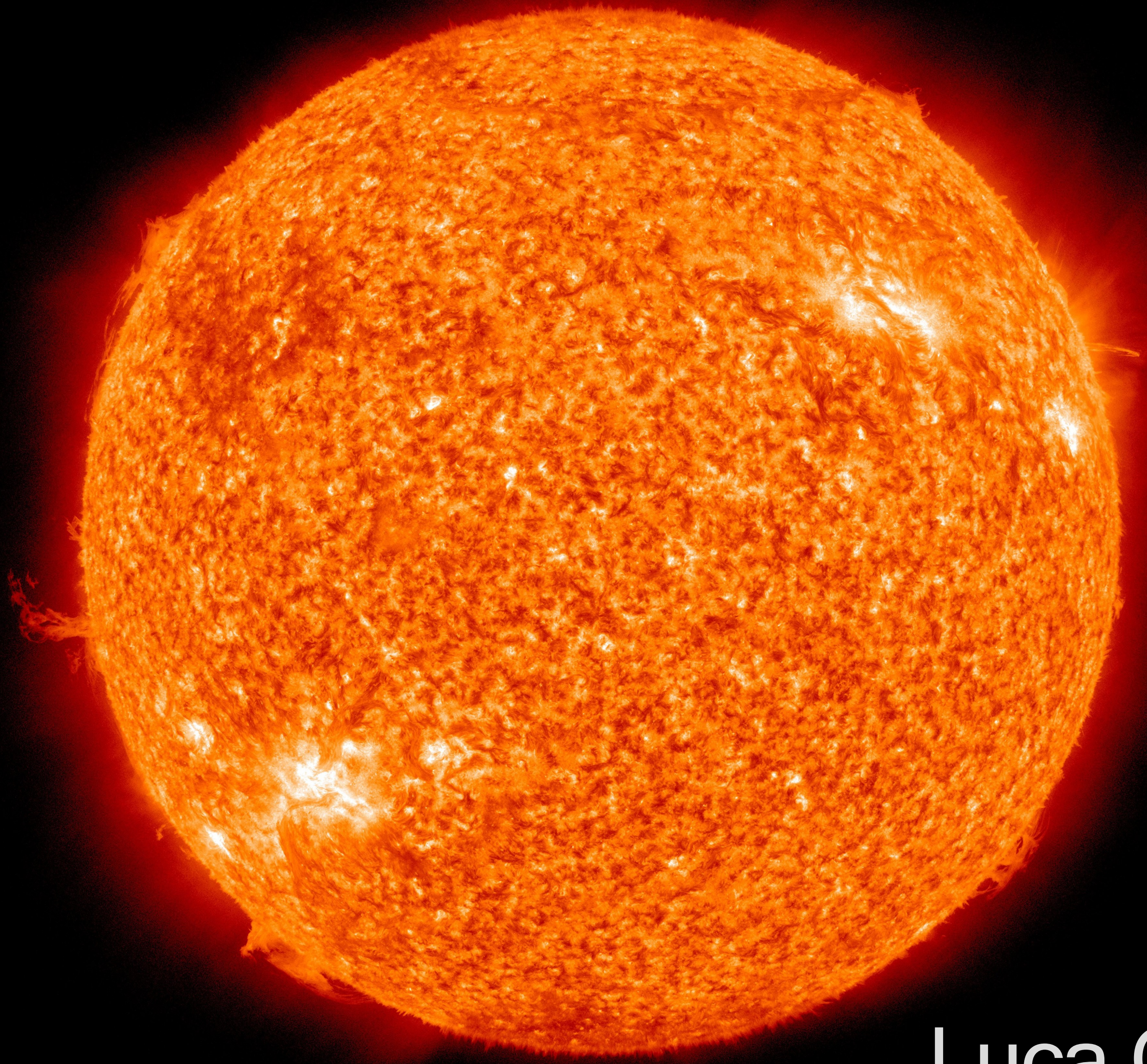
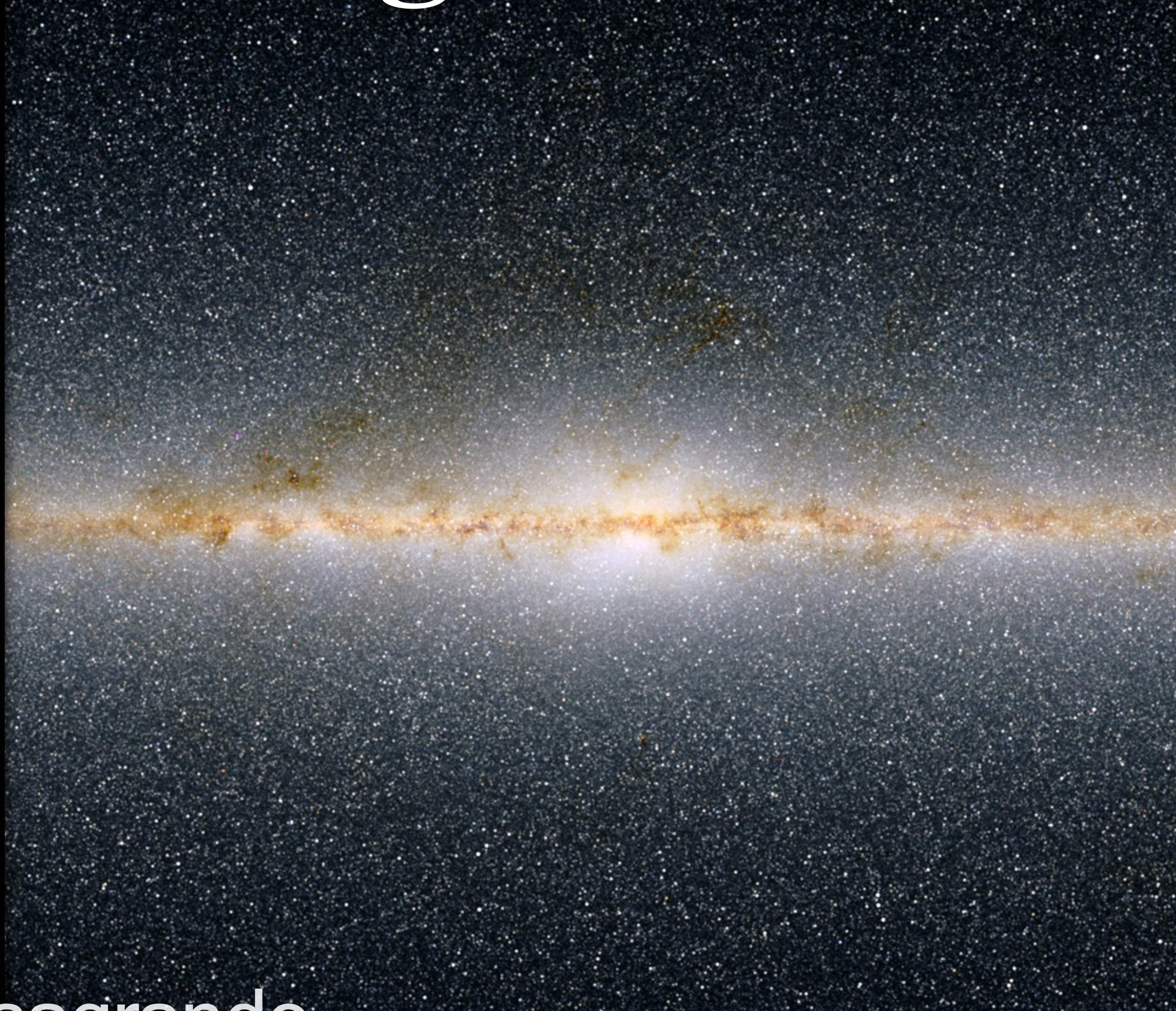
Asteroseismology & better stellar ages

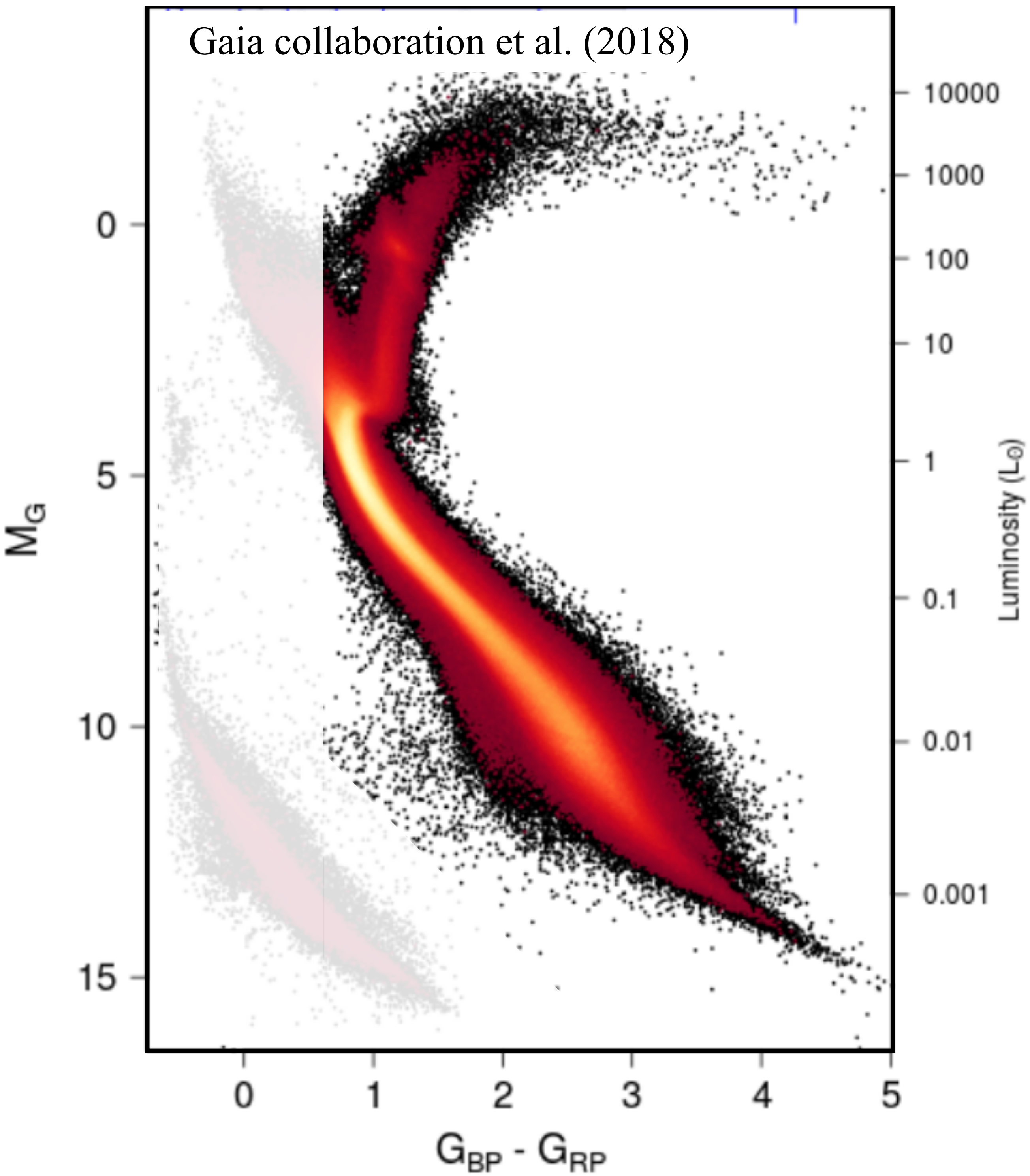


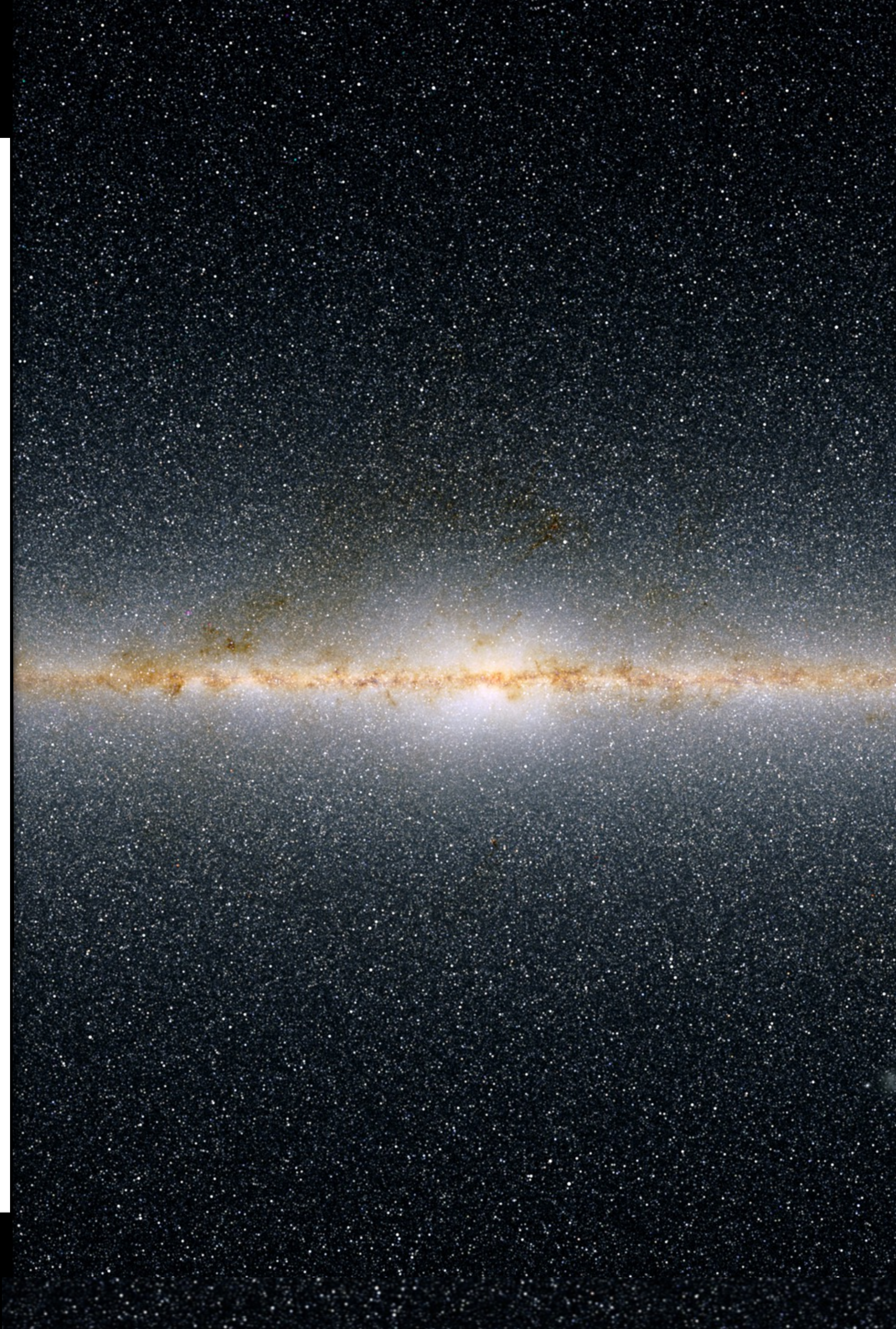


Luca Casagrande

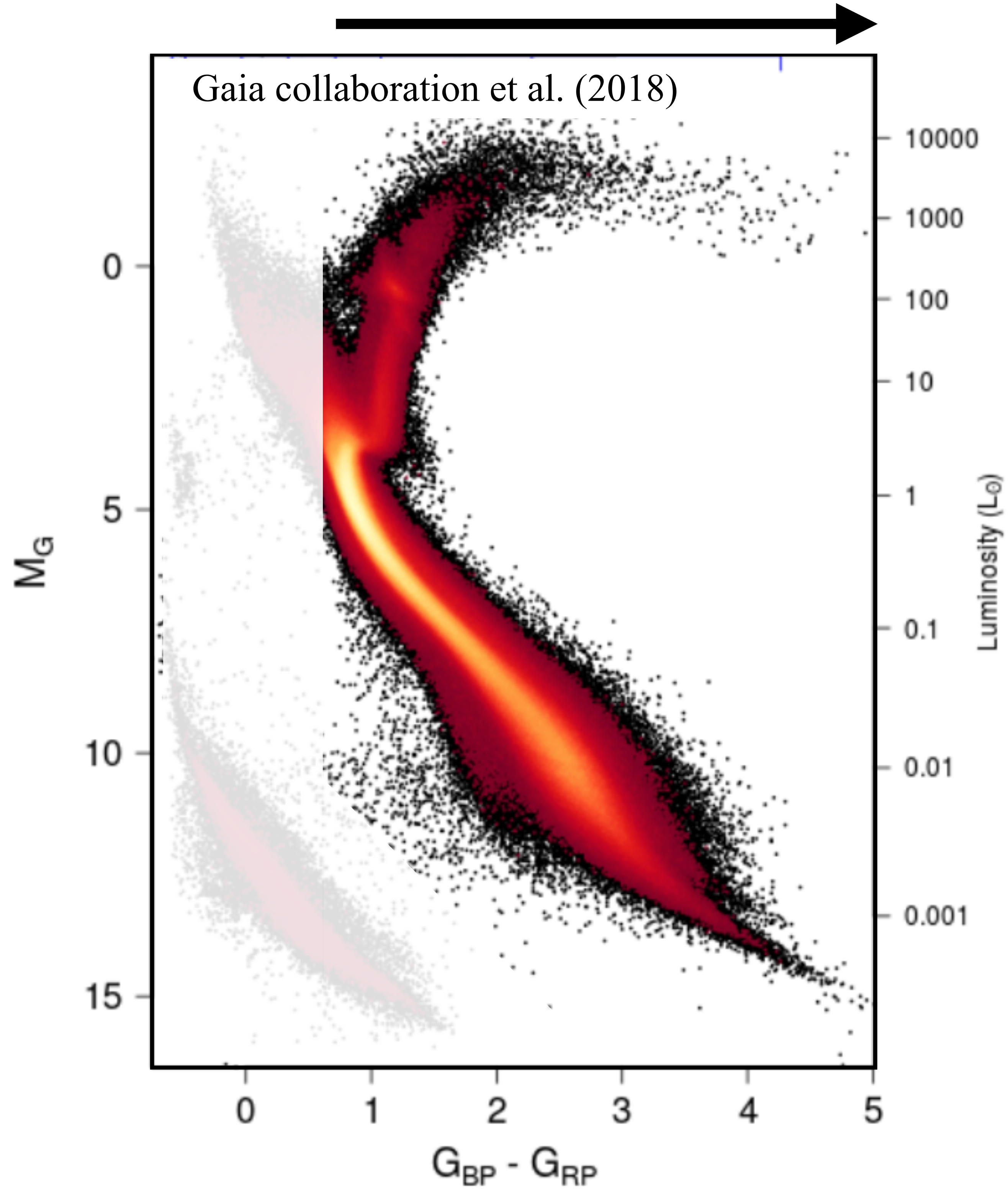
Australian National University

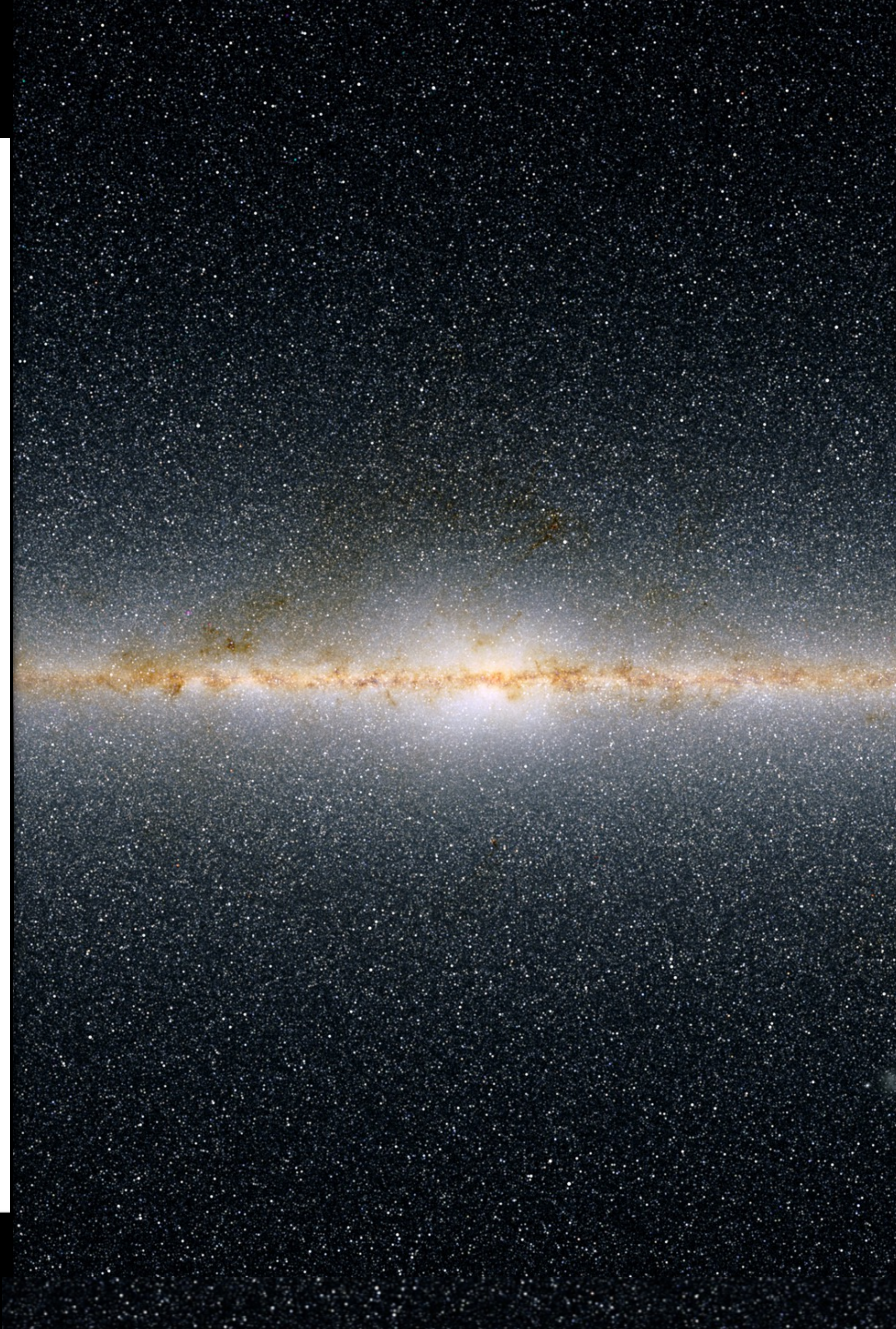
D. Huber, A. Miglio, B. Rendle, A. Serenelli, V. Silva Aguirre, D. Stello


Gaia collaboration et al. (2018)
M_G
0
5
10
15
10000
1000
100
10
1
0.1
0.01
0.001
Luminosity ($L_\odot$)
0
1
2
3
4
5
G_{BP} - G_{RP}



