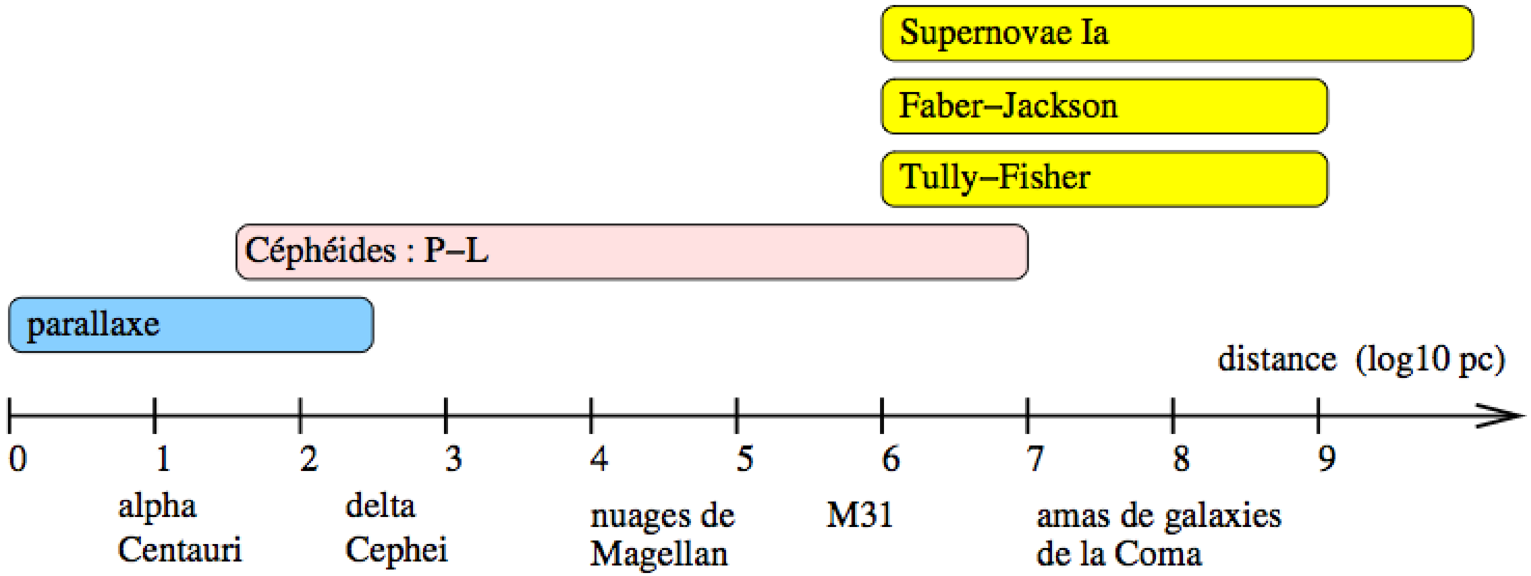
10 years of interferometric observations of Cepheids

Antoine Mérand (ESO-Chile)

Pierre Kervella (Paris Obs.)
Alexandre Gallenne (Paris Obs.)

10 years of VLTI – Garching 24-27 October 2011

- Cepheids used to measure distances: relation Period-Luminosity (P-L)
- Part of the distance scale:



- P-L calibration requires direct distances

A New Era In Cosmology
ASP Conference Series, Vol. 283, 2002
N. Metcalfe and T. Shanks, eds

Tammann et al. (2002)

Cepheids, Supernovae, H_0, and the Age of the Universe

$$H_0(\text{cosmic}) = 60.8 \pm 2.3. \qquad (16)$$

For all practical applications $H_0 = 60$ can be used everywhere, except in nearby high-density regions.

So far only statistical errors have been quoted. It comes as a surprise that the largest source of systematic errors is in the *shape* of the P-L relation (6%), followed by the metallicity dependence of Cepheids and the photometric HST zero point in the crowded fields of SNe Ia-calibrating galaxies (4%). The zero point of the P-L relation, the slope of the Δm_{15} correction of SNe Ia and the HST photometry may each contribute systematic 2-3% errors. Systematic errors due to absorption corrections for the nearby, calibrating SNe Ia and the distant SNe Ia are negligible, because the two sets have closely the same colors ($< B - V >= -0.01 \pm 0.01$; cf. Parodi et al. 2000). Unless there is a conspiracy of the individual systematic errors, the total systematic error is $< 10\%$.

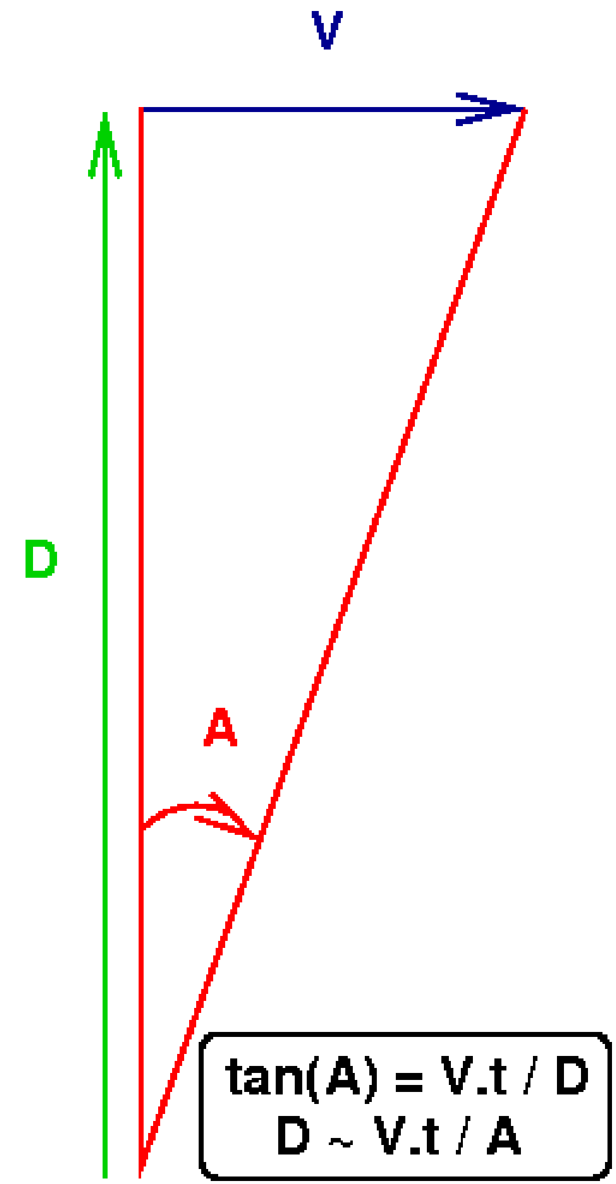
The resulting expansion age of $T = 15.7 \pm 1.5$ Gy ($H_0 = 60 \pm 5$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) gives sufficient room for the oldest dated objects in the Galaxy.

