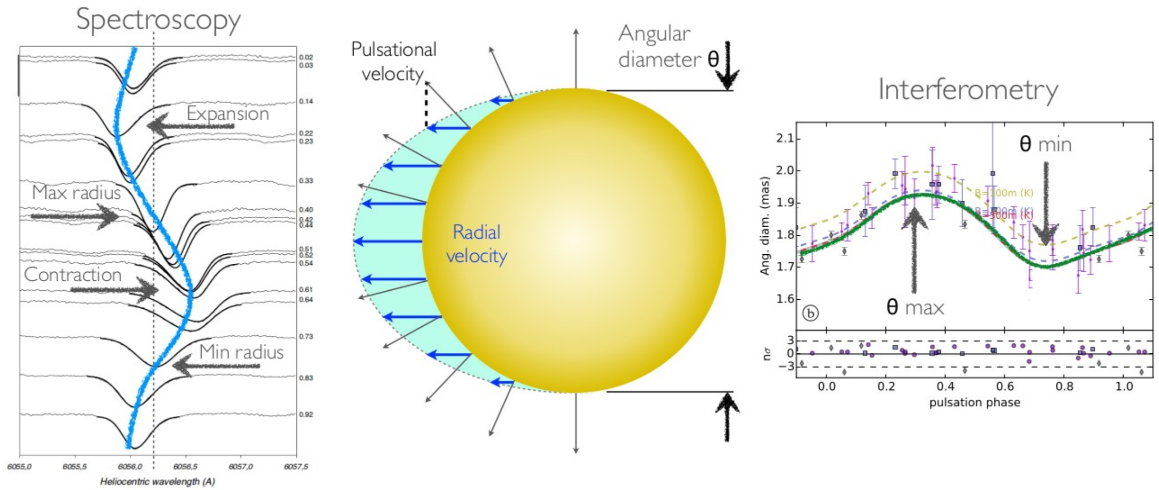
Improving Milky Way Cepheid distance estimations with high-resolution spectroscopy



Simon Borgniet

ANR *UnlockCepheids* : Pierre Kervella, Antoine Mérand, Nicolas Nardetto, Alexandre Gallenne, Eric Lagadec, Vincent Hocdé, Boris Trahin, Behnam Javanmardi & Louise Breuval

Outline

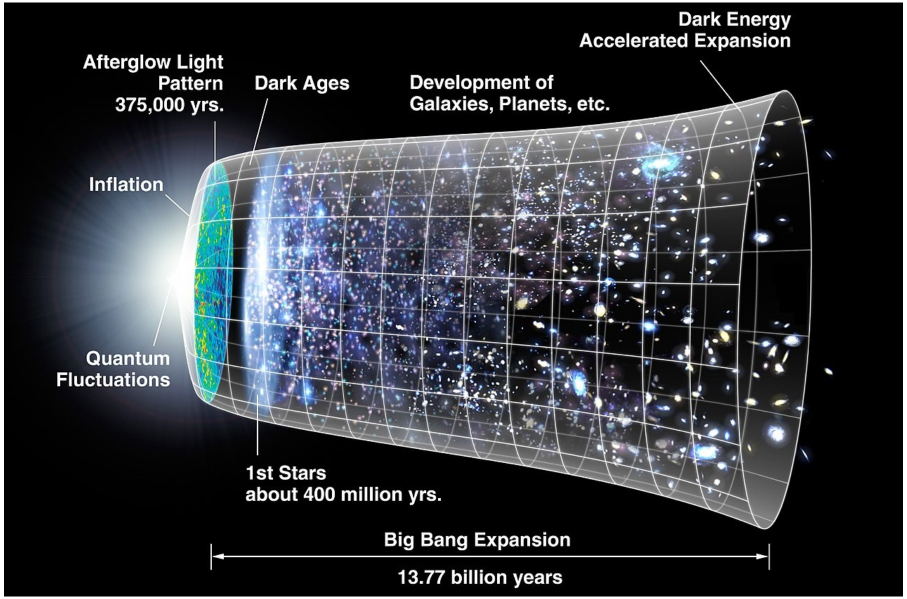
Context

- The (extra)-galactic distance scale in cosmology
- Cepheid variables as distance indicators

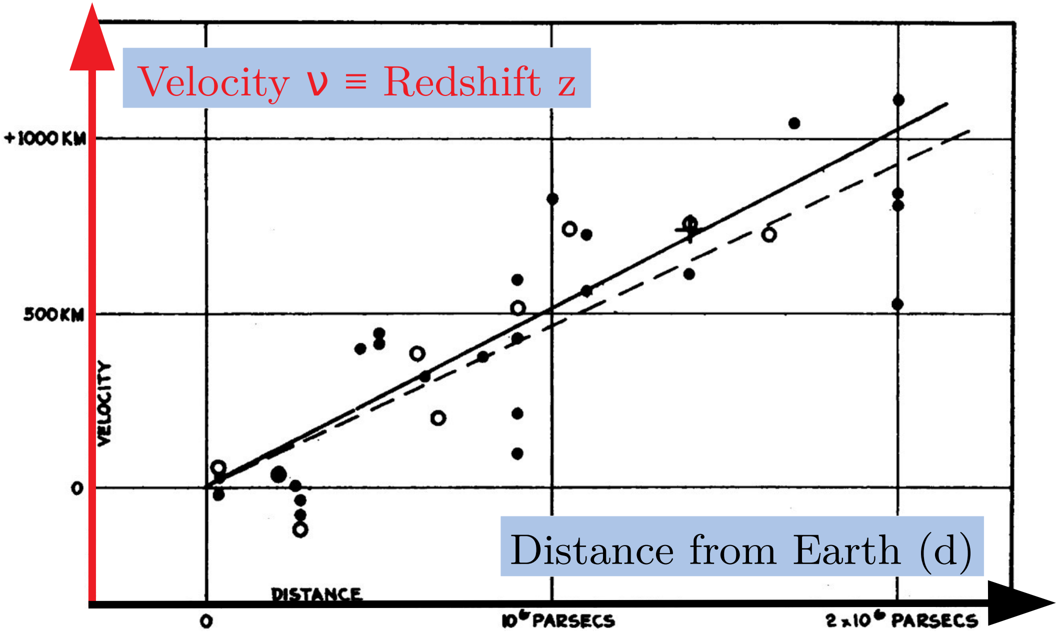
Contribution of Cepheid high-resolution spectroscopy

- Radial velocities
- Effective temperatures
- Line profile modeling

The Hubble constant and expanding universe



Credit: NASA/WMAP

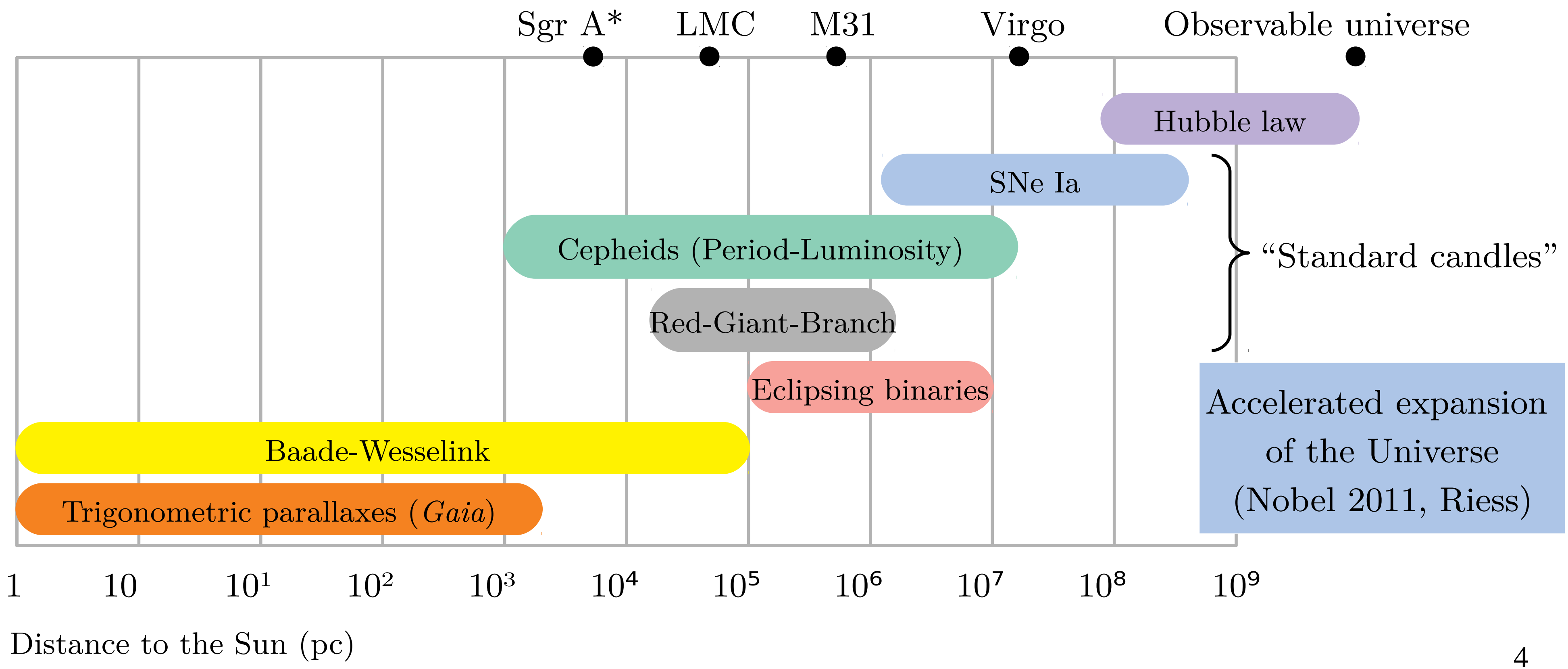


(Hubble, 1929)