Solar-like Oscillations





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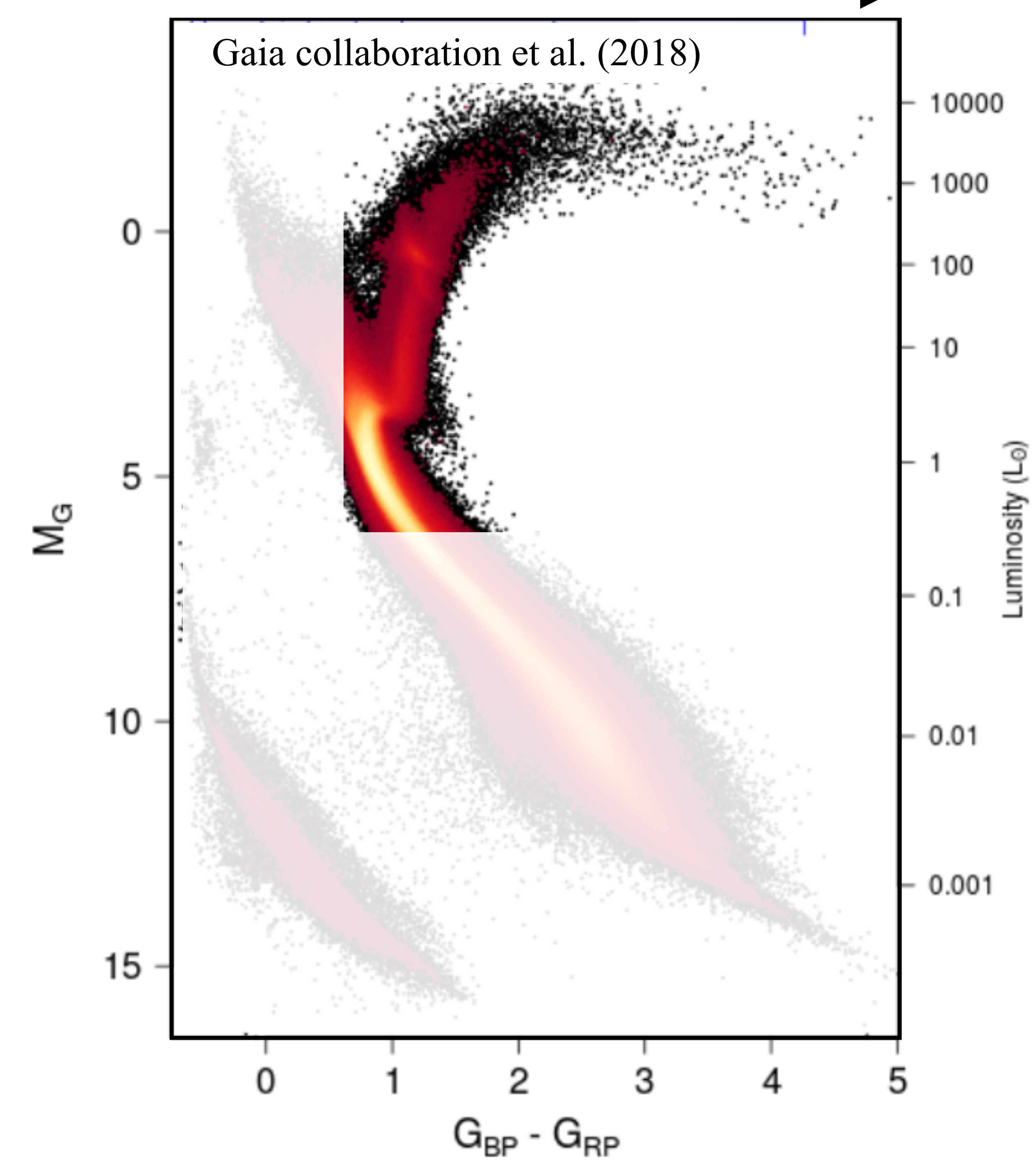
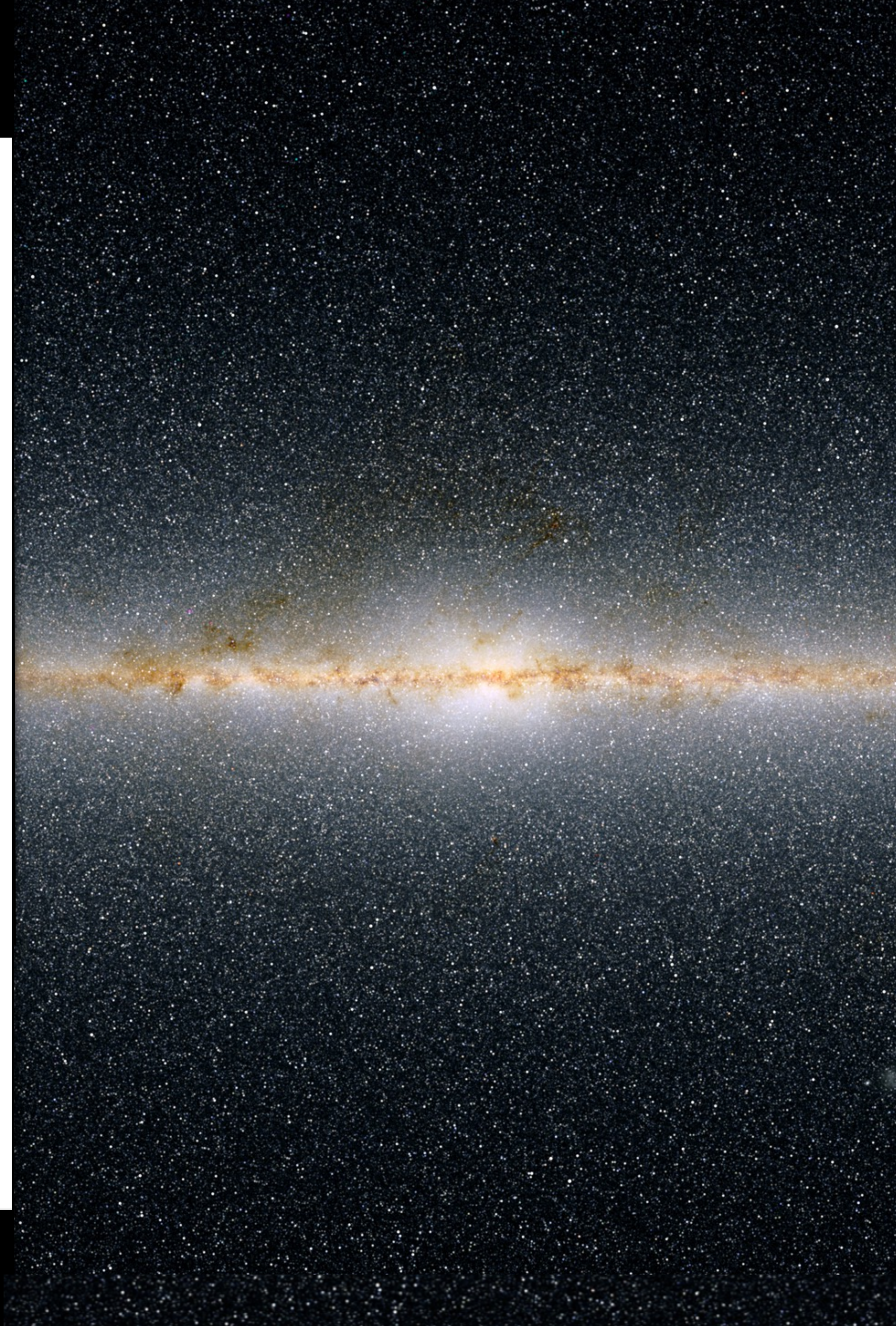
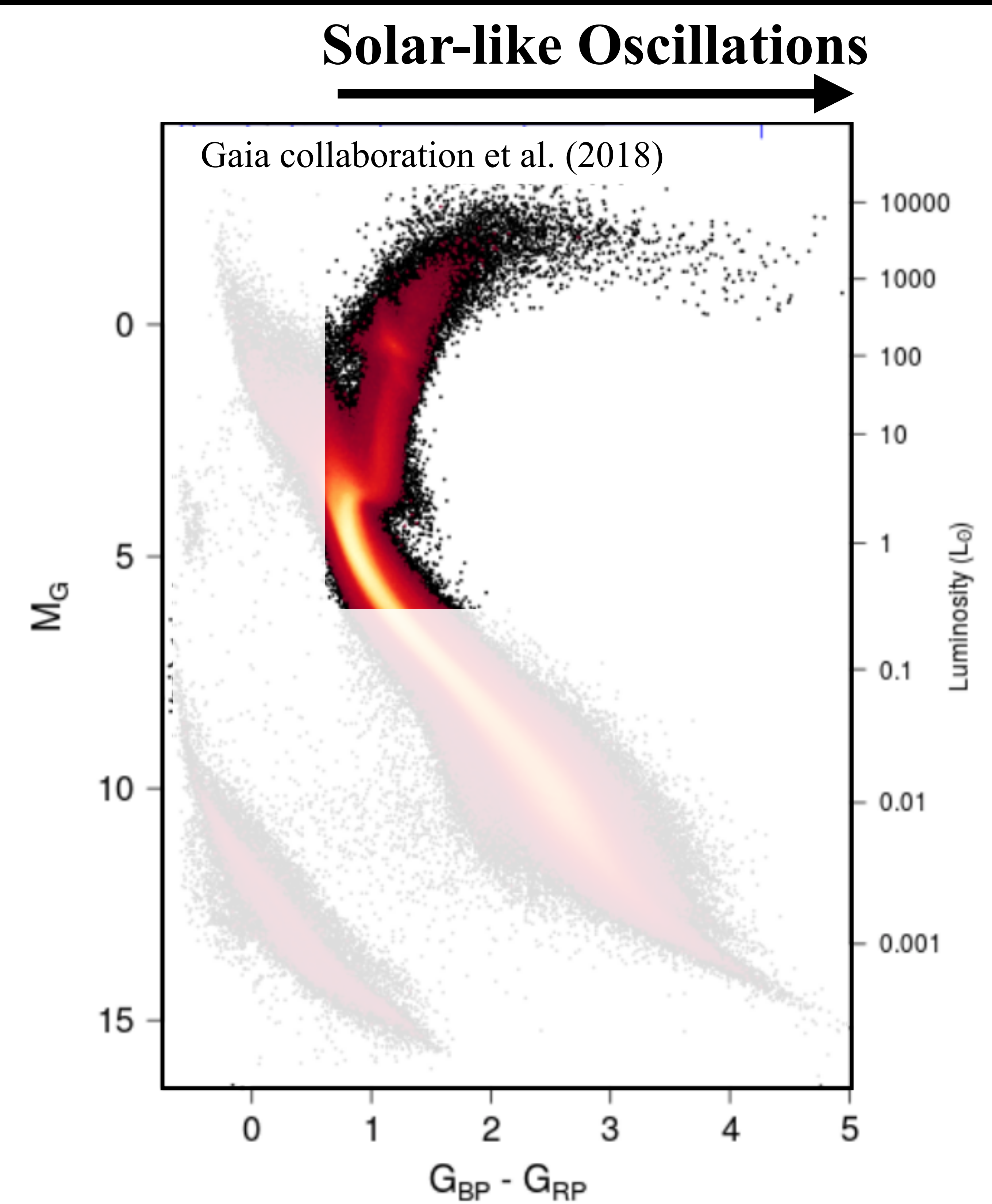




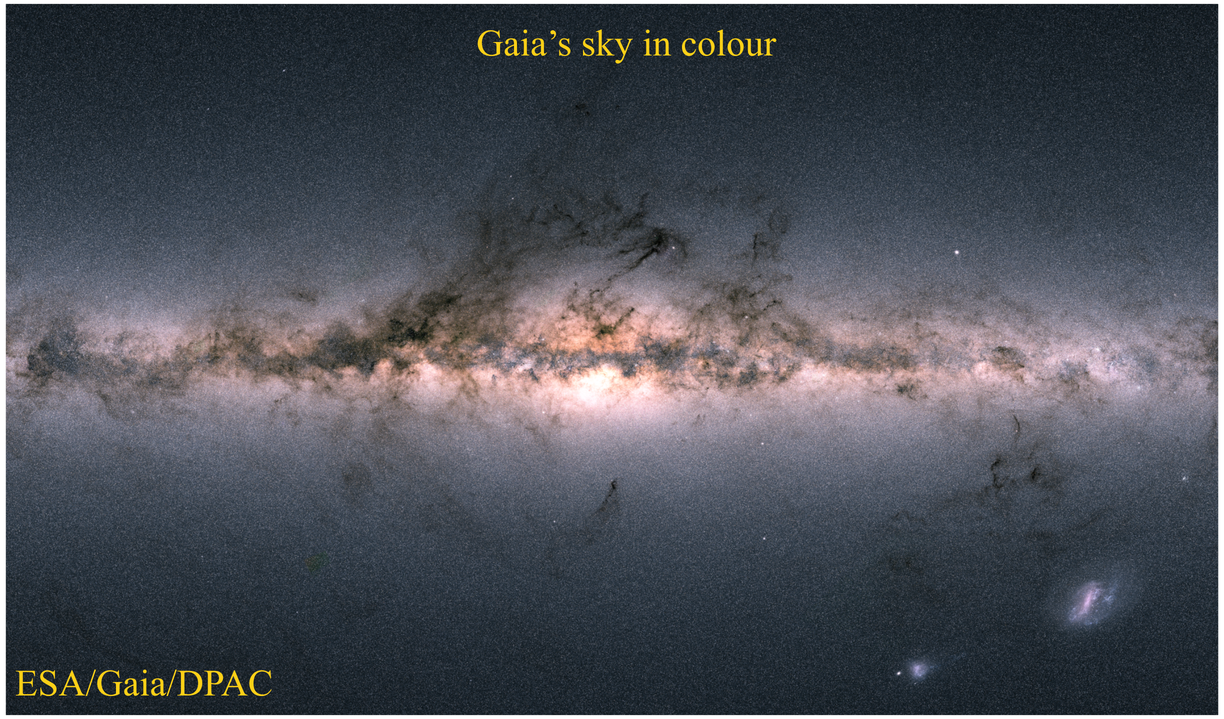


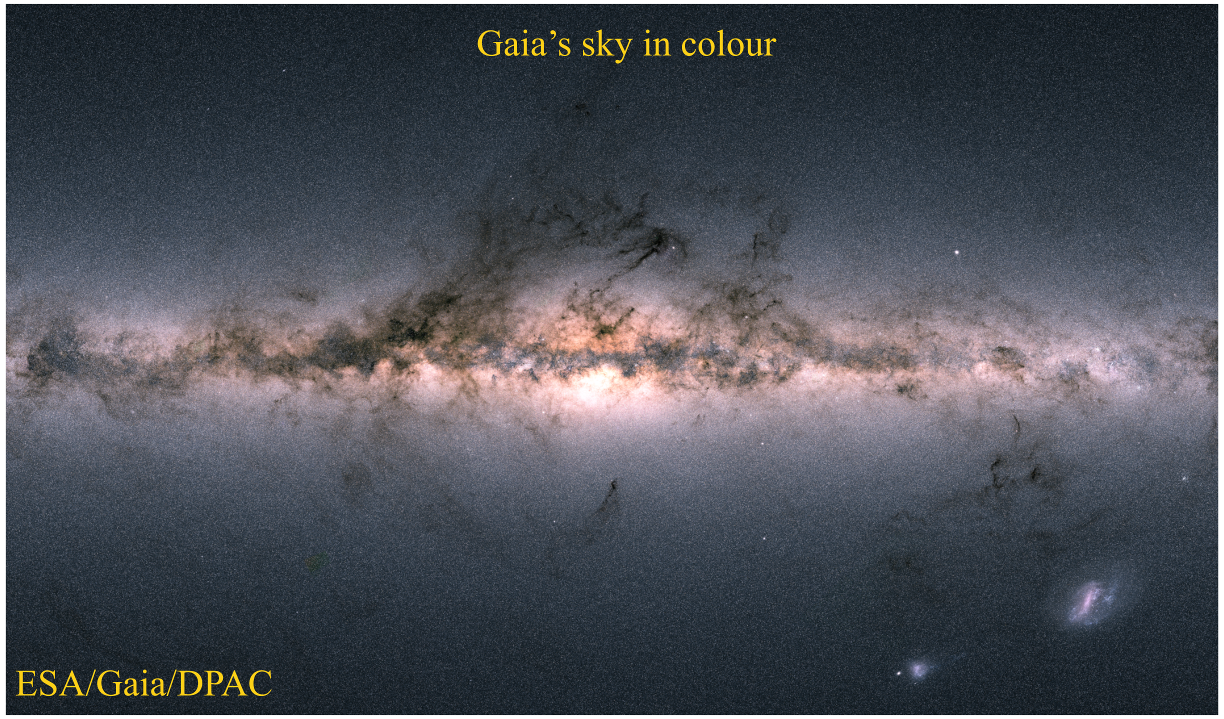
Is the distribution of stellar ages telling us about past star formation events?

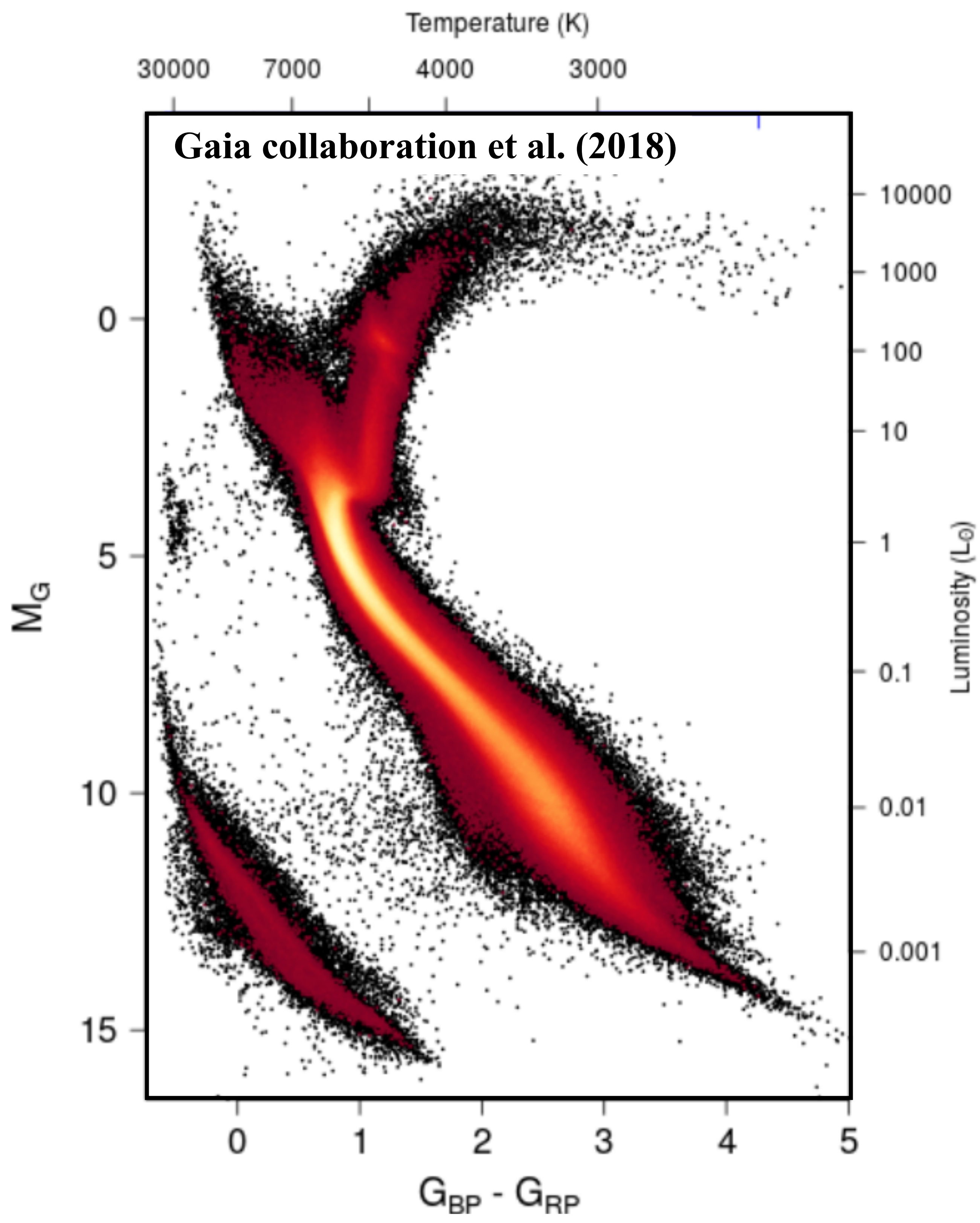
What's the interplay between chemistry, kinematic and ages?

Need for good ages

(and understanding target selection effects!)


Gaia's sky in colour
ESA/Gaia/DPAC

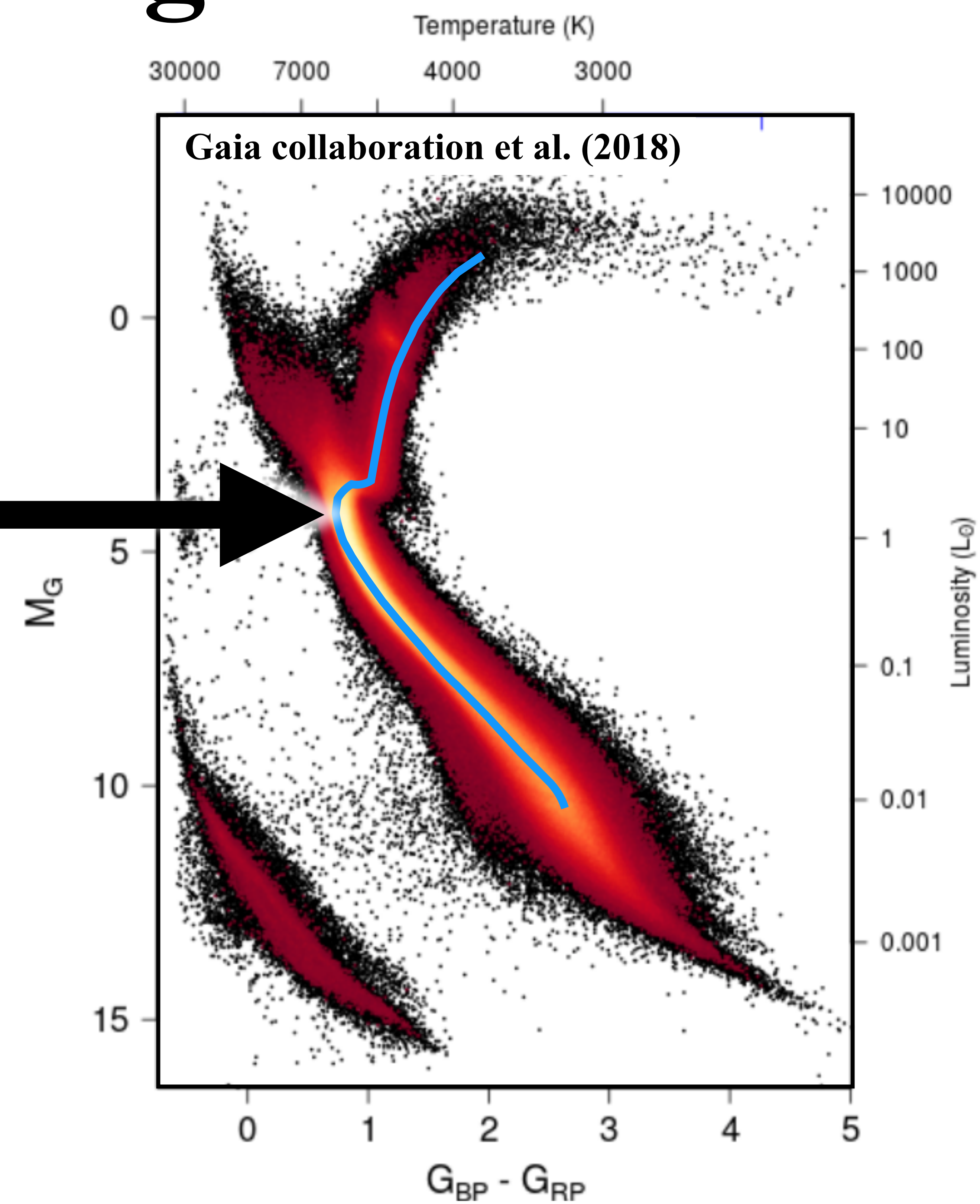

Gaia's sky in colour
ESA/Gaia/DPAC


Temperature (K)
30000
7000
4000
3000
Gaia collaboration et al. (2018)
10000
1000
100
10
1
0.1
0.01
0.001
Luminosity ($L_{\odot}$)
0
5
10
15
M_G
0
1
2
3
4
5
G_{BP} - G_{RP}

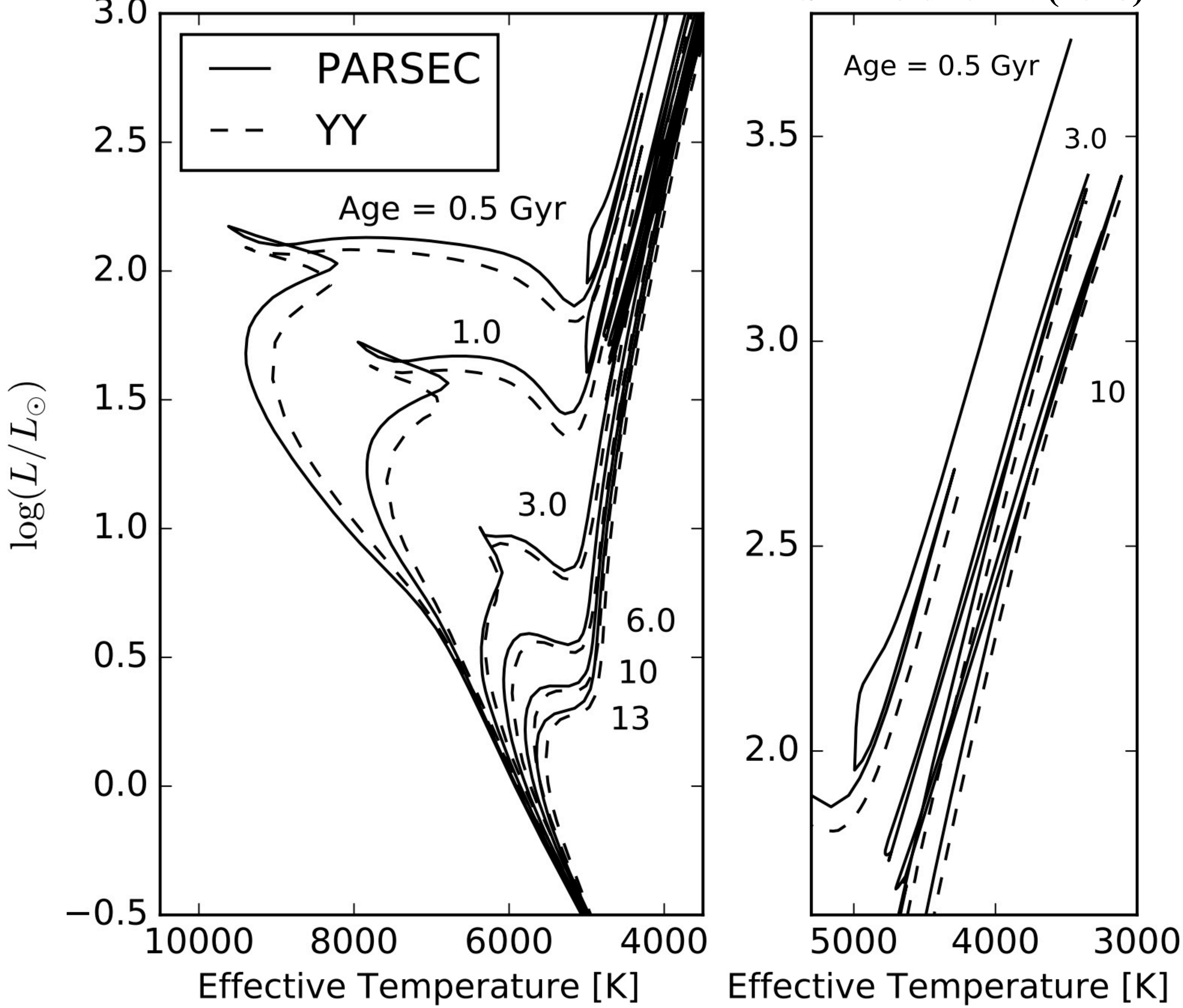
Stellar Ages

Astrometry

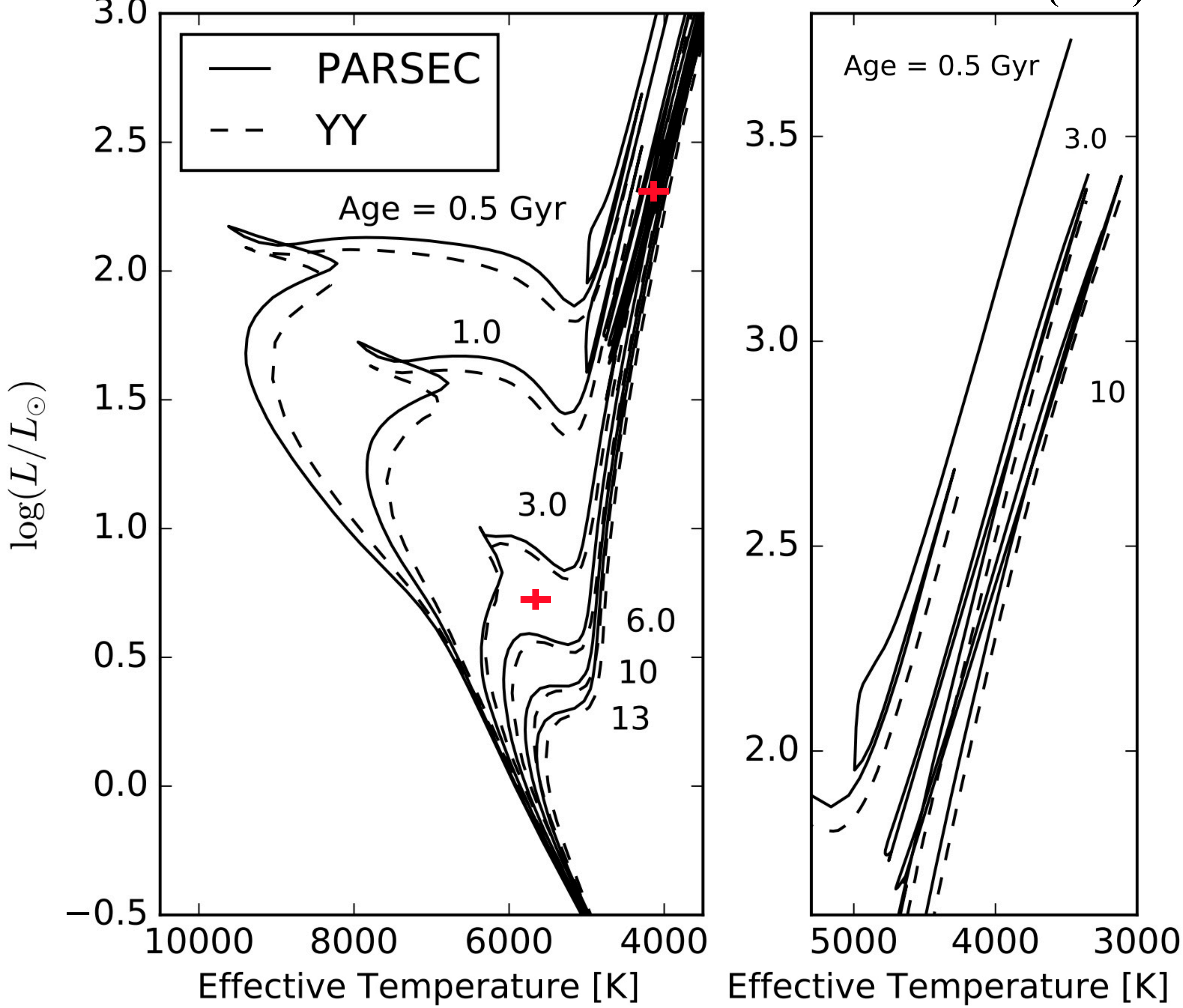
(Gaia distances+isochrones)



