What is rotating in the very metal-poor Milky Way: a disc or a halo

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(1st year PhD)

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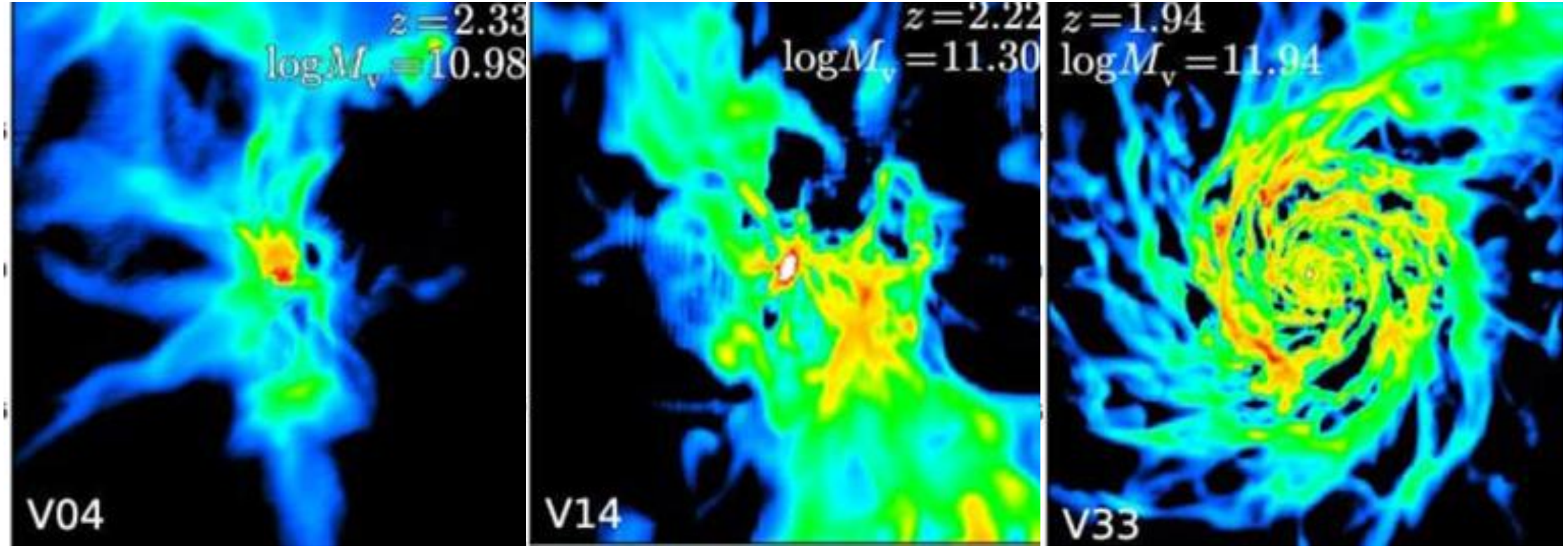
Mass triggered disc formation

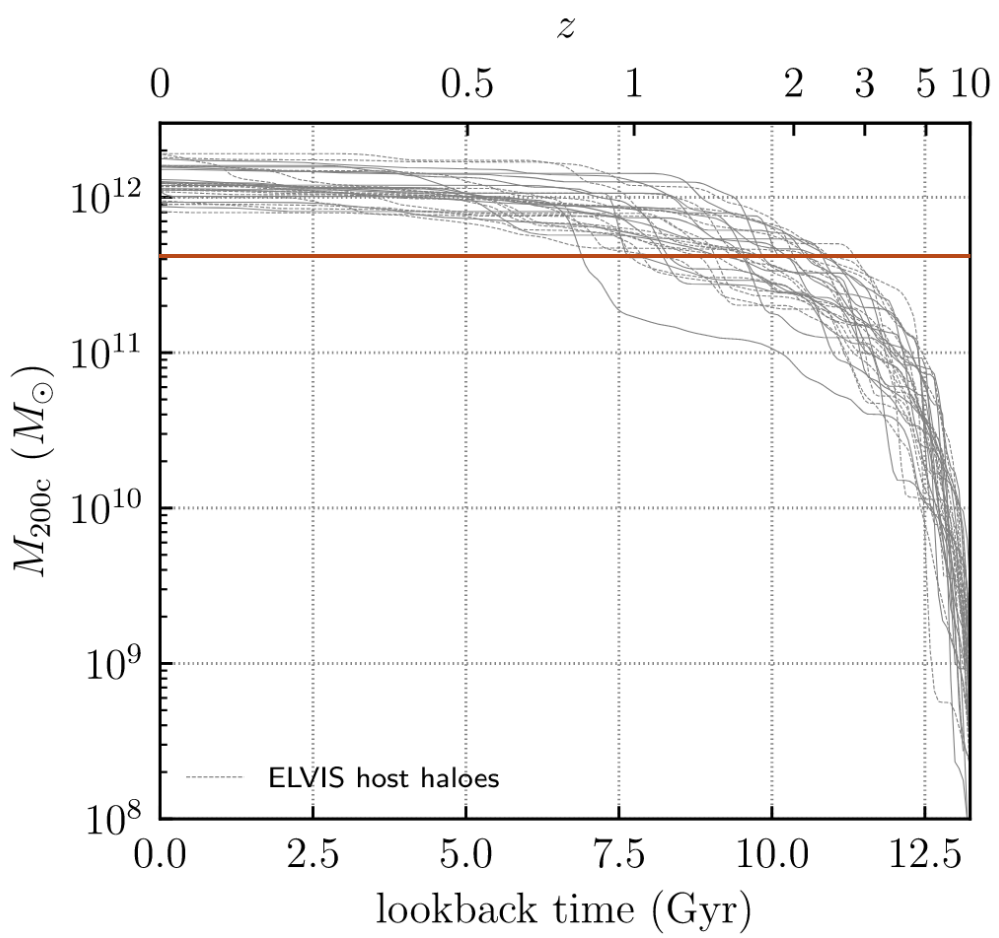
See also Semenov+23, Dillamore+23 to more on the correlation between the galaxy mass and the stable disc

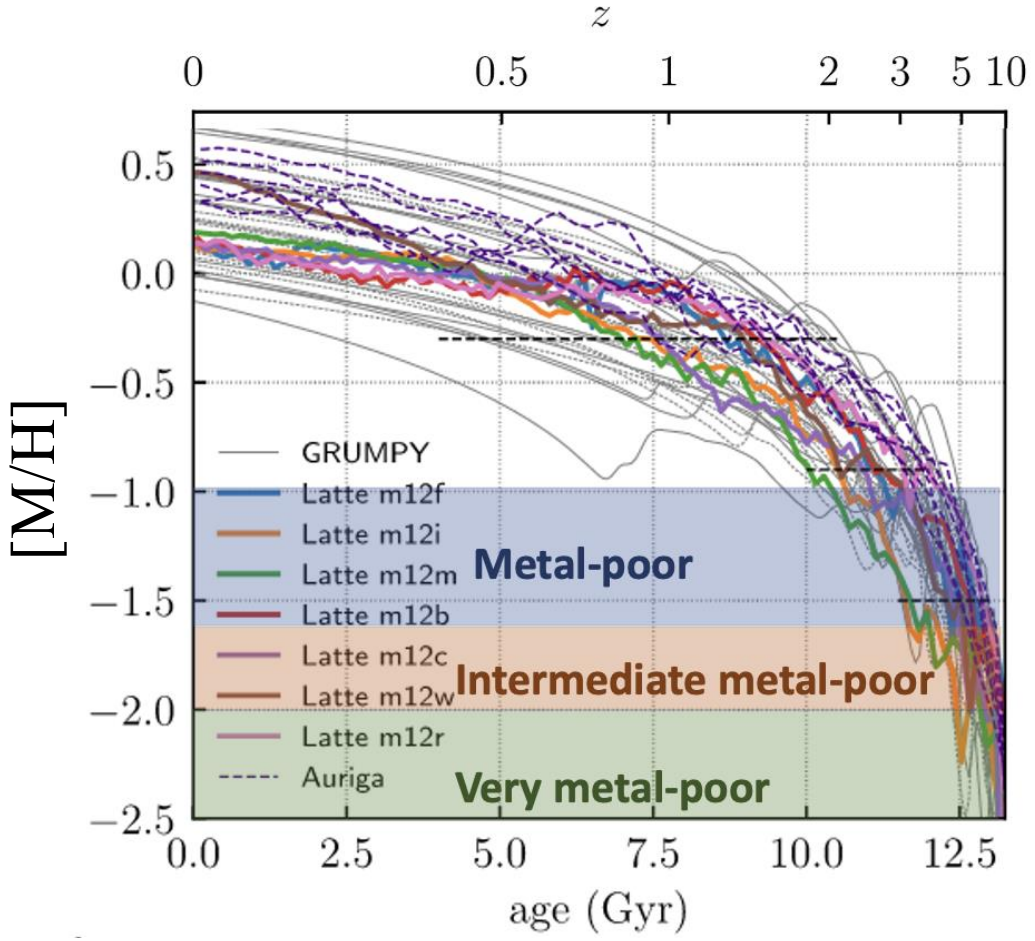
Dekel+20



Increasing mass

Disc formation epoch in the simulated MW

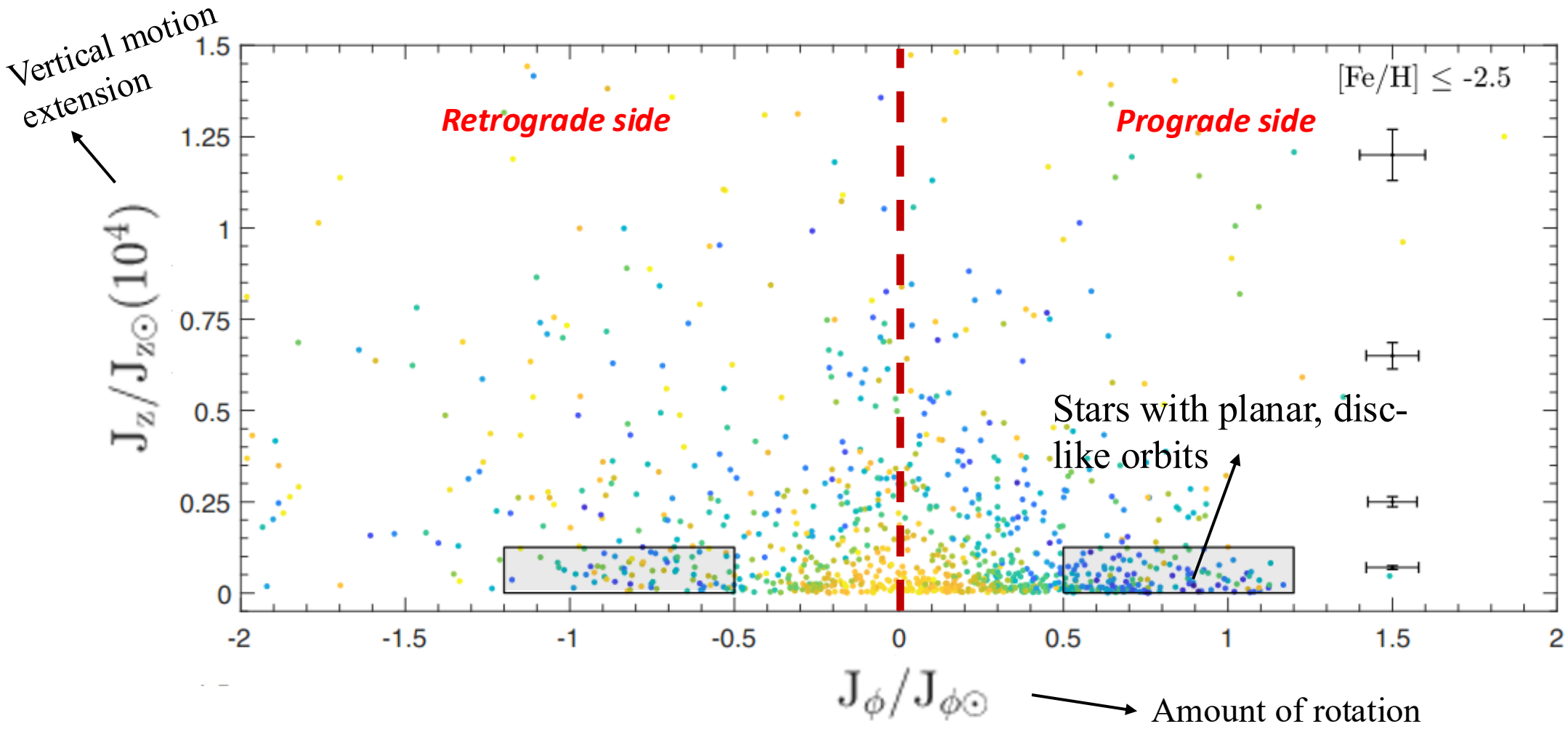




Belokurov & Kravtsov (2022)

Recent hints of a very metal-poor disc

Sestito et al. 2020



Many subsequent works follow the early disc scenario and argue that a stable disc formed in the early life stage of the Milky Way, e.g. Di Matteo+20; Sotillo-Ramos+23; Bellazzini+23 etc.

