Seminar at the Institute of Astronomy

V.N. Karazin Kharkiv National University

# Just-Jahreiß model of the Milky Way disk: basics, predictions and calibration against Gaia data

Kseniia Sysoliatina, Andreas Just

Astronomisches Rechen-Institut (ARI), Heidelberg, Germany

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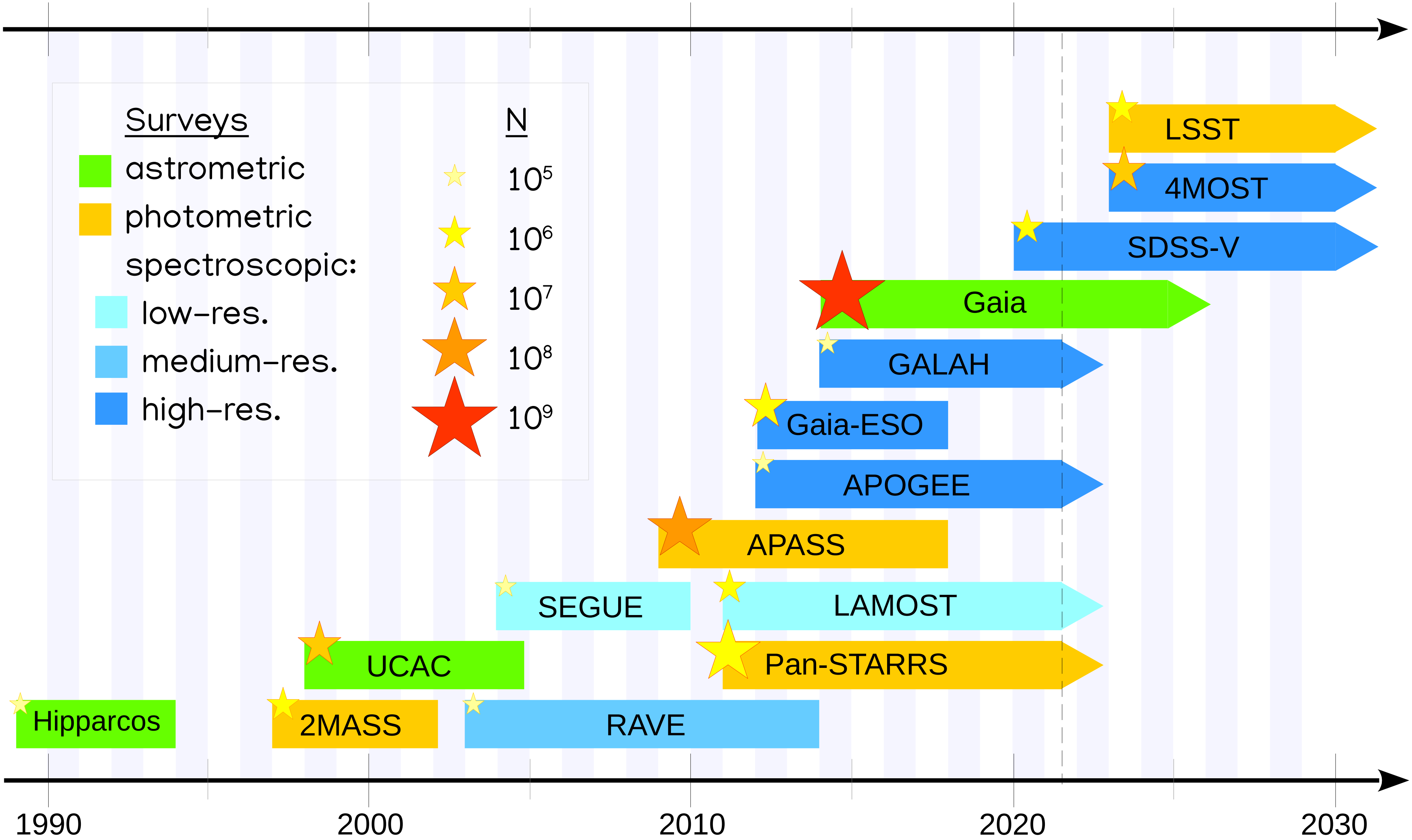
# Outline

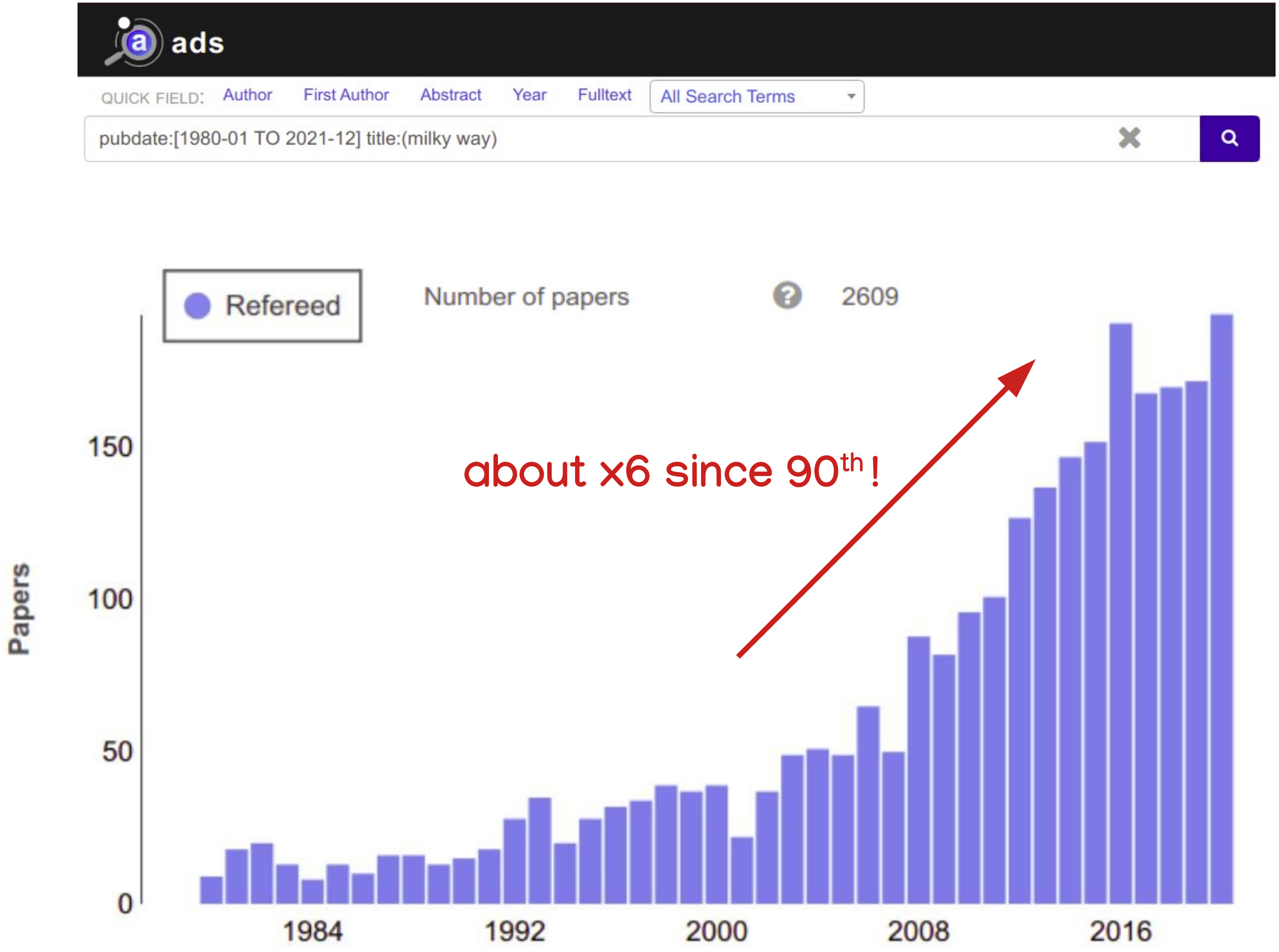
- Properties of the Milky Way
- Galactic simulations and semi-analytic models
- Just-Jahreiß (JJ) model of the Galactic disk
- Local calibration against Gaia
- Global JJ model (4 kpc < R < 14 kpc)
- Conclusions


Galactic studies.
What do we know about the Milky Way?

# Timeline of the MW surveys

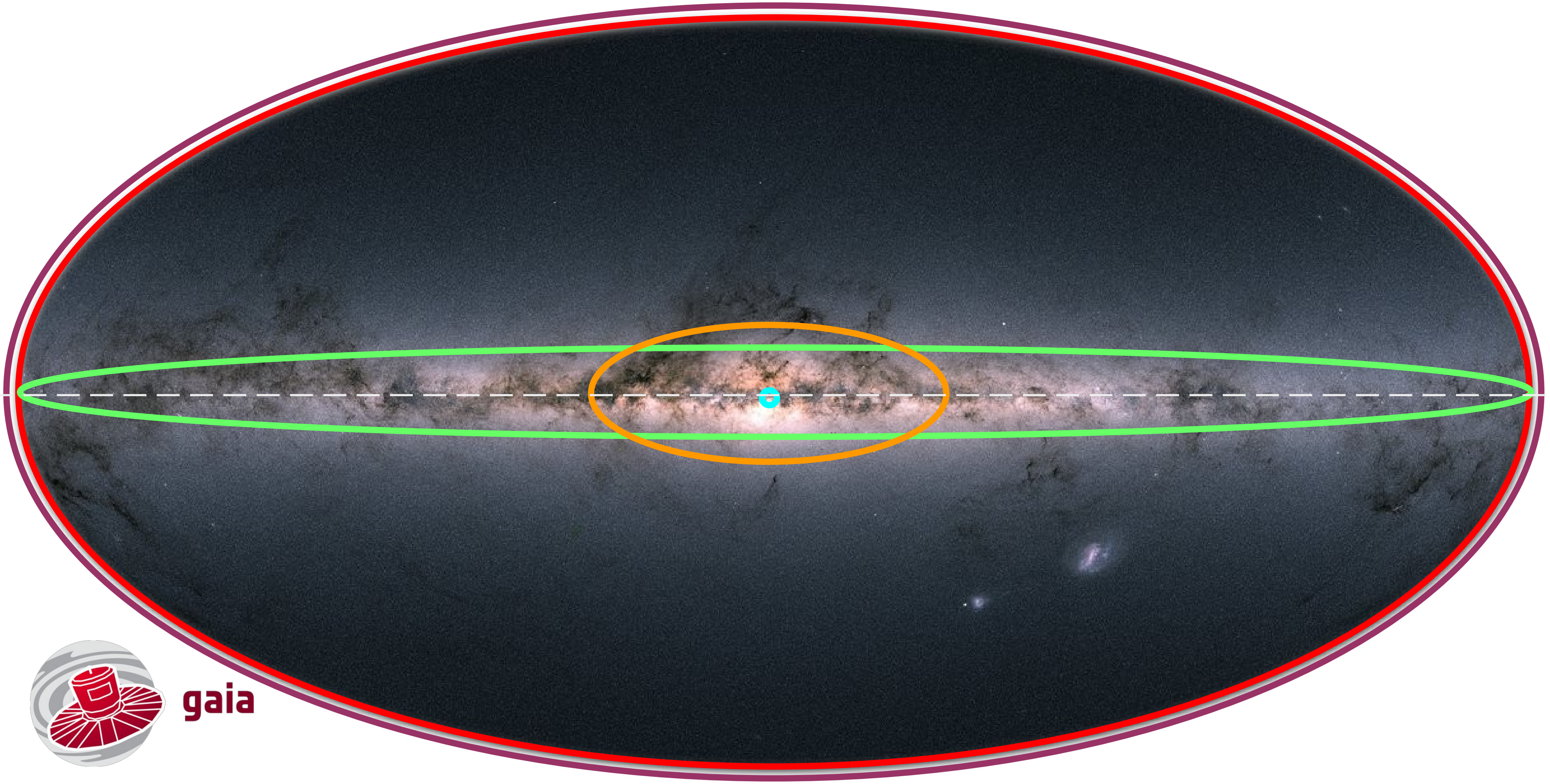


# MW-related publication rate

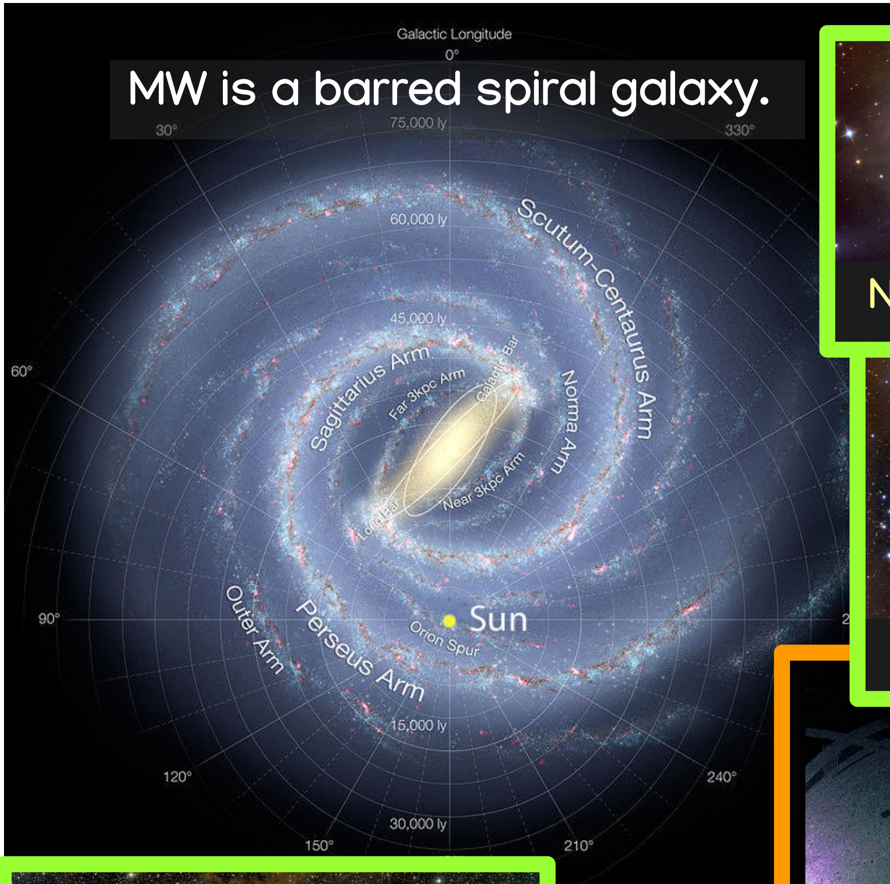


# MW morphology and components

NSC with SMBH   Bulge with the bar   Disk (thin and thick)   Halo (stars and DM)



