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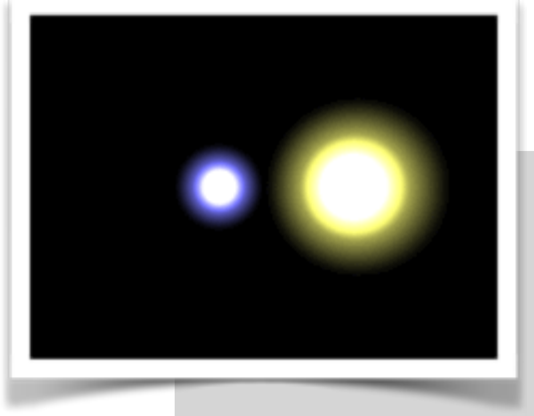
Binary stars

The challenge of distance (parallax) measurement, Rotation & pulsation (Asteroseismology)

Aug. 20, 2020 anya.samadi@mail.udp.cl **Departamento de Astronomía de la Universidad de Chile**



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Outlines

Why do I care about studying binary stars?

Distance measurements for Binary stars

- Why distance measurements for Binary stars are important?
- What is the main question we tried to answer in this field?
- What is the steps we followed to answer this main question (the methodology)?
- Presenting some of the main results and non-expected issues
- What are our future steps to take to answer the new questions and the first ones?

Asteroseismology of A/F-type Binary stars

1. What are stellar global pulsations (and Asteroseismology)?
2. What are the type of pulsations I'm interested in (γ Dor - δ Scuti)
3. What are the type of the binary stars that I considered for my studies (Eclipsing, SB2)
4. Some case studies: (KIC 6048105 & KIC 8975515)
    - Why these individual targets are important?
    - Where the data (spectroscopy, photometry) comes from?
    - The method for driving stellar parameter
    - The most important results

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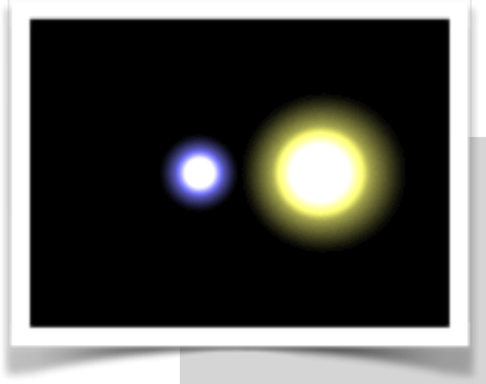

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Why do I care about studying binary stars?

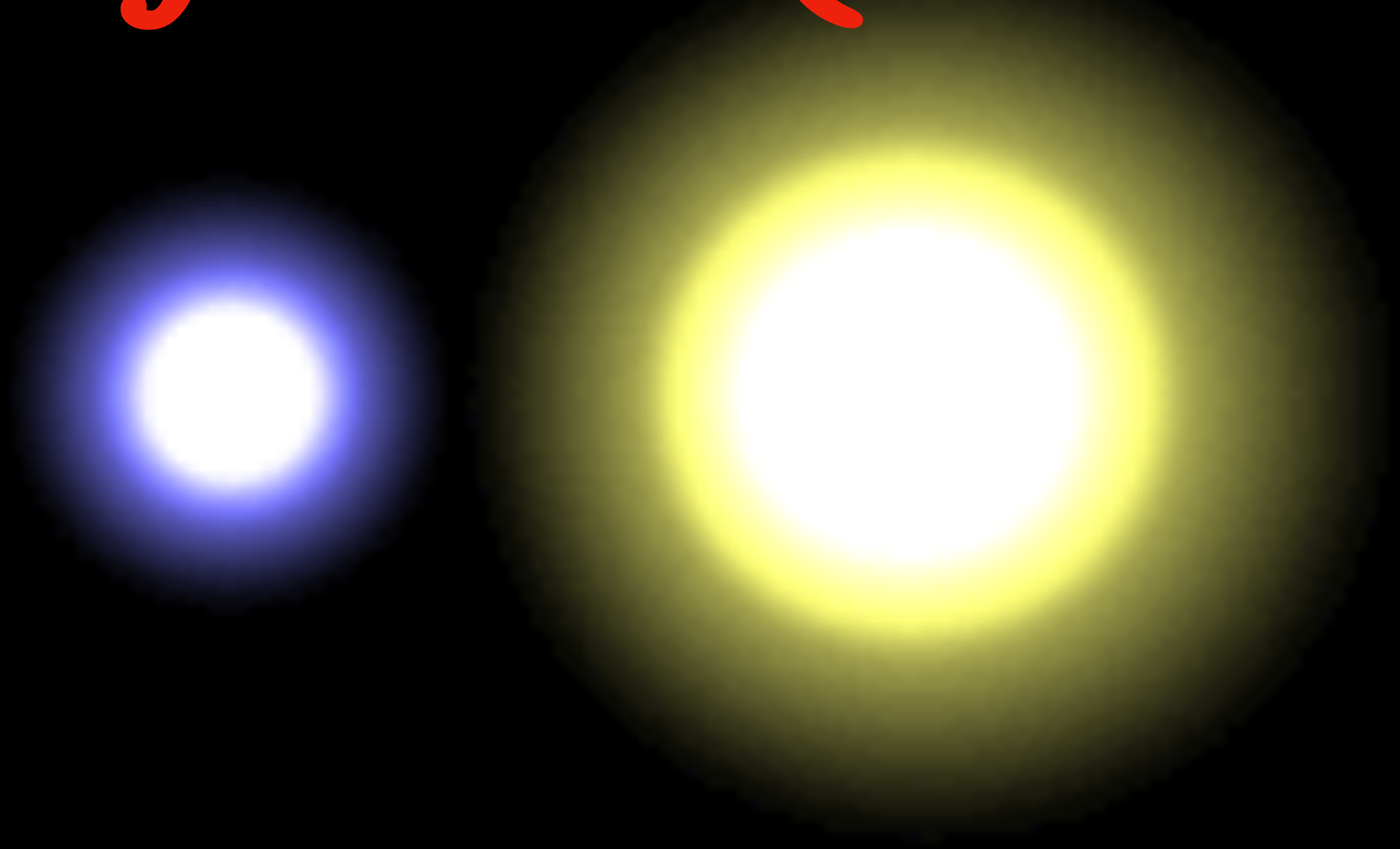
- Fraction of multiple systems (MF) in main sequence population: (e.g. from solar type to high mass) varies from 44±2% to ≥60%
- The formation of first stellar systems (multiplicity)
- If we understand their evolution, we understand how mass is apportioned among younger stars from old multiple systems
- Some events are the production of a binary star evolution: e.g. Supernovae of type Ia, the most massive stars …
- Eclipsing/SB2 binaries can be used to determine precise, model-independent mass and radius measurements compared to normal/single stars

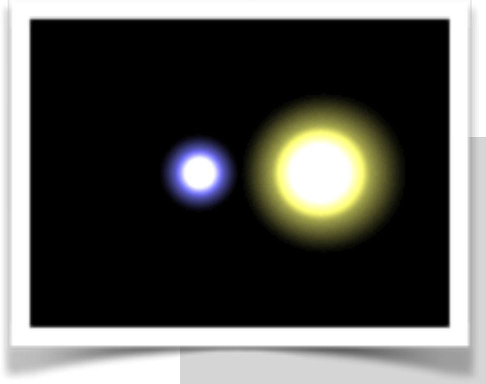
- We get the opportunity to study the influence of binarity:
    - possibility of spots (magnetic fields),
    - mass transfer (in Algols),
    - tides (in short-period binaries)
    - synchronization (rotation and spin)
    - etc …

on stellar evolution and the excited oscillation modes.

Section I

The challenge of Distance measurements for binary stars (Gaia DR2)





Binary stars and the precise stellar parameters

We want binaries for the Masses

SB2 —> RVs (high precision) —> orbital elements

vsini —> projected semi-major axis $asini$

Hence **SB2** with mass ratio only yield **projected masses**!

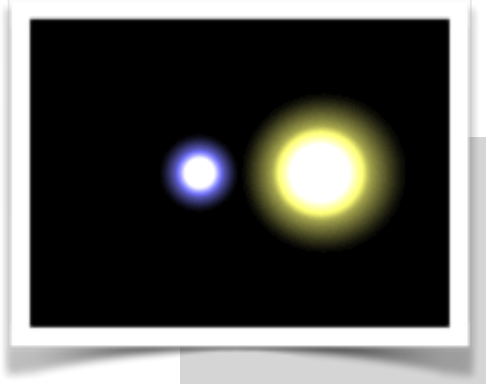
$$M_{1,2}sin^3i$$

EBs —> lift the degeneracy of the masses & semi-major axis

EBs accurate radii —> Roche geometry
==> **photometric mass ratio**

1-2% precision

Photometry : precision: 1-2.
& LC: well detrended
Spectroscopy: precision: S/N & spectra
free of systematic errors
+ adequate **stellar modeling codes**
We have **radii** and the **Mases** of stars!



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Binary stars and the precise stellar parameters

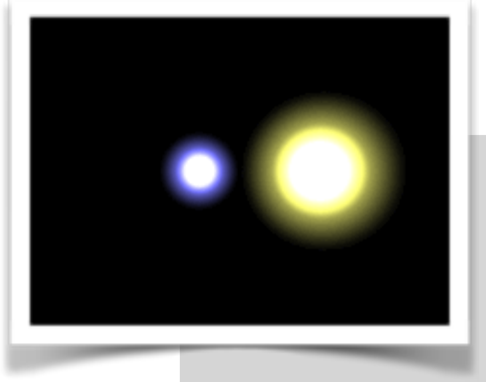
Luminosities
calibrated temperatures
absolute magnitudes <== **Parallaxes** <== good quality photometry
correct for interstellar reddening ==> precise intrinsic brightness of the star

Finally ages stellar evolutionary tracks and so on

gaia

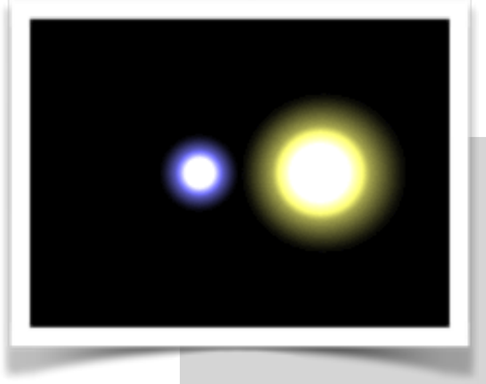
~1/3 all variable stars are EBs

So **Gaia's** Binaries (EBs) can make so much advance in astrophysics



Evaluating the uncertainties in distance measurements for binary/multiple systems in comparison to single stars, from large spectroscopic surveys (Gaia DR2)

By employing the
least model-dependent spectroscopic method
for determination of stellar distances (Twin method)



Gaia DR2 and distance measurement precision for Binary stars

> 6,000,000 Gaia DR2 targets with

RV calculations (n_RV) >4

> 300,000 targets of RAVE DR5 spectroscopic survey

Their parallaxes has driven (Jofre+2017MNRAS) by:

Twin method (Jofre+2015MNRAS)

> 90,000 targets of RAVE DR5 /Gaia DR2 with lower RV uncertainties (than Binary stars)

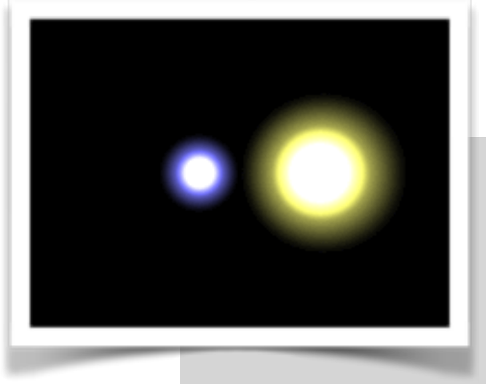
Single stars

> 11,000 targets of RAVE DR5 / Gaia DR2 with high RV uncertainties

But parallax measurement uncertainties better than 20%

Binary stars

- RAVE, the Radial Velocity Experiment, is a spectroscopic astronomical survey of stars
- The data from the spectrograph with R~7500
- is delivered for 10 years from 2003 to 2013.
- The wavelength coverage 841.0 to 879.5 nm,
- gives spectra of more than 520000 star



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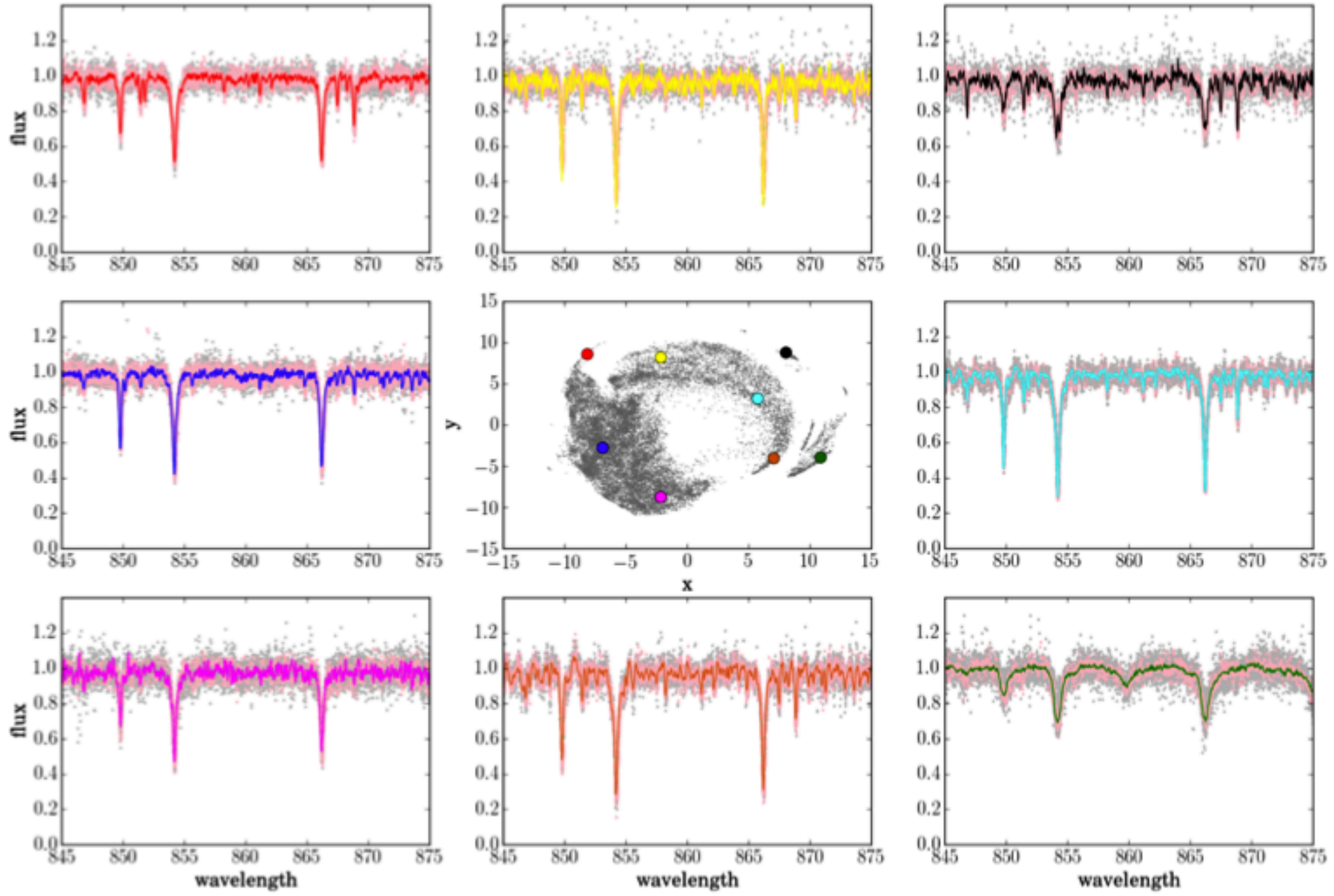
Gaia DR2 and distance measurement precision for Binary stars

