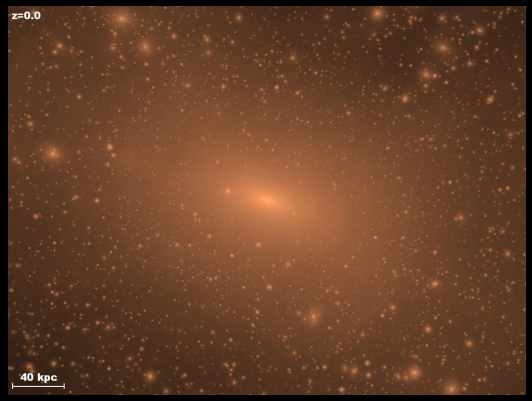
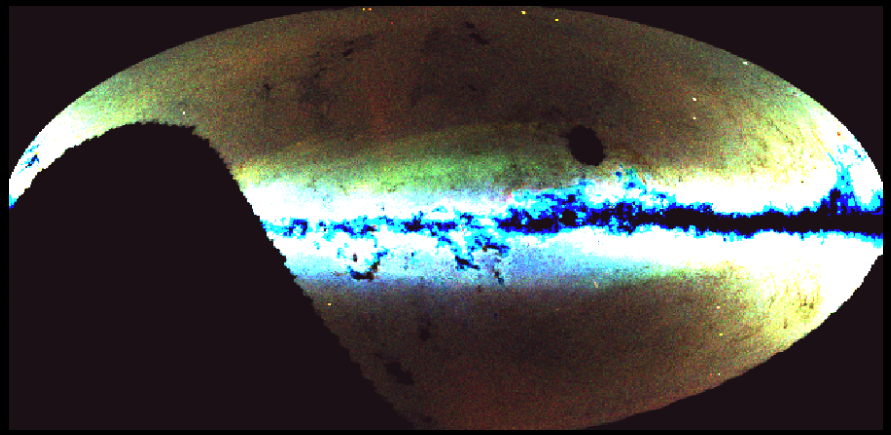
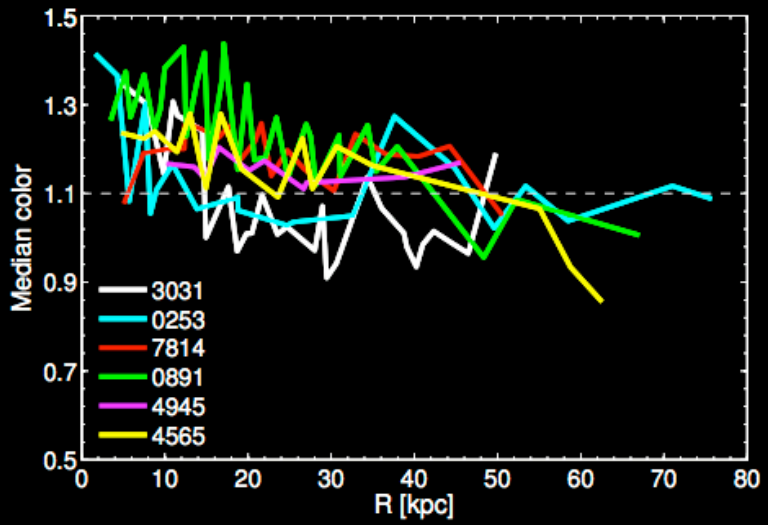
The stellar halos of disk galaxies reflect the growth histories of their dark matter halos



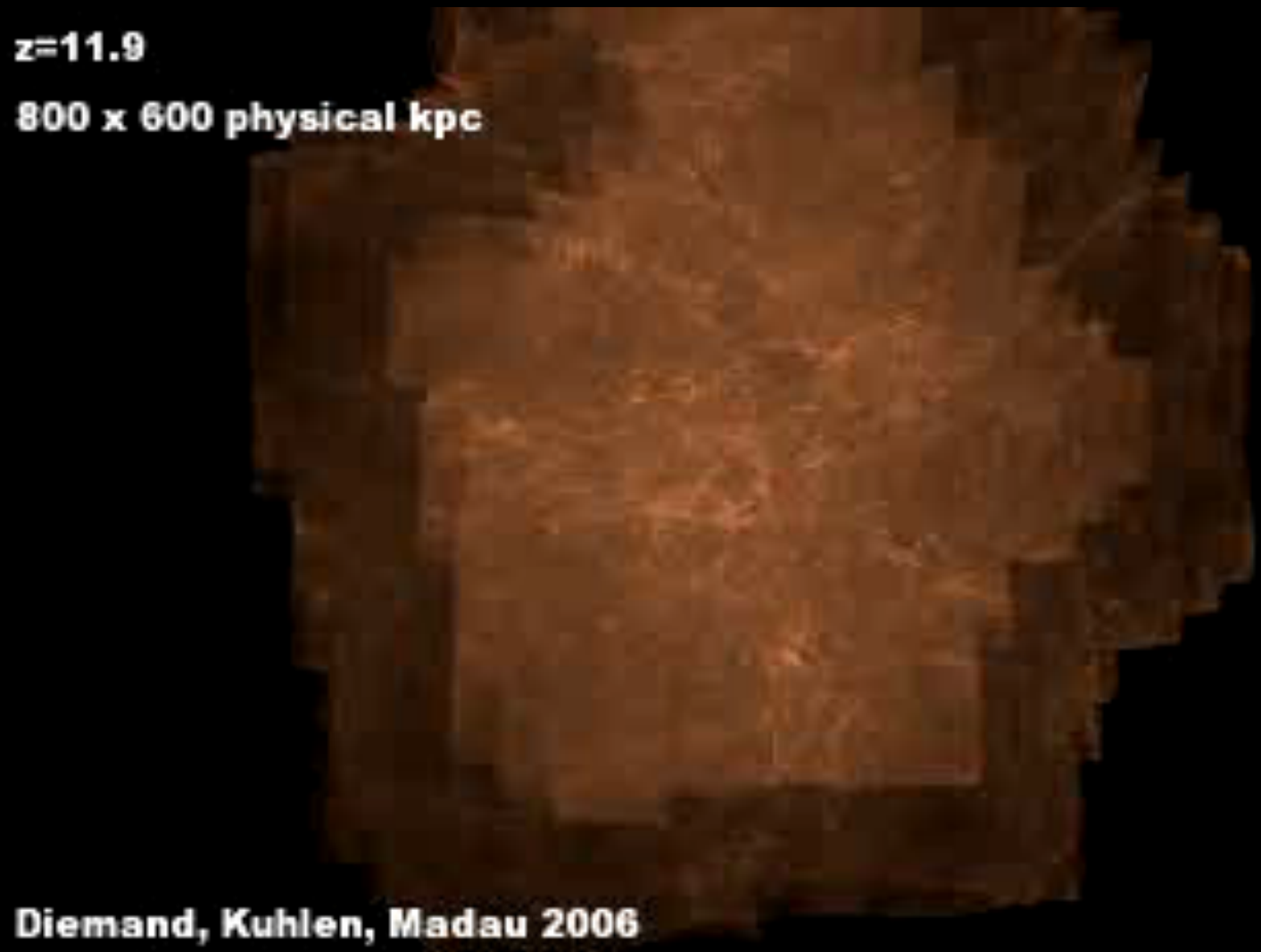


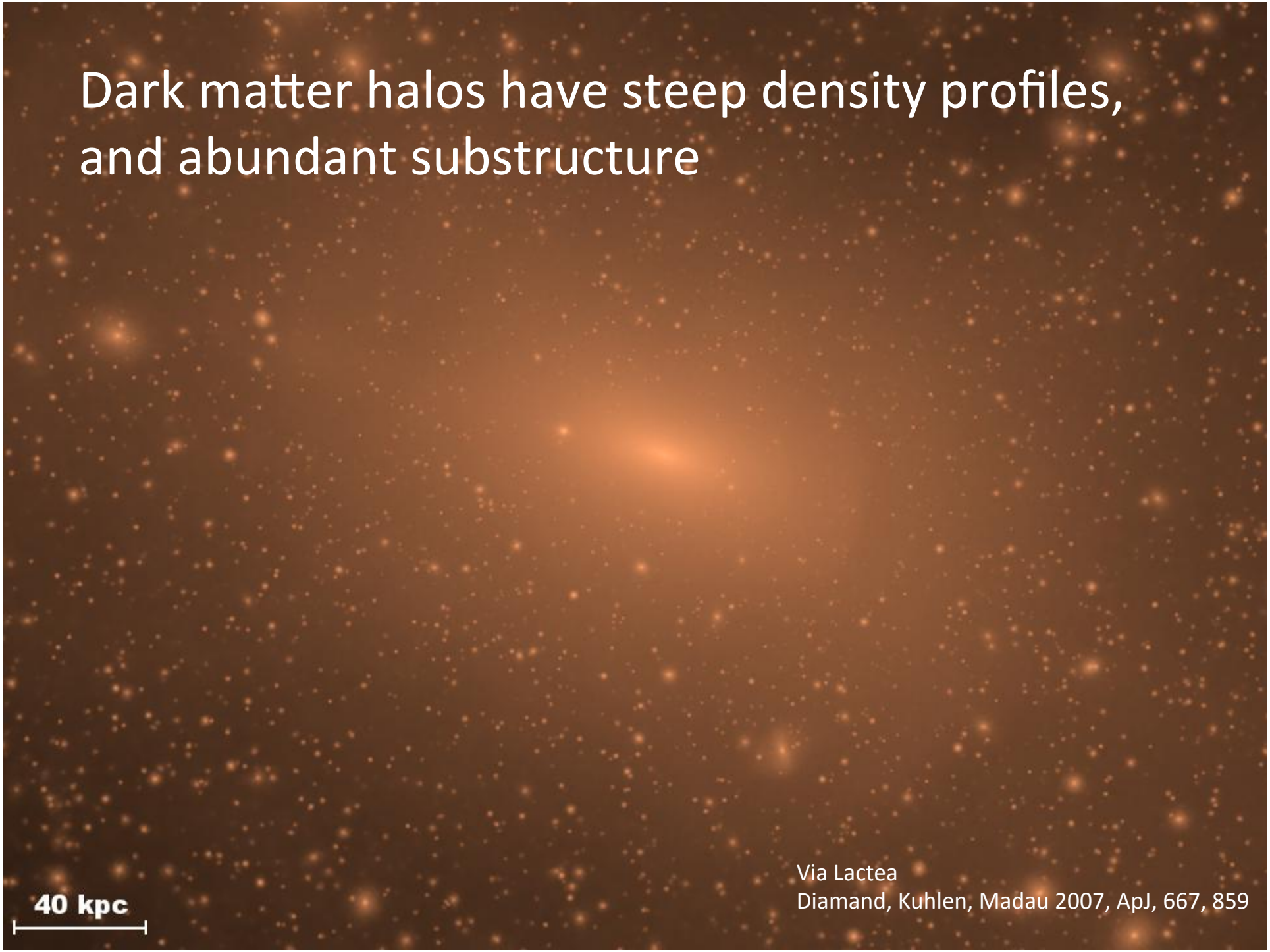


Eric Bell, University of Michigan

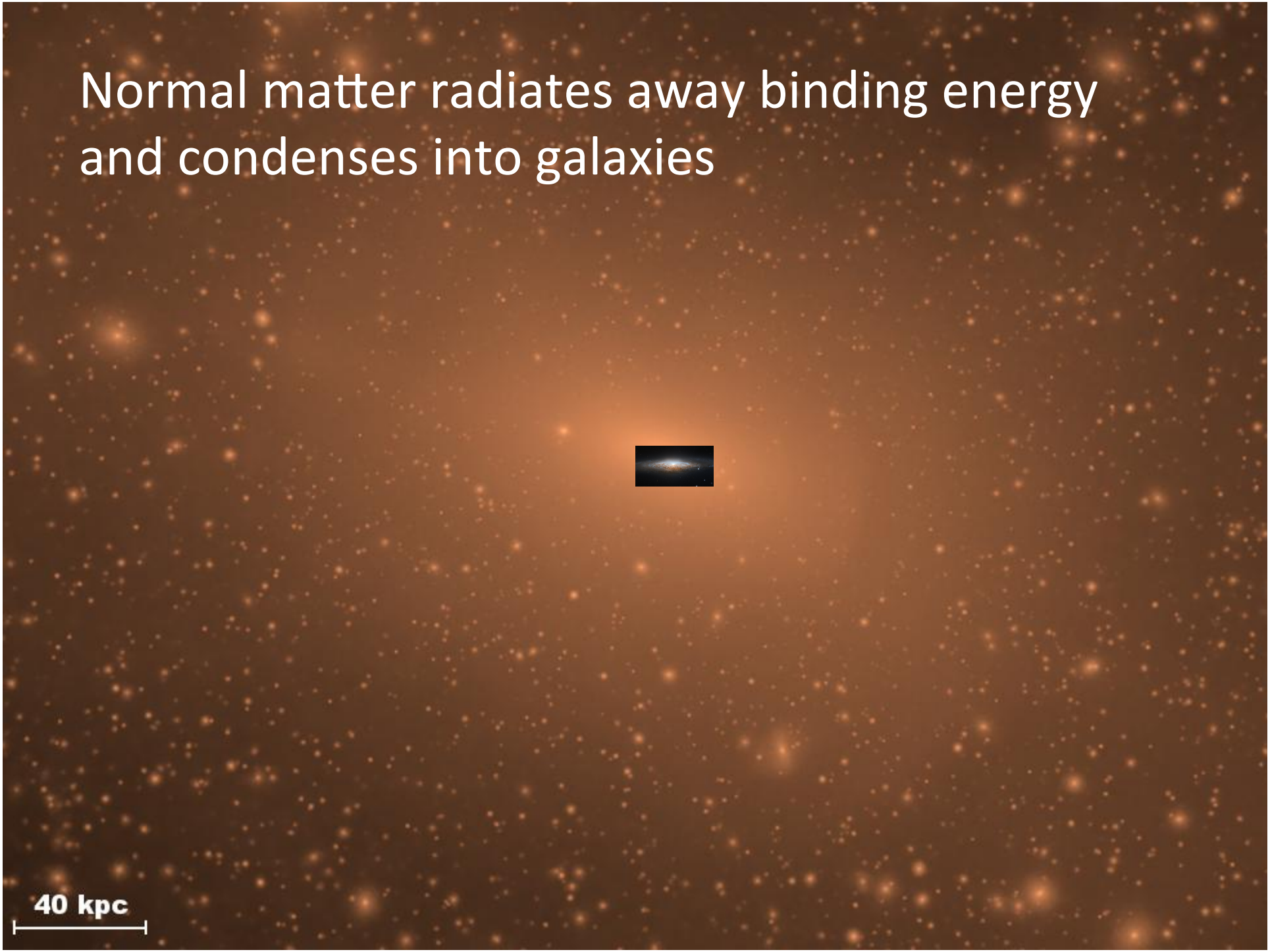
Colin Slater, Antonela Monachesi,
Benjamin Harmsen, Jeremy Bailin
PanSTARRS-1 team, GHOSTS team

Dark matter is thought to be the central driver of galaxy formation and evolution

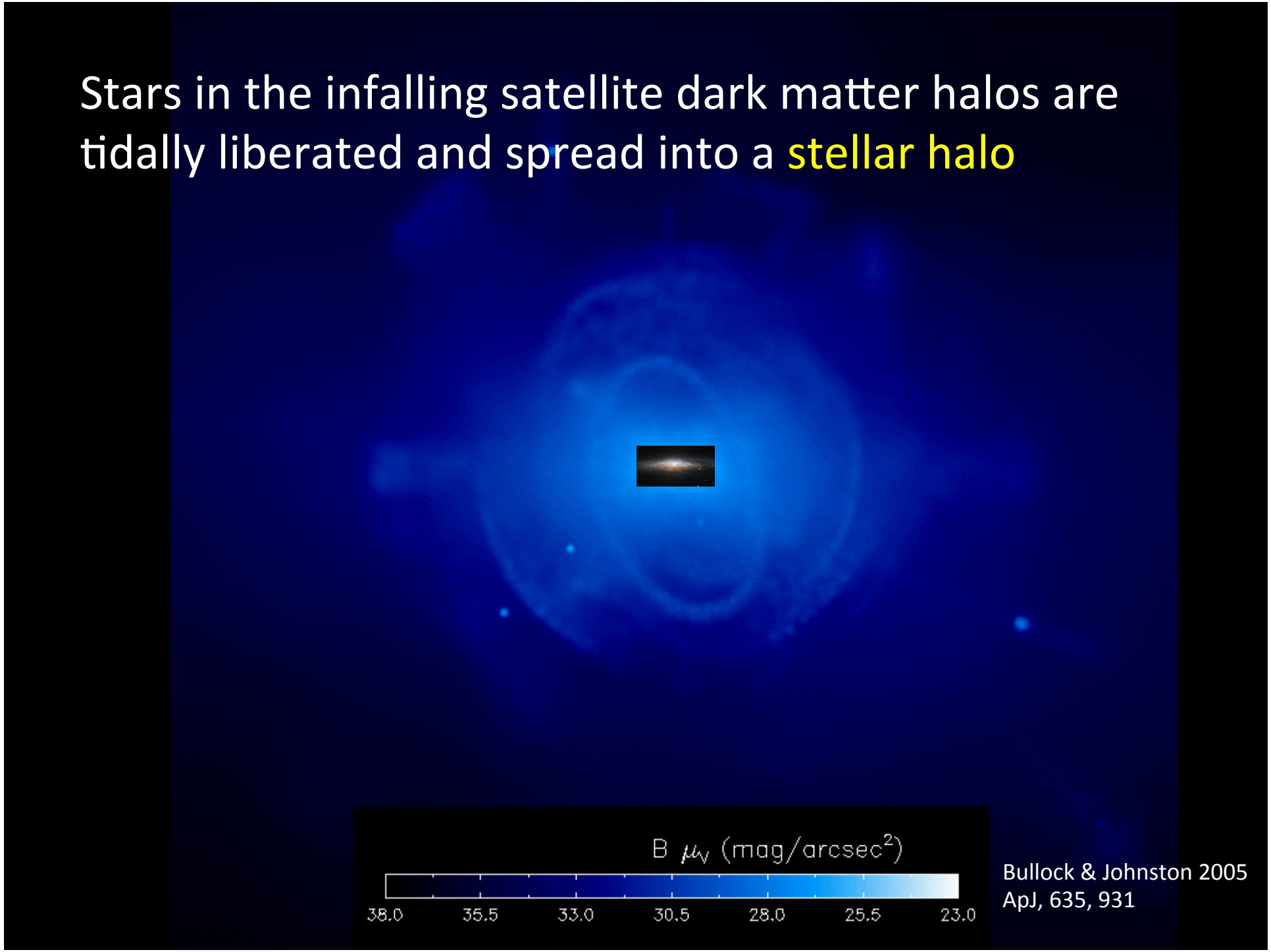



Dark matter halos have steep density profiles,
and abundant substructure
40 kpc
Via Lactea
Diamand, Kuhlen, Madau 2007, ApJ, 667, 859

