Chronology of our Galaxy from Gaia CMD-fitting:
dynamically evolved star formation histories of the Milky Way

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ChronoGal core team:

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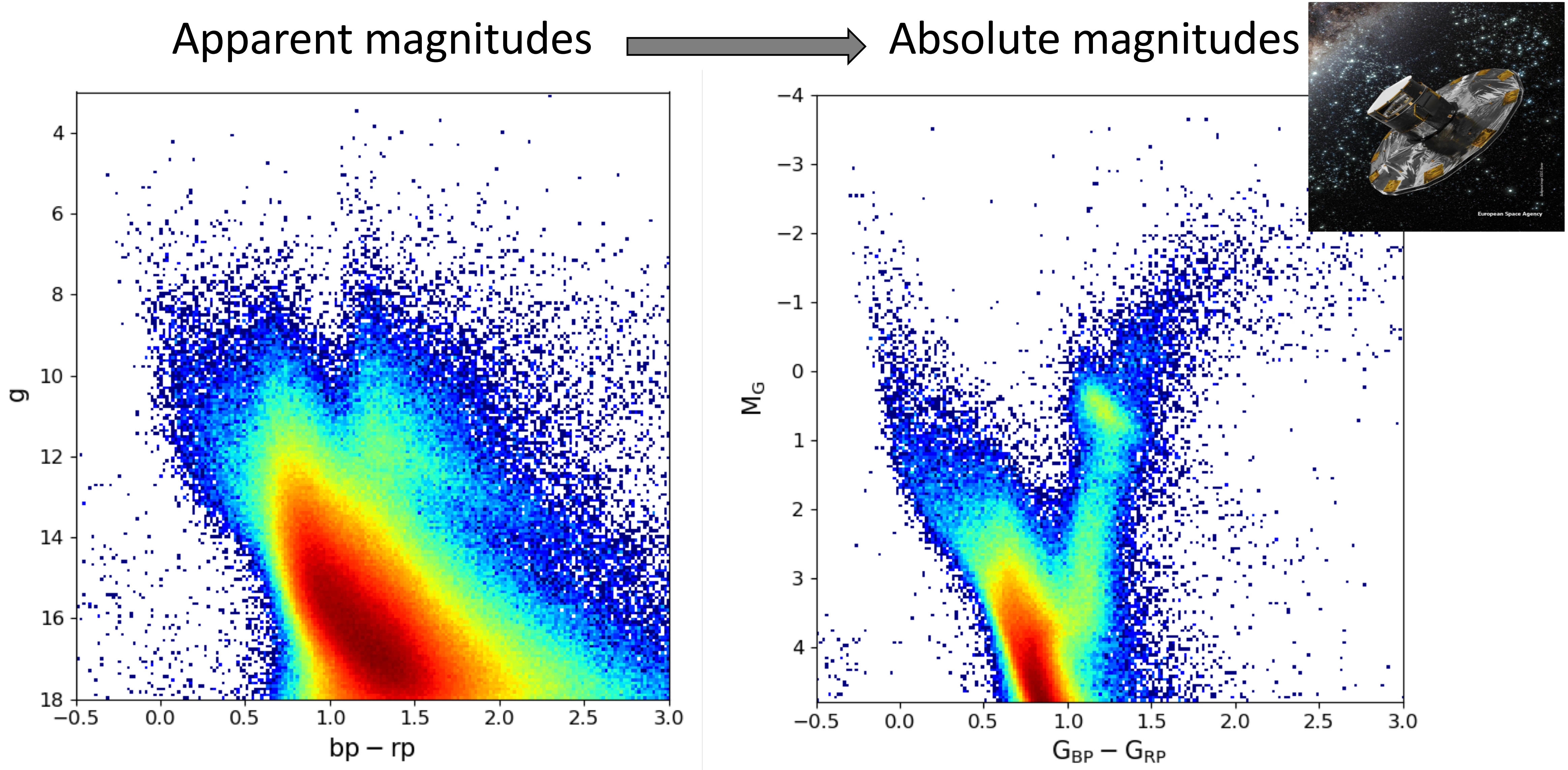
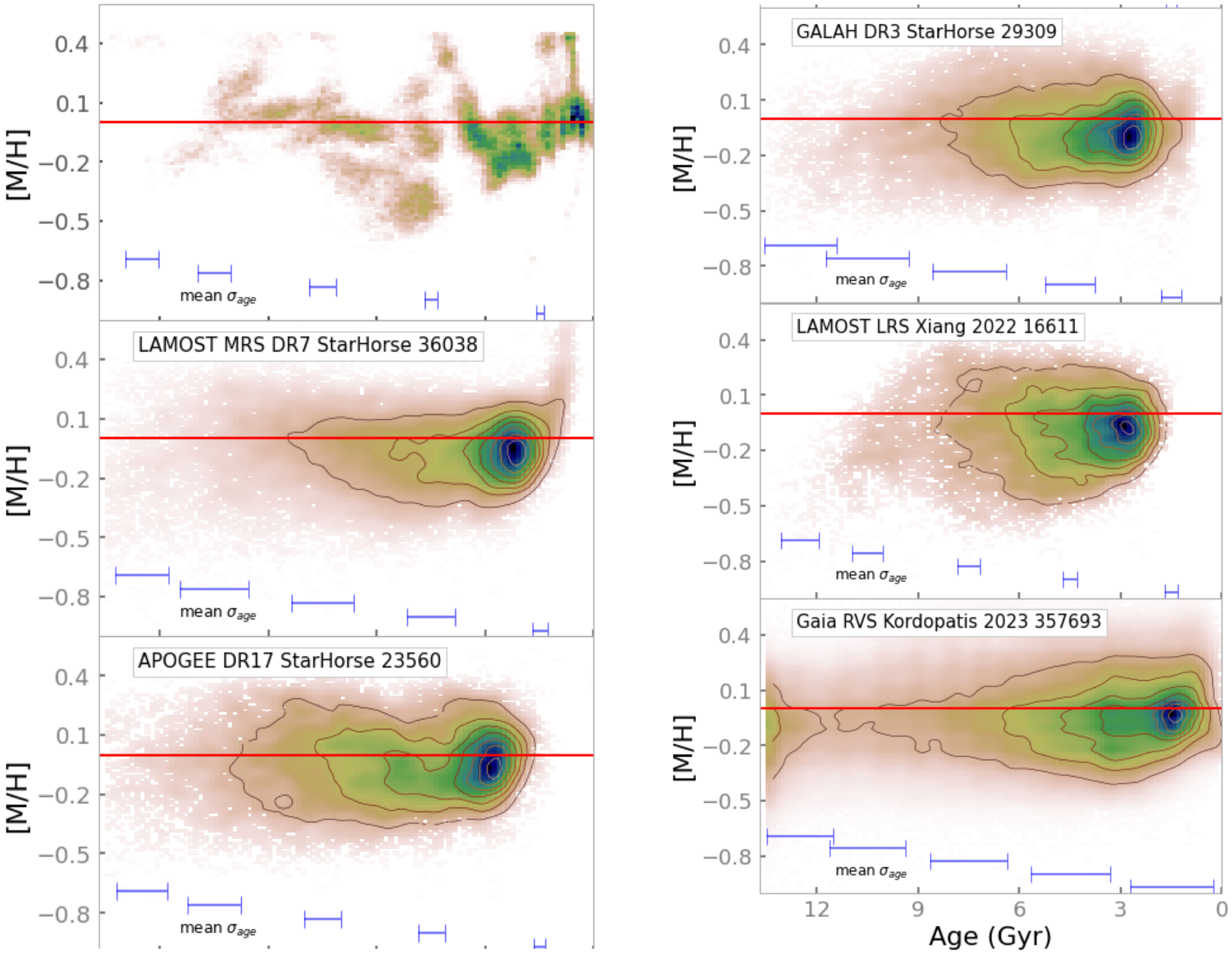
esa gaia

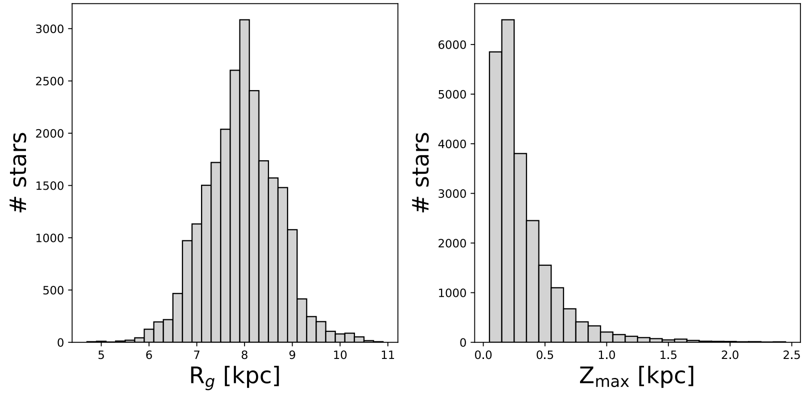
Derivation of the **Milky Way SFH** through **Gaia CMD fitting**

Apparent magnitudes → Absolute magnitudes



Comparison with age-metallicity distributions from individual star ages





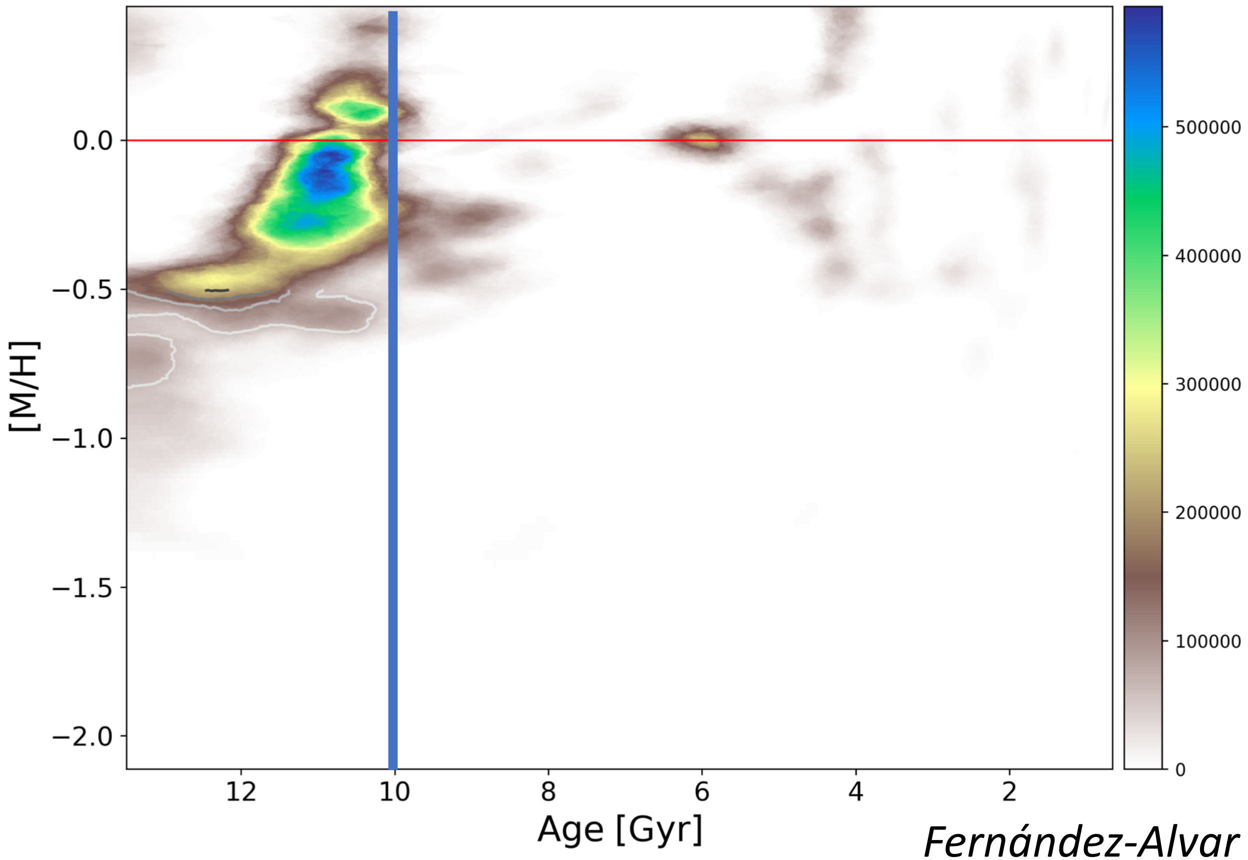
-The difference is due to the **increased precision** in age and [M/H]

-An important difference, not visually apparent, is that **we provide the actual number of stars in the different events of star formation//mass involved**

-We **don't derive individual stellar ages.**

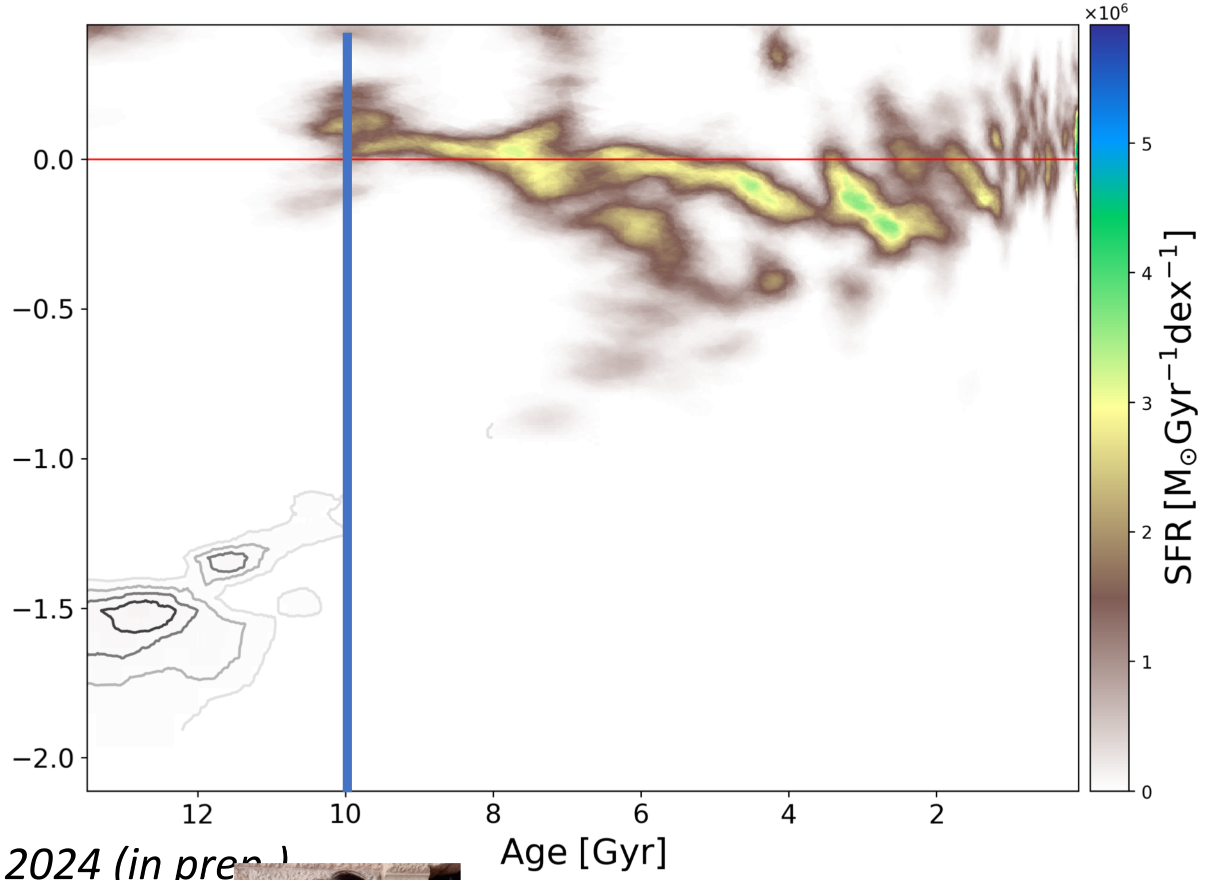
Thick disc SFH

Formed BEFORE 10 Gyrs ago



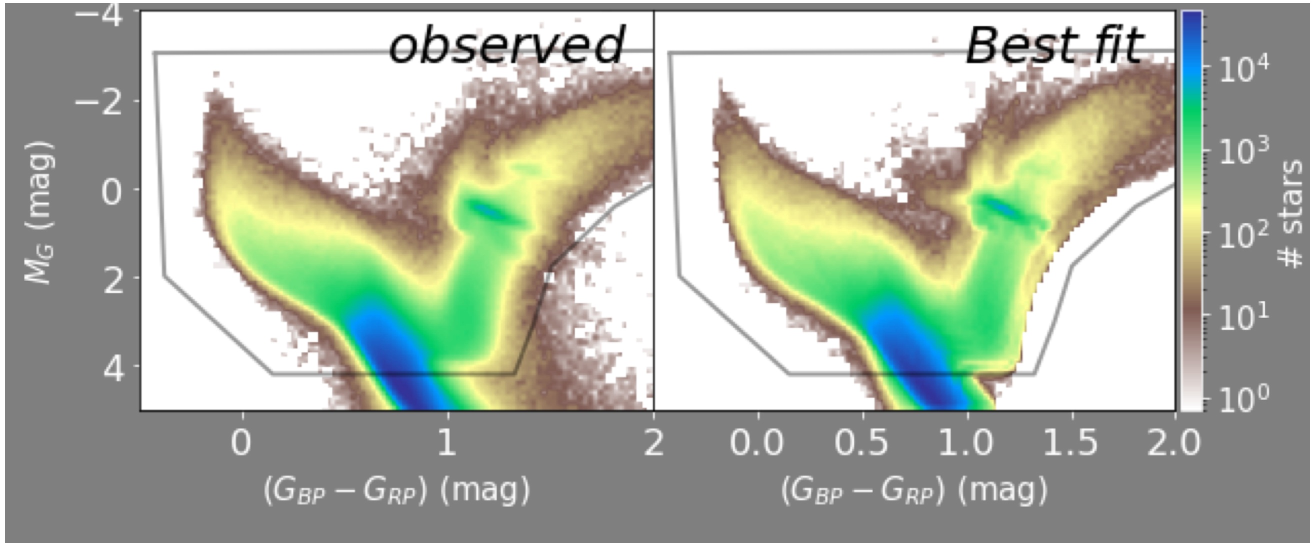
Thin disc SFH

Formed AFTER 10 Gyrs ago

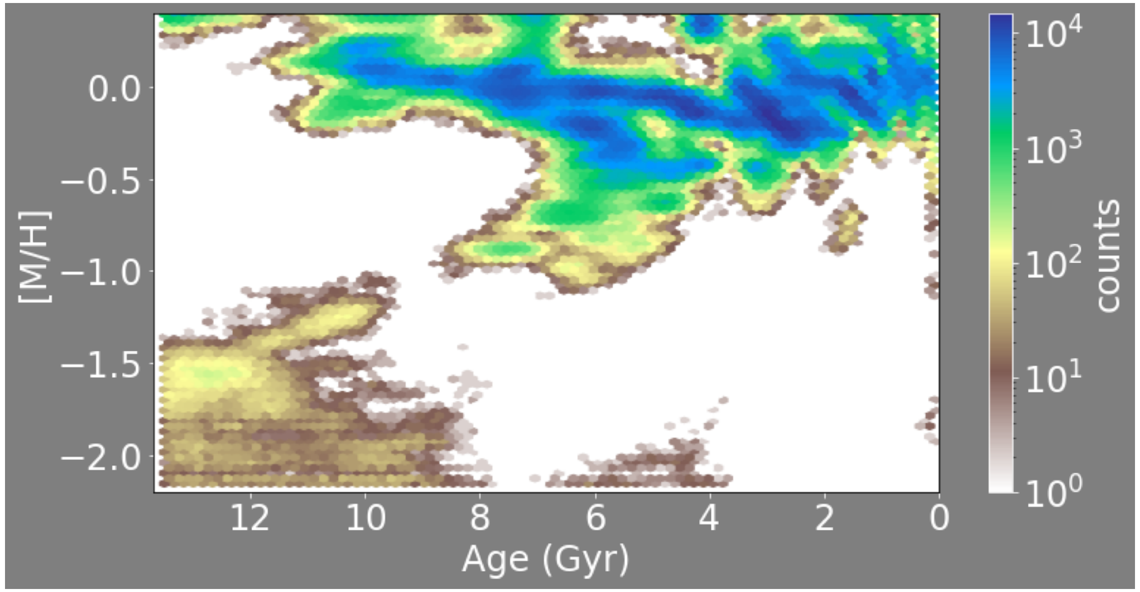


Fernández-Alvar + 2024 (in prep.)

Emma Fernández-Alvar talk
On Tuesday



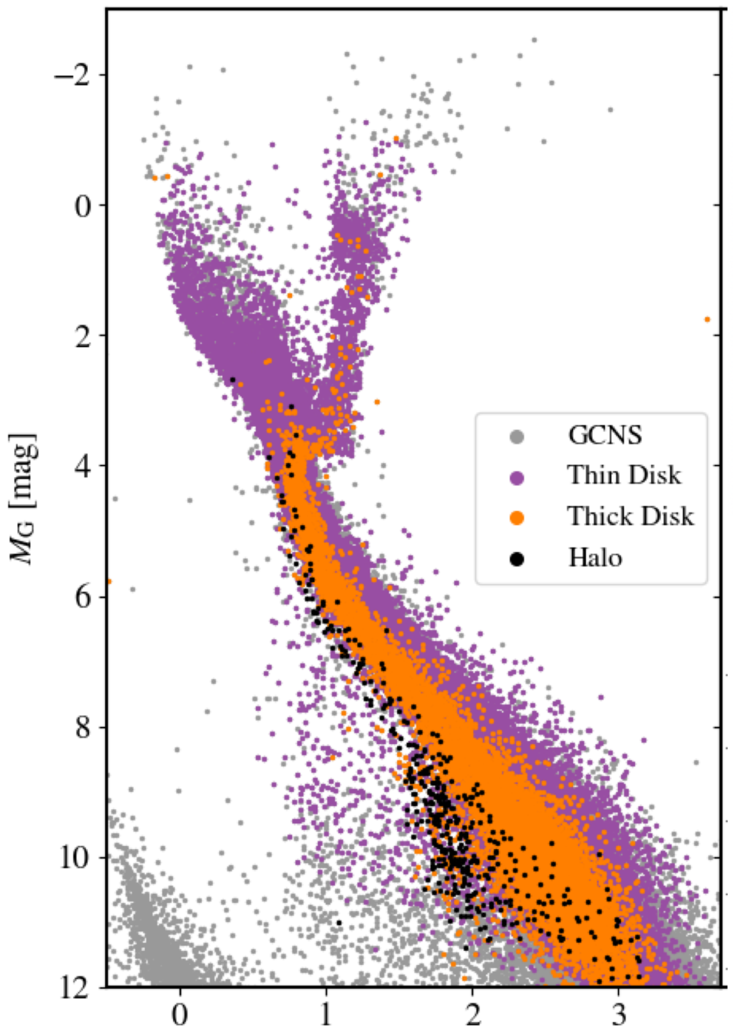
Low metallicity stars in the thin disk



Queiroz+ 2024, in prep

Anna Queiroz talk On Wednesday

A&A, in press



Chronology of our Galaxy from Gaia Colour-Magnitude Diagram-fitting (ChronoGal). I. The formation and evolution of the thin disk from the Gaia Catalogue of Nearby Stars

Carme Gallart[1,2], Francisco Surot[1], Santi Cassisi[†,3,4], Emma Fernández-Alvar[†,1,2], David Mirabal[†,2], Alicia Rivero [†,2], Tomás Ruiz-Lara[†,5,6], Judith Santos-Torres[†,2,7], Guillem Aznar-Menargues[2], Giuseppina Battaglia[1,2], Anna B. Queiroz[1,2], Matteo Monelli[1,2], EugeneVasiliev[8], Cristina Chiappini[9], Amina Helmi[10], Vanessa Hill[11], Davide Massari[12], and Guillaume F. Thomas[1,2]

Two goals

-Present our CMD fitting methodology applied to Gaia data: CMDft.Gaia

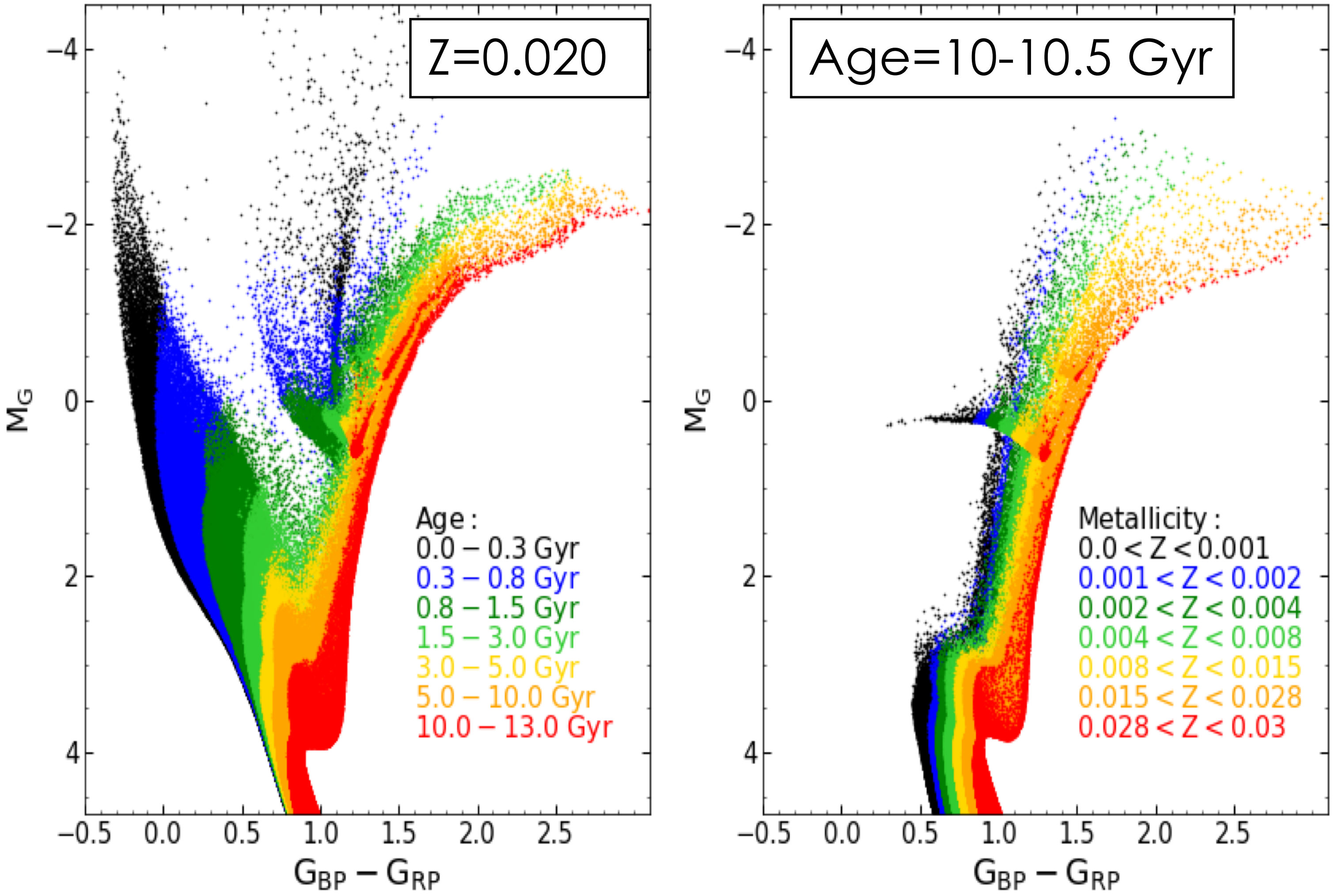
-Quantitatively study the deSFH and current age-metallicity distribution of the close solar neighbourhood (d<100pc)

deSFH Mass, per unit time and metallicity, that has been transformed into stars somewhere in the galaxy to account for the stars that are today in the studied volume

Derivation of the **SFH** with **CMD fitting**

AGE AND METALLICITY INFORMATION IN THE COLOR-MAGNITUDE DIAGRAM

Synthetic CMD computed with BaSTI (Pietrinferni et al. 2004) stellar evolution models

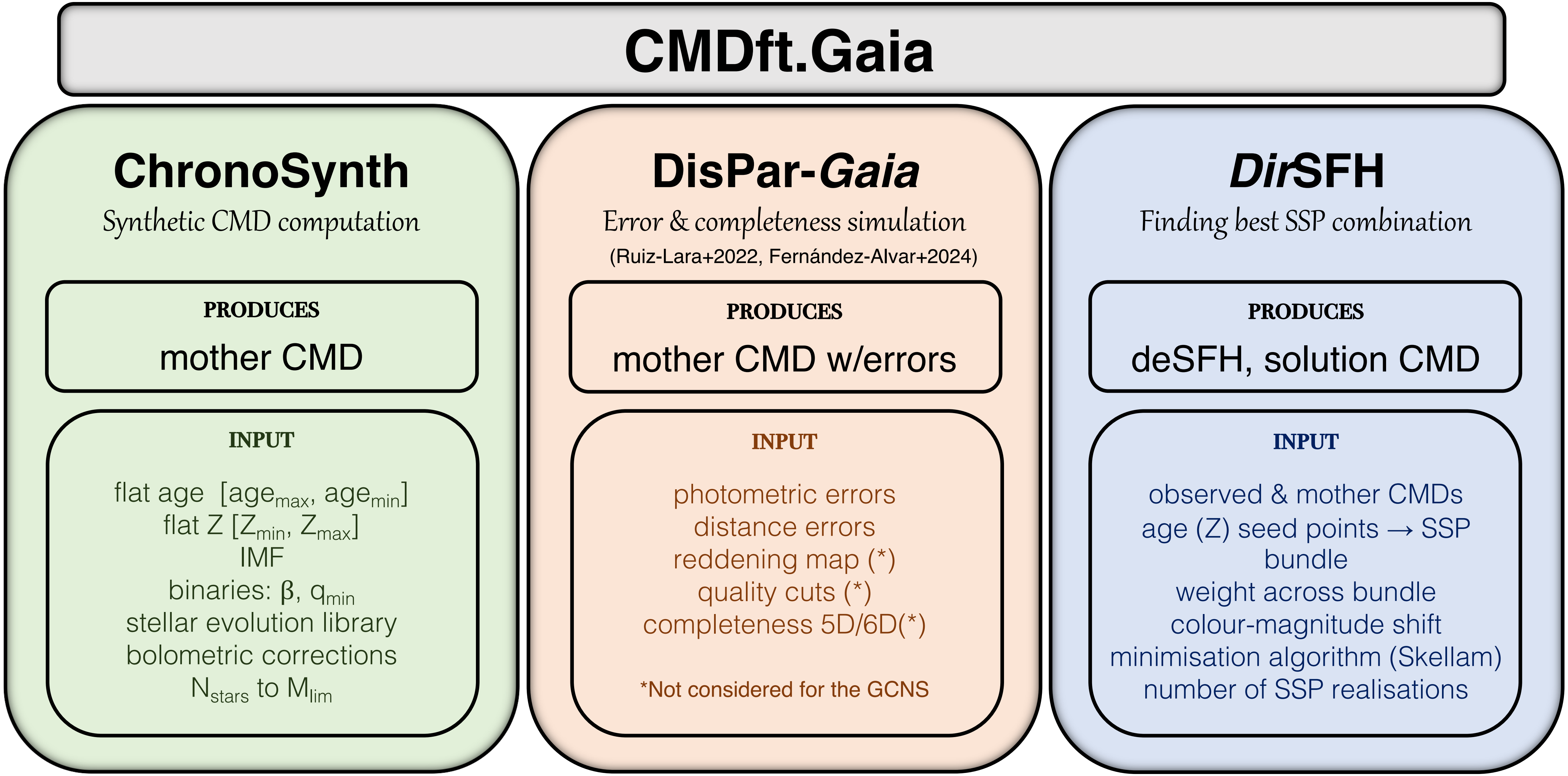


The age-metallicity degeneracy in the CMD affects mainly RGB stars, and it is very successfully broken when stars in the main sequence, down to the old turnoff **(oMSTO)**, are observed.