RAVE
RADIAL VELOCITY EXPERIMENT

> 50% of RAVE targets have TGAS parallaxes from Gaia DR1

For the other half either:
- without parallax values
- ***with lower parallax precision (uncertainties larger than 20%.) —> Twin method***

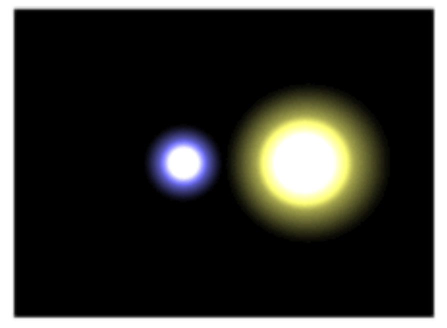


RAVE catalog using t-SNE approach
(t-student stochastic neighbor embedding)

This approach clusters the stars with the same spectrum morphology in the same region on a 2D map.

SAME LUMINOSITY ➔ SAME SPECTRA
DIFFERENT APPARENT MAGNITUDES ➔ DIFFERENT DISTANCE

$$m_1 - m_2 = -5\log(\varpi_2/\varpi_1)$$



Gaia DR2 and distance measurement precision for Binary stars

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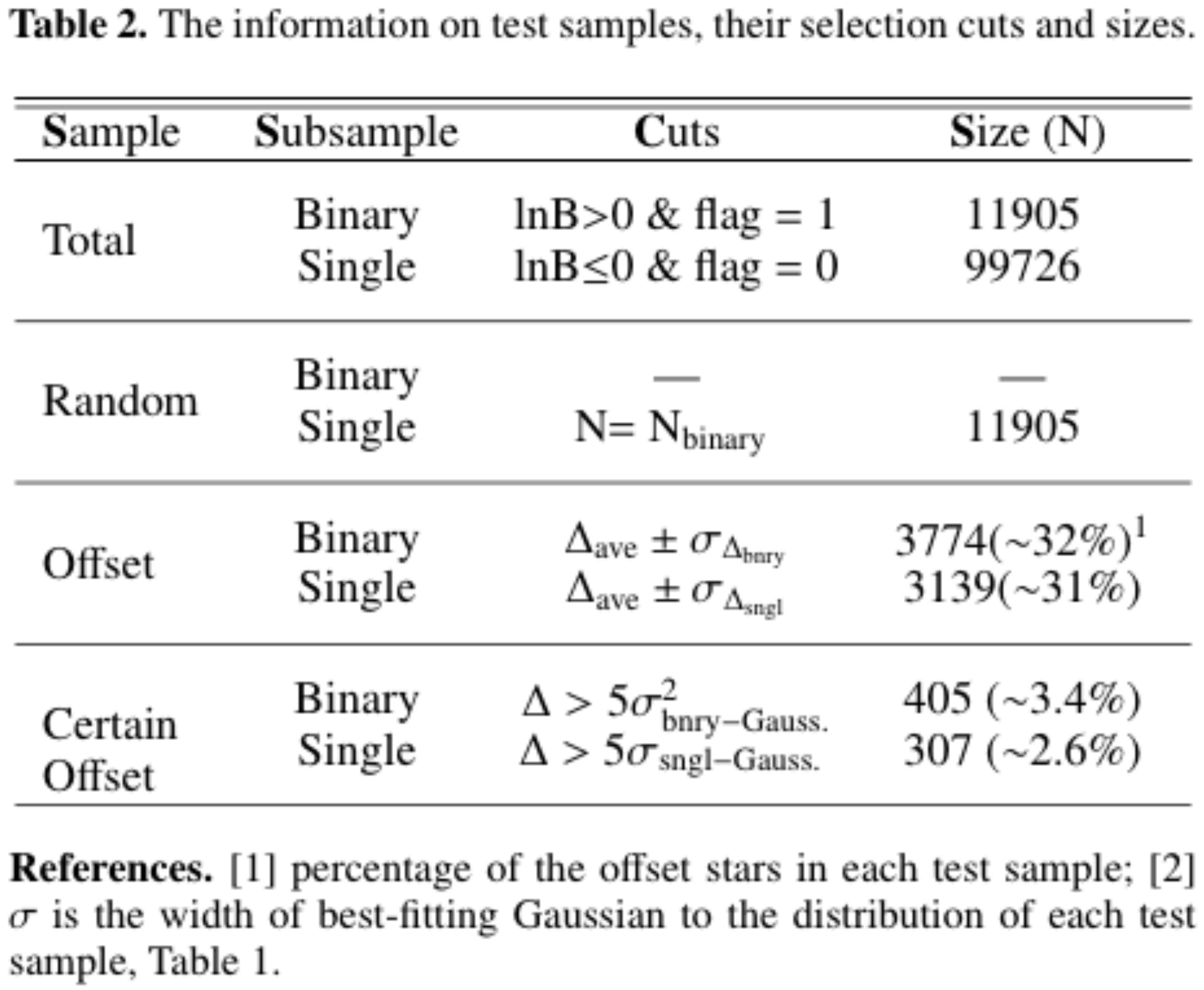
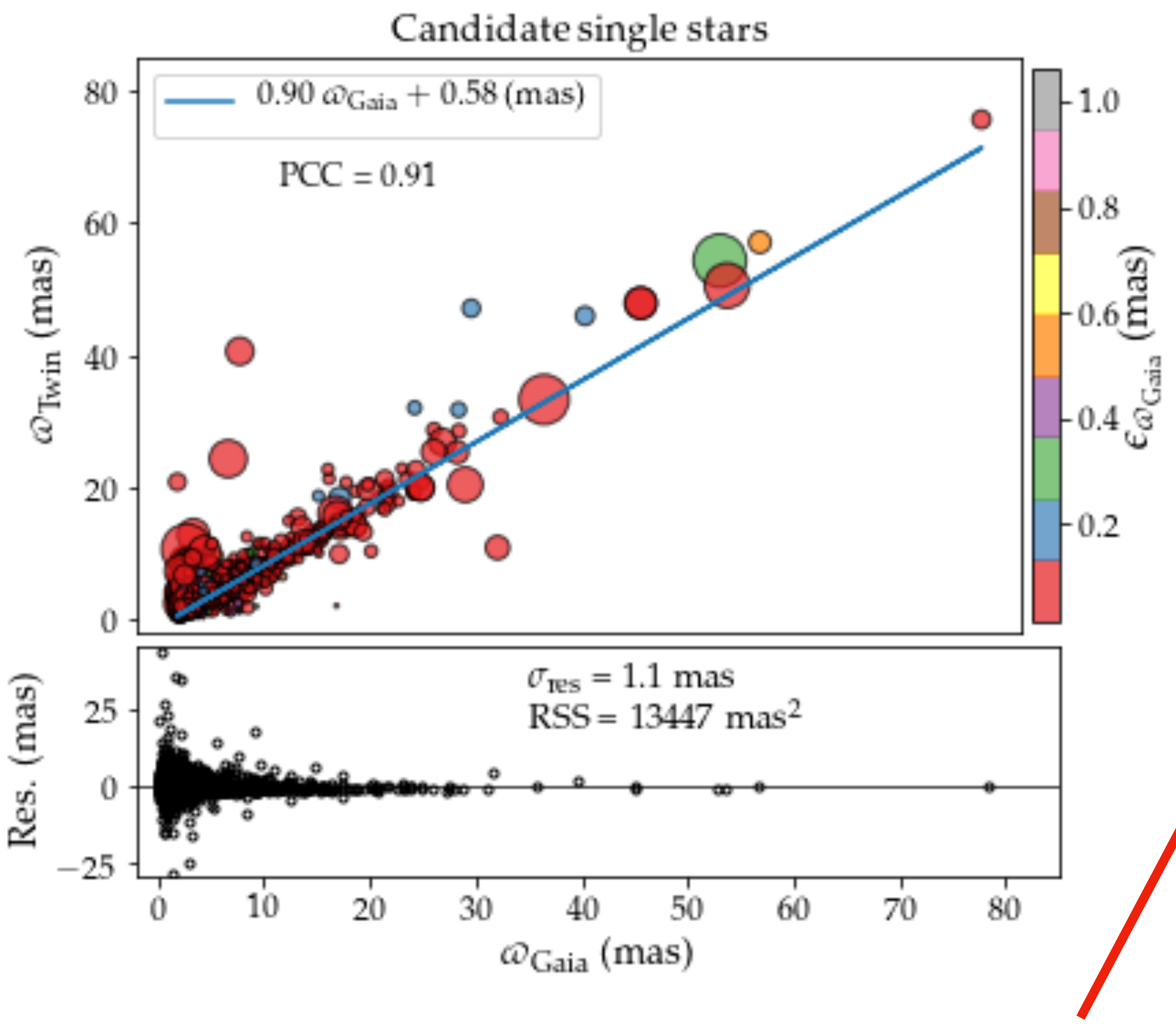
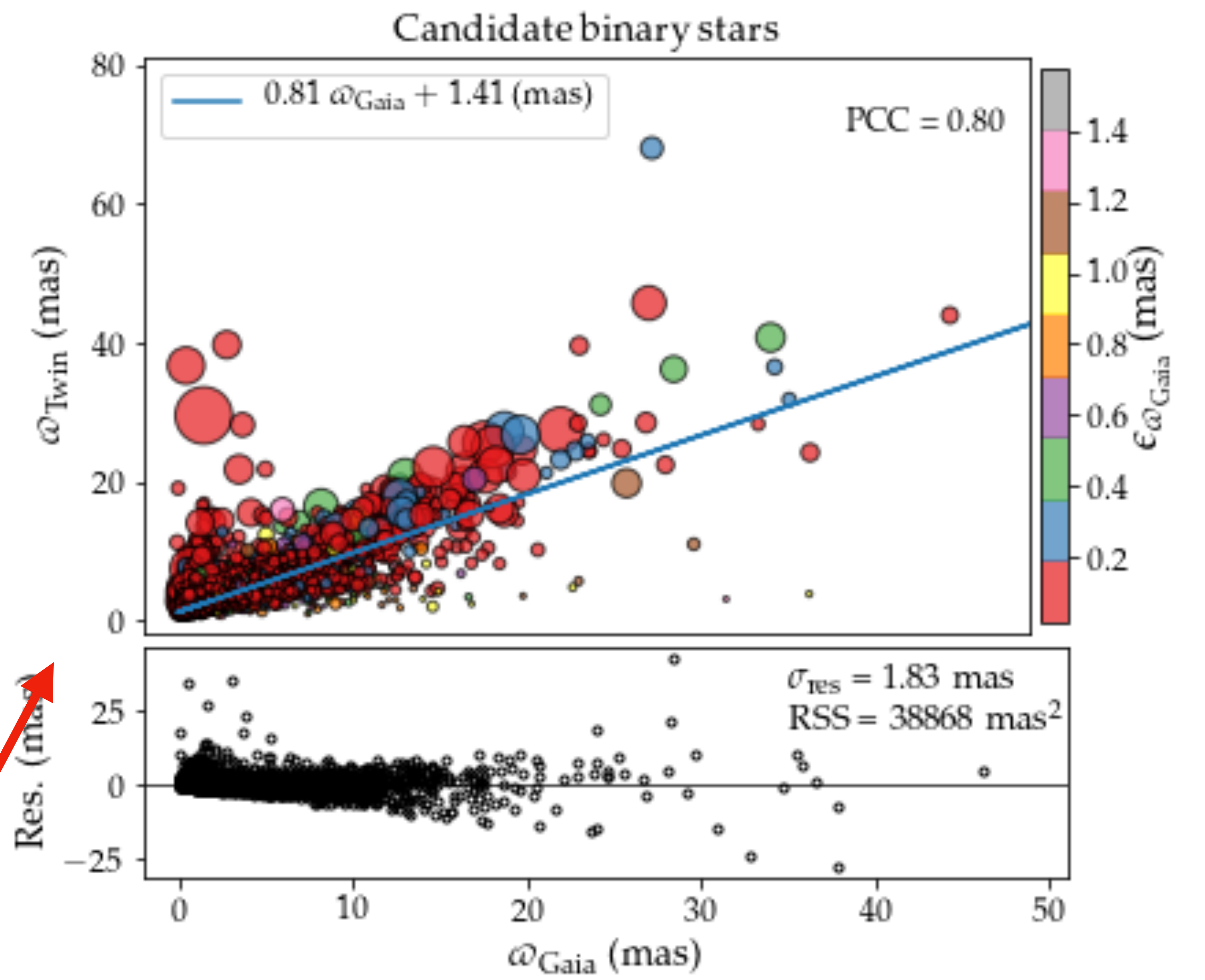


Table 2. The information on test samples, their selection cuts and sizes.