Normal matter radiates away binding energy and condenses into galaxies

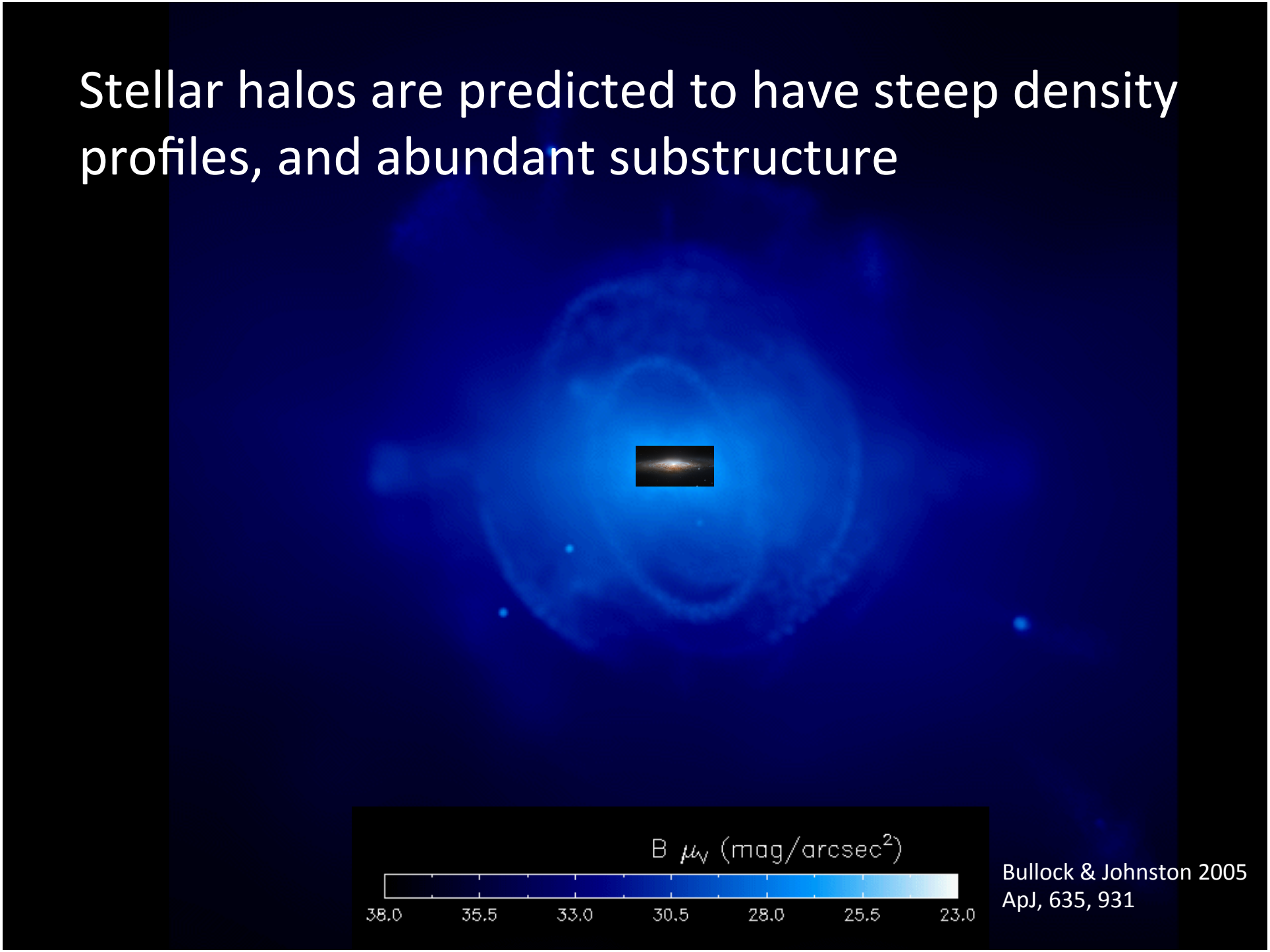

Normal matter radiates away binding energy
and condenses into galaxies
40 kpc

Stars in the infalling satellite dark matter halos are tidally liberated and spread into a stellar halo



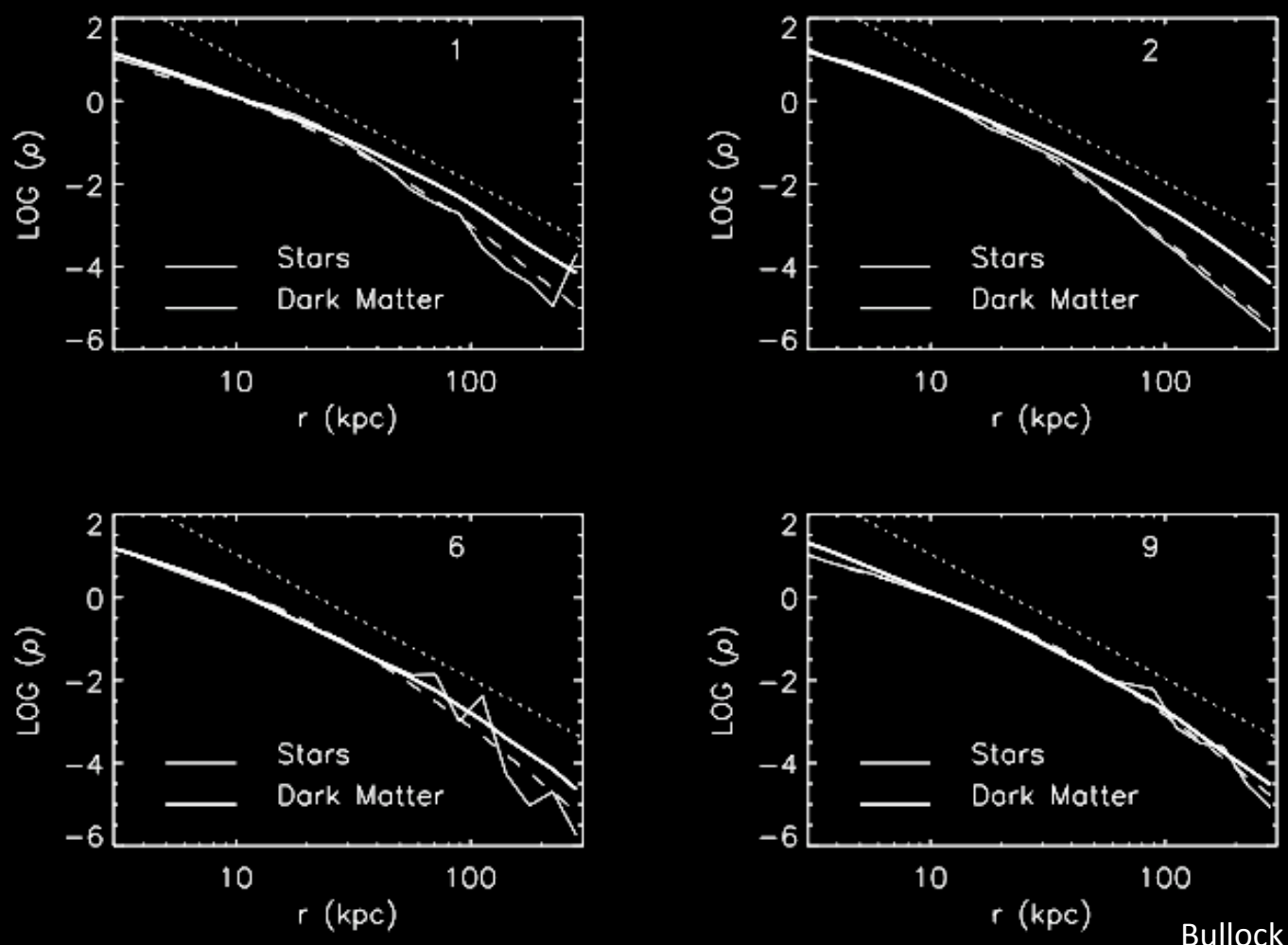
Bullock & Johnston 2005
ApJ, 635, 931

Stellar halos are predicted to have steep density profiles, and abundant substructure



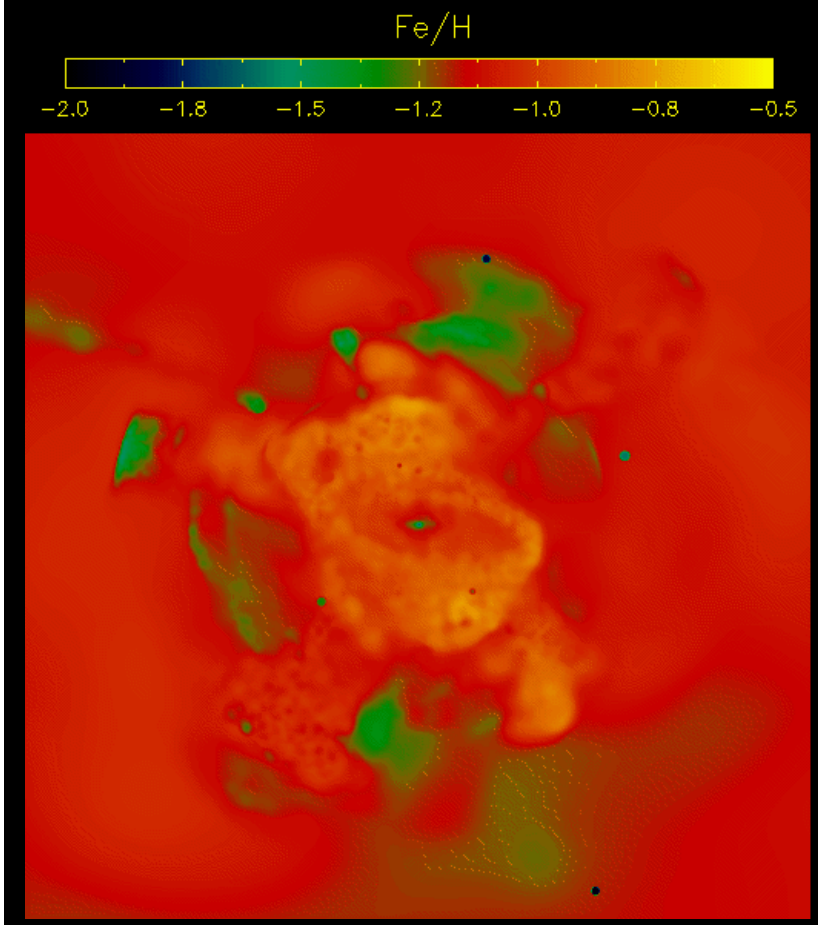
Bullock & Johnston 2005
ApJ, 635, 931

Stellar halos are predicted to have steep density profiles, and abundant substructure

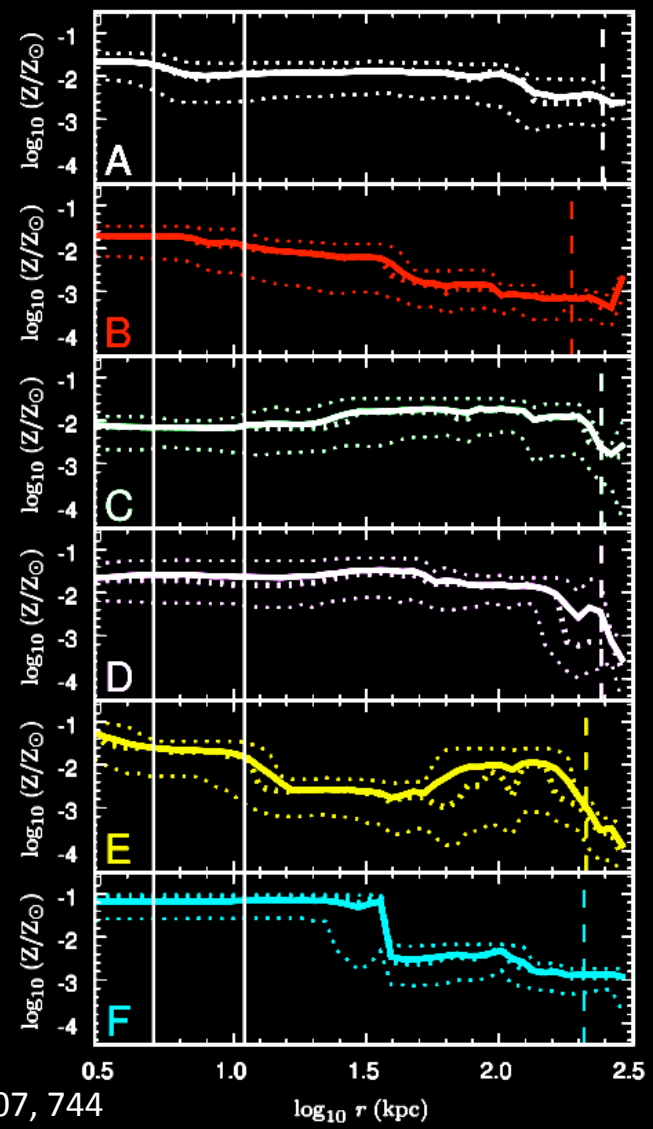


Bullock & Johnston 2005
ApJ, 635, 931

The stellar populations of halos should reflect the satellites that form them

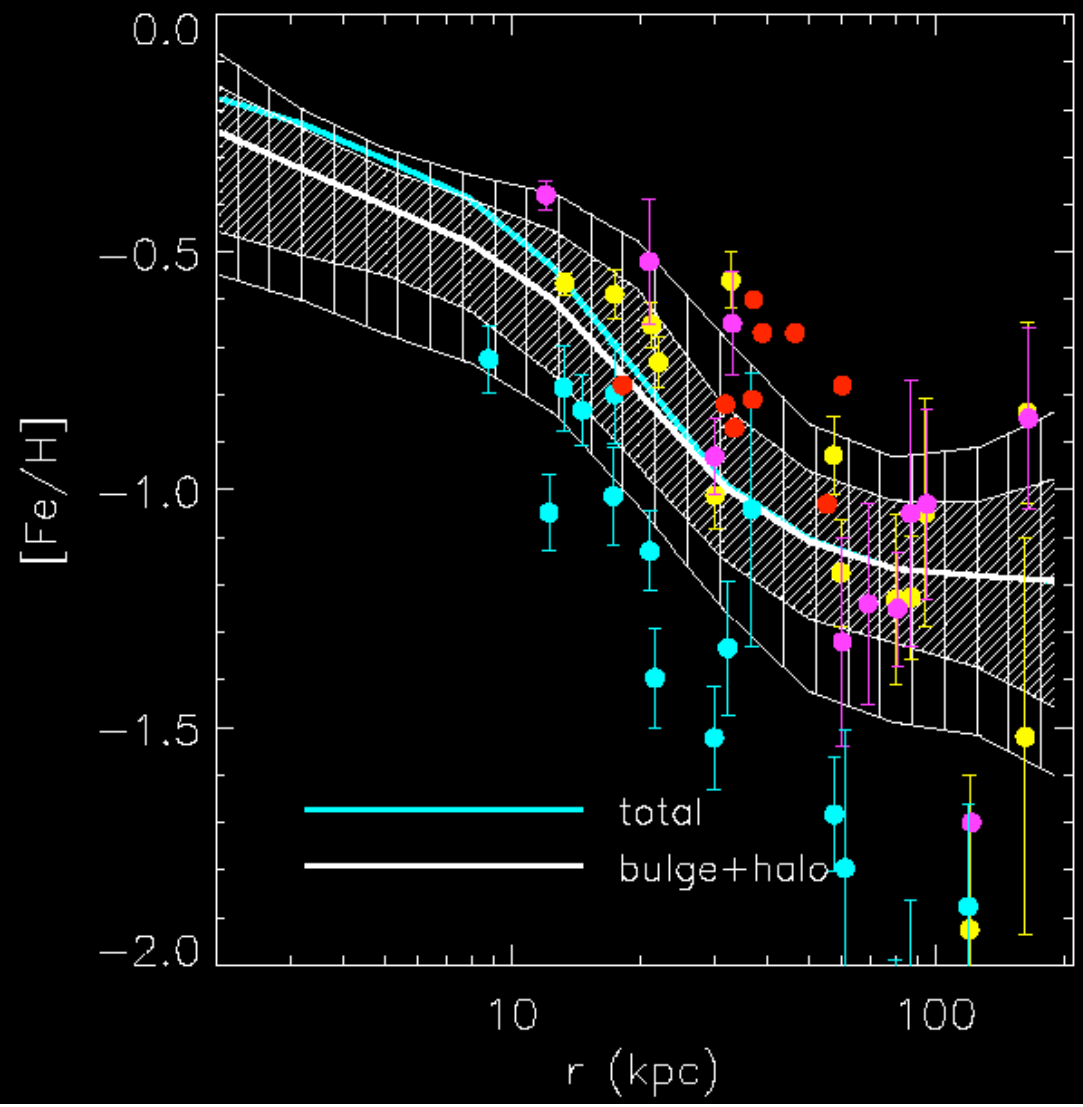


Bullock & Johnston 2005
ApJ, 635, 931



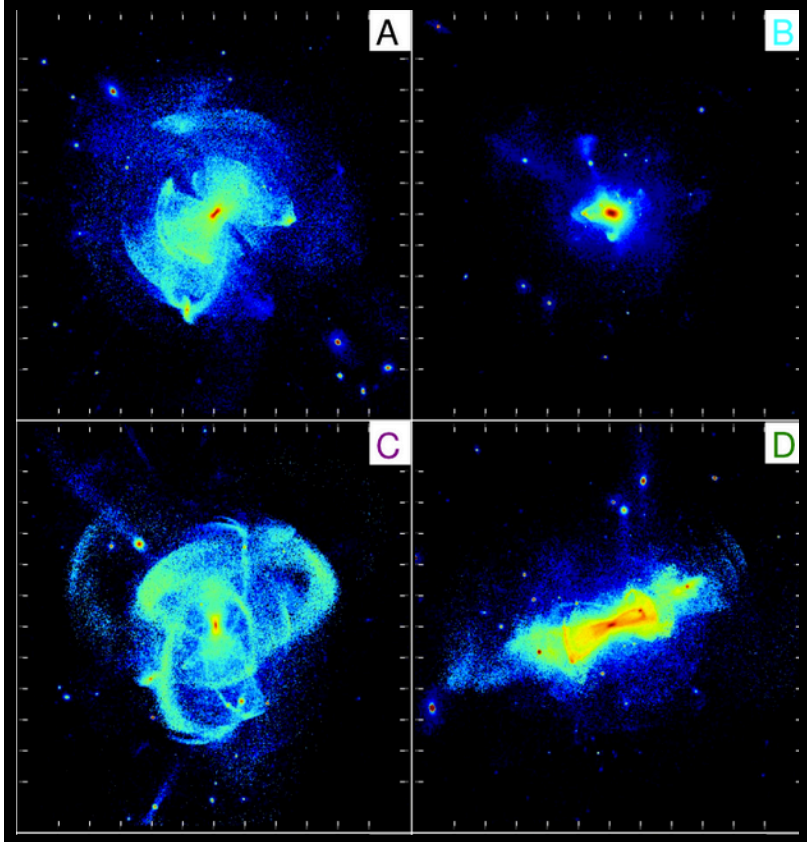
N-body only accreted halos
Cooper et al. 2010, MNRAS, 407, 744

Metallicity gradients should be large if many halo stars are kicked-up from the disk