Hubble-Lemaître law: $\nu = H_0.d$

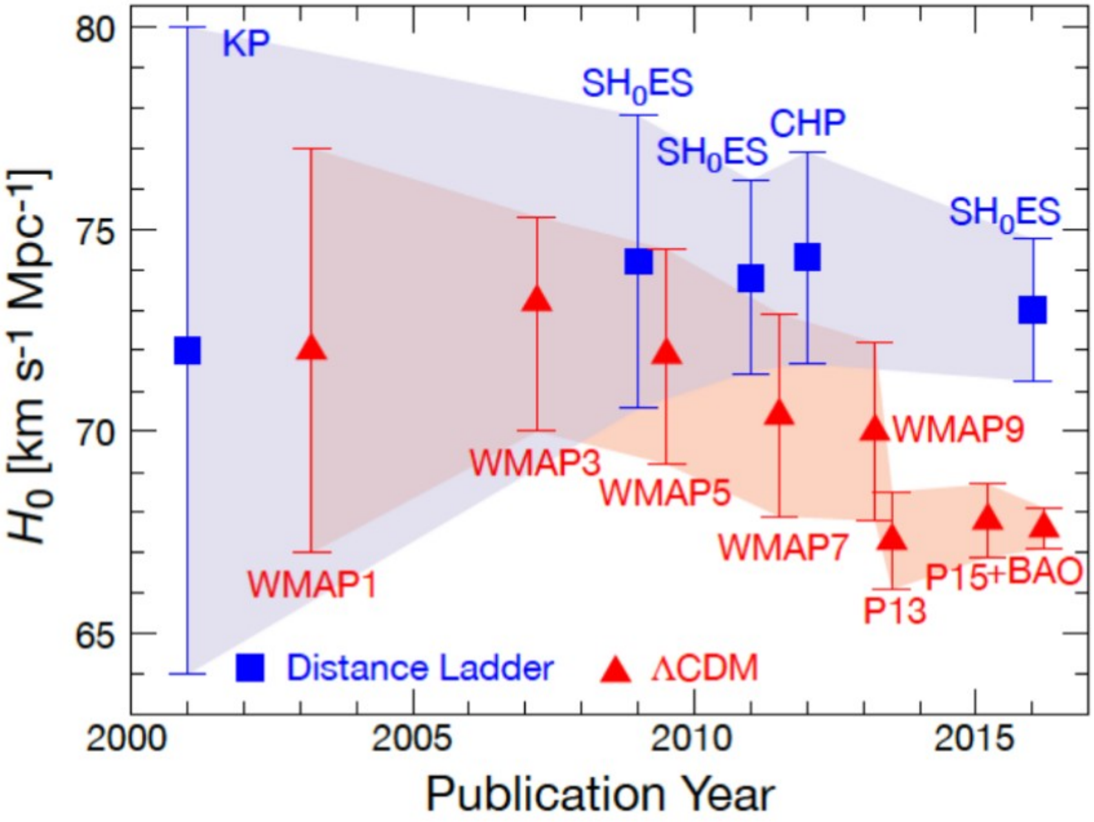
$H_0 \approx$ 70-75 (km/s)/Mpc

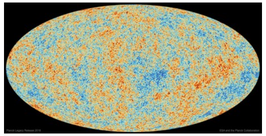
The cosmological distance scale



The H_0 tension

Distance scale
(z < 1)
$H_0 \sim 74 \pm 2$ km/s/Mpc





ΛCDM model + Planck
(z ~ 10^3)
$H_0 \sim 66.9 \pm 0.6$ km/s/Mpc

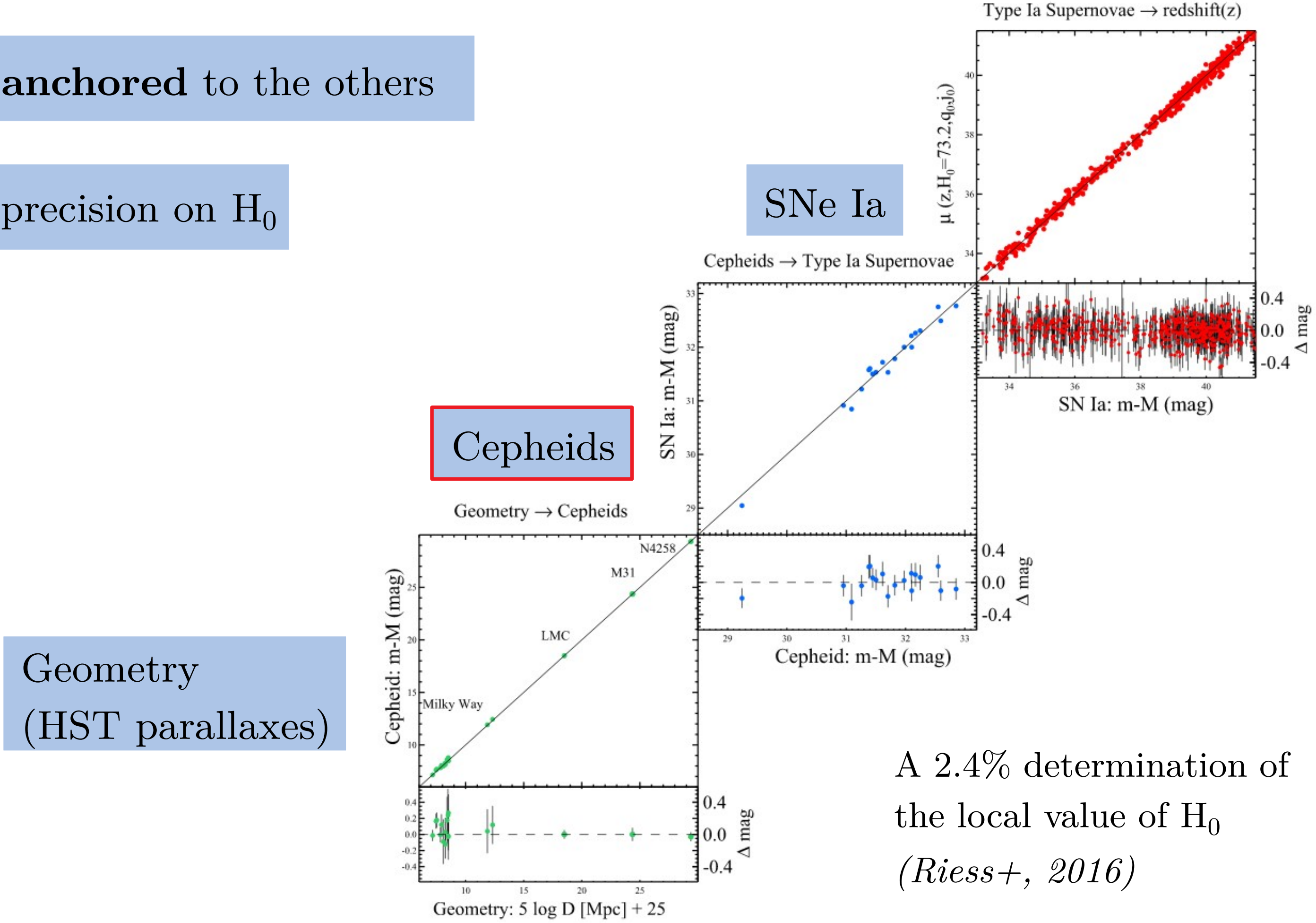
>3.5σ tension

(*Freedman 2017*)

Climbing the distance ladder

Each distance indicator is **anchored** to the others

3 methods → towards 1% precision on H_0

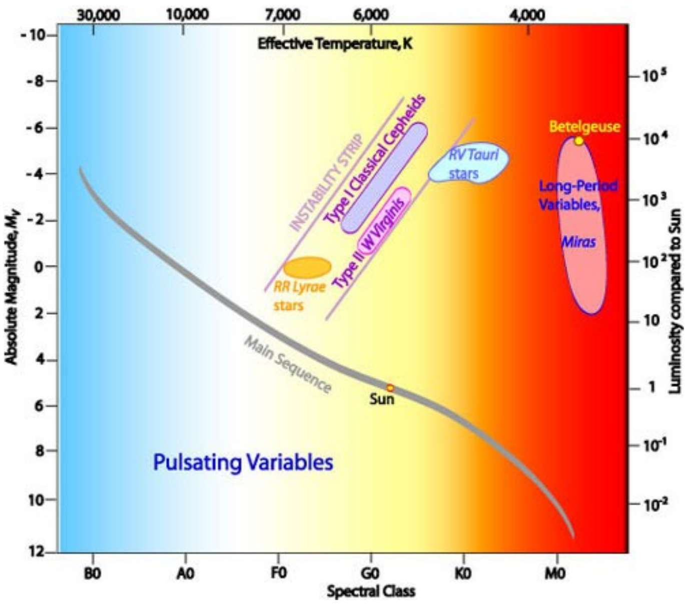


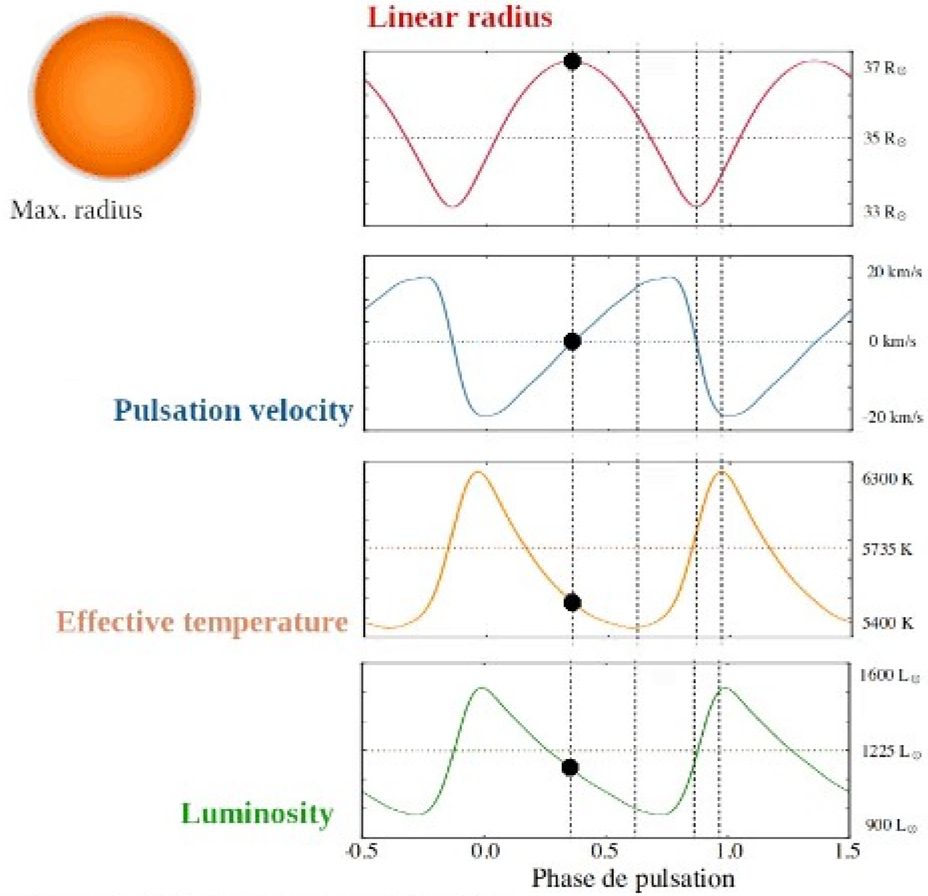
A 2.4% determination of the local value of H_0 *(Riess+, 2016)*

Classical Cepheid variables

Radially pulsating stars (1< P <100 days)

Bright (~10^5 $L_\odot$) supergiants (type I)





Credit: J. Breitfelder, PhD thesis, 2015, tel-01238712

Cepheids as standard candles : the Period-Luminosity (P-L) relation(s)

$$M_i = a_i \log(P) + b_i$$

5-10% uncertainty:

Metallicity

≠ relations in photometric bands

Interstellar reddening

Contamination

(binaries, circumstellar envelopes)

Necessity of independent distance calibration

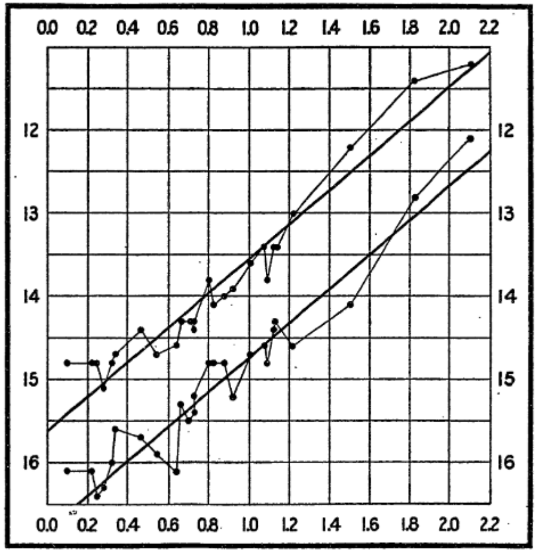
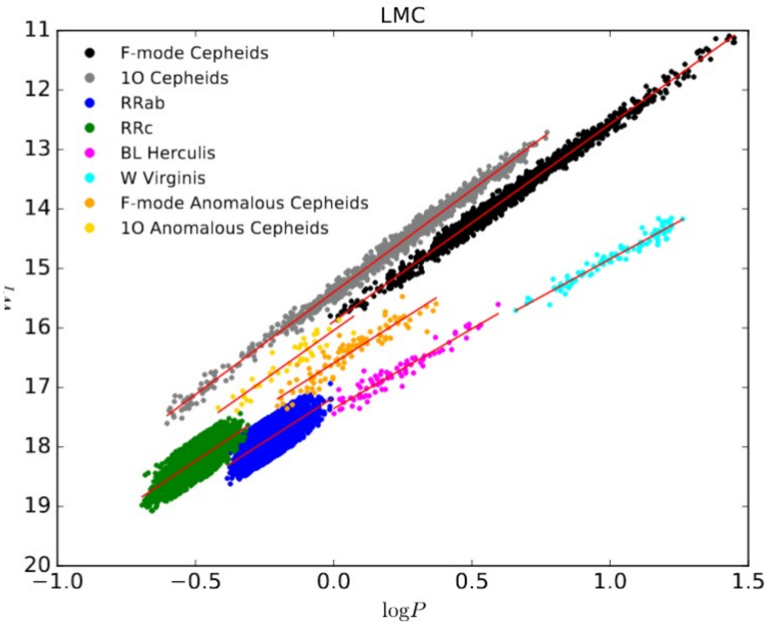


FIG. 2.

(Henrietta Leavitt, 1912)



(Iwanek+ 2018)

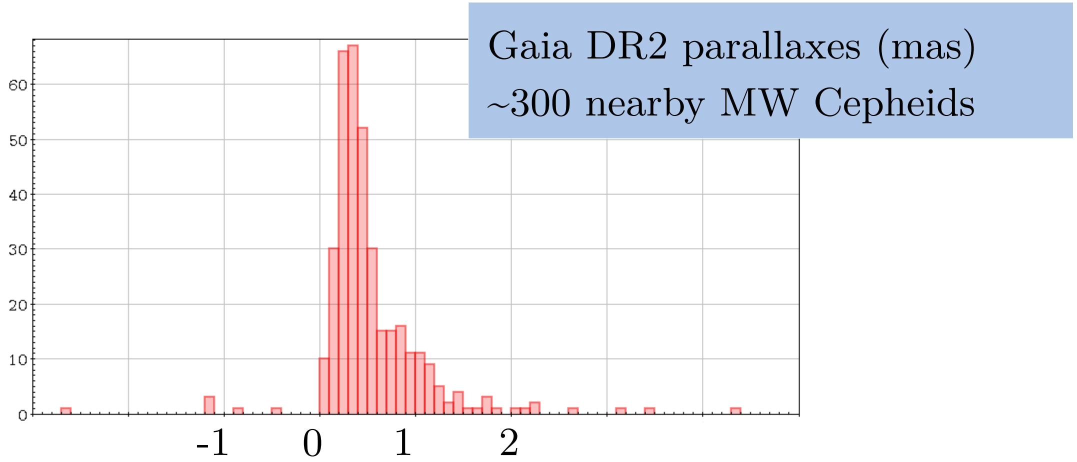
Cepheid parallaxes ?

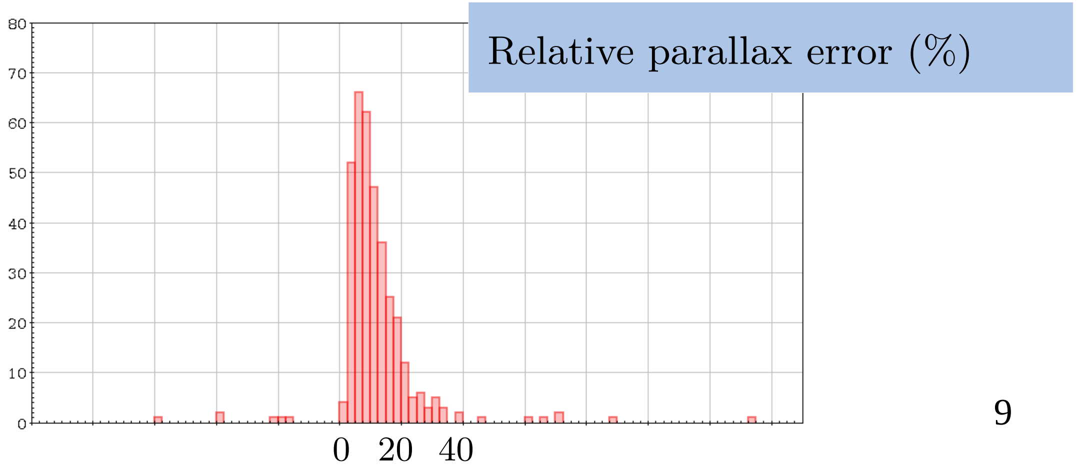
Gaia DR2:

→ Systematics (parallax offsets)

→ Astrometric bias (Cepheid variability)

"Too uncertain" so far (*Ripepi+ 2019*)

