

The Metallicity Distribution Function of the disc with Gaia DR1+RAVE



Georges Kordopatis

Laboratoire Lagrange, Observatoire de la Côte d'Azur

Importance of the MDF

(and link with V_ϕ)

- Metallicity distribution function:
 - Radial and Vertical changes
 - Integrated star formation history
 - Hints of Radial migration (orbits desired)
 - Related to scale-lengths and scale-heights of the discs
 - Thick Disc formation scenarios
 - Cloud collapse?
 - Accretion of stars?

→ How does the MDF change when Gaia-DR1 is taken into account?

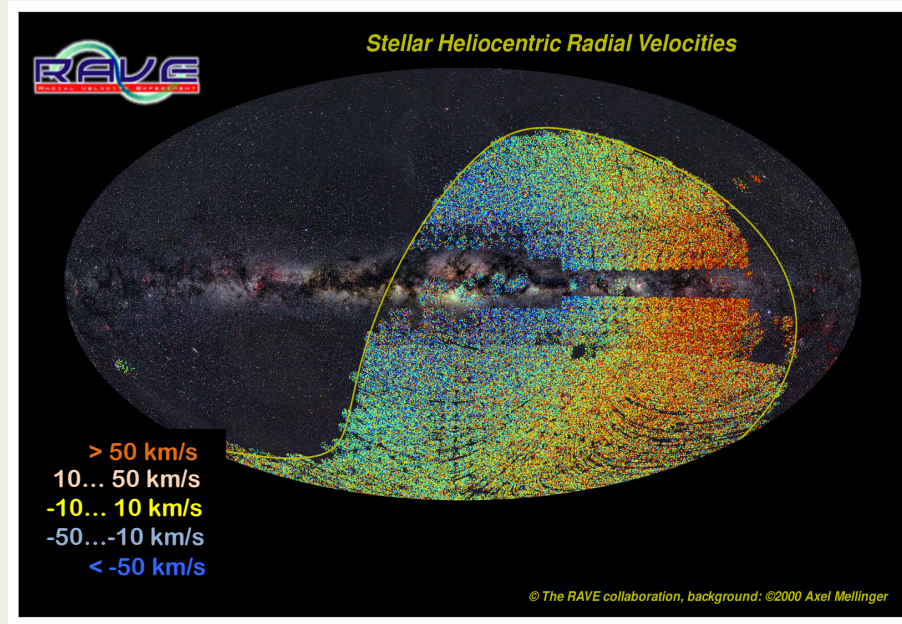
RAVE: 5th public data release

Kunder, Kordopatis et al. 2017

- Intermediate resolution ($R \sim 7500$)
- 457 588 stars,
- 520 781 spectra (*DR4: 482 430 stars*)
- $9 < I < 12$ mag

Database:

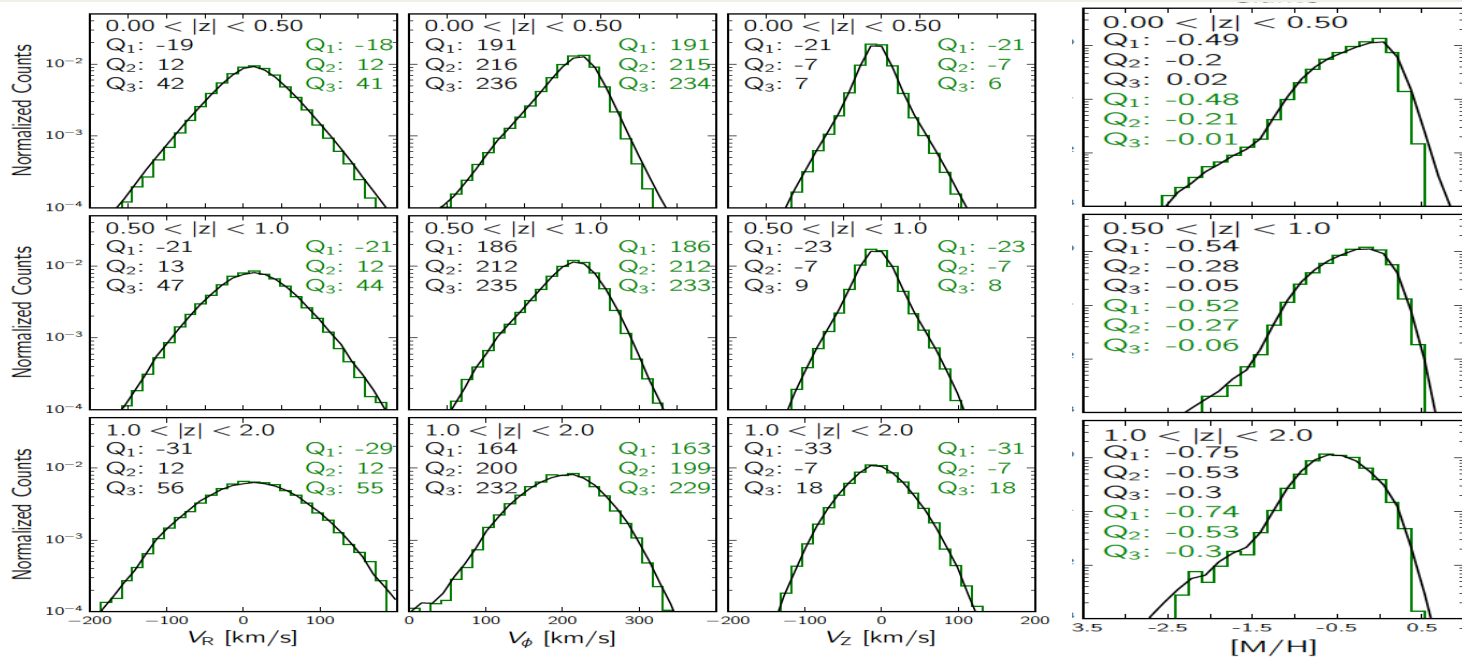
- ✓ Radial velocities
- ✓ Spectral morphological flags
- ✓ T_{eff} , $\log g$, $[M/H]$
- ✓ Line-of-sight Distances
- ✓ *Mg, Al, Si, Ti, Ni, Fe*
- ✓ Photometry:
2MASS, APASS
- ✓ Proper motions:
UCAC4, UCAC5, HSOY, PPMXL, Tycho-2, TGAS



RAVE DR5: selection function

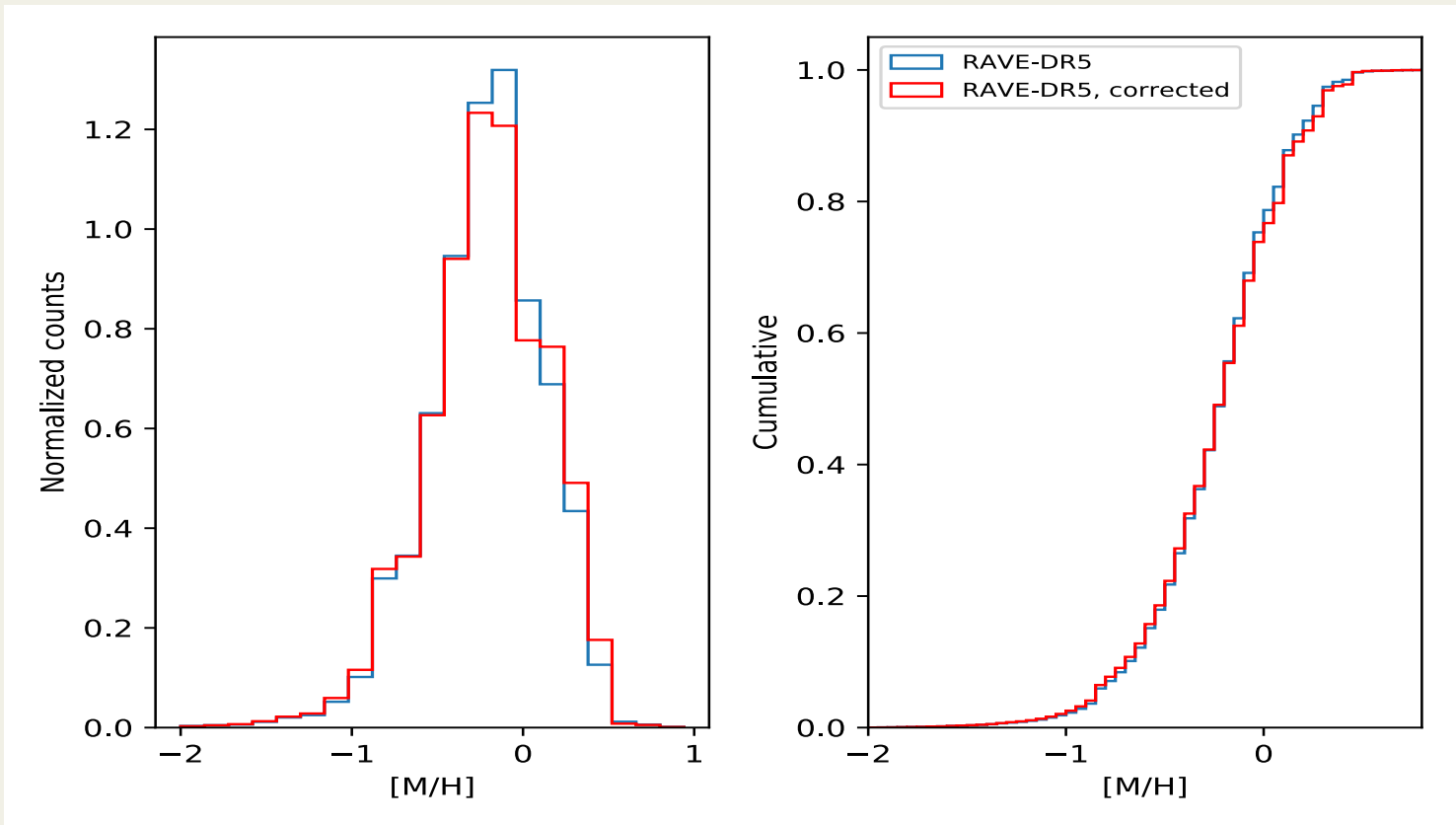
Wojno, Kordopatis et al. (2017)

Kinematically and chemically unbiased for $9 < I < 12$



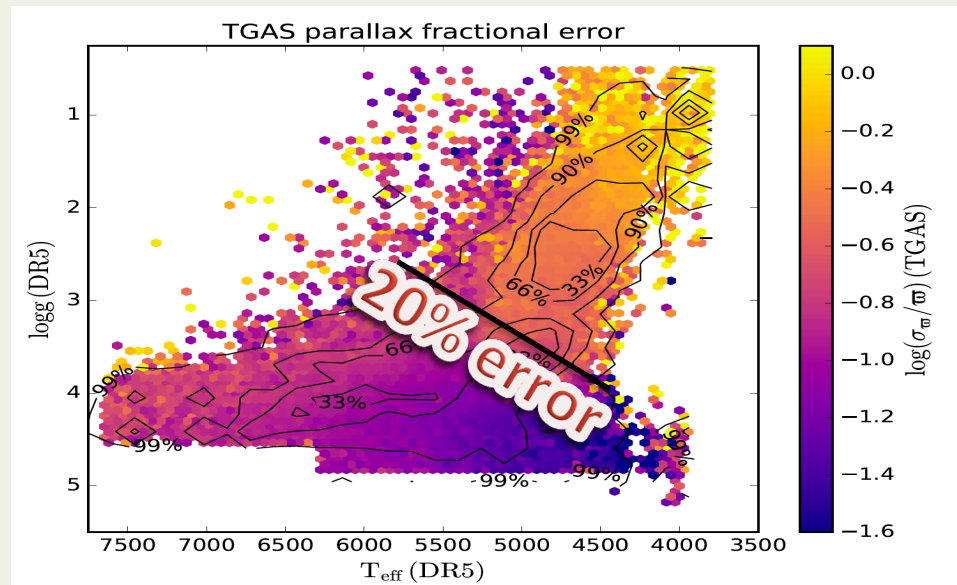
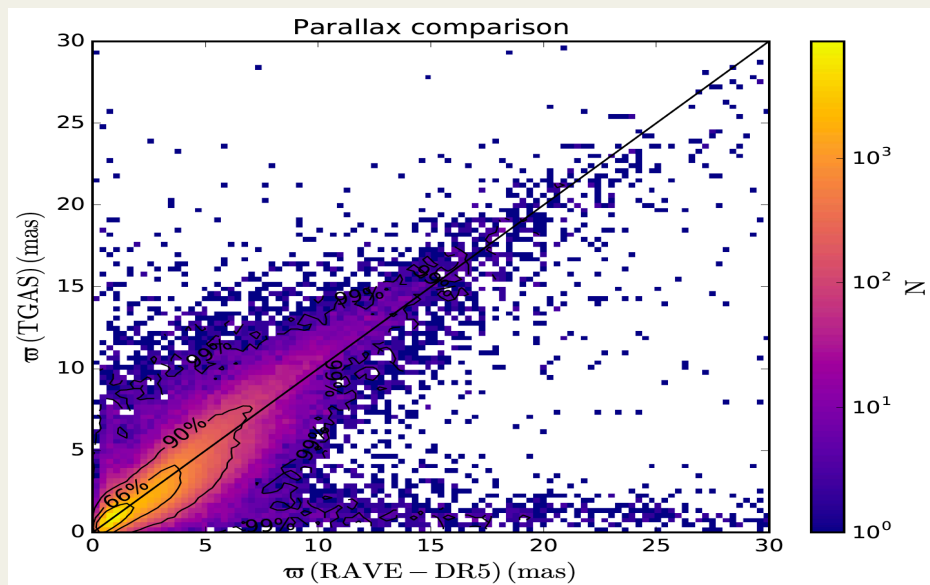
Parent sample
Mock RAVE

