# Chronology of our Galaxy from Gaia CMD-fitting:

## Spatially resolved star formation histories of the Milky Way thin and thick disk and halo


**Carme Gallart (IAC, Spain)**

**&**

**ChronoGal core team:**

Emma Fernández-Alvar, Anna B. Queiroz,
Santi Cassisi, Tomás Ruiz-Lara, Francisco Surot,
Guillem Aznar-Menargues, Yllari González-Koda, David Mirabal, Alicia Rivero

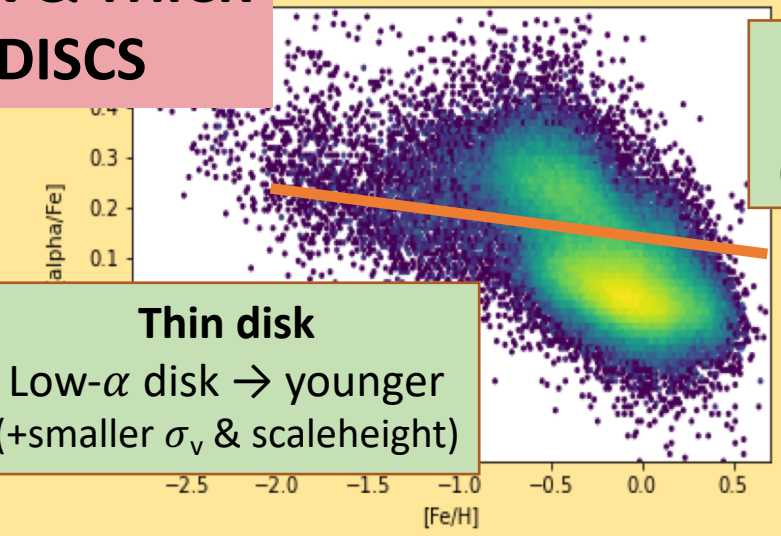
IAC/ULL, Spain - INAF, Italy - U. Granada, Spain

# ENORMOUS PROGRESS IN GALACTIC ARCHAEOLOGY: GAIA DR2 + SPECTROSCOPIC SURVEYS

& Spectroscopic surveys:
APOGEE, GALAH, LAMOST…

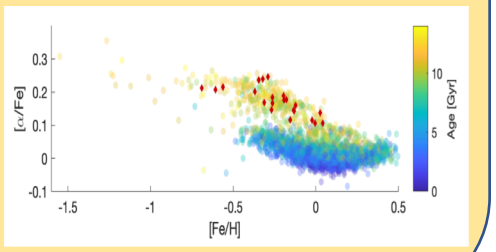
## THIN & THICK DISCS

*Hayden+2015, Queiroz+2023*




**Thick disk**
High-$\alpha$ → older
(+larger $\sigma_v$ & scaleheight)

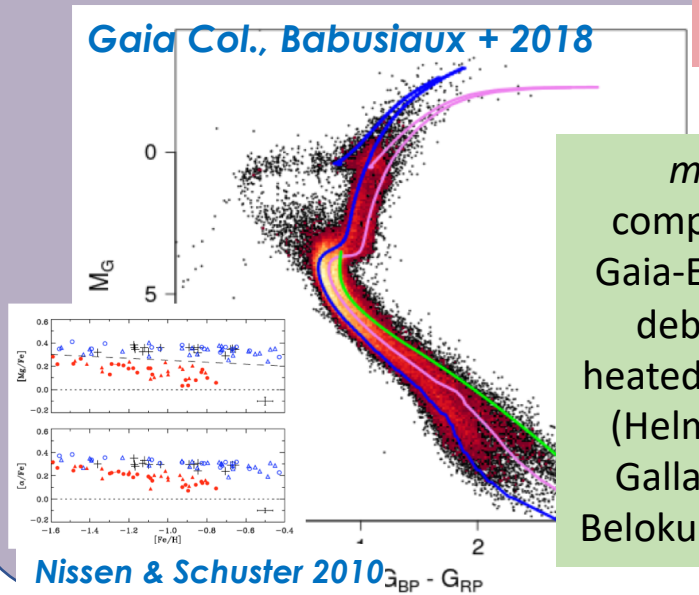
**Thin disk**
Low-$\alpha$ disk → younger
(+smaller $\sigma_v$ & scaleheight)




*Miglio+2021*

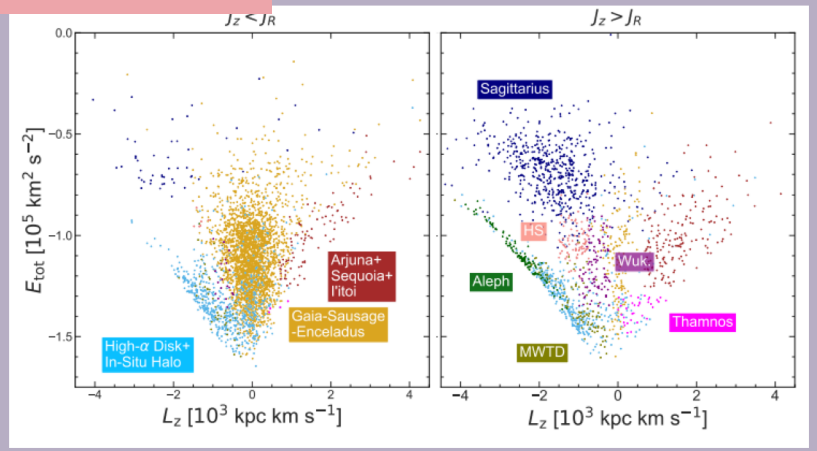
## LOCAL HALO

*Gaia Col., Babusiaux + 2018*



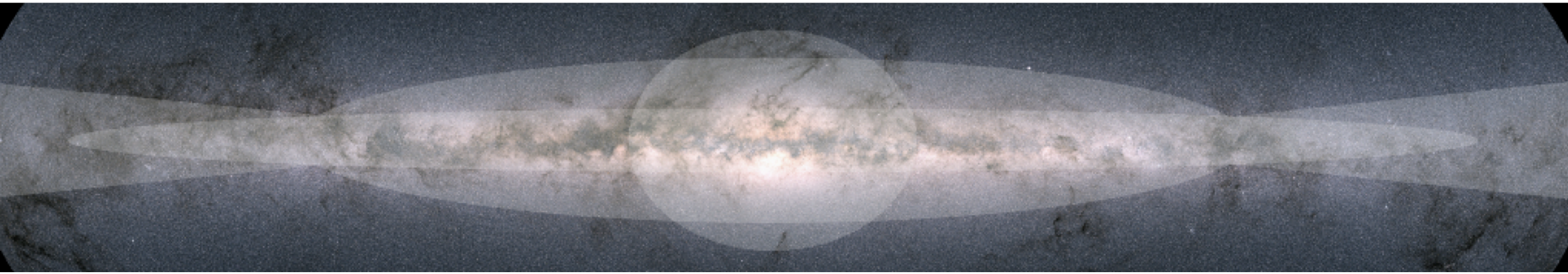

*Nissen & Schuster 2010*

*mainly* composed by Gaia-Enceladus debris and heated disk stars (Helmi+2018; Gallart+2019 Belokurov+2020)




And indications of many other mergers (e.g. Naidu+2020, Dodd+2023)

# UNSOLVED QUESTIONS ABOUT THE FORMATION AND EVOLUTION OF THE MILKY WAY DISK & HALO



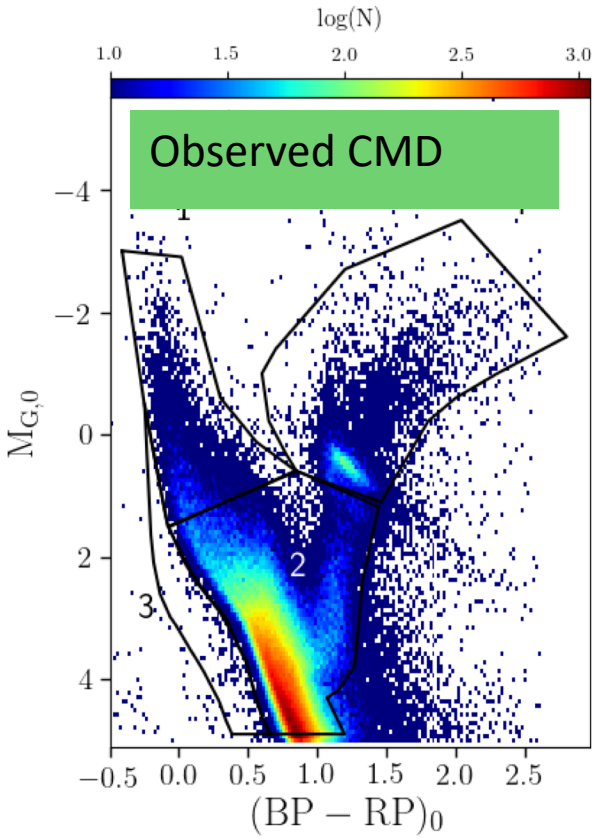
**The current greatest challenge for further progress is**
*the* difficulty to determine
***precise stellar ages***
*for* ***unbiased & large samples of stars***.

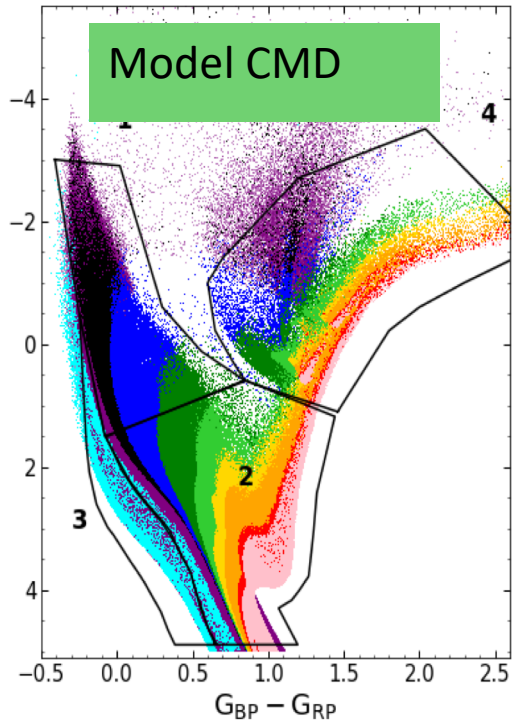
**Ages** are essential to stablish a temporal sequence of events

Many efforts, e.g. Miglio+2021; Sahlholdt+2021; Xiang & Rix 2022, Queiroz+2023, Pinsonneault+2024

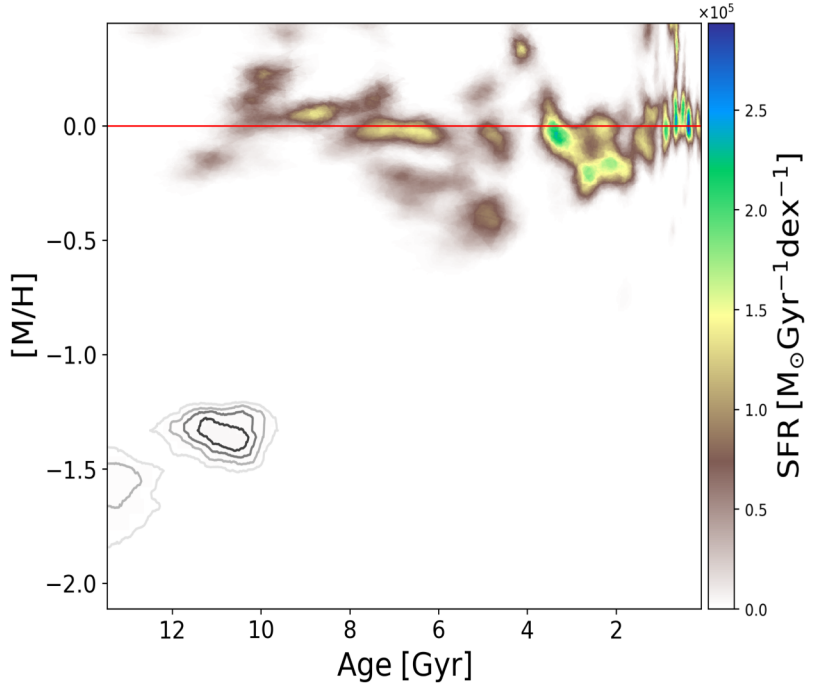
- **When** did the dominant stellar disk of the Milky Way emerge?
- Is there an **early**, very metal poor thin disk?
- What is the **age**-metallicity distribution across the disk (in Z and R)?
- On the origin of MW disk high/low $\alpha$ populations:
  - **How long** did the high- $\alpha$ phase last?
  - Did the high- and low- $\alpha$ phases **overlap in time**?
- What is the role of mergers (particularly **Gaia-Enceladus**) in the MW disk formation and evolution?

