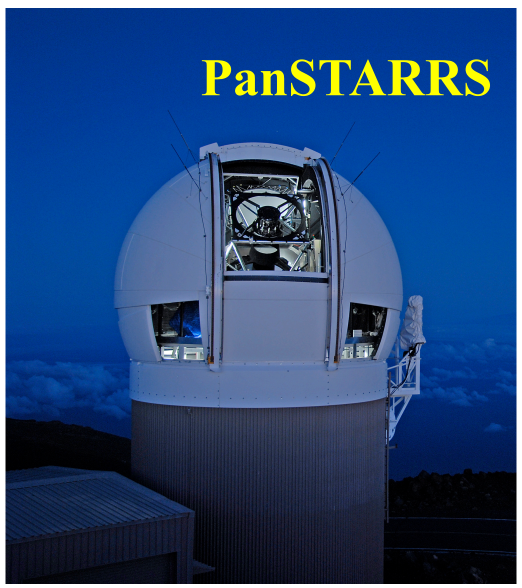
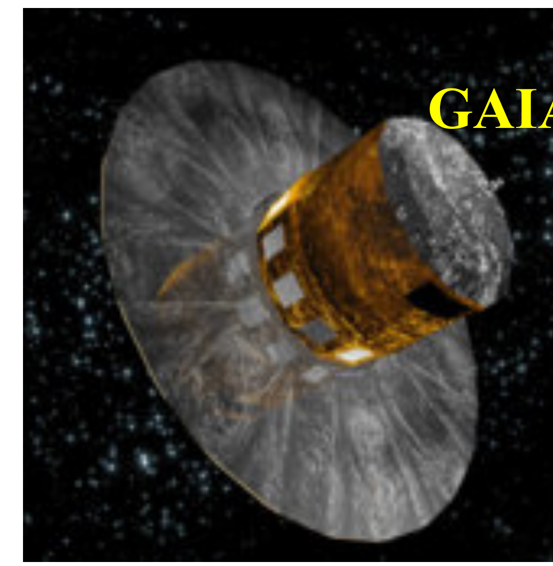
The Halo of the Milky Way





Xiang-Xiang Xue (薛香香)
National Astronomical Observatories,CAS

collaboration with Hans-Walter Rix, Glenn van de Ven, Matthias Steinmetz, Branimir Sesar, Heather Morrison, Jo Bovy, Zhibo Ma, William Janesh, Timothy Beers, Chao Liu, Xi Kang, Gang Zhao, Yan Xu, Chengqun Yang, Meng Zhai, Lan Zhang, Juntai Shen, Sarah Bird

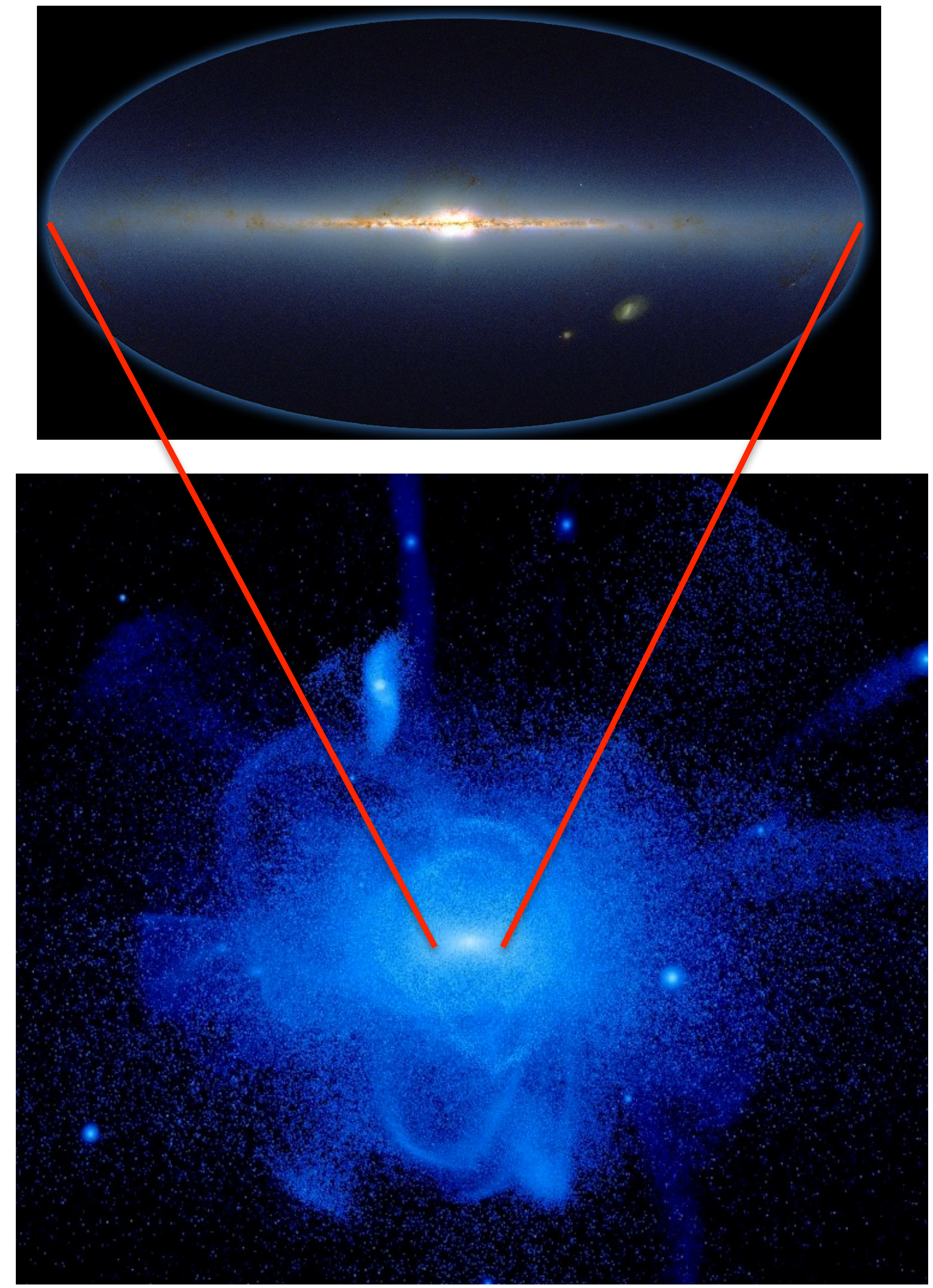
Outline

- Background
- What has been well known for Galactic halo?
- What we have done using the large samples of halo stars?
- Summary

Theorists View of MW halo

- The Λ cold dark matter (CDM) cosmological model predicts
  - “in-situ” formation (inside)
  - many mergers have occurred (large radii)
  - at large radii: VERY long orbital period (>0.5 Gyr)

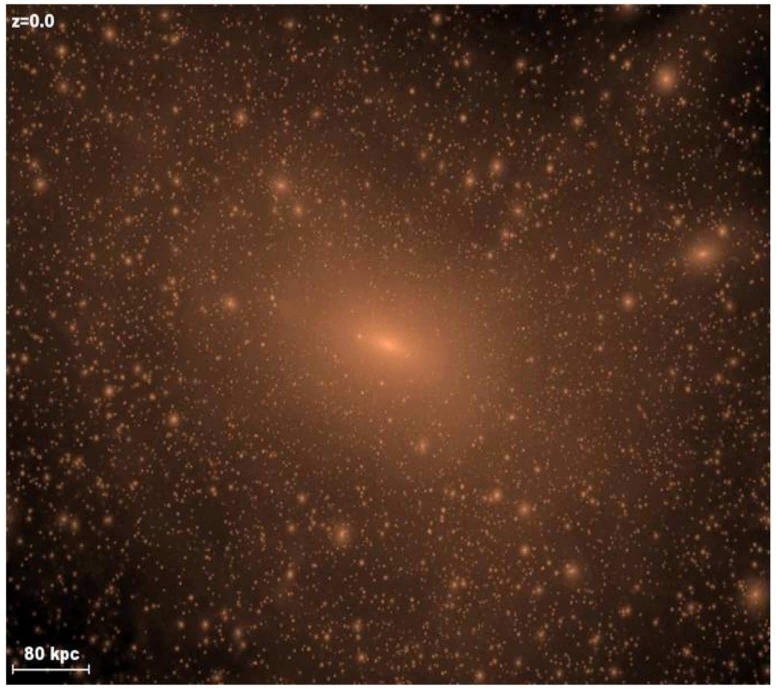
    —> remnants of disrupted satellites are still apparent
- Great deal of variation among MW-like simulated galaxies
- A few anomalies when comparing to MW and its neighbours

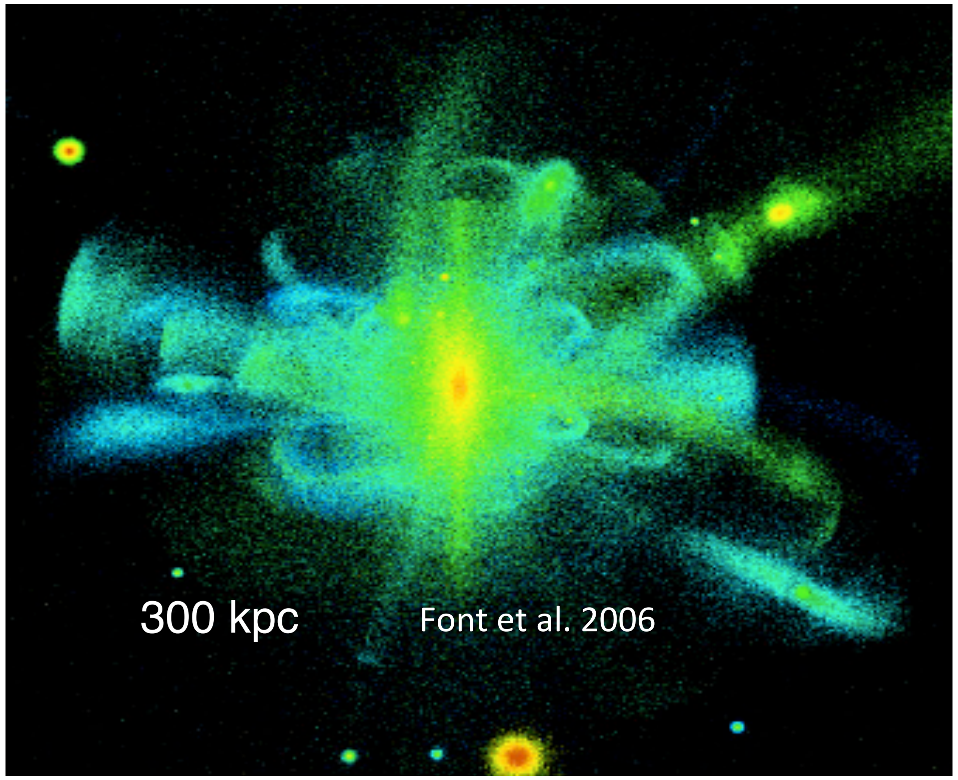


Exploring the Galactic halo

needs kinematic tracers with r(α,δ,D), v_{los}, μ and [Fe/H] to

- constrain the dynamics
  - the shape and radial density profile
  - the mass of the dark matter halo
    - M_{star}/M_{halo} (baryon fraction)
    - missing satellites?
    - Dynamics of the local group
      -->> M31 infall, LMC bound?
- reconstruct the accretion history
  - quantify stellar streams & position-velocity substructures & I.o.M subs.
- explore early enrichment
  - "oldest stars"
  - metallicity distribution function

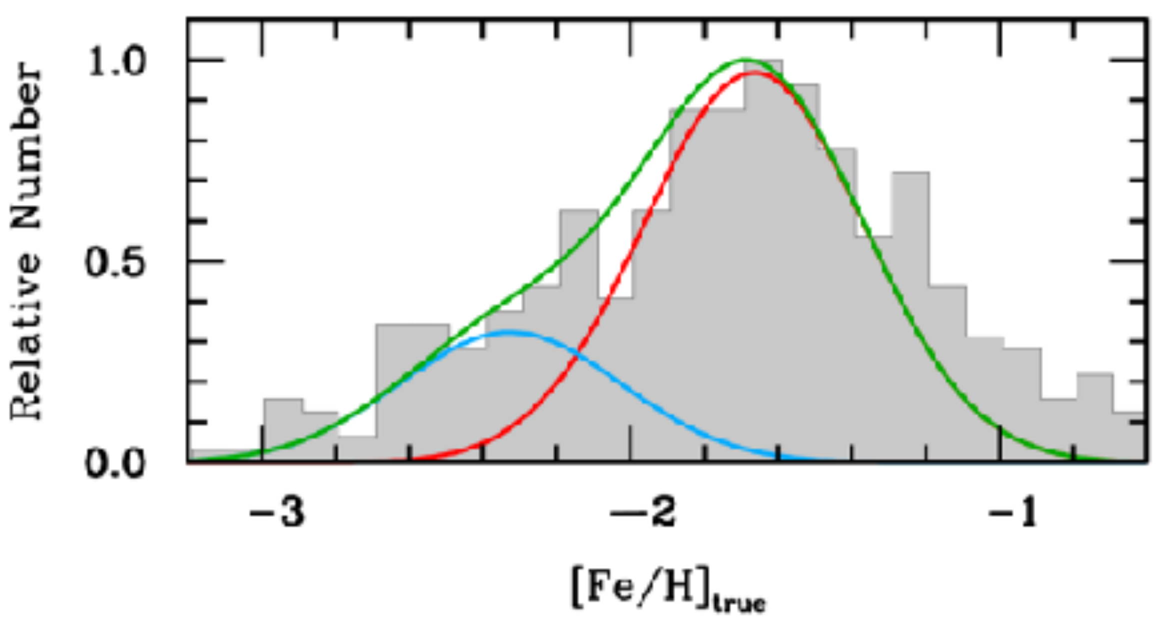




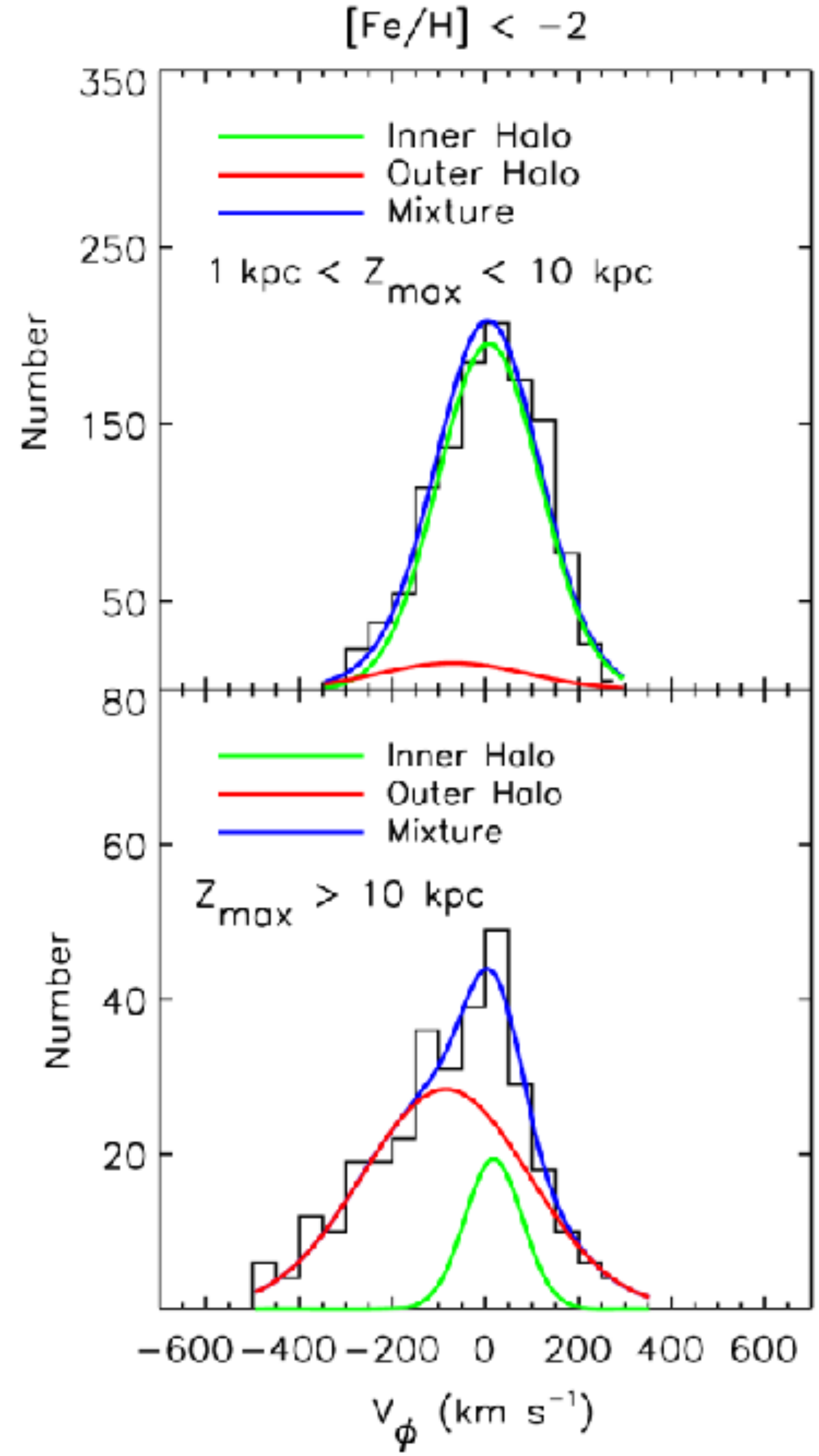
What has been well known for MW halo in the past 20 years?

Galactic Stellar Halo

- has ~1% of all stars in MW.
  metal-poor, old, highly eccentric orbits
- Local kinematics (6D) and [Fe/H]
  inner halo: < 20kpc, non-rotation,
  <[Fe/H]>=-1.6
  outer halo: > 20kpc, retrograde
  rotation, <[Fe/H]>=-2.2



Deokkeun+ 2013

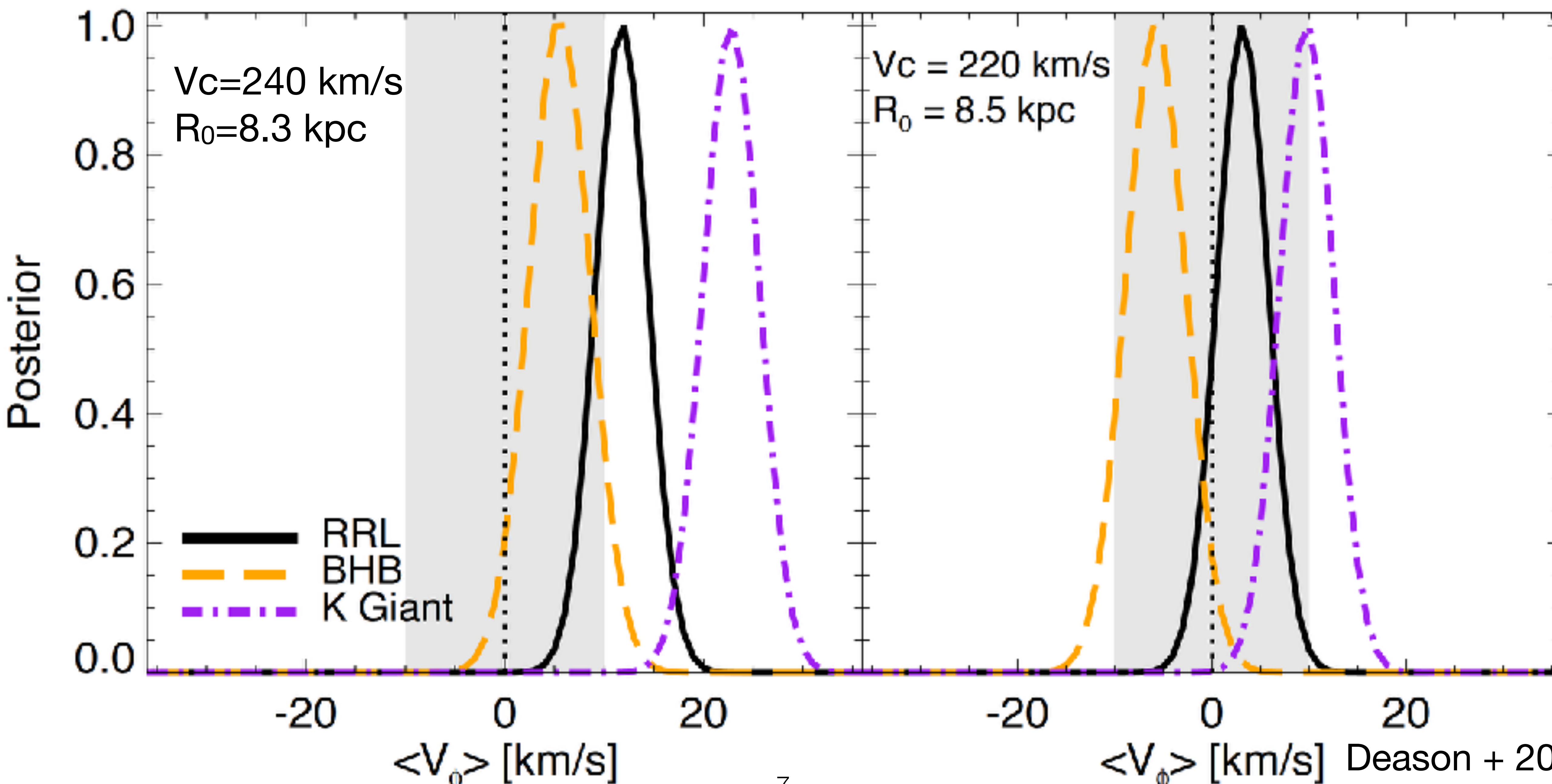


Carollo+ 2007, 2010, 2012, Beers+ 2012

Does the stellar halo spin?

- Distant kinematics (5D), without $V_{los.}$ gently rotating prograde signal out to 50 kpc depending on Vc and R_0

$$P(v_r, v_\theta, v_\phi | \sigma_r, \sigma_\phi, \sigma_\theta, \langle V_\phi \rangle) = \frac{1}{(2\pi)^{3/2}\sigma_r\sigma_\theta\sigma_\phi} \exp\left[-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{(v_\phi - \langle V_\phi \rangle)^2}{2\sigma_\phi^2} \right] \quad (3)$$



Deason + 2017

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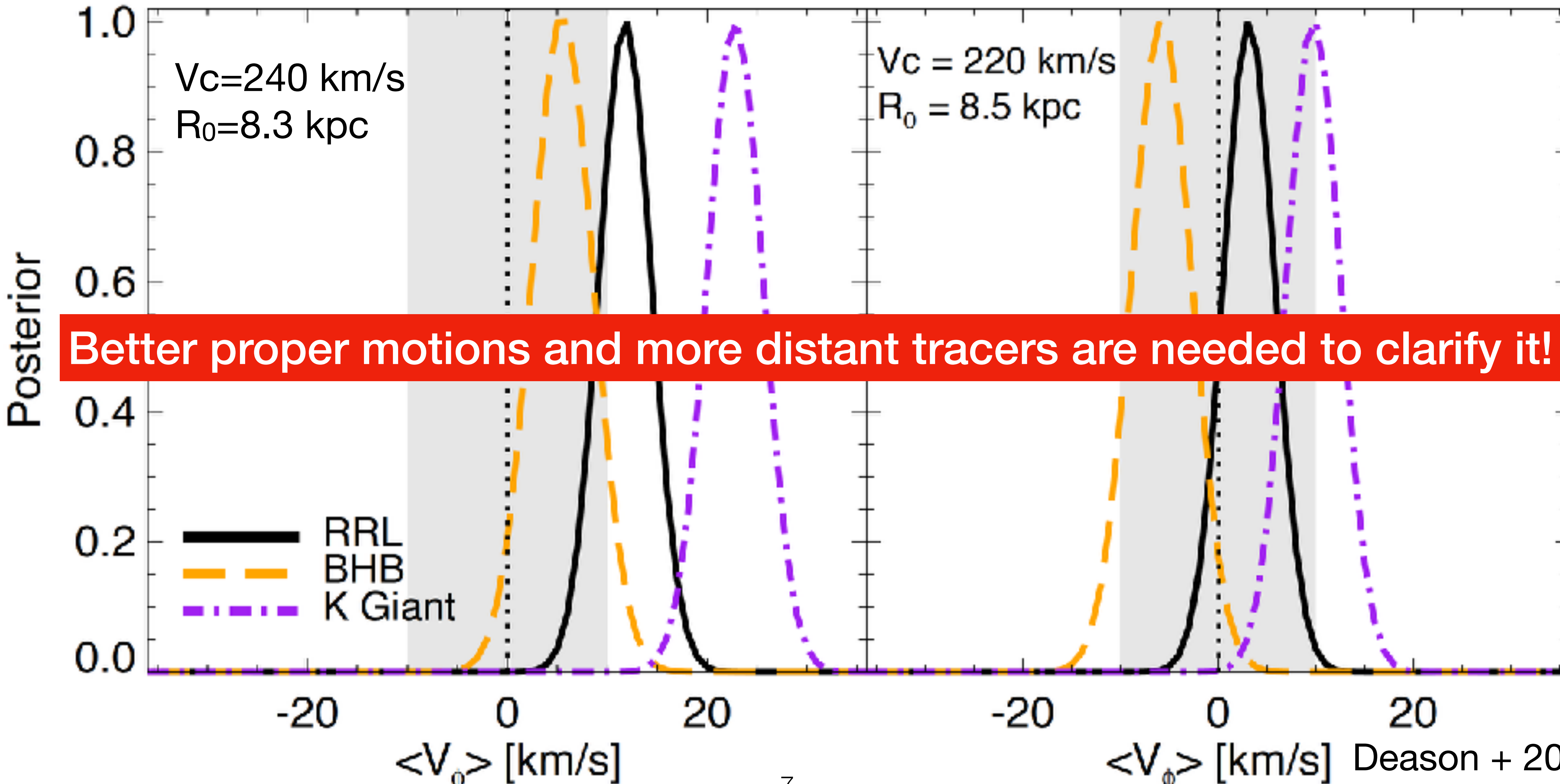


Better proper motions and more distant tracers are needed to clarify it!

Deason + 2017

Galactic Stellar Halo (cont.)

- Distant kinematics (4D) and [Fe/H]

  line-of-sight velocity dispersion —> constrain the dark matter halo mass

  $M_{vir}=0.5\sim2.5\times10^{12}M_\odot$

  Beers+ 2000, Battaglia+ 2005, 200 tracers

  $M_{vir}=1\pm0.2\times10^{12}M_\odot$

  Xue+ 2008, 2400 SDSS tracers

- has substructure

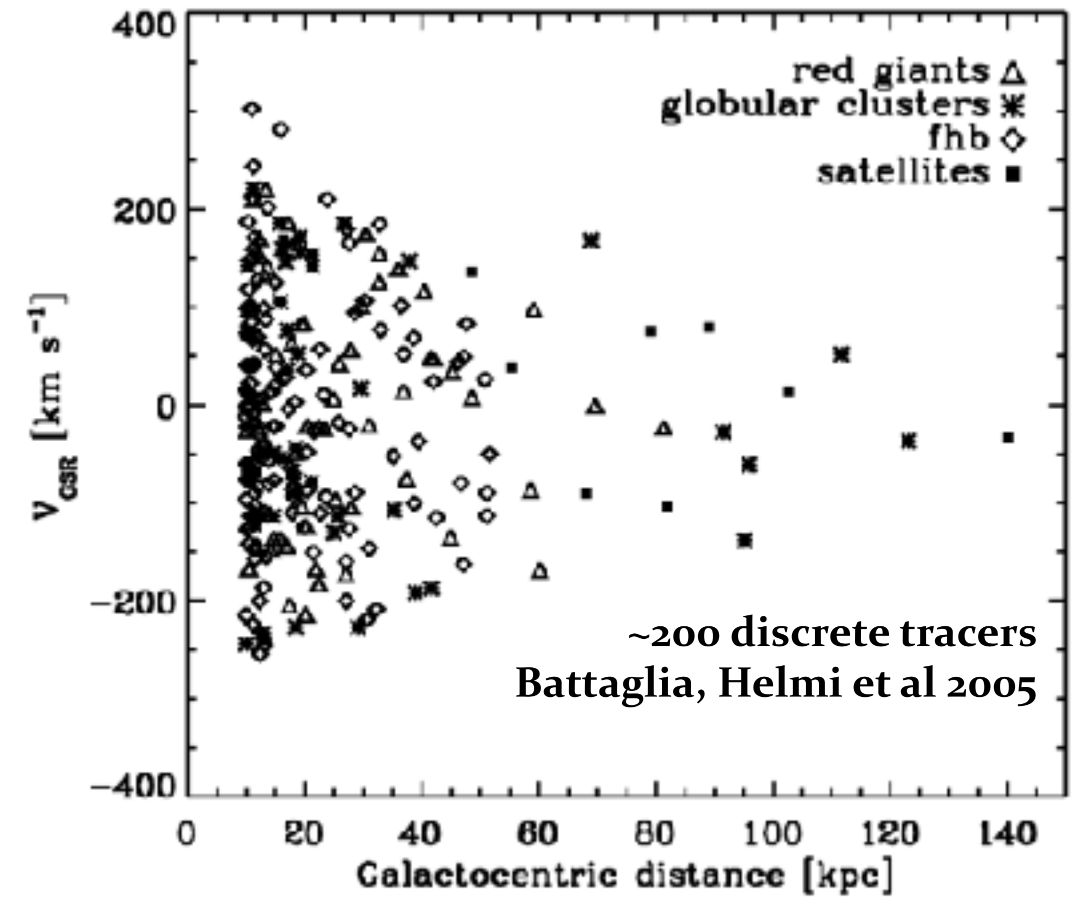
  field of streams

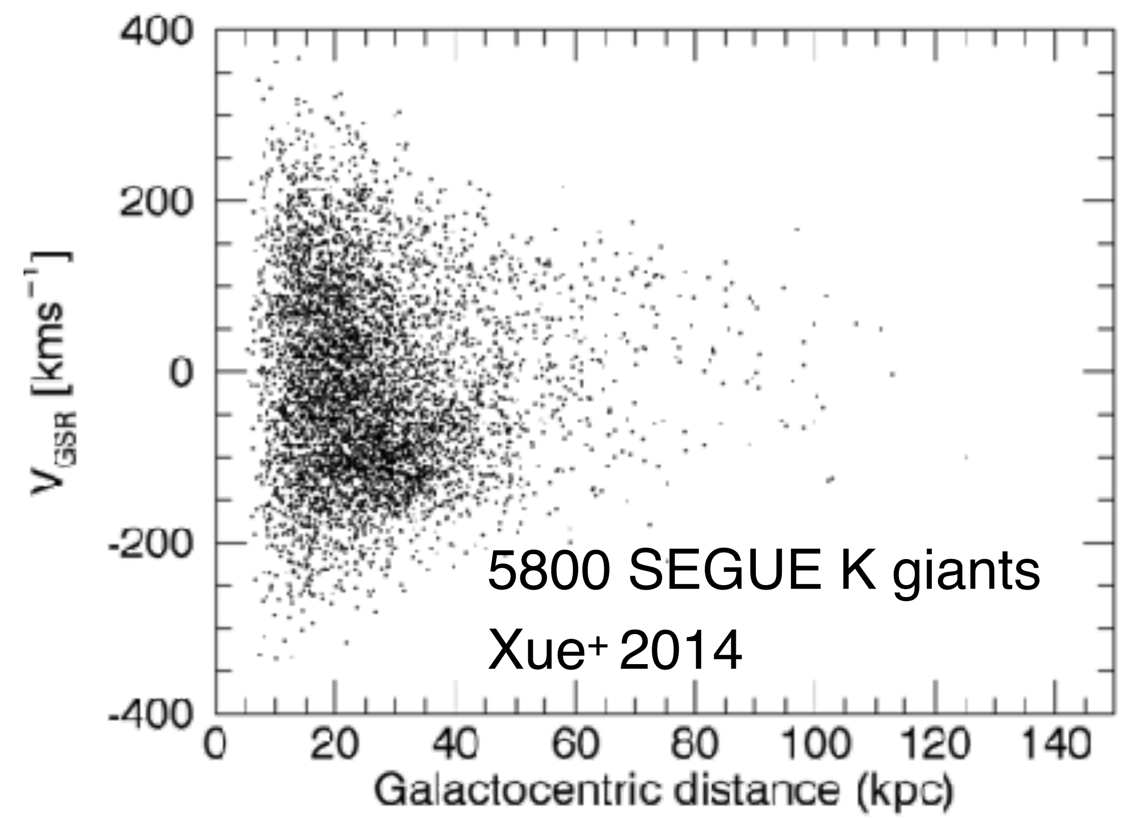
  position-velocity substructure

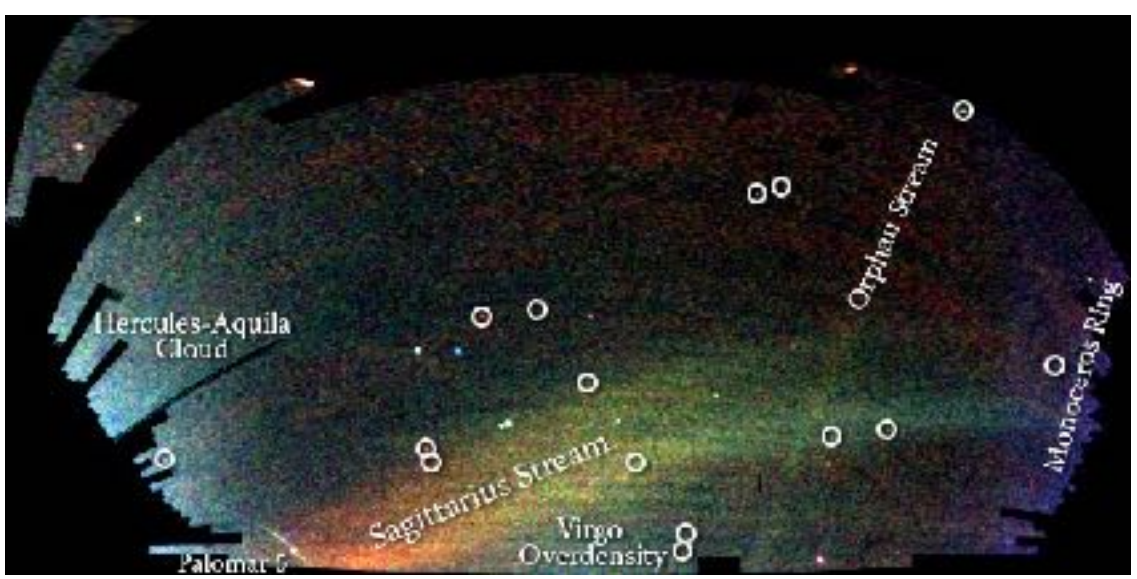
  features differ in different populations

  Ibata+ 2001, Majewski+ 1996, 2003

  Bell+ 2008, Starkenburg+ 2009, Xue+ 2011







Credit: V. Belokurov and the Sloan Digital

What are ideal tracers to study MW halo?

