Decoding Galaxy Assembly with Andromeda

I. Global Properties of the Stellar Halo

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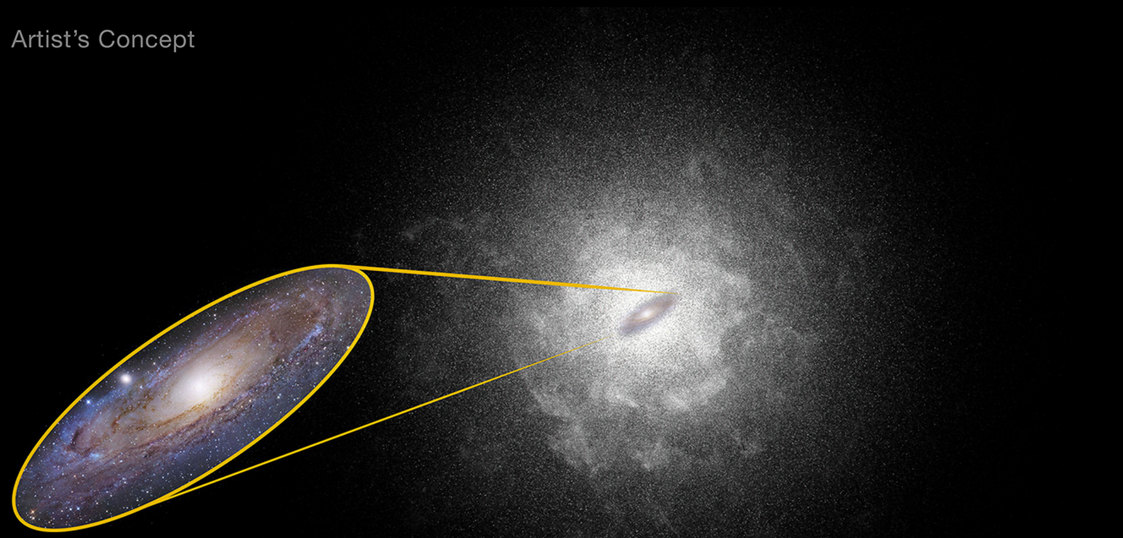


Image credit: NASA, Joseph Olmsted (STScI)

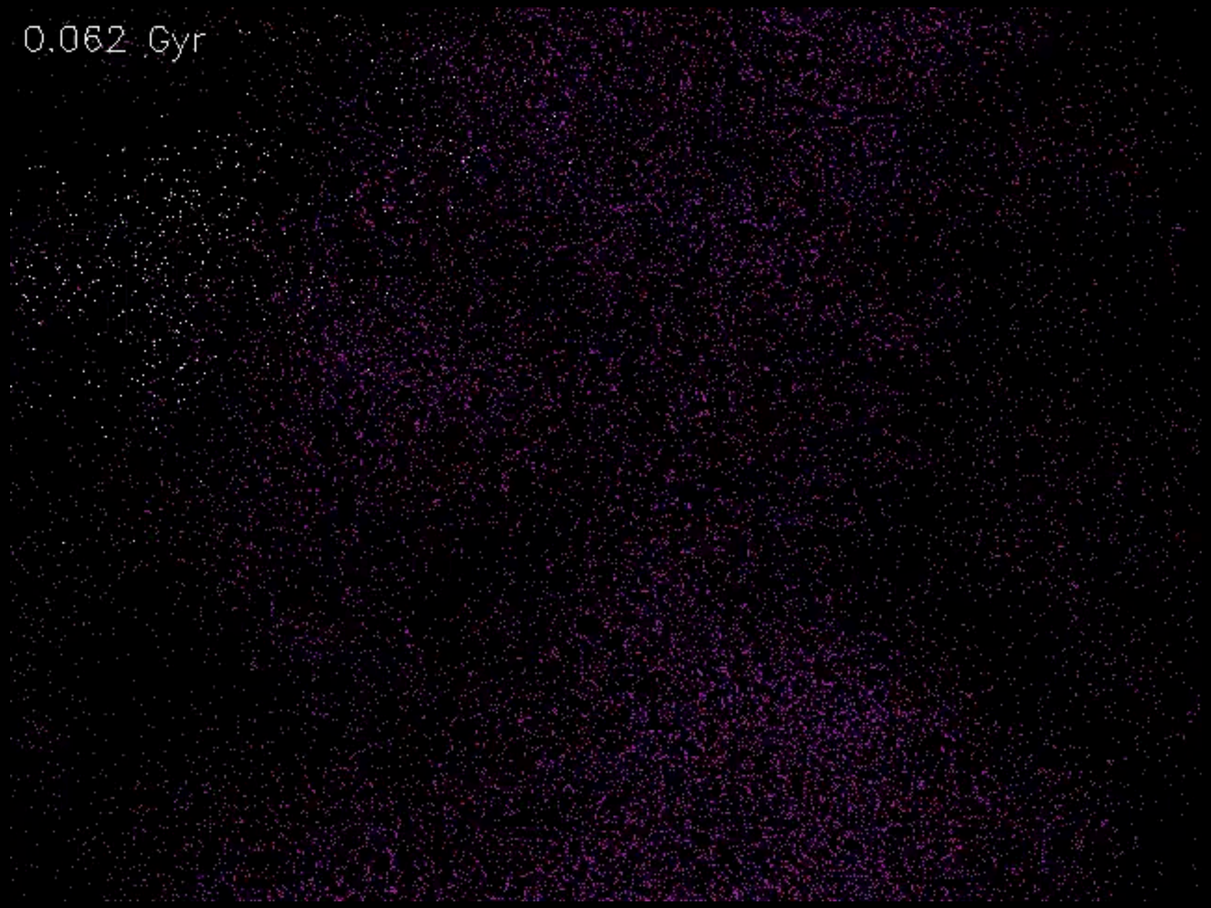
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Outline

- Stellar halo formation
- Discovery of M31's stellar halo
- Global halo properties
  - Star formation history
  - Metallicity gradients
  - Surface brightness profile
  - Velocity dispersion profile
- Future advances and summary

Stellar halos partially form from the accretion of external galaxies

Build-up of a Milky Way
like galaxy from simulations



streams - ribbon-like features

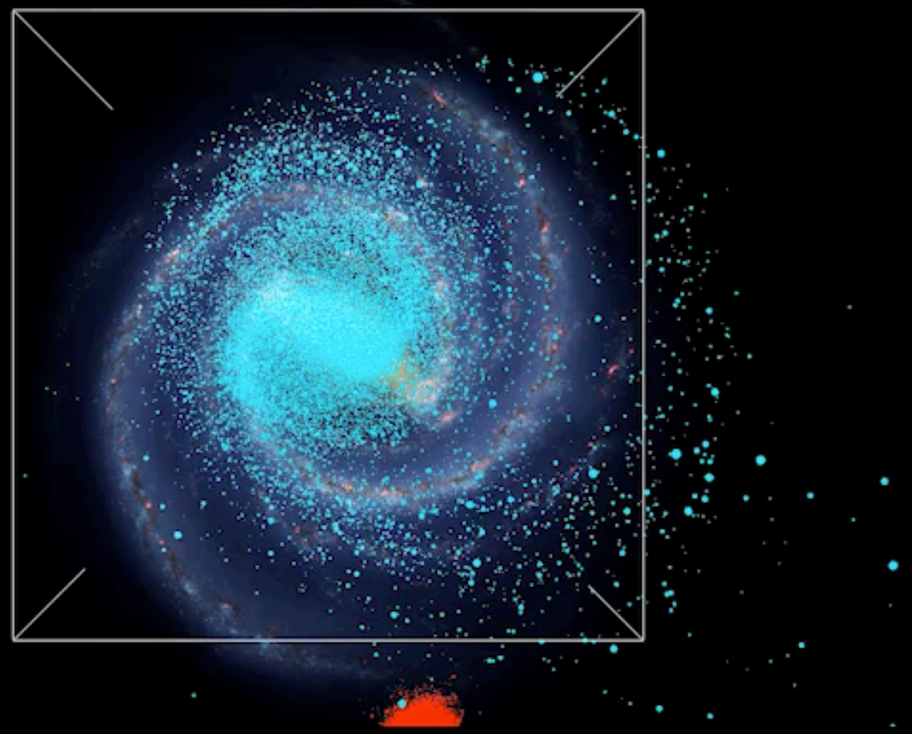
shells - fan-like features

halo - streams, shells,
and extended debris

Video credit: Cooper+10, Helmi+11

Stellar halos can also have contributions from stars born within the disk of the host galaxy