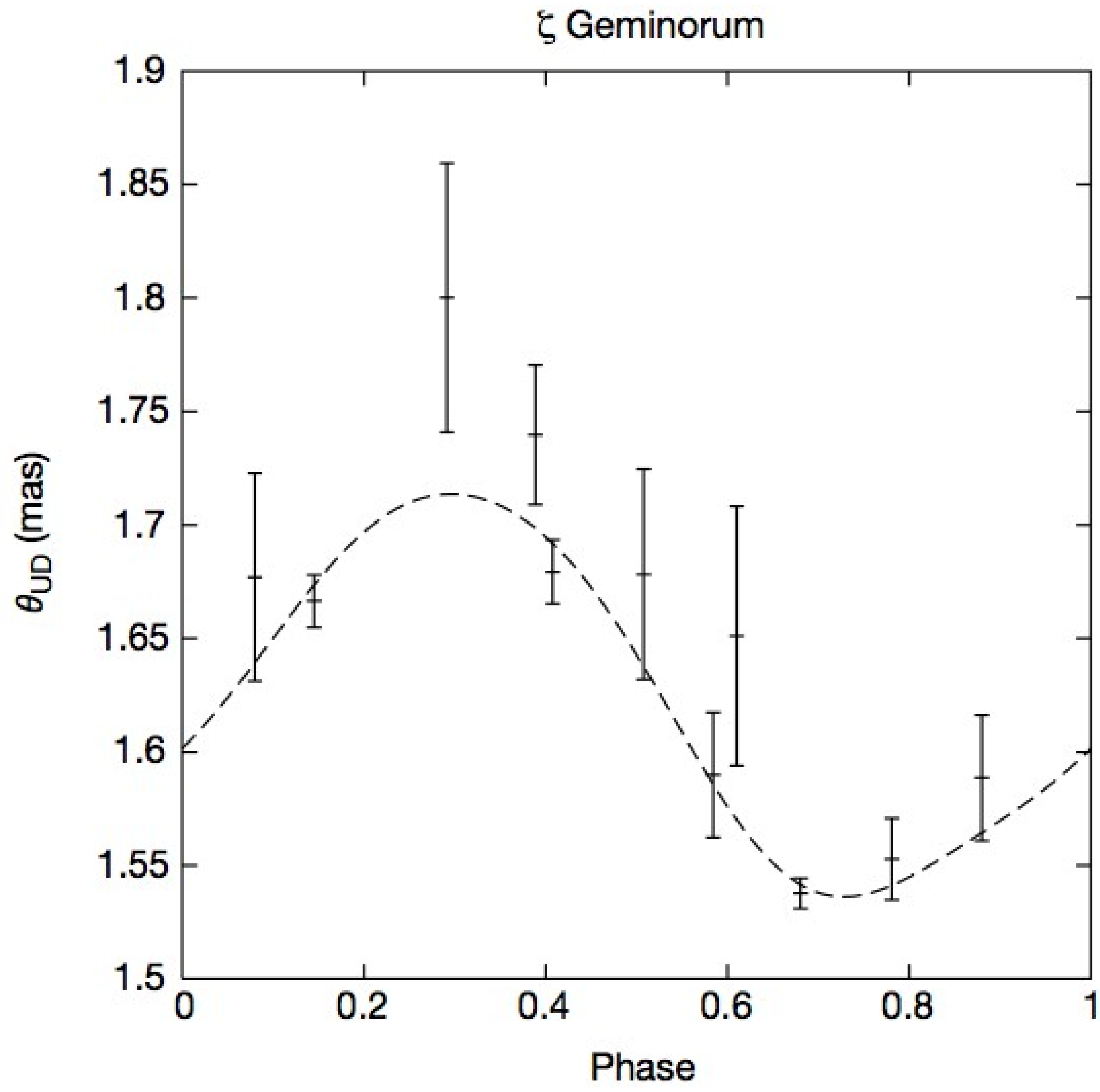
Parallax of pulsation

- Combining pulsation velocity Vp (spectroscopy) to angular diameter θ (interferometry)
- Geometric distance to a pulsating star:

$$\theta(t) = \theta(t=0) + \frac{2}{d}\int_0^t v_p(\tau)\,d\tau$$

Known as the Baade-Wesselink method





Lane et al., Nature 407-485 (2000)

Simple problem

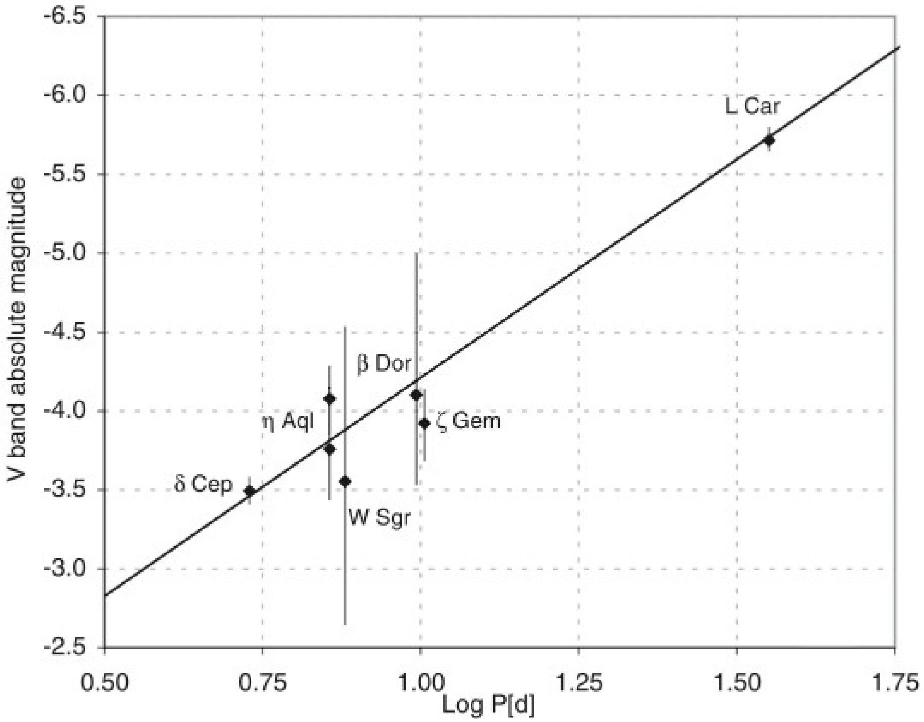
- Accurate angular diameters: VLTI/VINCI
- Still not as good as infrared surface brightness (IRSB) determination:

$$F_\lambda = 4.2207 - 0.1\, m_{\lambda_0} - 0.5 \log \theta_{LD}$$

$$F_B = -0.1199_{\pm 0.0006}\,(B-K) + 3.9460_{\pm 0.0007}$$

$$F_V = -0.1336_{\pm 0.0008}\,(V-K) + 3.9530_{\pm 0.0006}.$$

... but these need to be calibrated by interferometry too



	β_V	$\pm\sigma_{stat}$	$\pm\sigma_{syst}$
GFG98	−4.063	±0.034	
LPG99	−4.21	±0.05	
This work, all stars	**−4.209**	**±0.075**	**±0.001**
Without δ Cep and ℓ Car	−4.358	±0.197	±0.010

Kervella et al. (2004)

Simple problem?