RAVE DR5: Corrected MDF



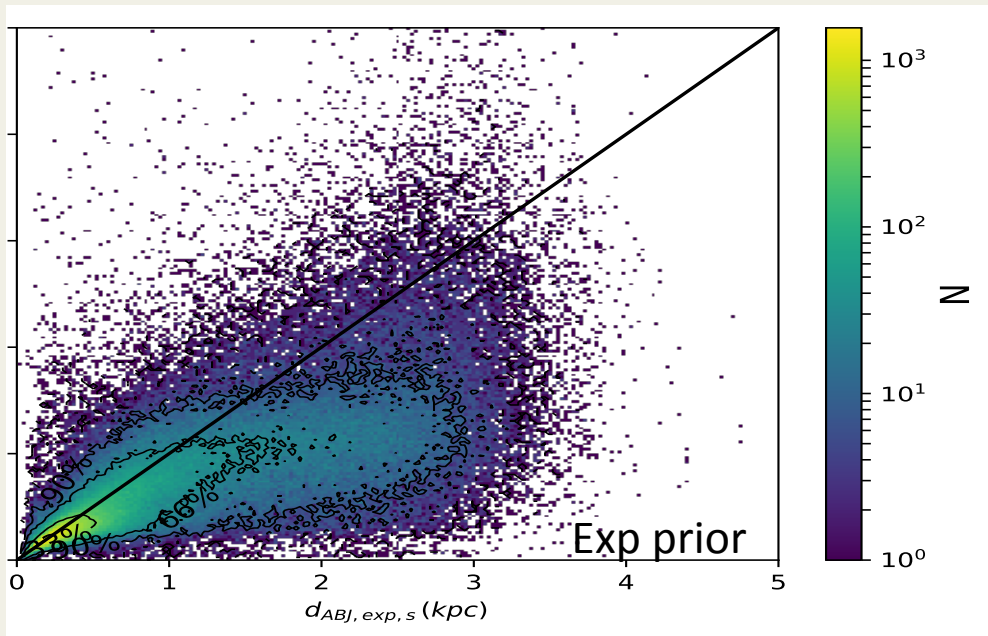
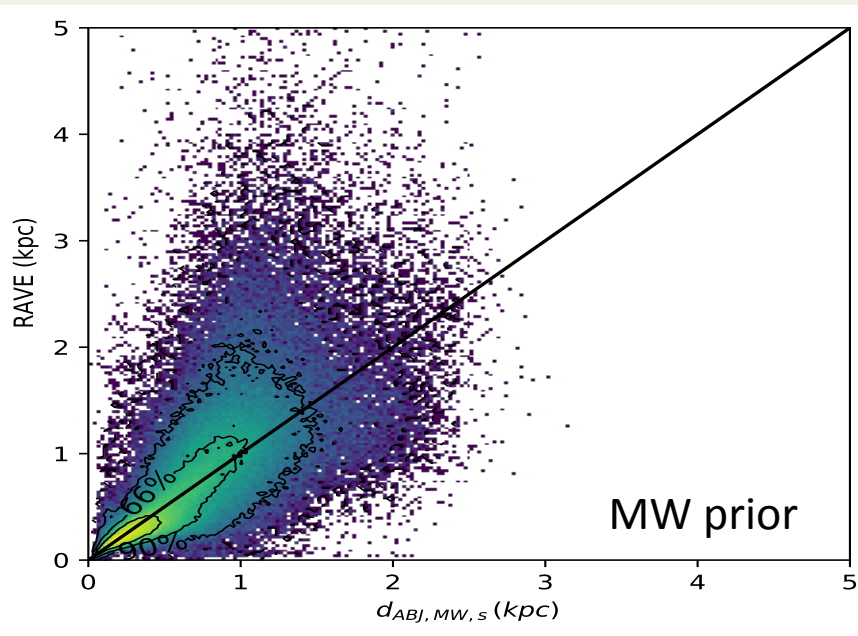
RAVE-TGAS catalogue

● *215 590 targets*



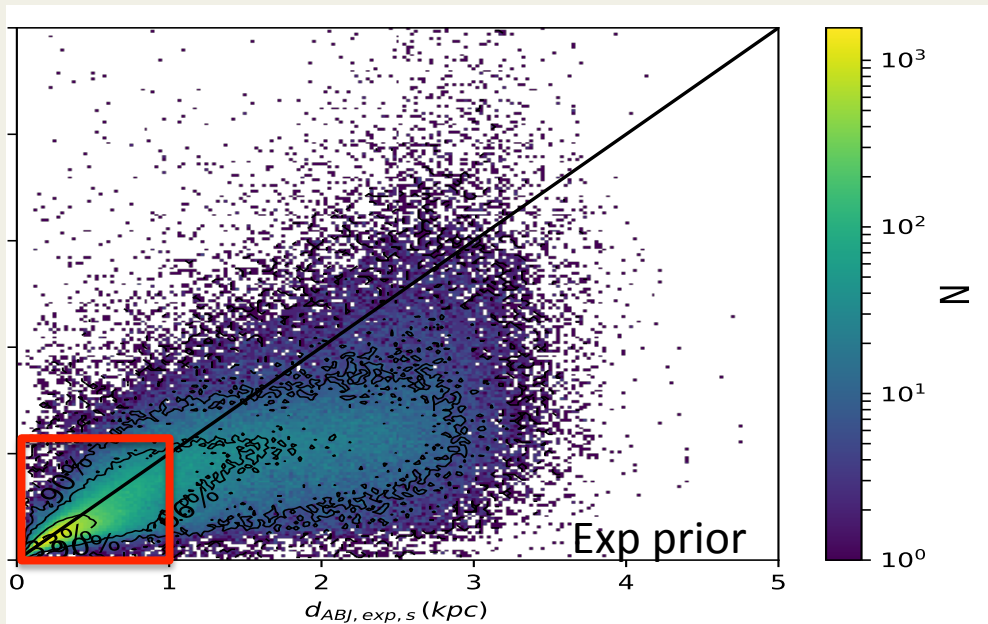
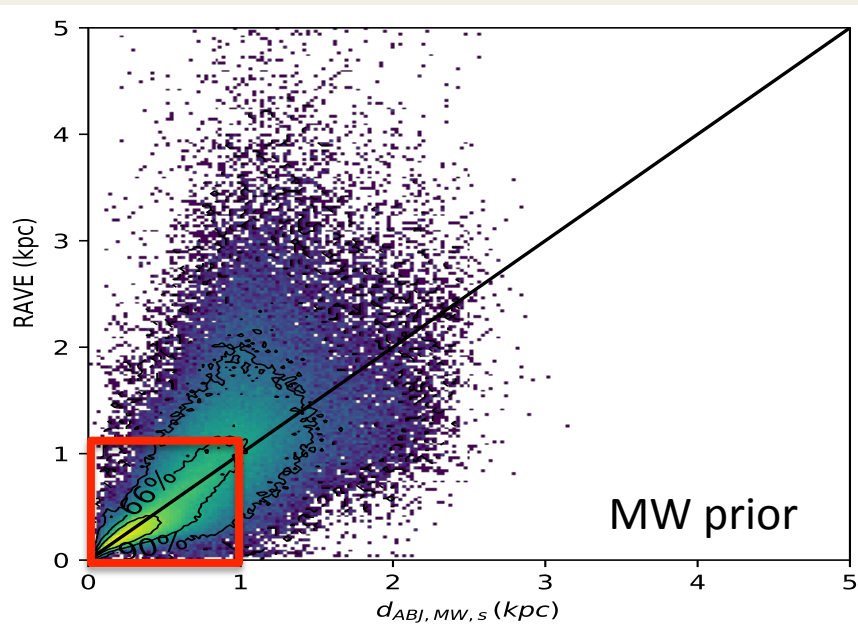
RAVE-TGAS catalogue

Astraatmadja & Bailer-Jones distances



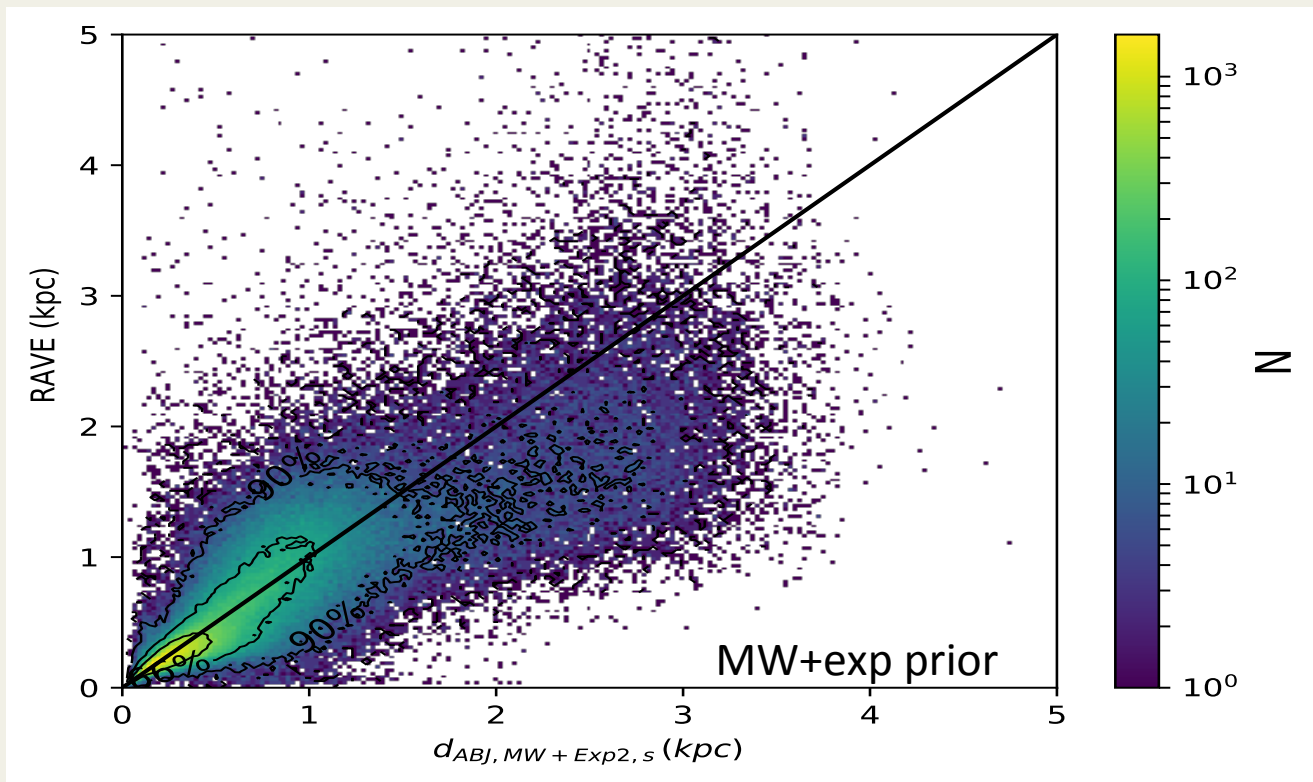
RAVE-TGAS catalogue

Astraatmadja & Bailer-Jones distances



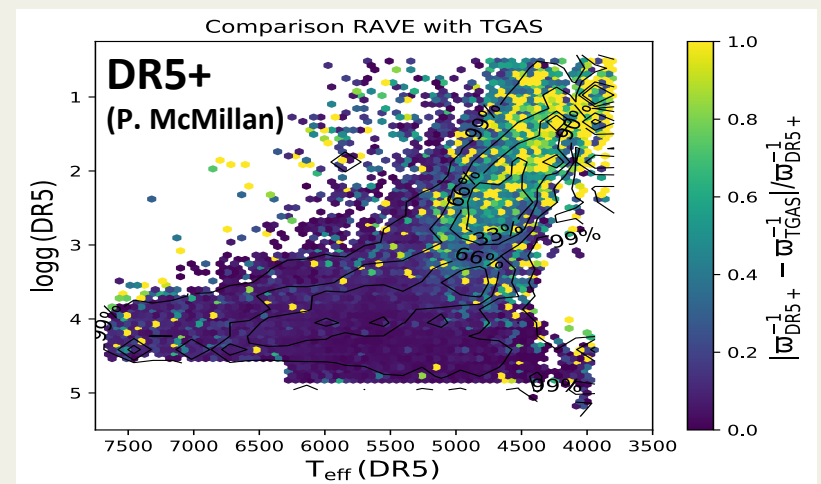
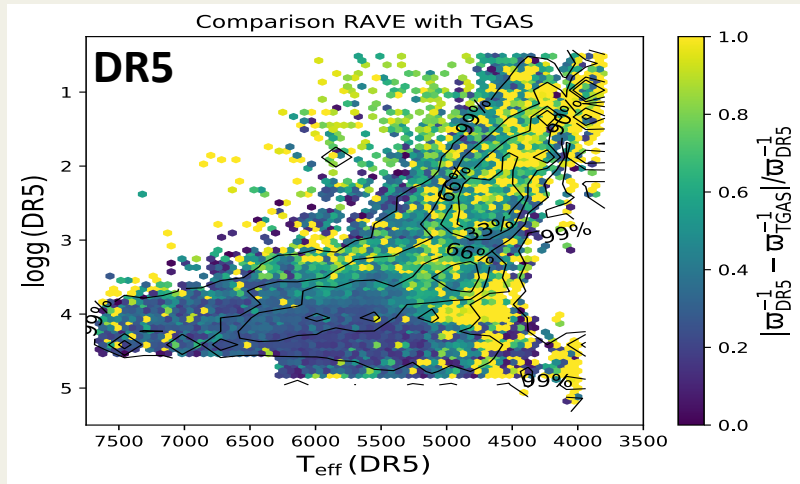
RAVE-TGAS catalogue

