# Testing stellar evolution in clusters using asteroseismology and Gaia

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Established by the European Commission

ASTERO CHRONOMETRY

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# A SIMPLE PLAN

1

testing stellar models using Gaia + asteroseismology + spectroscopy in controlled environments

2

new data for when the feast is over?

ideas for a space mission dedicated to asteroseismology of clusters

# TESTING STELLAR MODELS

- clusters as probes of the MW's structure, chemical and dynamical evolution:

inferences rely heavily on models of stellar structure and evolution

e.g.

- age inference via isochrone fitting
- mapping photospheric abundances to those of the ISM at birth

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e.g.

- age inference via isochrone fitting
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⇨ clusters ideal environments to expose shortcomings of stellar models

# TESTING STELLAR MODELS

(too) many examples to choose from, I will limit to red giant stars, considering additional constraints brought by the detection of solar-like oscillations

a. key processes that are being tested/calibrated

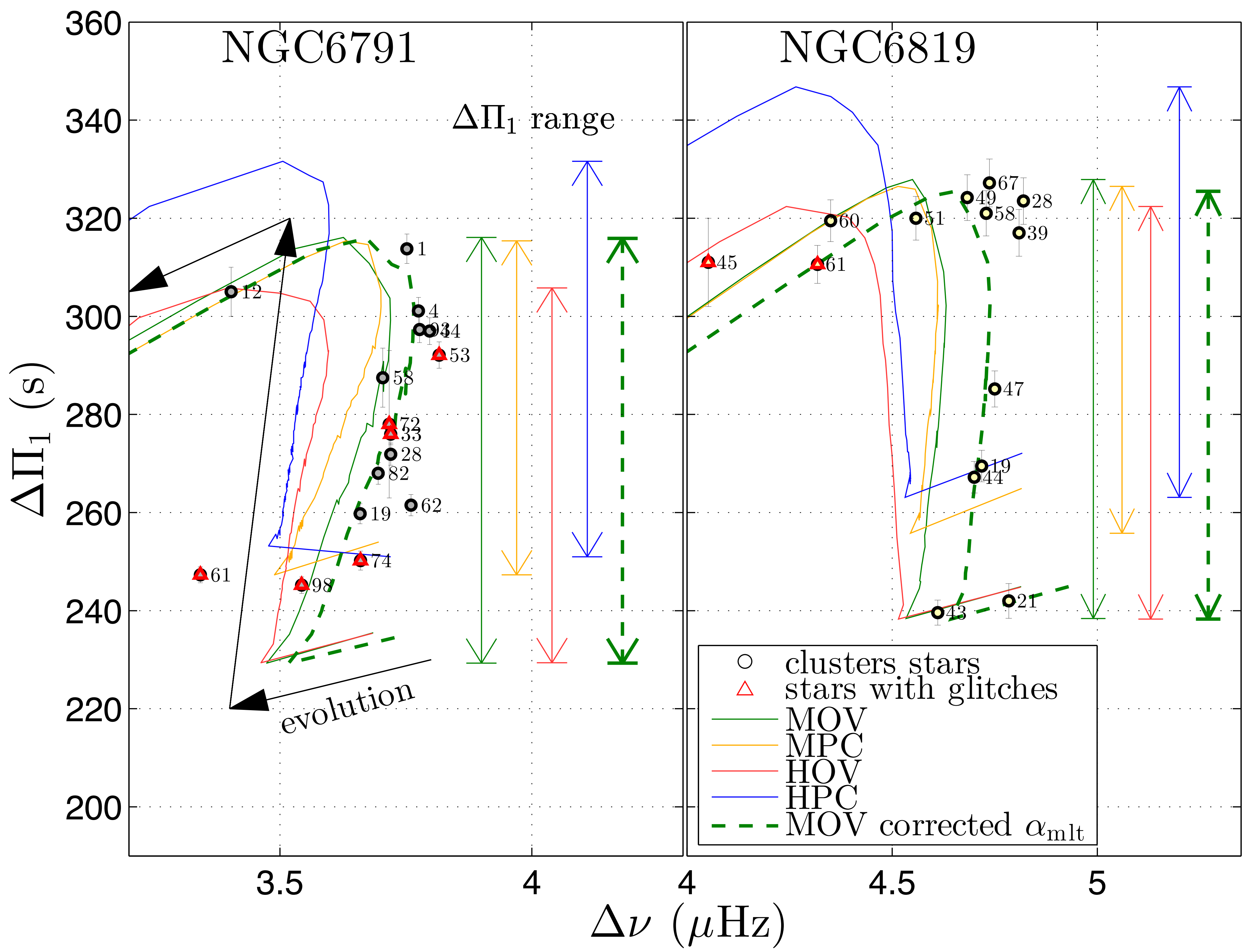
- mixing from convective cores (e.g. in RC stars)
- first dredge-up efficiency
- mass loss
- extra mixing, Li production?
- products of mass transfer / merger
- rotation

b. clusters as benchmarks for the asteroseismic distance, mass, and age scale

# TESTING STELLAR PHYSICS

- convective boundary mixing core (He burning)

Bossini et al. 2017



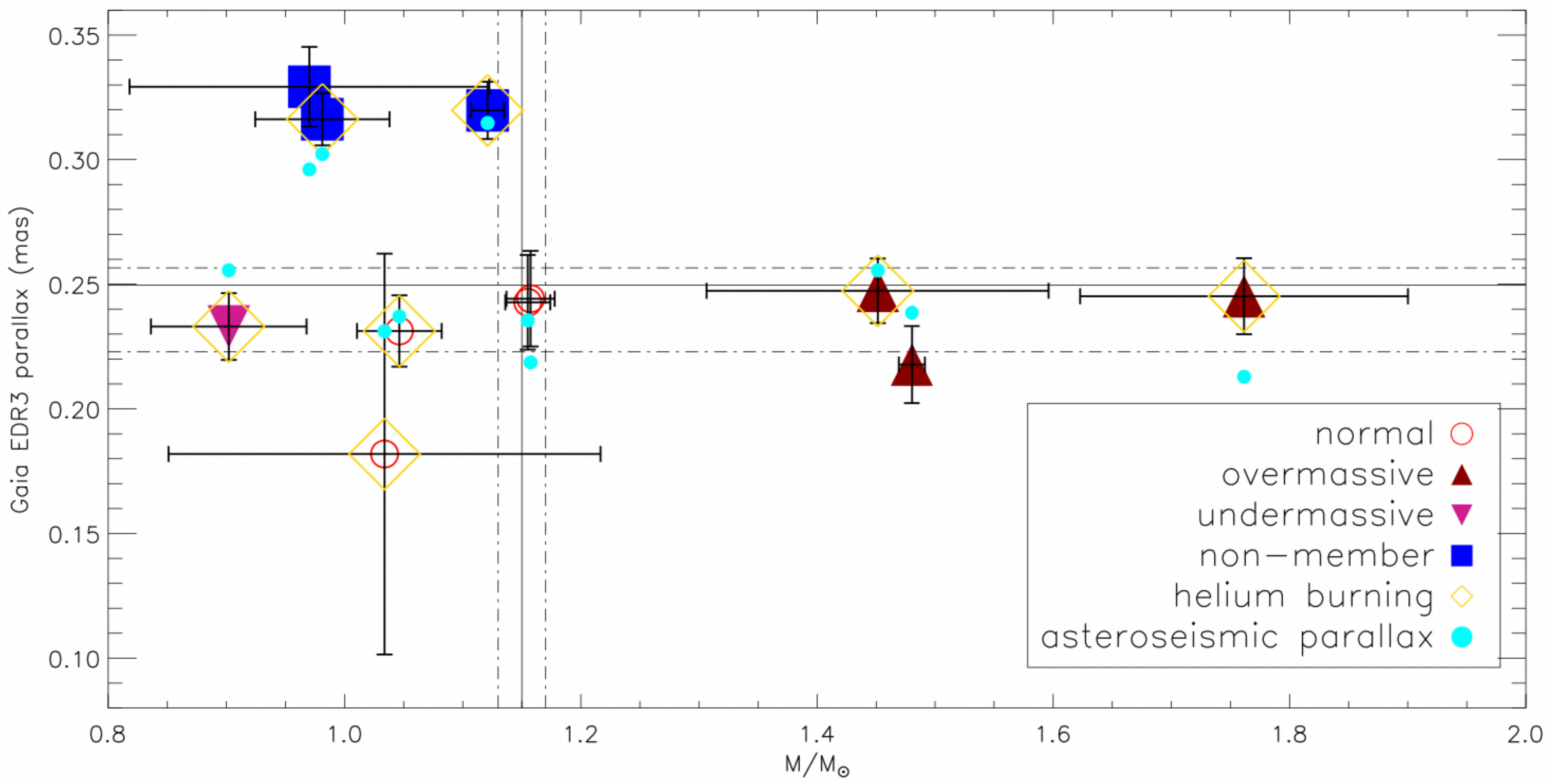

see also Montalban et al. 2013, Bossini et al. 2015, Constantino et al. 2015

# TESTING STELLAR PHYSICS

- likely products of binary interaction / coalescence

NGC6791

Brogaard et al. 2021




~10% overmassive stars

# TESTING STELLAR PHYSICS

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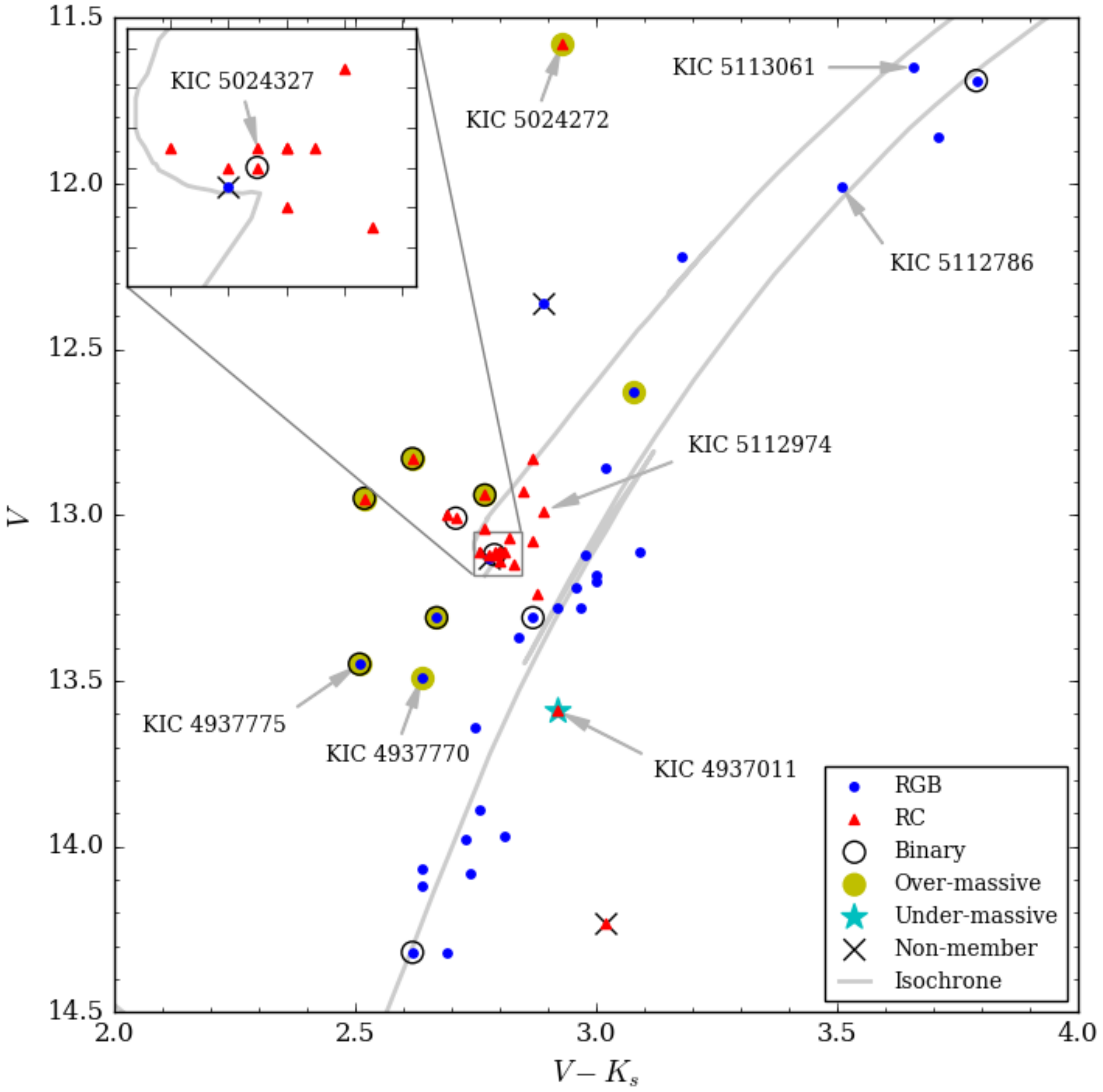
NGC6819

[Fe/H]≃0

Age~ 2 Gyr

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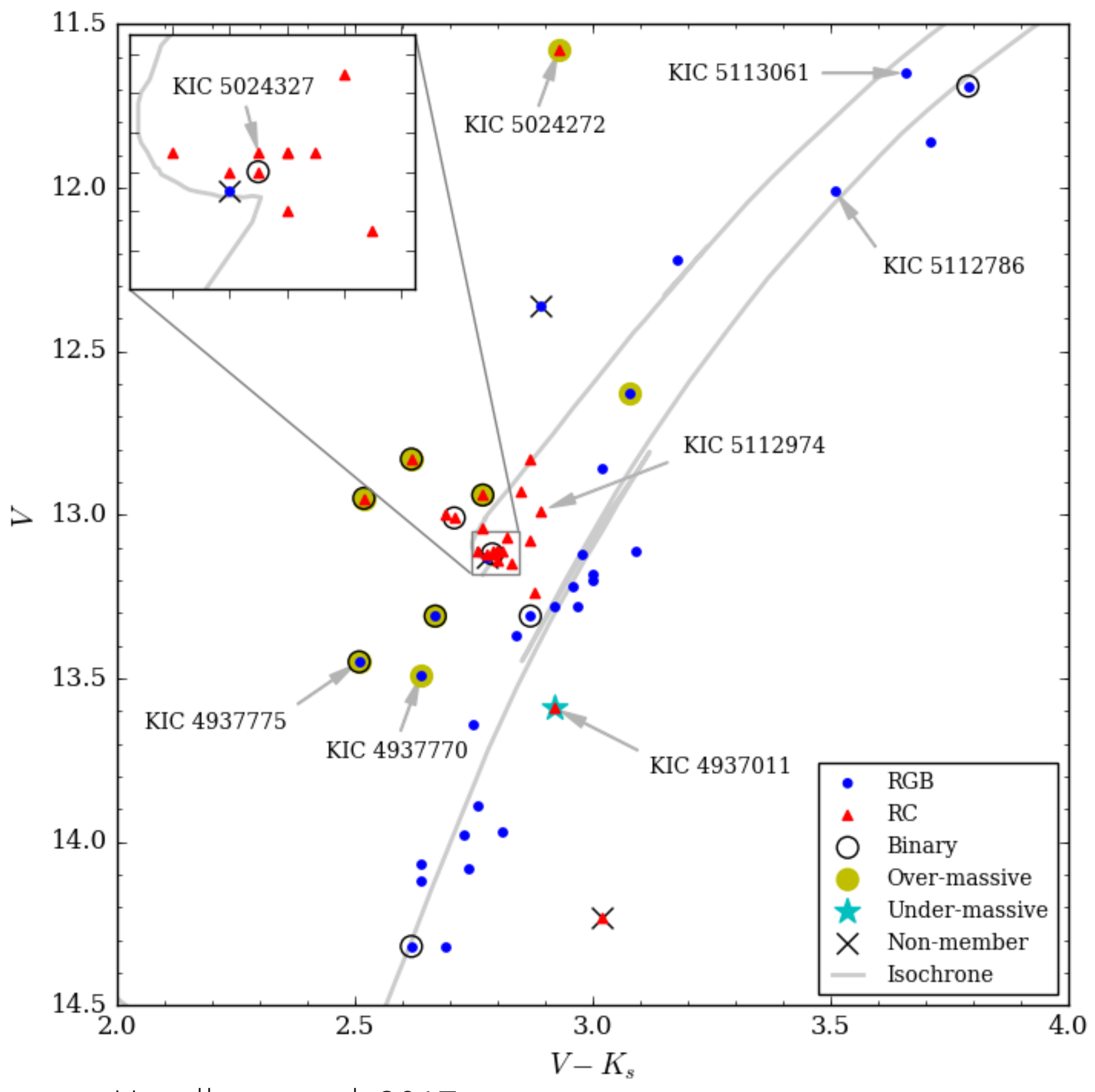