Additional information for the fit:

for a population of stars of given age and metallicity, the number counts in different portions of the CMD are related through

- the relative lifetimes of the stars in different stellar evolution phases (information provided by the stellar evolution models)
- the initial mass function (IMF), which is reasonably known (at least for $M>1M_\odot$)


CMDft.Gaia
ChronoSynth
Synthetic CMD computation
PRODUCES
mother CMD
INPUT
flat age [age_max, age_min]
flat Z [Z_min, Z_max]
IMF
binaries: β, q_min
stellar evolution library
bolometric corrections
N_stars to M_lim
DisPar-Gaia
Error & completeness simulation
(Ruiz-Lara+2022, Fernández-Alvar+2024)
PRODUCES
mother CMD w/errors
INPUT
photometric errors
distance errors
reddening map (*)
quality cuts (*)
completeness 5D/6D(*)
*Not considered for the GCNS
DirSFH
Finding best SSP combination
PRODUCES
deSFH, solution CMD
INPUT
observed & mother CMDs
age (Z) seed points → SSP bundle
weight across bundle
colour-magnitude shift
minimisation algorithm (Skellam)
number of SSP realisations

ChronoSynth

Synthetic CMD computation

PRODUCES

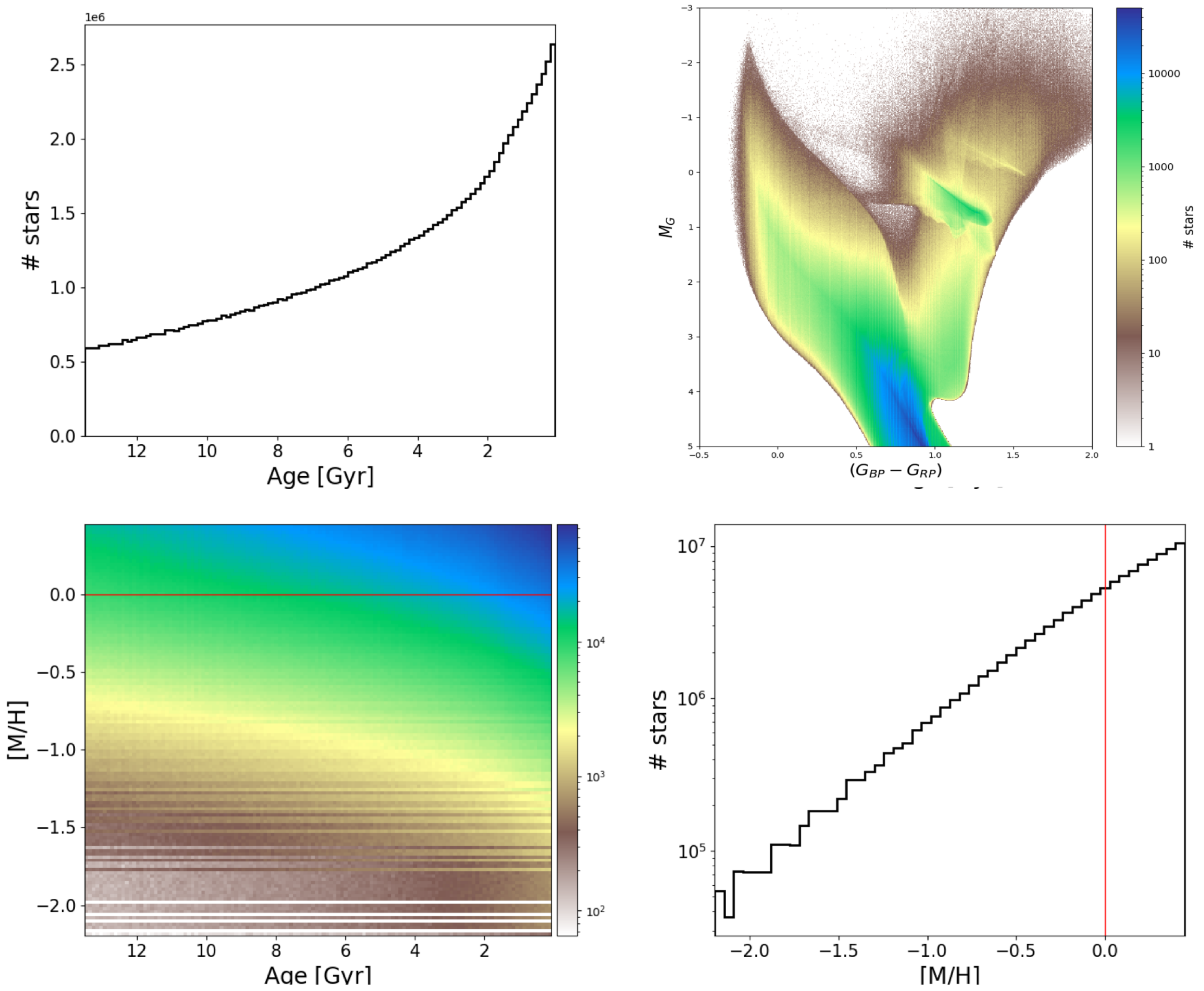
mother CMD

INPUT

flat age [age_{max}, age_{min}]
flat Z [Z_{min}, Z_{max}]
IMF
binaries: β, q_{min}
stellar evolution library
bolometric corrections
N_{stars} to M_{lim}

Age: 13.5—0.02 Gyr
[Fe/H]=-2.2—0.45
IMF: Kroupa+1993
$\beta = 0.3$, q=0.1
BaSTI-IAC
1.2 x10^8 stars to M_G=5

☆ Isochrone interpolation
Continuous distribution of stars of any
age and metallicity in the required intervals



DisPar-*Gaia*

Error & completeness simulation

(Ruiz-Lara+2022, Fernández-Alvar+2024)

PRODUCES

mother CMD w/errors

INPUT

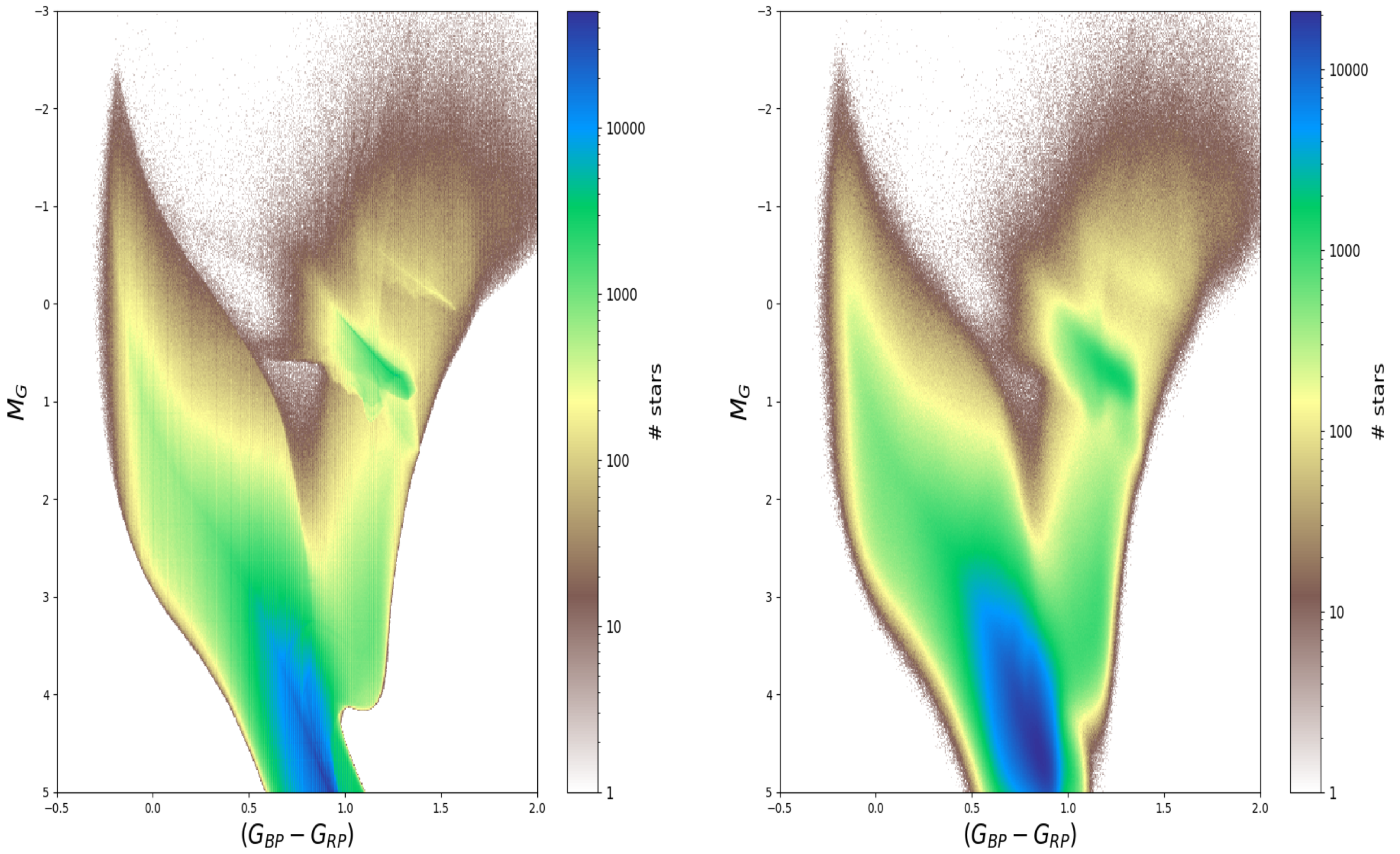
photometric errors
distance errors
reddening map (*)
quality cuts (*)
completeness 5D/6D(*)

*Not considered for the GCNS

Restricting to volumes with low errors and high completeness down to the oMSTO.
Also in v_{rad}!

Mother, no errors

Mother, with errors



Example of error and completeness simulation for a volume with |Z|=1600-2300pc, R_{sun}=1Kpc

***Dir*SFH**

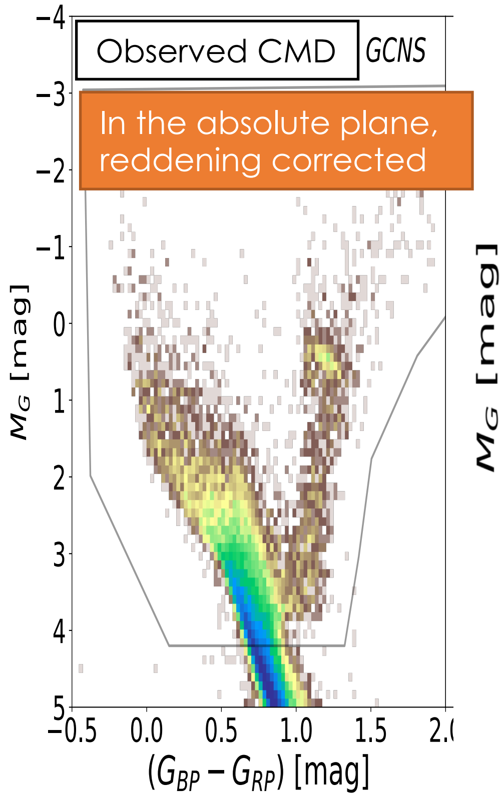
Finding best SSP combination

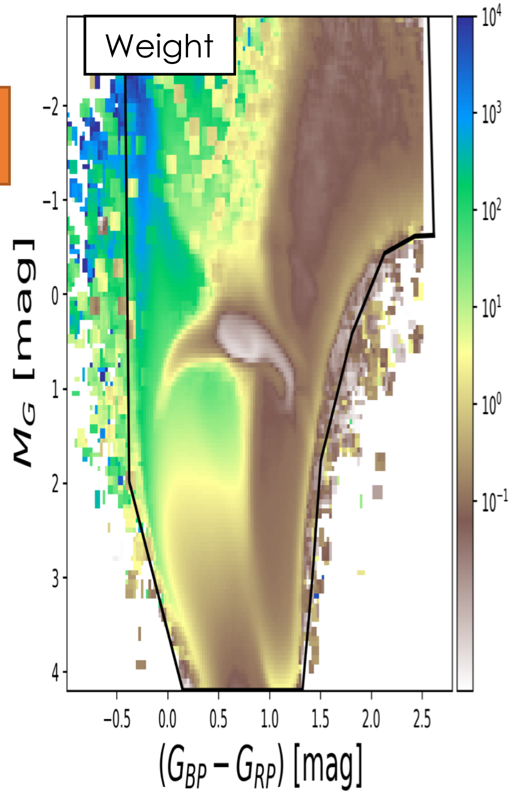
PRODUCES

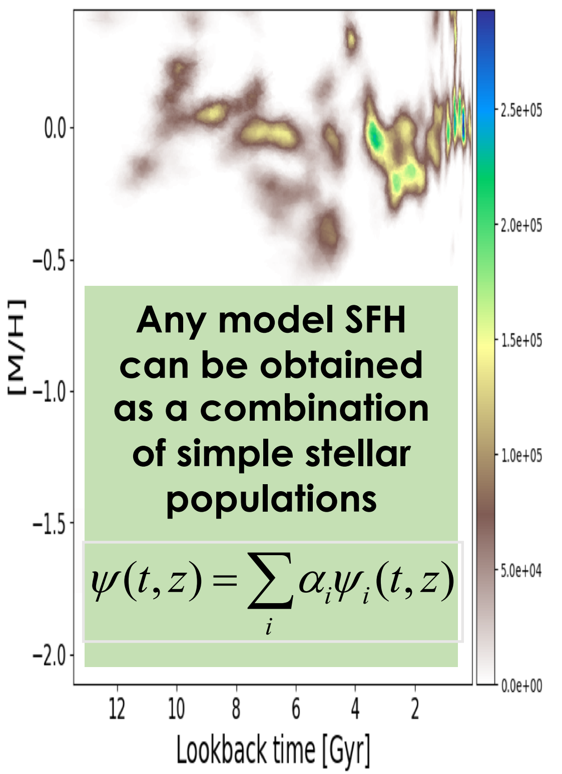
deSFH, solution CMD

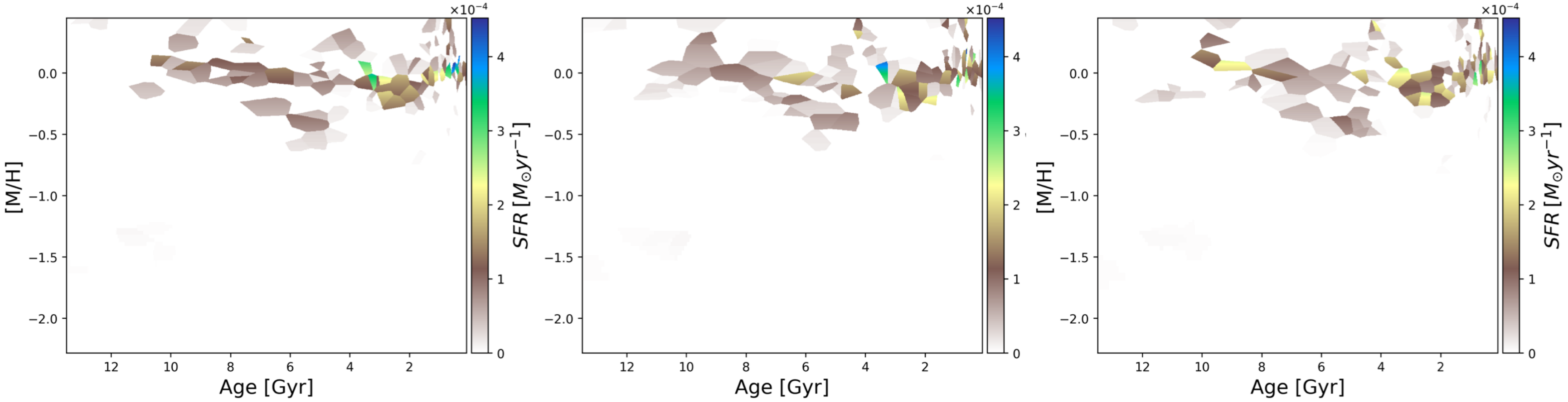
INPUT

observed & mother CMDs
age (Z) seed points → SSP bundle
weight across bundle
colour-magnitude shift
minimisation algorithm (Skellam)
number of SSP realisations



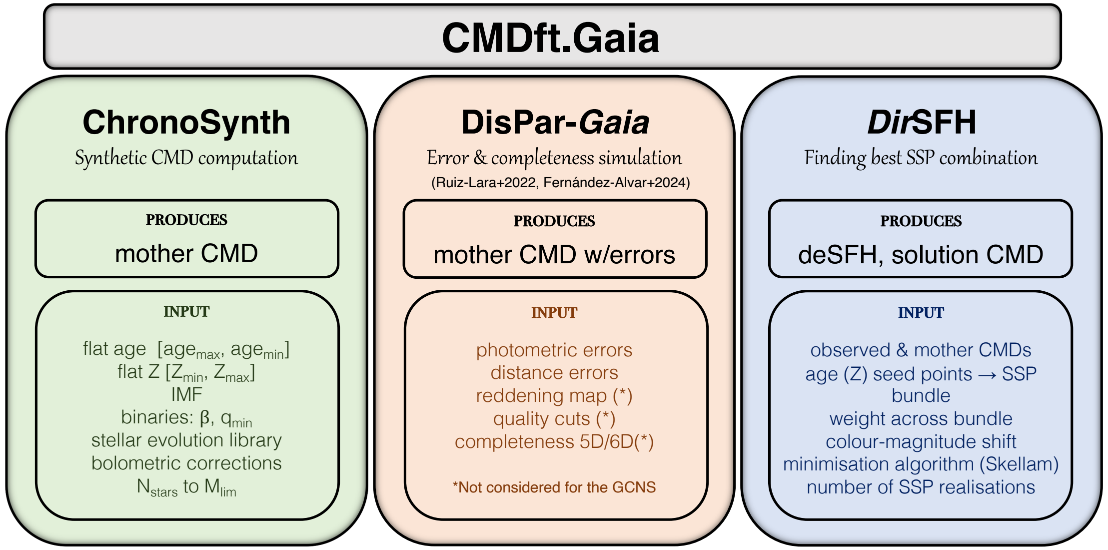






★ SSPs are ***Dir***ichlet-Voronoi tesselations in age-met

→ Many (>50) realisations of the SSPs. Average solution



★ CMD.ftGaia produces deSFH that are:

→ **robust** (against sensible changes in input parameters, e.g. binaries, SSPs 'size', stellar models, size of mother, weights, reddening map...)

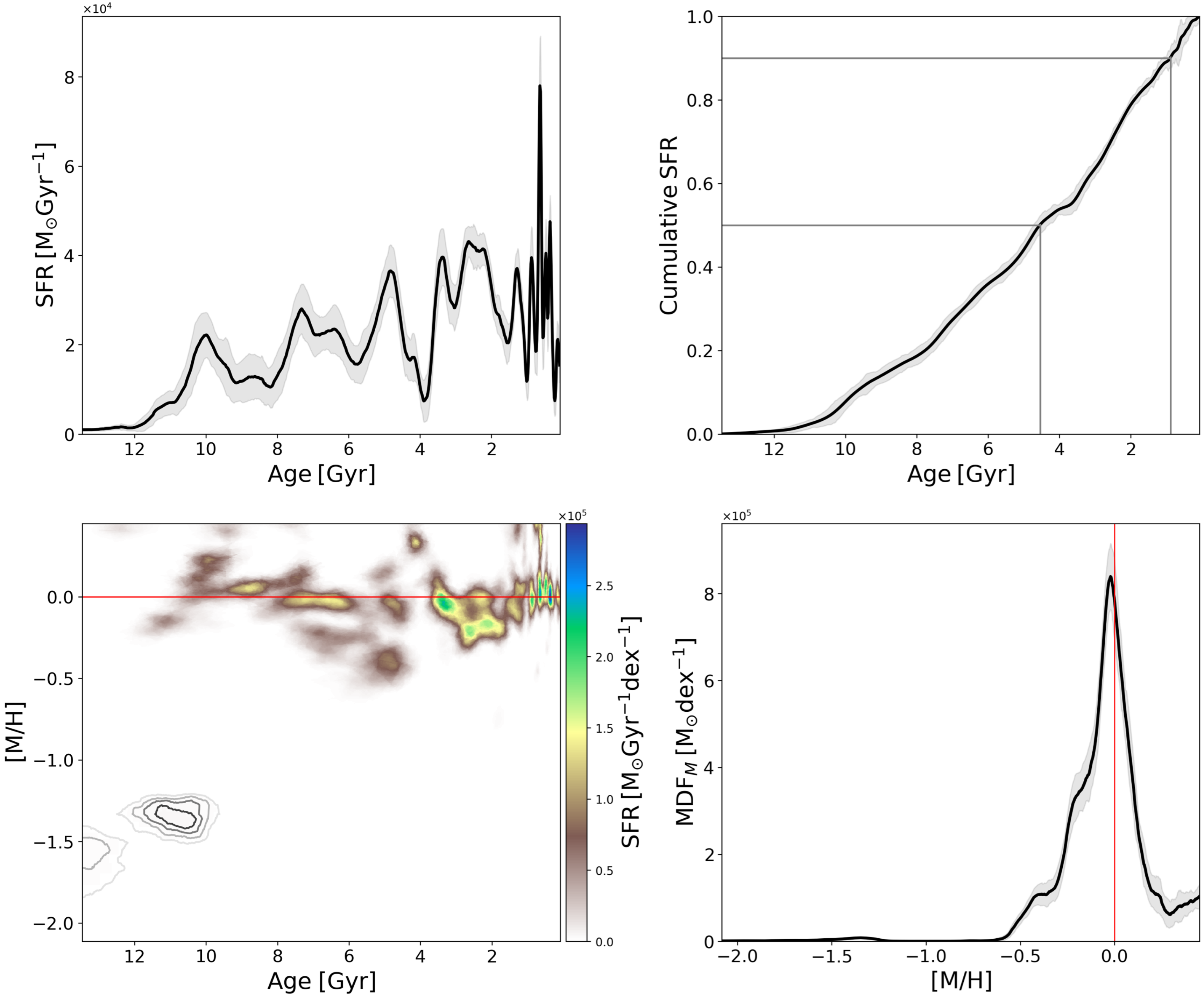
→ **precise** (better than 5-10%, depending on age)

→ **accurate** (ages systematically overestimated by a maximum of 6%)

output of CMD.ftGaia

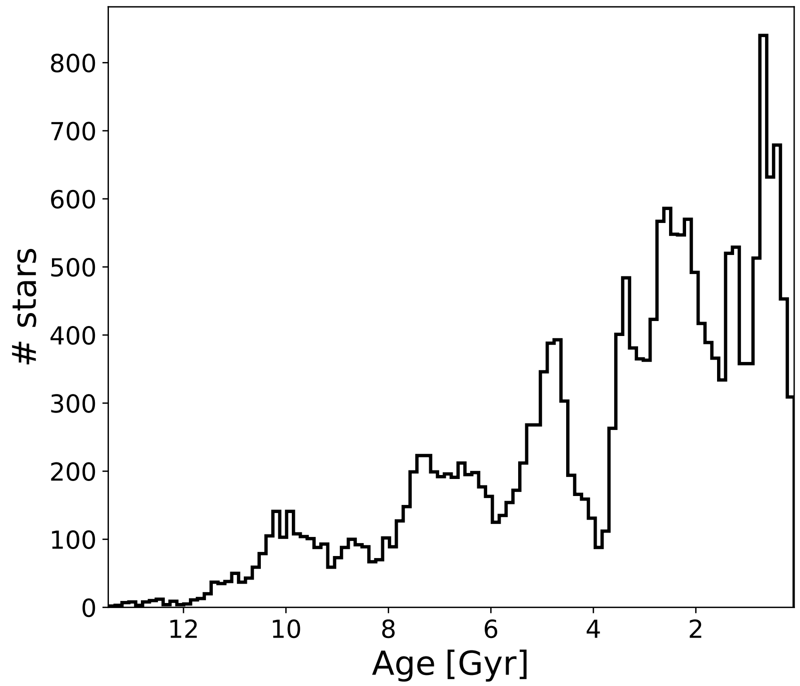
dynamically evolved Star Formation History “deSFH” Within 100 pc from the Sun

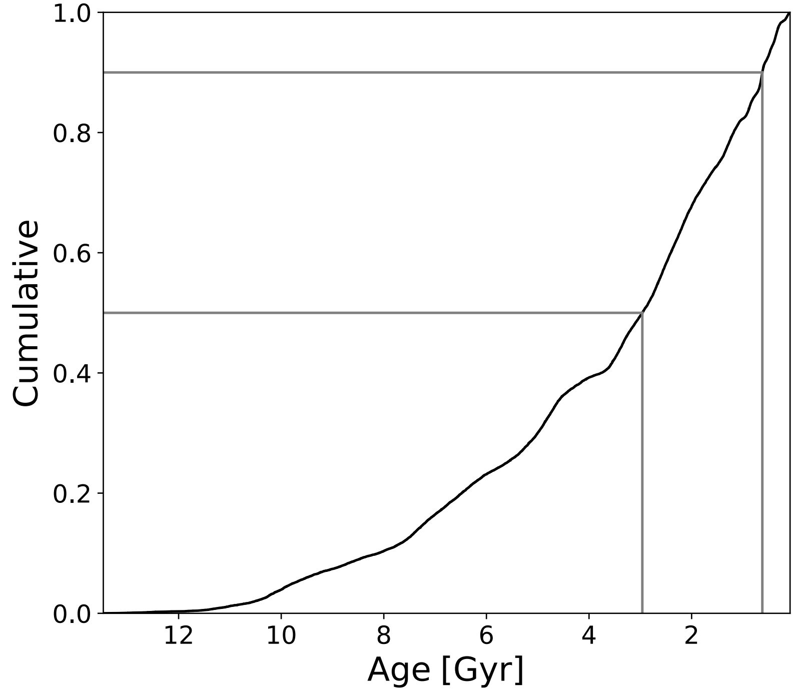
deSFH: Mass, per unit time and metallicity, that has transformed into stars, somewhere in the Galaxy, to account for the stars currently present in the analysed volume.

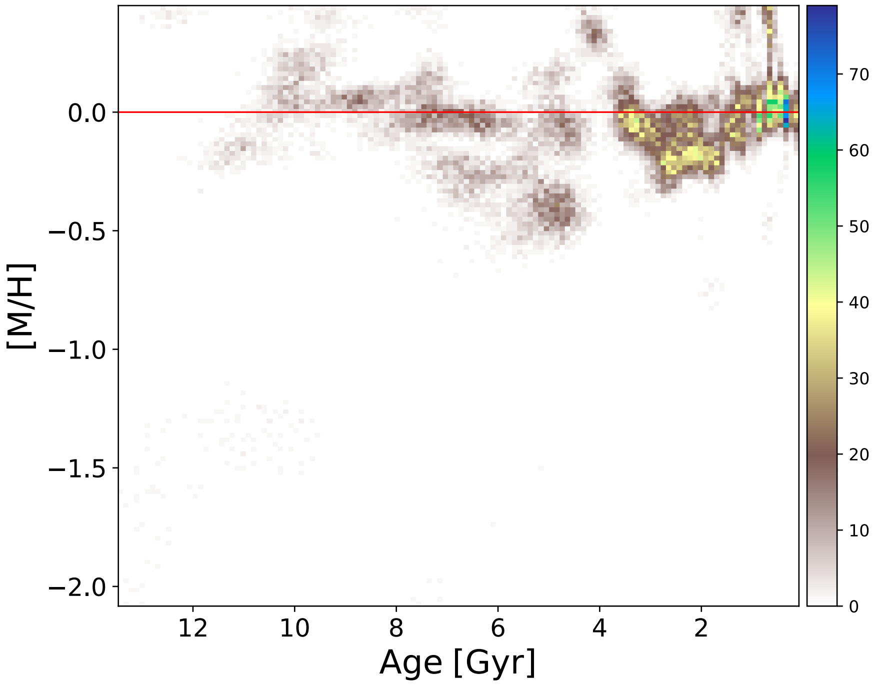


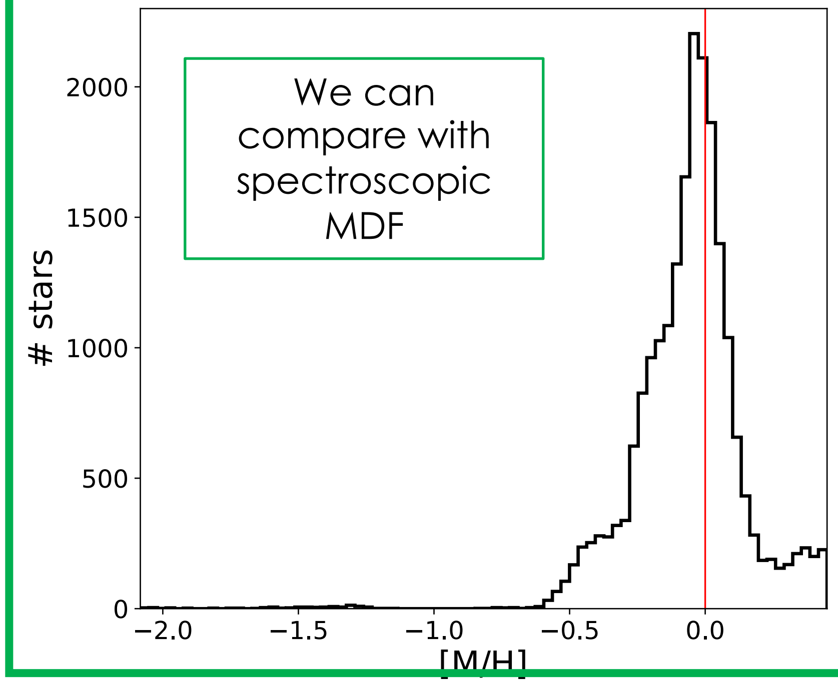
output of CMD.ftGaia

Stellar Age and Metallicity Distribution "AMD" of the stars currently within 100 pc of the Sun



