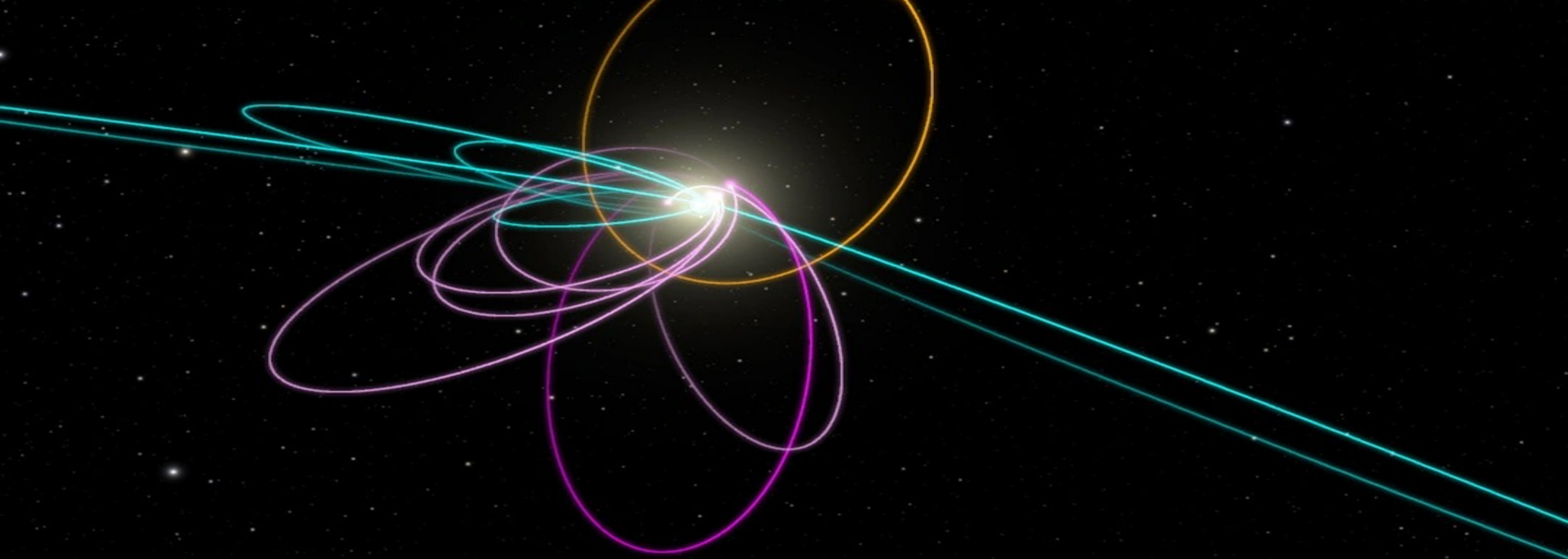
Universidad Andrés Bello | Facultad de Ciencias Exactas

Accurate determination of binary star masses and distances using optical long-baseline interferometry



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Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

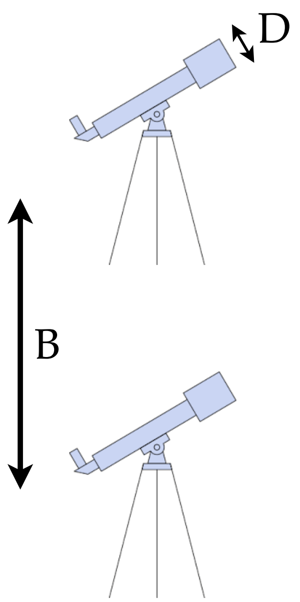
Introduction

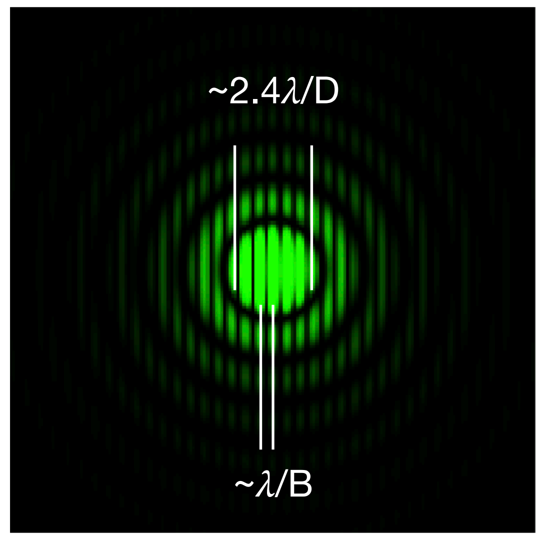
- Pros:
  - ➡ Simple method by combining radial velocities and astrometry
  - ➡ Unique objects to determine both the masses and the distance of a system
  - ➡ Can test the evolutionary models
  - ➡ Can test/validate the Gaia parallaxes
  - ➡ For binary Cepheids we can test the P-L relation

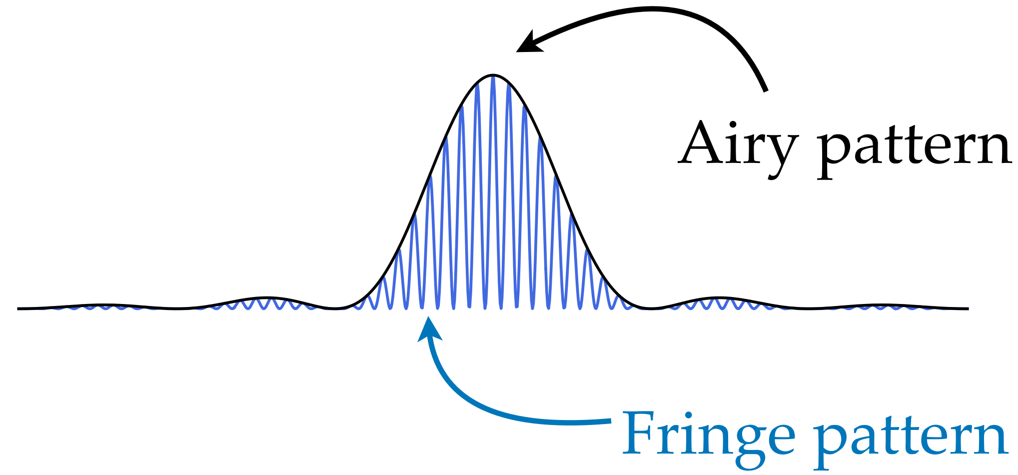
- Cons:
  - ➡ Lines of both components must be detectable (SB2) to measure RVs and remove the degeneracy mass/distance
  - ➡ Need to be spatially resolved for astrometric measurements
  - ➡ AO imaging ➠ long orbital periods

Long-baseline interferometry provides accurate & precise astrometry below the diffraction limit

Introduction





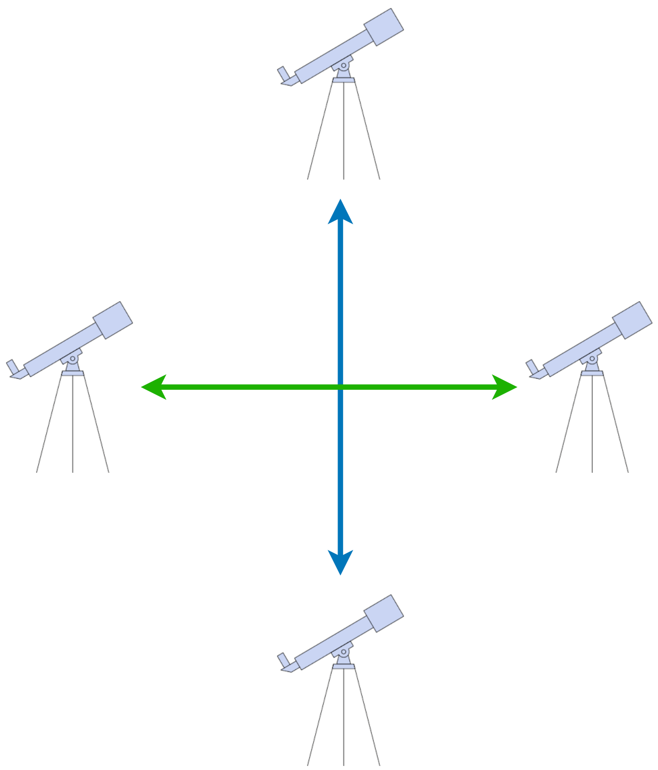


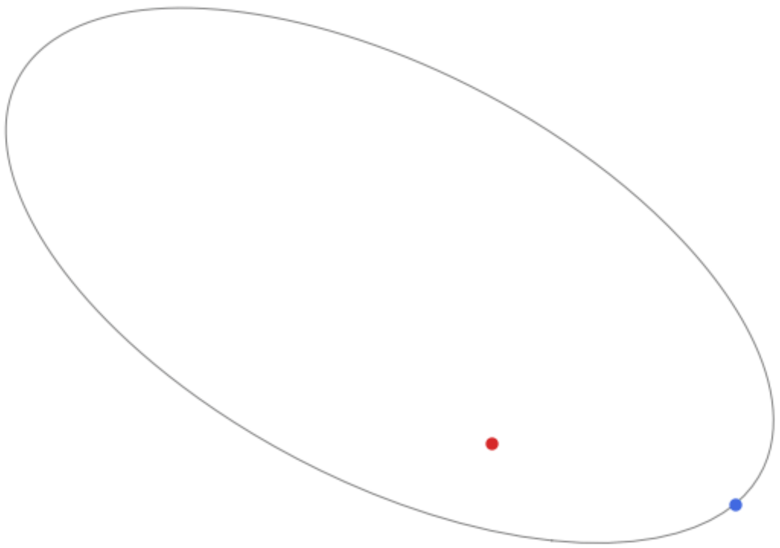
- Some numbers in H band (1.6μm):
  - ➡ VLT (D~8.2m): ~40mas
  - ➡ ELT (D~39m): ~8.5mas
  - ➡ VLTI (B~200m): ~1.5mas
  - ➡ CHARA (B~330m): ~1mas

