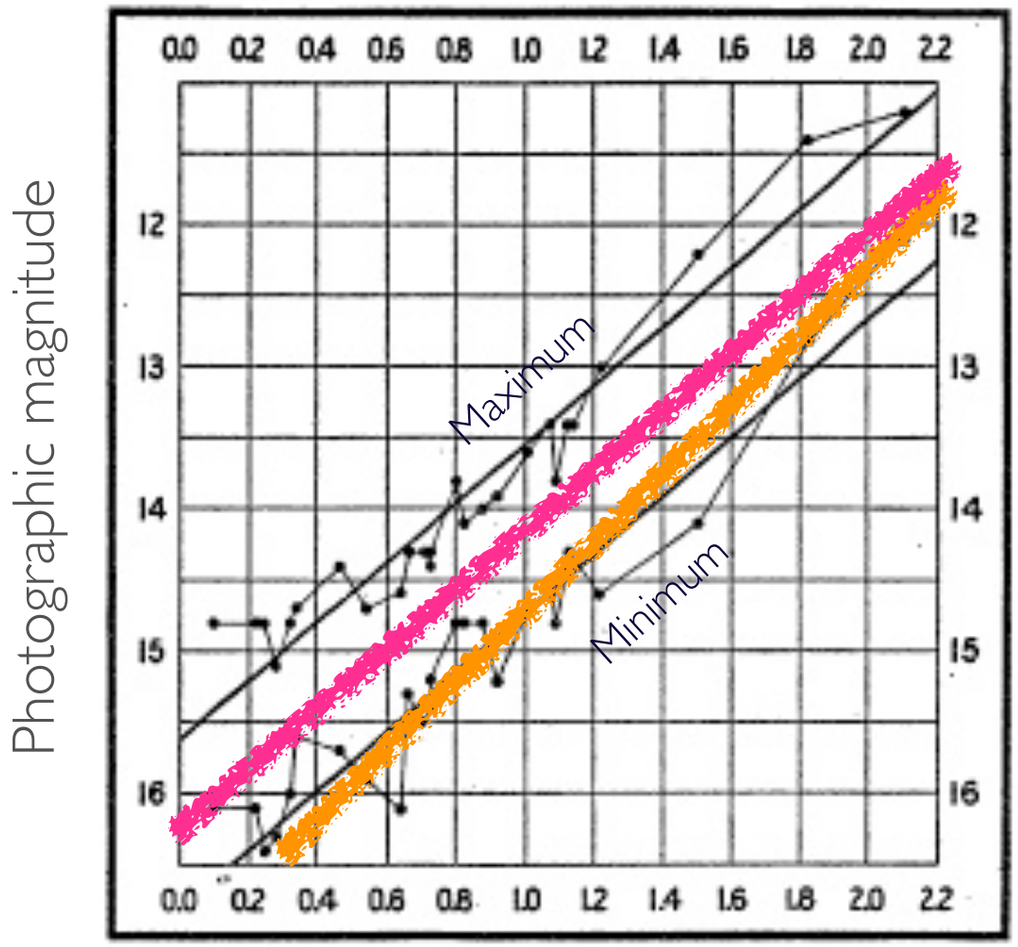
Leavitt & Pickering 1912



Leavitt, H. S. & Pickering E. C.1912, Harvard College Observatory Circular, vol. 173, pp.1-3

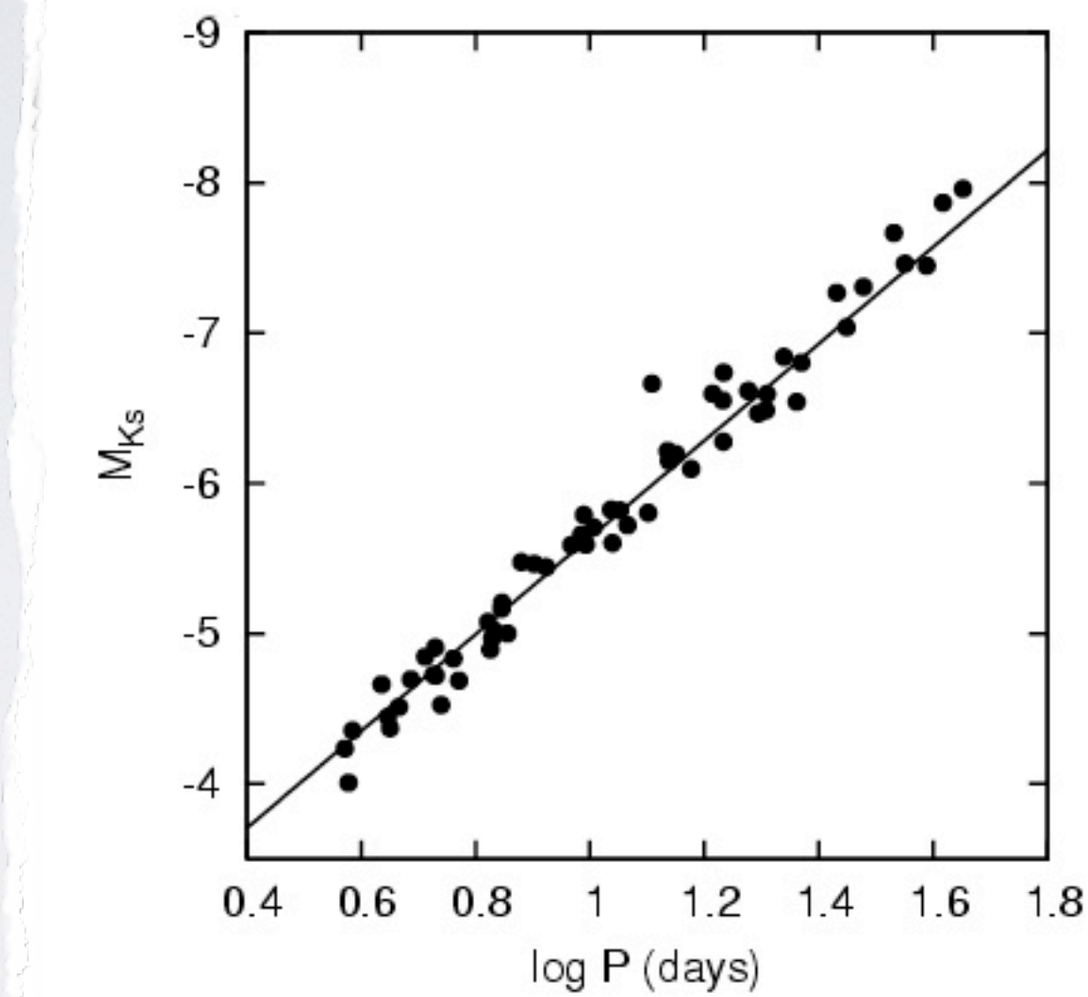
Leavitt & Pickering 1912

Fouqué et al. 2007 (Rc)



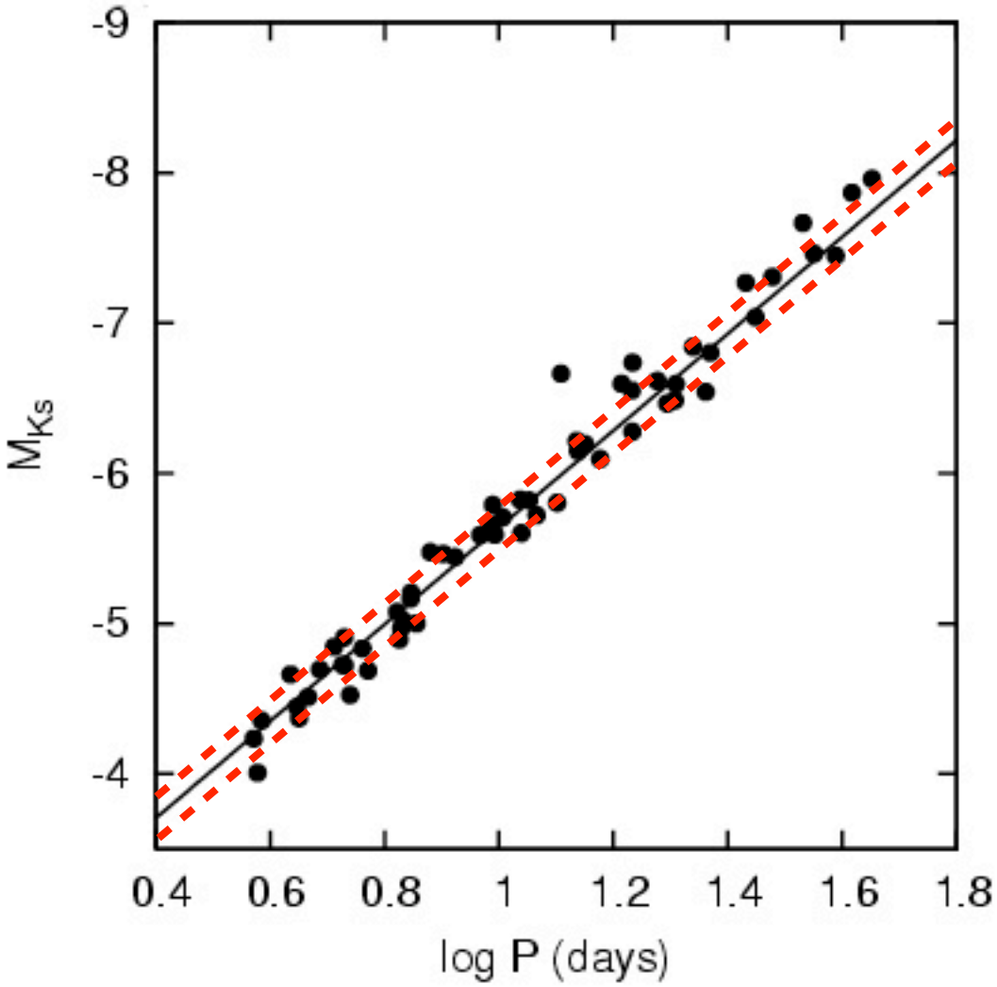
Leavitt, H. S. & Pickering E. C.1912, Harvard College Observatory Circular, vol. 173, pp.1-3

