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Touching the Void: A Striking Drop in Stellar Halo Density Beyond 50 kpc

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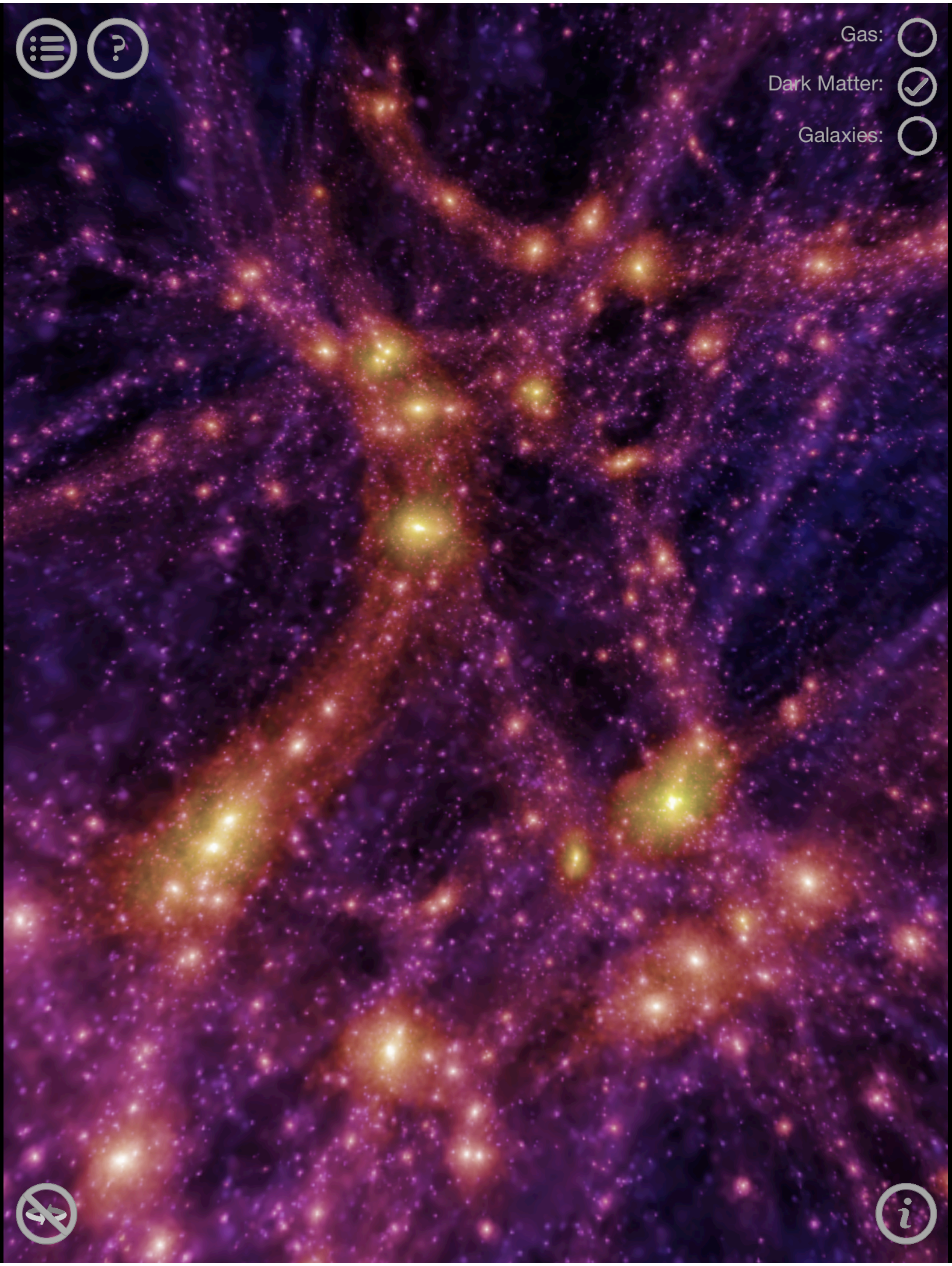
EAGLE
Simulation

Credit:
Cosmic Universe App
Virgo Consortium



Dark Matter

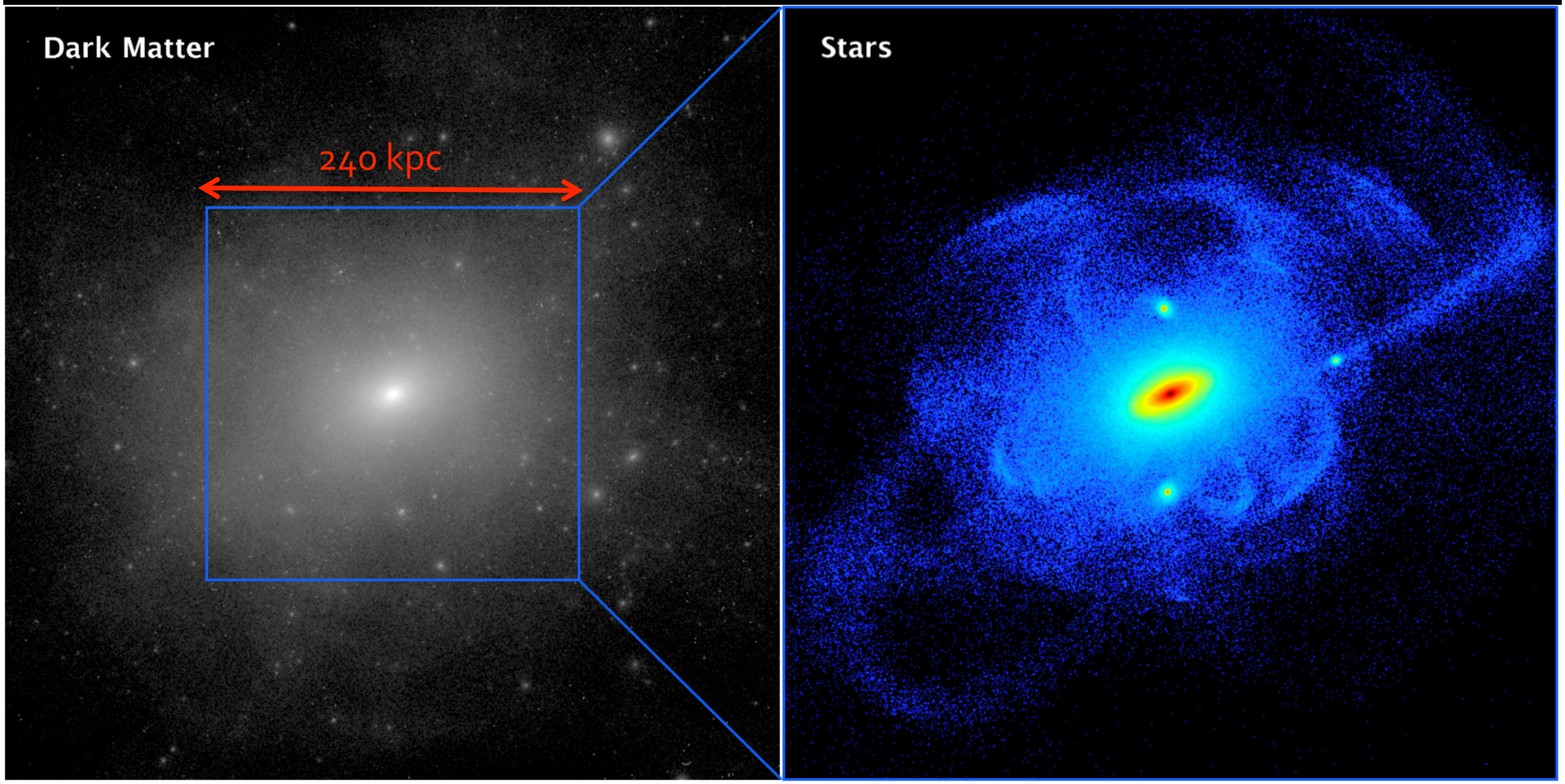
EAGLE
Simulation

Credit:
Cosmic Universe App
Virgo Consortium

Stars

ERIS Simulation: High Resolution Milky Way Type Galaxy

Image Credit: Annalisa Pillepich



480 kpc

Stellar halo --- only ~1% of the total luminosity of the Galaxy, but allows us to trace the dark matter out to ~r_{vir}

Milky Way Mass

- Halo stars tracers of Galactic potential

Tracer Radial Velocity Dispersion

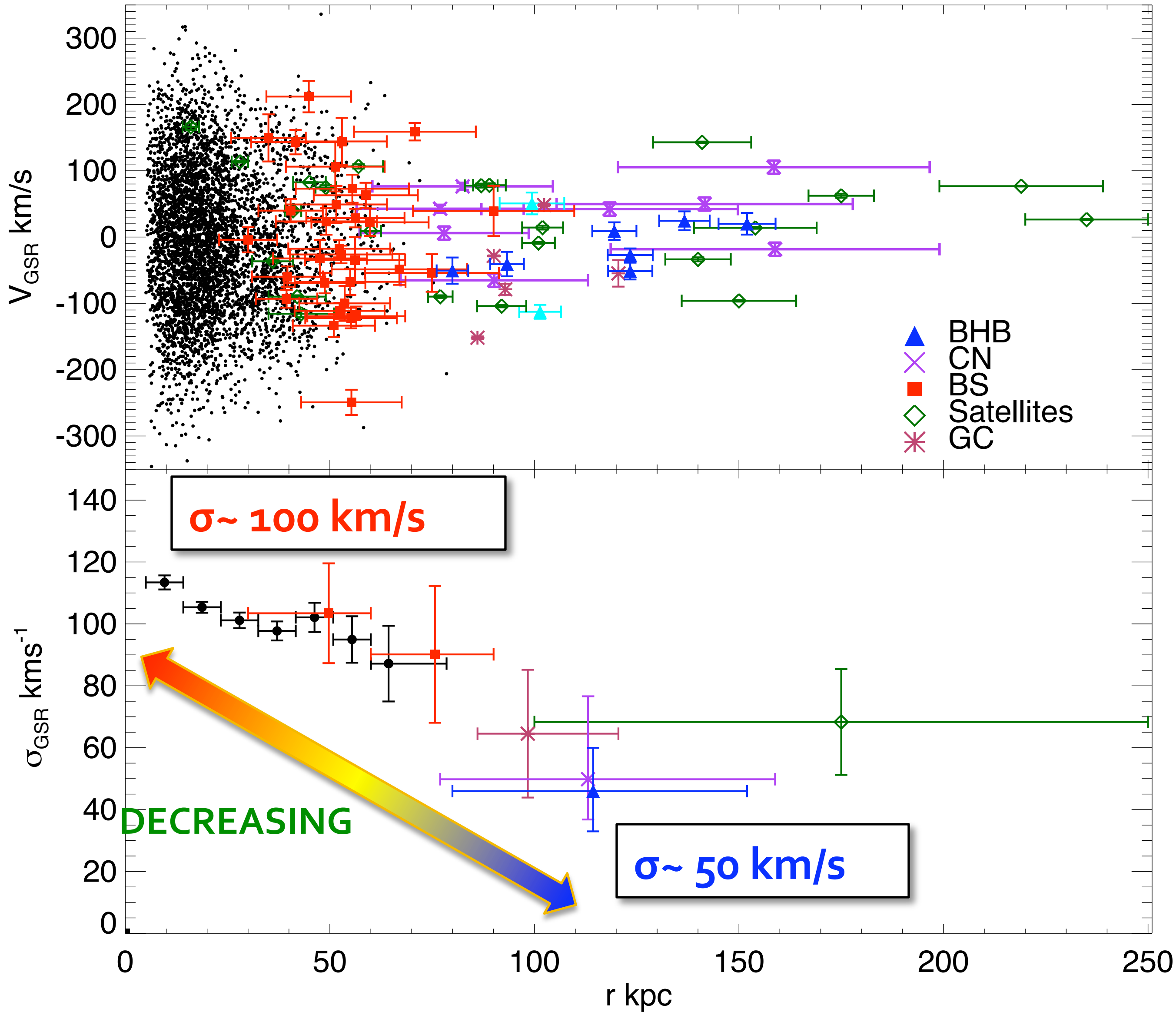
$$M(<r) = \frac{r\sigma_r^2}{G}\left(-\frac{\mathrm{d}\ln\rho_{\mathrm{tr}}}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln\sigma_r^2}{\mathrm{d}\ln r} - 2\beta\right)$$

