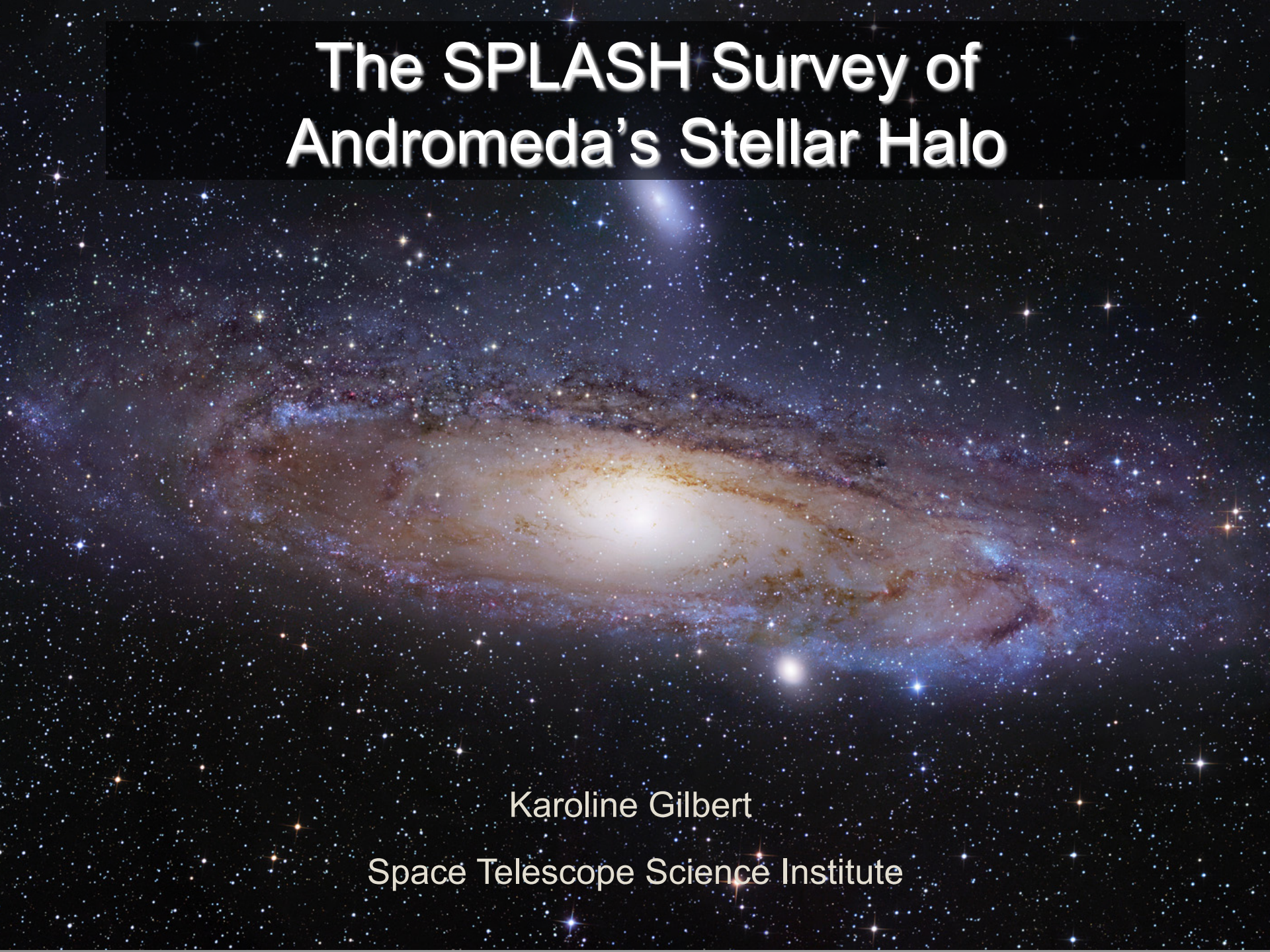
# The SPLASH Survey of Andromeda's Stellar Halo



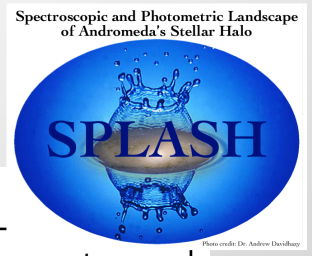
Karoline Gilbert

Space Telescope Science Institute

# Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo

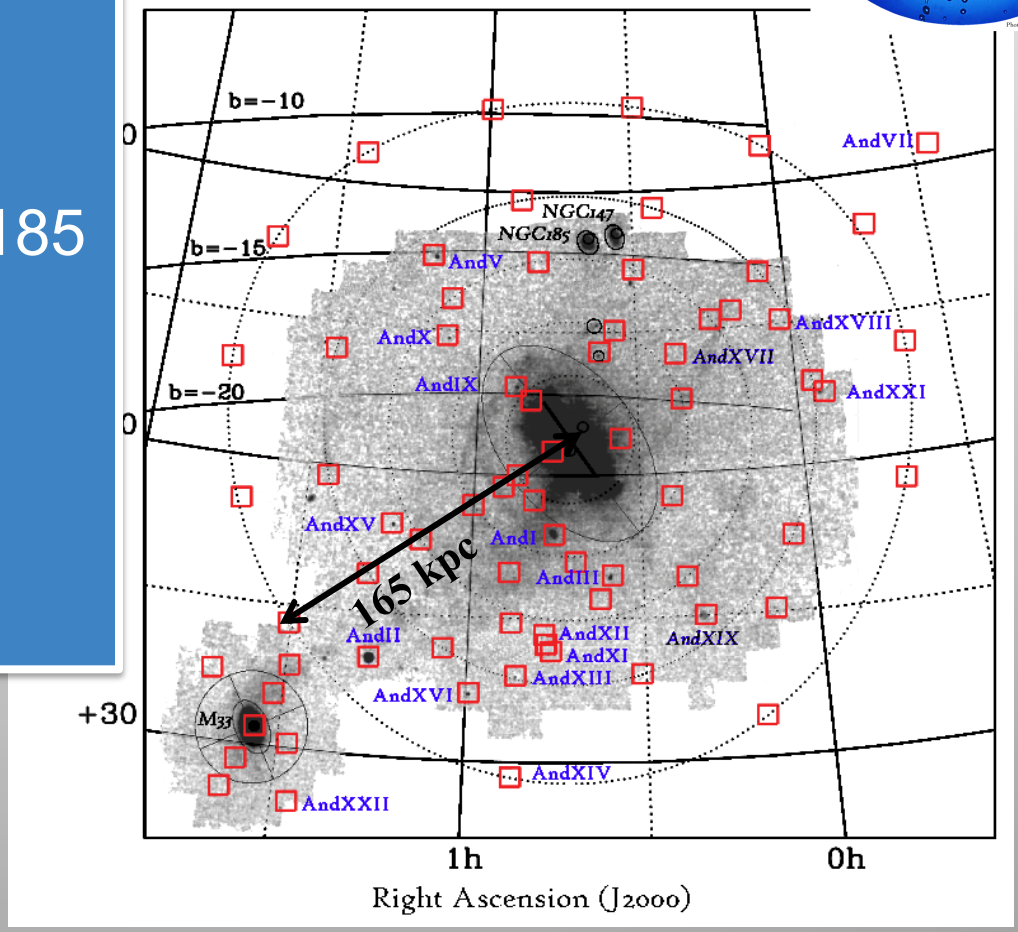

*Raja Guhathakurta* (UCSC)
*Steve Majewski* (U Virginia)
*Marla Geha* (Yale)
*James Bullock,* (UC Irvine)
*Rachael Beaton* (Carnegie)
*Erik Tollerud* (Yale)
*Evan Kirby* (Caltech)
*Jason Kalirai* (STScI)
*Claire Dorman* (UCSC)
*Katie Hamren* (UCSC)
*Kirsten Howley* (LLNL)
*Mark Fardal* (U Mass)
*Ricky Patterson* (U Virginia)
*Andreea Font* (ARI Liverpool)
*Kathryn Johnston* (Columbia U)
*Tom Brown* (STScI)

# SPLASH Observations



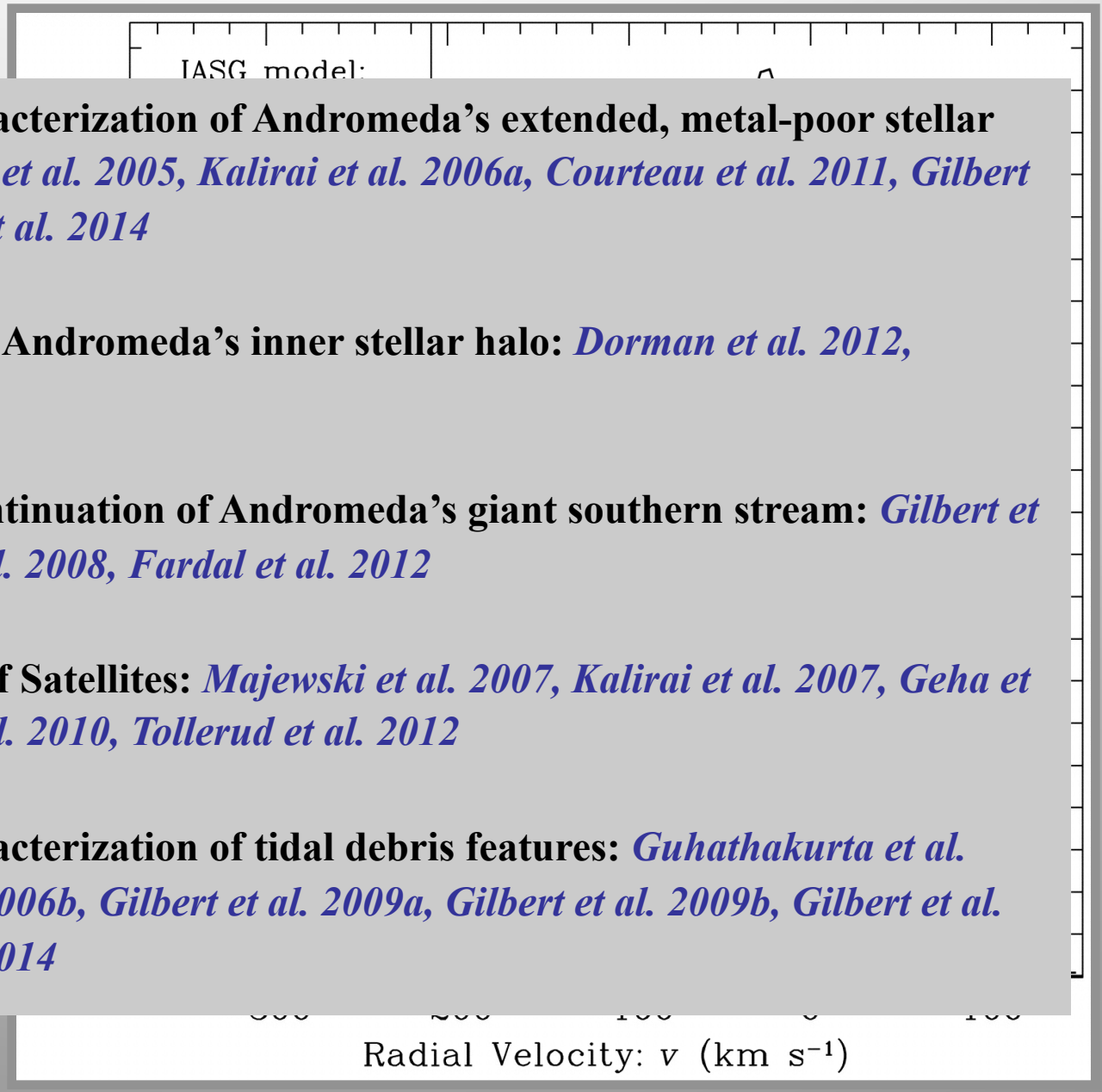

- Halo Fields
- Tidal Debris Features
- Dwarf Satellite Fields
  - NGC 147 and NGC 185
  - NGC 205
  - M32
  - 15 dSph galaxies
- M31's Inner Spheroid
- M31's Disk


~170 Individual Masks
~20,000 individual M31 stellar spectra
PI: Guhathakurta & Bullock




*PANDAS Survey Map from Richardson et al. 2011*

# Isolating a clean sample of M31 RGB stars




- **Discovery and characterization of Andromeda's extended, metal-poor stellar halo:** ***Guhathakurta et al. 2005, Kalirai et al. 2006a, Courteau et al. 2011, Gilbert et al. 2012, Gilbert et al. 2014***
- **Characterization of Andromeda's inner stellar halo:** ***Dorman et al. 2012, Dorman et al. 2013***
- **Discovery of the continuation of Andromeda's giant southern stream:** ***Gilbert et al. 2007, Fardal et al. 2008, Fardal et al. 2012***
- **Andromeda's Dwarf Satellites:** ***Majewski et al. 2007, Kalirai et al. 2007, Geha et al. 2010, Kalirai et al. 2010, Tollerud et al. 2012***
- **Discovery and characterization of tidal debris features:** ***Guhathakurta et al. 2006, Kalirai et al. 2006b, Gilbert et al. 2009a, Gilbert et al. 2009b, Gilbert et al. 2012, Gilbert et al. 2014***

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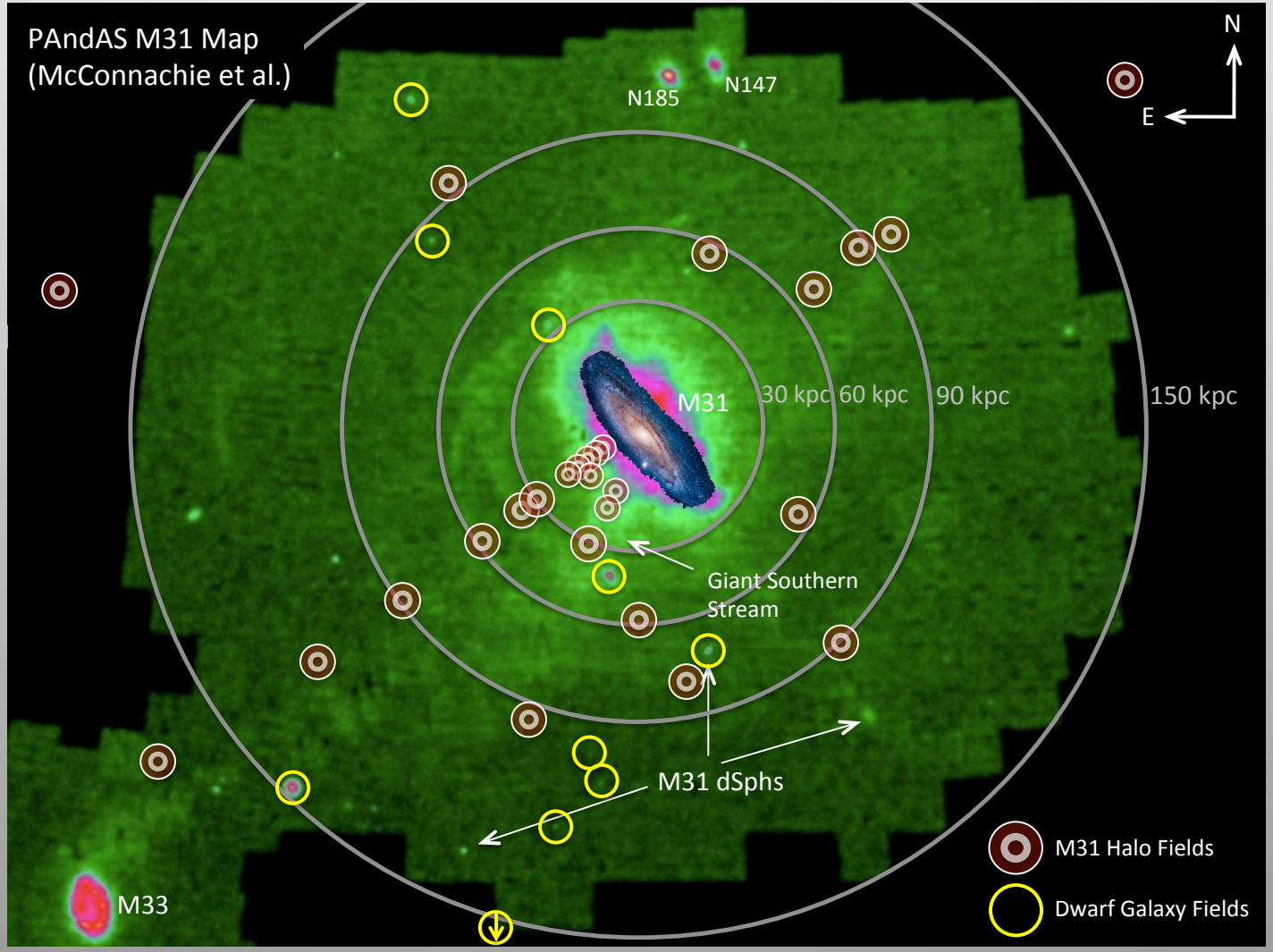
***(2006, ApJ)***

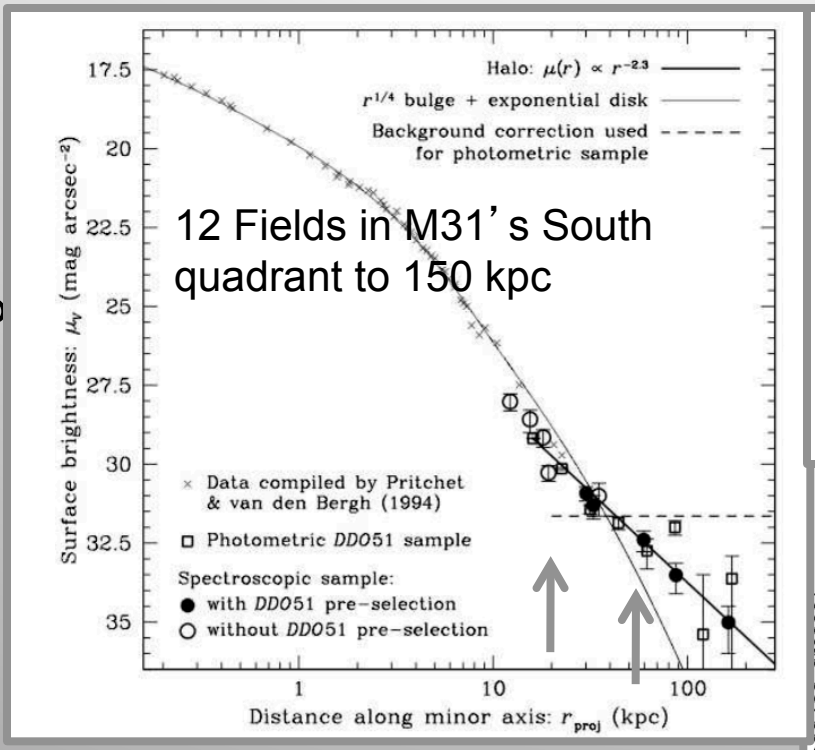
# Global Properties of Andromeda's Halo

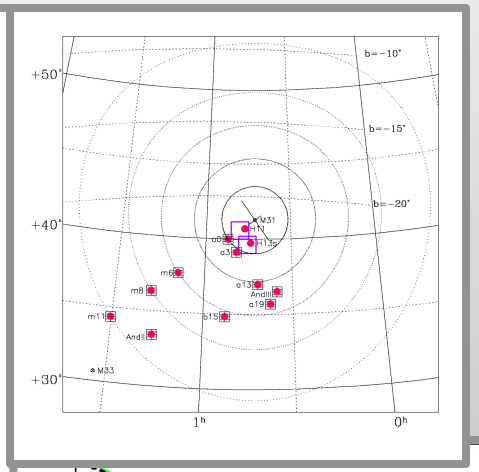


# Surface Brightness Profile of M31

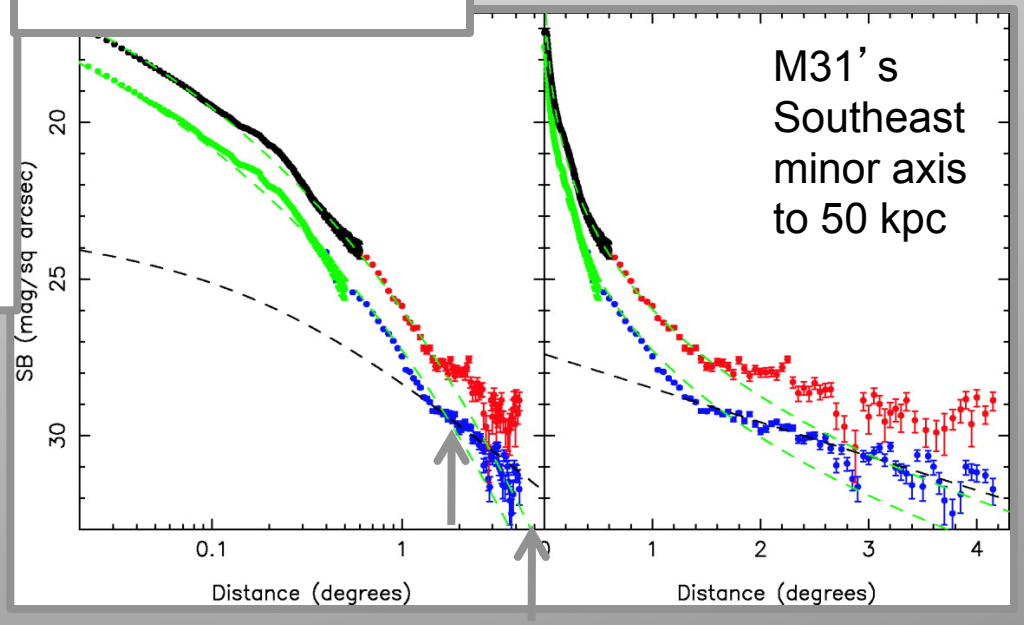
Counts of spectroscopically confirmed M31 RGB stars in outer fields ($R$ = 30 to 150 kpc) lie well above extrapolation of Sersic-law inner spheroid; $R^{-2}$ power law halo

