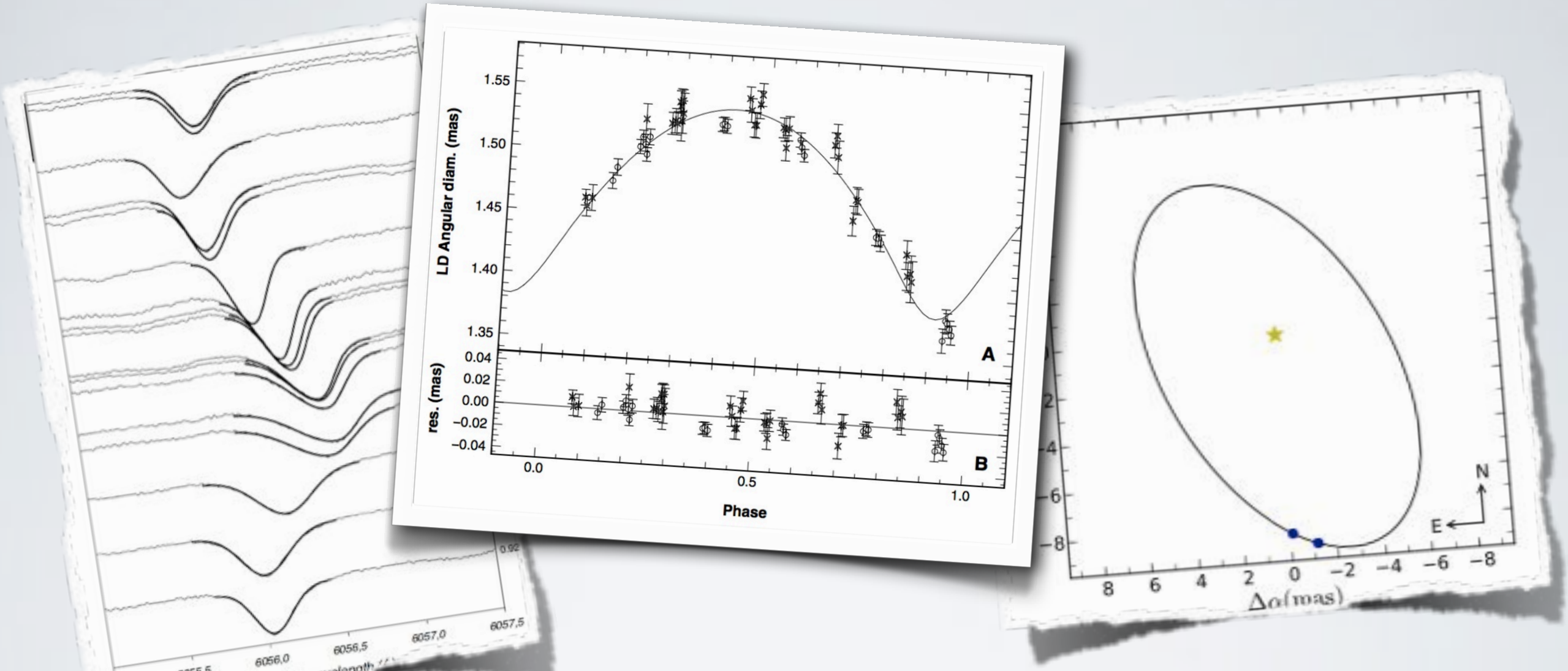
THE VLTI+CHARA CEPHEID PROGRAM



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

THE CEPHEID PROGRAM

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- A long-term effort started in 2001 at VLTI (VINCI, then PIONIER) and in 2004 at CHARA

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- Three "sub-programs":

1. Distances (B-W): FLUOR, PIONIER, VEGA
2. Circumstellar envelopes: FLUOR, VEGA
3. Cepheids in binary systems: MIRC, PIONIER

THE INTERFEROMETRIC BAADE-WESSELINK TECHNIQUE (IBW)

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Gives the radius and the distance of a pulsating star

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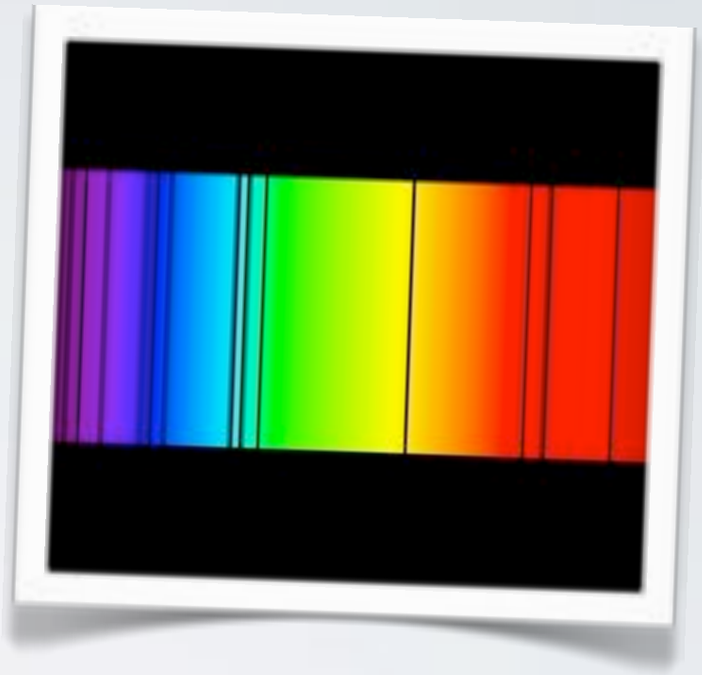


Based on two types of data:

1. Radial velocity from spectroscopy

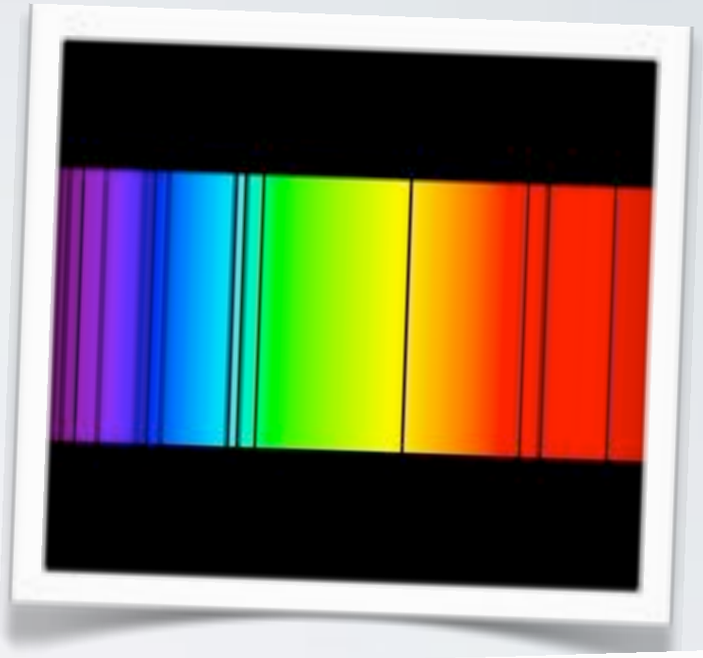
THE INTERFEROMETRIC BAADE-WESSELINK TECHNIQUE (IBW)

Gives the radius and the distance of a pulsating star

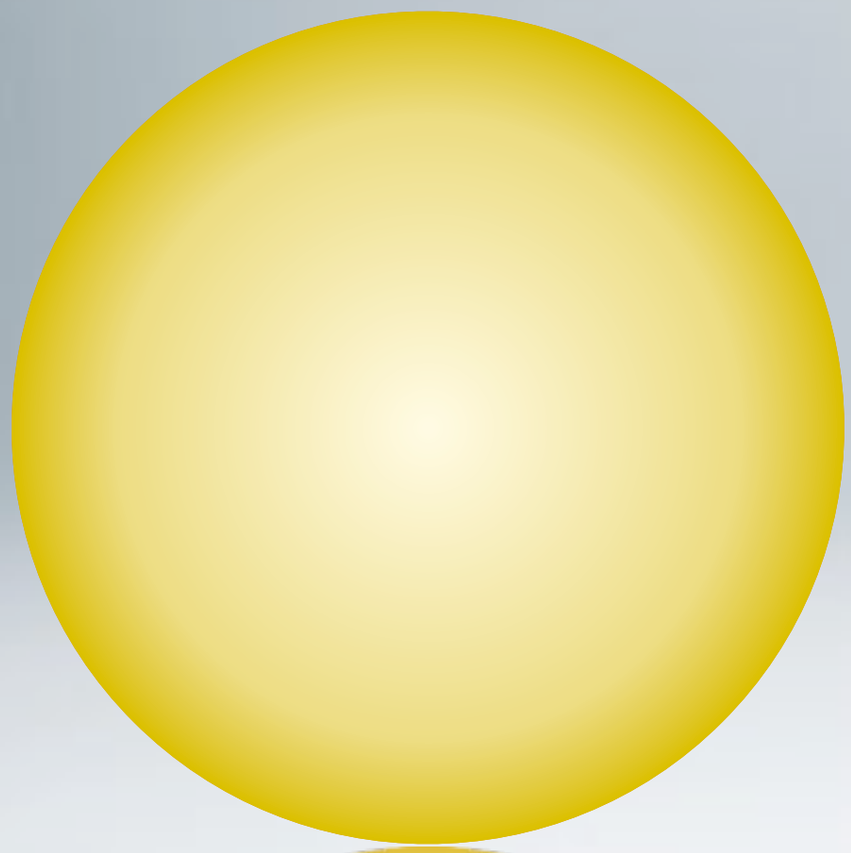
Based on two types of data:

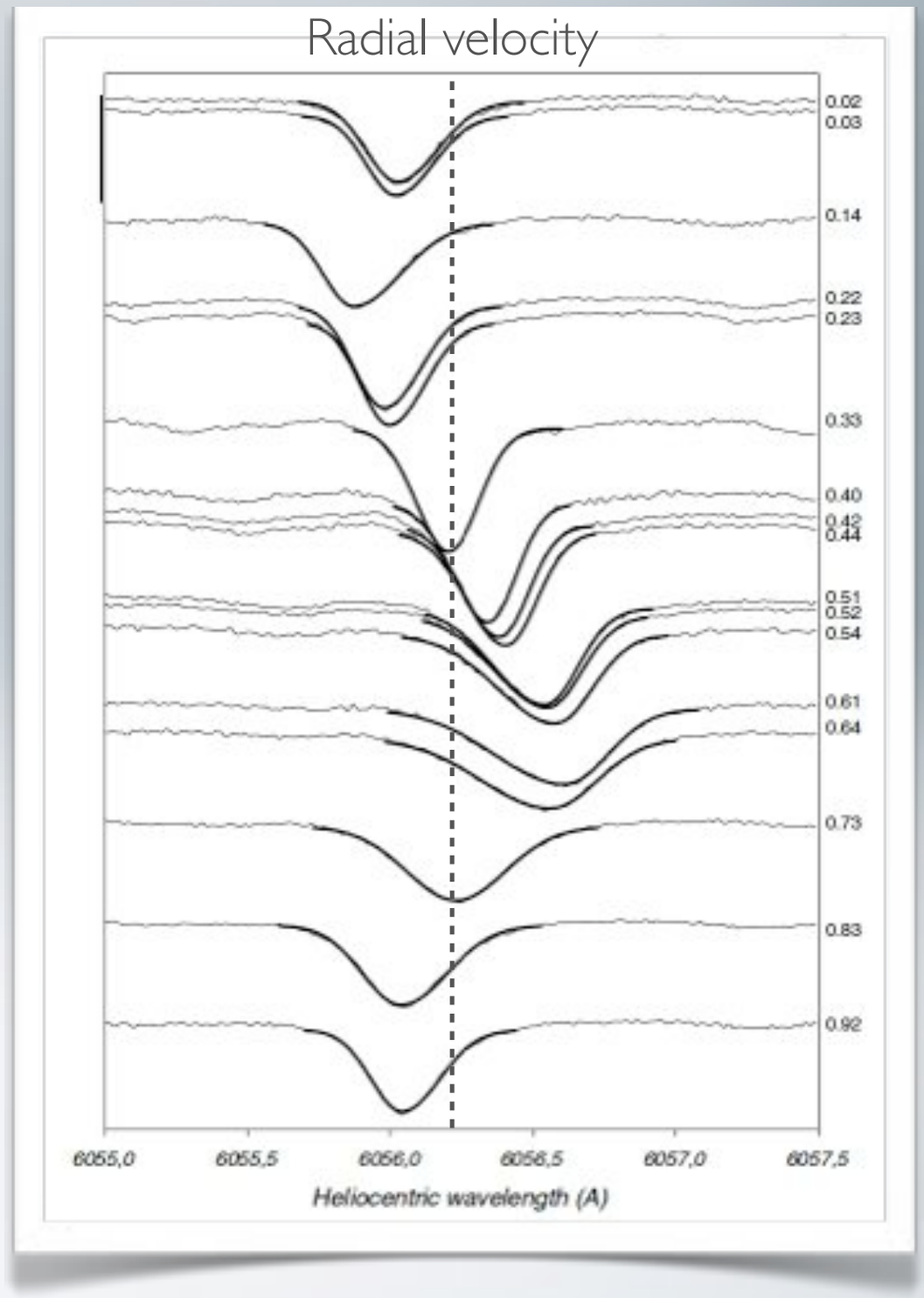
1. Radial velocity from spectroscopy

2. Angular size from interferometry



1. SPECTROSCOPY





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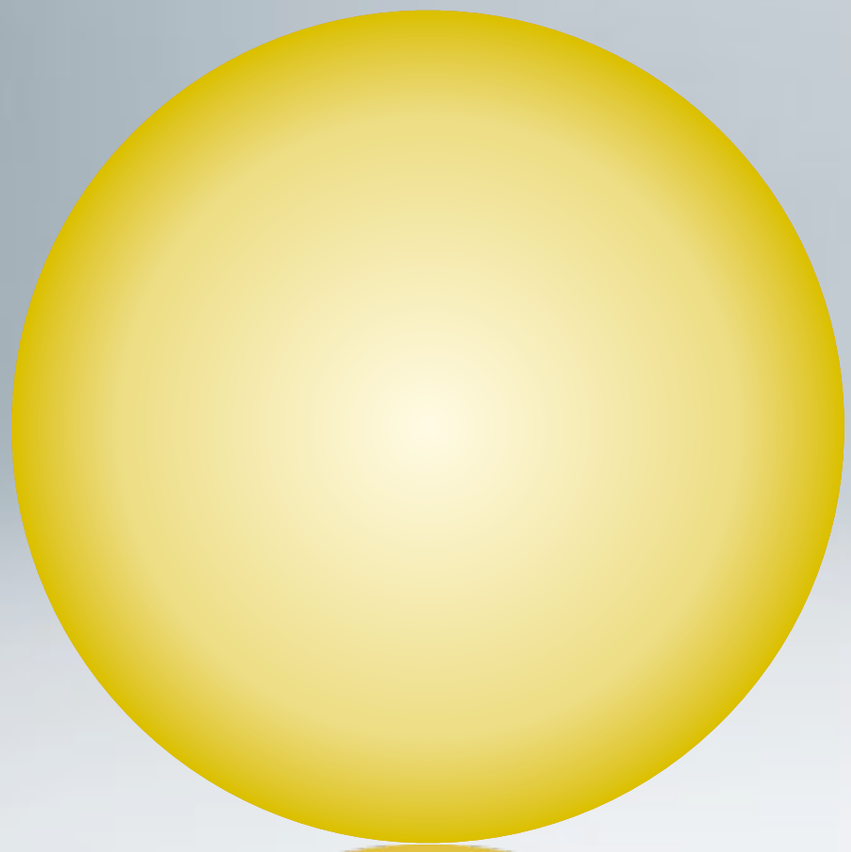
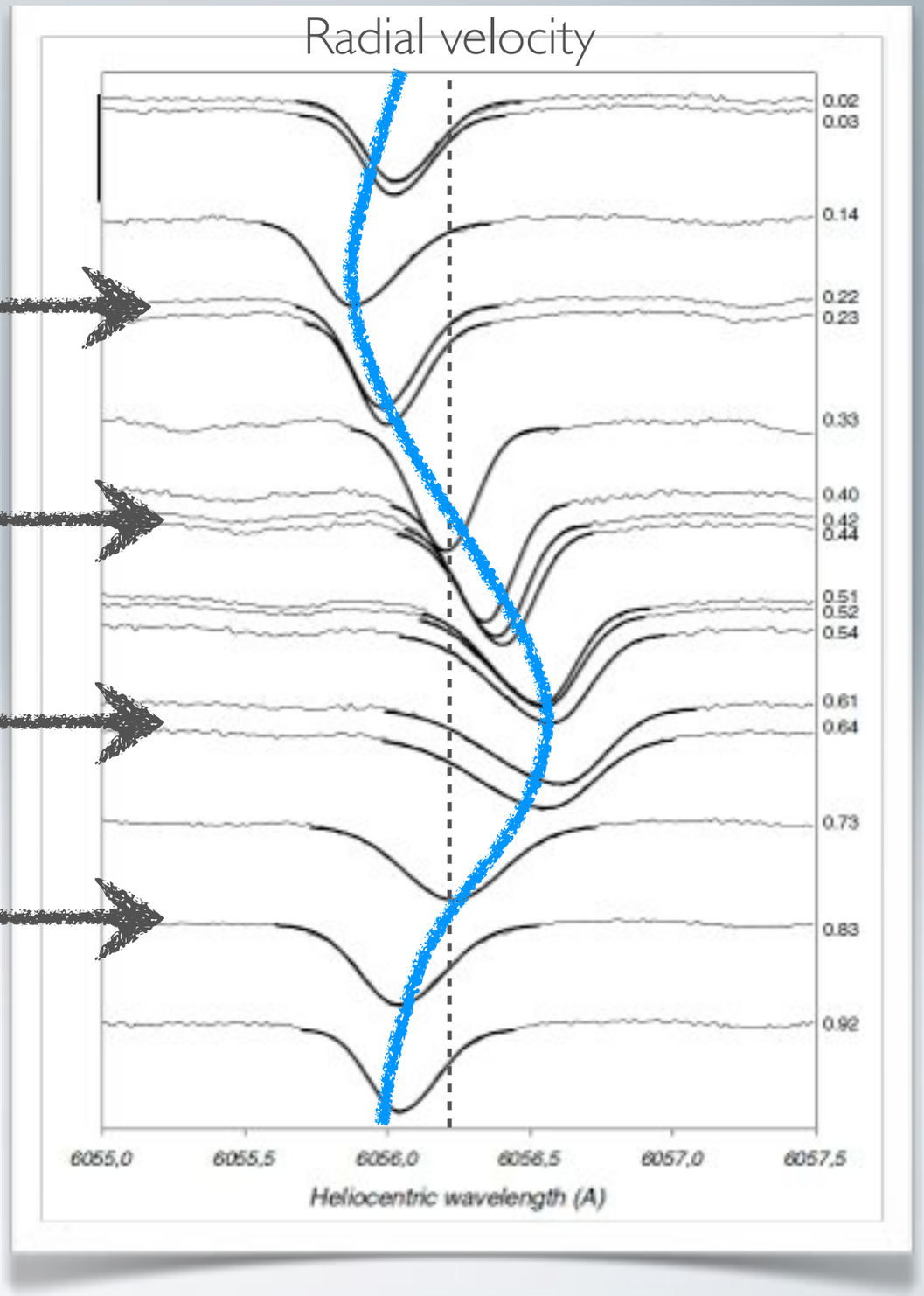


Expansion

Max radius

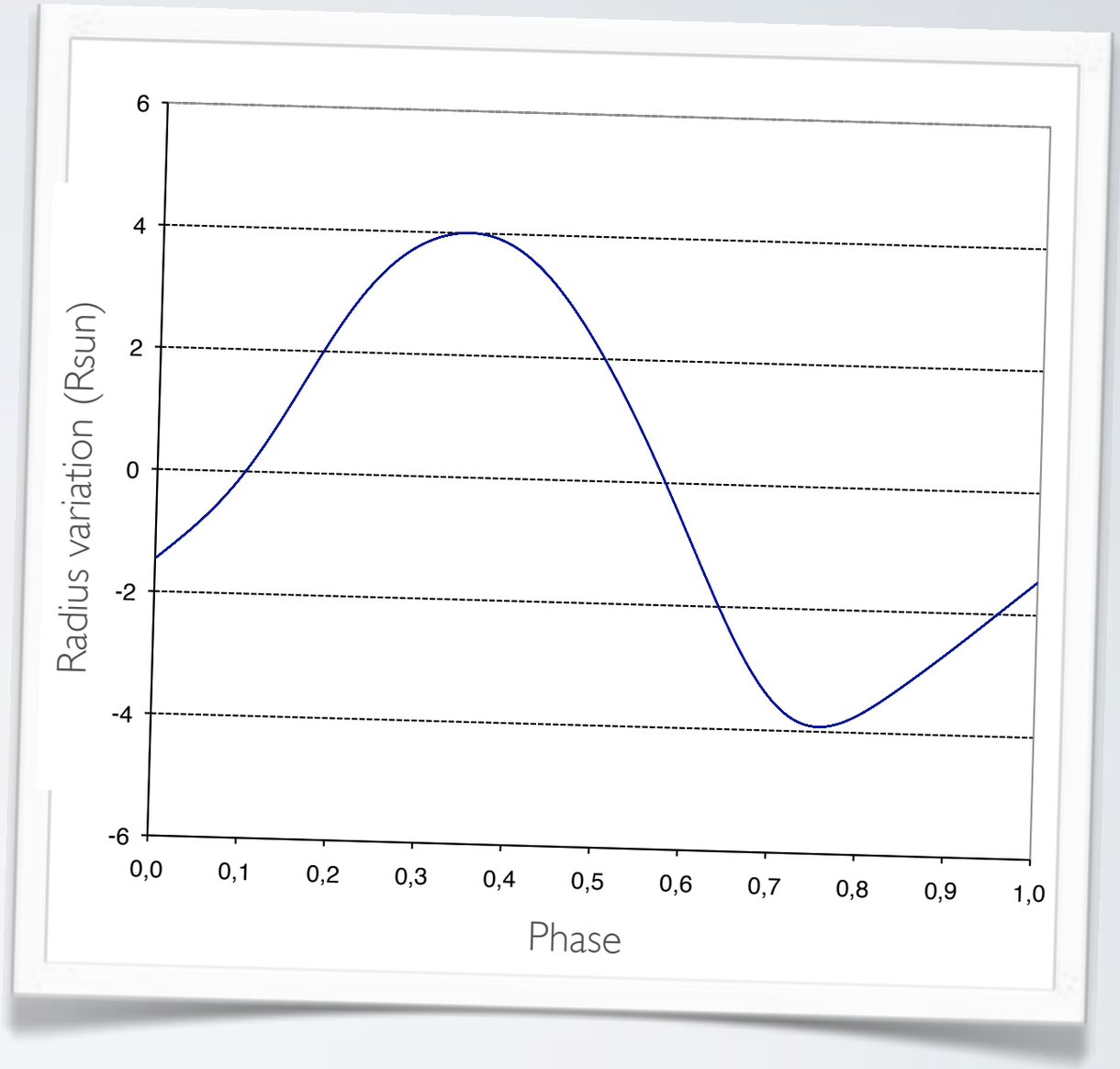
Contraction

Min radius



Spectroscopy gives the *variation* in linear radius of the star from:

$$\delta R(T) = -p \int_0^T v_{\mathrm{rad}}(t)\, dt$$

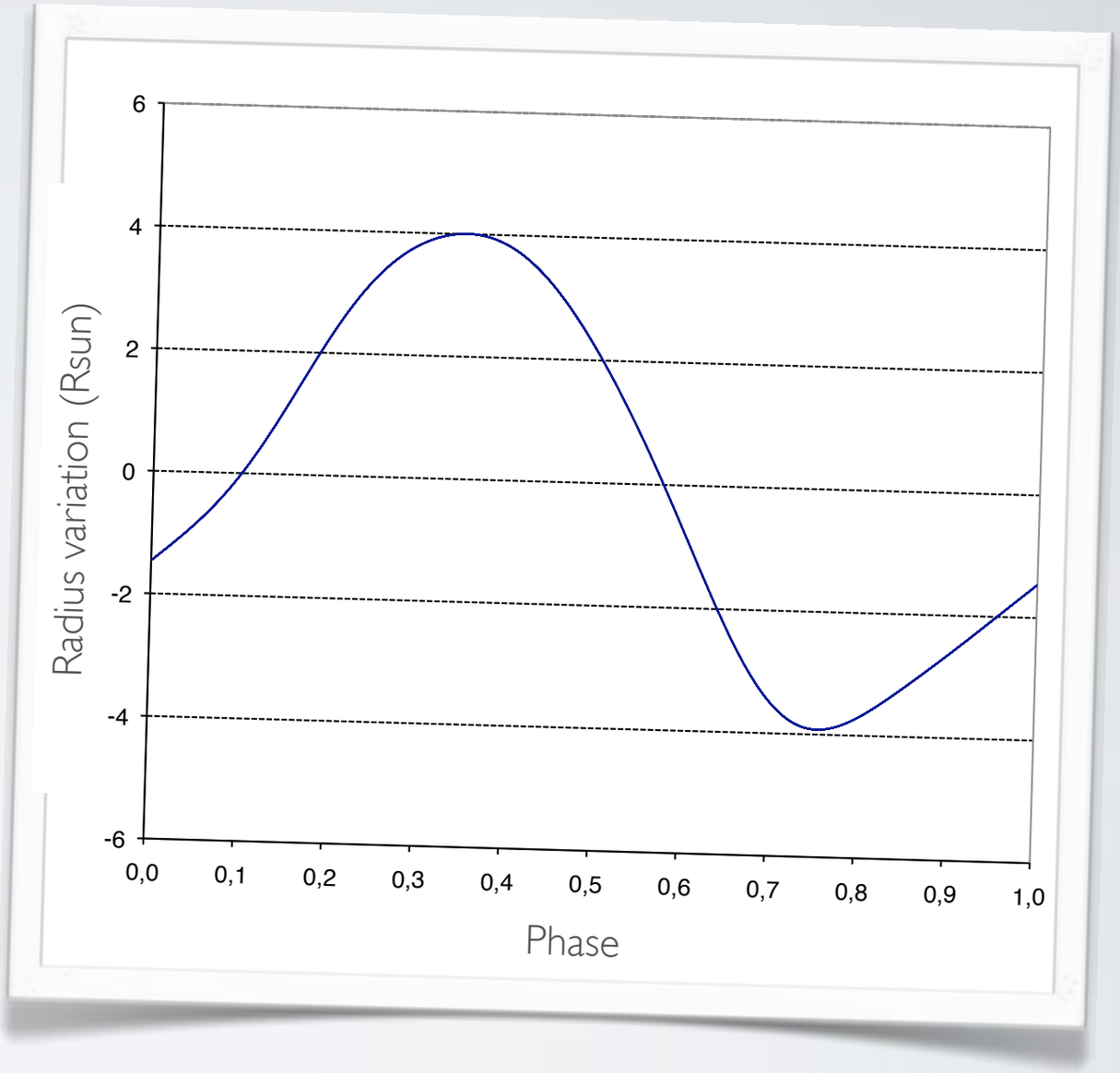


Spectroscopy gives the *variation* in linear radius of the star from:

