SCIENTIFIC EXPLOITATION OF TESS, K2 AND KEPLER

AGE DETERMINATION THROUGH ROTATION AND BINARY SYSTEM CHARACTERIZATION

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I. Scientific Context

II. Methods, Tools and Sources

III. Work so Far

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1. SCIENTIFIC CONTEXT

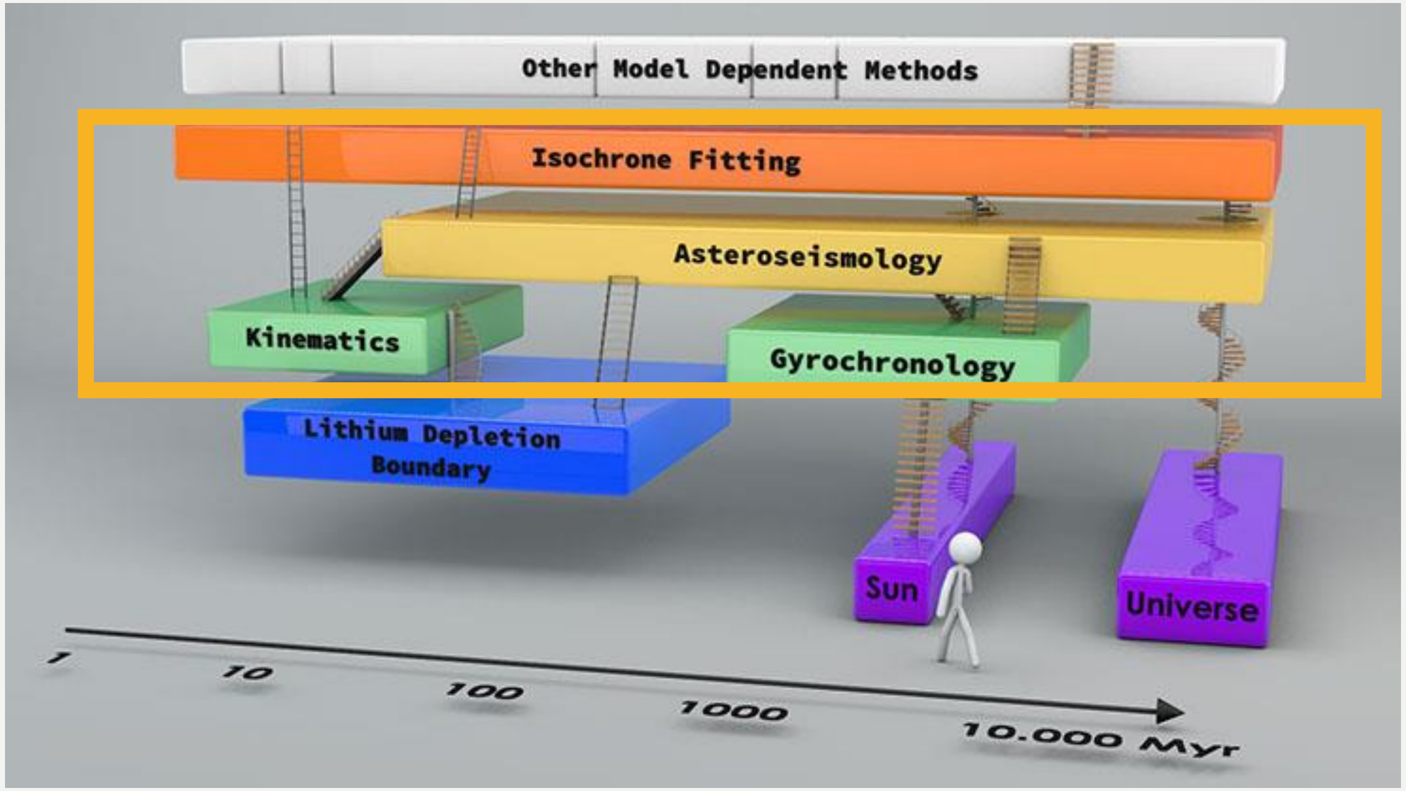
- The age of an individual star cannot be '**measured**', only estimated through empirical properties or model-dependent methods ('*The Ages of Stars*', D. R. Soderblom, 2010).

- **Stellar associations** (open clusters, moving groups) are priviledged astrophysical laboratories since their members are coeval and chemically homogeneous. They offer the possibility to implement a variety of methods with their own complementary strenghts.

1.1. CHRONOS PROJECT

The goal of the project is to deliver "a complete, coherent and accurate method to estimate the age of stars and stellar associations over the entire time domain, from the youngest to oldest ages. The availability of reliable and accurate ages will profoundly transform our ability to interpret the phenomena observed in the Universe (…)"

Application of modern Bayesian statistics and Markov Chain Monte Carlo (MCMC) techniques to explore all parameter spaces and perform a statistically rigorous and complete analysis of error propagation.

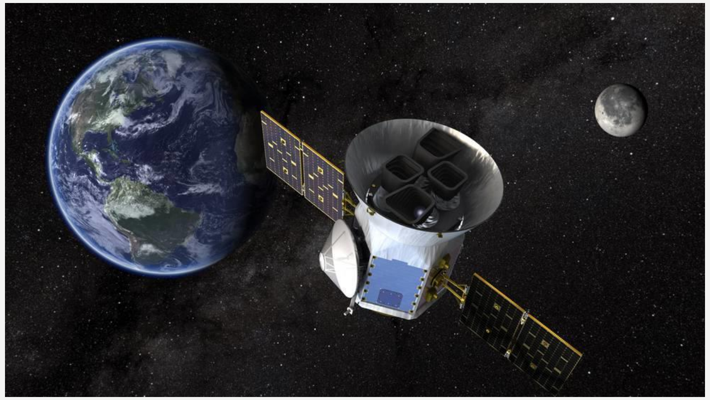


My PhD thesis is placed here: I focus on a hollistic approach of age estimation through 3 pillars: Isochrone Fitting, Gyrochronology and Binary Star Charachterization.

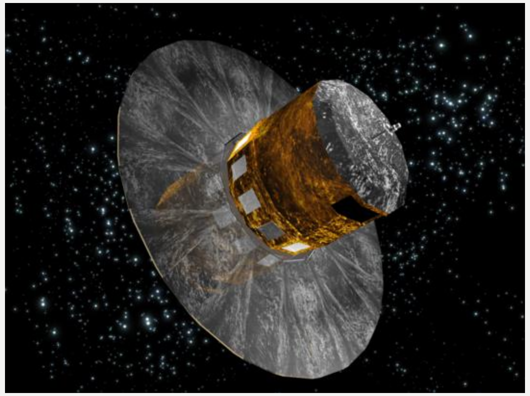
Source: David Barrado-Navascués, personal site.