Simulation of a merger between the Milky Way disk and a dwarf galaxy



Video credit: Koppelman, Villalobos, & Helmi 2018

M31 is ideal for studies of stellar halo formation and galaxy assembly beyond the MW

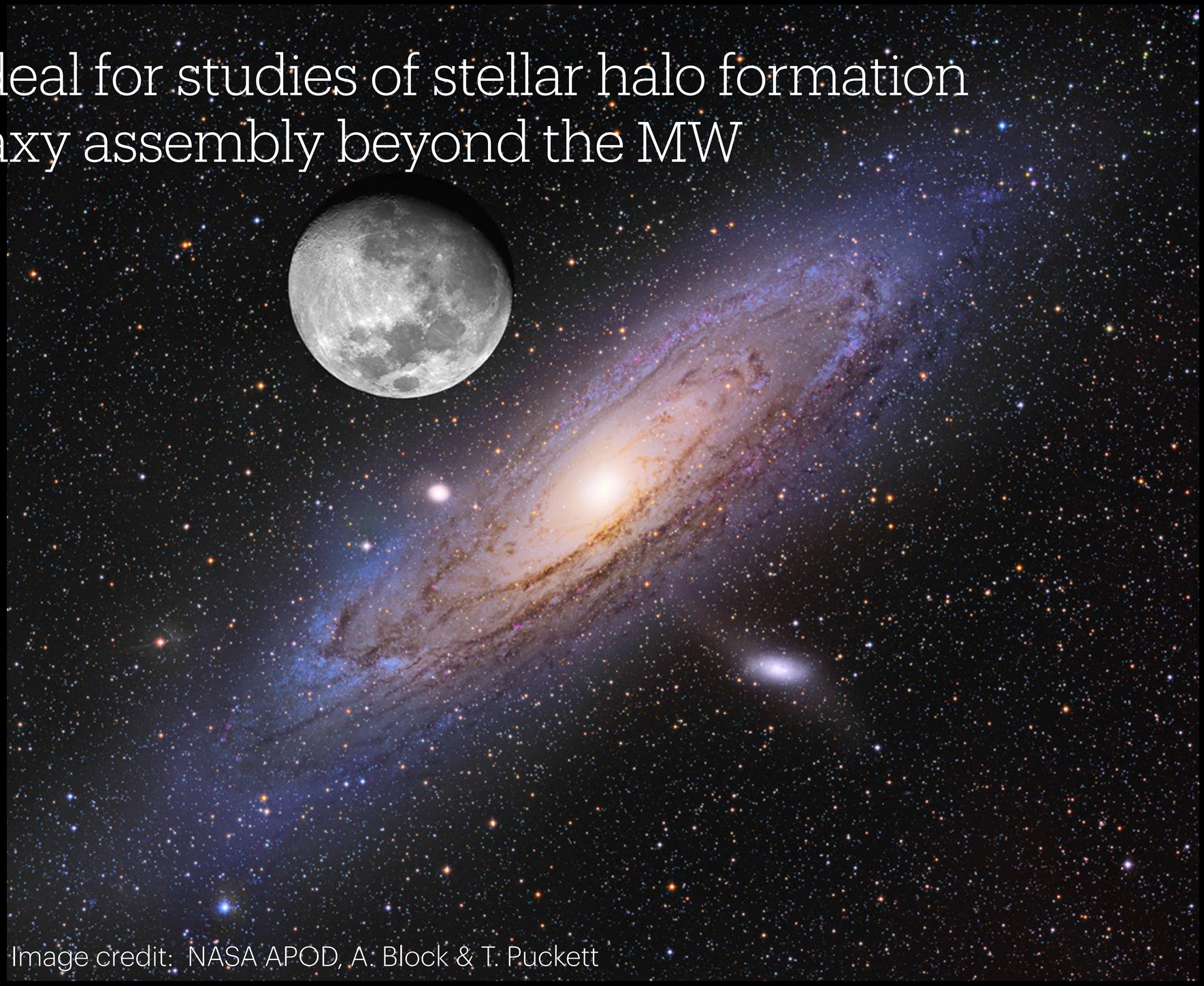
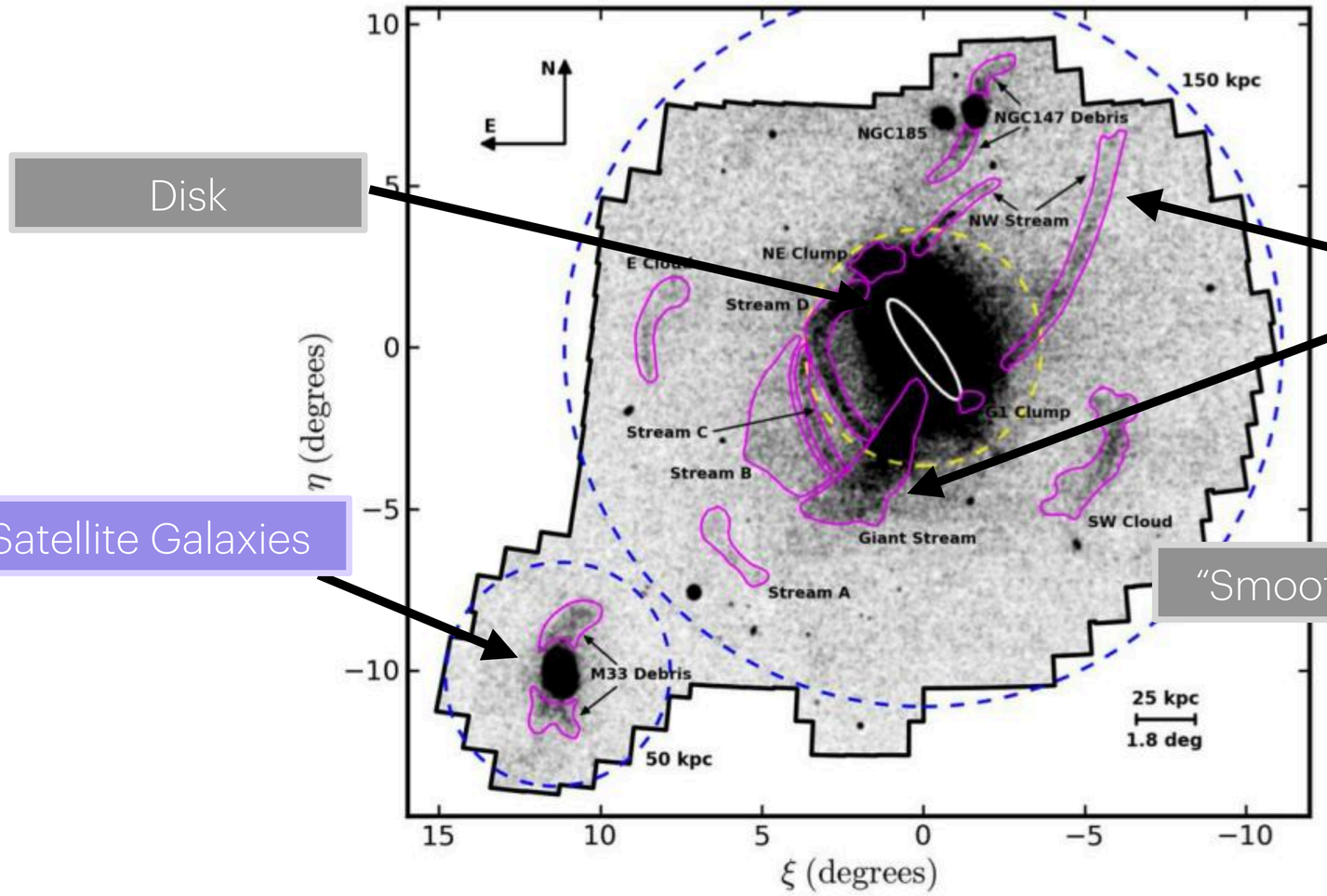