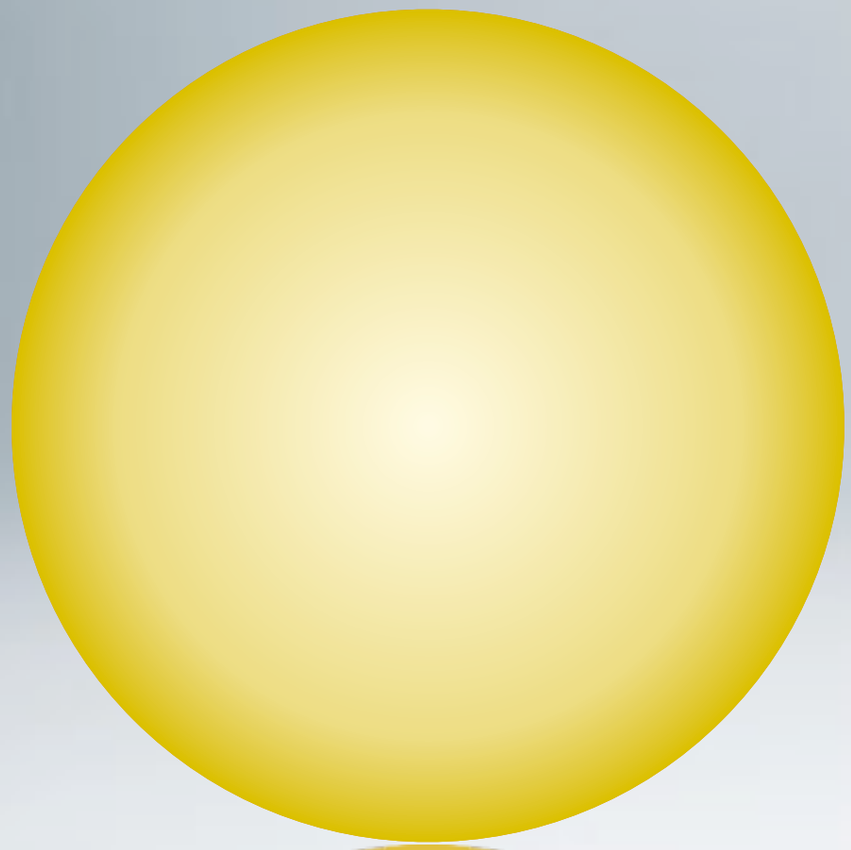
$$\delta R(T) = -p \int_0^T v_{\mathrm{rad}}(t)\, dt$$

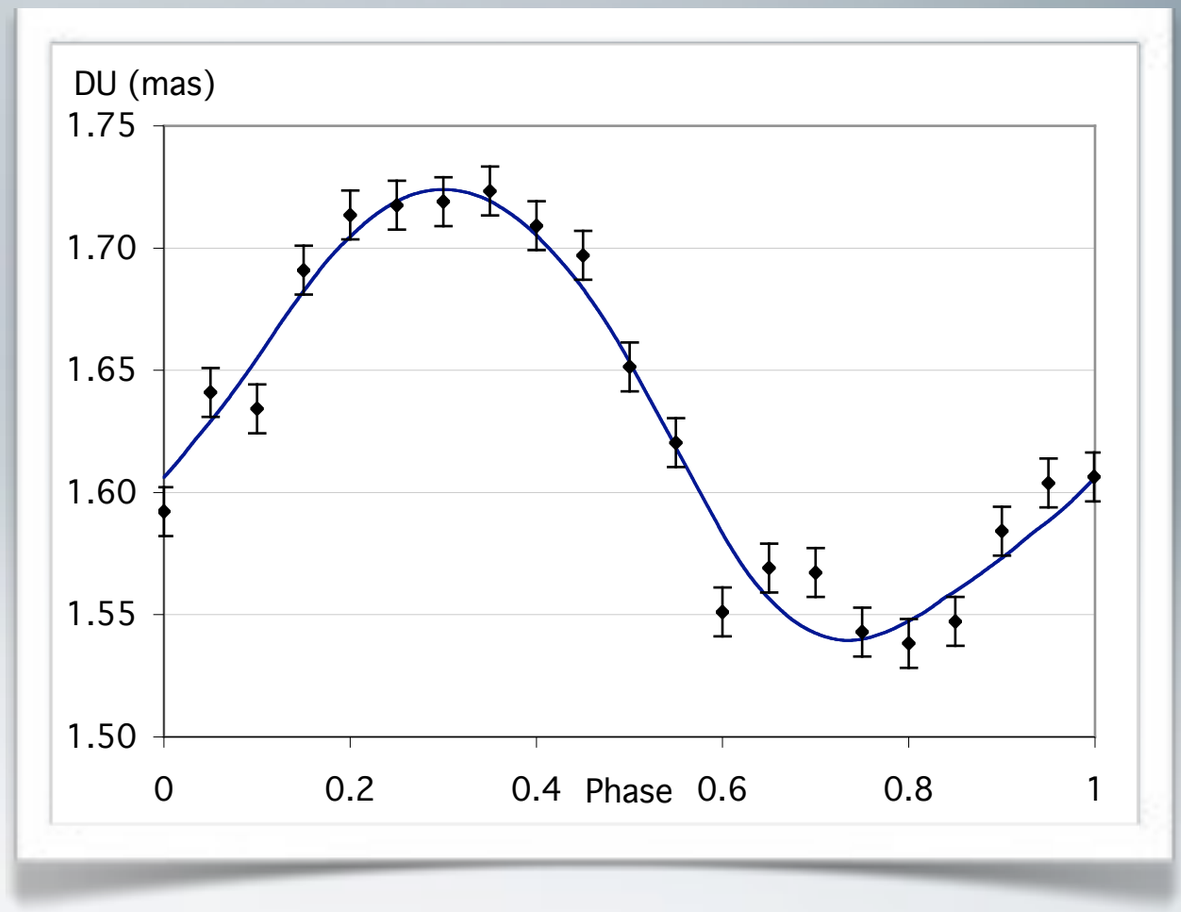
p = projection factor
$= V_{puls} / V_{rad}$
~ 1.3

measured on **δ** Cep + models



2. INTERFEROMETRY





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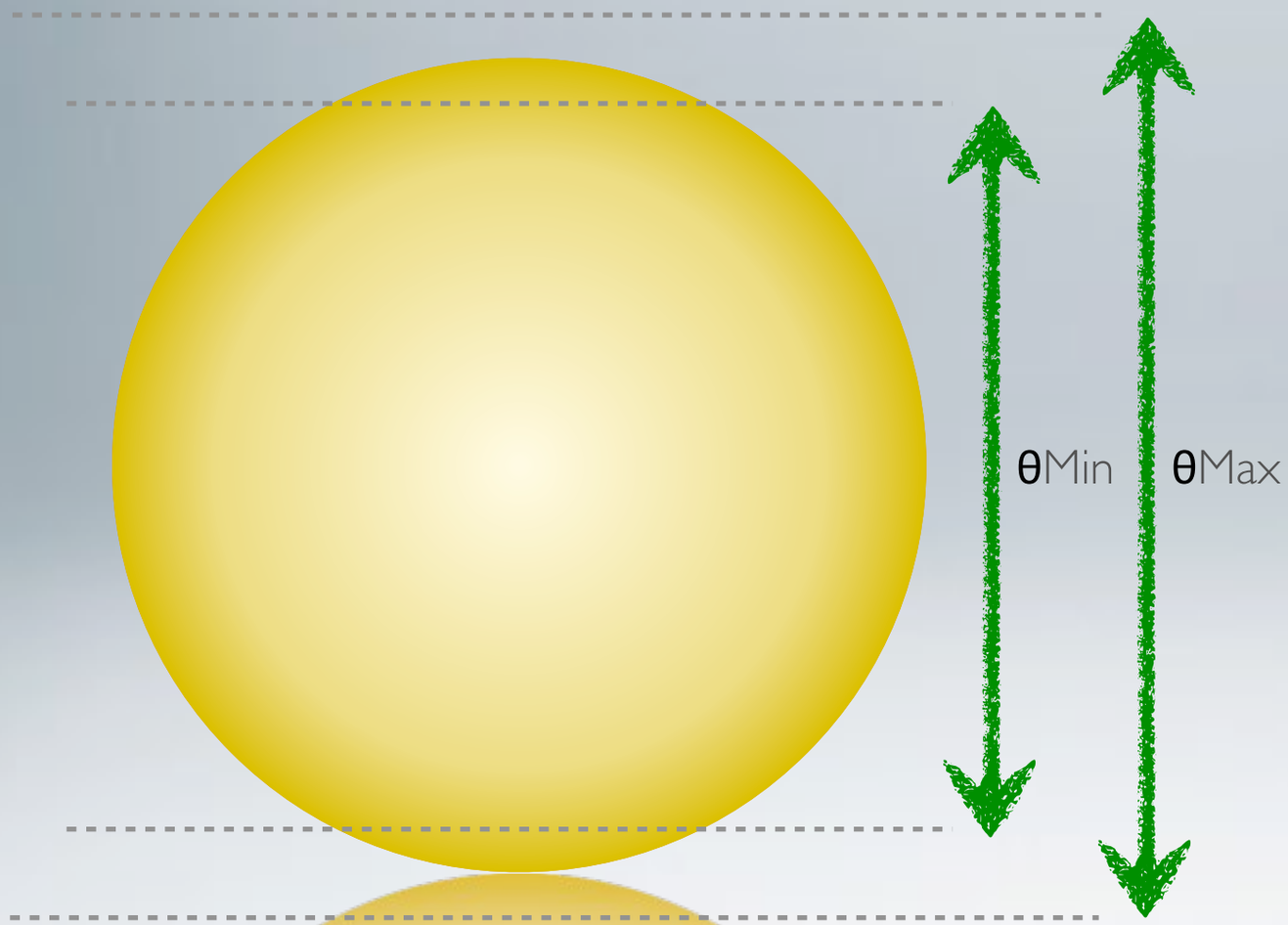

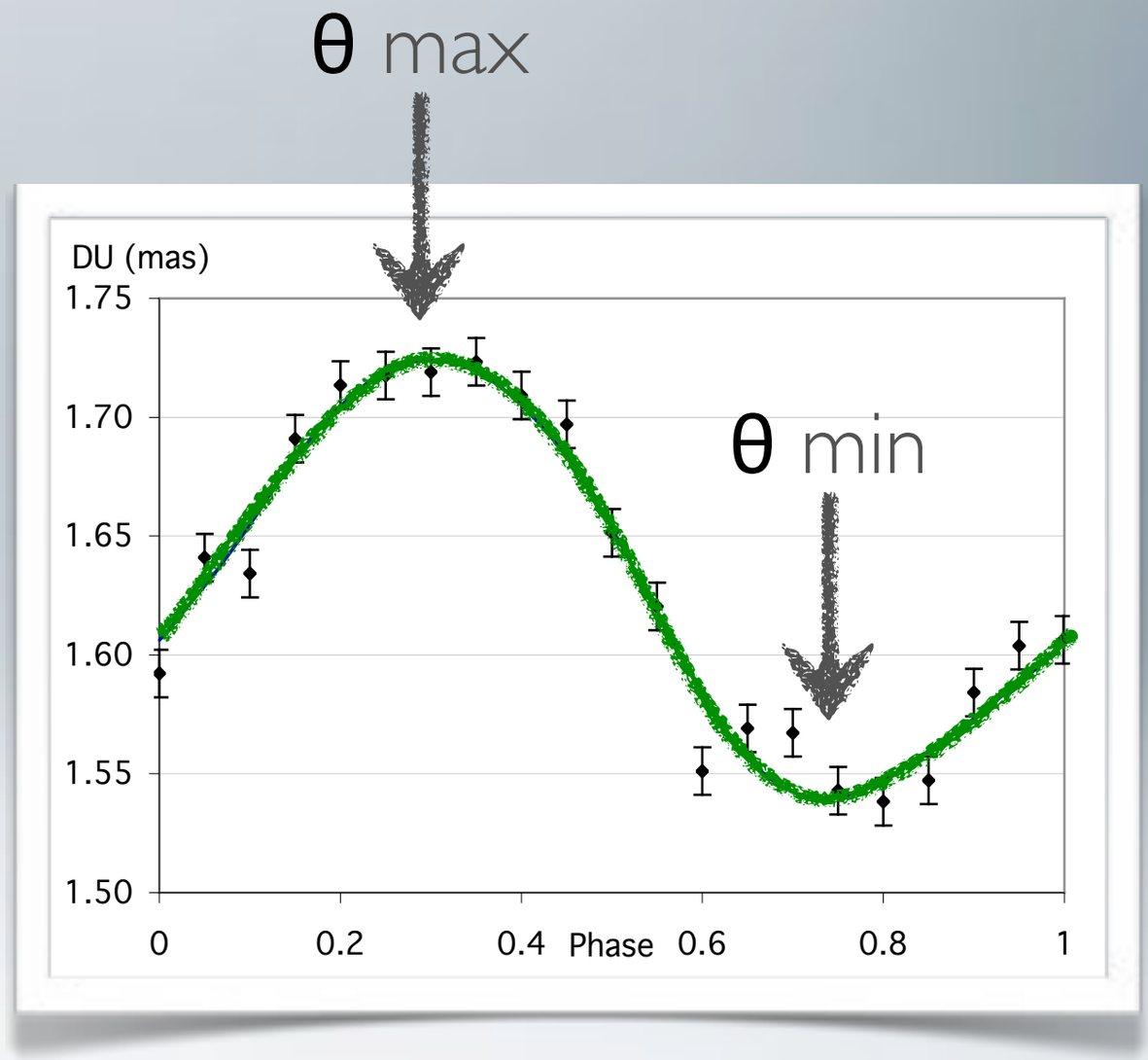

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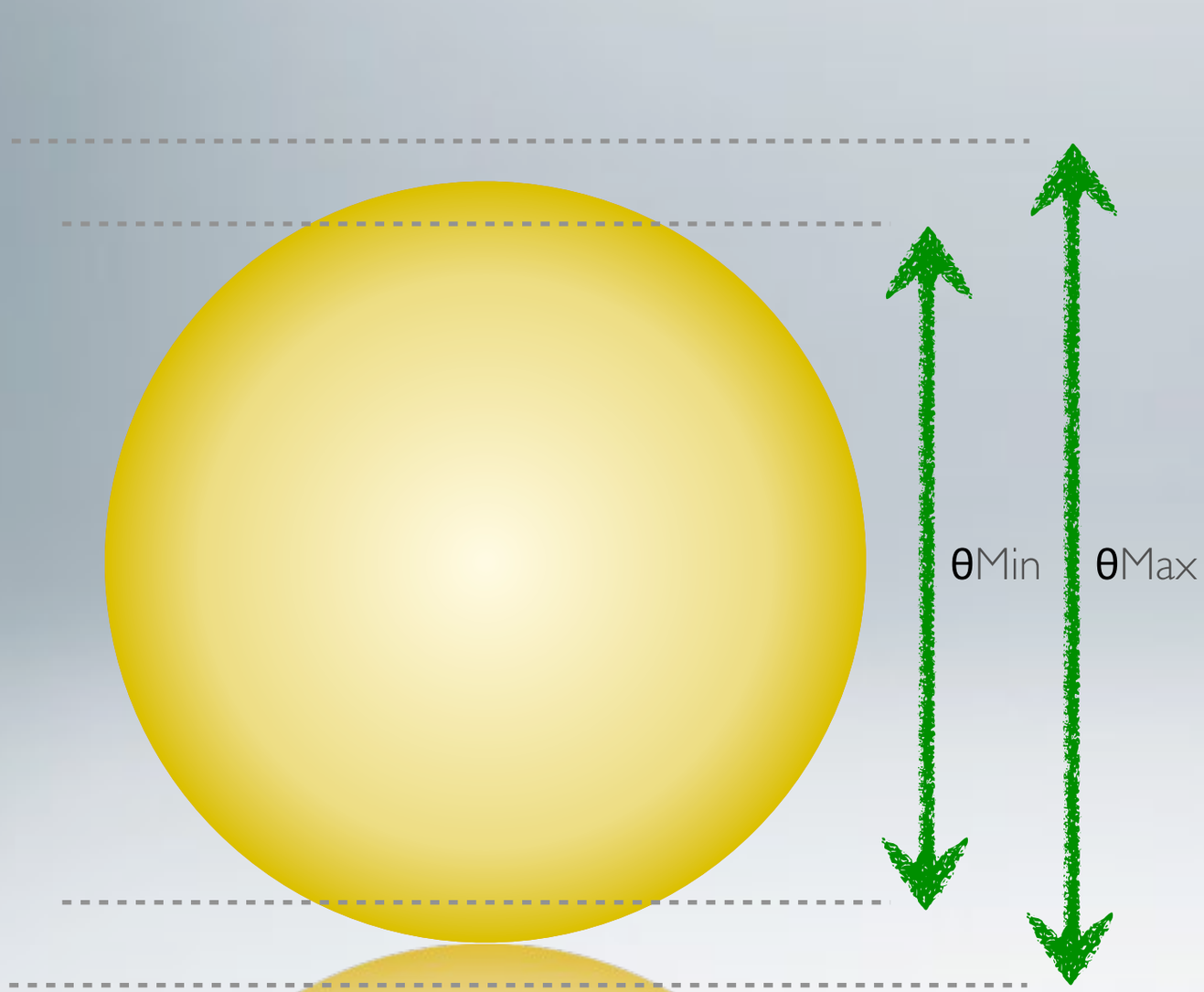
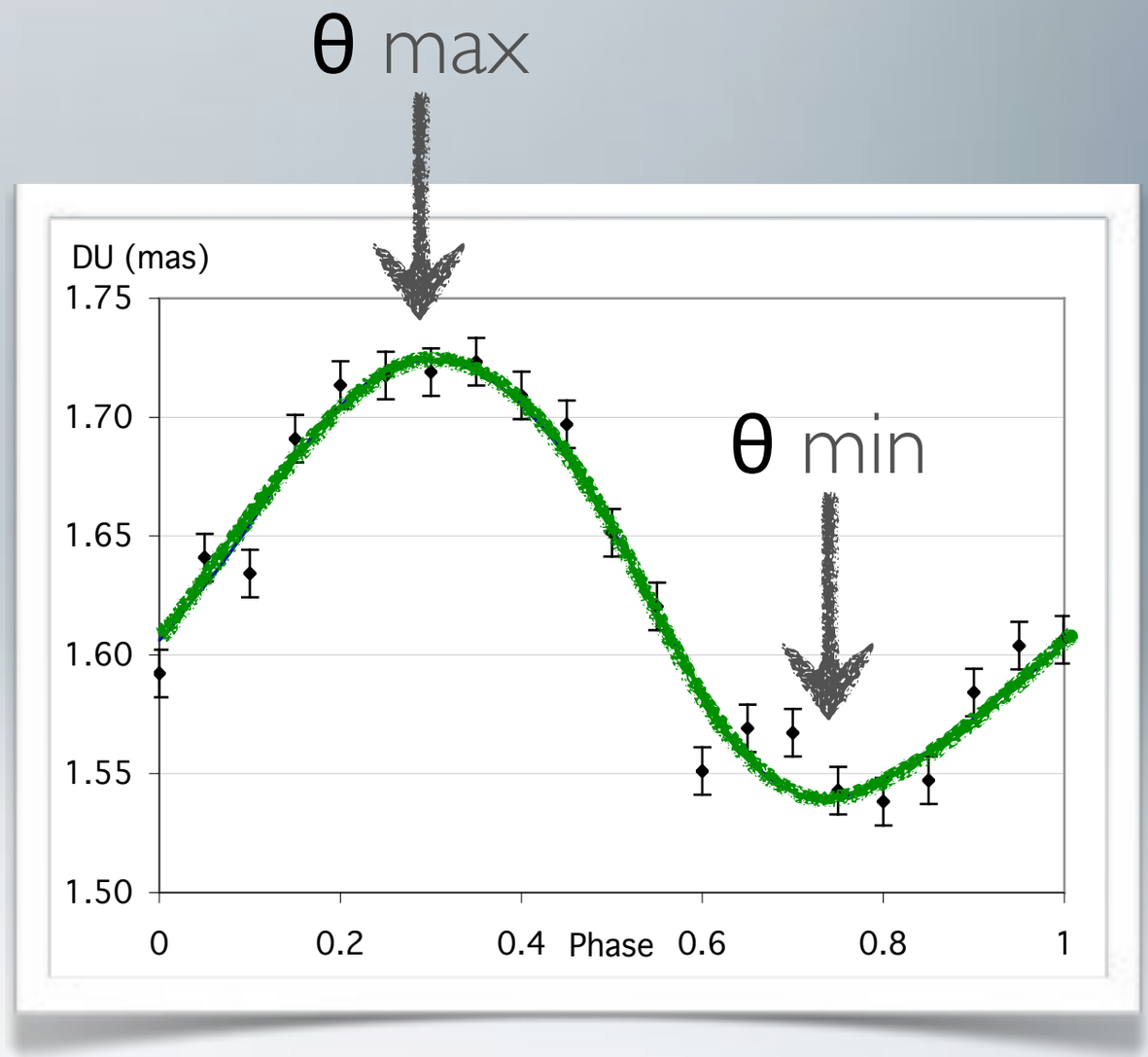
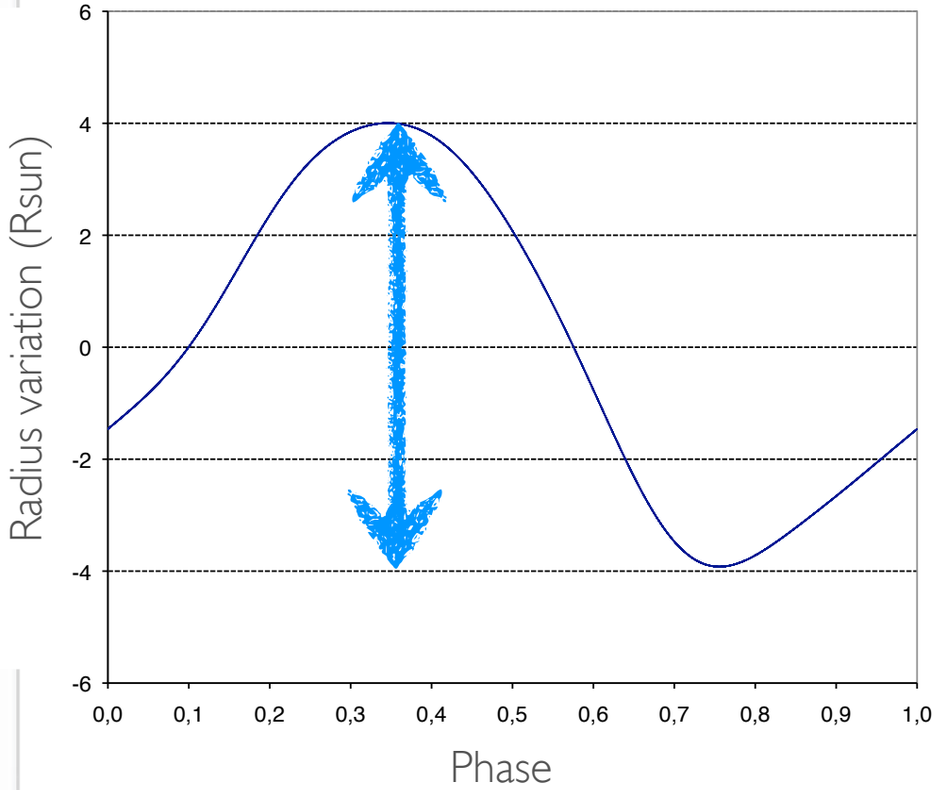


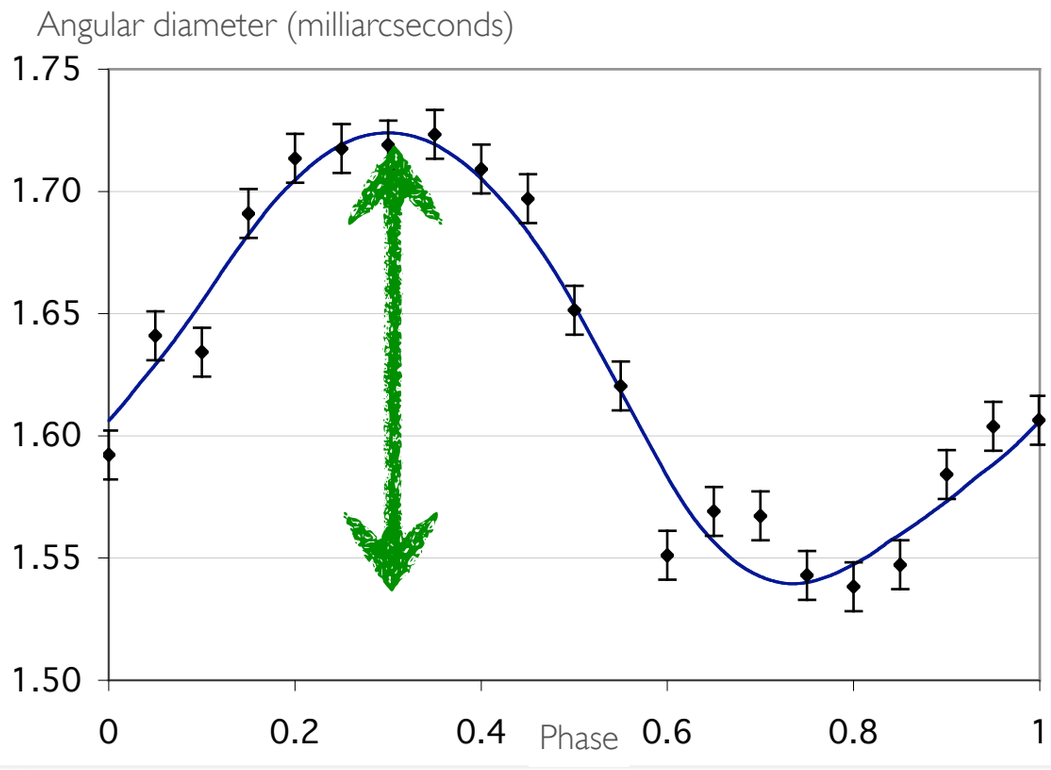


Gives the *angular size variation* of the star

Spectroscopy



Interferometry



The distance d is given by the relation:

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

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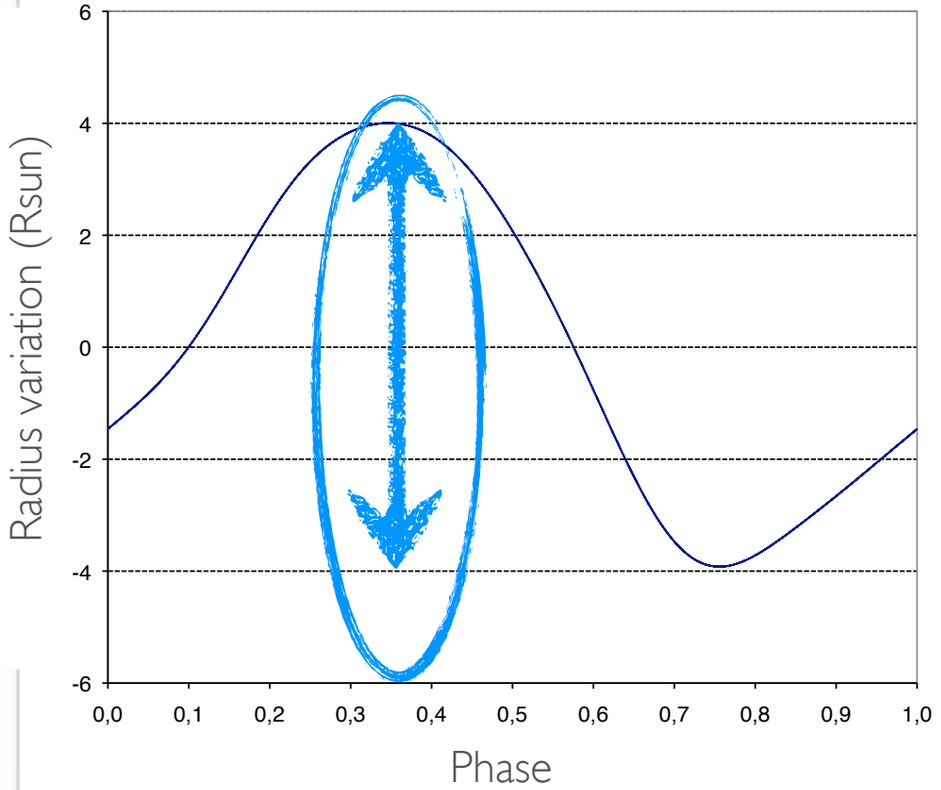

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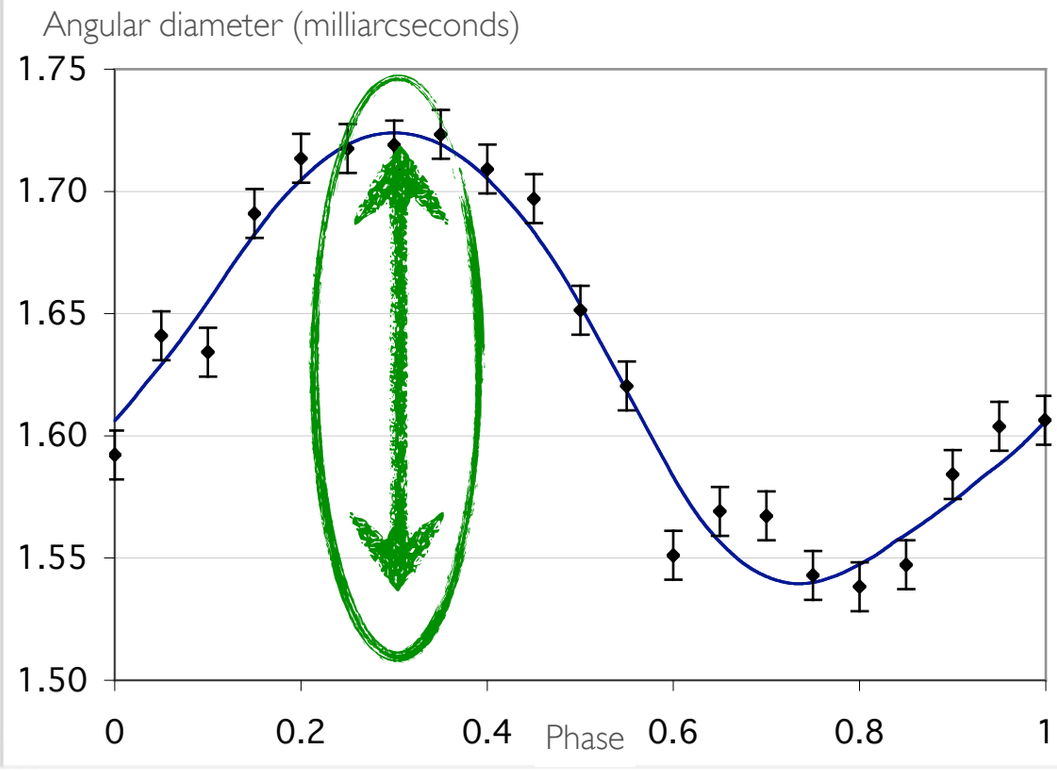

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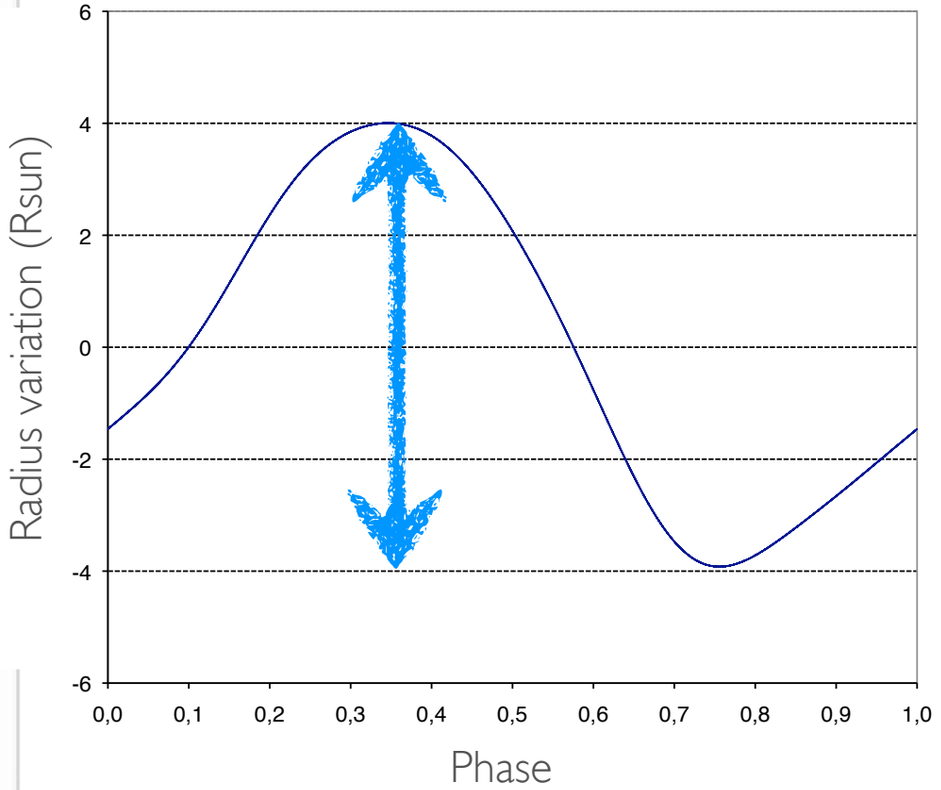

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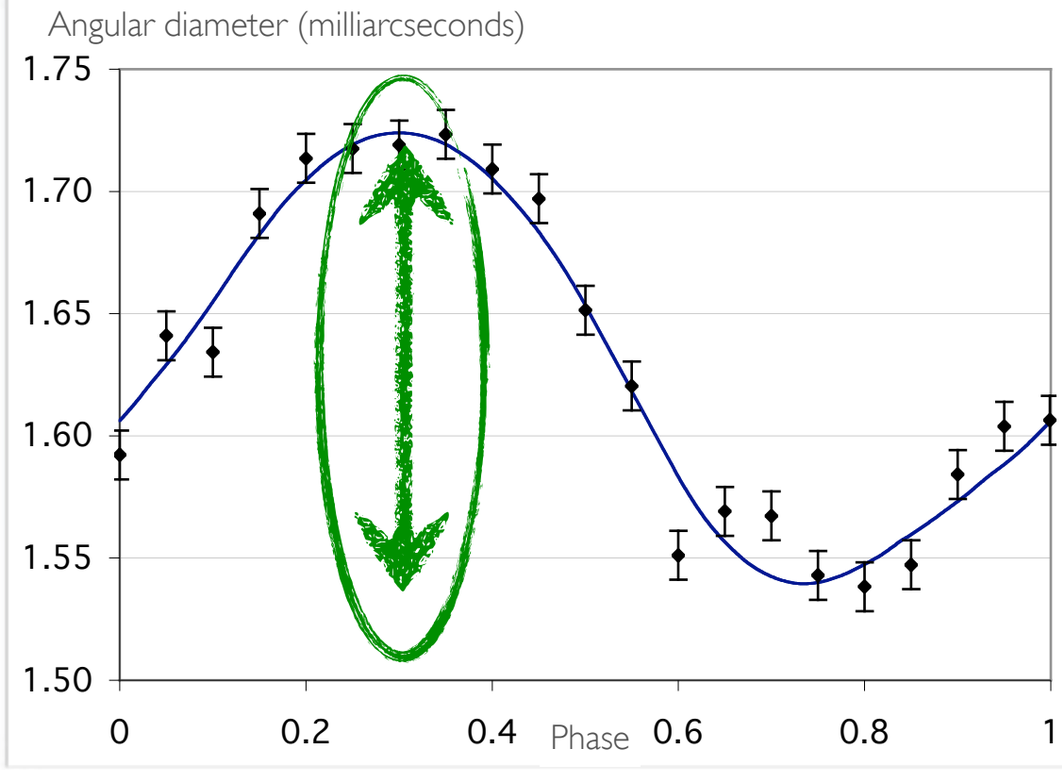

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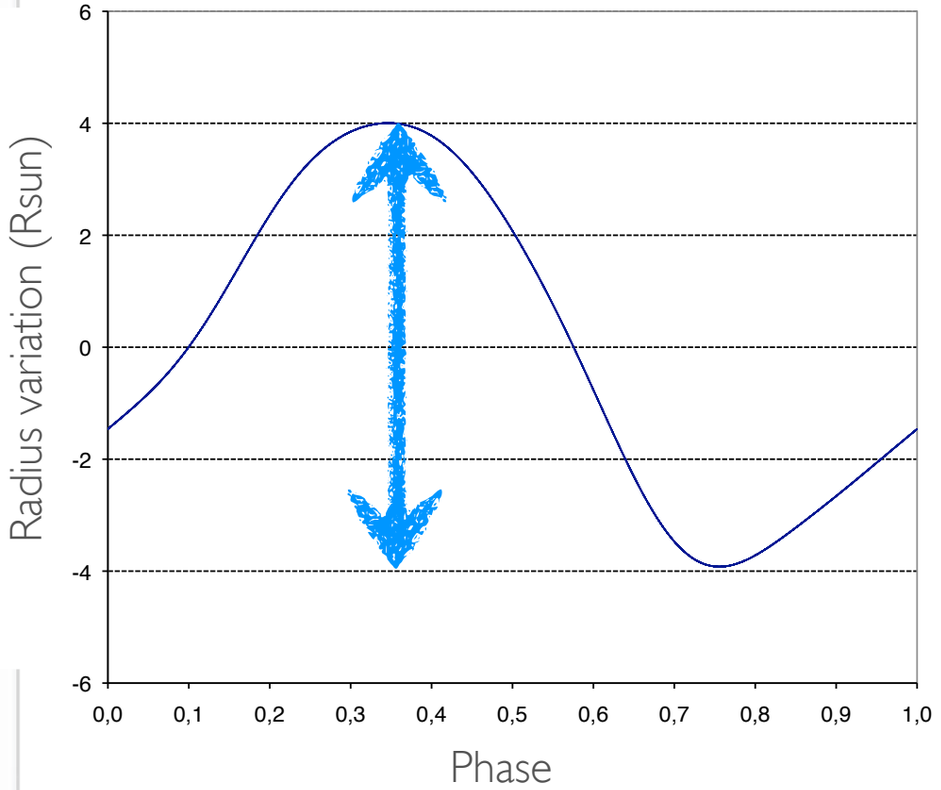

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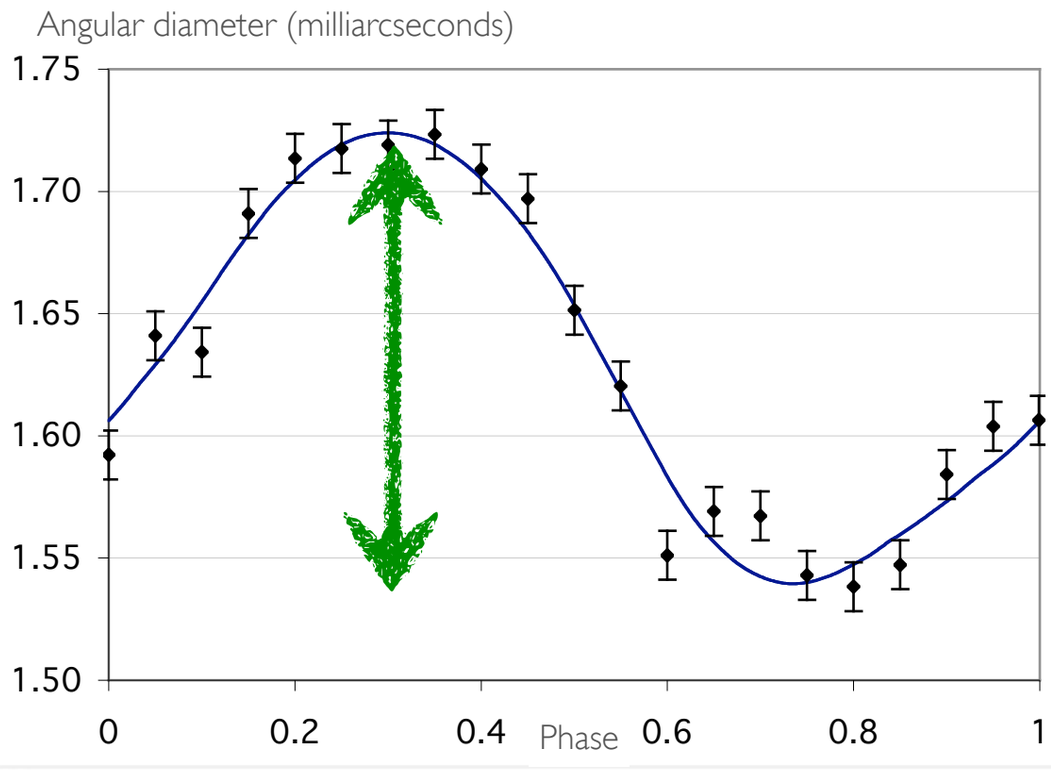

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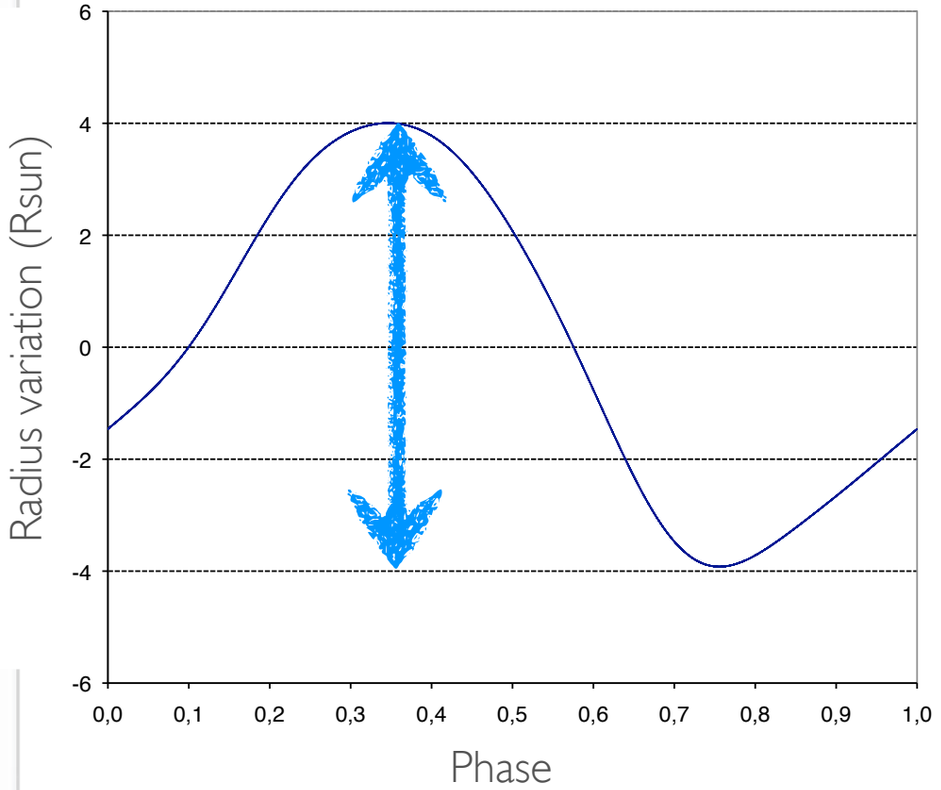

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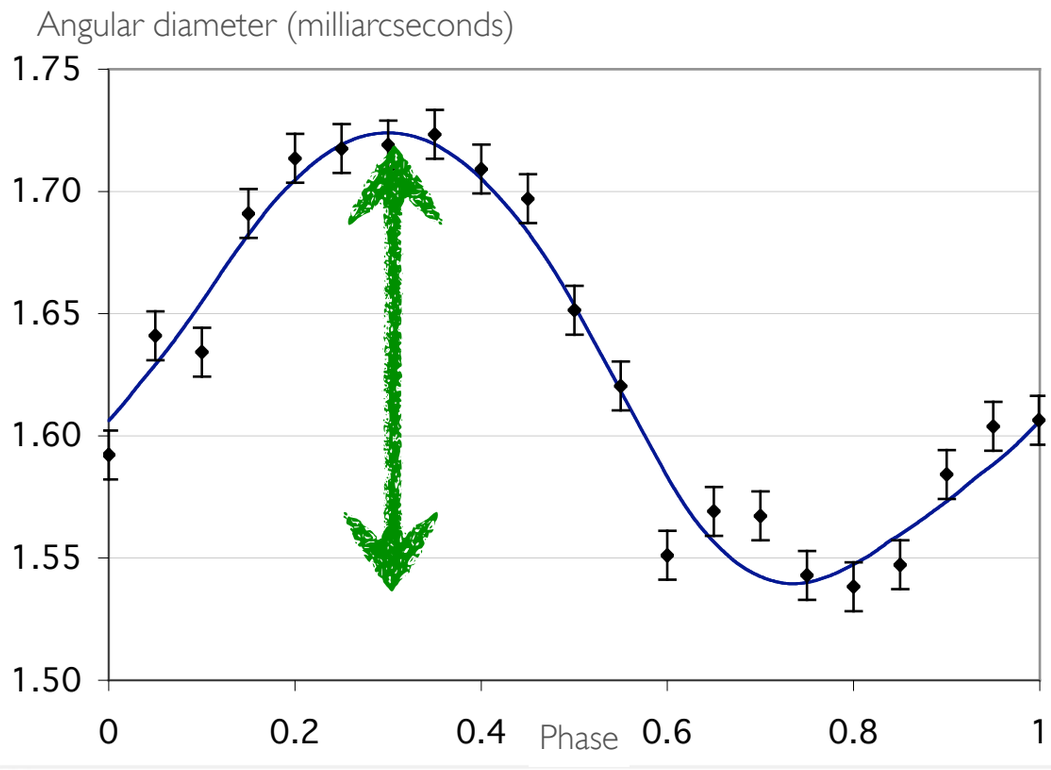

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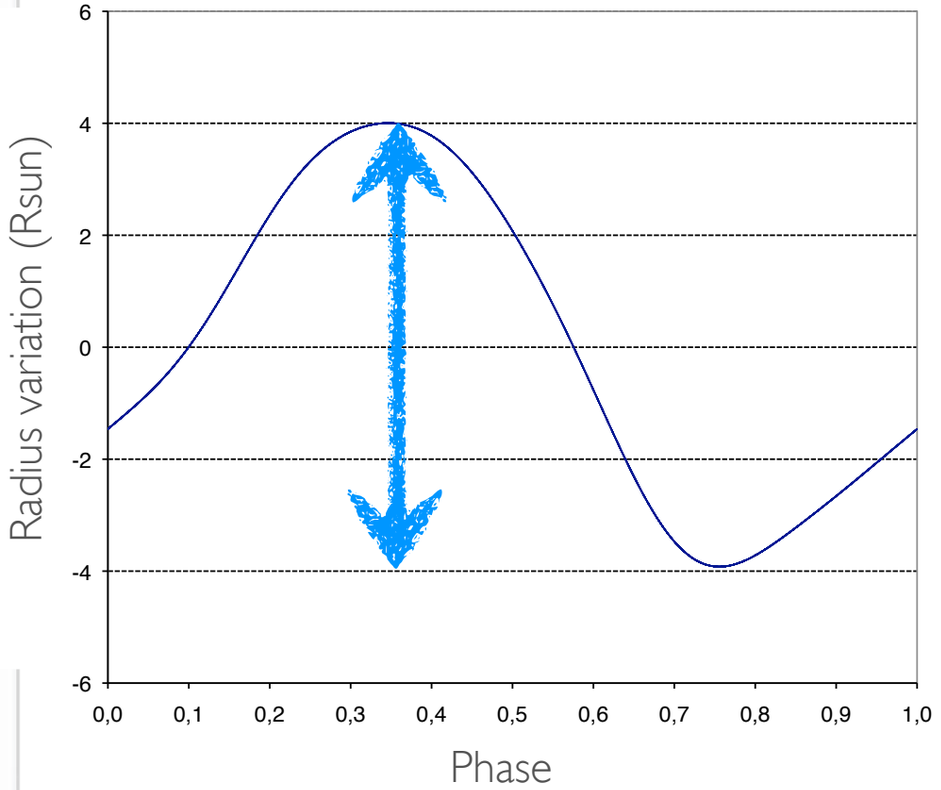
k = limb darkening correction (from models)

$= \theta_{UD} / \theta_{LD}$

~ 0.94 in visible, 0.98 in IR

Spectroscopy



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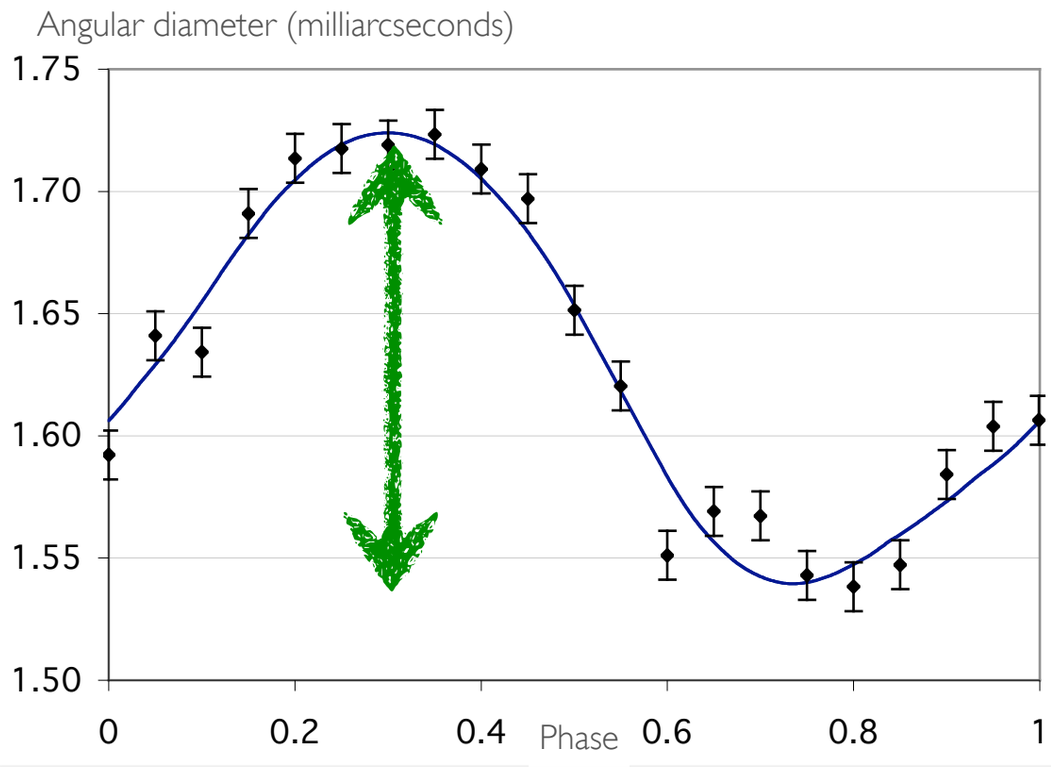

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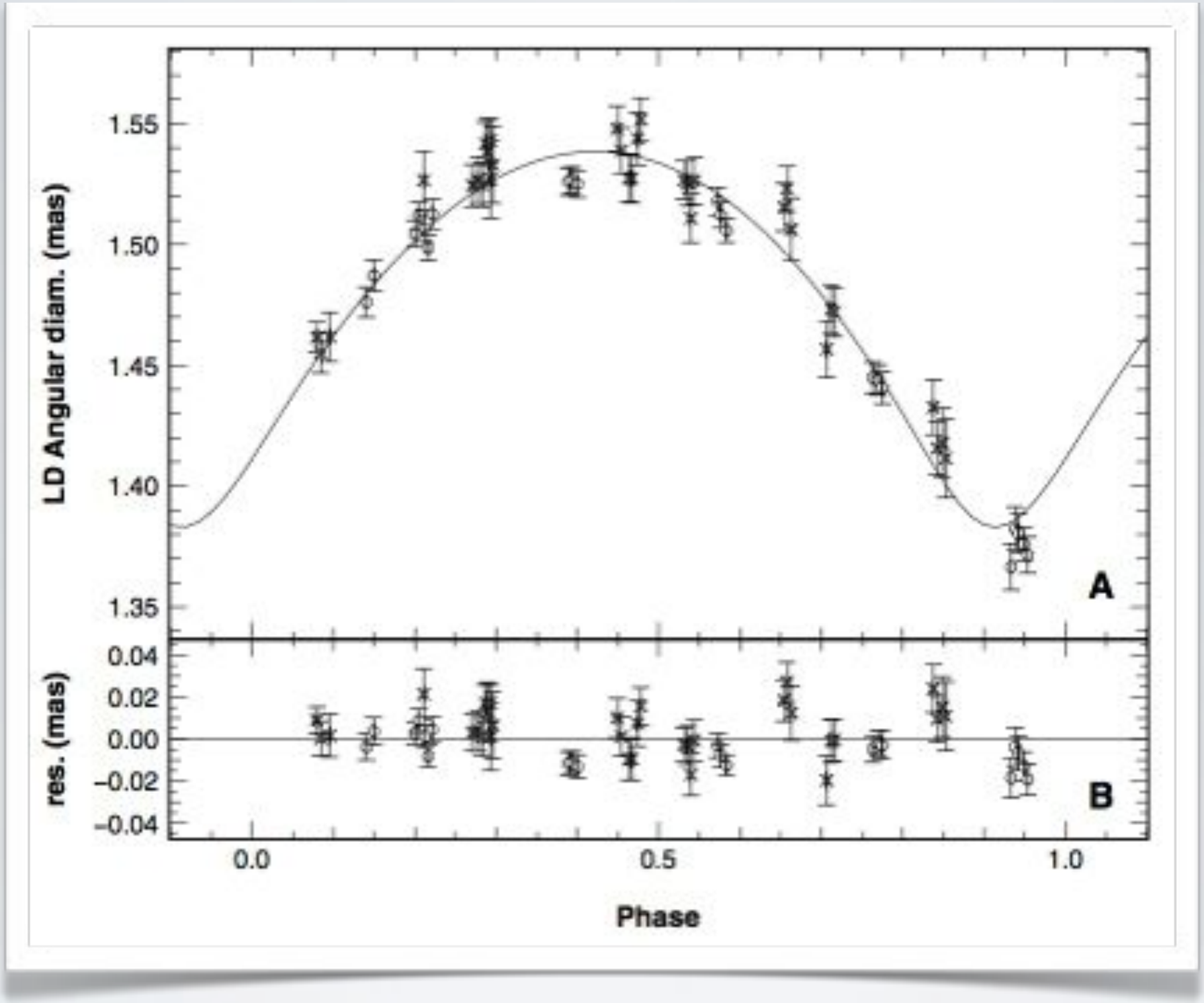
δ CEP : A MEASUREMENT OF p