Surface Brightness




*Guhathakurta et al. 2005*

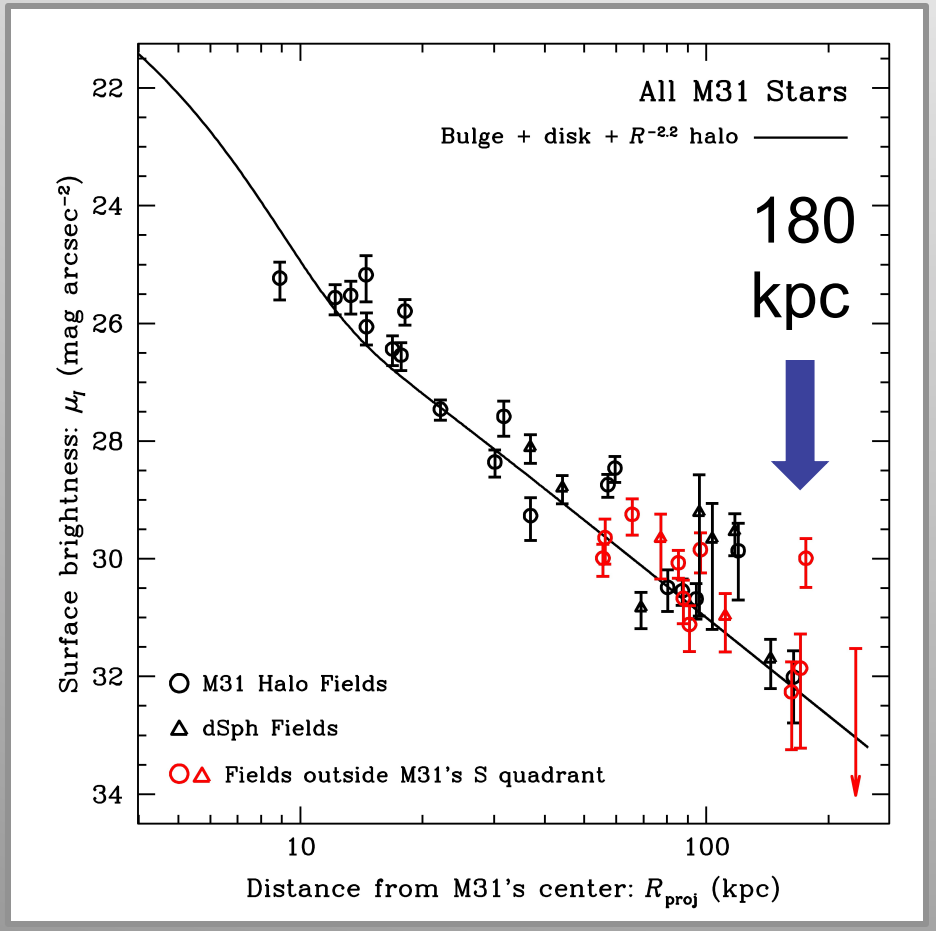


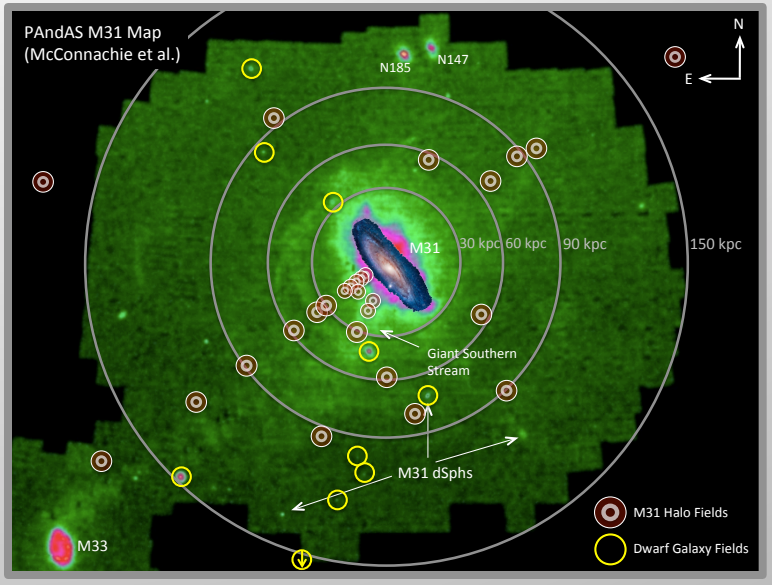

*Irwin et al. 2005*

*Also Ibata et al. 2007, Tanaka et al. 2010, Courteau et al. 2011*

# Surface Brightness Profile of M31

38 spectroscopic fields throughout M31's stellar halo




Fields in M31's South quadrant

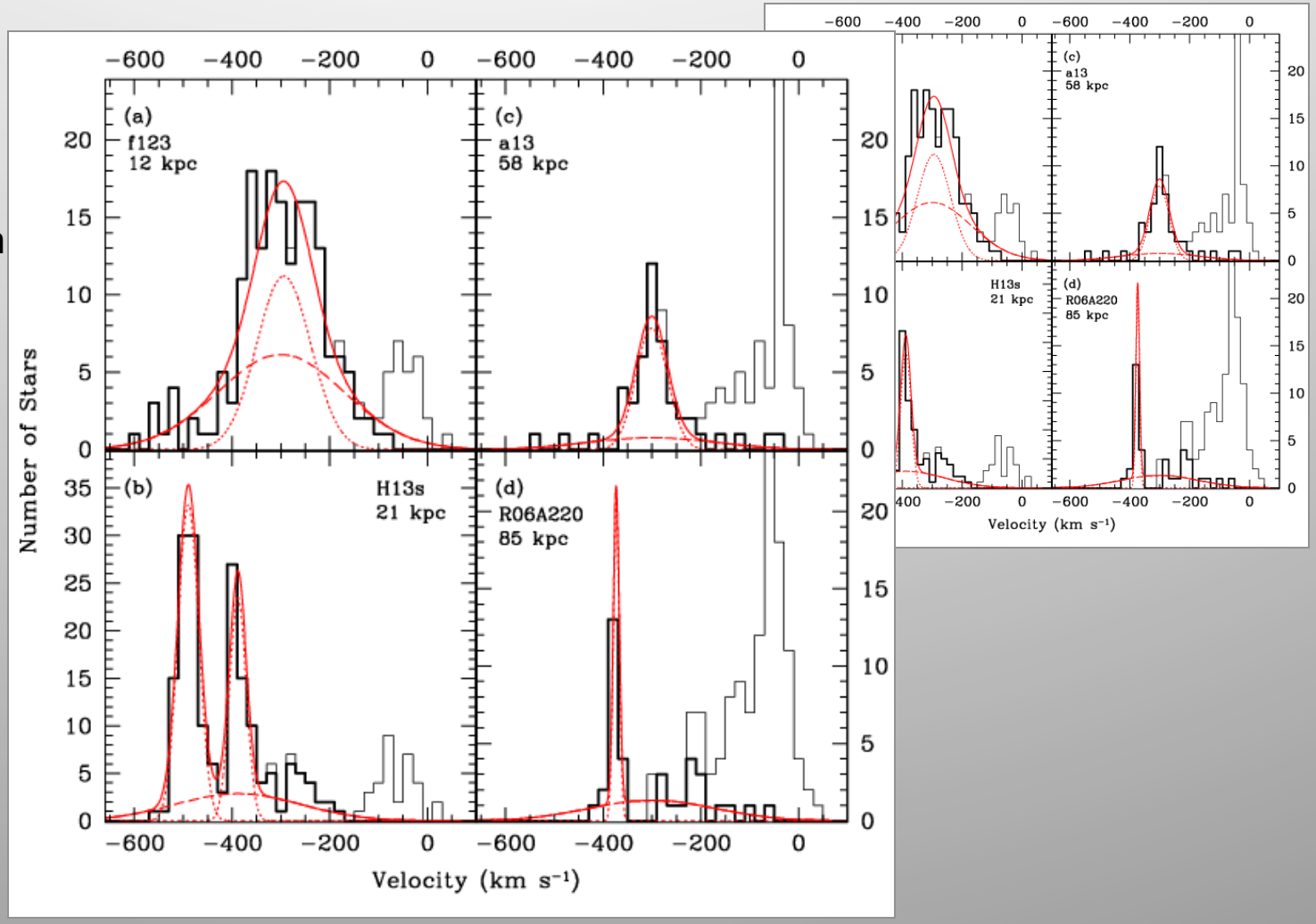
Fields in M31's other quadrants

*Gilbert et al., 2012*

# Surface Brightness Profile of M31

Spectroscopy allows us to statistically remove substructure in fields.

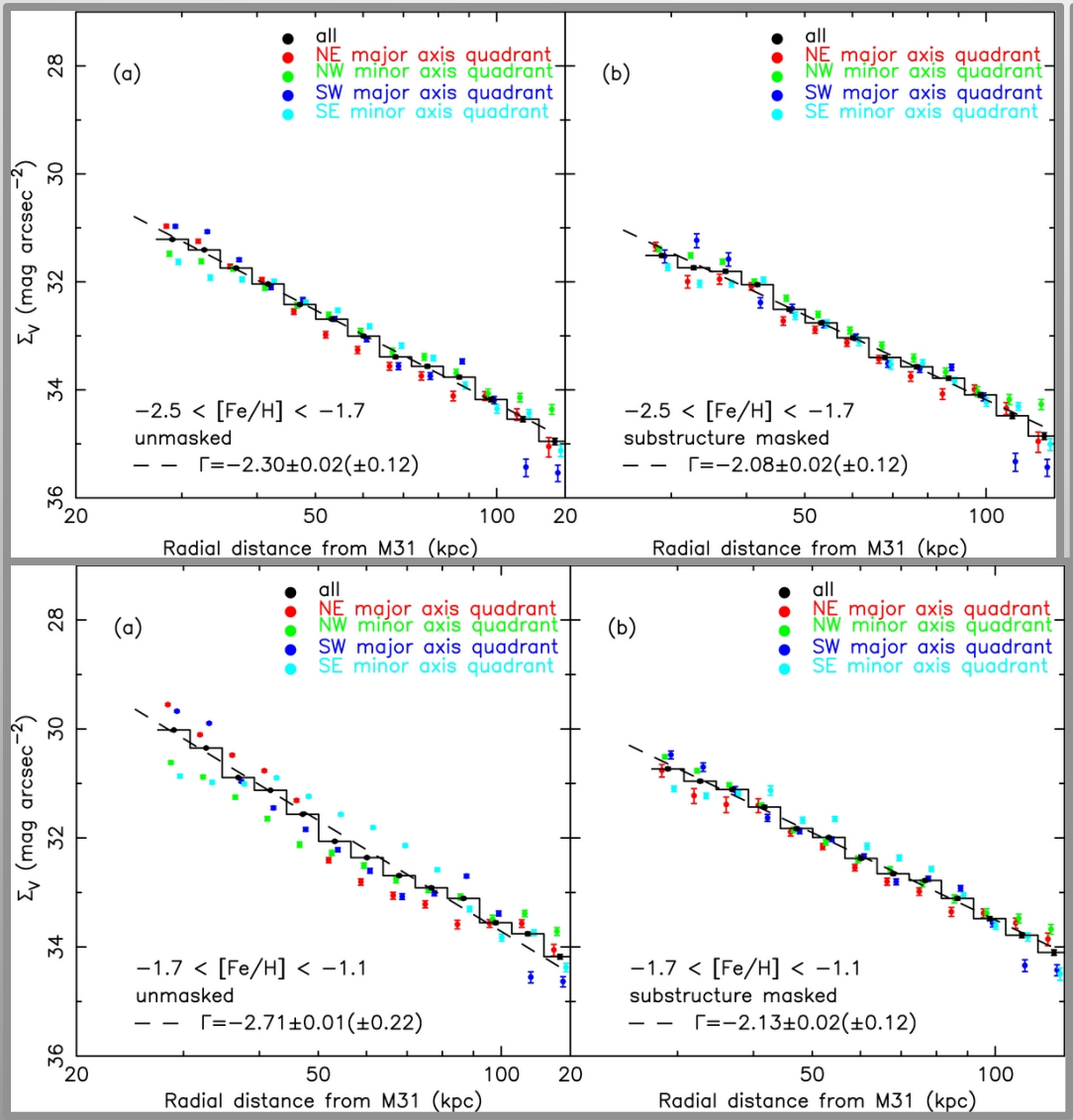
- Fields in M31's South quadrant
- Fields North of M31's semi-major axis

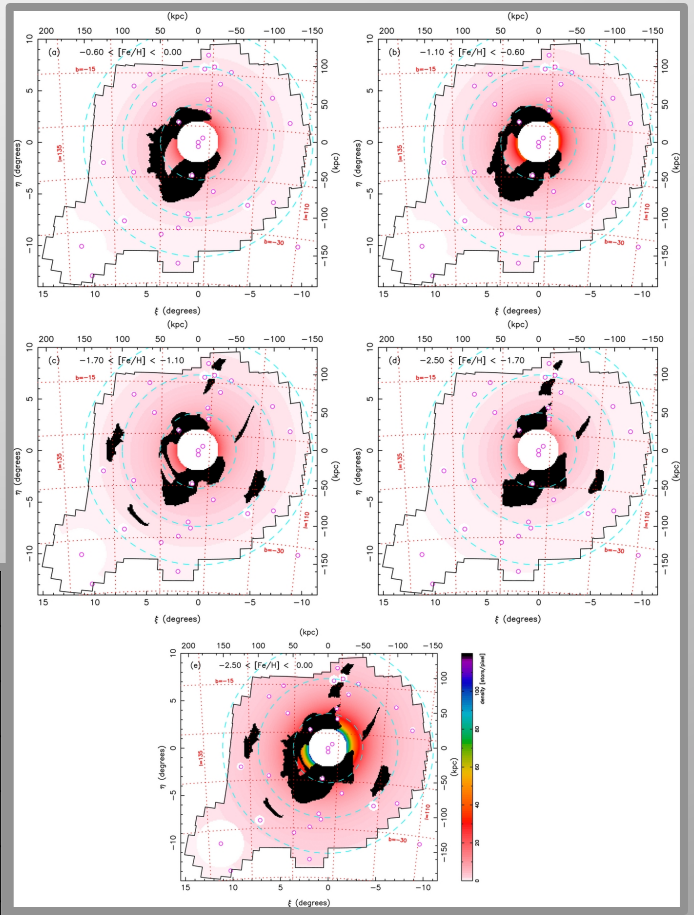



*Gilbert et al., 2012*

# Surface Brightness Profile of M31

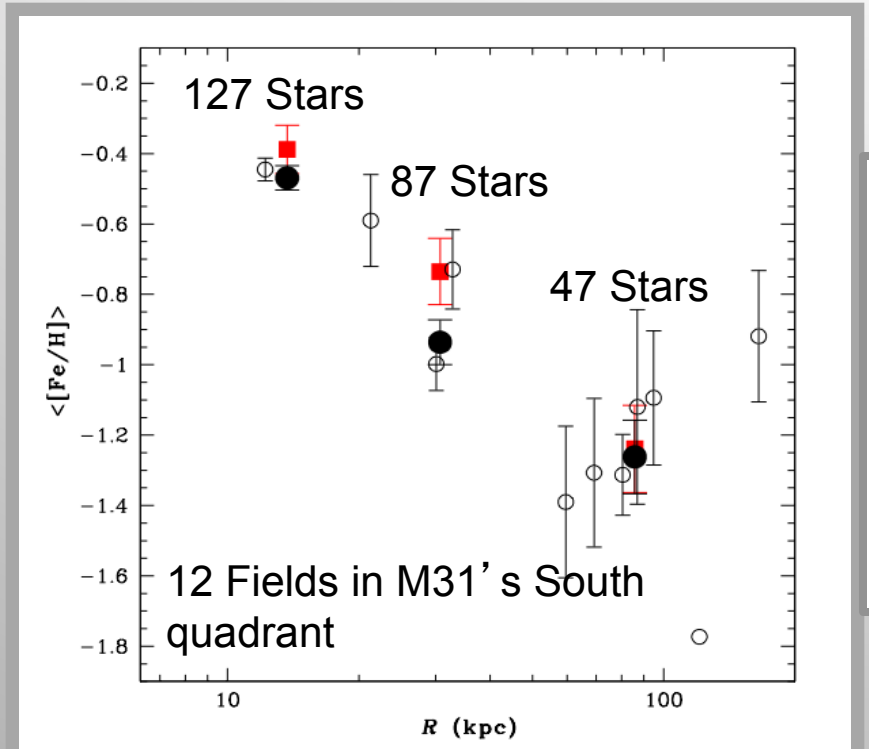
Full PAndAs dataset: agrees well with profile from SPLASH fields



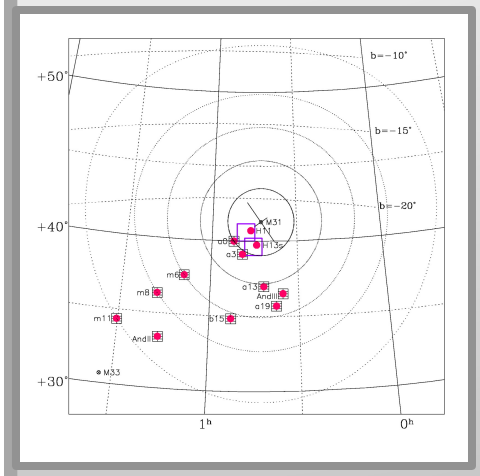

*Ibata et al., 2014*

# Radial Metallicity Gradient



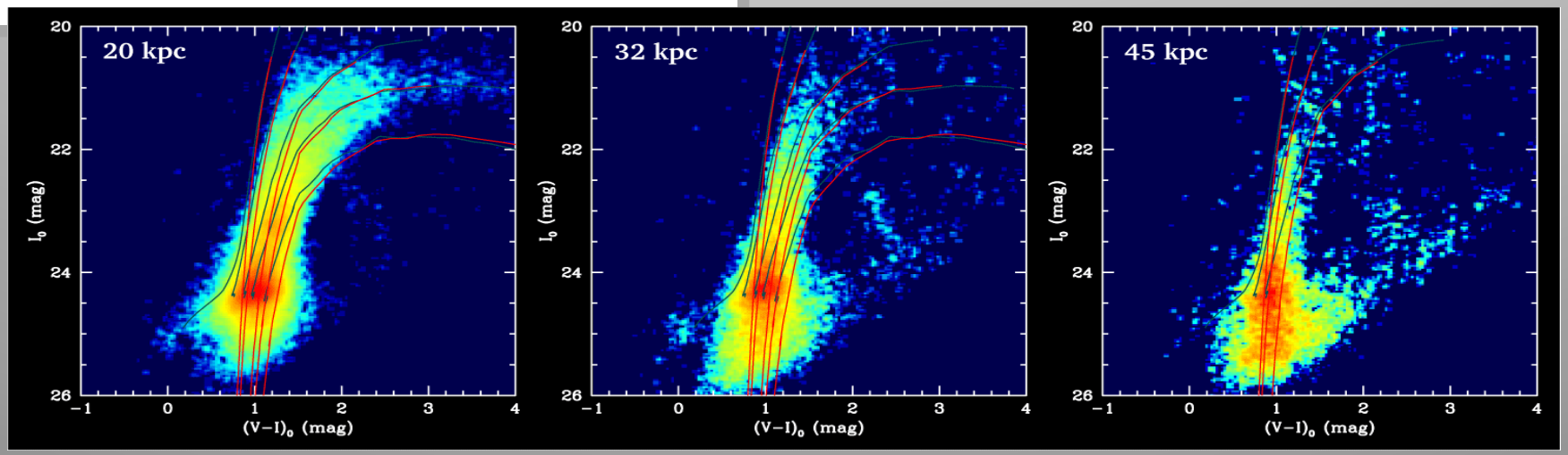

Keck/DEIMOS Spectroscopy

*Kalirai, Gilbert et al. 2006*



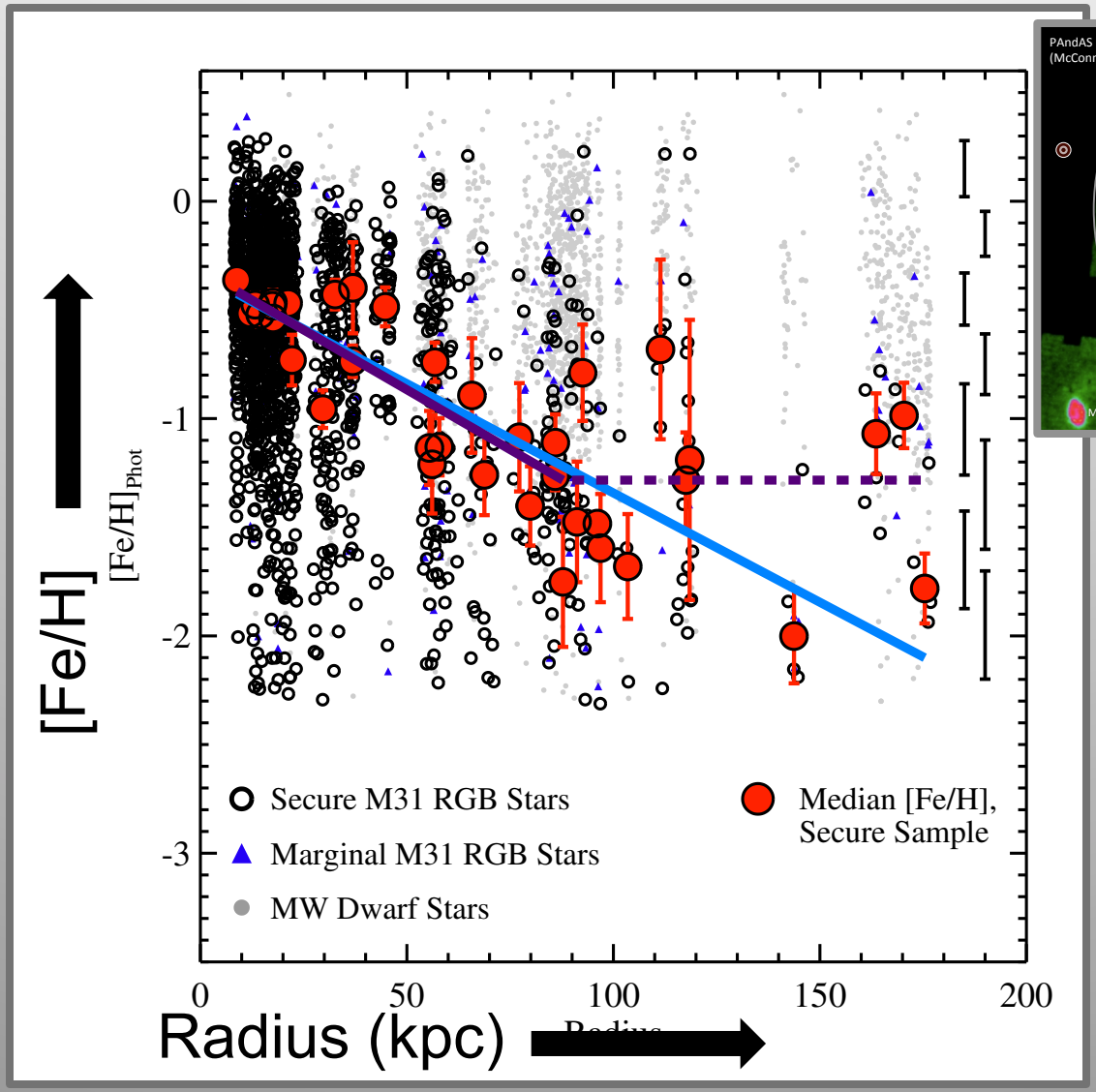
Subaru/SuprimeCam Imaging

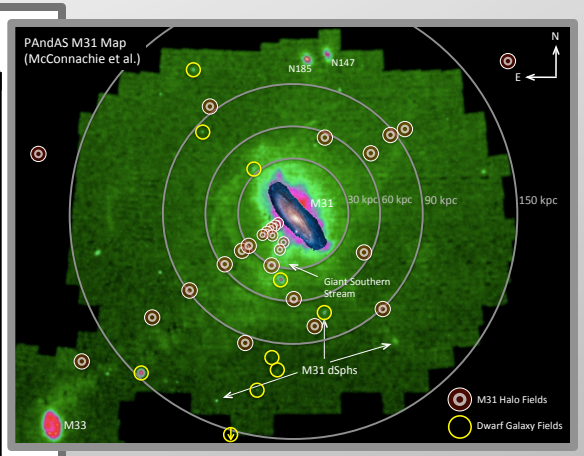
*Tanaka et al. 2010*



# Metallicity Profile of M31

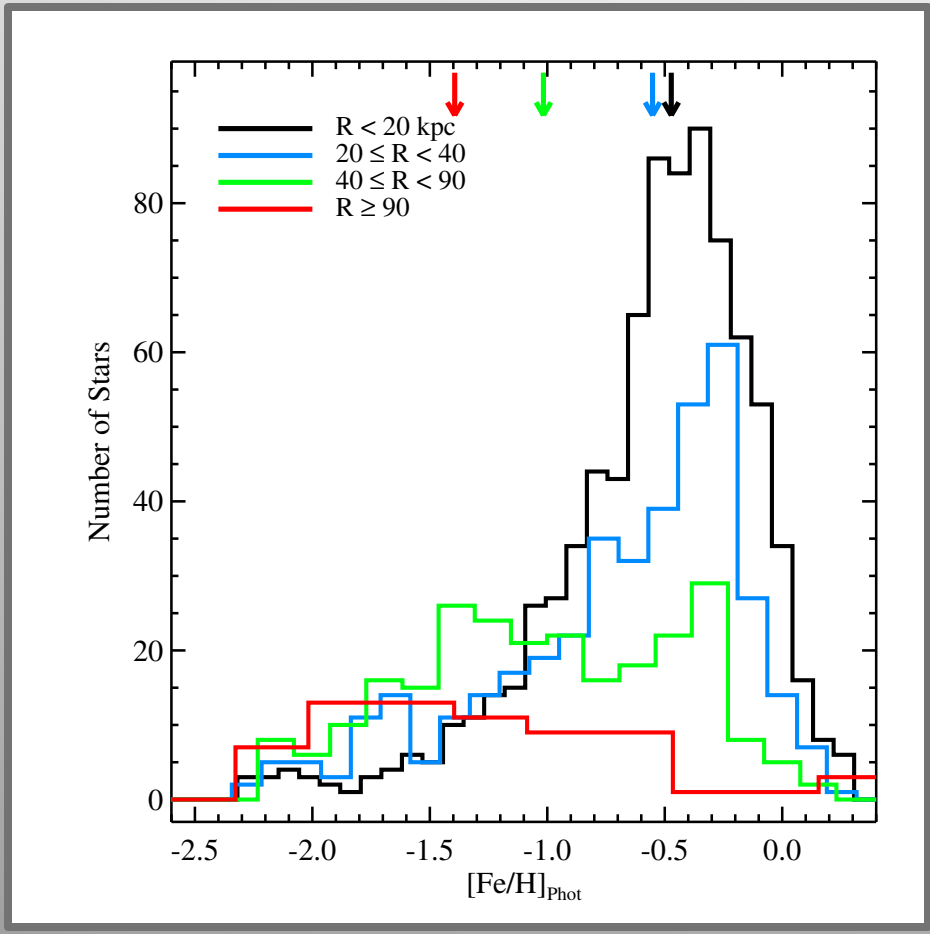
Spectroscopy enables us to identify a sample of more than 1500 M31 Halo Stars.