Sahlholdt et al. (2018)



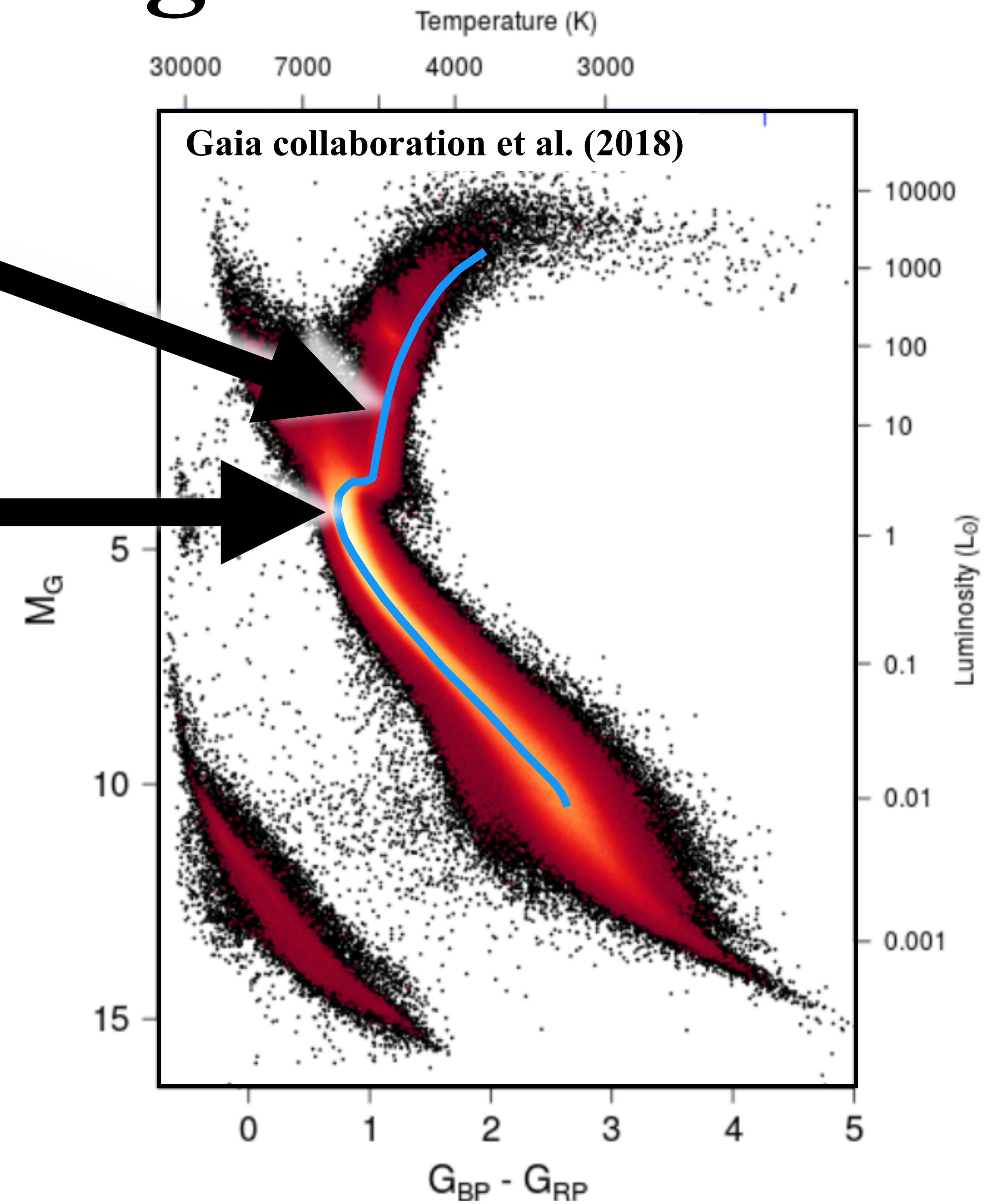
Sahlholdt et al. (2018)



Stellar Ages

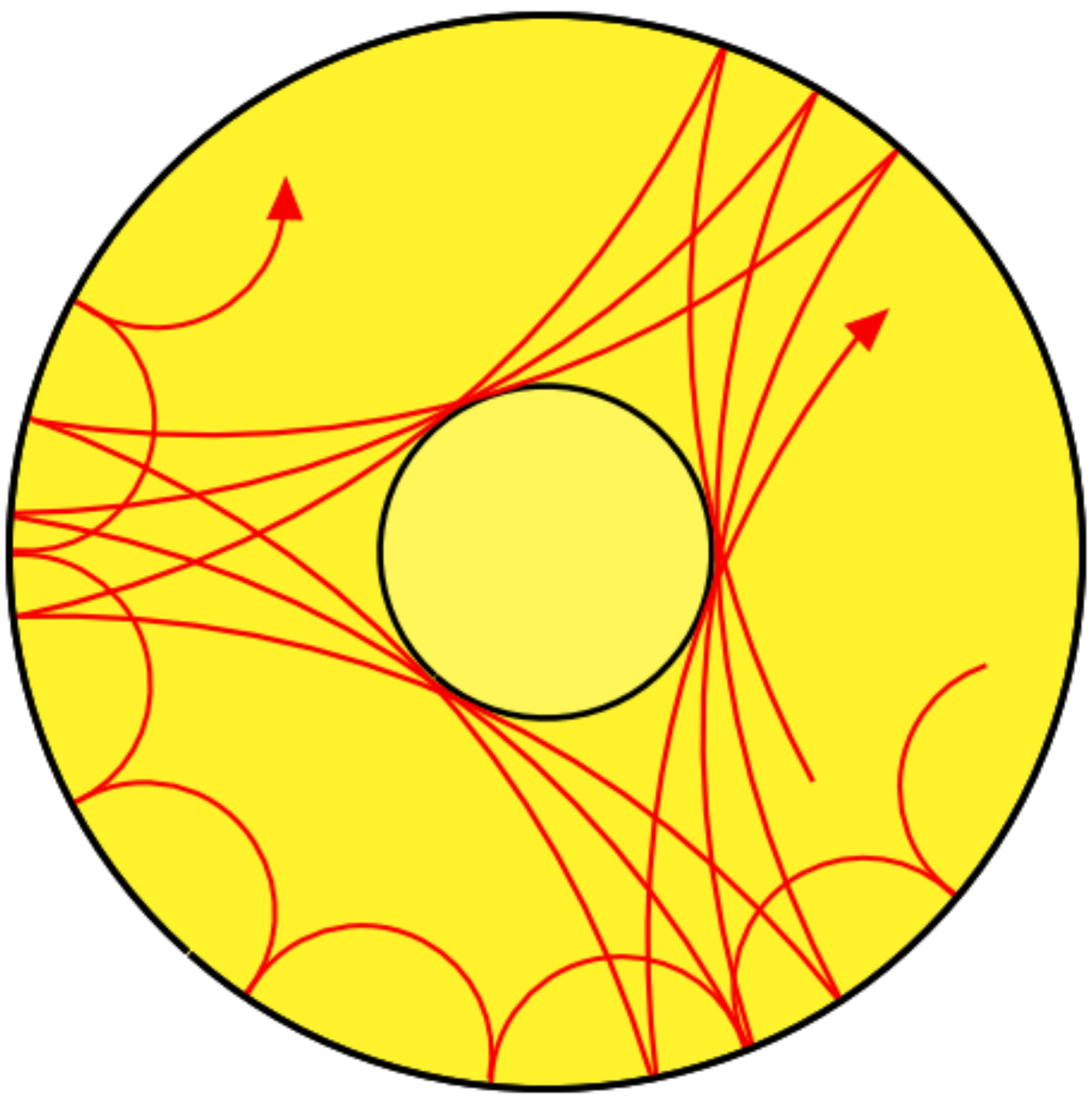
Asteroseismology
(stellar oscillations)

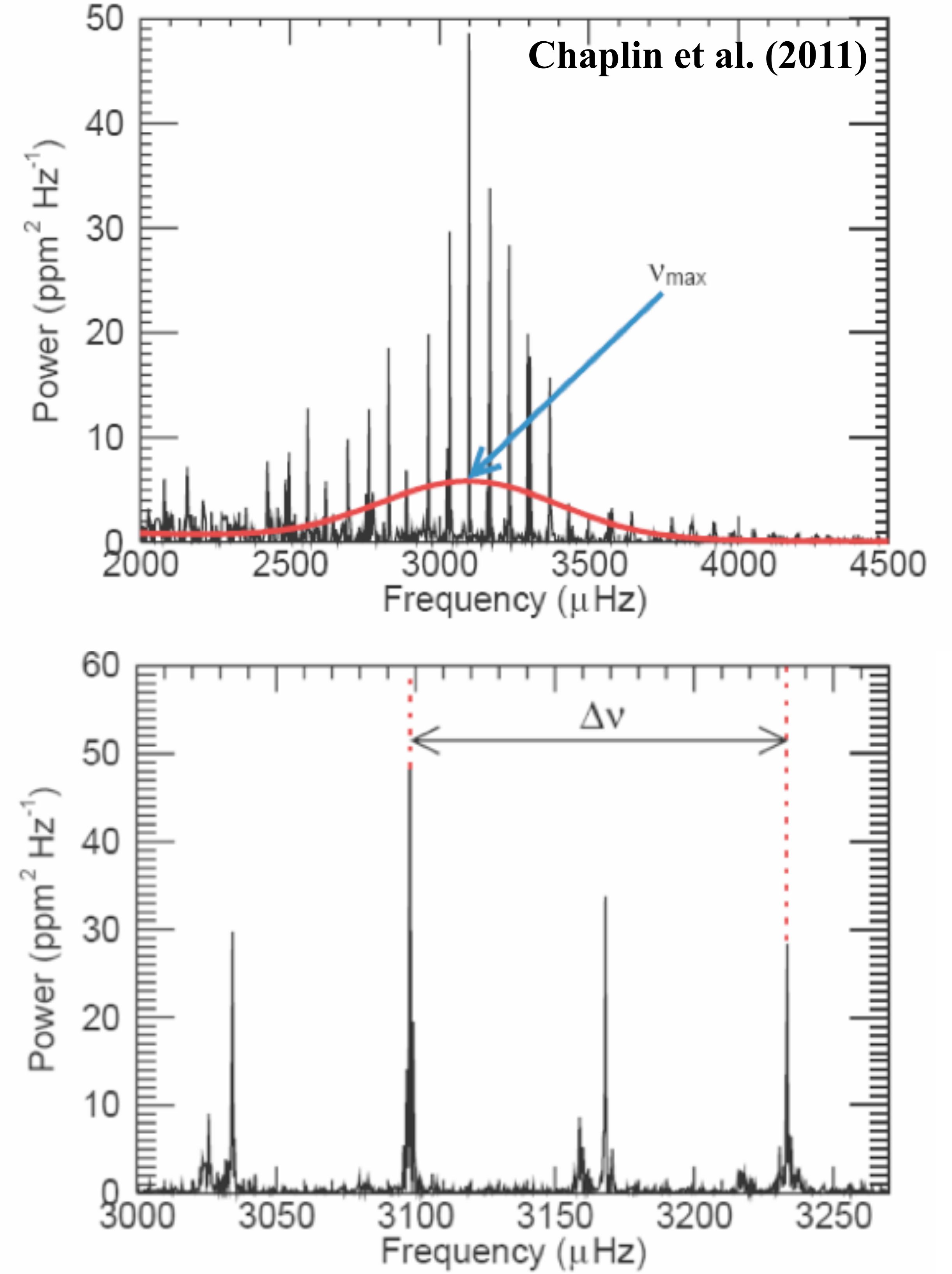
Astrometry
(Gaia distances+isochrones)



Ages for red giant stars allow us to probe a large volume of the Milky Way.

Solar-like oscillations





Scaling relations

Brown et al. (1991), Kjeldsen & Bedding (1995)

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

$$\nu_{\rm max} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

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Brown et al. (1991), Kjeldsen & Bedding (1995)

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

$$\nu_{\rm max} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

solve to get mass and radius

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

e.g., Stello et al. (2008)

Scaling relations

Brown et al. (1991), Kjeldsen & Bedding (1995)

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2} \qquad \nu_{\max} \propto \frac{M}{R^2\sqrt{T_{\mathrm{eff}}}}$$

solve to get mass and radius

age

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{1/2}$$

e.g., Stello et al. (2008)

distance

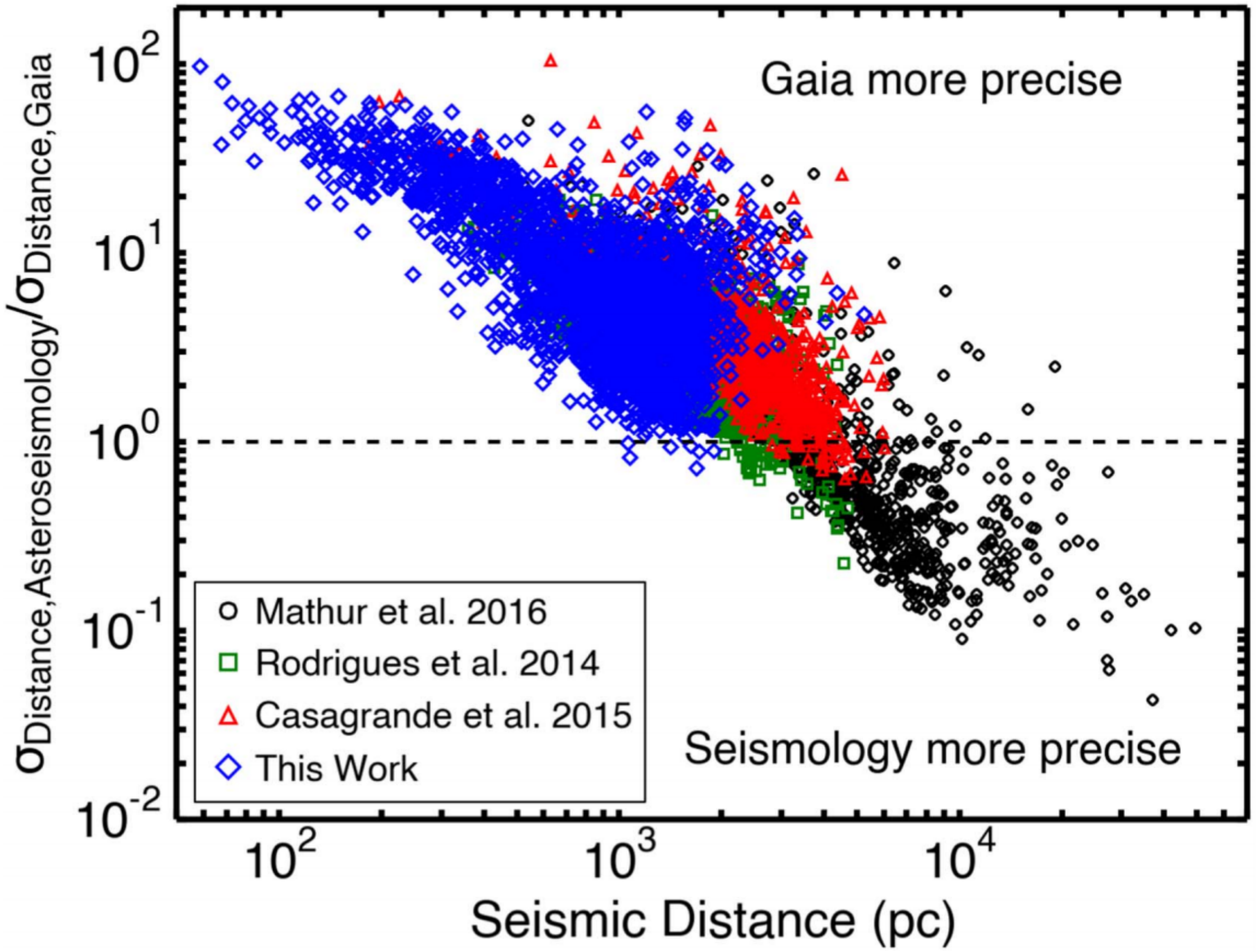
Scaling relations

Brown et al. (1991), Kjeldsen & Bedding (1995)

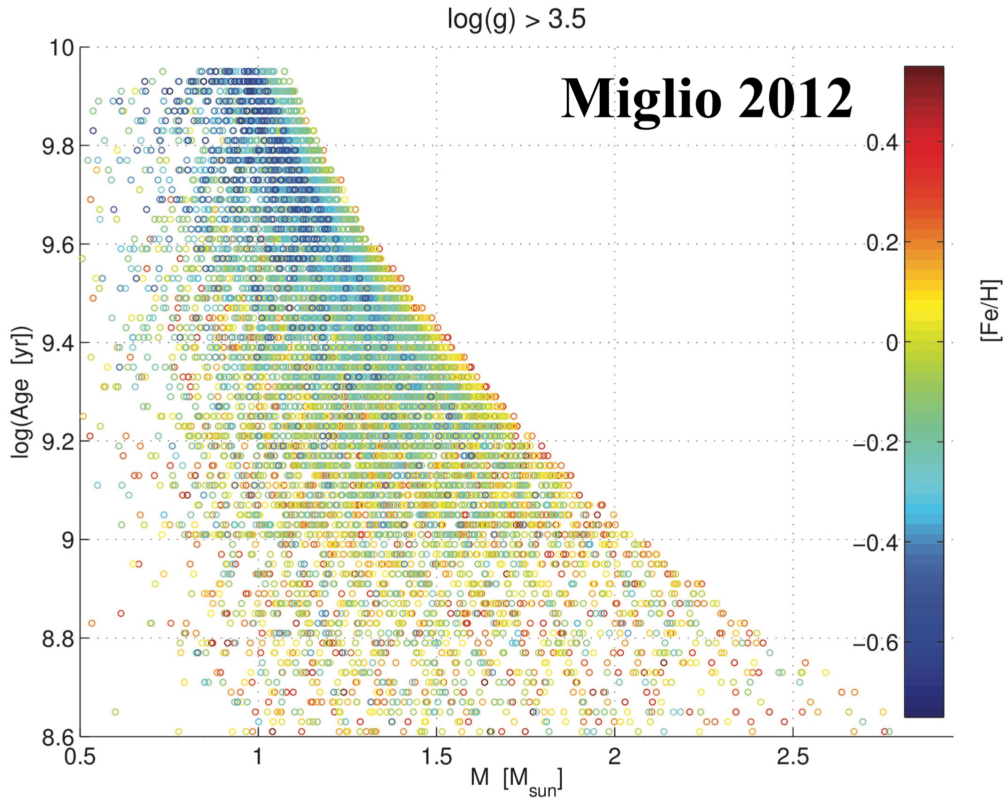
$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

$$\nu_{\rm max} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

Huber et al. (2017) (also Chen et al. 2017)