Tracer Density Profile

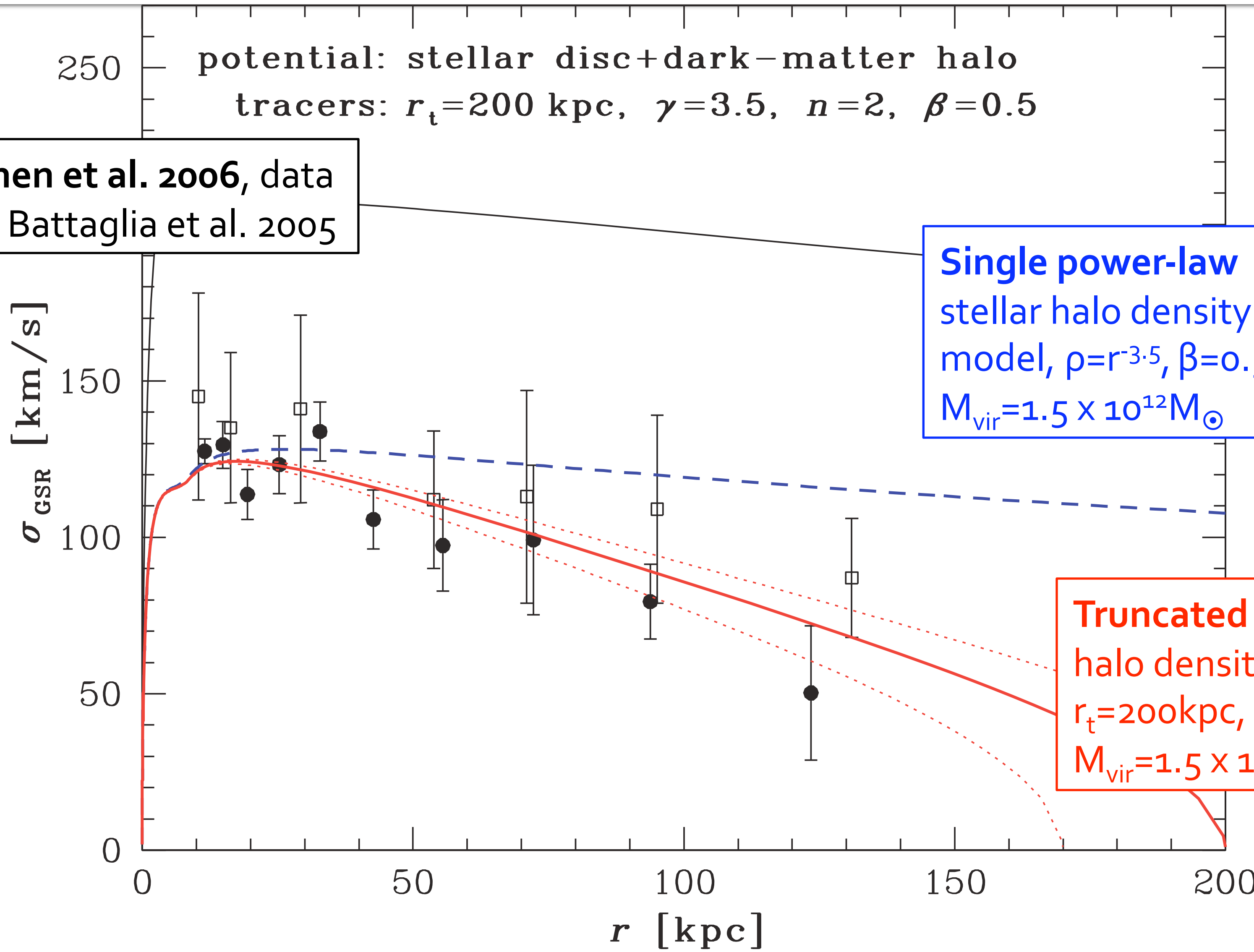
Tracer Velocity Anisotropy
(i.e. tracer orbits)

Radial Velocities of Halo Tracers

Deason et al. 2012



The Mass-Anisotropy-*Density* Degeneracy



Dehnen et al. 2006, data from Battaglia et al. 2005

Single power-law stellar halo density model, $\rho=r^{-3.5}$, β=0.5, M_{vir}=1.5 x $10^{12} M_\odot$

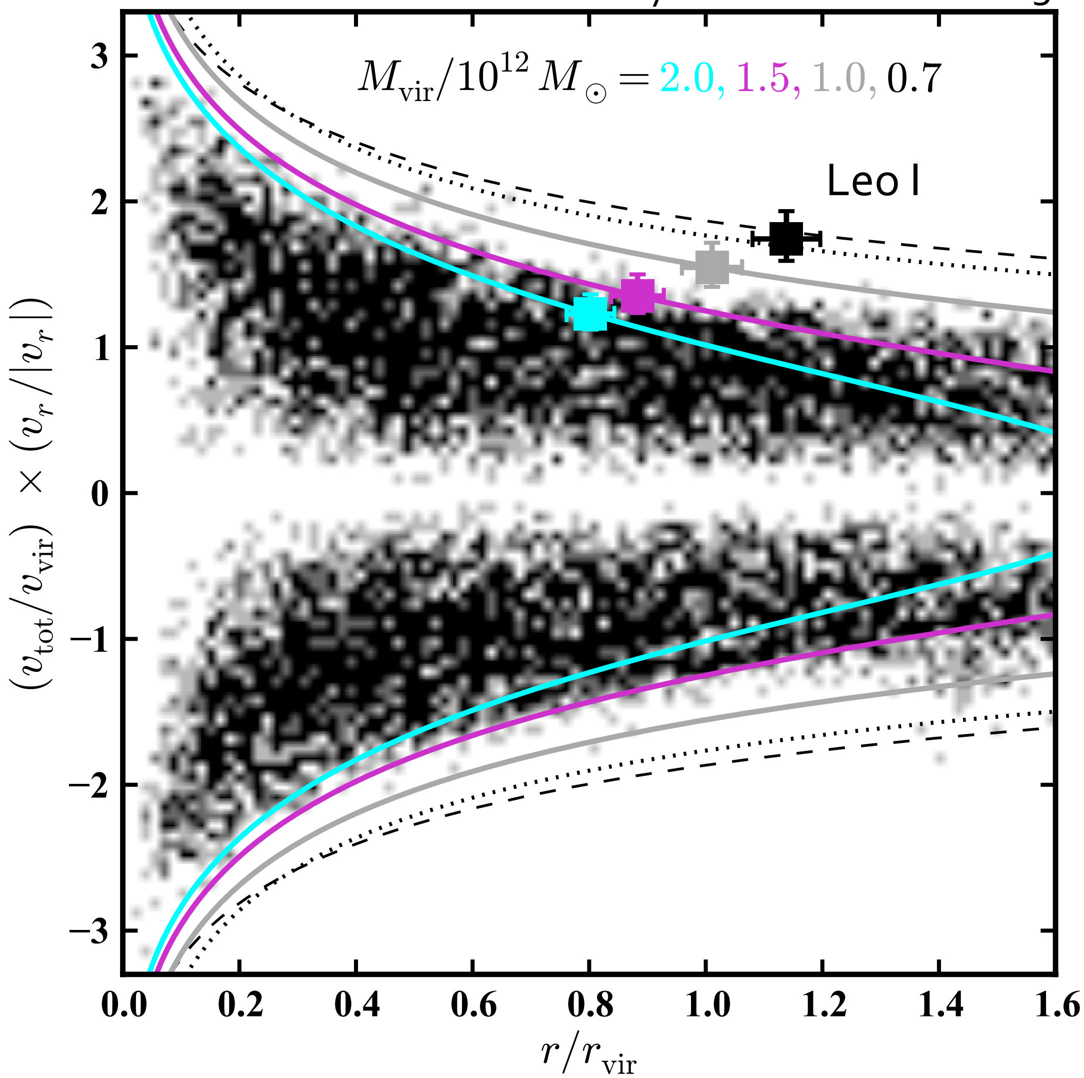
Truncated stellar halo density models: r_t=200kpc, β=0.5, M_{vir}=1.5 x $10^{12} M_\odot$

Other Mass Estimates

(non-exhaustive, biased towards constraints from simulations)