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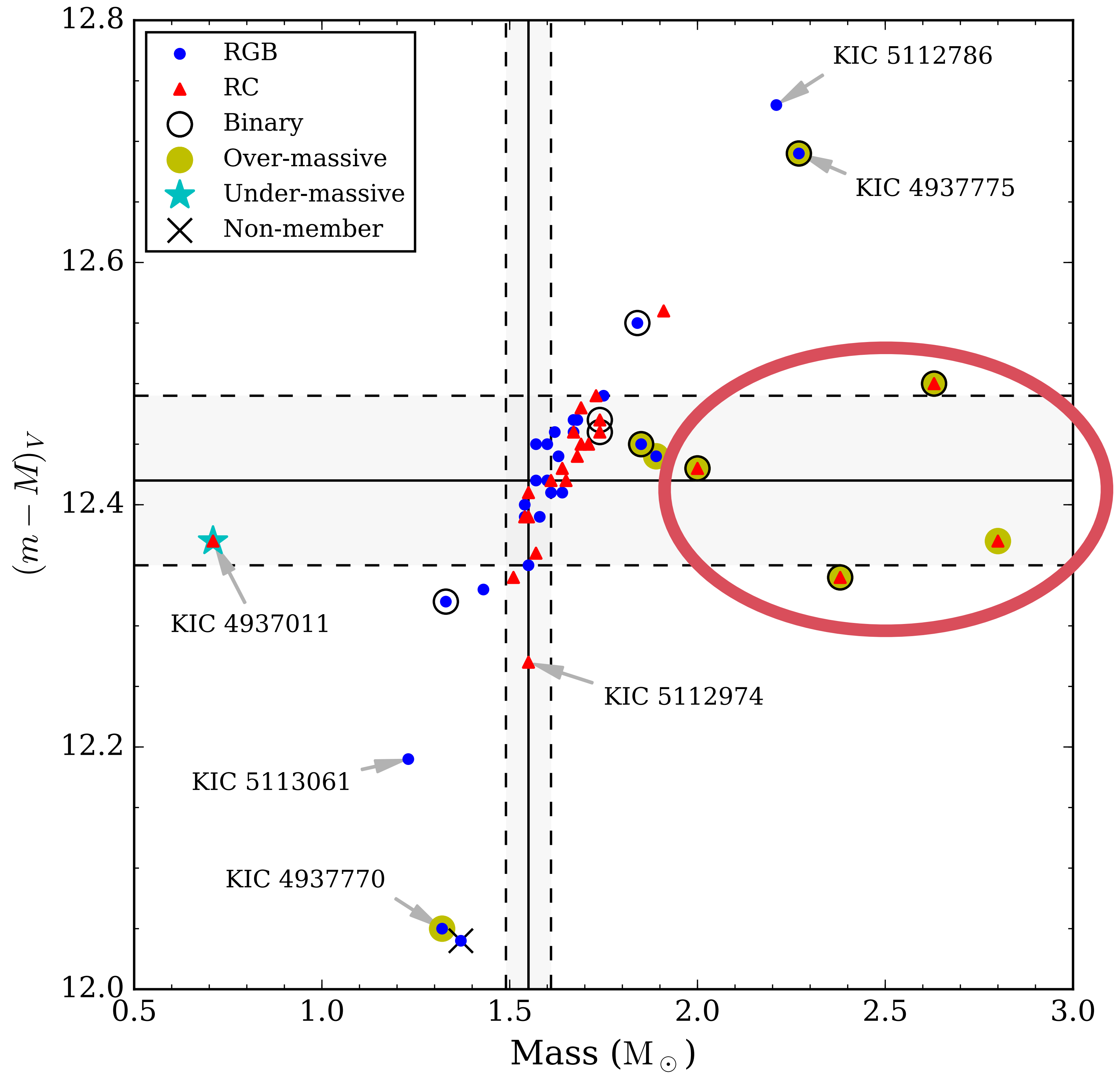


evidence for "over-massive stars"

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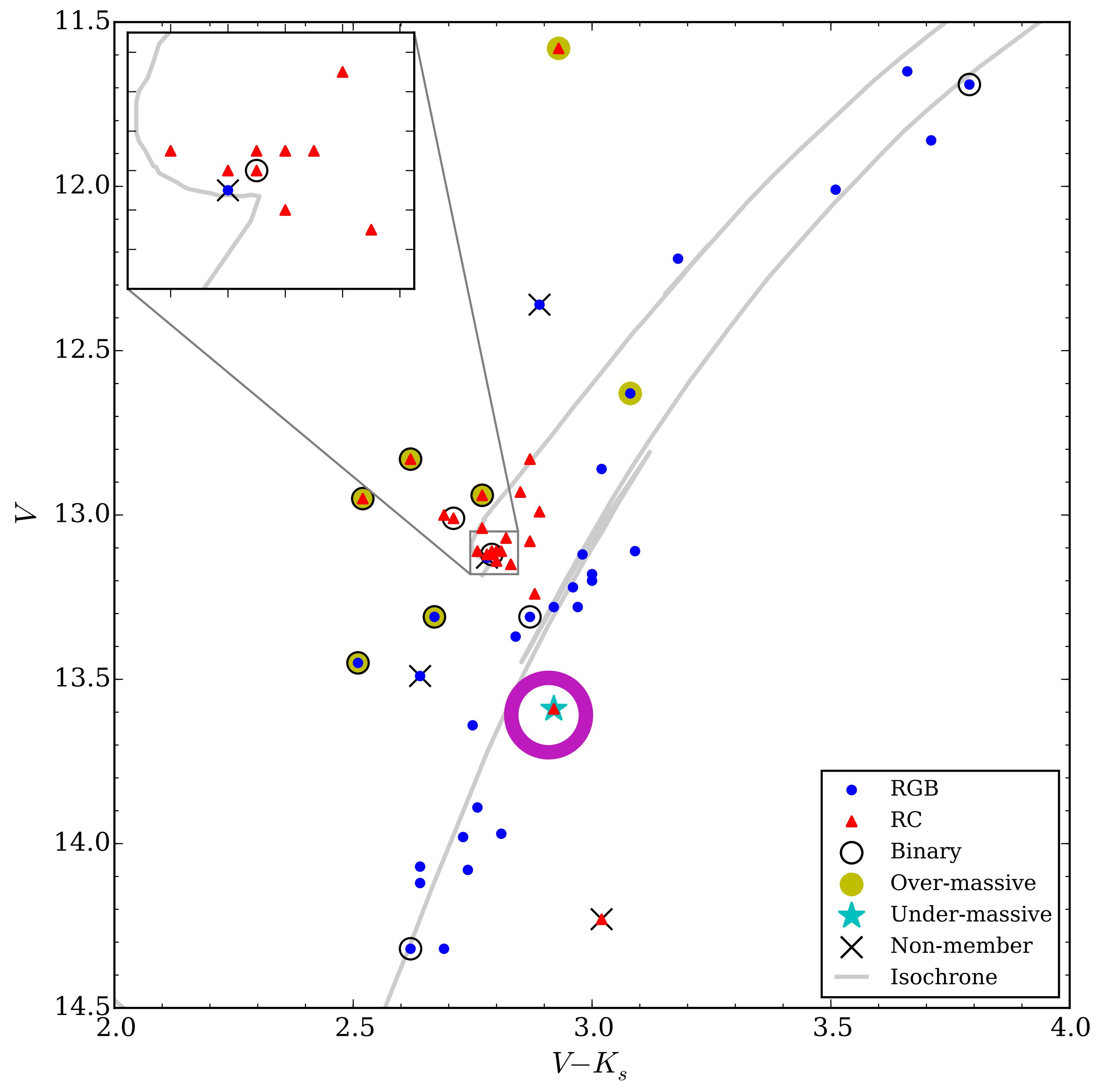
a Li-rich1.6 $M_{sun}$ RGB star

Carlberg et al. 2015 Anthony-Twarog et al. 2013

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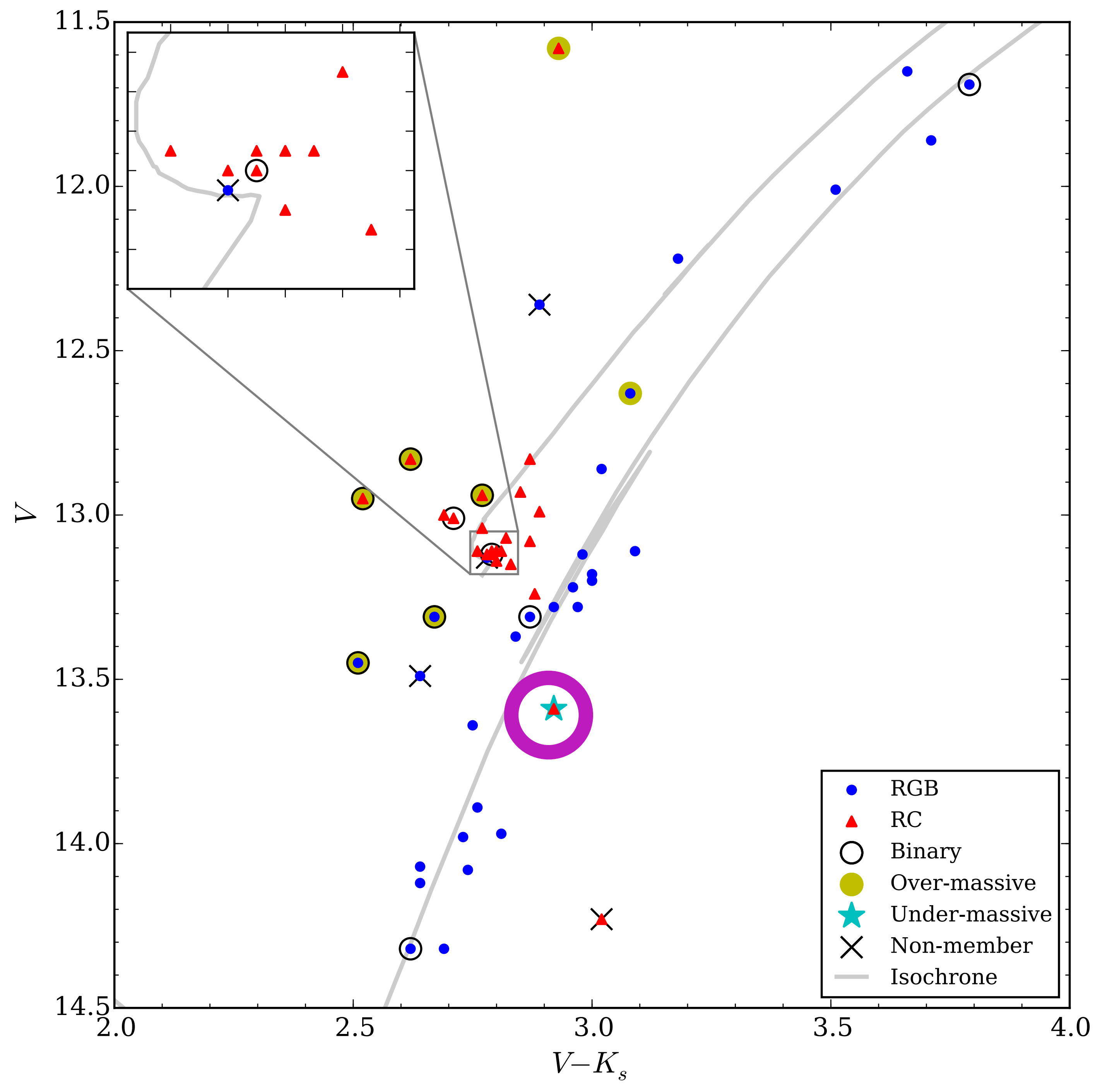


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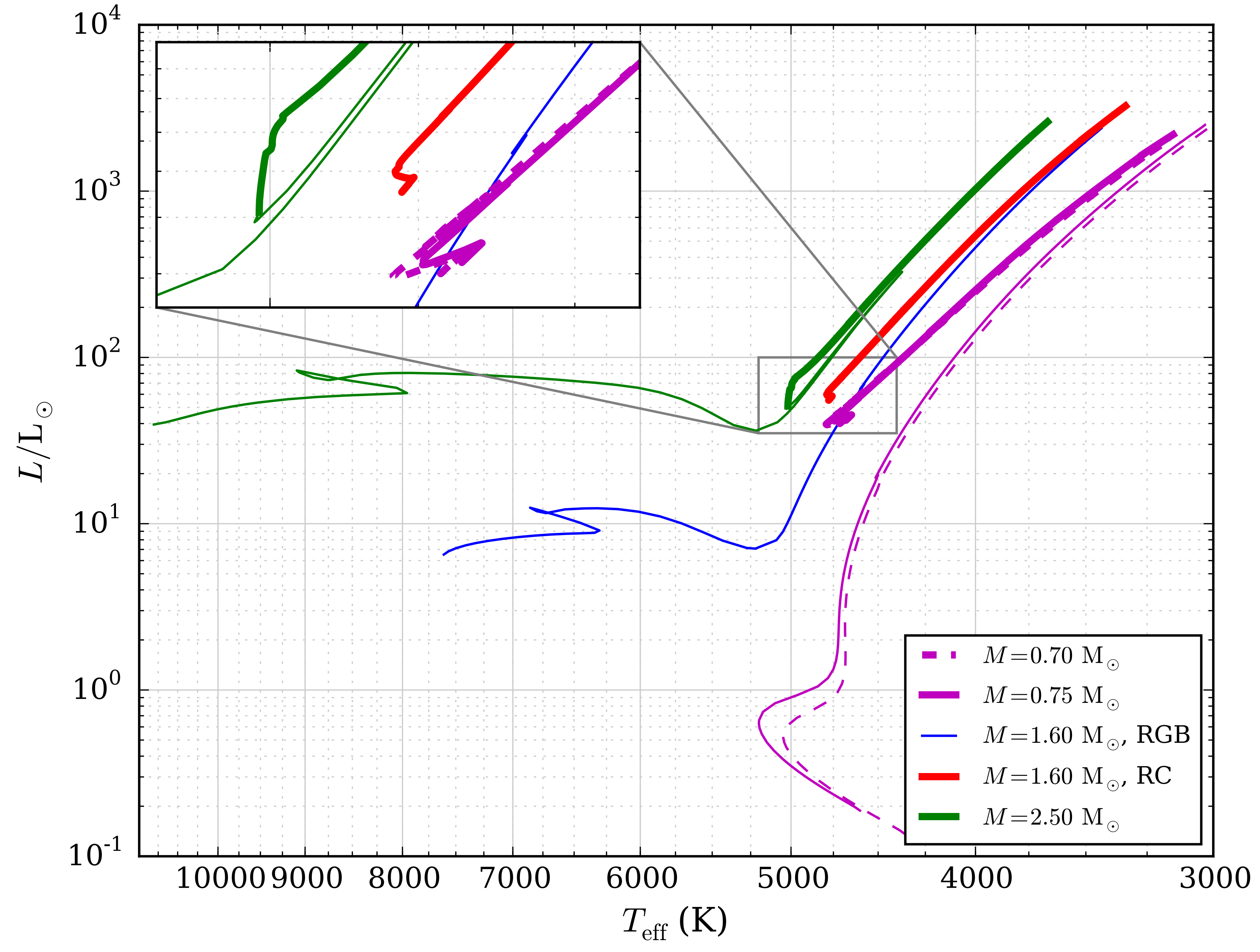

