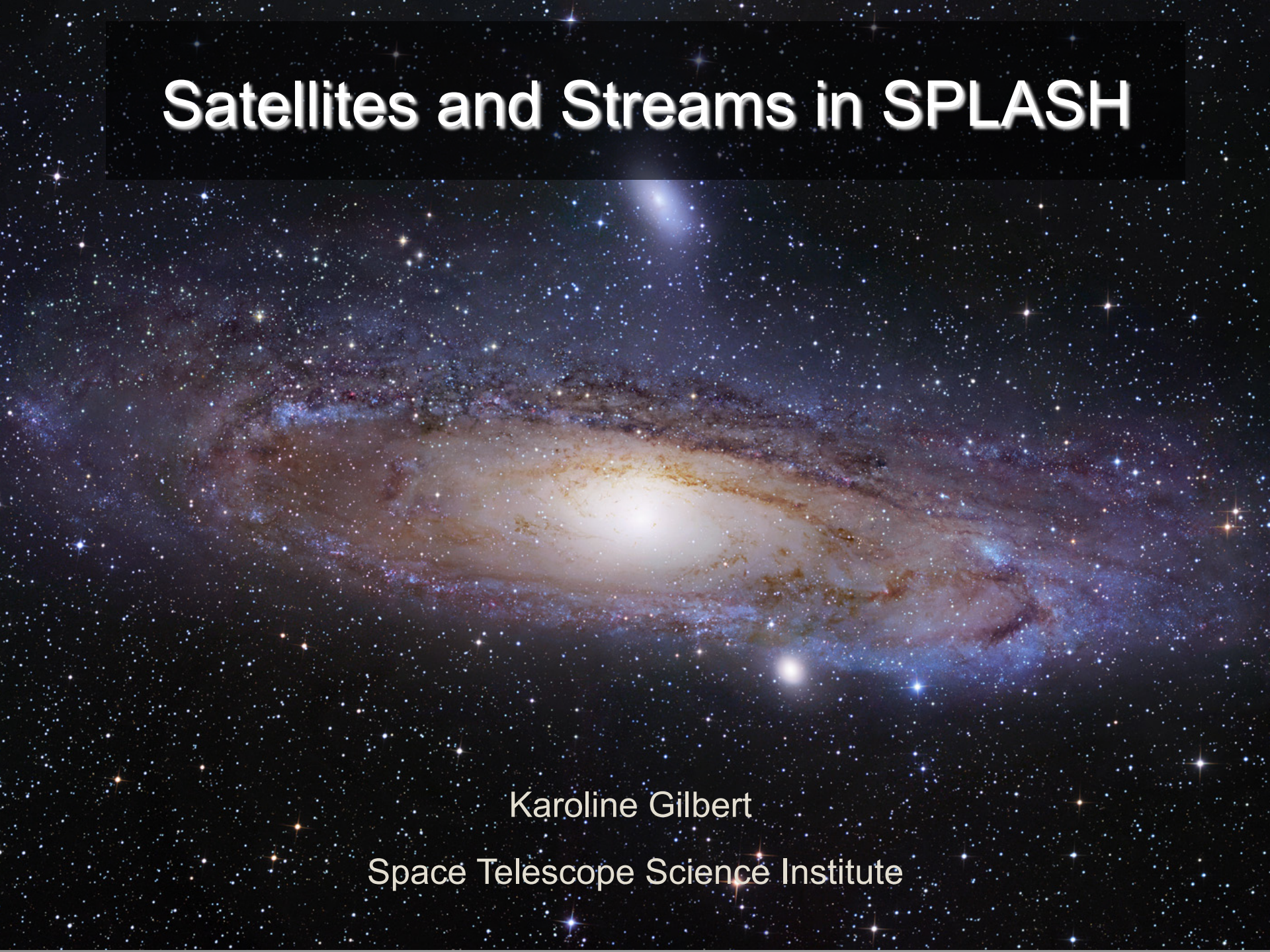
Satellites and Streams in SPLASH



Karoline Gilbert

Space Telescope Science Institute

Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo

Photo credit: Dr. Andrew Davidhazy

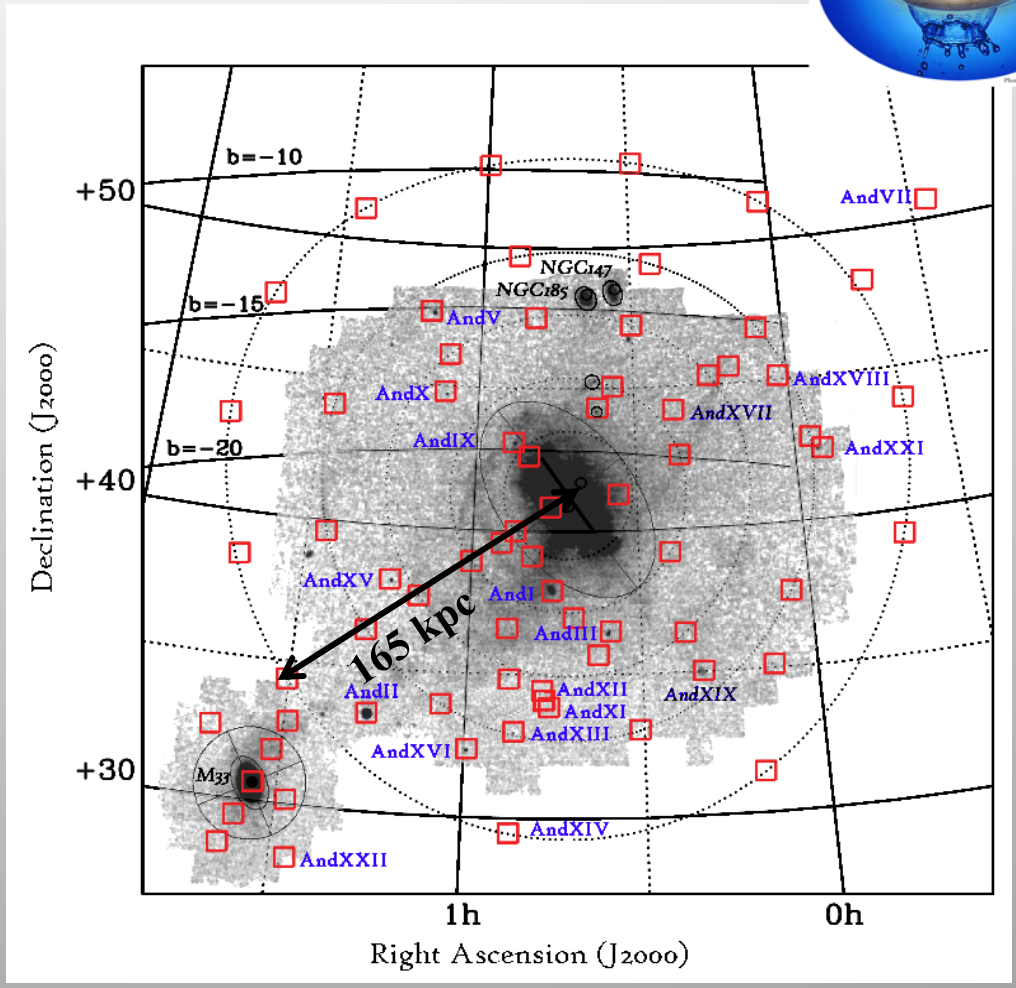
Raja Guhathakurta (UCSC)
Steve Majewski (U Virginia)
Marla Geha (Yale)
James Bullock (UC Irvine)
Rachael Beaton (Carnegie)
Erik Tollerud (Yale)
Evan Kirby (Caltech)
Jason Kalirai (STScI)

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

78 Fields in M, T2, DD051
9 Observing Seasons
PIs: Majewski & Beaton

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



PANDAS Survey Map from Richardson et al. 2011

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
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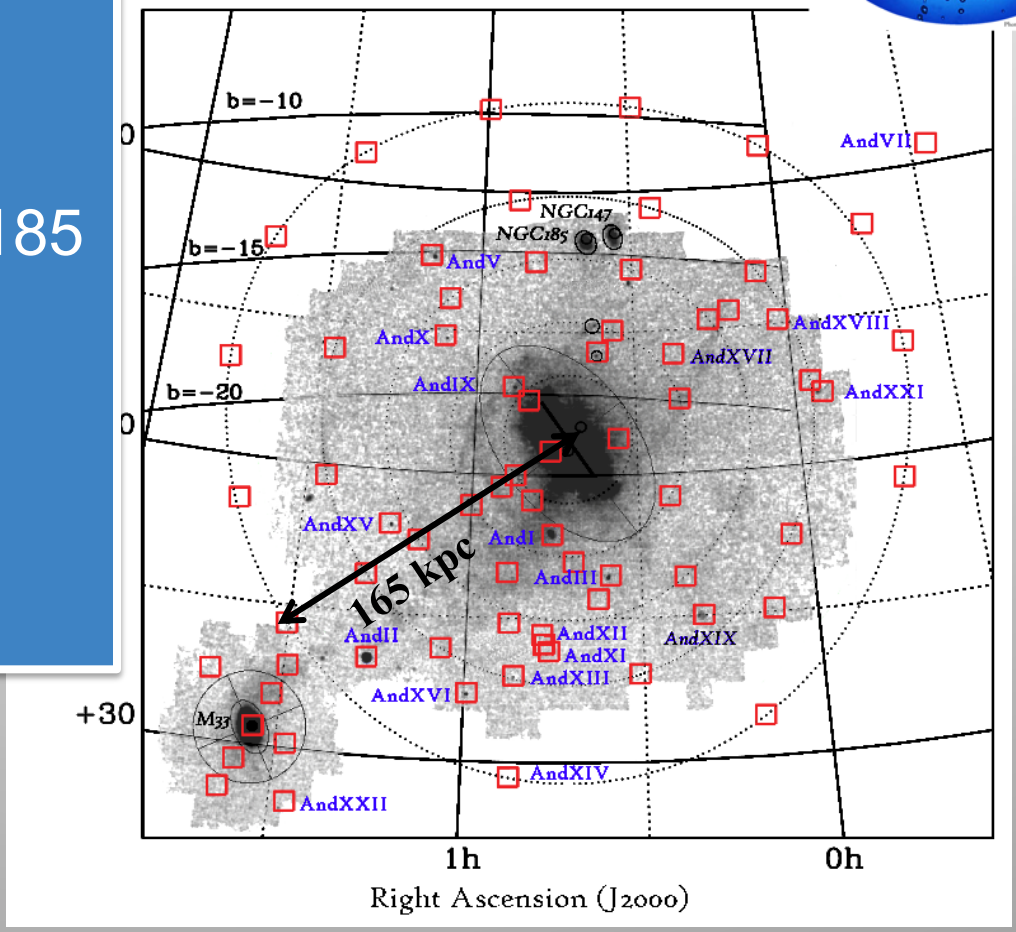


PANDAS Survey Map from Richardson et al. 2011

SPLASH Observations

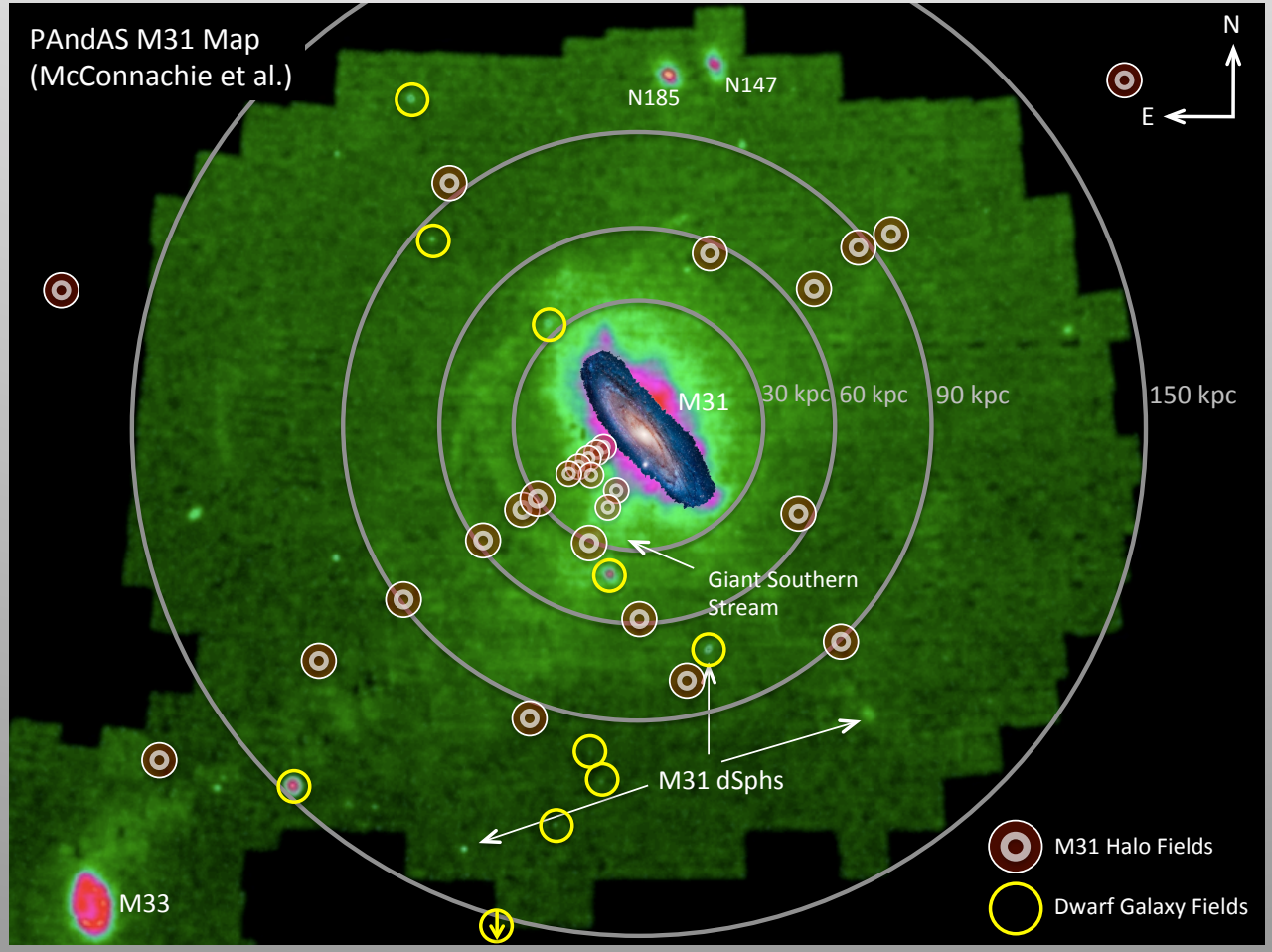
- **Discovery and characterization of Andromeda's extended, metal-poor stellar halo:** ***Guhathakurta et al. 2005, Kalirai et al. 2006a, Courteau et al. 2011, Gilbert et al. 2012, Gilbert et al. 2014***
- **Characterization of Andromeda's inner stellar halo:** ***Dorman et al. 2012, Dorman et al. 2013***
- **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, Howley et al. 2008, Geha et al. 2010, Kalirai et al. 2010, Tollerud et al. 2012, Ho et al. 2012, Howley et al. 2013***
- **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***