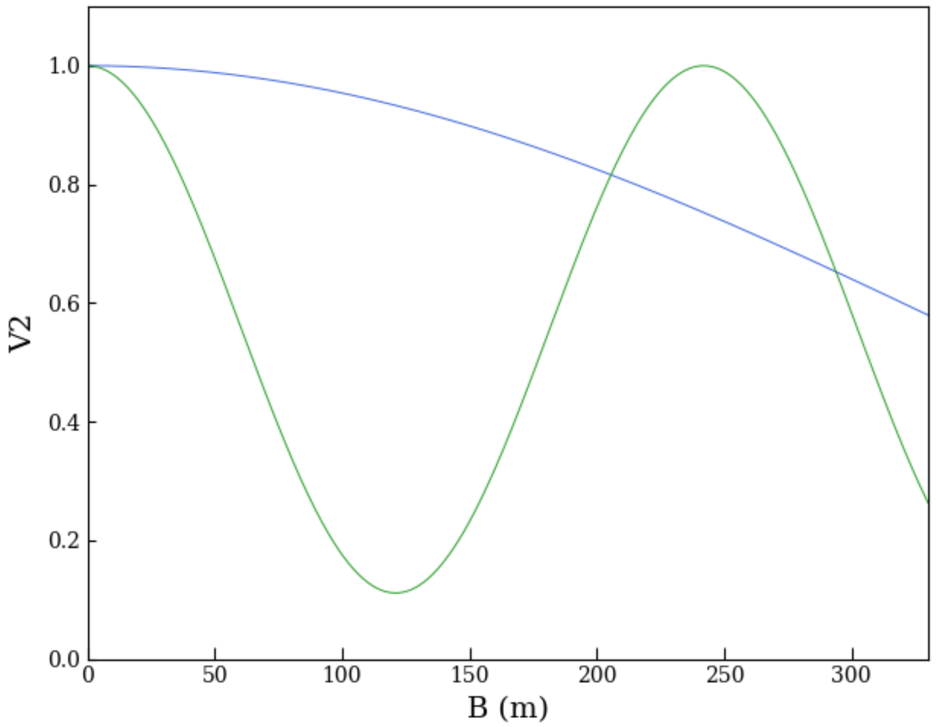
VLTI resolution~ 25xVLT ~ 6xELT

But sensitivity of a single telescope still better than interferometry

Introduction

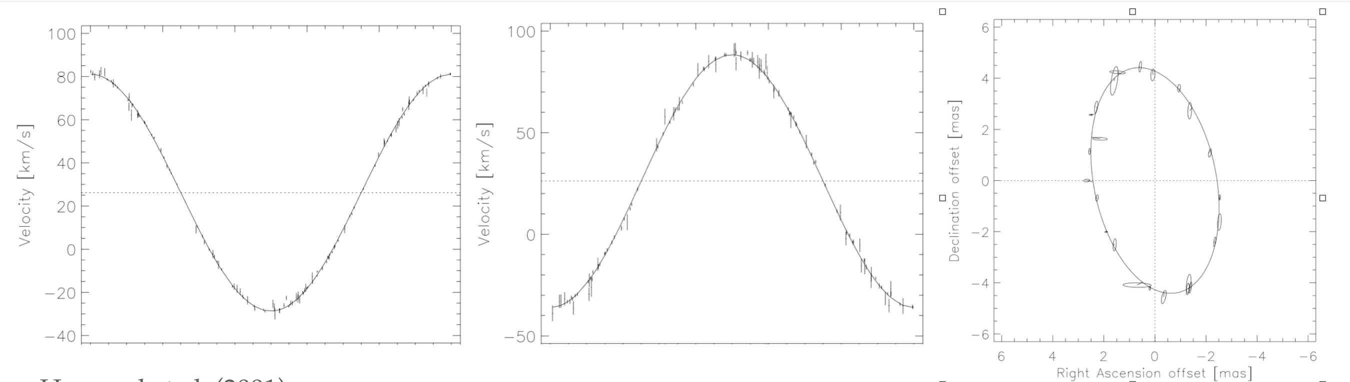






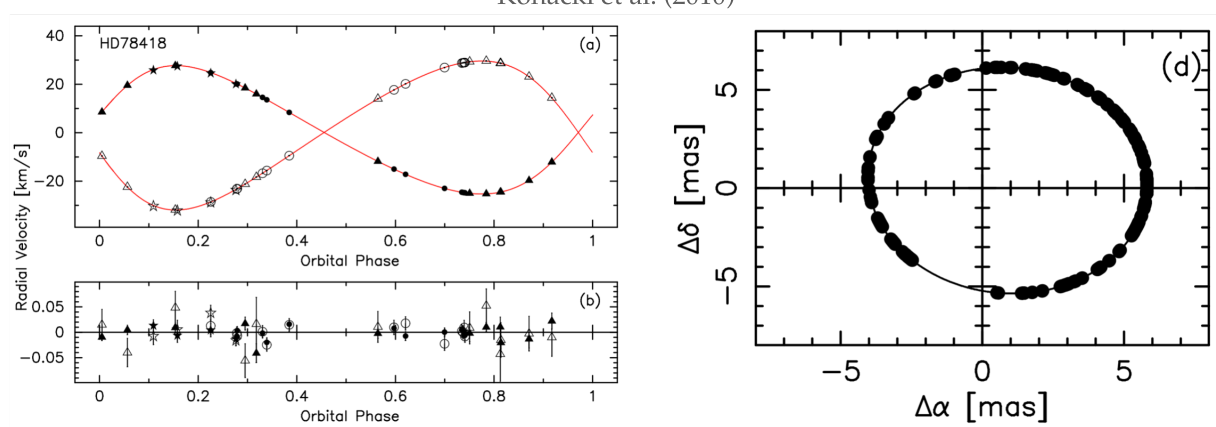
Introduction

- Not new! Already done in the past



Hummel et al. (2001)

Konacki et al. (2010)



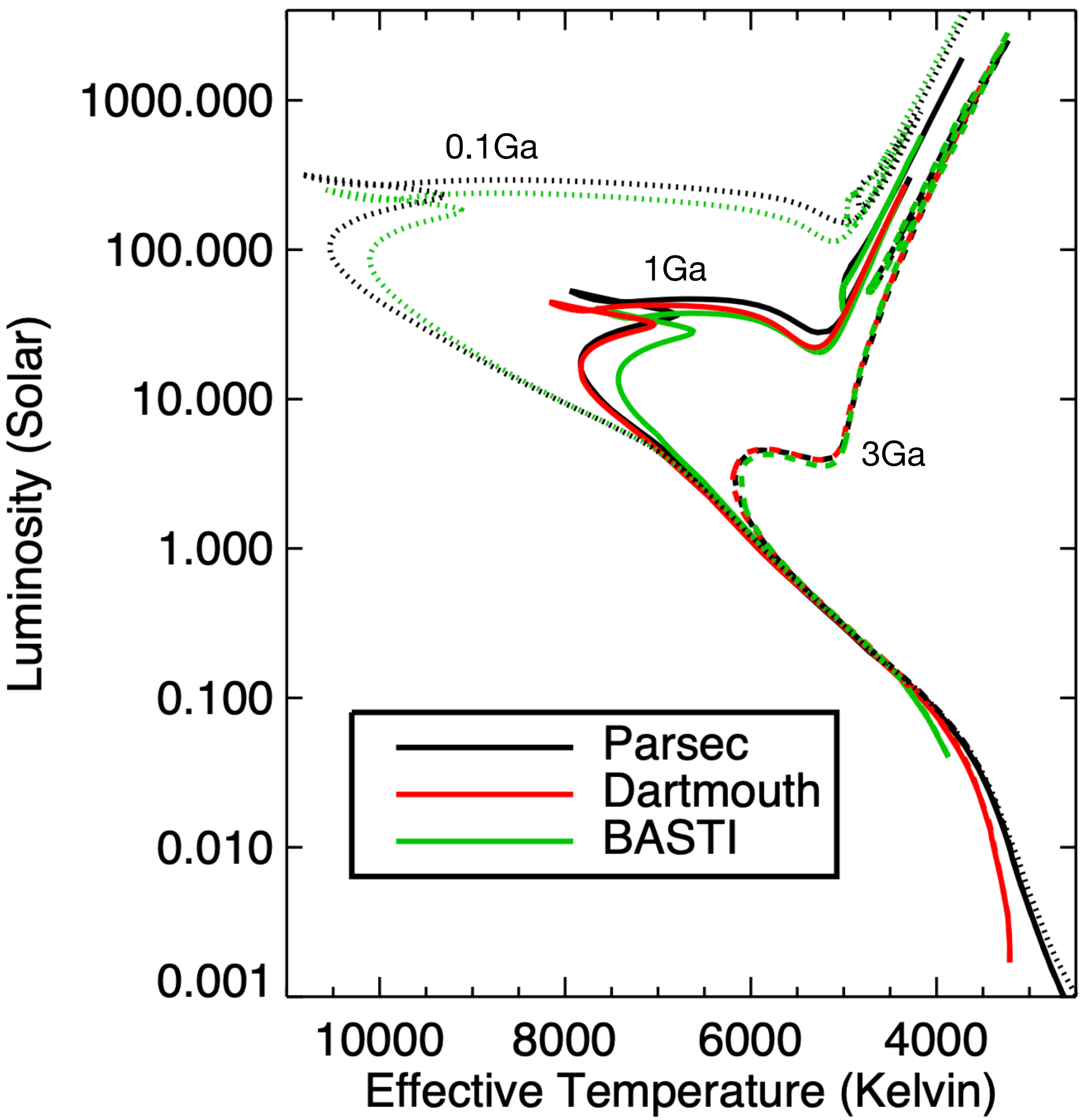
~0.5% precision on the masses
~0.2% precision on the distance ⚠

~2% precision on the masses
~0.2% precision on the distance ⚠

- But new instruments now allow to reach higher-contrast systems with a higher precision
  - RVs ~ m/s
  - Astrometry ~ μas

"Simple" Binary Stars

Huber et al. (2016)



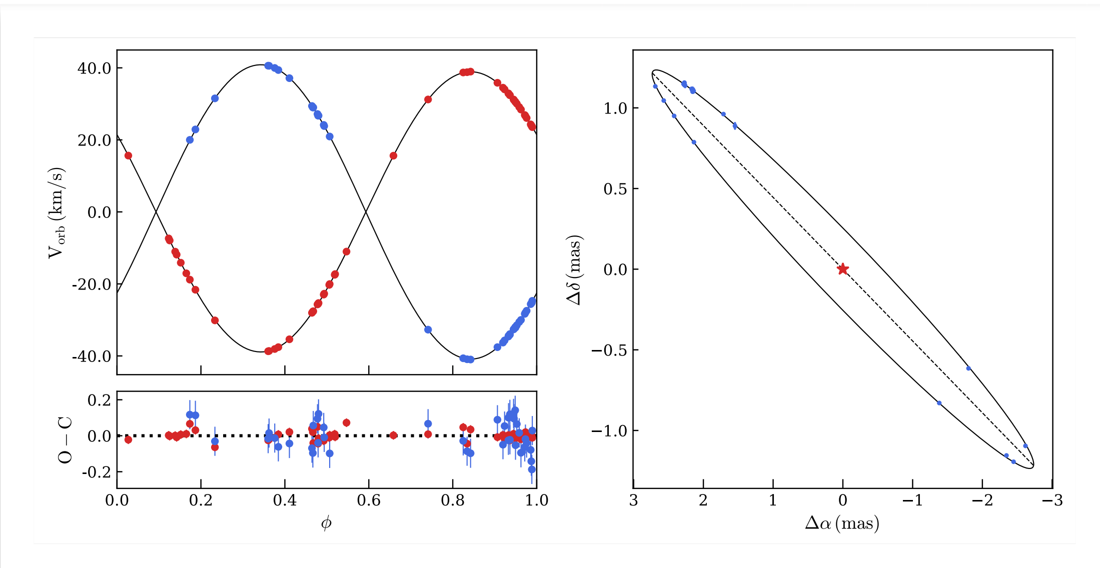
- For a given age, these 3 models differ
- Differences for high and low mass stars are mostly due to variations in poorly constrained input physics
- Models agree well for stars similar to the sun
- Uncertainties in the description of convective core overshooting lead to different main-sequence lifetimes for intermediate mass stars
- Uncertainties in the treatment of convection lead to different predictions of radii for low-mass dwarfs
- For red giants, major uncertainties include interior angular momentum transport and mass loss

- Accurate and precise masses should help to calibrate the models
- Binary stars are perfect objects for that purpose
- In addition to benchmark stars for Gaia