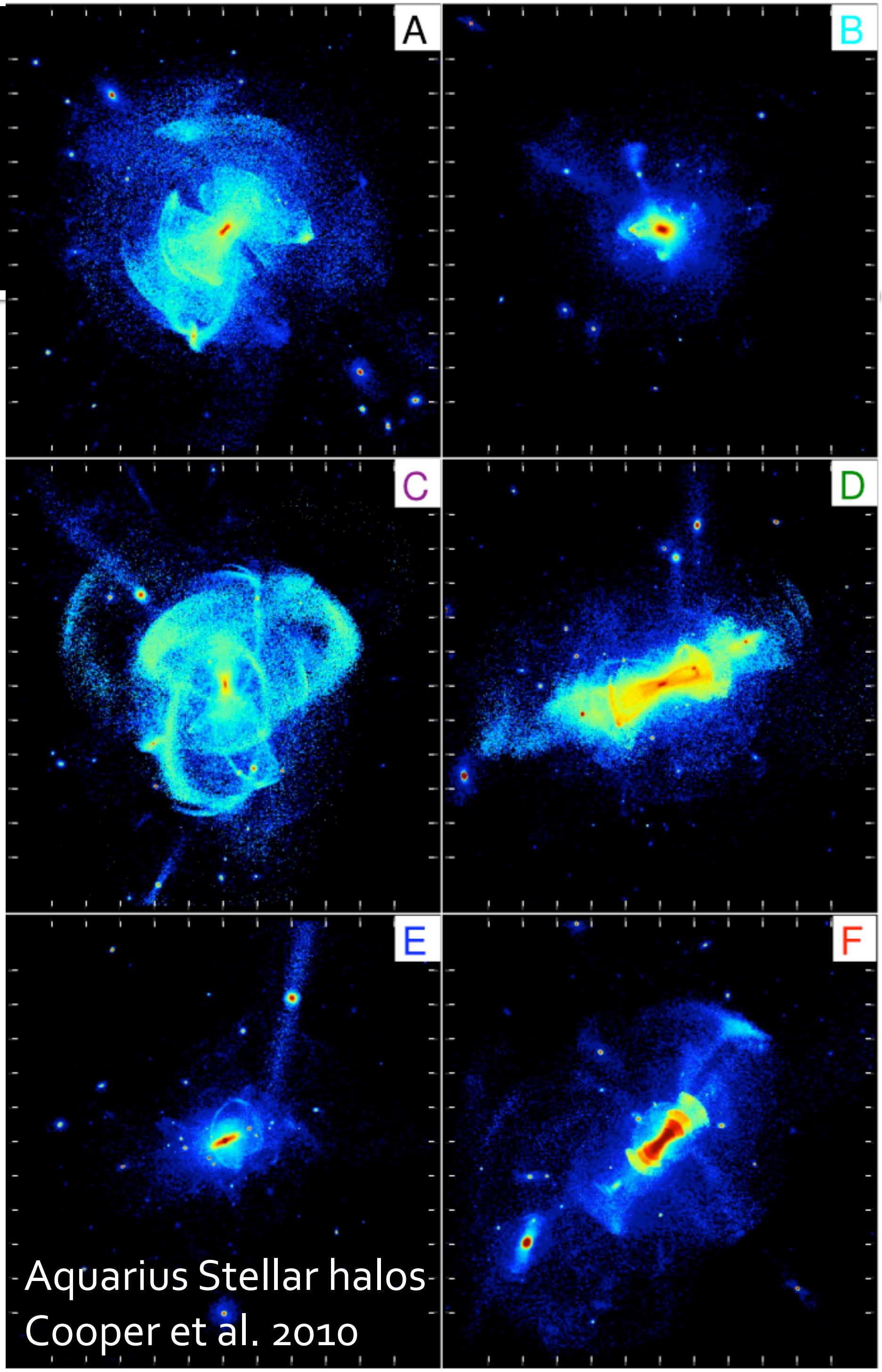
- If Leo I is bound, **M_{vir} > $10^{12}M_{\odot}$** (Boylan-Kolchin et al. 2013)
- Abundance matching predicts **M_{vir} ~ 2 x $10^{12}M_{\odot}$** (Guo et al. 2010; Moster et al. 2013)
- ΛCDM+MCs, **M_{vir} ~ 1.2 x $10^{12}M_{\odot}$** (Busha et al. 2010)
- *Mass estimates from halo stars on the **low side** relative to predictions from simulations. But significant degeneracies remain.*

Boylan-Kolchin et al. 2013



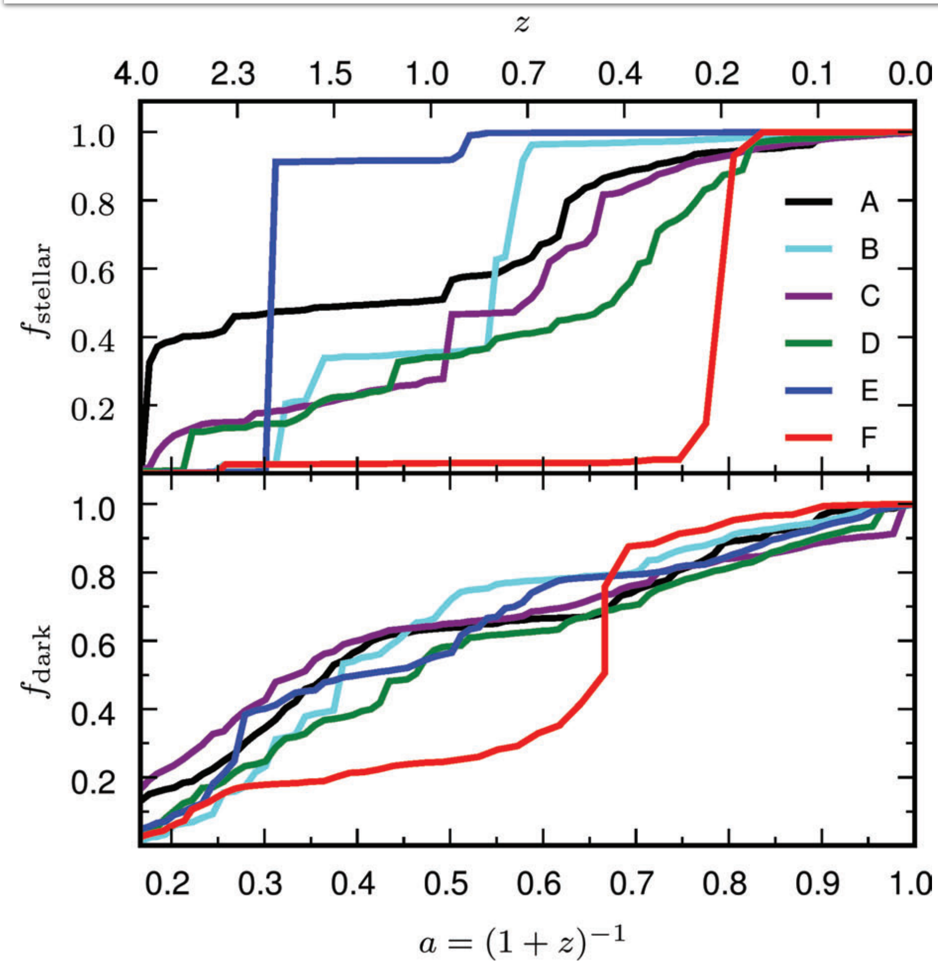
Accretion History from Halo Stars

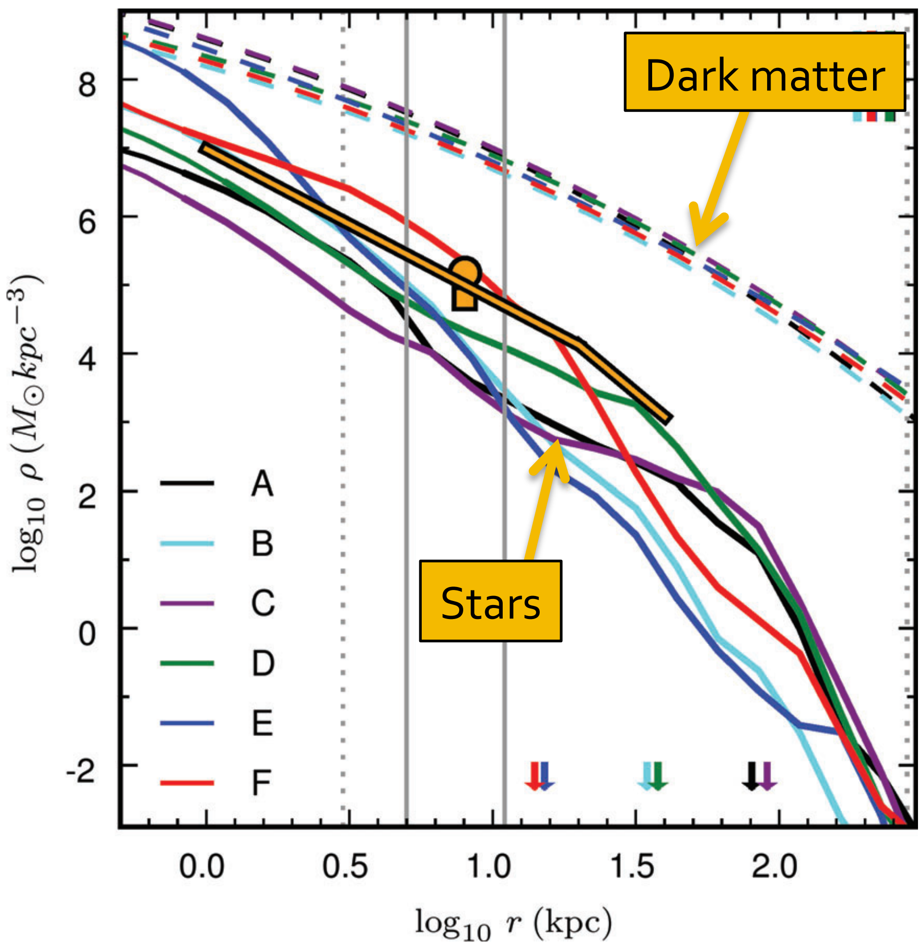
- Dark matter halos are approximately **universal** (e.g. NFW).
- Stellar halo formation is a much more **stochastic** process:
  - Plummeting star formation efficiency in low mass dwarfs (and likely lots of scatter in stellar mass-halo mass relation).
  - Deeply embedded in dark halos (get stripped later)
- Lumpier accretion plus extremely long mixing times leads to a **greater variety of stellar halo profiles**.