# OUR APPROACH: STAR FORMATION HISTORIES FROM CMD-FITTING



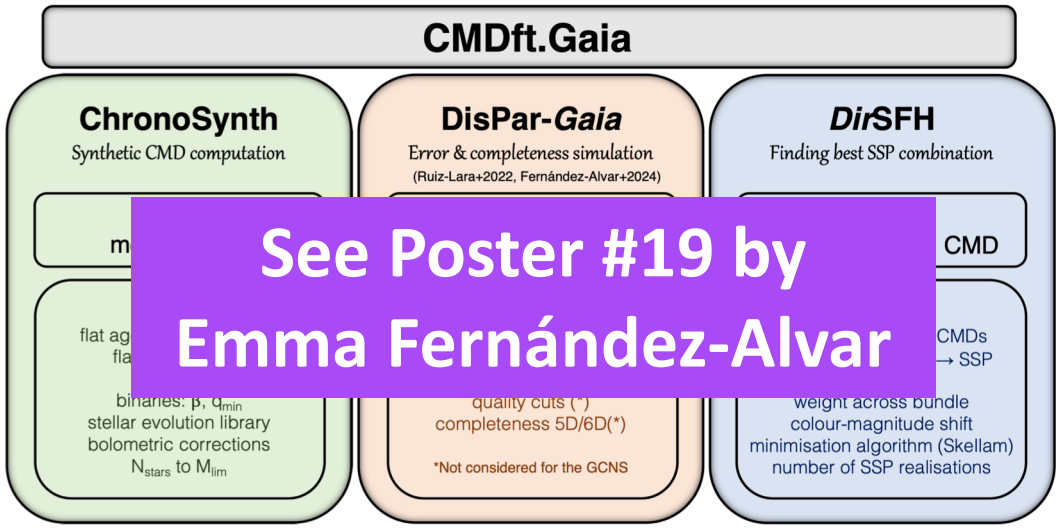

*Gallart & ChronoGal, 2024*



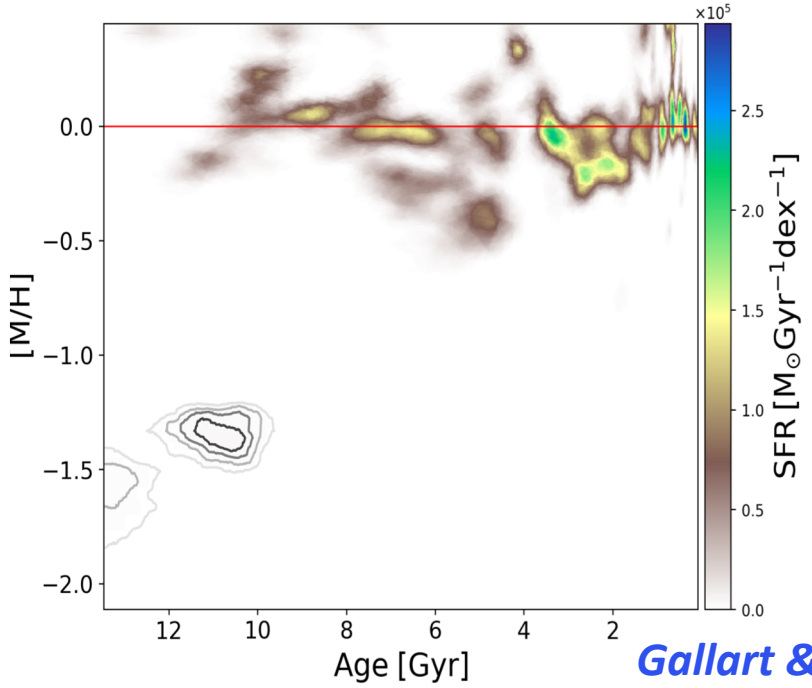

**deSFH:** Mass, per unit time and metallicity, that has transformed into stars, somewhere in the Galaxy, to account for the stars currently present in the analysed volume.

**dynamically evolved**
Star Formation History
**"deSFH"**
within $R_{sun}$=100 pc

# OUR APPROACH: STAR FORMATION HISTORIES FROM CMD-FITTING




**See Poster #19 by Emma Fernández-Alvar**




**dynamically evolved**
Star Formation History
**"deSFH"**
within $R_{sun}$=100 pc

**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.

*Gallart & ChronoGal, 2024*

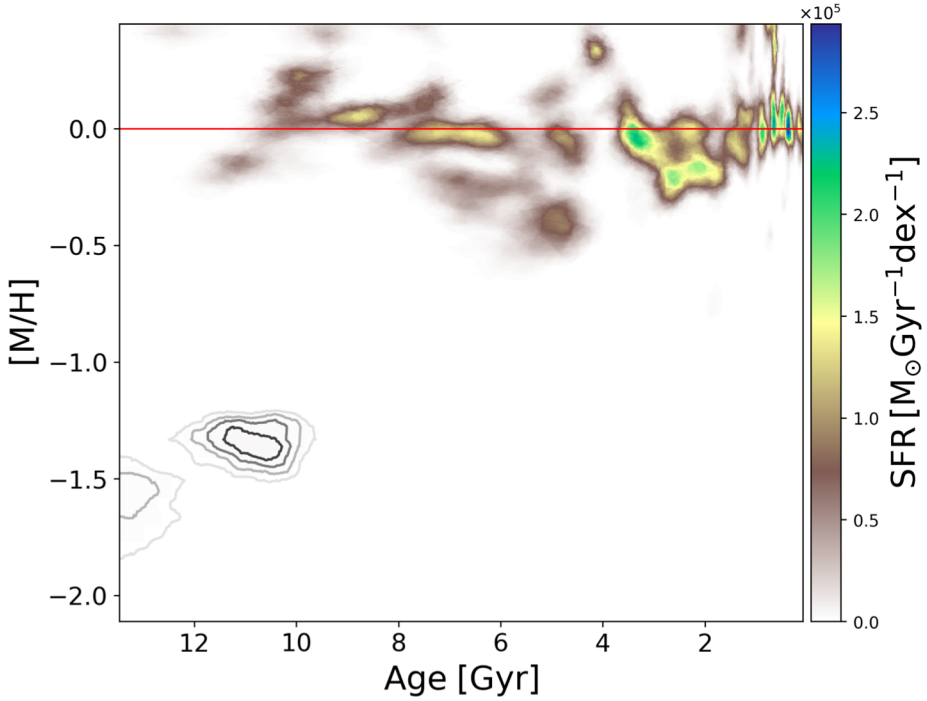
## ★ CMDft.Gaia produces deSFH that are:

→ **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)

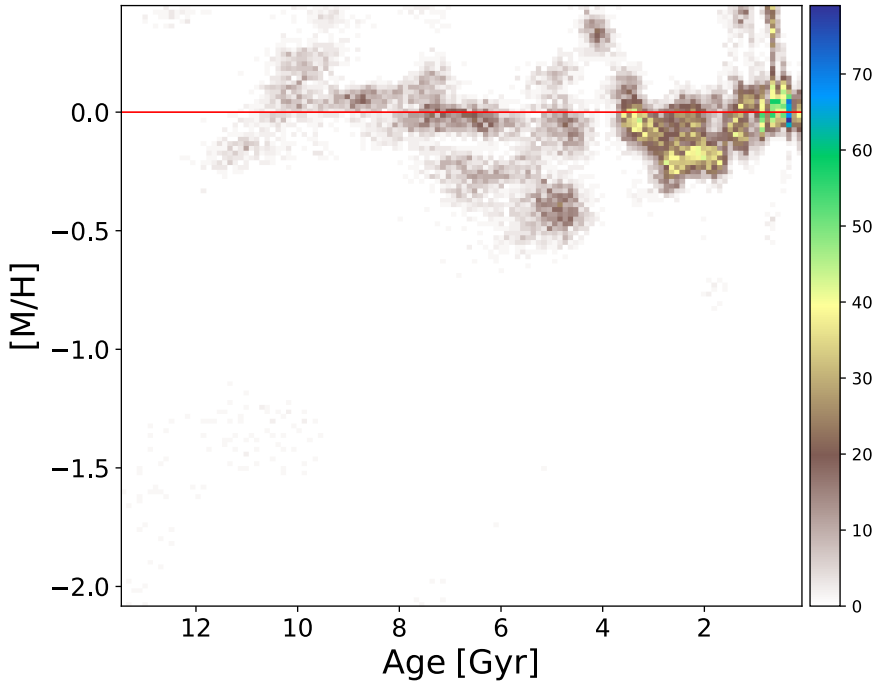
→ **accurate** (ages systematically overestimated by a maximum of 6%)