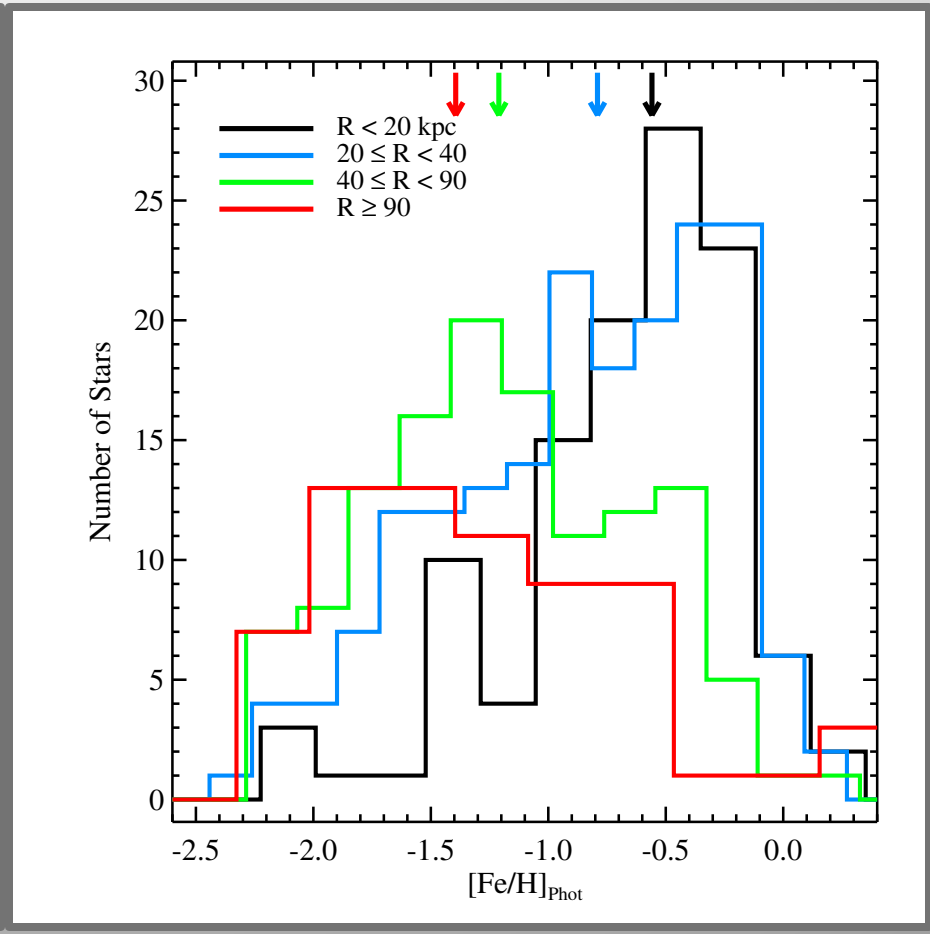



*Gilbert et al. 2014*

# Metallicity vs. Radius

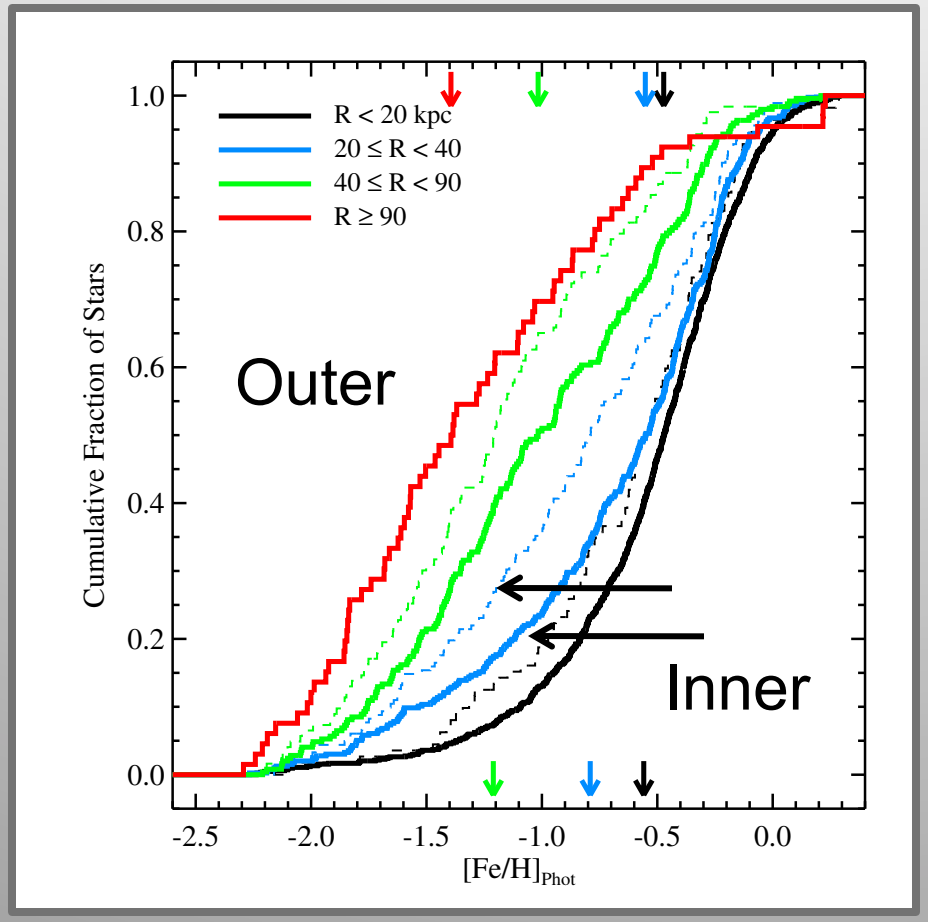


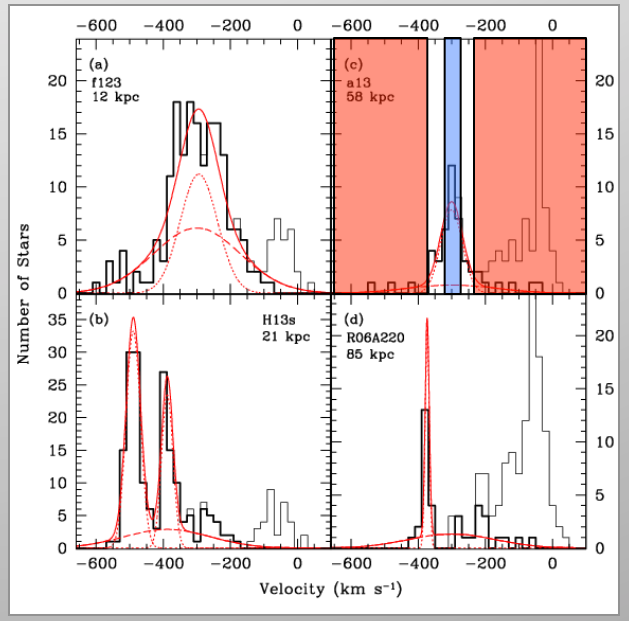




[Fe/H] ➡

*Gilbert et al. 2014*

# Metallicity vs. Radius

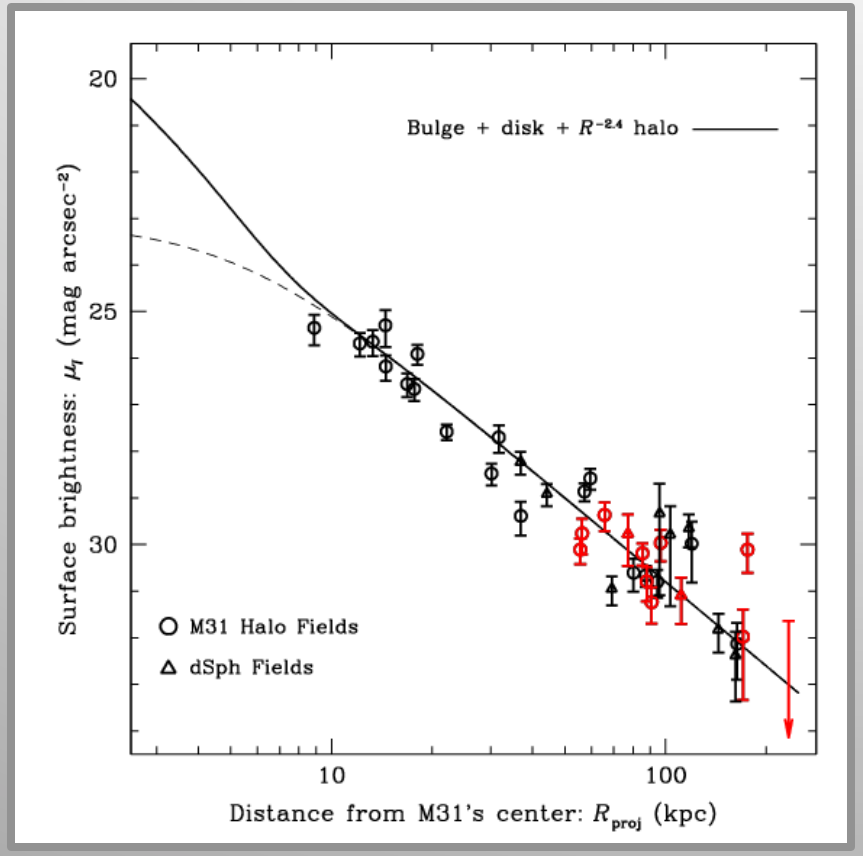


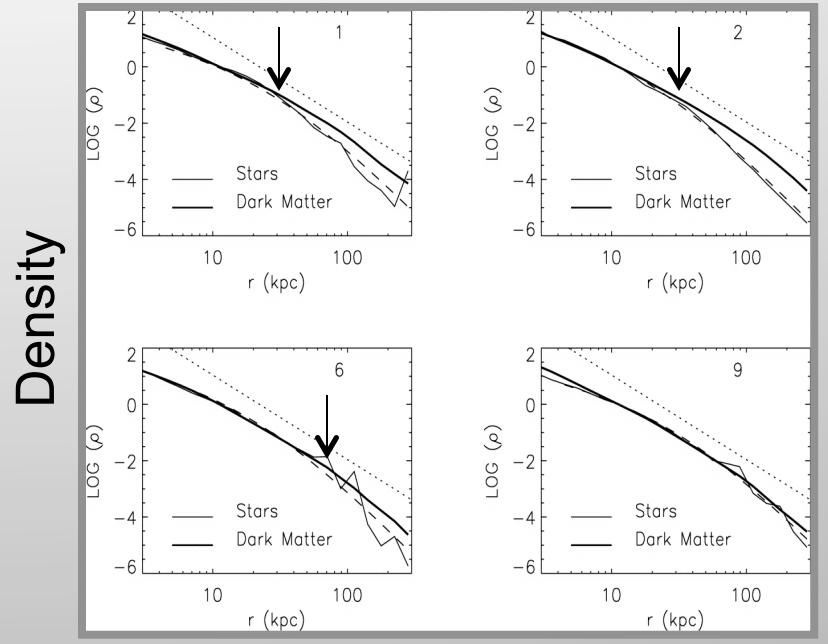




[Fe/H] ➡

*Gilbert et al. 2014*

# Global Properties of M31's Halo: Implications for M31's Merger History



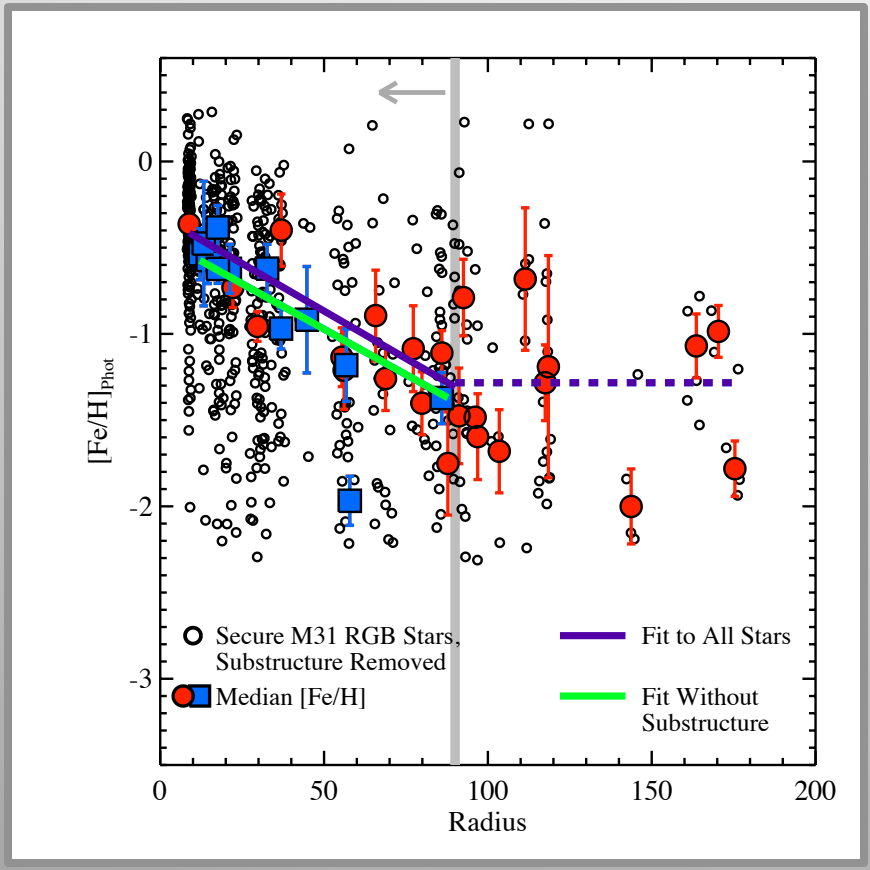

**Observed: Lack of break in density profile, Increased variation at large radii**

*Implication: Large number of recent low-mass accretions at large radii*

*Gilbert et al. 2012*

*Bullock & Johnston (2005) models*

# Global Properties of M31's Halo: Implications for M31's Merger History




**Observed: Significant metallicity gradient to large radii, even after removal of GSS**

*Implication: M31 halo built largely from one to a few early, relatively massive (>$10^9$ $M_{sun}$) accretion events*

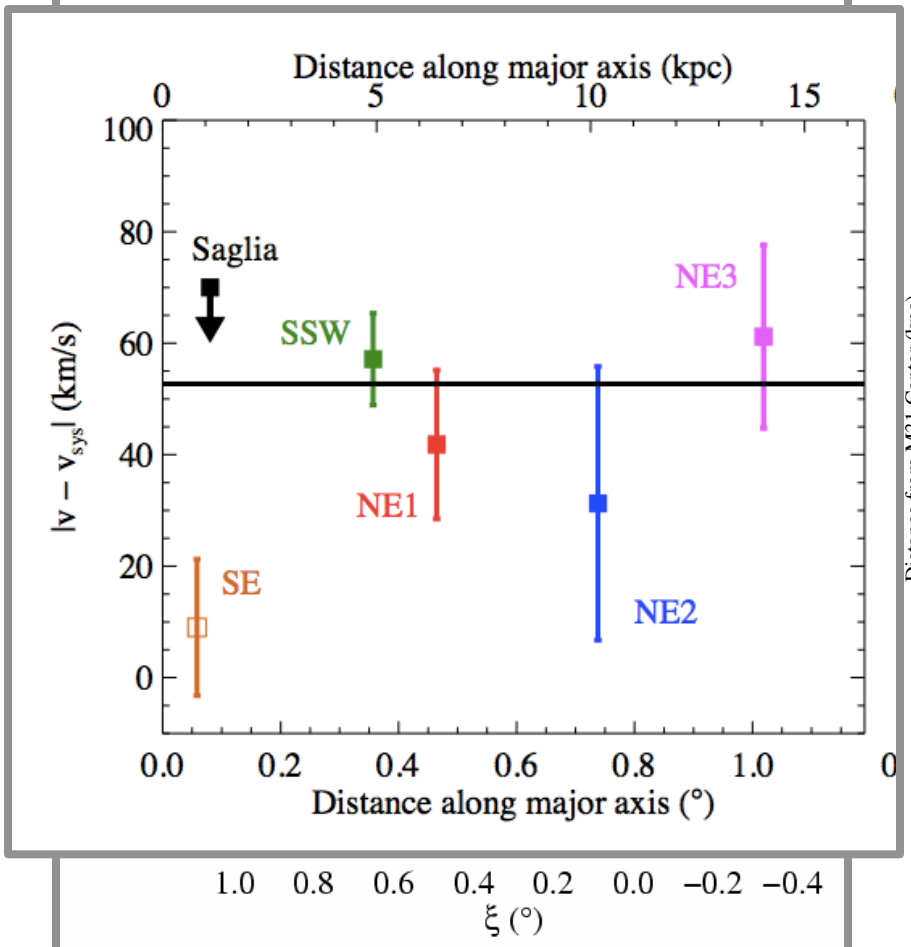
*Tissera 2014, Cooper 2010*

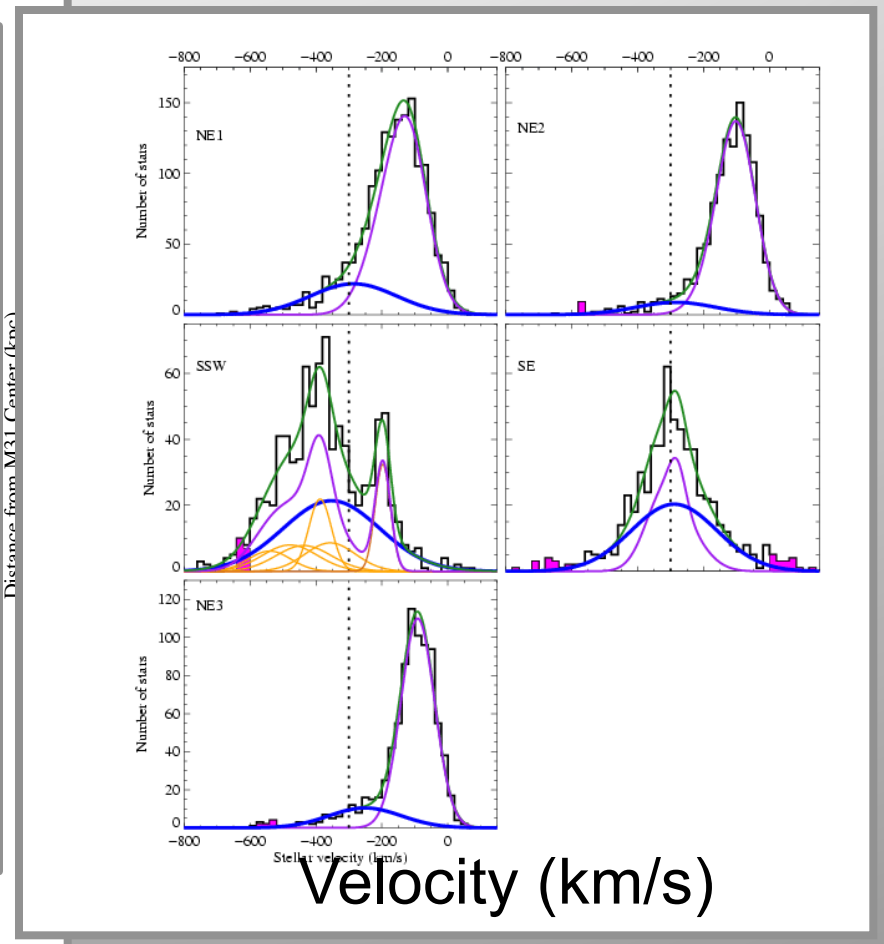
*Gilbert et al. 2012, 2014*

# Evidence for an In Situ Halo Component

Kinematics of M31's Disk and Inner Halo

***Significant rotation of the halo about M31's center***

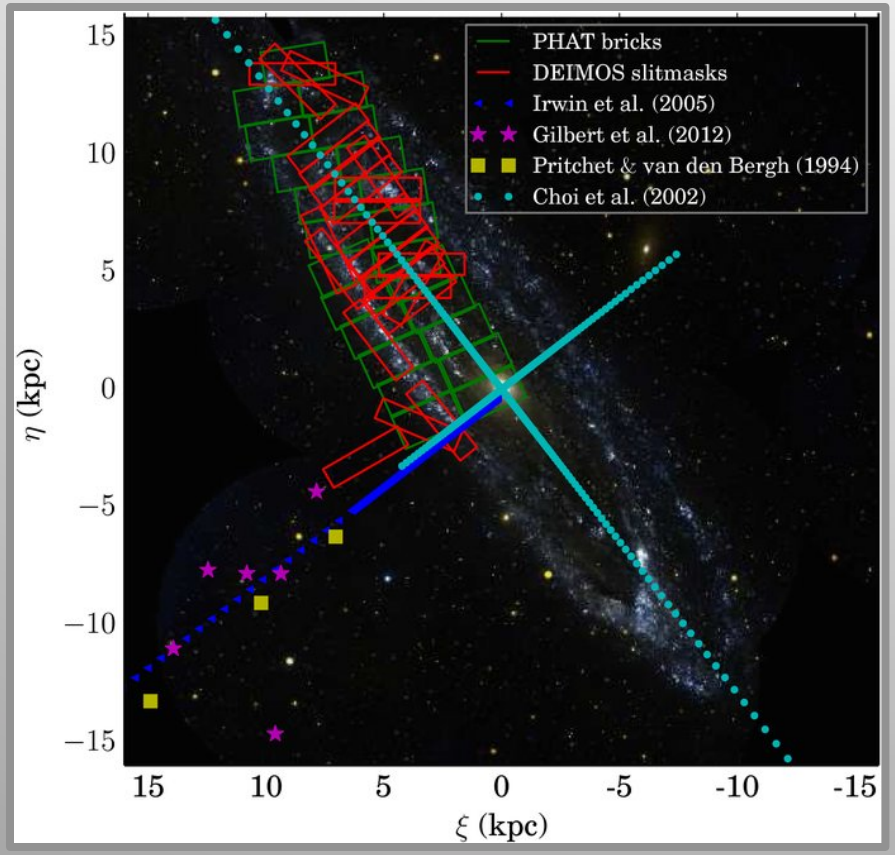


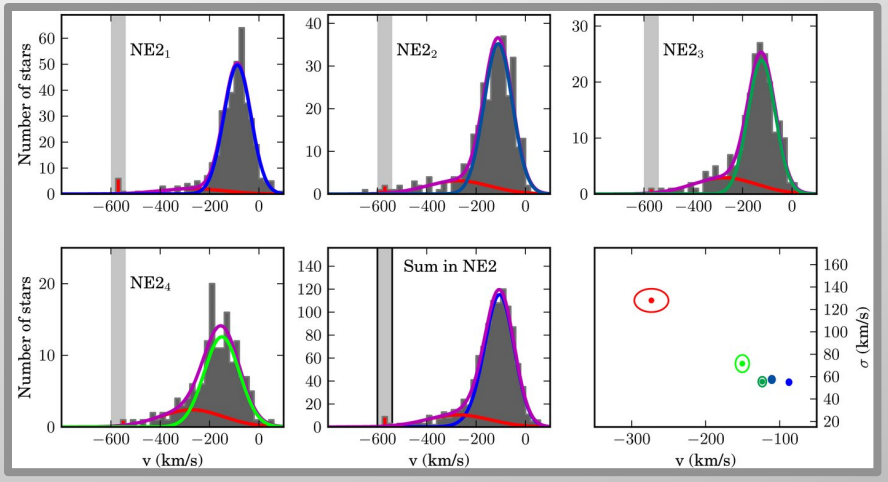



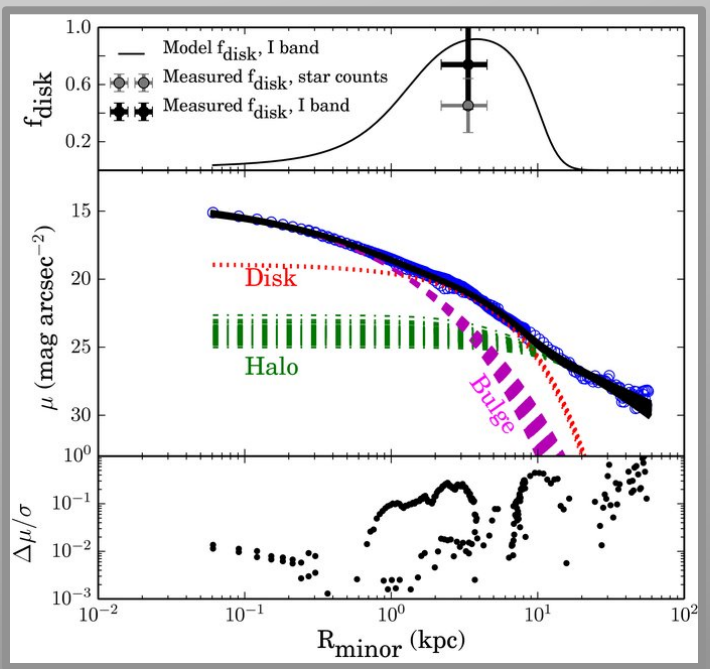

*Dorman et al. 2012*

# Evidence for an In Situ Halo Component

Modeling M31's Structural Components from 4 kpc: Kinematics, Luminosity Function of Resolved Stars, and Unresolved Surface Photometry