Aquarius Stellar halos
Cooper et al. 2010

Accretion History from Halo Stars



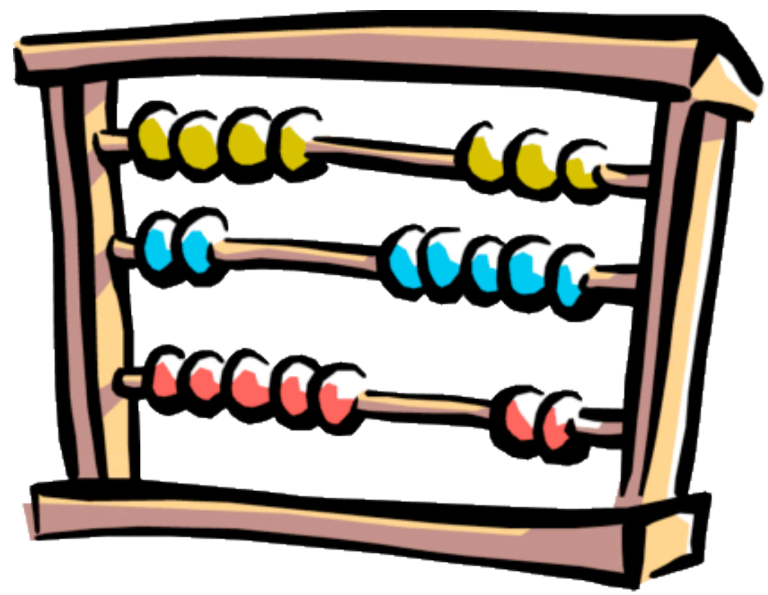


Figures from
Cooper et al. 2010

Fossil record of MW accretion history encoded in distribution of halo stars

Stellar Halo Density Profile is Key

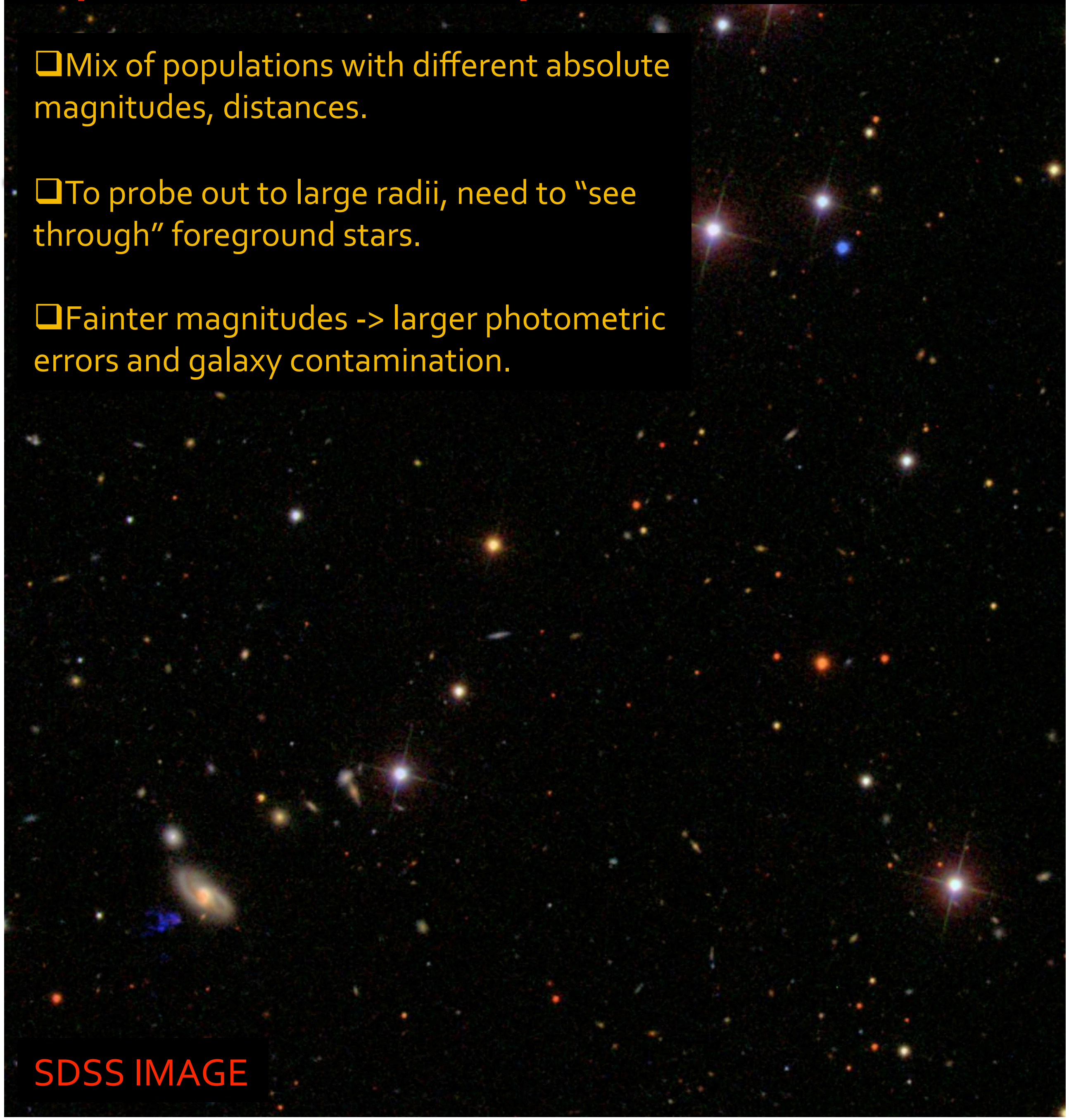
Simple(?) task of **“counting stars”** is key for constraining total **mass** and **accretion history** of the Galaxy.

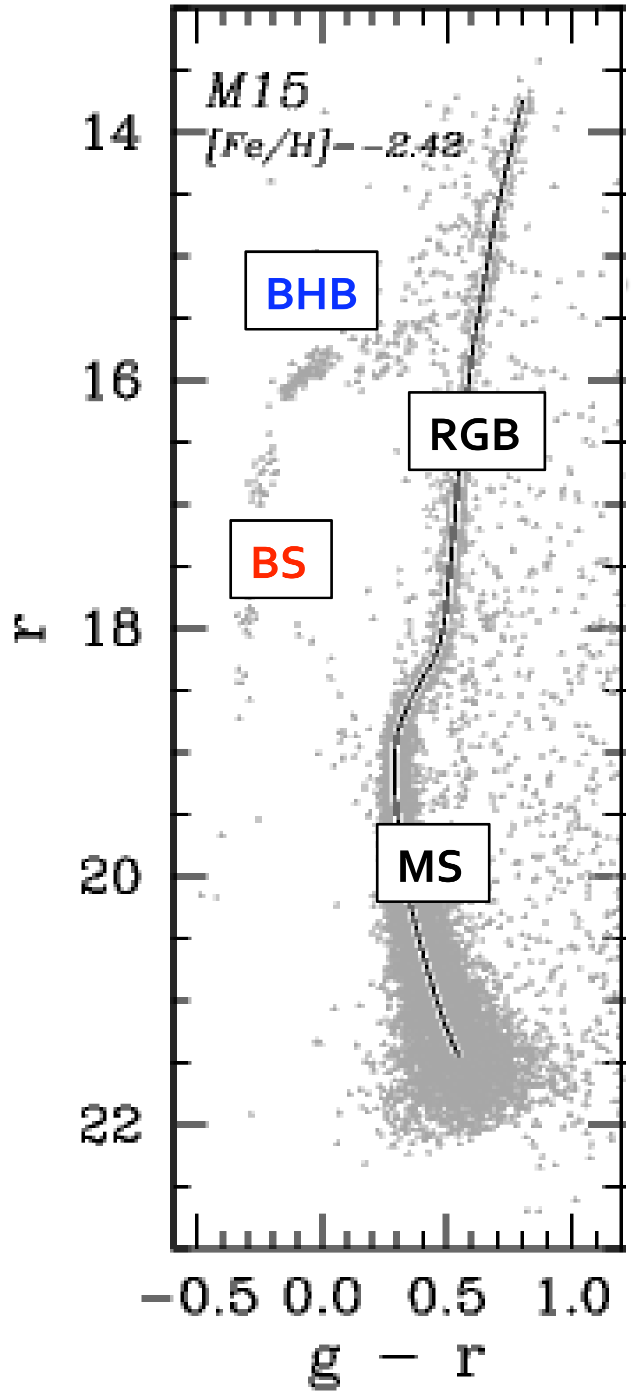


Exciting prospect for studies of stellar halos **beyond the local group** – surface brightness profiles (see later).

In practice, not so simple…

- ❑Mix of populations with different absolute magnitudes, distances.
- ❑To probe out to large radii, need to “see through” foreground stars.
- ❑Fainter magnitudes -> larger photometric errors and galaxy contamination.



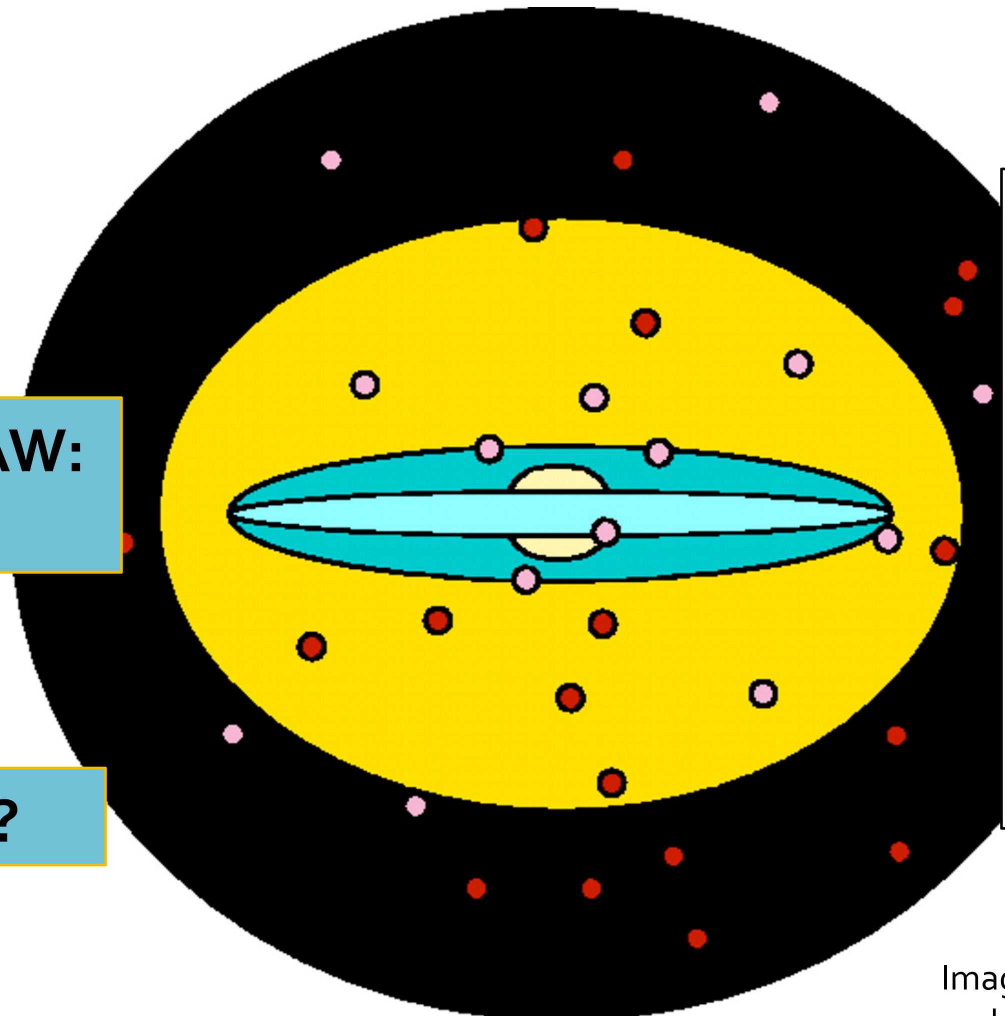


The Milky Way Stellar Halo Density Profile (r < 30 kpc) Pre-2010(ish) large area surveys

OBLATE

POWER-LAW: α~3.5

SMOOTH?