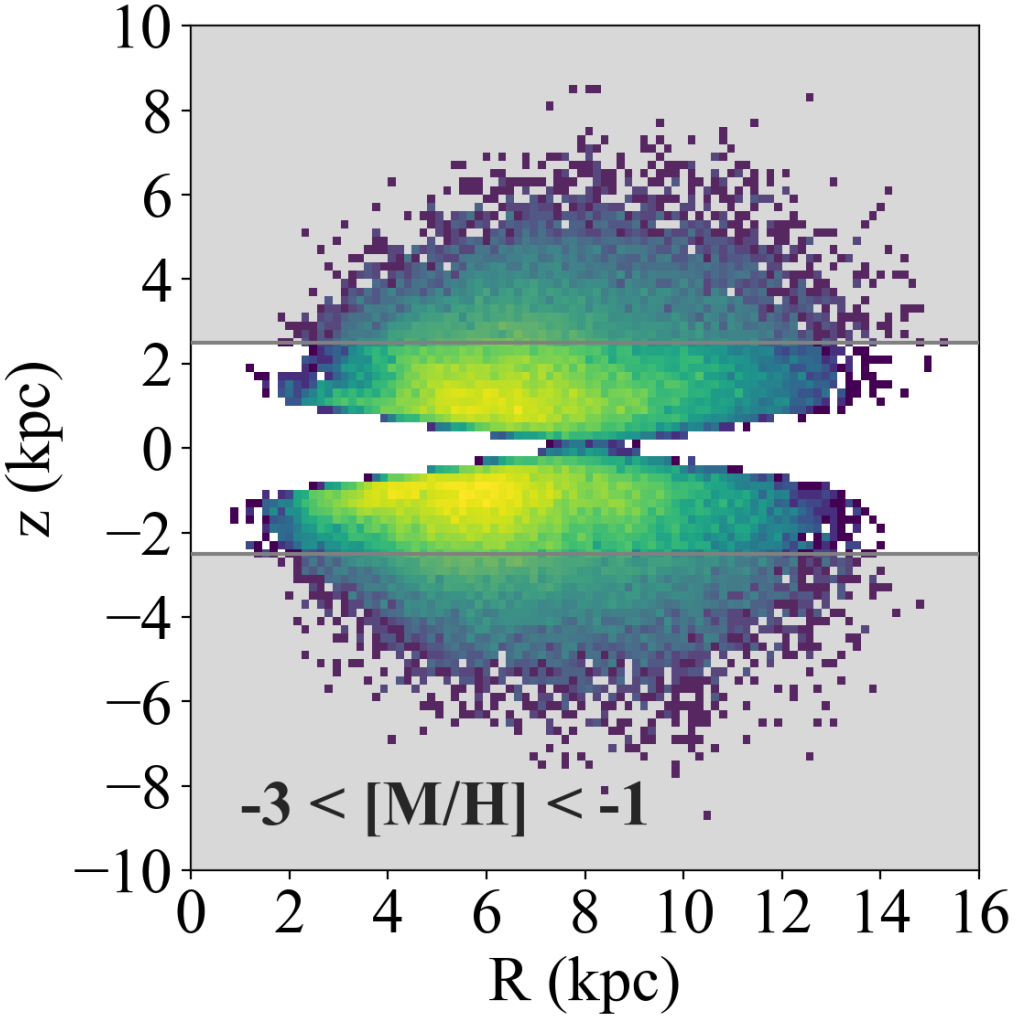
Sample construction

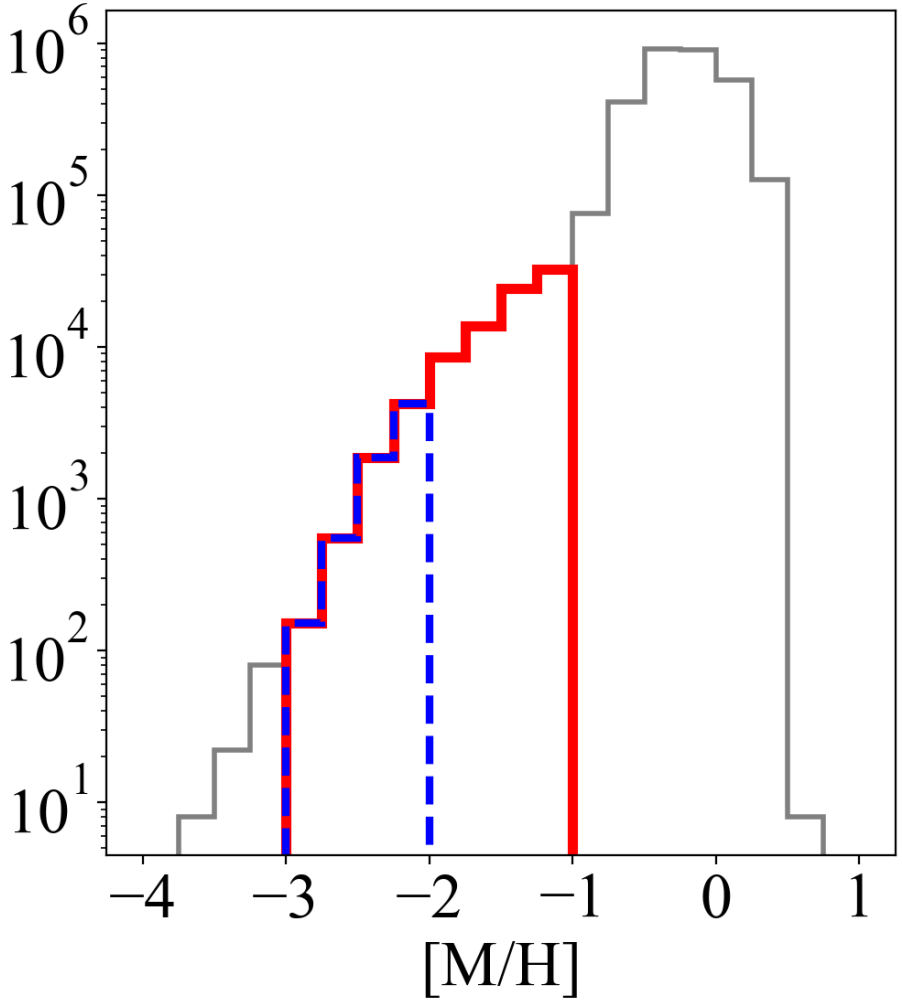
- Gaia DR3 release XP spectrum parameters for ~220 million stars

- Andrae *et.al* (2023) provide stellar parameters ([M/H], T_{eff}, $\log g$) for ~175 million stars using data-driven method

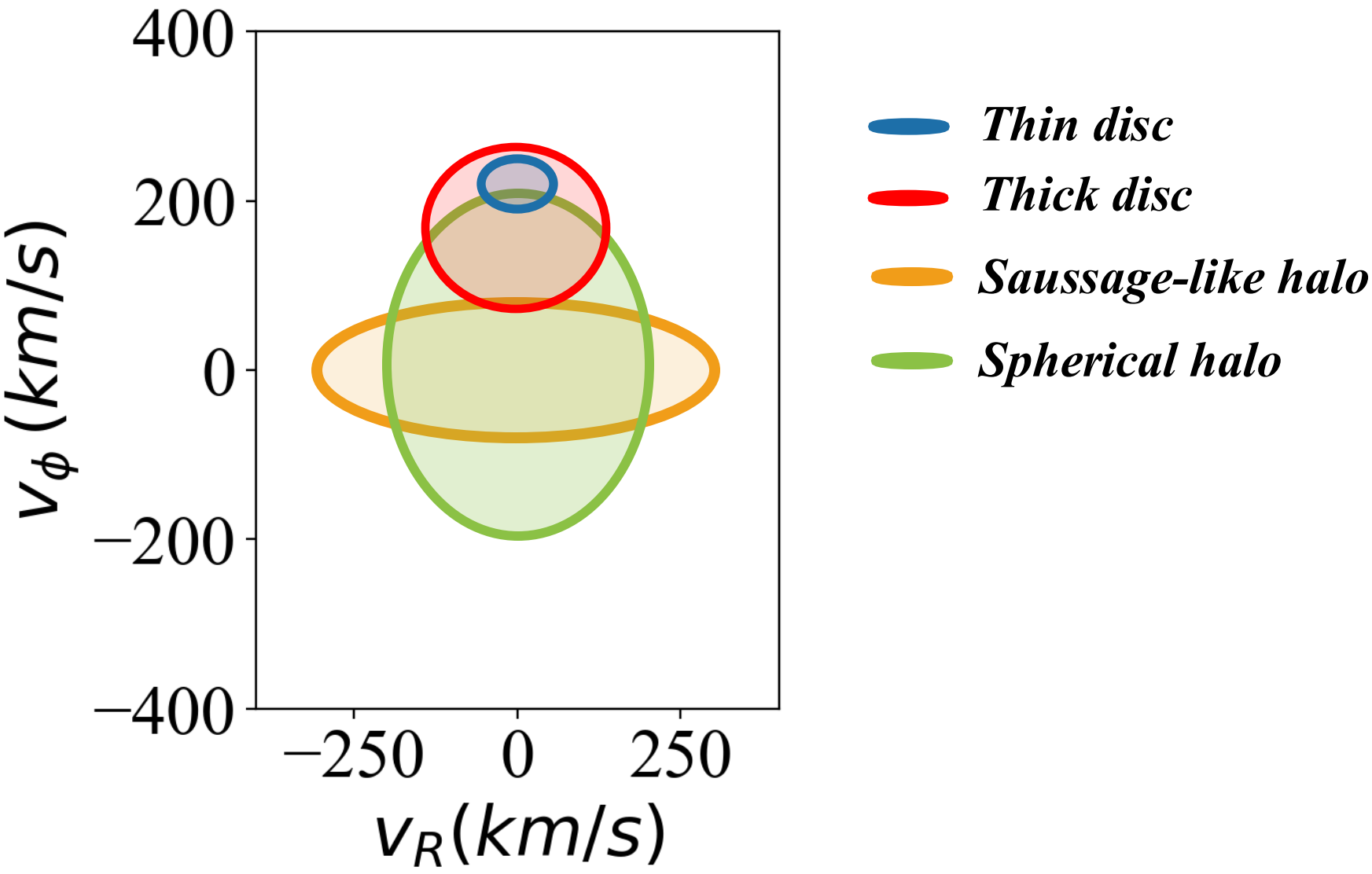
- A red giants sample with ~10 million stars with high confidence parameters are selected, and tested to be robust against many spectroscopic survey

