The Stellar Peripheries of Galaxies

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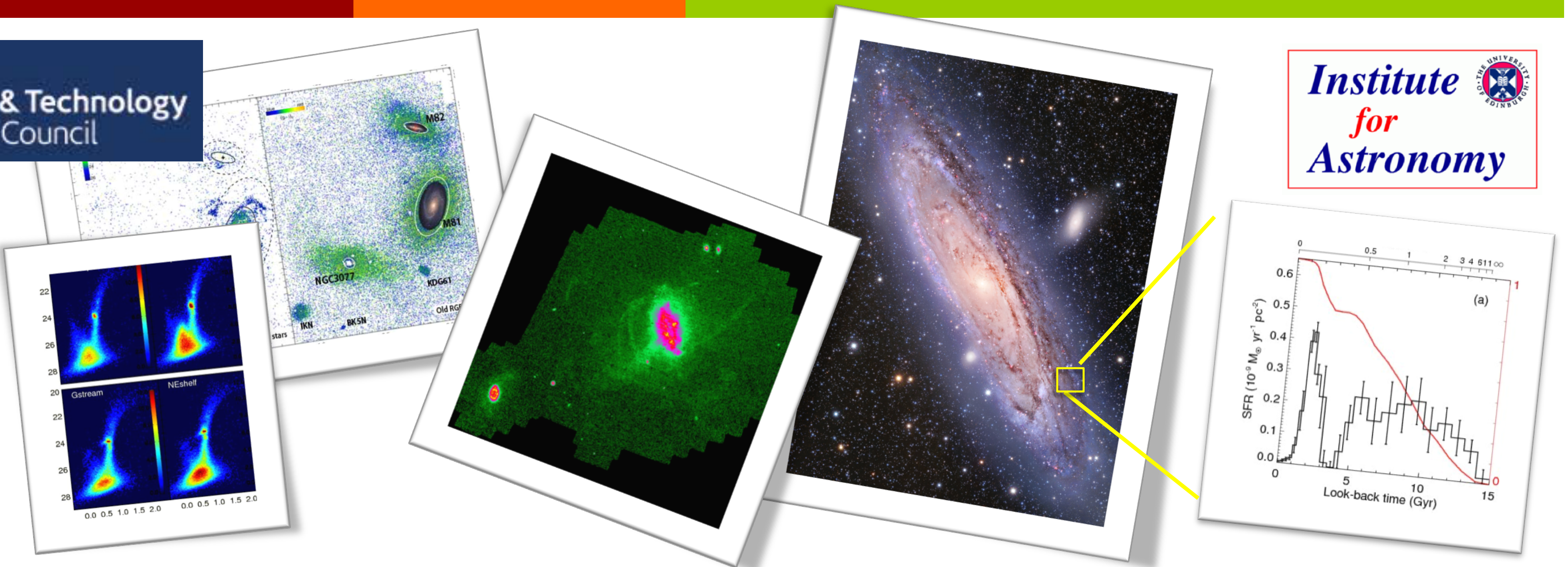
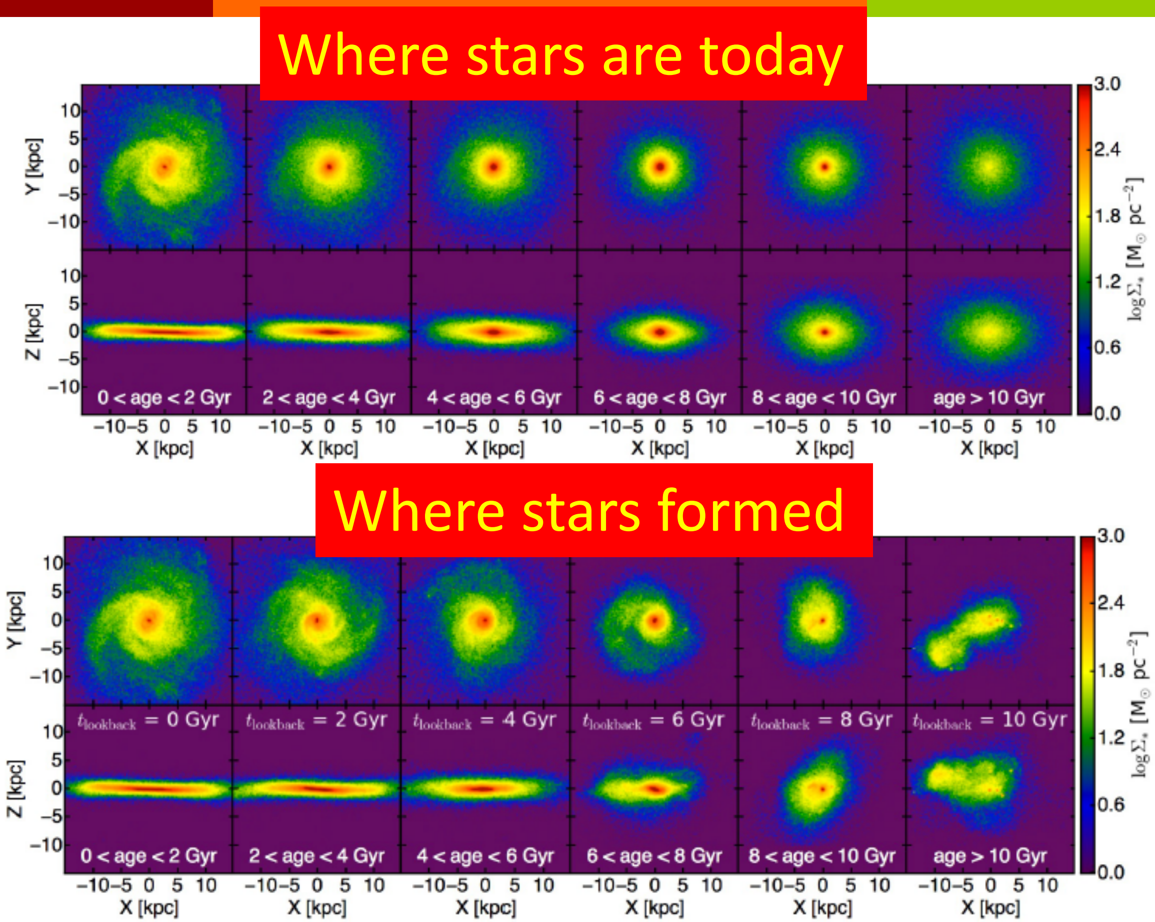


Institute for Astronomy

Galaxy Peripheries Tell Us About Disc Assembly

Ma et al, 2017, FIRE simulations

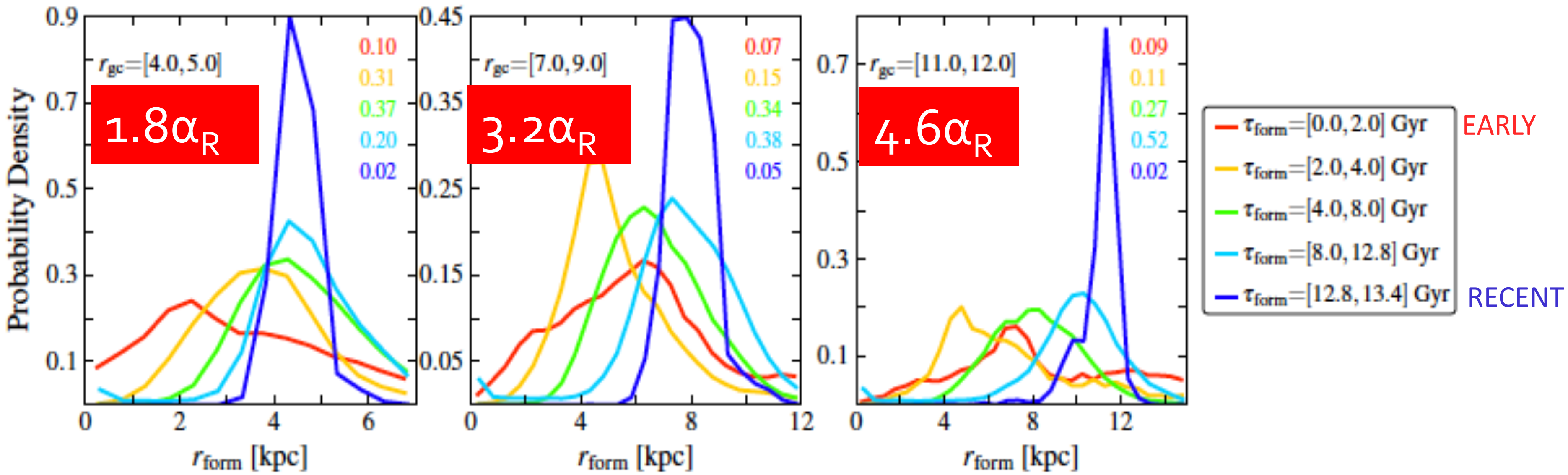


Cosmological hydro sims can now produce `realistic' multi-component MW-like disc galaxies at z=0.

But does the stellar content and internal structure of these galaxies agree with observations??

Galaxy Peripheries Tell Us About Disc Assembly

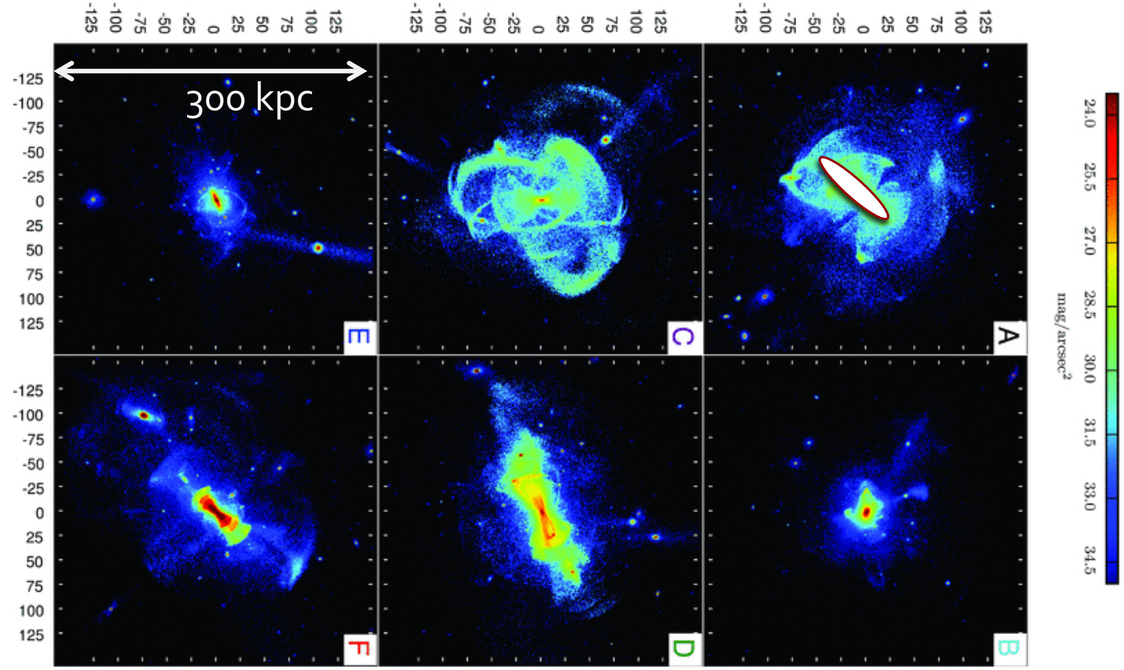
Bird et al. 2013



Changes in orbital angular momentum caused by resonant interactions with spiral arms, bars etc can move stars far from their birth places. How efficient is this radial migration process in typical large disc galaxies?

