# Optical Interferometry of Binary stars

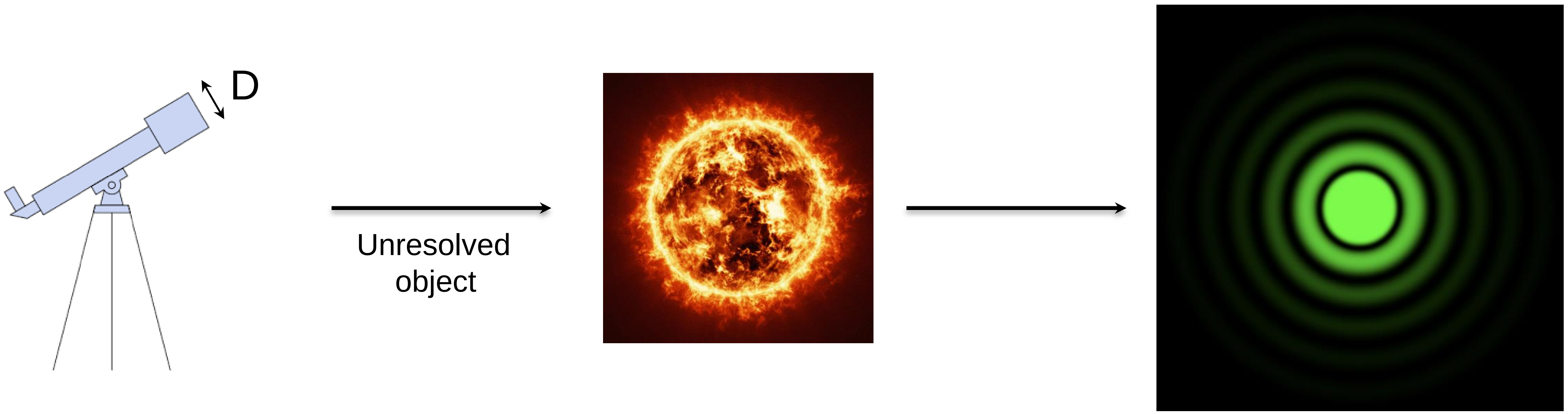
Alexandre Gallenne
*French-Chilean Laboratory for Astronomy (CNRS-IRL)*
*Universidad de Concepcion*

# Content

1. What is Long-Baseline Interferometry?
2. Why Binary Stars?
3. Binary Cepheids
4. Binary Stars in general
5. Comparison with Gaia

# What is Long-Baseline Interferometry ?

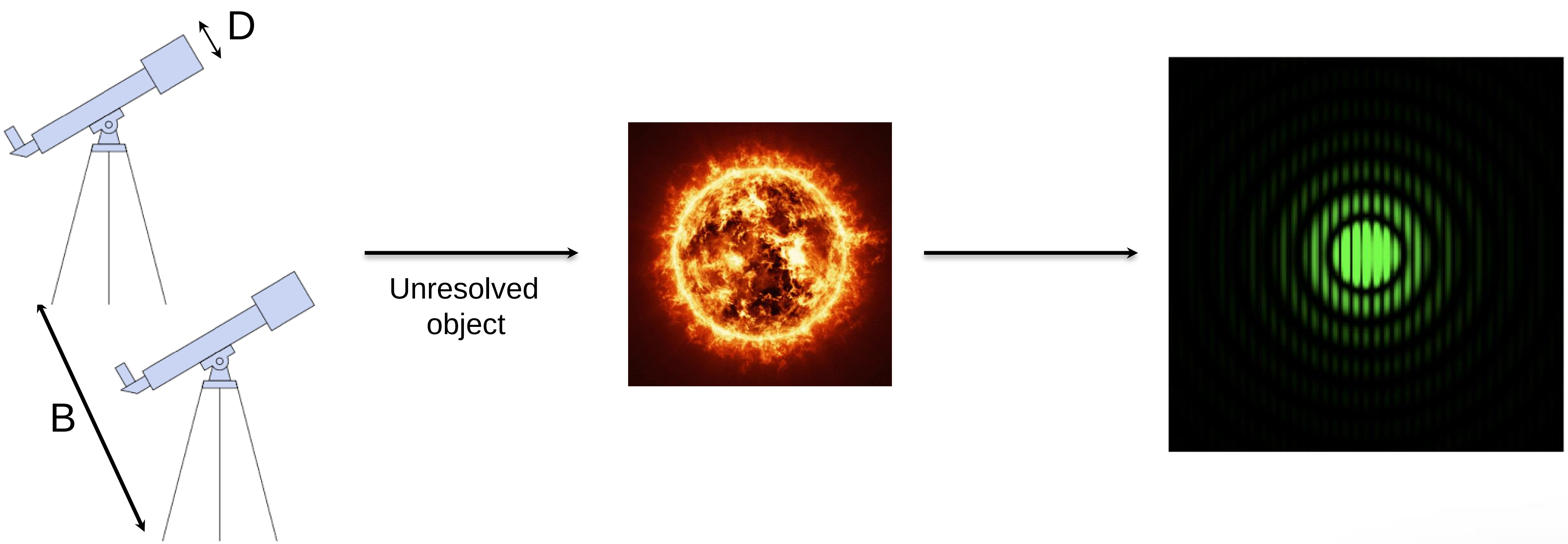
- Combines the light from several telescopes to form interference fringes
- Astrophysical information are extracted from the fringe patterns




➤ Airy pattern from diffraction (PSF)
➤ Resolution ~ $\lambda$/D

# What is Long-Baseline Interferometry ?

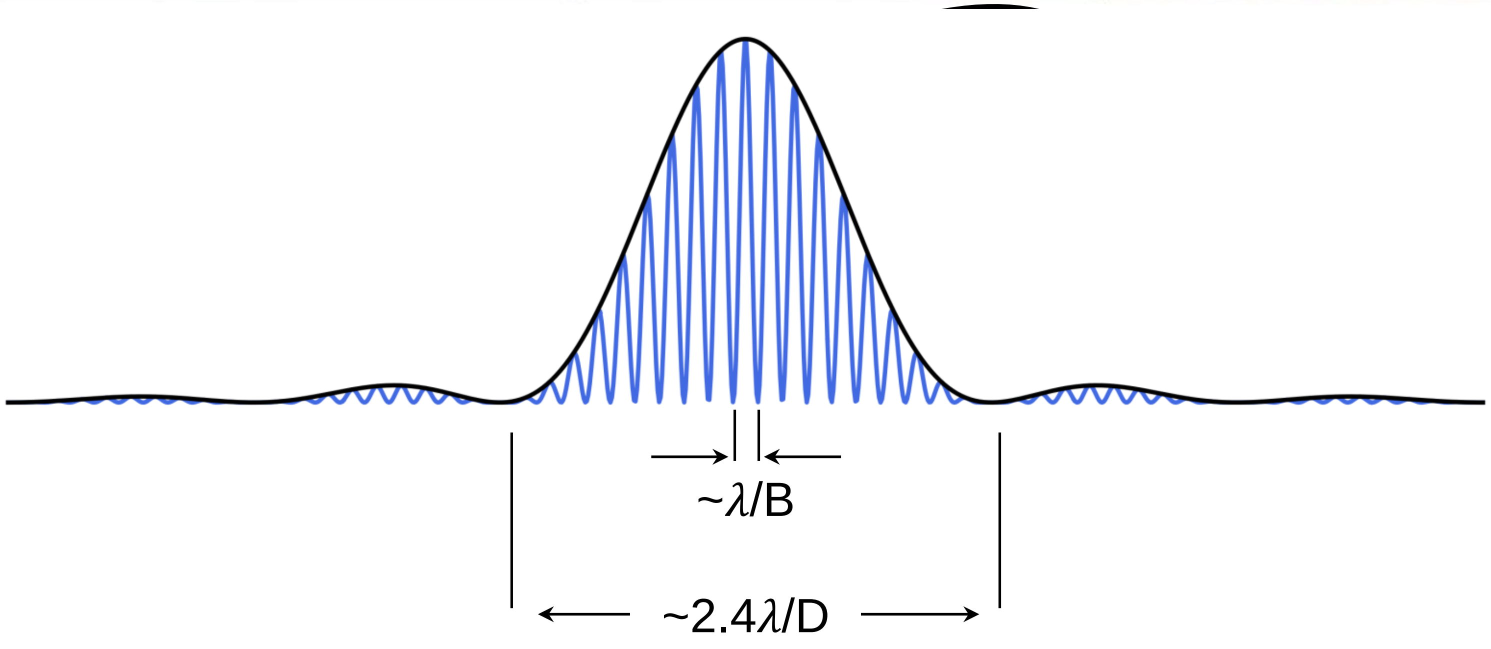
- Interference fringes depend on the separation between the telescopes
- B >> D

