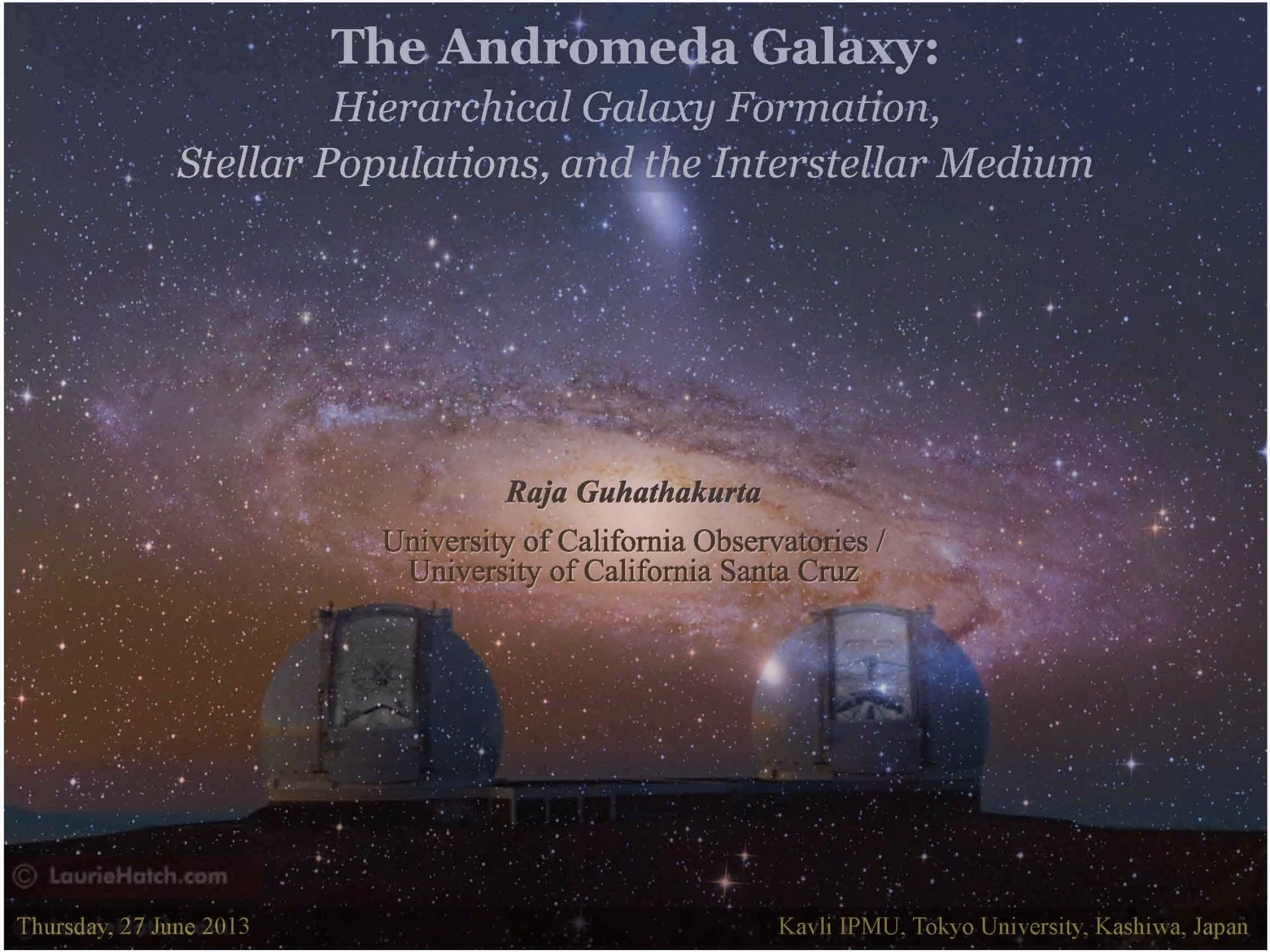
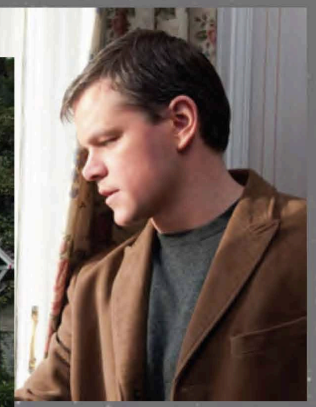
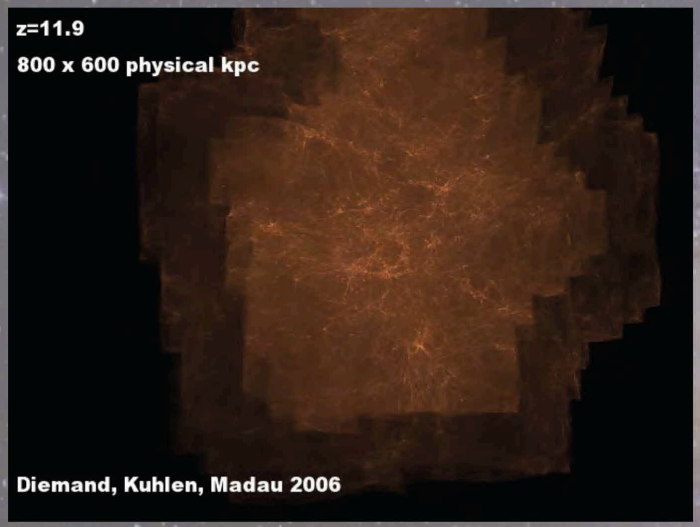

The Andromeda Galaxy:
Hierarchical Galaxy Formation,
Stellar Populations, and the Interstellar Medium
Raja Guhathakurta
University of California Observatories /
University of California Santa Cruz
© LaurieHatch.com
Thursday, 27 June 2013
Kavli IPMU, Tokyo University, Kashiwa, Japan

Outline

The house next door

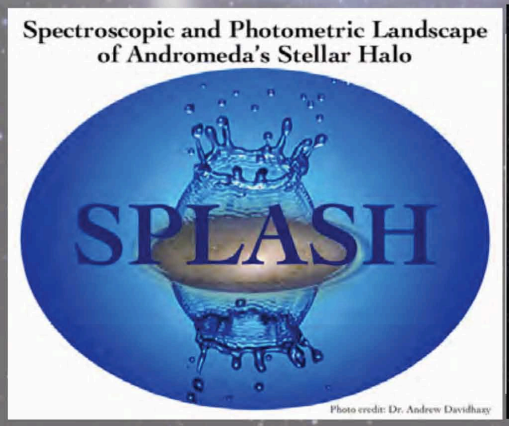


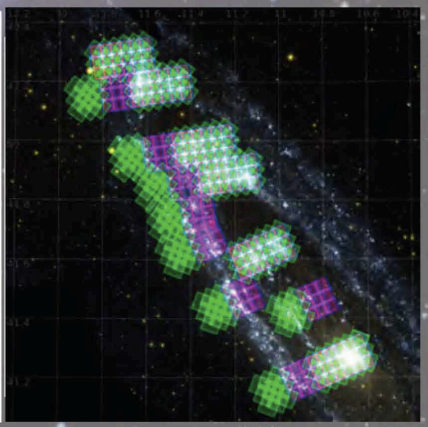


Laboratory for galaxy assembly studies

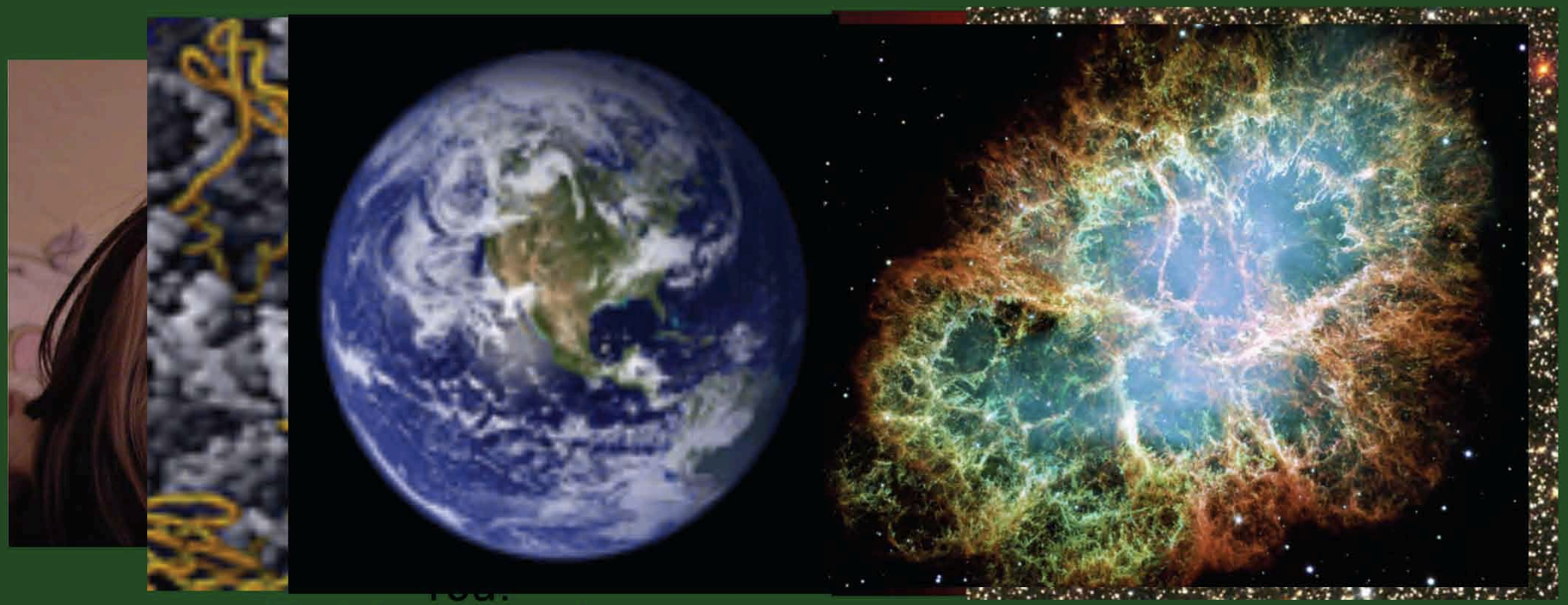
Laboratory for stellar population studies

Laboratory for interstellar dust/gas and intergalactic medium studies





Our Place in the Cosmos



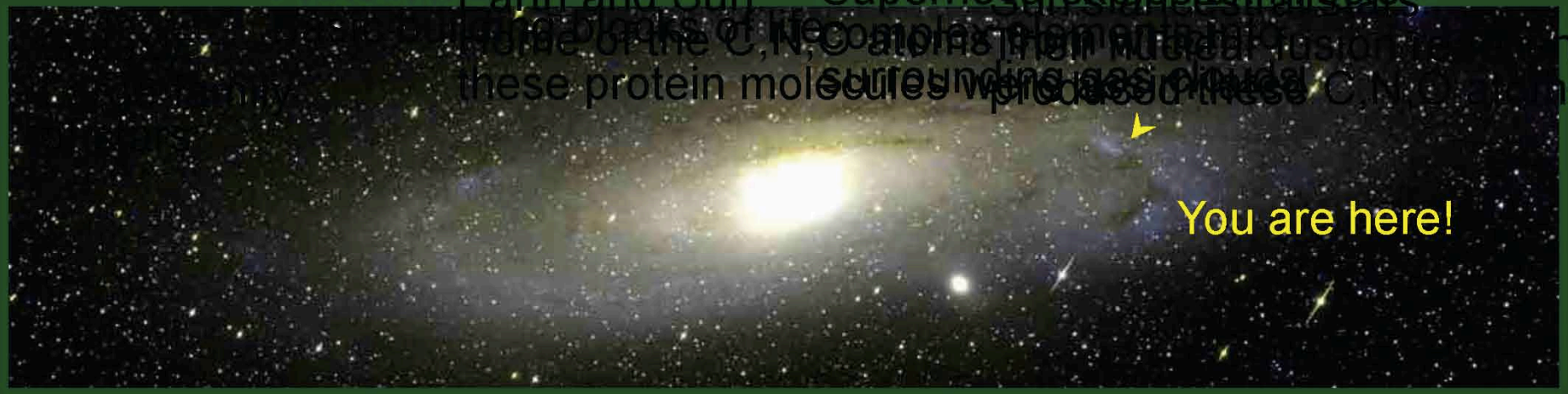
You:

Protein molecules:

Earth and Sun:

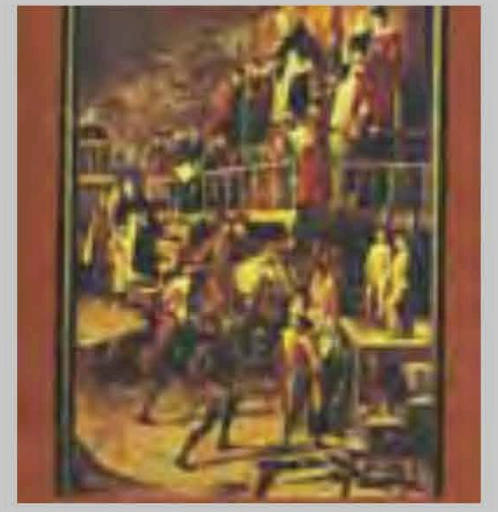
Supernova explosion injects

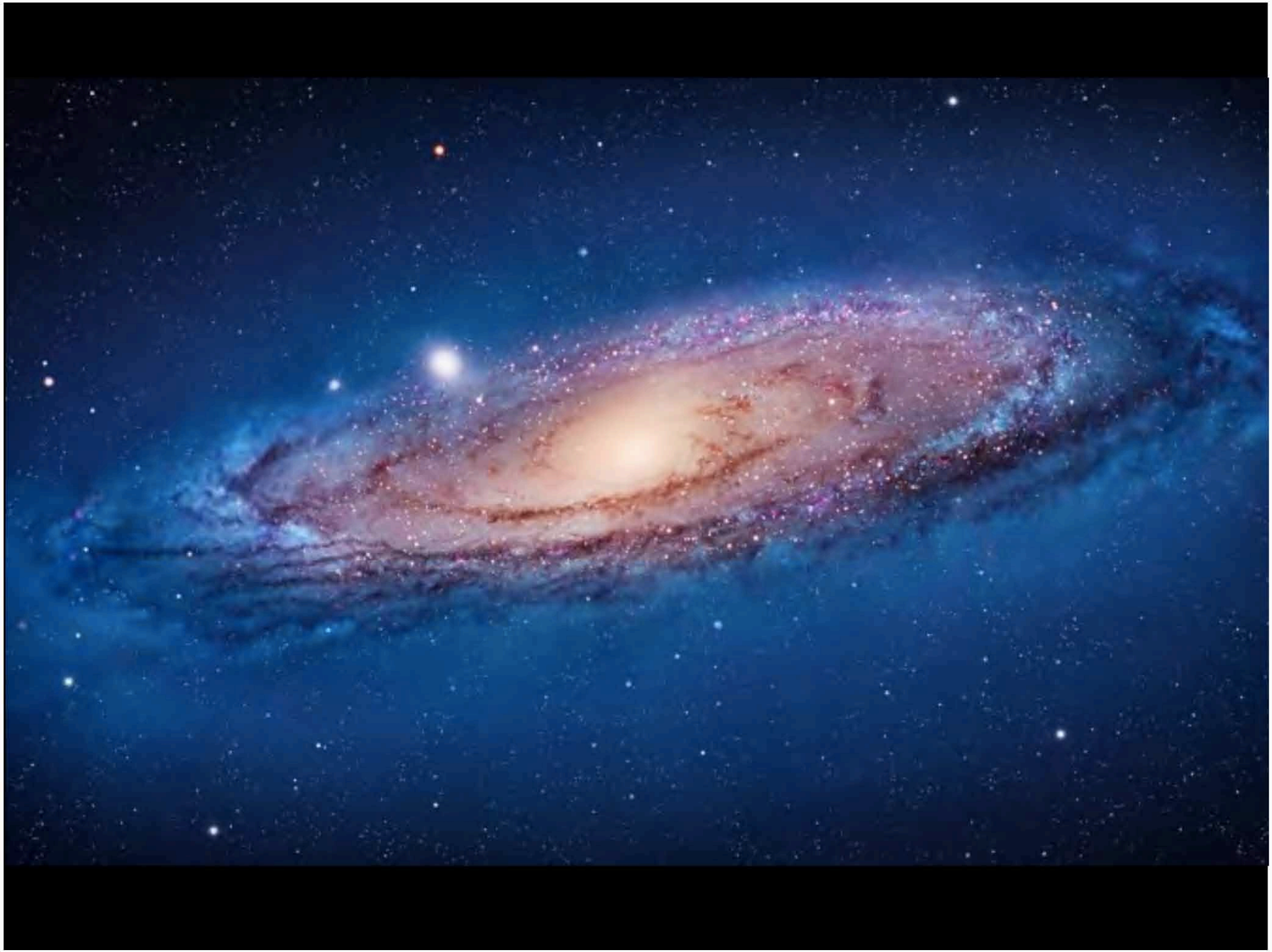
these protein molecules

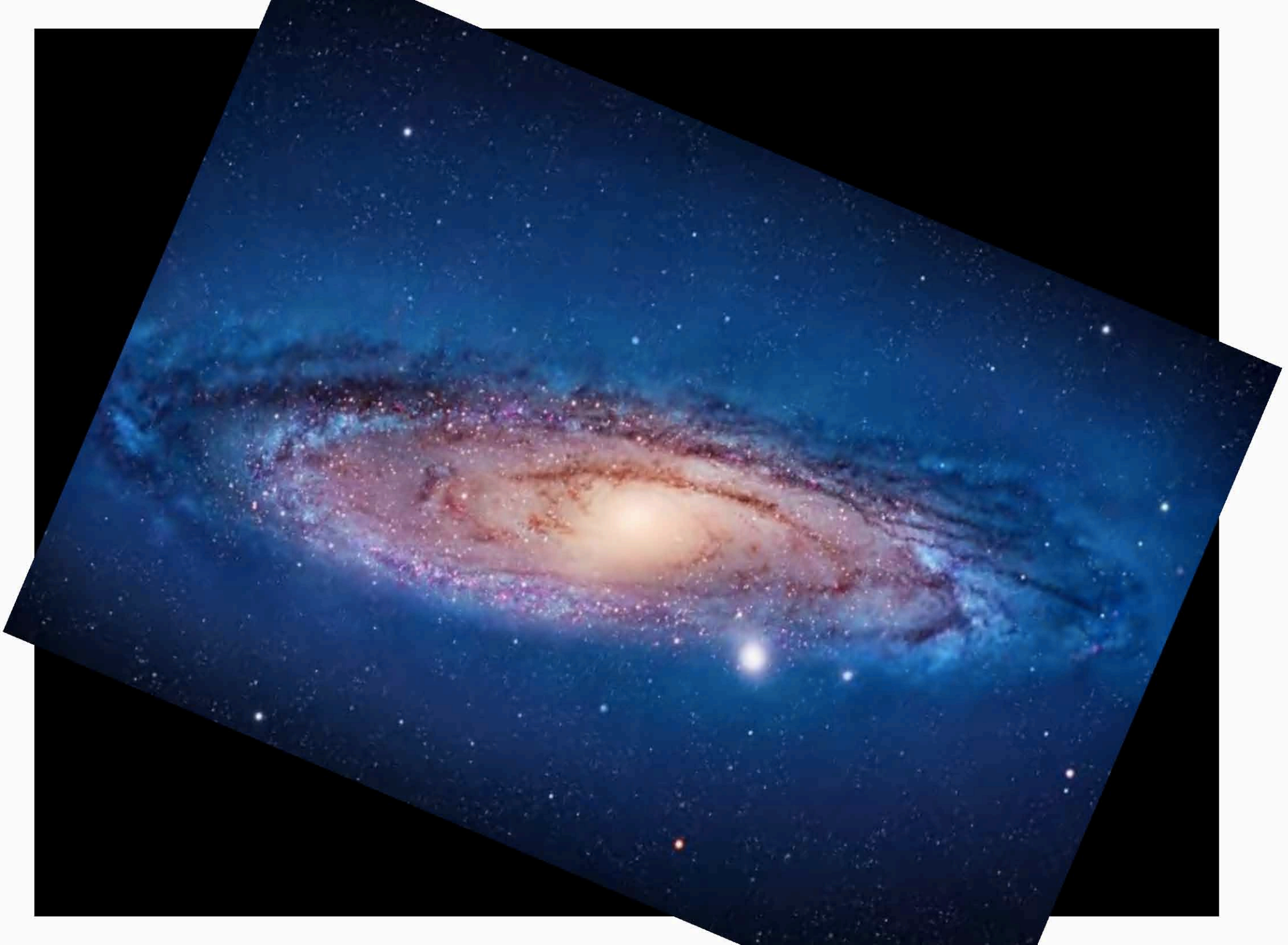


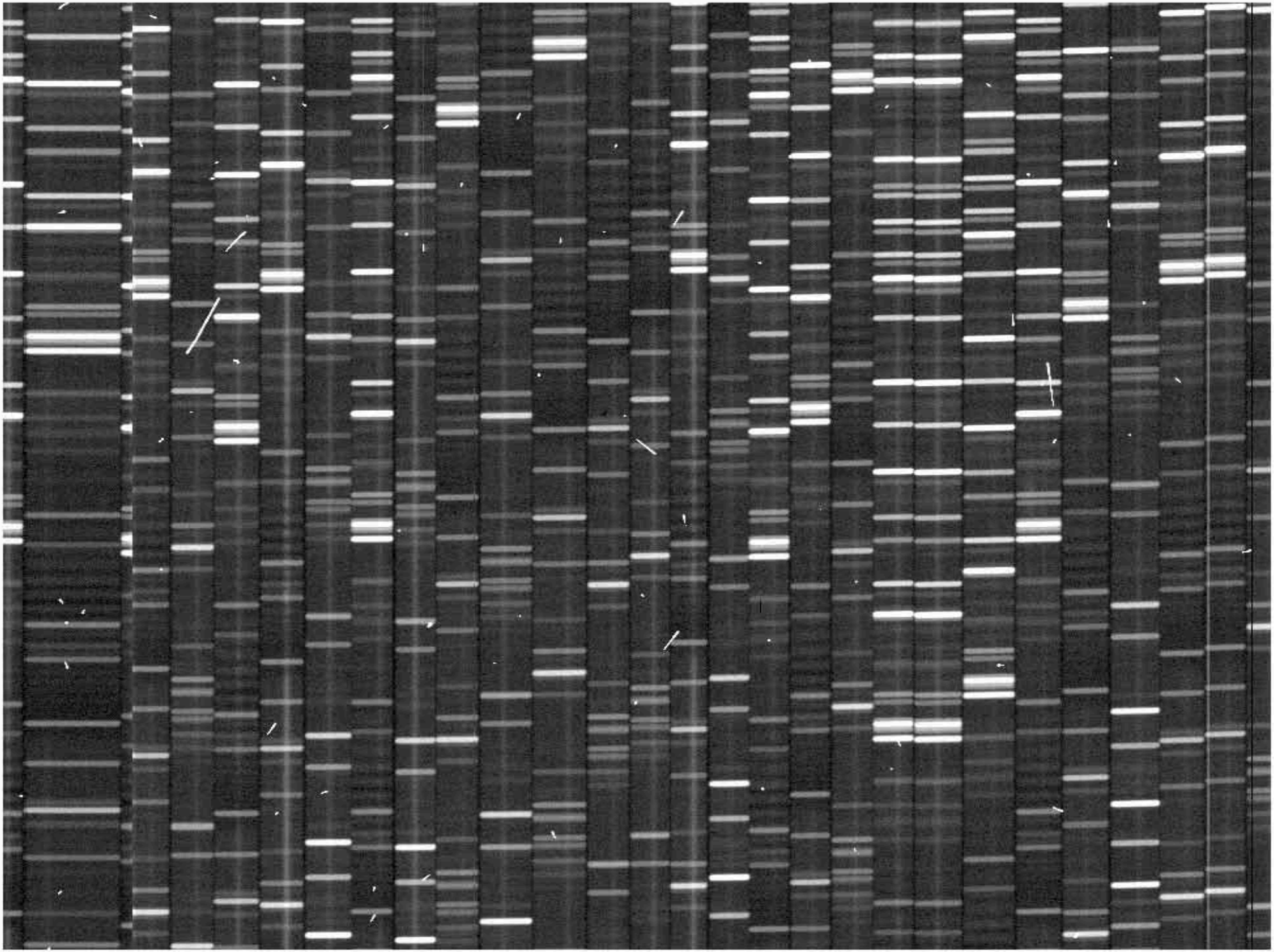
Direct Look Back to Early Epochs

Deep
Extragalactic
Evolutionary
Probe
1/2/3









Galaxy Formation Studies

– Stellar halo formation scenarios:
accretion, kicked-up disk, and *in situ* populations

– Dwarf satellites of the Local Group

– M31's unusual inner spheroid

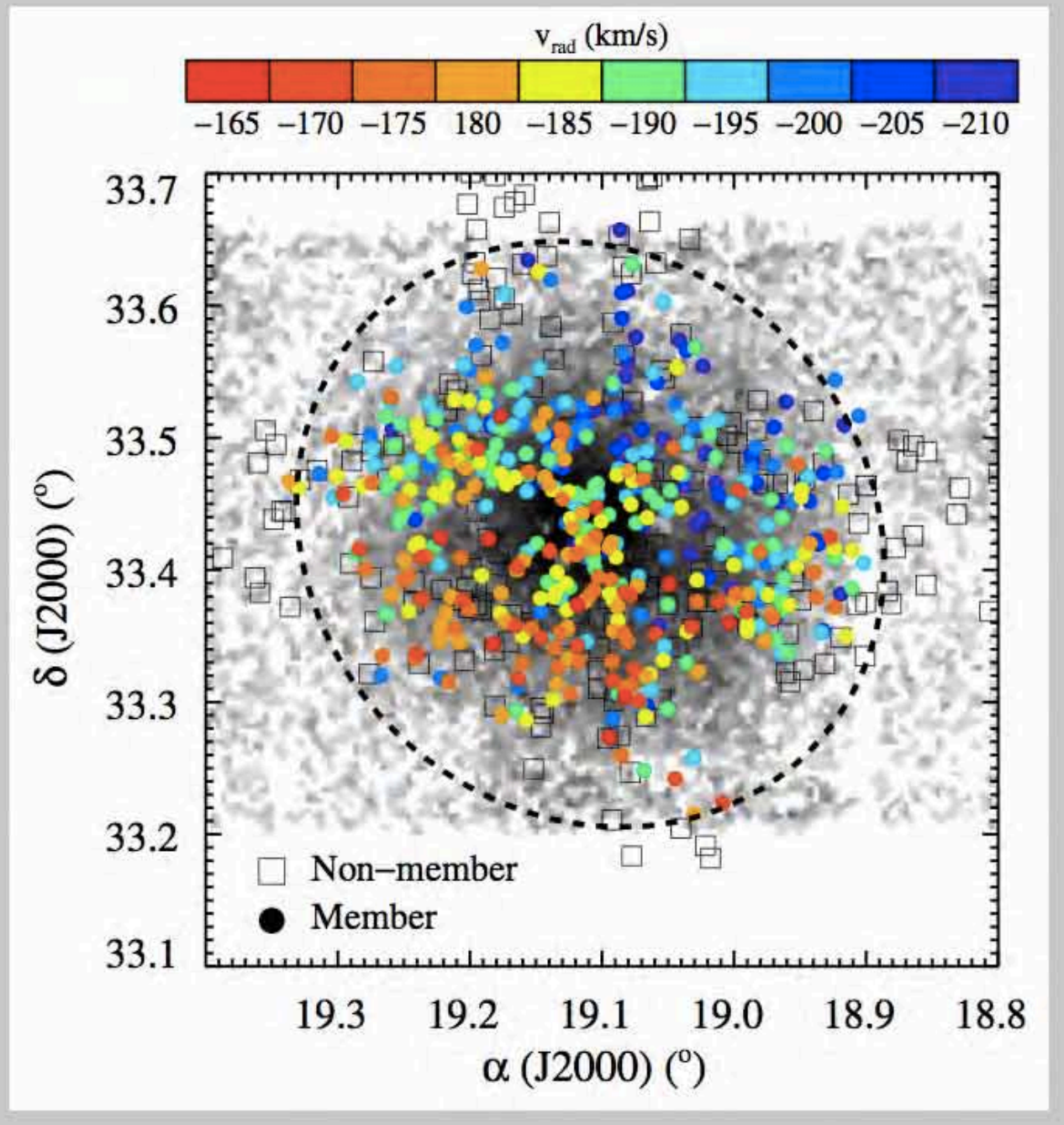
– Individual accretion events in the halo