2.1. DATA SOURCES

- Photometric/Astrometric surveys such as **Gaia DR2 & DR3**, Tycho, APOGEE…
- We infere physical properties for the stellar association members from their Spectral Energy Distribution (SED) fitting via the **Virtual Observatory Sed Analyzer** (VOSA).
- Lightcurve analysis from **TESS, Kepler, K2** data archives, as well as terrestrial telescopes like the **Zwicky Transient Facility (ZTF).** We study the available lightcurves and look for:
    I. Reliable eclipses that invite to a further characterization in radial velocity.
    II. Reliable rotation periods that can serve as anchors for the gyrochronological age estimation.



TESS satellite. Source: nasa.gov



GAIA Spacecraft. Source: esa.int

Zwicky Transient Facility. Source= ztf.caltech.edu

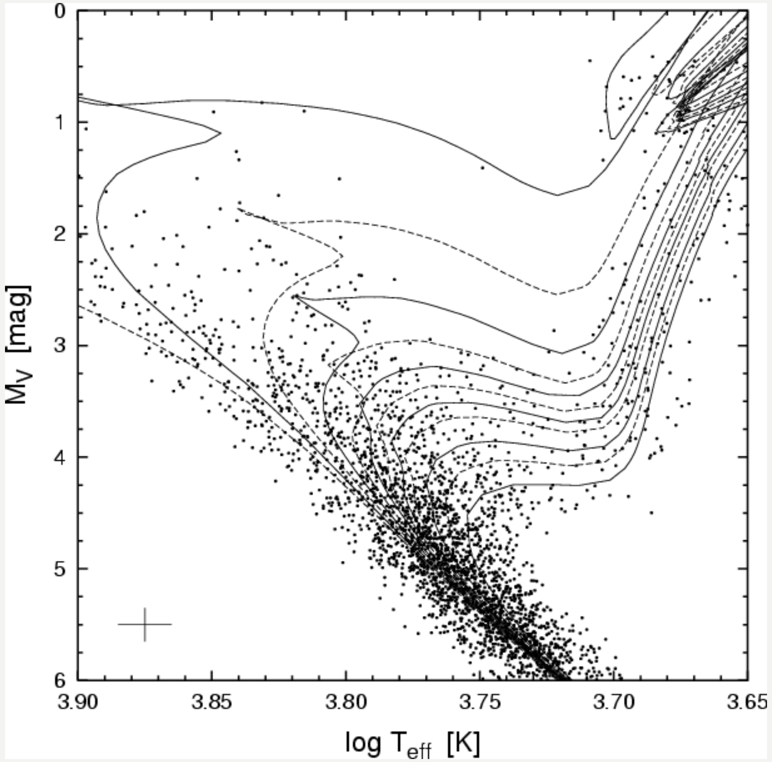
2.2. METHODS EXPLORED IN THE THESIS

We base our age estimates on three pillars:

- Isochrone Fitting
- Gyrochronology
- Binary System Characterization

We carry a systematic analysis of large data samples belonging to a variety of stellar associations of different age scales (20 Myr – 2 Gyr so far).

2.1. ISOCHRONE FITTING



Source: "Determination of stellar ages from isochrones: Bayesian estimation versus isochrone fitting", Jorgensen et al., 2005, volume 436, pp 127-143

Based on the steady change of the color-magnitude, or temperature - luminosity morphology as a consequence of the consumption of its nuclear fuel.

Relies on large samples of stars with limited individual accuracy in their parameters, in order to improve estimates for the whole population.

Isochrones tend to show degeneracy in the models when there is not a clearly populated turn-off from the main sequence.

2.2. GYROCHRONOLOGY: THE ROTATIONAL CLOCK

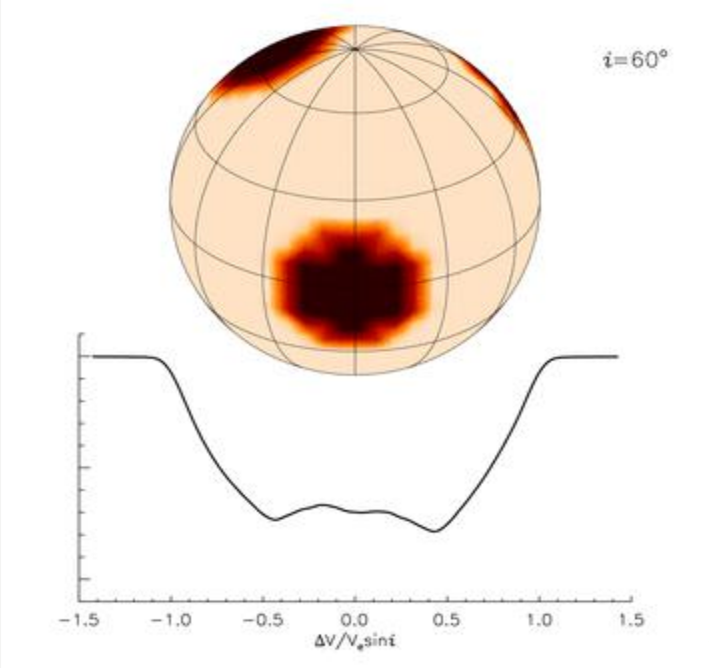
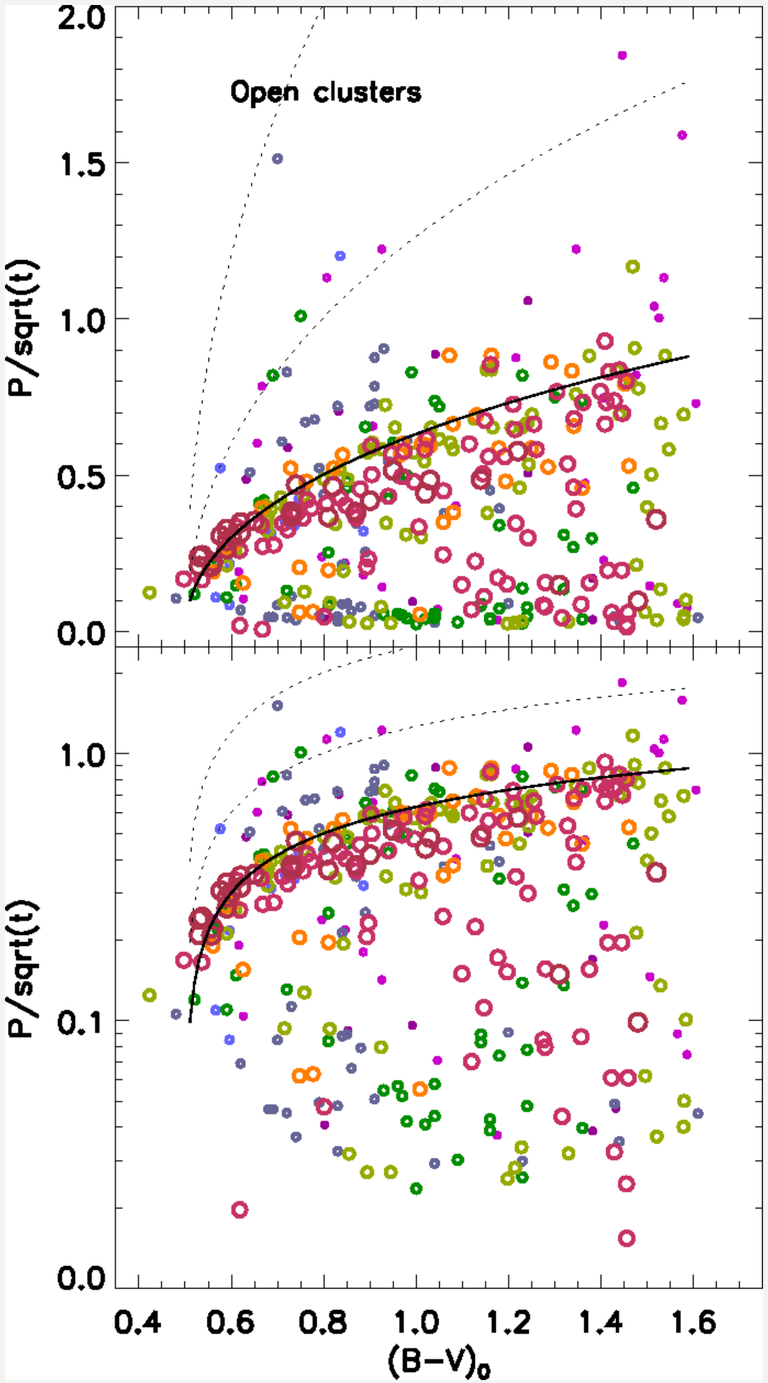