Galaxy Peripheries Tell Us About Accretion

Cooper et al. 2010, Aquarius simulations



μ_V in mag/sq. arscec

μ_V~27 → 1% sky

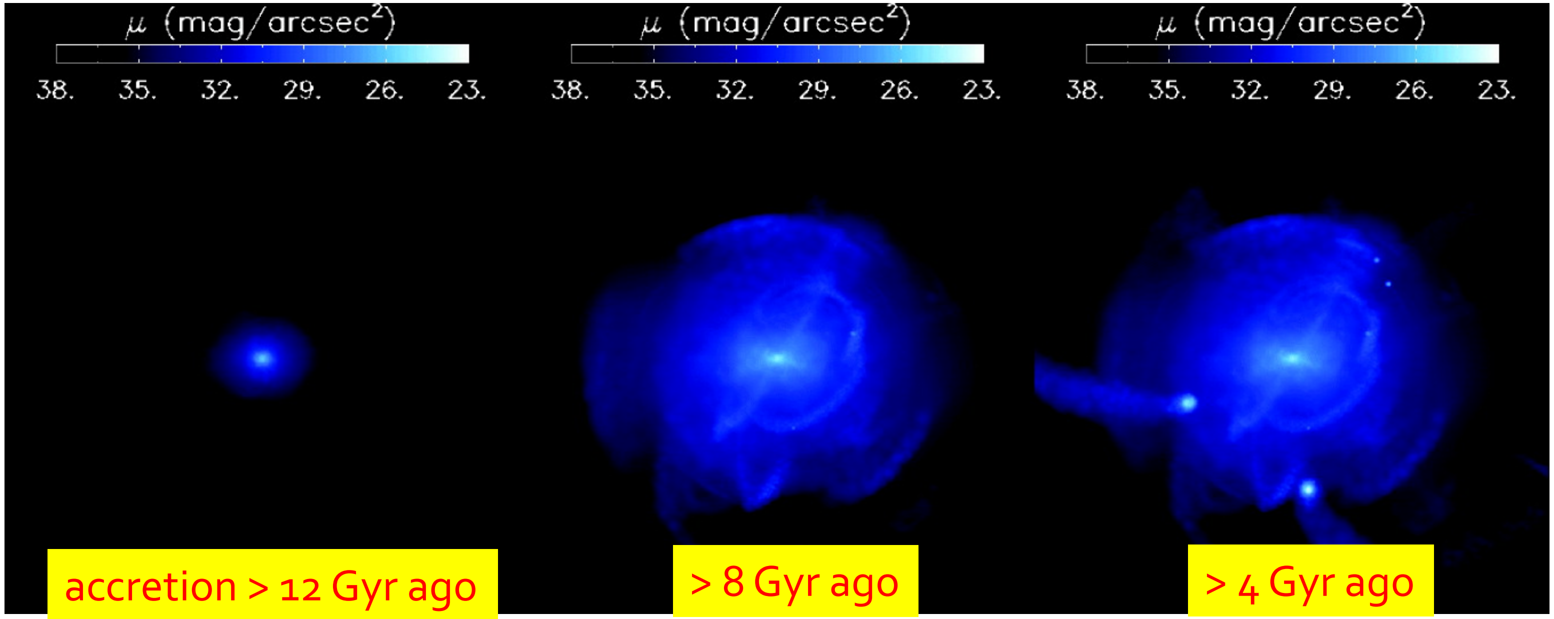
μ_V~29 → 0.1% sky

μ_V~32 → 0.01% sky

Expect lots of faint substructure in galaxy outskirts, the amount and morphology of which reflect precise details of the host galaxy's accretion history (expect variance even at fixed dark halo mass).

Galaxy Peripheries Tell Us About Accretion

Bullock & Johnston 2005,
Johnston et al. 2008



Dynamical timescales long hence little mixing – brightest features come from the most recent events. Observing the amount and types of substructure in galaxy outskirts can yield insight into cosmological accretion histories.

Galaxy Peripheries Tell Us About Accretion

SUMMARY OF GENERAL TRENDS FOR STELLAR HALO INTERPRETATION

Observable Property	Interpretation	Implication
Fraction in substructure	Recent accretions	High fraction $\Rightarrow$ many recent events Low fraction $\Rightarrow$ few recent events
Scales in substructure	Luminosity function (and orbit type) of recent events	Large $\Rightarrow$ high-luminosity events Small $\Rightarrow$ low-luminosity events
Number of features	Number of recent events	Large $\Rightarrow$ many events Small $\Rightarrow$ few events
Morphology of substructure	Orbit distribution	Clouds/plumes/shells $\Rightarrow$ radial orbits Great circles $\Rightarrow$ circular orbit
[Fe/H]	Luminosity function	Metal-rich $\Rightarrow$ high-luminosity events Metal-poor $\Rightarrow$ low-luminosity events
[α/Fe]	Accretion epoch	α-rich $\Rightarrow$ early accretion epoch α-poor $\Rightarrow$ late accretion epoch

Caveat: Not all substructure is accreted!

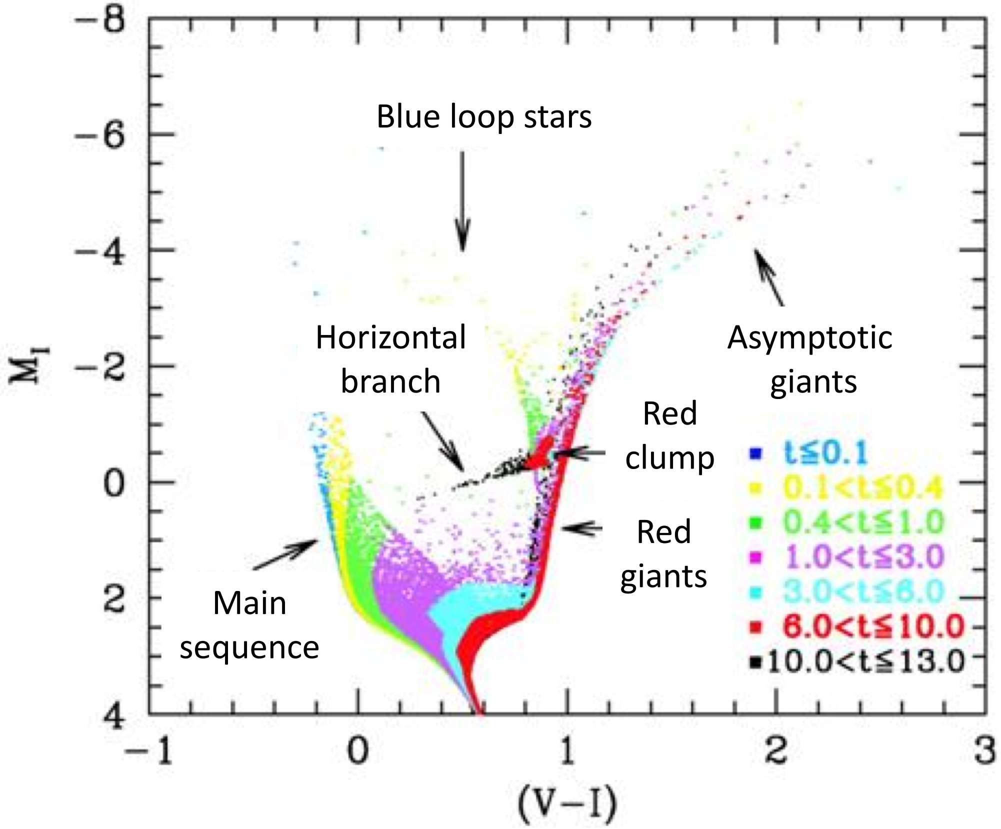
Johnston et al. 2008; see also Hendel & Johnston 2015, Pillepich et al. 2014, Amorisco 2017 ++

Galaxy Peripheries: Some Key Questions

- How common are extended stellar envelopes around galaxies and what are their properties and origins?
- How often is stellar substructure seen in galaxy outskirts? How does the frequency of this tidal debris vary across the galaxy population and how can we use this to constrain the accretion rates onto galaxies?
- What is the star formation history of outer discs? How important is radial migration for redistributing material to these parts?
- Halo stars, globular clusters and dwarf satellites: how are they related?
- Where do the stellar components of galaxies really end? Relevant for many fields: e.g. energetics/composition of circumgalactic medium, “hostless” SNe/transients, galaxy baryon budget, fluctuations in background light..