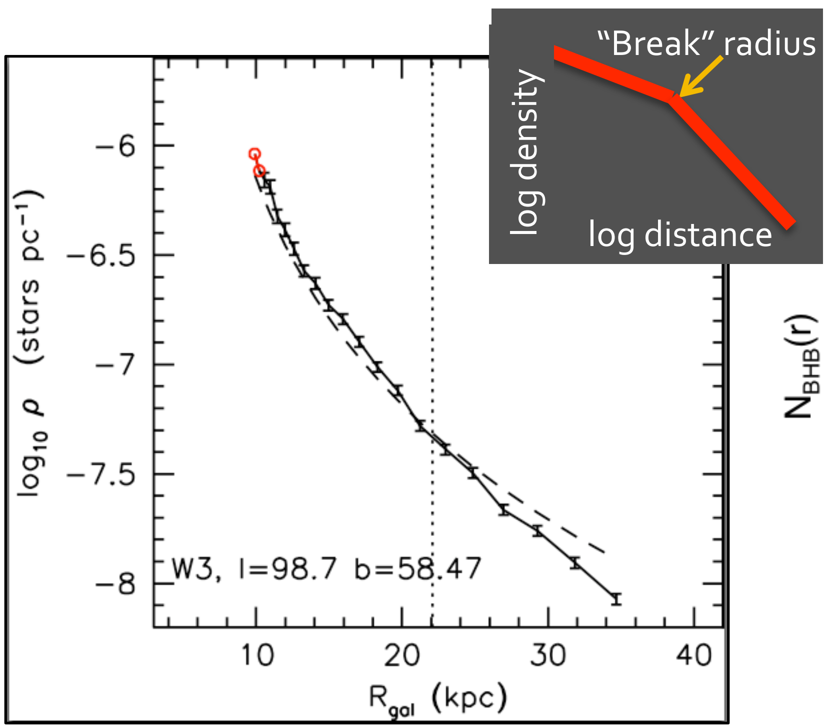
Non-exhaustive list of references:

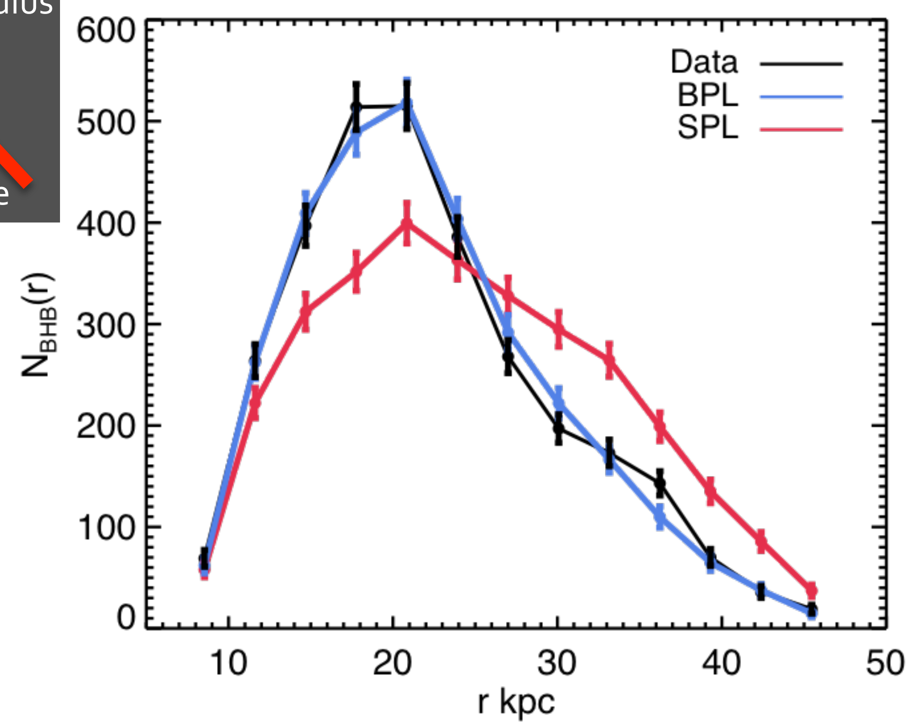
Hartwick 1987
Preston et al. 1991
Sluis & Arnold 1998
Robin et al. 2000
Yanny et al. 2000
Siegel et al. 2002
Newberg & Yanny 2006
Juric et al. 2008
De Propris et al. 2010

Image Credit: Joss Bland-Hawthorn and Ken Freeman 2000, Science

The “Broken” Milky Way Stellar Halo

- **Beyond r ~ 25 kpc**, the stellar density in the Milky Way falls off more rapidly; Sesar et al. 2011 (MSTO, CFHTLS), Deason et al. 2011 (BHB, SDSS)
- See **Deason, Belokurov, Evans, Johnston 2013** for possible origin of break.
- Does this decline continue to larger distances?





Touching the Void

Deason, Belokurov, Koposov, Rockosi 2014, ApJ, 787, 30, arXiv:1403.7205

THE ASTROPHYSICAL JOURNAL, 787:30 (16pp), 2014 May 20 doi:10.1088/0004-637X/787/1/30

TOUCHING THE VOID: A STRIKING DROP IN STELLAR HALO DENSITY BEYOND 50 kpc

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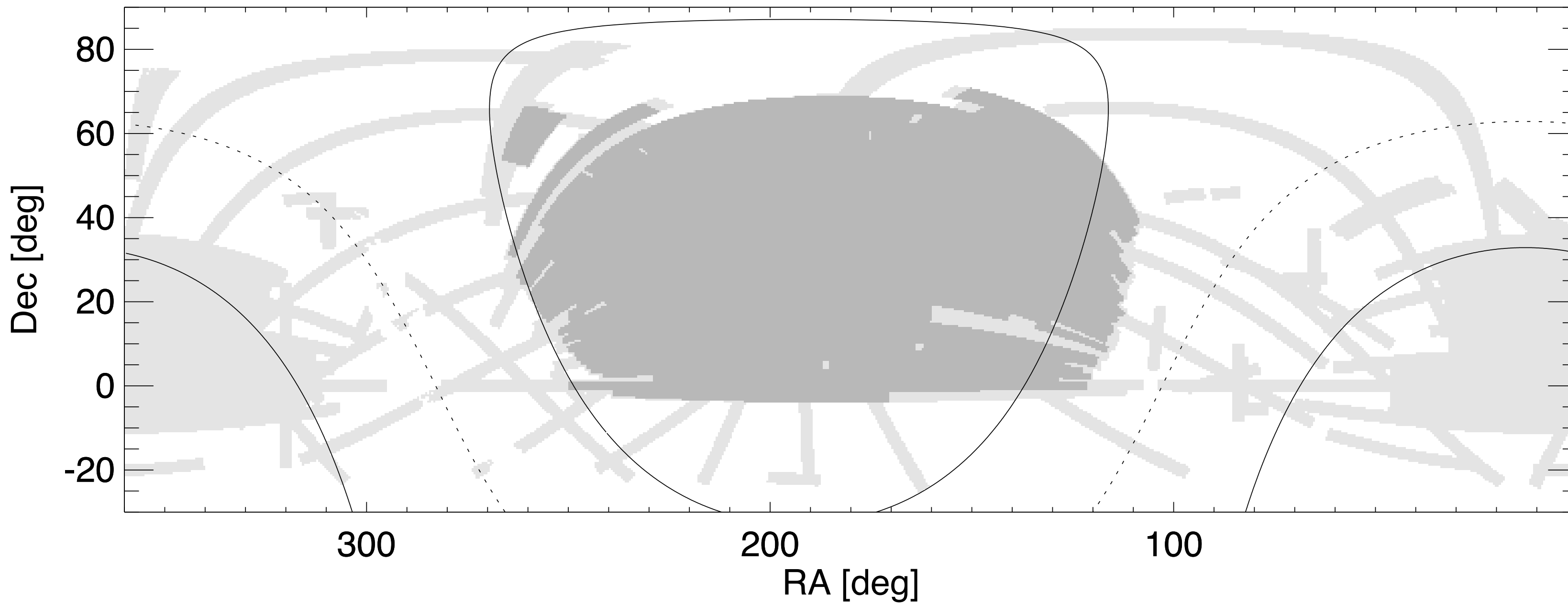
ABSTRACT

We use A-type stars selected from Sloan Digital Sky Survey data release 9 photometry to measure the outer slope of the Milky Way stellar halo density profile beyond 50 kpc. A likelihood-based analysis is employed that models the *ugr* photometry distribution of blue horizontal branch and blue straggler stars. In the magnitude range $18.5 < g < 20.5$, these stellar populations span a heliocentric distance range of: $10 \lesssim D_{\rm BS}/{\rm kpc} \lesssim 75$, $40 \lesssim D_{\rm BHB}/{\rm kpc} \lesssim 100$. Contributions from contaminants, such as QSOs, and the effect of photometric uncertainties, are also included in our modeling procedure. We find evidence for a very steep outer halo profile, with

Pushing SDSS to the Limit



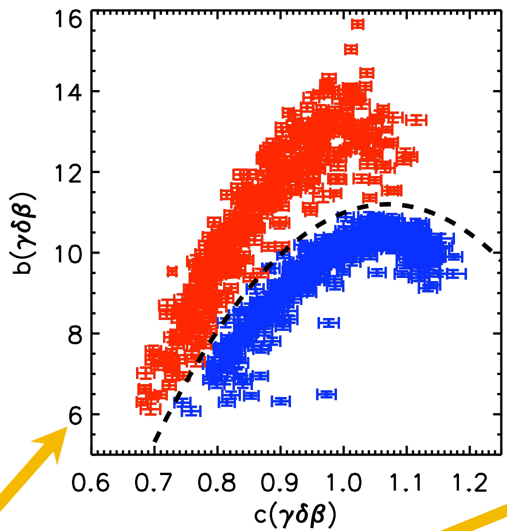
- Northern and Southern sky coverage (14,000 deg^2)
- |b| > 30°: exclude low latitudes
- 18.5 < g < 20: probes distances out to ~100 kpc using Blue Horizontal Branch stars (BHBs)
- **BHBs** – bright, approximate standard candles
- **Photometric errors** and **contamination** an issue at fainter magnitudes.

