Gaia-ESO Survey Second Science Meeting
Nov 10th 2014

Jason Sanders (Oxford → IoA) — with James Binney & Tilmann Piffl

Extended Distribution Functions for the Galactic Disc

1. Action-based disc modelling
2. Extending DF to include chemistry
3. Fitting to GCS data
4. Predicting SEGUE G dwarfs and RAVE

Sanders & Binney (2014, submitted)

Motivation

Modern surveys provide abundances → more info for dynamics

Ongoing/Upcoming surveys and dynamics

Lots of surveys providing chemical data (**Gaia-ESO**, APOGEE, LAMOST, GALAH, Gaia)

Most dynamical modelling has considered stars at point masses — only concerned with density in position and velocity space.

Selection Functions

All surveys are subject to some selection function.

Even though we may not **explicitly** select in velocity, kinematics are linked to age and metallicity and only stars of certain ages and metallicities may be observed.

Must include chemical information to correctly account for selection effects

Action-angle modelling

- Convenient to use actions ($\mathbf{J}$) & angles ($\boldsymbol{\theta}$)
  - Functions of ($\mathbf{x}$, $\mathbf{v}$) depending on potential, $\Phi(\mathbf{x})$
  - Canonical coordinates
  - Simple equations of motion

$$\boldsymbol{J} = \text{const.},$$

$$\boldsymbol{\theta} = \boldsymbol{\Omega}(\boldsymbol{J})t + \boldsymbol{\theta}(0).$$

- When considering steady-state models, we must satisfy

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0.$$

- Can use the actions as arguments of f

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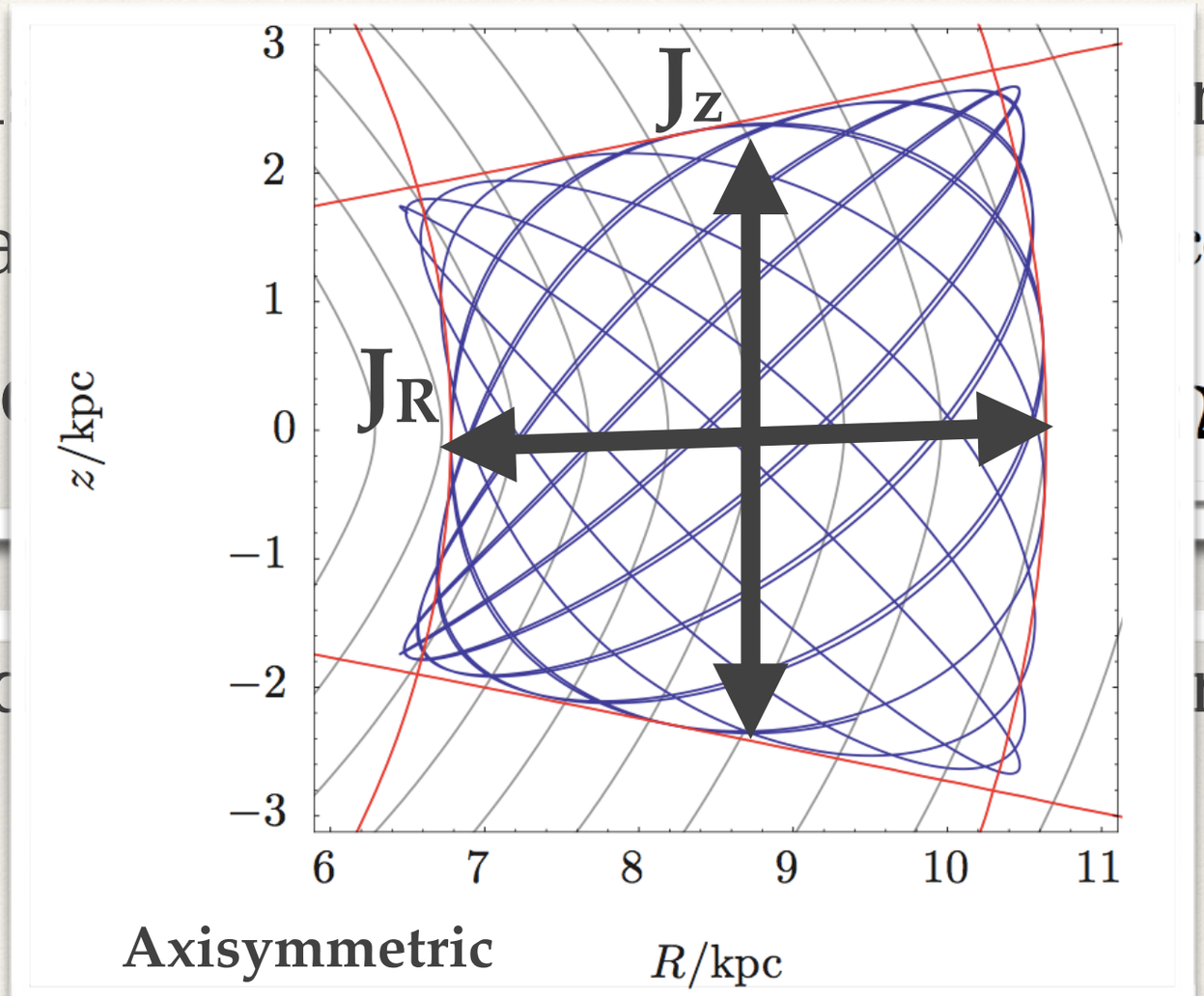

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Brief recent history of f(**J**) disc models

- Binney (2010) introduced the quasi-isothermal DF

$$f_{\sigma_R,\sigma_z}(J_R,J_z,L_z) = f_{\sigma_R}(J_R,L_z)f_{\sigma_z}(J_z,L_z)$$

$$f_{\sigma_R}(J_R,L_z) \equiv \frac{\Omega}{2\pi^2 R_d^2 \sigma_R^2 \kappa}\bigg|_{R_c} [1+\tanh(L_z/L_0)]\mathrm{e}^{-\kappa J_R/\sigma_R^2}\mathrm{e}^{-R_c/R_d}$$

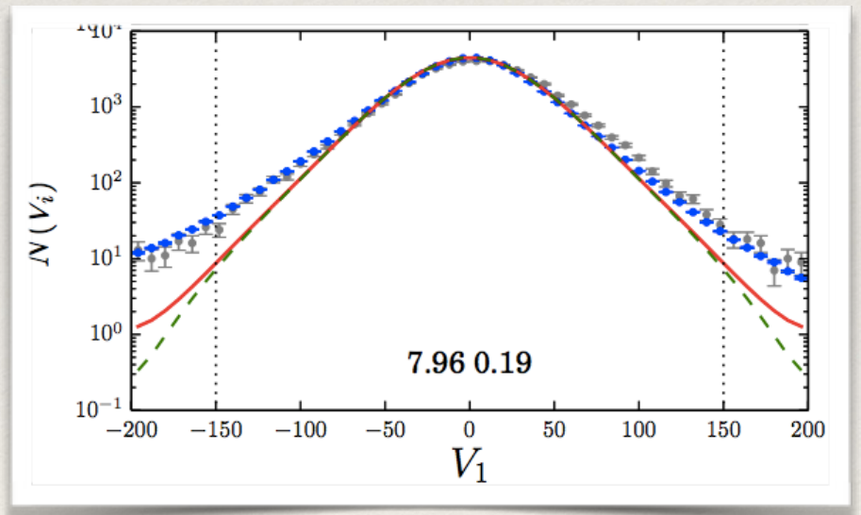
$$f_{\sigma_z}(J_z,L_z) \equiv \frac{\nu}{2\pi\sigma_z^2}\mathrm{e}^{-\nu J_z/\sigma_z^2}$$

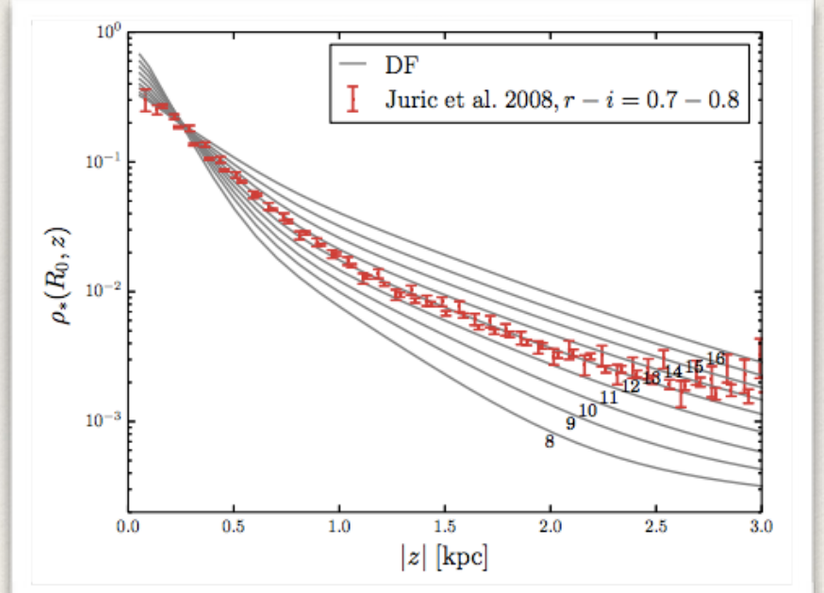
- Binney (2012b) improved action calculation using the **Stäckel Fudge** (Binney 2012a).

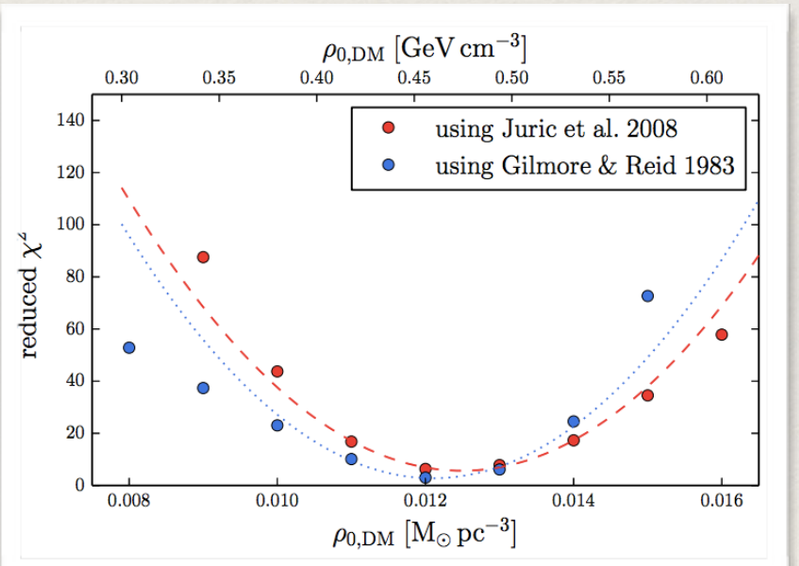
- Binney et al. (2013) applied these models to RAVE data
- Thin & thick discs are distinct components (we stick with this picture).

Brief recent history of f(**J**) disc models

- **Piffl et al. (2014)** simultaneously fitted f(**J**) models and the potential to a RAVE giant sample.
- Combined with other constraints on potential and density information from Juric et al. (2008) and Gilmore & Reid (1983)



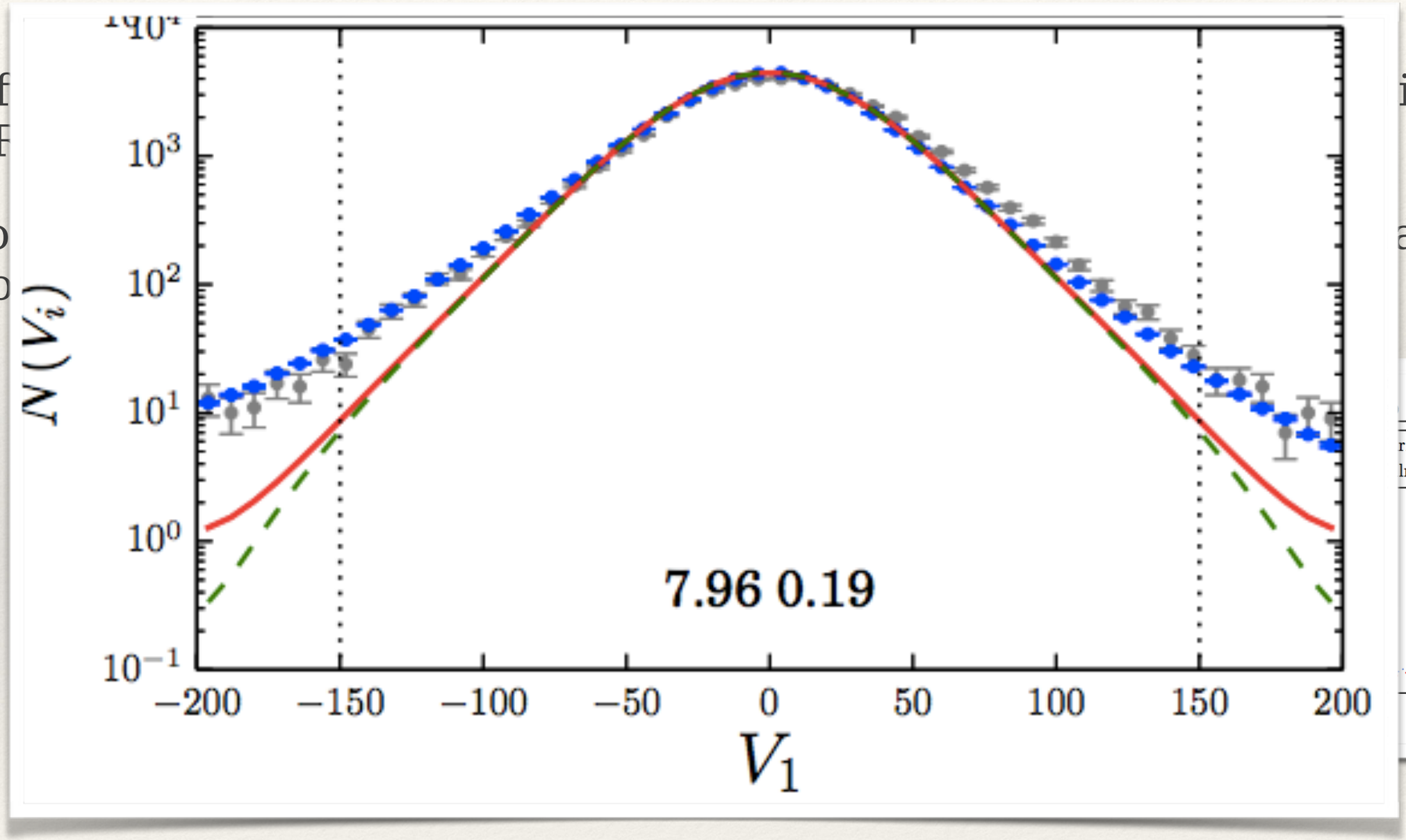


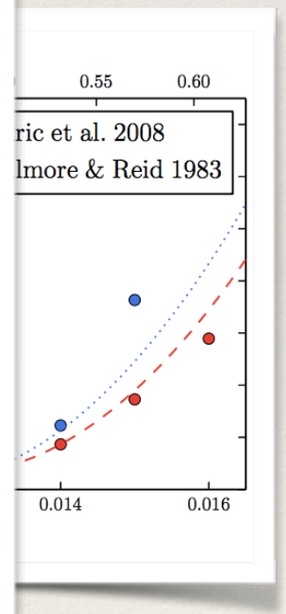


$$\mathbf{f(J) \rightarrow f(J, Z)}$$

Brief recent history of f(**J**) disc models

- Pif … ial to a F…
- Co… ation fro…





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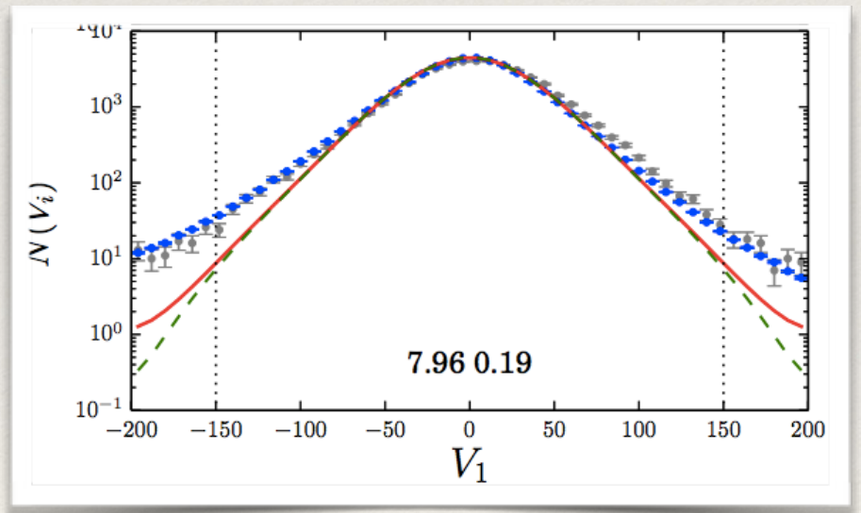

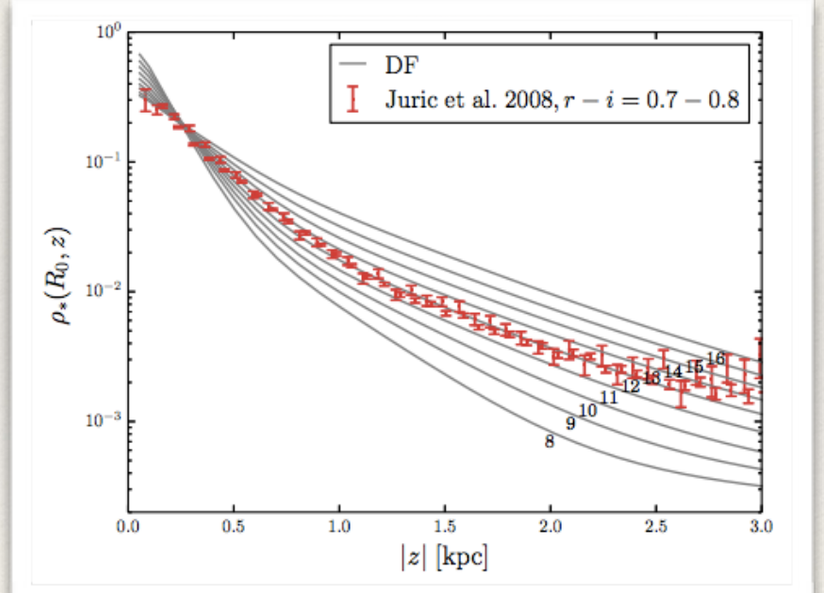

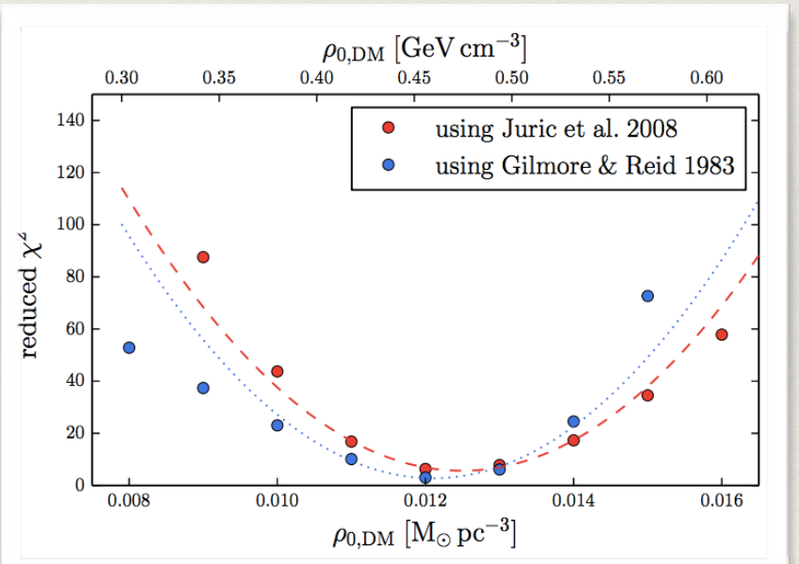

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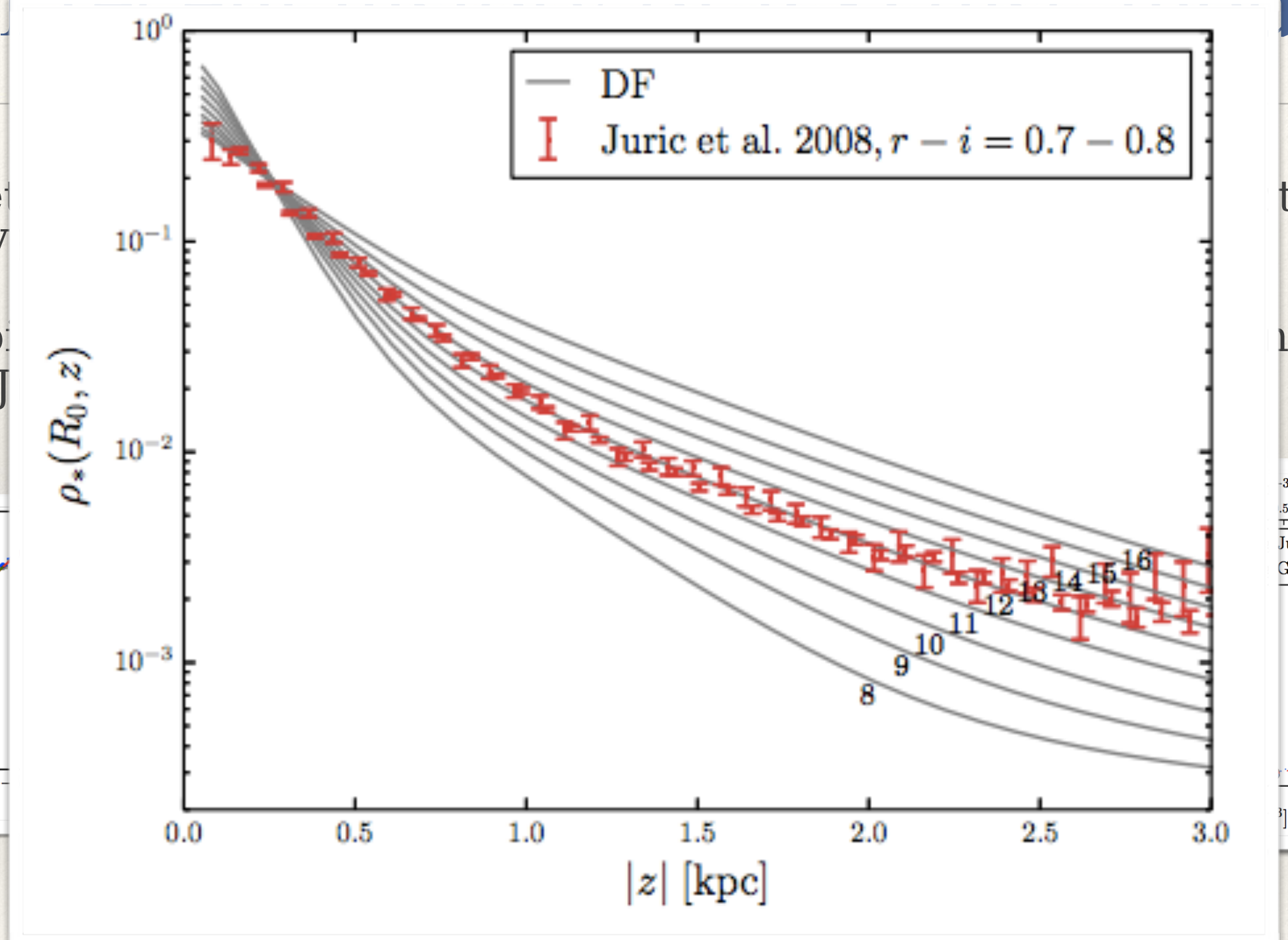
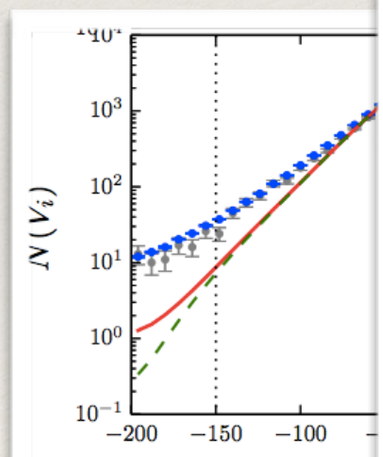
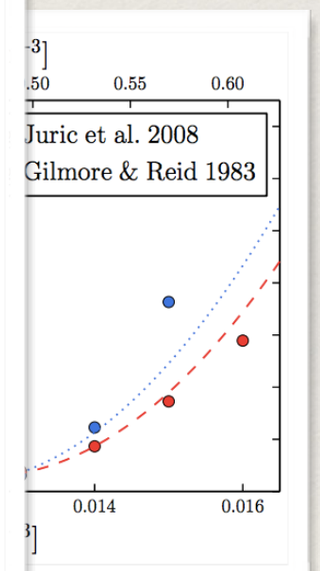
Brief recent history of f(J) disc models