Using Resolved Stars To Study Galaxy Peripheries

Aparicio & Gallart et al. 2005

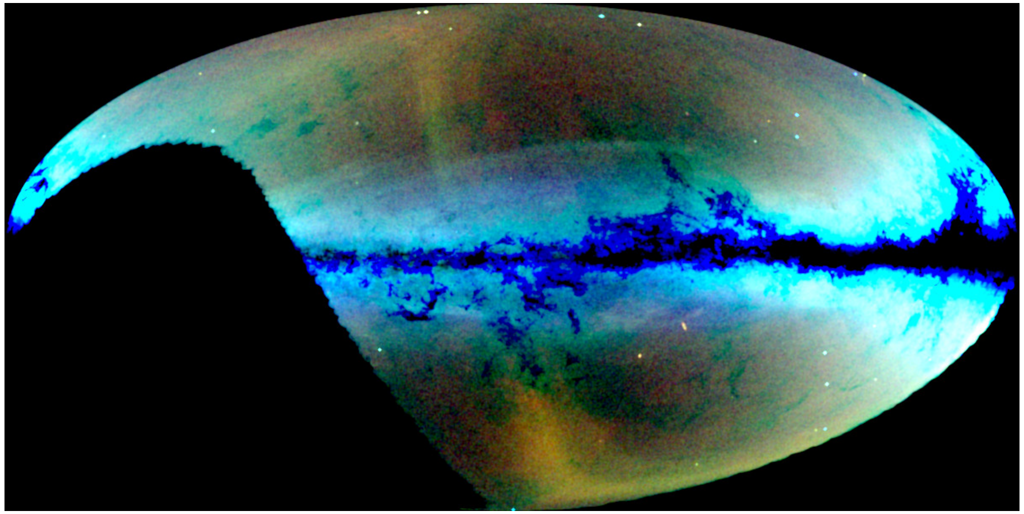


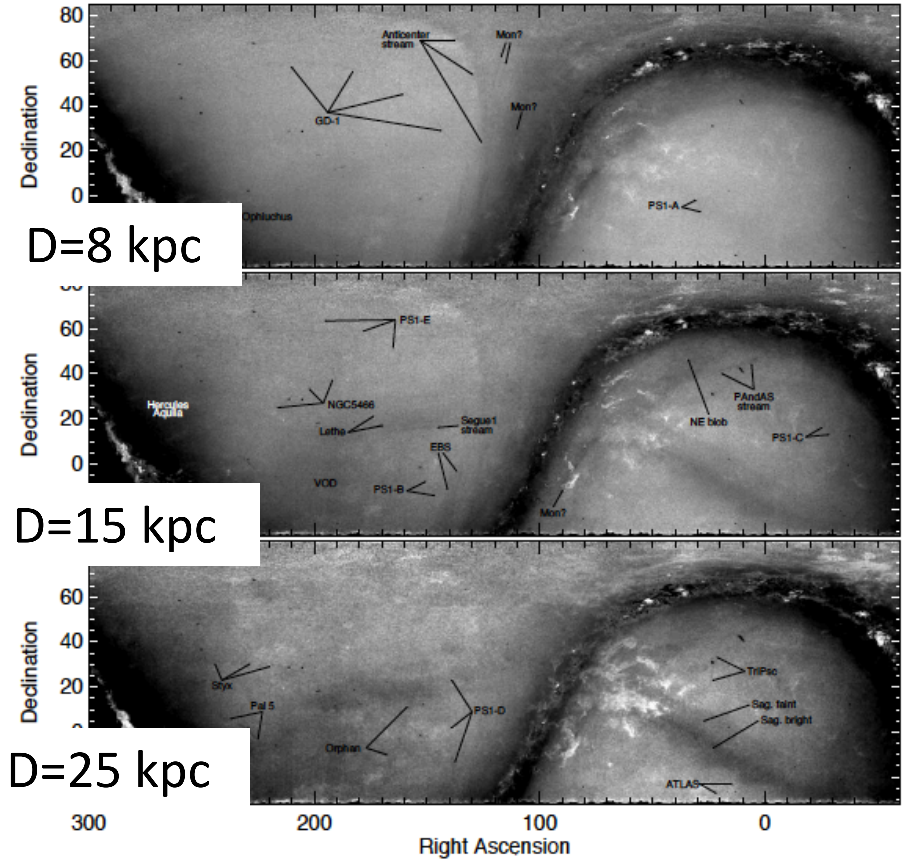
Resolved stars populate regions of a colour-magnitude diagram (CMD) according to their masses, ages and metallicities.

The main sequence turn-off (MSTO) is the key age diagnostic, while the position of a star on the red giant branch (RGB) is mostly affected by metallicity, and less so by age.

The Stellar Outskirts of the Milky Way

Credit: Edouard Bernard PS1



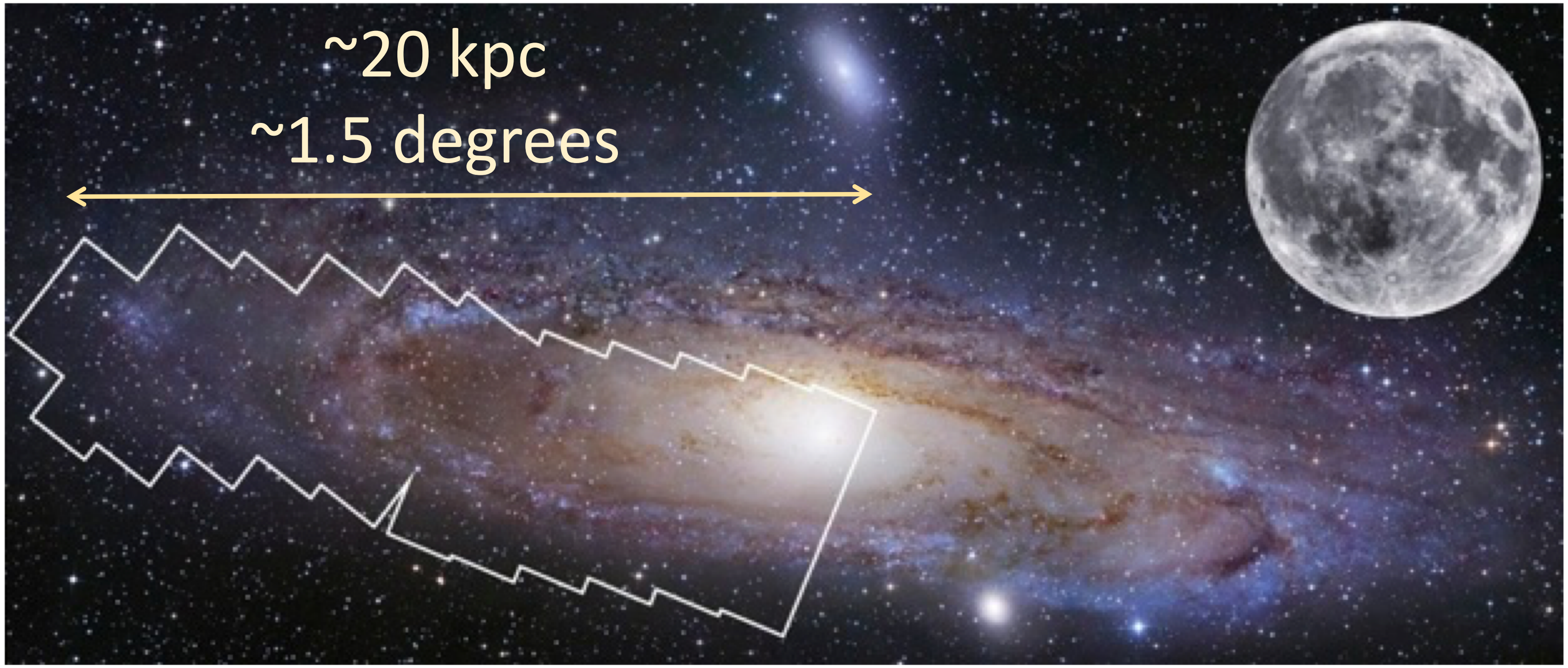


Bernard, Ferguson et al. 2016 PS1

Many complex structures are already known in the Milky Way halo, but we do not yet have a global view (info especially lacking for R>40 kpc, and at low latitude).

M31: Our Nearest Large Neighbour

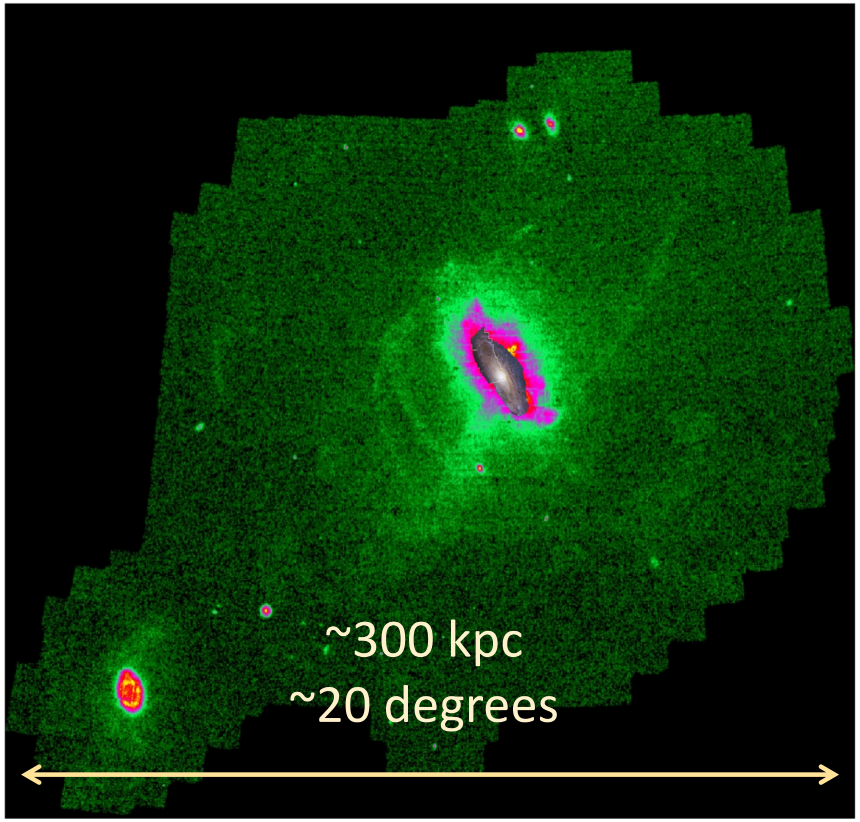
Credit: PHAT + Robert Gendler



D=780 kpc

PHAT Survey: 0.5 sq. degrees, 828 HST orbits, 2 orbits per pointing, six filters UV-NIR (Dalcanton et al. 2012).

The Pan-Andromeda Archaeological Survey



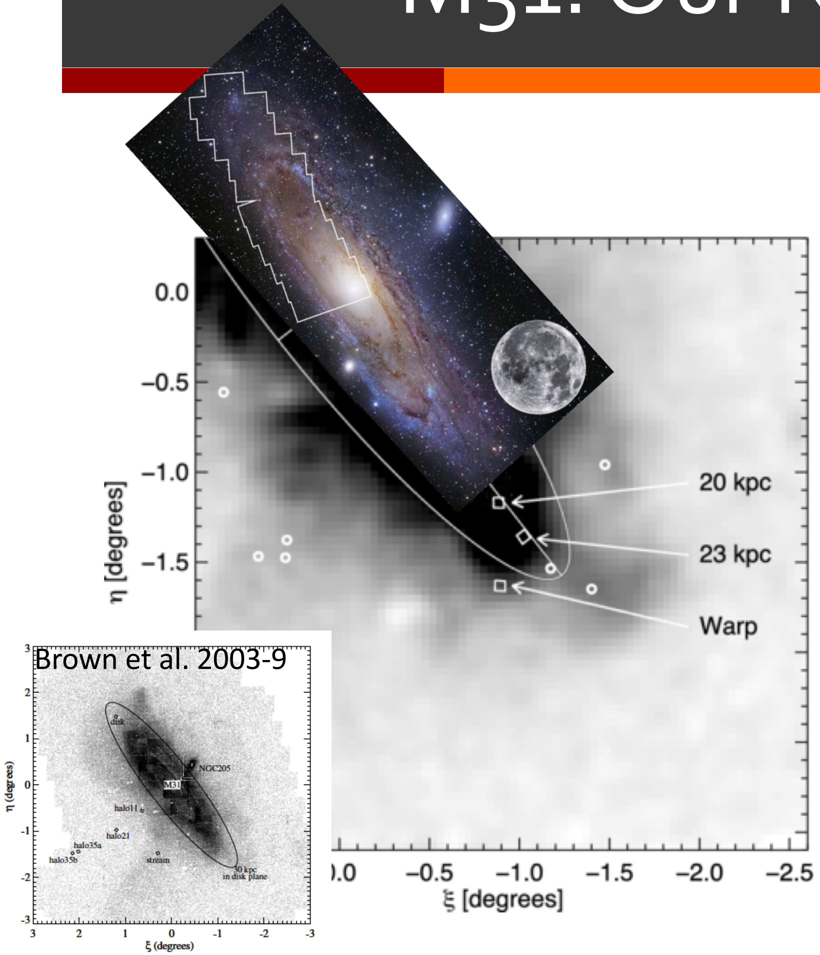
CFHT/MegaCam survey of individual red giant branch stars in M31 over 380 sq. deg in g and i. Median IQ ~0.7".