**dynamically evolved Star Formation History "deSFH" within $R_{sun}$= 100 pc**

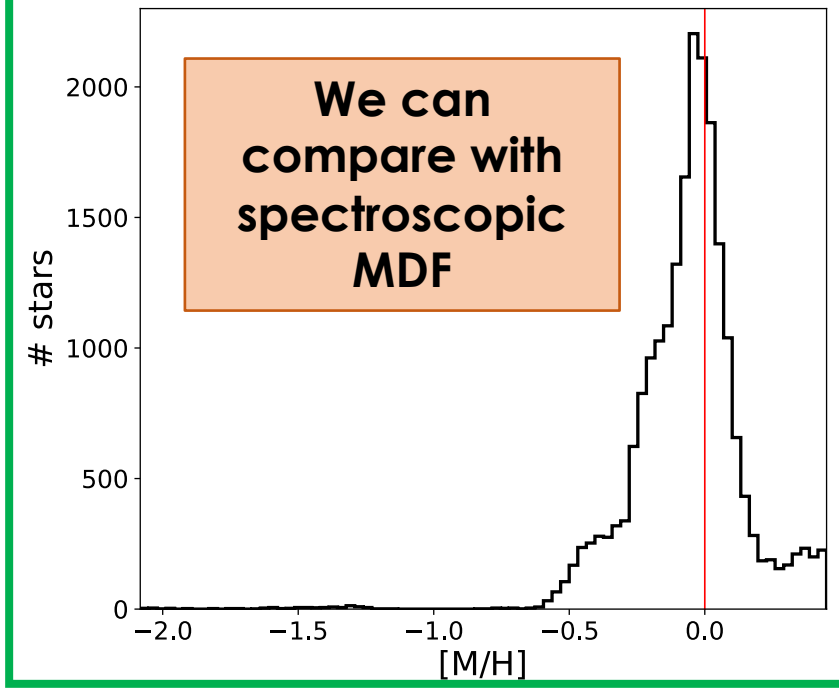



*Gallart & ChronoGal, 2024*

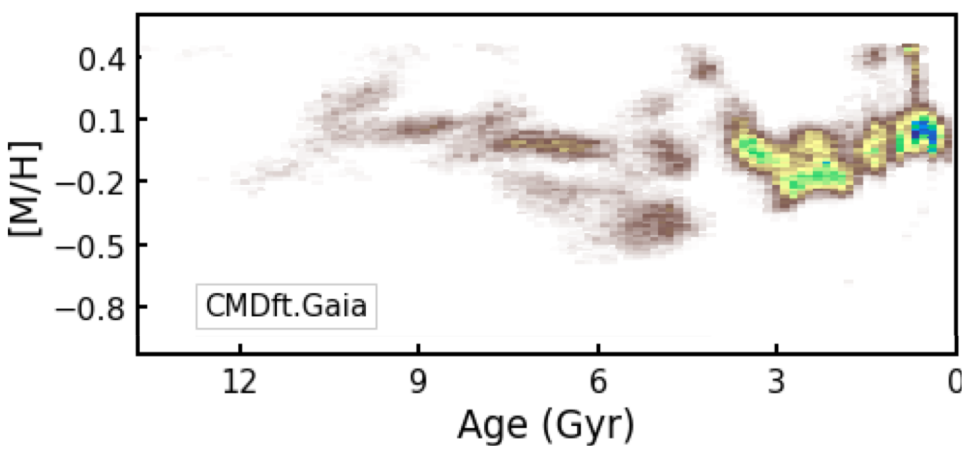
**Stellar Age and Metallicity Distribution "AMD" of the stars currently within 100 pc of the Sun**

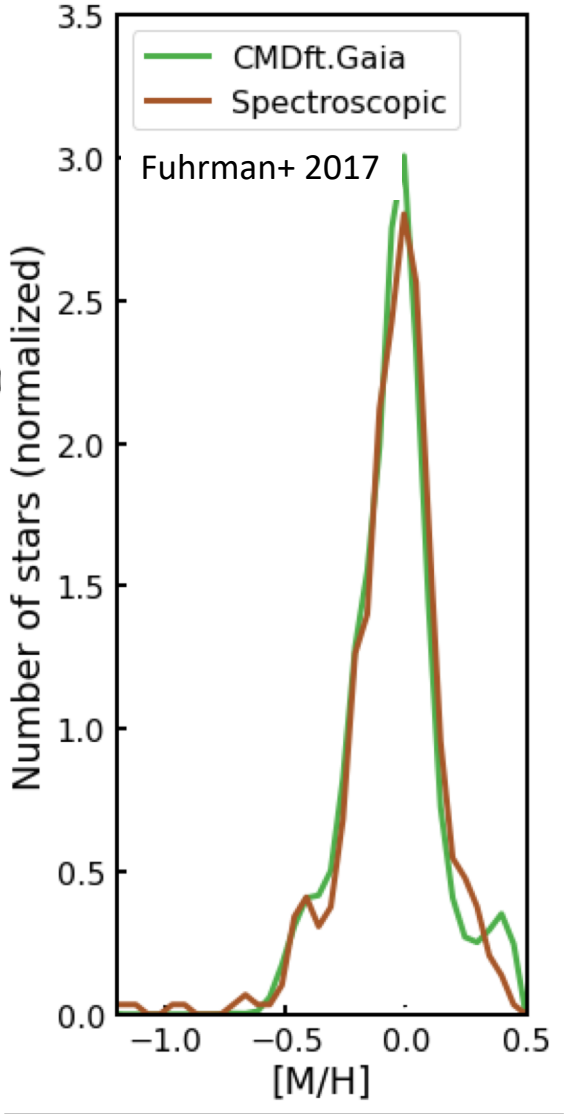



**We can compare with spectroscopic MDF**



# Accuracy and precisión of the derived MDF



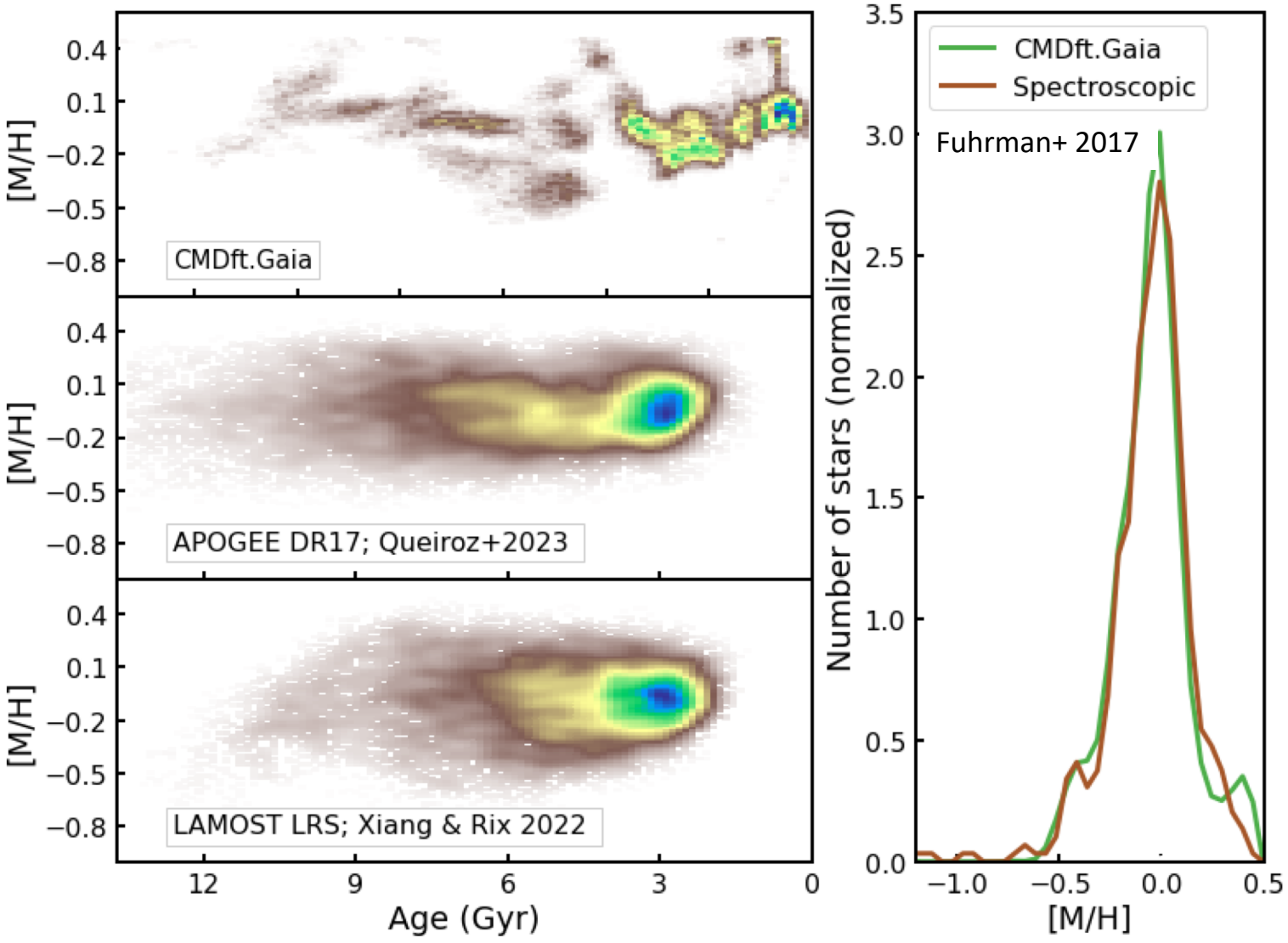




Comparison of the derived MDF with Fuhrman's spectroscopic MDF:

**Almost perfect match**

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

# ★ Accuracy and precisión of the derived MDF







Comparison of the derived MDF with Fuhrman's spectroscopic MDF:

**Almost perfect match**

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

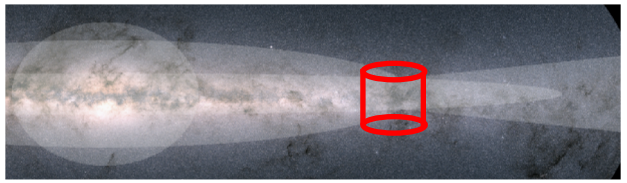
-The difference with age-metallicity distributions derived star-by-star is due to the **increased precision** in age and [M/H] with CMD-fitting

-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.**

# deSFHs OF THE KINEMATICALLY DEFINED THICK AND THIN DISKS

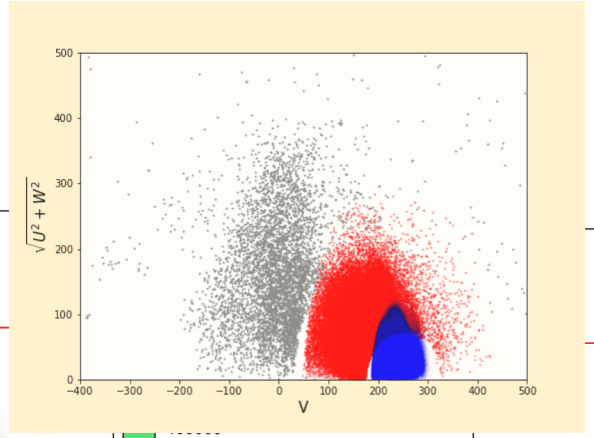
**See Poster #19 by Emma Fernández-Alvar**