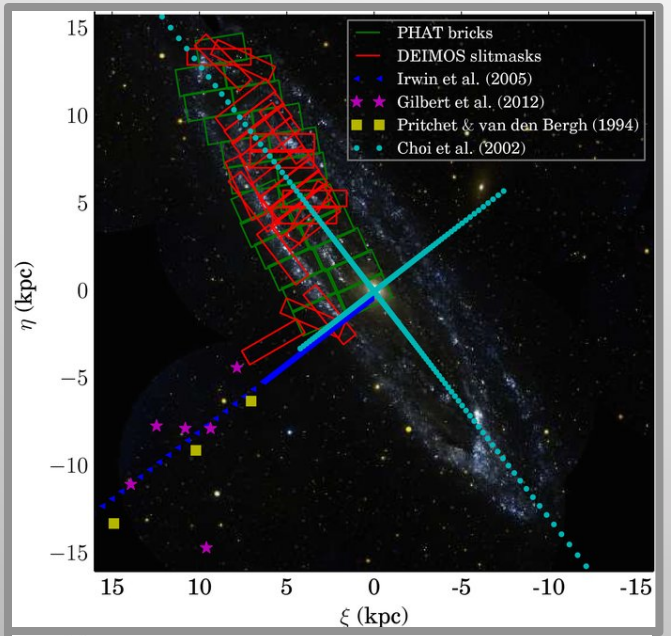



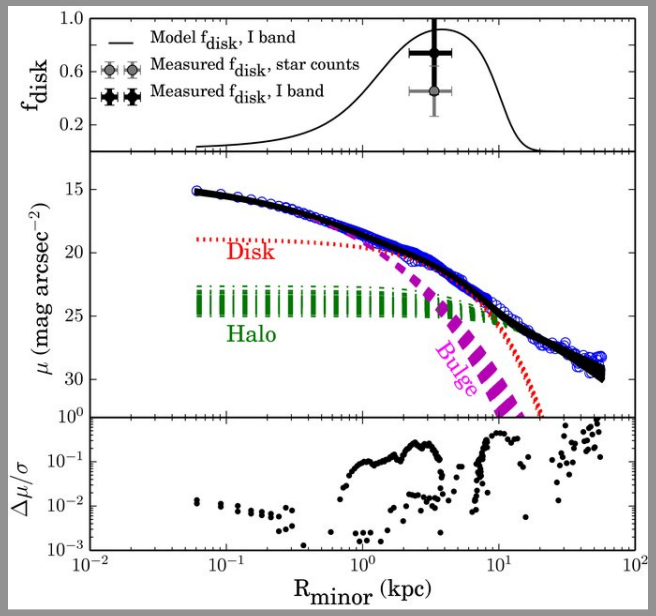

Spectra of > 5000 M31 Stars

Luminosity Function of > 1.5 Million M31 Stars

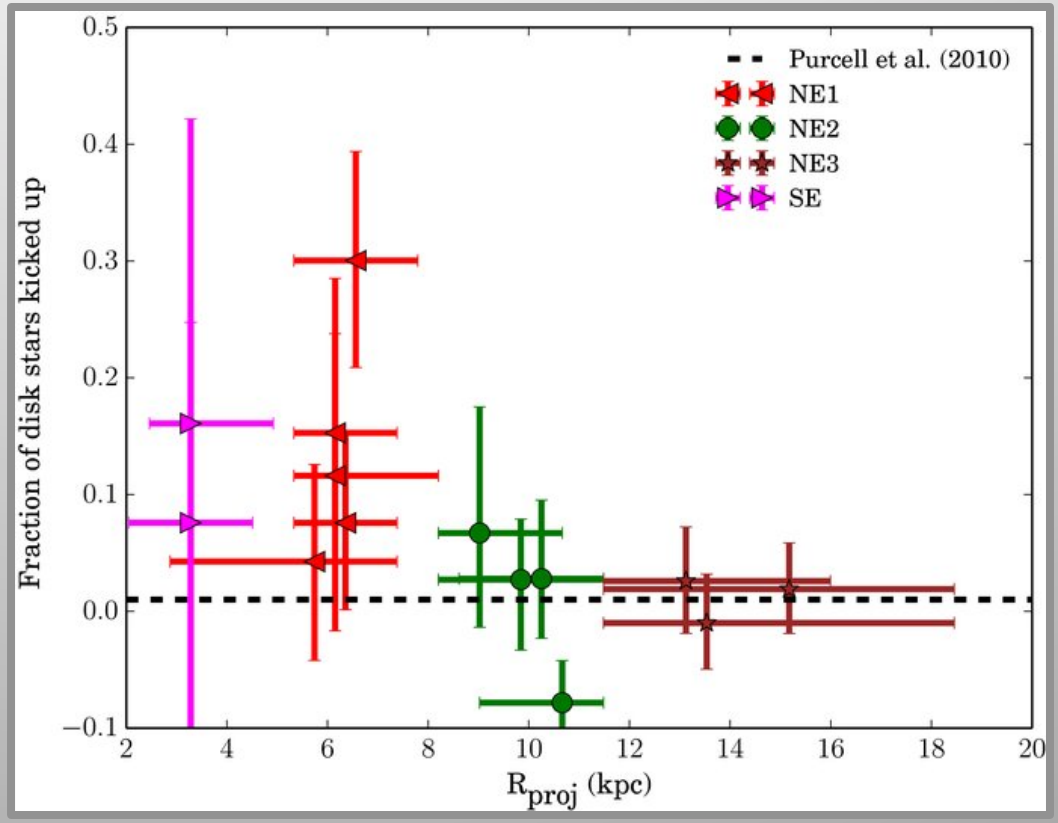
***Dorman et al. 2013***

# Evidence for an In Situ Halo Component



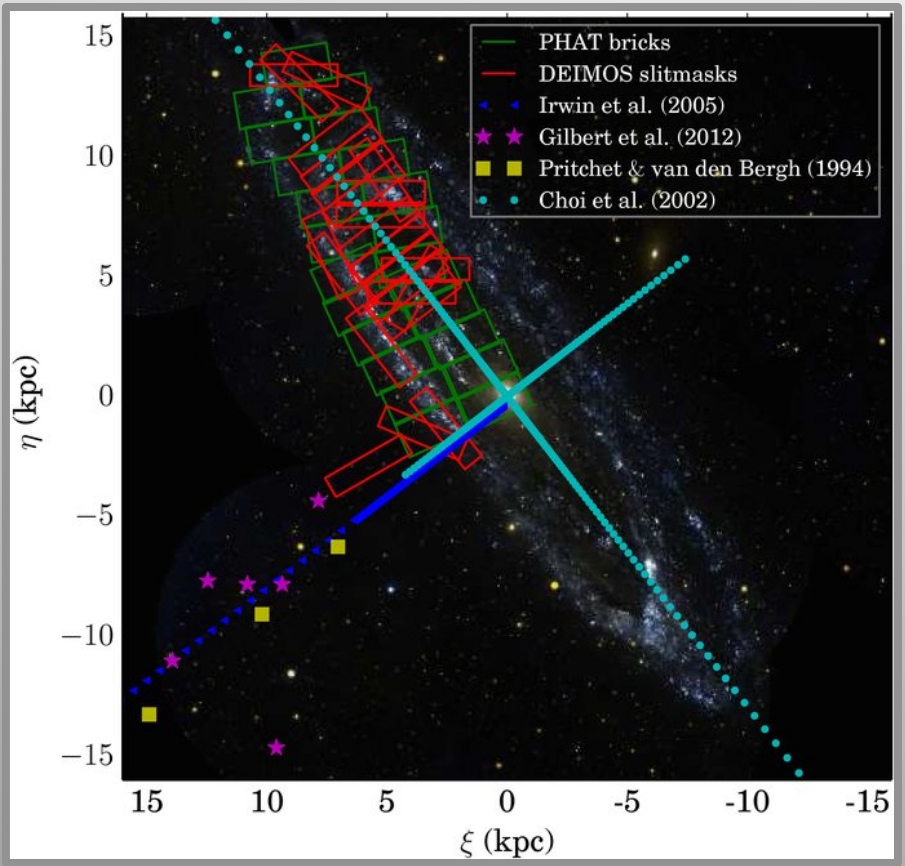




Evidence for disk stars with spheroid-like kinematics.




*Dorman et al. 2013*

# Evidence for an In Situ Halo Component

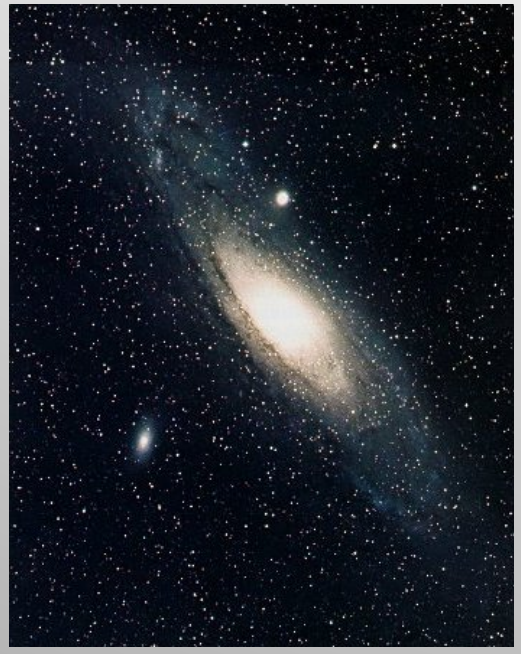



**Observed: Stars with spheroid-like kinematics and a disk-like luminosity function. Significant rotation in inner spheroid.**

*Implication: Inner region of M31's halo has a significant population of stars that once belonged to the disk.*

*Dorman et al. 2013*

# Tidal Debris in the Andromeda Galaxy



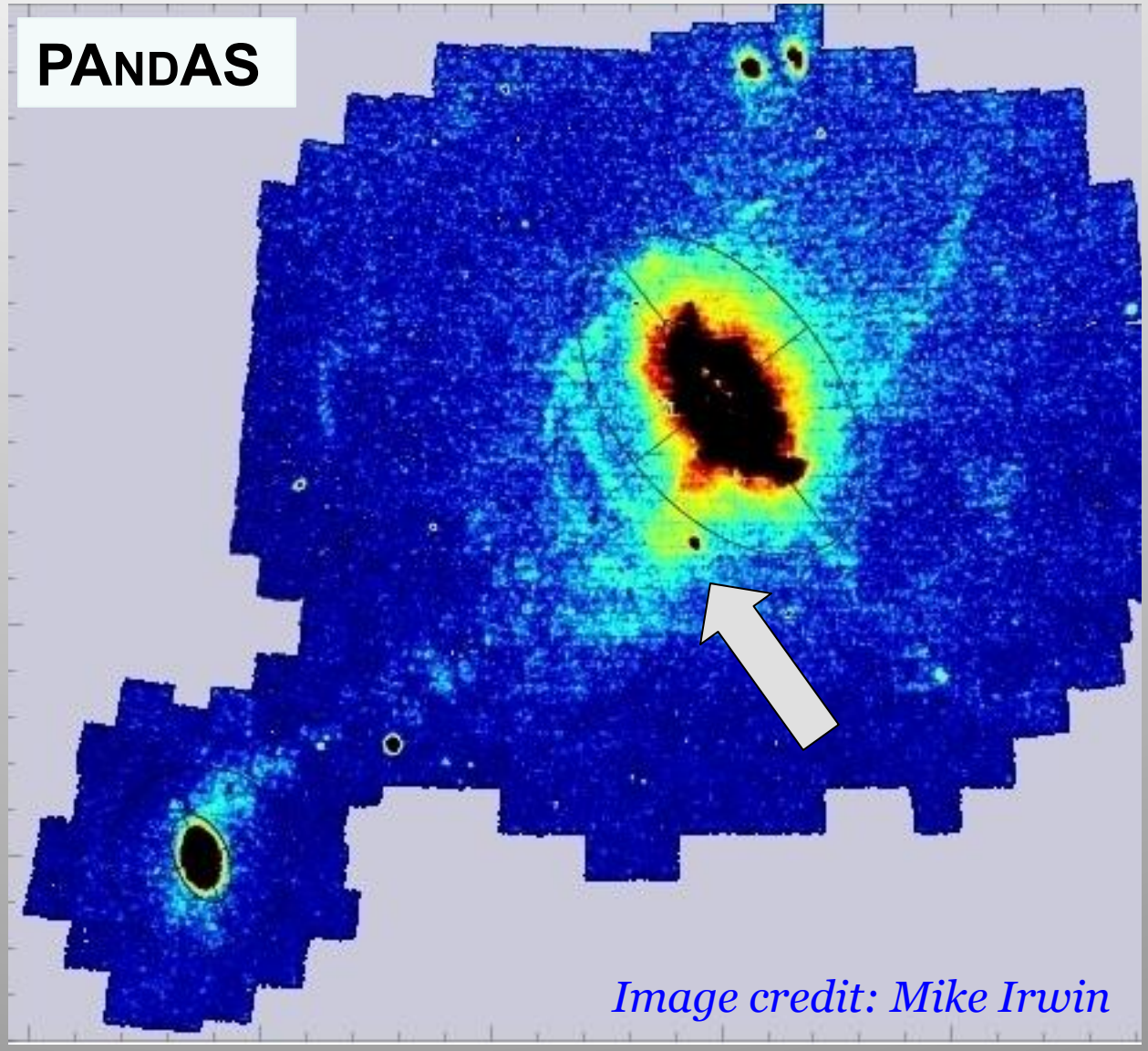
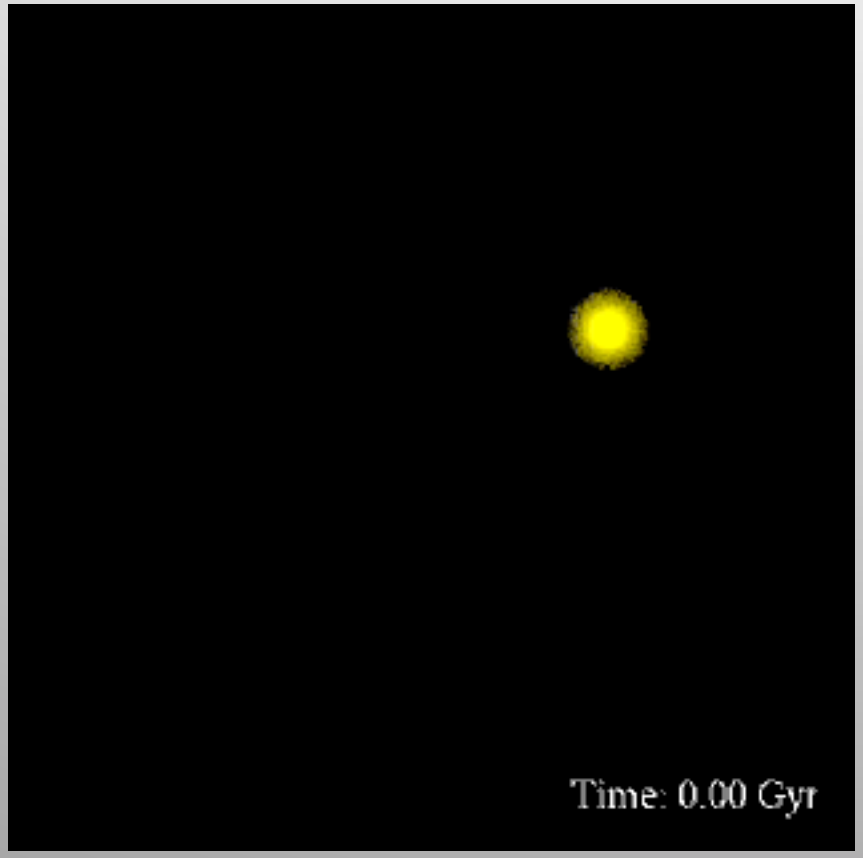