– Effect of satellite bombardment on M31's stellar disk

– Statistical properties of the accreted halo population

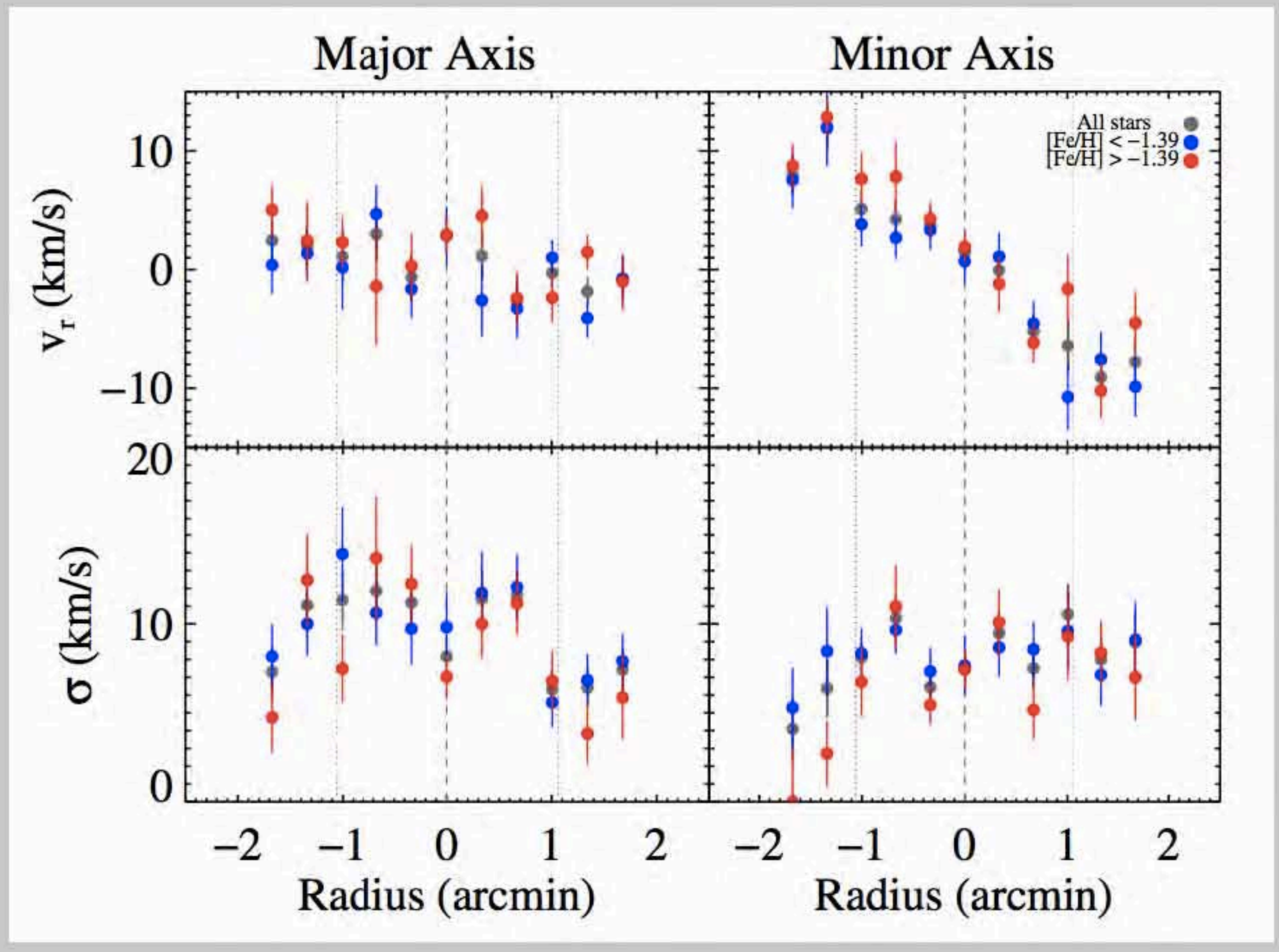
– Impending M31 / MW collision
– Shell in the MW at $r \sim 25$ kpc?
– Prospects with TMT

And II's unusual internal stellar kinematics



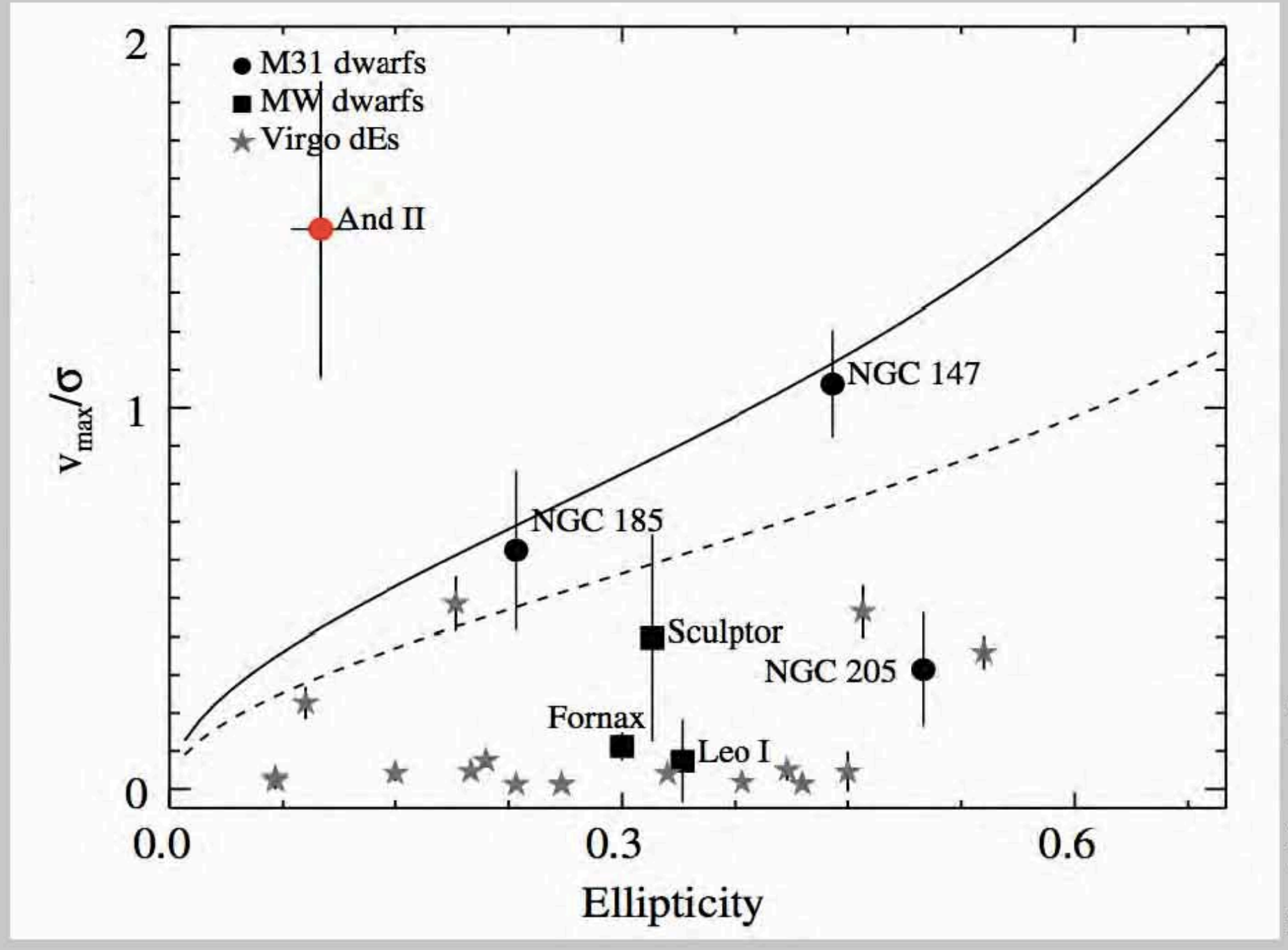
Ho et al (2012, ApJ)

And II's unusual internal stellar kinematics



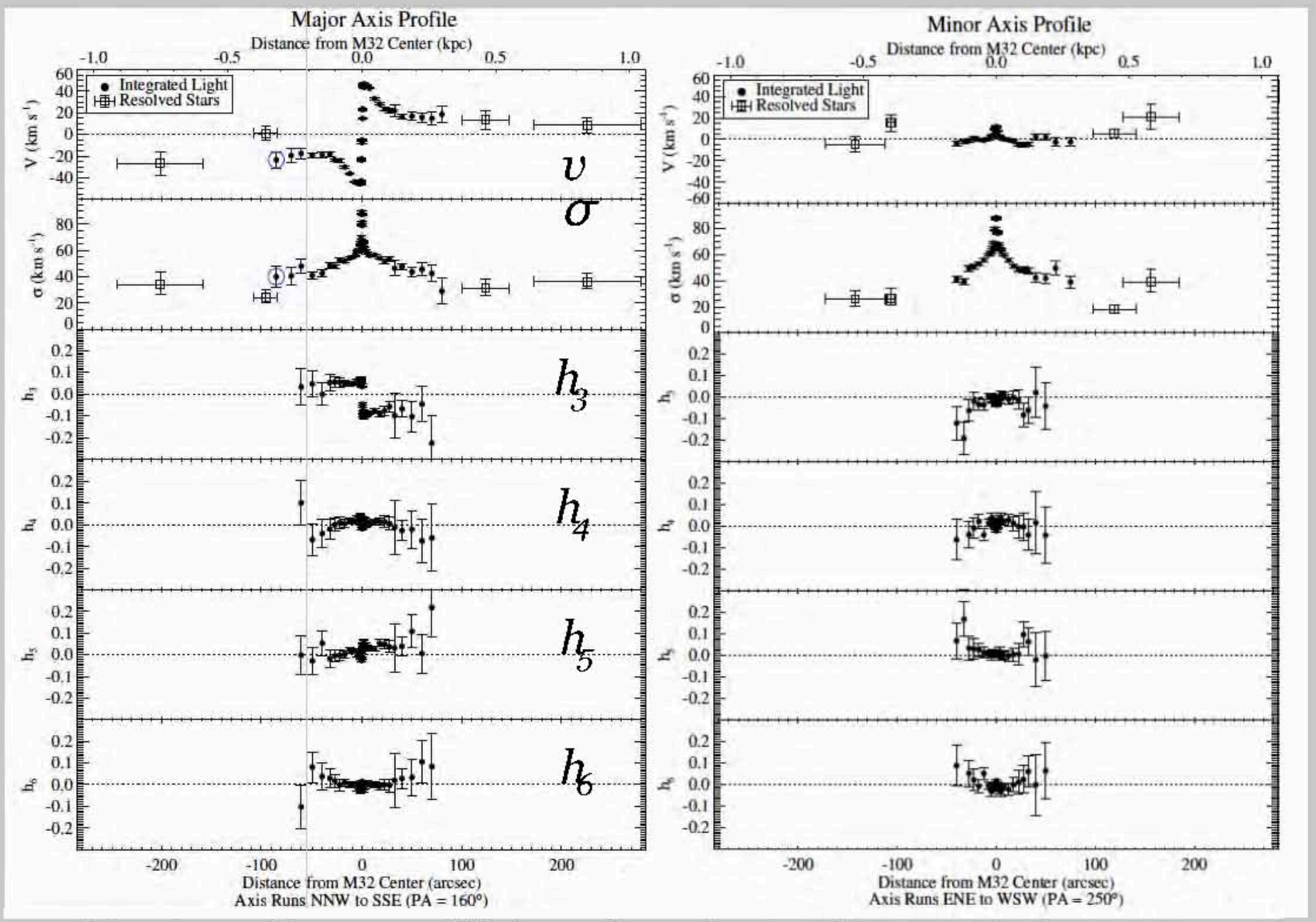
Ho et al (2012, ApJ)

And II's unusual internal stellar kinematics



Ho et al (2012, ApJ)