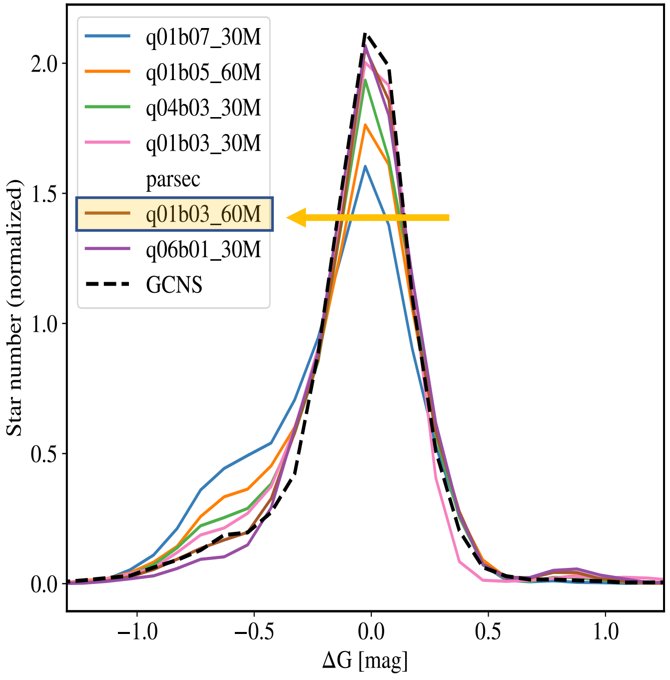




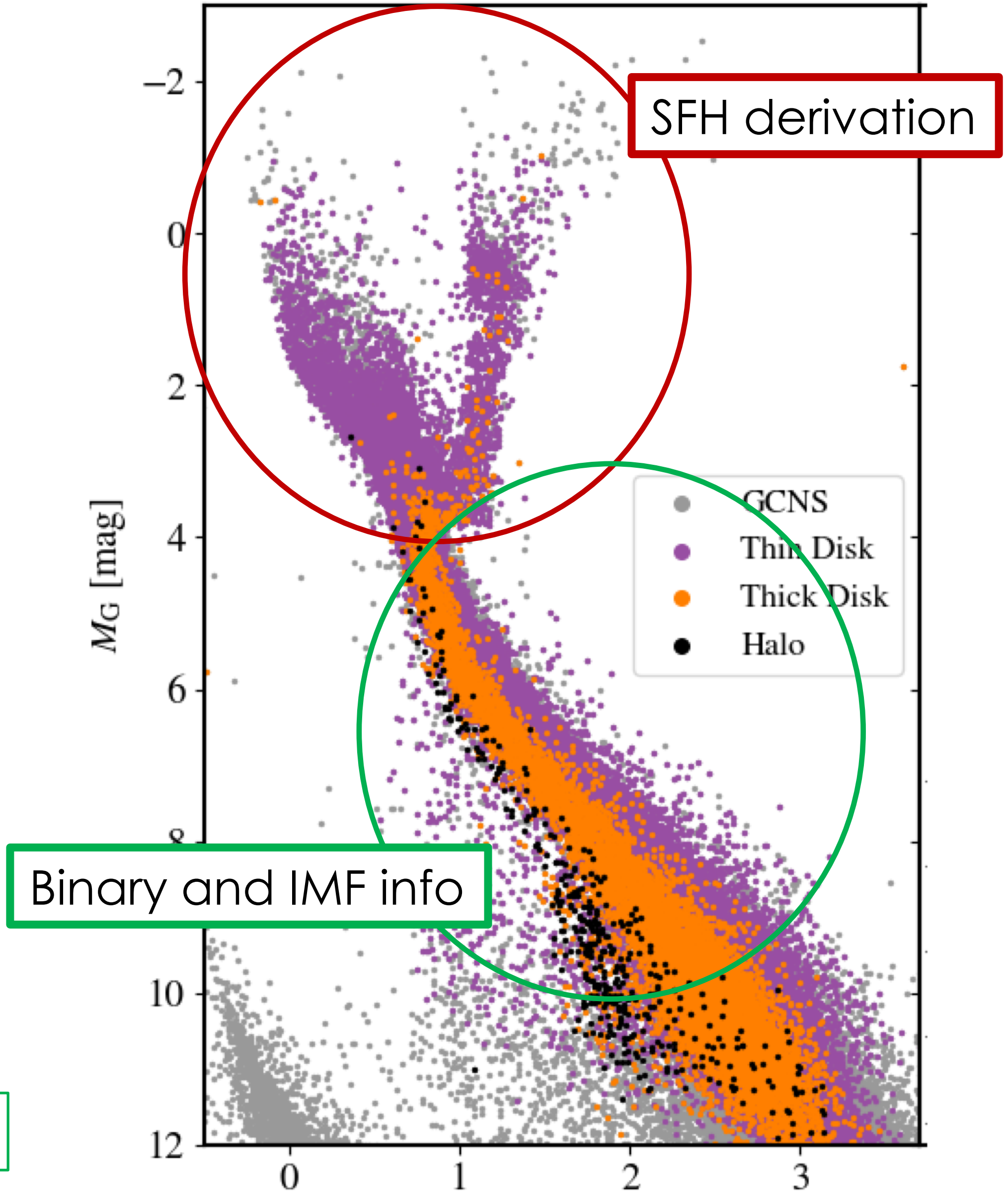


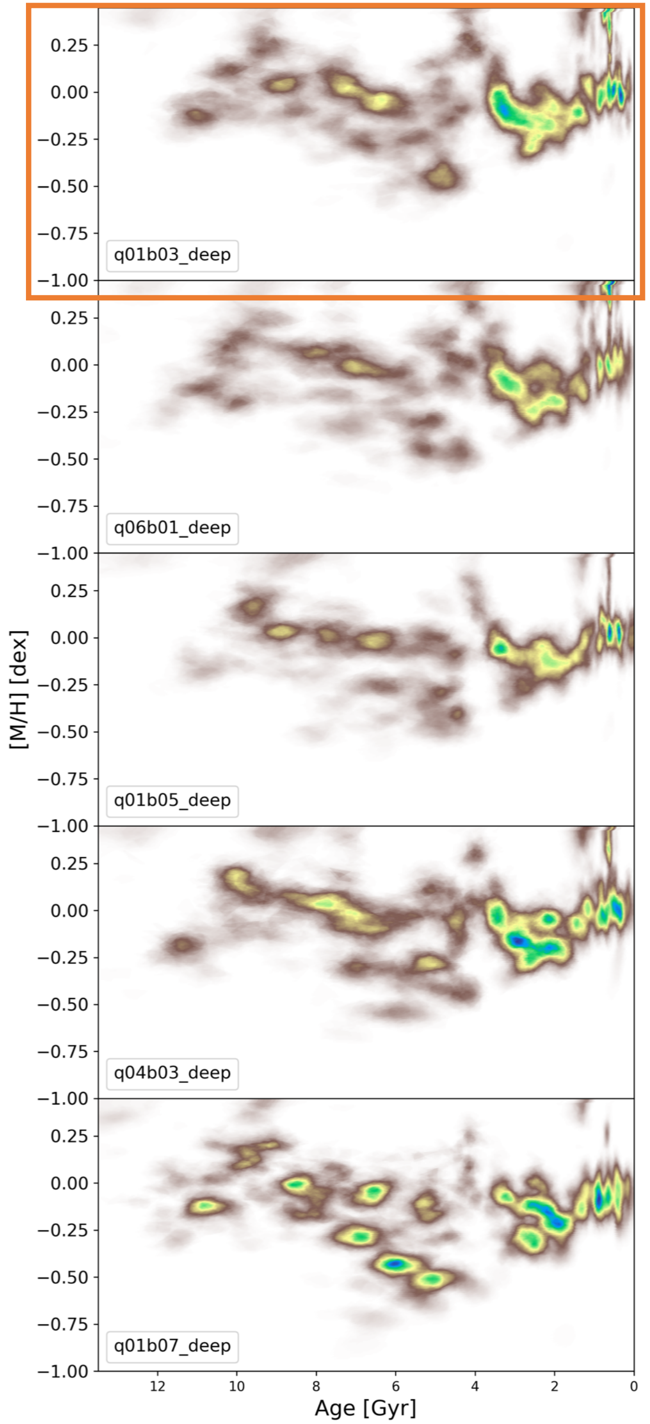
Robustness

Effect of binaries



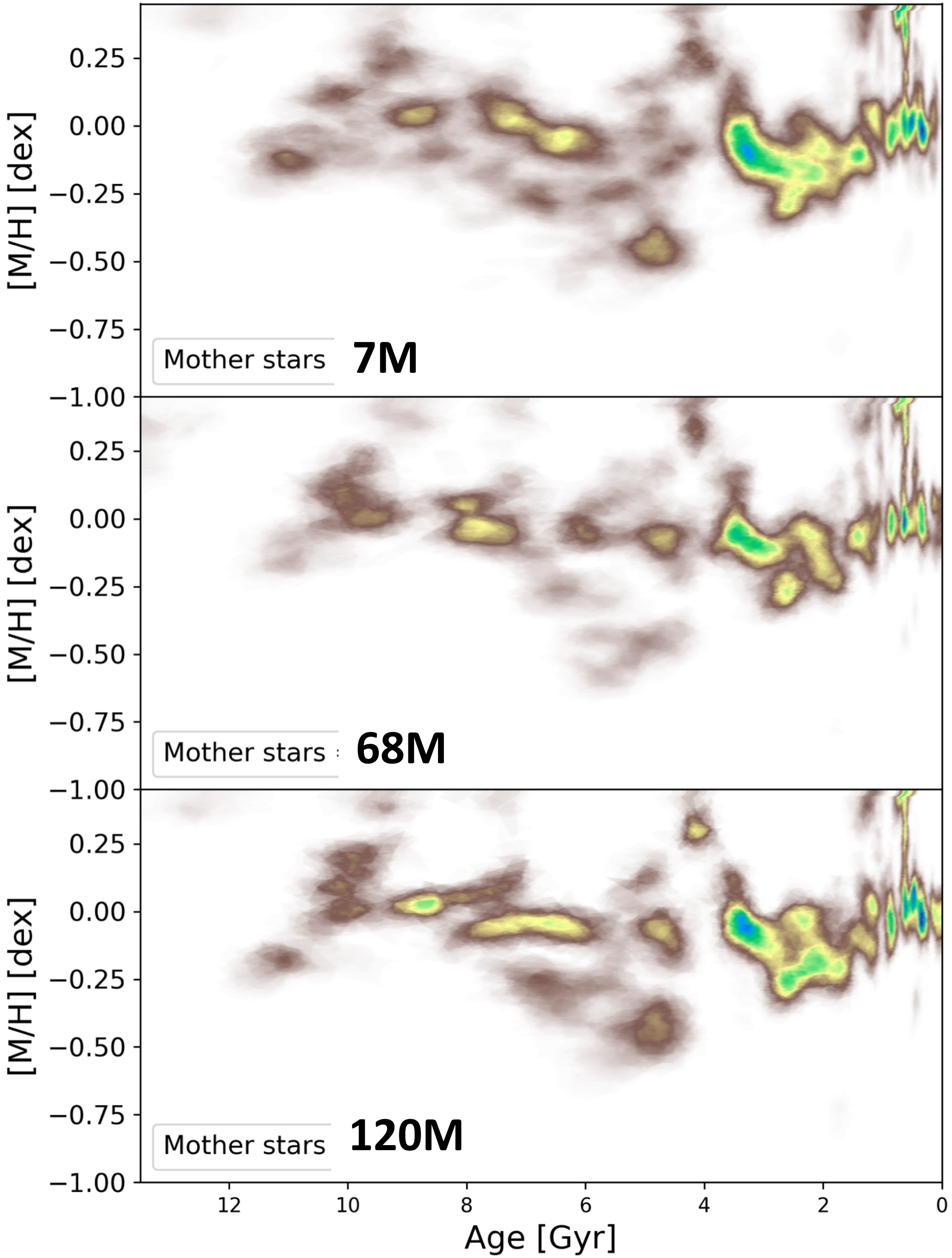
Gallart+ChronoGal, 2024





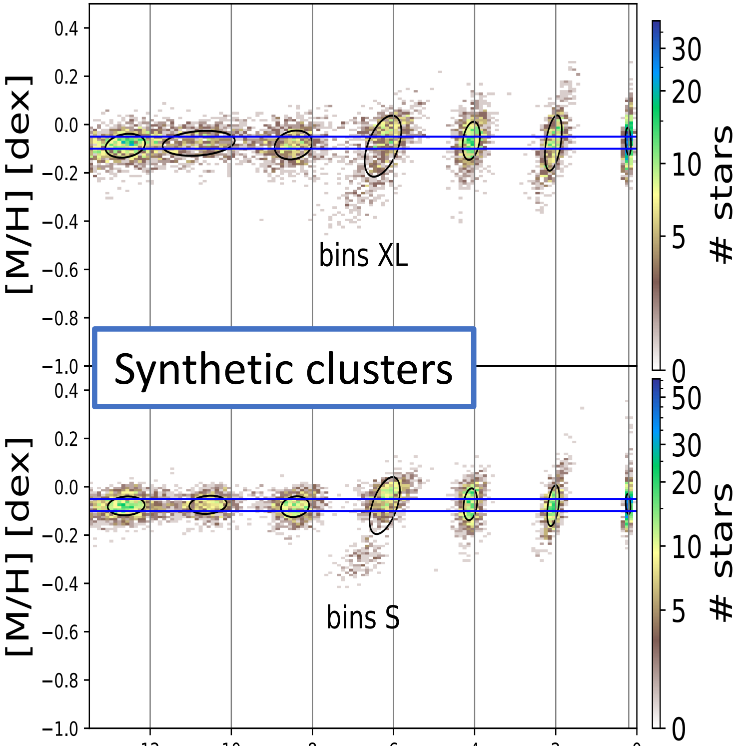
★ Robustness

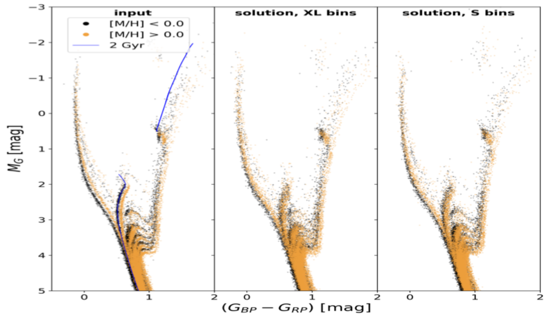
Effect of mother CMD size

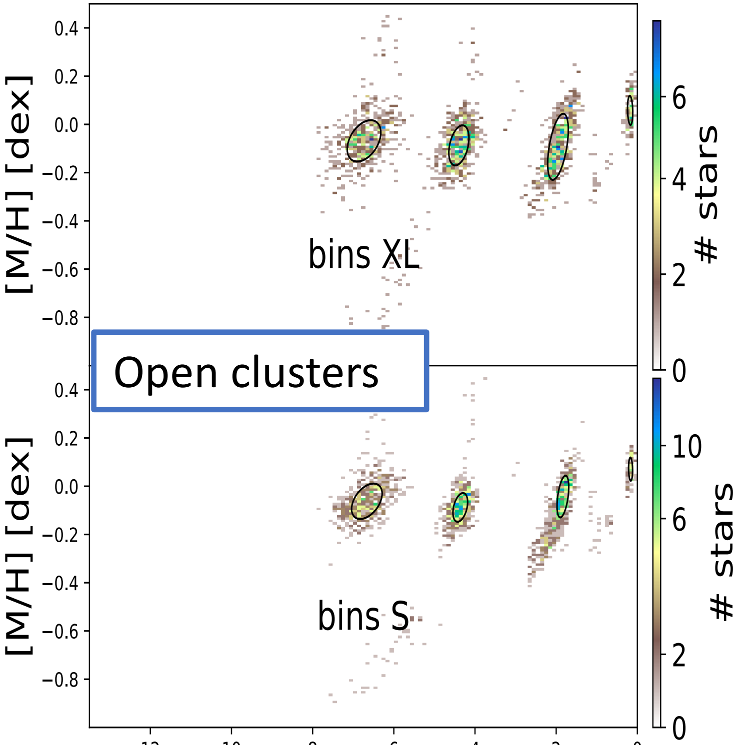


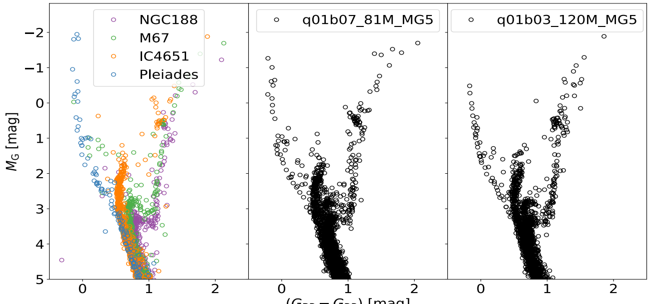
★ Robustness/precision

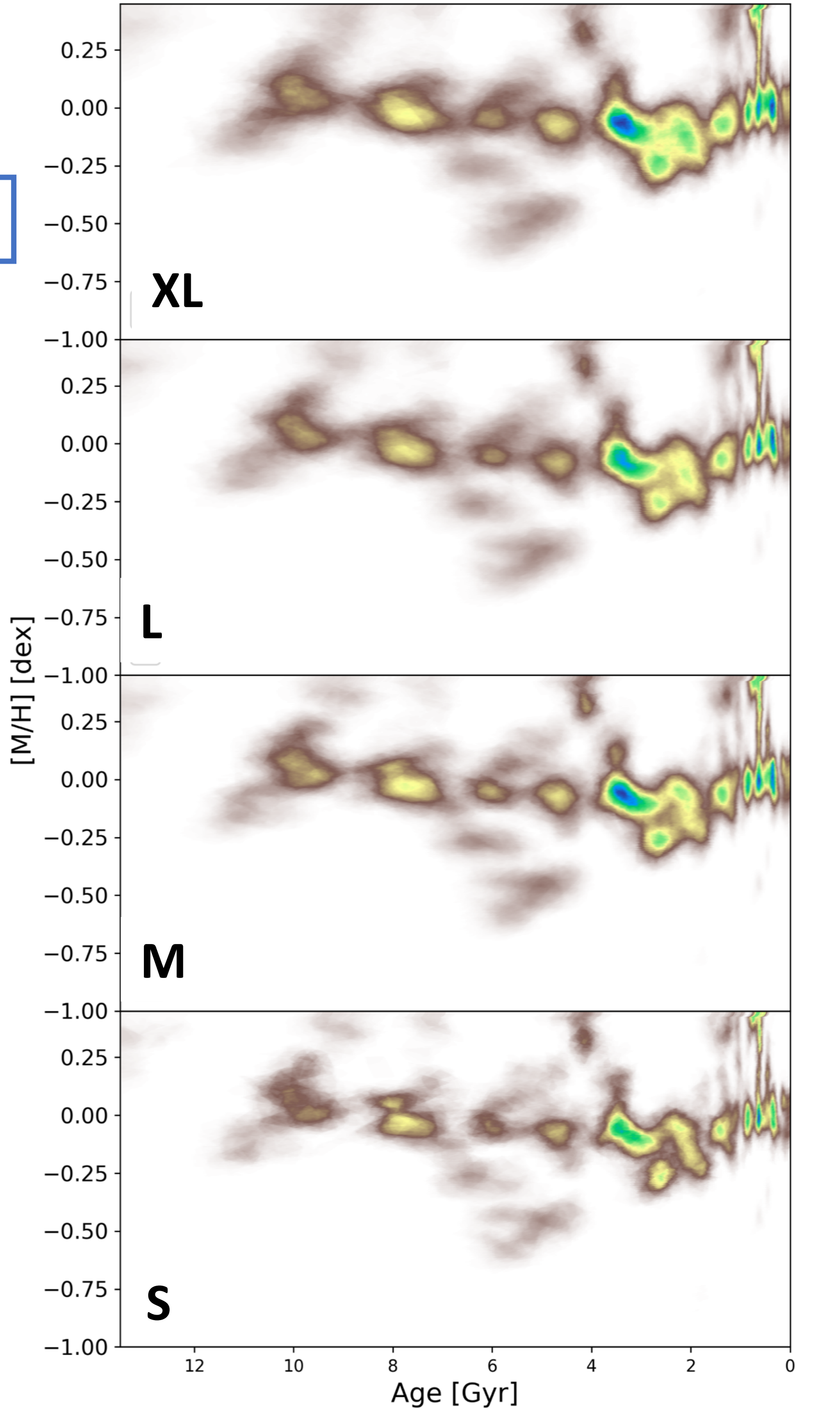
Effect of SSP size. Tests with observed and synthetic star clusters





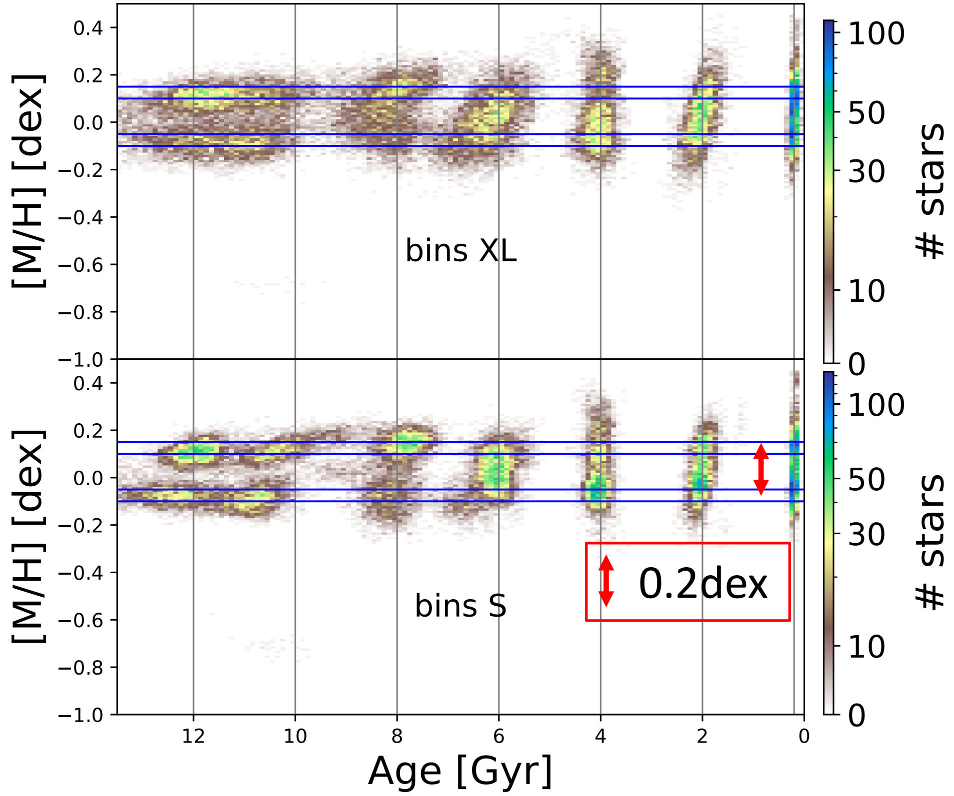


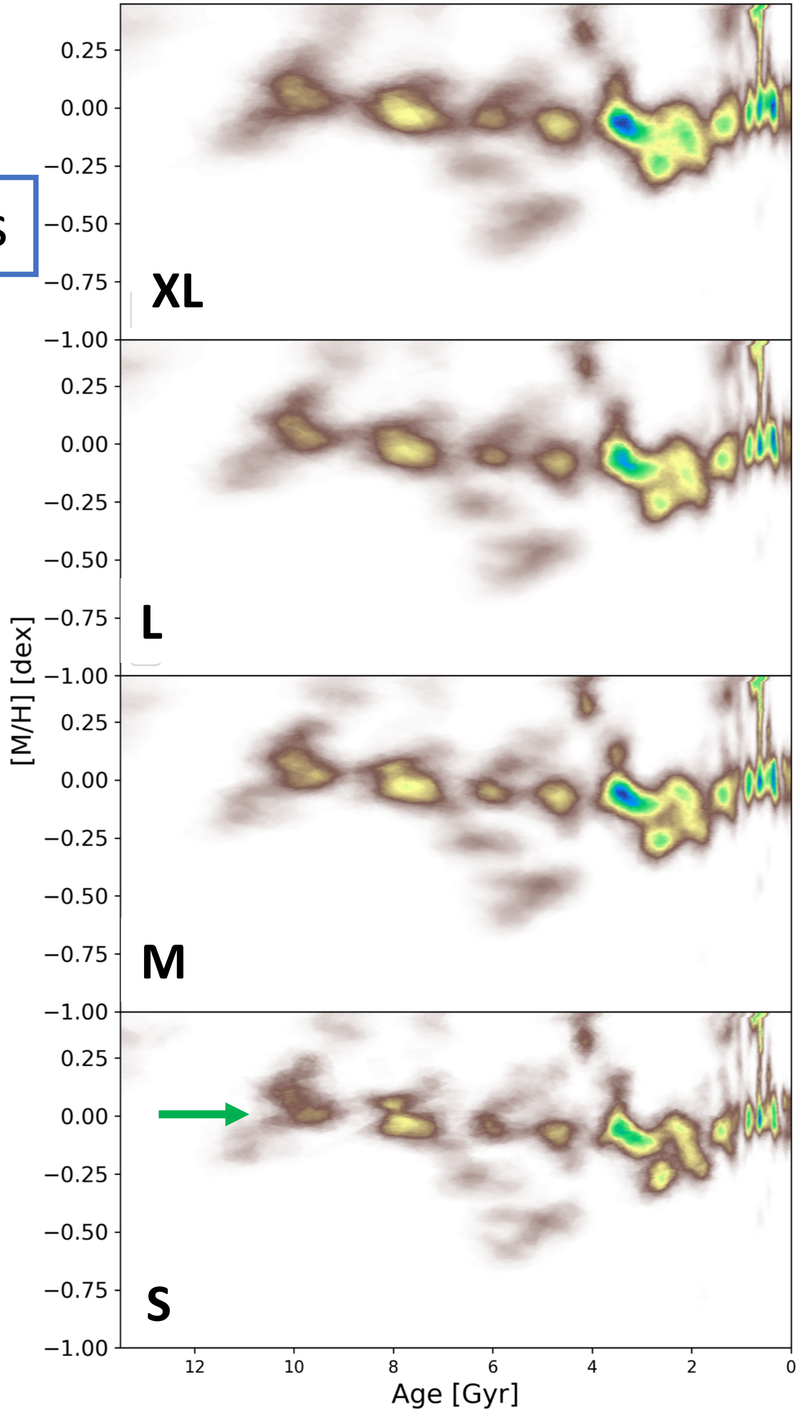




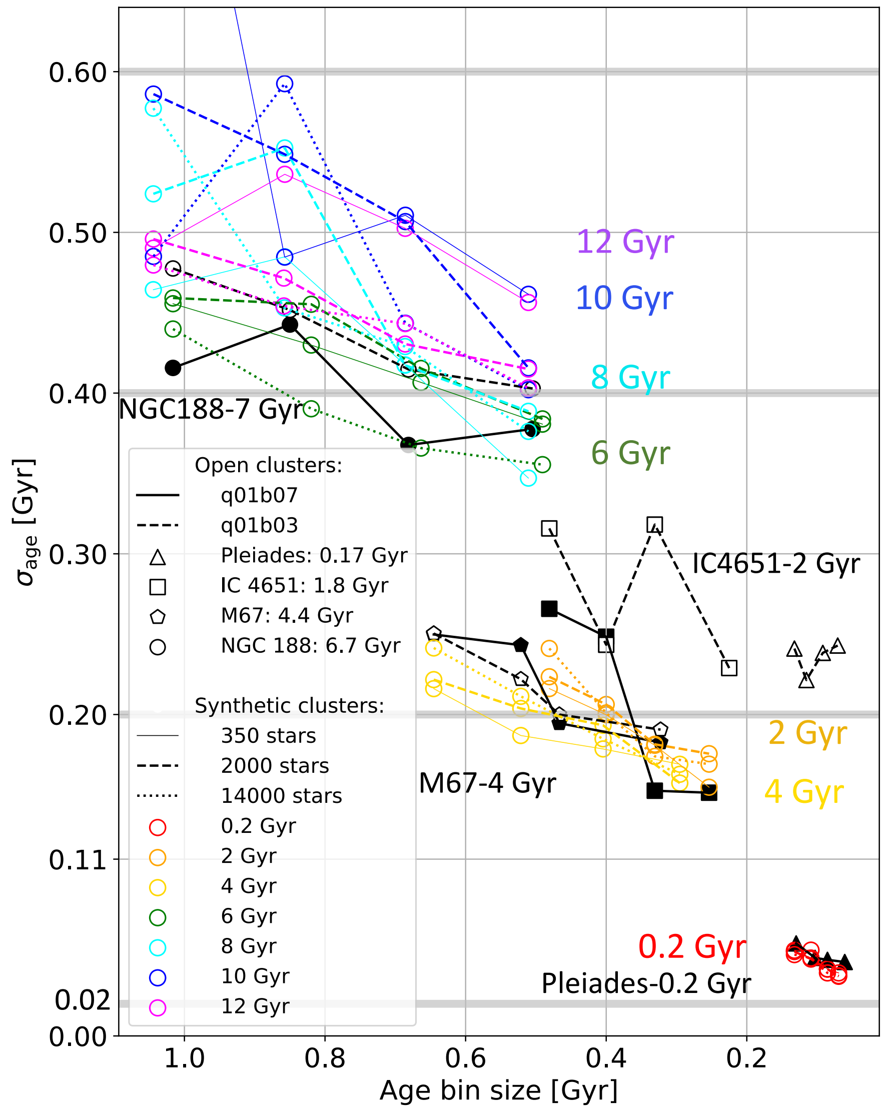
Robustness/precision

Effect of SSP size. Tests with observed and synthetic star clusters



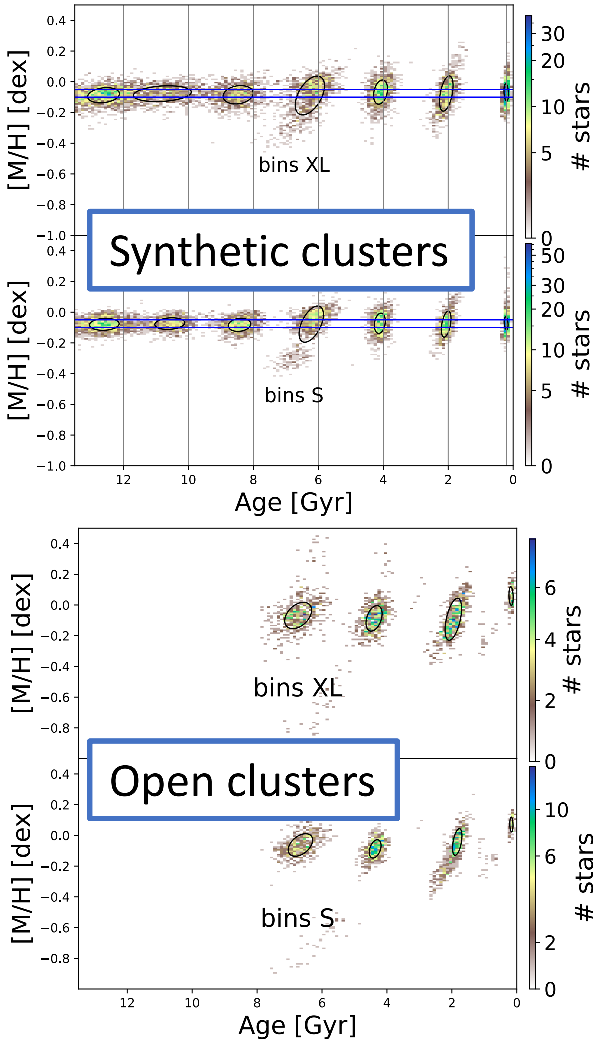


Precision and accuracy:



Effect of SSP size. Tests with observed and synthetic star clusters

For the adopted S bins, the ages of the 2-12 Gyr old clusters recovered with precisión better than 5%

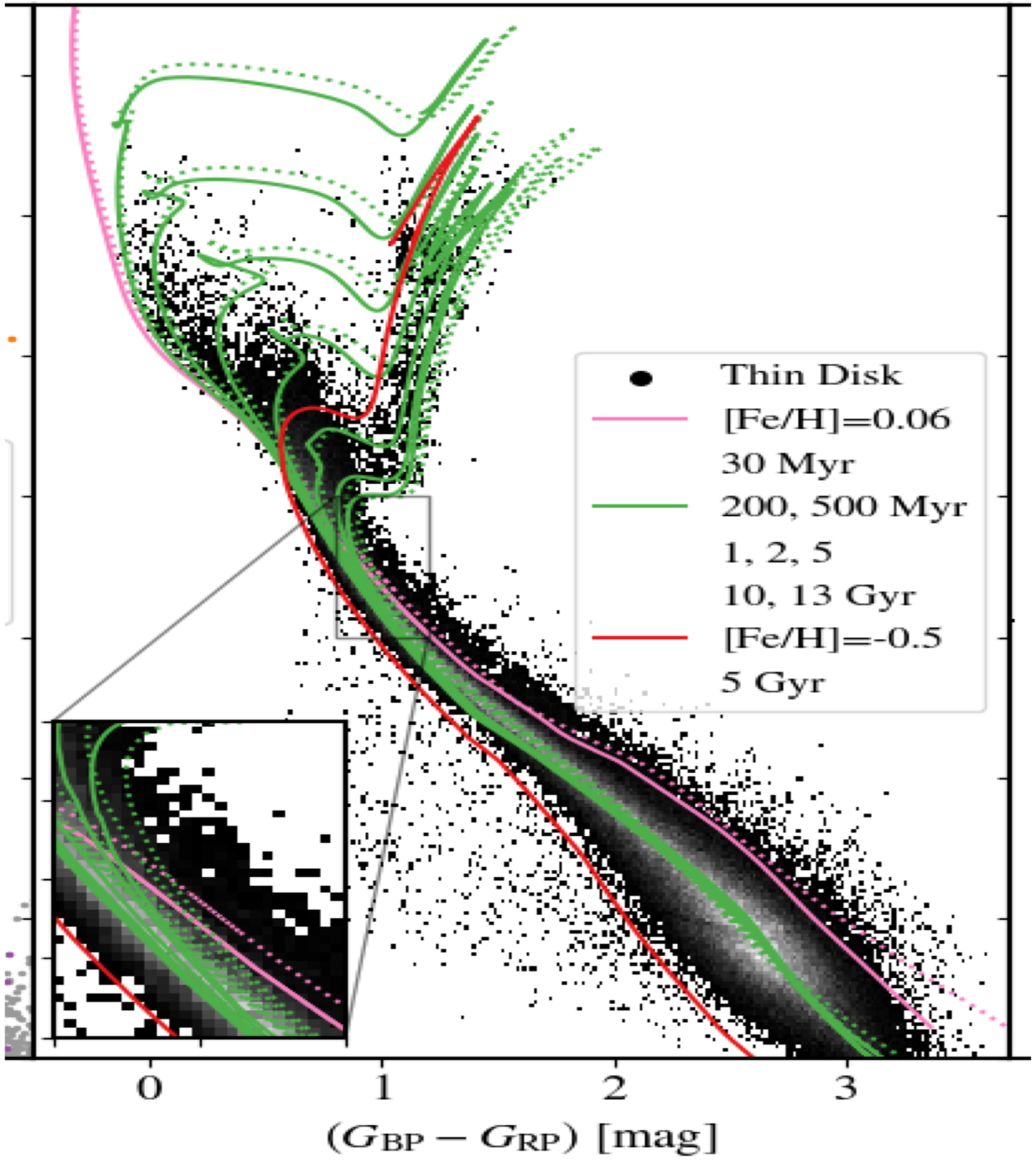


★ Robustness against change of stellar evolution models

BASTI-IAC, solid lines vs. PARSEC, dotted lines

BaSTI-IAC models slightly hotter (bluer) and fainter

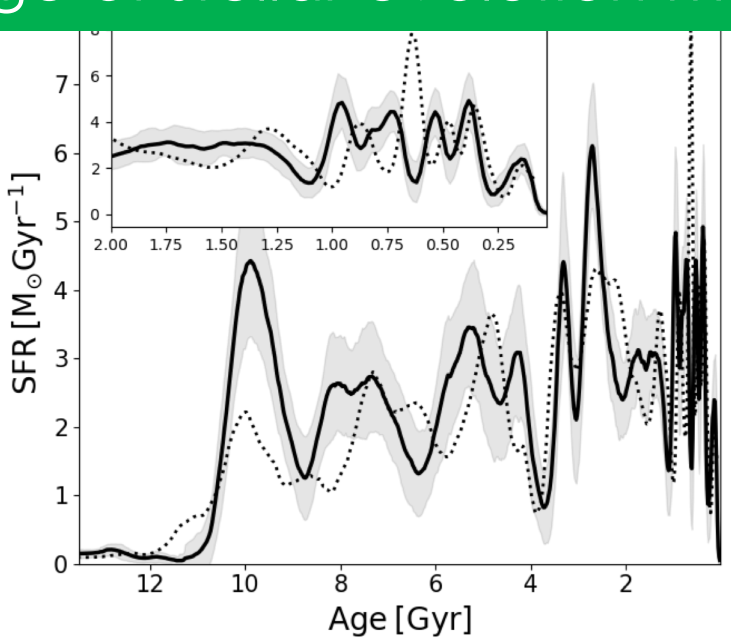
Expect slightly more metal rich, younger solutions with BaSTI

