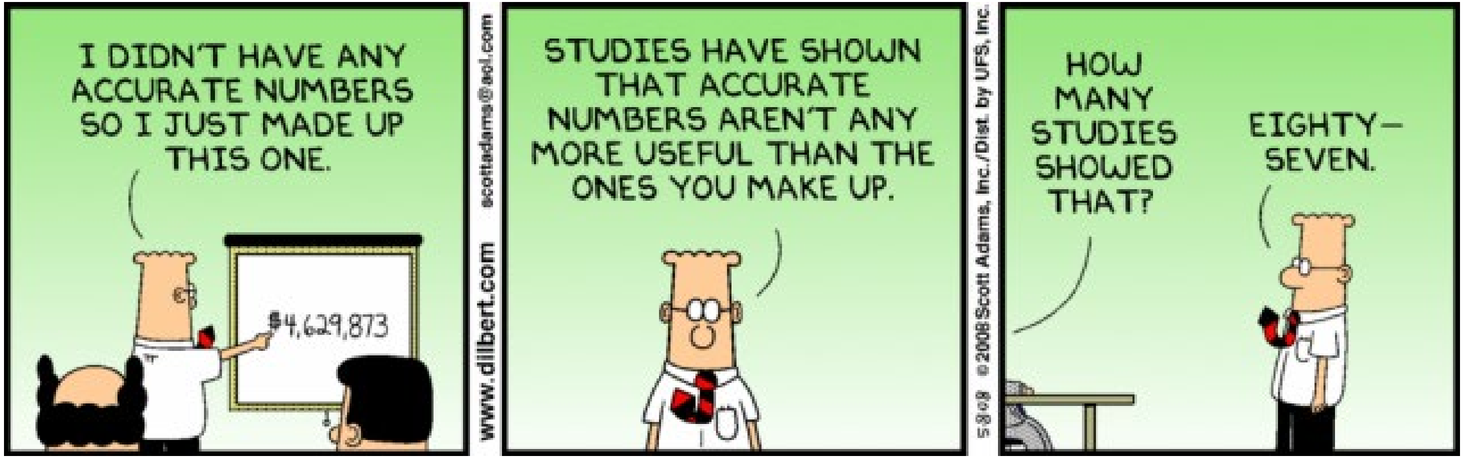


# Precision and accuracy of stellar age estimates

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European Research Council
Established by the European Commission

ASTERO CHRONOMETRY

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

# Outline

- (Some) methods for age estimation for stars
- Methods for age accuracy estimation of (some) stars
- Basics:
  Colour-magnitude diagrams
  Detached eclipsing binary stars
  Asteroseismology of solar-like oscillators
- Examples of combinations
- A few words on Machine Learning methods
- Haydn
- Summary & Conclusions

# (some) methods for age estimation for stars

$M + [Fe/H] + [X/Fe] \Rightarrow L(t)\ ,\ T_{eff}(t),\ R(t)$

"Primary"
Colour-magnitude diagrams of star clusters
Detached eclipsing binary stars
Asteroseismology

"Secondary"
Gyrochronology
Chemical clocks [Y/Mg], A(Li), [C/N] +others – talk by Giada Casali today
Machine learning using "features"

Note also the invited talk by J. Meynet later today!

# Methods for age accuracy estimation of stars

1) Comparison to model-independent estimates

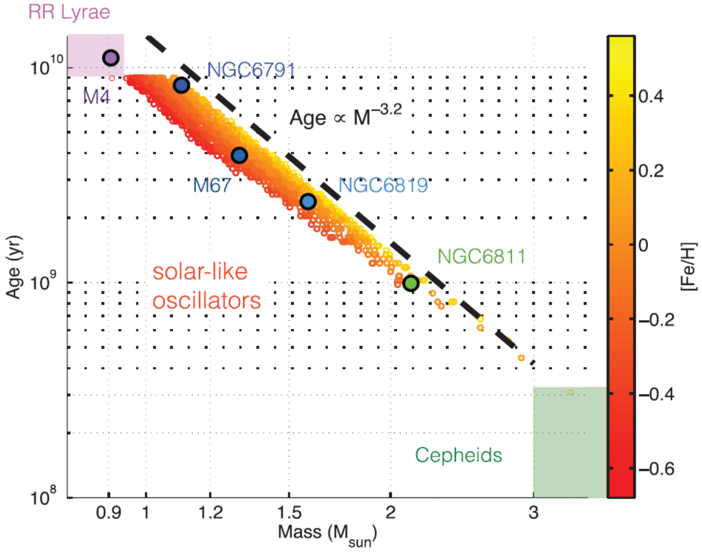
..but few exist for age! For the Sun we used the independent estimate already.

2) Self-consistency tests

One should get the same age (within statistical uncertainties) using

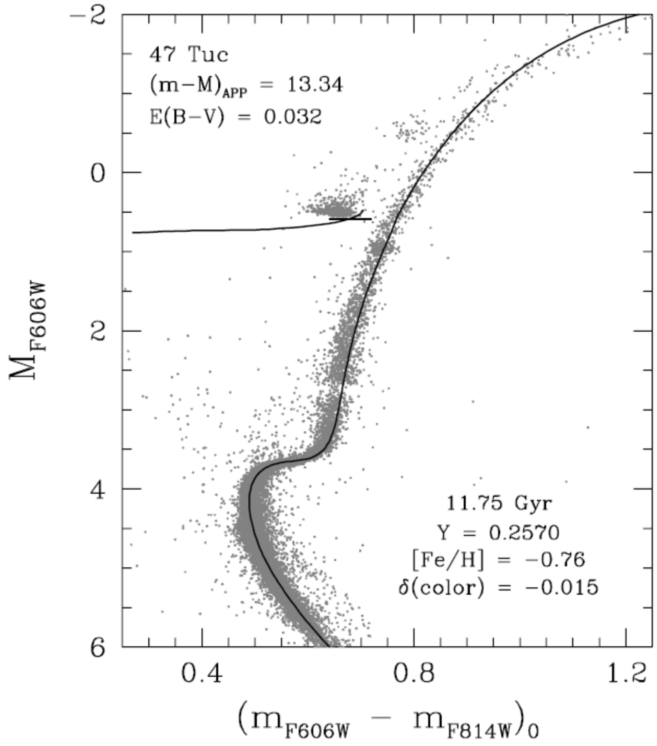
- different methods
- different constraints
- ensembles

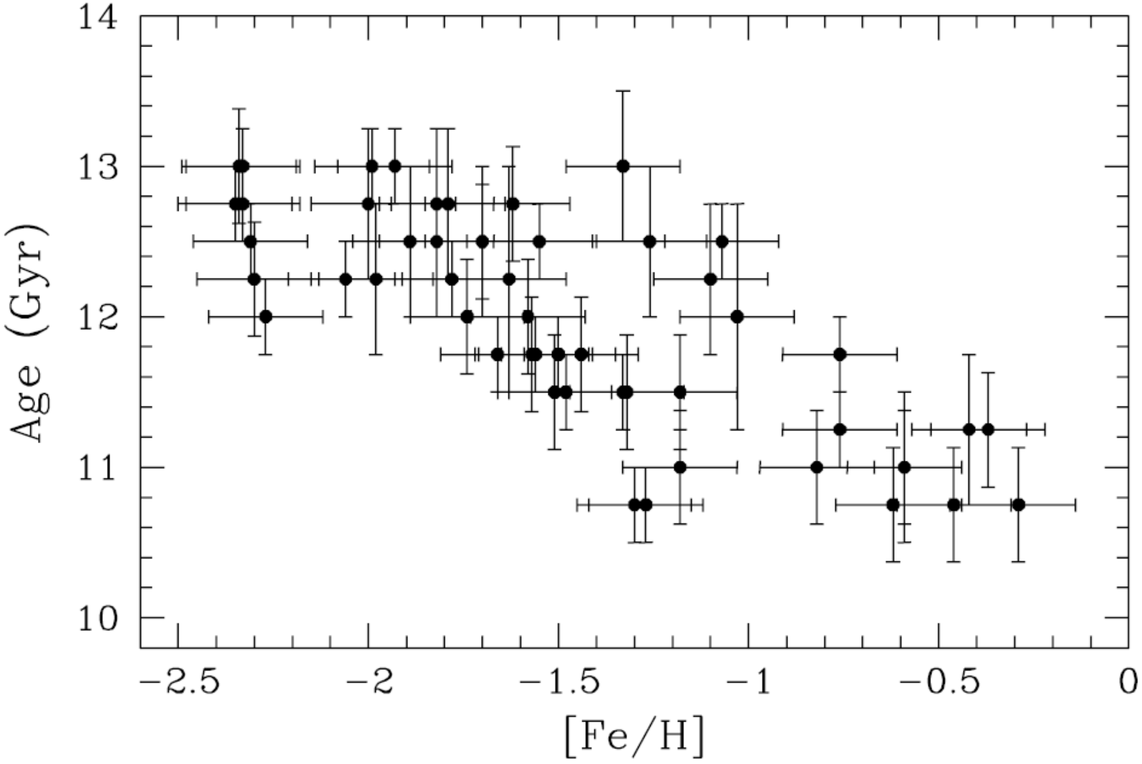
This does not gurantee that that the age is correct.