- Piffl et … tial to a RAV…
- Combi… nation from J…







$$f(\mathbf{J}) \rightarrow f(\mathbf{J}, \mathbf{Z})$$

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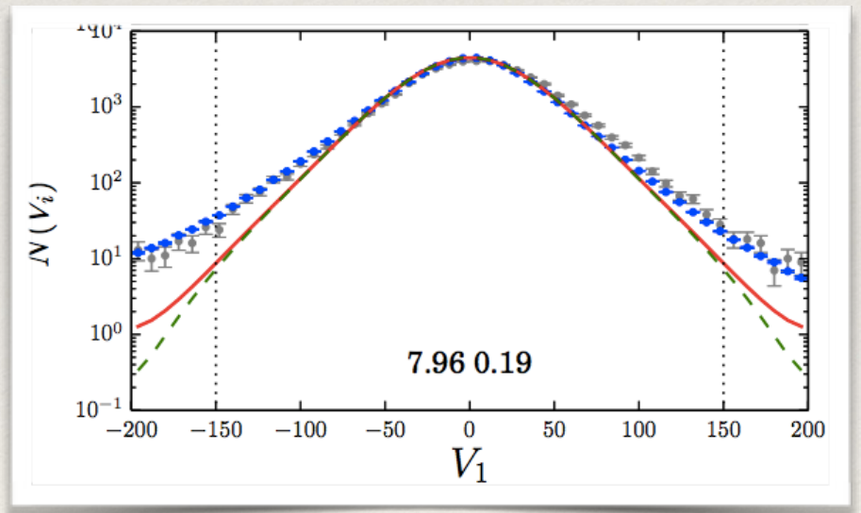

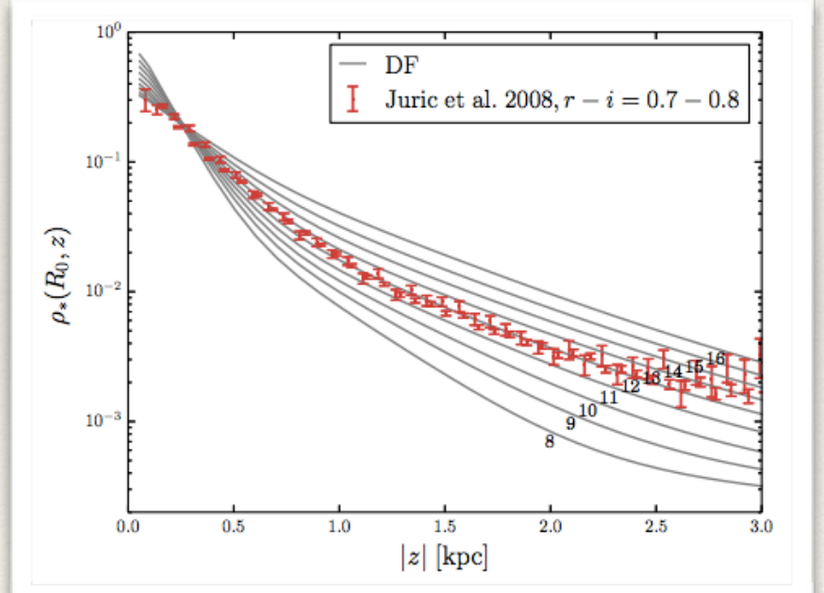

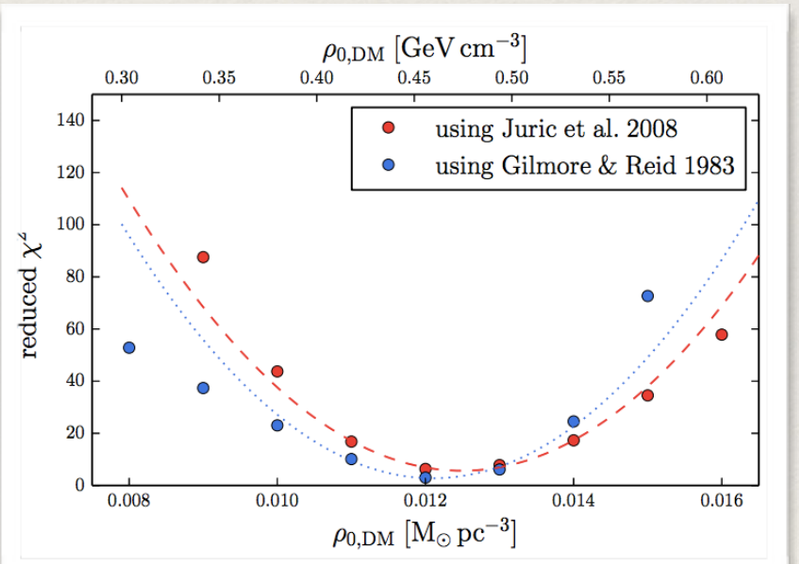

$$\mathbf{f(J)} \rightarrow \mathbf{f(J, Z)}$$

Bri…lels

- Piff…tial to a R…
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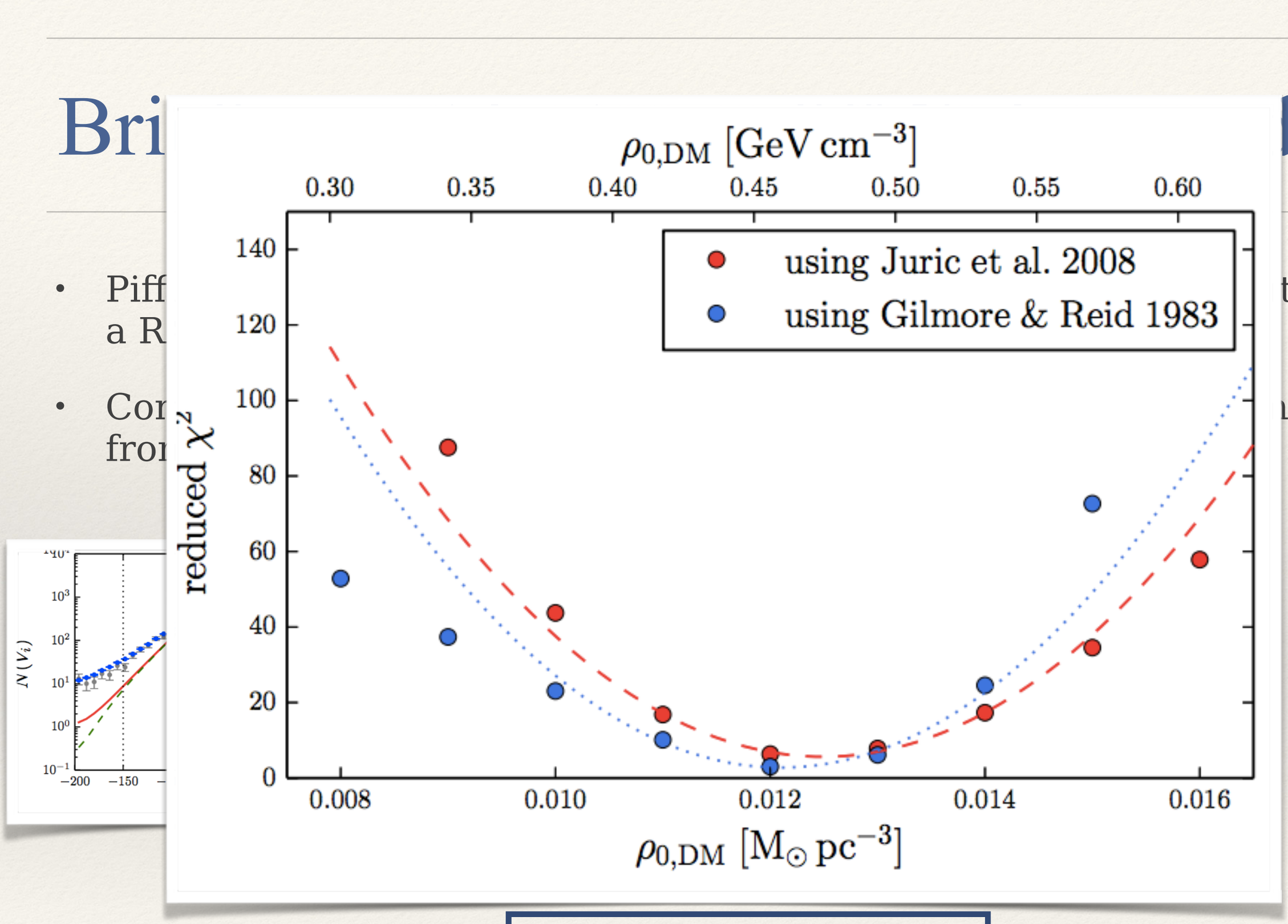
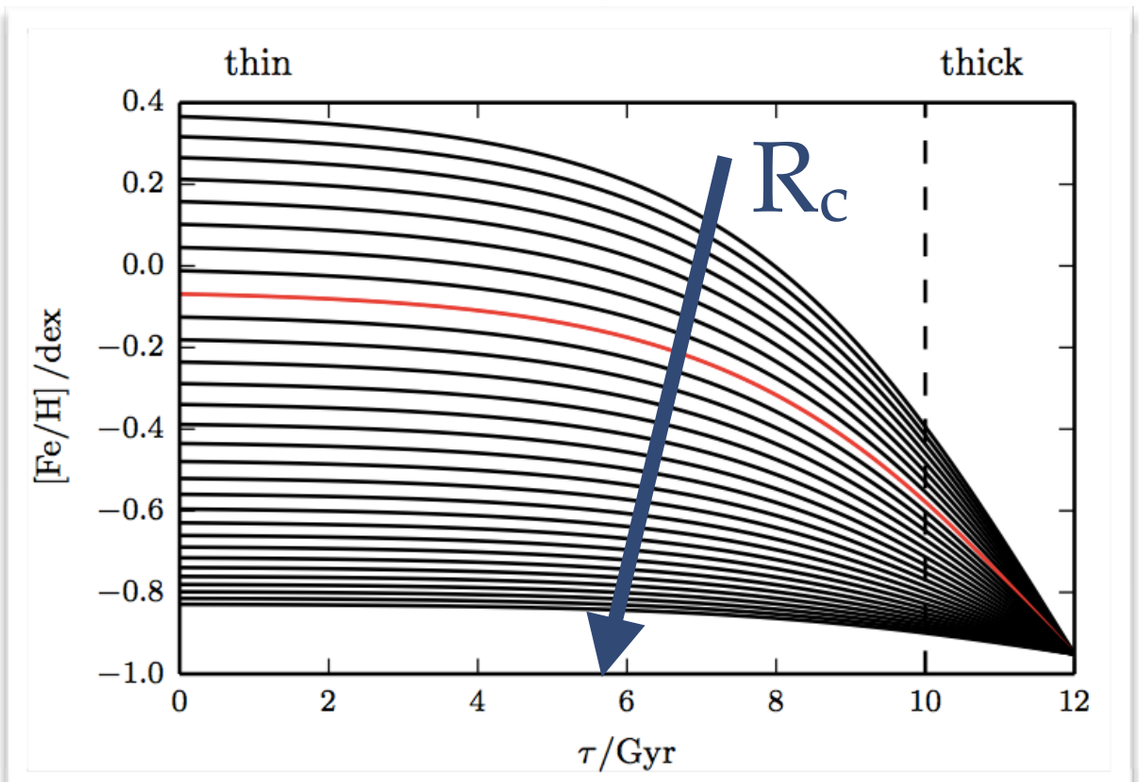


$$\mathbf{f(J) \longrightarrow f(J, Z)}$$

Extended DFs
Using chemical information

Use a fixed potential (modified Dehnen & Binney, 1998)
Two discs, bulge & halo

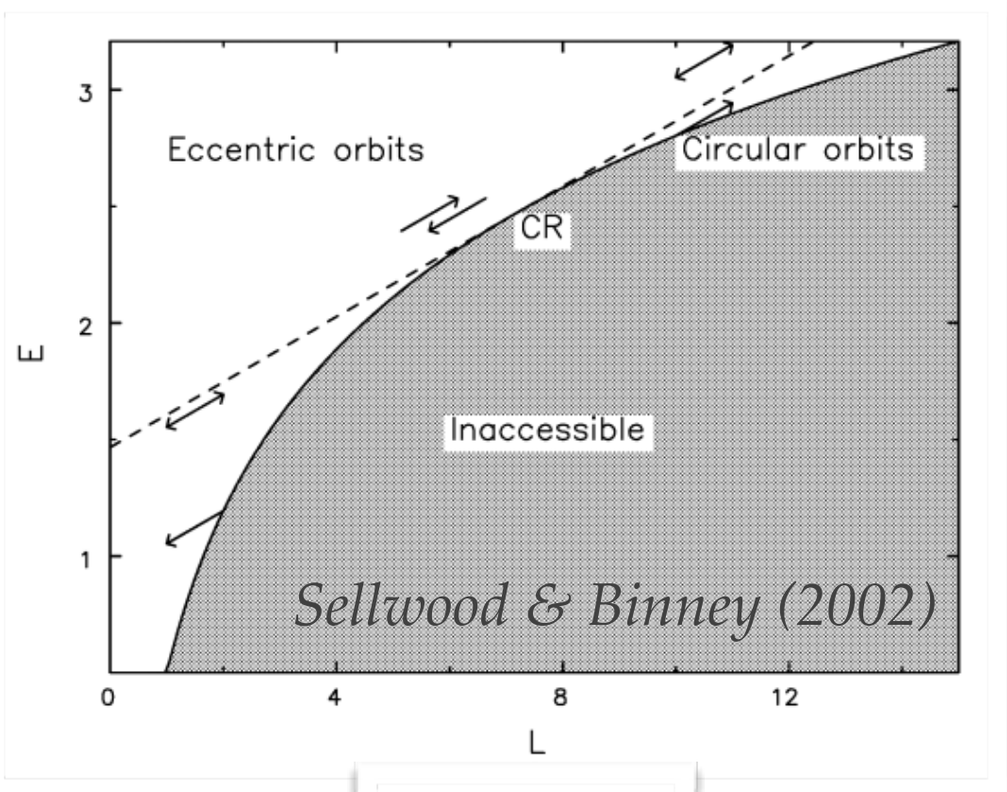
Analytic metallicity with age



$$[\mathrm{Fe/H}](R,\tau) = F(R,\tau) \equiv F(R) + [F(R) - F_m]\left[\tanh\left(\frac{\tau_m - \tau}{\tau_F}\right) - 1\right].$$

SFR (exponential decay) & IMF (Kroupa)

Radial migration



$$\frac{e^{-(L_z - L_z')^2/2\sigma_L^2}}{\sqrt{2\pi\sigma_L^2}}$$

Isochrones (BaSTI, Pietrinferni et al. 2004)

Lifetime of star (our picture)

Born **dynamically cold** time τ ago on a circular orbit of radius R_c'

$Z(R_c', \tau)$

Star born with metallicity, Z, and actions $(0, L_z', 0)$

Birth

Lifetime

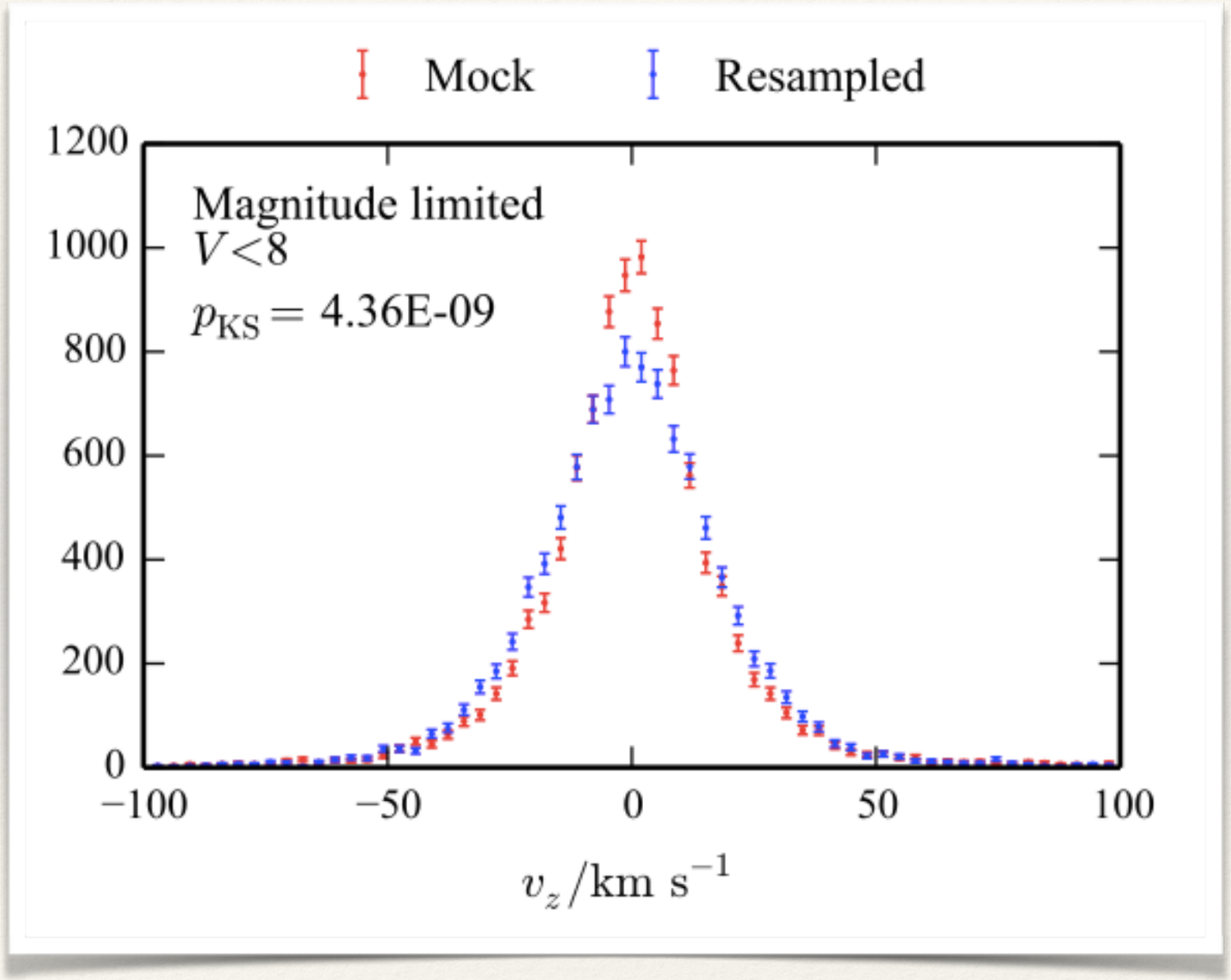
Stars **heated** (change in J_R and J_z) and **radially migrate** (change in L_z)

Now

Star observed with metallicity, Z, age, τ, and actions (J_R, L_z, J_z)