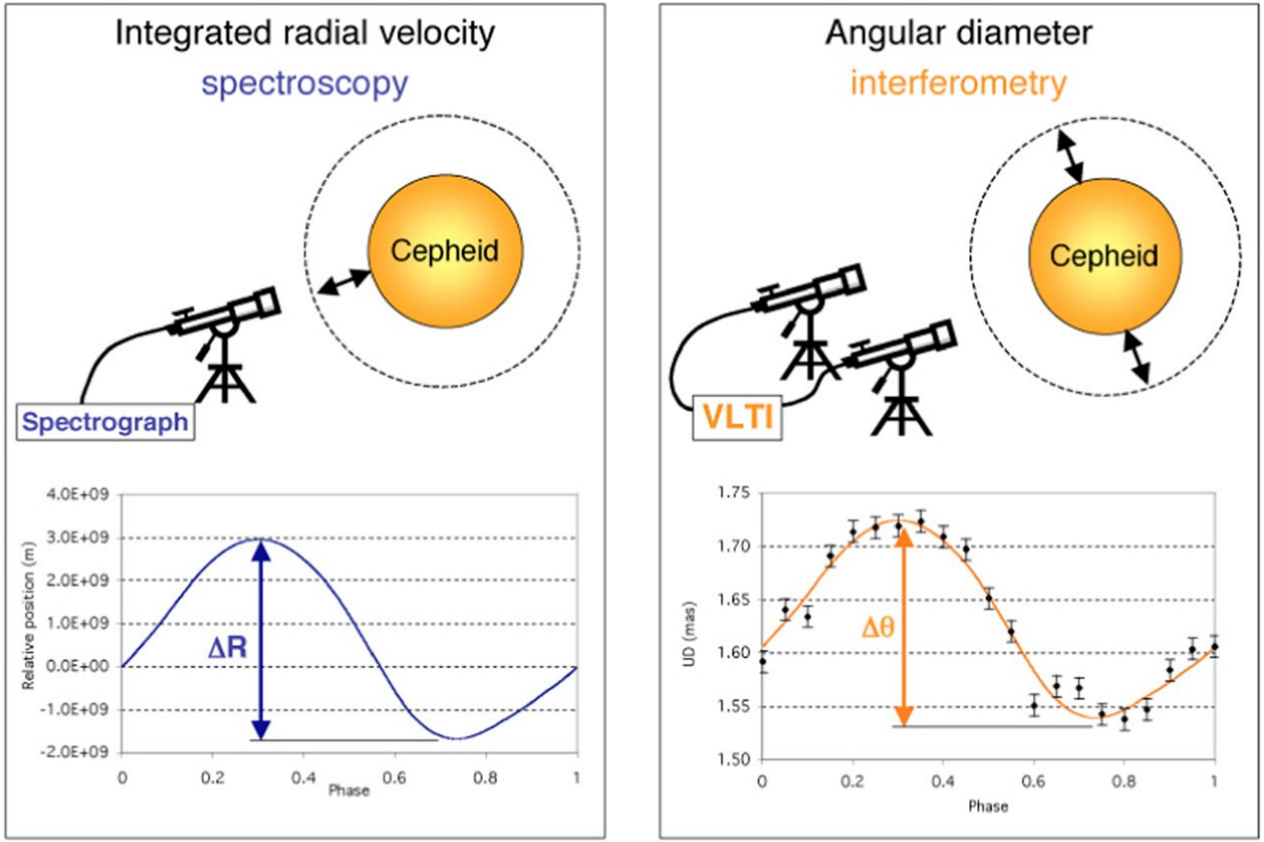




The parallax-of-pulsation (PoP) method

Baade-Wesselink (1918)

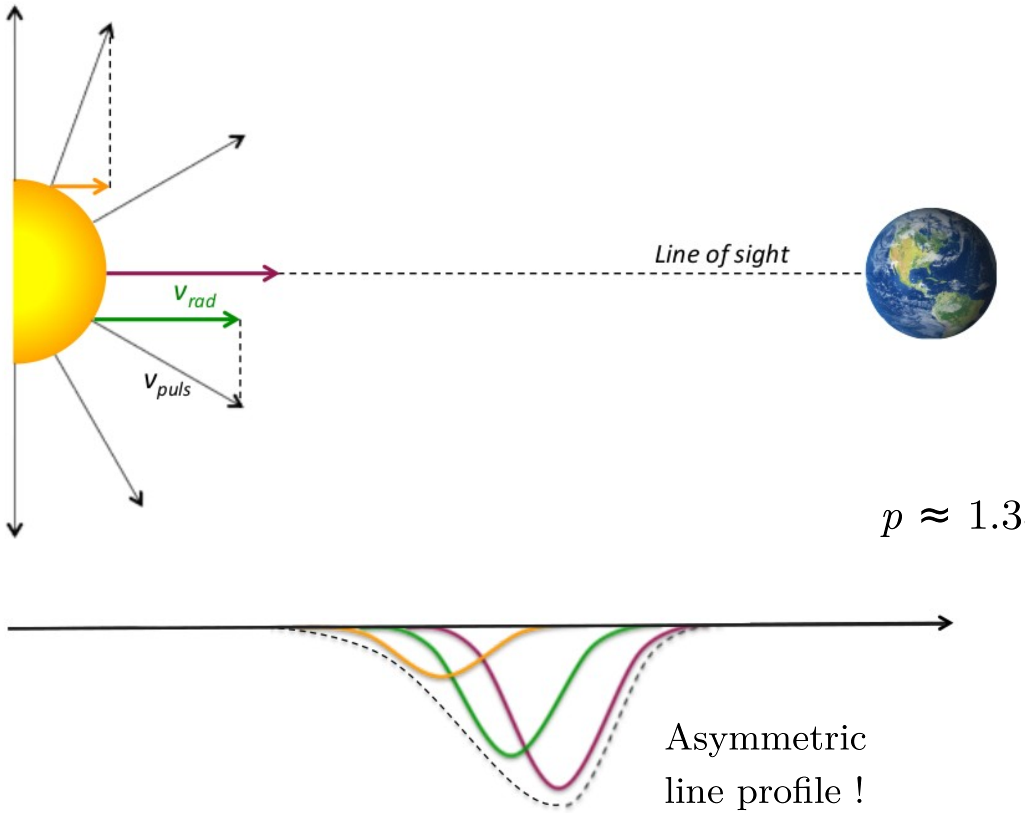
d α $\Delta R / \Delta\theta$



Credit : ESO

d [pc] = 9.305 **ΔR** [$R_\odot$] / **Δθ** [mas]

The projection factor (p)



Asymmetric line profile !

$$\Delta R = \int v_{puls} = p.\int v_{rad}$$

$p \approx 1.35 \pm 0.10$

- Geometry ($p = 1.5$)
- Limb-darkening
- Atmosphere dynamics (velocity gradient)

$\rightarrow d/p$ (2-7% uncertainty)

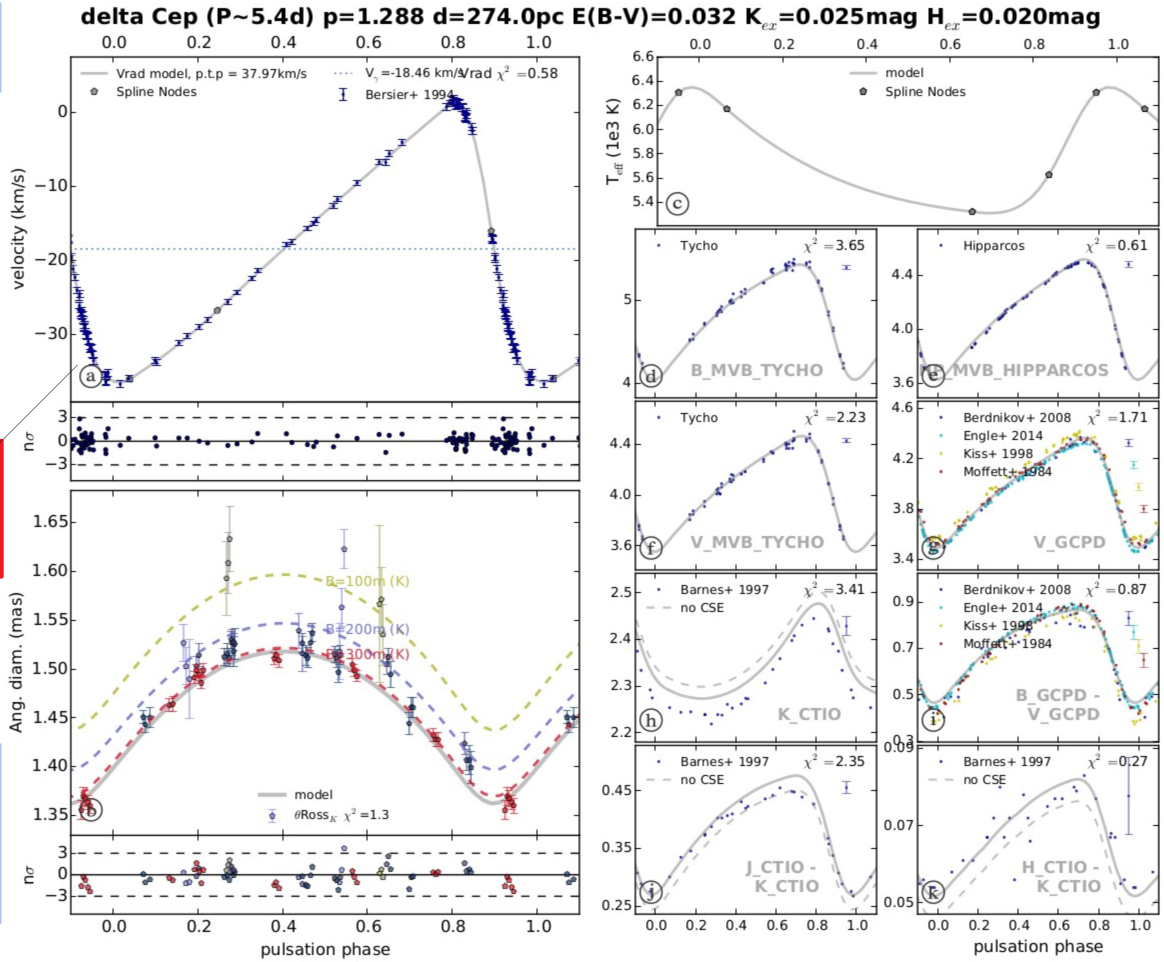
Credit: J. Breitfelder

SPIPS: a global implementation of the PoP method

Spectro-Photo-Interferometry of Pulsating Stars

→ 2% precision on d/p (*Mérand+ 2015*)
→ Calibration of Cepheid p-factors (*Breitfelder+ 2015*, *Kervella+ 2017*)

→ Work on CSEs by Vincent, Nicolas, Eric



Spectroscopy: Radial velocities

Interferometry (VLTI/CHARA): angular diameters

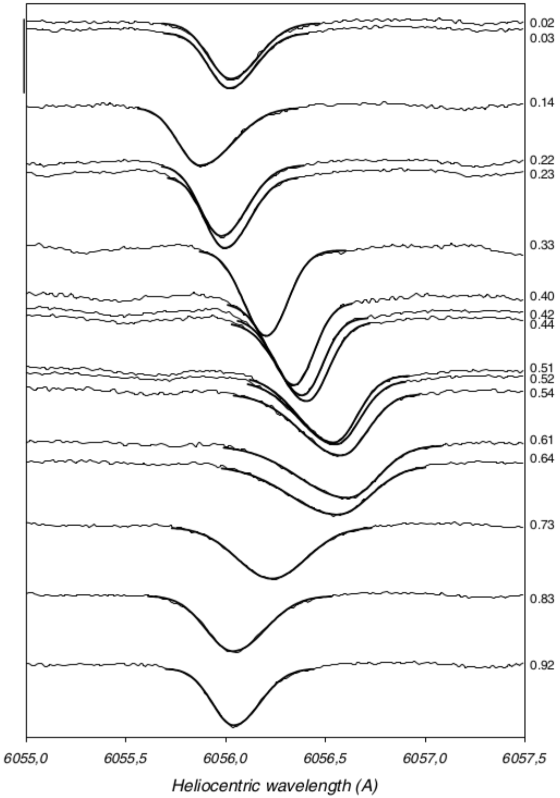
High-resolution spectroscopy of Milky Way Cepheids

PoP method issues

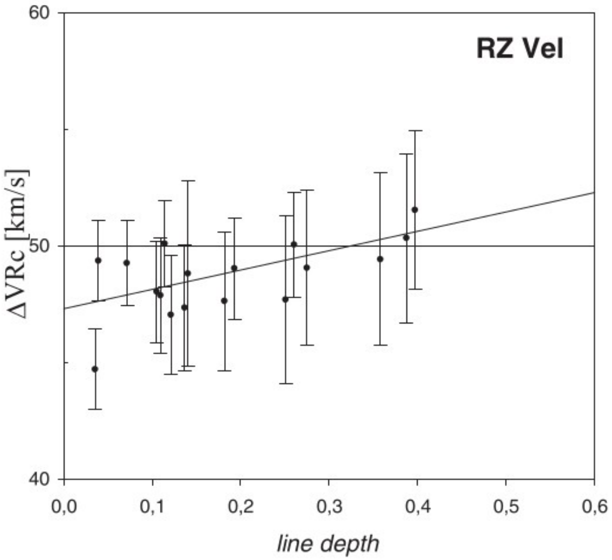
1/ Cepheid v_{rad} consistency:
asymmetric lines, velocity gradient

2/ decreased PoP robustness
if no diameters (faraway Cepheids)

3/ *p*-factor limitation
$\rightarrow$ v_{puls} estimation ?

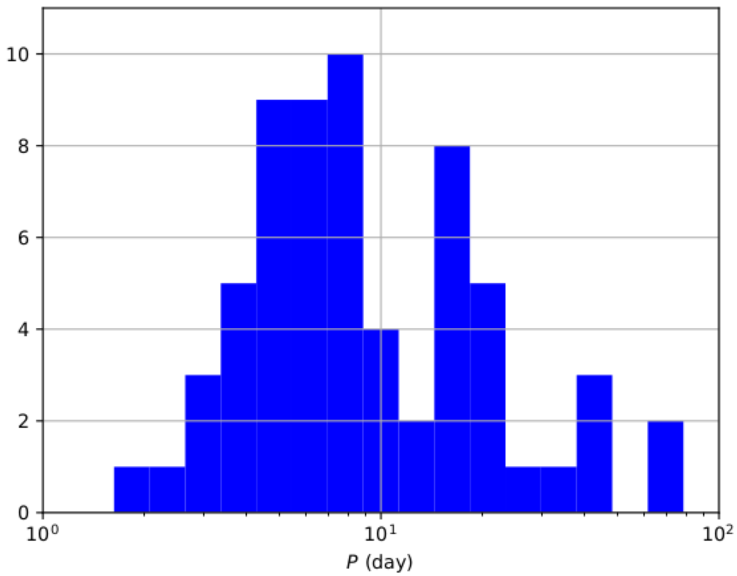


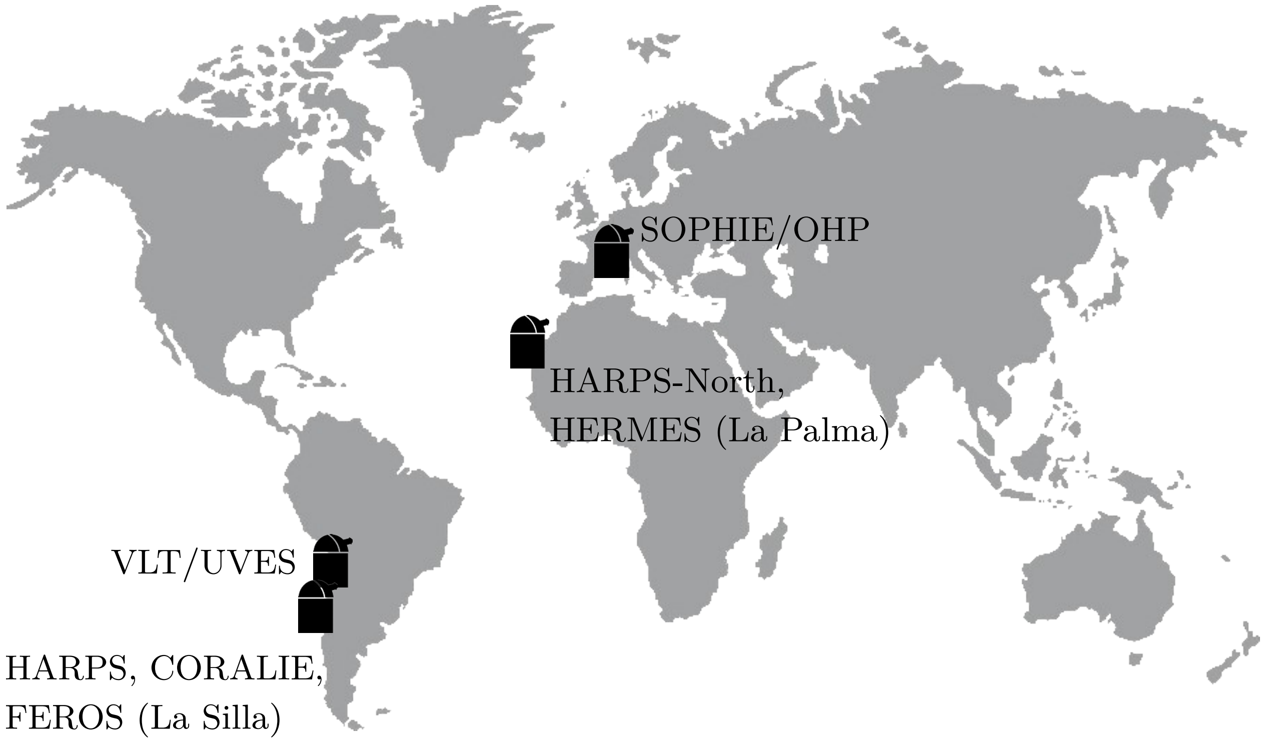
Line asymmetry
(*Nardetto+ 2006*)