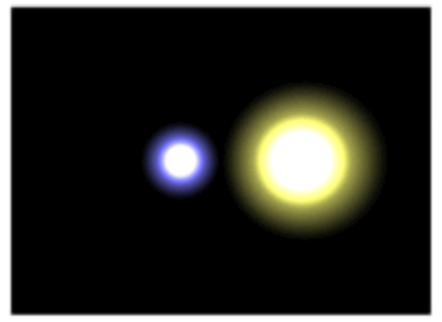
Sample	Subsample	Cuts	Size (N)
Total	Binary Single	lnB>0 & flag = 1 lnB≤0 & flag = 0	11905 99726
Random	Binary Single	— N= N_{binary}	— 11905
Offset	Binary Single	$\Delta_{ave} \pm \sigma_{\Delta_{bnry}}$ $\Delta_{ave} \pm \sigma_{\Delta_{sngl}}$	3774(~32%)[1] 3139(~31%)
Certain Offset	Binary Single	$\Delta > 5\sigma^{2}_{bnry-Gauss.}$ $\Delta > 5\sigma_{sngl-Gauss.}$	405 (~3.4%) 307 (~2.6%)

References. [1] percentage of the offset stars in each test sample; [2] σ is the width of best-fitting Gaussian to the distribution of each test sample, Table 1.





The parallax values from two methods show larger scatter for binary stars!



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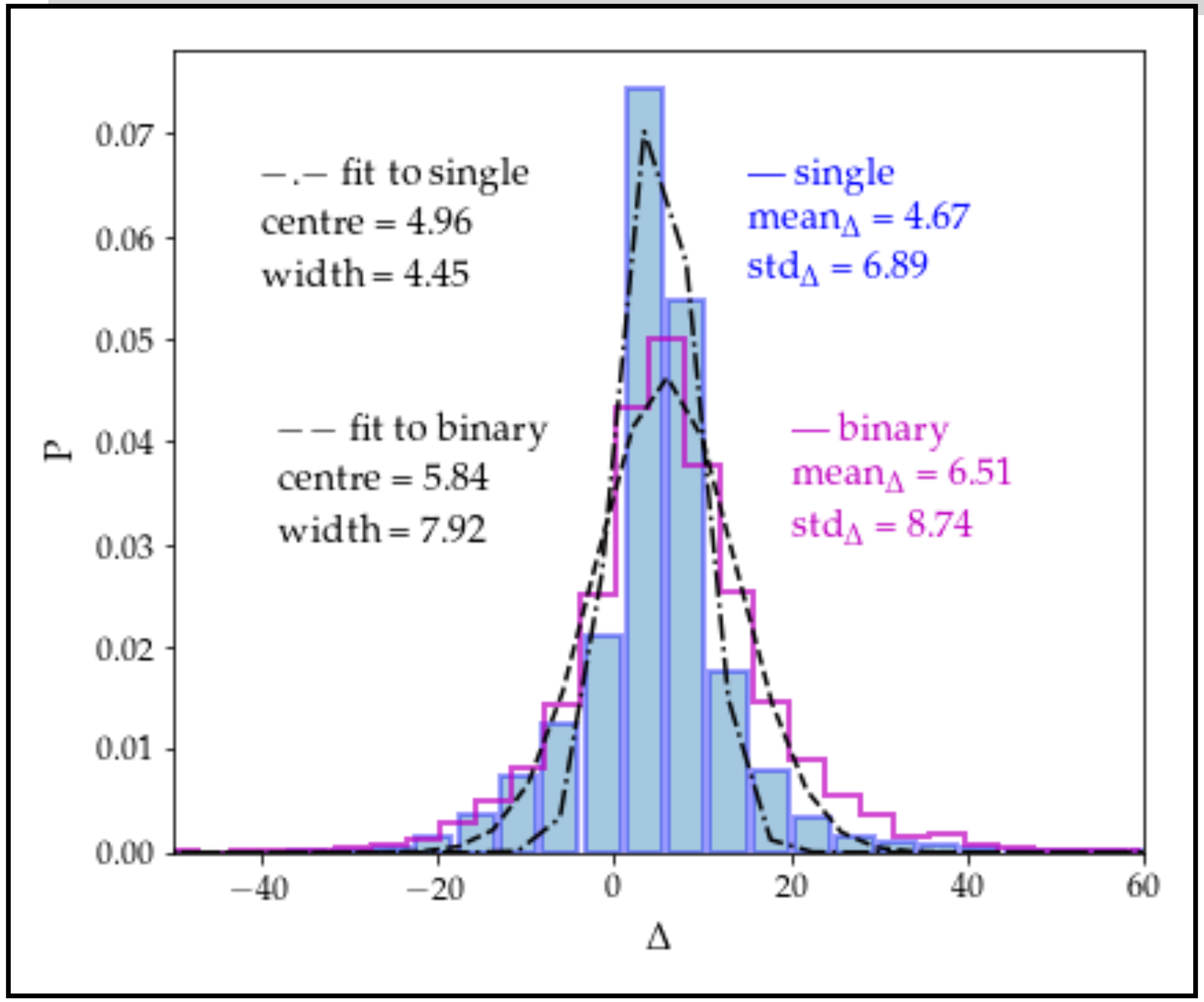
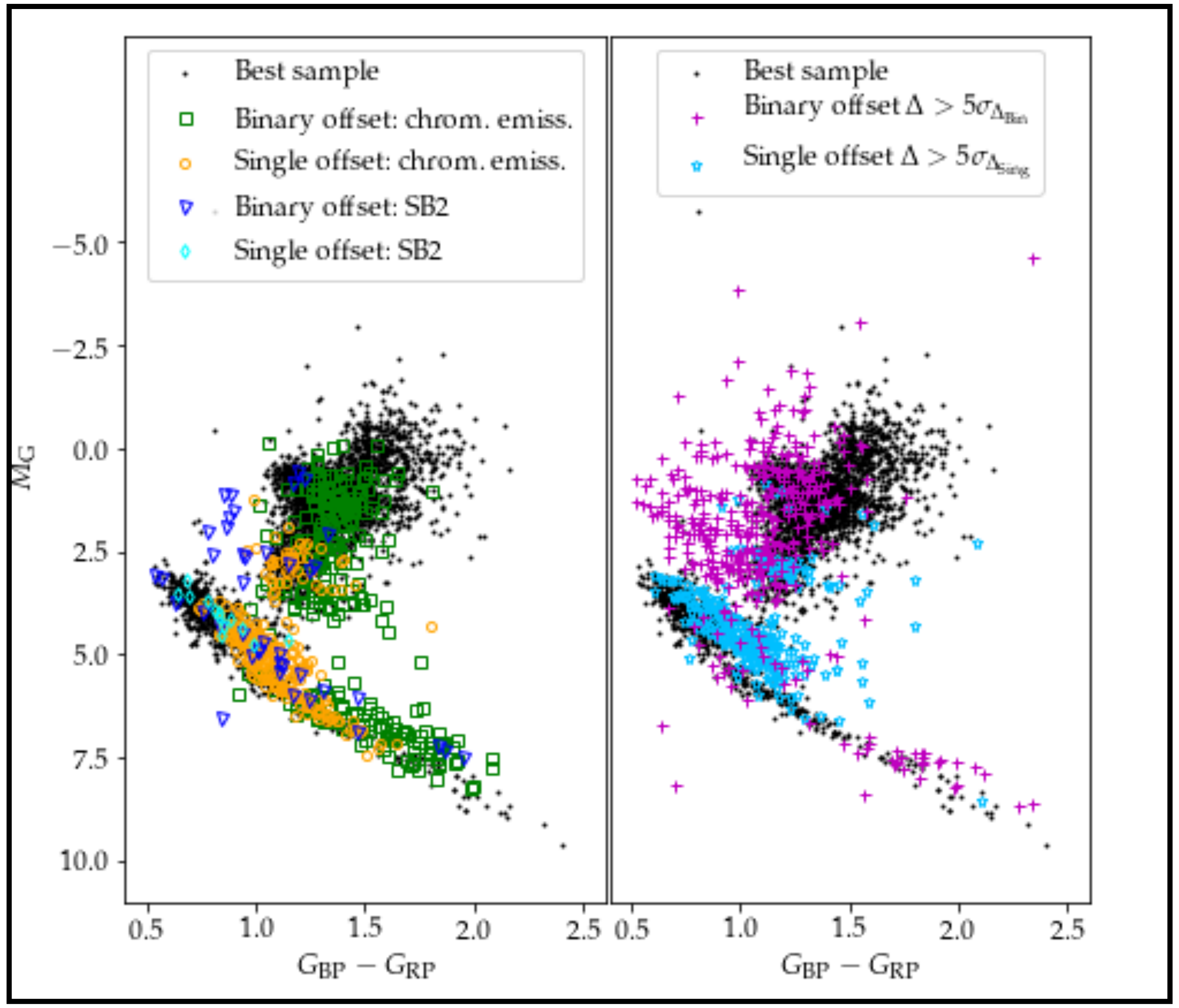
Gaia DR2 and distance measurement precision for Binary stars





Comparison tools

$$\Delta = \frac{\varpi_{\rm Twin} - \varpi_{\rm Gaia}}{\sqrt{\epsilon^2_{\varpi_{\rm Twin}} + \epsilon^2_{\varpi_{\rm Gaia}}}}$$

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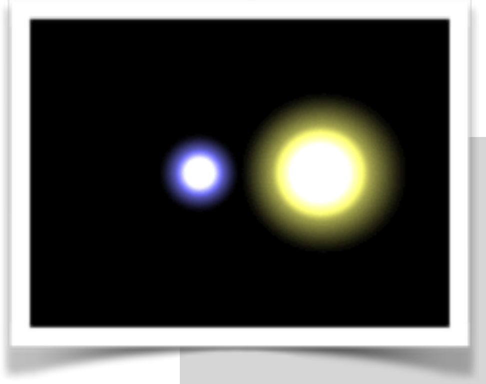


Gaia DR2 and distance measurement precision for Binary stars

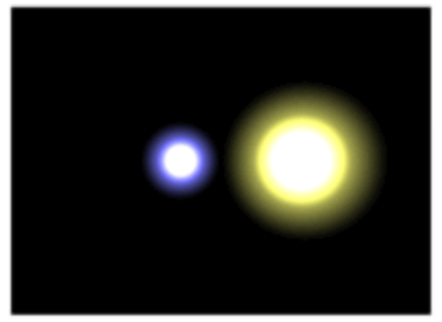
The parallax differences distribution for both of binary and single stars is the the SAME (for ~70% of each sample)!

Most of the targets that have very larger discrepancy between two parallaxes ('Offset sample') are flagged as SB2 or chromospherically active stars by RAVE DR5.

- What is the source of "5σ difference" in overall value of two methods?

Colors zero points, distance of the reference stars ,…

- What is the nature of the stars for which spectroscopic distances and Gaia parallaxes differ significantly?
    - Biased observations and cuts in catalogues
    - Clear evidence of stellar chromospheric activity , SB2 flagged in RAVE