# MW morphology and components









MW component:
- flattened
- spheroidal

**<u>The Milky Way objects:</u>**

- Field stars
- Star clusters
  - open – young (Myr), sparse, ~$10^3$ stars, trace spiral arms
  - globular – old (Gyr), dense, $10^5$ stars, located in bulge and halo
- Stellar streams (debrises of GCs and dwarf galaxies)
- Gas (mostly H), dust, star formation regions
  - Molecular clouds
  - Warm atomic component
  - Hot gas (e.g. SNe explosions)
  - Dark clouds

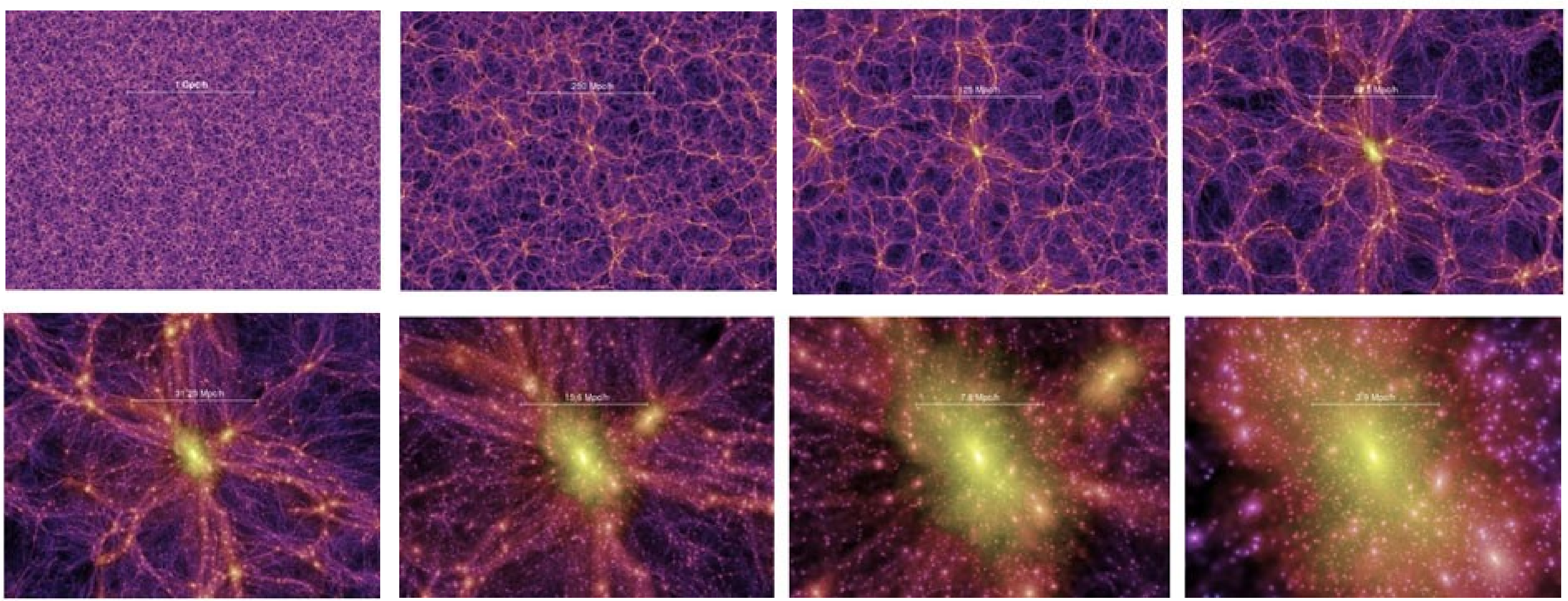

Realistic galaxy simulations - easy or difficult?

# Galaxy as a system of N bodies

Newton's law:

$$m_i \ddot{\vec{R}}_i = \vec{F}_i \quad \text{with} \quad \vec{F}_i = G \sum_{j \neq i} \frac{m_i m_j (\vec{x}_i - \vec{x}_j)}{|\vec{x}_i - \vec{x}_j|^3}$$

MIllenium simulation – N–body simulation of DM halos



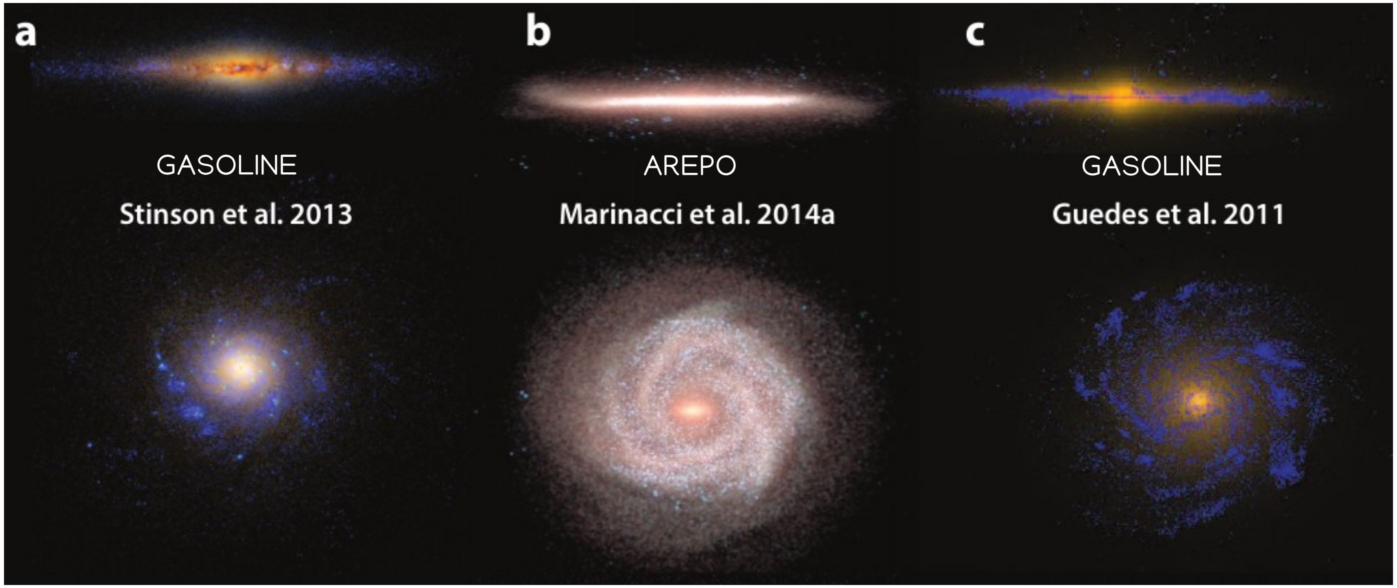
Springel+2005

# Feedback processes in galaxy evolution

**Not possible to simulate realistic MW-like galaxies with self-gravitating DM only.**

Hydrodynamic simulations of large cosmological volumes include
**DM** + **baryonic** matter, **gravity** + **feedback** processes:

- ➔ Interstellar gas cooling and heating depending on its ρ, T, [M/H], UV and AGN radiation
- ➔ Models of star formation in cold and dense regions
- ➔ Distribution of the energy and metals generated by the stars into the surrounding gas
- ➔ SN Ia and SN II explosions with injection of their energy in the surrounding gas
- ➔ SMBH formation and feedback



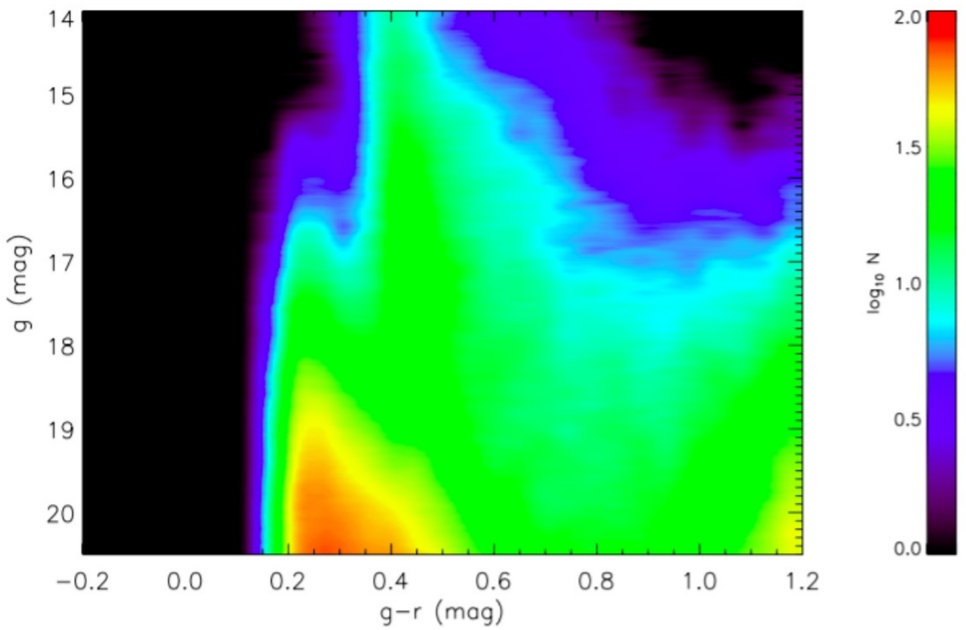

Cosmological simulations allow statistical study of the MW-like galaxies, not of the MW itself.

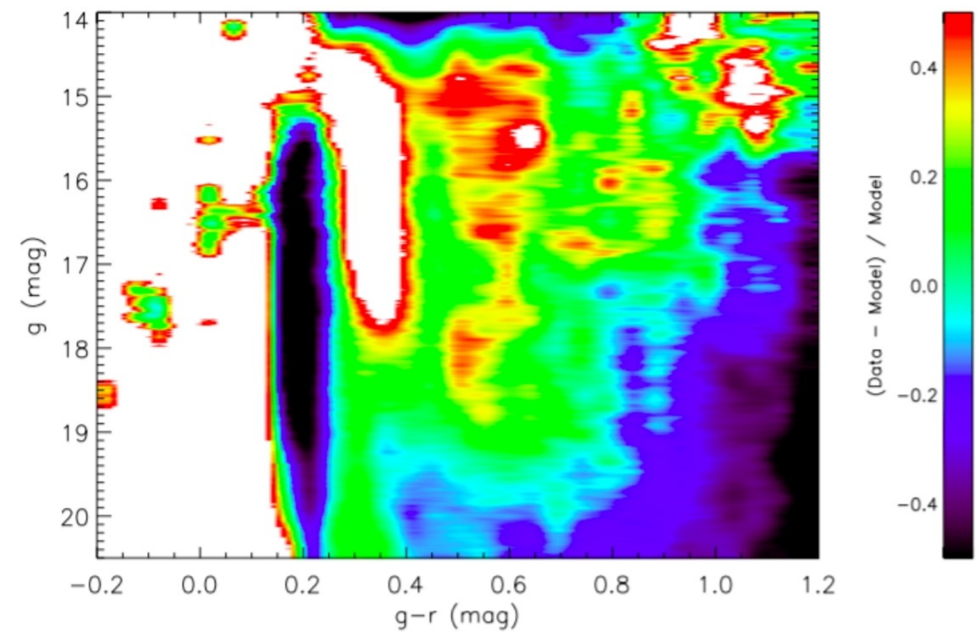

Semi-analytic Milky Way models (SAMs)

# Kinematic models: TRILEGAL code

Assumed density profiles of the MW components → Predicted star counts

TRILEGAl = the TRI-dimensional modeL of thE GALaxy (Girardi et al. 2002, 2005; 2012)




TRILEGAL model with the best parameters against SDSS data: median discrepancy (data-model) is as large as 25%. (Gao et al. 2013)

# Stellar dynamics

We can build a galaxy model relying on the basic principles of stellar dynamics, with the stellar evolution/feedback included in a semi-empirical way.

**Poisson Eq. (PE)**

$$\Delta\Phi = 4\pi G\rho$$

1. Thin-disk approximation: $z/R \ll 1$
2. Disk is axisymmetric (no spiral arms): $\partial/\partial\phi = 0$

$$\cancel{\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\Phi}{\partial R}\right)} + \frac{\partial^2\Phi}{\partial z^2} = 4\pi G\rho$$

$$z(\Phi) = \int_0^{\Phi}\left(8\pi G\int_0^{\Phi'}\rho(\Phi'')\,d\Phi''\right)^{-1/2} d\Phi'$$

**Collisionless Boltzmann Eq. (CBE)**

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\frac{\partial f}{\partial \boldsymbol{r}} - \frac{\partial\Phi}{\partial\boldsymbol{r}}\frac{\partial f}{\partial\boldsymbol{v}} = 0\,, \qquad f = f(t, \boldsymbol{x}, \boldsymbol{v})$$

3. Disk rests in a steady state, i.e, $\partial/\partial t = 0$

First moment of CBE assuming 1–3:

$$\sigma_{z,i}^2\frac{\partial\rho_i}{\partial z} = -\frac{\partial\Phi}{\partial z}\rho_i \qquad \text{(1M-CBE)}$$

$$\rho_i = \rho_{i,0}\,e^{-\Phi/\sigma_{z,i}^2}$$

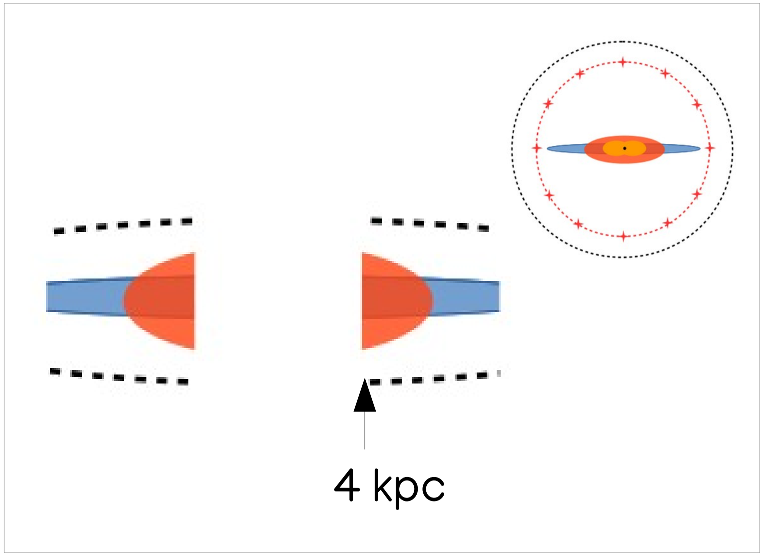
Combined Poisson-Boltzmann Eq. (PBE)

$$\boxed{z(\Phi) = \int_0^{\Phi}\left(8\pi G\int_0^{\Phi'}\sum_i \rho_{0,i}\,e^{(-\Phi''/\sigma_{z,i}^2)}\,d\Phi''\right)^{-1/2} d\Phi'}$$

# Semi-analytic models of the MW

**Reconstruction of the MW potential:**

1. Disk (+ other components) is approximated as a zero-thickness layer (ZTL). $\Phi(R,0)$ is calculated (for ZTL, analytic solutions exist).
2. Iteratively solve PBE at the different R and, as a result, get a self-consistent pair $\{\Phi(R,z), \rho(R,z)\}$.