Image source: https://www.physics.uu.se

Rotational periods can be infered from photometric time series thanks to stellar spots. Also estimated from spectral line shapes.

Its an evolutionary, empirical method based on the physical dependance between the rotational period of a star, its mass and its age.

- Reference work: *Ages for illustrative field stars using gyrochronology: viability*, limitations and errors. Sydney A. Barnes, 2007, The Astrophysical Journal.
- It yields average uncertainties of ~ 15% for late F, G, K and early M stars.
- Good agreement with chromospheric ages for all but the bluest stars. Works best where isochrone is at its weakest, the main sequence (S. Barnes, 2007).



It is an interesting approach that keeps feeding and calibrating on the increasingly large amount of rotational data from the recent space missions and terrestrial telescopes.

Derived and calibrated from previously well-known samples of clusters and field stars with known ages, photometry and rotational periods, **as well as the Sun**.

Empirical model:

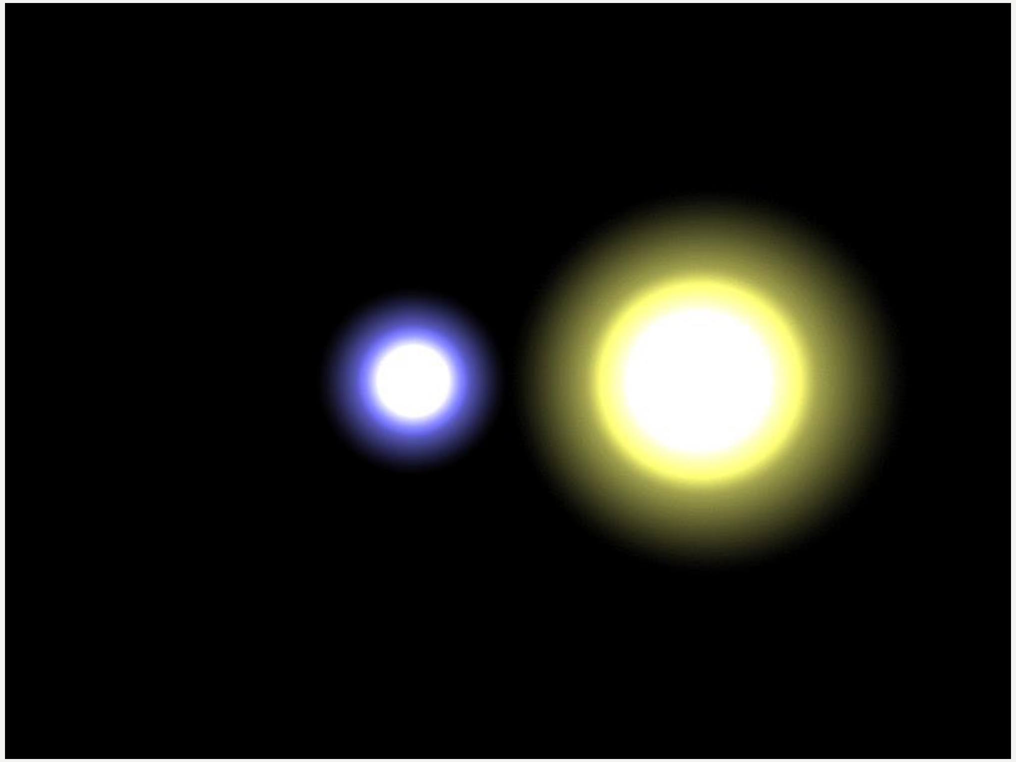
$$P = f(B - V) \cdot g(t)$$

Independent of distance.

The model predicts the behavior of the '*Interface sequence*' (I-sequence): an outlying array of stars unsaturated in the X-ray regime.

Image source: Ages for illustrative field stars using gyrochronology: viability, limitations and errors," S. Barnes, 2007, The Astrophysical Journal

2.3. BINARY SYSTEMS



Source: *Merikanto*, Wikipedia.org

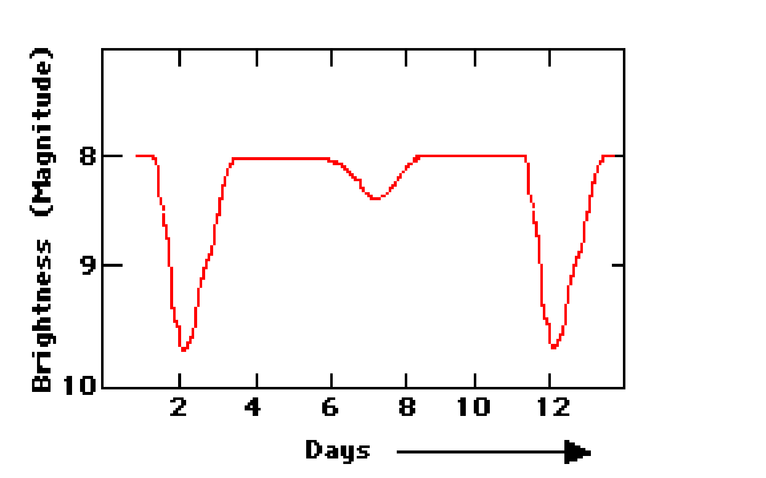
Most stars in the Universe live in binary systems.

Binarity can be infered in a variety of ways.

- Hints: 'excess' of color on a color-magnitude diagram, strong X-activity or infrarred emissions…
- Proof:
    - Analysis of the chemical spectra, displaying a coexistence of two (or more!) spectral types (SB2) or consisent radial velocity variations (SB1).
    - Photometric eclipses.

THE 'OPTIMAL' BINARY CLOCKS

Those systems that exhibit clear eclipses (primary and secondary) as well as radial velocity variations are the most suitable candidates for a full system characterization, this is: radii, masses and orbital inclination.