Miglio et al. (2017)

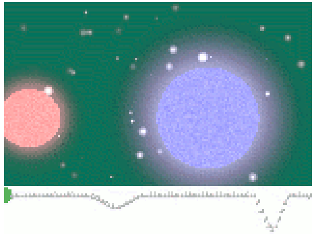
# Colour-magnitude diagrams of star clusters

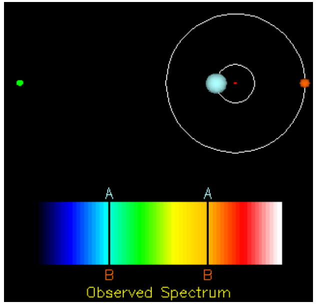


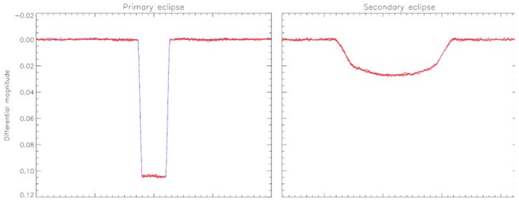



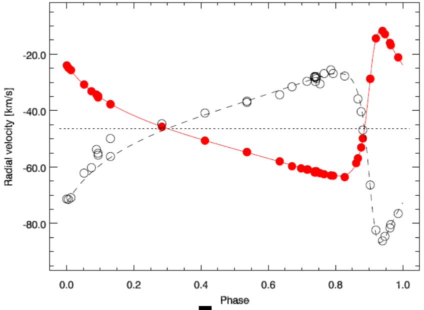

VandenBerg, Brogaard, Leaman & Casagrande (2013)

# Detached eclipsing binary measurements






$[Fe/H]$

$T_{\rm eff}$

$\log g$

$L, d$

$R_{1,2}/a$

$i$

$P$

$+$

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

$a \sin i$

$=$

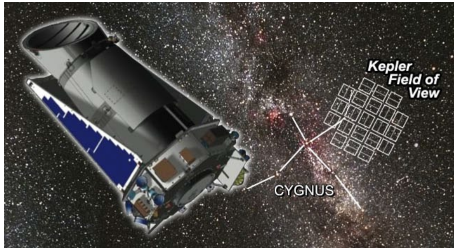
$M_{1,2}$

$R_{1,2}$

# Asteroseismology of solar-like oscillators

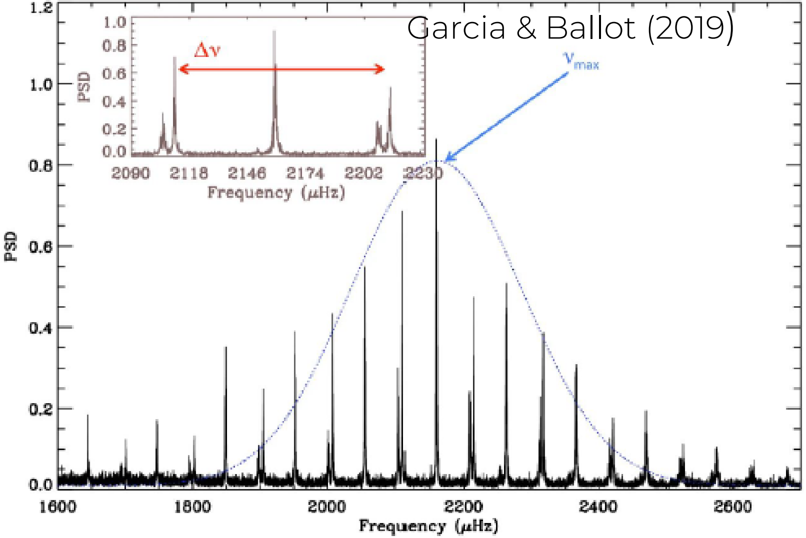
$$\frac{\Delta\nu}{\Delta\nu_\odot} \approx f_{\Delta\nu}\left(\frac{\rho}{\rho_\odot}\right)^{0.5},$$

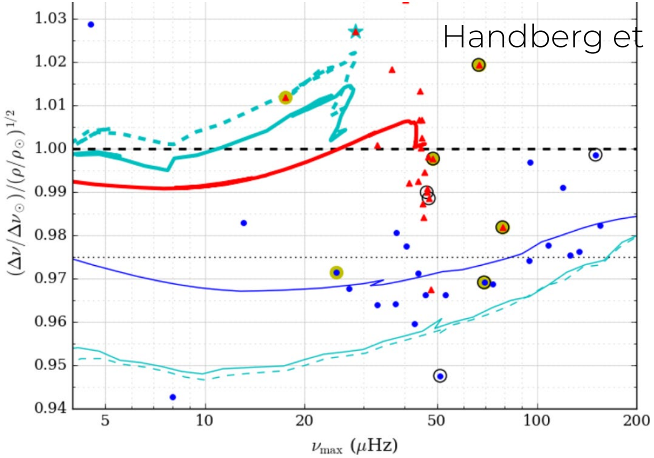
$$\frac{\nu_{\max}}{\nu_{\max,\odot}} \approx f_{\nu_{\max}}\frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-0.5}$$




$$\frac{M}{M_\odot} \approx \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\,\nu_{\max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{f_{\Delta\nu}\,\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5}$$

$$\frac{R}{R_\odot} \approx \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\,\nu_{\max,\odot}}\right)\left(\frac{\Delta\nu}{f_{\Delta\nu}\,\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5}.$$

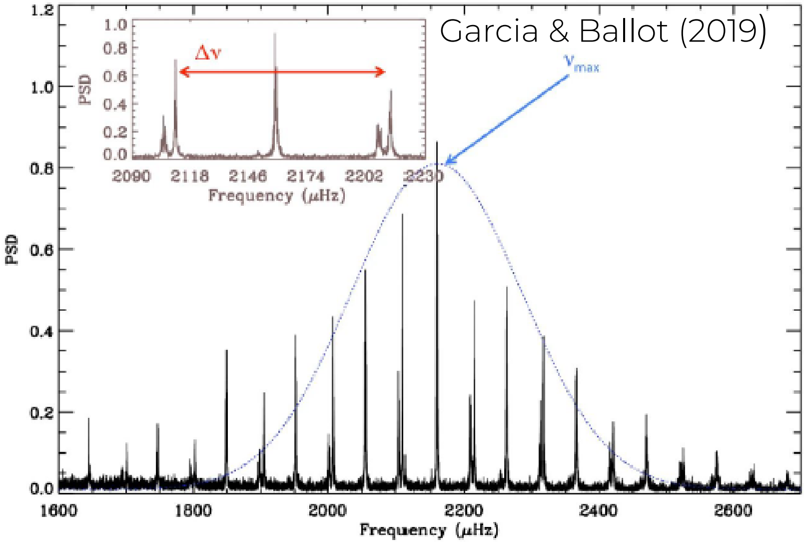


# Asteroseismology+Gaia

$$\frac{\Delta\nu}{\Delta\nu_\odot} \approx f_{\Delta\nu}\left(\frac{\rho}{\rho_\odot}\right)^{0.5},$$

$$\frac{\nu_{\max}}{\nu_{\max,\odot}} \approx f_{\nu_{\max}}\frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-0.5}$$