Sample construction





Distribution in velocity space



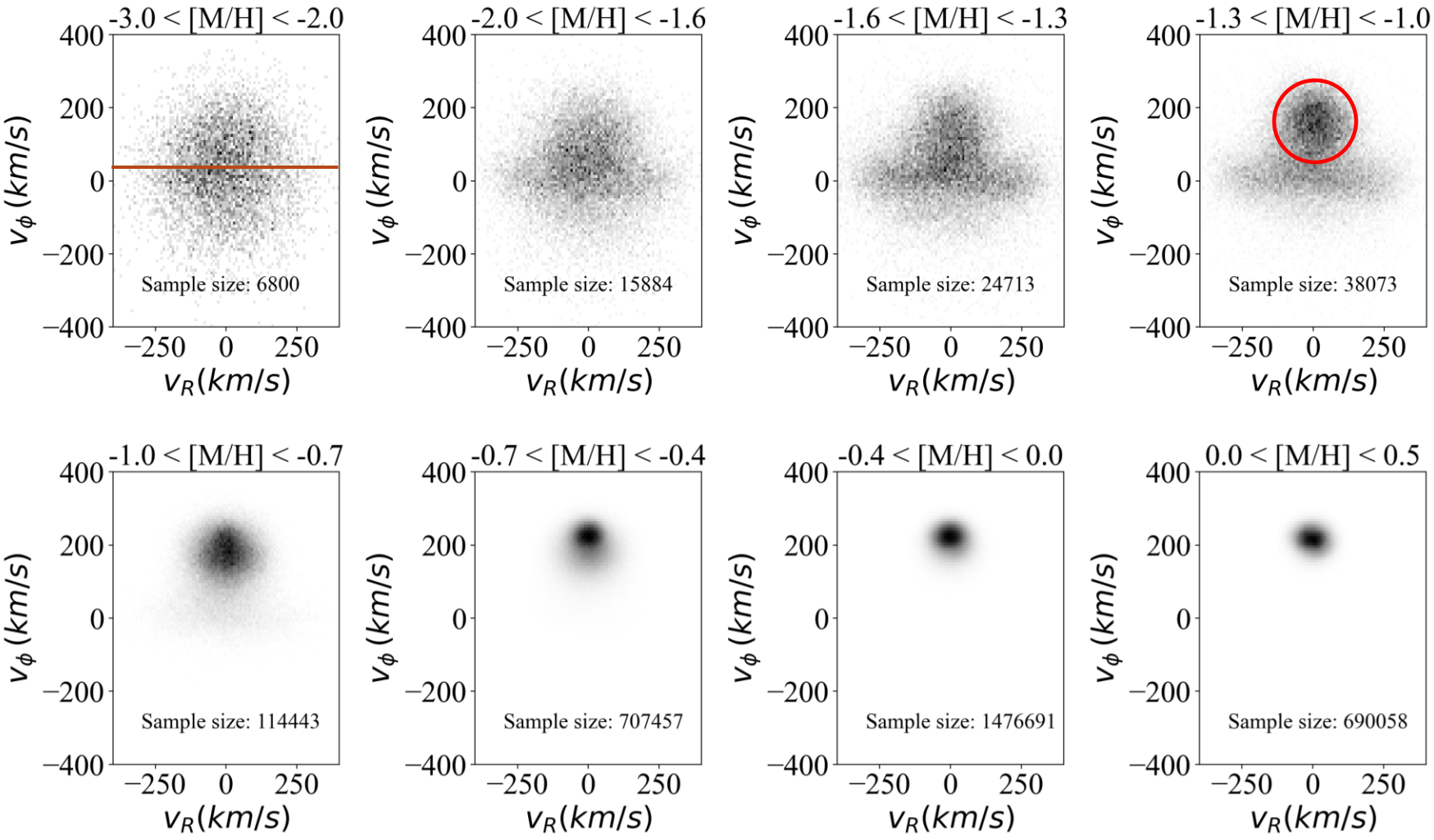
Distribution in velocity space

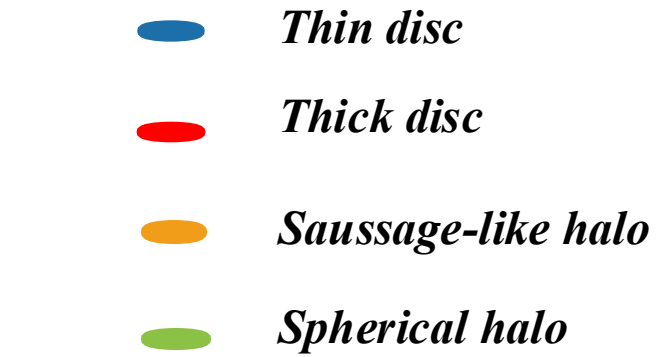
Very metal-poor

Intermediate metal-poor

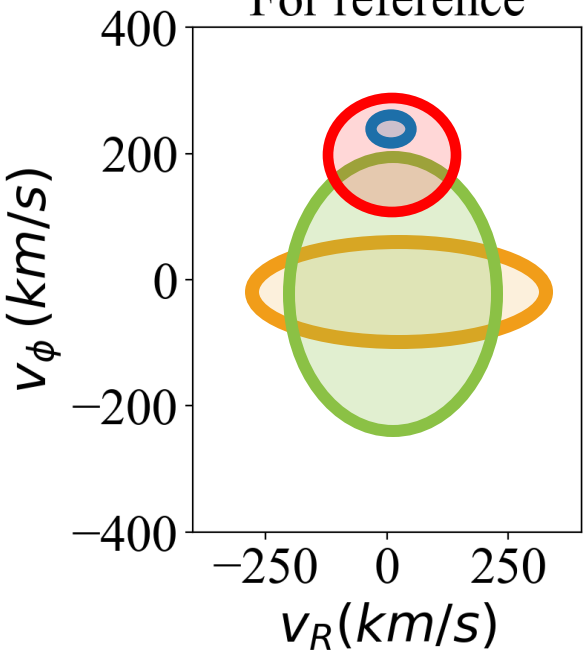
metal-poor

metal-poor





For reference

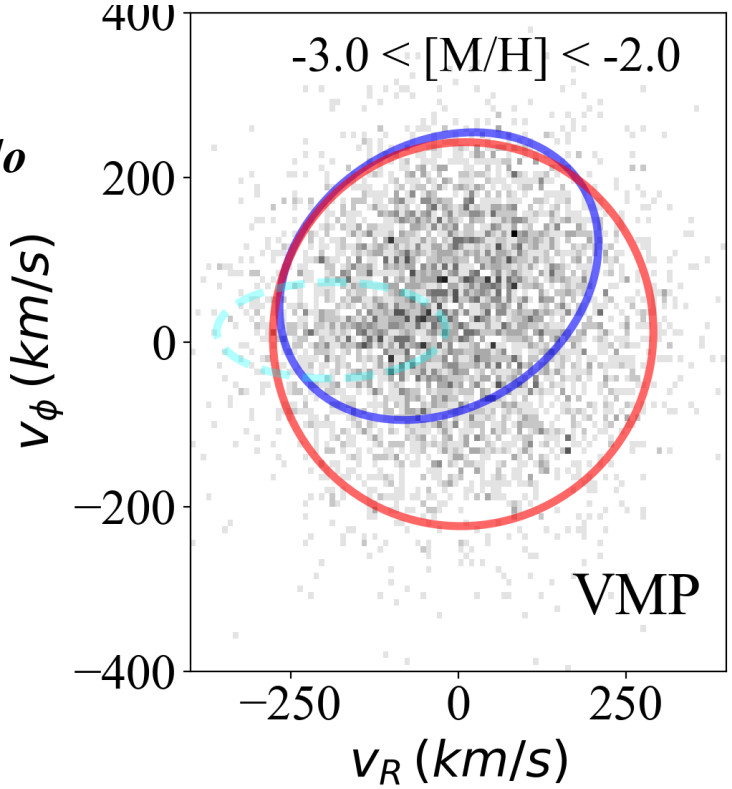


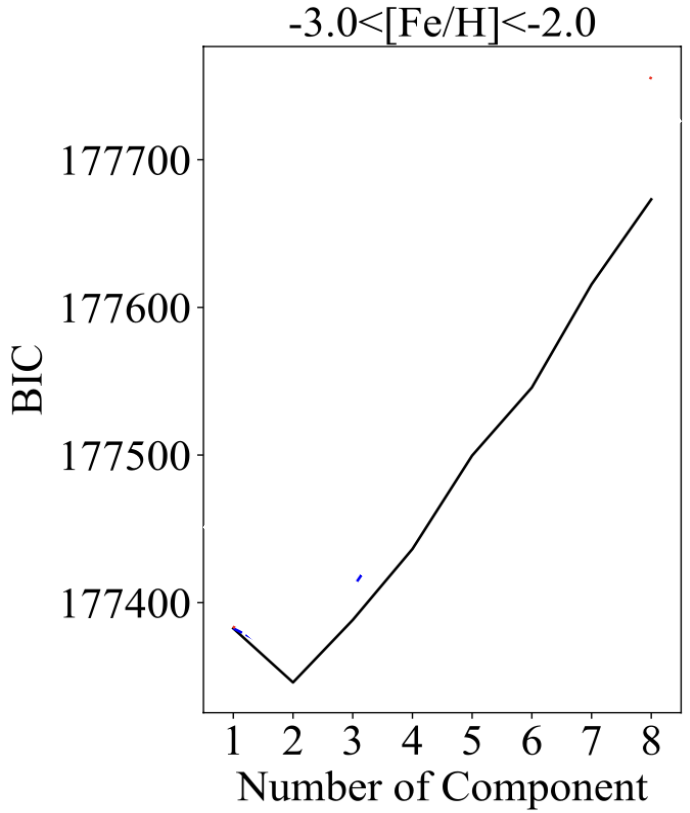
Gaussian Mixture Model (GMM)

An unsupervised classification algorithm by assuming the whole population is the mixture of N Gaussian population

Prograde halo

Stationary halo



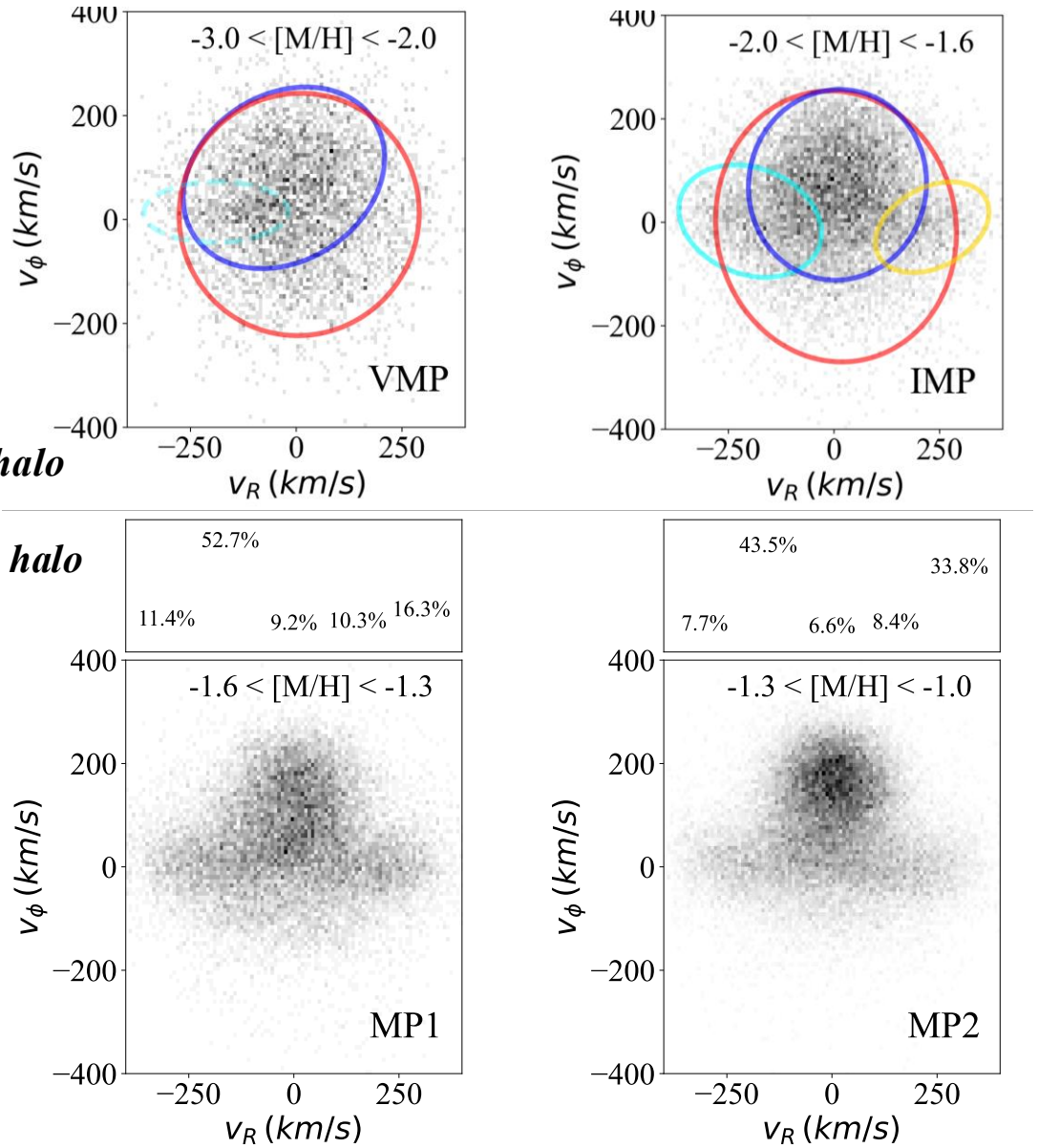


Bayesian Information Criteria (BIC) = $k \ln(n)$ $- 2 \ln L$

Penalty term ✚ *Negative log-likelihood term*

Also see Arentsen+ 24 for a 2-halo population

Gaussian Mixture Model (GMM)