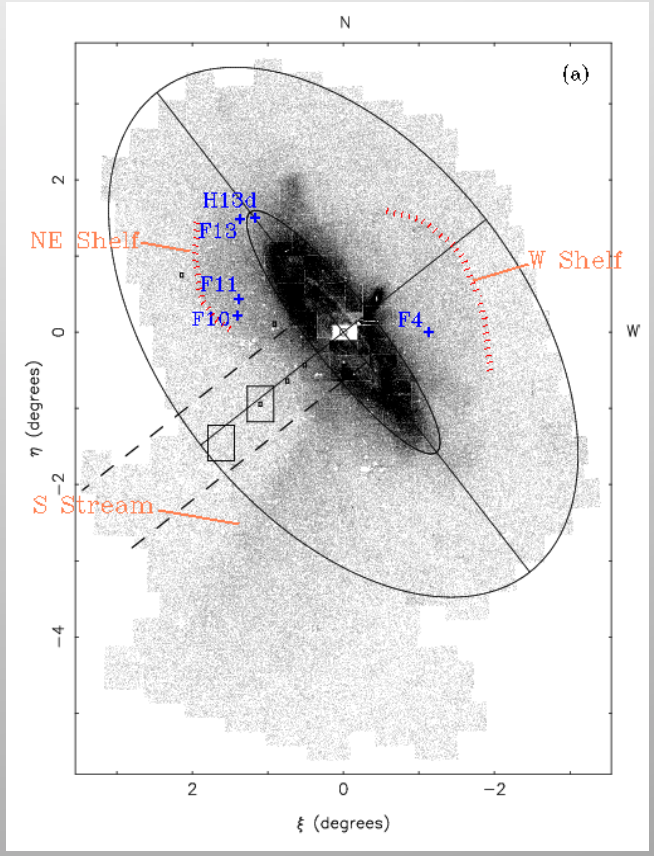

*Image credit: Mike Irwin*

*McConnachie et al. 2009*

# The Merger of a Dwarf Galaxy with Andromeda



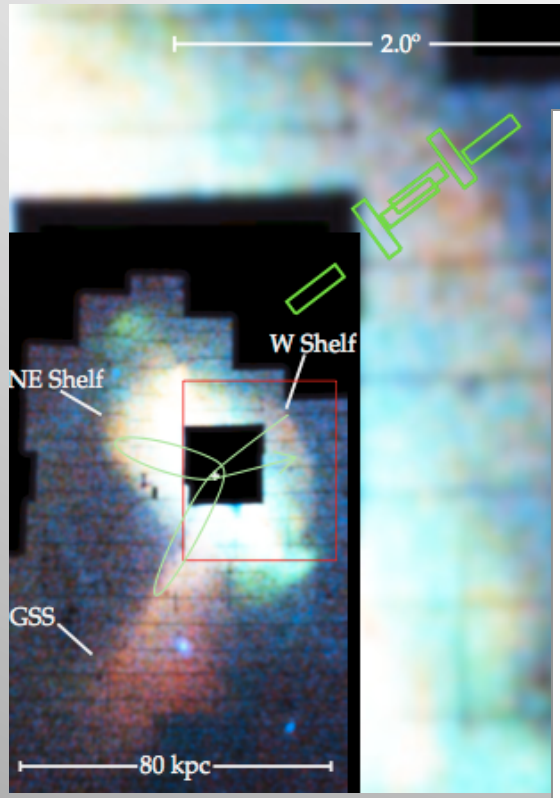

*Fardal et al. 2007, MNRAS*



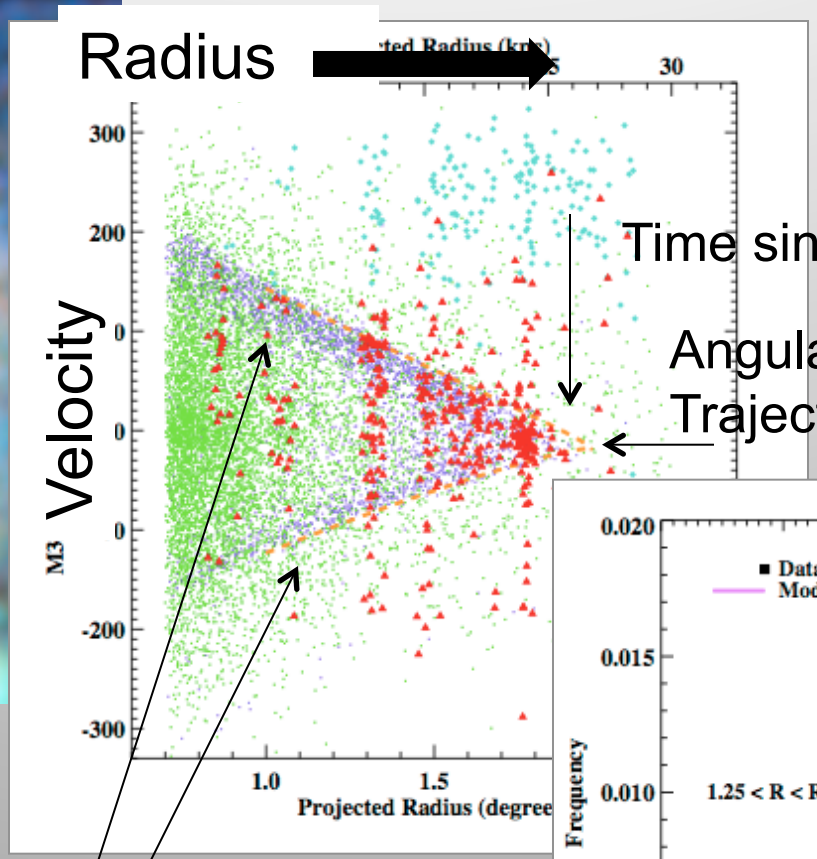

*Ferguson et al. 2002, AJ*

# Detailed Dissection of Past Collision Events

## What Can This Exercise Teach Us?

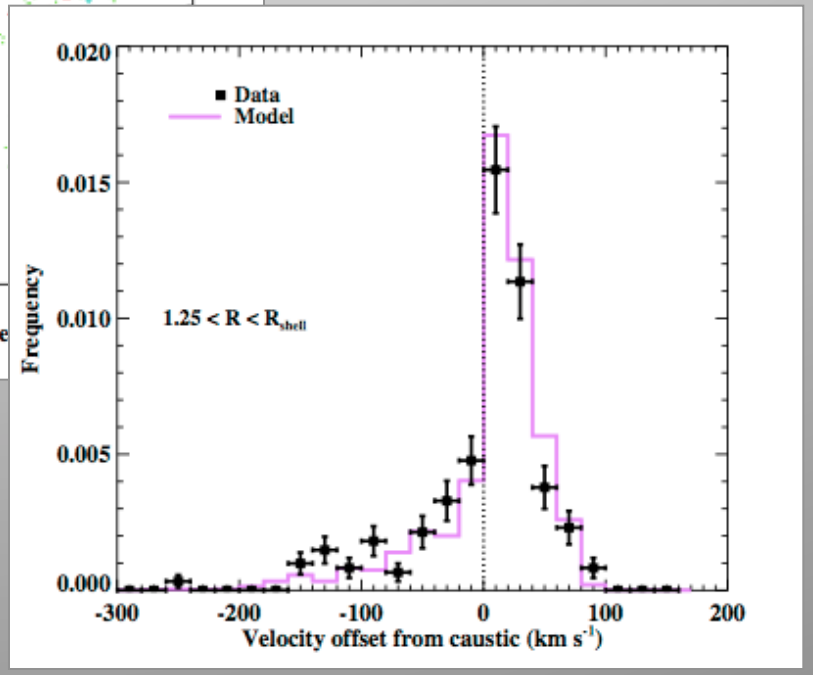



*Fardal et al. 2012*




Time since collision

Angular momentum of stars:
Trajectory of progenitor

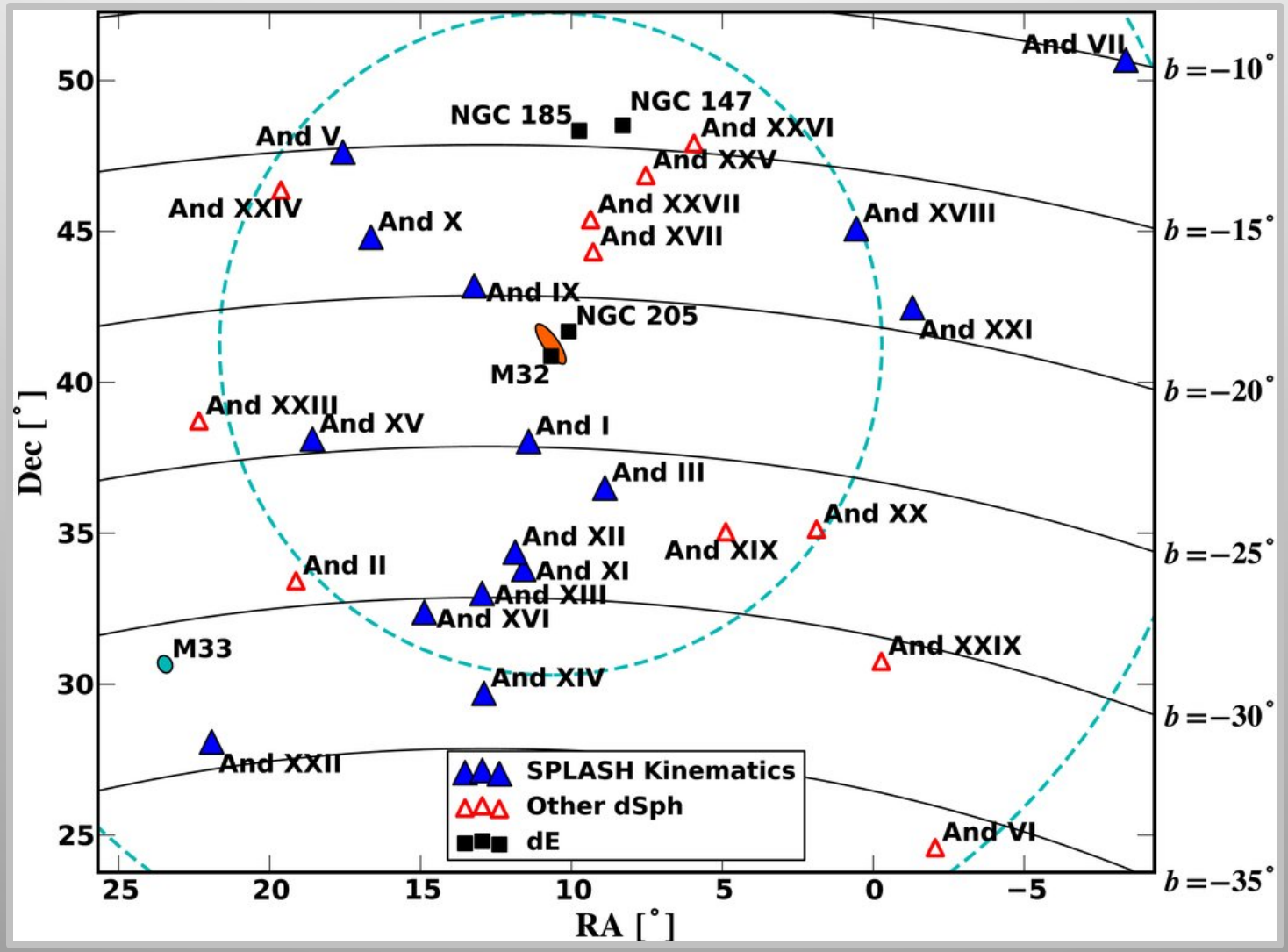



Ratio of stars: density gradient along stream

log(M200) = 12.3 +/- 0.1

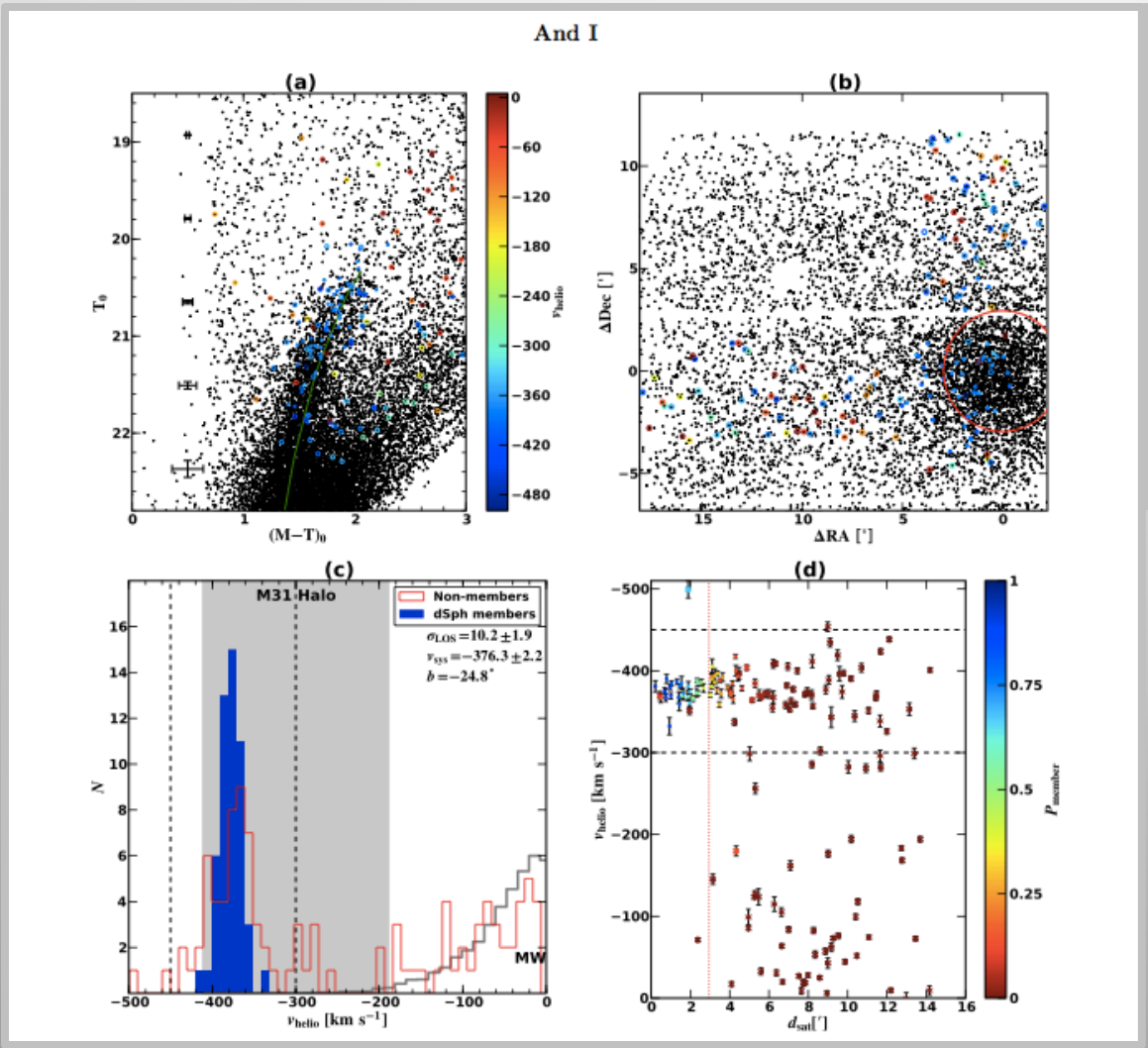
*Fardal et al. 2013*

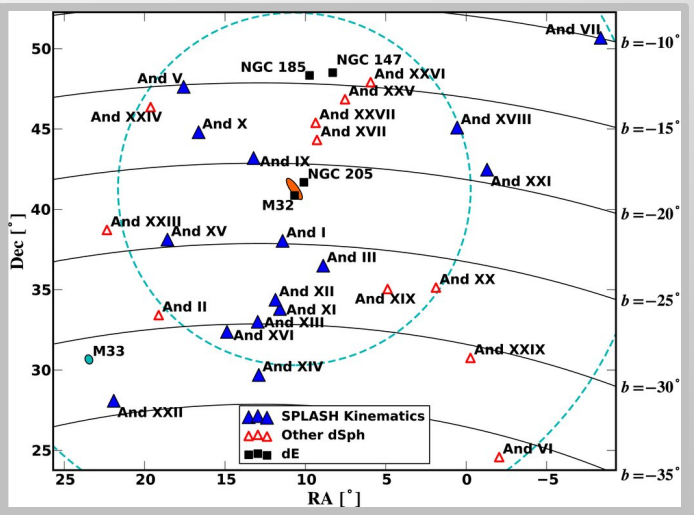
# M31 Dwarf Satellites




*Tollerud et al. 2012*

# 15 M31 Dwarf Satellites

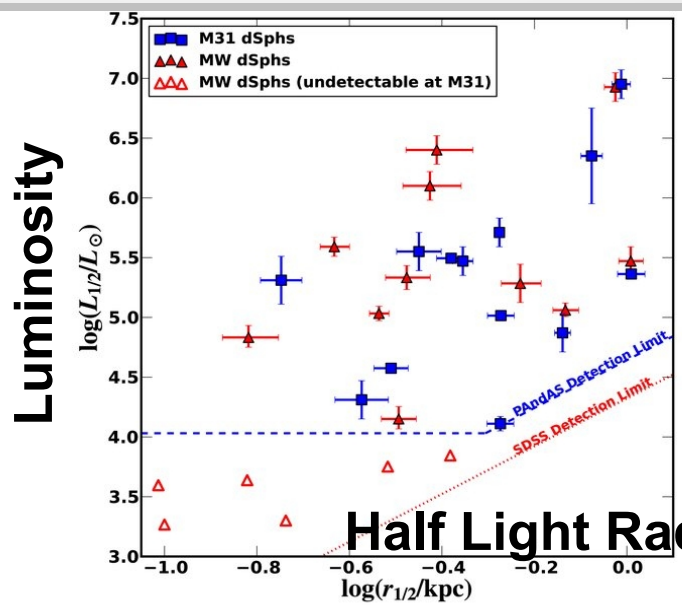


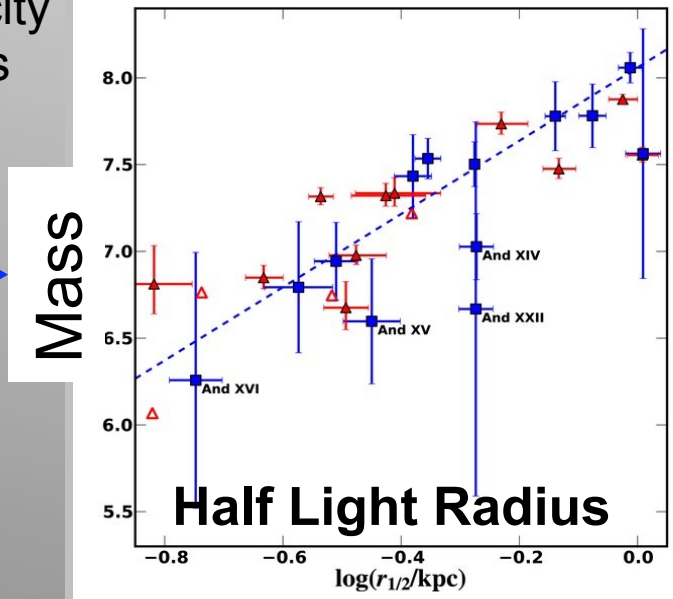

Confirmed kinematics of And XVIII, XXI, and XXII consistent with bound, dark matter dominated galaxies

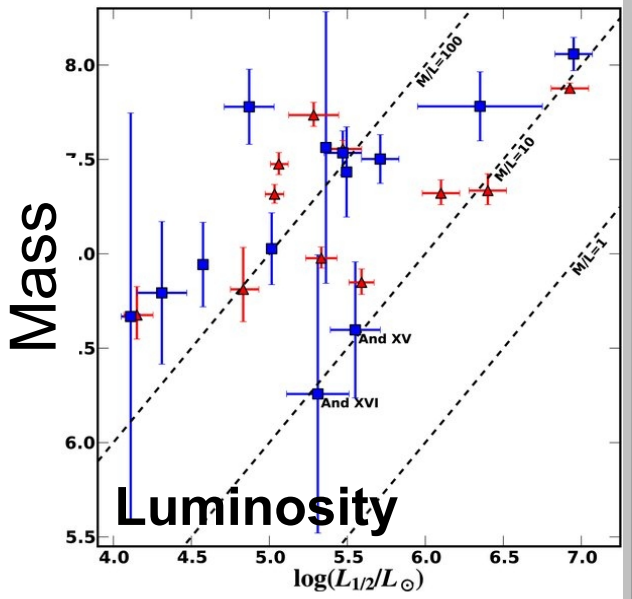
*Tollerud et al. 2012*

# M31 vs. MW: Dwarf Satellites




From Velocity Dispersions

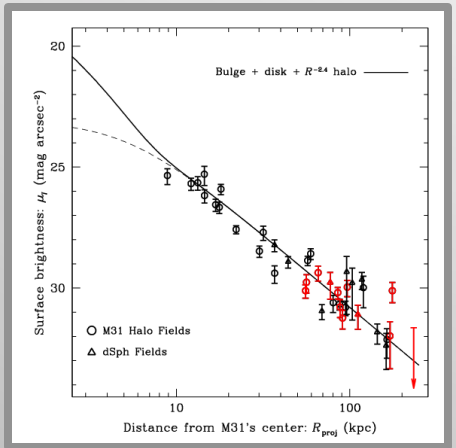


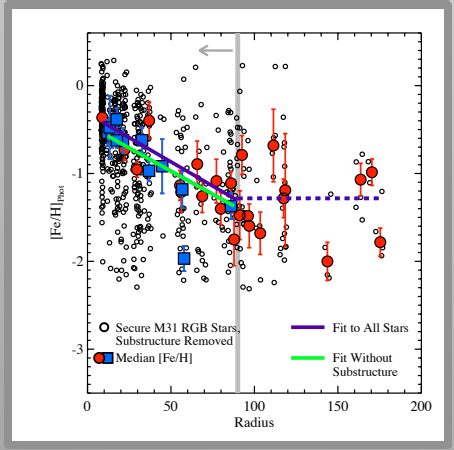




*Tollerud et al. 2011*

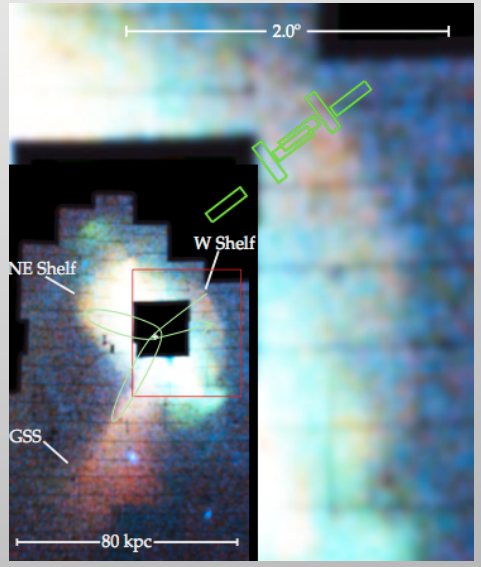
# M31 halo as a microcosm of the destroyed dwarf galaxy population

# Formation History of Andromeda's Stellar Halo



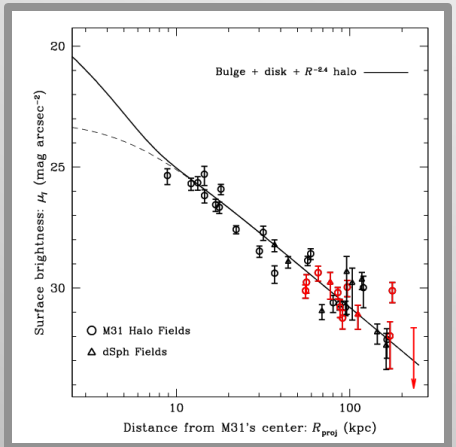



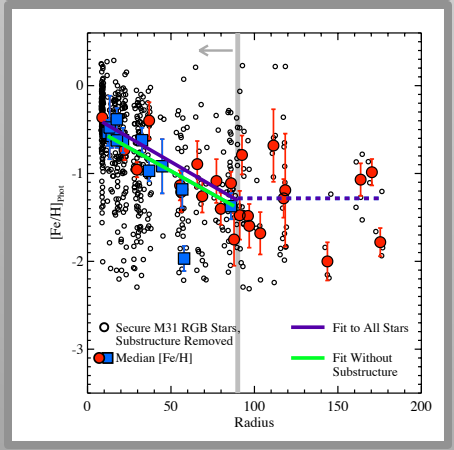

Global halo Properties



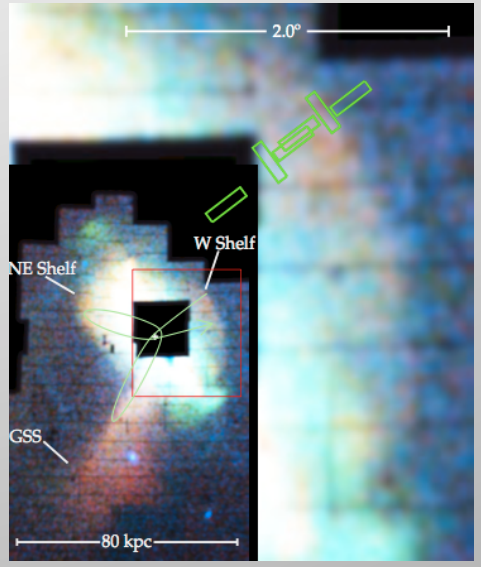

Large, recent tidal debris features

# Formation History of Andromeda's Stellar Halo



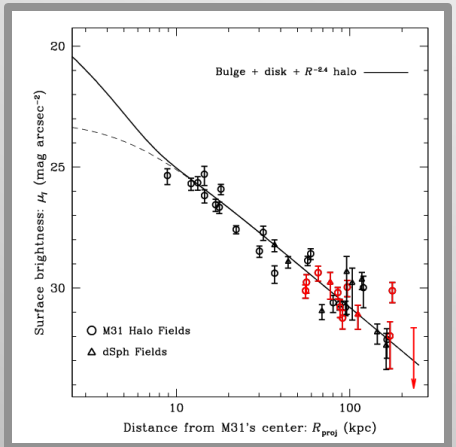

- Accretion History Profile
- Relative importance of accreted and in situ populations

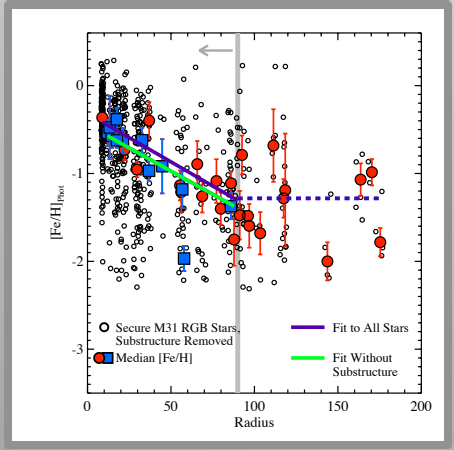



- ~ LMC sized system
- Collided 760 Myr ago

- Early, relatively massive accretion events
- Large numbers of recent low-mass accretions

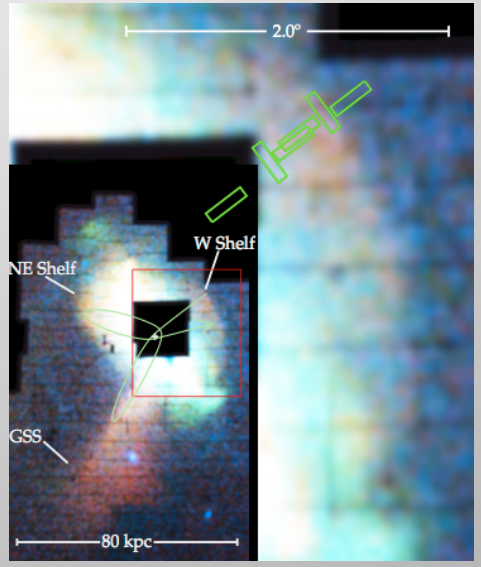
# Formation History of Andromeda's Stellar Halo




**Accretion History Profile**

Mass, Time of Accretion of Accreted Satellites




- ~ LMC sized system
- Collided 760 Myr ago

- Early, relatively massive accretion events
- Large numbers of recent low-mass accretions

