The Stellar Halos of Galaxies: An Observer's Perspective

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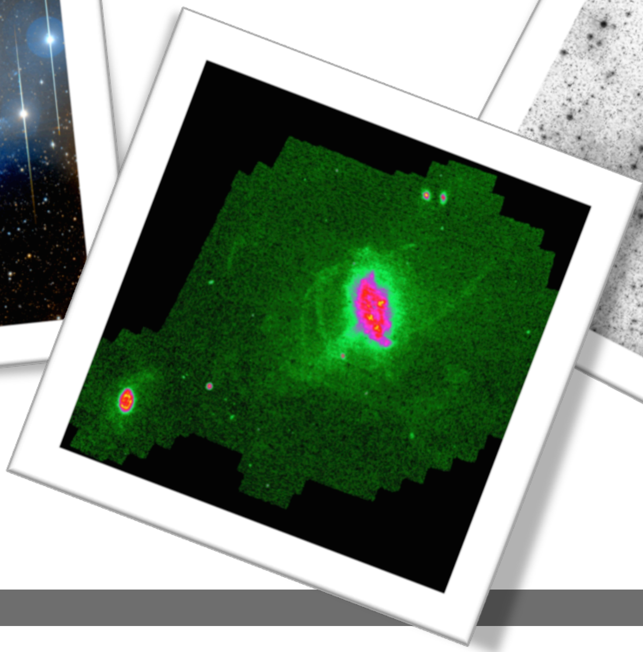
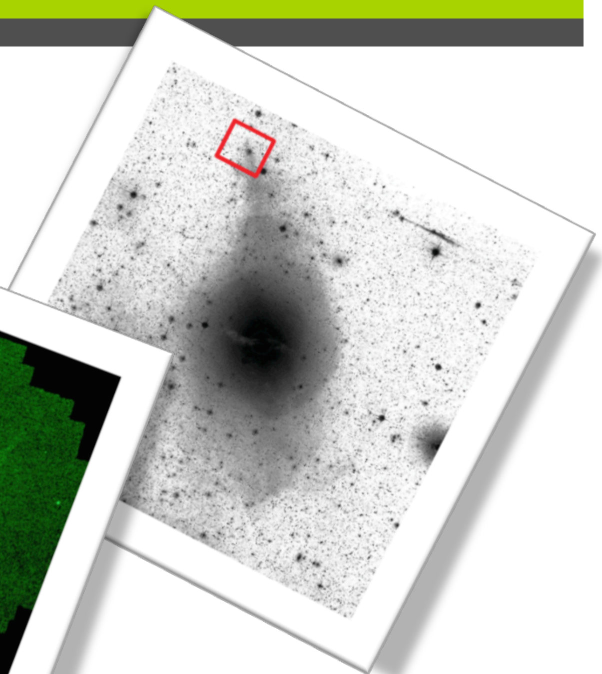
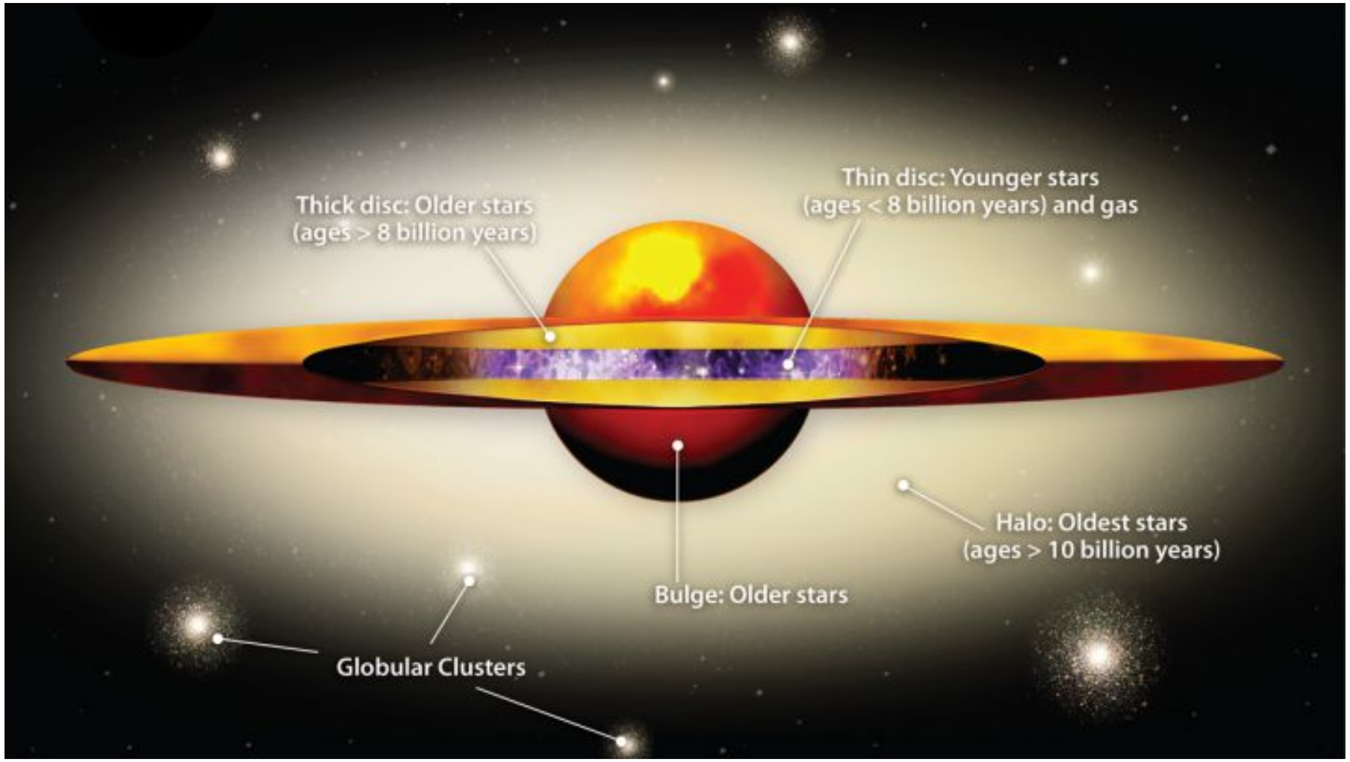



Stellar Halos: Basic Facts

- ❖ Ultra-faint – typically require depth of μ_V ~ 30 mag per sq. arcsec to detect smooth halos i.e. ~9-10 magnitudes (0.05%) below the surface brightness of the dark night sky
- ❖ Huge – expect 100 -200 kpc extent around a MW-sized galaxy?
- ❖ Tiny fraction of the overall stellar mass and light in a galaxy – expect 1-few %.
- ❖ But these regions are known to punch far above their weight in terms of importance – e.g. they a preserve record of the accretion history and serve as DM halo probes.