Modeling *ugr* Photometry

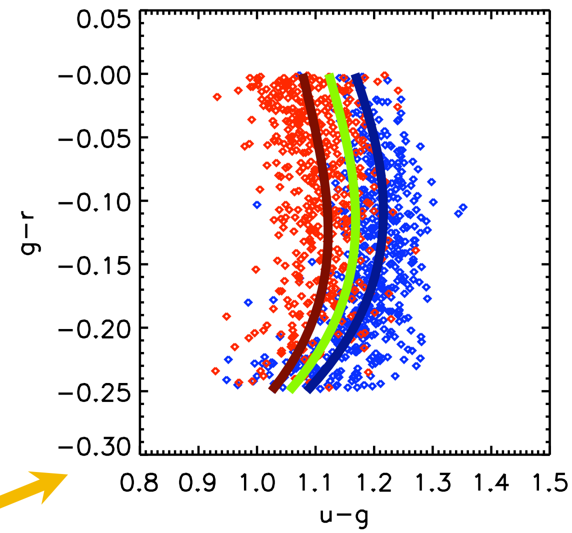
Deason et al. 2011
16 < g < 18.5

Deason et al. 2014
18.5 < g < 20

Spectroscopy

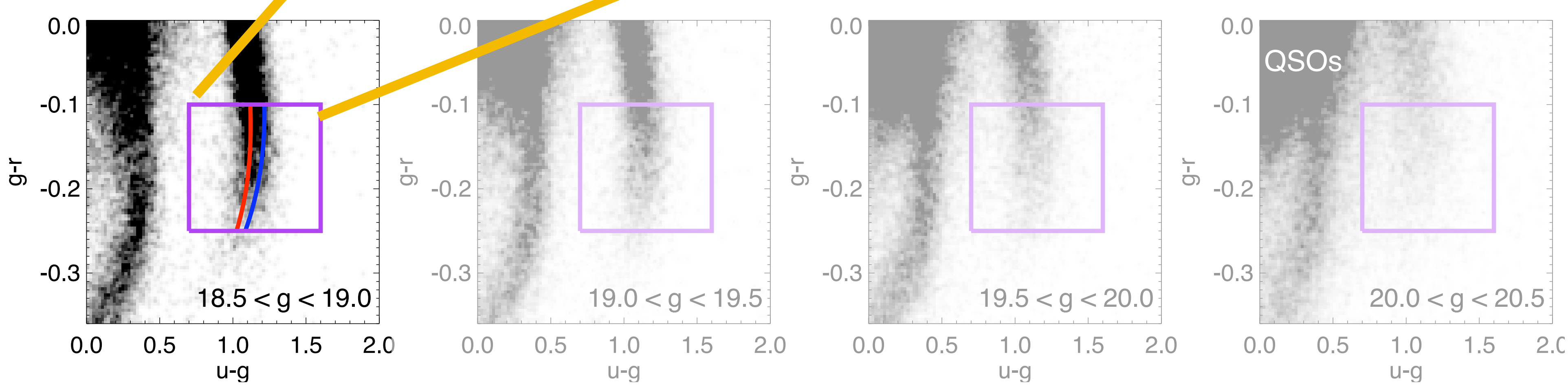


Photometry



BHB and **BS**
A-type stars

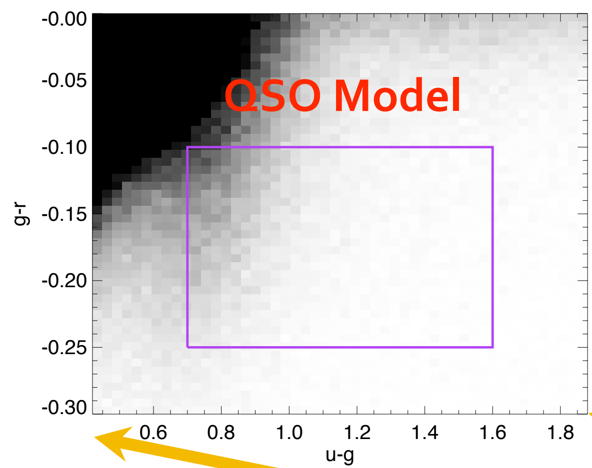
Deason et al. 2011

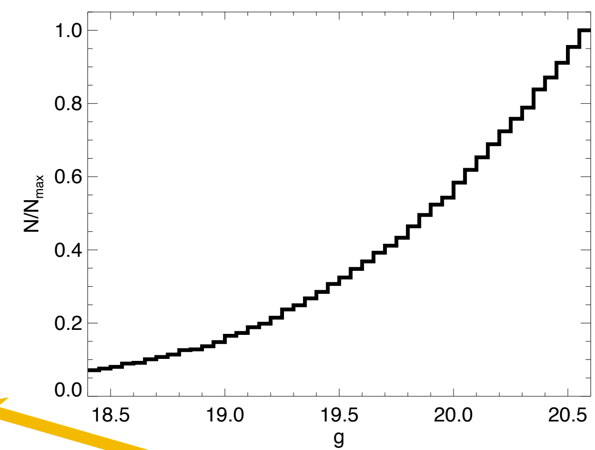


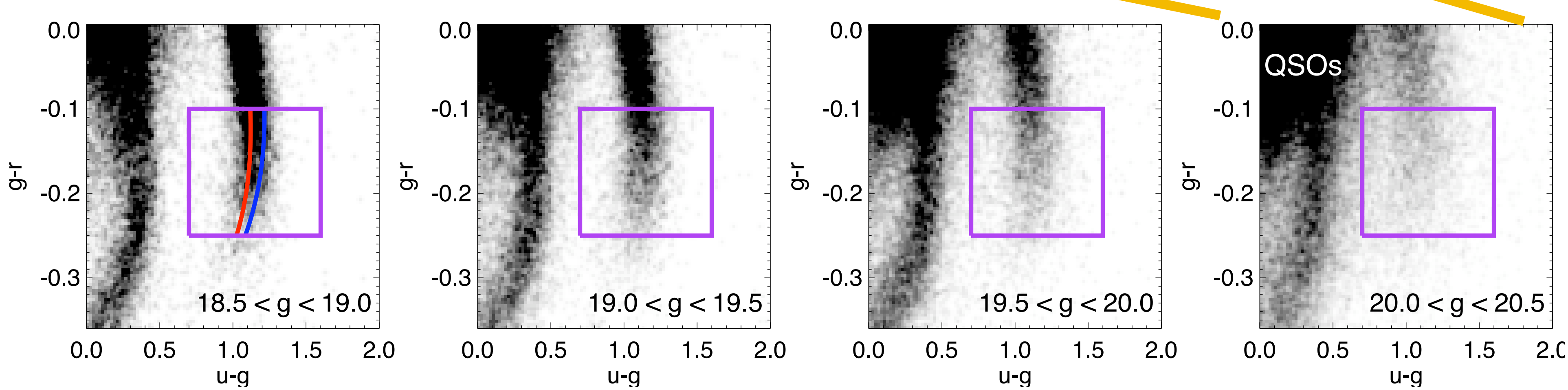
Modeling *ugr* Photometry

QSO model from **Bovy et al. 2011** XDQSO algorithm

QSOs: important at fainter magnitudes







Likelihood Method

A-type star model depends on 1) **density profile** parameterization and 2) **absolute magnitude** calibration for BHB and BS stars.

Intrinsic QSO model fixed.

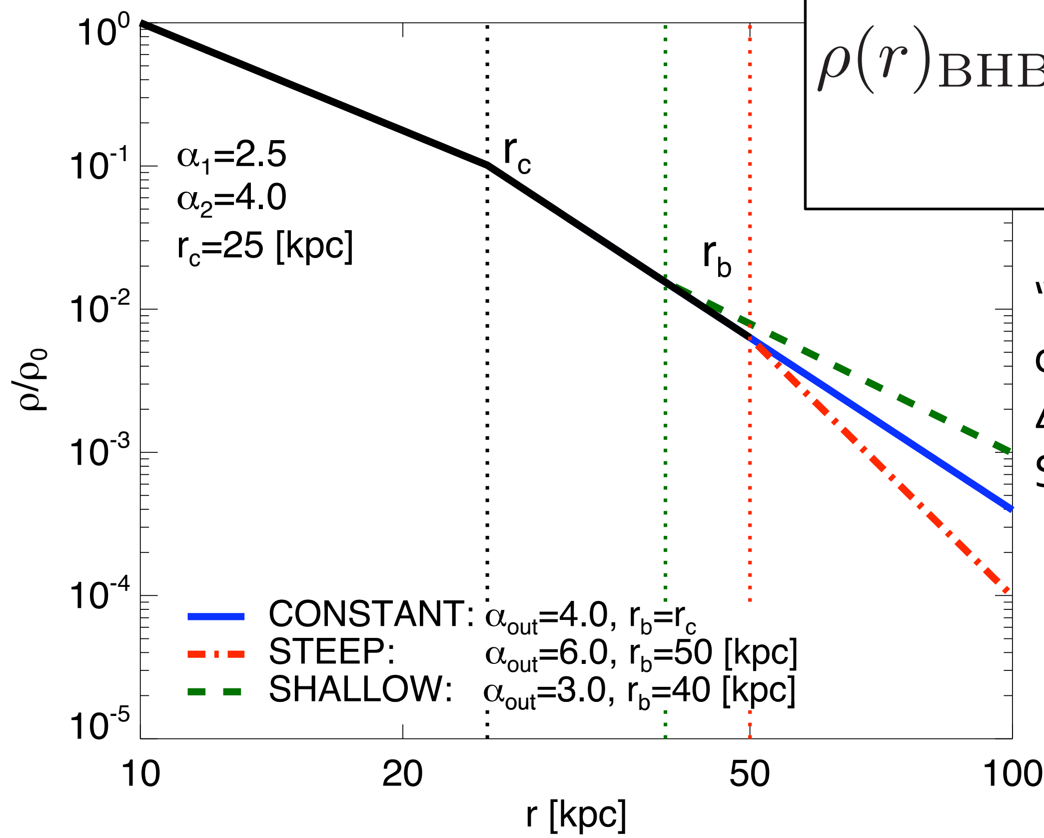
1. Define **intrinsic** A-type star and QSO models in *ugr* space.

2. **Convolve** intrinsic model with photometric uncertainties: takes into account populations scattering in/out of *ugr* selection box.