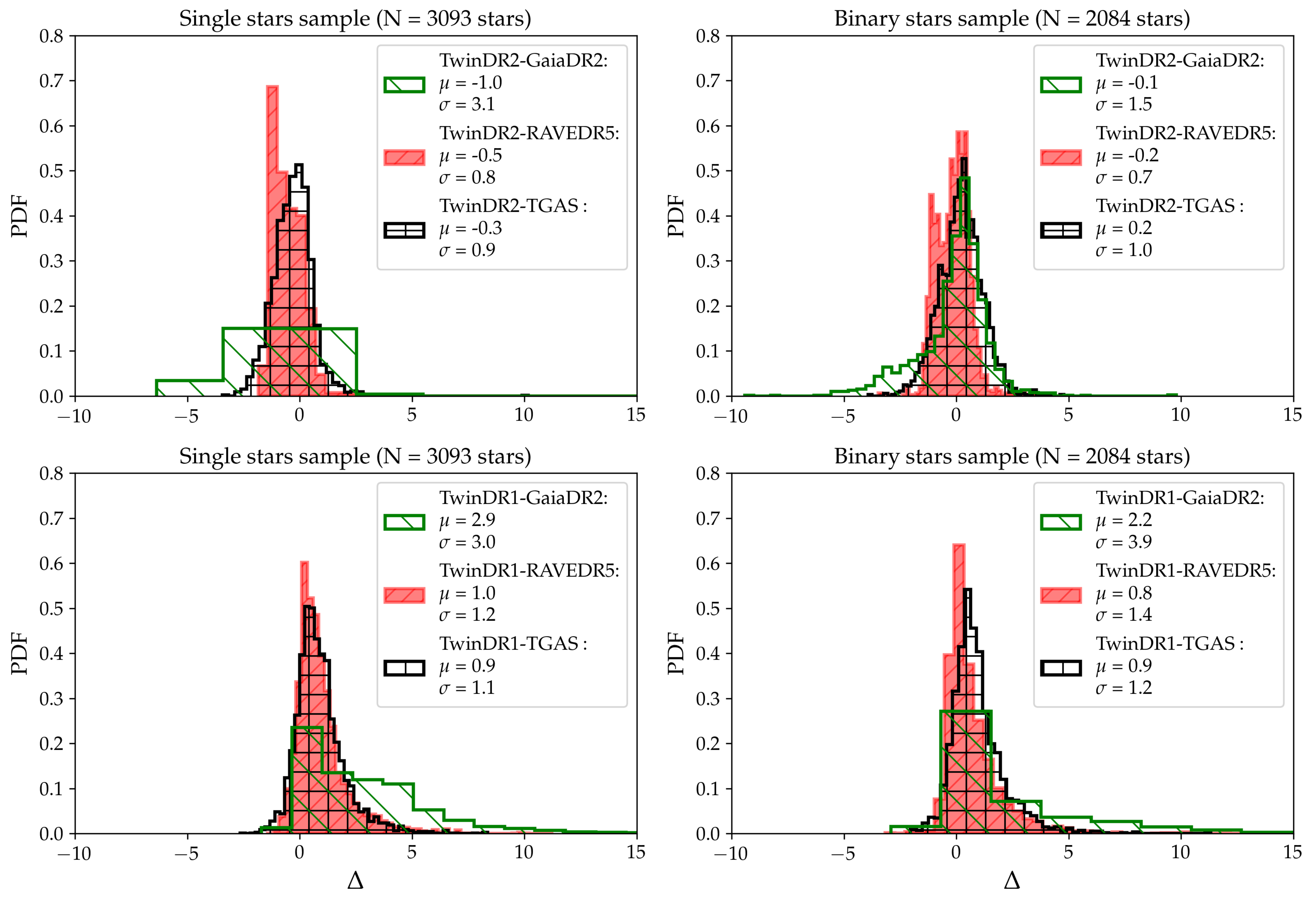


Gaia DR2 and distance measurement precision for Binary stars

PHASE 2

1. Repeating Twin method for these targets by using Gaia DR2 parallaxes, AG and G for the reference stars

2. Check the performance of G, AG from Gaia DR2



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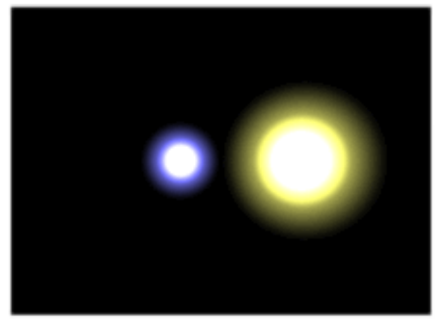
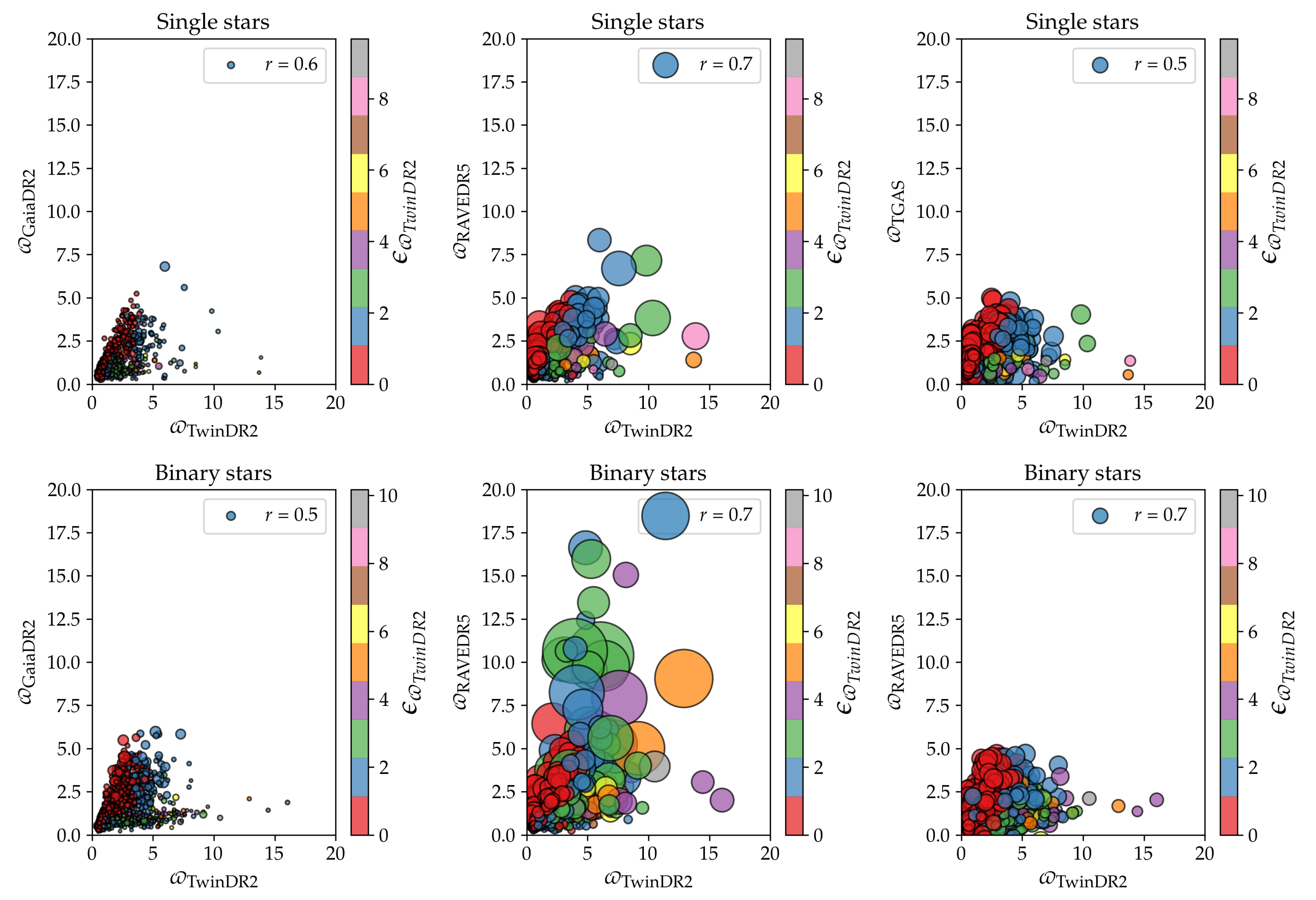
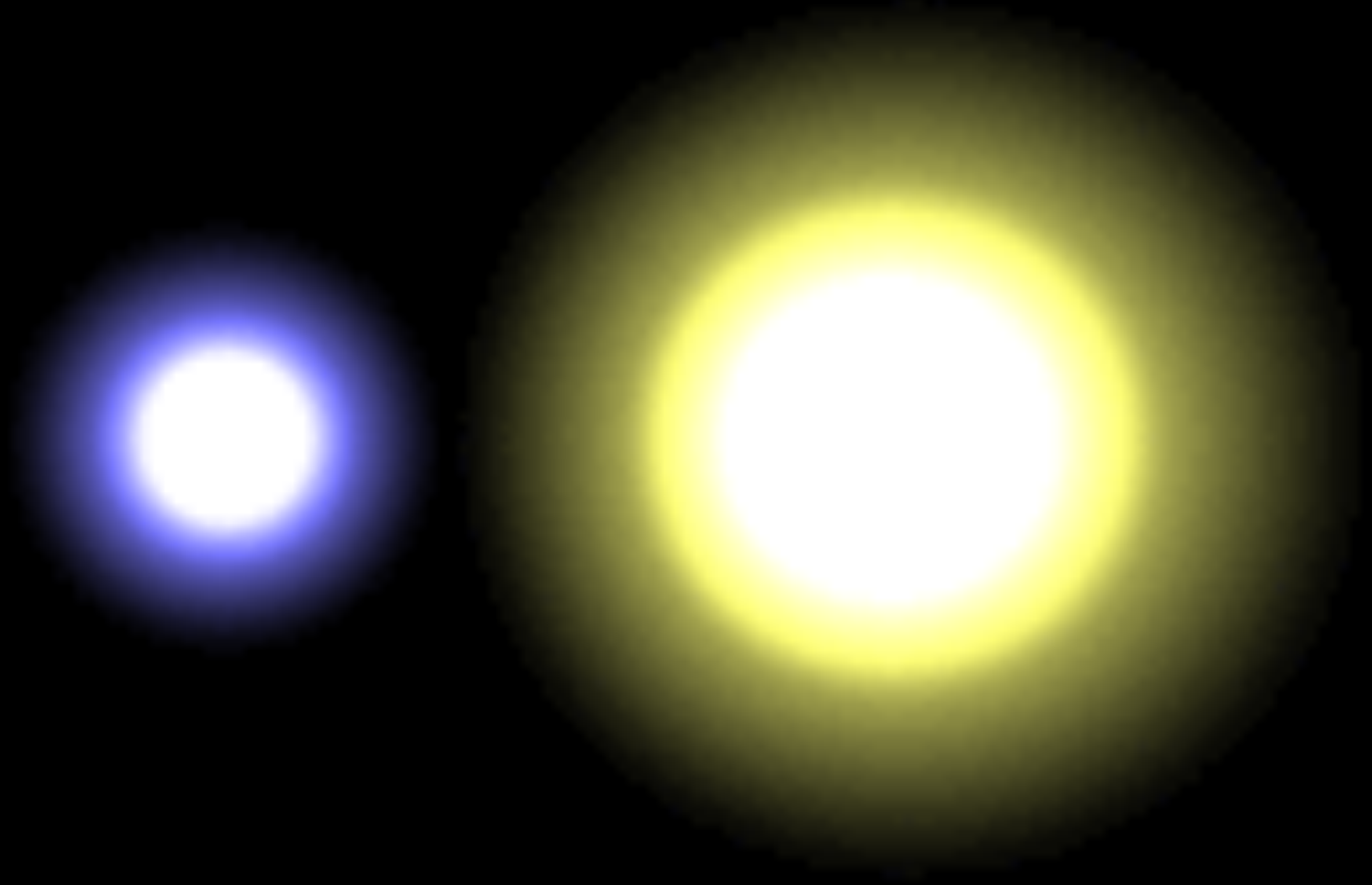


Gaia DR2 and distance measurement precision for Binary stars



Section II

Asteroseismology of A/F-type Binary stars



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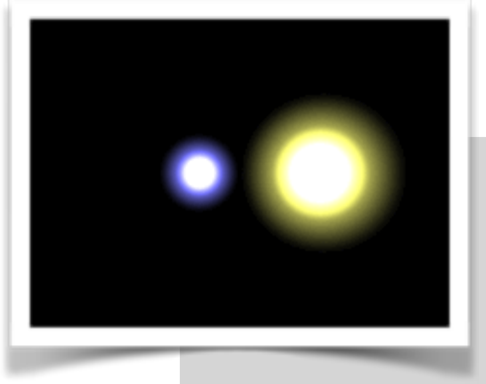


What are stellar global pulsations?

non-radial oscillations

What do they look like?

in a 3D spherical star $\xrightarrow{\text{looks like}}$ the vibration modes of a 1D string

How are they excited?

perturbed from equilibrium ↔ a resorting force takes it back to equilibrium

Driving mechanism
energy fed into the pulsation via driving mechanisms

- **Heat engine** (e.g. κ mechanism)

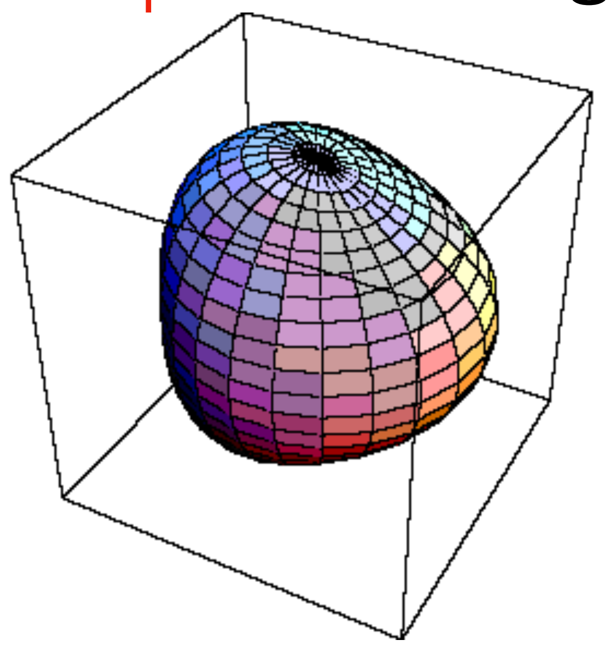
  Converting thermal energy to mechanical energy

- **Stochastic driving**

  Convective motions near stellar surface reaches speeds close to that of the sound excites normal modes of the star to the observed amplitudes

- **Convective blocking**

  Luminosity perturbation is blocked at the base of the convection zone leading to heating in phase with compression



$$f, \quad A, \quad n$$

Frequency, Amplitude, number of the nodes (overtones)

What are stellar global pulsations?

fluid elements displacement from their equilibrium position

$$\xi(\xi_\theta, \xi_\phi, \xi_r) \propto Y_{lm}(\theta, \phi) \rightarrow P_l^m(\theta, \phi)$$

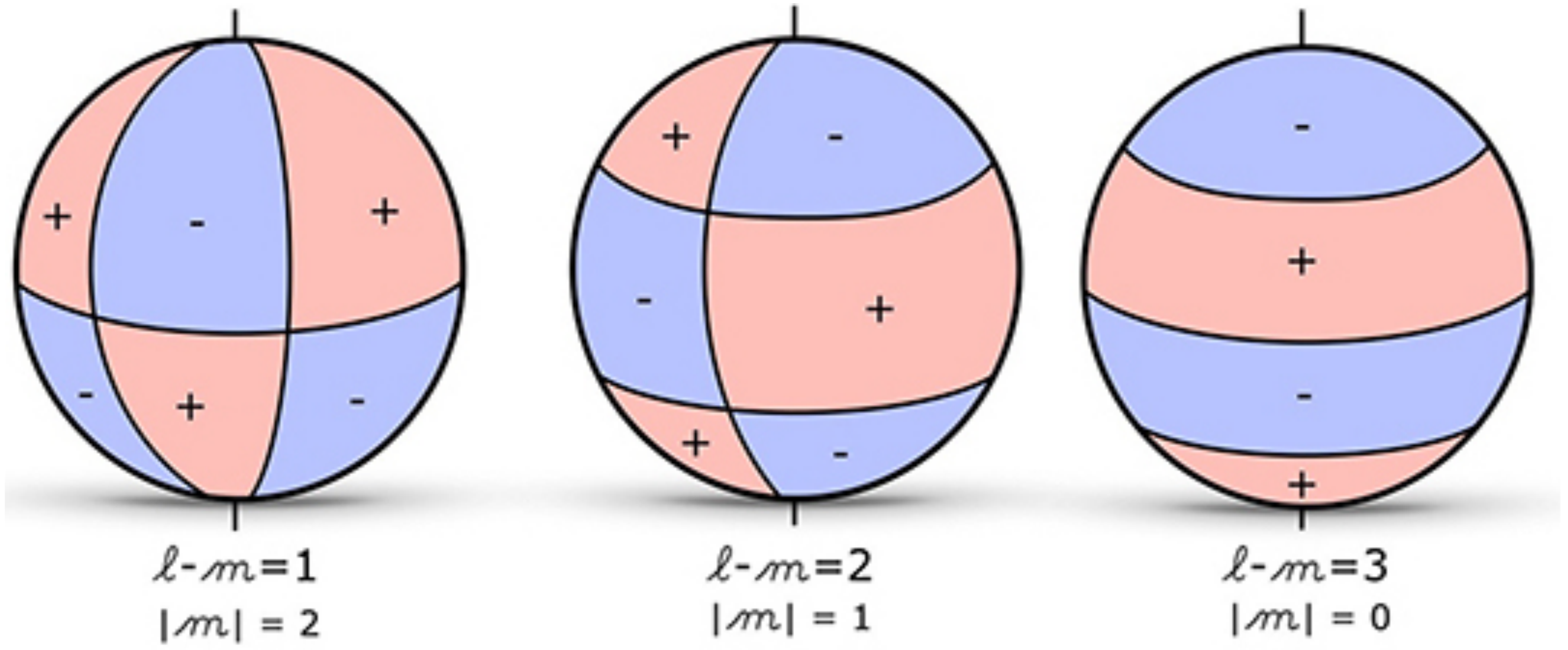
ϕ: symmetric axis of the modes

Indicating the nodes of a non-radial mode

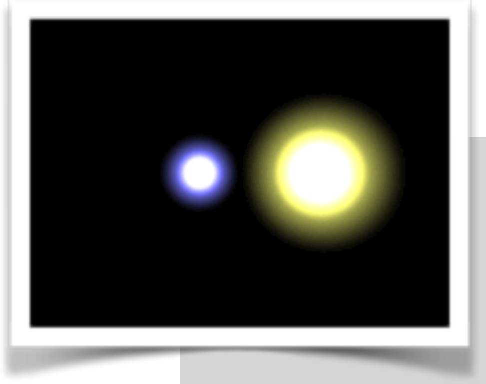
$$(n, l, m)$$

l: Number of the node lines on the stellar surface

m: Number of nodes line on the stellar surface which pass through symmetry axis



Pulsating Stars, Lamers, Henny J.G.L.M. and M. Levesque, Emily (2017)



