Preliminary comparisons between a Galaxy model and Gaia DR1

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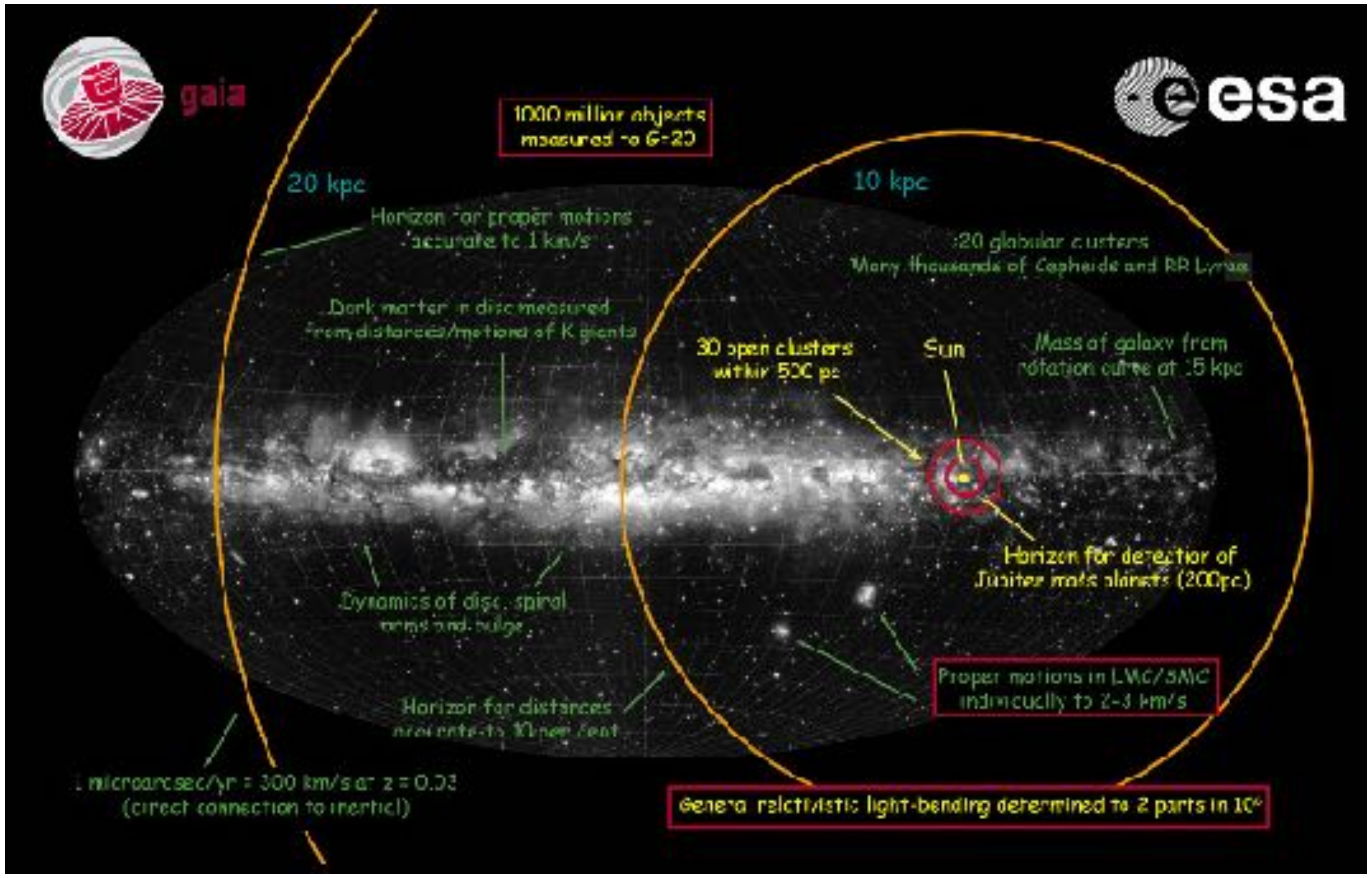
Outline

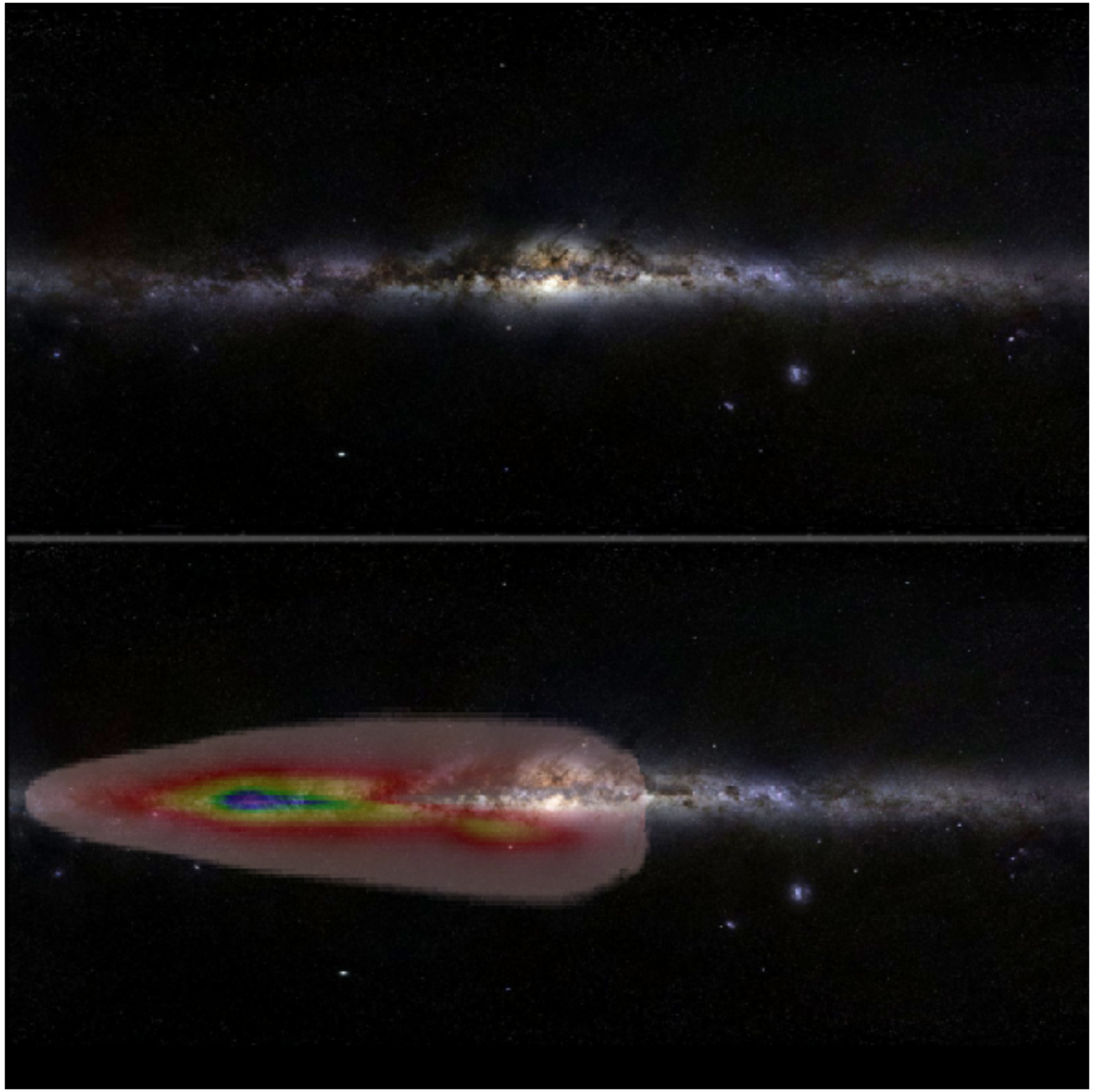
- Introduction
- Population synthesis approach
- Preliminary star count comparisons : DR1 tests for completeness
- RAVE+TGAS synergy: Constraints on the disc kinematics
- Perspectives

Gaia

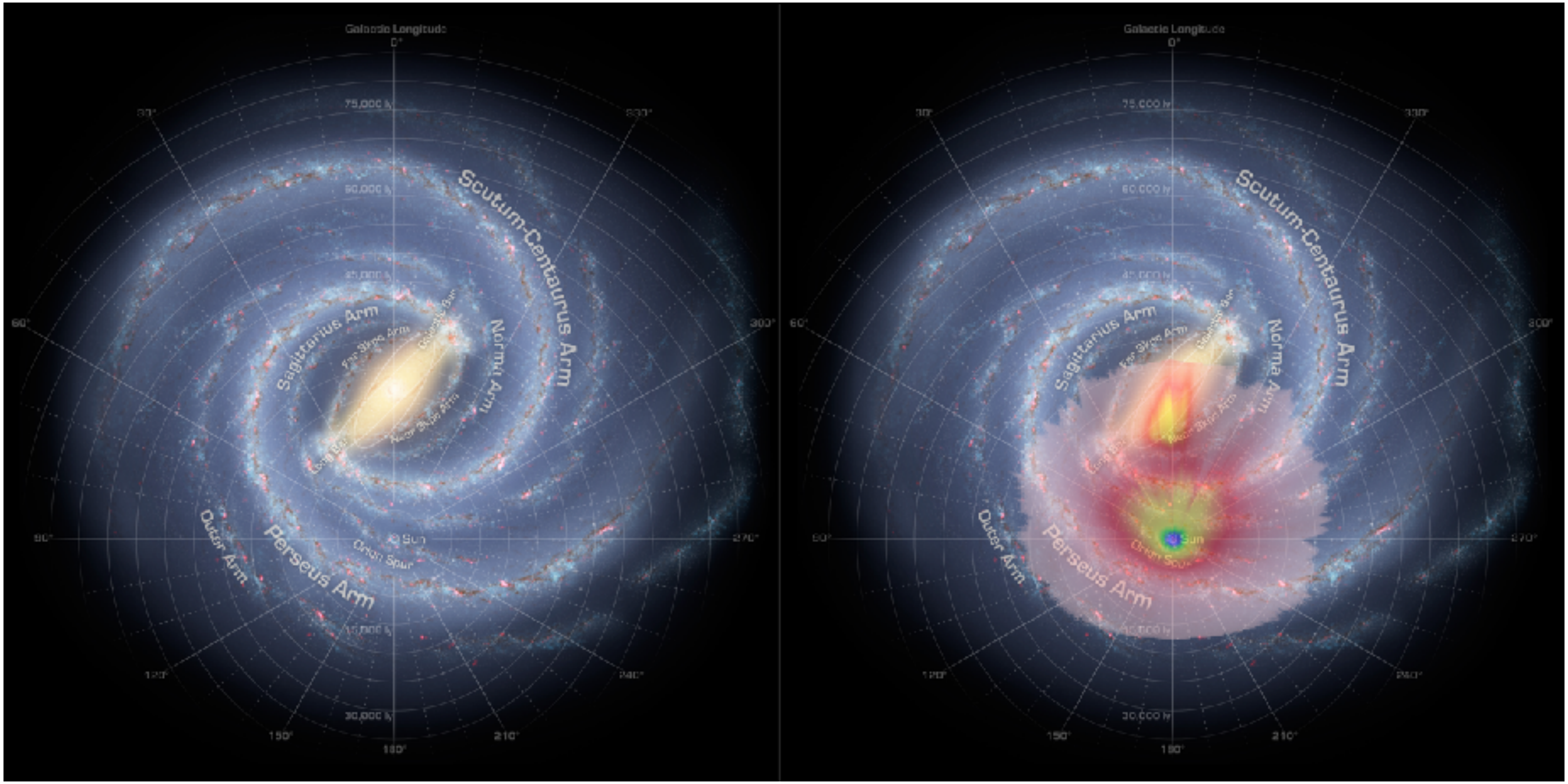


- Revisiting our understanding of Galaxy formation and evolution
- 6D space explored for hundreds of million stars, 4D for 2 billion stars

Gaia challenge : Find efficient methods to analyse and interpret data in terms of Galaxy evolution & dynamics



- Estimates for the density of detected stars (GUMS10)



- artiste’s view of the MW from top
- => Gaia will revolutionize this view (at least for a quarter of the Galactic plane)

Population Synthesis Modelling

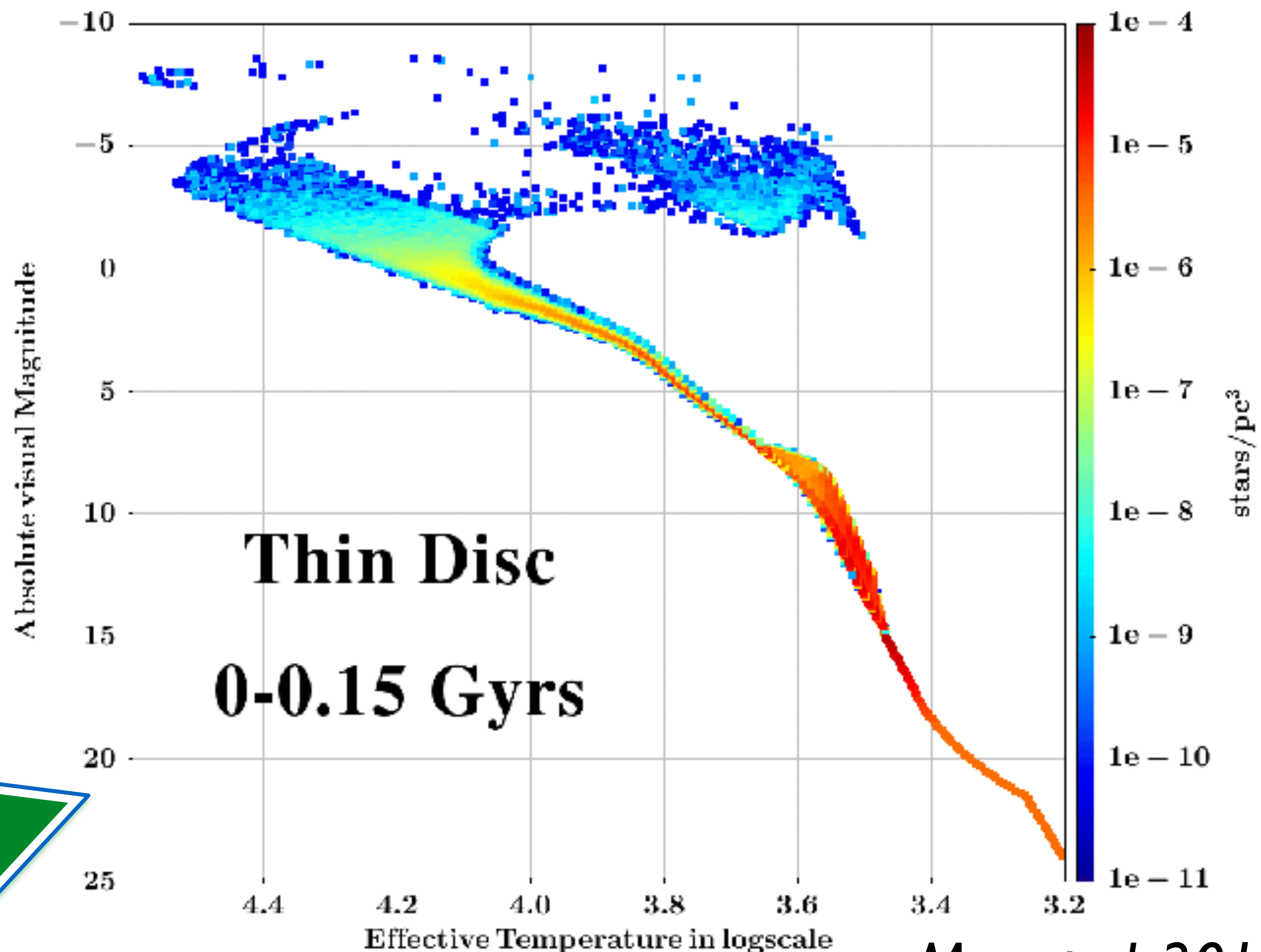
- Population synthesis approach: many parameters but **more understanding**
- **Statistical treatment** : no individual distances and ages, but for groups of stars
- Link between **scenarios** and **observations**
- **Increasing** complexity (start simple…)
- **Confronted to many observables** : magnitudes, colors (many bands), proper motions, radial velocities, Teff, logg, [Fe/H],[alpha/Fe], asterosismic paramaters in the future