Astraatmadja & Bailer-Jones distances

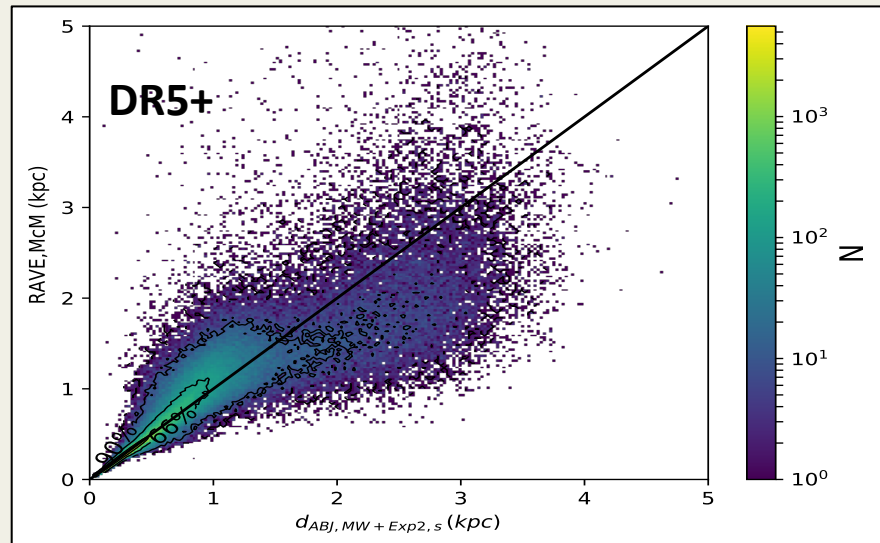
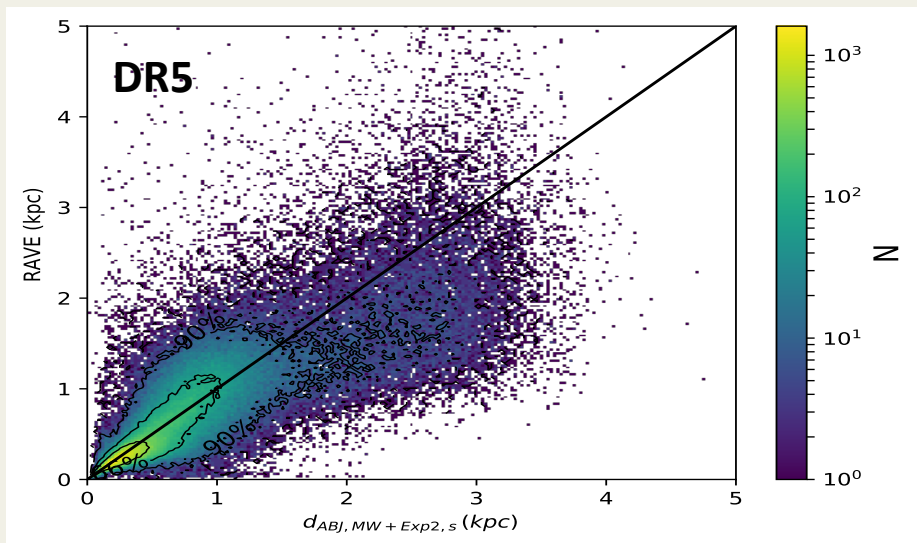


New distances for the RAVE-TGAS catalogue

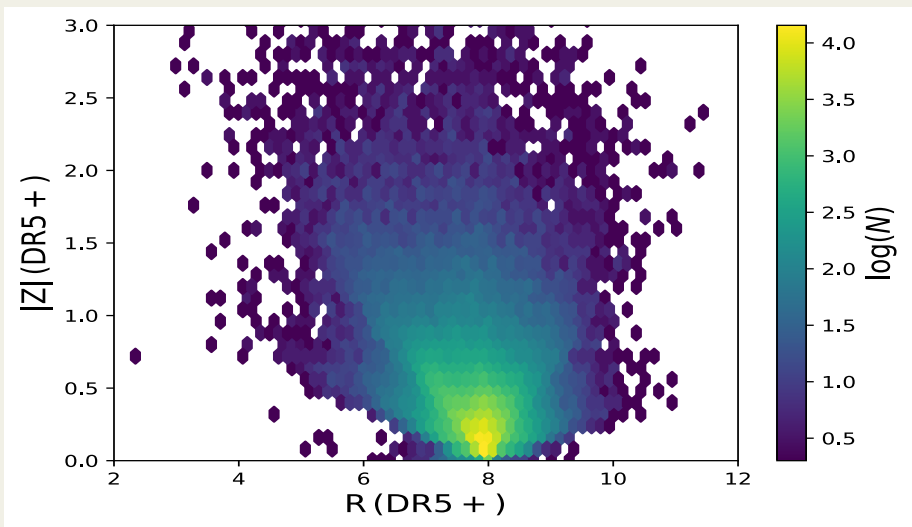
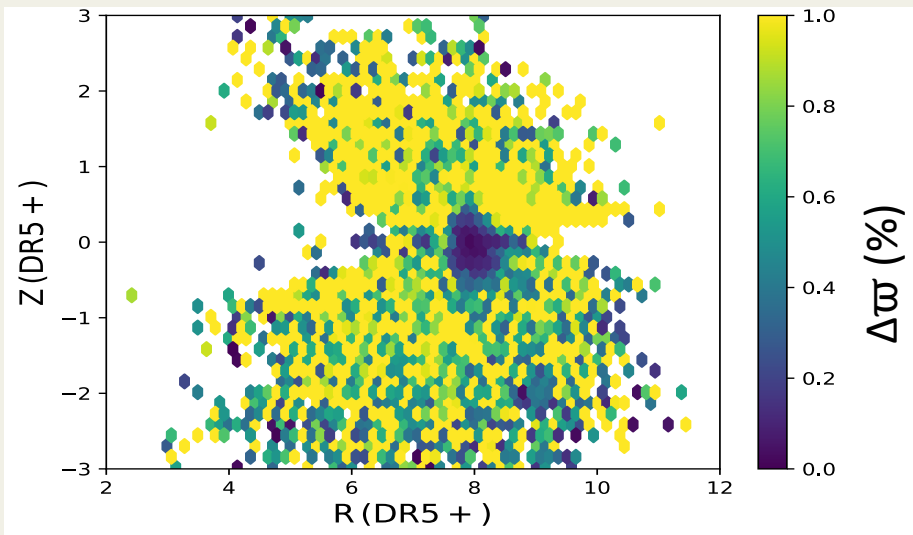
- New distances (*c.f.* P. McMillan's poster C22)
 - Use of T_{eff} , $\log g$, $[M/H]$ + ϖ + underlying Galactic model
 - 200% better than RAVE DR5 alone
 - 55% better than TGAS alone ($\log g < 3.5$)



New distances for the RAVE-TGAS catalogue

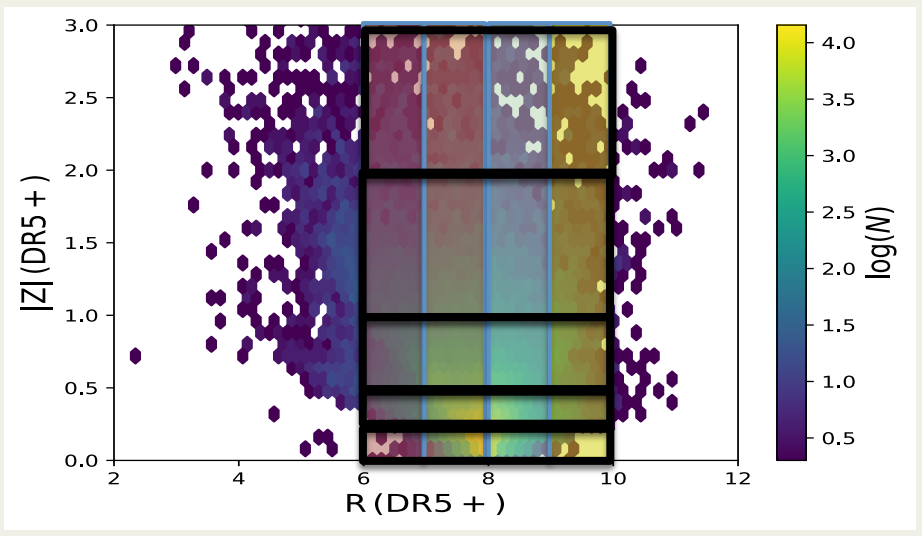
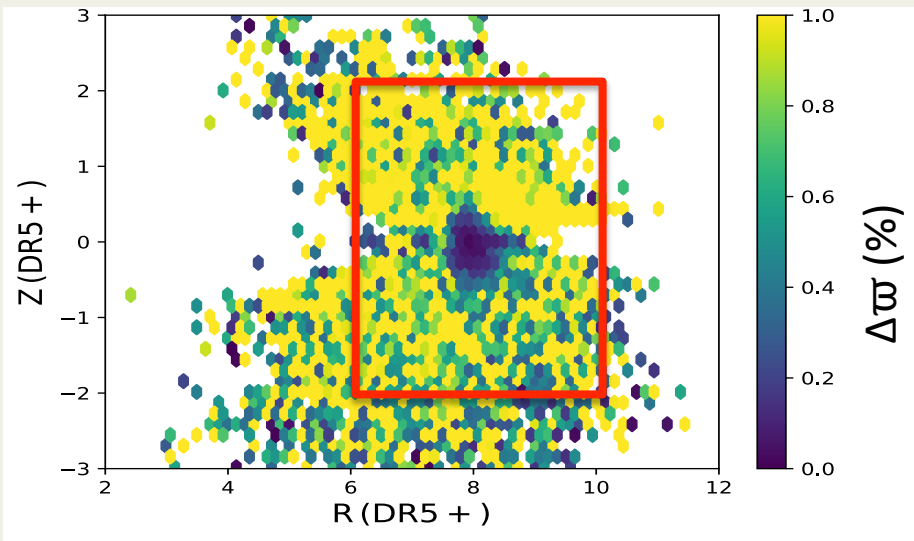


New distances for the RAVE-TGAS catalogue



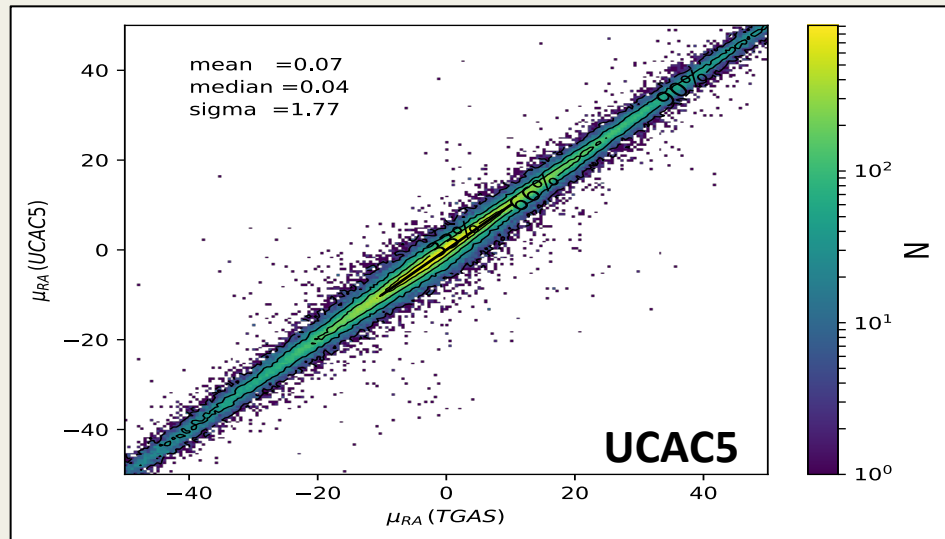
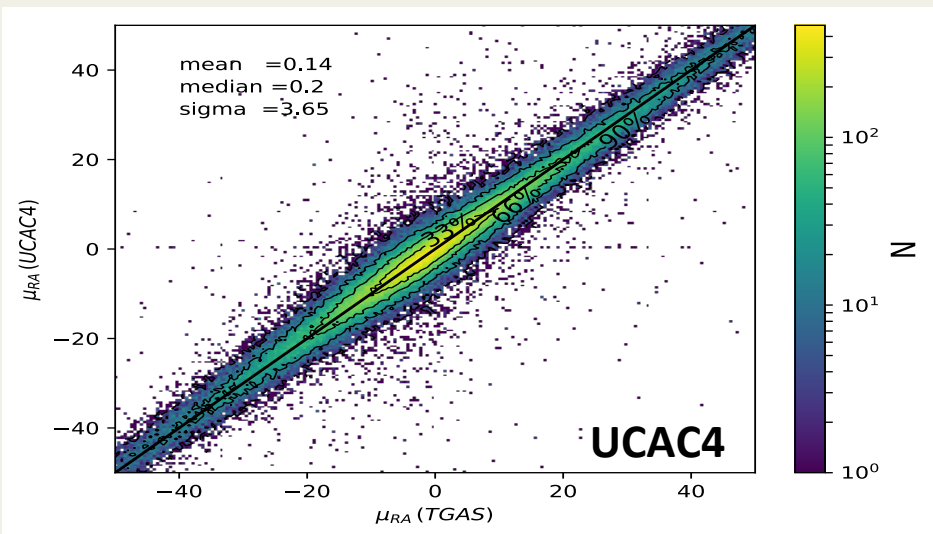
Metallicity Distribution Function

- 5 Radial distance bins:
 - $6 < R < 7$ kpc, $7 < R < 8$ kpc, $8 < R < 9$ kpc, $9 < R < 10$ kpc
- 5 Vertical bins:
 - $0 < |Z| < 0.25$ kpc, $0.25 < |Z| < 0.5$ kpc, $0.5 < |Z| < 1$ kpc, $1 < |Z| < 2$ kpc, $2 < |Z| < 3$ kpc