Type of the pulsation modes

g modes

- The resorting force is gravity (buoyancy)
- Internal gravity waves
- ξ_r varies mostly close to the core
- Low-frequency

p modes

- The resorting force is pressure gradient
- Acoustic waves
- ξ_r varies close to the surface
- High-frequency modes

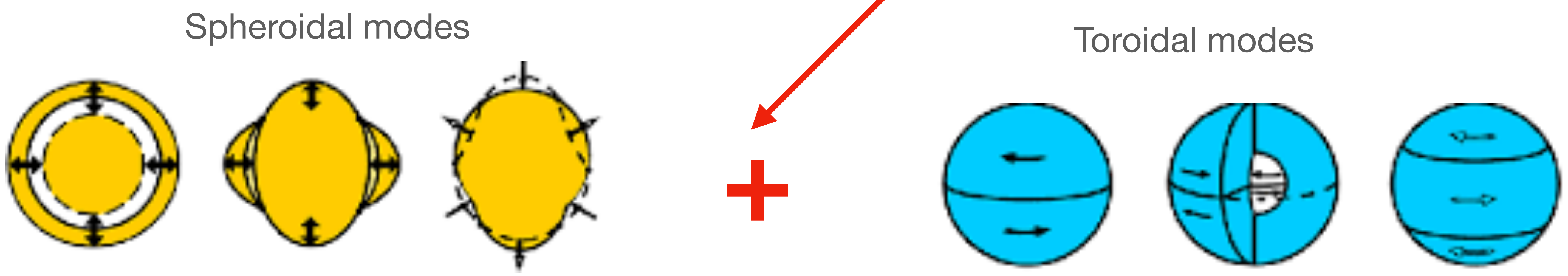
Ignored ←

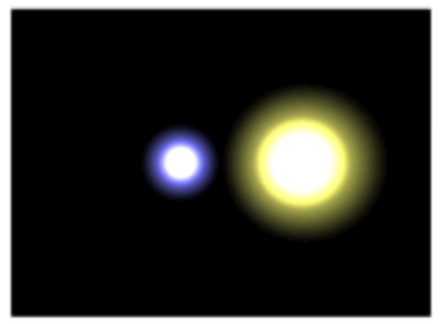
Coriolis force
(rotation)
&
Lorentz force
(magnetism)

→ **Considered**

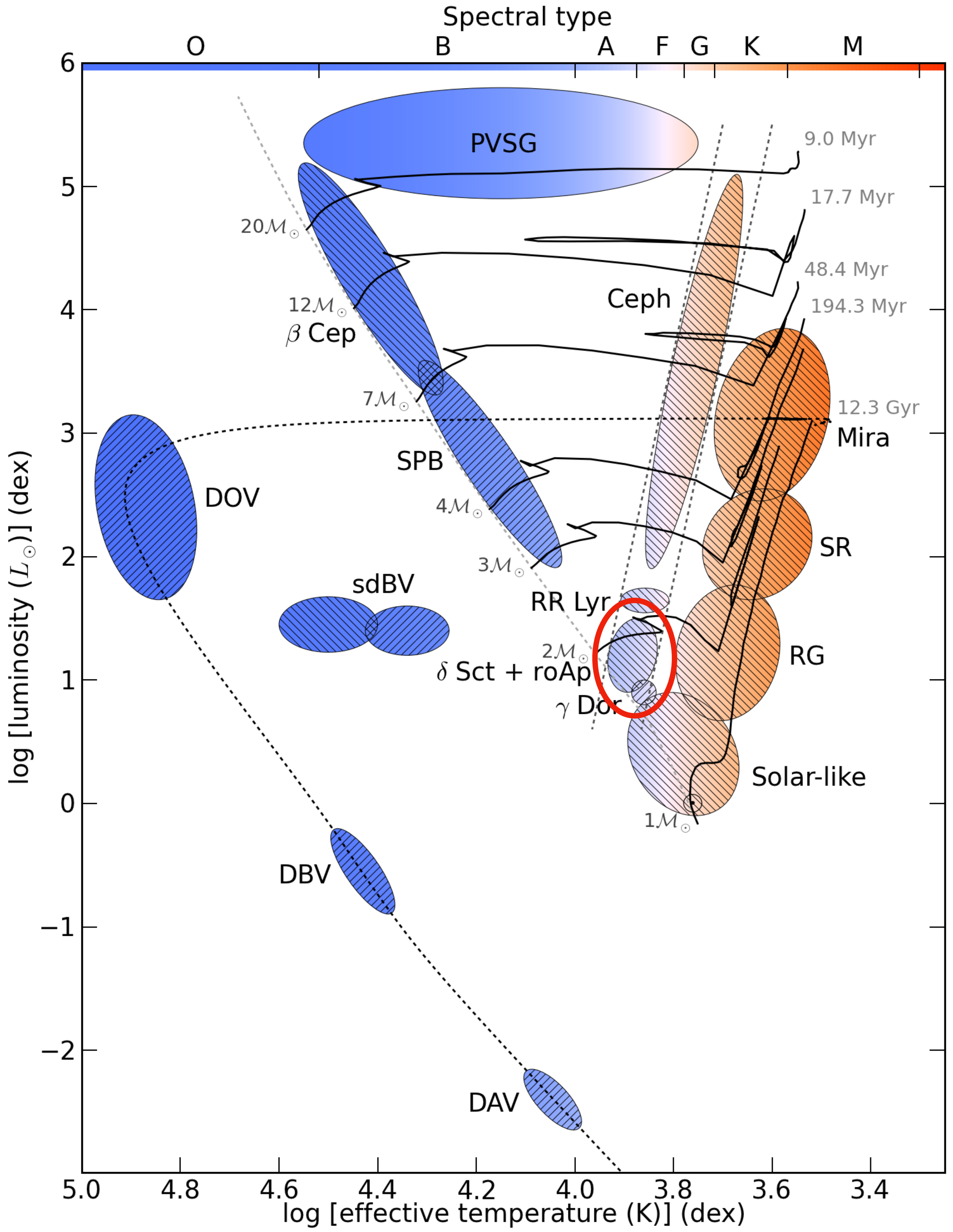
r modes

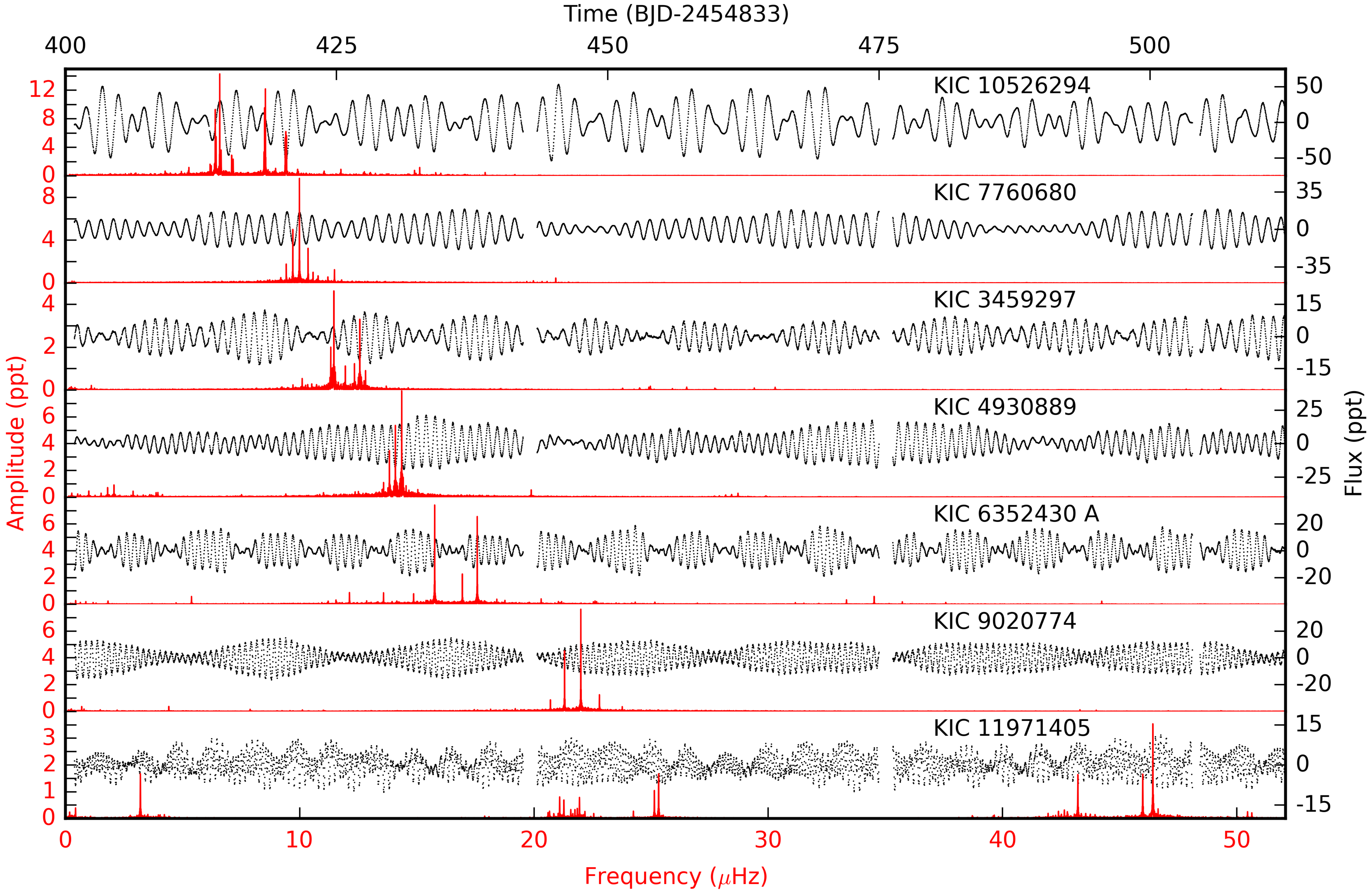
- Toroidal normal modes only become nonzero in a rotating star
- Rossby waves
- Low-frequency modes
- Frequencies below the rotation frequency
- The period spacing of consecutive radial order (n-1, n, n+1) increases with increasing mode period ($1/f$)





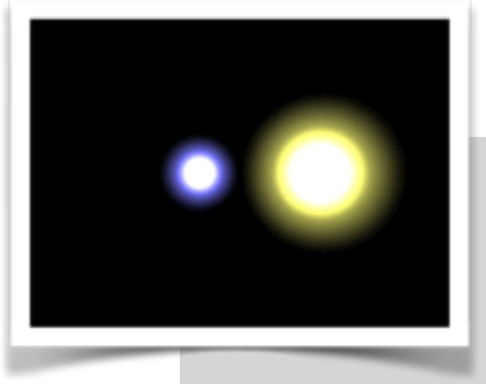
γ Dor - δ Scuti pulsations (& Hybrid stars)





Aerts, C. 2019

- Mar. 2009 - Nov. 2018
- Photometry data (ppt)
- Light curves are provided for each quarter (~93 days)
- White band (430–890 nm)



γ Dor - δ Scuti pulsations (& Hybrid stars)

classical A/F-type pulsators

δ Scuti variables

- $T_{\rm eff}$: 6900-8900 K
- M: 1.5 to 2.5 M⊙
- Mode driving mechanism: heat engine (κ mechanism: opacity of H-He ionization layers)
- low-degree (l = 1 – 3) and low-radial order (n = 0,1,2,3,…) p **modes**
- Typical pulsation periods: 0.01 to 0.25 d

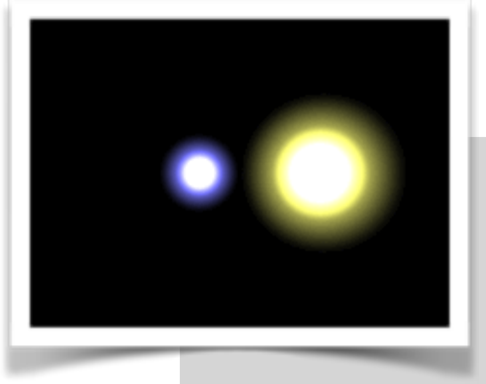
Hybrid stars

γ Dor - δ Scuti pulsations
Together
If intermediate- to fast-rotators
r modes
may also appear

γ Dor variables

- $T_{\rm eff}$: 6700-7400 K
- M:1.5-1.8 M⊙
- Mode driving mechanism: Convective flux blocking
- low-degree (l≪ 4) and high-radial order (20≤ n≤120) g **modes**
- Typical pulsation periods: 0.3 to 3 days

- g **modes** occur in the radiative zones close to the stellar core ⇒ reflecting chemical gradient of the different near-core convective structures
- p **modes** excited near the surface and reflect the physical properties of the stellar envelope
- Studying their rotation ⇒ information on their differential rotation (core-to-surface) and the angular momentum transport between the layers



Individual targets: KIC 8975515

What we know of this target

- **HERMES spectra:** (Lampens+ 2018 A&A)
  - Two components of (Kmag=9.5mag):
  - similar T_{eff} (~7400 K)
  - similar mass (q = 0.83±0.05)
  - dissimilar rotation velocities

  ($v \sin i$ = 32±1, 162±2 km/s)
  - Long-period, eccentric orbit

  (P_{orb} = 1603 ±9 d, e = 0.41±0.01)
- **Kepler light curves (4 year)**:
  - Q0-Q17: 1407 d (LC)
  - Q2,Q5: 122 d (SC)
  - The system has *hybrid* pulsations

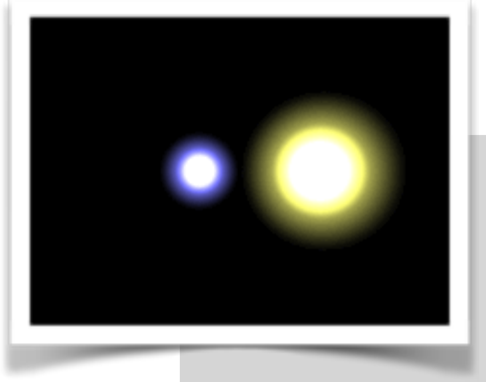
- A double-lined spectroscopic binary system: SB2
- Detached
- The companions are twins
- one/both of companions Hybrid pulsations

- Different rotation velocities: How the rotation affects the the pulsations?
- Twin companions: Are both pulsating? Are both Hybrid pulsators?