**Limitations:**

- Works at low z;
- Not applicable to the bulge region;
- May be imprecise for very young populations;
- Predictions for large volumes.

**Advantages:**

- Does not require extensive computation power and long time;
- Effective parameter space exploration.

# Example of SAM: Just-Jahreiß model

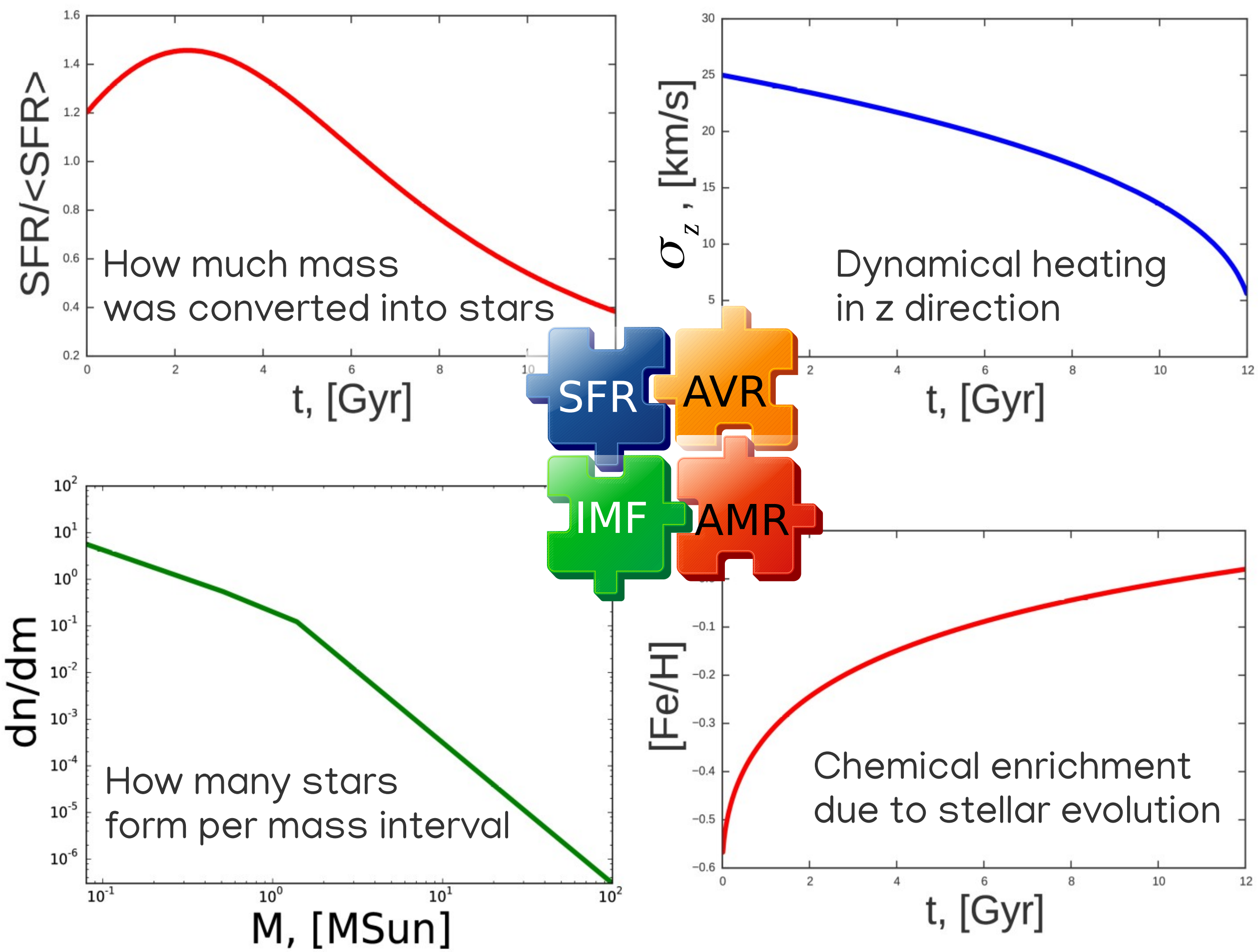
# Just-Jahreiß model of the MW disk

**Just-Jahreiß (JJ) model:**
semi-analytic model of the MW disk, self-consistent {Φ,ρ} reconstructed from PBE.

**JJ model includes:**

- Stellar disk
  - Thin
  - Thick
- Gaseous disk
  - Molecular
  - Atomic
- Halo
  - Stellar
  - DM

**Thin disk is described by analytic functions:**

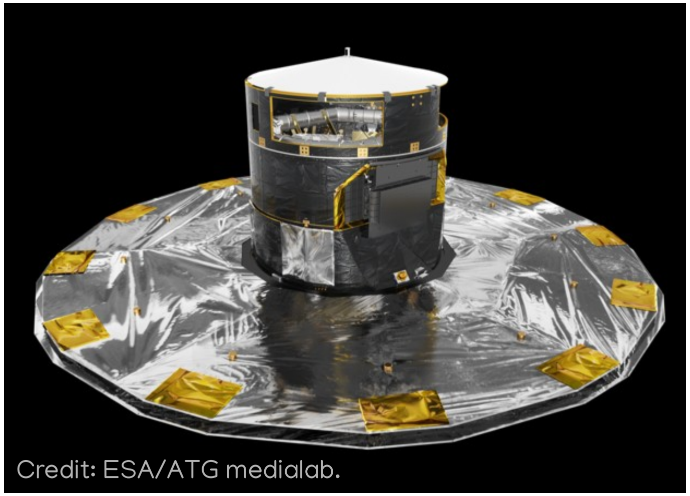



Calibrated in the Solar neighbourhood against Hipparcos and Catalog of Nearby Stars (CNS) (Just & Jahreiß 2010, Rybizki & Just 2015), SDSS (Just et al 2011), APOGEE and Gaia data (Sysoliatina & Just 2021).


Sysoliatina & Just (2021)

# Gaia – the billion star surveyor


Gaia launch from the European Spaceport in Kourou, French Guiana on 19 Dec 2013.



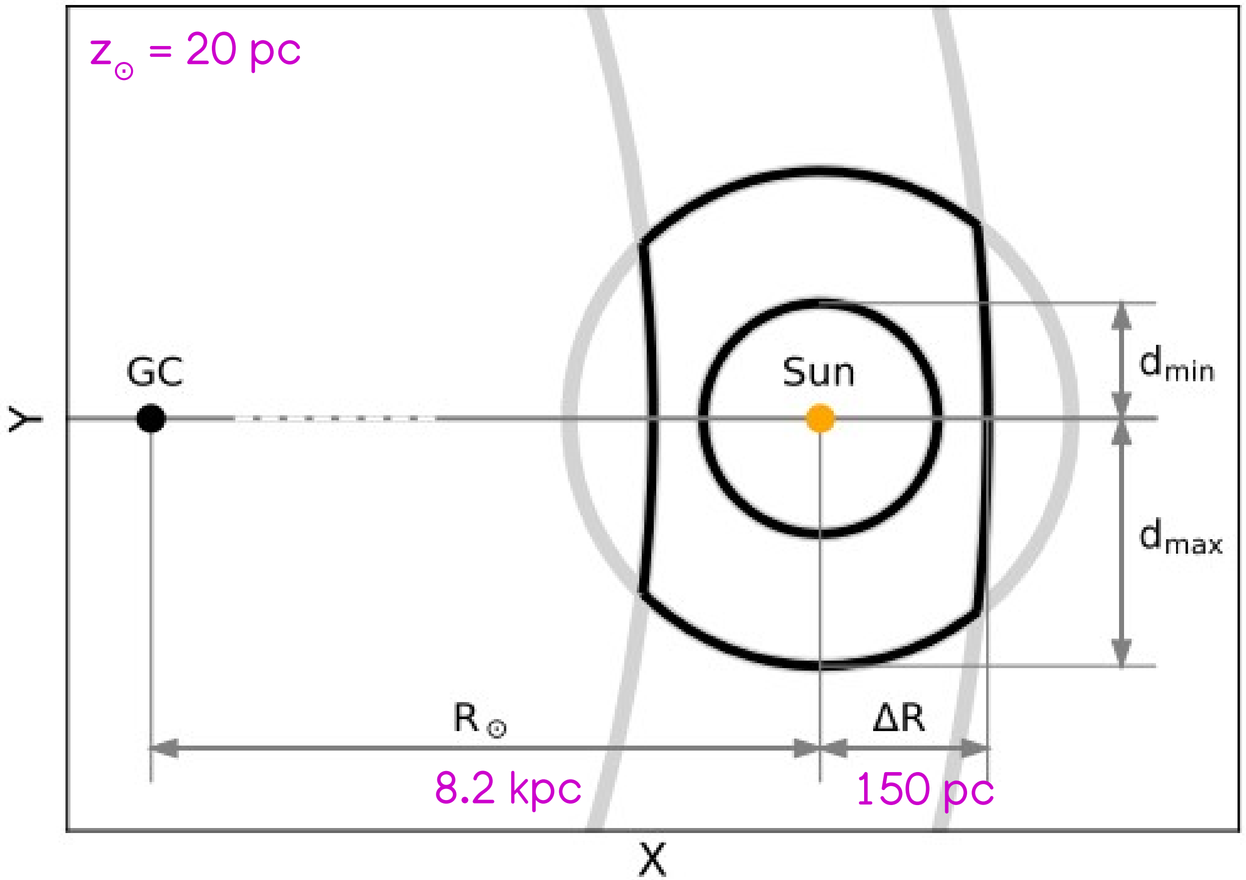

Equipped with
– two identical telescopes and imaging system;
– blue and red photometers;
– radial-velocity spectrometer.

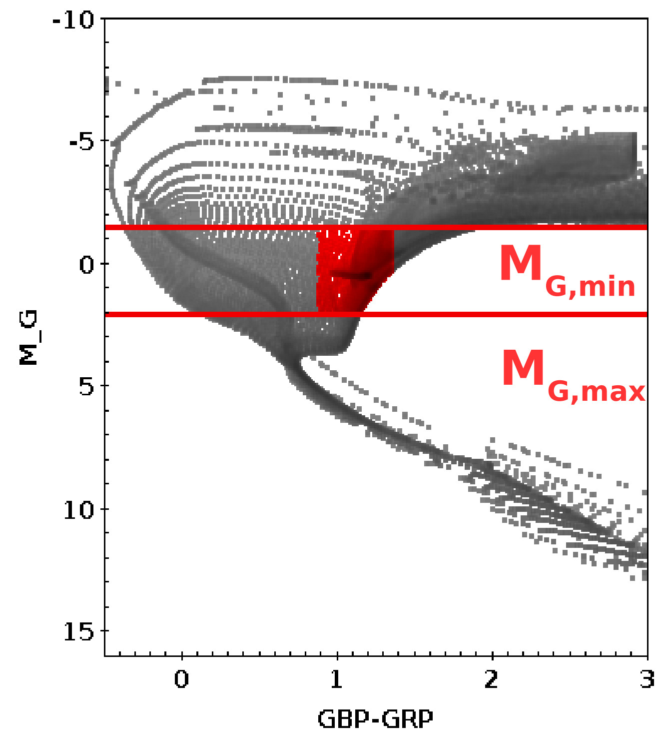
**Objectives of the ESA mission Gaia:**

- Measure positions of ~1 billion stars (in MW and other Local Group members), with an accuracy down to 24 mas.
- Perform spectrophotometric measurements of all objects.
- Derive space velocities of the MW stars.
- Create a three-dimensional structural map of the MW.

The latest release: EDR3 (3 Dec 2020) ~1.5 billion stars with positions, parallaxes and proper motions.