3. Given model density parameterization and SDSS DR9 photometry find **likelihood**.

$$\log\mathcal{L} = \sum_{i=1}^{N_{\rm tot}} \log\left[\{(1 - f_{\rm Q})\tilde{\nu}_*(ugr_i, m_{g,i}, \ell_i, b_i) + f_{\rm Q}\tilde{\nu}_{\rm Q}(ugr_i, m_{g,i}, \ell_i, b_i)\}\cos b_i\right].$$

Stellar Halo Density Model



$$\rho(r)_{\mathrm{BHB,BS}} \propto \begin{cases} r^{-\alpha_1} & r \leq r_c \\ r^{-\alpha_2} & r_c < r \leq r_b \\ r^{-\alpha_{\mathrm{out}}} & r > r_b \end{cases}$$

"Inner" stellar halo parameters consistent with previous work within 40-50 kpc (e.g. Deason et al. 2011; Sesar et al. 2011)

$$r_c \in [20, 30]\mathrm{kpc}$$

$$\alpha_1 = 2.5$$

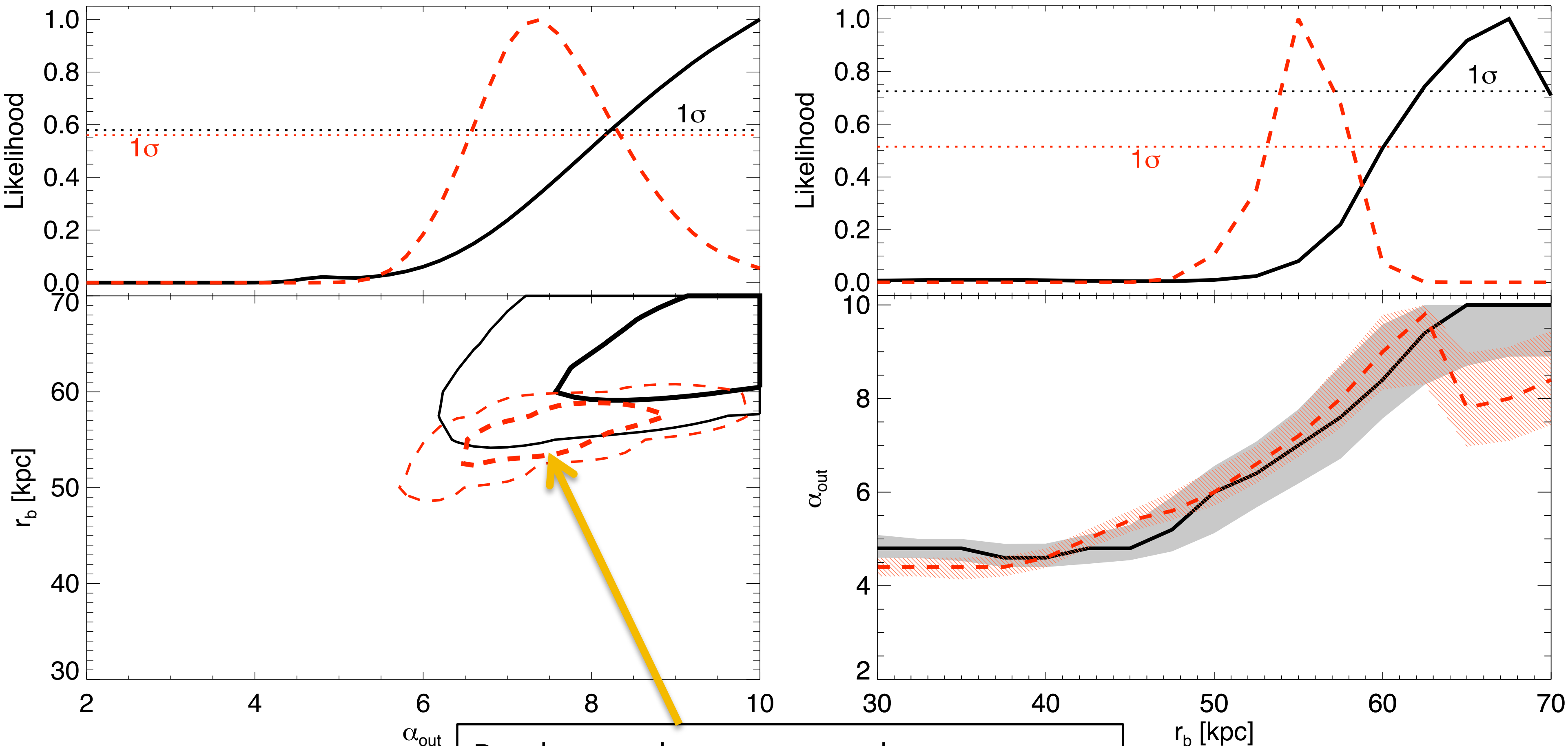
$$\alpha_2 \in [3.5, 5.0]$$

Results

Very steep outer halo profiles favored, even if large structures like SGR are included or excluded.

α ~ 6 beyond 50 kpc, cf. α ~ 3-3.5 in M31

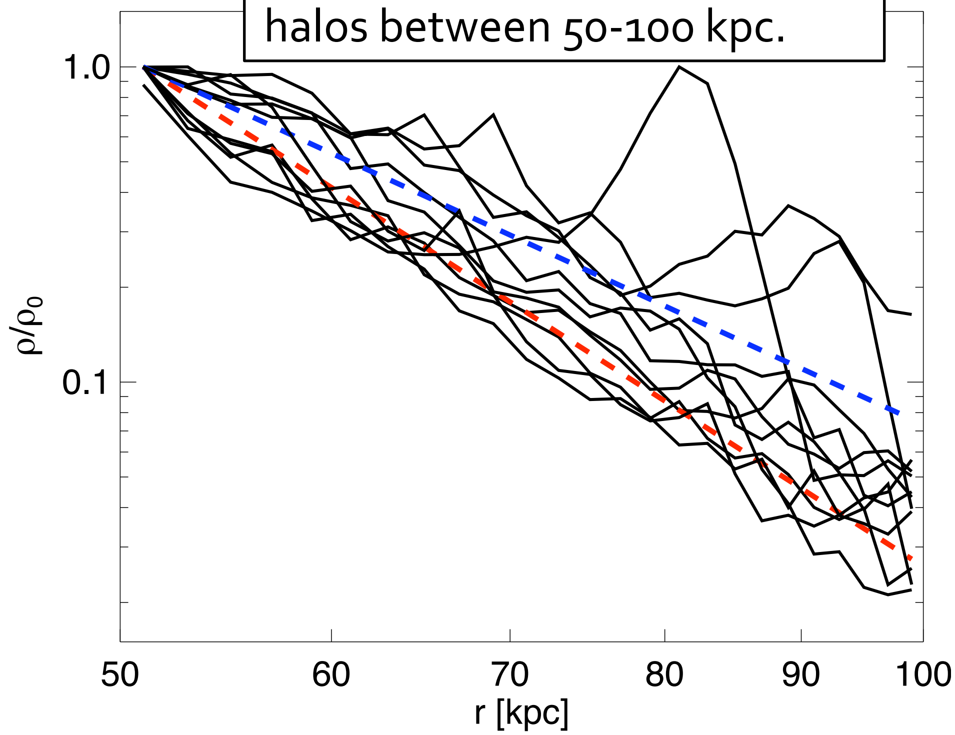
RED = inc SGR, BLACK = exc. SGR

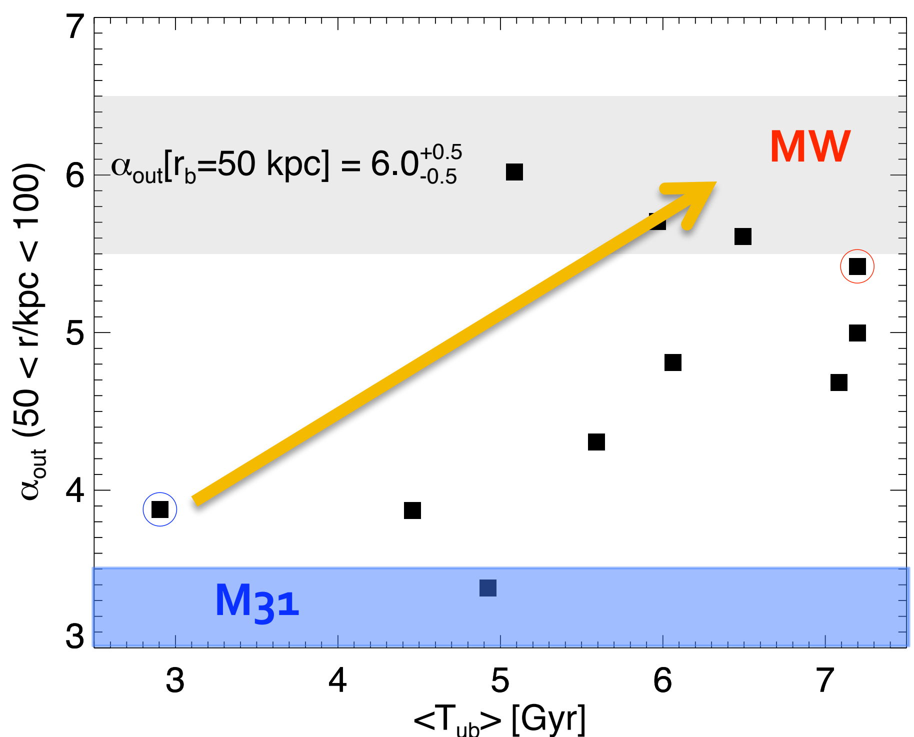


Break at ~50 kpc: corresponds to apocenter of SGR leading arm (Belokurov et al. 2014)

Implications for Milky Way (and M31) Accretion History

Density profiles of B&J stellar halos between 50-100 kpc.