Source: nasa.gov

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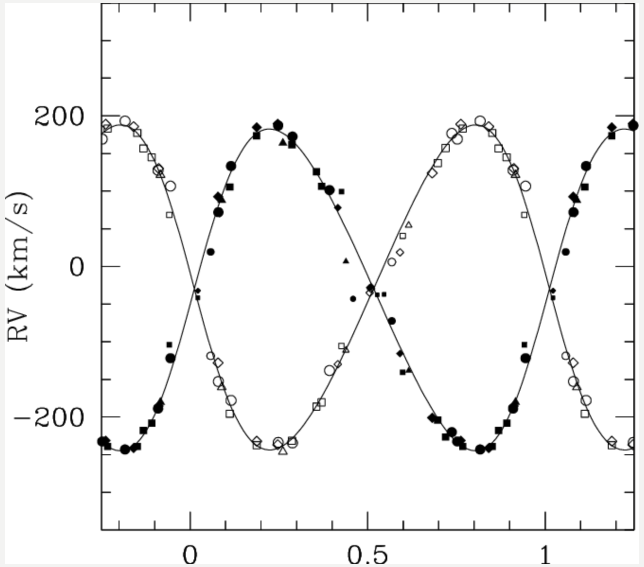

Source: **O Iiject{HD 152248}: Evidence for a colliding wind interaction, Hugues Sana, 2001.**

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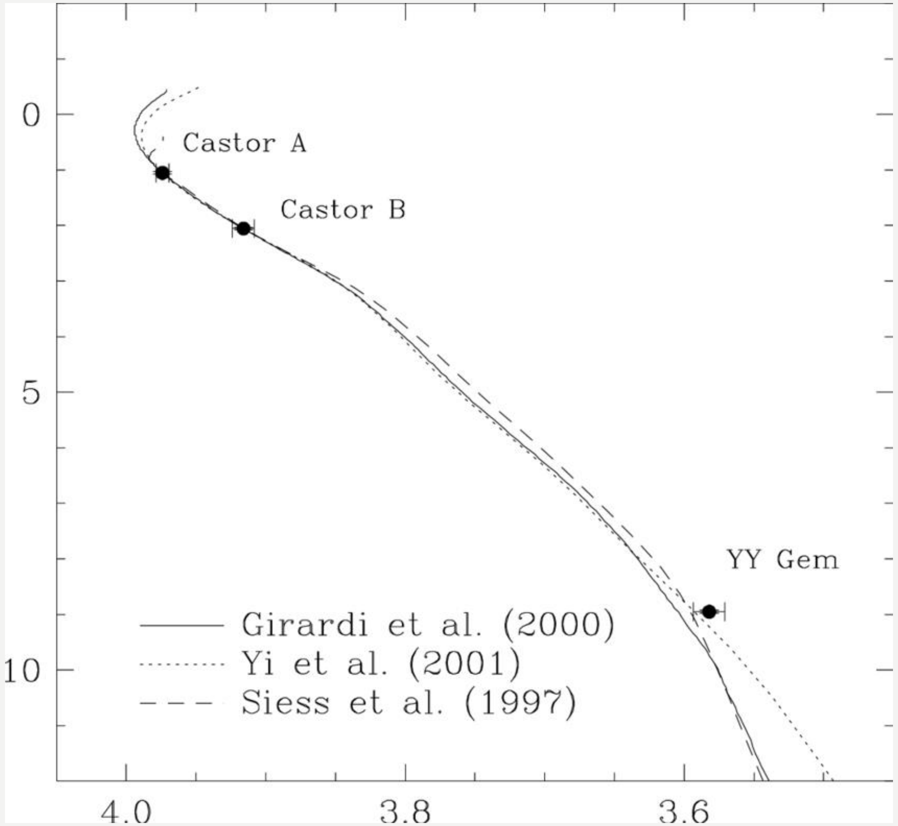
Masses
Radii
Inclination

Better estimate of the evolutionary state of both stars

Narrower constraints and calibration on evolutionary models with less individual accuracy (isochrones, gyrochronology).

2.4. SETTING CONSTRAINTS ON THE MODELS



Source: 'Absolute Dimensions of the M-Type Eclipsing Binary YY Geminorum (Castor C): A Challenge to Evolutionary Models in the Lower Main Sequence', Ignasi Ribas, 2001, The Astrophysical Journal, volume 567.

LIGHTCURVE ANALYSIS: STEPS

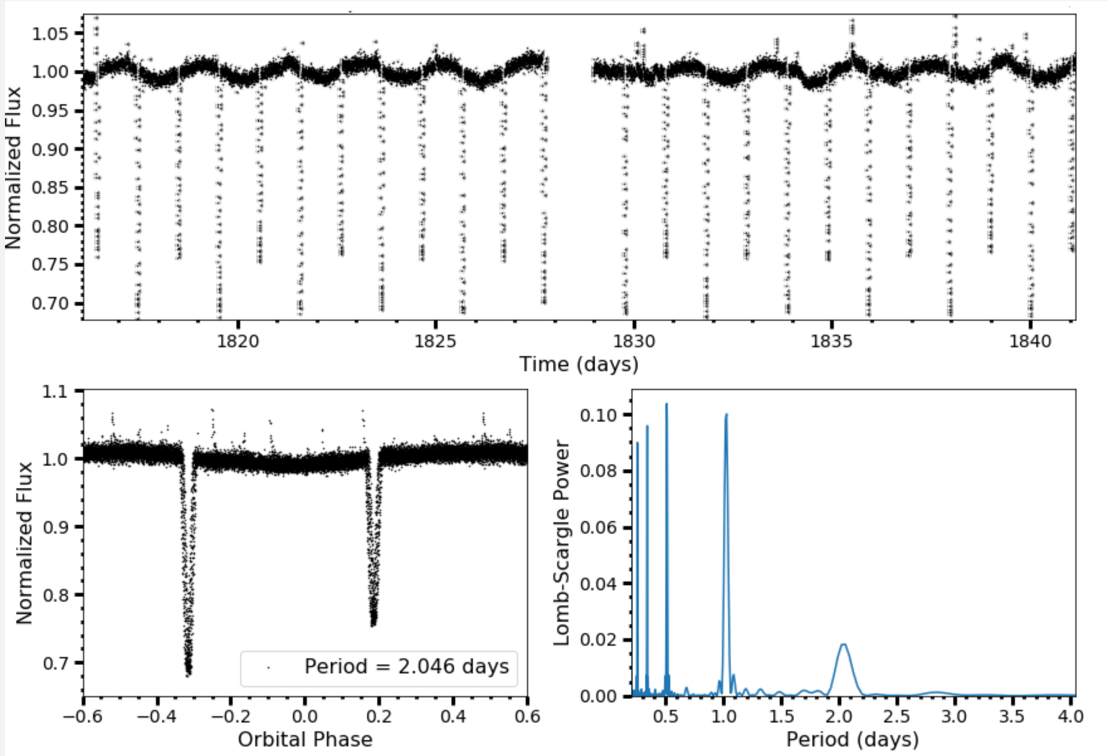
An algorithm was developed in order to, given the coordinates or Gaia identifier of the objects, search for their lightcurves within the TESS, Kepler and K2 archives. Our goal is to find eclipsing binaries that have not been fully characterized by both **transit analysis and radial velocity.**