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0.75 RC

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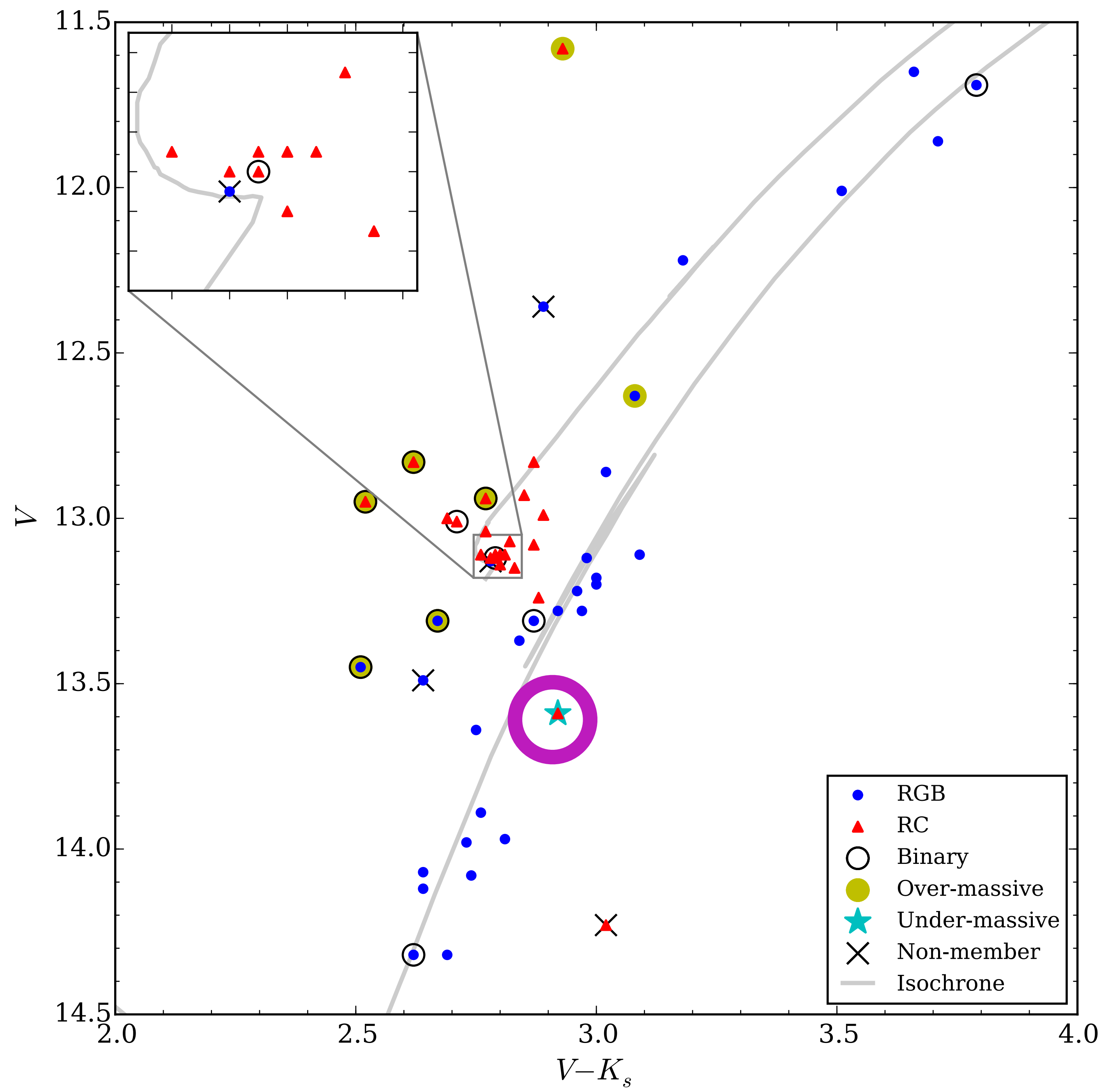


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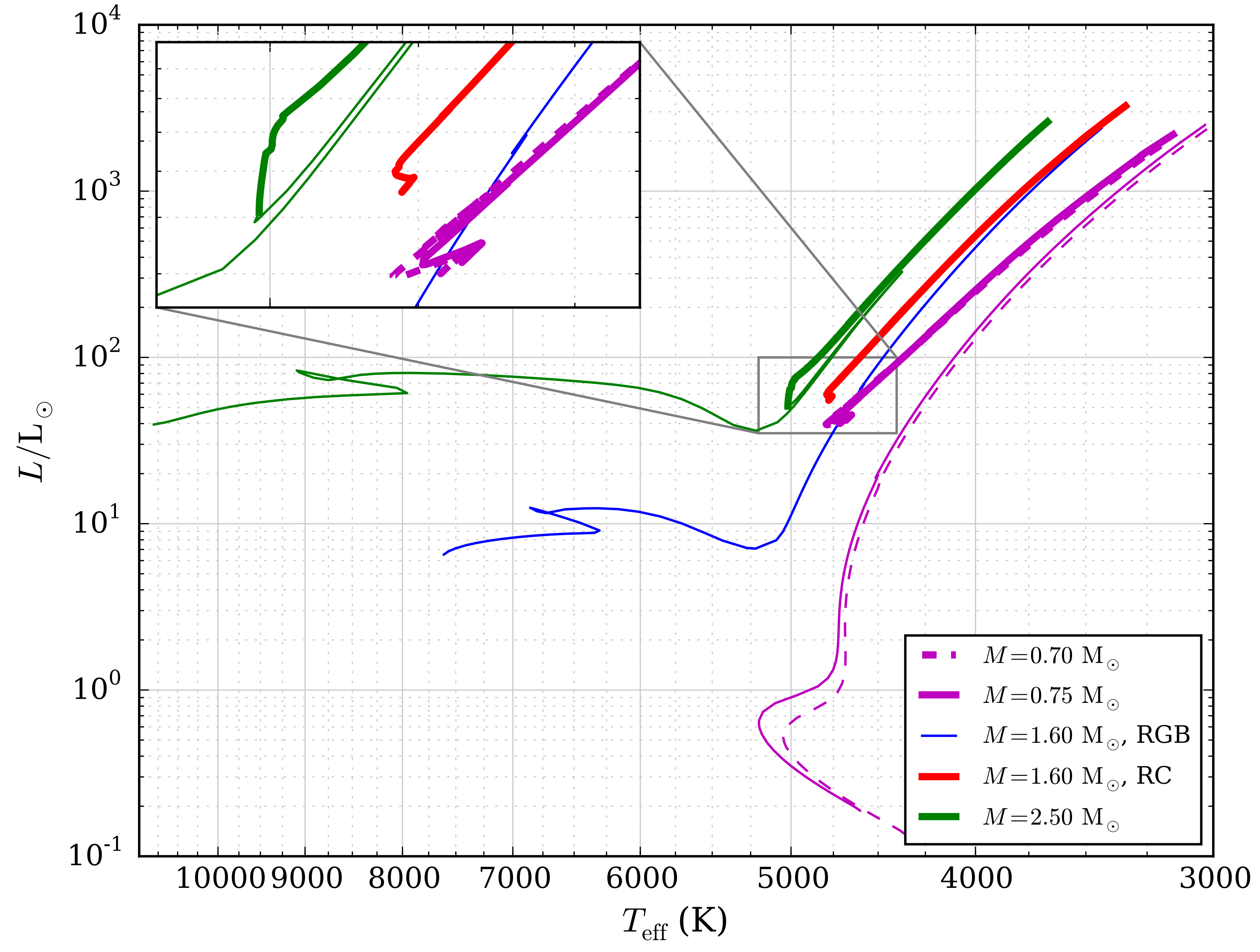


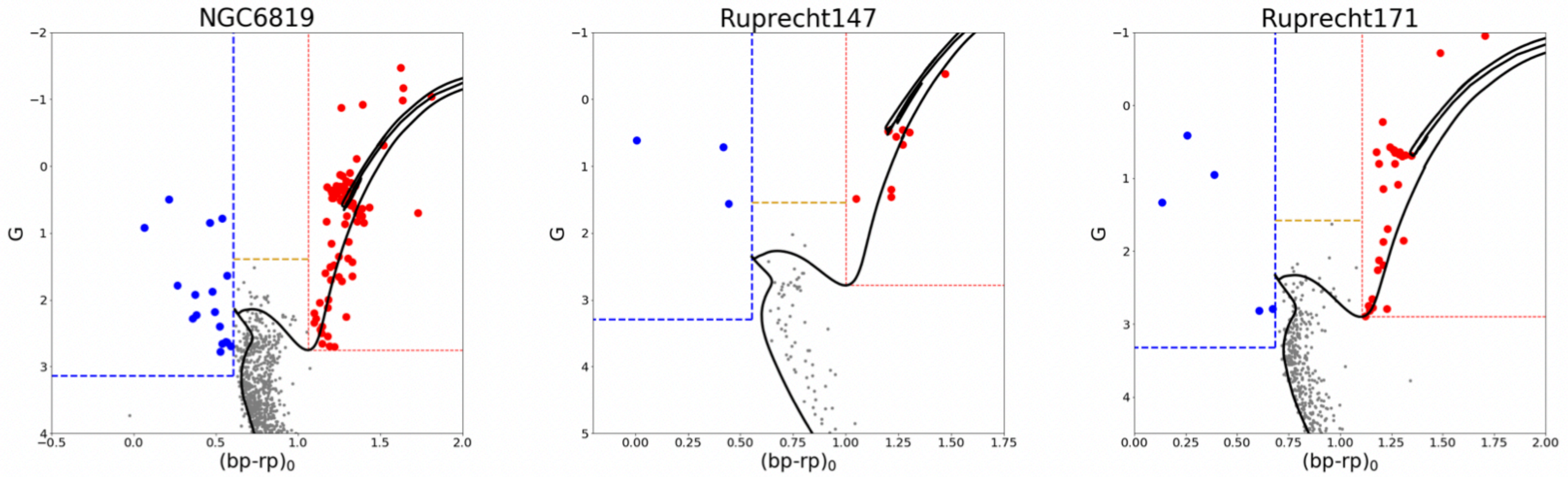
# TESTING STELLAR PHYSICS

- couple with constraints on blue stragglers

  Leiner&Geller 2021

  Rain et al. 2021

  Jadhav & Subramaniam 2021



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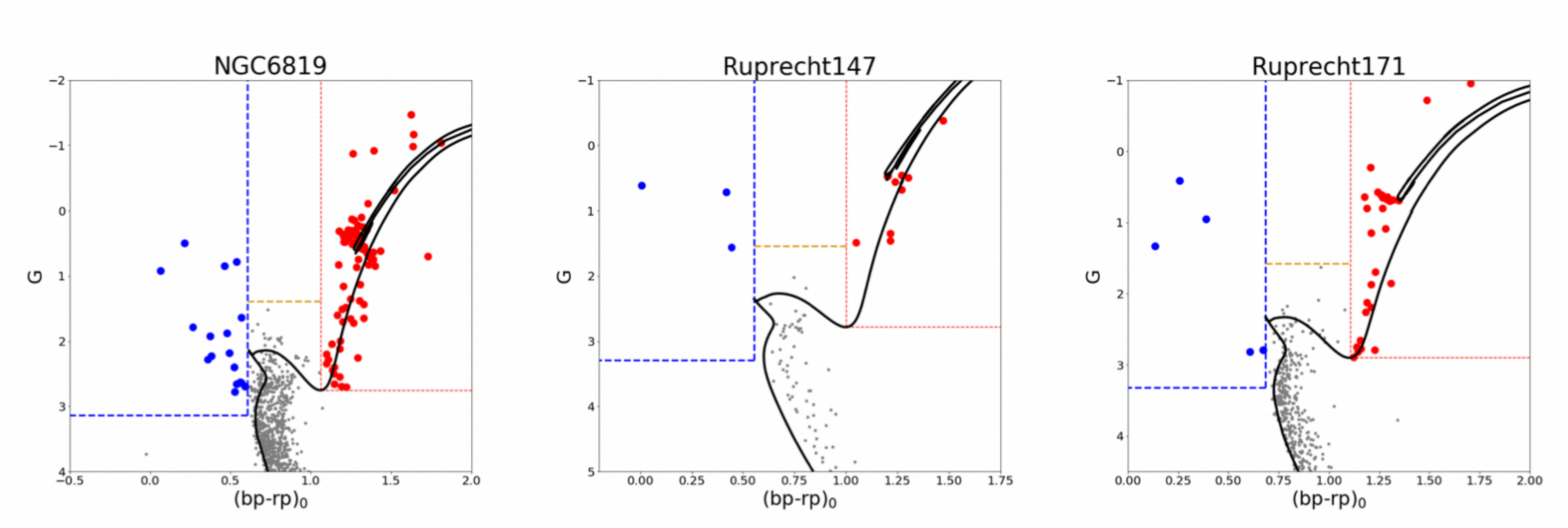



- occurrence rate, formation channels of formation of these objects

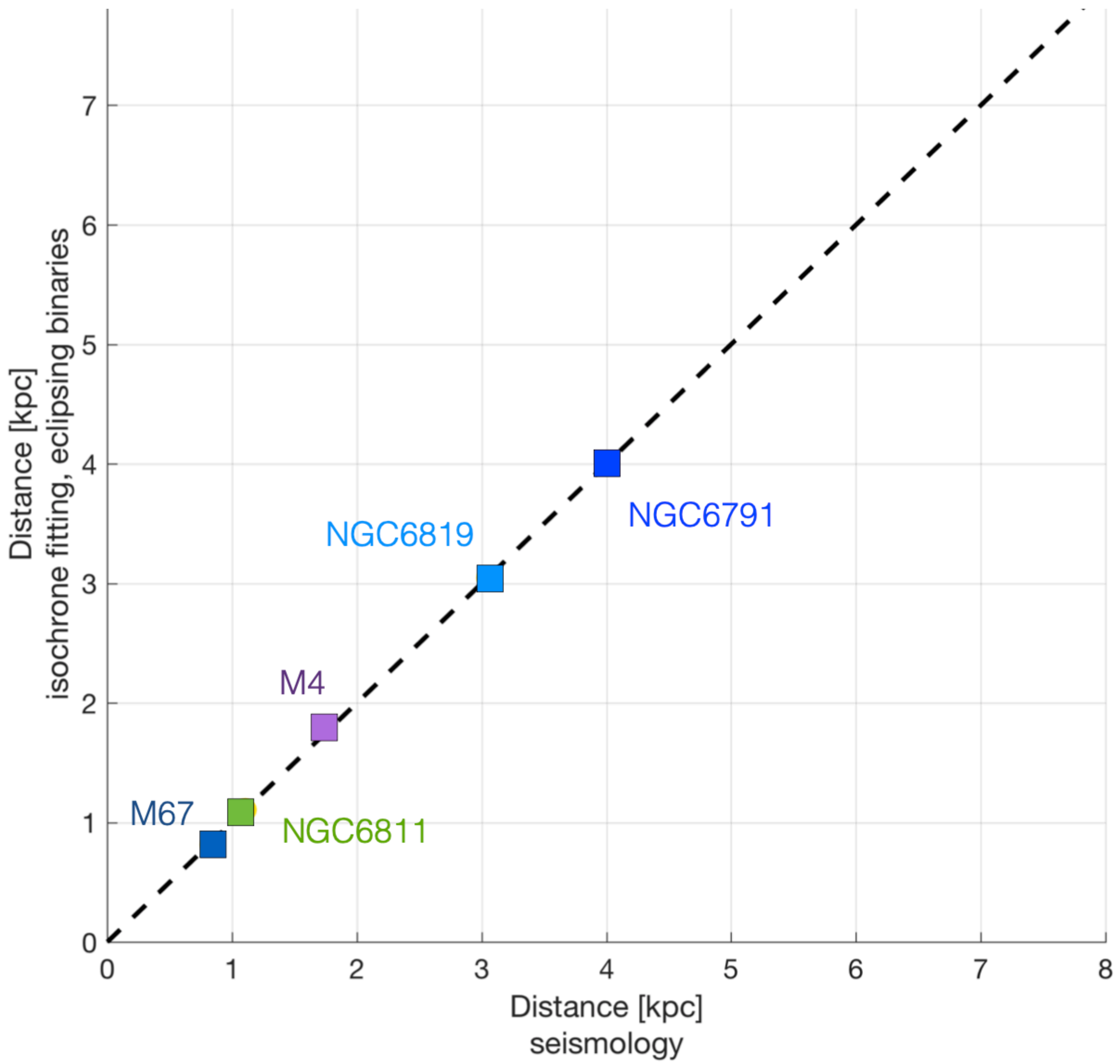
  comparison with interacting binary populations (a' la Izzard et al. 2017, Leiner & Geller 2021)