Ideal tracers:

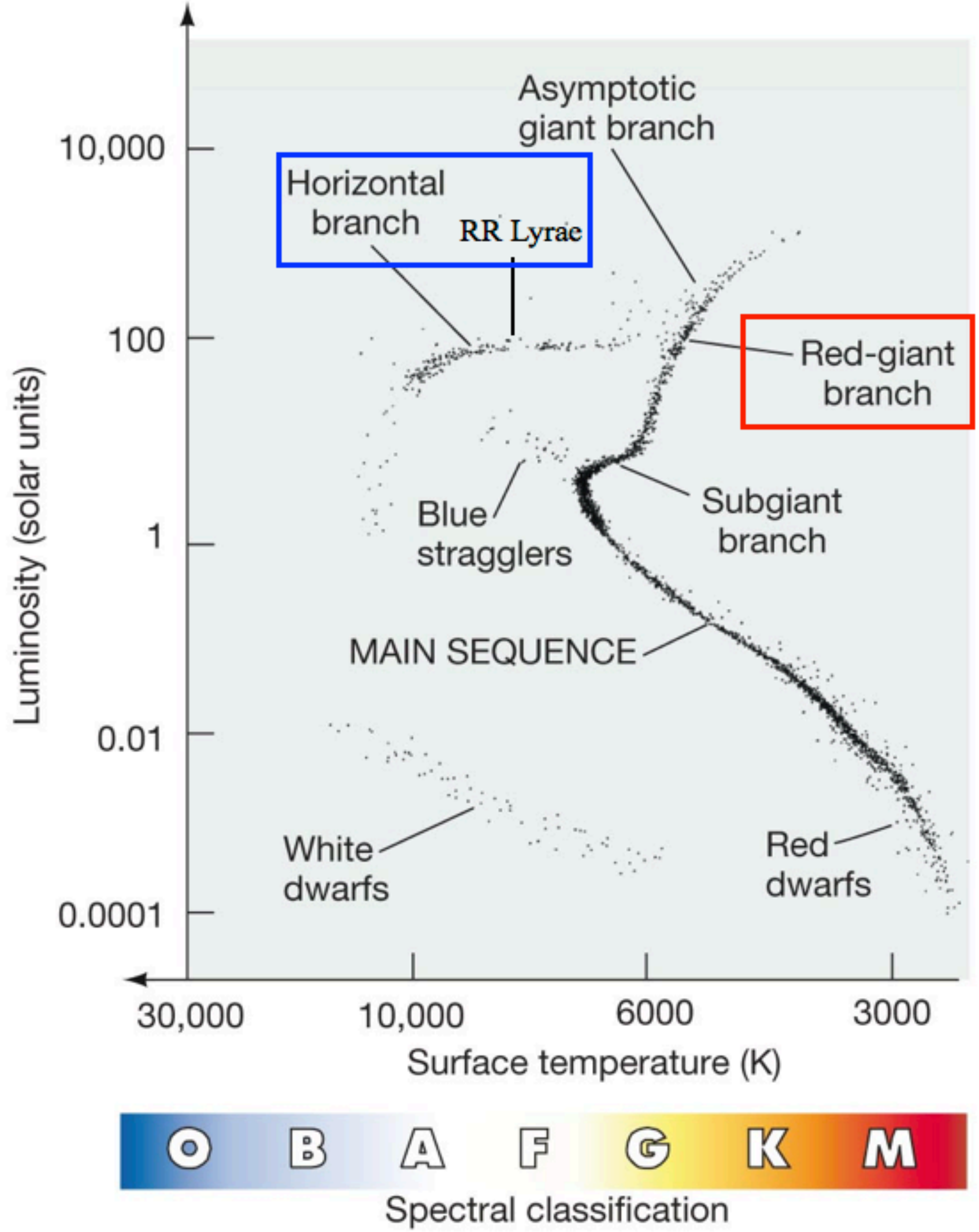
0<r_{gc}<250kpc

good distances (~10%)

known abundance

clear relation

n_{tracer} (r) <—> ν(r)



(b)

Ideal tracers:

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$n_{tracer}(r) \longleftrightarrow \nu(r)$

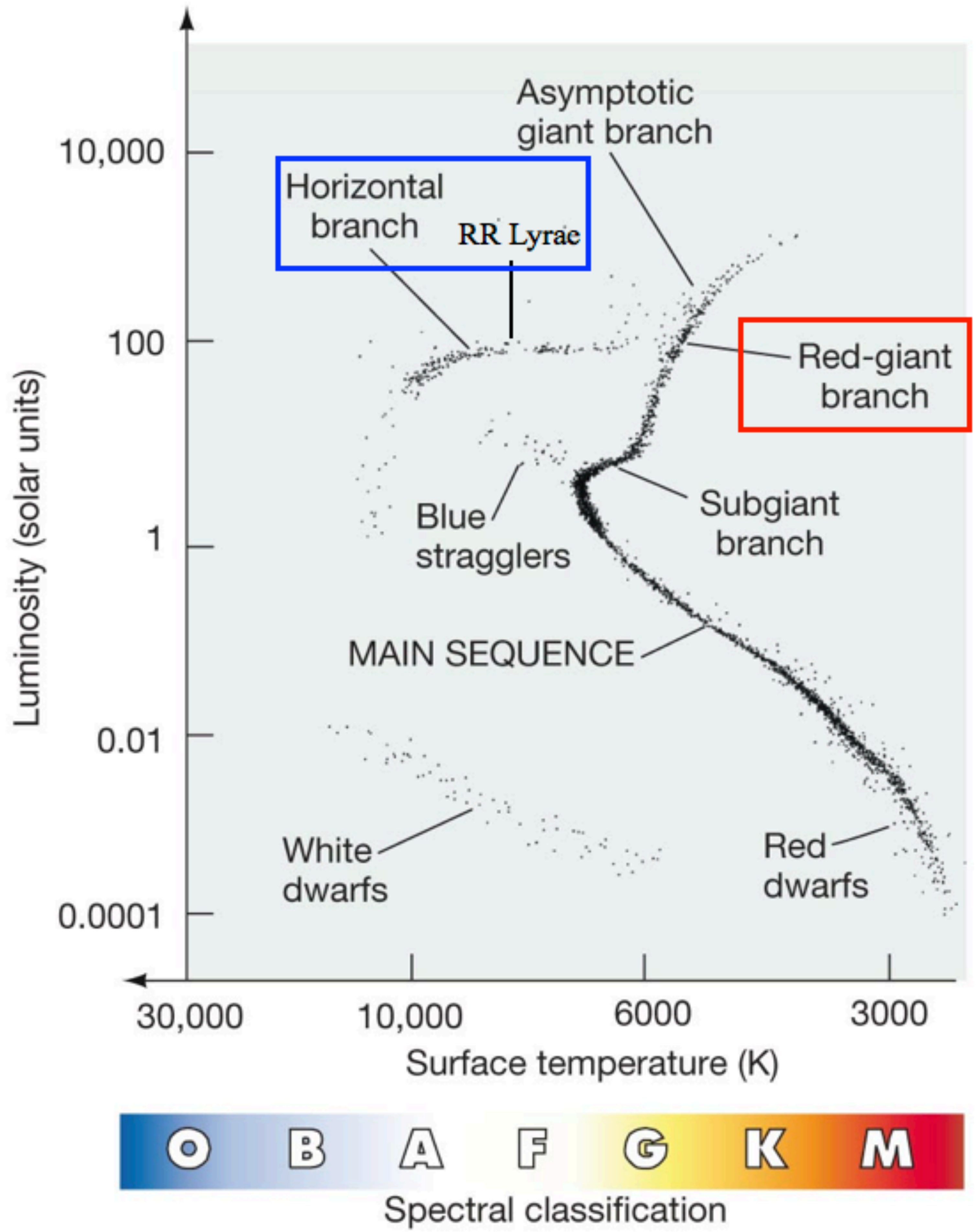
✦Blue-horizontal branch stars

old, metal-poor, good distance, but poorly known n_{BHB}/M_*

✦ Red Giants

- more representative
- predominantly K type giants.
- well-defined n_{KG}/M_*,
- but $-3<M_r<1$

—> less precise distances



(b)

Our work based on SDSS BHBs

The most reliable MW DM halo mass

- The MW mass is a fundamental, but poorly known Galactic parameter

  Values range 0.8 - 2.5×10^{12} $M_\odot$

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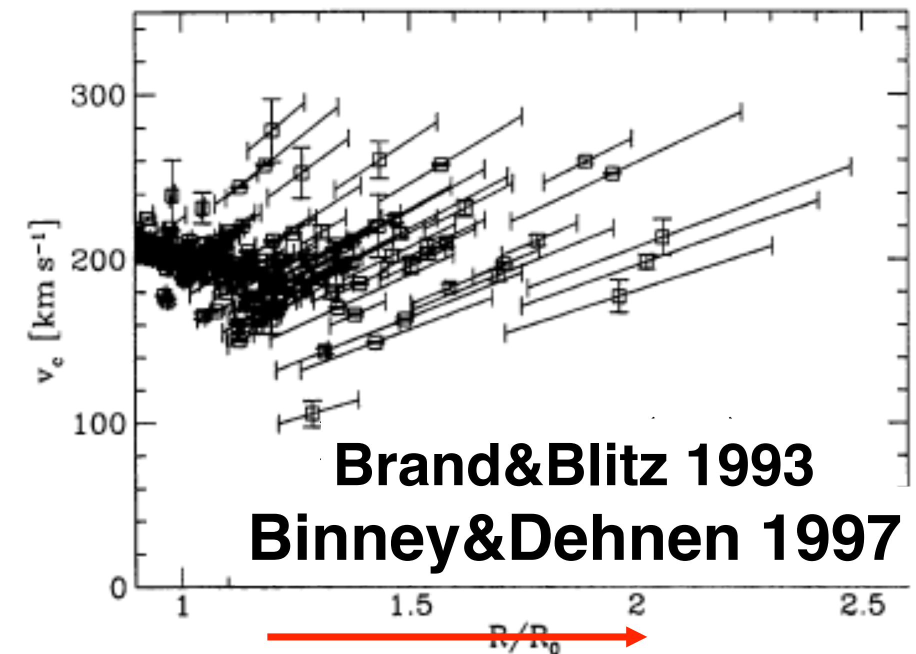
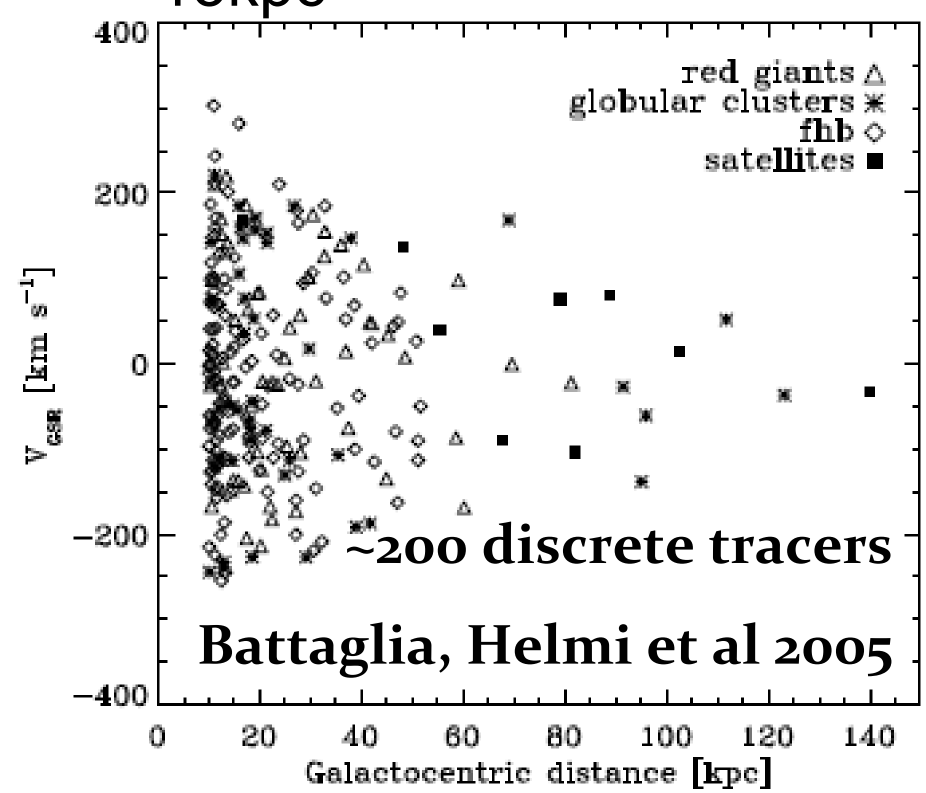
Problems:

- We are in it.
- the paucity of spectroscopic halo stars (x,y,z,v_{los},[Fe/H])
- rotation curve is only to 20 kpc



15kpc



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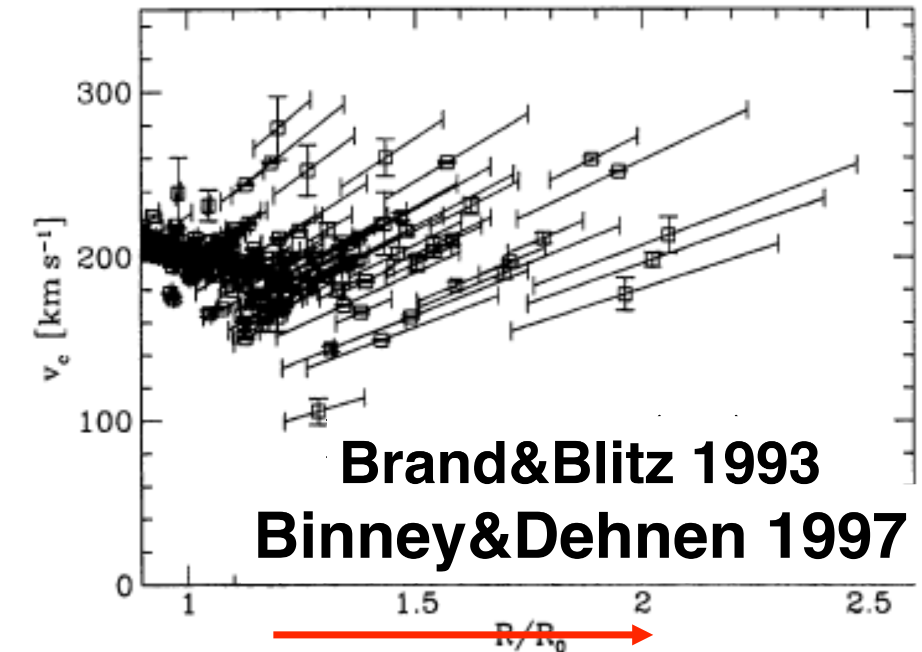
SDSS can provide halo star samples of sufficient size and quality!



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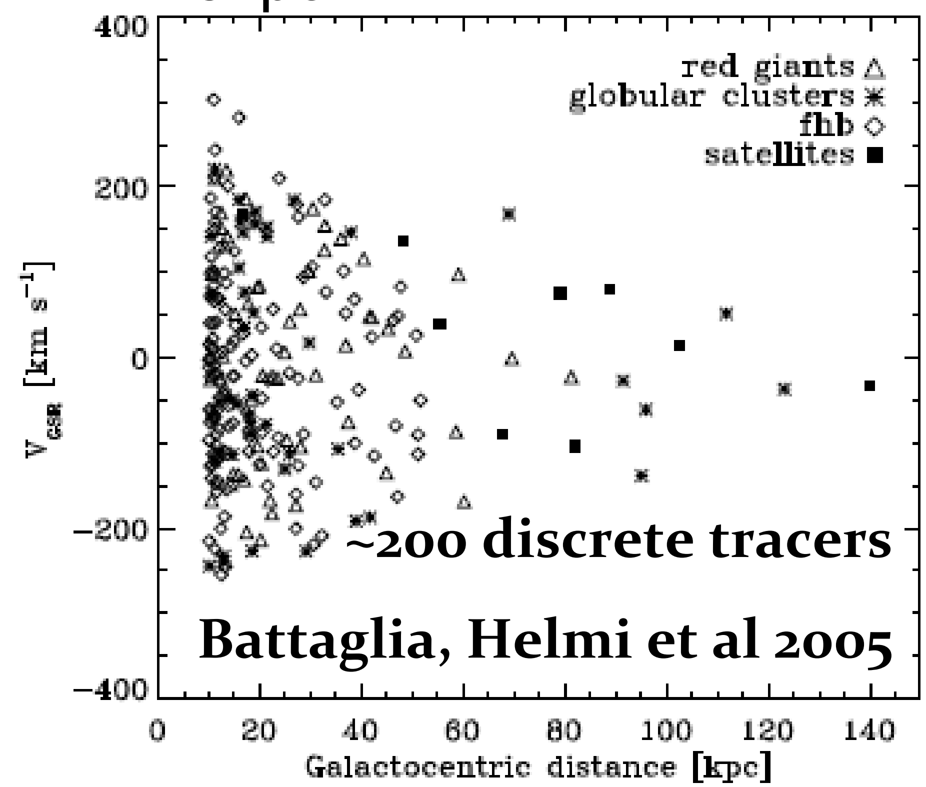

How to estimate MW halo mass?

Basic approach:

A) Assemble a large and well defined set of distant kinematic tracers from SDSS DR6

2400 BHBs with 5% distances to 60 kpc,
$\delta v \sim 10$ km/s + [Fe/H] estimates

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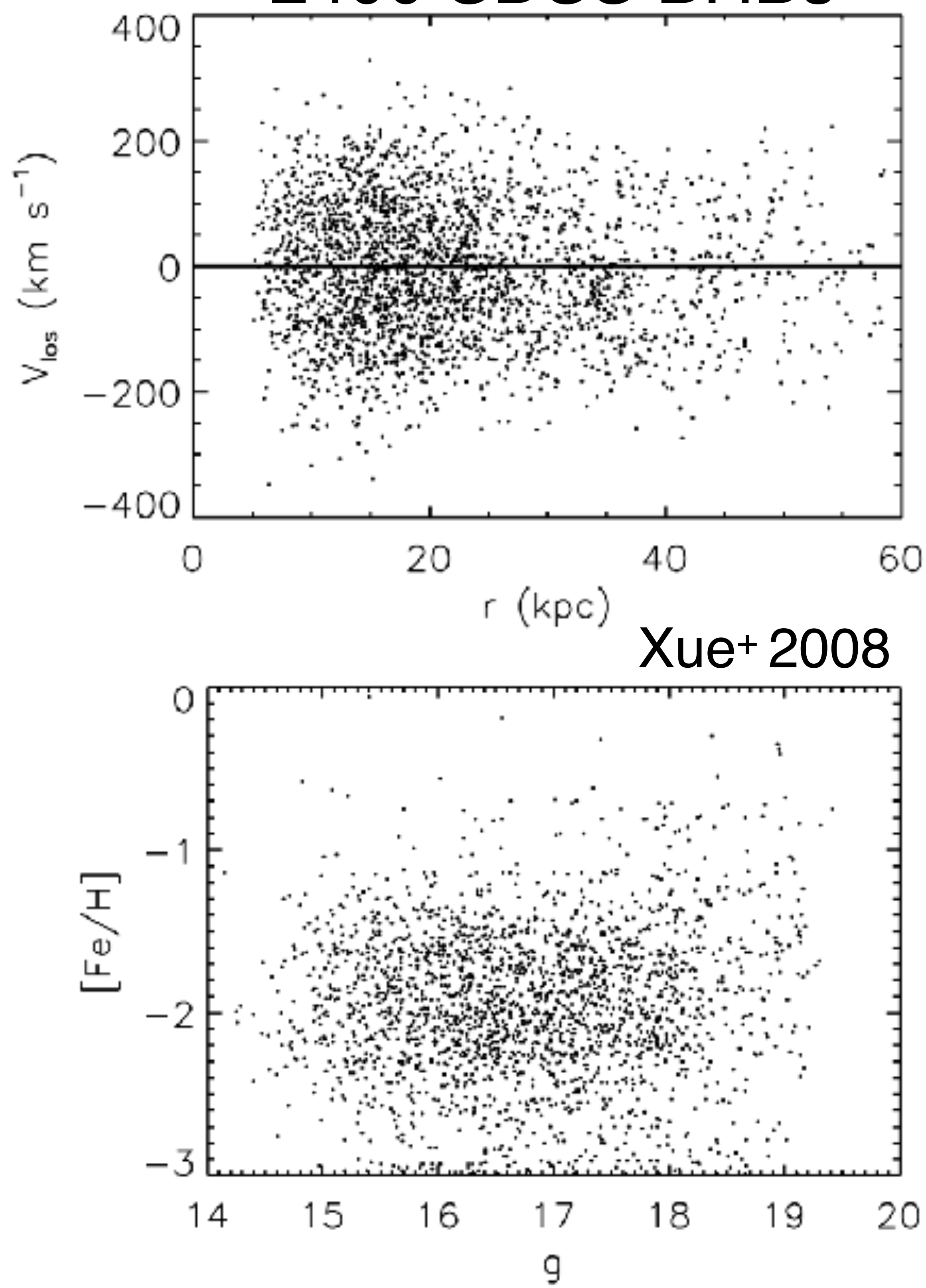

Xue+ 2008

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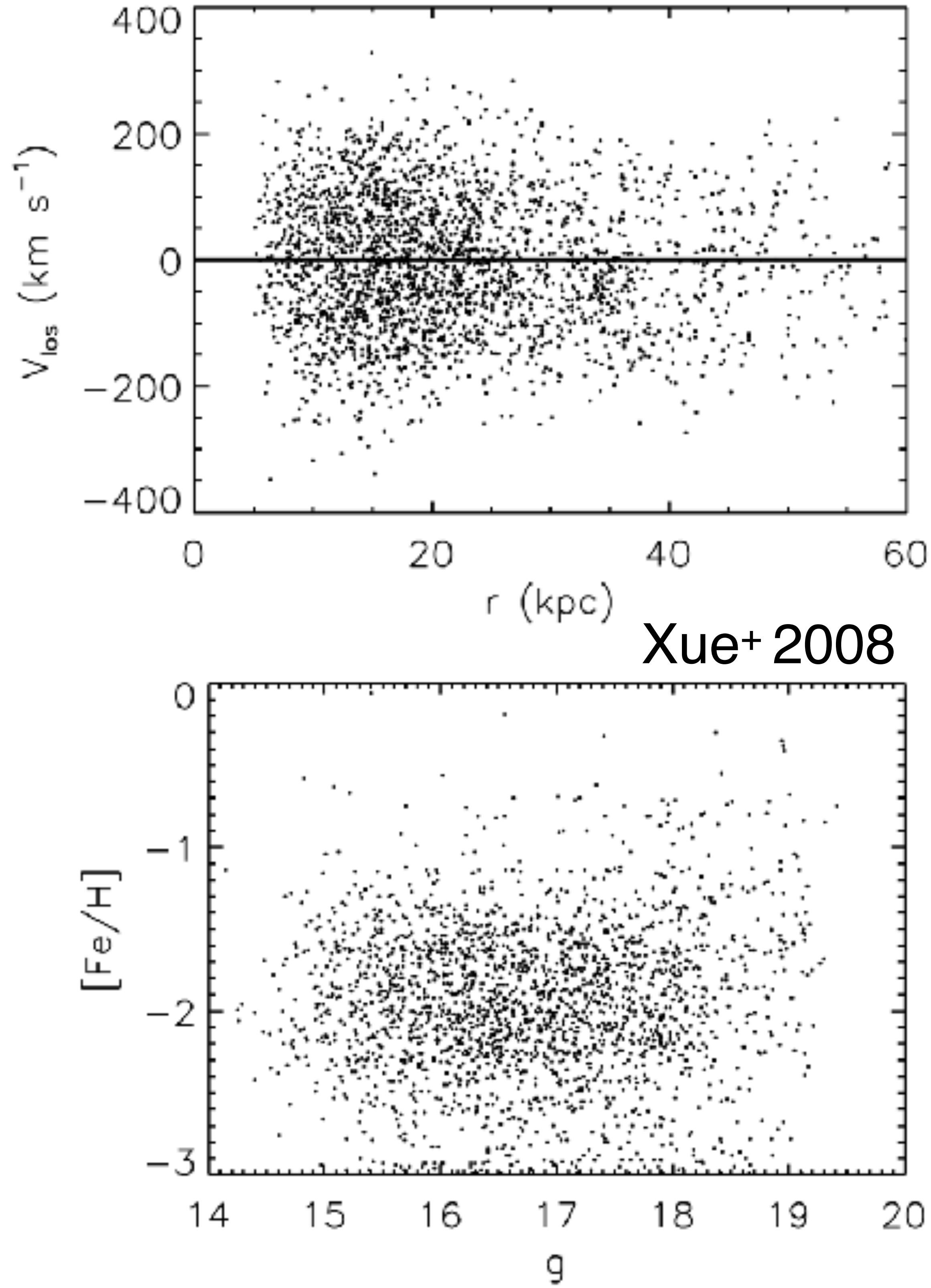

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Method 1:

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$$-\frac{r}{\rho}\frac{d(\sigma_r^2\rho)}{dr} - 2\beta\sigma_r^2 = V_{\mathrm{cir}}^2(r).$$

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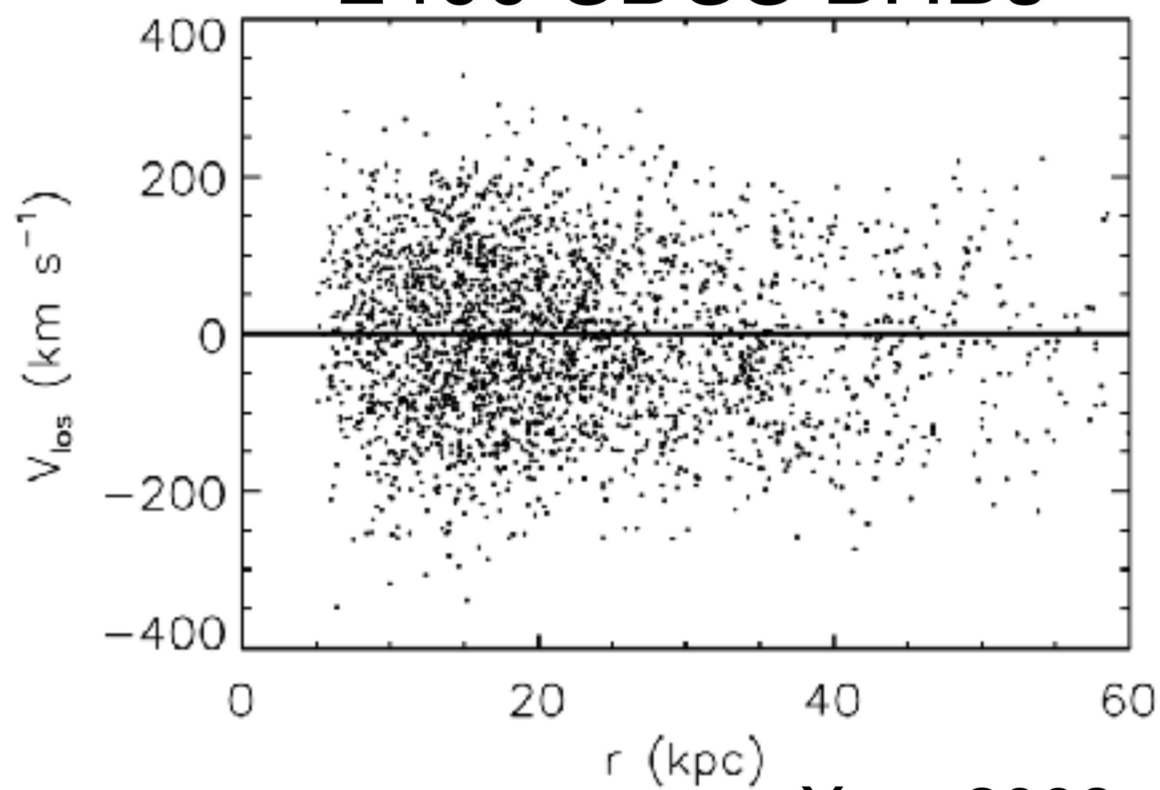

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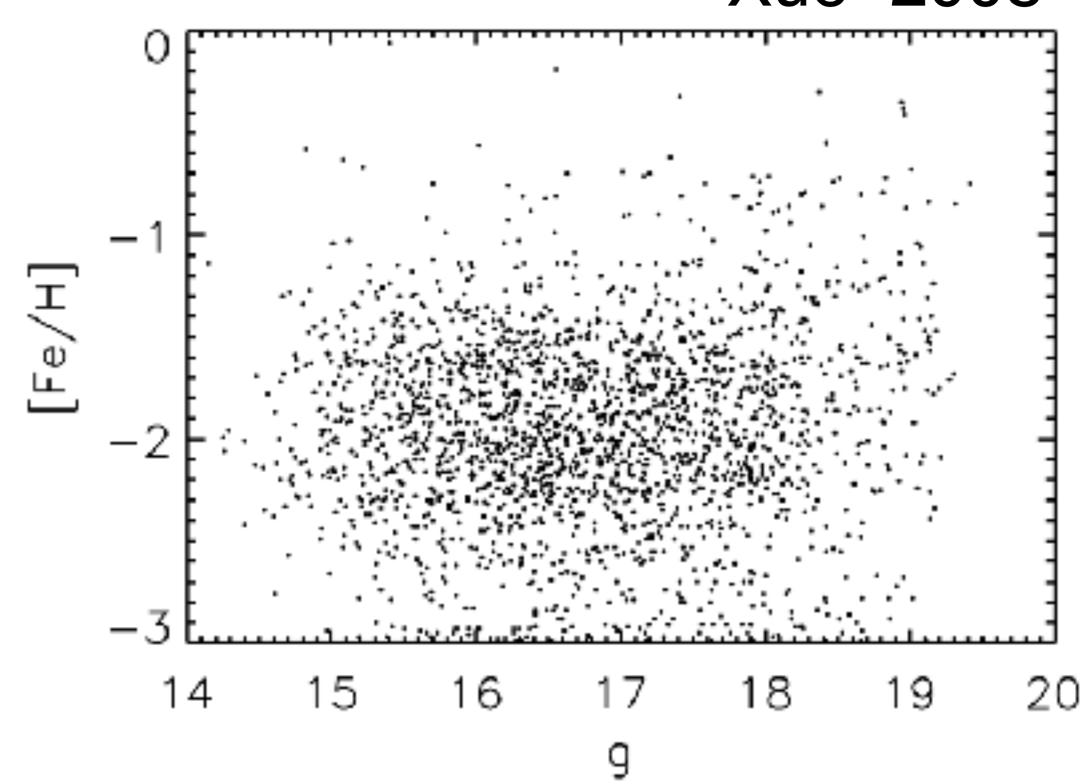