The Classical View of a Stellar Halo

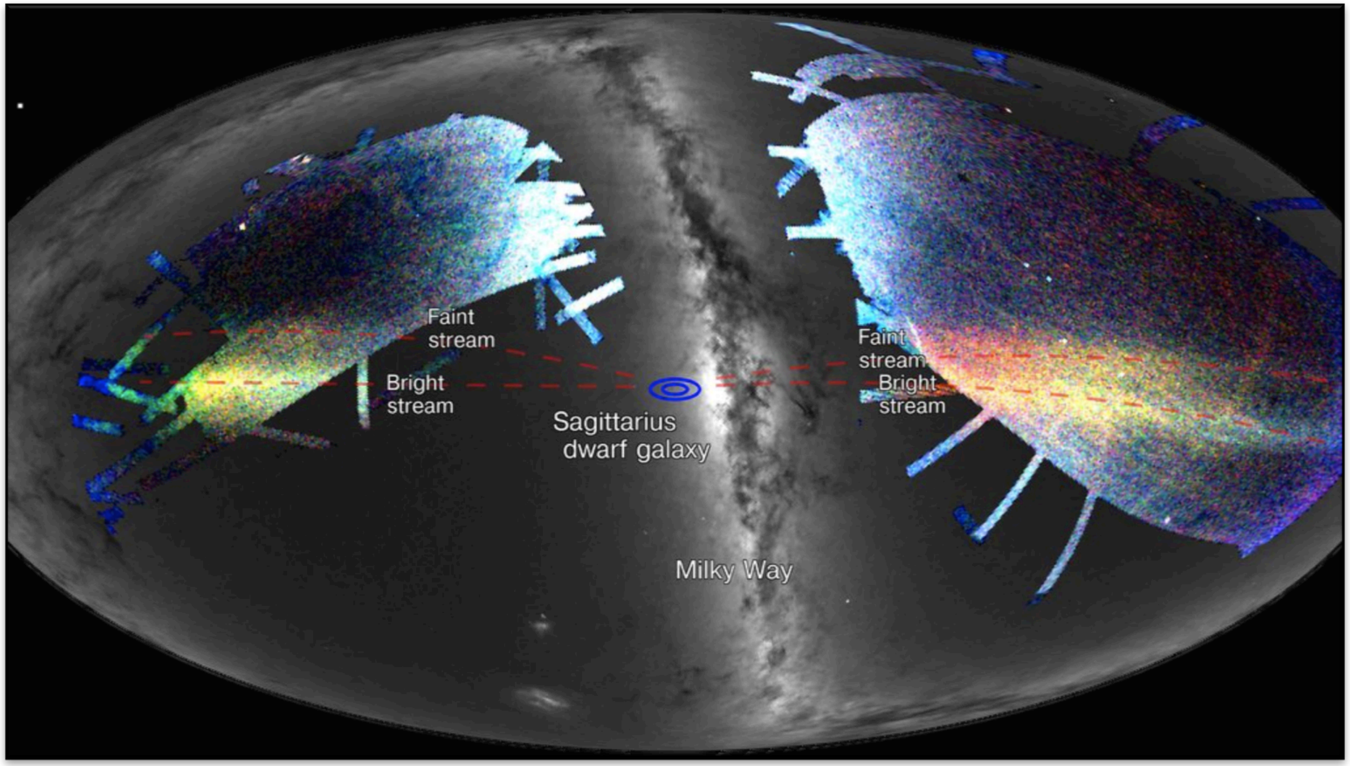
Credit: IoA Cambridge



A stellar cocoon that is smooth, spherical, pressure-supported and composed of ancient metal-poor stars.