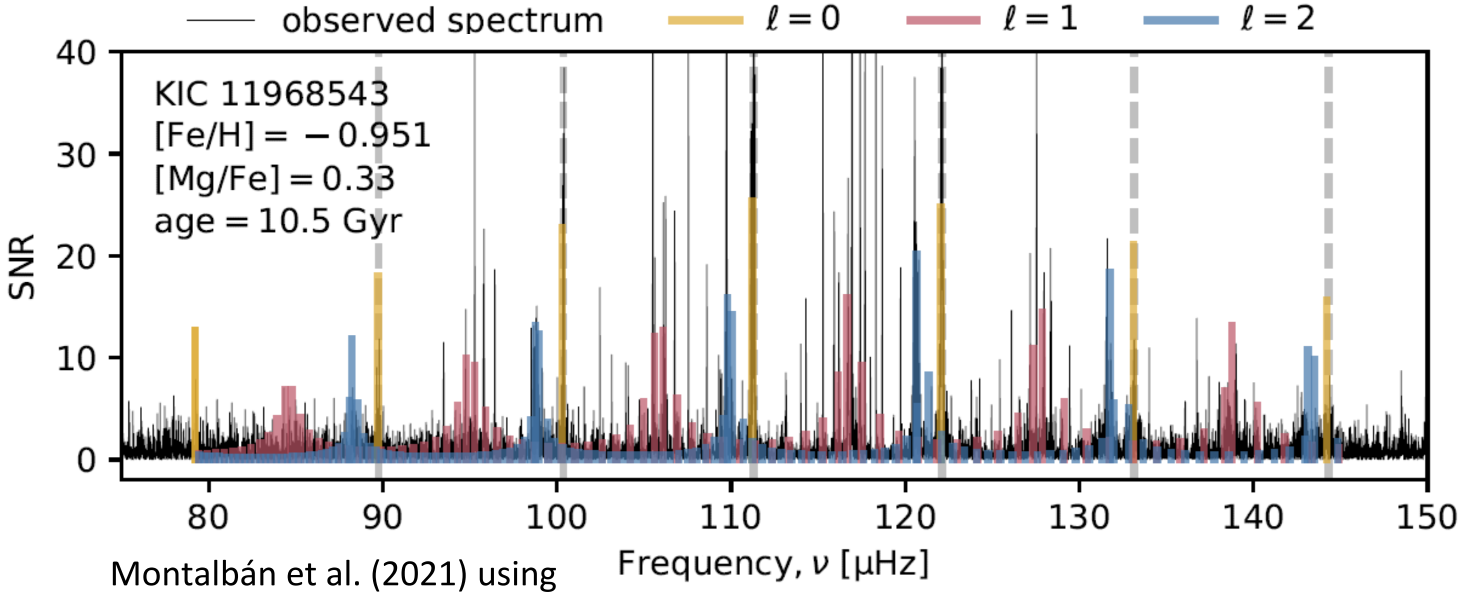

$$\frac{M}{M_\odot} \approx \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\,\nu_{\max,\odot}}\right)^3\left(\frac{\Delta\nu}{f_{\Delta\nu}\,\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5}$$

$$\frac{R}{R_\odot} \approx \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\,\nu_{\max,\odot}}\right)\left(\frac{\Delta\nu}{f_{\Delta\nu}\,\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5}.$$

$$\left\{\begin{array}{l}
\frac{M}{M_\odot} = \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\nu_{\max,\odot}}\right)^3\left(\frac{\Delta\nu}{f_{\Delta\nu}\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}, \\
\frac{M}{M_\odot} = \left(\frac{\Delta\nu}{f_{\Delta\nu}\Delta\nu_\odot}\right)^2\left(\frac{L}{L_\odot}\right)^{3/2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-6}, \\
\frac{M}{M_\odot} = \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\nu_{\max,\odot}}\right)\left(\frac{L}{L_\odot}\right)\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-7/2}, \\
\frac{M}{M_\odot} = \left(\frac{\nu_{\max}}{f_{\nu_{\max}}\nu_{\max,\odot}}\right)^{12/5}\left(\frac{\Delta\nu}{f_{\Delta\nu}\Delta\nu_\odot}\right)^{-14/5}\left(\frac{L}{L_\odot}\right)^{3/10}.
\end{array}\right.$$

See Poster **27** by K. Brogaard et al. for an example

# Asteroseismology – modelling absolute frequencies




Montalbán et al. (2021) using
AIMS: Asteroseismic Inference on a Massive Scale (Reese 2016)

Talk by Josefina Montalbán today:
New view of Galactic discs : unveiling precise ages with individual oscillation modes

# NGC6791: Likely the most precise age estimate of an old open cluster

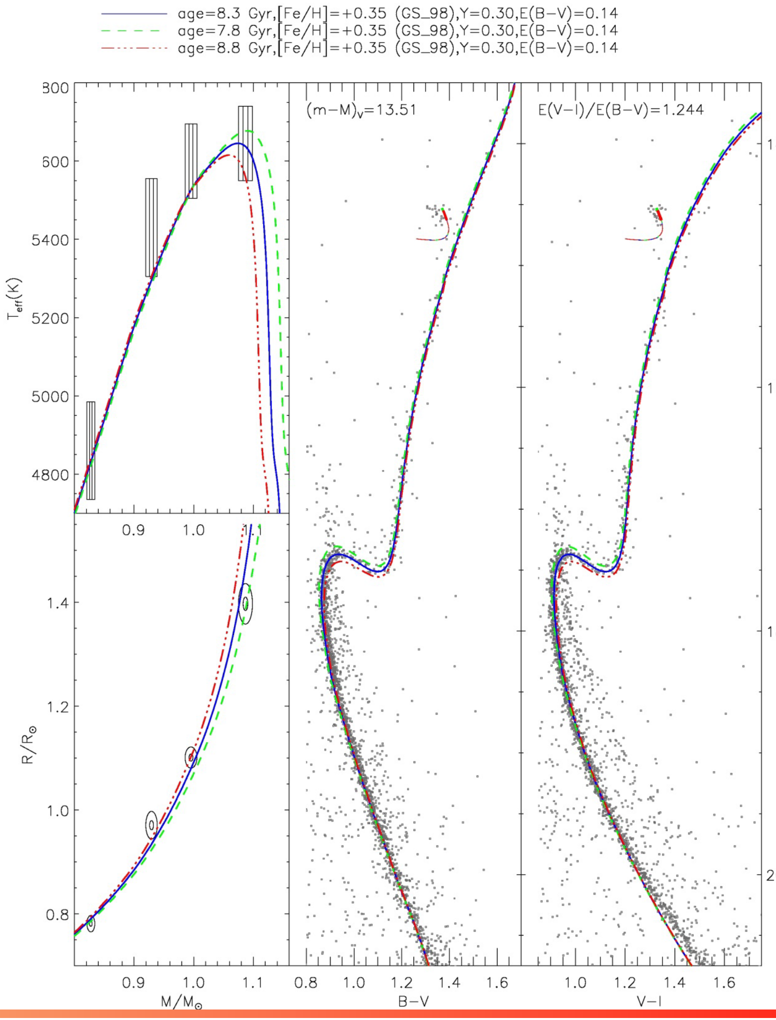
Brogaard et al. (2012):

Two dEBs + CMDs

Helium content constrained!
Main age uncertainty is now abundances

Isochrones in the CMDs is not a fit except at binary locations

Later supported by analysis of eclipsing system with a giant component (Brogaard et al. 2014) and non-eclipsing binary with a subgiant component (Brogaard et al. 2021)



# NGC6791:
# Also the first tests of asteroseismology!

dEBs + CMDs (without Kepler!):