Selection Effects

A simple example

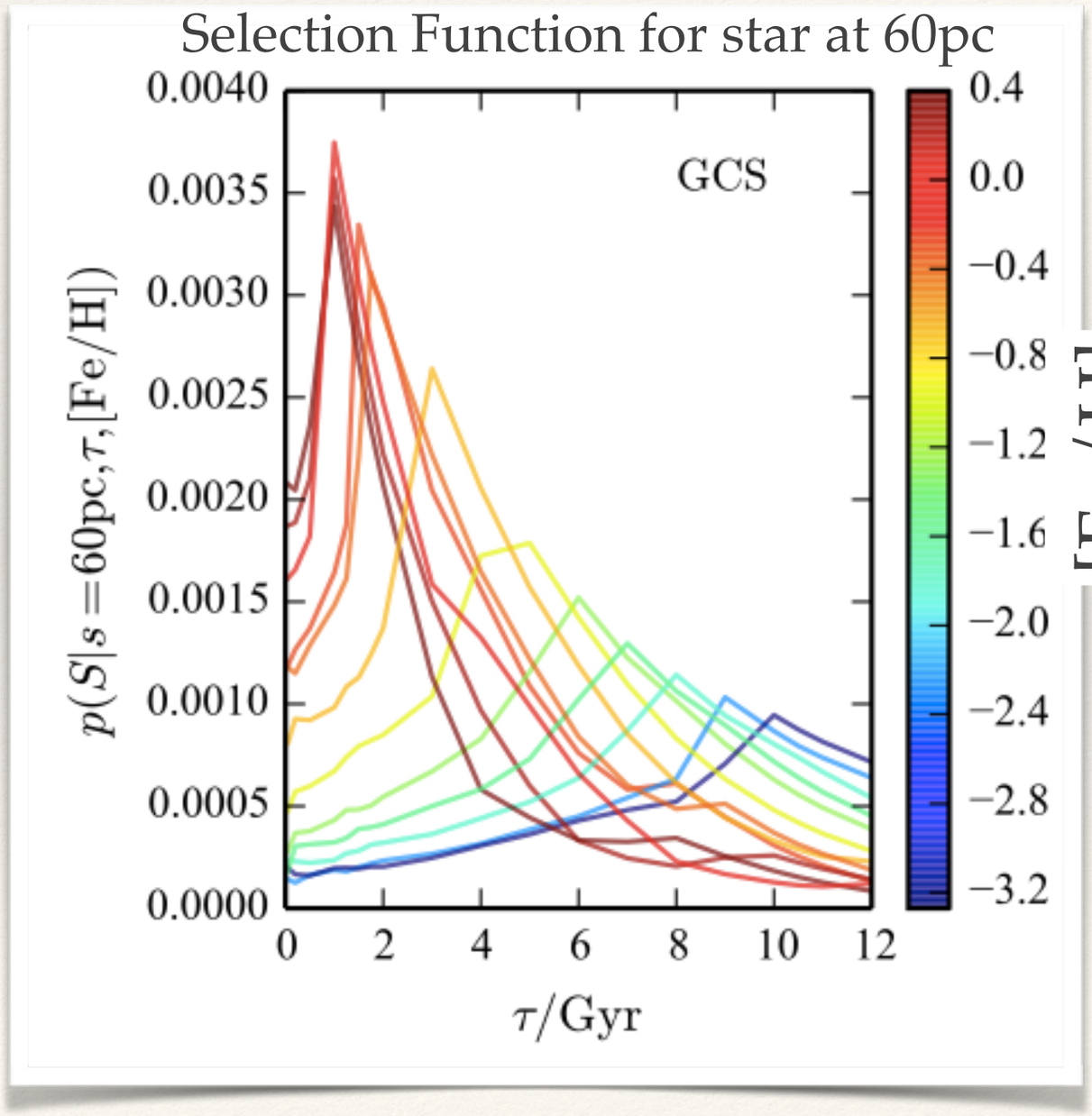


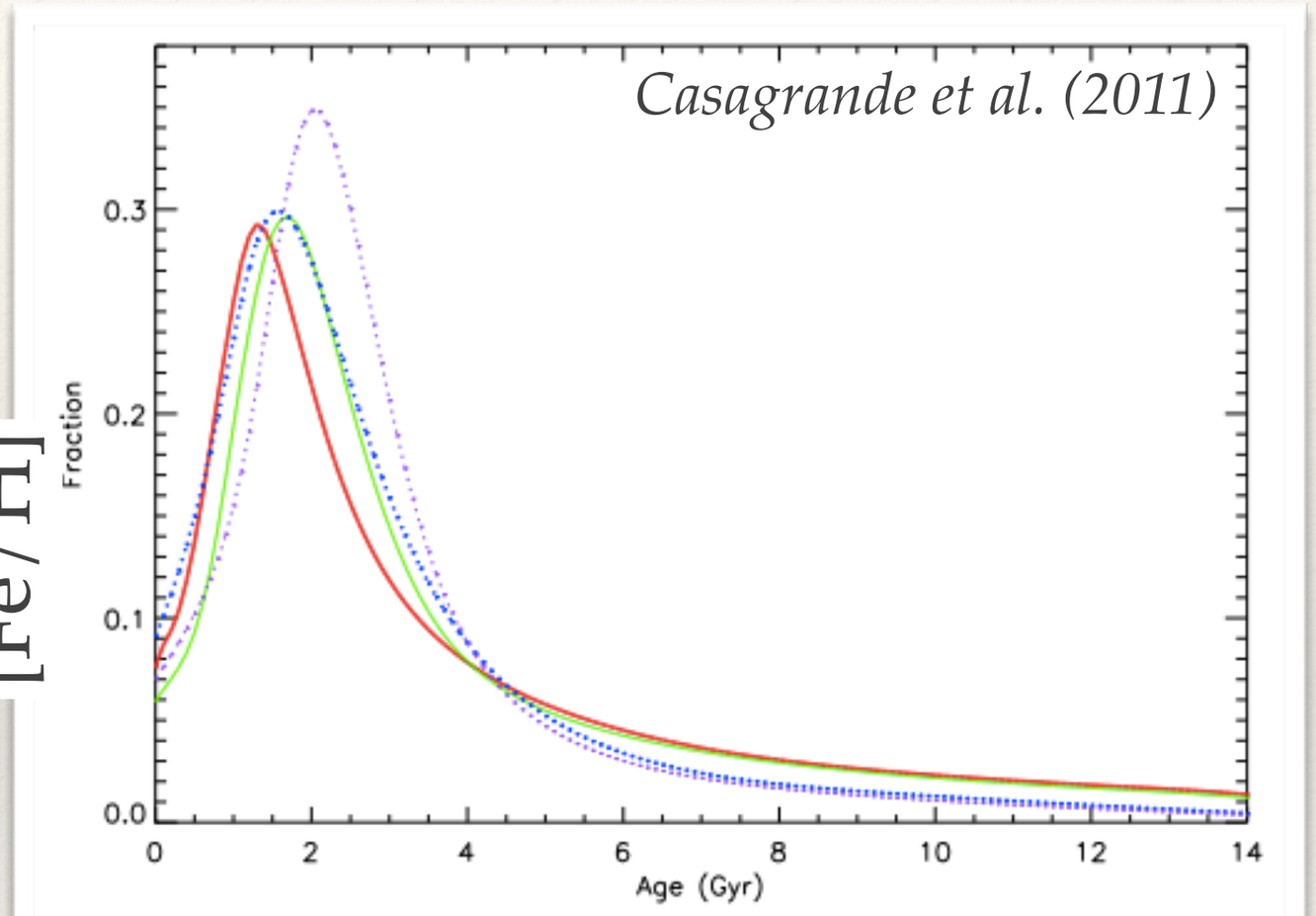
- All surveys have some selection function.
- Sample along a single line-of-sight with V<8 (RED).
- Resample velocities at the positions of the catalogue without selection function (BLUE).
- RED sample has **more young bright stars**.
- These are dynamically cold so the distribution is narrower than BLUE.

Geneva-Copenhagen Survey

Selection Function taken from Schönrich & Binney (2008)

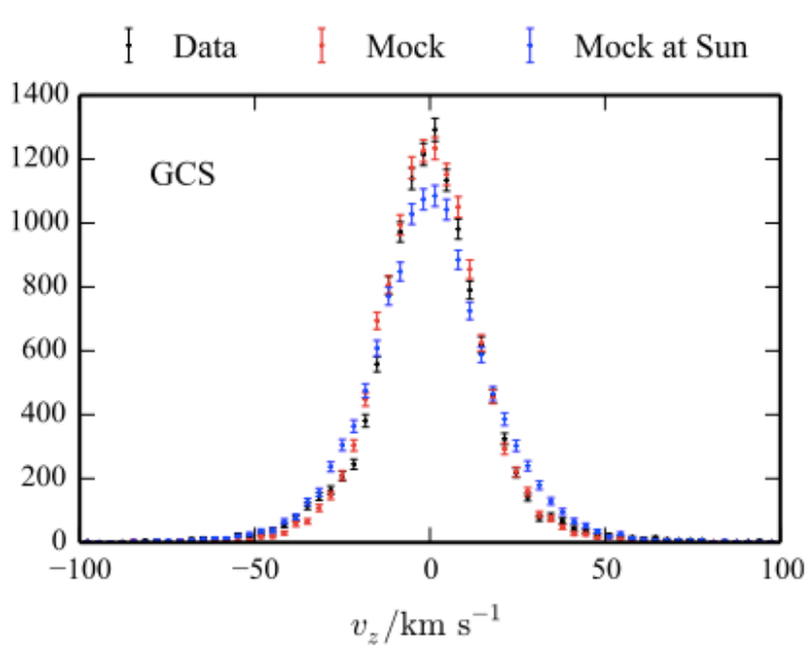
[selects F & G stars (dwarfs and some turn-off)]

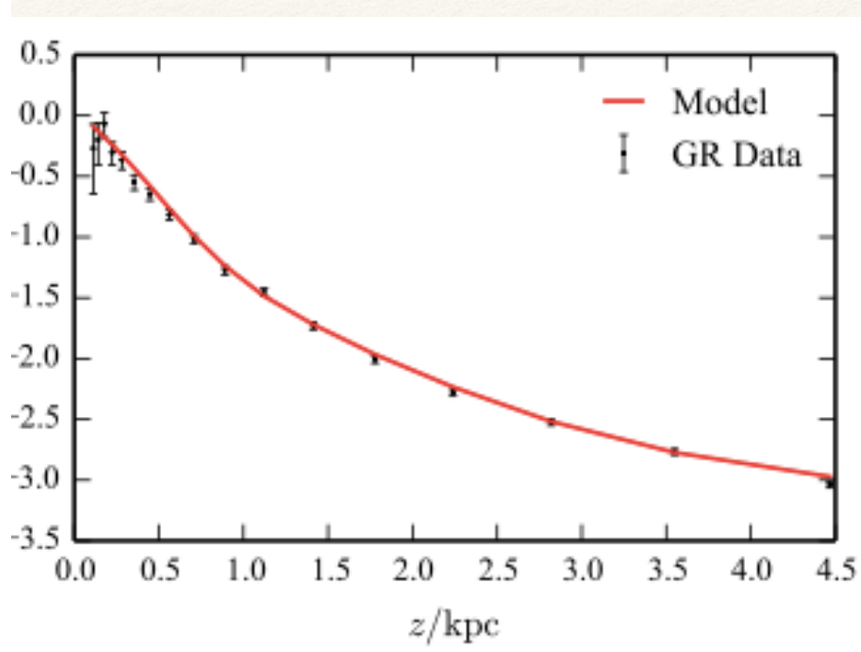


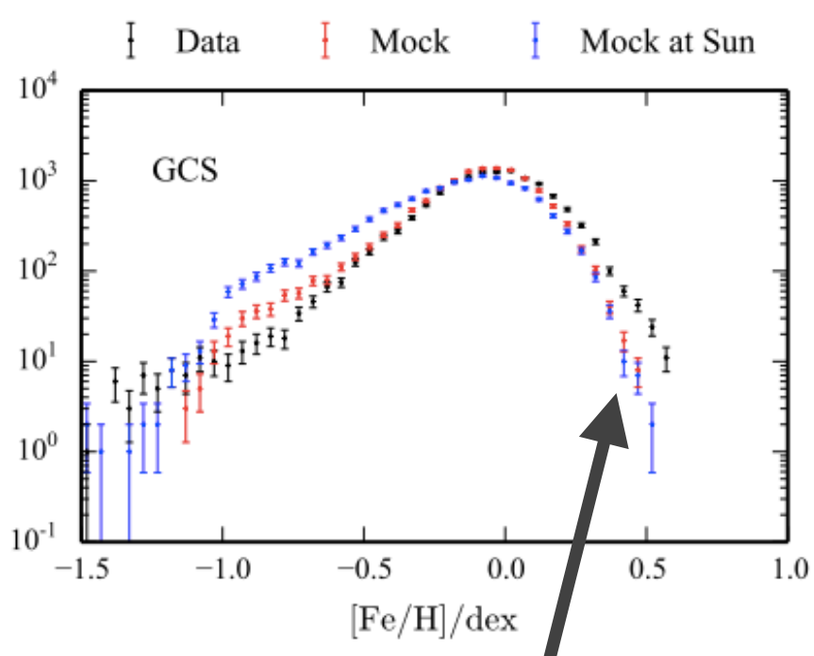


GCS preferentially contains stars of ~2 Gyr

Maximise log-likelihood of GCS + Gilmore & Reid







Kinematics well fit

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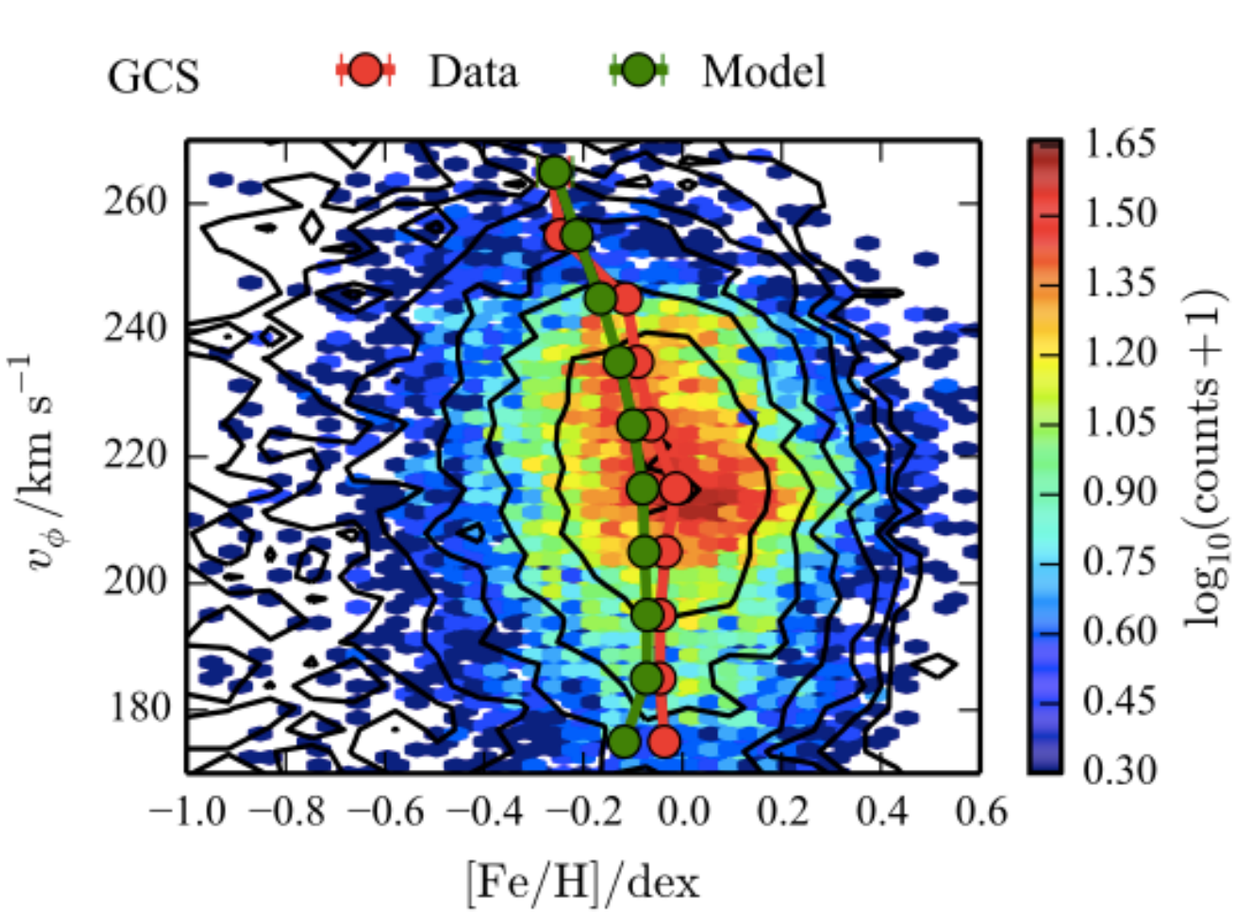
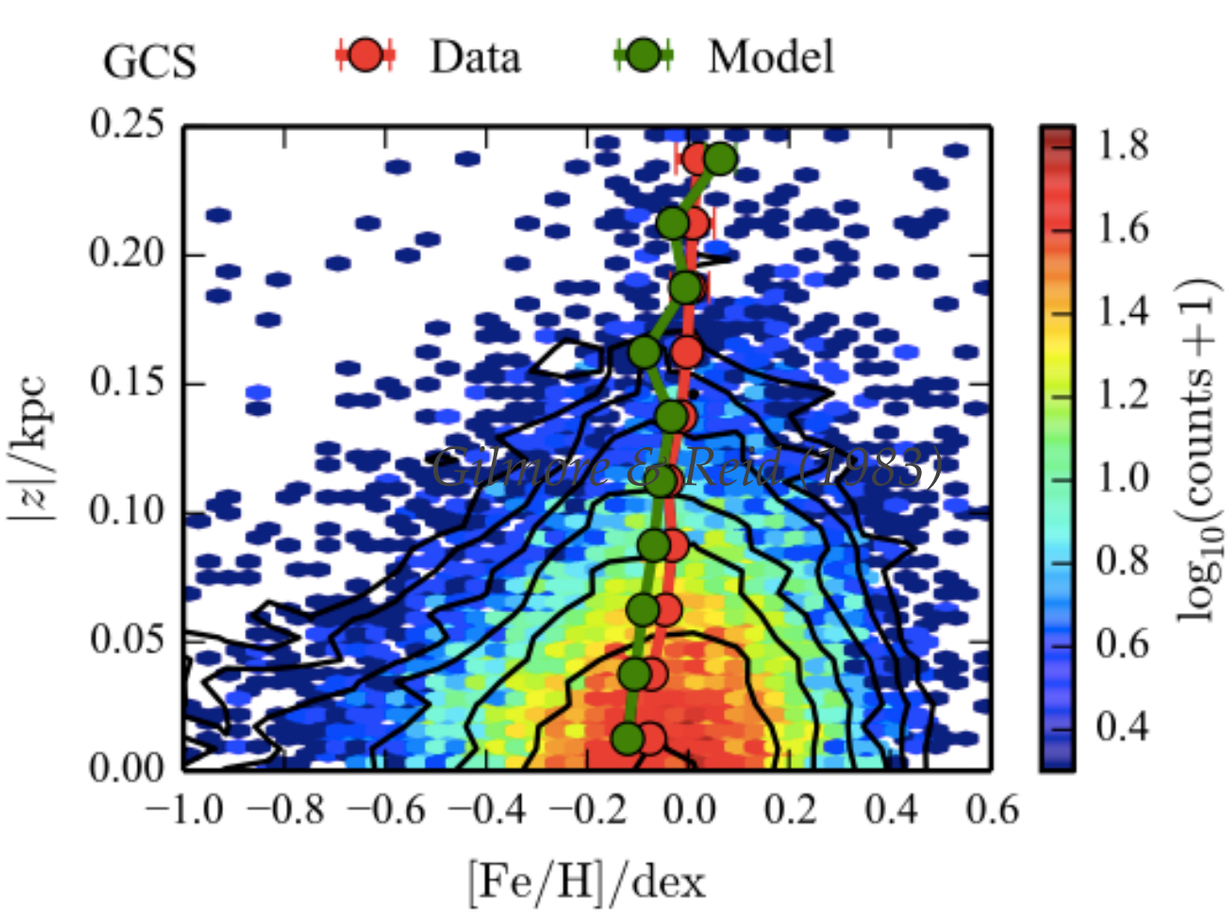
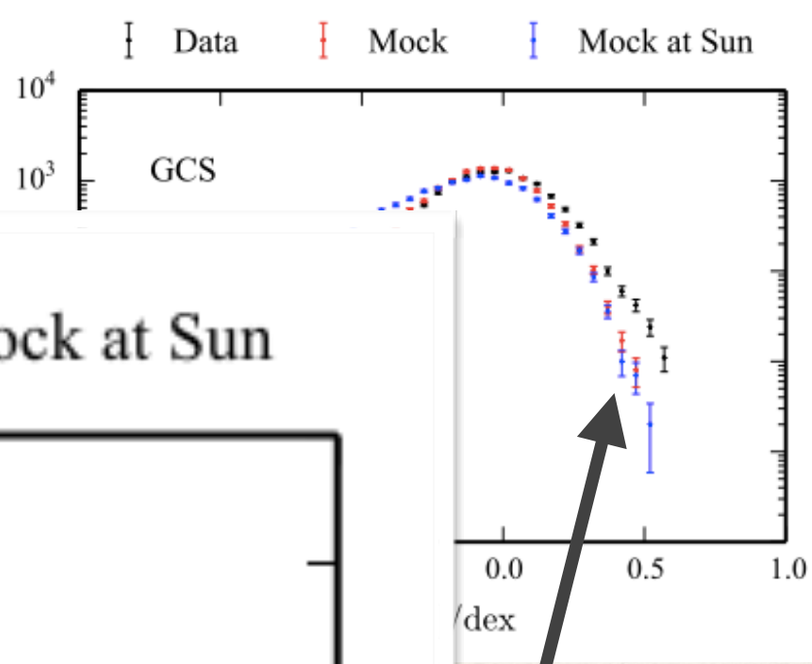
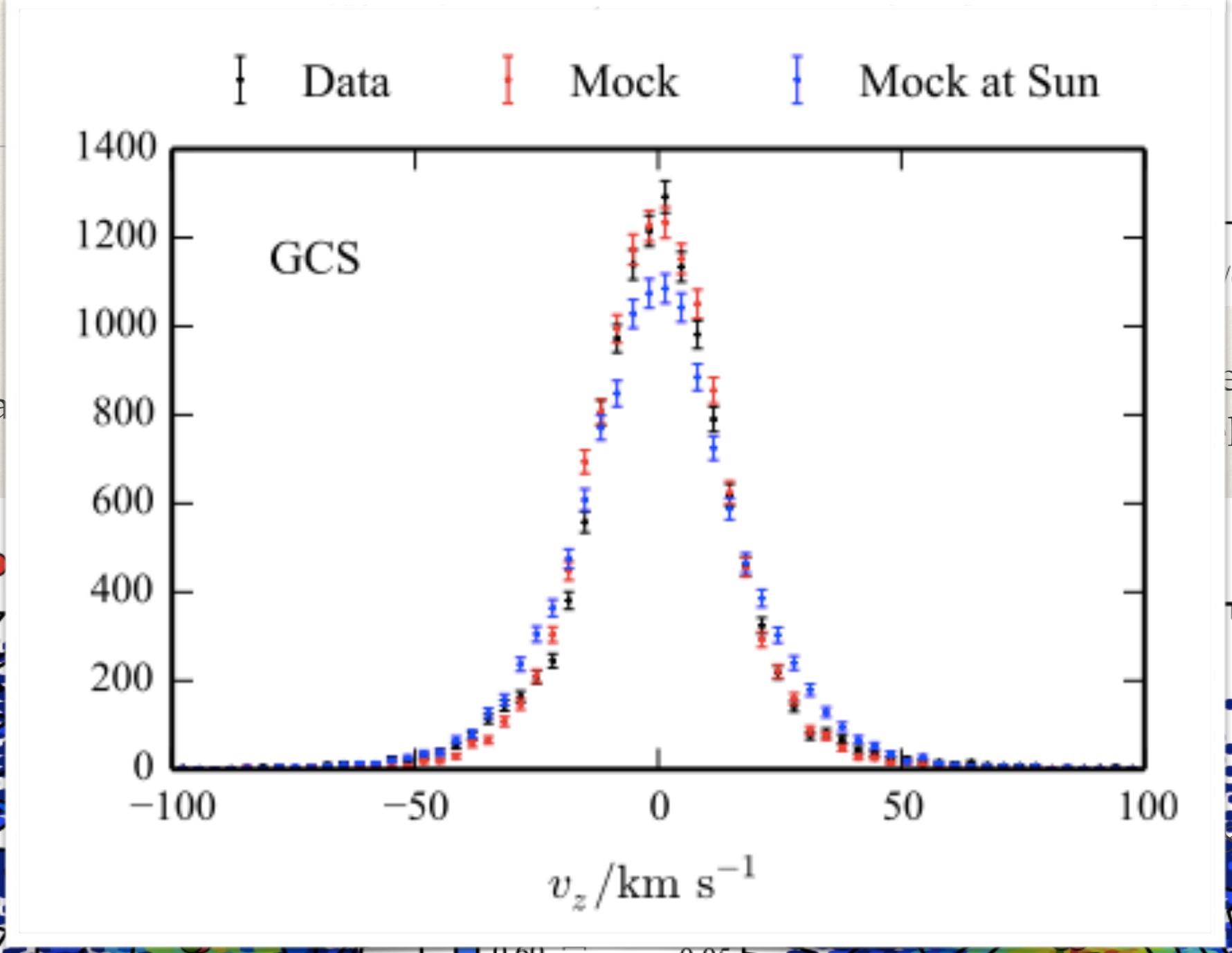
Not enough metal-rich stars but trends well recovered