CALIBRATION



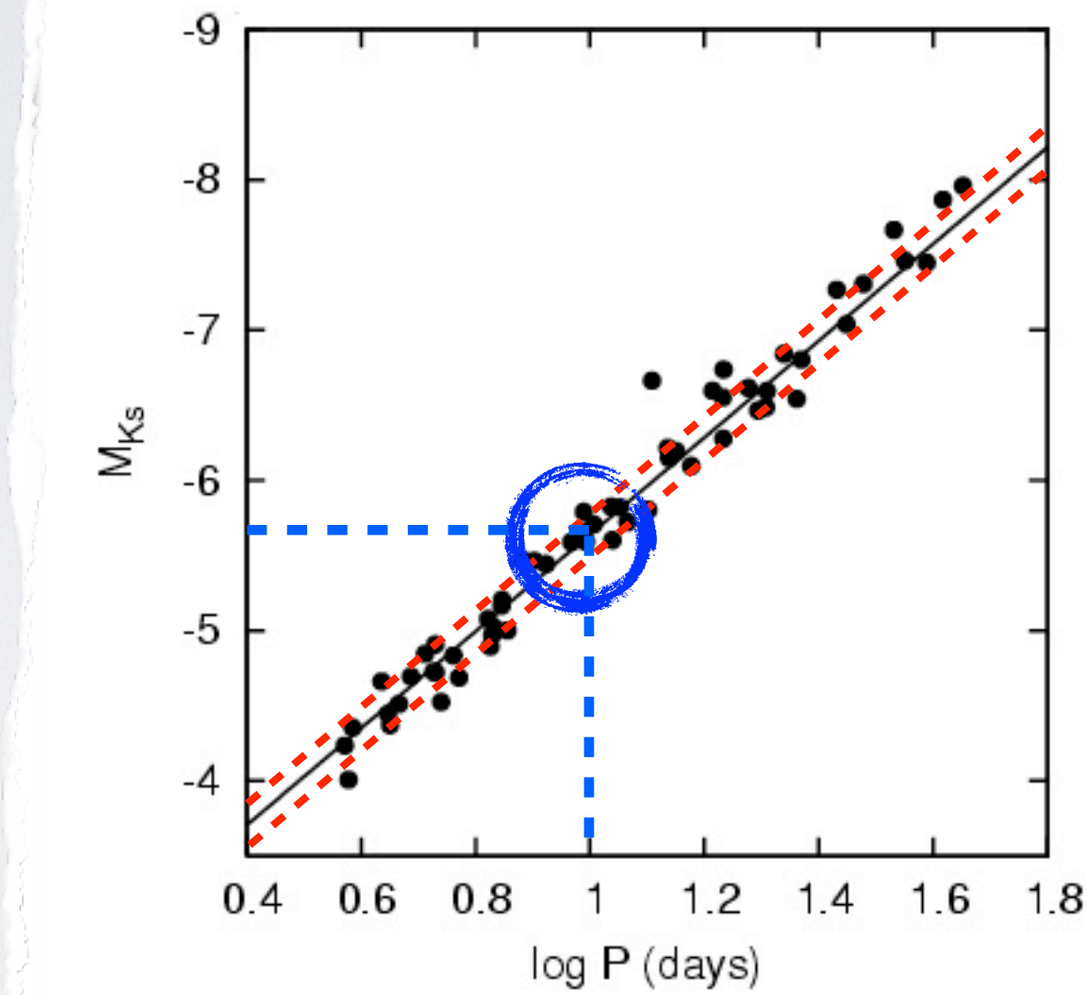
Fouqué et al 2007, A&A, 476, 73

CALIBRATION



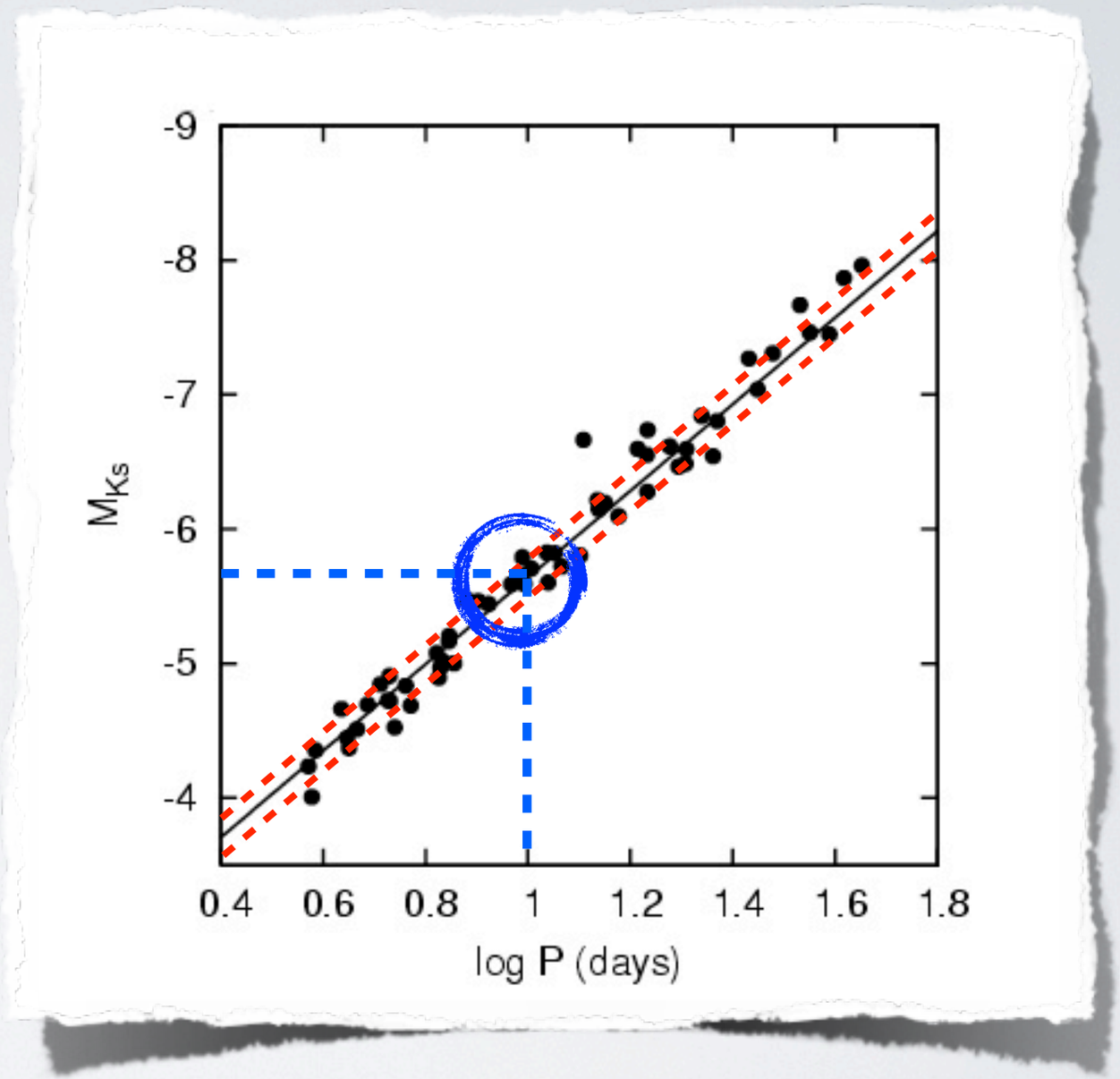
Fouqué et al 2007, A&A, 476, 73

CALIBRATION



Fouqué et al 2007, A&A, 476, 73

CALIBRATION

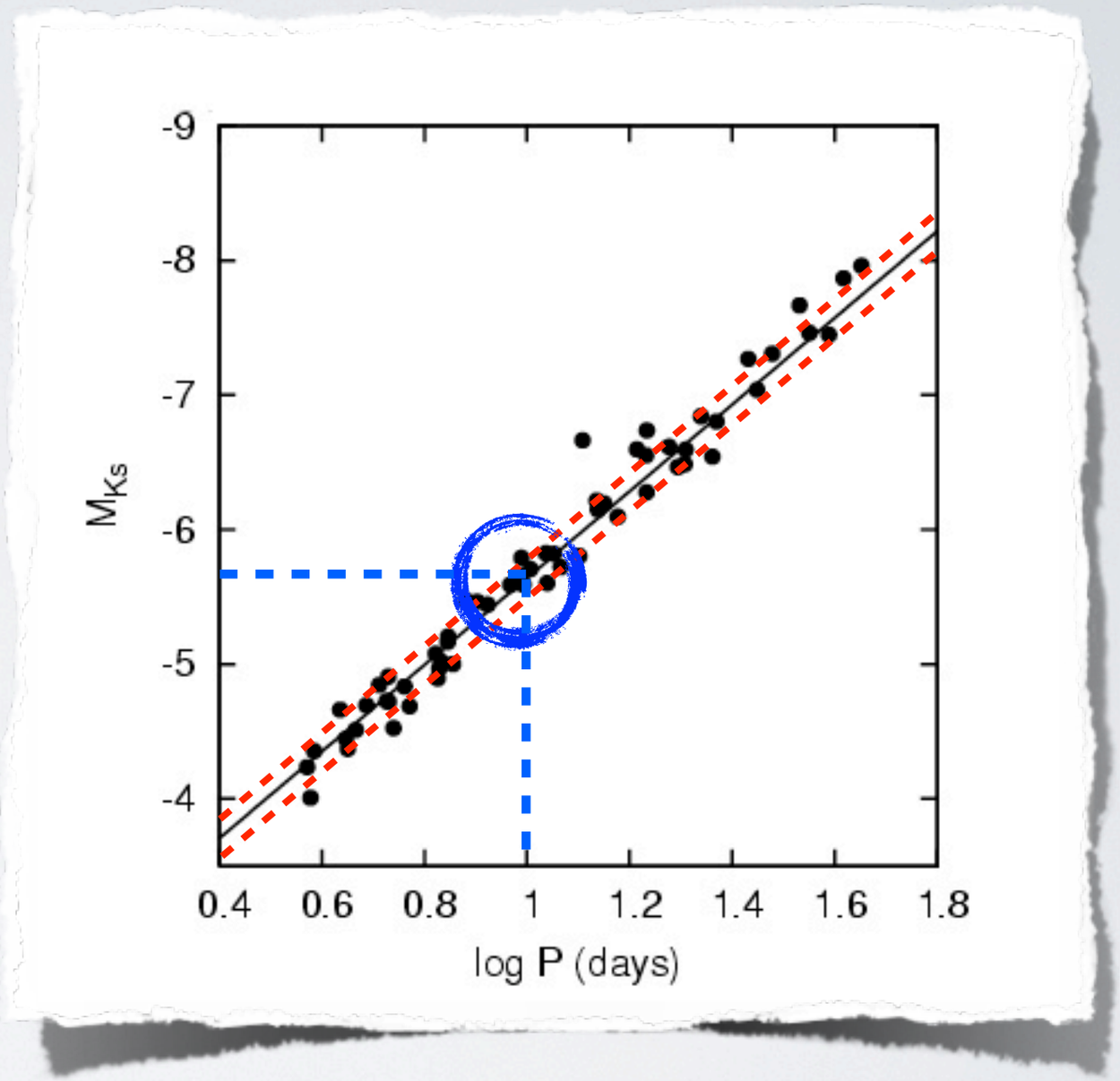


Fouqué et al 2007, A&A, 476, 73

CALIBRATION

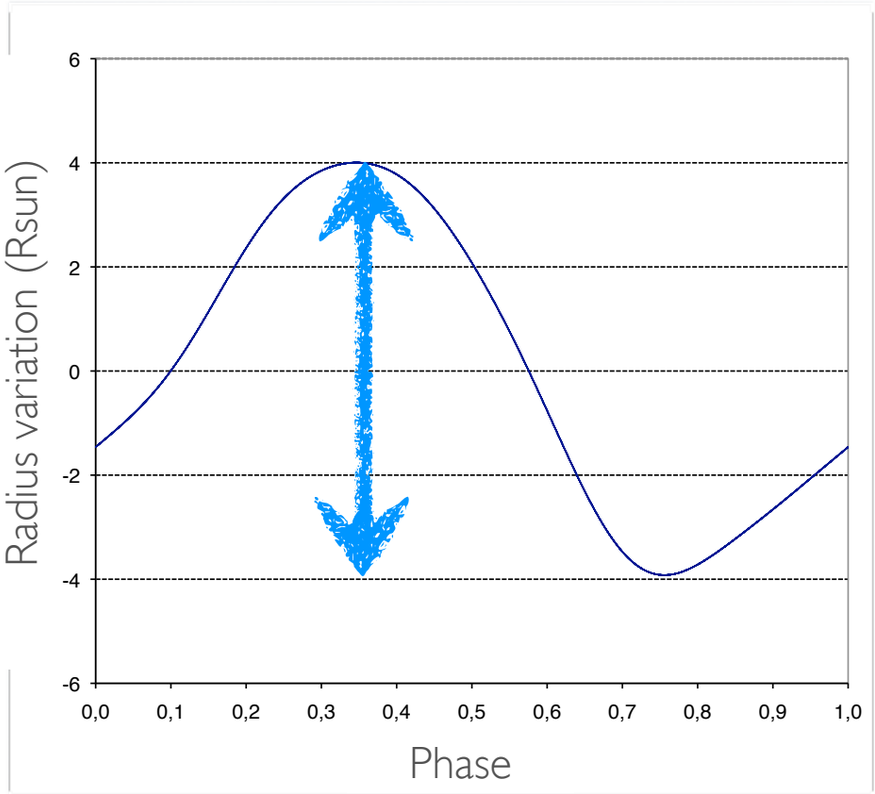
Parallax of pulsation

Cepheids in binaries

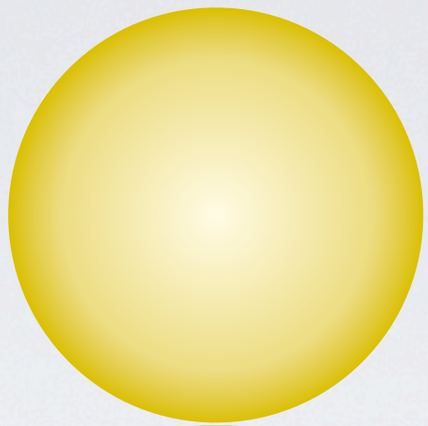


Fouqué et al 2007, A&A, 476, 73

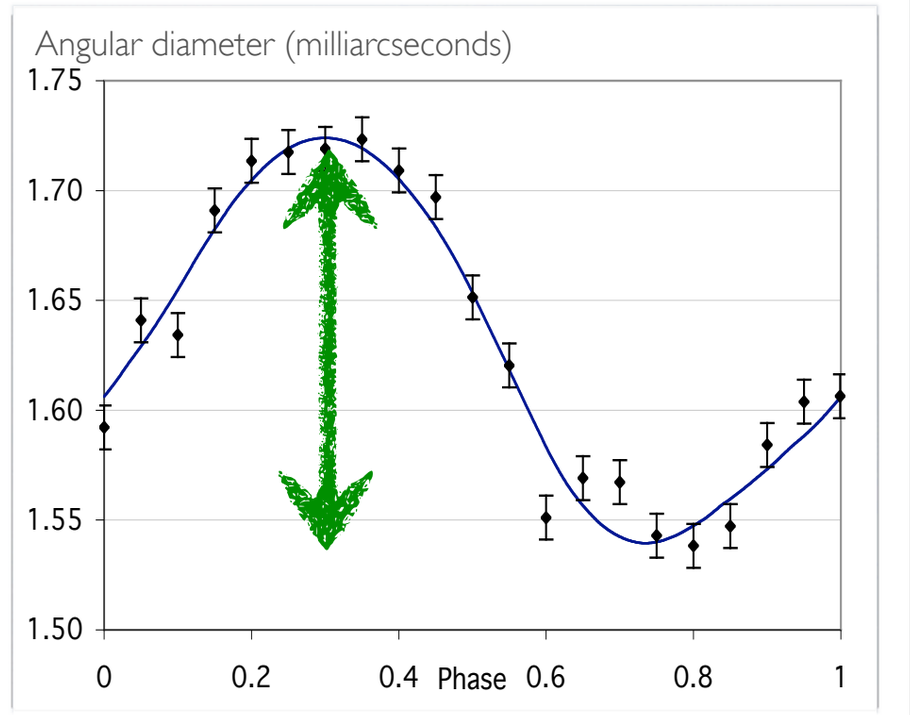
Spectroscopy



IBW



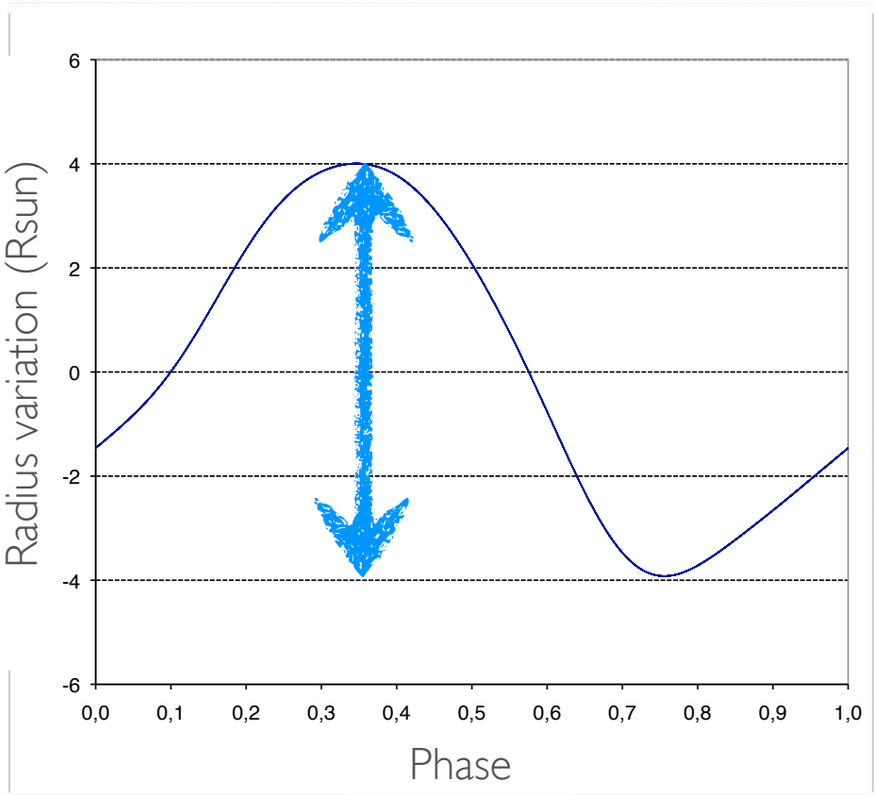
Interferometry



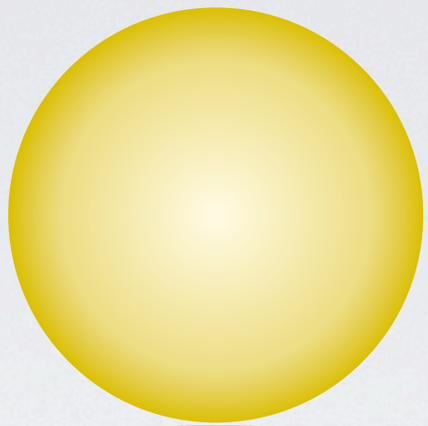
The distance d is given by the relation:

$$d = \frac{2\delta R(T)}{\delta\theta(T)} = \frac{-2\,k\,p\,\int_0^T v_{\mathrm{rad}}(t)\,dt}{\theta_{\mathrm{UD}}(T) - \theta_{\mathrm{UD}}(0)}$$

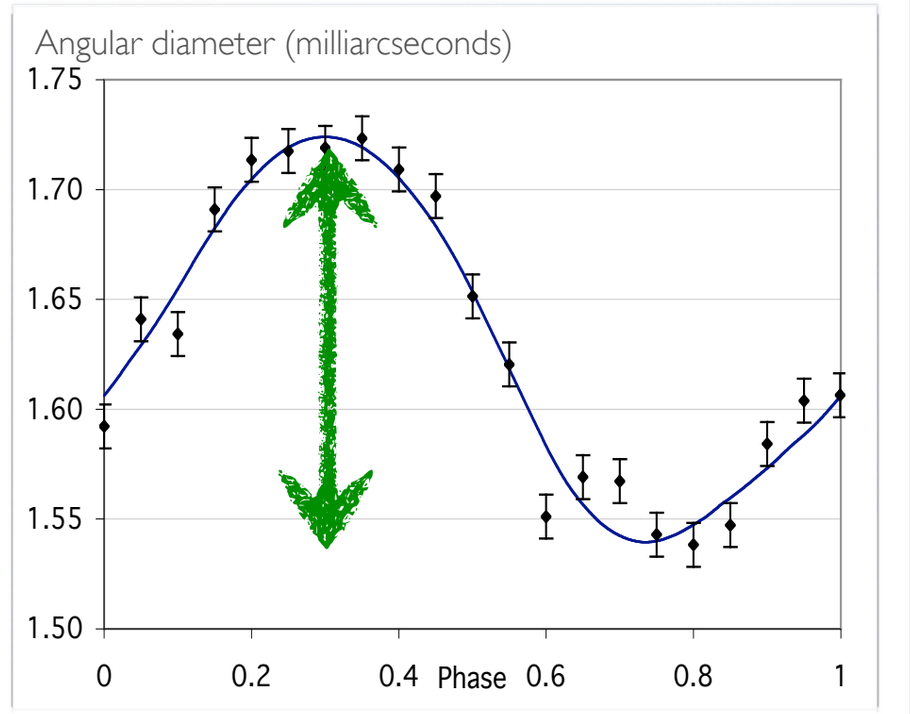
Spectroscopy



IBW



Interferometry



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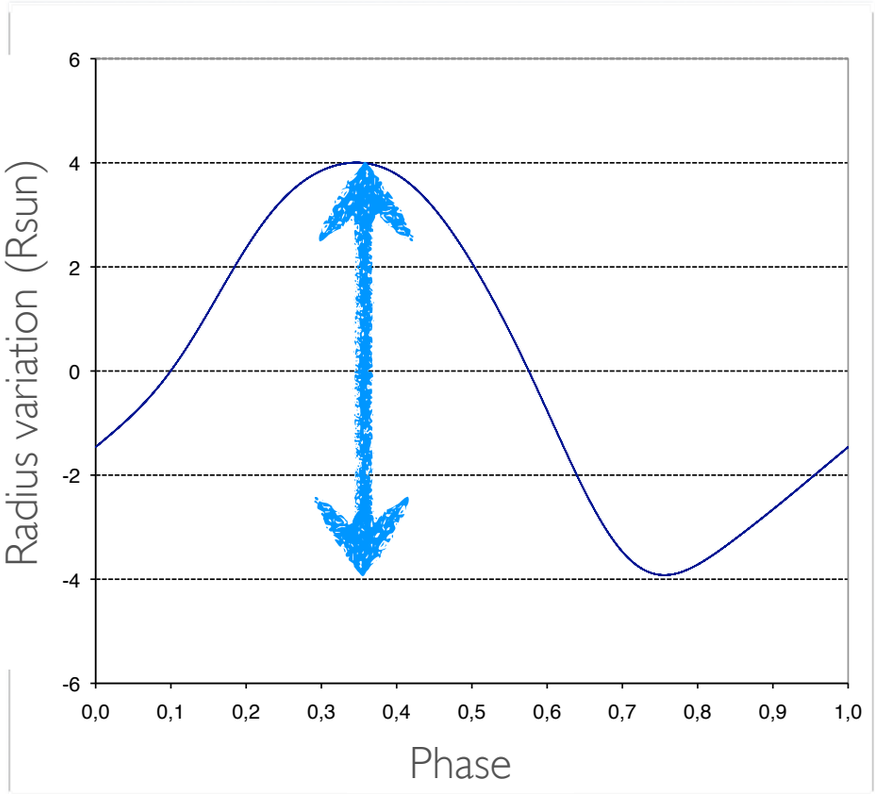