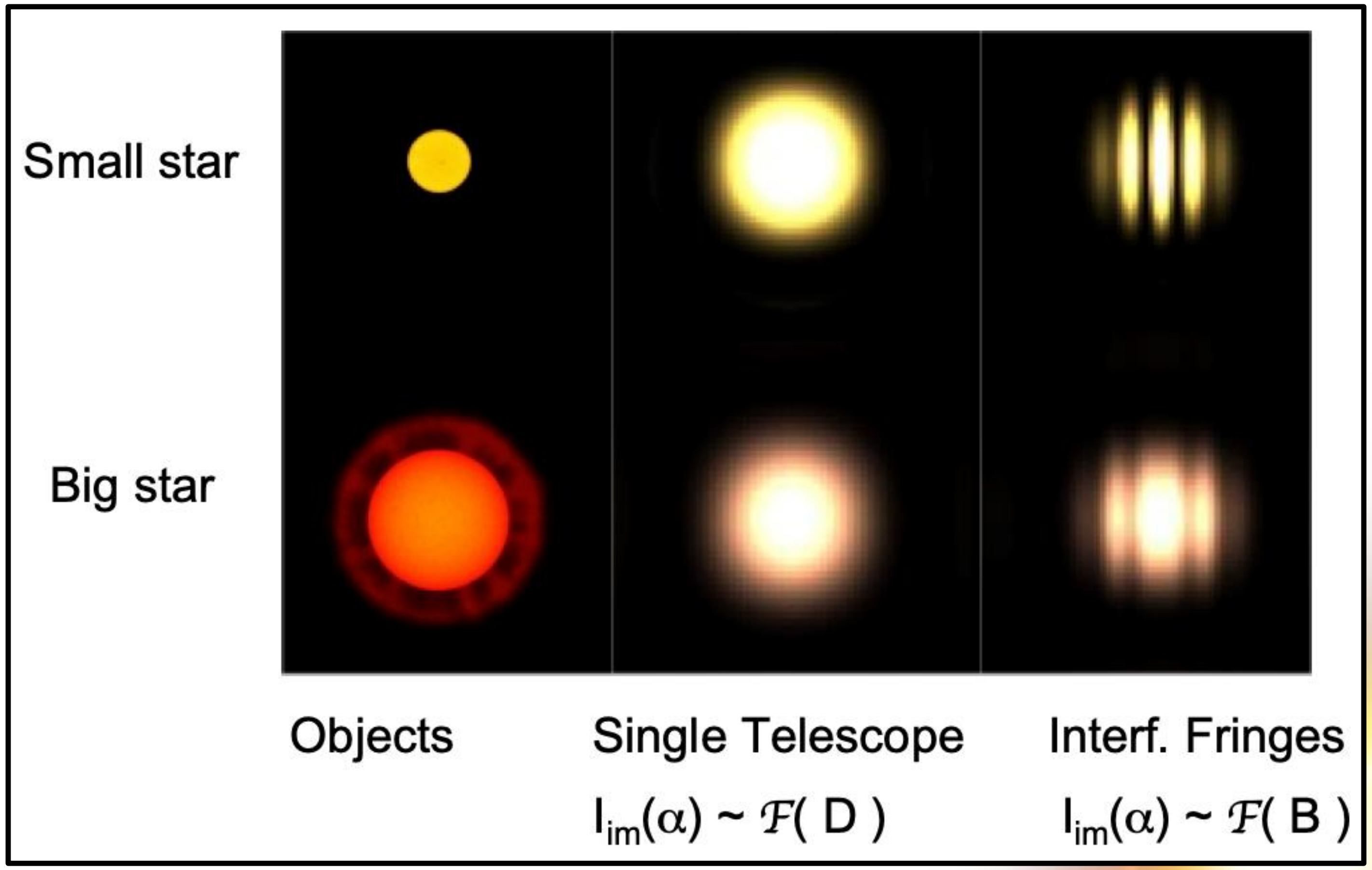



➤ Airy pattern becomes an "envelope" defining the intensity distribution of the  interference pattern

➤ Resolution ~ $\lambda$/B

# What is Long-Baseline Interferometry ?

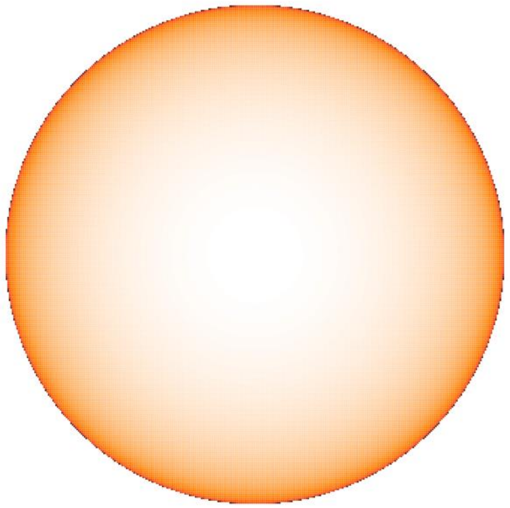


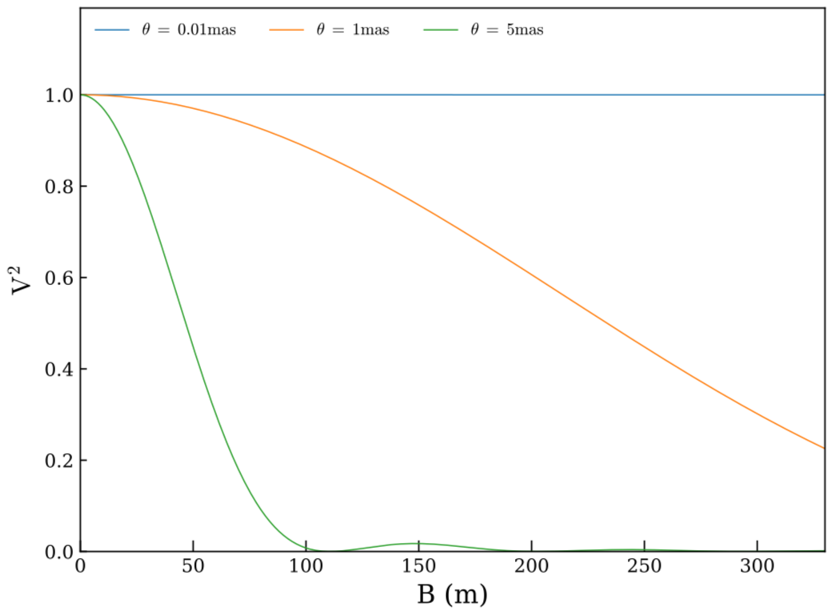



# What is Long-Baseline Interferometry ?

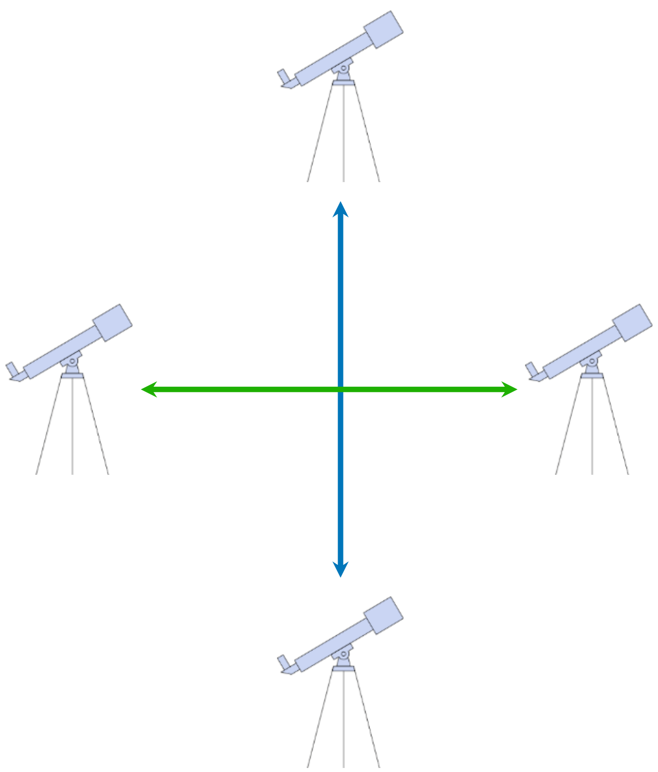
- Basically what we measure is the contrast and position of the fringes
- This is parametrize with the visibility function $V(B,\lambda)$
- Main observables are $V^2$, $T3 = V_1V_2V_3^*$