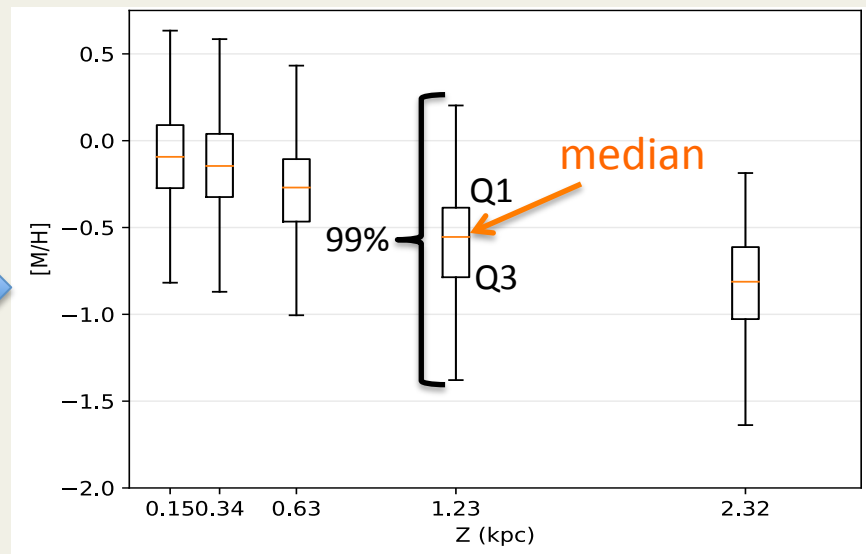
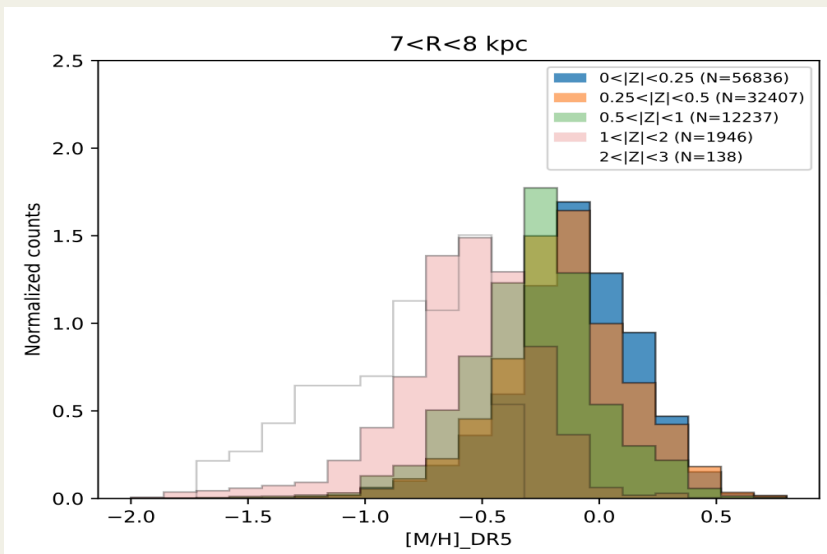


TGAS & UCAC5

- *UCAC5* (Zacharias et al. 2017): Improved p.m. for the TGAS stars, and new pm for the rest of the catalogue, based on Gaia-DR1 positions

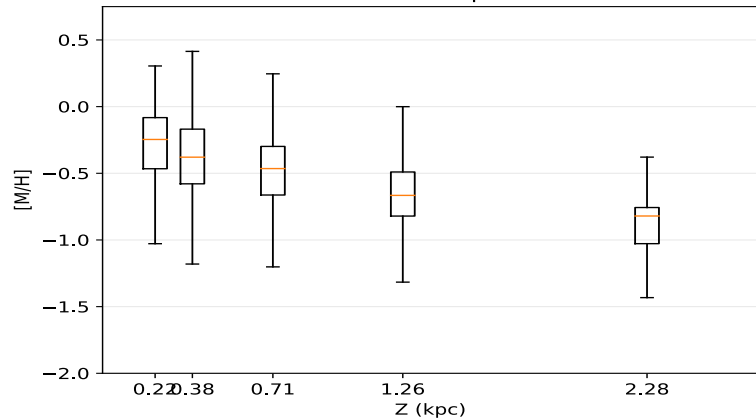


Metallicity Distribution Function

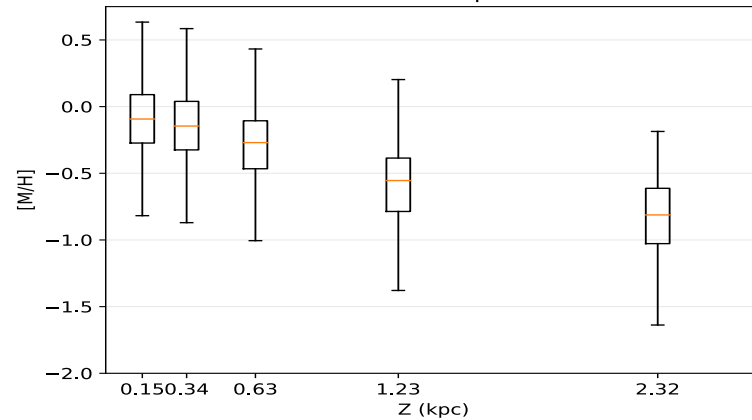


- MDFs are not Gaussian, even for a single population.
 - Multi-Gaussian decomposition,
 - chemical ($[\alpha/\text{Fe}]$) decomposition,
 - kinematic decomposition

6 < R < 7 kpc

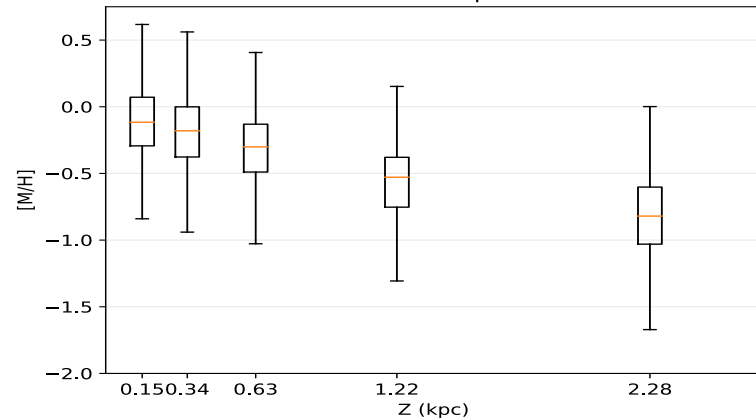


7 < R < 8 kpc

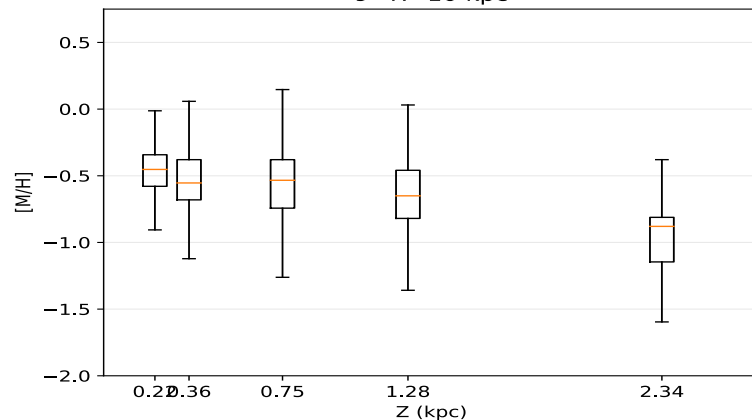


RAVE-DR5(McM) + UCAC5

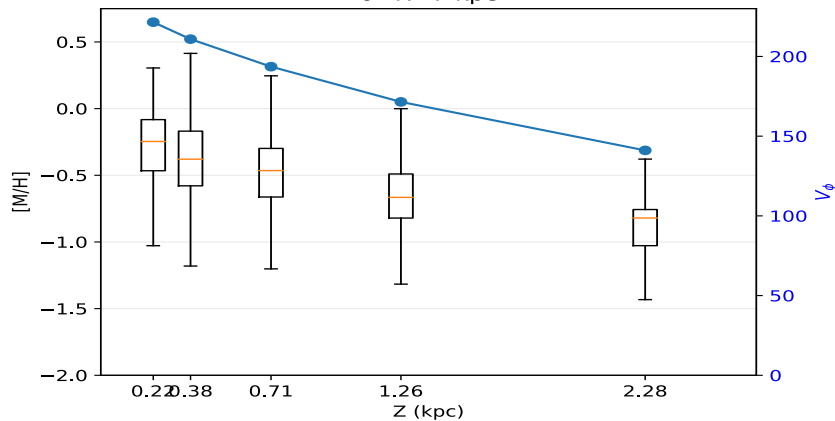
8 < R < 9 kpc



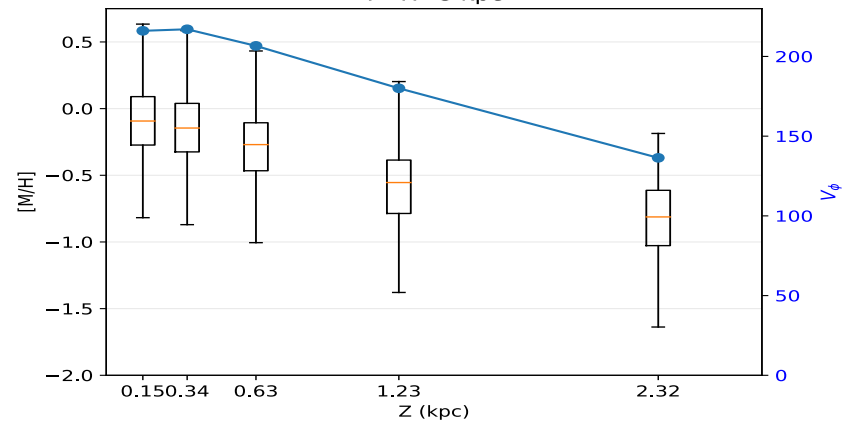
9 < R < 10 kpc



6 < R < 7 kpc

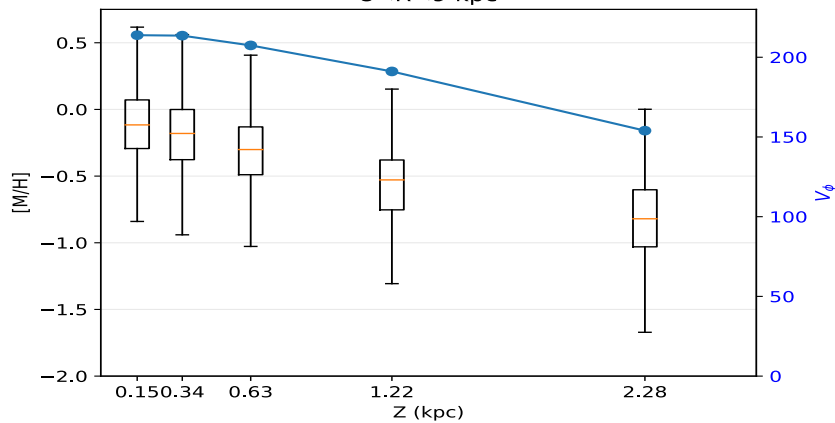


7 < R < 8 kpc

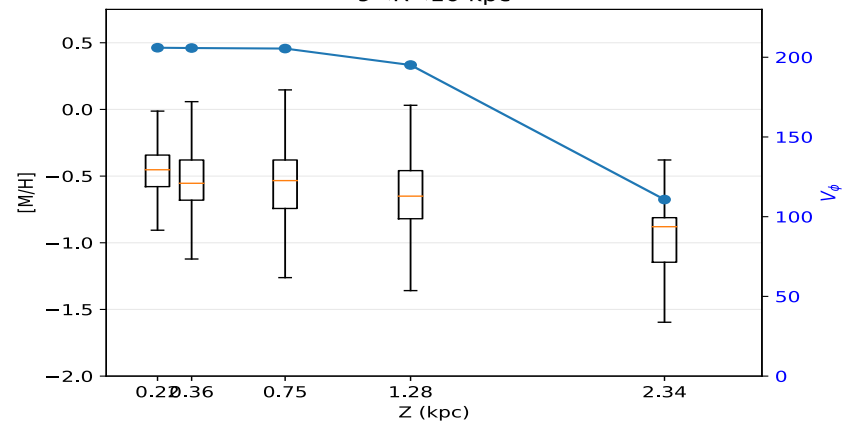


RAVE-DR5(McM) + UCAC5

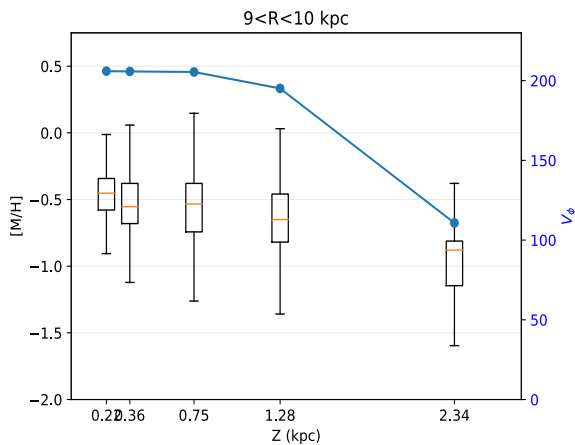
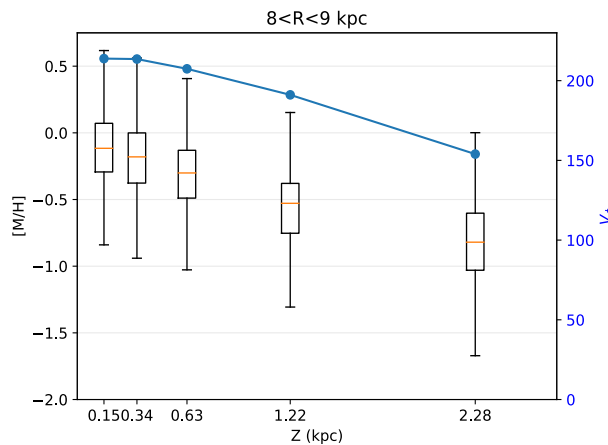
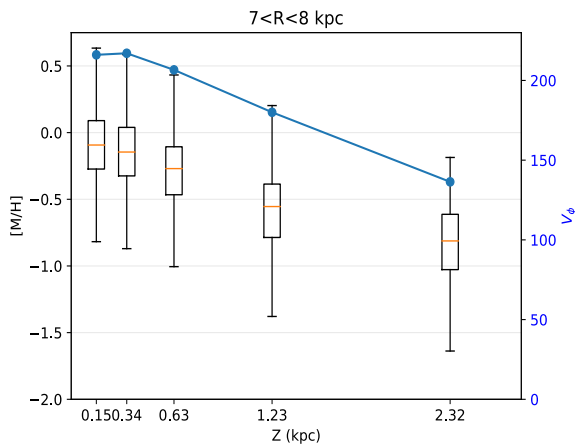
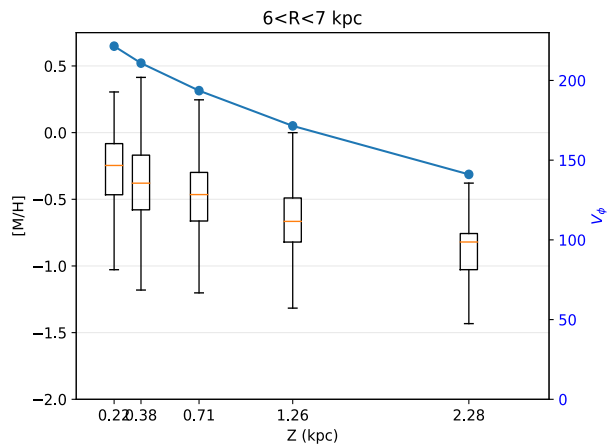
8 < R < 9 kpc