Spectroscopic pulsation velocities:

- Projected at the surface of the star
- Weighted by the **center-to-limb darkening**
- Asymmetric absorption line: **projection factor**

Interferometric angular diameters:

- Derived from morphology (**center-to-limb darkening**),
- Using a **model of the visibility**

Photometric IRSB:

- Estimate **reddening**; Calibrate the **SB relations**
- Are pulsating / static **photospheres** comparable?

No longer a such a simple, unbiased distance measurement...

$$k\,\boxed{\theta_{\mathrm{UD}}} = 2\frac{R_0}{d} - \frac{2p}{d}\int_0^t \boxed{v_r}(\tau)d\tau$$

Model independant observables

No longer a such a simple, unbiased distance measurement...

$$k\,\theta_{\mathrm{UD}} = 2\frac{R_0}{d} - \frac{2p}{d}\int_0^t v_r(\tau)d\tau$$

Bias estimated from atmospheres' models

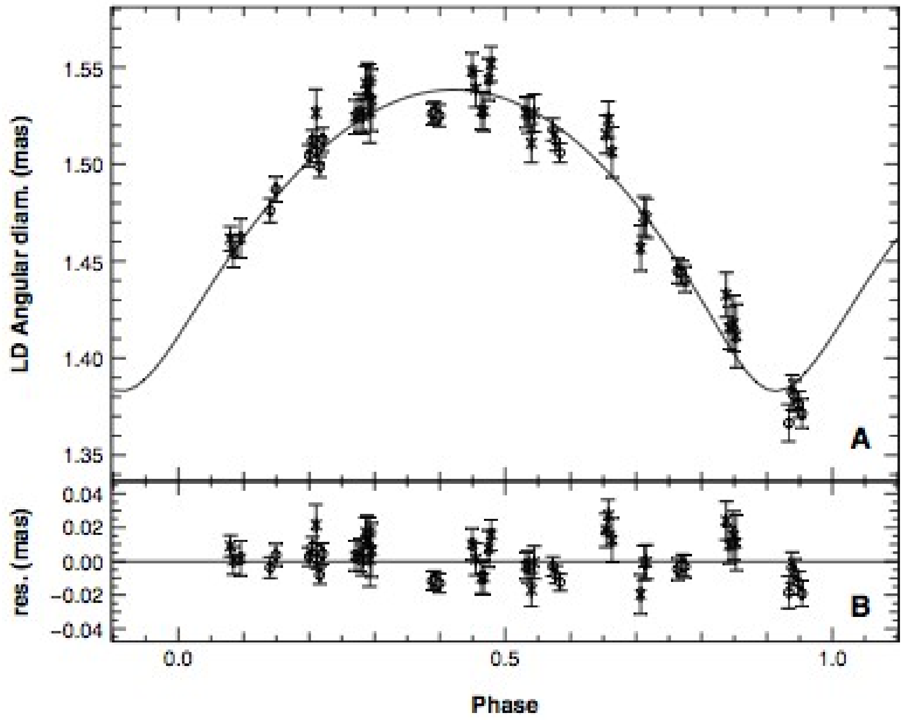
Fit

The case of δ Cep

- HST Parallax at 4% (Benedict et al. 2002)
- **Deduced p-factor: p=1.27±0.06**
- Models give from 1.36 to 1.47

There is something we do not understand

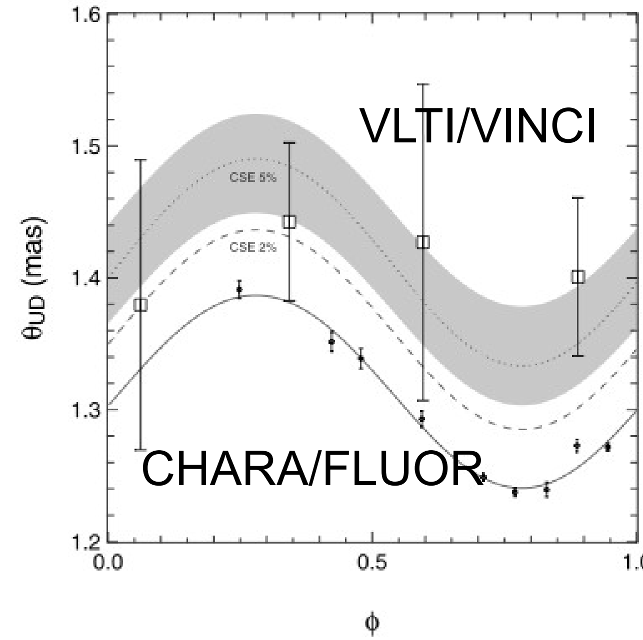
Interferometry could provide ~2% distances

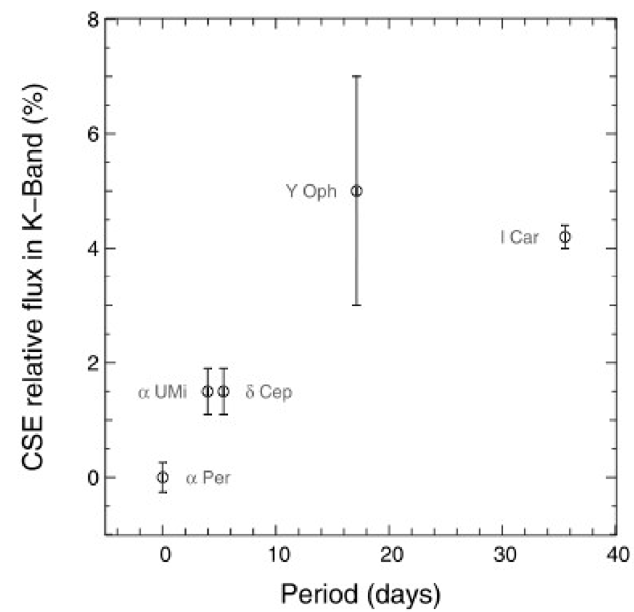


Mérand et al. 2005

Another complication...

- Cepheids appear *larger* at *shorter* baselines
- Interpreted as presence of a CSE (mass loss)
- Depends on the period of pulsation:
  - K band (Mérand et al. 2007)
  - N band (Gallenne et al. in prep)
  - Bias in slope of P-L ?