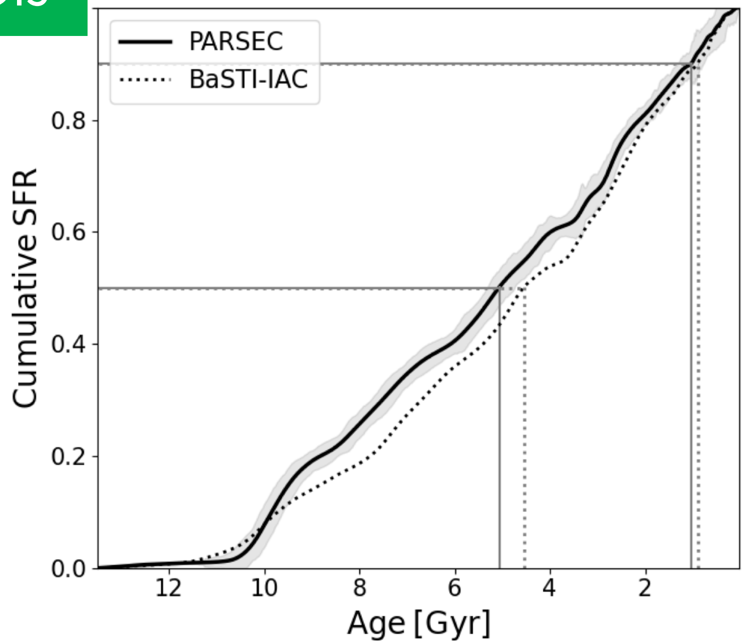


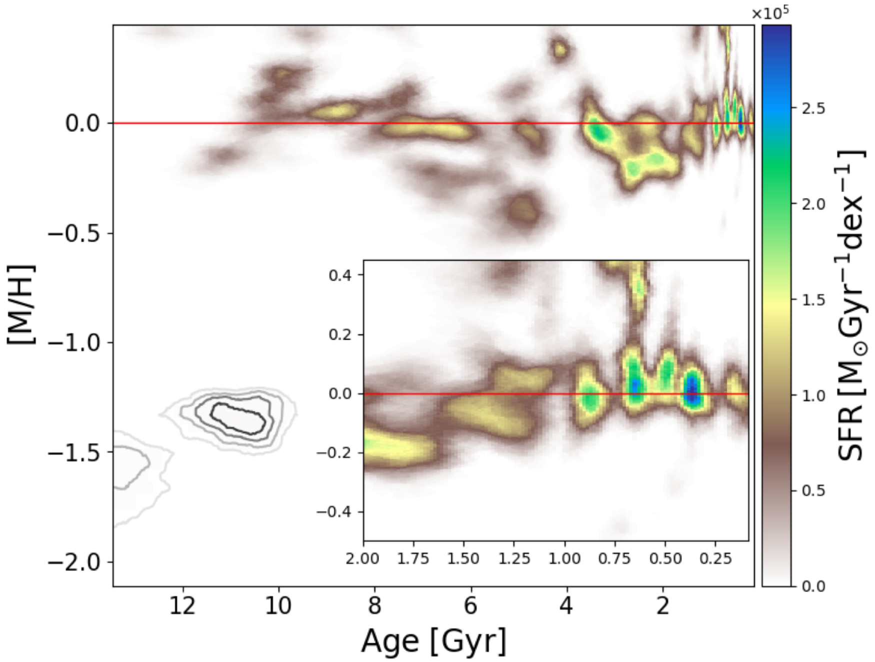
Robustness against change of stellar evolution models

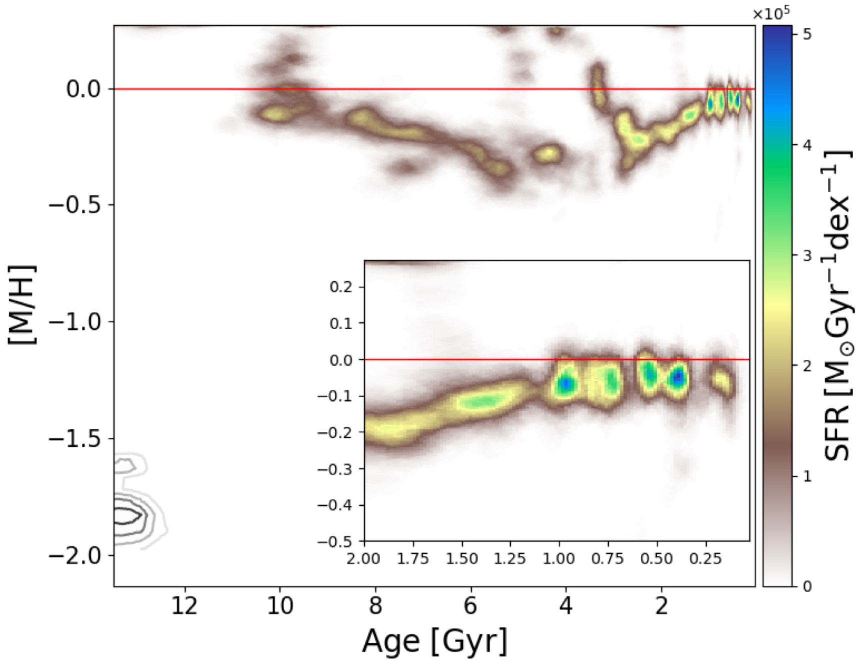
BASTI-IAC
vs.
PARSEC

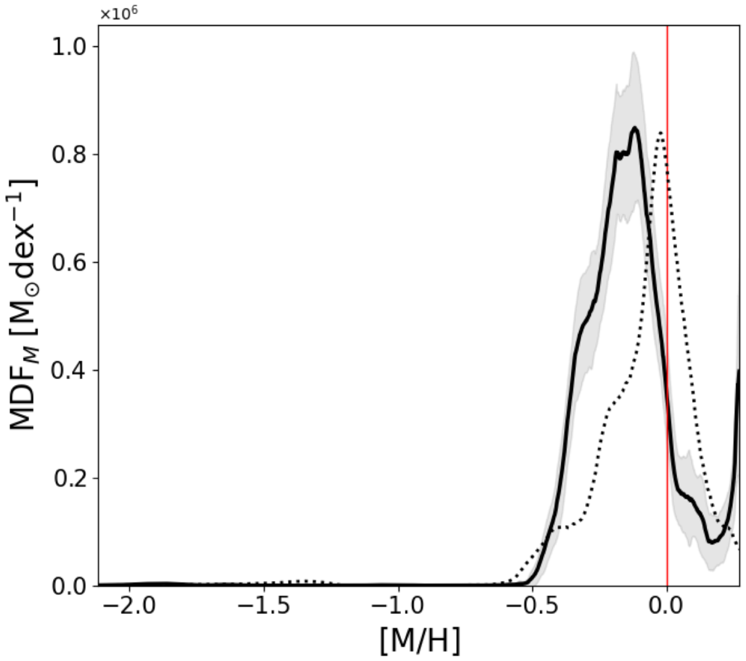
Which solution is ‘BEST’?



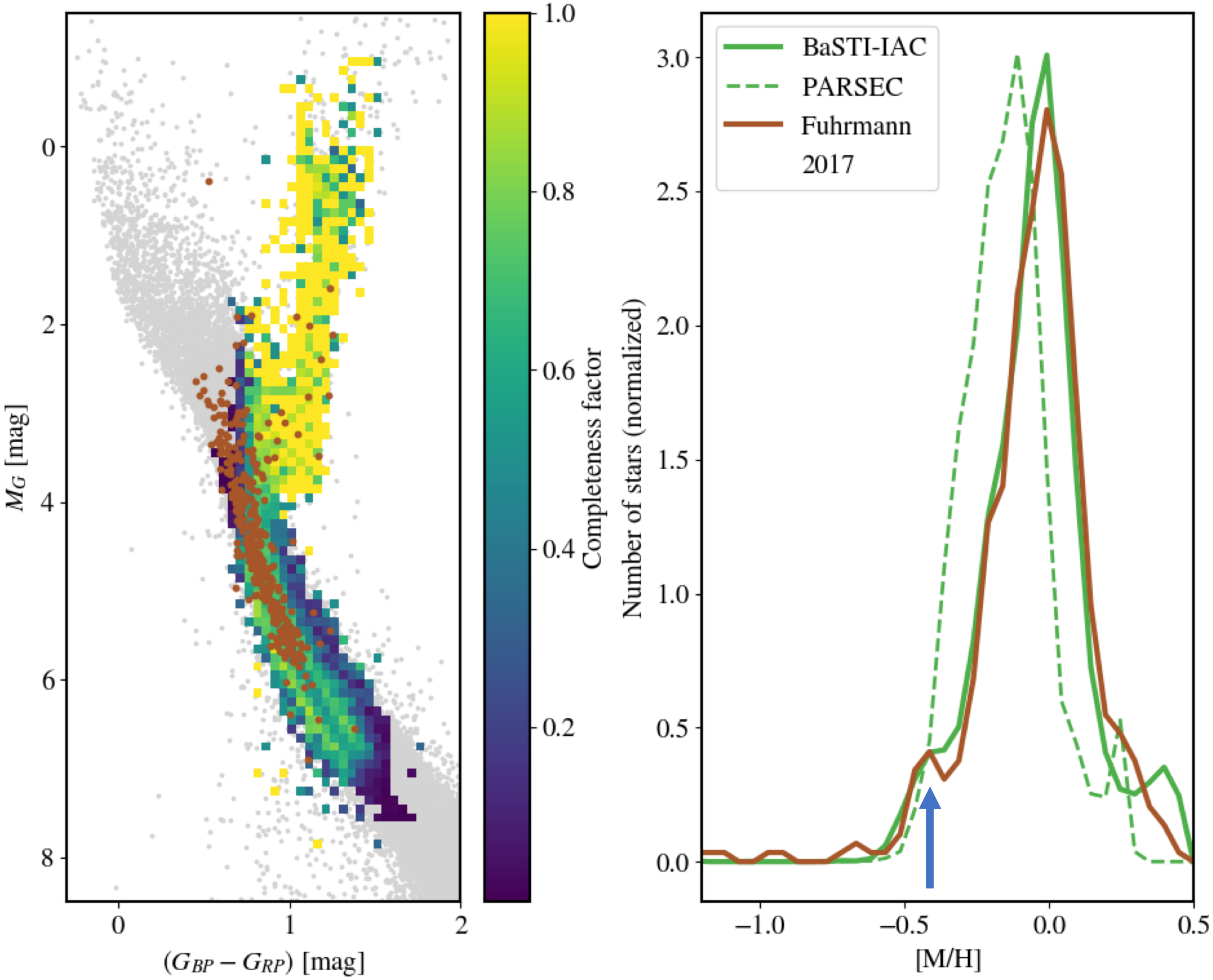








★ Accuracy and precisión of the derived MDF



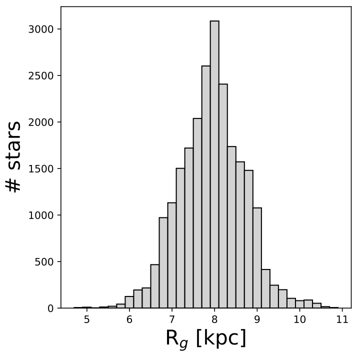
Fuhrman+ 2017

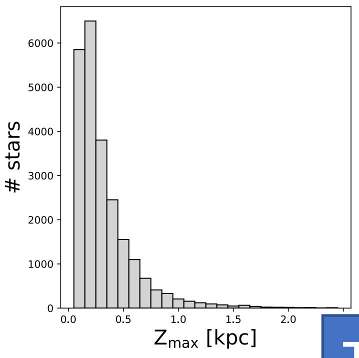
Comparison between the derived MDF and Fuhrman's spectroscopic MDF:

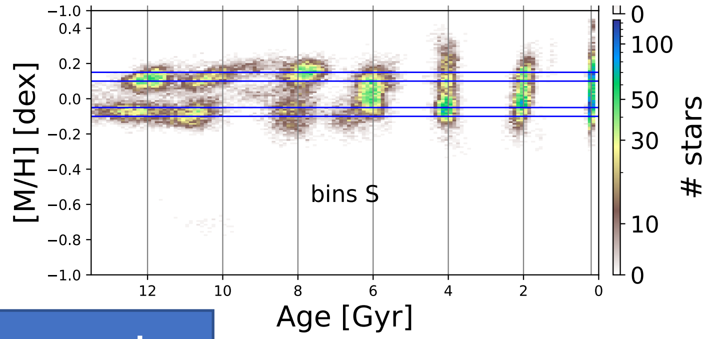
- **Almost perfect match with the BaSTI-IAC MDF**
- **Worse match with the PARSEC MDF**

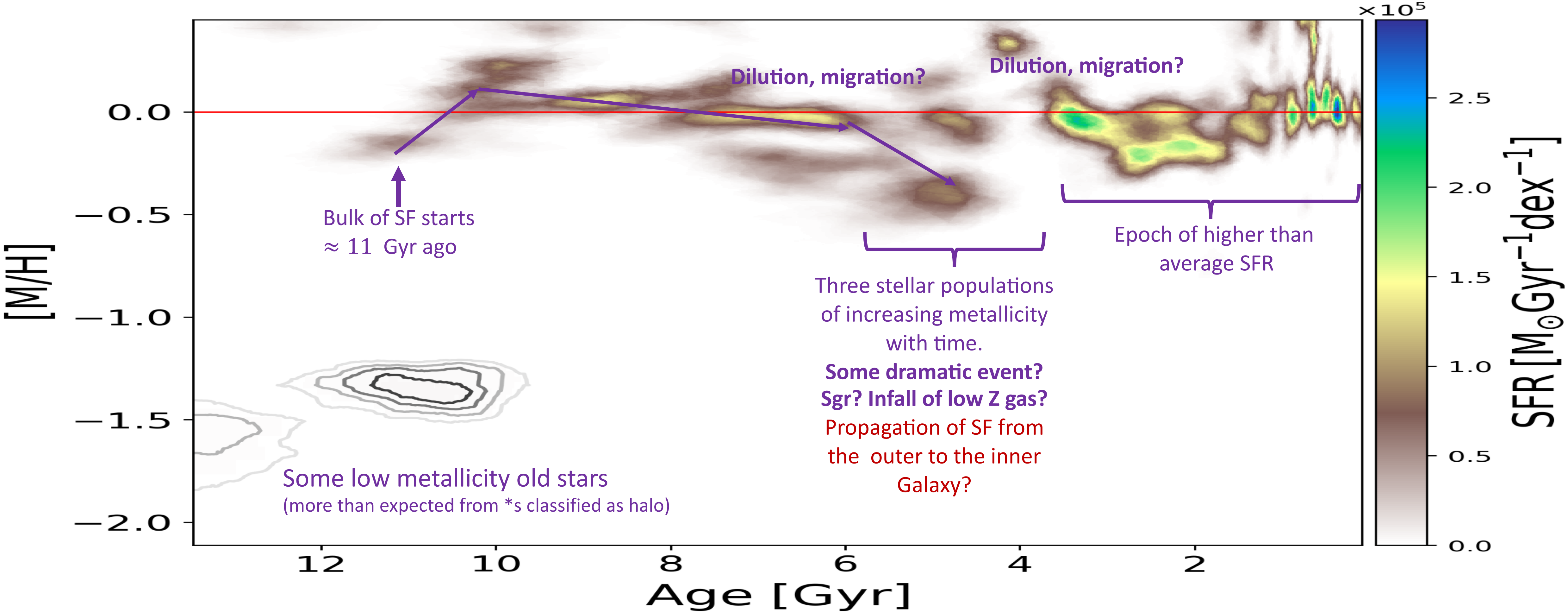
Note that no assumptions have been made regarding metallicity in the CMD-fitting process

The deSFH of the solar neighbourhood

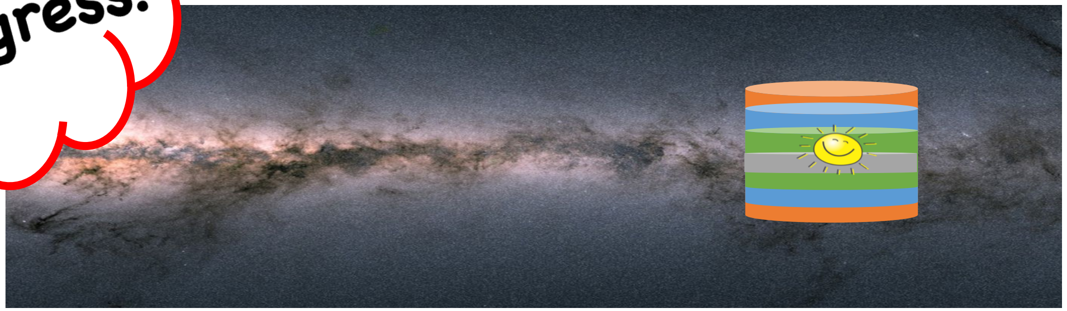








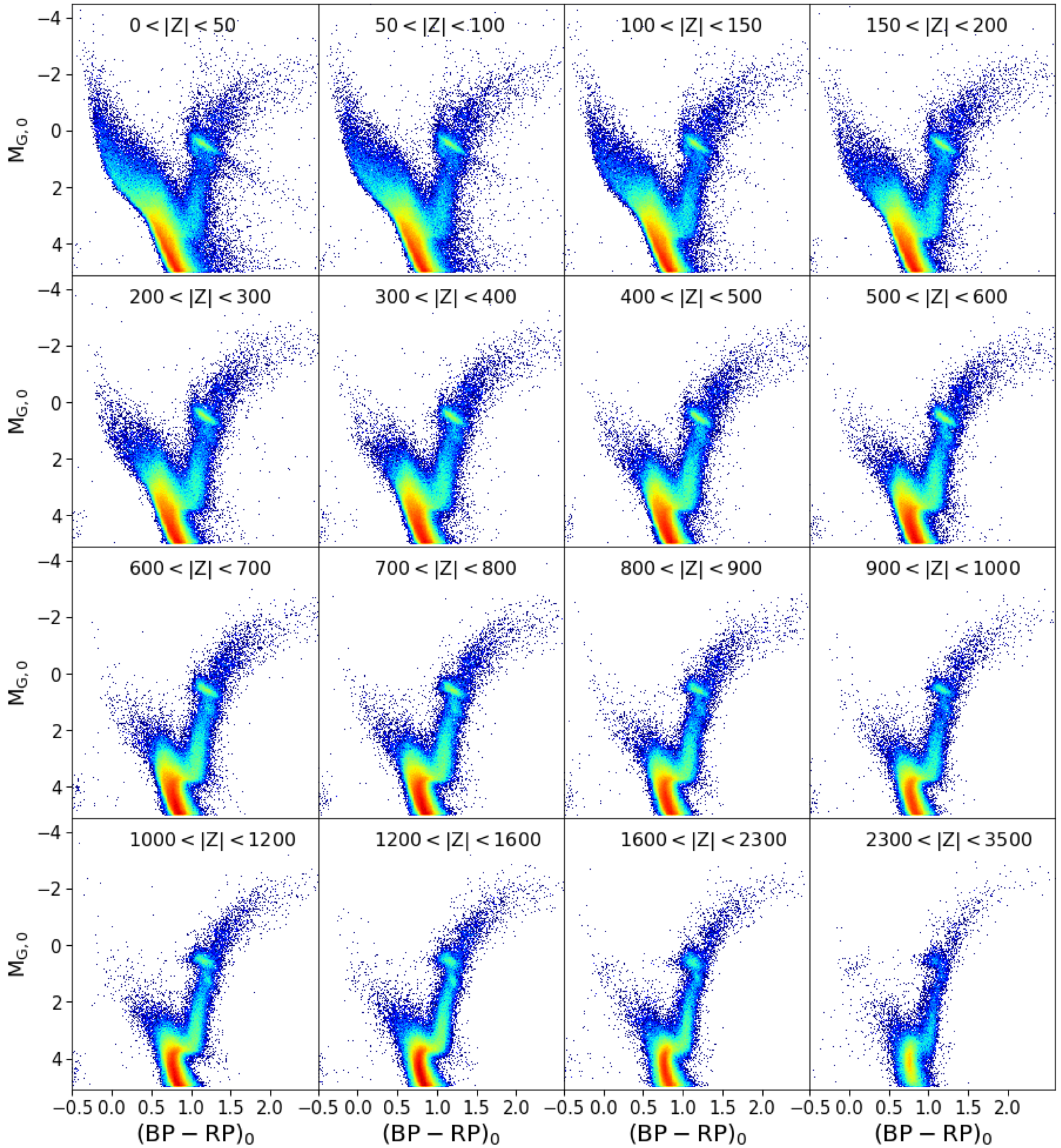
The spatially resolved star formation history of the Milky Way disk



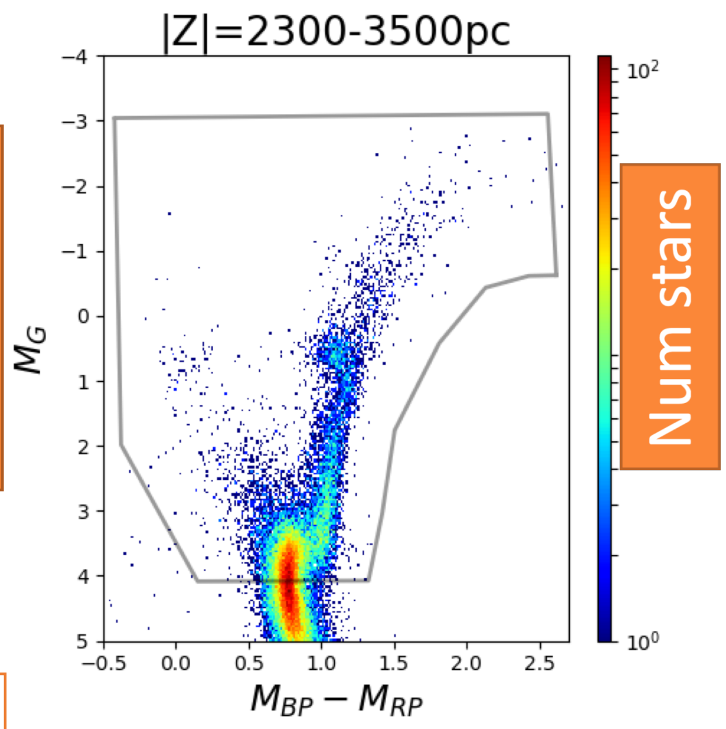
We are analyzing a cylinder of
R = 1 Kpc and
0 < |Z| < 3.5 Kpc
to determine disk SFH(Z)
(stars with halo-like kinematics removed)

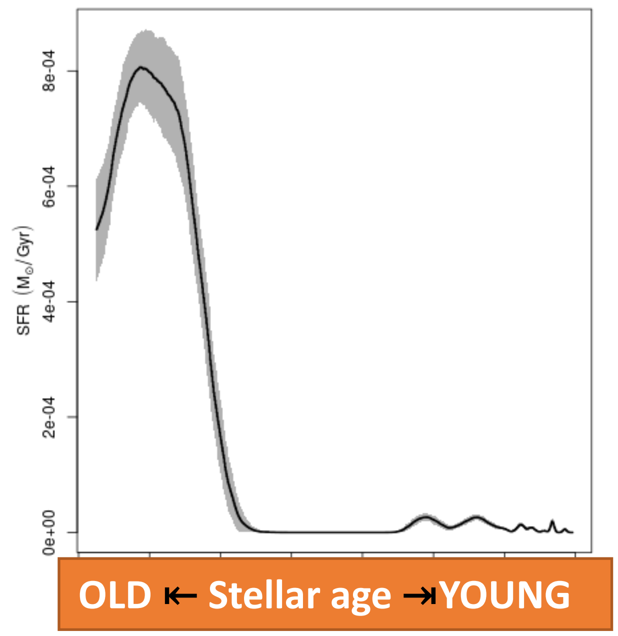
-What is the stellar **age/metallicity distributions** across the disk(s)?

-Do accretion events induce star formation in the disk?



The variation of **SFR**(t,[M/H]) across the Milky Way disk



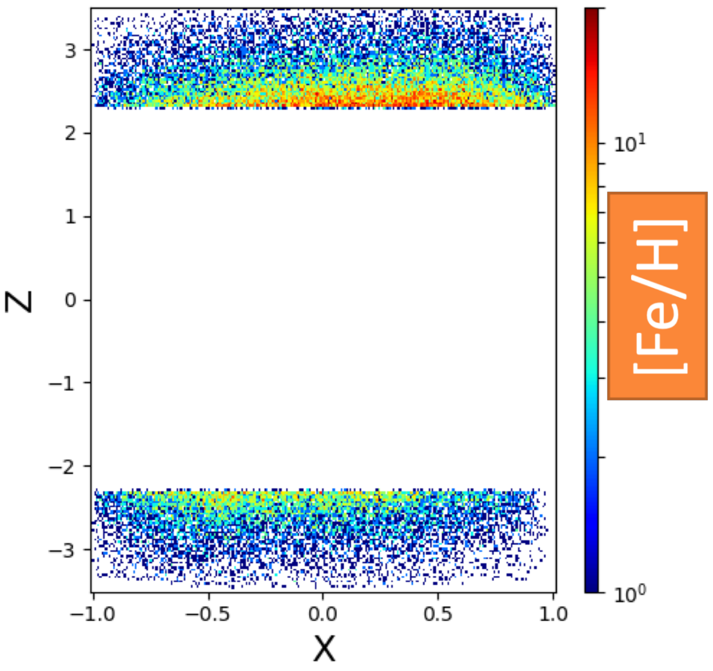


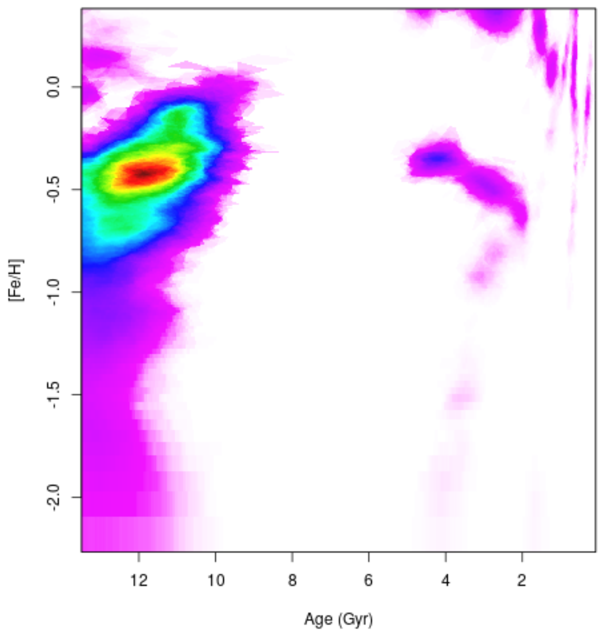
Let's focus first on the SFR(t)