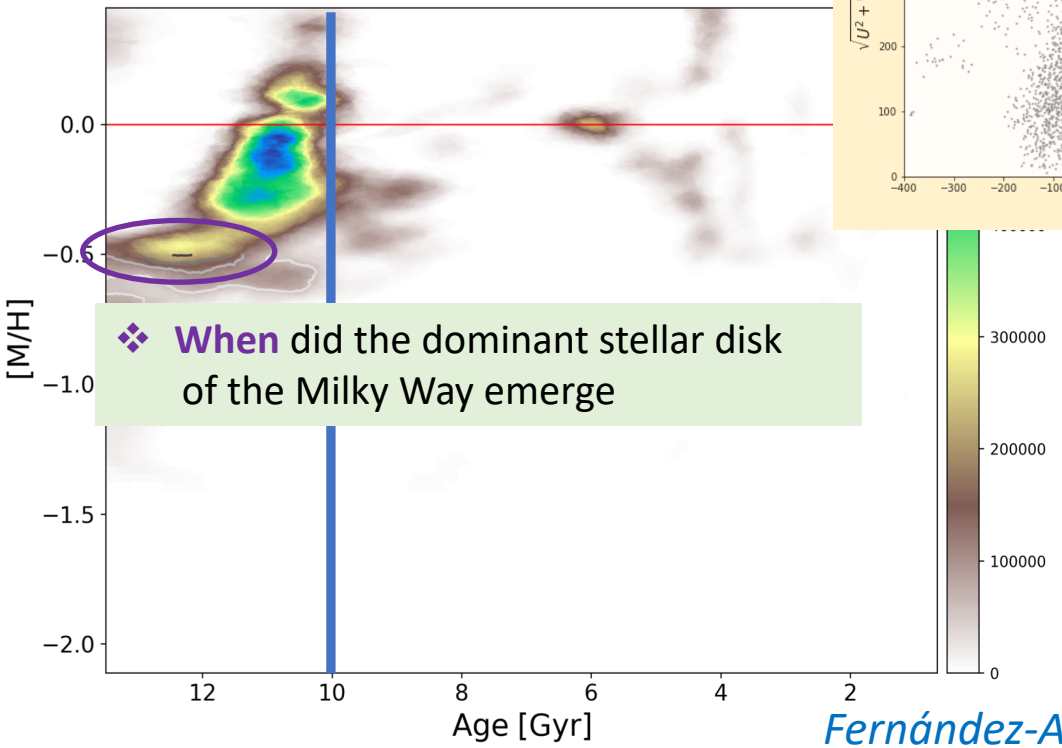


Within cylinder centered in the Sun, radius = 250 pc, height = +/- 500 pc

## Thick disc deSFH

Formed BEFORE 10 Gyrs ago

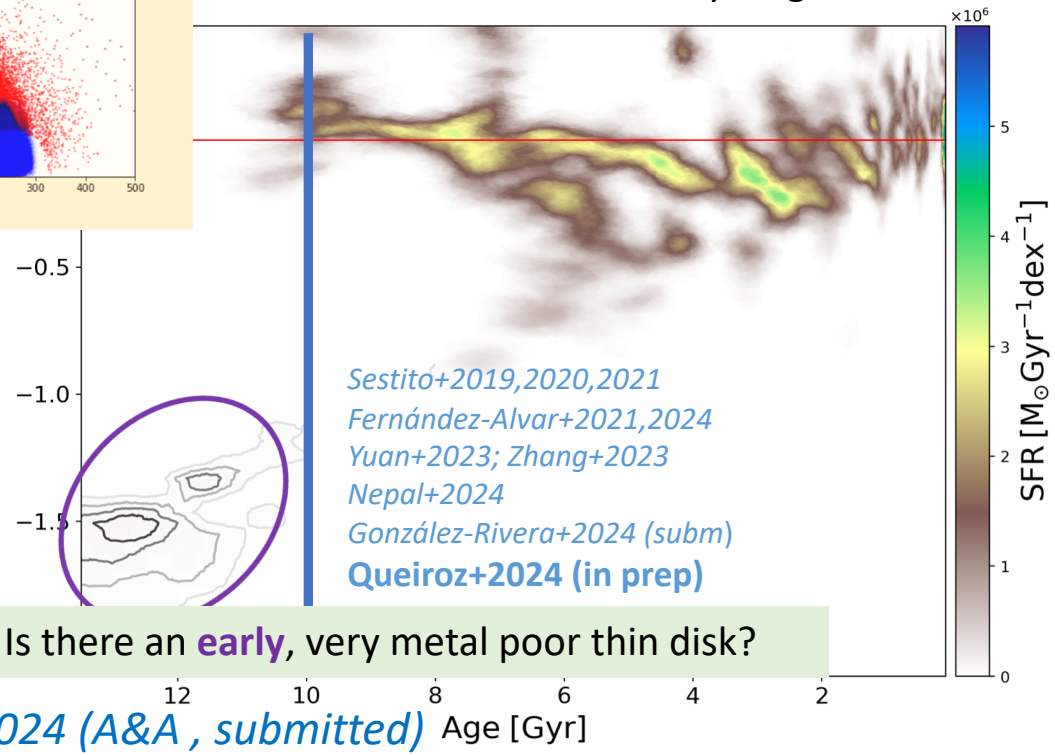



❖ **When** did the dominant stellar disk of the Milky Way emerge

## Thin disc deSFH

Formed AFTER 10 Gyrs ago




*Sestito+2019,2020,2021*
*Fernández-Alvar+2021,2024*
*Yuan+2023; Zhang+2023*
*Nepal+2024*
*González-Rivera+2024 (subm)*
**Queiroz+2024 (in prep)**

❖ Is there an **early**, very metal poor thin disk?

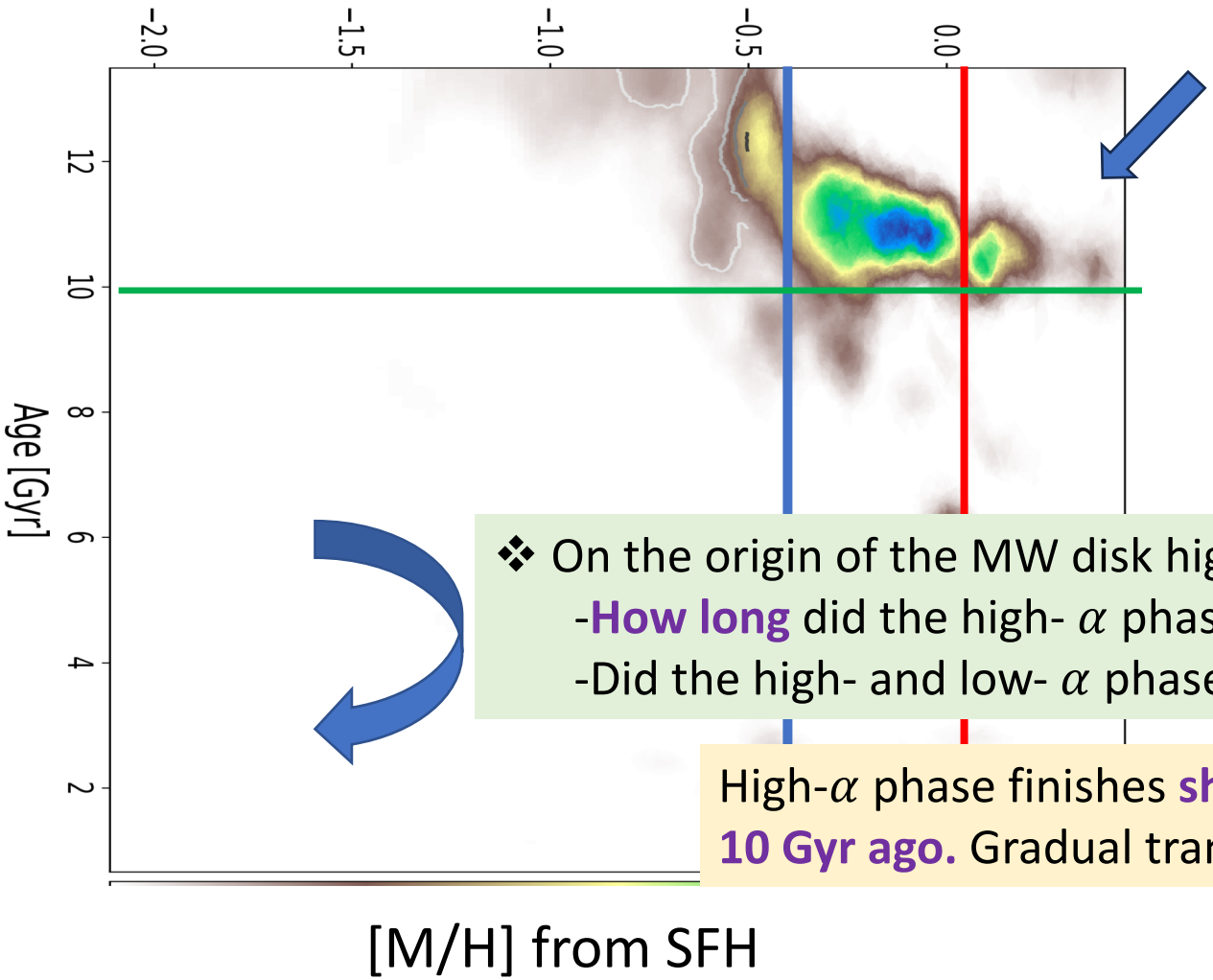
*Fernández-Alvar + 2024 (A&A , submitted)*

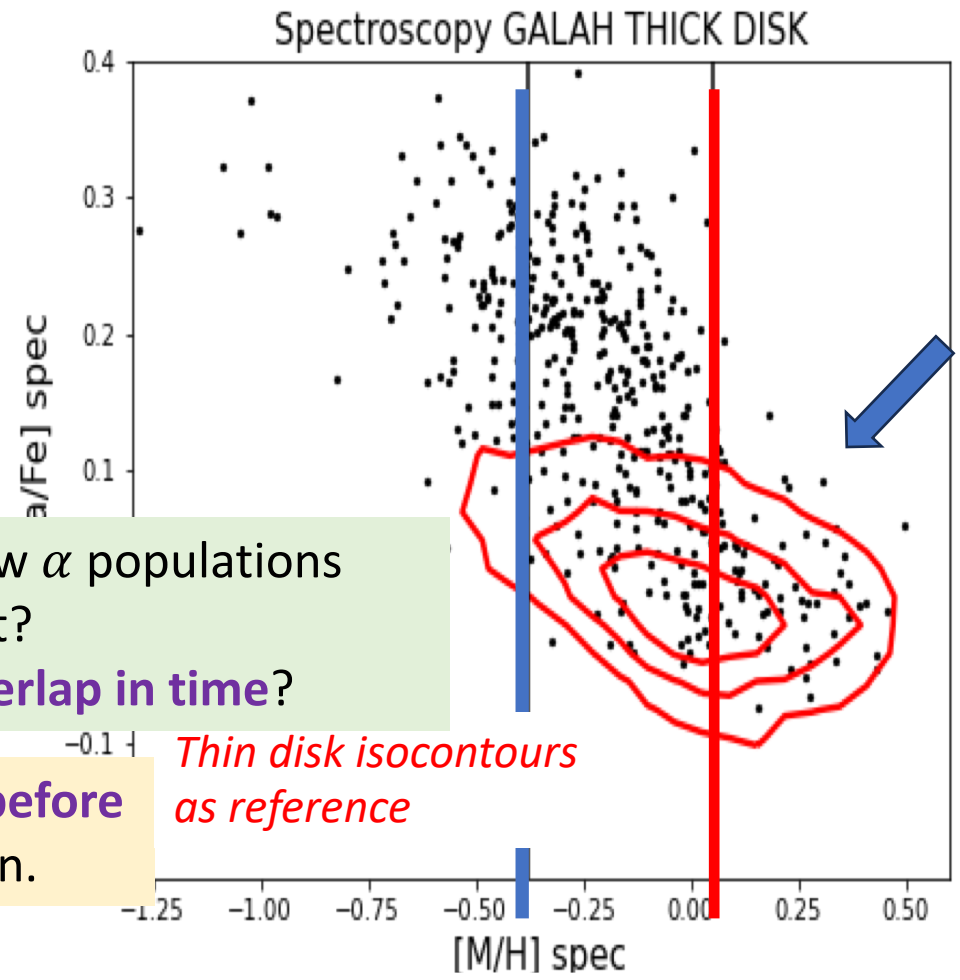
$[M/H] = [Fe/H] + \log(0.694 \times 10^{[\alpha/Fe]} + 0.301)$