δ CEP : A MEASUREMENT OF *p*



Mérand et al. 2005, A&A 438, L9

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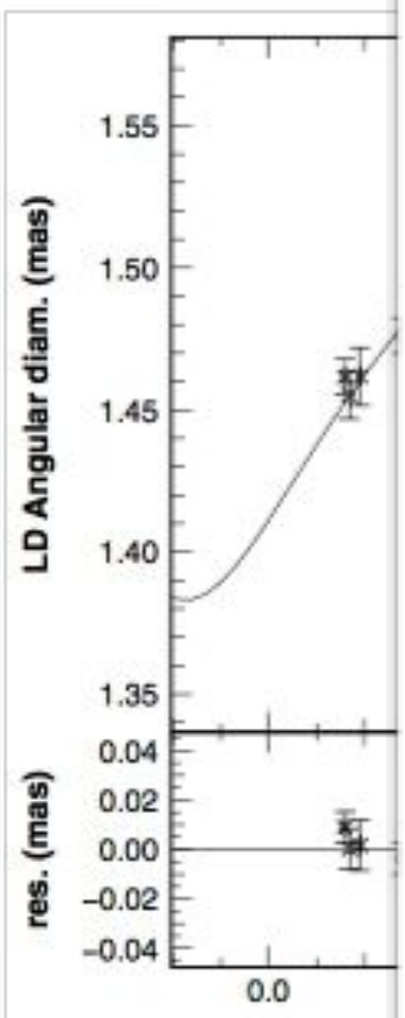

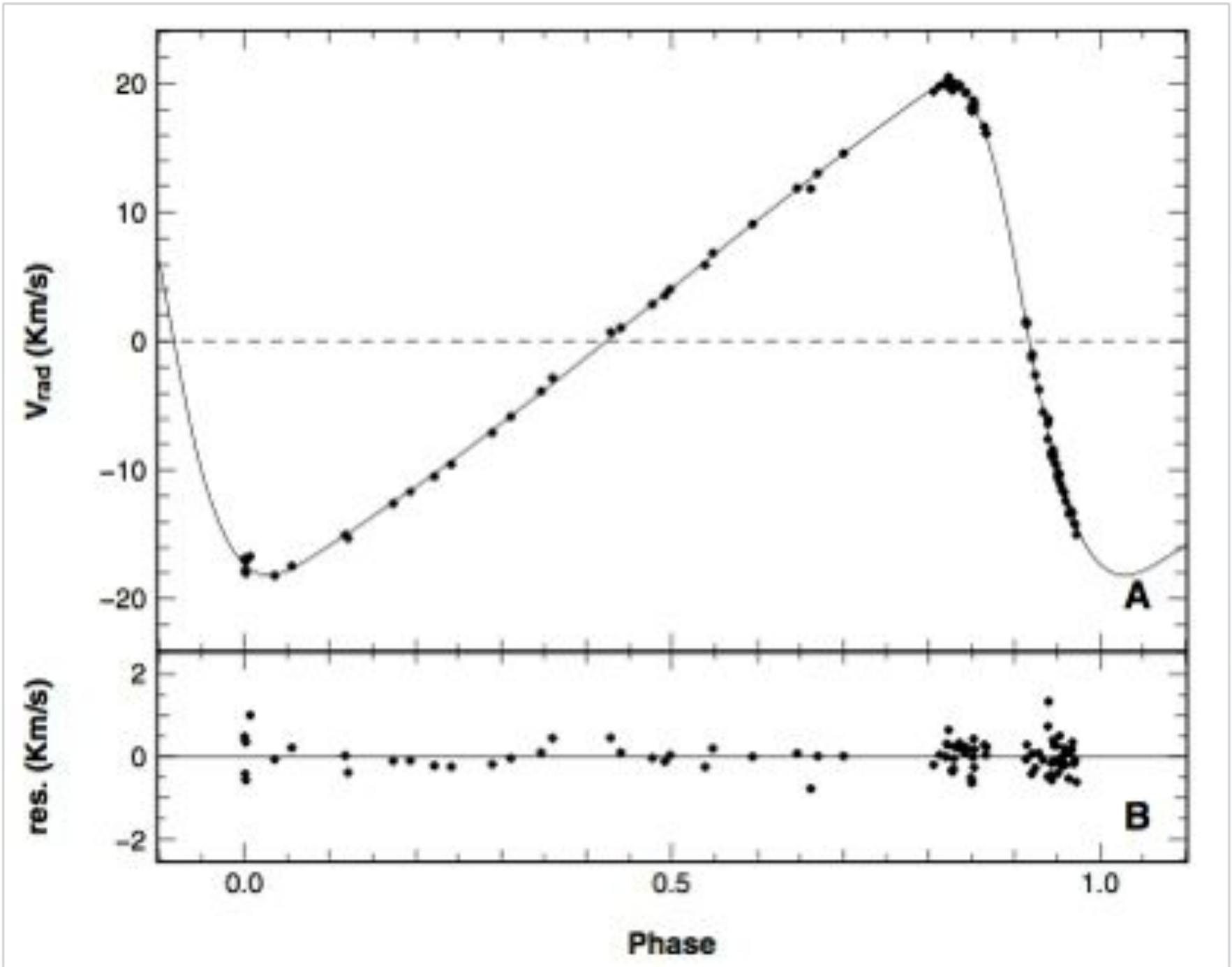

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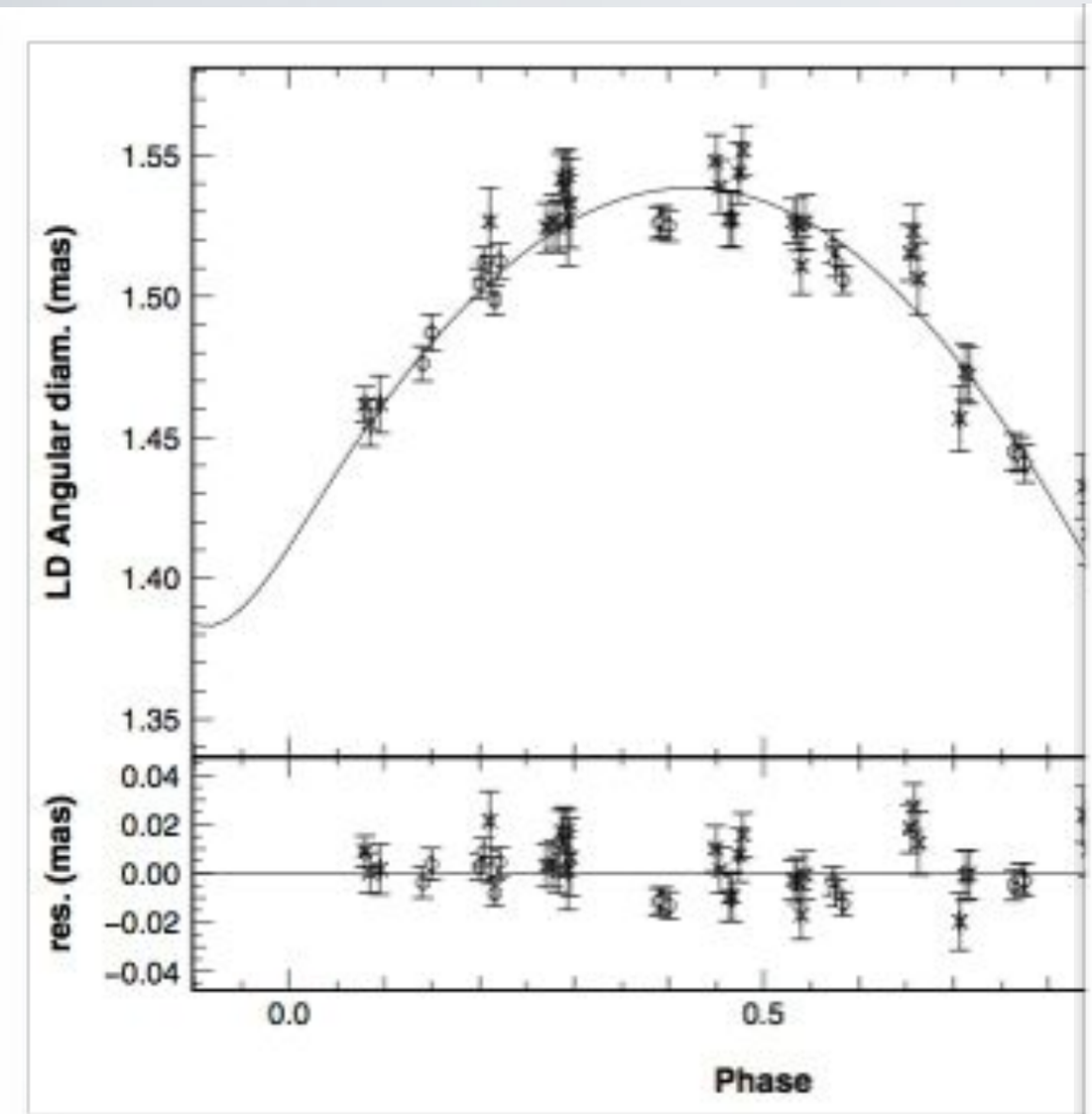
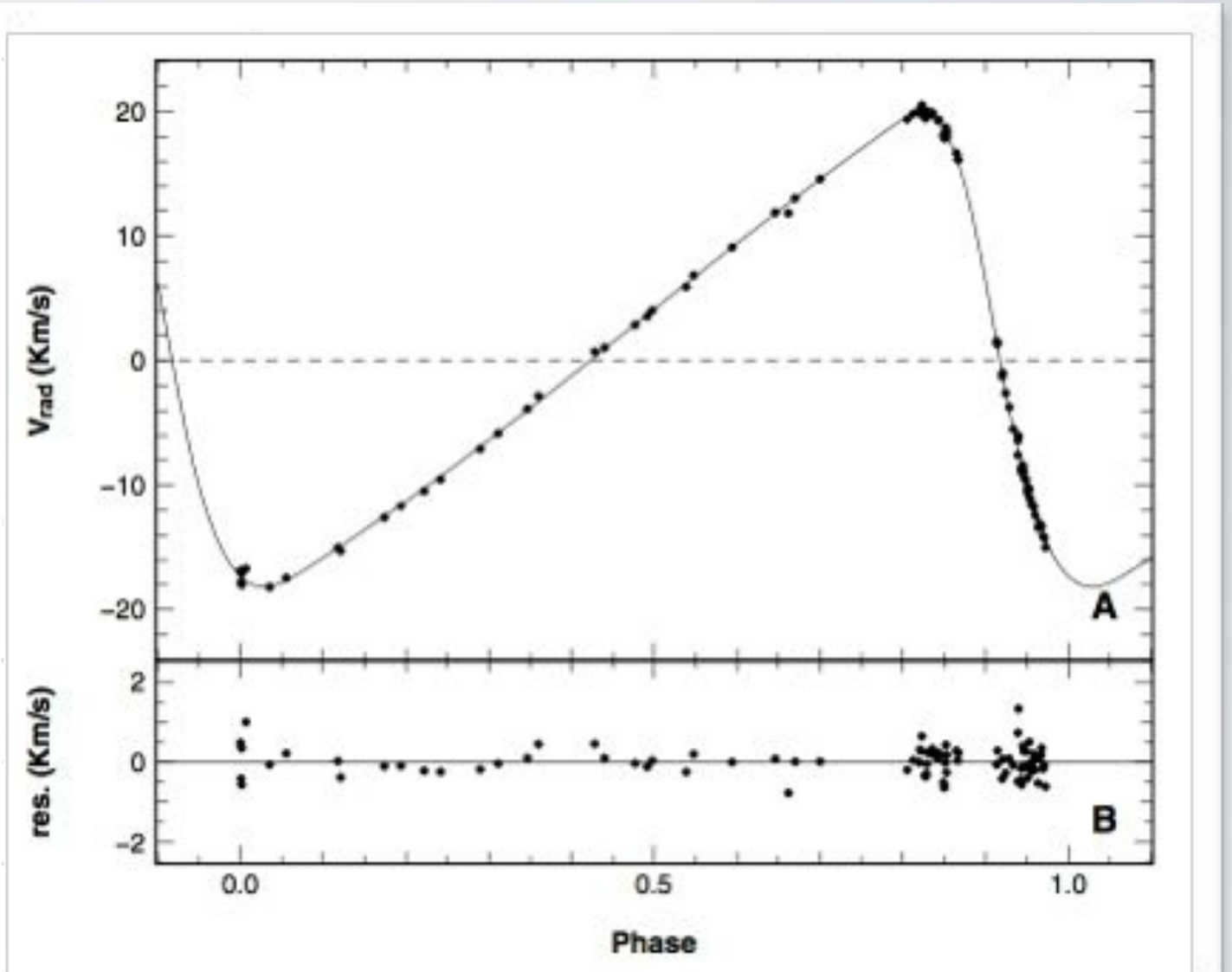
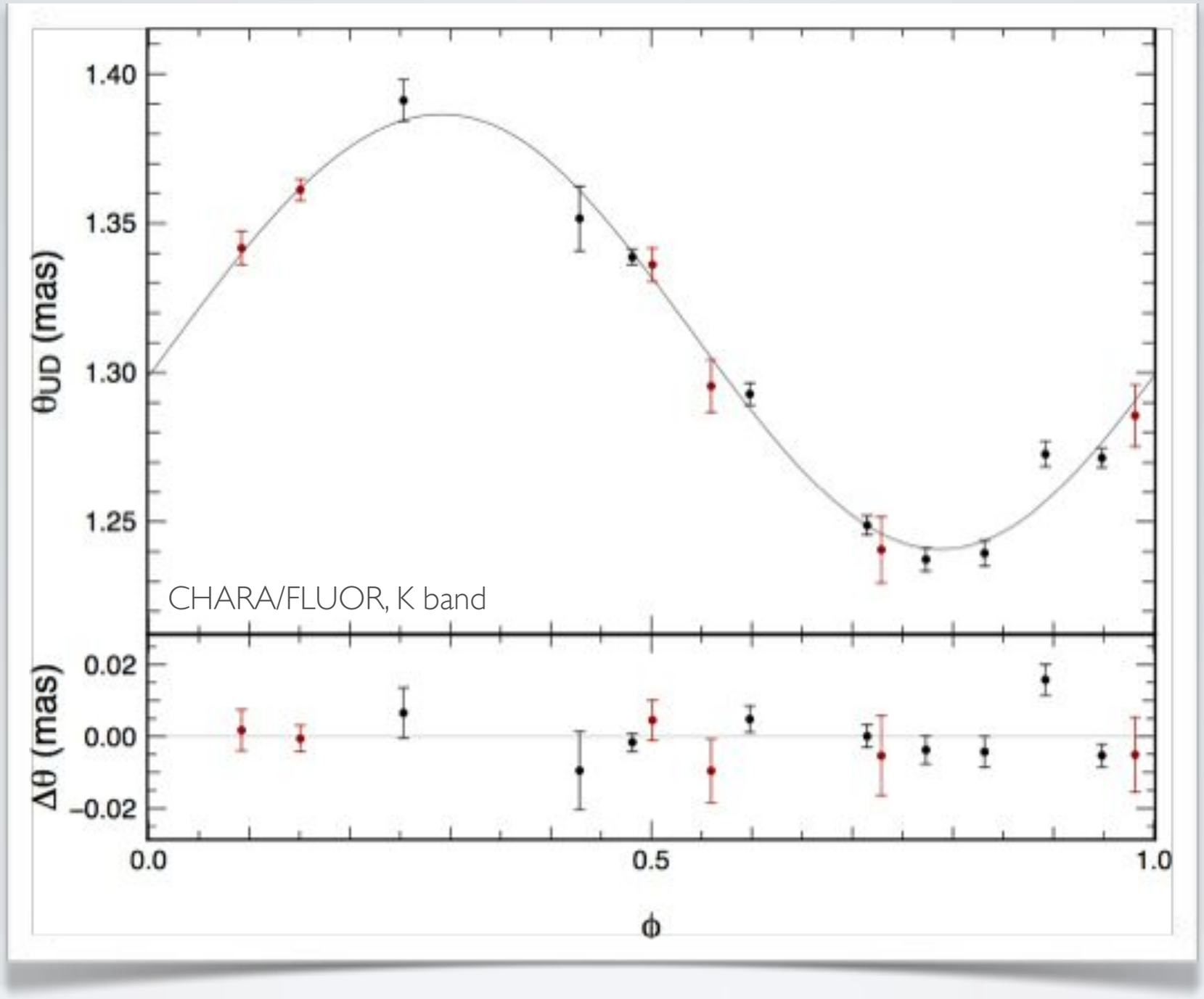




p-factor = 1.27 ± 0.06, with d=274 ± 11 pc from HST-FGS

Mérand et al. 2005, A&A 438, L9

Y OPH (CHARA/FLUOR)



Mérand et al. 2007, ApJ 664, 1087
Gallenne et al. 2013, in prep.

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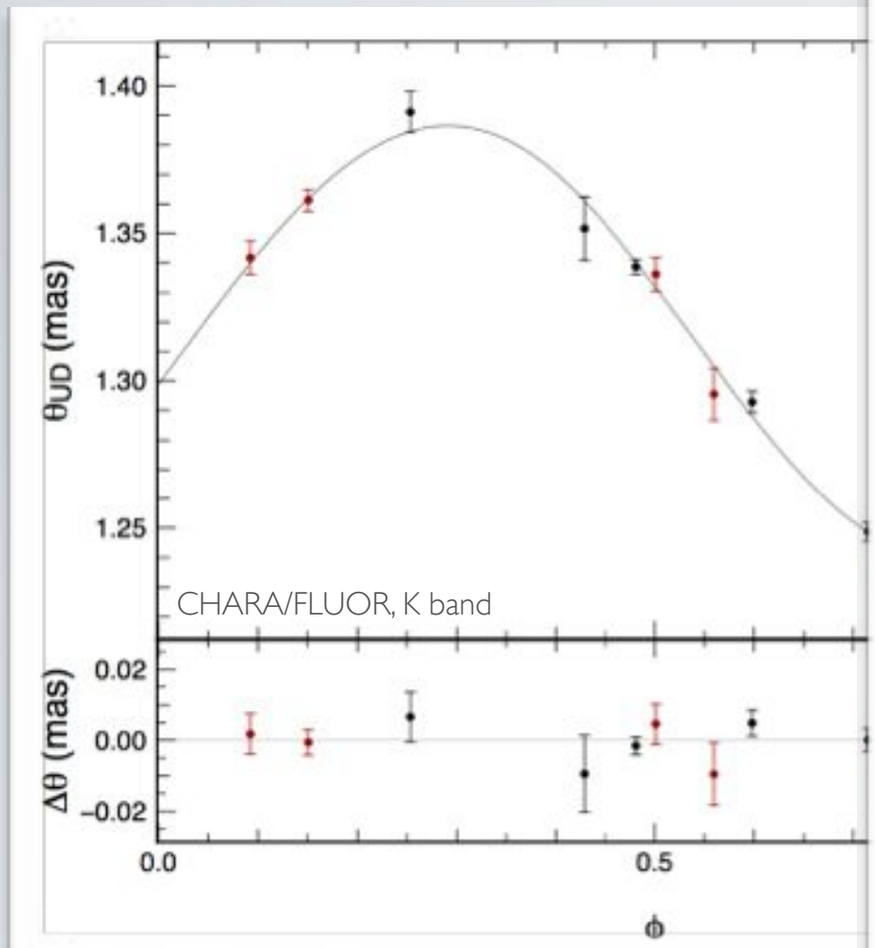

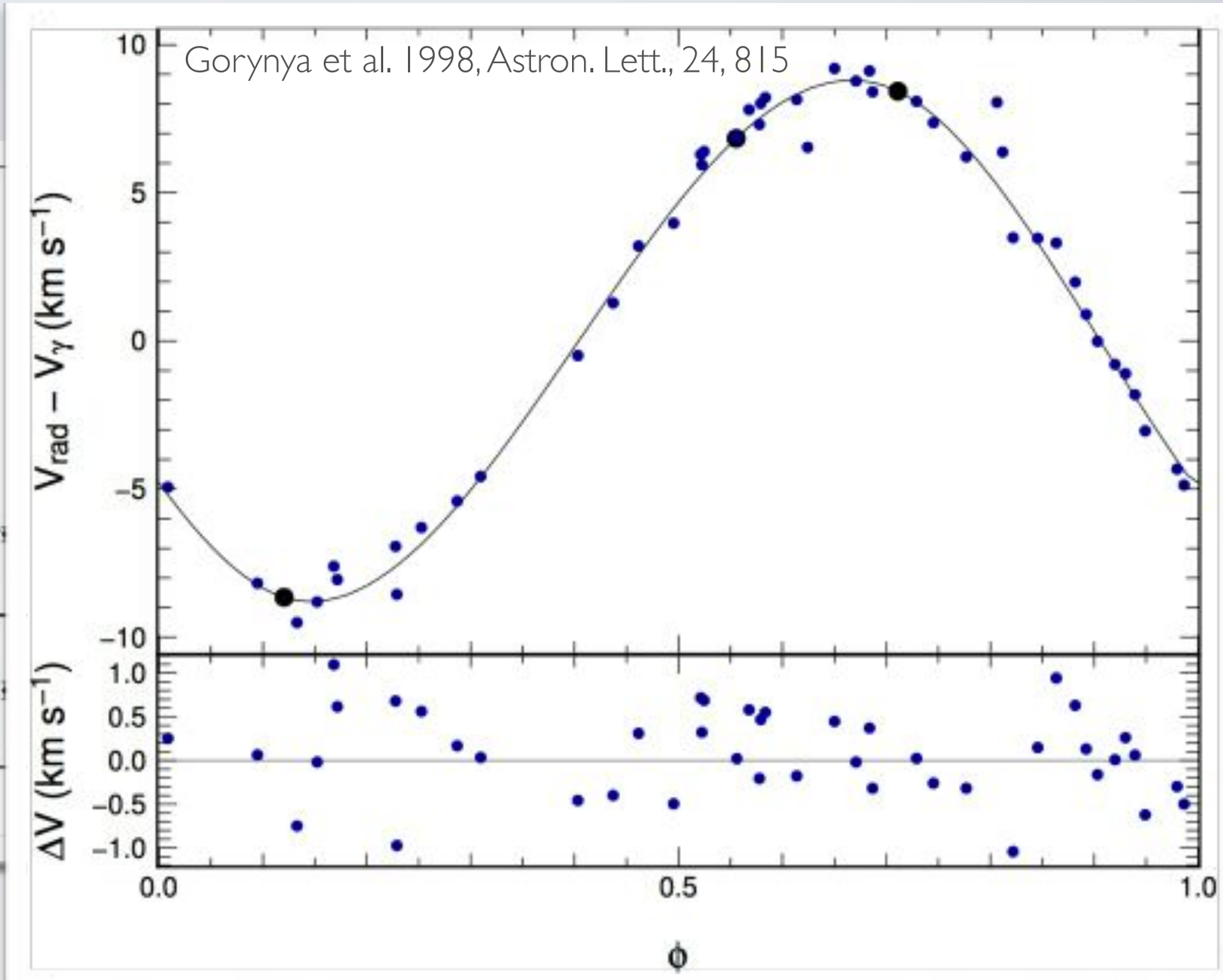

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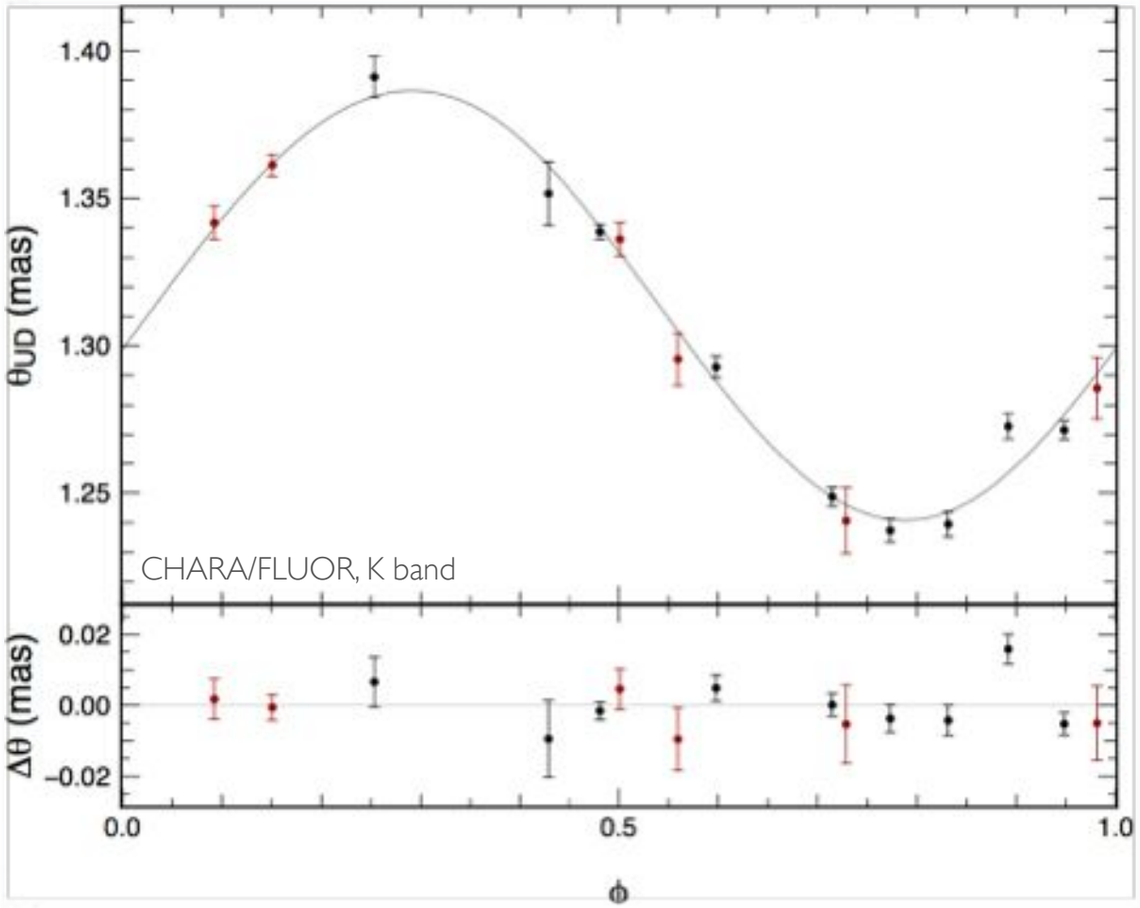