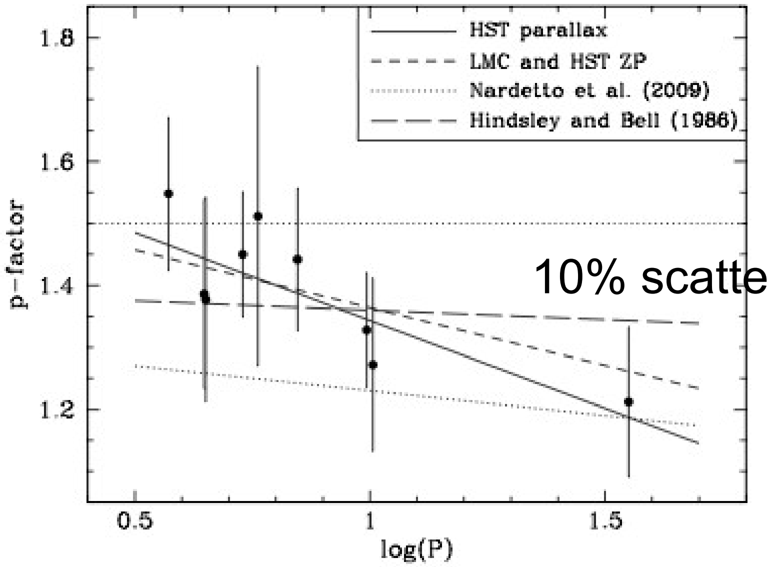




Mérand et al. 2007

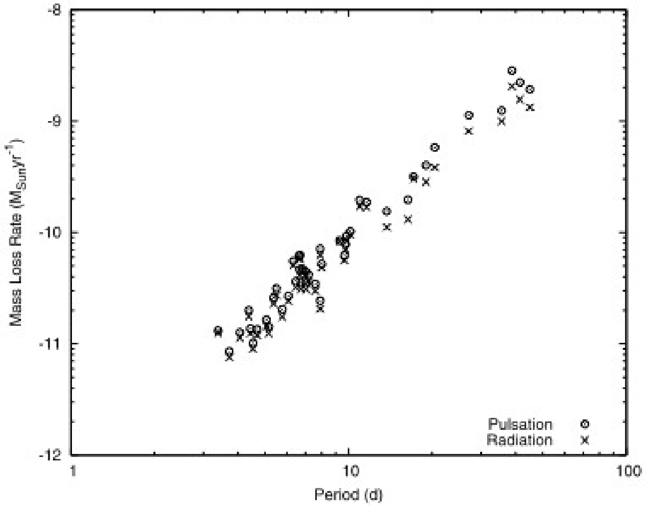
New directions in the field...

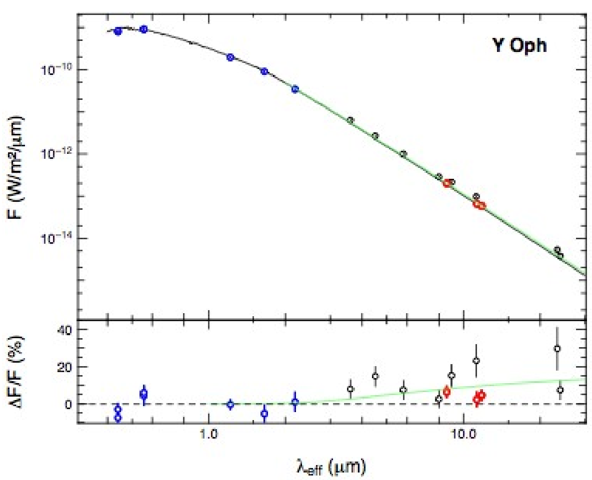
Storm et al. 2011: observations of distance to LMC as function of period
Nardetto et al. 2009: models of pulsating atmospheres



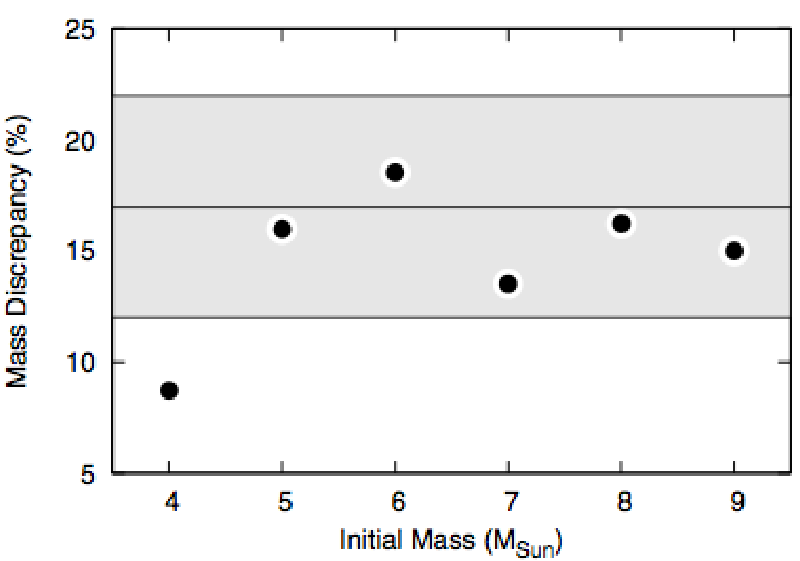
10% scatter!!!

Neilson et al. 2008: mass loss models to reproduce observed dependency with period



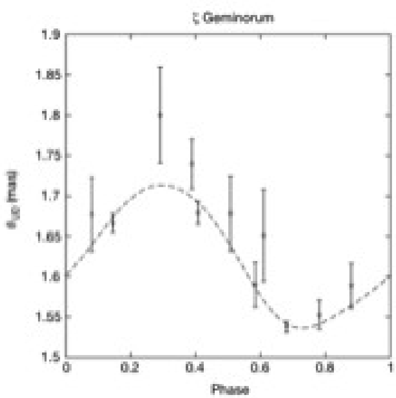


Neilson et al. 2011: mass loss models to explain mass discrepancy between **evolution** and **pulsation**



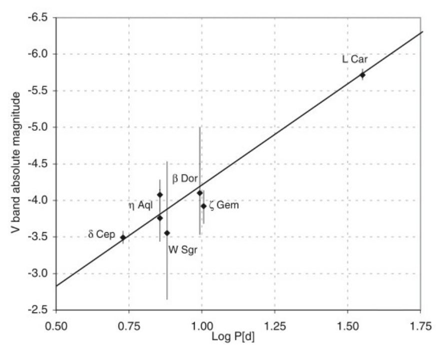
Gallenne et al. (in prep):
N band photometry and **VLTI/MIDI** observations

Interferometric Baade-Wesselink
Decennial time line



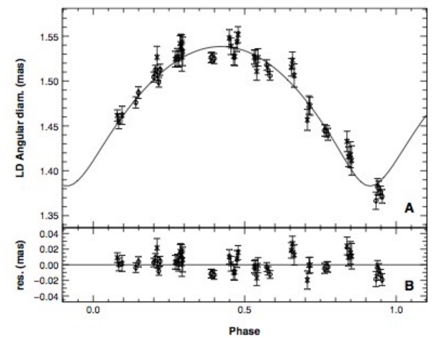
Lane et al. (2000):
First interferometric detection
of the a Cepheid's pulsation

PTI



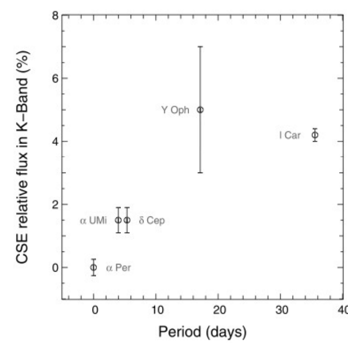
Kervella et al. (2004)
Interferometric
Calibration of P-L

VLTI/VINCI



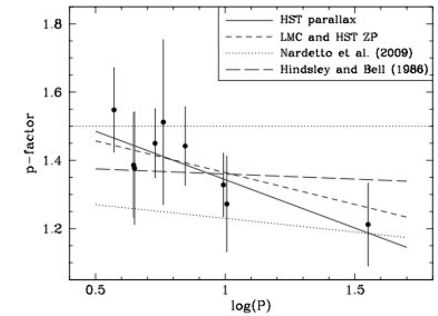
Mérand et al. (2005)
Interferometric
p-factor