Evidence for extended and highly (sub-) structured stellar distrbution out to at least R ~150 kpc.

~20 new satellite galaxies and ~100+ new globular clusters also found in the halo.

McConnachie (PI) et al 2009, 2010, 2018 (in prep); Ibata et al. 2014

M31: Our Nearest Large Neighbour



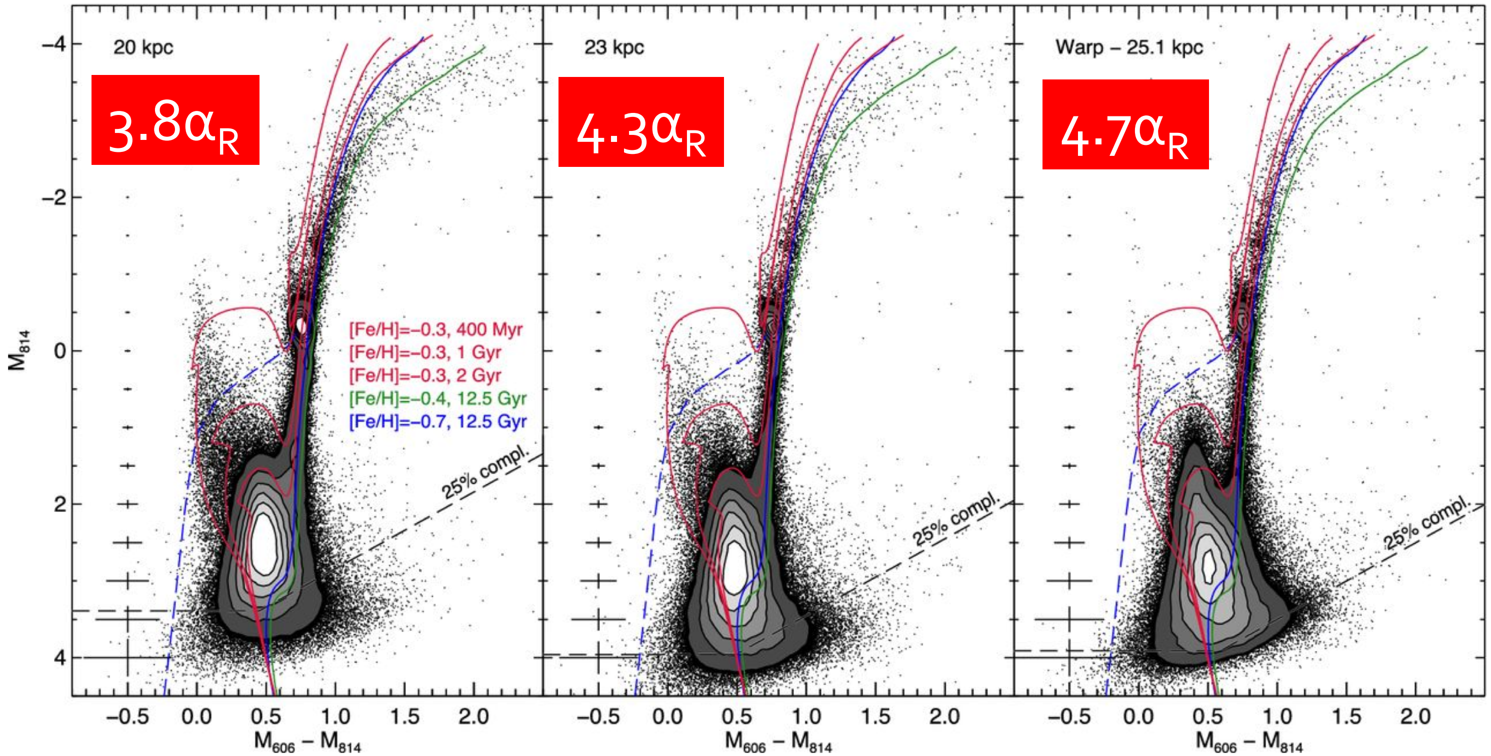
HST ACS/WFC programs to study the old stellar populations in the extended portions of M31

- 14 fields targeting <u>inner halo and low latitude substructures</u>, reaching to ~4 magnitudes below the red clump (Ferguson et al. 2005, Richardson et al. 2008, Bernard et al. 2015a)

- Plus very deep photometry at 3 locations in <u>the extended stellar</u> disc along the SW major axis, reaching to the oldest MSTOs (Bernard et al. 2012, 2015b)

The Extended Stellar Disc of M31

Bernard, Ferguson et al 2015b



185-300K stars per pointing

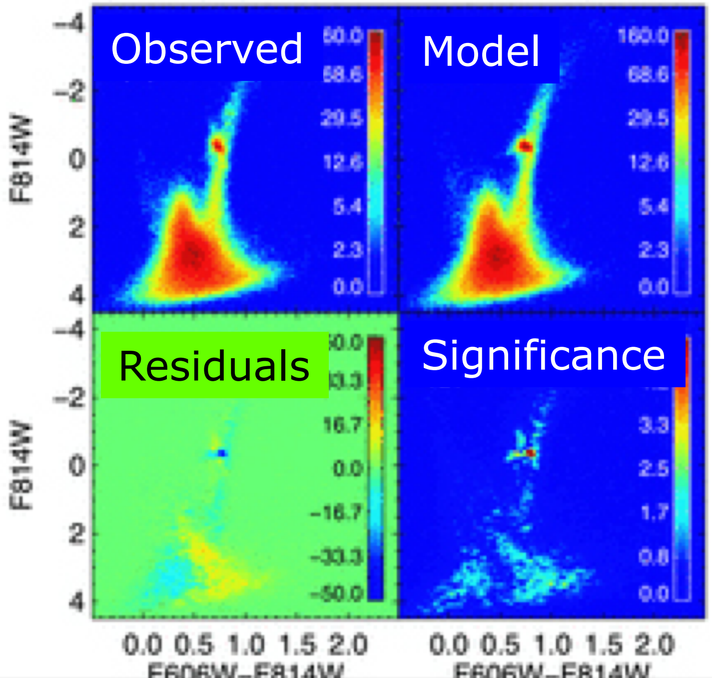
Note that the Sun lies at ~3.7α_R in the Milky Way.

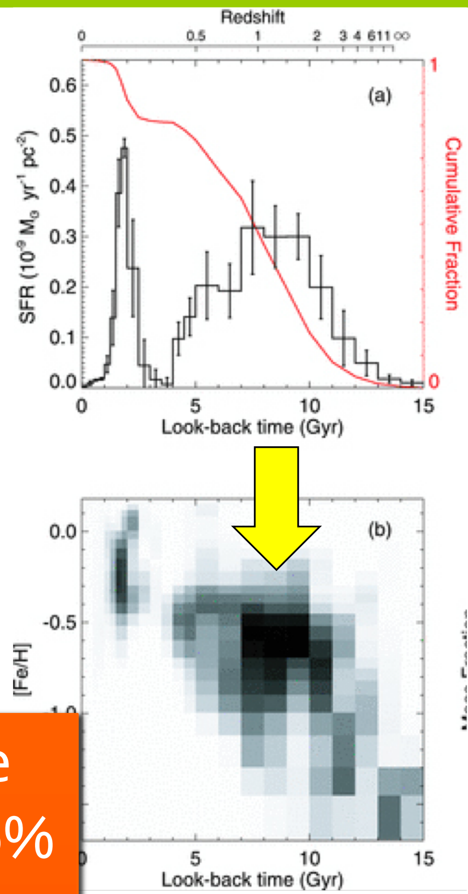
Deep HST photometry obtained at 3 locations along M31's SW major axis, reaching to the oldest MSTOs.

Calculating Star Formation Histories

SFR and metallicity profoundly effect CMD morphology

Model CMD using synthetic libraries with range in age and metallicity to extract SFR and [Fe/H] evolution.

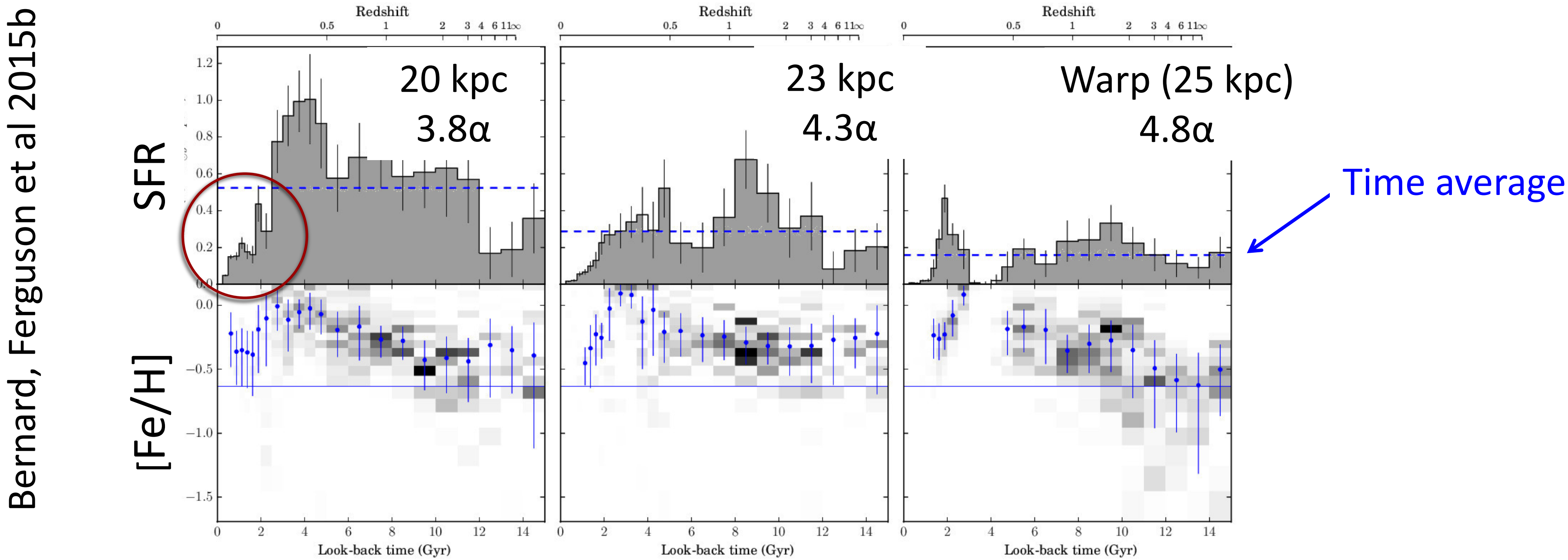




When reaching the oMSTO, estimate age and metallicity to typically ~10-20% precision at all epochs