Three Major Phases of Minor Mergers

(1) Intact Satellites ← Yet to be Accreted

(2) Stellar Streams ← Accreting

(3) "Smooth" Stellar Halo ← Accreted



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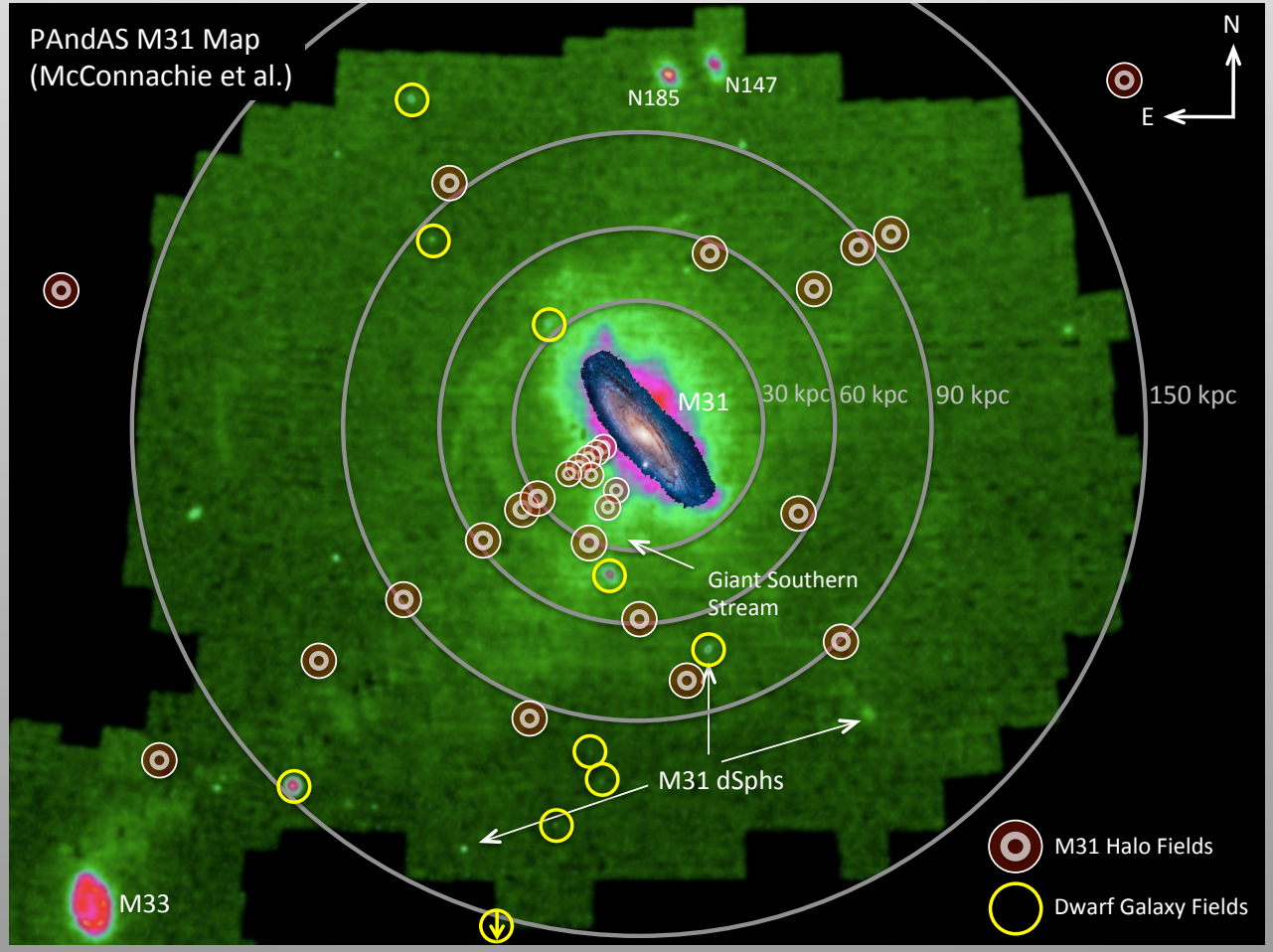
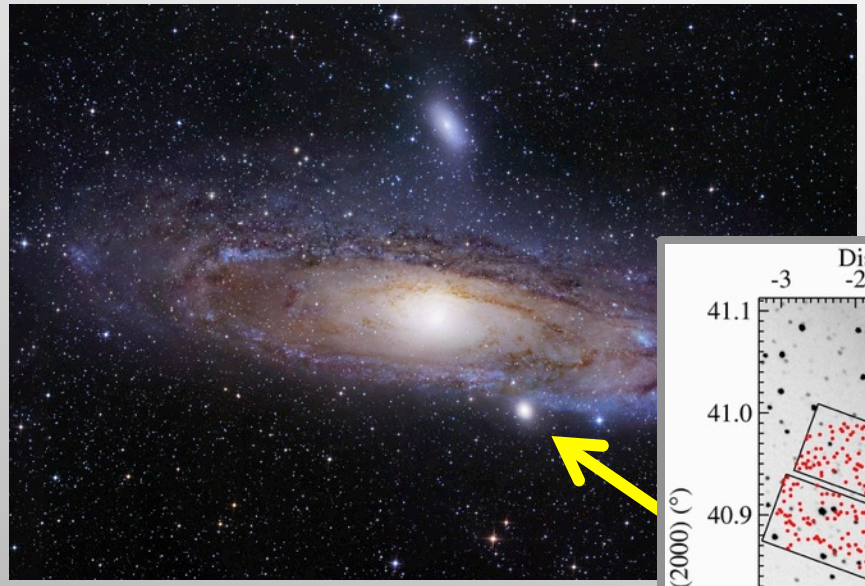
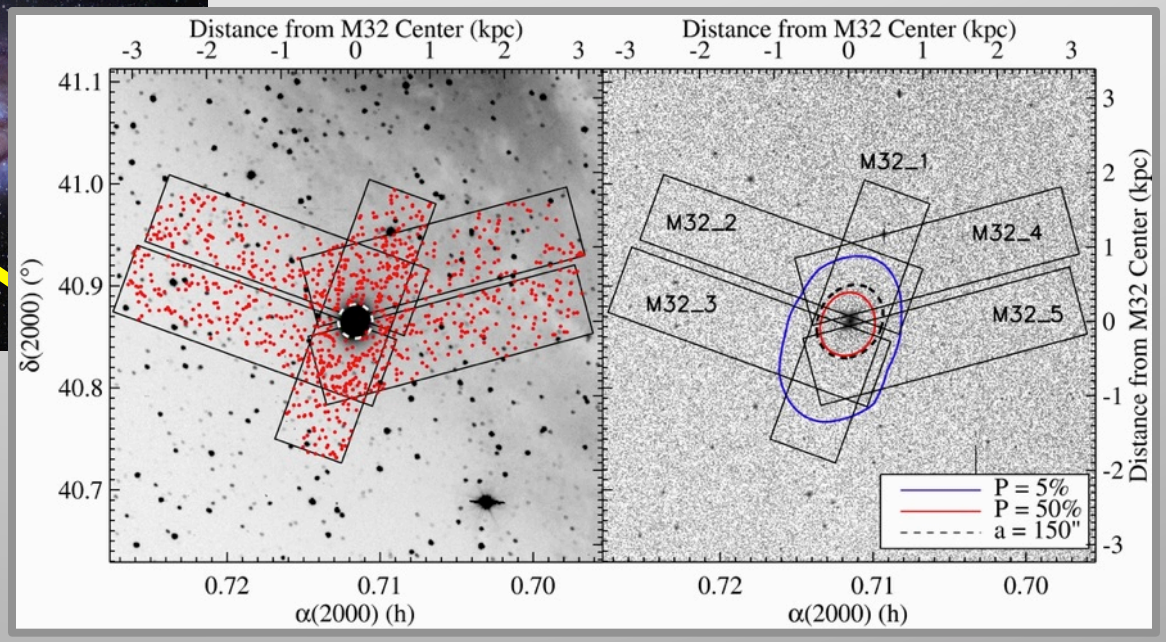


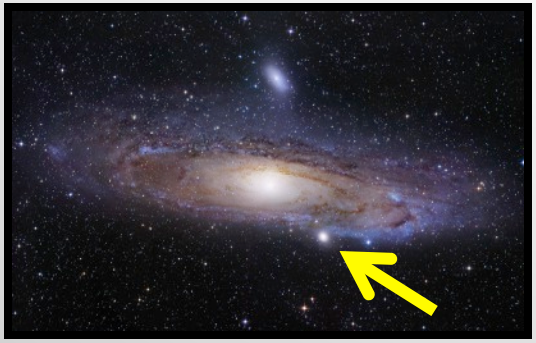
Internal Stellar Kinematics of M32





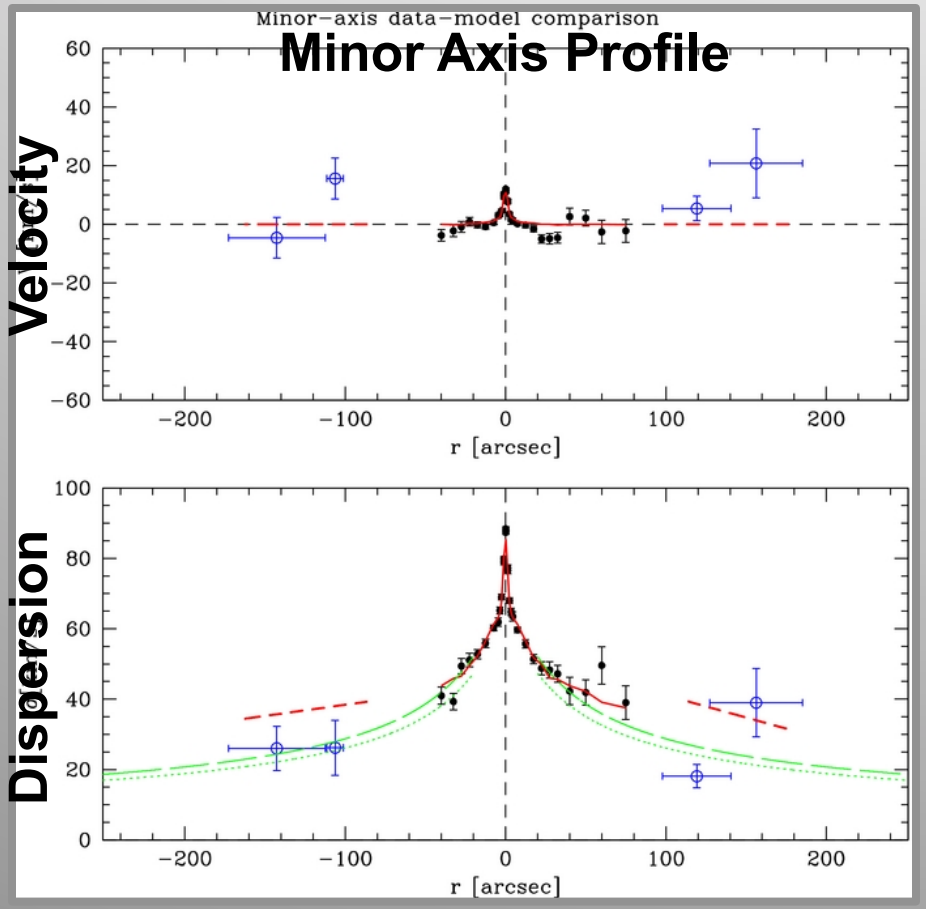
Integrated light (at small radii) + resolved stellar spectroscopy

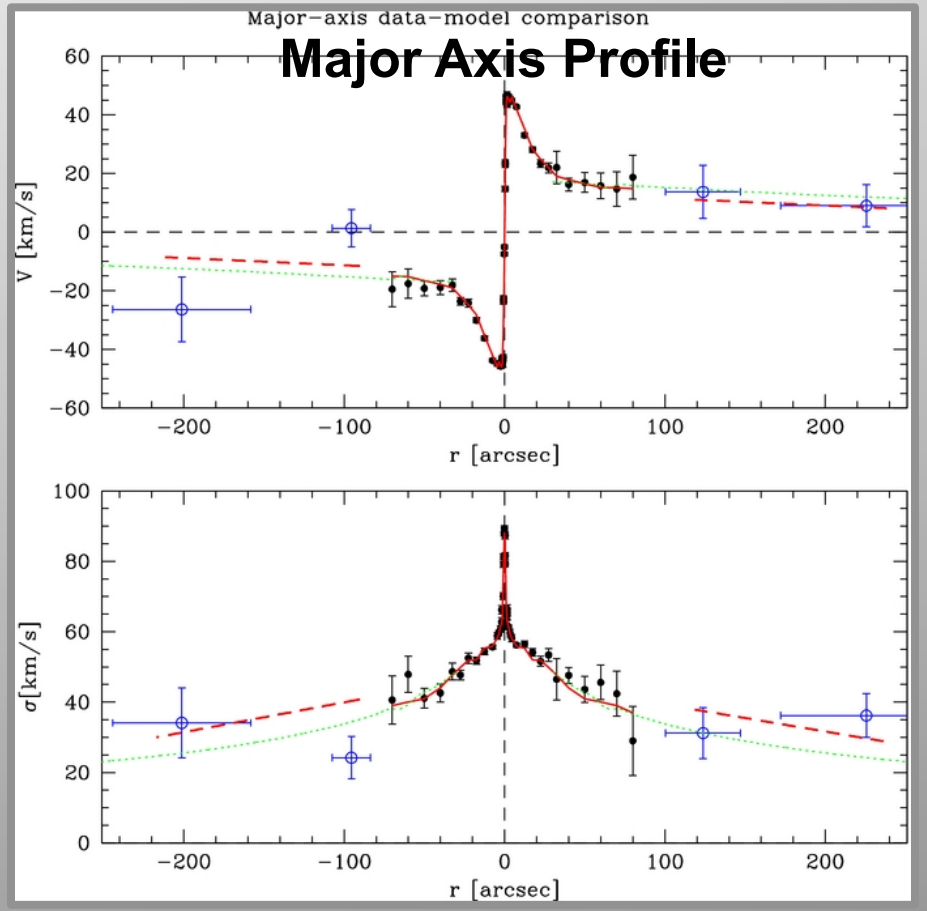
Howley et al. 2013



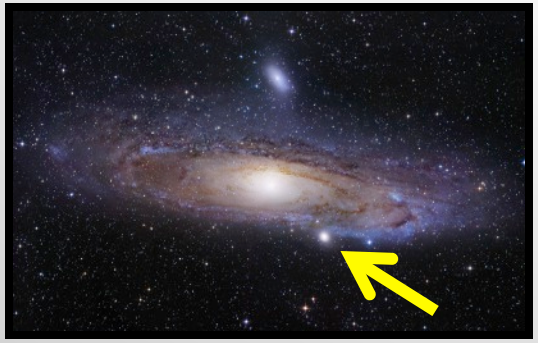
Kinematics of M32

- Mean Velocity and dispersion measured to > 6 r_{eff}
- Rotation curve and dispersion profile extend well beyond where isophotes become distorted – kinematics appear regular and symmetric