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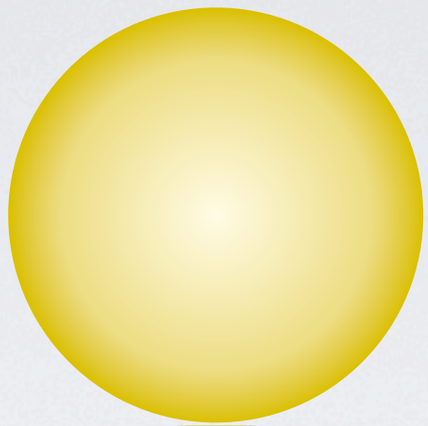
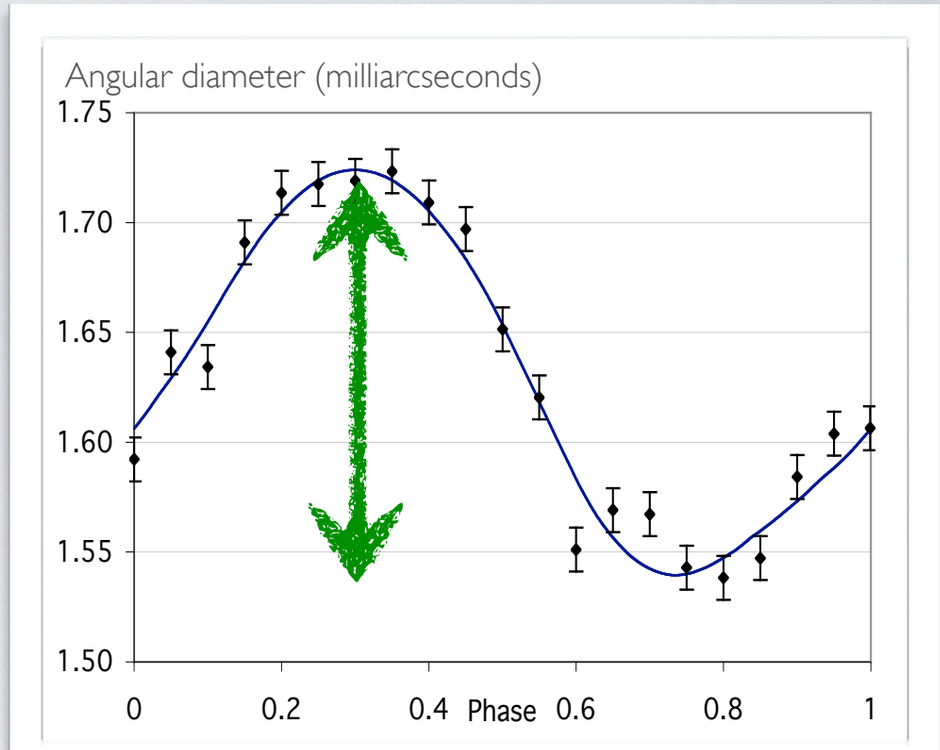


Interferometry



The distance *d* is given by the relation:

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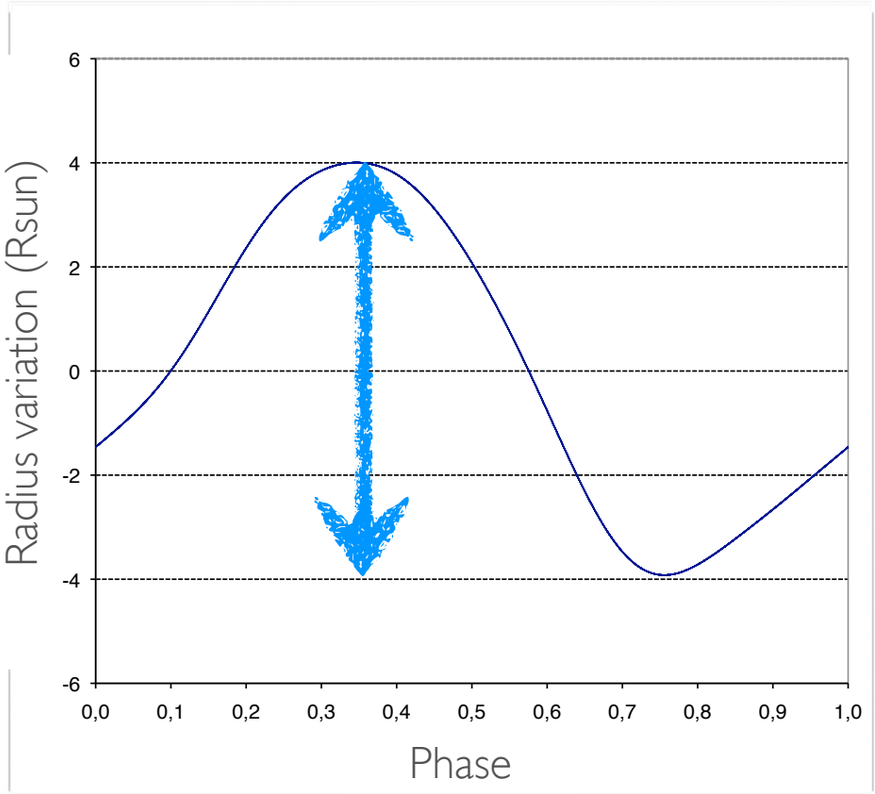
p = projection factor
$= V_{puls} / V_{rad} \sim 1.3$

Spectroscopy



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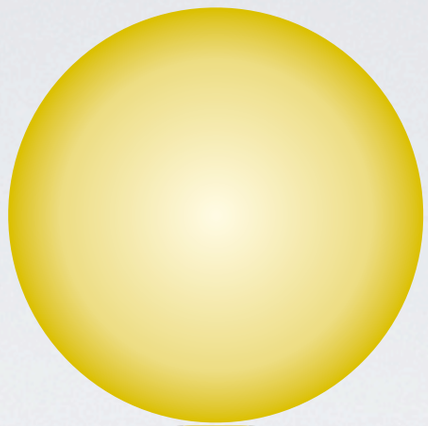
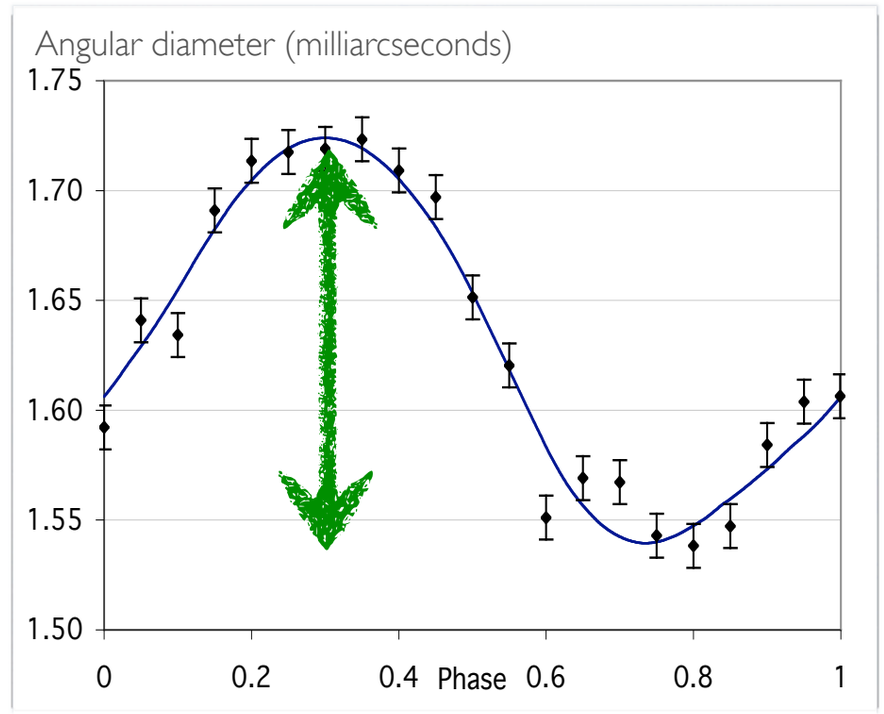


Interferometry



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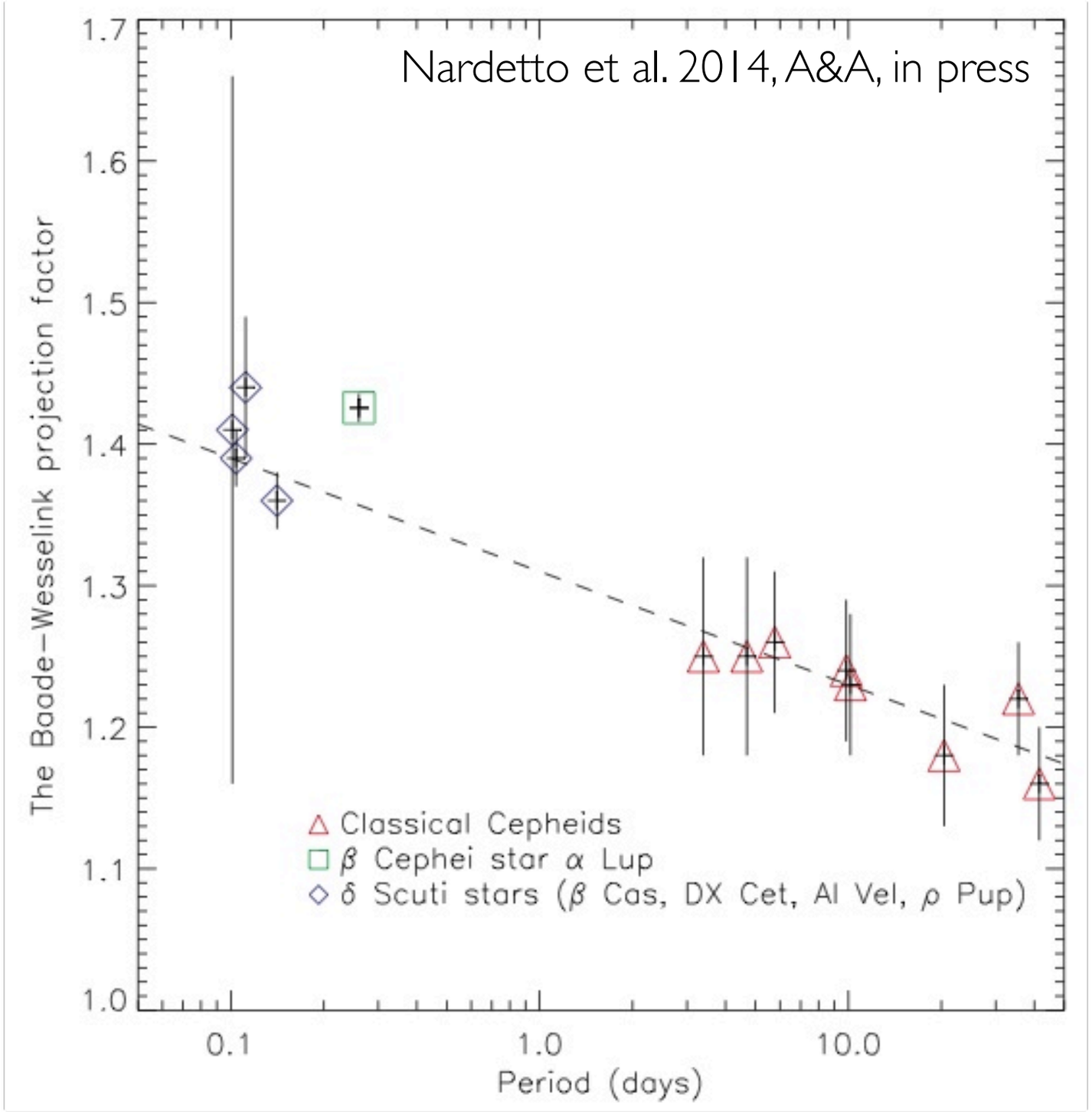
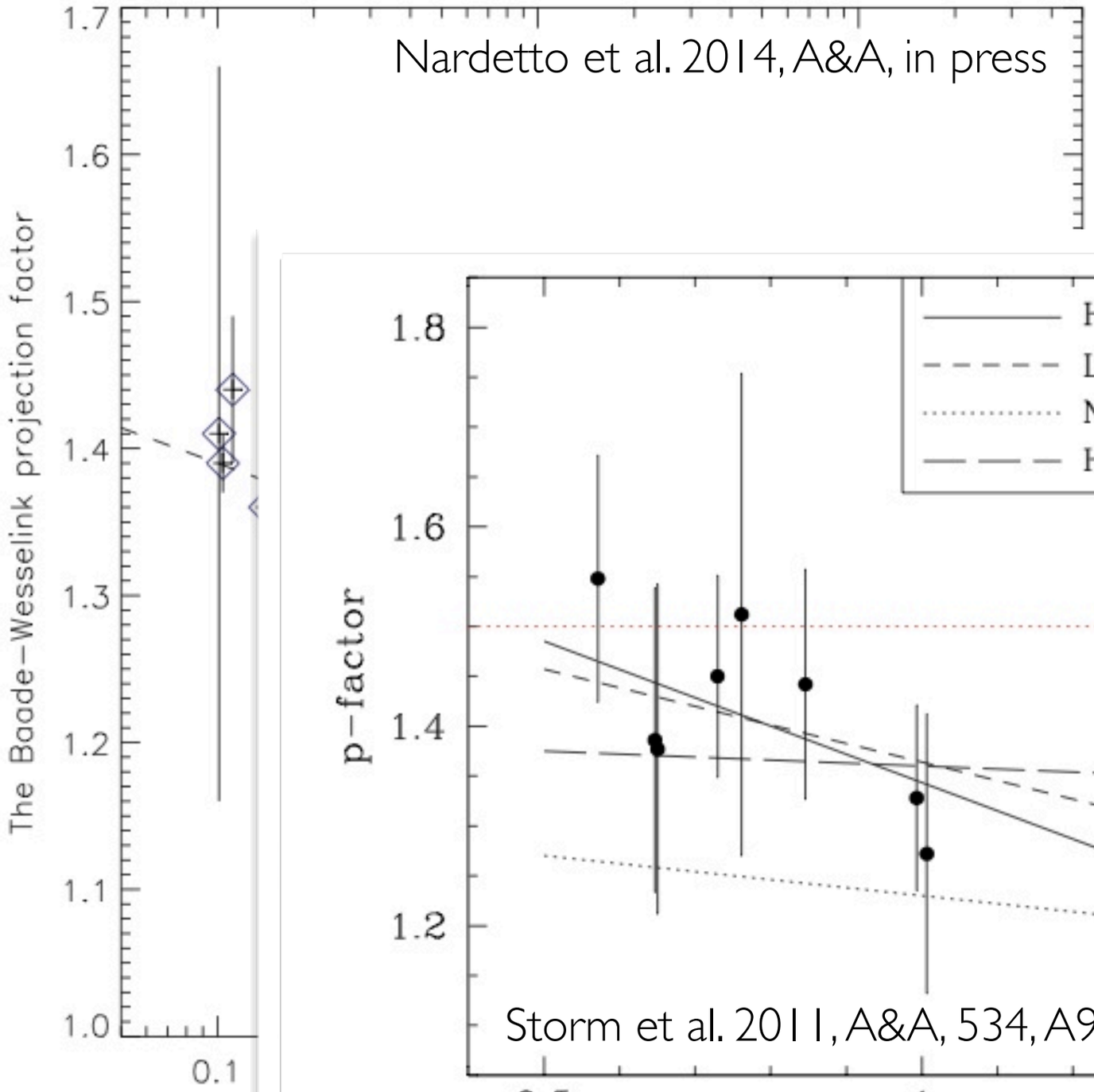
k = limb darkening
$= \theta_{UD} / \theta_{LD}$
$\sim$ 0.94 in visible, 0.98 in IR

P-FACTOR


Nardetto et al. 2014, A&A, in press
The Baade–Wesselink projection factor
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.1
1.0
10.0
Period (days)
Classical Cepheids
β Cephei star α Lup
δ Scuti stars (β Cas, DX Cet, Al Vel, ρ Pup)