"Simple" Binary Stars

- Observations of binaries triggered by a project about eclisping binaries

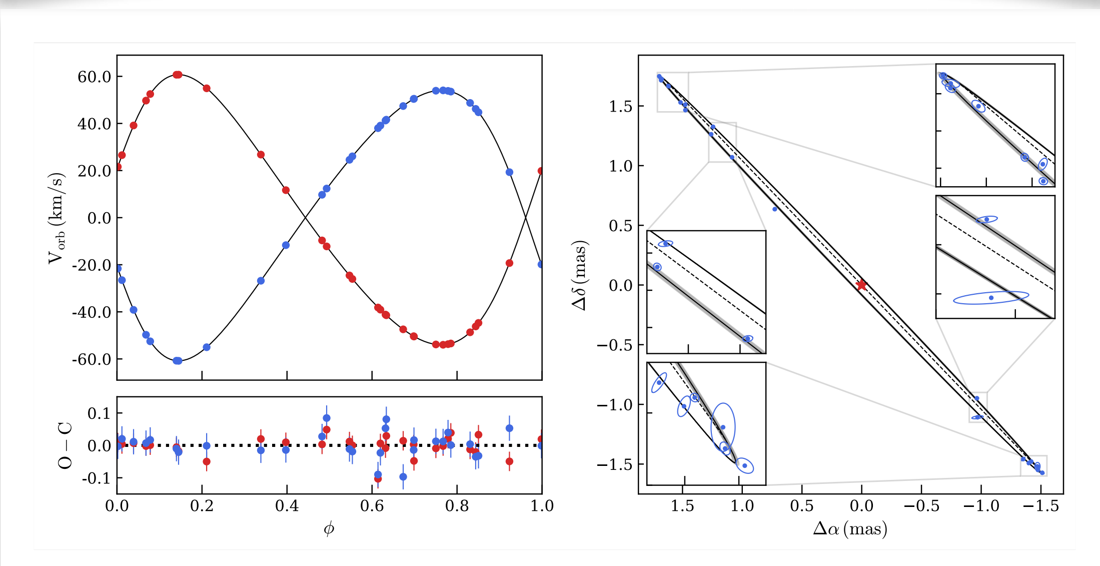
TZ For



Gallenne et al. (2016)

Masses~0.05% & distance~0.4%

AL Dor

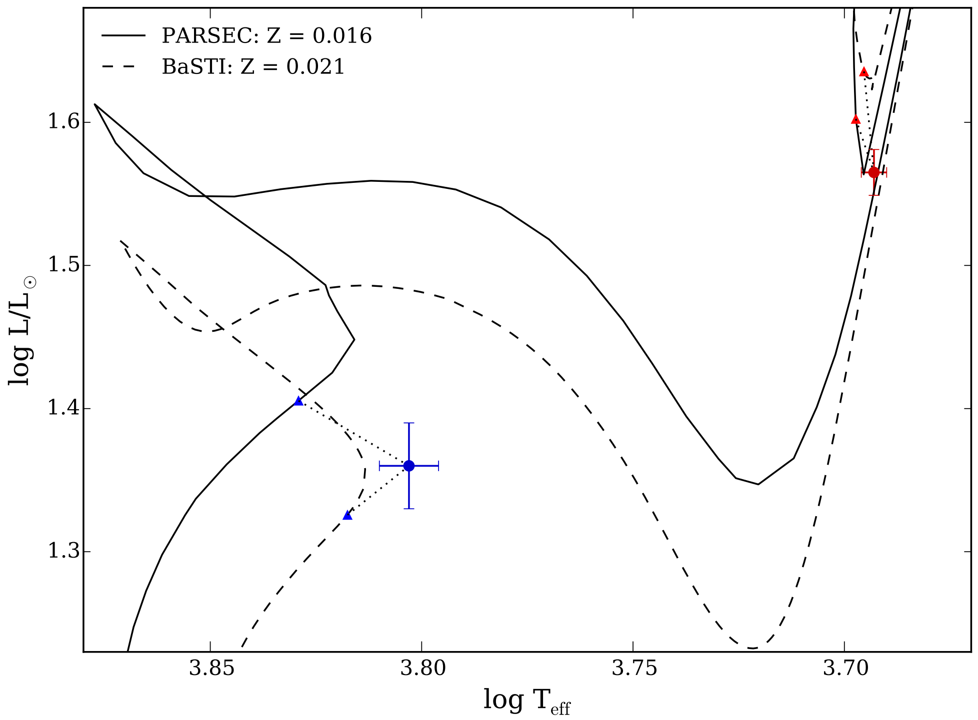


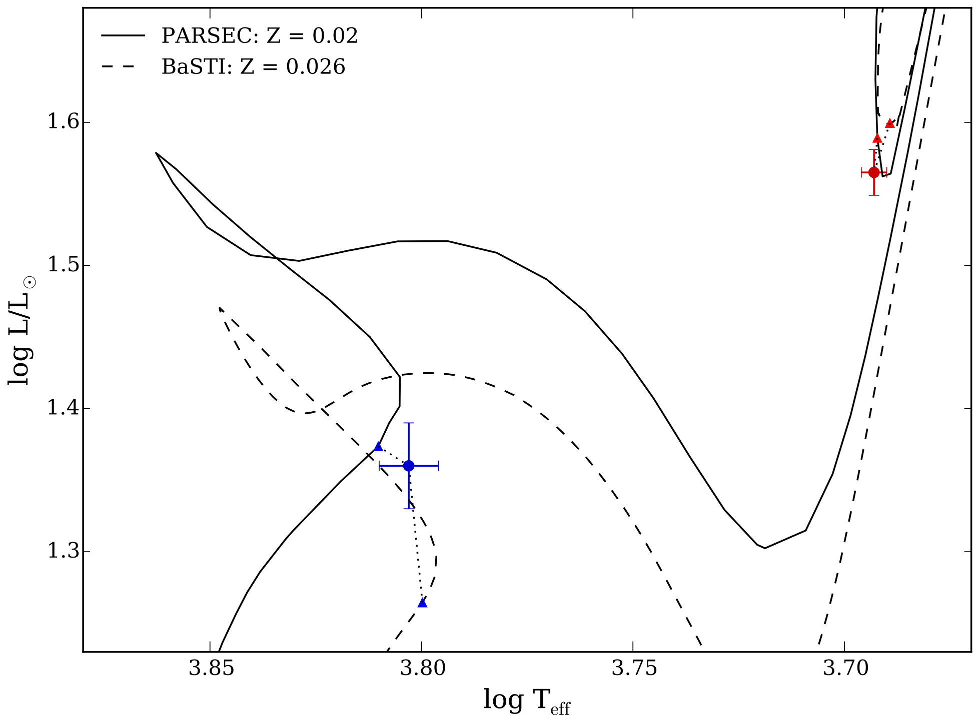
Gallenne et al. (2019)