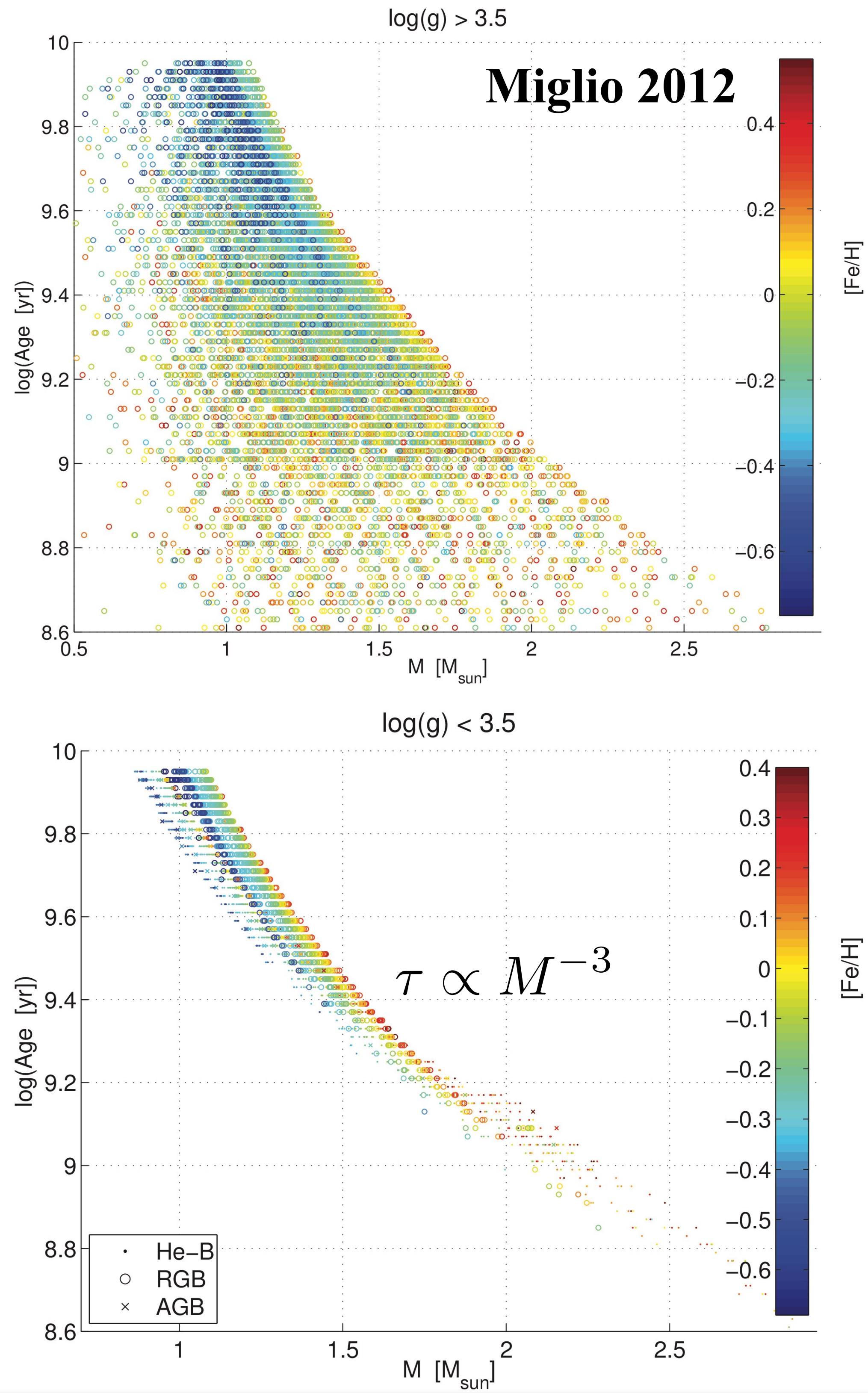
Mass is an excellent proxy for age



log(g) < 3.5

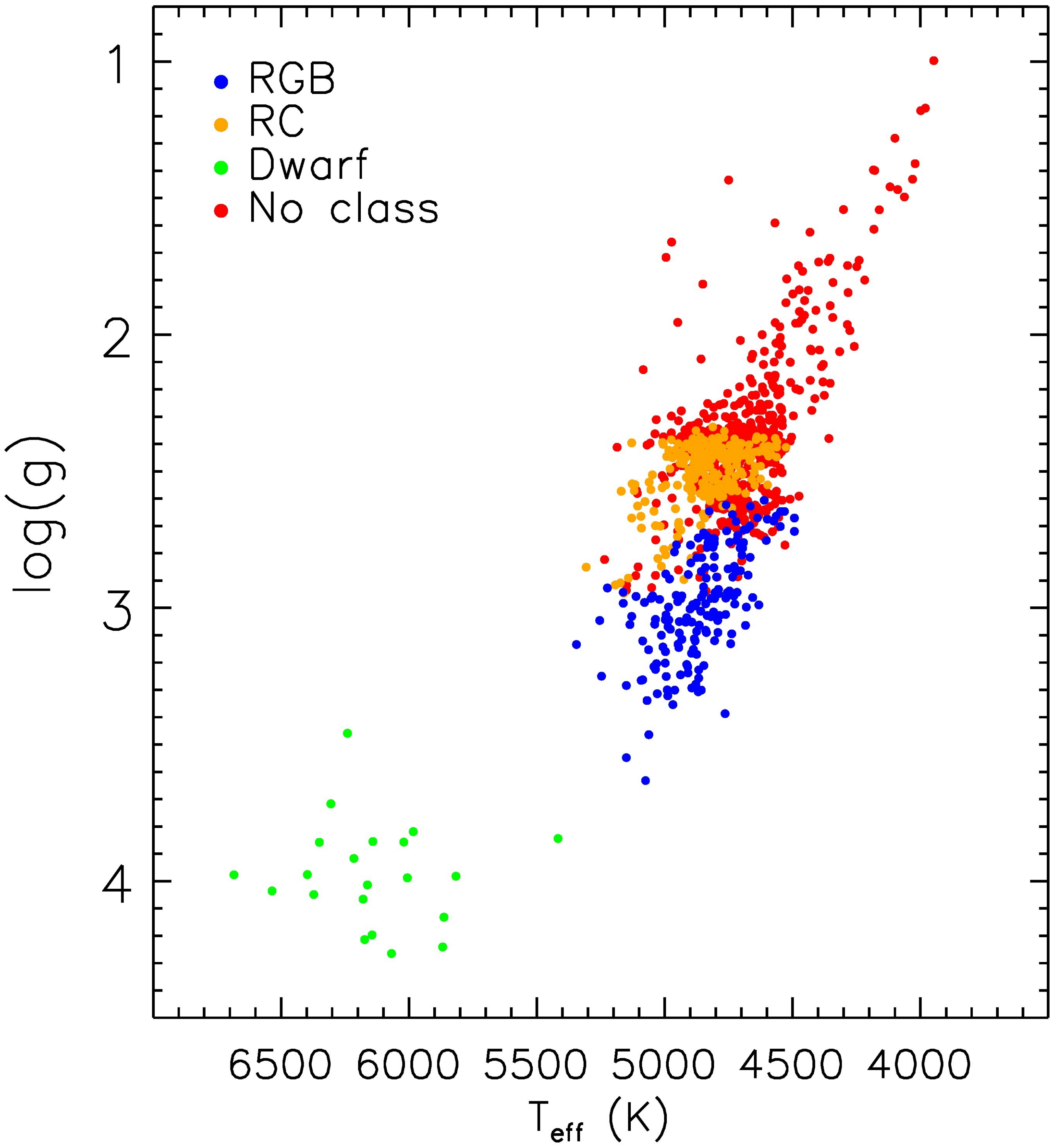
Mass is an excellent proxy for age

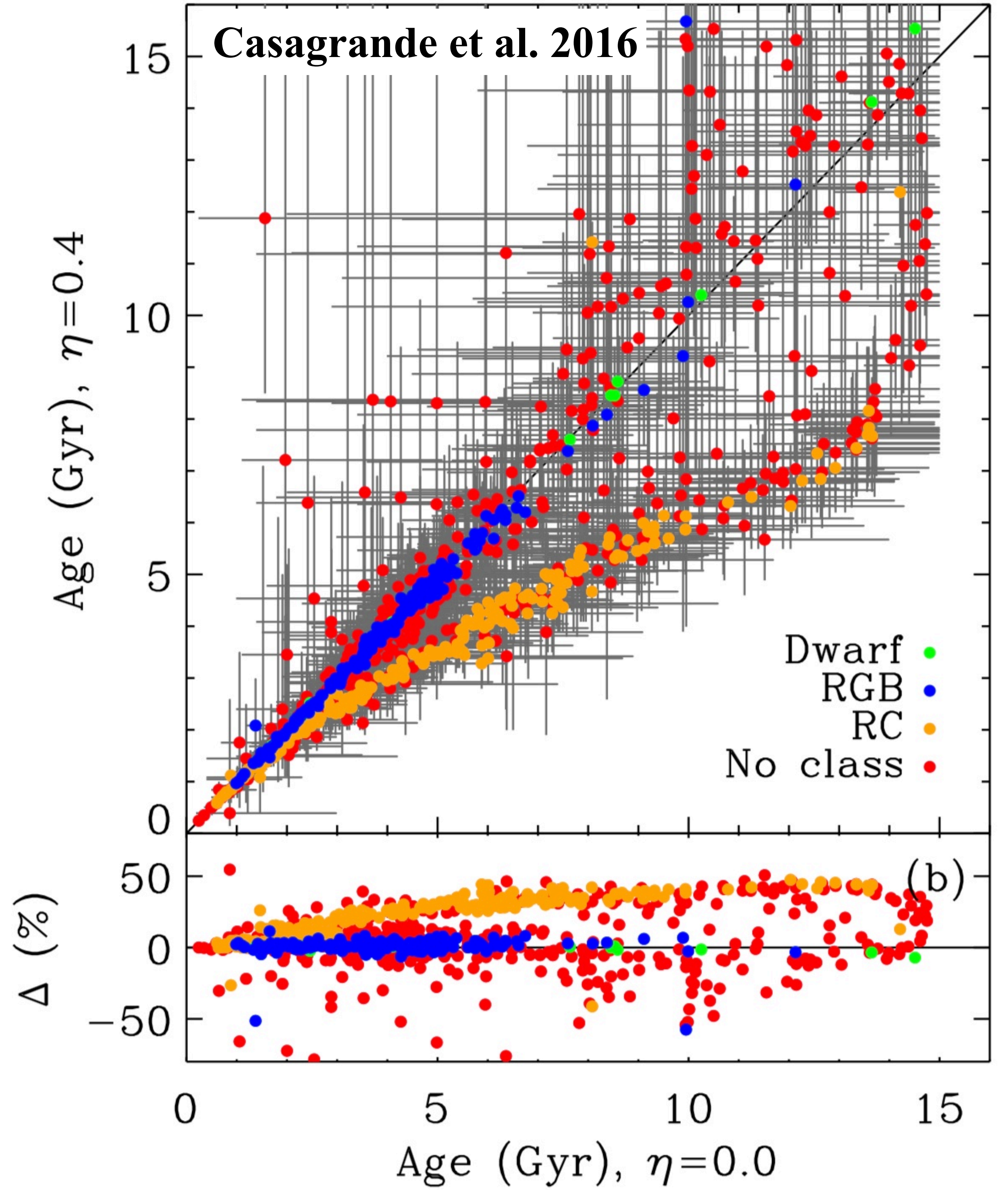
Once a star has evolved to the red-giant phase, its age is determined to good approximation by the time spent in the core-hydrogen burning phase, and this is predominantly a function of mass.



Australian National University

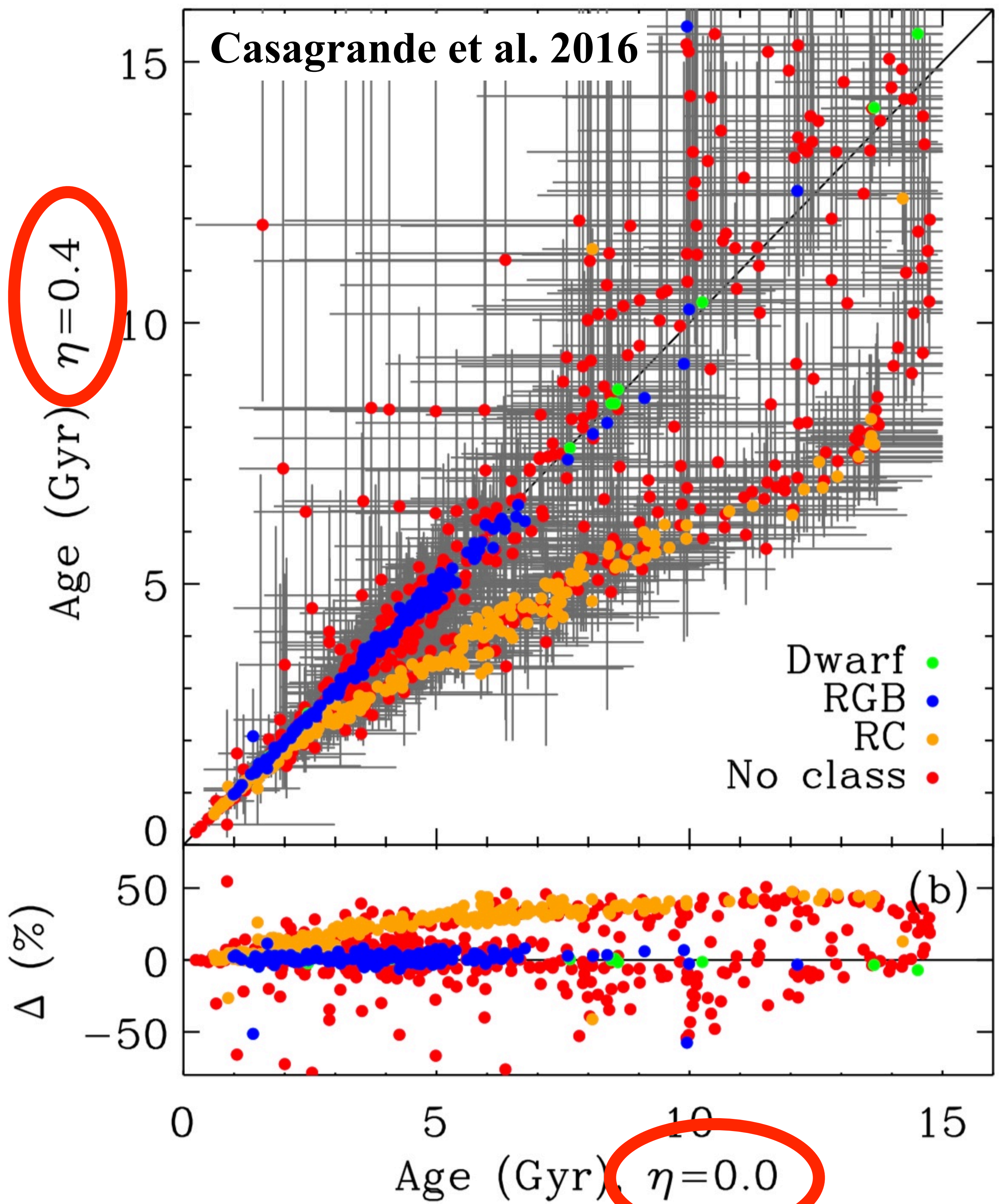
But RGB stars lose mass!





But RGB stars lose mass!

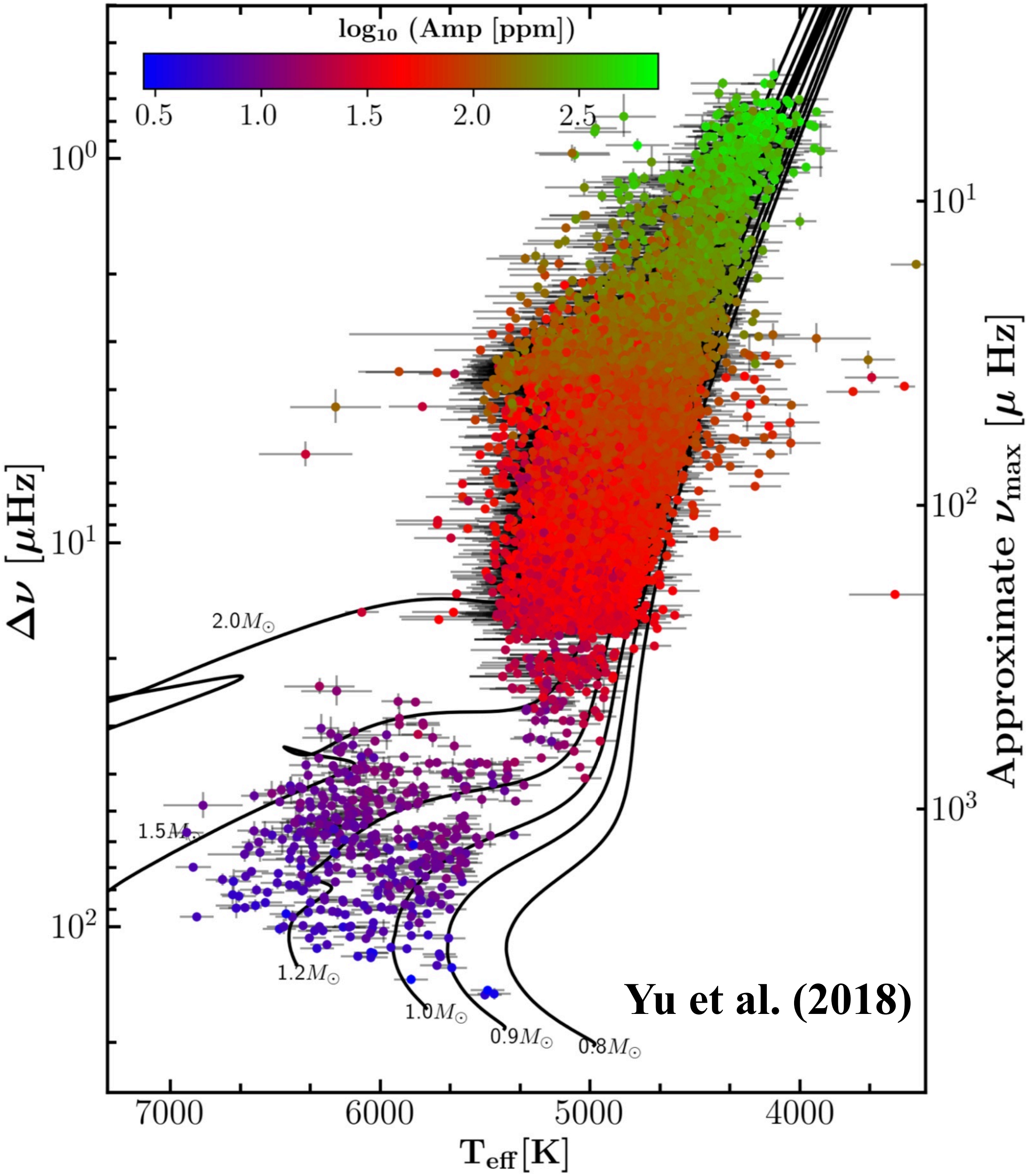
Good news is that for disc metallicities, mass-loss seems to be moderate ($\eta \sim$ 0.1 or 0.2, see Miglio et al. 2012, Handberg et al. 2017).



Scaling relations to rule them all?

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$



House of cards?

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

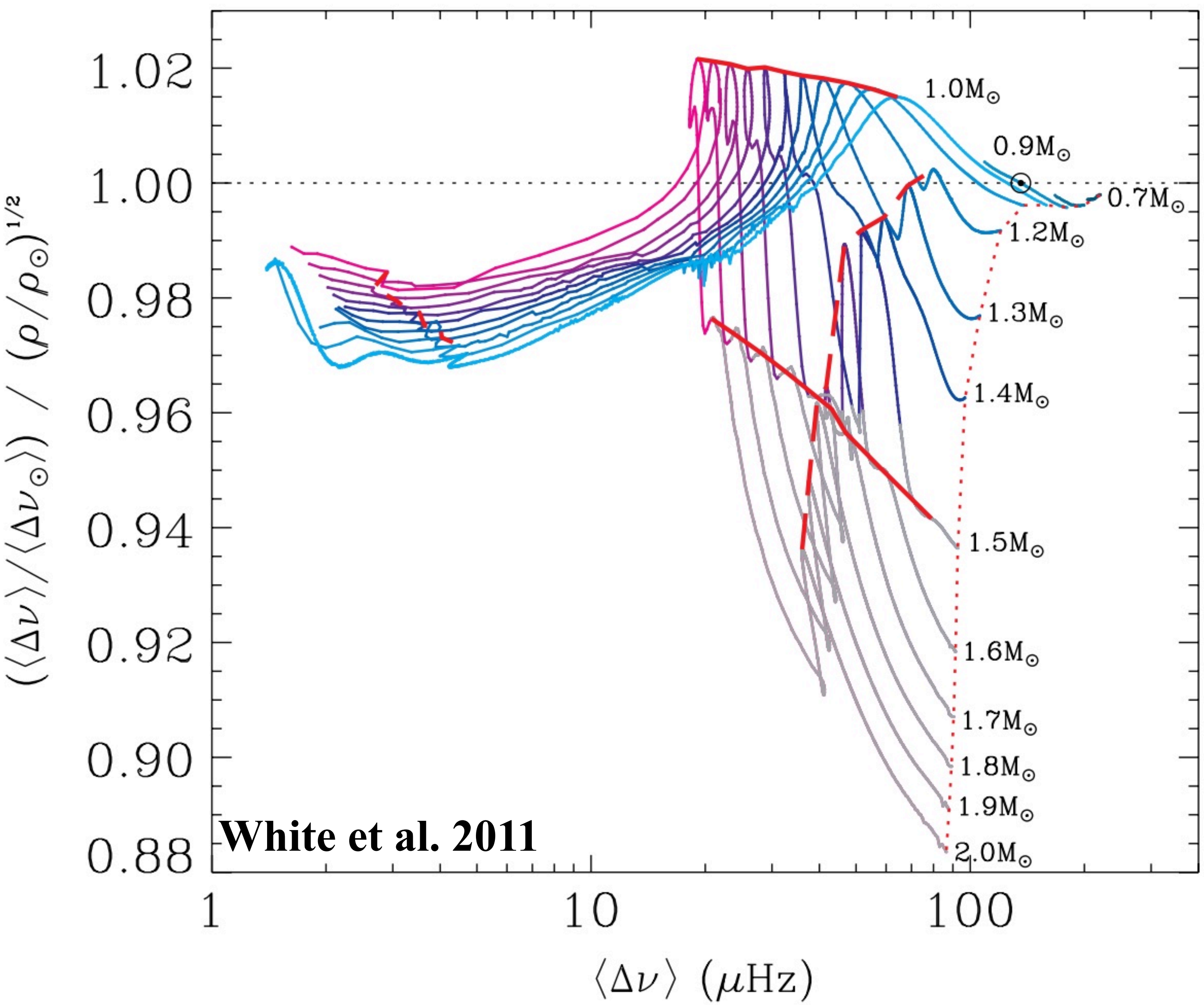
$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

Galactic Archaeology

mass and radius

The Δν scaling relation

Approximate, but departures well understood from theoretical models.



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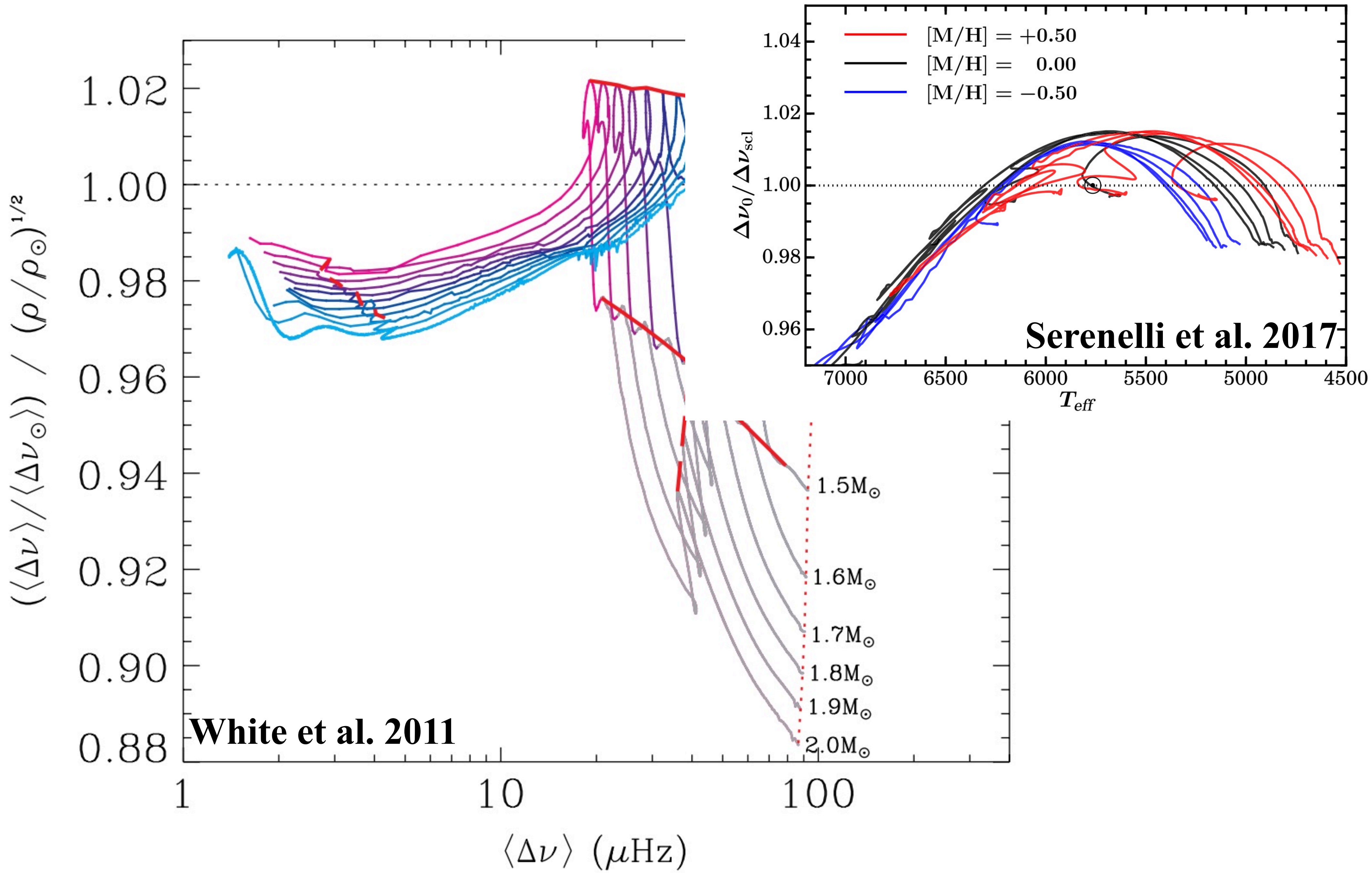
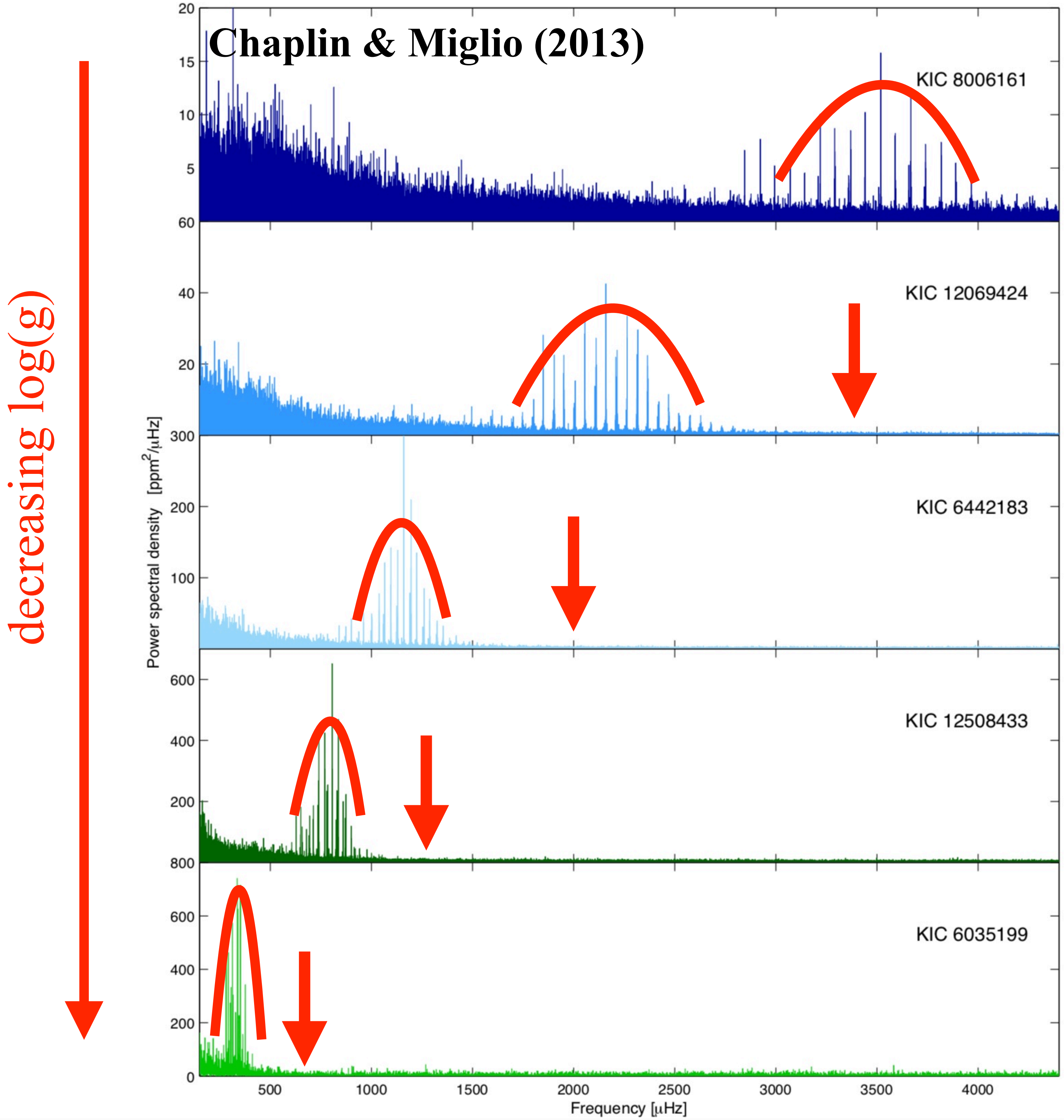


The ν_{max} scaling relation



$$\nu_{\max} \propto \nu_{ac} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

Scaling relation *assumes* ν_{max} is a fixed fraction of ν_{ac} (Brown et al. 1991).