New Besançon Galaxy model

Czekaj et al, 2014
Robin et al, 2014
Bienaymé et al 2015
Lagarde et al 2017

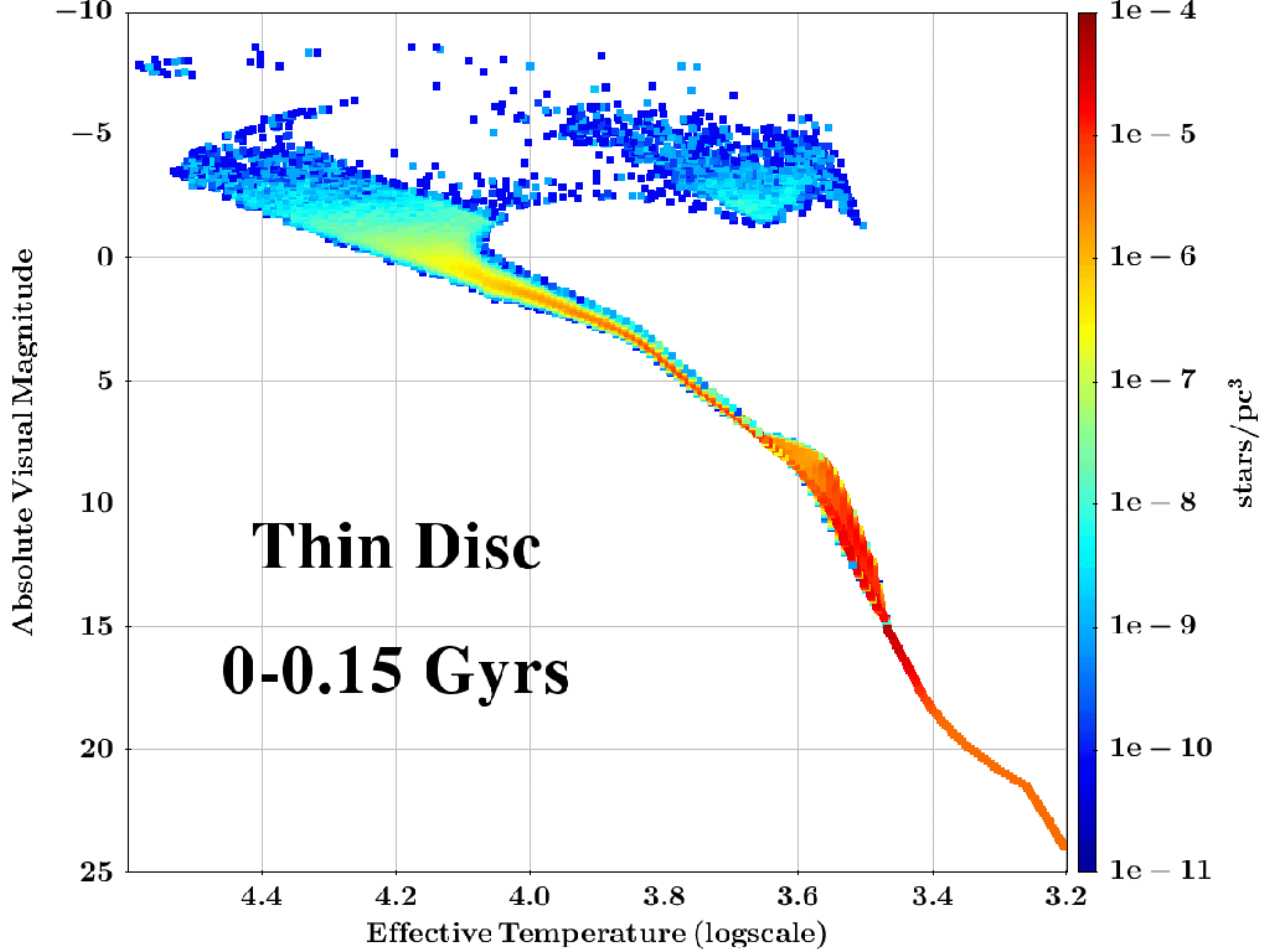
Binarity included

φ(Teff, logg) for a thin disc decreasing SFR over 10 Gyr

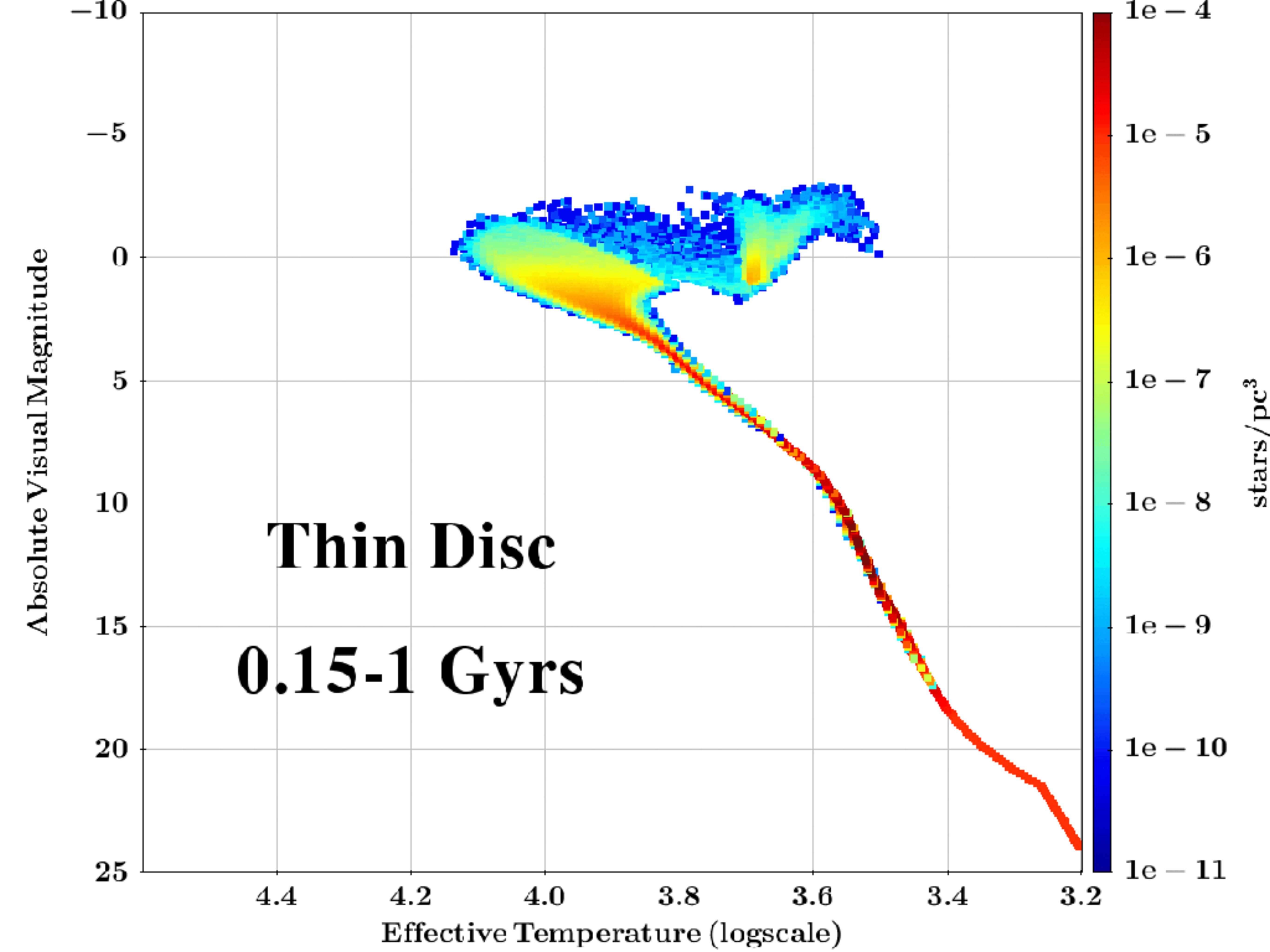


Mor et al, 2016

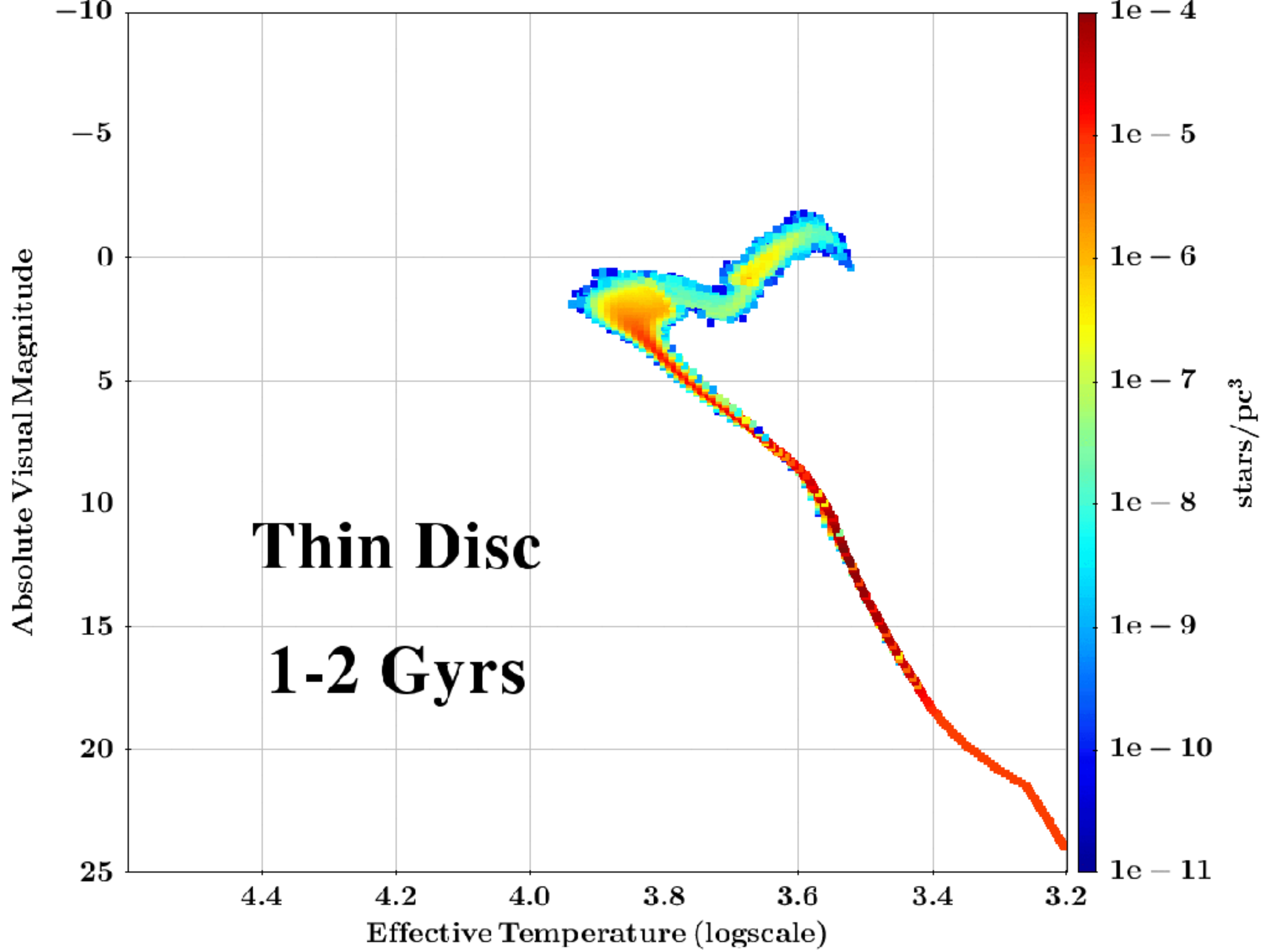
3D Extinction model (Mashall et al, 2006)