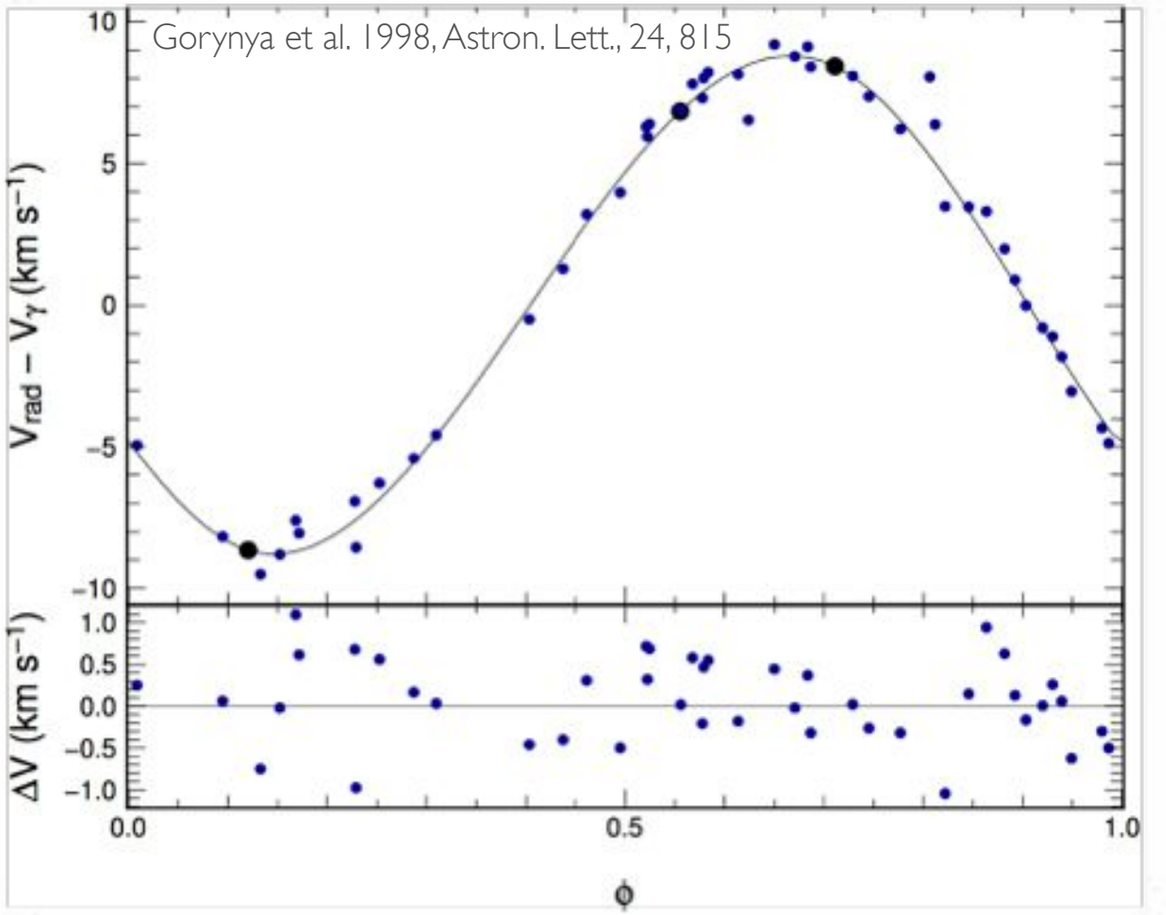

Distance: 472 ± 18 pc (4%)

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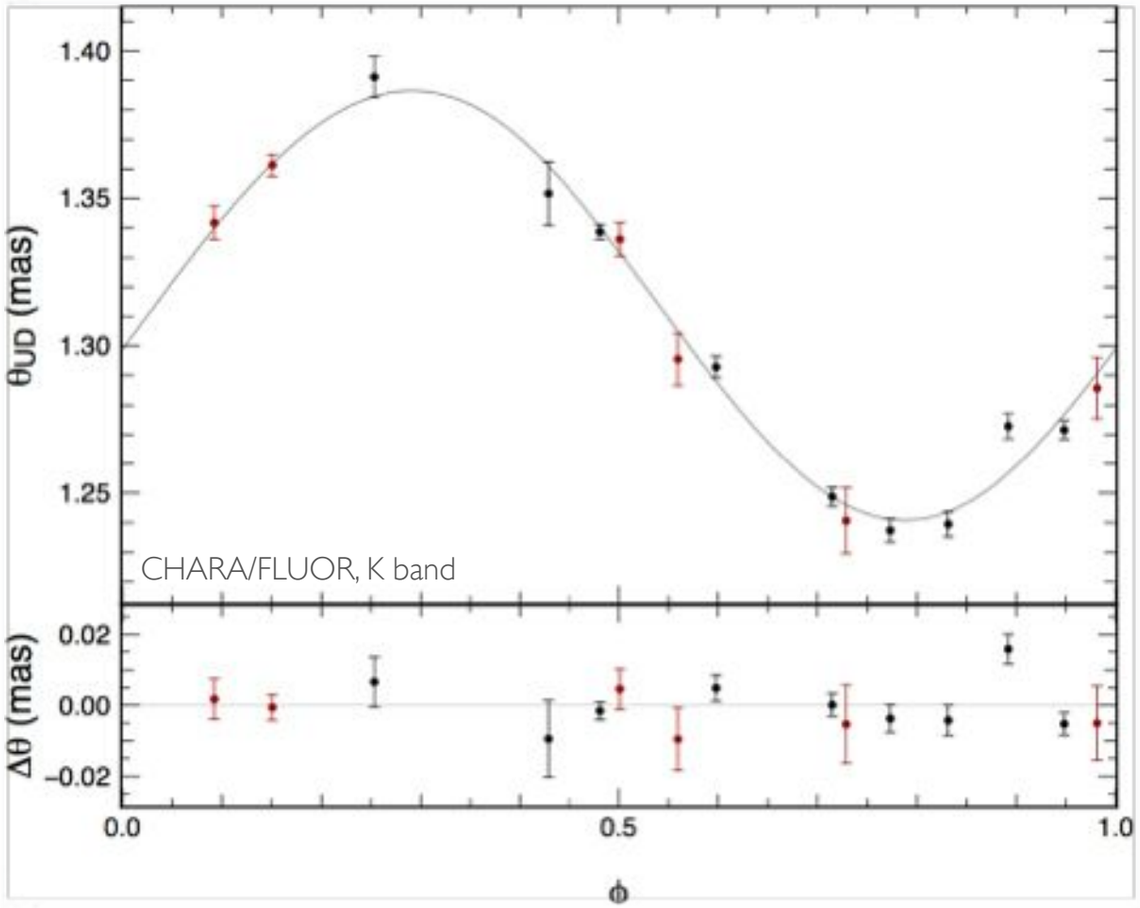
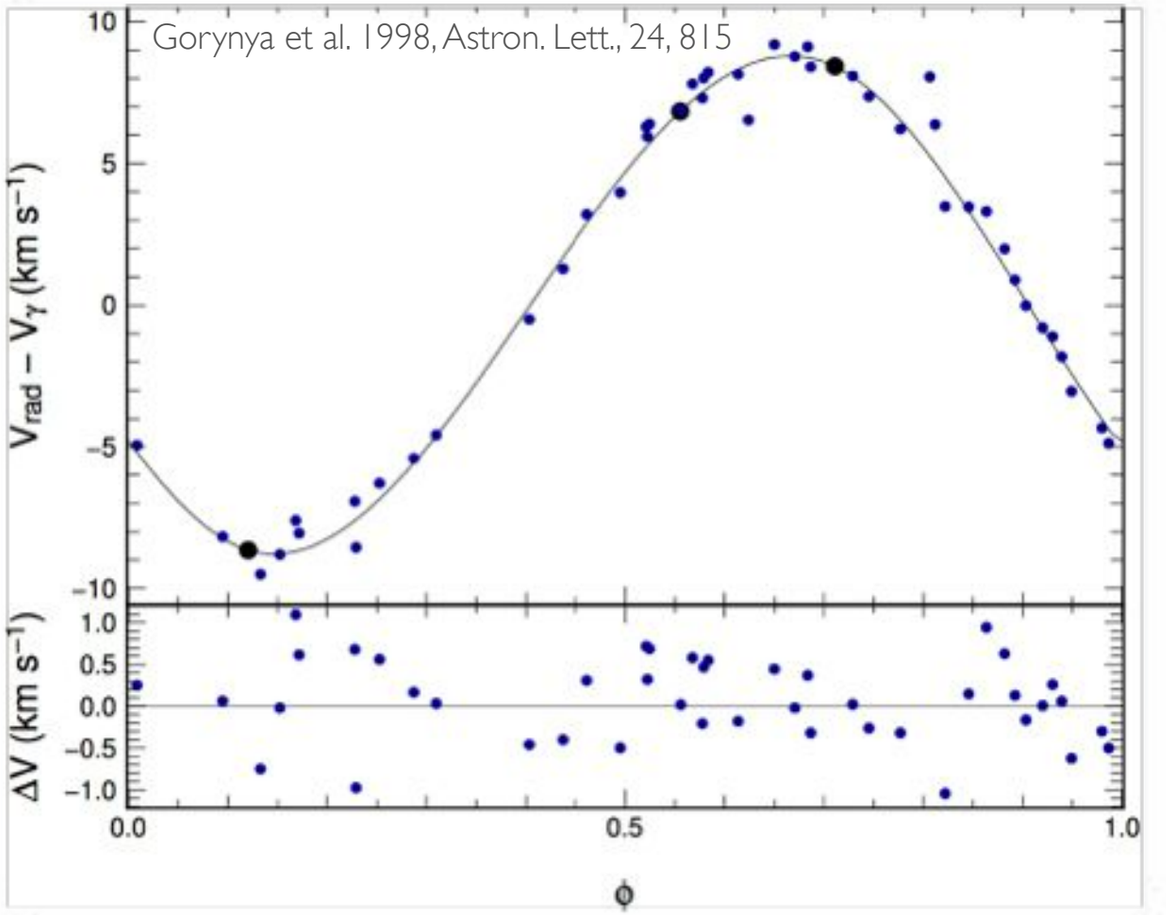
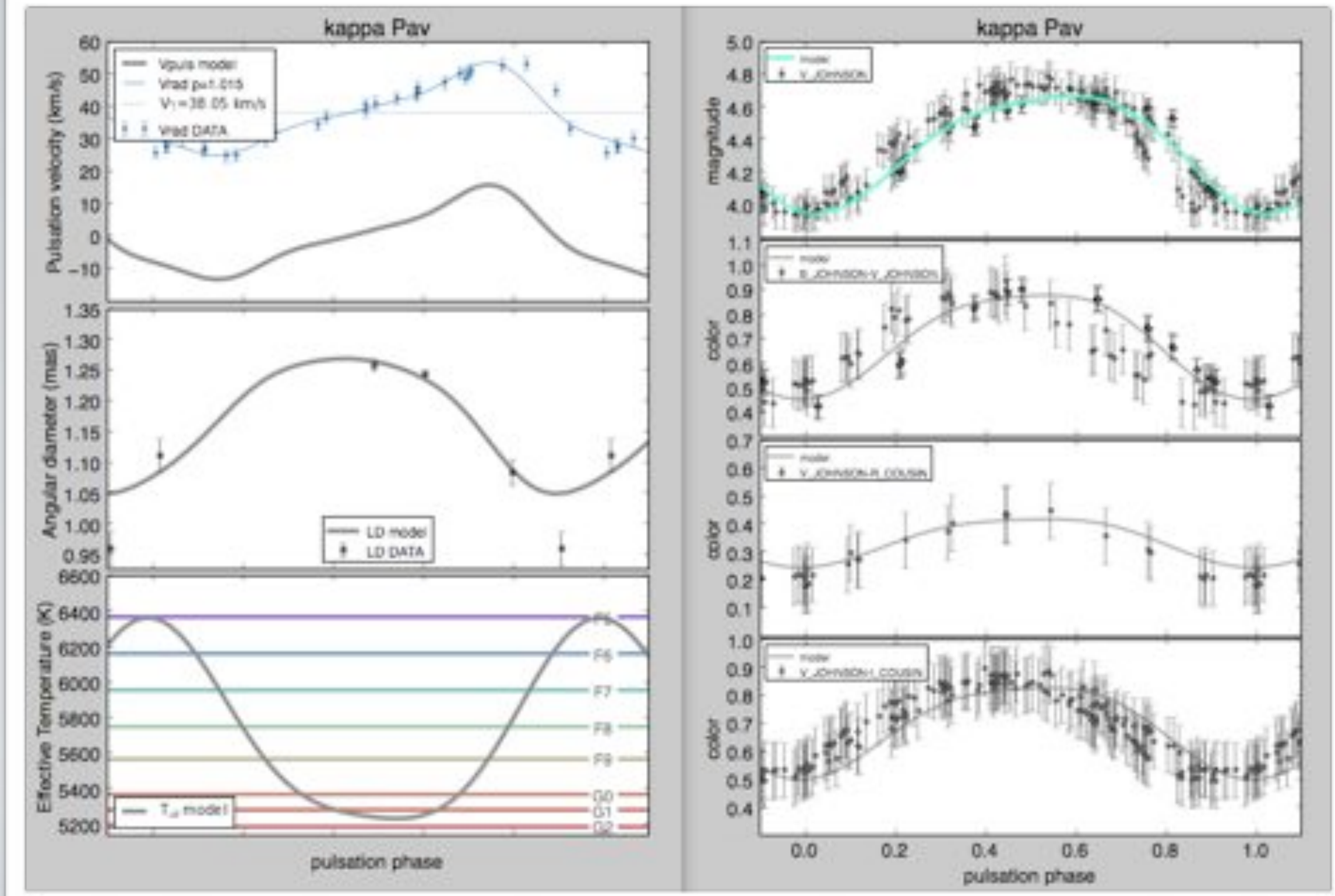




Distance: 472 ± 18 pc (4%) for $p = 1.27$ and $k = 0.983$

Mérand et al. 2007, ApJ 664, 1087
Gallenne et al. 2013, in prep.

KAPPA PAV (PIONIER, P91)



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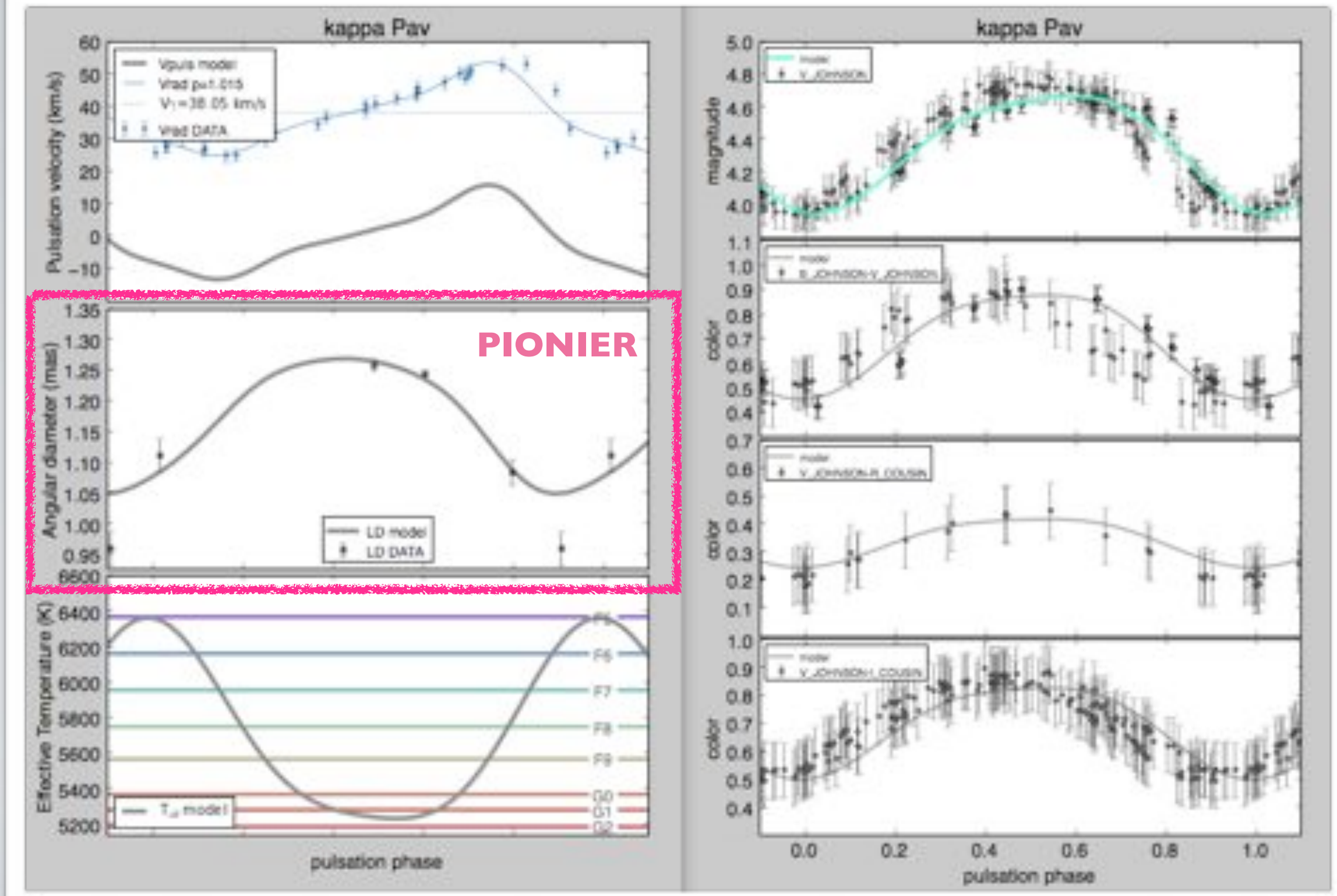

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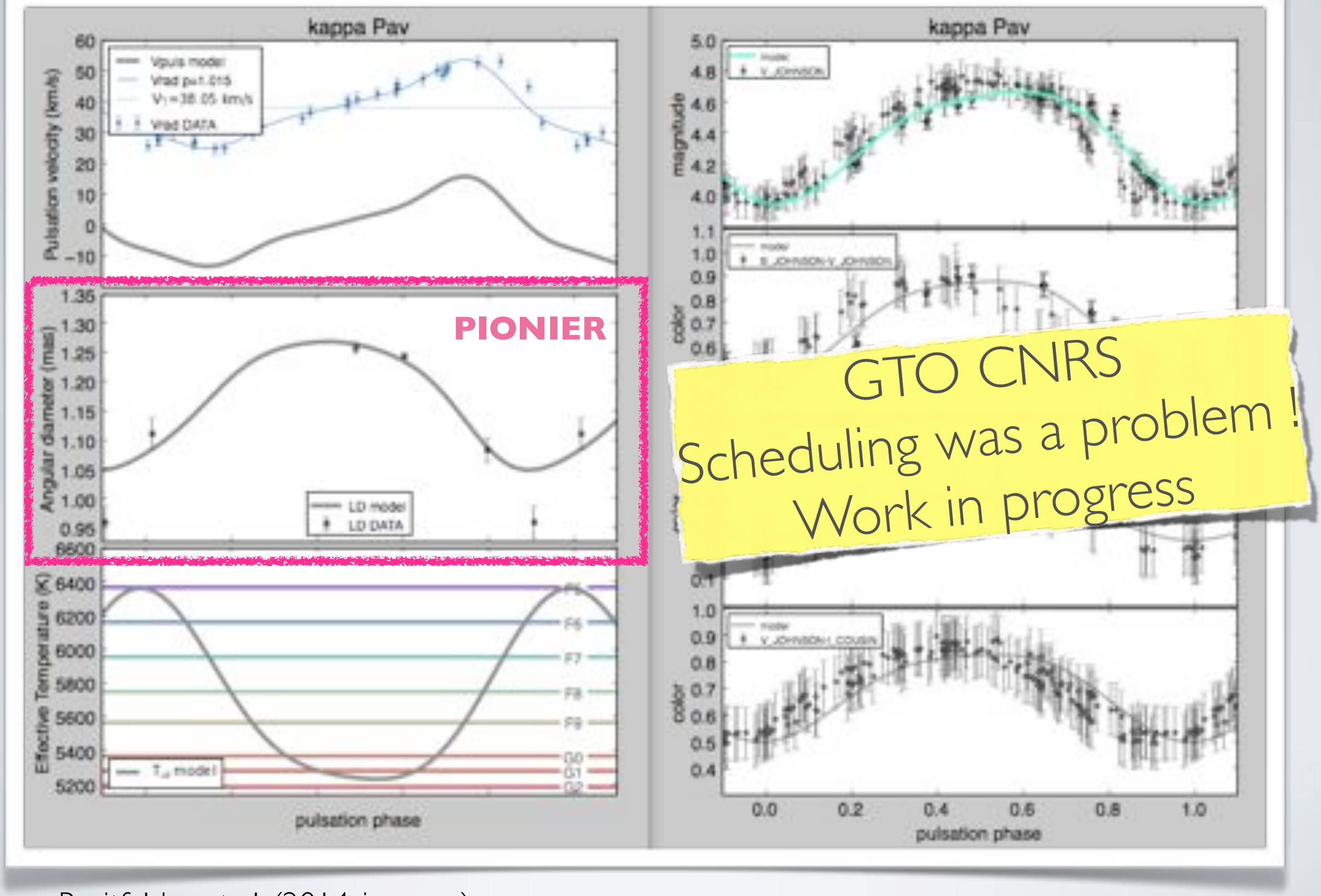

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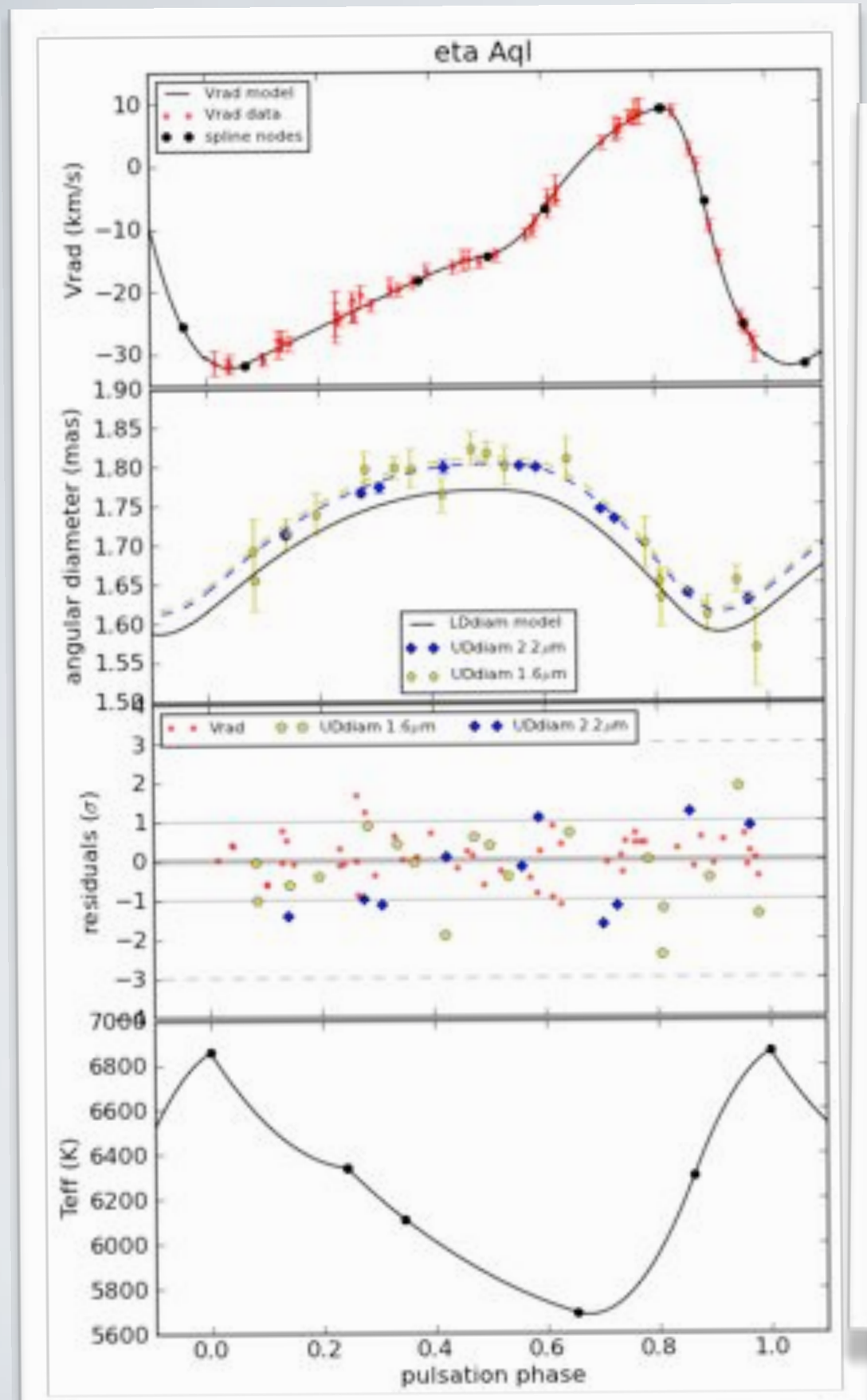
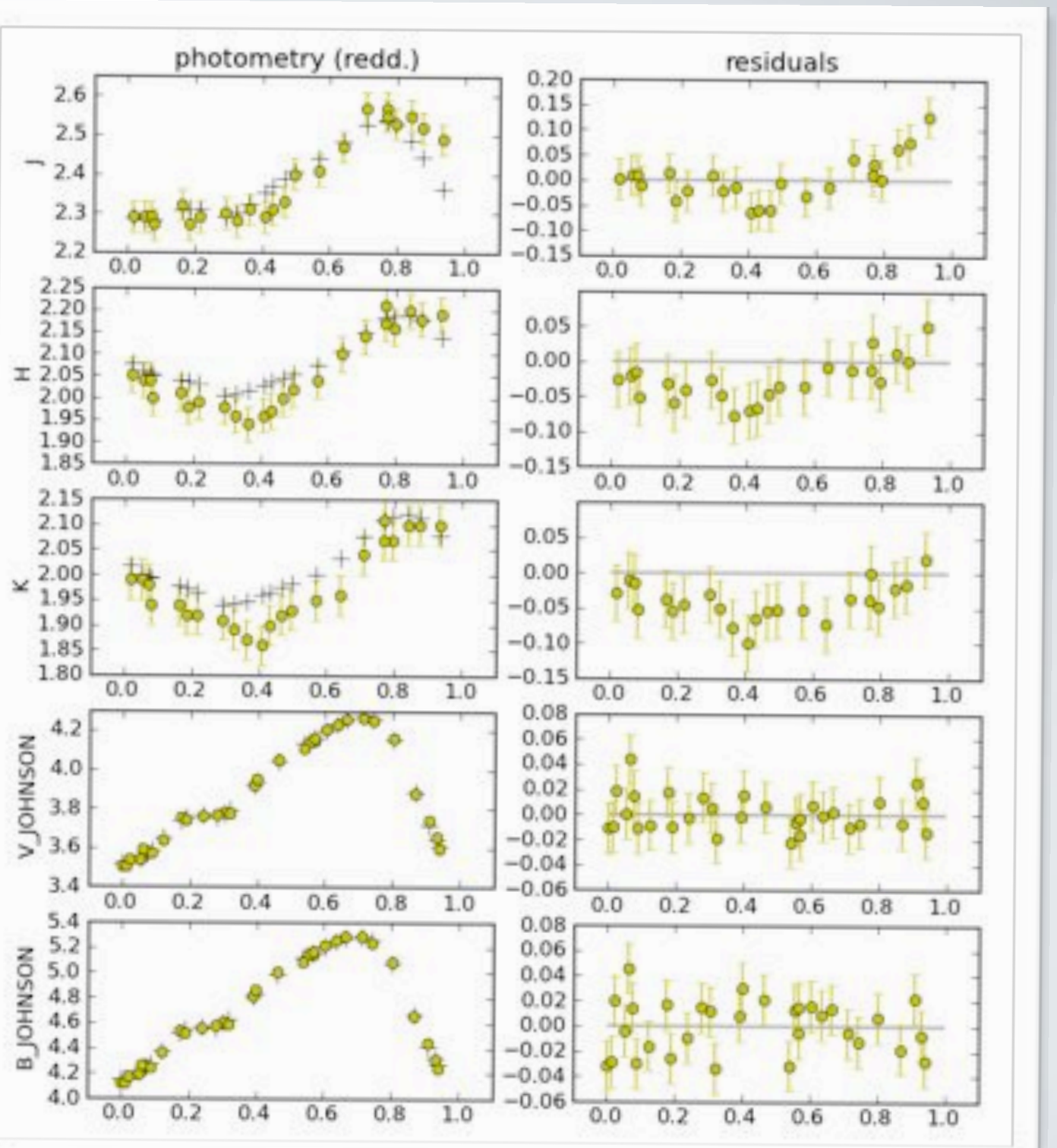
η AQL