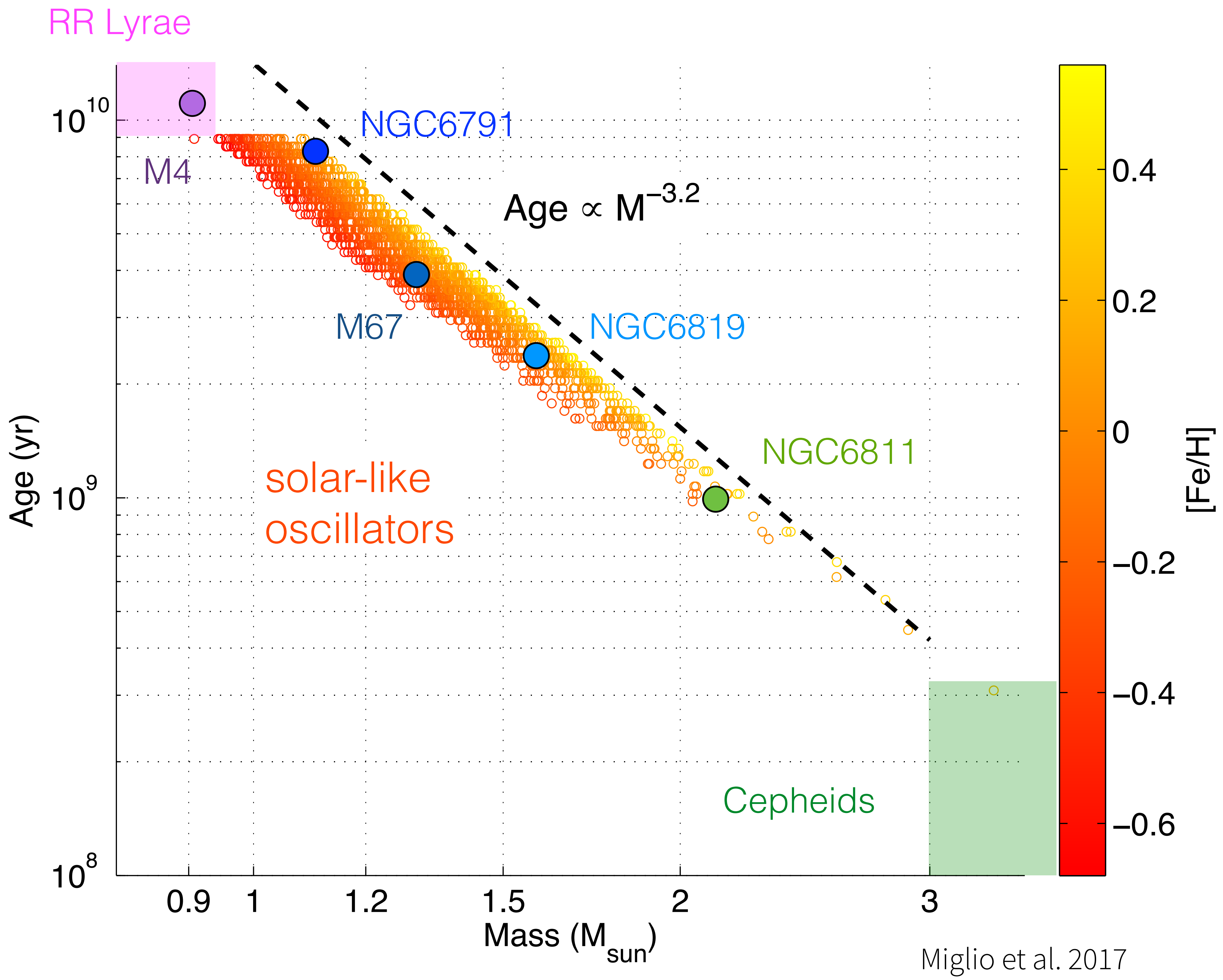
  use all info available (chemical composition, surface rotation, seismic inference on internal structure)

  evidence for overmassive stars in the field   see e.g. Fuhrmann 2011, Martig 2015, Chiappini 2015, Jofré et al 2016, Izzard et al. 2017, 2018, Silva-Aguirre 2018, Miglio et sl.2021

# CLUSTERS AS BENCHMARKS

- testing the asteroseismic distance, mass, and age scales




Miglio et al. 2017

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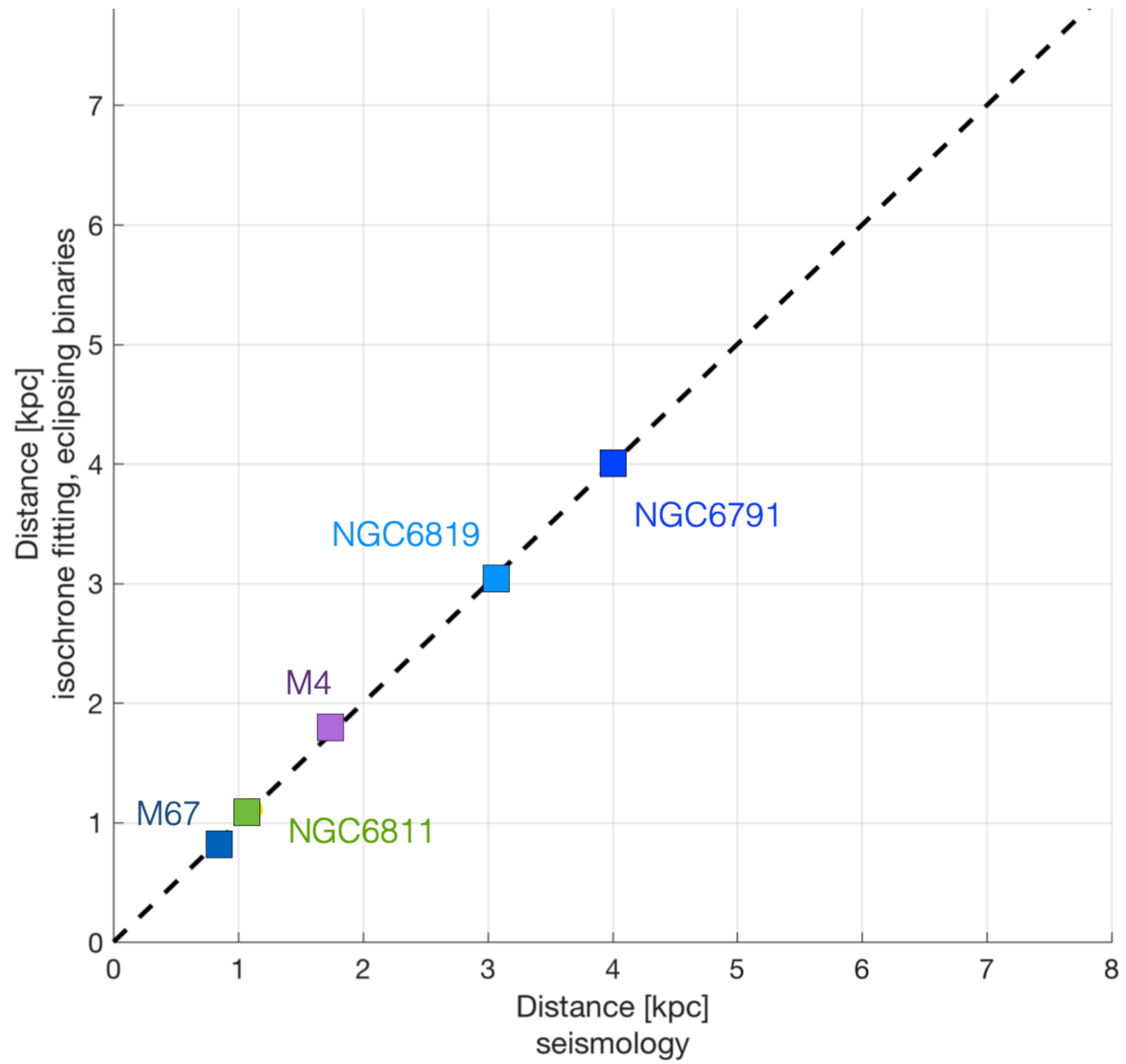


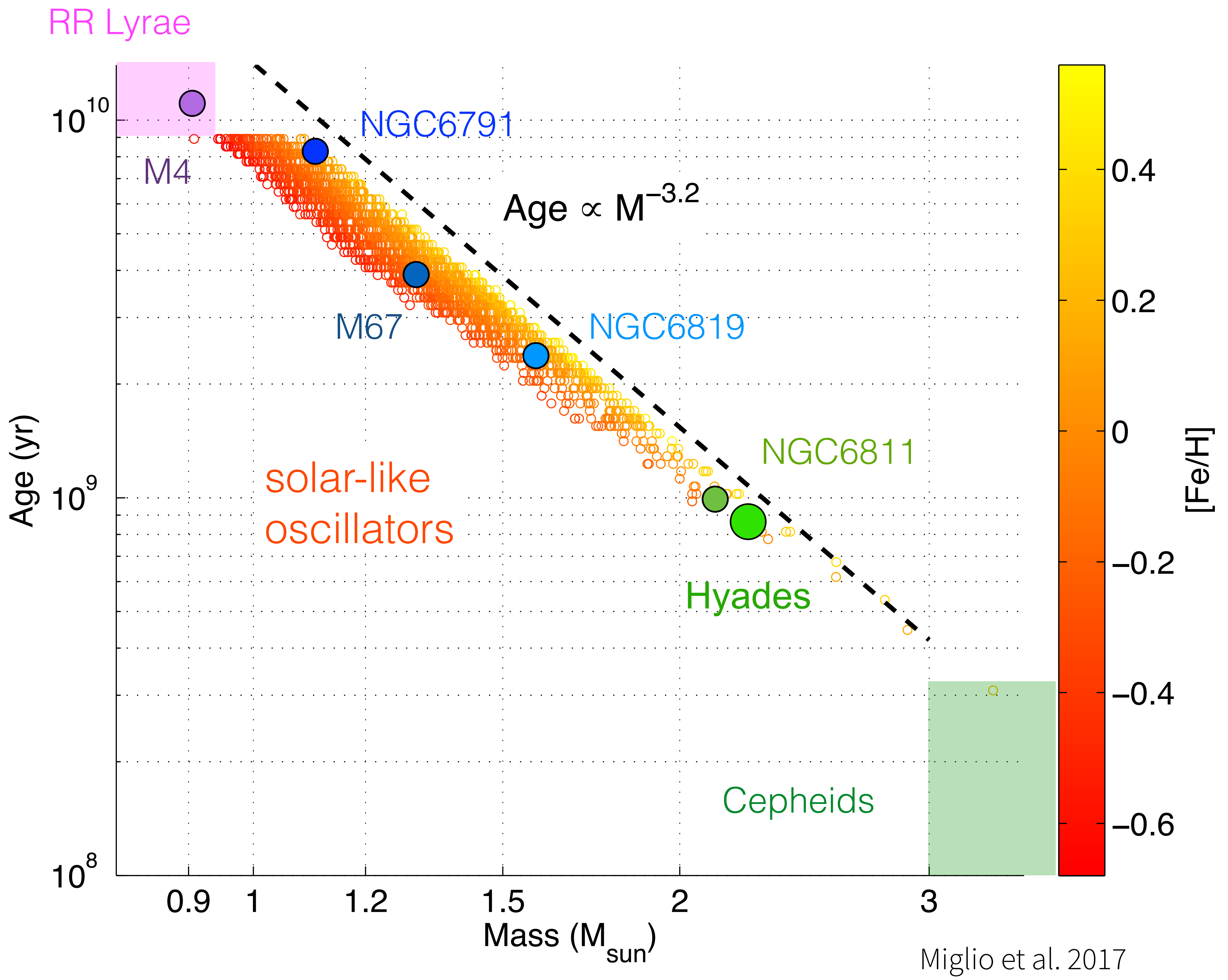


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- Hyades

MS EB+ seismology of ε Tau

Brogaard et al. 2021

*consistency checks: issue with parallax?*

| IDs | HD 28305, $\epsilon$ Tau |
|---|---|
| $V$ (mag) | 3.53 |
| $T_{\rm eff}$(K) | 4950 ± 22 (*) |
| $BC_V$ (mag) | −0.257 |
| $\nu_{\rm max}$($\mu$Hz) | 56.4 ± 1.1 (*) |
| $\Delta\nu$($\mu$Hz) | 5.00 ± 0.01 (*) |
| $\theta_{\rm LD}$ (mas) | 2.493 ± 0.019 (*) |
| Parallax, *Gaia* DR2 (mas) | 20.31 ± 0.43 |
| Parallax, HIPPARCOS (mas) | 22.24 ± 0.25 |

| Asteroseismic parameters constrained by HIPPARCOS $\pi$, This work: | |
|---|---|
| $\nu_{\rm max}$($\mu$Hz) | 55.3 |
| $M(M_\odot)$ | 2.458 |
| $R(R_\odot)$ | 12.17 |
| Parallax, derived (mas) | 22.03 |

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Gaia EDR3 parallax: 22.37 ± 0.17 mas