Kinema





etal-rich stars
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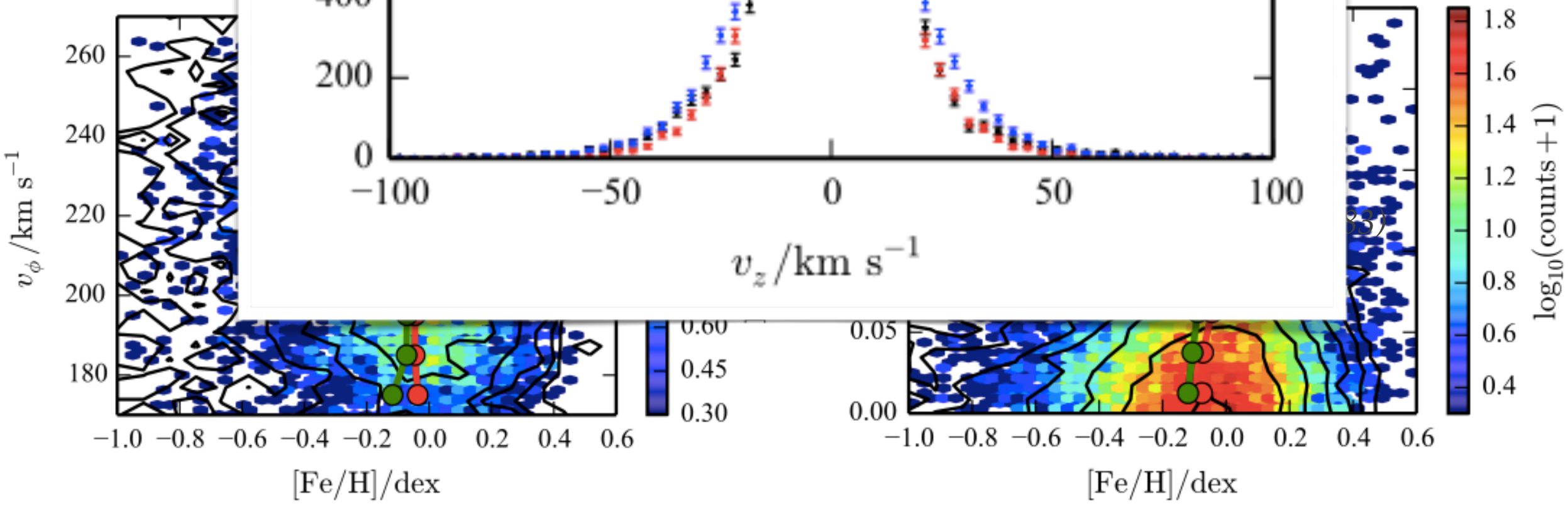

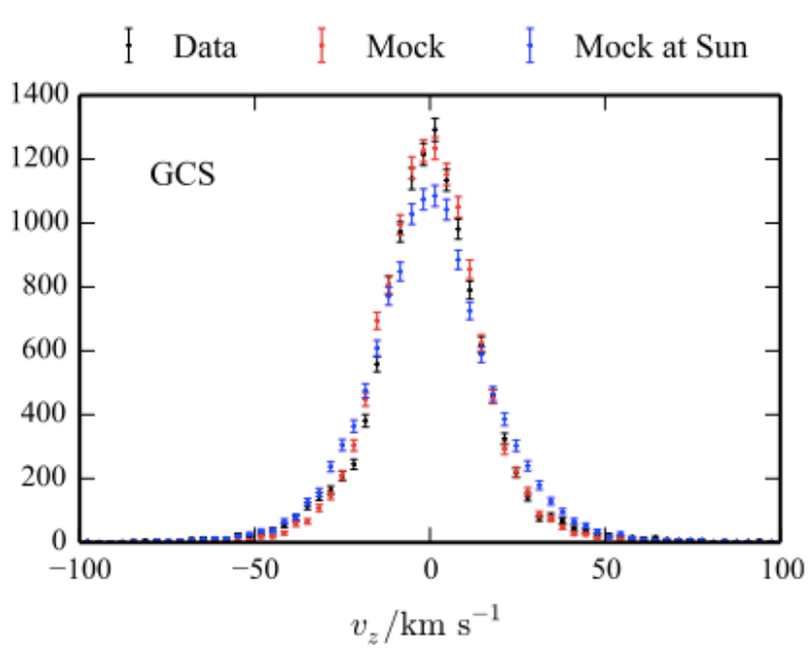

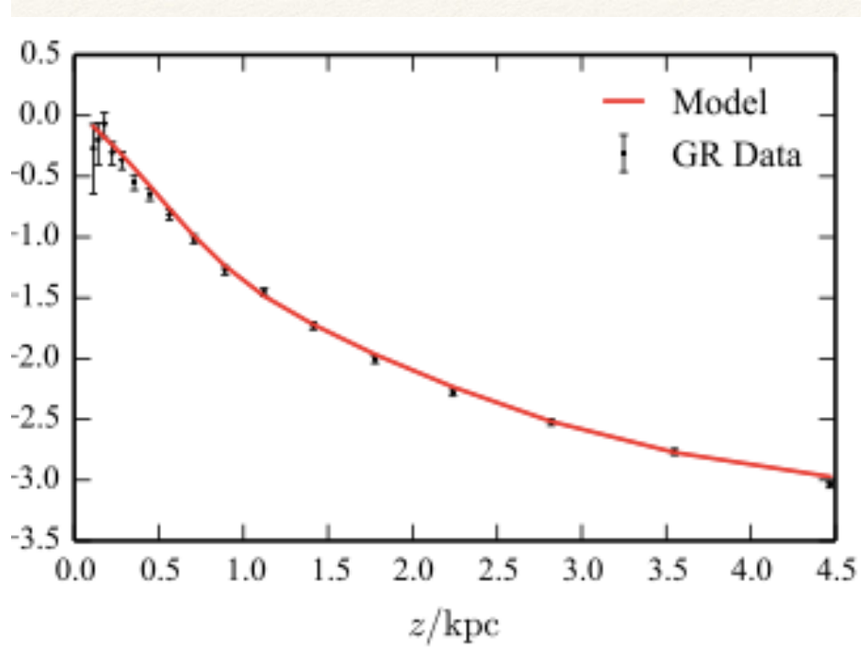

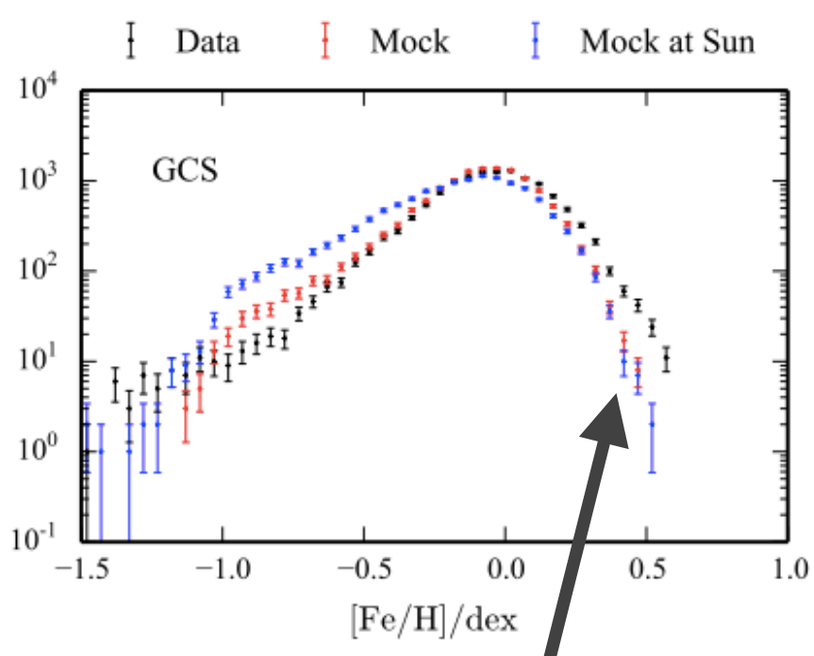

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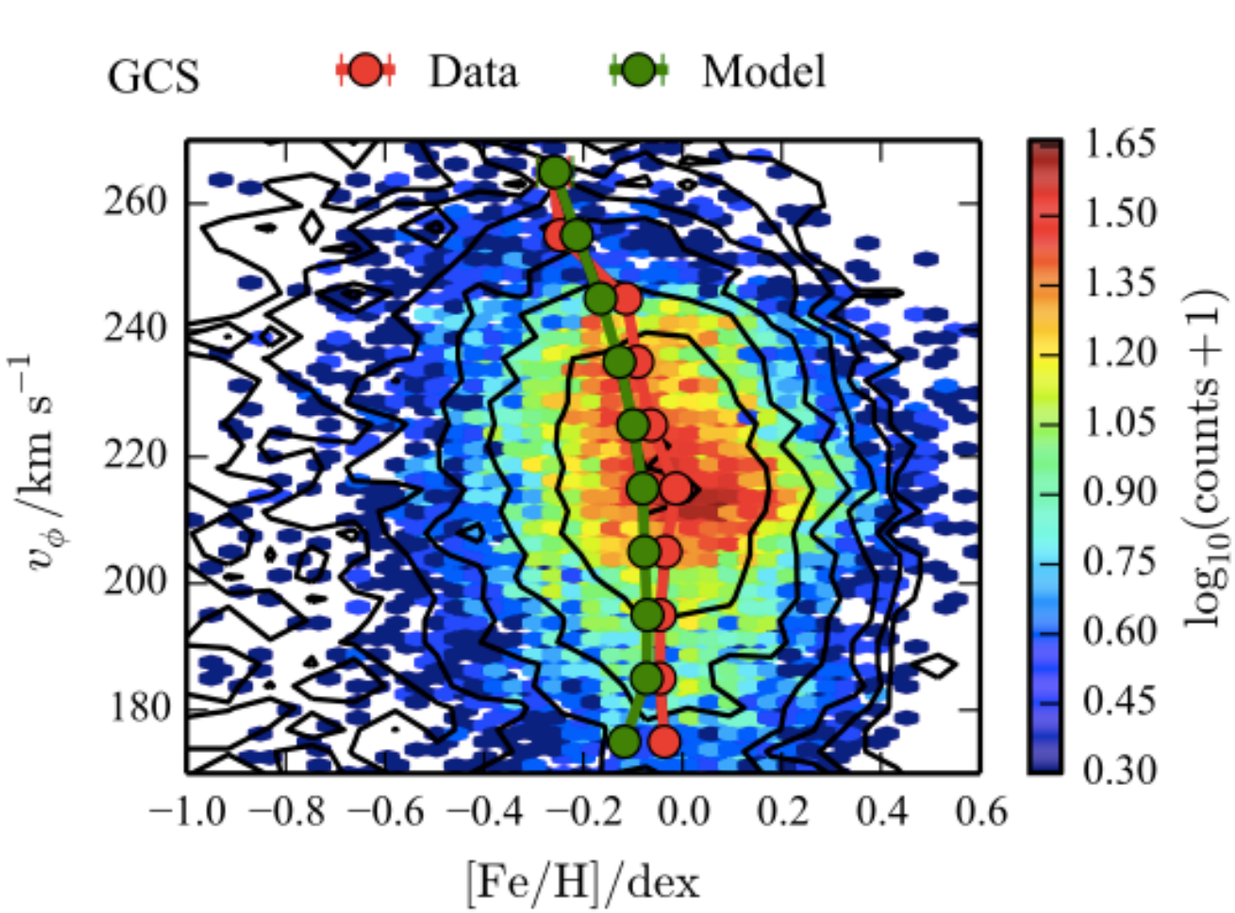

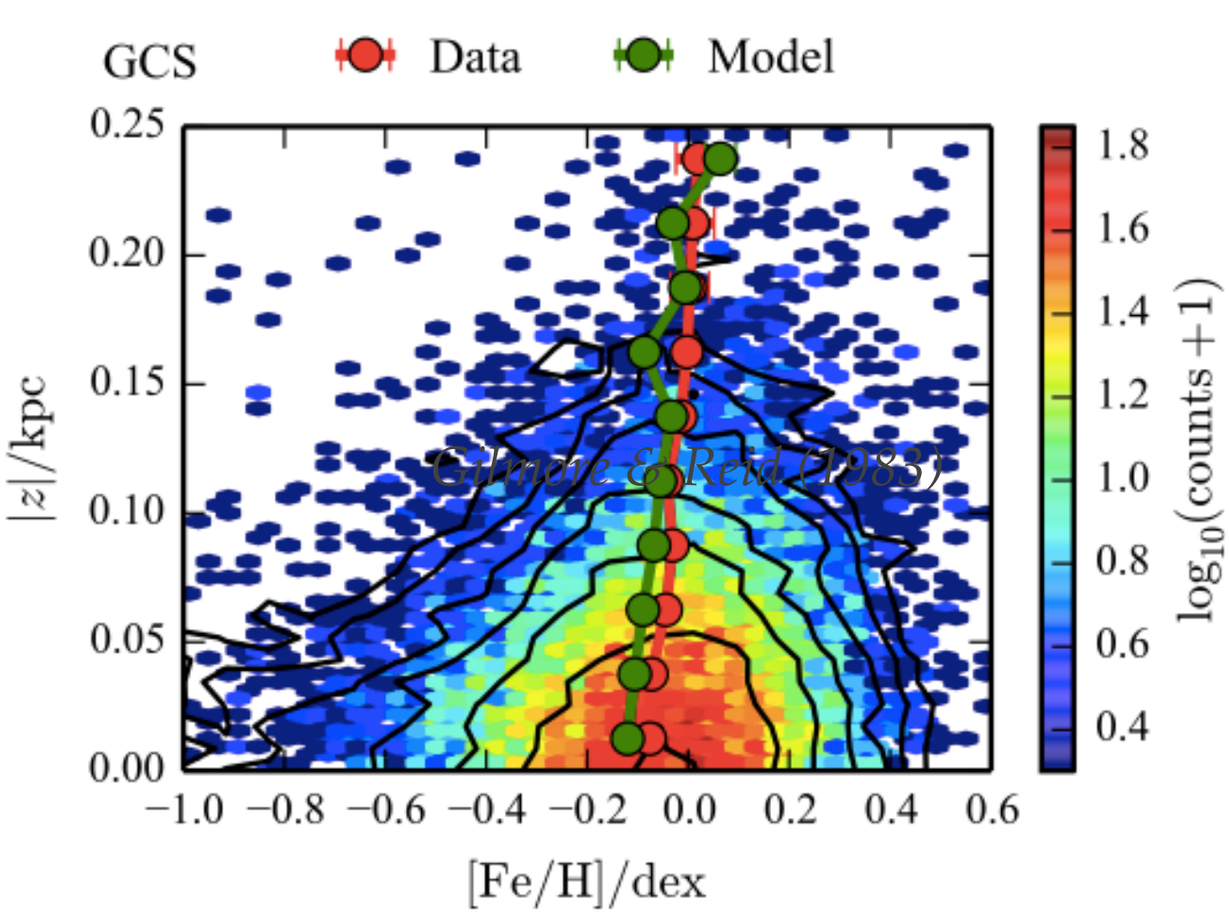

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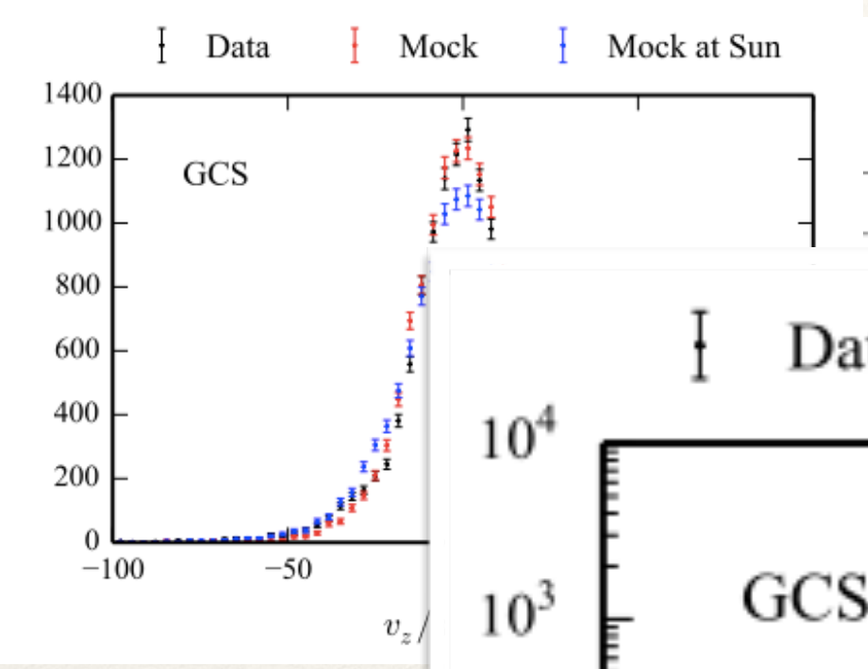