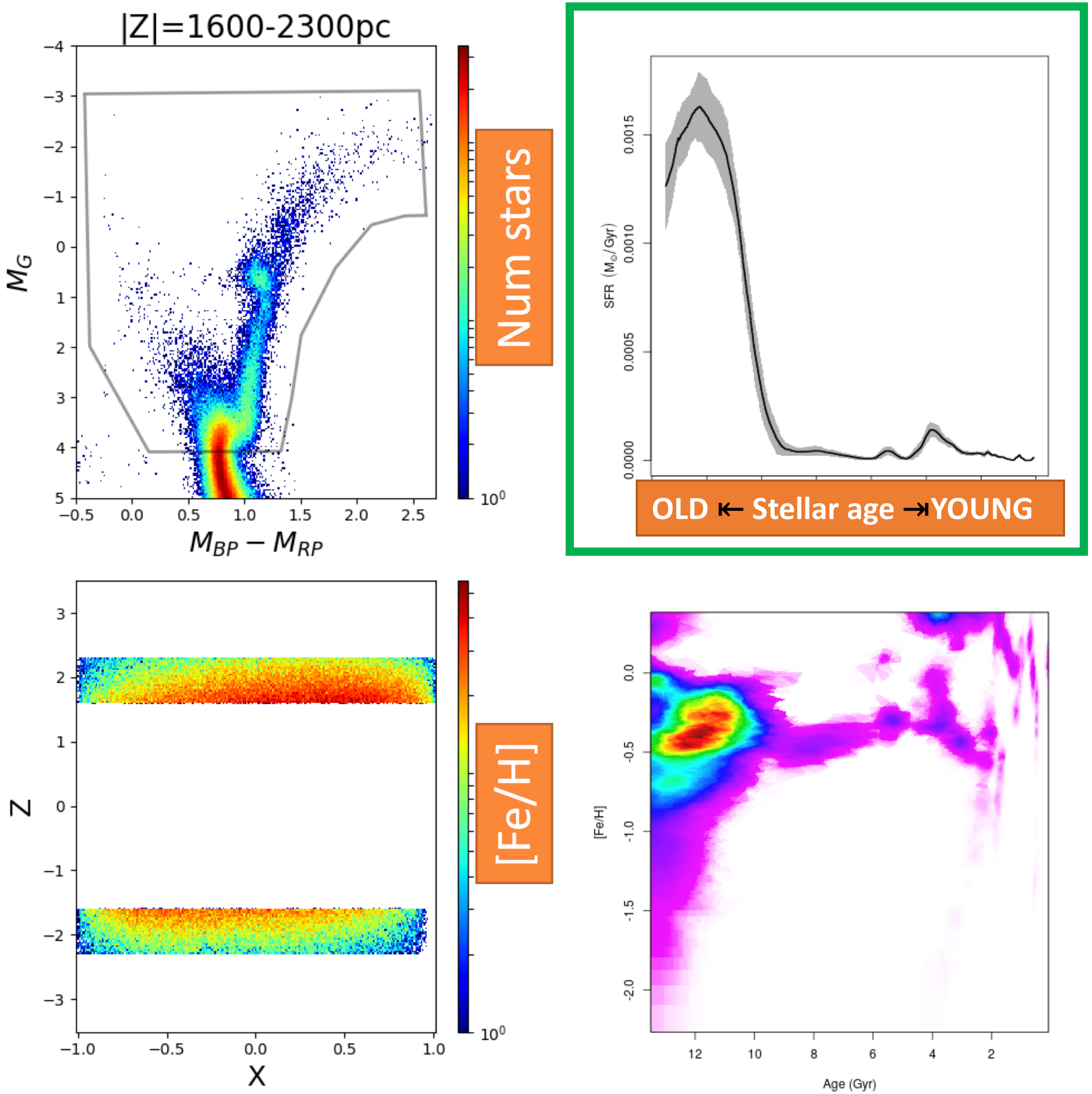
<u>We will see:</u>

-How the age-metallicity relation evolves across the Milky Way disk

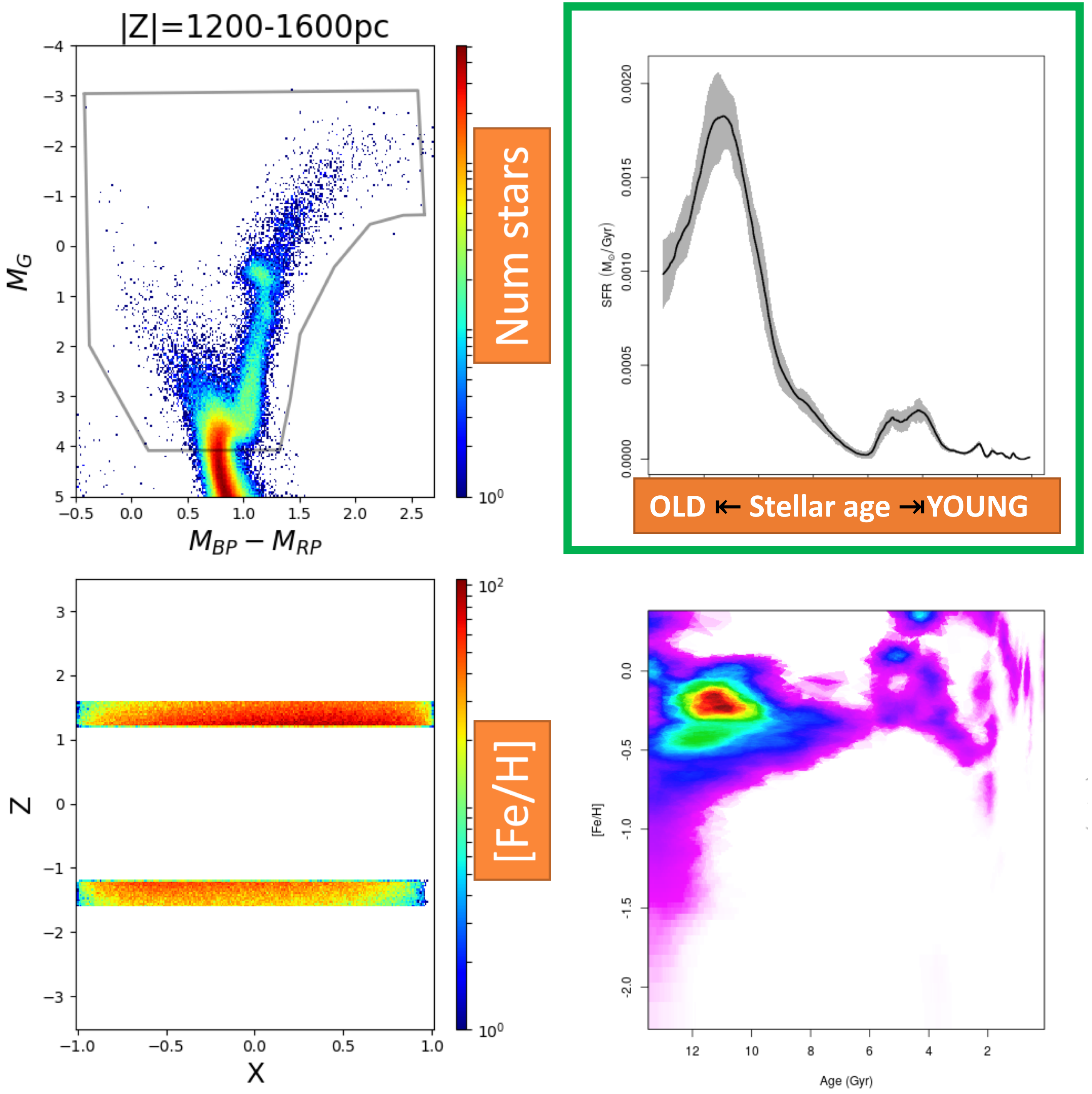
-There are distinct star formation episodes



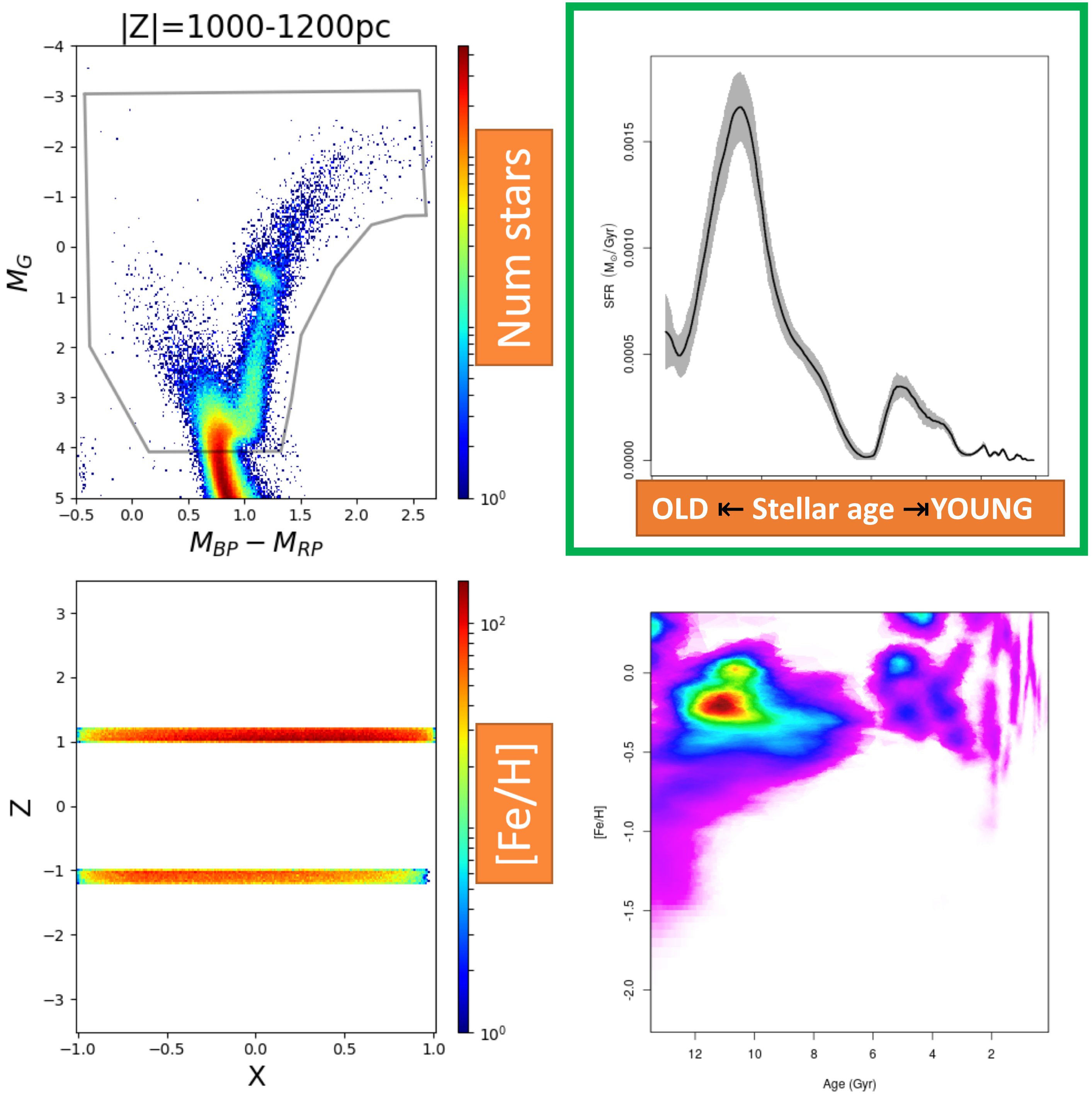




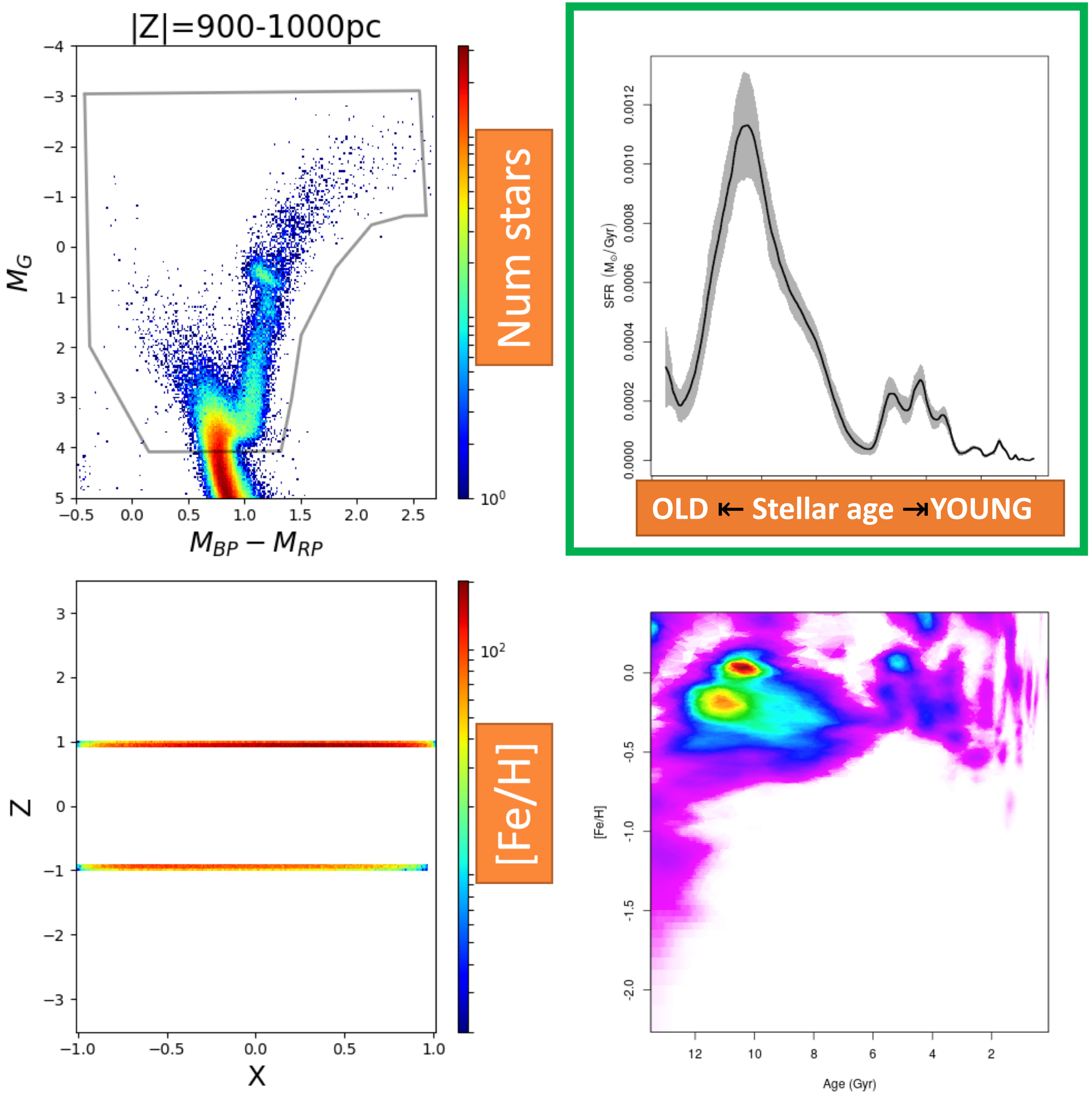
|Z|=1600-2300pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
10^0
[Fe/H]
Age (Gyr)

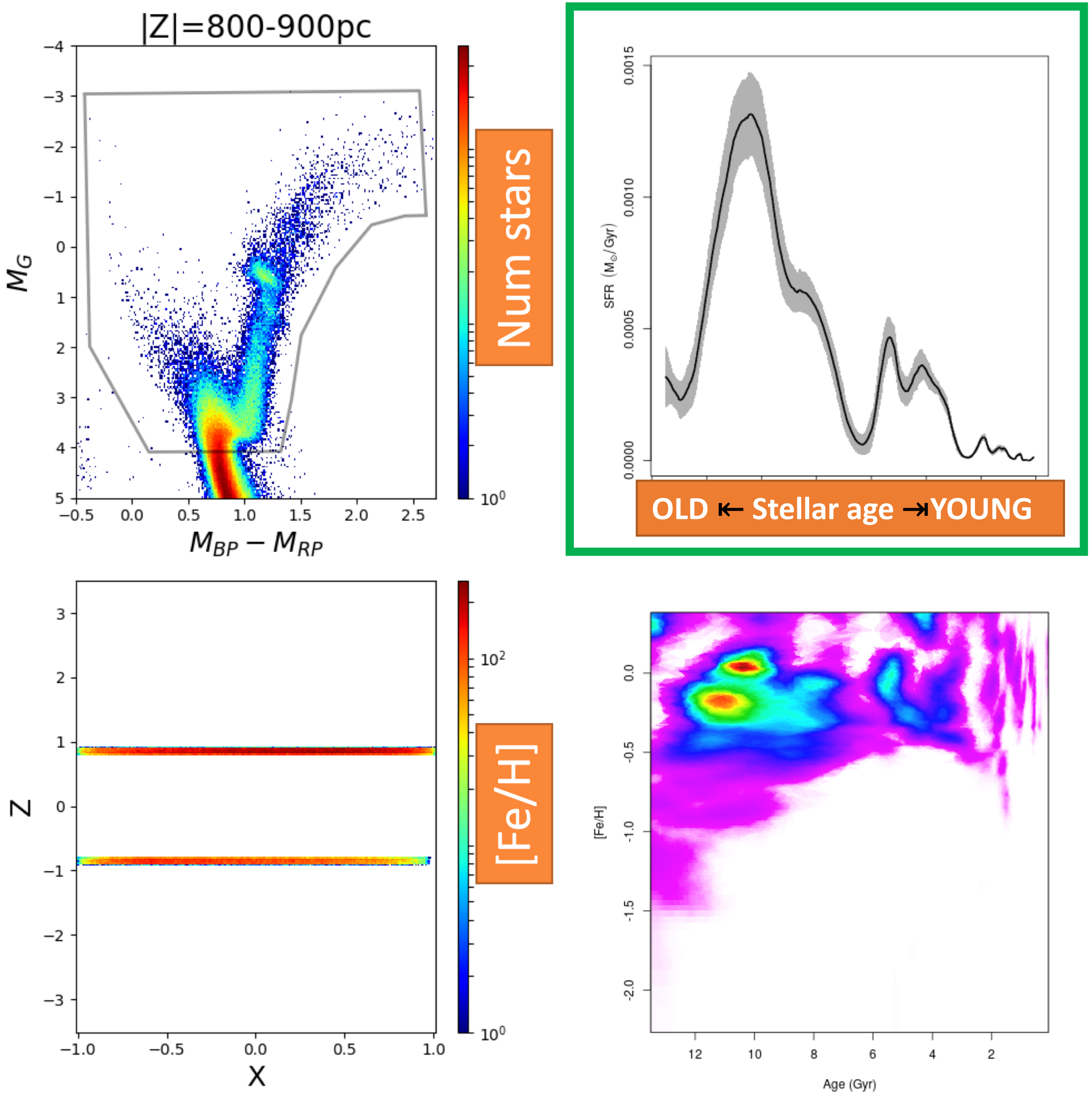


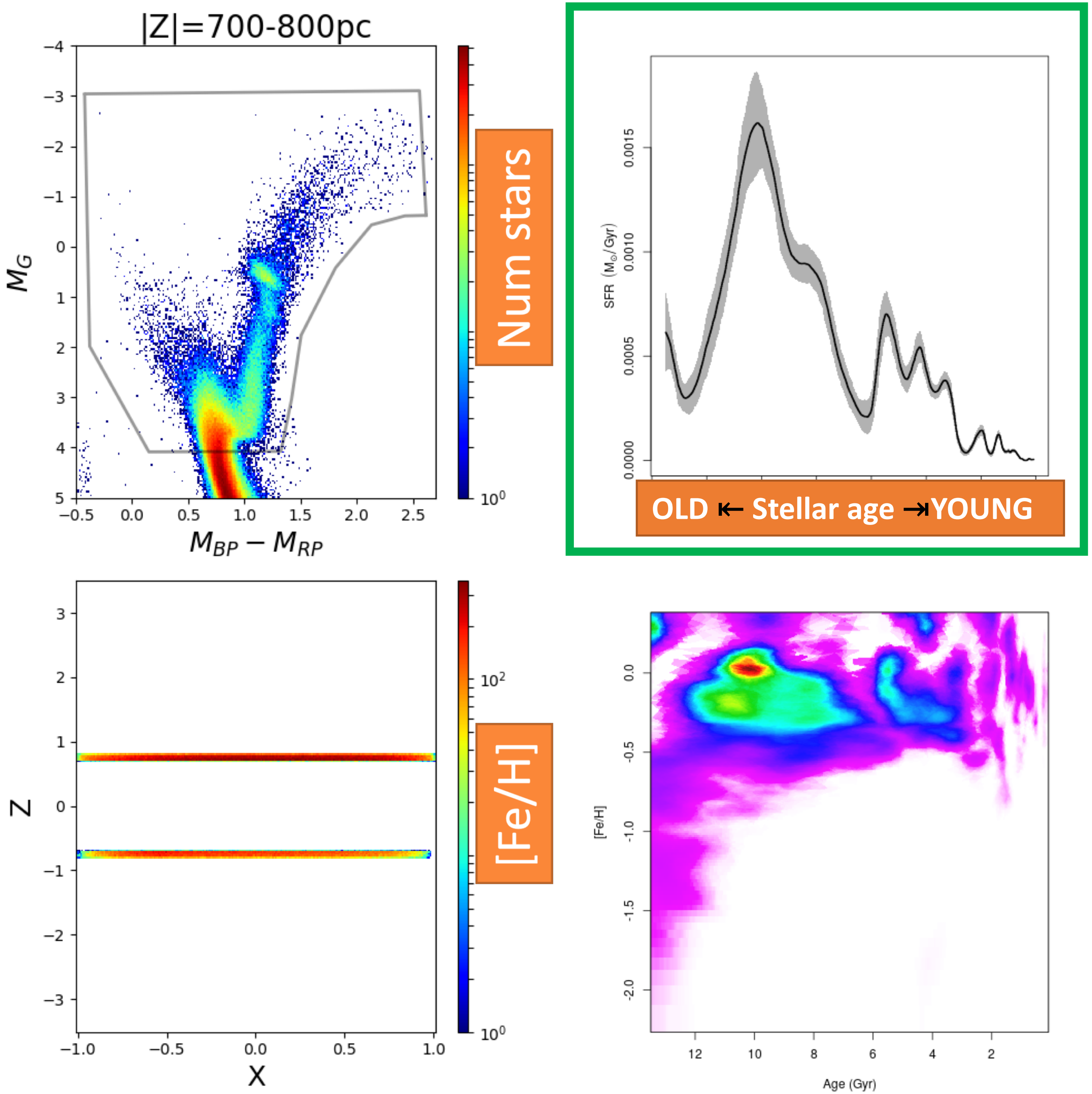
|Z|=1200-1600pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥ YOUNG
Z
X
[Fe/H]
10^2
10^0
[Fe/H]
Age (Gyr)



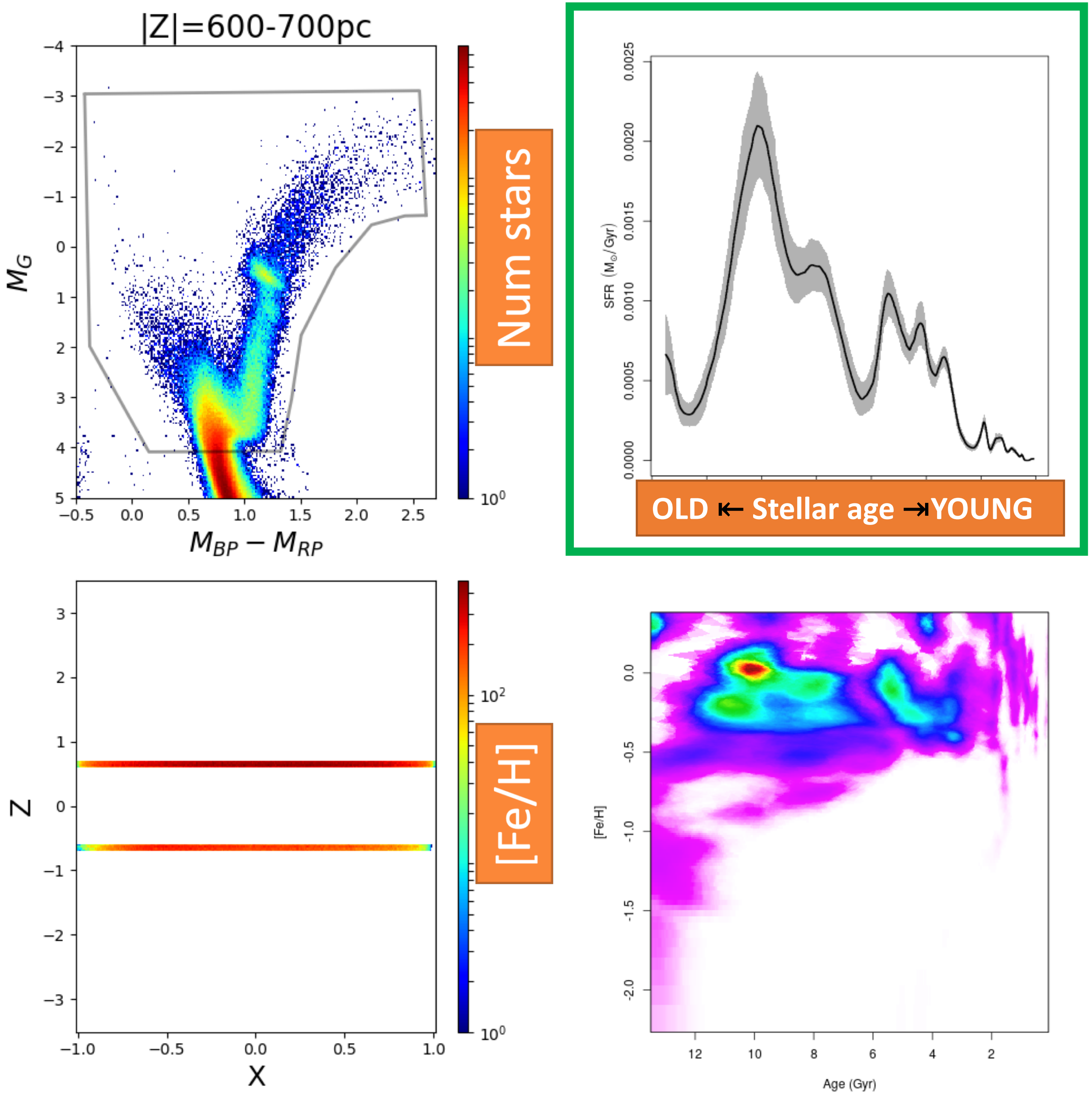
|Z|=1000-1200pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
10^2
10^0
Age (Gyr)


|Z|=900-1000pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
10^2
[Fe/H]
[Fe/H]
Age (Gyr)

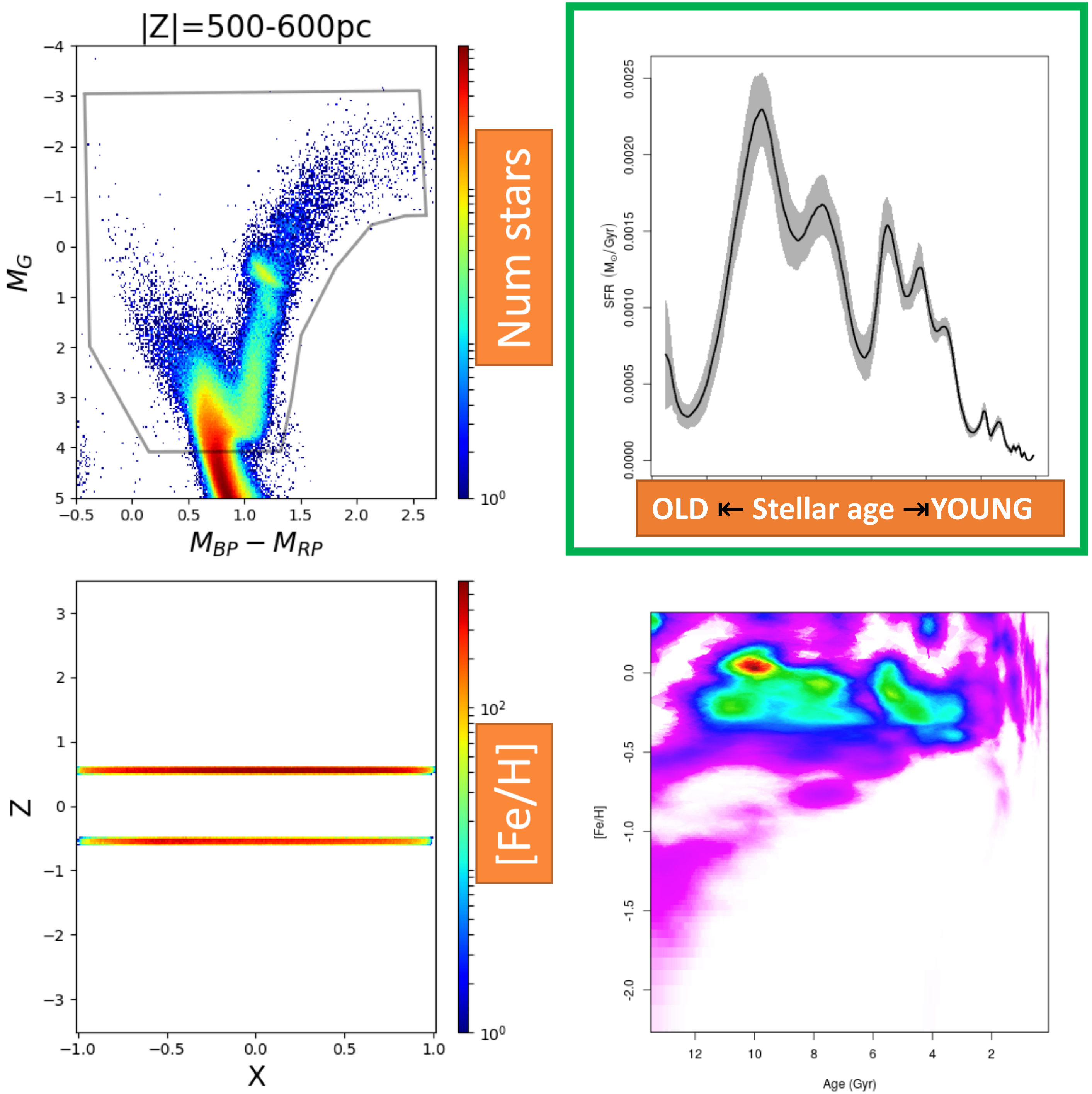

|Z|=800-900pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR (M⊙/Gyr)
0.0015
0.0010
0.0005
0.0000
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
10^2
10^0
[Fe/H]
Age (Gyr)

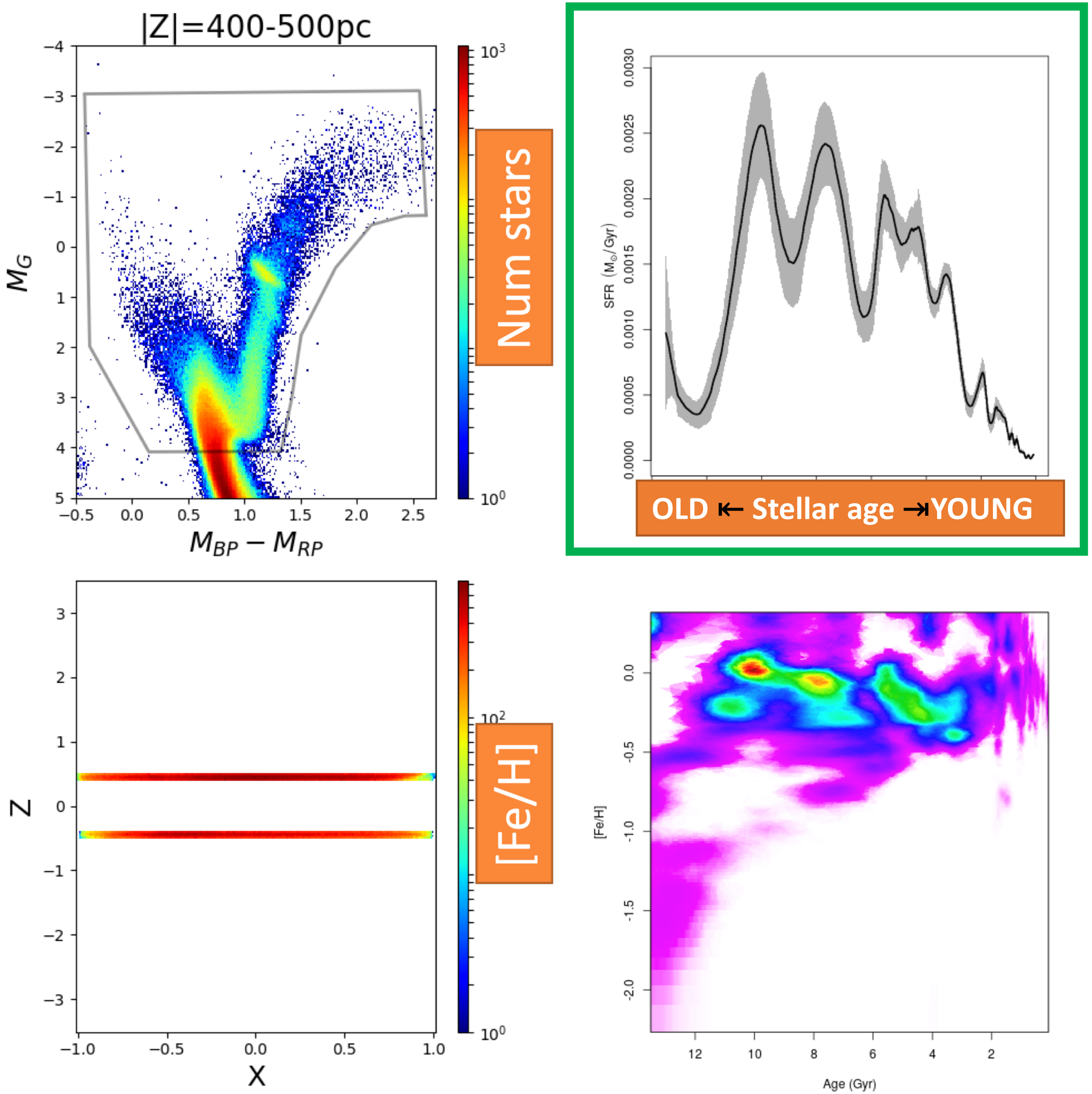


|Z|=700-800pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ← Stellar age → YOUNG
Z
X
10^2
[Fe/H]
Age (Gyr)