P-FACTOR

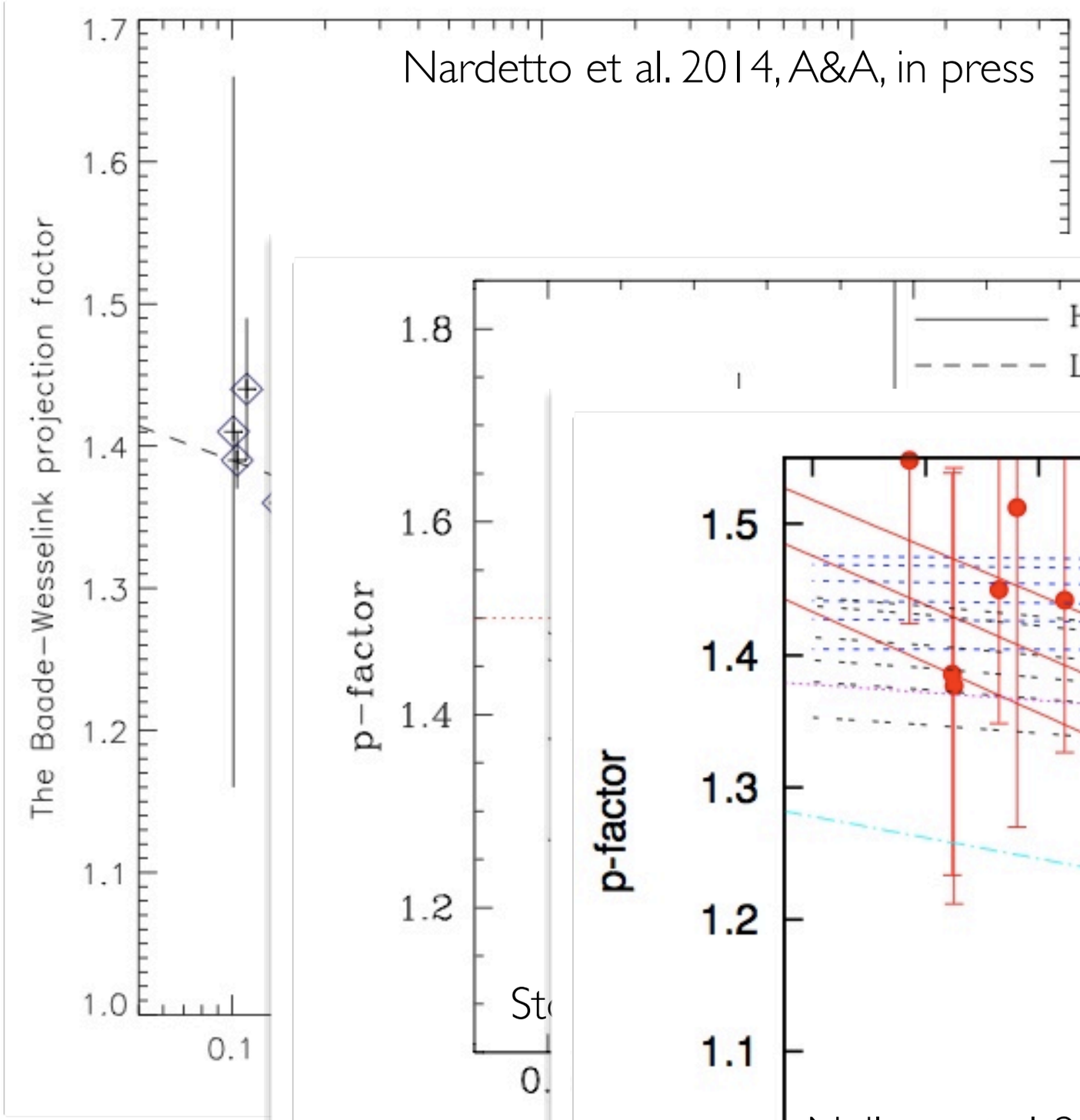
Nardetto et al. 2014, A&A, in press



Storm et al. 2011, A&A, 534, A94

P-FACTOR

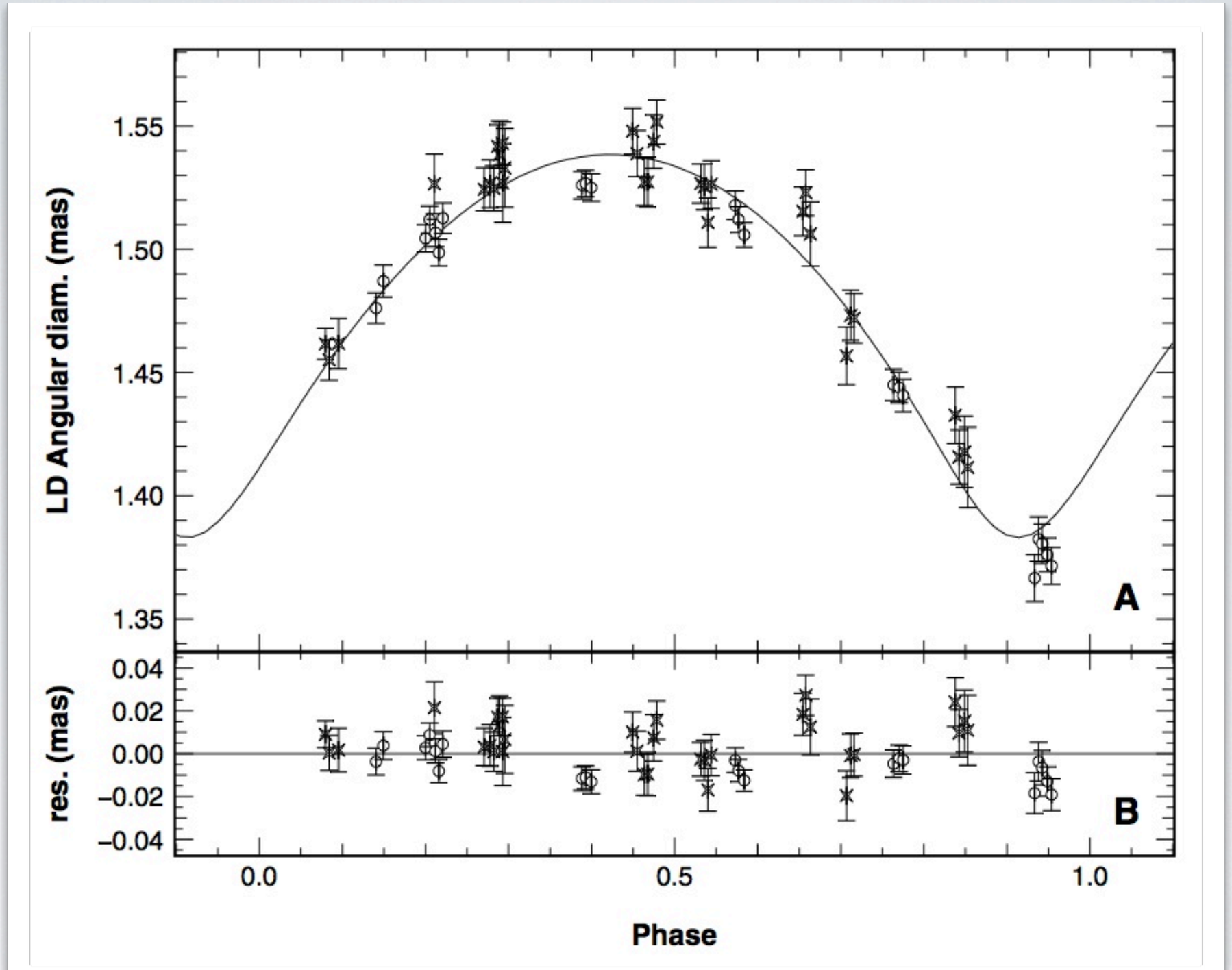
Nardetto et al. 2014, A&A, in press



Neilson et al. 2012, ASSP, arXiv:1201.0802

δ CEP : A MEASUREMENT OF p

δ CEP : A MEASUREMENT OF *p*



Mérand et al. 2005, A&A 438, L9

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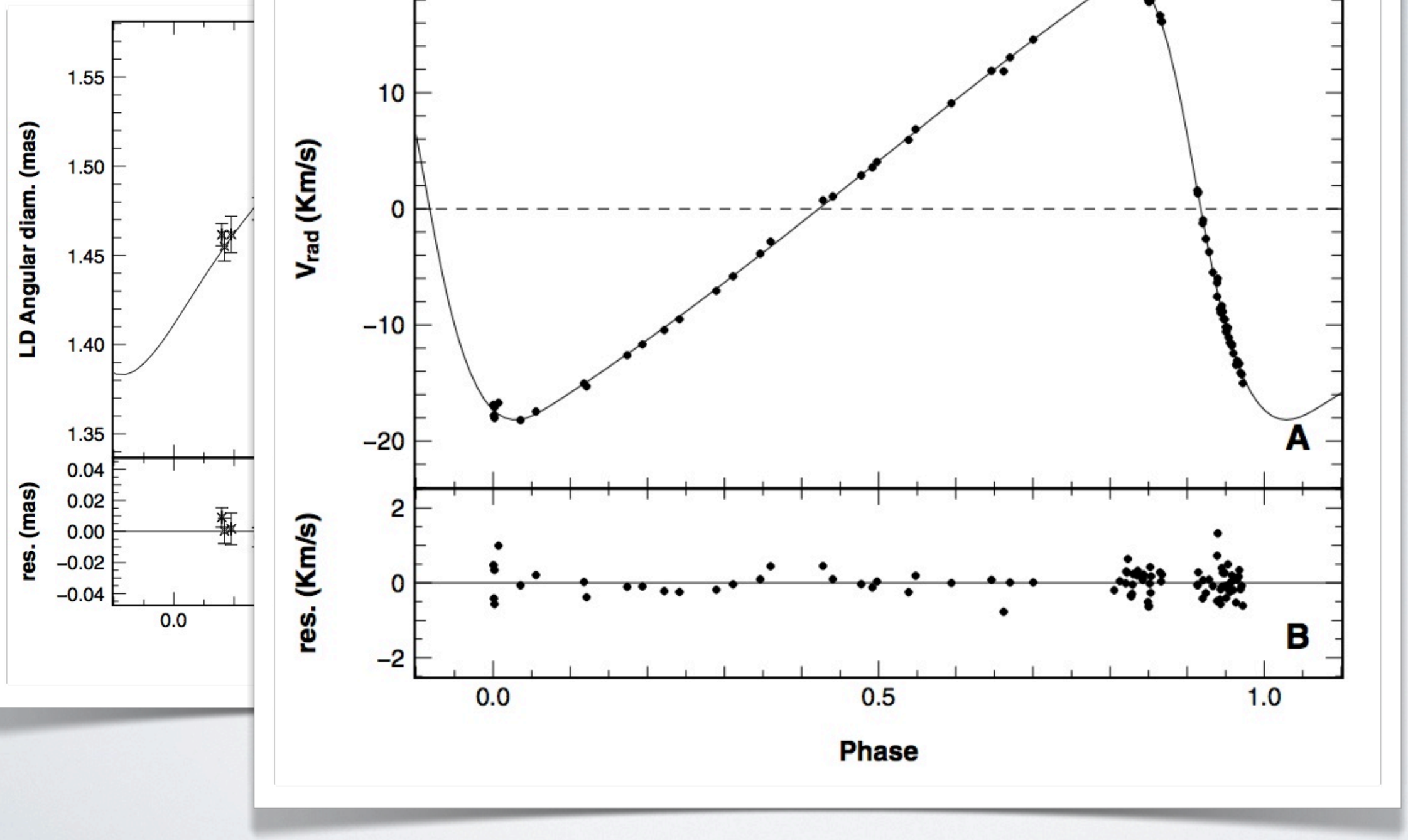
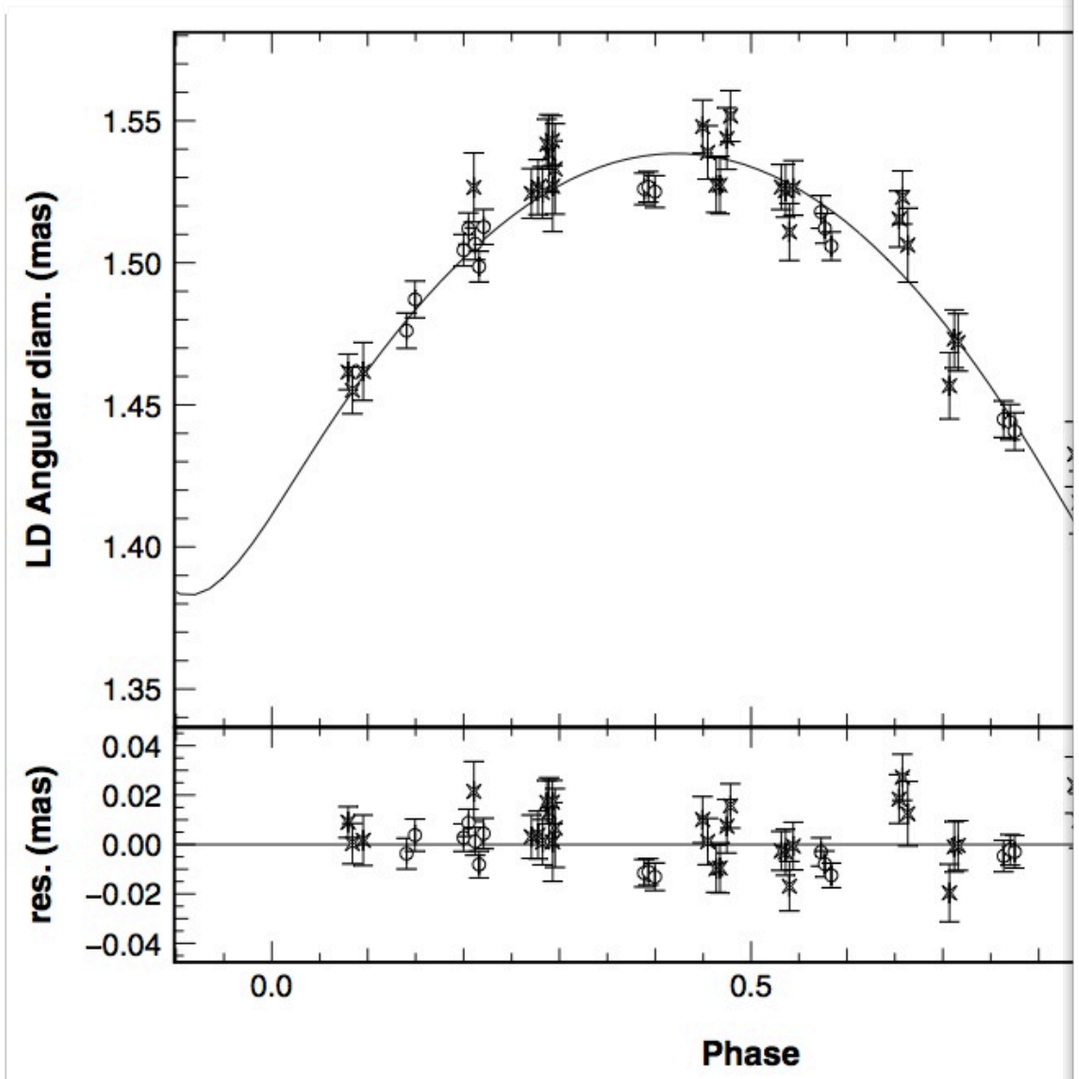
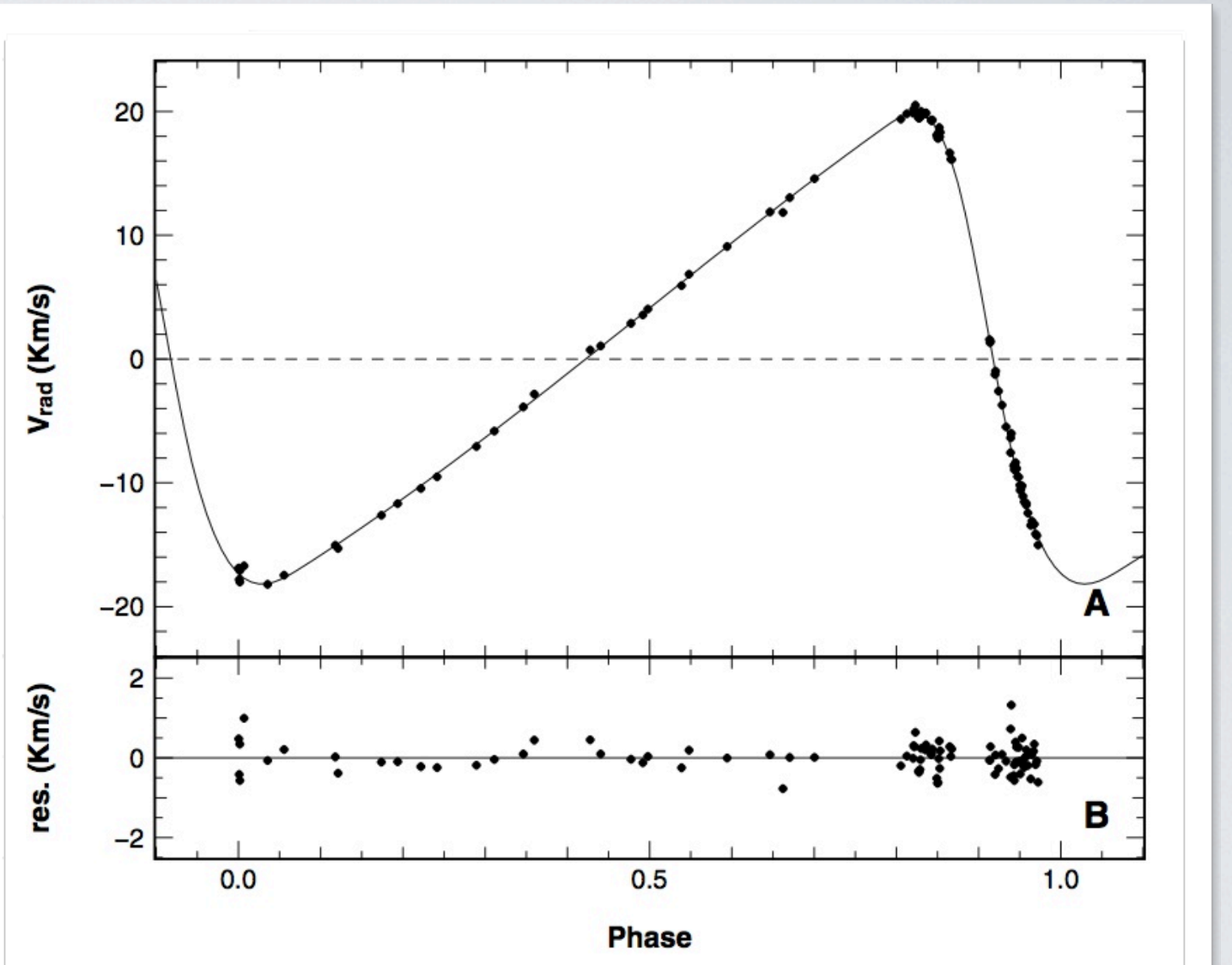