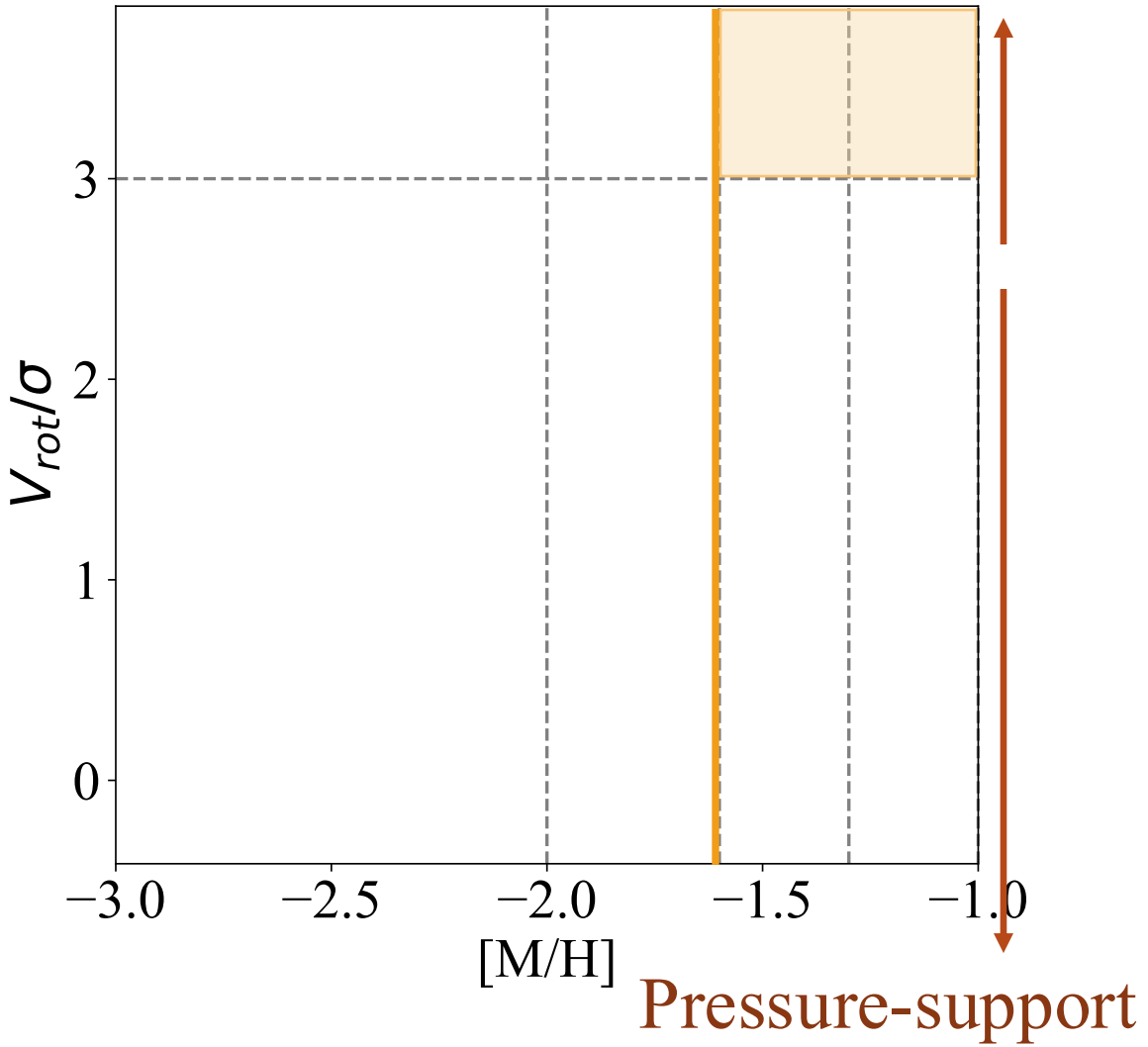
Prograde halo

Stationary halo

GS/E

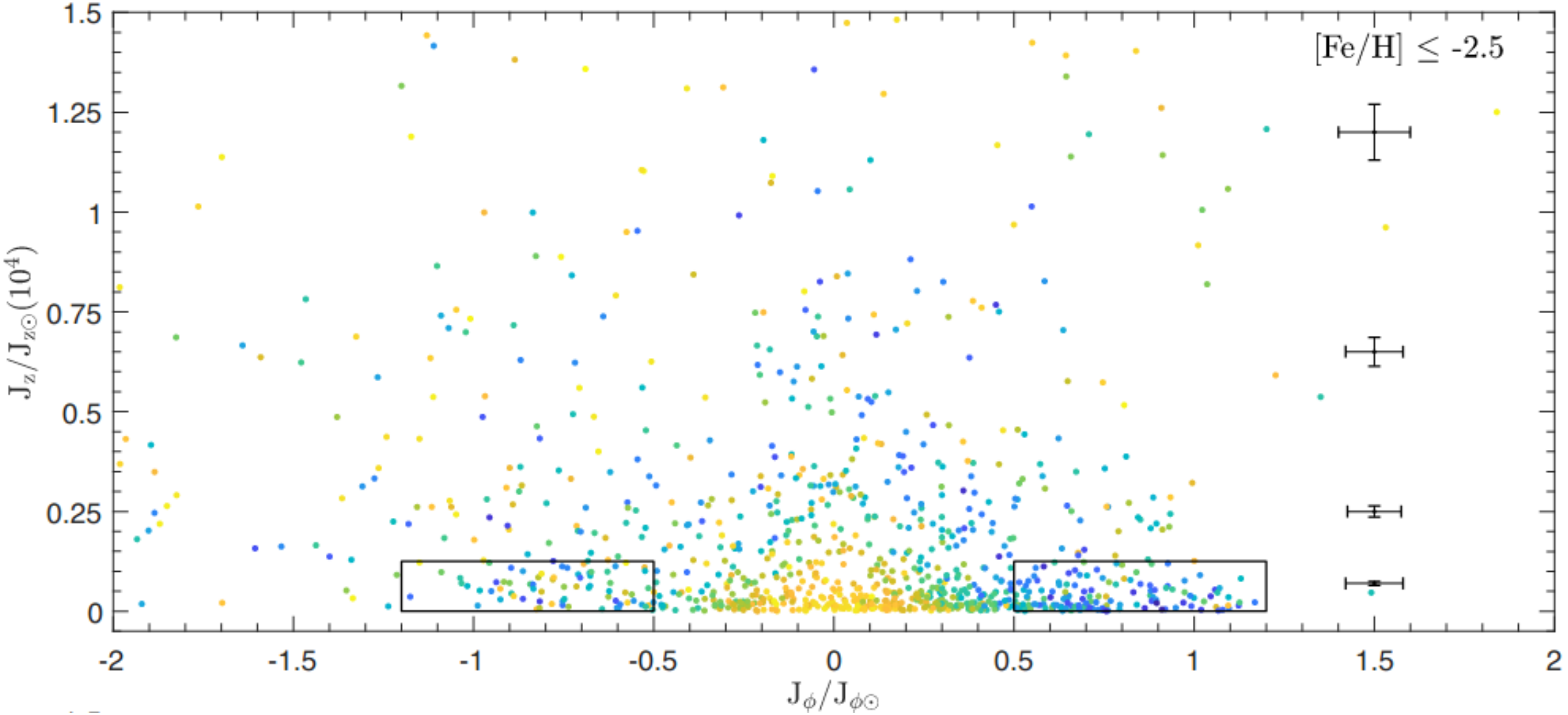
Disc

Rotation-support



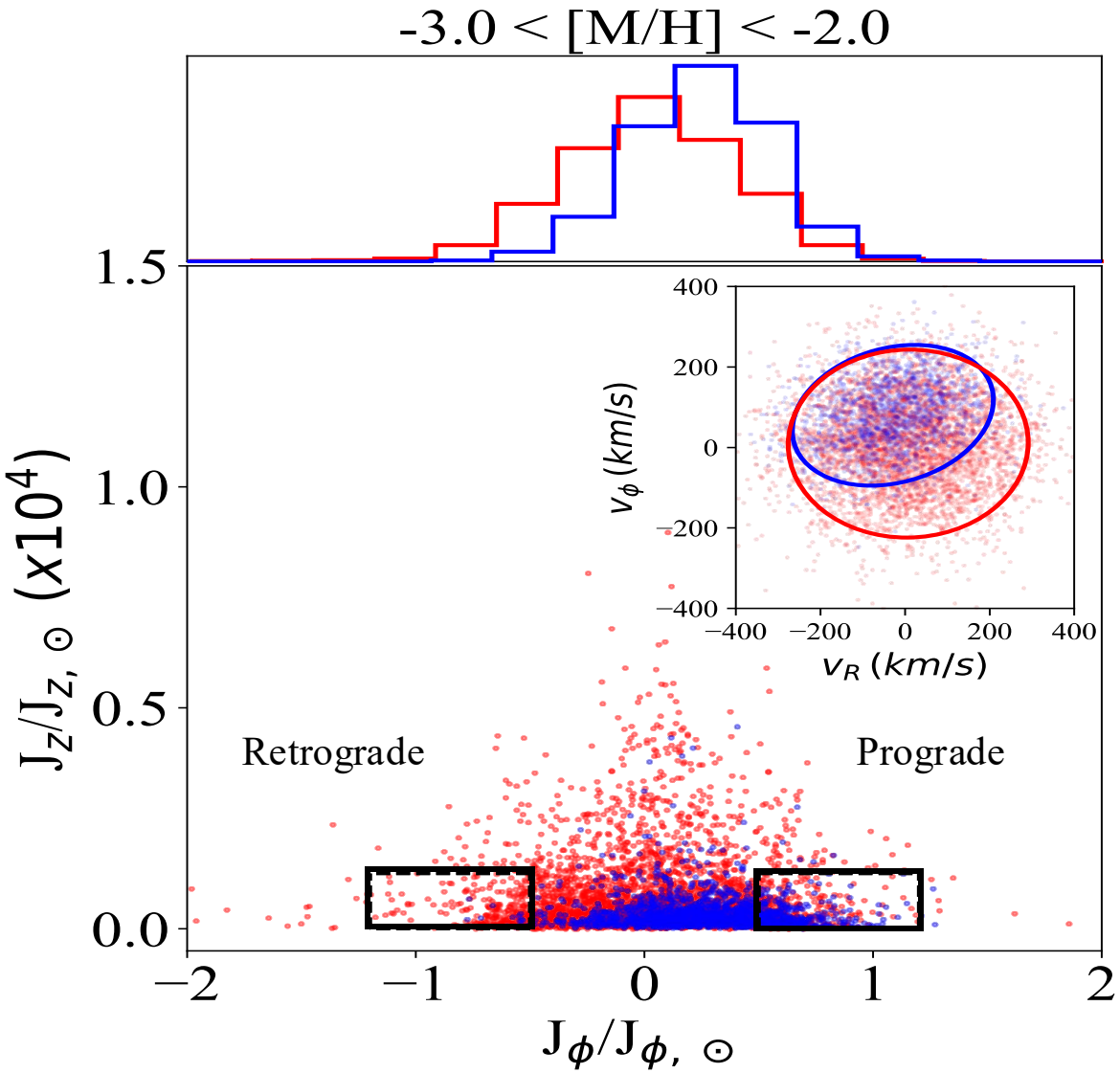
Pressure-support

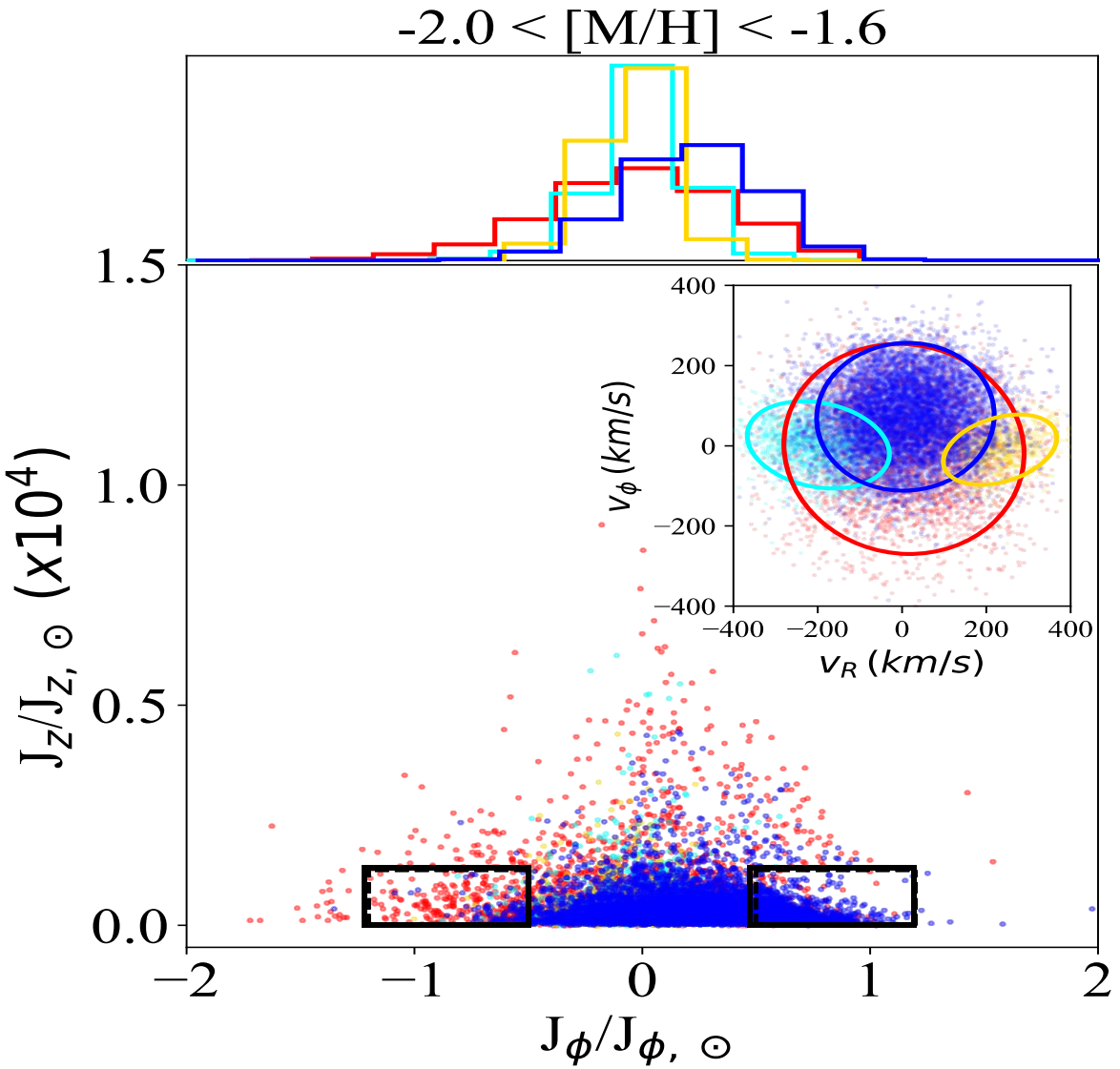
How we explain the previous evidence?



The prograde halo could be responsible for prograde planar stars !