Howley et al. 2013



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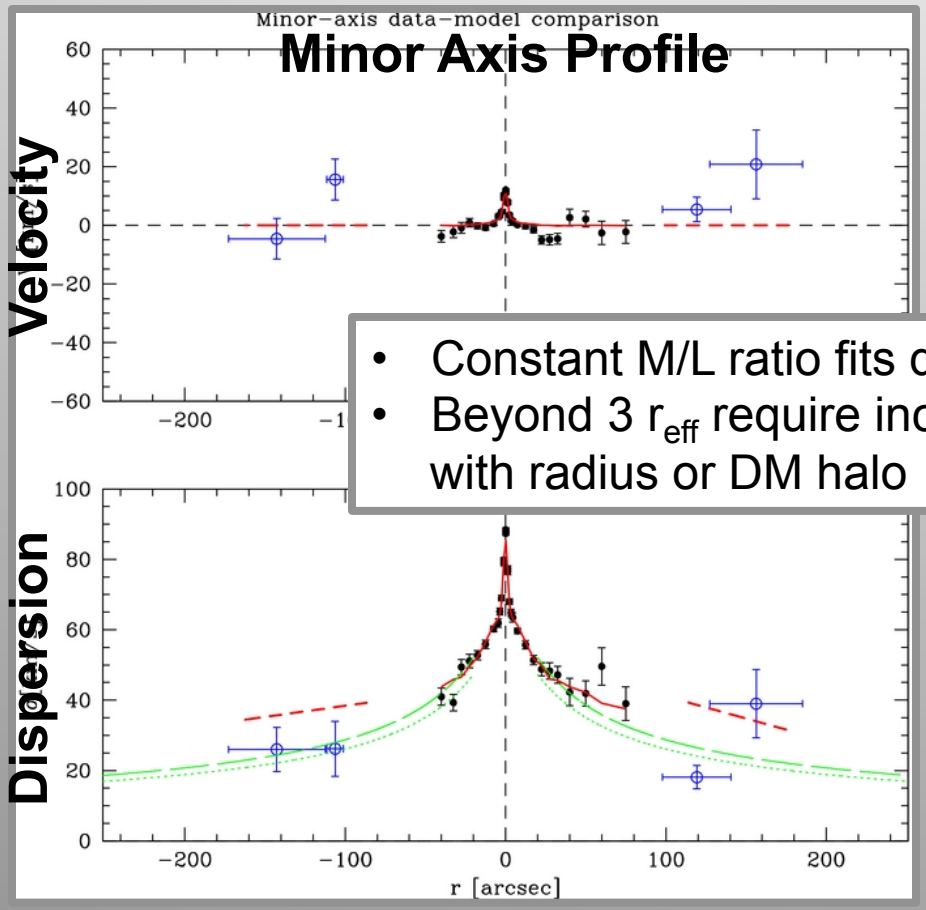
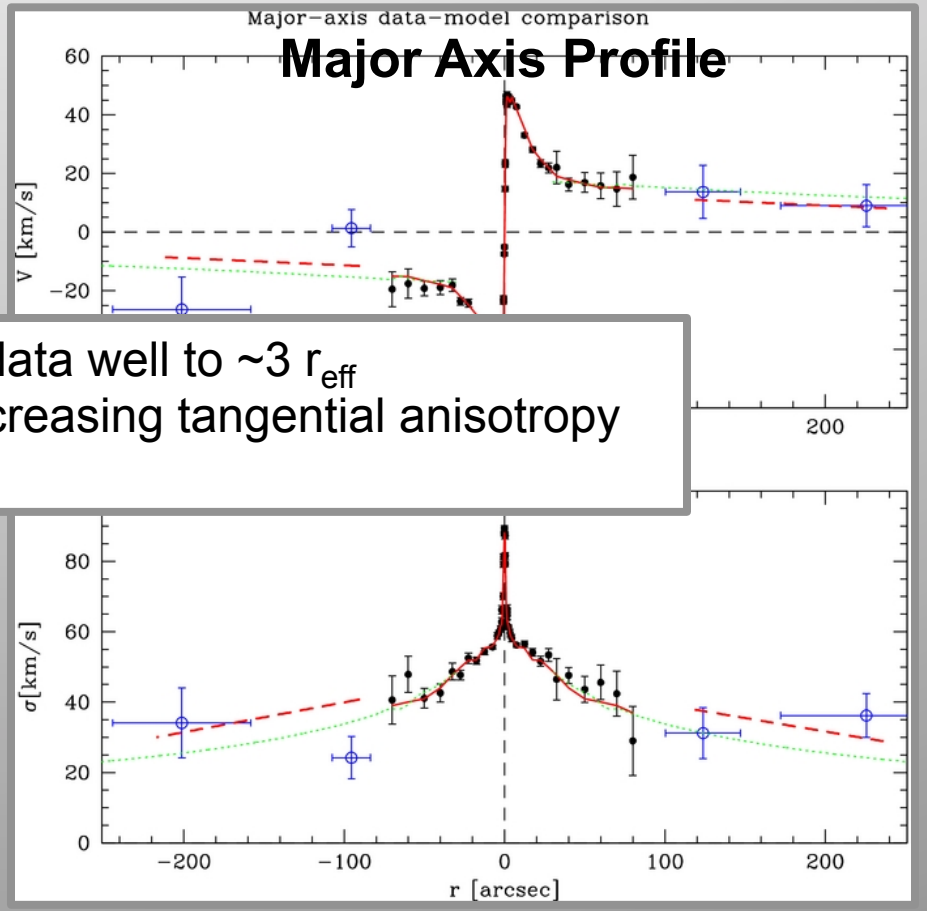
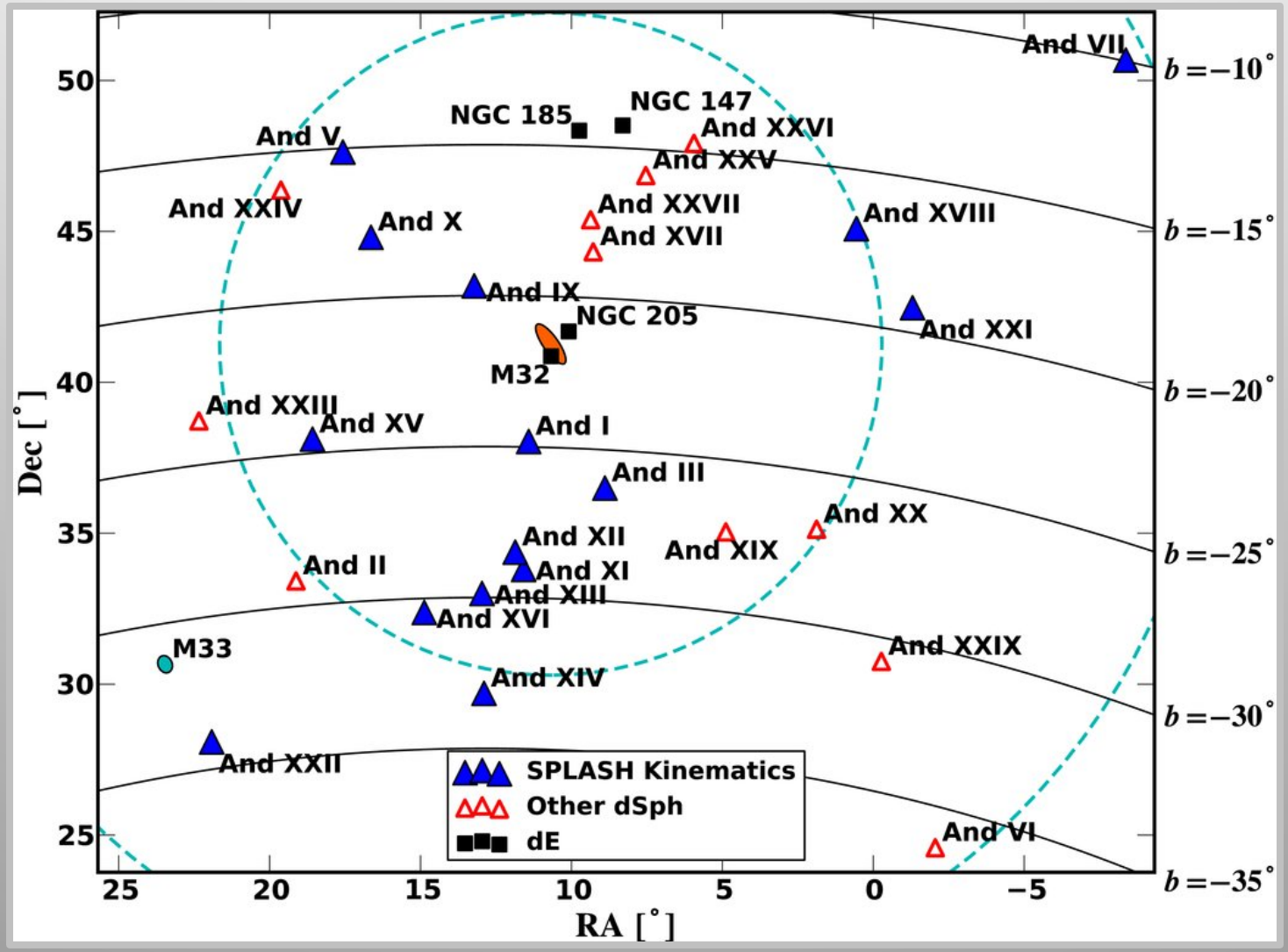




- Constant M/L ratio fits data well to ~3 r_{eff}
- Beyond 3 r_{eff} require increasing tangential anisotropy with radius or DM halo