Velocity gradient
(*Nardetto+ 2007*)

Sample



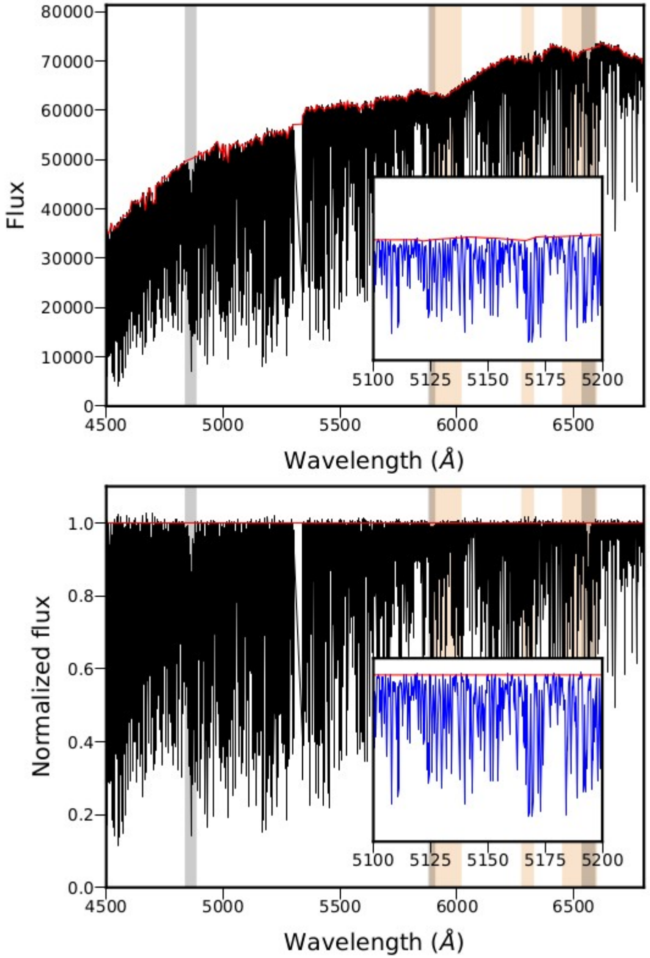


64 Milky Way Cepheids
Seven spectrographs
$>$ 3900 spectra

Input spectra

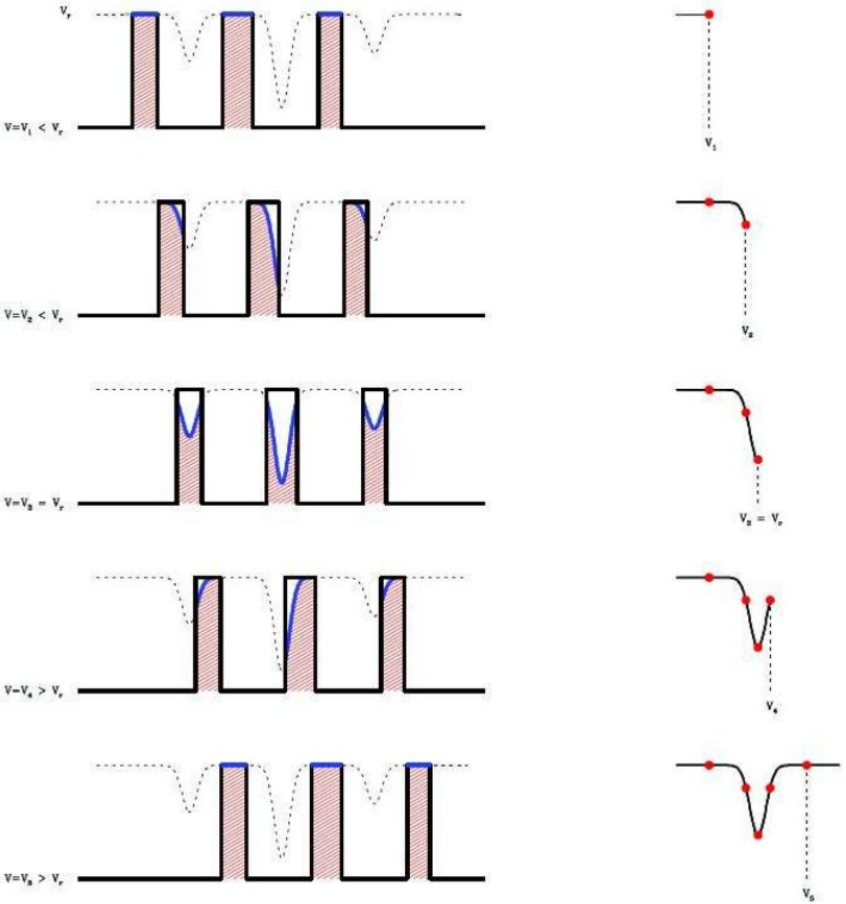
High-res: $42{,}000 \leq R \leq 115{,}000$
High-S/N (~50-150)
1d format (flux = f(λ))

Same pre-defined λ ranges
Same normalisation
→ Maximize consistency



Cross-Correlation Functions (CCFs)

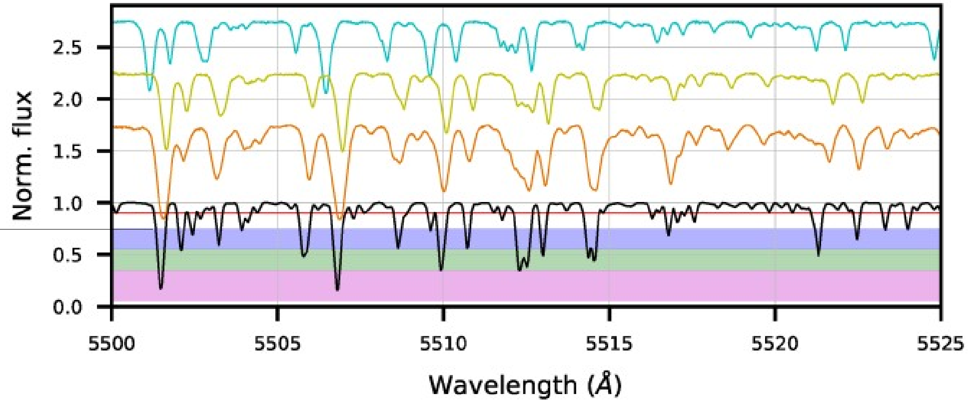
CCF ≈ mean line profile
→ Higher S/N than single lines
→ Quick
→ Common



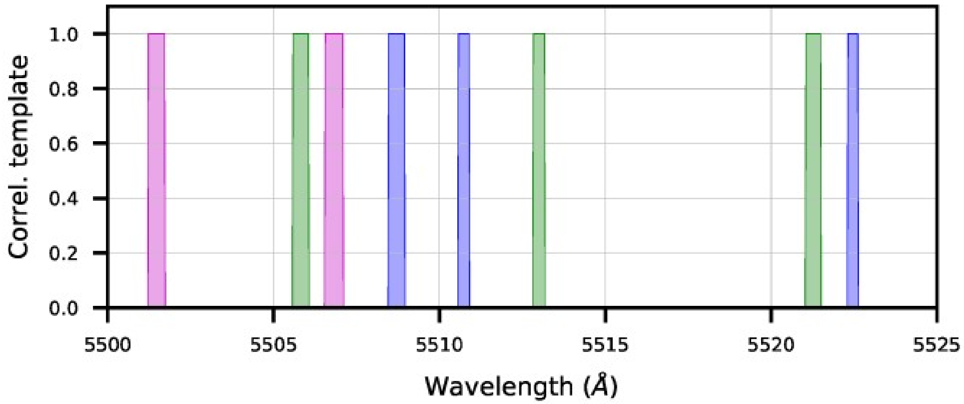
Tailored correlation templates

δ Cep
β Dor
ℓ Car

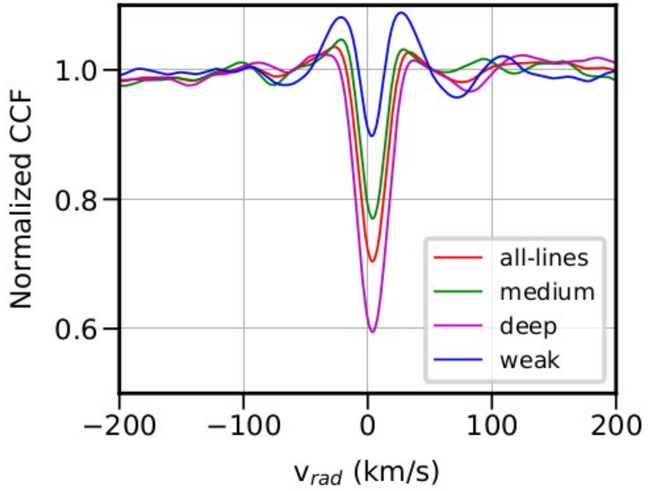
Synthetic
Cepheid spectrum



Line selection:
4 templates



Tailored CCFs

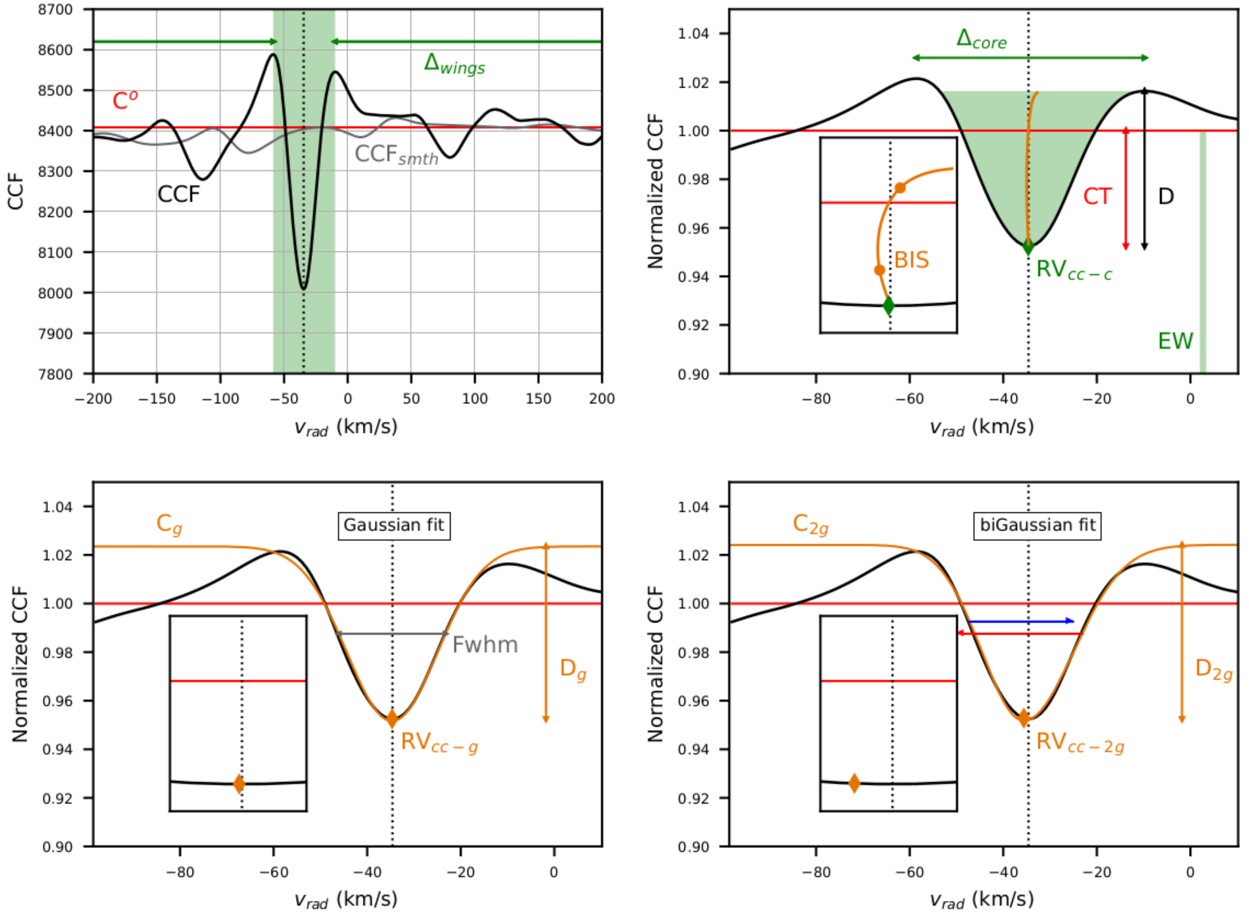


Radial velocities

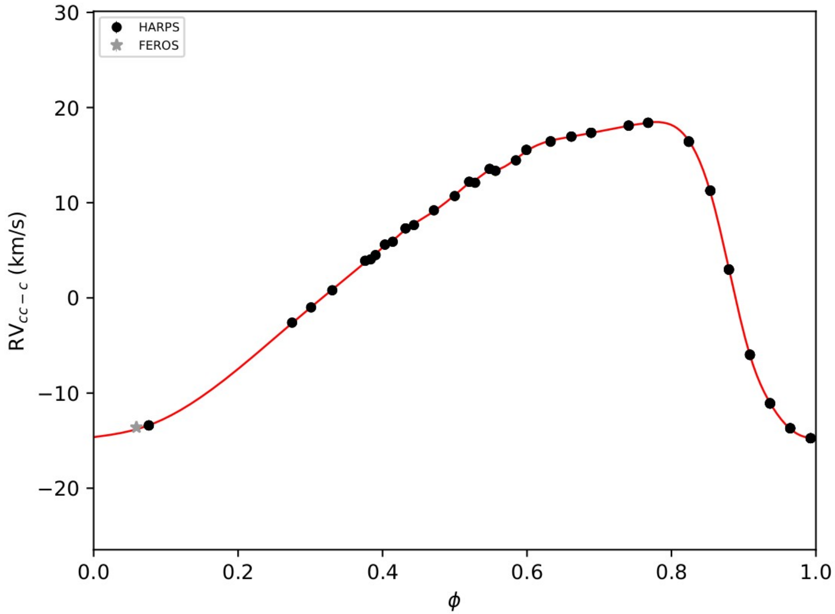
Centroid v_{rad} (first moment)