➡ Radial velocities precise and accurate at 100m/s

➡ Astrometry precise and accurate better than 50μas

TZ For

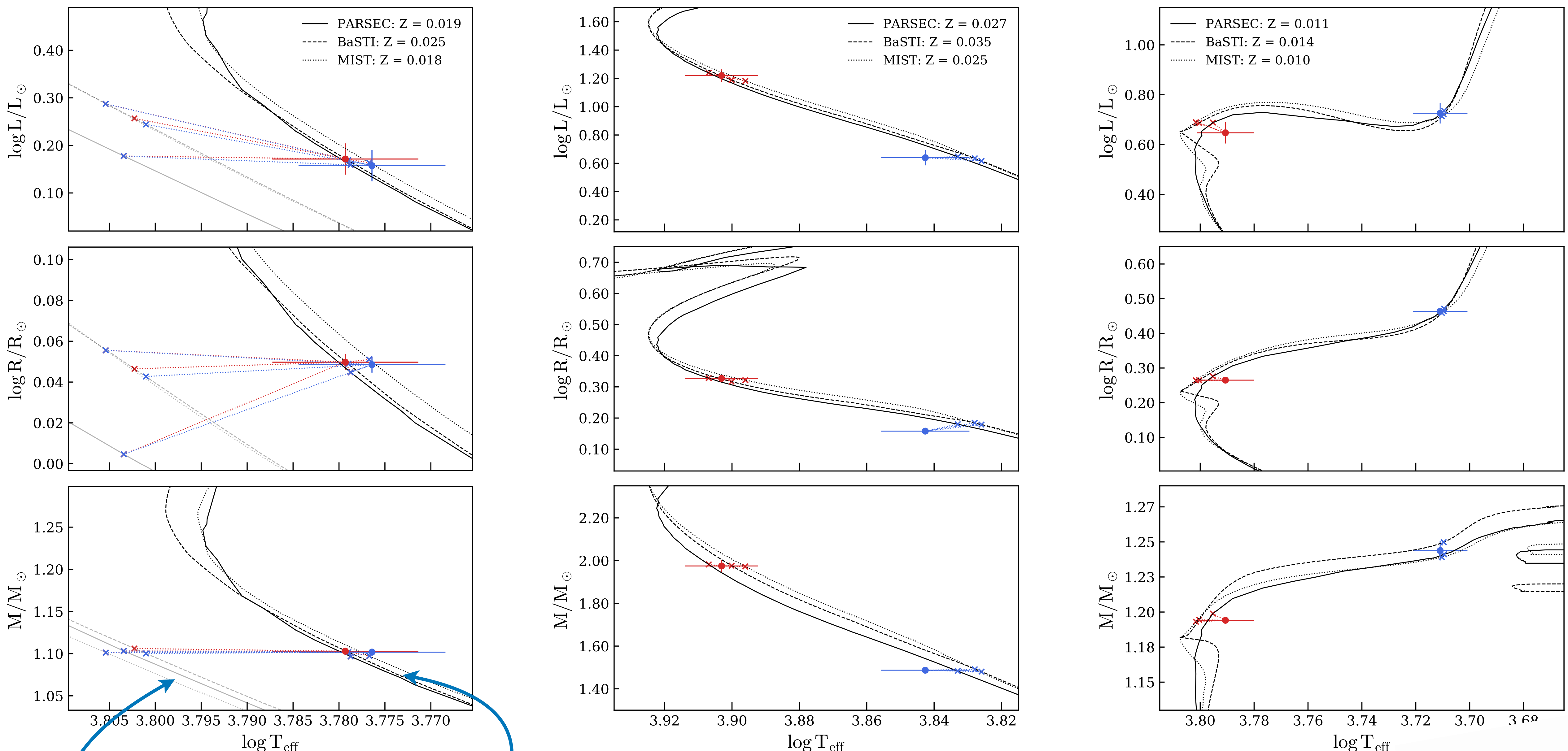




Similar age ~ 1.3 Ga

"Simple" Binary Stars

AL Dor | **KW Hya** | **AI Phe**

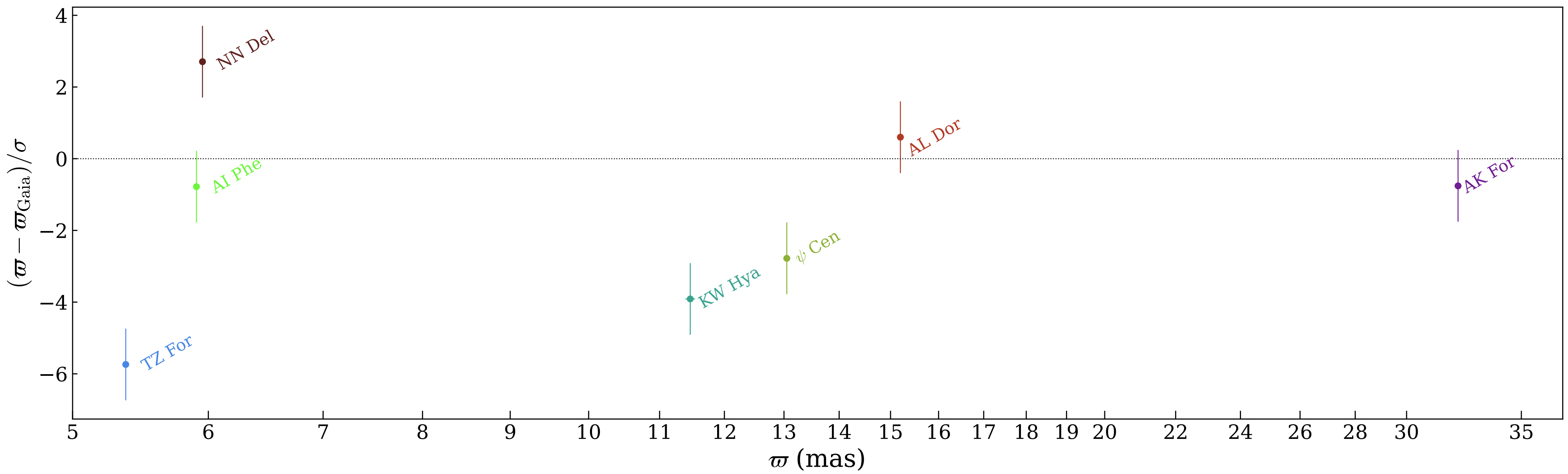


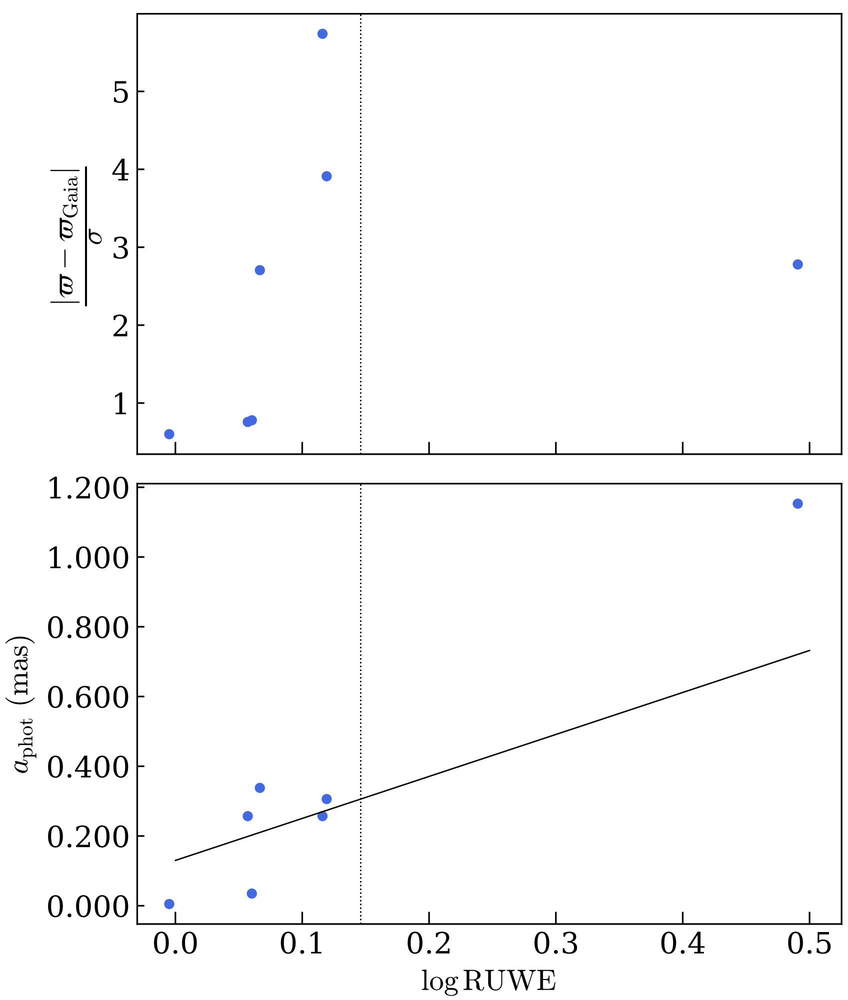
Measured
Fe/H = - 0.21dex

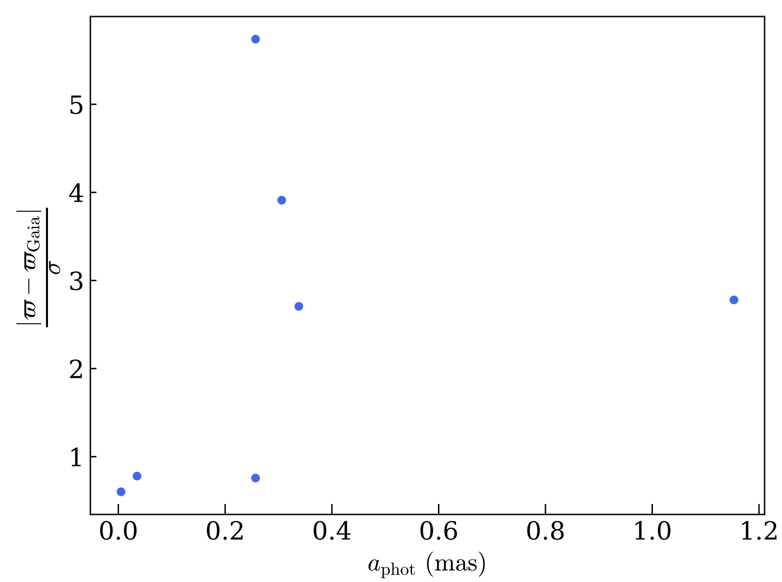
Assumed
Fe/H = 0.1dex

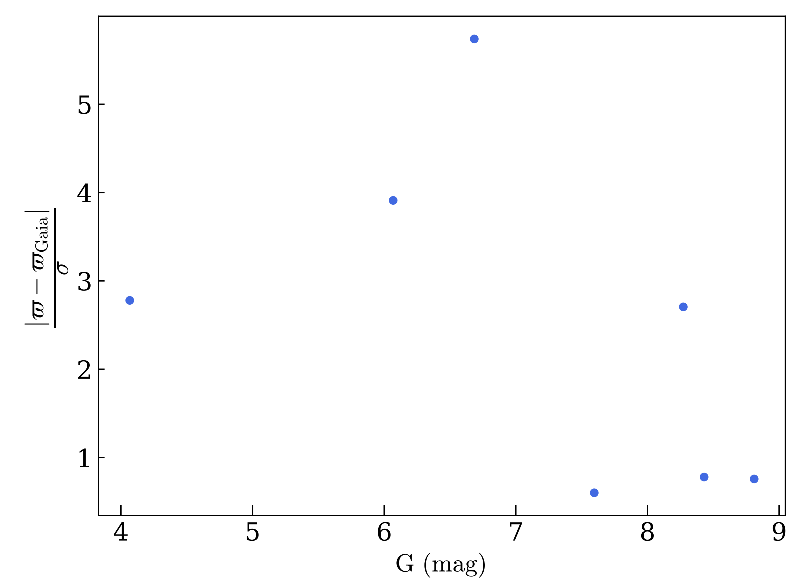
"Simple" Binary Stars

- Comparison with Gaia DR3 parallaxes:









"Simple" Binary Stars

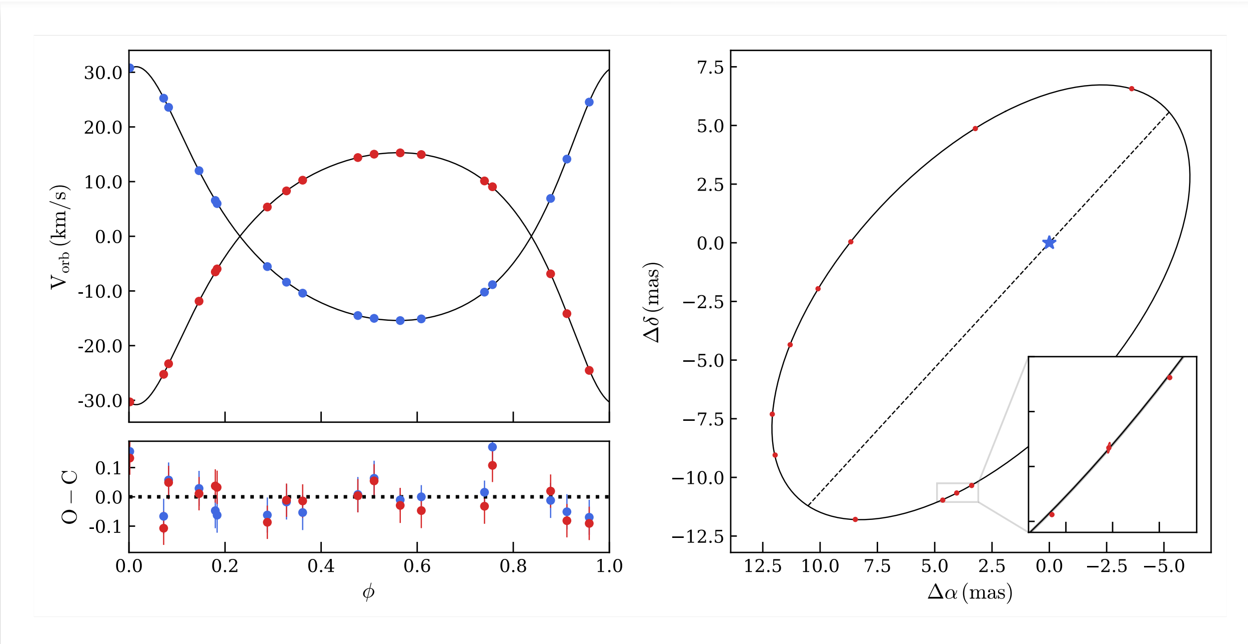
- PIONIER instrument was used:

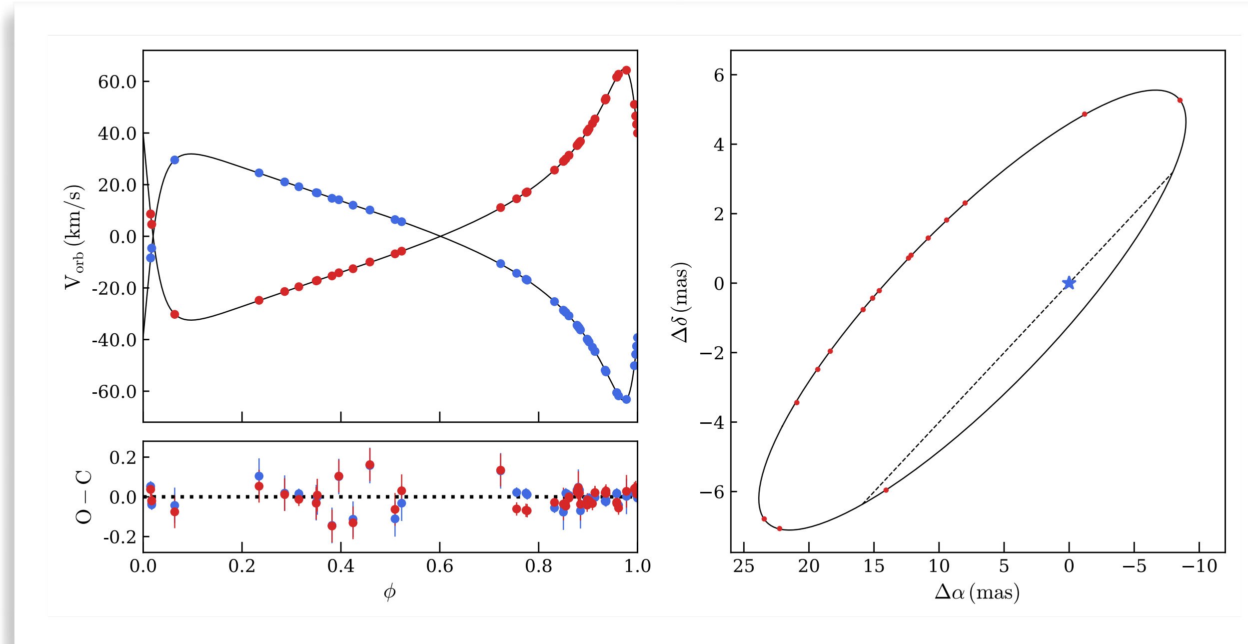
  - ✓ Higher angular resolution (H band)
  - ✓ Fast aquisition (~15mn)
  - ✗ Wavelength calibration accurate to 0.35%