# Deducing Properties of Destroyed Satellites

Surface Brightness of stellar streams is easily observed…

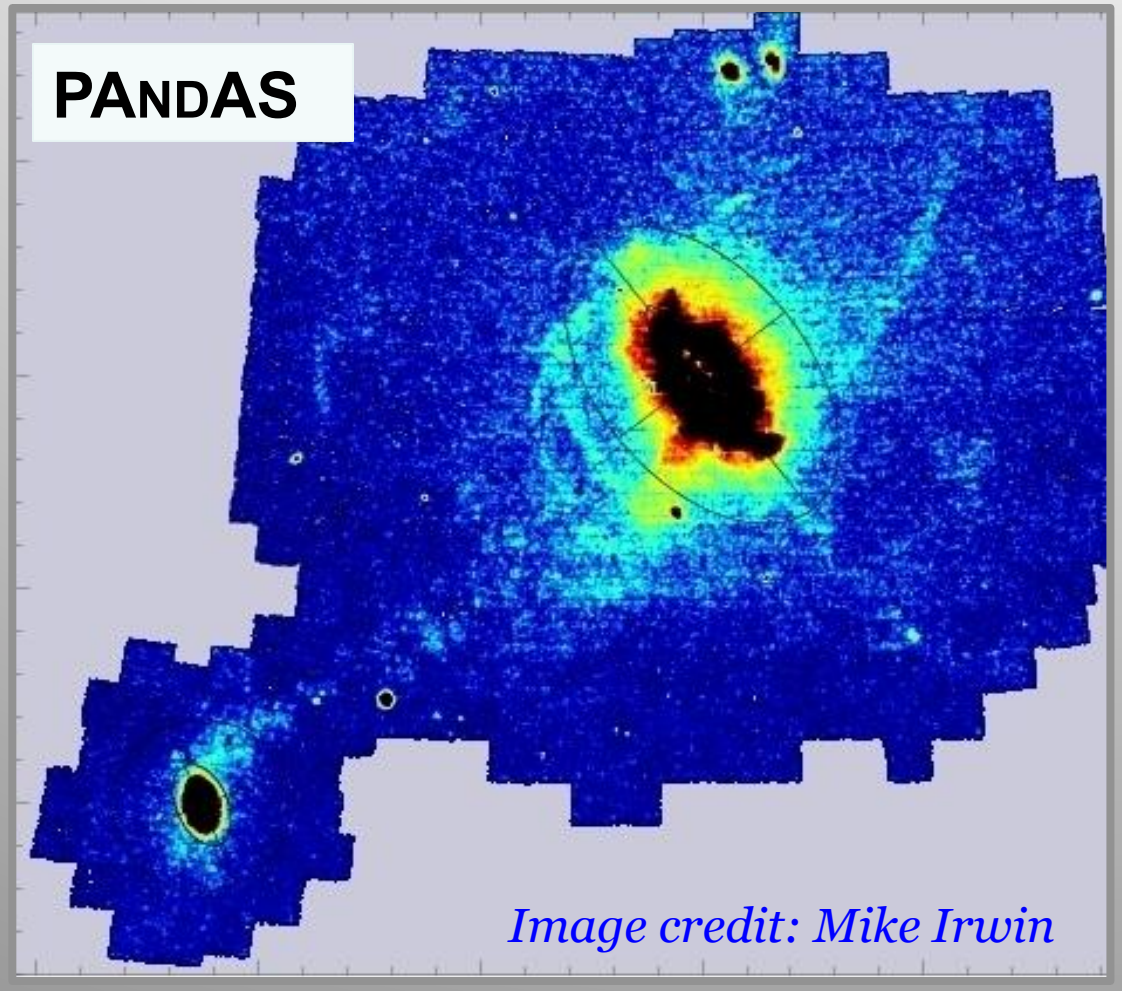
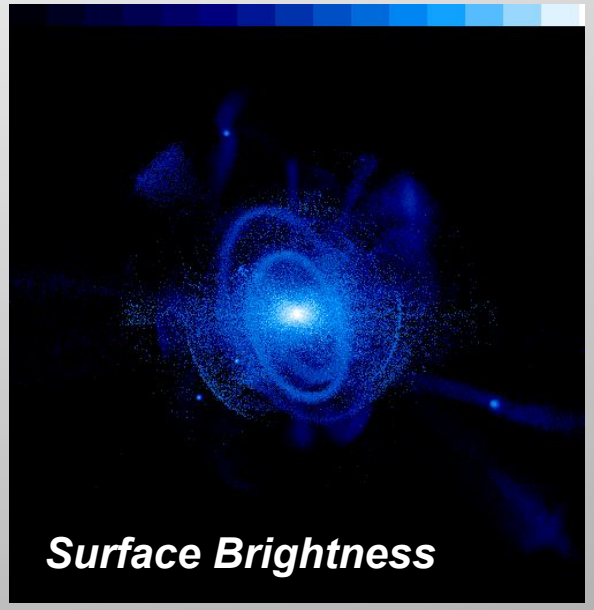



*Image credit: Mike Irwin*

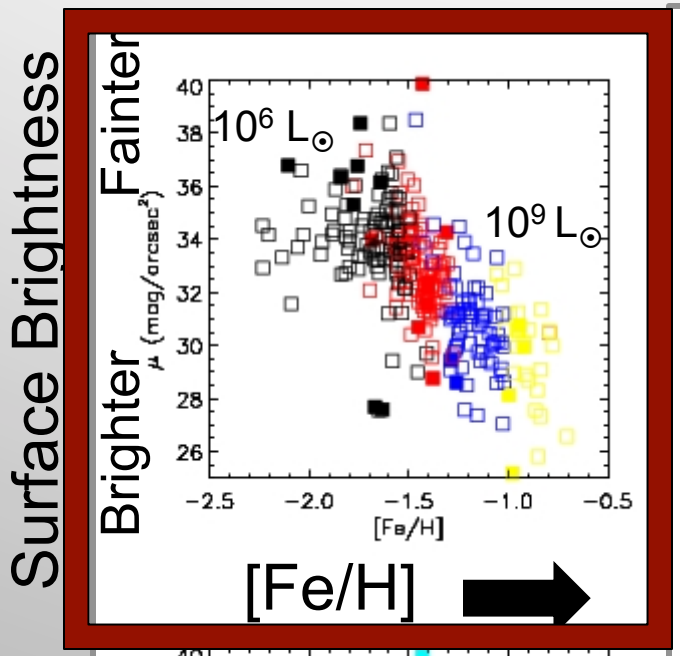
*McConnachie et al. 2009*

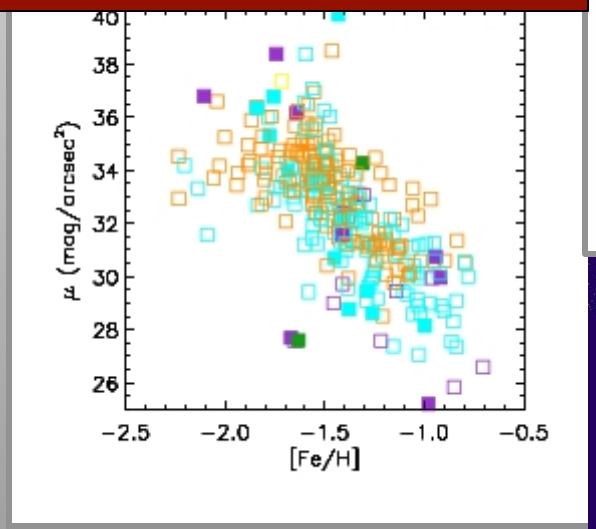


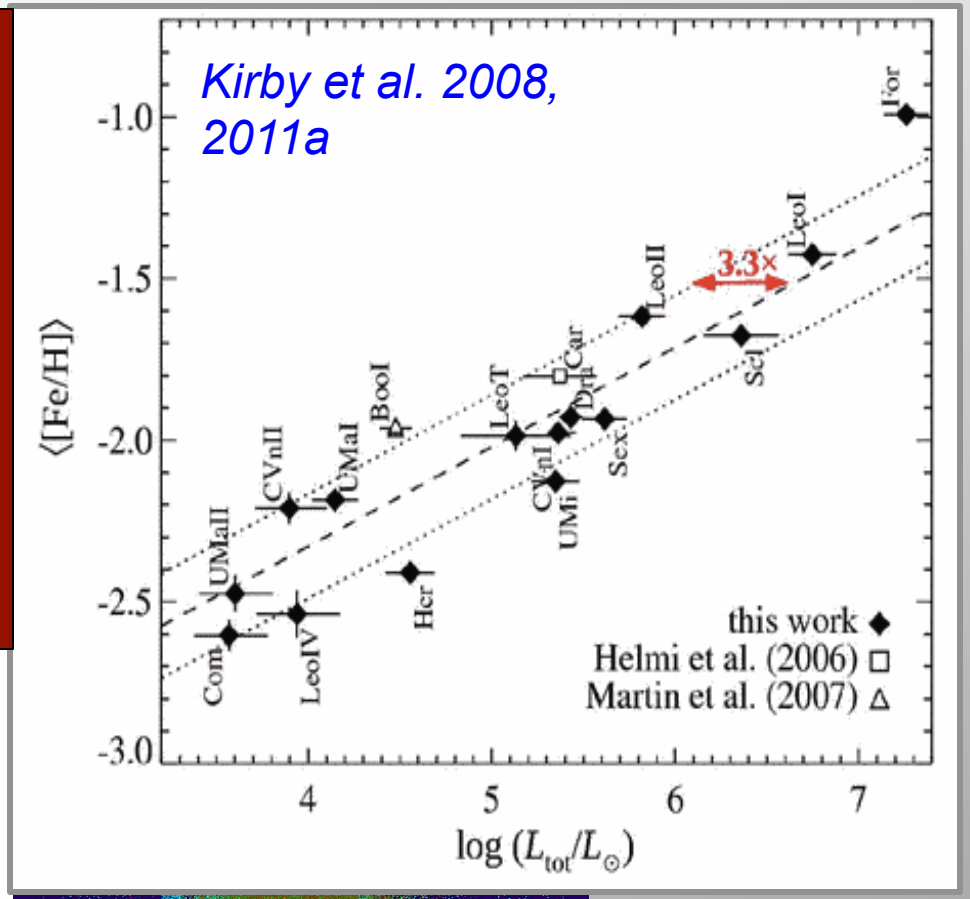

*Bullock & Johnston (2005) models*

**But depends on luminosity of accreted satellite *and* time since accretion.**

# Deducing Properties of Destroyed Satellites



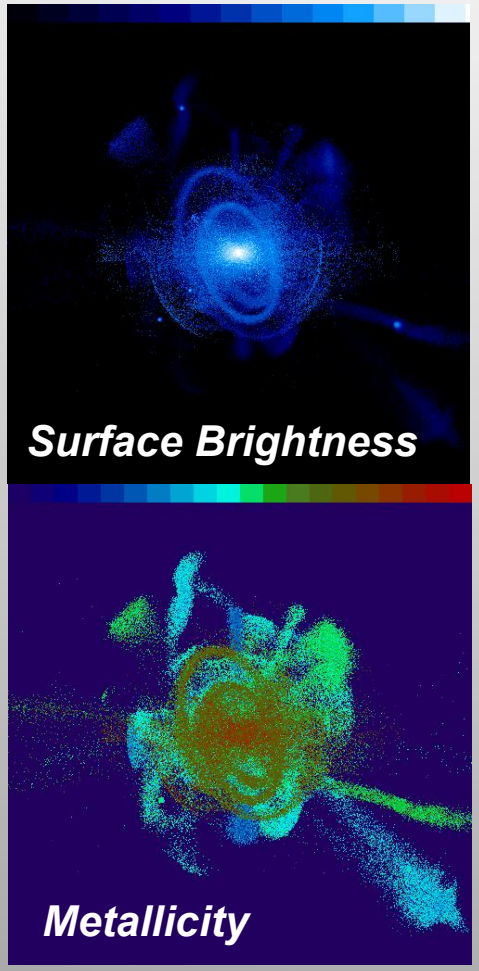



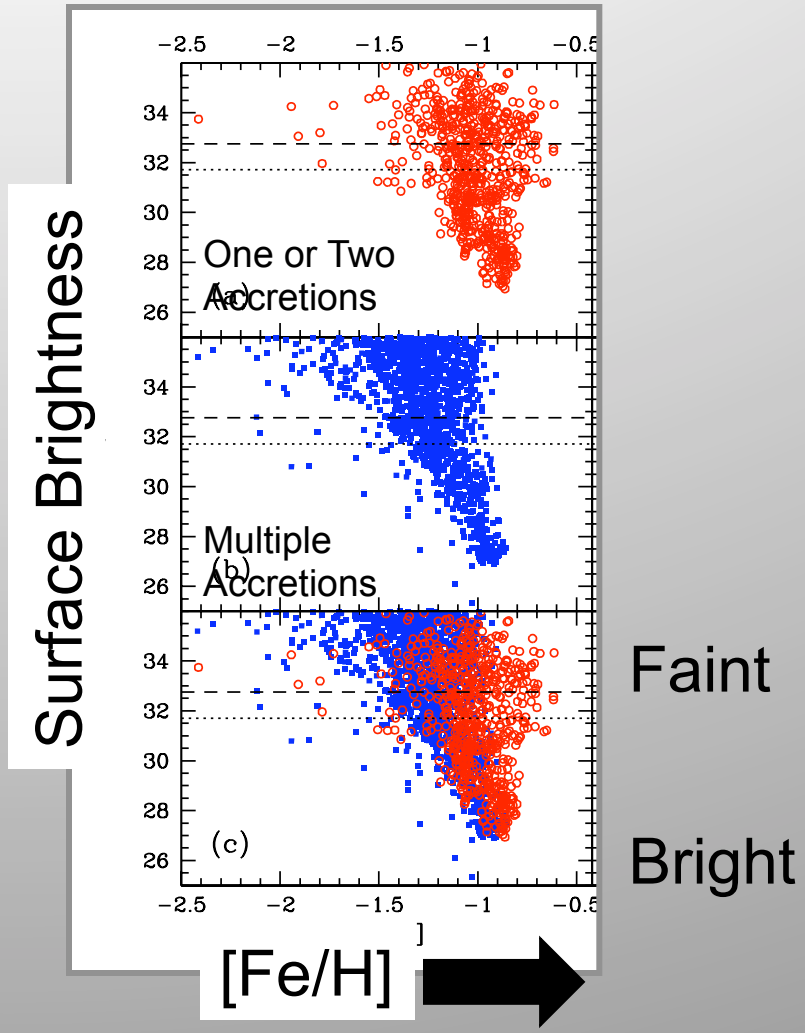





*Johnston et al. 2008, Gilbert et al. 2009*
*Bullock & Johnston (2005) models*

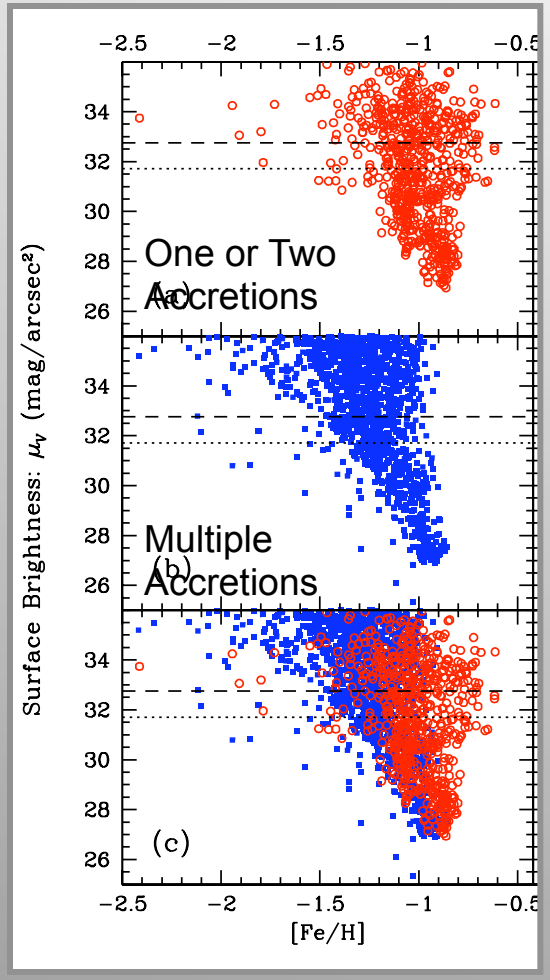
# Deducing Properties of Destroyed Satellites



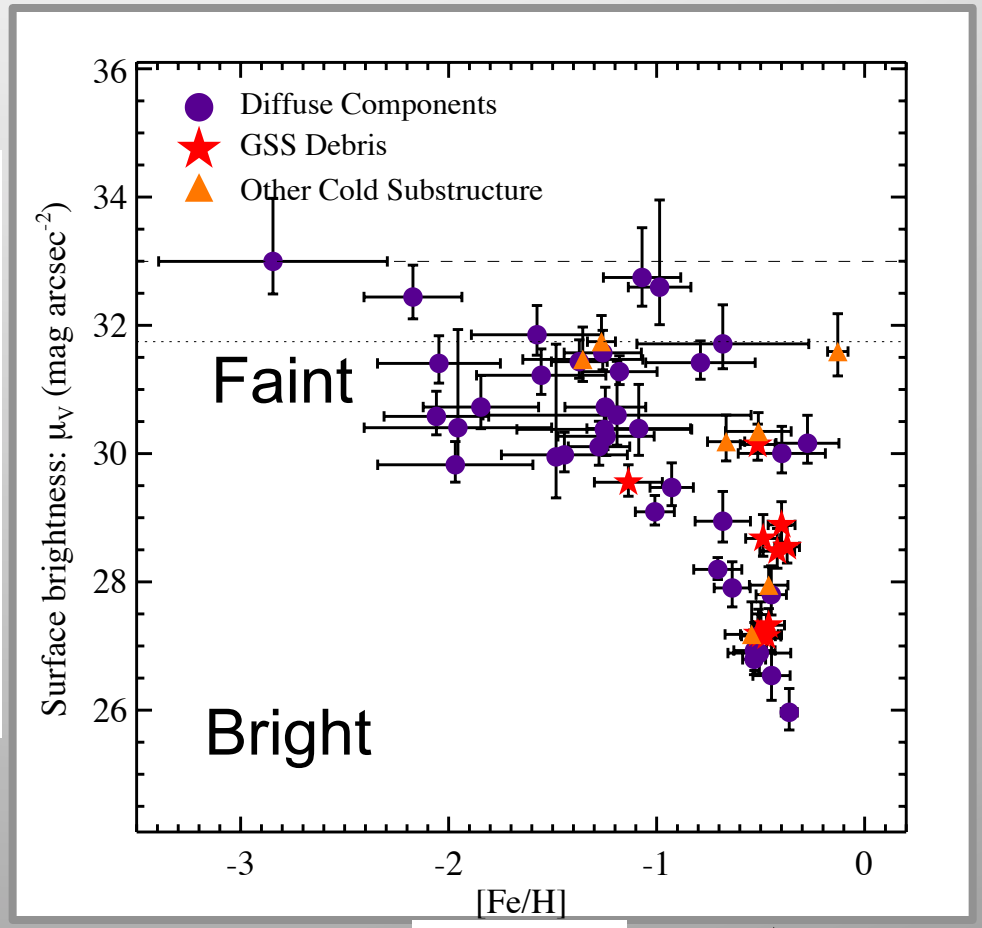

*Bullock & Johnston (2005) models*
*Robertson et al. 2005, Font et al. 2006*
*Gilbert et al. 2009*

# Deducing Properties of Destroyed Satellites
## *Comparing Simulations and Observations*




*Bullock & Johnston (2005) models*
*Robertson et al. 2005, Font et al. 2006, Gilbert et al. 2009*

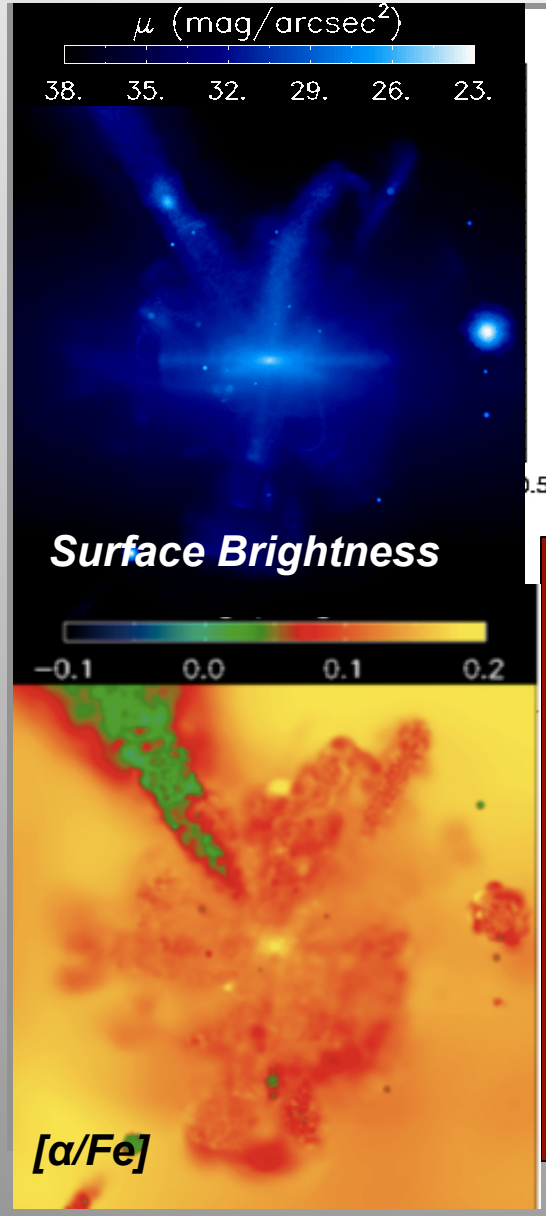
Surface Brightness

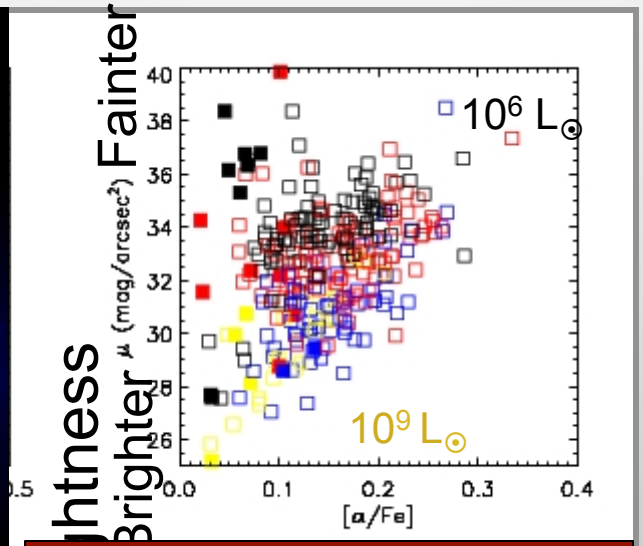


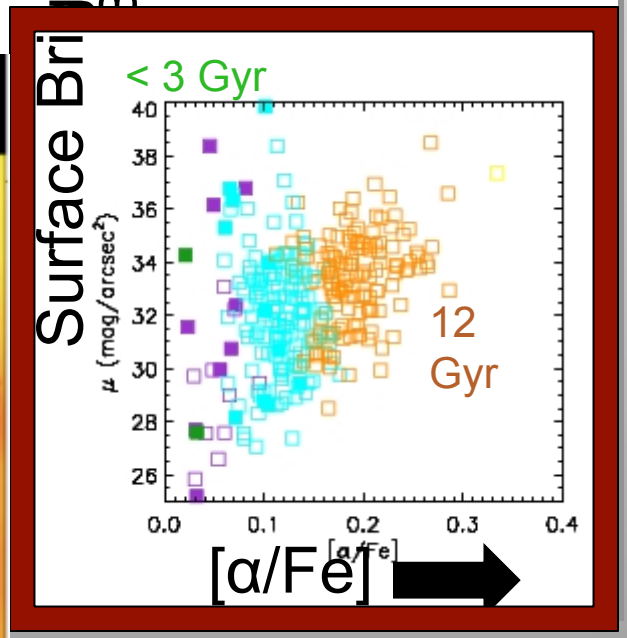

[Fe/H] →

*Gilbert et al. 2014*
*Gilbert et al. (2009)*

# Deducing Properties of Destroyed Satellites



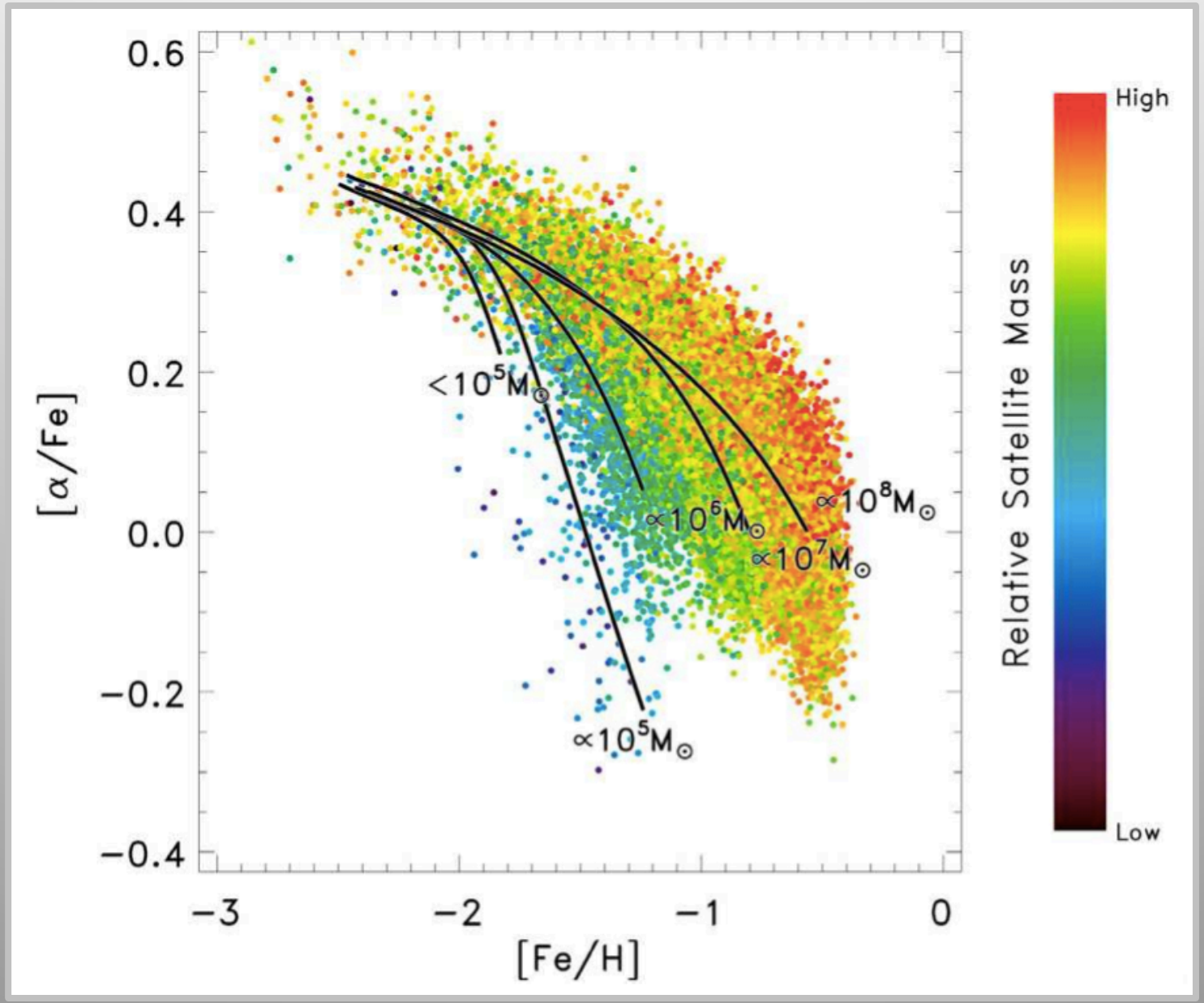

First Star Formation

Type II SNe – α elements

Time passes….