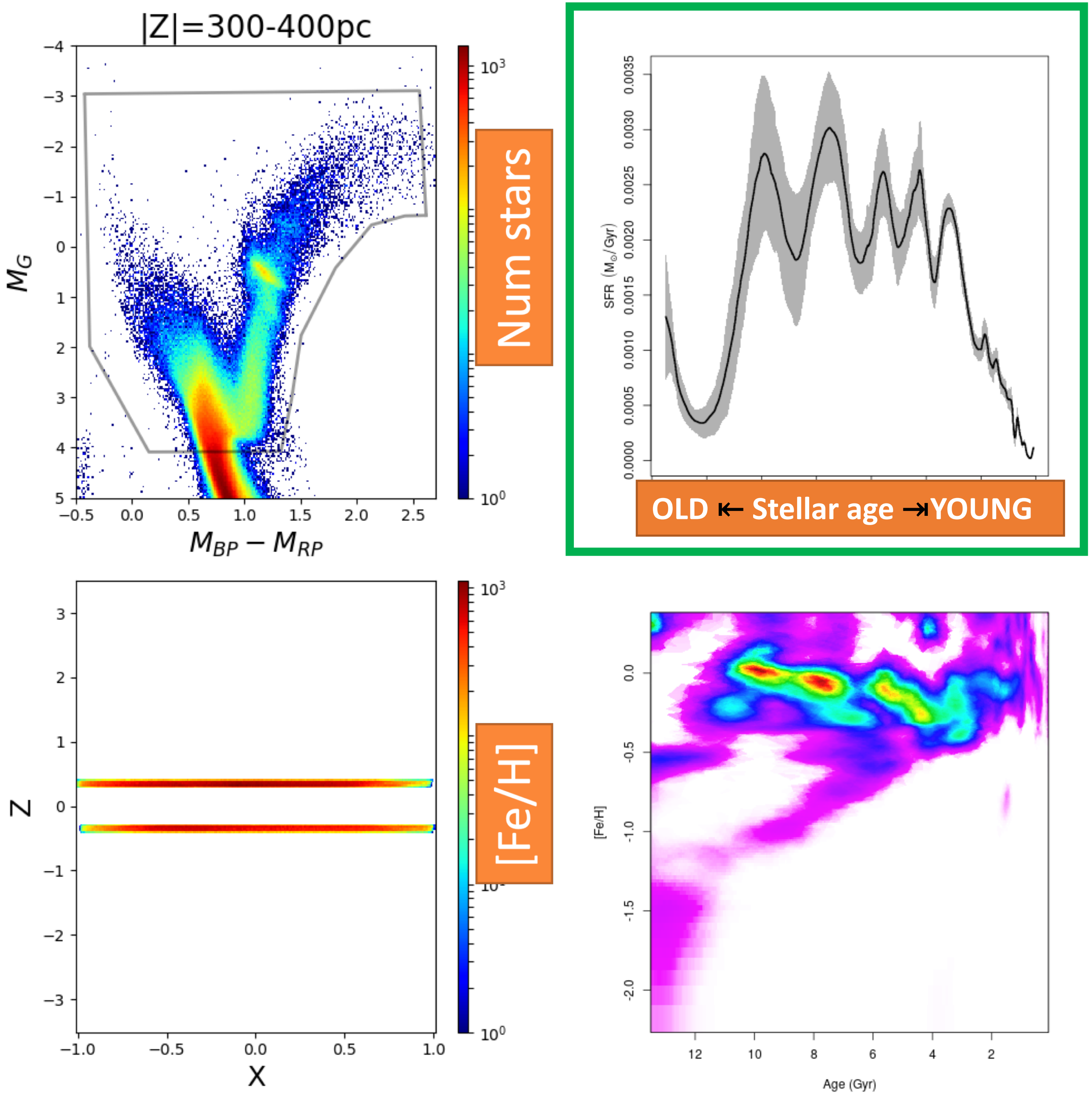


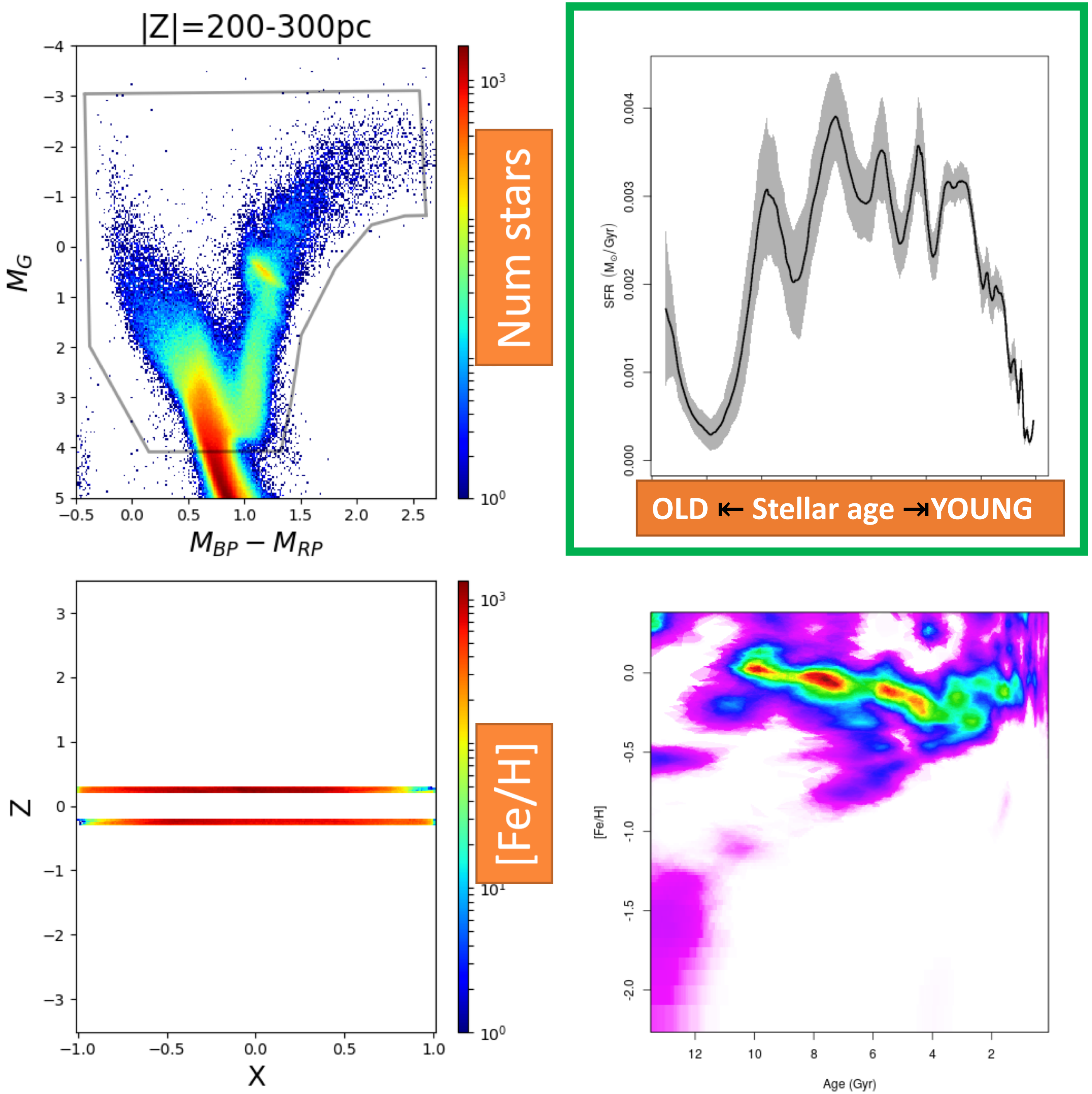
|Z|=600-700pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
Z
X
[Fe/H]
10^2
10^0
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
[Fe/H]
Age (Gyr)

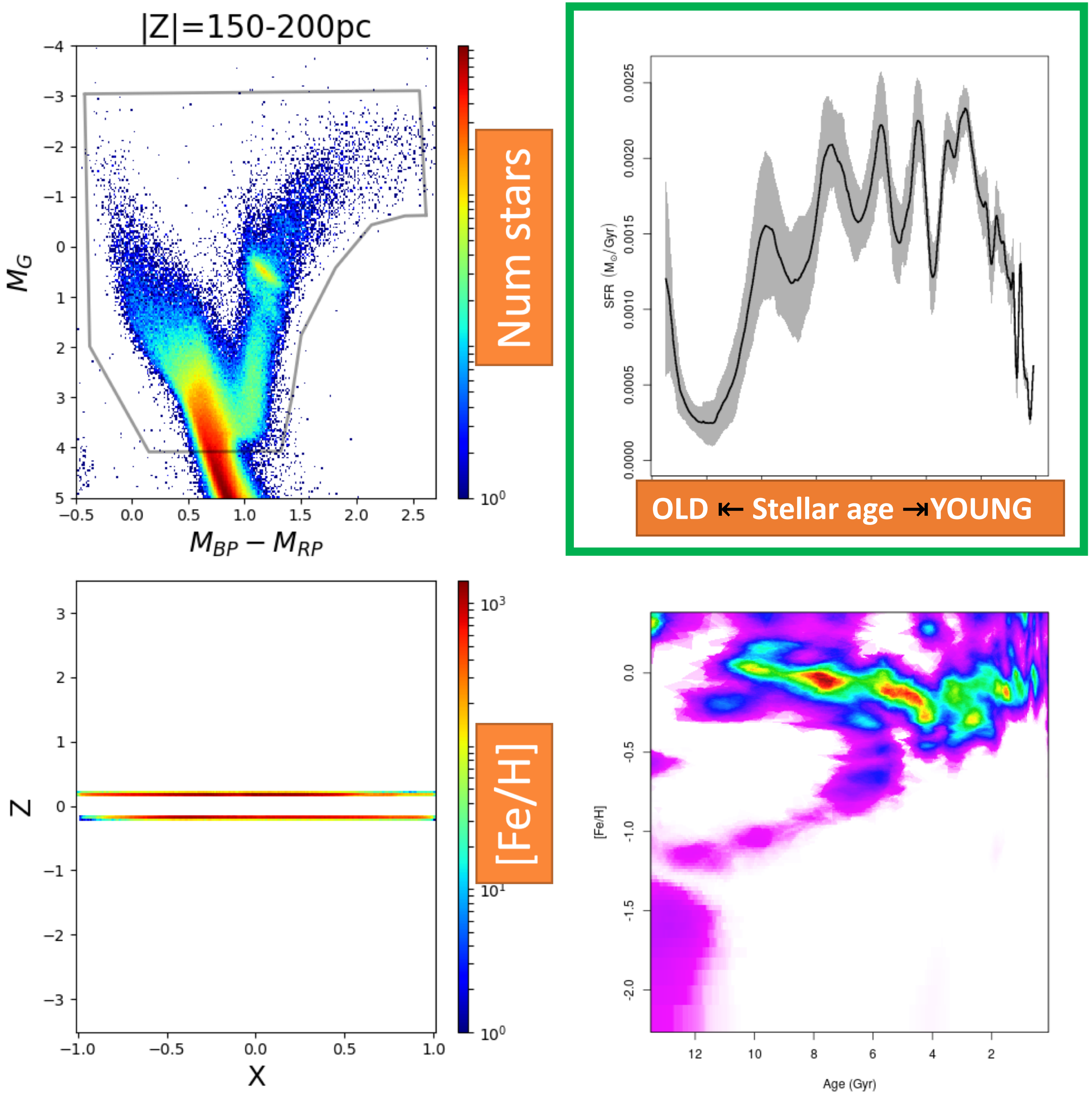

|Z|=500-600pc
M_G
M_BP − M_RP
Num stars
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)

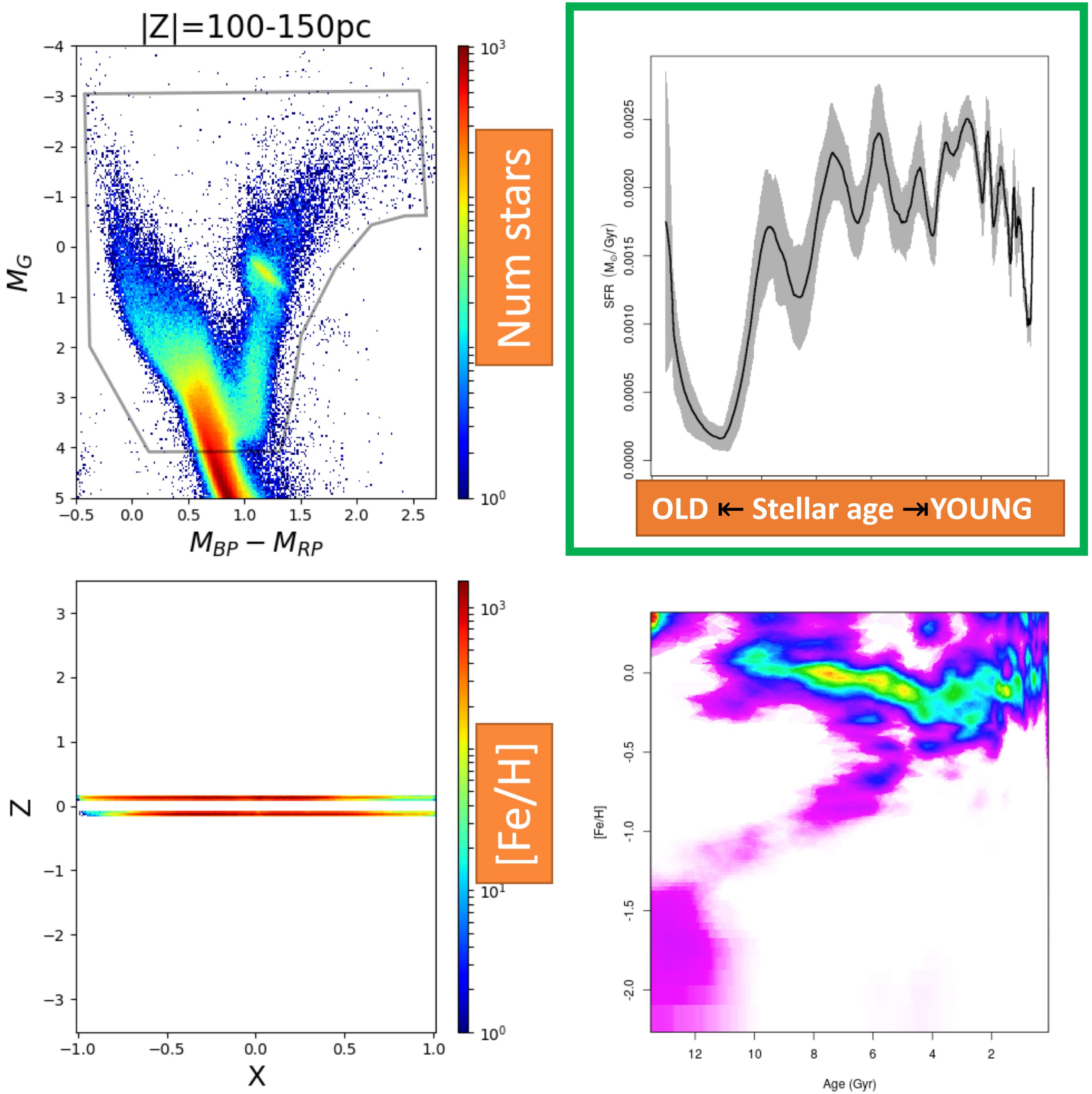


|Z|=400-500pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
Age (Gyr)

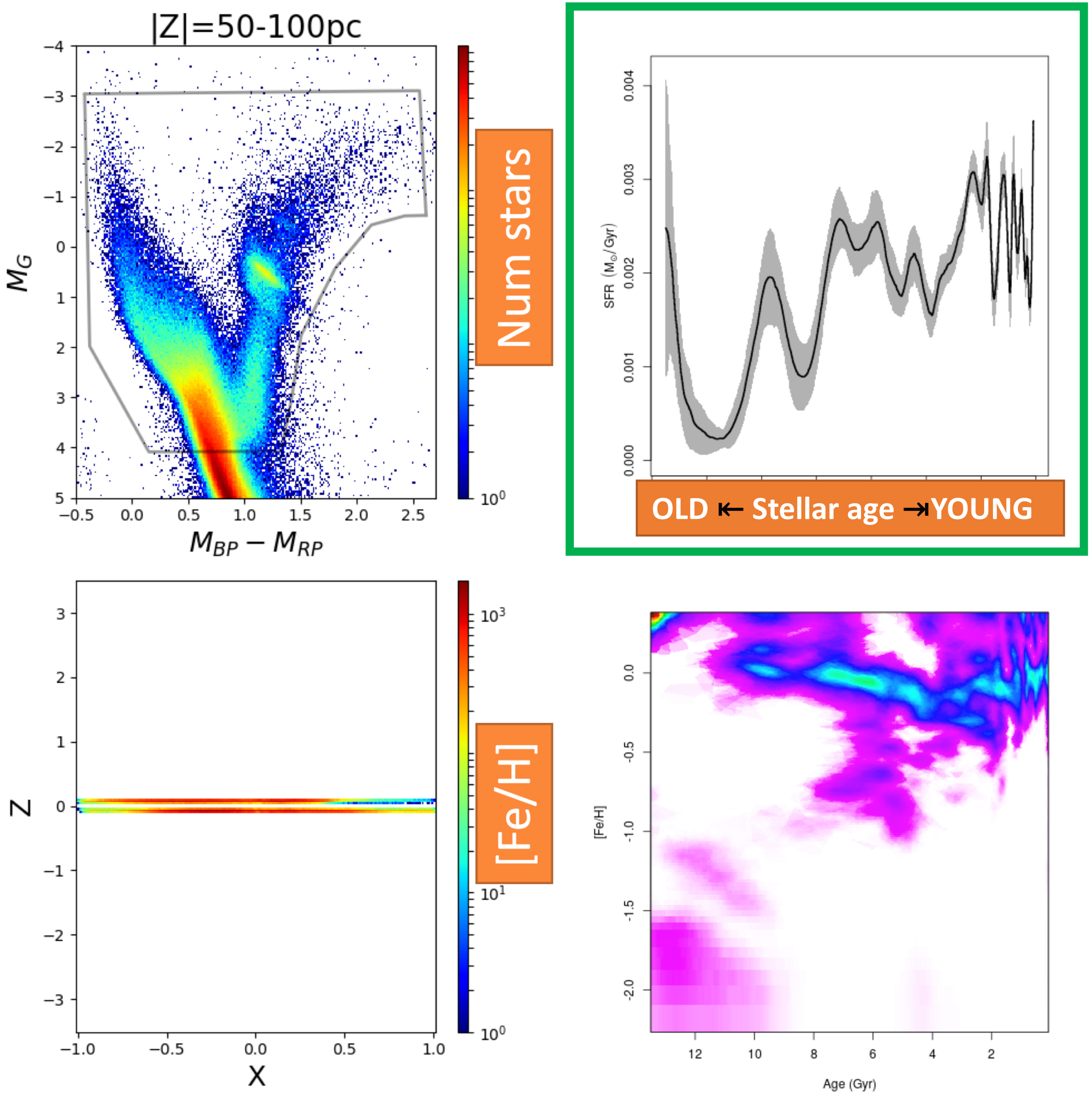

|Z|=300-400pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^3
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥ YOUNG
Z
X
[Fe/H]
Age (Gyr)


|Z|=200-300pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR (M⊙/Gyr)
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)

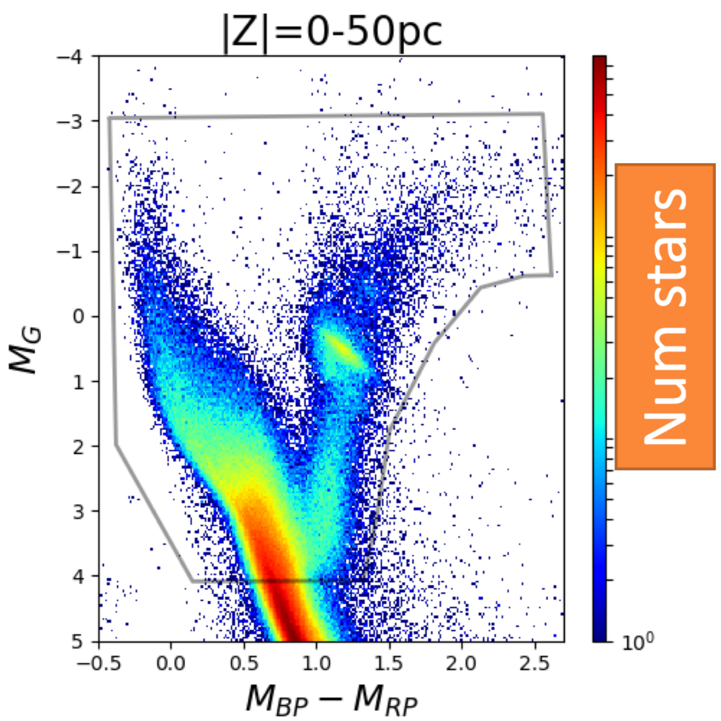

|Z|=150-200pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
10^3
10^1
10^0
[Fe/H]
Age (Gyr)

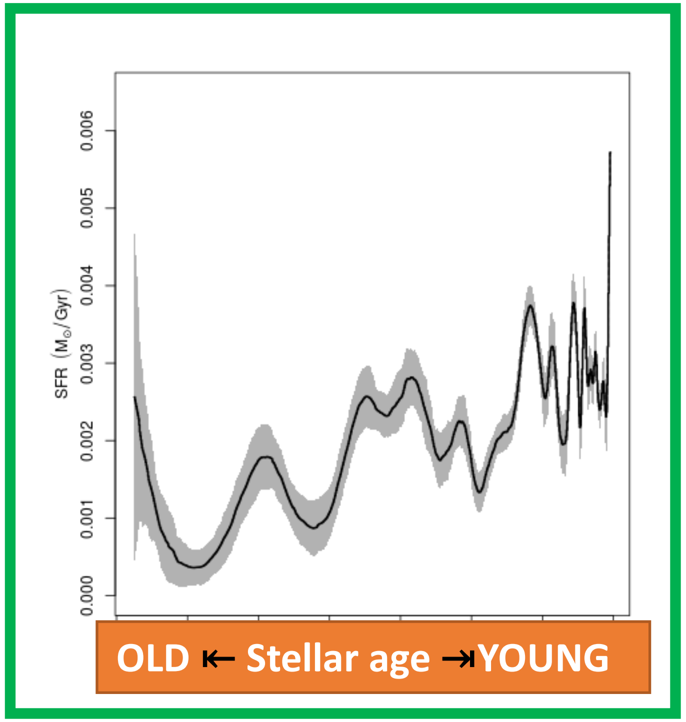


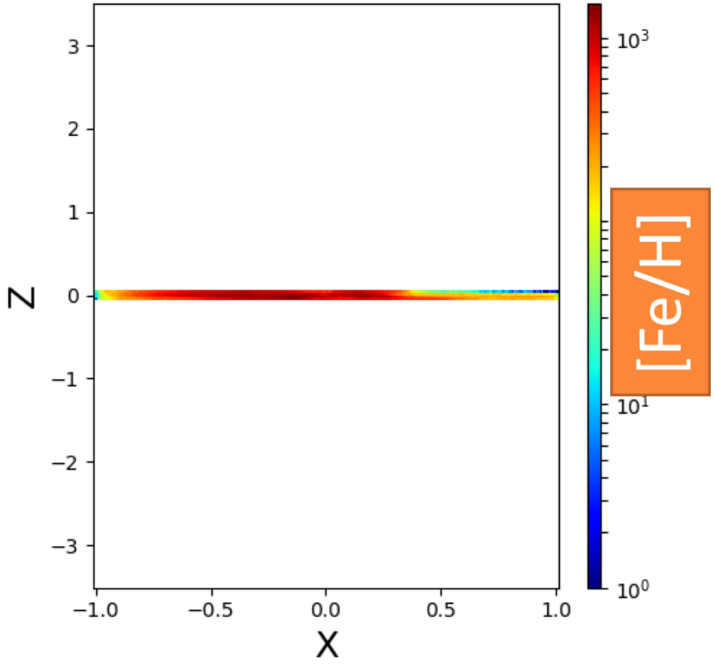
|Z|=100-150pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)

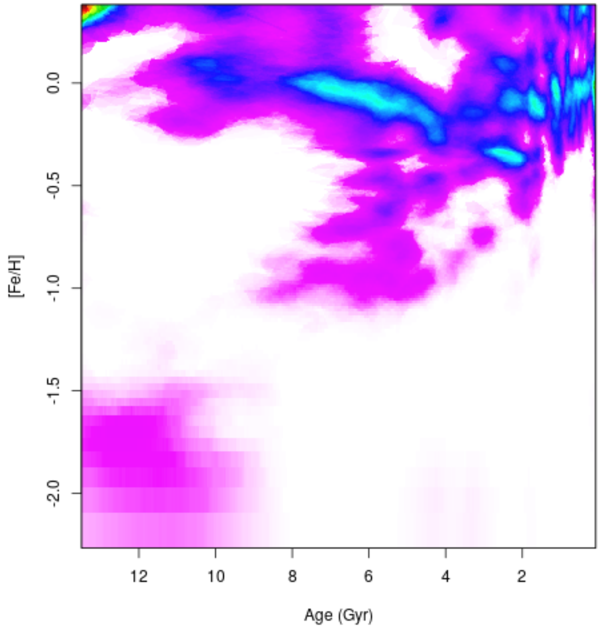


|Z|=50-100pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)


|Z|=0-50pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0

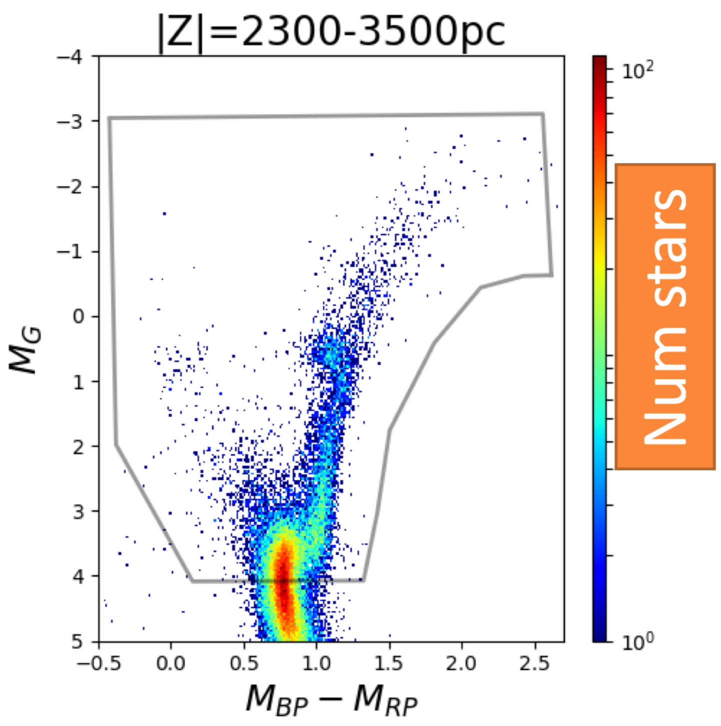

SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG

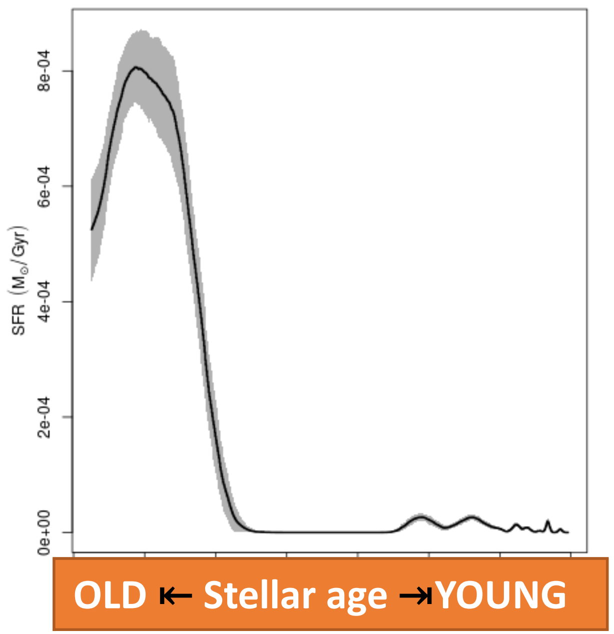

Z
X
[Fe/H]
10^3
10^1
10^0

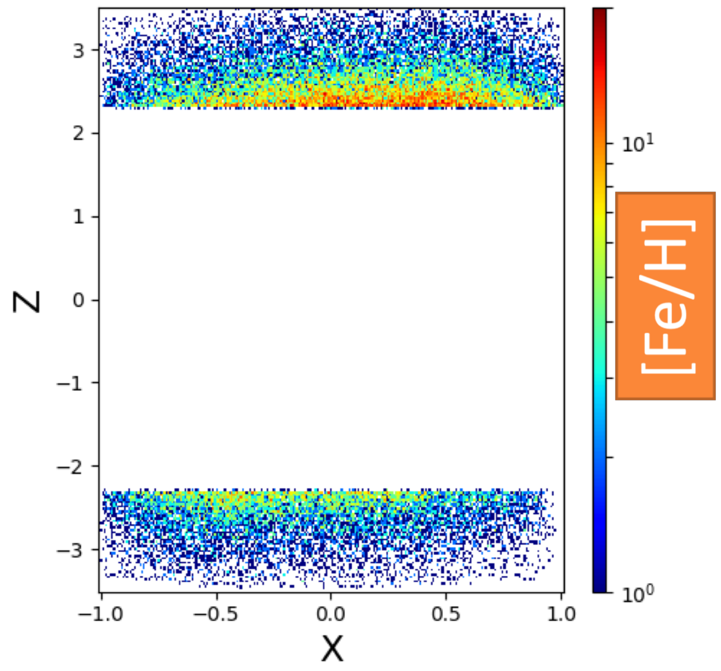

[Fe/H]
Age (Gyr)

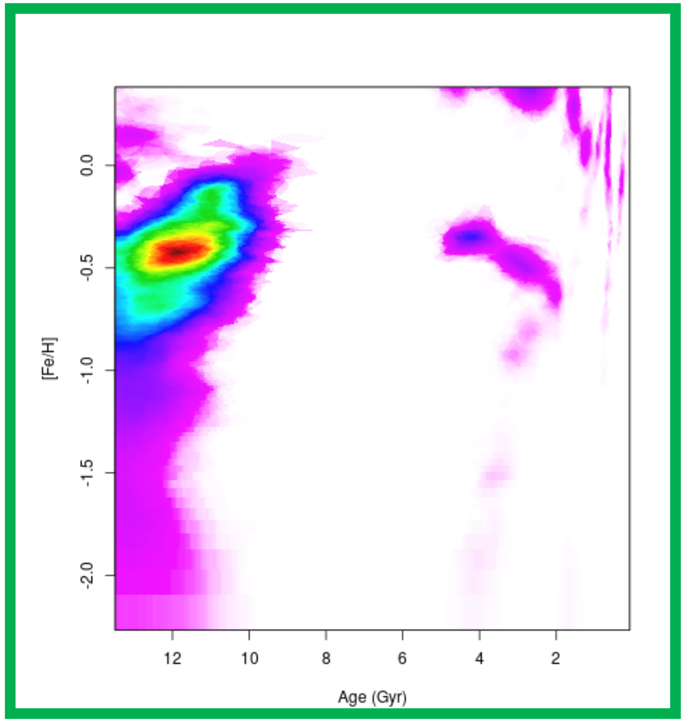
AGAIN!