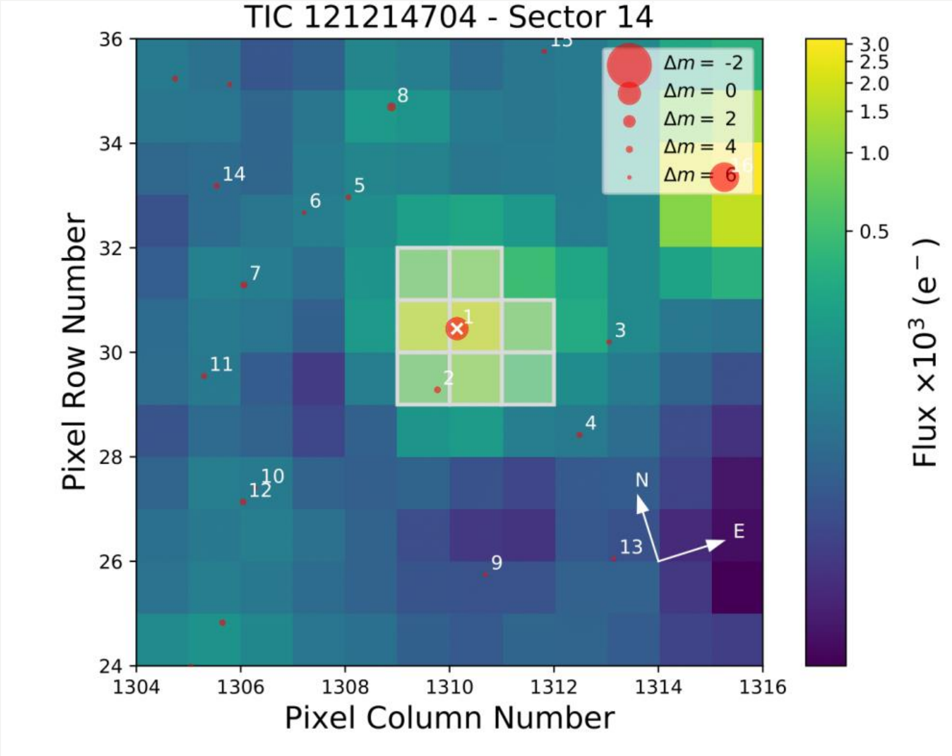
We also aim to extract rotation periods from the lightcurves automatically.

Sources: Full-Frame Images via Eleanor & lightkurve, MAST archive for Kepler, K2 and TESS (2 minute & 30 min cadence products).

We generate their periodograms, phase-fold their lightcurves, and check the vecinity for contamination.

VISUAL EVALUATION





Eclipsing binary within a cluster. We plot both the whole lightcurve for all available sectors, the power-period diagram generated by a Lomb-Scargle algorithm, and the phase-folded lightcurve. Source: TESS (SPOC, 2 min cadence), self-ellaboration.

Beyond the importance of the lightcurve itself, it is essential to check for possible contamination from neighbours, specially given TESS large pixel size (21"/pixel). Source: TPFplotter (A. Aller et al., 2019).

WORK SO FAR

3.1. AGE ESTIMATION OF M39 (NGC 7092)

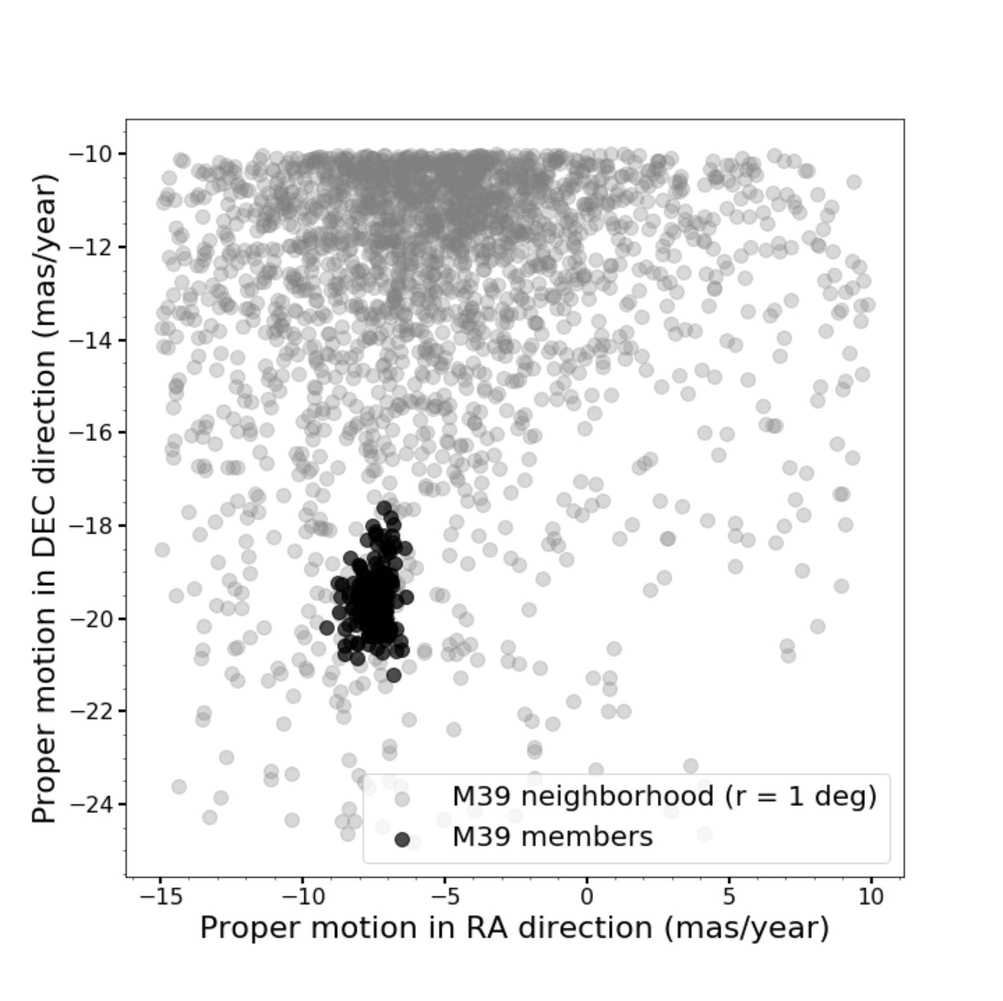
- M39 is a relatively young cluster (200-400 Myrs) at a distance of ~1010 parsecs.

