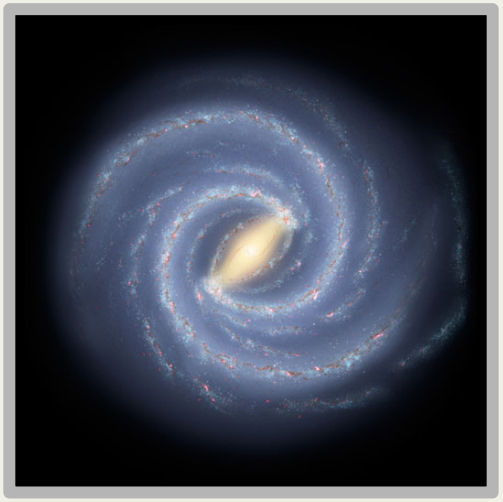
Evidence from the RAVE survey for stellar radial migration



G. Kordopatis

IoA, Cambridge

AIP, Potsdam

Gaia-ESO Survey 2nd Science Meeting

Porto, November 2014

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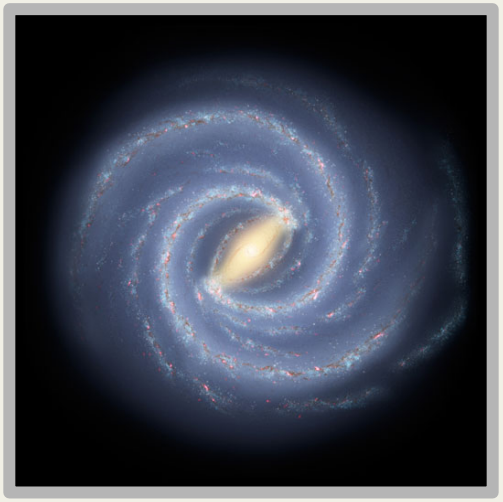

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P. Hatfield,[5,1] E. K. Grebel,[6] M. Steinmetz,[2] J.F. Navarro,[7] G. Seabroke,[8] I. Minchev,[2]
C. Chiappini,[2] O. Bienaymé,[9] J. Bland-Hawthorn,[10] K.C. Freeman,[11] B. K. Gibson,[12,13]
A. Helmi,[14] U. Munari,[15] Q. Parker,[16,17,18] W.A. Reid,[16,17] A. Siebert,[8] A. Siviero,[19] T. Zwitter[20]

AIP

Gaia-ESO Survey 2nd Science Meeting
Porto, November 2014

ioa

Outline

① Super-Solar metallicity stars & Radial migration

② Detection of Metal-rich stars in RAVE
- Spatial distribution
- Evolution of the MDF as a function of R,z
- Orbital characterisation

③ Spiral history of the Milky Way

Introduction: Super-Solar Metallicity stars

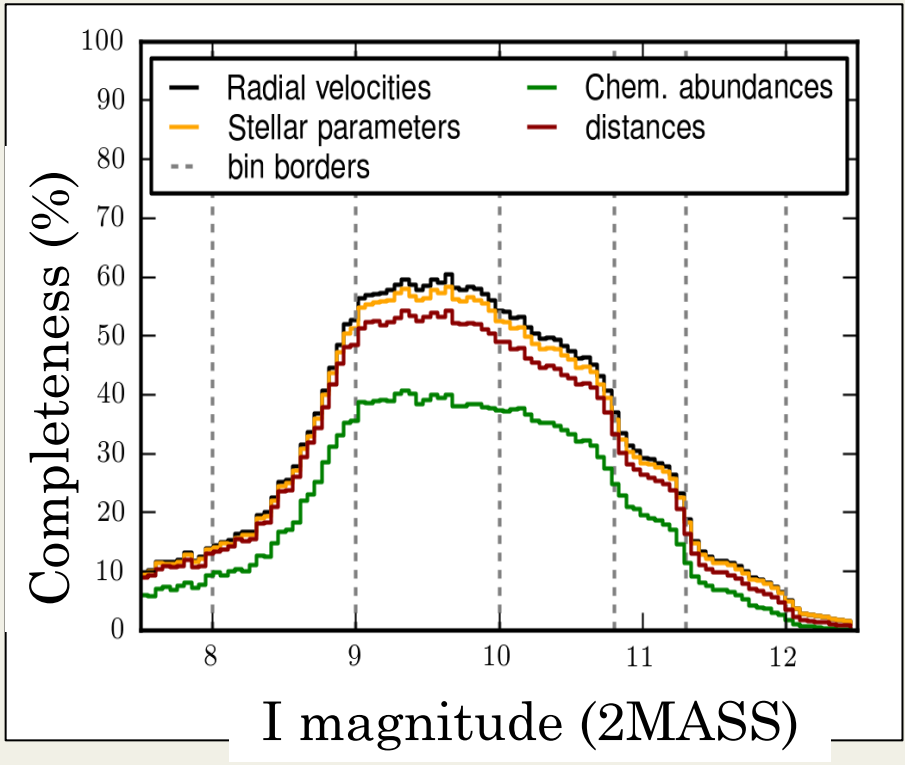
- ISM's [M/H]: increasing function of time
  - Information on the local stellar formation history
- ISM at the Solar neighbourhood: ~0dex
  - Homogeneous over few 100 pc (Cartledge+06)
- Stellar [M/H]: imprint of ISM's metallicity where and when a star was born

Super-Solar Metallicity stars at the Solar neighbourhood:

➢ **Not born locally**

RAVE catalogue:

- Intermediate resolution (R~7500)
- 425 561 stars,
- 482 430 spectra *(DR3: 77 461 stars)*
- 9 <I< 12 mag



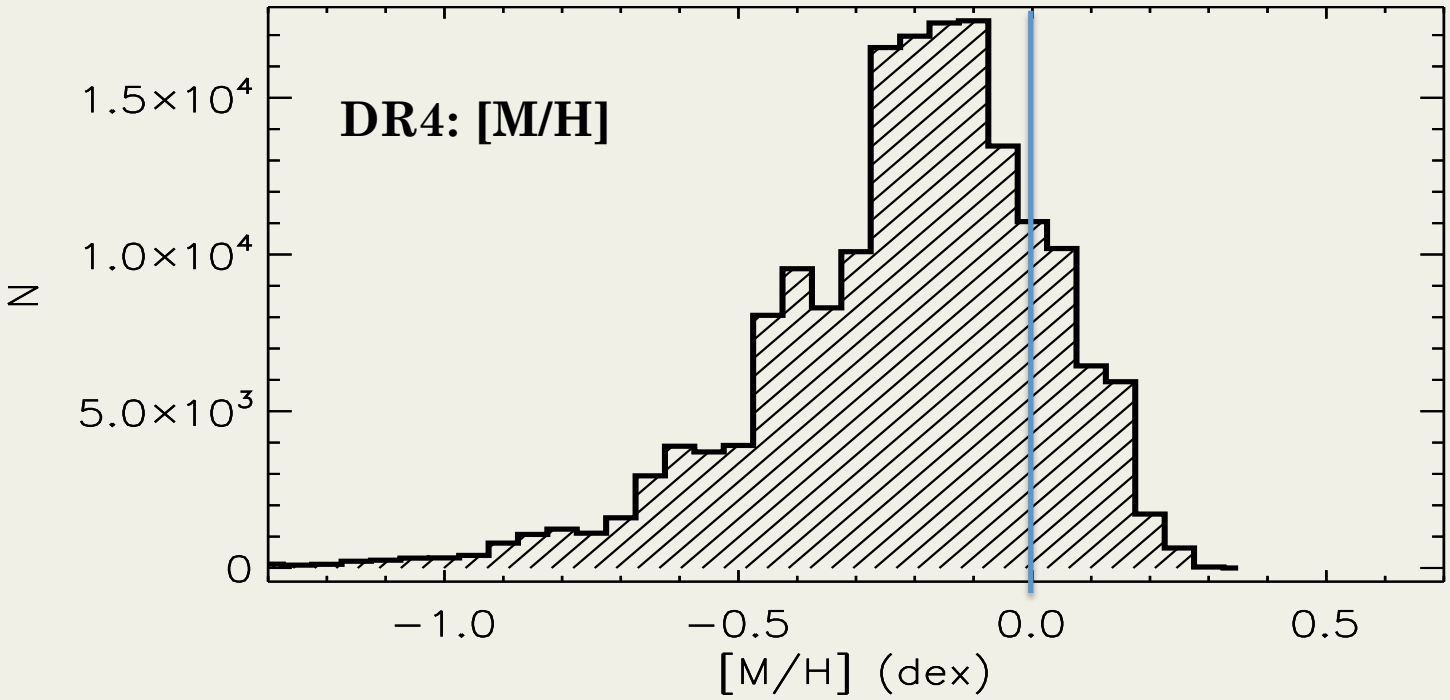
Kordopatis+13b

Database:

- ✓ **Radial velocities**
- ✓ **Spectral morphological flags**
- ✓ **T_{eff}, logg, [M/H], [X/Fe]**
- ✓ **Distances**
- ✓ **Photometry**:
  DENIS, USNOB, 2MASS, APASS
- ✓ **Proper motions:**
  UCAC4, PPMX, PPMXL, Tycho-2, SPM4

RAVE's MDF

- DR4: lacking metal-rich calibrators



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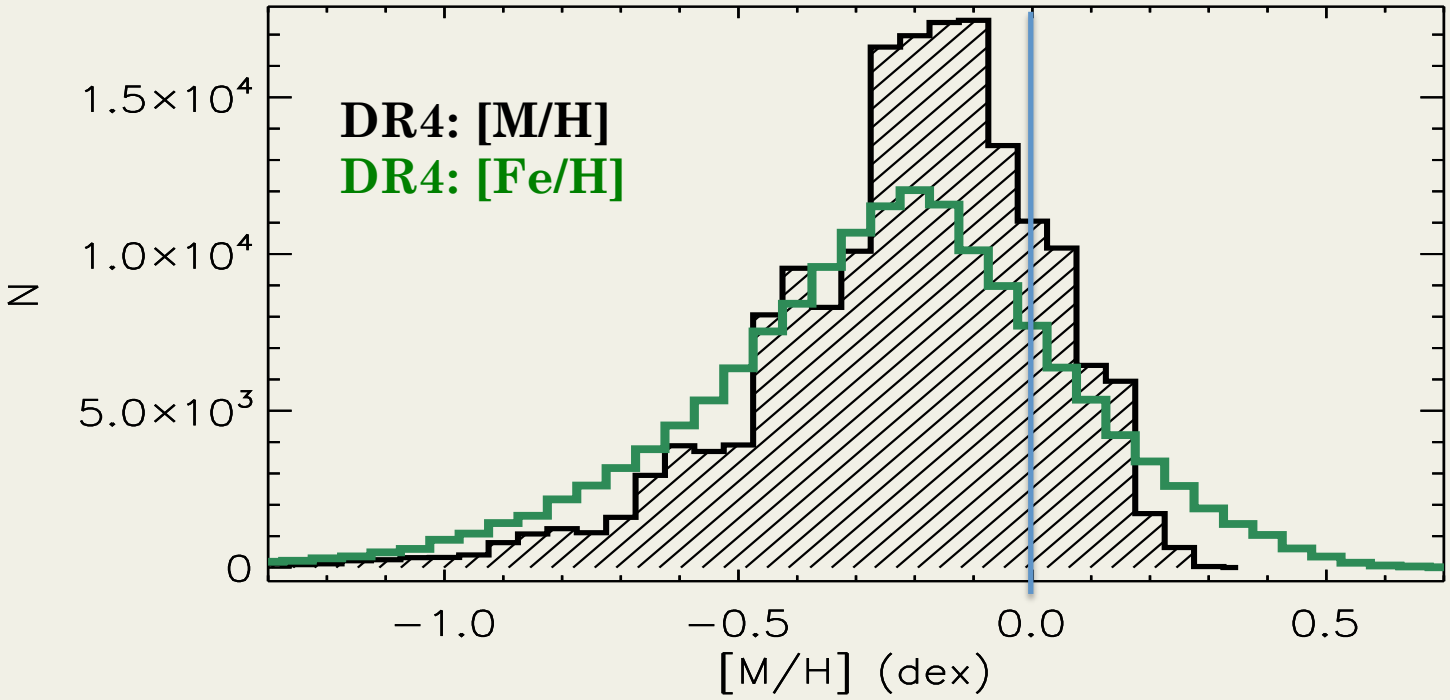
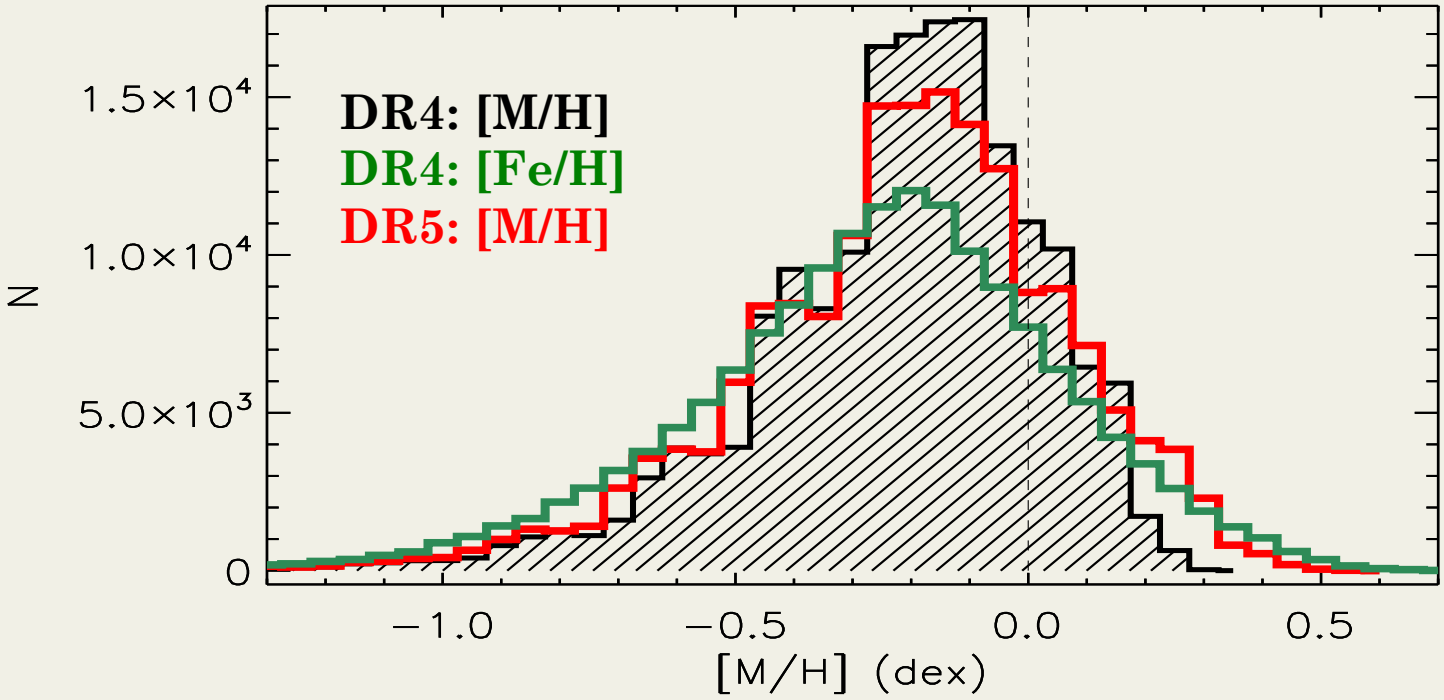