Classify stars by their position in the $v_R - v_\phi$ plane



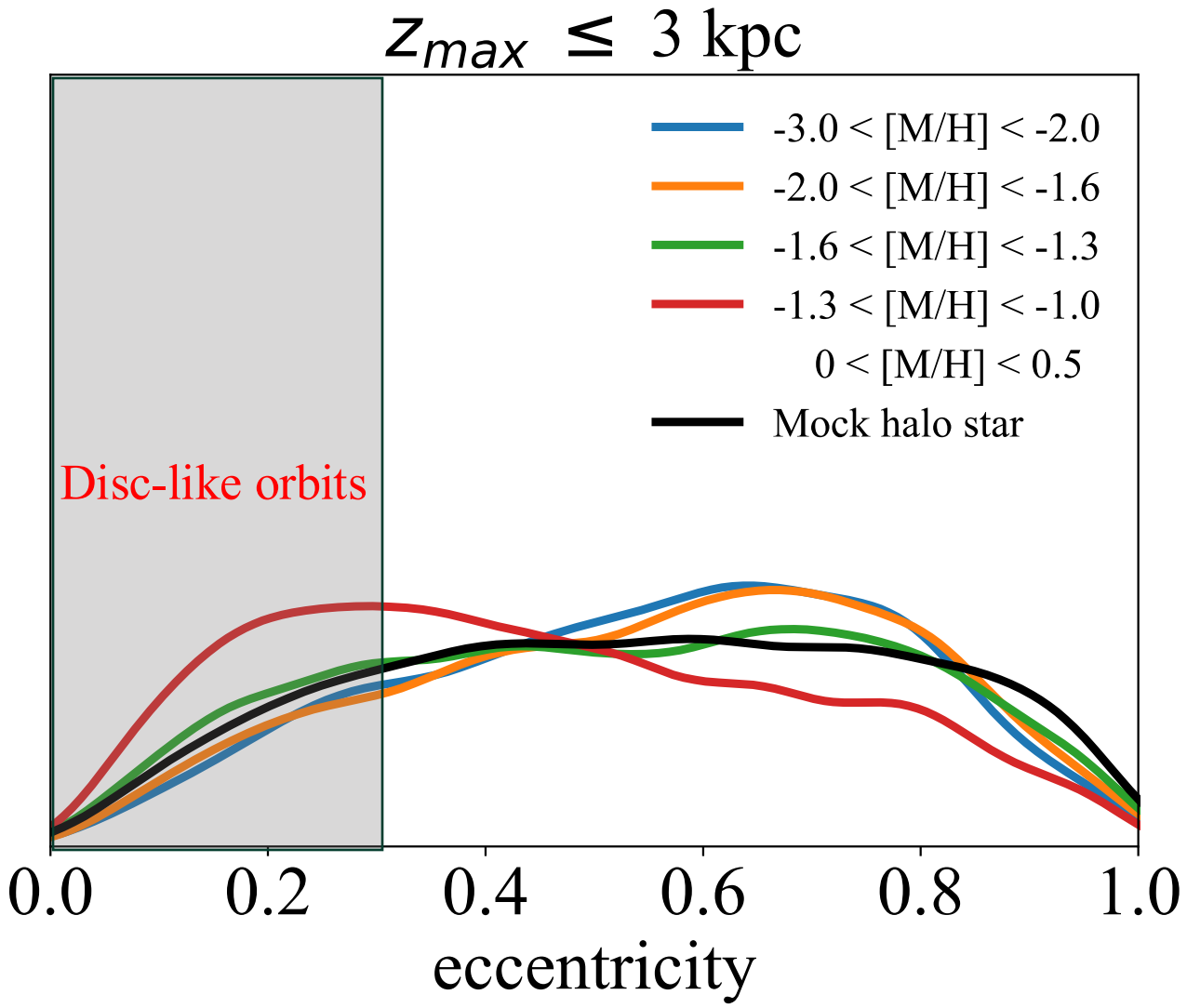


A test particle demonstration

a) generating stars from an isotropic, *non-rotating* NFW distribution function;

b) integrate these stars in the Milky Way potential to get the eccentricity

c) apply the selection function



Interpretation & Conclusion

- No statistically significant evidence can claim for an early-formed, very metal-poor disc in the Milky Way
  - 0 – 3% disc population fraction in the very metal-poor regime ([M/H]<-2)
  - Disc emerged at [M/H] ~ -1.3, which agrees better with simulation and previous disc measurements

- The early Milky Way is still halo-dominated, but some prograde signature is present
  - Disc-like VMP stars could be a sub-population of the prograde halo or just halo.

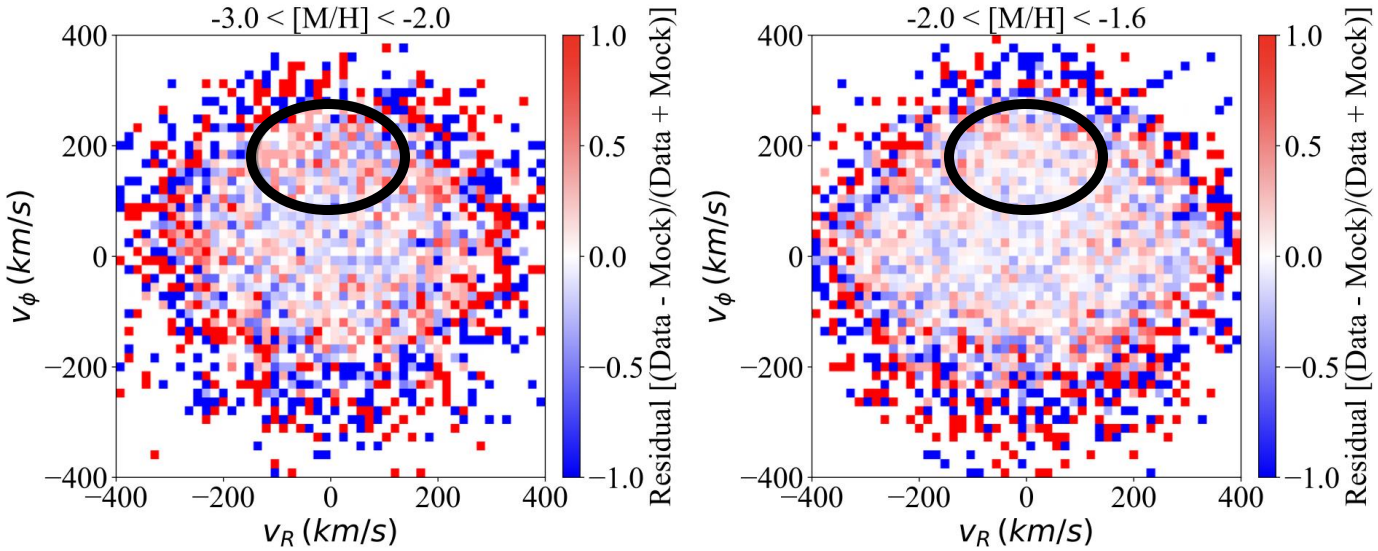
See arxiv:2311.09294 for more detailed and quantative discussion

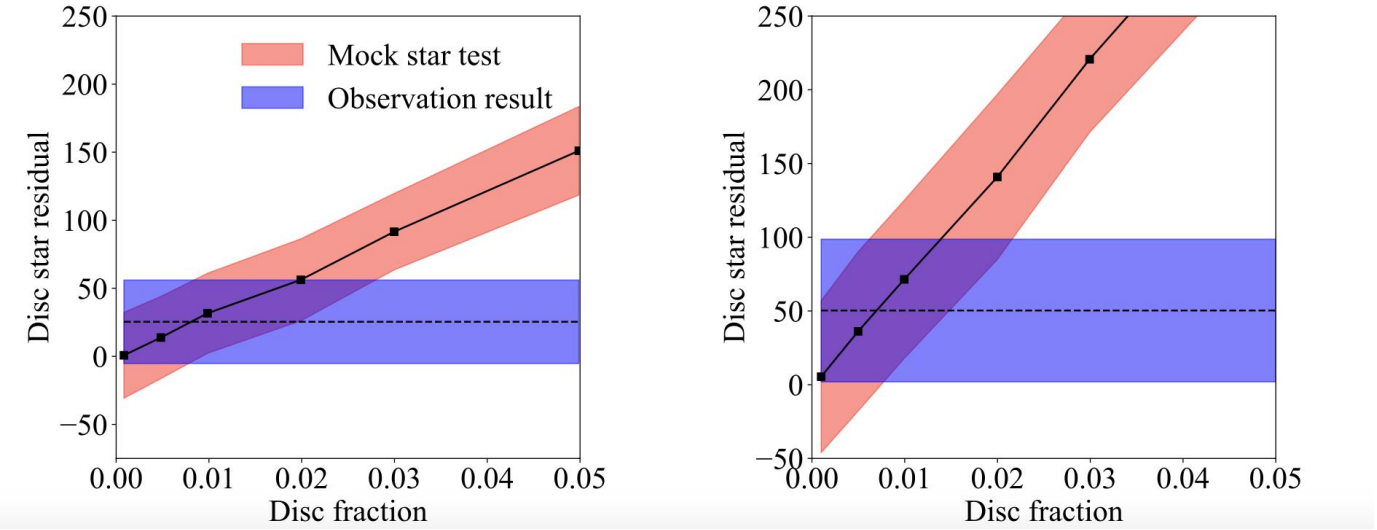
Testing the robustness of GMM (Residual)

$\sim 0 - 3\%$ disc fraction in the VMP and IMP regime !

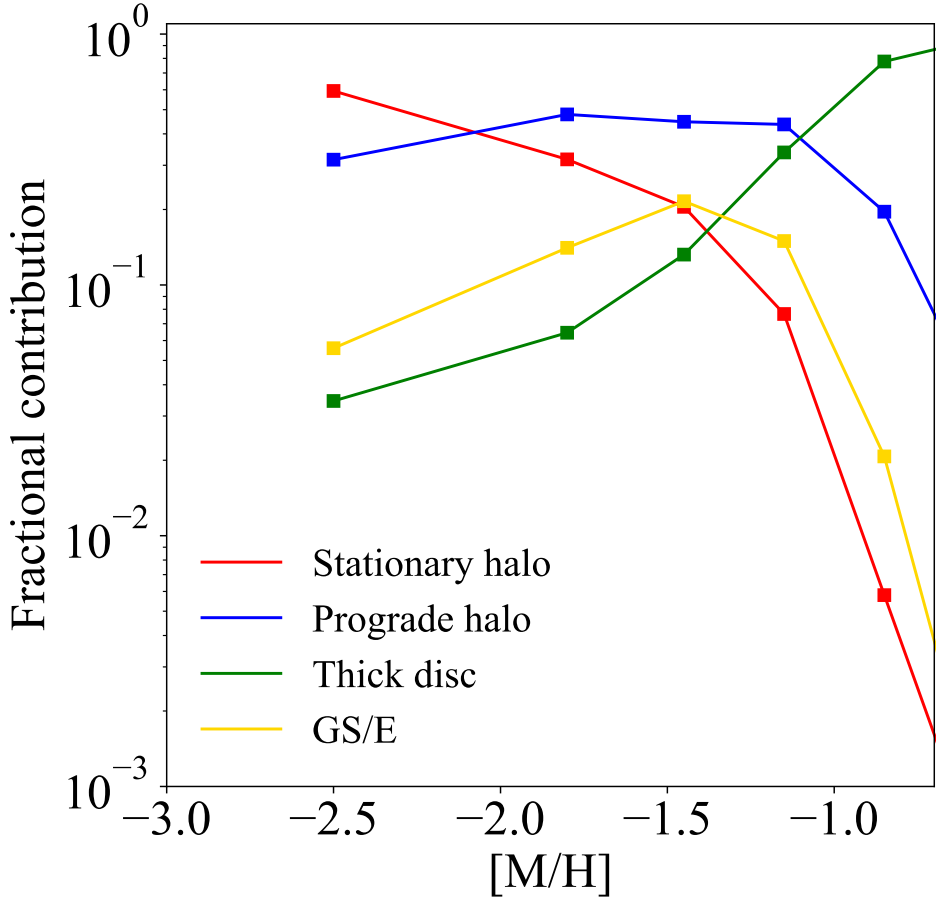
Disc residual: Subtract observation by the GMM model; count residual in the grey ellipse

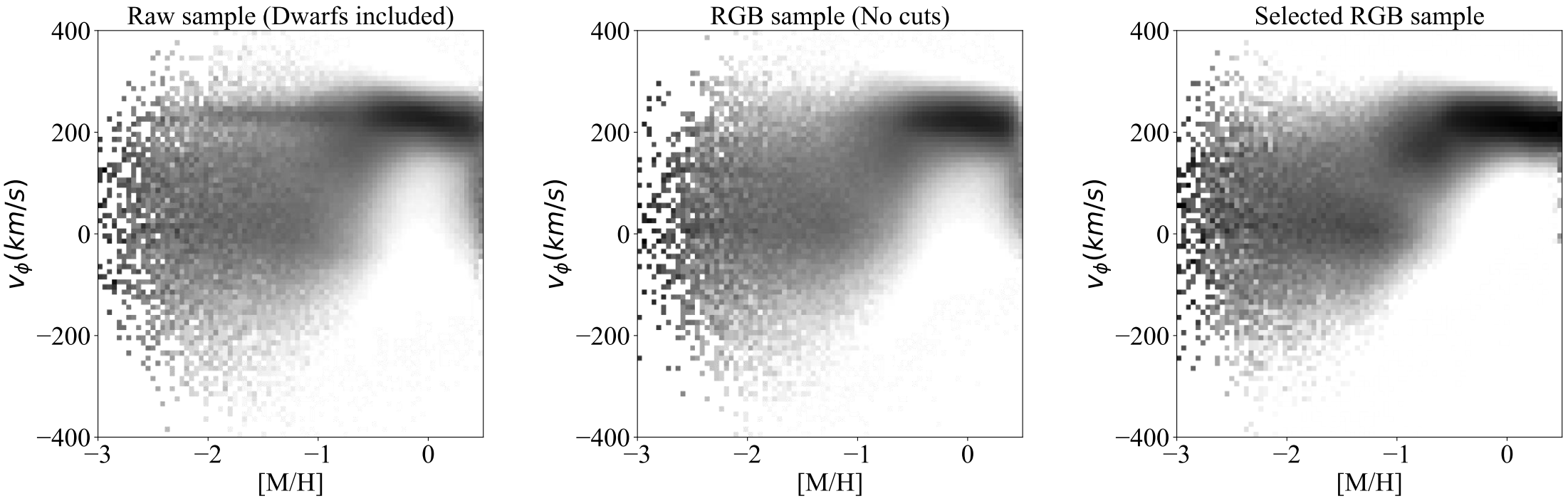
Mock sample: Manually insert disc stars, so there is a known disc star fraction





Testing the robustness of GMM (Frozen componet)




Raw sample (Dwarfs included)
RGB sample (No cuts)
Selected RGB sample
$v_\phi(km/s)$
[M/H]
400
200
0
−200
−400
−3
−2
−1
0

Testing the robustness of GMM (Residual)

~ 0 − 3% disc fraction in the VMP and IMP regime !