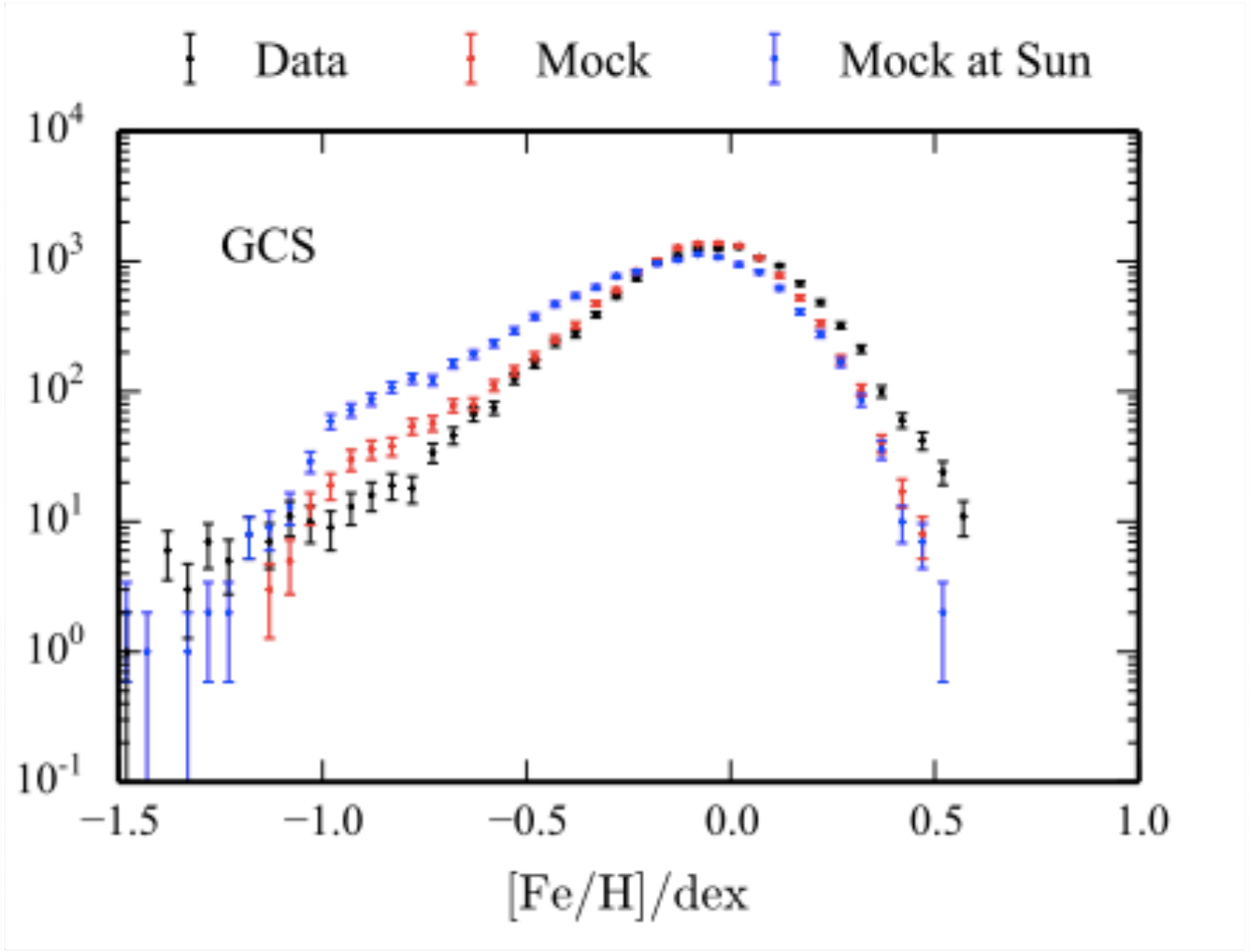

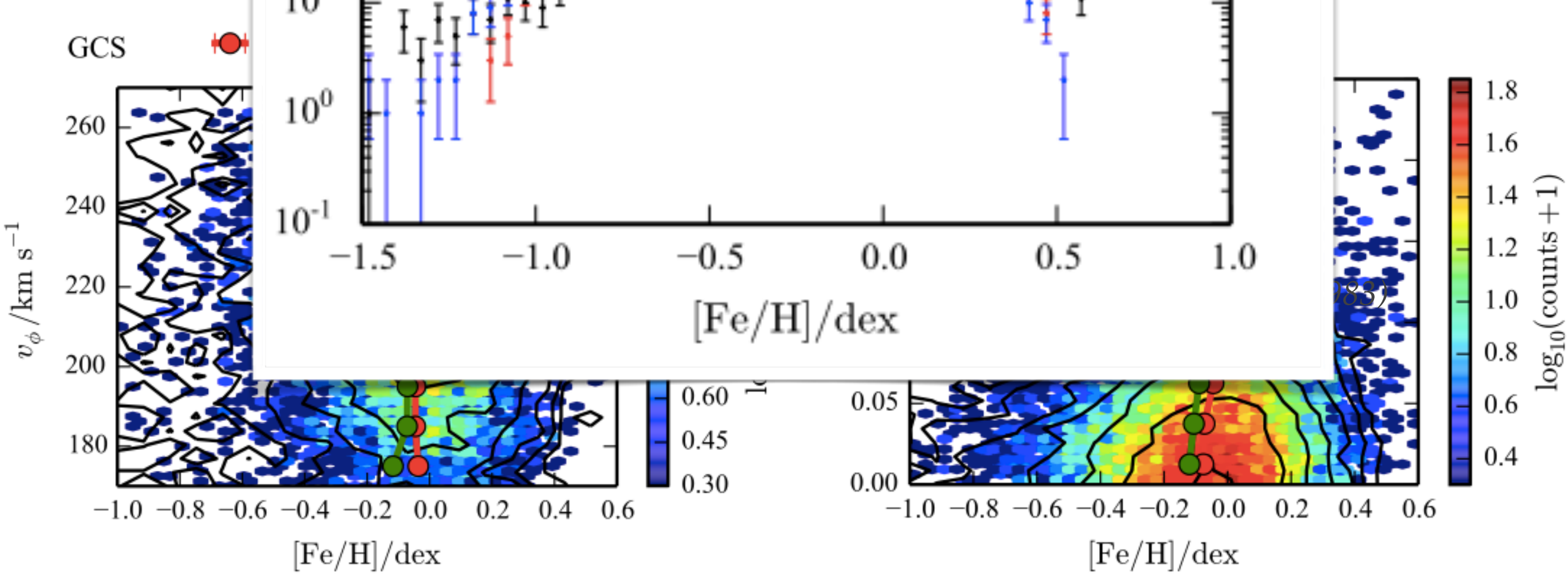

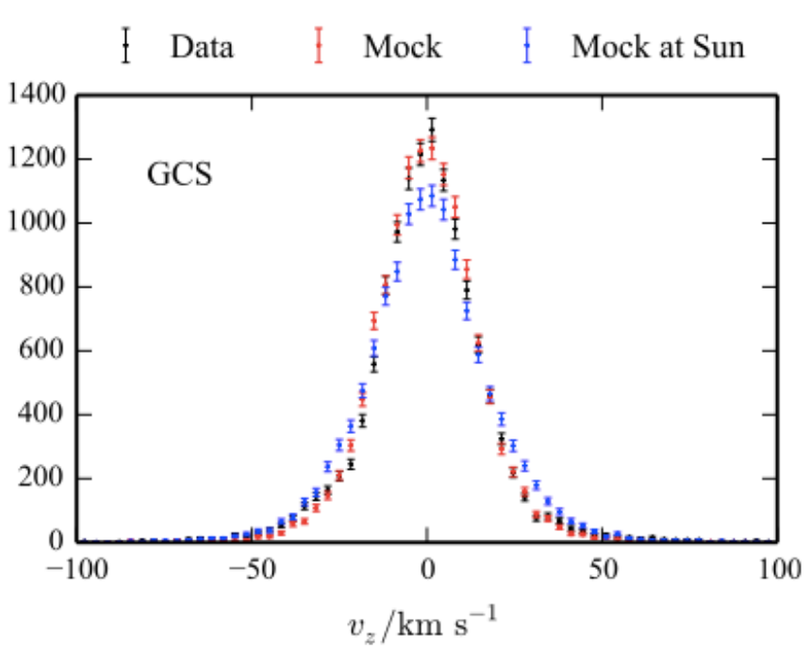

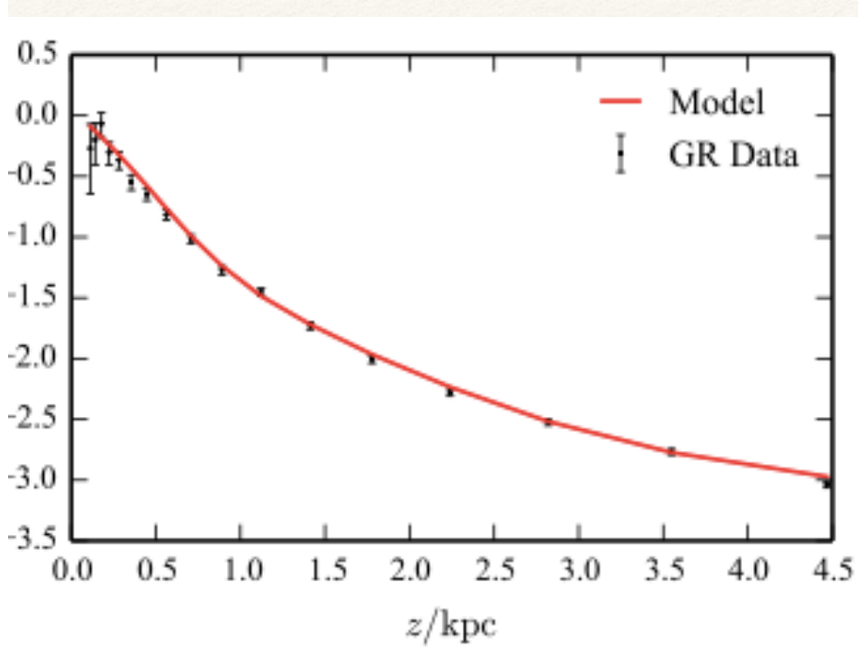

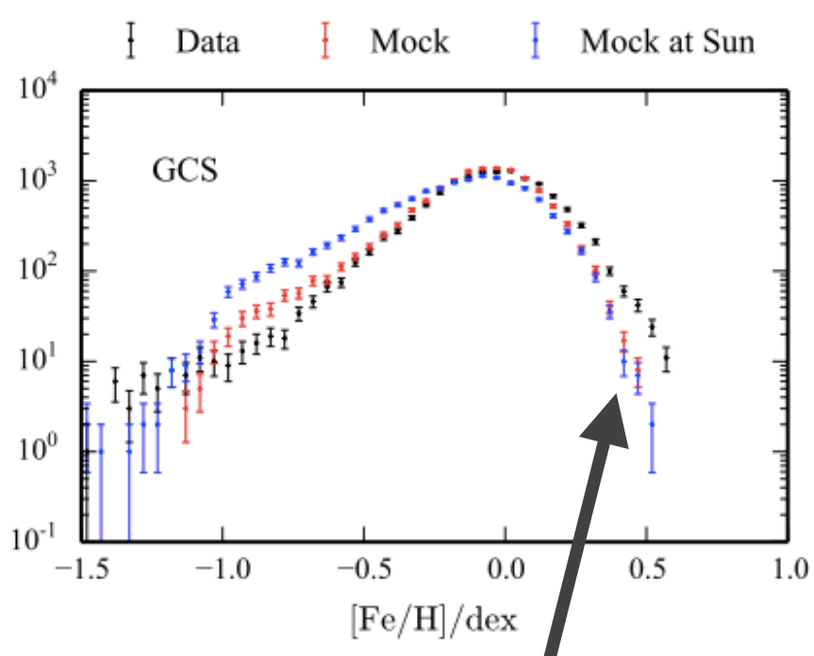

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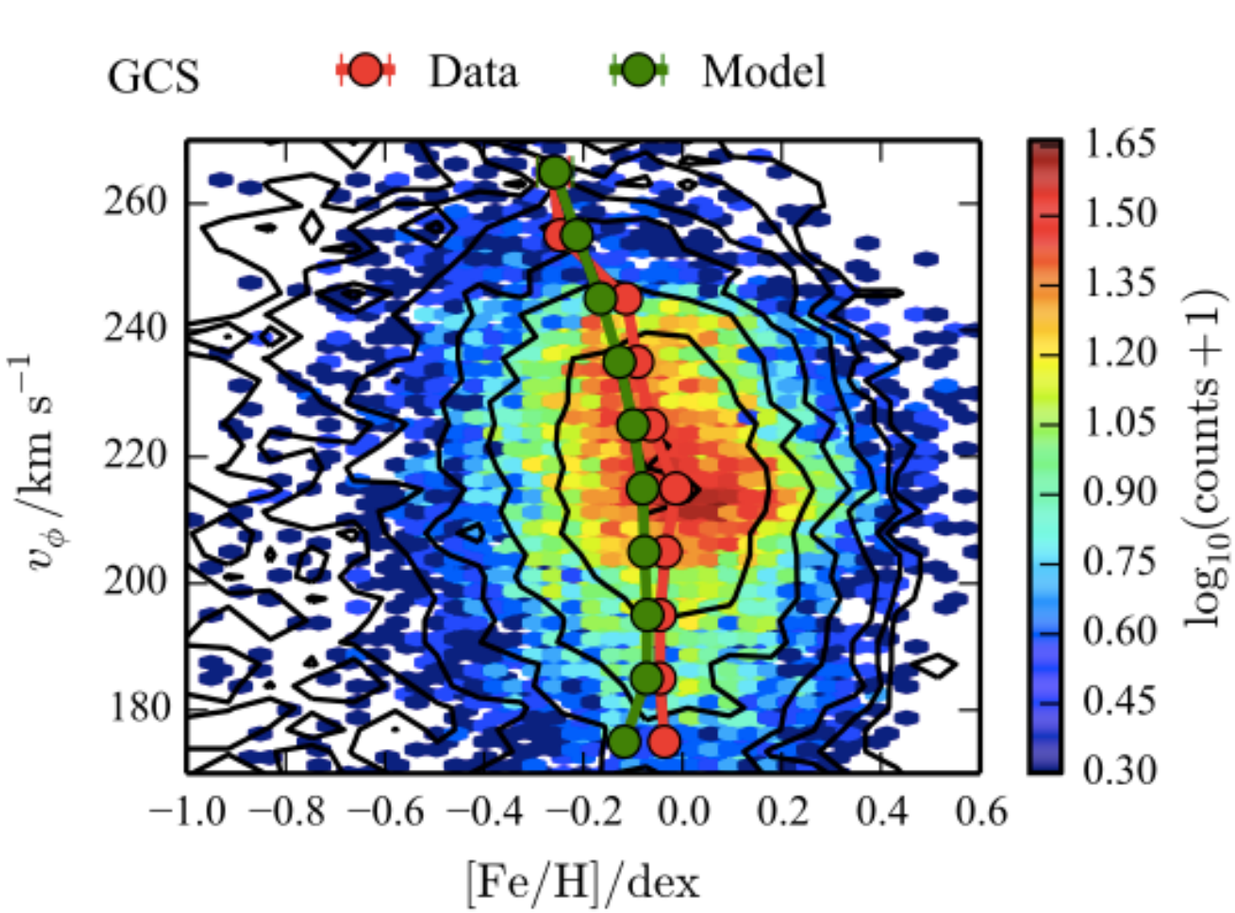
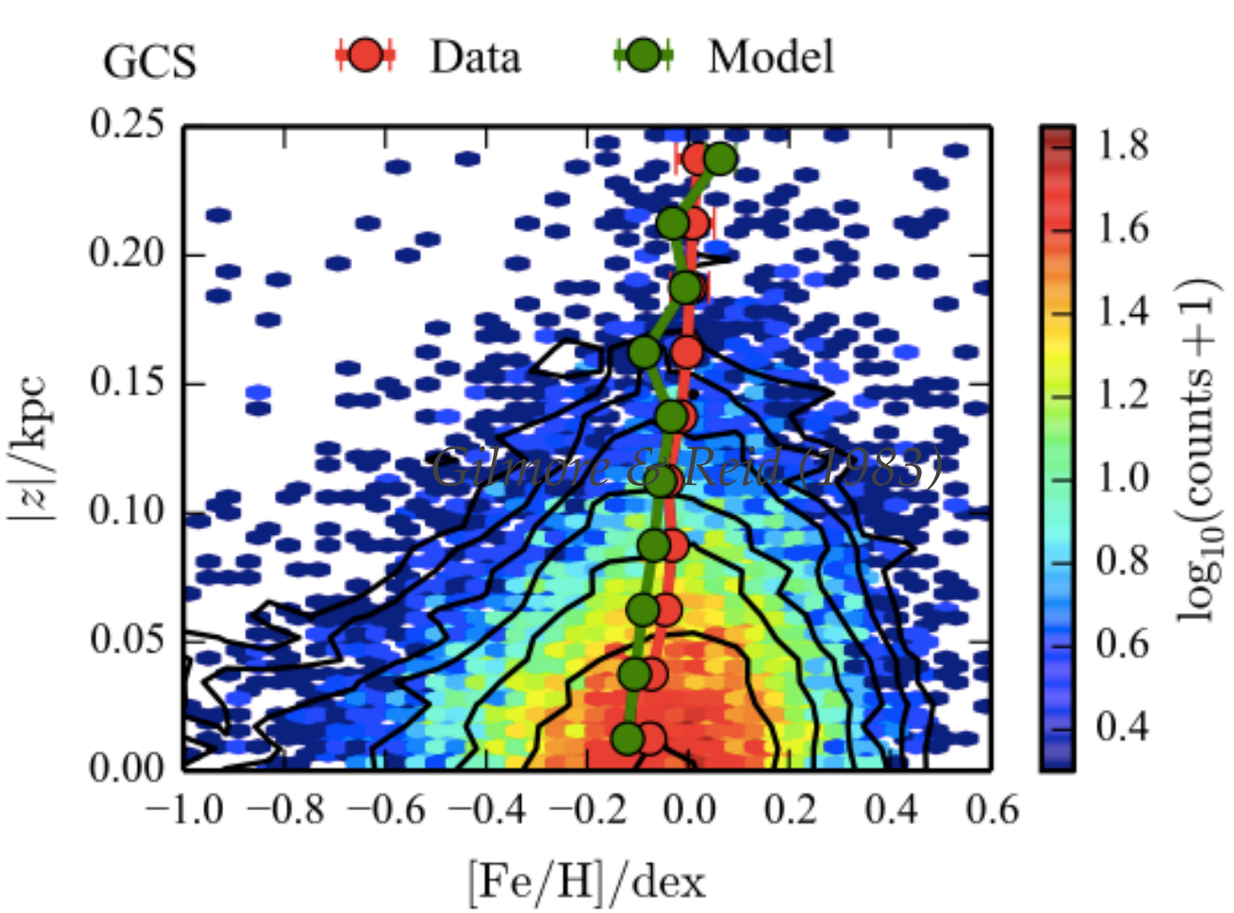


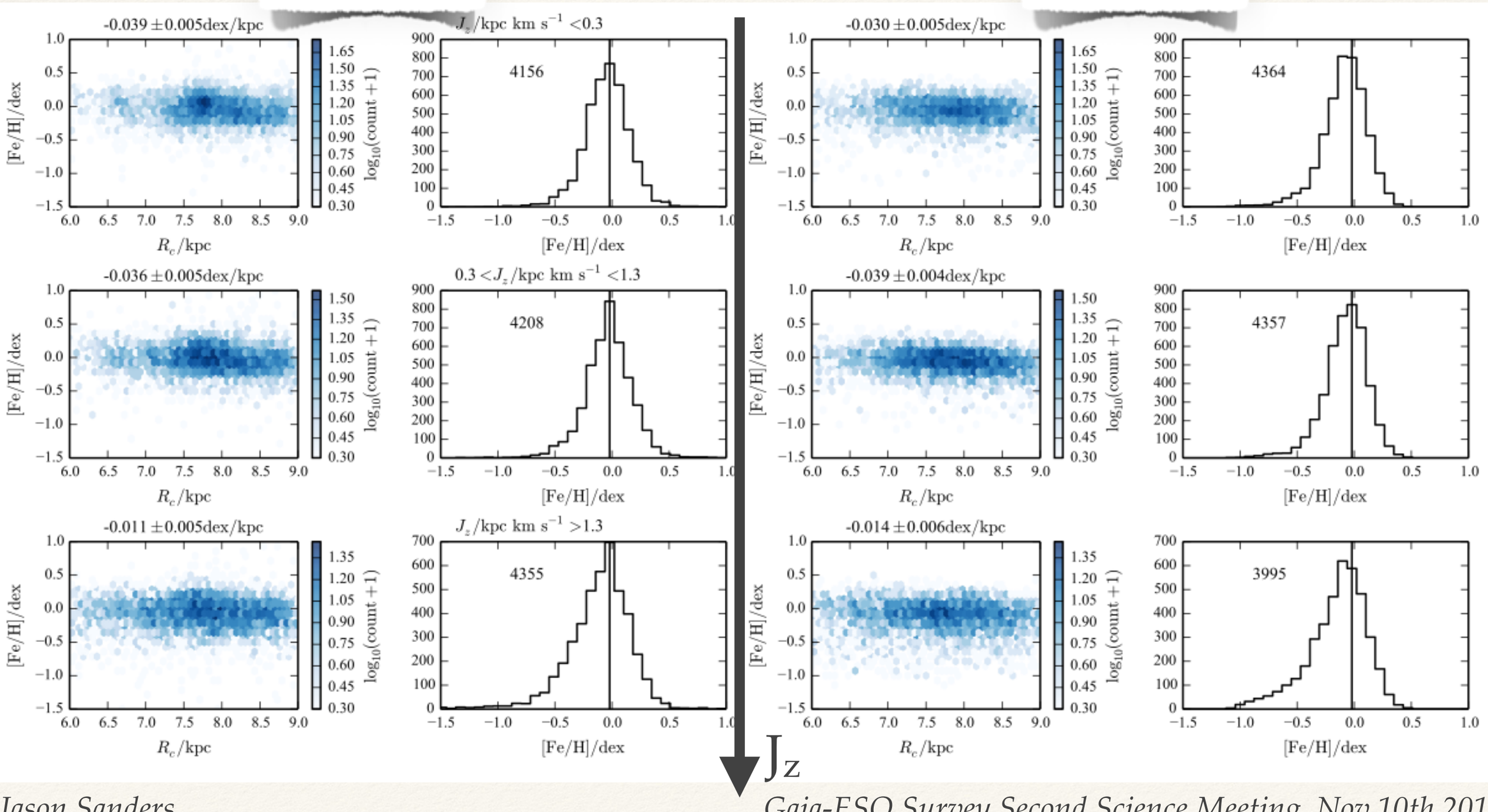


Radial metallicity gradients

Current metallicity gradient = −0.058 dex/kpc

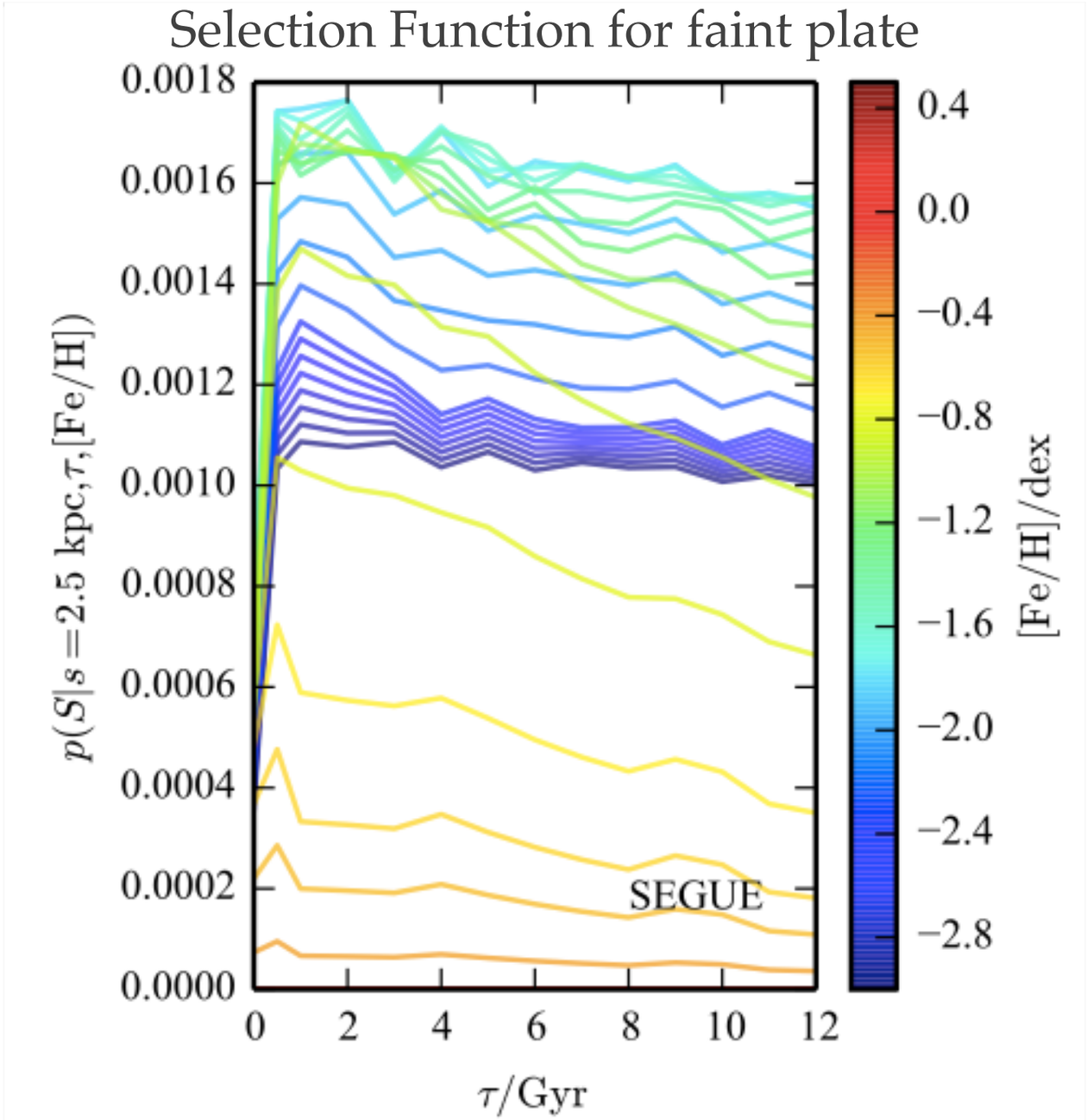
DATA

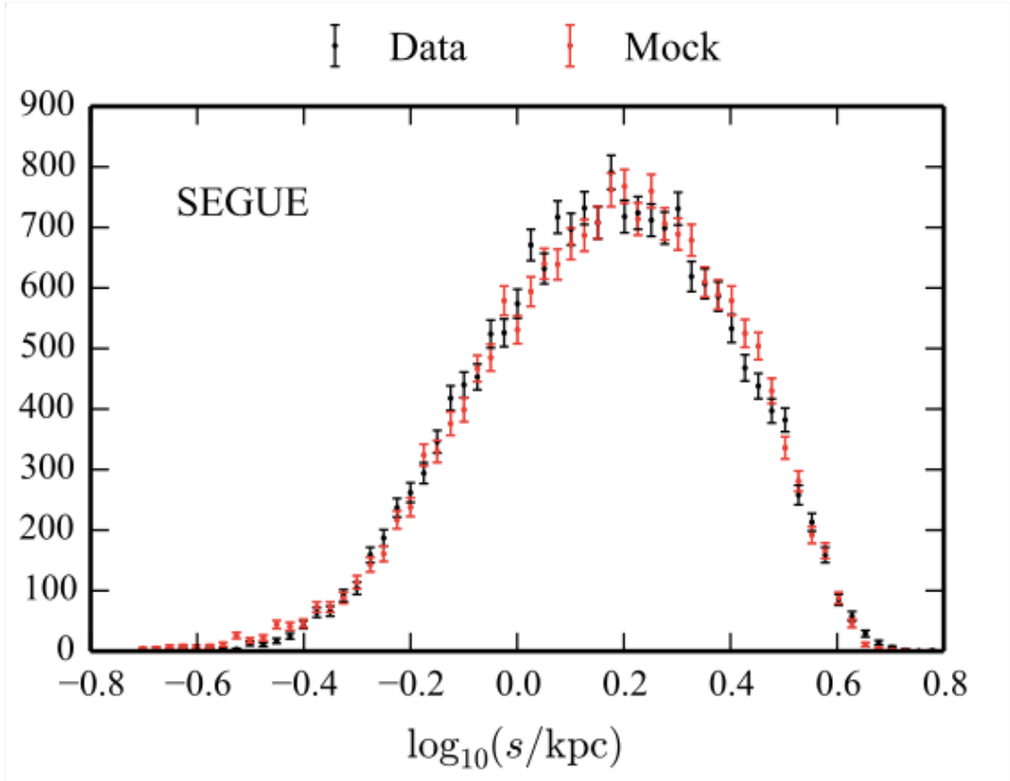
MOCK



SEGUE G dwarfs

Using selection function from Bovy et al. (2012)