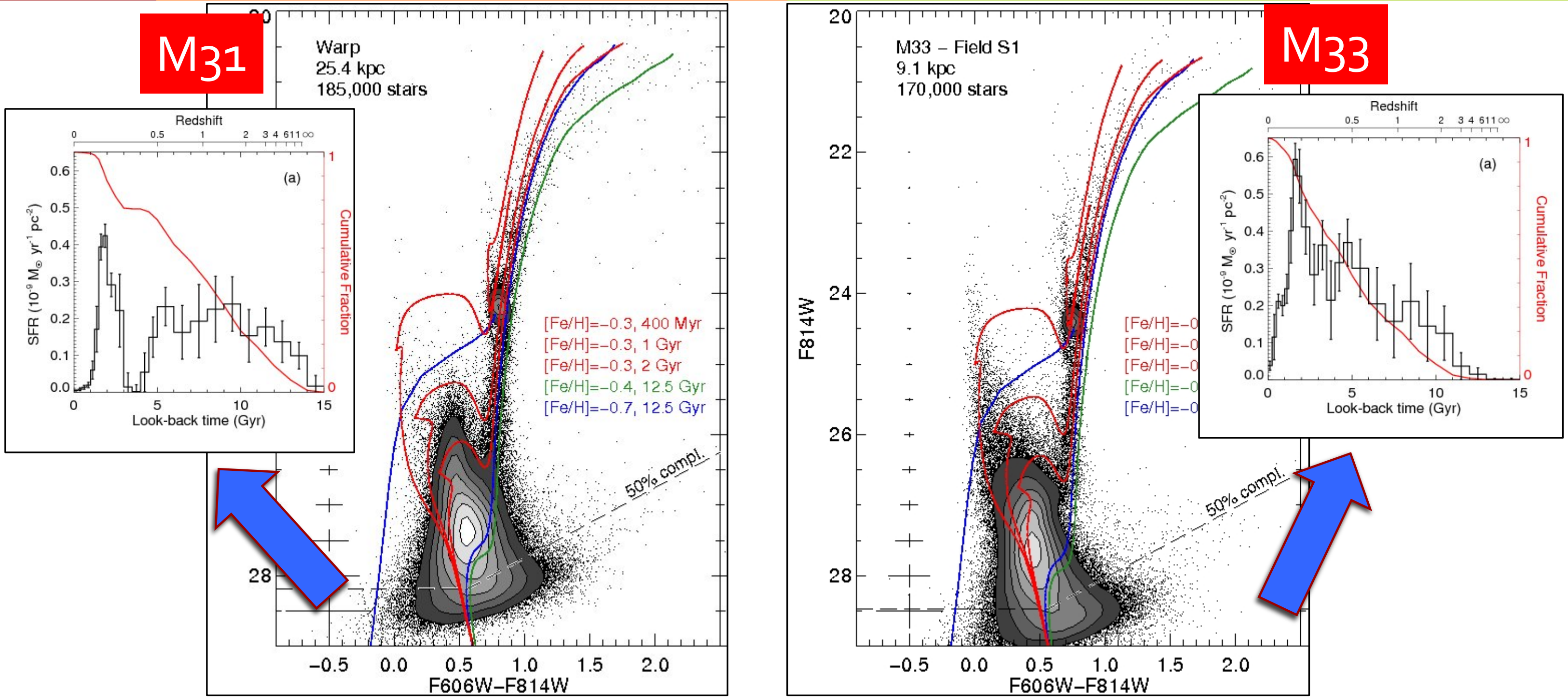
Bernard, Ferguson et al. 2012, 2015a,b

The Extended Stellar Disc of M31



In all fields, star formation began early on and occurred more or less continuously across the history of the disc with sharp decline at recent epochs.

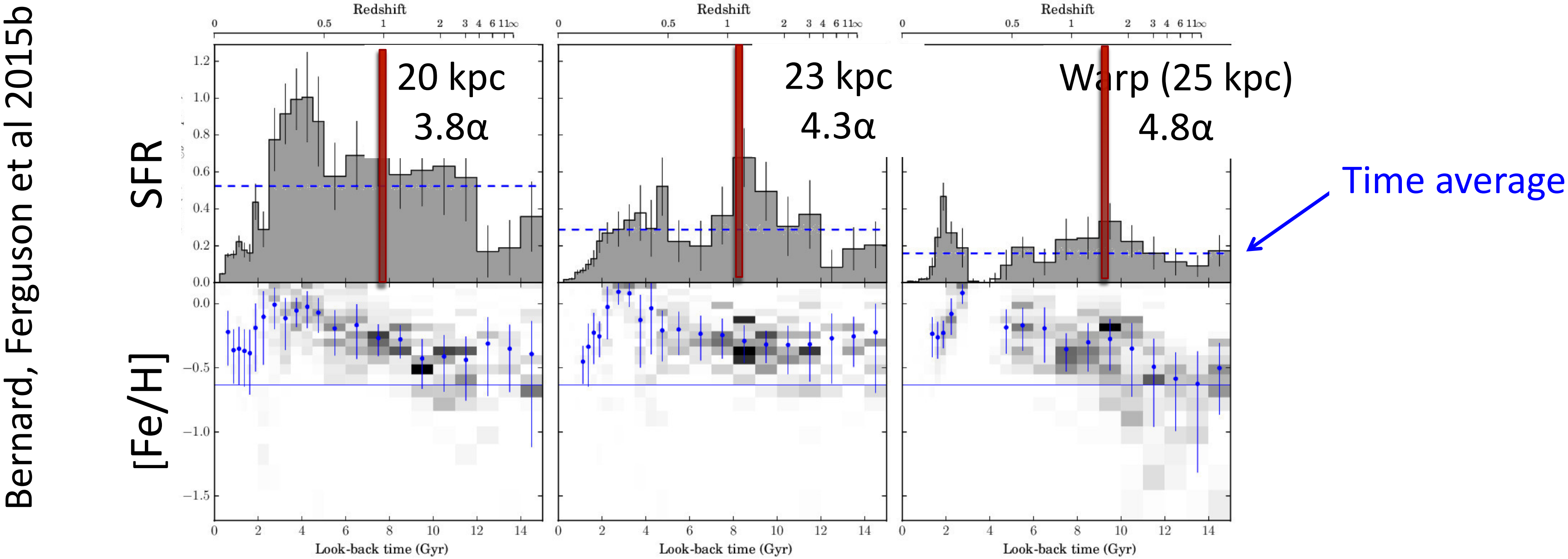
The Extended Stellar Disc of M31



Bernard, Ferguson et al 2012

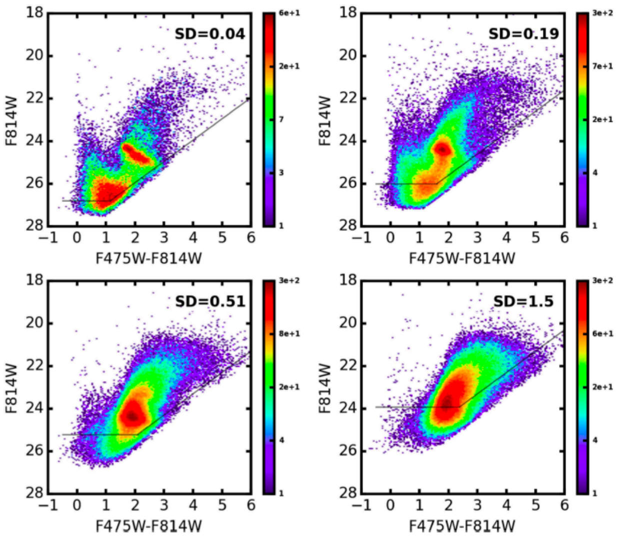
Note old stars are not an artefact of the method → deep outer disc M33 CMD does not show a significant old component!

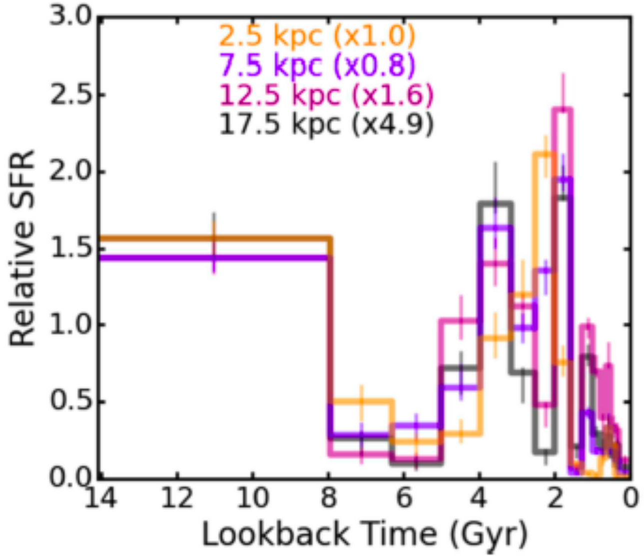
The Extended Stellar Disc of M31



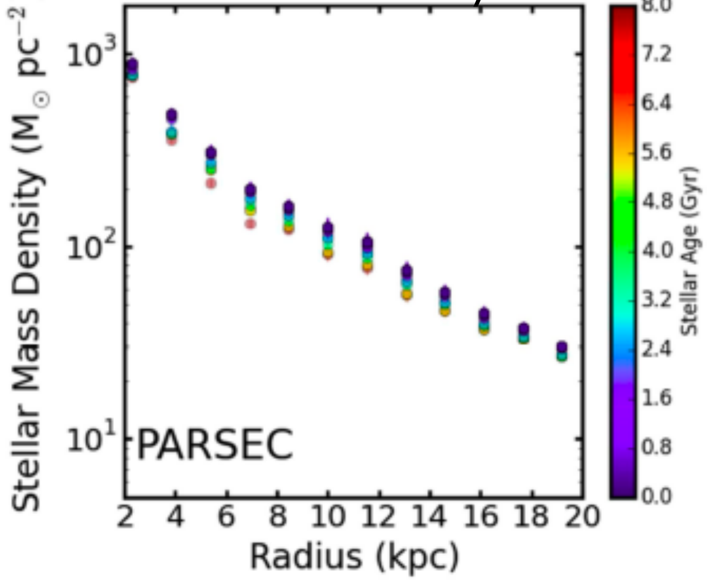
In all fields, 50% of the stellar mass in place by z~1 (~7-9 Gyr). Over the ~1 radial scalelength probed, no evidence for strong age gradient.