Gaussian v_{rad}

biGaussian v_{rad}

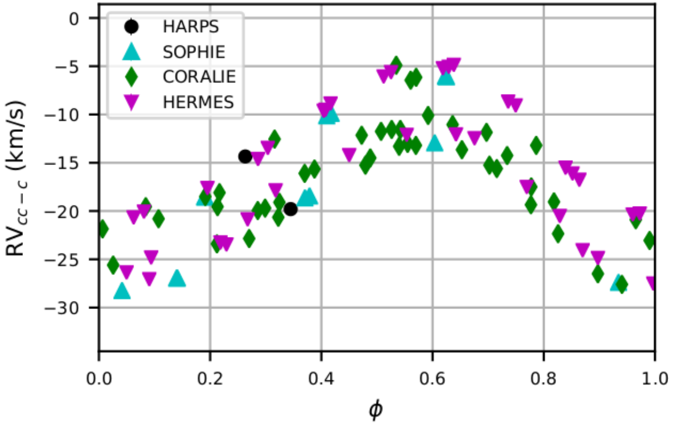


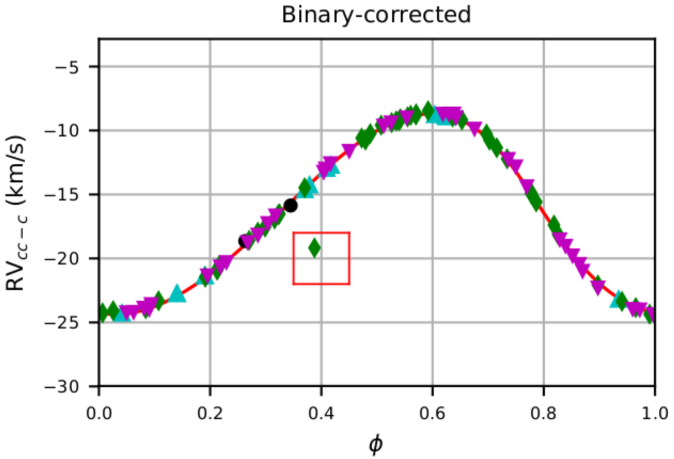
Cepheid v_{rad} curves



ℓ Car

$P = 35.56$ days

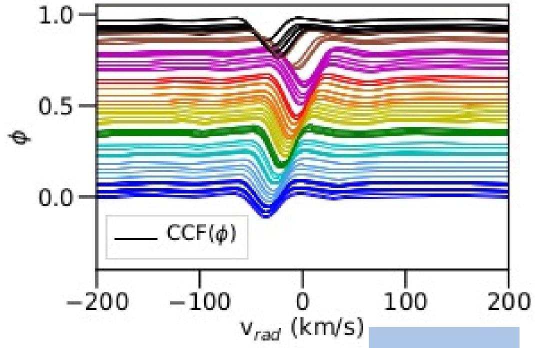




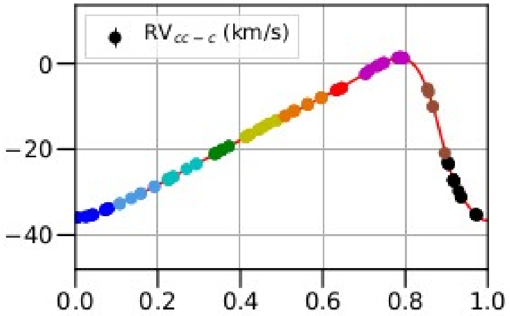
FF Aql

$P = 4.47$ days

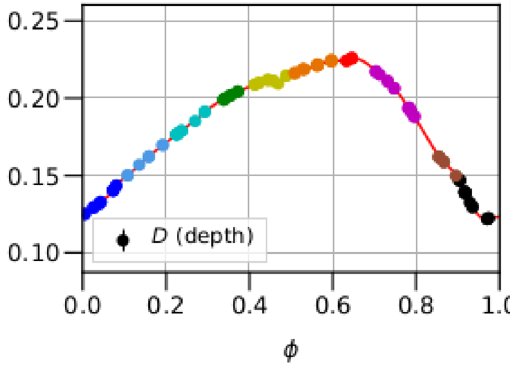
Characterizing the CCFs



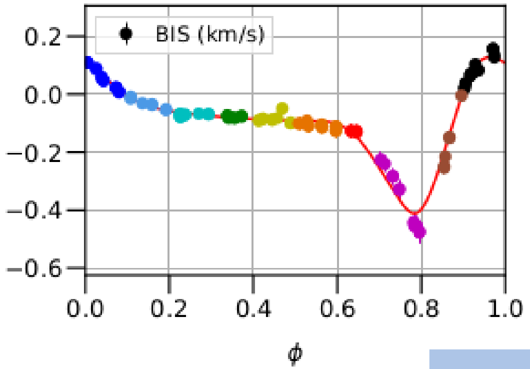
CCFs

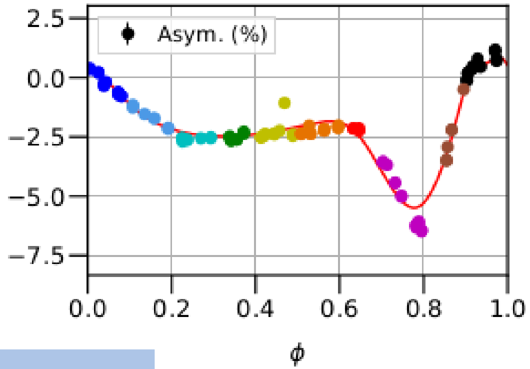


Doppler shift

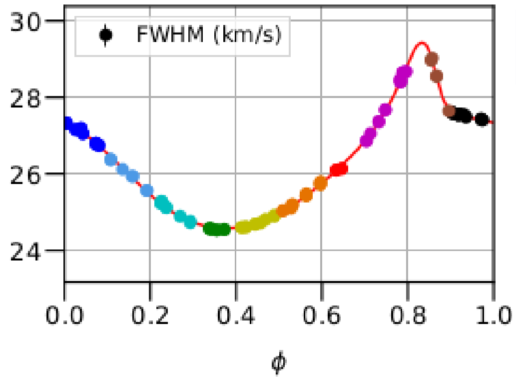


Depth





Asymmetry



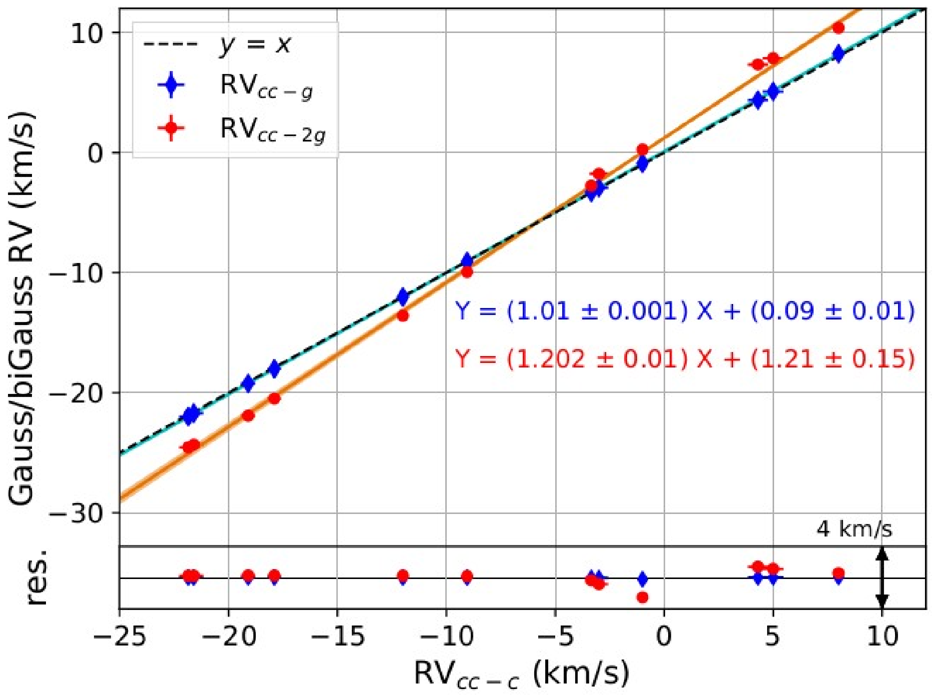
Width

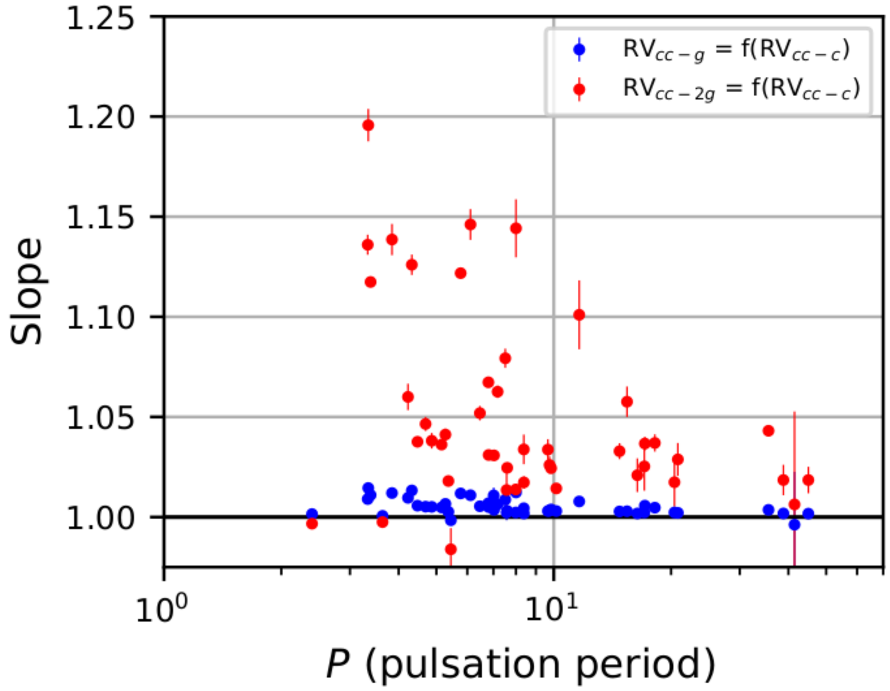
Results: v_{rad} methods

v_{rad} amplitudes:

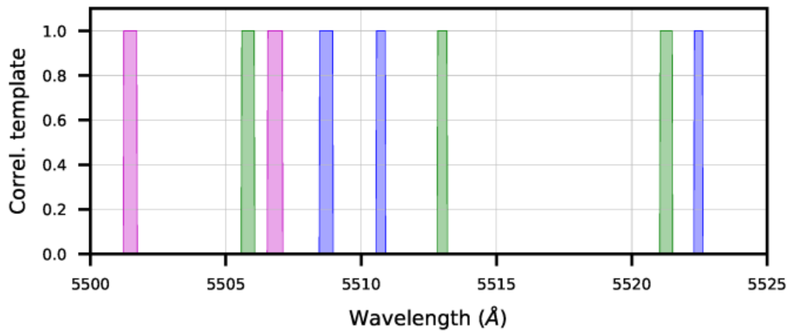
biGaussian >> Gaussian > Centroid

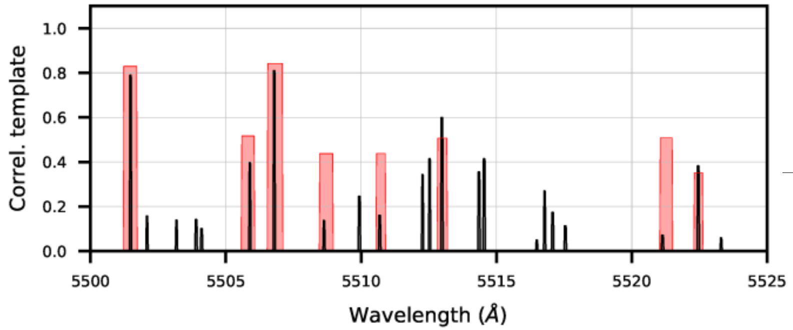
≠ *p*-factors
≠ distances





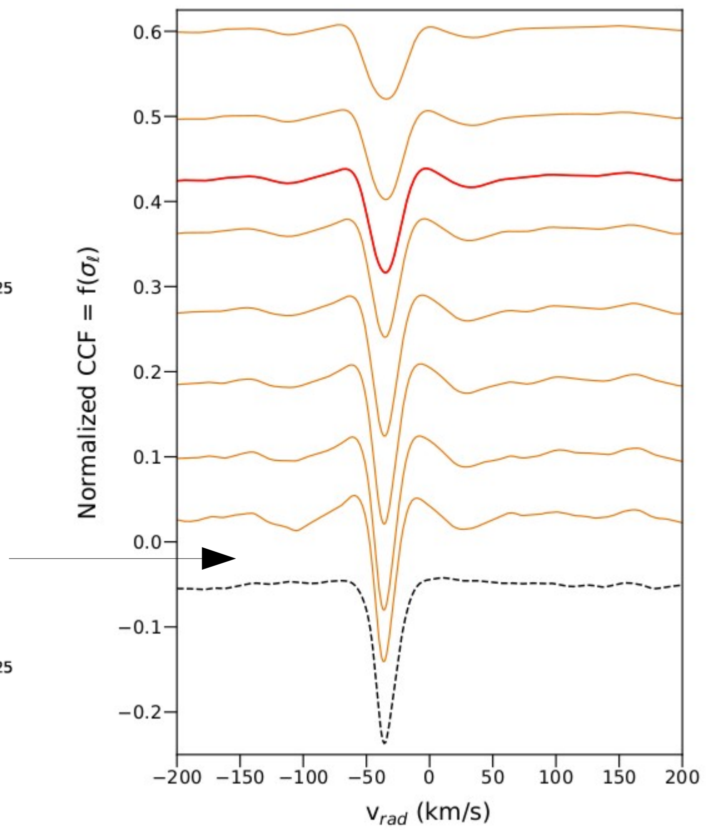
Results: template box width





tailored all-line template

G2 classical template



Increased box width:

→ reduces CCF asymmetry

→ reduces v_{rad} amplitudes

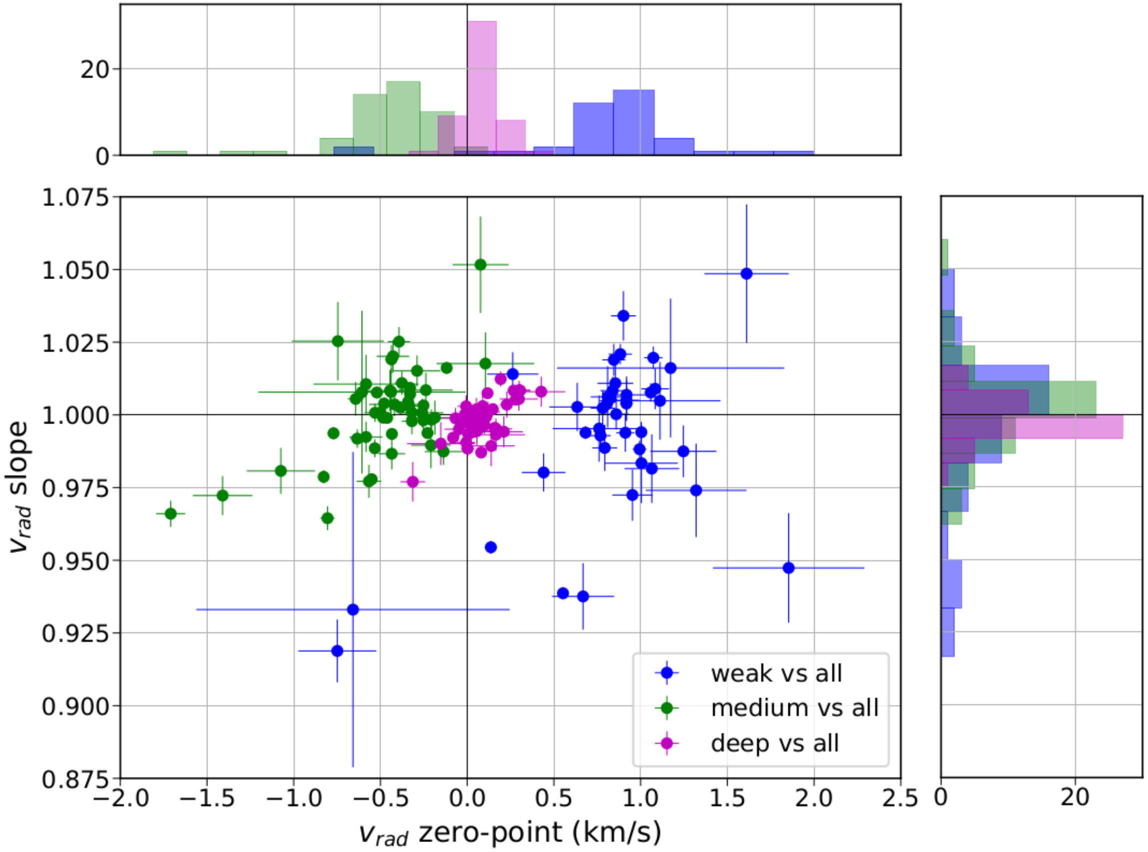
Results: line-depth templates

Radial velocities vs. line depth:

→ clear v_{rad} offsets

→ No clear v_{rad} gradient

→ deeper lines are more robust



How to get robust Cepheid v_{rad}

Minimize CCF asymmetry !

→ Centroid v_{rad}
→ Stronger/deeper lines
→ Wider template boxes

Astronomy & Astrophysics manuscript no. aa35622-19
September 7, 2019

Consistent radial velocities of classical Cepheids from the cross-correlation technique⋆,⋆⋆

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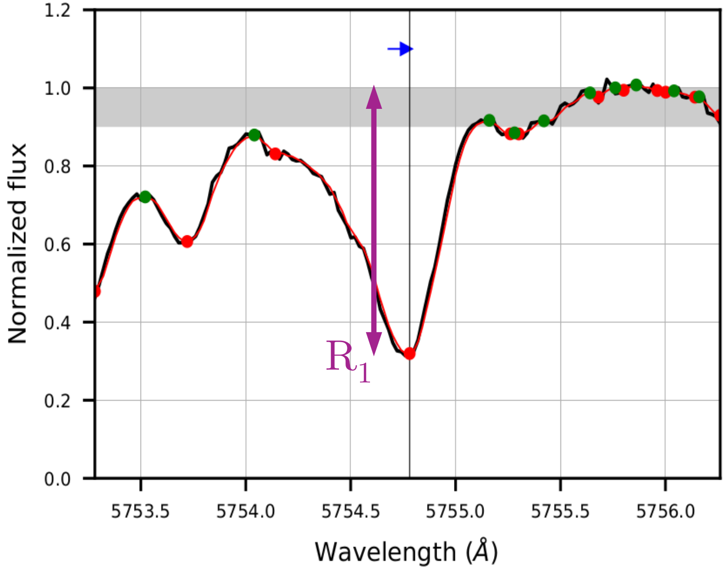
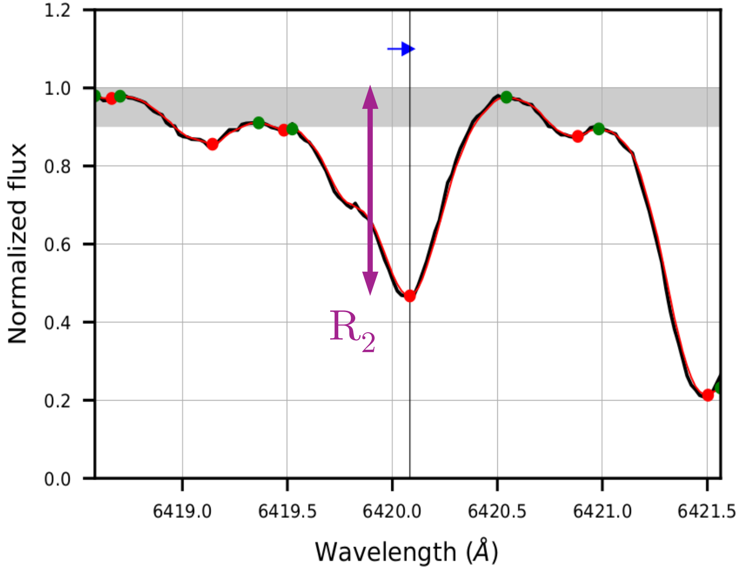
Cepheid spectroscopic effective temperatures





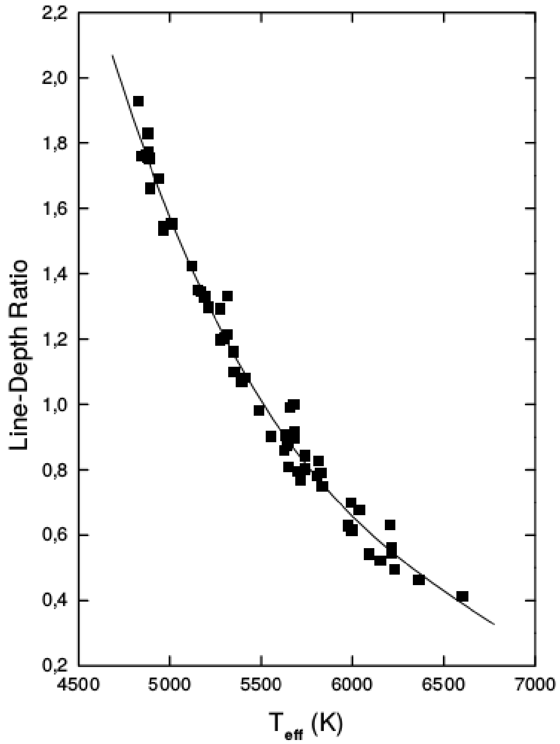


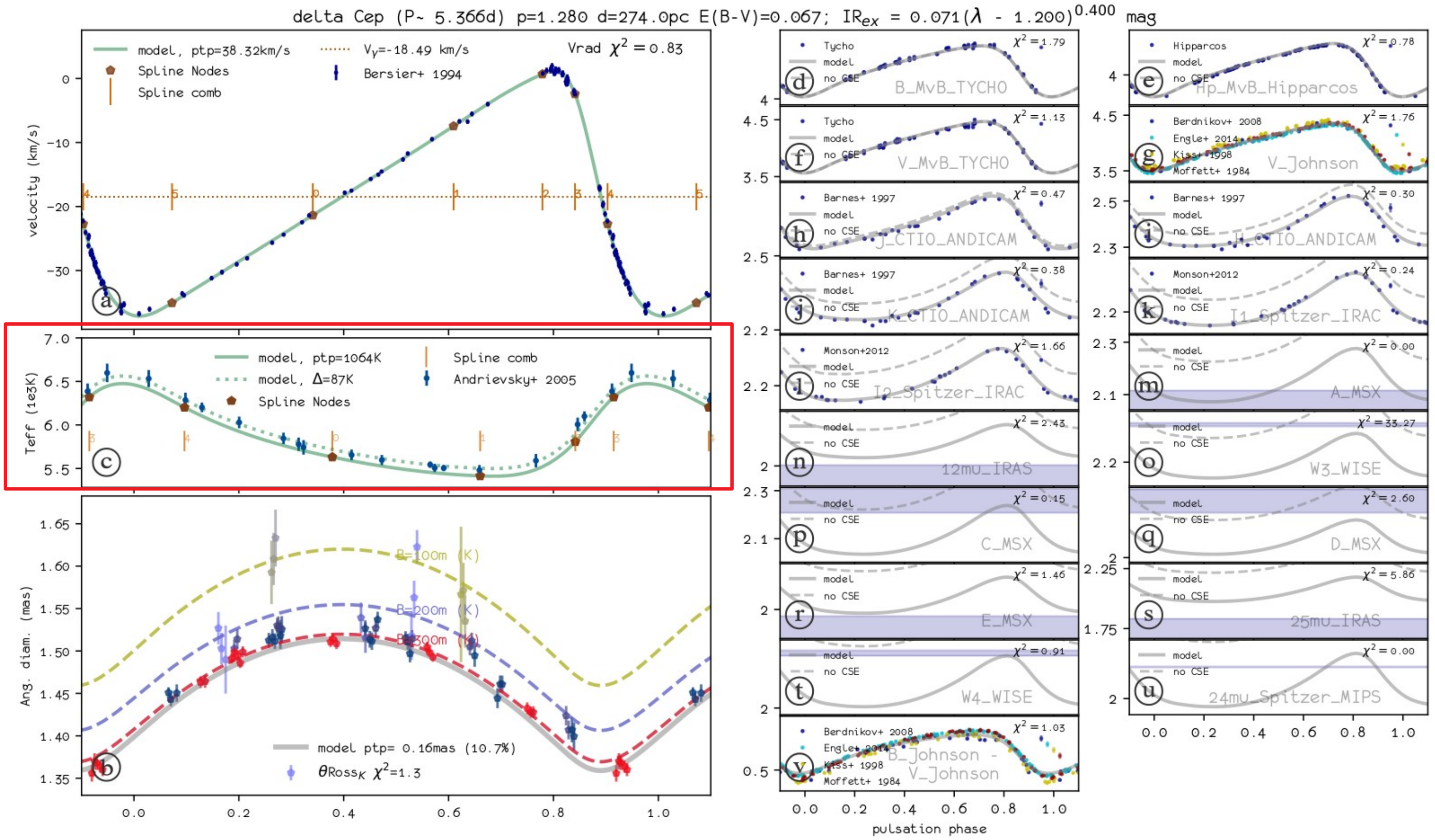
Fig. 1. A typical calibration curve. The ratio of spectral line-depths, λ 6090.21 Å VI to λ 6091.92 Å SiI (calibration No. 10 from Table 1), is shown as a function of effective temperature.

Line-Depth Ratios (LDRs):
$T_{eff} \propto R_1/R_2$
(polynomial)

(Kovtyukh & Gorlova 2000)