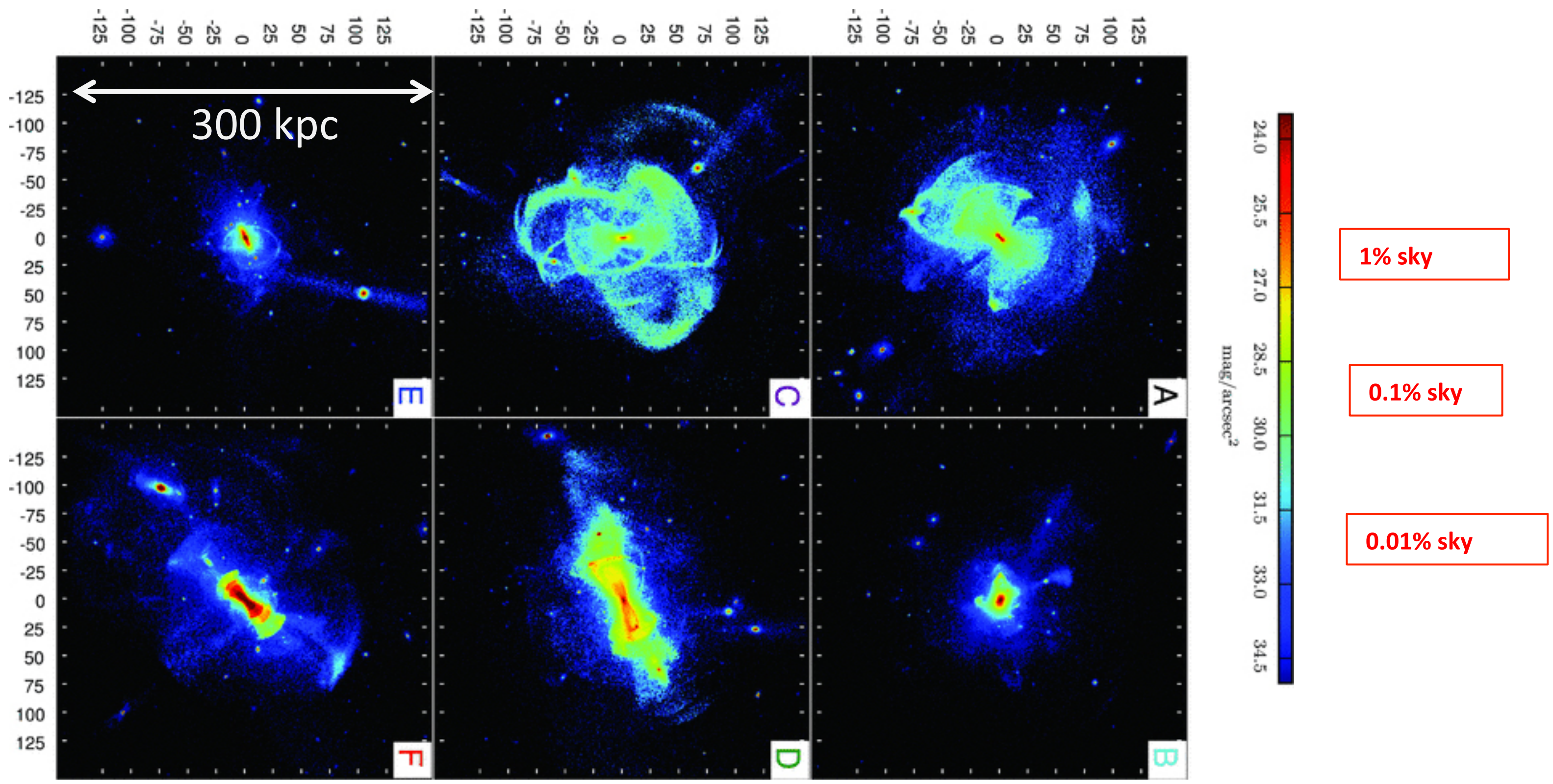
The Modern View of a Stellar Halo

Credit: Koposov et al, SDSS



A complex multi-component structure that is highly sub-structured, of variable shape, possibly rotating and composed of a mixed stellar population.

The Modern View of a Stellar Halo

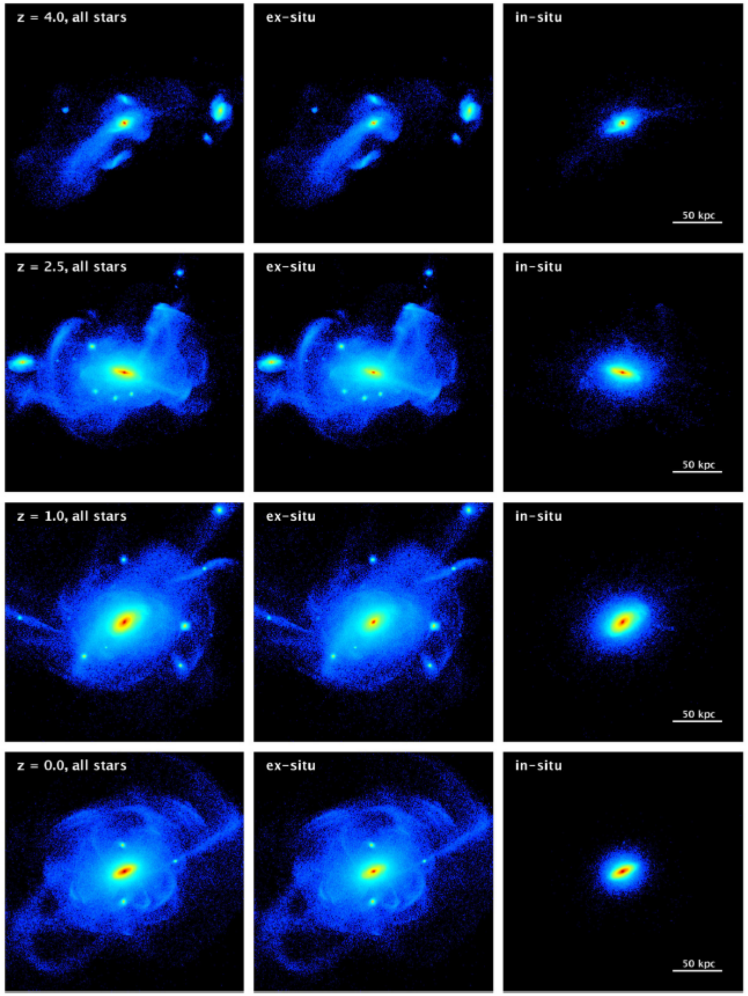


Cooper et al. 2010

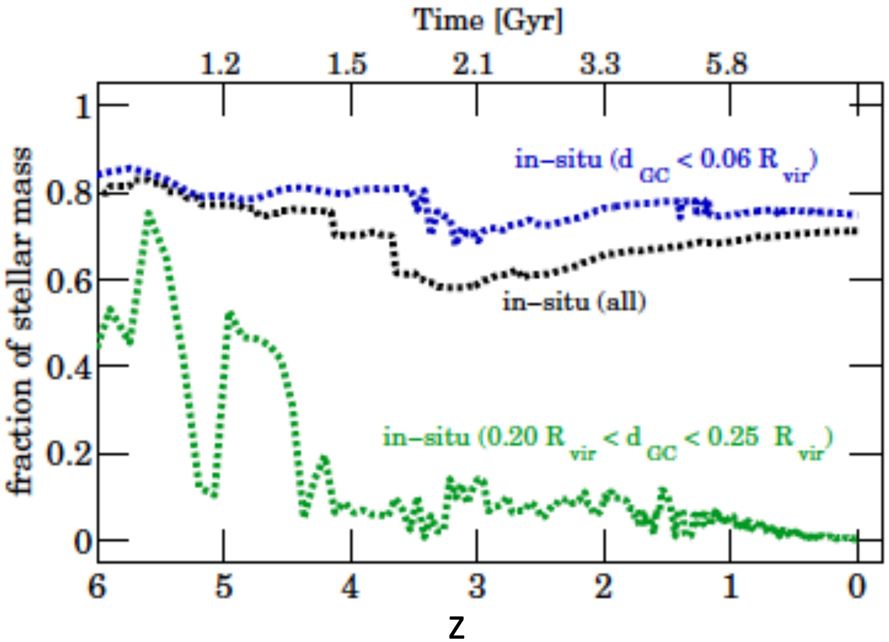
Expect significant galaxy-to galaxy variance at fixed (dark) halo mass, reflecting precise details of the accretion history.