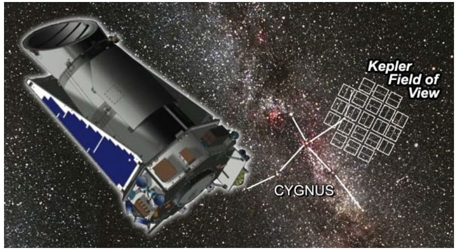
M_RGB=1.15±0.02
(Brogaard et al. 2012)

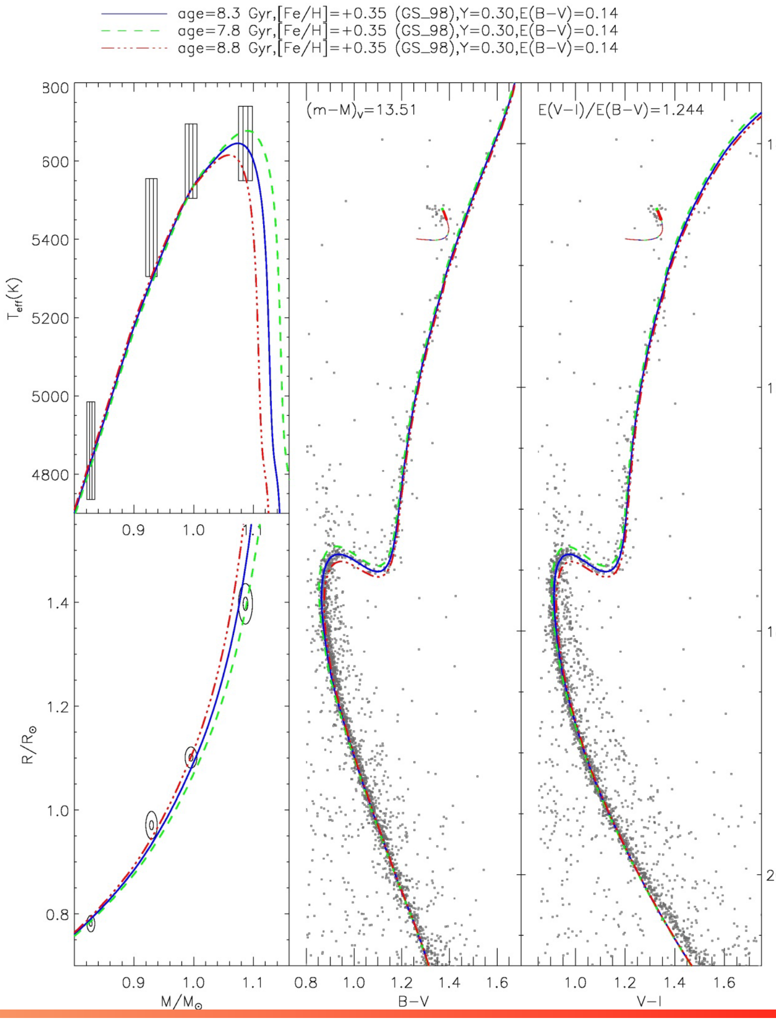
Asteroseismology of red giants:

M_RGB=1.20±0.01
(Basu et al. 2011)

M_RGB=1.22±0.02
(Miglio et al. 2012)

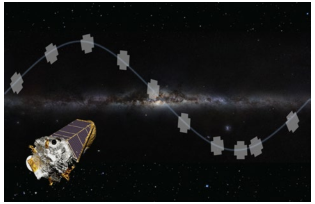
Significantly higher!

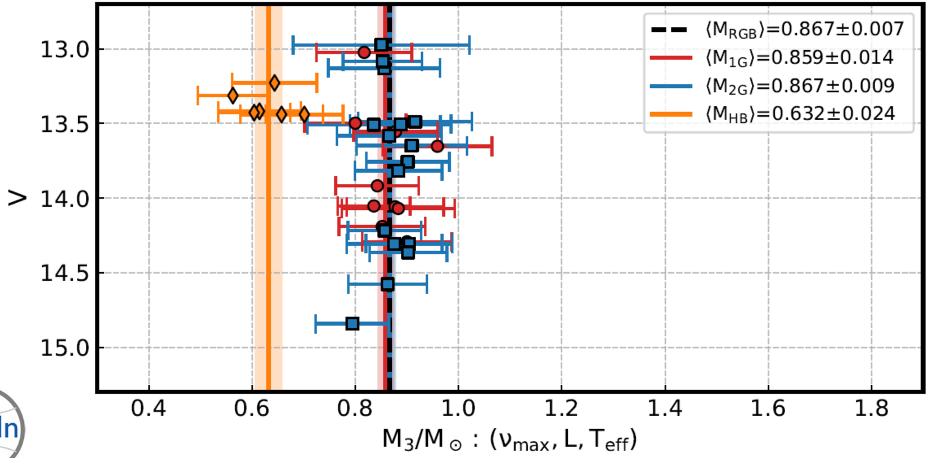


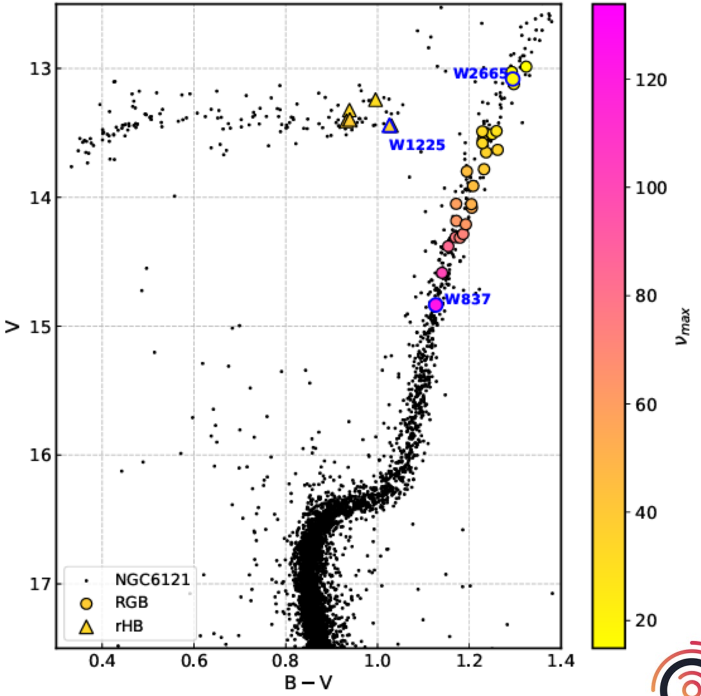



# Globular cluster M4

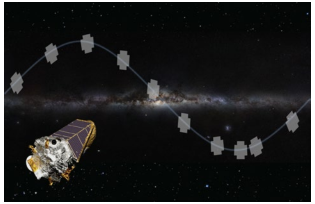
Miglio et al. (2016)
Tailo et al. (2022)