Period spacing of the high radial-order low-degree g modes

In the absence of the rotation (& magnetic activity)

$$\Delta P \equiv P_{nl} - P_{n-1l} = \Pi_0/\sqrt{l(l+1)}.$$



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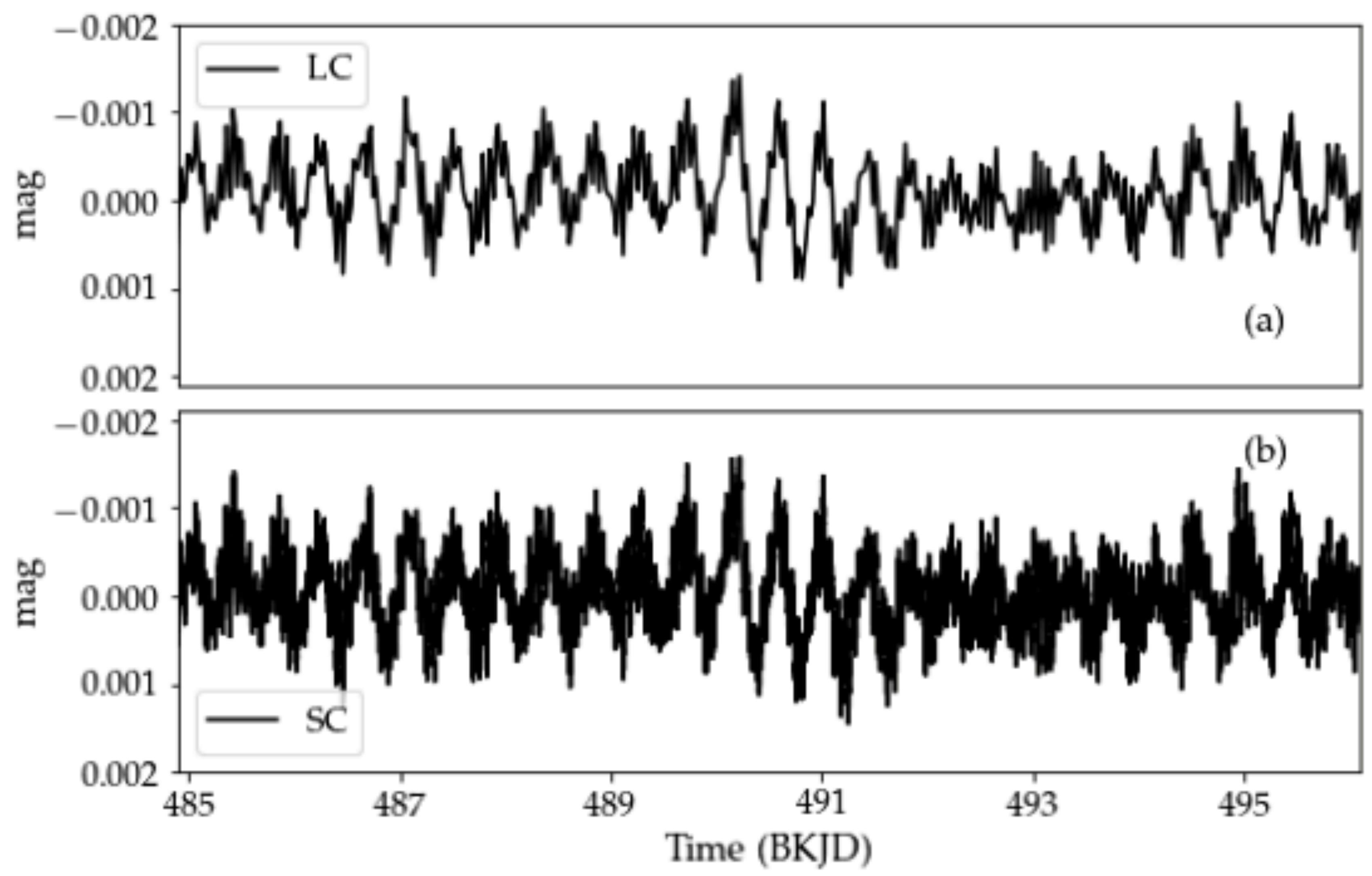
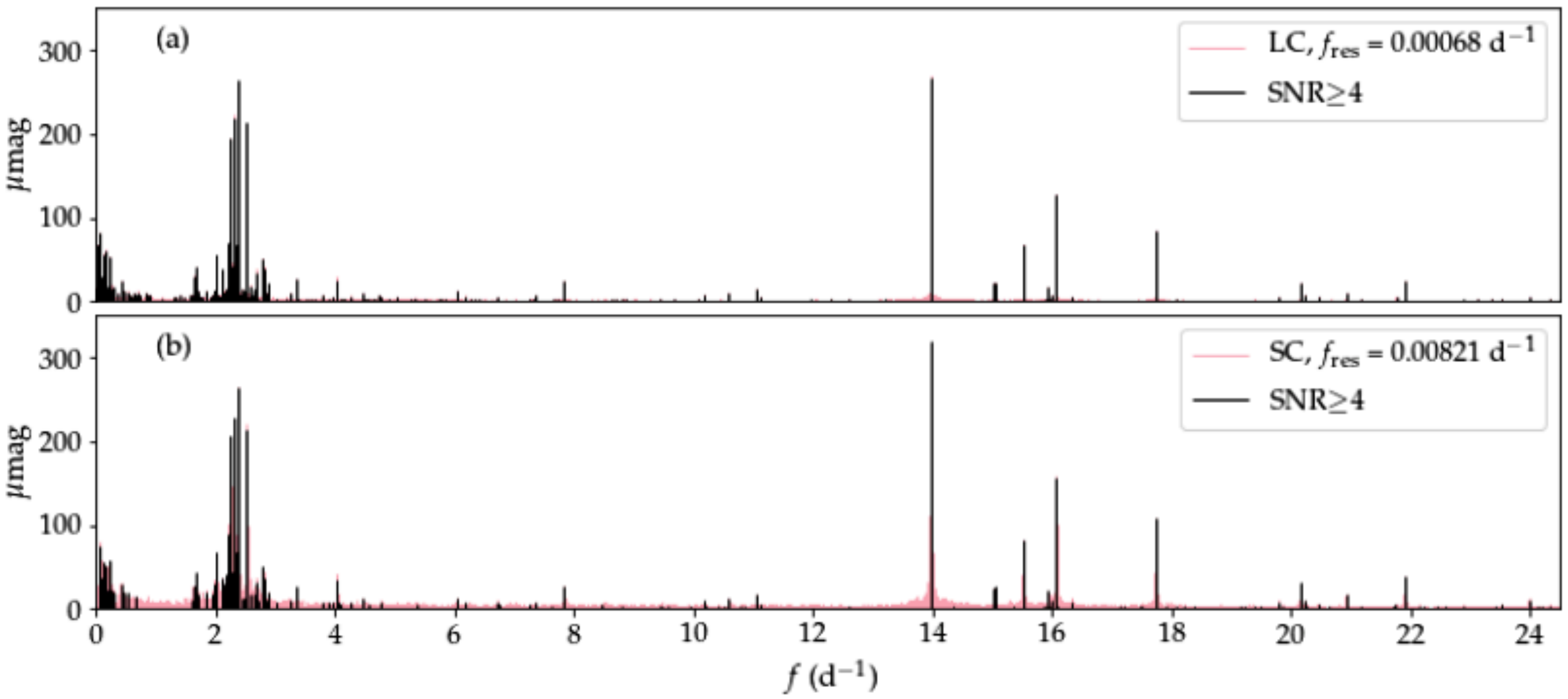
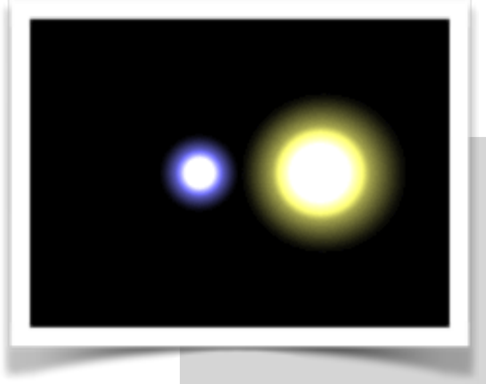
KIC 8975515

An 11 day of the light curves with two different samplings



Fourier spectrum of the full light curves





Individual targets: KIC 8975515

Pulsation Study: the effect of rotation

If rotation (& magnetic activity)

g modes

influenced by Rotation —> their period spacing

$$\Delta\nu_{n,\ell,m} = m(1 - C_{n,\ell})\Omega$$

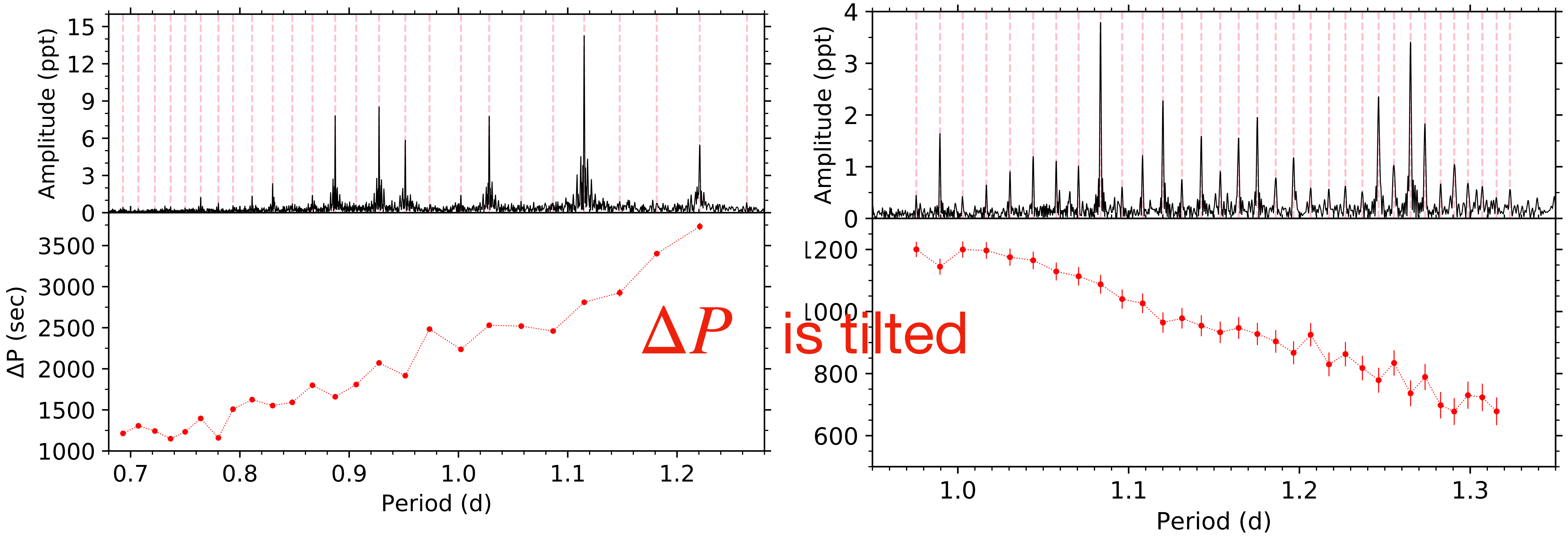
$$\Delta\Pi_{n,\ell} \propto \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}n$$

$\Omega/2\pi$: stellar rotation frequency

$C_{n,\ell}$ is the Ledoux constant for g modes $\propto \ell$

m>0 modes traveling in the direction of rotation: prograde

m<0 modes traveling in the opposite direction of the rotation: retrograde



ΔP is tilted

KIC 11721304, Van Reeth et al. (2015)

p modes

$$\langle P_{\rm rot}\rangle = \frac{1}{\Delta f_{\rm rot}}(1 - C_{n,\ell})$$

- For the p modes $C_{n,\ell}$ = 0
- $\Delta f_{\rm rot}$ rotational split

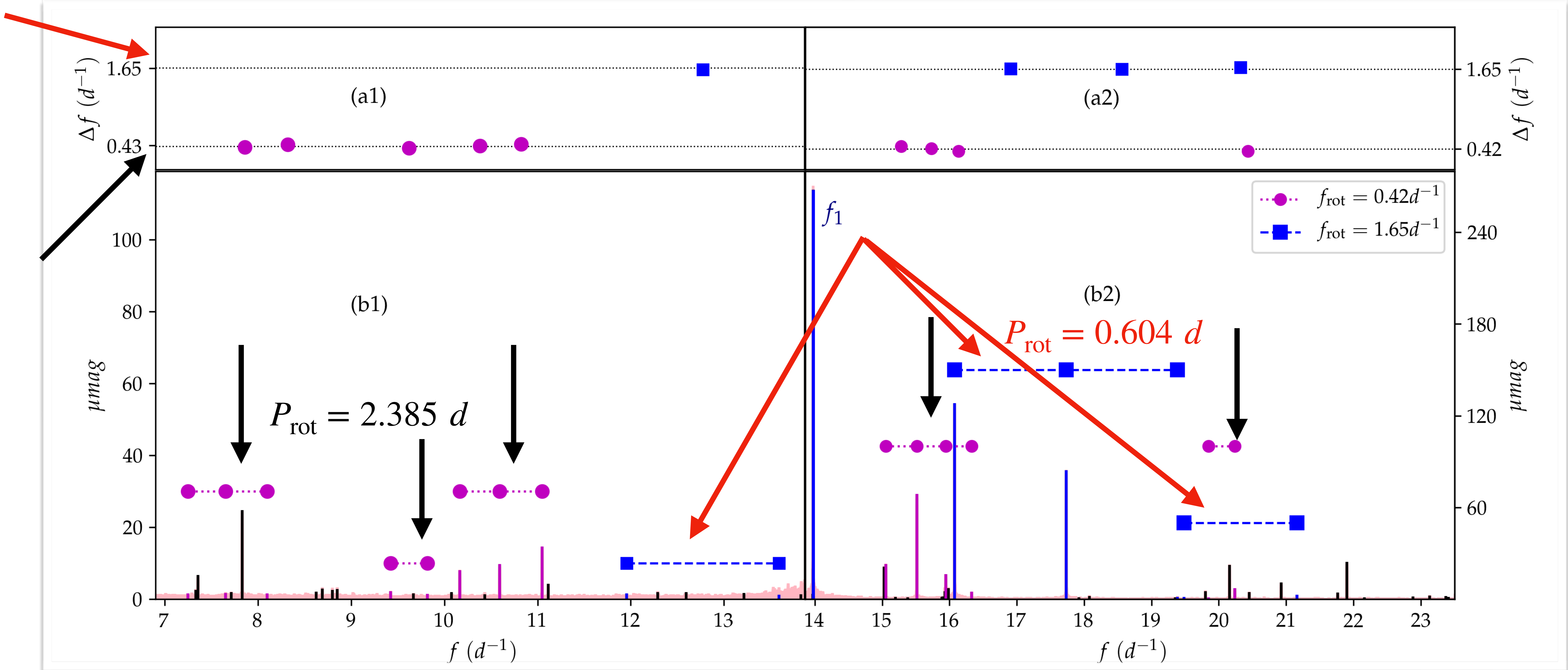
Individual targets: KIC 8975515

Pulsation Study: I. High frequency region

Slowly rotating: Veq = 46 km/s

Fast rotating : Veq = 182 km/s

($v \sin i$ = 32±1, 162±2 km/s)