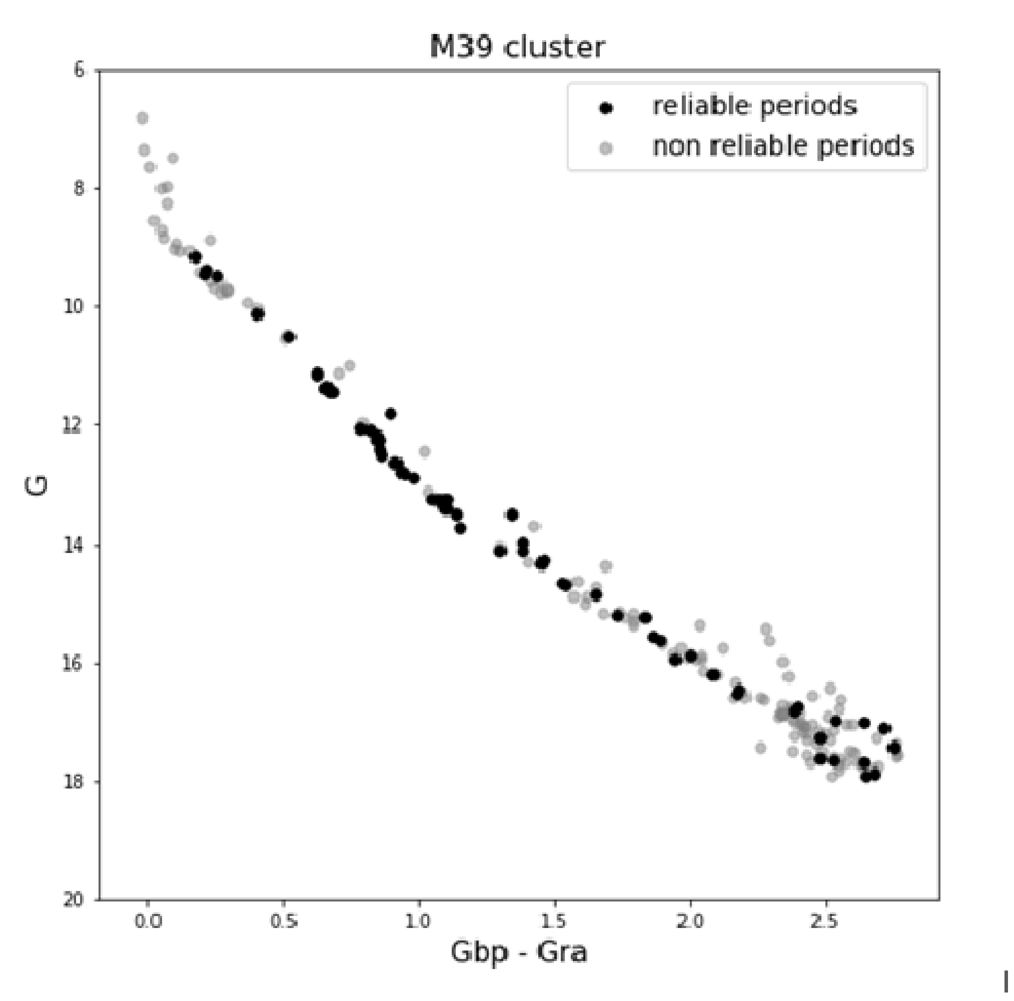
- Our team has updated the membership, fitted new evolutionary models and updated the binary frequency of the cluster. We have worked with a population of 205 members. No eclipsing binary was characterized so far within the cluster. There are *suspects*, though, undergoing analysis of radial velocity measurements.

- The cluster was observed by TESS and the ZTF, allowing for lightcurve analysis throughout the whole cluster.