Mérand et al. 2005, A&A 438, L9

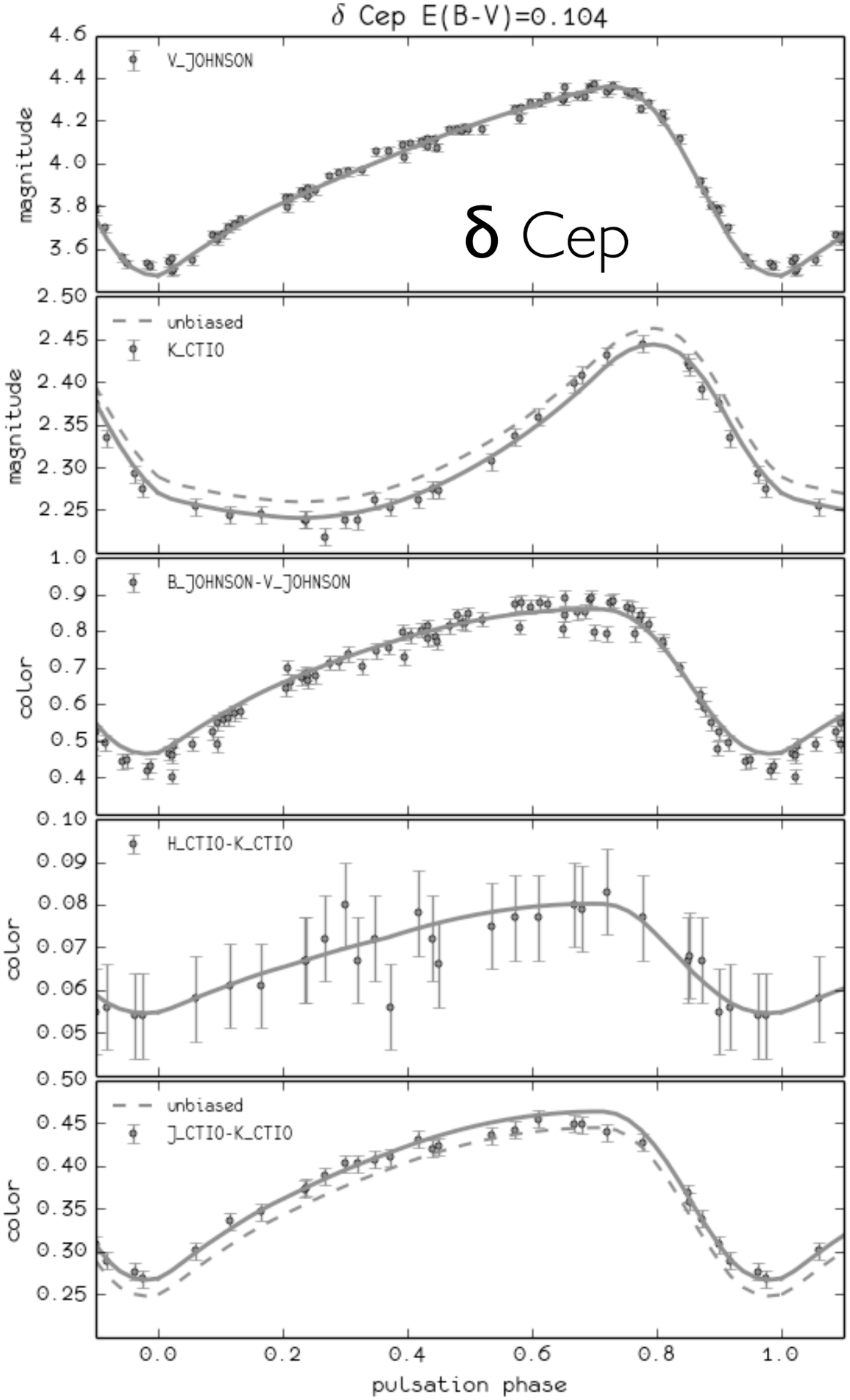
δ CEP : A MEASUREMENT OF *p*



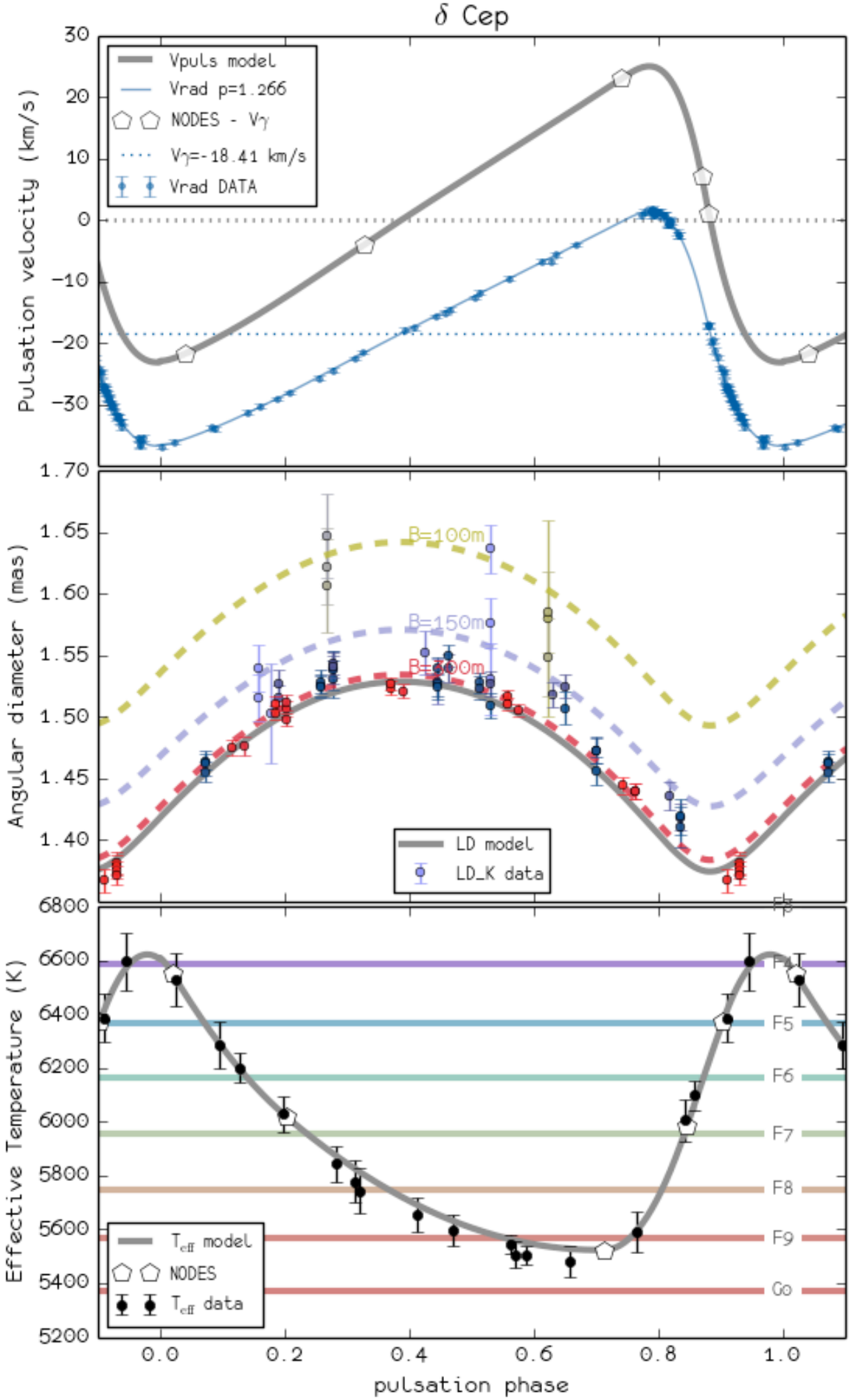


p-factor = 1.27 ± 0.06, with d=274 ± 11 pc from HST-FGS

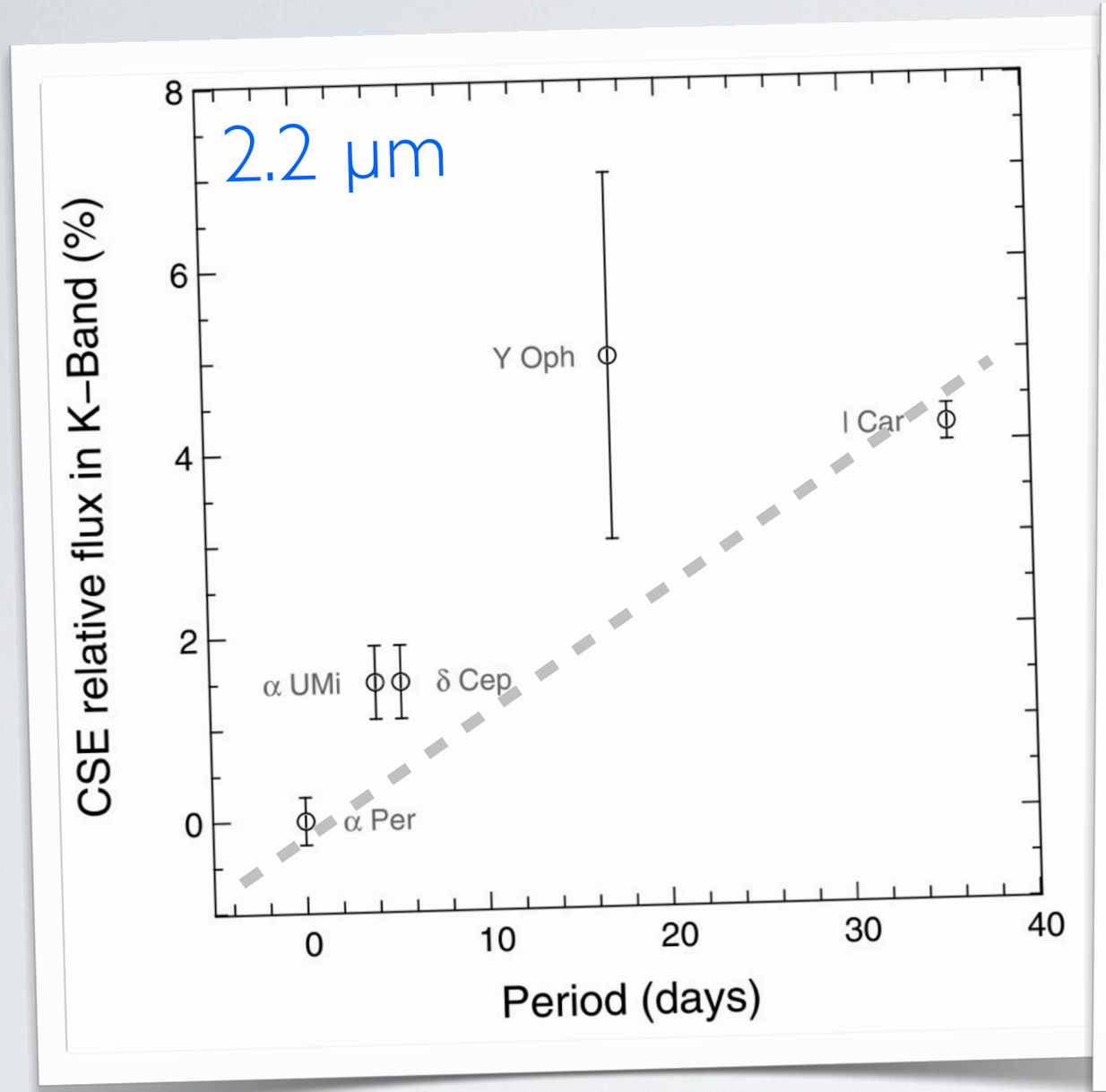
Mérand et al. 2005, A&A 438, L9

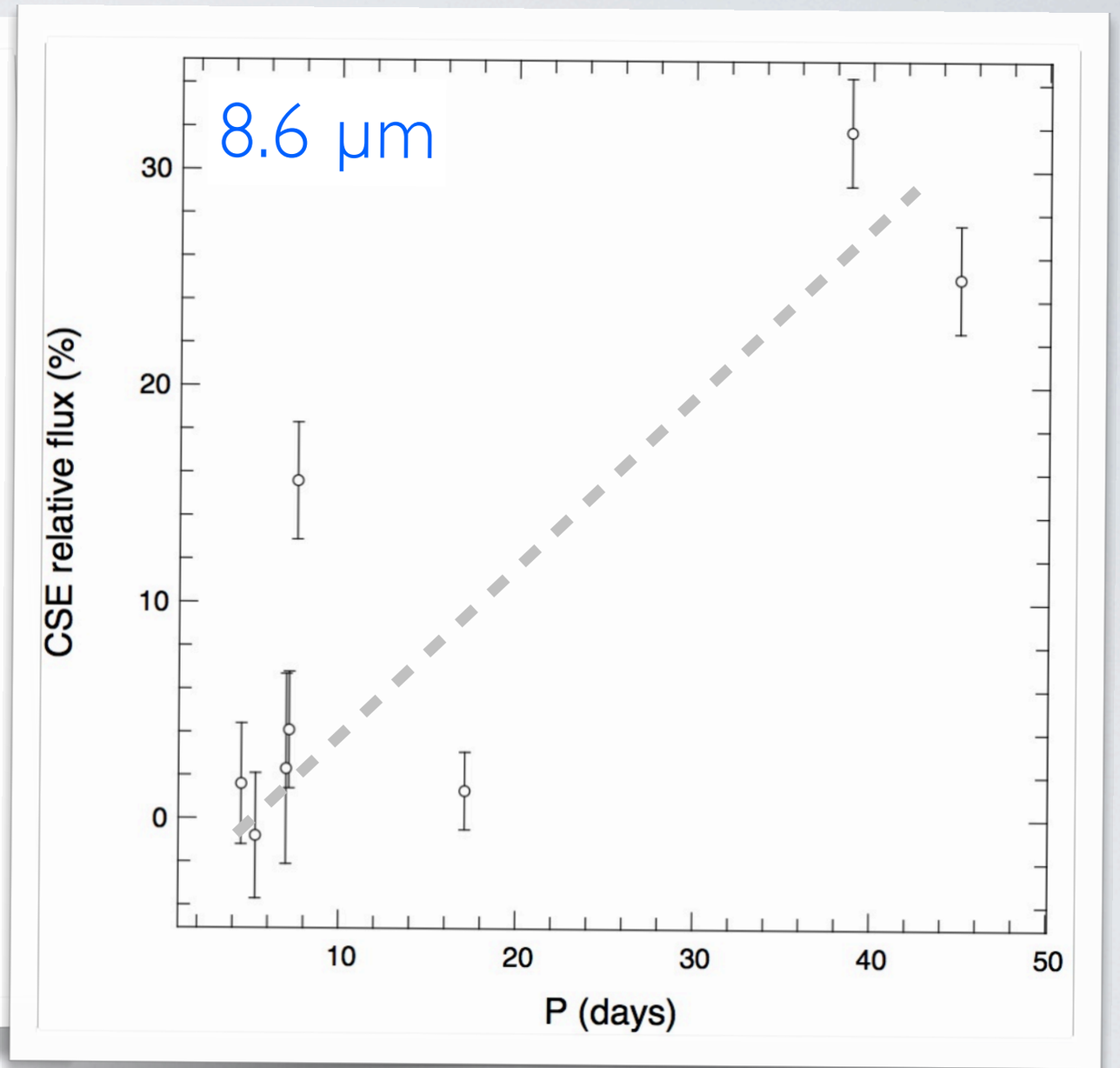

δ Cep E(B-V)=0.104
V_JOHNSON
magnitude
unbiased
K_CTIO
magnitude
B_JOHNSON-V_JOHNSON
color
H_CTIO-K_CTIO
color
unbiased
J_CTIO-K_CTIO
color
pulsation phase

δ Cep


δ Cep
Vpuls model
Vrad p=1.266
NODES - Vγ
Vγ=-18.41 km/s
Vrad DATA
Pulsation velocity (km/s)
B=100m
B=150m
B=200m
LD model
LD_K data
Angular diameter (mas)
F3
F4
F5
F6
F7
F8
F9
Go
Teff model
NODES
Teff data
Effective Temperature (K)
pulsation phase