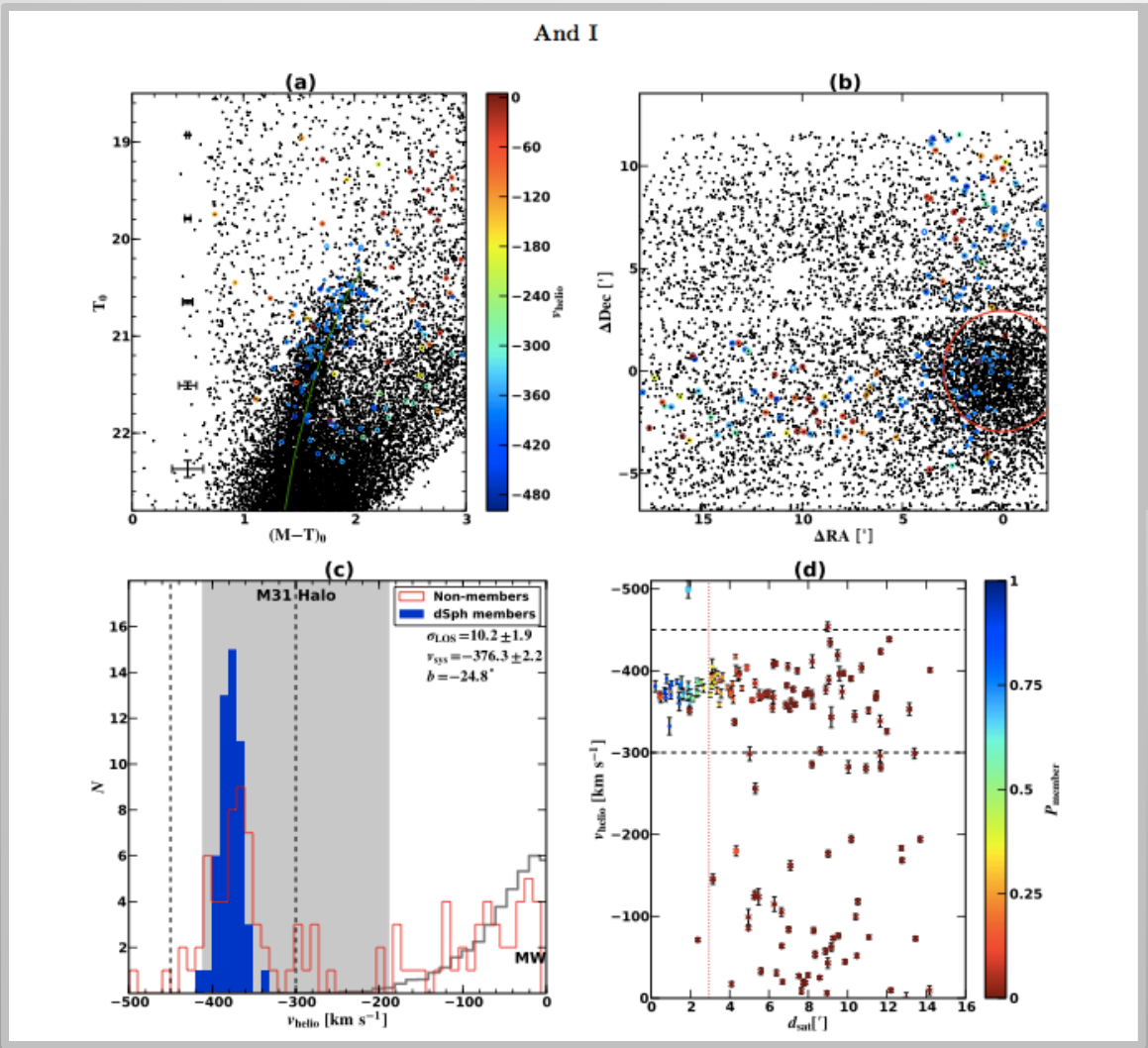
Howley et al. 2013

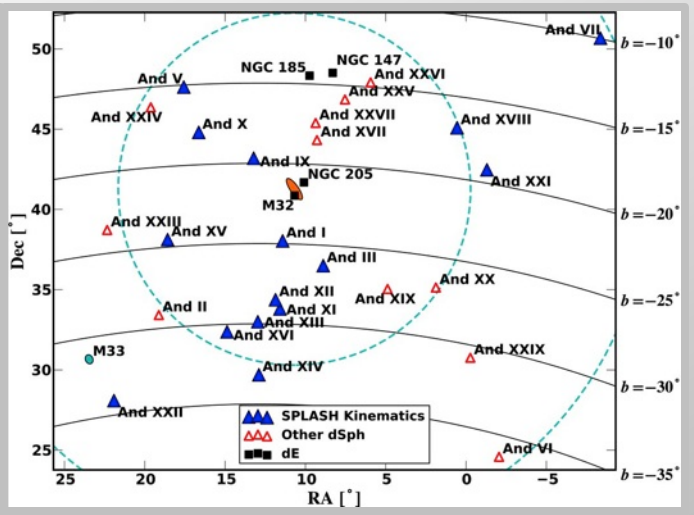
Compilation of M31 Dwarf Satellites



Tollerud et al. 2012

15 M31 Dwarf Satellites

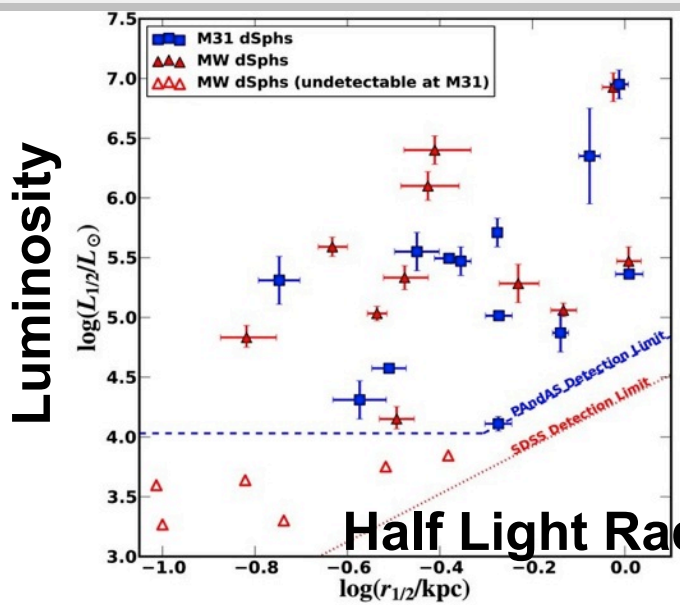




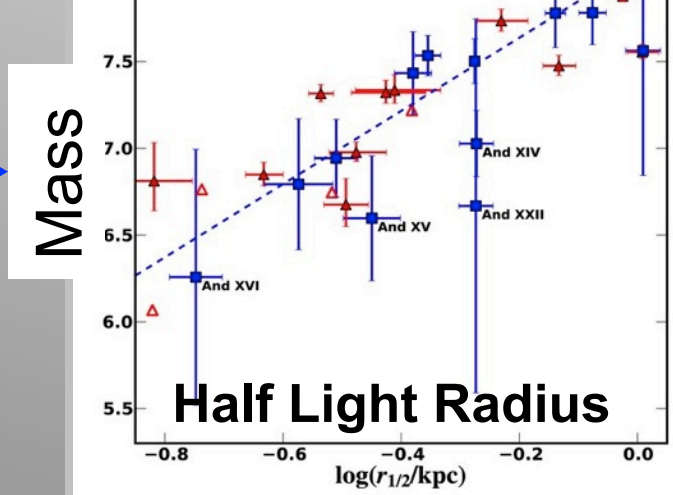
Confirmed kinematics of And XVIII, XXI, and XXII consistent with bound, dark matter dominated galaxies

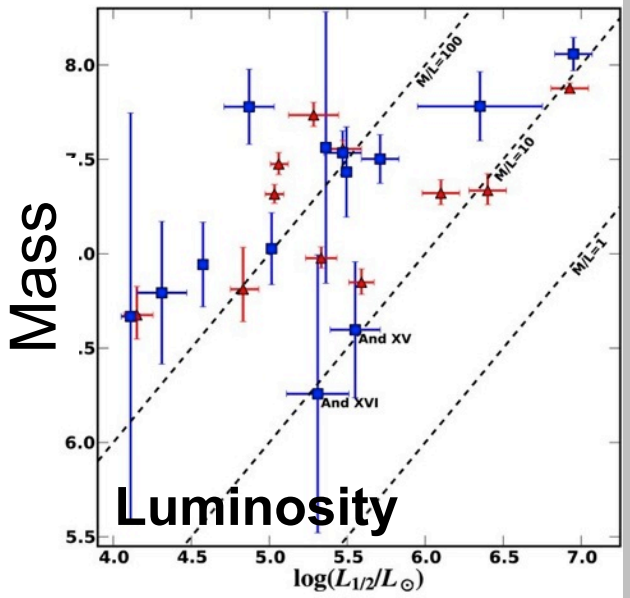
Tollerud et al. 2012

M31 vs. MW: Dwarf Satellites



From Velocity Dispersions





Tollerud et al. 2011

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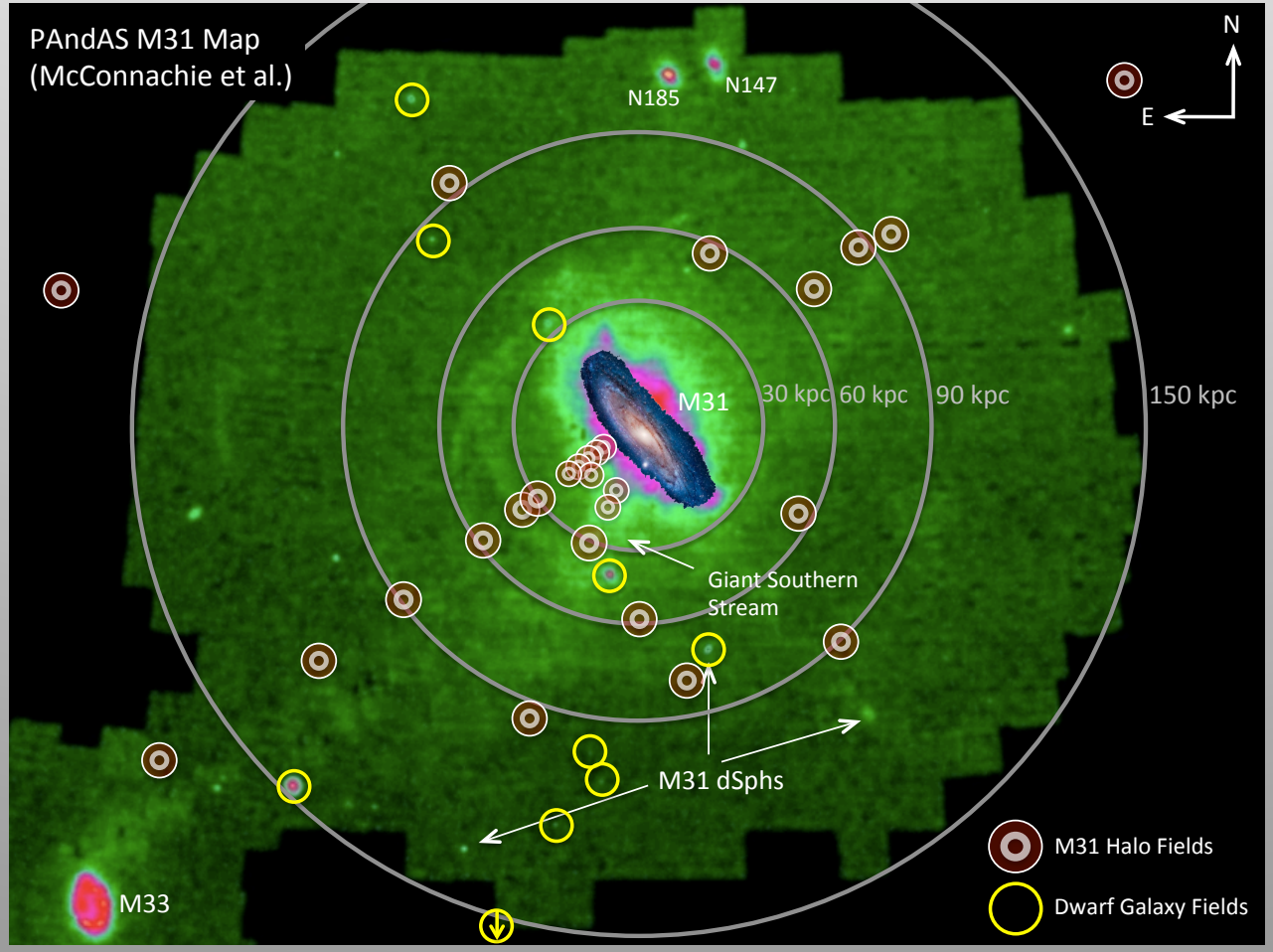
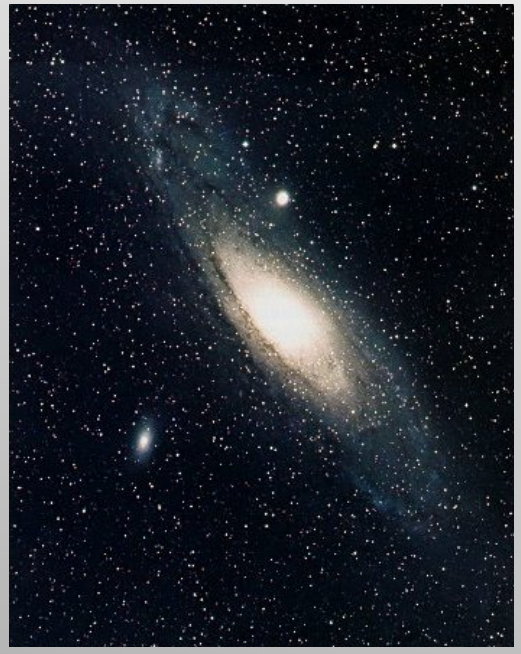


Tidal Debris in the Andromeda Galaxy



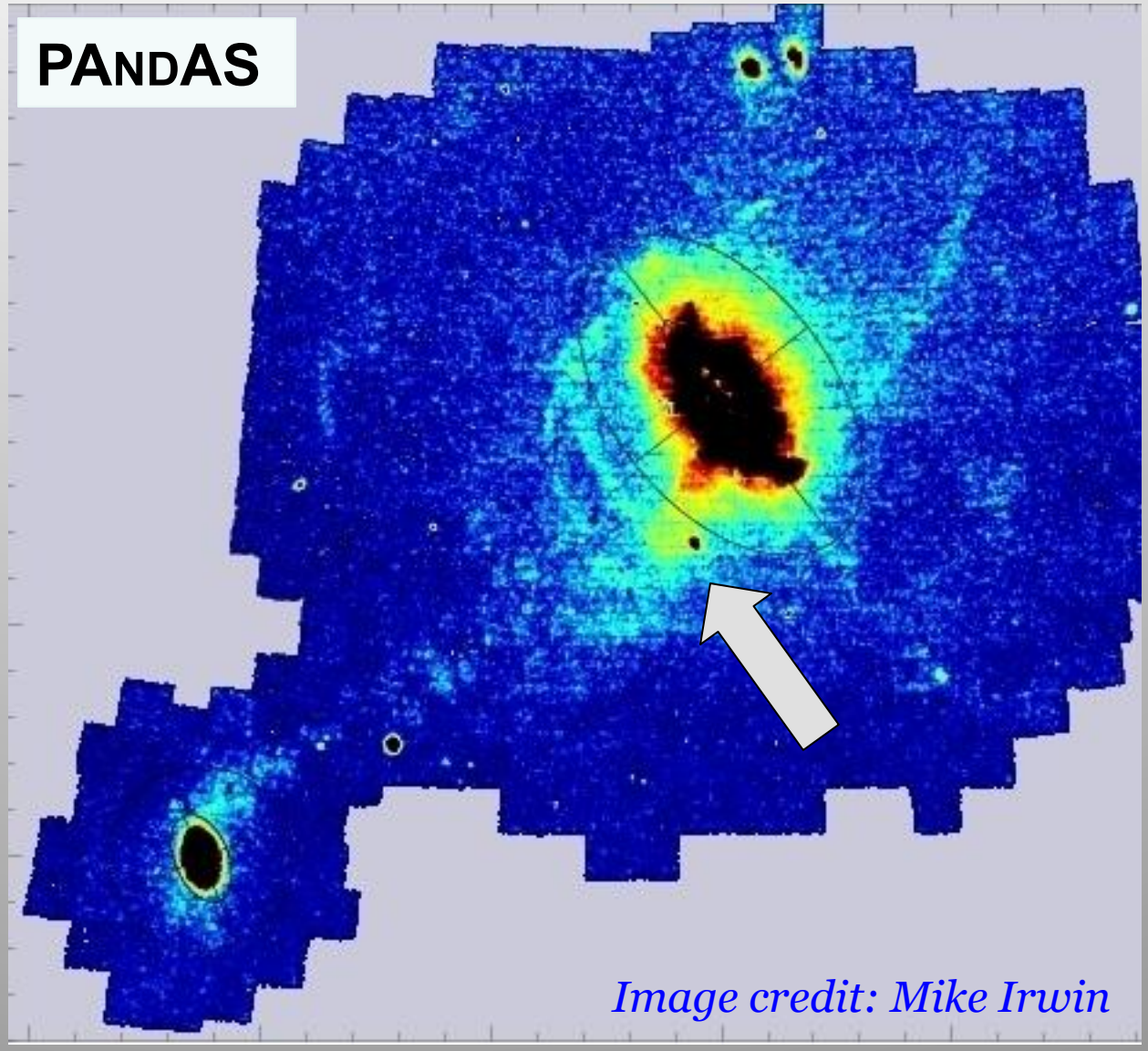
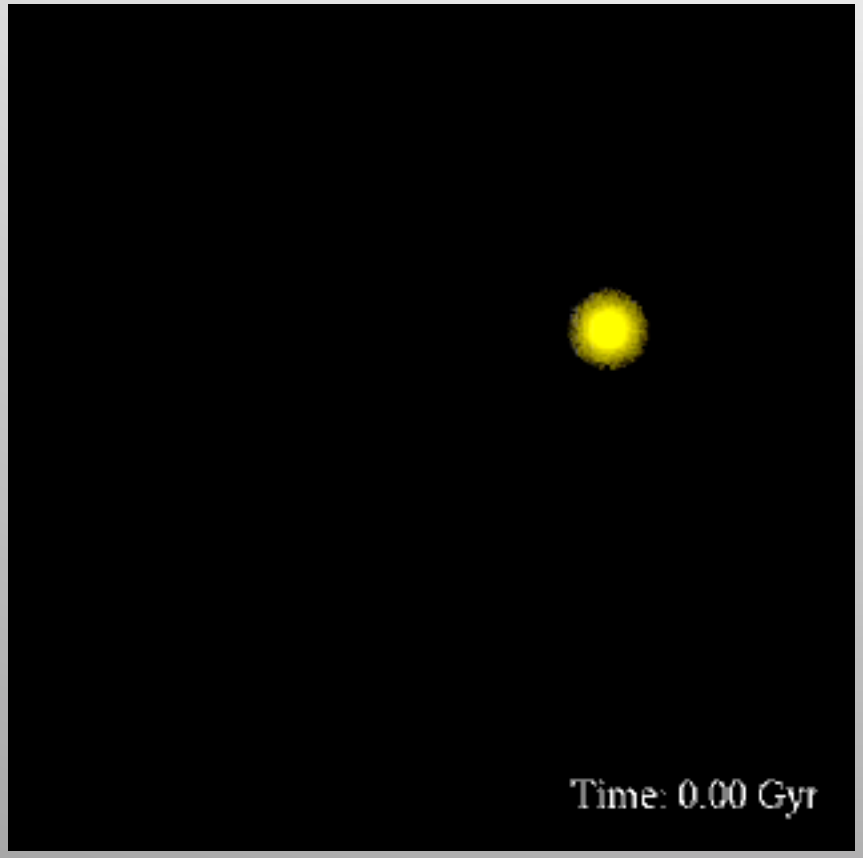