Now, let’s focus on the age-metallicity plane

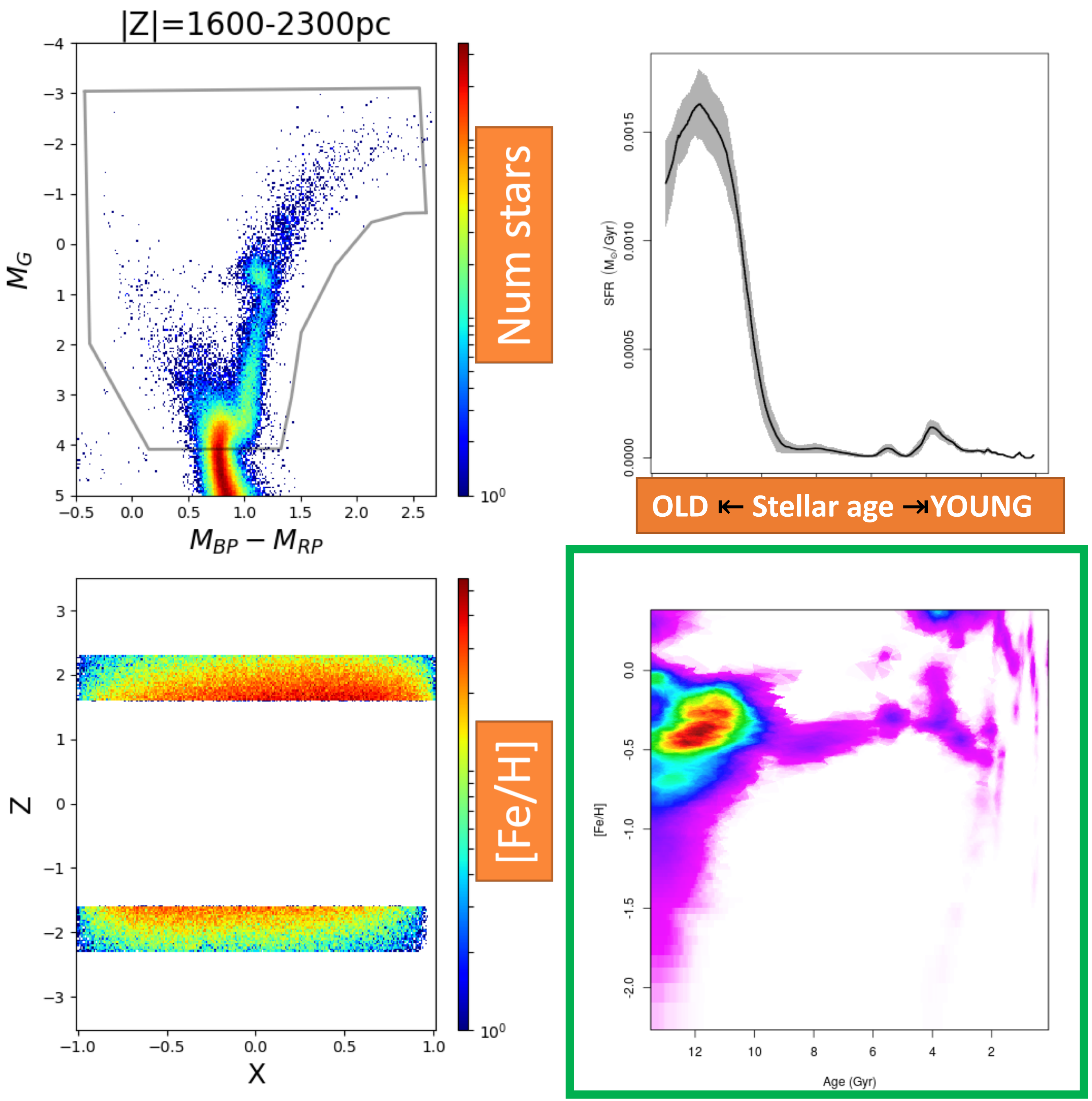




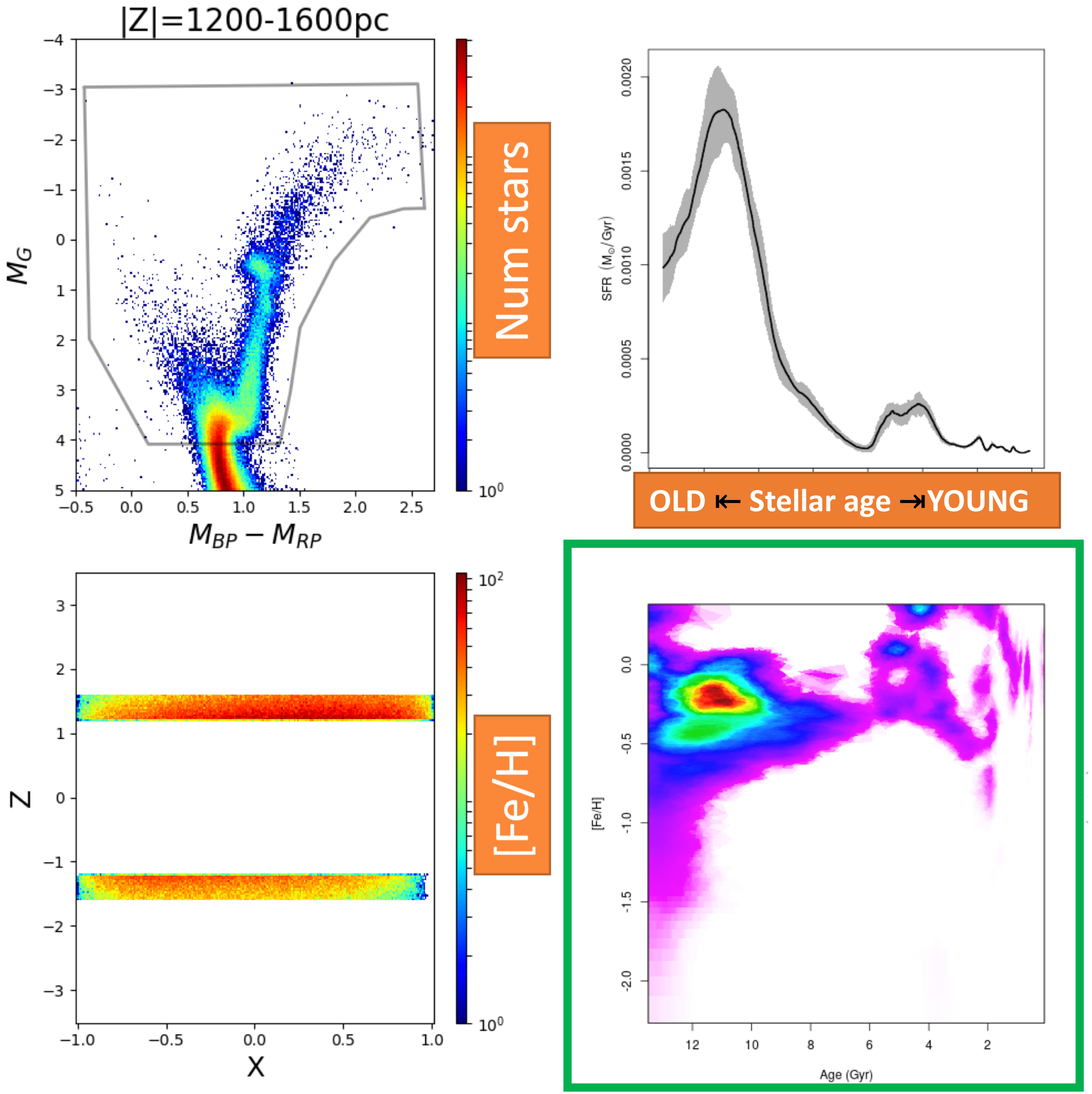


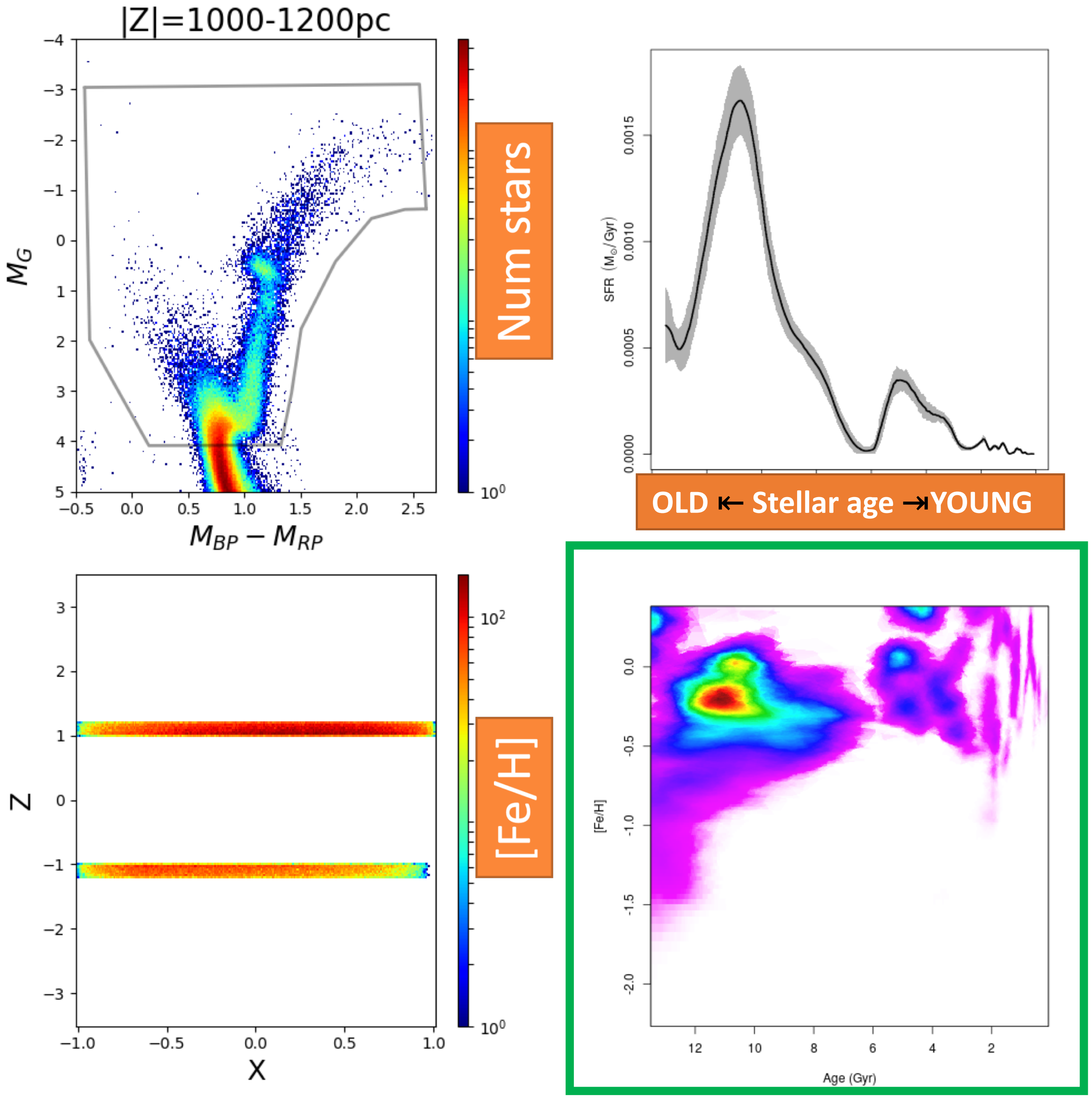


AGAIN!
Now, let's focus on the age-metallicity plane

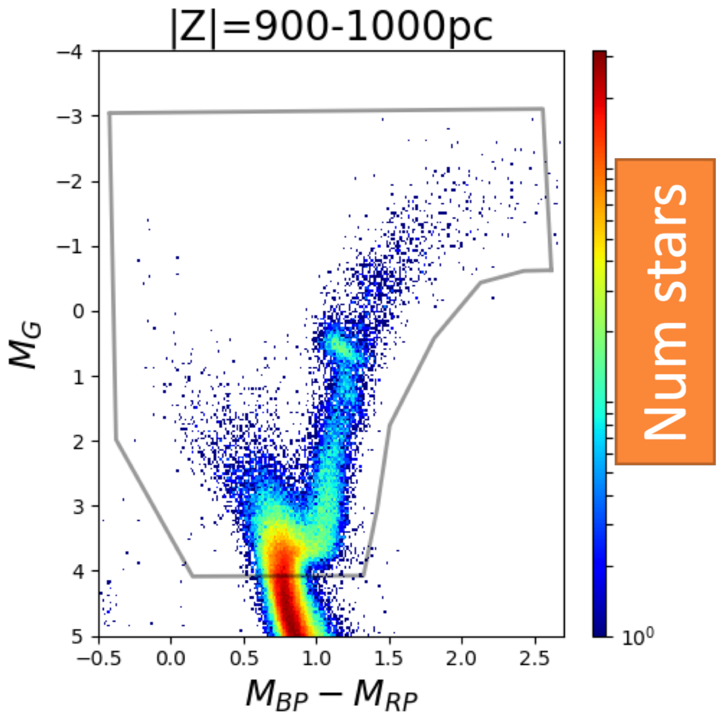


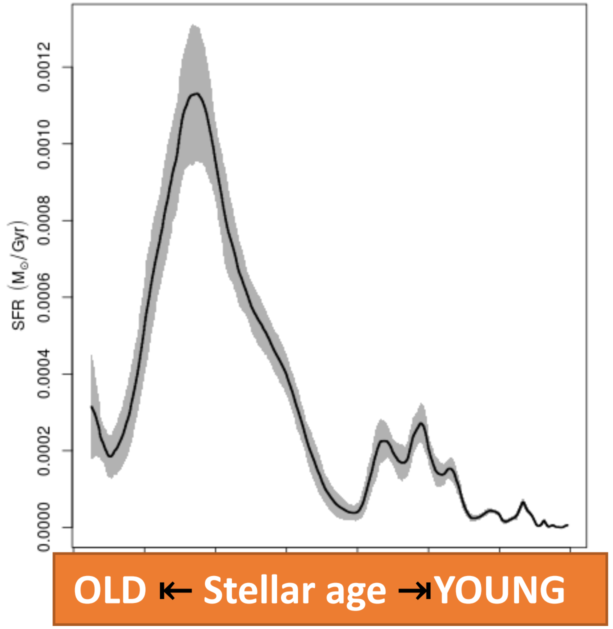
|Z|=1600-2300pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR (M☉/Gyr)
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
10^0
[Fe/H]
Age (Gyr)

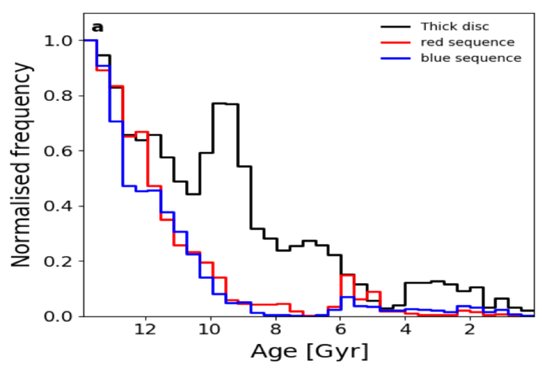

|Z|=1200-1600pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
10^2
[Fe/H]
10^0
[Fe/H]
Age (Gyr)

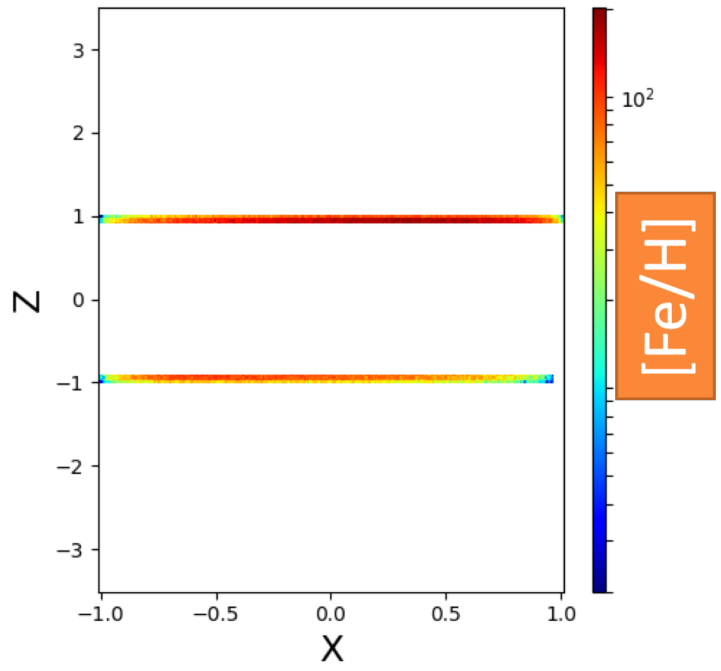


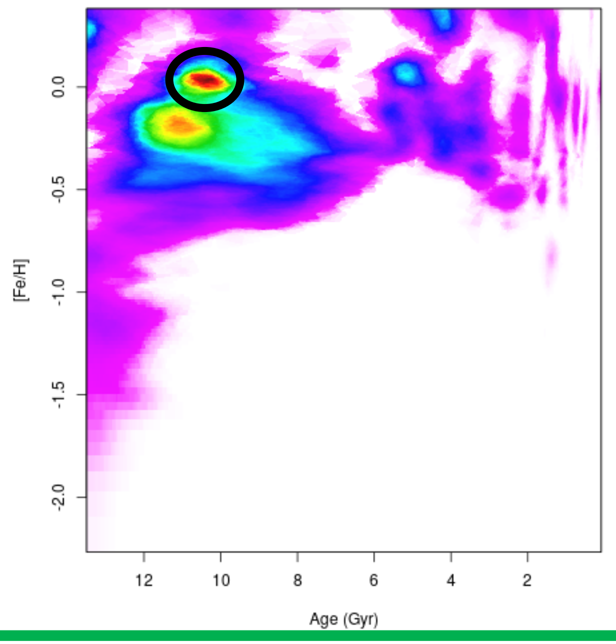
|Z|=1000-1200pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
0.0015
0.0010
0.0005
0.0000
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
10^2
10^0
[Fe/H]
Age (Gyr)
12
10
8
6
4
2



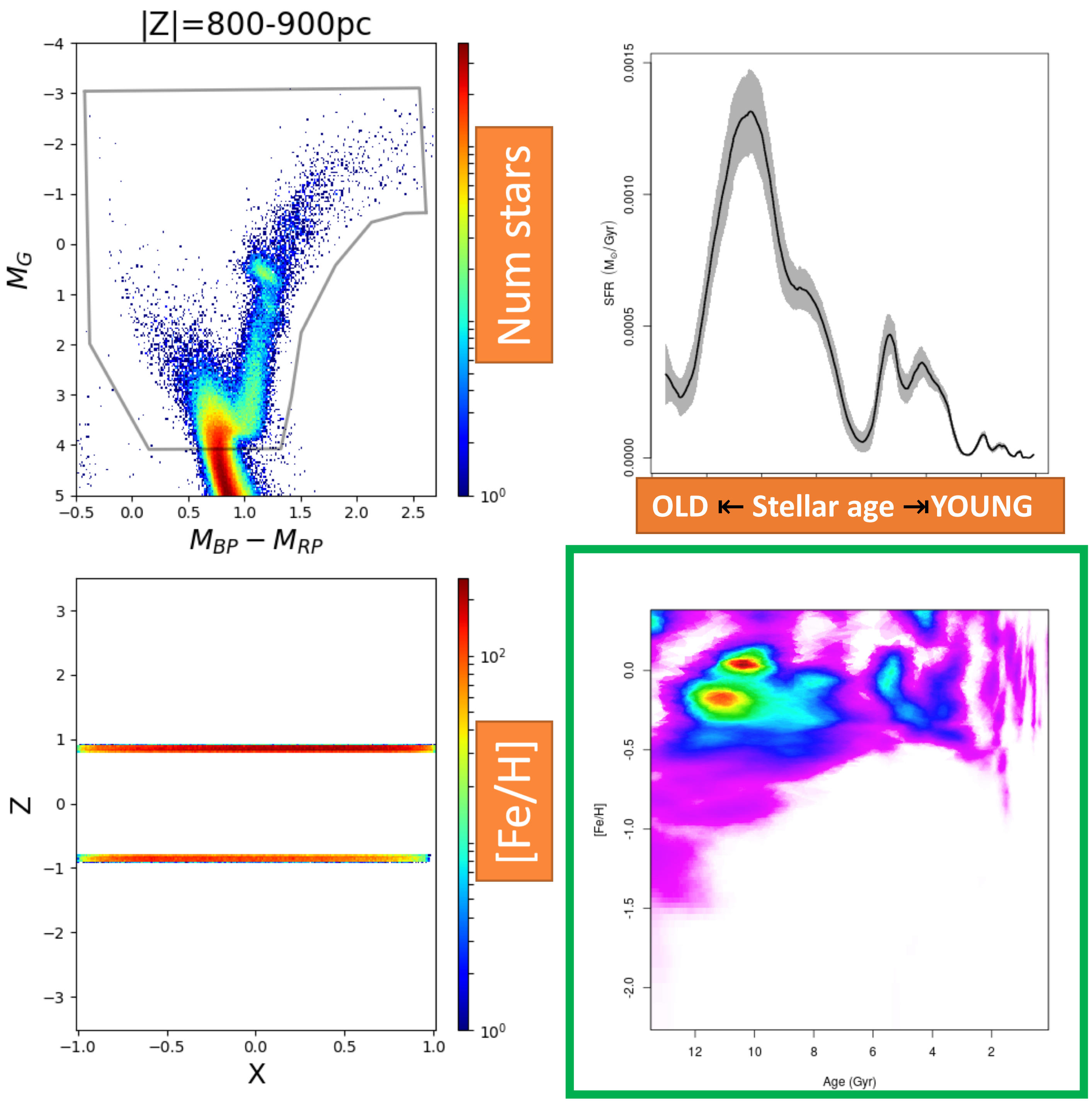




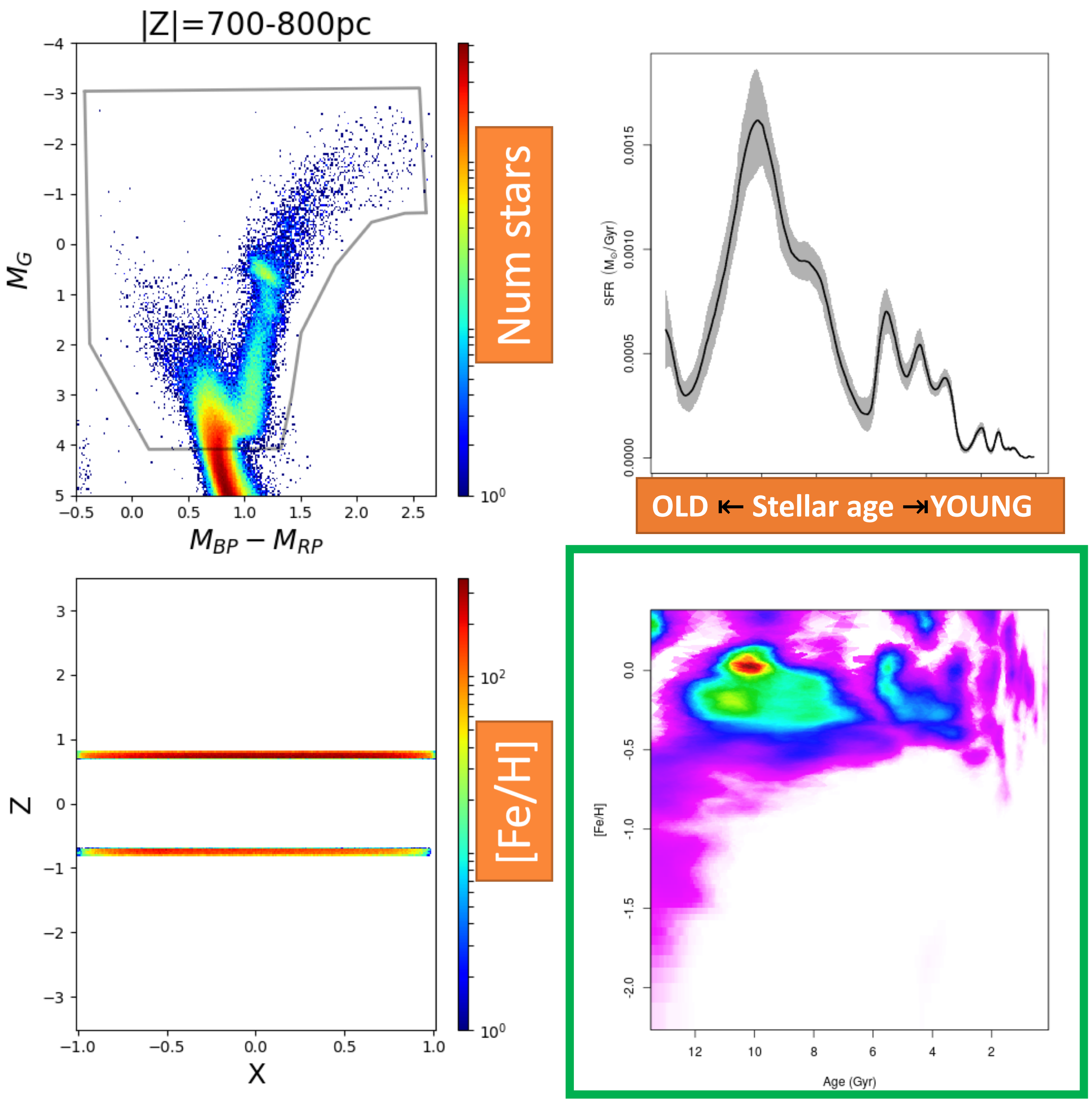




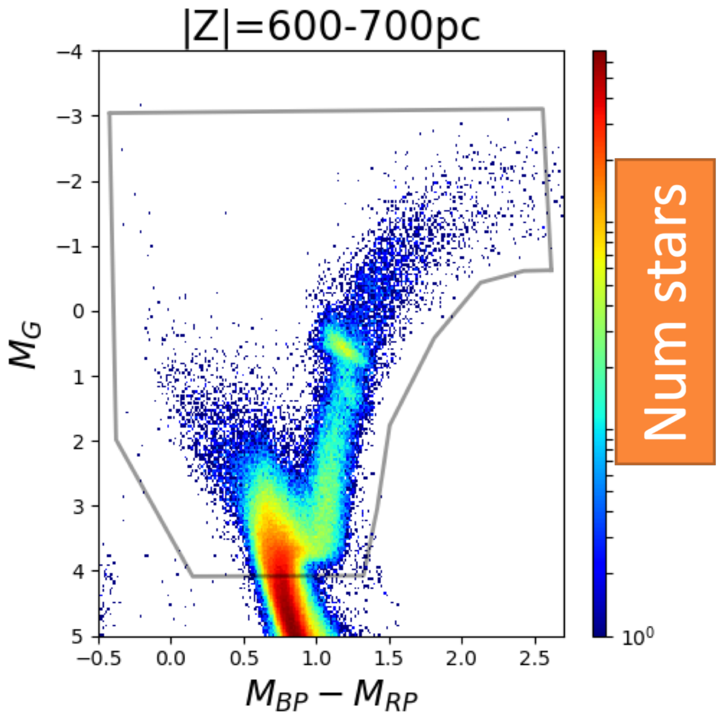
Gallart+ 2019:
the early accretion of Gaia-Enceladus induces a burst of star formation in the Milky Way thick disk

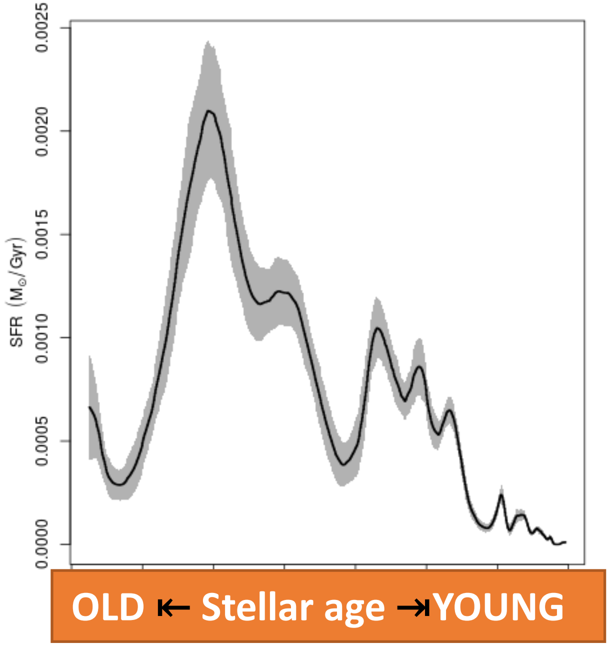


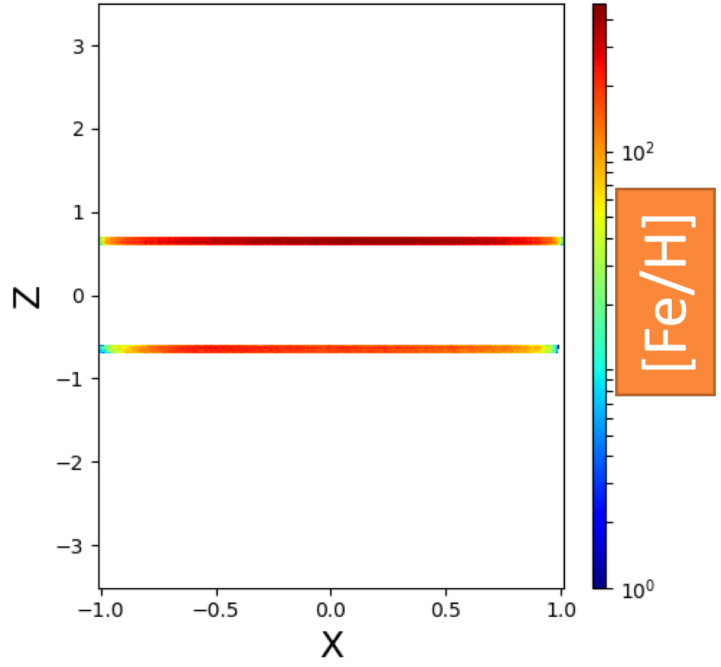
|Z|=800-900pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
10^2
10^0
[Fe/H]
Age (Gyr)

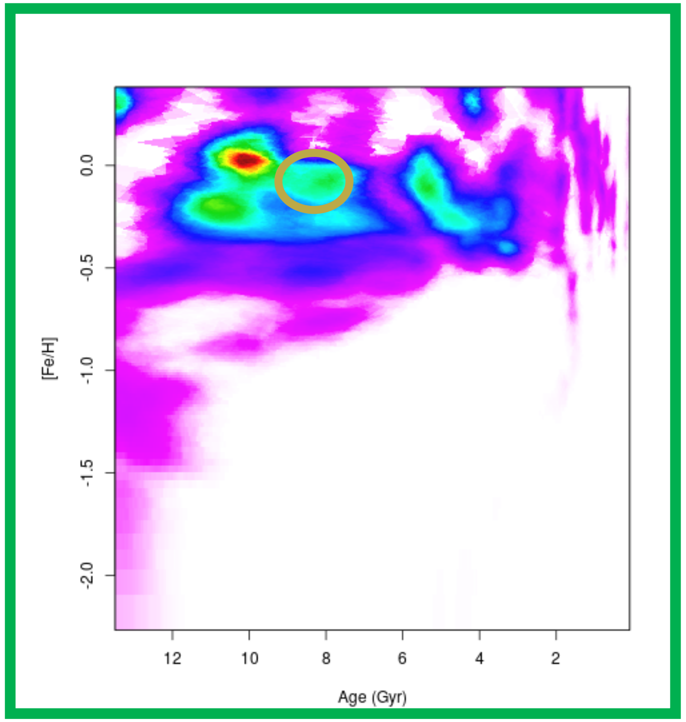


|Z|=700-800pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR (M☉/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
10^2
10^0
[Fe/H]
Age (Gyr)



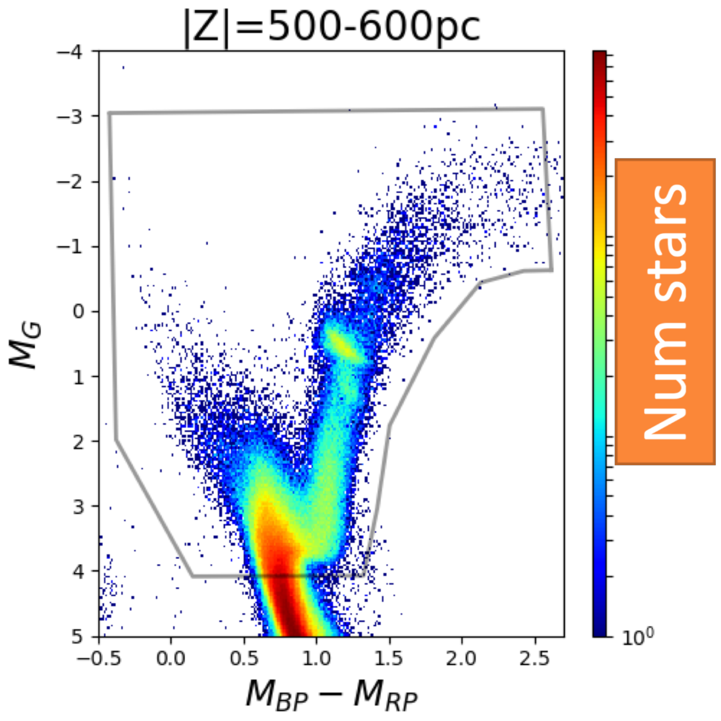


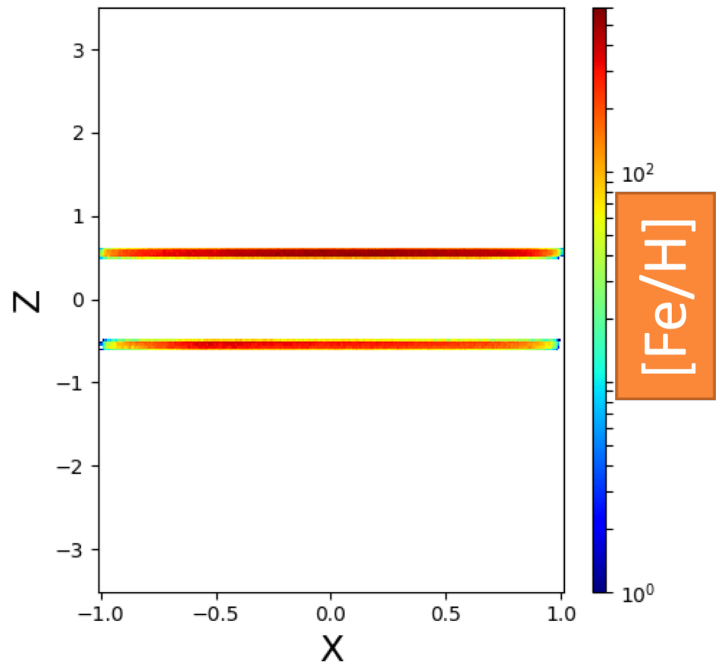


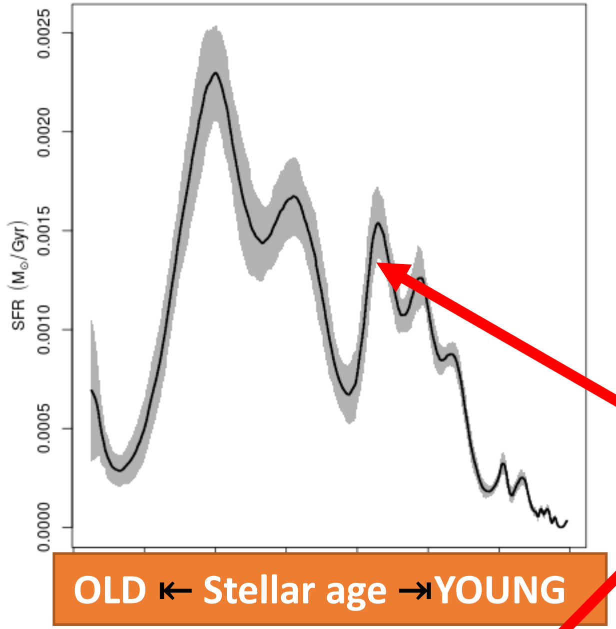


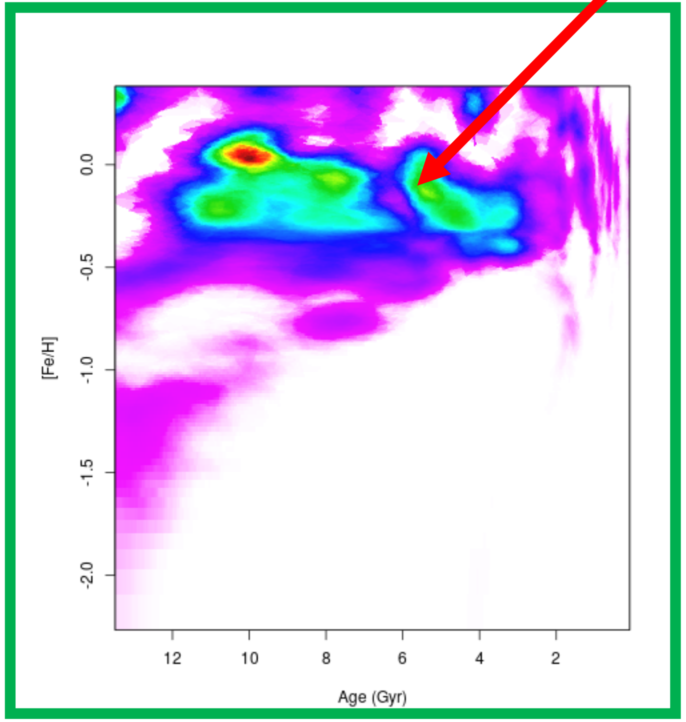
New features appear, with splits in age and metallicity.