Image credit: NASA APOD, A. Block & T. Puckett

M31 is ideal for studies of stellar halo formation and galaxy assembly beyond the MW



Disk

Stellar Streams

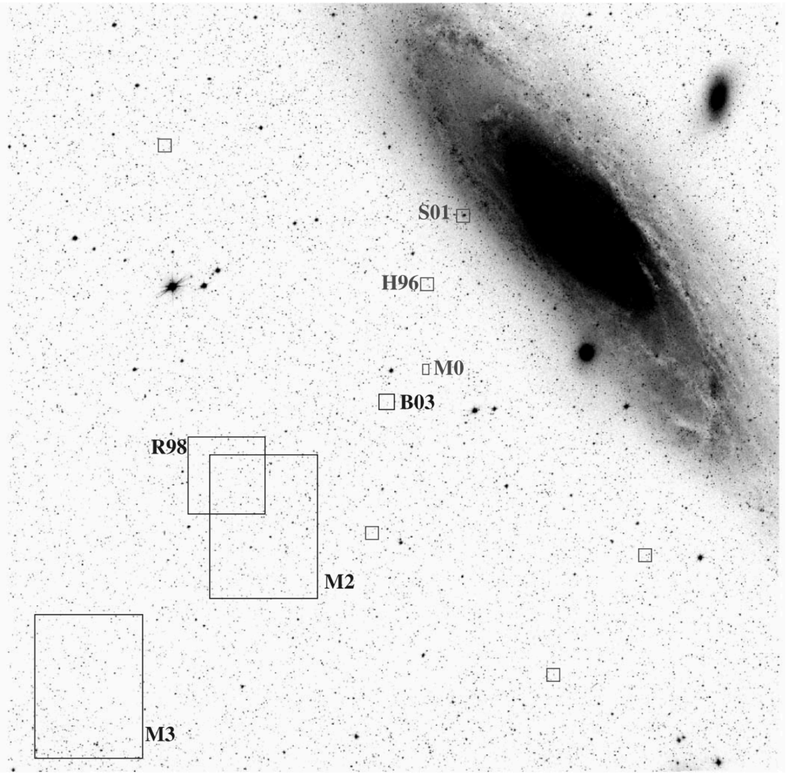
Tidal substructure to be discussed more in Lecture 2

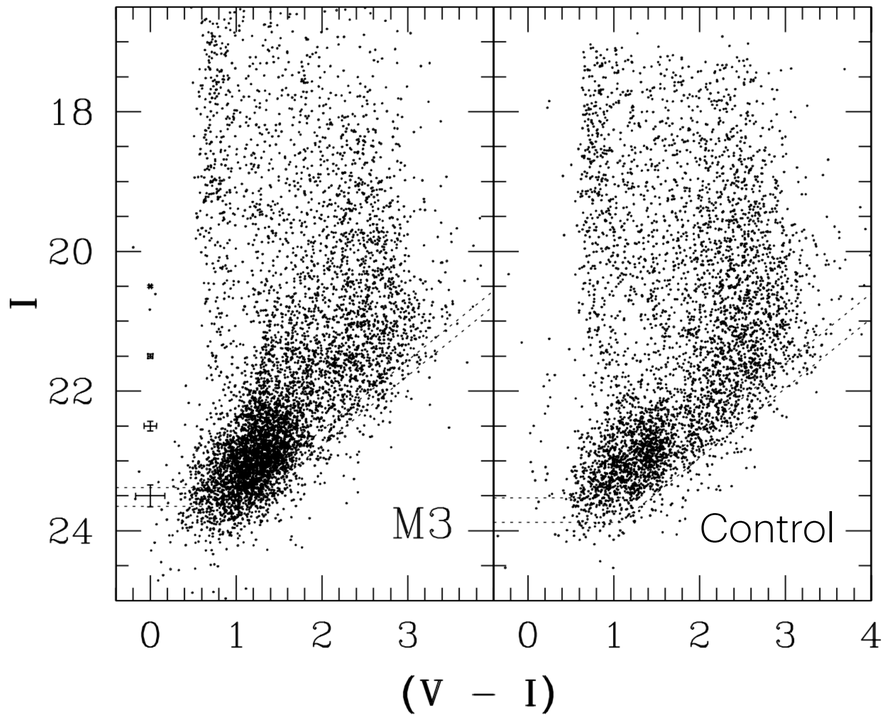
Intact Satellite Galaxies

"Smooth" Stellar Halo

Image credit: PAndAS collaboration, A. Ferguson & D. Mackey
e.g., Ibata+01,07; Ferguson+02; McConnachie+09