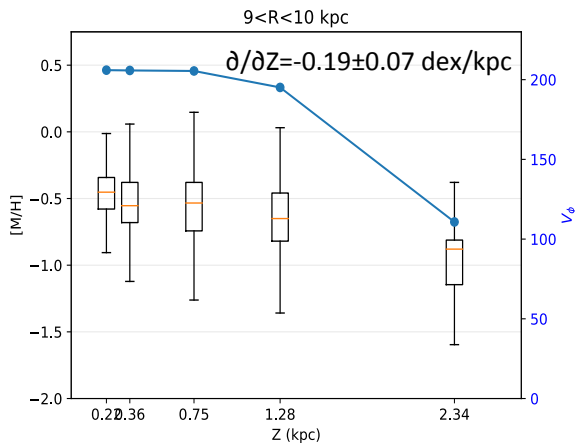
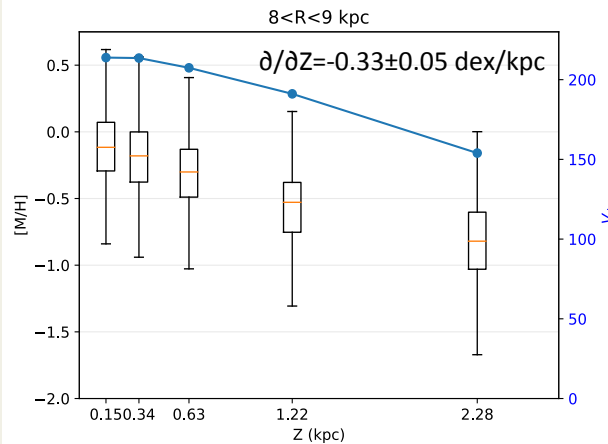
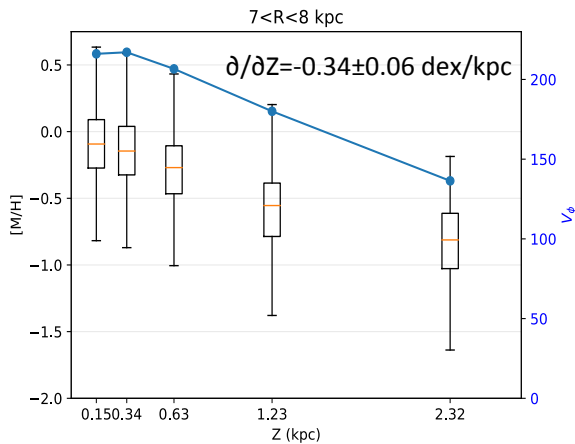
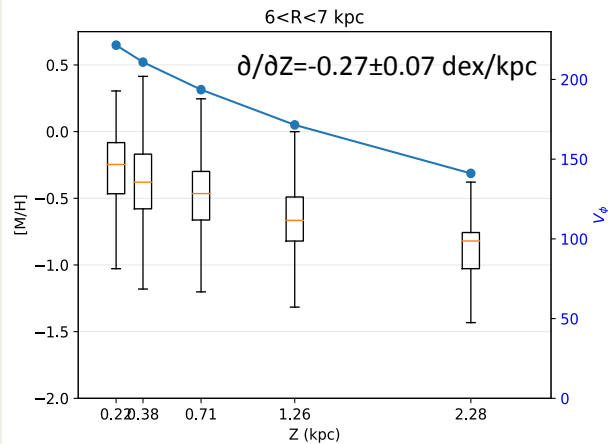


9 < R < 10 kpc

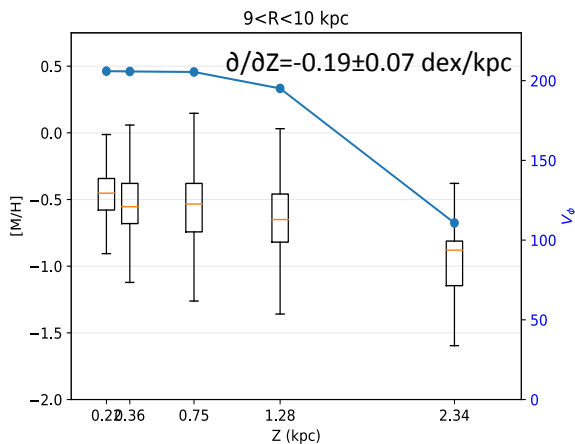
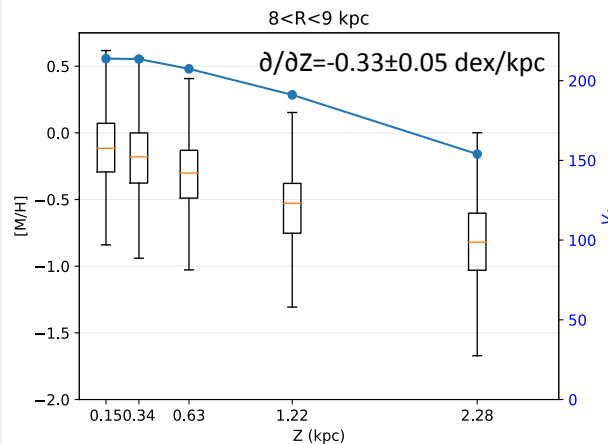
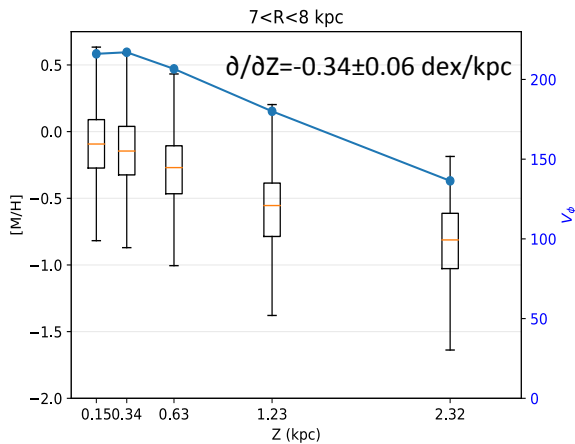
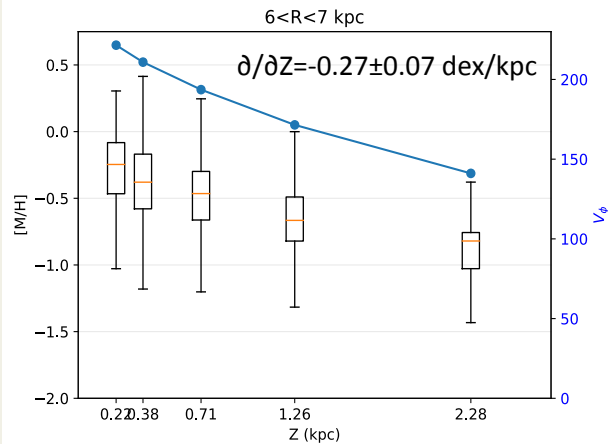


- MDFs at $7 < R < 8$ kpc & $8 < R < 9$ kpc very similar

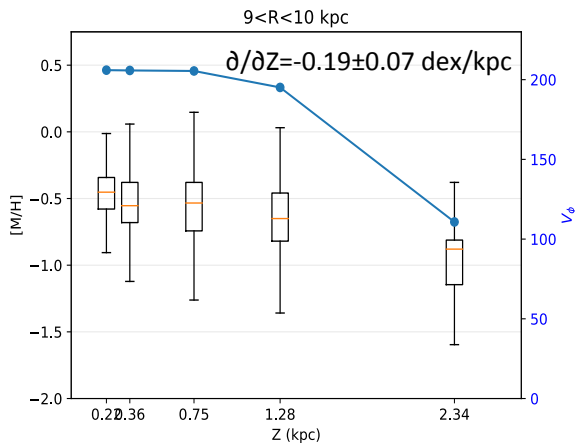
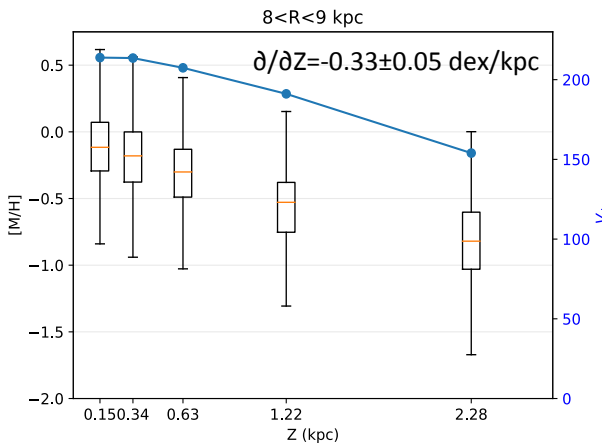
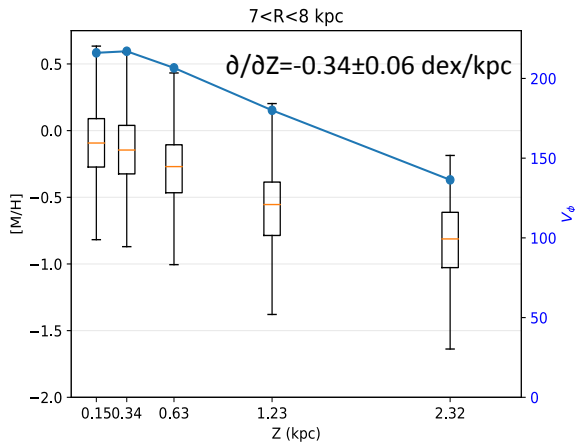
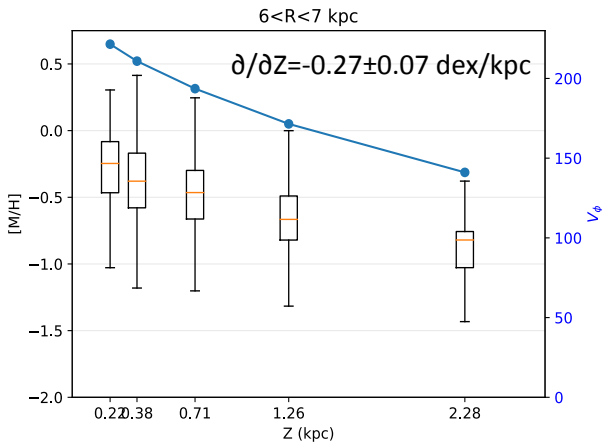




- MDFs at 7 < R < 8 kpc & 8 < R < 9 kpc very similar
 - outside this range biases exist, but vertical gradients excluding the closest bins agree
- Schlesinger et al. 2014 (using SEGUE's G dwarfs): -0.243 ± 0.05 dex/kpc