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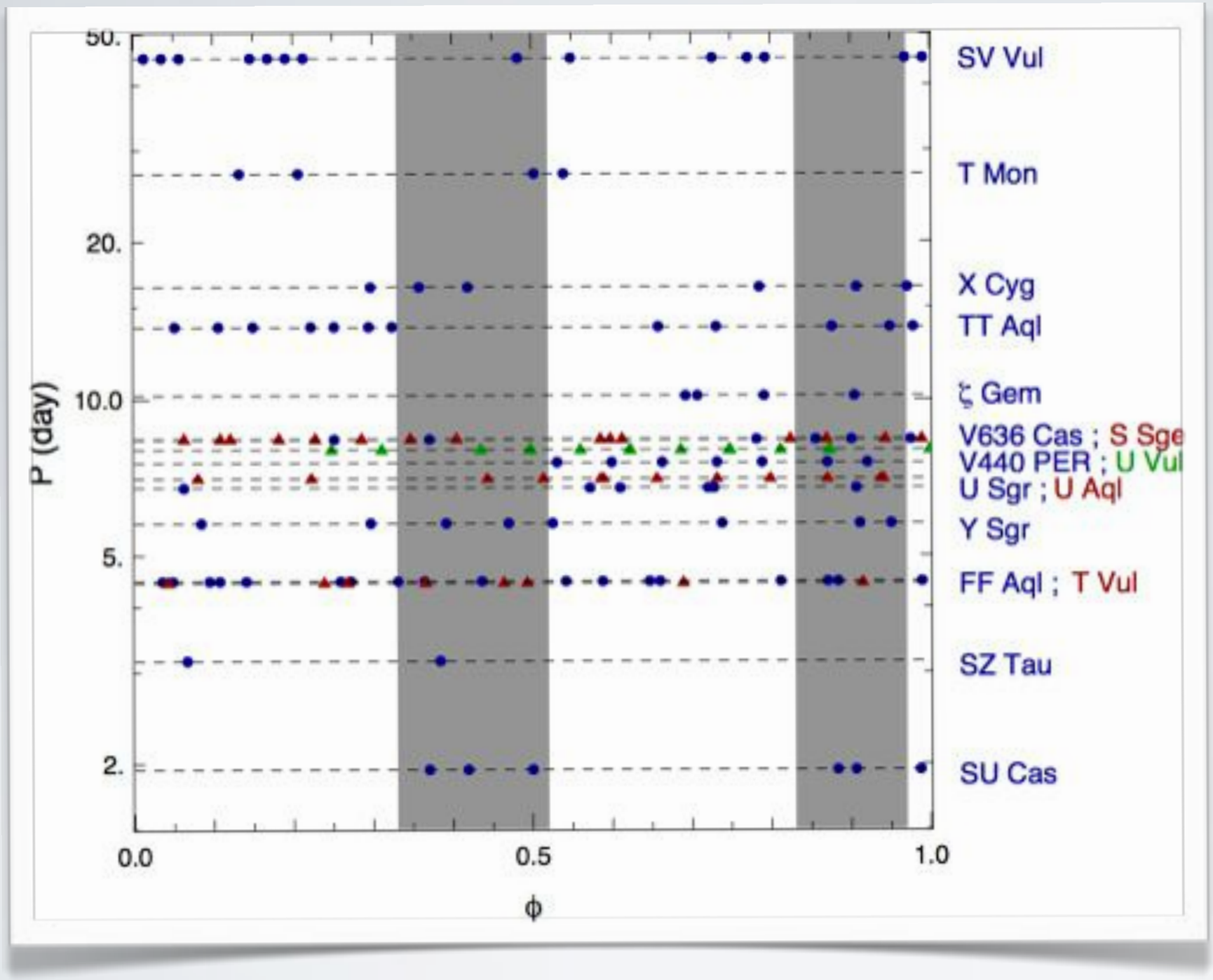
CEPHEIDS OBSERVED BY INTERFEROMETRY



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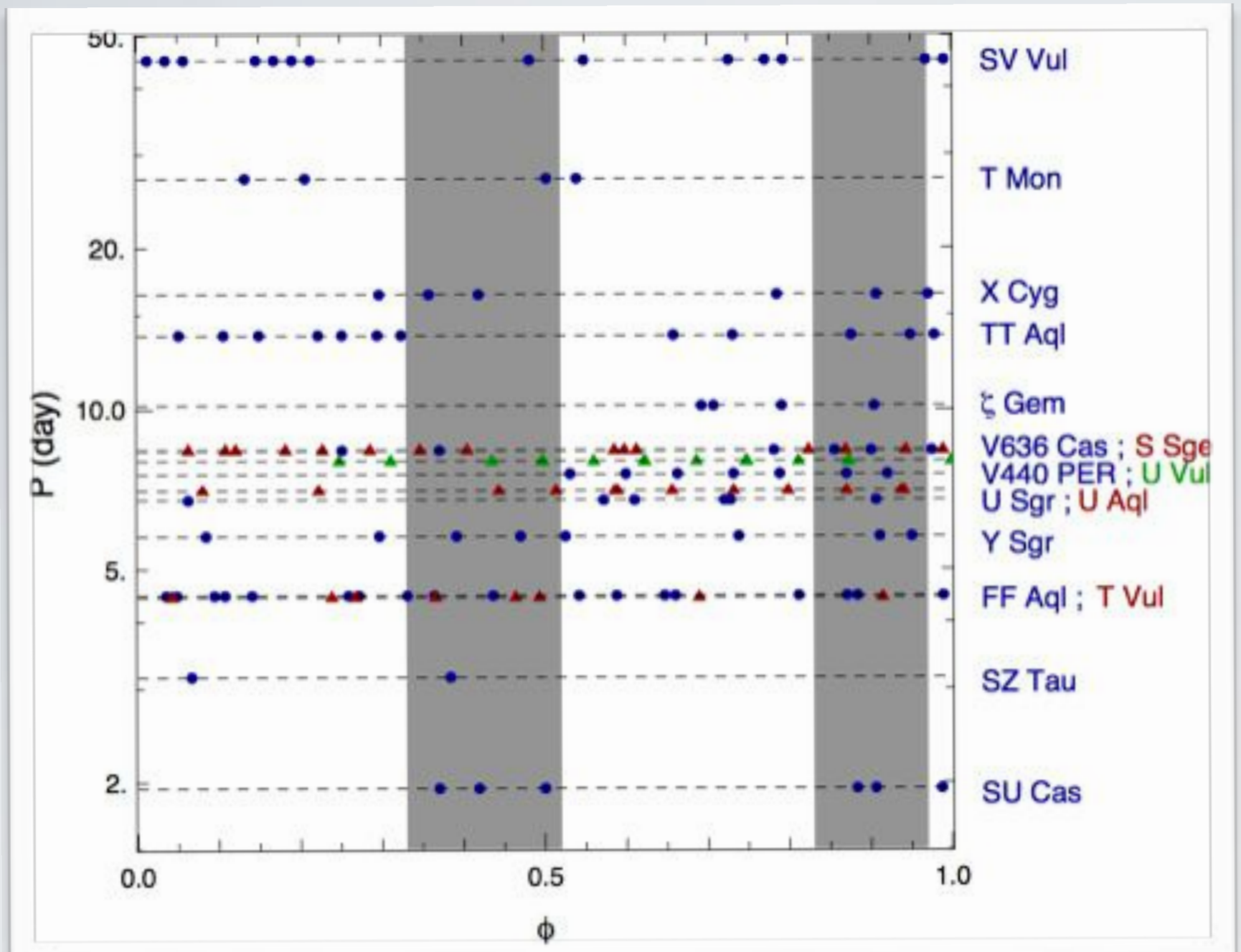

[Polaris] (3.97 d)
δ Cep (5.36 d)
X Sgr (7.01 d)
η Aql (7.17 d)
W Sgr (7.59 d)
β Dor (9.84 d)
L Car (35.6 d)
[RS Pup] (41.4 d)

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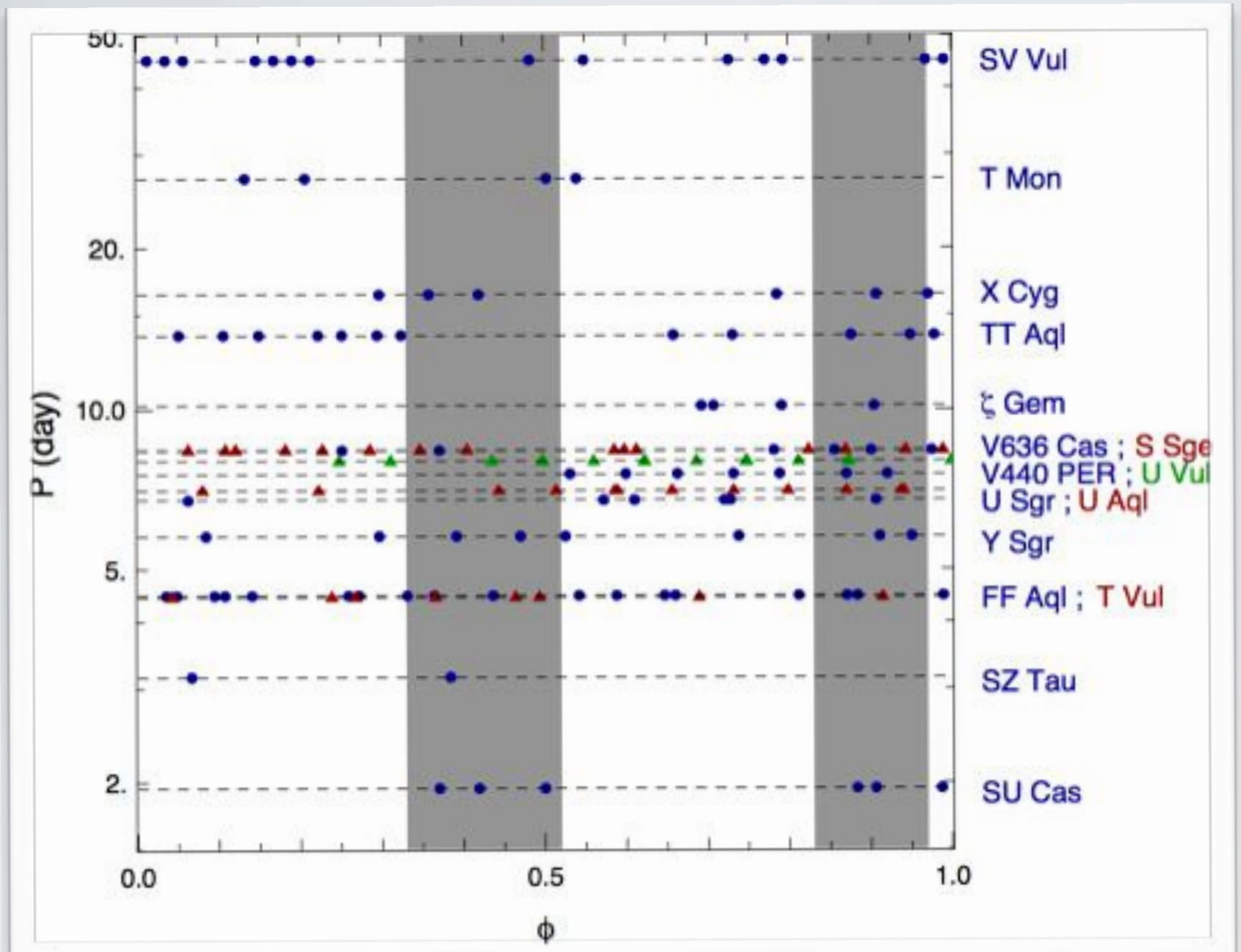

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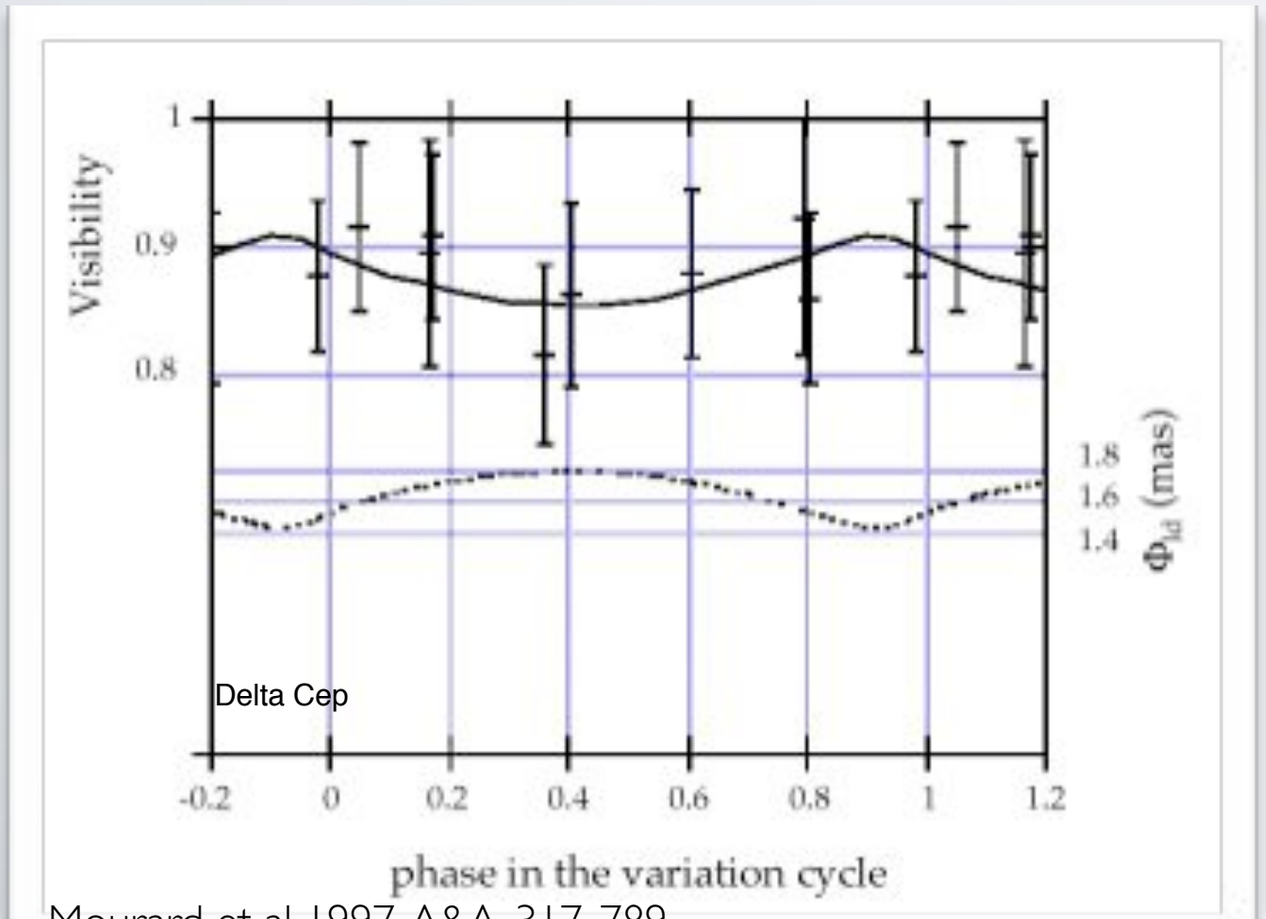
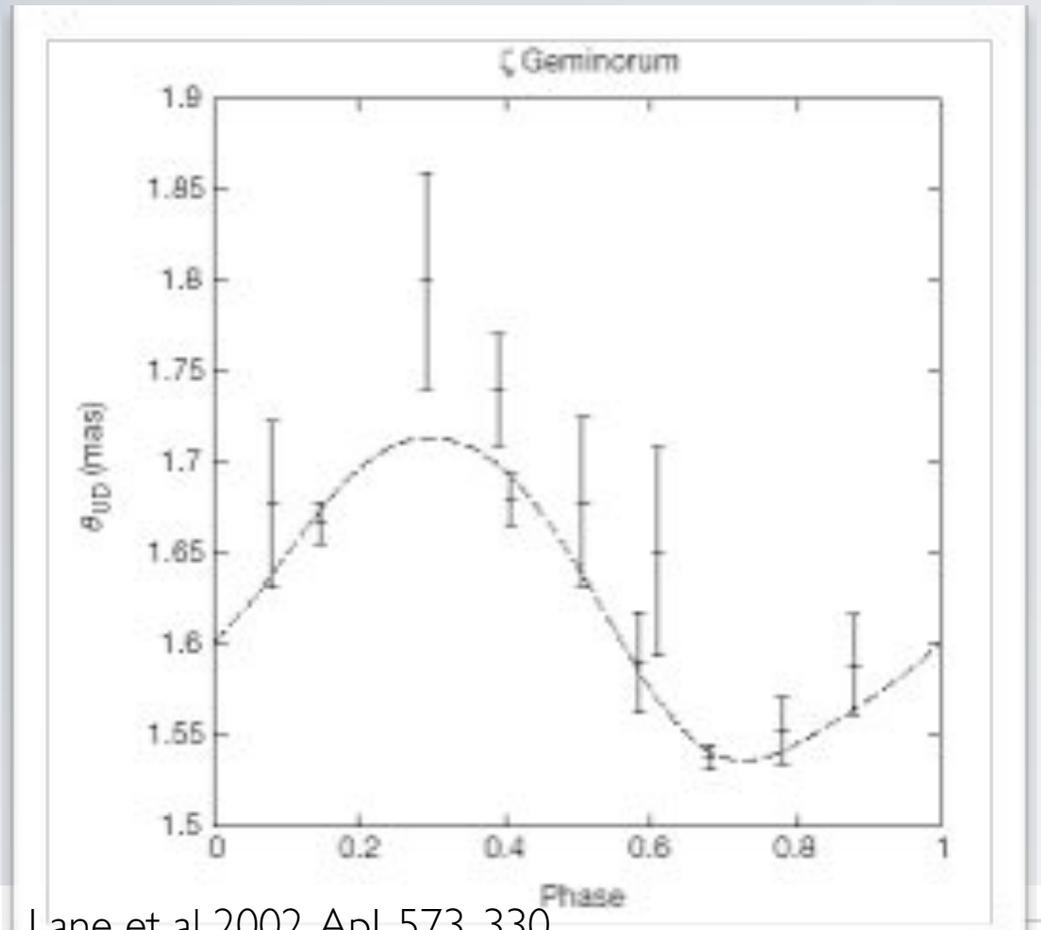
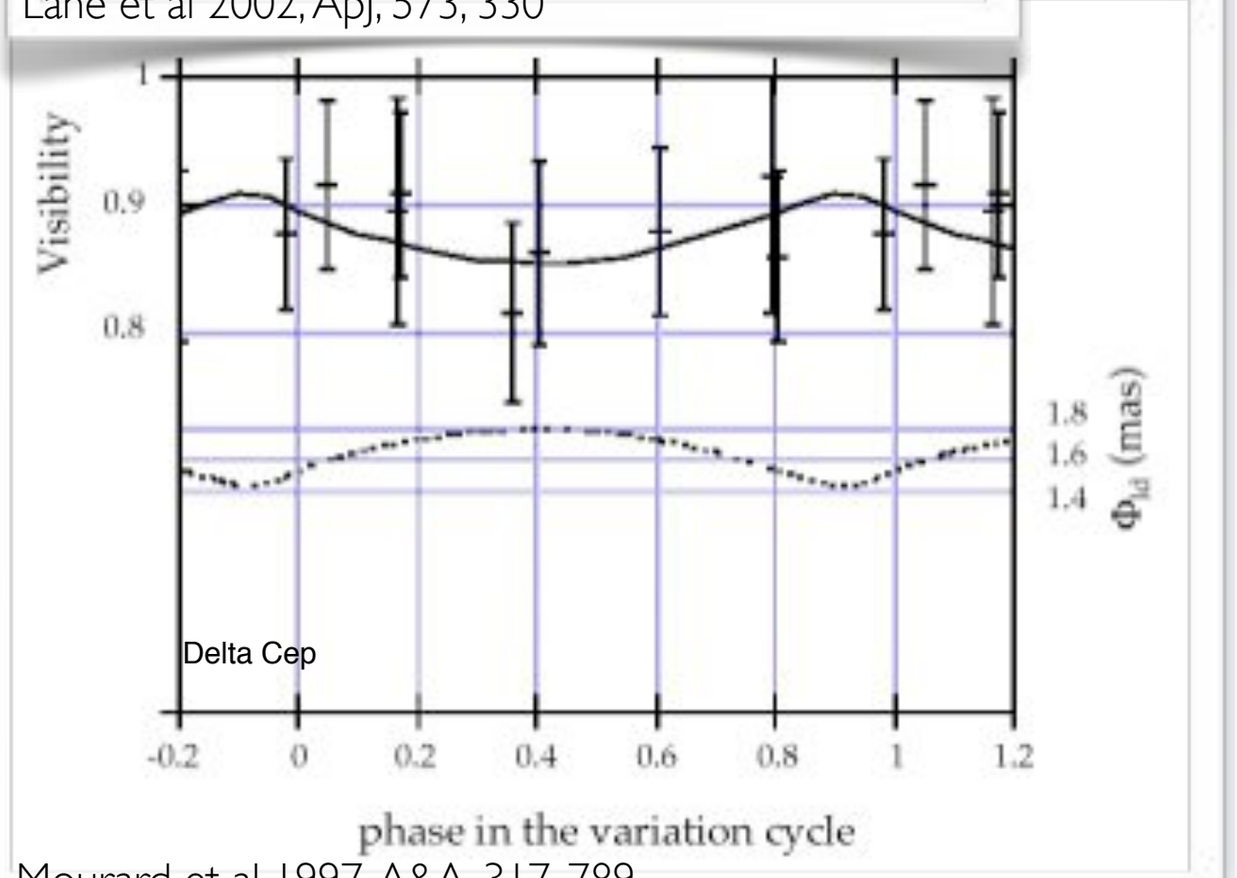
24 stars, with 22 stars suitable for IBW distance
P93 program with PIONIER (5 stars) + VEGA (5 stars)