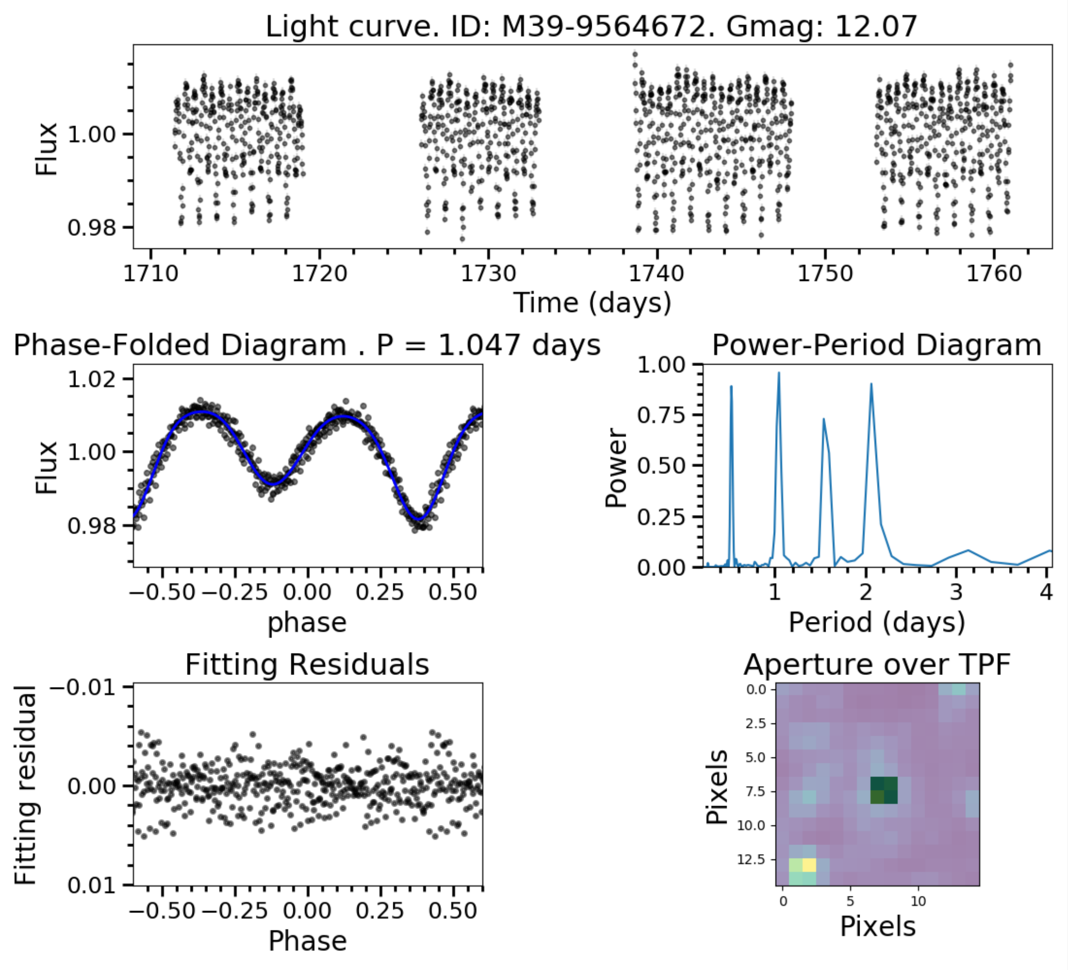
Source: noirlab.edu

3.1.1. MEMBERSHIP & COLOR-MAGNITUDE DIAGRAM (CMD)



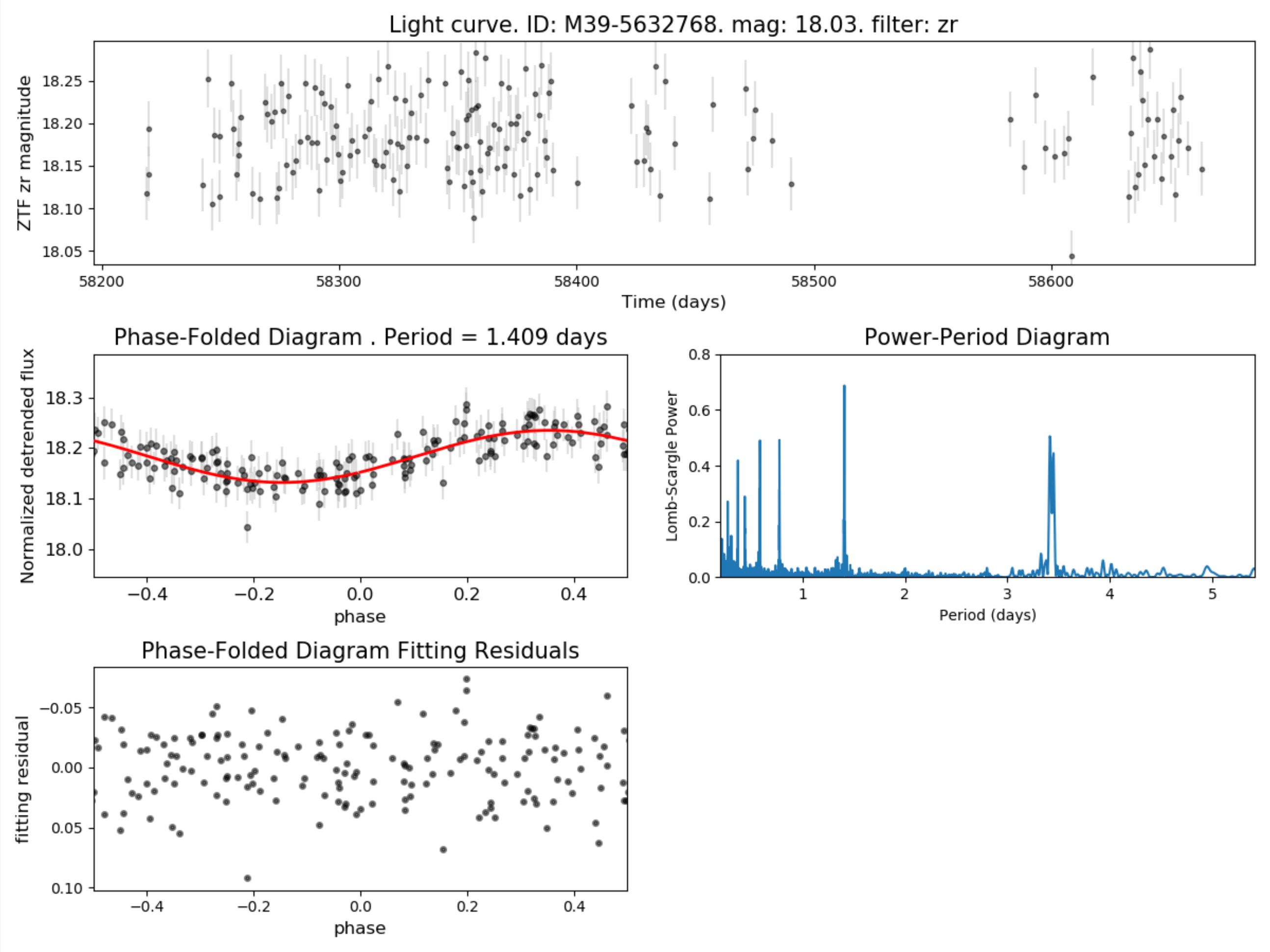


TESS:
Magnitud G (Gaia) < 14



Tamaño pixel: 21”

ZTF:
Magnitud G (Gaia) > 12.2



Tamaño pixel: 1”