# Ruprecht 147

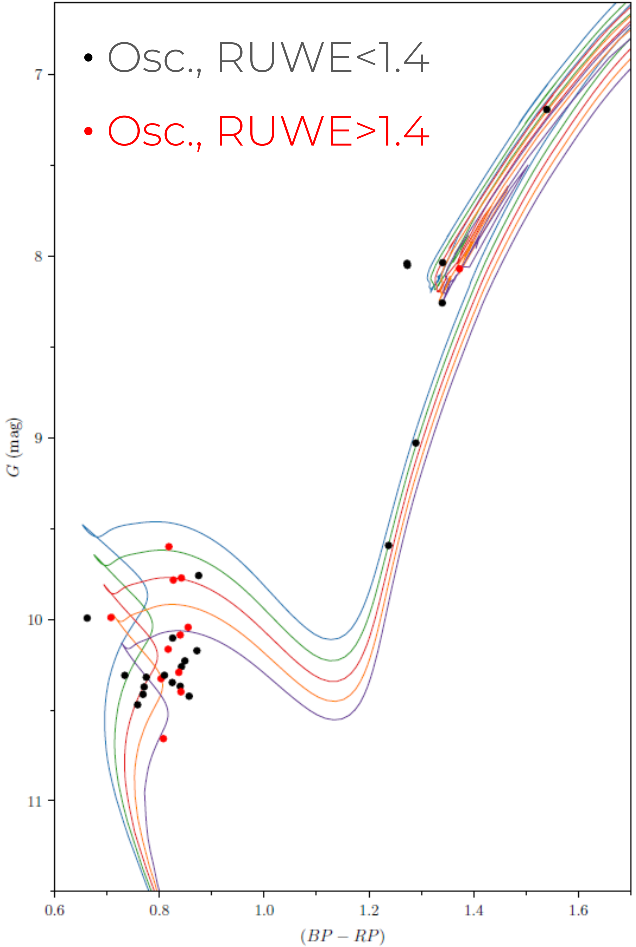


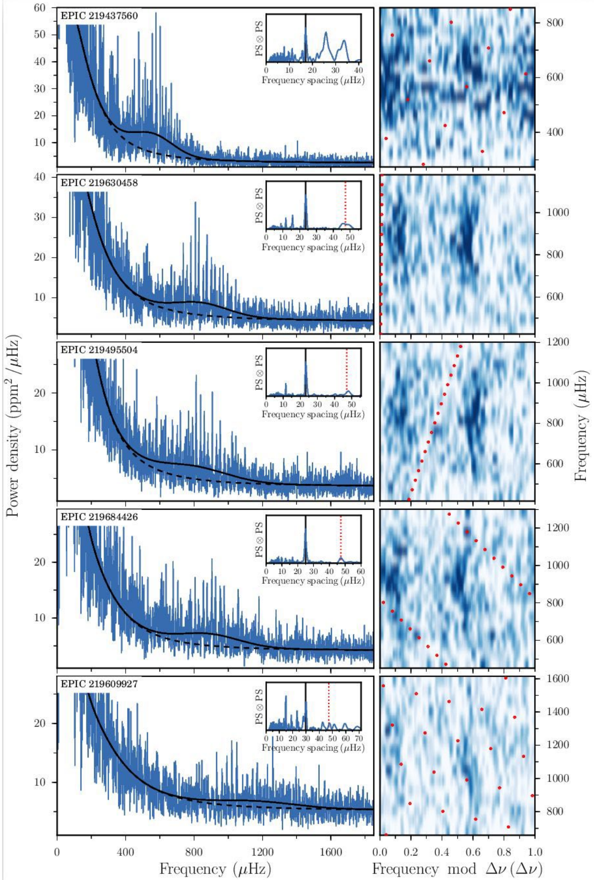
Lund et al., in prep.
K2 mission data

33 oscillating cluster members covering the MS-SGB-RGB

Spectroscopy from MIKE, TRES, UVES, and GIRAFFE observations

4 known EBs in cluster!

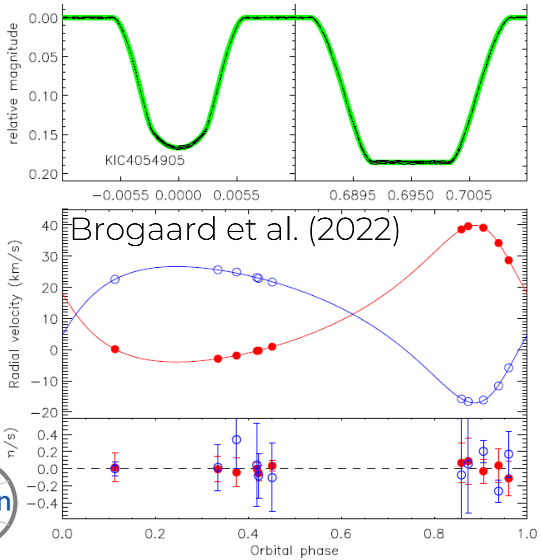


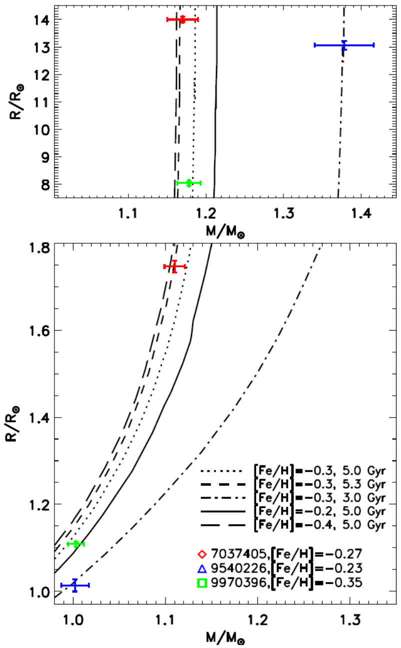



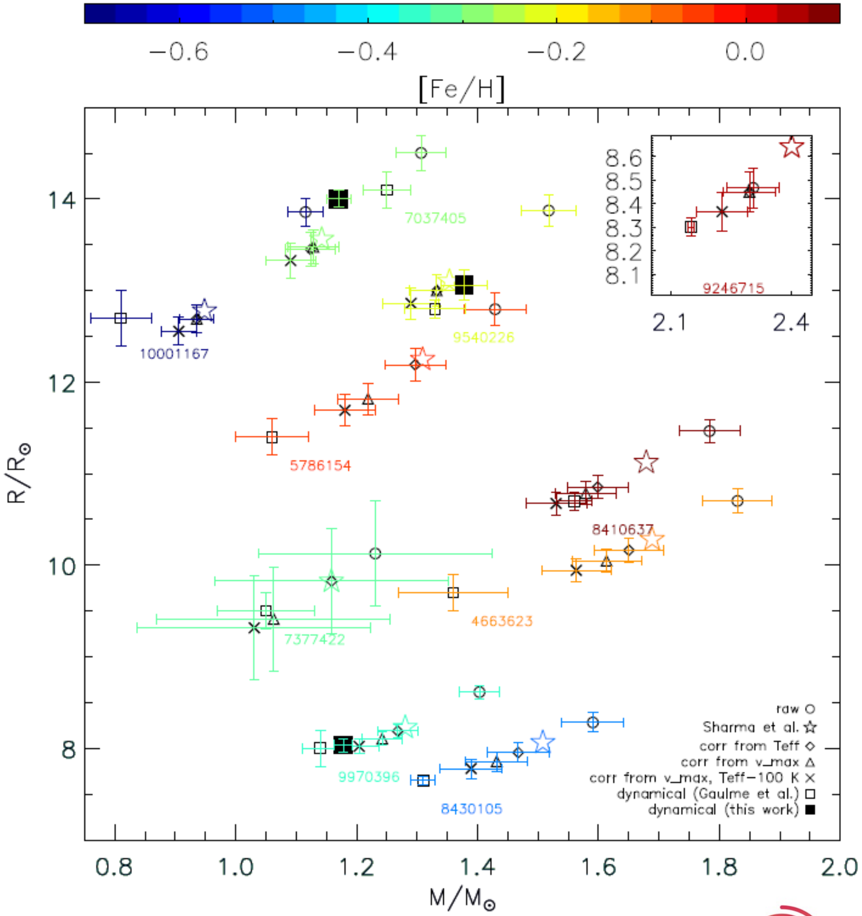

See also poster **9** by Lorenzo Briganti for future work on clusters to be observed by PLATO