Early studies of M31's spheroid revealed a metal-rich, bulge-like structure

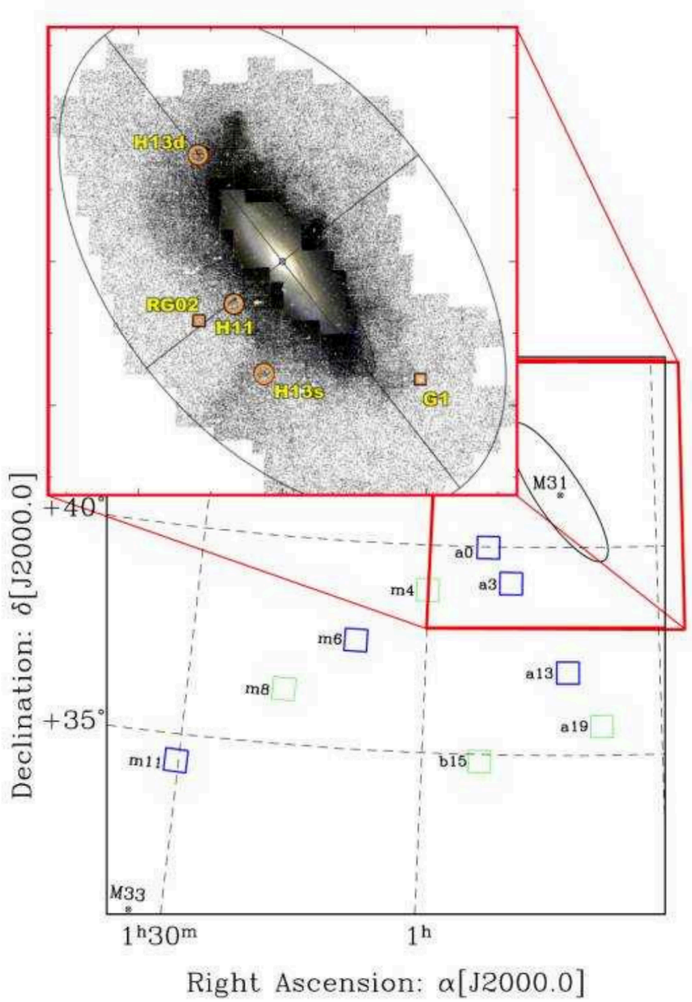


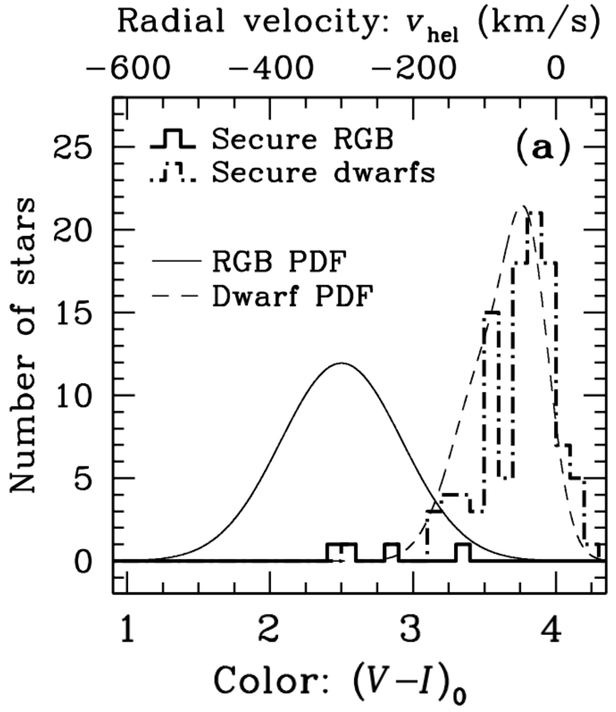


- <30 kpc, uniformly metal-rich, no metallicity gradient
- Fundamentally different halo component in M31 than MW?
- *Assumptions: 30 kpc is outer halo, minor-axis probes "smooth" halo*

Durell+04
e.g., Mould & Kristian 86; Pritchet & van den Bergh 94; Durrell, Harris & Pritchet 01

A true metal-poor, extended stellar halo was discovered via resolved stellar spectroscopy

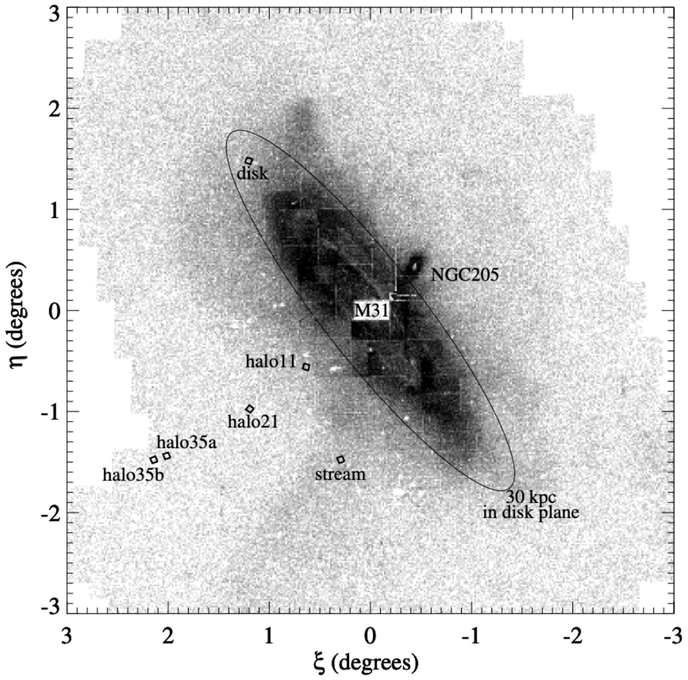


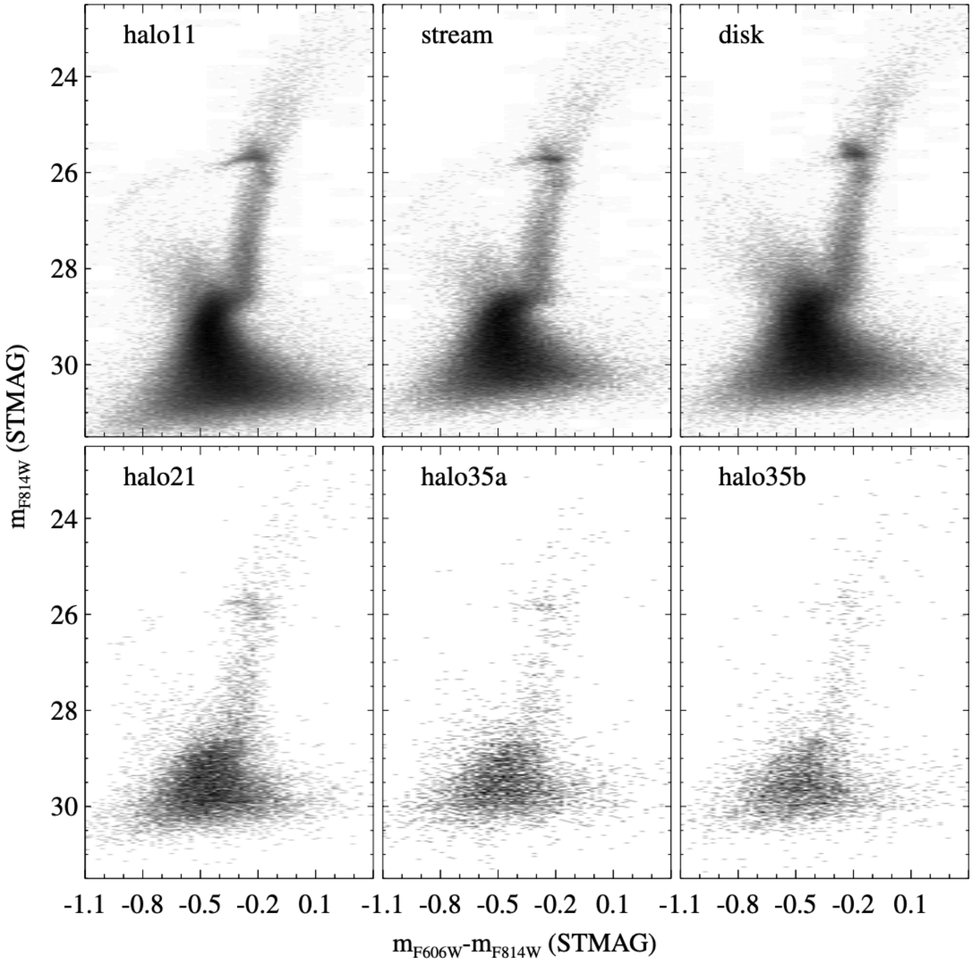


- Fields probing >60 kpc from M31's center, [Fe/H]~ -1.5
- Difficult to identify faint M31 halo from MW foreground stars without spectroscopy
- Halo detected out to 165 kpc

Image credit: Guhathakurta+05 (left), Gilbert+06 (right)
e.g.,Reitzel & Guhathakurta 02; Guhathakurta+04; Irwin+05; Chapman+06; Kalirai+06

Deep Hubble Space Telescope imaging revealed that M31's halo is not purely ancient, but has intermediate-age stars that were accreted