The Modern View of a Stellar Halo

Pillepich et al. 2015



Expect the properties of even a single halo to vary over time, reflecting the nature of the last significant accretion.



How To Define a Stellar Halo?

- all stars/tracers beyond some fiducial radius?

  --- risk contamination from thick disk, thin disk and tidal debris.

  --- for e.g. some disks extend to at least 40 – 70 kpc in radius (e.g. Ferguson et al 1998, Ibata et al. 2005, Mihos et al. 2013, van Dokkum et al 2014) and are often clumpy or warped

- all stars/tracer beyond some fiducial radius that *do not* belong to visible and/or kinematic substructure?

  --- could miss most of the stellar mass at large radius.

  --- for e.g. in M31, only ~50% of the stars at R>30 kpc do not belong to substructure (Ibata et al. 2014, Gilbert et al. 2012)

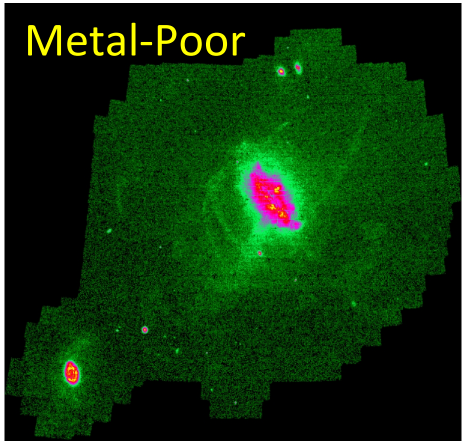
  -- is there a divide between observers and simulators on this?

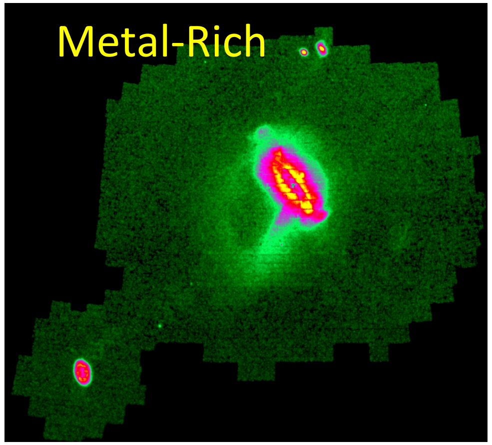
How To Define a Stellar Halo?

- all stars/tracers that belong to an extended hot and/or very metal poor (e.g. [Fe/H]<-1.5 dex) component?

--- could miss most of the stellar mass at large radius.
--- for e.g. in M31, only ~5% of the stars at R>30 kpc have [Fe/H]< -1.7 (Ibata et al. 2014)
--- most halo substructure is moderately metal-rich (e.g. Font et al. 2008)

PAndAS Maps of the M31 Halo to 150 kpc McConnachie et al. 2009





How To Define a Stellar Halo?

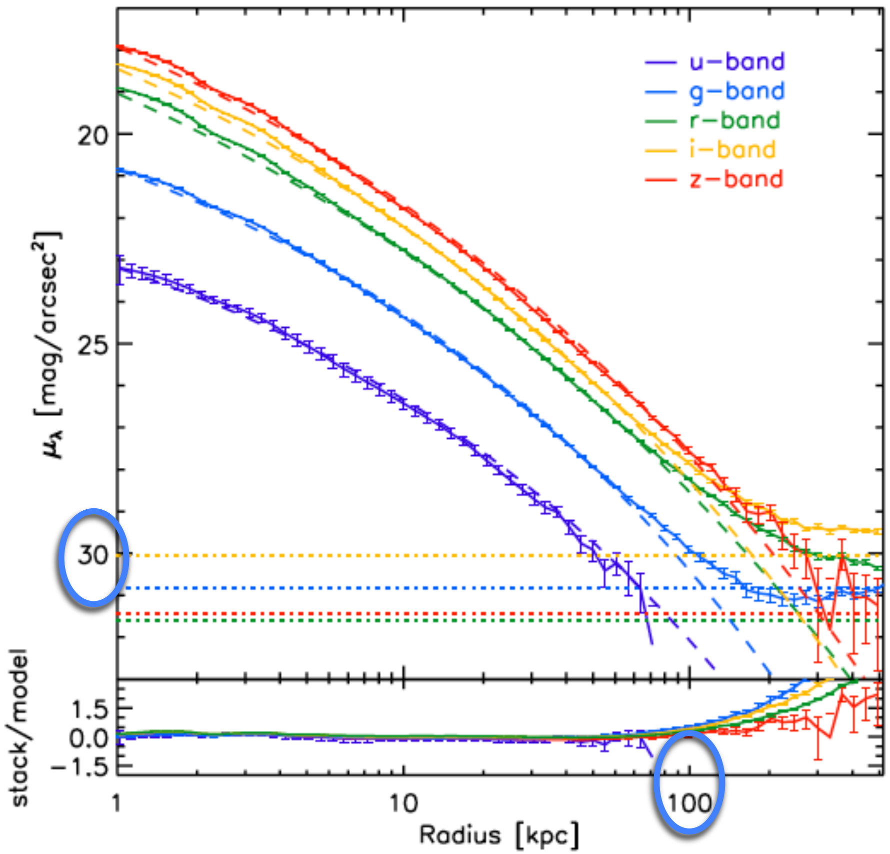
- should we aim to separate stellar halo populations from thick disk populations? Are they really different?

  --- *do thick disks represent co-planar accretions?*

- all stars/tracers located beyond a break in the outer surface brightness profile? Can we be sure such breaks indicate the transition from in situ to accreted star domination?

The correct answer is unclear – and it probably depends on the science question of interest – but what does matter is that definitions are used consistently across theory and observation!

Observing Stellar Halos: Stacking



~42,000 LRGs at z~0.3
Tal & van Dokkum 2011

Stacking analyses can reach μ_V~30-32 mag/□" but average over large numbers of galaxies so no information about variance. Also technically non-trivial….