*(Salaris + 1993; Pietrinferni + 2021)*

# Thick disc chemical trends

*Fernández-Alvar + 2024 (in prep.)*



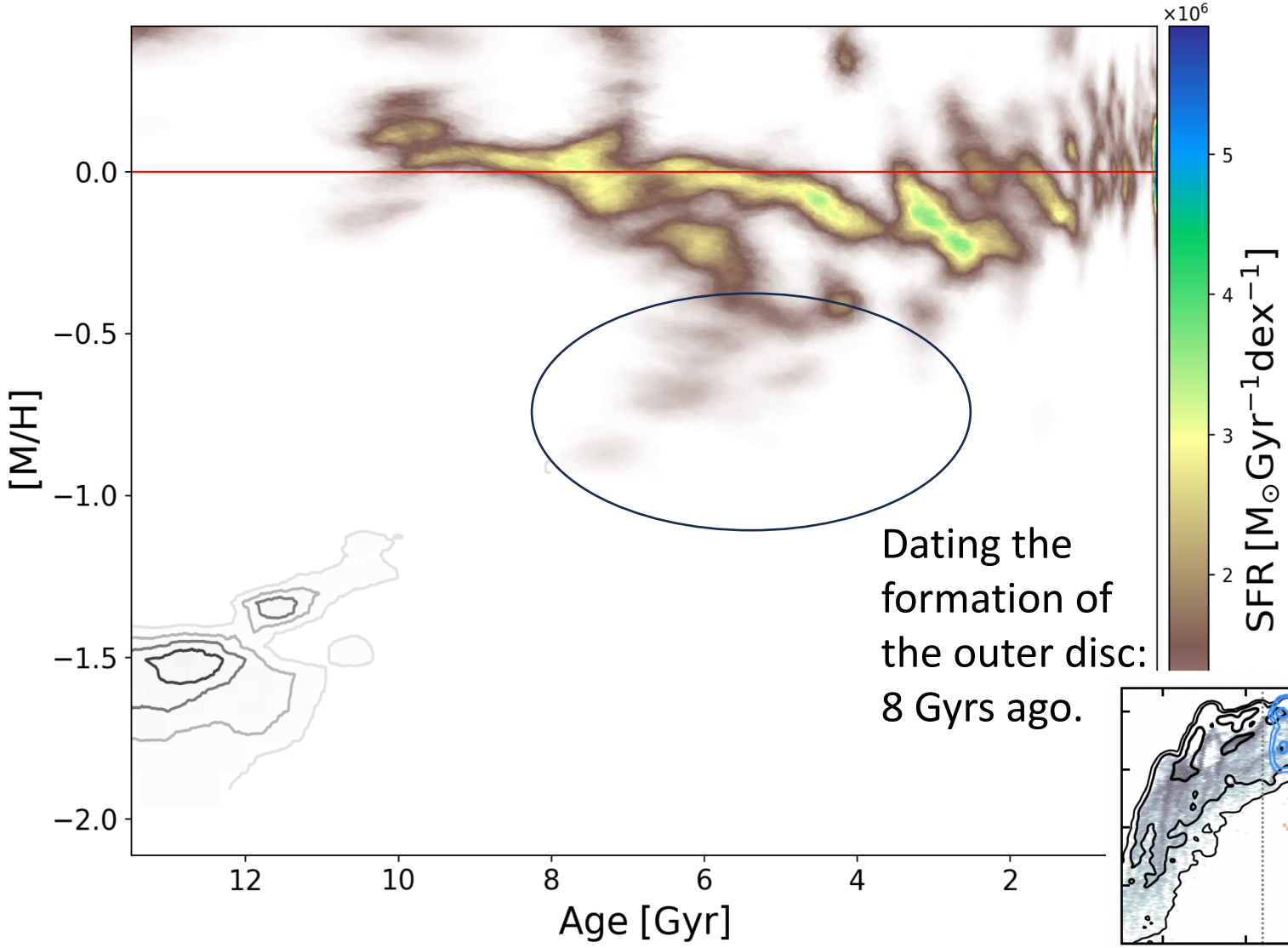

❖ On the origin of the MW disk high/low $\alpha$ populations
-**How long** did the high- $\alpha$ phase last?
-Did the high- and low- $\alpha$ phases **overlap in time**?

High-$\alpha$ phase finishes **short before 10 Gyr ago.** Gradual transition.

*Thin disk isocontours as reference*

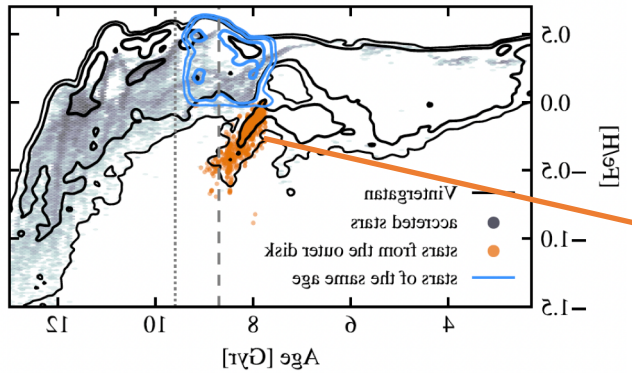
# Thin disc SFH

*Fernández-Alvar + 2024 (in prep.)*




Dating the formation of the outer disc: 8 Gyrs ago.

The age-metallicity distribution is a mix of populations:
stars born in the solar neighbourhood and stars migrated from the inner and the outer disc.



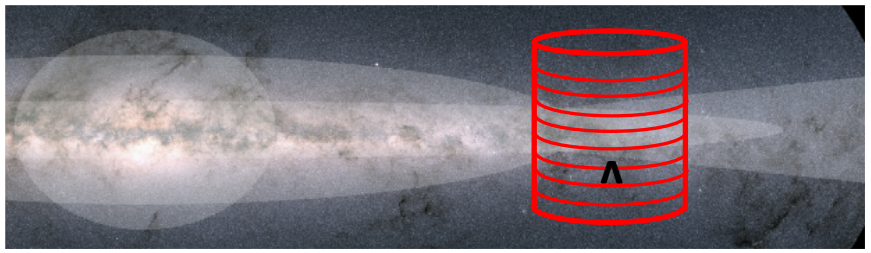
*Renaud+2020*
*Vintergatan simulation*

stars from the outer disk

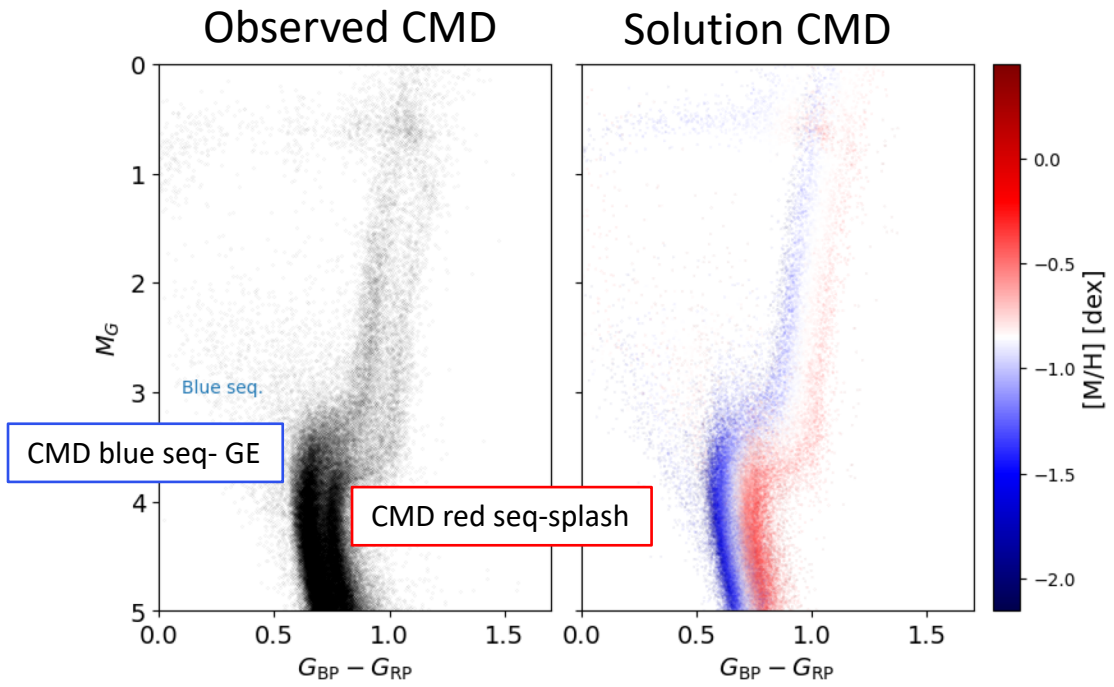
# ROLE OF G-E MERGER IN THE MW DISK FORMATION AND EVOLUTION?

Gaia DR3 data

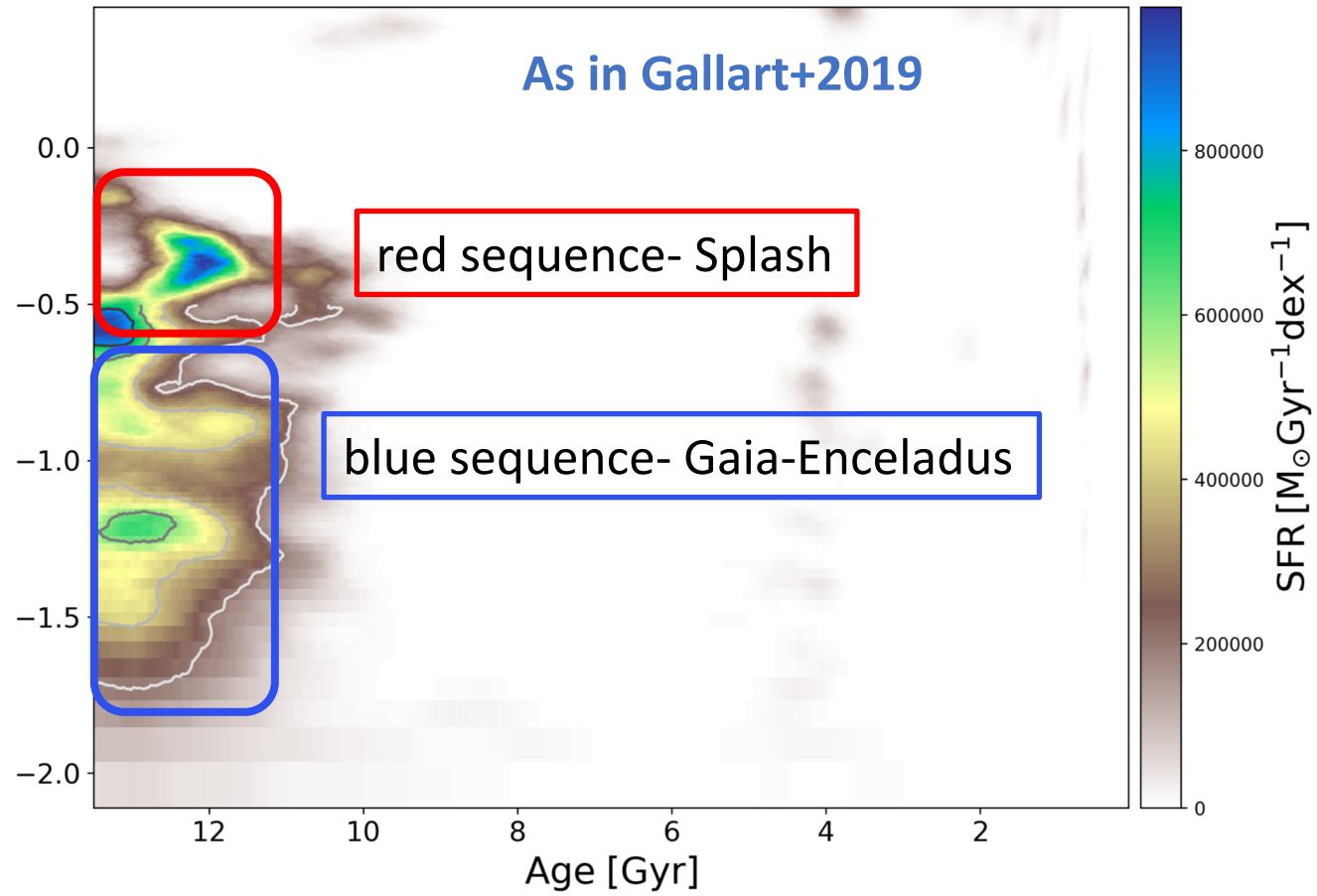
Larger cylinder centered in the Sun, radius = 1 kpc, height = +/- 3500 pc