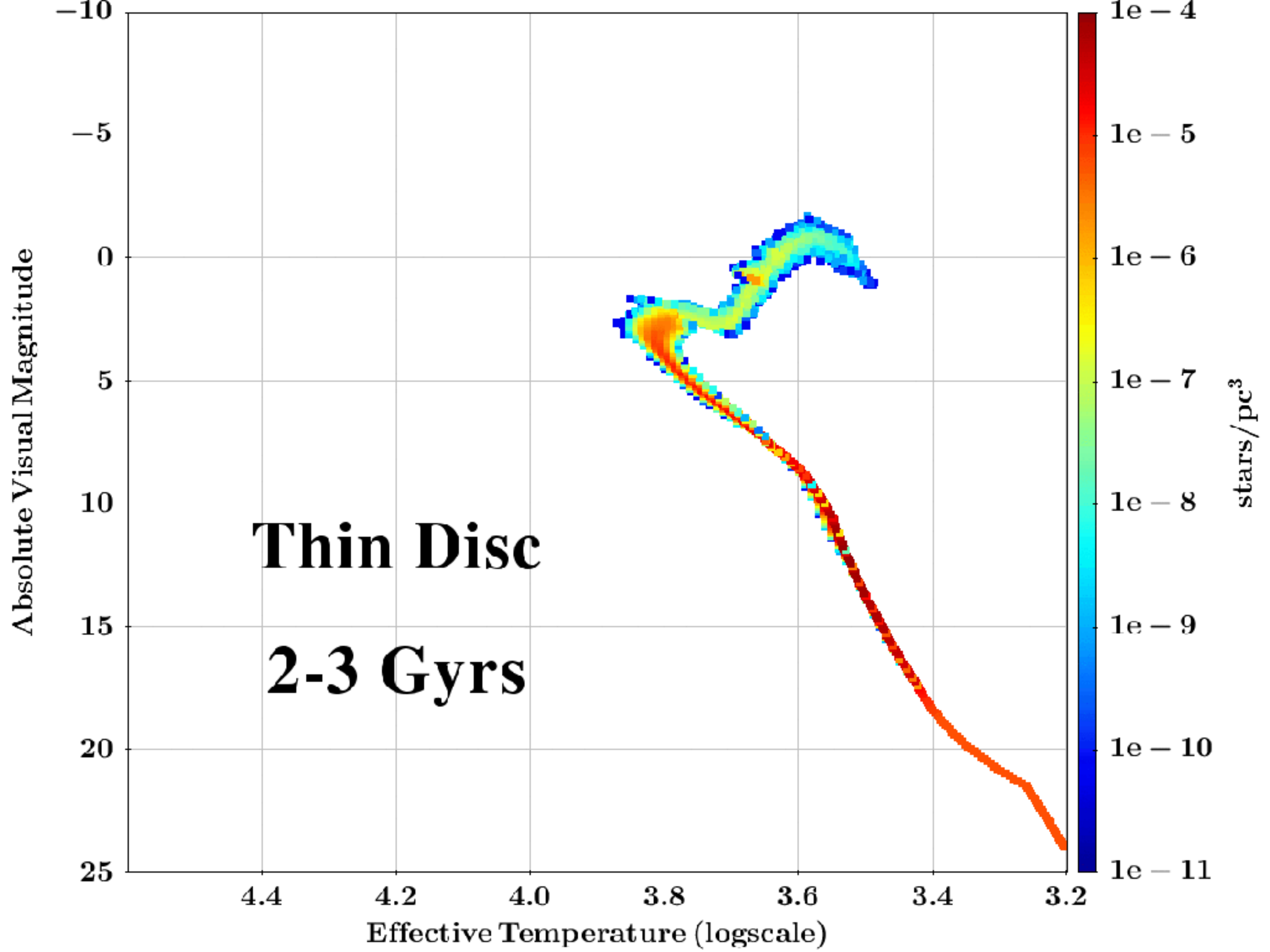
Thin Disc
0-0.15 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc^3
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11



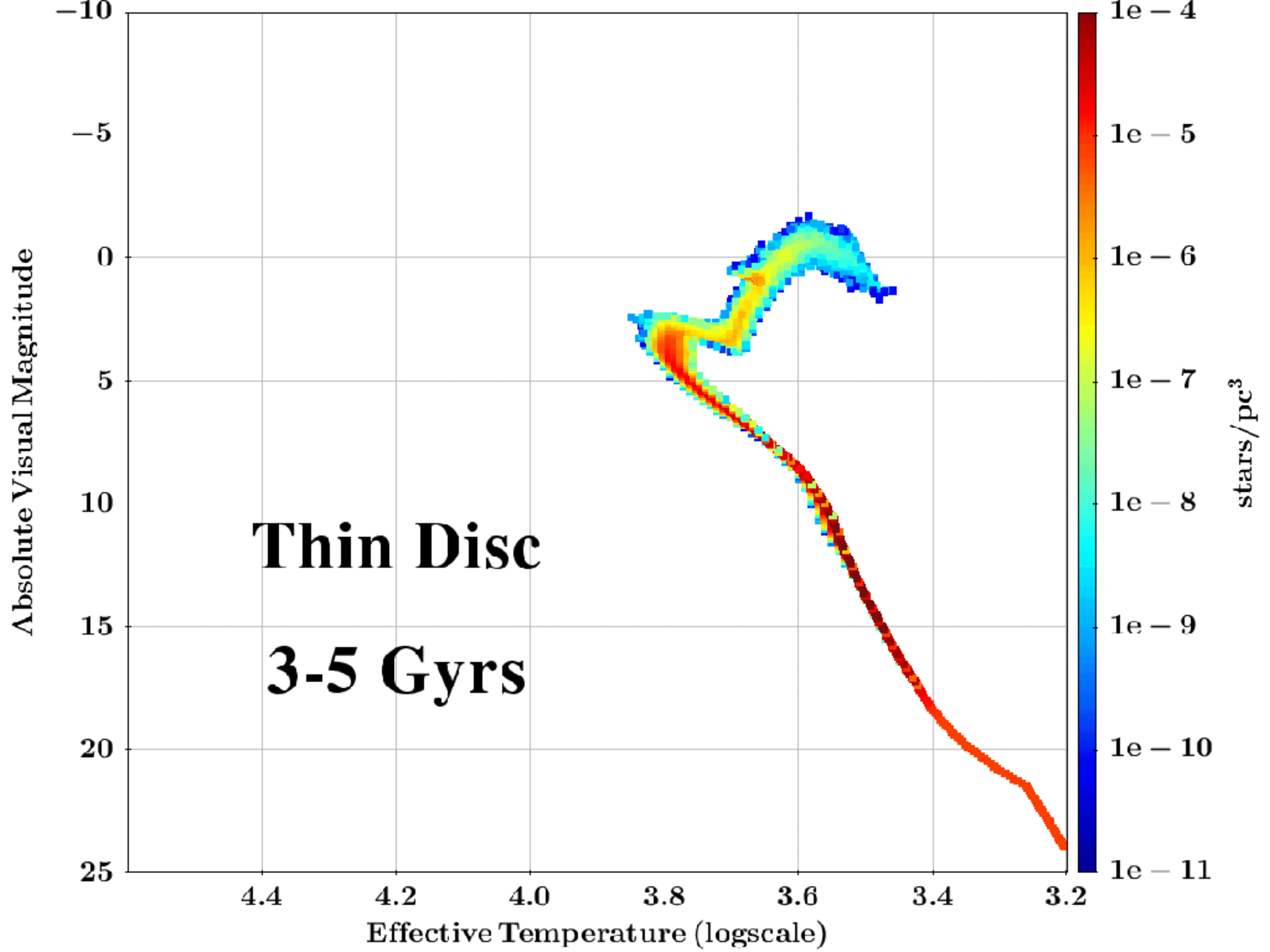
Thin Disc
0.15-1 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc^3
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11



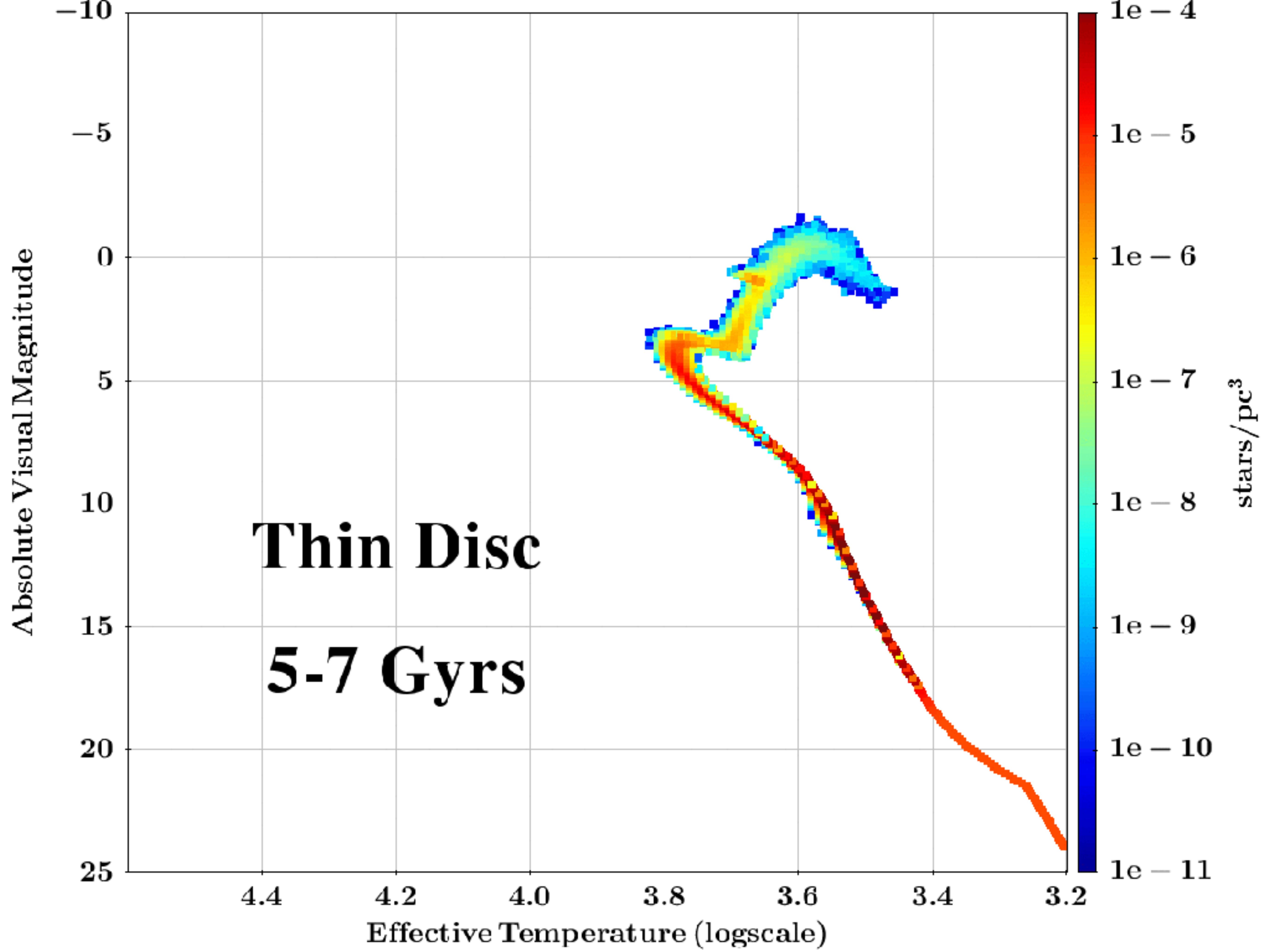
Absolute Visual Magnitude
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
Effective Temperature (logscale)
Thin Disc
1-2 Gyrs
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11
stars/pc³