Further Evidence for An Old M31 Disc from PHAT



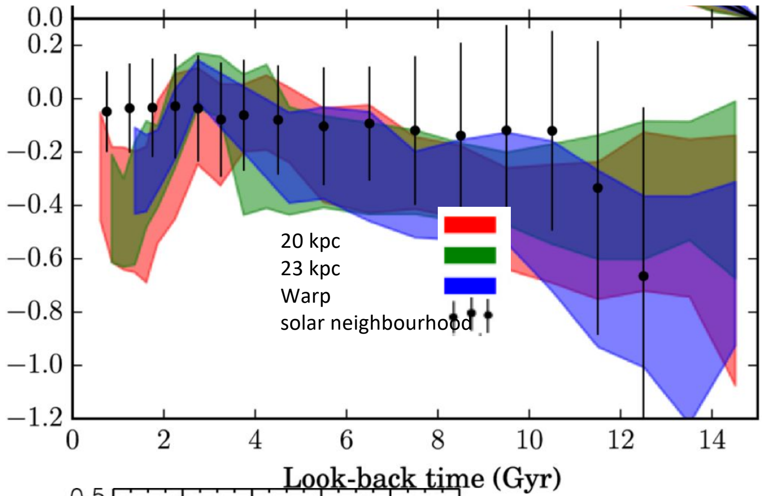


Williams et al. 2017

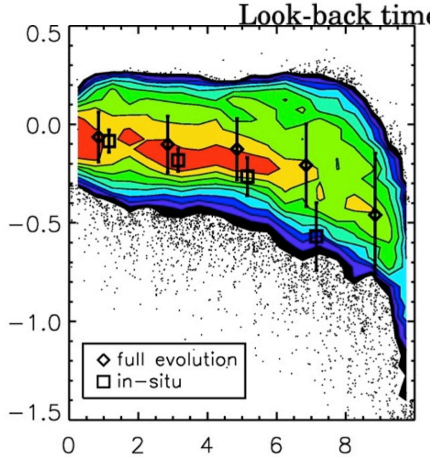


- ❖ PHAT is much shallower and relies solely on the more uncertain evolved stages of stellar evolution to model the SFH
- ❖ Nonetheless, their findings support the existence of an old extended disc with no clear signature of inside-out formation.

The Extended Stellar Disc of M31



Bernard, Ferguson et al 2015b



Roskar et al. 2008 Simulation w/ radial migration

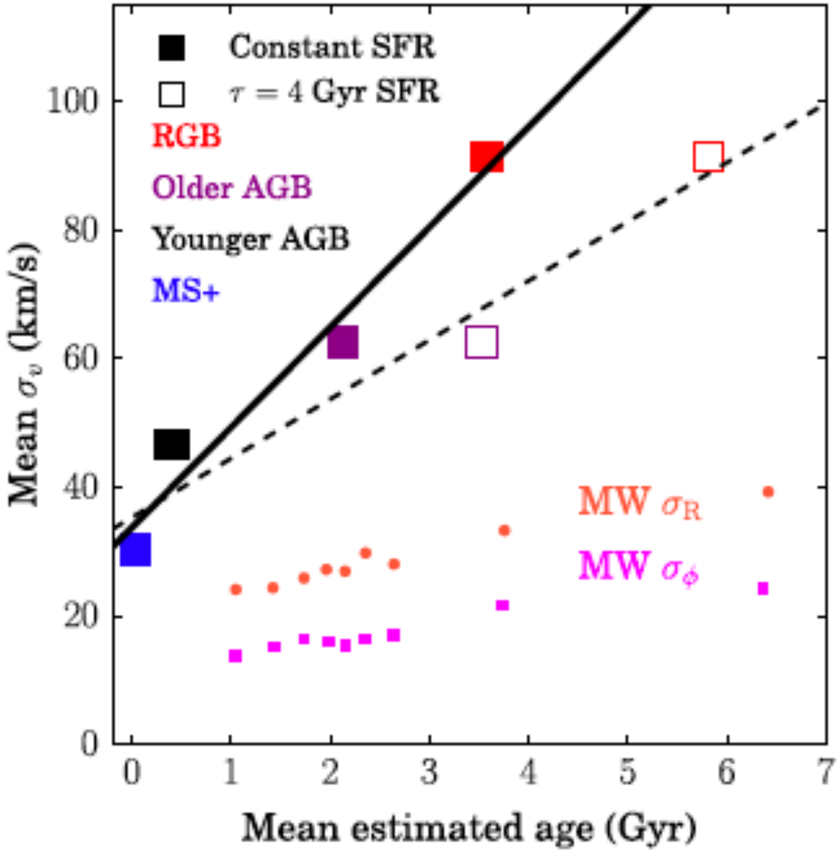
- ❖ Age-metallicity relations for all 3 fields are similar over last 10 Gyr of evolution: increase of ~0.4 dex from 10 to 3 Gyr ago
- ❖ Evidence for moderate level of pre-enrichment, and more metal-poor old stars in the warp
- ❖ Behaviour very different from the solar neighbourhood (~3.7α_R) and unlike predictions if radial migration were dominant!

The Extended Stellar Disc of M31

❖Efficiency of radial migration may be strongly dependent on the vertical velocity dispersion – e.g. Vera-Ciro et al. 2014

❖ Stellar velocity dispersion measured to be 3x higher in the M31 disc than in the Milky Way ....

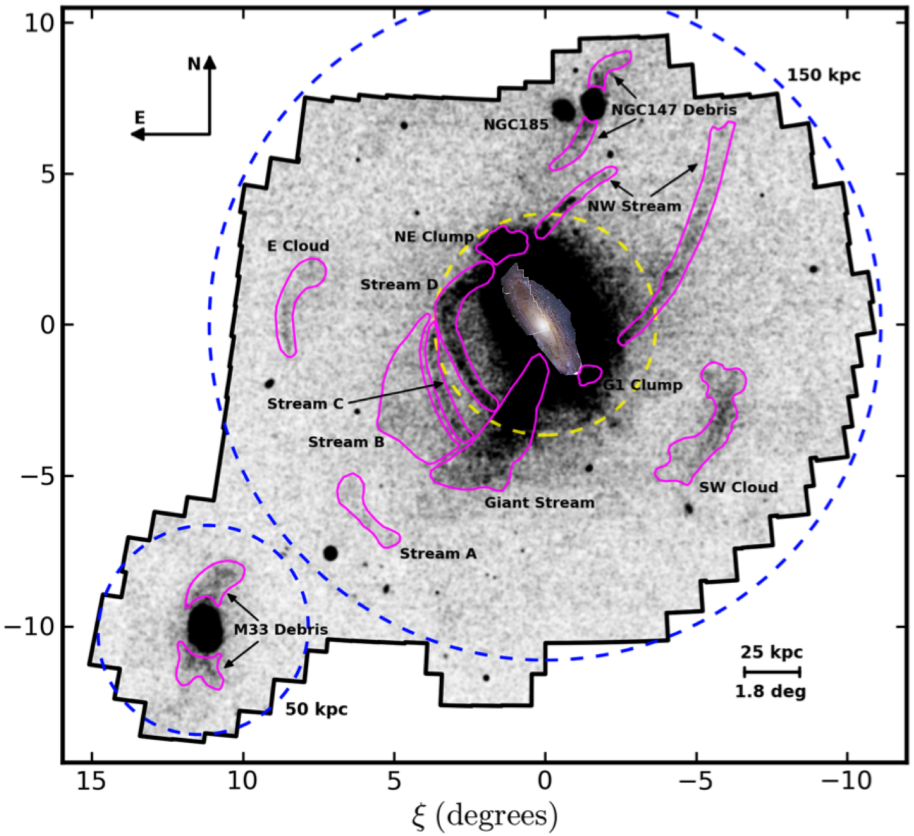
❖ Could this explain why apparently less radial migration in M31 than in MW?



Dorman et al. 2015

M31's Far Outer Halo

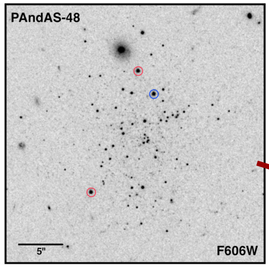
Ferguson & Mackey 2016



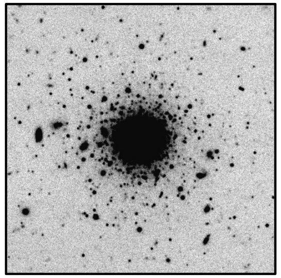
- M31's outer halo (R > 50 kpc) is dominated by thin streams, clumps and arcs and is mostly metal-poor ([Fe/H]~-1.3.
- Features are so faint that detailed characterisation has thus far proven difficult.
- Globular clusters offer a very promising way forward.