CHARA/FLUOR

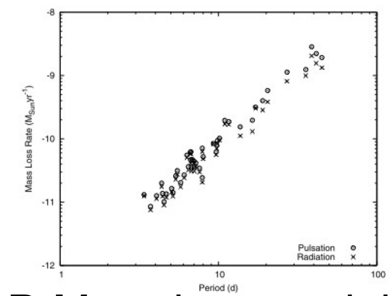


Kervella et al. (2005)
Mérand et al. (2006)
Mérand et al. (2007)
CSE around 4 Cepheids

CHARA/FLUOR
VLTI/VINCI
VLTI/AMBER

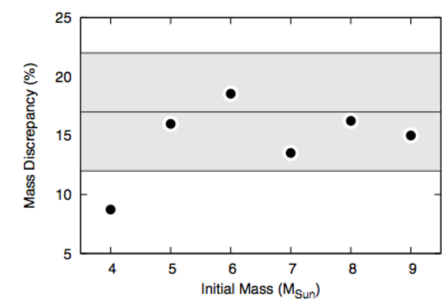


Projection factor crisis

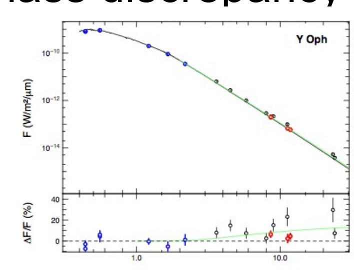


P-Mass loss models

All >2008



Mass loss models and mass discrepancy



N band excesses

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

The Nobel Prize in Physics 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory


Photo: Belinda Pratten, Australian National University


Photo: Homewood Photography

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

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"*.

Distance ladder systematics

Riess et al. 2011

H_0 Error Budget for Cepheid and SN Ia Distance Ladders[a]

Term	Description	Previous LMC	R09 N4258	Here N4258	Here All Three[b]
$\sigma_{\rm anchor}$	Anchor distance	5%	3%	3%	1.3%
$\sigma_{{\rm anchor}-PL}$	Mean of *P*–*L* in anchor	2.5%	1.5%	1.4%	0.7%[c]
$\sigma_{{\rm host}-PL}/\sqrt{n}$	Mean of *P*–*L* values in SN hosts	1.5%	1.5%	0.6 %	0.6%
$\sigma_{\rm SN}/\sqrt{n}$	Mean of SN Ia calibrators	2.5%	2.5%	1.9%	1.9%
σ_{m-z}	SN Ia *m*–*z* relation	1%	0.5%	0.5%	0.5%
$R\sigma_{\lambda,1,2}$	Cepheid reddening, zero points, anchor-to-hosts	4.5%	0.3%	0.0%	1.4%
σ_Z	Cepheid metallicity, anchor-to-hosts	3%	1.1%	0.6 %	1.0%
$\sigma_{\rm PL}$	*P*–*L* slope, Δlog *P*, anchor-to-hosts	4%	0.5%	0.4%	0.6%
$\sigma_{\rm WFPC2}$	WFPC2 CTE, long-short	3%	0%	0%	0%
Subtotal, σ_{H_0}		10%	4.7 %	4.0%	2.9%
Analysis systematics		NA	1.3%	1.0%	1.0%
Total, σ_{H_0}		10%	4.8 %	4.1%	3.1%

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σ_{PL}	P–L slope, $\Delta \log P$, anchor-to-hosts	4%	0.5%	0.4%	0.6%
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The Nobel Prize in Physics 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

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Contribution of Cepheids in H_0

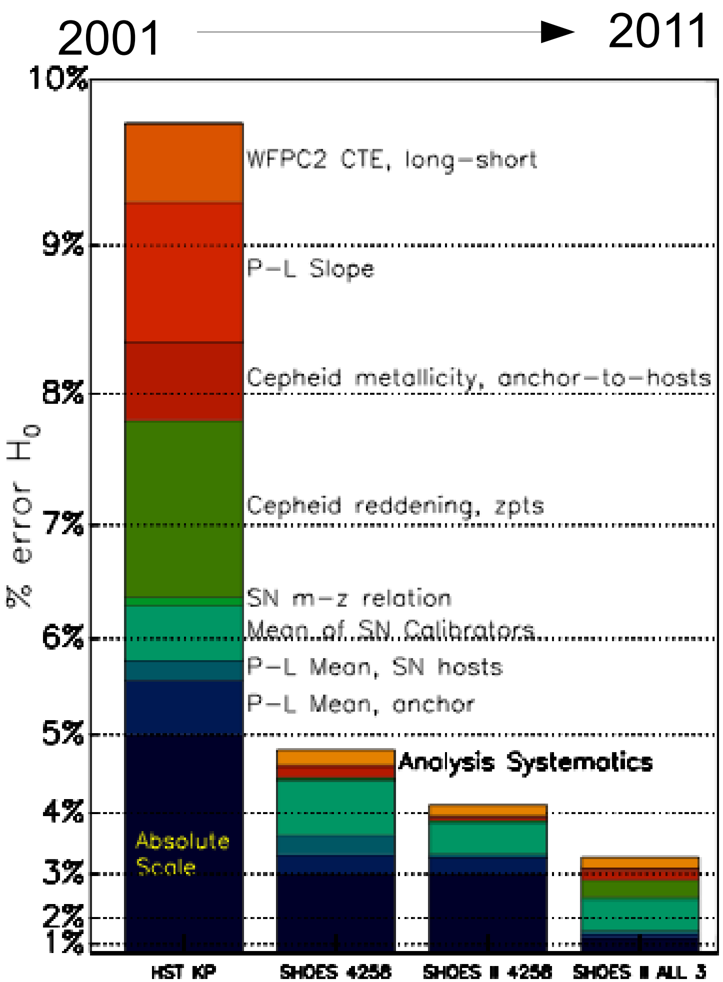


Figure 9. Uncertainties in the determination of the Hubble constant. Uncertainties are squared to show their contribution to the quadrature sum. These terms are given in Table 5.

Riess et al. (2011)

- Dramatic drop in systematics
- What has changed in 10 years?
- Do we understand better Cepheids?

Did I miss something?

3% H_0 by Riess et al. (2011)

How they gain:

- Use of single instrument (WFC3) to reduce cross calibration systematics
- Do not suffer from "p-factor crisis" by using HST parallaxes

But...