# Dynamical vs asteroseismic scaling mass and radius

**KIC 4054905, an eclipsing binary with two 10 Gyr thick disk RGB stars**



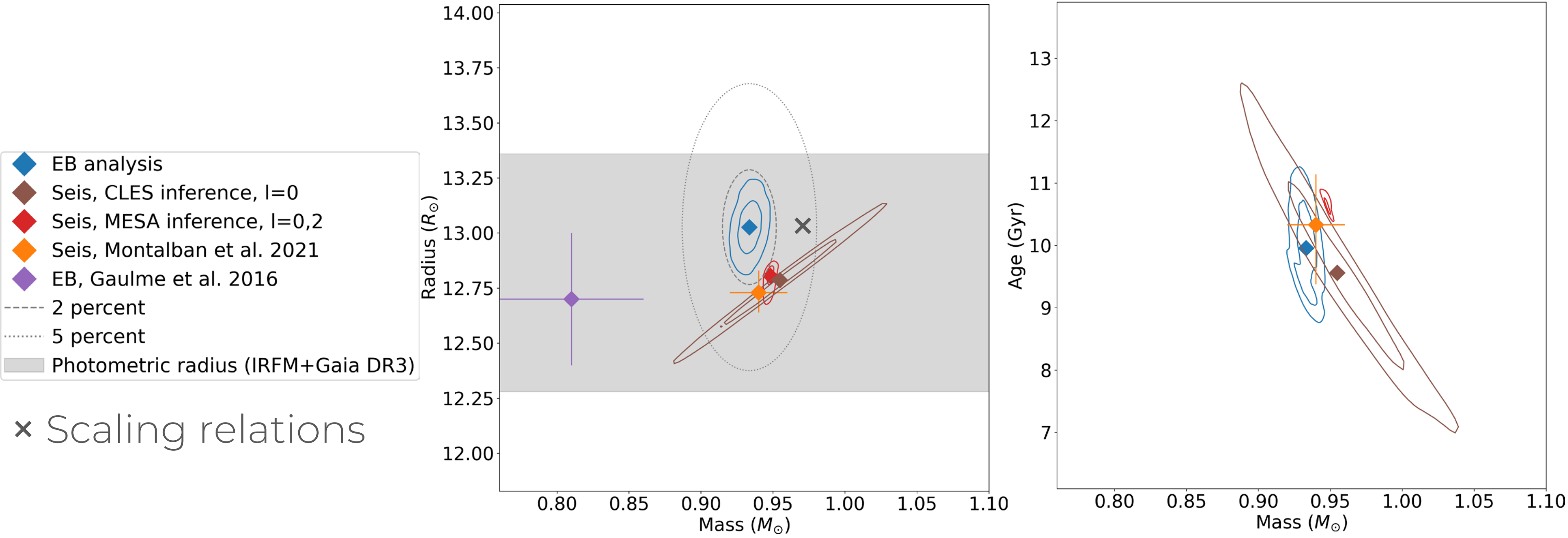



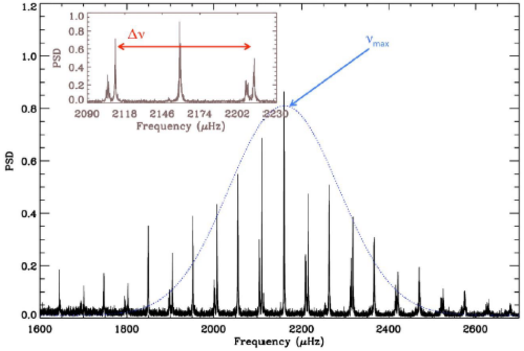

Brogaard et al. (2018)

See also Thomsen et al. (2021), Gaulme et al. (2016), Frandsen et al. (2013), Benbakoura et al. (2021), Themessl et al. (2018)

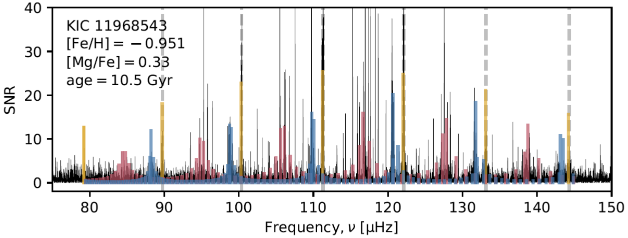
# KIC10001167: Poster **25** by Jeppe S. Thomsen

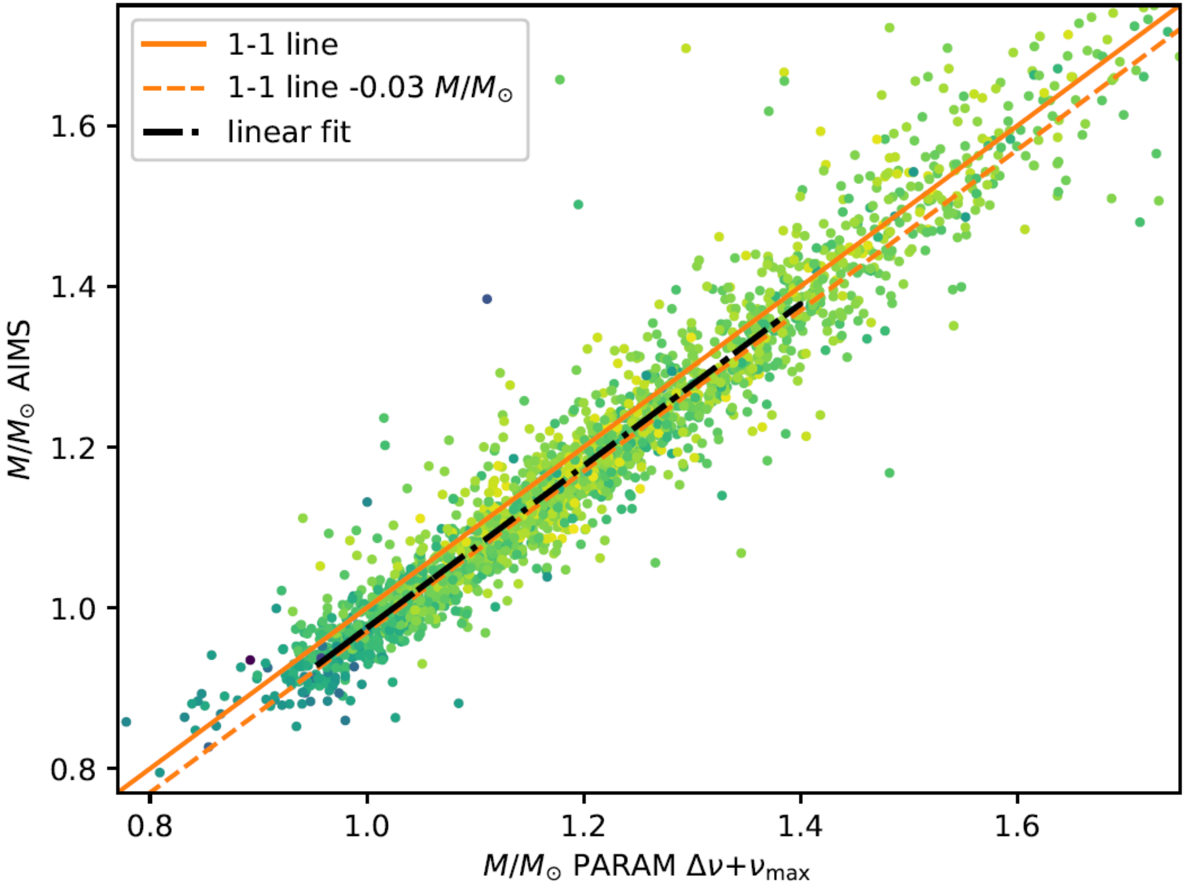


# PARAM vs AIMS




VS



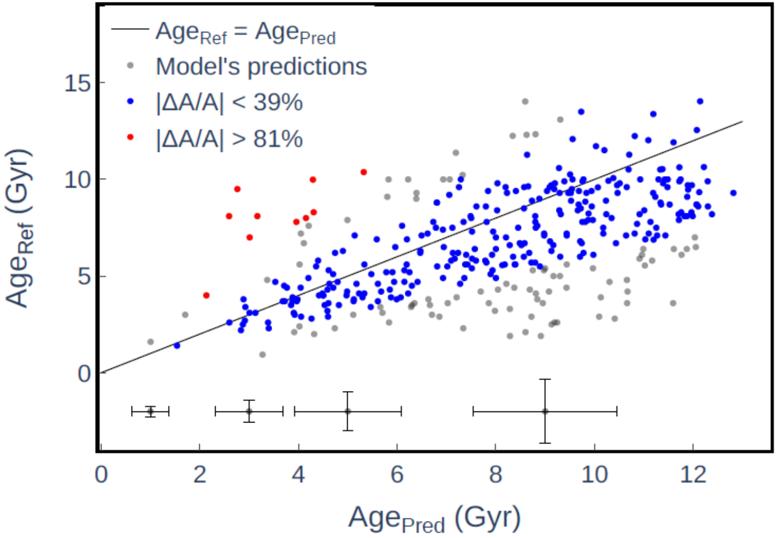




Sources: Willett et al. in prep. (PARAM), Montalbán et al. in prep. (AIMS)