Surprisingly, it seems to work, although it is not fully understood why! However, see Belkacem et al. (2011), Zhou et al. (2018).

Corrections to scaling relations

$f_{\nu_{\rm max}}$ $f_{\Delta\nu}$

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

No correction applied to $\nu_{\rm max}$ scaling relation due to its poor theoretical understanding.

Various corrections to $\Delta\nu$ scaling relation are nowadays used in the literature (e.g., White et al. 2011, Sharma et al. 2016, Guggenberger et al. 2016, Kallinger et al. 2018, Serenelli et al. 2018).

Testing of scaling relations

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

The validity of this relation has been tested in several ways by means of interferometry and/or astrometric distances:

Huber et al. (2012, 2017),
Silva Aguirre et al. (2012),
Chen et al. (2017),
Sahlholdt et al. (2019).

Accuracy < 5%

Testing of scaling relations

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

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

Testing mass is more difficult because of the paucity stars with empirical mass-measurements (eclipsing binaries). Indirect tests are often used:

Epstein et al. (2014),
Gaulme et al. (2016),
Miglio et al. (2016),
Brogaard et al. (2016, 2018)
Pinsonneault et al. (2018).

~10% (i.e. ~30% in age)

However, in relative sense, age precision is better than 30%

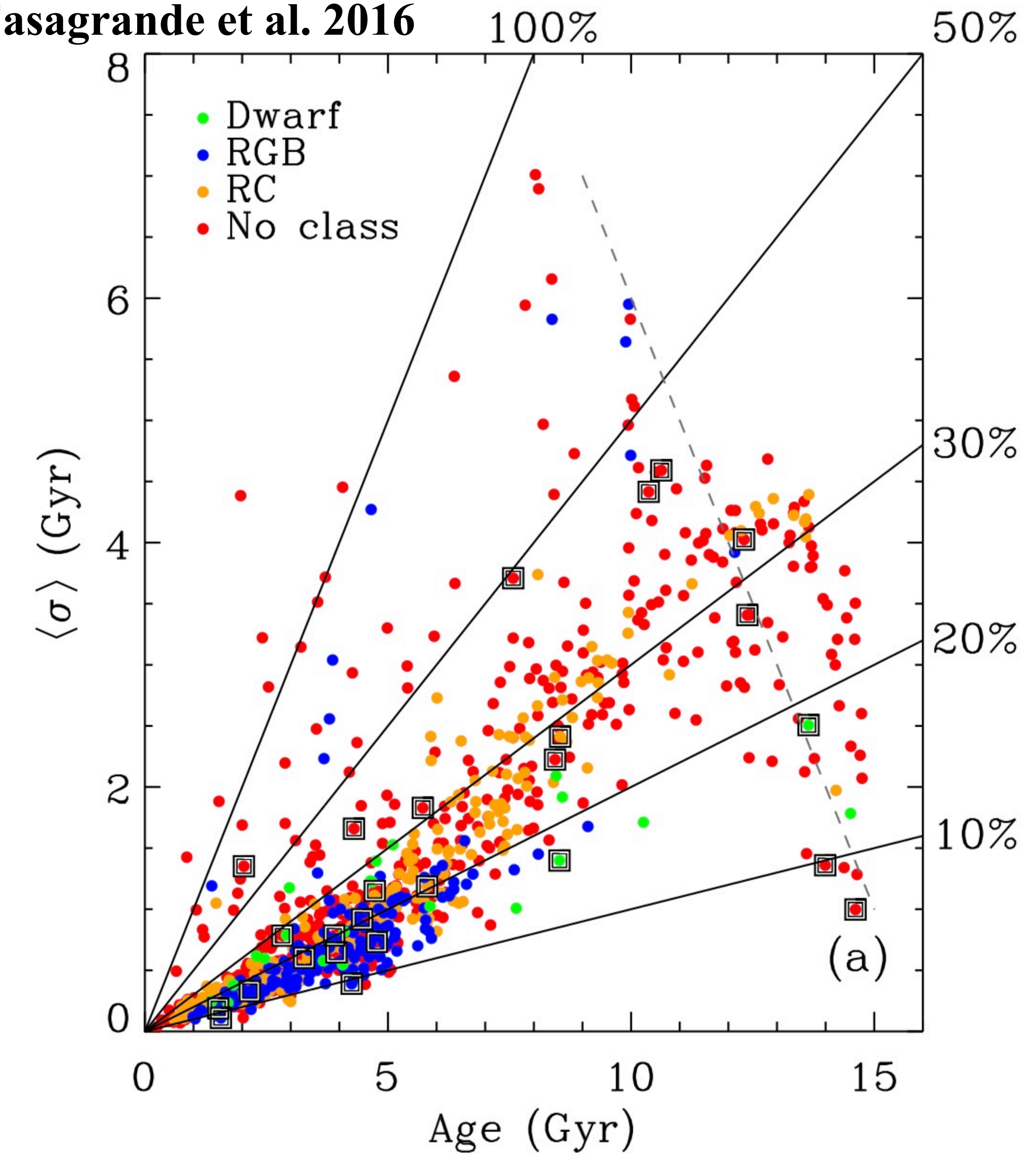
Asteroseismic ages

Scaling relations

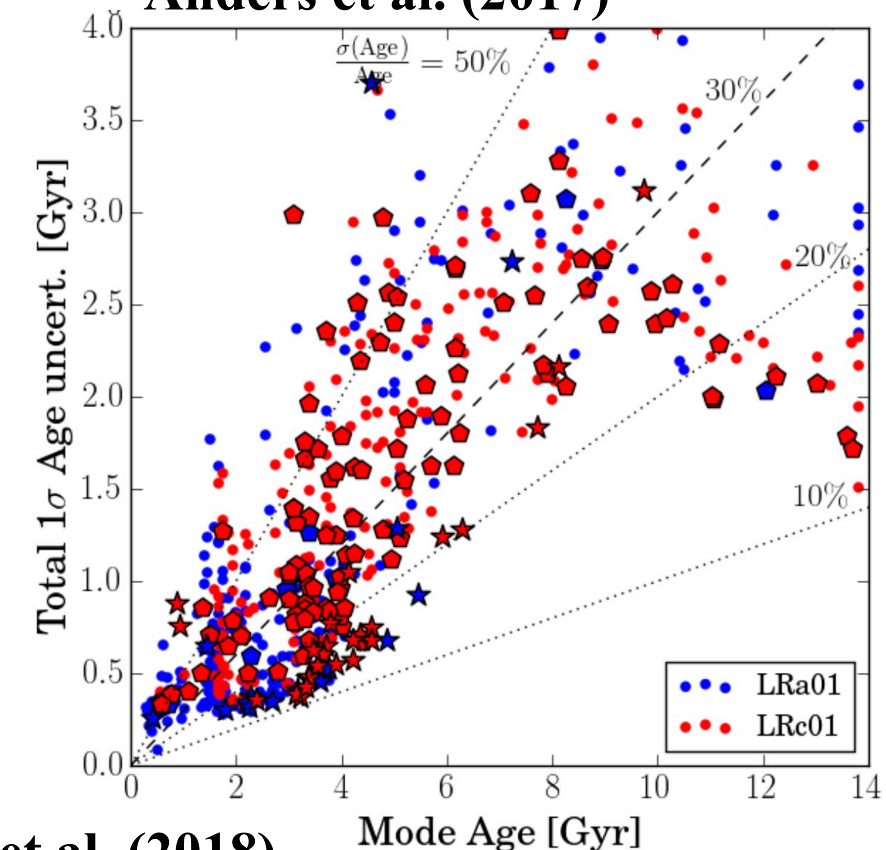
Rather than pure scaling relations, grid-based modelling usually adopted (i.e. fitting for [Fe/H], Teff, $\Delta\nu$, ν_{max}).

Uncertainties on asteroseismic ages

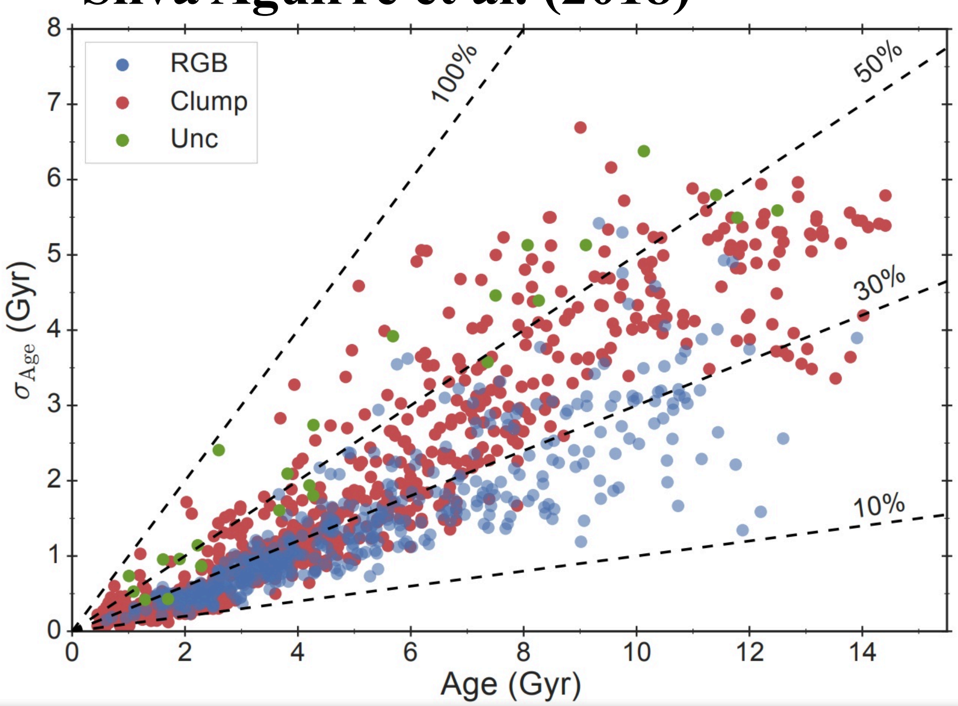
Casagrande et al. 2016



Anders et al. (2017)



Silva Aguirre et al. (2018)



Asteroseismic ages

Scaling relations

Individual frequencies

e.g., Silva Aguirre et al. (2017), Handberg et al. (2017) Buldgen et al. (2018).

Asteroseismic ages

Scaling relations

Individual frequencies

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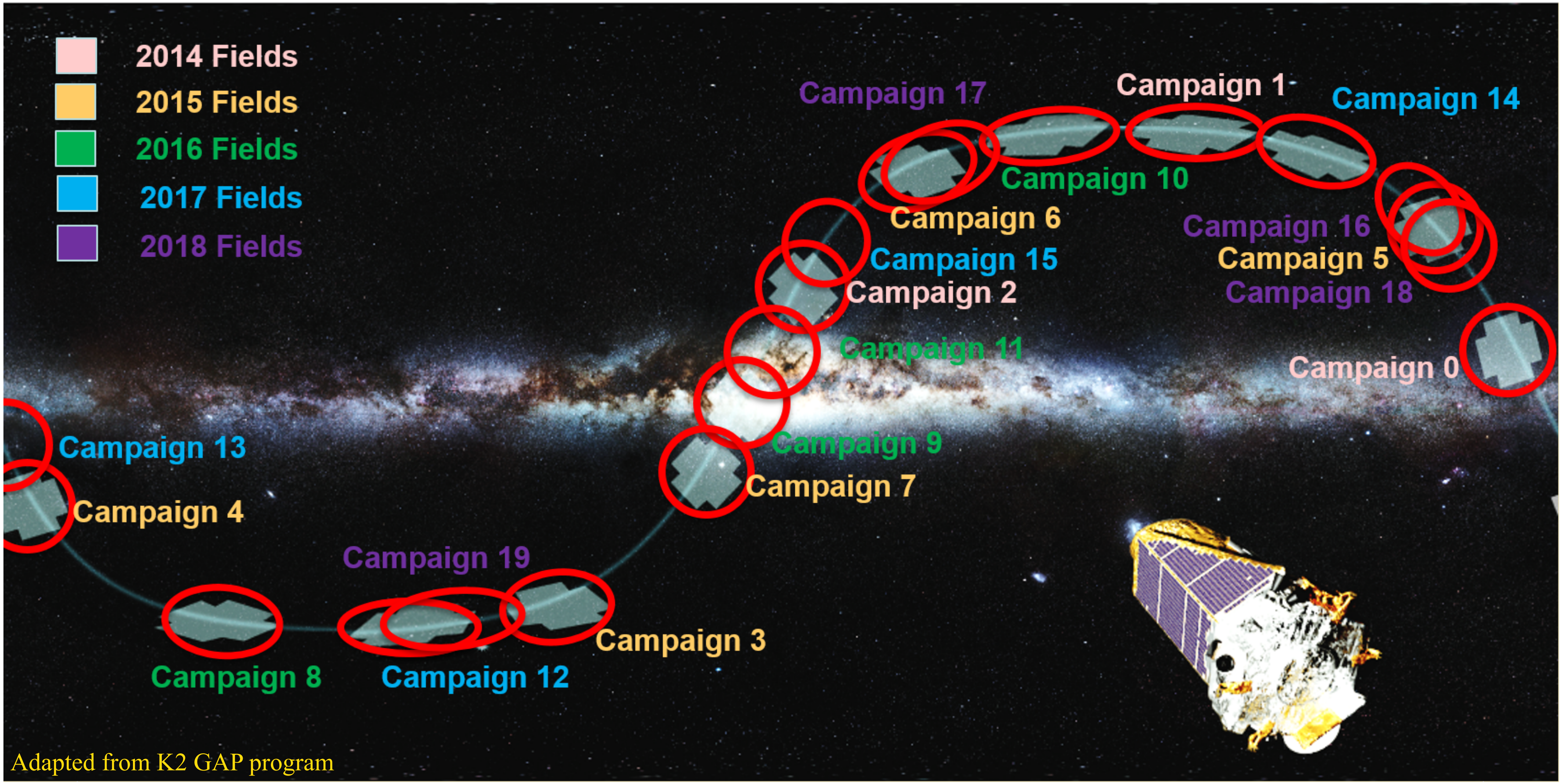
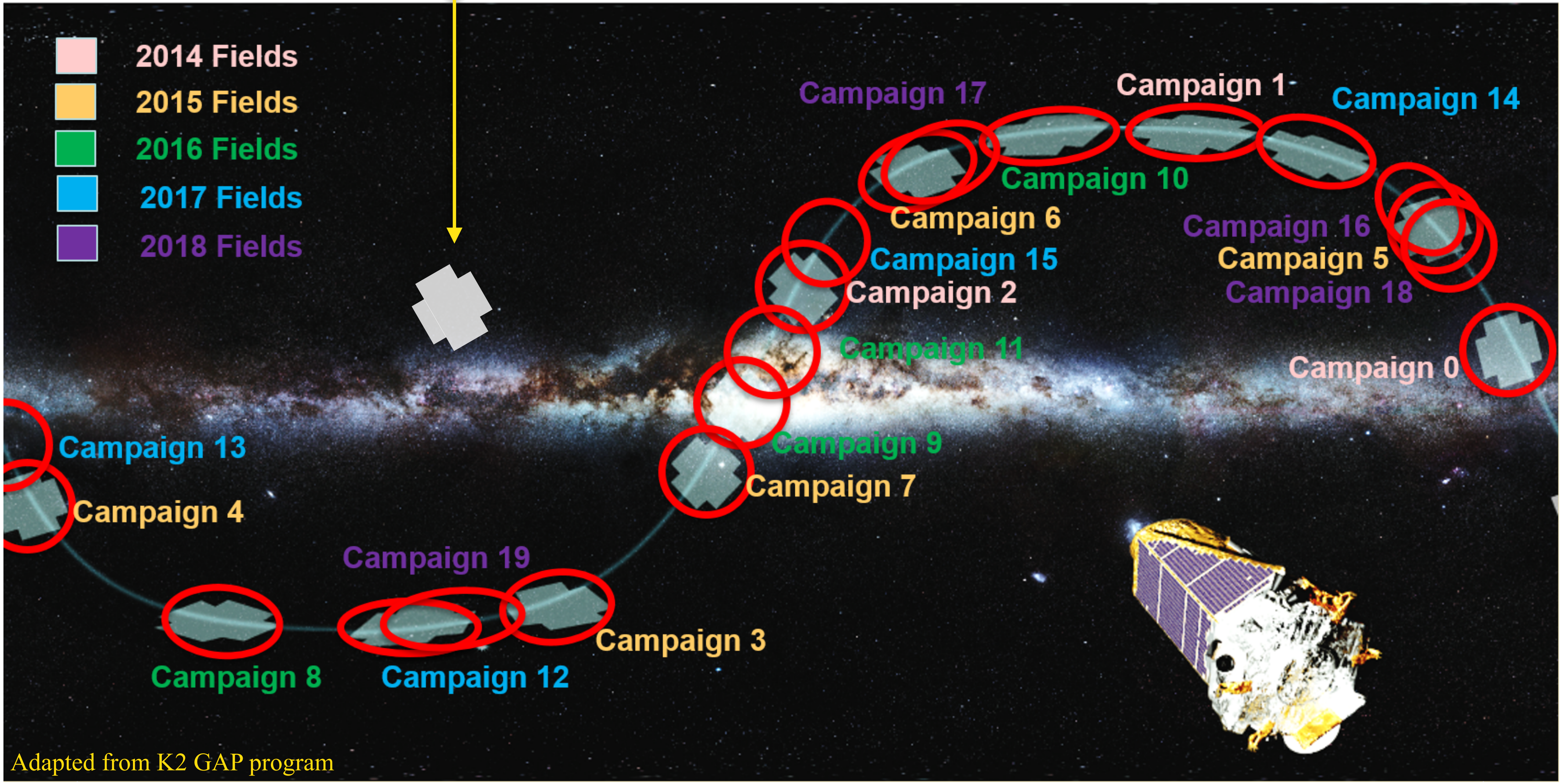
Data galore


2014 Fields
2015 Fields
2016 Fields
2017 Fields
2018 Fields
Campaign 17
Campaign 1
Campaign 14
Campaign 10
Campaign 6
Campaign 16
Campaign 15
Campaign 5
Campaign 2
Campaign 18
Campaign 11
Campaign 0
Campaign 13
Campaign 9
Campaign 7
Campaign 4
Campaign 19
Campaign 3
Campaign 8
Campaign 12
Adapted from K2 GAP program

Data galore

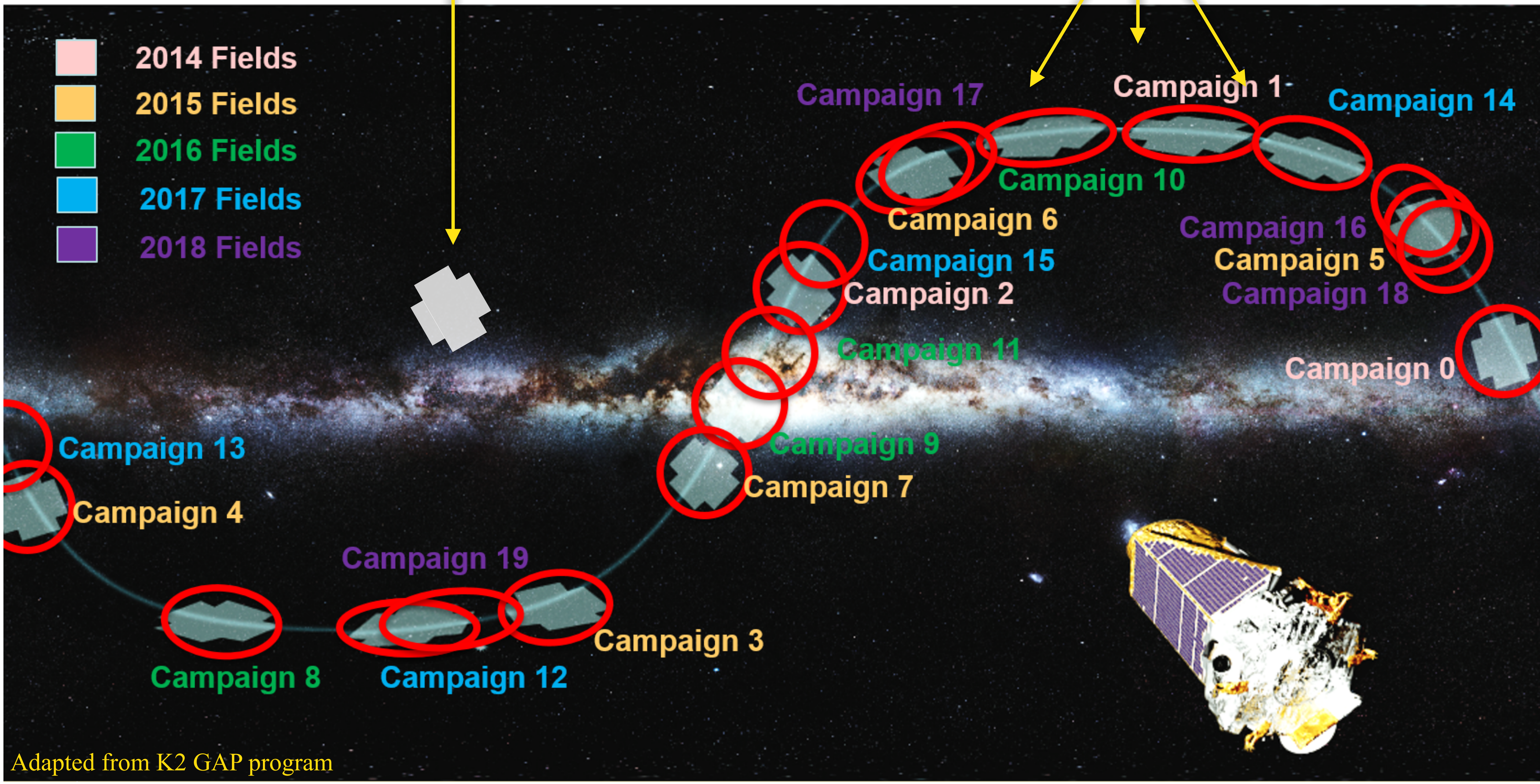
Kepler (4 years)



Data galore

Kepler (4 years)

K2 (80 days)



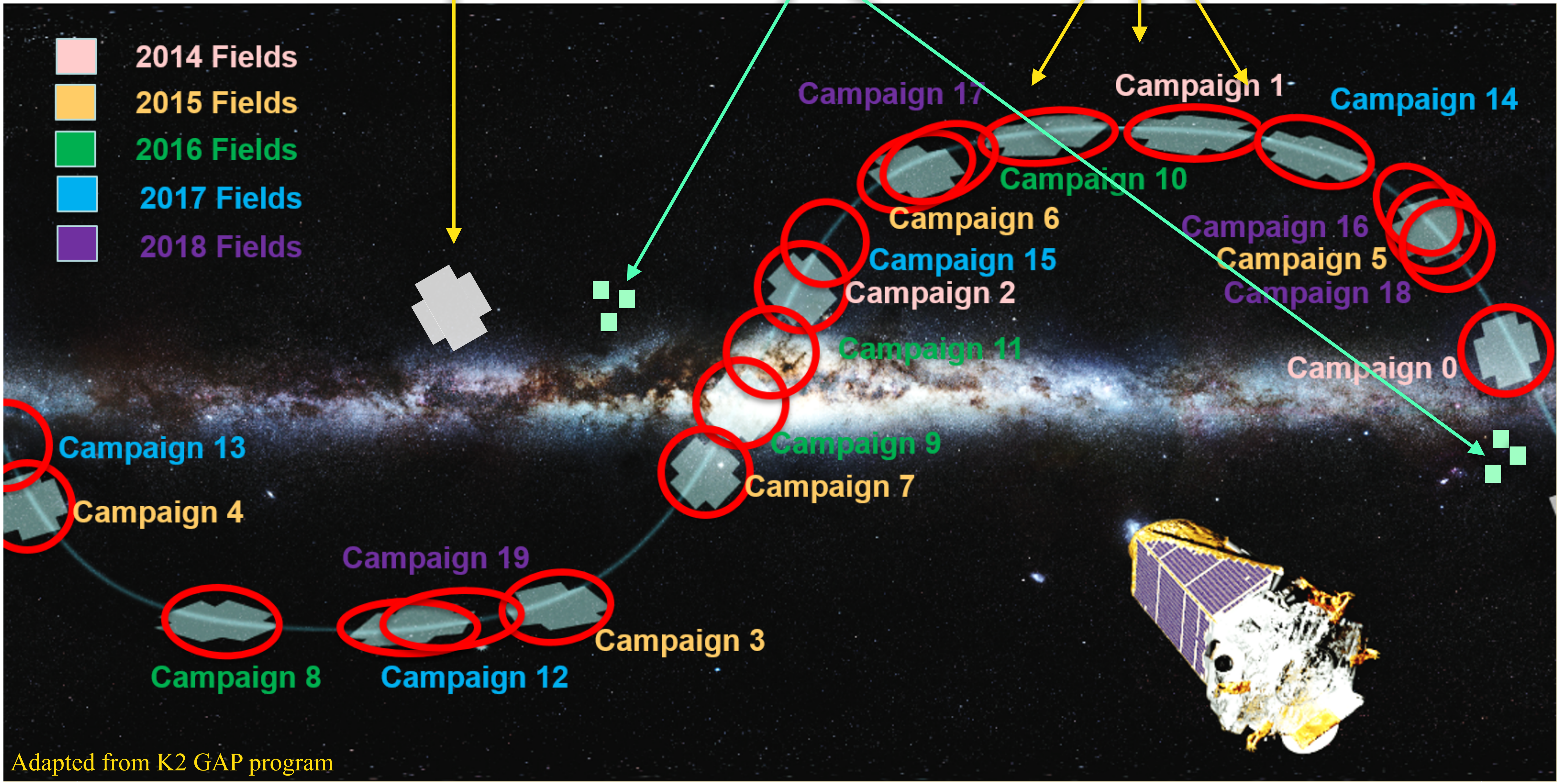
Adapted from K2 GAP program

Data galore

Kepler (4 years)

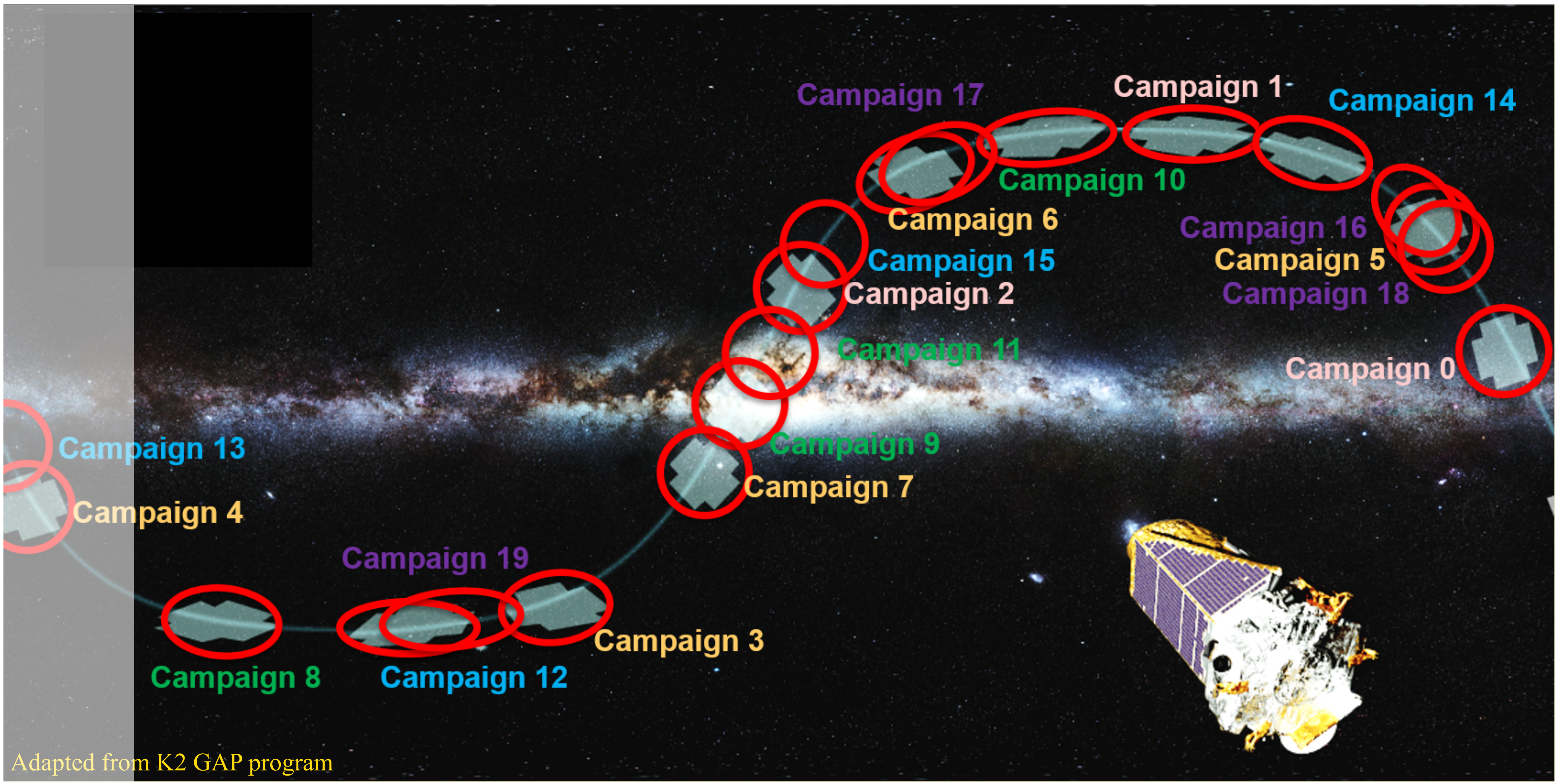
CoRoT

K2 (80 days)



Data galore

and now much more with TESS!