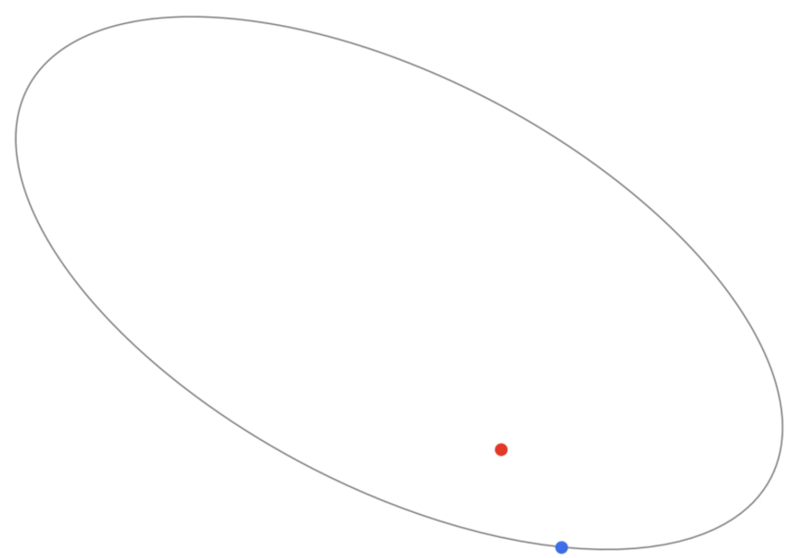
- For an unresolved object $V^2 = 1$, while $V^2 = 0$ for a fully resolved object

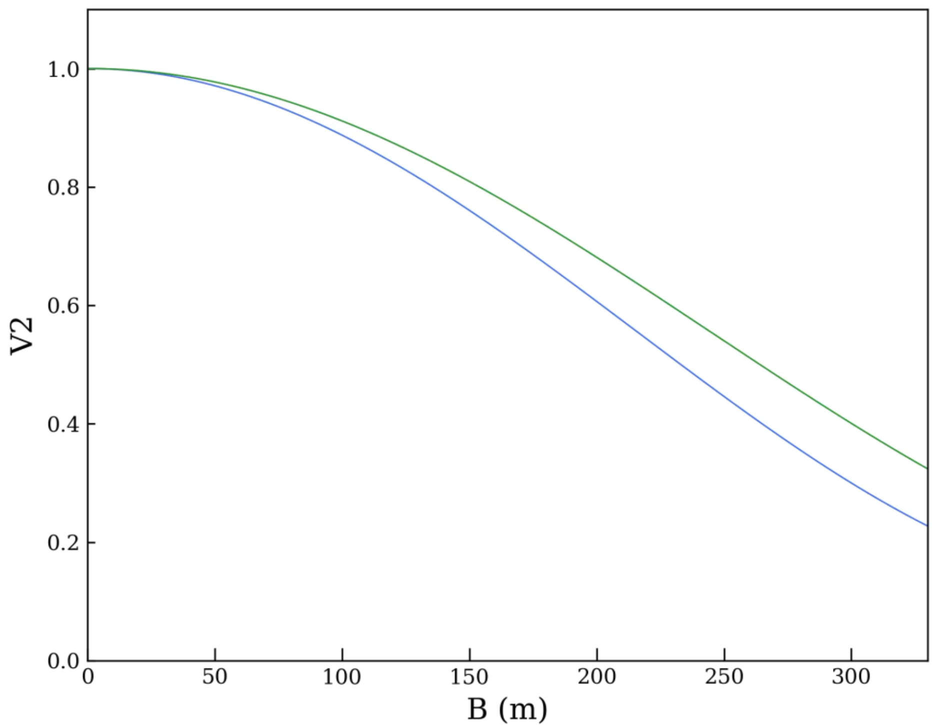




# What is Long-Baseline Interferometry ?







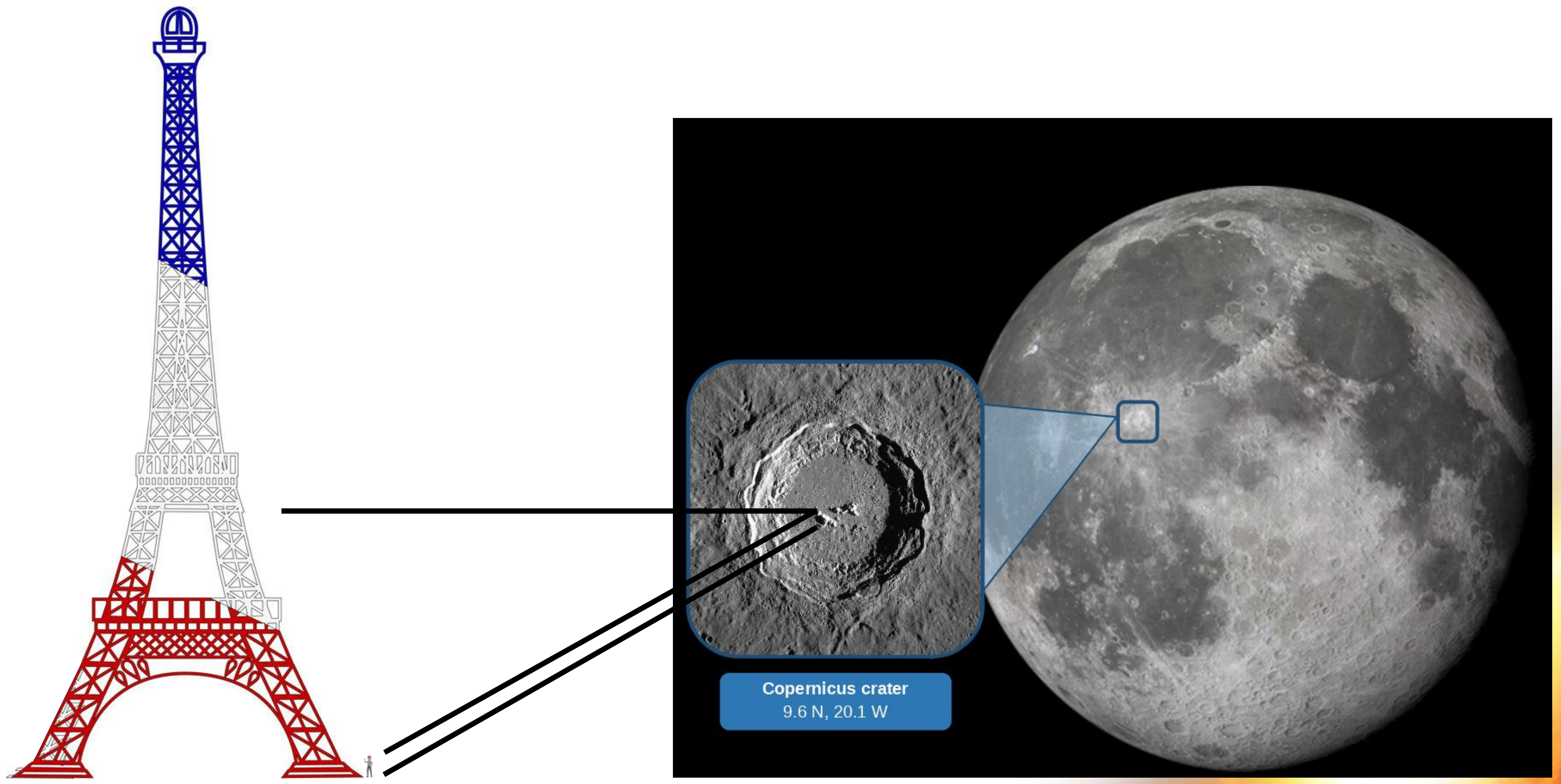
# What is Long-Baseline Interferometry ?