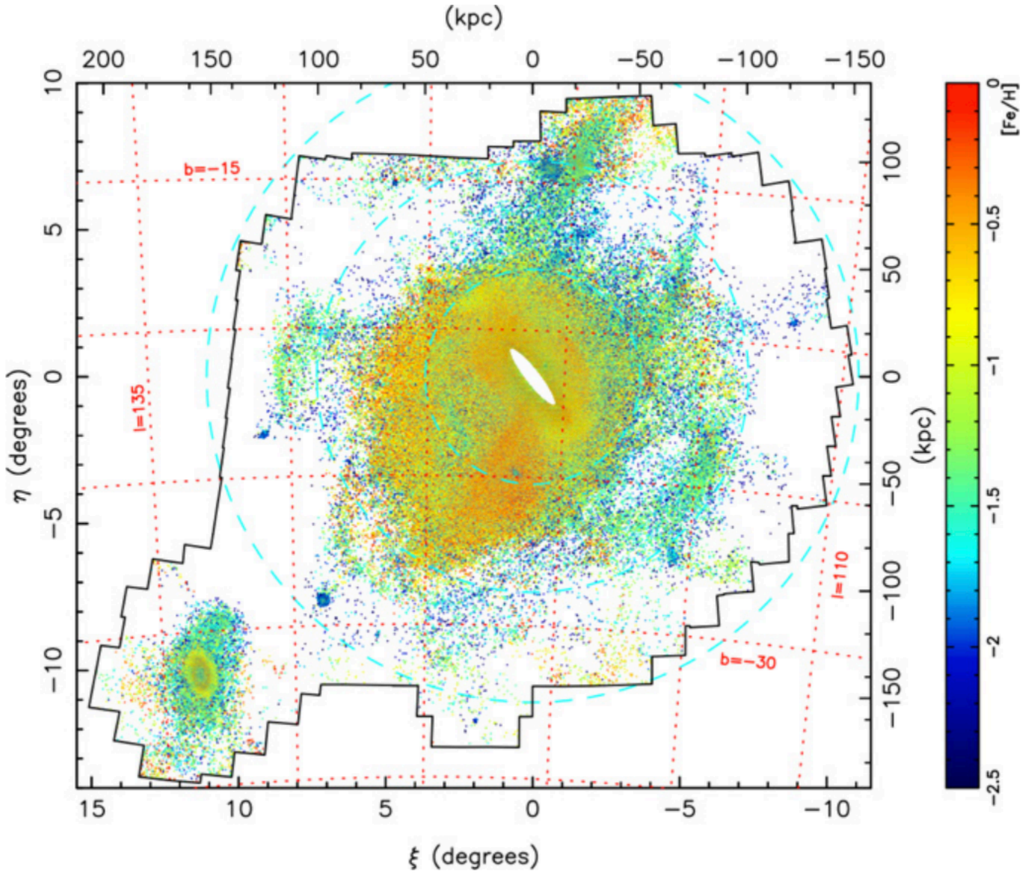




- At 11 kpc, 30% of stars are 6-8 Gyr old
- Inner halo and GSS have similar star formation histories
- At 20-30 kpc, stars older on average, but still show range of anges

Brown+09
e.g., Brown+03,06,07,08; Richardson+09
See also Ferguson+05; Richardson+08

The large-scale metallicity gradient of M31's halo suggests different inner vs. outer halo formation mechanisms are at play



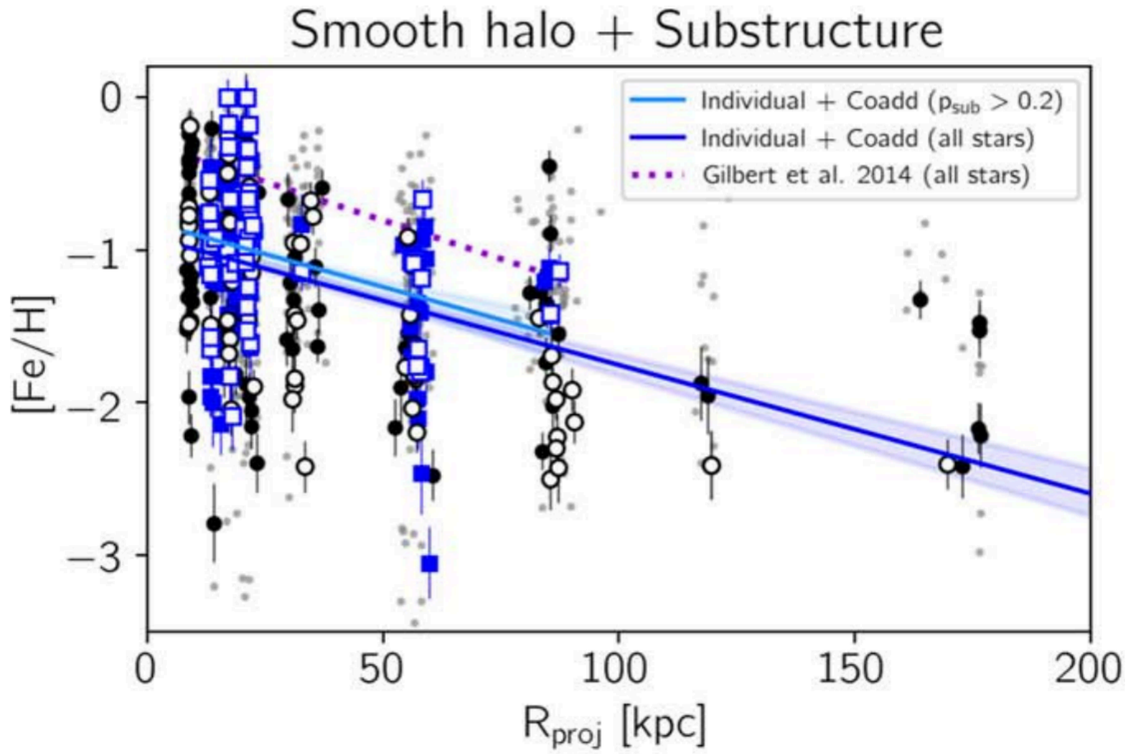
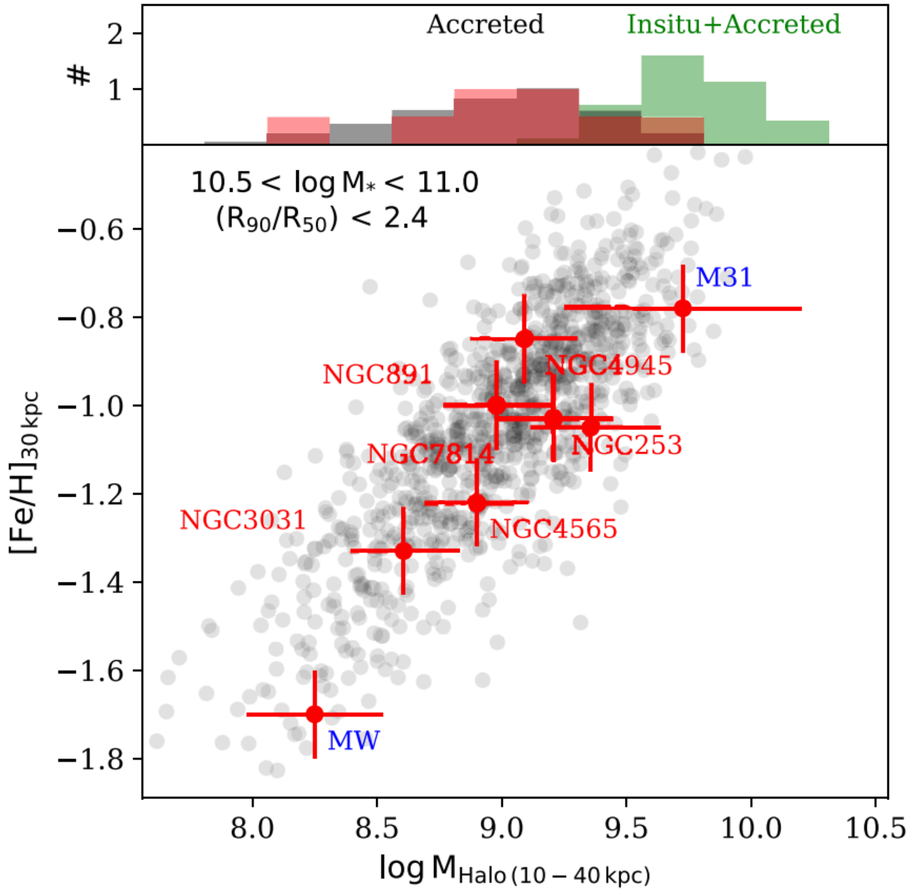