# Machine Learning

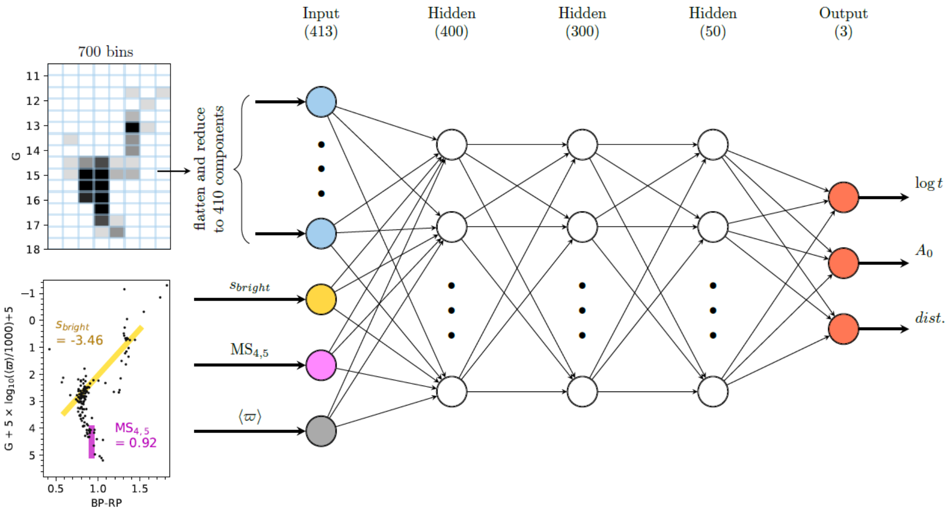
**A catalogue of asteroseismically calibrated ages for APOGEE DR17**

**The predictions of a CatBoost machine learning model based on the [Mg/Ce] chemical clock and other stellar parameters**★




Boulet (2024)

**Painting a portrait of the Galactic disc with its stellar clusters**



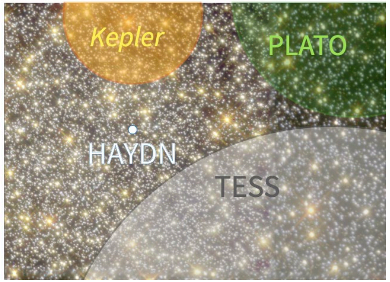

Cantat-Gaudin (2022)

# haydn

high-precision asteroseismology in dense stellar fields


Miglio, Girardi, Mosser et al. 2021

https://www.asterochronometry.eu/haydn




| | |
|---|---|
| SG1 | high-precision stellar astrophysics |
| SG2 | evolution and formation of stellar clusters |
| SG3 | assembly history of the Milky Way's bulge and dwarf galaxies |
| SG4 | dependence of the occurrence rate of exoplanets on the environment |

# Conclusions and outlook

Self-consistency tests indicate that a mass accuracy of <2% is reachable for the very best cases of asteroseismology of solar-like oscillators.

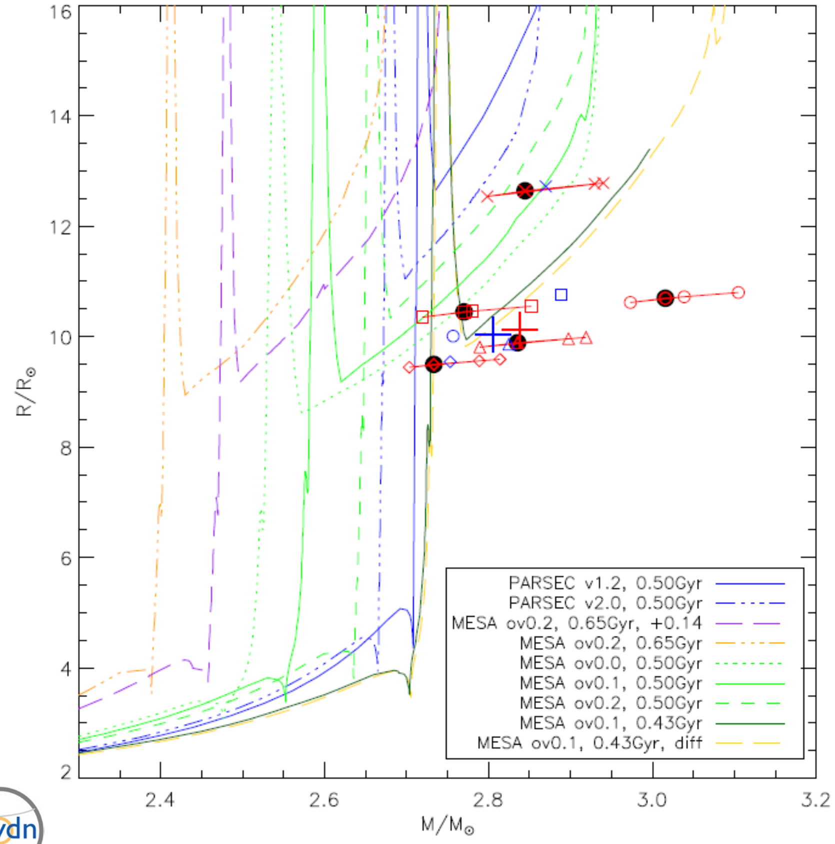
Comparisons between global asteroseismology and detailed frequency modelling for red giant stars show a mass-offset of ~0.03 Msun, suggesting that accuracy can also be calibrated for global asteroseismology.

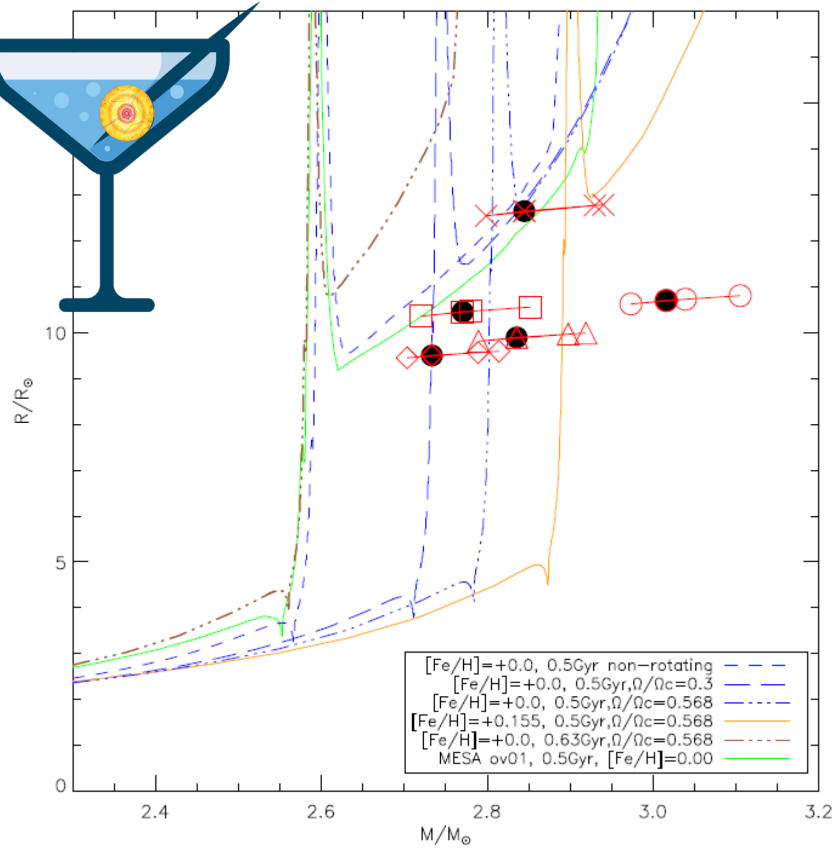
Uncertainties for secondary age indicators are much larger!

Much more work on binary stars and star clusters is needed and on-going.