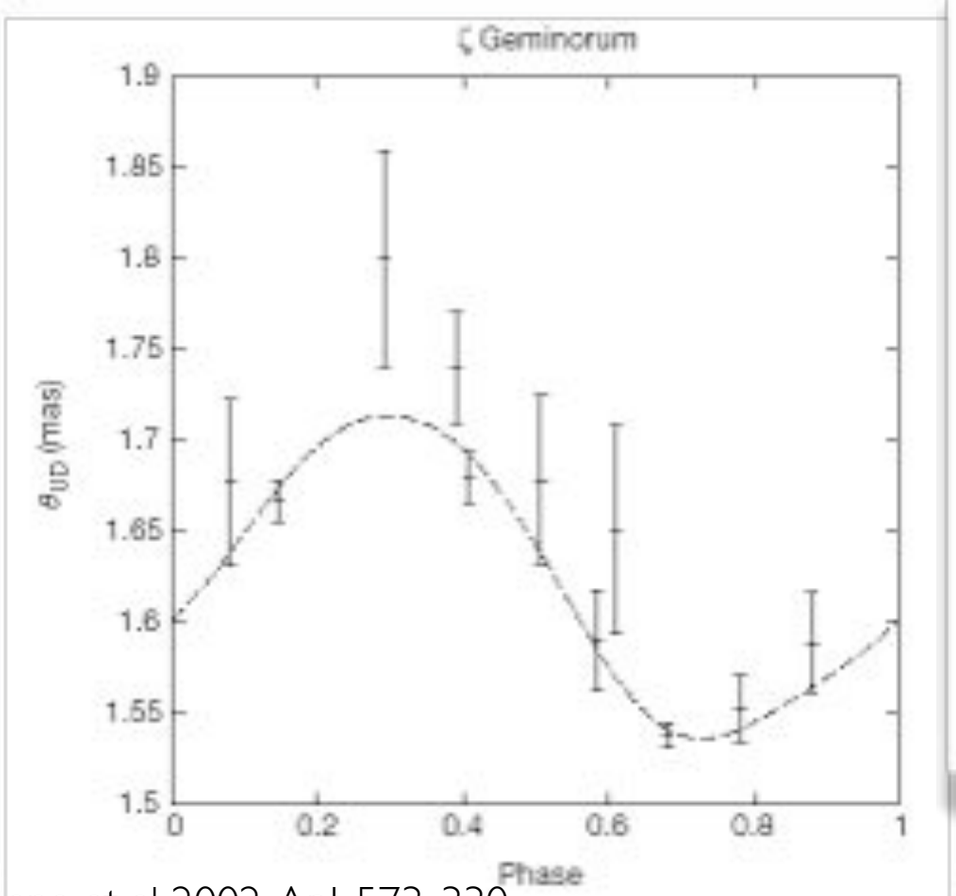
Mourard et al 1997, A&A, 317, 789



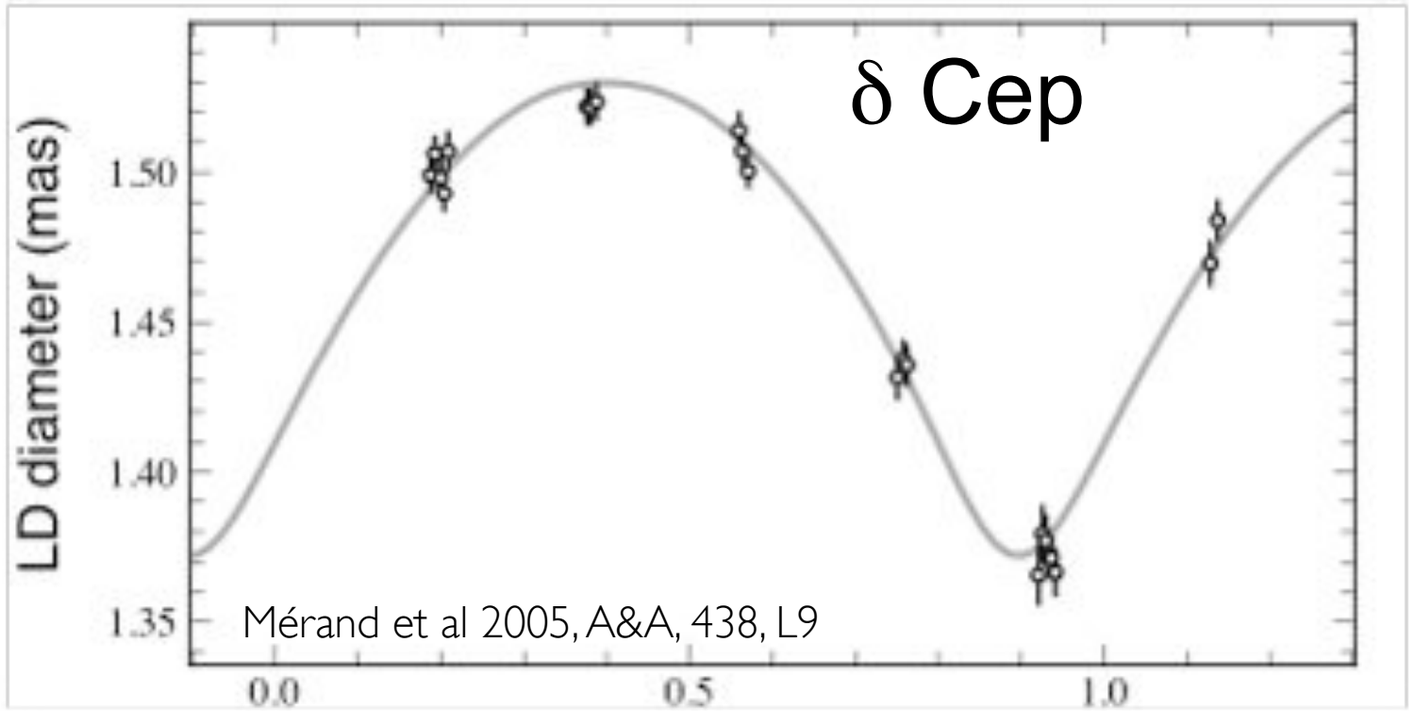
Lane et al 2002, ApJ, 573, 330

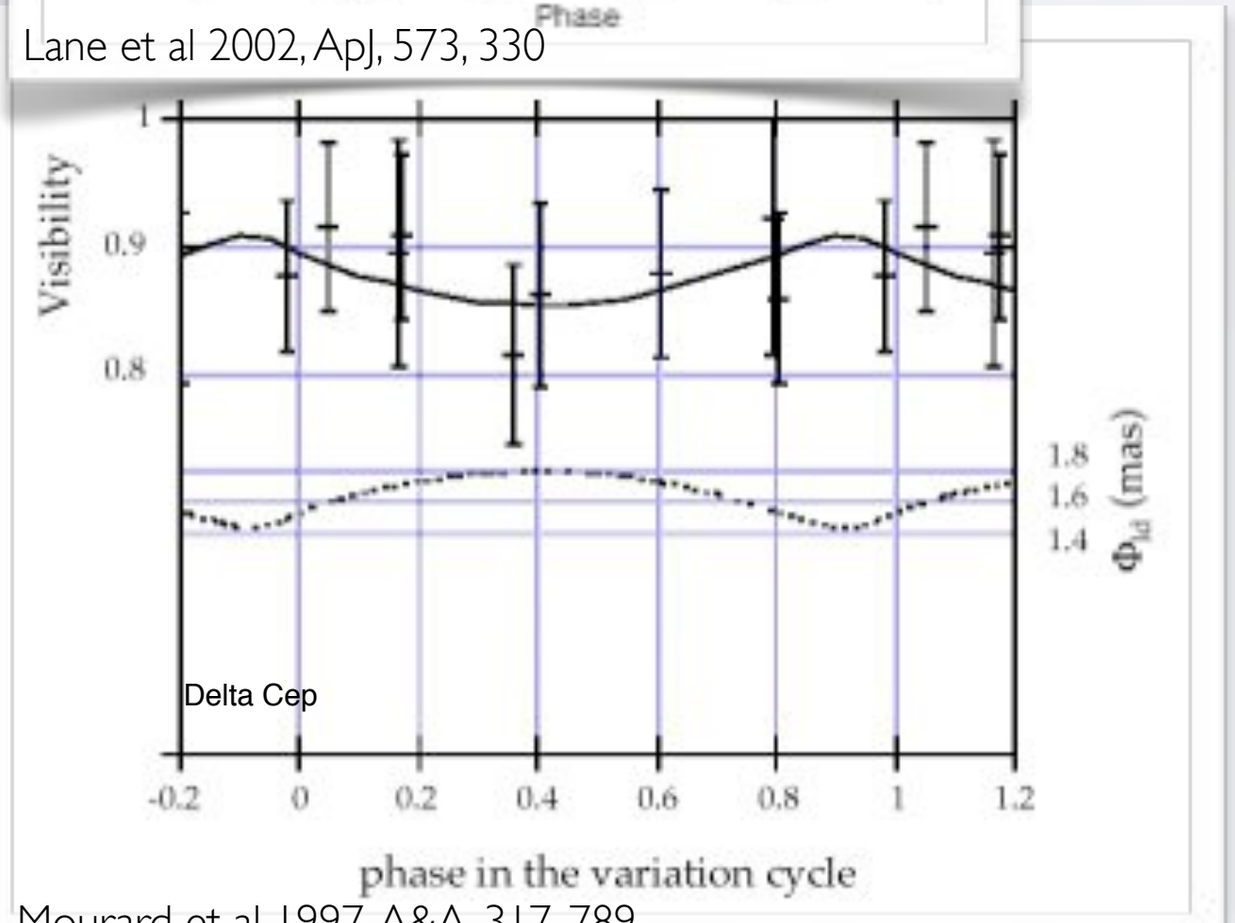


Mourard et al 1997, A&A, 317, 789

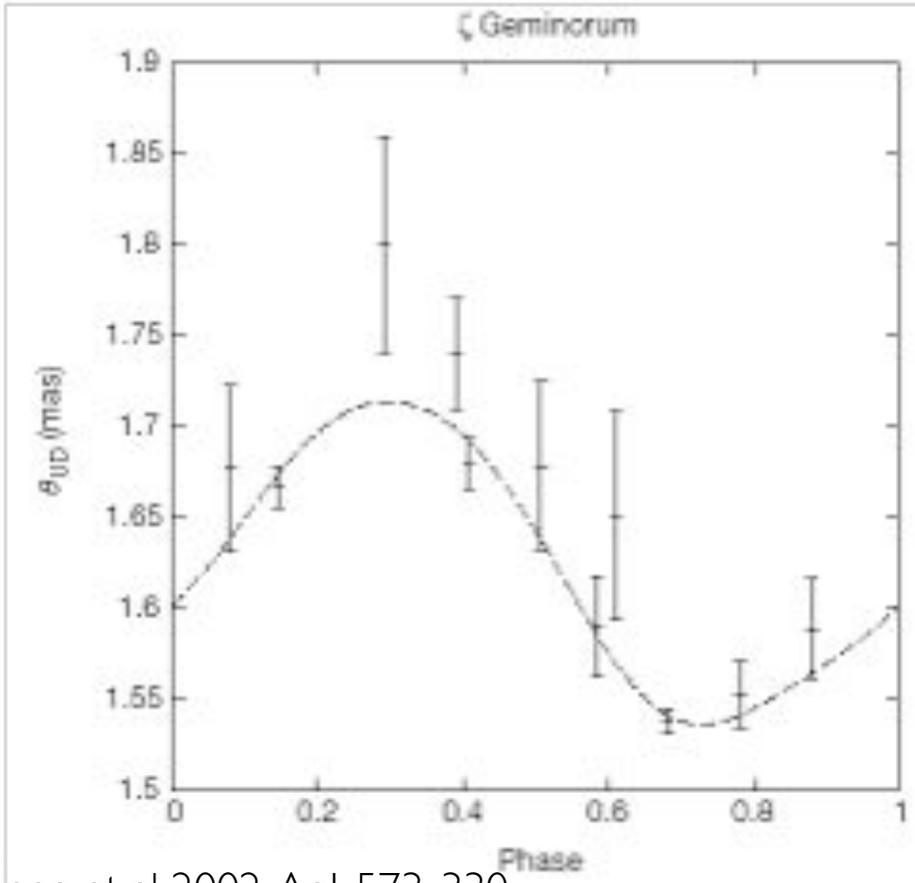


Lane et al 2002, ApJ, 573, 330

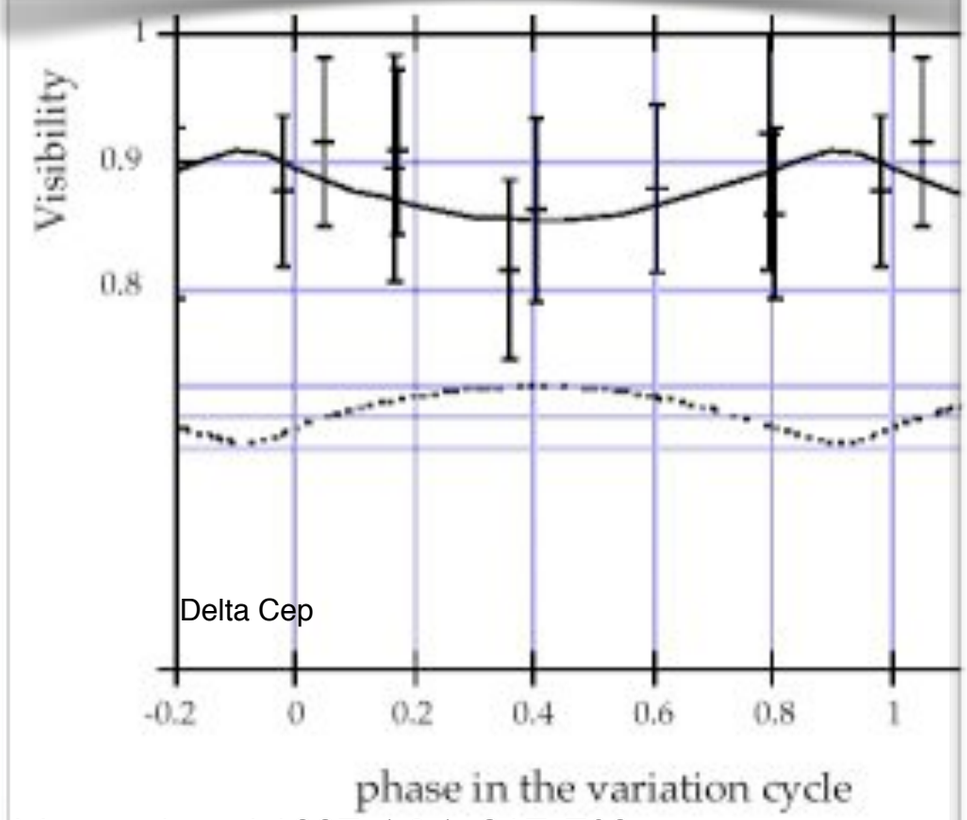




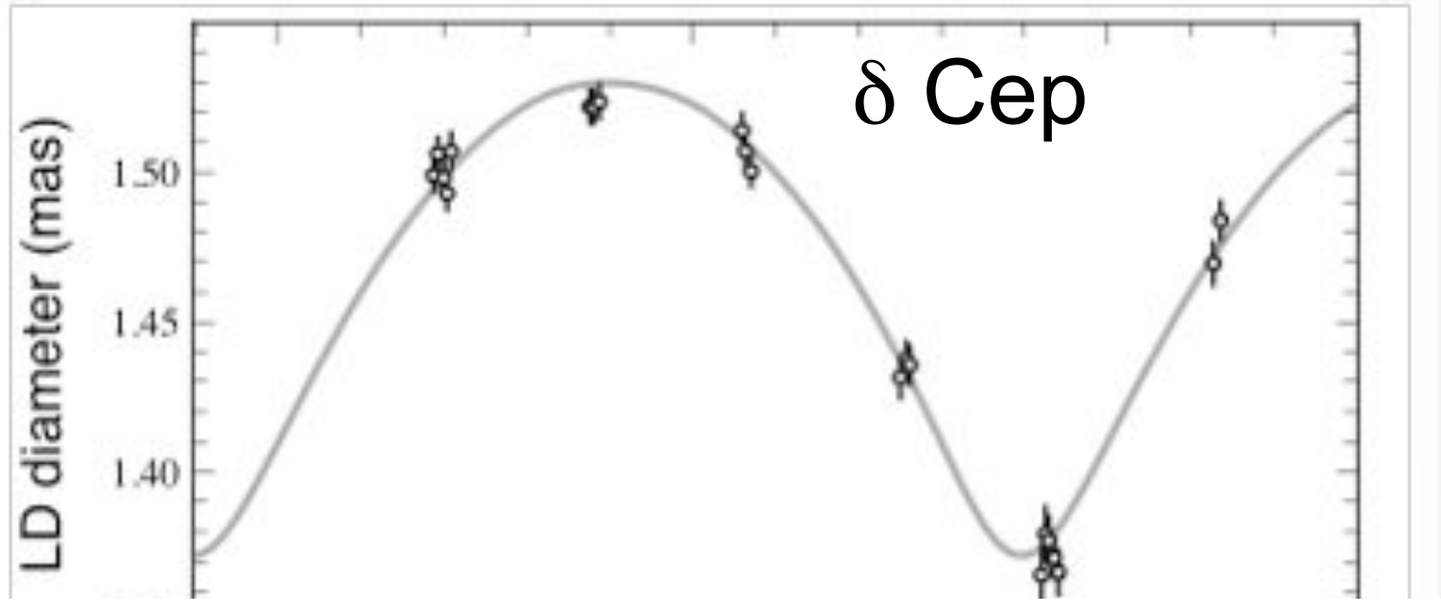
Mourard et al 1997, A&A, 317, 789

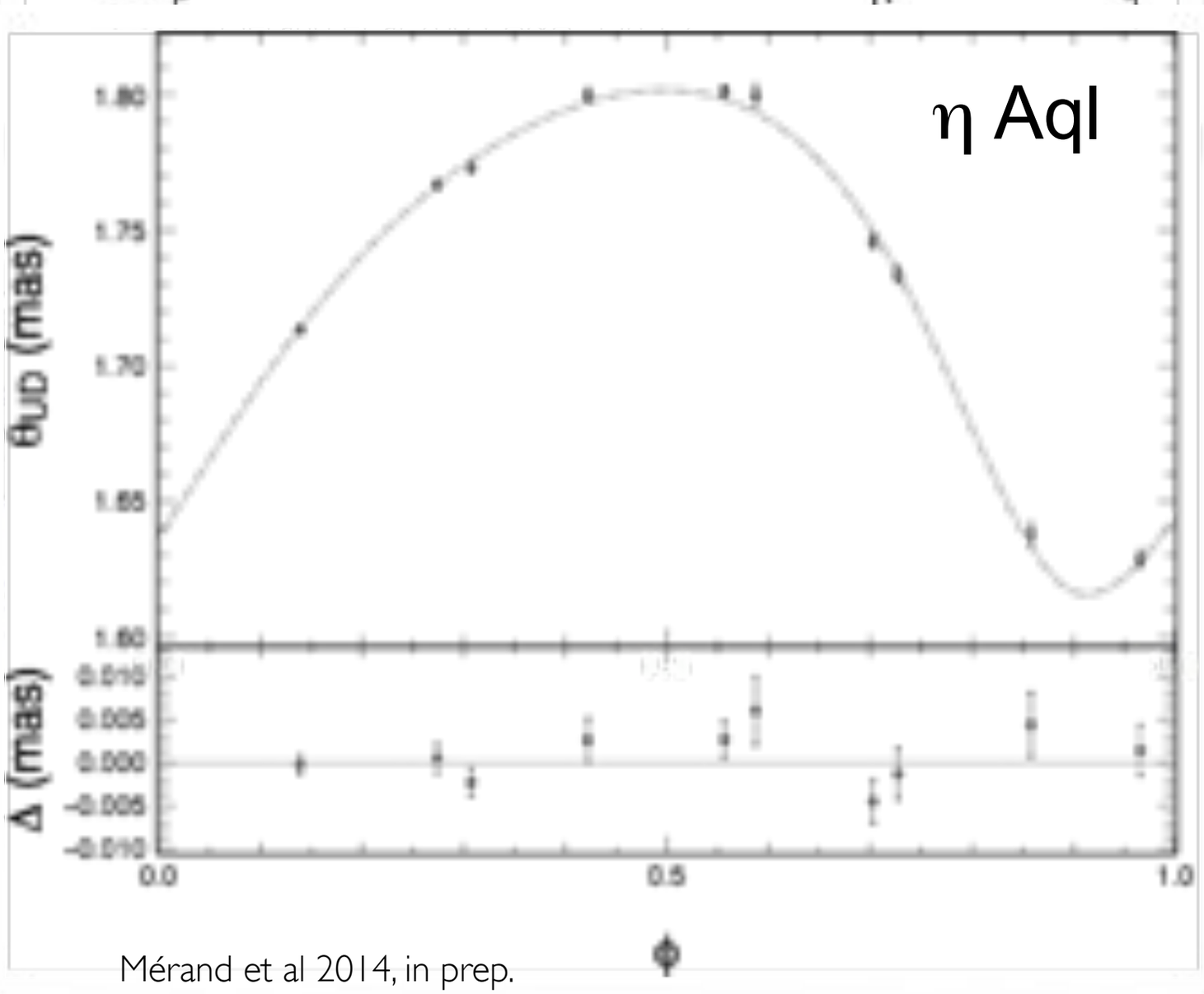


Lane et al 2002, ApJ, 573, 330



Mourard et al 1997, A&A, 317, 789





Mérand et al 2014, in prep.

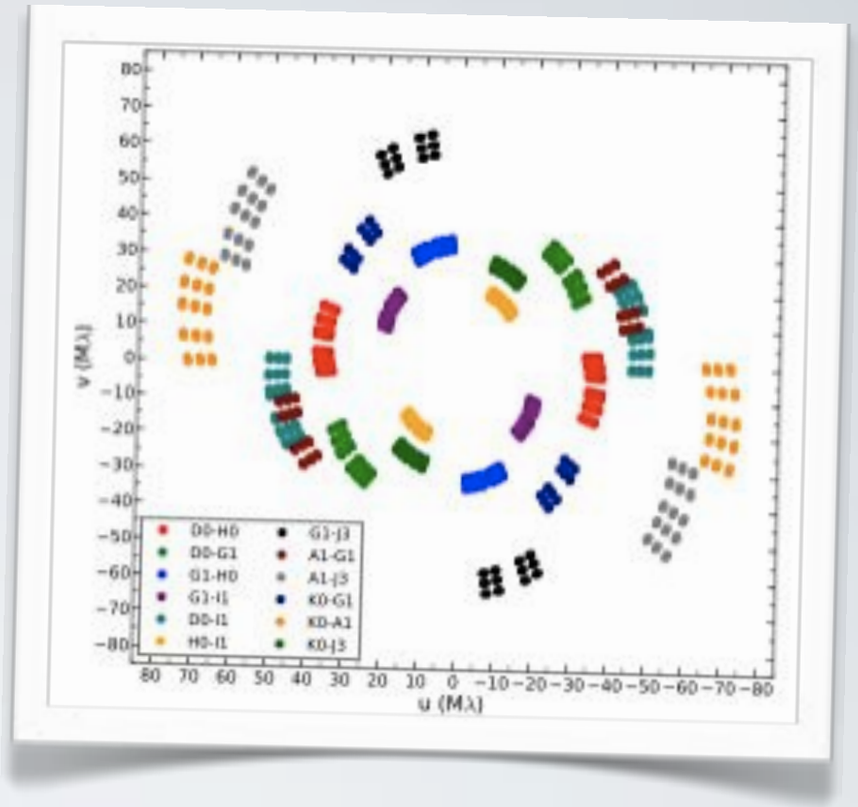
CEPHEIDS IN BINARIES

- Binary systems are very useful to derive masses and distances
- Cepheids are extremely bright (10^3 - 10^5 Lsun), companions are difficult to detect
- Only a handful discovered using UV spectroscopy (essentially by Nancy Evans et al.)
- 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

AX CIR (VLTI/PIONIER)

Primary:

- Classical Cepheid
- Puls. P=5.27 days
- d ~ 500 pc
- H = 3.85



Gallenne et al. A&A 561, L3 (2014)

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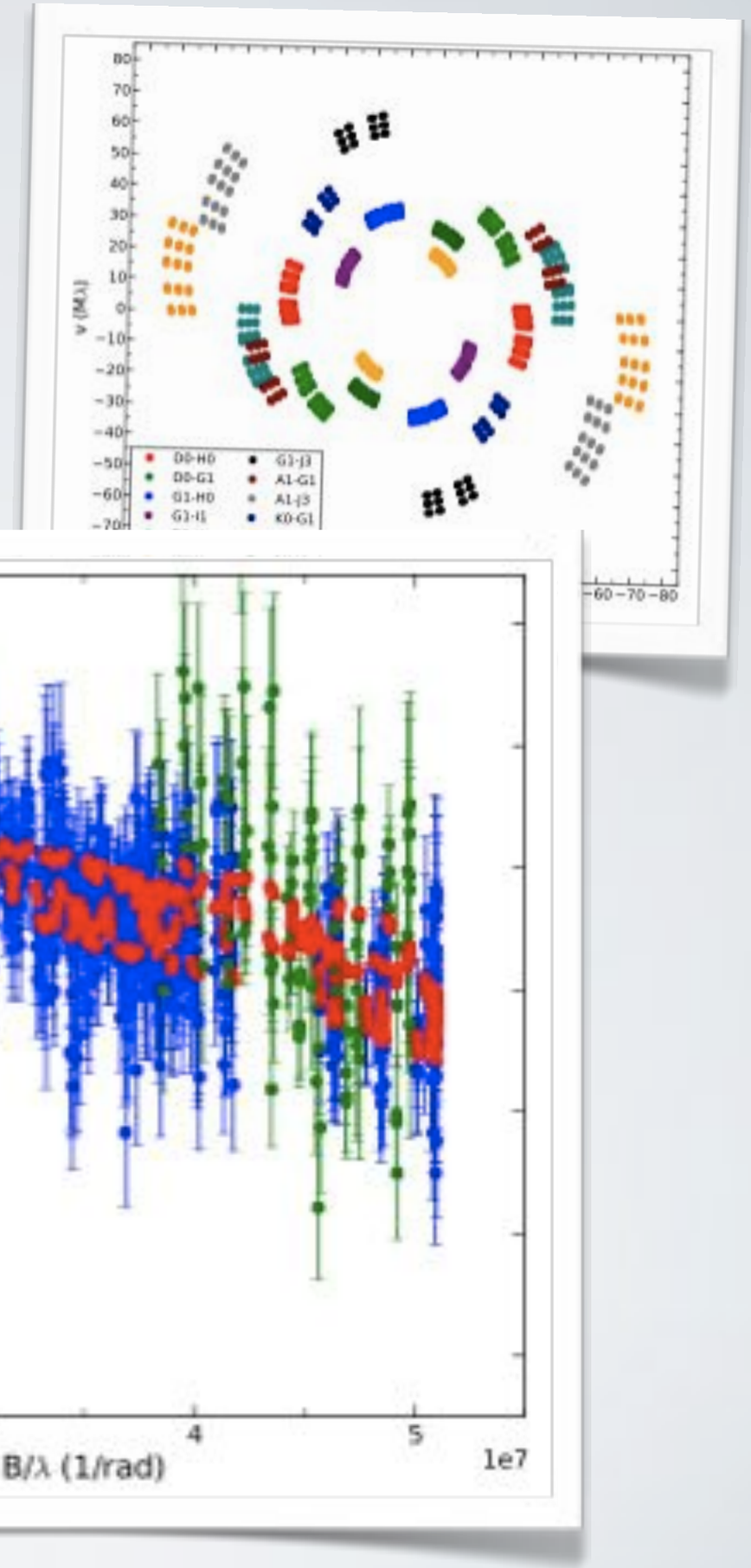
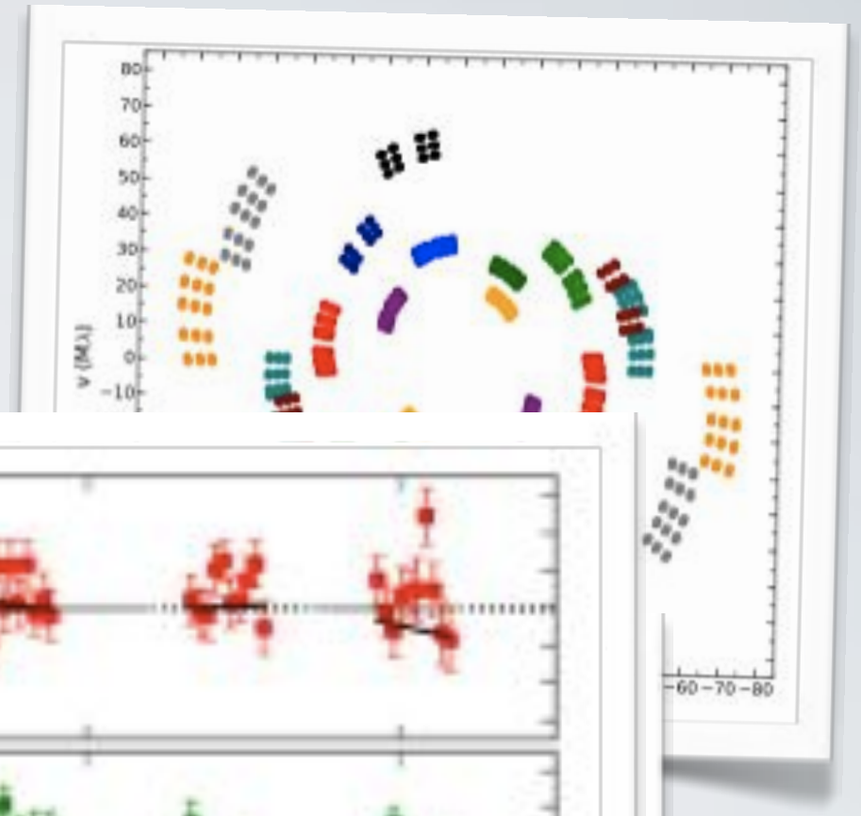