RAVE's MDF

- DR4: lacking metal-rich calibrators
- DR5 (in prep):~150 metal-rich calibrators
  (Adibekyan+12, Worley+13)

  + Benchmark stars *(Joffré+13)*



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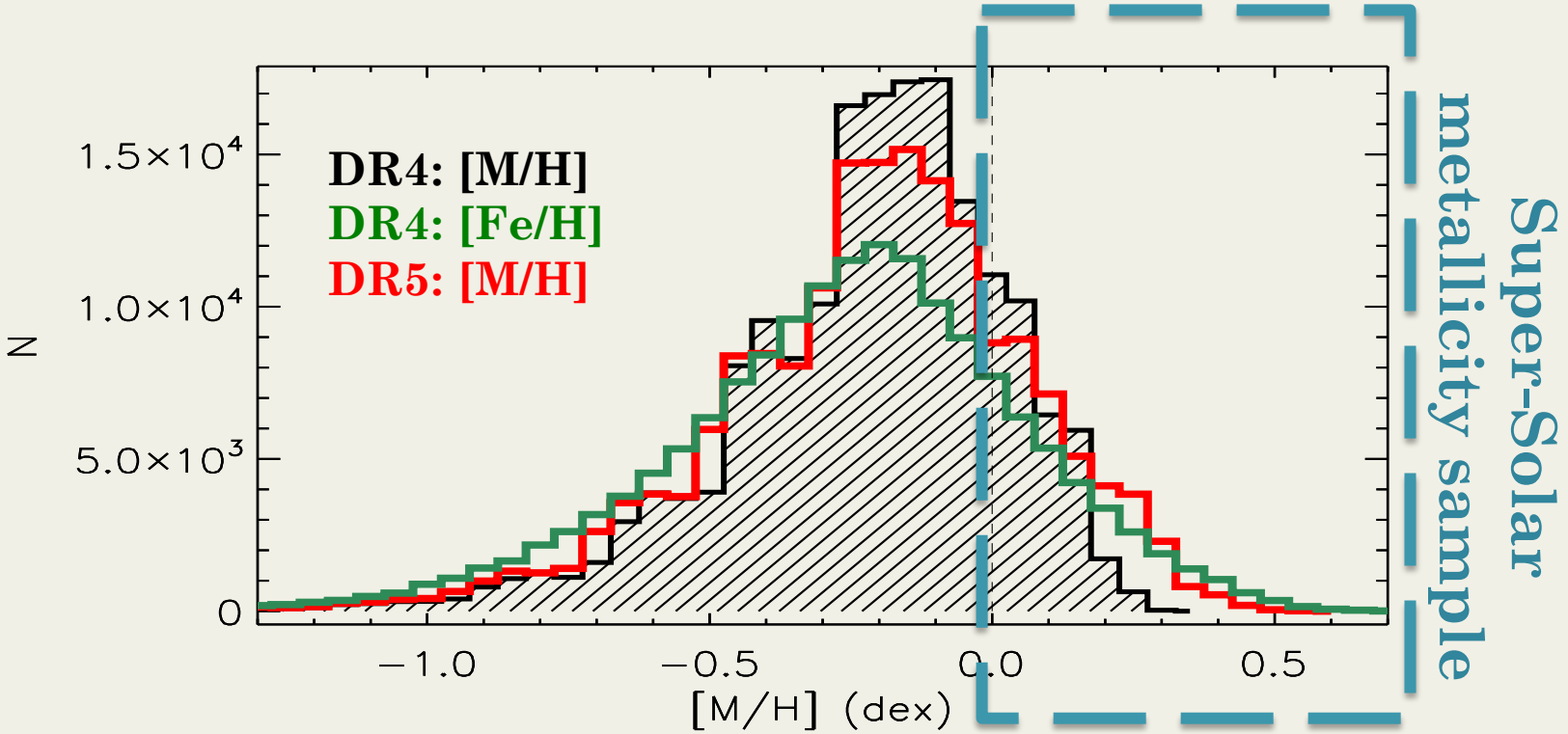
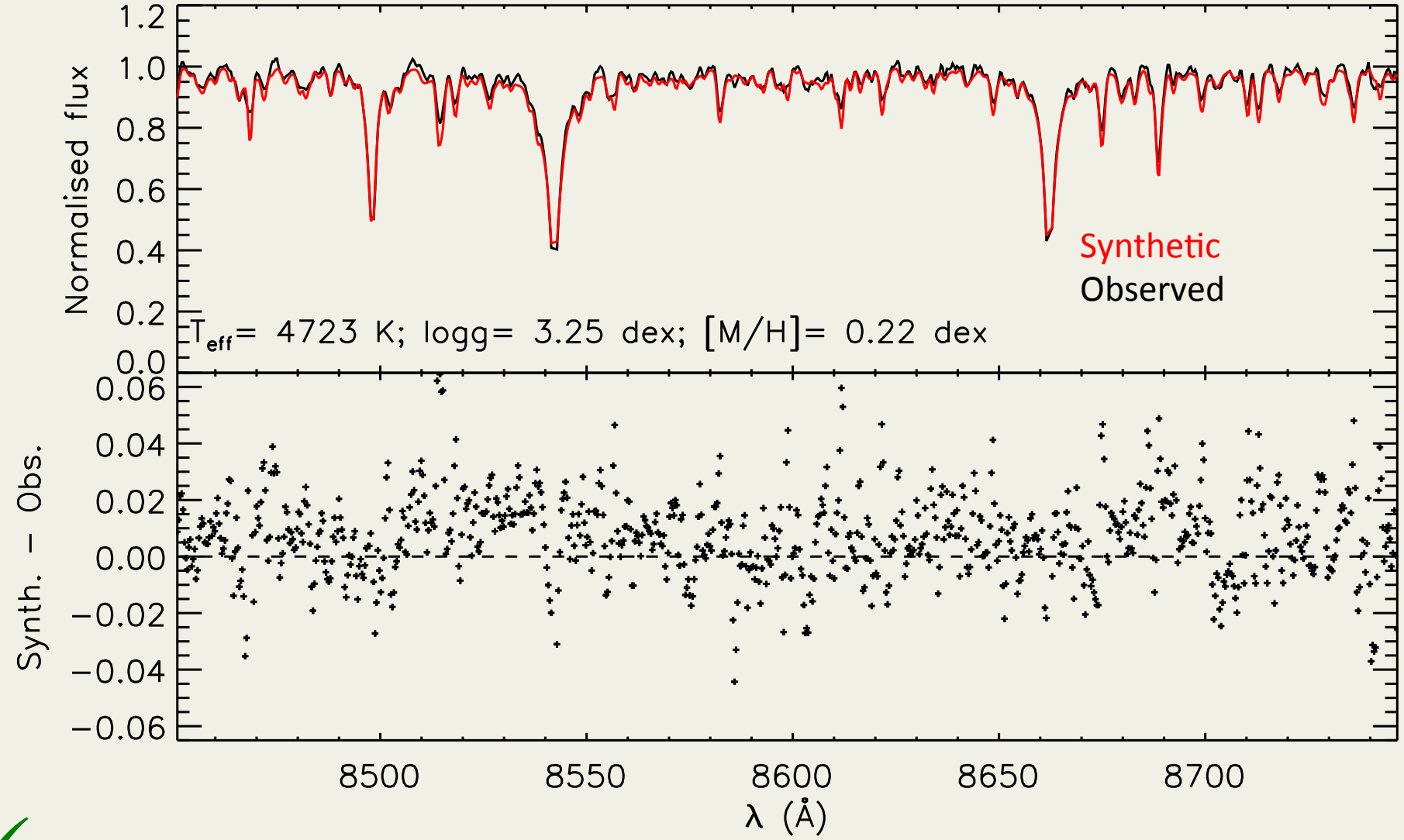
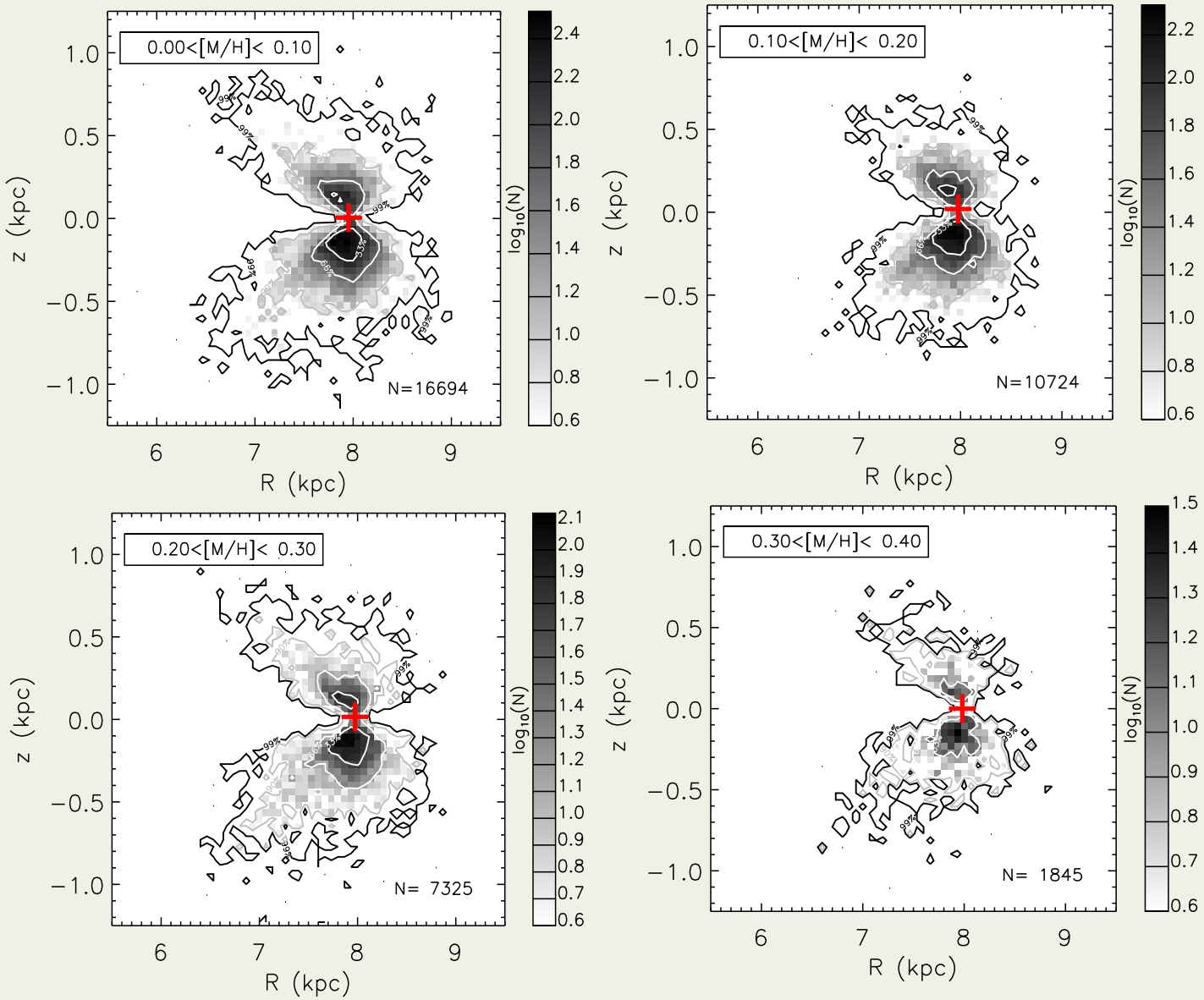