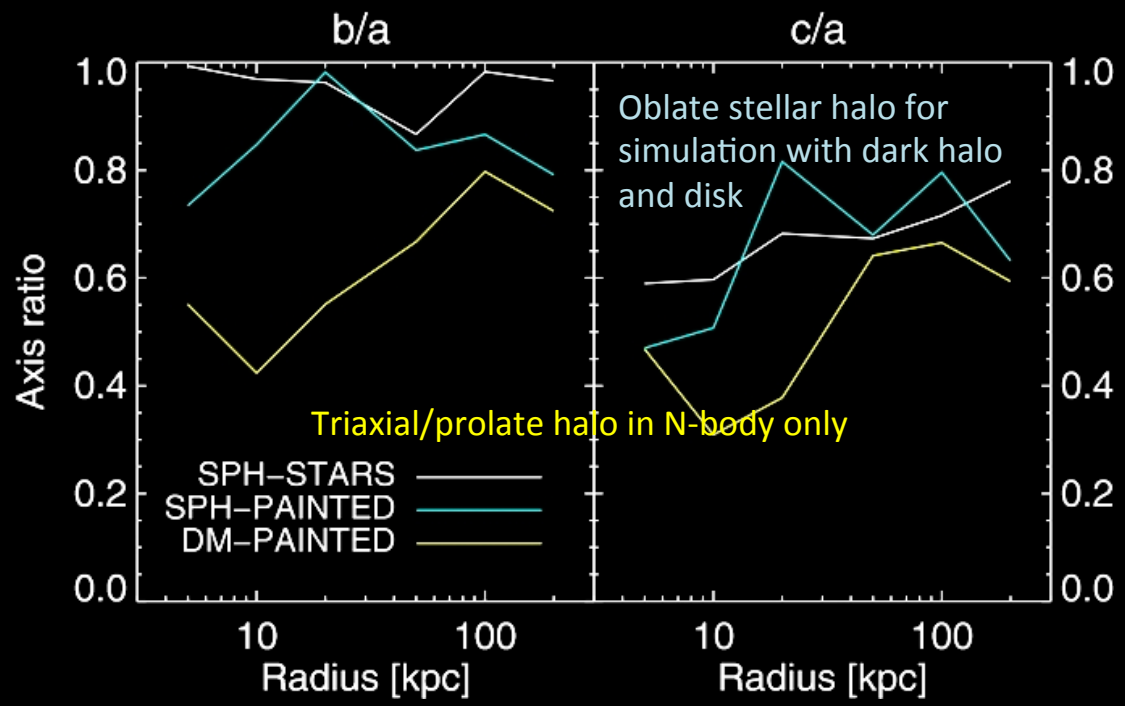


Font et al. 2011
MNRAS, 416, 2802

The dark and stellar halos may be made oblate by the influence of the disk gravity

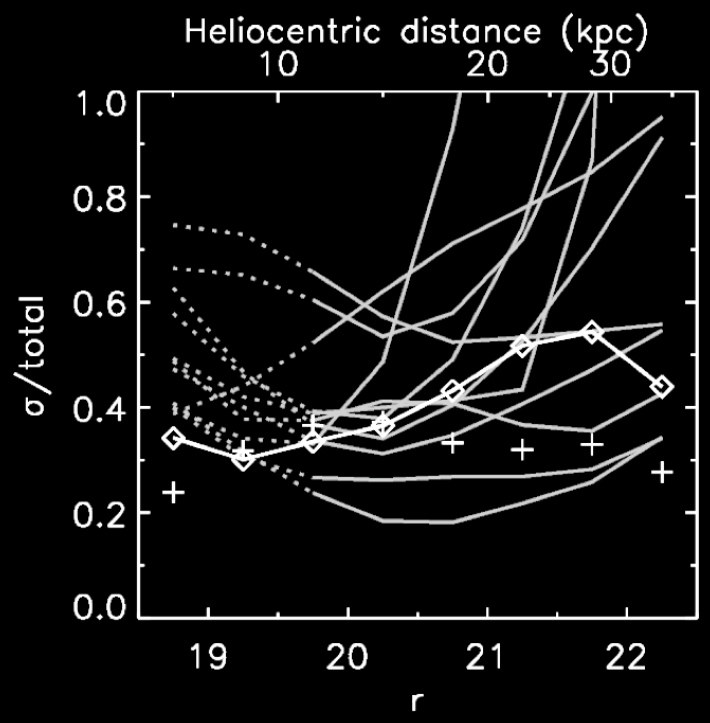


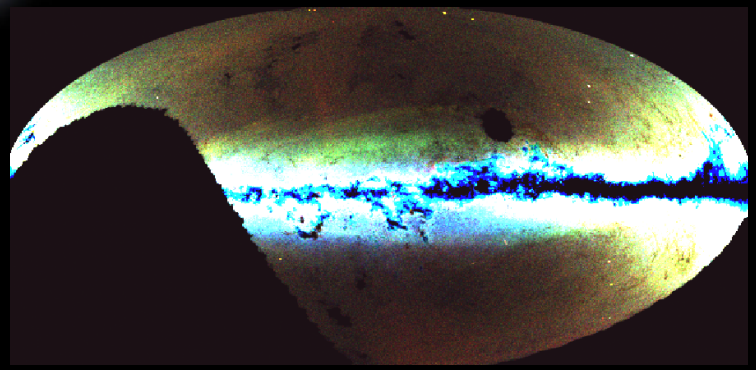
N-body only triaxial halos – 300kpc boxes
Cooper et al. 2010, MNRAS, 407, 744



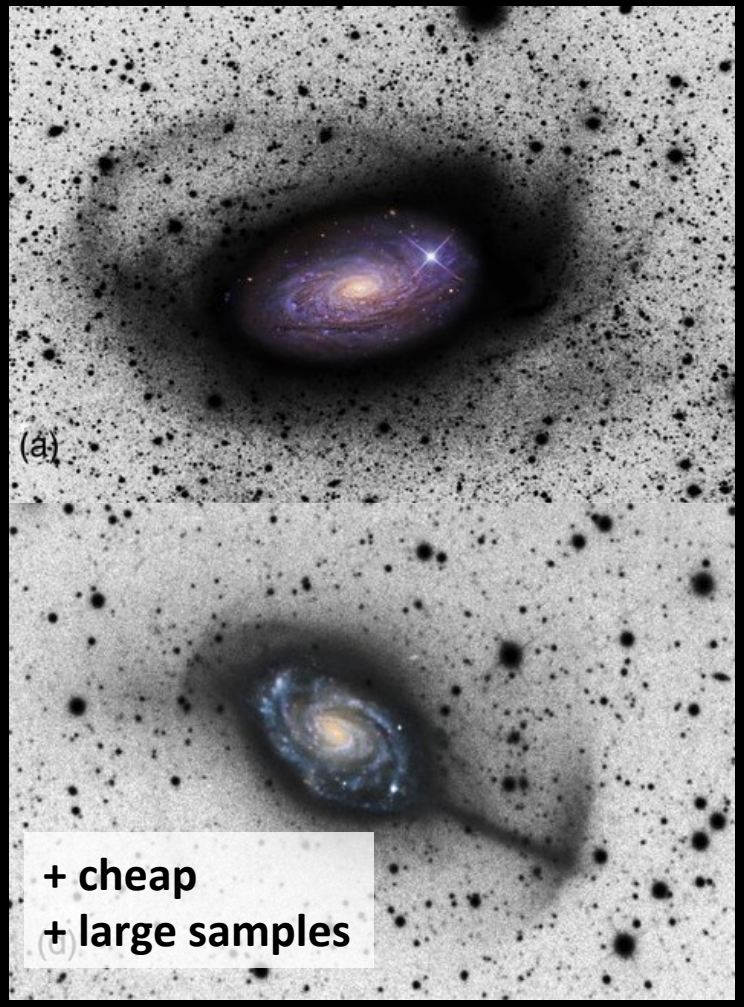
Bailin, Bell et al. 2014, ApJ, 783, 95

My goal has been to measure the structures, stellar populations and shapes of stellar halos

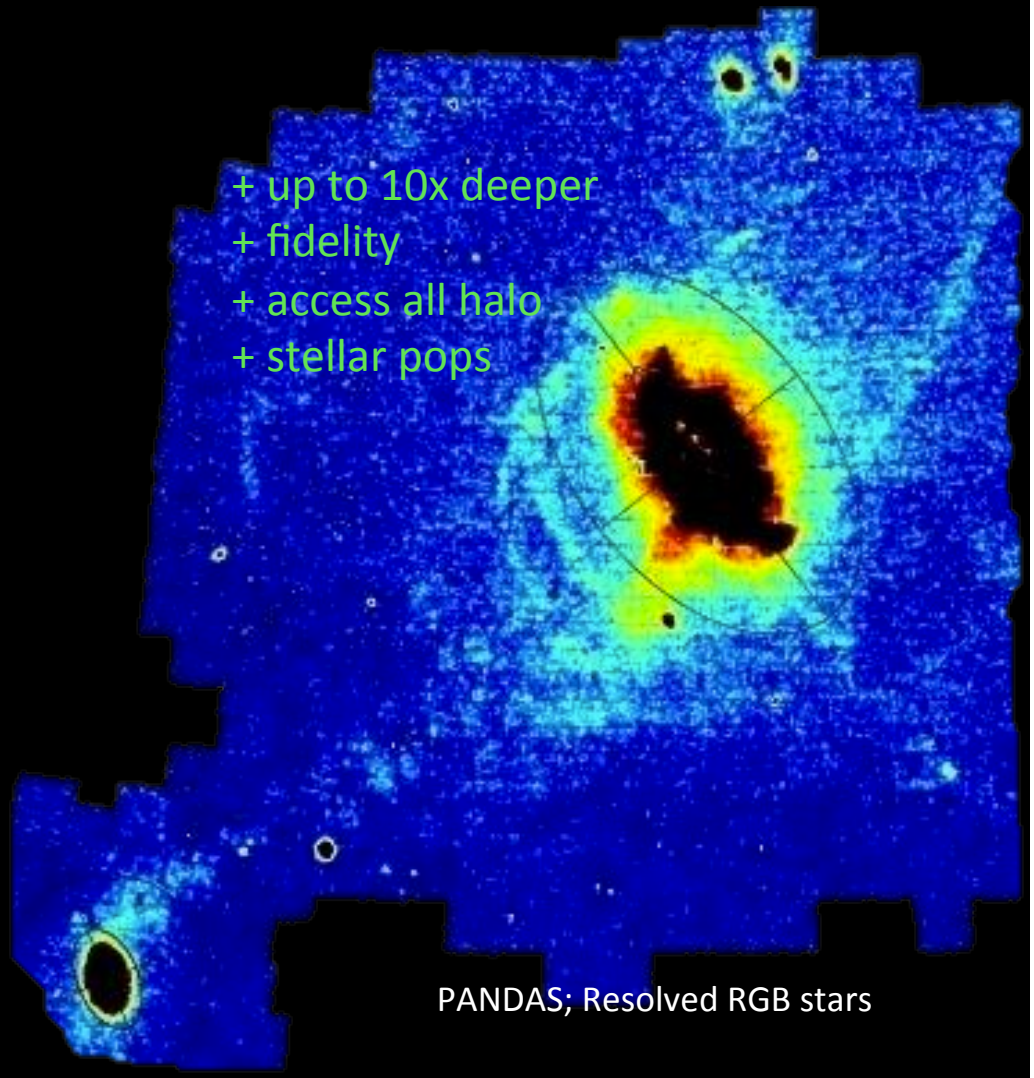




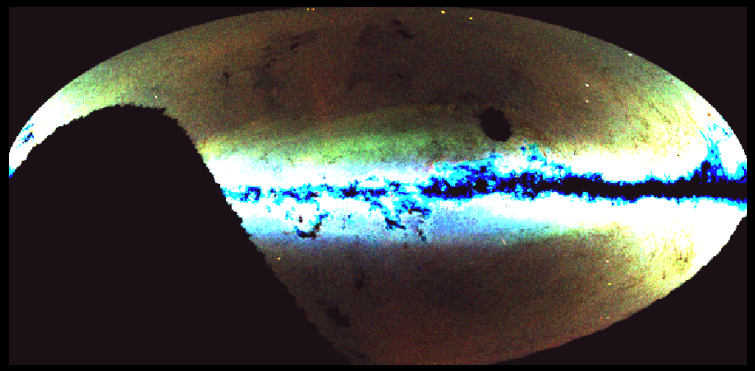
Resolving the stars in halos is a sensitive way to quantify their structures and stellar populations



Martinez-Delgado et al. 2010; AJ,140, 962

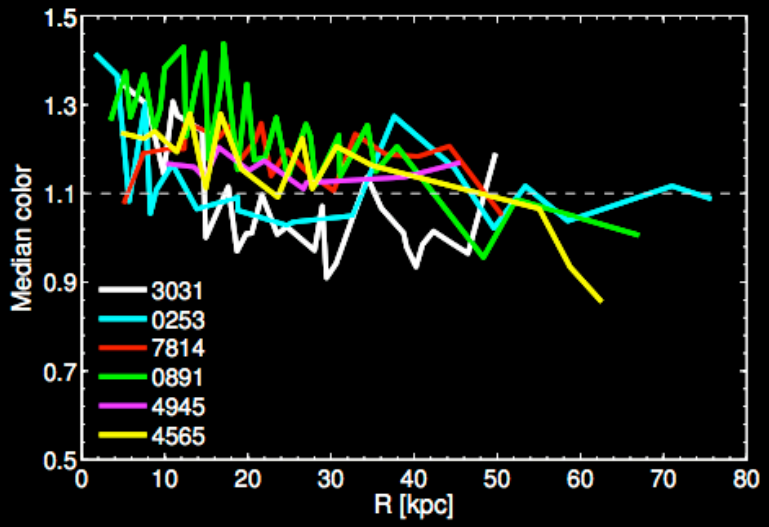


Stellar halos are an excellent way to understand galaxy growth

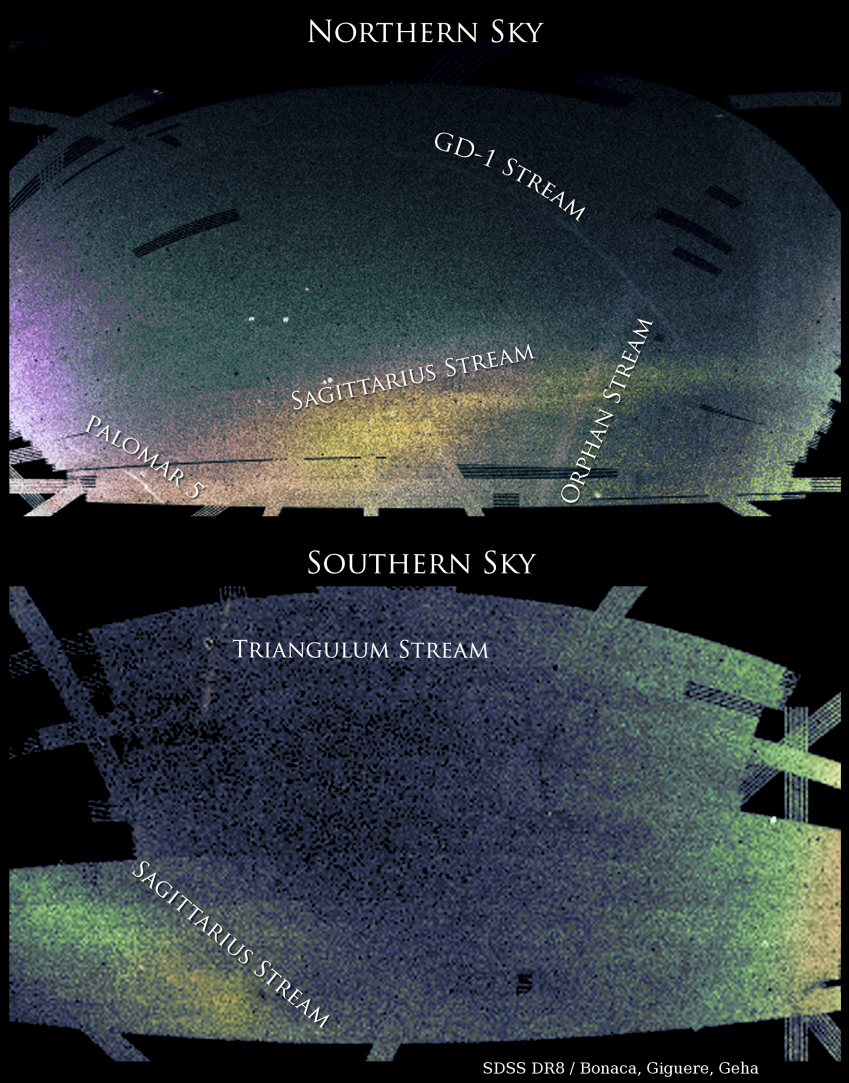


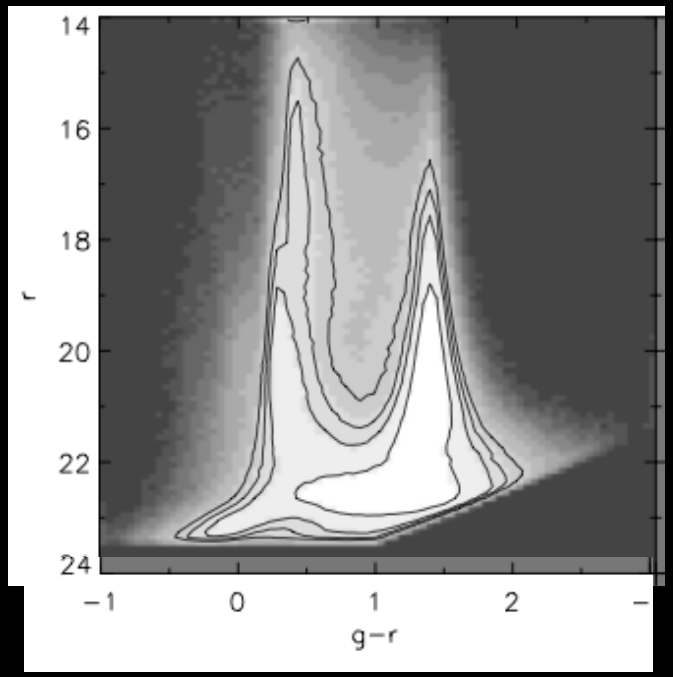
Part I : What are the properties of the Milky Way's halo?

Part II : How does this generalize to other ~Milky Way mass galaxy halos?



What is the Milky Way stellar halo like?