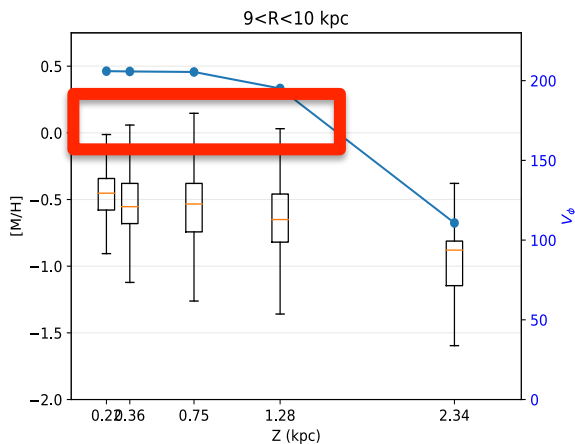
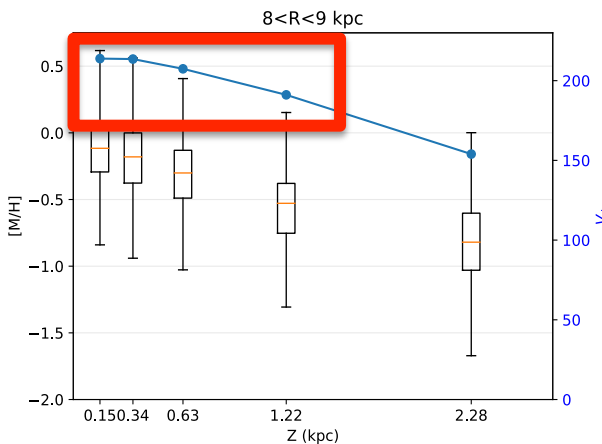
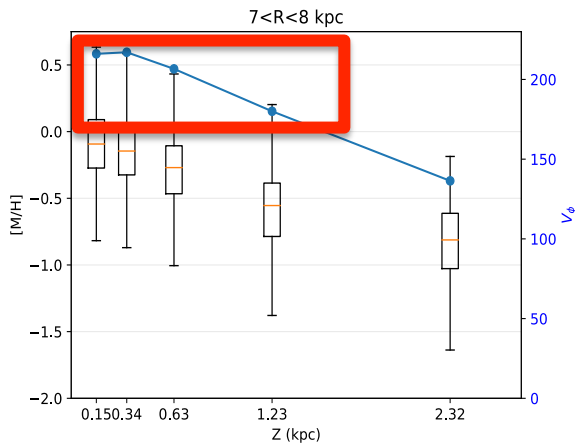
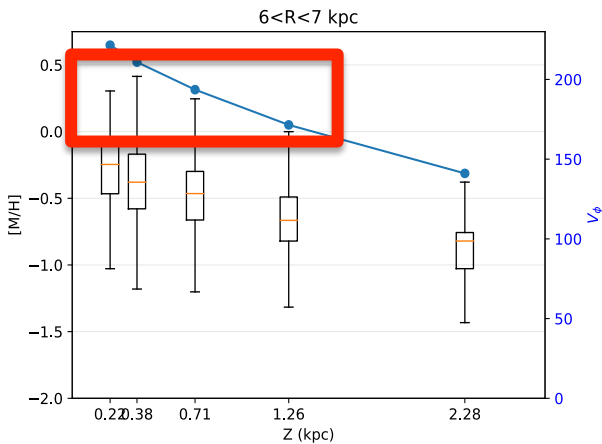


- MDFs at 7 < R < 8 kpc & 8 < R < 9 kpc very similar
- outside this range biases exist, but vertical gradients excluding the closest bins agree
 - ➔ Schlesinger et al. 2014 (using SEGUE's G dwarfs): -0.243 ± 0.05 dex/kpc
- signs of flaring of the thin disc at the outer regions



- MDFs at 7 < R < 8 kpc & 8 < R < 9 kpc very similar
- outside this range biases exist, but vertical gradients excluding the closest bins agree
 - ➔ Schlesinger et al. 2014 (using SEGUE's G dwarfs): -0.243 ± 0.05 dex/kpc
- signs of flaring of the thin disc at the outer regions

Compared to pre-Gaia results: smoother gradients, very well characterised correlations between V_ϕ and [M/H], no indication of inversion of the skewness (see Hayden et al. 2015), but need to correct for the selection function



SMR stars seen up to 1kpc from the plane, within 6 < R < 9 kpc
 Stars with [M/H] ~ 0.4 dex
 → formed at very small Galactocentric radii

Super-Solar metallicity stars → Eccentricity determination

Same procedure as in Kordopatis et al. 2015

3 discs:
$$\rho(R, z) = \frac{\Sigma_0}{2z_d} \exp \left[- \left(\frac{R_h}{R} + \frac{R}{R_d} + \frac{|z|}{z_d} \right) \right]$$

2 spheroids:

$$\rho(R, z) = \frac{\rho_0}{m^\gamma (a + m)^{\beta - \gamma}} \exp[-(mr_0/r_{\text{cut}})^2]$$

$$m(R, z) \equiv \sqrt{(R/r_0)^2 + (z/qr_0)^2}$$

Table 1. Parameters for the adopted mass model of the Milky Way.

Disc	Thick	Thin	Gas
Σ_0 ($M_\odot \text{ kpc}^{-2}$)	7.30×10^7	1.11×10^9	1.14×10^8
R_d (kpc)	2.4	2.4	4.8
z_d (kpc)	1.0	0.36	0.04
R_h (kpc)	0	0	4
Spheroid	Dark halo	Bulge	
ρ_0 ($M_\odot \text{ kpc}^{-3}$)	1.26×10^9	7.56×10^8	
q	0.8	0.6	
γ	-2	1.8	
β	2.21	1.8	
r_0 (kpc)	1.09	1	
r_{cut} (kpc)	1000	1.9	

(Dehnen & Binney 98, Binney12)

Super-Solar metallicity stars → Eccentricity determination

Same procedure as in Kordopatis et al. 2015

3 discs:
$$\rho(R, z) = \frac{\Sigma_0}{2z_d} \exp \left[- \left(\frac{R_h}{R} + \frac{R}{R_d} + \frac{|z|}{z_d} \right) \right]$$

2 spheroids:

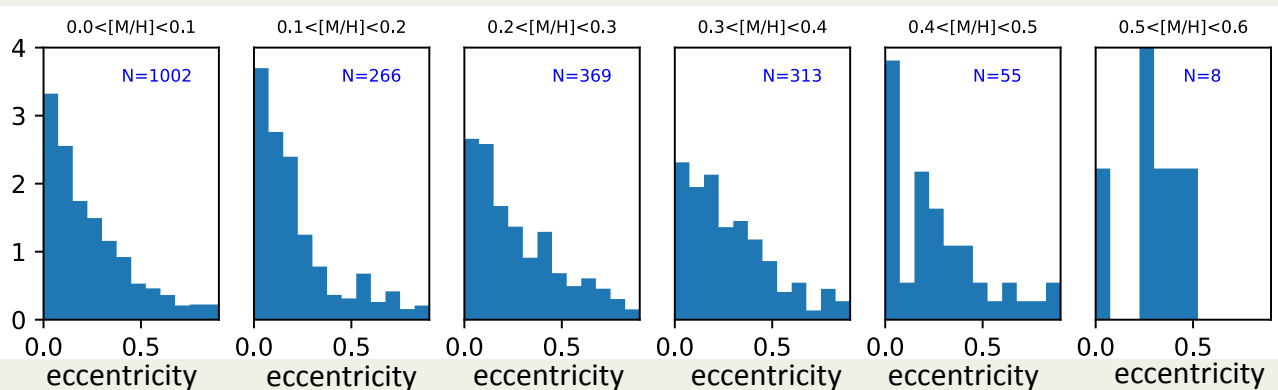
$$\rho(R, z) = \frac{\rho_0}{m^\gamma (a + m)^{\beta - \gamma}} \exp[-(mr_0/r_{\text{cut}})^2]$$

$$m(R, z) \equiv \sqrt{(R/r_0)^2 + (z/qr_0)^2}$$

Table 1. Parameters for the adopted mass model of the Milky Way.

Disc	Thick	Thin	Gas
Σ_0 ($M_\odot \text{ kpc}^{-2}$)	7.30×10^7	1.11×10^9	1.14×10^8
R_d (kpc)	2.4	2.4	4.8
z_d (kpc)	1.0	0.36	0.04
R_h (kpc)	0	0	4
Spheroid	Dark halo	Bulge	
ρ_0 ($M_\odot \text{ kpc}^{-3}$)	1.26×10^9	7.56×10^8	
q	0.8	0.6	
γ	-2	1.8	
β	2.21	1.8	
r_0 (kpc)	1.09	1	
r_{cut} (kpc)	1000	1.9	

(Dehnen & Binney 98, Binney12)



Distances DR5+

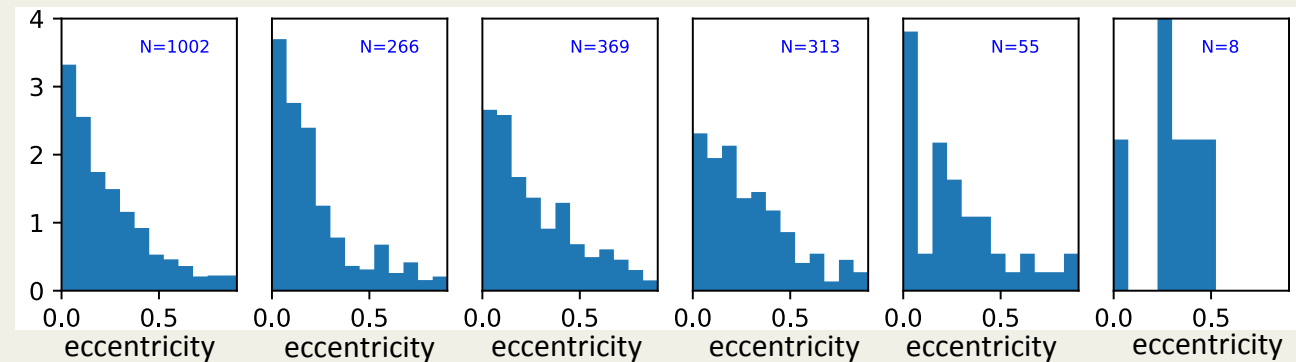
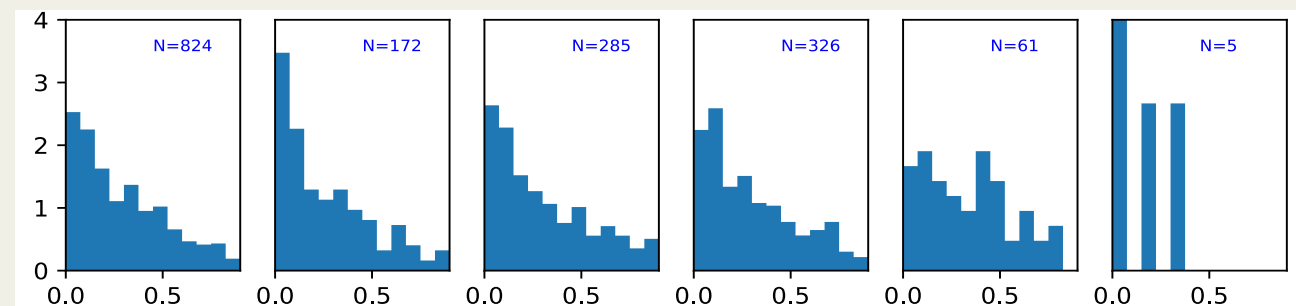
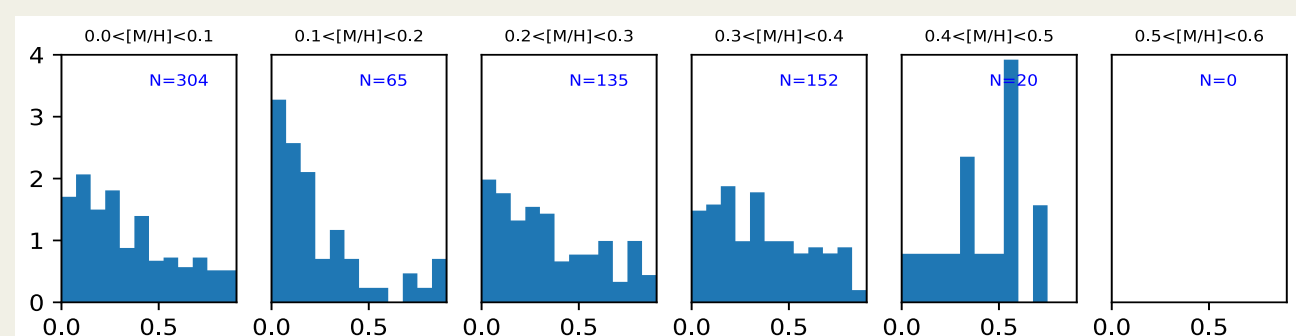
|Z| < 0.25 kpc