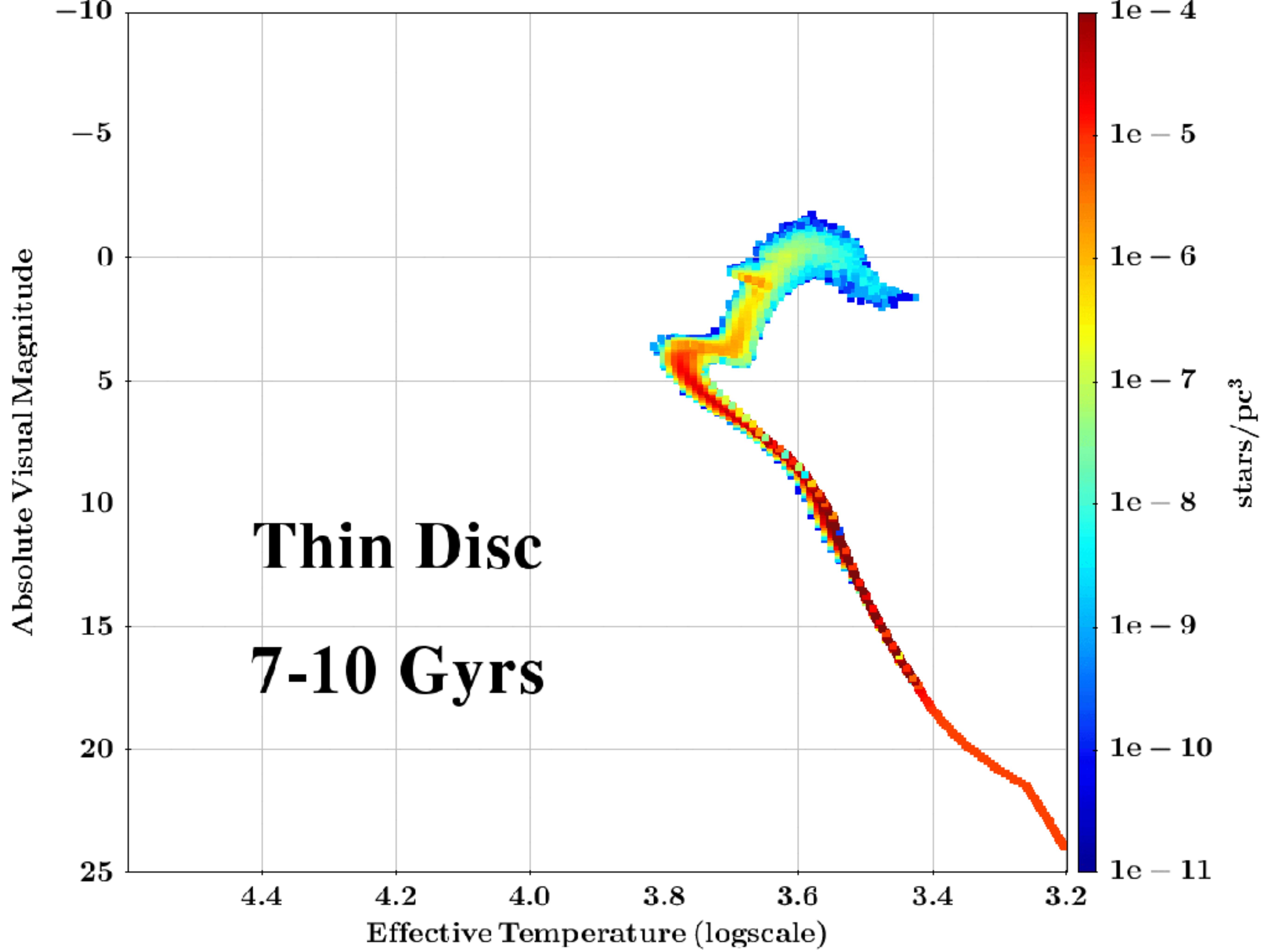


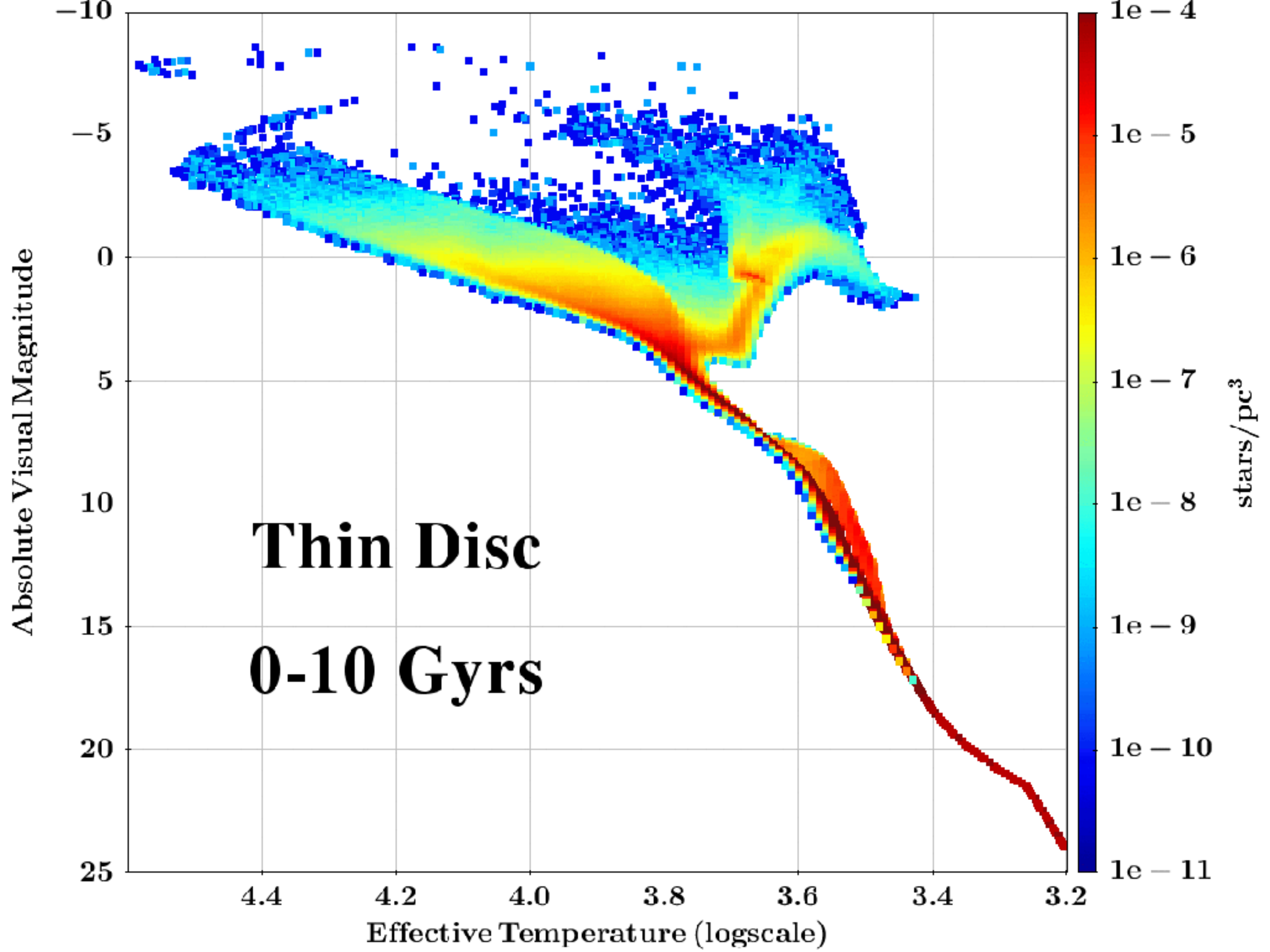
Thin Disc
2-3 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc^3
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11



Thin Disc
3-5 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc³
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11

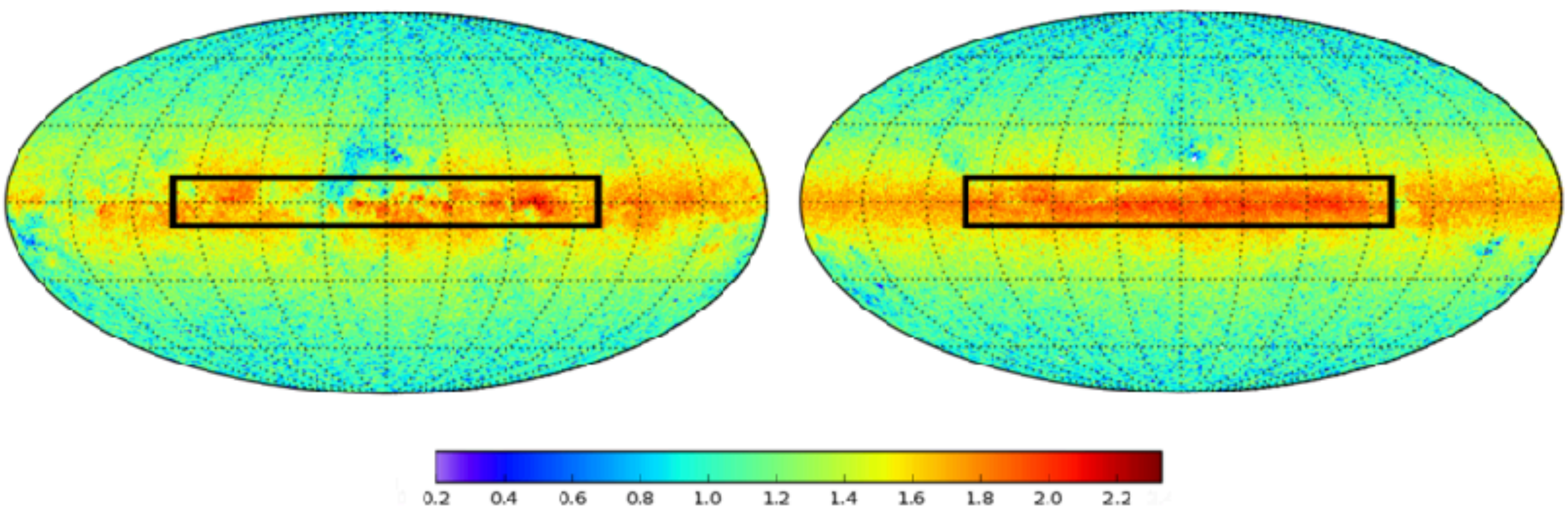

Thin Disc
5-7 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc^3
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11


Thin Disc
7-10 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc^3
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11


Thin Disc
0-10 Gyrs
Absolute Visual Magnitude
Effective Temperature (logscale)
stars/pc³
−10
−5
0
5
10
15
20
25
4.4
4.2
4.0
3.8
3.6
3.4
3.2
1e − 4
1e − 5
1e − 6
1e − 7
1e − 8
1e − 9
1e − 10
1e − 11

Comparison to bright star counts

Tycho-2: $V_T < 11.5$ BGM



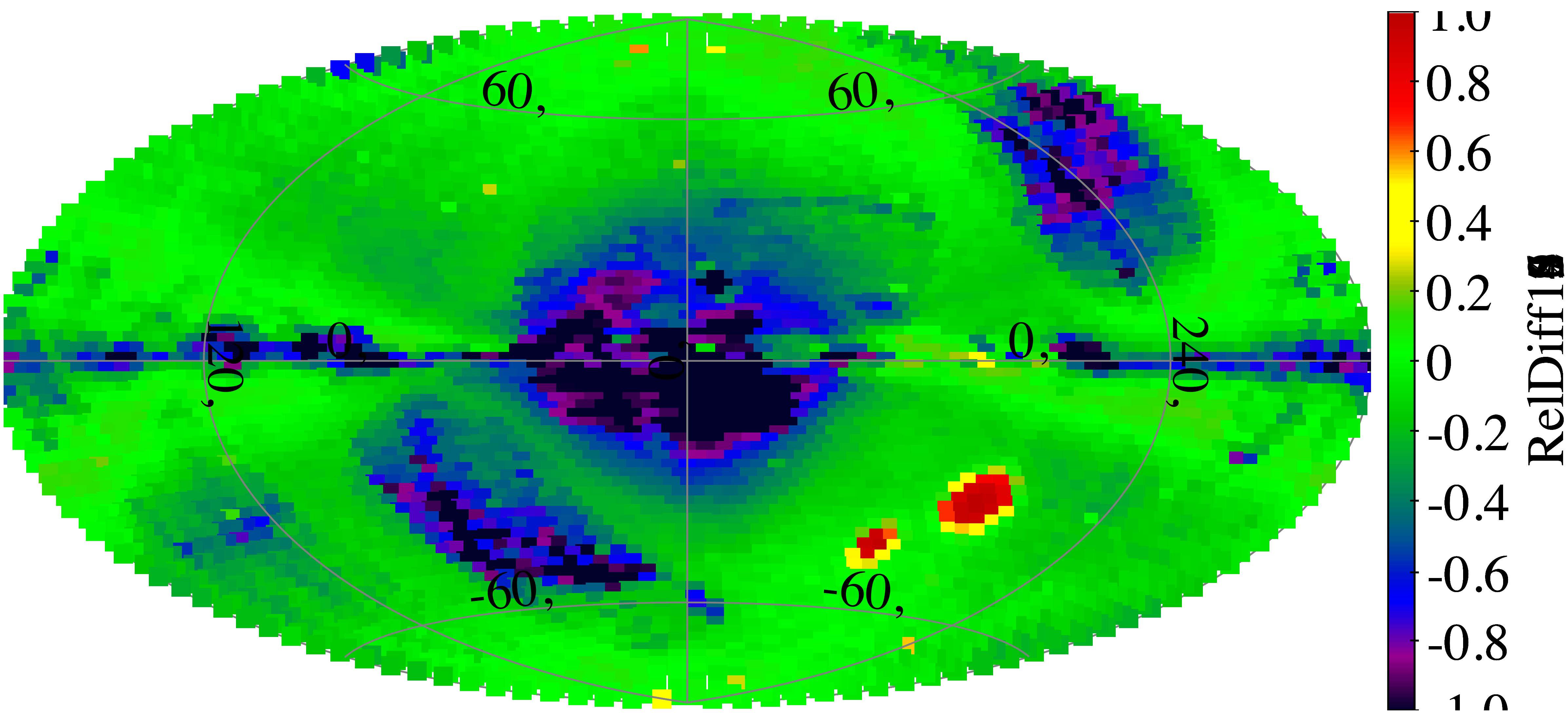
Mor et al, 2016

=> Good at |b|>10°

But Need for a better extinction model (low distances) at |b|<10°

Comparisons with DR1

Relative differences between Gaia-DR1 and BGM (GOG18)
in magnitude bins



12<G<13 13<G<14 14<G<15 15<G<16 16<G<17 17<G<18 18<G<19 19<G<20

Tests for completeness

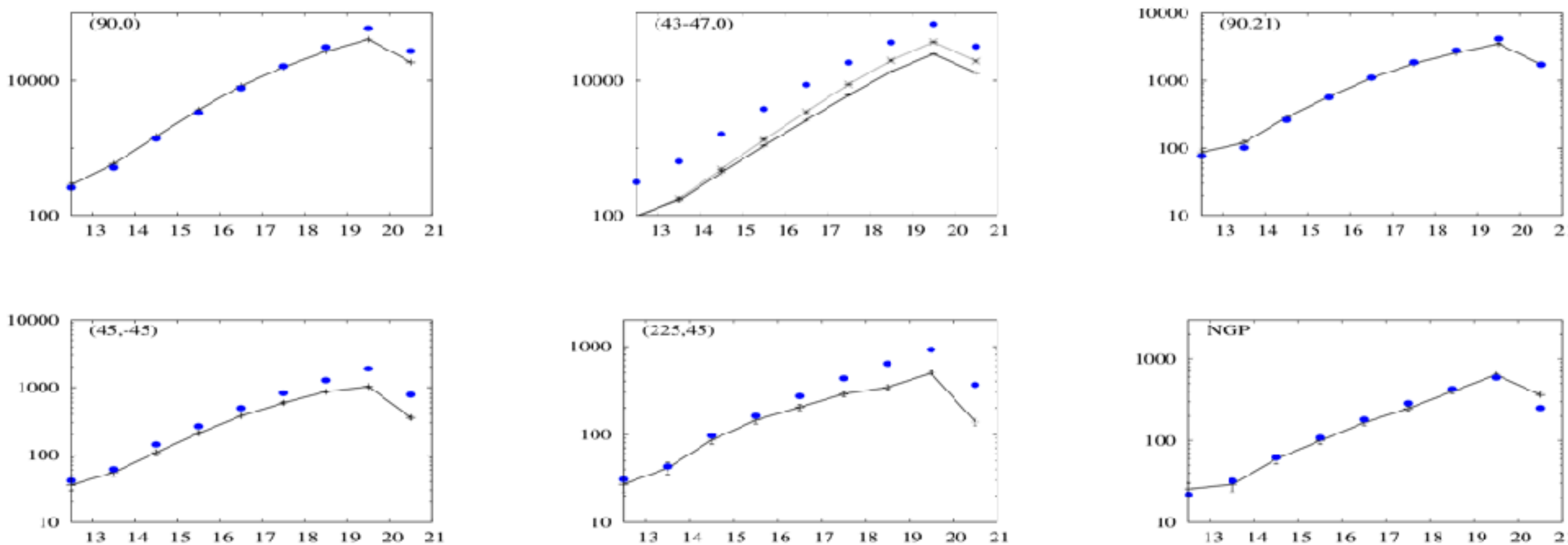
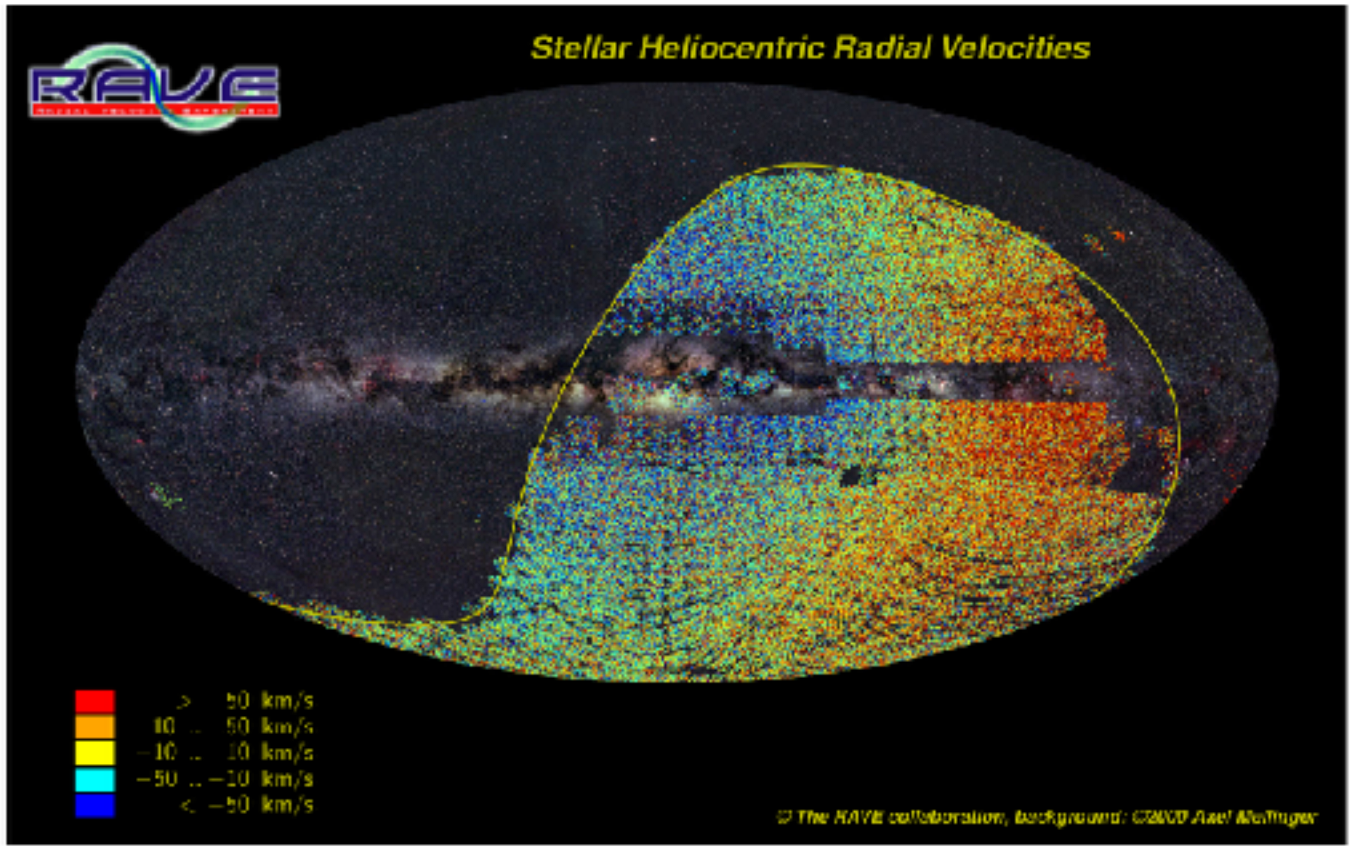


Fig. 9. Star counts per square degree as a function of magnitude in several (l, b) directions. Crosses linked with lines are for *Gaia* DR1 data, filled blue circles are simulations from GOG18. Error bars represent the Poisson noise for one square degree field. The *bottom* row shows two regions impacted by the scanning law and the filtering of stars with a low number of observations.