CEPHEID ENVELOPE CONTRIBUTIONS

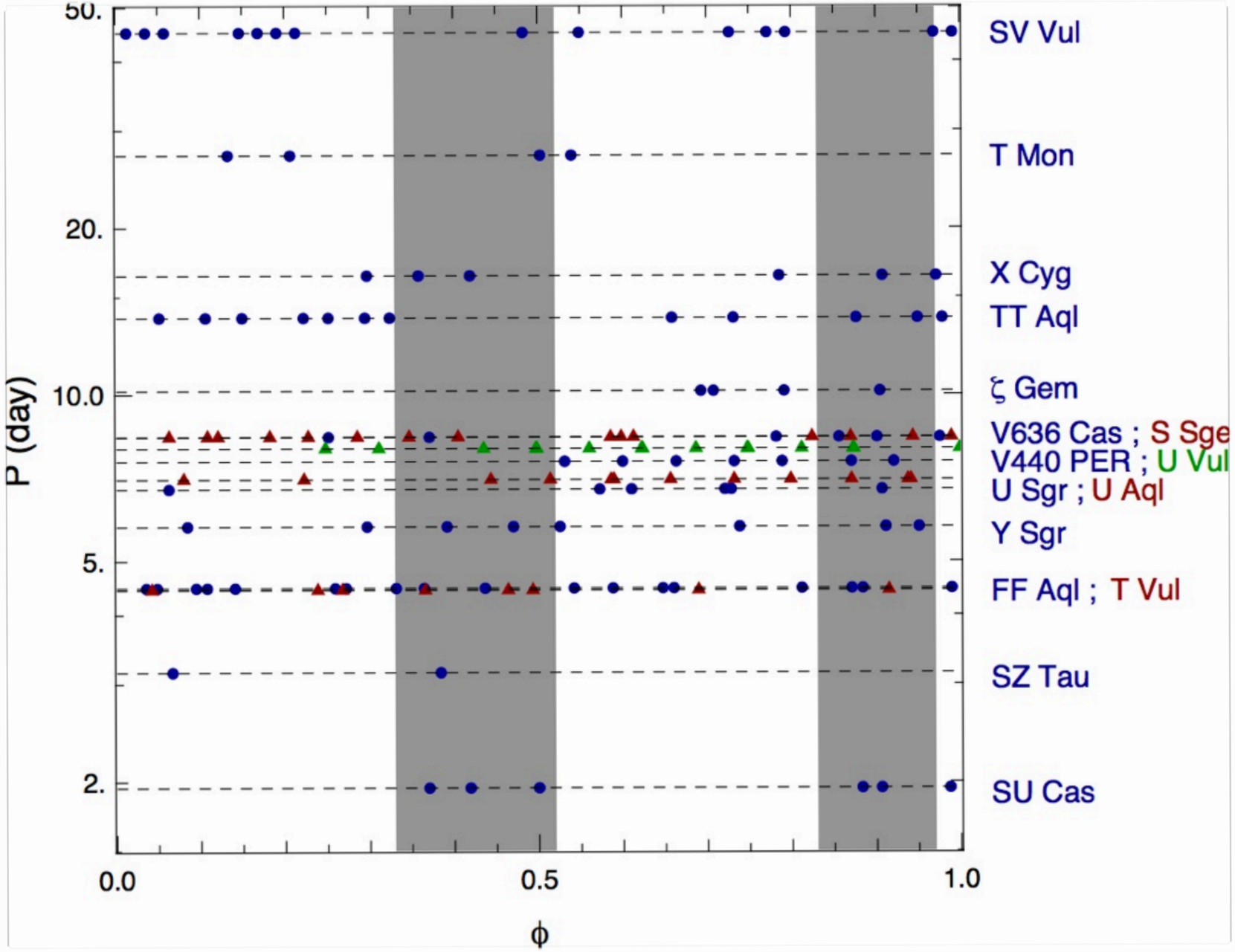




Mérand et al. 2007, ApJ 664, 1087

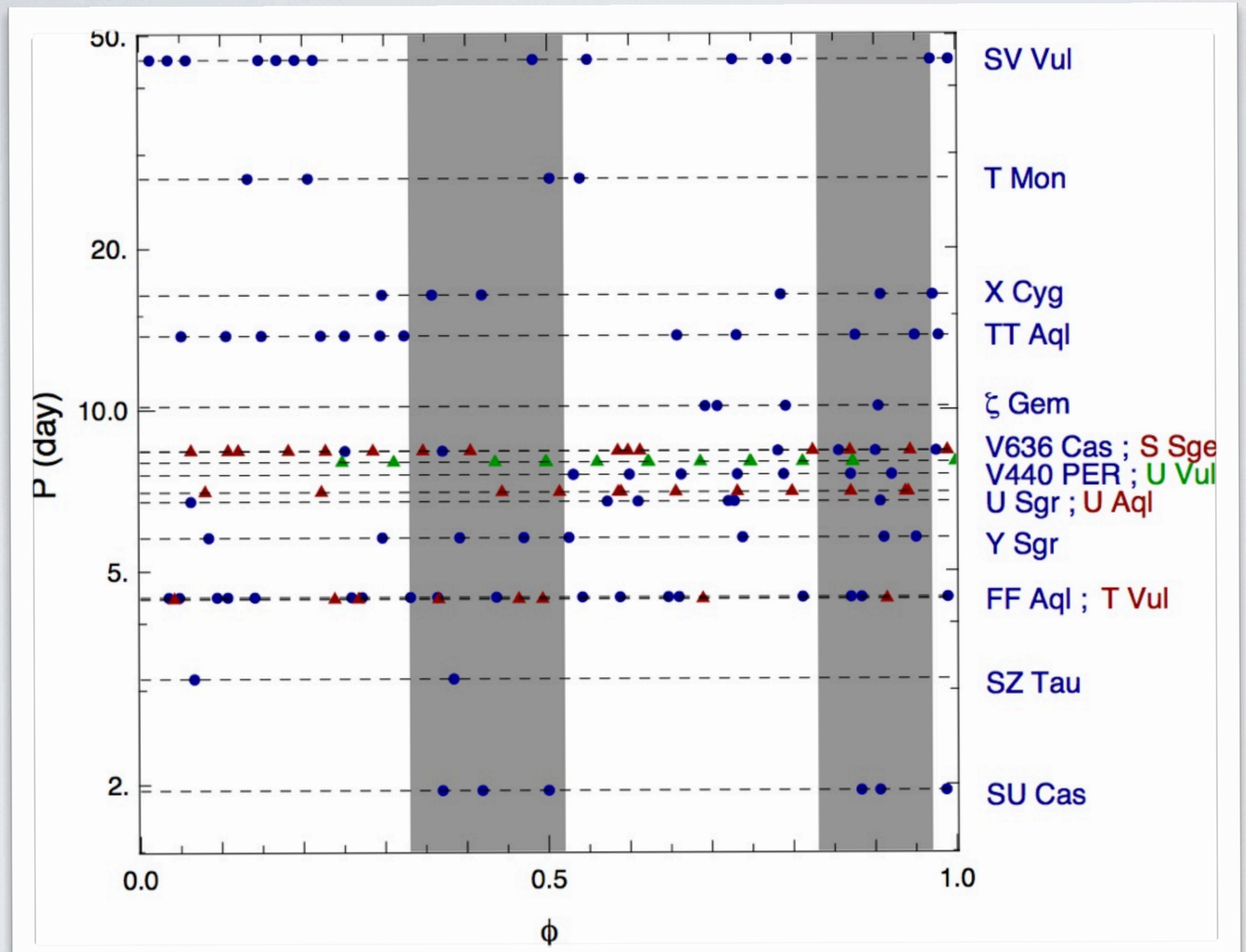
Gallenne et al. 2012, A&A, 538, A24

CEPHEIDS OBSERVED BY INTERFEROMETRY



[Polaris] (3.97 d)
δ Cep (5.36 d)
X Sgr (7.01 d)
η Aql (7.17 d)
W Sgr (7.59 d)
β Dor (9.84 d)
L Car (35.6 d)
[RS Pup] (41.4 d)

CEPHEIDS OBSERVED BY INTERFEROMETRY



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W Sgr (7.59 d)
β Dor (9.84 d)
L Car (35.6 d)
[RS Pup] (41.4 d)

24 stars, with 22 stars suitable for IBW distance
P93 program with PIONIER (5 stars) + VEGA (5 stars)

HARD POINTS ON IBW DISTANCES OF CEPHEIDS

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- Subtraction of the envelope contributions from interferometry

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- Radial velocity data with sufficient accuracy (not necessarily a very large number of measurements)

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- Radial velocity data with sufficient accuracy (not necessarily a very large number of measurements)
- Projection factor *p*-*P* law calibration
- Reliable limb-darkening models as a function of phase (visible, IR)
- Up-to-date photometry in the visible and near-IR

SURFACE BRIGHTNESS-COLOR RELATIONS

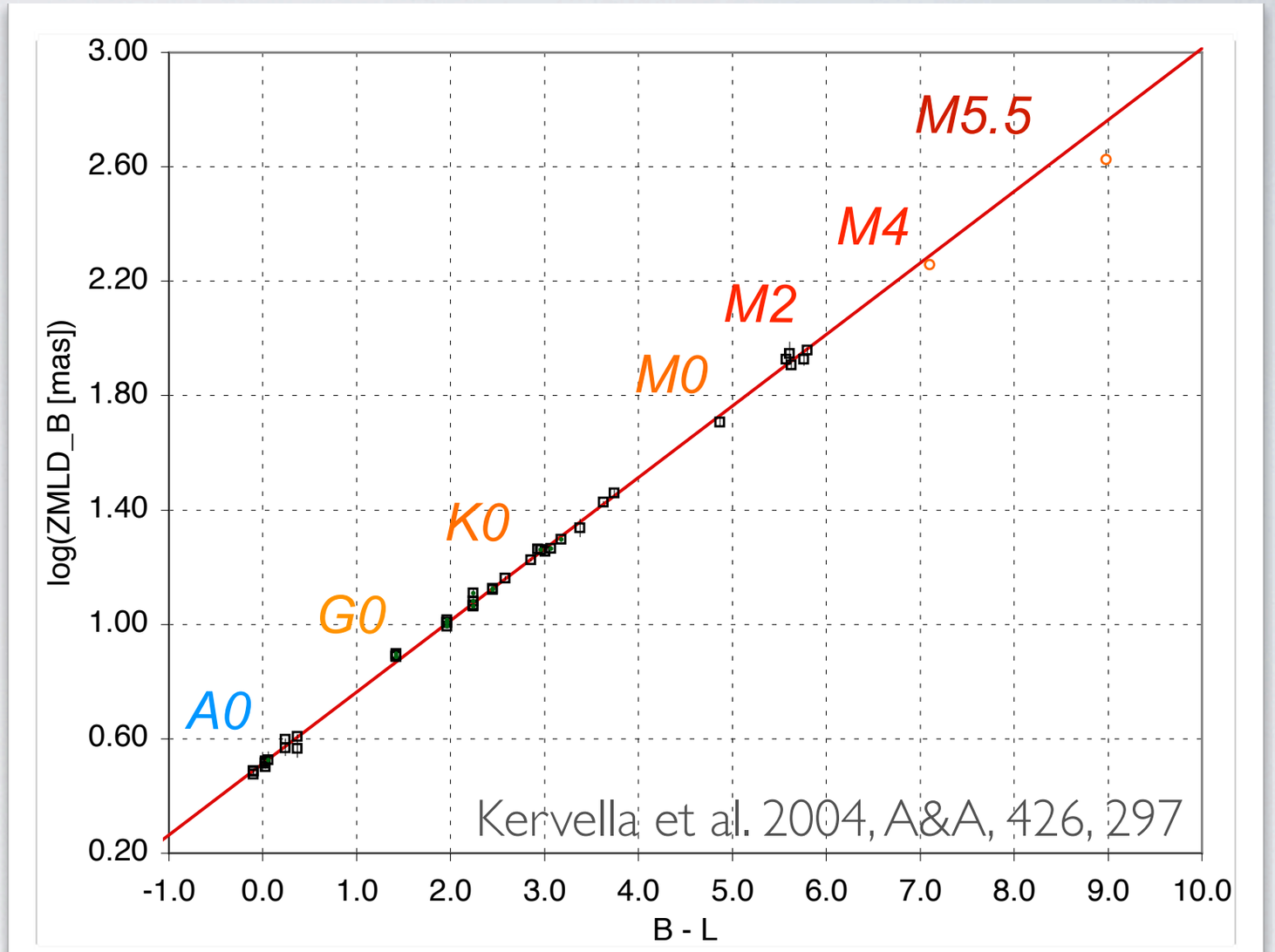
$$f \sim L / R^2 \sim T^4$$

$$F_B = a\,(B\text{-}L) + b$$

$$F_B = 4.2207 - 0.1B - 0.5\log(LD)$$

Limb darkened angular diameter

$$\log LD = c\,(B\text{-}L) + d - 0.2\,B$$



Very accurate prediction of angular diameters from photometry
Useful for calibrators and the classical BW technique