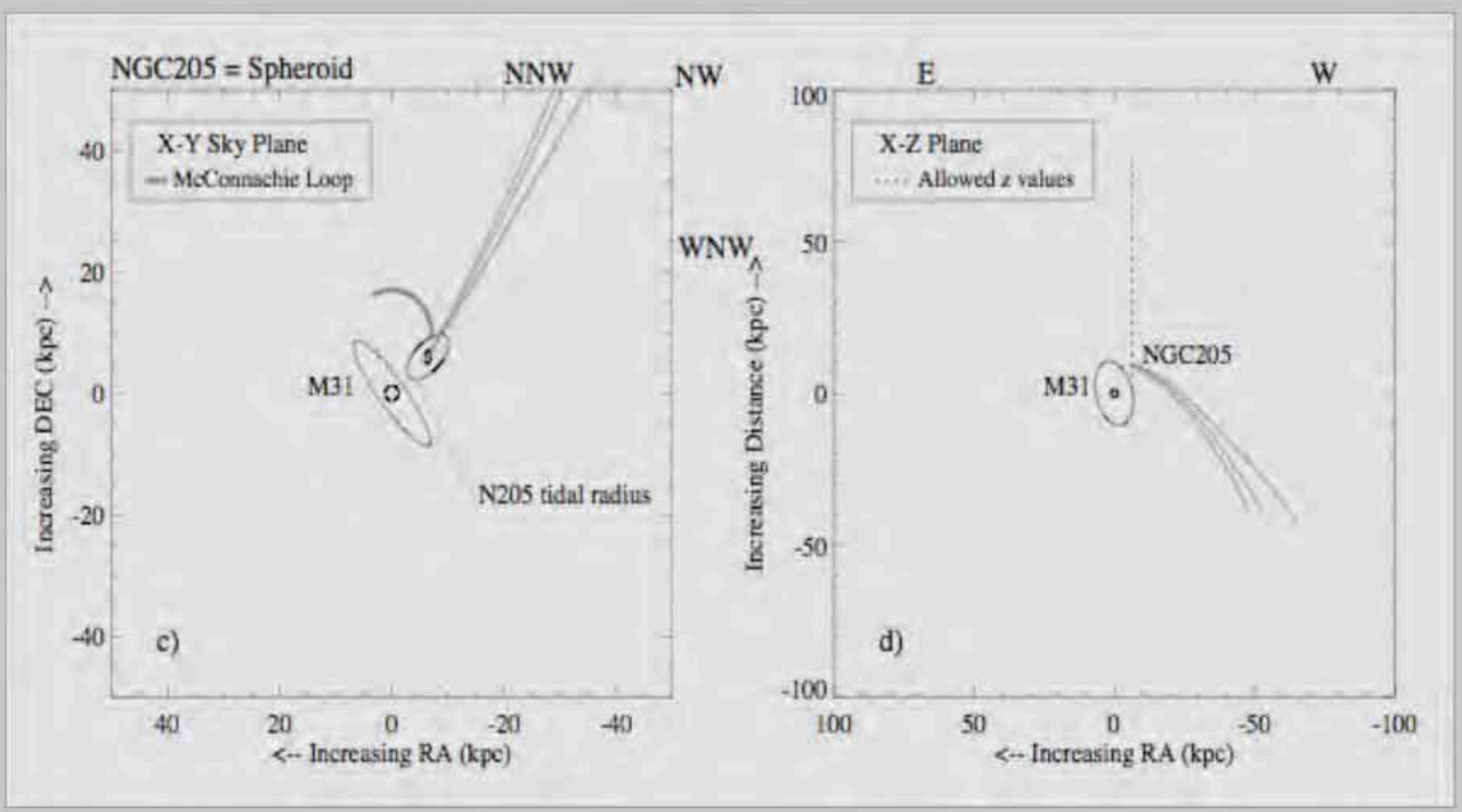
M32's remarkably regular internal kinematics



Howley, PG, et al (2013, ApJ)

A combination of integrated light and resolved stellar population spectroscopy

Effects of tidal distortion on NGC 205's morphology & kinematics

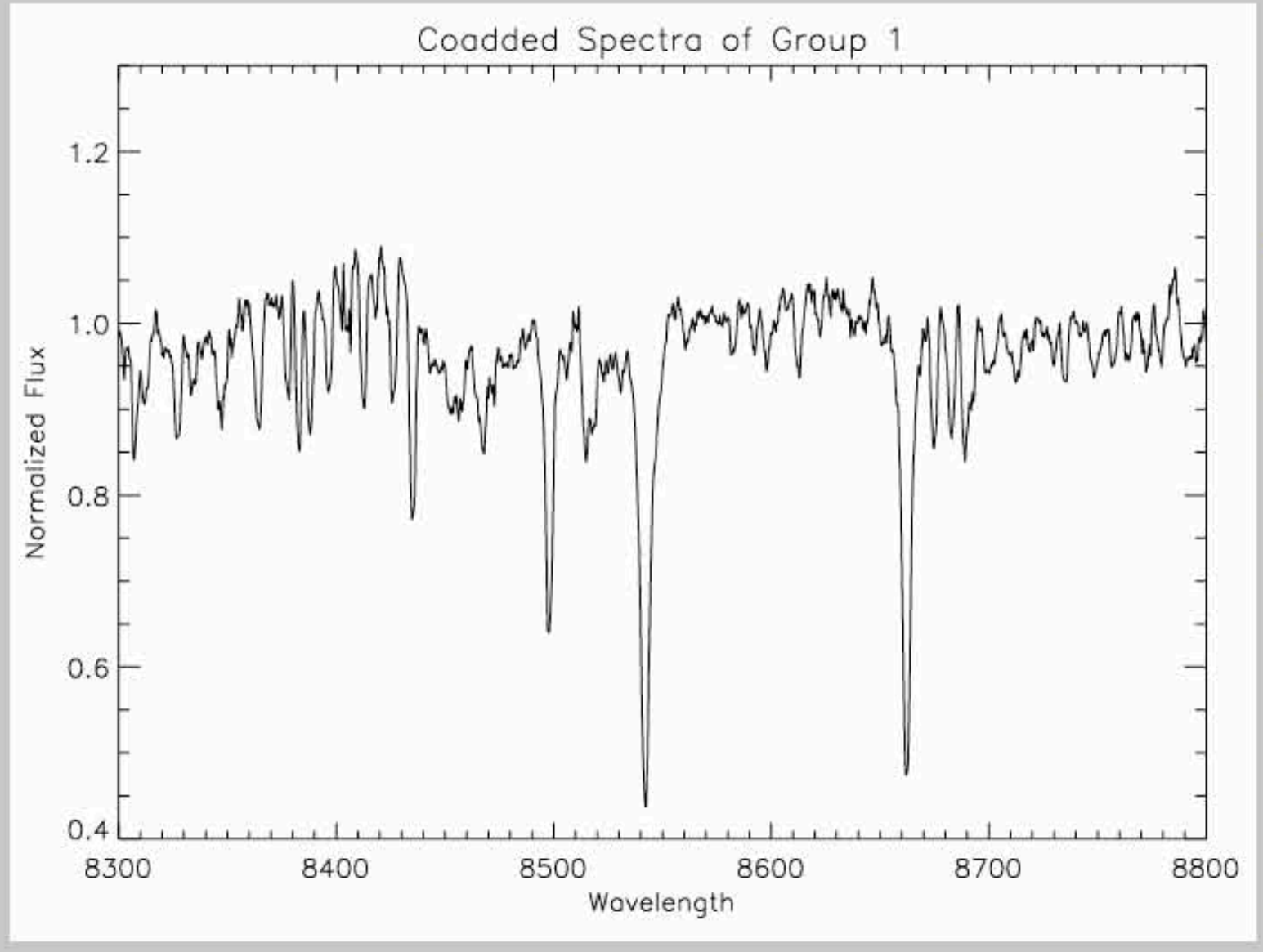


Dynamical modelling using a genetic algorithm indicates that NGC 205 is approaching from the NW, on a very eccentric orbit, possibly on its first close passage. Observations can be reproduced with a dynamically cold rotating or hot non-rotating progenitor.

Geha, PG, Rich & Cooper (2006, AJ)

Howley et al. (2008, ApJ)

Series of *co-added* spectra of red giant stars in the luminous Andromeda satellite, NGC 147

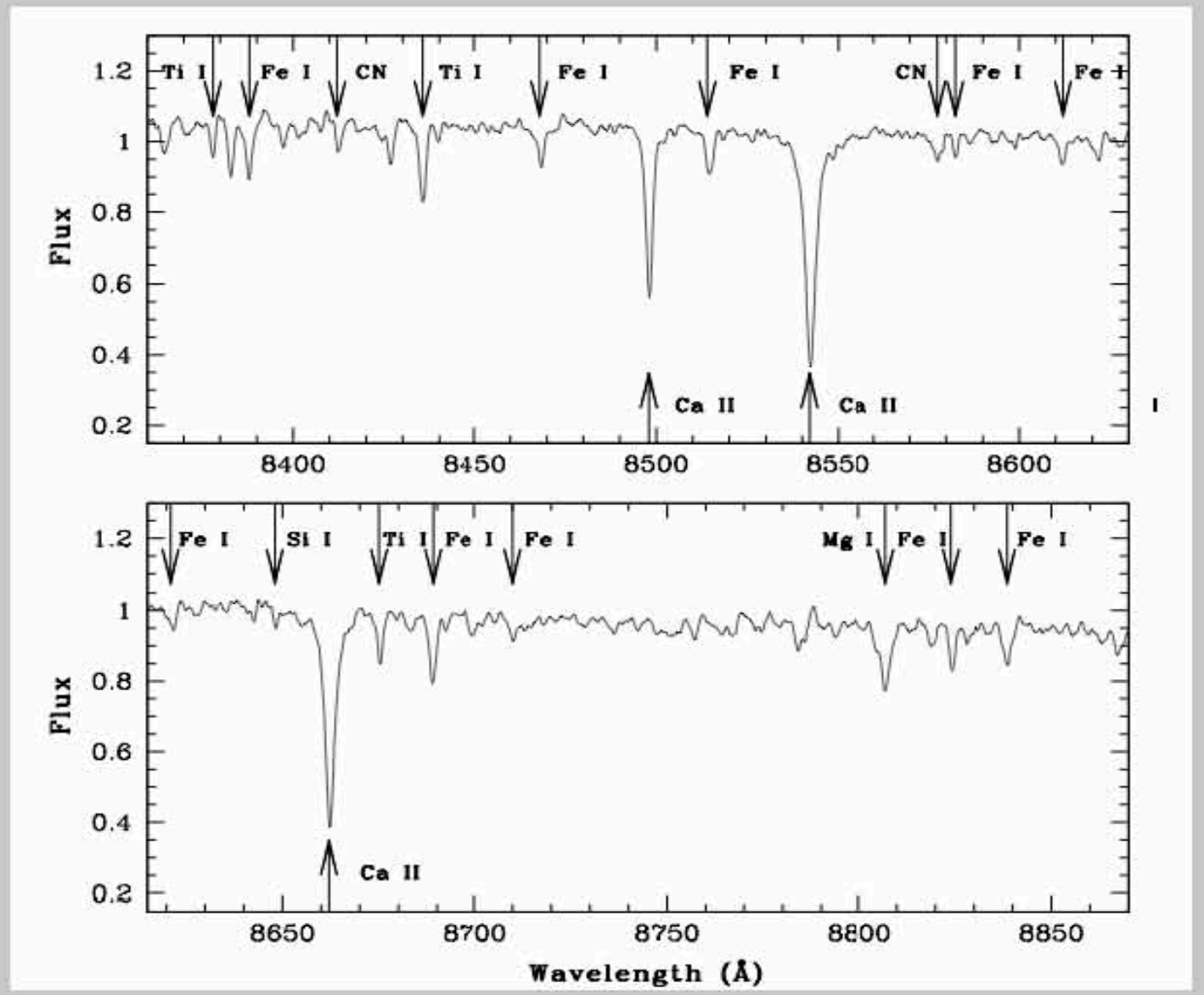


Lucy Cheng
Harker High School
(summer intern at UCSC)

Lei Yang
KIAA/Peking Univ
(visiting student at UCSC + Caltech)

Detailed chemical abundances from co-added spectra of RGB stars in M31 dSph/dE galaxies (paper in prep)

Weak "metal" absorption lines are clearly detectable in co-added spectra



Evan Kirby, PhD thesis, UCSC

Detailed chemical abundances from Keck/DEIMOS spectra of individual red giant stars in MW GCs and dSph satellite galaxies:

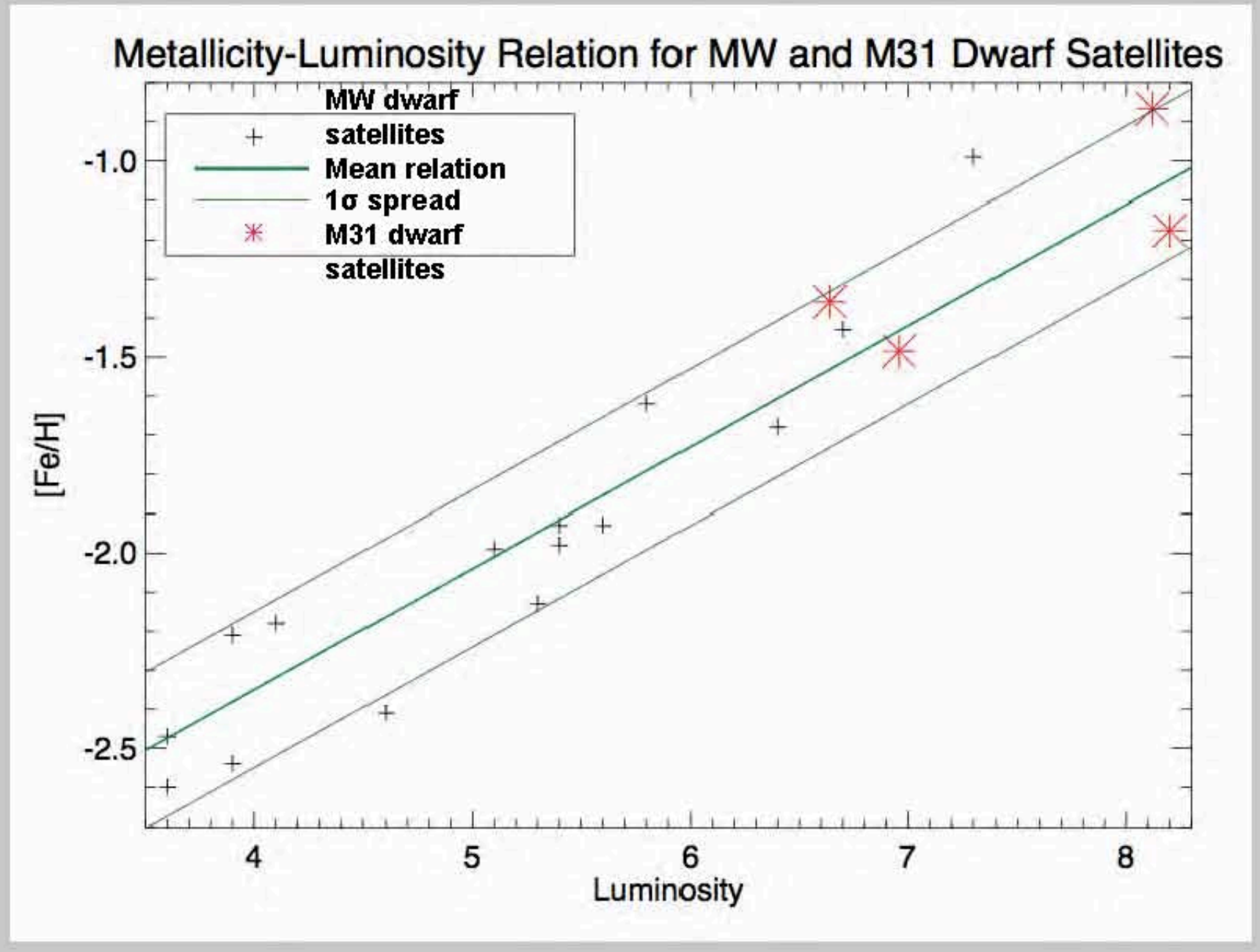
– Kirby, PG & Sneden (2008, ApJ)