Super-Solar metallicity stars



✓ Good agreement between observations and synthetic spectra

Super-Solar metallicity stars

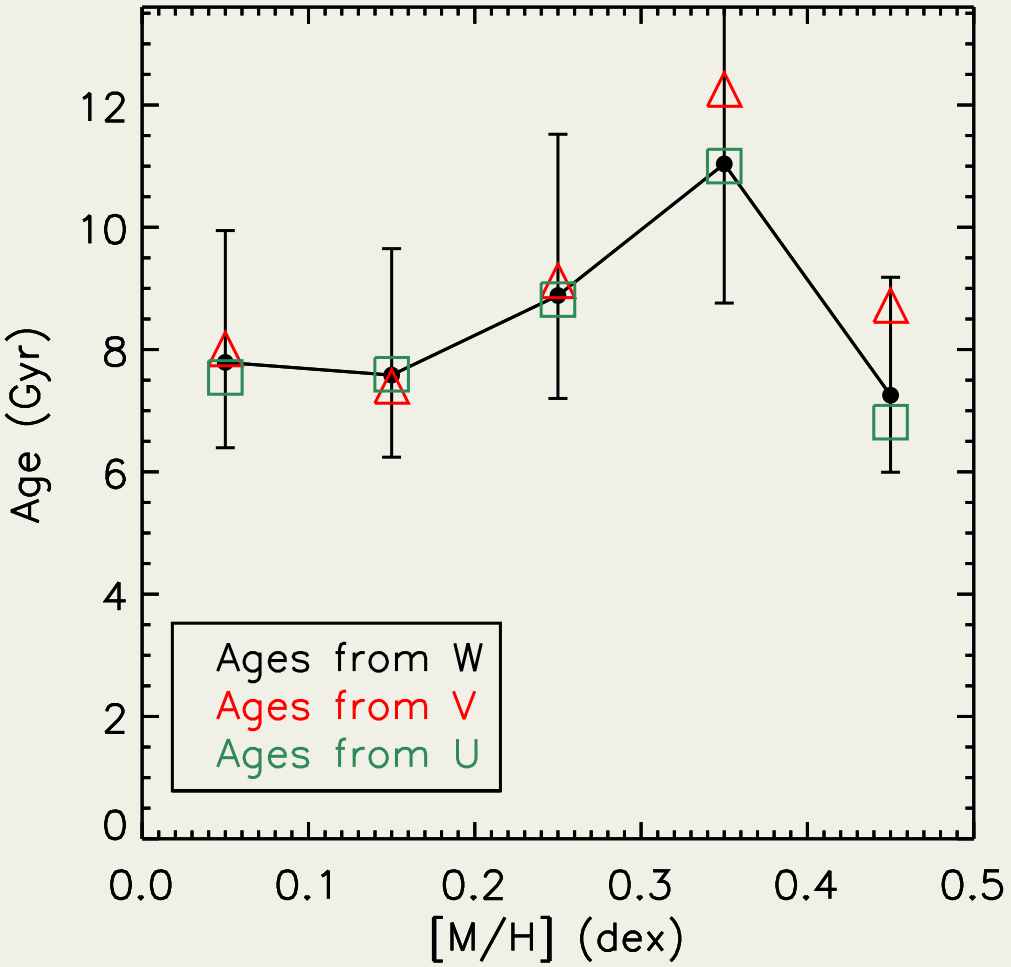


Stars mainly located close to the plane.

- **But also:**

Fair amount of stars between $0.4 < z < 1$ kpc

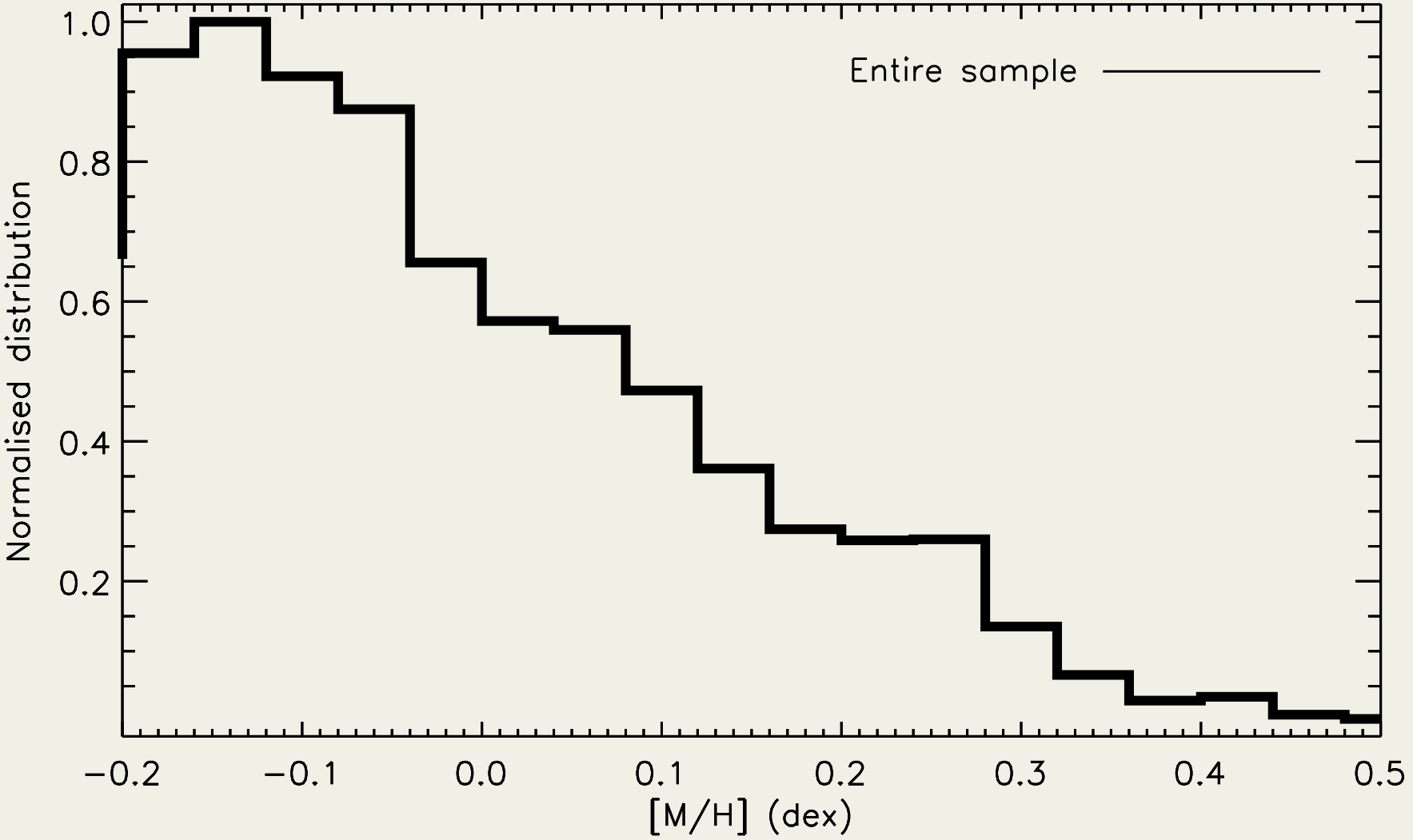
Age estimation



Ages obtained from the age-velocity dispersion relation
(Nordstrom+04, Sharma+14)

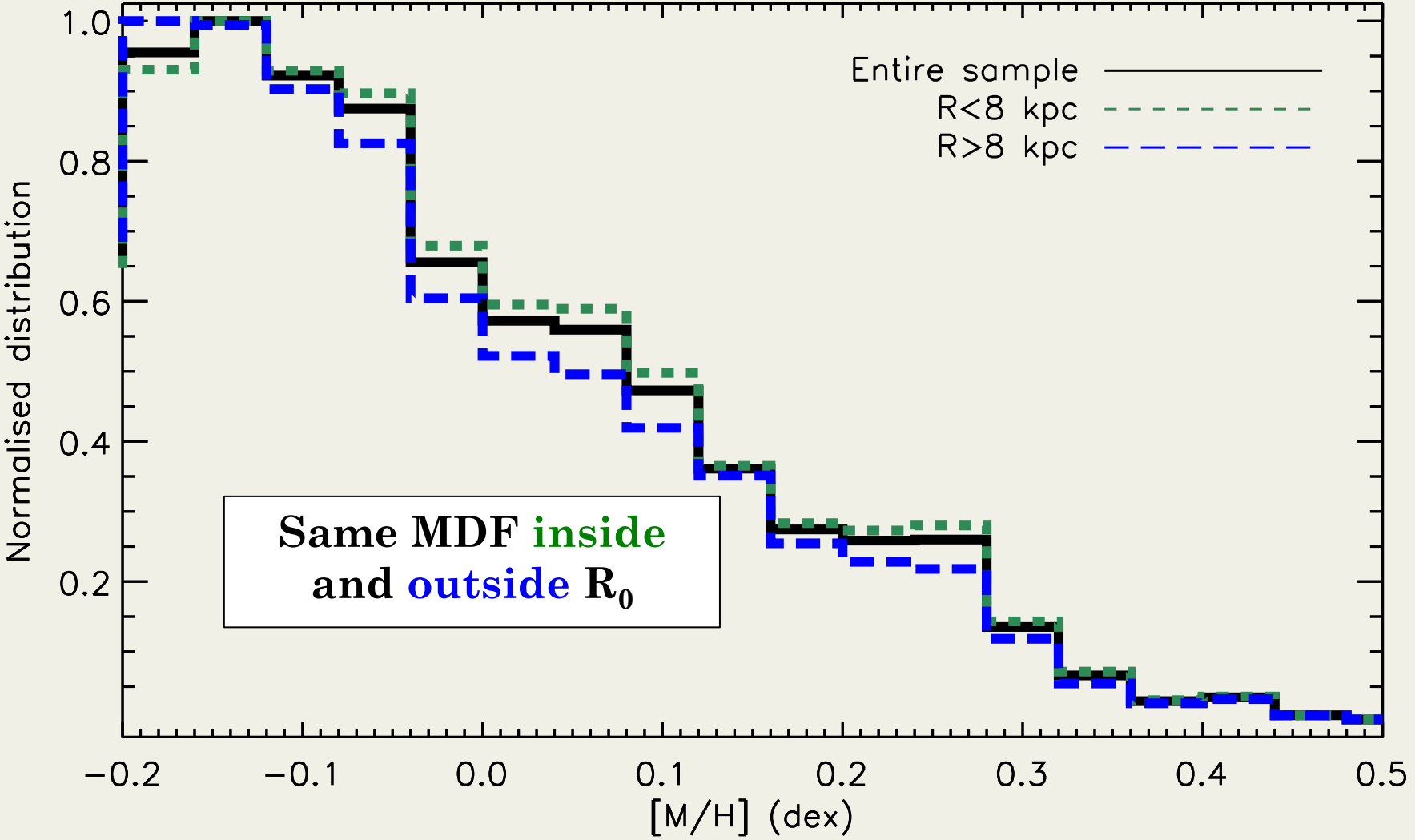
- **Consistent with being old populations**