Image credit: Ibata+14 (left), Wojno+23 (right)
e.g., Kalirai+06; Chapman+06; Koch+08; Gilbert+14; Ogami+25
Escala+20b; Gilbert+20; Kirby+20

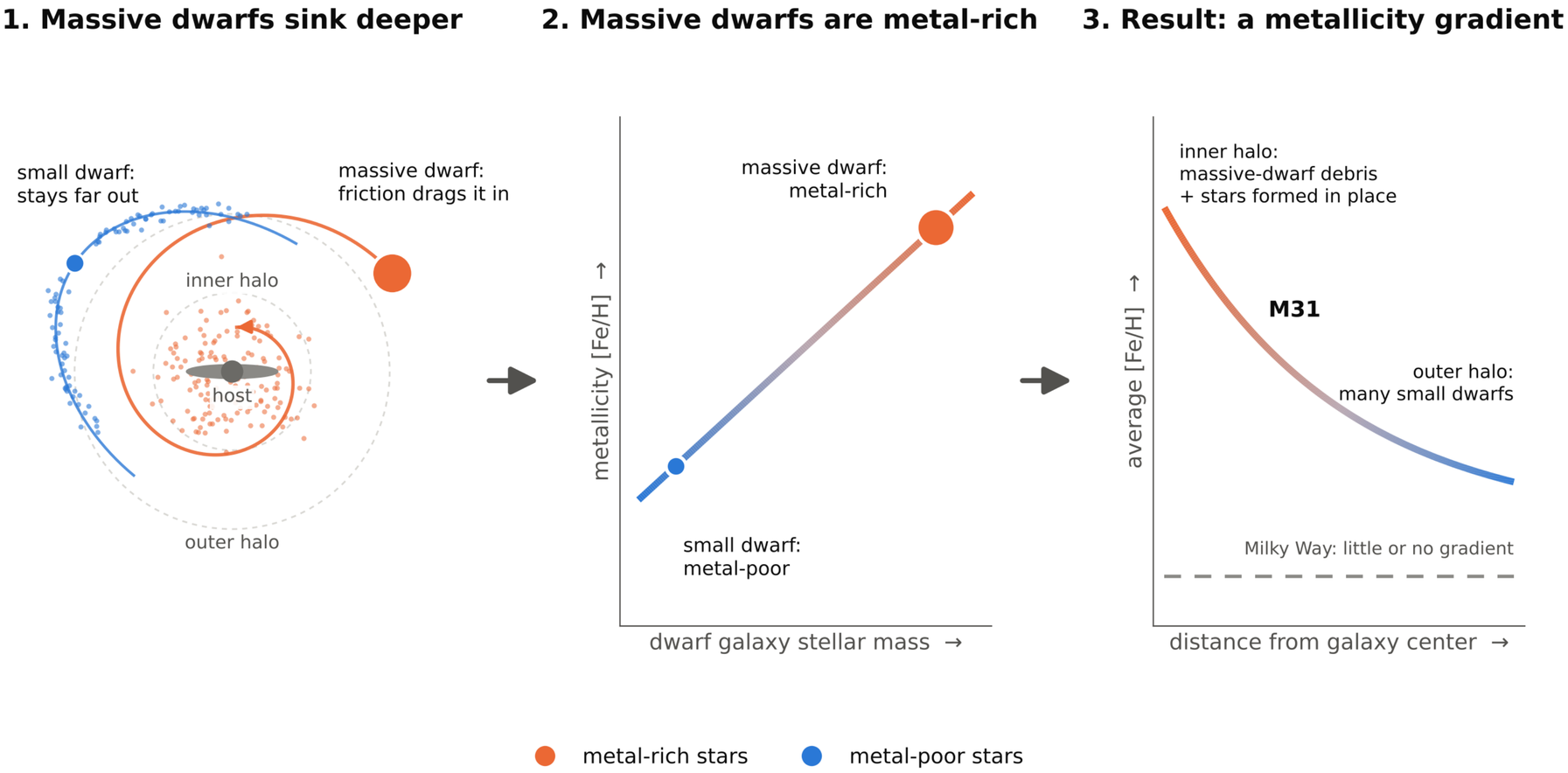
M31's massive, metal-rich halo points to a single dominant, accreted progenitor in a cosmological context



- M31 sits at the upper end of the relation, suggesting a more massive and later accretion than the MW
- *Caveat: Photometric metallicties are degenerate and biased metal-rich, MW values pre-GSE*

D'Souza & Bell 2018a
e.g., Deason+16, Harmsen+17

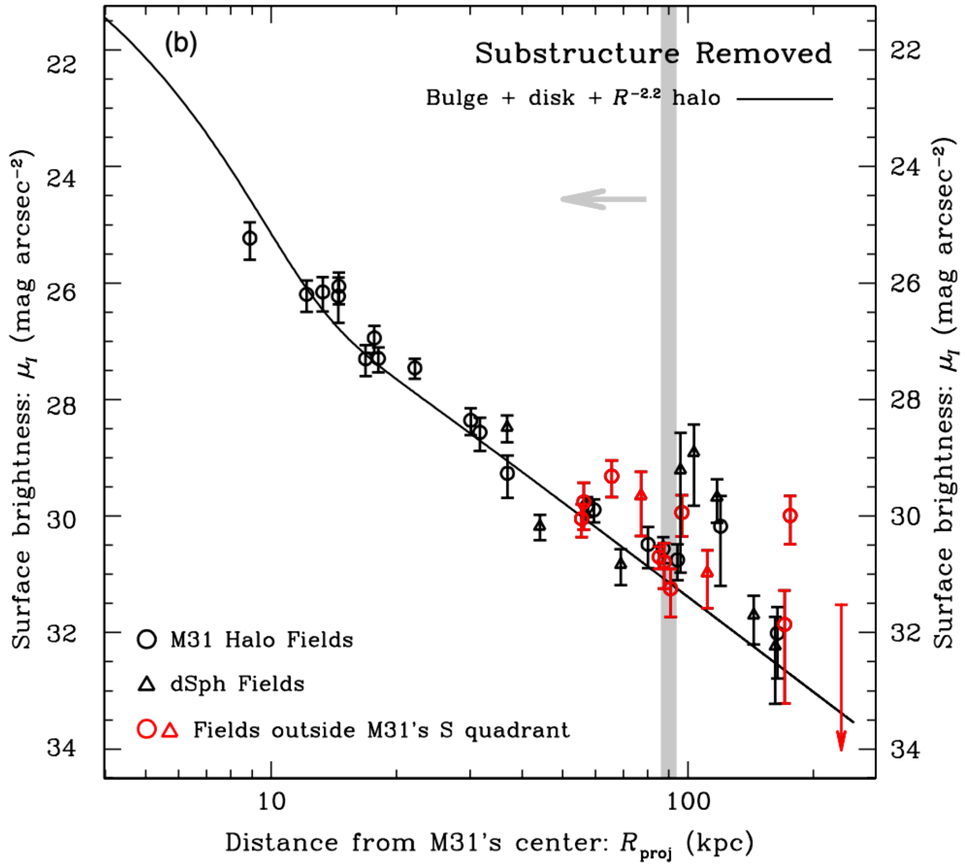
M31's inner halo also has contributions from stars formed in place, and smaller dwarf galaxies that dominate in the outskirts



Schematic. Based on Amorisco 2017; Kirby et al. 2013; Cooper et al. 2010; Font et al. 2011; Monachesi et al. 2019.