- 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

⚠ Sensitivity of a single big telescope still better than interferometry

- In the near infrared, angular resolution ~ 50mas at the VLT



# Why Binary Stars ?

- Simple geometric method combining radial velocities and astrometry
- Unique objects to determine both the masses and the distance of a system
- Can test stellar evolution models
- Can check the Gaia parallaxes
- For binary Cepheids we can test the P-L relation

- Need to detect the lines of both components (SB2)
- Challenging for high contrast binaries (Cepheids)

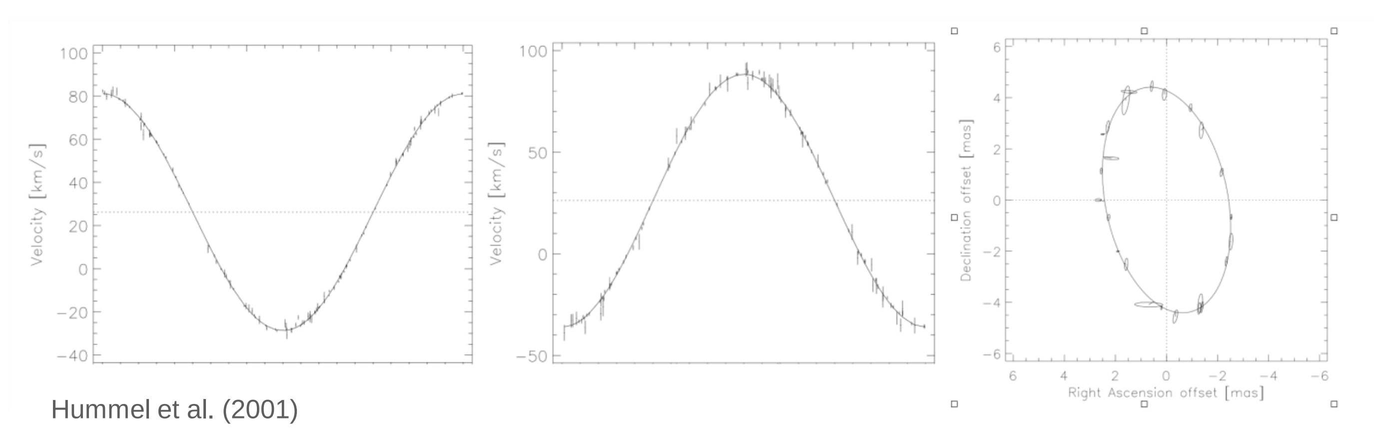
Spectroscopy

- Need to spatially resolve the companion for astrometry
- AO imaging ➠ long orbital periods

Interferometry

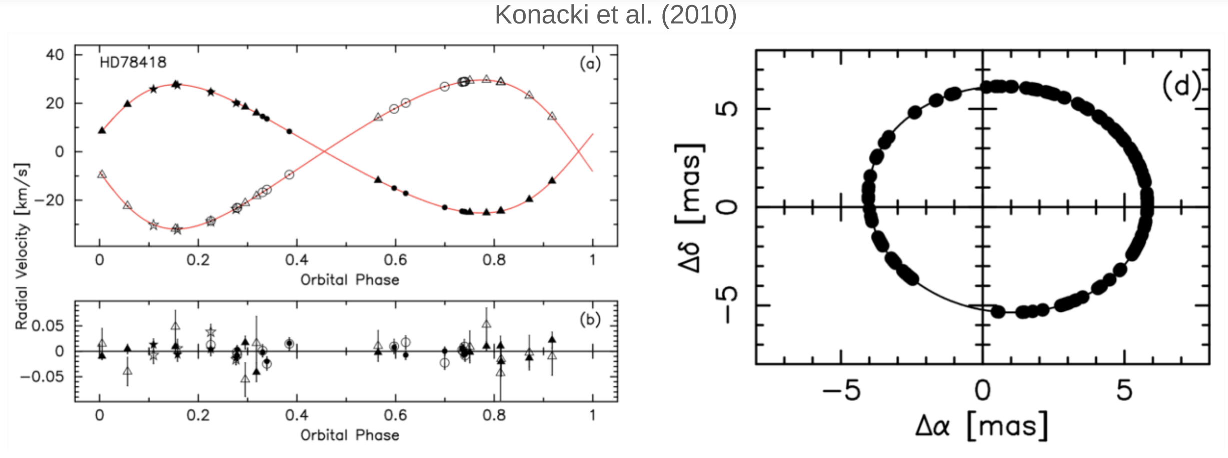
# Why Binary Stars ?

- Not new! Already done in the past



Hummel et al. (2001)

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

Konacki et al. (2010)



~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

# 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

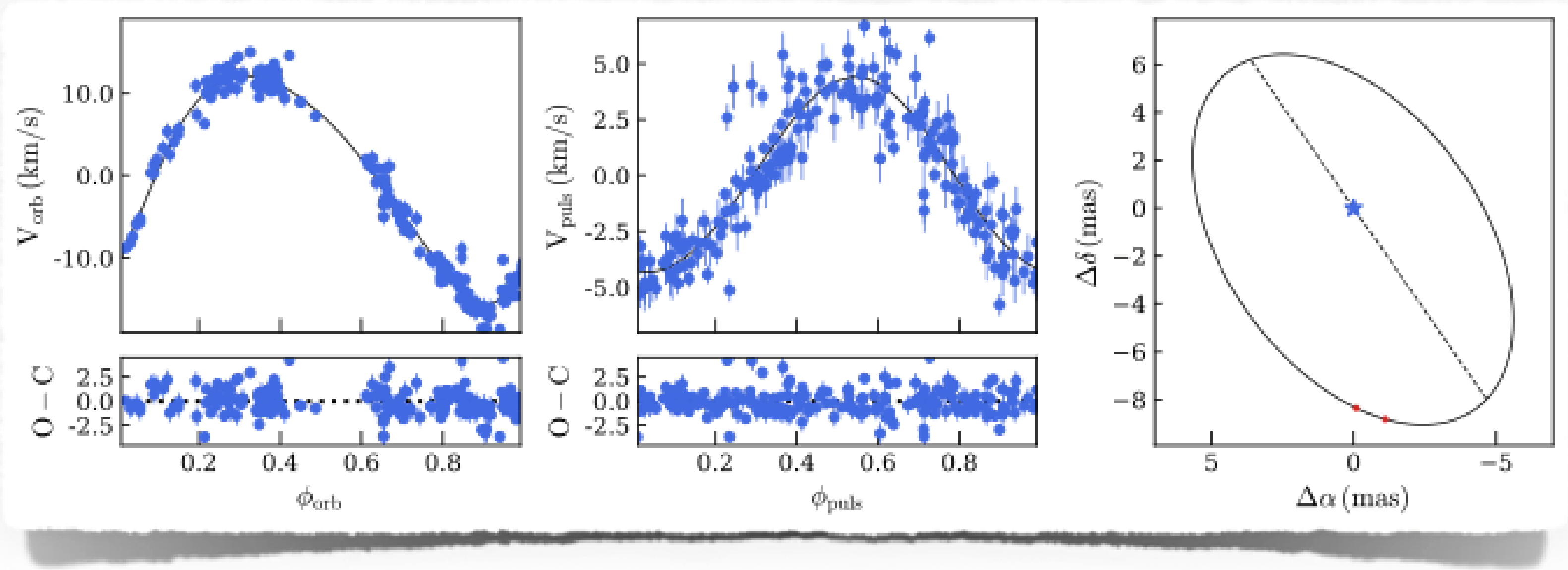
- Challenging targets because we need to detect the companions both spectrally and spatially:
  - Companions are mostly early-type main-sequence → high contrast
  - Lines are usually broad and blended
  - Orbits are within 50mas

UV spectroscopy necessary to observe lines from the companions

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

# Binary Cepheids

- First Cepheid observed with interferometry was V1334 Cyg ($P_{puls}$ = 3.33d)

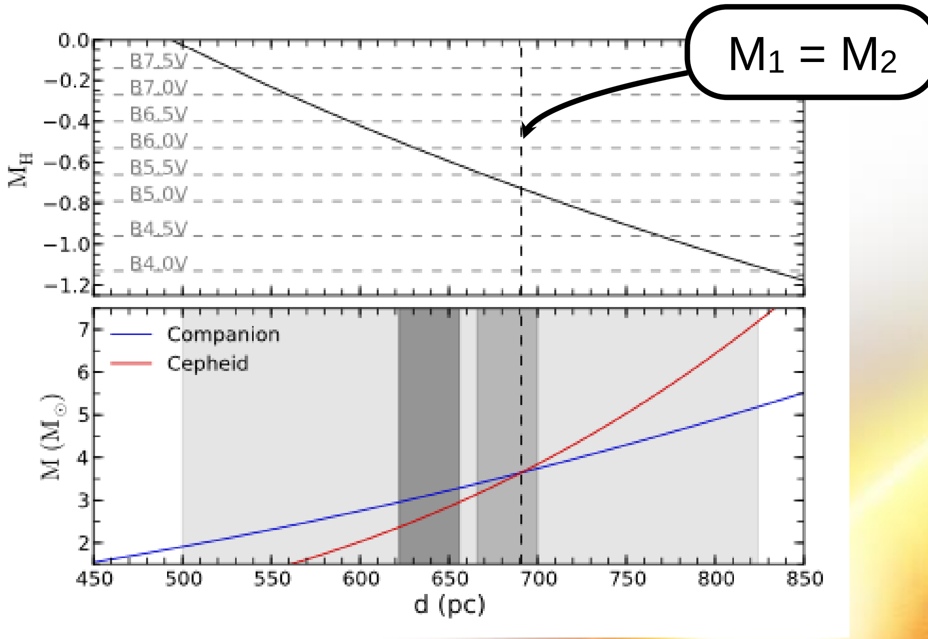



Gallenne et al. (2013)