Metallicity distribution function



Metallicity distribution function

1) R separation



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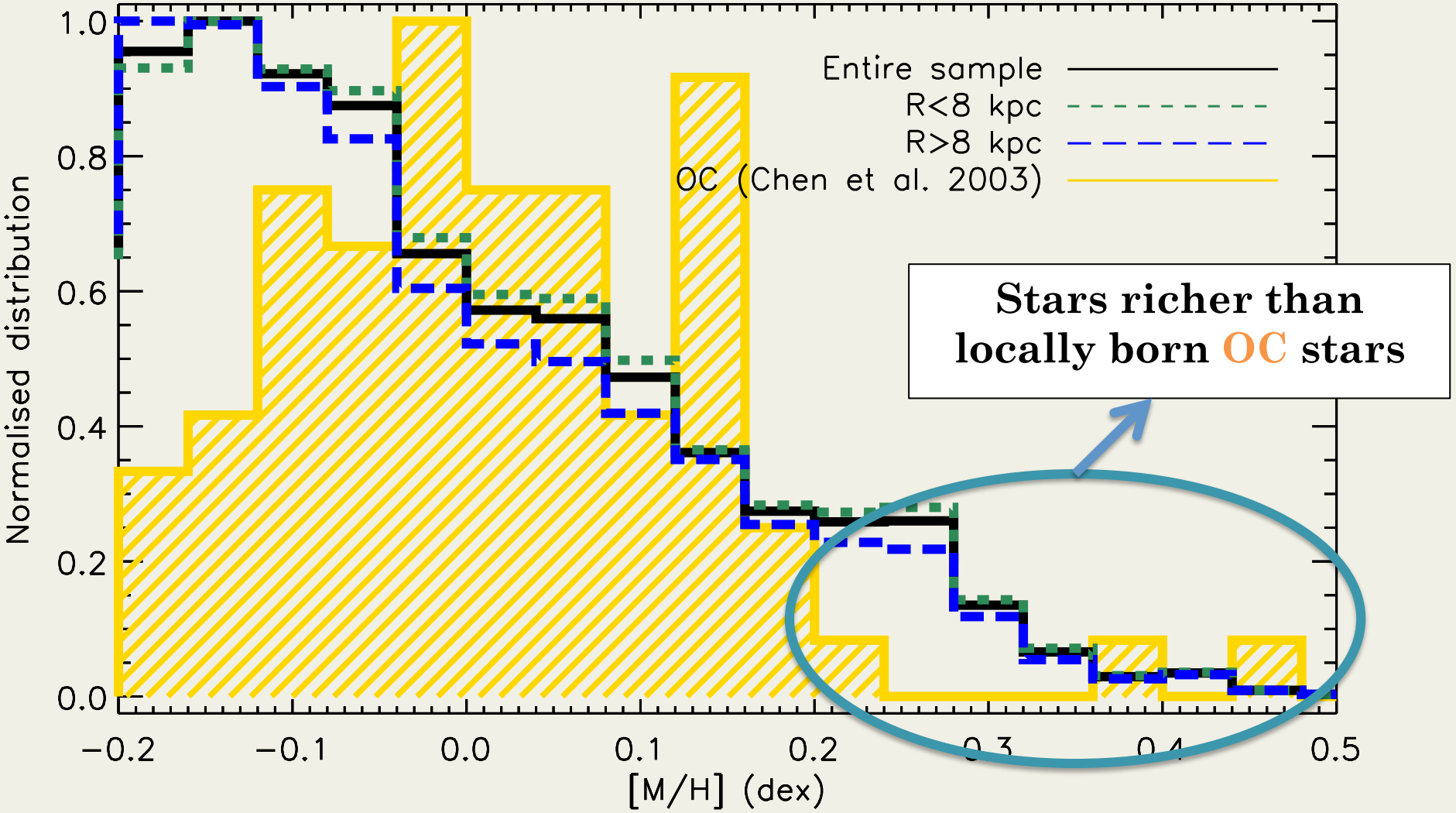
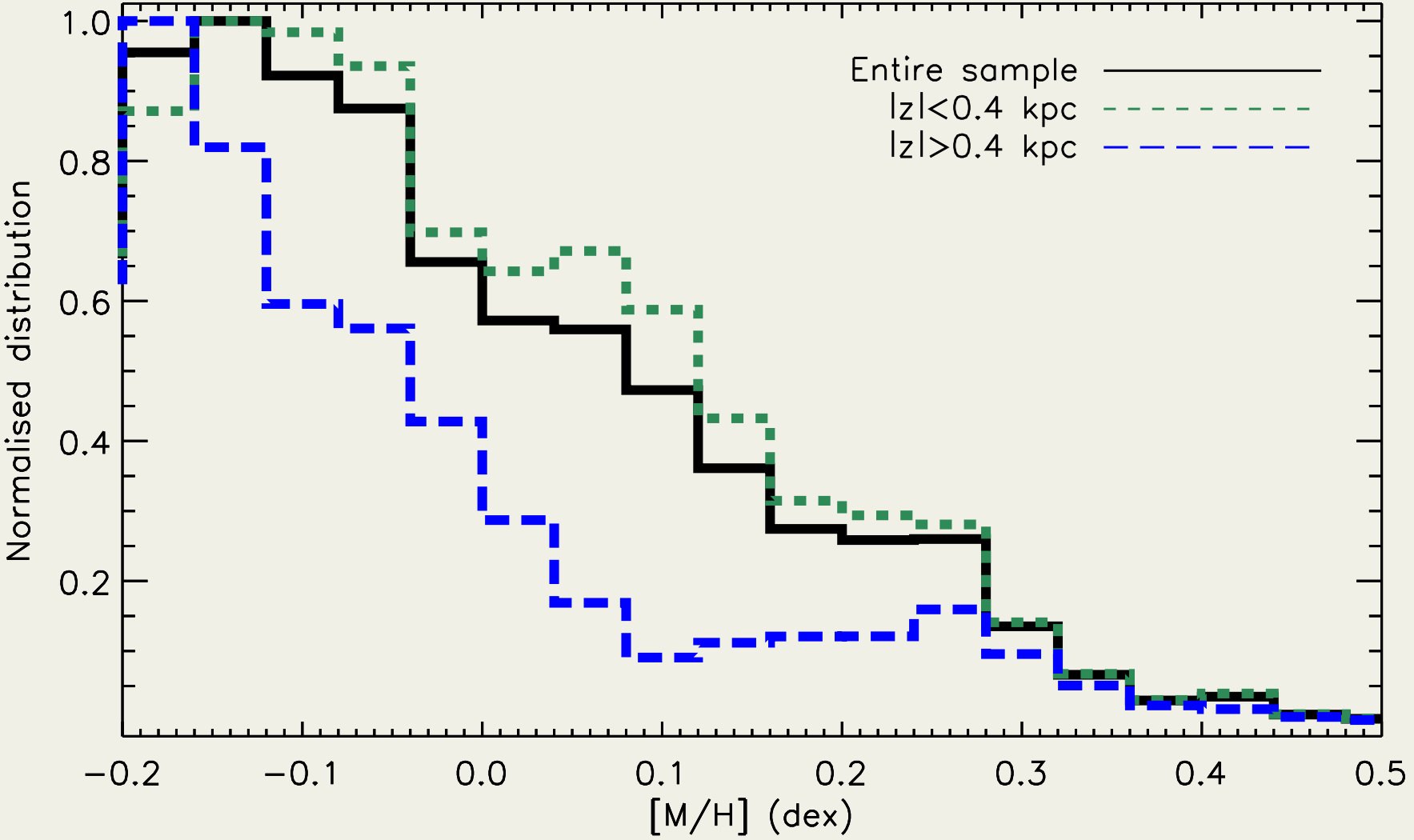


Metallicity distribution function

2) Z separation



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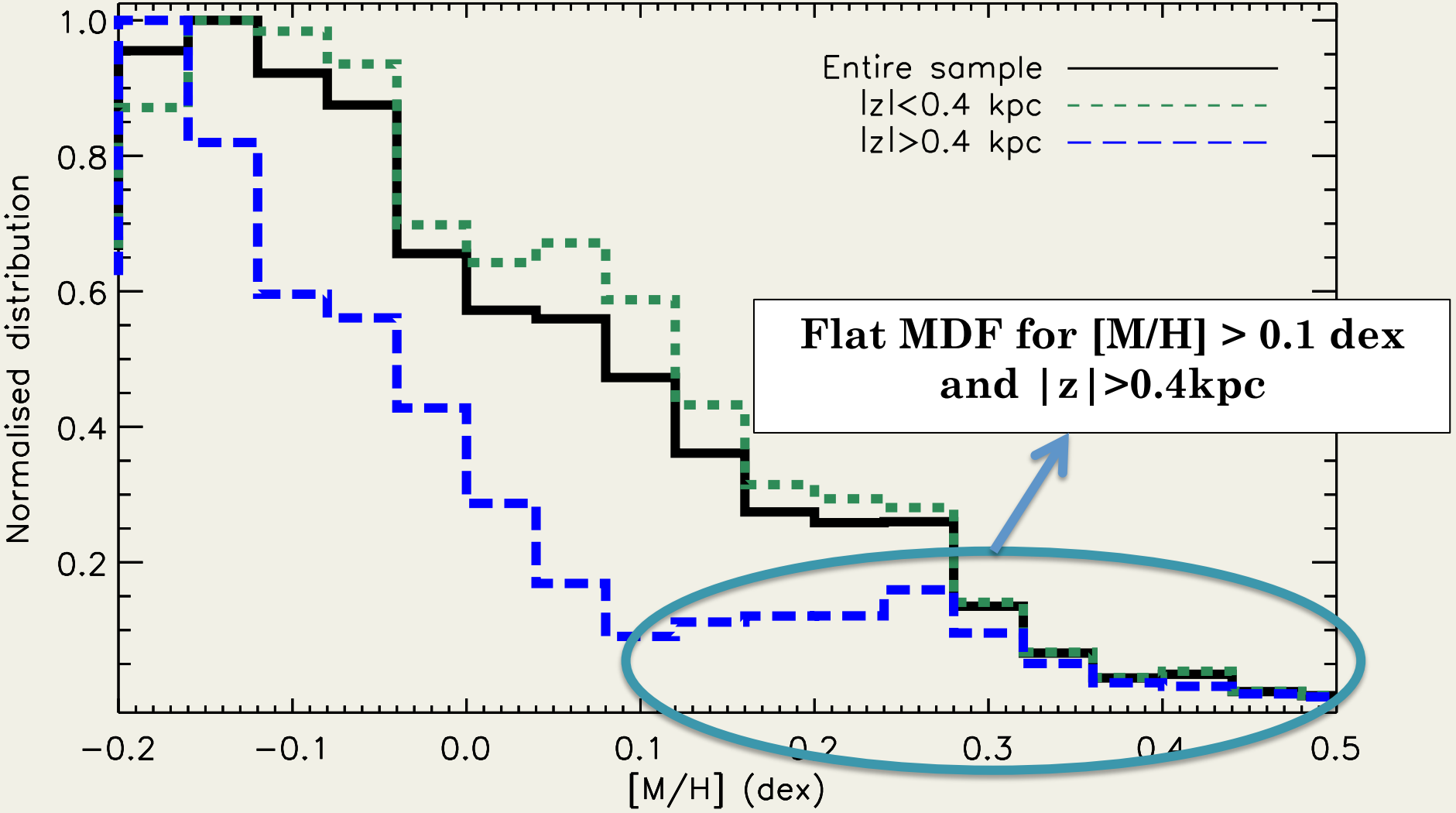

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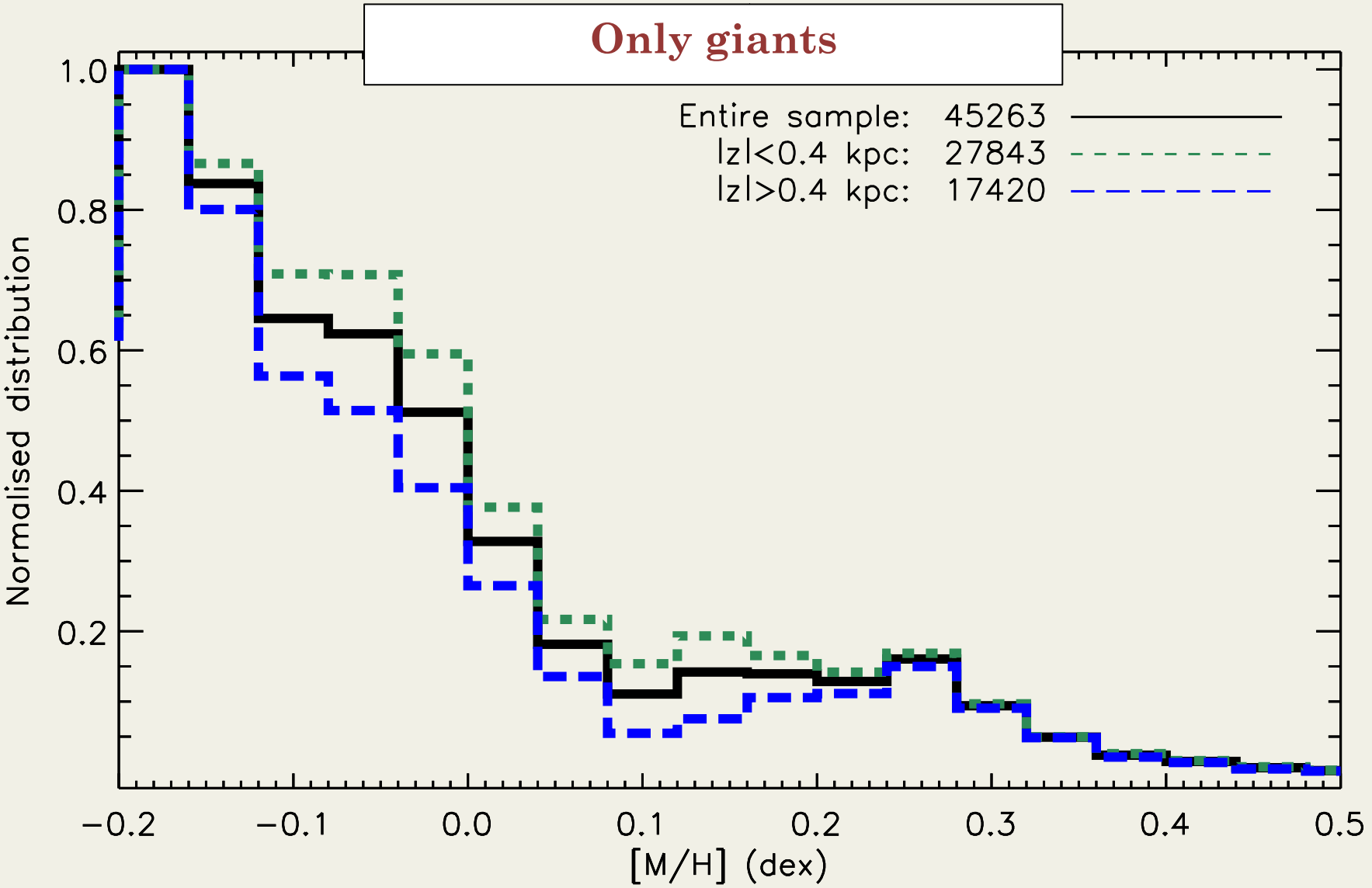