Arenou et al, 2017, A&A 599, A50

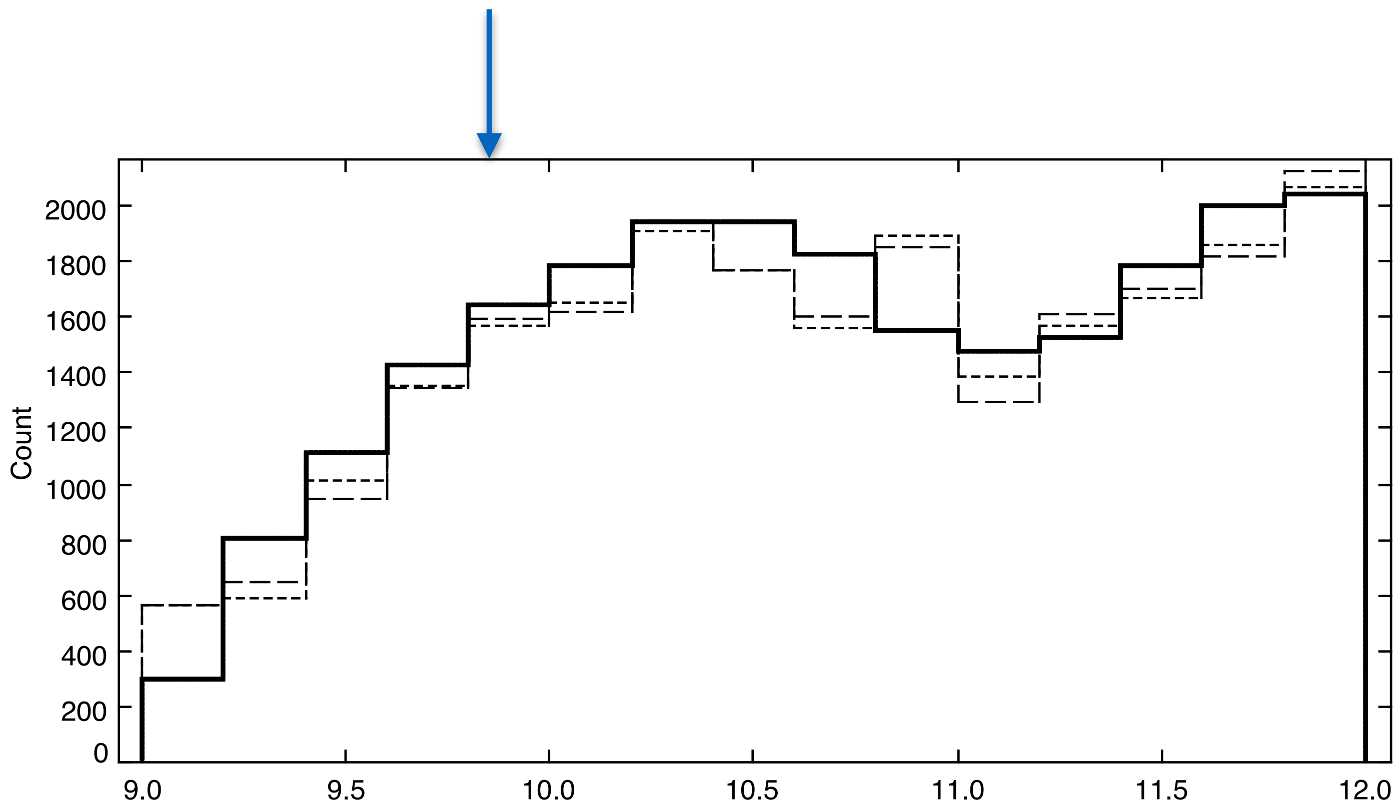
Disc kinematics: RAVE + TGAS



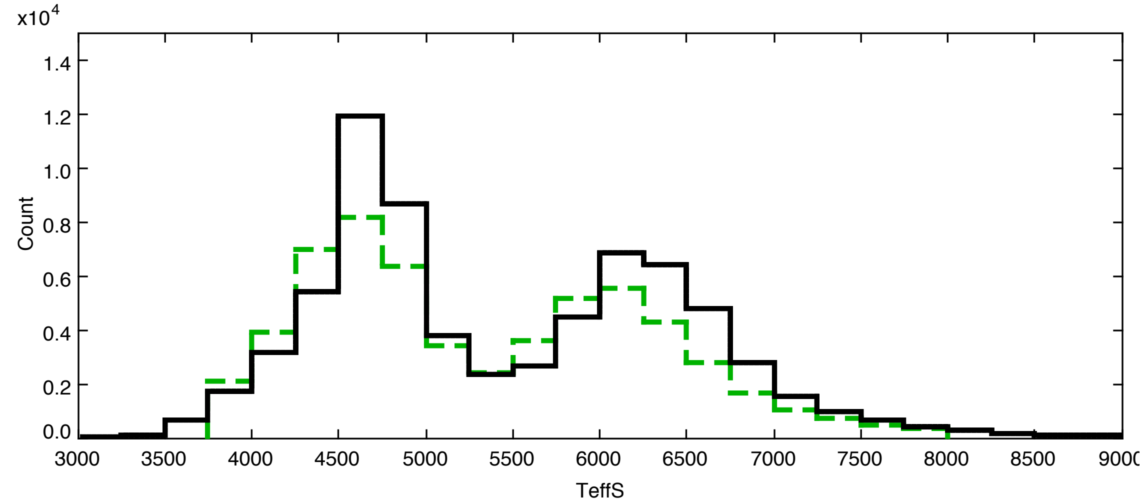
- Complementarity betwee
(TGAS): radial velocities
- RAVE based on Tycho-2 :
- TGAS p.m. 1st epoch fror
- RAVE simple selection function (random subsets)
- However TGAS incomplete at V_T>10.5

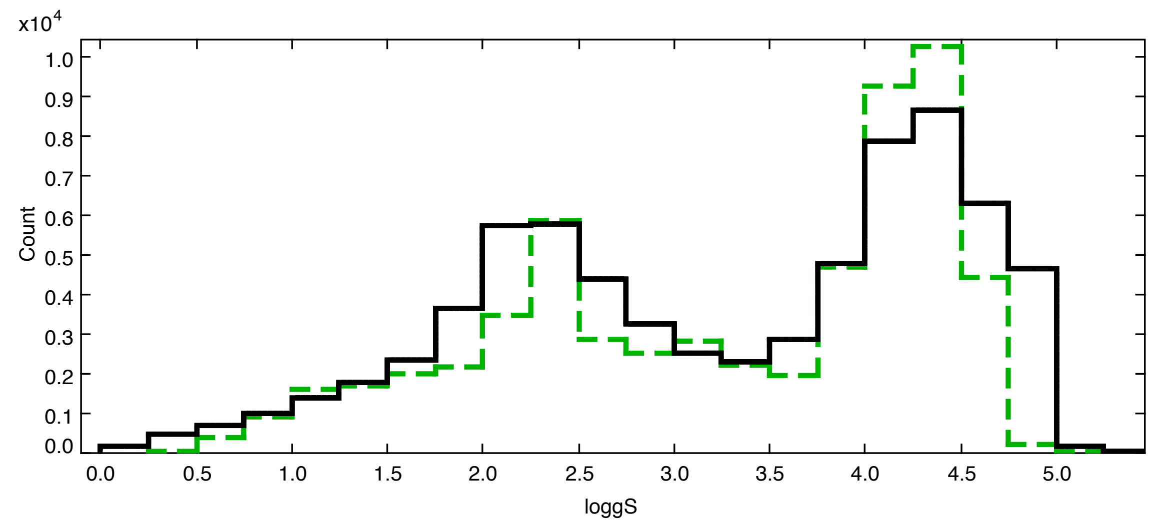
RAVE selection test

- BGM simulation applying RAVE selection function on I magnitude



Resulting Teff / logg





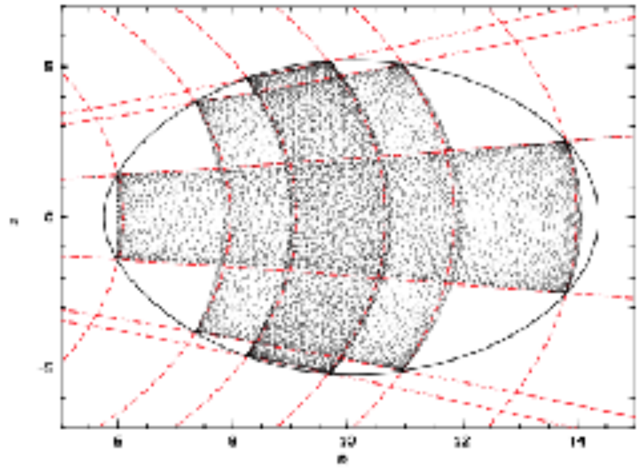
Galactic dynamics

Bienaymé et al 2015

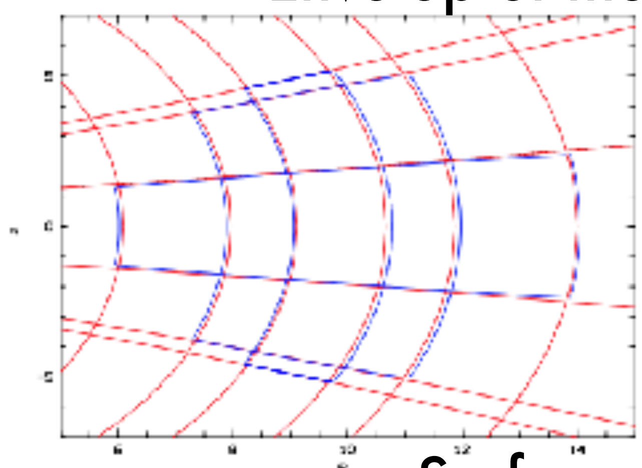
- To obtain self-consistent distribution functions : Determine third integral of motion.
- Approximate potential of the BGM with a Stäckel potential=> Fitting orbits to obtain the Stäckel parameters => 3rd integral
- Compute potential, vertical and radial forces self-consistently
- Describe the asymmetric drift as a function of Rgal, Zgal

Bienaymé et al 2015

Meridional projection of 3 orbits



Envelop of the orbits (analytical)



Surfaces of section

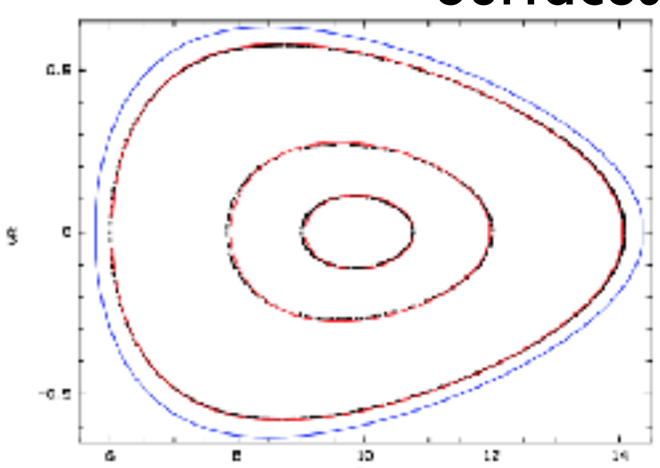
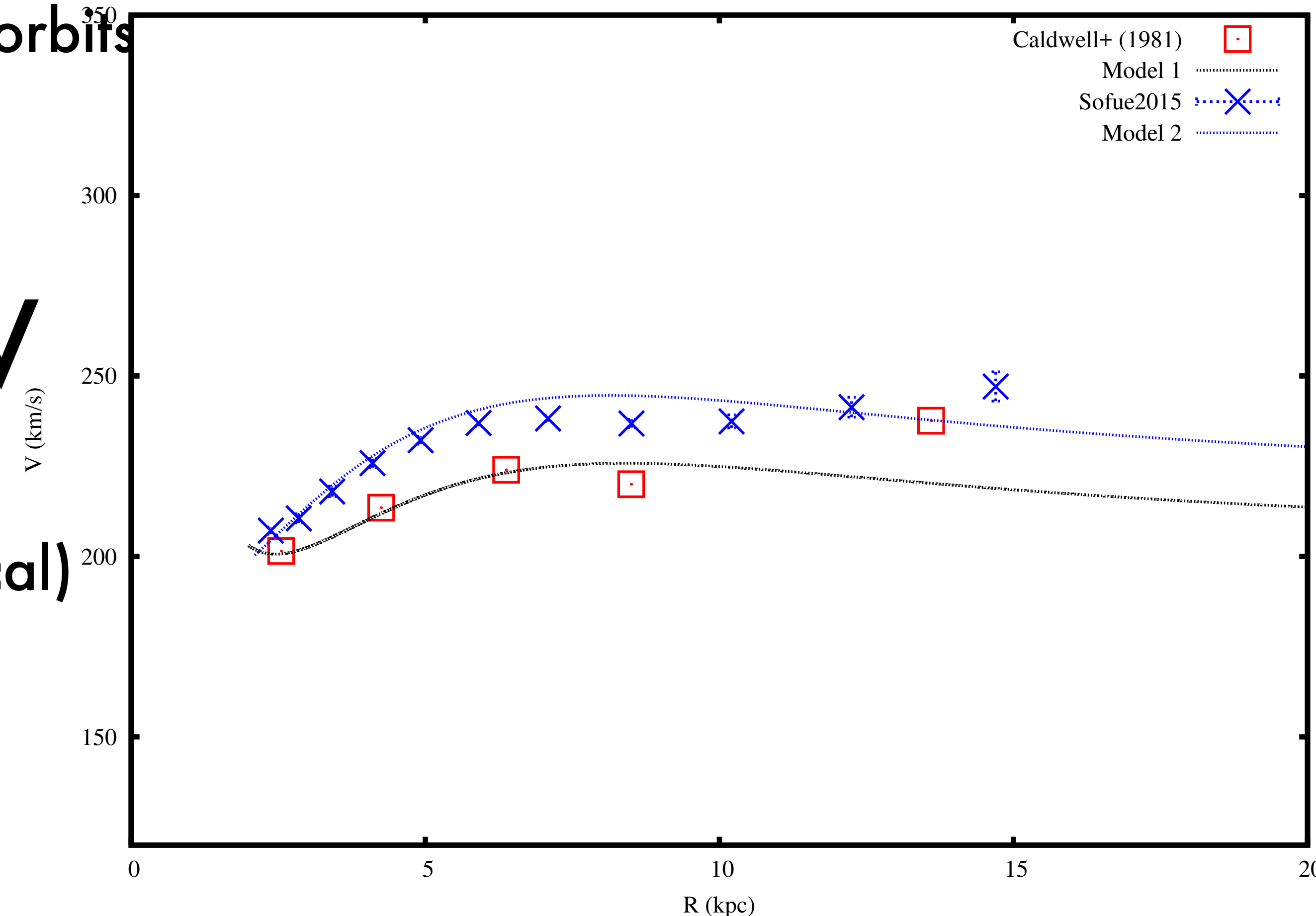


Fig. 1. Top: Meridional projection for three orbits within the logarithmic potential with L_z=8.5 and ΔE=0.2. The zero velocity curve and some coordinate curves of the elliptic coordinates (with z_0=5.9) are drawn. Middle: Analytical determination of the envelope of the orbit. Bottom: Surfaces of section for the same three orbits. Black crosses: numerically computed orbits. Red lines: the corresponding sections obtained from Eqs 1-3. Blue line: surface of section of the orbit confined in the mid-plane (i.e. v_z=0).