Data galore

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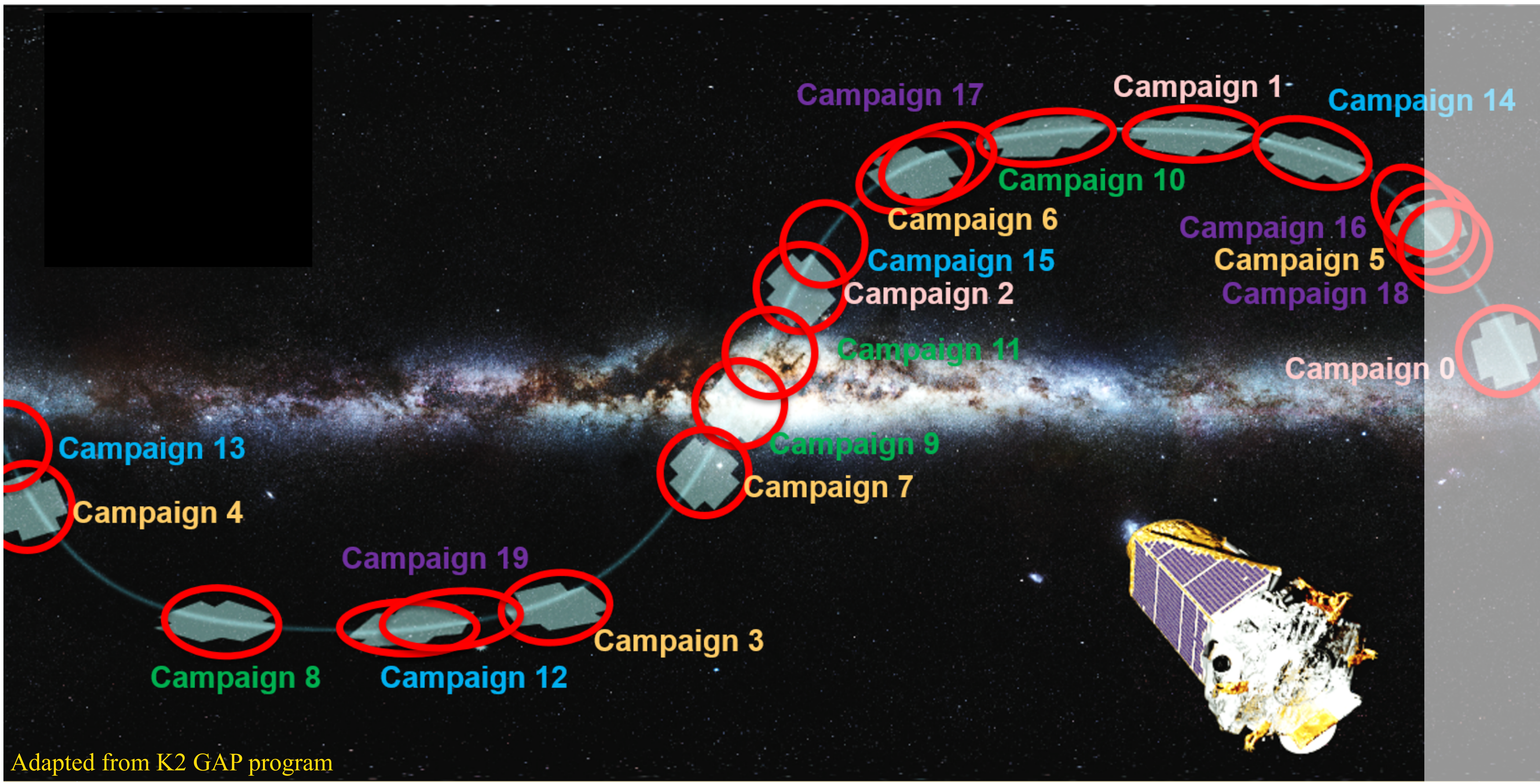
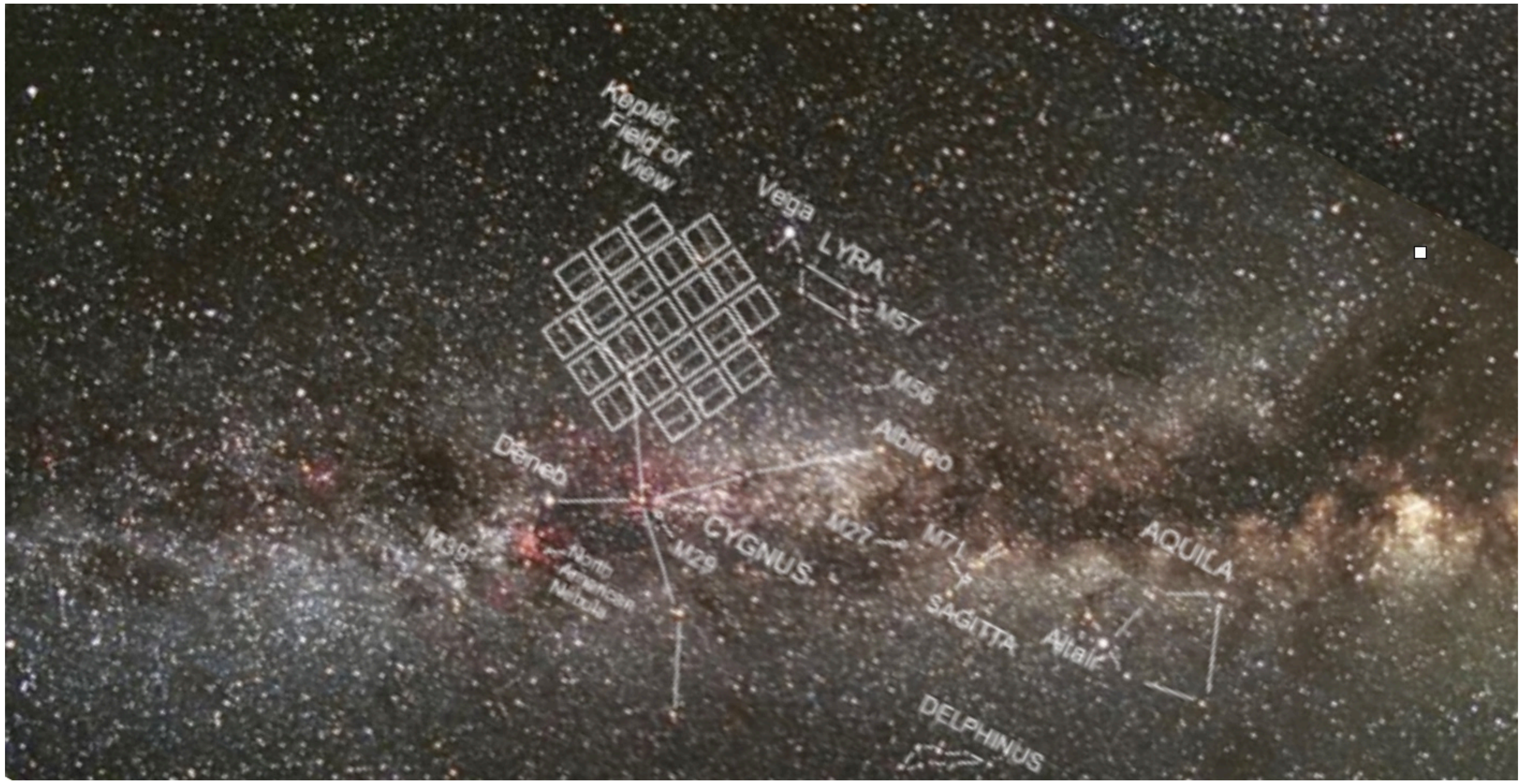
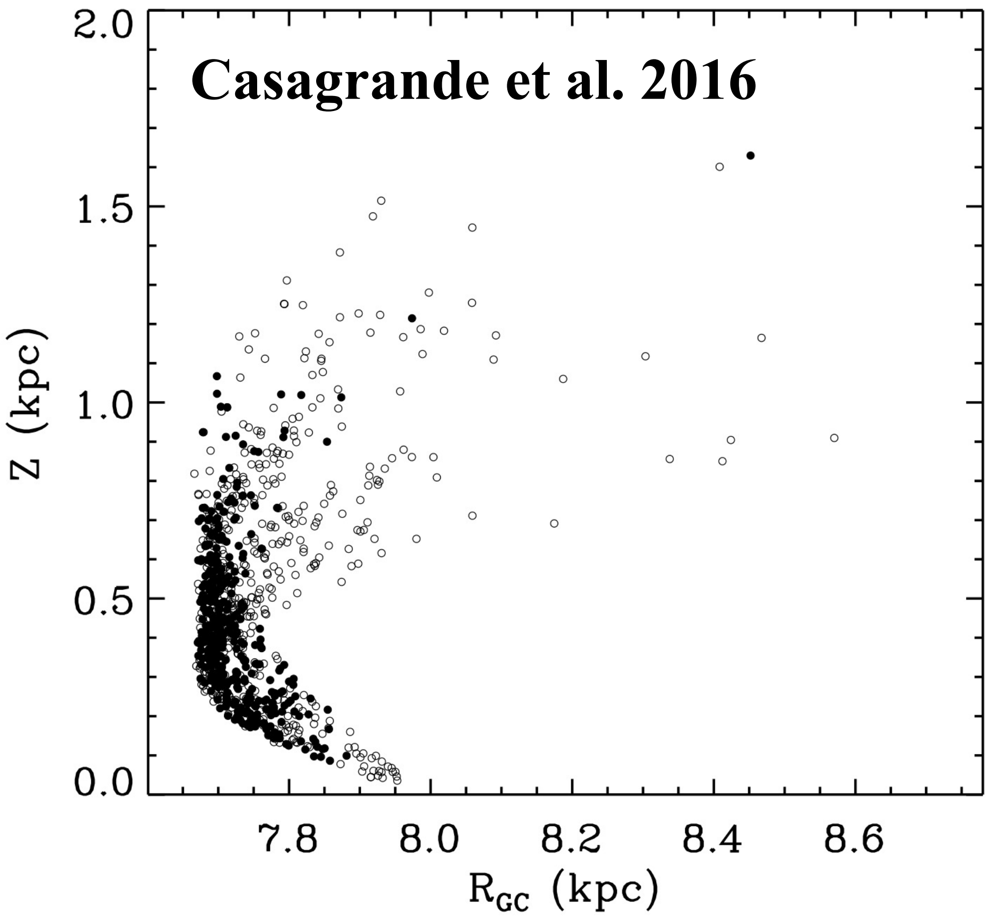


Kepler field

Nearly constant Galactocentric radius, thus making it ideal to study the vertical structure of the disc.





Strömgren surveys for Asteroseismology

Casagrande et al. (2014, 2016)

There was not a selection function for Kepler seismic targets (only for exoplanets).

Photometric surveys on the INT telescope, to derive stellar parameters, and to recover a proper selection function for seismic targets.

Kepler

Strömgren surveys for Asteroseismology

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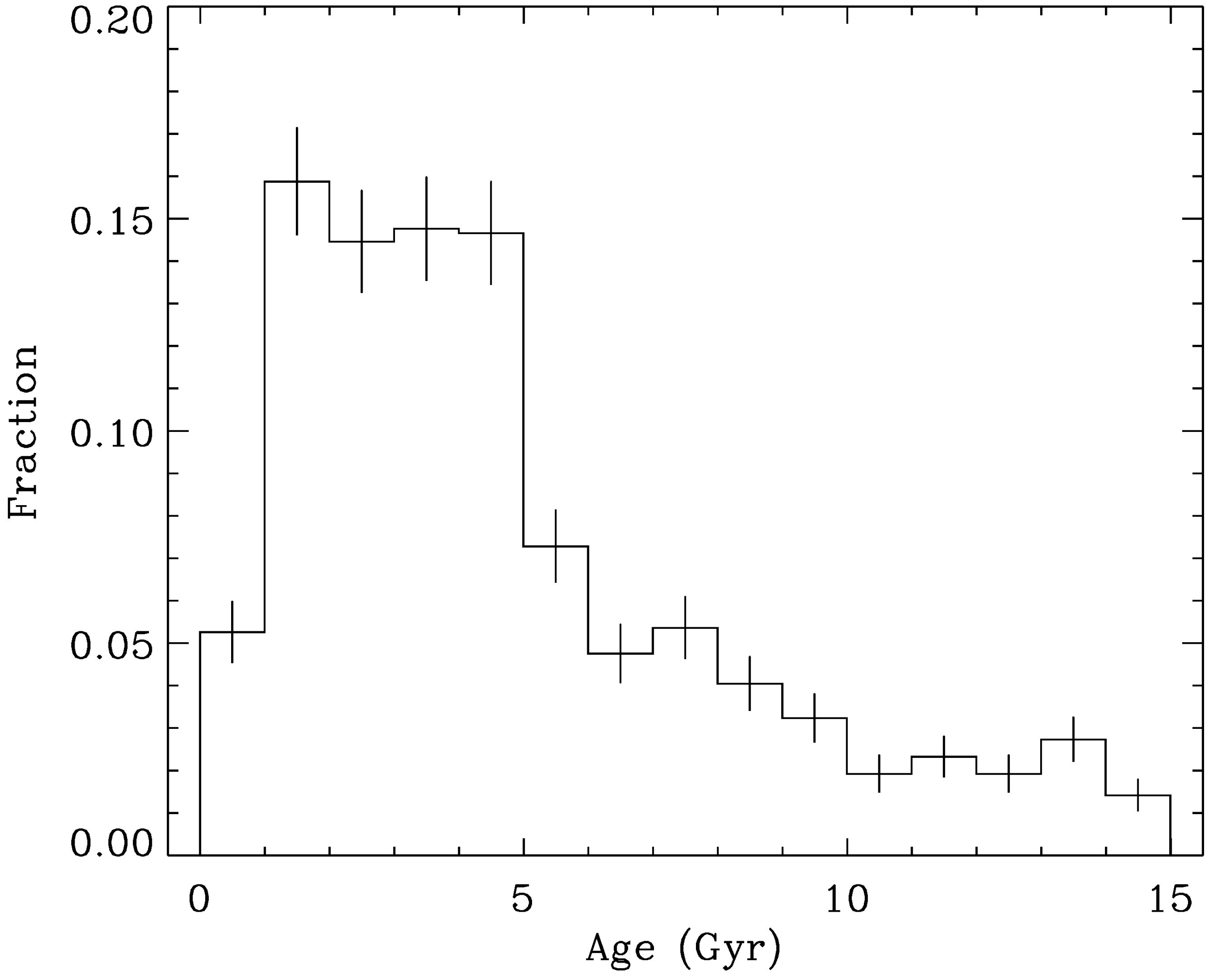
distribution of stellar ages



Strömgren surveys for Asteroseismology

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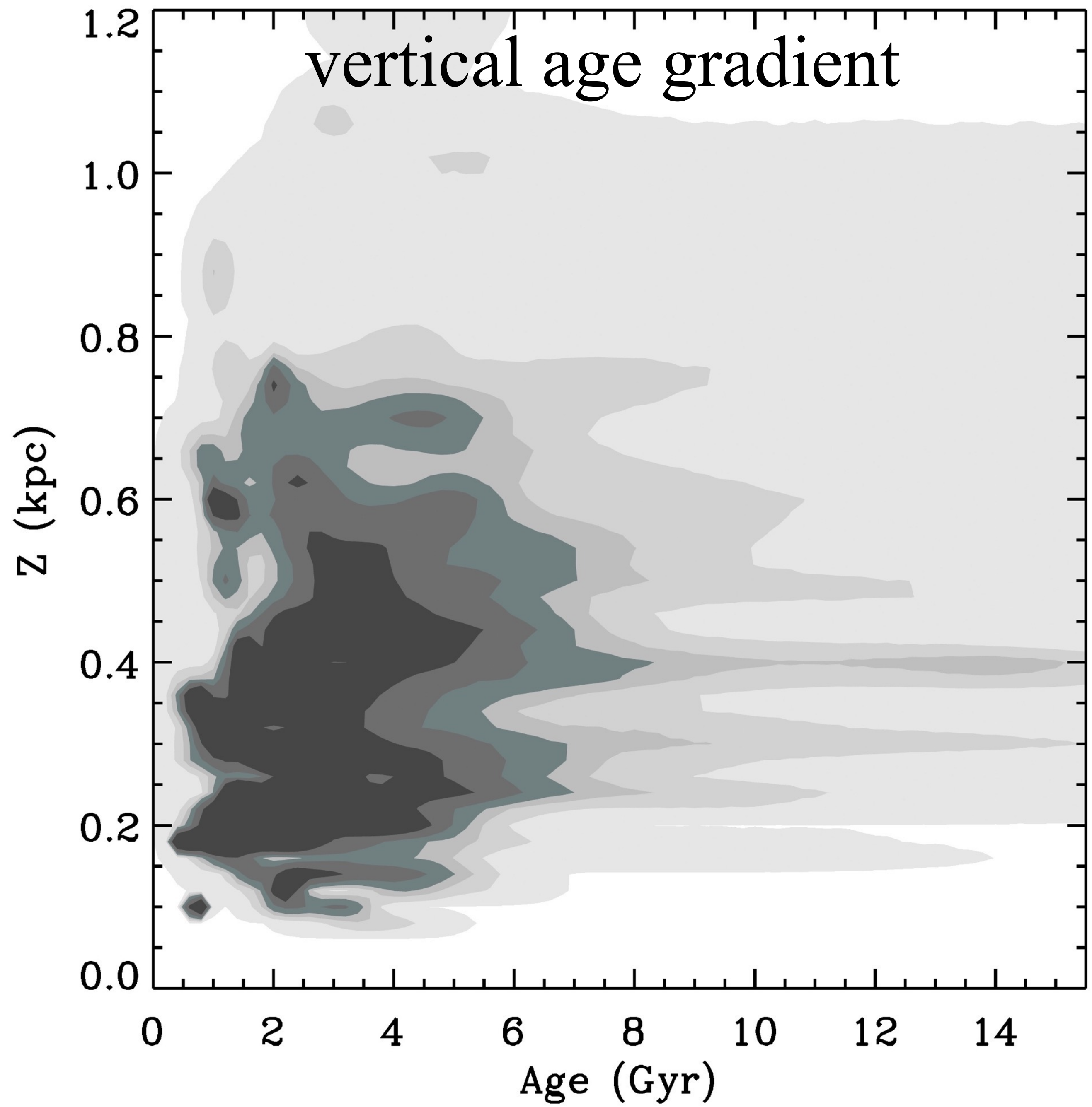
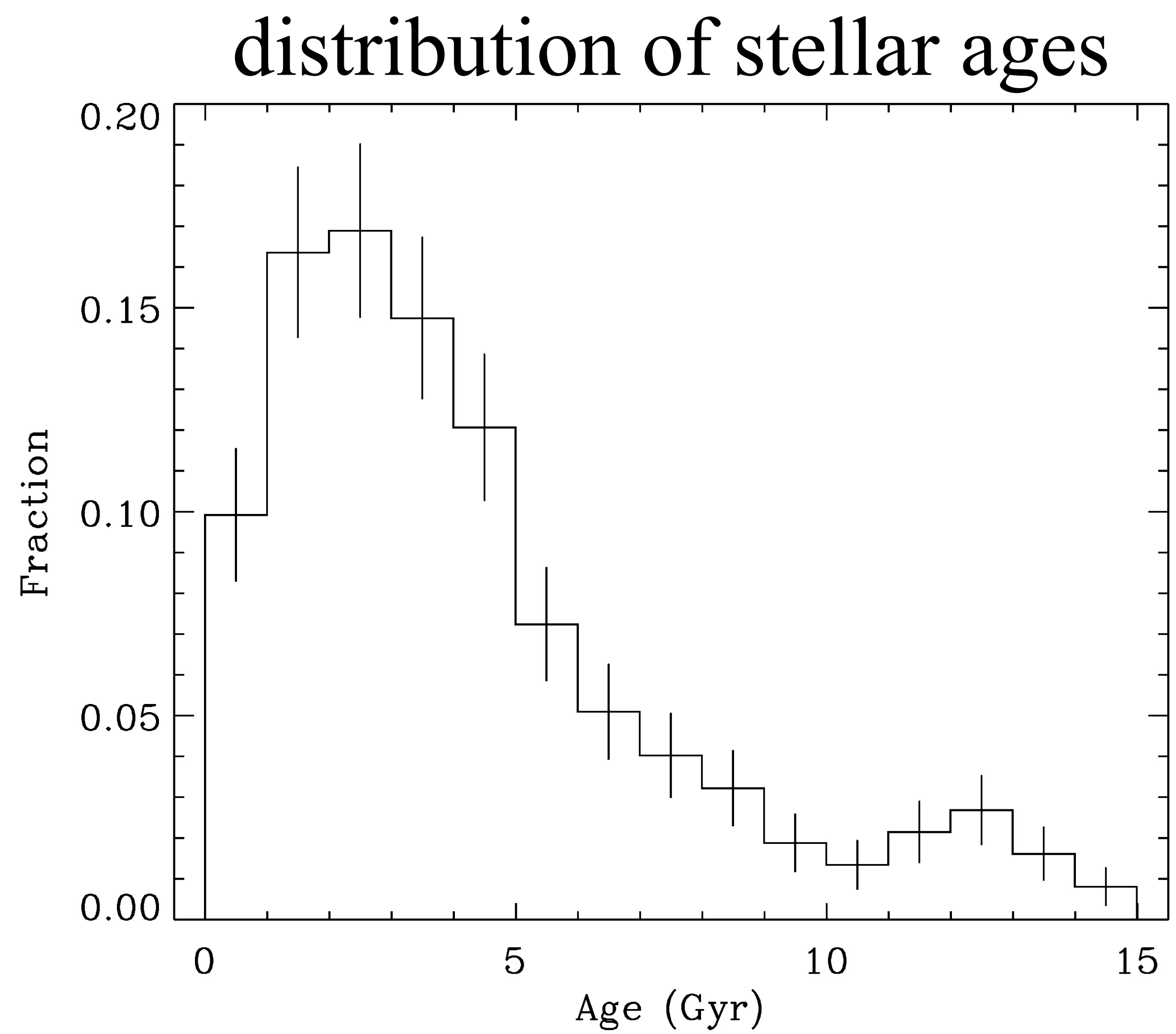
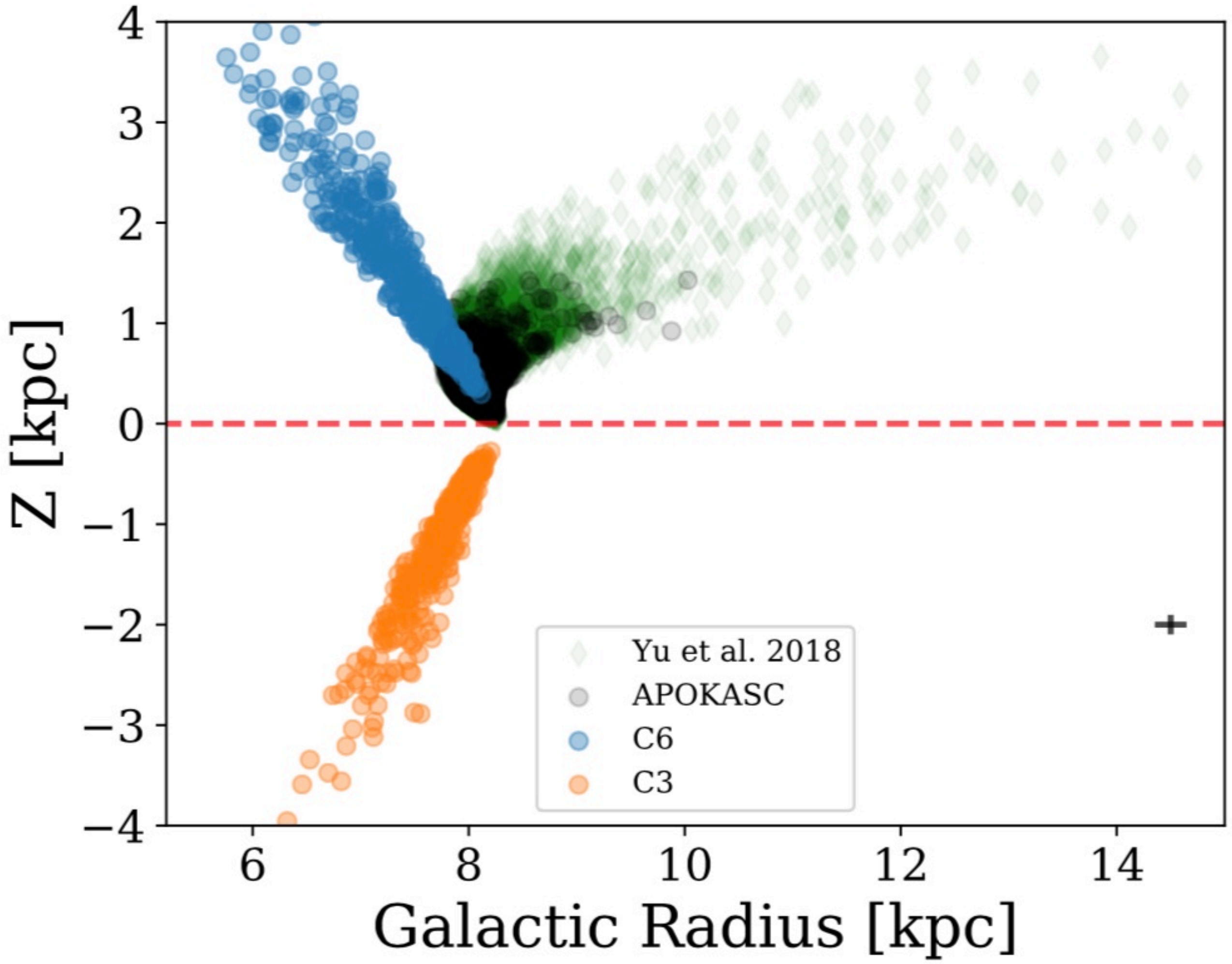