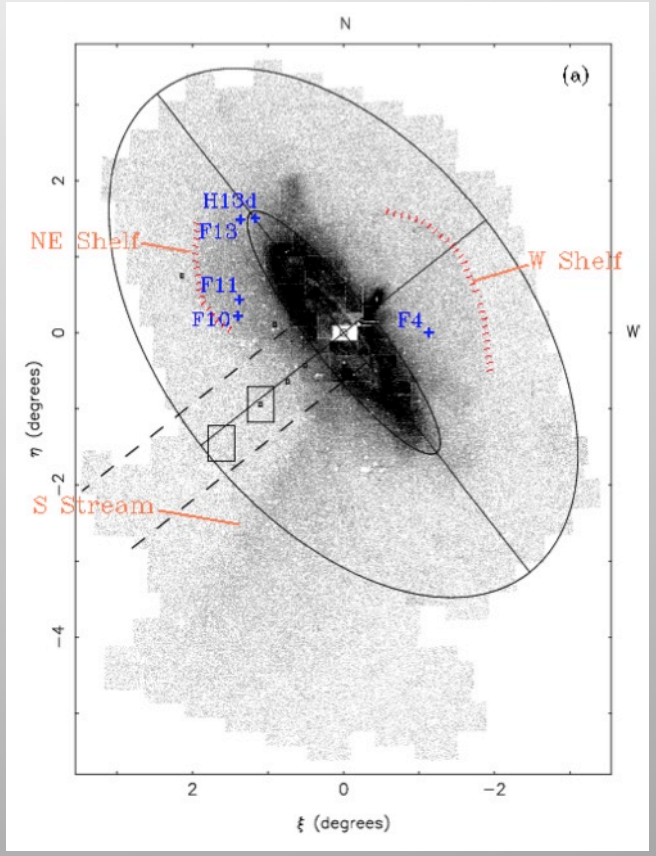
Image credit: Mike Irwin

McConnachie et al. 2009

The Merger of a Dwarf Galaxy with Andromeda

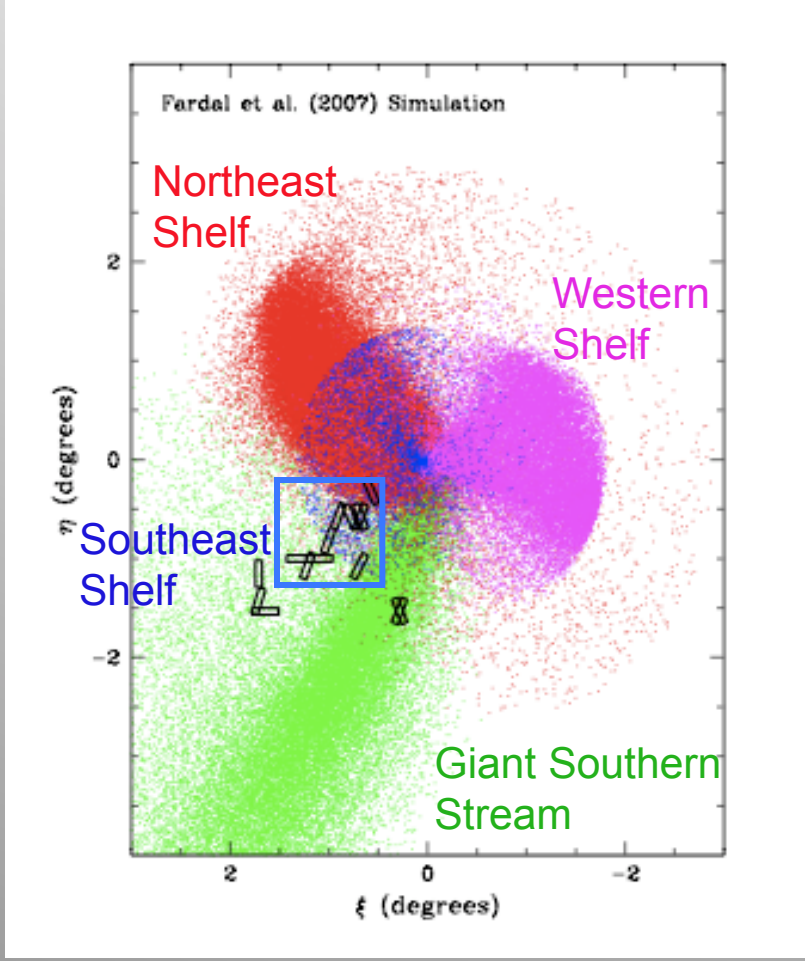


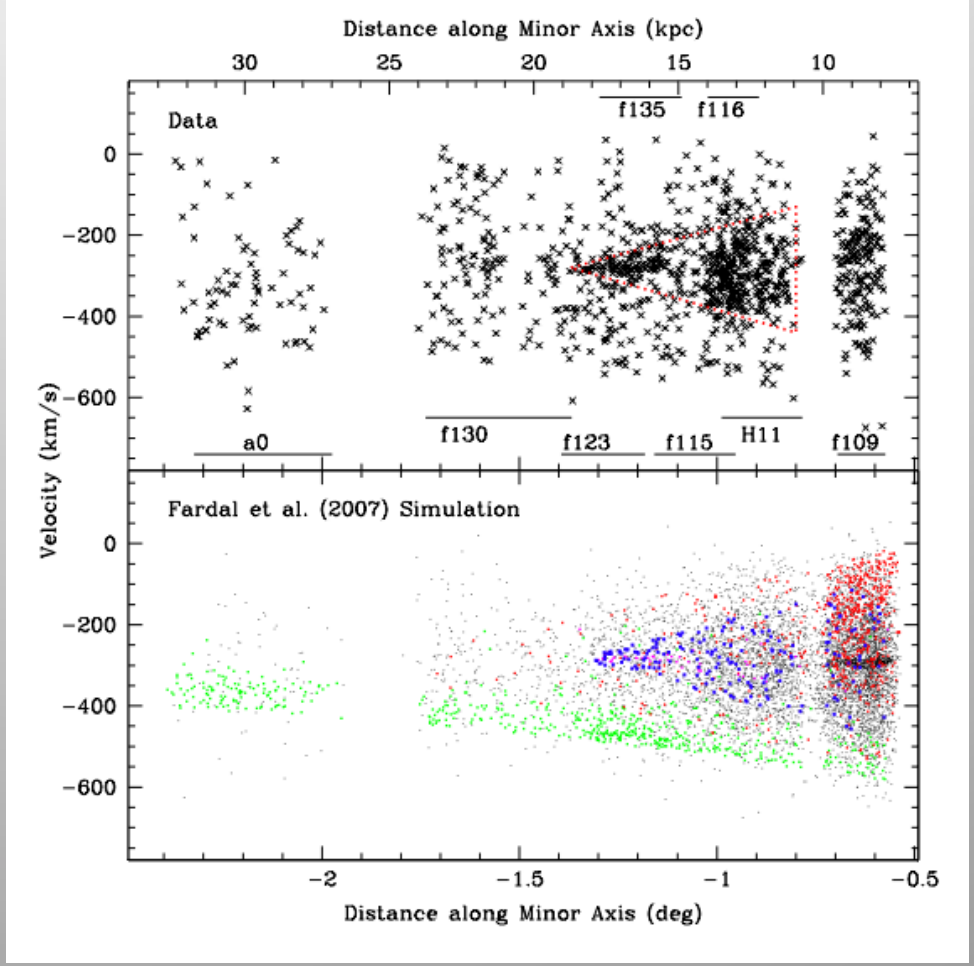
Fardal et al. 2007, MNRAS



Ferguson et al. 2002, AJ

Comparison of Data to Simulations



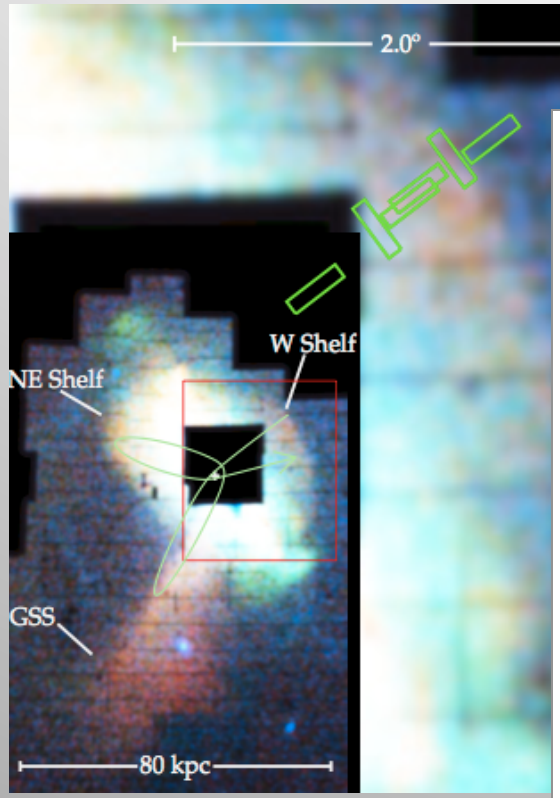


Gilbert et al. 2007

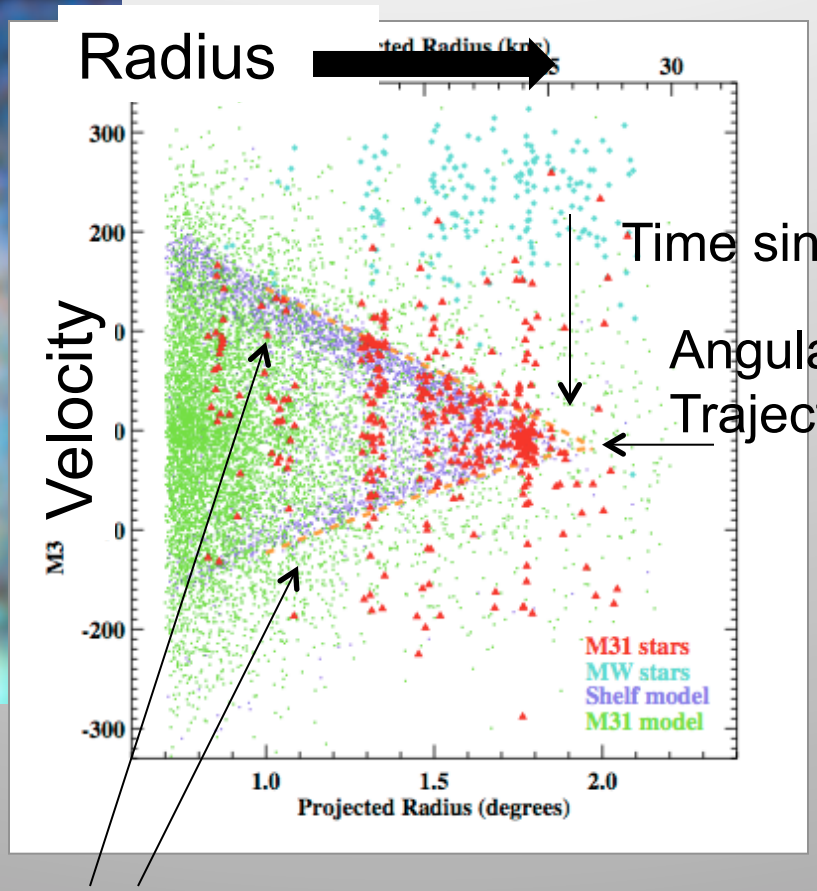
See also Fardal et al. 2007

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

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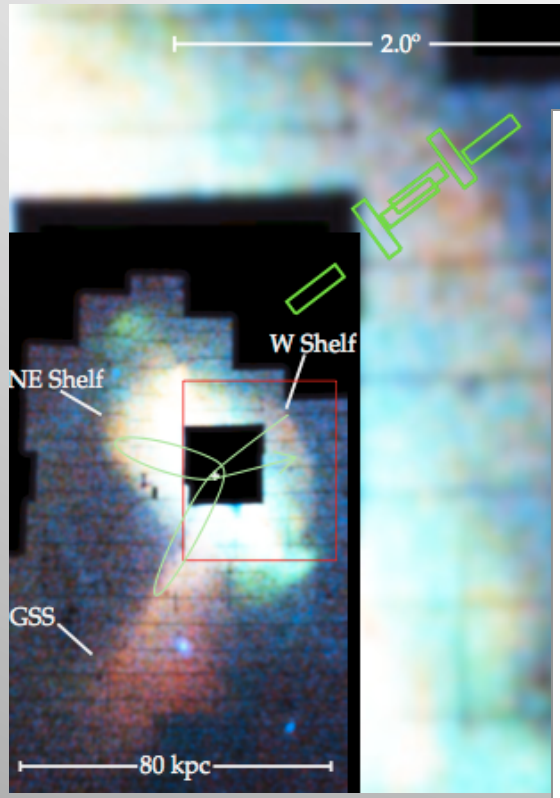