– Kirby et al. (2009–2011)

Lei Yang, MS thesis, KIAA/PKU (+ UCSC + Caltech)

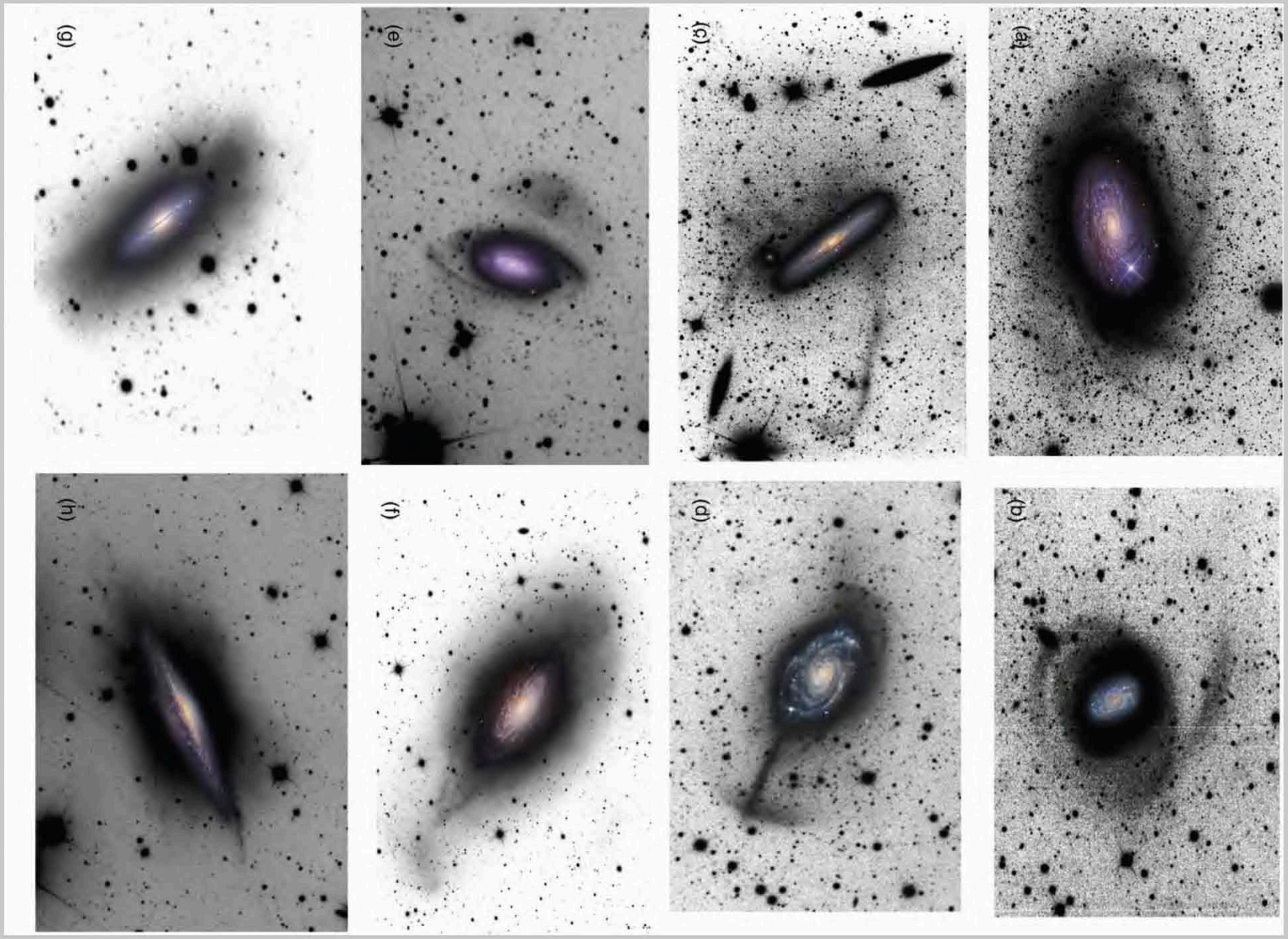
Detailed chemical abundances from coadded spectra of RGB stars in M31 dSph/dE galaxies (paper in prep)

Andromeda satellites resemble their Milky Way counterparts



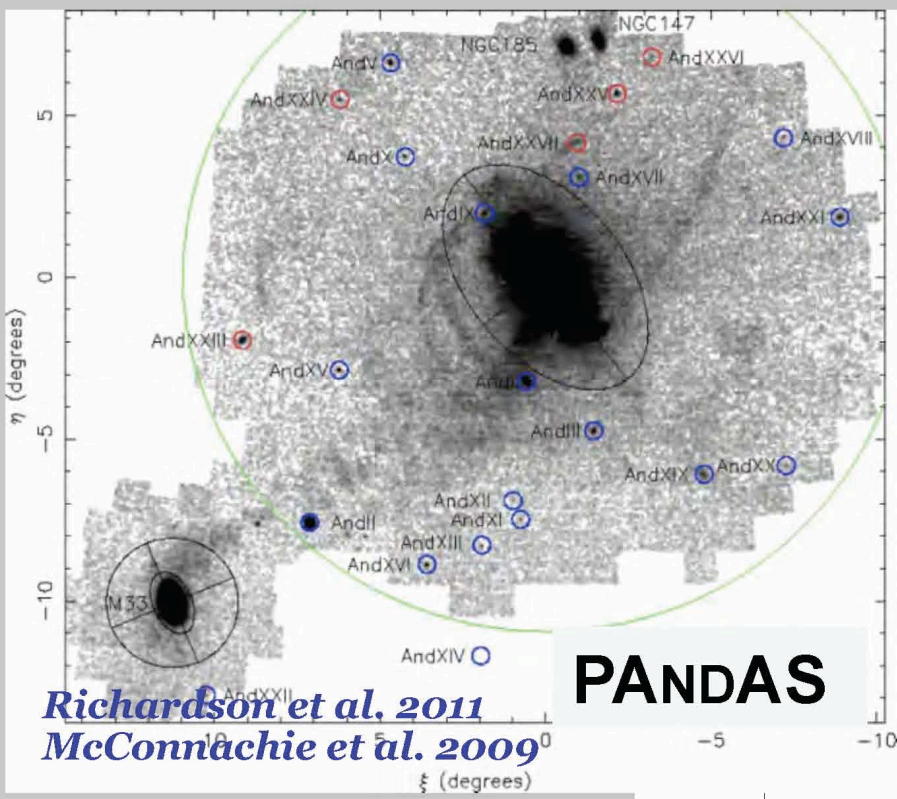
Lucy Cheng (SIP 2011/2012; Harker School / Harvard Univ)

Cannibalism in progress in the Local Volume



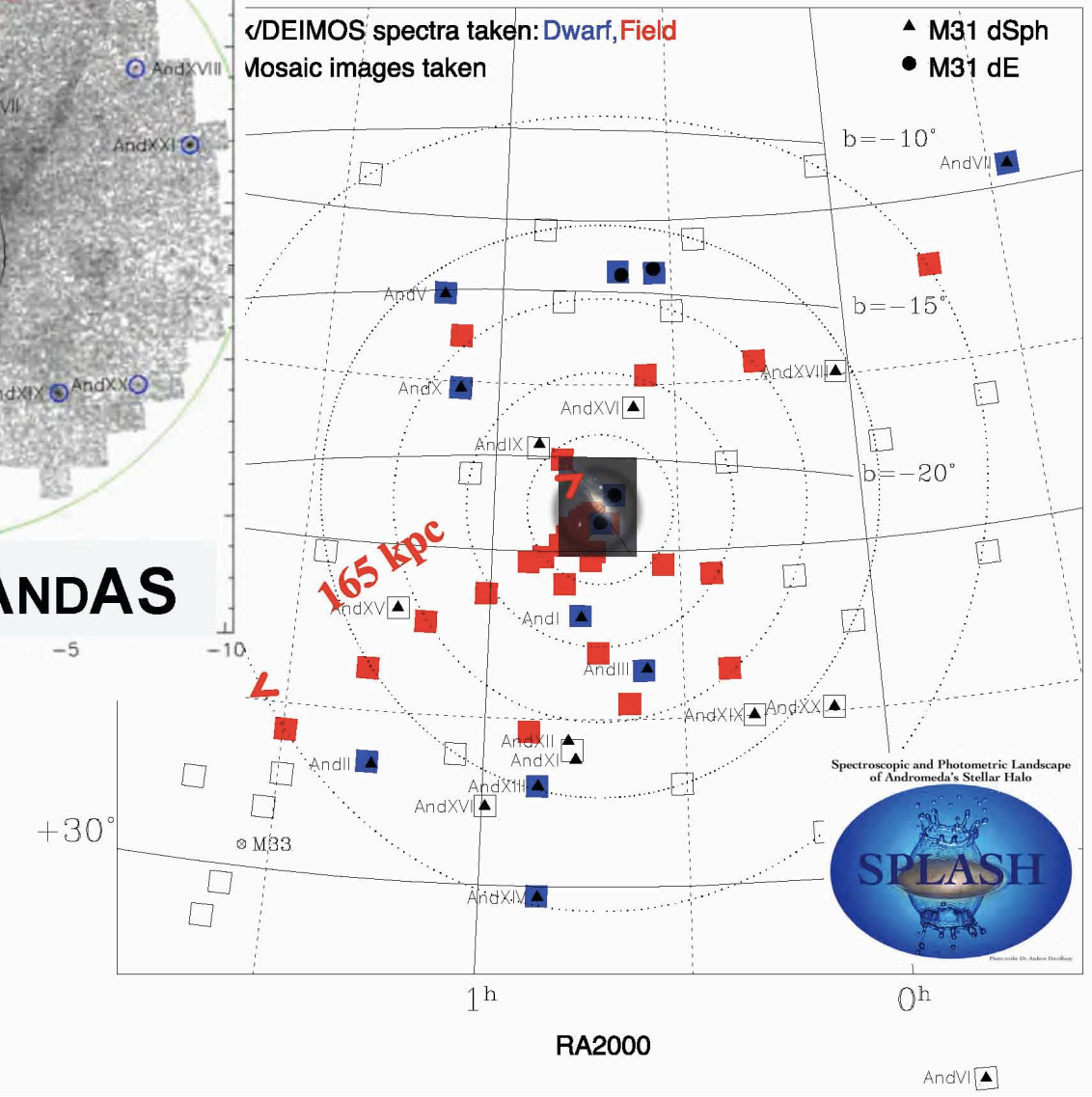
Martinez-Delgado et al. 2010

Remote outer stellar halo of Andromeda



Richardson et al. 2011
McConnachie et al. 2009

PANDAS



KPNO/Mosaic imaging

Keck/DEIMOS Spectroscopy:

Andromeda Field

Dwarf Satellite Field

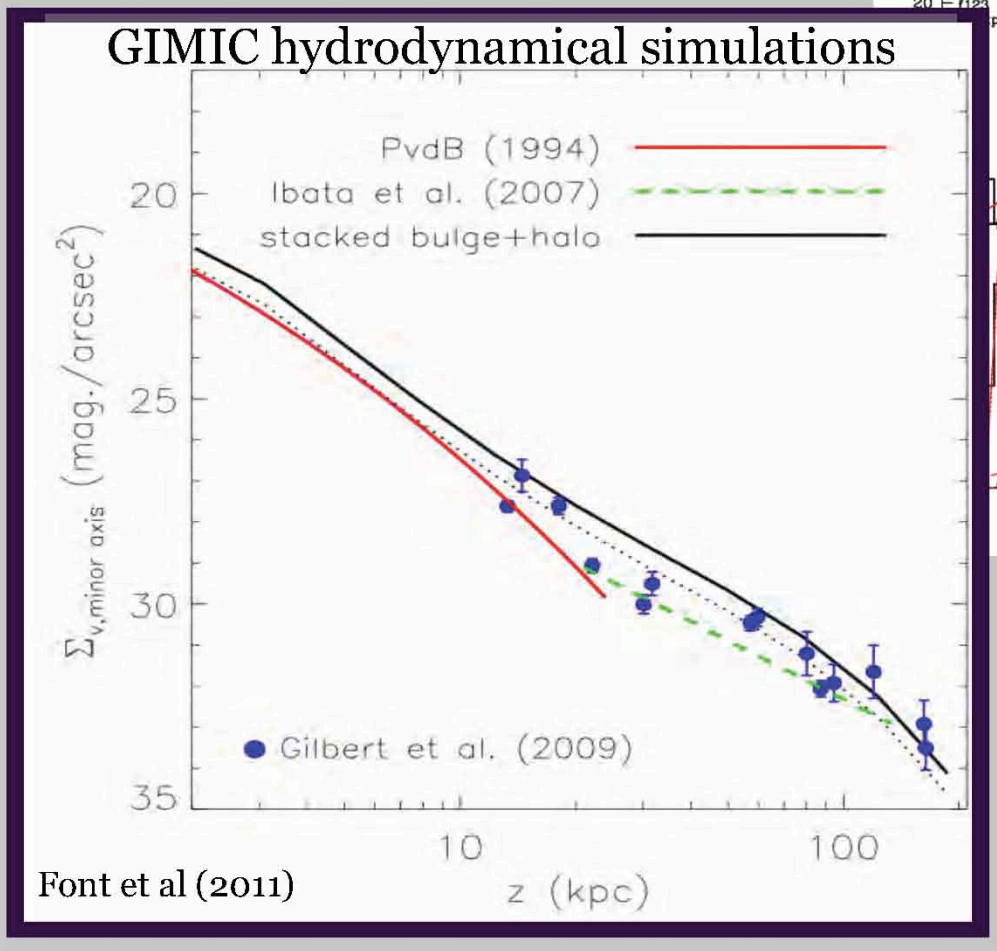
Ostheimer (2002, PhD thesis), Beaton et al. (in prep)