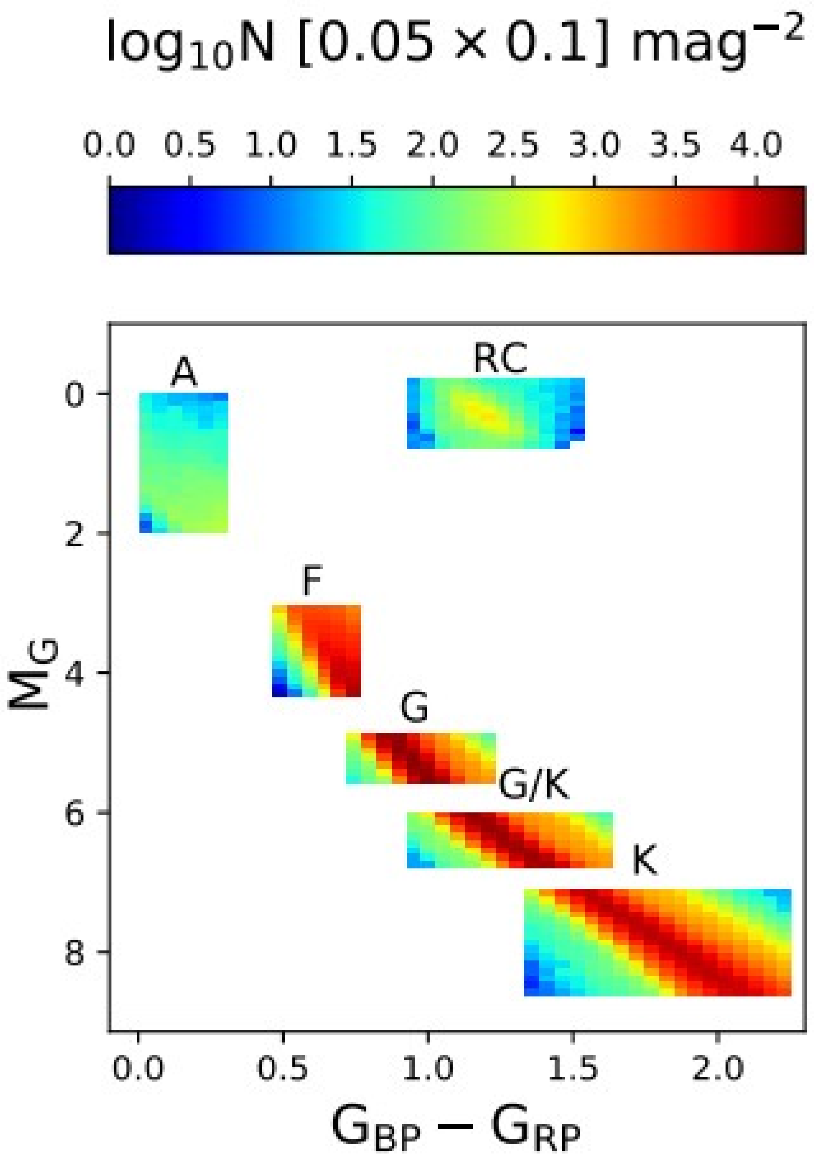
# Data-motivated sample geometry

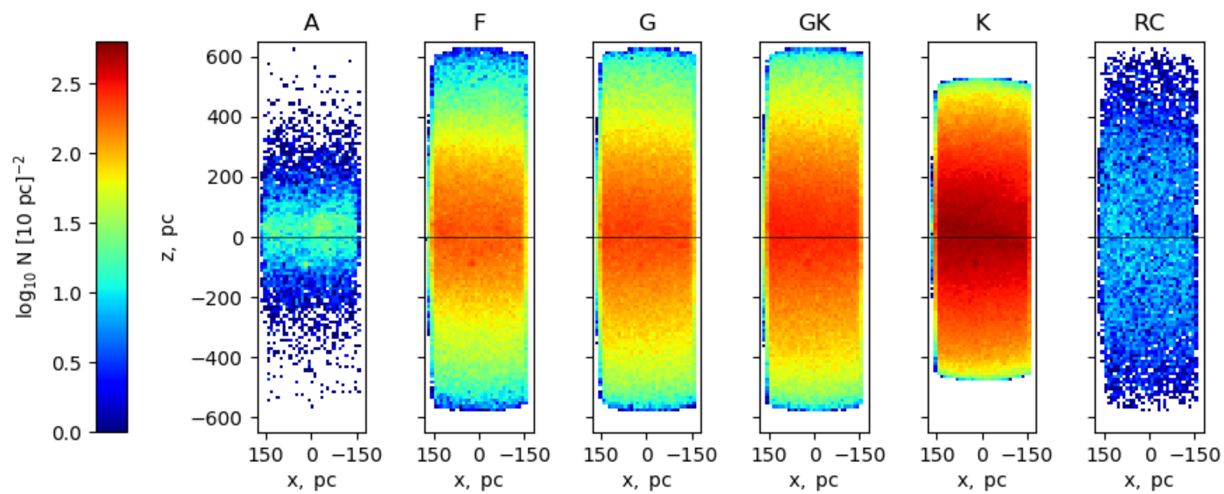


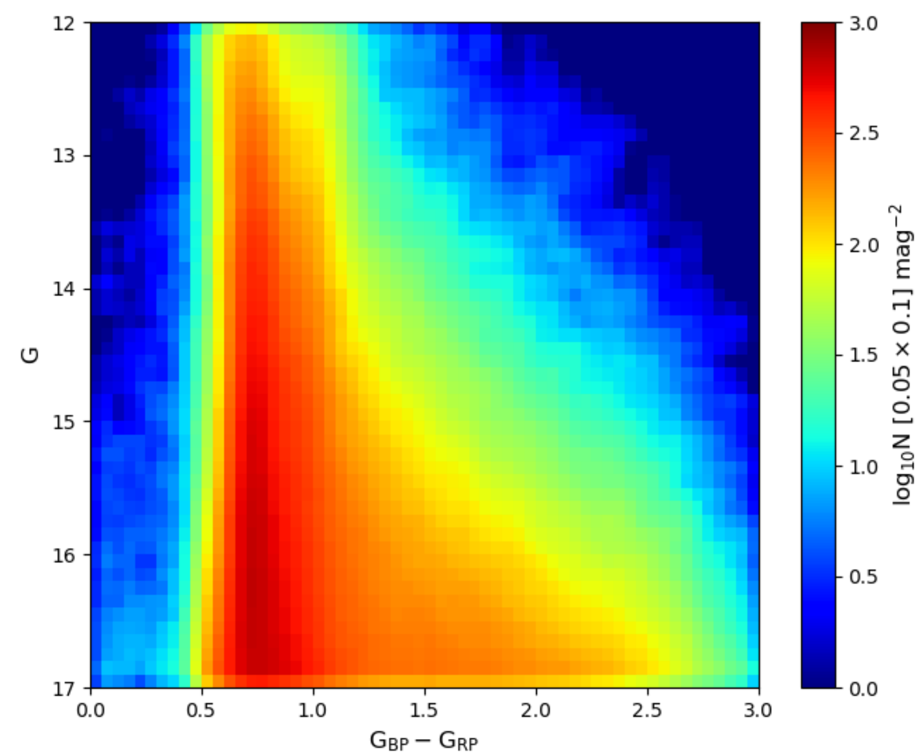




1. Populations defined on the CMD
2. ($d_{min}$, $d_{max}$) chosen such, that G belongs to the range where data are 99% complete & parallax errors are small (a few %).

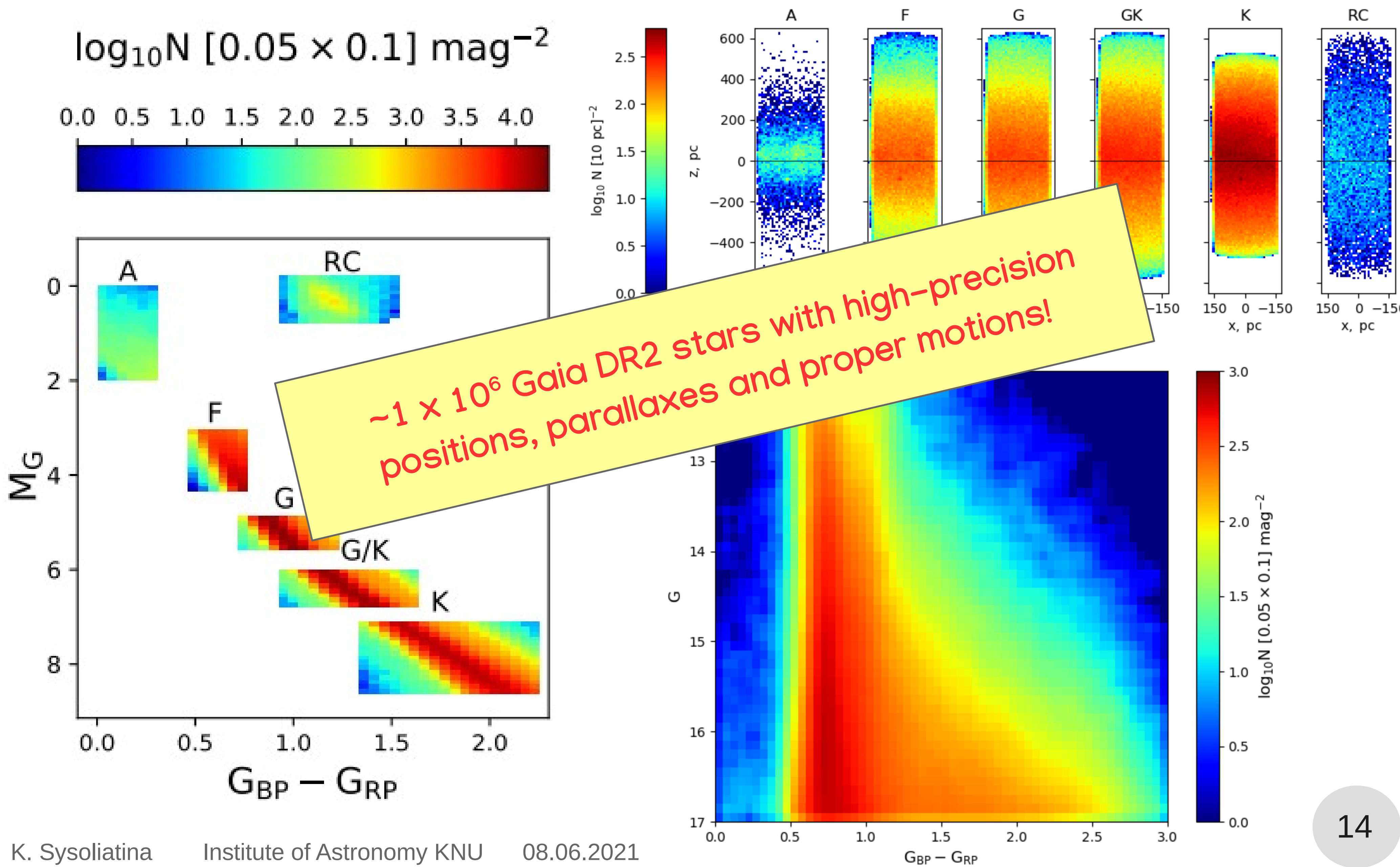
# Gaia DR2 samples in the local volume



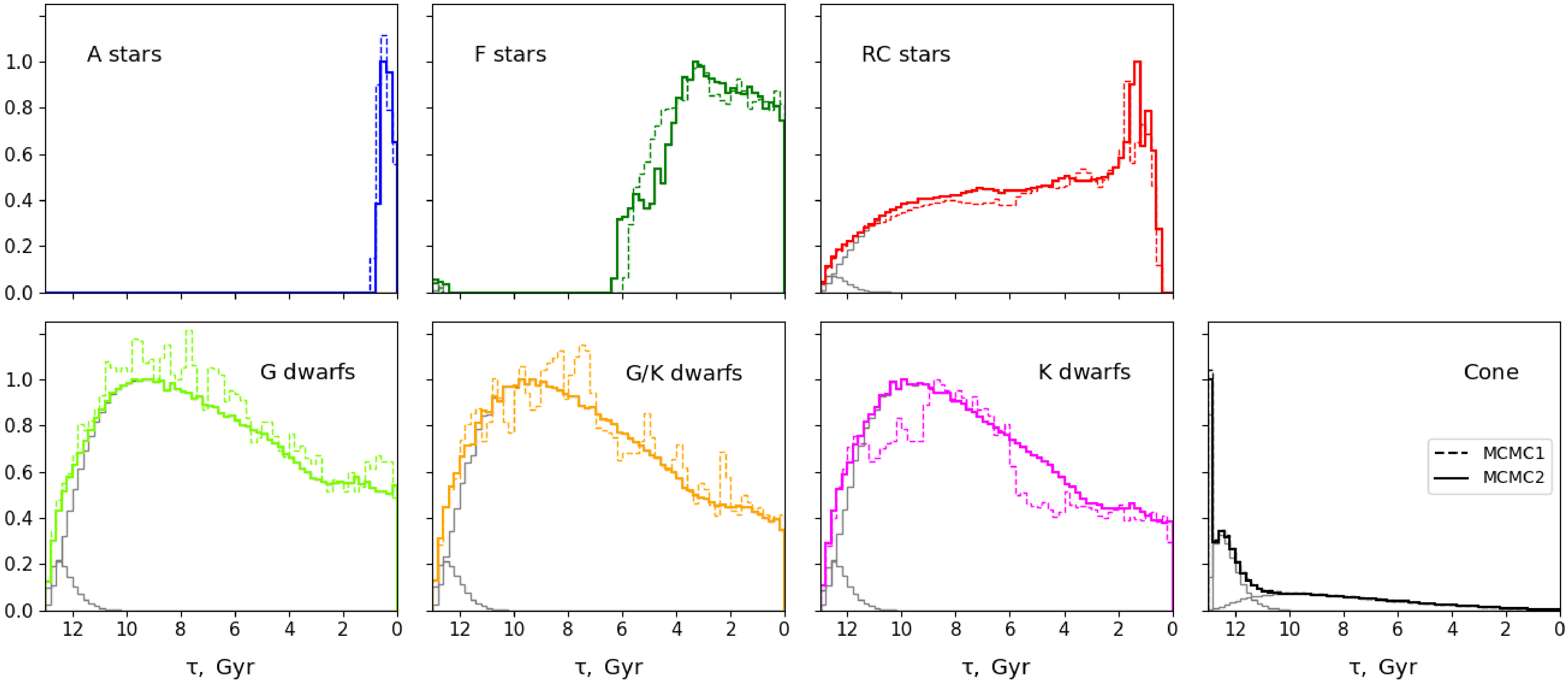



# Gaia DR2 samples in the local volume




~1 × 10⁶ Gaia DR2 stars with high-precision positions, parallaxes and proper motions!