- 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 |
| $v_\gamma$ (km s$^{-1}$) | −1.8 ± 0.1 | −1.9 ± 0.1 |
| $\omega$ (°) | 226.3 ± 2.9 | 228.7 ± 1.6 |
| $\Omega$ (°) | – | 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 |

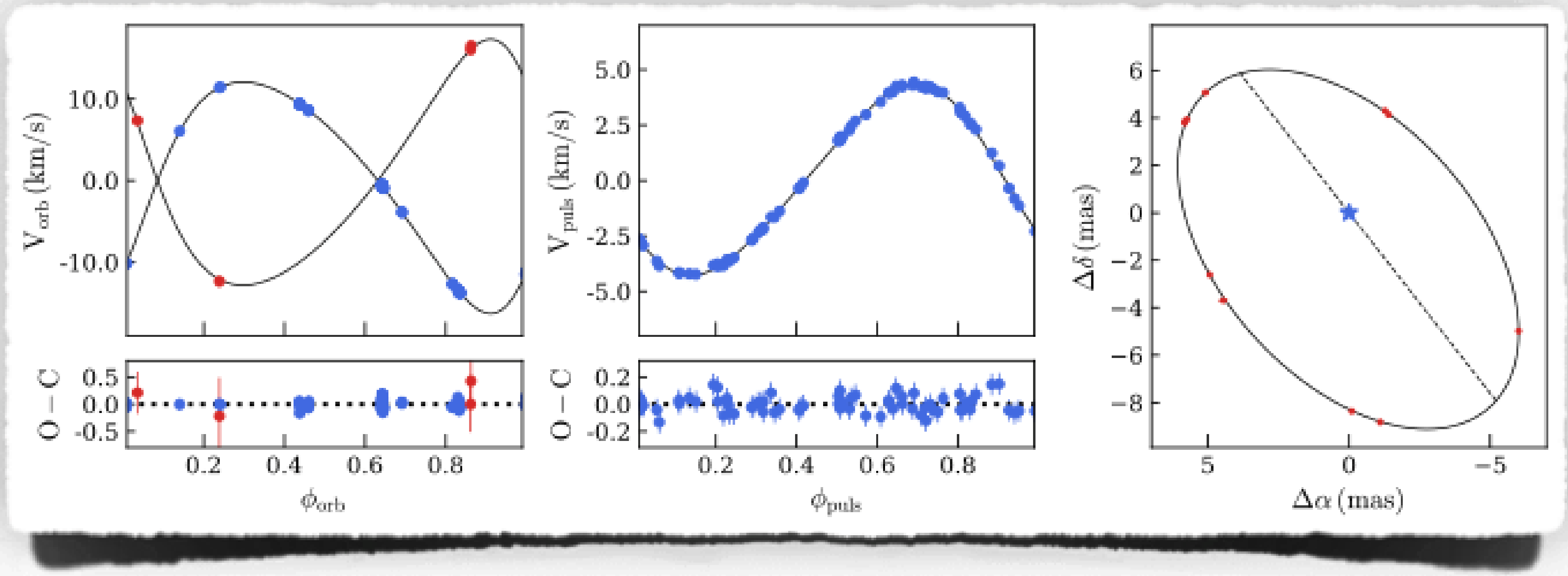



d ≥ 690pc
$M_2 \geq 3.6 M_\odot$

# Binary Cepheids

- We monitored the orbit with several instruments

2018




New HST/STIS RV2

New ground-based RV1

More astrometry

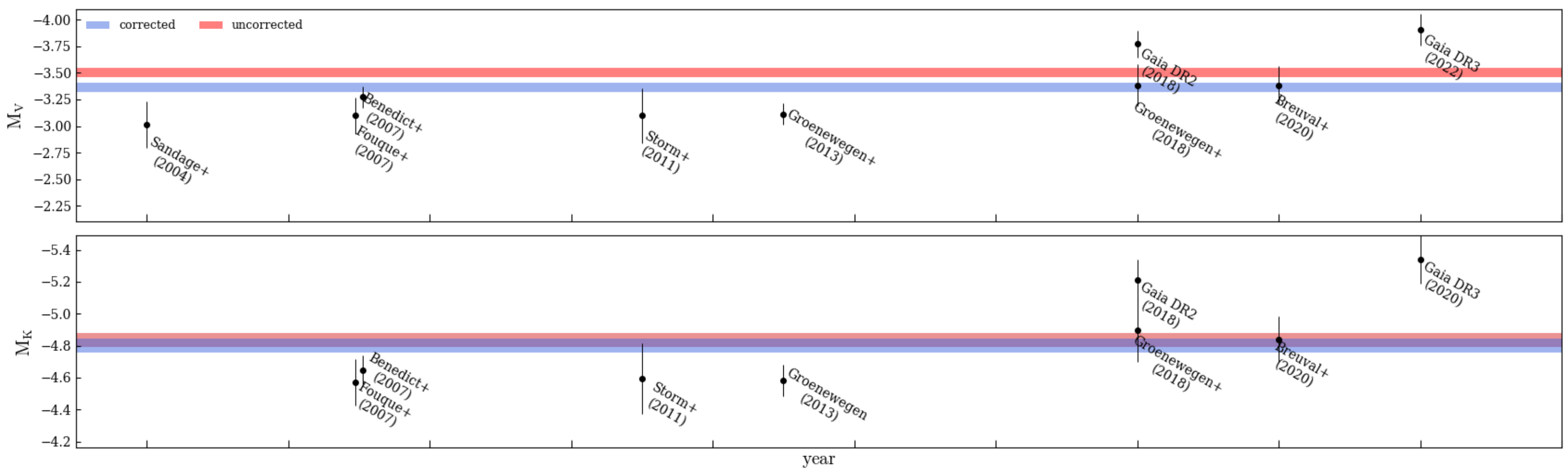
Gallenne et al. (2018)

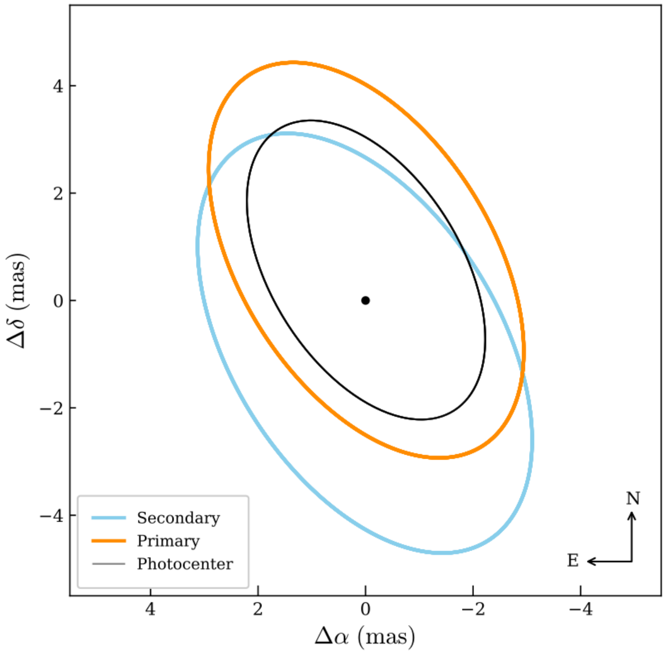
➤ Most accurate & precise distance of a Cepheid (1%)

➤ Most accurate & precise mass of a Galactic Cepheid (3%)

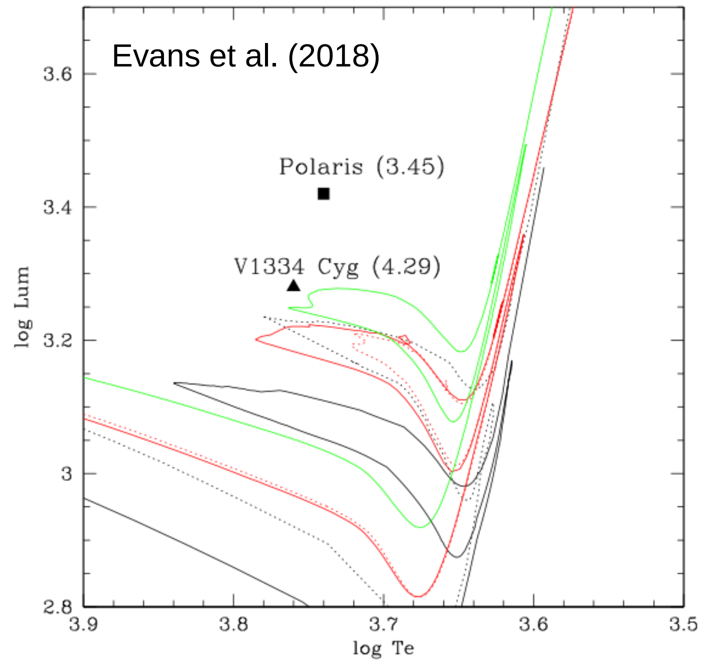
# Binary Cepheids

- Comparison with Gaia and P-L relations:




- Comparison with predictions from evolutionary models:

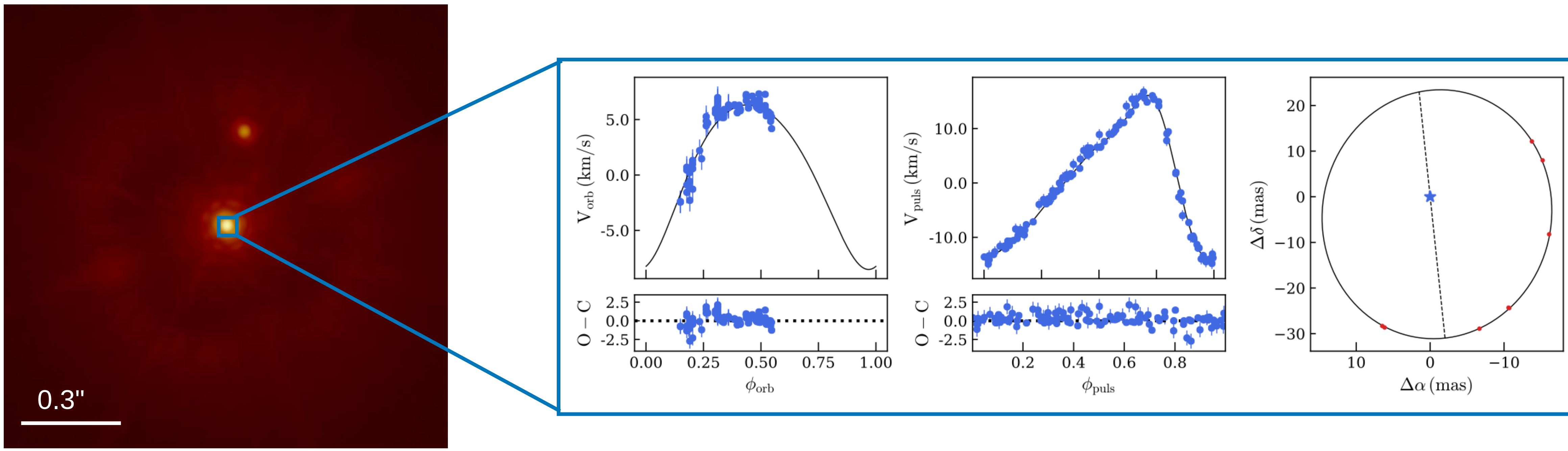


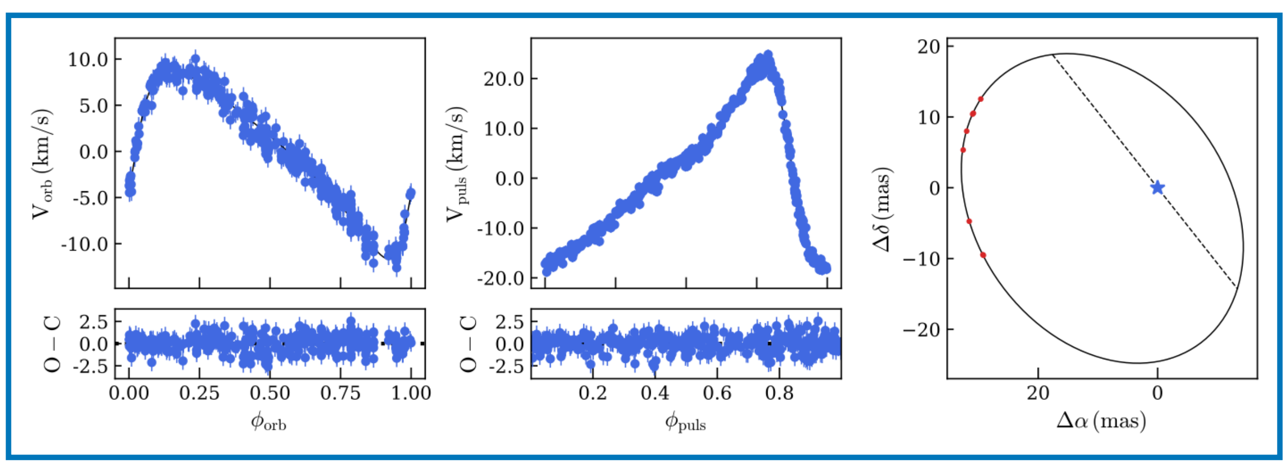

- Black: 5M⊙ Geneva models
- Red: 5M⊙ MIST models
- Green: 5M⊙ PARSEC models
- Dotted lines include significant rotation

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

# Binary Cepheids

- Other promising systems:



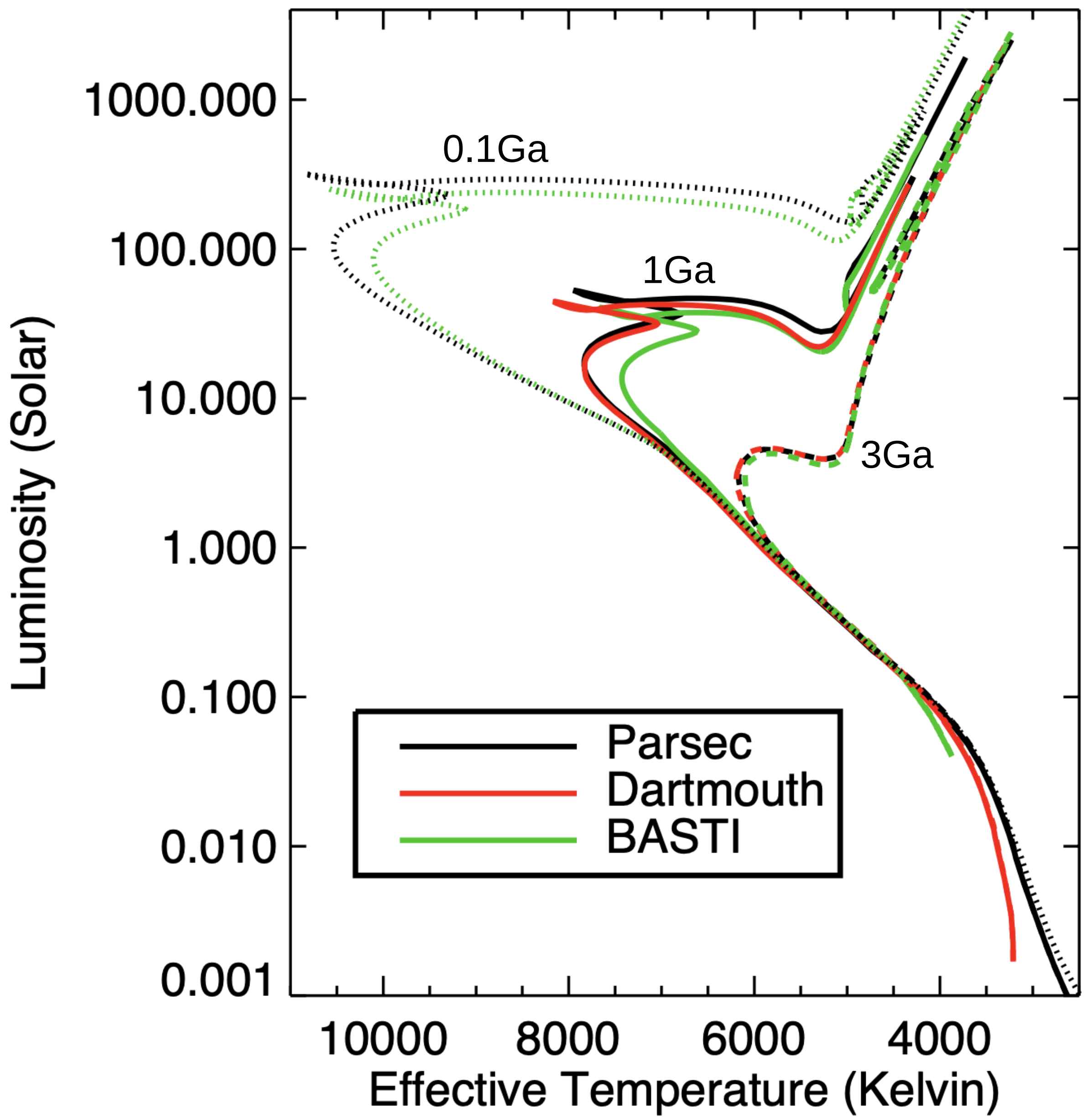

Gallenne et al. (2014)