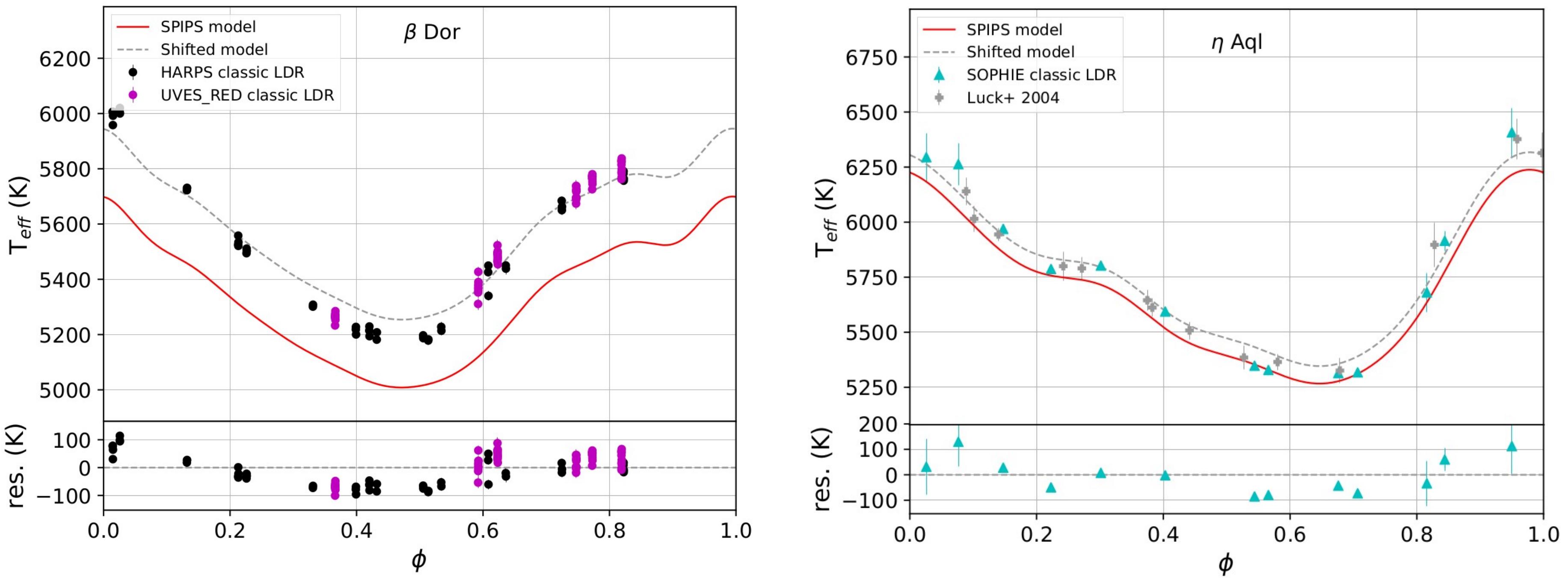
Input for the PoP method / SPIPS

Constraint on model T_{eff} curve



T_{eff} impact on SPIPS models

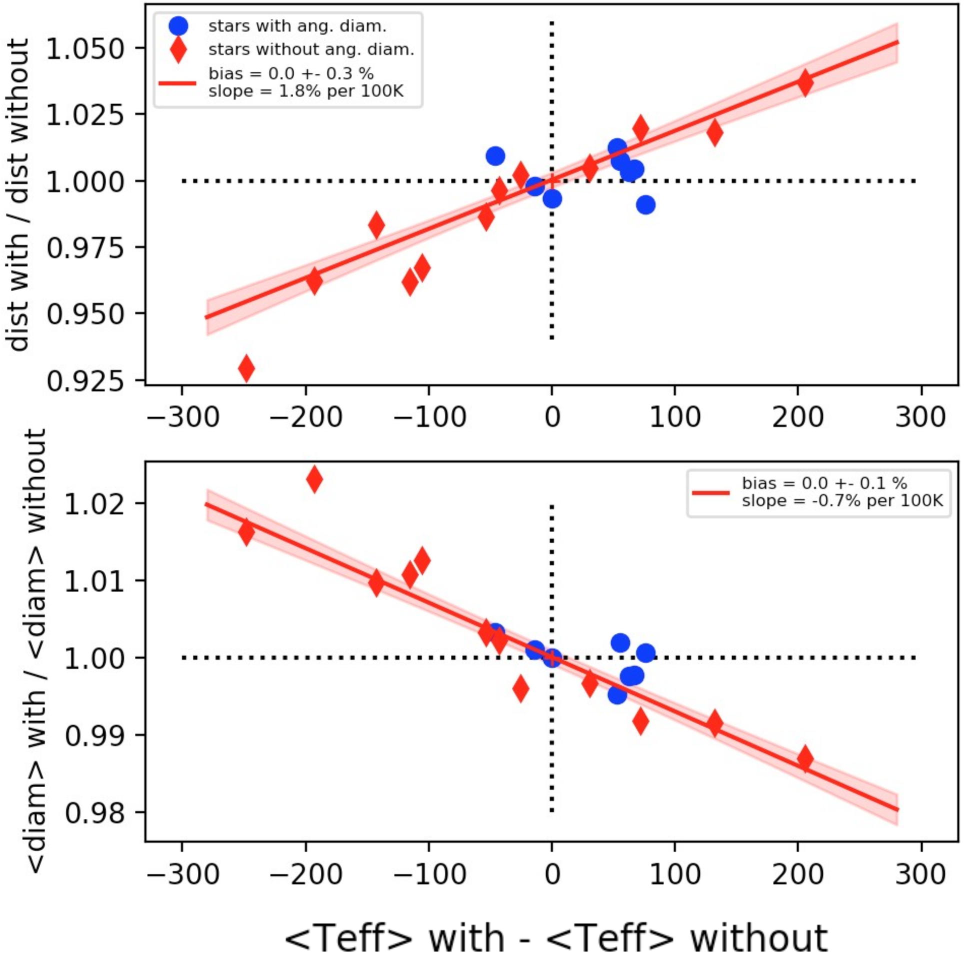
113 line pairs appropriate for LDR (from literature)
→ Phased T_{eff} curves



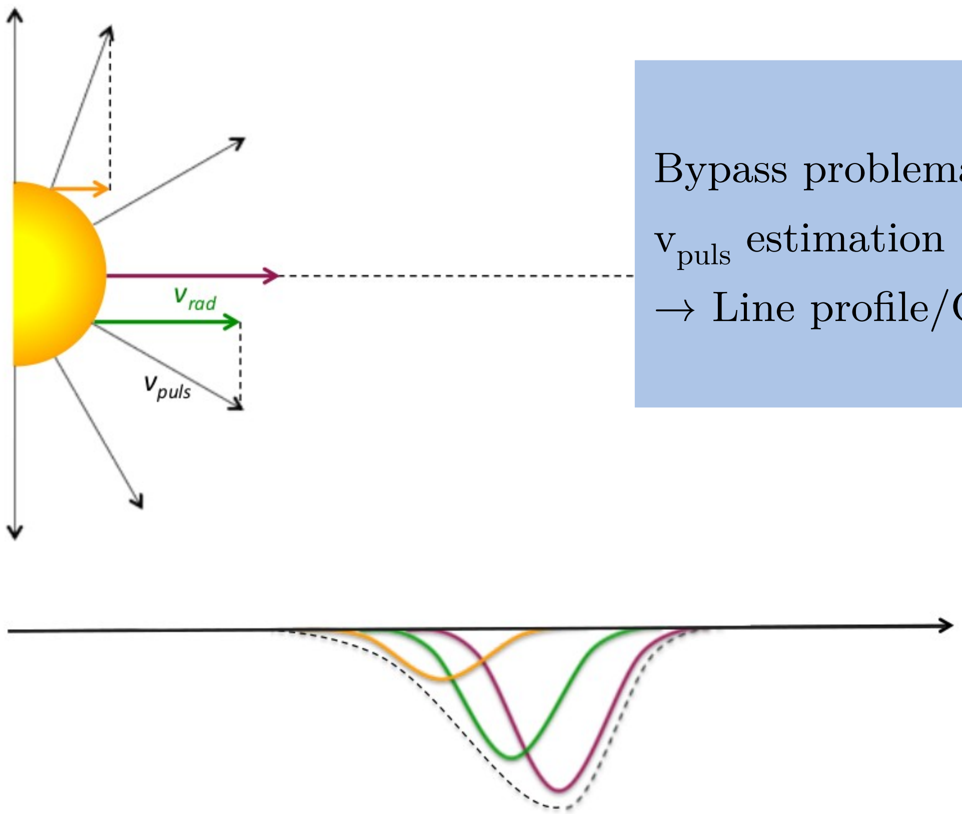
Alternative to angular diameters

For distant Cepheids
(no interferometric θ):

LDR T_{eff} in SPIPS
→ breaks degeneracy between
modeled T_{eff} and interstellar reddening



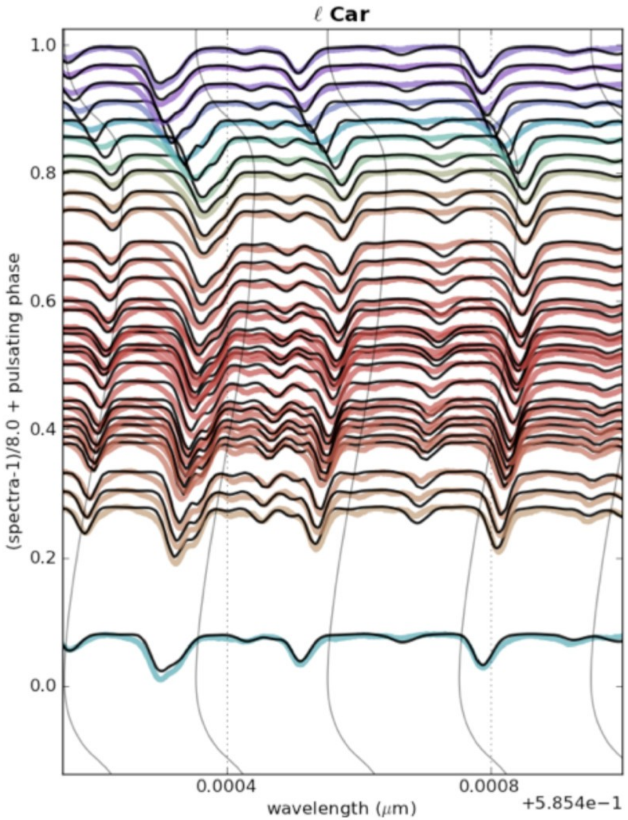
A new approach to the *p*-factor issue



Bypass problematic Cepheid v_{rad}:

v_{puls} estimation !

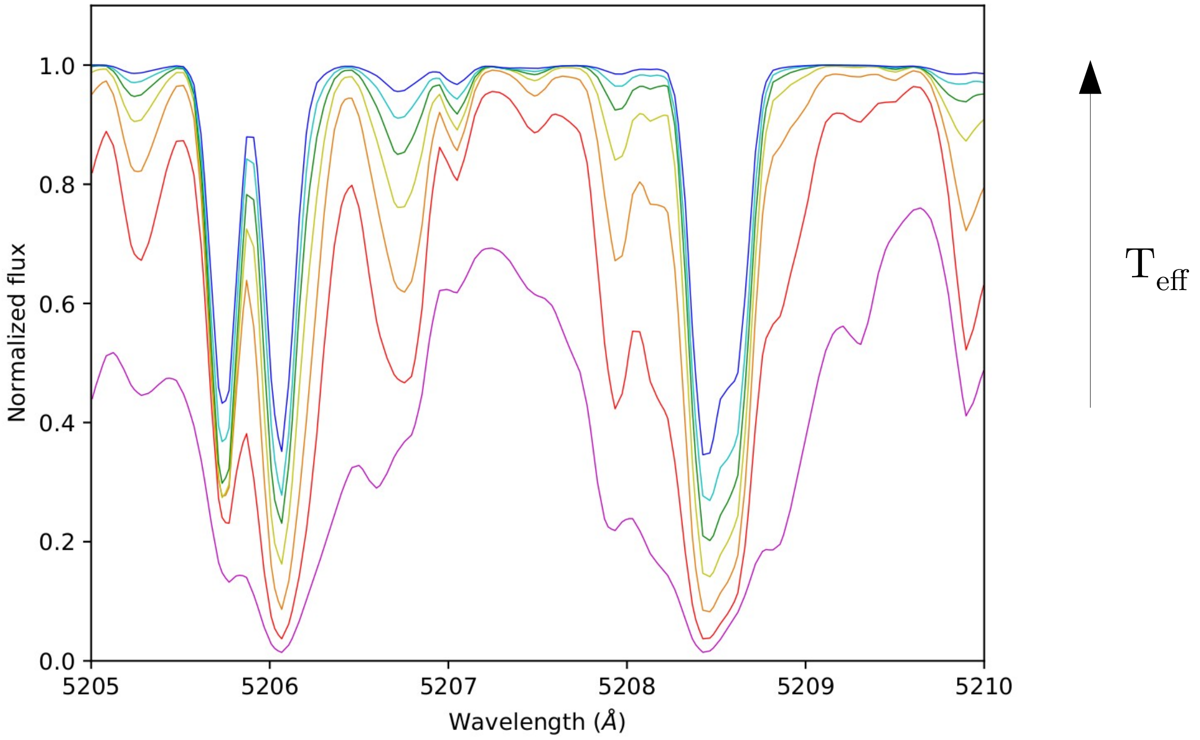
→ Line profile/CCF modeling



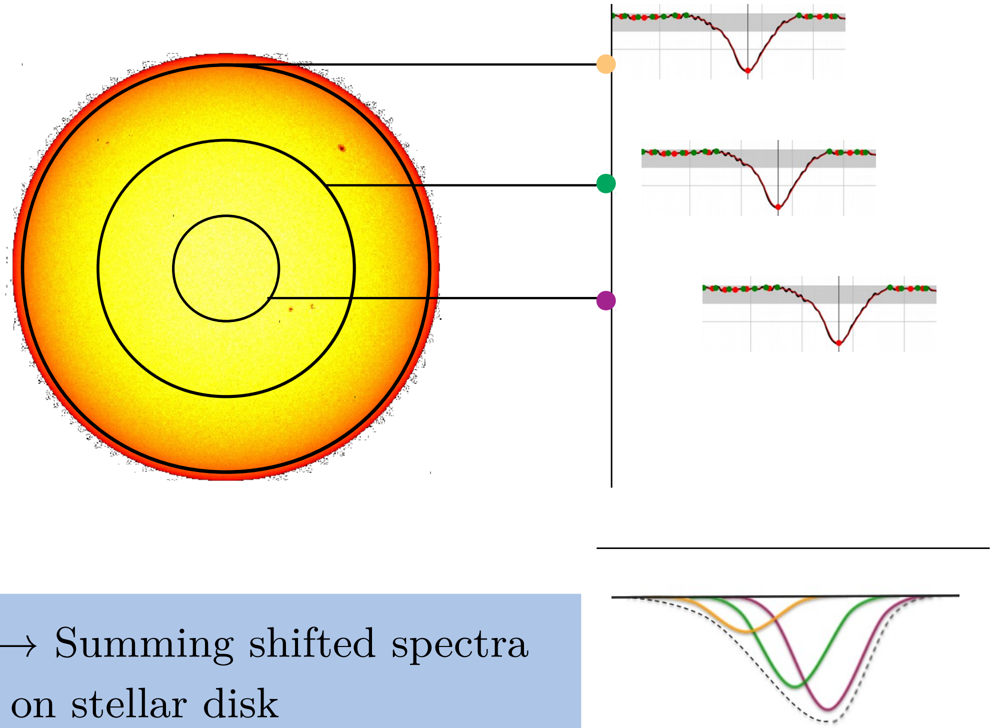
(Credit: Antoine Mérand)

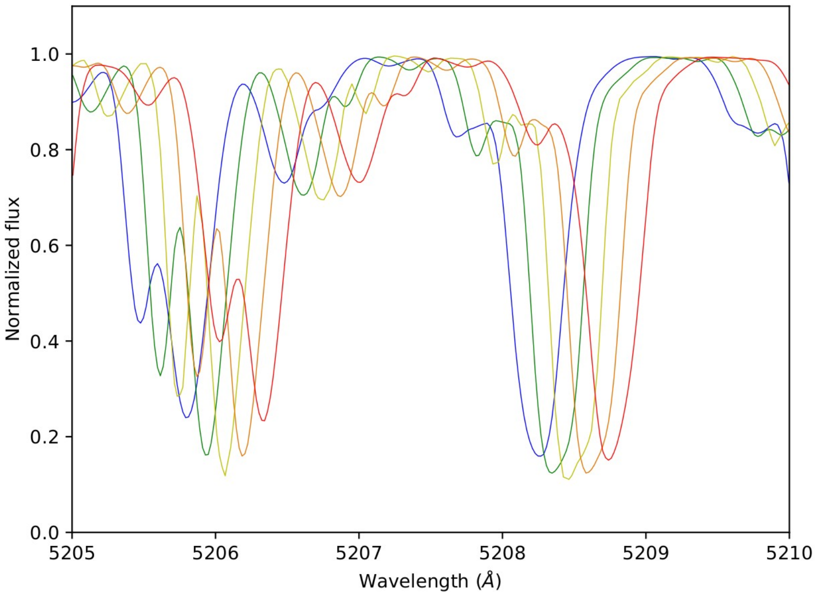
Synthetic Cepheid spectra

PHOENIX atmosphere models
Solar metallicity
$\log g$ 0.6 – 2.4
T_{eff} 4,000 – 7,000 K
v_{mic} = 2 km/s