Validation procedure:

Generate N stars according the GMM fitting

↓

Subtract the number of observed stars in each pixel

↓

Count residual in the grey ellipse (disc region)

Generate N_{GMM} stars according the GMM fitting

+

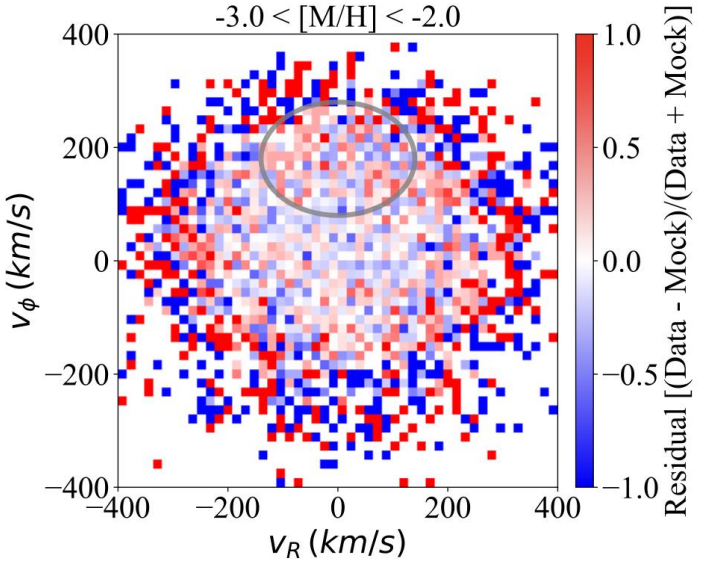
Generate N_{disc} stars according the grey ellipse

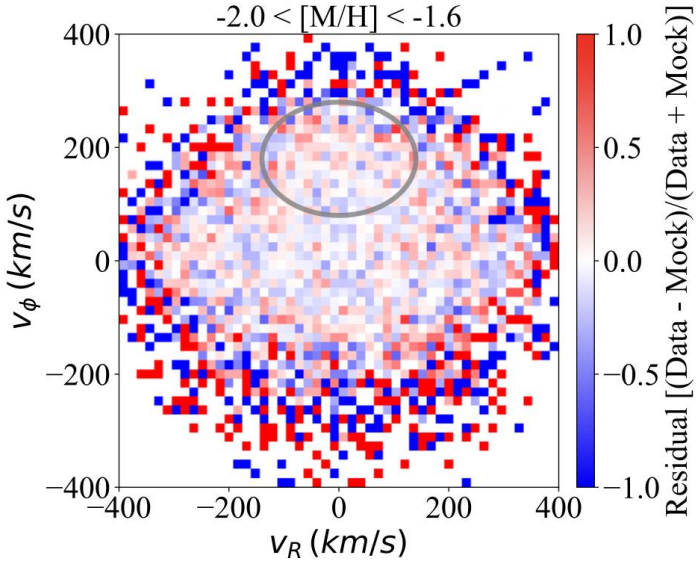
↓

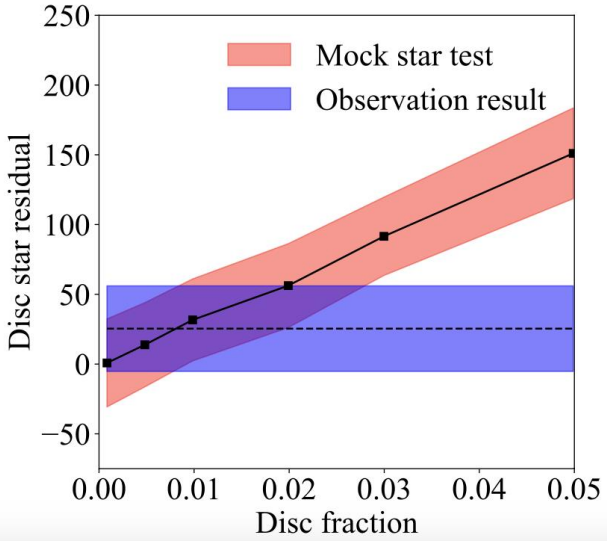
Generate $N_{GMM} + N_{disc}$ stars according the same GMM

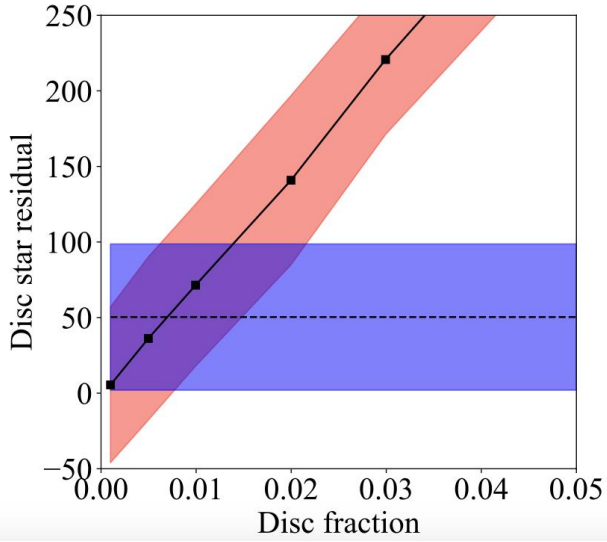
↓

Subtract two mock population and find disc residual









Justification of the VMP planner stars

Classification routine:

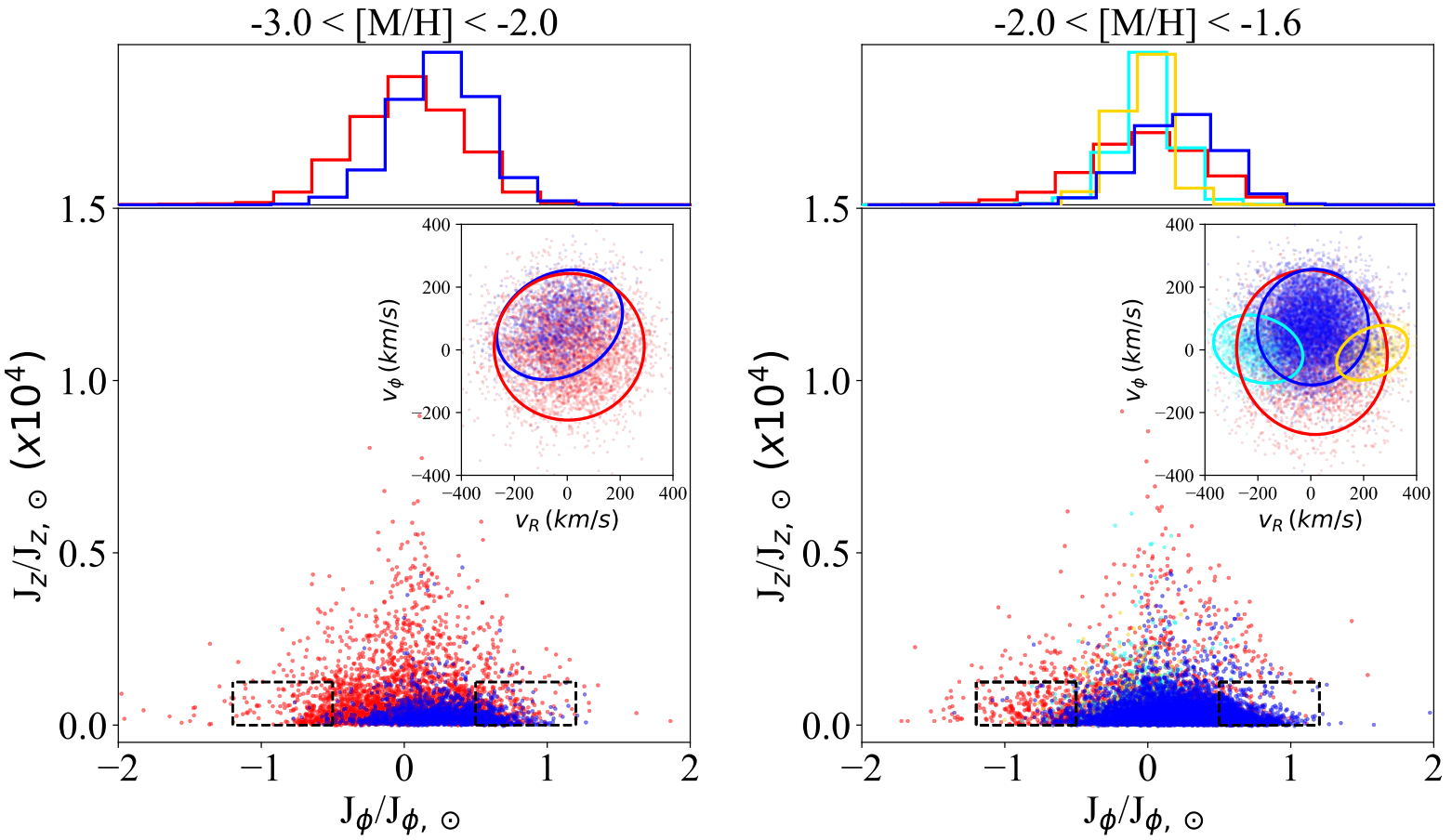
Generate N stars according to the GMM model

↓

For observed star, finding the closest match of the generated stars in the $v_R - v_\phi$ plane