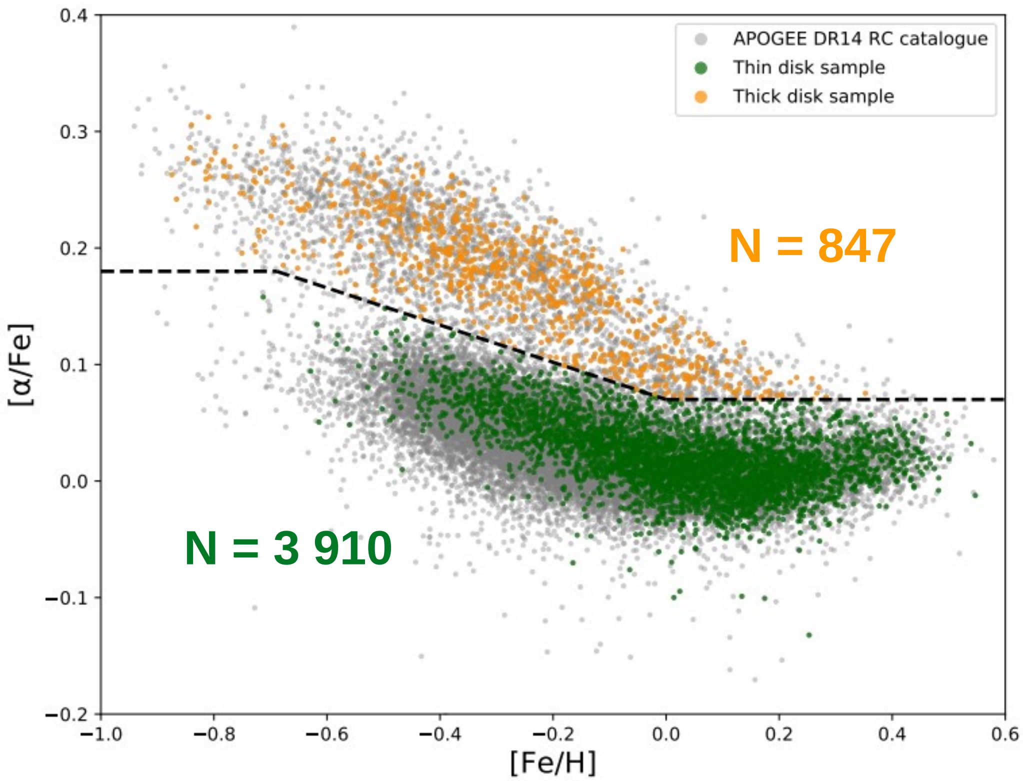
# Age distributions of the samples

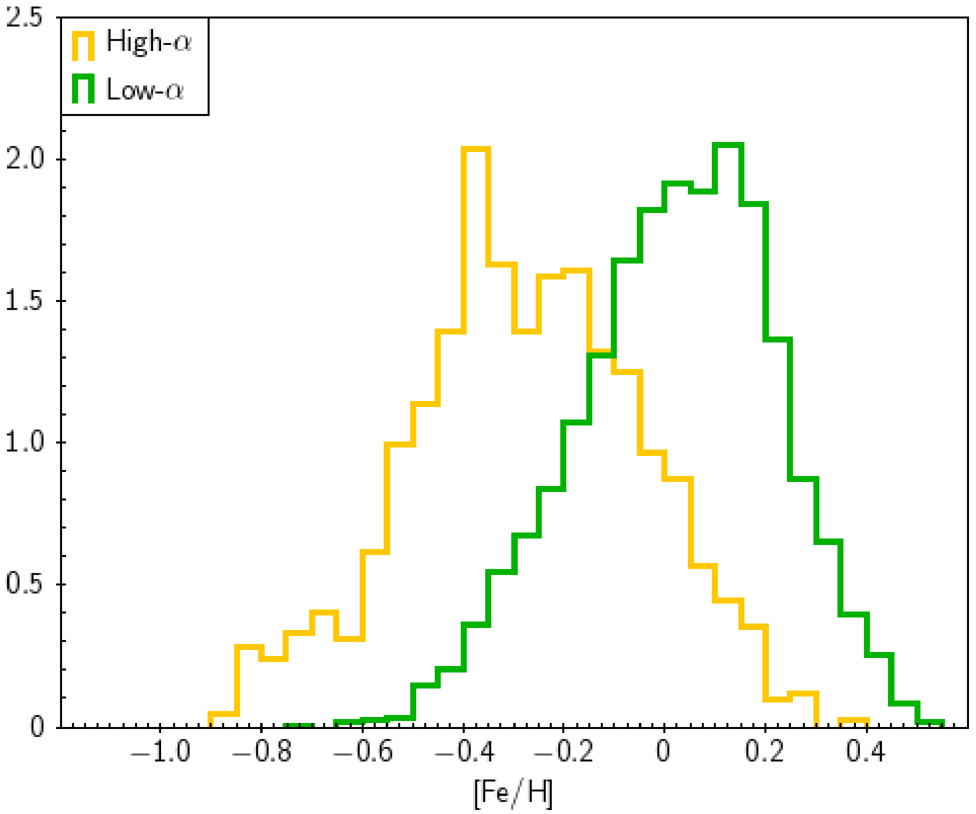



**All ages are well represented.**

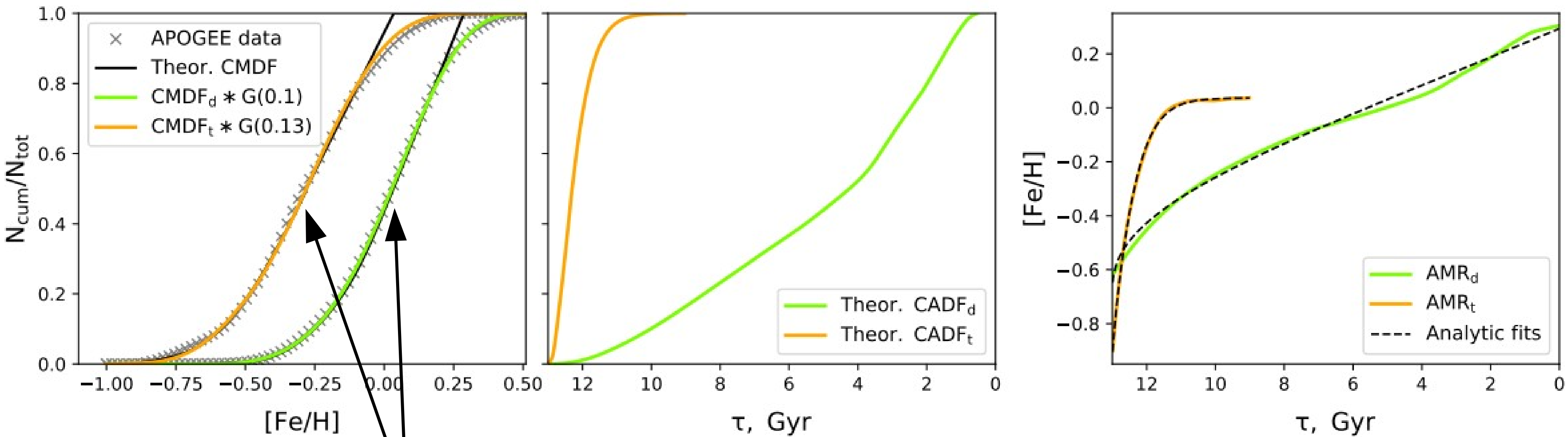
# Chemical information from APOGEE

Red Clump (RC) stars selected in the Solar annulus $R_\odot \pm 500$ pc:



# Constraining input functions: AMR



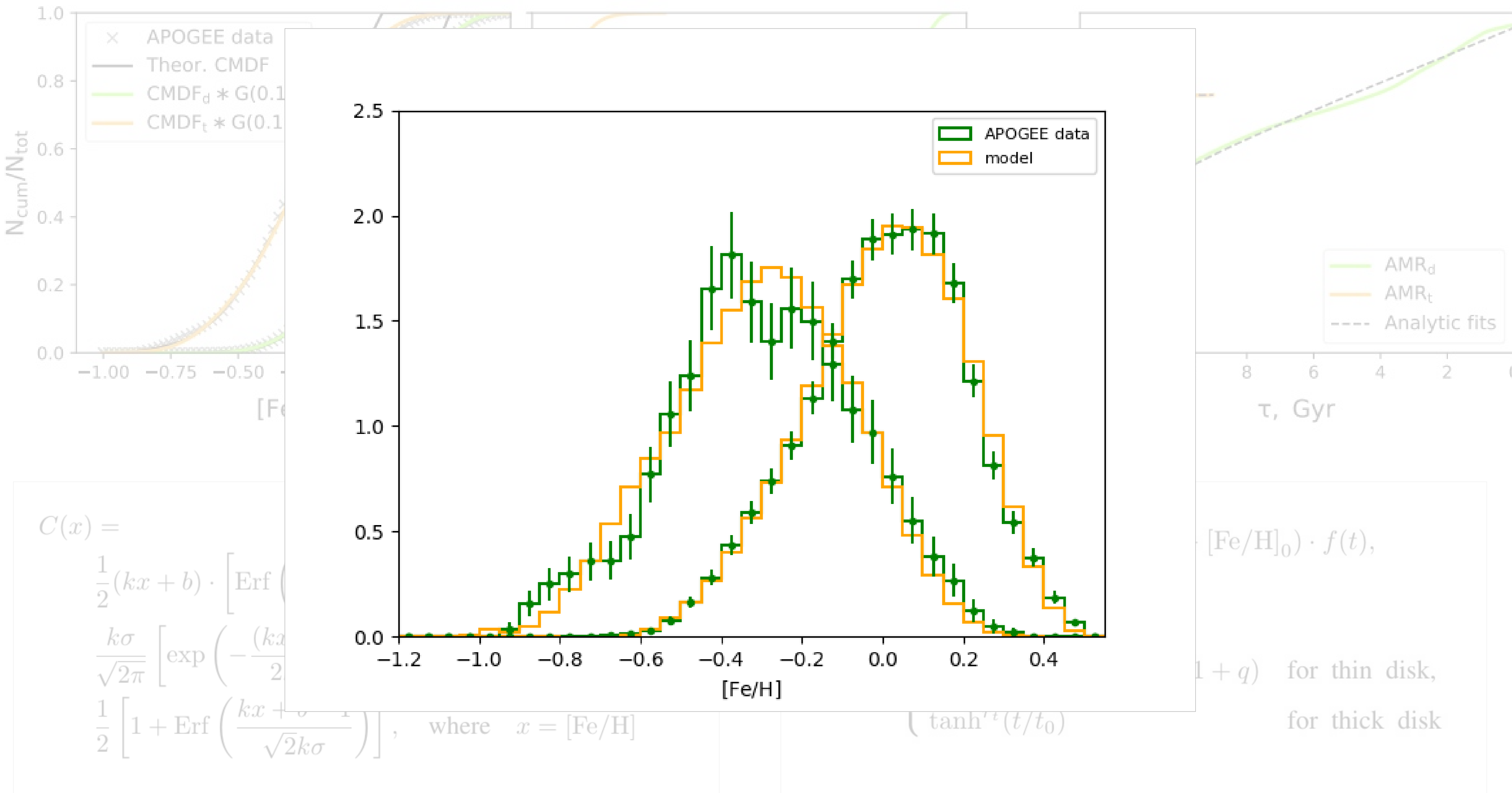

$$
\begin{aligned}
C(x) = \\
& \frac{1}{2}(kx+b)\cdot\left[\mathrm{Erf}\left(\frac{kx+b}{\sqrt{2}k\sigma}\right) - \mathrm{Erf}\left(\frac{kx+b-1}{\sqrt{2}k\sigma}\right)\right] + \\
& \frac{k\sigma}{\sqrt{2\pi}}\left[\exp\left(-\frac{(kx+b)^2}{2k^2\sigma^2}\right) - \exp\left(\frac{(kx+b-1)^2}{2k^2\sigma^2}\right)\right] + \\
& \frac{1}{2}\left[1+\mathrm{Erf}\left(\frac{kx+b-1}{\sqrt{2}k\sigma}\right)\right], \quad \text{where} \quad x = [\mathrm{Fe/H}]
\end{aligned}
$$

$$[\mathrm{Fe/H}](t) = [\mathrm{Fe/H}]_0 + ([\mathrm{Fe/H}]_p - [\mathrm{Fe/H}]_0)\cdot f(t),$$

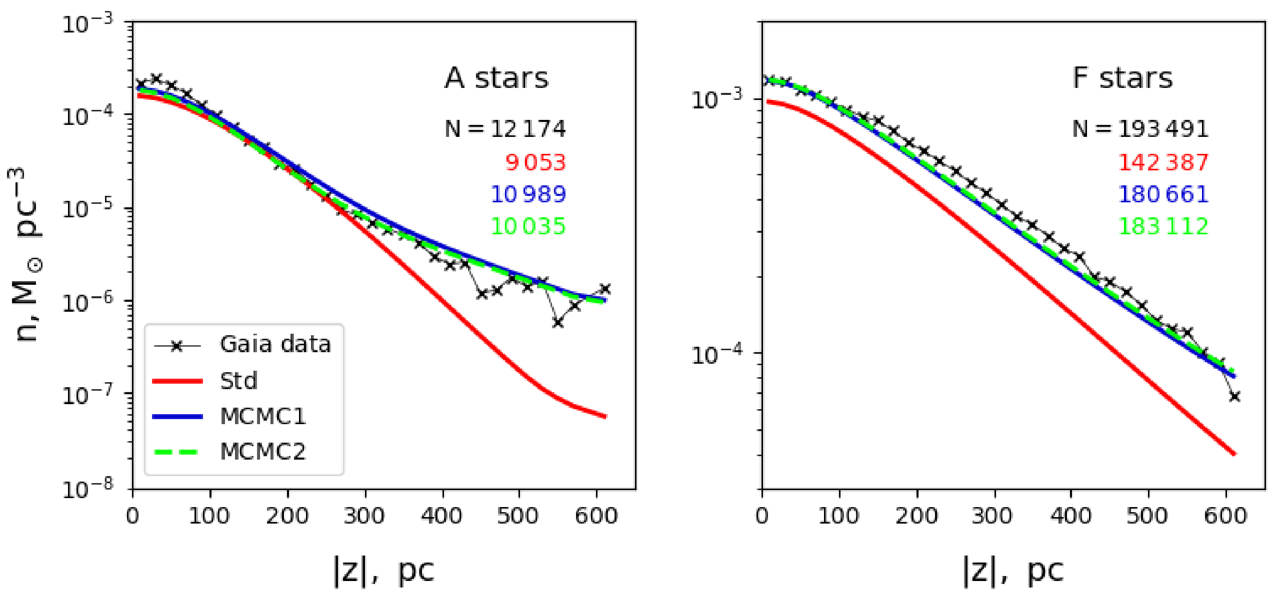
where

$$f(t) = \begin{cases} \log(1+q(t/t_p)^{r_d})/\log(1+q) & \text{for thin disk,} \\ \tanh^{r_t}(t/t_0) & \text{for thick disk} \end{cases}$$

# Constraining input functions: AMR



# JJ model calibration: density profiles




Problem:

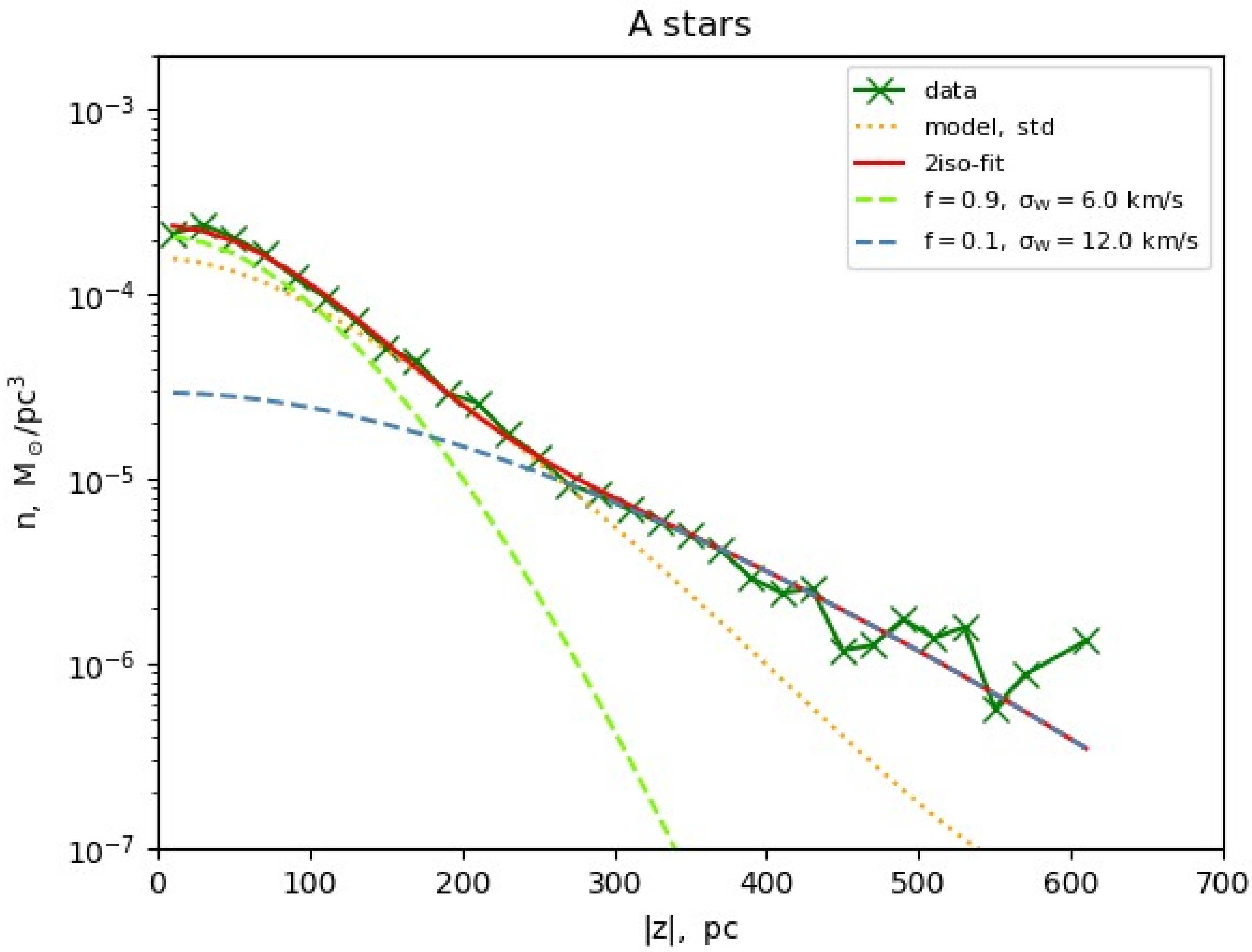
1. Not enough A and F stars (ages < 4–5 Gyr)
2. Density profile is too steep in the model

Attempt of solution:

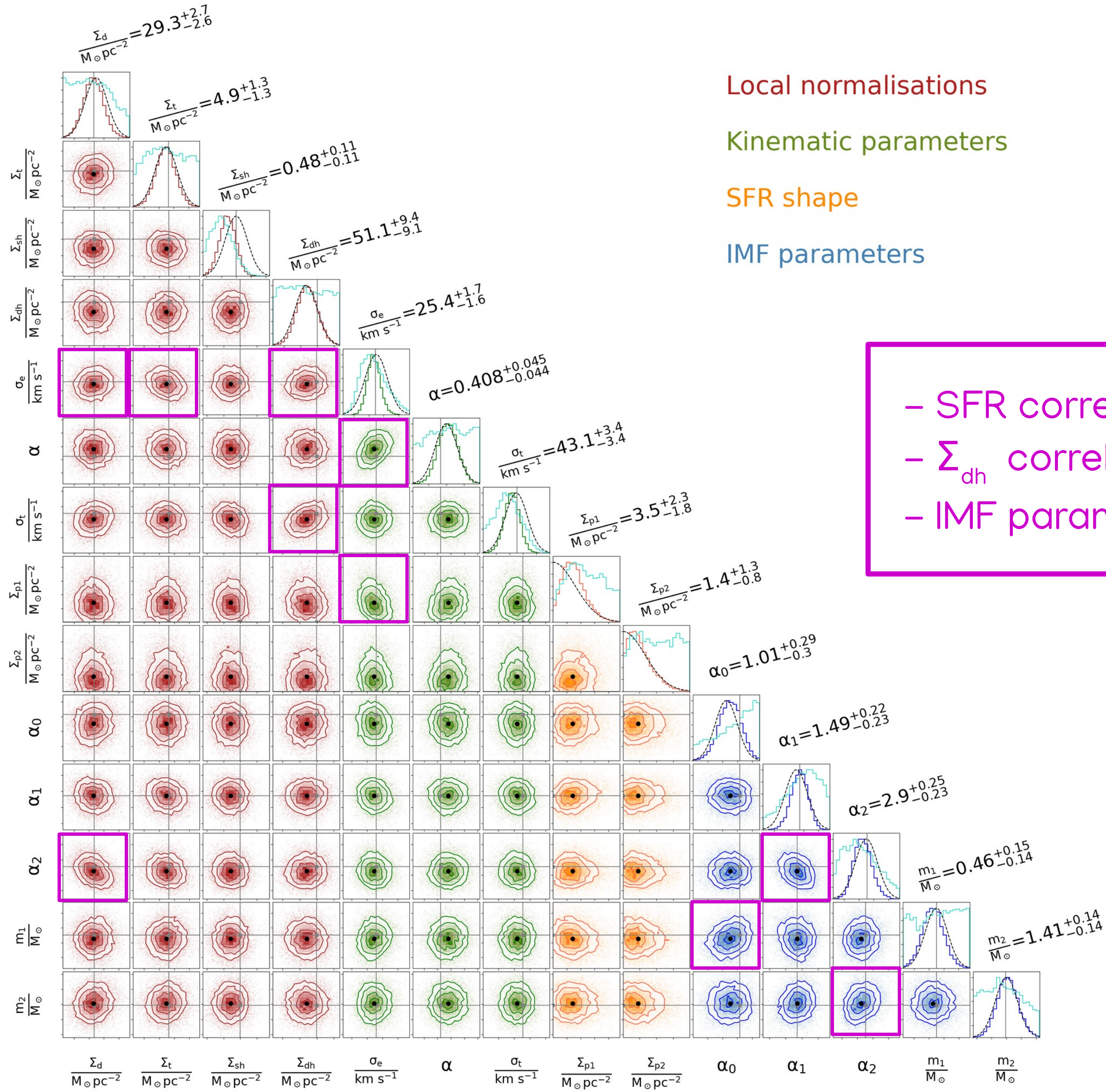
– Add stars of young ages (modification of SFR)

– Allow these extra stars to be more dynamically heated than expected from AVR

# JJ model calibration: density profiles



# Optimized parameters



Local normalisations

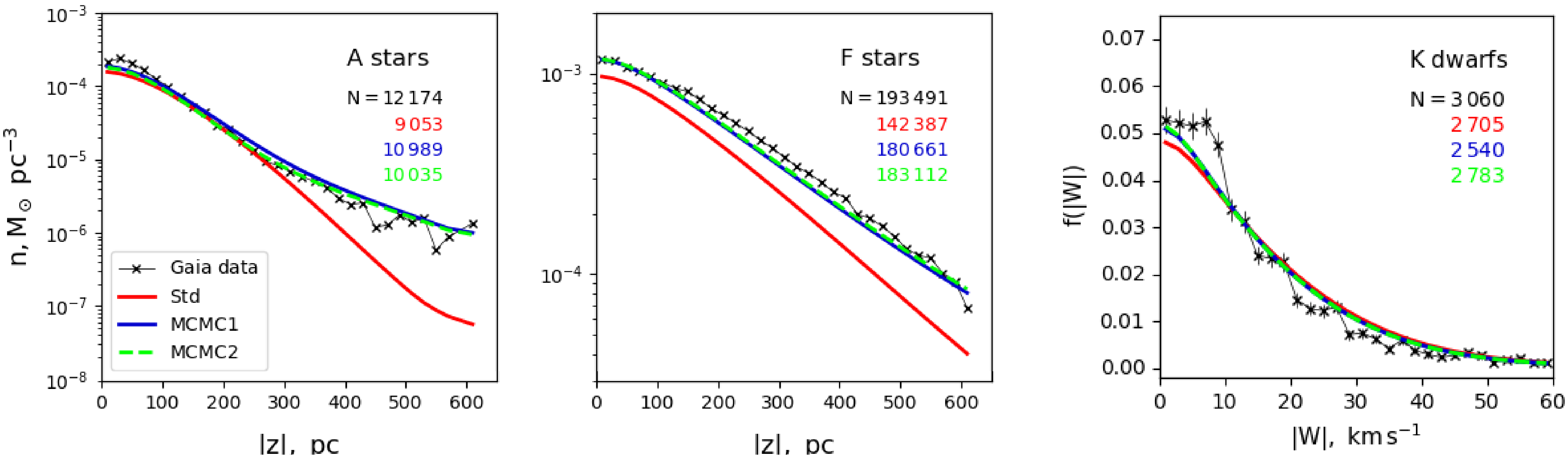
Kinematic parameters

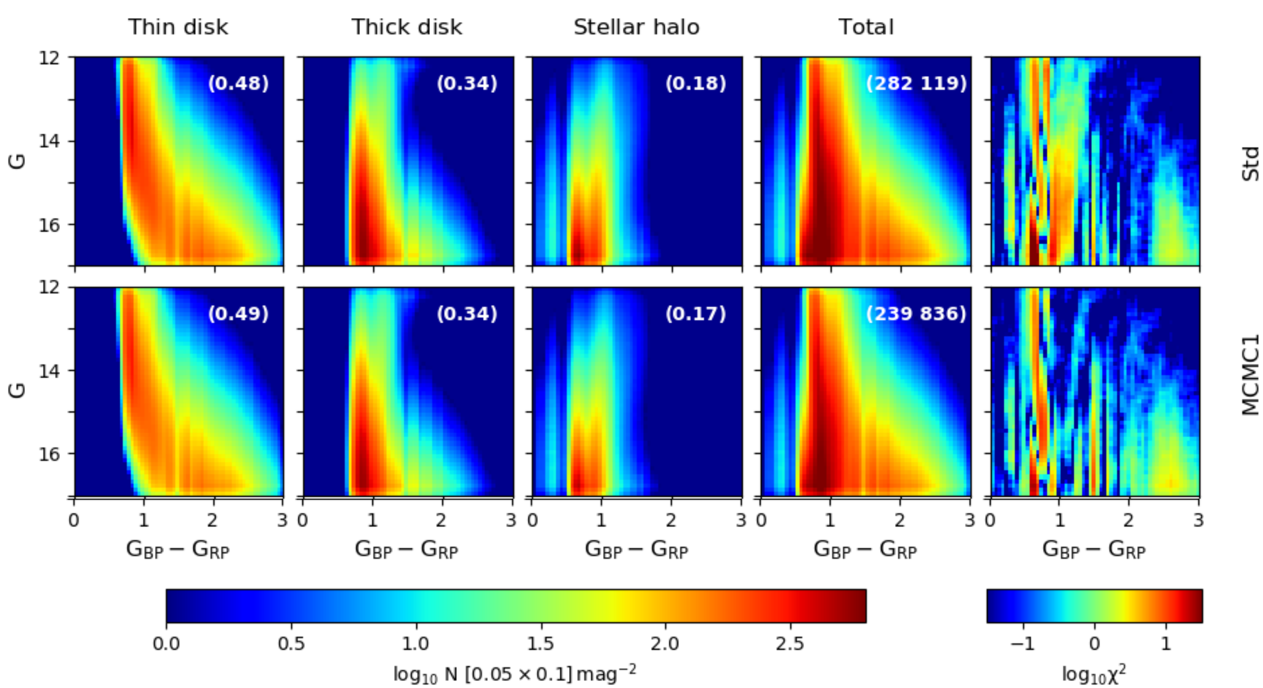
SFR shape

IMF parameters

- SFR correlates with both IMF & AVR
- $\Sigma_{dh}$ correlates with thick-disk kinematics
- IMF parameters are not independent