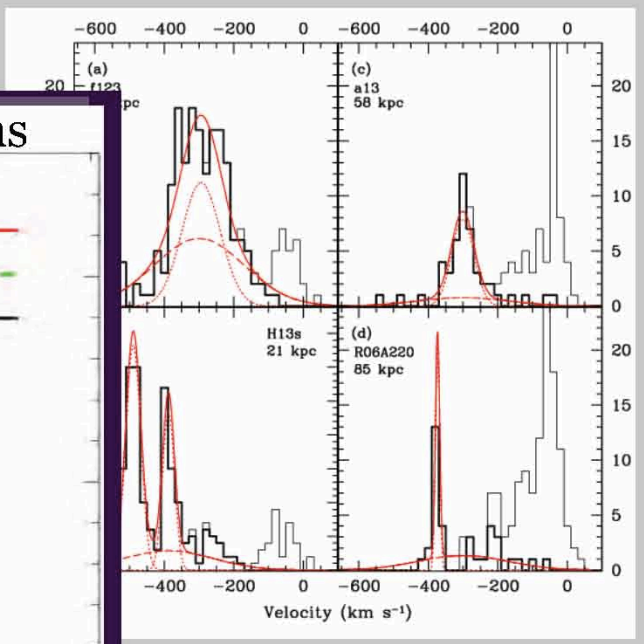
Andromeda clearly has a virialized stellar halo

Spectroscopy allows us to statistically remove substructure (partially digested former dwarf satellite galaxies) in different fields

Fields in M31's South quadrant

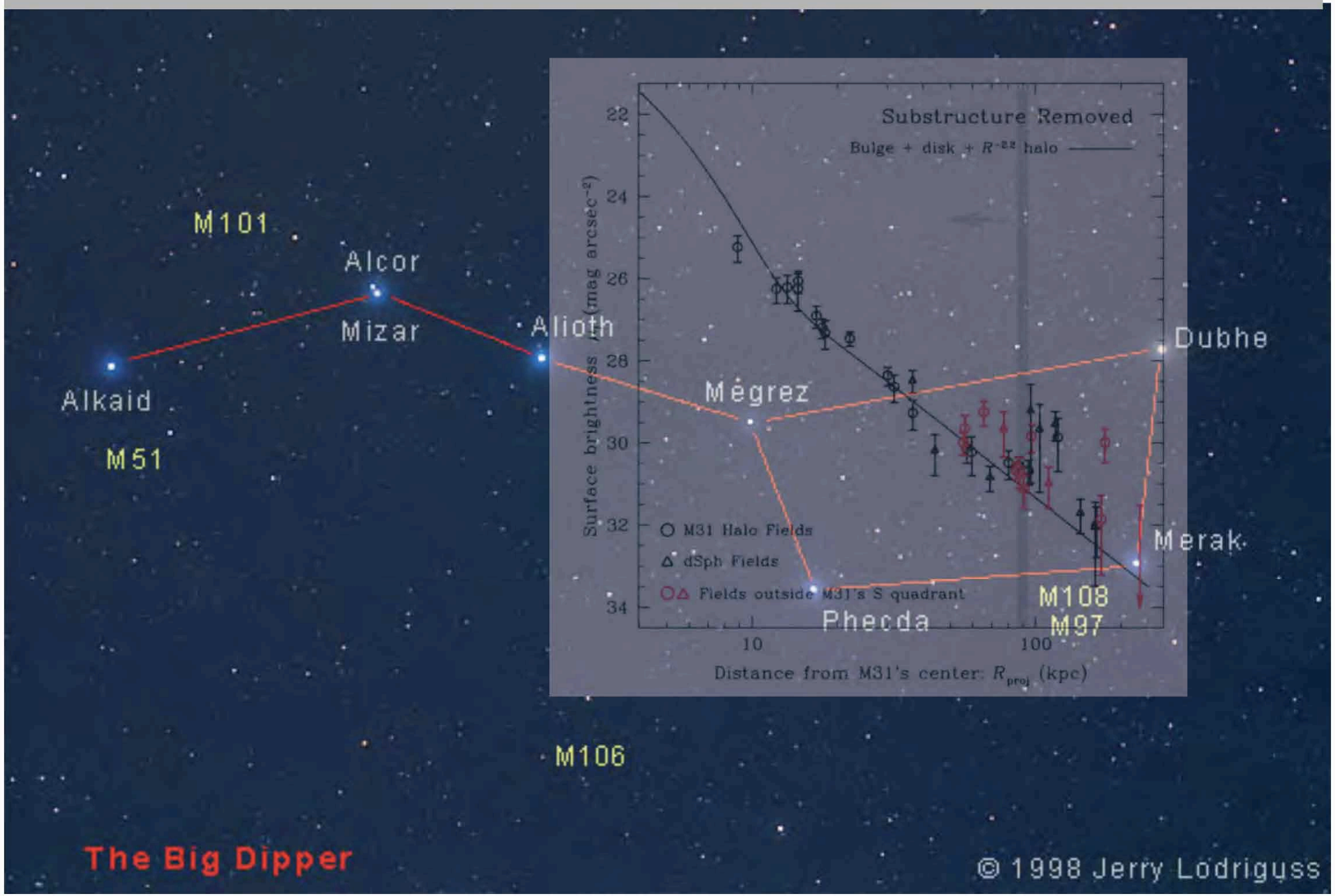
Fields North of M31's semi-major axis



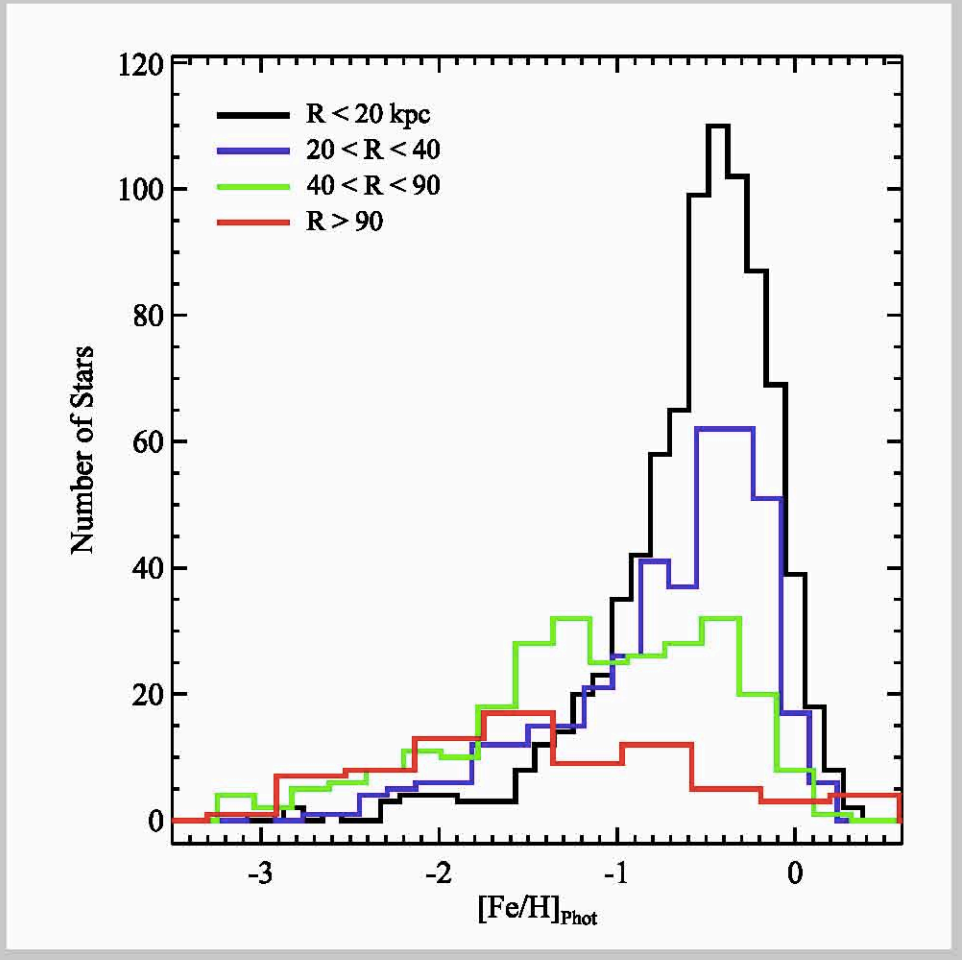


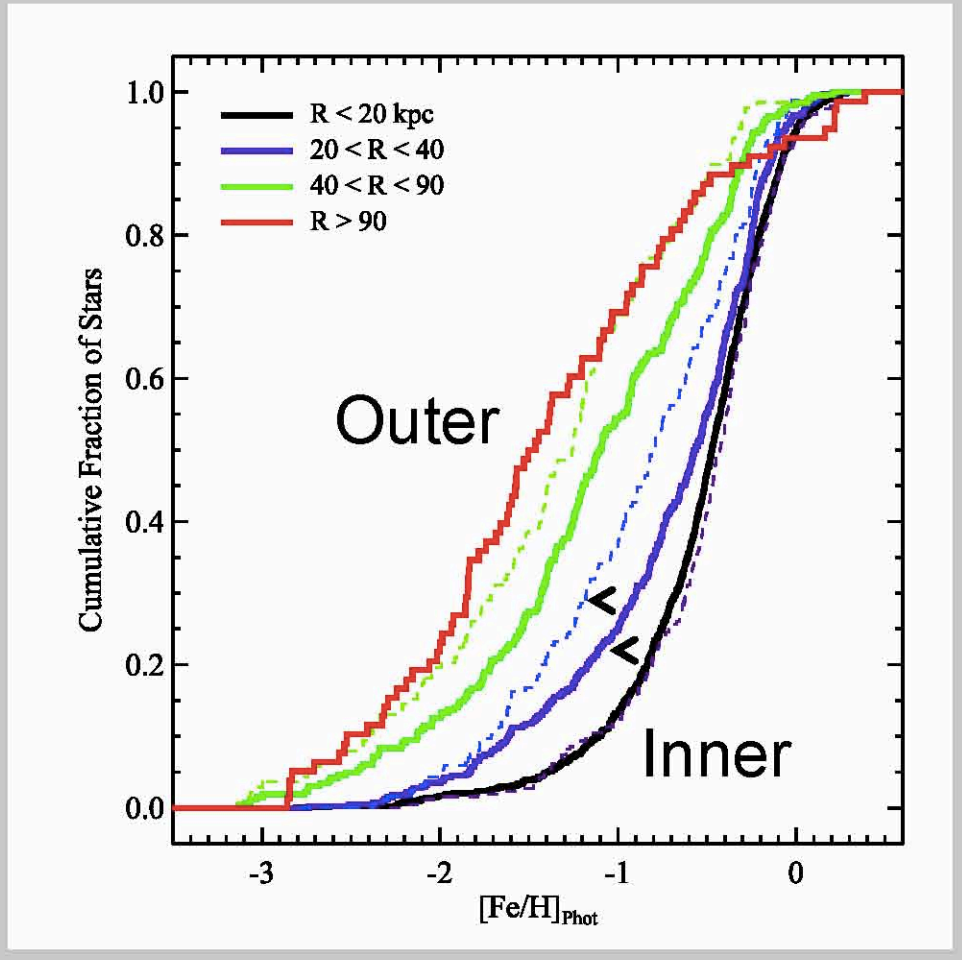
Gilbert et al., 2012

Andromeda is big on the sky, very big!