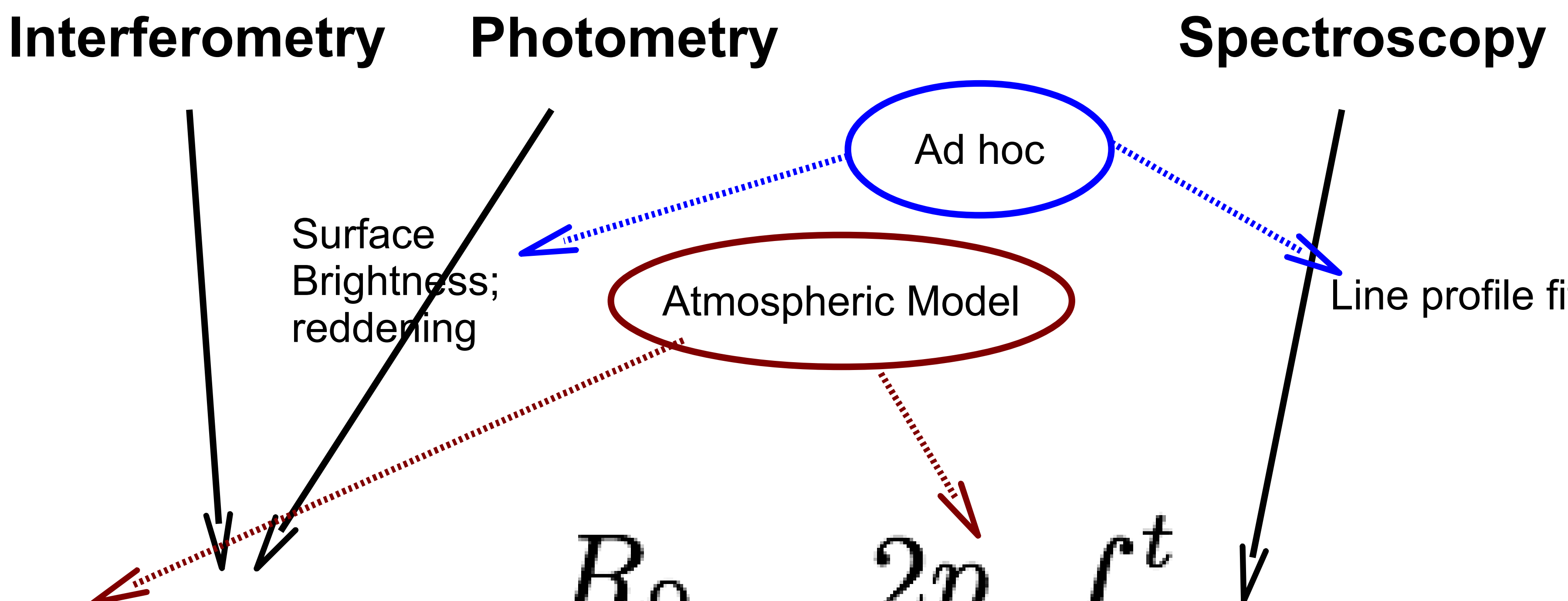
- 10 HST parallaxes of ~8%, model based
- 10 Galactic Cepheids *optimistically* averaged to get 2.5%
- Use Cepheids of P~10d and extrapolate to P~100d
- Do not have a way to ensure the reddening correction are correct (Rv=3.1)

Role of interferometry

- Better calibration of 0-point than HST based on 10 parallaxes (typical err of 8%)
  - Get direct distances measurements
- Better understanding of the physics of Cepheids to:
  - Validate extrapolations (10d -> 100d)
  - Control systematics (e.g. infrared excesses)

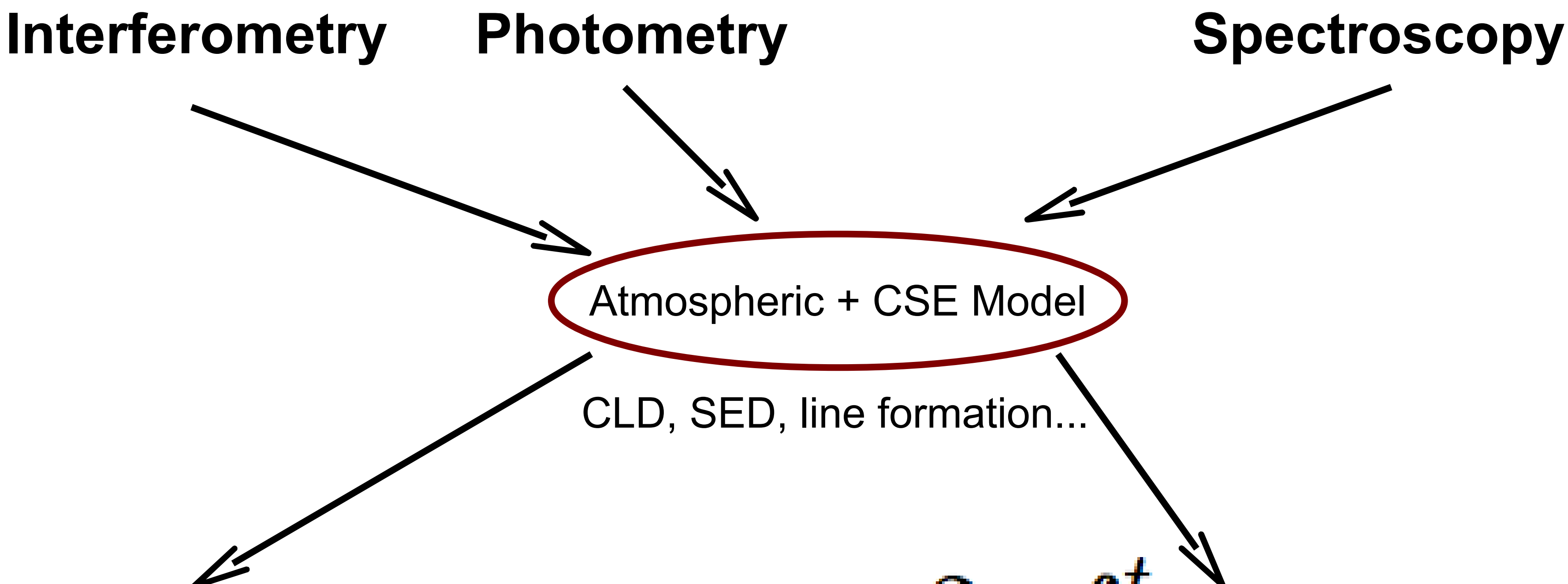
The Baade-Wesselink technique is a very powerful tool to address both!

Current BW implementation



$$k\;\theta_{\mathrm{UD}} = 2\frac{R_0}{d} - \frac{2p}{d}\int_0^t v_r(\tau)d\tau$$

Better BW implementation



$$\theta(t) = \theta(t=0) + \frac{2}{d}\int_0^t v_p(\tau)d\tau$$

Put the (single) model in the front, instead of hiding it

Model to compute:

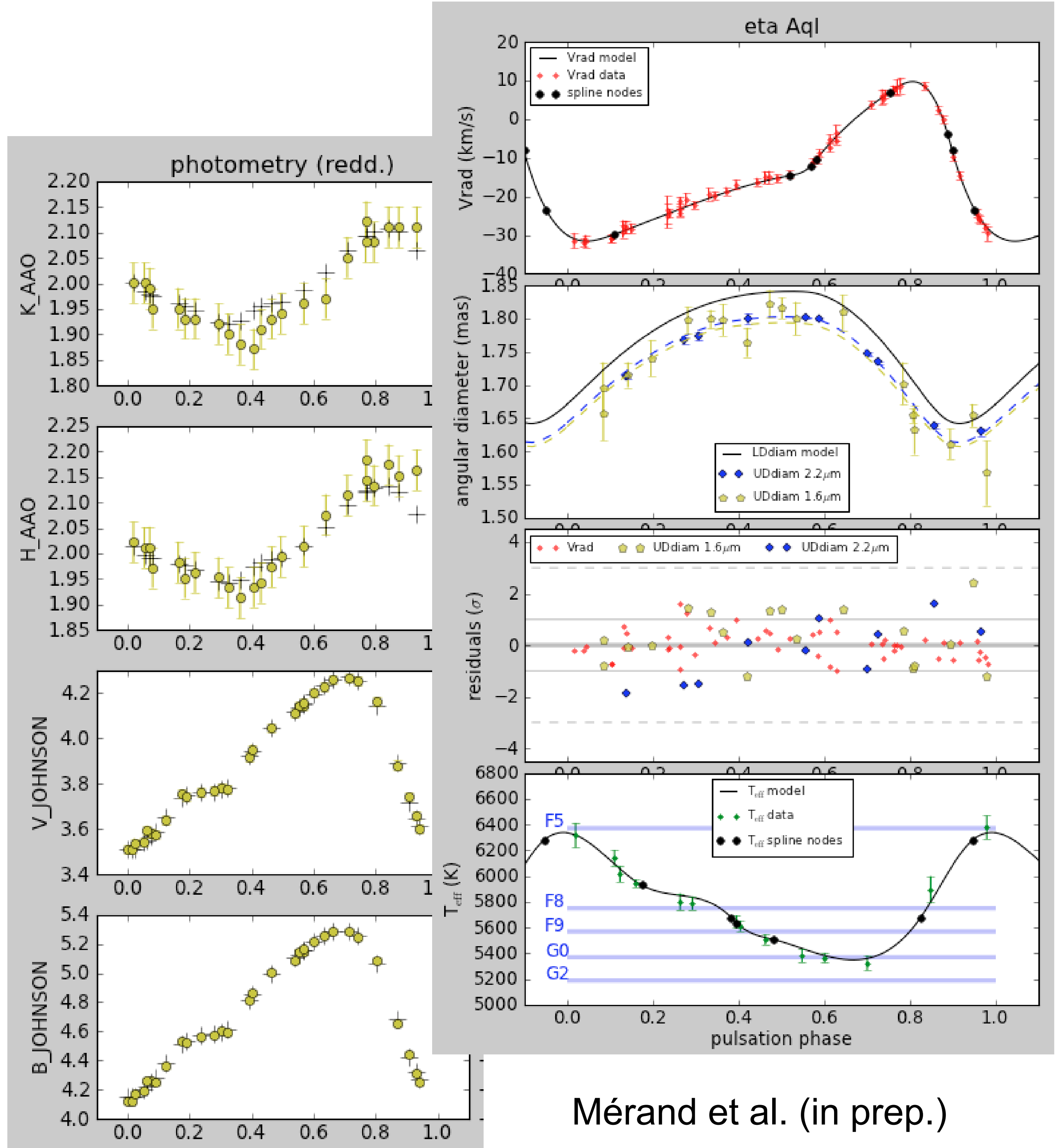
- CLD
- Teff, logg
- Photometry
- Radial velocity

Make use of redundancies in the data

- Diam: Phot. / interf.
- CLD: Spectr. / interf.

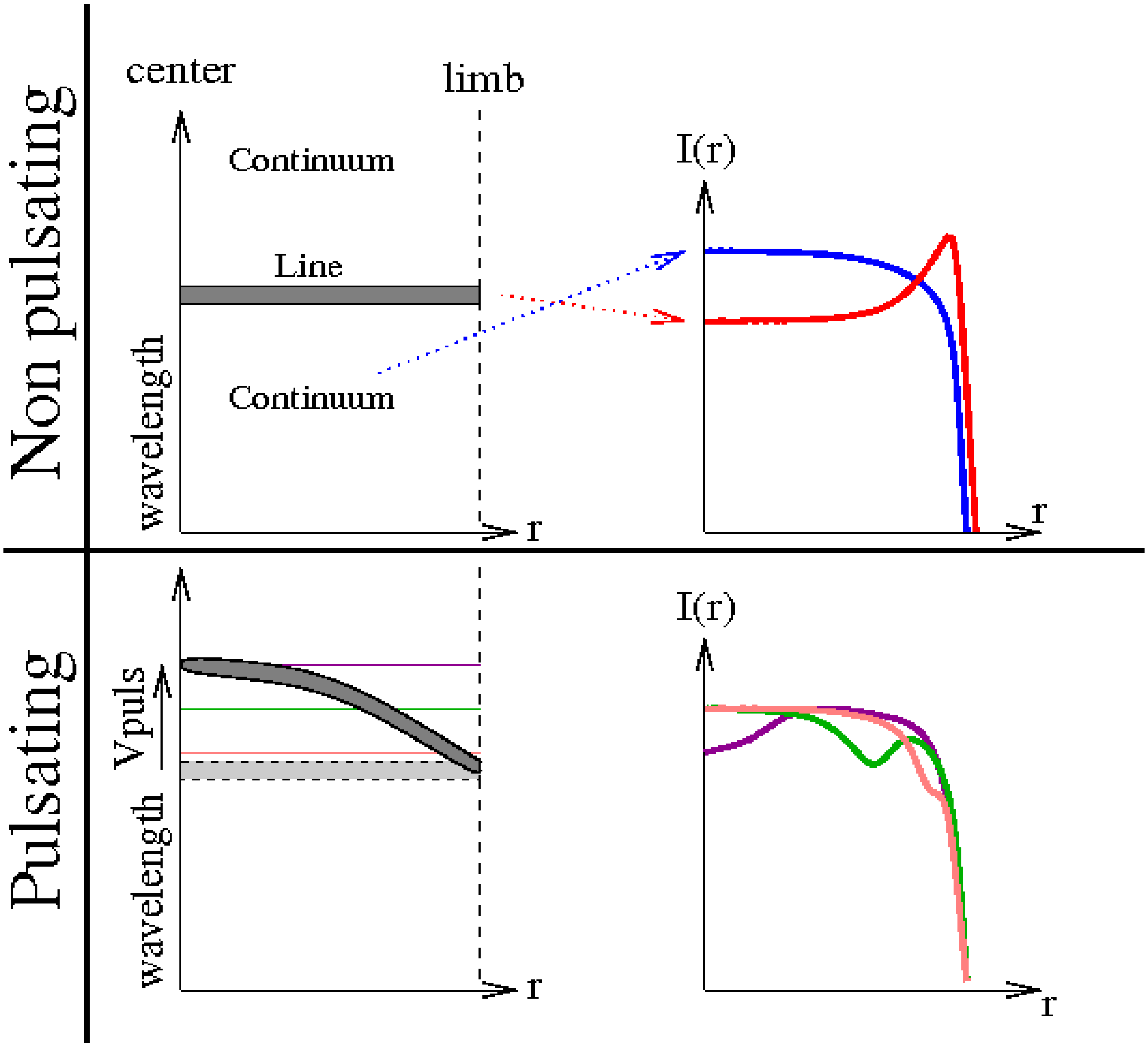
Distance down to 2%, reduced systematics

(We have ~25 stars with VLTI/VINCI and/or CHARA/FLUOR)