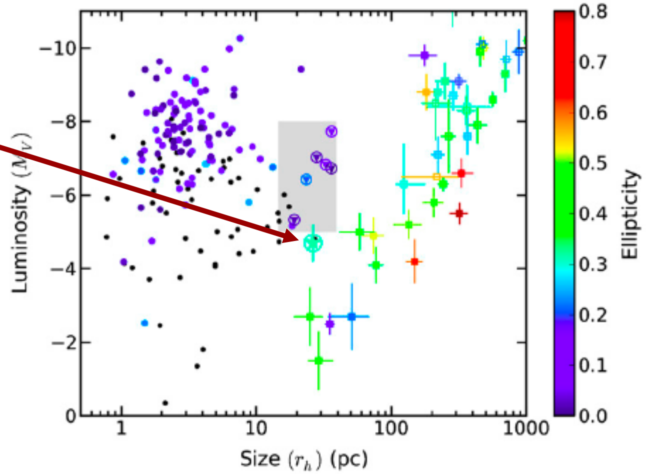
M31's Outer Halo Globular Clusters

R_{M31}=150 kpc

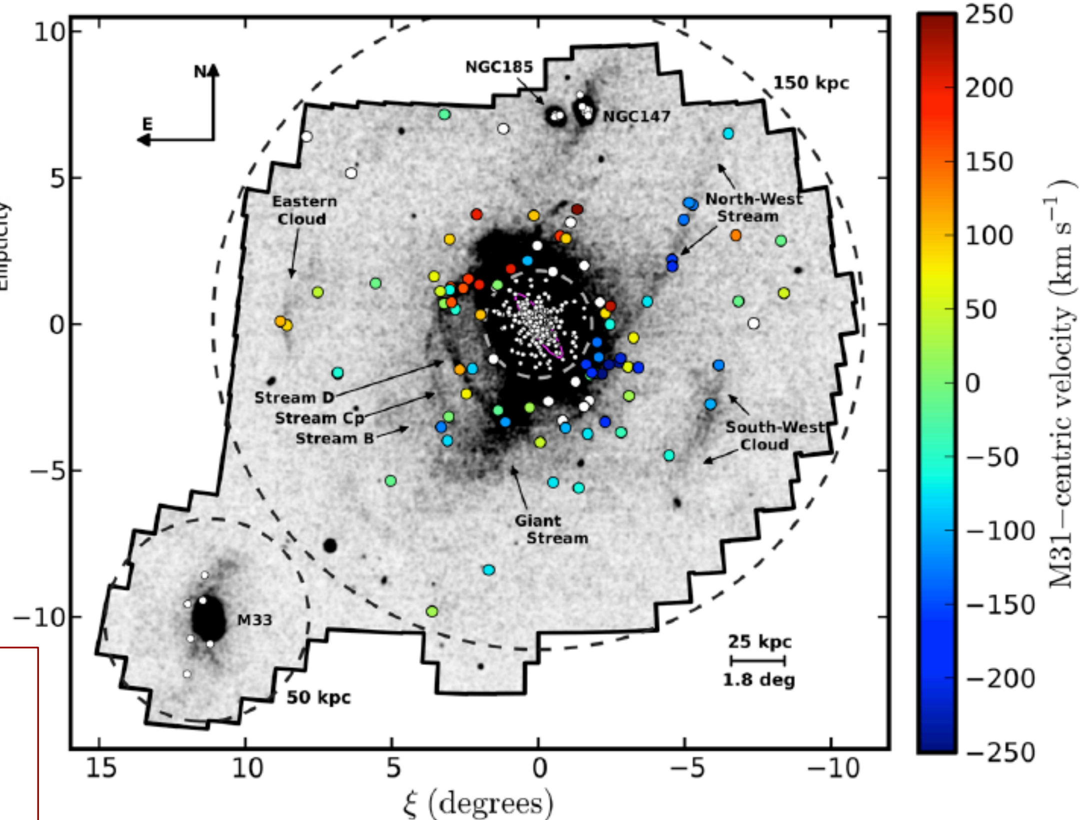


R_{M31}=200 kpc





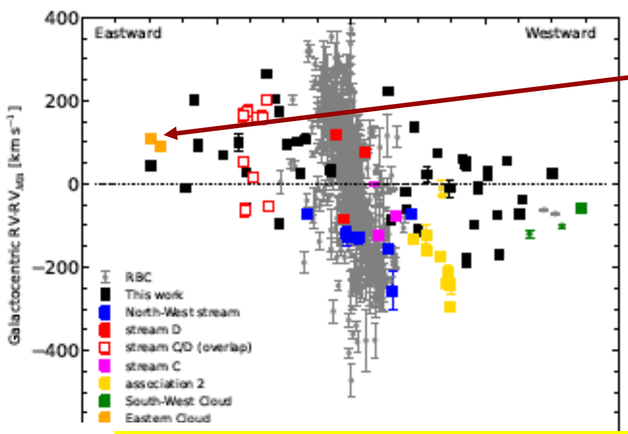
40-70% of the newly-discovered M31 halo GCs are associated with stellar streams!



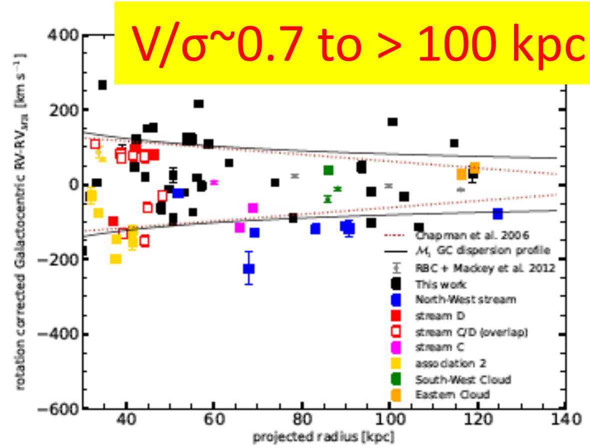
Mackey et al. 2010, 2018 (in prep)

M31's Outer Halo Globular Clusters

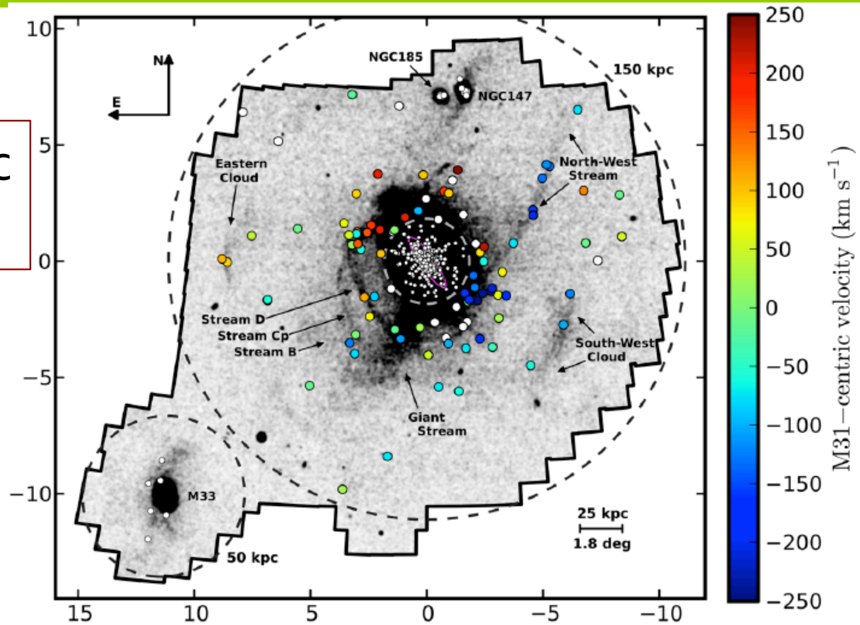
Veljanoski et al. 2013, 2014



Cold kinematic features



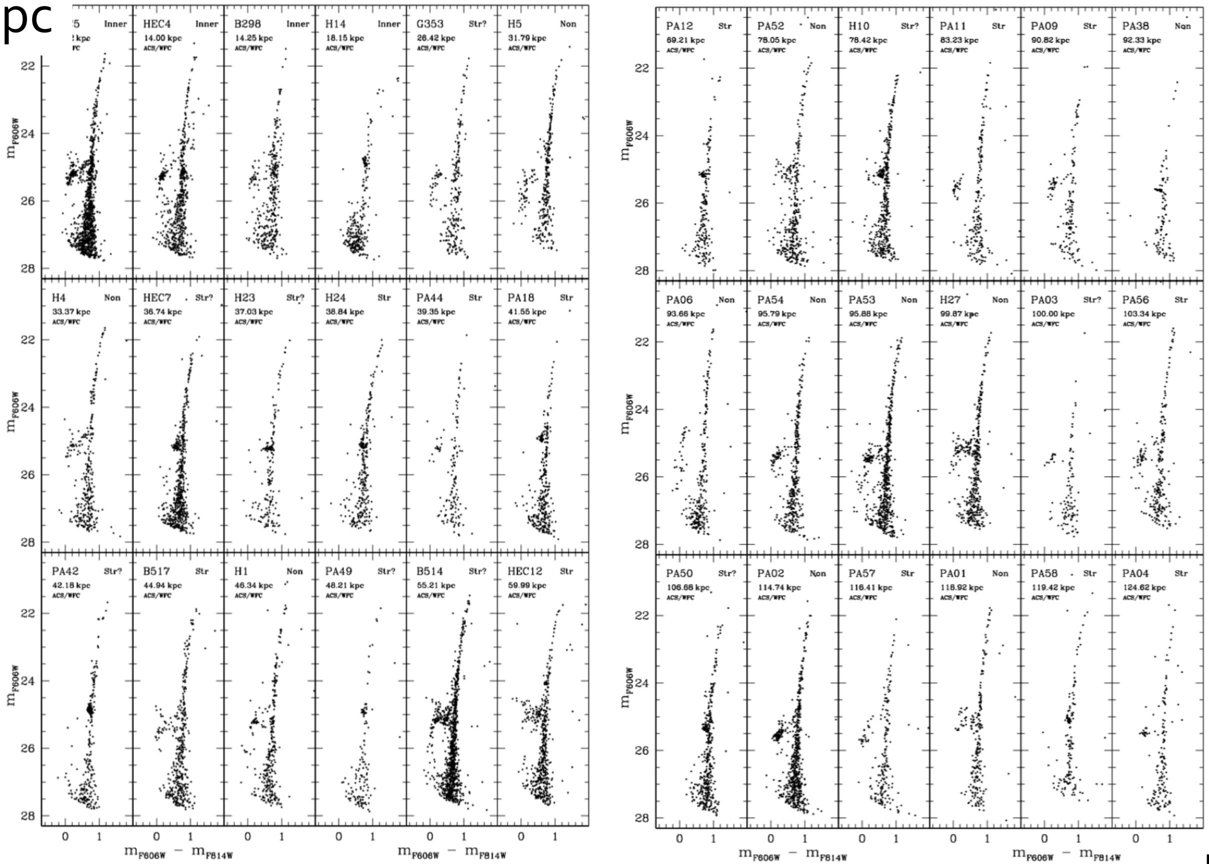
V/σ~0.7 to > 100 kpc



Bulk rotation seen in the outer halo GC population – consistent with that seen in the inner halo but lower amplitude. How to reconcile with an origin in many accretions??