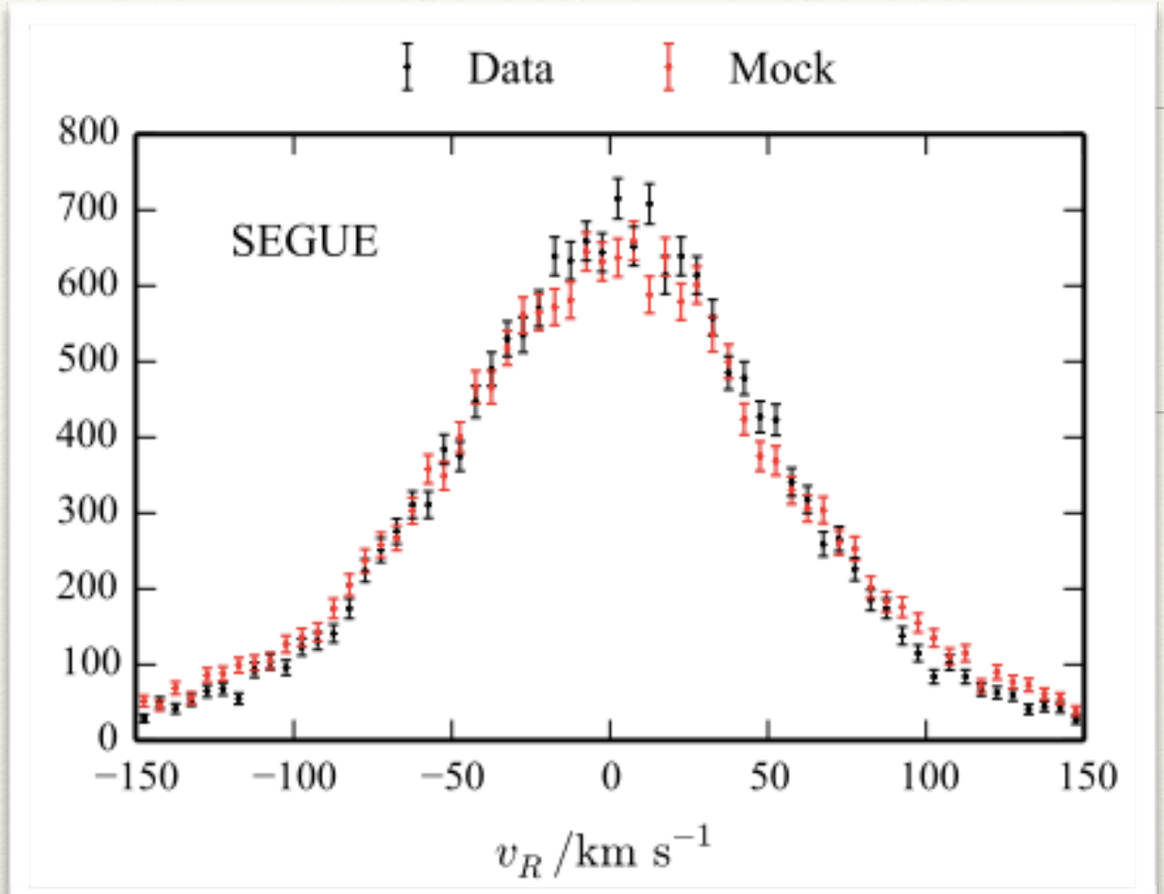


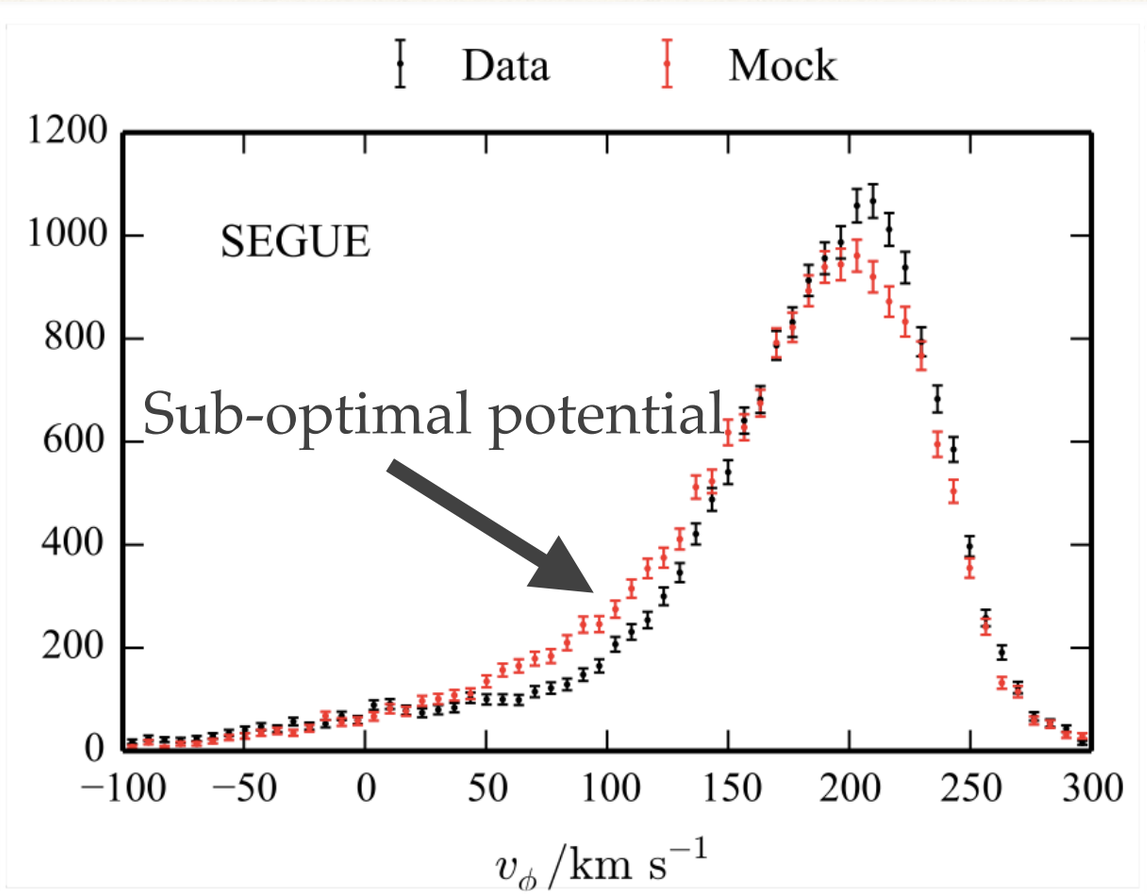


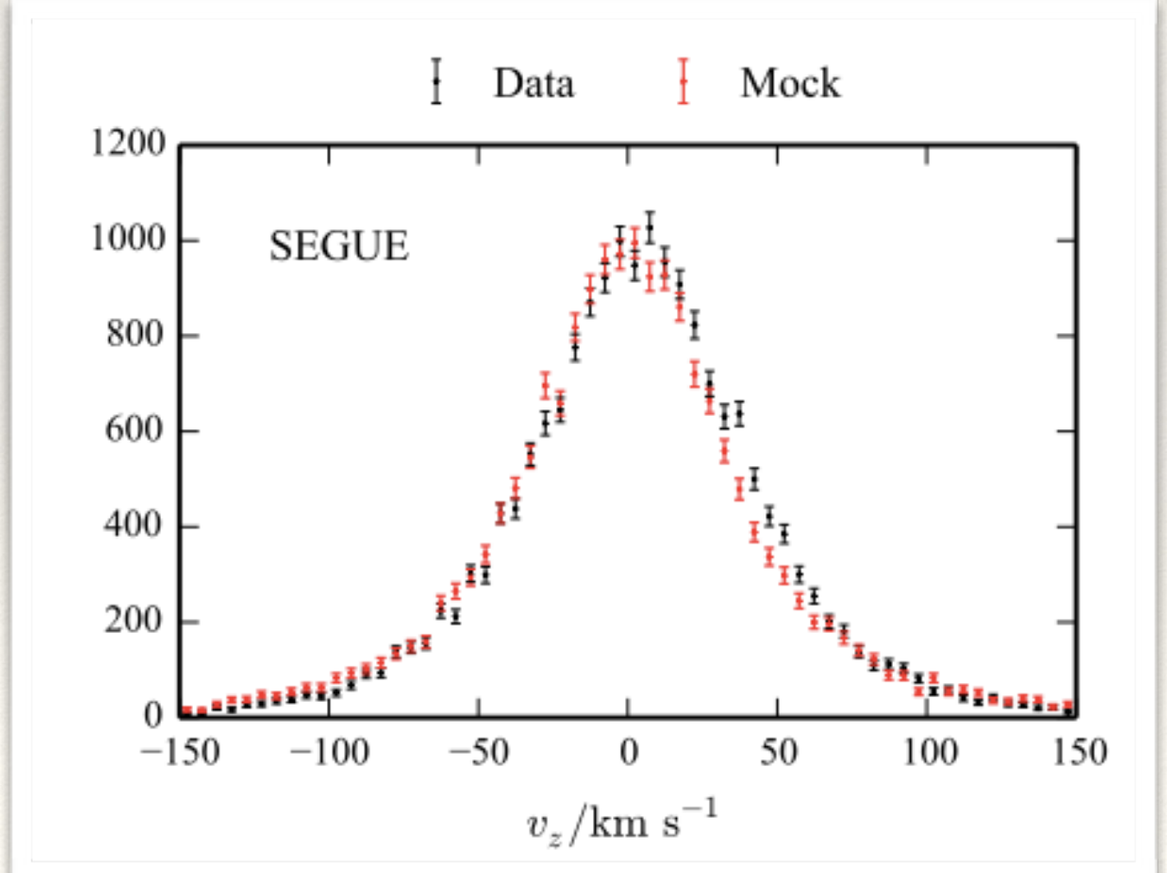
$14 < r < 20.2$ and $0.48 < (g - r) < 0.55$

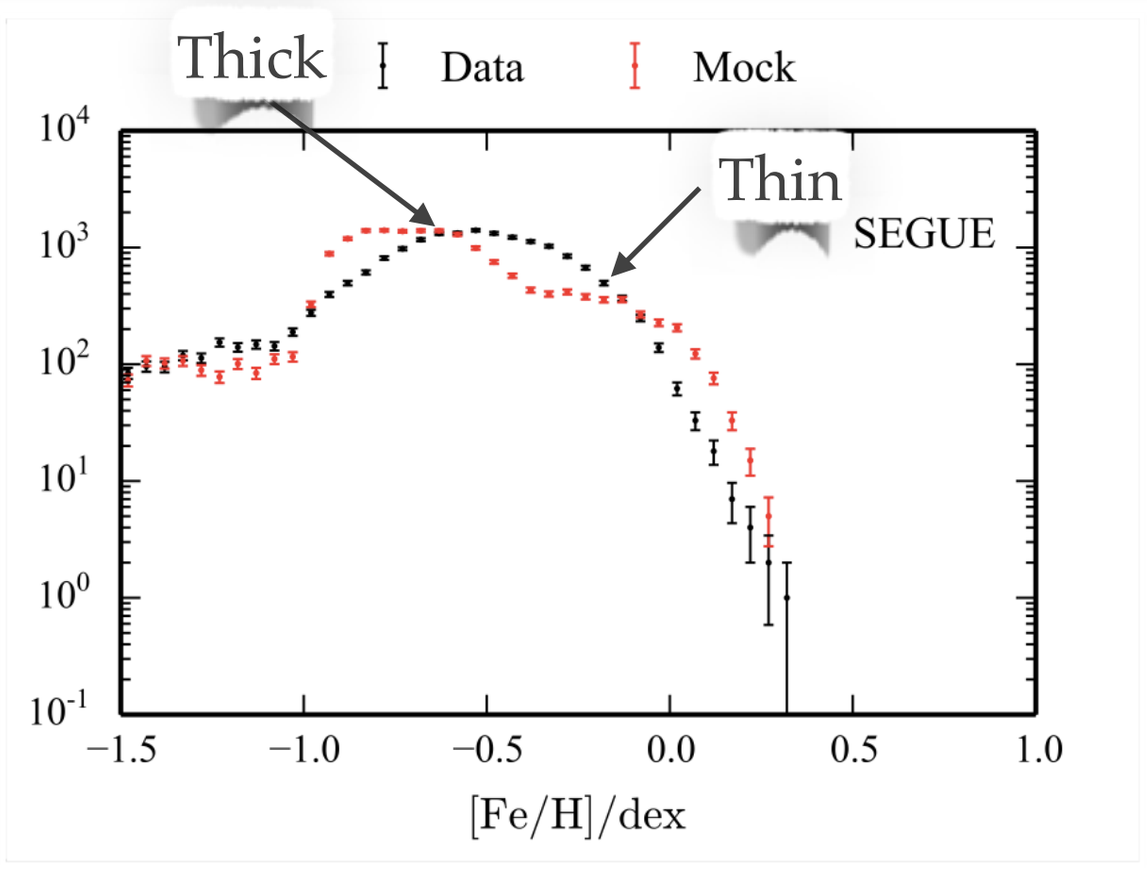
$S/N > 15$ and $\log g > 4.2$

Distances estimated from isochrones assuming τ=10 Gyr


Data
Mock
SEGUE
v_R /km s^{-1}


Data
Mock
SEGUE
Sub-optimal potential
v_ϕ /km s^{-1}


Data
Mock
SEGUE
v_z /km s^{-1}

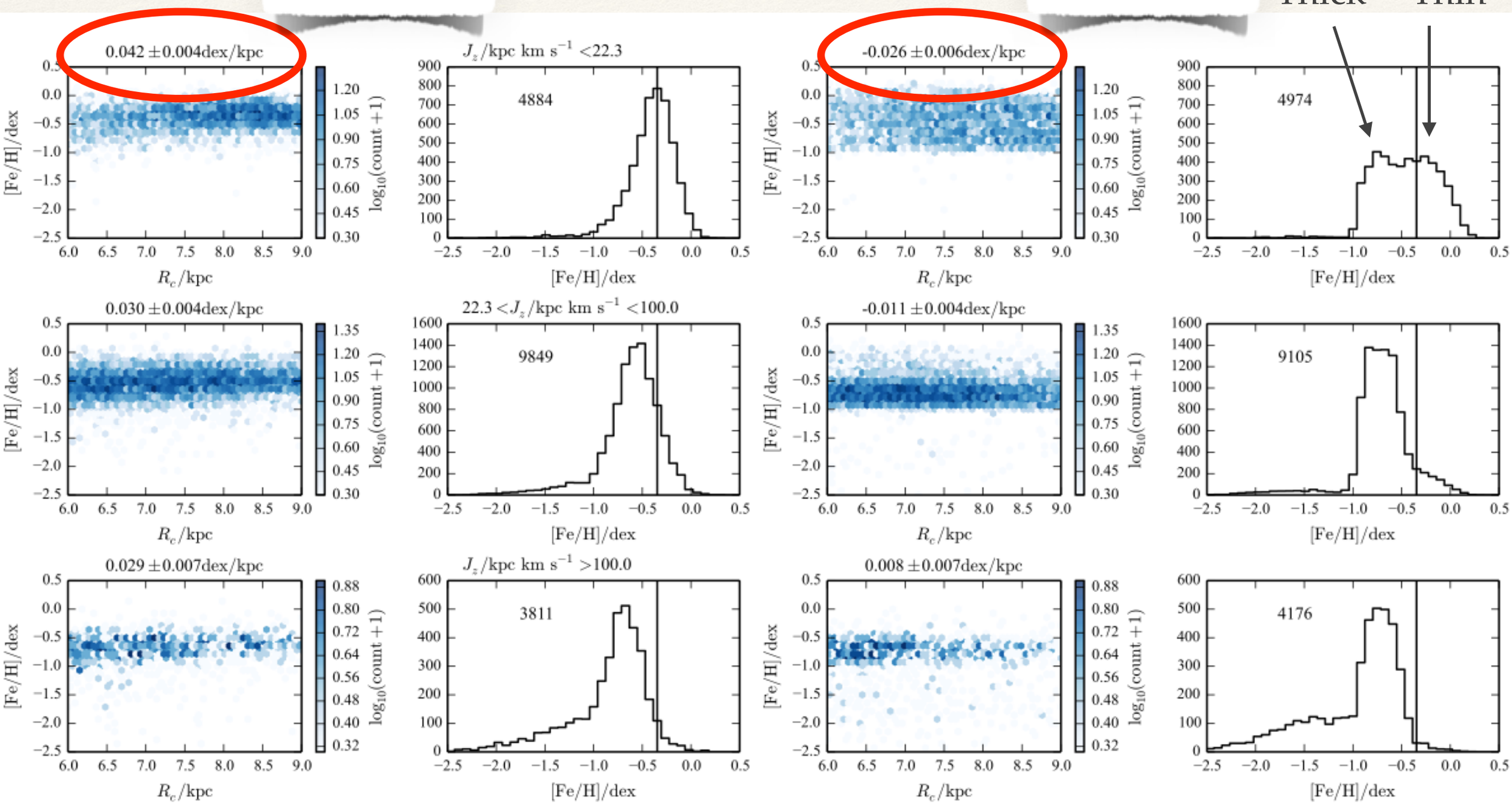

Thick
Data
Mock
Thin
SEGUE
[Fe/H]/dex

Model shows clear thin-thick dichotomy not seen in data

DATA

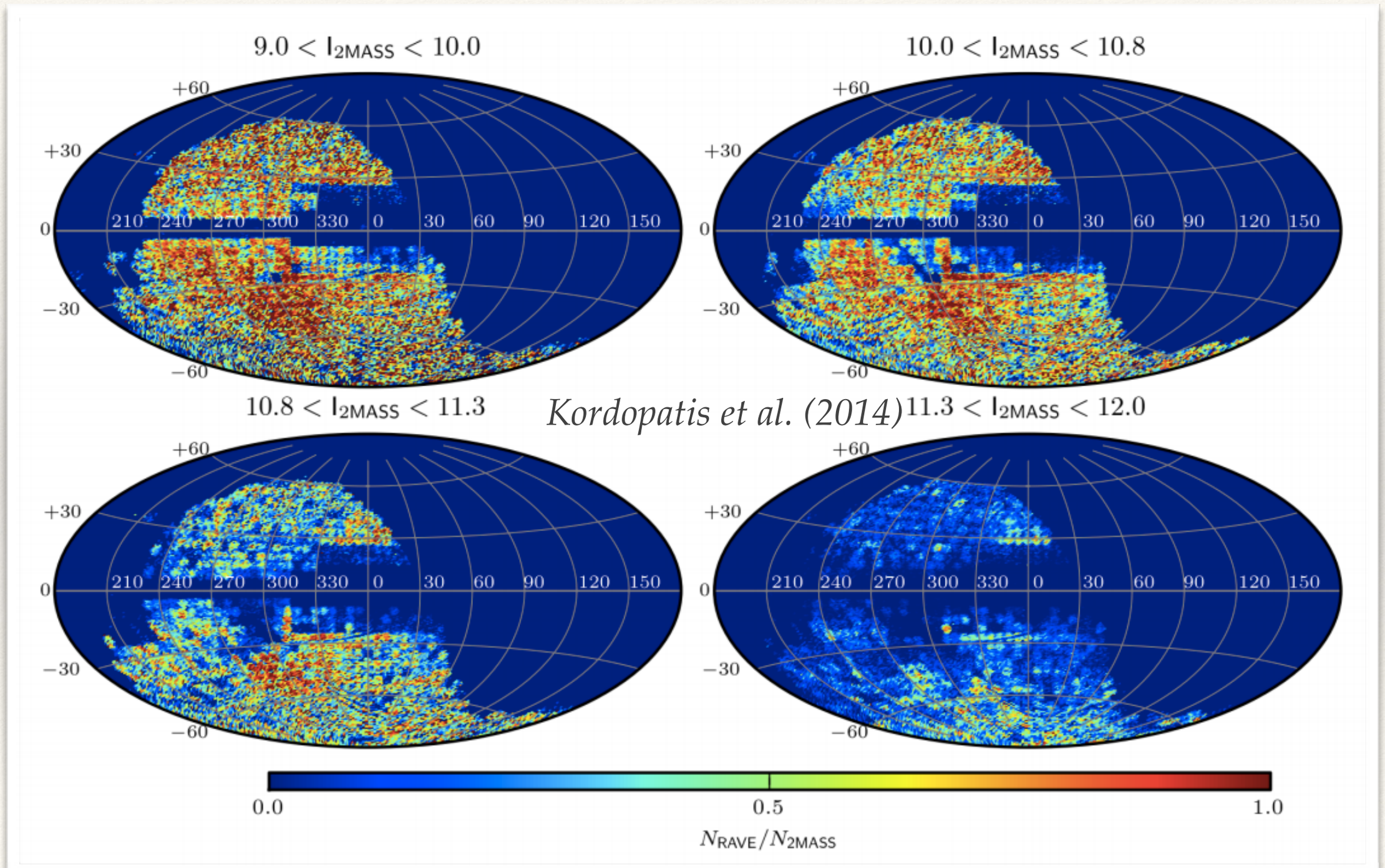
MOCK

Thick Thin



RAVE (WIP)