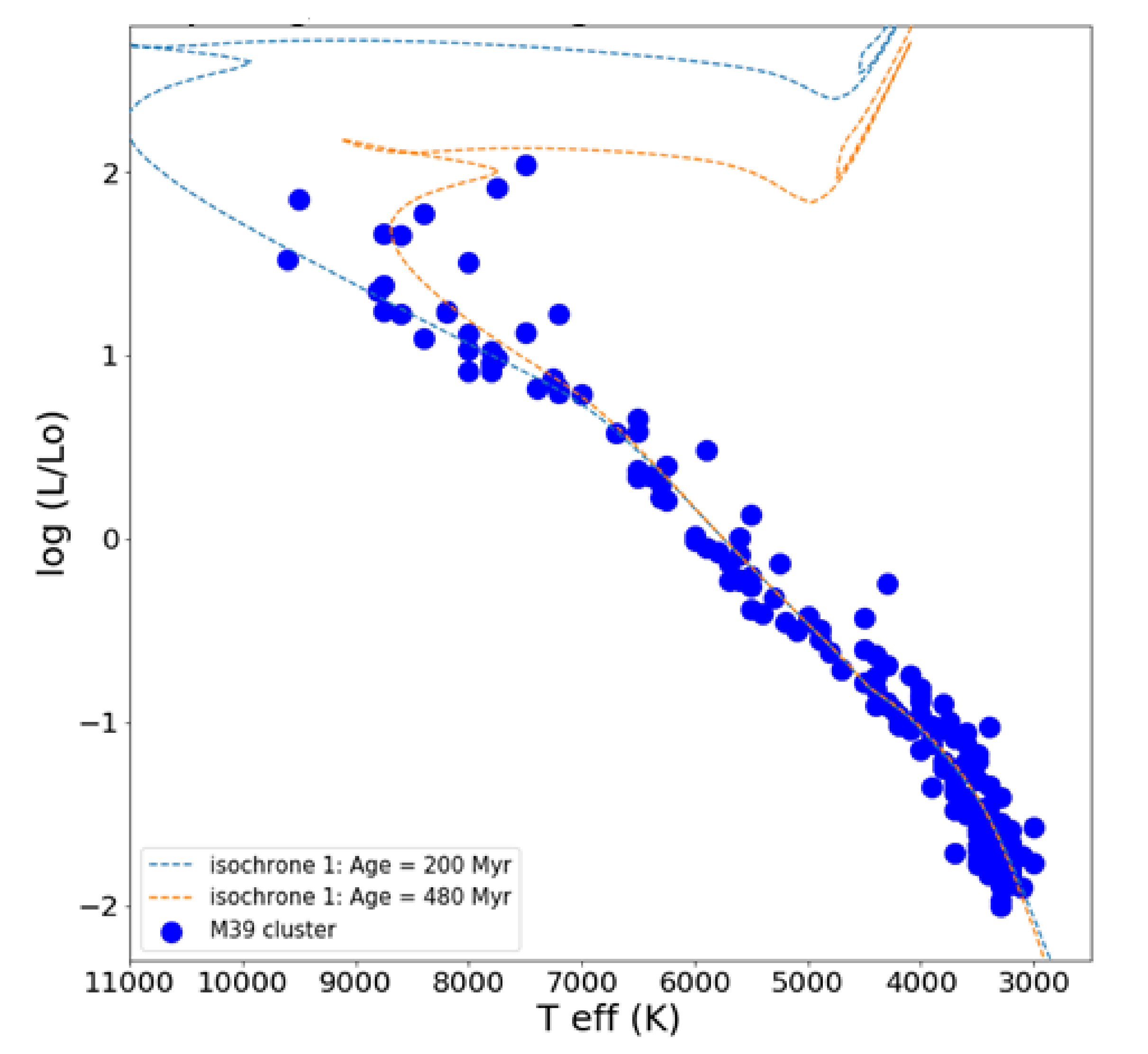
3.1.2. ISOCHRONE FITTING

Latest literatura isochronal age estimate: 316-343 Myr based on isochrone fit to a Gaia CMD (*Age determination for 269 Gaia Open Clusters,* Bossini et al., 2019).

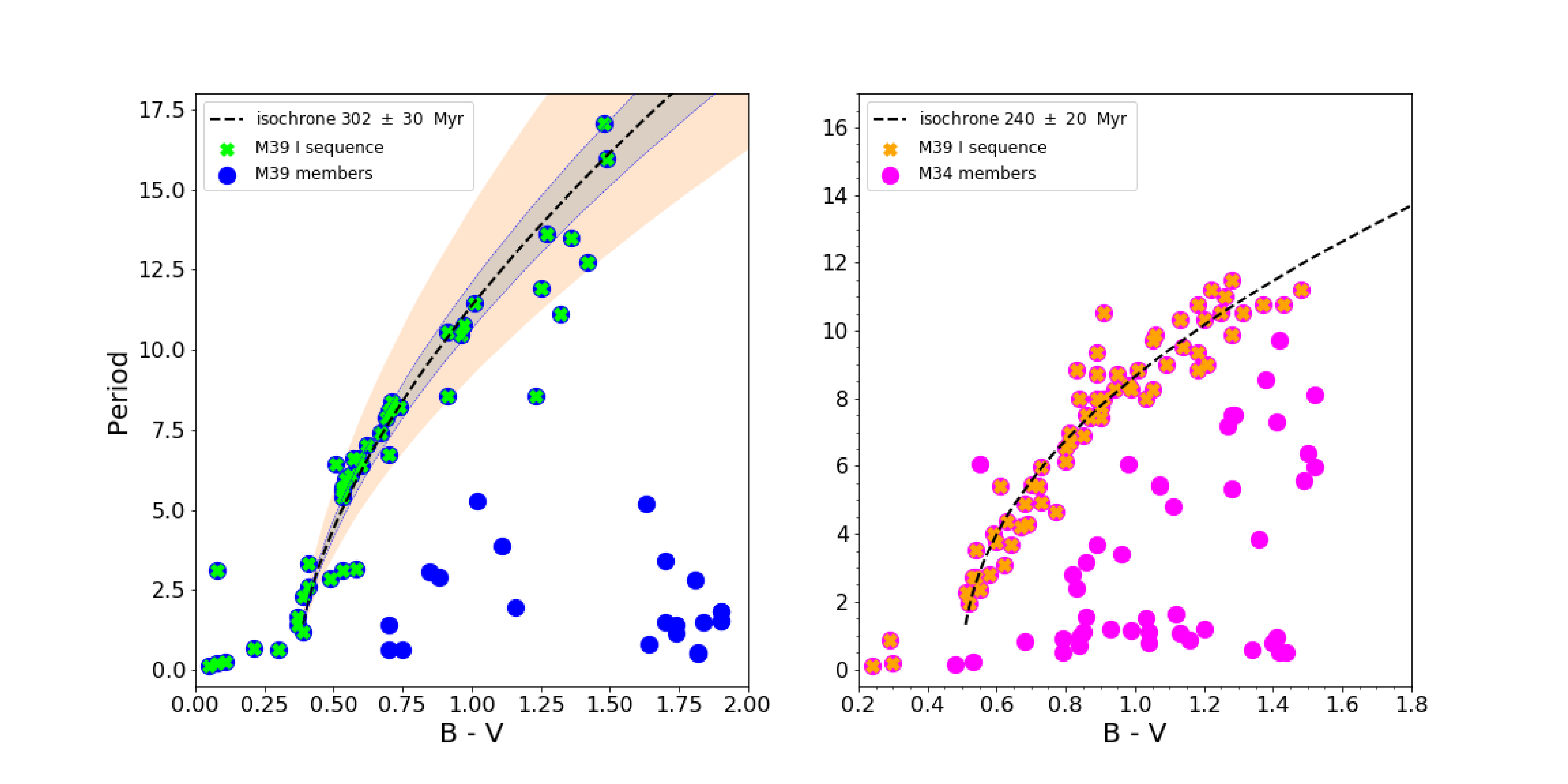
Bolometric luminosity and effective temperature were obtained via the **Virtual Observatory SED Analyzer (VOSA).**

PARSEC isochrones were fitted to the cluster data. Parameter mapping was carried between 200 and 600 Myr and metallicities between 0.01 a 0.06.

Isochronal age estimation: **340 ± 140 Myr.**



3.1.3. GYROCHRONOLOGY



Comparisson: gyrochronological diagram of M39 vs M34 (Meibom et al, 2011). Same empirical relationship, but different coefficient values (calibrated with different samples).

3.1.4. M39 FOR DISCUSSION

- Isochronal age is limited by the lack of a reliable and nourished population near the part of the turn-off sequence. Degeneracy in the models.

- Gyrochronological diagrams display a clear I-sequence that allows for narrower constraints on the age. The gyrochronological models still offer room for calibration and testing of other gyrochronological coefficients from recent works, a as well as room for improvement in the reliability of some of the periods and I-sequence members.

There is yet a pending analysis on one member that displayed potential eclipsing events. It is a confirmed binary star, a A2 type star (primary component) with previous radial velocity measurements from the literature, yet with some uncertainty due to the broadened lines.

It has been included in two observing proposals to Calar Alto (CAFE instrument, 2021B) and Mercator (Hermes instrument) at La Palma, along with other targets from other clusters.

Binary frequency has been enriched and radial velocity measurements were taken in previous campaigns (STELLA 2020B, CAFE 2020B, CAFE 202IA) to complement values from other authors and constrain the orbital periods.

4. FUTURE WORK

- Age estimation for 15 other clusters 'in store': isochrone fitting, gyrochronology and binary characterization with updated memberships. Search for new eclipsiging binaries, <u>hopefully previously unnoticed!</u> We already own a small sample of eclipsing binaries without previous radial velocity characterization, part of which is included in observing proposals currently under evaluation.

- Our own calibration of the gyrochronological empirical formula.

- Implementation of bayesian techniques to combine our different age estimates for a sample of clusters to obtain more accurate constraints on age than those yielded by individual methods.

Thank you for your atention