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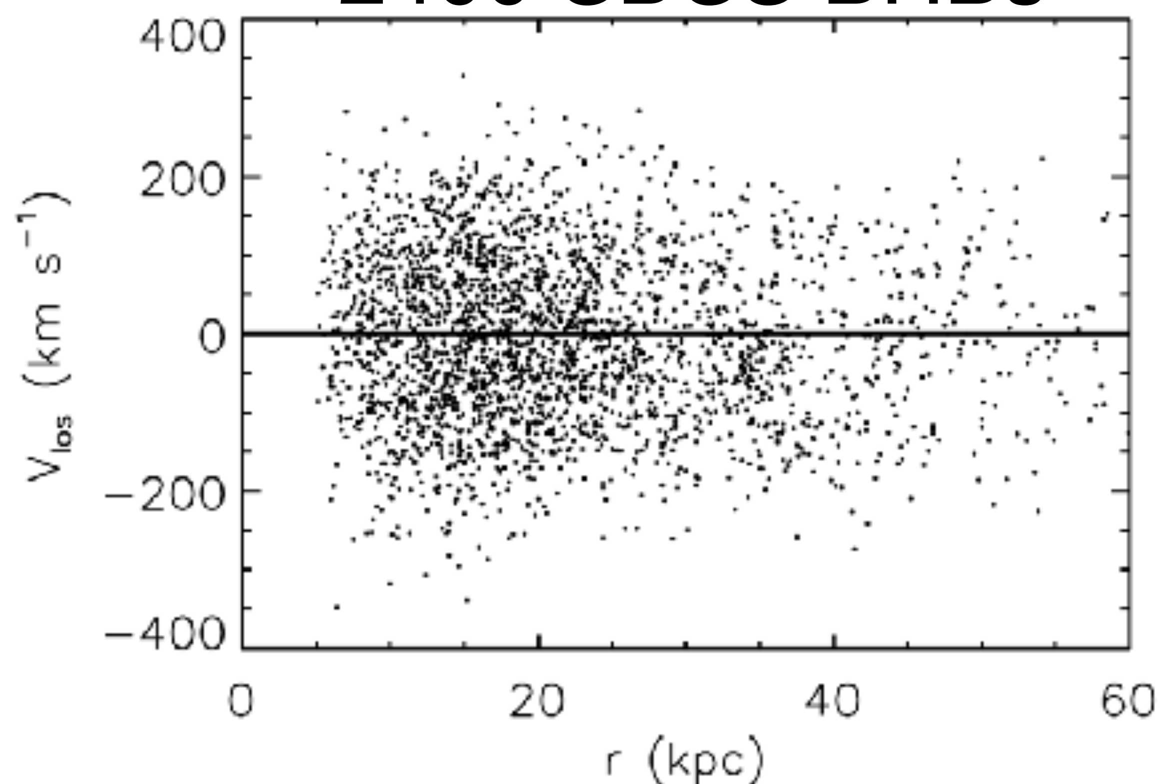

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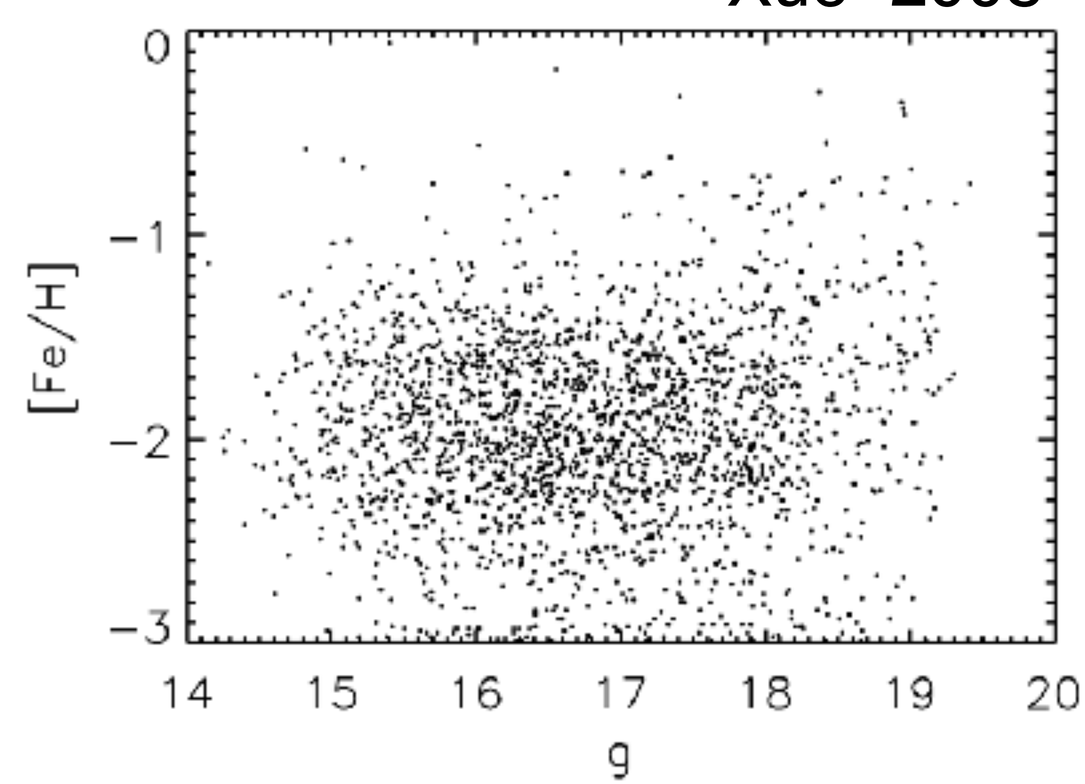

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$$-\frac{r}{\rho}\frac{d(\sigma_r^2\rho)}{dr} - 2\beta\sigma_r^2 = V_{cir}^2(r),$$

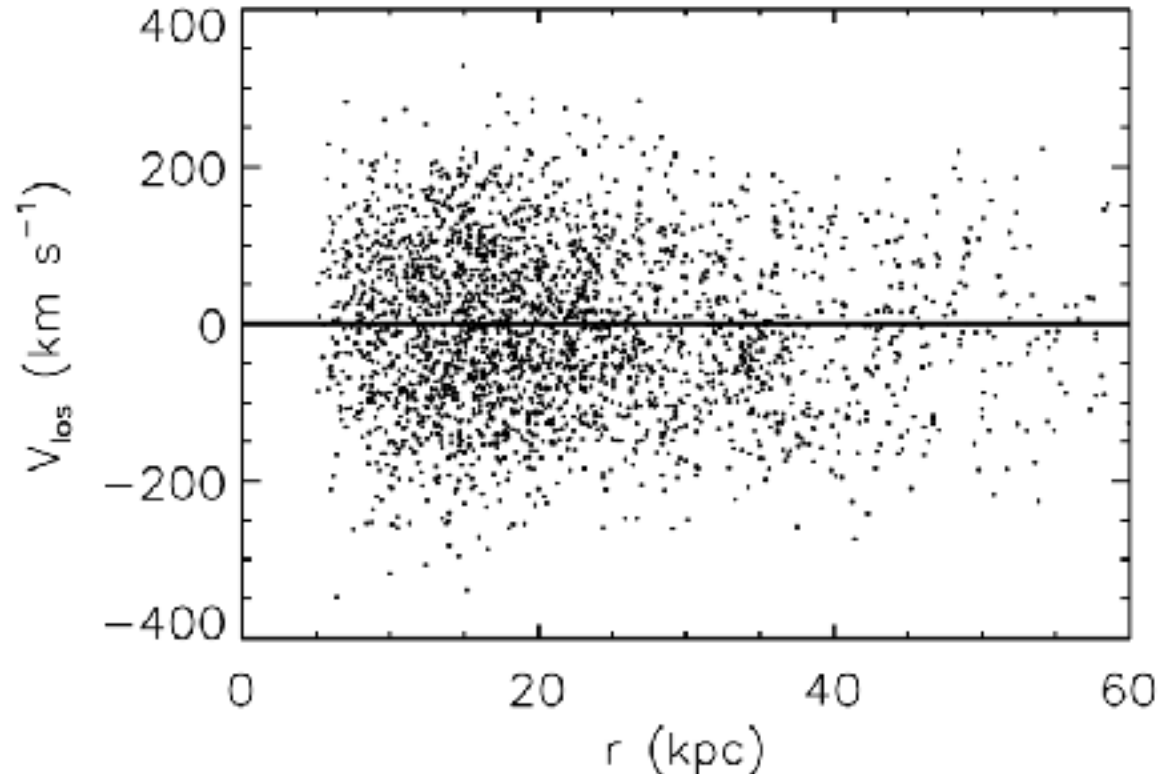
Method 2:

- Compare to kinematics in simulated halos that have been scaled to different halo mass

  $P(V_{los}/V_{cir}, obs) = P(V_{los}/V_{cir}, sim)$

- Fit $V_{cir}(r)$ to the NFW DM halo+ Hernquist bulge+ exponential disk

2400 SDSS BHBs



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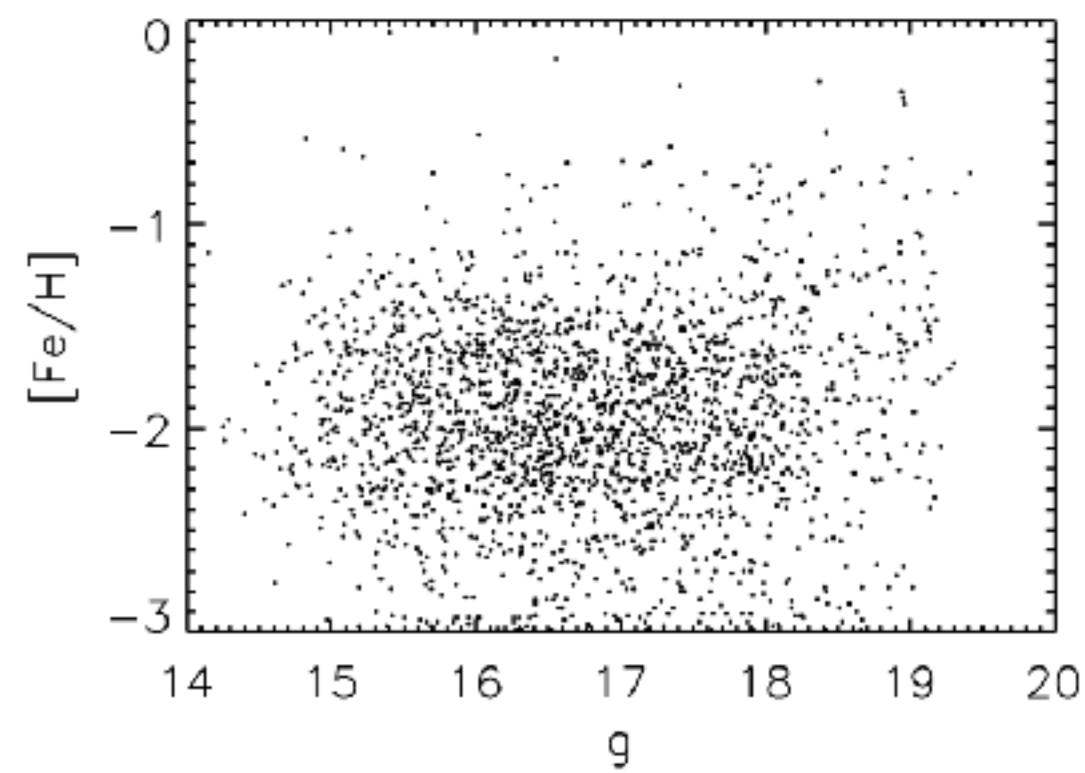


Mass estimate based on BHBs

- Robust measurement (2sims+Jeans Eq.)

  $M\ (r<60\ \text{kpc}) = 4.0 \pm 0.7 \times 10^{11}\ M_\odot$

- $V_{circ}(R)$ is not constant but gently falling.

- If DM halo is NFW then

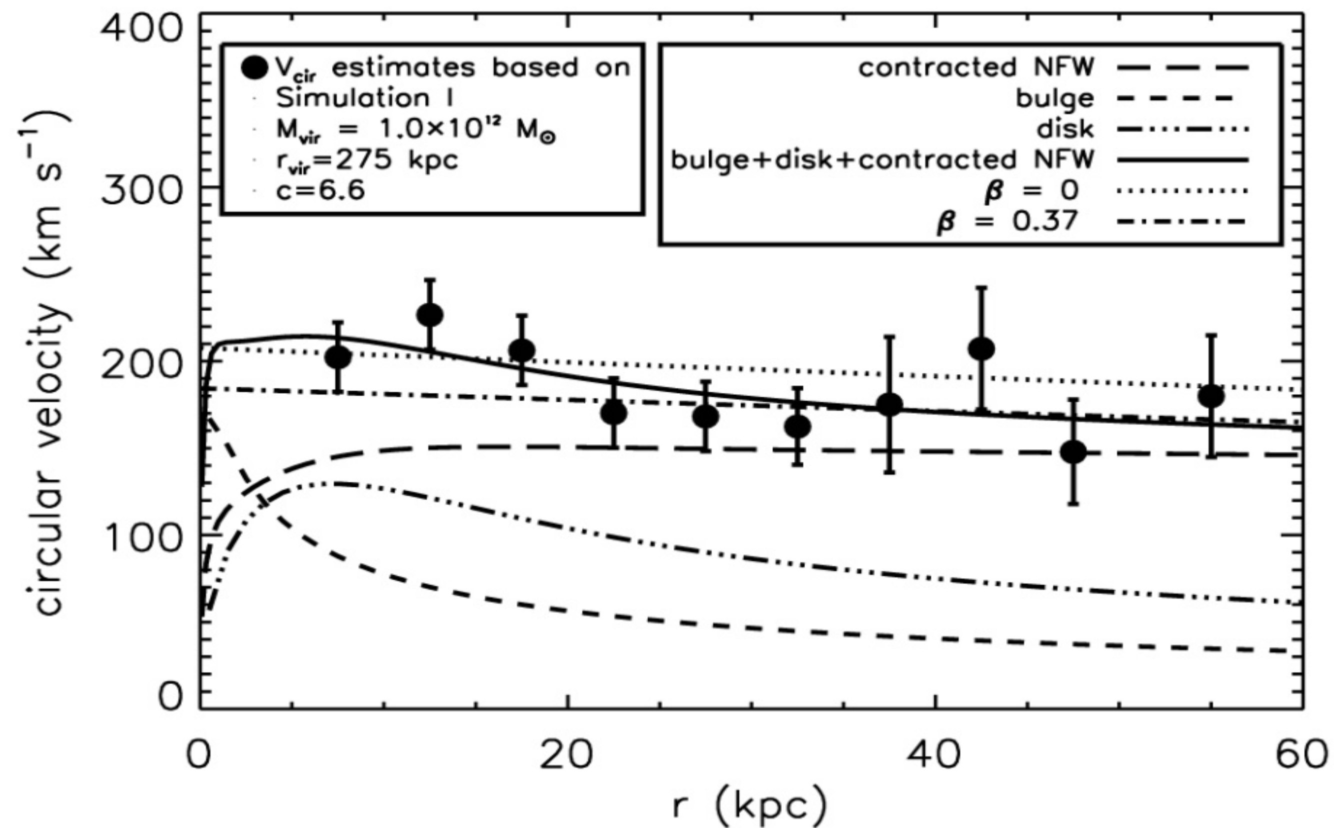
  $M_{340}\ (\sim 275\text{kpc}) = 1.0 \pm 0.3 \times 10^{12}\ M_\odot$ $(\Omega_m = 0.3)$

  consistent with previous estimates,

  but more precise!

- Imply (high) 40% of baryons end up as stars

- LMC and other satellites marginally bound



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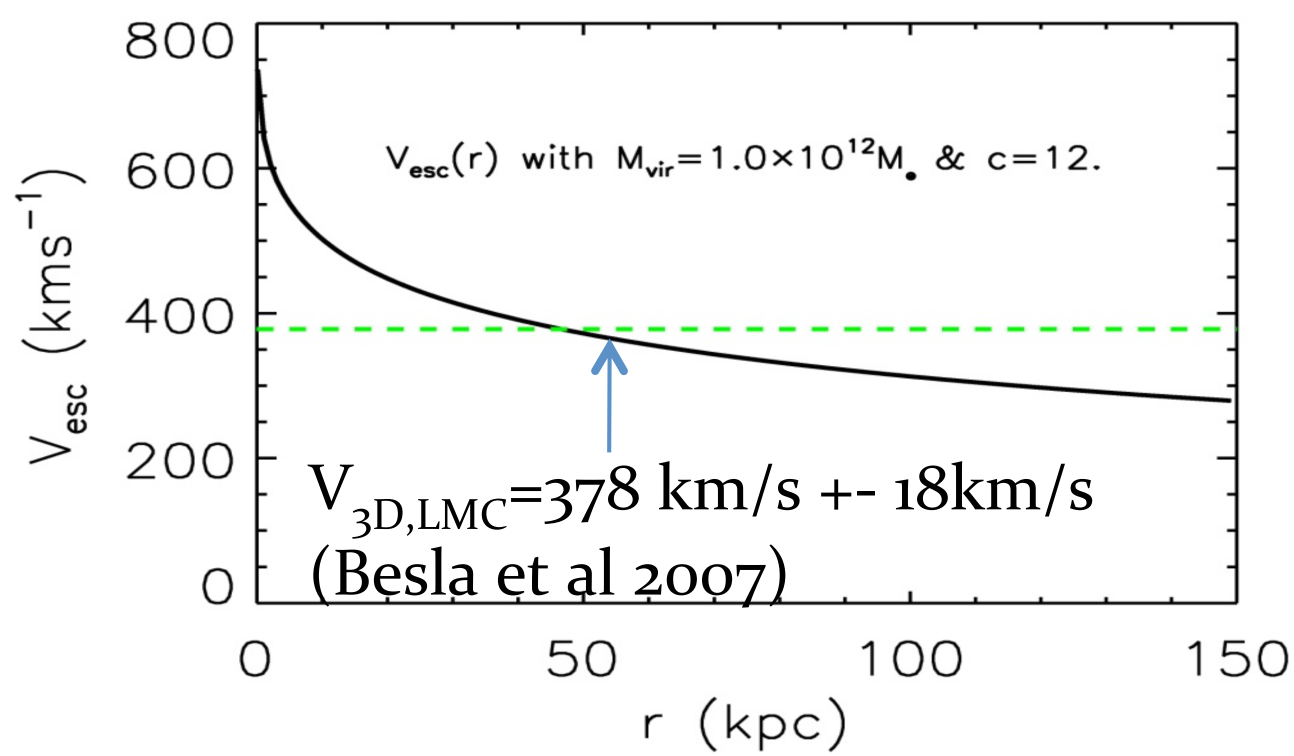
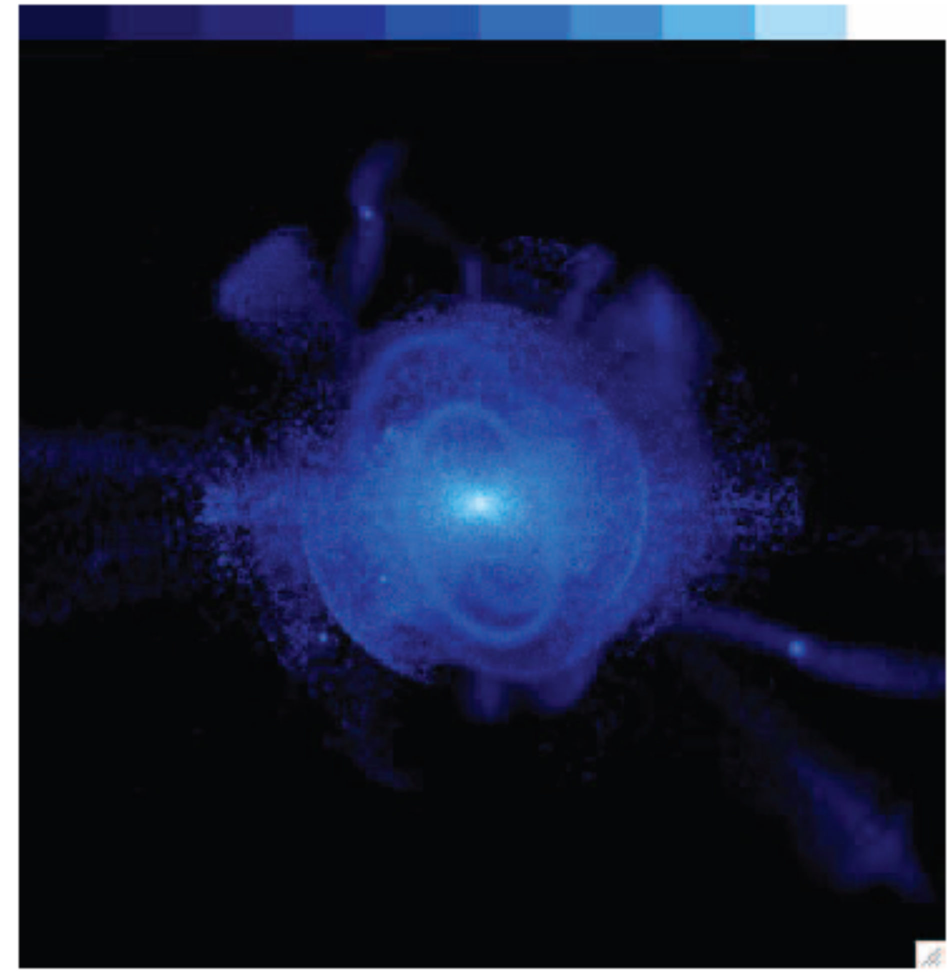


Quantifying the kinematic substructure in BHB sample



“External galaxy” view Bullock & Johnston 2005

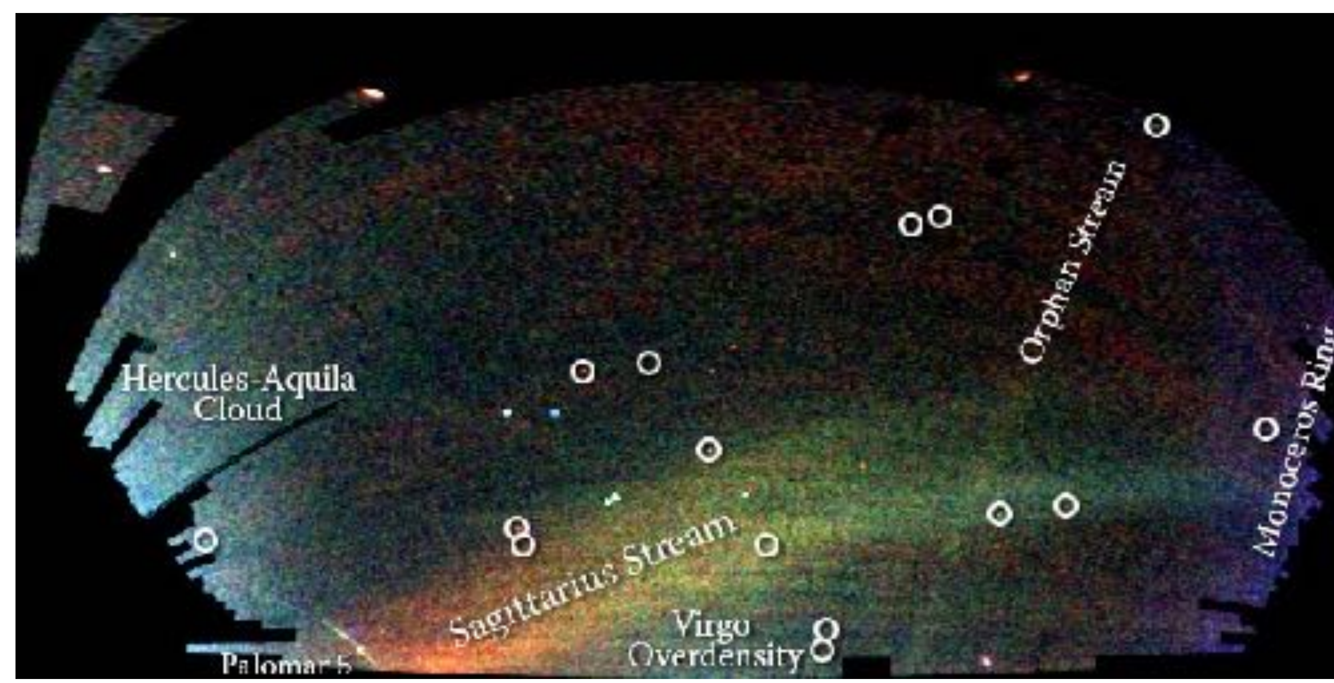
➡ ΛCDM model predicts the Galactic stellar halo should contain fossil record of assembly.

➡ Some direct observed evidences have been found.

But,

what do they actually tell us about how our Galaxy formed ?

--> Require an analysis of substructures in the position–velocity(-abundance) space.



Credit: V. Belokurov and the Sloan Digital Sky Survey

How to quantify the kinematic substructure?

- Statistic: 4-distance

The distance between two stars in 4-dimension space (α,δ,d,vlos) (Starkenburg+ 2009)

$$F = w_{\theta}\theta^2 + w_{\Delta d}(\Delta d)^2 + w_{\Delta Vlos}(\Delta V_{los})^2$$

The best statistical quantification of position-velocity substructure in the Galactic halo

- Construct *null-hypotheses* by drawing random d and v independently
- Compare to smooth model to quantify the substructure

Substructure in BHBs:

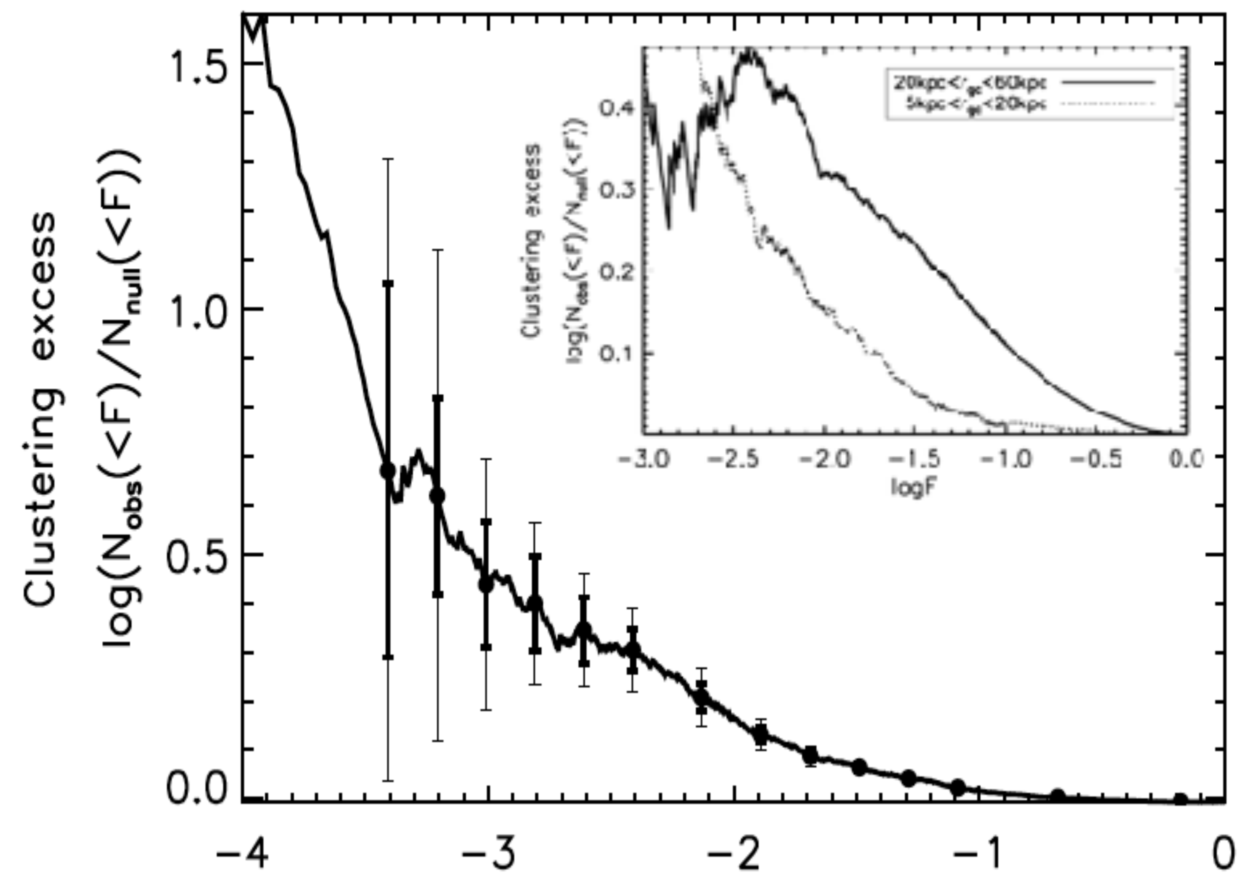
- We found very clear signal for position-velocity substructure in BHB sample for the first time.
- The outer halo exhibits a stronger kinematic substructure signal than the inner halo.
- Quantitatively, most simulations produce a stronger substructure signal.

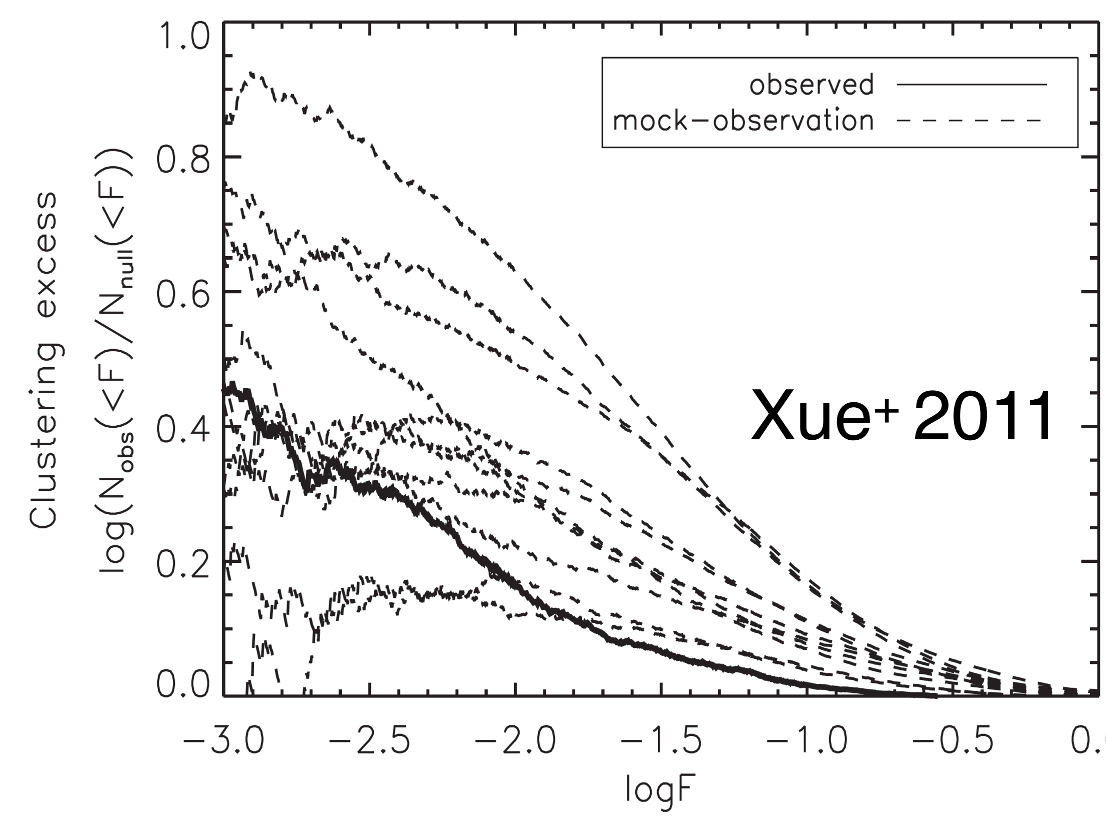
BHB stars are overrepresented in the oldest sub-populations of the stellar halo.

turn to K giants !!

more representative!

$$F = w_\theta \theta^2 + w_{\Delta d}(\Delta d)^2 + w_{\Delta V los}(\Delta V_{los})^2$$





Our work based on more representative halo tracers: K giants

Why are K giants?