Age: 0.9 ± 0.1 (stat) ±0.1 (sys) Gyr

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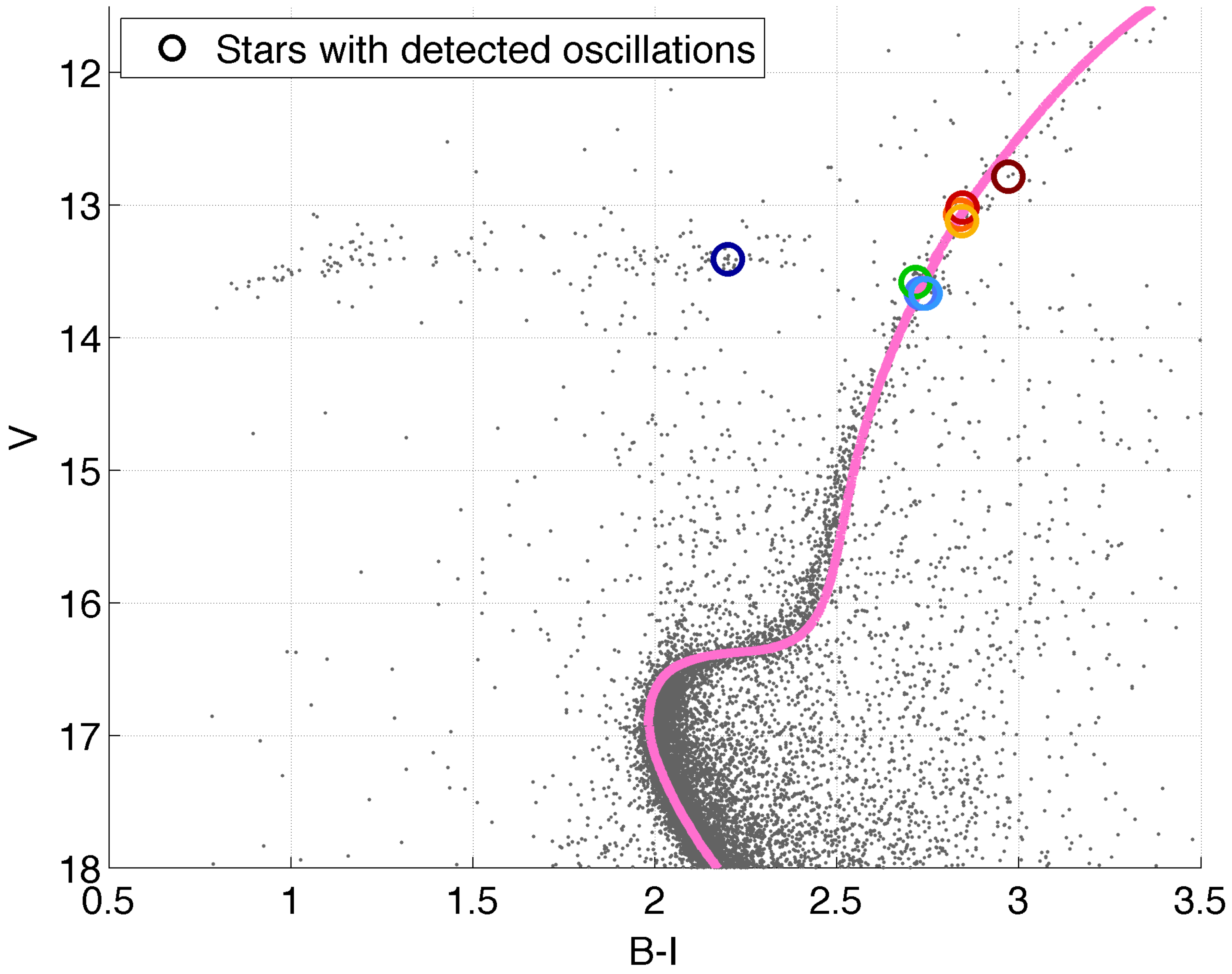
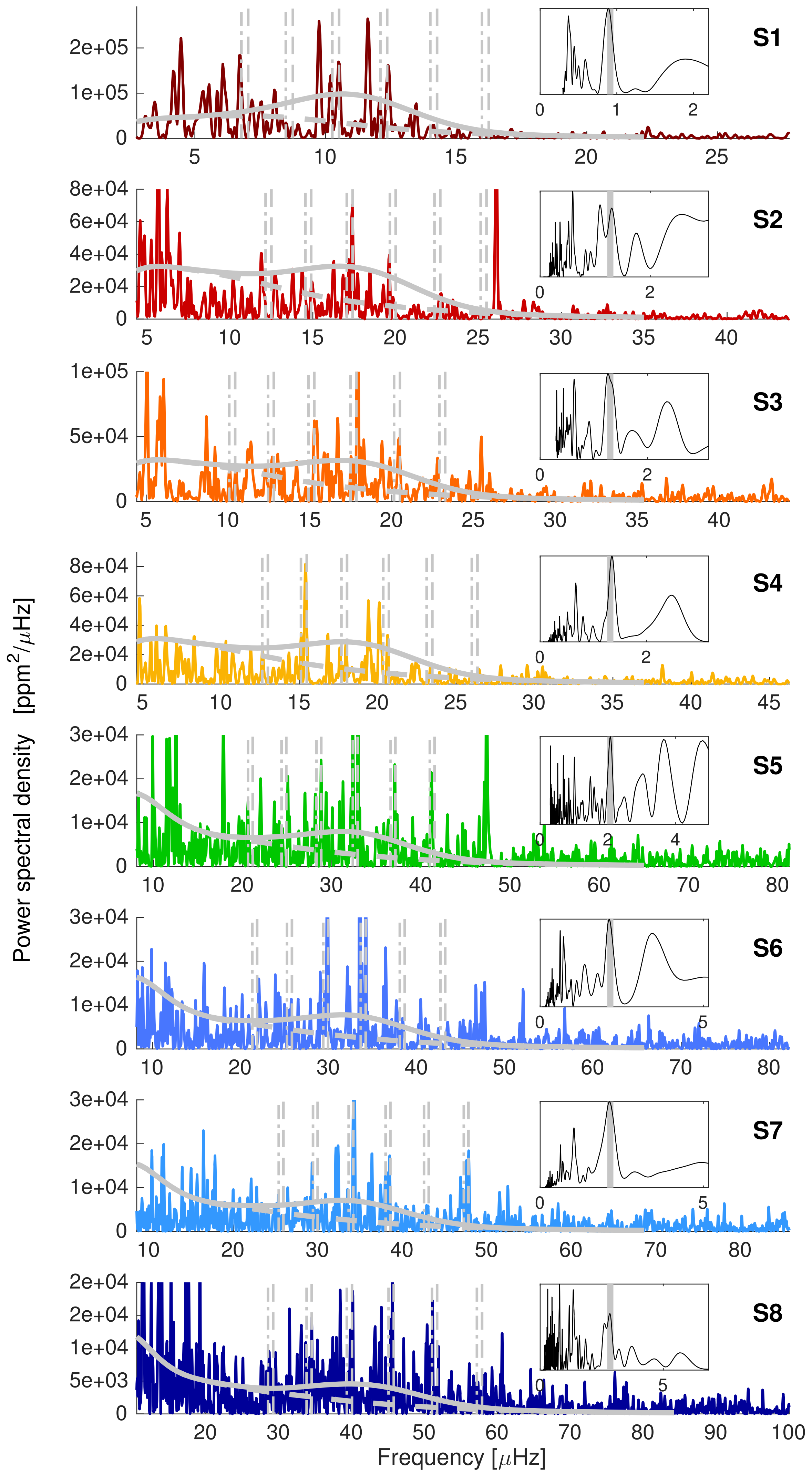
- M4

K2 observations




Miglio et al. 2016



# CLUSTERS AS BENCHMARKS

- M4

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{3/2},$$

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^2 \left(\frac{L}{\mathrm{L}_\odot}\right)^{3/2} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{-6},$$

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{L}{\mathrm{L}_\odot}\right) \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{-7/2},$$

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| Eq. | $\overline{M_{\mathrm{RGB}}}$ | $\overline{\sigma_{\mathrm{M}}}$ | $\sigma_{\overline{M}}$ | $N$ | $M_{\mathrm{RHB}}$ |
|---|---|---|---|---|---|
| (1) | 0.99 | 0.05 | 0.02 | 7 | 0.79 ± 0.10 |
| (2) | 0.78 | 0.09 | 0.01 | 7 | 0.53 ± 0.12 |
| (3) | 0.84 | 0.06 | 0.01 | 7 | 0.61 ± 0.08 |
| (4) | 0.94 | 0.04 | 0.02 | 7 | 0.73 ± 0.07 |
| | | | $\Delta\nu_{\mathrm{CORR}}$ | | |
| (1) | 0.84 | 0.04 | 0.02 | 7 | 0.86 ± 0.11 |
| (2) | 0.84 | 0.09 | 0.01 | 7 | 0.51 ± 0.12 |
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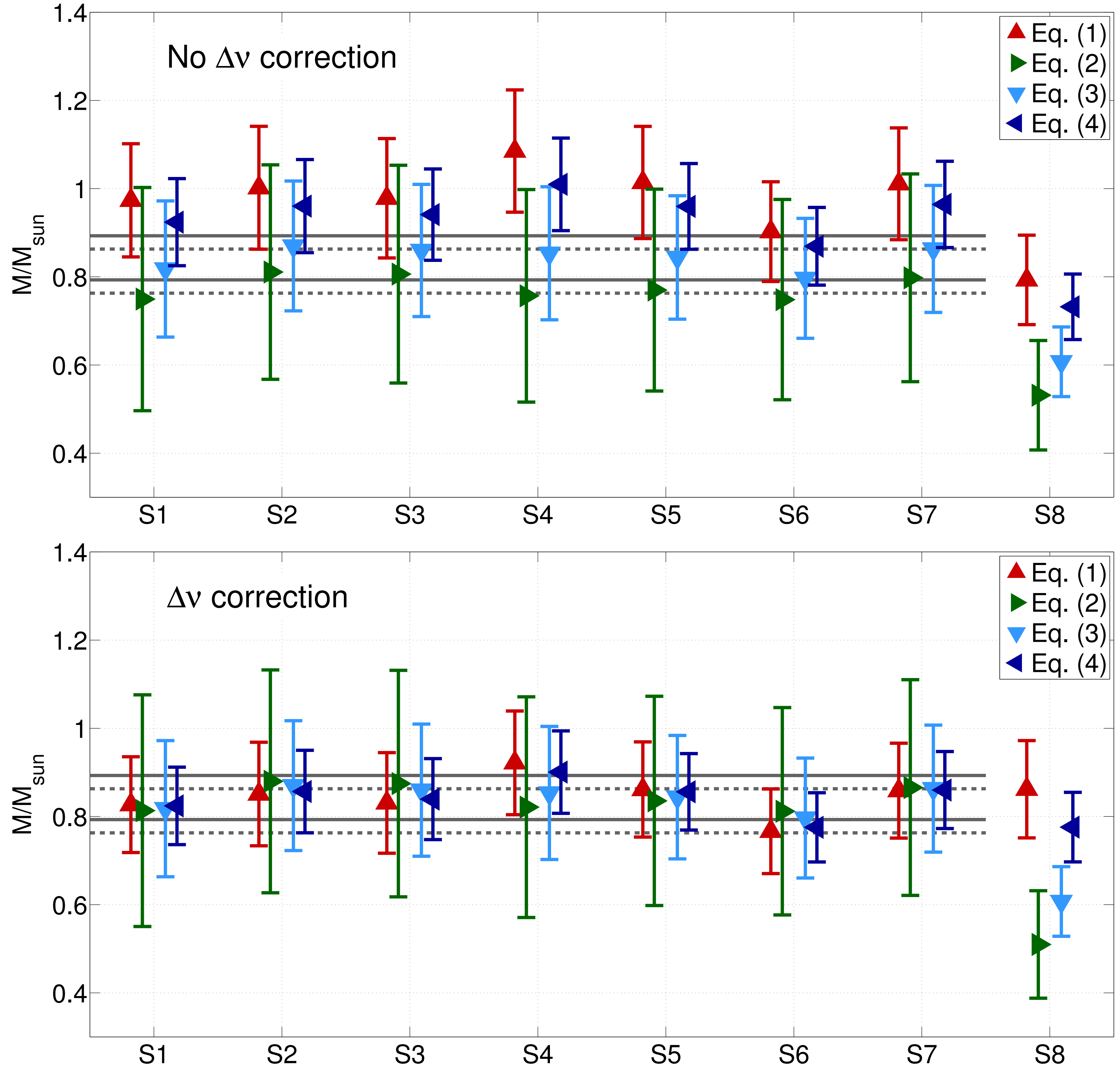


Miglio et al. 2016

see also Valentini et al. 2018

# CLUSTERS AS BENCHMARKS

- revisiting M4

ongoing work lead by Enrico Corsaro
Marco Tailo

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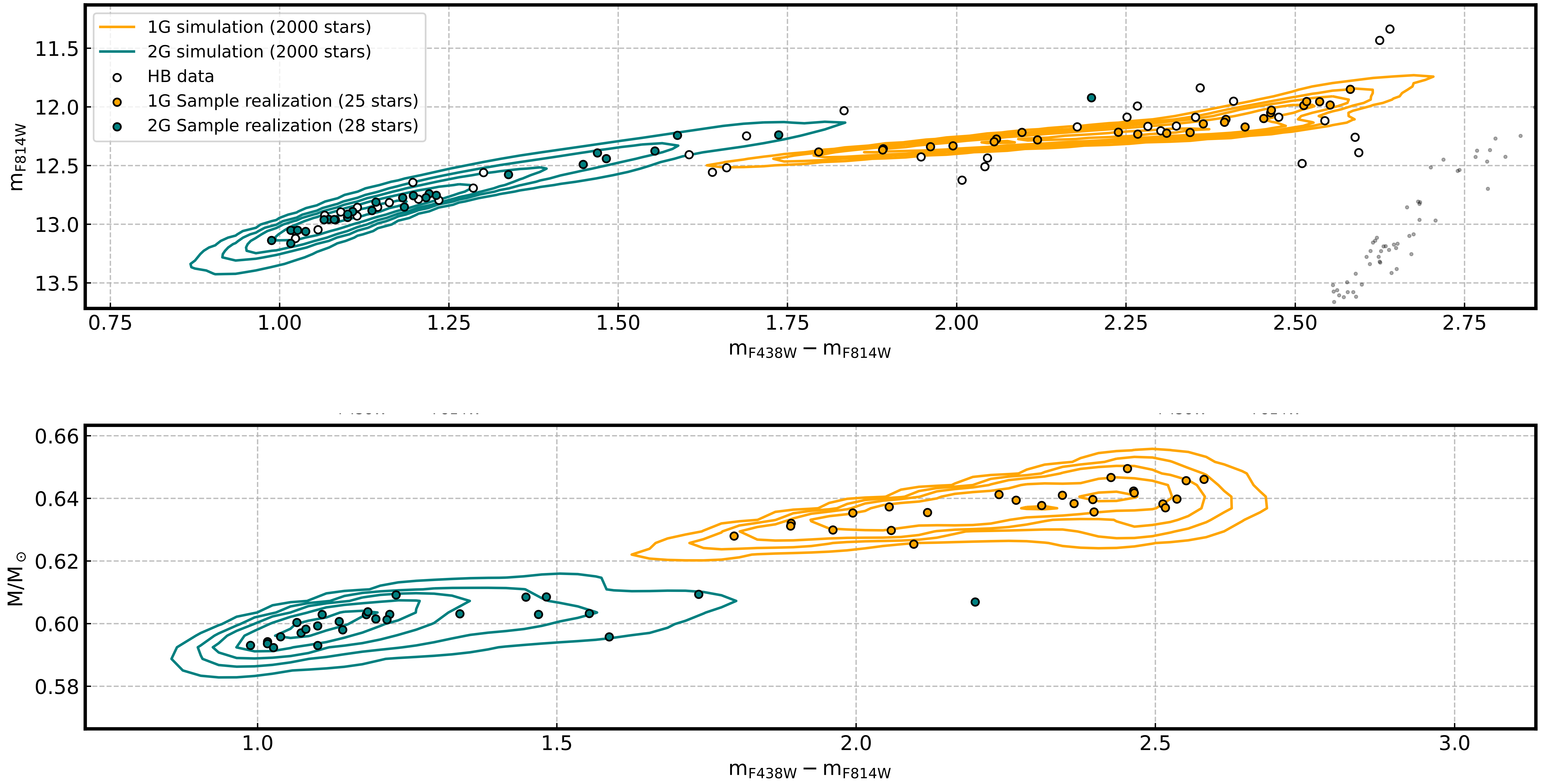