Andromeda gets progressively more chemically anemic as one marches from its center to the outskirts

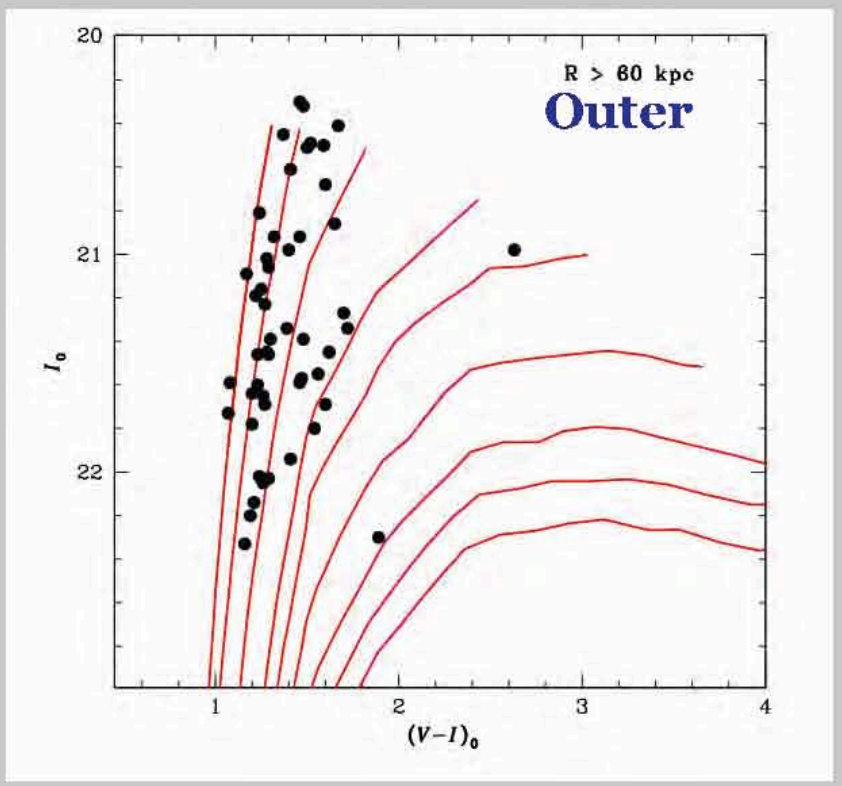


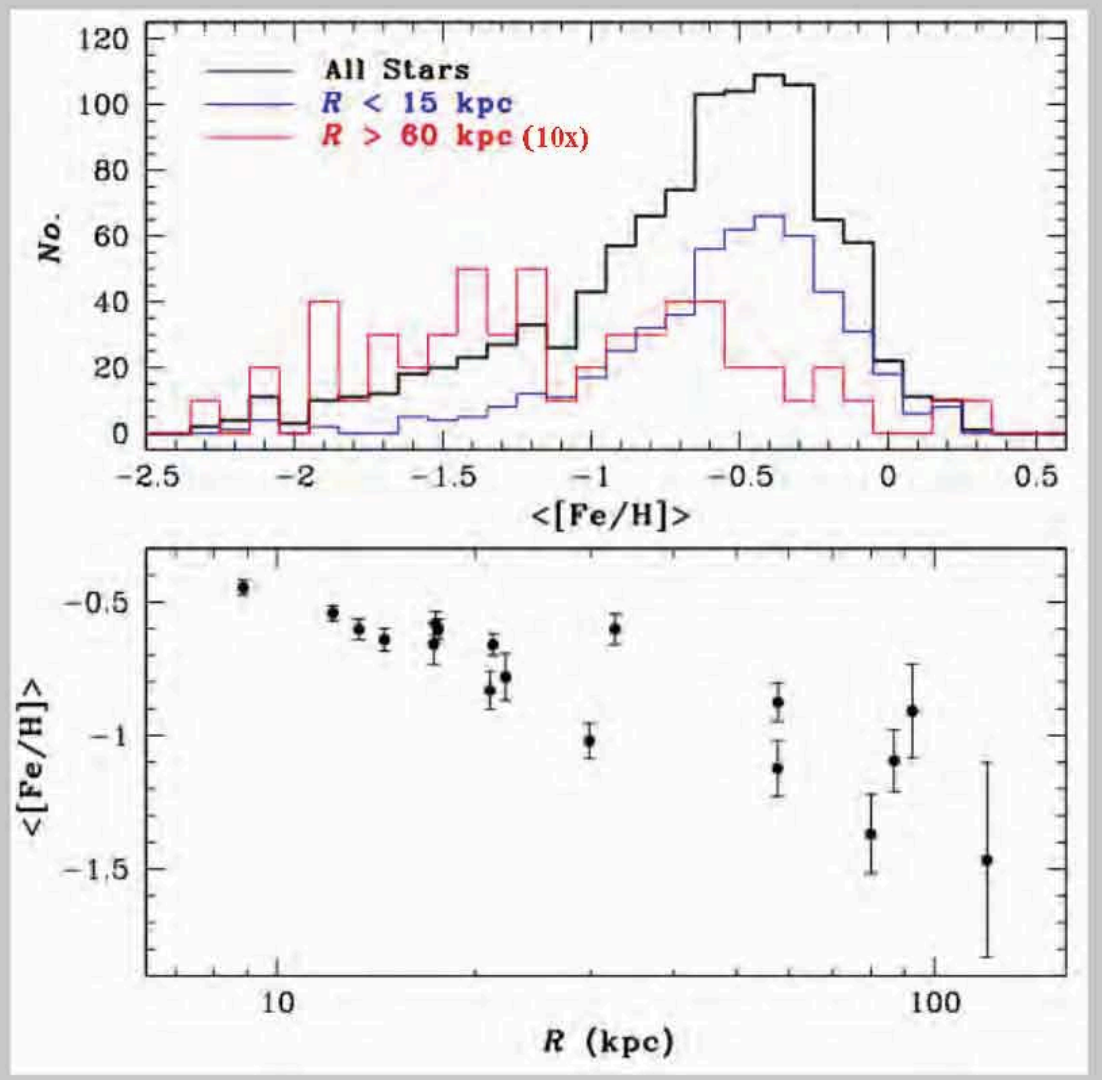


[Fe/H] ⟶

Kalirai et al. (2006, ApJ)
Gilbert et al. (2013, in prep)

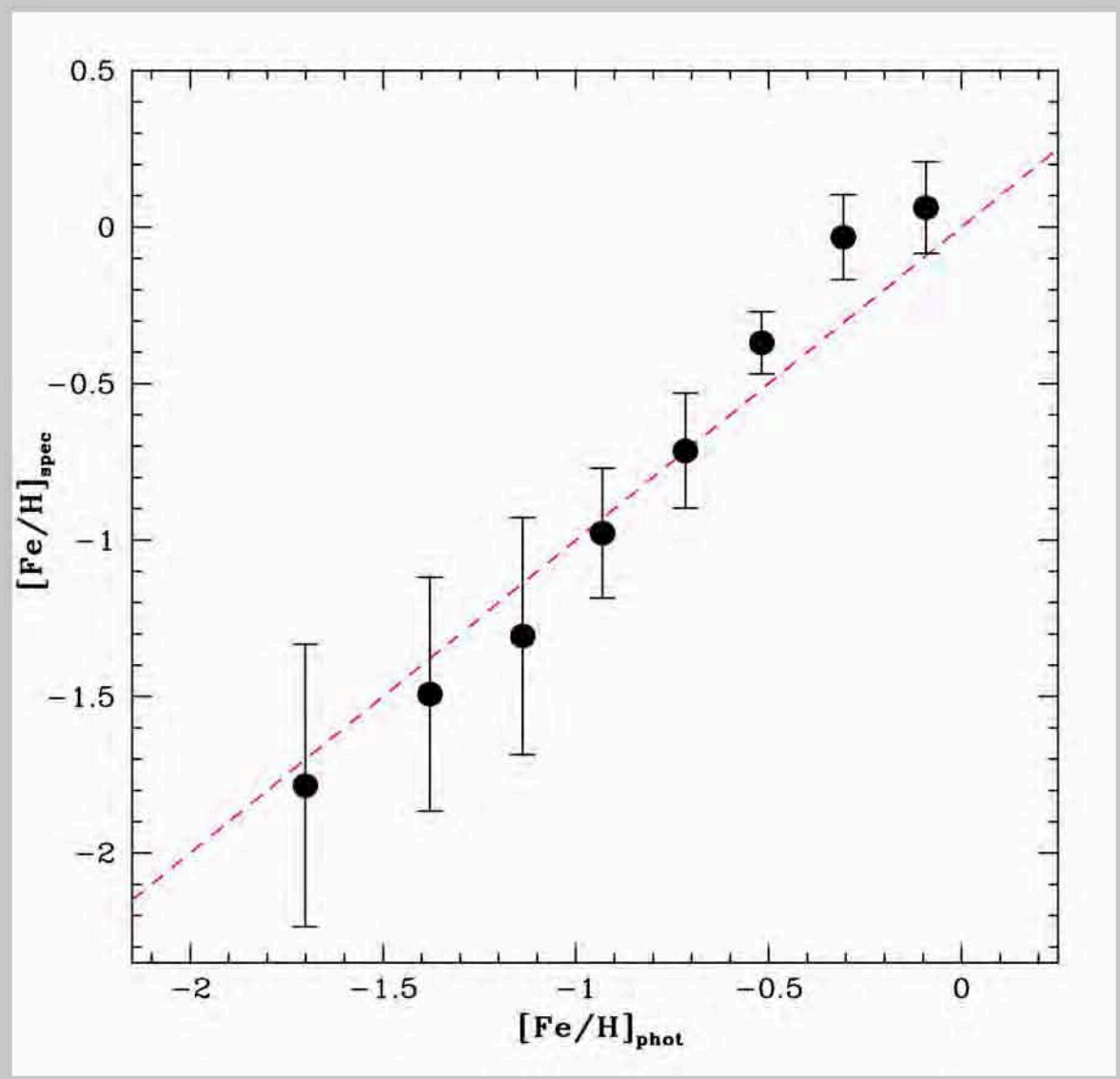
Radial Gradient in Metallicity





Kalirai, Gilbert, PG, et al. (2006b, ApJ); Gilbert et al. (in prep)

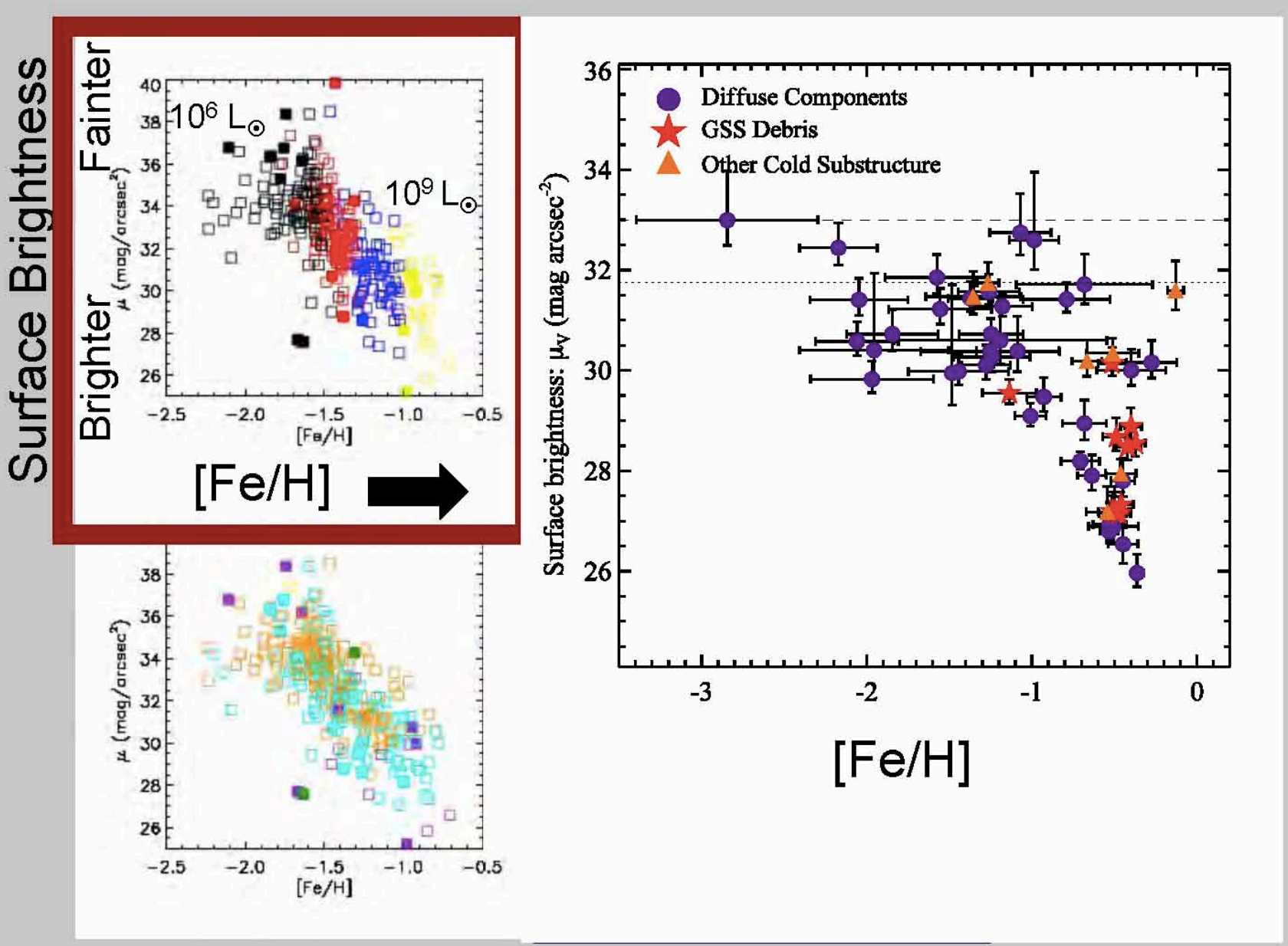
Photometric vs. Spectroscopic [Fe/H] Estimates



Kalirai, Gilbert, PG, et al. 2006b, ApJ

It is reassuring to see that there is a reasonably good correlation between the photometric and spectroscopic [Fe/H] estimates

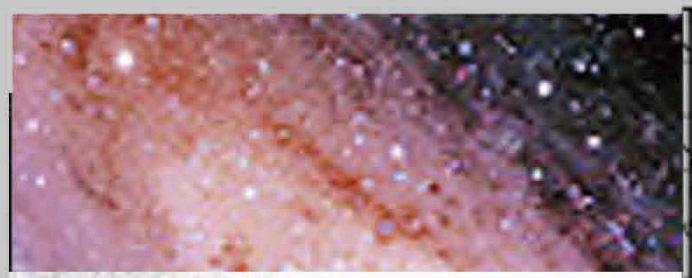
Deducing the statistical properties of disrupted satellites