V



0 R (kpc) 20

Good Stäckel approximation (<1%) for a wide Galactic range (3<Rgal<12 kpc, -6<Zgal<6 kpc)

Kinematical model

Kinematics of each star computed (in heliocentric reference frame) from

- Galactic rotation curve (from potential)
- Asymmetric drift (from potential)
- Solar motion (3 free parameters)
- Age - velocity dispersion relation (3-4 free parameters)
- Radial velocity gradients (2 free parameters)
- Vertex deviation (2 free parameters)

Asymmetric drift

Older stars rotated slower than young stars and gas   Mihalas (1968)

density gradient   velocity disp. gradient

$$\Theta_m - \Theta_{\text{circ}} = \frac{\langle \Pi^2 \rangle}{2(A-B)} \left[\frac{\partial \ln \nu}{\partial r} + \frac{\partial \ln \langle \Pi^2 \rangle}{\partial r} + \frac{1}{R_0}\left(1 - \frac{\langle \vartheta^2 \rangle}{\langle \Pi^2 \rangle}\right) + \frac{1}{R_0}\left(1 - \frac{\langle Z^2 \rangle}{\langle \Pi^2 \rangle}\right) \right]$$

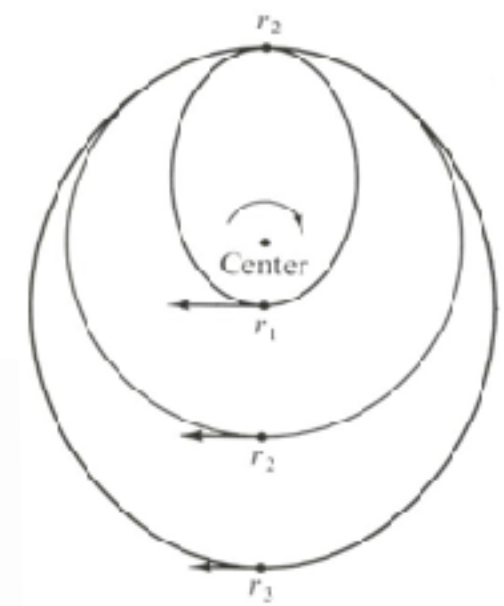
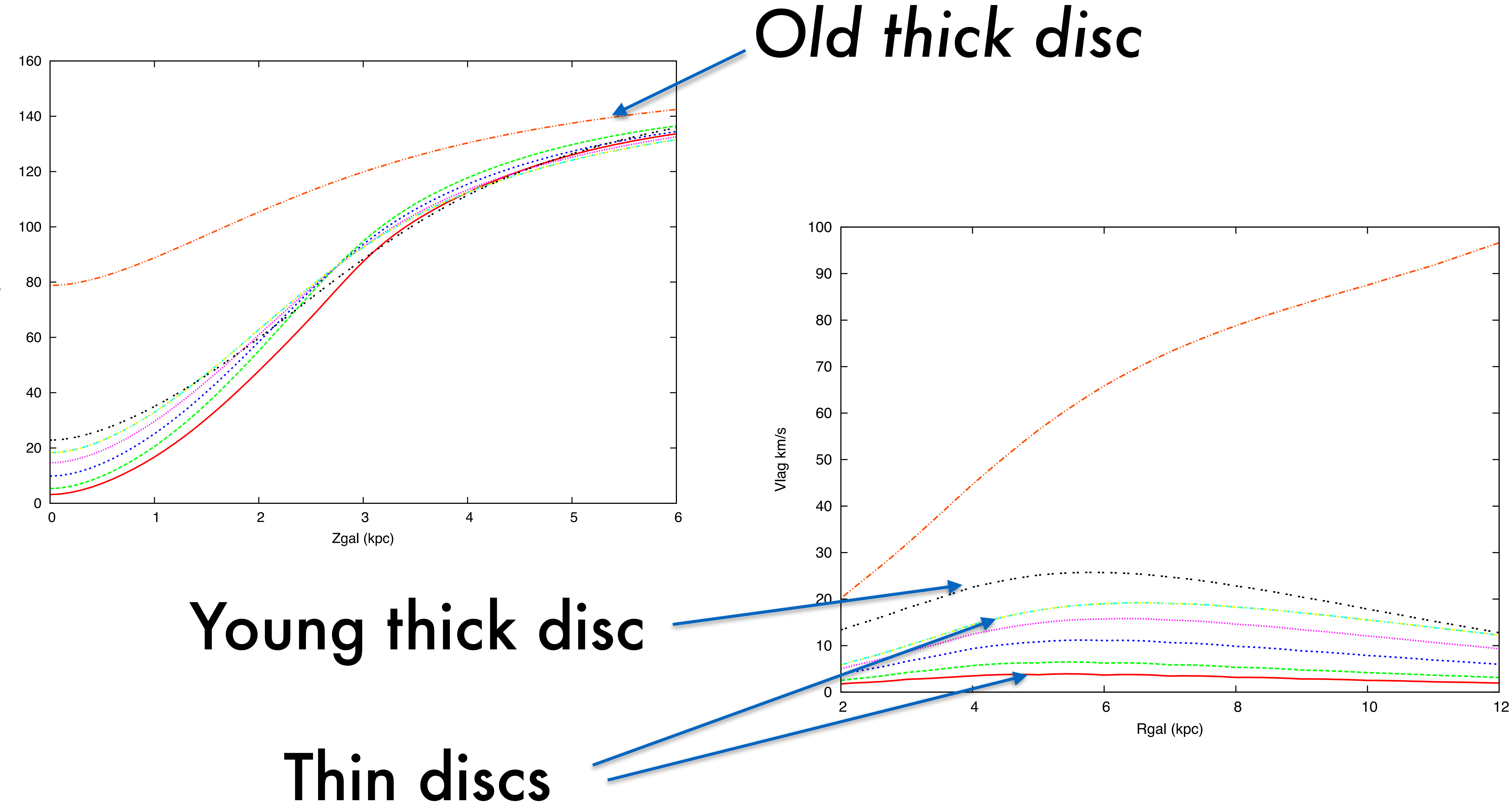


FIG. 12-10. Stars at r_2 are assumed to mo
Stars at r_1 can reach r_2 if $\Theta(r_1) > \Theta_{\text{circ}}(r_1)$.
$\Theta < \Theta_{\text{circ}}(r_1)$. Stars at r_3 can reach r_2 if $\Theta(r_3) <$
have $\Theta > \Theta_{\text{circ}}(r_2)$. Since the density of stars i
will be for stars at r_2 to lag behind the true circ

Generally assumed to be the same out of the plane,
but not the case in reality (Binney et al, 2010,2012), Bienaymé et al 2015)

In this self-consistent dynamical model

Dependency of the asymmetric drift with R and z



Kinematical constraints at the Solar neighborhood

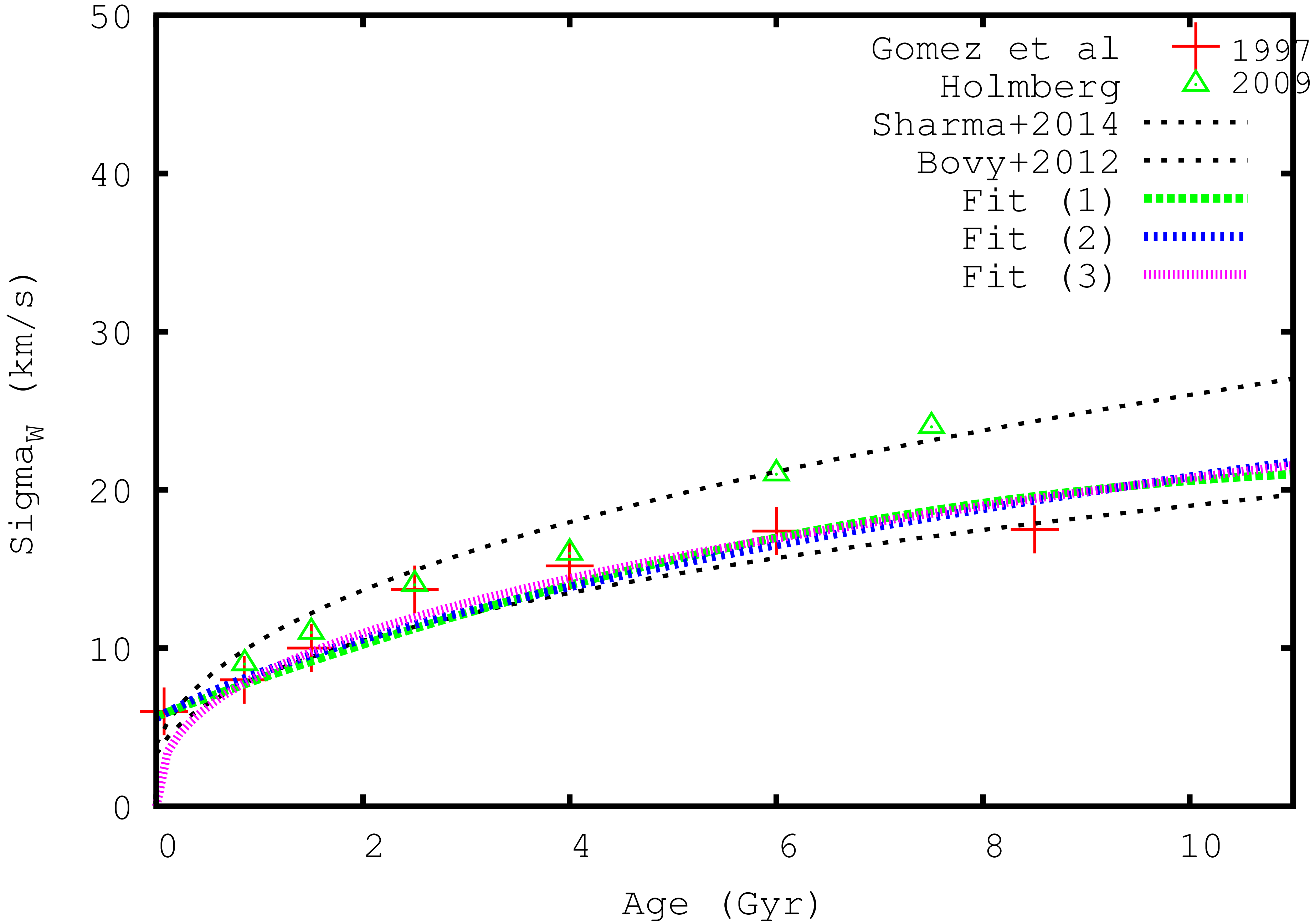
- Simulating the RAVE survey selection function, radial velocities
- Gaia TGAS : accurate proper motions for the RAVE stars
- Separate stars by metallicity (4 bins) and by temperature (cool/hot)
- $|b|>25°$ to avoid extinction problems (and complex selection function)
- Fit kinematic model for the thin and thick discs (ABC-MCMC)

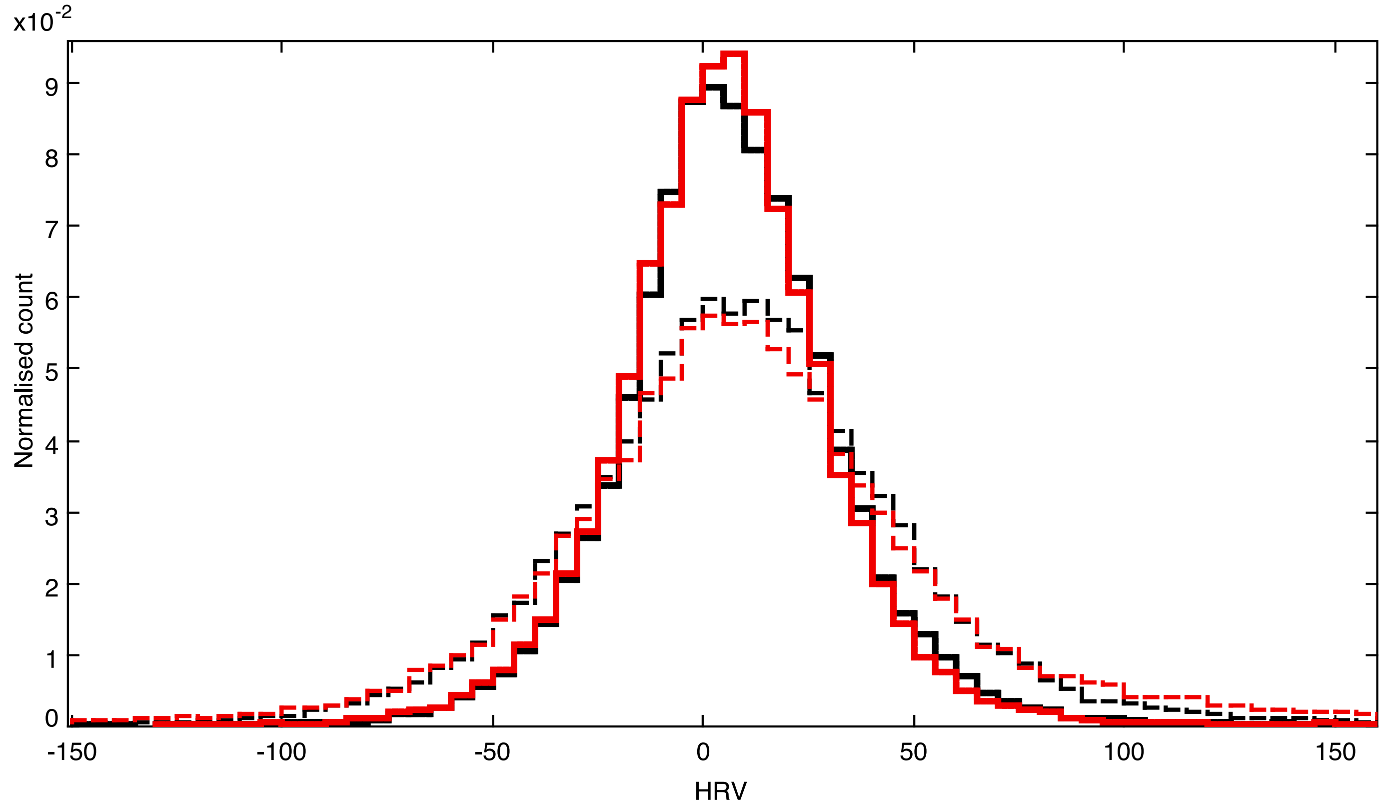
Robin, Bienaymé, Reylé, Fernandez-Trincado, 2017, 2017arXiv170406274R