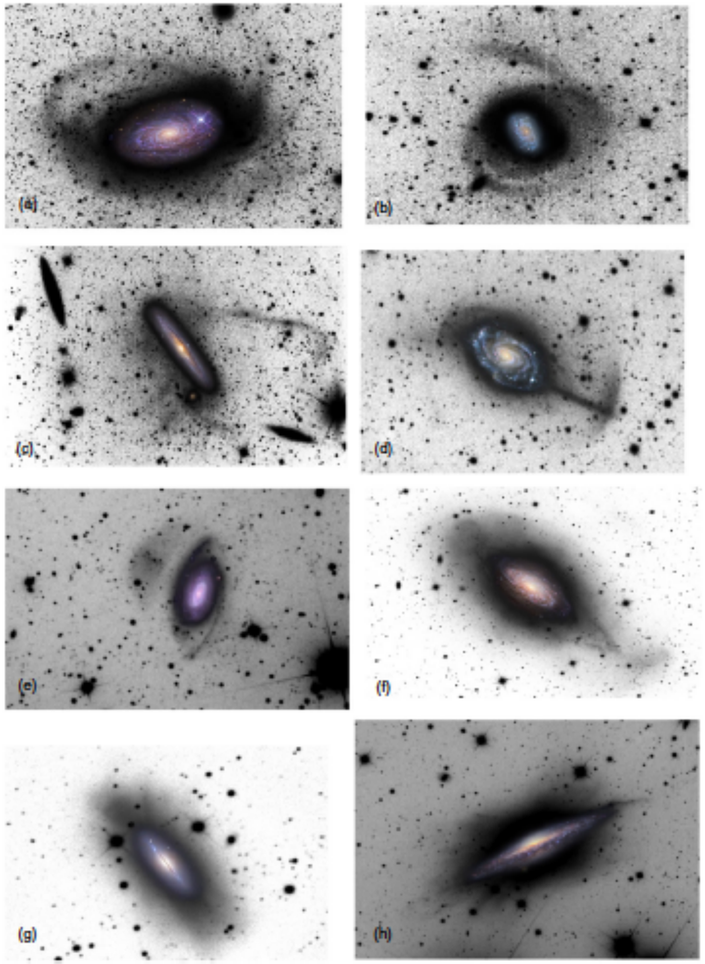
Involve integrated light analyses → limited stellar populations constraints.

See also Zibetti et al. 2004, 2005, Bergvall et al. 2010, d'Souza et al. 2014 and others.

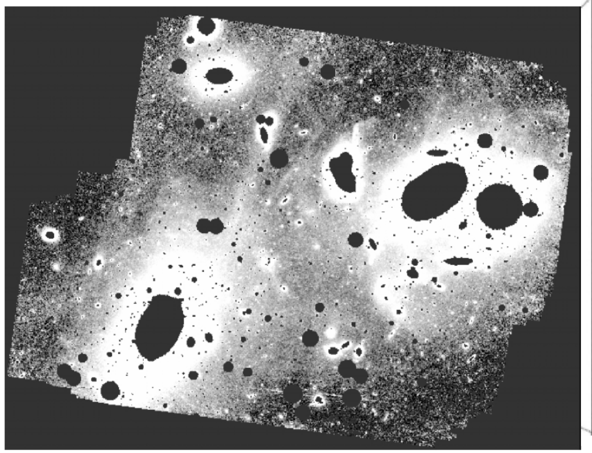
Observing Stellar Halos: Integrated Light

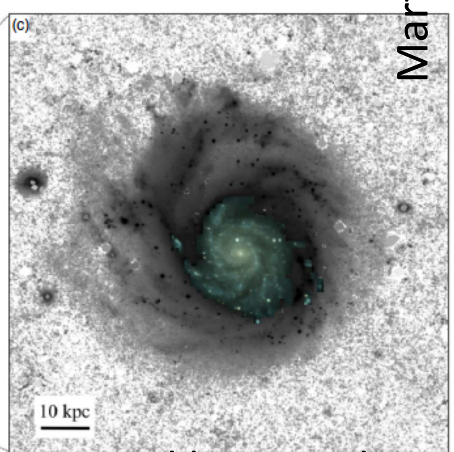
Duc et al. 2015

Martinez-Delgado et al. 2010



Mihos et al. 2005





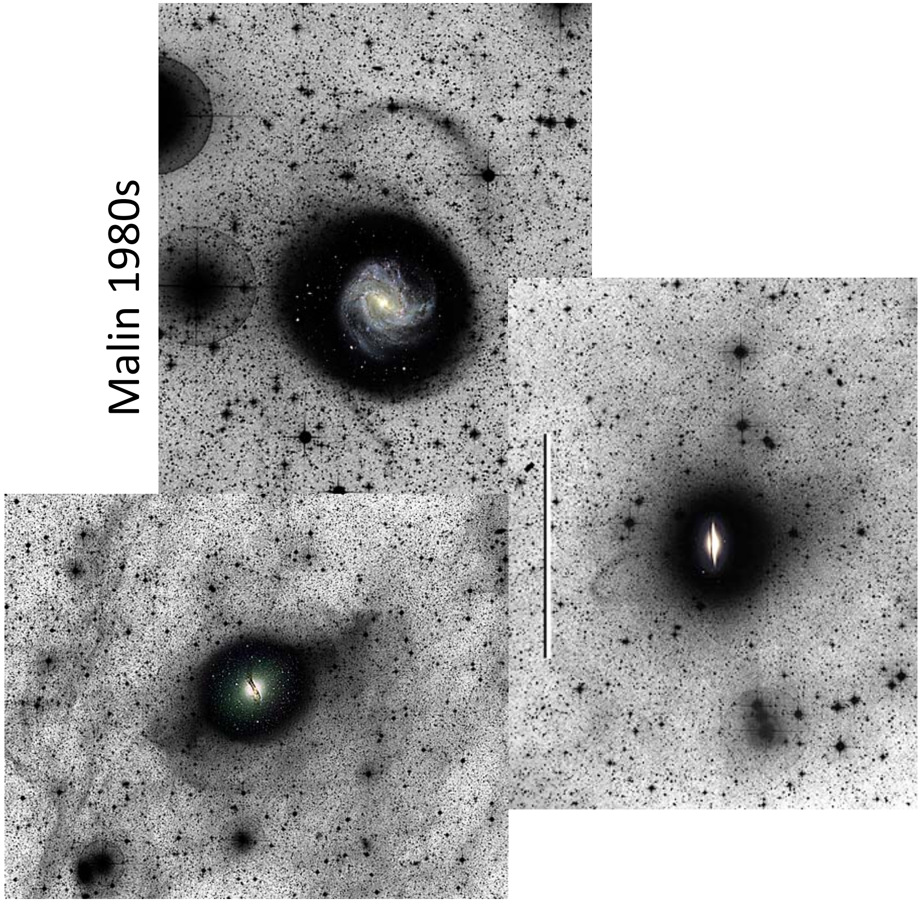
Van Dokkum et al 2014

Observing Stellar Halos: Integrated Light

Can detect emission to typically μ_V~27.5-29 (32?) mag/□”

Flat-field & sky background uncertainties, bright star halos as well as cirrus limit what can be achieved for individual galaxies.