Tailo et al. 2019, Tailo et al. in prep

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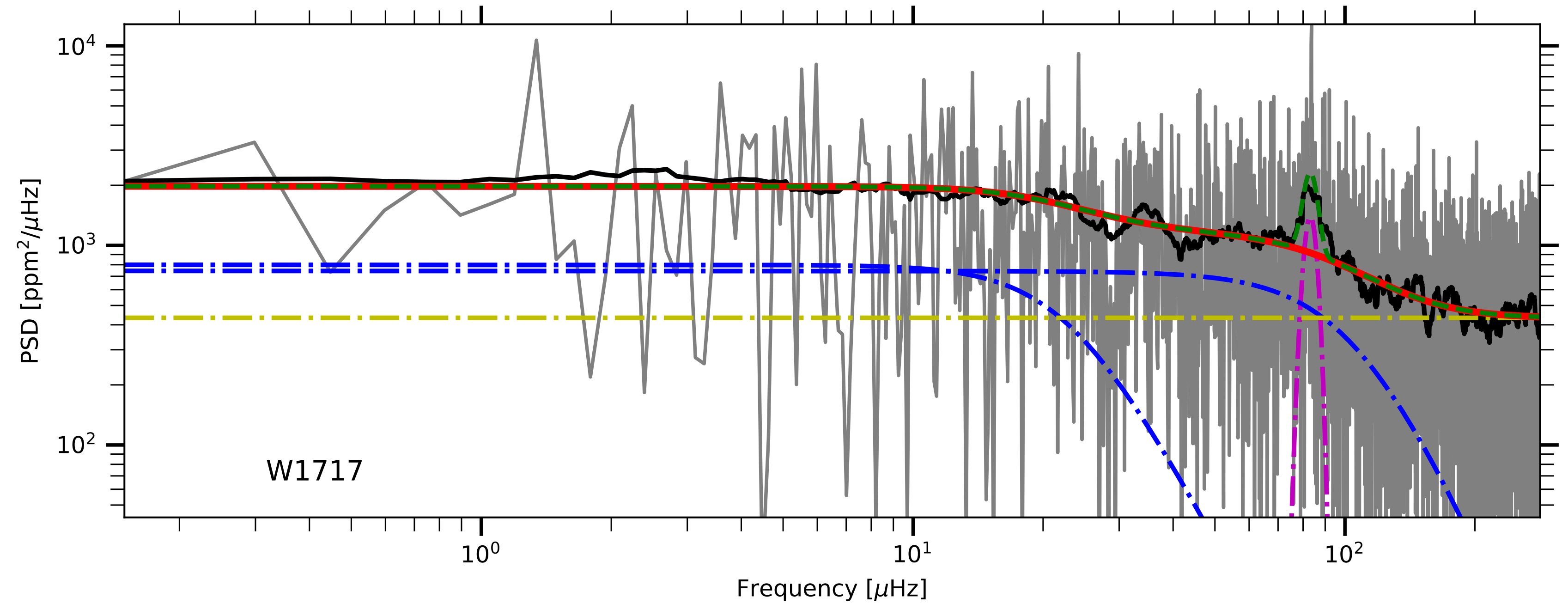
K2



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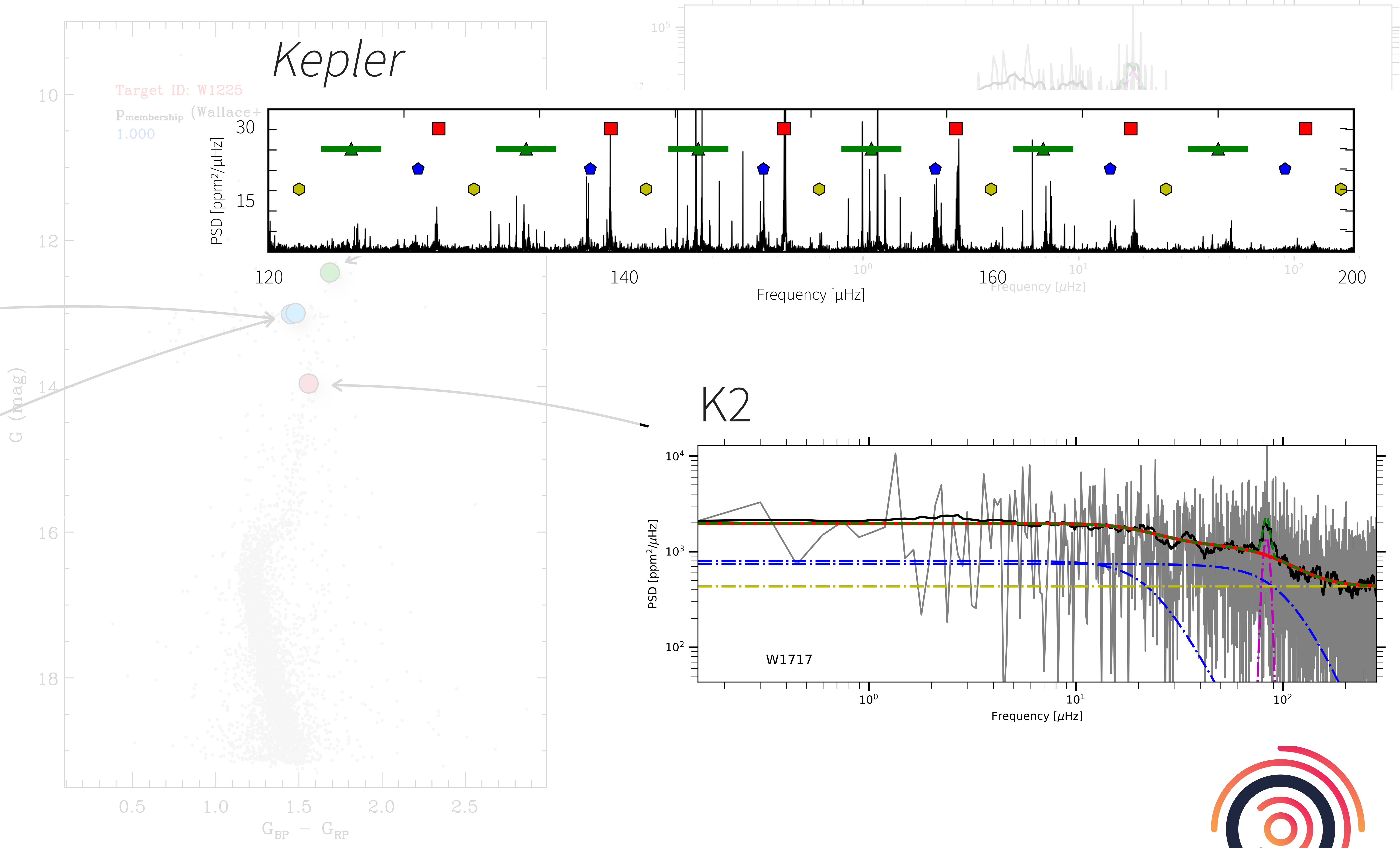

# PART 2

- asteroseismology in *Kepler* clusters has whet our appetite …

.. is there a need for better data?

…nomy
…g/10.1007/s10686-021-09711-1
…INAL ARTICLE

Check for updates

HAYDN

High-precision AsteroseismologY of DeNse stellar fields

Andrea Miglio[1,2,3] · Léo Girardi[4] · Frank Grundahl[5] · Benoit Mosser[6] · Nate Bastian[7] · Angela Bragaglia[3] · Karsten Brogaard[5,8] · Gaël Buldgen[9] · William Chantereau[7] · William Chaplin[1] · Cristina Chiappini[10] · Marc-Antoine Dupret[11] · Patrick Eggenberger[9] · Mark Gieles[12,13] · Robert Izzard[14] · Daisuke Kawata[15] · Christoffer Karoff[5] · Nadège Lagarde[16] · Ted Mackereth[1,17,18,19] · Demetrio Magrin[4] · Georges Meynet[9] · Eric Michel[20] · Josefina Montalbán[1] · Valerio Nascimbeni[4] · Arlette Noels[11] · Giampaolo Piotto[21] · Roberto Ragazzoni[4] · Igor Soszyński[22] · Eline Tolstoy[23] · Silvia Toonen[1,24] · Amaury Triaud[1] · Fiorenzo Vincenzo[1,25]

Received: 29 July 2020 / Accepted: 9 February 2021 / Published online: 26 March 2021
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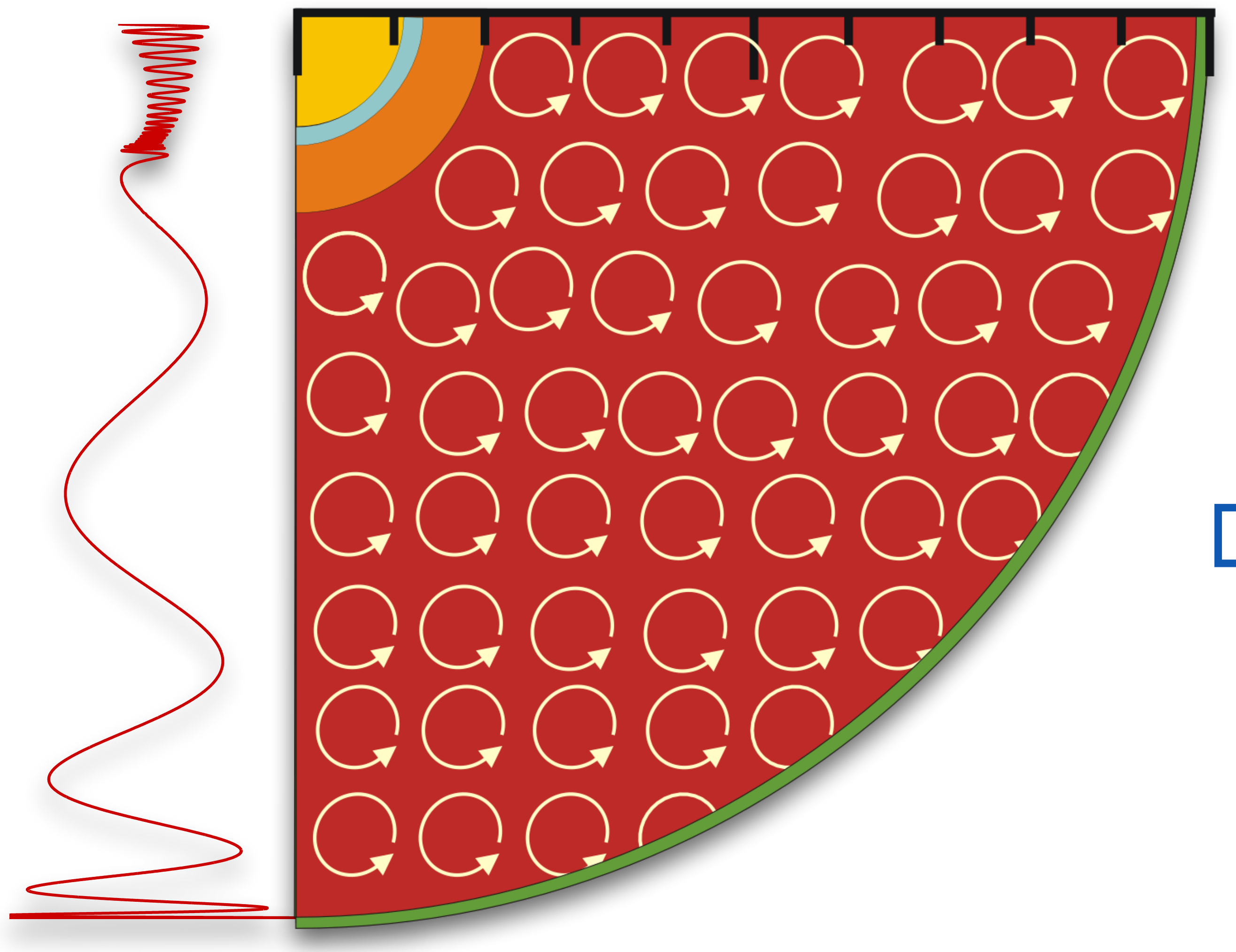
**Abstract**
In the last decade, the *Kepler* and CoRoT space-photometry missions have demonstrated the potential of asteroseismology as a novel, versatile and powerful tool to perform exquisite tests of stellar physics, and to enable precise and accurate characterisations of stellar properties, with impact on both exoplanetary and Galactic astrophysics. Based on our improved understanding of the strengths and limitations of such a tool, we argue for a new small/medium space mission dedicated to gathering high-precision, high-cadence, long photometric series in dense stellar fields. Such a mission will lead to breakthroughs in stellar astrophysics, especially in the metal poor regime, will elucidate the evolution and formation of open and globular clusters, and aid our understanding of the assembly history and chemodynamics of the Milky Way's bulge and a few nearby dwarf galaxies.

**Keywords** Stars: low-mass · Globular clusters · Galaxy: bulge · Galaxies: dwarf · Asteroseismology

# HAYDN: THE CONTEXT

the space photometry revolution: discovering the potential of asteroseismology

## B. high-precision stellar physics



e.g.

- chemical composition gradients
- density stratification
- internal rotational profile

stellar interiors and their evolution accessible to our investigations

# HAYDN: THE CONTEXT

- CoRoT, *Kepler*-K2 — have demonstrated the potential of asteroseismology (in clusters)

- TESS
- PLATO

observational strategy not optimised for stellar / galactic science

designed primarily for planet searches: wide field, bright targets, large pixel sizes

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observational strategy not optimised for stellar / galactic science

designed primarily for planet searches: **wide field**, **bright targets**, **large pixel sizes**

overcoming these limitations i.e.

obtaining *Kepler*-like observations in crowded stellar fields

⇩

breakthroughs in stellar and Galactic science

# HAYDN: SCIENCE GOALS

- having now a better understanding of the strengths and limitations of asteroseismology, we can propose a mission design that will lead to breakthroughs in three broad areas:

| | |
|---|---|
| SG1 | high-precision stellar astrophysics, especially in the metal poor regime |
| SG2 | evolution and formation of stellar clusters |
| SG3 | assembly history and chemical evolution of the Milky Way's bulge and few nearby dwarf galaxies. |

# HAYDN: SCIENCE GOALS

SG1 high-precision stellar astrophysics: need to perform tests in controlled environments, i.e. stellar open and globular clusters

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SG1 high-precision stellar astrophysics: need to perform tests in **controlled environments**, i.e. stellar open and globular clusters

- Transport of chemical elements in the stellar interior
- Core rotation and transport of angular momentum
- Mass loss on the RGB
- Occurrence of mergers / products of binary evolution
- Tests of fundamental physics