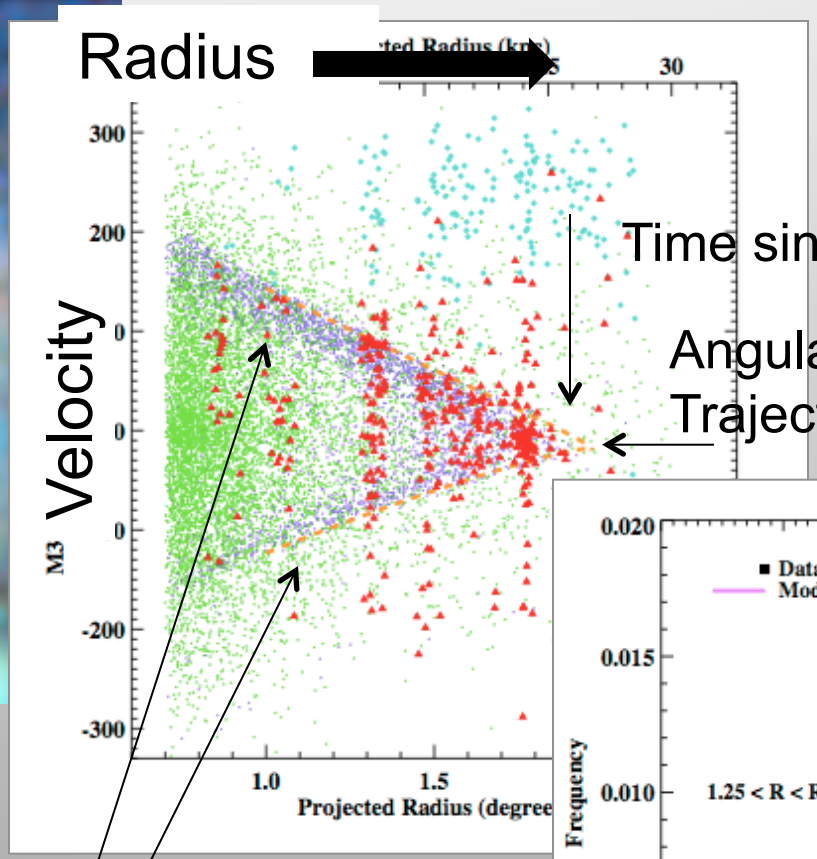


Fardal et al. 2012



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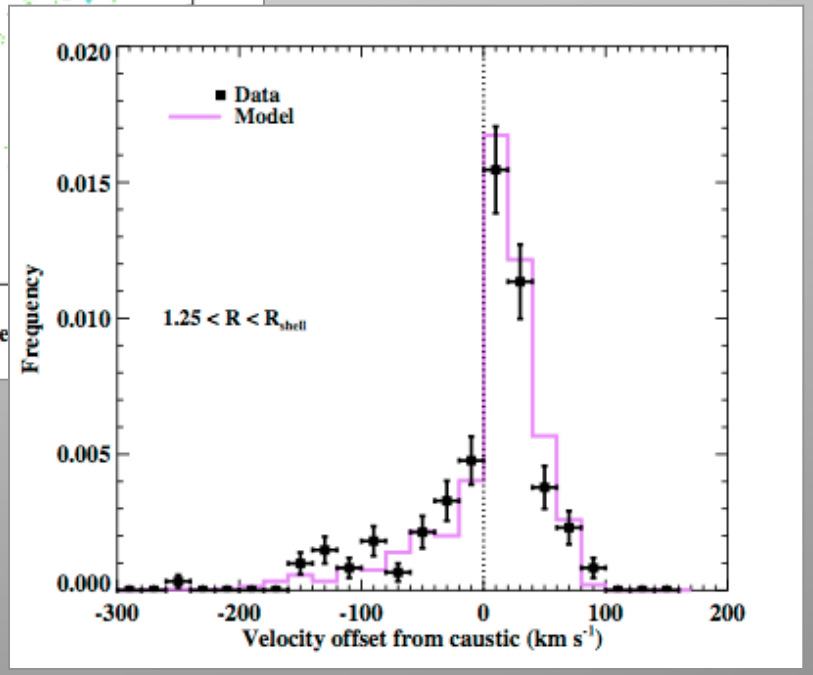

Ratio of stars: density gradient along stream

log(M200) = 12.3 +/- 0.1

Fardal et al. 2013

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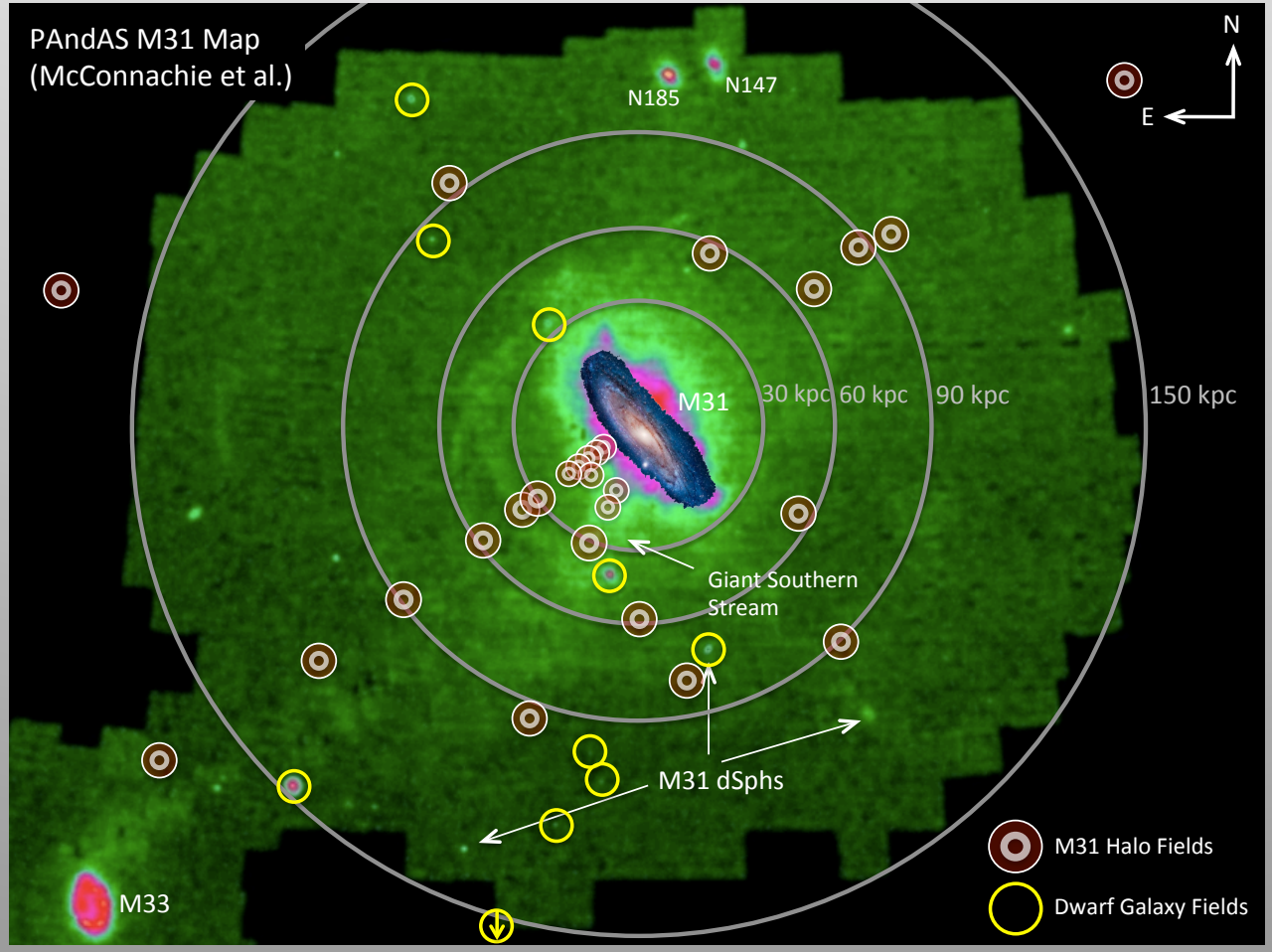
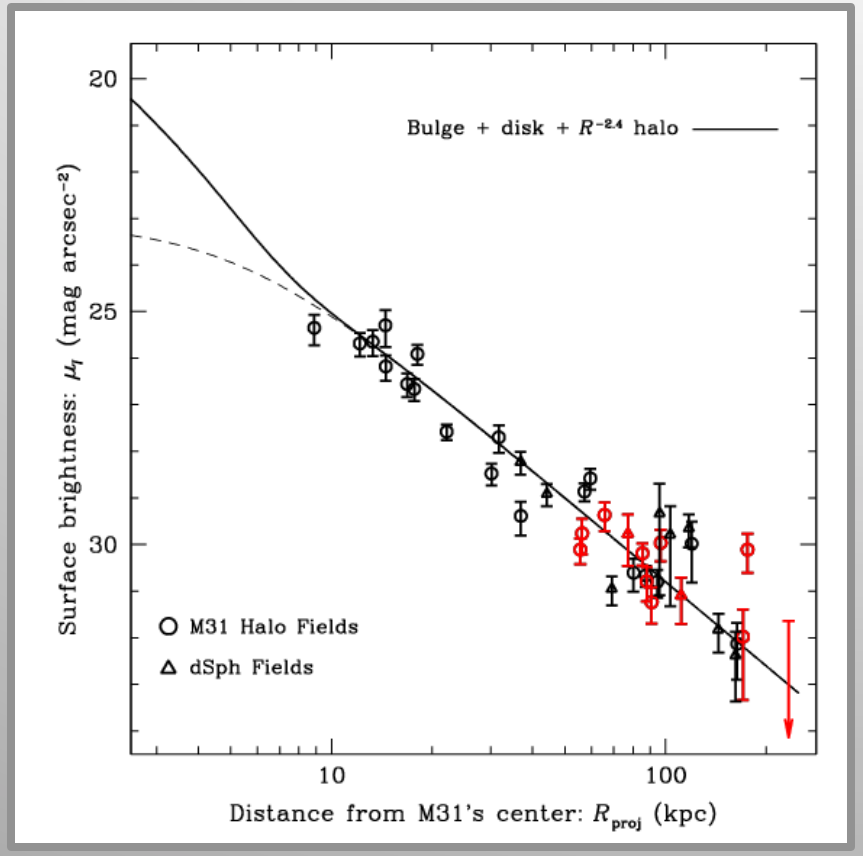
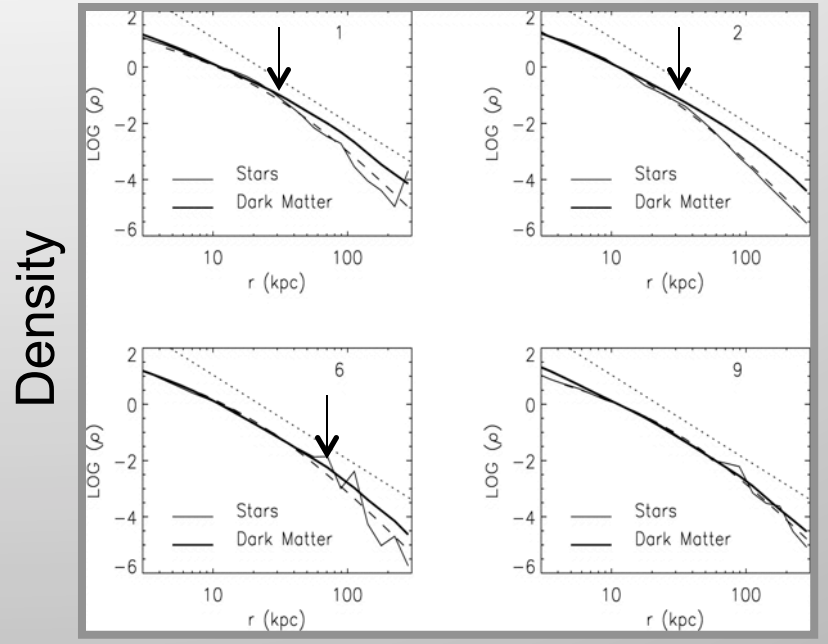


Global Properties of M31's Halo: Implications for M31's Merger History





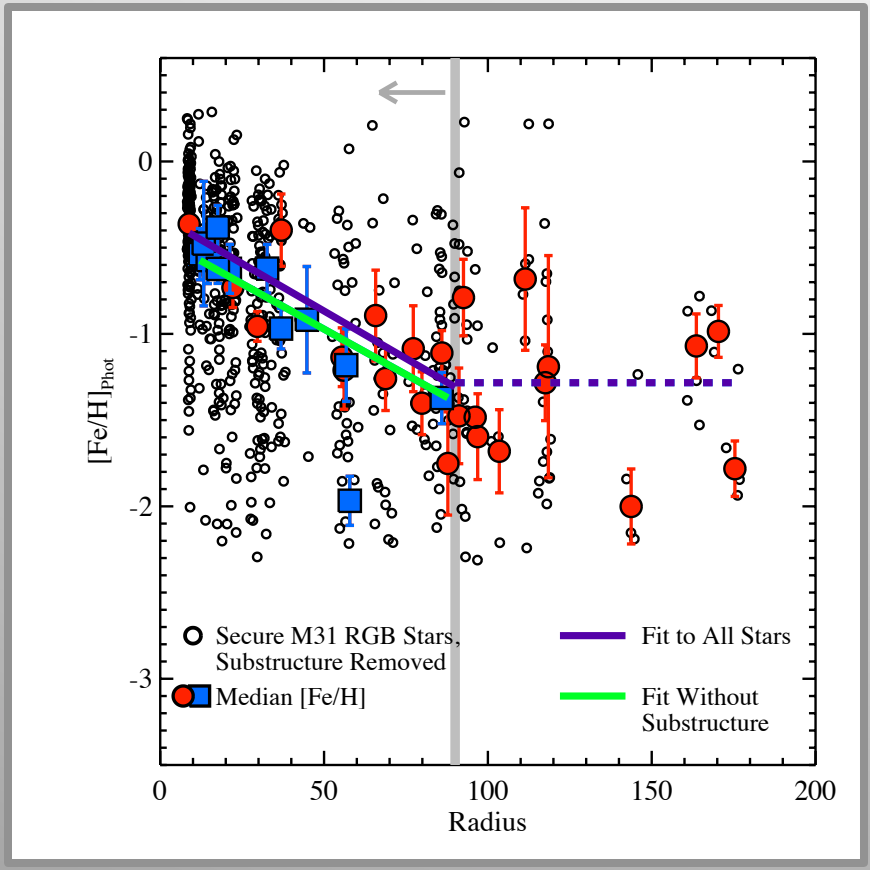
Observed: Lack of break in density profile, Increased variation at large radii