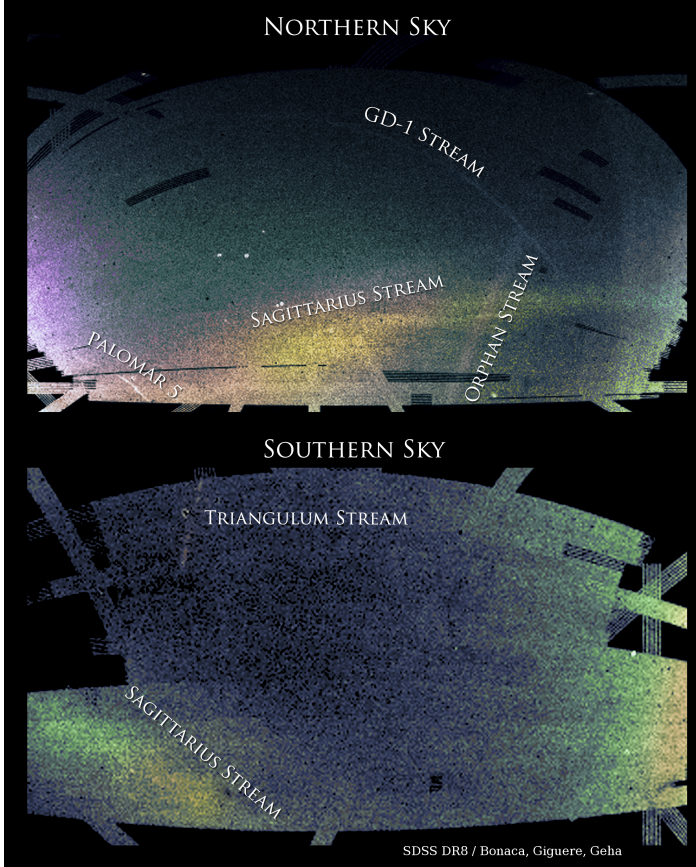


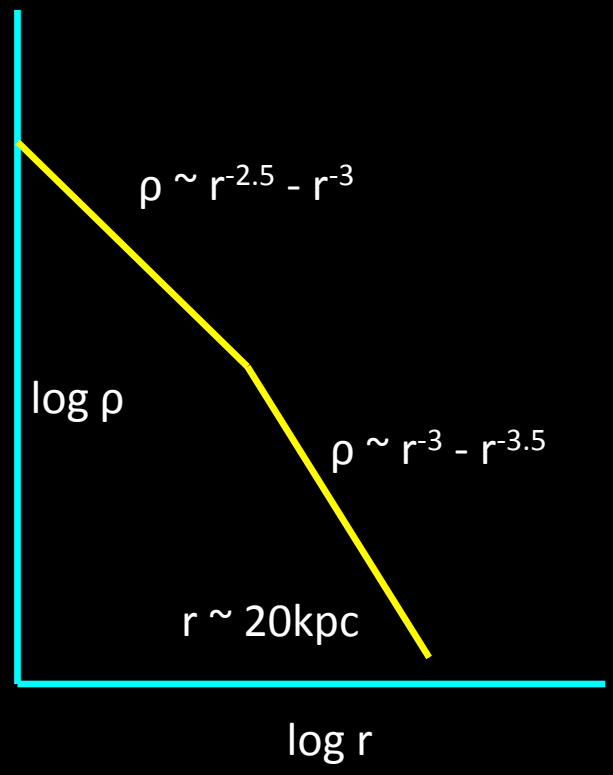
SDSS DR8 (Bonaca/Geha)

Stars with MSTO colors (0.2<g-r<0.4; 19<r<22.5)
approximate standard candles

Blue ~ 8kpc Red ~ 25kpc

At r<30kpc, the Milky Way's stellar halo has a r^{-3} profile with $M<\sim10^9\ M_\odot$, and axis ratio c/a ~ 0.6



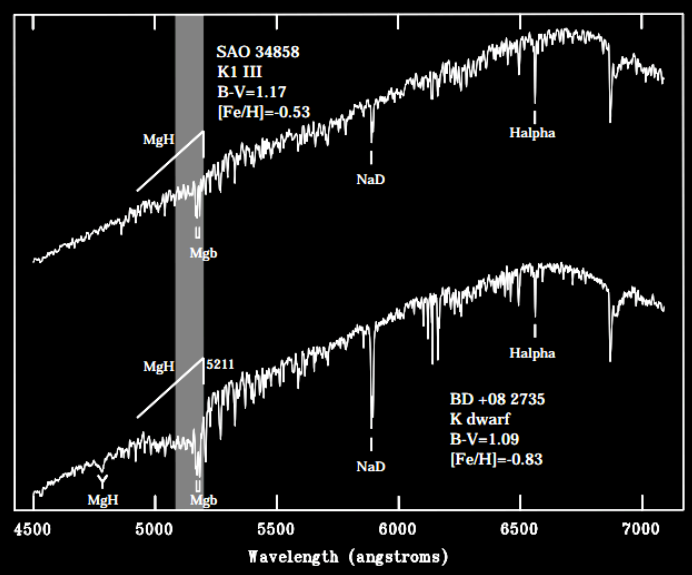


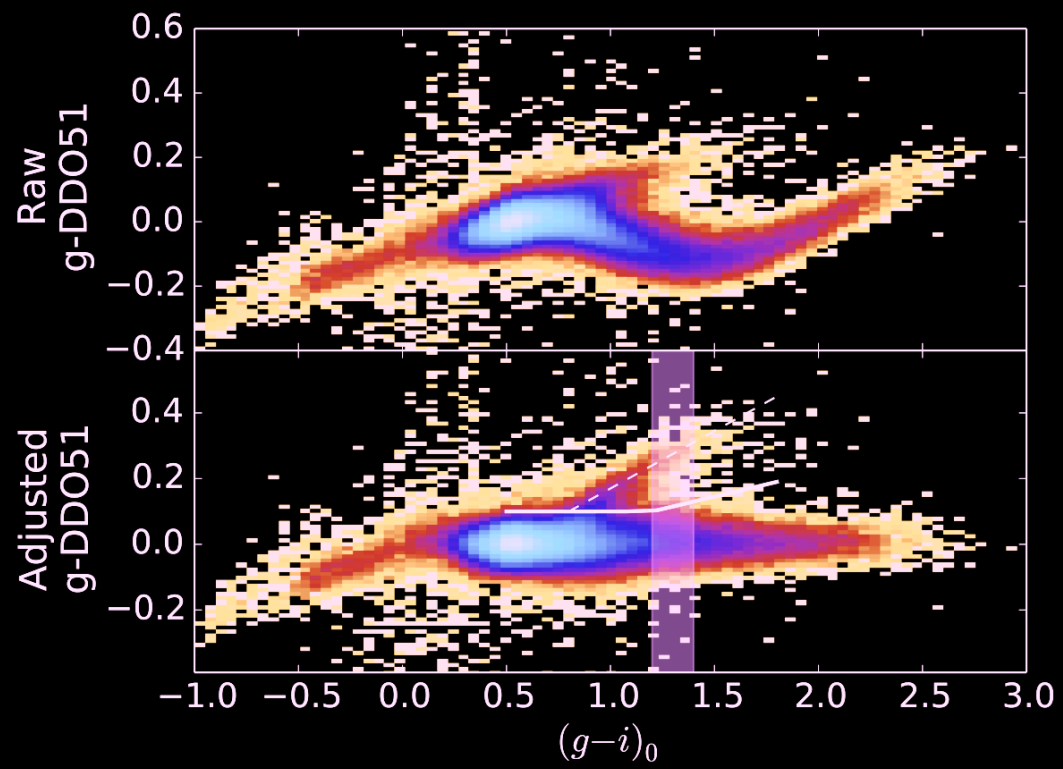
Morrison et al. 2000
Chiba & Beers 2000
Ivesic et al. 2000
Lemon et al. 2004
Xu et al. 2006
Newberg, Yanny et al. 2007
Bell et al. 2008

$\rho \sim r^{-3}$

c/a ~ 0.6
i.e., stellar halo is oblate

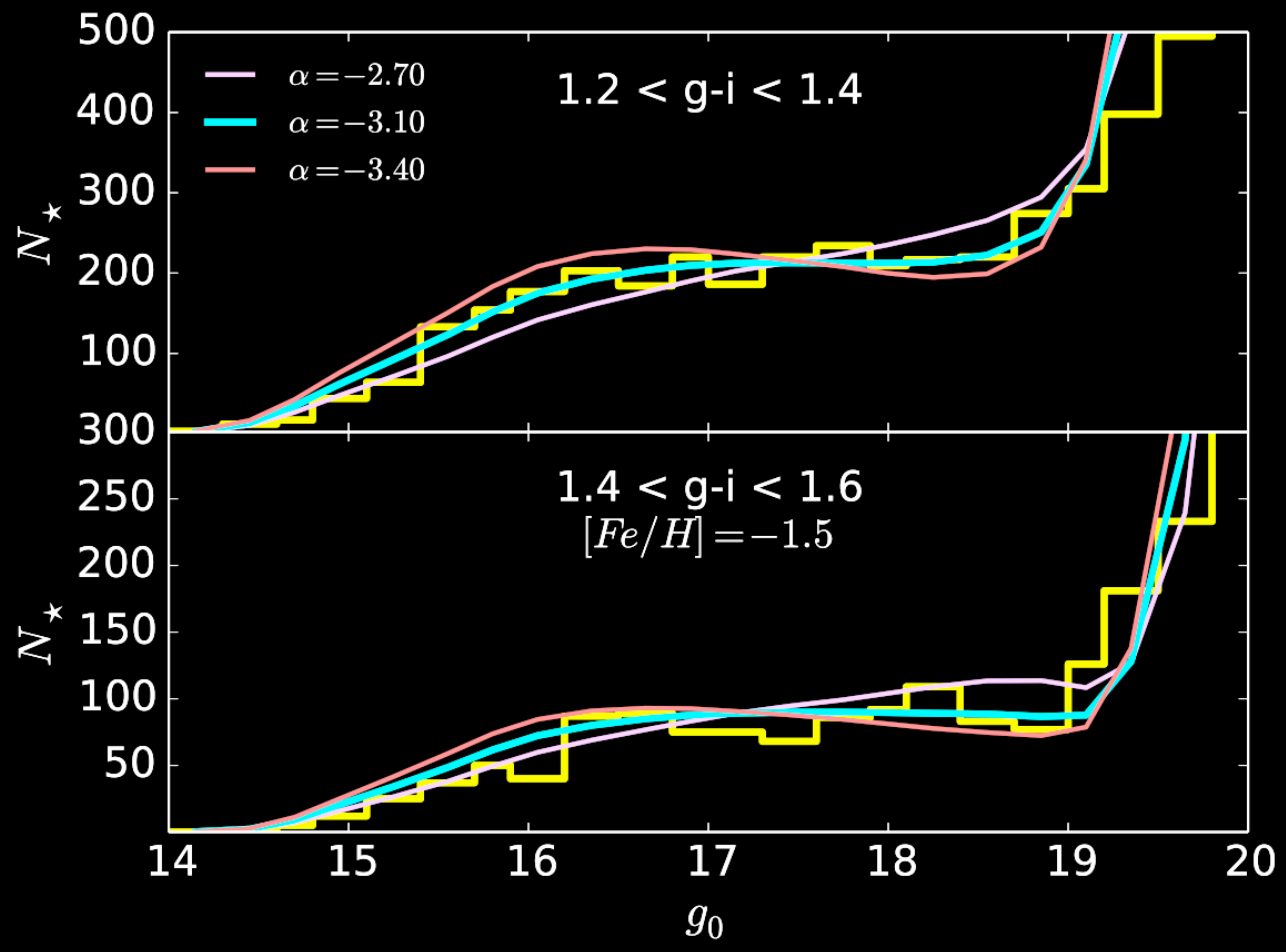
At r>30kpc, we use a large photometric K-giant survey to measure stellar halo structure





Colin Slater, David Nidever, Jeff Munn, Eric Bell

At 30<r/kpc<100, the Milky Way's stellar halo has a r^{-3} profile with M<~10^9 $M_\odot$



Colin Slater, David Nidever, Jeff Munn, Eric Bell

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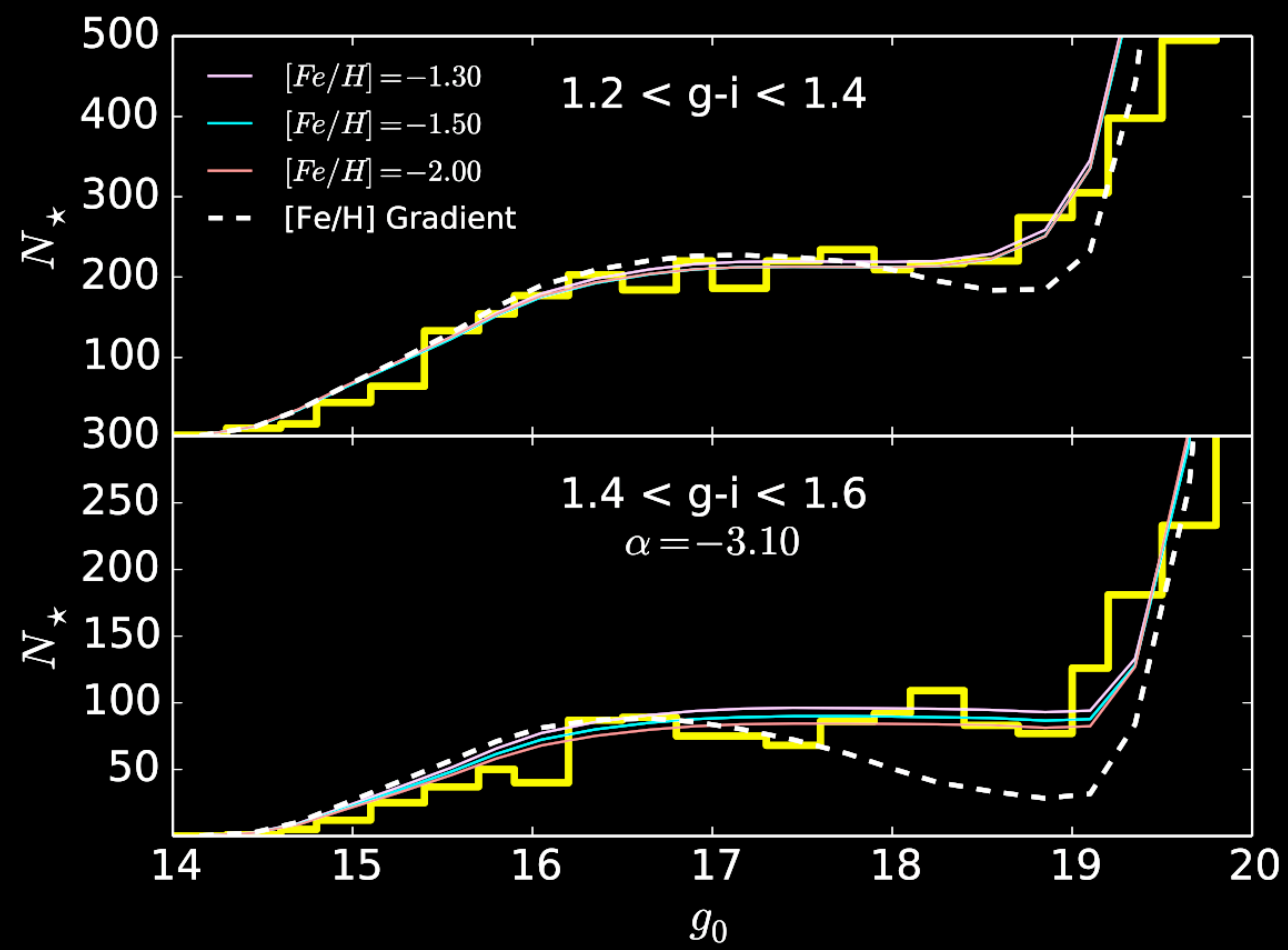

Colin Slater, David Nidever, Jeff Munn, Eric Bell

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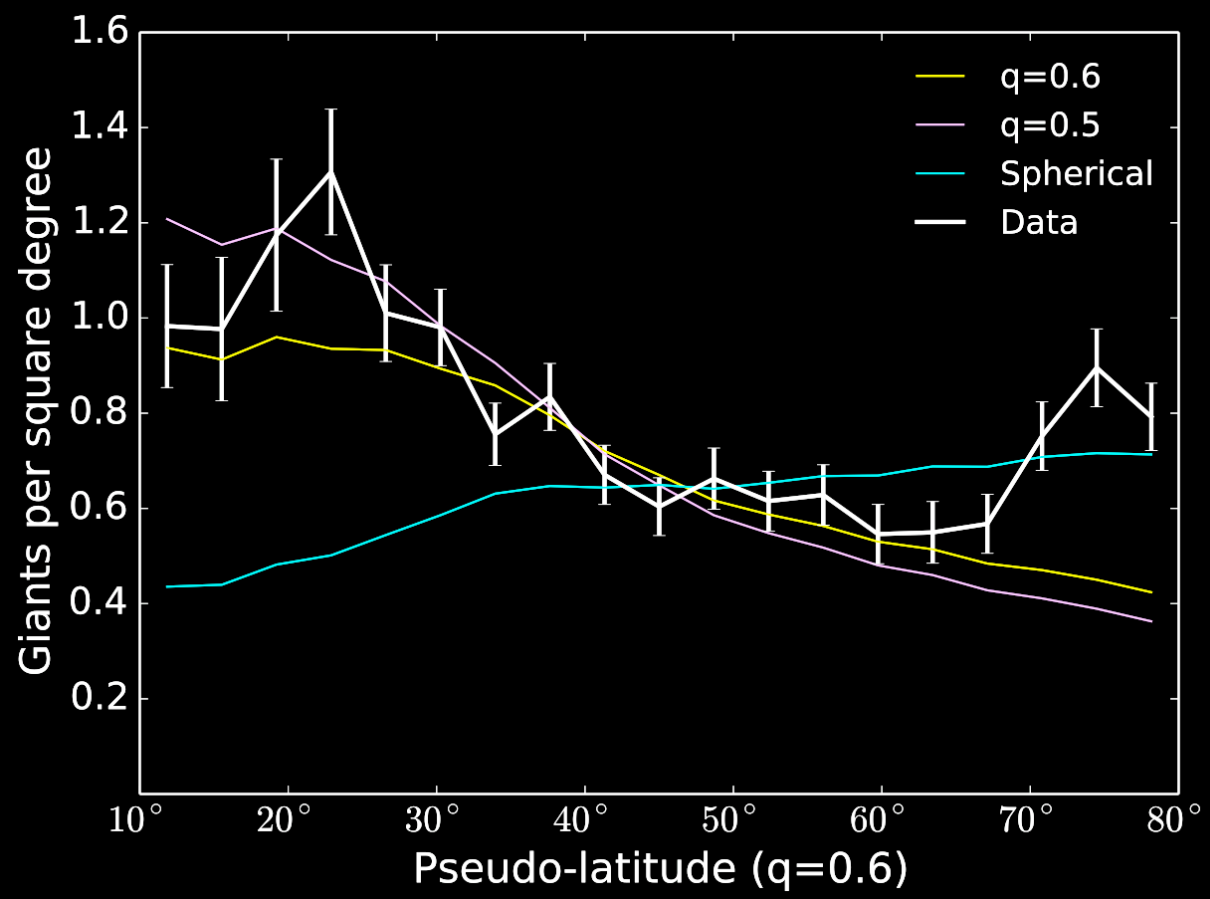
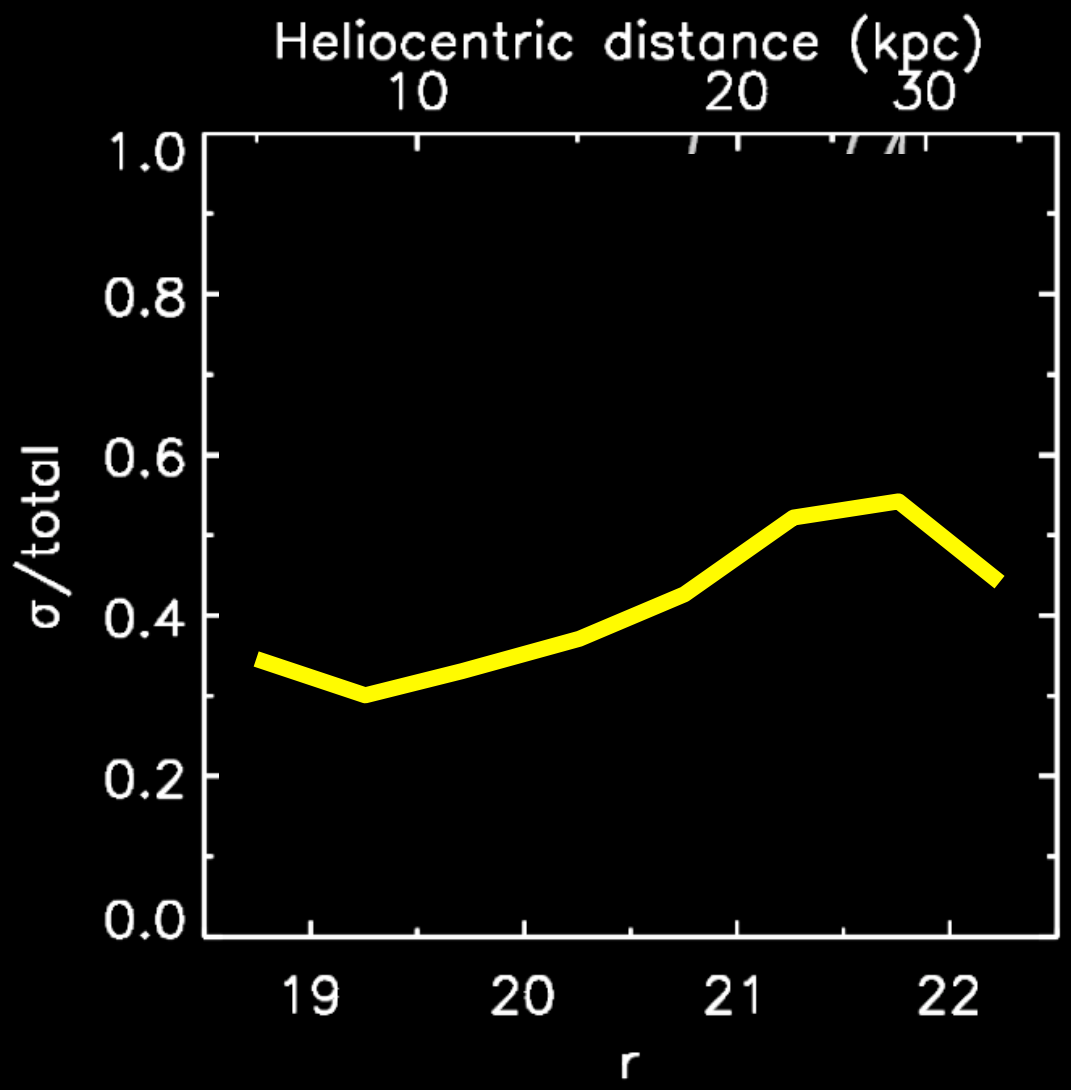
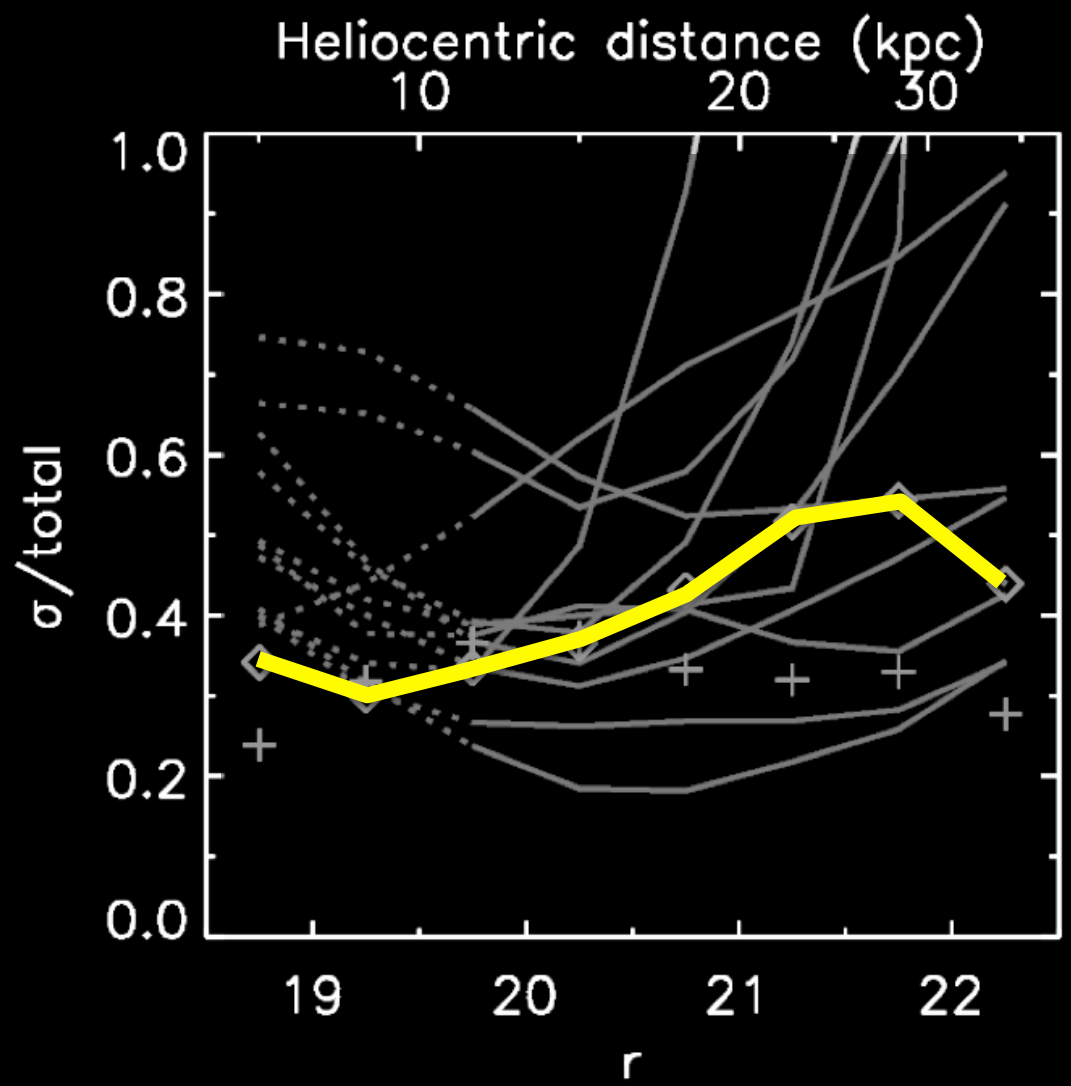