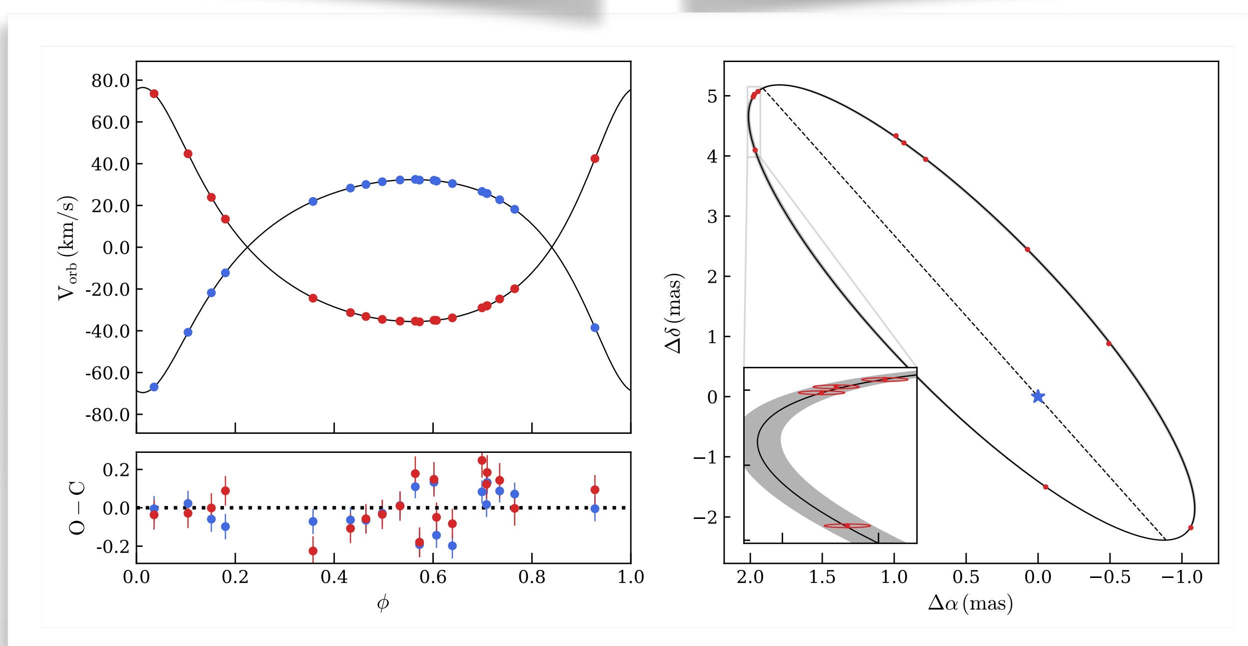
- New ongoing program to observe 40 binary systems with GRAVITY (non eclipsing):

  - ✗ Lower angular resolution (K band)
  - ✗ Slower acquisition (~50mn)
  - ✓ Wavelength calibration accurate to 0.02%

"Simple" Binary Stars





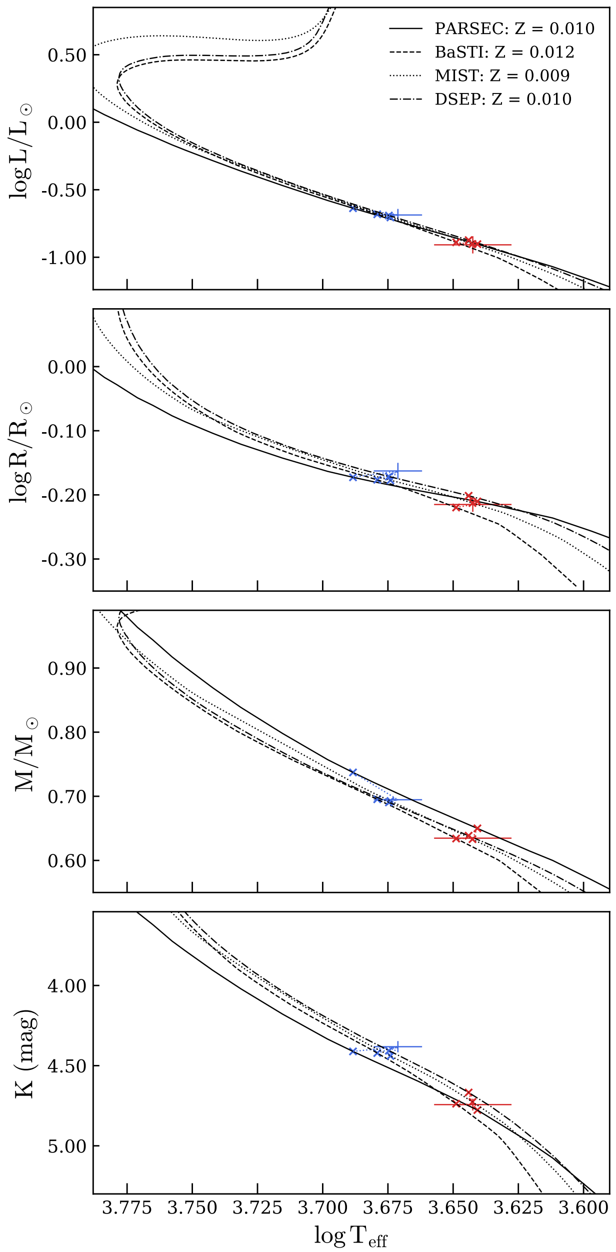


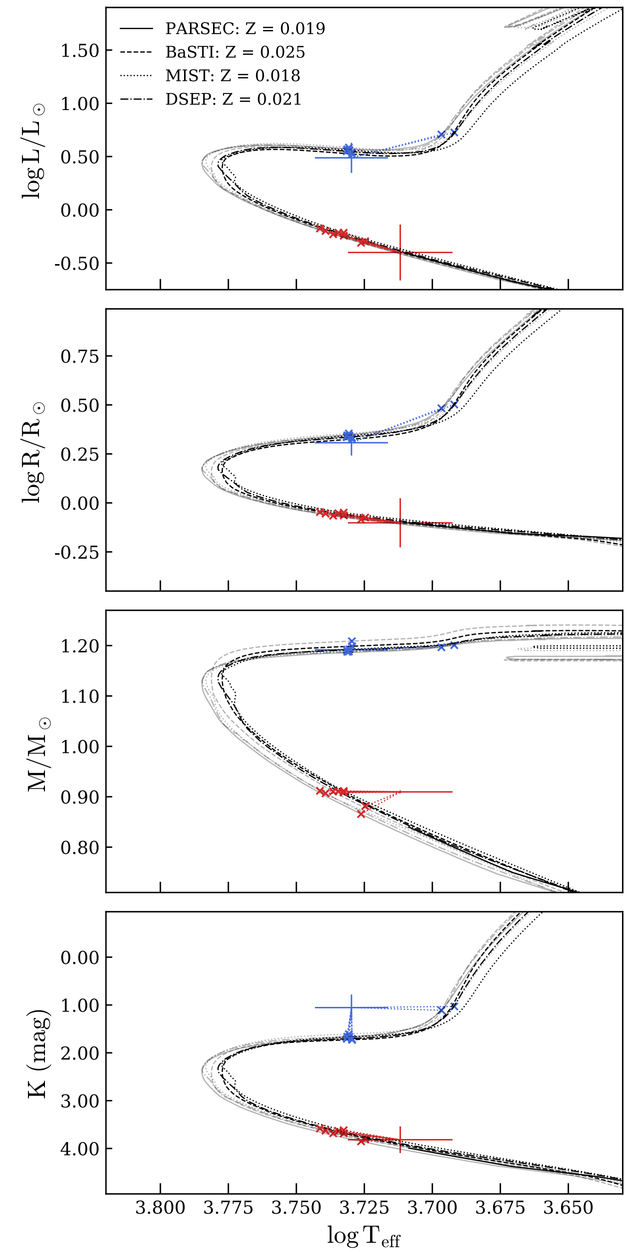
Gallenne et al. (2023)