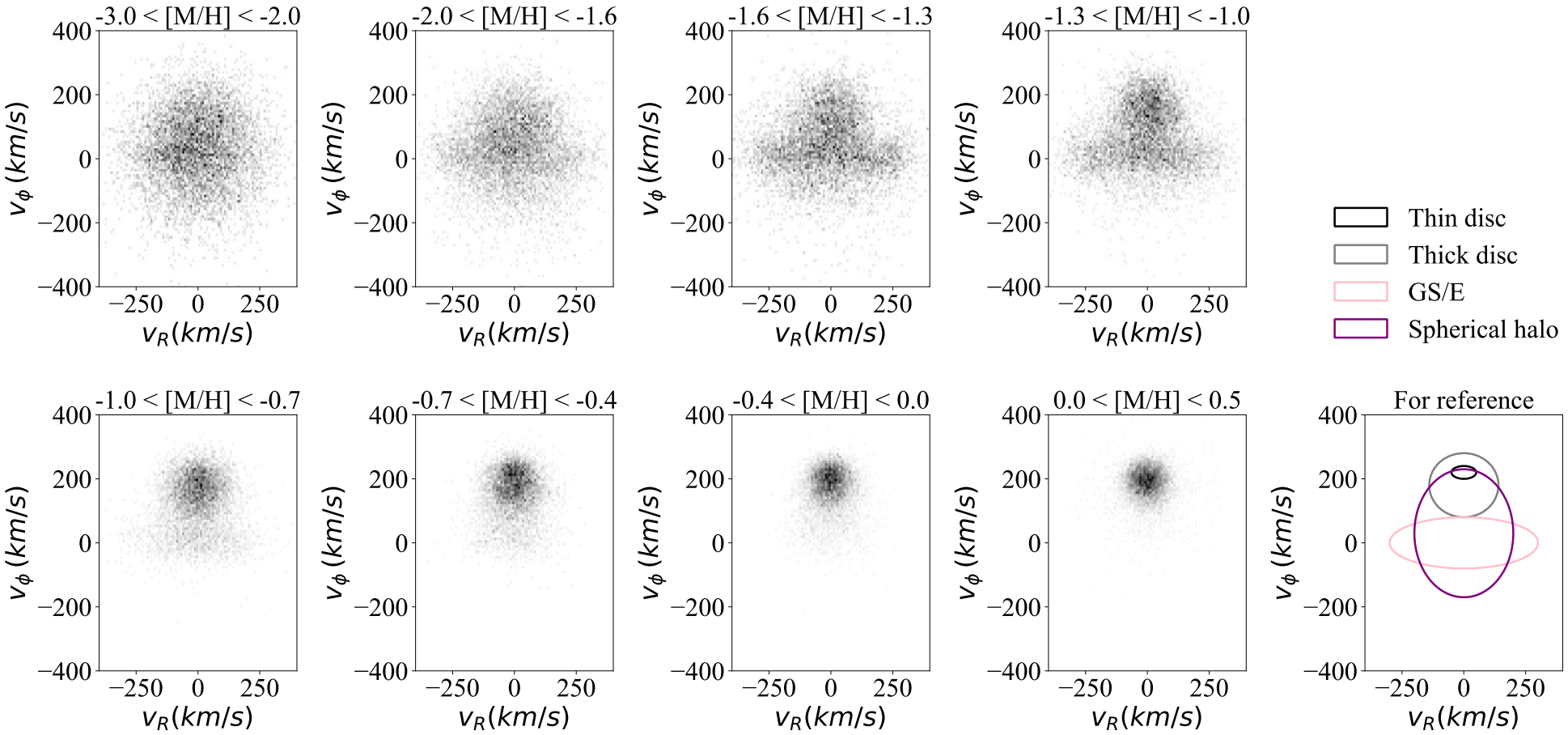
↓

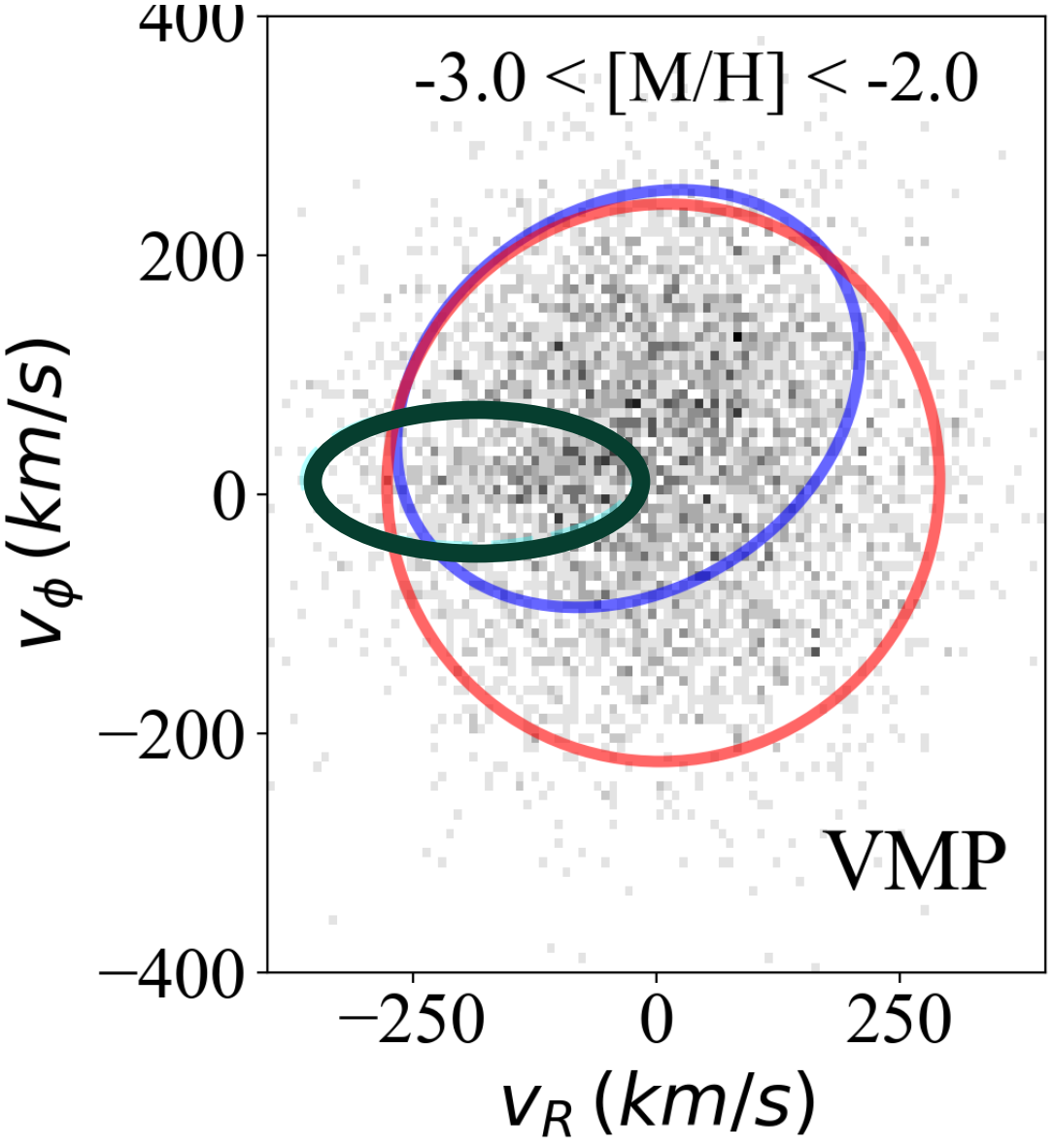
Assign the membership of the generated star to the observed star

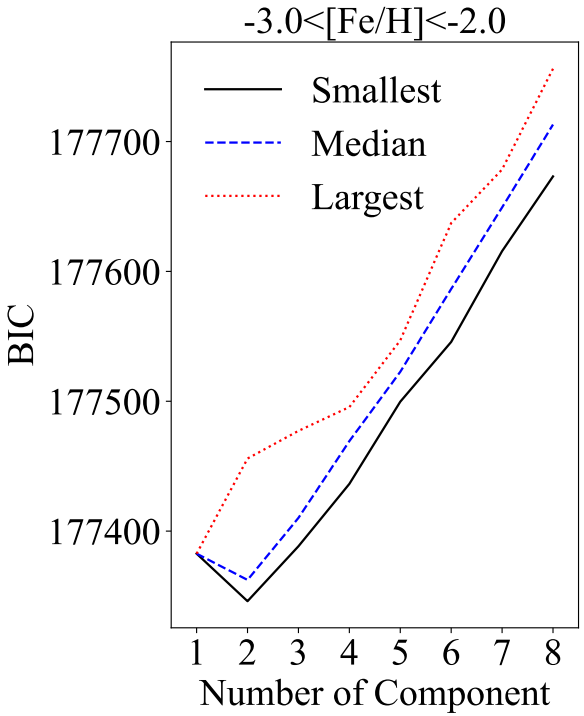


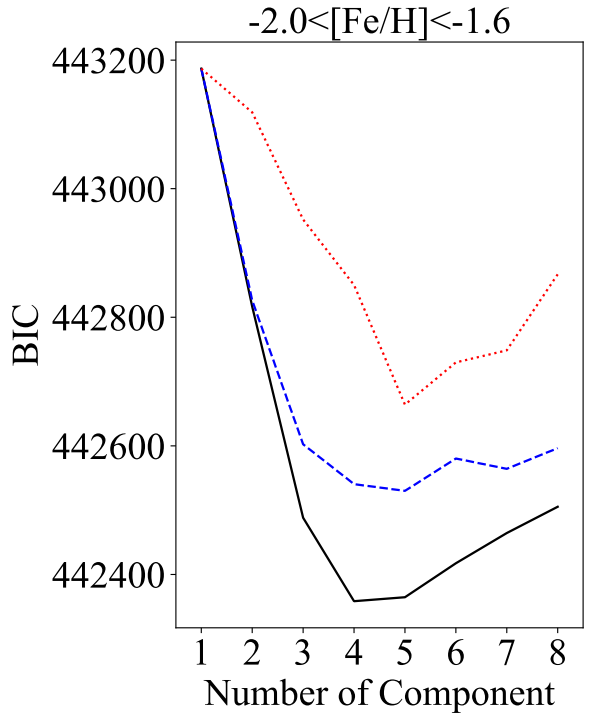
The prograde halo could be responsible for those prograde planner stars !

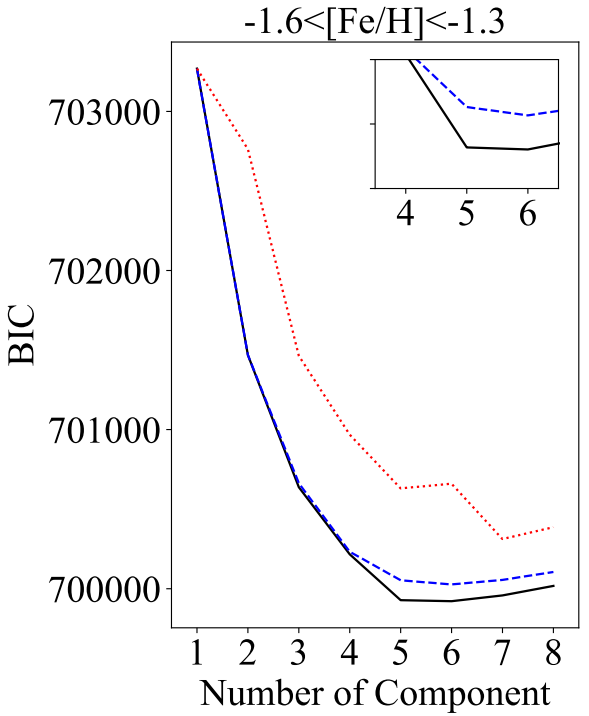
How robust the result is against the selection function

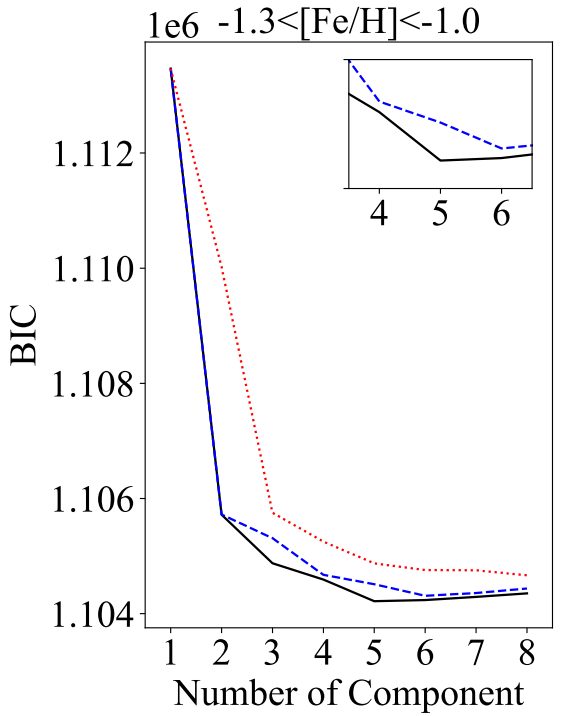


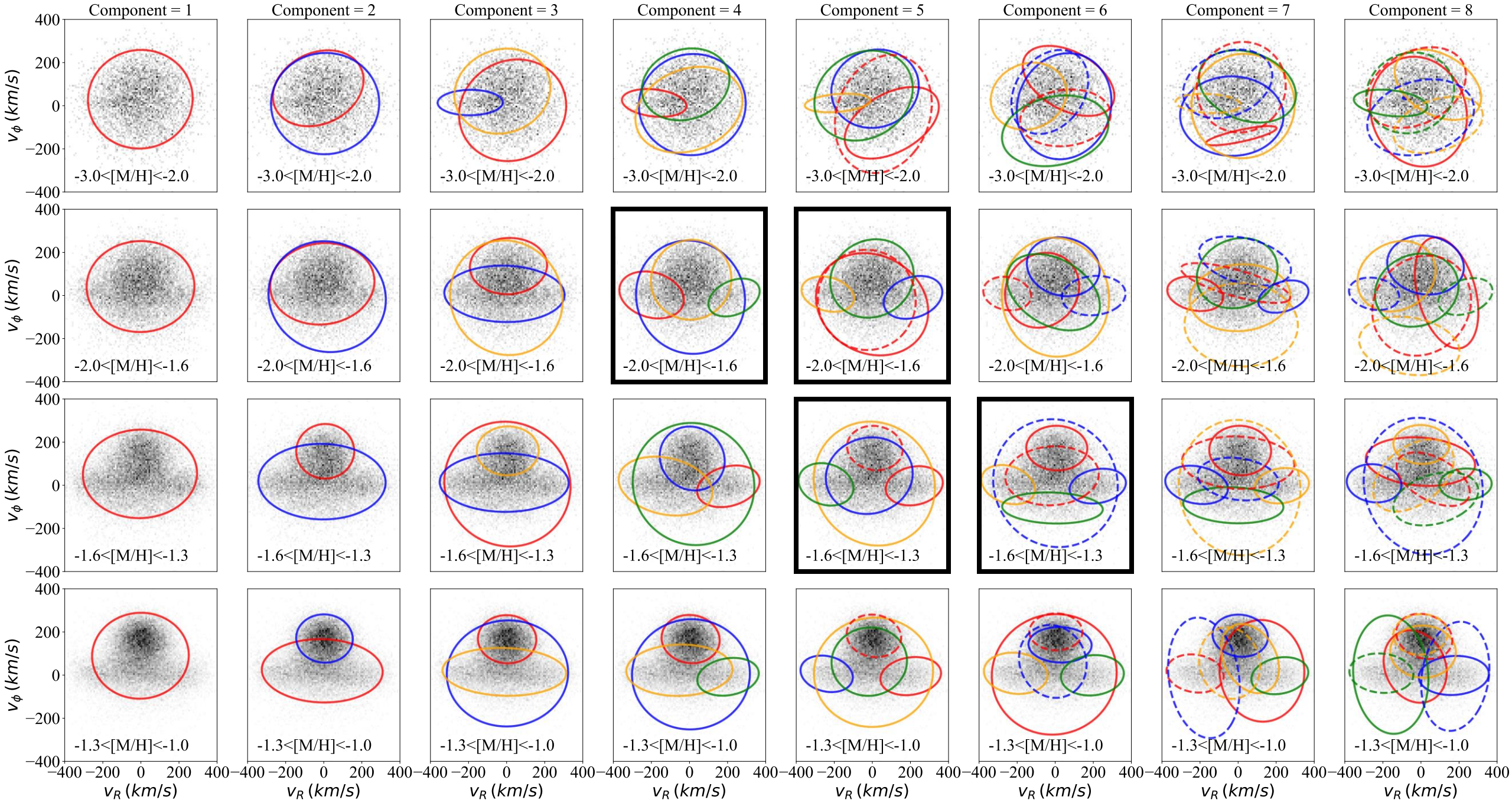

-3.0 < [M/H] < -2.0
VMP
400
200
0
−200
−400
−250
0
250
v_ϕ (km/s)
v_R (km/s)