Type 1 SNe

# Deducing Properties of Destroyed Satellites

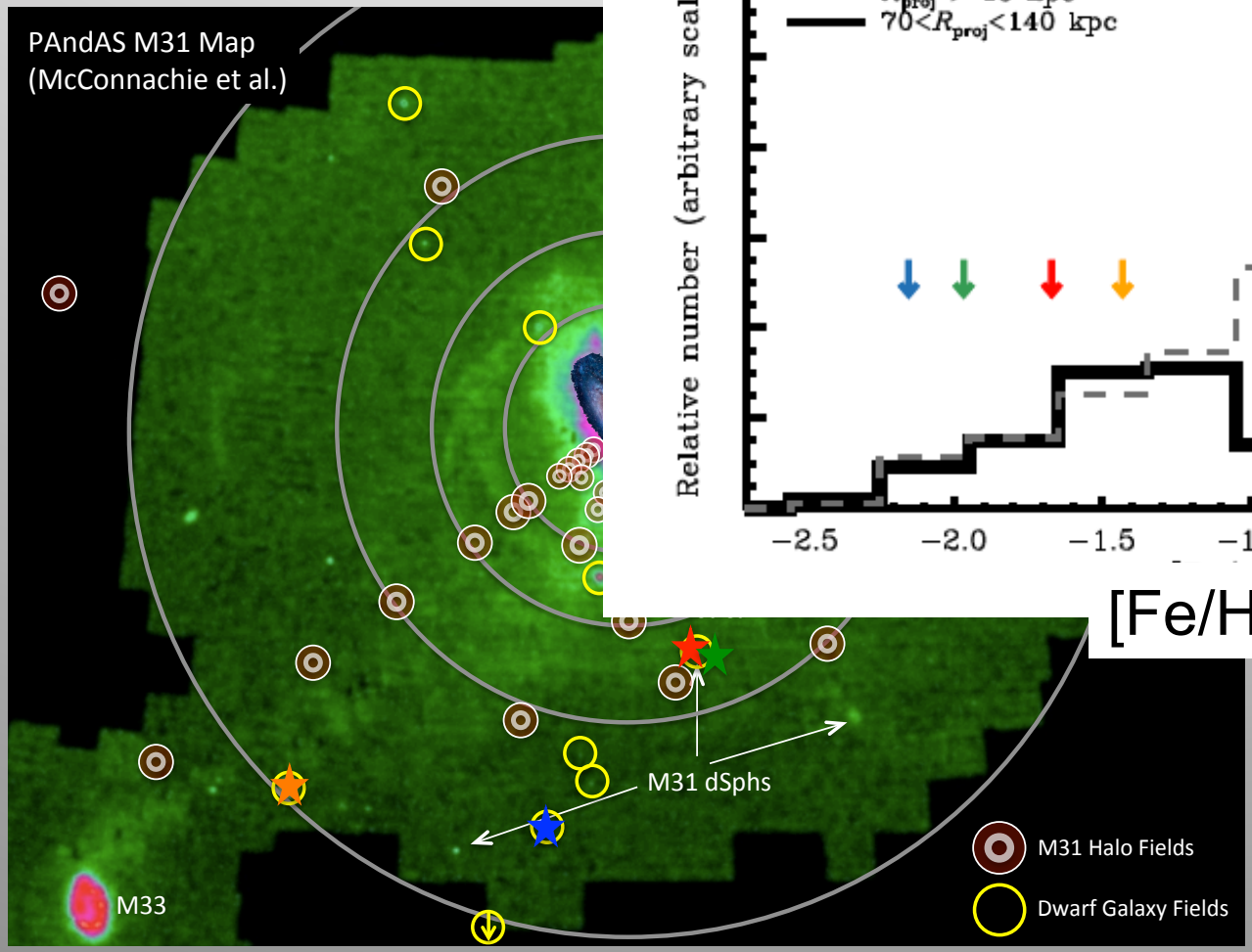


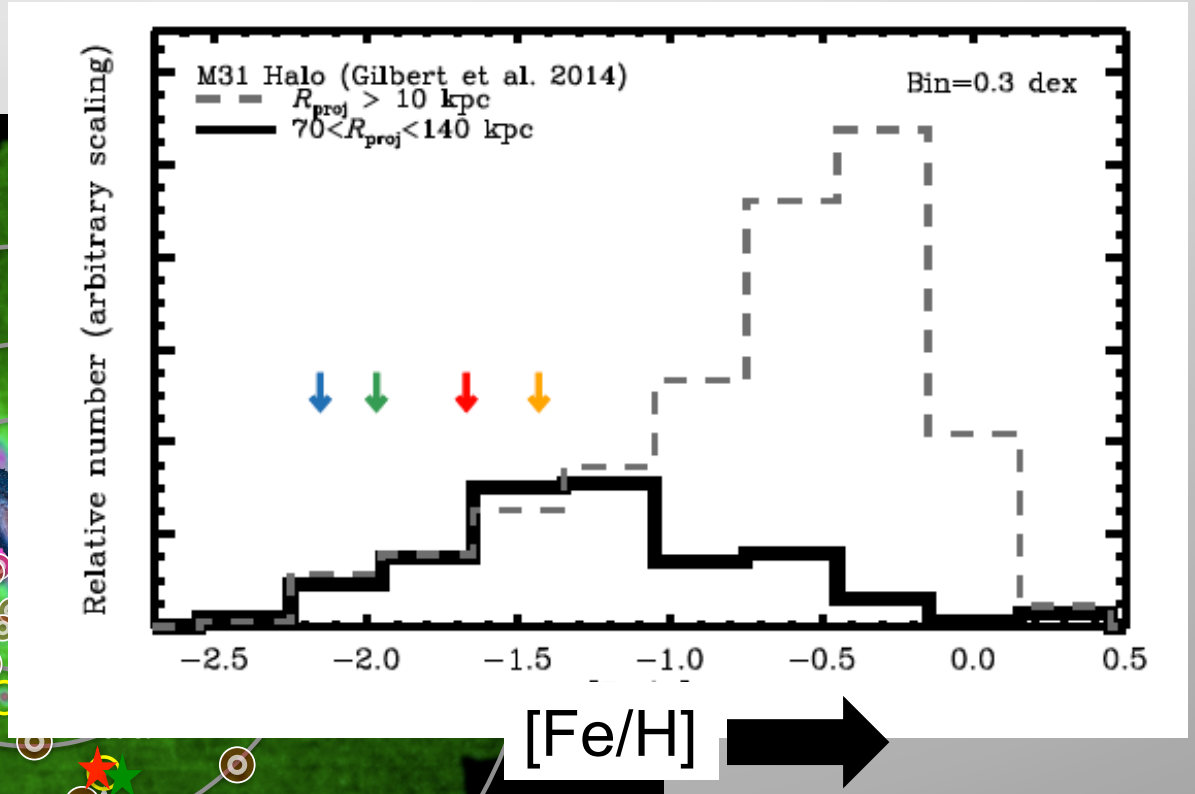

*Based on BJ05 simulations*

*D. Lee et al. 2014 (arXiv)*

# First Measurements of [α/Fe] in M31's Stellar Halo

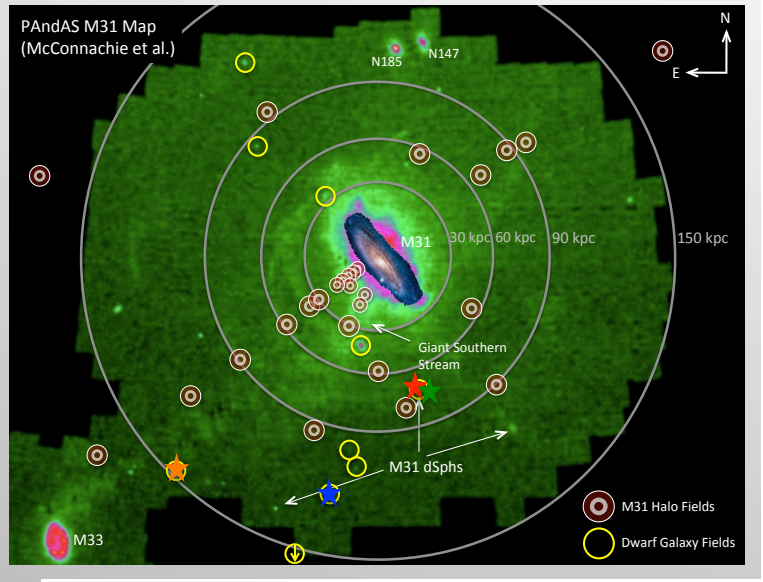
Vargas et al. 2014a: 226 stars in 9 M31 dwarf galaxies
Vargas et al. 2014b: 4 M31 halo stars

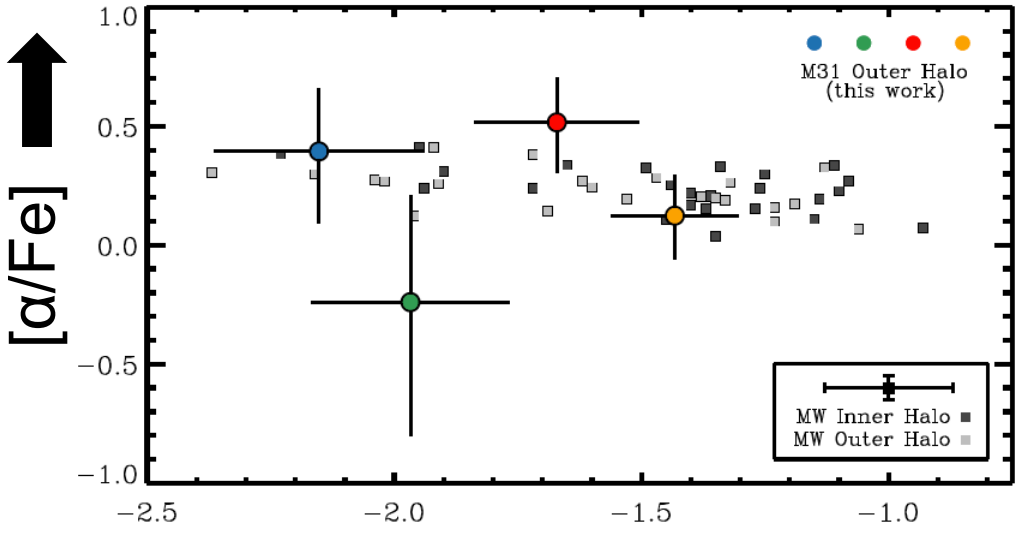


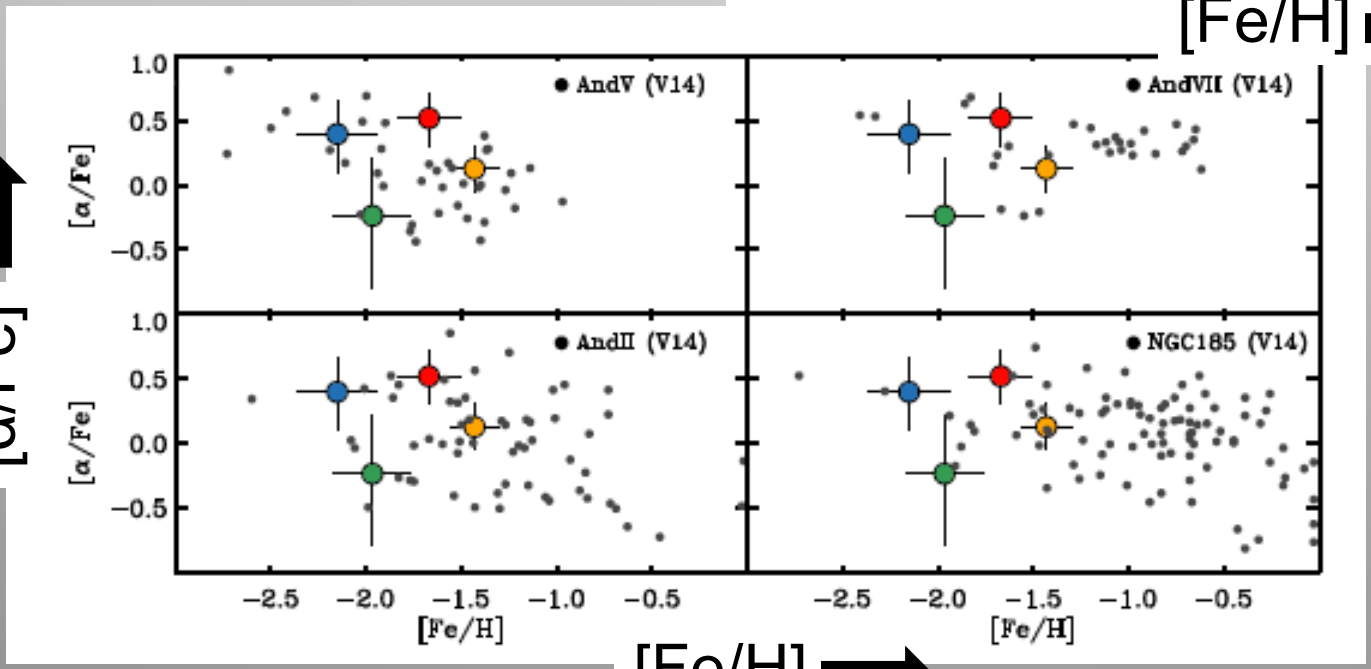




*Vargas, Gilbert et al. 2014*

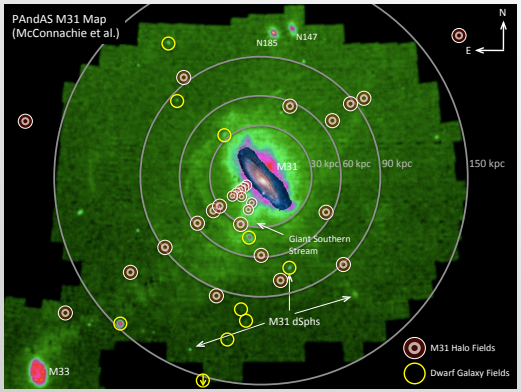
# First Measurements of [α/Fe] in M31's Stellar Halo



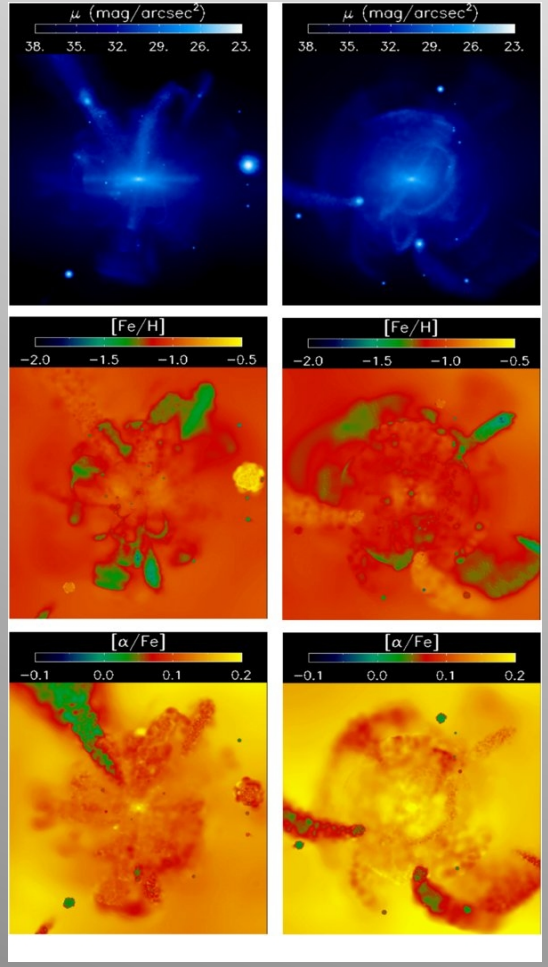




*Vargas, Gilbert et al. 2014*




# Not Just One Galaxy…

## Dwarf Galaxies accreted, accreting, yet to be accreted




**μ**

**[Fe/H]**

**[α/Fe]**

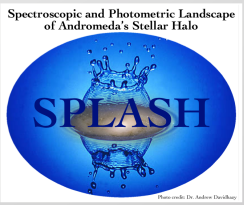
***Luminosity Function of Accreted Satellites***

***Time of Accretion***

*Image Credit Sanjib Sharma*

# Conclusions

**Andromeda's stellar halo shows clear evidence of being built through mergers with smaller galaxies. It preserves a fossil record of the stellar populations of these long-destroyed dwarf galaxies.**




**Splash Survey:**

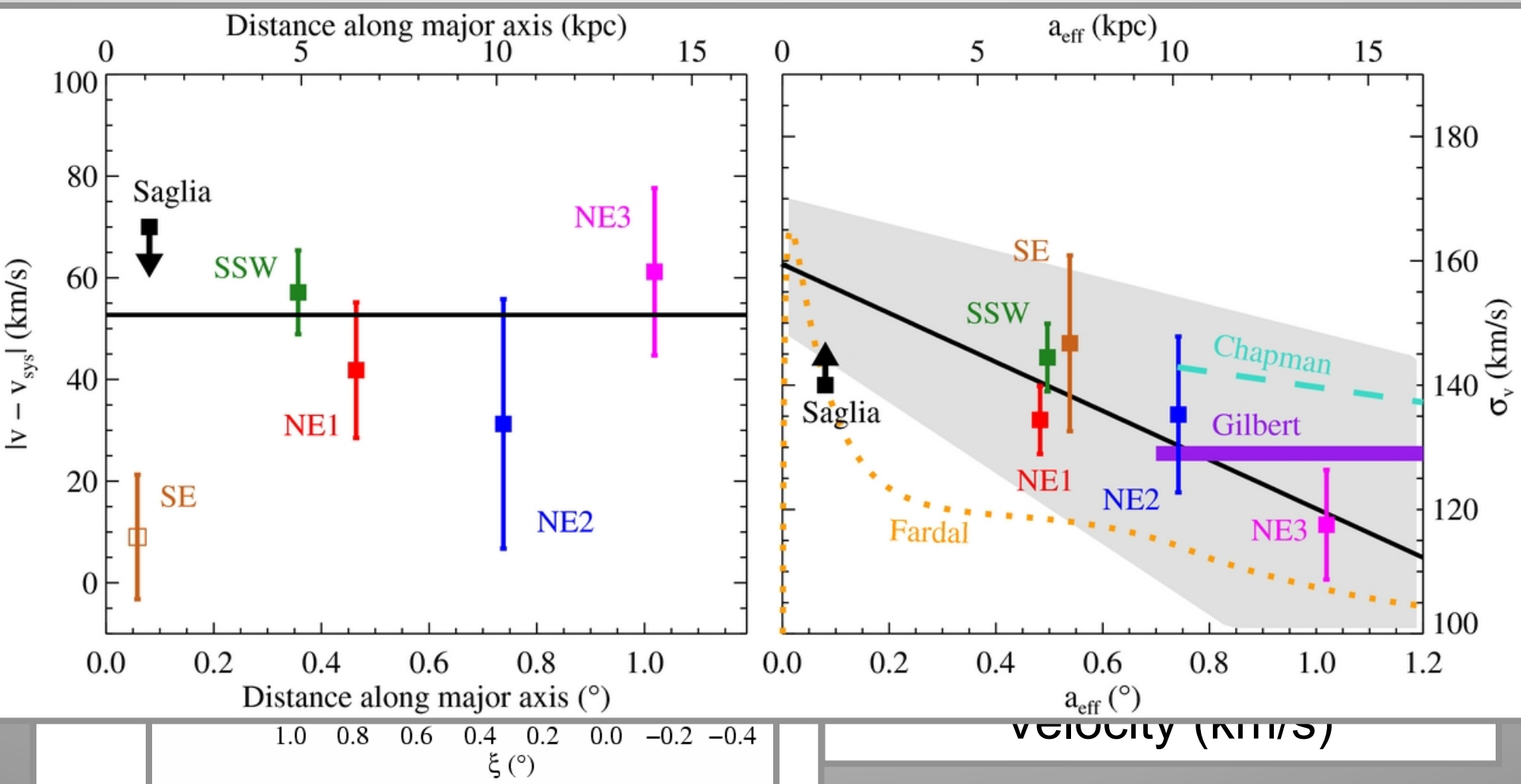
- **Spectroscopy provides secure identification of M31 stars: sensitivity to extremely sparse populations (R=180 kpc)**
- **Spectroscopy provides kinematics: the ability to identify faint tidal debris features and study their effect on measurements of global halo properties**

**Science Highlights:**

- **Extended, power-law profile halo extending to at least 175 kpc, with a metallicity gradient to at least 100 kpc; both imply a very active merging history**
- **Tidal debris features are systematically more metal-rich than the smooth component of the halo except in the innermost regions – consistent with expectations from hierarchical formation**
- **Inner halo shows rotation, and may be partially comprised of kicked up disk stars**
- **We have made the first [α/Fe] measurements of stars in M31's halo – and there will be more to come!**

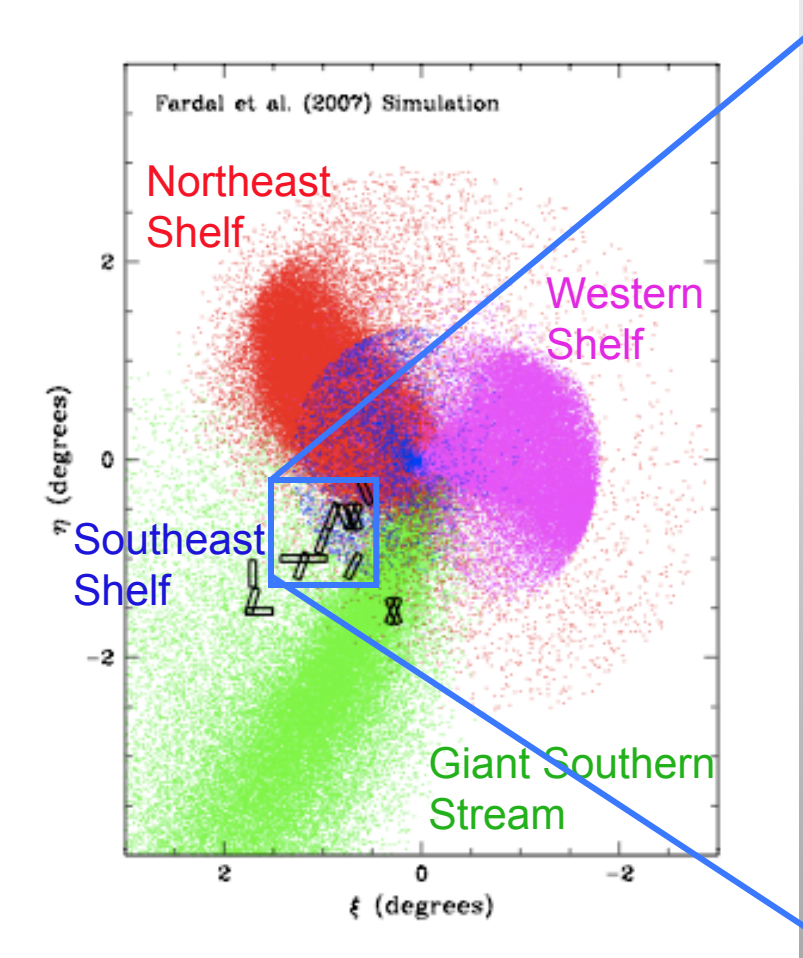
# Evidence for an In Situ Halo Component