Gallenne et al. (2019)

➤ SB1 systems but Gaia DR4 should provide the parallaxes to measure the masses

# Binary Stars in general

Huber et al. (2016)

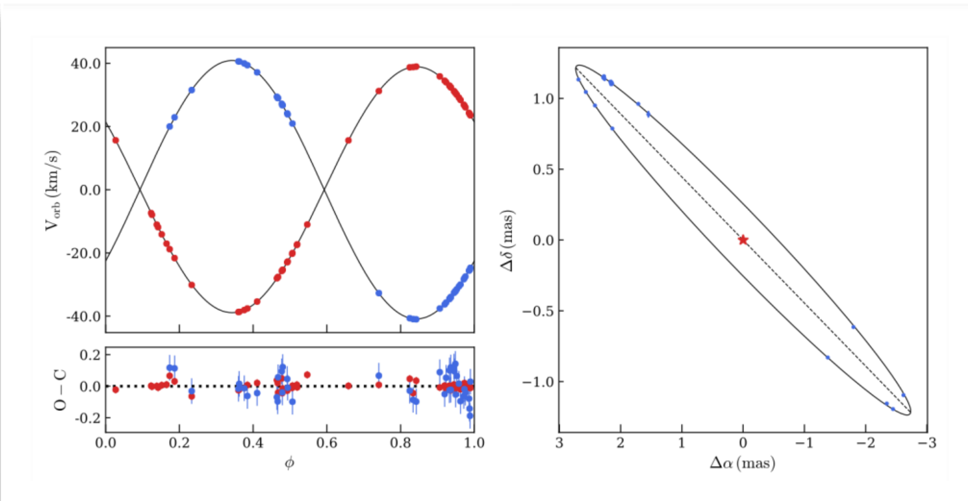



- For a given age, these 3 models differ
- Differences for high and low mass stars are mostly due to variations in poorly constrained input physics
- Models agree well for stars similar to the sun
- Uncertainties in the description of convective core overshooting lead to different main-sequence lifetimes 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

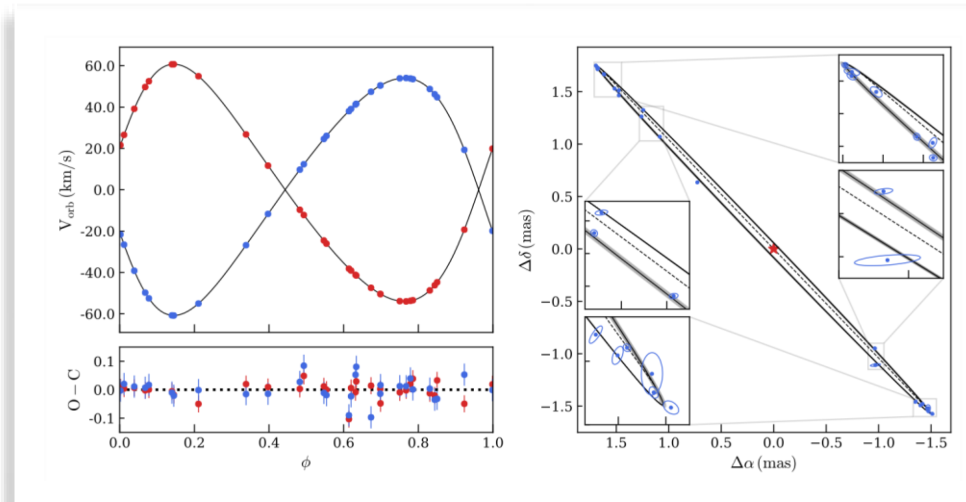
# Binary Stars in general

- Observations of binaries triggered by a project about eclisping binaries




Gallenne et al. (2016)

Masses~0.05% & distance~0.4%



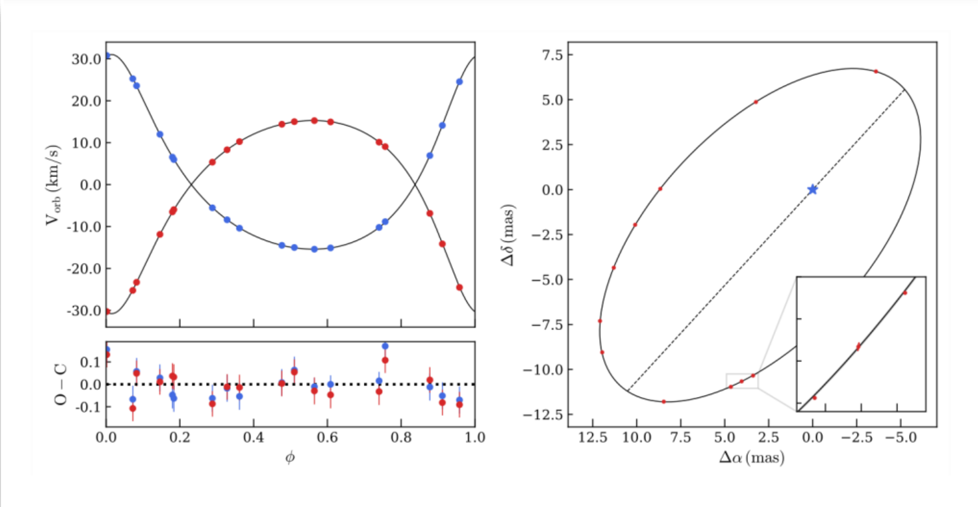

Gallenne et al. (2019)

Masses~0.05% & distance~0.4%

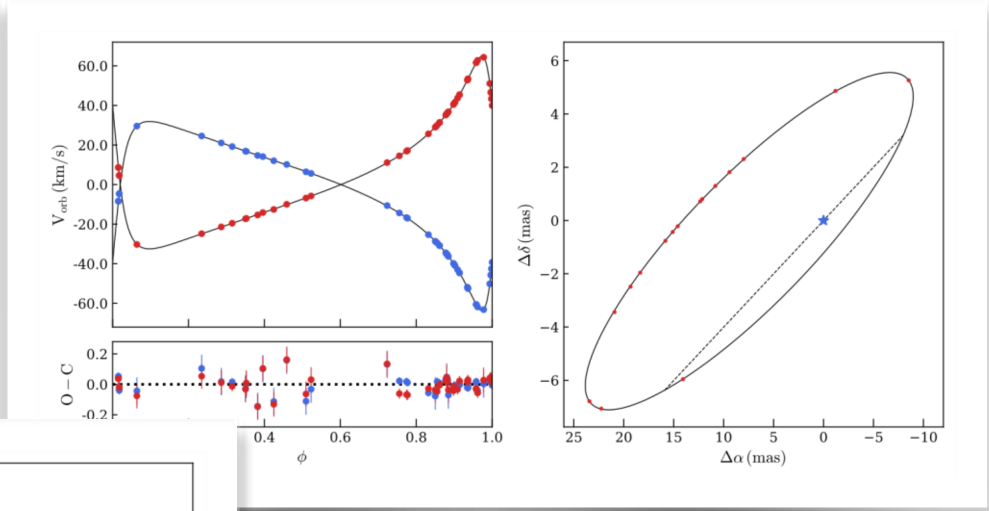
➤ Radial velocities precise and accurate at 100m/s
➤ Astrometry precise and accurate better than 50µas

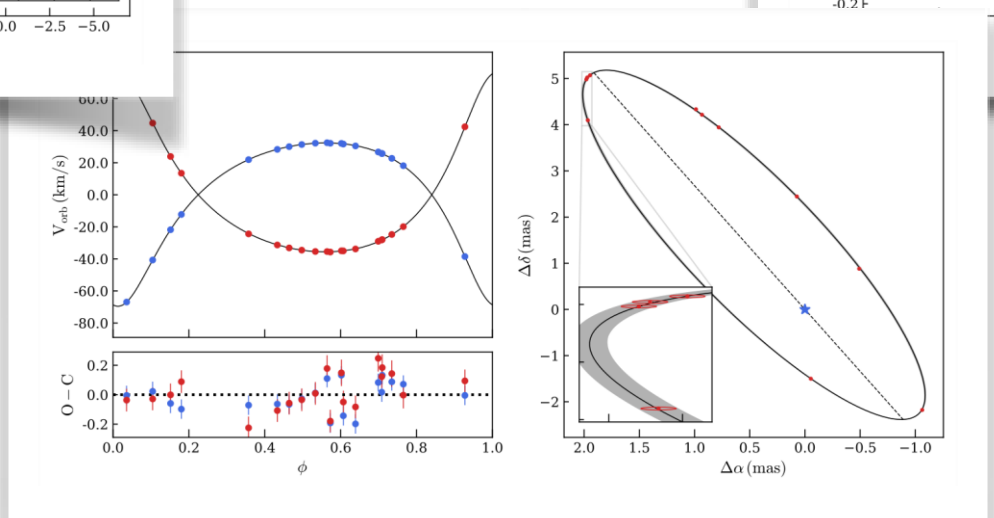
# Binary Stars in general

- On-going observing program to observe ~40 binary systems




Gallenne et al. (2023)