For the next big leap forward, we need Haydn:
http://www.asterochronometry.eu/haydn/

# NGC6866: New insights into core-overshoot and rotation

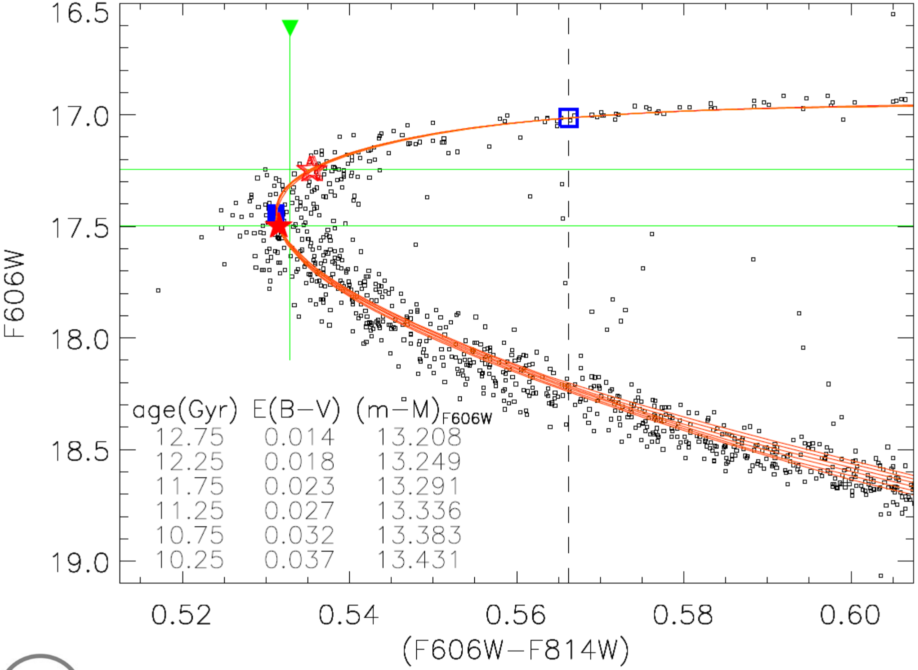


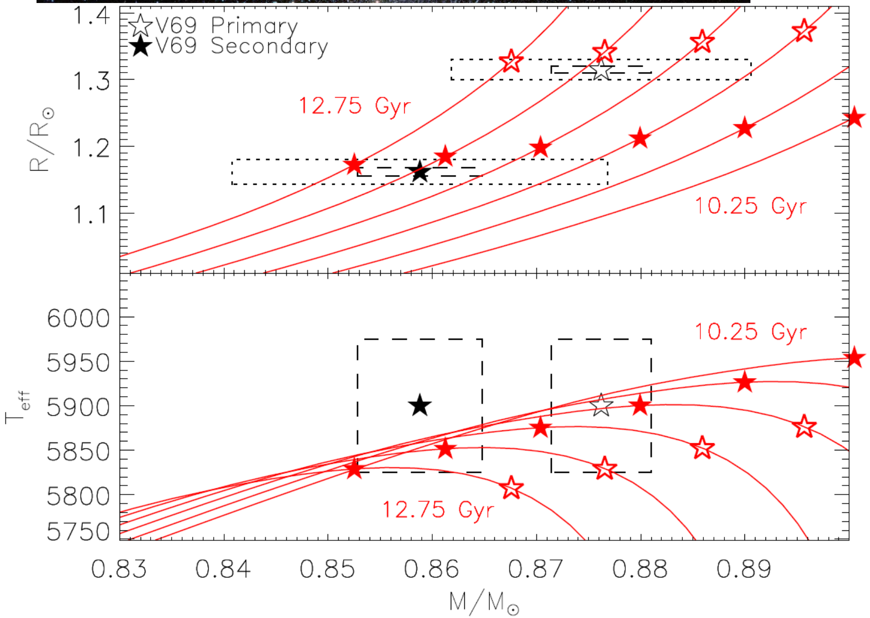




Brogaard et al. (2023)

Additional relevant works: Hyades: Brogaard et al. (2021), NGC6633: Brogaard et al. (submitted)

# V69 in 47 Tucanae

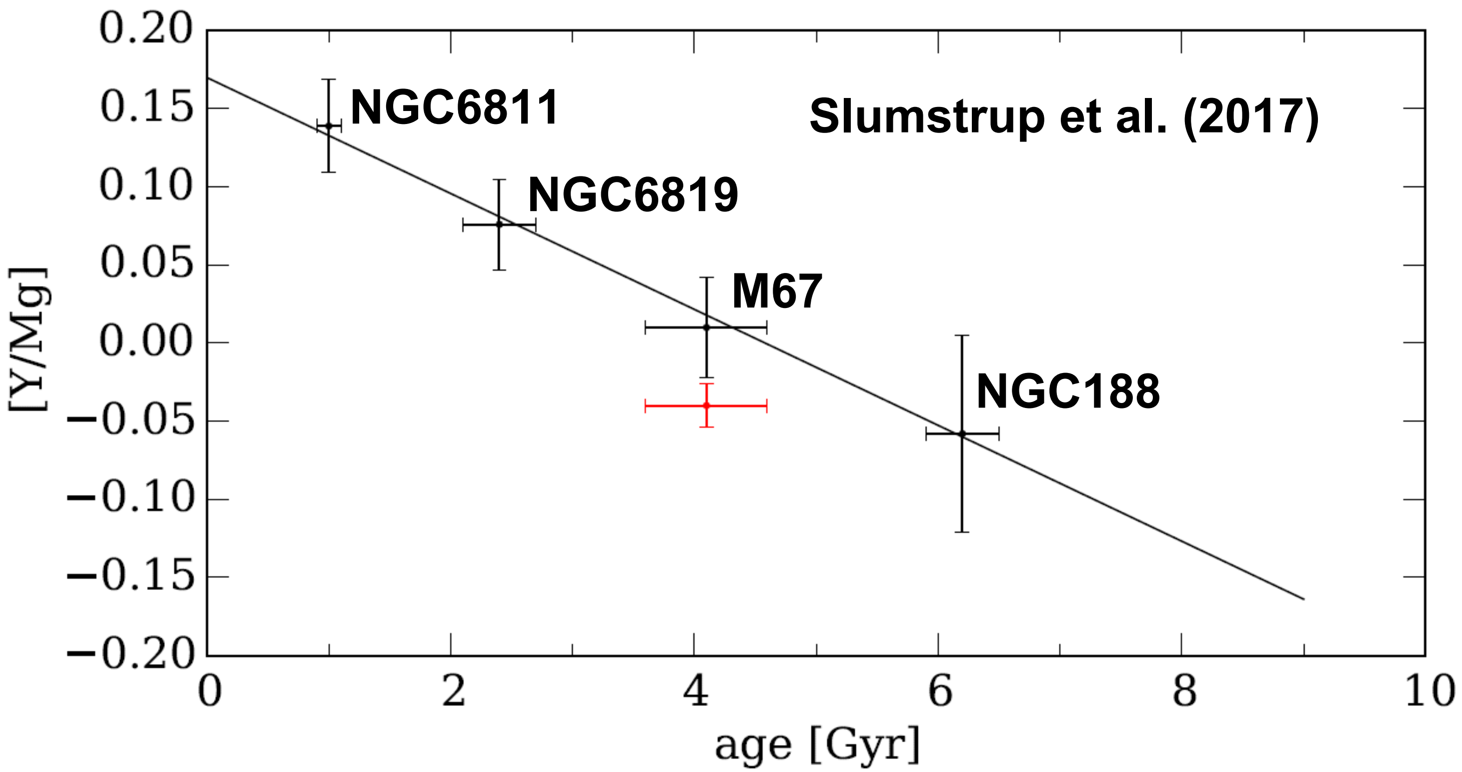



☆ [Fe/H]=−0.70 [α/Fe]=+0.4 [O/Fe]=+0.6 Y=0.250

Brogaard et al. (2017)

# chemical clocks




Line is not a fit! It is derived from solar twins by Nissen (2016)

More on chemical clocks in the talk by G. Casali!