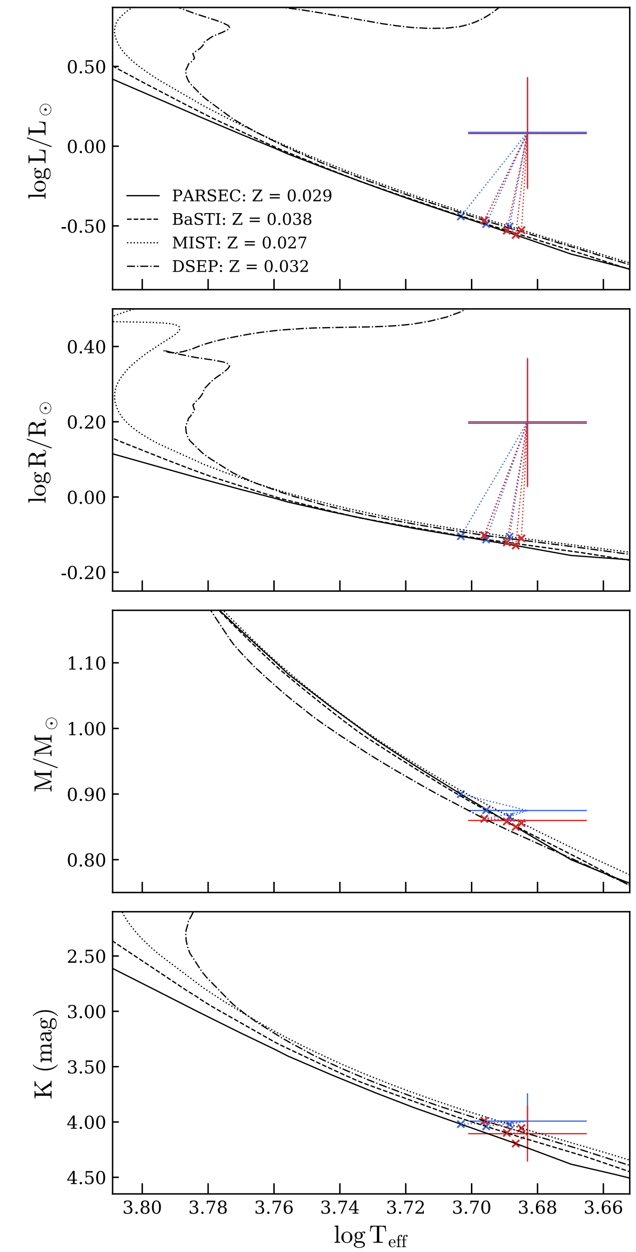
Masses & distances ~0.03%

➡ Astrometry precise and accurate at 15μas

"Simple" Binary Stars





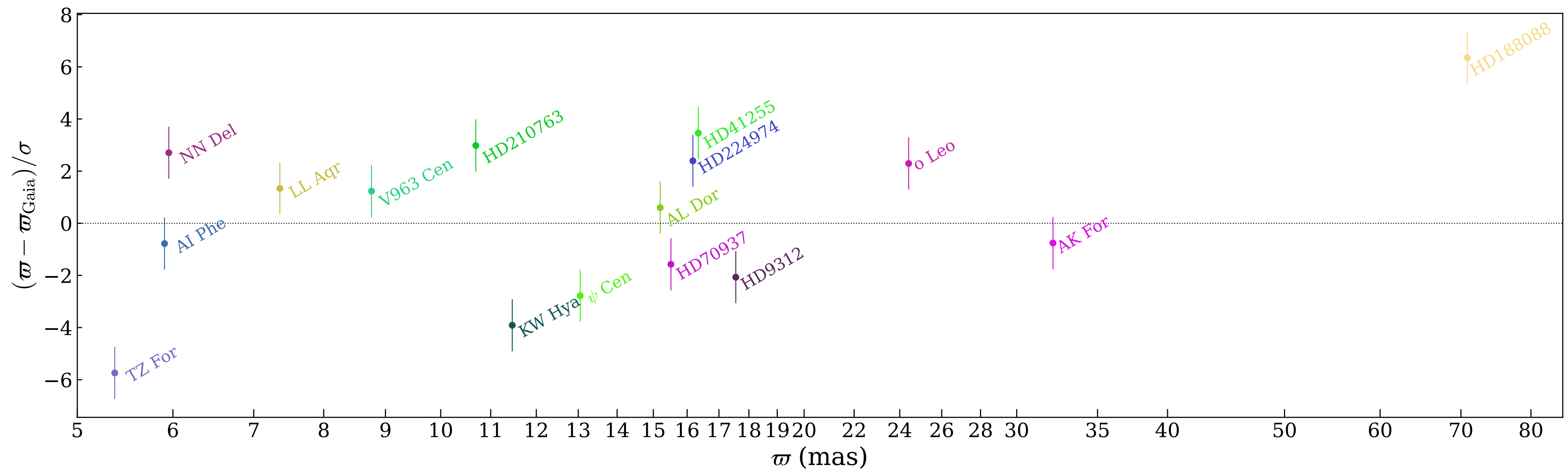


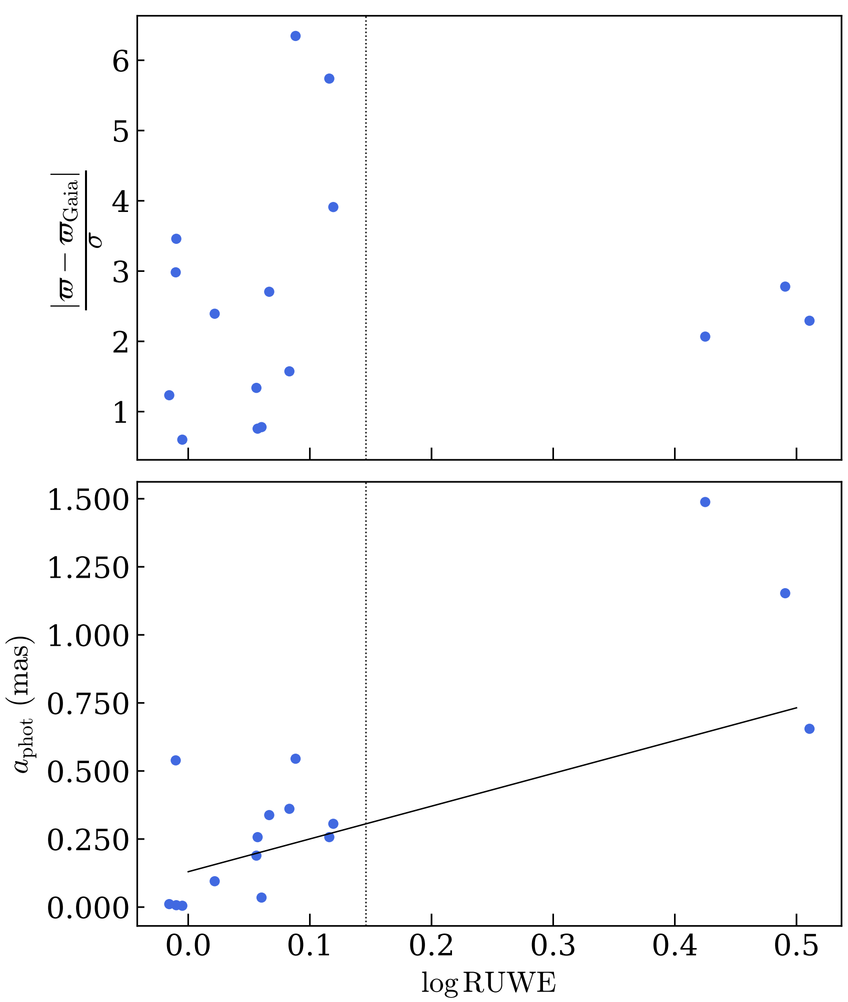
	basti	dartmouth	mist	parsec	fitted
Kmag1	-1.13	-0.71	-1.64	-0.84	*
Kmag2	0.16	2.07	0.46	-0.93	*
M1	-0.99	5.18	2.42	-53.23	*
M2	1.14	-7.78	3.2	-30.6	*
logL1	-0.11	0.09	0.41	-1.11	
logL2	-0.29	-0.54	-0.1	-0.08	
logR1	1.09	0.69	1.15	0.79	*
logR2	0.41	-1.2	-0.2	-0.42	*
logT1	-0.86	-0.37	-0.31	-1.86	*
logT2	-0.43	-0.11	-0.01	0.12	*
age	8.92+/-0.62	8.62+/-1.41	6.11+/-2.21	1.88+/-4.22	
chi2r	0.88	2.41	2.2	14.47	

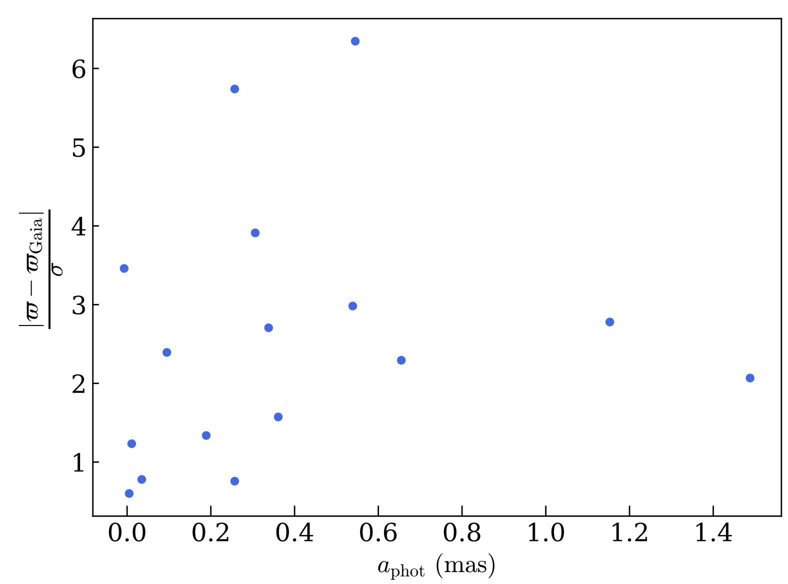
	basti	dartmouth	mist	parsec	fitted
Kmag1	-2.42	-2.25	-2.06	-0.21	*
Kmag2	0.48	0.68	0.85	-0.12	*
M1	-4.7	1.14	0.99	-1.38	*
M2	-0.31	1.09	-0.8	16.95	*
logL1	-0.37	-0.56	-0.68	-1.56	
logL2	-0.65	-0.77	-0.86	-0.35	
logR1	-0.41	-0.57	-0.72	-2.7	
logR2	-0.29	-0.37	-0.44	-0.13	
logT1	0.01	-0.12	-0.07	2.46	*
logT2	-1.28	-1.43	-1.54	-0.75	*
age	5.46+/-0.61	5.71+/-0.29	5.64+/-0.37	5.59+/-0.27	
chi2r	2.19	2.23	2.12	1.57	

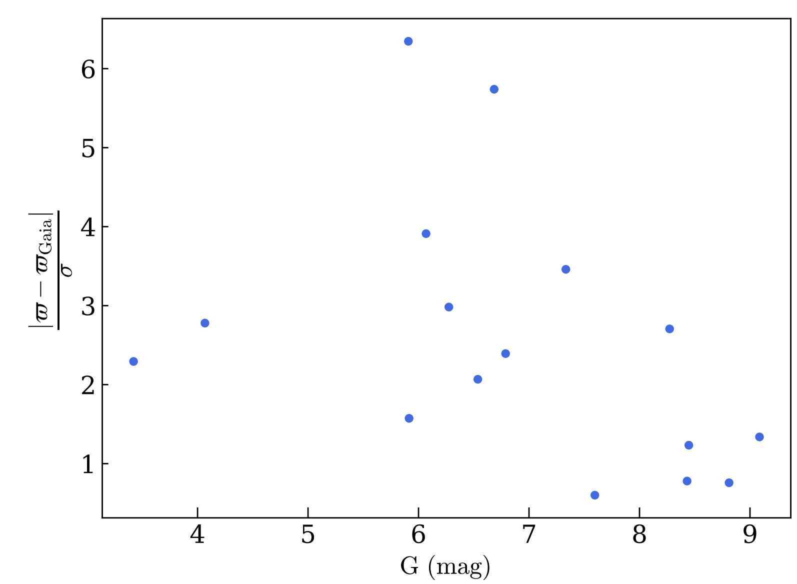
	basti	dartmouth	mist	parsec	fitted
Kmag1	-0.19	0.01	-0.12	-0.11	*
Kmag2	0.03	0.46	0.2	-0.35	*
M1	-1.3	41.88	31.48	-83.48	*
M2	5.23	-8.46	13.29	32.85	*
logL1	1.66	1.59	1.7	1.52	
logL2	1.75	1.57	1.74	1.83	
logR1	1.84	1.78	1.8	1.79	
logR2	1.86	1.75	1.8	1.91	
logT1	-0.7	-0.73	-0.3	-1.12	*
logT2	-0.35	-0.73	-0.1	-0.2	*
age	0.91+/-0.43	3.29+/-3.31	1.88+/-4.3	0.33+/-5.3	
chi2r	2.53	3.55	2.22	1.98	

- Comparison with Gaia DR3 parallaxes:









Galactic Binary Cepheids

- Cepheids are important standard candles for the extragalactic distance scale
- When in a binary system (> 80%), we should be able to:
  - Have an independent distance measurement: test Gaia and P-L relations
  - Measure the dynamical mass: test evolutionary models

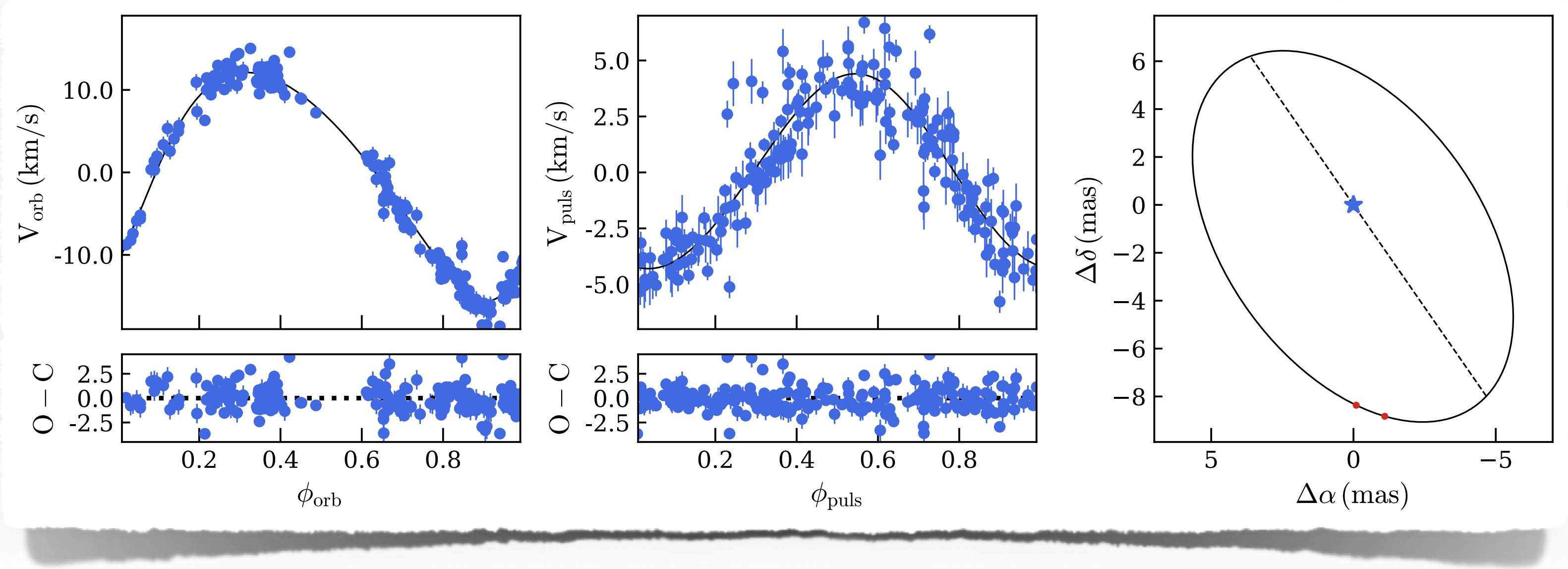
- Challenging targets because we need to detect the companions both spectrally and spatially:
  - Companions are mostly early-type main-sequence ➙ high contrast
  - Lines are usually broad and blended
  - Orbits are within 50mas