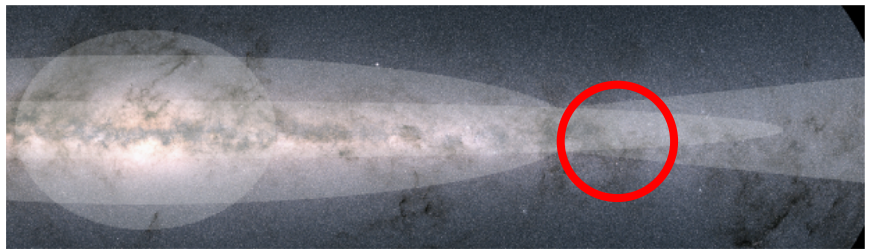
$$V_T = 4.74/\varpi \sqrt{\mu_{\alpha*}^2 + \mu_\delta^2}. > 200 \text{ km s}^{-1}$$

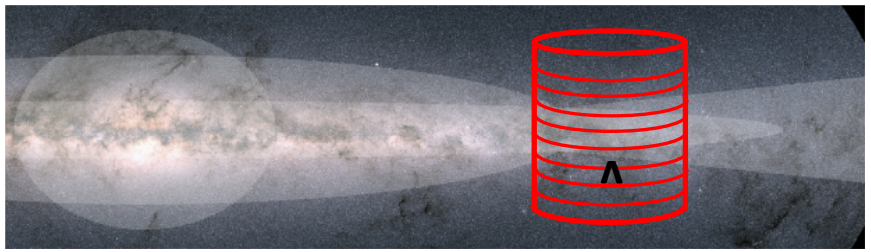



## deSFH of a kinematically defined halo



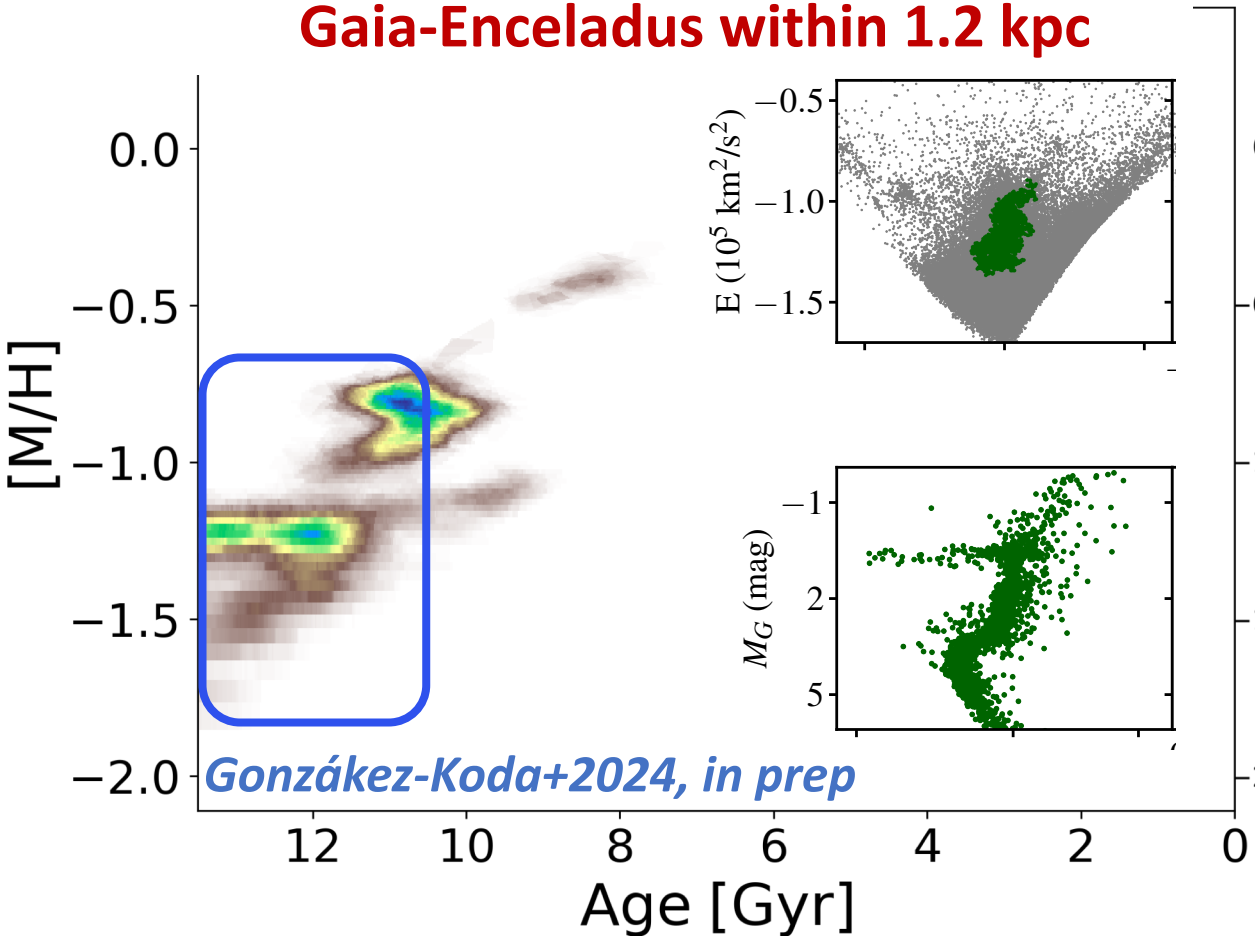
# ROLE OF G-E MERGER IN THE MW DISK FORMATION AND EVOLUTION?

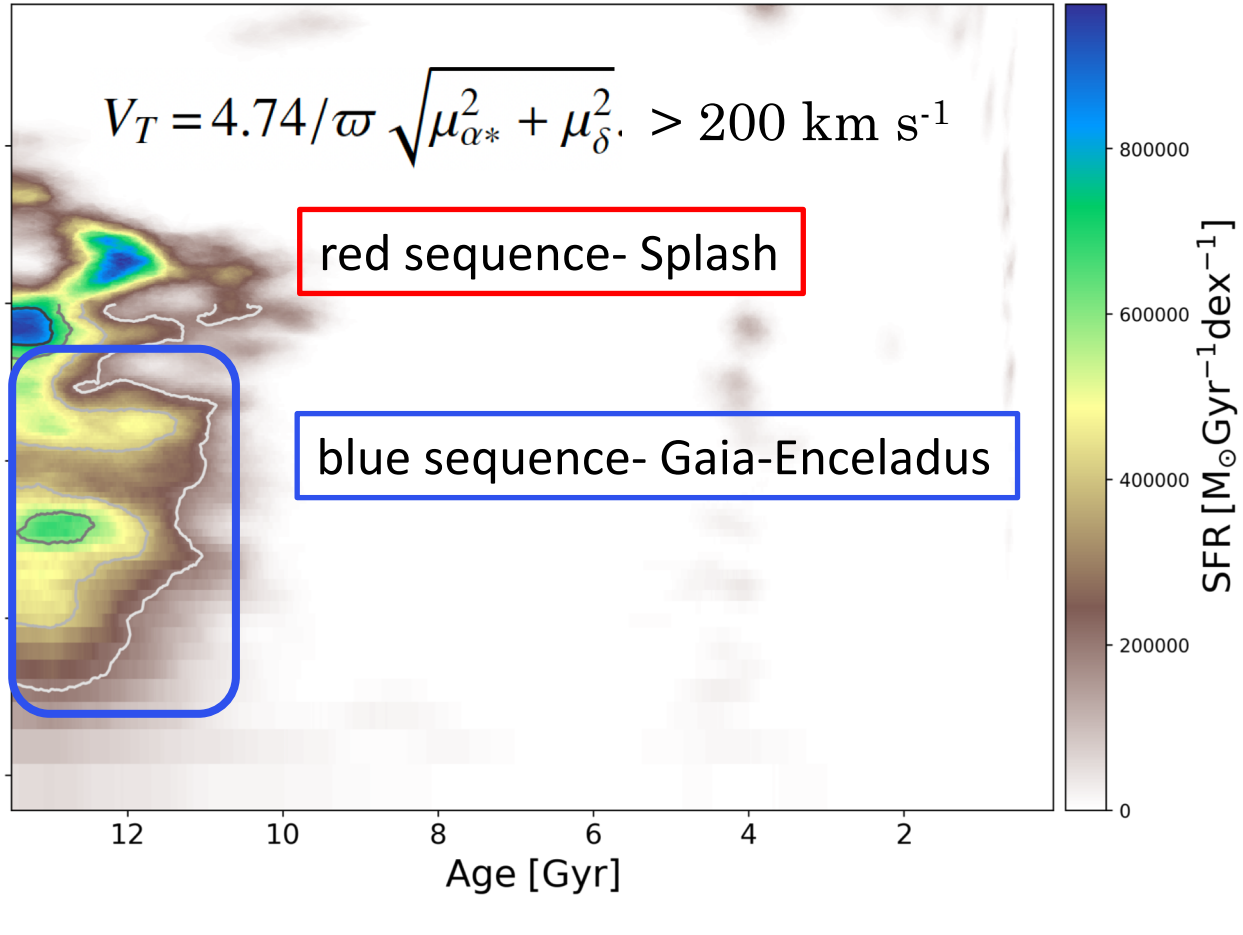




## First SFH of 6D selected Gaia-Enceladus within 1.2 kpc

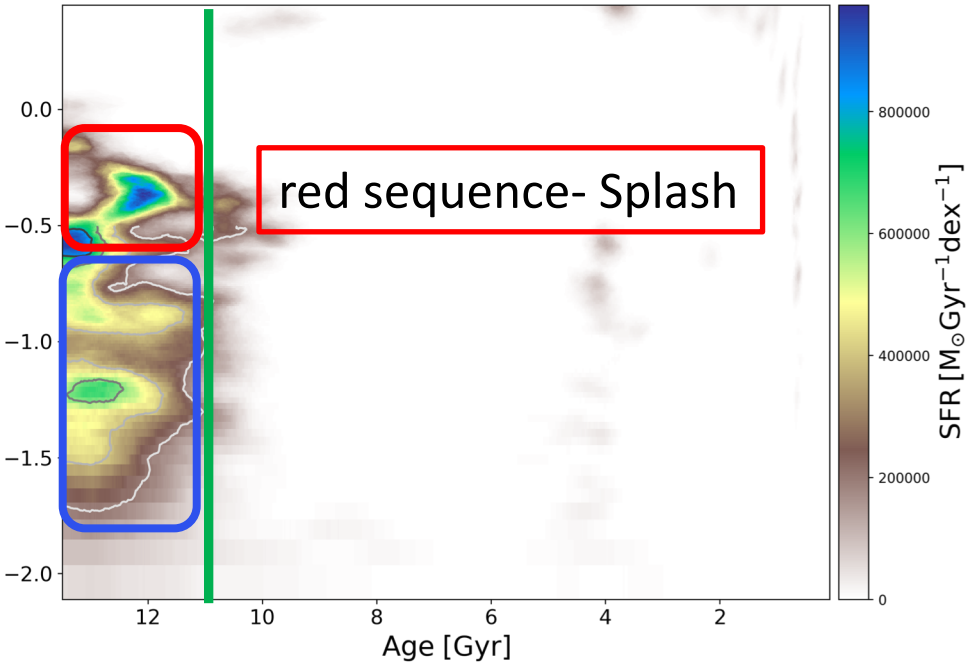
## deSFH of a kinematically defined halo