Vertical age structure beyond Kepler

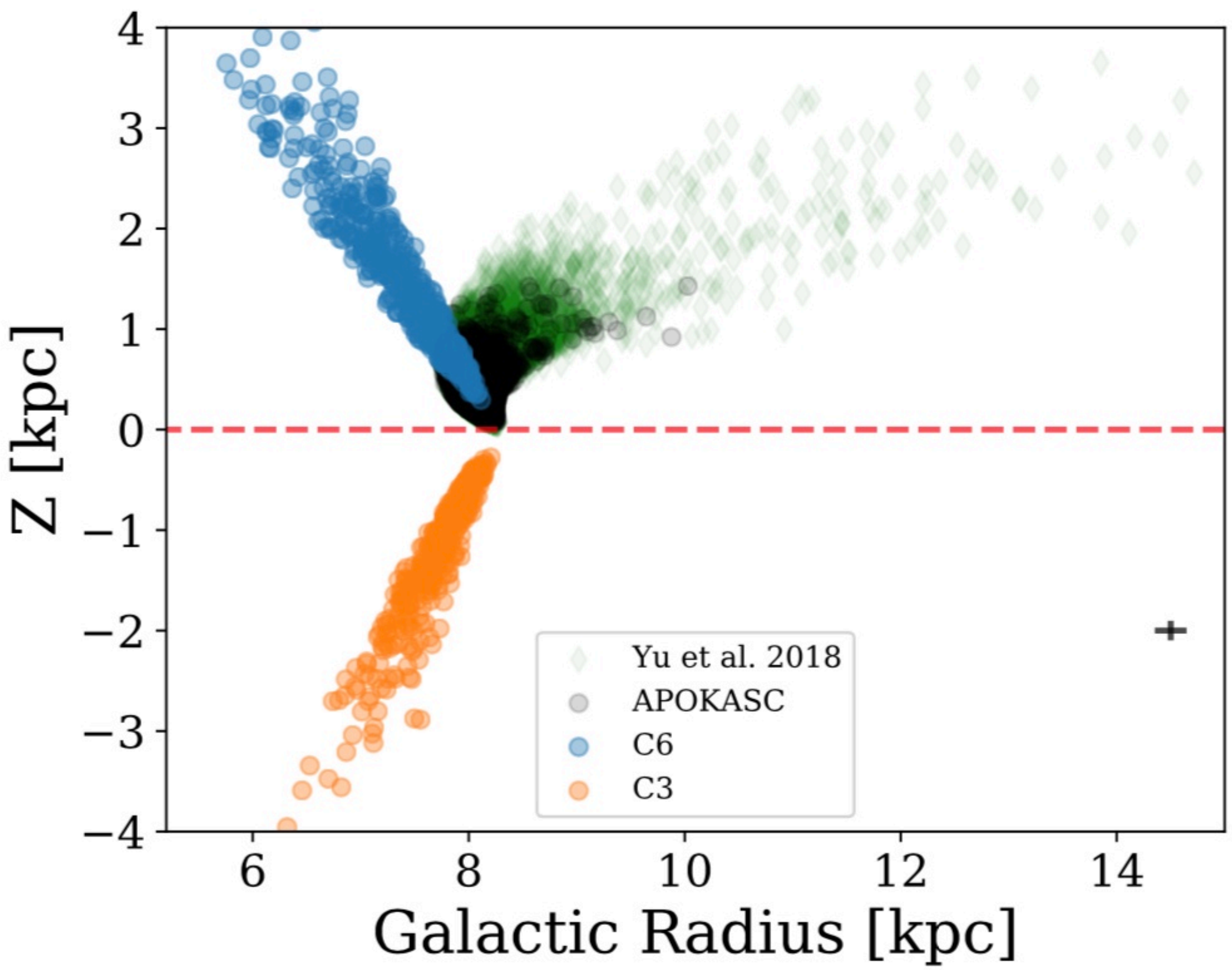
Rendle et al. (submitted)



Survey	C3	C6
K2	483	929

Vertical age structure beyond Kepler

Rendle et al. (submitted)



Survey	C3	C6
K2	483	929
K2 SM	377	646
RAVE	85	83
Gaia-ESO	38	-
APOGEE	101	25
K2 Spec.	128	102

70-80% of targets

10-20% of targets

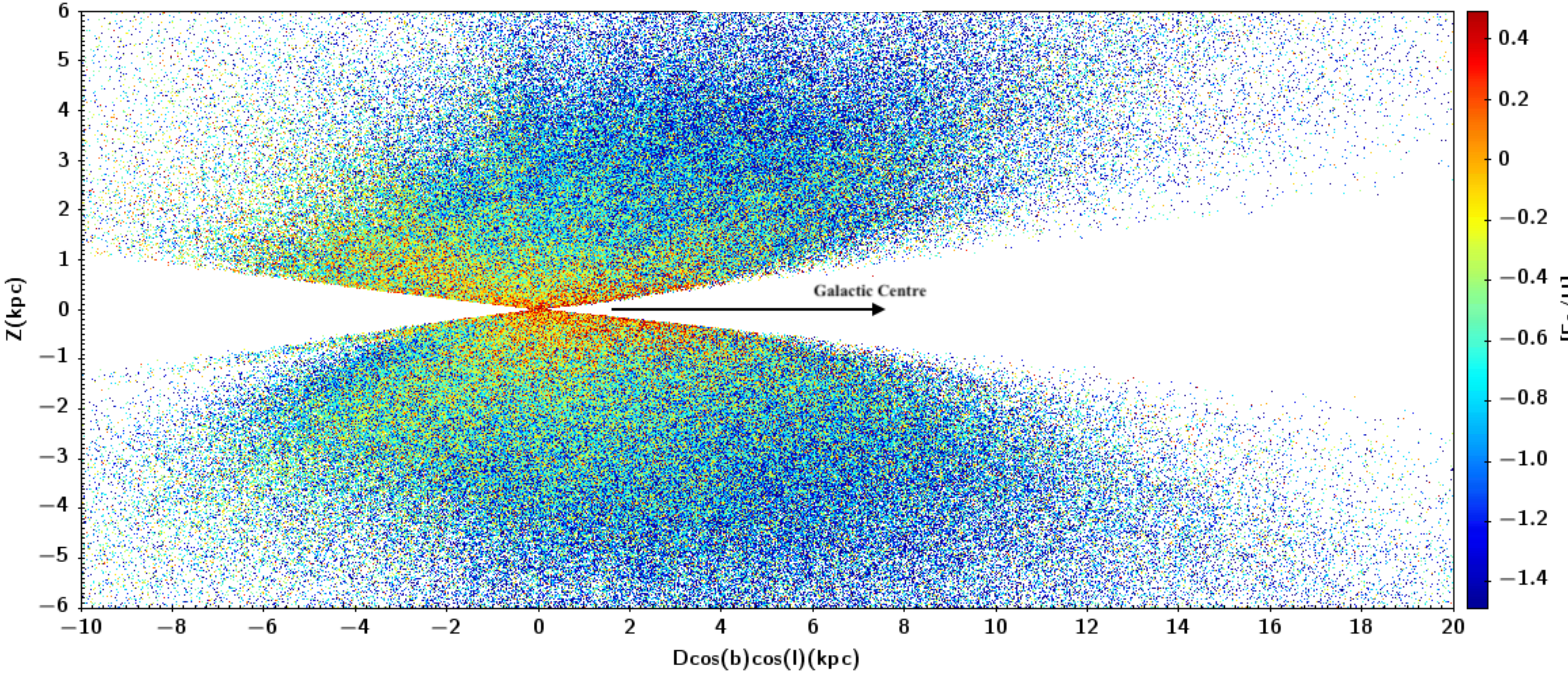
SkyMapper Southern Sky Survey

Wolf et al. (2018), Onken et al. (2019)

uvgriz photometry (300-1000nm) for the entire southern sky.
Ideal to derive stellar parameters.

SkyMapper metallicities for 9 million stars

Casagrande et al. (2019)



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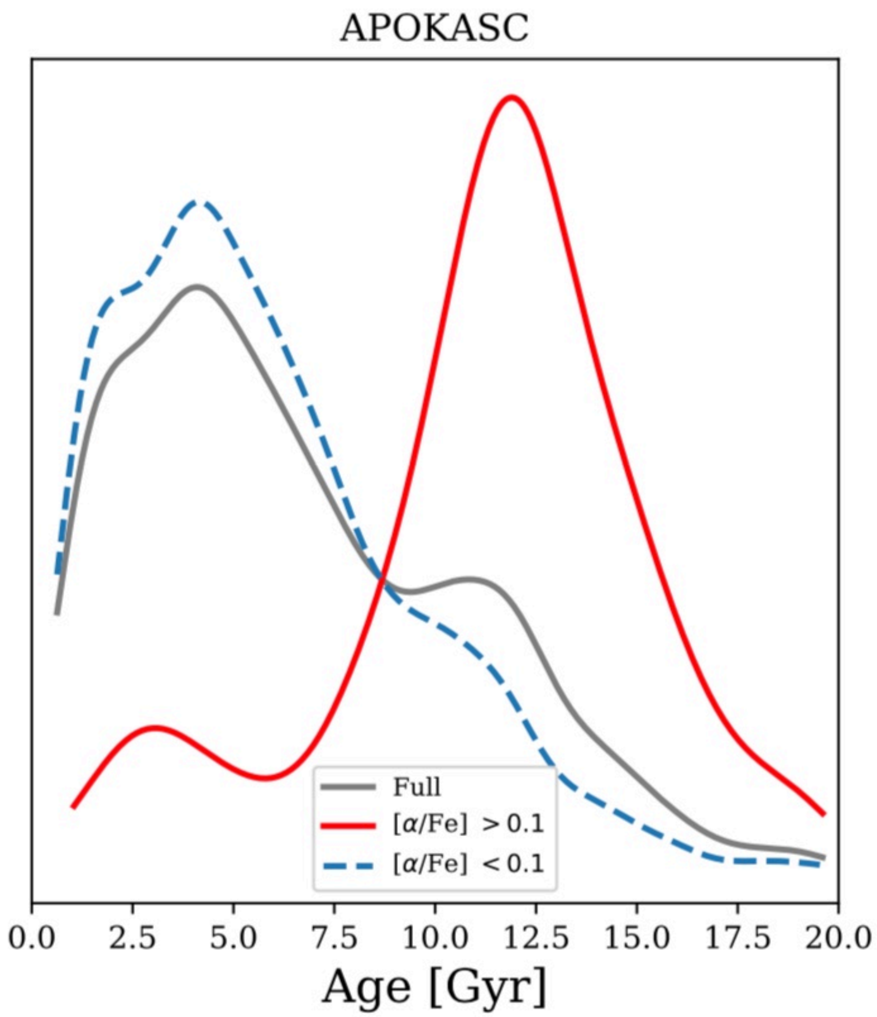


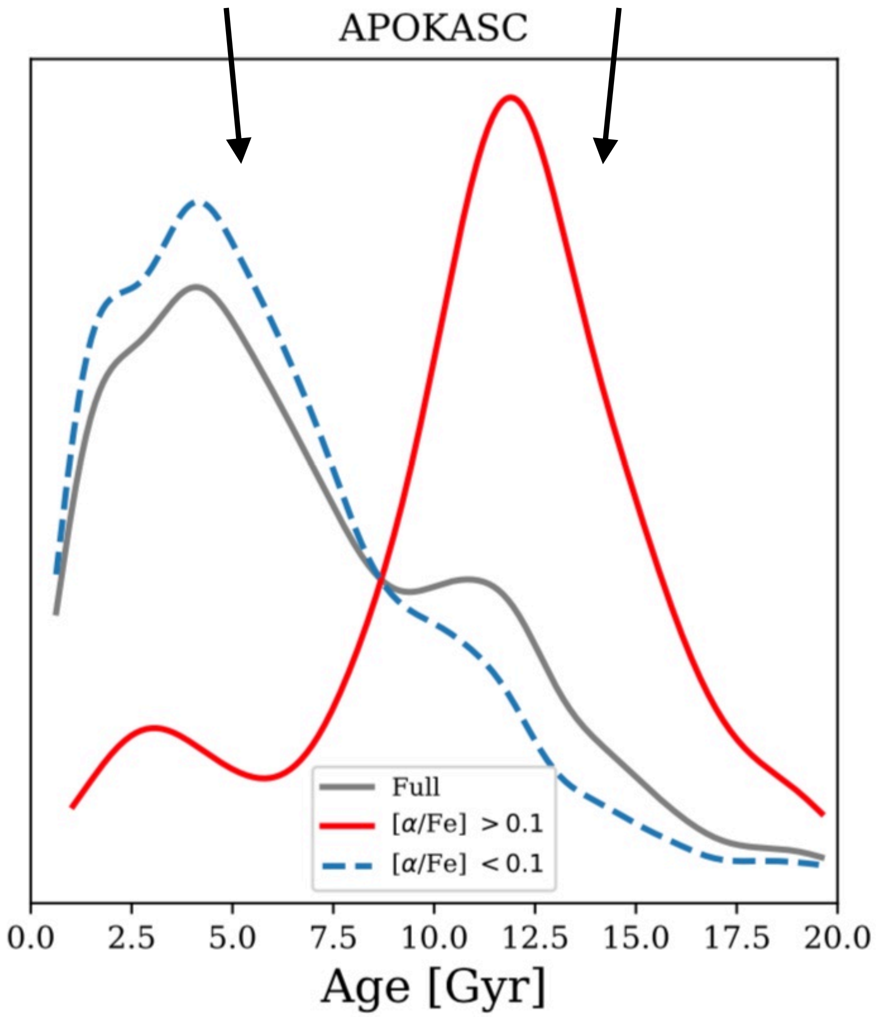
all distributions are normalised to equal area

Vertical age structure beyond Kepler

Rendle et al. (submitted)

thin thick

see also Silva Aguirre et al. (2018)
and talk by Jane Lin tomorrow



all distributions are normalised to equal area

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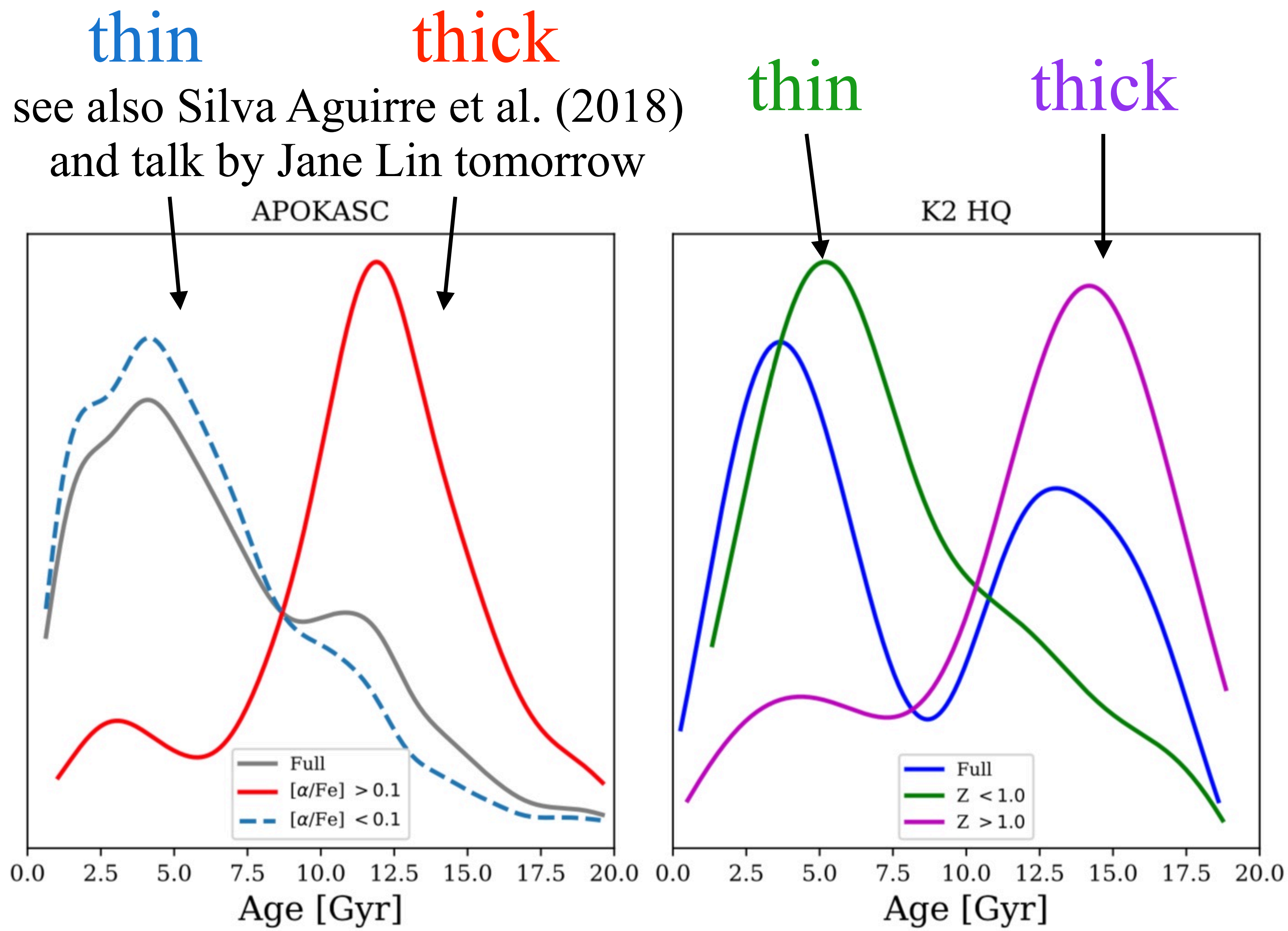