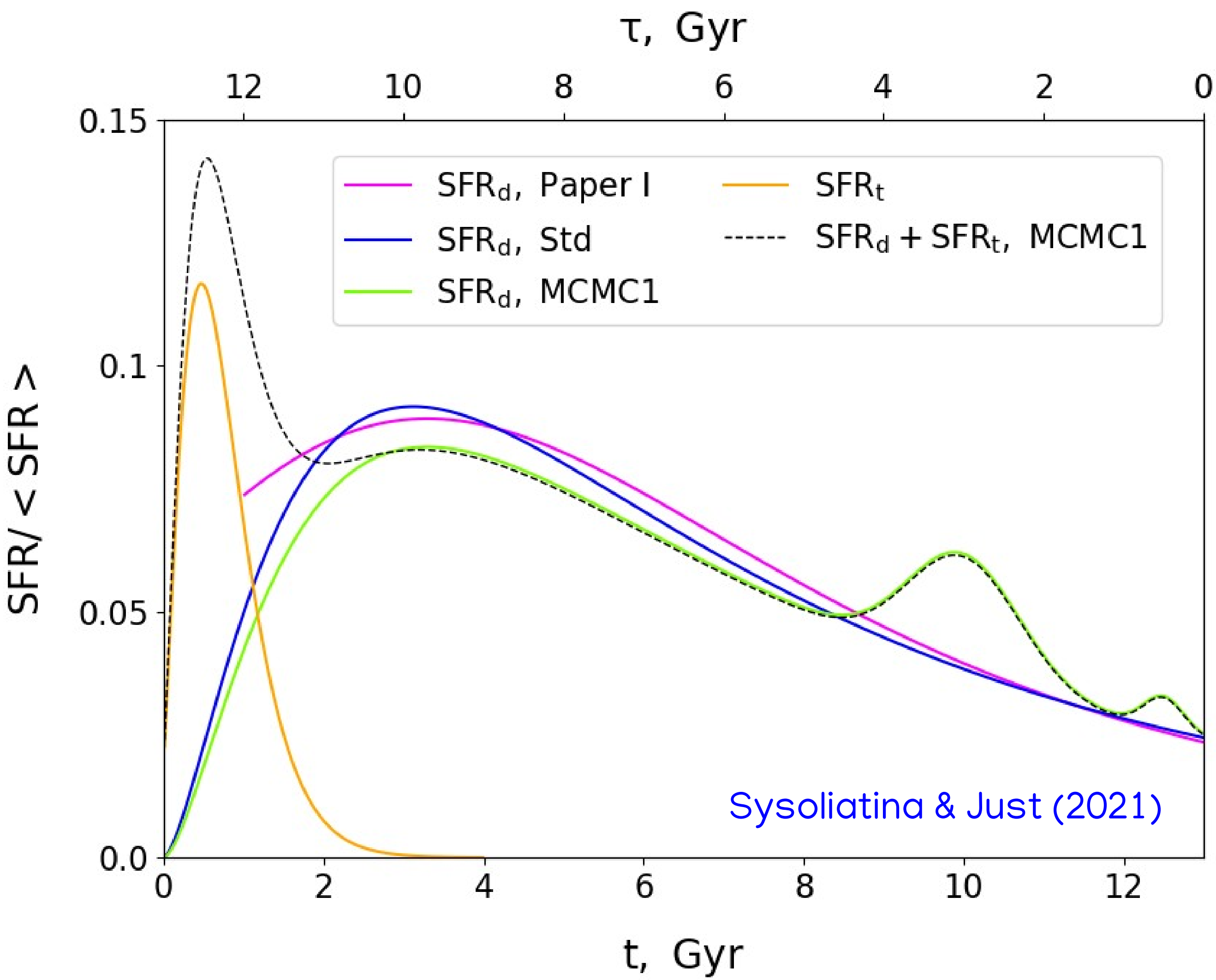
# JJ model calibration

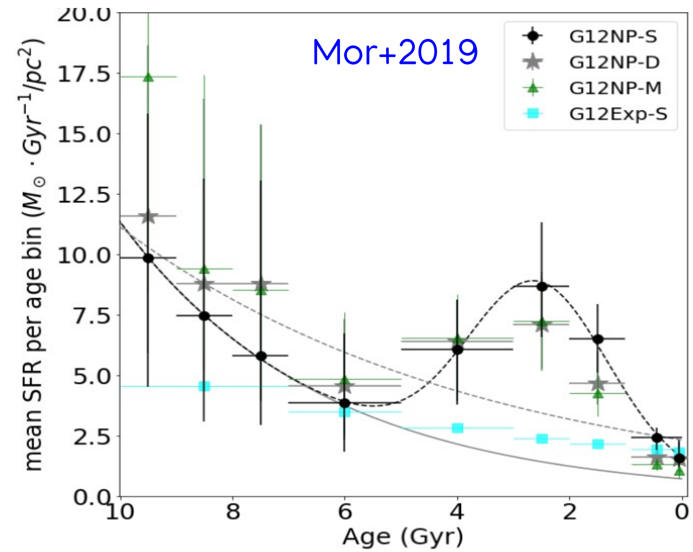



22 JJ model parameters optimized self-consistently with MCMC algorithm.

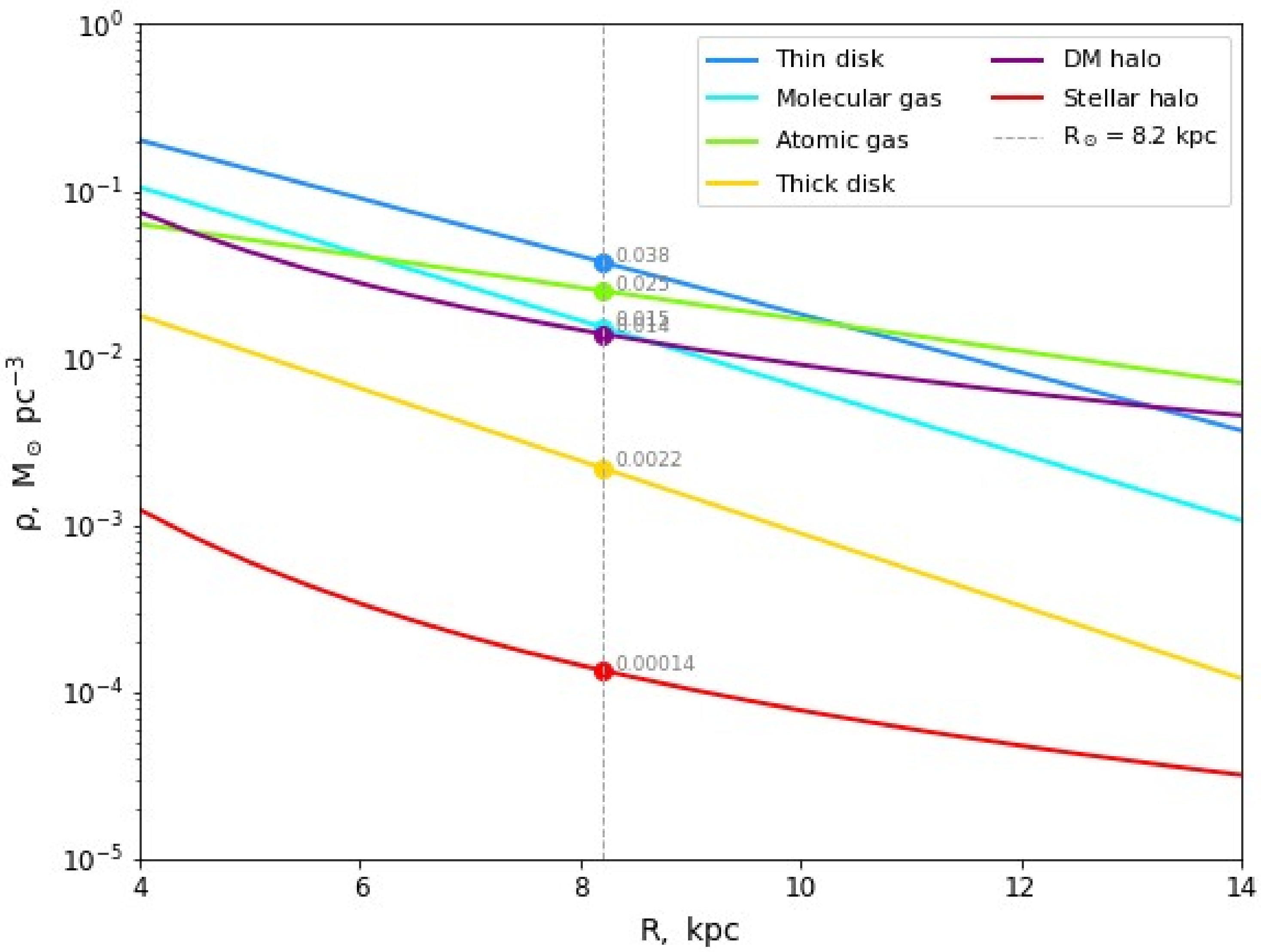
# Optimized SFR reveals recent SF bursts

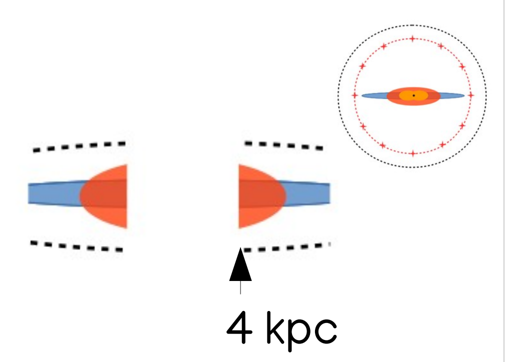


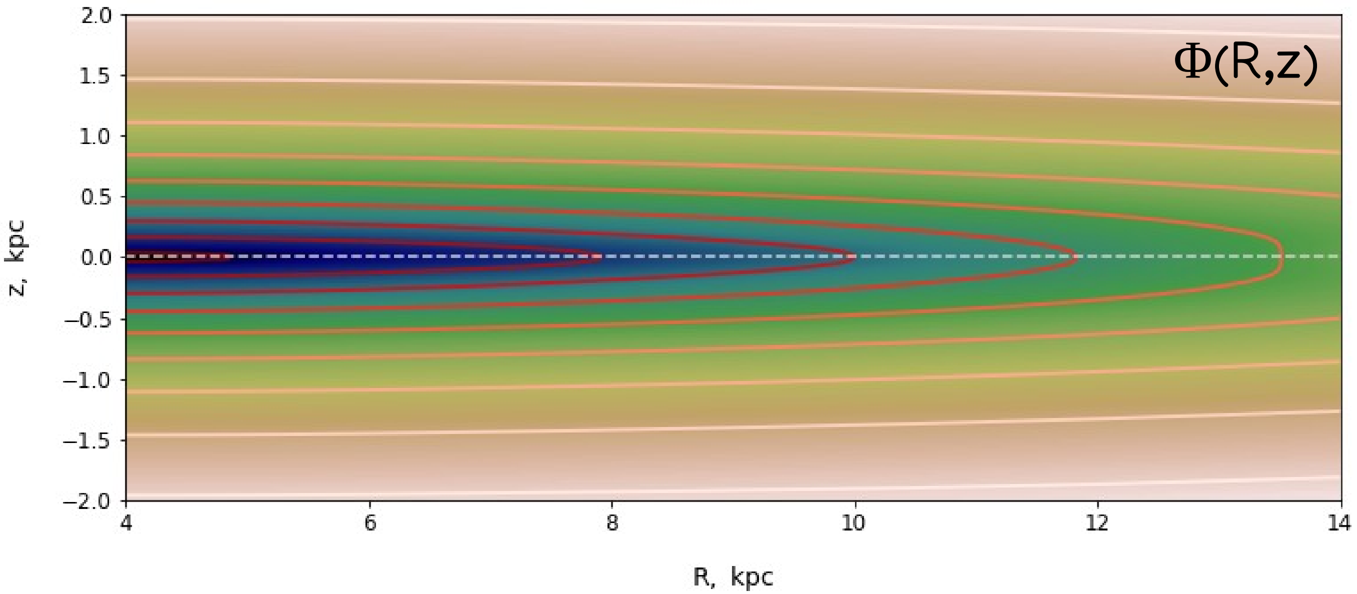

Global JJ model (R > 4 kpc)