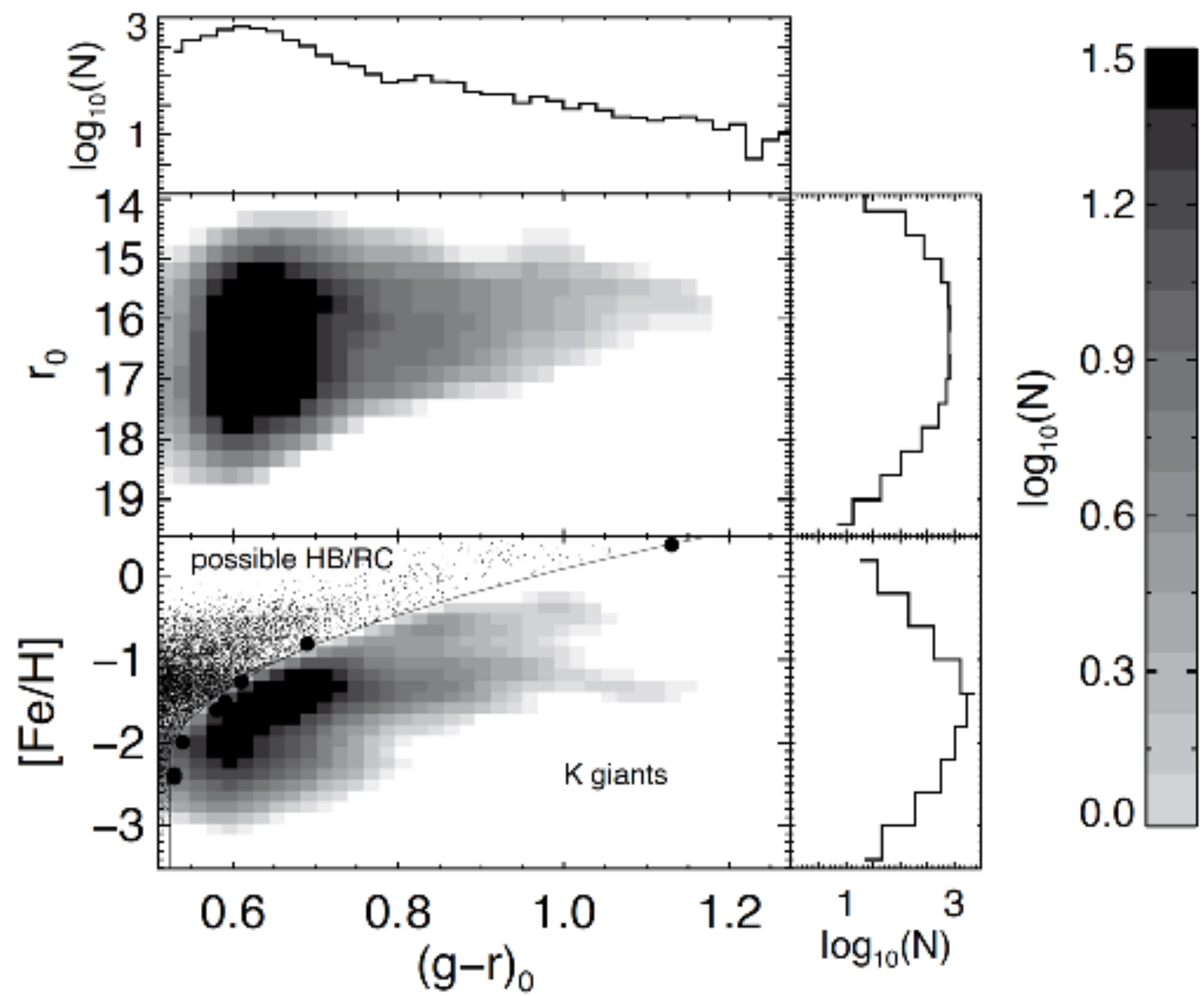
K-giant stars

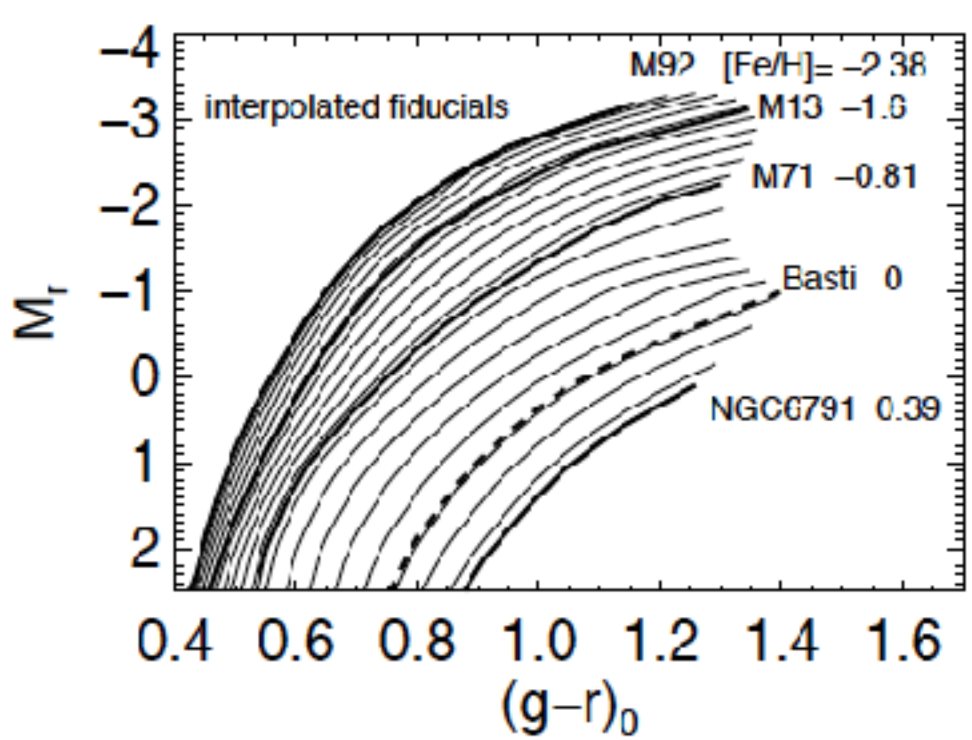
- are luminous to visible to >100kpc
- have well-defined n_{tracer}/M_*
- are more representative than BHB

—>> SEGUE K-giant stars

- but -3<Mr<1
- How to get good distances?

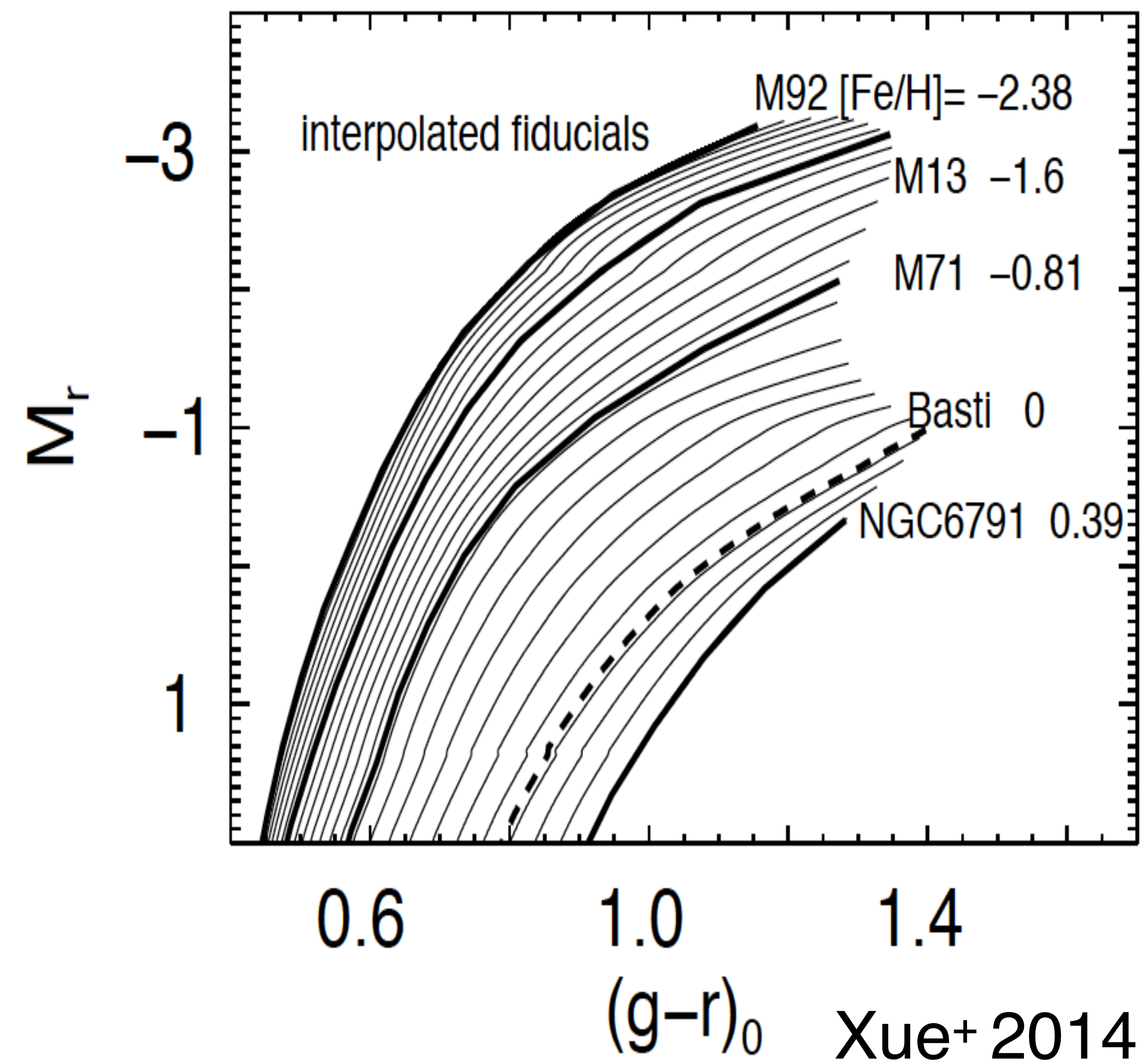
SEGUE K giants





Xue+ 2014

How to get good distances for giants?



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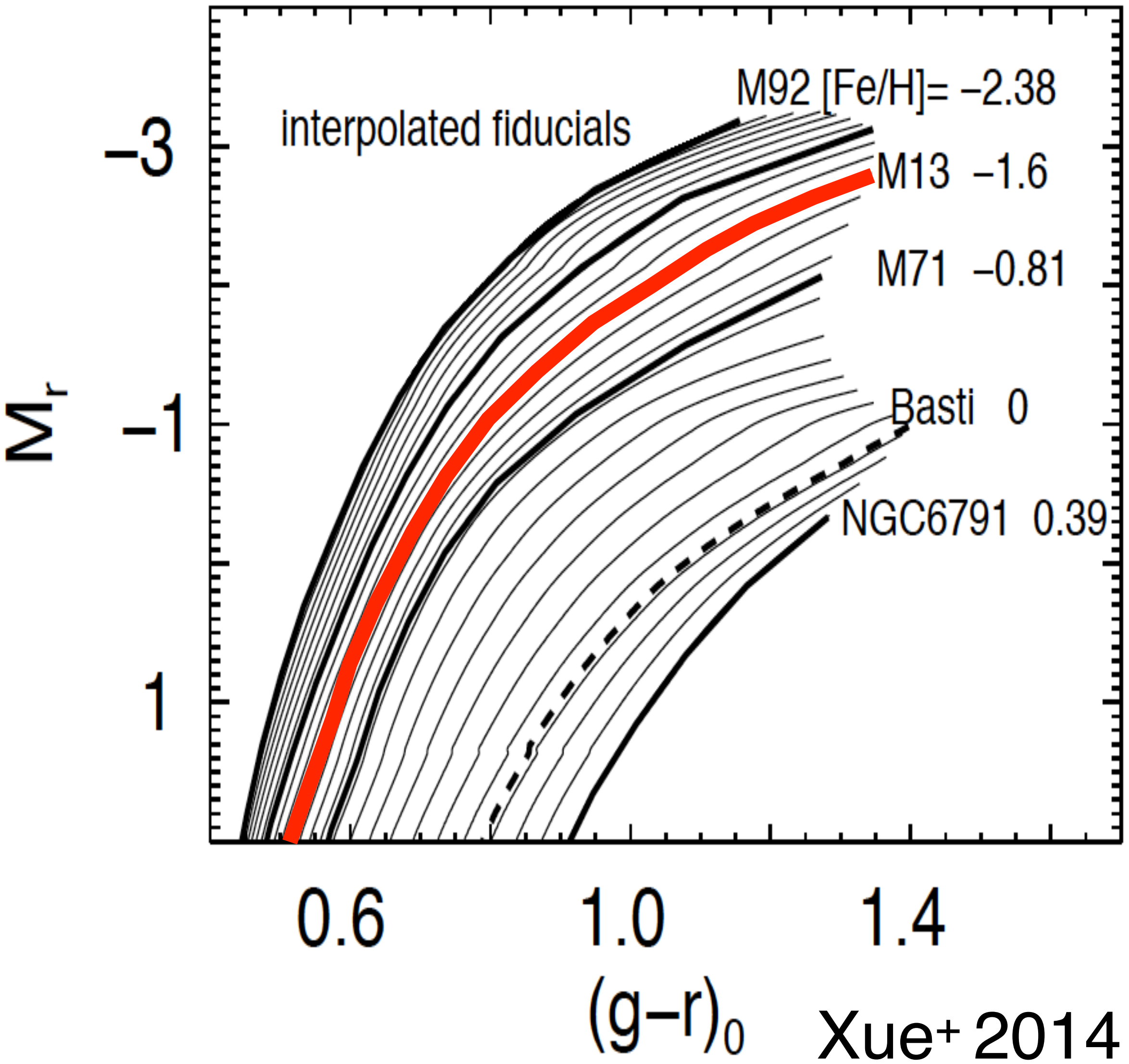
How to get good distances for giants?

- [Fe/H] from SEGUE spectra



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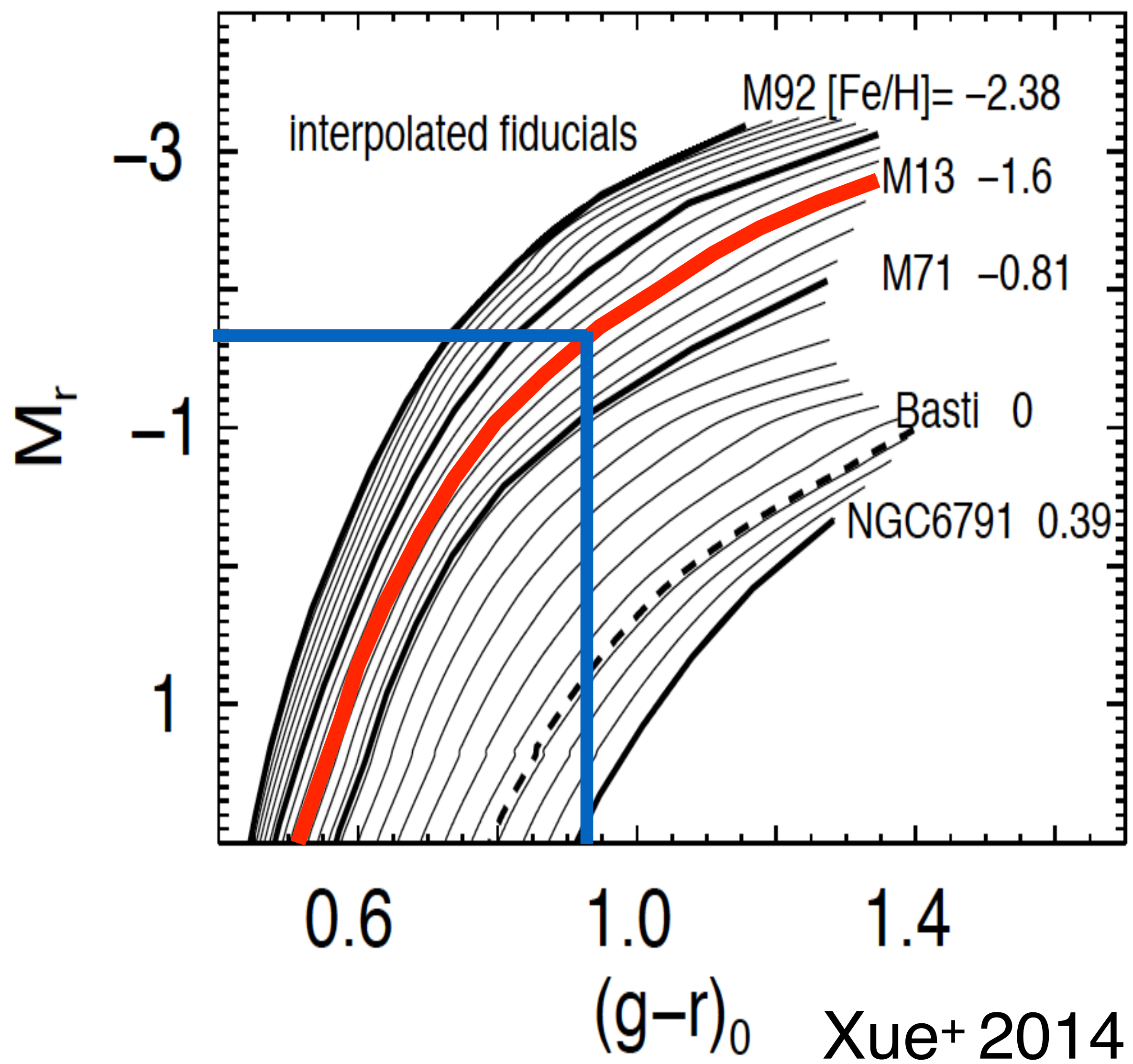
How to get good distances for giants?

- [Fe/H] from SEGUE spectra
- (g-r) from SDSS photometry
- DM = m_r-M_r(g-r, [Fe/H])



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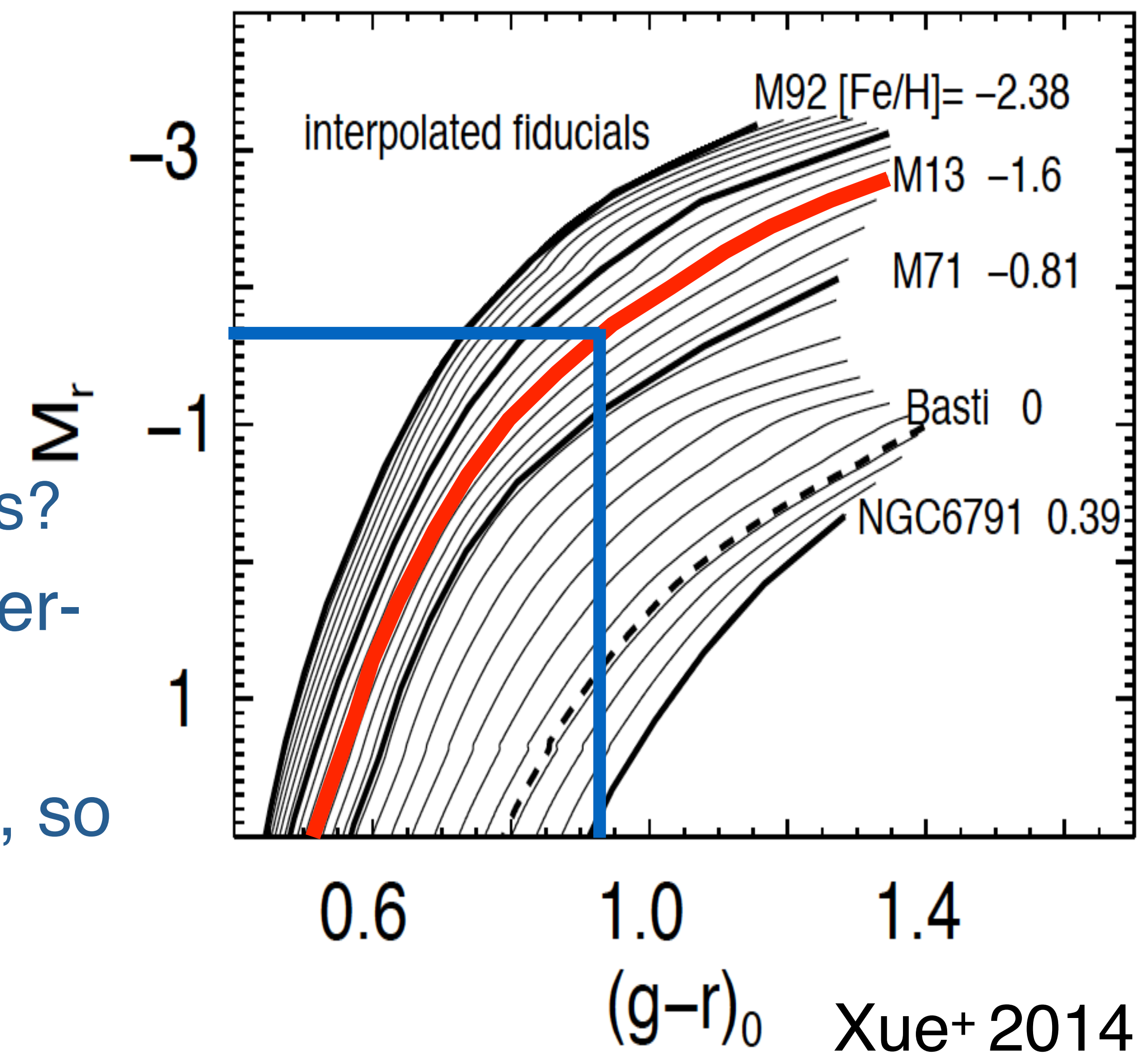

Xue+ 2014

But!!!

- How to incorporate [Fe/H] and g-r errors?
- p(L)~L^{-2}: flat p(L) is more likely to over-estimate L, so over-estimate DM
- Very high/low [Fe/H] values are rare, so cause systematic errors.

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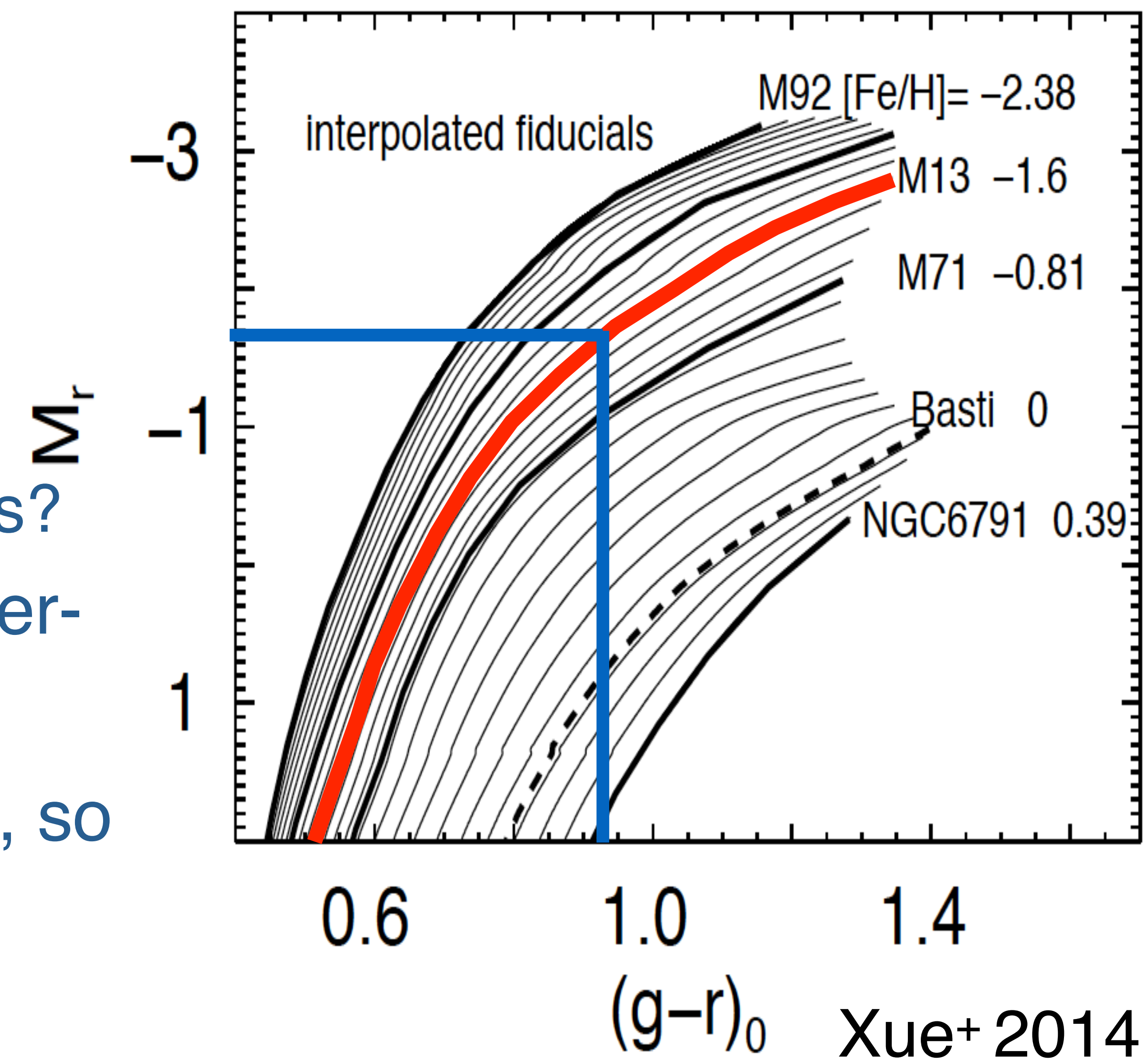

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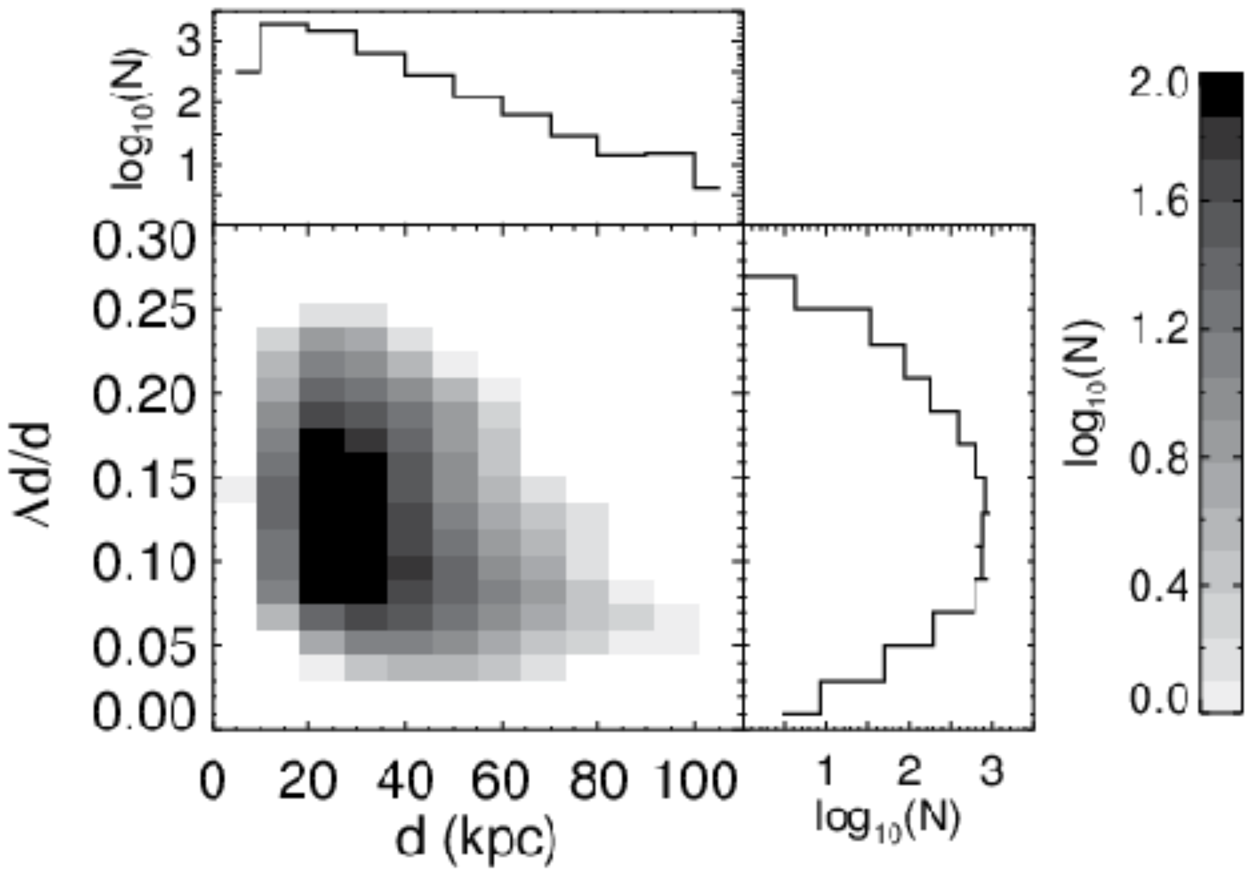
Bayesian approach