Solving for

- ☑ Solar motion
- ☑ Thin disc velocity dispersion as a fct of age
- ☑ Thick disc velocity ellipsoid
- ☑ Kinematical gradients

Age-velocity dispersion relation in the local thin disc

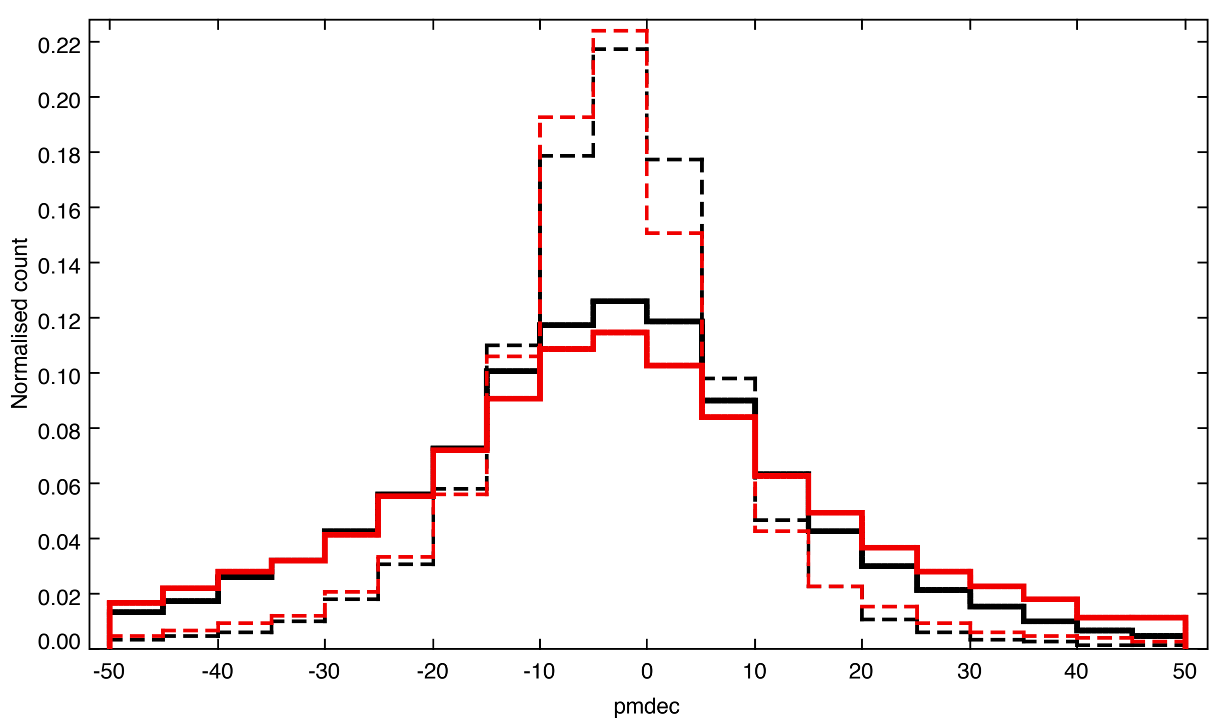




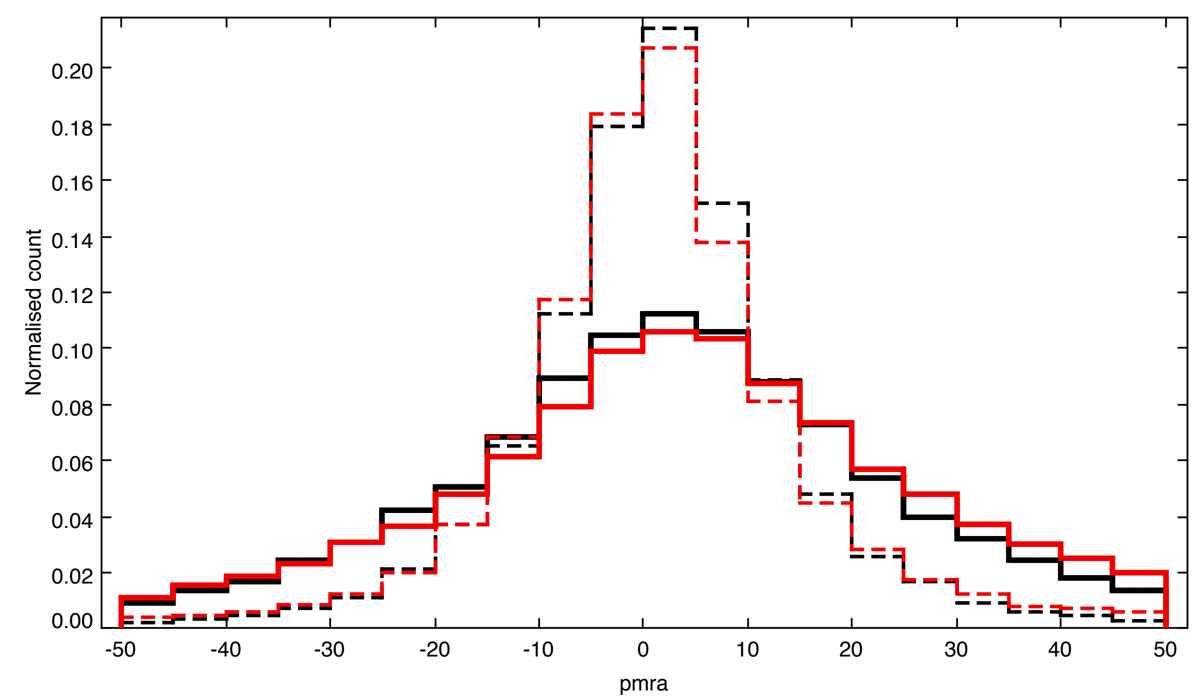
V_{los}

Hot: solid
cool: dashed

Data
Model



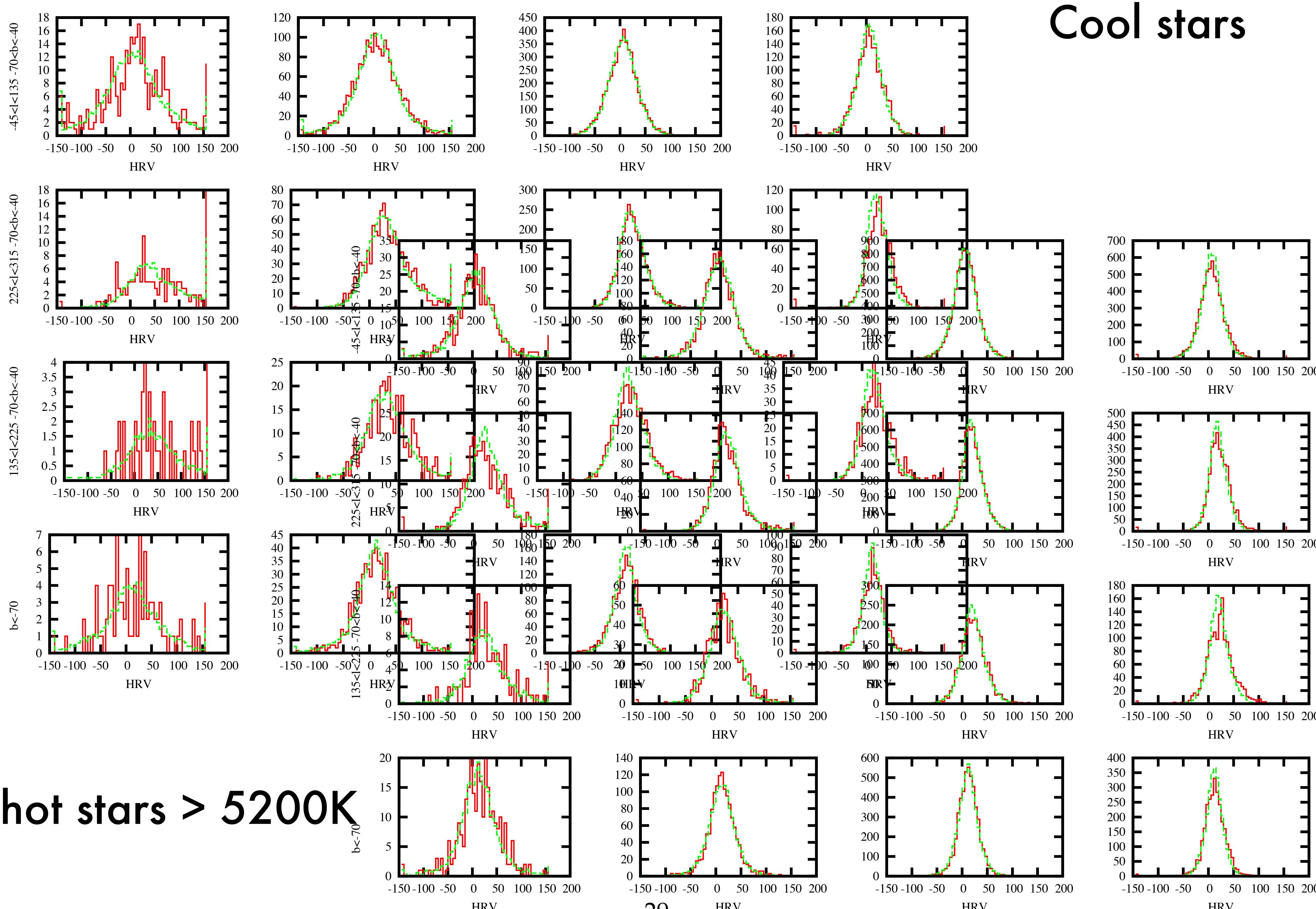
pm_{ra}



pm_{dec}

-1.2<[Fe/H]<-0.8 -0.8<[Fe/H]<-0.4 -0.4<[Fe/H]<0 0<[Fe/H]<0.4

Cool stars

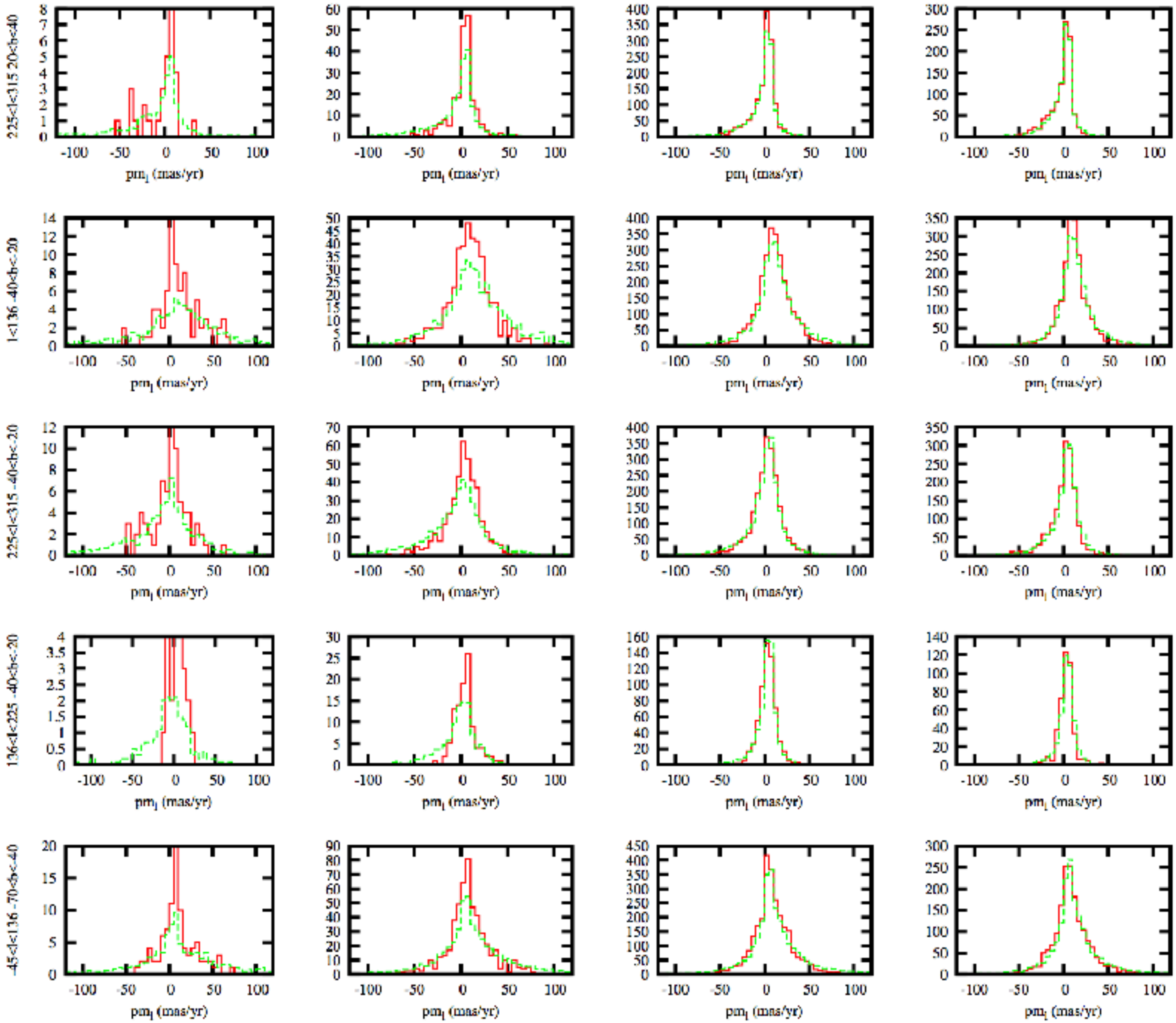


hot stars > 5200K

-1.2<[Fe/H]<-0.8 -0.8<[Fe/H]<-0.4 -0.4<[Fe/H]<0 0<[Fe/H]<0.4

Gaia proper motions

hot stars



	U	V	W
Sun velocities	11.9	0.9	7.1
Velocity dispersions Thick disc 10 Gyr	42±2	31±2	27±1
Thick disc 12 Gyr	80±8	57±9	62±6

Thick disc dynamical evolution: confirms the contraction between 12 Gyr and 10 Gyr, determined from the scale height and scale length (R+2014)

Solar motion

- New determination of the Solar motion
- $(U_o, V_o, W_o) = (13,1,7)$ km/s : good agreement for U and W with literature
- V_o smaller than previous determinations
- Literature values for V_o: from 3 to 26 km/s !