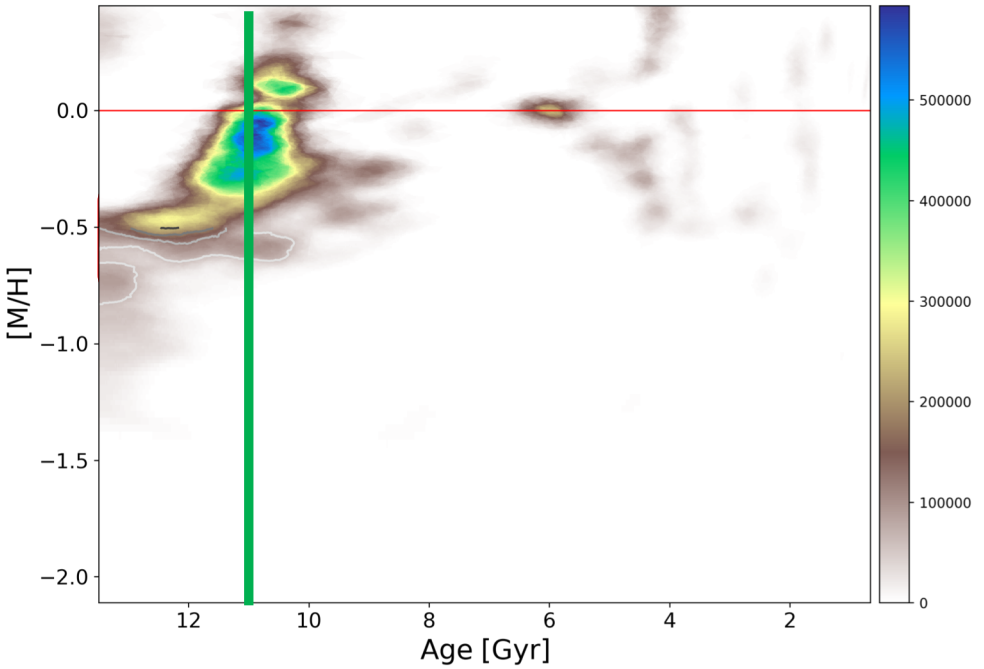



# ROLE OF G-E MERGER IN THE MW DISK FORMATION AND EVOLUTION?

## Kinematic halo SFH




## Thick disc SFH




Accretion of GES

❖ What is the role of mergers (particularly **Gaia-Enceladus**) in the MW disk formation and evolution?

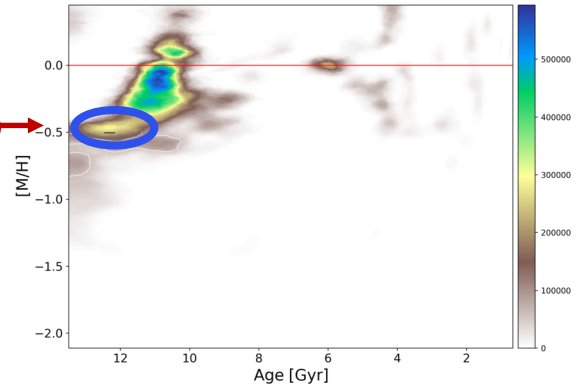
Gallart et al. 2019, NatAs

The merger of G-E seems to have triggered **an episode of enhaced star formation that created the bulk of the thick disk mass**

# WHEN AND HOW DID THE MILKY WAY DISK FORM? HOW DID IT EVOLVE

❖ When did the dominant stellar disk of the Milky Way emerge?

Very early, >12 Gyr ago

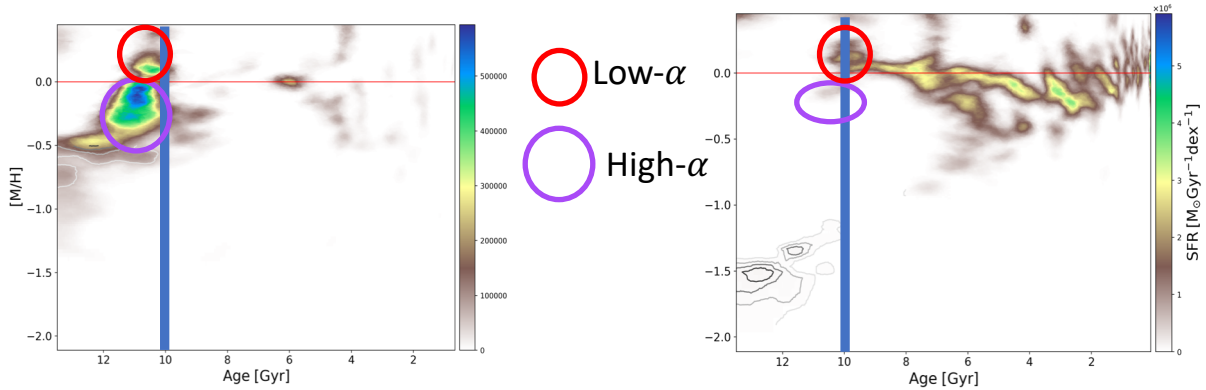



❖ On the origin of MW disk high/low $\alpha$ populations:

-What was special about the high- $\alpha$ phase? How long did it last?

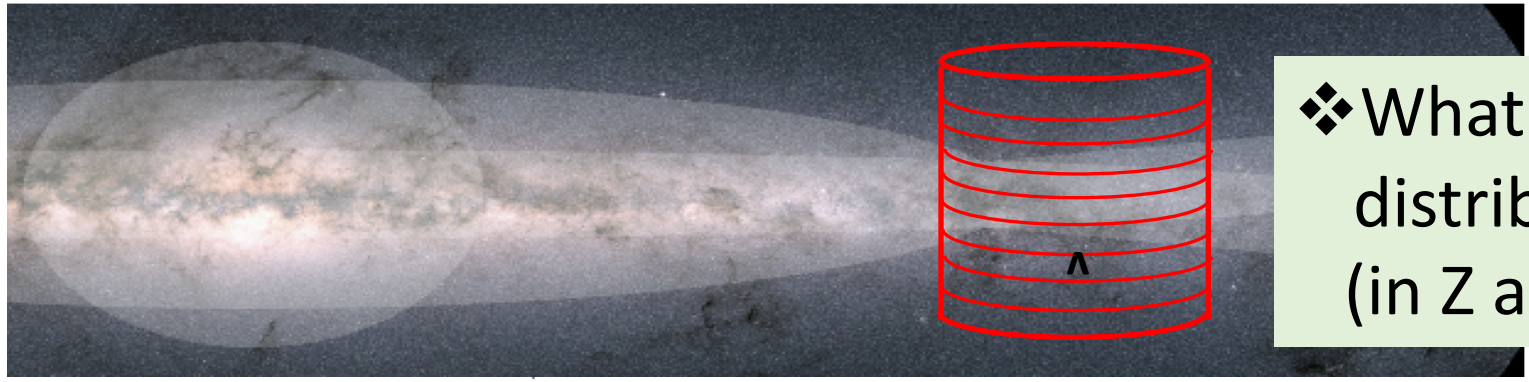
A strong star formation burst induced by the first pericenters of GES after an initial quiescent phase. By 10 Gyr ago the high-$\alpha$ phase was over.

-Did the high- and low- $\alpha$ phases overlap in time? Very slightly

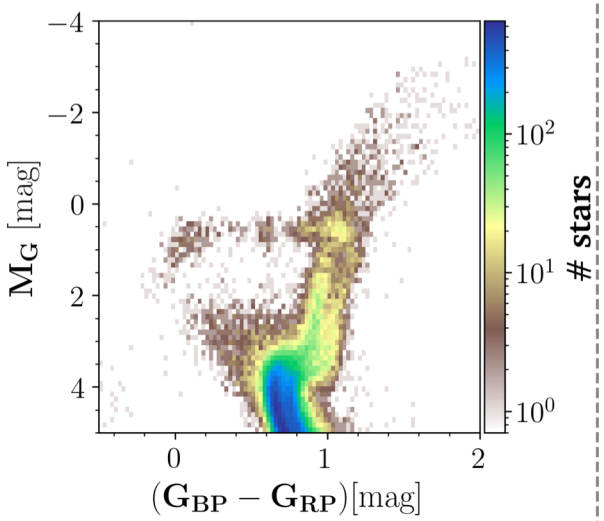


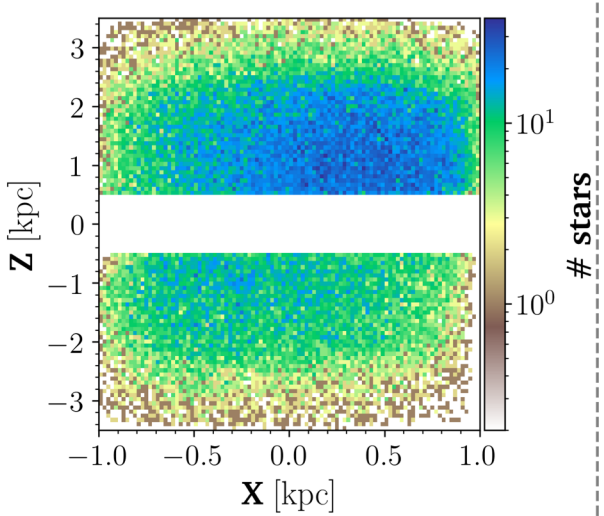

❖ What is the role of mergers (particularly **Gaia-Enceladus**) in the MW disk formation and evolution?