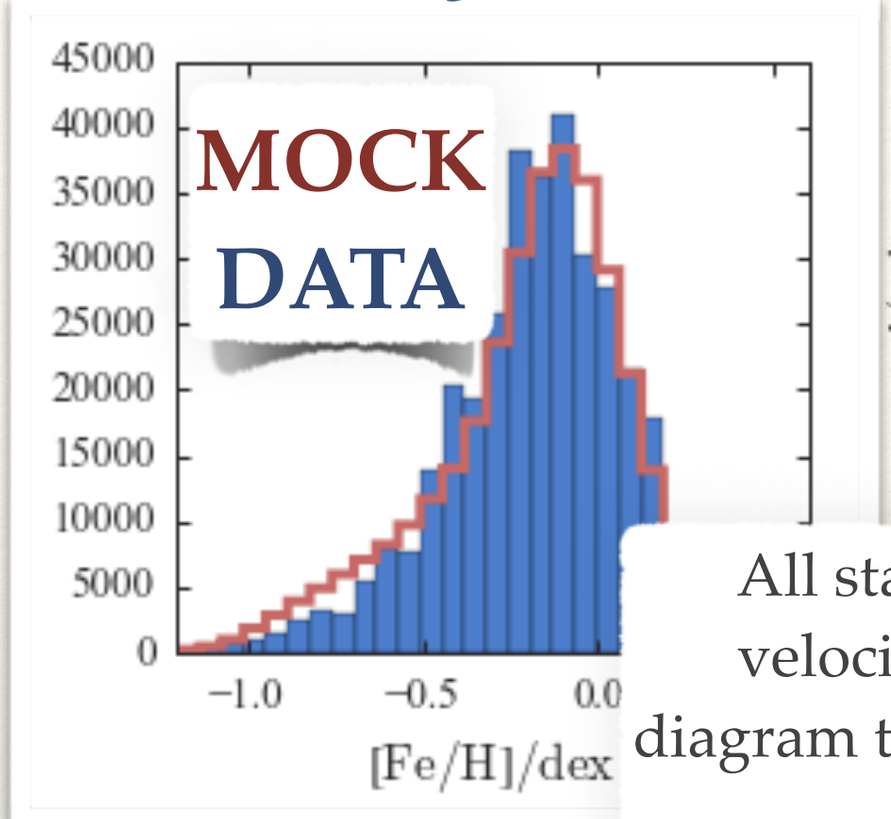
Selection function: Sky split into HEALPix and bins in I_{2MASS} = estimated from J,K_s (also J-K>0.5 if |b|<25º)

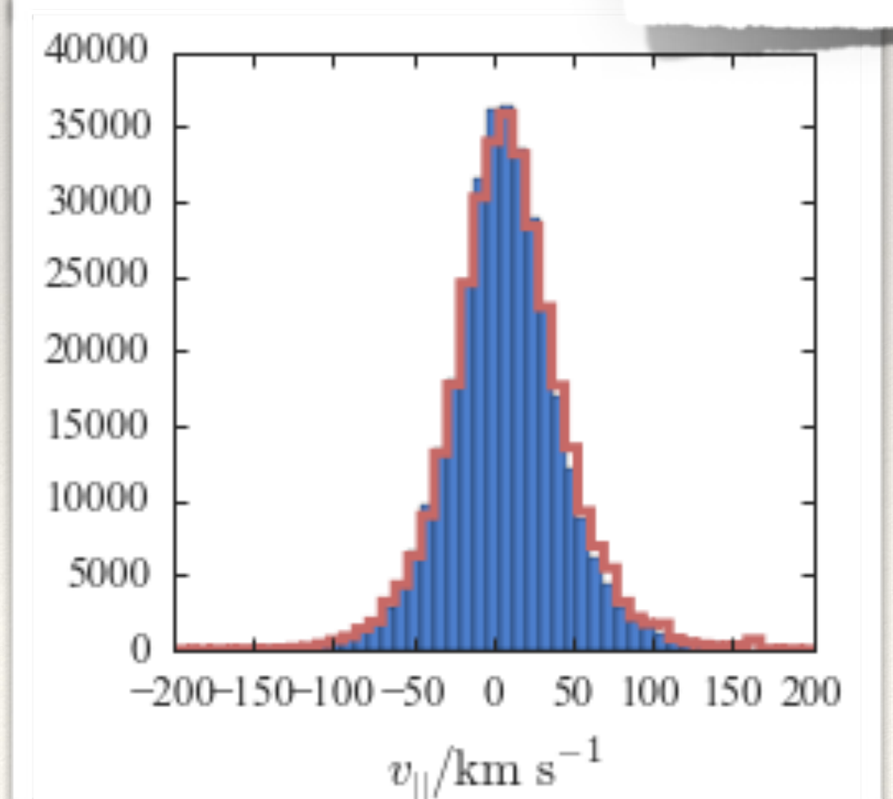


Kordopatis et al. (2014)

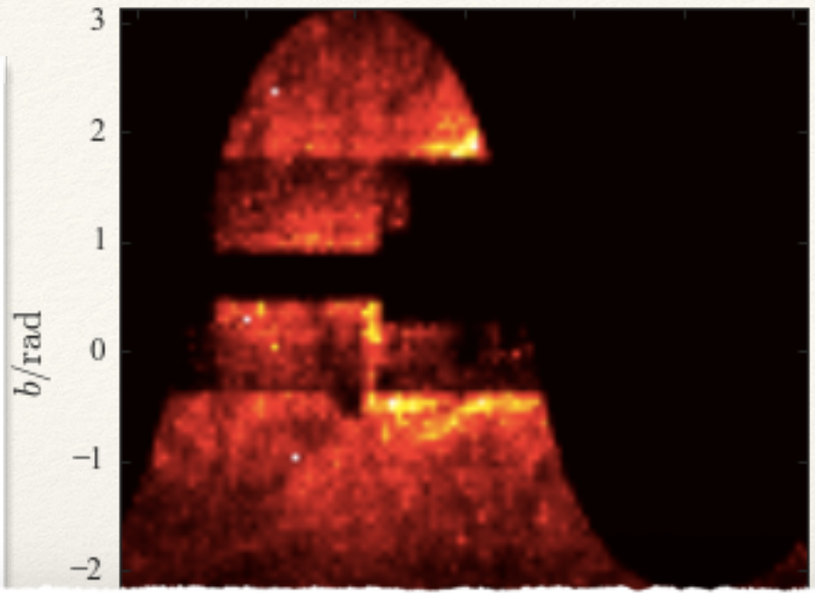
Modelling RAVE

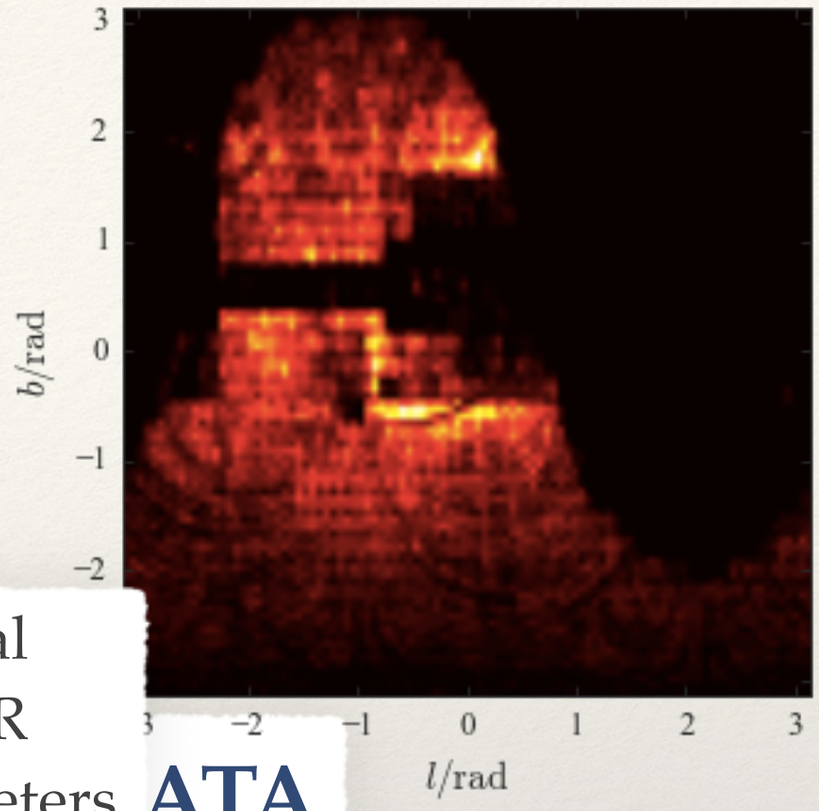
Model tweaked slightly to match metallicity distribution





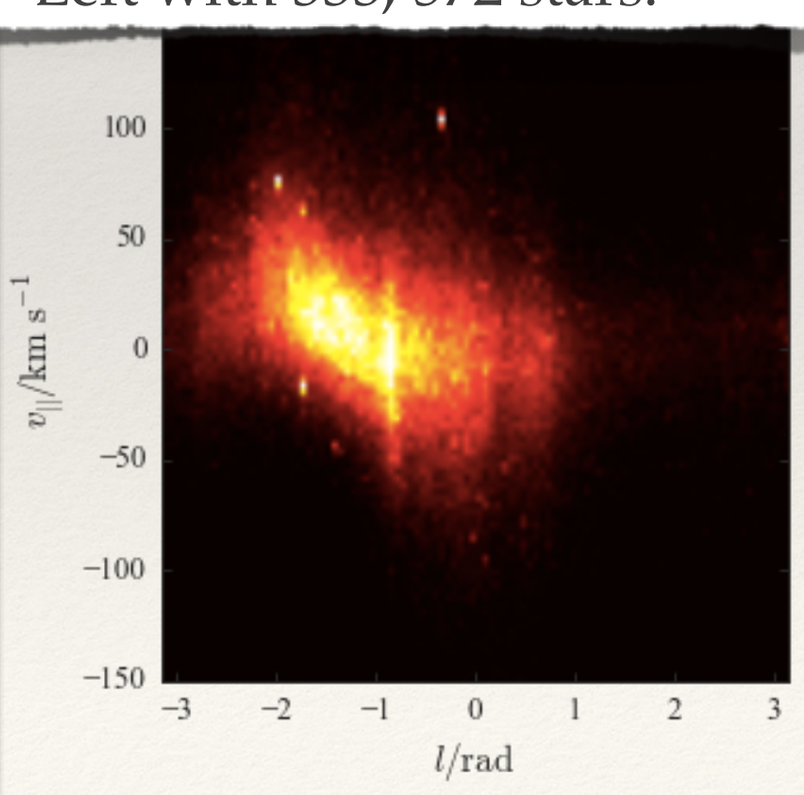
Folded with errors by finding using nearest true RAVE star in T_{eff}, log g and [Fe/H]

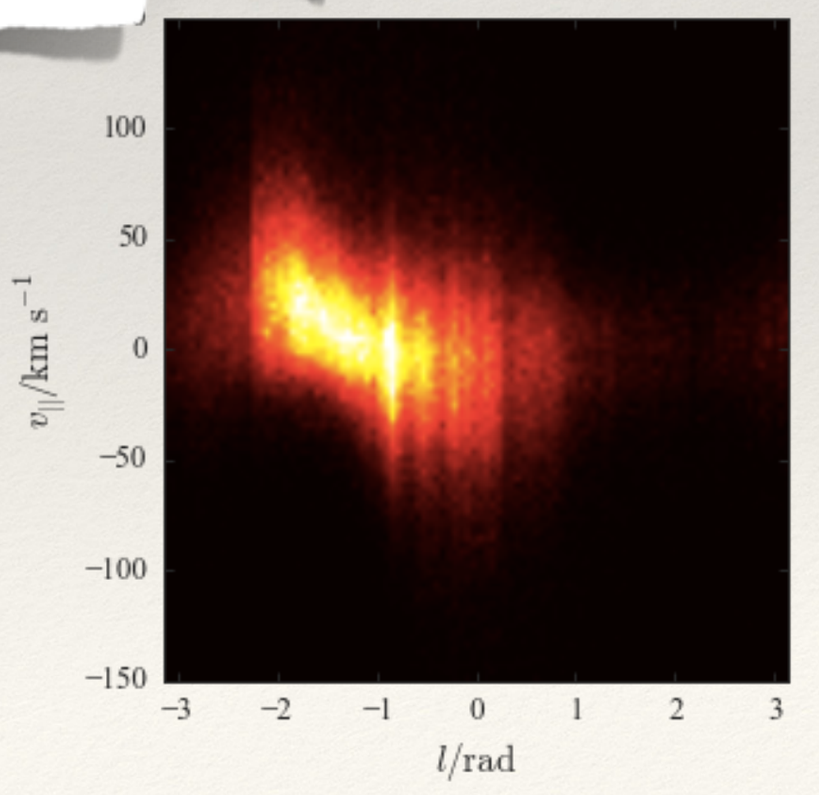




All stars with S/N>20, reliable radial velocities & removed parts of the HR diagram that produce unreliable parameters. Left with 333, 572 stars.

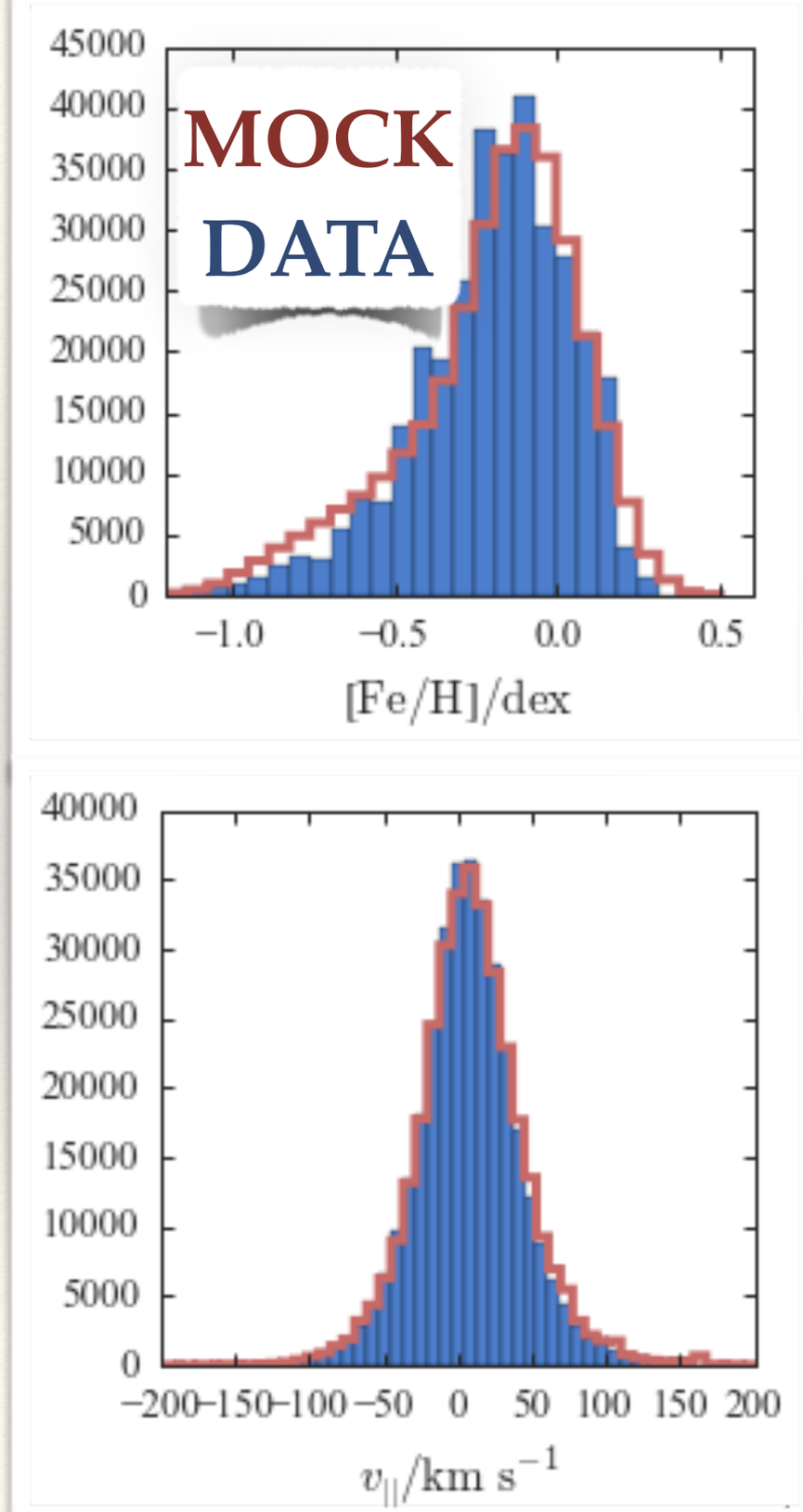
ATA



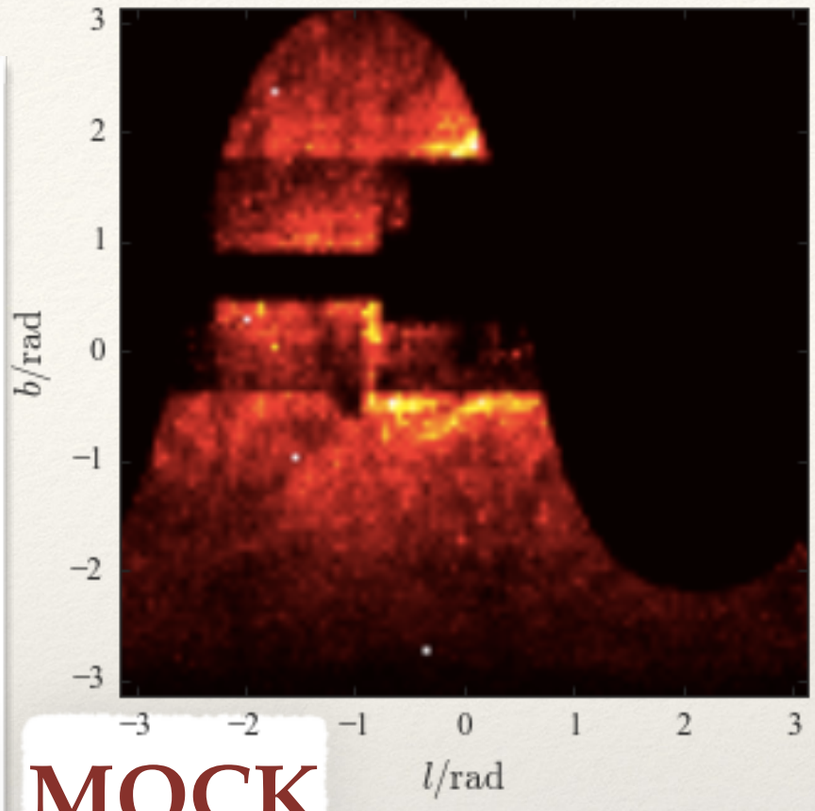


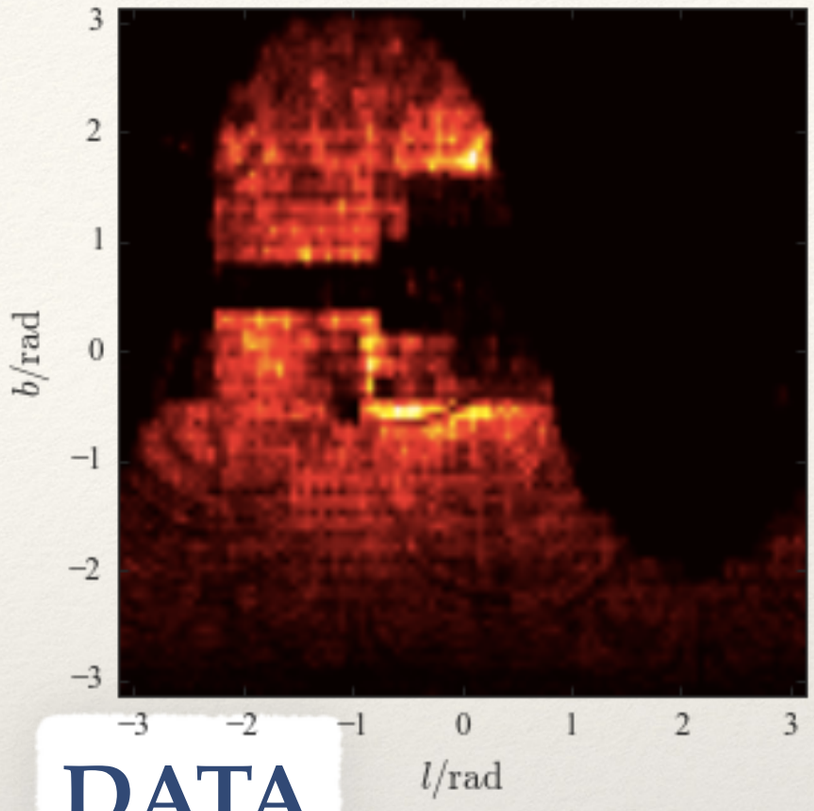
Modelling RAVE

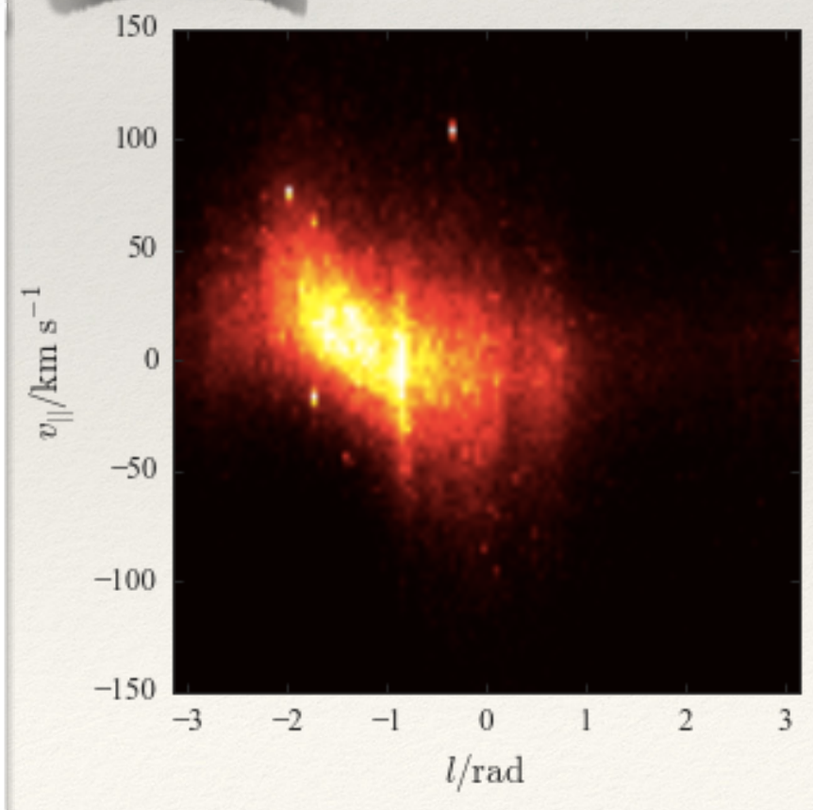
Model tweaked slightly to match metallicity distribution