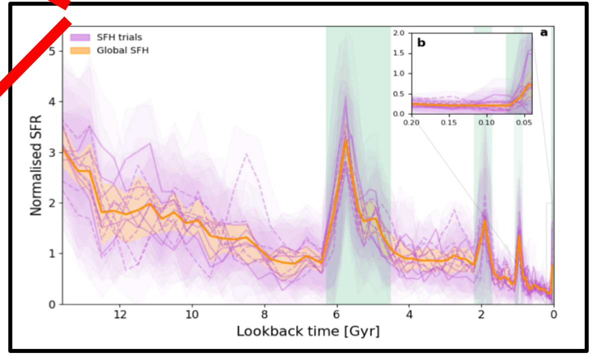
Is the feature at 8 Gyr ago linked to Helmi Streams accretion? (Ruiz-Lara+2022)





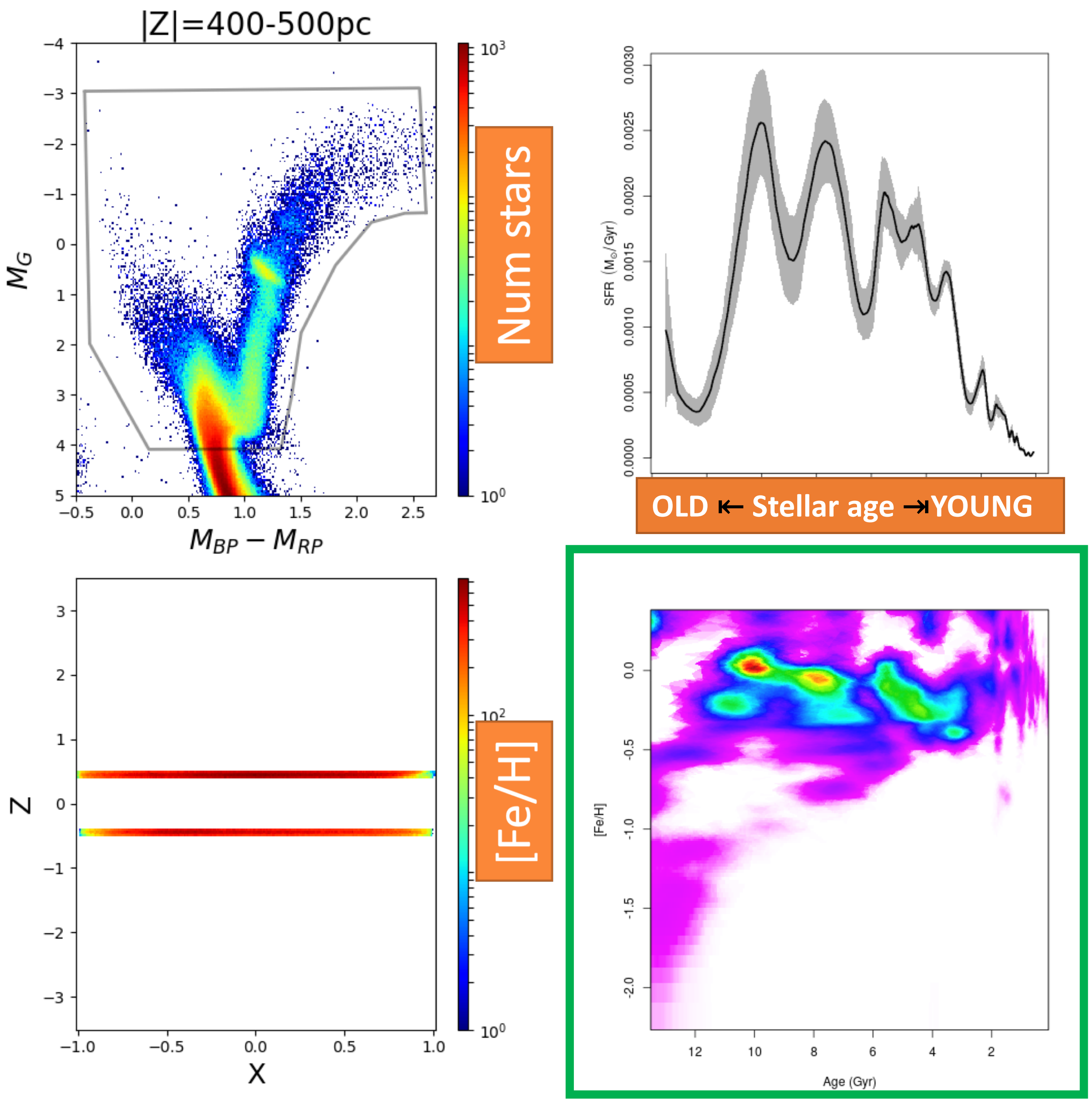


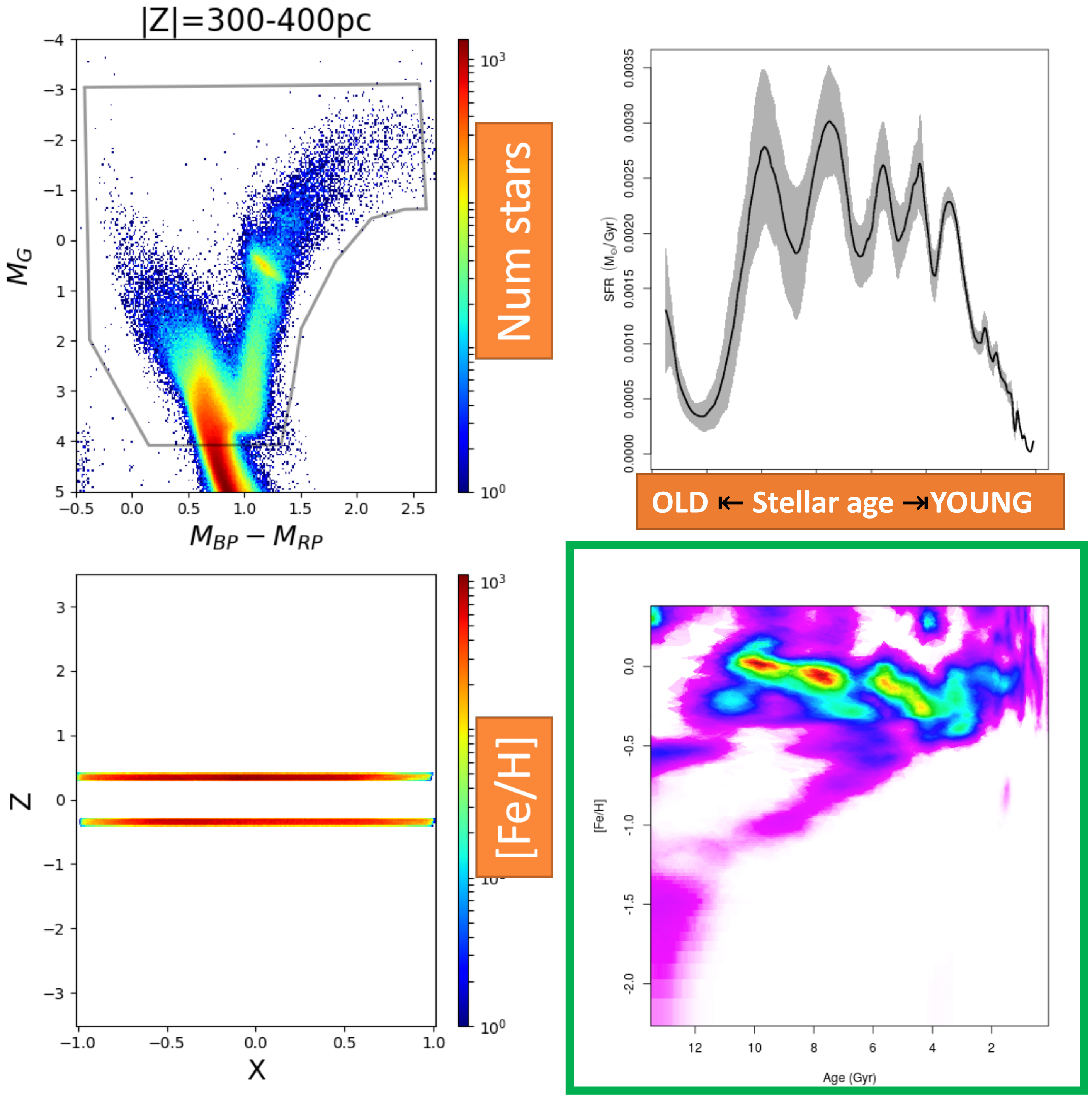




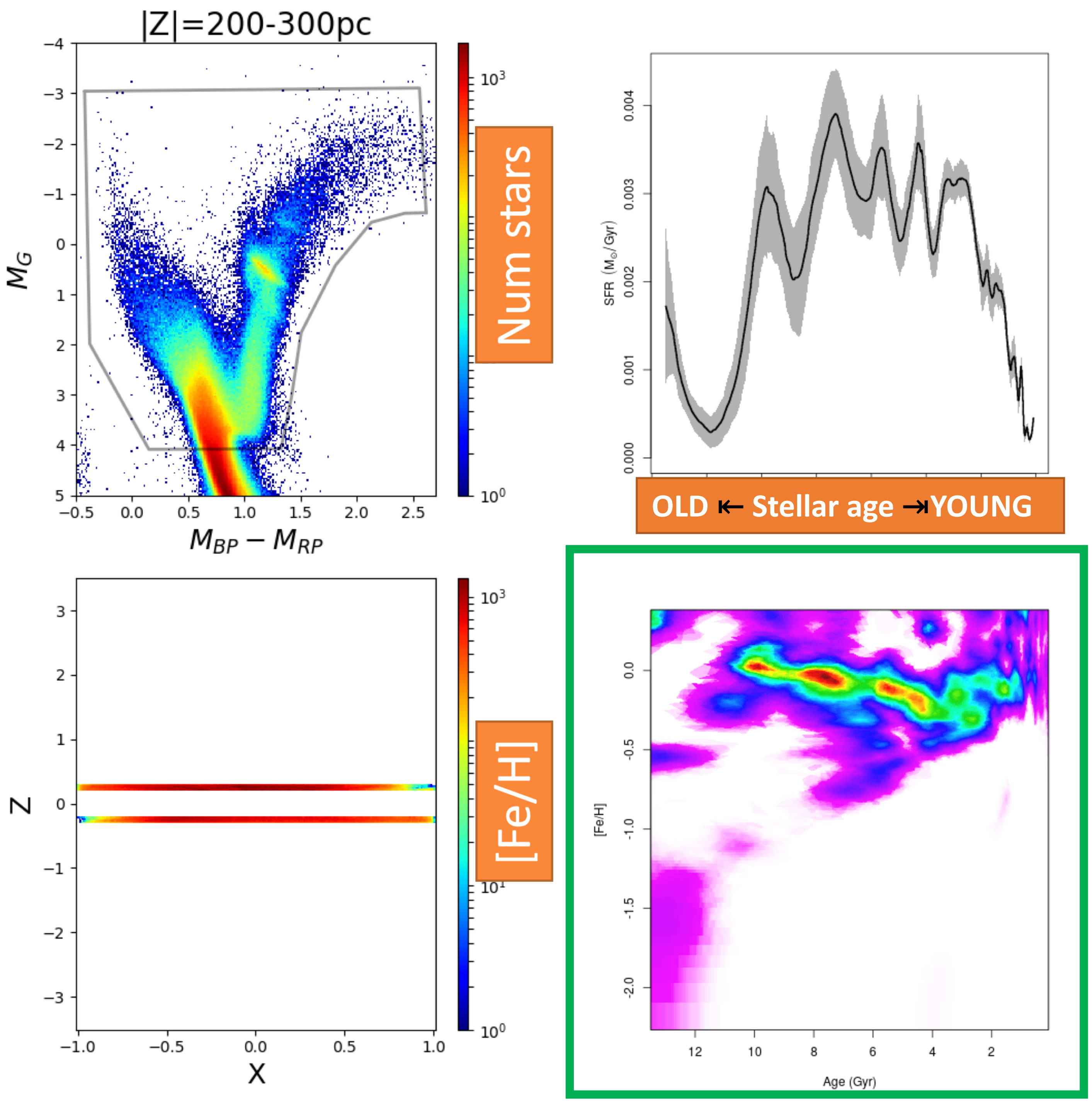
Ruiz-Lara, CG+ 2020

the accretion of Sagittarius induces another burst of star formation in the Milky Way disk

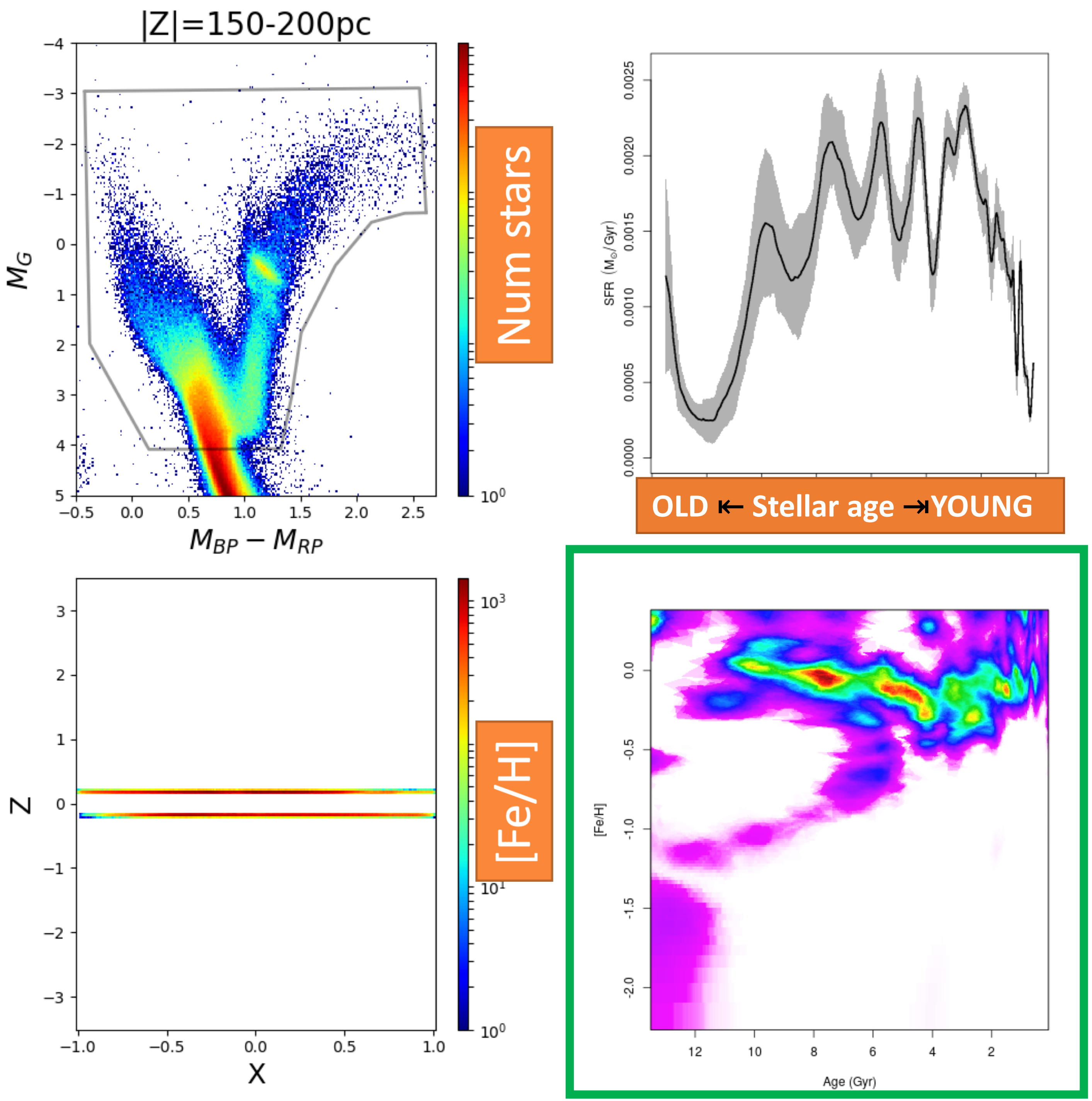

|Z|=400-500pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
Age (Gyr)

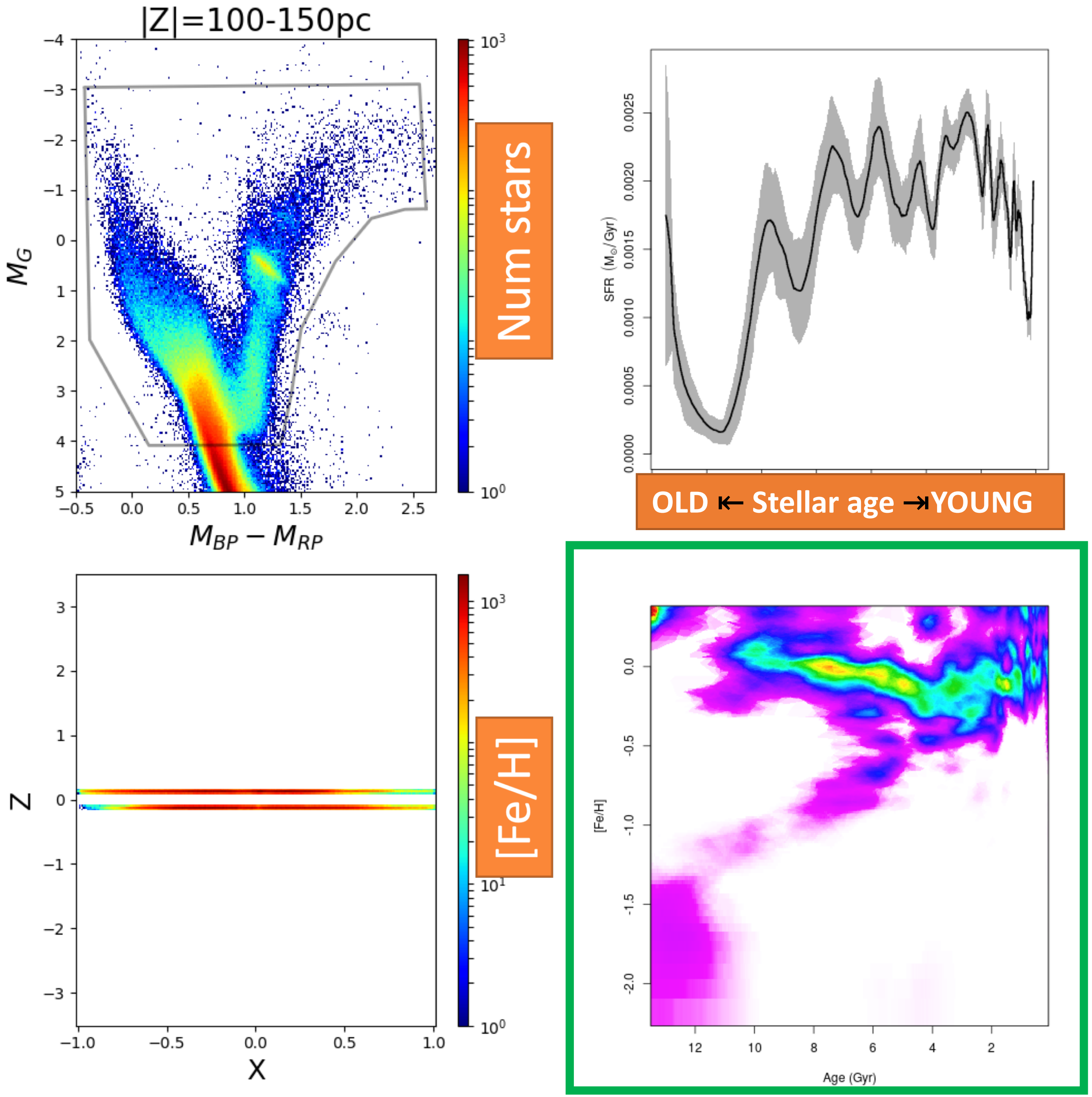


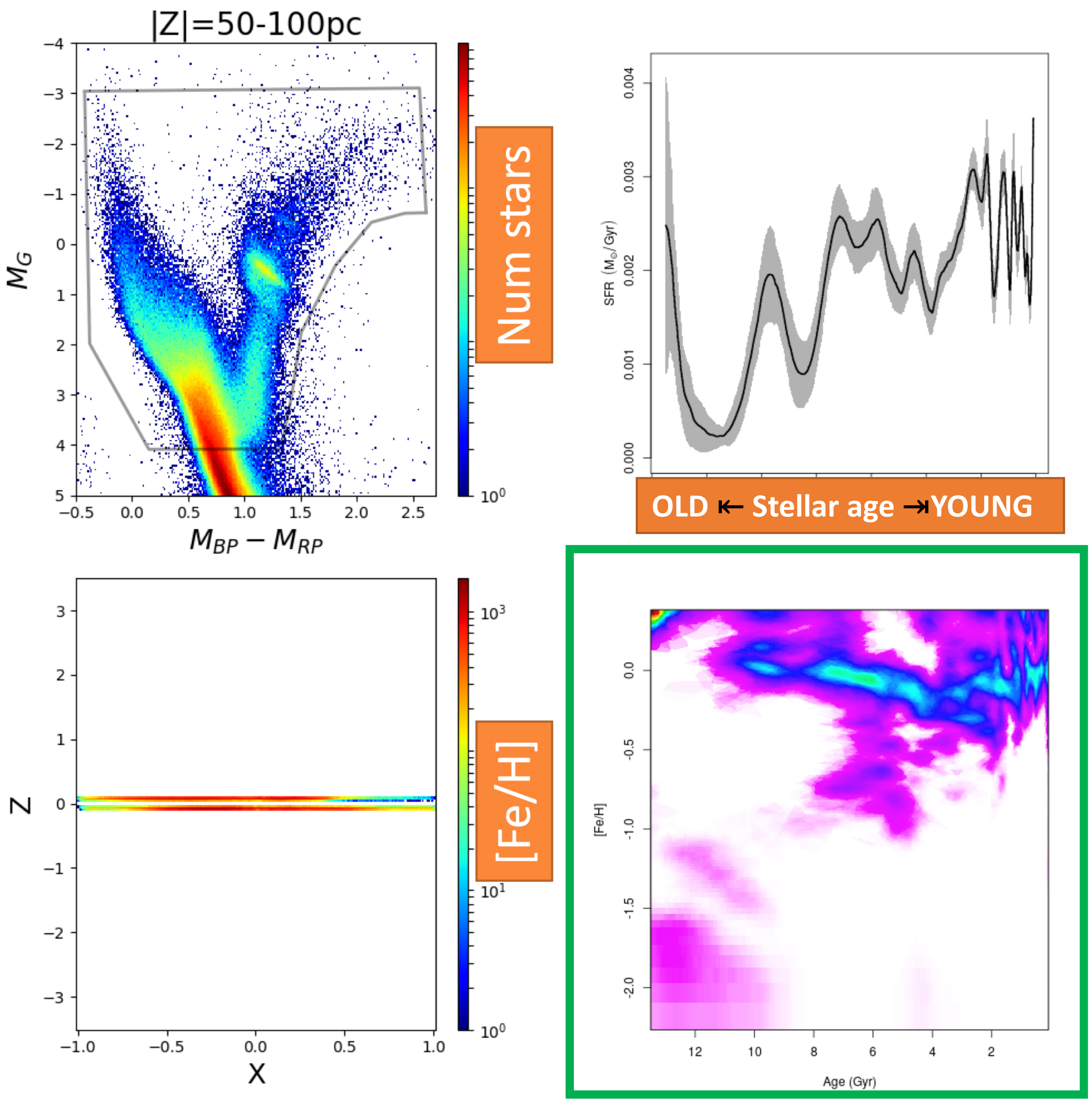
|Z|=300-400pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR (M⊙/Gyr)
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)



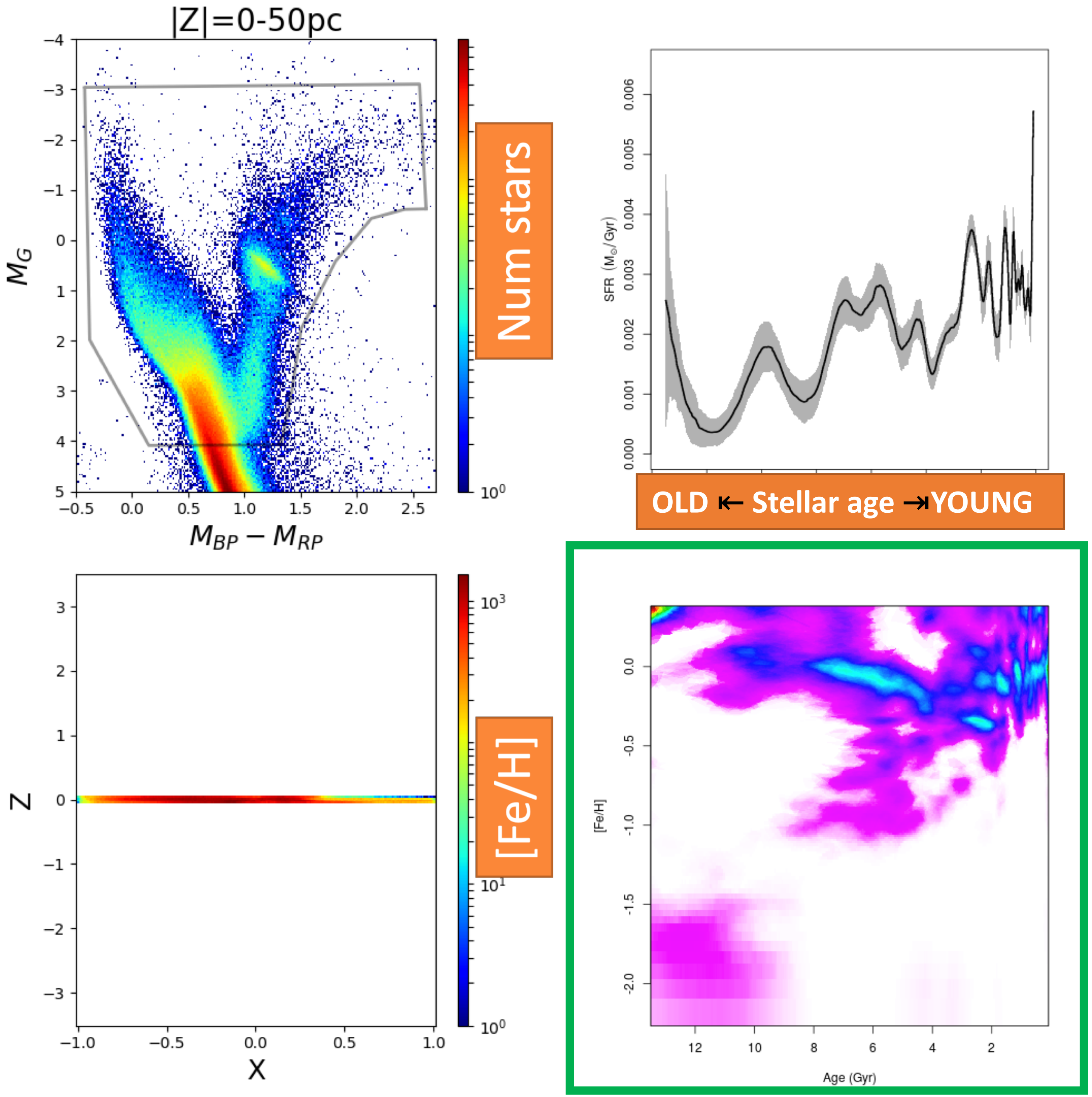
|Z|=200-300pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR (M⊙/Gyr)
OLD ⇤ Stellar age ⇥YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)


|Z|=150-200pc
M_G
$M_{BP} - M_{RP}$
Num stars
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥ YOUNG
Z
X
[Fe/H]
Age (Gyr)


|Z|=100-150pc
M_G
$M_{BP} - M_{RP}$
−4
−3
−2
−1
0
1
2
3
4
5
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
10^3
10^0
Num stars
SFR ($M_\odot$/Gyr)
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
OLD ⇤ Stellar age ⇥YOUNG
Z
X
3
2
1
0
−1
−2
−3
−1.0
−0.5
0.0
0.5
1.0
10^3
10^1
10^0
[Fe/H]
[Fe/H]
0.0
-0.5
-1.0
-1.5
-2.0
12
10
8
6
4
2
Age (Gyr)



|Z|=50-100pc
M_G
$M_{BP} - M_{RP}$
Num stars
10^0
SFR ($M_\odot$/Gyr)
OLD ⇤ Stellar age ⇥ YOUNG
Z
X
10^3
10^1
10^0
[Fe/H]
[Fe/H]
Age (Gyr)



|Z|=0-50pc
M_G
M_BP − M_RP
Num stars
SFR (M⊙/Gyr)
OLD ← Stellar age → YOUNG
Z
X
[Fe/H]
[Fe/H]
Age (Gyr)

★ CMD.ftGaia produces deSFH that are:

→ **robust** (against sensible changes in input parameters, e.g. binaries, SSPs 'size', stellar models, size of mother, weights, reddening map…)
→ **precise** (better than 5-10%, depending on age)
→ **accurate** (ages systematically overestimated by a maximum of 6%)
→ **Unbiased *age and metallicity distributions,*** *quantitative SFHs* can be obtained for millions of stars in all evolutionary phases, over a large MW volume
→ Possibility to explore the age-metallicity distributions as a function of position in MW and for diferente MW components.