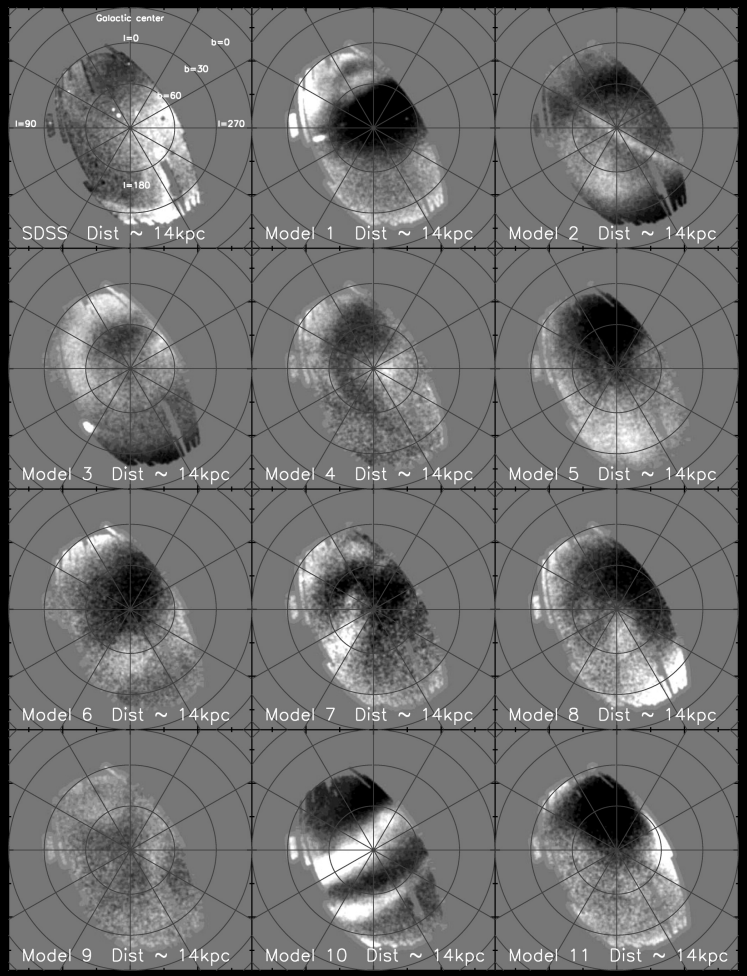
Colin Slater, David Nidever, Jeff Munn, Eric Bell

Our stellar halo is poorly fit by a smooth model



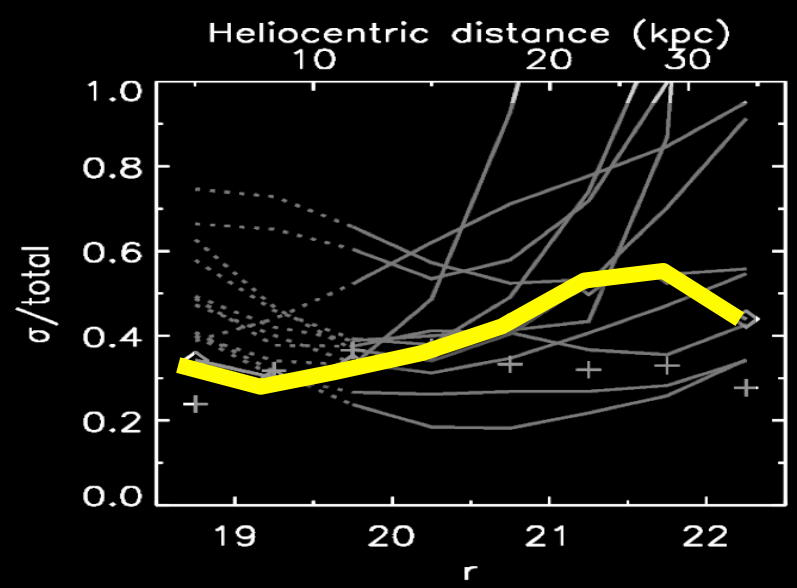
Substructure is quantitatively in accord with simulations of halo formation in a cosmological context

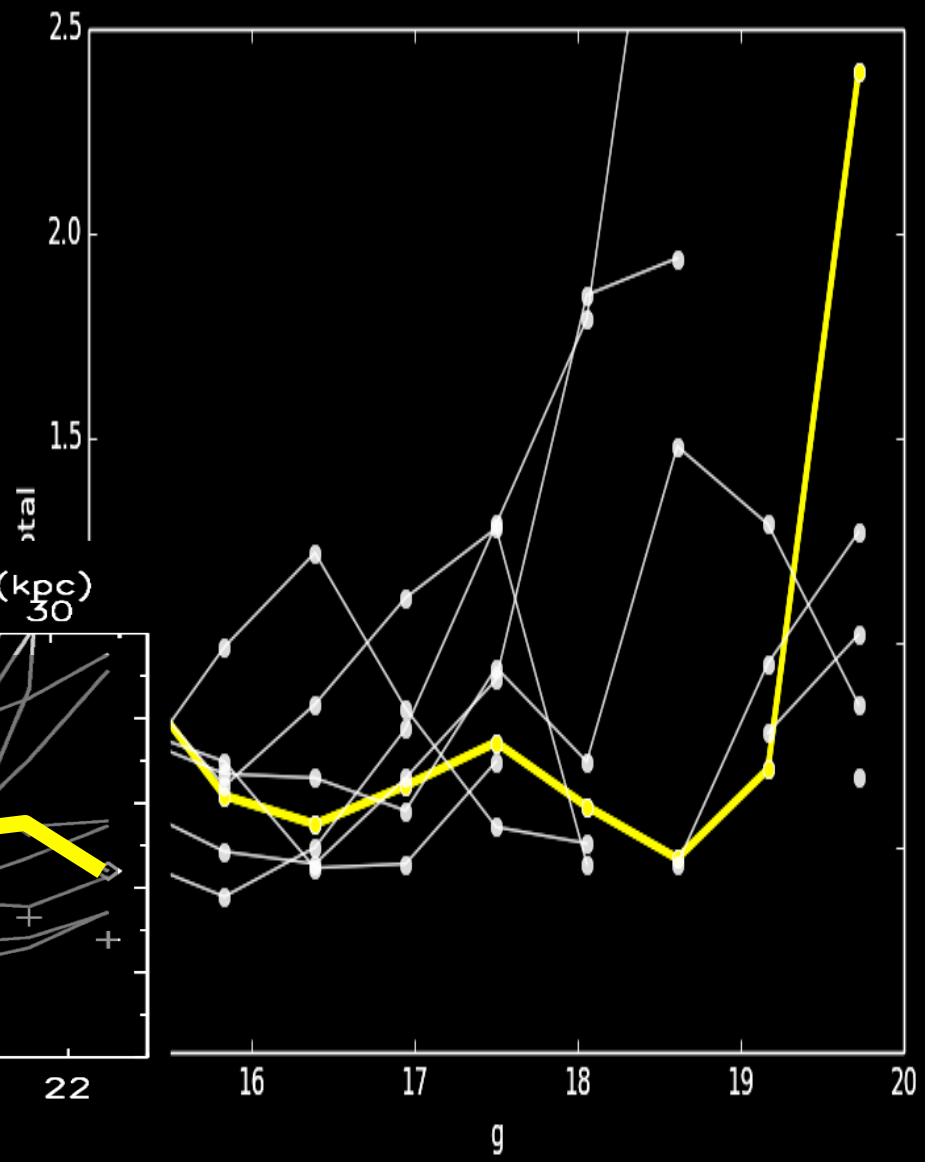




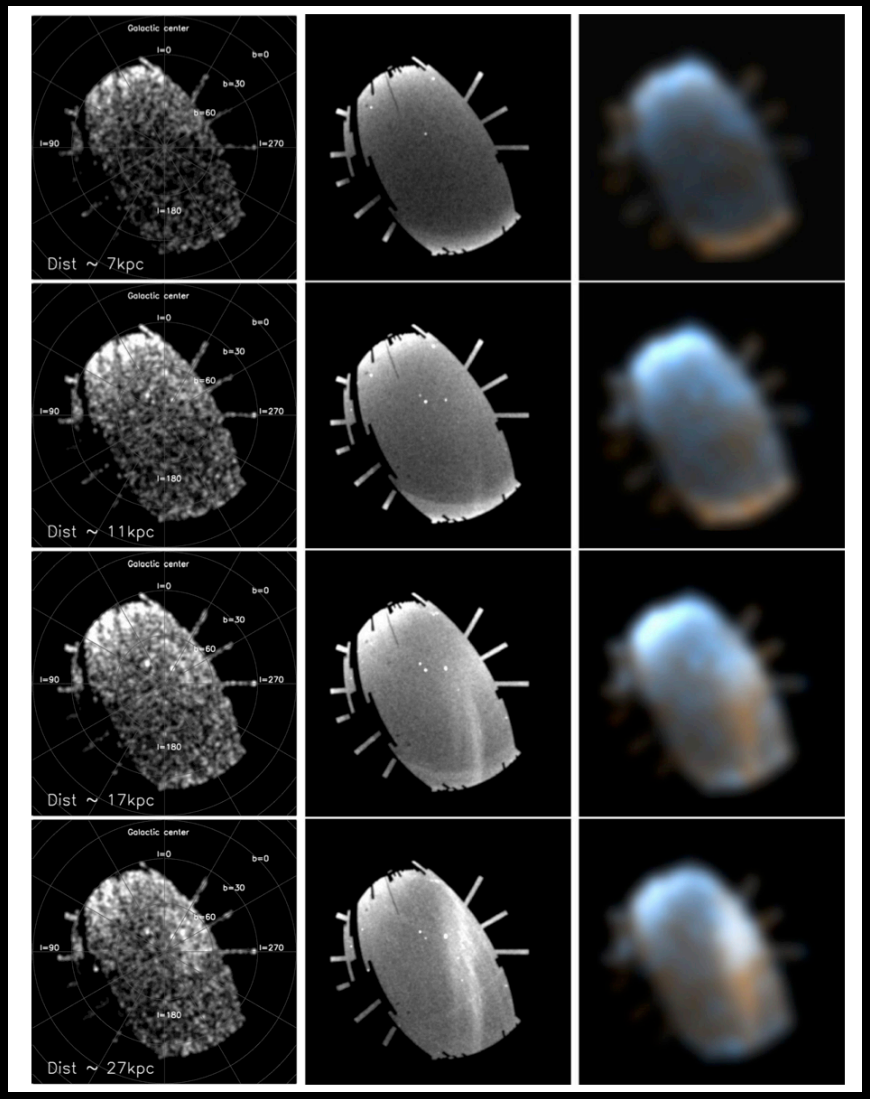
Substructure stays at a similar level out to 100kpc, consistent with the less structured of the simulations

Slater et al.,
very preliminary



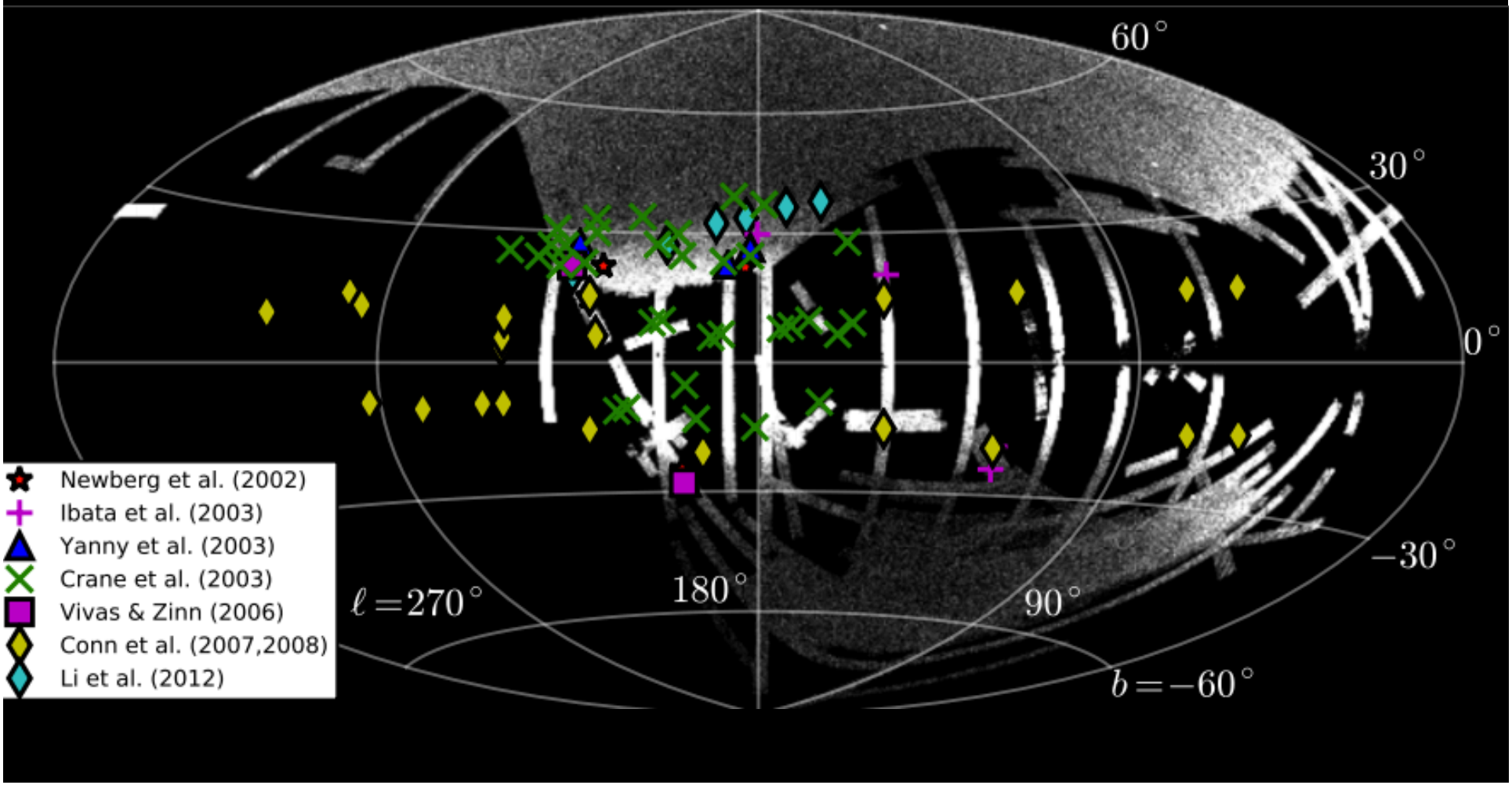


Stellar population variations are seen to correlate with structures using BHB/main sequence turn off ratio