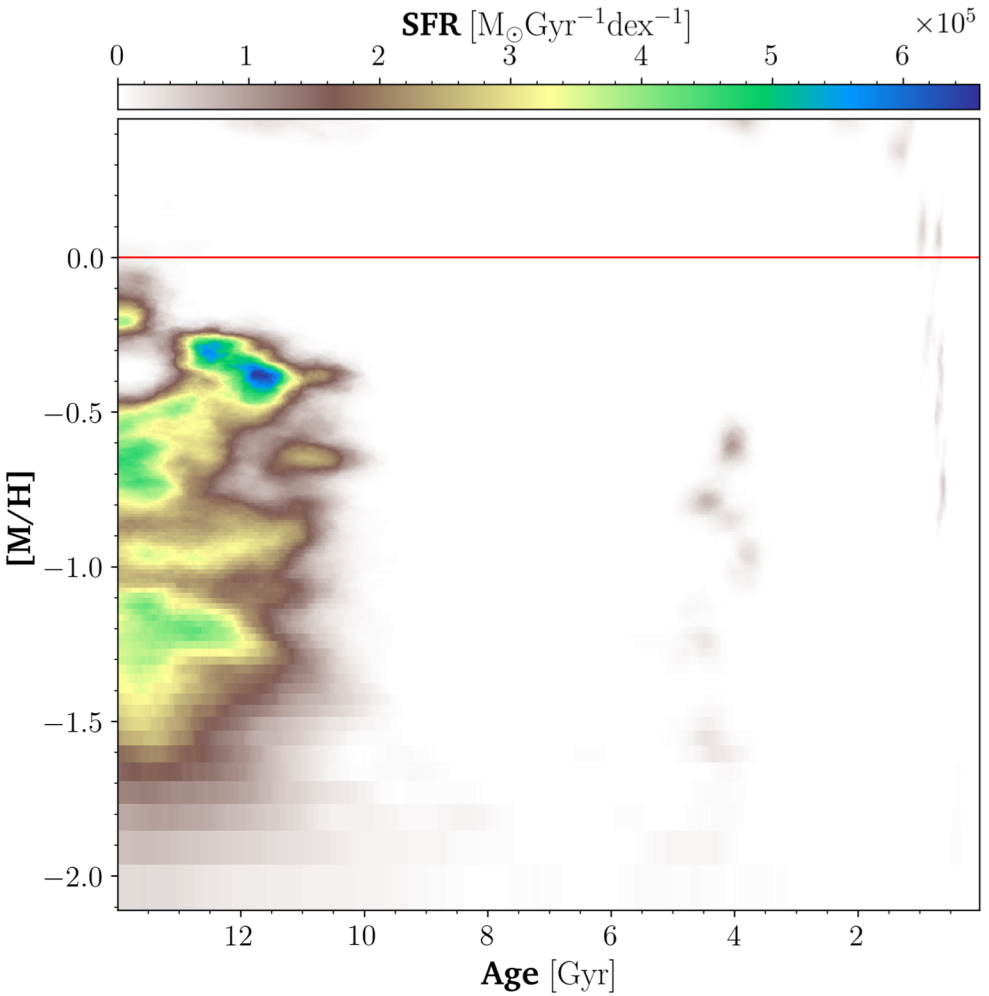
Gaia-Enceladus induced the first intense burst of star formation in the MW disk; soon after, the disk became $\alpha$-poor; other mergers (Sagittarius?) induced later star formation?



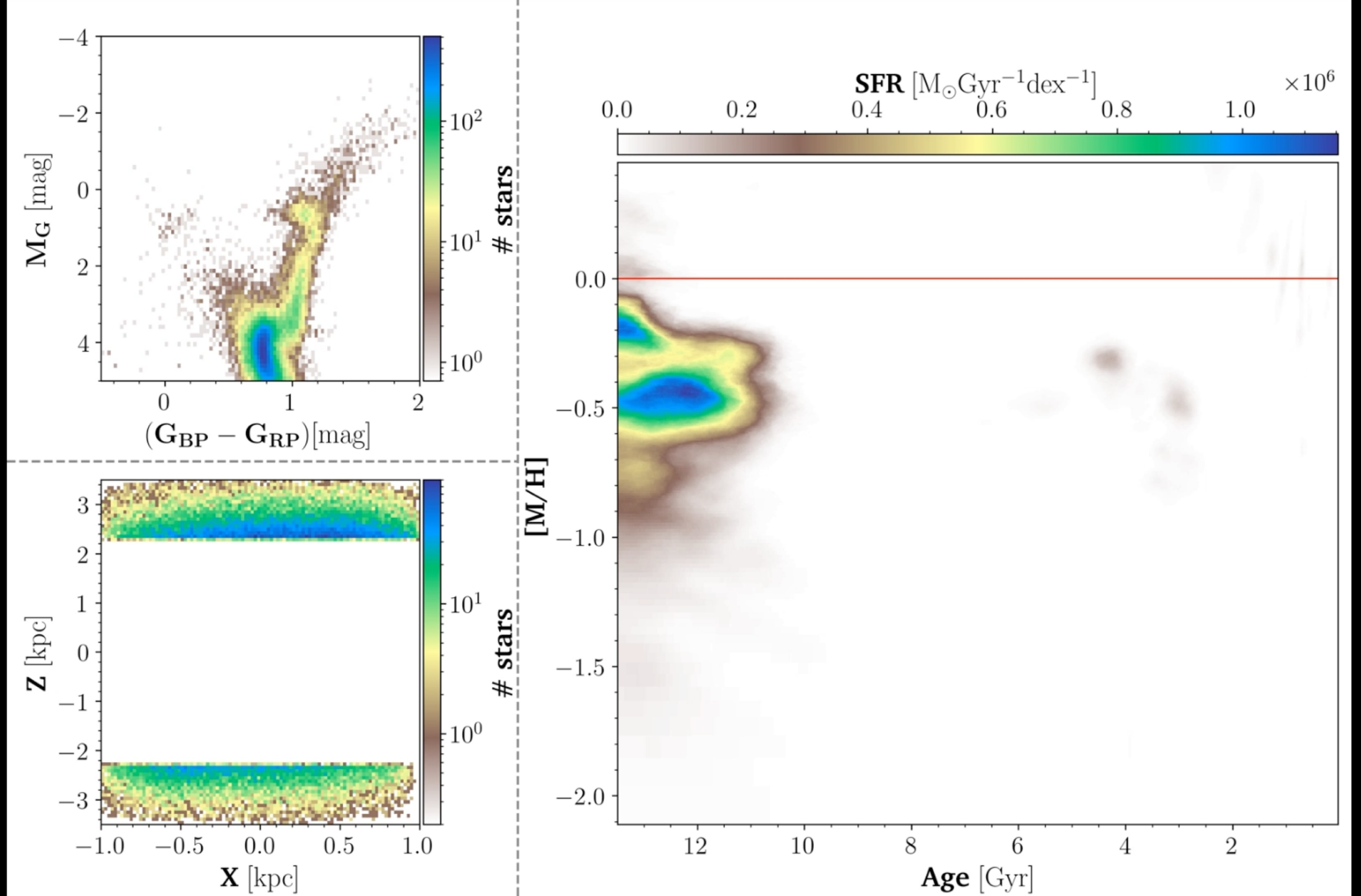
❖What is the **age**-metallicity distribution across the disk (in Z and R)?




**deSFH as a function of |Z| across a cylinder of |Z|<3.5 kpc and $R_{sun}$<1 Kpc**


$M_G$ [mag]
$(G_{BP} - G_{RP})$[mag]
# stars
Z [kpc]
X [kpc]
# stars
SFR [$M_\odot Gyr^{-1} dex^{-1}$]
$\times 10^6$
[M/H]
Age [Gyr]

**The current greatest challenge to interpret this wealth of information is**

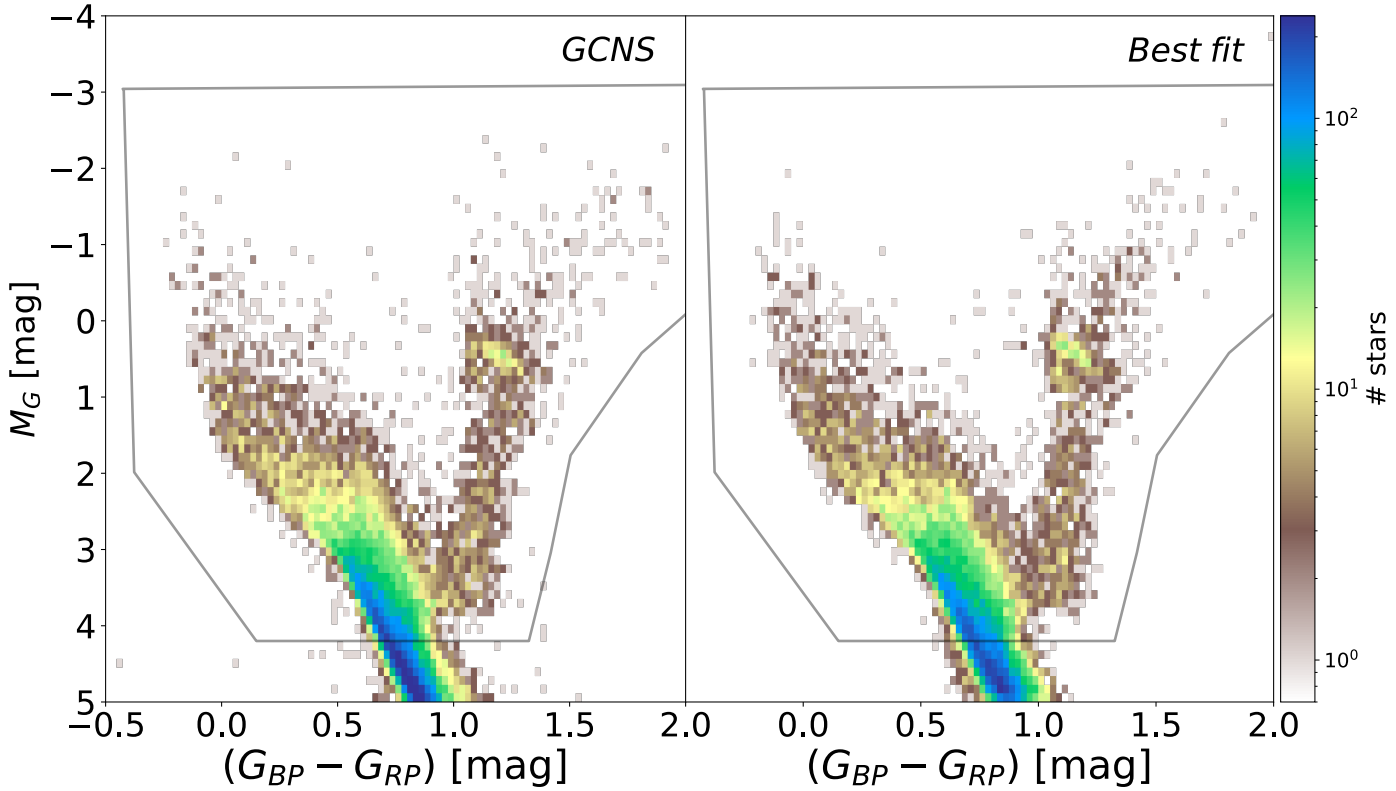
*the* difficulty to determine ***precise stellar ages*** *for* ***unbiased & large samples of stars.***

Ages are essential to stablish a temporal sequence of events, and to correctly interpret the measured properties in the context of galaxy evolution models.

e.g. **Miglio+ 2017**: "Plato as it is: a legacy mission for Galactic archaelogy": **need ages with 10% precision**

## Our approach to derive SFH: CMD-fitting of Gaia data

ChronoGal



# Chronology of our Galaxy from Gaia CMD-fitting:
## On the formation of the Milky Way thin and thick disks


Carme Gallart (IAC, Spain)

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