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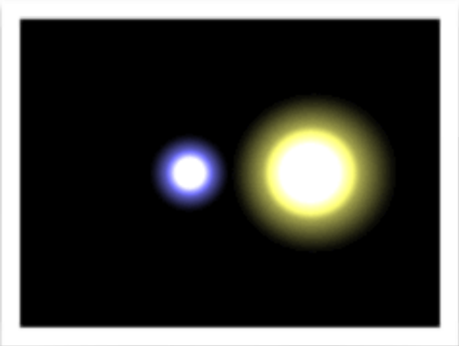
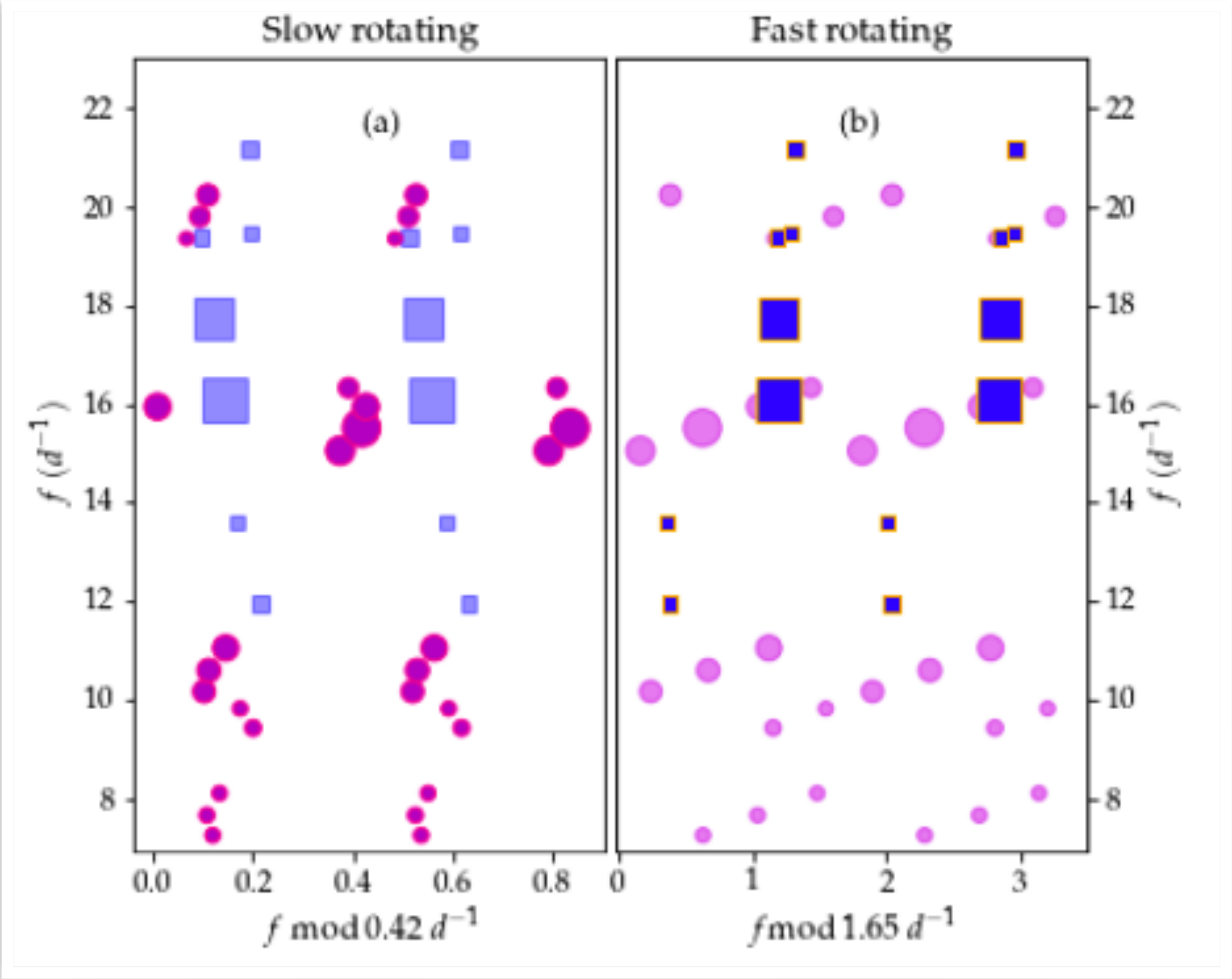


Individual targets: KIC 8975515

Pulsation Study: I. High-frequency region

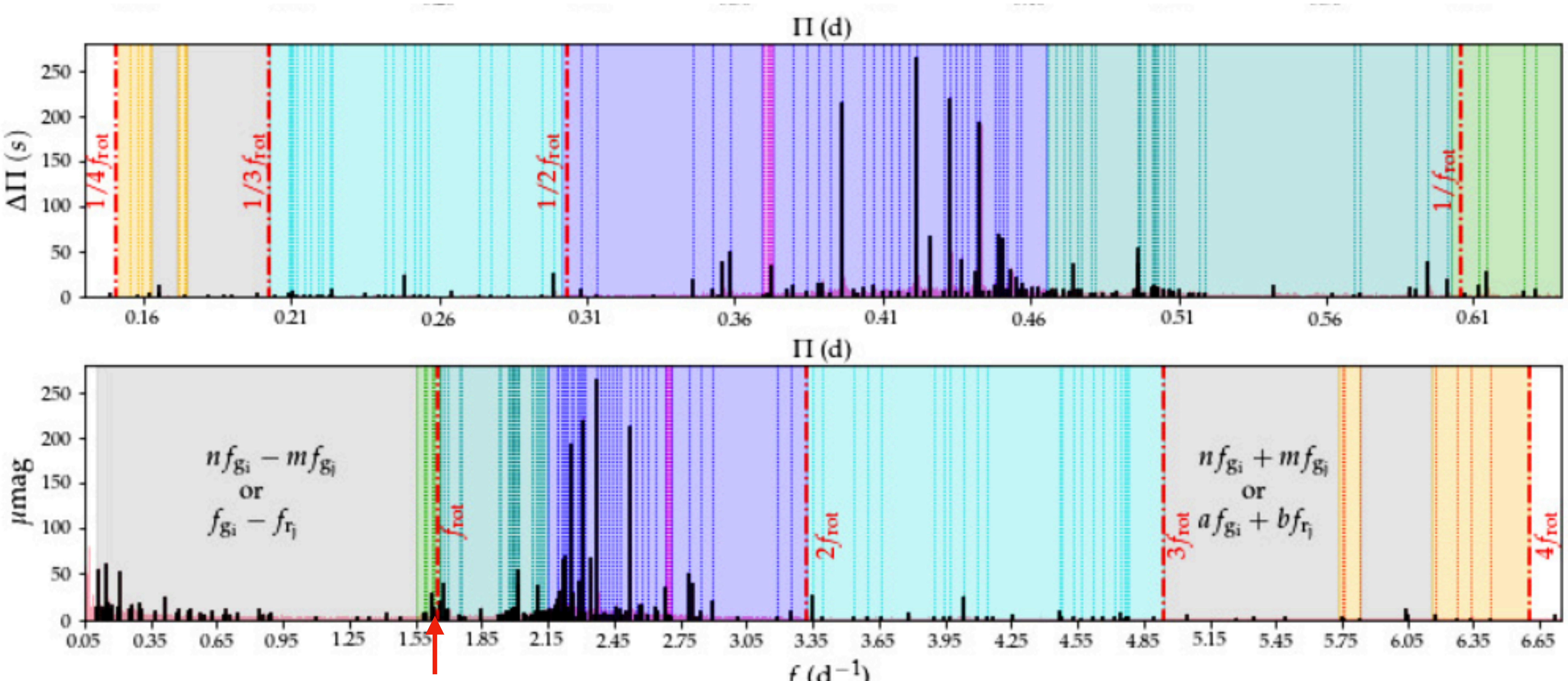
1. Both companions are pulsating
2. And have δ Scuti pulsations
3. And we could say which modes are coming from which companion



Samadi-Ghadim+ 2020 A&A

Individual targets: KIC 8975515

Pulsation Study: II. Low-frequency region



$1.647 \pm 0.0001\ d^{-1} \simeq f_{rot}(1.654 \pm 0.018\ d^{-1})$

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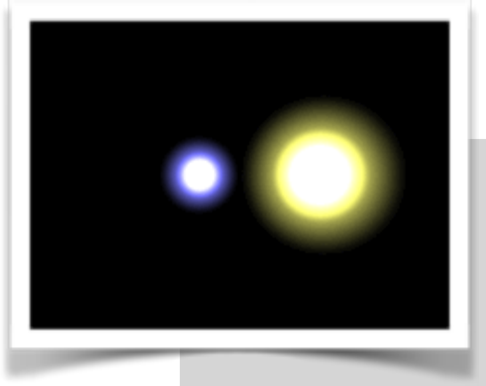
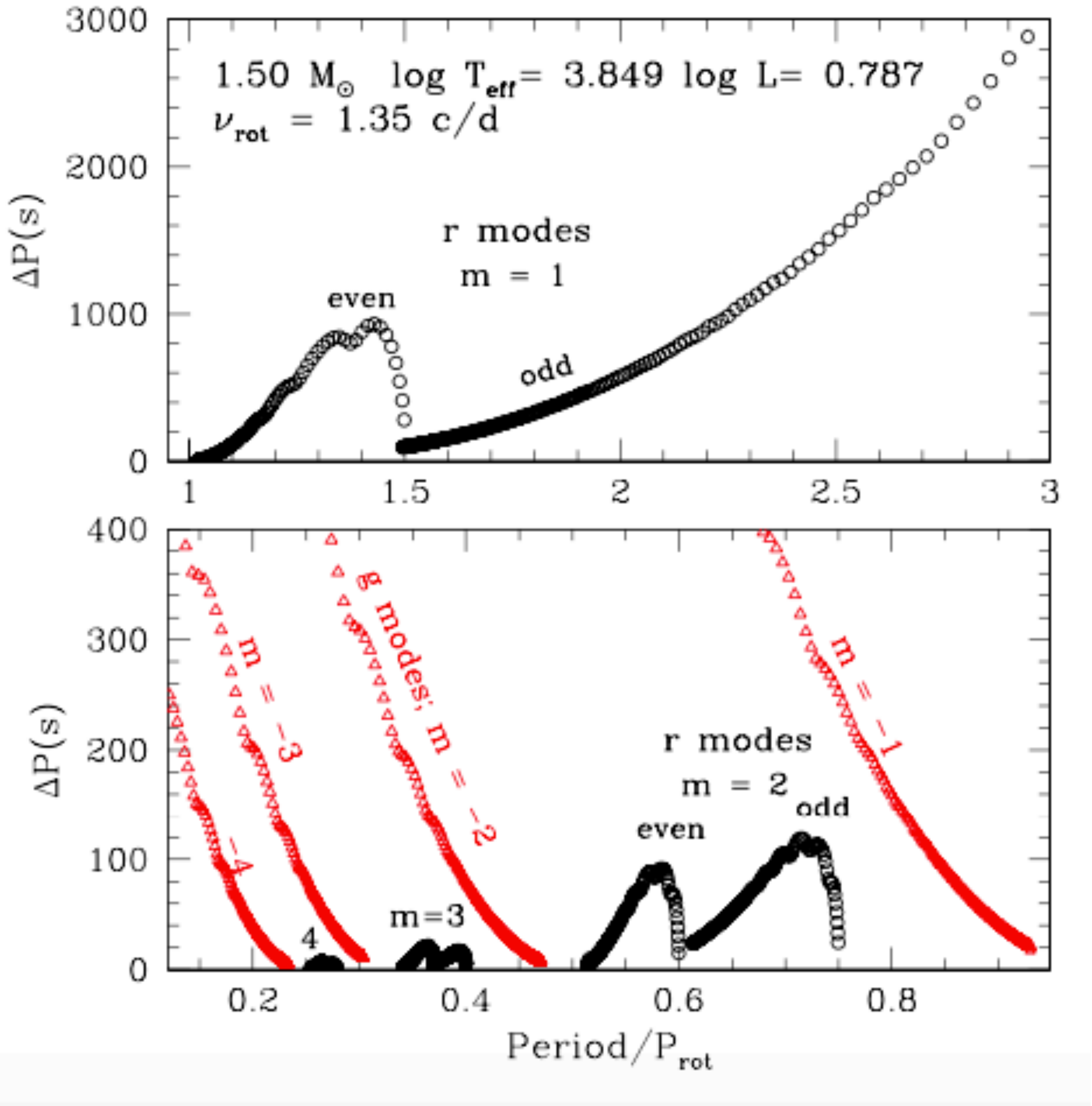