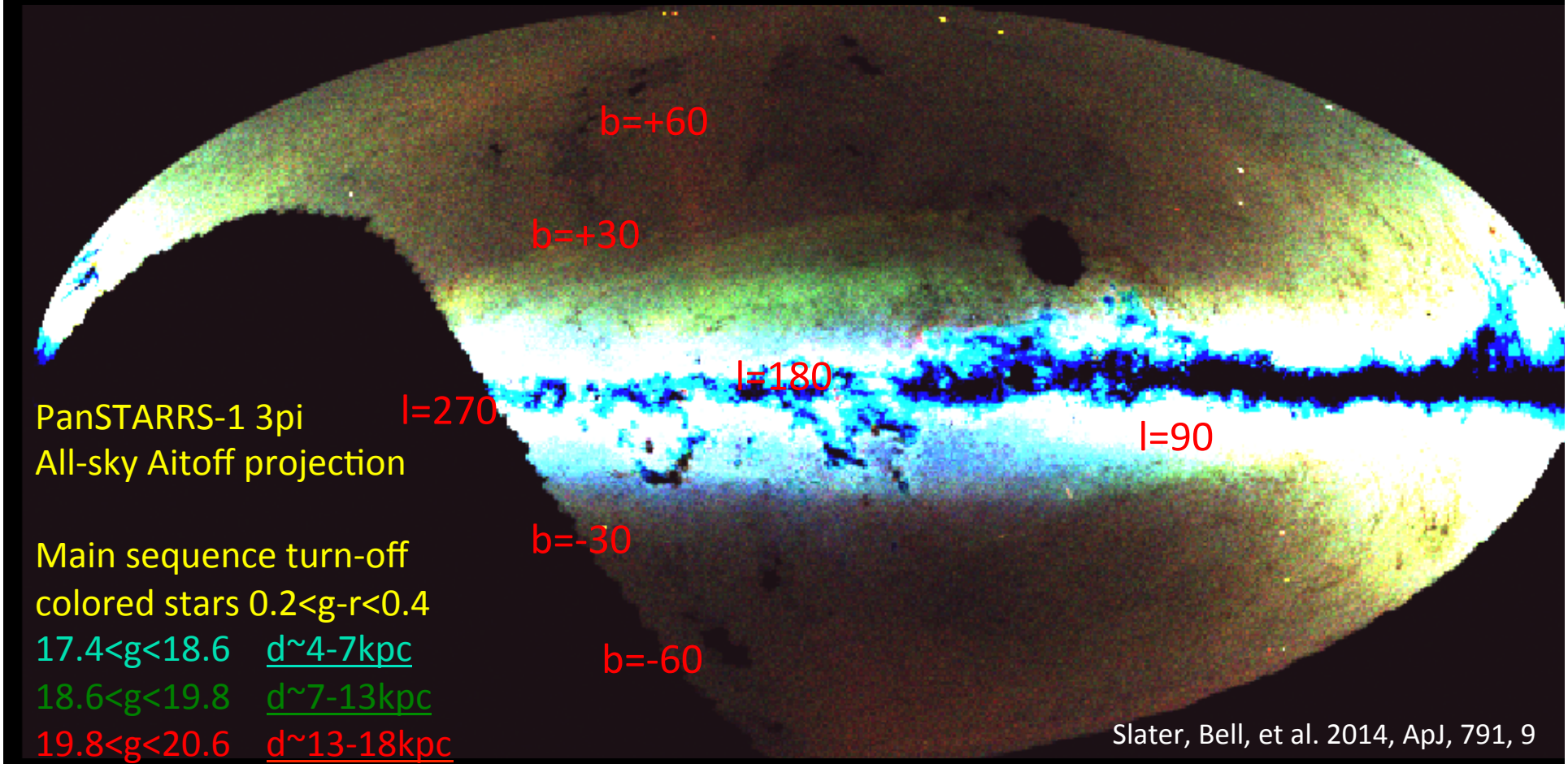


Bell et al. 2010,
AJ, 140, 1850

Fragmentary coverage of overdensities at |b|<~30 deg made testing its origin hard – warp, flare, tidal debris?



PanSTARRS-1 3pi survey permits the first large scale map ever of low-latitude ring / Monoceros

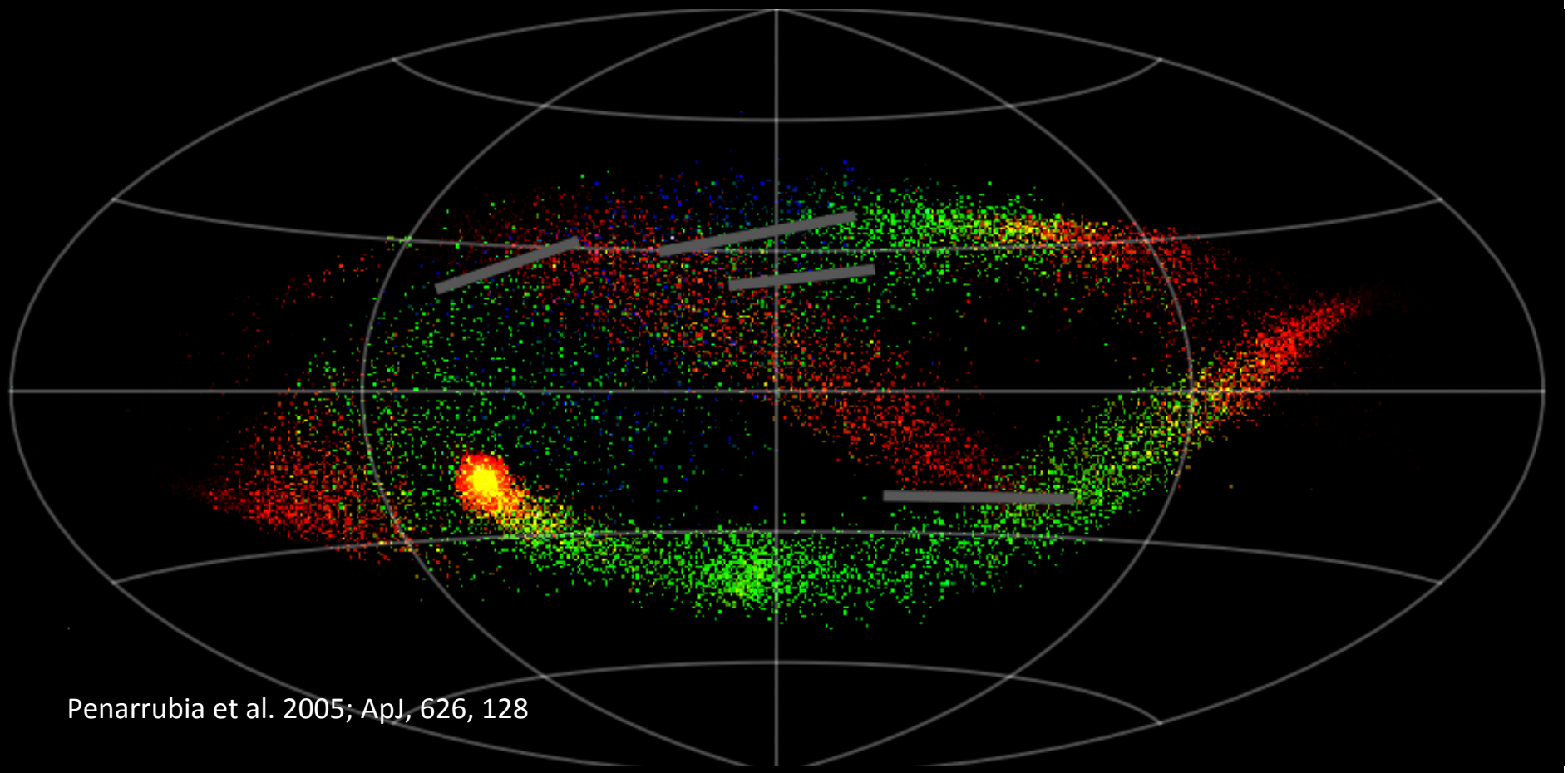


PanSTARRS-1 3pi
All-sky Aitoff projection

Main sequence turn-off
colored stars 0.2<g-r<0.4
17.4<g<18.6 d~4-7kpc
18.6<g<19.8 d~7-13kpc
19.8<g<20.6 d~13-18kpc

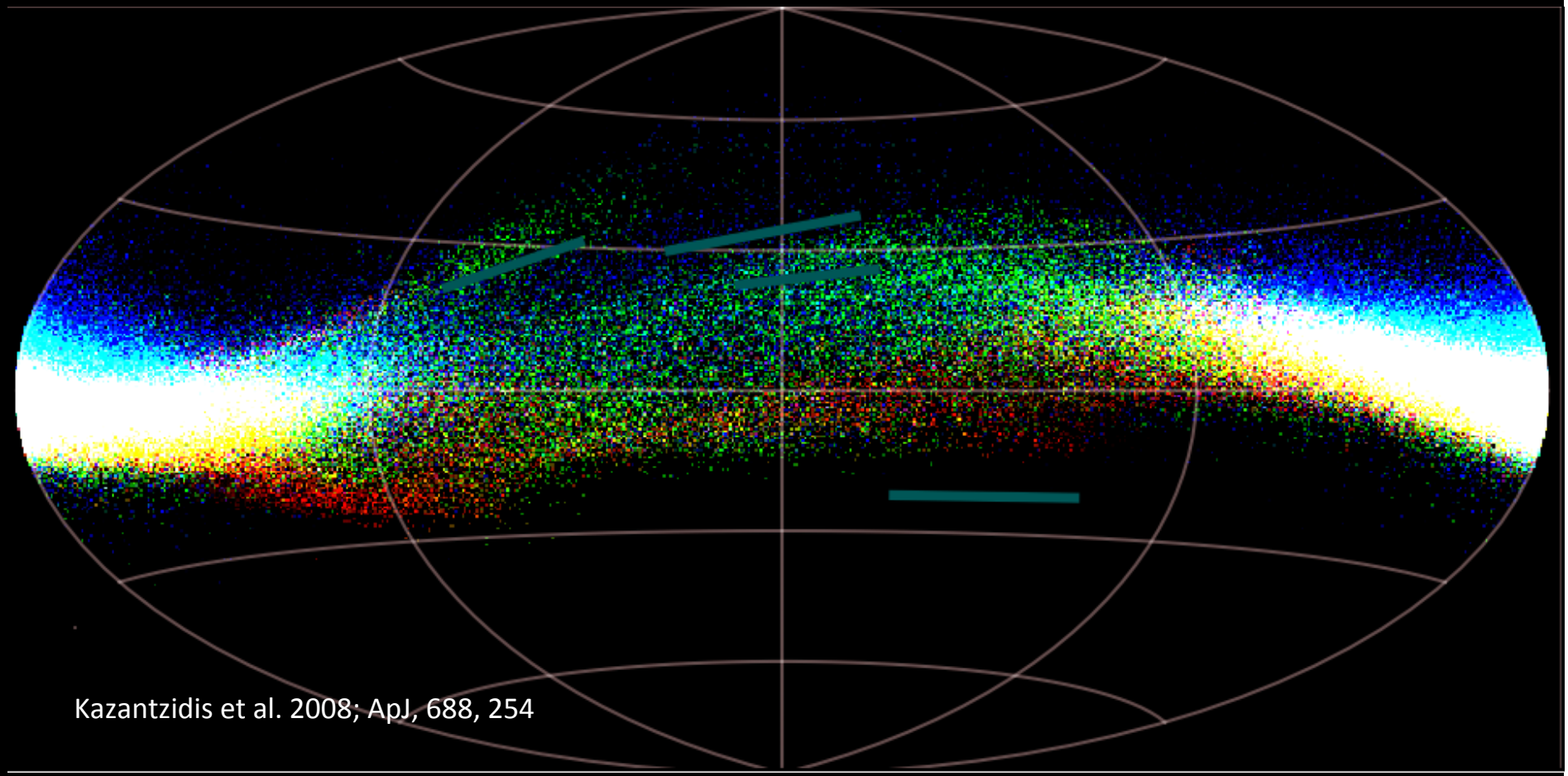
Slater, Bell, et al. 2014, ApJ, 791, 9

A model of satellite disruption on a near-equatorial orbit results in debris at too large a range of distances



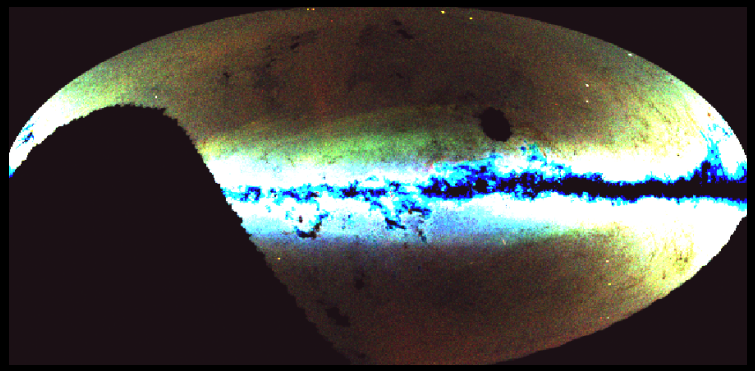
Penarrubia et al. 2005; ApJ, 626, 128

A model of disk disruption by satellites produces reasonable structure but too large of a disk warp

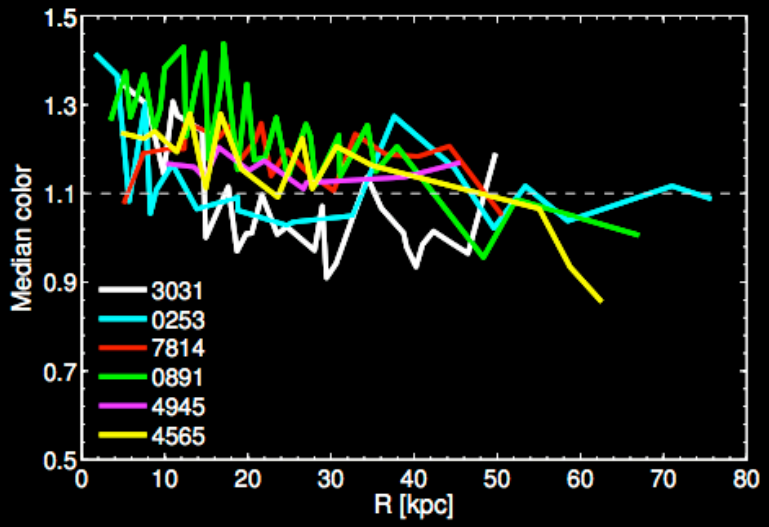


Kazantzidis et al. 2008; ApJ, 688, 254

The MW stellar halo has a r^{-3} profile out to 100kpc, M<~10^9 $M_\odot$, c/a ~ 0.6, abundant substructure and shows signs of disk disruption



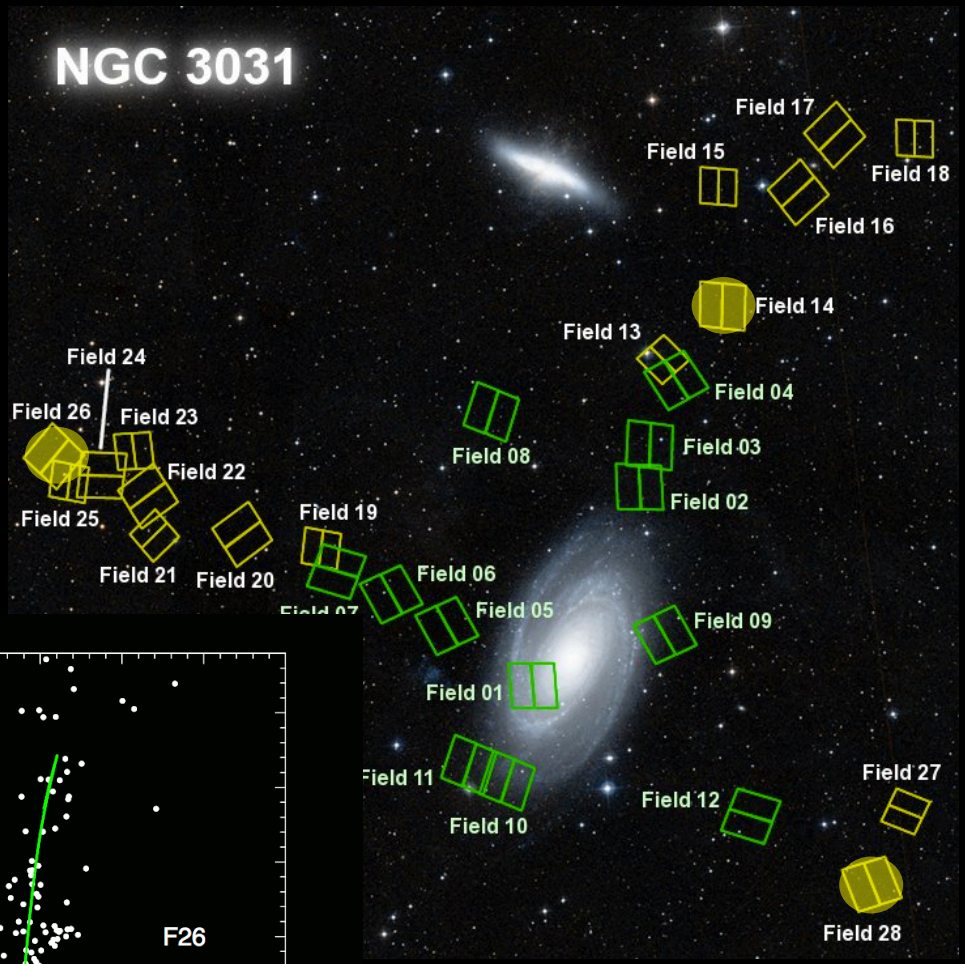
How does this generalize to other ~Milky Way mass galaxy halos?