SURFACE BRIGHTNESS-COLOR RELATIONS

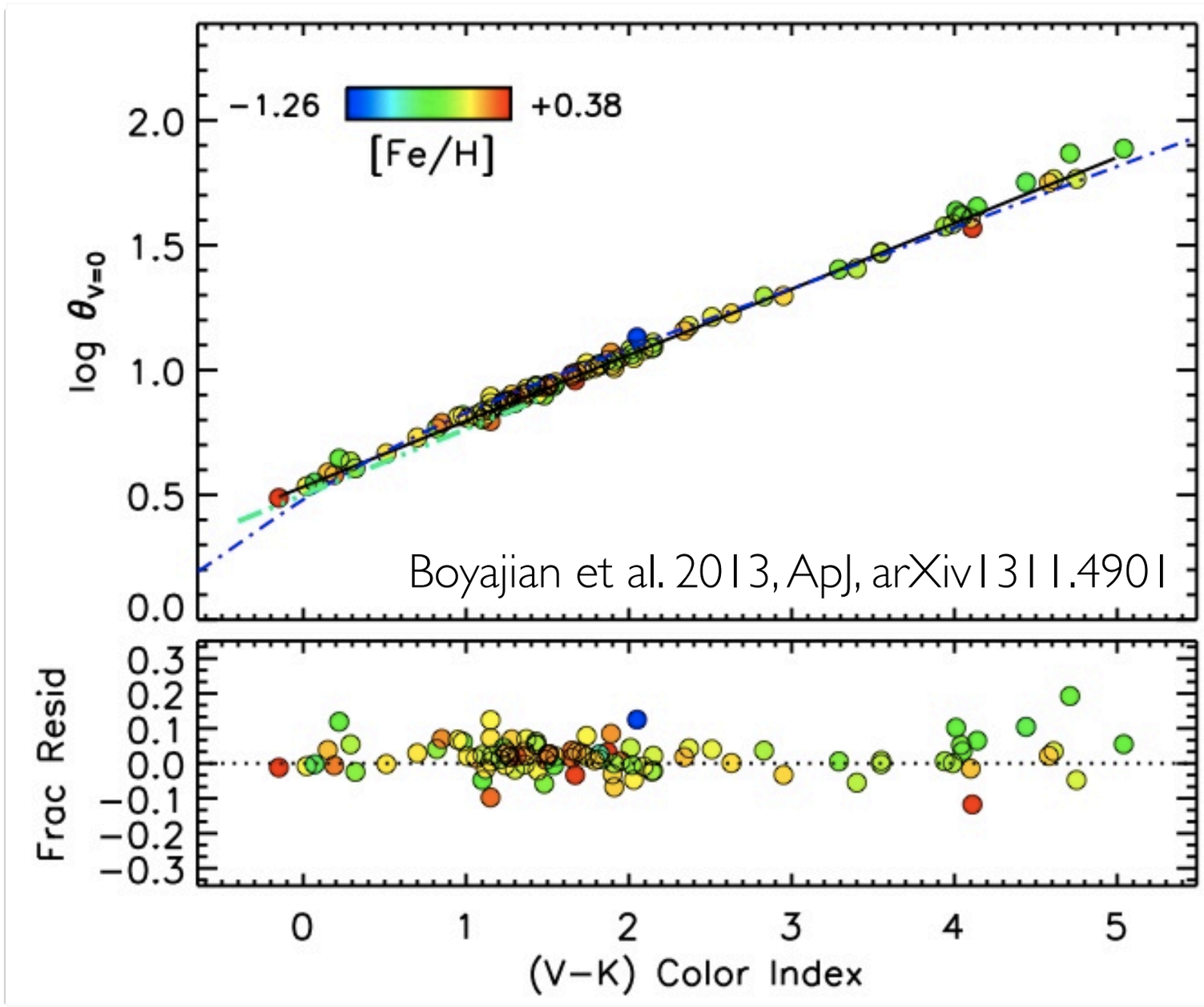
f

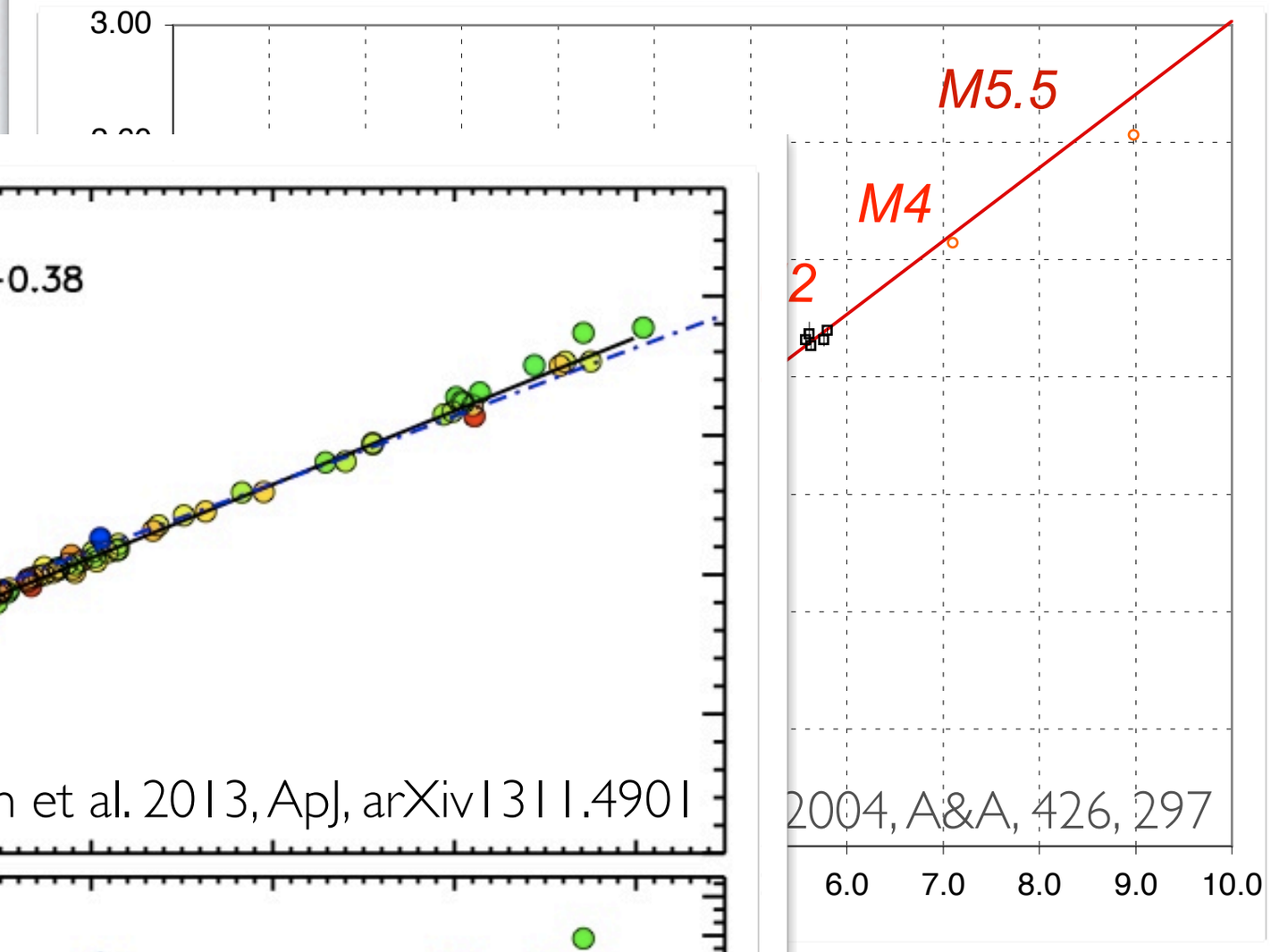
F_B

$F_B = 4.22($

Limb (

log LD =

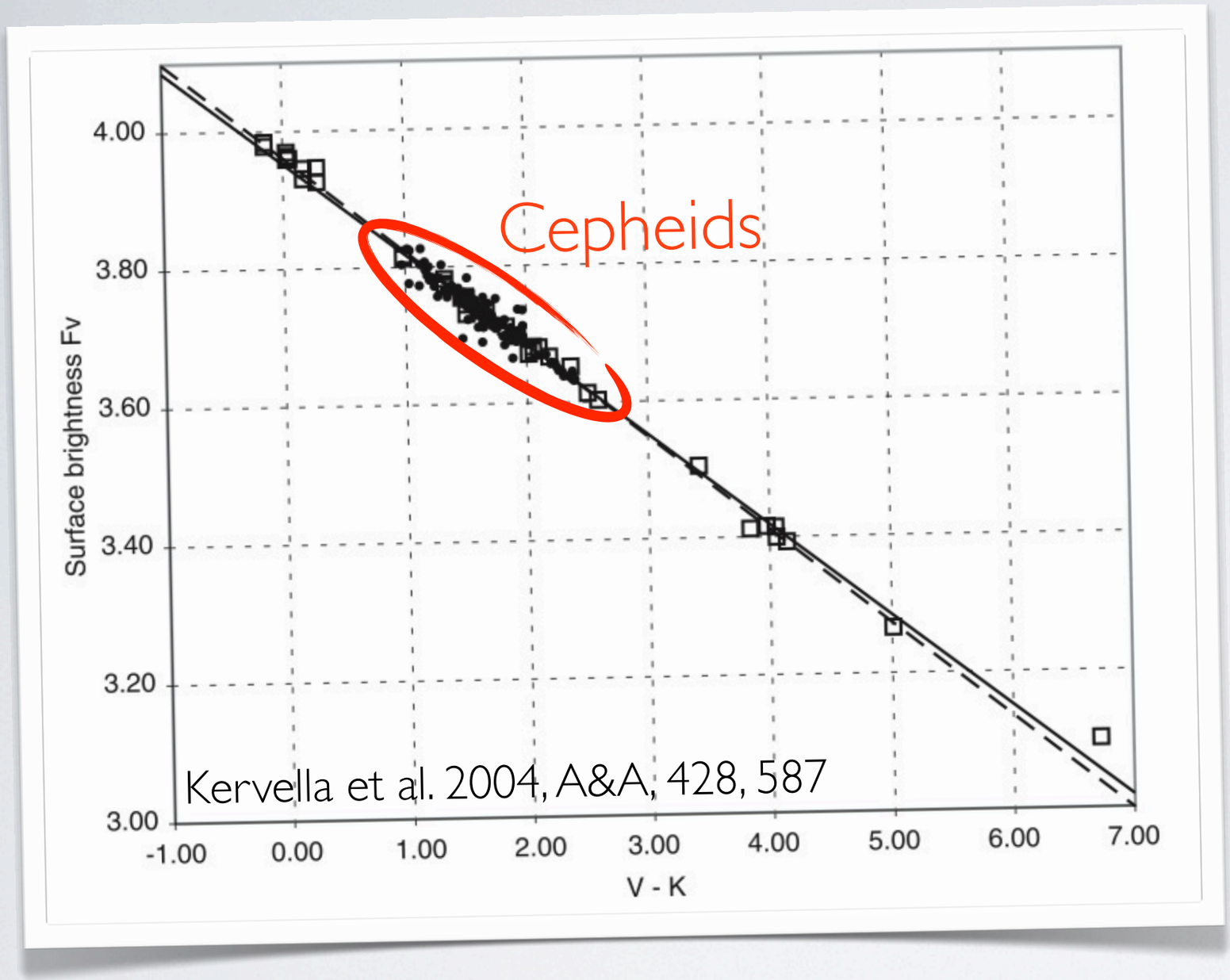




Very ac photometry

Useful e

CEPHEID SBC RELATIONS



- Similar to dwarf SBC relations for visible-infrared colors
- Calibration is part of our interferometric observing program

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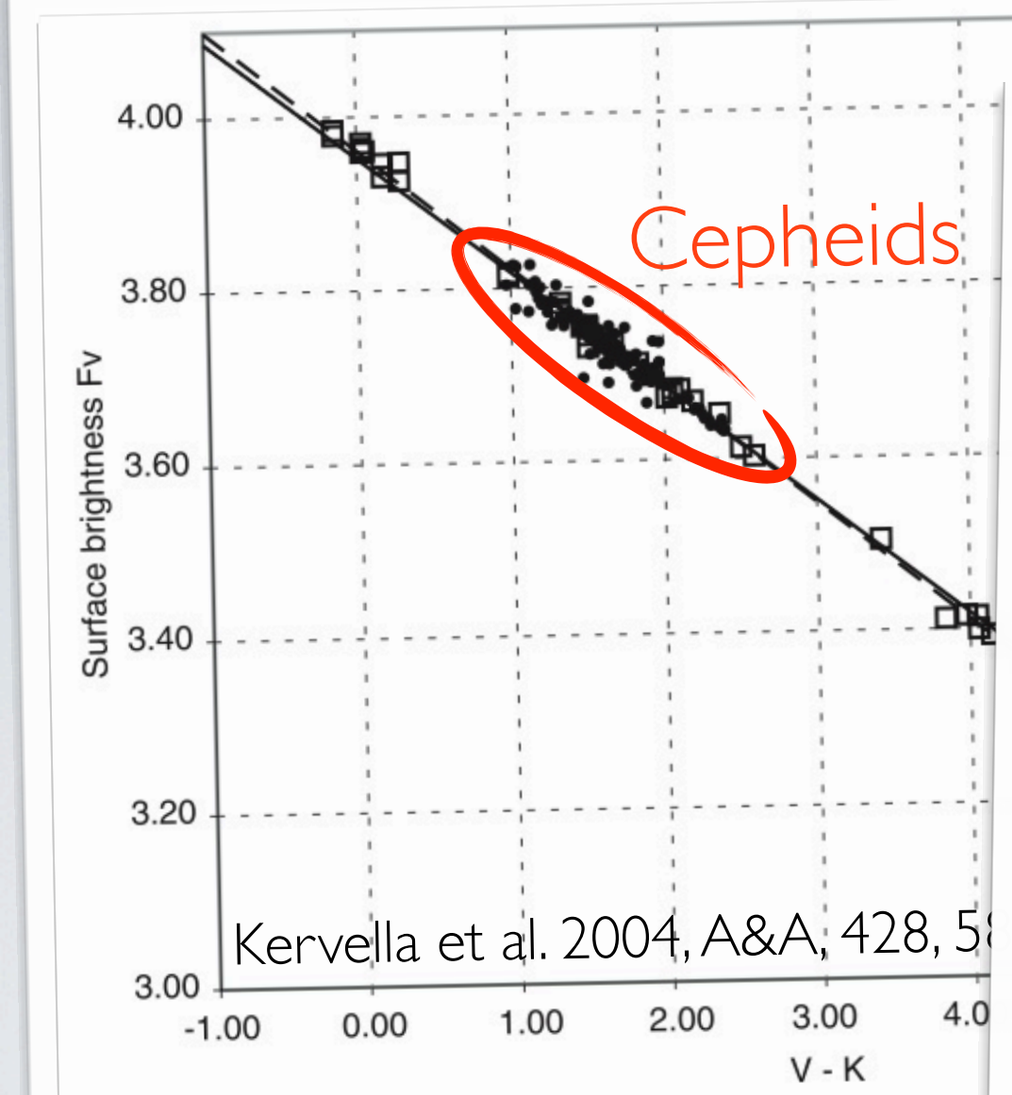
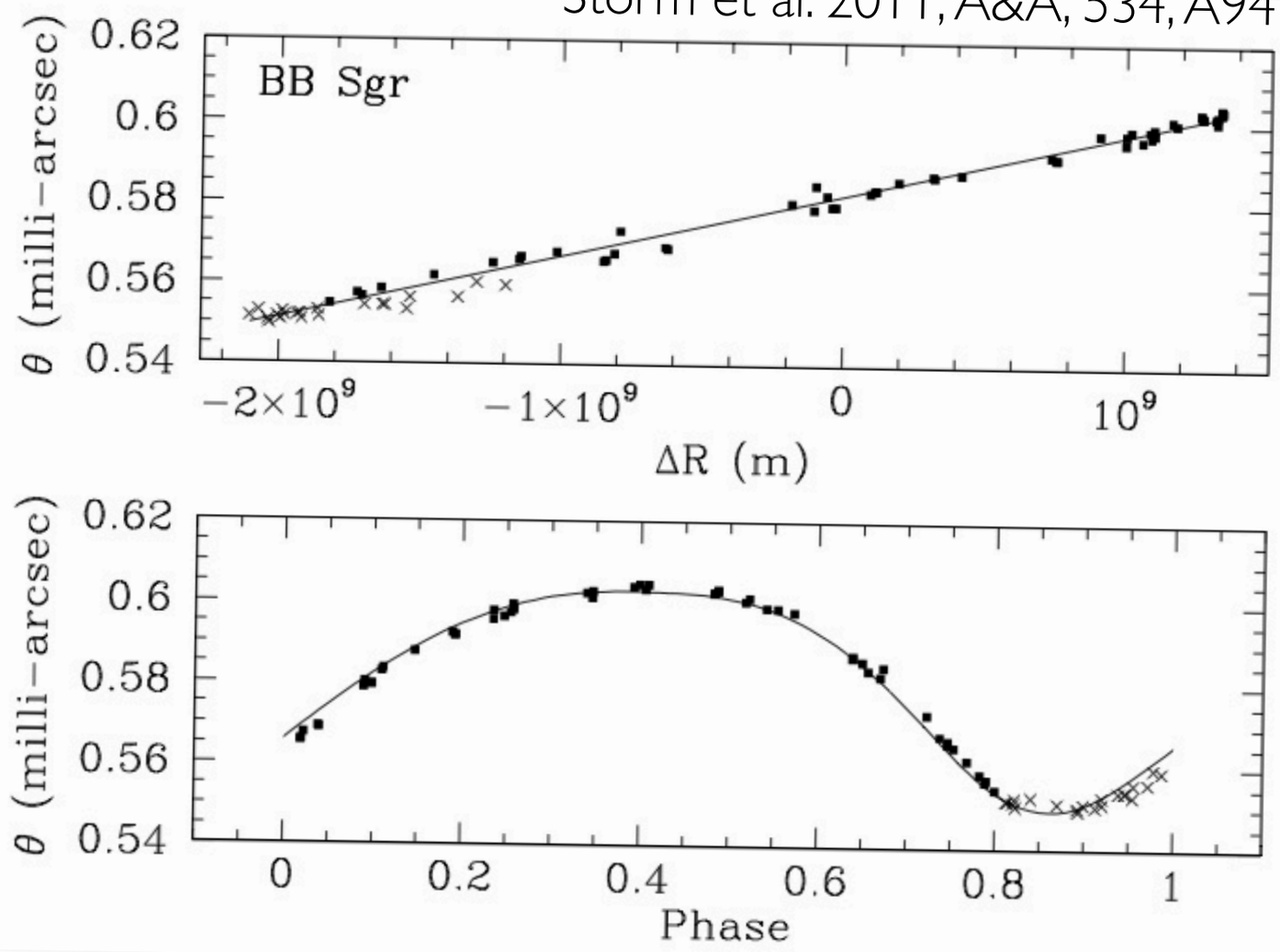


Storm et al. 2011, A&A, 534, A94



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CEPHEIDS IN BINARIES

- Binary systems are very useful to derive masses, distances and *p-factor* (when SB2+visual/interferometric orbit available)

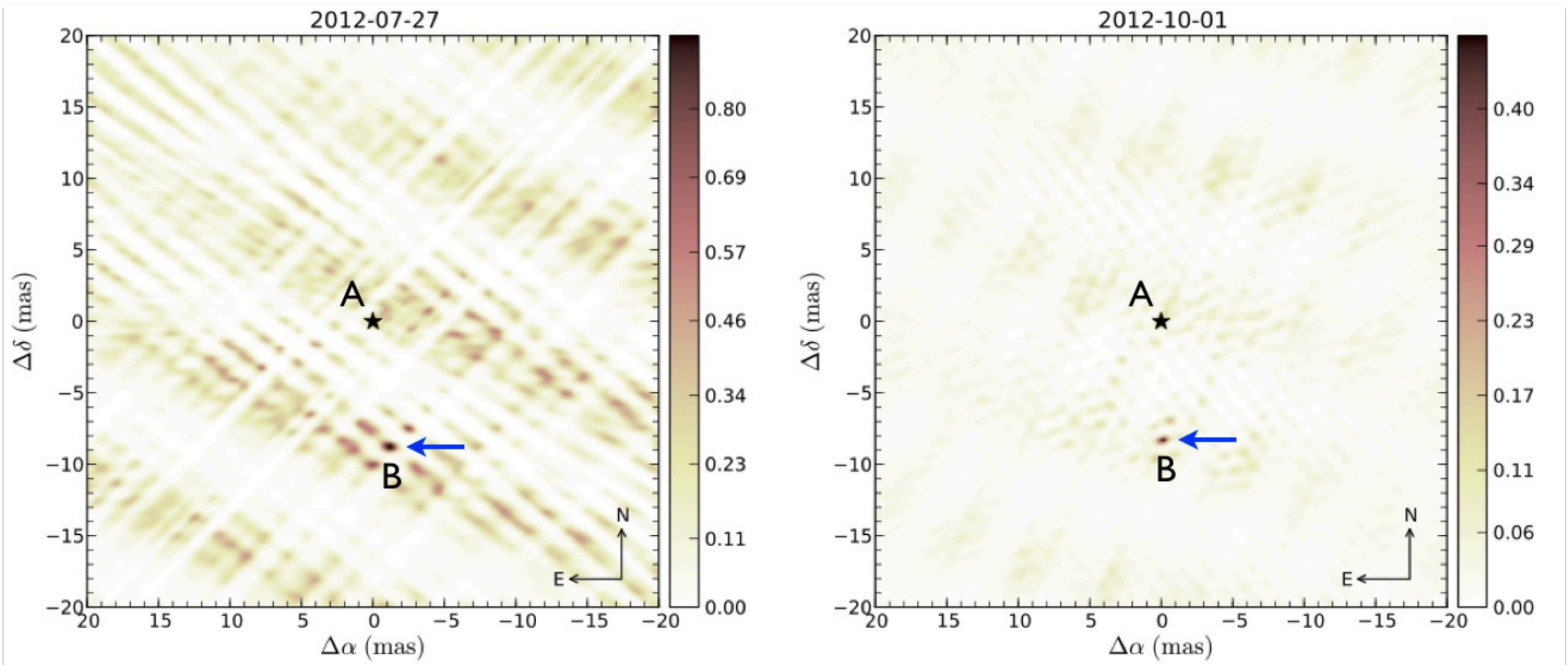
- Cepheids are extremely bright (10^3 - 10^5 Lsun), companions are difficult to detect due to contrast in the IR

- Only a handful discovered using UV spectroscopy (IUE)

- Most systems are unresolved SB1, except Polaris and distant companions on multi-century orbits