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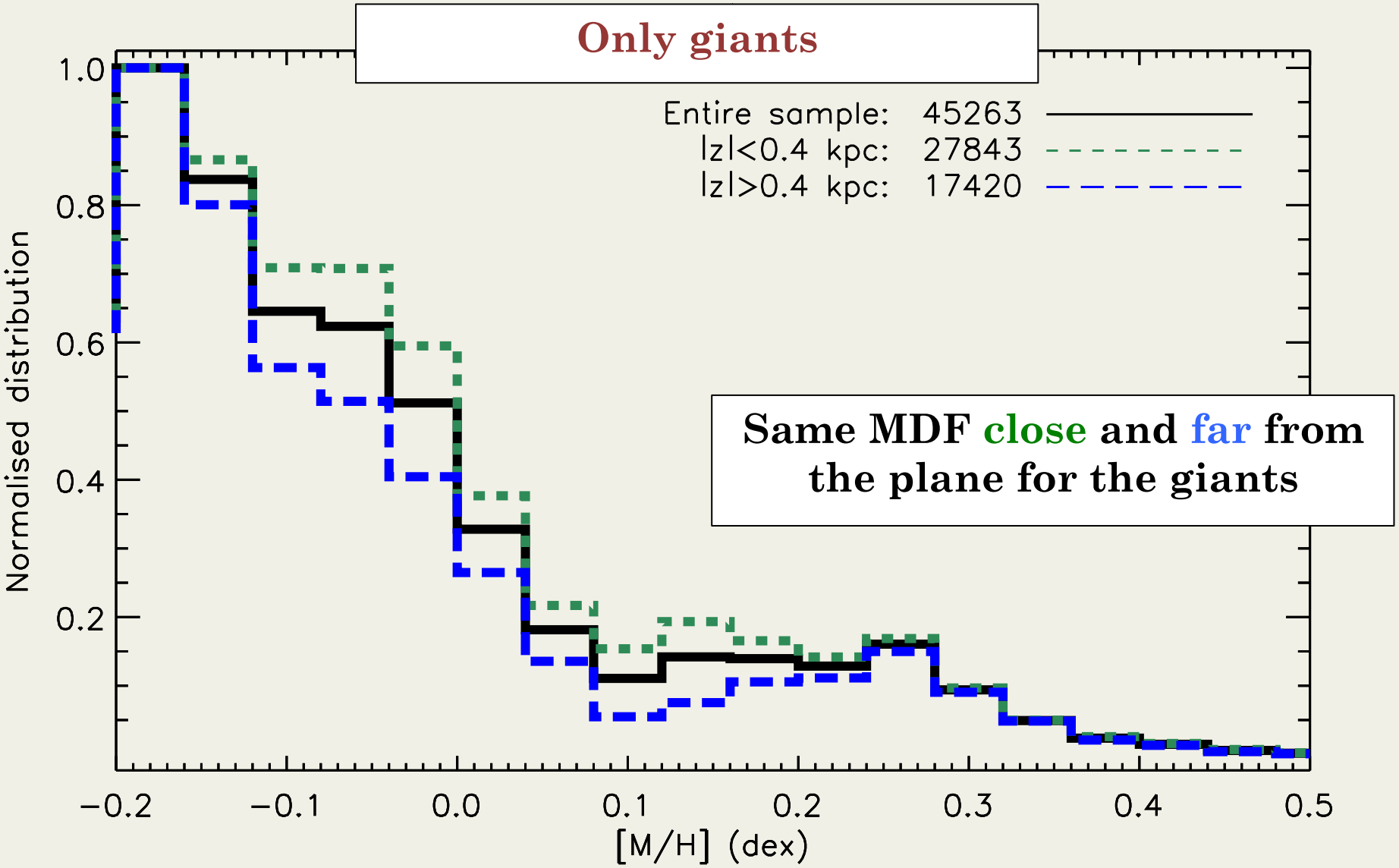

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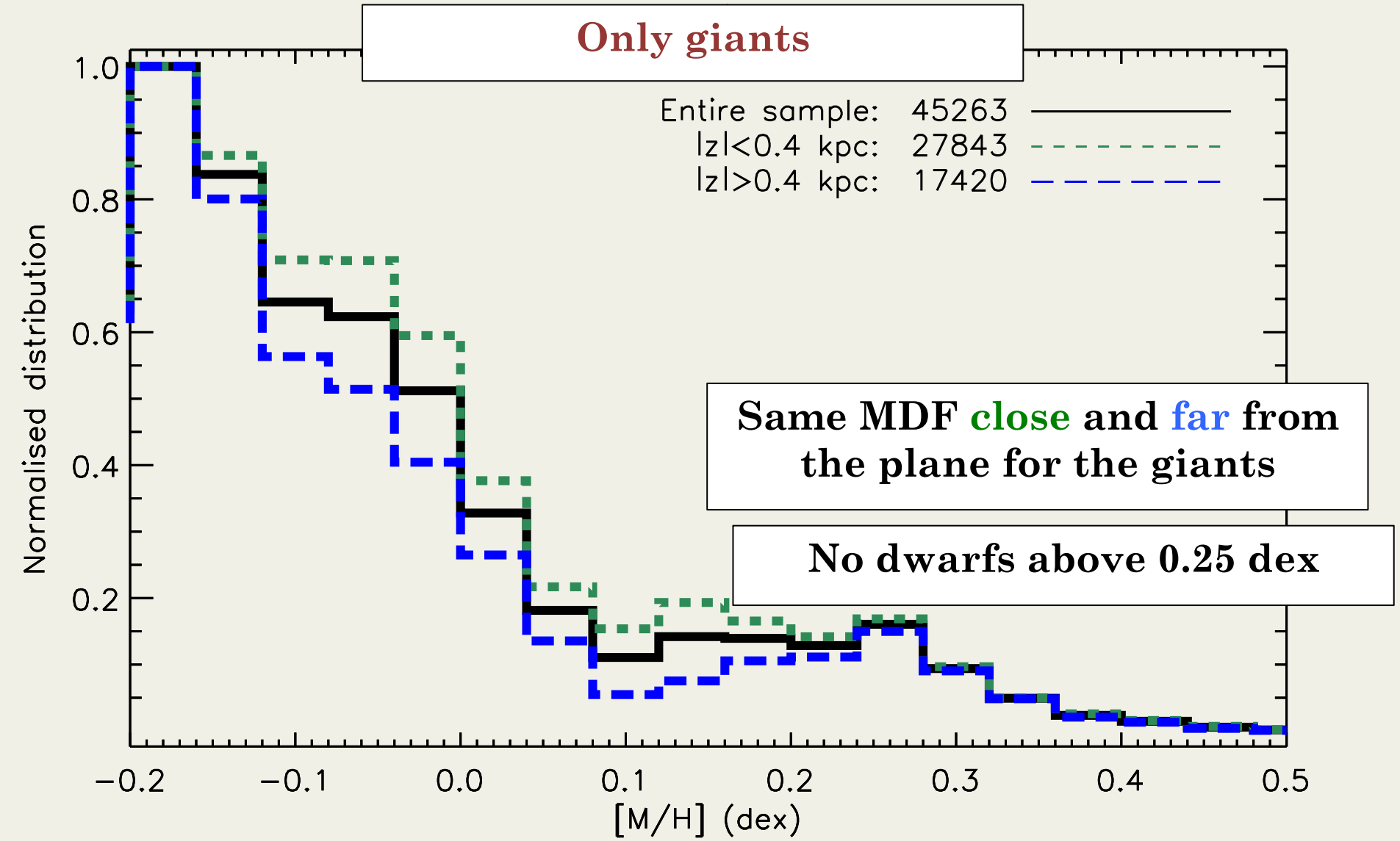
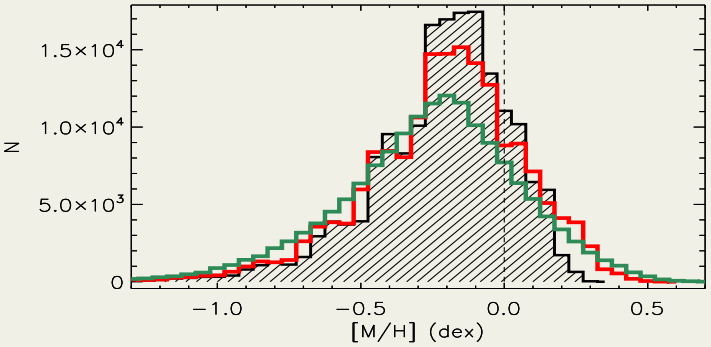
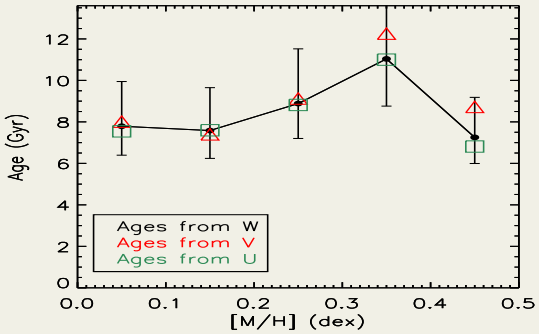
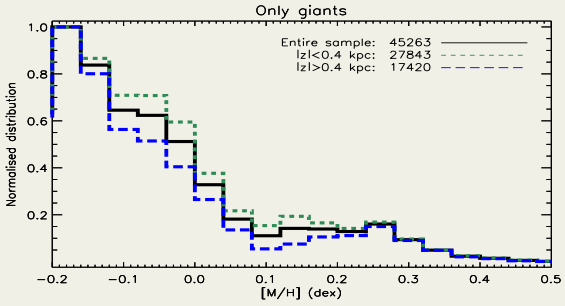


Summary of the Observations

- ✓ RAVE is rich in metal-rich stars
- ✓ Old population (>6-8 Gyr)
- ✓ Same (R,z) distribution for giants
- ✓ Almost flat MDF for [M/H]>0.2 dex







Where do these stars come from?