Image credit: I. Escala (Claude Opus 5.5)
e.g. Zolotov+09; Purcell+10; Cooper+10; Font+11; Tissera+14; Monachesi+19; D'Souza & Bell 2018a
See Gilbert+14 and Wojno+23 for observational interpretation for M31

M31's smooth halo follows a single power law out to at least 176 kpc, with no downward break as seen in the MW

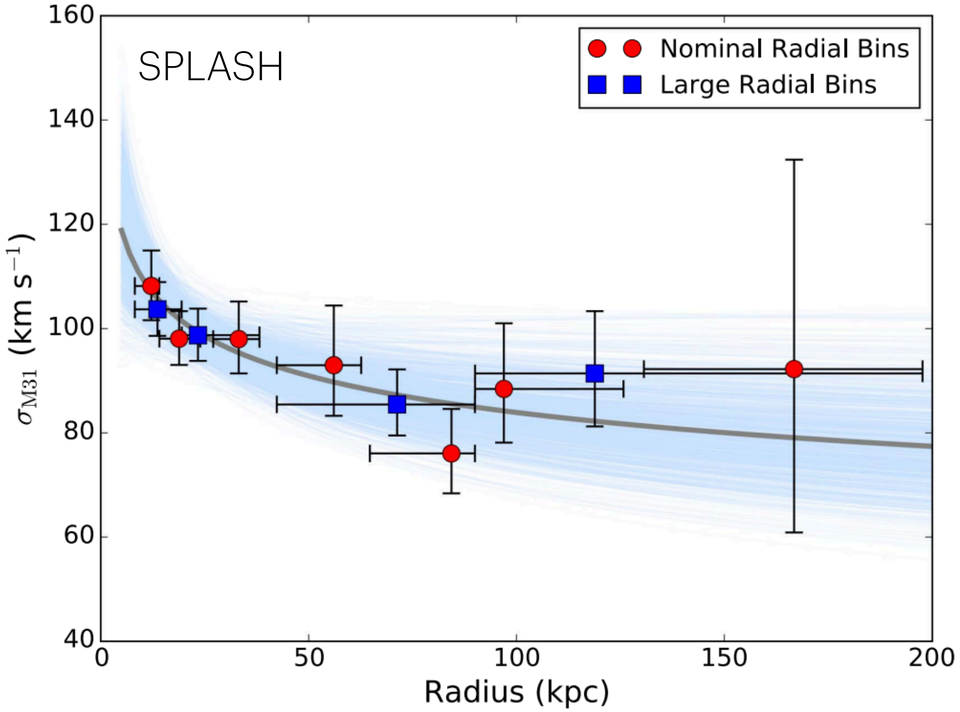


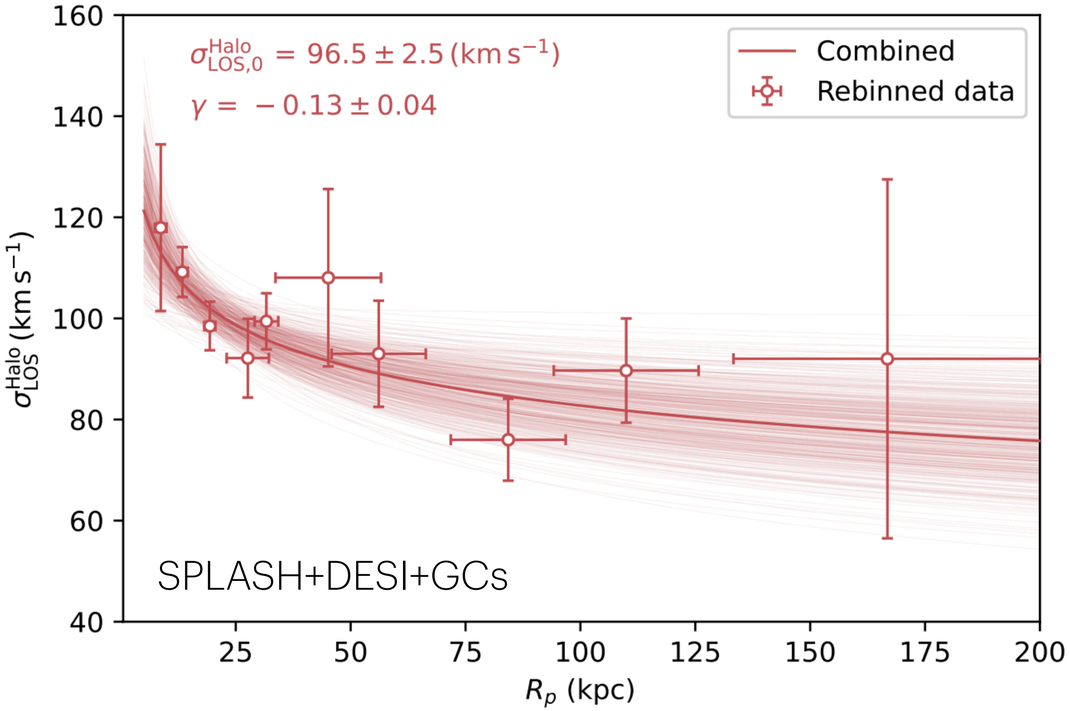
- MW's halo falls off steeply after 20-30 kpc
- No break argues against an *early*, single-event dominated history
- Metal-rich population has steeper profile than metal-poor one (Ibata+14; Ogami+25)

Gilbert+12
e.g. Deason+11,13,18; Cunningham+16; Courteau+11; Ibata+14; Monachesi+19; Ogami+25

M31's halo has a relatively flat line-of-sight velocity dispersion profile, but this cannot yet tell us about M31's accretion history