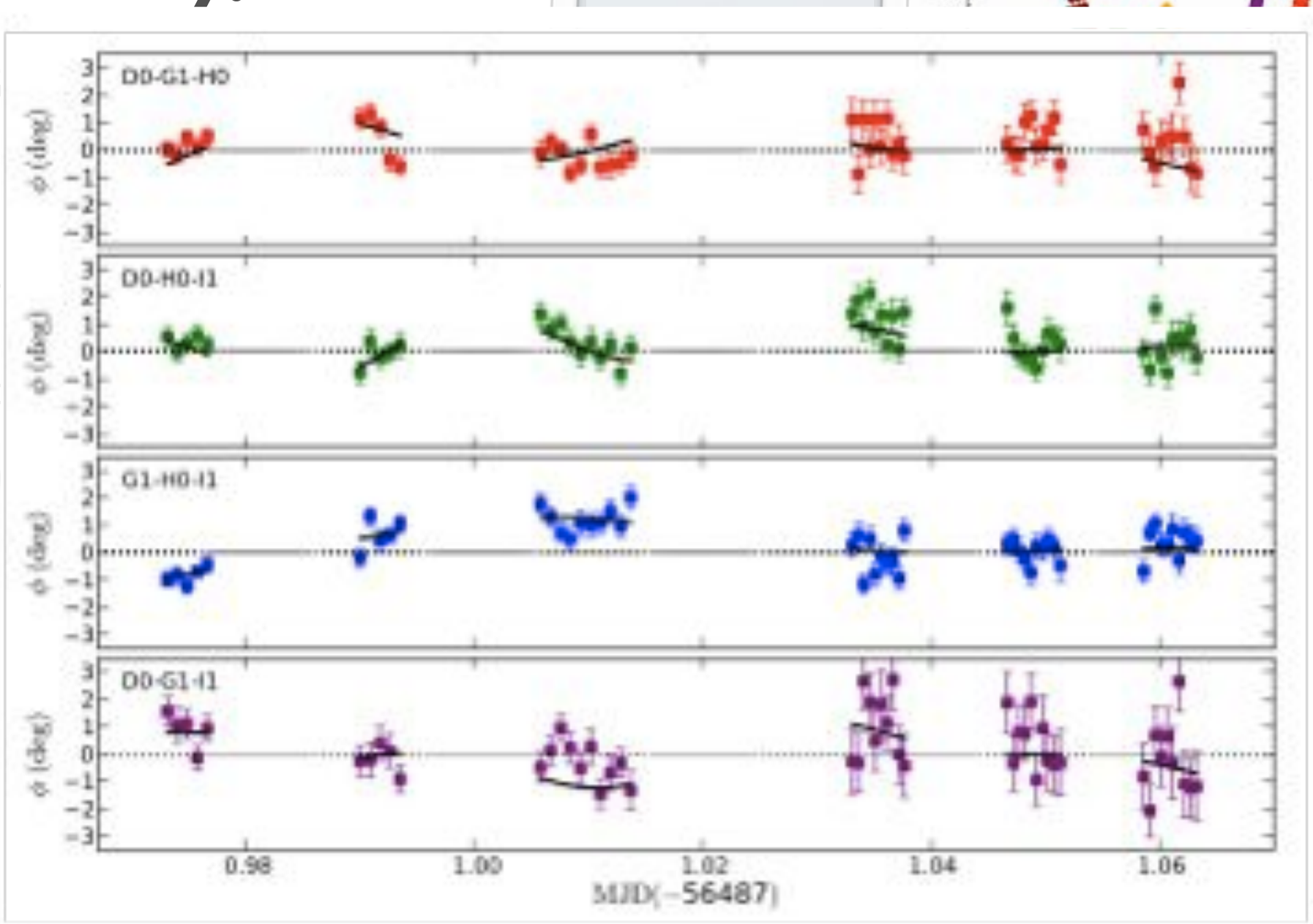
Gallenne et al. A&A 561, L3 (2014)

AX CIR (VLTI/PIONIER)

Primary:

- C
- Pu
- d
- H





Gallenne et al. A&A 561, L3 (2014)

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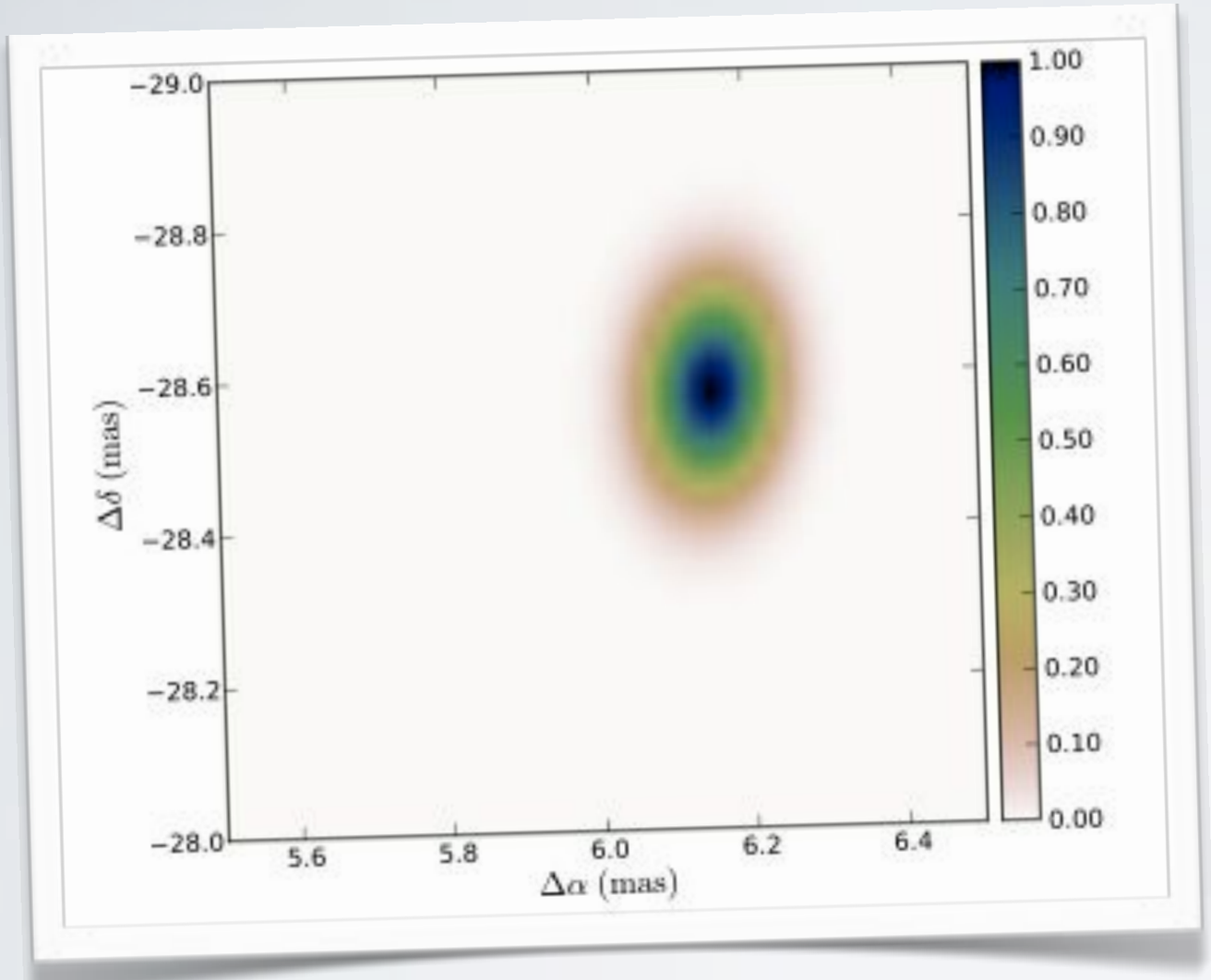
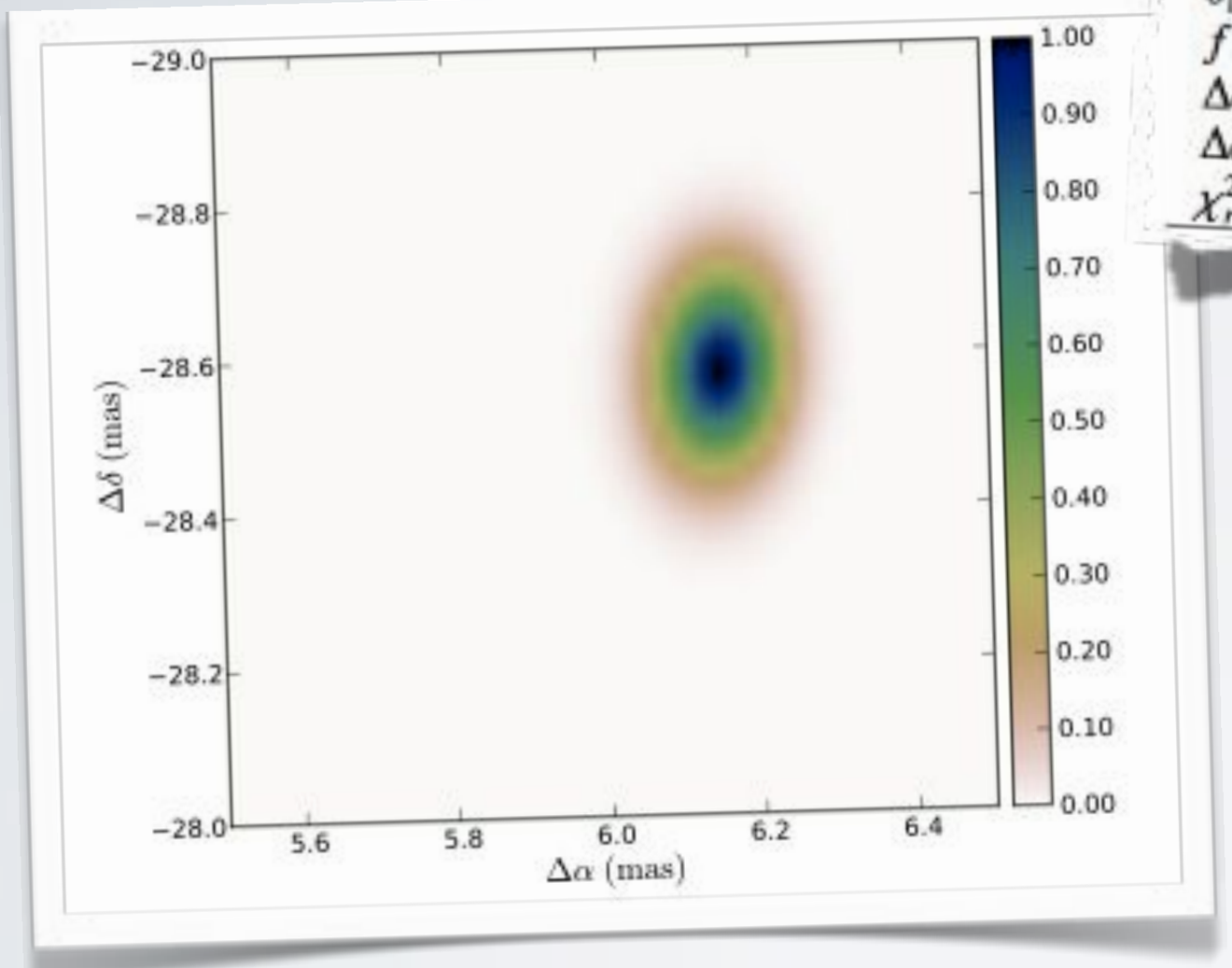


Gallenne et al. A&A 561, L3 (2014)

AX CIR (VLTI/PIONIER)



	2013-07-11	2012-07-14
Single star model		
θ_{UD} (mas)	0.770 ± 0.016	0.931 ± 0.019
θ_{LD} (mas)	0.787 ± 0.016	0.952 ± 0.020
χ^2_r	1.45	1.09
Binary model		
θ_{UD} (mas)	0.726 ± 0.020	0.821 ± 0.022
θ_{LD} (mas)	0.742 ± 0.020	0.839 ± 0.023
f (%)	0.75 ± 0.17	0.90 ± 0.10
$\Delta\alpha$ (mas)	6.421 ± 0.198	6.153 ± 0.155
$\Delta\delta$ (mas)	-28.366 ± 0.366	-28.584 ± 0.229
χ^2_r	1.17	0.72

Gallenne et al. A&A 561, L3 (2014)

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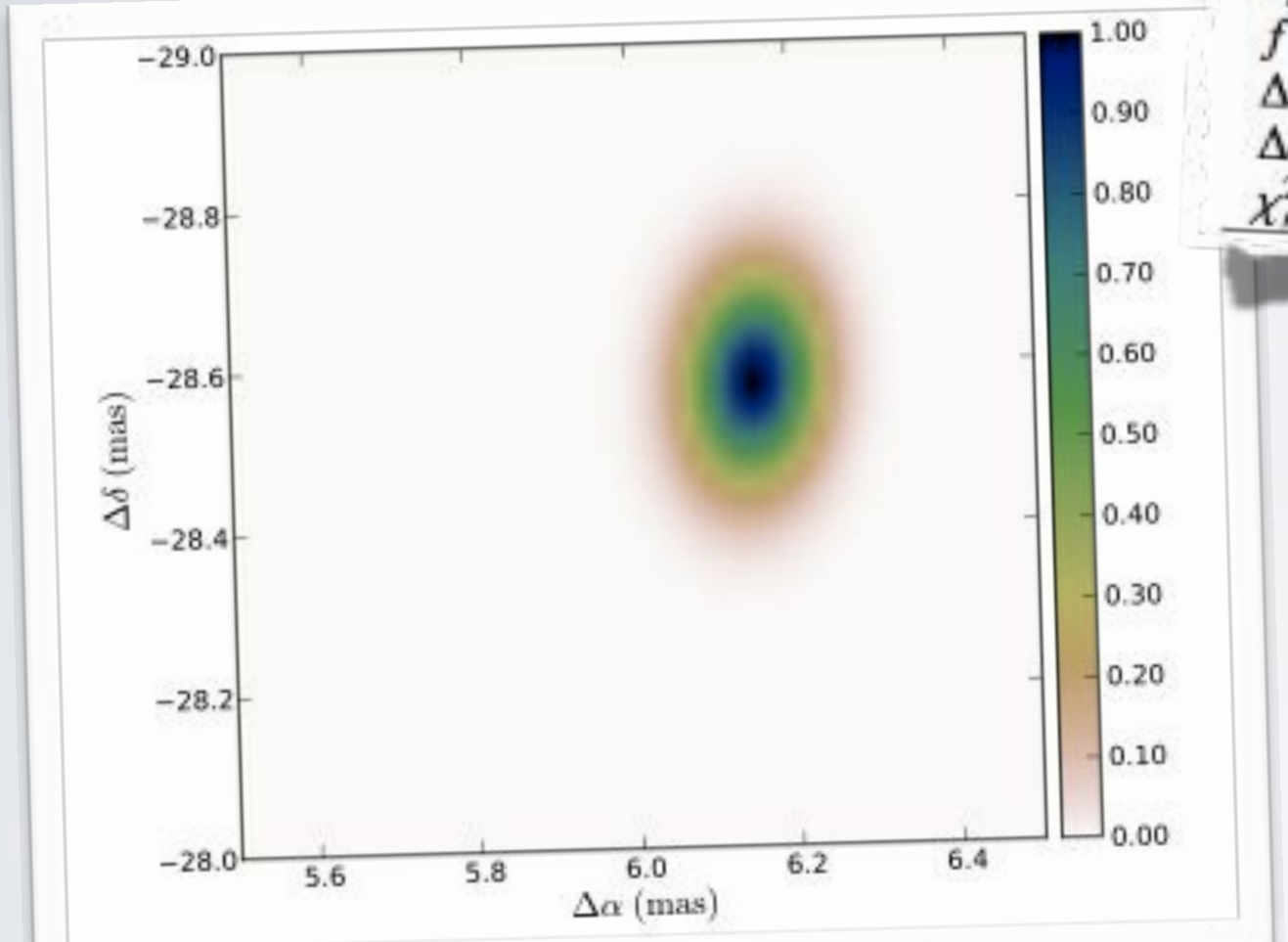
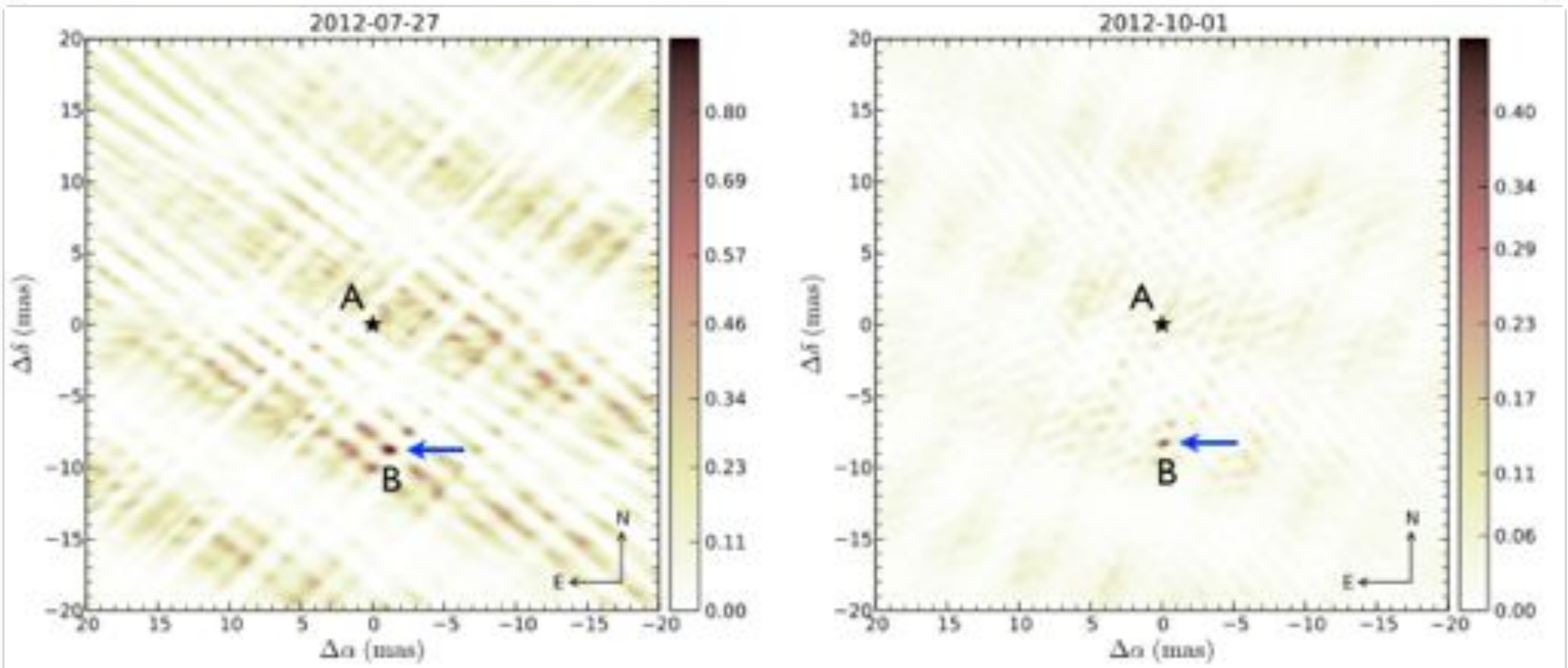


Gallenne et al. A&A 561, L3 (2014)

Secondary:

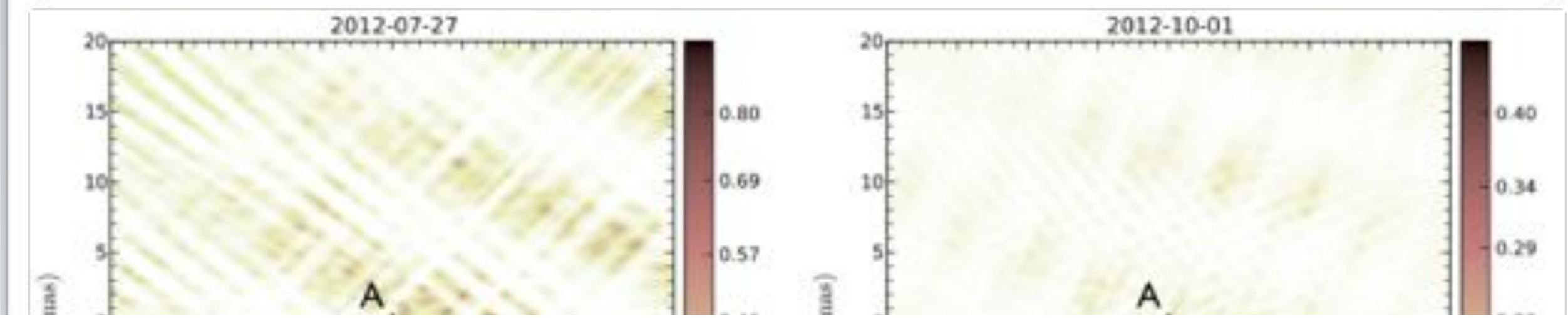
- B6V dwarf
- Orbit 17.9 years
- sep. ~ 30 mas
- f=0.83 +/- 0.17 %

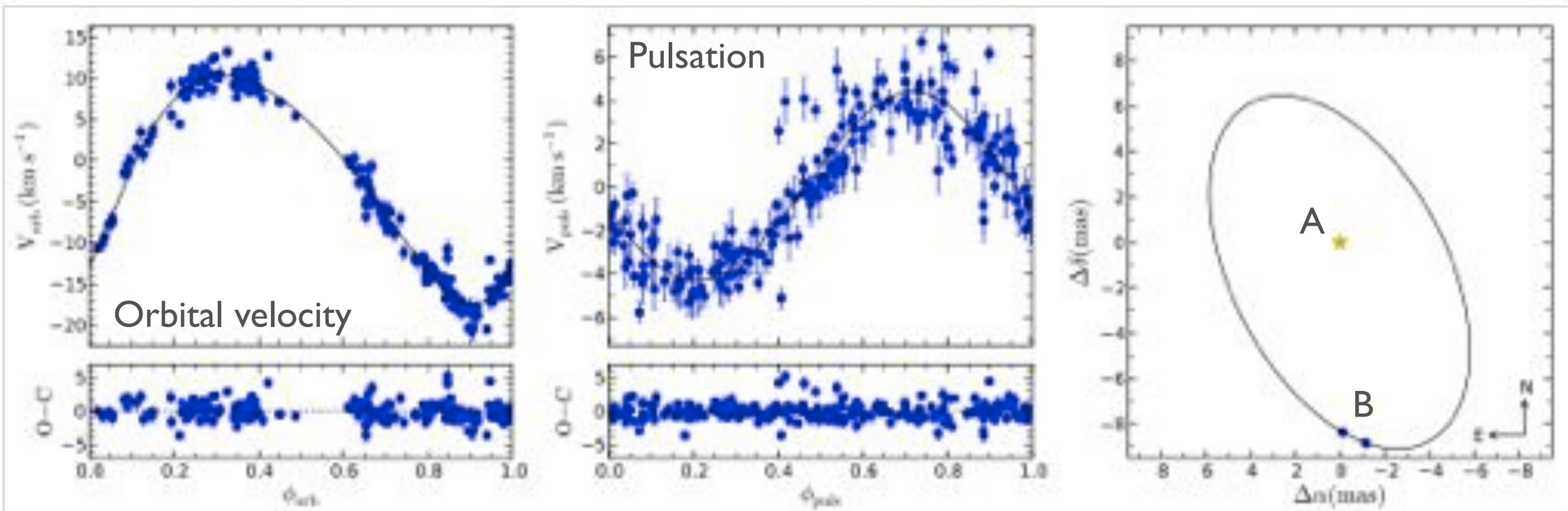
V1334 CYG (CHARA/MIRC)



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

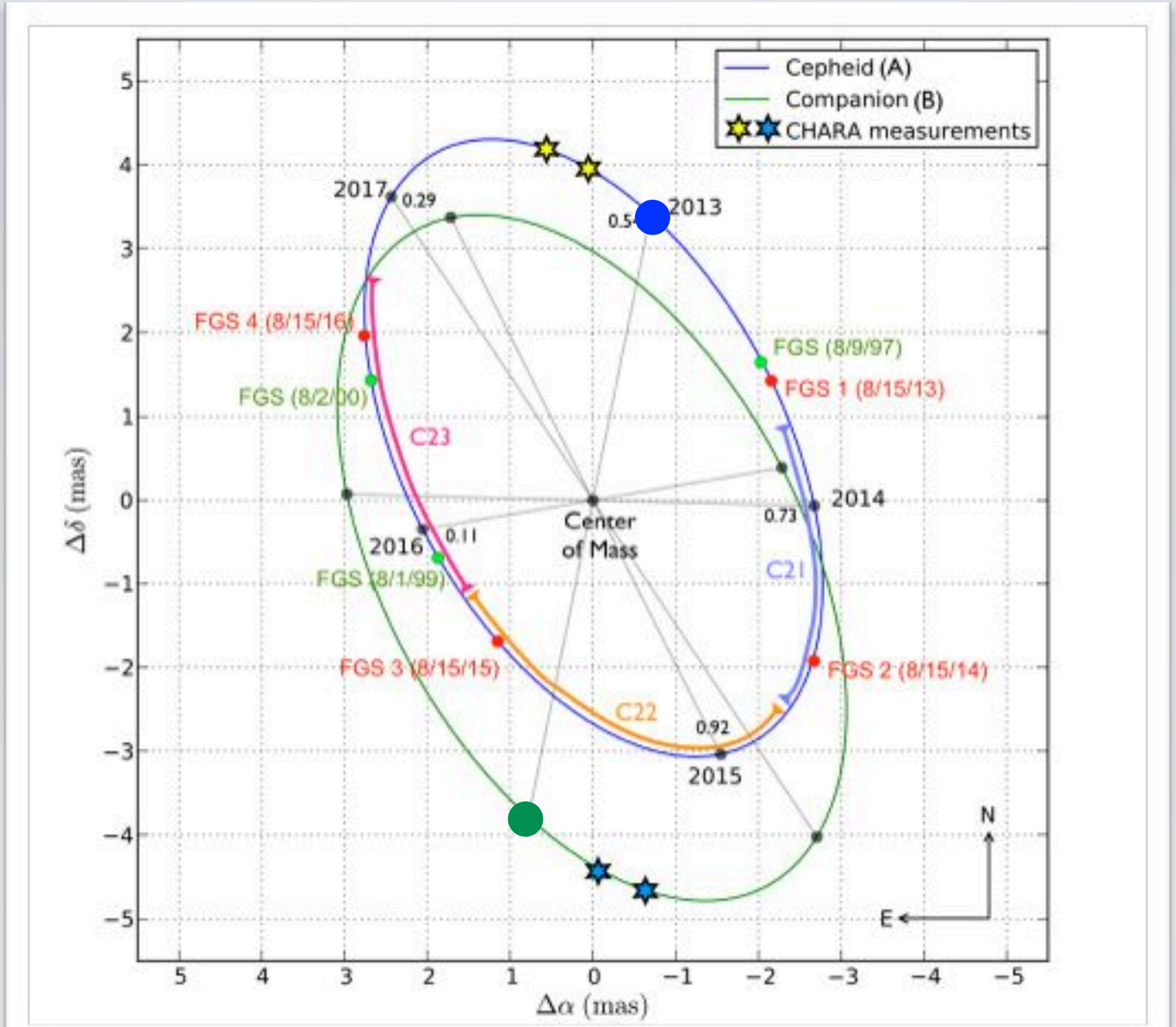
V1334 CYG (CHARA/MIRC)





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 and masses to 1%