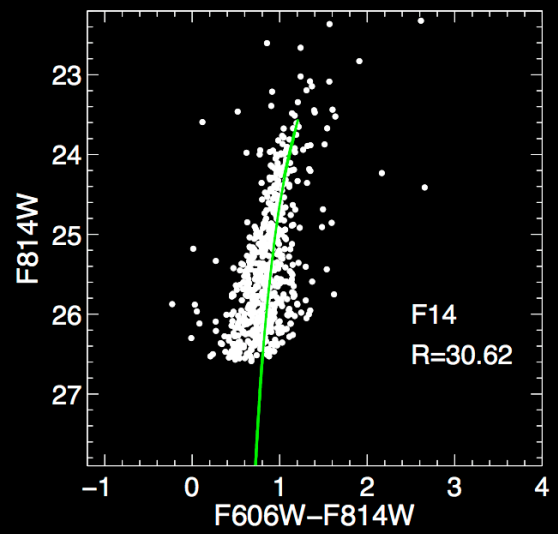


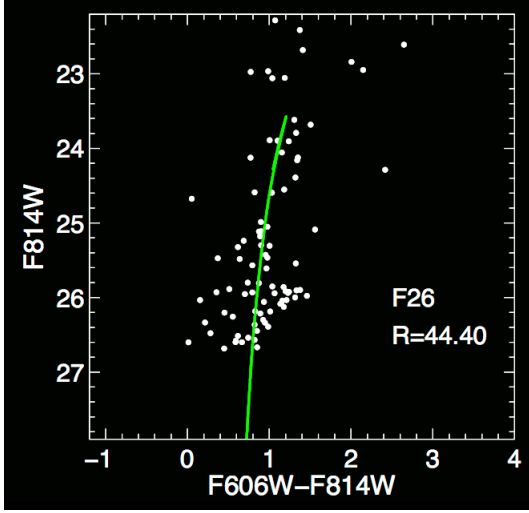
Models predict substantial galaxy-to-galaxy scatter, motivating study of other stellar halos

GHOSTS
PI Roelof de Jong
Antonela Monachesi
David Radburn-Smith
Eric Bell
Jeremy Bailin
Ben Harmsen
+others

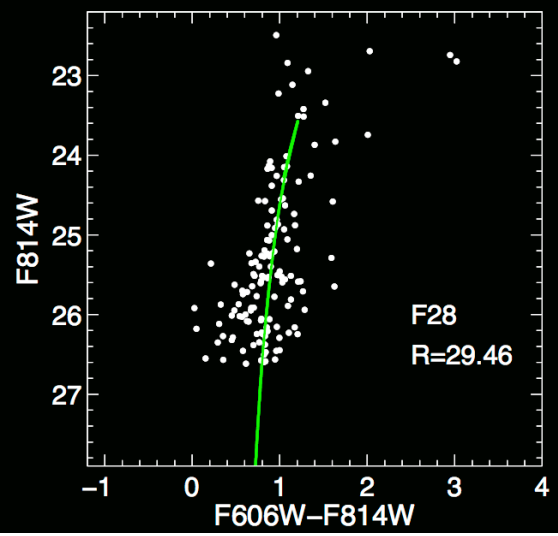
HST resolves red giant branch stars and measures stellar density and metallicity



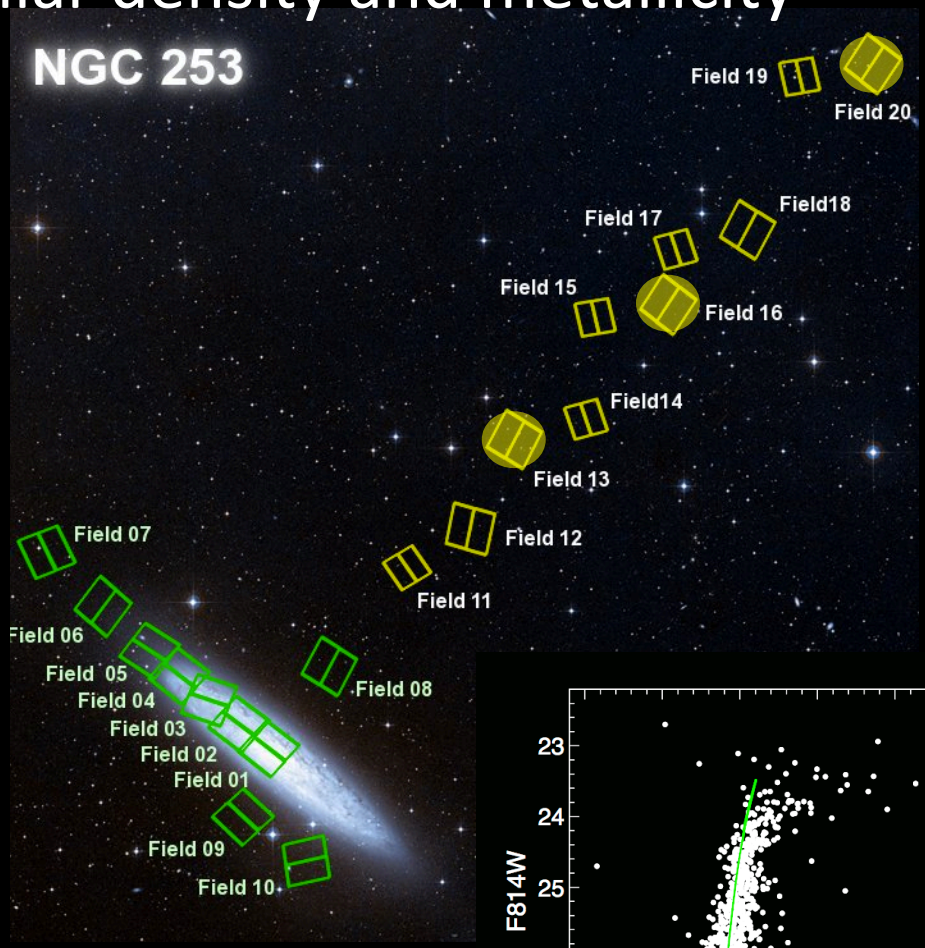




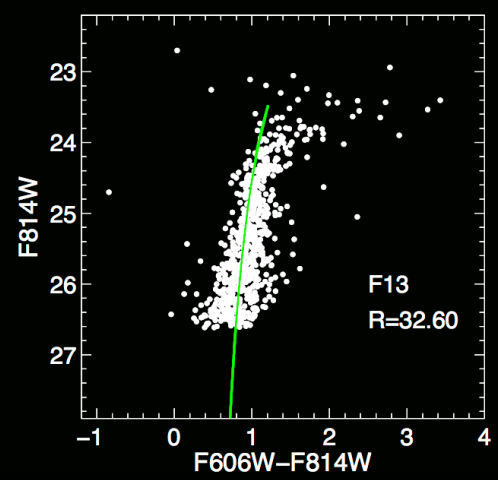
D ~ 3.7Mpc
v ~ 224km/s

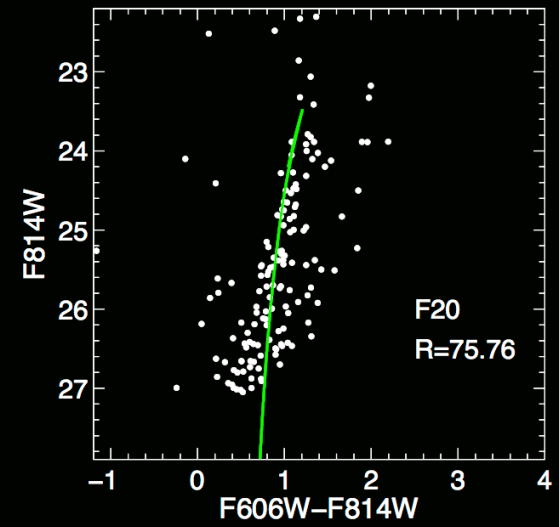


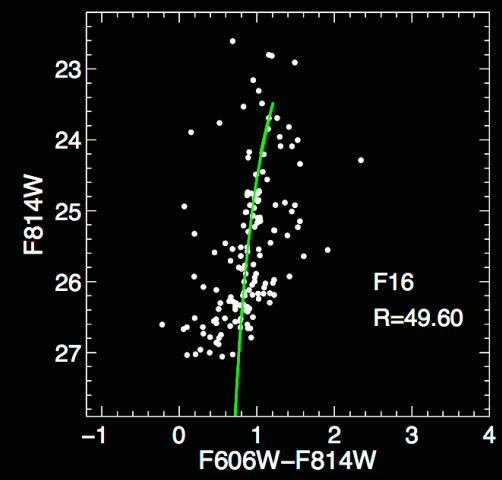
HST resolves red giant branch stars and measures stellar density and metallicity



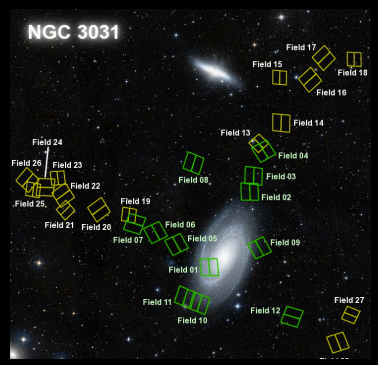
D ~ 3.5Mpc
v ~ 194km/s

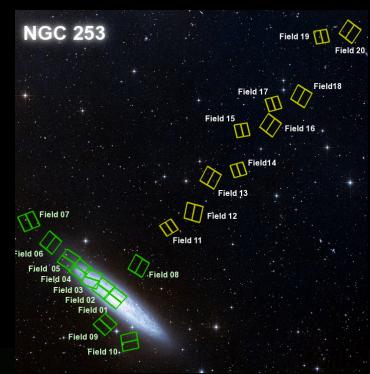




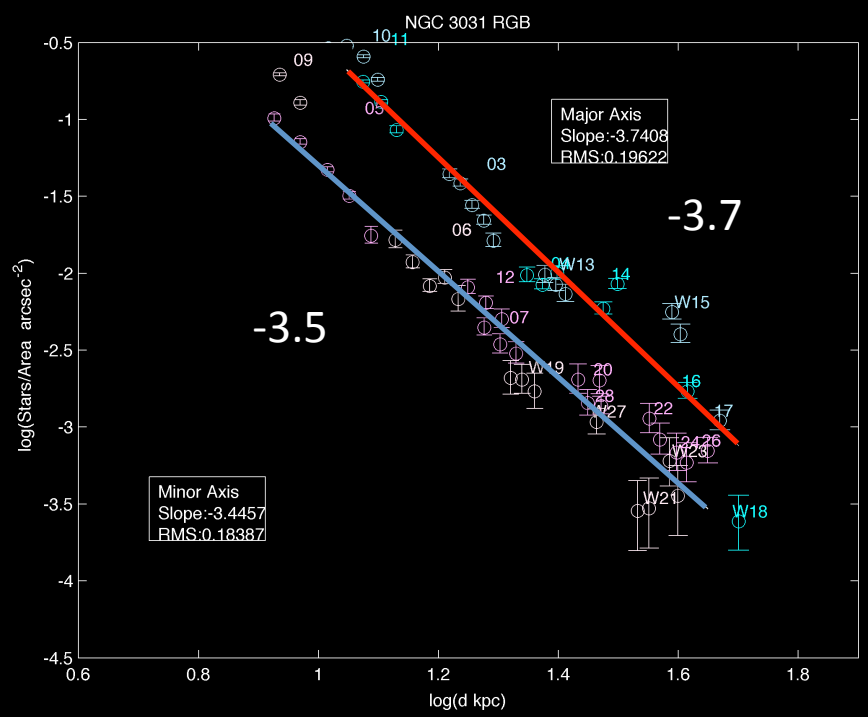


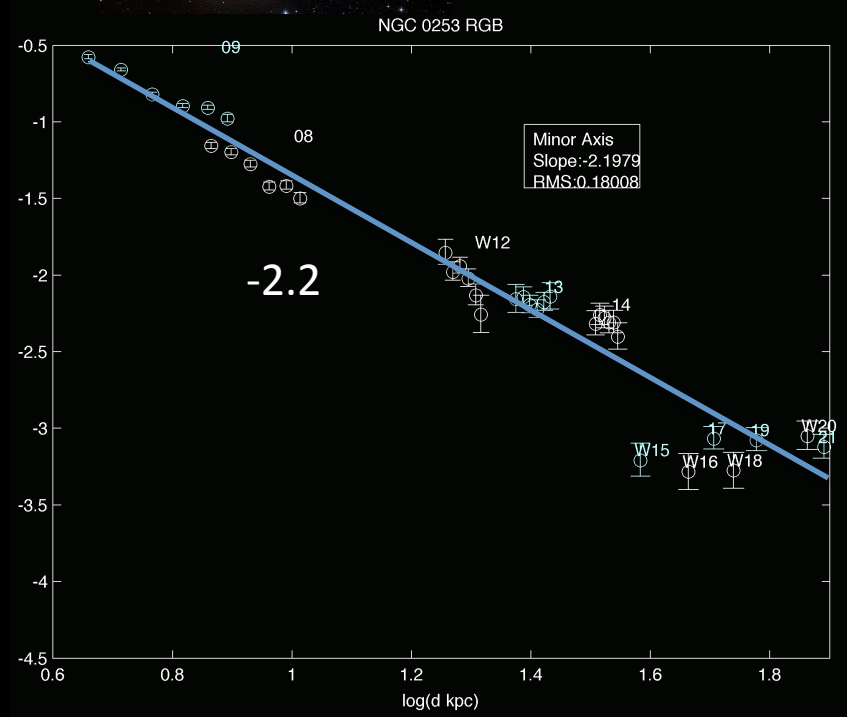
Our stellar halos have projected density profiles $r^{-\alpha}$ where $-2>\alpha>-3.5$ over 10 to 75 kpc



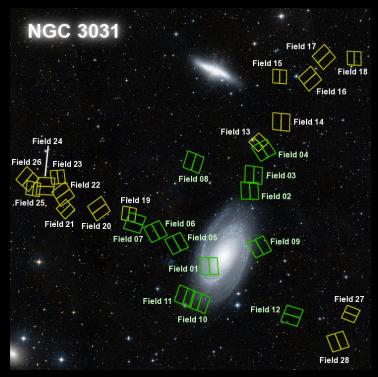


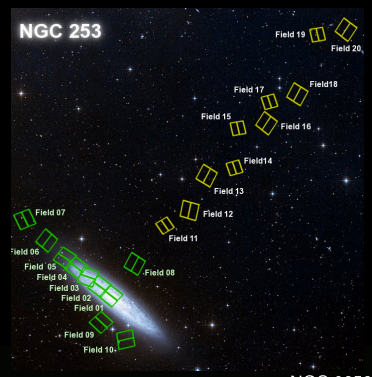
Harmsen et al.
in preparation

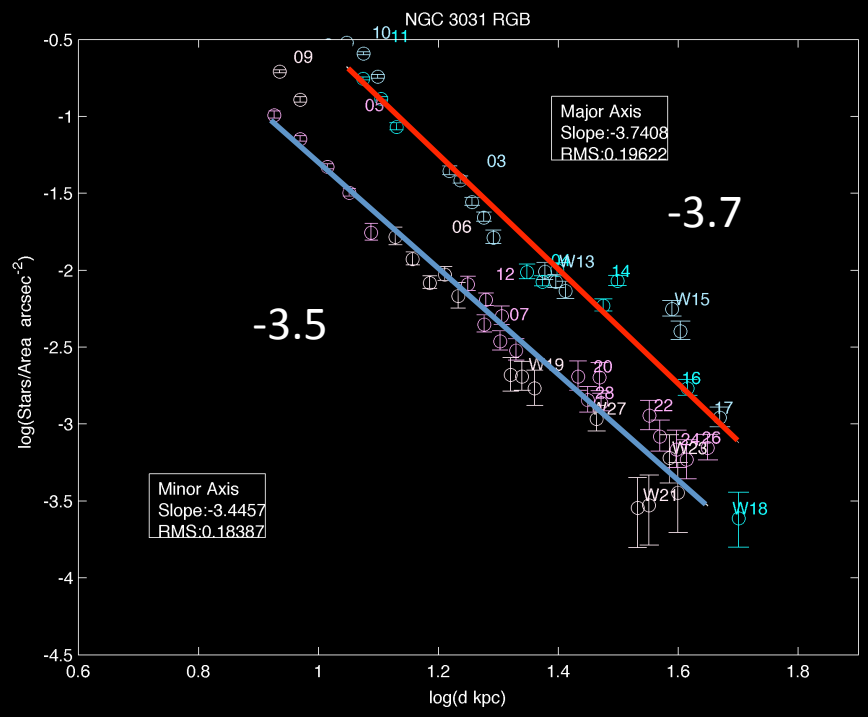


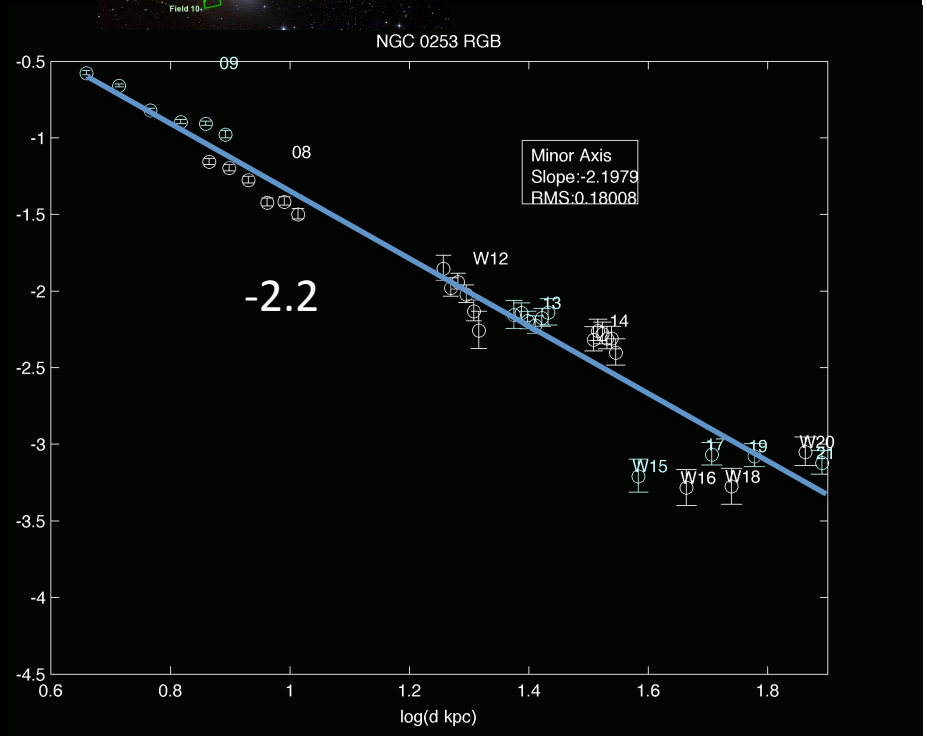


Scatter around these power law profiles is roughly 0.15 dex (40%, similar to MW halo)