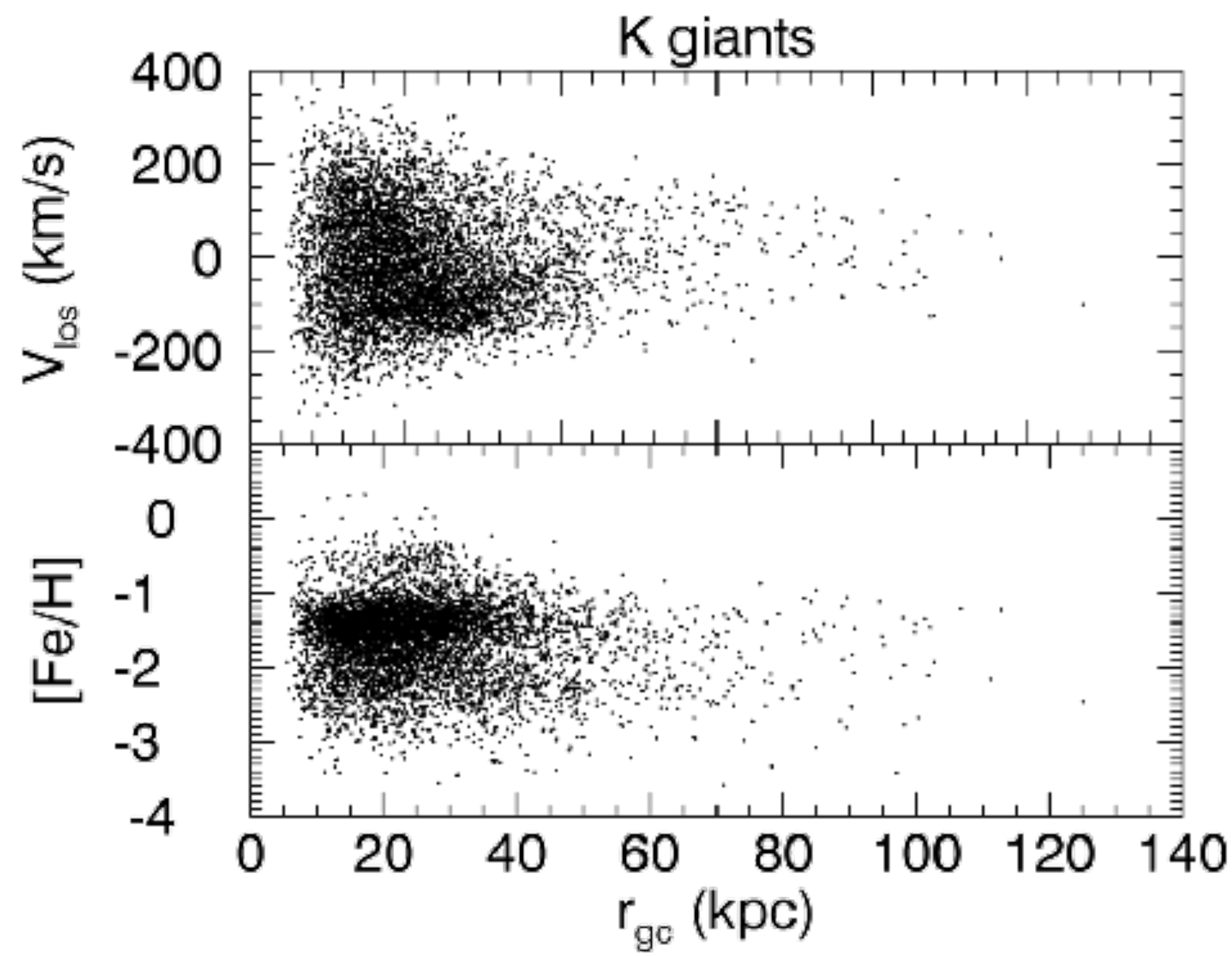
$$\mathscr{L}(\mathcal{DM}) = \int\int p(\{m, c, [Fe/H]\} \mid \mathcal{DM}, M, [Fe/H]) p_{prior}(M) p_{prior}([Fe/H]) dM d[Fe/H]$$

observables
with Gaussian errors

priors

SEGUE K giants



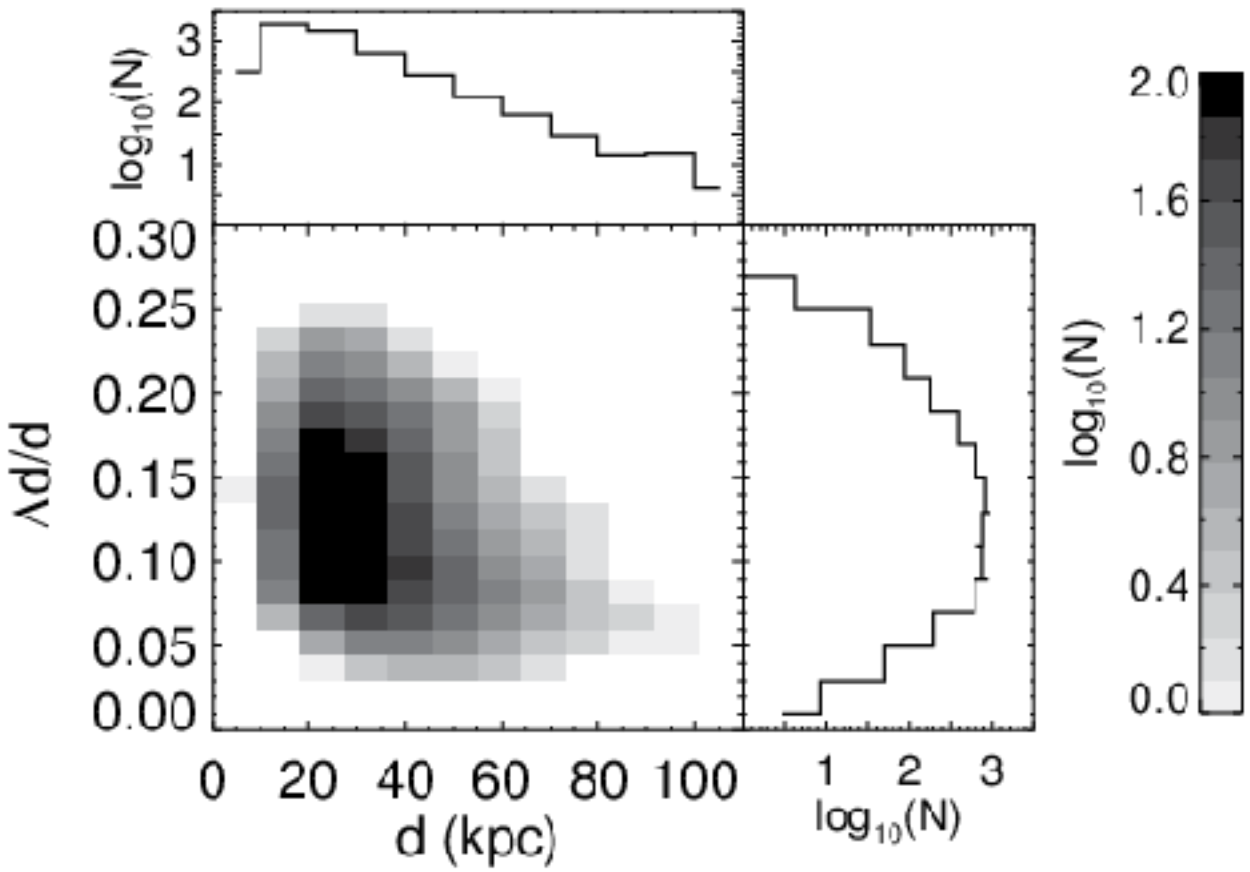


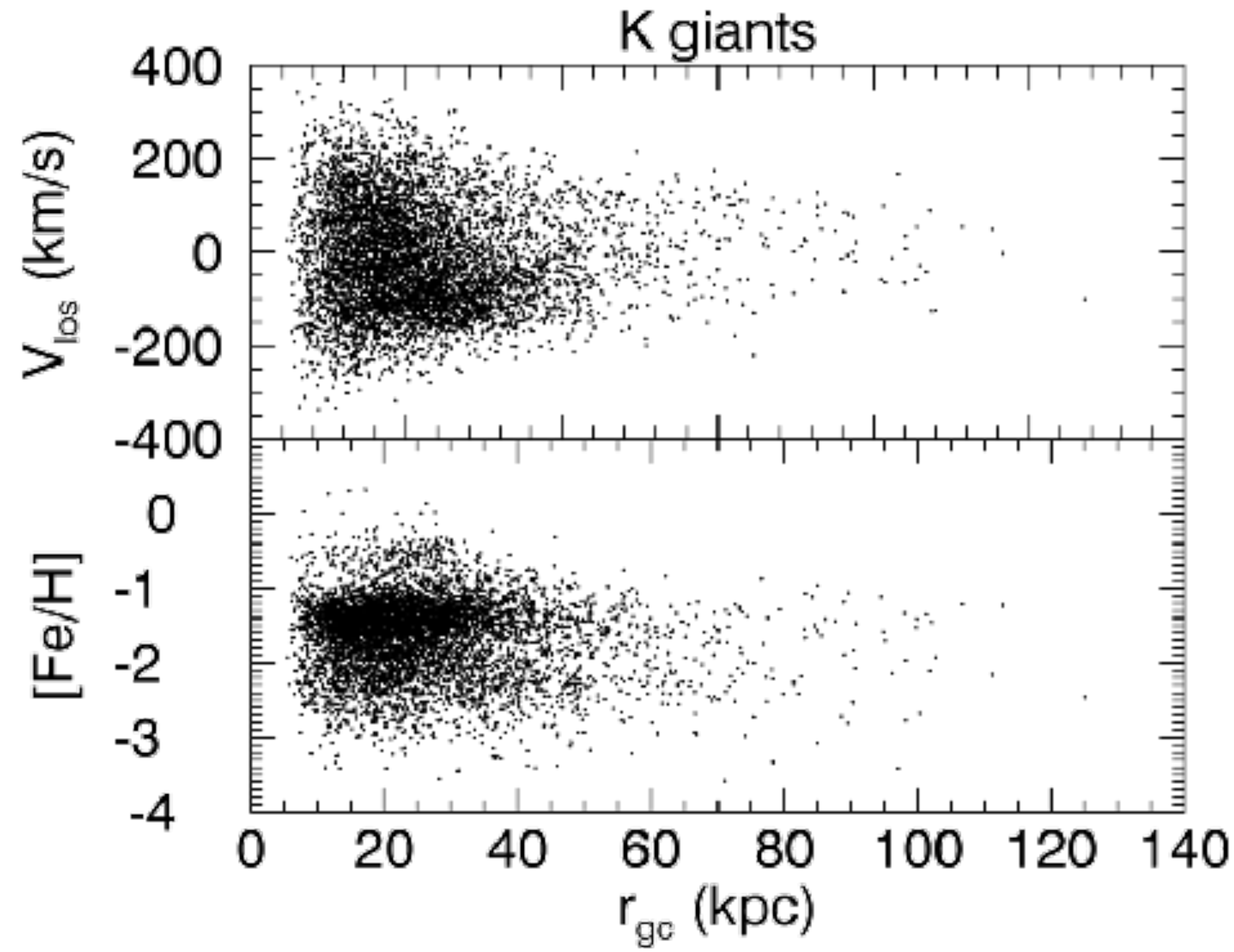
Xue+ 2014

6306 K giants with distances

- good to ~16%
- Distances are most precise at ~100kpc
  - tip of the giant branch
- 283 K giants with r>50kpc
  - previous samples: ~20

SEGUE K giants





6306 K giants with distances

- good to ~16%
- Distances are most precise at ~100kpc
  - tip of the giant branch
- 283 K giants with r>50kpc
  - previous samples: ~20

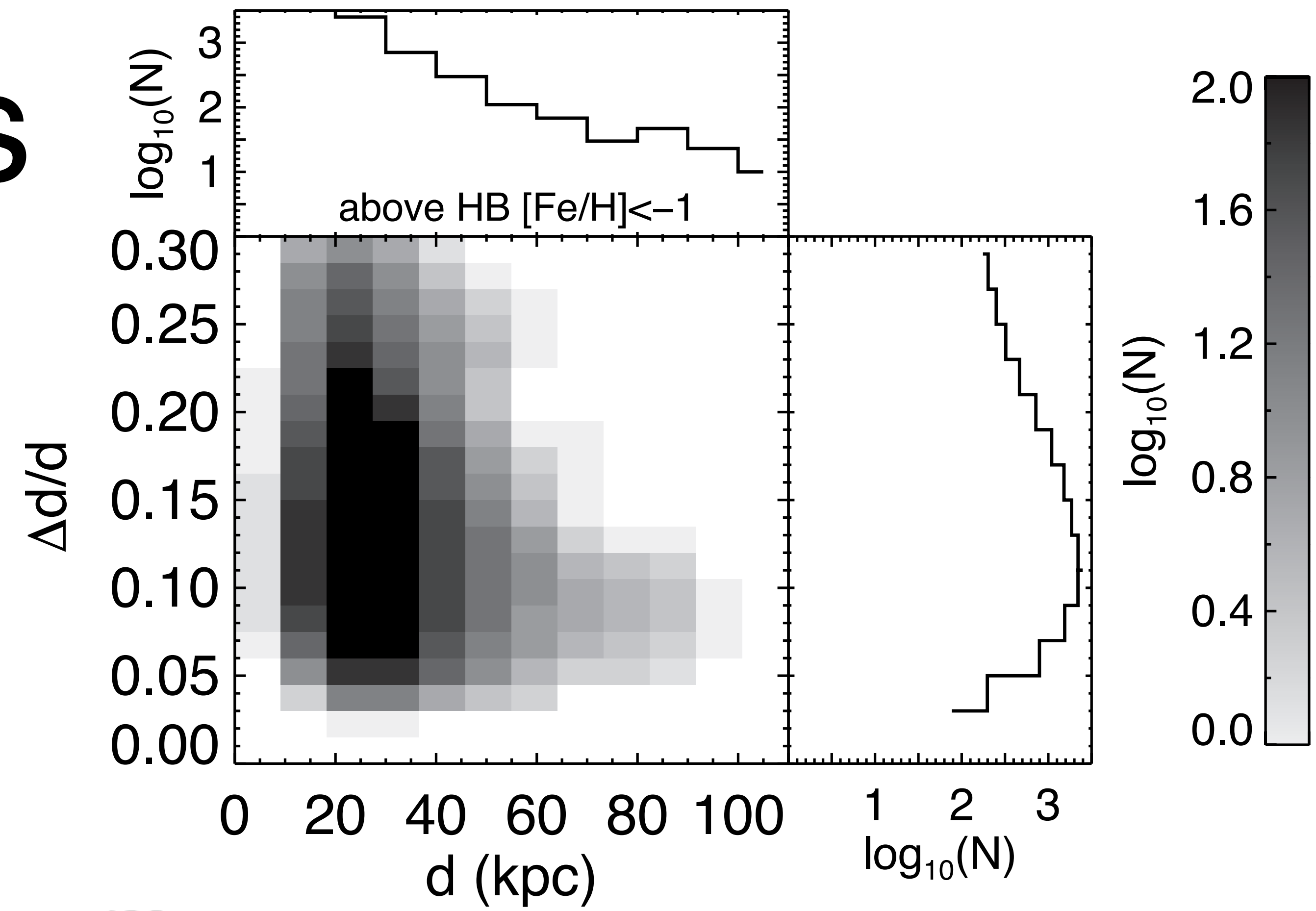
Xue+ 2014

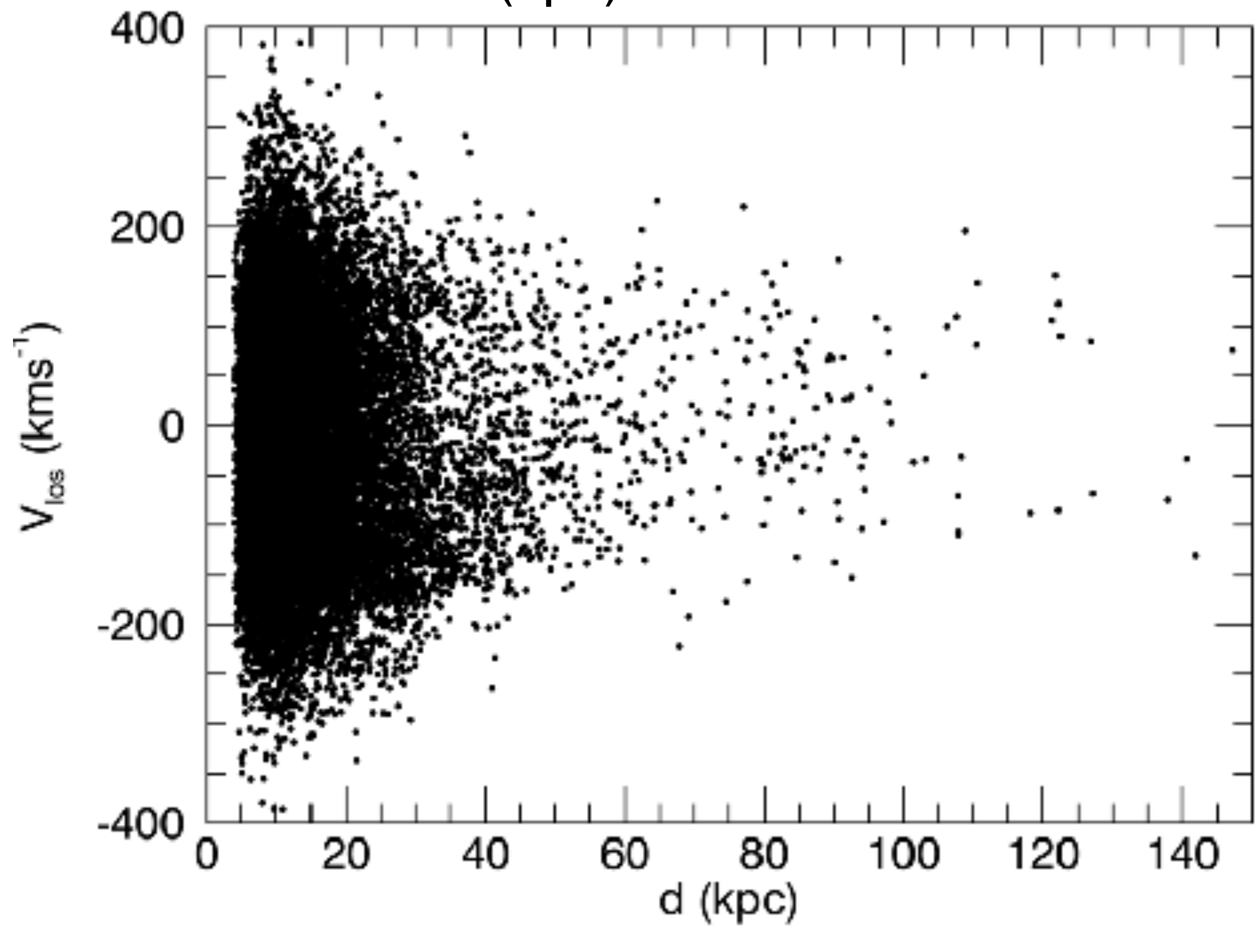
How about LAMOST K giants?

LAMOST K giants

15000 K giants with distances

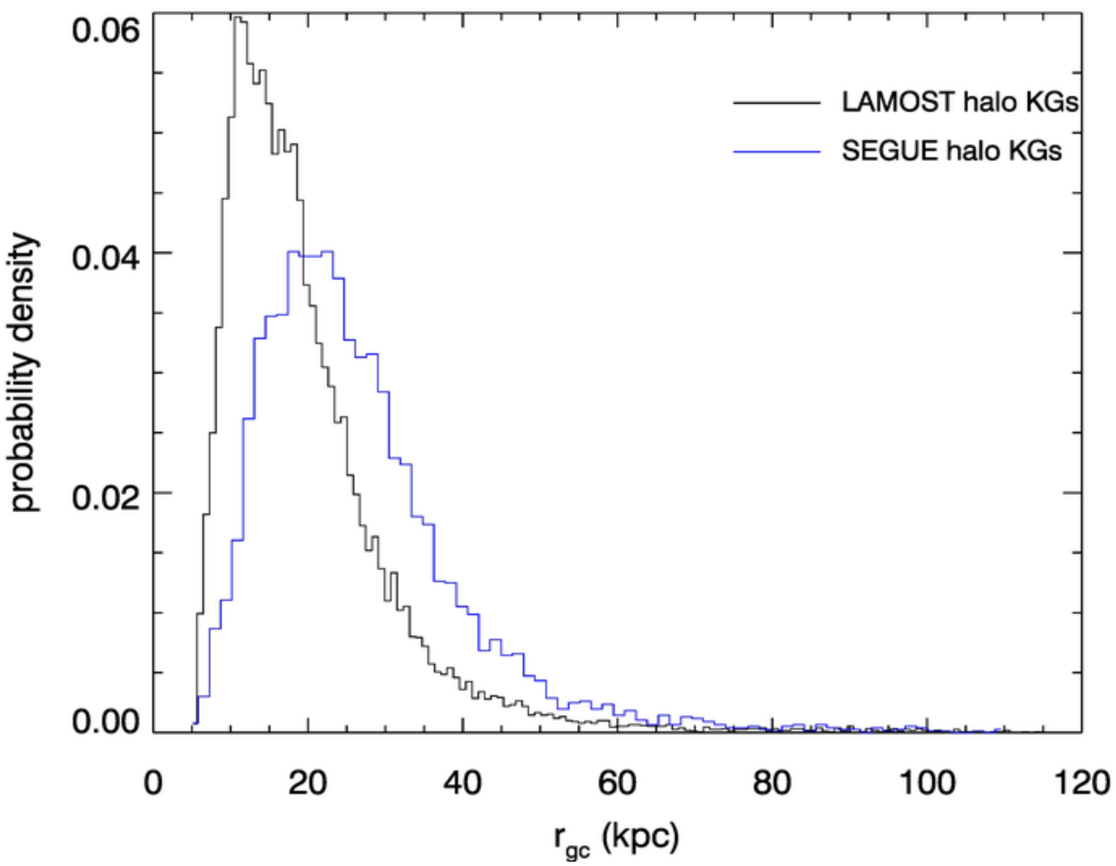
- Vs. SEGUE: ~5000 KG
- good to ~13%
- Distances are most precise at
  - tip of the giant branch
- 388 K giants with r>50kpc
  - Vs. SEGUE: 283