Pulsation modeling



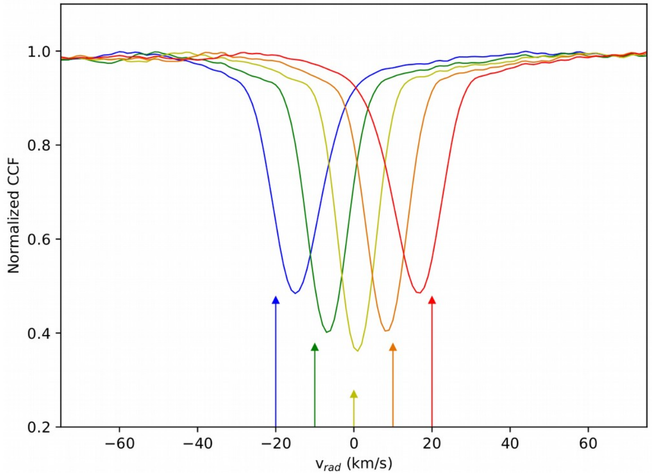


→ Summing shifted spectra on stellar disk
→ Quasi-static approximation (Vasilyev+ 2018)

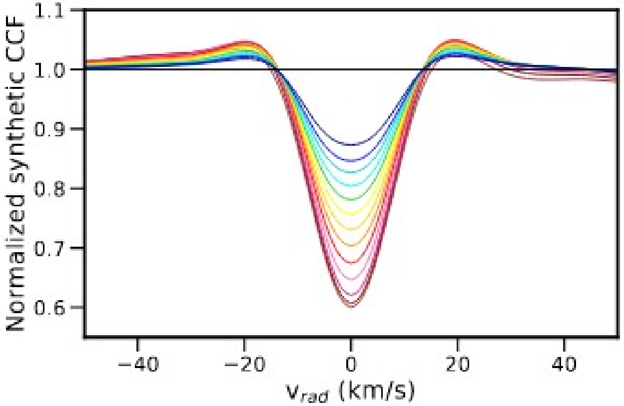
v_{puls} -50 – 50 km/s

Synthetic Cepheid CCFs

v_{puls}



T_{eff}



Fitting observed CCFs

CCF grid:
→ Correlation template
→ Input T_{eff}
→ Input v_{puls}
> 20,000 synthetic CCFs

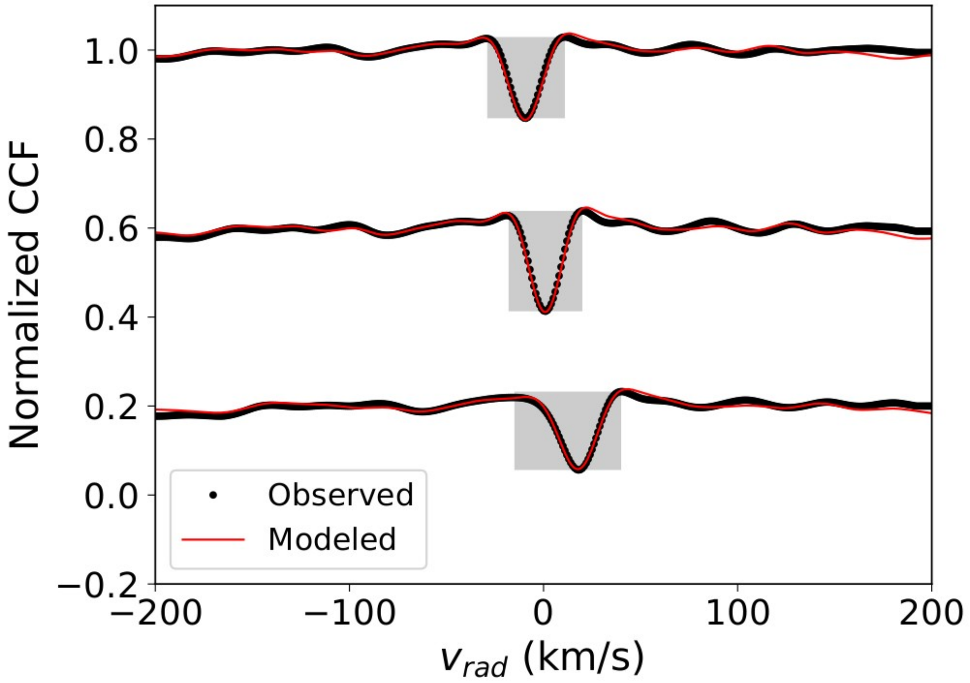
Additional parameter:
→ CCF broadening

} fixed

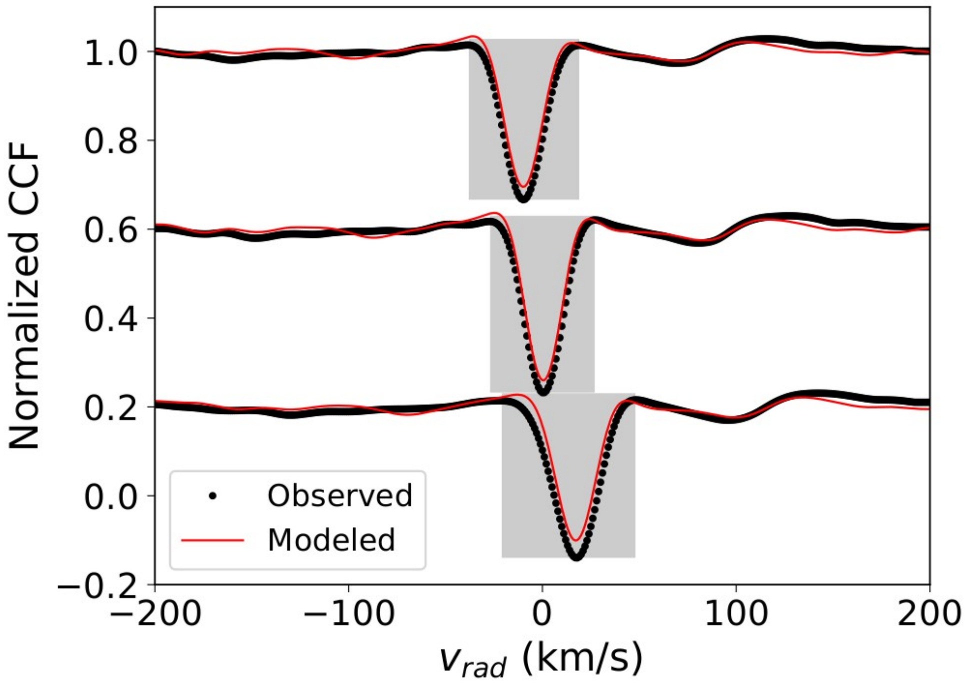
} free

CCF modeling

Test on δ Cephei (Cepheid prototype)

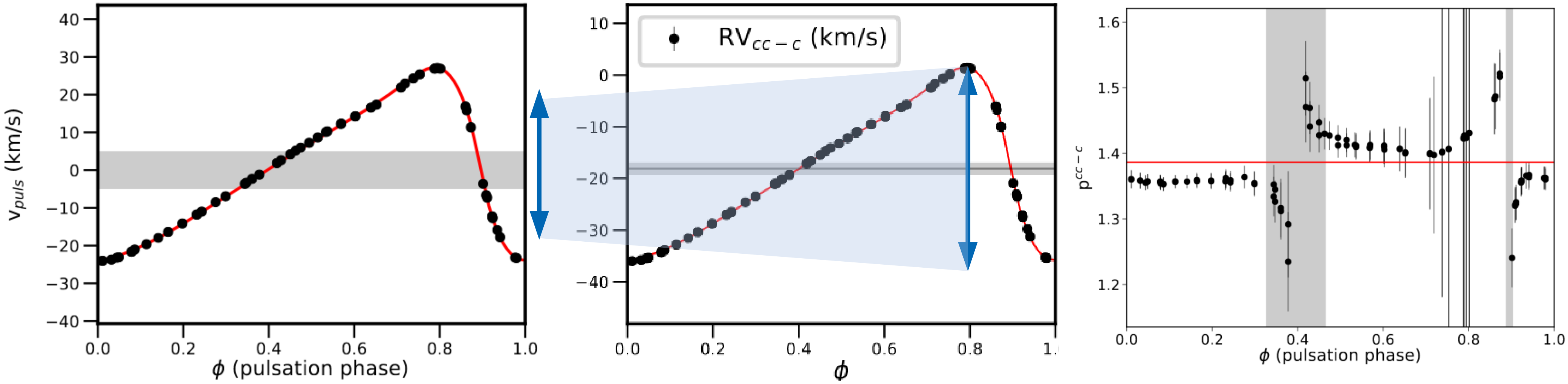


Median-line template



Strong-line template

Photospheric pulsation velocities (v_{puls})



v_{puls} from CCF modeling

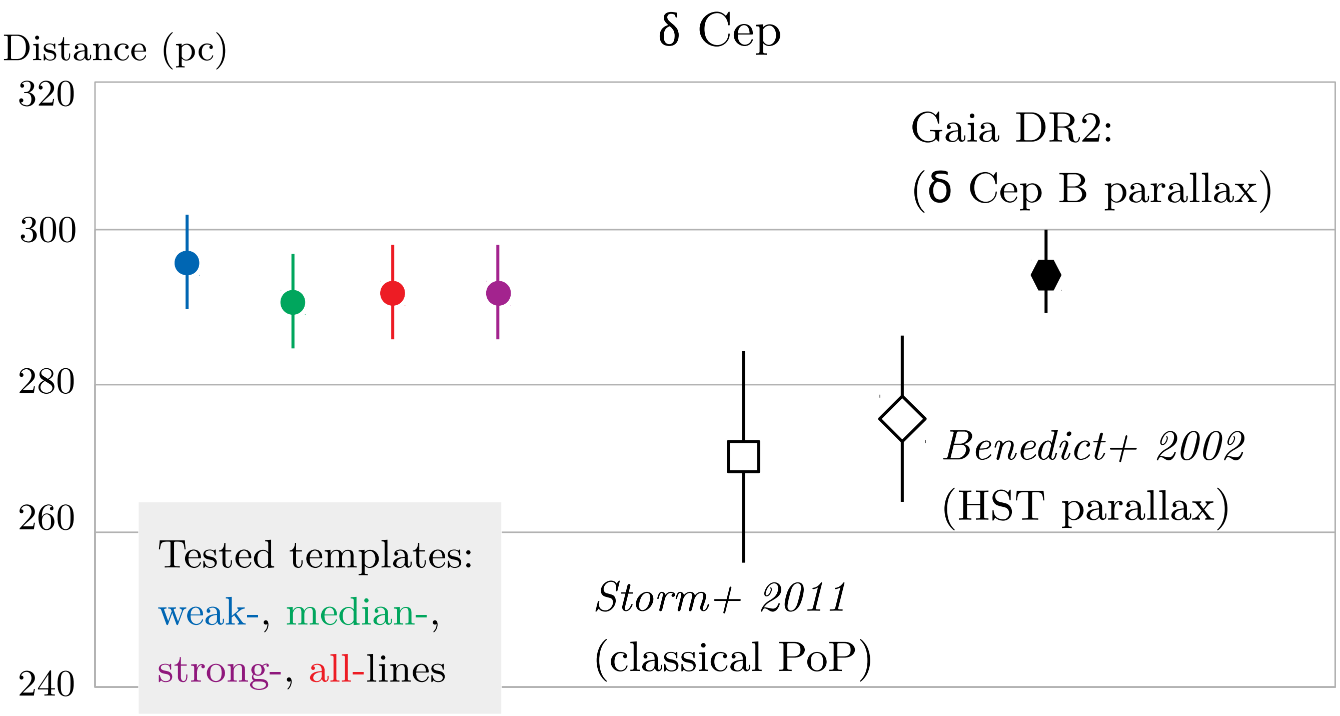
Centroid v_{rad}

$p = v_{puls} / v_{rad}$

Direct distance estimation

PoP (SPIPS) + v_{puls} instead of v_{rad}

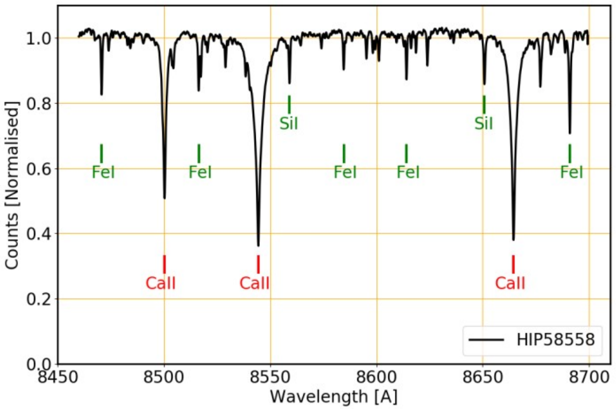
→ d instead of d/*p*



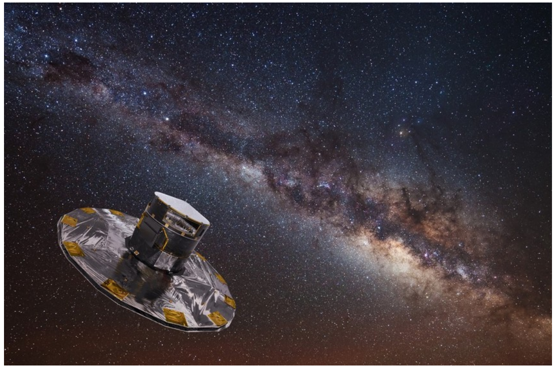
Conclusions & perspectives

Key role of **high-resolution spectroscopy**
→ Milky Way Cepheid distances
→ Period-Luminosity calibration

Perspectives in the *Gaia* era
→ 1000s Cepheids
→ v_{rad} time series (*Gaia* RVS / DR4)



Gaia RVS typical spectrum (*Katz+ 2018*)



ESA

Thank you !