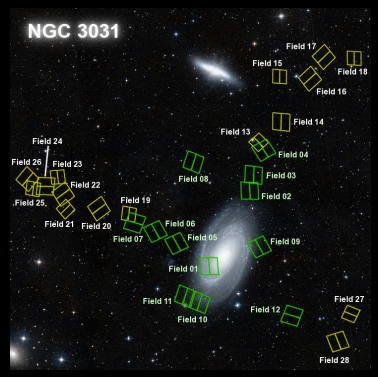


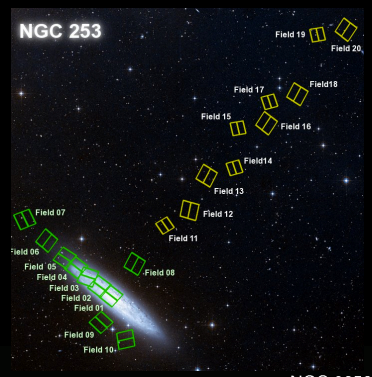


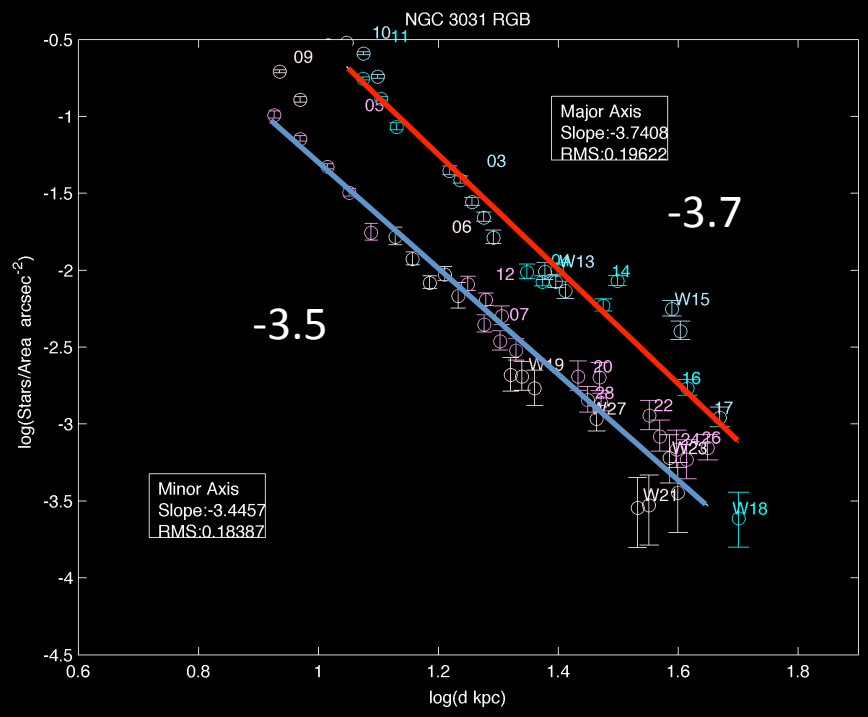


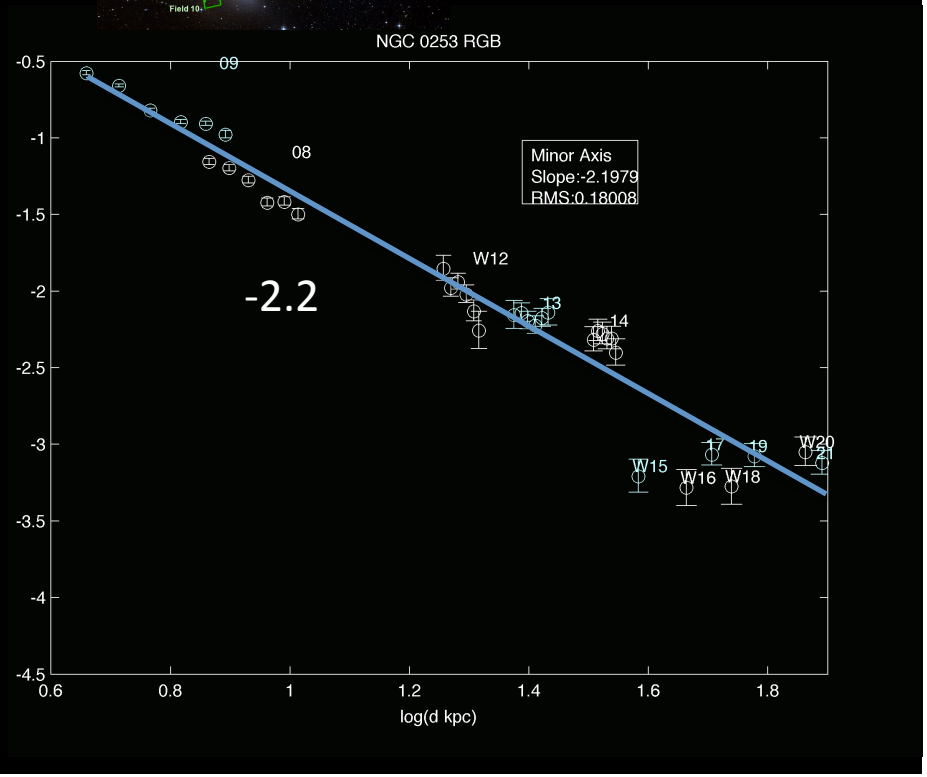


Where we can measure axis ratio, the halos appear flattened with 0.4<c/a<0.7

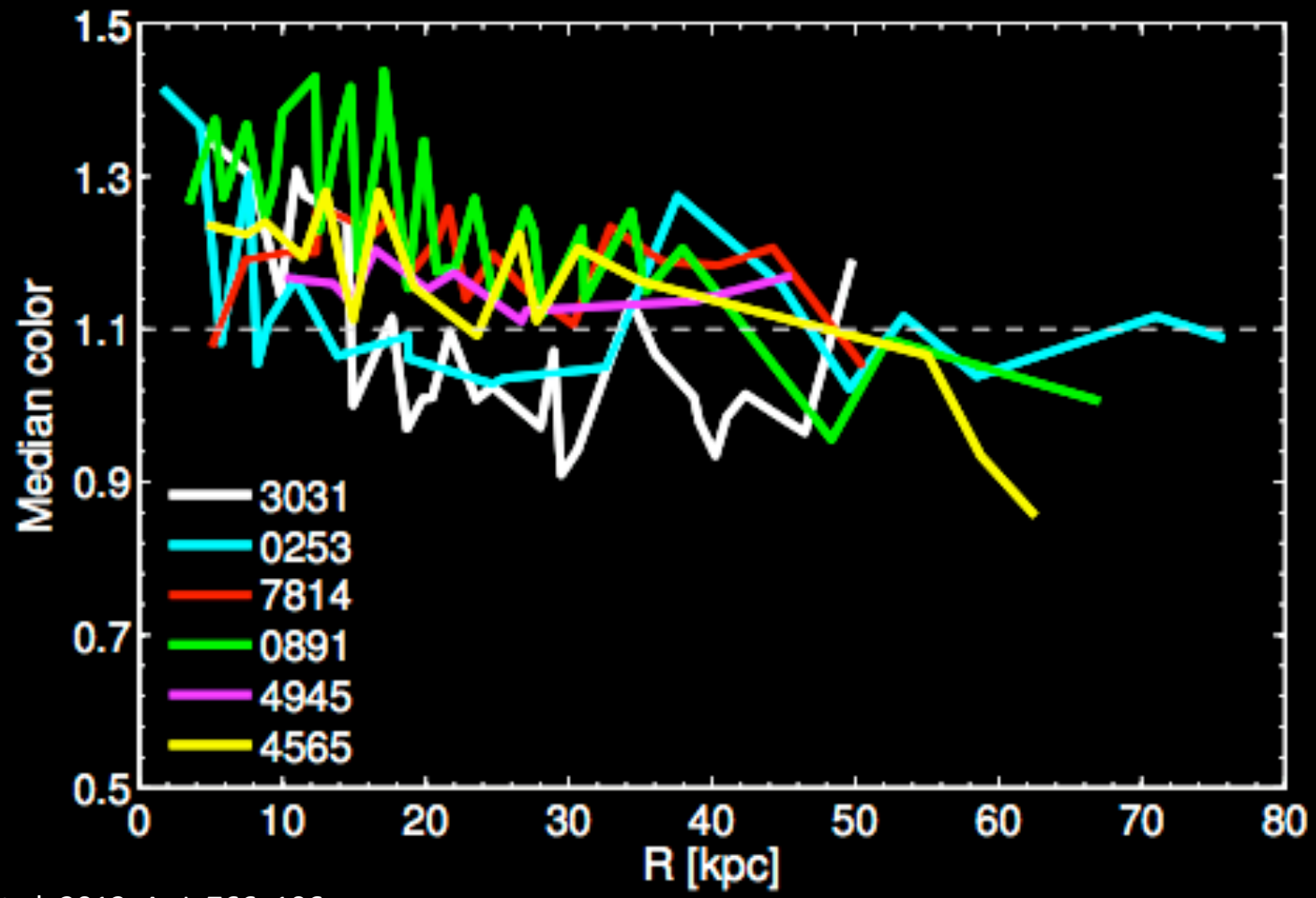






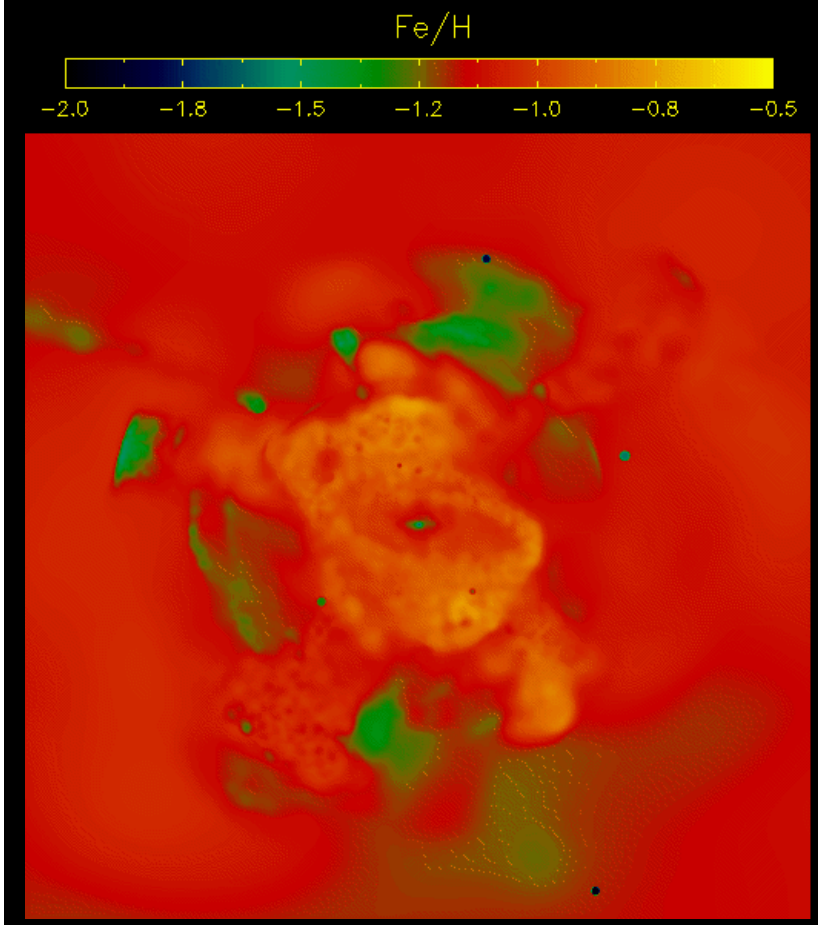


Red giant branch color gradients reveal likely metallicity gradients in 2/6 systems, absent in 4/6

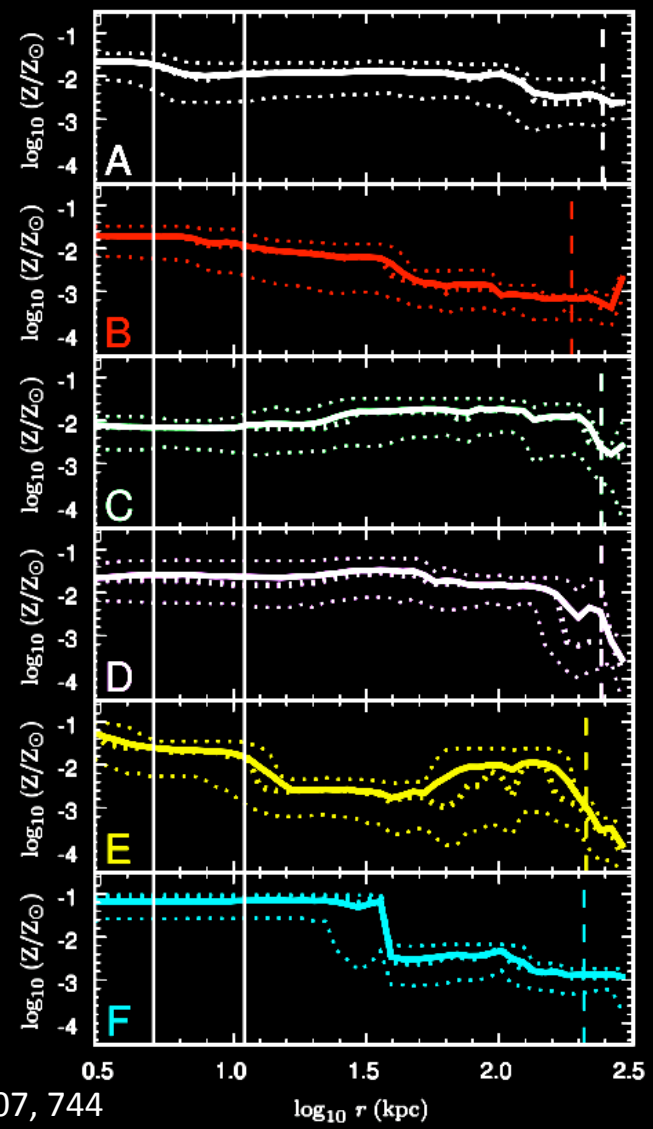


Monachesi et al. 2013, ApJ, 766, 106
and in preparation

This is consistent with accretion-only models, which have gradients <~1/2 of the time

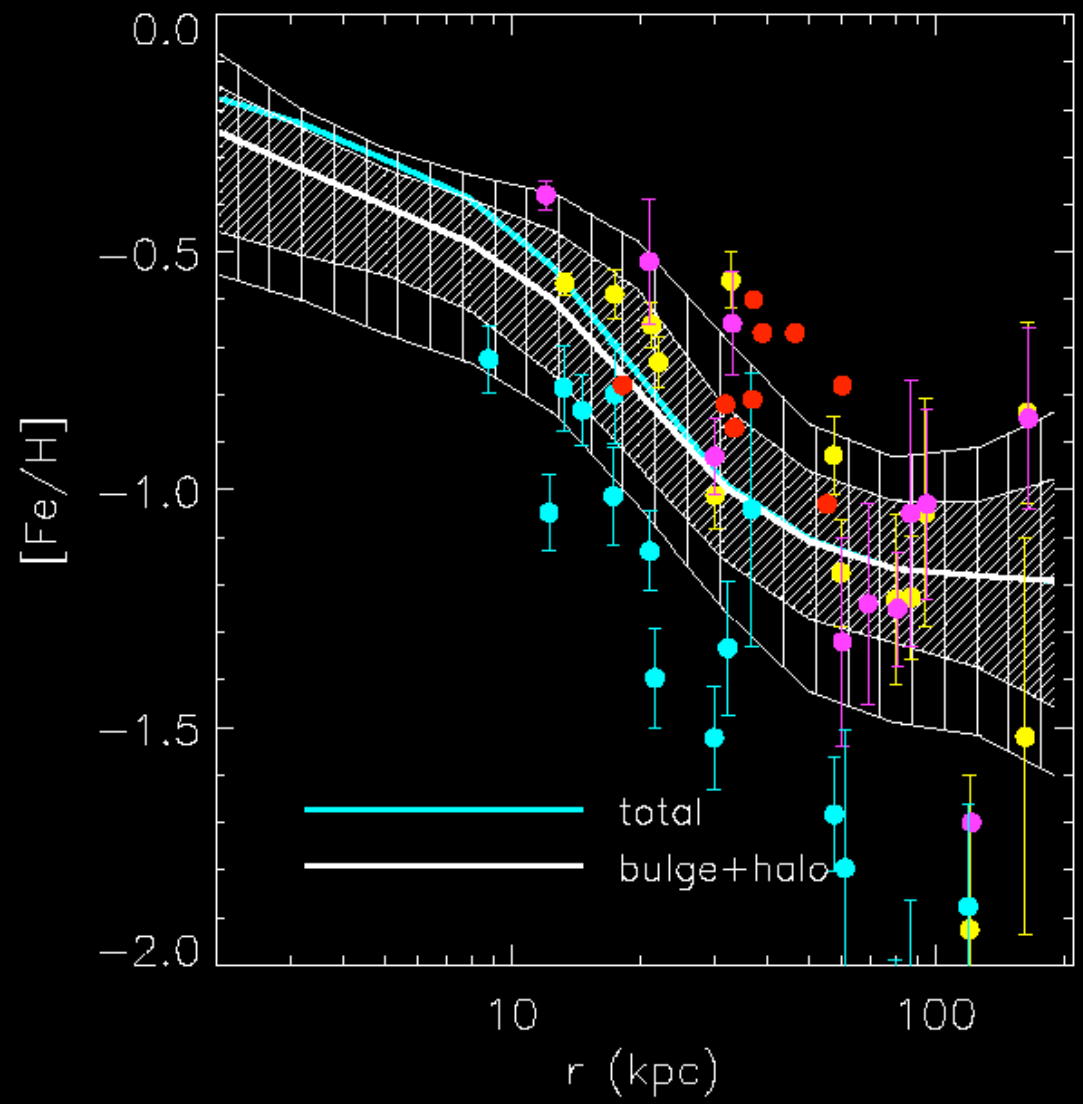


Bullock & Johnston 2005
ApJ, 635, 931



N-body only accreted halos
Cooper et al. 2010, MNRAS, 407, 744

Large in situ halos impose metallicity gradients, so in situ halos are modest or happen only sometimes



Font et al. 2011
MNRAS, 416, 2802

Stellar halos are a powerful probe of dark matter-driven galaxy growth

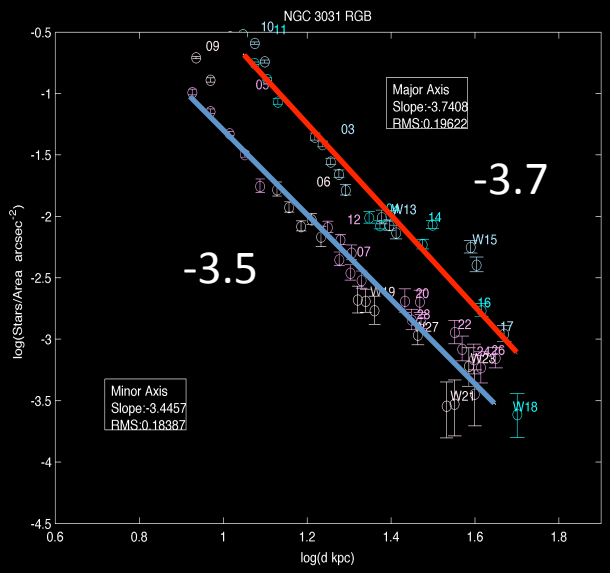
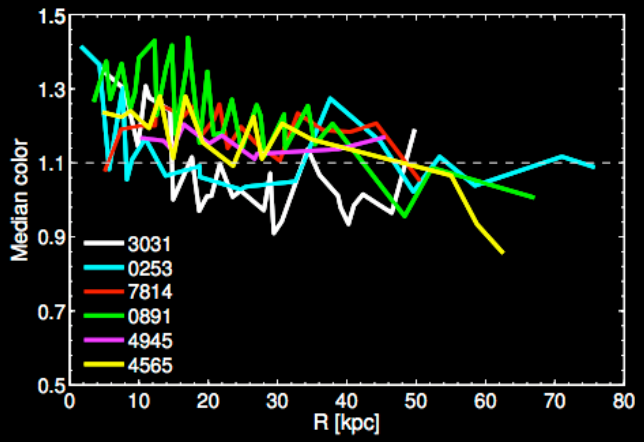
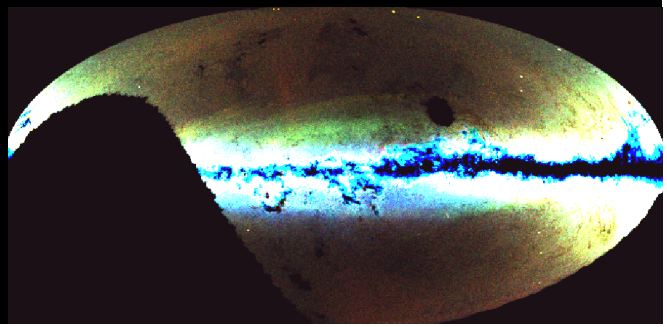
Stellar halos are common

Eight stellar halos have projected density profiles $r^{-\alpha}$ where $-2>\alpha>-3.5$ over 10 to 100 kpc

Stellar halos show substructure at ~40% RMS level

Stellar halos are flattened with $0.4<c/a<0.7$

Stellar halos show stellar populations variations, and metallicity gradients <~1/2 of the time

These properties are consistent with accretion only models

Some contribution from kicked-up disk stars is likely