➢ **Computation of the orbits**

Eccentricity determination

3 discs:

$$\rho(R,z) = \frac{\Sigma_0}{2z_\mathrm{d}} \exp\left[-\left(\frac{R_\mathrm{h}}{R} + \frac{R}{R_\mathrm{d}} + \frac{|z|}{z_\mathrm{d}}\right)\right]$$

2 spheroids:

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

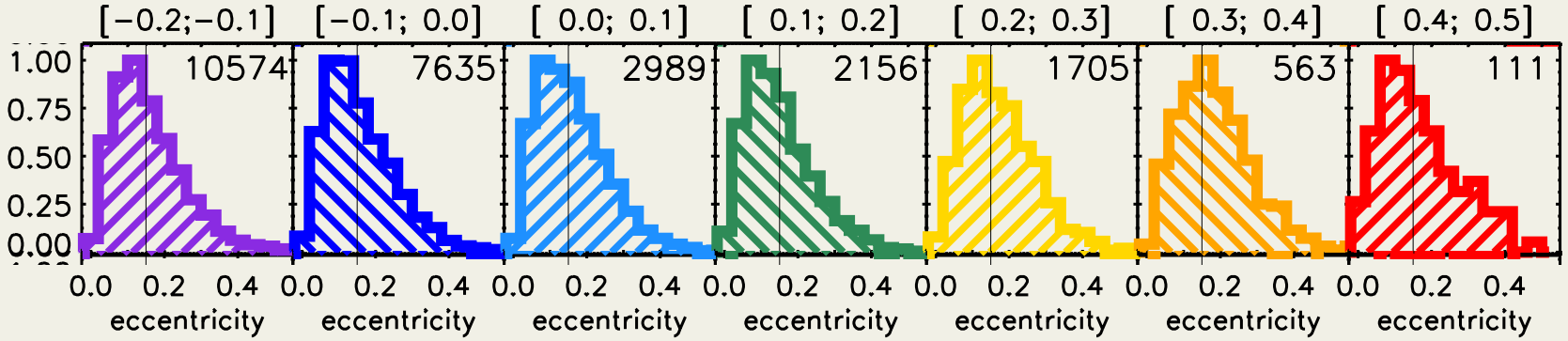
$$m(R,z) \equiv \sqrt{(R/r_0)^2 + (z/qr_0)^2}$$

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

Disc	Thick	Thin	Gas
Σ_0 ($M_\odot$ 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 ($M_\odot$ 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)

Solar neighbourhood:



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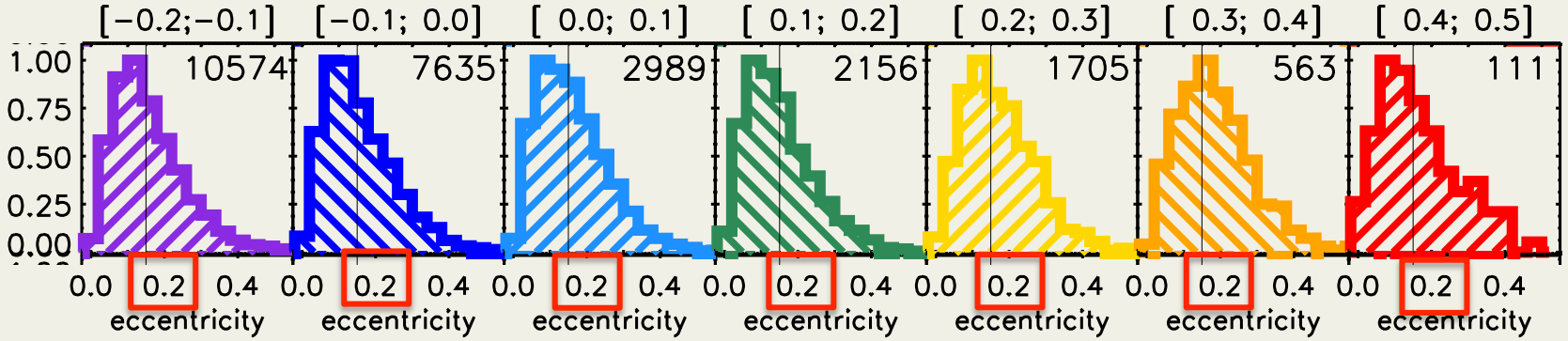
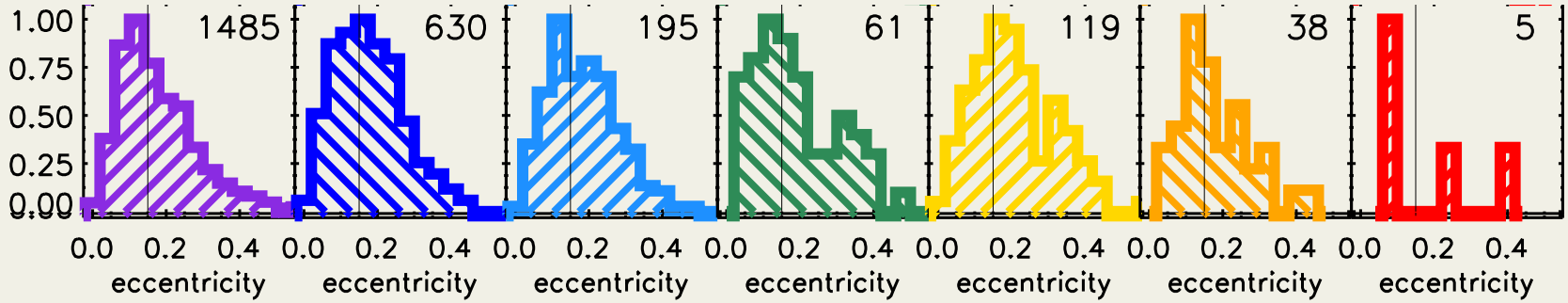


Eccentricity determination

Outer Galaxy:



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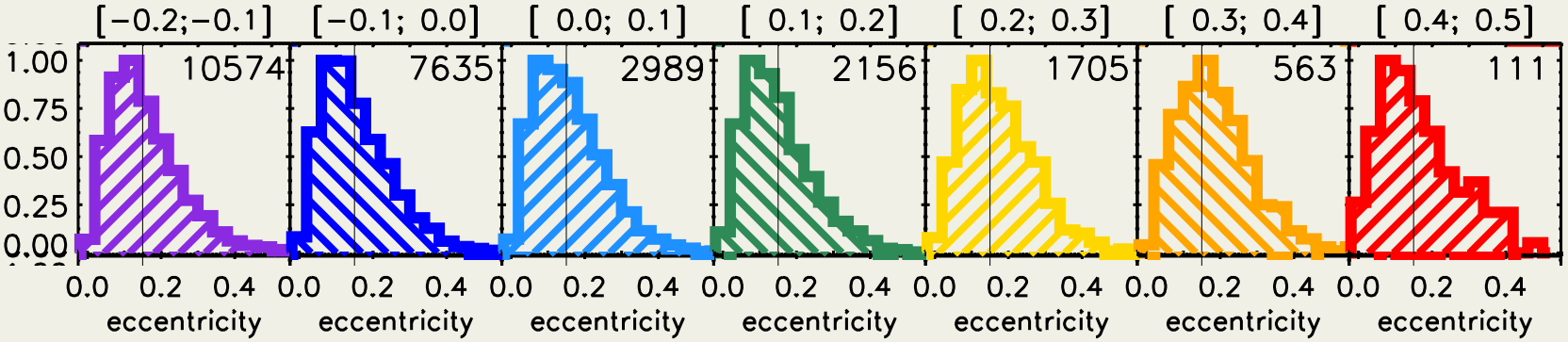
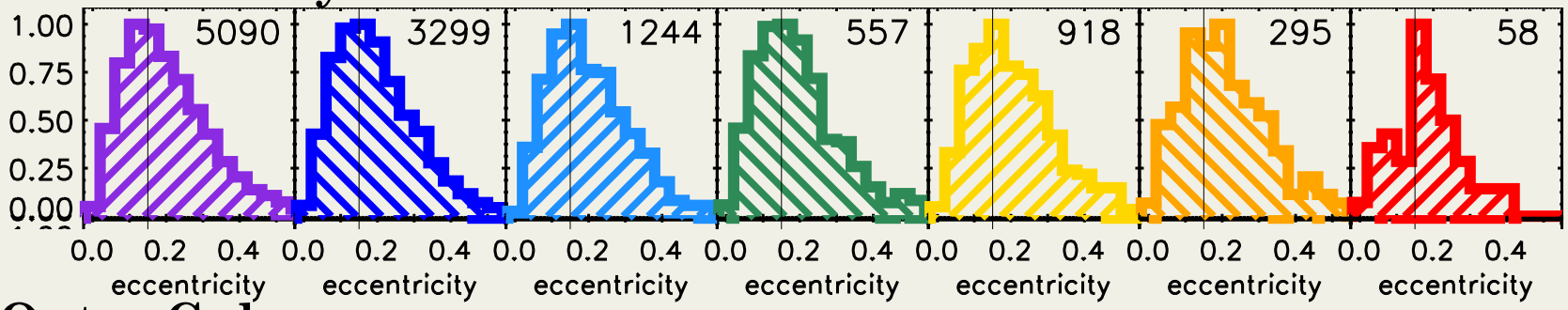


Eccentricity determination

Inner Galaxy:



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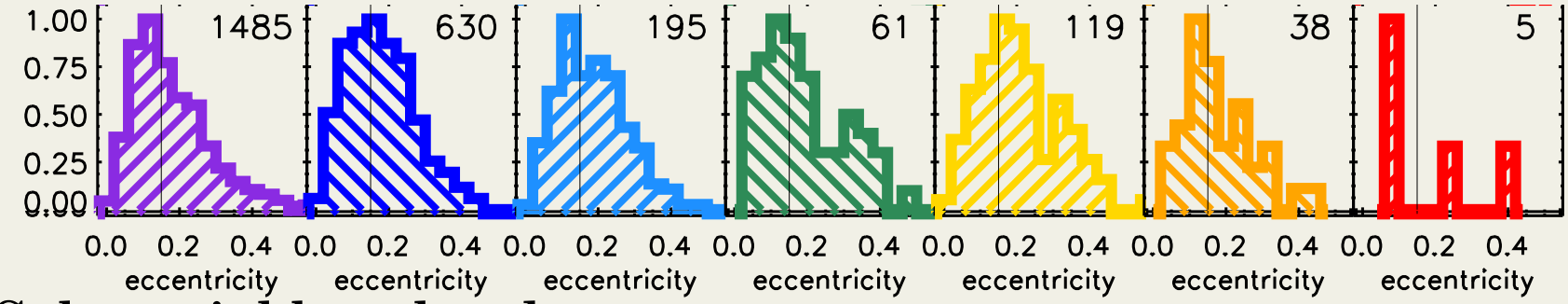

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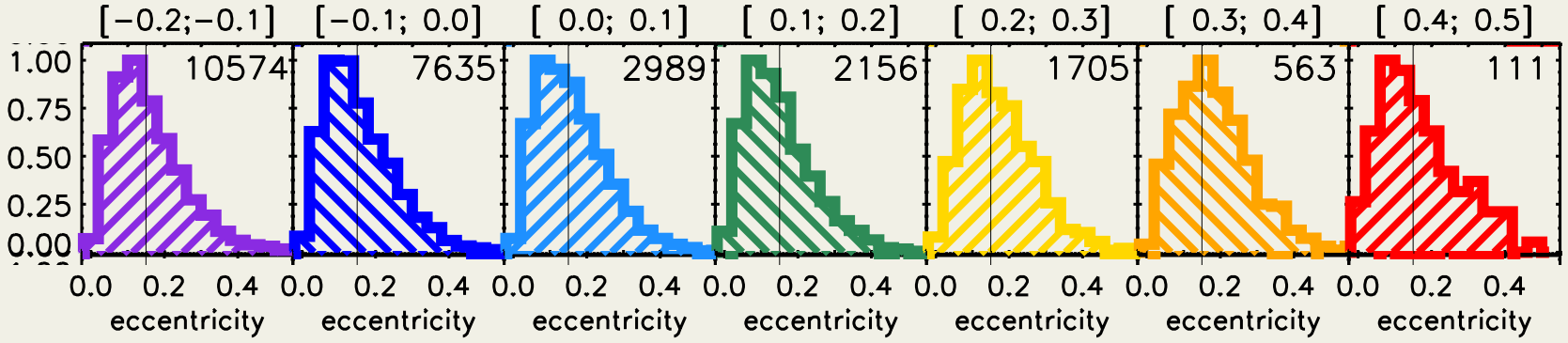

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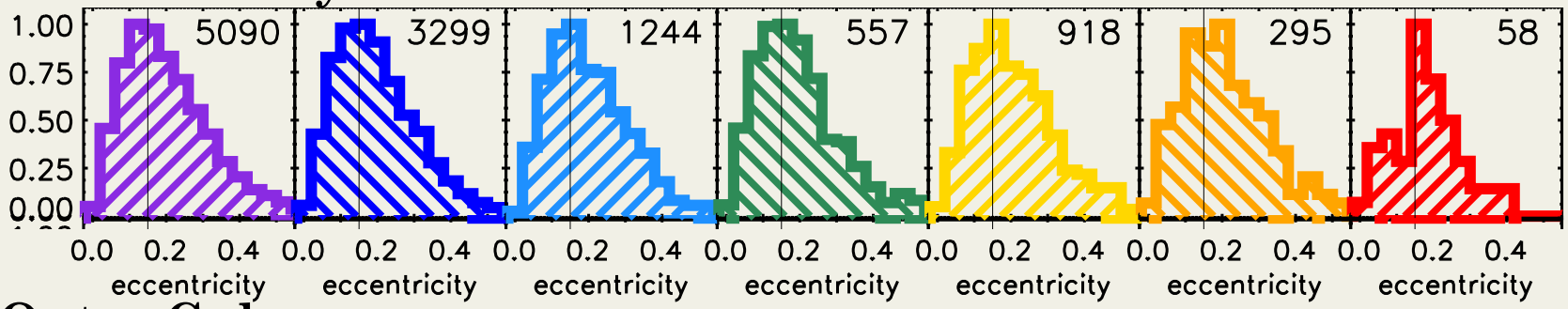