Integrated light so limited stellar population constraints + the nature of debris features not always clear.



See also Martinez-Delgdao et al. 2010, Tal et al. 2009, Jablonka et al. 2010, Duc et al. 2015, Mihos et al. 2013, 2014, van Dokkum et al. 2014

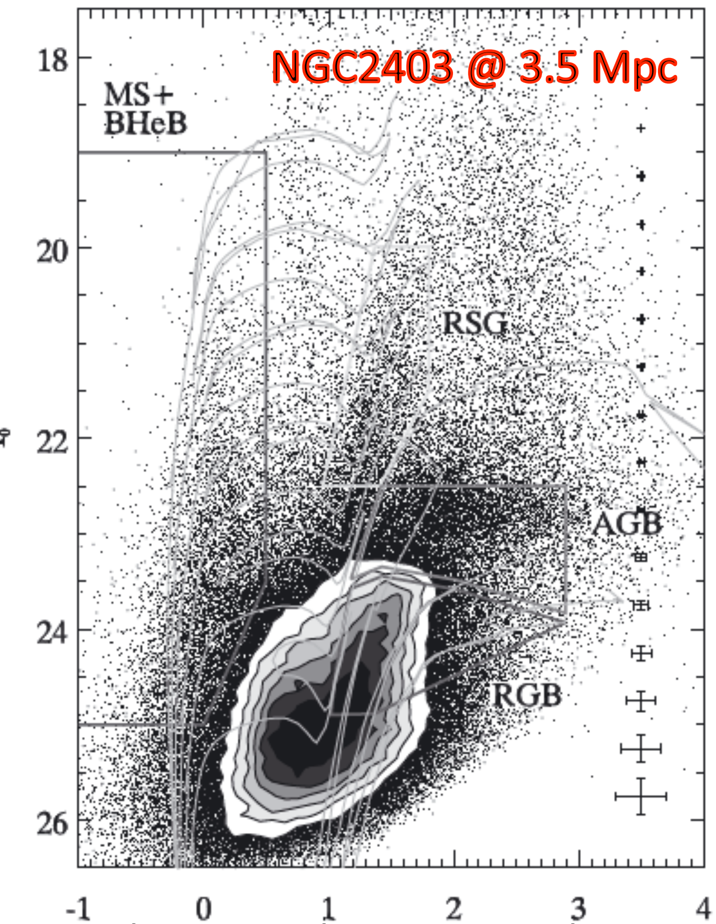
Observing Stellar Halos: Resolved Stars

Has potential to probe individual galaxies to very low surface brightness levels, μ_V~33 mag/□”.

Immune to flat-field/sky background uncertainties but highly susceptible to back/foreground contamination.

CMD information so can constrain stellar composition and (sometimes) kinematics.

Barker et al. 2012



e.g. INT/WFC and PAndAS Surveys. Also Barker et al. 2009, Mouhcine et al. 2010, Tanaka et al.2011, Bailin et al. 2011, Monachesi et al. 2013, Crnojevic et al. 2013, Rejkuba et al. 2014 +

Observing Stellar Halos: Resolved Stars

Limited to systems where populations can be resolved into individual stars (typically ~5 Mpc from the ground, ~10-15 Mpc from space) → i.e. small samples.....

Such nearby galaxies span large angular extents on the sky → i.e. studies often just see tinyl chunks...

Small FOV (e.g. HST) studies carry increased risk of contamination by other components and by uncertain background.

M81 @ 3.6 Mpc

Barker et al. 2009

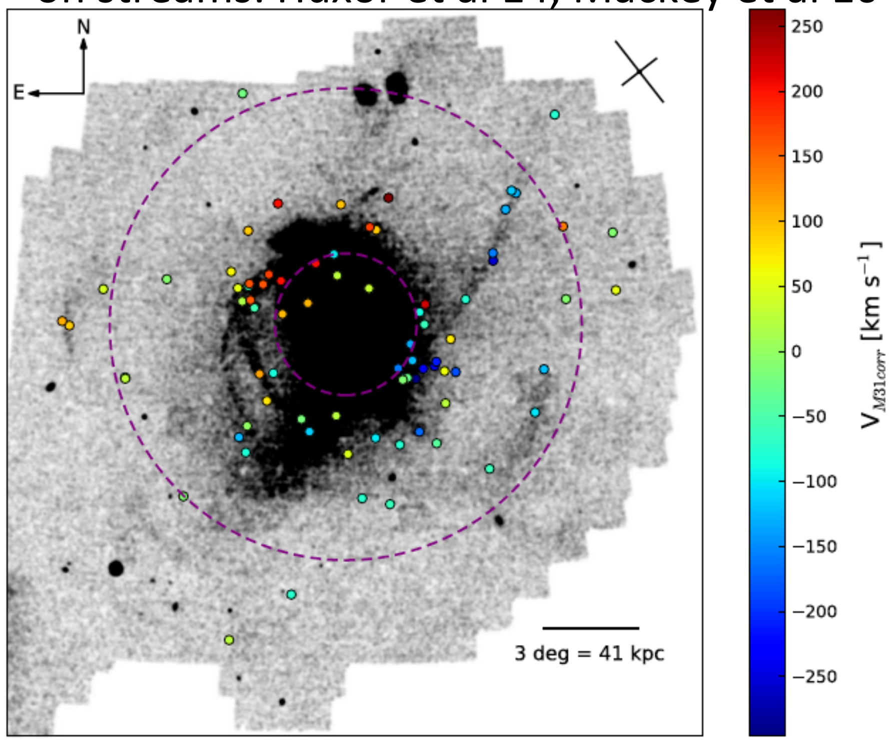
Observing Stellar Halos: Tracers

PNe and GCs are typical tracers used in external galaxy studies. They are bright and fairly numerous, at least in ETGs.