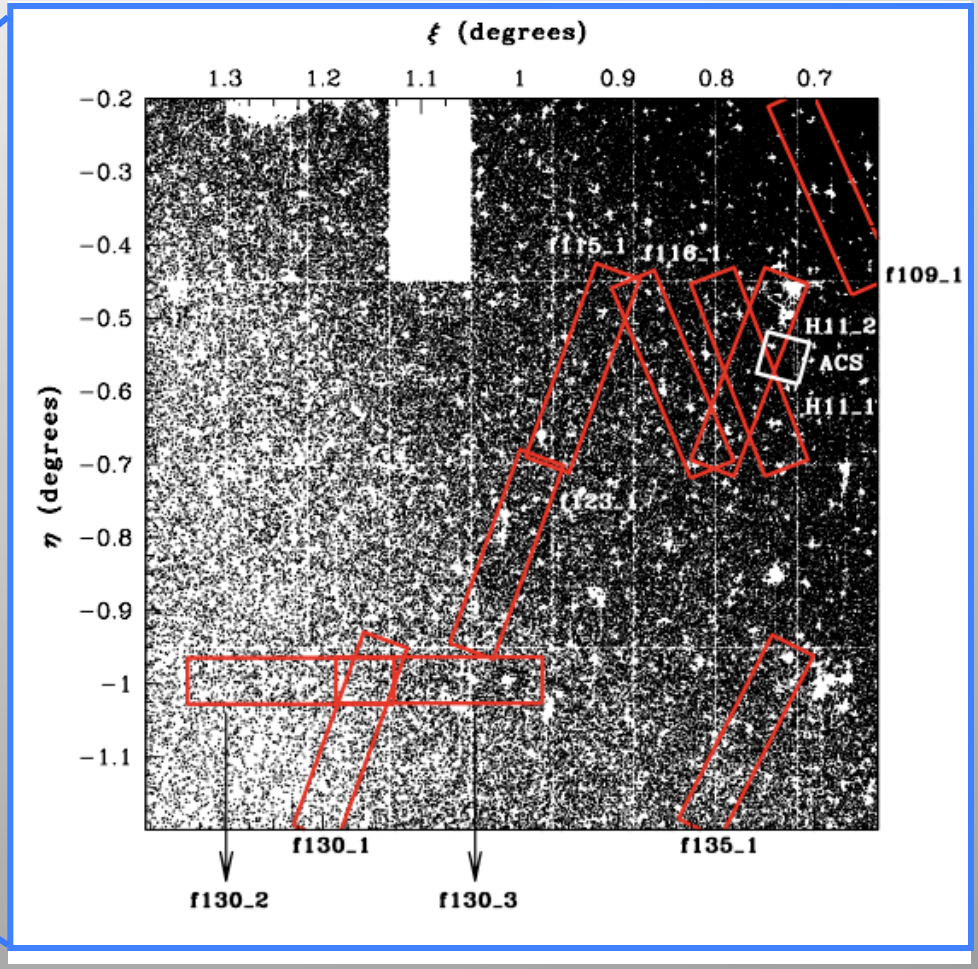
Kinematics of M31's Disk and Inner Spheroid




*Dorman et al. 2012*

# Comparison of Data to Simulations

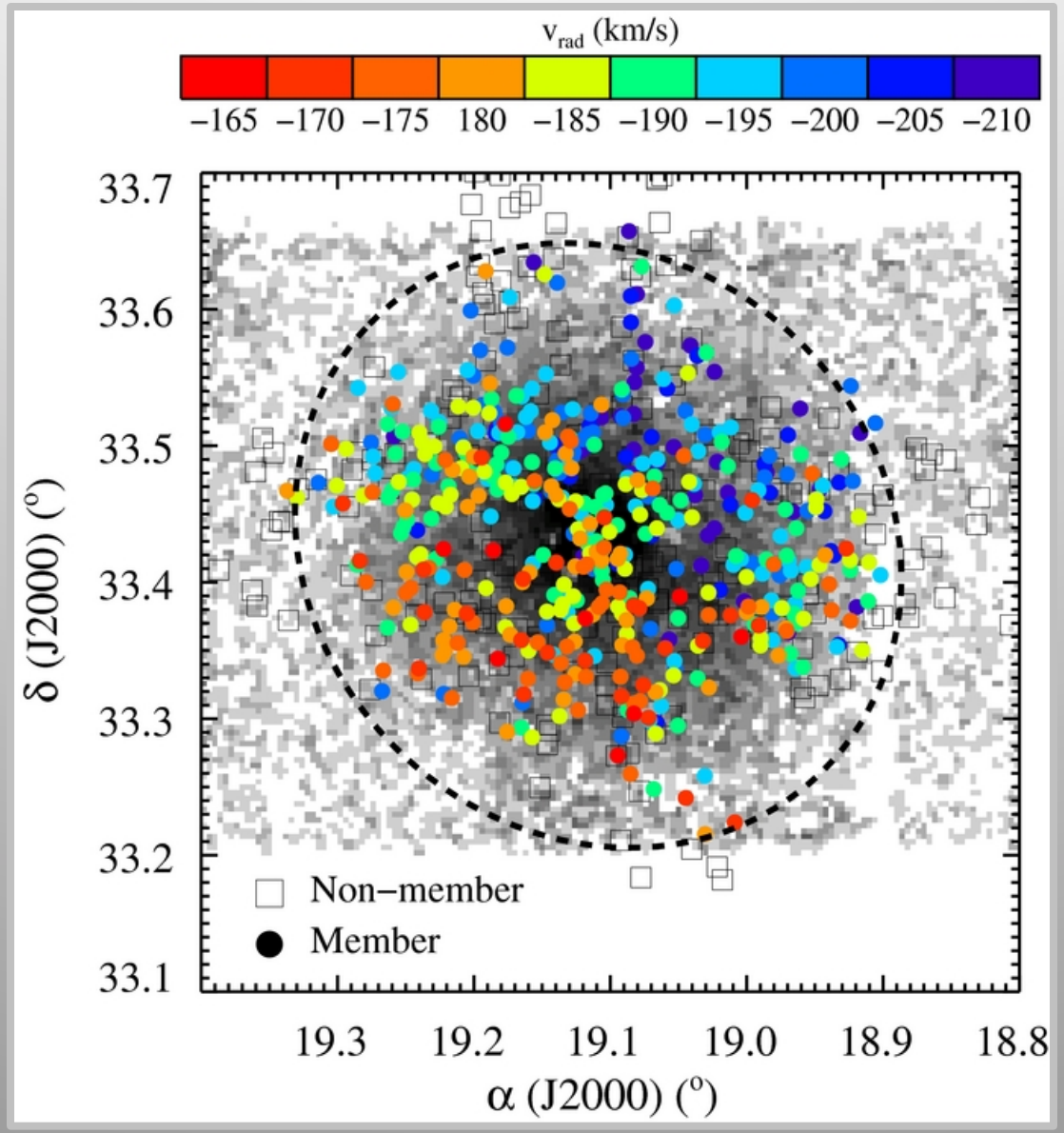



*Gilbert et al. 2007*

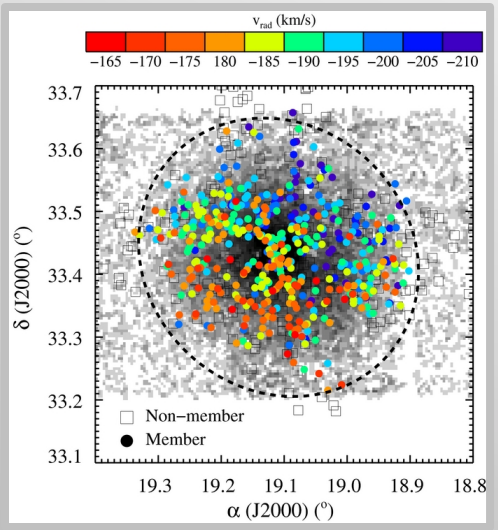
*See also Fardal et al. 2007*

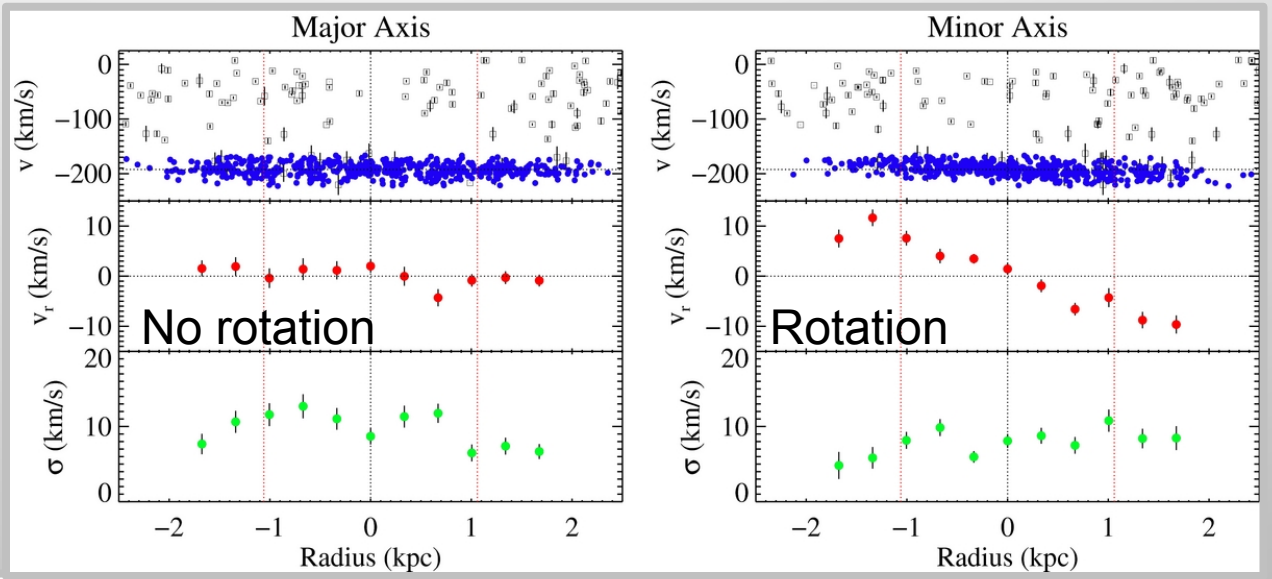
# M31 Dwarf Satellites: And II

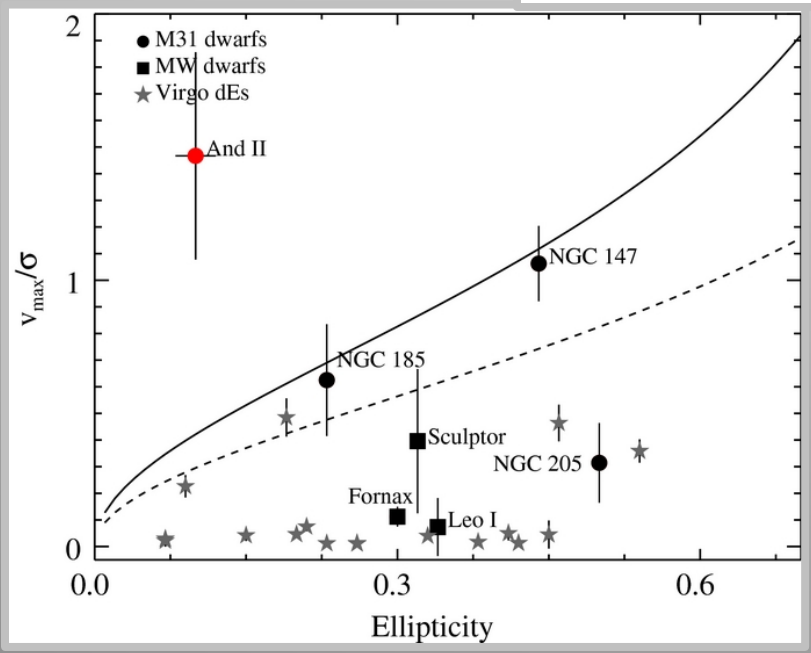



*Ho et al. 2012*

# M31 Dwarf Satellites: The Curious Case of And II



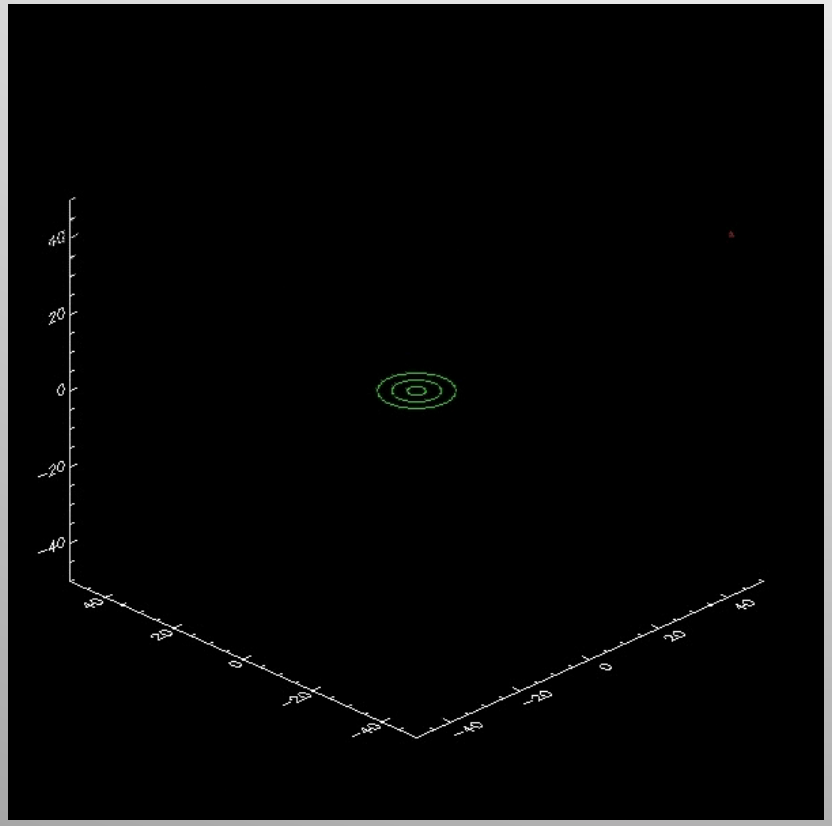



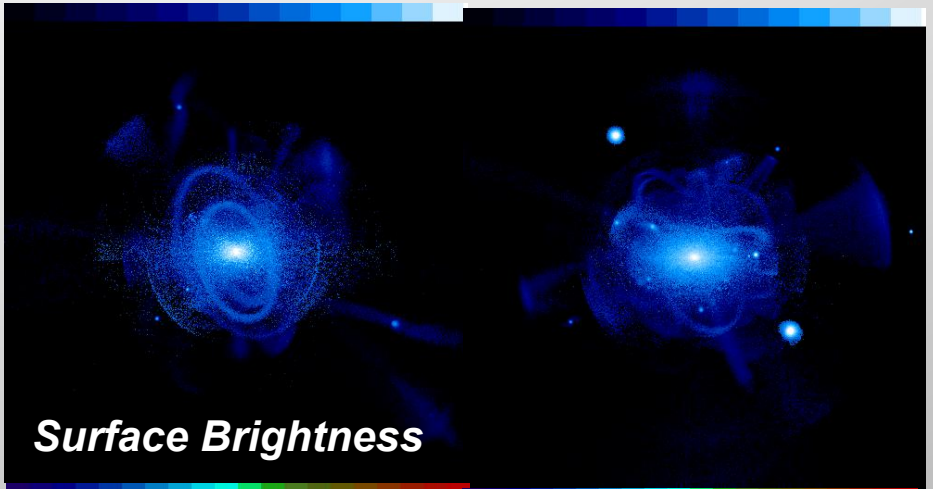



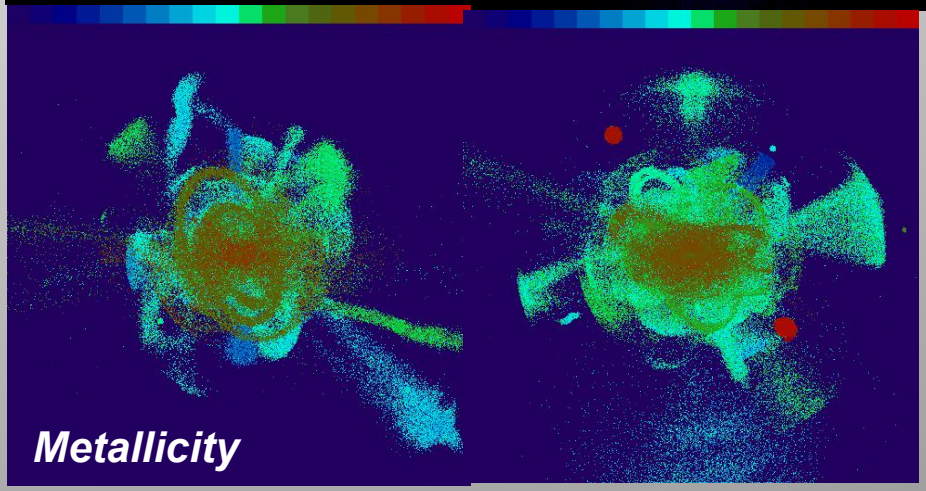

*The kinematical major axis is misaligned to the isophotal major axis by 67 degrees!*

*Ho et al. 2012*

# Stellar Halo Build-up through Minor Mergers





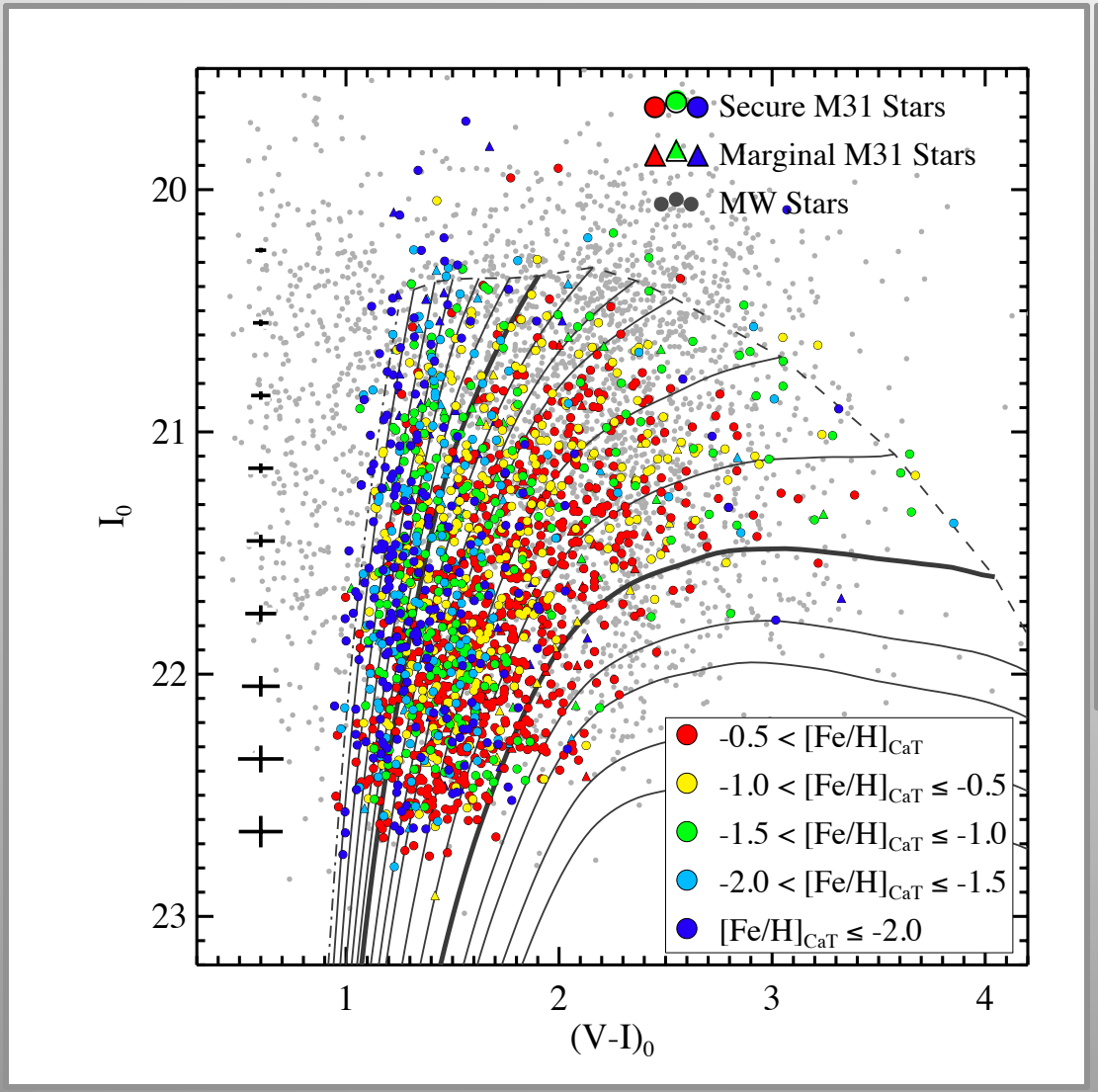



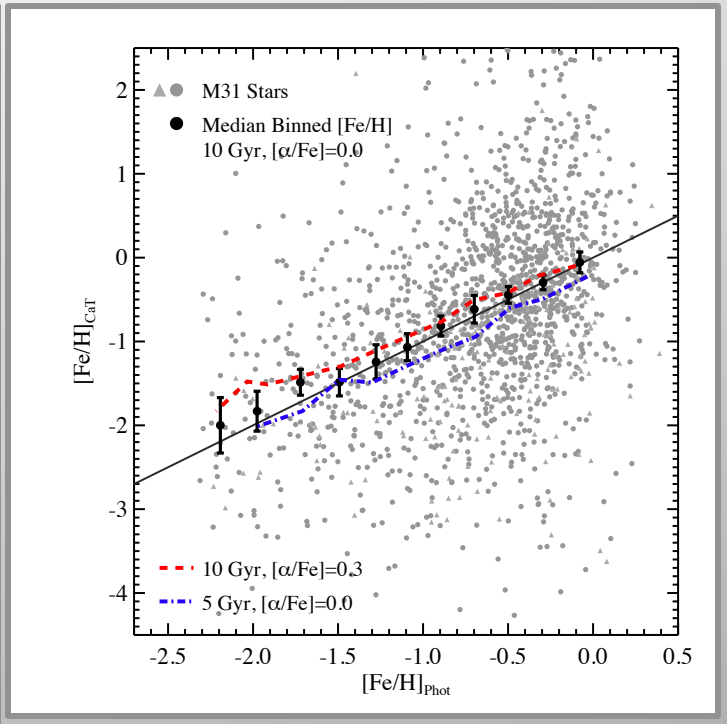

**Over the life-time of a galaxy, many minor mergers can build up a stellar halo.**

*Bullock & Johnston 2005; Font et al. 2006*

# Comparison of Metallicity Estimates

On average, photometric and spectroscopic estimates agree.




*Gilbert et al. 2014*