Individual targets: KIC 8975515

Pulsation Study: II. Rossby modes



Saio, H.+2018 MNRAS

$$\nu_{rm}^{in} < m\nu_{rot}$$

- $|k|$: Even and odd symmetries with respect to the equator
    - *even* if $|k|$ is zero or an even number
    - *odd* if $|k|$ is an odd number
- For r modes $k \leq -1$, while for g modes $k \geq 0$
- period spacings of r modes —> increase with period
- period spacings of g modes —> decrease with period

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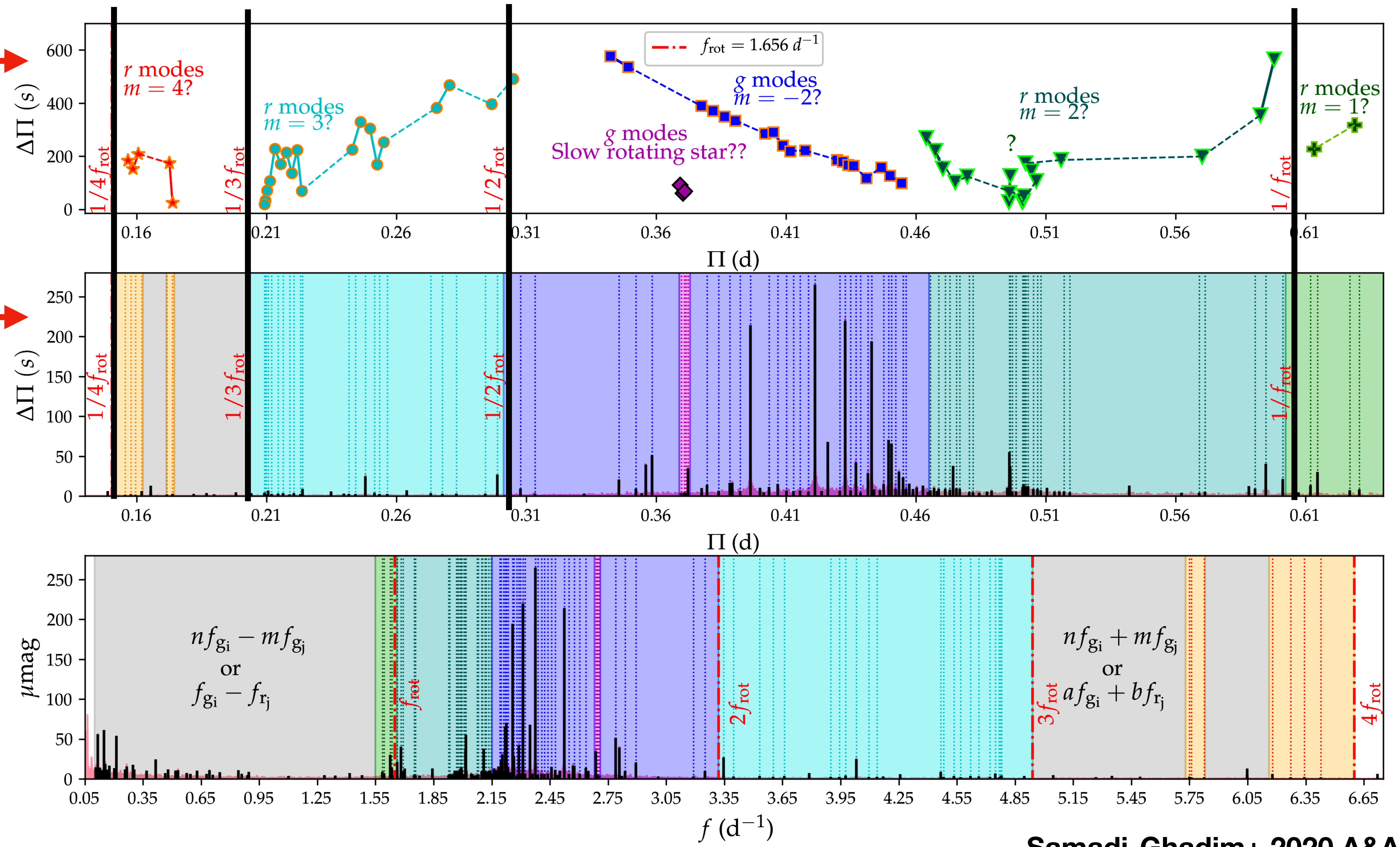
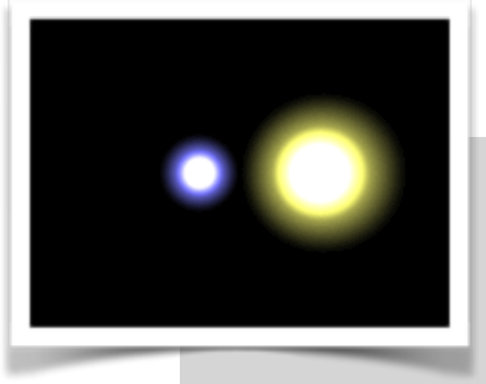
Individual targets: KIC 8975515

Pulsation Study: II. Low-frequency region



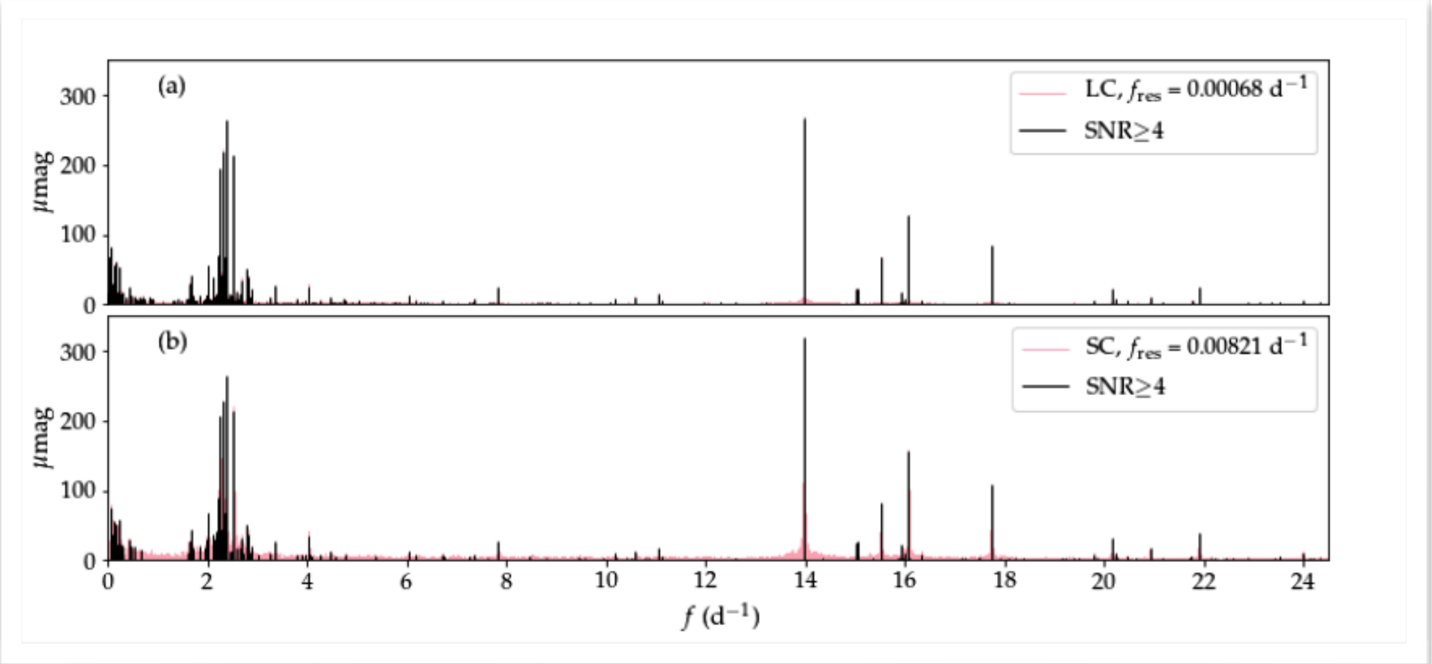
Samadi-Ghadim+ 2020 A&A



Individual targets: KIC 8975515

- A double-lined spectroscopic binary system: SB2
- Detached
- The companions are twins
- They were only different in rotation
- one/both of companions Hybrid pulsations

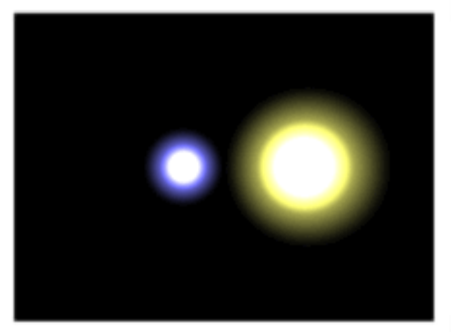
Rotational frequency splitting of g & p modes
Period spacing of g modes



Fast-rotating star: a Hybrid + Rossby modes

Slow-rotating star: a δ Scuti

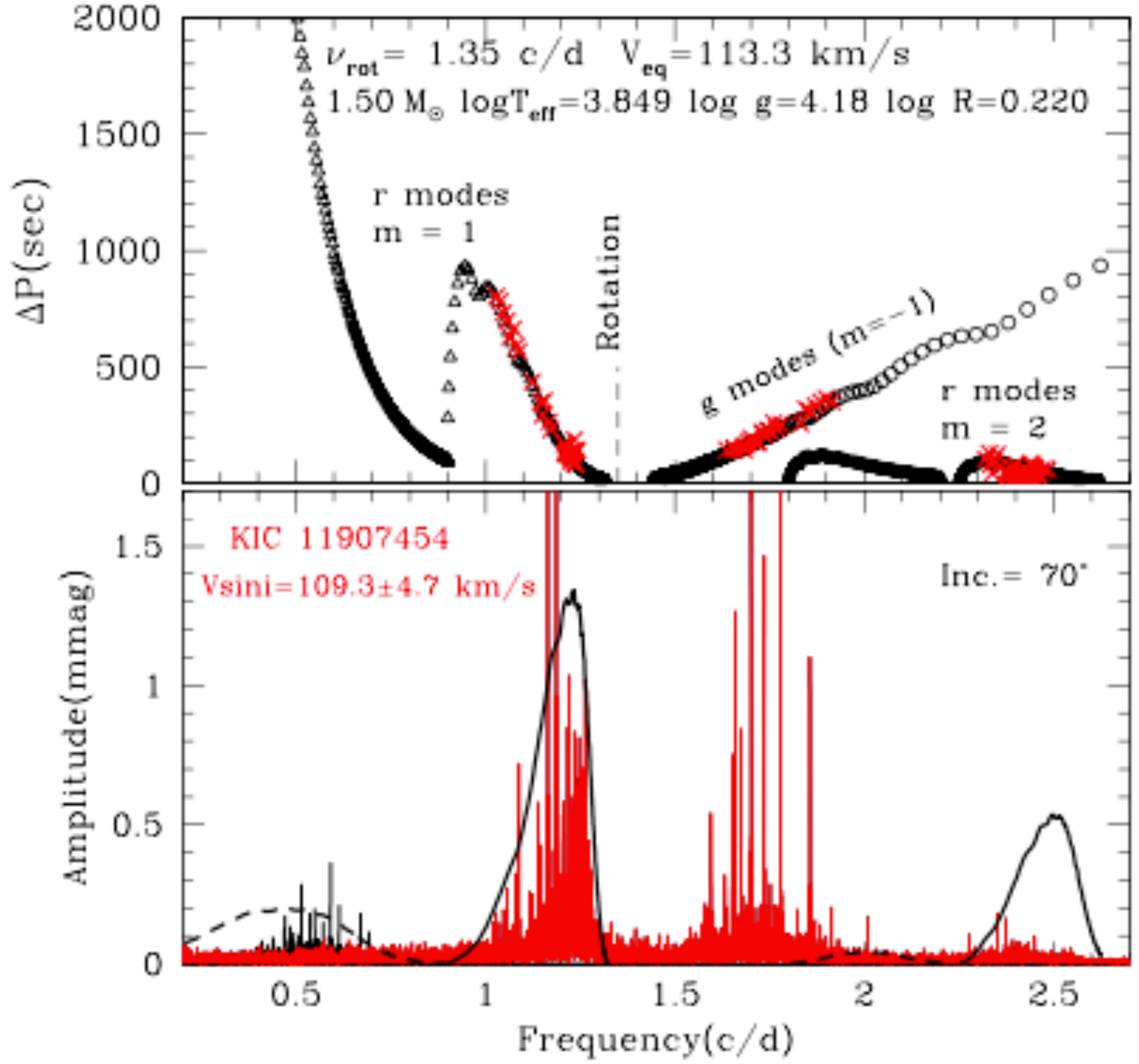
We could also detect the rotational frequency of the fast rotating



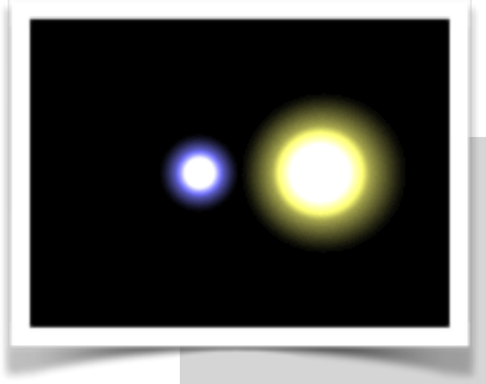
Prospective

- Where and how theory fits to the observation (seismic modeling)…
- Some clues about the detected unknown modes …
- How rotation influences a pair of twins…
- Making the sample of fast rotating SB2 stars larger with the similar targets

MESA GYRE



Saio, H.+2018 MNRAS



Take home messages

- Rotation is very helpful in detecting the mode origins in twin binary stars.
- Seismic modeling is needed to join observations in order to understand how rotation can change the pulsation scenario of a pair of twin stars in a binary system.
- Tidal forces in close binary stars influence the high frequency modes very strongly (tidal splitting).
- For the close binary systems with the short period it is necessary to subtract the contribution of the binary from light curve to detect the stellar pulsations.
- We detected that excited r modes as a result of fast rotation in stars are agree well with what theory expects however we are far from understanding exactly what is the limit of rotation rate to excite or not excite r modes
- There is a difference between Gaia calculated distances and Twin distances that is Twin distances are shorter.
- The scatter in distances (parallaxes) from two methods is 61% larger for binary stars than for single stars
- For ~3.4% of both binary candidates and 2.6% of single stars Gaia and Twin parallax show very larger discrepancy (The “offset” sample).
- We detected star which mostly flagged as Chromospherically active stars and SB2, among the both single and binary offset samples.