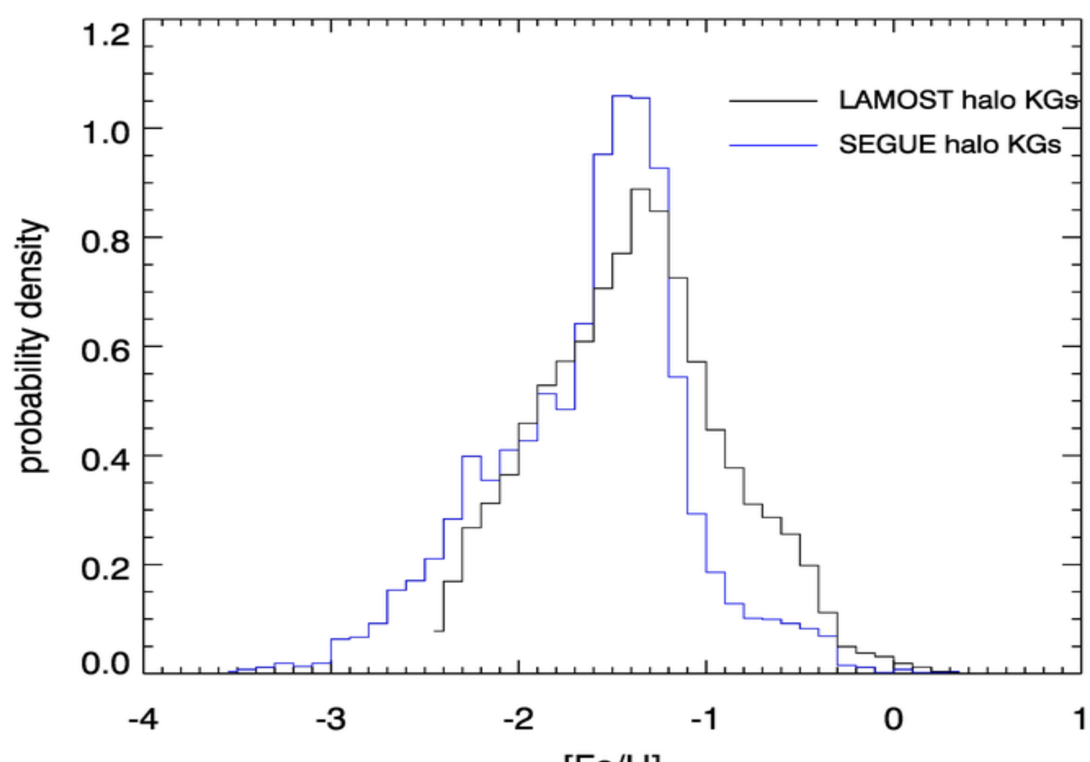


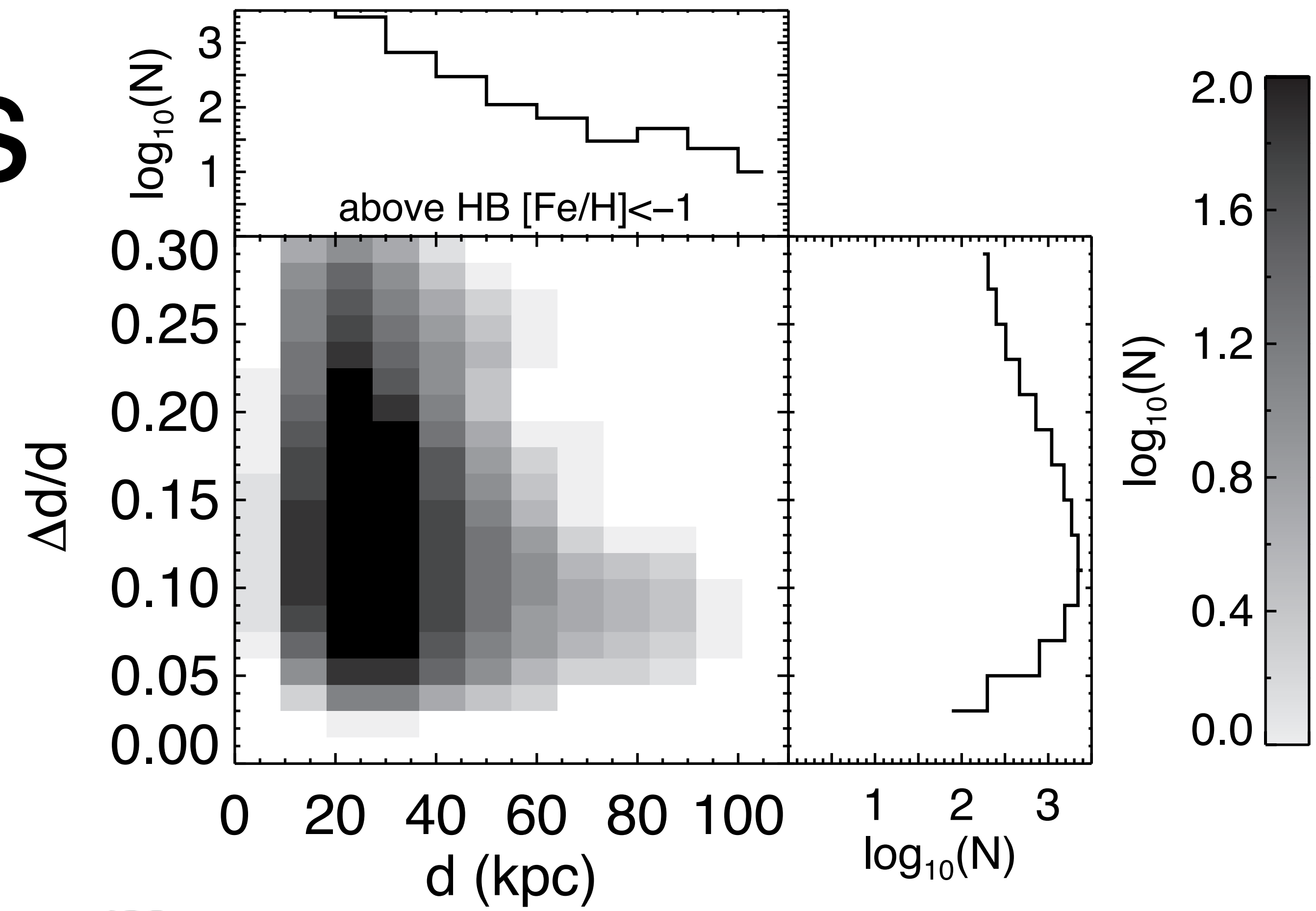


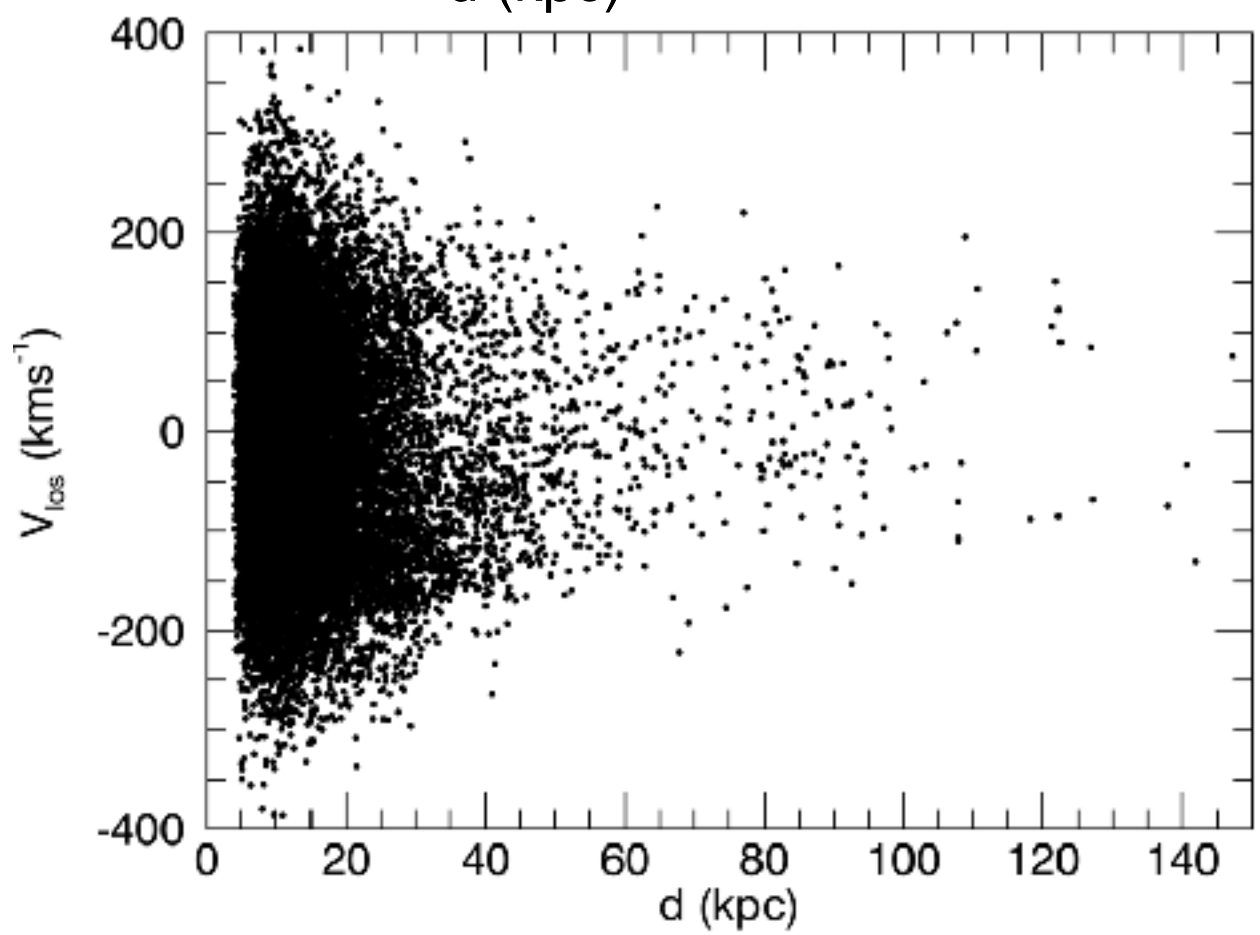
Xue+ to submit 2018

LAMOST K giants





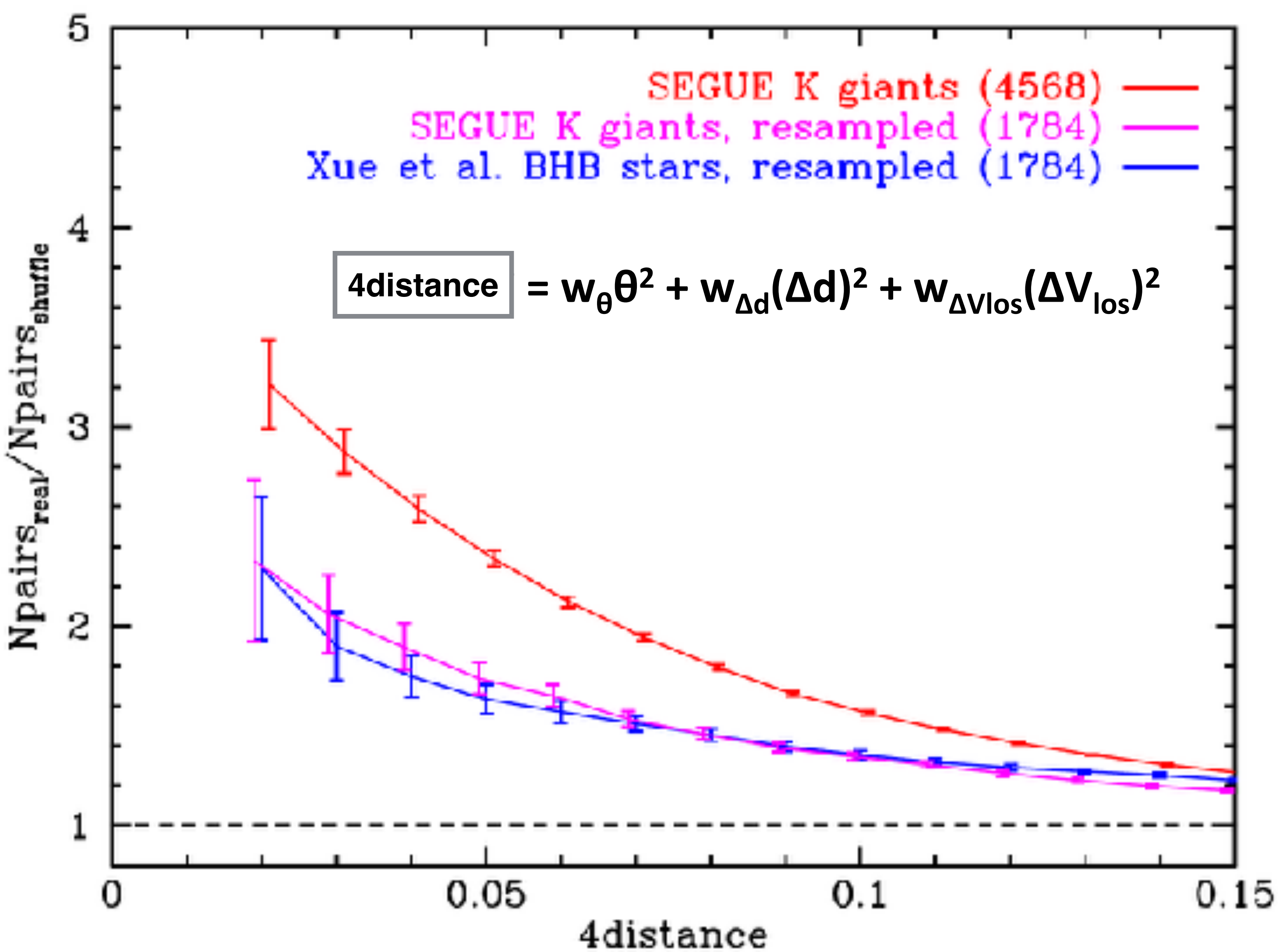


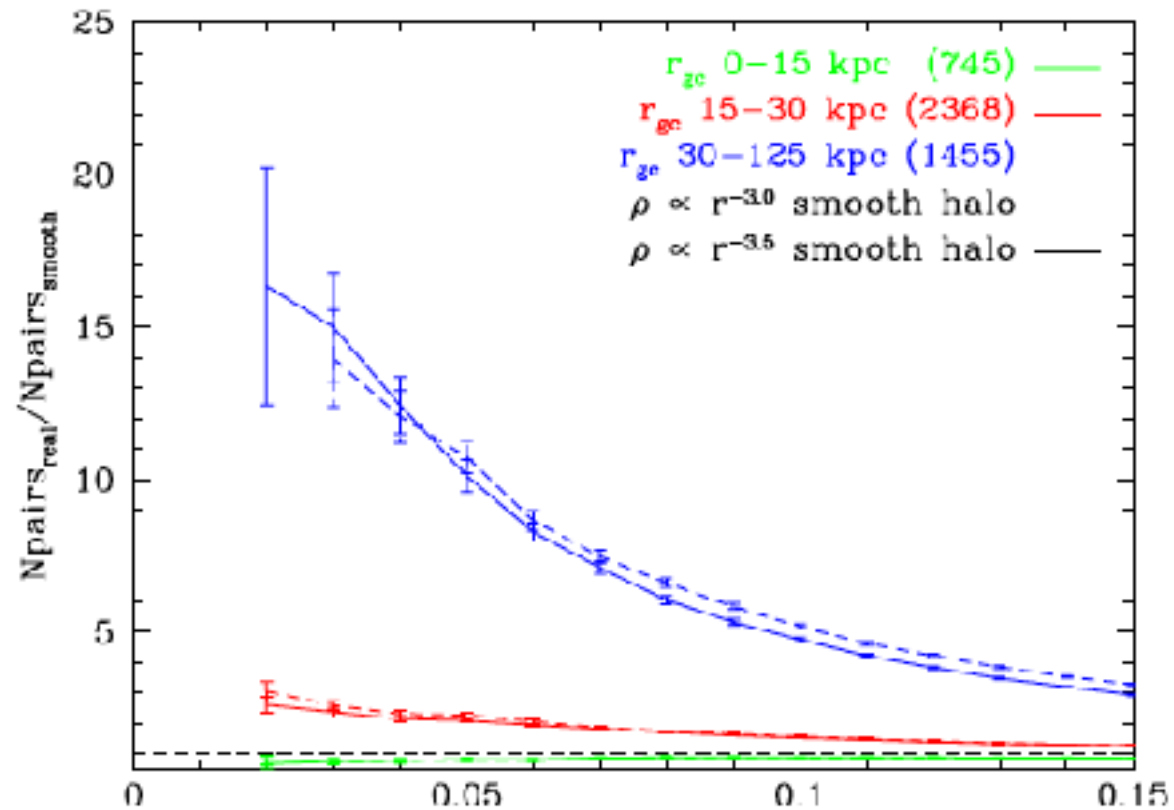


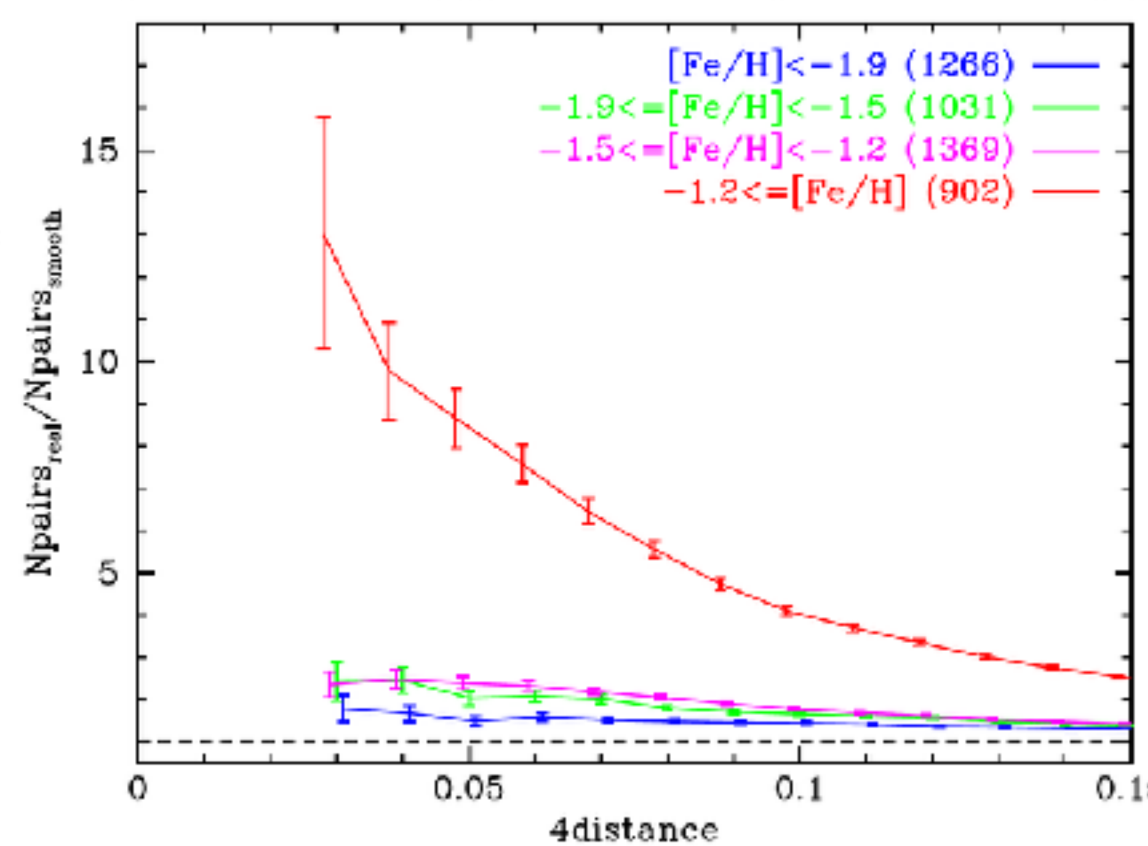
Xue+ to submit 2018

Does K-giant sample show stronger substructure than BHB sample?

Substructure in SEGUE K giants





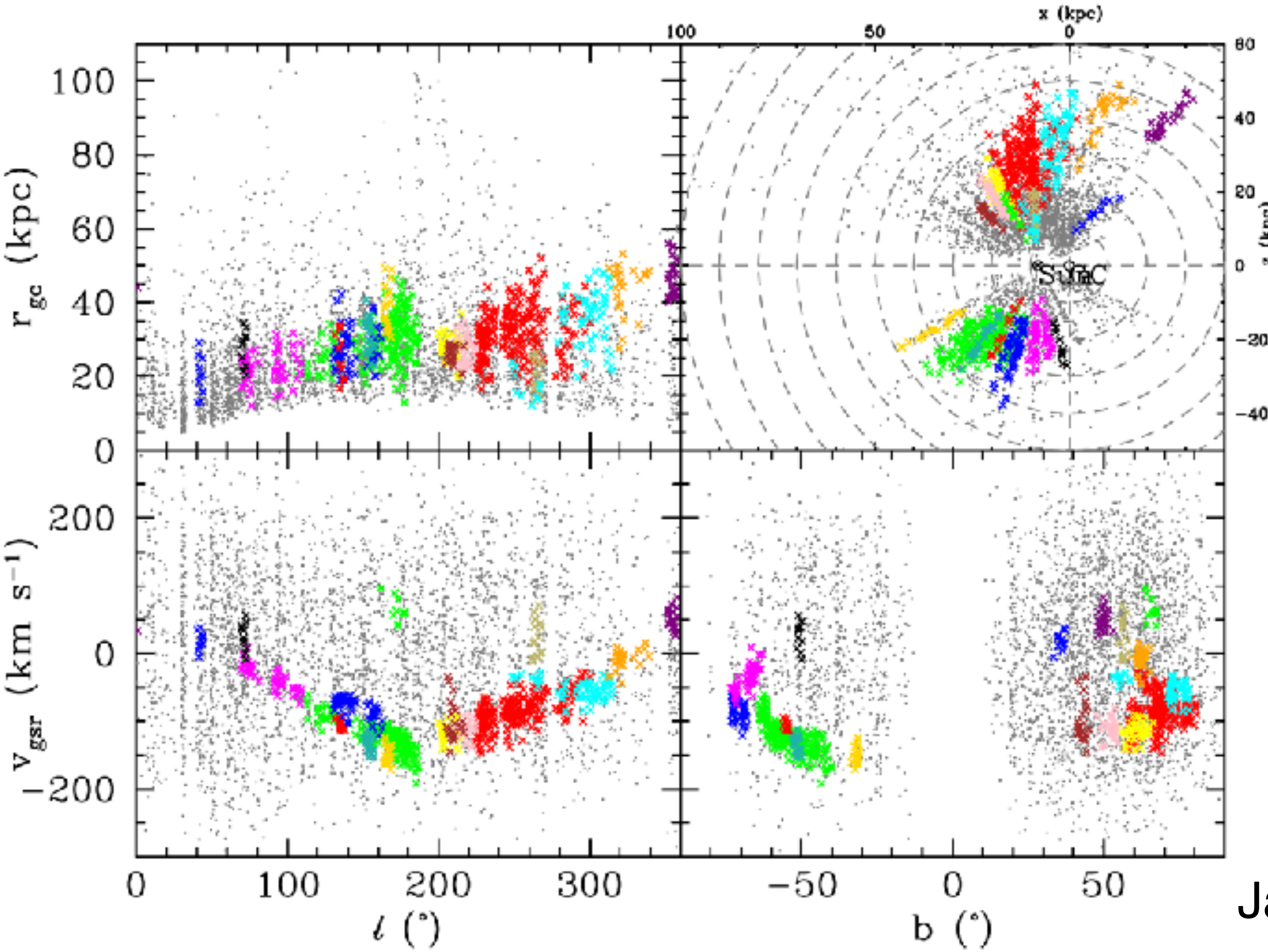


Janesh,Xue+ 2016

- The K-giant sample shows twice as much substructure than BHB sample.
- Outer halo shows stronger substructure.
- More metal-rich stars have more substructure.

=> Sgr is a quite massive satellite.

Substructure identification in SEGUE K giants



Friends-of-friends works by drawing a circle around each point, with a radius of 4distance=0.03 (Maximum physical size θ=5.4°, Δd=6kpc, Δv=15km/s)

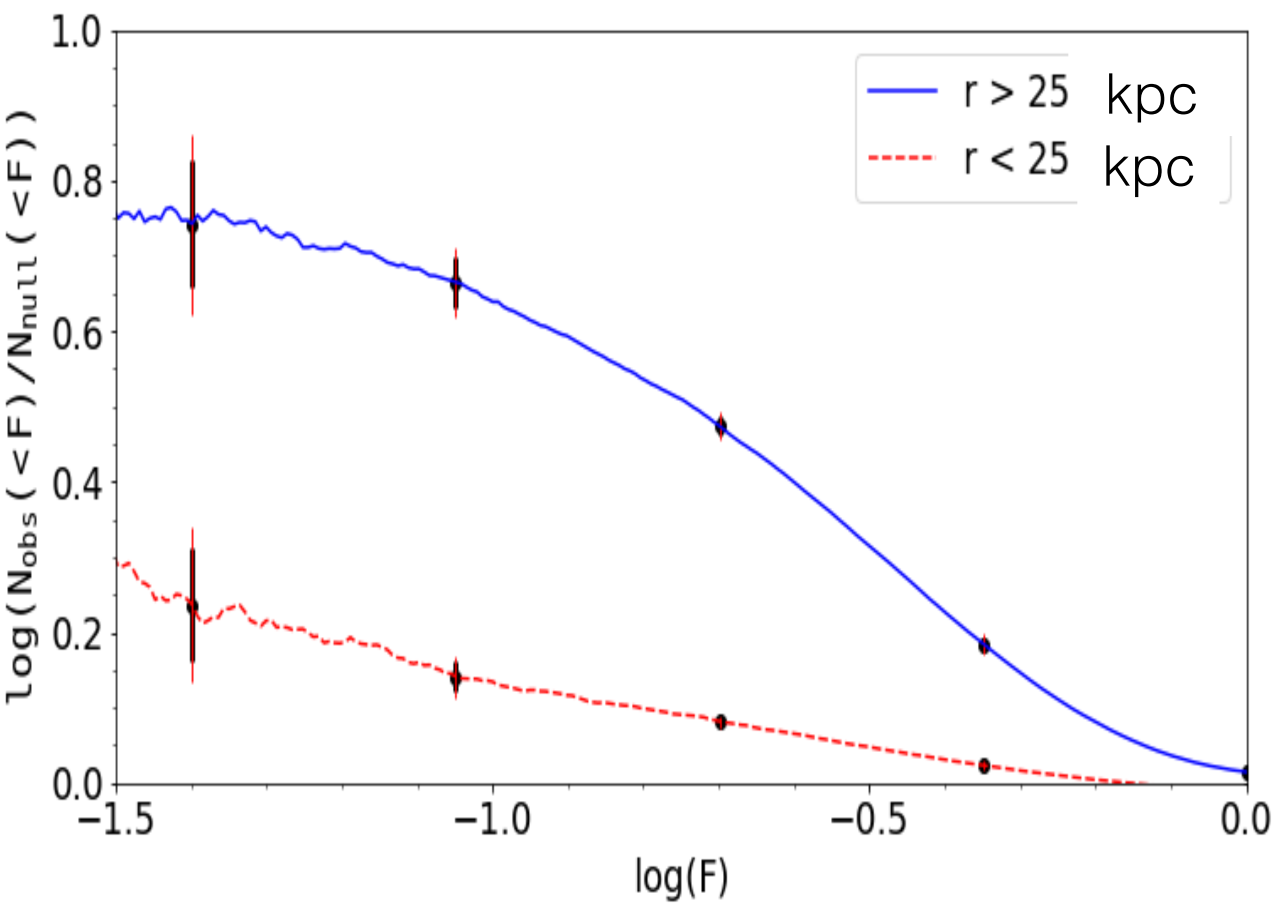
Colors:

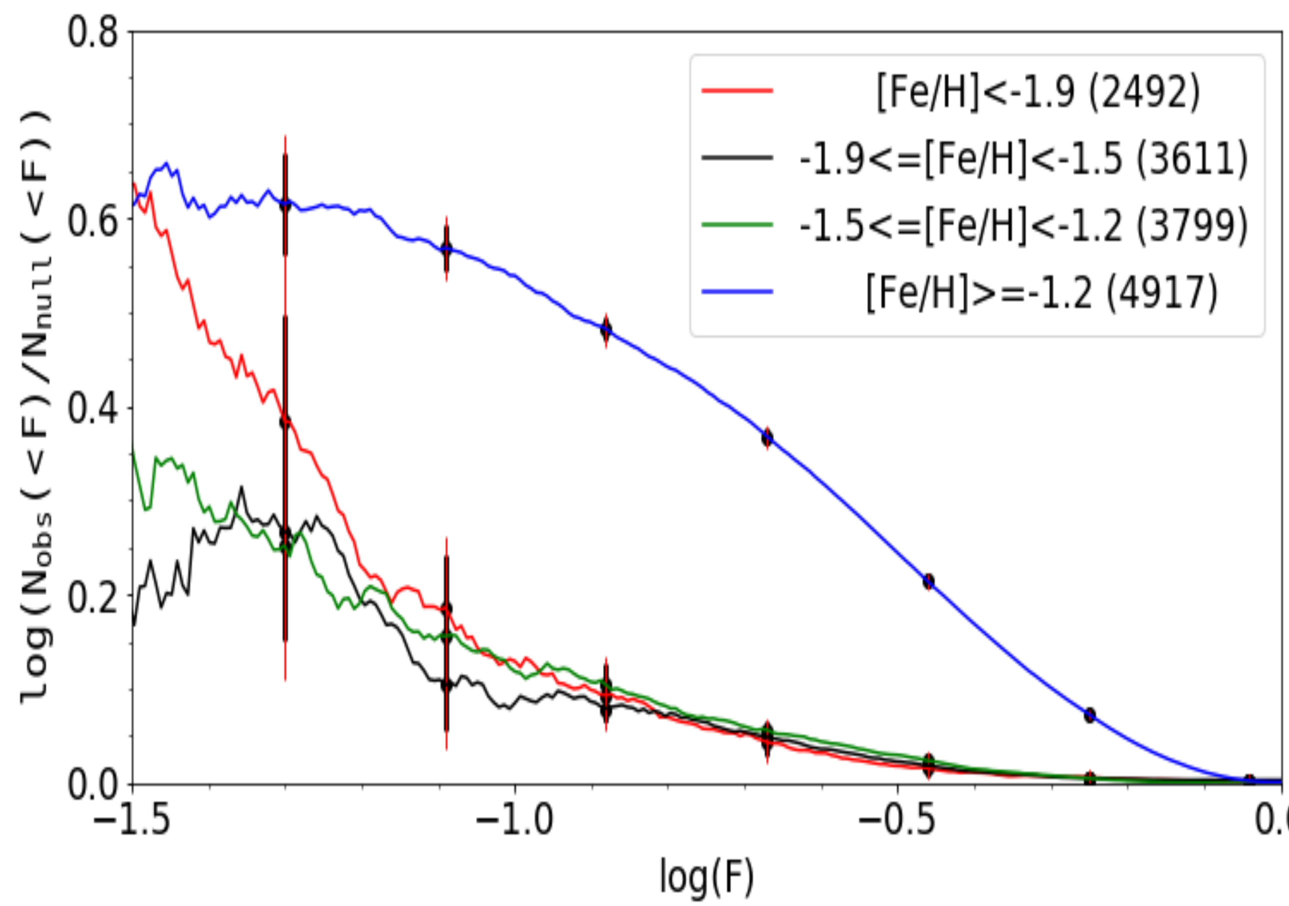
The friends-of-friends groups with >= 10 members

Janesh,Xue+ 2016

- K giants belonging to Sgr streams, Orphan streams, Cetus Polar stream, and other unknown substructures are identified.
- 27% of the K giants are in substructures, and Sgr stream dominates.

Substructure in LAMOST K giants confirmed the finding in SEGUE KG

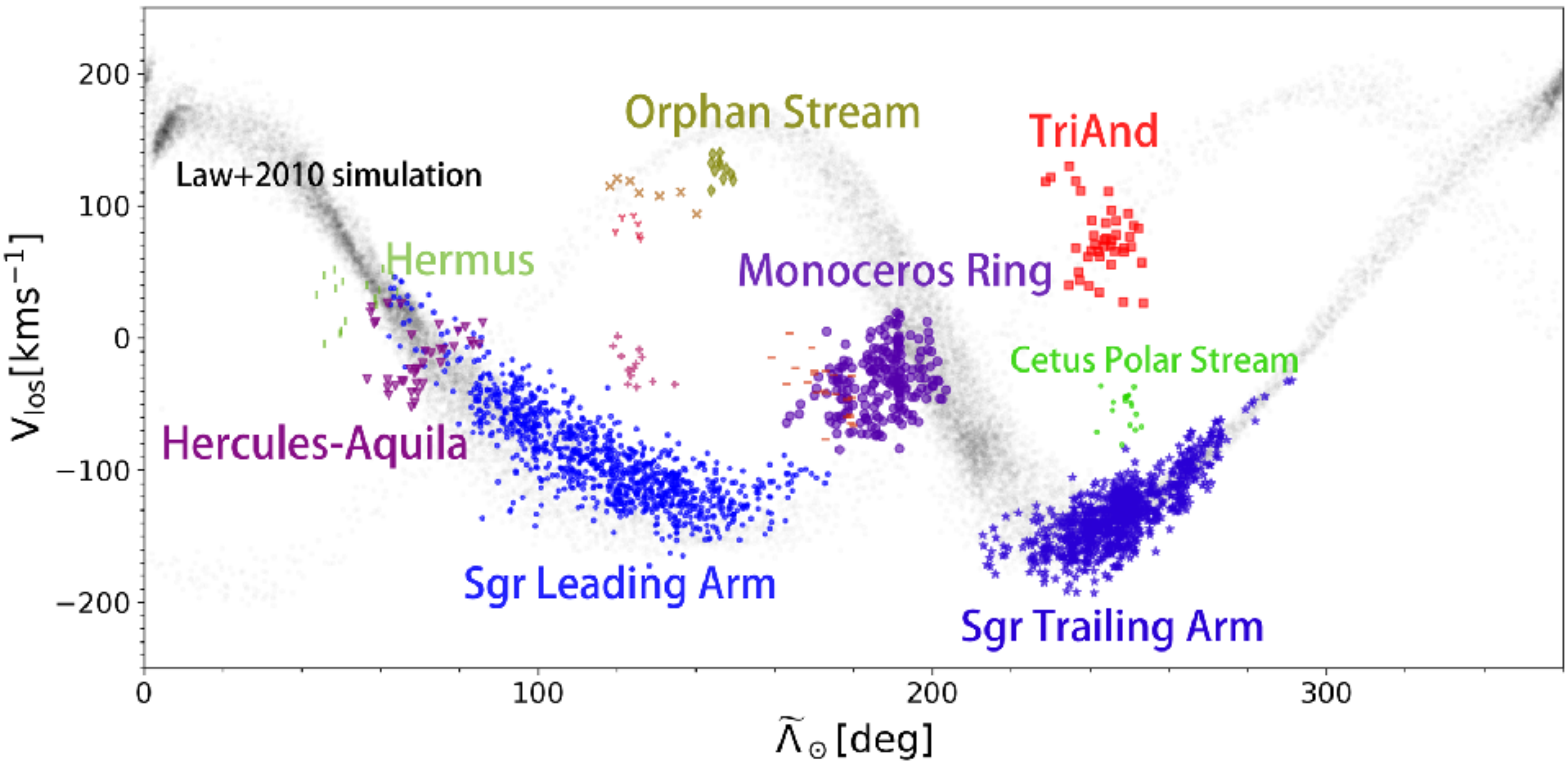




Stronger substructure in outer halo

Stronger substructure in metal-rich stars

Substructure identification in LAMOST K giants



Yang, Xue+ to submit 2018

- K giants reach to 100 kpc, so they can lead to a more reliable constrain on halo mass.
- But, K giant sample shows much more substructures than BHB.
- Need to excise them to measure MW halo mass.

Halo density profile are important for M(<r)

Yet, at present there is little consensus on the shape and the radial profile of the stellar halo

$$M(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\upsilon}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

Table 1. Incomplete list of recent stellar halo profile fits

reference	origin	tracer	sample size	distance(kpc)	model	parameters
Iorio (2017)	GAIA + 2MASS	RR Lyrae	21600	$D < 28$	Triaxial	n=2.96, p=1.27, $q = f(r)$, $q_0 = 0.57$, $q_{inf} = 0.84$, $r_0 = 12.2kpc$
Das et al. (2016)	SEGUE2	BHB		$r_{GC} < 70$	BPL SPL	$n_{in} = 3.61$, $n_{out} = 4.75$, $r_{break} = 29.87$, q=0.72 n=4.65, $q = f(r_{GC})$, $q_0 = 0.39$, q_{inf}=0.81, $r_0 = 7.32Kpc$
X15	SEGUE2	K giants	1757	$10 < r_{GC} < 80$	BPL Einasto SPL	$n_{in} = 2.8$, $n_{out} = 4.3$, $r_{break} = 29$, q=0.77 n=2.3, $r_{eff} = 18$, q=0.77 n=4.4, $q = f(r_{GC})$, $q_0 = 0.3$, q_{inf}=0.9, $r_0 = 9Kpc$
Pila-Diez et al. (2015)	CFHTS & INT	near MSTO		$r_{GC} < 60$	SPL Triaxial BPL BPL_q	n=4.3, q=0.79 n=4.28, q=0.77, $\omega = 0.87$ $n_{in} = 2.4$, $n_{out} = 4.8$, $r_{break} = 19$, q=0.77 $n_{in} = 3.3$, $n_{out} = 4.9$, $q_{in} = 0.7$, $q_{out} = 0.88$
Deason et al. (2011)	SDSS DR8	BS,BHB	~ 20000	$4 < D < 40$	BPL	$n_{in} = 2.3$, $n_{out} = 4.6$, $r_{break} = 27$, q=0.6
Deason et al. (2014)	SDSS DR9	BS,BHB		$10 < D_{BS} < 75$ $40 < D_{BHB} < 100$	BPL	$n_{outer} = 6 - 10$, $r_{break} = 50$
Watkins et al. (2009)	Stripe82	RRly	417	$5 < r_{GC} < 117$	BPL	$n_{in} = 2.4$, $n_{out} = 4.5$, $r_{break} = 25$
Sesar et al. (2011)	CFHTLS	near MSTO	27544	$D < 35$	BPL	$n_{in} = 2.62$, $n_{out} = 3.8$, $r_{break} = 28$, q=0.7
Juric et al. (2008)	SDSS	MS		$D < 20$	SPL	$n = -2.8$, q=0.64
Bell et al. (2008)	SDSS	MS	4 million	$D < 40$	SPL	$2 < n < 4$, $0.5 < q < 0.8$
Siegel et al. (2002)	Kapteyn		70000		SPL	$n = 2.75$, $q = 0.6$
Robin et al. (2000)	PB				SPL	$n = 2.44$, $q = 0.76$

Halo density profile are important for M(<r)

$$M(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\upsilon}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

- Halo maps before exist:
  - photometric only (poor metallicity),
  - local (<10 kpc) —> extrapolation needed,
  - BHB stars: very old population.
- we want stellar halo's
  - radial profile & shape (flattening),
  - beyond 40 kpc,
  - using more representative tracers

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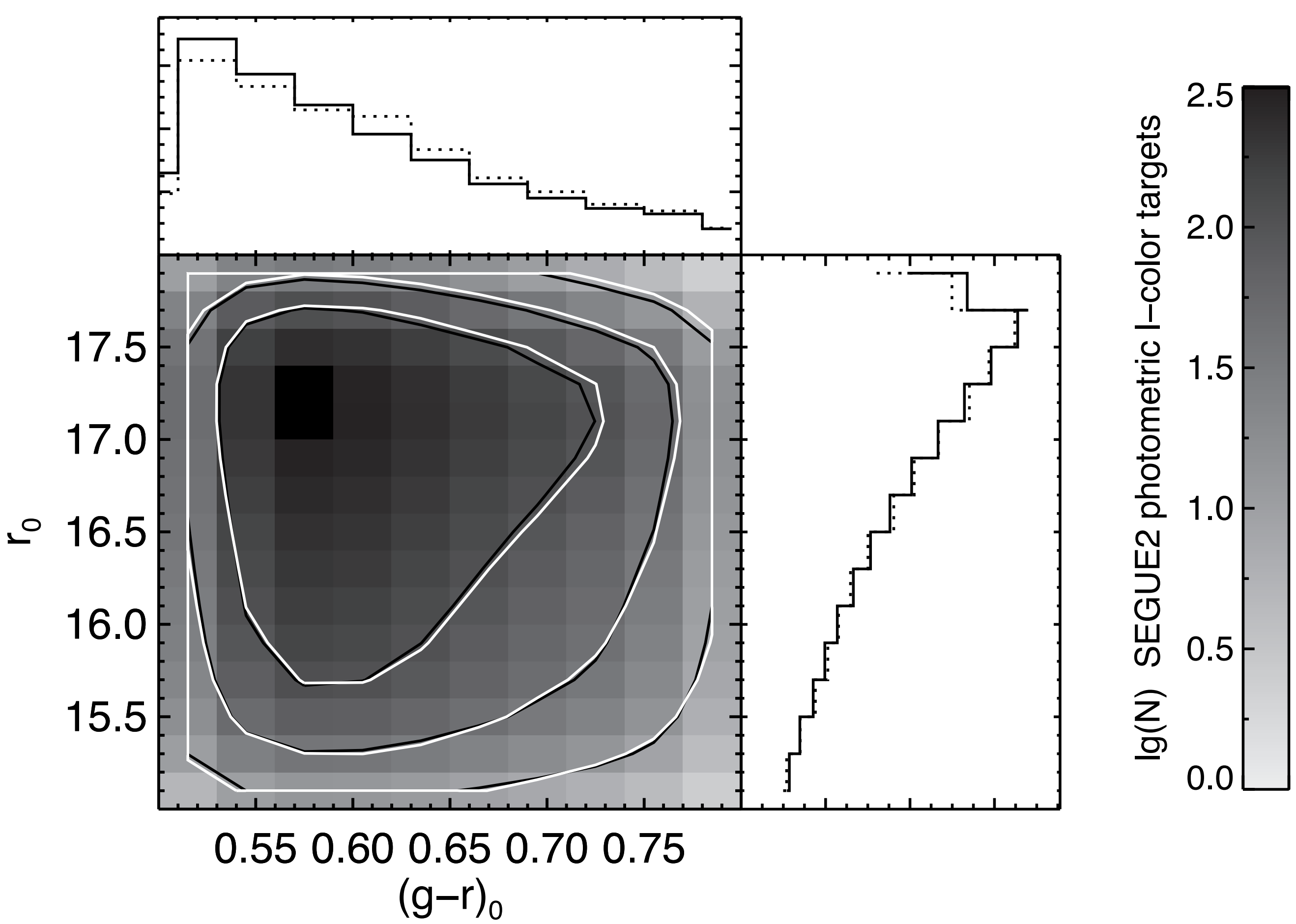

Xue+ 2015

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  - using more representative tracers

2400 SEGUE-2 K giants in SDSS spectroscopic surveys (incomplete sample)

↓

the underlying stellar halo density profile.

- |z|>4kpc & [Fe/H]<-1.2
- excising substructures is more important for K-giants than for BHBs!
- need correct all selection effects!