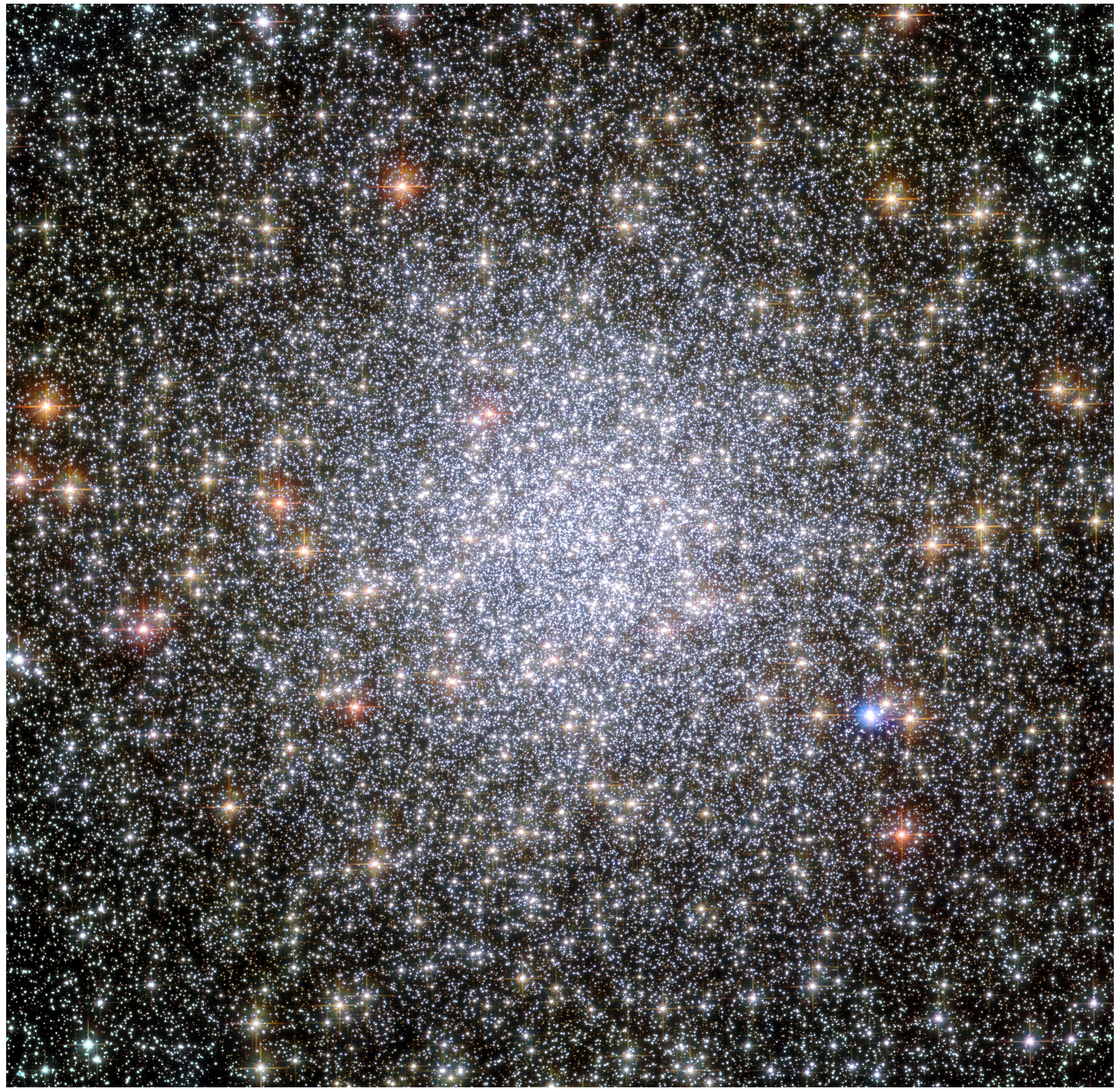
⇨ high-precision tests of stellar models, especially in the metal-poor regime (early Universe)

# HAYDN: SCIENCE GOALS

SG2 evolution, formation and dynamics of stellar clusters

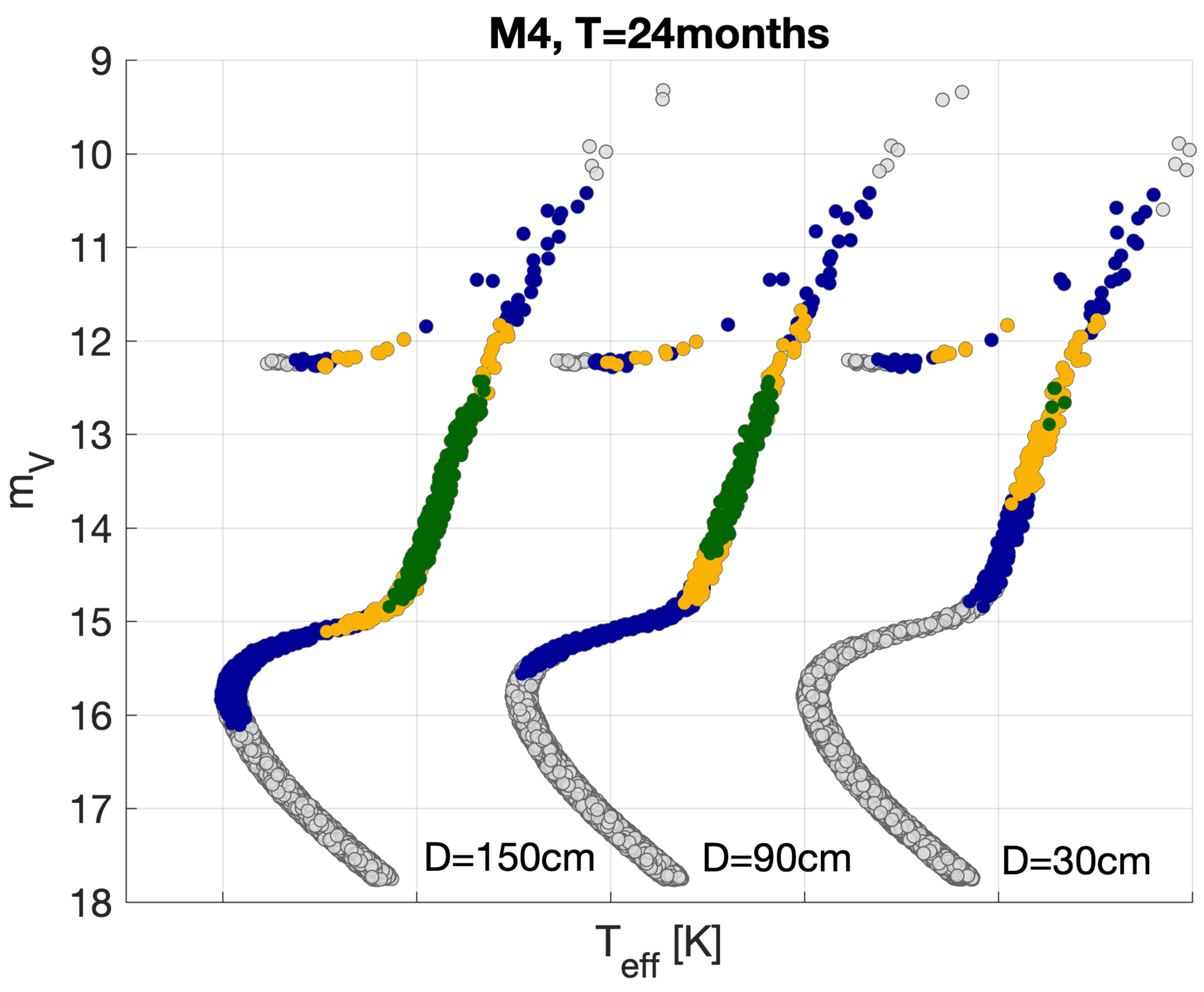
- Globular clusters formation from absolute ages
- Origin of multiple populations
- Measuring helium content in GCs with asteroseismology
- Redistribution of angular momentum from inclination of stellar spin axes

47 Tuc

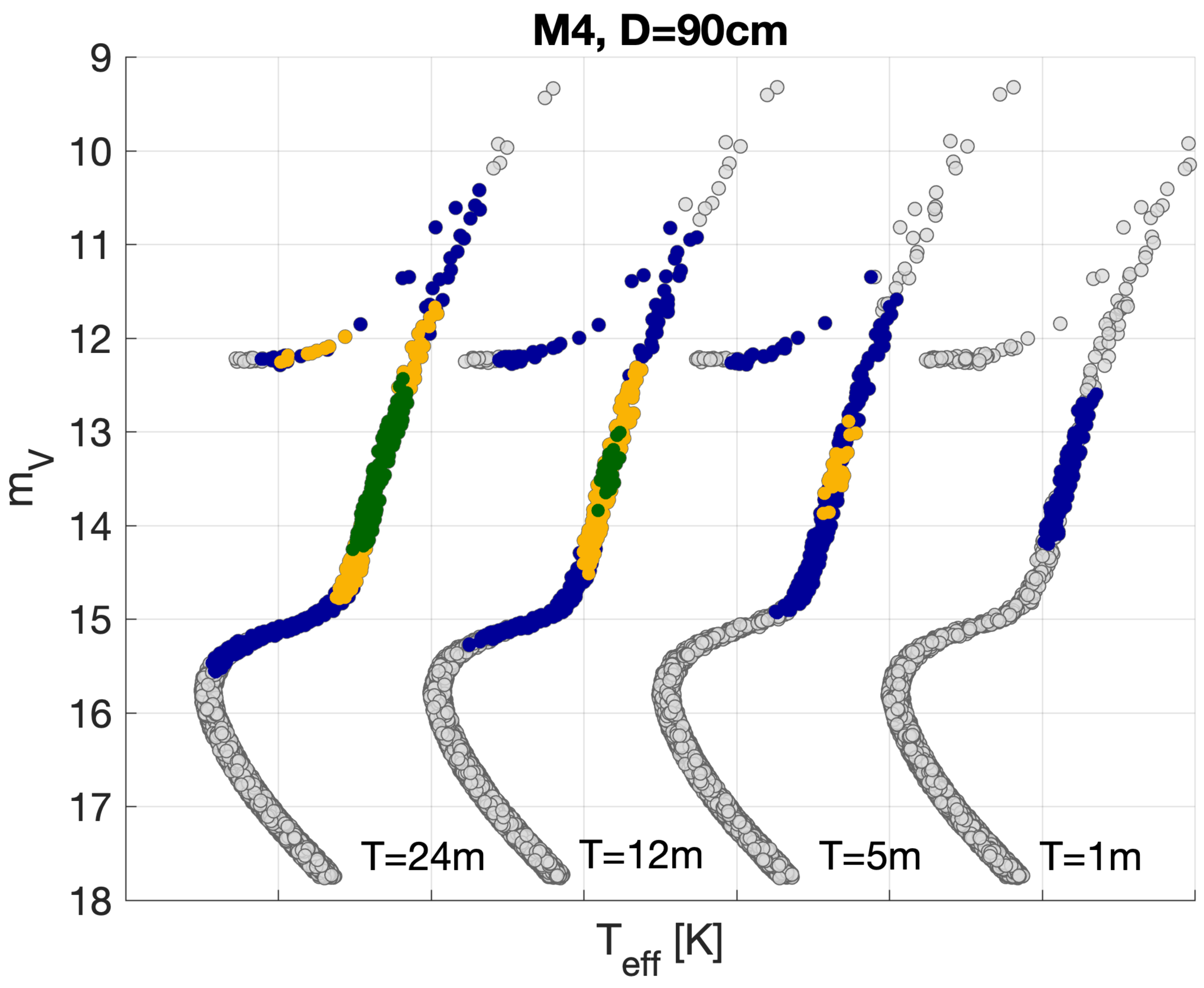


NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
Acknowledgment: J. Mack (STScI) and G. Piotto (University of Padova, Italy)

# HAYDN: MISSION PROFILE




all stars
oscillations detectable
+ g modes period spacing
+ internal rotation




all science objectives achievable with D=90 cm and a combination of 6-24 months-long runs

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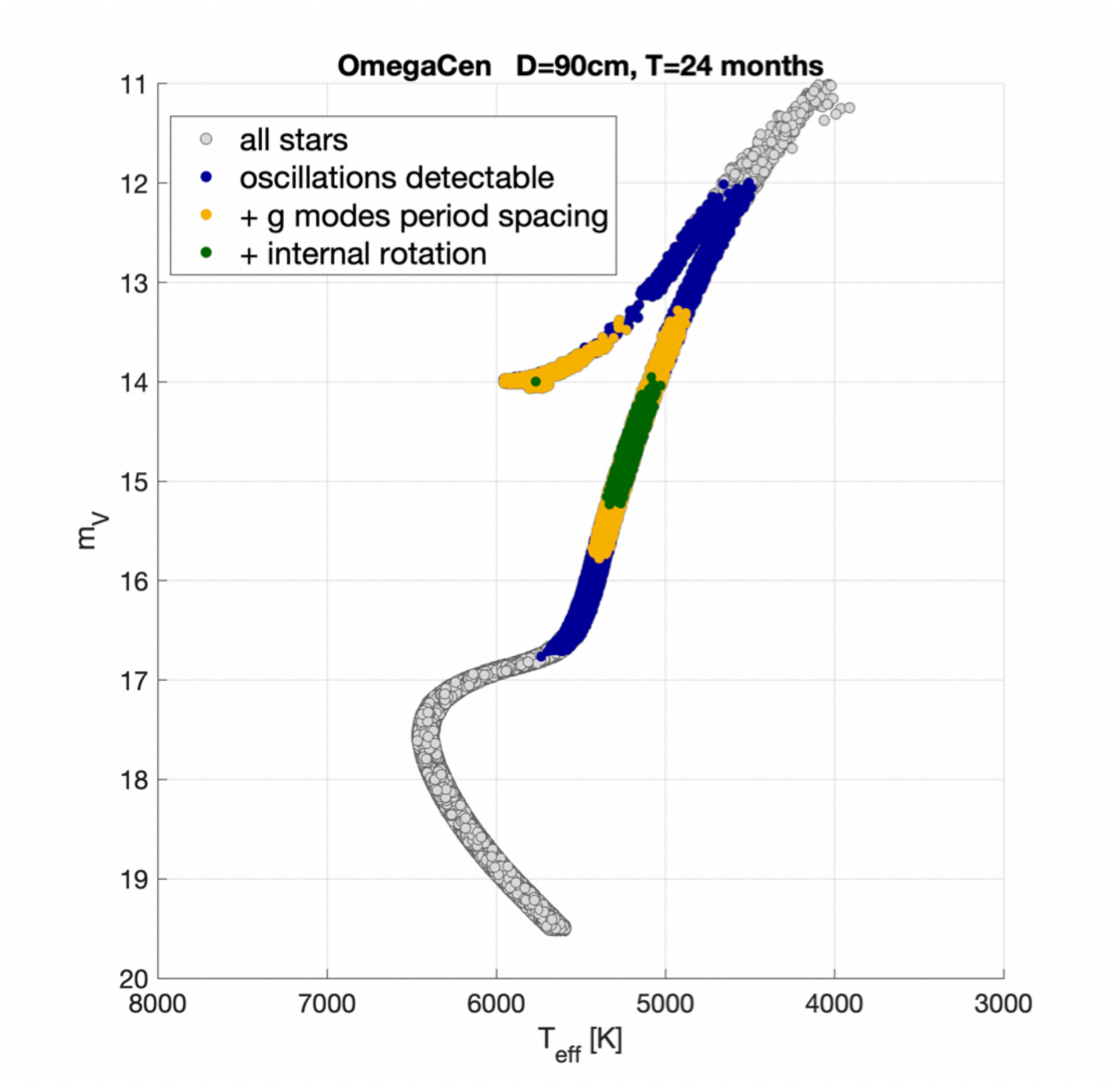