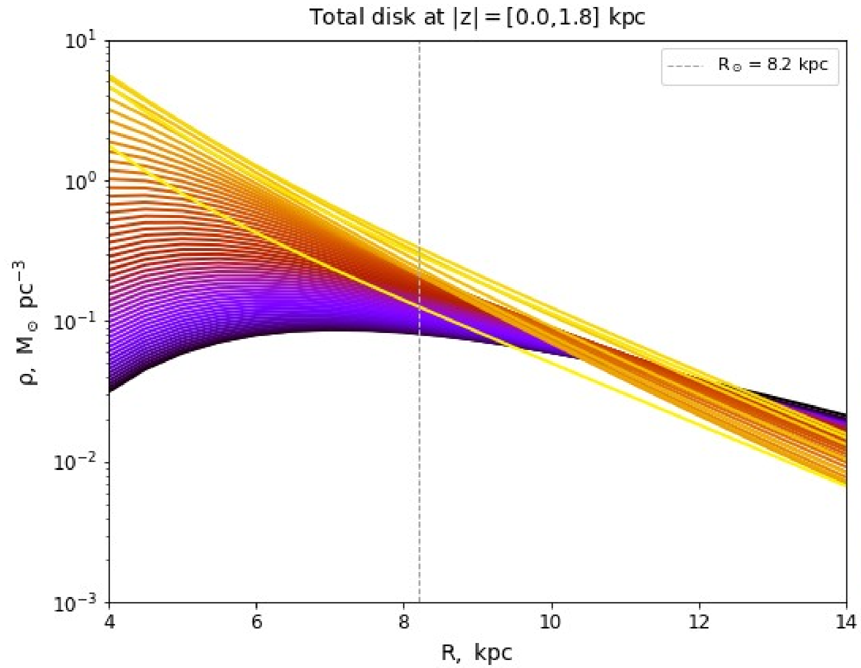
# Radial structure of the MW

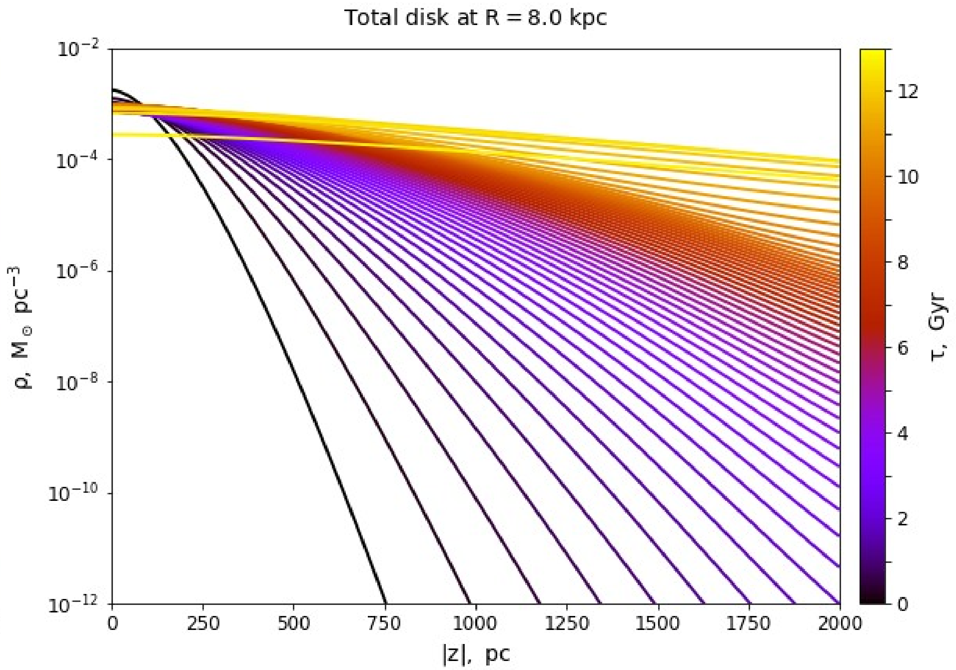


# Predicted potential and density

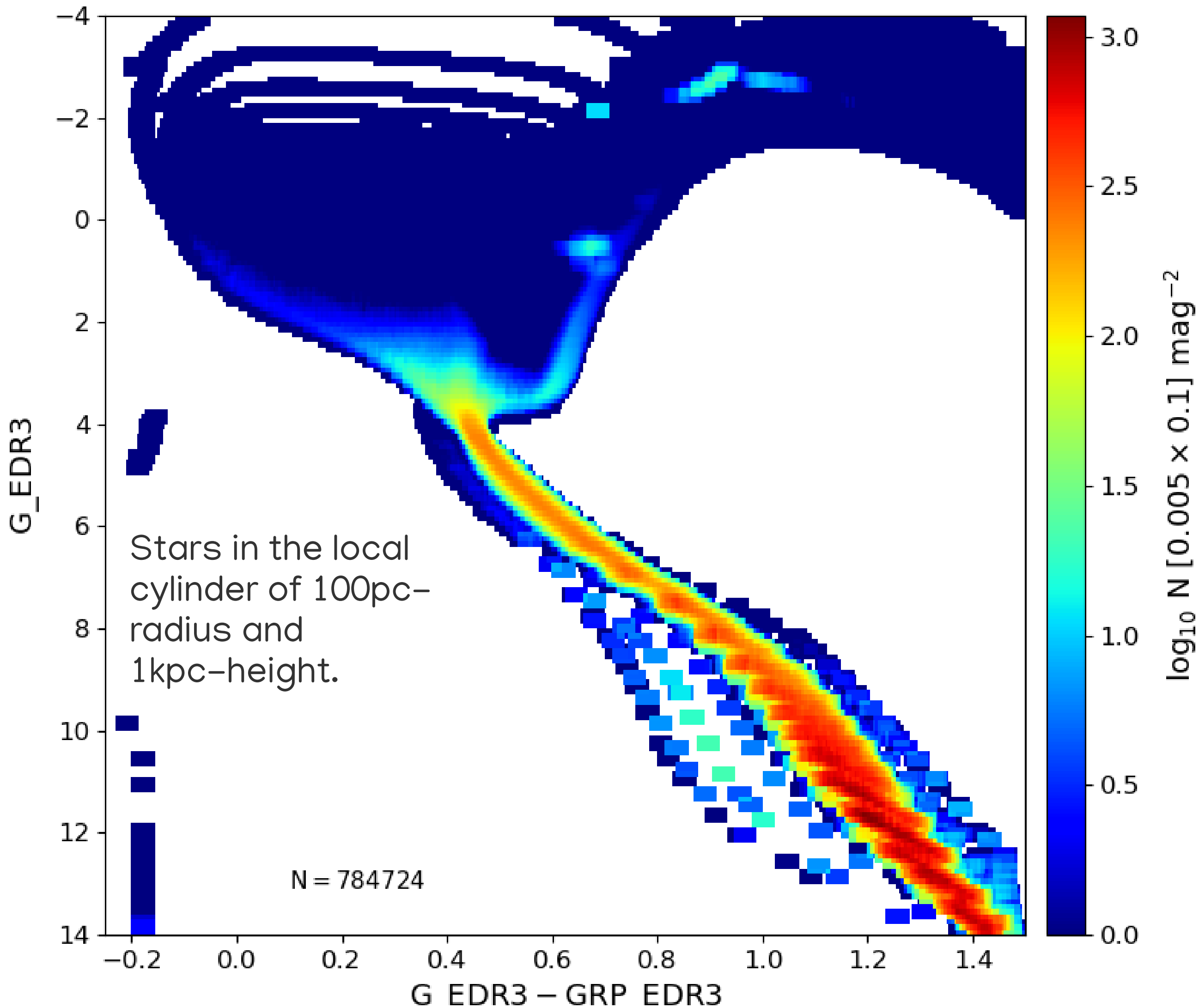


# Stellar population synthesis

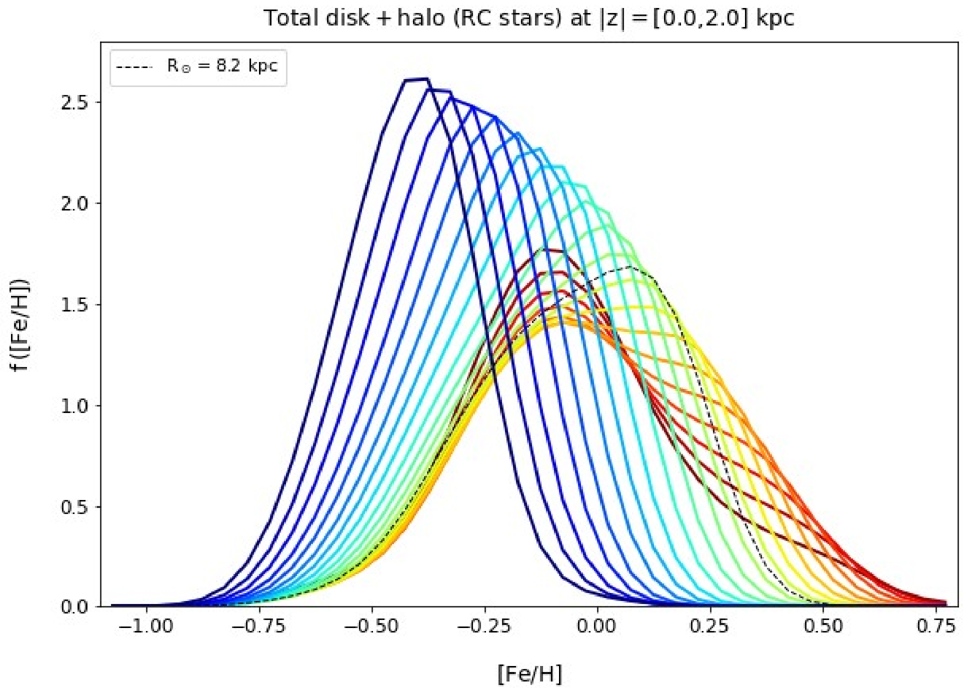
JJ model + Padova / MIST stellar evolution library = predicted CMD.

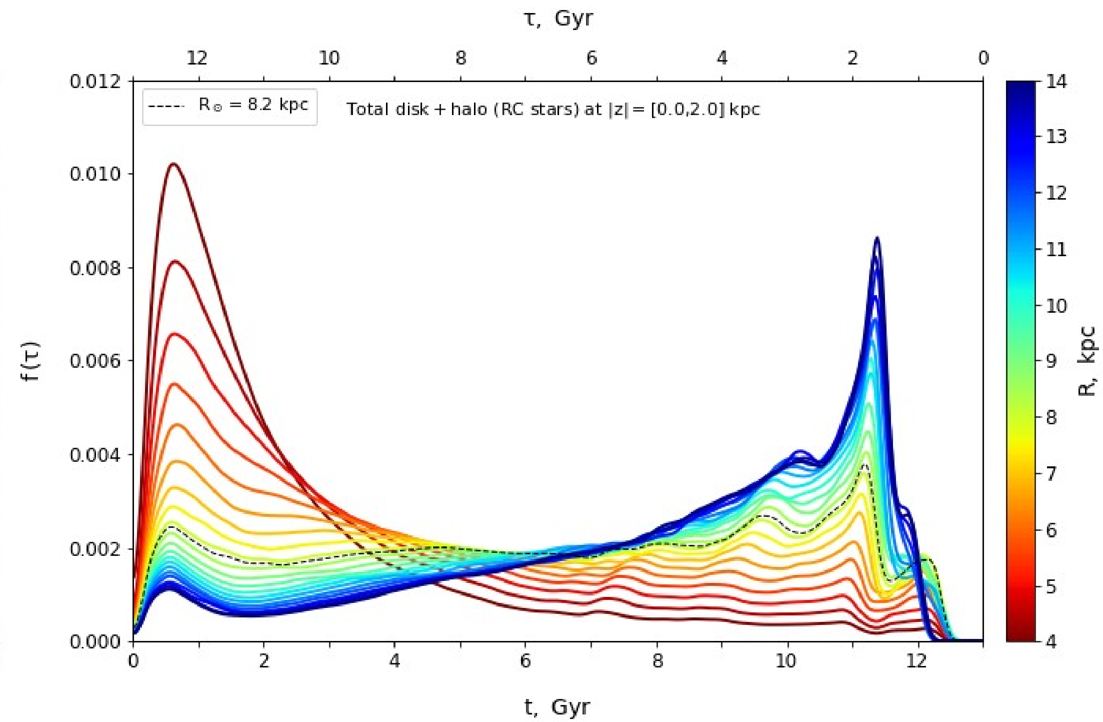


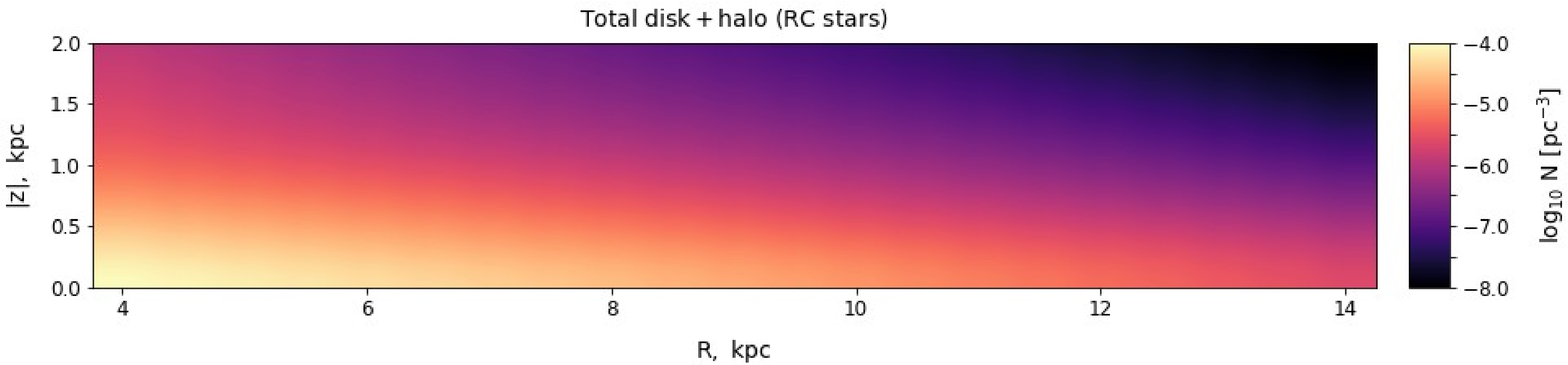

Available volume options:

- Solar-centered sphere
- Solar-centered cylinder
- R–φ–z "box"

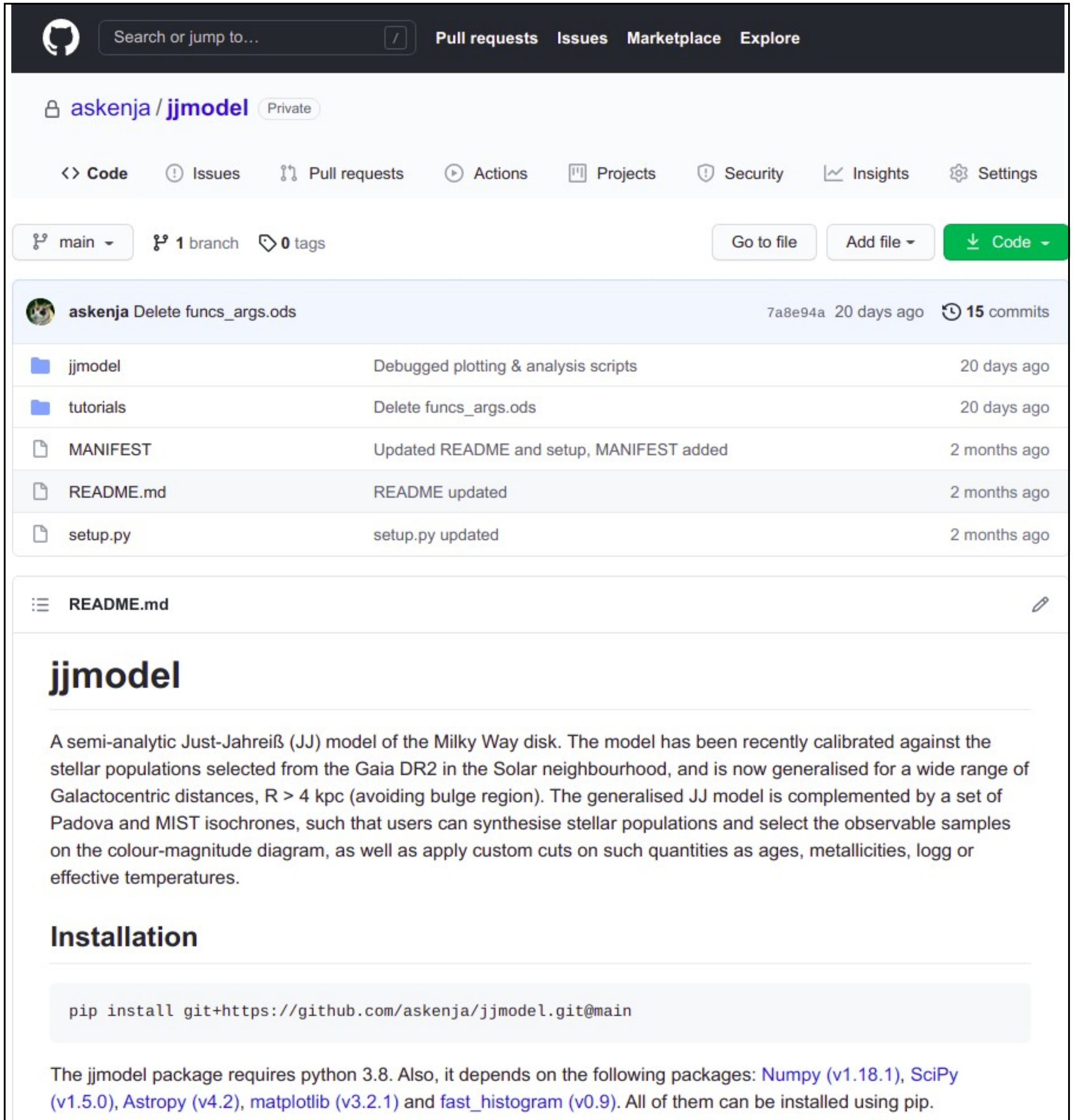
# Special populations (e.g. Red Clump)



# The JJ model code becomes public!




- Code (will be) available on github
- Published with the next paper on the global JJ model
- Installable as python package
- Tutorials available
- Isochrones provided separately
- I'm open for user feedback, questions, suggestions, bug reports, etc...

# Conclusions

- SAMs built on the basic principles of stellar dynamics can give a realistic description of the present-day state of the Galaxy.
- The abundant data from astrometric, spectroscopic and photometric large-scale Galactic surveys provide constraints on many SAMs' parameters.
- **By constraining SAMs' parameters at the different radii, we can reconstruct the MW evolution history.**
- JJ model provides a detailed insight into the vertical structure of the MW disk. It is complemented with a stellar evolution library, and therefore, can be used for studying the observable stellar samples.
- Recently, **the JJ model has been calibrated against the Gaia DR2 data** in the Solar neighbourhood; 22 model parameters were self-consistently optimized. **The new thin-disk SFR reveals two episodes of the recent SF enhancement which may point to the recent gas infall.**
- **The python code of the JJ model becomes public this year!**

Thank you for your attention!