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



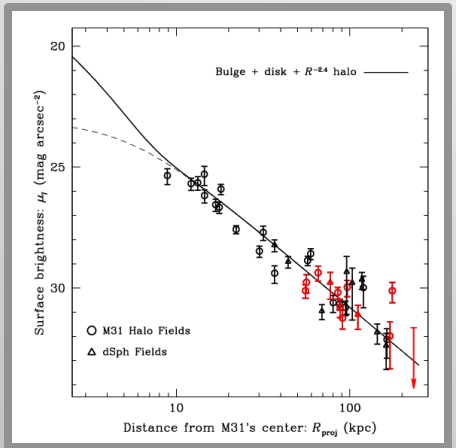
Observed: Significant metallicity gradient to large radii, even after removal of GSS

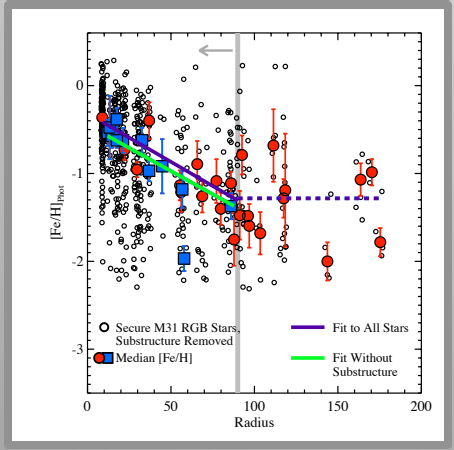
Implication: M31 halo built largely from one to a few early, relatively massive (>10^9 M_{sun}) accretion events

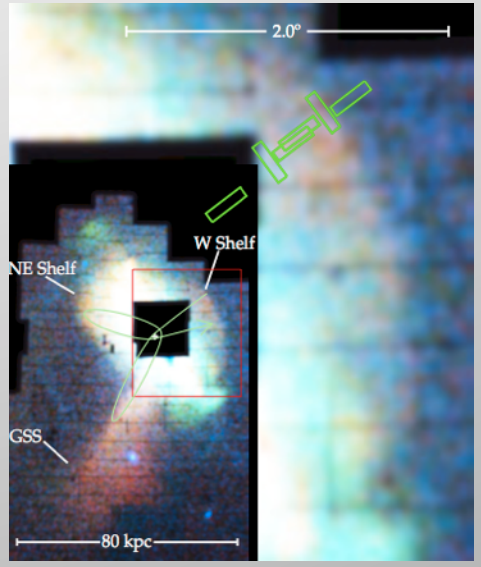
Tissera 2014, Cooper 2010

Gilbert et al. 2012, 2014

Formation History of Andromeda's Stellar Halo







- ~ LMC sized system
- Collided 760 Myr ago

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

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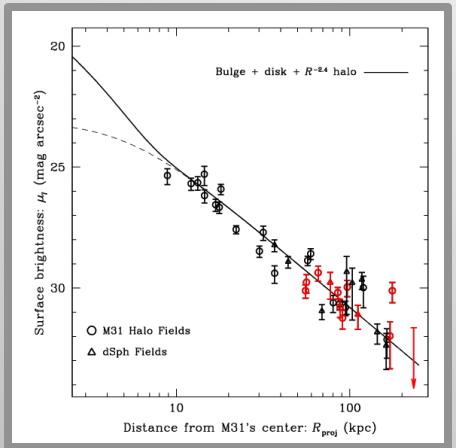
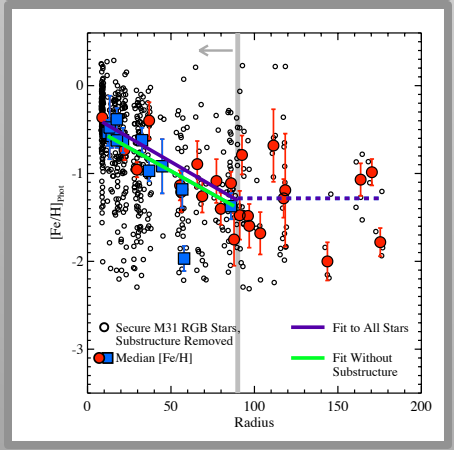
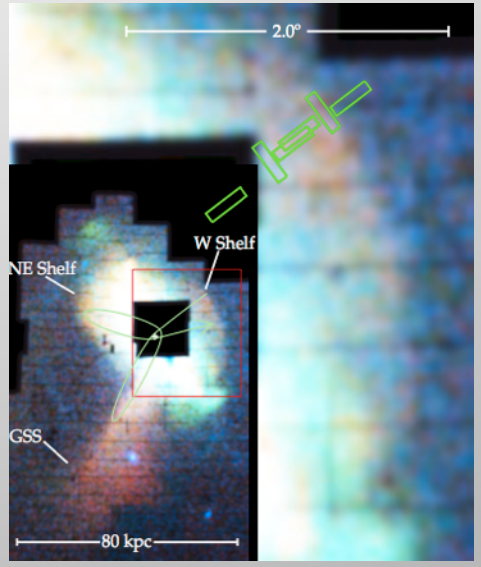




Accretion History Profile

Luminosity Function, Time of Accretion of Accreted Satellites



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Deducing Properties of Destroyed Satellites

Surface Brightness of stellar streams is easily observed…

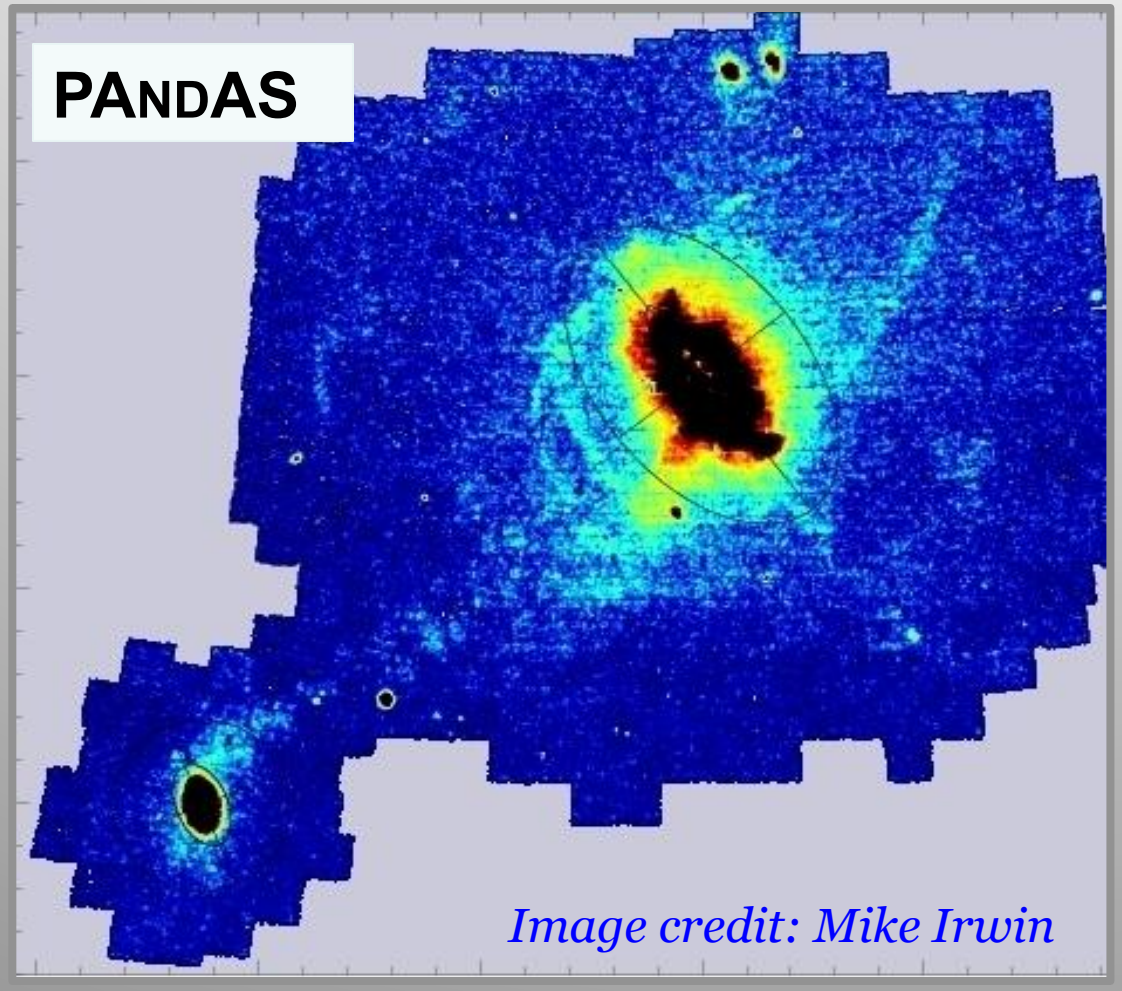
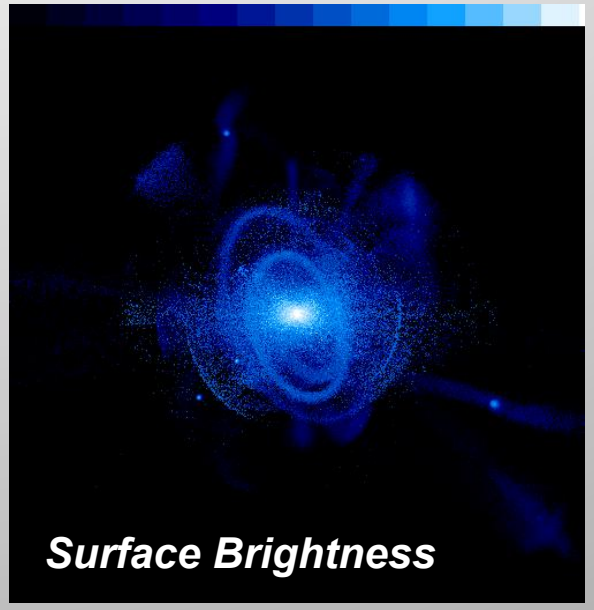