Solar V velocity

- **Results depend on**
  - **tracer used** (…UCAC4 => TGAS)
  - kinematical models (including asymmetric drift f(z) or not, …)
  - rotation curve / Sun - Galactic centre distance
  - local/non local determination
  - Method for fitting
  - use of distances or direct observables (magnitudes, Vrad, proper motions)

- V_o uncertainty always larger than the internal accuracy of the fit

Gomez et al 1977

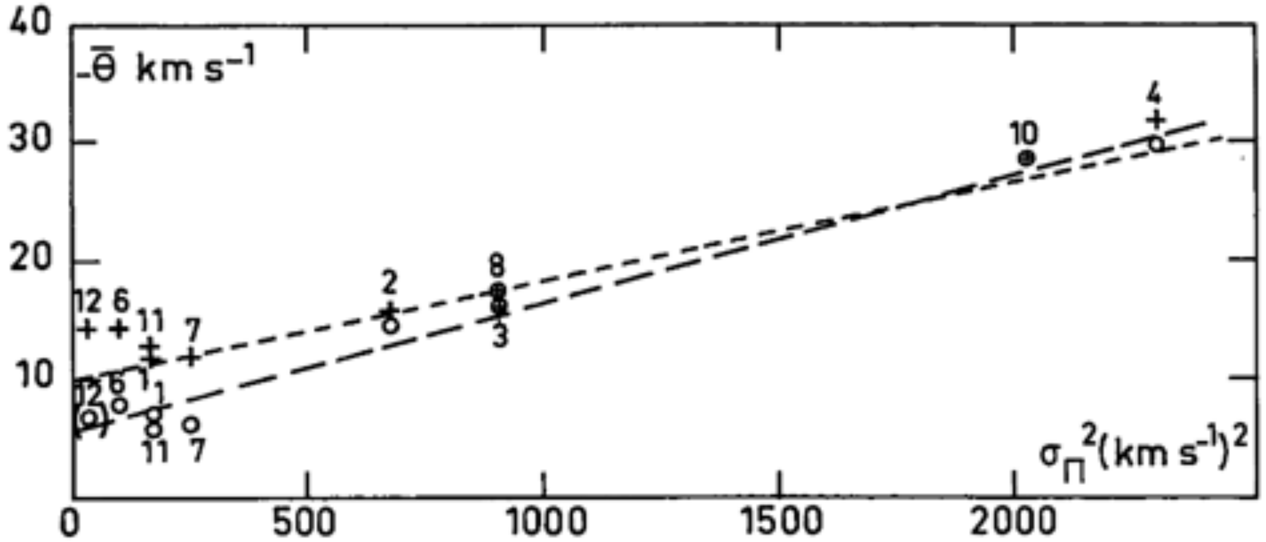
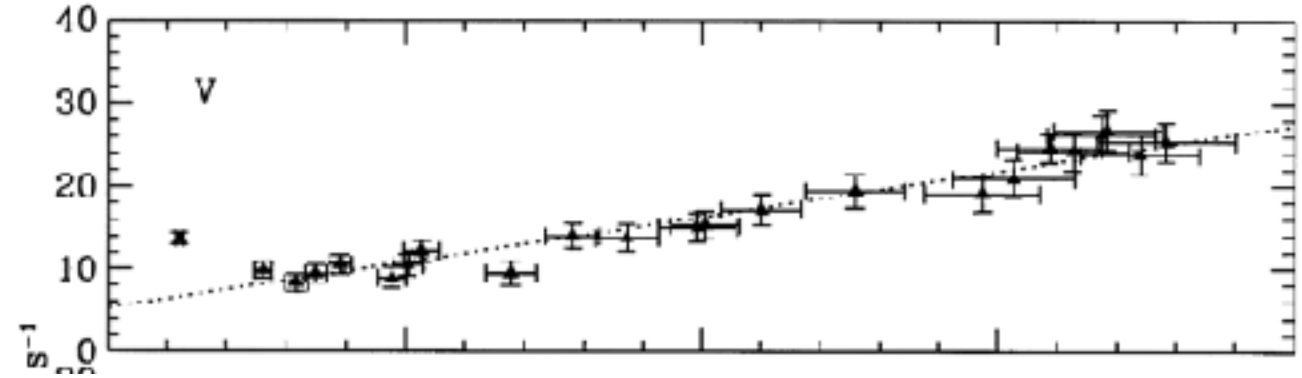
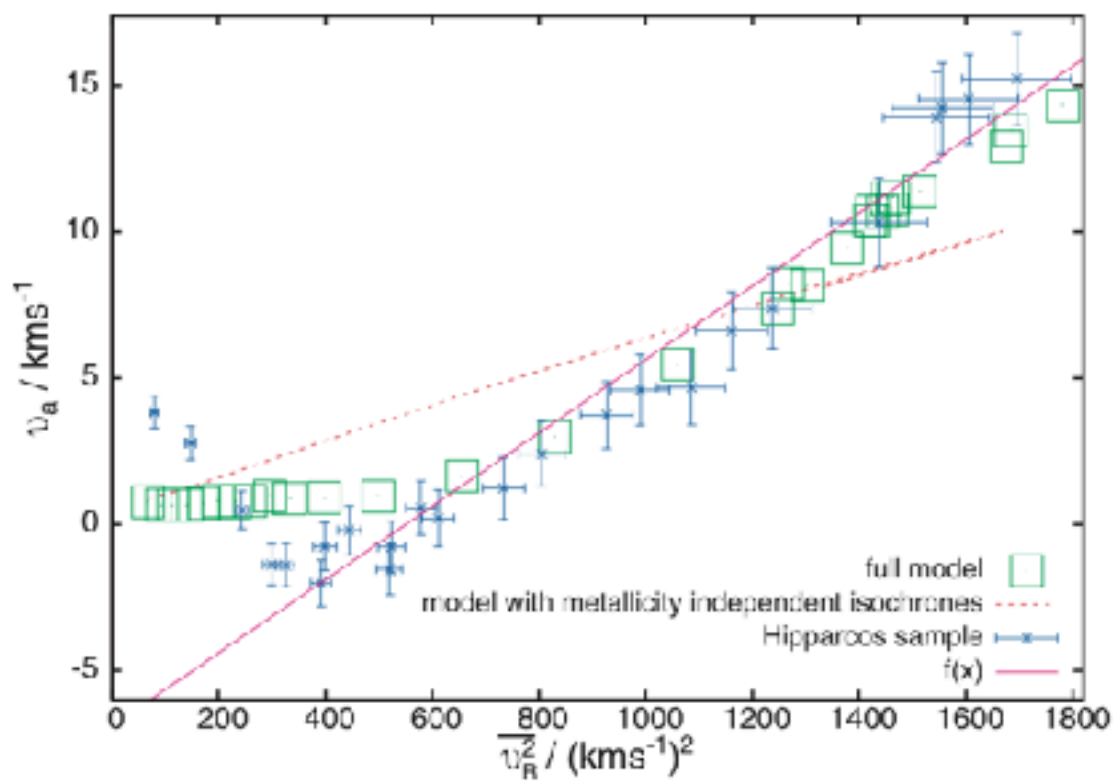


Fig 4. Relation between the Θ mean velocity component and the variance of the Π components, σ_Π^2. Estimates given by Delhaye (1965) (+), and corrected by the influence of the spiral structure (○). The numbers correspond to the different samples: 1 supergiants, 2gA-gF, 3gF-gM, 4 carbon stars, 6 BO, 7 dA, 8 dF-dM, 10 Planetary nebulae, 11 classical cepheids, 12 Interstellar Ca II[2]

Dehnen & Binney 1998





Schönrich & Binney (2010)

Figure 3. Green squares: the asymmetric drift for synthetic stellar subsamples defined by $B - V$ colour plotted against their radial velocity dispersion

Solar V velocity

- Results depend on
  - tracer used (…UCAC4 => TGAS)
  - **kinematical models** (including asymmetric drift f(z) or not,…)
  - rotation curve / Sun - Galactic centre distance
  - local/non **local** determination
  - **Method** for fitting
  - use of **distances** or **direct observables** (magnitudes, Vrad, proper motions)

=> Considerable spread in determinations (**from 3 to 26 km/s**)

V_o (among others)

- Dehnen & Binney (1998): from 15,000 stars Hipparcos: 5.25 ± 0.62 km/s^{-1}
- Aumer & Binney (2009): Hipparcos re-reduction: ~5 km/s
- Binney (2010): GCS + SDSS and new dynamical model: 11 km/s
- Schönrich & Binney (2010): 12.24 ± 0.47 km/s
- Sharma et al (2014): RAVE + GCS: 7.6 km/s

Schönrich, Binnen & Dehnen, 2010

In common:

- Self-consistent dynamical models (but different)

Main differences:

Schönrich et al. 2010

- Hipparcos + GCS
- Distances from spectrophotometric parallaxes
- Vo=12 km/s

This work (astroph.1704.06274)

- Radial velocities from RAVE
- Proper motions from Gaia-TGAS
- No distances assumed (space of observables)
- Vo=1km/s

Sharma et al 2014

In common:

- Self-consistent dynamical models (but different)
- RAVE data
- In the space of observables
- MCMC exploration

Main differences:

Sharma et al. 2014	This work (astroph.1704.06274)
• Proper motions from **UCAC4**	• Proper motions from **Gaia-TGAS**
• Shu distribution fct	• Gaussian distribution fct
• Vo= 7 km/s	• Vo= 1 km/s

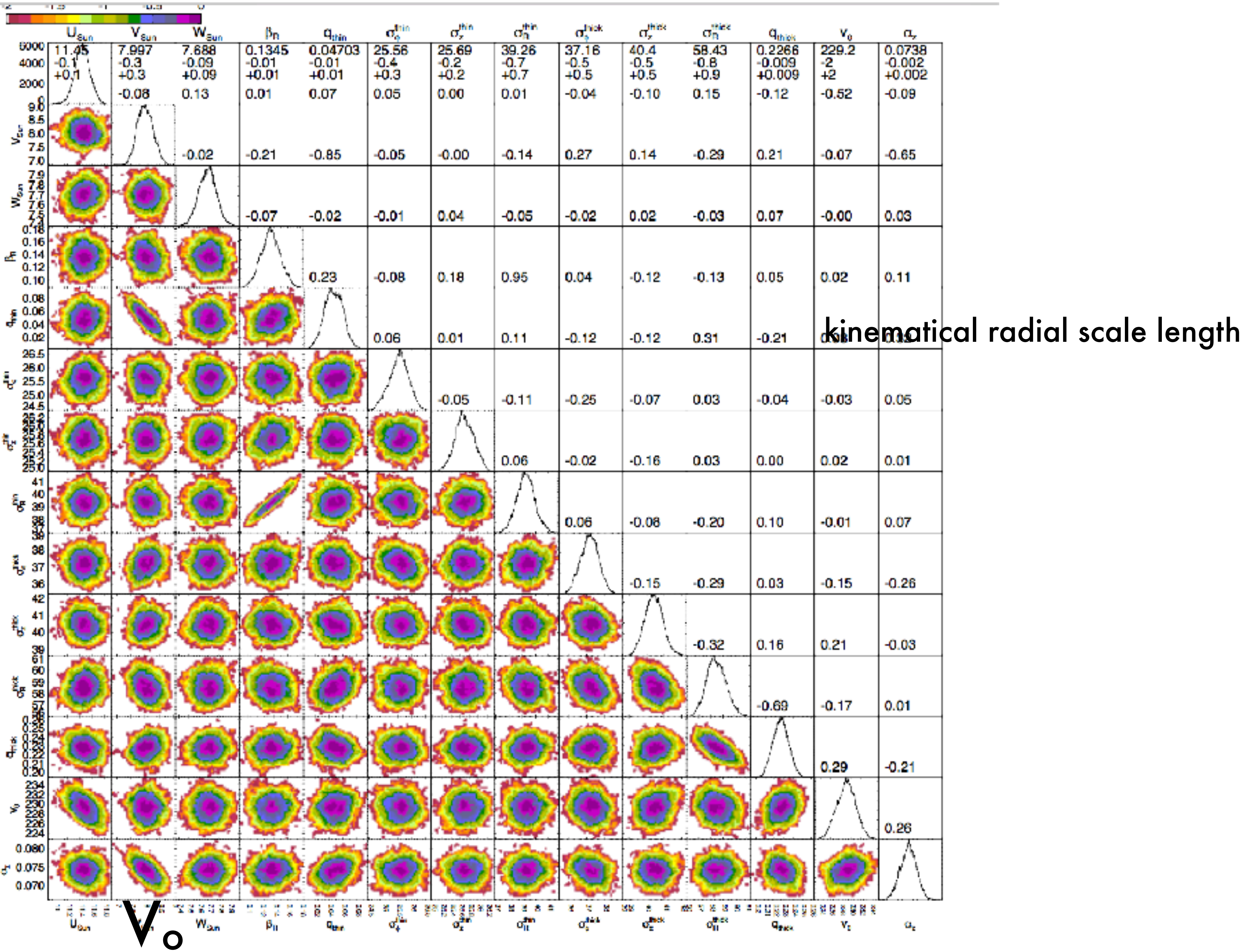


FIG. 12.— Marginalized posterior distribution of model parameters. The numbers are the linear Pearson correlation coefficient. Shown is the case of Gaussian model for RAVE data. Strong dependency can be seen between β and $\sigma^{\rm thin}$ values. Additionally, $(q_{\rm thin}, V_\odot)$ and $(q_{\rm thick}, \sigma_R^{\rm thick})$ also show dependency. Finally, the v_c is anti-correlated to $U_\odot$ and correlated to $V_\odot$.

Sharma+2014

Summary

- New dynamical self-consistency model with a Stäckel potentiel
- A correct asymmetric drift modeling is important for determining the solar motion
- Need to be confirmed from Gaia-DR2

- Still an axisymmetric model
- Exploration of non-axisymmetries (bar) using test-particle simulations from the BGM potential (Fernandez-Trincado in preparation)

Perspectives

- **Gaia DR2** coming soon
- Extend this analysis to Gaia DR2 data, with radial velocities and proper motions
- Consider using parallaxes with good accuracies
- Combine RAVE+APOGEE+Gaia data sets => wide Galaxy portion with reliable data, new constraints on radial velocity gradients
- **Improve dynamical model and explore non-axisymmetries**

Improved BGM (v. 2016) available http://model2016.obs-besancon.fr and web service http://model2016.obs-besancon.fr/ws

Thanks for your attention