PNe are direct descendants of halo stars and should be good tracers.

But how good are outer halo GCs? Do they preferentially trace accreted material (i.e. streams)?

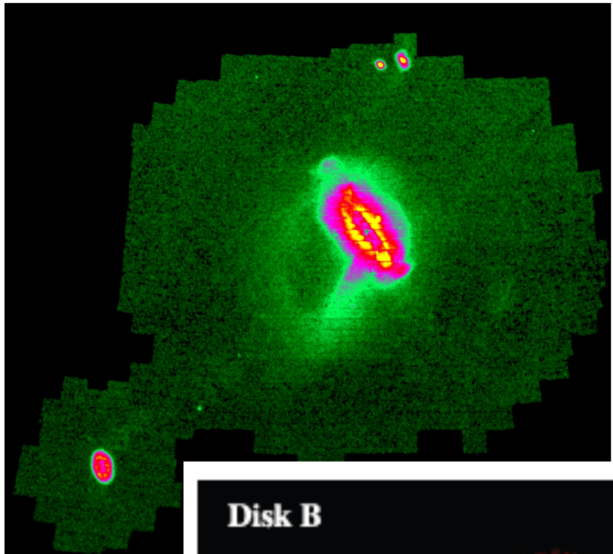
PANdAS outer halo GCs lie on streams: Huxor et al 14, Mackey et al 10

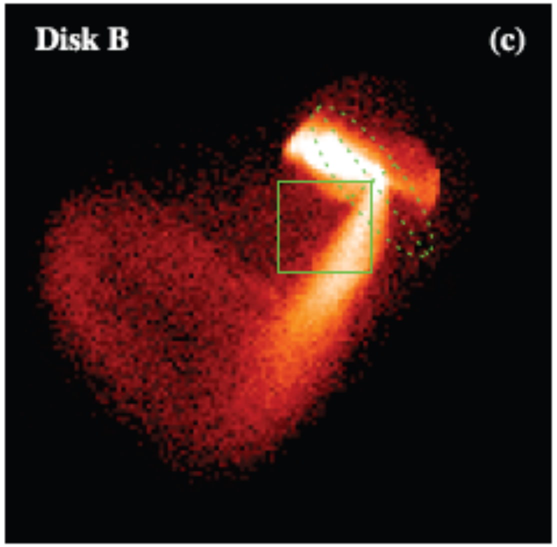


Veljanoski et al. 2014
See talk on Friday!

Method of Halo Study	Wide View (several tens of kpc contiguous)	Extreme Depth (>30 mag per square arcsec)	Large Samples (more than a few 100 galaxies)	Sensitivity to Variance within sample	Stellar populations constraints
Stacking	✔	✔	✔✔	✖	Poor
Integrated Light	✔	Rarely, but improving	✔	✔	Poor
Resolved Stars – Ground	Usually, but painful	✔✔	✖	limited	✔
Resolved Stars - HST	✖	?	✖	limited	✔✔
Tracers	✔	?	✖	✔	✖

Understanding M31's Inner Halo





The Giant Stream is the most significant substructure in M31's inner halo.

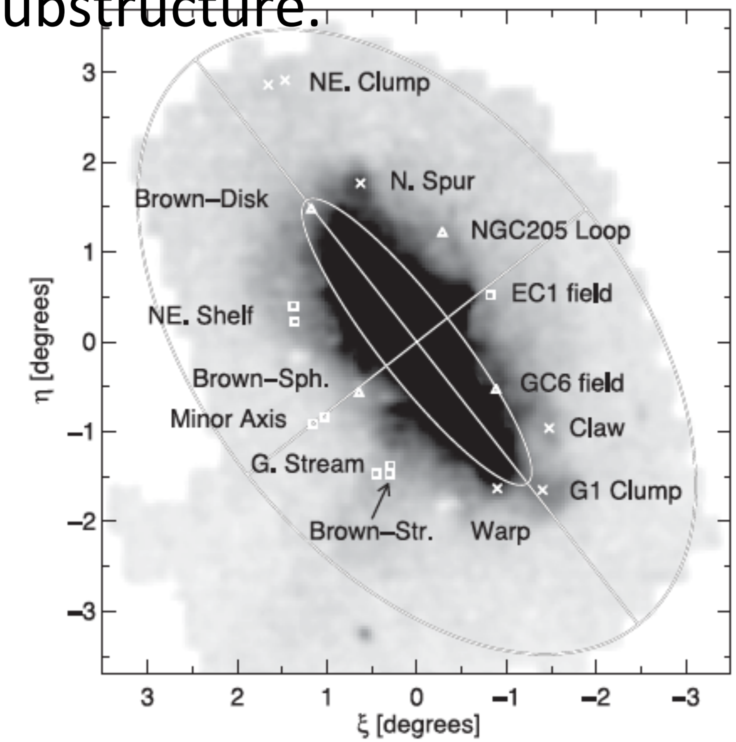
Modelled as the recent (~1 Gyr ago) accretion of a 10^9 M_{sun} object on a highly radial orbit.