Image credit: Mike Irwin

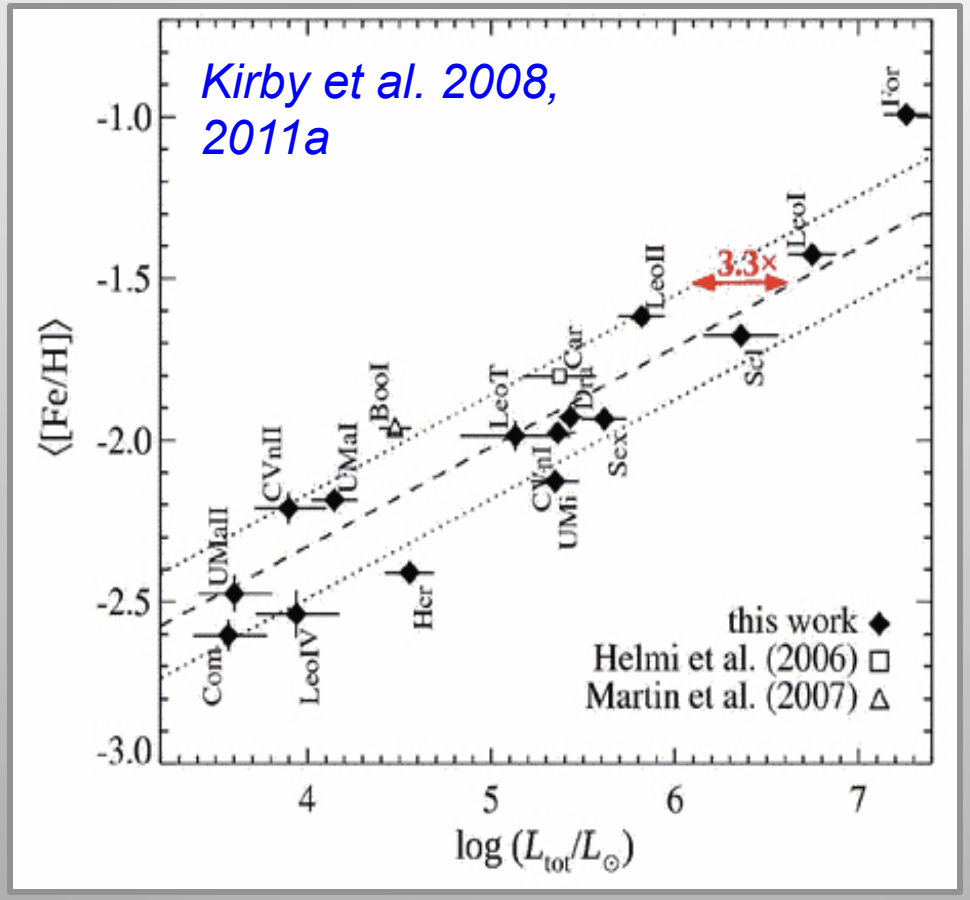
McConnachie et al. 2009

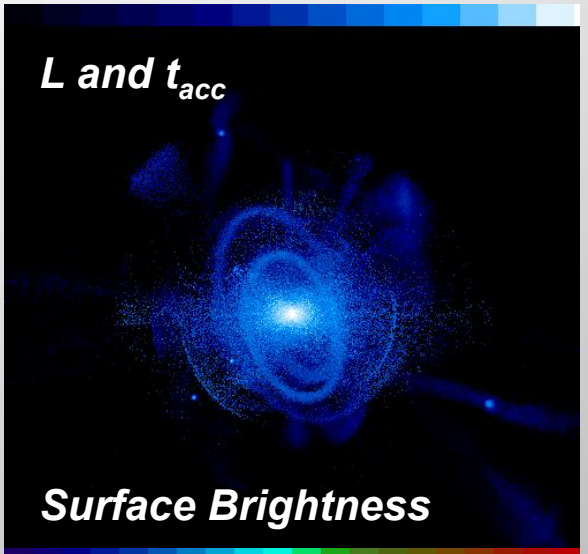


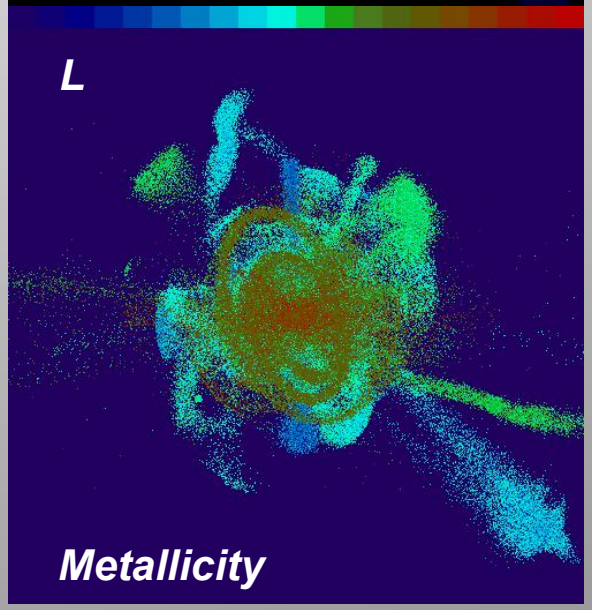
Bullock & Johnston (2005) models

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

Deducing Properties of Destroyed Satellites



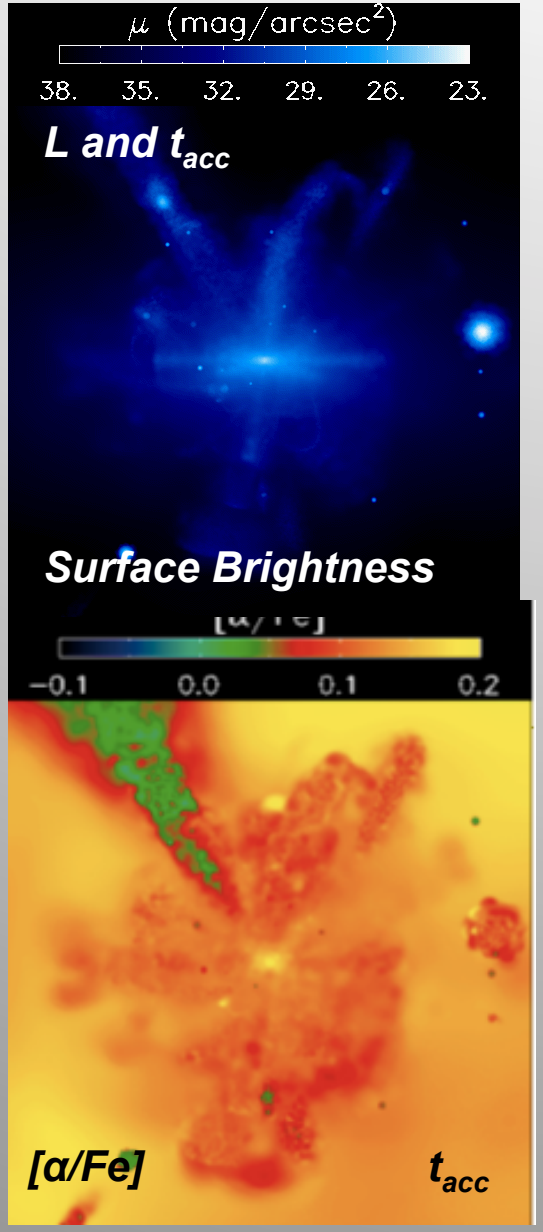


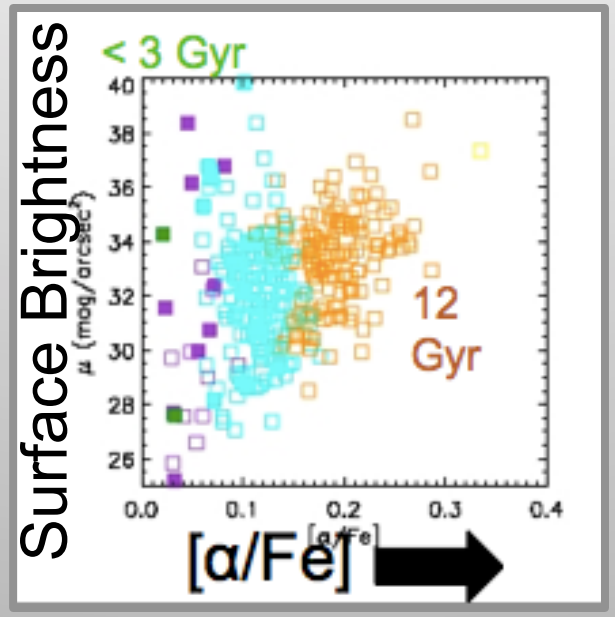


The mean metallicity of a stream is related to the luminosity of the accreted satellite.

Johnston et al. 2008
Bullock & Johnston (2005) models

Deducing Properties of Destroyed Satellites





First Star Formation

Type II SNe – α elements

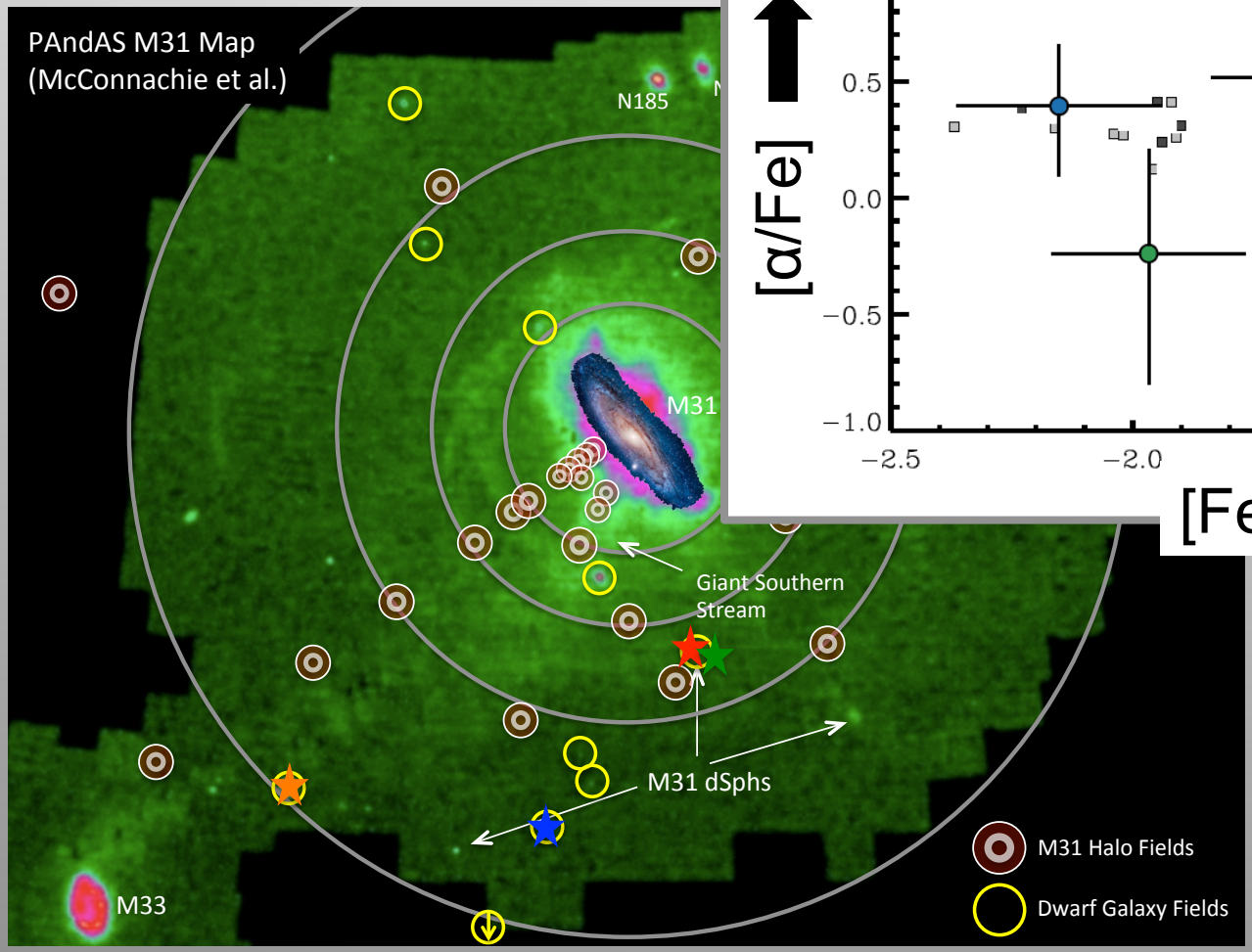
Time passes….

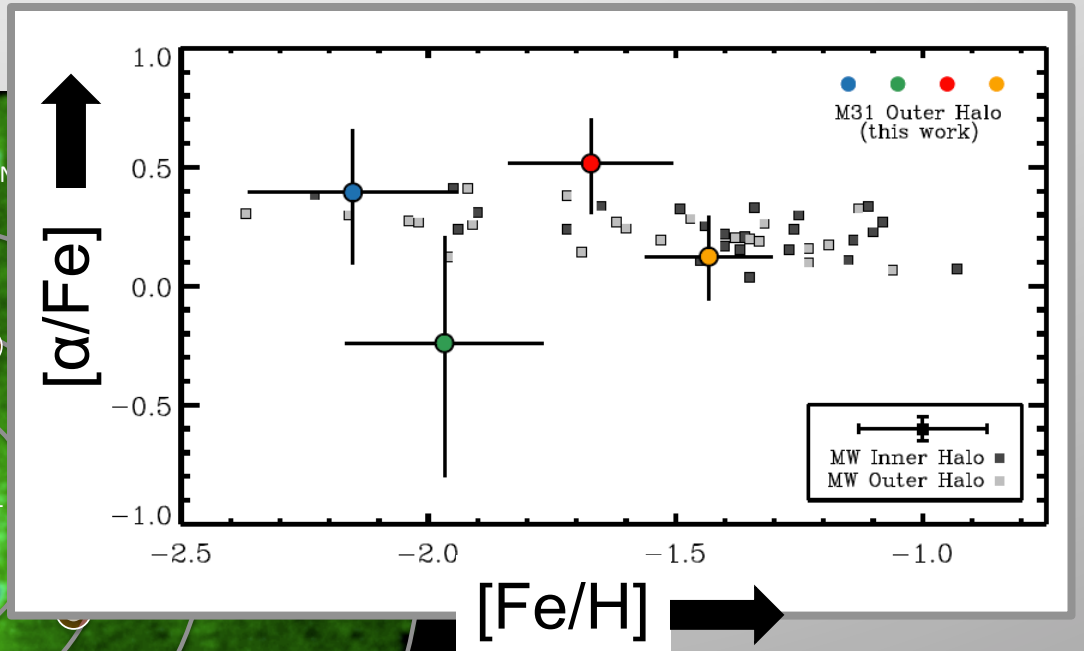
Type 1 Sne – Fe

The α/Fe abundance of a stream is related to the length of star formation in the accreted satellite.

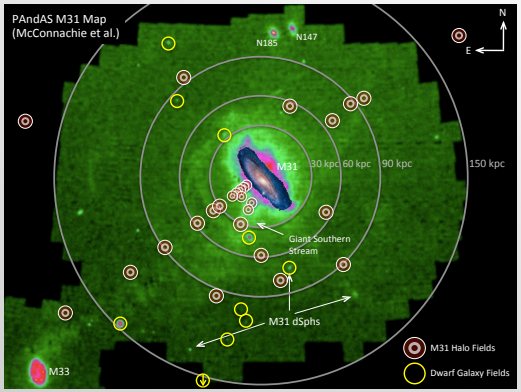
First Measurements of [α/Fe] in M31's Stellar Halo

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

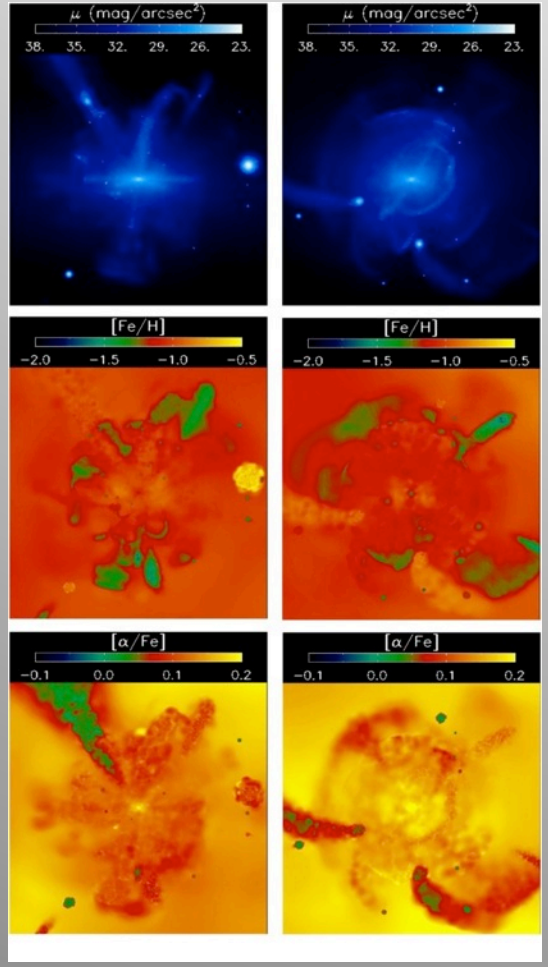




Vargas, Gilbert et al. 2014



Dwarf Galaxies accreted, accreting, yet to be accreted



μ

[Fe/H]

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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:

- **Secure identification of M31 stars: sensitivity to extremely sparse halo, stream, and satellite populations**
- **Kinematics: the ability to identify faint tidal debris features and study their effect on measurements of global halo properties**
- **SPLASH has studied the three Major Phases of Minor Mergers:**
  - **Intact Satellites (dEs (M32, NGC 147, 185, 205) and dSphs)**
  - **Stellar Streams (giant southern stream, other halo streams)**
  - **"Smooth" Stellar Halo**