Method to derive the density profile

Method to derive the density profile

- Assume a halo density profile and a metallicity distribution model

density model: Einasto profile/broken power-law + constant/varying flattening

metal-model: combination of two Gaussians

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$$\lambda(\mathrm{M_r}, \mathcal{DM}, [\mathrm{Fe/H}], \mathrm{l}, \mathrm{b} | \mathrm{p_H}, \mathrm{p_{Fe}}) = |\mathrm{J}(\mathrm{x}, \mathrm{y}, \mathrm{z}; \mathcal{DM}, \mathrm{l}, \mathrm{b})| \times \nu_\star\big(\mathrm{r_q}(\mathcal{DM}, \mathrm{l}, \mathrm{b}) | \mathrm{p_H}\big) \times \rho([\mathrm{Fe/H}] | \mathrm{r_q}, \mathrm{p_{Fe}}) \times \mathrm{p}(\mathrm{M_r}) \times \mathrm{S}([\mathrm{Fe/H}]) \times \mathrm{S}(\mathrm{z}(\mathcal{DM}, \mathrm{b})) \times S(M_r \mid [\mathrm{Fe/H}]) \times S(l, b) \times S\big(m(\mathcal{DM}, M_r), c(M_r, [\mathrm{Fe/H}])\big). \quad (5)$$

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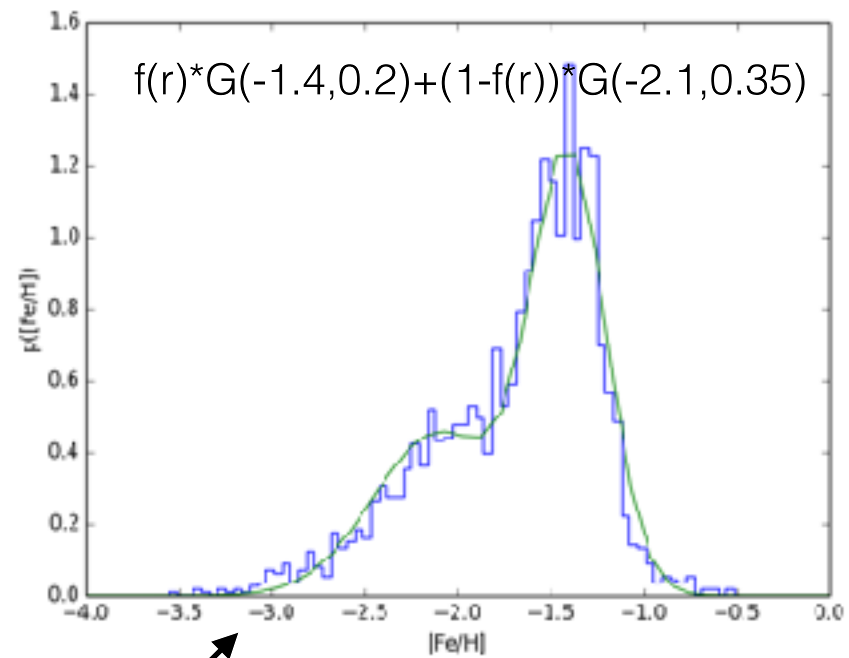

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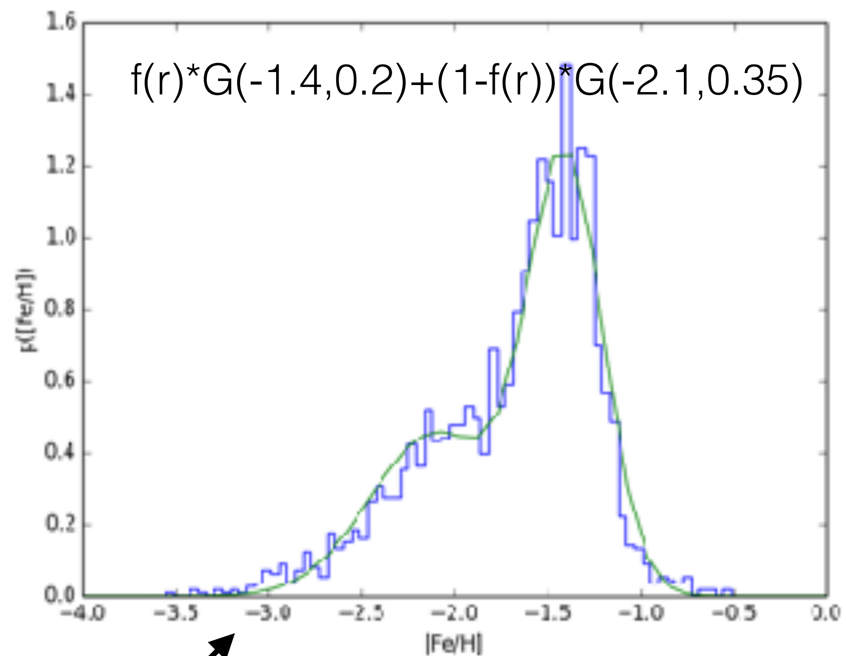

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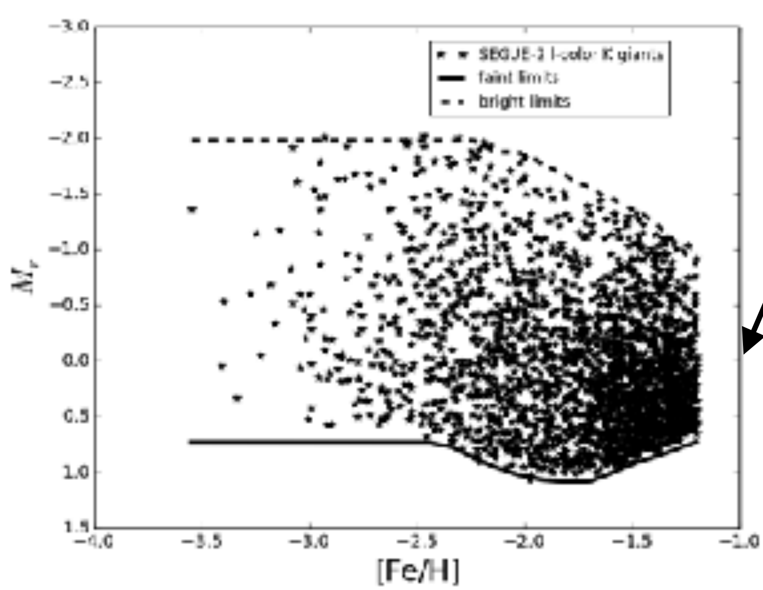

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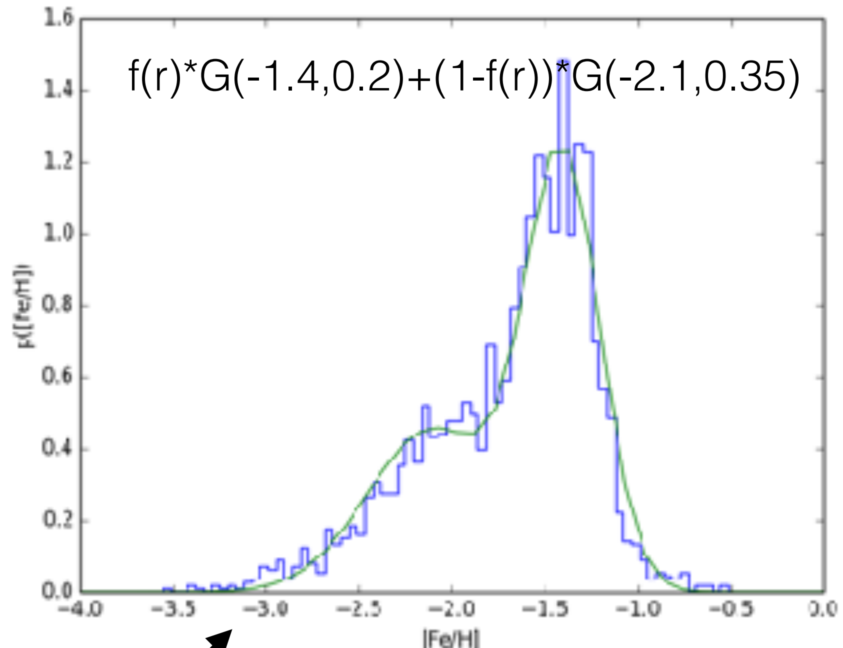

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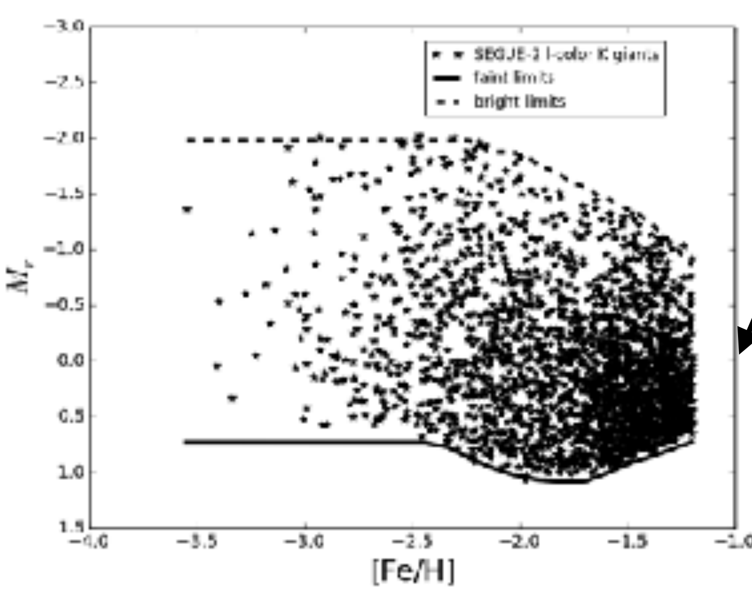
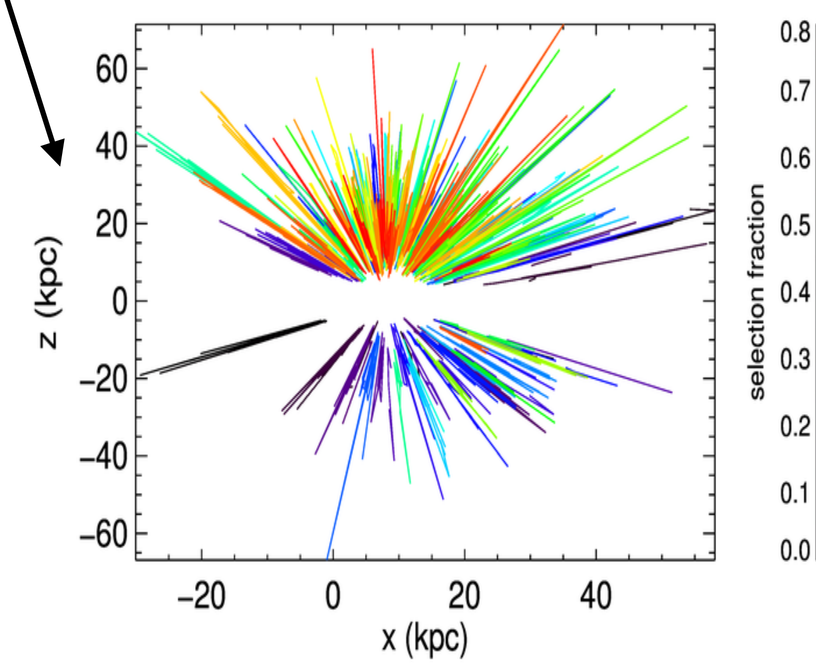
$$\lambda(M_r, \mathcal{DM}, [Fe/H], l, b | p_H, p_{Fe}) = |J(x, y, z; \mathcal{DM}, l, b)| \times \nu_*(r_q(\mathcal{DM}, l, b)|p_H) \times \rho([Fe/H]|r_q, p_{Fe}) \times p(M_r) \times S([Fe/H]) \times S(z(\mathcal{DM}, b)) \times S(M_r \mid [Fe/H]) \times S(l, b) \times S(m(\mathcal{DM}, M_r), c(M_r, [Fe/H])). \quad (5)$$





X

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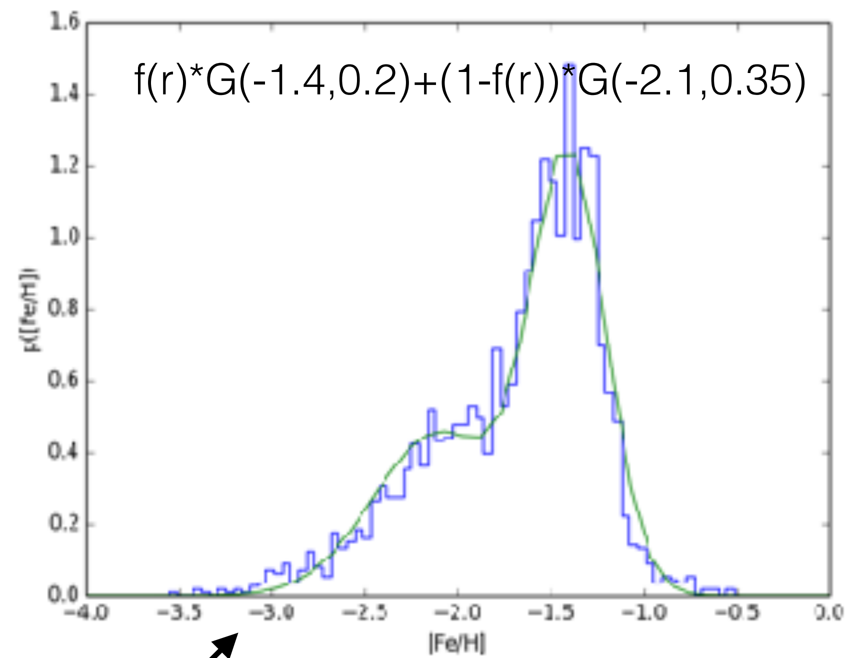

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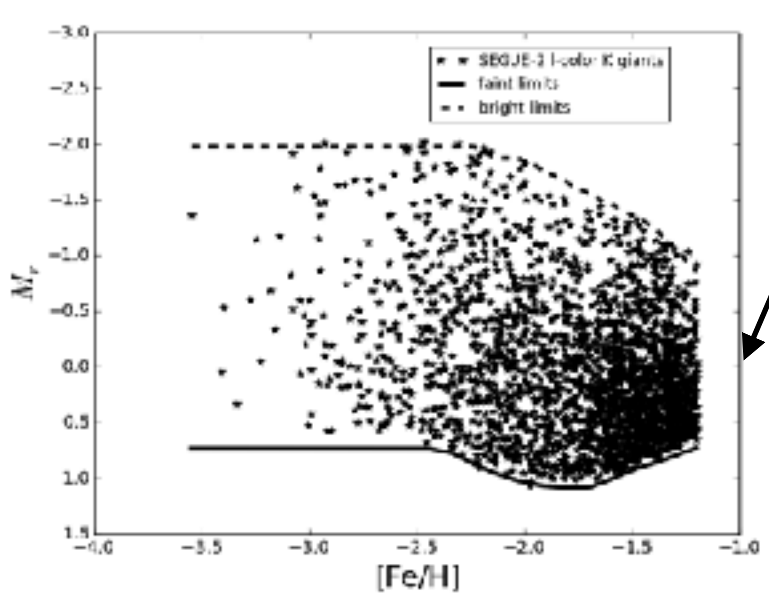
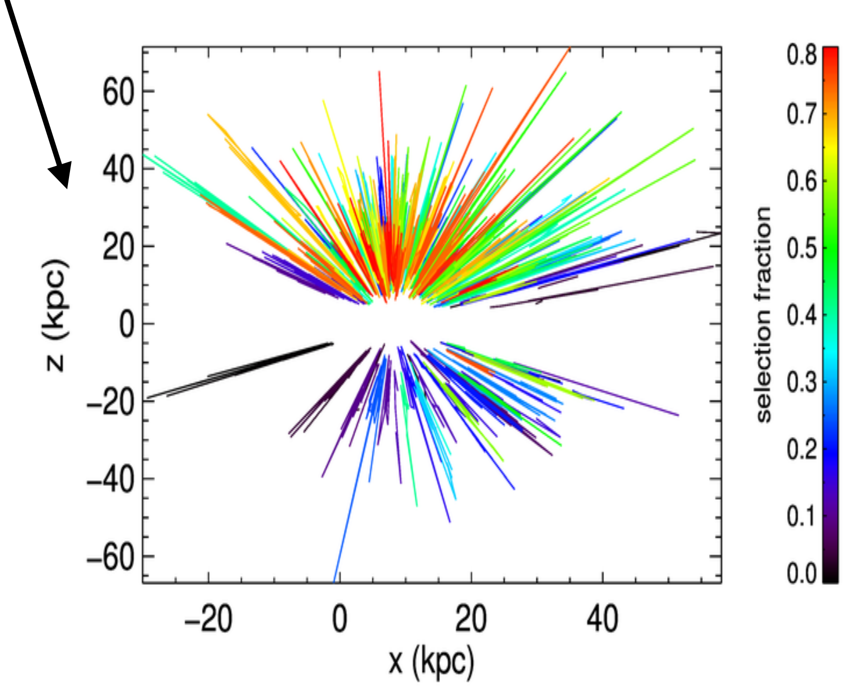


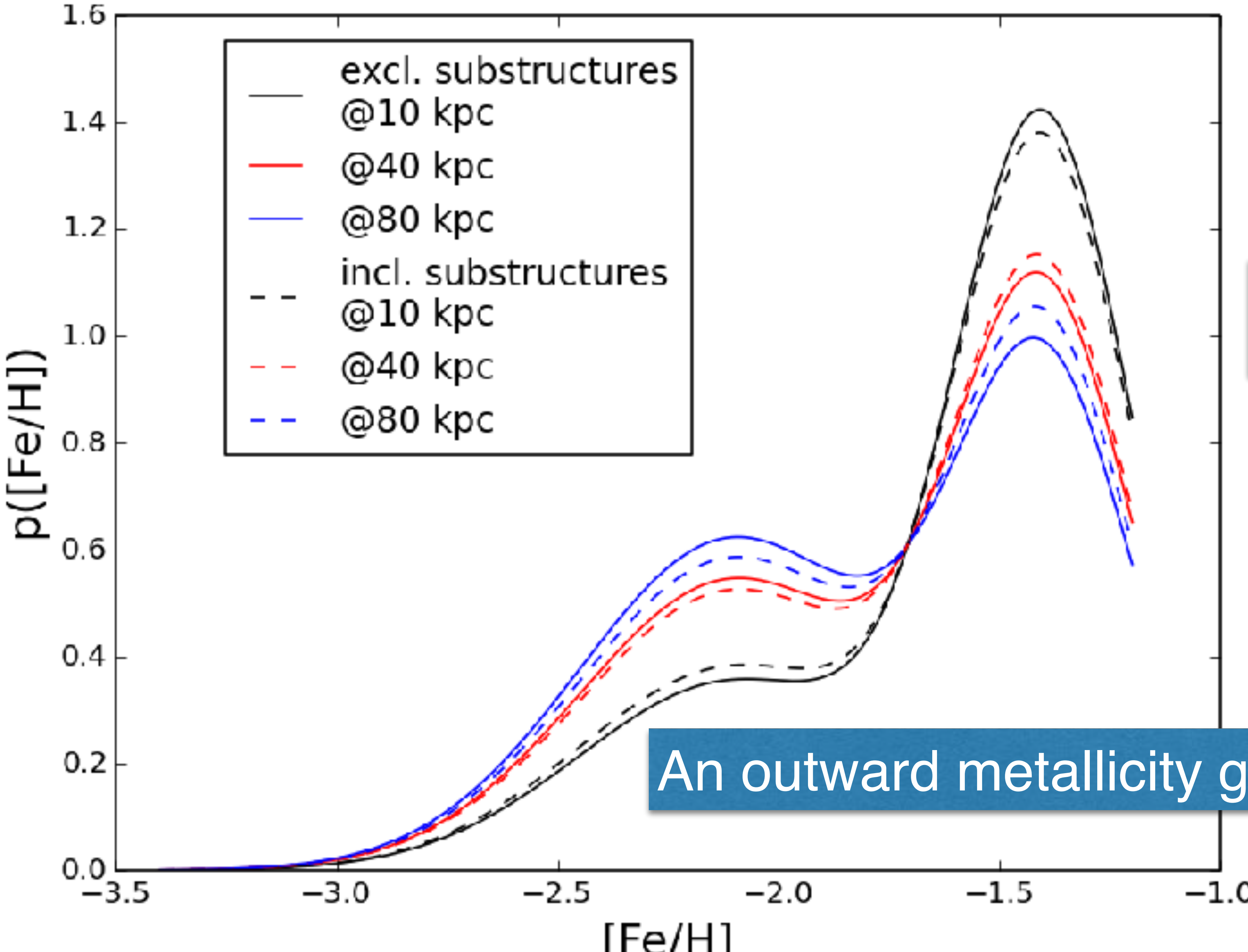


- The likelihood of the data for given (p_H, p_{Fe}) is

$$\mathscr{L}(\mathrm{data_i}|\mathrm{p_H}, \mathrm{p_{Fe}}) = \mathrm{c}_\lambda^{-\mathrm{N_{KG}}} \prod_{\mathrm{i}=1}^{\mathrm{N_{KG}}} \lambda(\mathrm{M_{ri}}, \mathcal{DM}_\mathrm{i}, [\mathrm{Fe/H}]_\mathrm{i}, \mathrm{l_i}, \mathrm{b_i}|\mathrm{p_H}, \mathrm{p_{Fe}})$$

X

Metallicity gradient in stellar halo

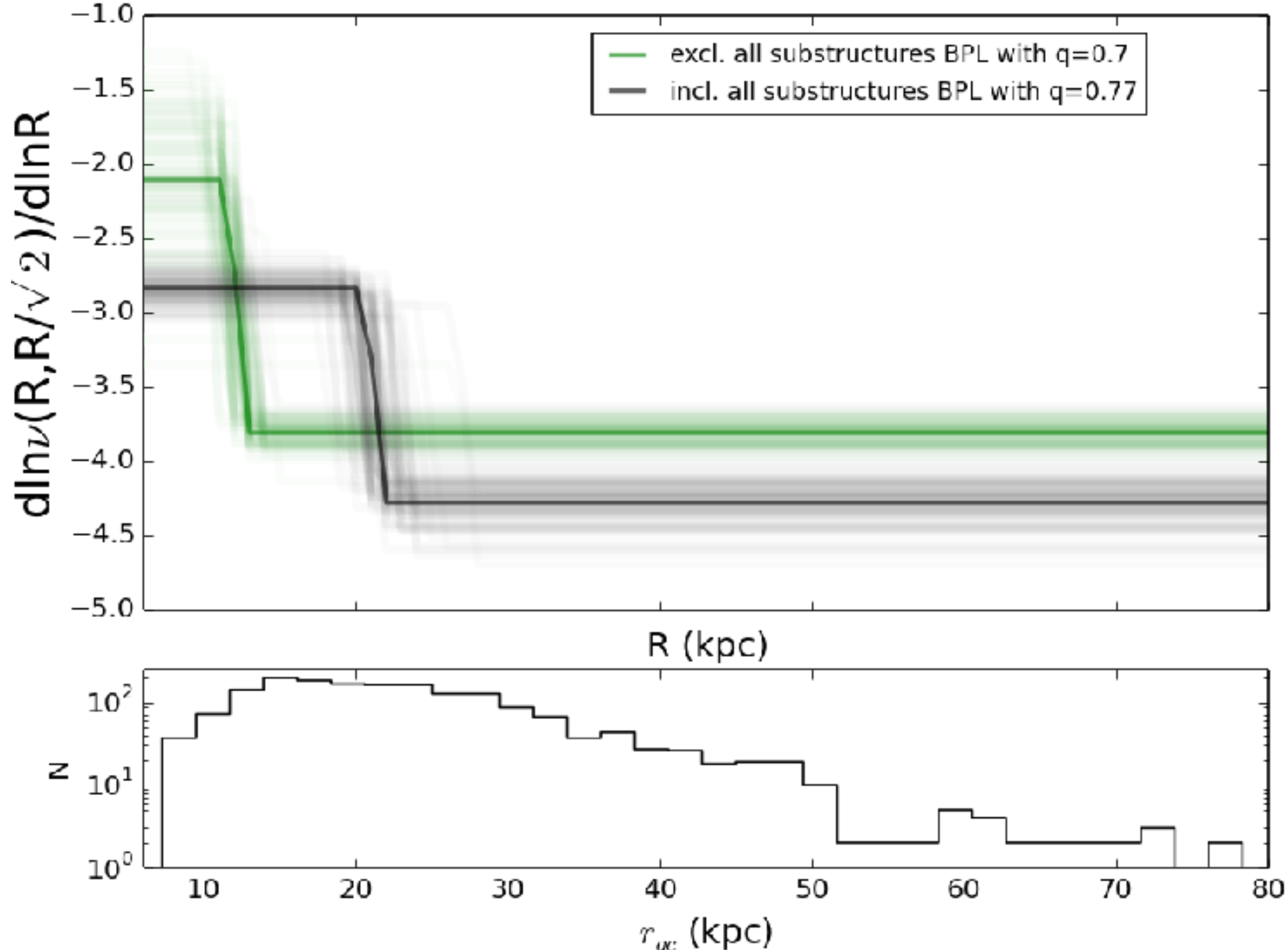


An outward metallicity gradient

Substructure affects metallicity gradient little !

X

Density profile traced by SEGUE KG



$$M(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\upsilon}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

Xue+ 2015

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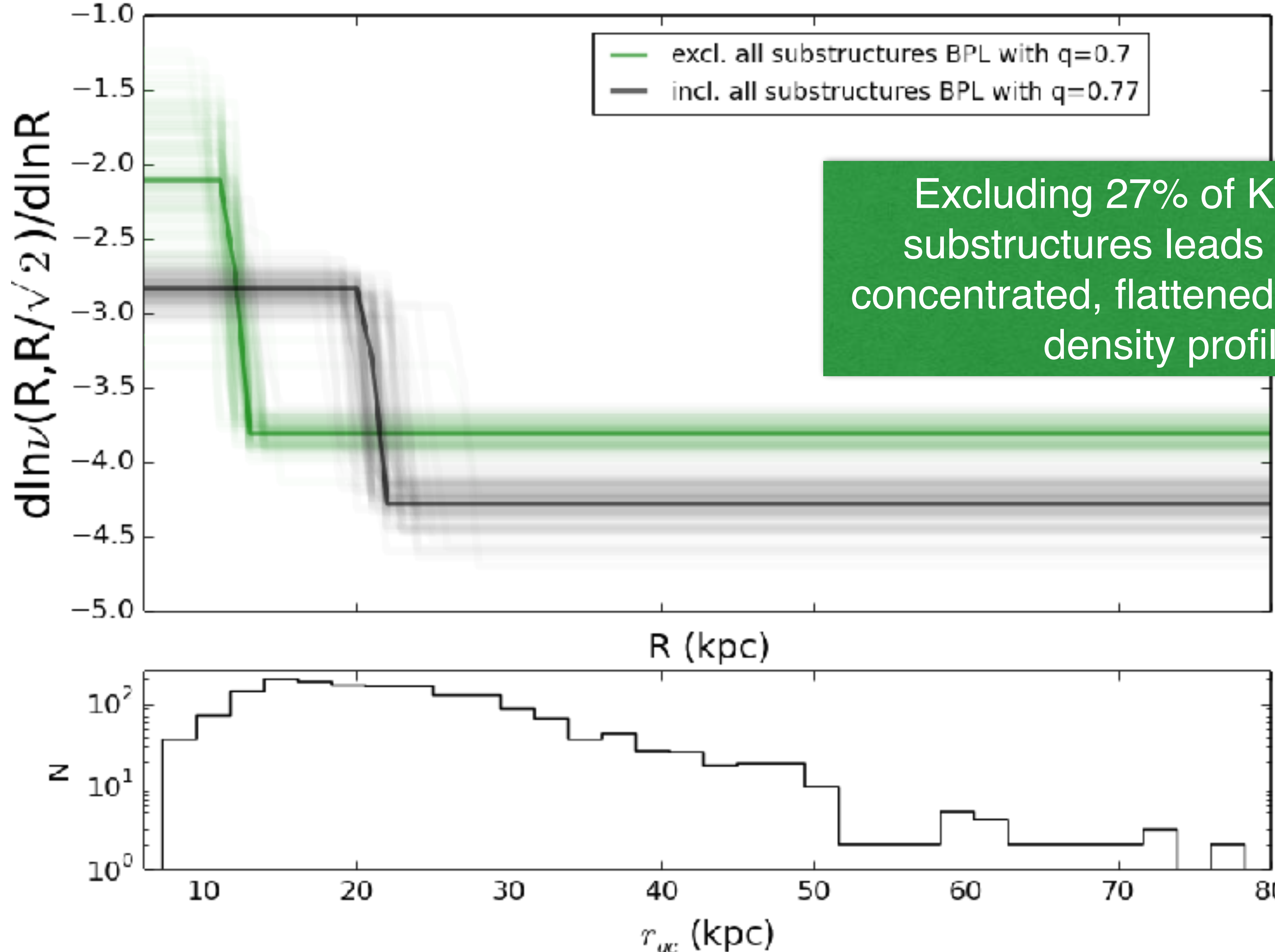


Excluding 27% of K giants in substructures leads to a more concentrated, flattened and shallow density profile.

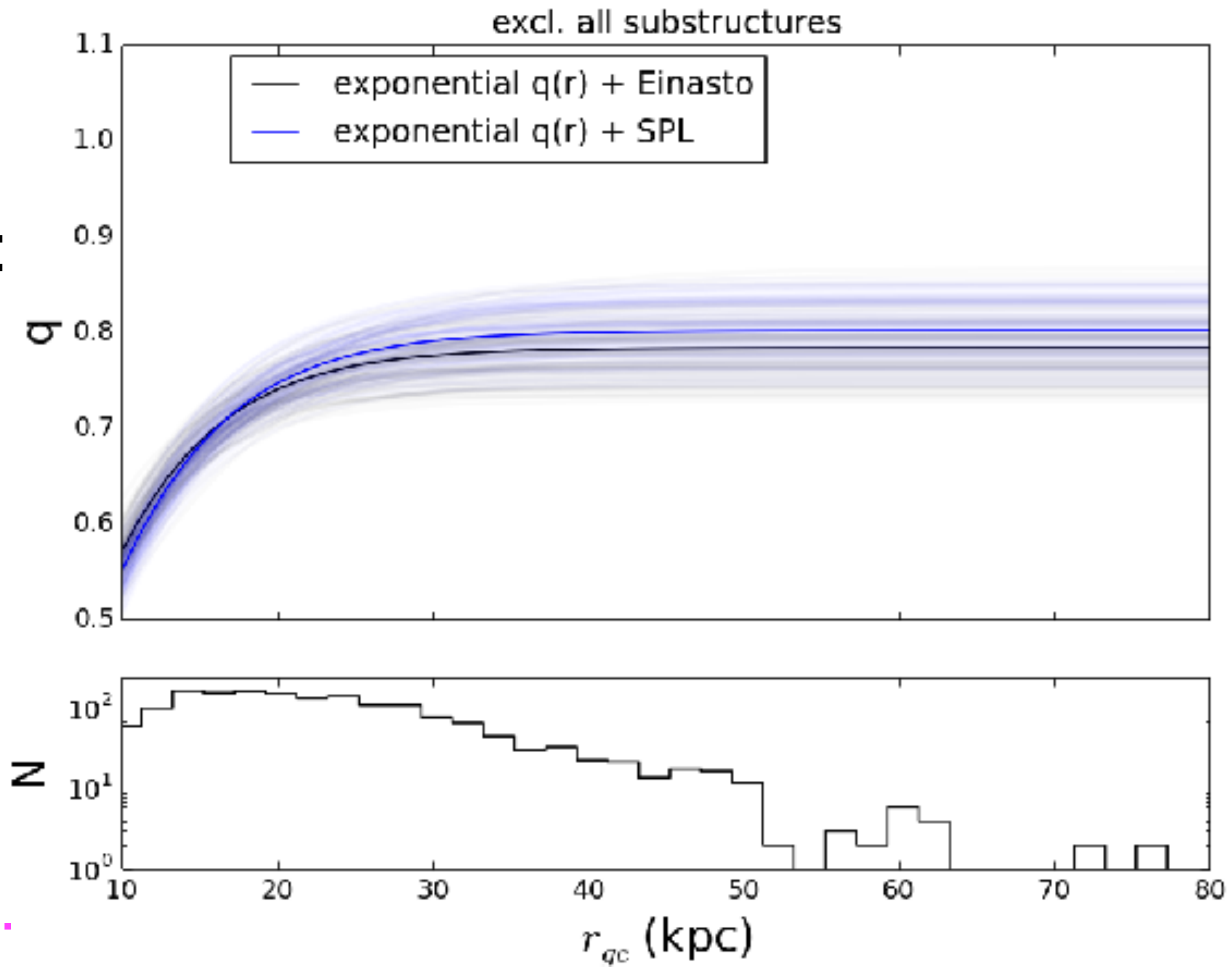
$$M(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\upsilon}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

Xue+ 2015

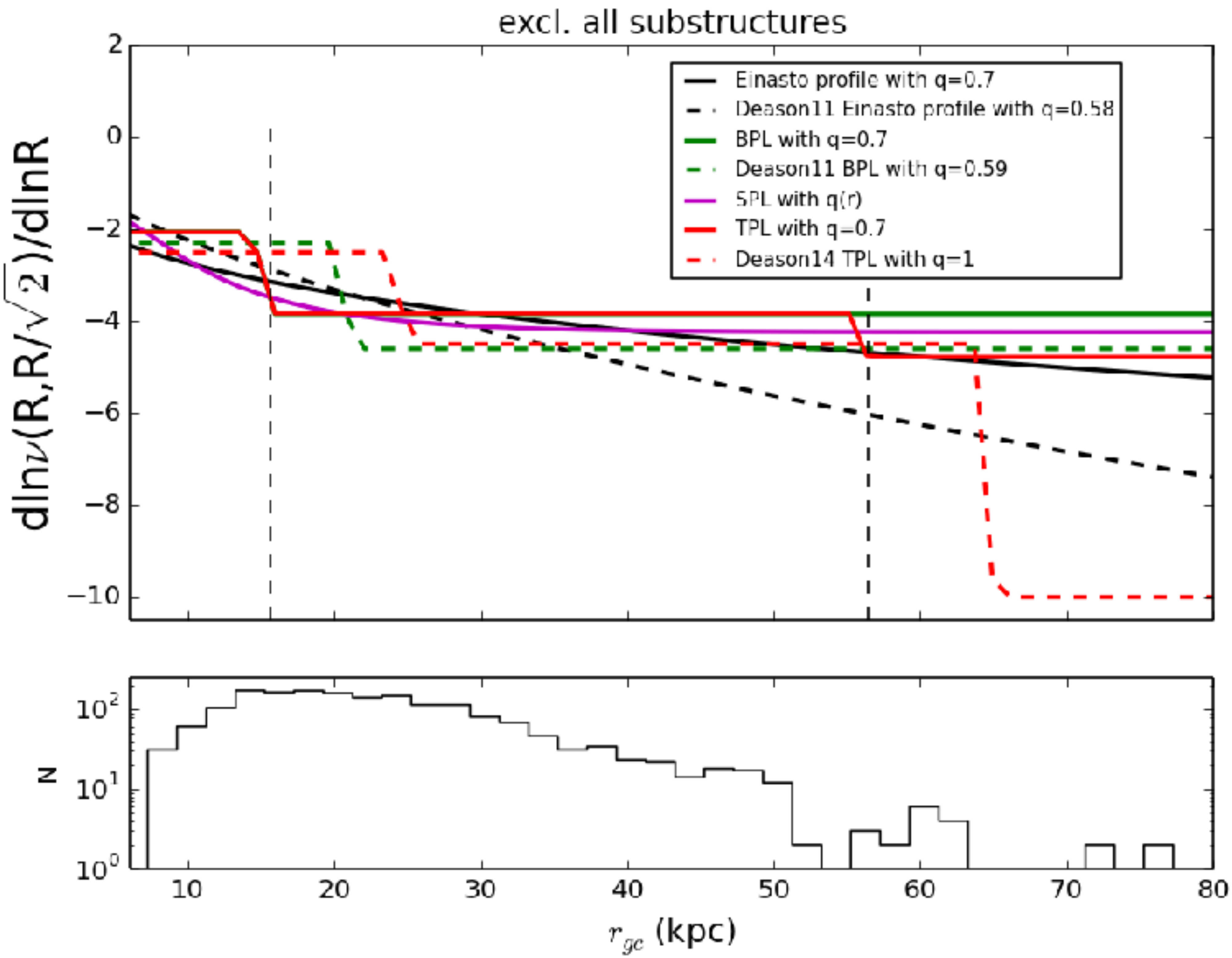
Radial variation of halo flattening

Fit the SEGUE halo K giants to different forms of density profile with varying flattening:

- q changes from 0.57 at 10 kpc to 0.78 at large radii.
- well-fit by $\sim r_q^{-4.2}$
- SPL+q(r) fit the data best, but other models are hard to reject.
- a break in flattening, but no break in the radial profile



Xue[+] 2015 submitted

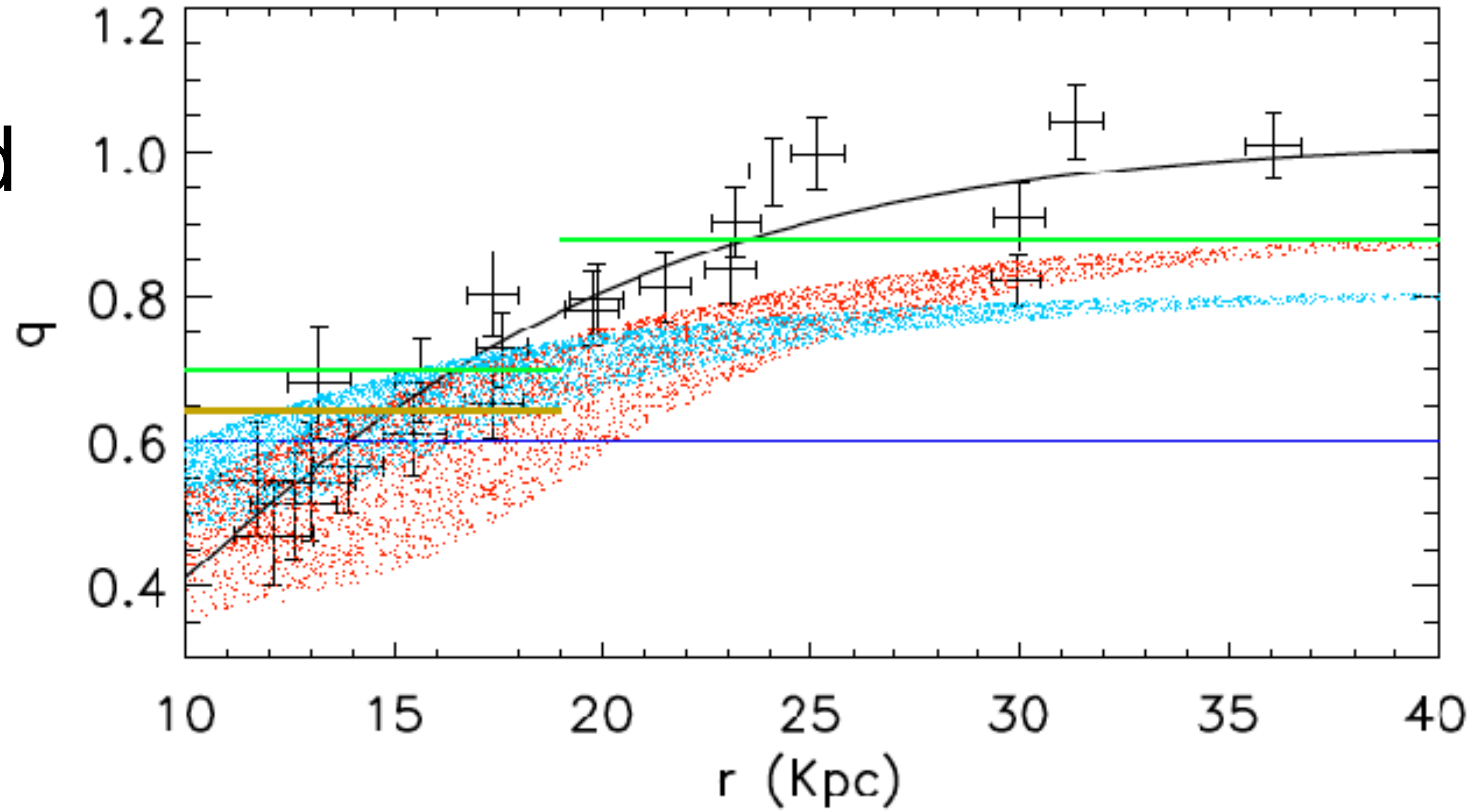


Xue+ 2015

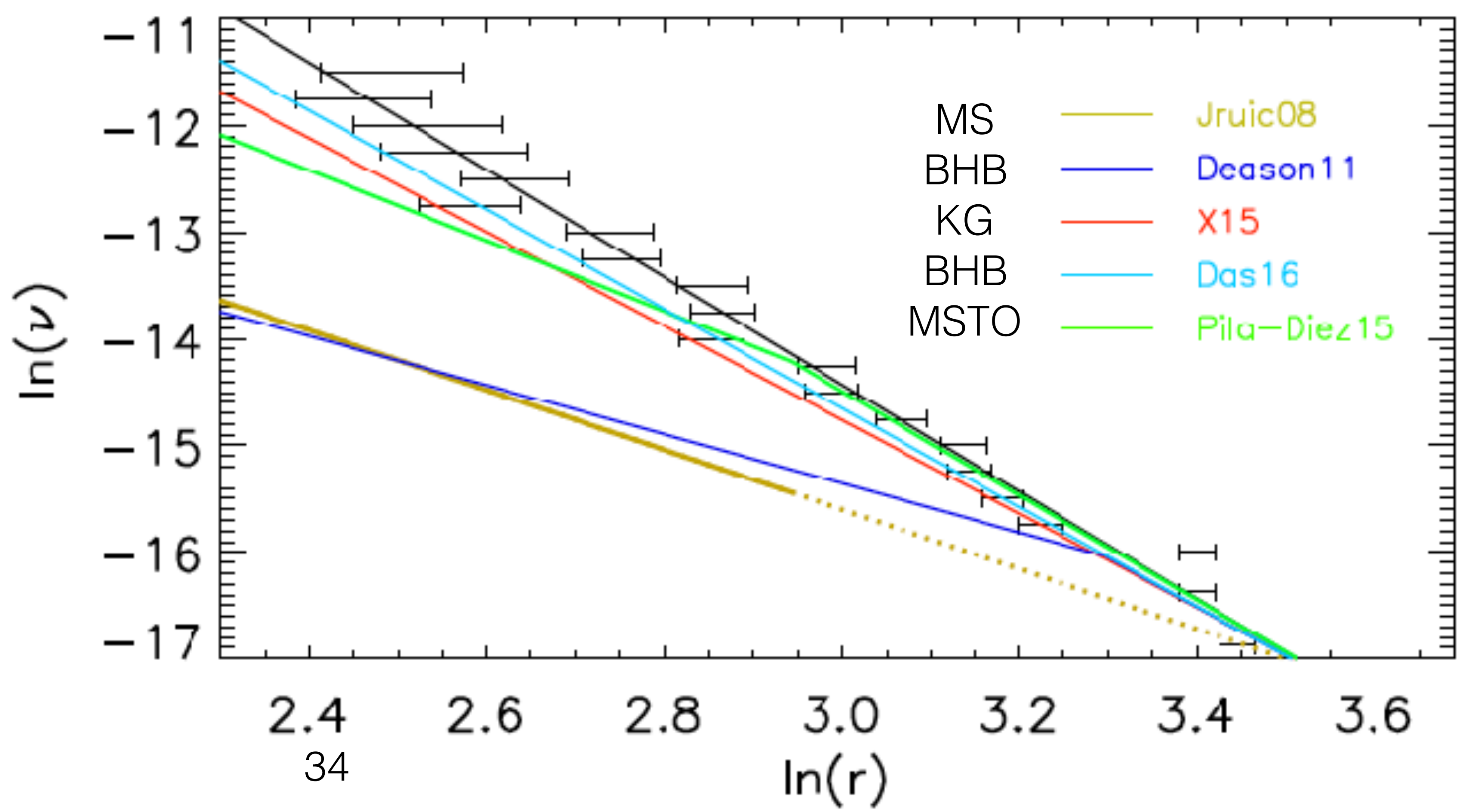
- All models have very similar predictions for the slope within 65 kpc.
- Our results are consistent with Deason+11 within 65 kpc, but show no strong drop beyond 65 kpc. --- the paucity of distant K giants

Density profile traced by LAMOST KG

- Model-independent
- Radial variation of halo flattening
- Single power-law $\sim r_q^{-5}$
- BHB, KG, MS may have different density profile



Xu, Liu, Xue+ 2018



Mass distribution based on K giants

Basic approach:

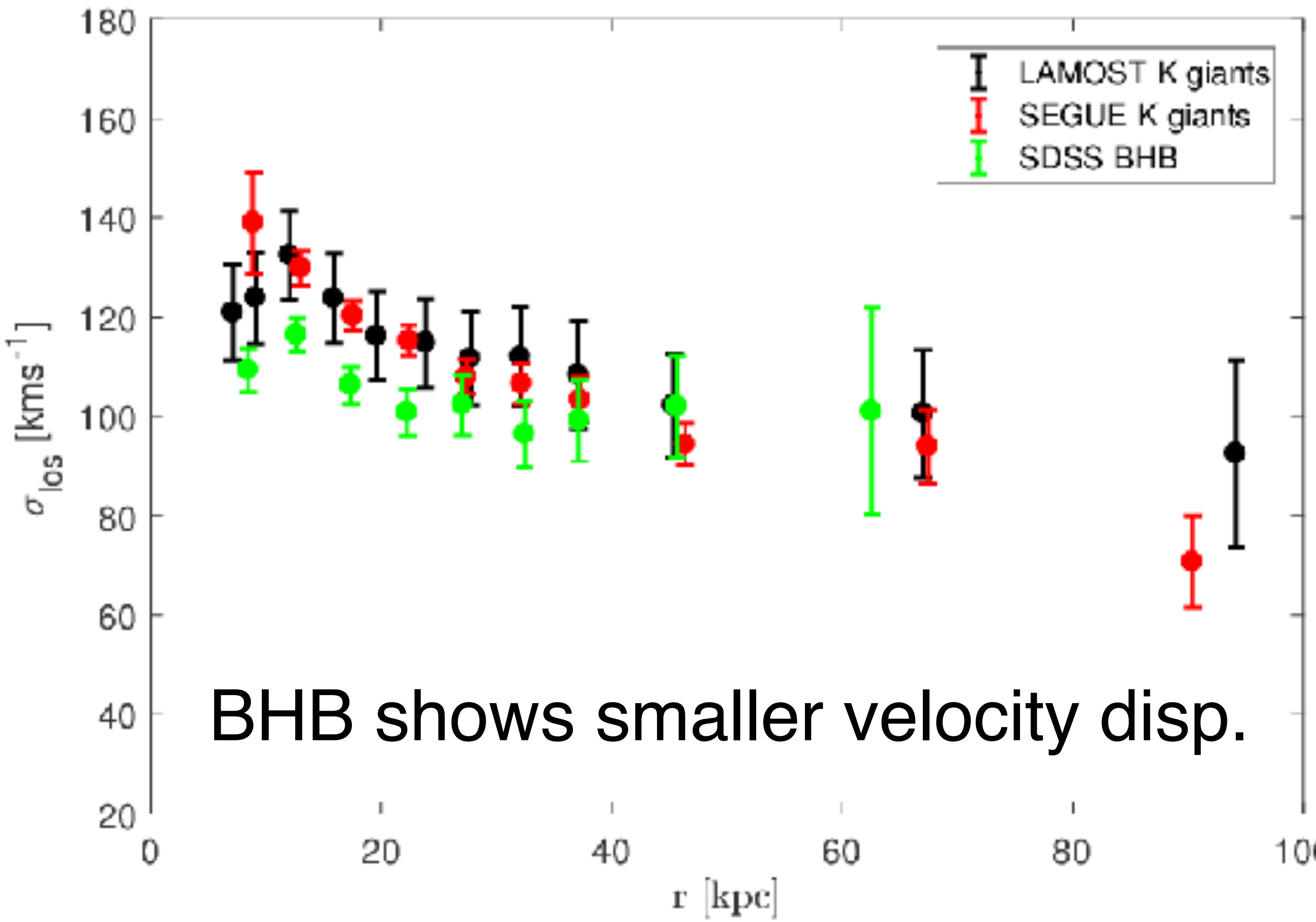
$$M(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\upsilon}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

Inputs to Jeans Equation

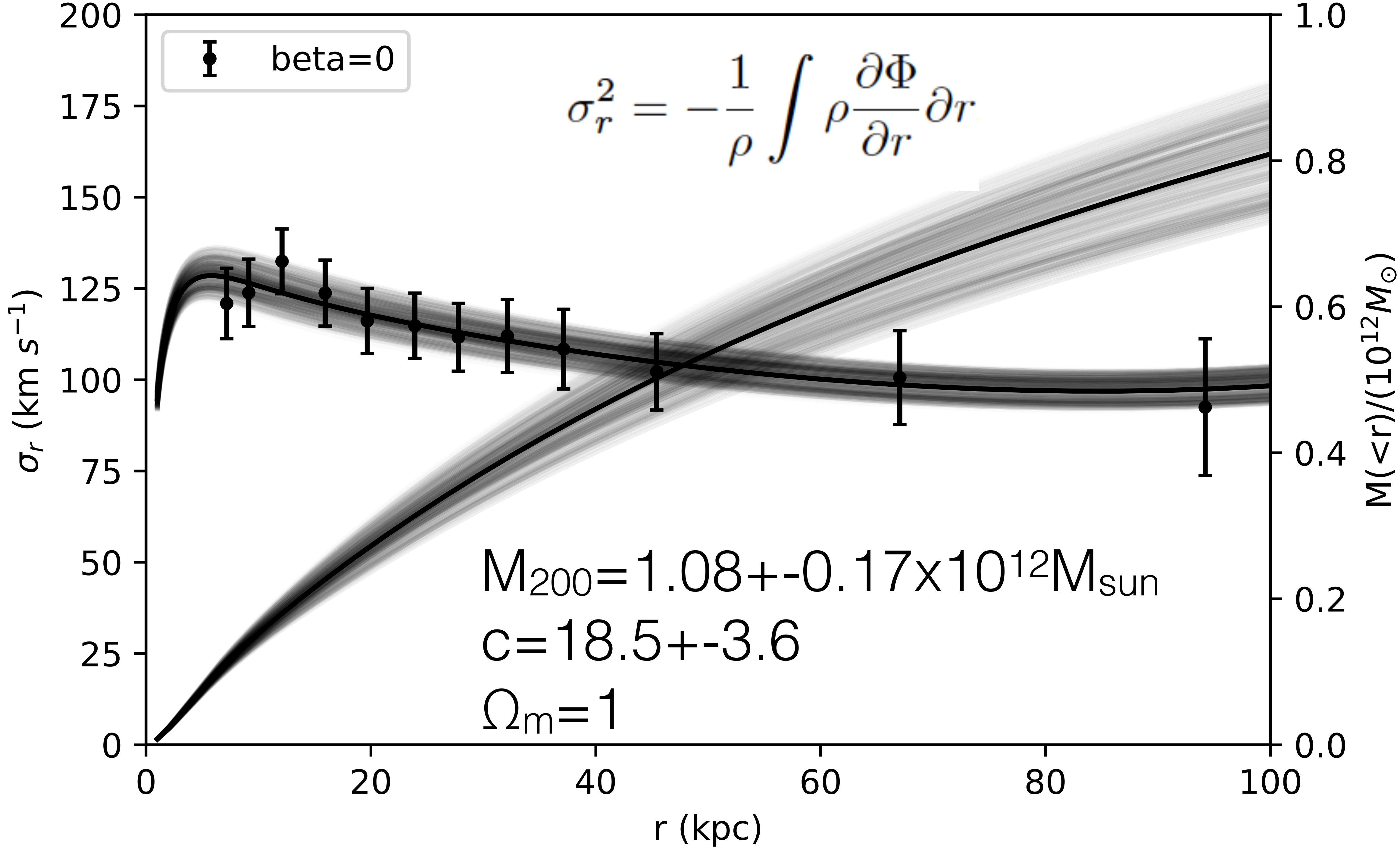
- ✓ The shape and density profiles traced by K giants
- ✓ line-of-sight velocity dispersion of K giants
- ✓ assume anisotropy
- ✓ assume NFW profile + fixed disk

M_{vir} & M(<r)

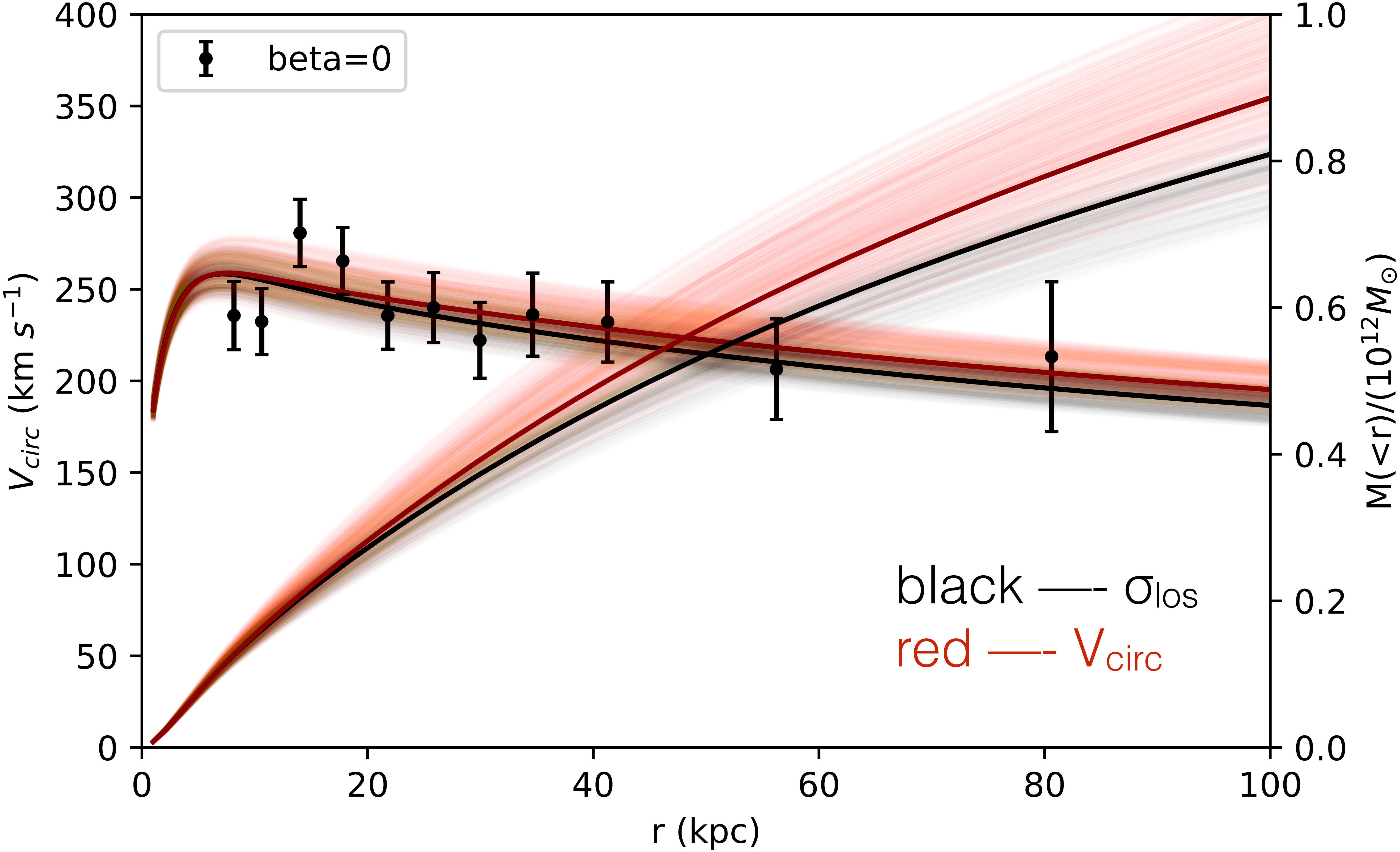
velocity dispersion of KG and BHB



Mass distribution based on LAMOST K giants



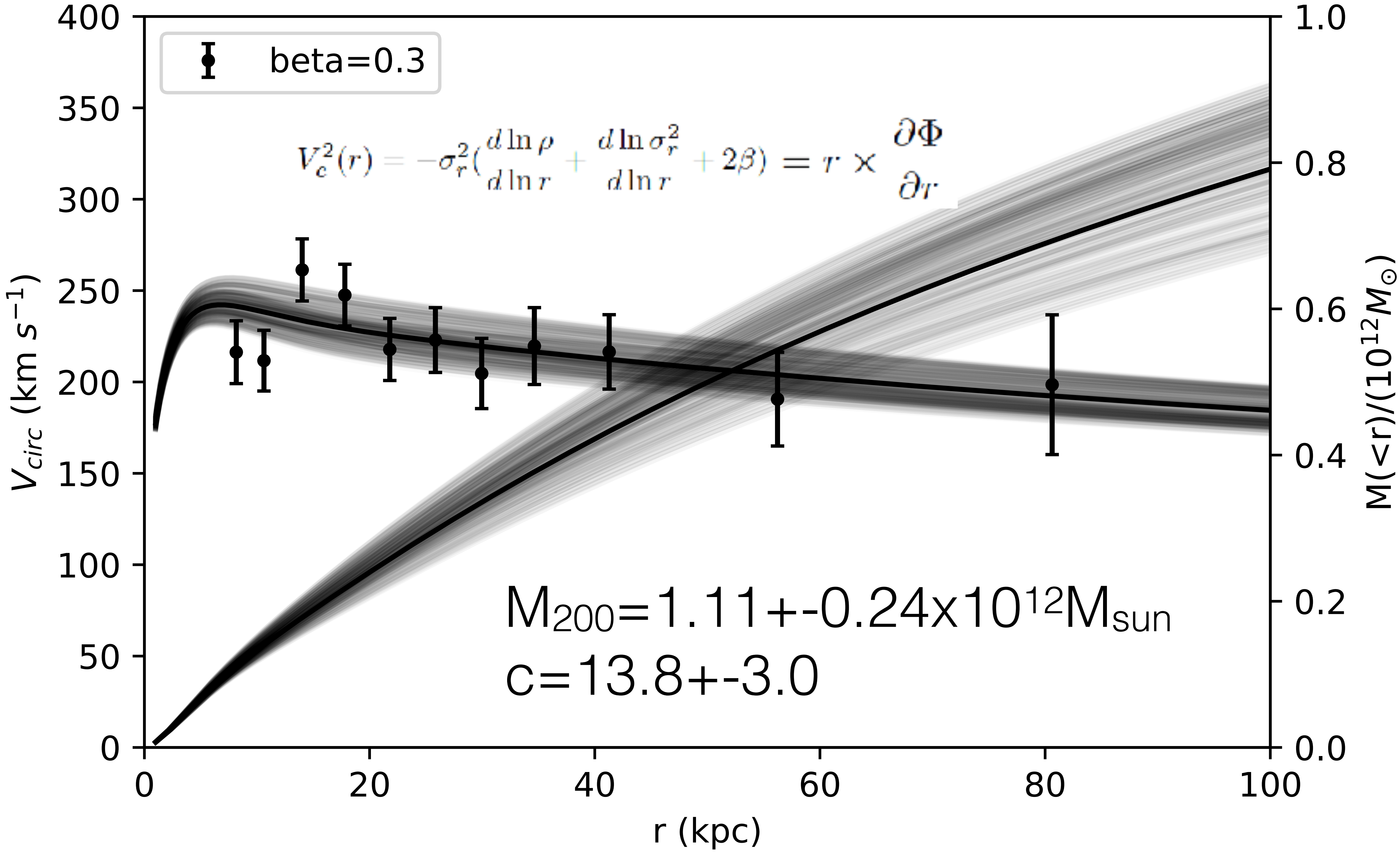
Zhai, Xue+ submitted



beta=0
V_{circ} (km s^{-1})
M(<r)/($10^{12} M_\odot$)
r (kpc)
black —- σ_{los}
red —- V_{circ}
0
50
100
150
200
250
300
350
400
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100

X

Mass distribution based on LAMOST K giants



Zhai, Xue+ submitted

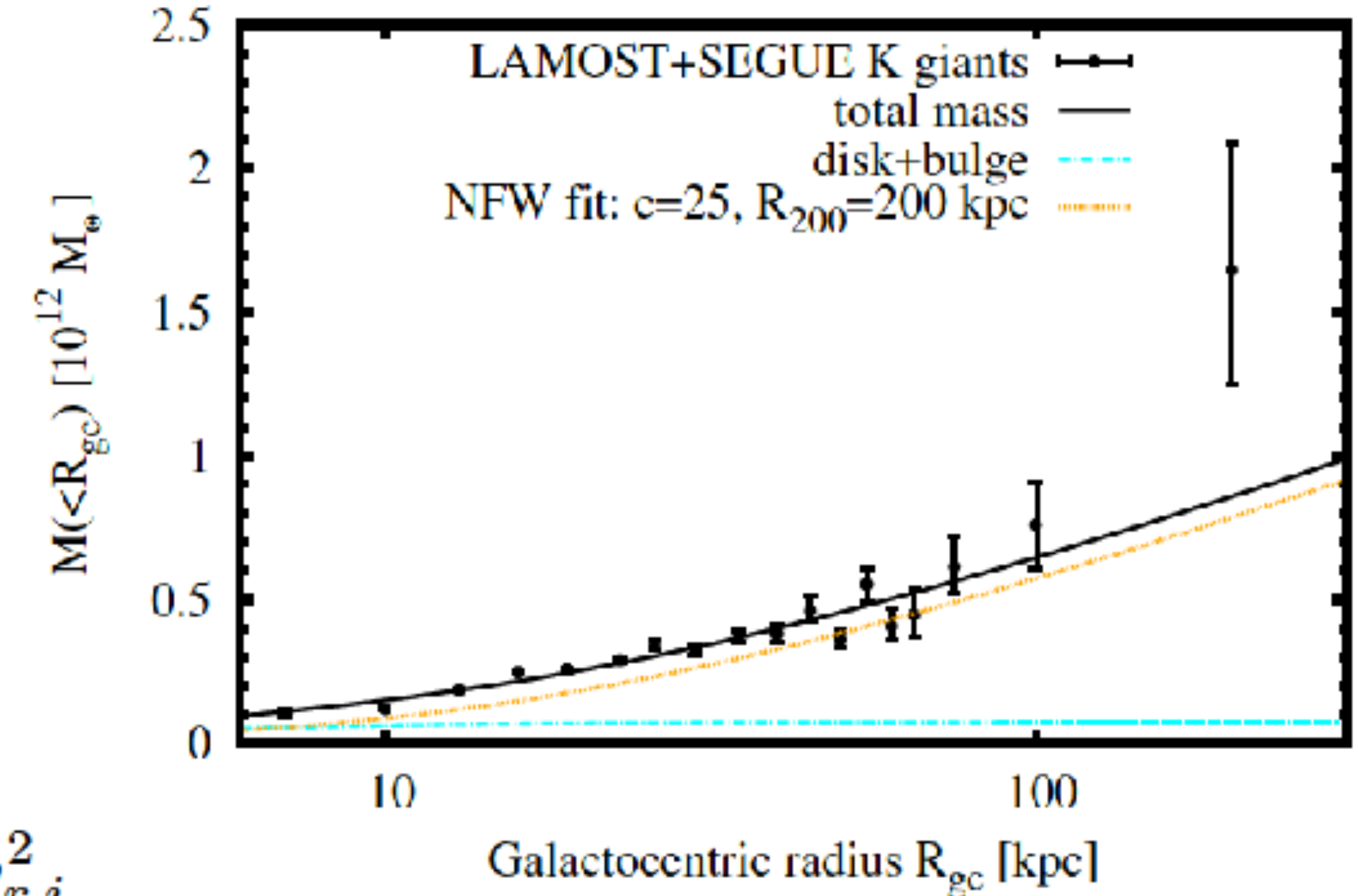
Mass distribution from LAMOST KG using mass estimator (Evans+ 2011)

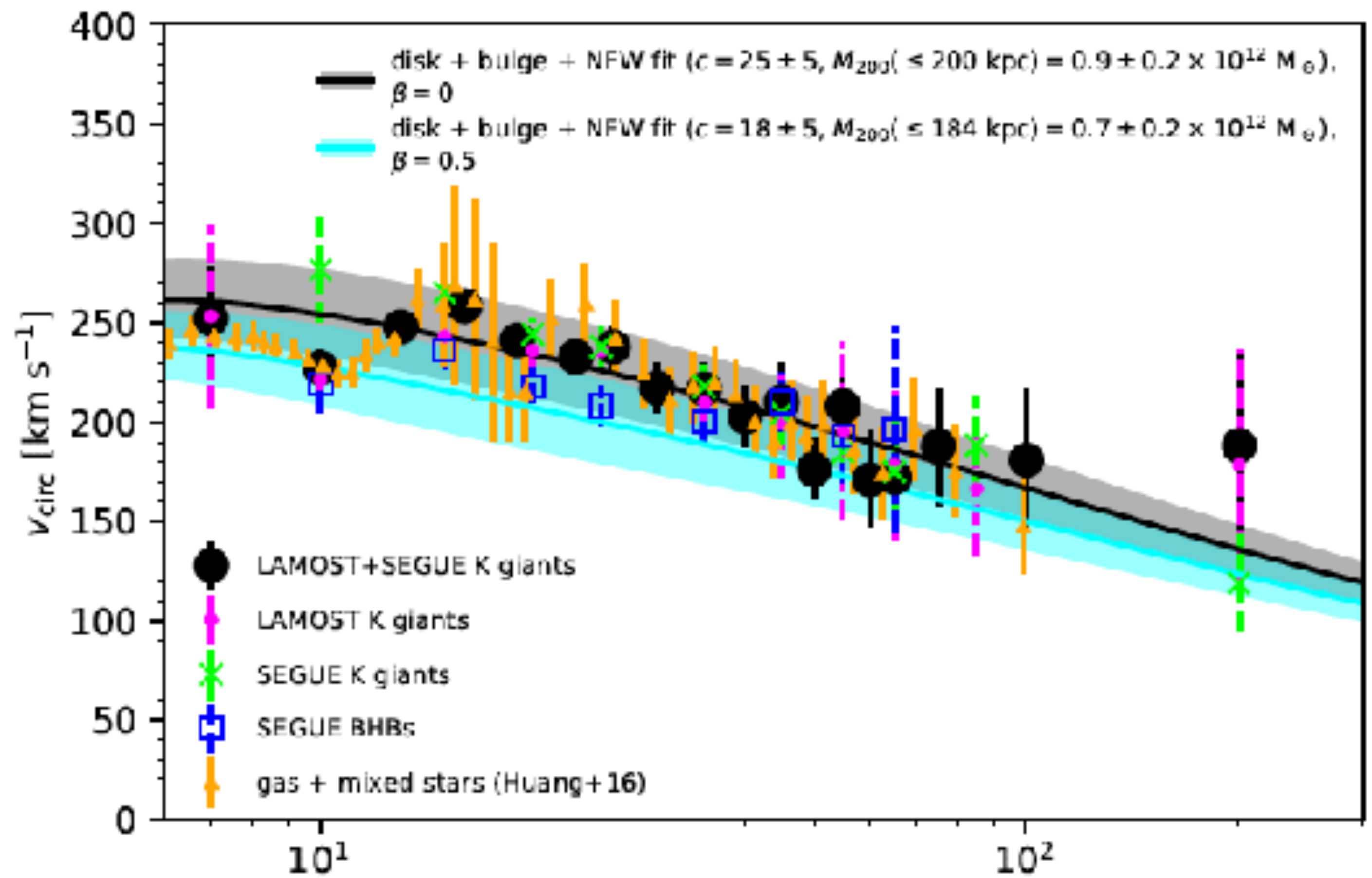
$$M_{\rm out} \approx \frac{R_{\rm out}^{0.5}(\alpha+\gamma-2\beta)}{GN}\sum_{i=1}^{N} R_i^{0.5} v_{r,i}^2$$

M_{200}=0.9+-0.2x$10^{12}M_{sun}$

c=25+-5

Sarah, Xue+ submitted





I need your help on

Which case should I use for MW dark matter halo?

- M_{200}, independent c and M_{200}, Ω_m=1
- M_{340}, independent c and M_{340}, Ω_m=0.3
- Should I use relation of $c(M_{vir})$ derived by simulations?

Summary&Thanks

- Halo is more flattened and more metal rich at radii < 20kpc
- The radial profile follows a single power-law $\sim r^{-4.2}$, **if** allowing flattening variation.

  The break might be in flattening, not in radial density.

- Radial profile & kinematics —> Halo mass $M_{vir} = 1.0 \pm 0.2 \times 10^{12} M_{\odot}$ (light halo!)
- Degree of substructures varies strongly with distances and stellar pops.
- LAMOST halo K giants are potential to map the Galactic halo.