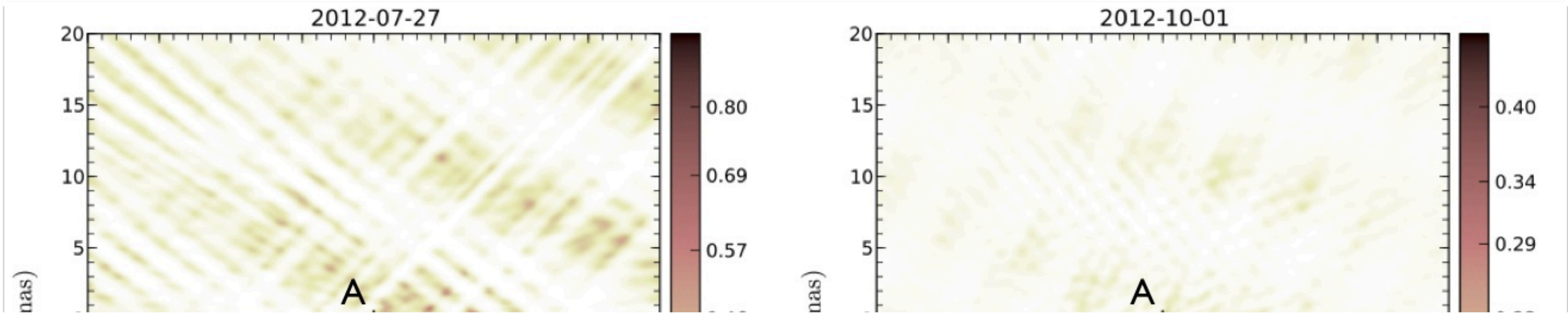
- Survey with CHARA/MIRC and VLTI/PIONIER: the companions of V1334 Cyg and AX Cir have been spatially resolved

V1334 CYG (CHARA/MIRC)



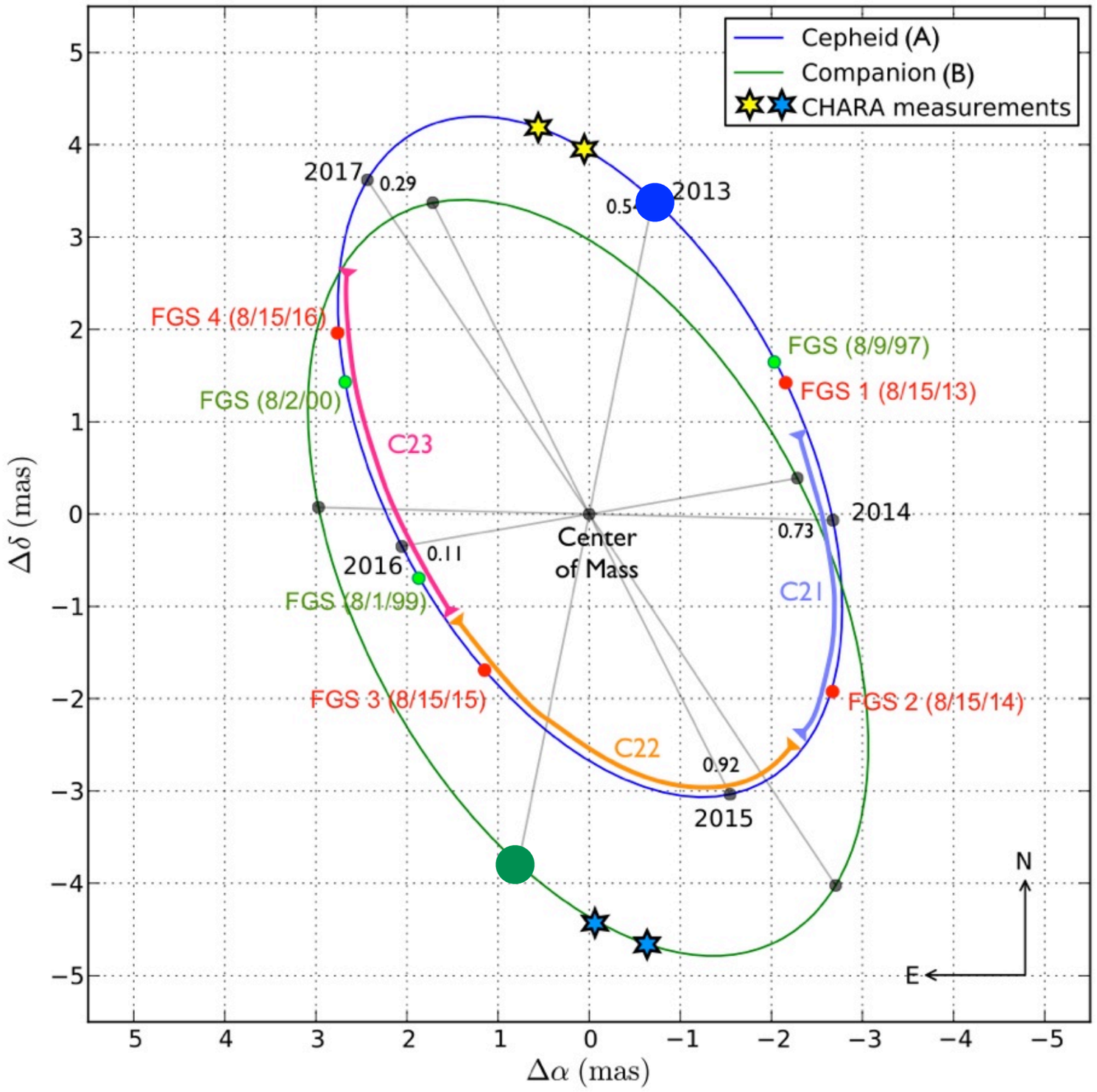
Gallenne et al. 2013, A&A, 552, A21

V1334 CYG (CHARA/MIRC)



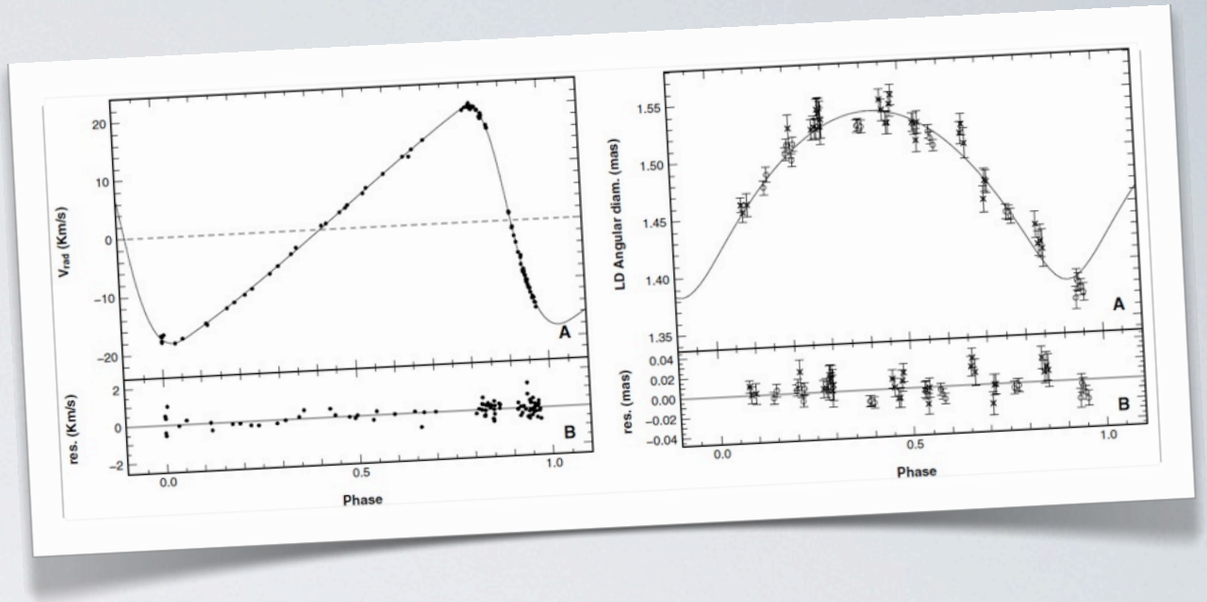
Separation = **8 mas**, Contrast (H) = **3.1%**, Period = **5.3 yr**

Gallenne et al. 2013, A&A, 552, A21



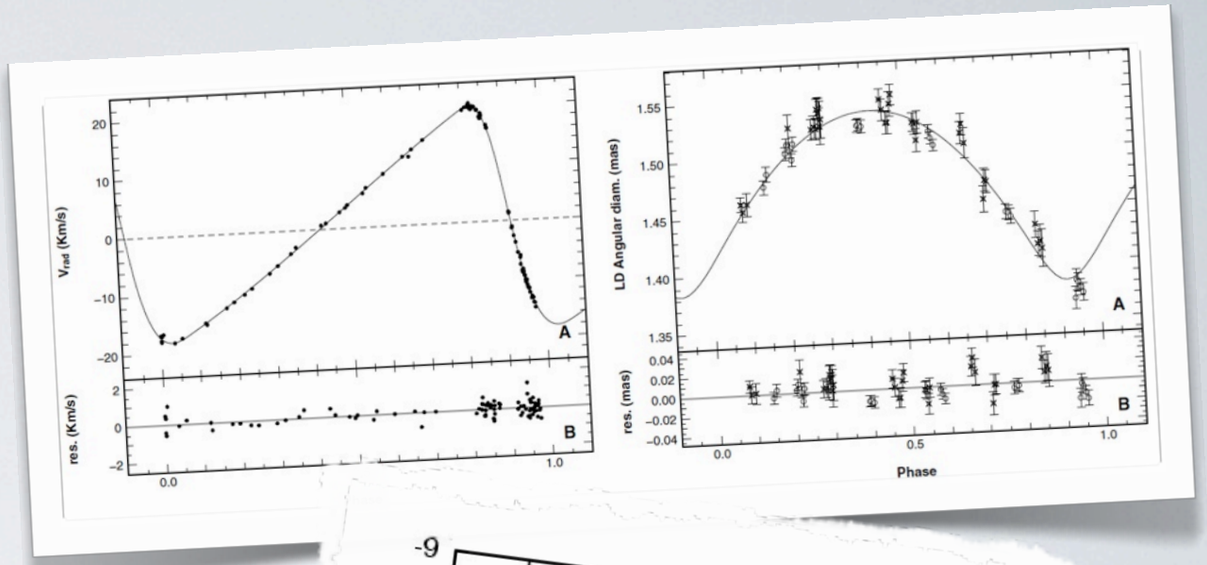
- HST/FGS astrometry and STIS spectroscopy in Cycle 21 to derive the distance, masses and p-factor to 1%

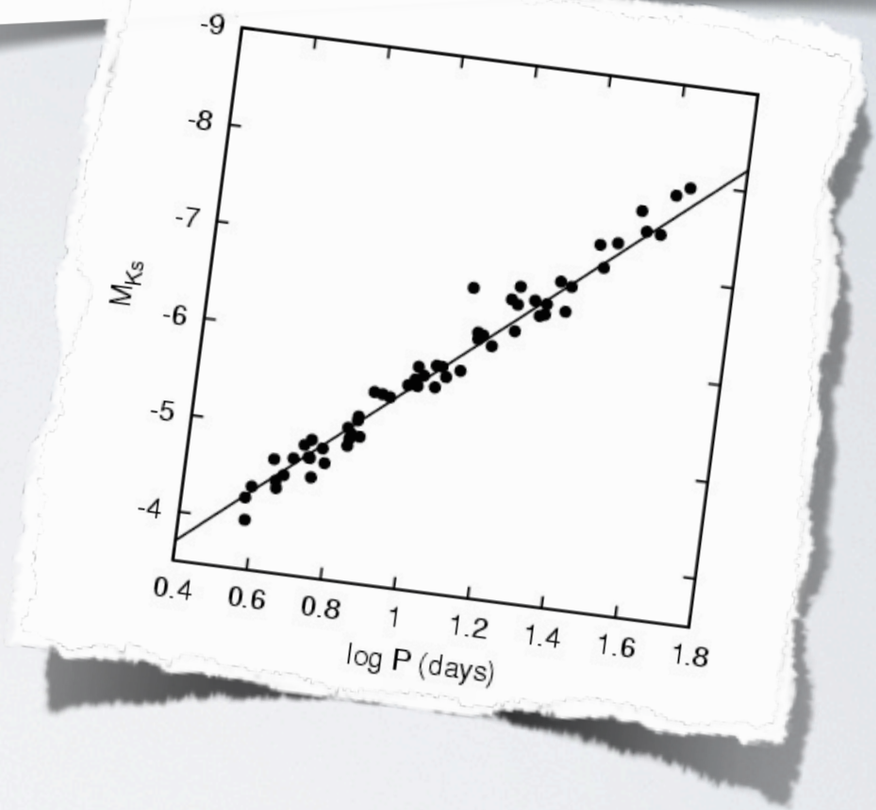
Interferometric BW has the potential to provide distances of ~20 nearby Cepheids to 1-4%



Interferometric BW has the potential to provide distances of ~20 nearby Cepheids to 1-4%

Objective: calibration of P-L zero point for Galactic Cepheids to ~1%





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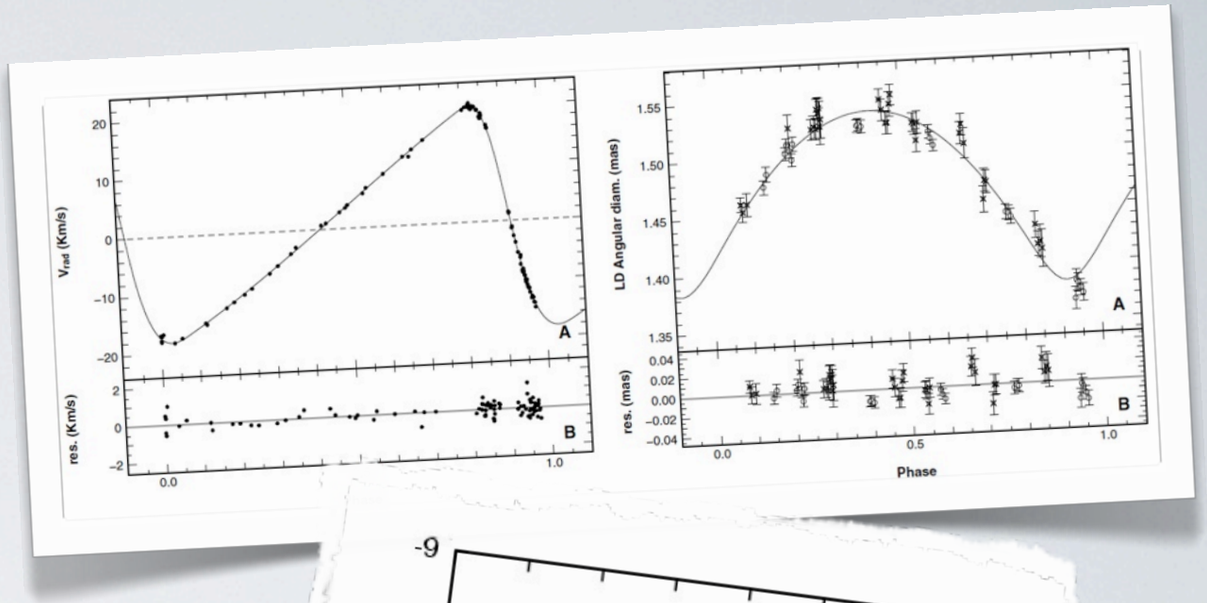
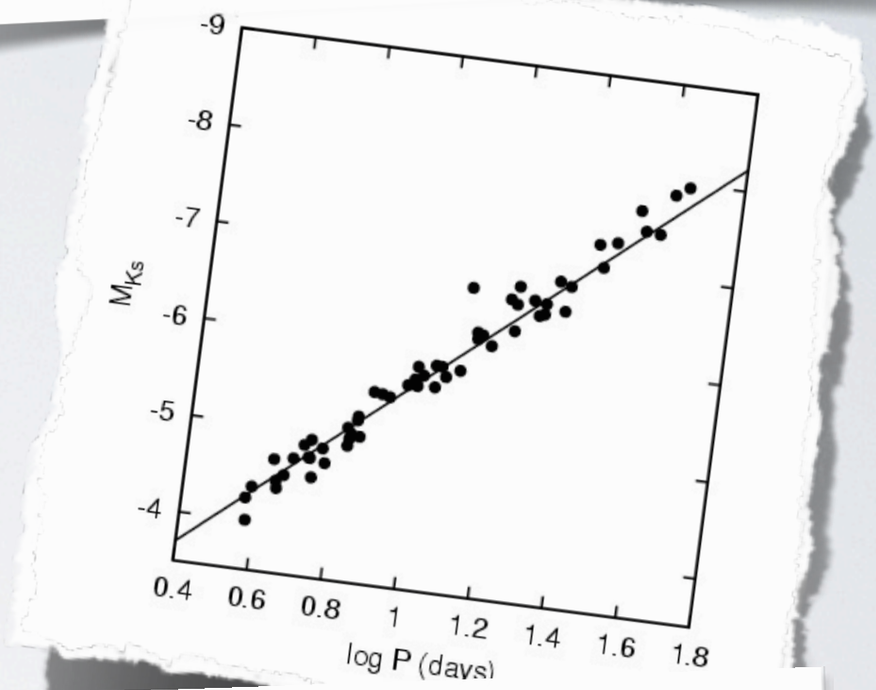
But... Cepheids are relatively complex objects (envelopes, atmosphere dynamics,...)





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New possibilities with the VLTI2 (GRAVITY/MATISSE)