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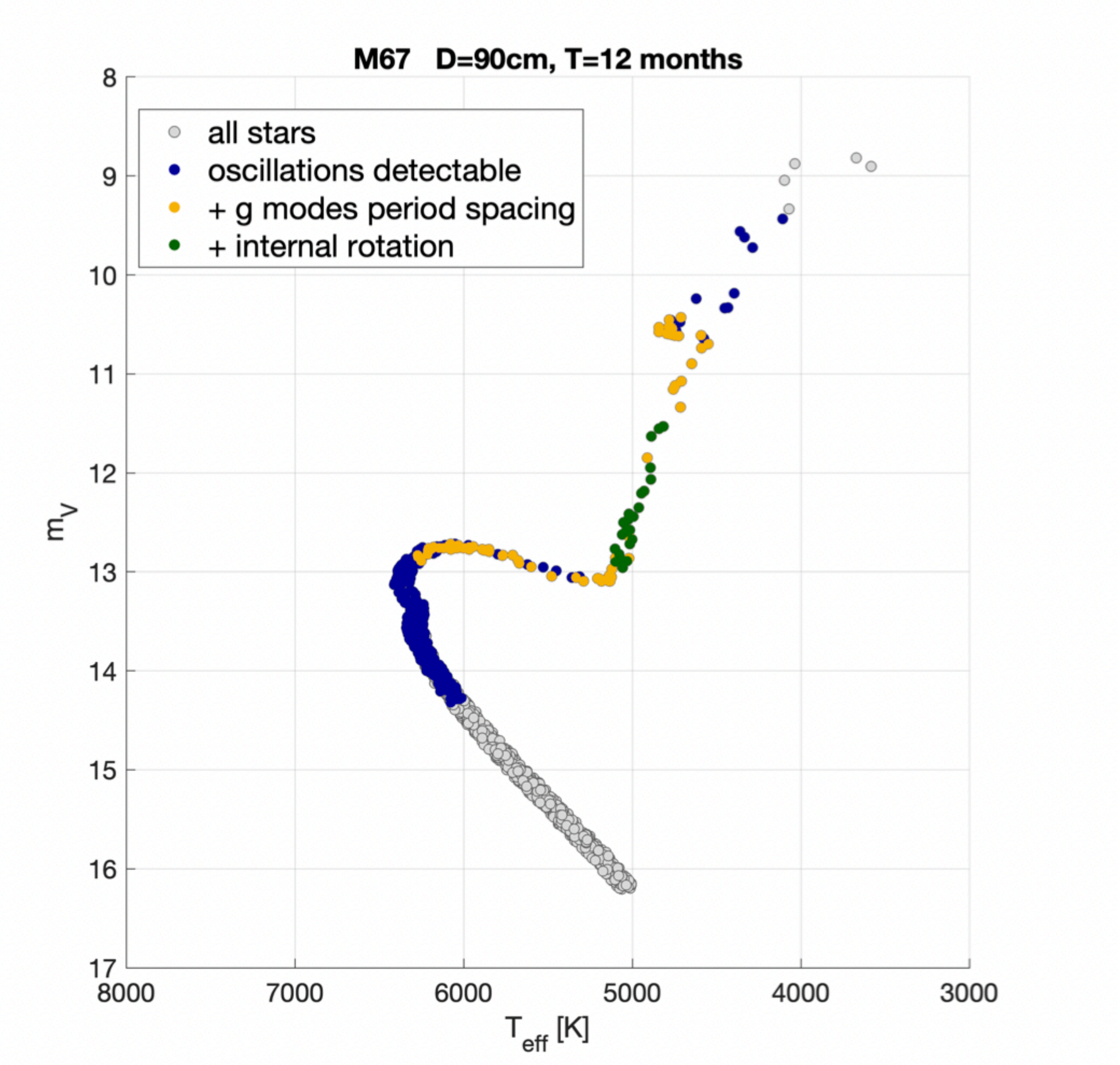
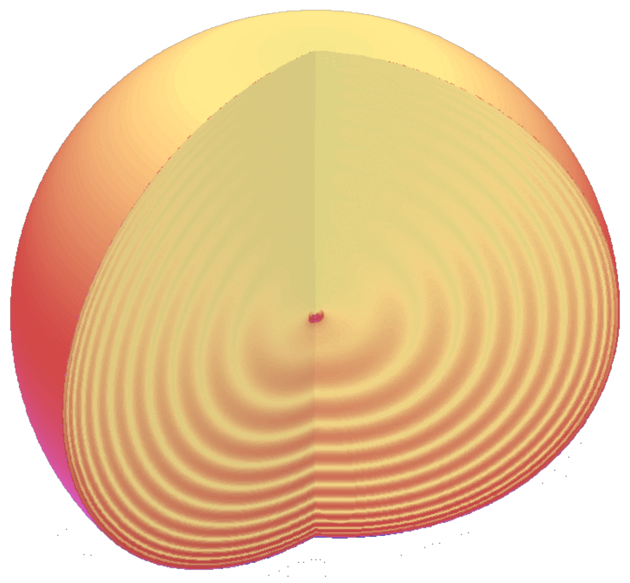



all science objectives achievable with D=90 cm and a combination of 6-24 months-long runs

# PART2: SUMMARY

- relevance and potential of asteroseismology demonstrated by CoRoT, *Kepler*



- ultimate tool to tests stellar physics
- infer precise, accurate ages

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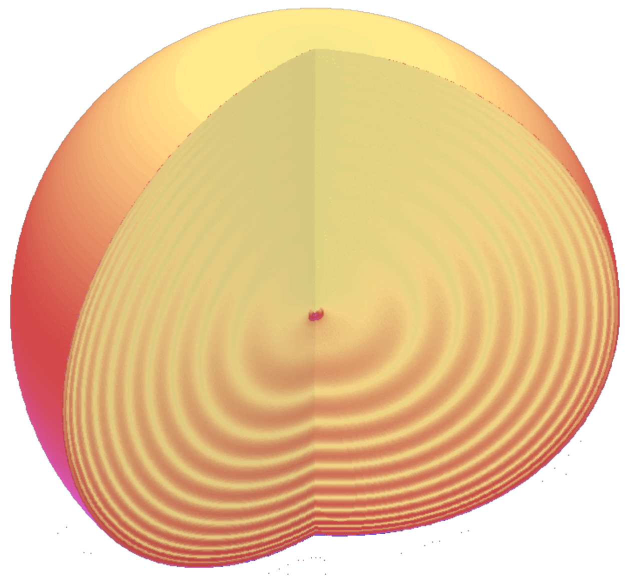

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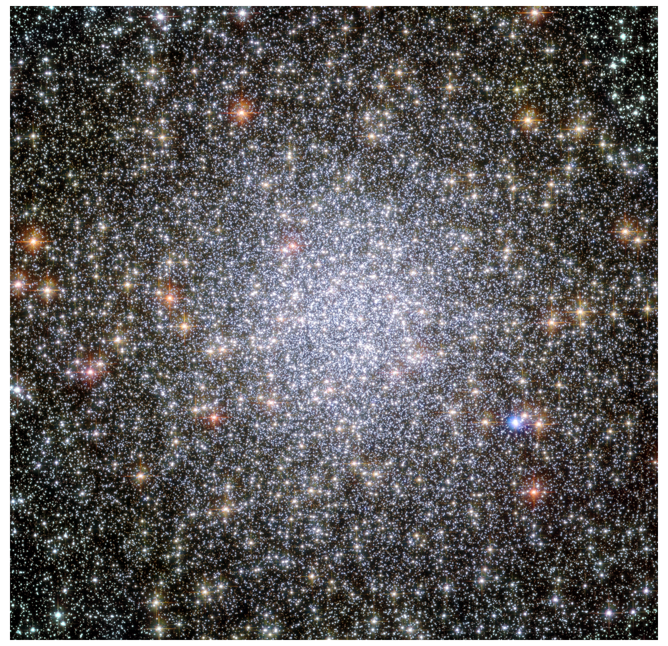
- simple mission concept would overcome limitations of past/current/planned missions



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SG2 evolution and formation of stellar clusters

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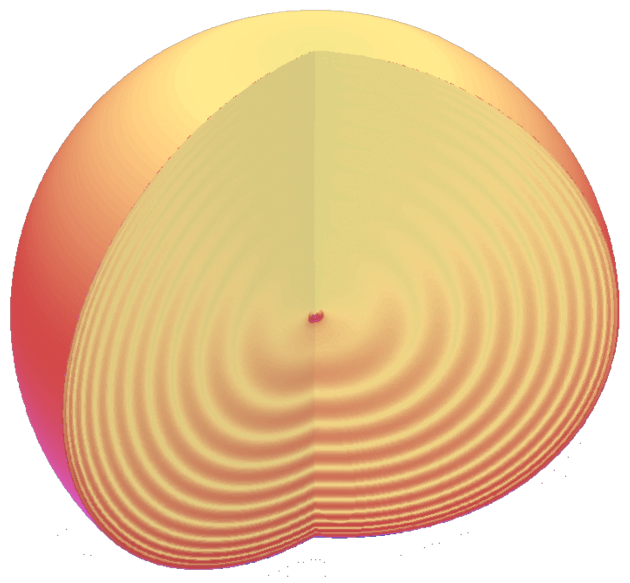

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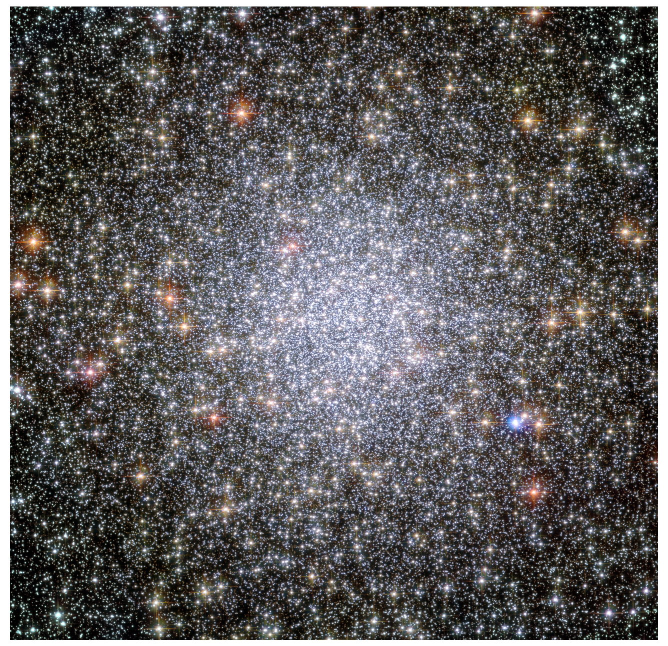
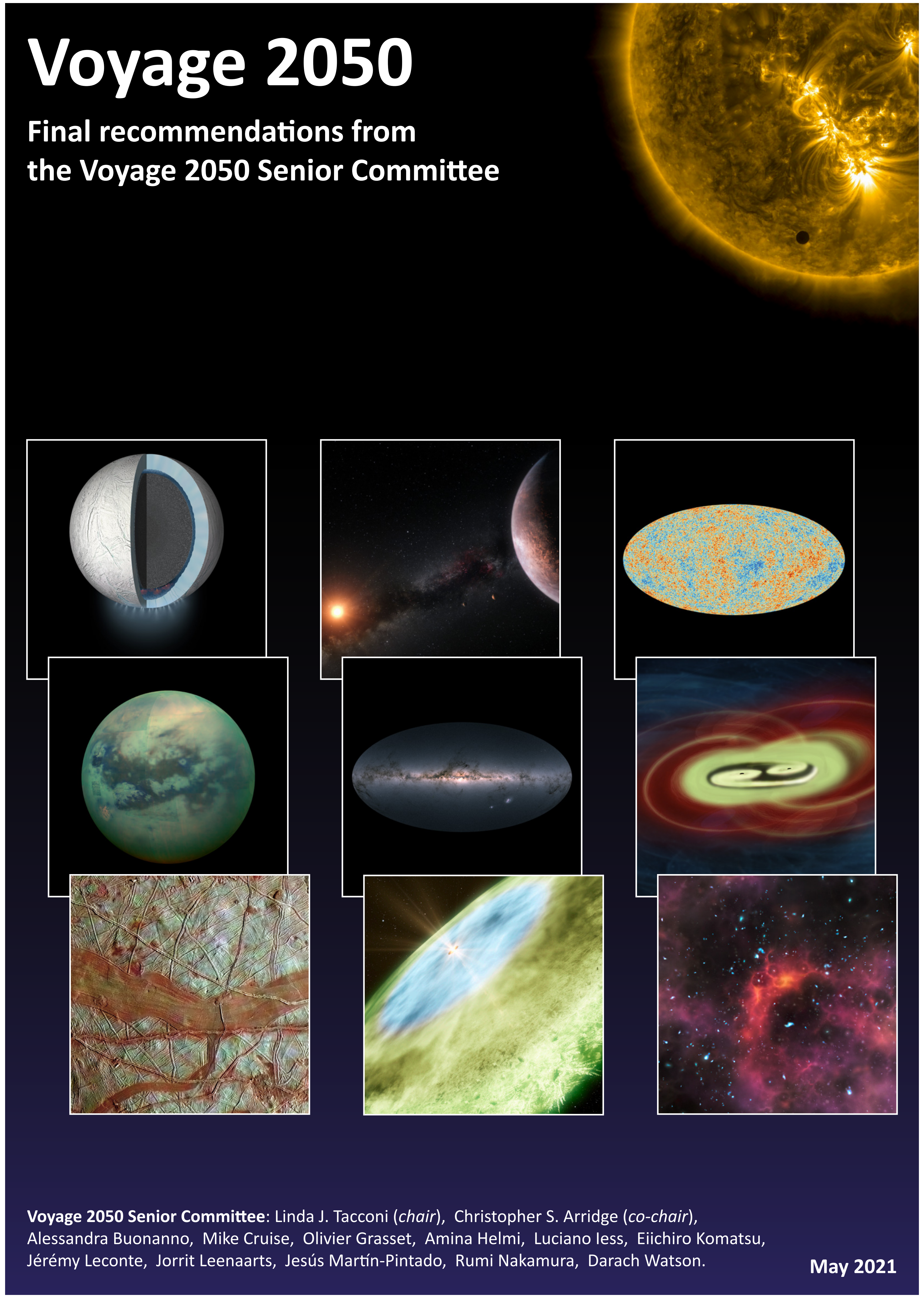


SG1 high-precision stellar astrophysics

SG2 evolution and formation of stellar clusters

SG3 assembly history of the Milky Way's bulge and dwarf galaxies.

⇨ promote development of the next generation of stellar models





SCIENCE & EXPLORATION

# Voyage 2050 sets sail: ESA chooses future science mission themes

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## 3 Potential Scientific Themes for Medium Missions

### 3.1.8 High Precision Asteroseismology

Asteroseismology is one of the most powerful tools for probing the structure of stars. It uses the variability of the light from the star produced by its pulsation modes to constrain the interiors of stars. Its final aim is to determine the physical properties and the internal structure of stars, such as how temperature, pressure, density, speed of sound, and chemical composition vary with radius. In the last decade, the research field of asteroseismology has experienced a revolution with the operation of several space missions whose main aim has been the detection of exoplanets, for example *Kepler*.

A Medium mission designed to carry out pure asteroseismology would characterise stars in a wider range of (relatively homogeneous) stellar environments such as dwarf galaxies or the Galactic bulge, as well as Red Giant Branch stars that are relatively close to the Sun. Such missions would provide key information on stellar physics that would allow testing of stellar evolution models, especially when 2-D and 3-D modelling become widely implemented. Furthermore, and in combination with *Gaia* and large ground-based spectroscopic surveys, they would provide new insights into the star formation history and different phases of the assembly of the Milky Way.

# haydn

high-precision asteroseismology in dense stellar fields

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thanks to:

*Frank Grundahl*
*Benoit Mosser*
*Nate Bastian*
*Angela Bragaglia*
*Karsten Brogaard*
*Gaël Buldgen*
*William Chantereau*
*Bill Chaplin*
*Cristina Chiappini*
*Marc-Antoine Dupret*
*Patrick Eggenberger*
*Mark Gieles*
*Rob Izzard*
*Daisuke Kawata*
*Christoffer Karoff*
*Nadege Lagarde*
*Ted Mackereth*
*Demetrio Magrin*
*Georges Meynet*
*Eric Michel*
*Josefina Montalbán*
*Valerio Nascimbeni*
*Arlette Noels*
*Giampaolo Piotto*
*Roberto Ragazzoni*
*Igor Soszynski*
*Eline Tolstoy*
*Silvia Toonen*
*Amaury Triaud*
*Fiorenzo Vincenzo*

ASTERO CHRONOMETRY
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
erc European Research Council
Established by the European Commission
INAF ISTITUTO NAZIONALE DI ASTROFISICA
INTERNATIONAL SPACE SCIENCE INSTITUTE
UNIVERSITY OF BIRMINGHAM SCHOOL OF PHYSICS AND ASTRONOMY