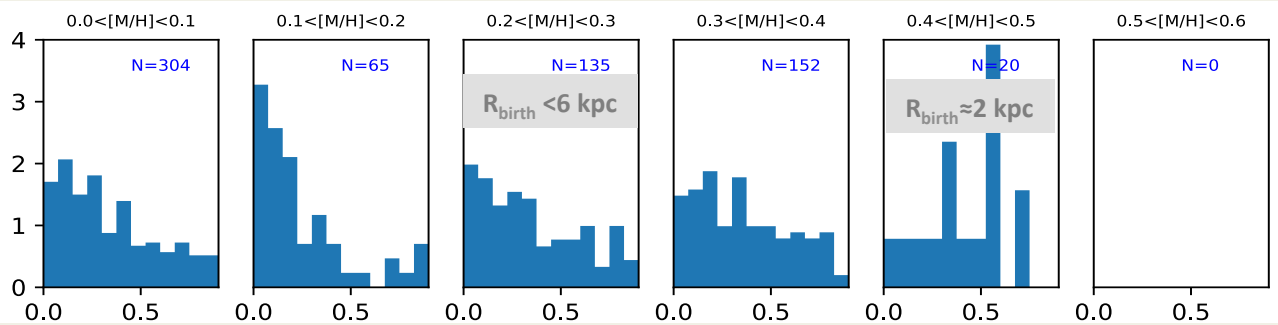
$0.5 < |Z| < 1$

$0.25 < |Z| < 0.5$

$|Z| < 0.25$ kpc

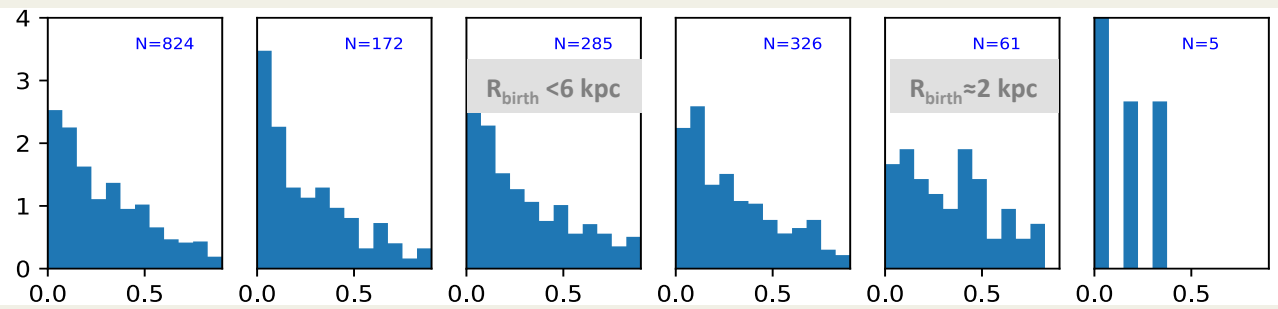
Distances DR5+





0.5 < |Z| < 1

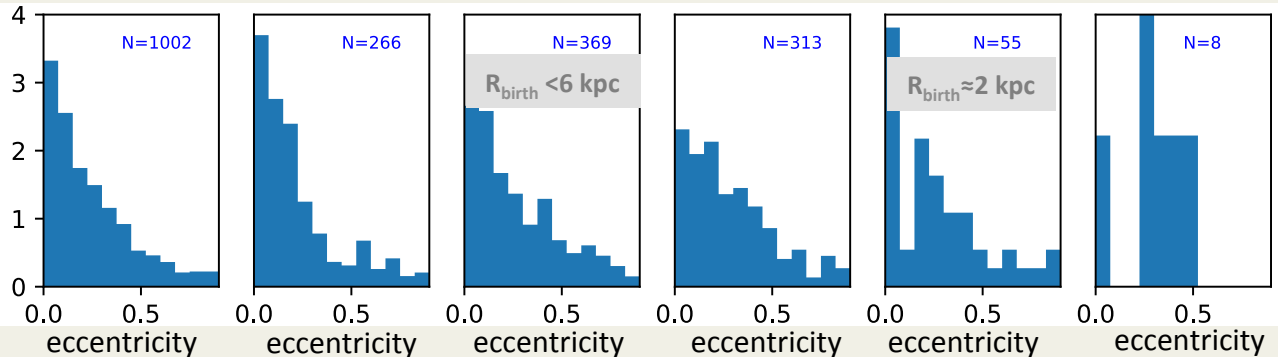
- ISM's metallicity gradient: $\partial[M/H]/\partial R \sim -0.06 \text{ dex kpc}^{-1}$ (Smartt & Rolleston 97; Balsem+11...)
- Stars born well inside R_o .



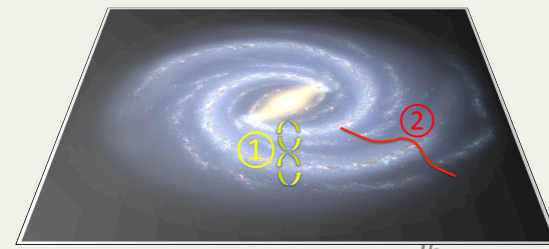
0.25 < |Z| < 0.5

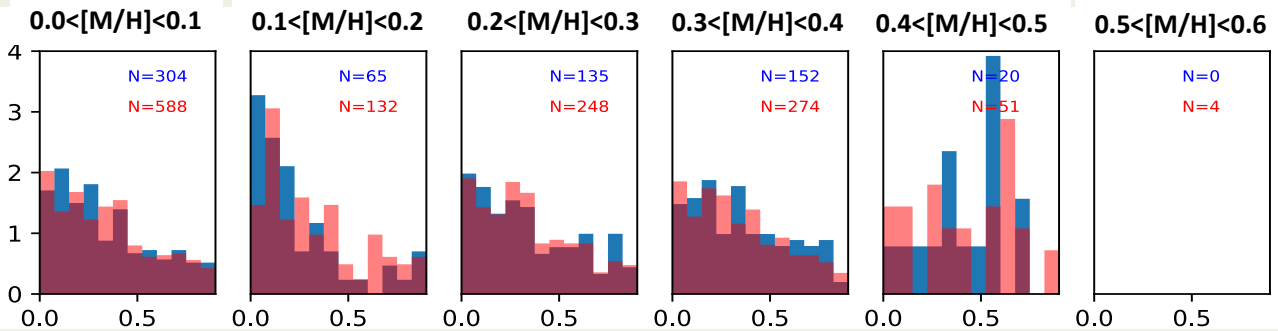
Radial migration: (Sellwood & Binney 02...)

- ① Churning: Co-rotation resonances $\Delta e/\Delta t \sim 0$
- ② Blurring: Lindblad resonances $\Delta e/\Delta t \neq 0$

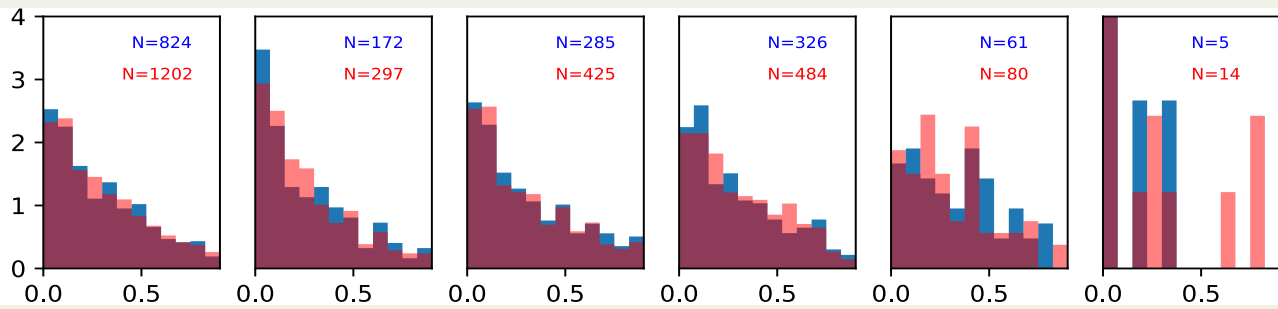


|Z| < 0.25 kpc

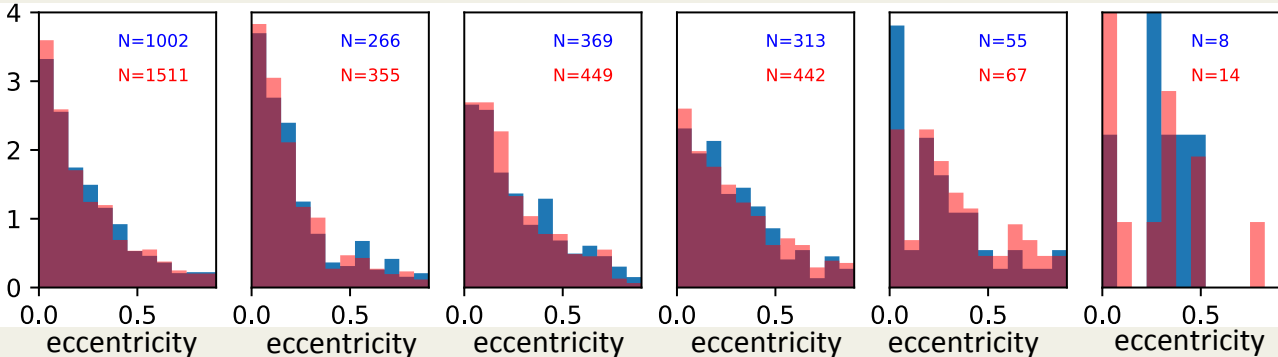




0.5 < |Z| < 1



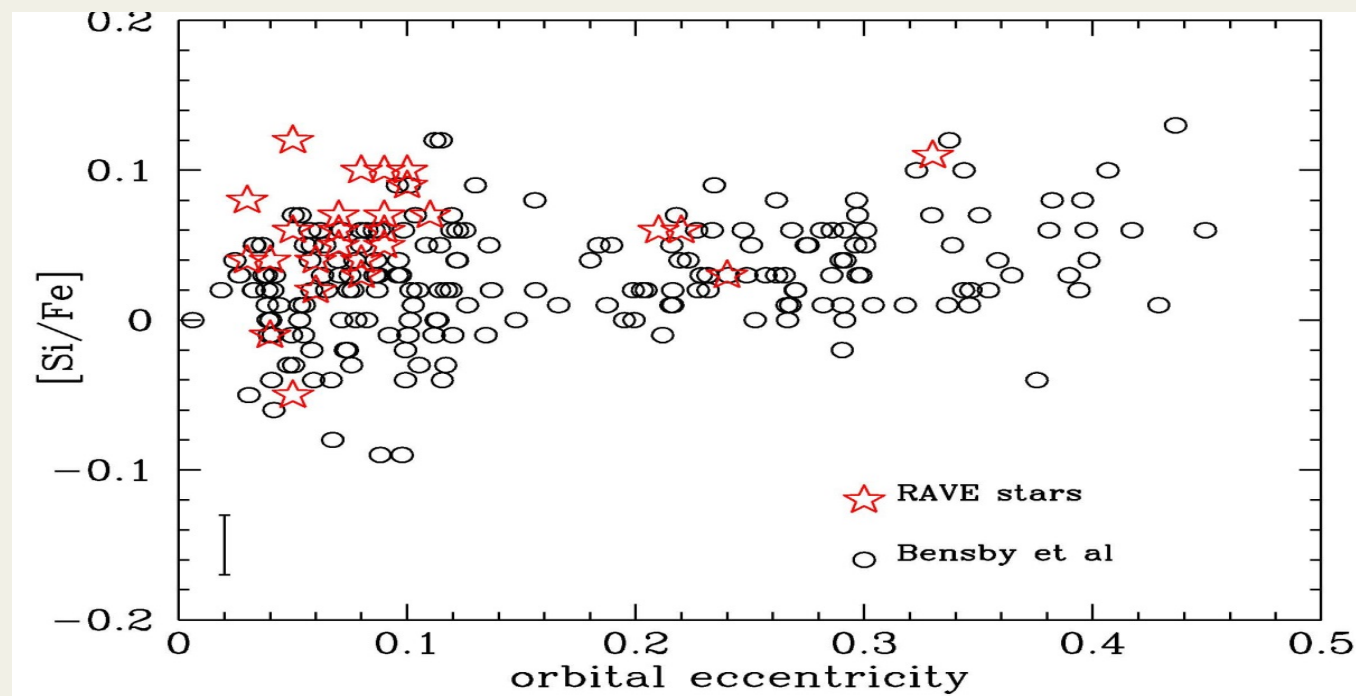
0.25 < |Z| < 0.5



|Z| < 0.25 kpc

Distances DR5+

Distances DR5



Wyse, Hawkins, Kordopatis, Ruchti (in prep)


- ~40 stars observed with APO/ARCES ($R=31\ 500$)
- Hints of larger scatter in $[Si/Fe]$ for lowest orbital eccentricity
 - Need larger samples, plus model predictions

Conclusions

- New distances and updated pm allowed a re-analysis of existent data-sets
- General trends well identified in previous works
 - SMR stars on low-e confirmed
 - Correlation between $[M/H]-V_{\phi}$ confirms existence of thick disc in the inner disc and absence of it at the outer.
- Skewness study to be performed taking into account the completeness fraction.
- Decomposition into thin and thick disc & age analysis with RAVE data is difficult, but in progress (see J. Wojno's poster)

Ages + thin & thick disc decomposition

See **J. Wojno's poster (C49)**
Ages by P. McMillan



Leibniz-Institut für
Astrophysik Potsdam

The age-metallicity relation in the solar neighbourhood as seen by RAVE

Jenssen Wojno¹, Georges Kordopatis², Matthias Steinmetz¹, Paul McMillan³, and the RAVE collaboration
¹ Leibniz-Institut für Astrophysik Potsdam (AIP), Germany; ² Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, France; ³ Lund Observatory, Lund University, Sweden

ABSTRACT
 Using RAVE data release 5 (DR5), we explore the connections between age and chemistry in the extended solar neighbourhood with a sample of ~25,000 FG stars. Ages are determined using an updated Bayesian method taking TGAS parallaxes as a prior, together with T_{eff} , log g, [M/H], and an underlying galactic model. For the first time, we have Bayesian age estimates available for a large volume ($T_{\text{eff}} > 4.5$ Gyr) of solar neighbourhood field stars. We separate our sample into two chemical disc components, an age (typically associated with the thick disc), and an α -low component (typically associated with the thin disc). We then investigate the nature of the age-metallicity relation in the solar neighbourhood, for both disc components. Overall, we find a flat trend in [Fe/H] as a function of age for our α -low disc, while for our α -high disc, we find a correlation between age and metallicity for the oldest ($T > 8$ Gyr) stars. When we deconstruct the age-metallicity relation into mono-abundance populations, we find a smoothly evolving trend between both disc components. Finally, we also find a positive gradient in [Mg/Fe] as a function of age for our oldest stars. Overall, we confirm age-metallicity trends found in more local, high-resolution studies now for a larger volume. These results have implications for models which include dynamical evolutionary processes in the disc, such as radial migration which brings metal-rich stars with a large range in age from the inner disc to the solar neighbourhood.

1. SAMPLE SELECTION

For this study, we select a local (l=mid-right distance < 1 kpc), high-quality (DR5 < 60) sample of turnoff stars from RAVE DR5 (Kunder et al. 2017). Our selection criteria in T_{eff} -log g space is shown in Figure 1 by the dashed red lines. For the whole RAVE/DR5 sample, half of the stars have age uncertainties greater than 1 Gyr. With our selection, ~50% of stars have age uncertainties less than 2 Gyr, and a sizable fraction (~15%) have age uncertainties less than 1 Gyr. Our final sample consists of 25,017 stars.

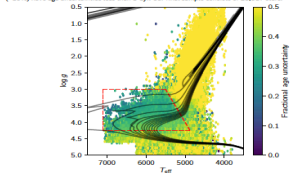


Figure 1. Turnoff diagram showing our parameter space selection (red dashed line). Stars are colour-coded by their average fractional age uncertainty. Stars with metallicities between -0.12 and 0.12 dex $[Fe/H]$ stars, are plotted in black.