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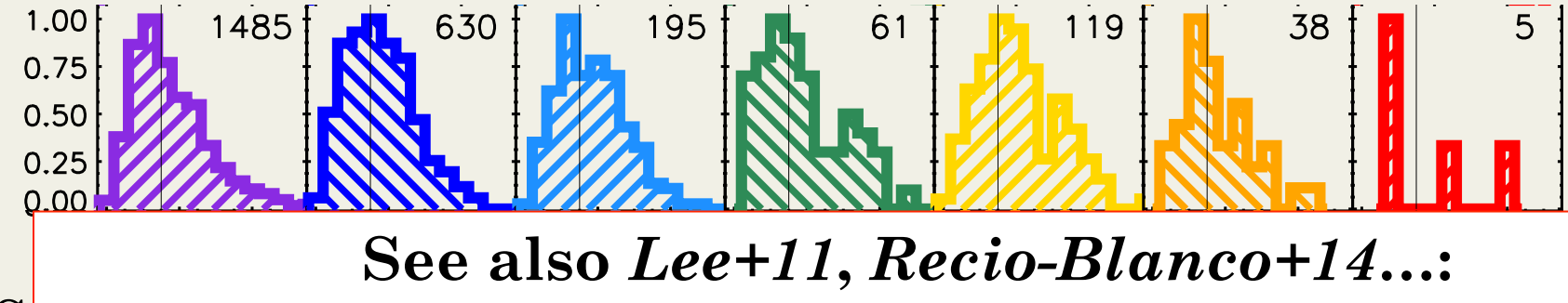
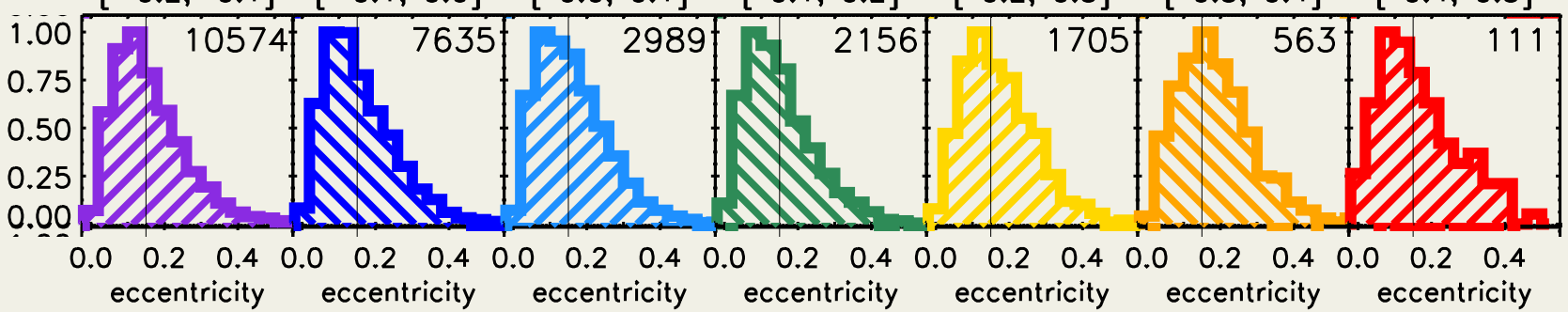


See also *Lee+11*, *Recio-Blanco+14*…:
Thin disc's eccentricity independent of [M/H]



Interpretation (1): Spiral history of the Milky Way

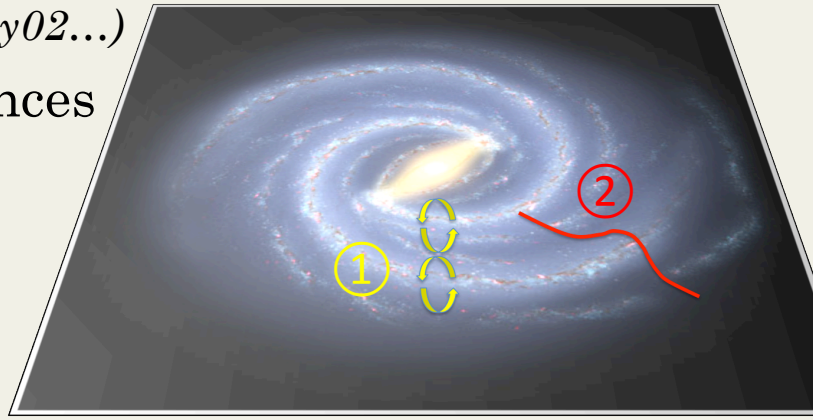
~Observation

- Given ISM's metallicity gradient:
  ∂[M/H]/∂R ~ -0.06 dex kpc^{-1} *(Smartt & Rolleston97; Balser+11…)*
  - ➢ **Stars born well inside R_o.**
    Stars with [M/H]=0.2 dex: R_{birth} < 6kpc
    Stars with [M/H]=0.4 dex: R_{birth} ~2kpc

Theory

- Radial migration: *(Sellwood&Binney02…)*
  ① Churning: Co-rotation resonances with spirals
  - ➢ **$\Delta e/\Delta t \sim 0$**

  ② Blurring: Lindblad resonances
  - ➢ **$\Delta e/\Delta t \neq 0$**



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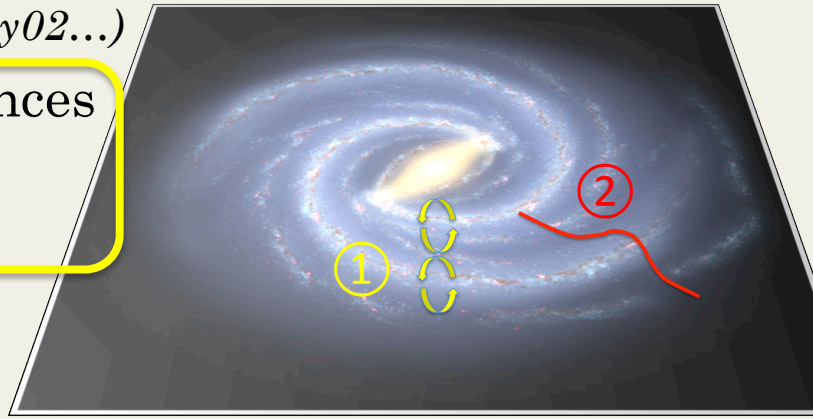
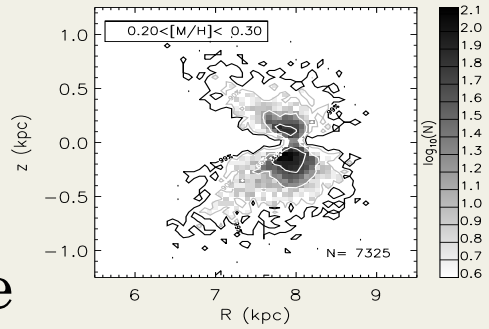


Interpretation (2):

~Observation

- *"Radially migrated stars seen >0.8kpc*
  - Radial migration probability is insensitive to the extent of a star's excursions perpendicular to the plane



Theory

- *Binney & Tremaine08*: "The gravitational field of a spiral structure with radial wavenumber k varies with $\exp(-k|z|)$"
  - ➢ Influence of a wave on stars: $< 1/k$ from the plane

➢ **The radial wavelength of spiral structure is no smaller than ~1kpc**

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~Observation

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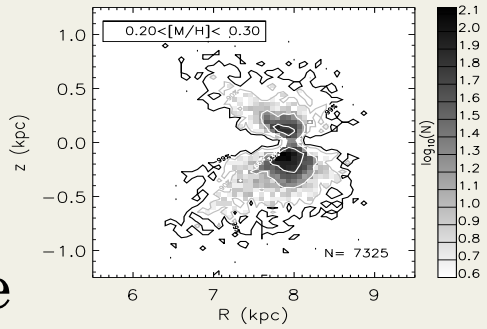
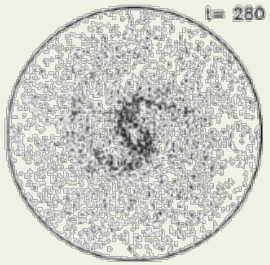
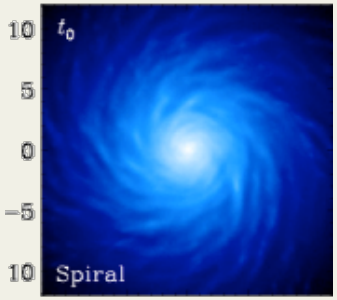


Theory

- *Solway+12*: Dynamically heated stars migrate as easily as dynamically cold stars



- *Vera-Ciro+14*: Only dynamically cold stars migrate.

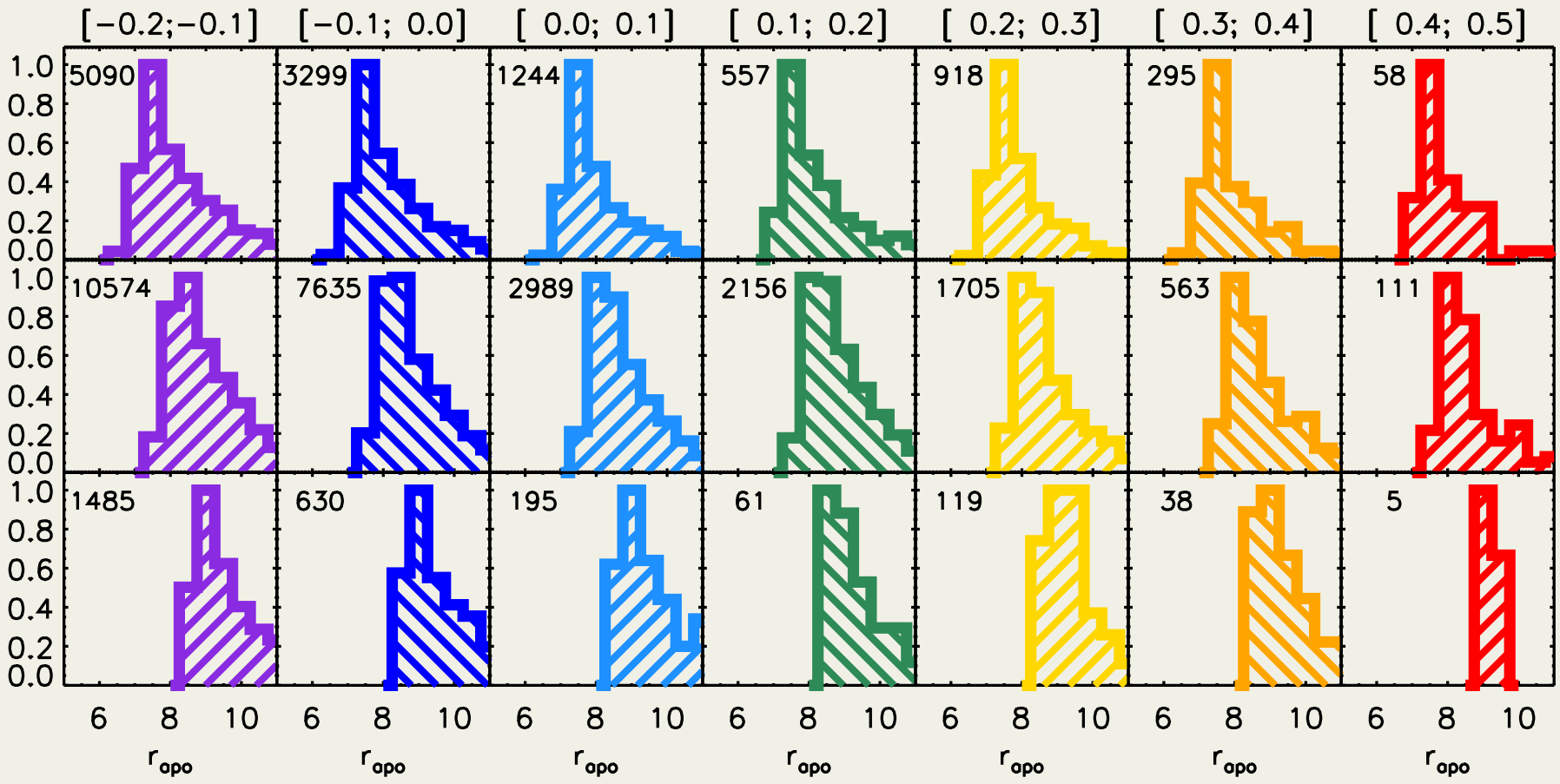


✓ **The radial wavelength of spiral structure is no smaller than ~1kpc**

Summary & Conclusions

- ✓ **Super Metal-rich giants in RAVE have a "flat" MDF from 0.1 < [M/H]< 0.35 dex**
- ✓ **Stars formed well inside R_o** (bar/bulge region?)
- ✓ **Located up to ~1 kpc from the plane**
- ✓ **Same distribution inner and outer Galaxy**
- ✓ **Circular orbits:**
  - ➢ **Stars scattered through co-rotational resonances with the spiral arms**
  - ➢ **Spirals in the MW are strong, with large spiral structure**

Thank you for your attention


[−0.2;−0.1]
[−0.1; 0.0]
[0.0; 0.1]
[0.1; 0.2]
[0.2; 0.3]
[0.3; 0.4]
[0.4; 0.5]
5090
3299
1244
557
918
295
58
10574
7635
2989
2156
1705
563
111
1485
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0.8
0.6
0.4
0.2
0.0
6
8
10
r_apo