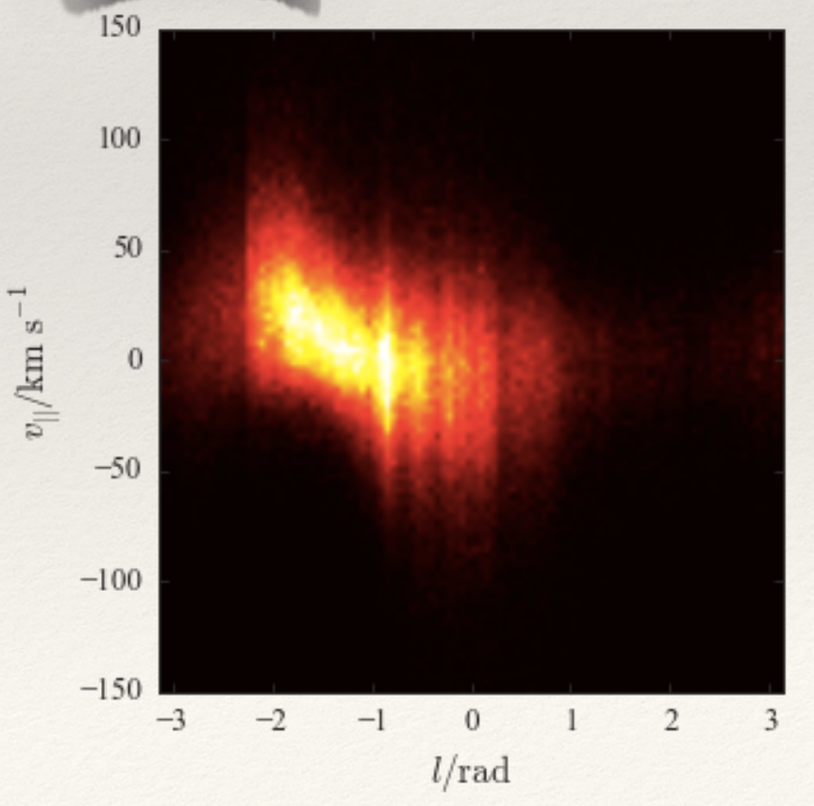


Folded with errors by finding using nearest true RAVE star in T_{eff}, log g and [Fe/H]



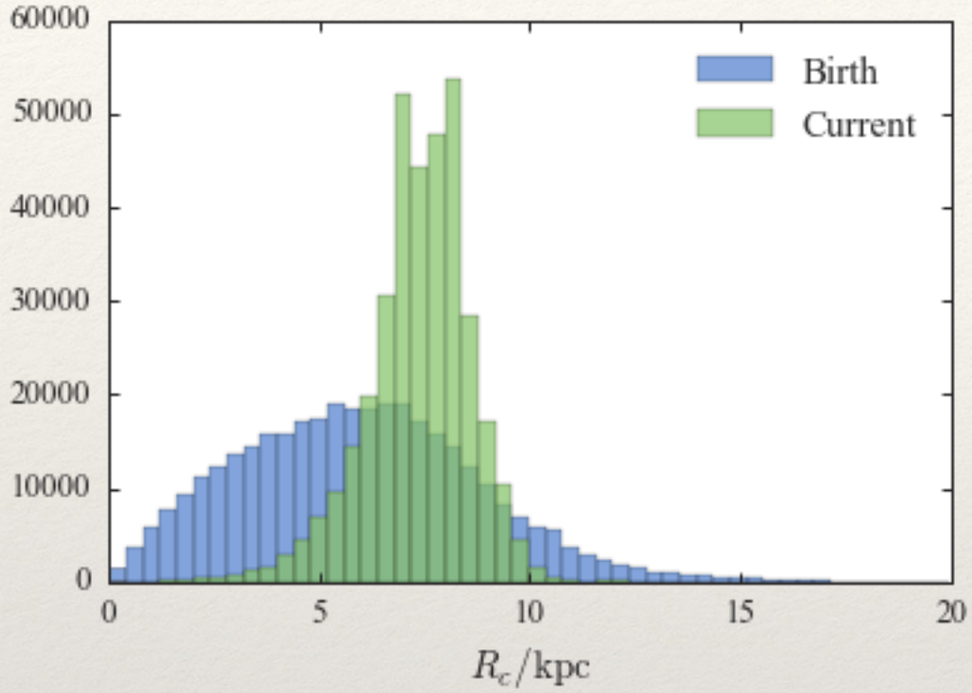


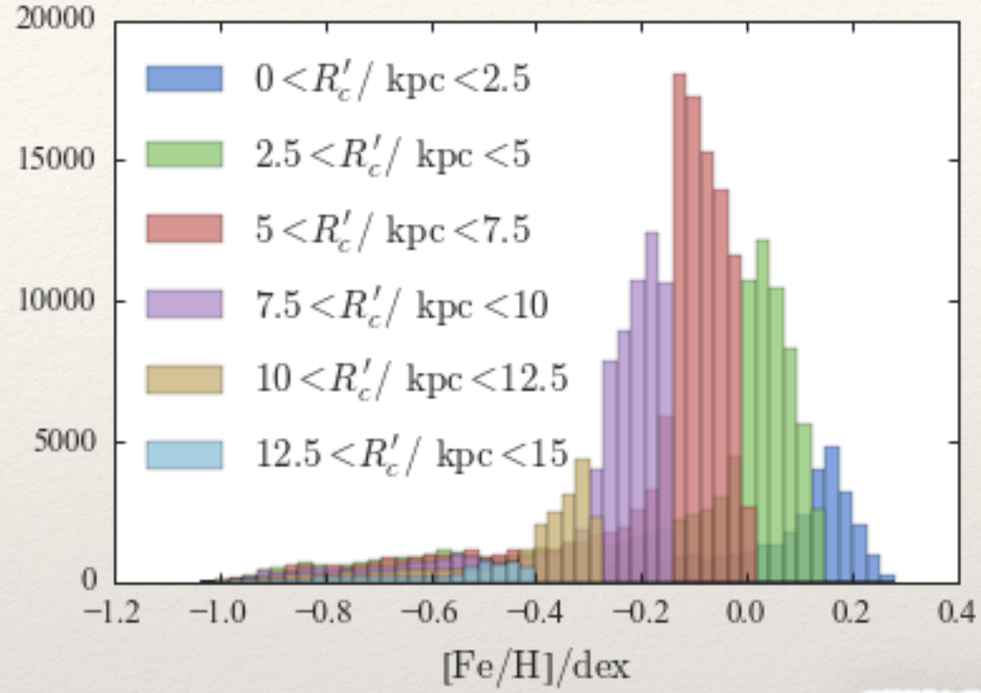


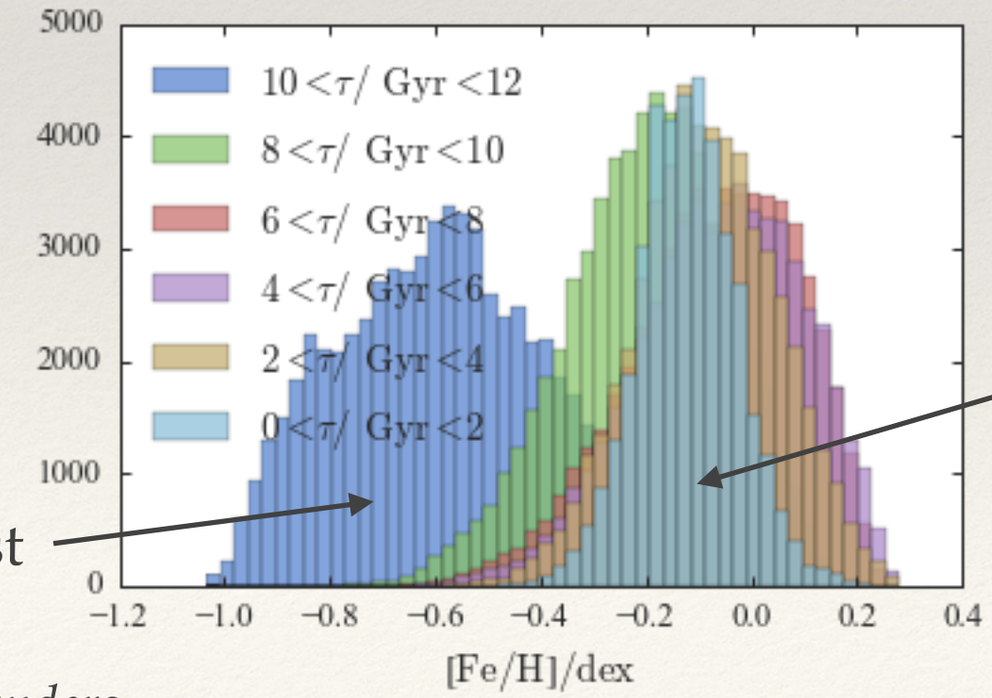


Properties of RAVE sample

Where and when were stars born?

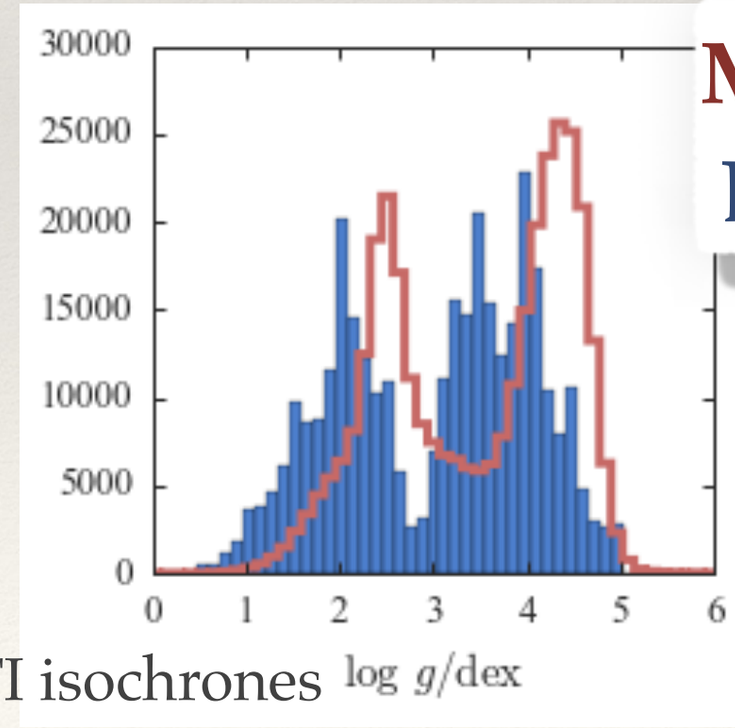






Oldest

Youngest



MOCK DATA

N.B. BaSTI isochrones

Alternative to discrete models

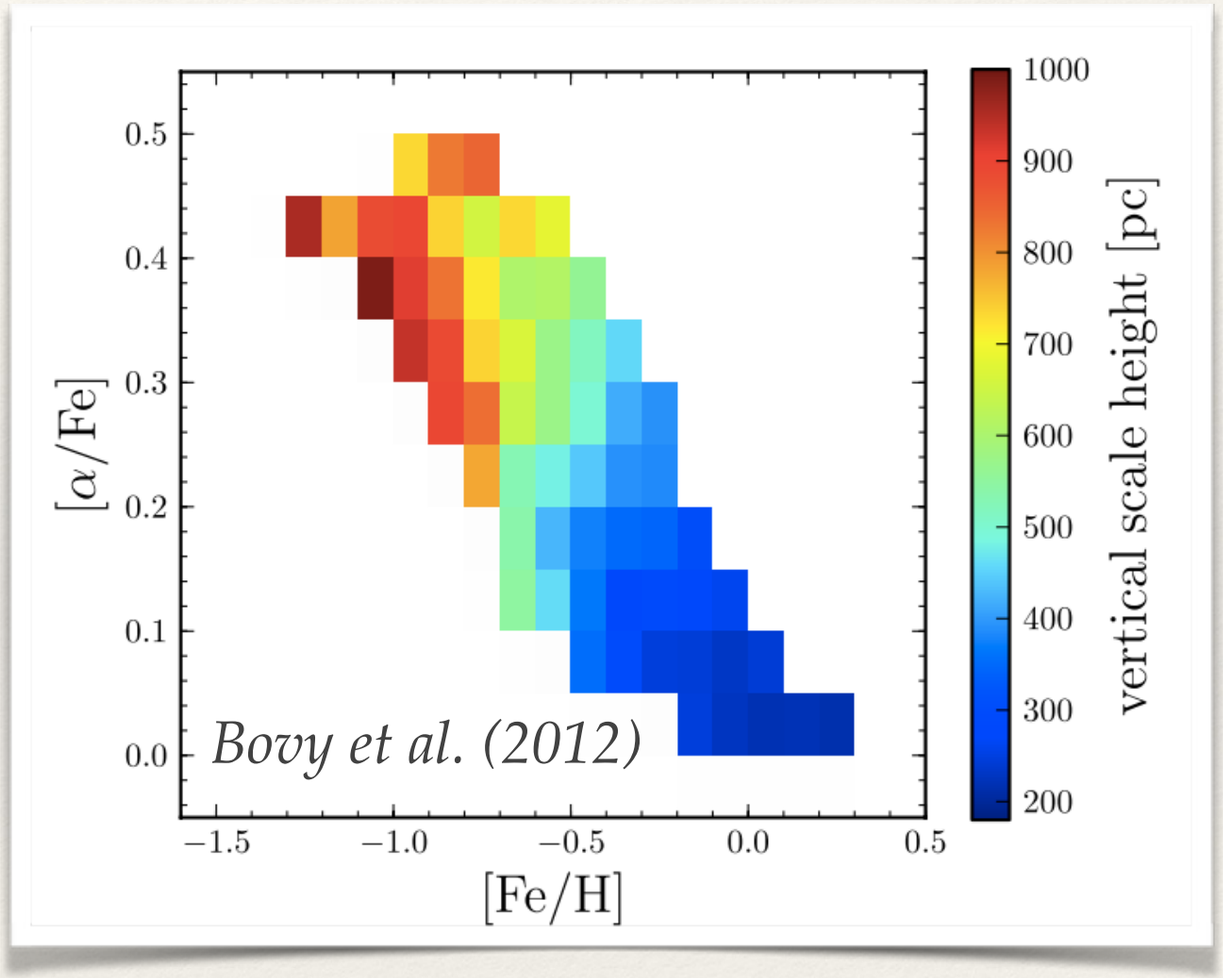
We have adopted f(**J**,**Z**) as opposed to $f_{\mathbf{Z}}(\mathbf{J})$

Disadvantages

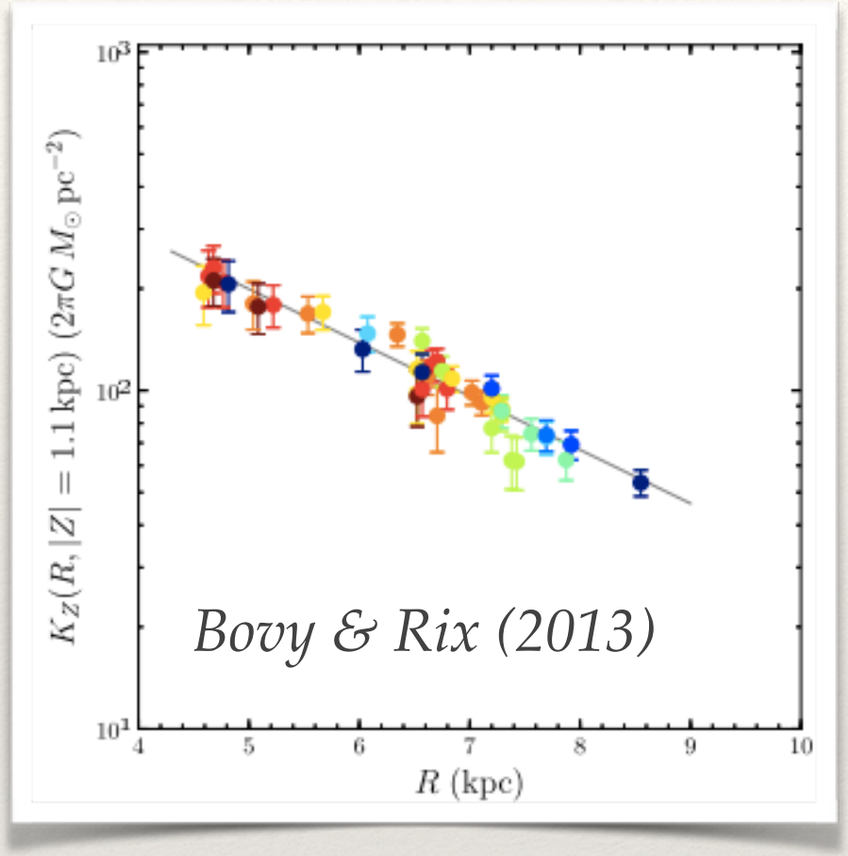
- Must pick functional form

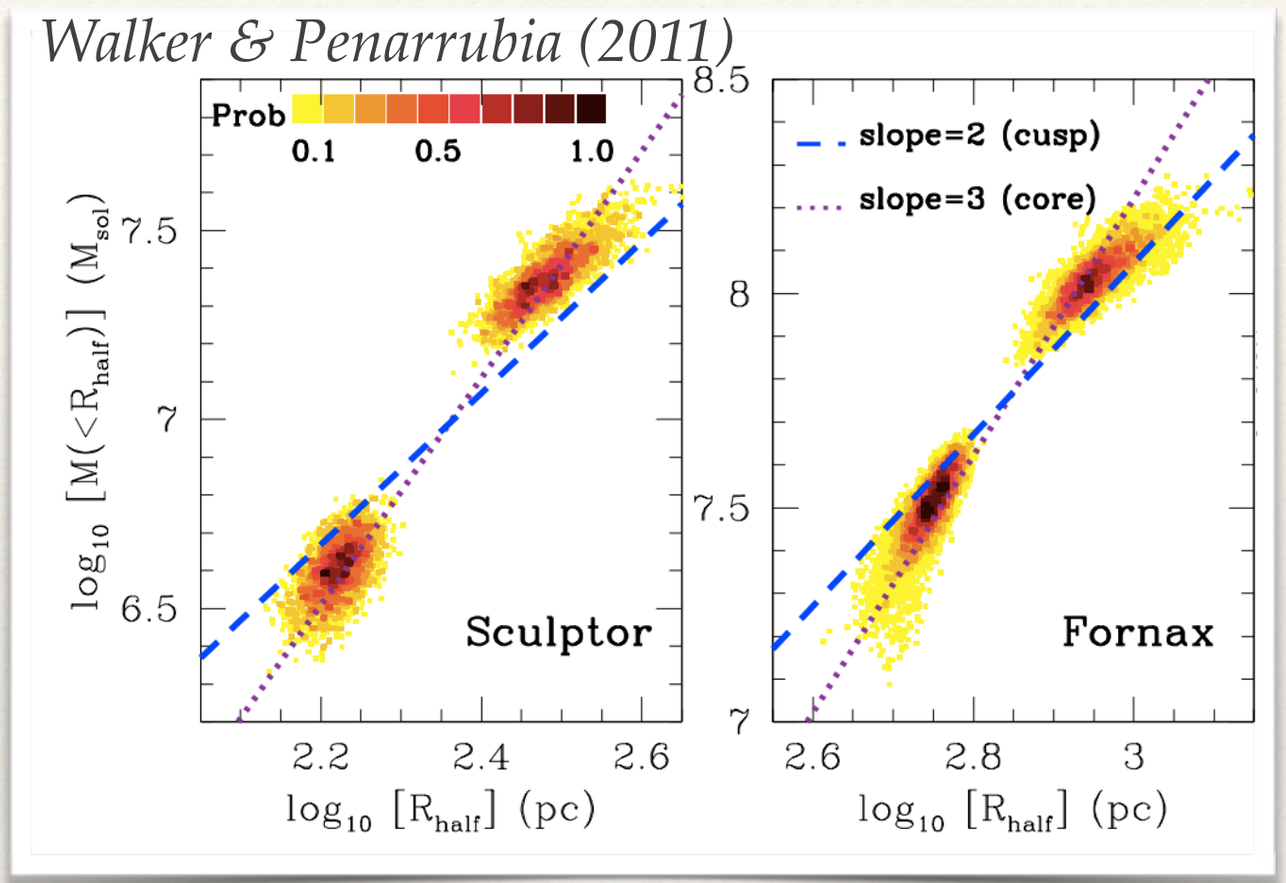
Advantages

- Picking bin size awkward
- Can properly handle contamination
- Many enrichment events should produce a smooth distribution in abundance plane.



Other advantages





- Constraining the potential — *e.g. Walker & Penarrubia (2011), Bovy & Rix (2013)*
- Descriptive model of the history of the Galaxy
- Lightweight model in comparison to full chemo-dynamical evolution model
- Interface between full N-body models and data

Conclusions

Model

Introduced an extended distribution function that describes the dynamics of different chemical populations

- Analytic metallicity dependence on metallicity and age
- Include radial migration and heating

Allows inclusion of selection effects

Fitted the model with Geneva-Copenhagen survey + Gilmore & Reid (1983)

Predictions

Made predictions for SEGUE G dwarfs and RAVE (WIP)

Thin-thick dichotomy not present in data

Require metallicity gradient to increase towards Galactic centre to produce more metal-rich stars in GCS sample