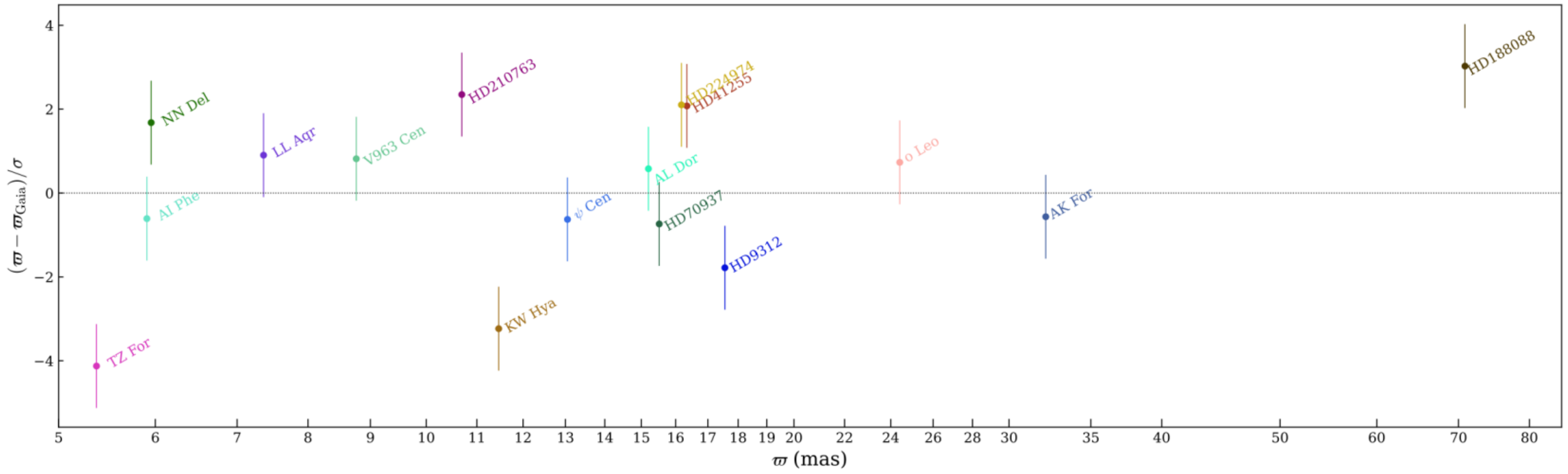



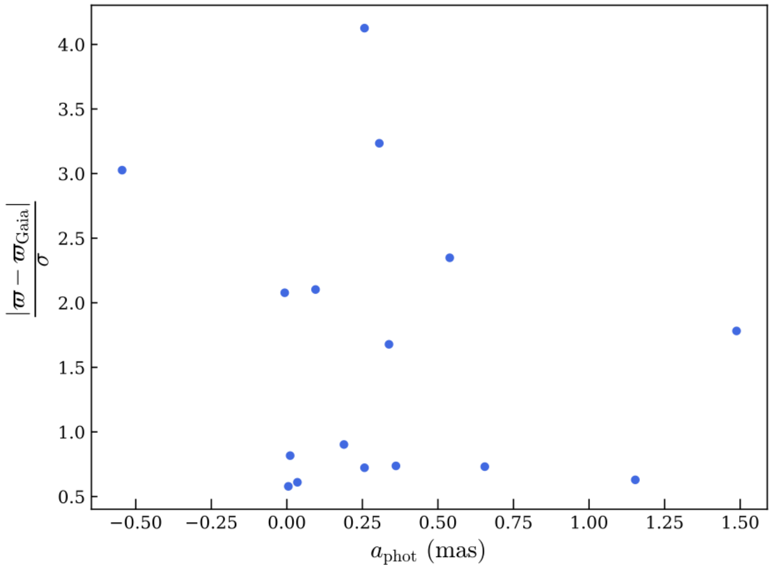

Masses & distances ~0.03%

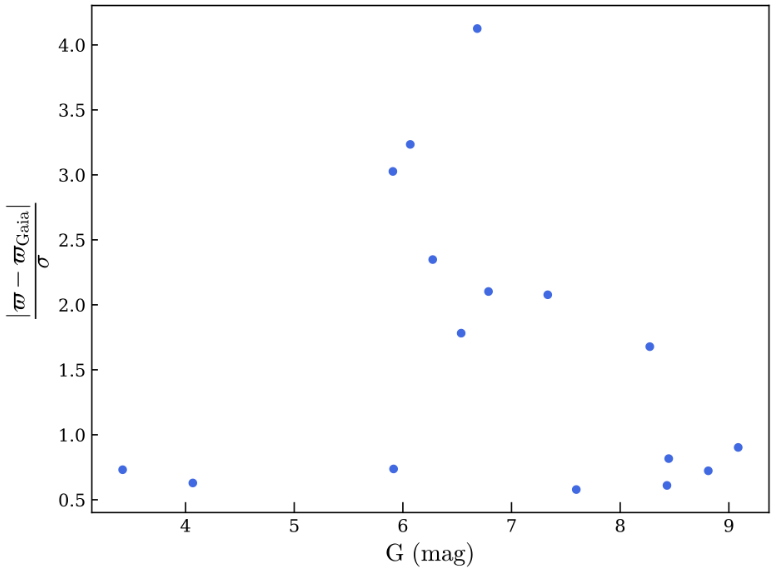
➤ Astrometry precise and accurate at 15µas

# Comparison with Gaia

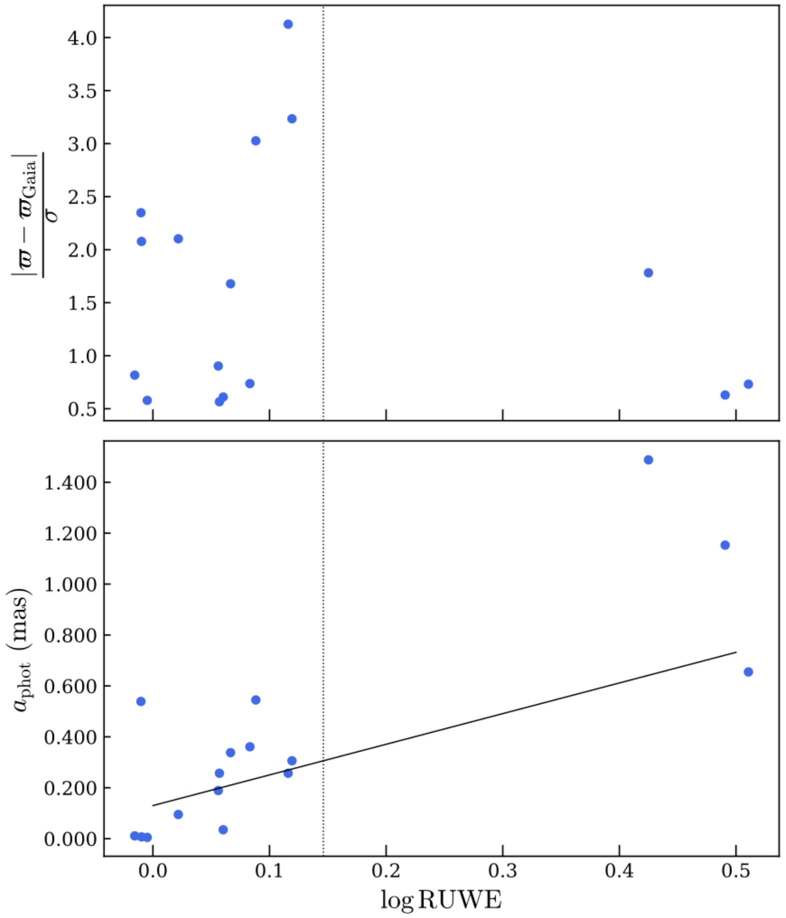
- 50% (8/16 stars) are > 1$\sigma$ away:



# Comparison with Gaia




- No correlation relative error/ruwe
- Correlation $a_{phot}$ wrt ruwe confirmed, even below the 1.4 cutoff


THANK YOU