UV spectroscopy necessary to observe lines from the companions

Long-baseline interferometry provides accurate & precise astrometry below the diffraction limit

Galactic Binary Cepheids

- First binary Cepheid observed with interferometry in 2012: V1334 Cyg

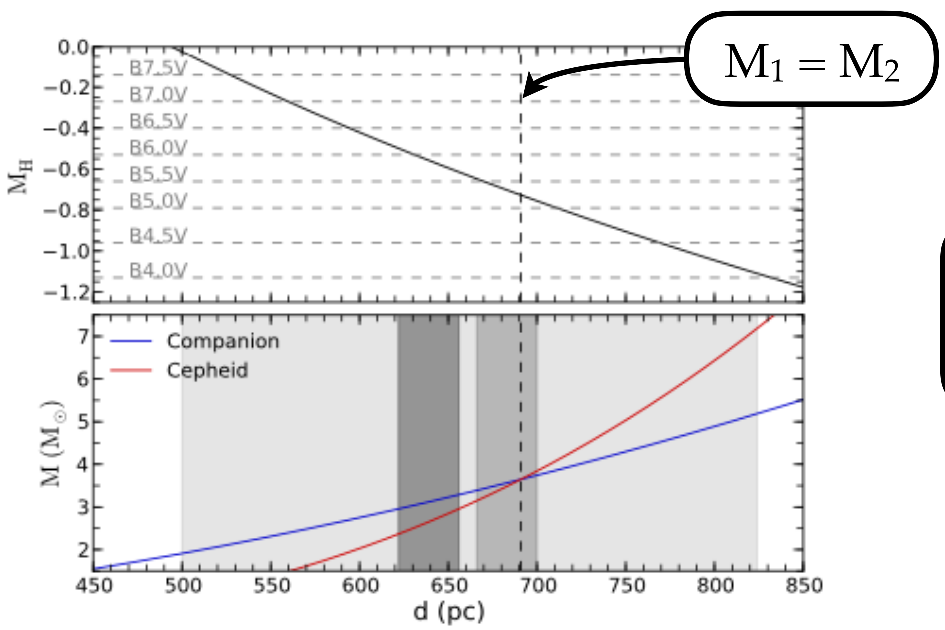


Gallenne et al. (2013)

- SB1 system so the masses and the distance are degenerate parameters

Full orbital solution

	Spectroscopy only (Evans 2000)	This work
Orbit		
P_{orb} (days)	1937.5 ± 2.1	1938.6 ± 1.2
T_p (HJD)	2 443 607 ± 14	2 443 616.1 ± 7.3
e	0.197 ± 0.009	0.190 ± 0.013
K_1 (km s^{-1})	14.1 ± 0.1	13.86 ± 0.17
v_γ (km s^{-1})	−1.8 ± 0.1	−1.9 ± 0.1
ω (°)	226.3 ± 2.9	228.7 ± 1.6
Ω (°)	–	206.3 ± 9.4
a (mas)	–	8.54 ± 0.51
i (°)	–	124.7 ± 1.8
m_H	–	8.47 ± 0.15
Pulsation		
P_{puls} (days)	3.33251 ± 0.00001	3.33250 ± 0.00002
T_0[a] (HJD)	2 440 124.5330	2 440 124.5330
A_1	–	4.35 ± 0.15
A_2	–	1.81 ± 0.11
B_1	–	0.08 ± 0.06
B_2	–	2.72 ± 1.30

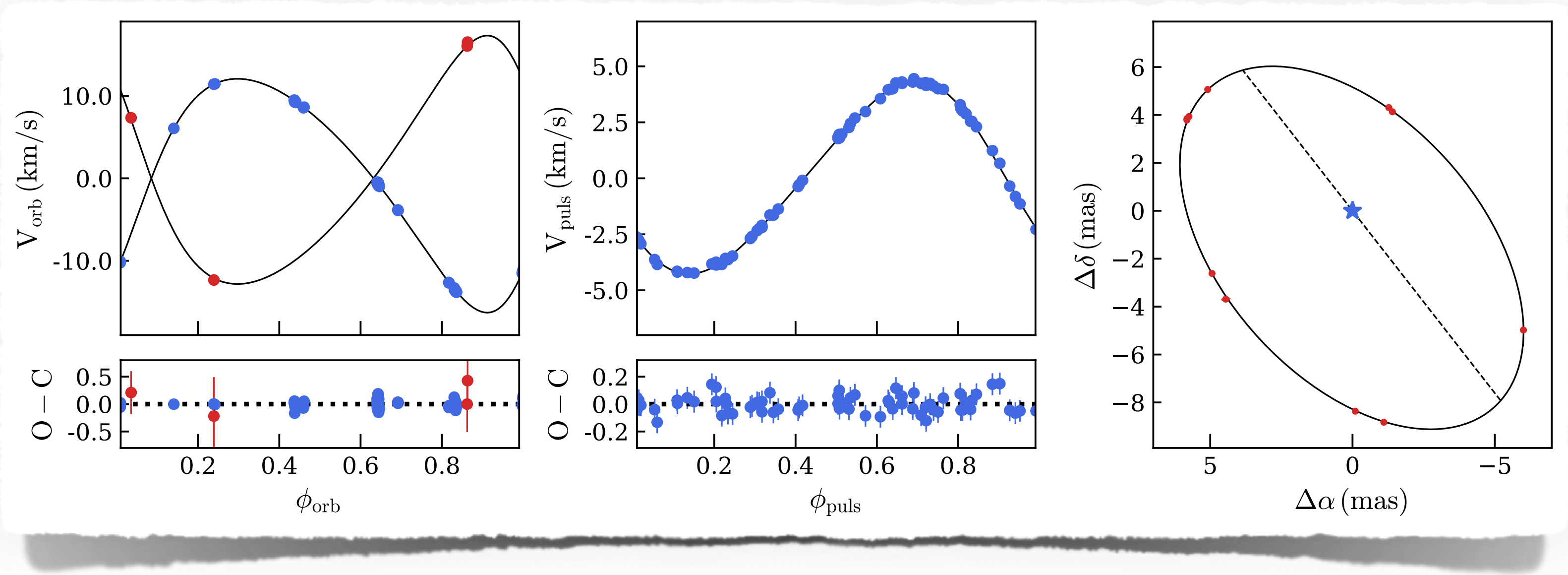


$d \geq 690$pc
$M_2 \geq 3.6 M_\odot$

Galactic Binary Cepheids

- I monitored the orbit with several instruments

2018



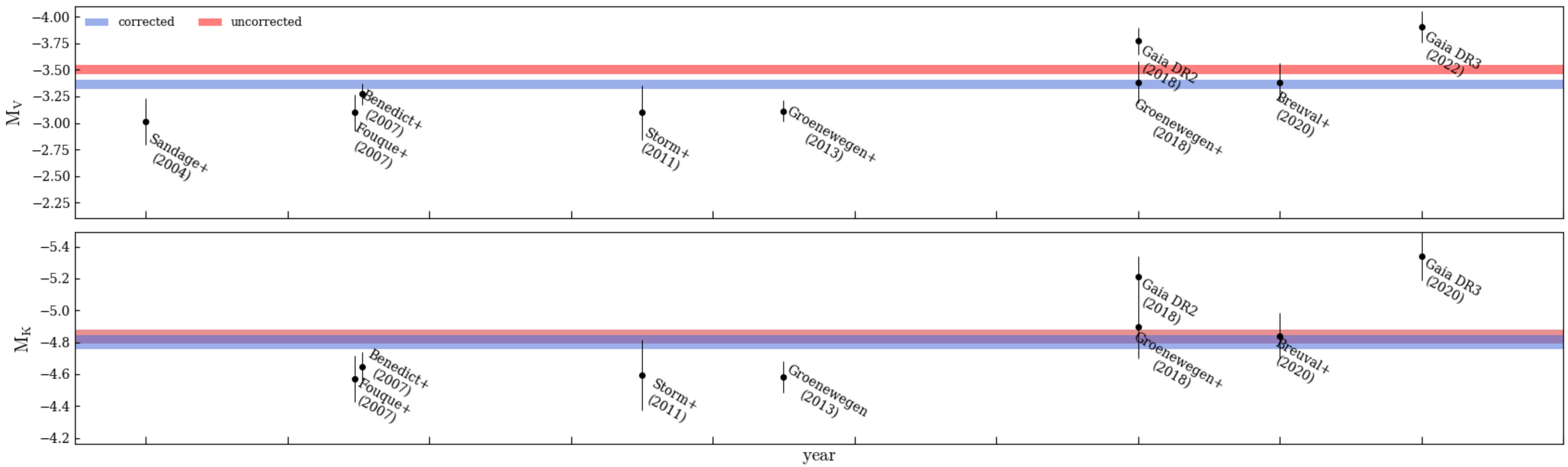
New HST/STIS RV2 | New ground-based RV1 | More astrometry

Gallenne et al. (2018)

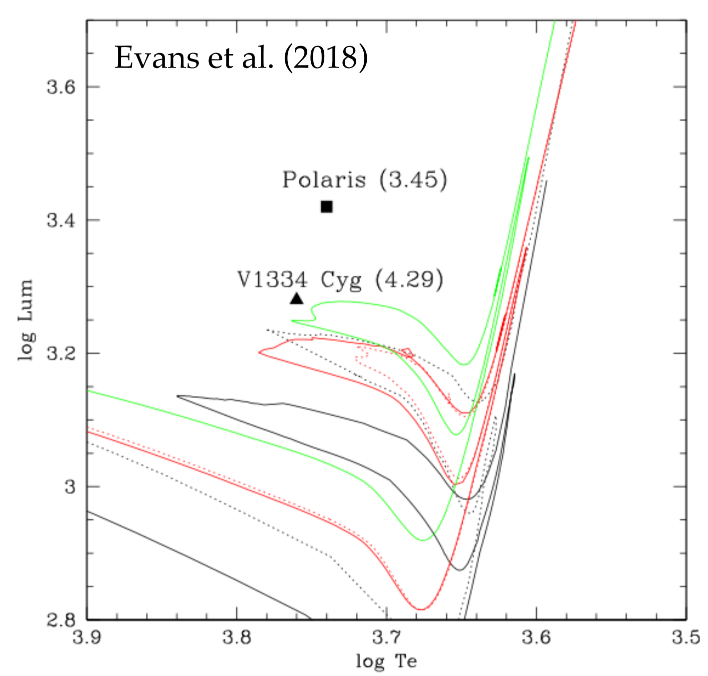
➡ Accurate & precise distance of a Cepheid (1%)

➡ Accurate & precise mass of a Galactic Cepheid (3%)

- Comparison with Gaia and P-L relations:



- Comparison with predictions from evolutionary models:

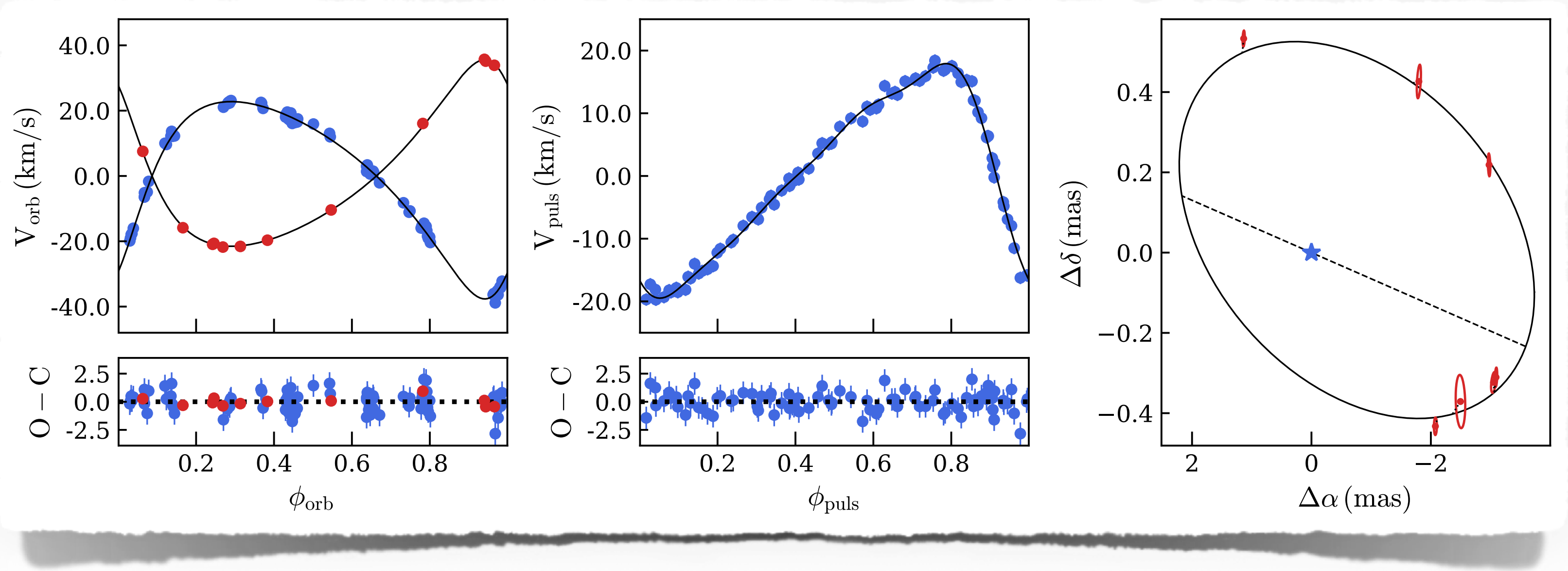


- Black: 5M⊙ Geneva models
- Red: 5M⊙ MIST models
- Green: 5M⊙ PARSEC models
- Dotted lines include significant rotation

Dynamical mass smaller than the predicted mass: mass loss, binary merger, evolutionary model?

Galactic Binary Cepheids

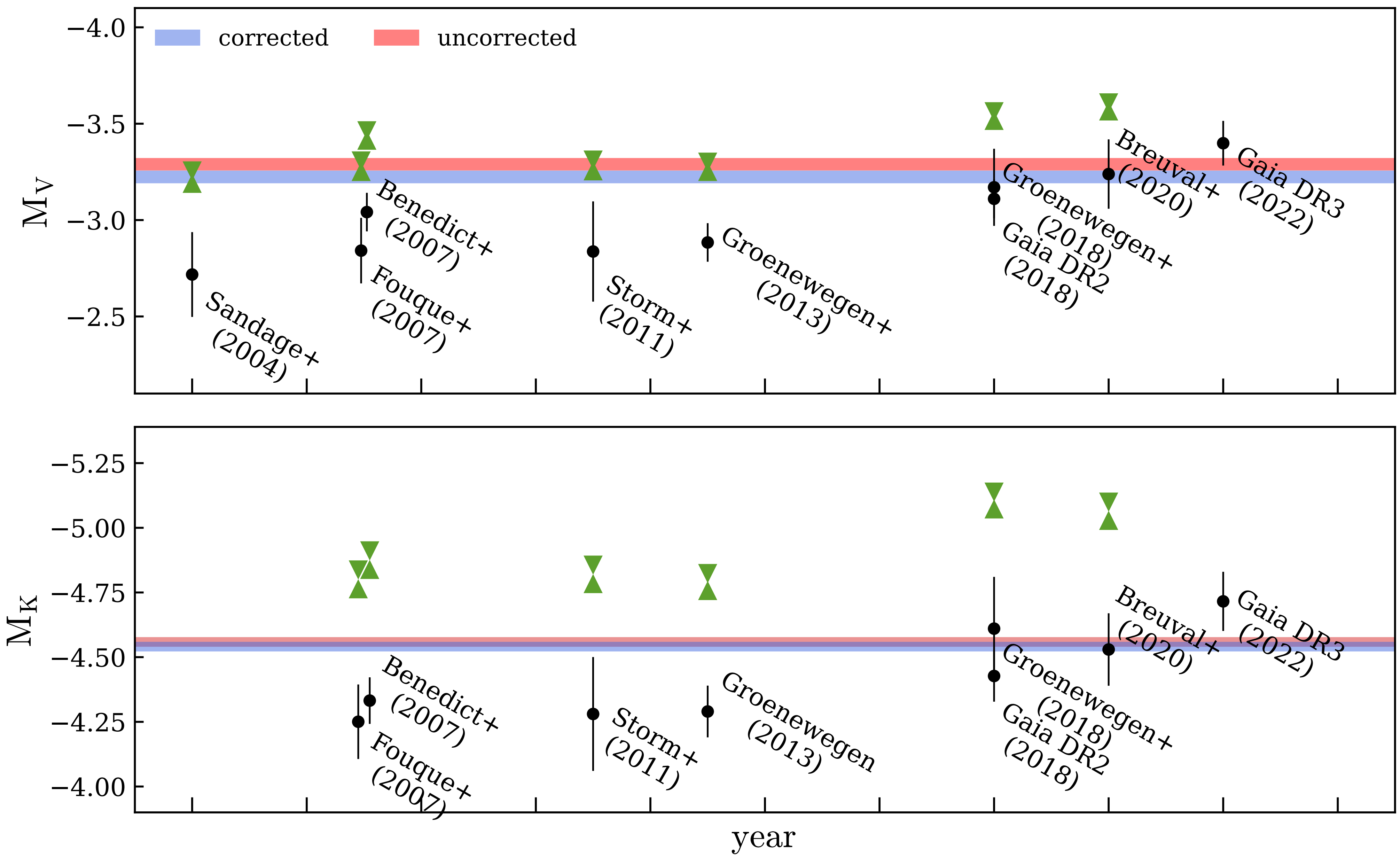
- New impresive results for another Cepheid SU Cyg (Gallenne et al. 2024, in prep.):



➡ Most accurate & precise distance of a Cepheid (0.7%)

➡ Most accurate & precise mass of a Galactic Cepheid (1%)

– Comparison with Gaia and P-L relations:

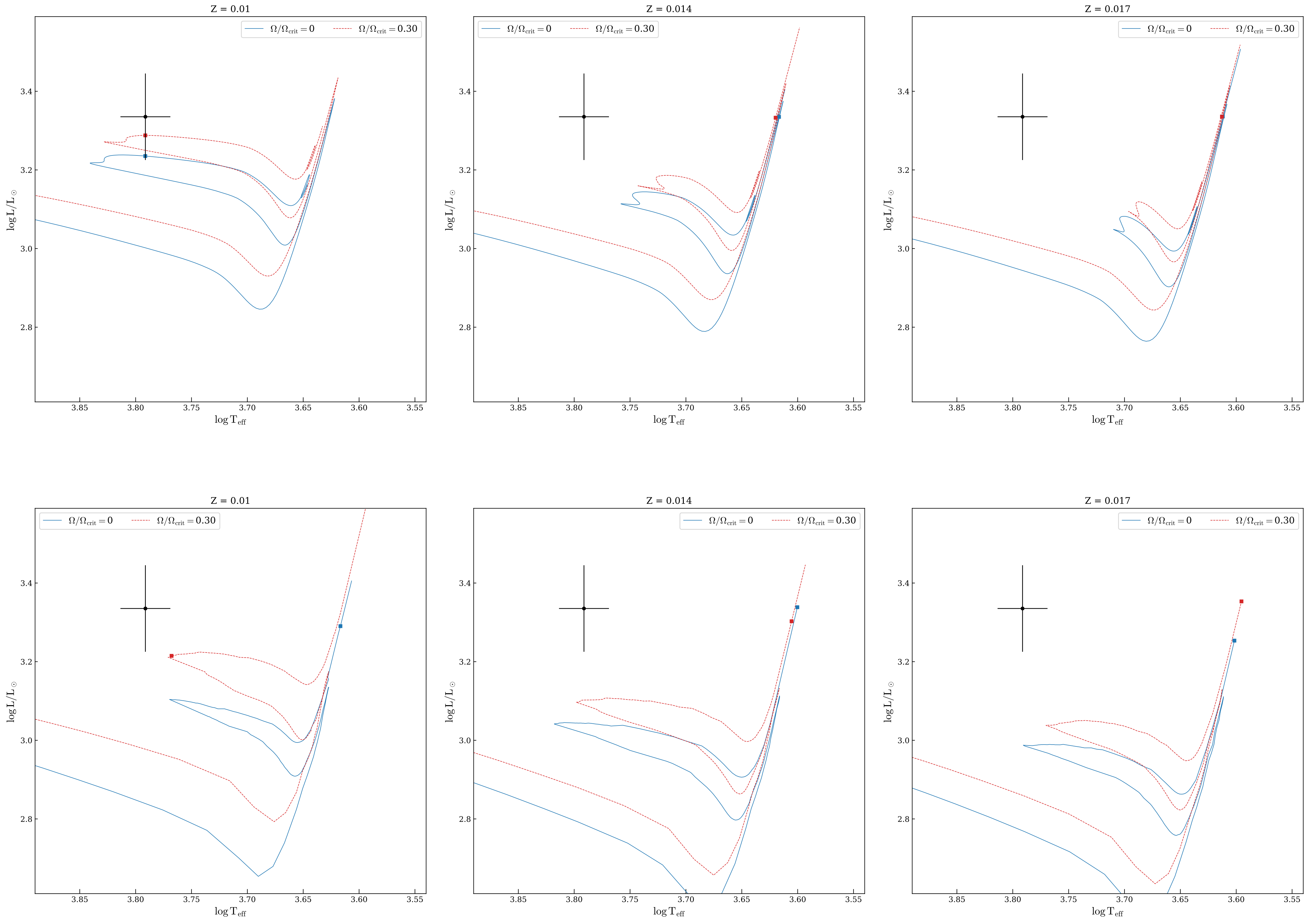


Galactic Binary Cepheids

- Comparison with predictions from evolutionary models:

PARSEC

GENEVA



Galactic Binary Cepheids

- Interferometry is a powerful technique for astrometry of close binary stars
- When combined with precise RVs, high-precision masses and distances can be measured

- Comparison of masses & other observables with evolutionary models shows some discrepancies
  - ➠ Stellar age can depend on the model used

- 60% (10/16 stars) of our measured distances are $> 1\sigma$ away from Gaia
  - ➠ No correlation relative error vs. ruwe
  - ➠ Correlation a_{phot} vs. ruwe confirmed, even below the 1.4 cutoff
  - ➠ Possible correlation with the brightness of the star (saturation effect?)

- For 2 Cepheids, measured distances differ by 10-20% with P-L relation calibrated from photometry, while relations calibrated from direct distance measurement are in better agreement
- Evolutionary models also predict larger masses than expected for the Cepheids

Thank you