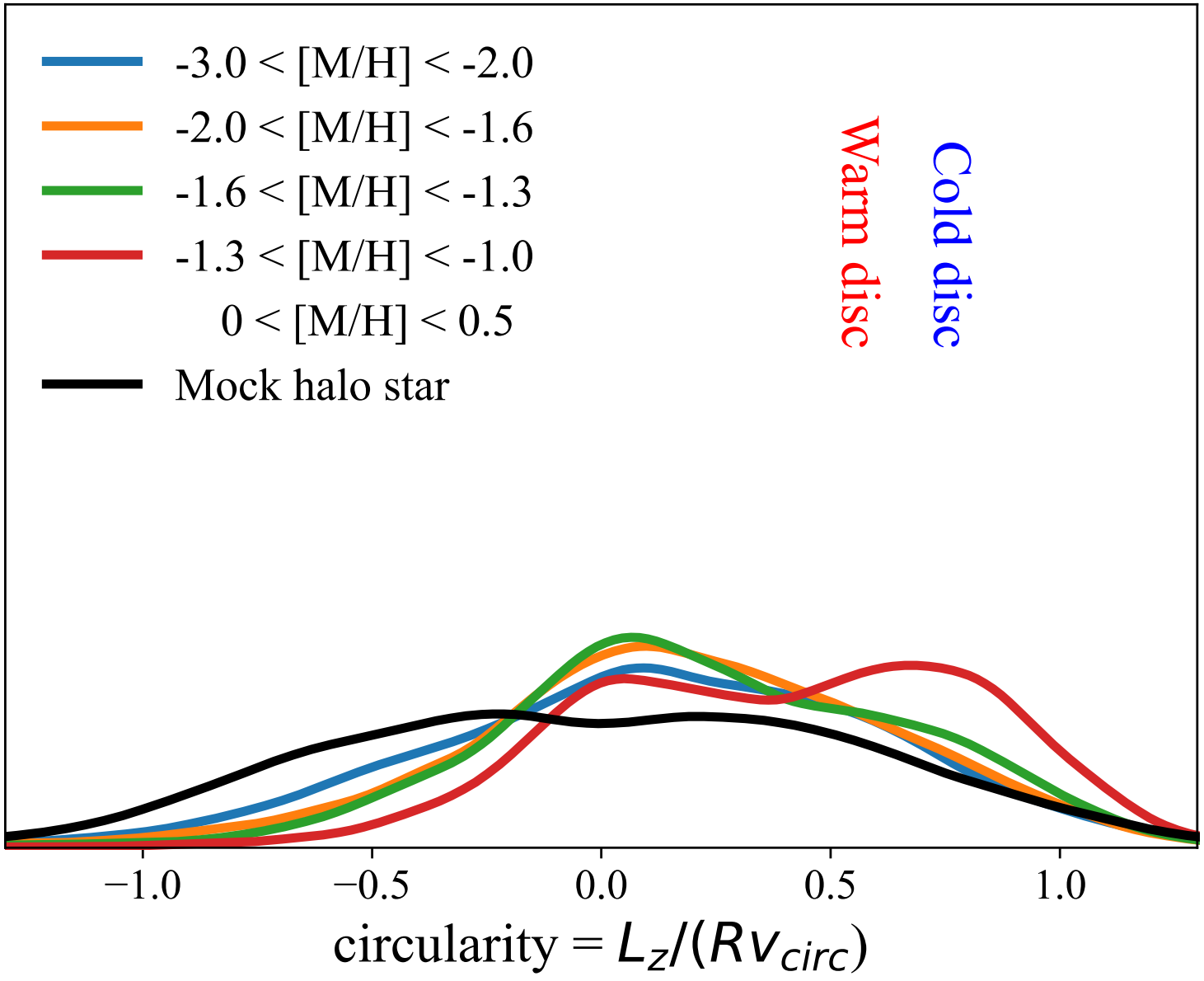

-3.0<[Fe/H]<-2.0
Smallest
Median
Largest
BIC
177700
177600
177500
177400
1 2 3 4 5 6 7 8
Number of Component

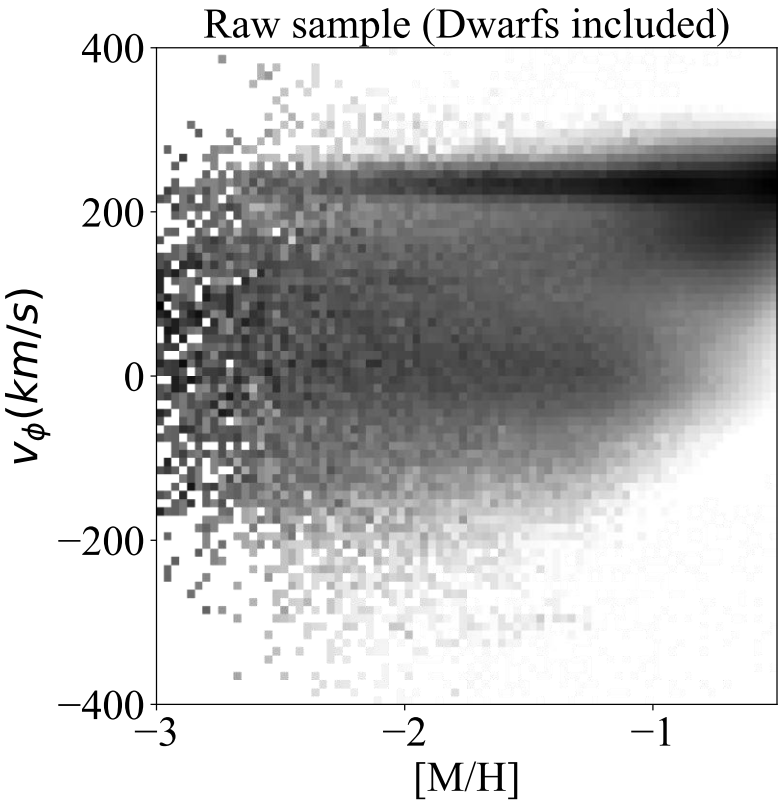

-2.0<[Fe/H]<-1.6
BIC
443200
443000
442800
442600
442400
1 2 3 4 5 6 7 8
Number of Component

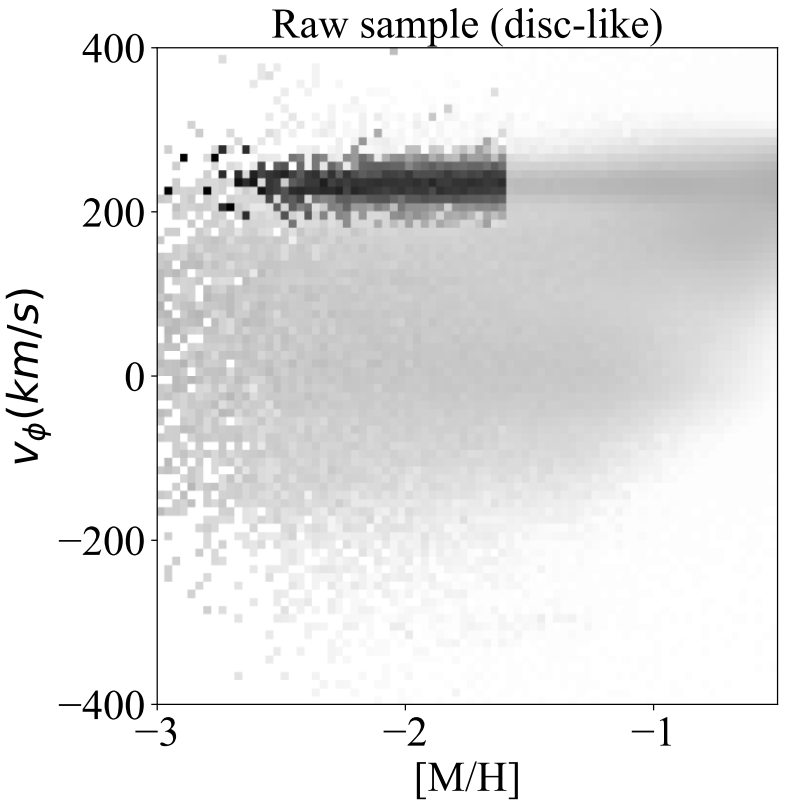

-1.6<[Fe/H]<-1.3
BIC
703000
702000
701000
700000
4 5 6
1 2 3 4 5 6 7 8
Number of Component

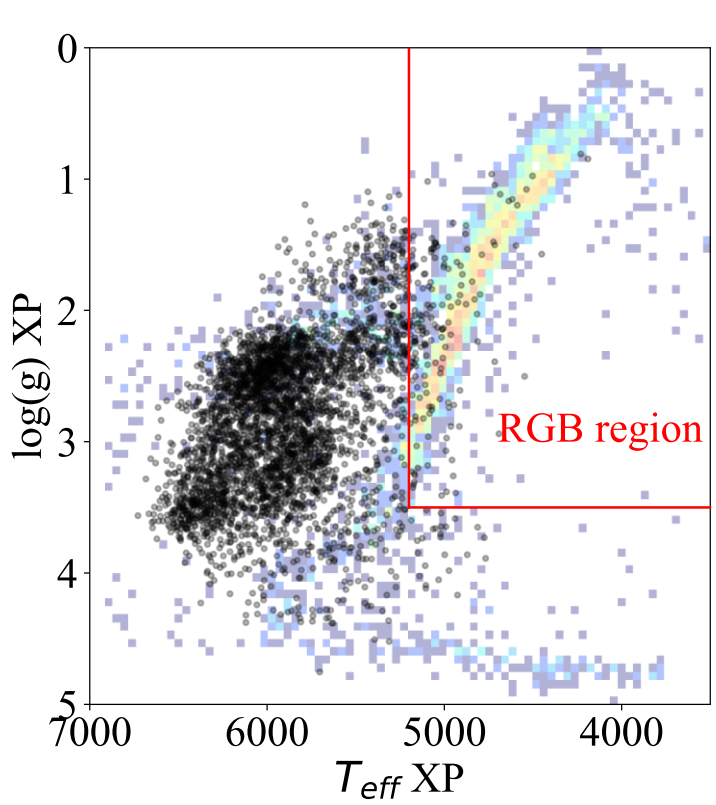

1e6
-1.3<[Fe/H]<-1.0
BIC
1.112
1.110
1.108
1.106
1.104
4 5 6
1 2 3 4 5 6 7 8
Number of Component

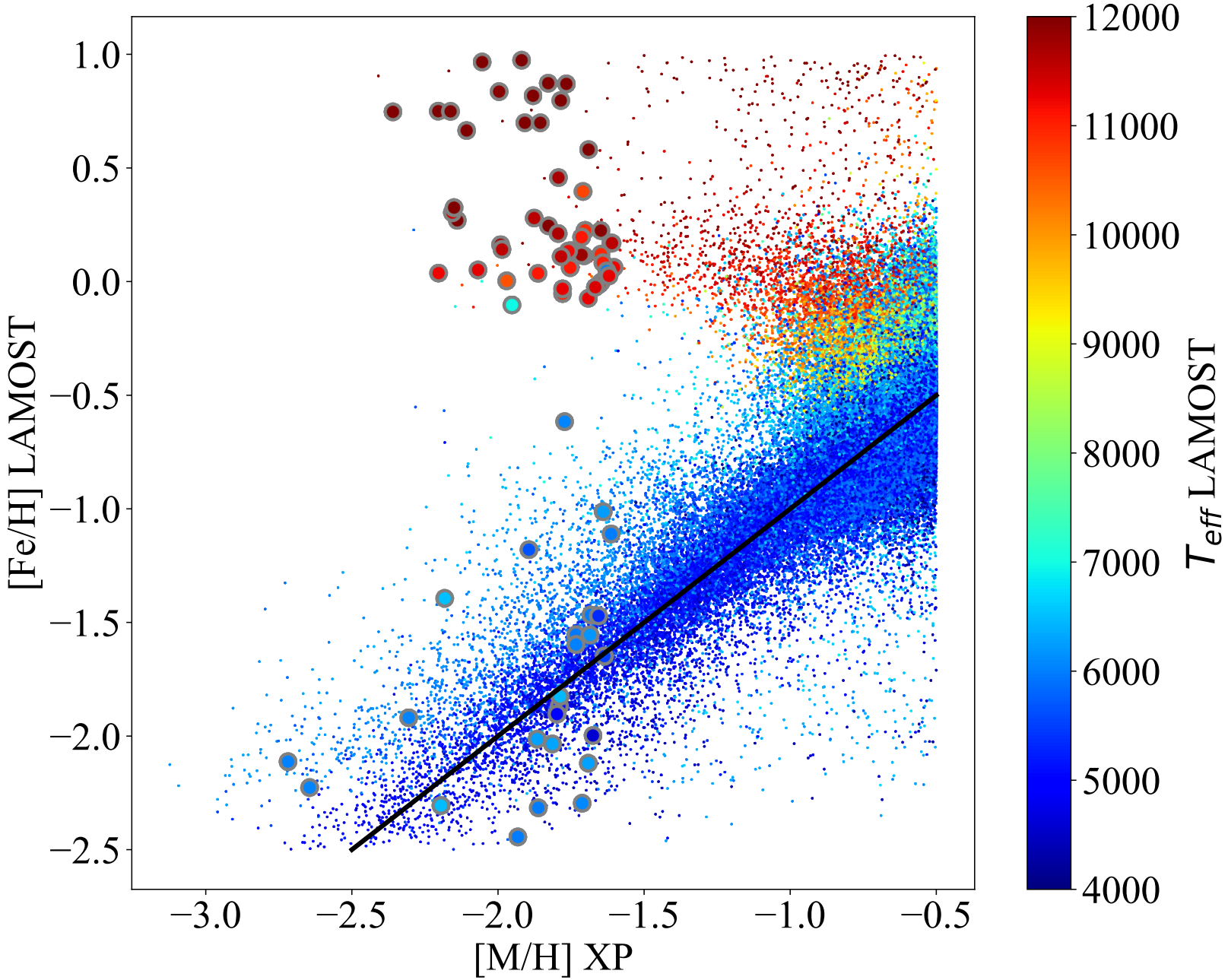

Component = 1
Component = 2
Component = 3
Component = 4
Component = 5
Component = 6
Component = 7
Component = 8
-3.0<[M/H]<-2.0
-2.0<[M/H]<-1.6
-1.6<[M/H]<-1.3
-1.3<[M/H]<-1.0
v_ϕ (km/s)
v_R (km/s)
400
200
0
−200
−400


-3.0 < [M/H] < -2.0
-2.0 < [M/H] < -1.6
-1.6 < [M/H] < -1.3
-1.3 < [M/H] < -1.0
0 < [M/H] < 0.5
Mock halo star
Warm disc
Cold disc
−1.0
−0.5
0.0
0.5
1.0
circularity = $L_z/(Rv_{circ})$


Raw sample (Dwarfs included)
400
200
0
−200
−400
$v_\phi(km/s)$
−3
−2
−1
[M/H]


Raw sample (disc-like)
400
200
0
−200
−400
$v_\phi(km/s)$
−3
−2
−1
[M/H]


0
1
2
3
4
5
log(g) XP
7000
6000
5000
4000
T_{eff} XP
RGB region


1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
[Fe/H] LAMOST
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
[M/H] XP
12000
11000
10000
9000
8000
7000
6000
5000
4000
T_{eff} LAMOST