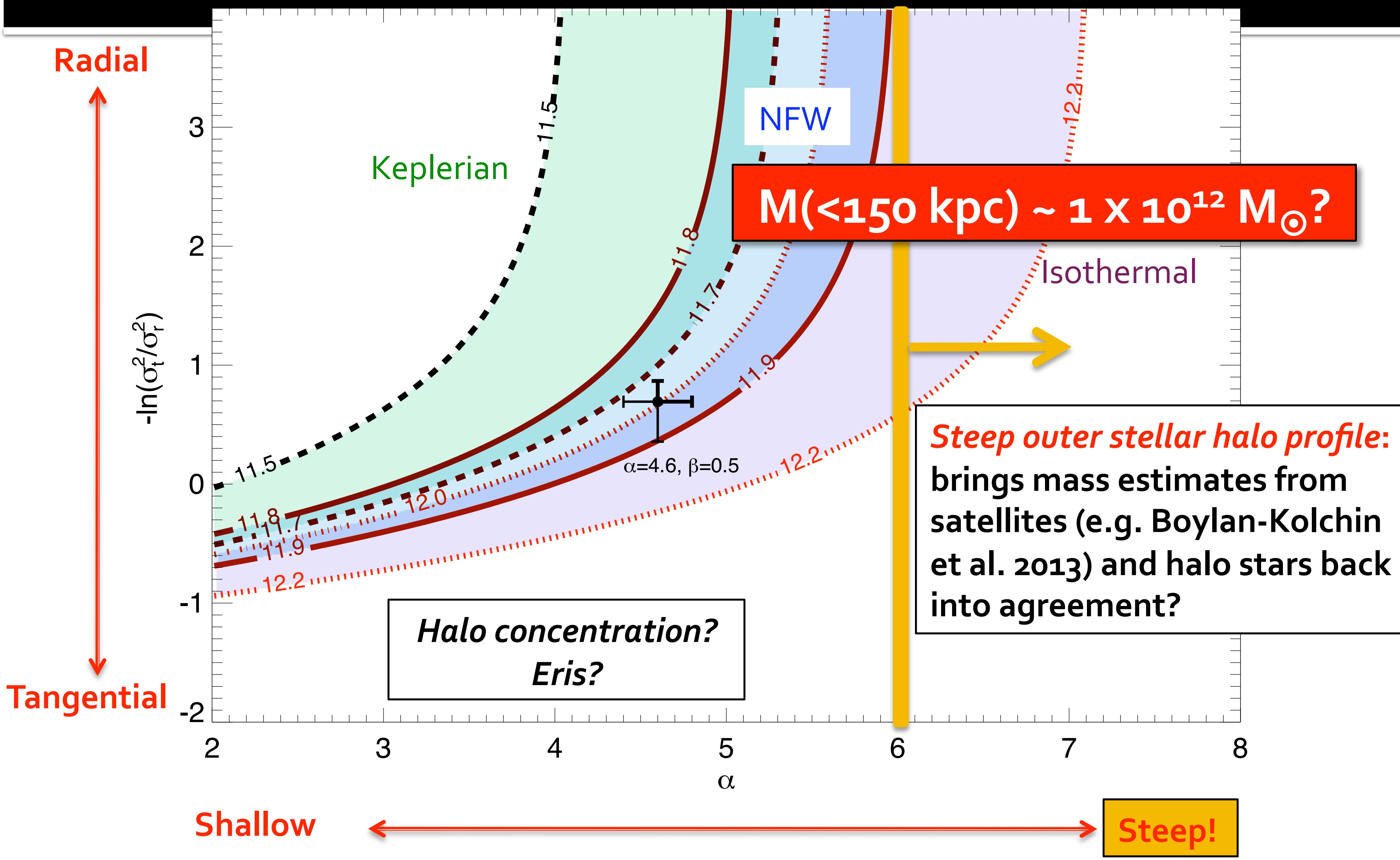


Shallower slopes = more recent accretion activity
Steeper slopes = relatively quiescent accretion history

Average time stripped halo stars become unbound from their parent dwarf galaxy

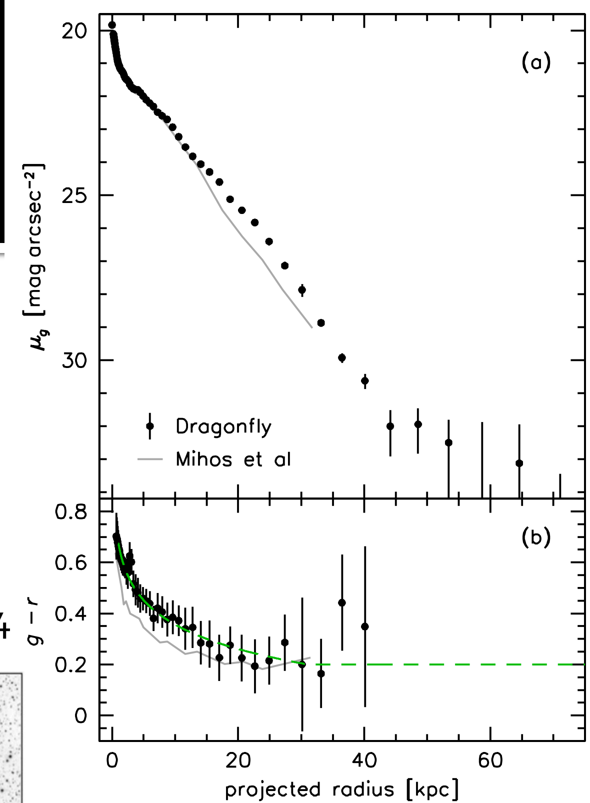
Implications for Milky Way Mass

Deason et al. 2012

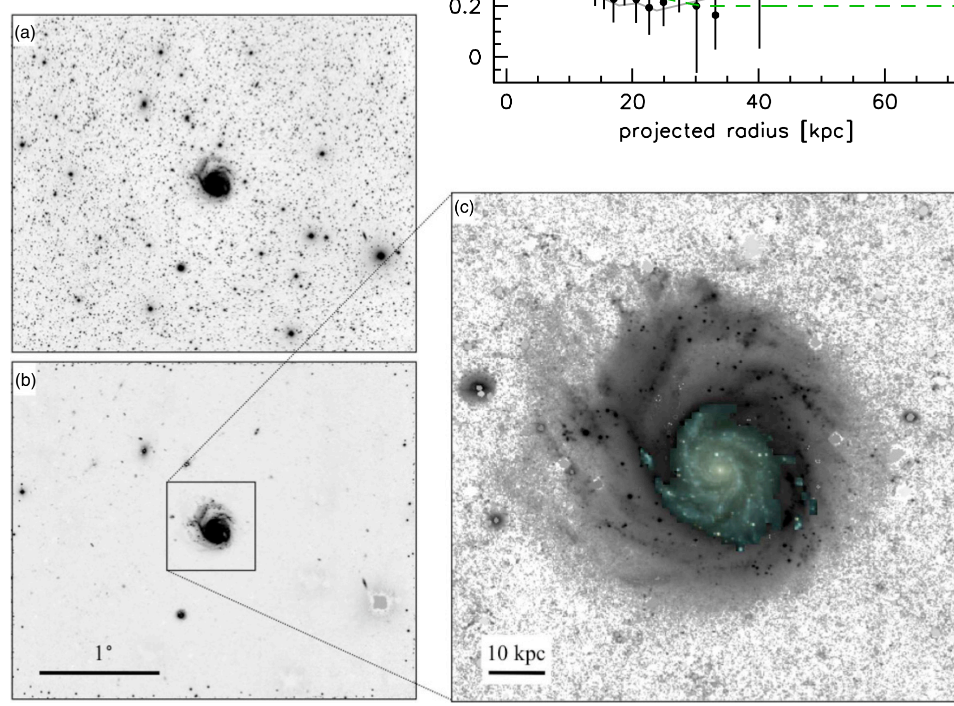


The Future: External Galaxies

- Stellar halo density profiles: accessible for galaxies **beyond the local group**.
- Potentially can constrain **accretion histories** for large samples of galaxies.
- DragonFly project, Ghosts (HST)
- **Stacking** can be useful, but lose detail on individual galaxies, and washes out diversity in stellar halos.

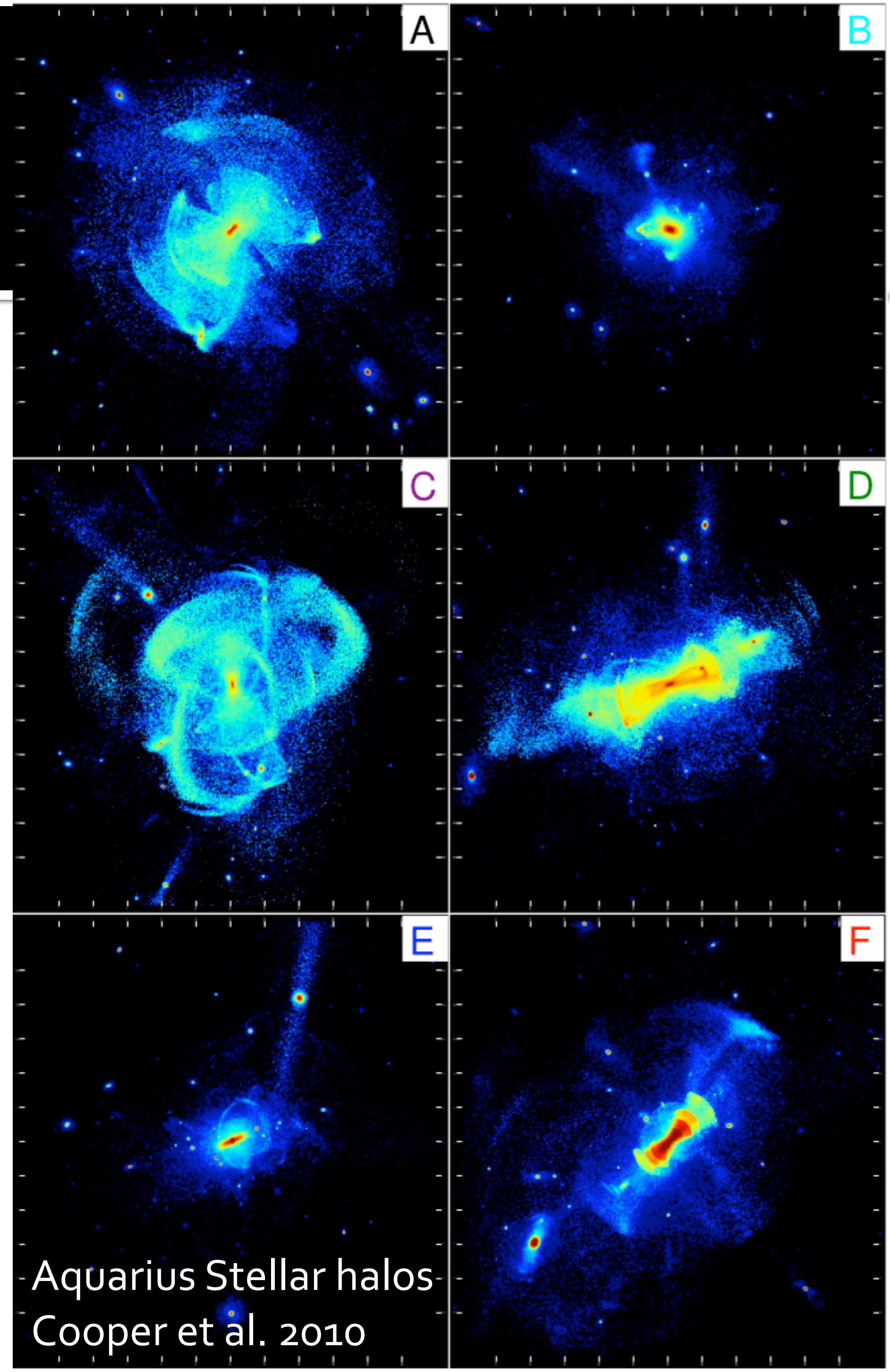


van Dokkum et al. 2014



The Future: Simulated Stellar Halos

- Large **halo-to-halo scatter** in stellar halo properties.
- Current samples limited to ~**6-11 halos**. Needs to increase substantially (i.e. 100's) to put MW/M31 accretion histories in context.
- Several groups working on this: **dm tagging** (Stanford/Wechsler et al., MIT/Frebel et al. – Caterpillar project, Cambridge/ Belokurov et al.), **hydro sims** (Arepo/Illustris, Virgo consortium/EAGLE)



Aquarius Stellar halos
Cooper et al. 2010

Summary

- Stellar halo density profile - key for constraining total **mass** and **accretion history** of the Galaxy.

- Steep fall off in MW stellar halo density beyond 50 kpc:
  - Suggests relatively quiescent recent accretion history for the MW (cf. M31)
  - May be the "missing information" needed to bring MW mass estimates from halo stars and satellites into agreement.

- Unlike several MW/M31 stellar halo properties, global density profile can be measured in galaxies **beyond the local group**. Exciting prospect for the future.