M31 mass estimates to be further discussed in Lecture 3

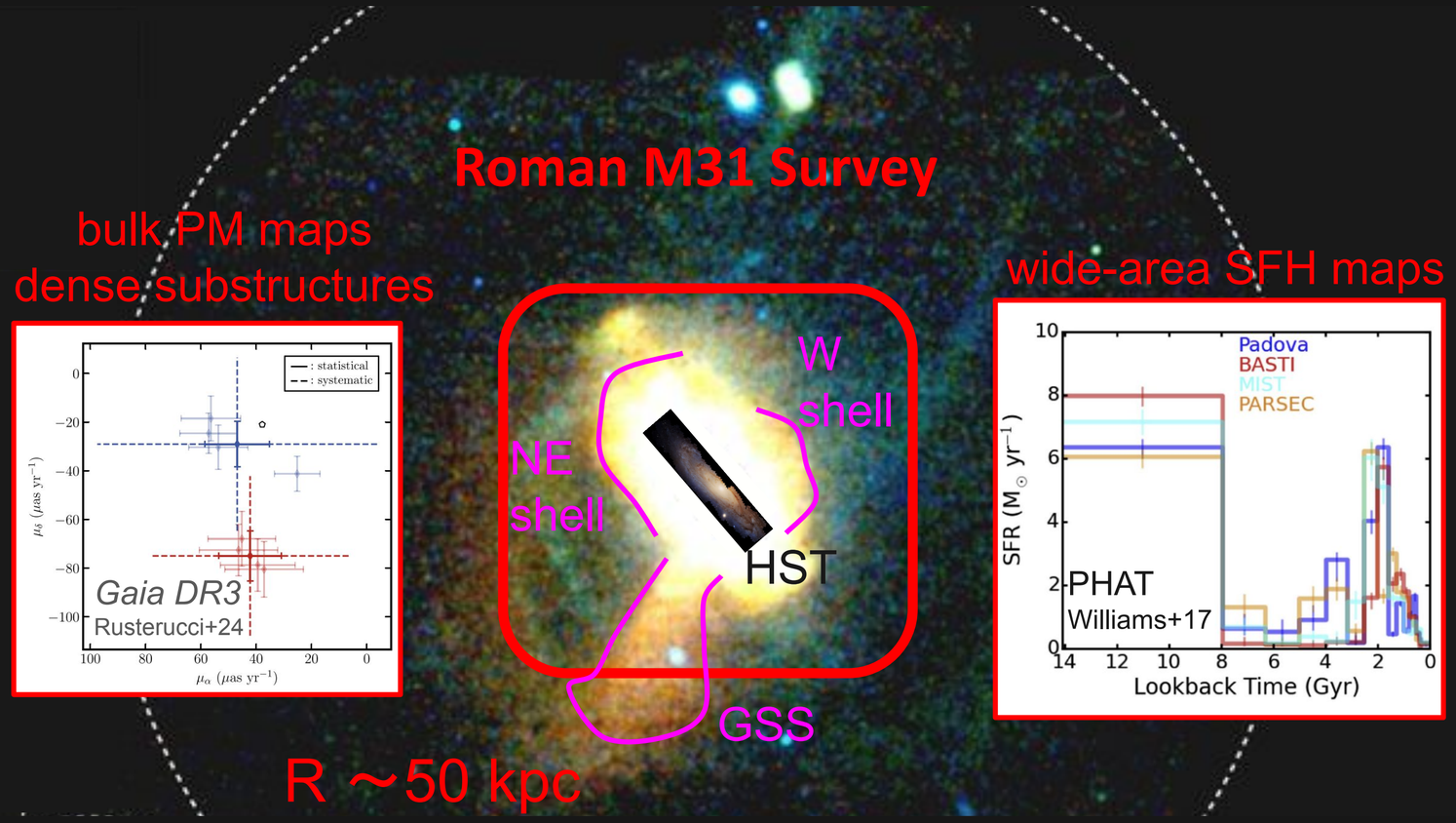




- *Assumption of dynamical equilibrium (does not hold with recent active accretion history), and unknown 3D halo motions. Kinematically cold substructure removed.*

Image credit: Gilbert+18 (left), Wu+26 (right)
Additional data from Dey+23 and Veljanoski+14

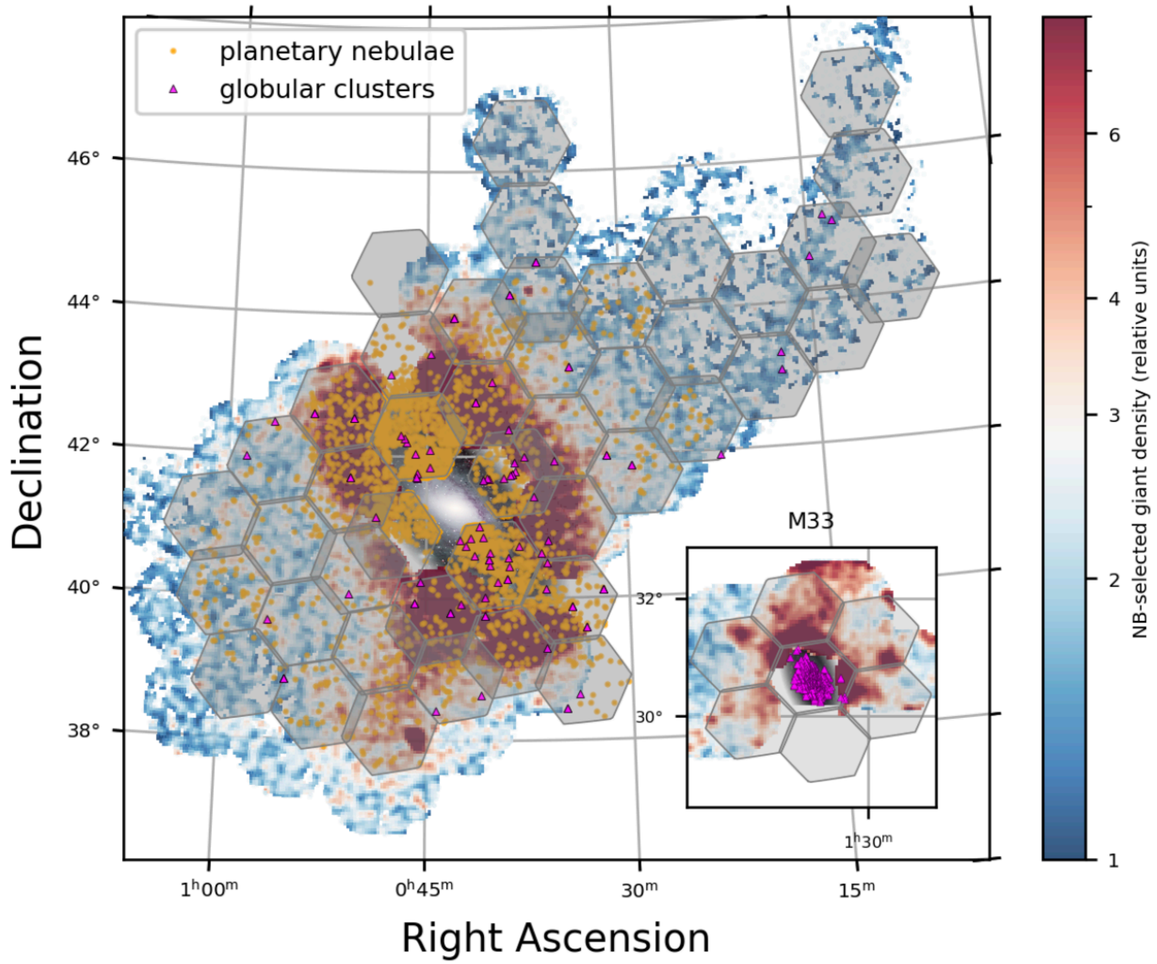
The Roman *Cycle 1* Legacy Survey of Andromeda and Triangulum will provide deep imaging out to 50 kpc in M31's halo



- More halo science with Roman:
  - Faint halo substructures
  - Ultra-faint dwarf galaxies in M31's halo (see Lecture 3)

Image credits: K. Gilbert, I. Escala, and the Andromeda with Roman team

Subaru PFS will measure the chemistry for tens of thousands of individual stars throughout M31's halo to disentangle its accretion history



- 2394 fibers per pointing, 44 pointings, 1.3 deg FOV, 30,000 stars with metallicities (15,000 with more detailed abundances)
- M31 giants selected with surface-gravity sensitive narrowband imaging (Ogami+25)
- Science questions
  - Inner vs. outer halo formation
  - Luminosity function of accreted satellites
  - Halo velocity dispersion and mass profile

Chiba+26

Summary: Global properties of M31's stellar halo

- **The inner halo is not purely ancient.** It contains intermediate-age, metal-rich stars delivered by recent accretion, matching debris from the Giant Stellar Stream. Farther out, the stars are older on average but still span a range of ages.

- **The halo is massive, smooth and unbroken.** Its density falls off smoothly with no break. That points to an accretion history spread over a longer period of time than the Milky Way's.

- **The metallicity gradient requires at least one massive progenitor.** The halo becomes steadily more metal-poor with distance. Its metal-rich inner regions were likely built from a massive accreted galaxy and/or stars that formed in place, whereas the outer regions are probably dominated by smaller accreted dwarf galaxies.

- **Halo motions are hot and smooth, but cannot yet reveal how the halo was assembled.** Independent surveys agree on how the stars move along our line of sight. The motions across the sky, which would record past mergers, have not been measured yet.

- **These features point to an active, prolonged accretion history for M31.** This is in contrast to the unusually quiescent accretion history of the Milky Way.

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