2. CHEMICAL SEPARATION OF DISC COMPONENTS

To our sample of turnoff stars, we apply the probabilistic chemical separation method described in Wojno et al. (2016). This method uses a model metallicity distribution function and alpha distribution function for both the α -low (thin disc) and α -high (thick disc) to determine the likelihood (likelihood) that a star belongs to each component. Stars are assigned to a disc component using the following criteria:

$$\log(\text{likelihood}) > 1.0 \Rightarrow \text{Thick disc}$$

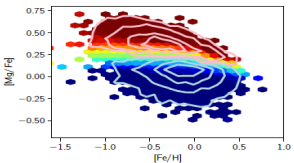
$$\log(\text{likelihood}) < -1.0 \Rightarrow \text{Thin disc}$$


Figure 2. Our sample in $[Fe/H]$ - $[Mg/Fe]$ space. Stars are colour-coded by the log(likelihood) of a star belonging to a given disc component. Contours show our selected thin and thick disc components in blue and red, and consist of 10,112 and 4,072 stars, respectively. The seven 10,000 stars which were not assigned to a component.

3. AGE-METALLICITY RELATION

We find different age-metallicity relations for our two chemical disc components. Our thin disc is consistent with a flat trend, i.e., no correlation between age and metallicity (see Figure 3, below). In contrast, we find a correlation between age and metallicity for our thick disc. When we consider the oldest stars ($T > 8$ Gyr) in the thick disc, we measure a gradient of -0.05 dex Gyr⁻¹. This falls between trends found by high-resolution studies (-0.2 dex Gyr⁻¹, e.g., Haywood et al. 2013, Berdyajev et al. 2014), and the recent study by Fuhrmann et al. 2017 (0.017 dex Gyr⁻¹).

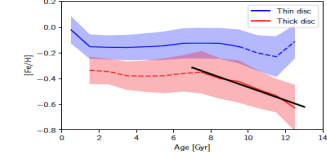


Figure 3. Trends in $[Fe/H]$ as a function of age for our selected thin (blue) and thick (red) components. Solid colored lines indicate the mean $[Fe/H]$ for a given age bin, while the shaded regions indicate the dispersion (1 σ). Dashed lines indicate regions where we assume a non-negligible amount of contamination between the disc components. The solid black line shows our fit of the AAR to the aged ($T > 8$ Gyr) thick disc sample.

4. AGE-METALLICITY RELATION, DECOMPOSED

When we decompose the age-metallicity relation for both disc components into bins of $[Mg/Fe]$, we find a smoothly evolving trend. For bins near $[Mg/Fe] = 0.2$, we find a relatively flat trend, consistent with the thin disc (see Figure 3). For bins with $[Mg/Fe] < 0.2$, we find trends similar to the thick disc component in Figure 3. For the most α -high bins, we find a correlation between age and metallicity over the whole range in age, with a gradient of -0.02 dex Gyr⁻¹.

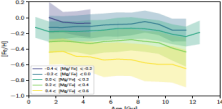


Figure 4. Age-metallicity relations for our sample, divided into 0.2 dex wide bins of $[Mg/Fe]$.

5. AGE-ALPHA RELATION

For the age-alpha relation, we find a flat trend for young stars ($T < 8$ Gyr), and a slight positive trend (<0.01 dex Gyr⁻¹) for the oldest stars. This trend is more shallow than those found by Berdyajev et al. (2014) and Haywood et al. (2015).

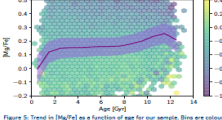
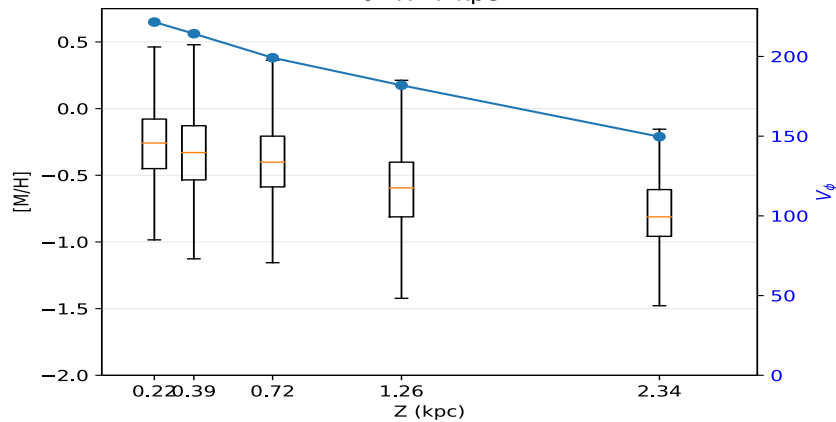


Figure 5. Trend in $[Mg/Fe]$ as a function of age for our sample. Stars are colour-coded by the average $[Fe/H]$ in a given bin. The solid purple line indicates the mean $[Mg/Fe]$ for a given age bin, while the shaded regions indicate the dispersion (1 σ).

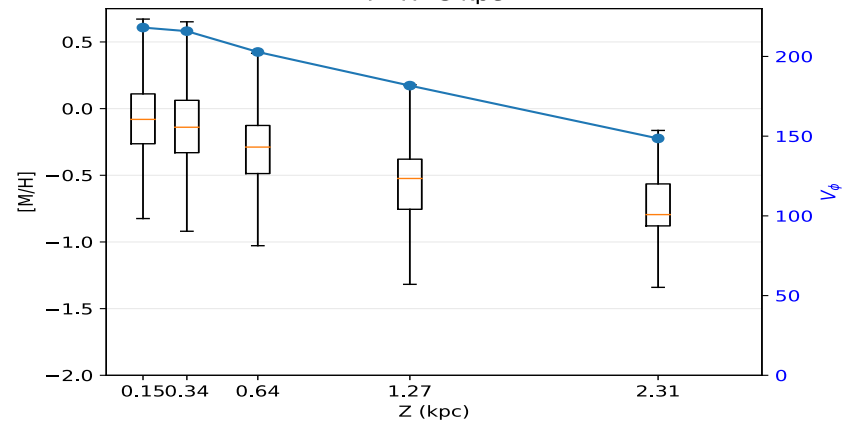
REFERENCES AND ACKNOWLEDGEMENTS
 Berdyajev, T., Prilling, S., Oey, M. S., 2014, A&A, 562, A71.
 Fuhrmann, J., Chen, K., Leshchinski, I., & Chen, J., 2017, MNRAS, 466, 2610.
 Haywood, P., Di Matteo, P., Lattanzi, M. D., Iorio, D., Gómez, A., 2016, MNRAS, 454, 4249.
 Fuhrmann, P., 2017, MNRAS, 466, 4139.
 Haywood, P., Di Matteo, P., Smith, G., & Lattanzi, M. D., 2014, MNRAS, 435, A47.
 Kordopatis, G., Kordopatis, G., Steinmetz, M., et al., 2017, AJ, 153, 79.
 Wojno, J., Kordopatis, G., Steinmetz, M., et al., 2016, MNRAS, 454, 4249.
 Funding for RAVE (www.raive.org) has been provided by institutions of the RAVE participants and by their national funding agencies.

Thank you

6 < R < 7 kpc

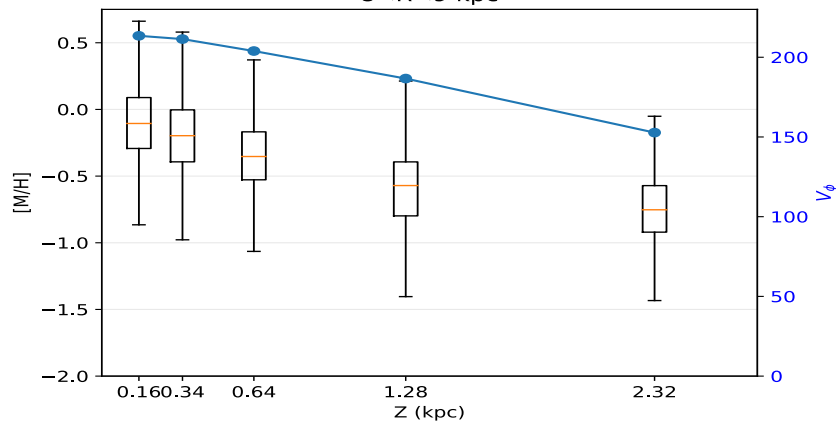


7 < R < 8 kpc

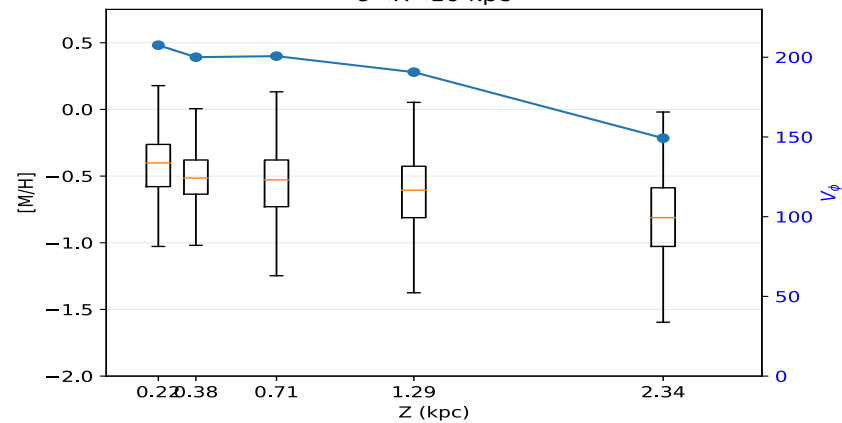


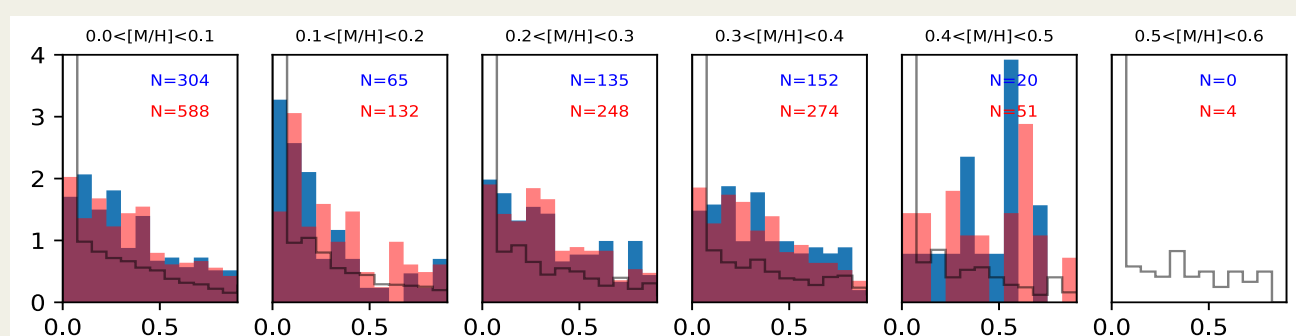
RAVE-DR5 + UCAC4

8 < R < 9 kpc

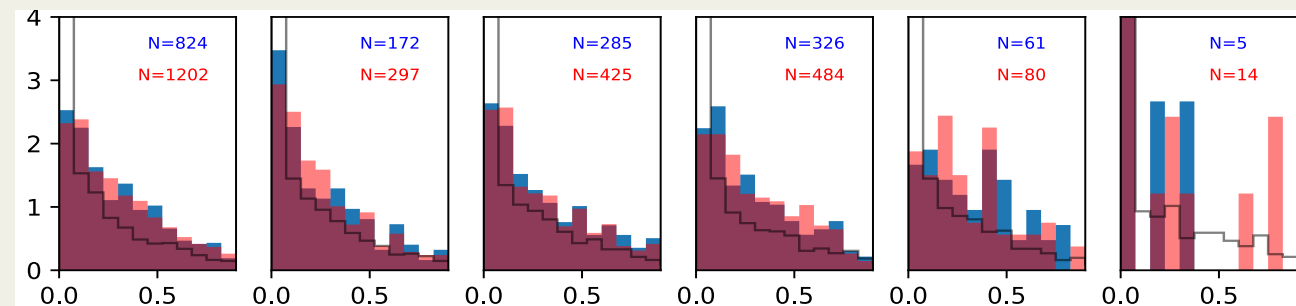


9 < R < 10 kpc

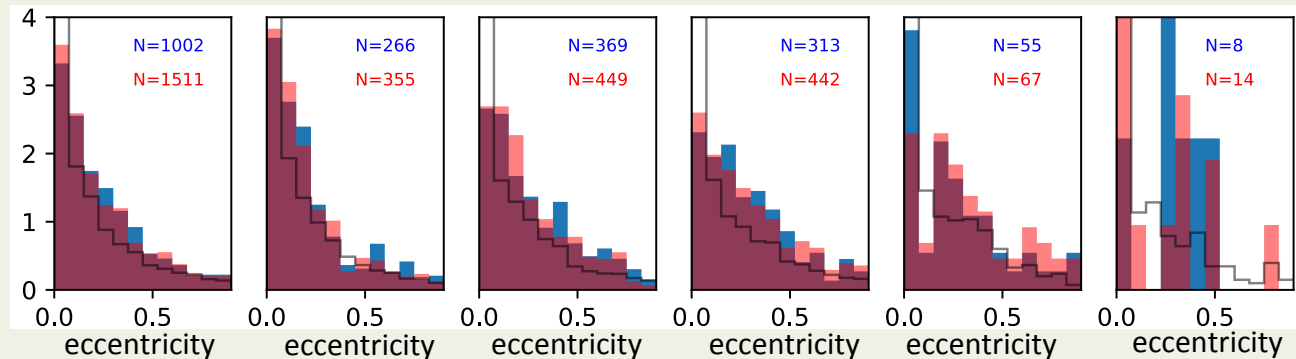




0.5 < |Z| < 1



0.25 < |Z| < 0.5



Distances DR5+
 Distances DR5
 Cannon

|Z| < 0.25 kpc