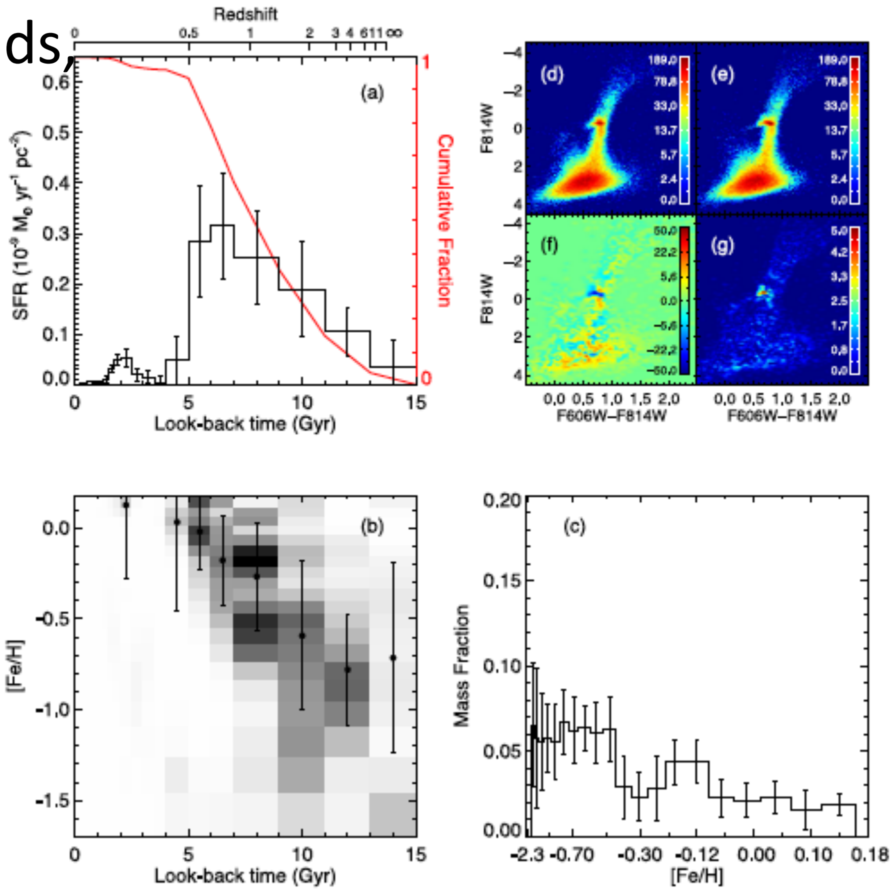
Debris predicted to contaminate most of M31's inner halo, but progenitor yet to be found.

Ibata et al. 2004, Fardal et al. 2007, 2008, 2013, Font et al. 2006 + many others

Understanding M31's Inner Halo

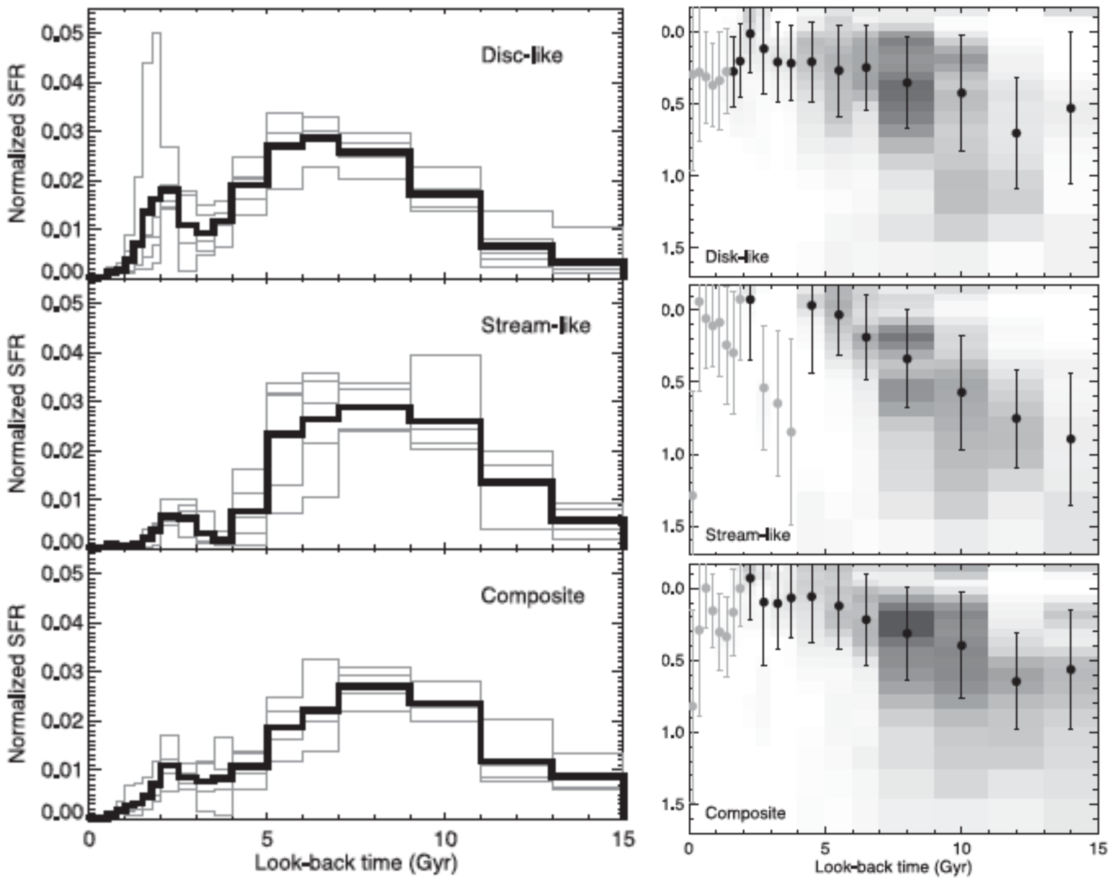
HST CMDs for 14 inner halo fields, many of which lie on coherent substructure.





Bernard et al. 2015, see also Ferguson et al. 2005, Richardson et al 2008, Bernard et al. 2012

Understanding M31's Inner Halo



Bernard et al. 2015, see also Ferguson et al. 2005, Richardson et al 2008, Bernard et al. 2012

Two distinct types of debris: wraps of the Giant Stellar Stream (in excellent agreement with model predictions) and disrupted disc.

→ Only one major accretion event at recent times in M31!
→ But all fields show a ~2 Gyr burst –disk heating in action??

Summary

The modern view of stellar halos indicates these enigmatic components are faint, complex, hetereogenous and dynamic → photometric depth, wide-field coverage, sample size are crucial for observational studies.

There are many ways to define a stellar halo -- different definitions will lead to the inference of different properties. Need homogeneity across studies, and between observers and theorists/simulators!

Observational techniques include stacking, integrated light, resolved stars and tracers -- each has pros and cons. Resolved stars holds the most potential for the detailed exploration of individual stellar halos but the main present-day limitation is sample size.