M31's Outer Halo Globular Clusters

R_p=14 kpc



R_p=125 kpc

Resolved observations for ~50 GCs from HST (ACS, WFC3), and ~15 from Gemini (GMOS)

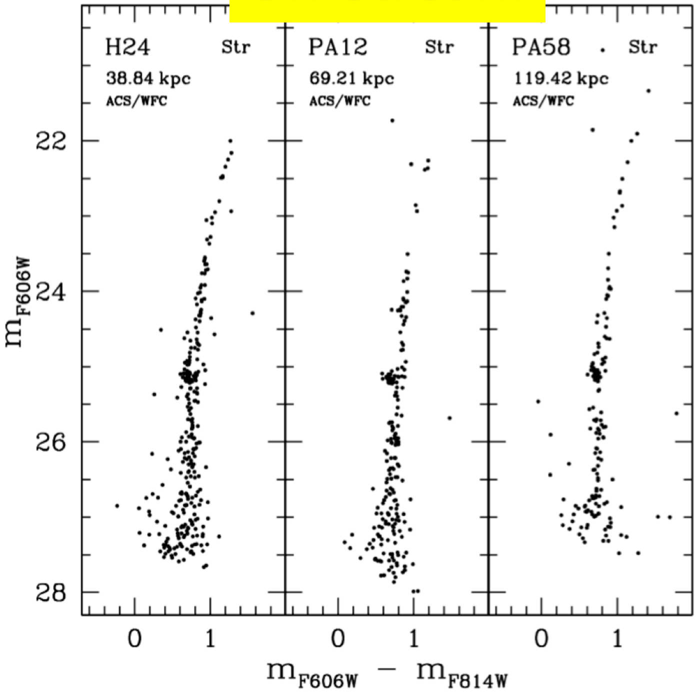
50 orbits in

Cycles 22, 23

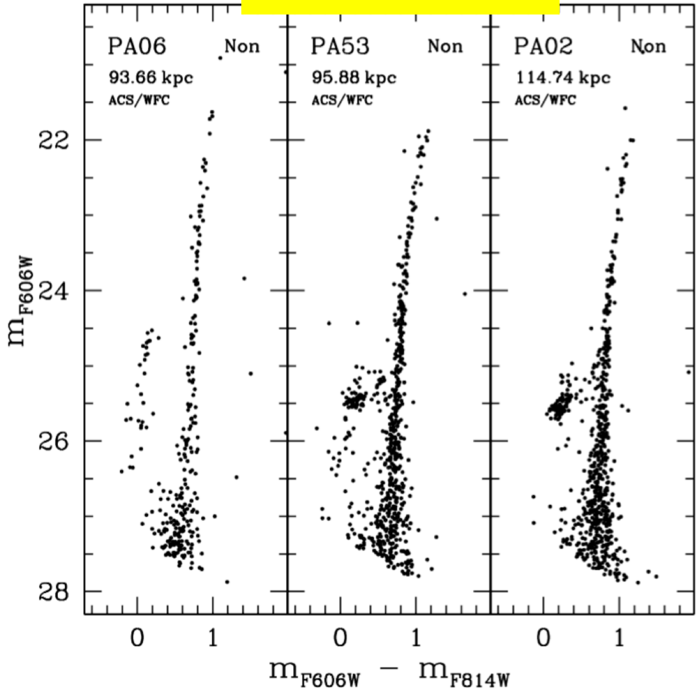
Mackey et al., 2018 in prep

Stream and Non-Stream GC Subgroups

On-Stream



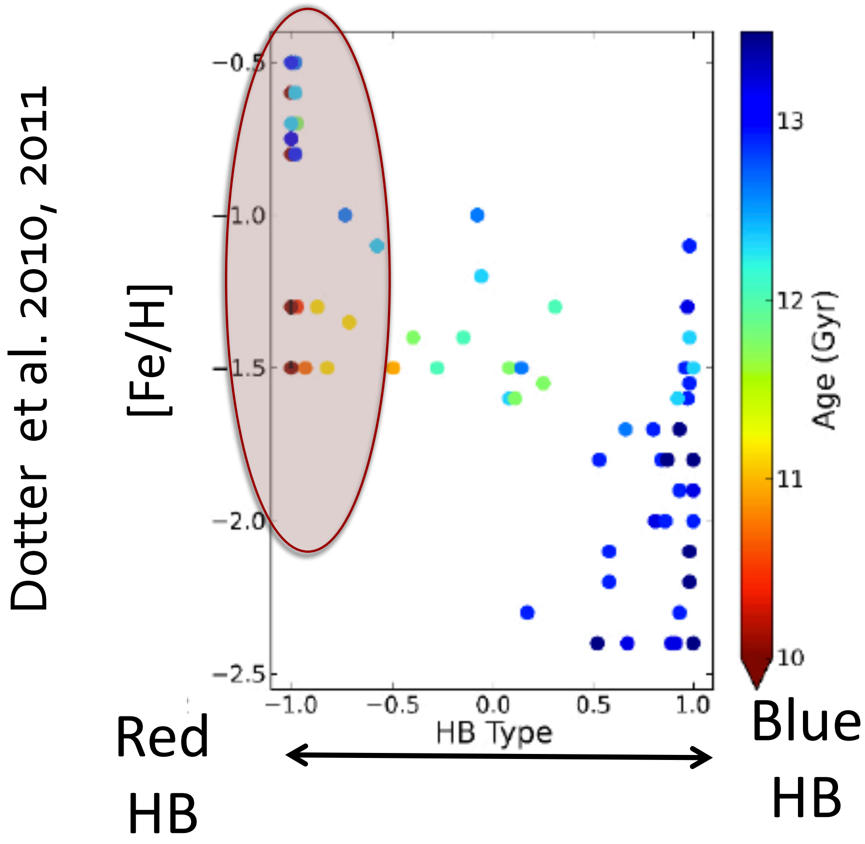
Off-Stream



Mackey et al., 2018, in prep

- 50% of "stream" GCs have very red horizontal branches (HBs)
- 100% of "non-stream" GCs have intermediate to blue HBs
- direct evidence in M31 that very red HB GCs been donated by now disrupted low mass galaxies!

Stream and Non-Stream GC Subgroups

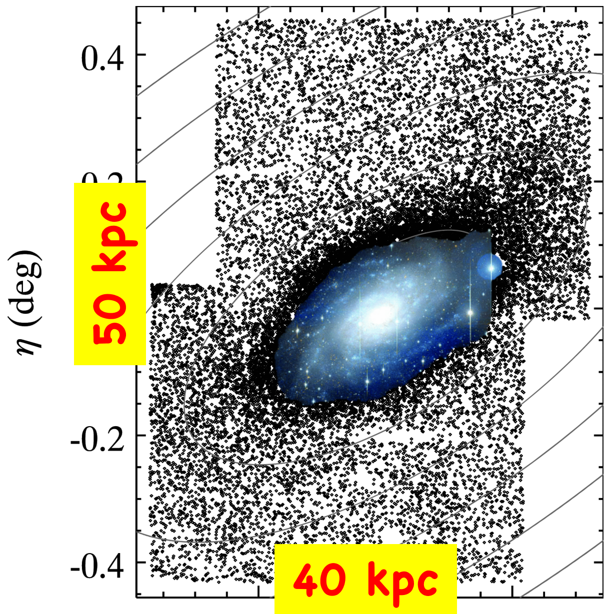


Mackey et al., 2018, in prep

- ❖ MW studies (R<40 kpc) suggest very red HB GCs either metal-rich ([Fe/H]~-0.7) or younger by 2-4 Gyr than blue HB GCs.
- ❖ Metallicity measurements (in progress) indicate M31 halo GCs are not <u>very</u> metal-rich → most likely reason for very red HBs is that they are slightly younger...
- ❖ Red HB halo GCs → accreted → slightly younger. As suggested by Searle & Zinn!

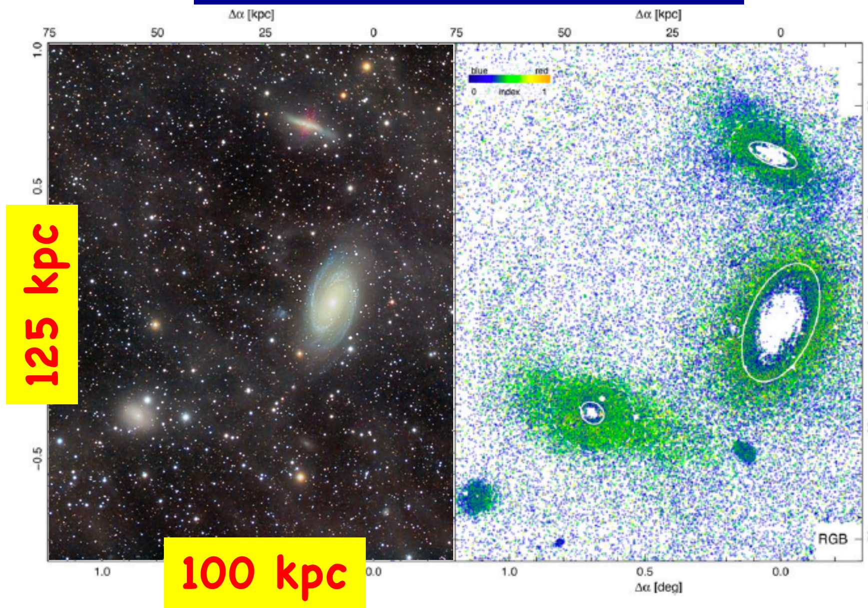
The Next Frontier: Increasing Sample Size

NGC2403 Sc @ 3.1 Mpc



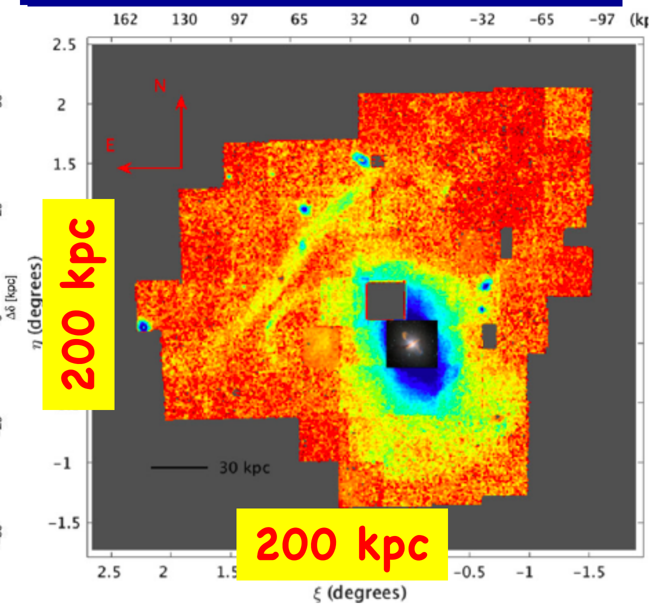
Barker et al. 2012
Subaru Suprime-Cam

M81 Sab @ 3.6 Mpc



Okamoto et al. 2015 (+ongoing)
Subaru Hyper Suprime-Cam

Cen A E/S0 @ 3.6 Mpc



Crnojević et al. 2016
Magellan Megacam

Summary

Galaxy peripheries preserve a unique fossil record of their assembly histories but their extreme faintness means that mining this information presents a formidable challenge.

Wide-field surveys and deep HST pencil-beam studies of M31 have shown the power of the resolved star approach – e.g. the existence of an old and extended thin disc (challenge for simulations?) and the discovery of a vast low surface brightness stellar halo containing immigrant globular clusters along with their now-disrupted host galaxies.

Major breakthroughs in low surface brightness galaxy periphery science will come from extending this type of work to larger samples → demands deep, wide-field surveys with excellent image quality. LSST, Euclid and WFIRST are all set to play key roles, as will JWST.

The future for studies of the dimmest parts of galaxies is extremely bright!!!