all distributions are normalised to equal area

Vertical age structure beyond Kepler

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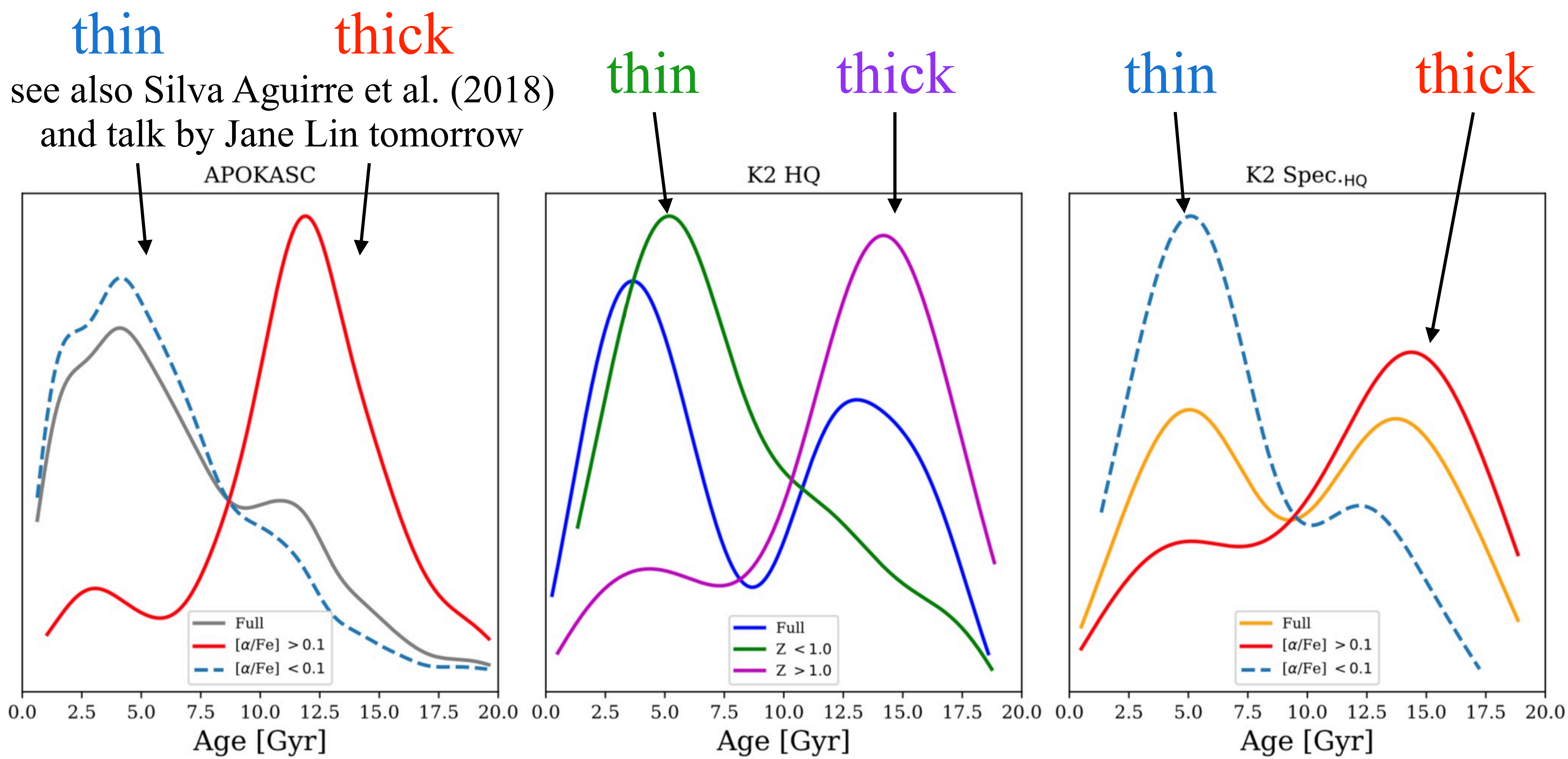
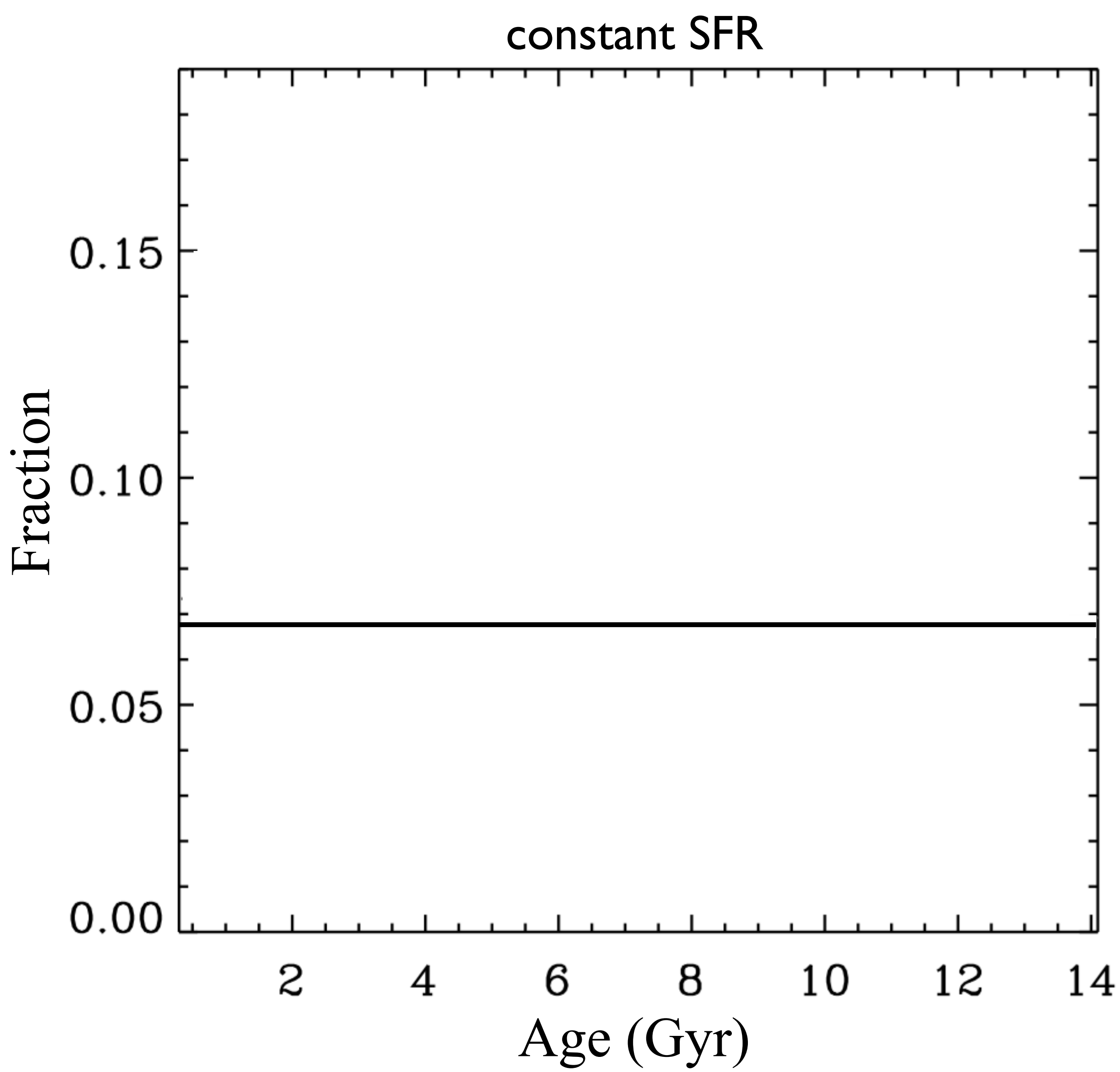
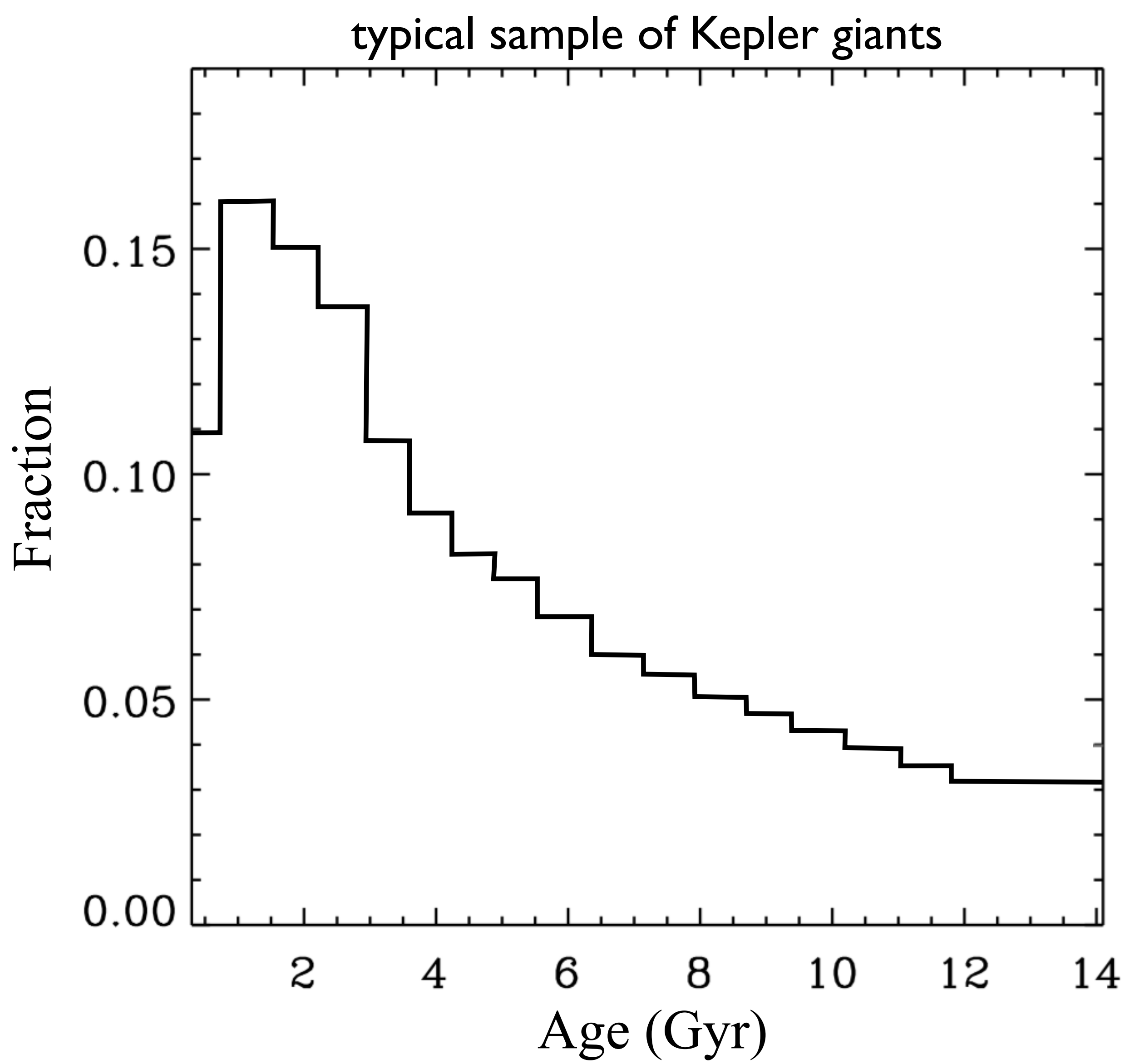


all distributions are normalised to equal area

Distribution of stellar ages

heavily biased by target selection effects





Distribution of stellar ages

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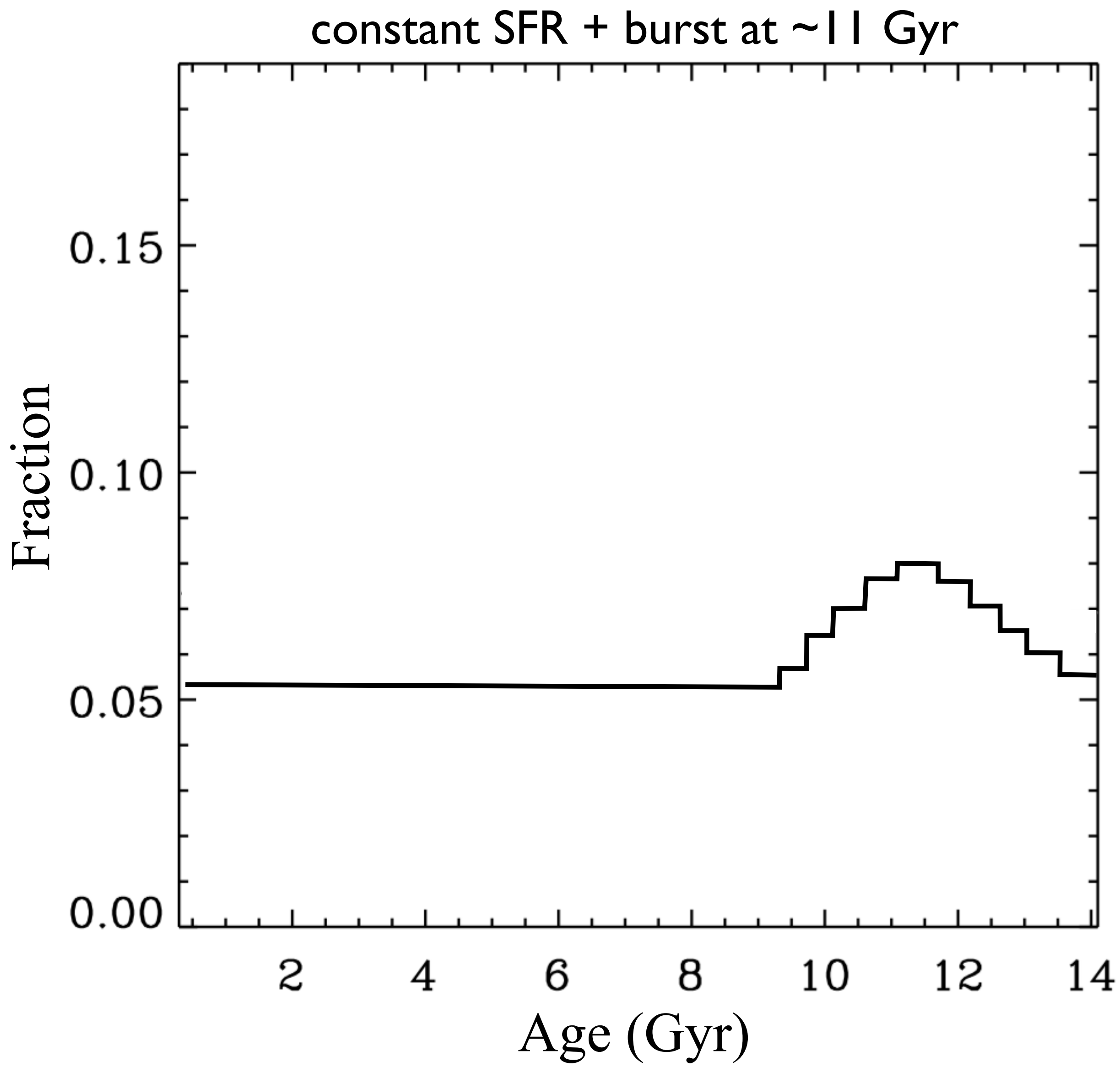
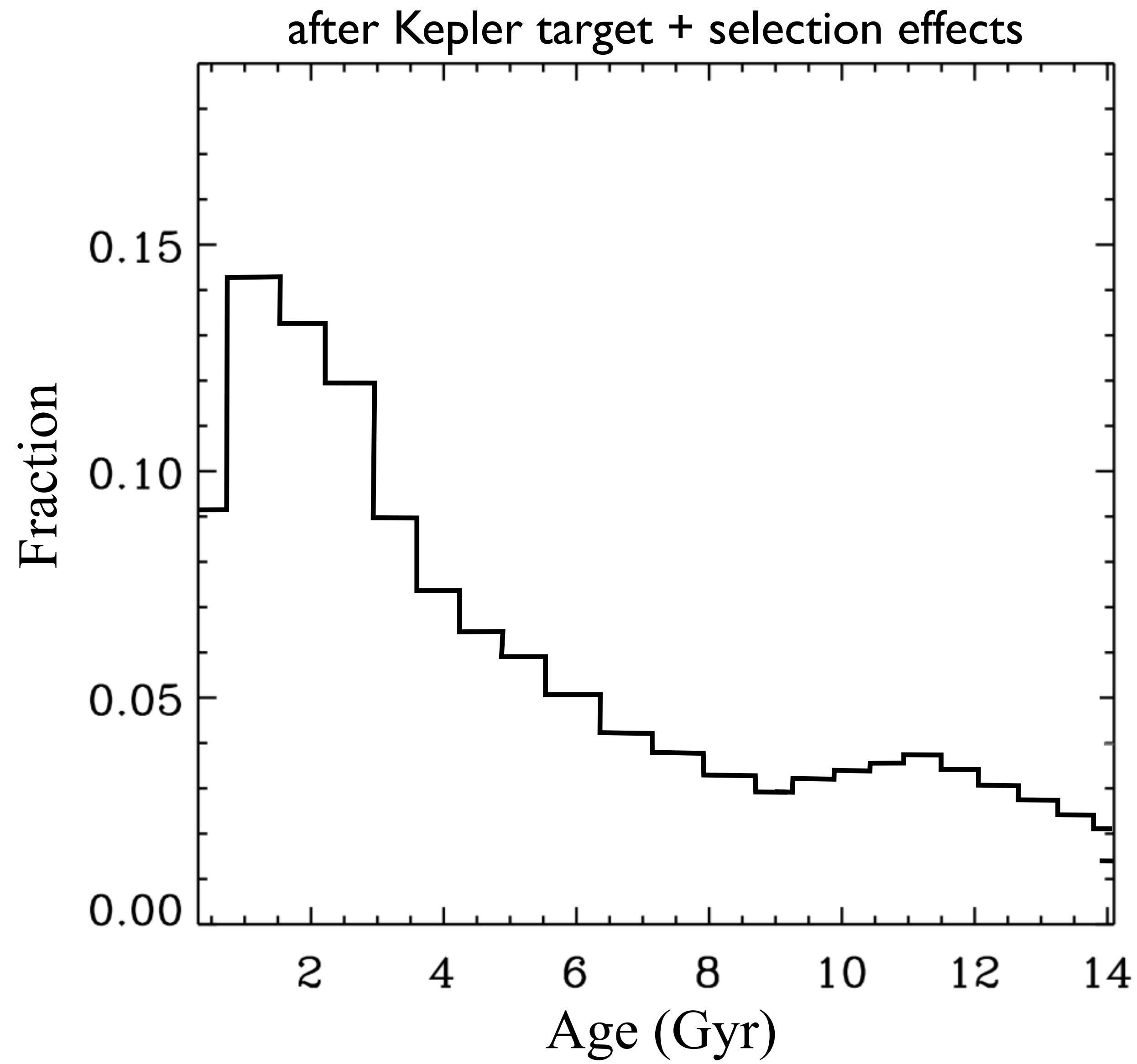
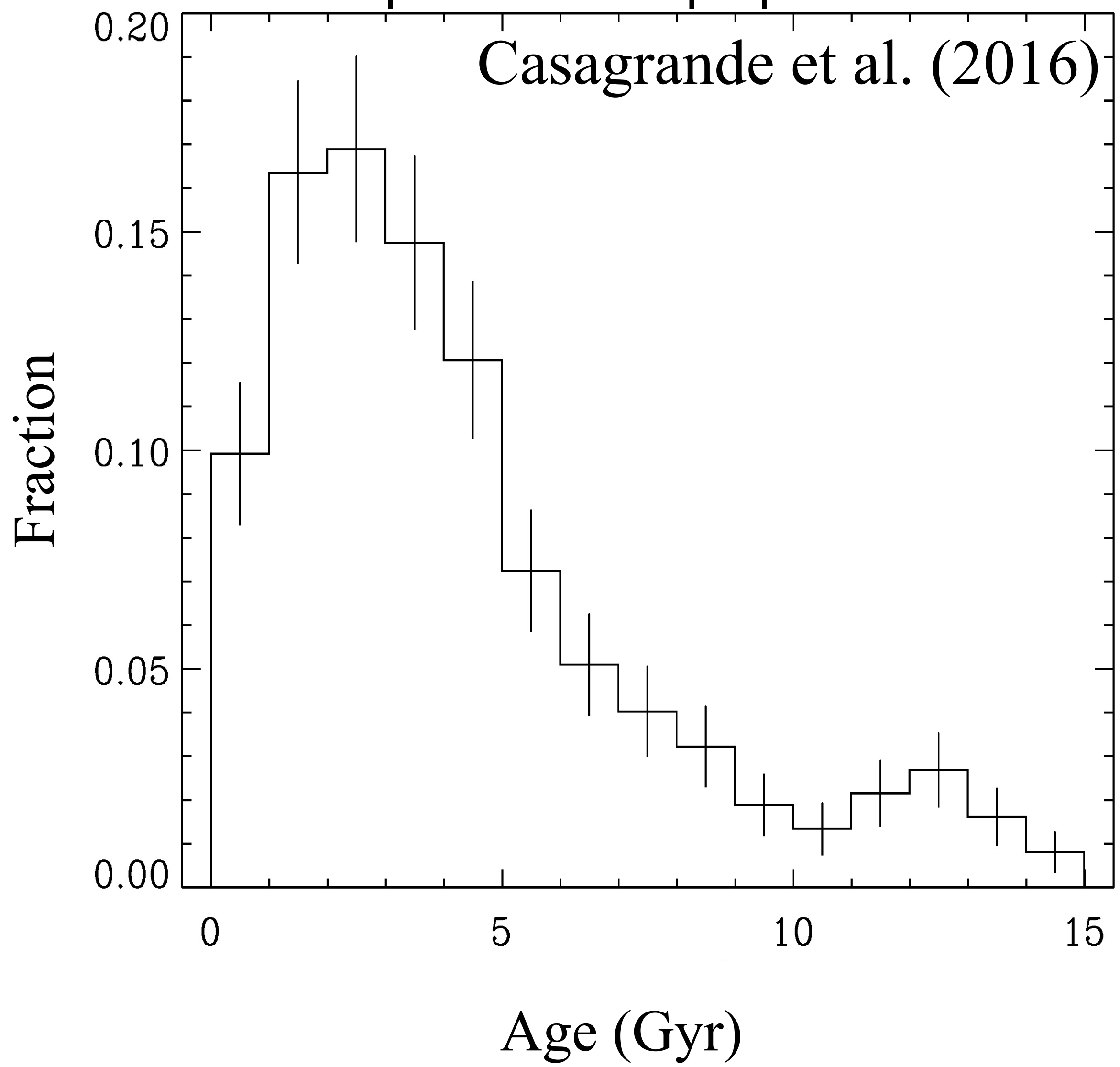




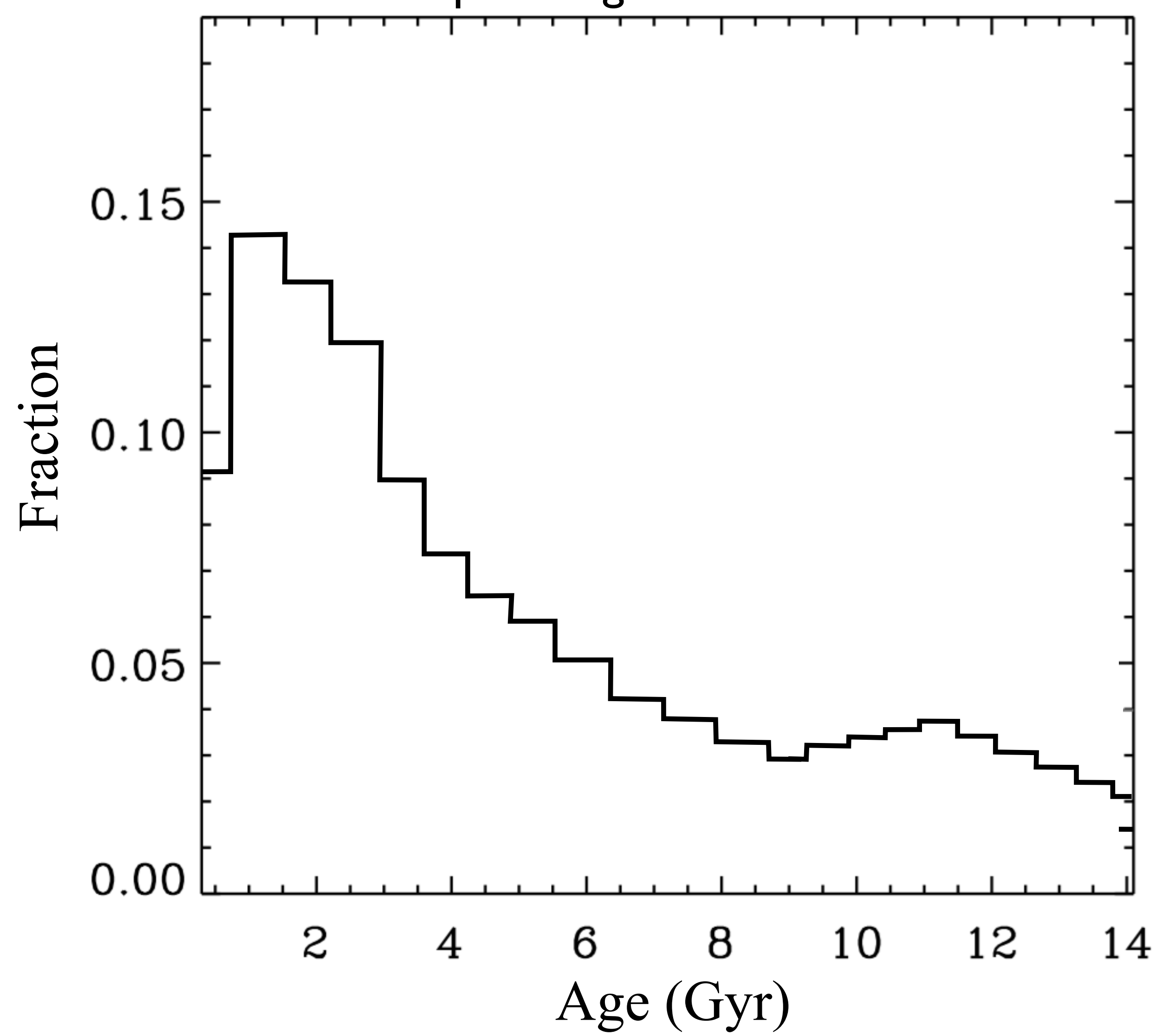
Distribution of stellar ages

heavily biased by target selection effects

observed in Kepler field with proper selection function

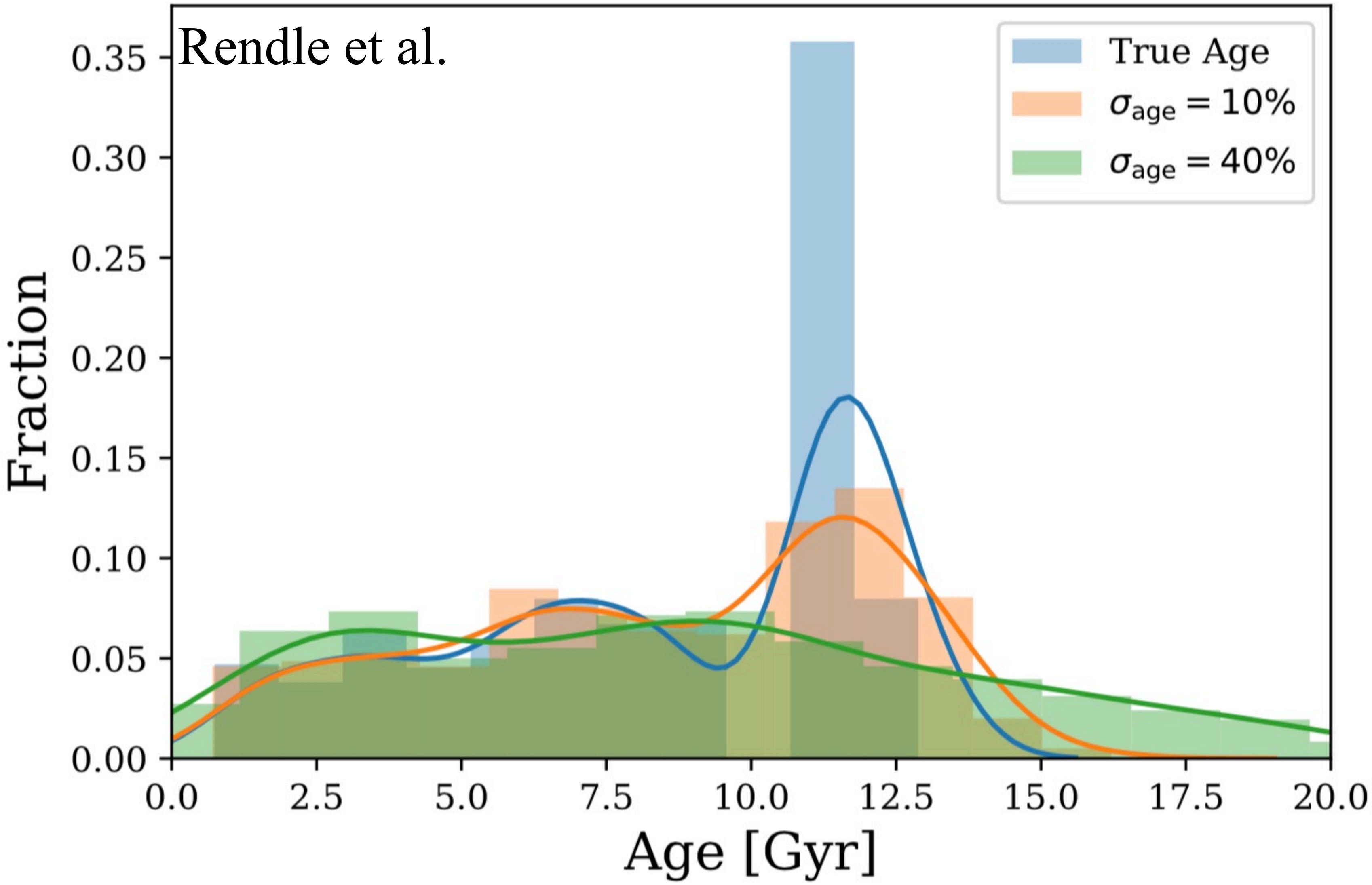


after Kepler target + selection effects



Distribution of stellar ages

smoothed by uncertainties



Age distribution from a synthetic Milky Way model (blue) once different age uncertainties are applied.

Asteroseismology & better stellar ages

Asteroseismic ages for solar-like oscillators

→ pure scaling relations

→ corrections to scaling relations

→ grid-based modelling

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Age uncertainties around 30%

Asteroseismology & better stellar ages

Asteroseismic ages for solar-like oscillators →

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Age uncertainties around 30%

Good enough to start seeing major events/epochs in the history of the Milky Way. However modelling of target selection effects is as important as having good ages.