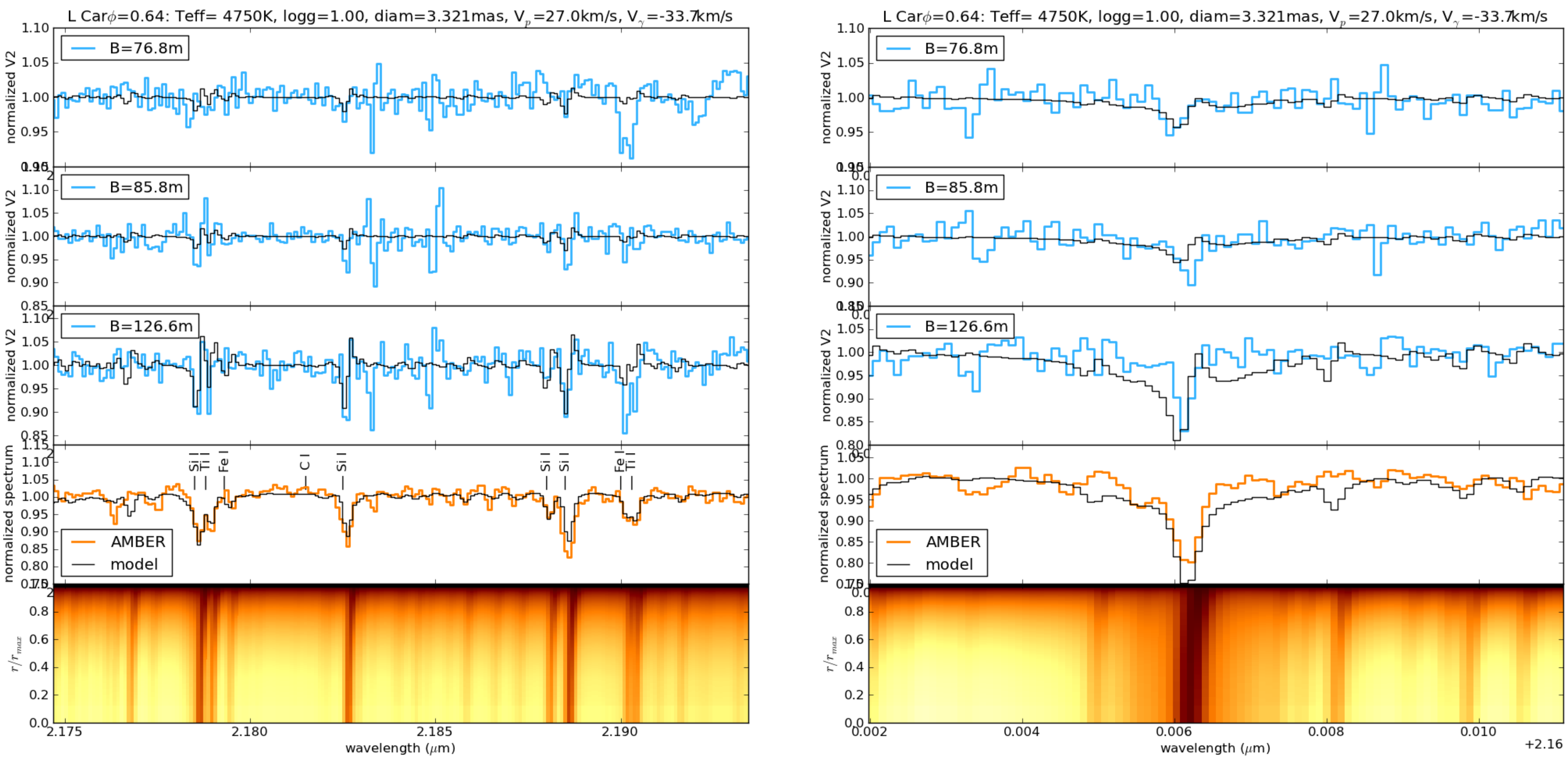
Mérand et al. (in prep.)

Resolved pulsation of an absorption line



Resolved pulsation by AMBER

+ PHOENIX models (coll. J. Aufdenberg)



Additional (and redundant) way to understand the pulsating atmosphere of Cepheids. (Mérand et al. in prep)

Conclusions

Cepheids are more relevant than ever

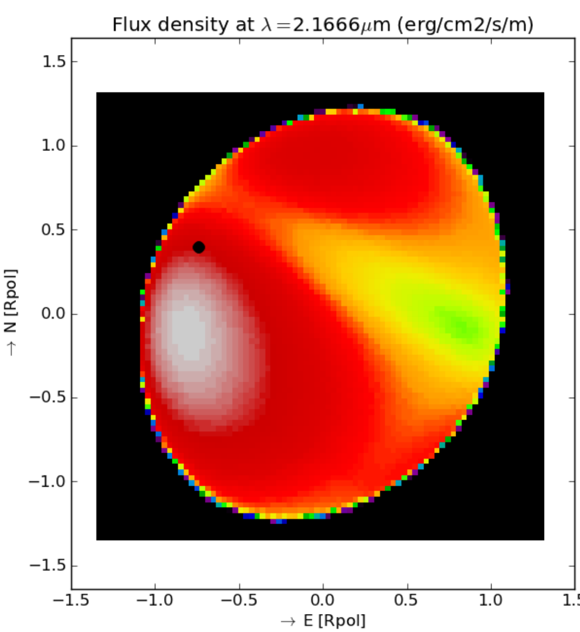
- Important in observational cosmology (Nobel 2011)
- P-L still limited by systematics (Riess et al. 2011)
- Systematics come from the physics of the Cepheids

Cepheids are more complex than we thought:

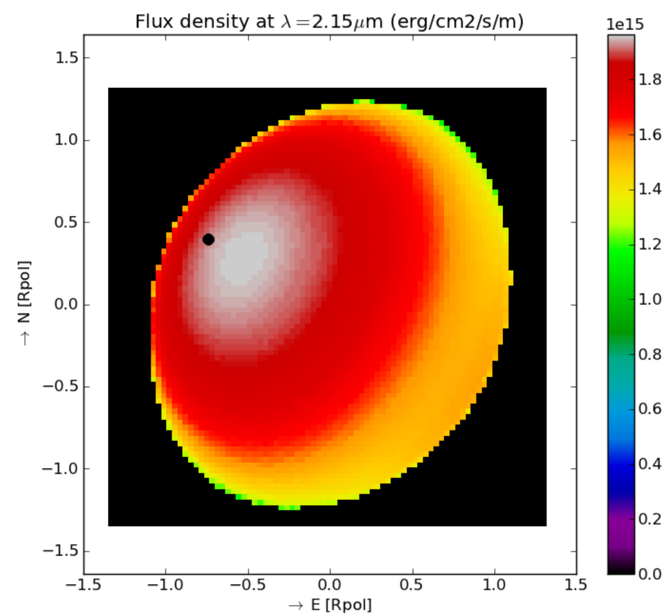
- An integrated BW method is required to understand biases: pulsating atmosphere, infrared excesses...
- Use every things we learned in stellar atmospheres
- Controlled systematics to reach bellow 3% for H_0
- GAIA and JWST will **NOT** address the systematics...

Side note: effects of rotation

AMBER data on Altair (A7V)



Model in the Br Gamma line



Model in the K band continuum