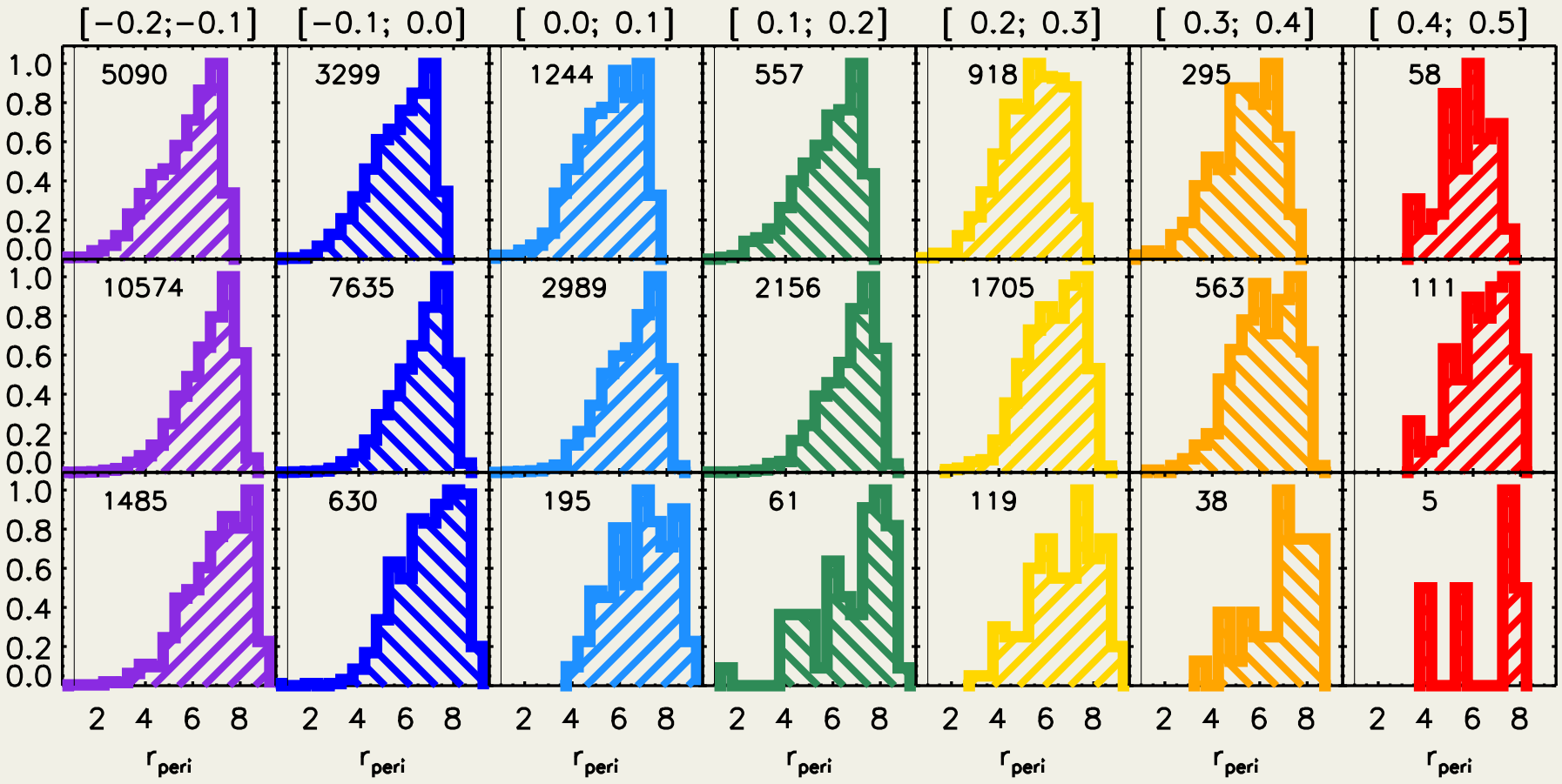
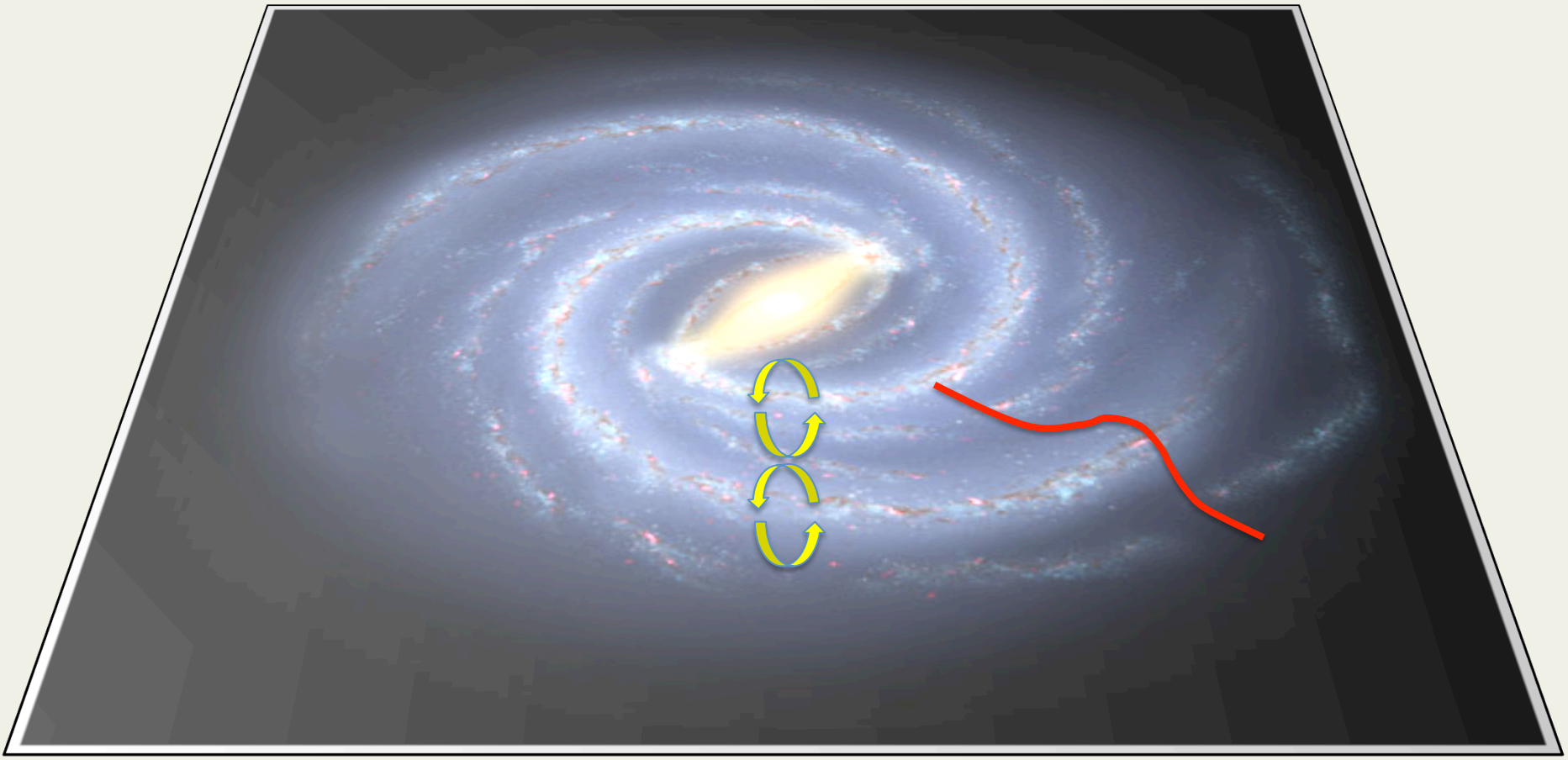

[−0.2;−0.1]
[−0.1; 0.0]
[0.0; 0.1]
[0.1; 0.2]
[0.2; 0.3]
[0.3; 0.4]
[0.4; 0.5]
5090
3299
1244
557
918
295
58
10574
7635
2989
2156
1705
563
111
1485
630
195
61
119
38
5
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
r peri

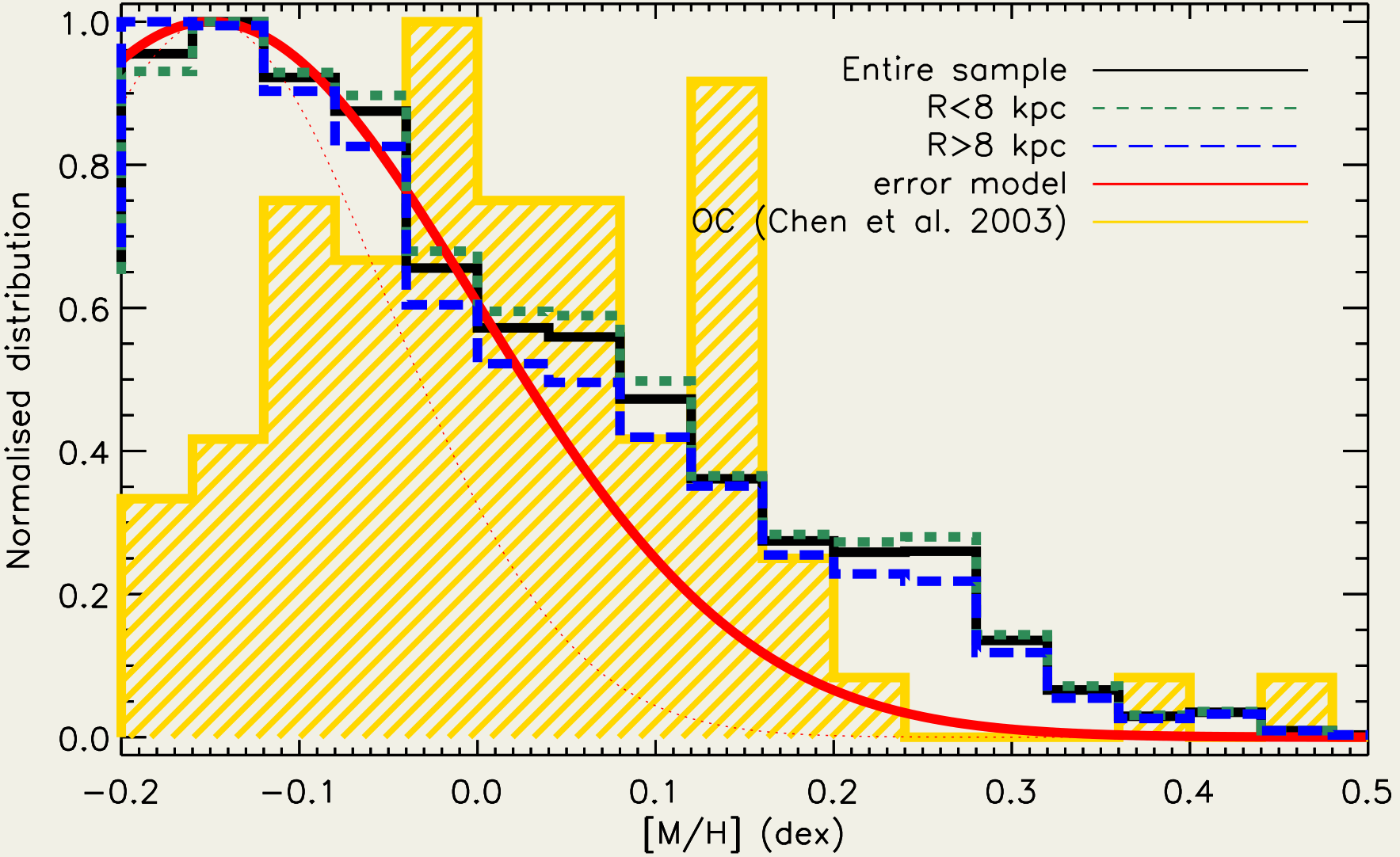
Table 2. Median and interquartile values of the eccentricity distribution of the selected RAVE giants quality sample at three Galactocentric regions.

Metallicity range (dex)	$[-0.2, -0.1]$	$[-0.1, 0.0]$	$[0.0, 0.1]$	$[0.1, 0.2]$	$[0.2, 0.3]$	$[0.3, 0.4]$	$[0.4, 0.5]$
$6.5 < R < 7.5$	$0.18^{+0.28}_{-0.12}$	$0.18^{+0.26}_{-0.11}$	$0.19^{+0.28}_{-0.12}$	$0.18^{+0.26}_{-0.11}$	$0.19^{+0.28}_{-0.12}$	$0.20^{+0.29}_{-0.12}$	$0.18^{+0.24}_{-0.13}$
$7.5 < R < 8.5$	$0.14^{+0.21}_{-0.09}$	$0.14^{+0.21}_{-0.09}$	$0.14^{+0.22}_{-0.09}$	$0.13^{+0.20}_{-0.08}$	$0.16^{+0.23}_{-0.10}$	$0.18^{+0.25}_{-0.12}$	$0.14^{+0.23}_{-0.09}$
$8.5 < R < 9.5$	$0.16^{+0.24}_{-0.10}$	$0.17^{+0.24}_{-0.11}$	$0.18^{+0.25}_{-0.11}$	$0.16^{+0.27}_{-0.10}$	$0.19^{+0.29}_{-0.13}$	$0.16^{+0.25}_{-0.12}$	$0.10^{+0.25}_{-0.07}$



Metallicity distribution function

1) R separation



Metallicity distribution function

2) Z separation