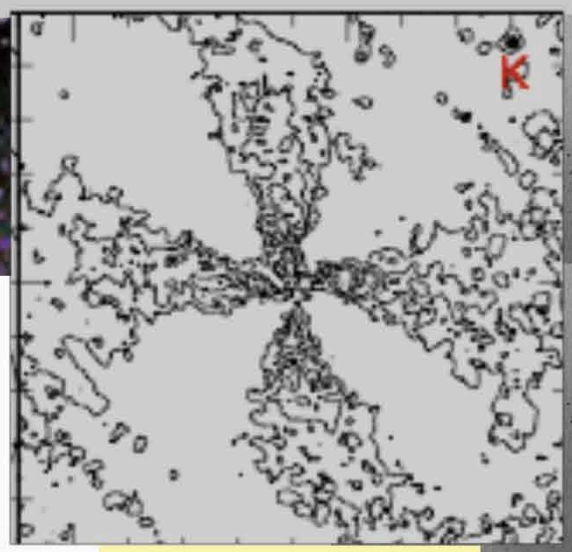


Johnston et al. 2008; Gilbert et al. 2009
Bullock & Johnston (2005) models

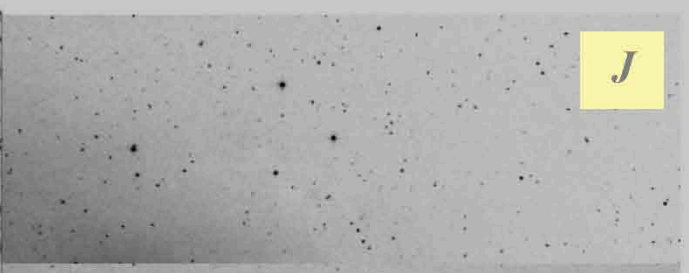
M31's Boxy Bulge and Central Bar

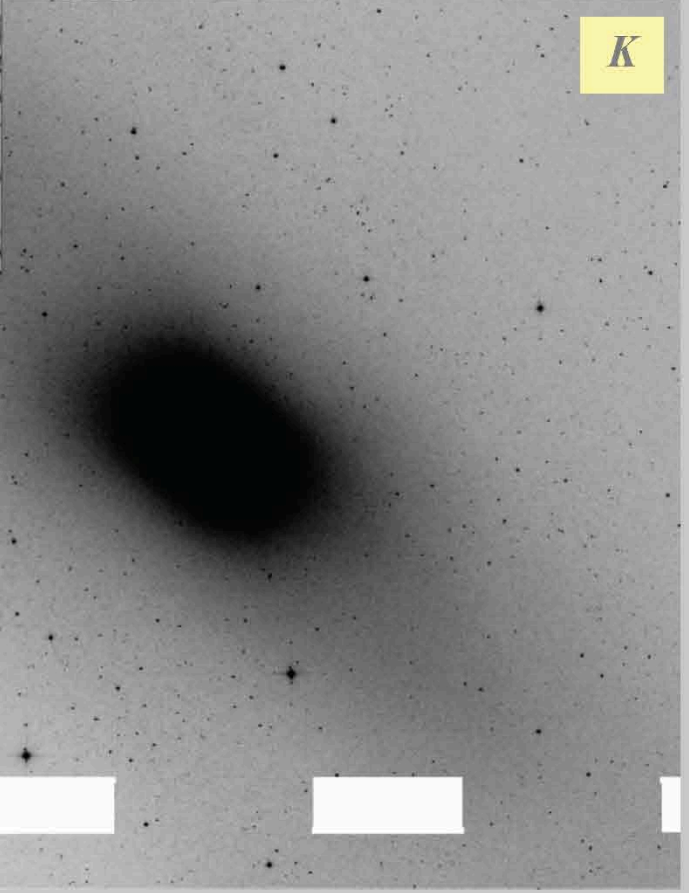
An Unobstructed Wide-field View in the Near Infrared

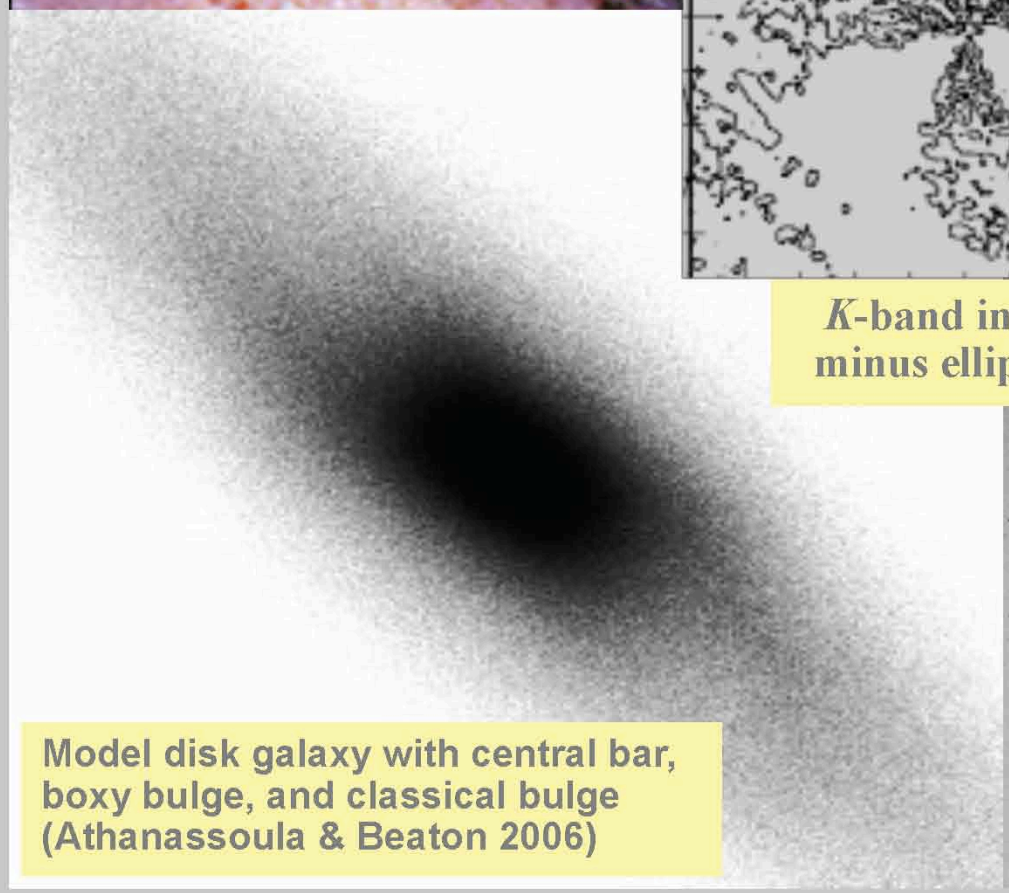




K-band image minus ellipse fit



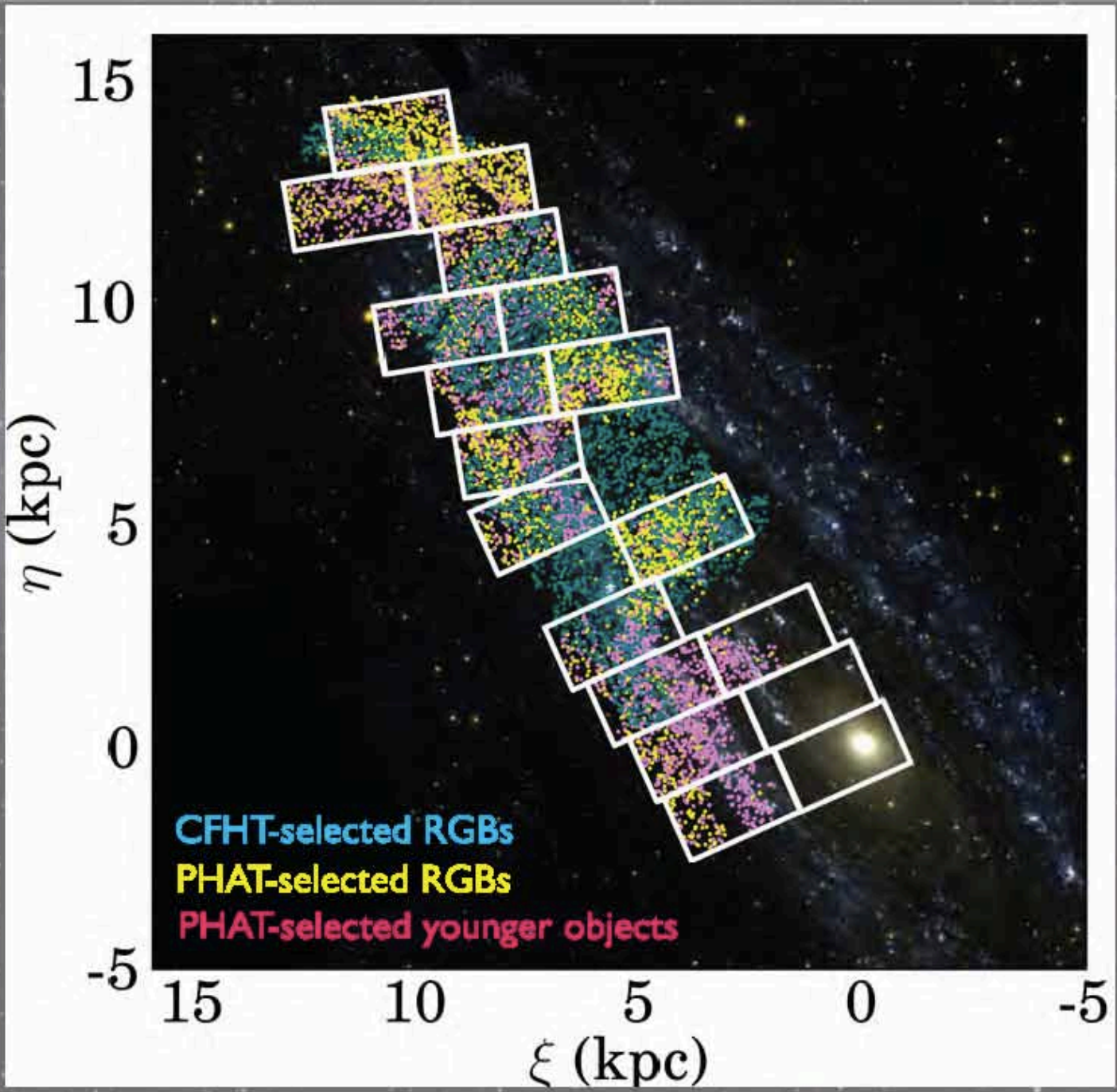




Model disk galaxy with central bar, boxy bulge, and classical bulge (Athanassoula & Beaton 2006)

Beaton et al. (2007, ApJL)
Athanassoula & Beaton (2006, MNRAS)

Spectra of 11,000 red giants in the inner region of M31

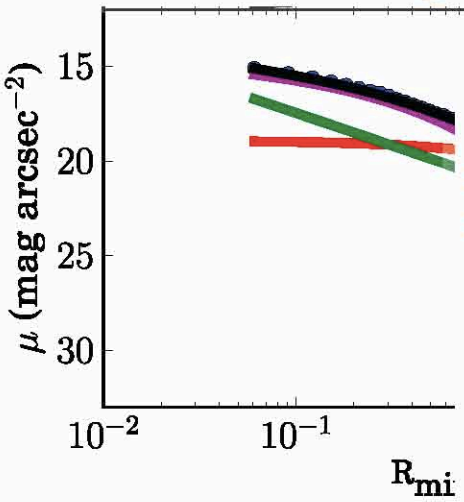


Dorman, PG, et al (2012, ApJ)

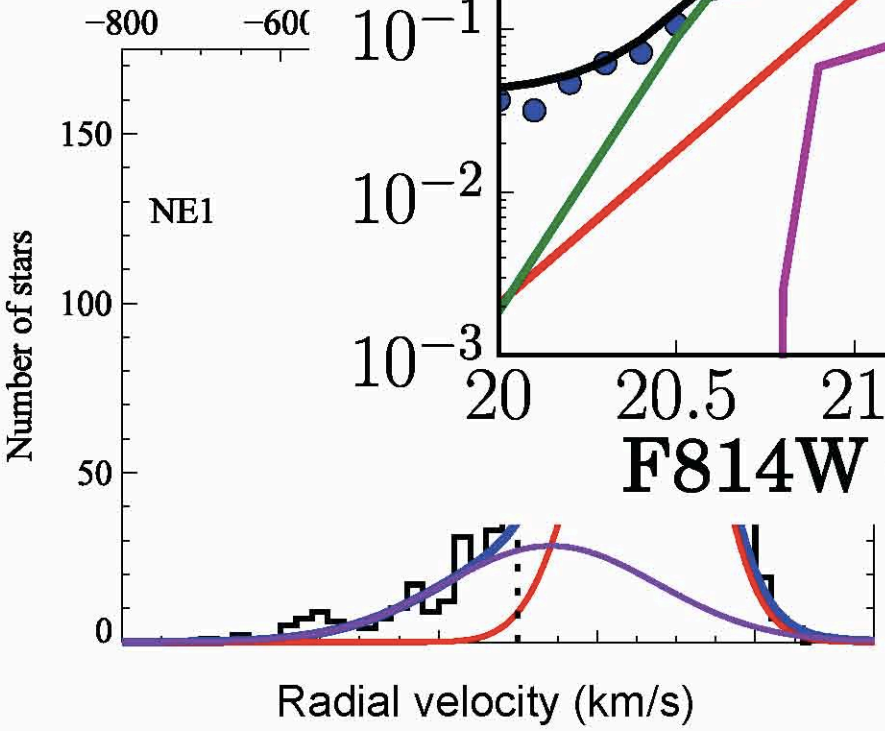
Disentangling bulge, disk, and halo of M31

Simultaneous fit to three data sets: surface brightness, stellar kinematics, luminosity function

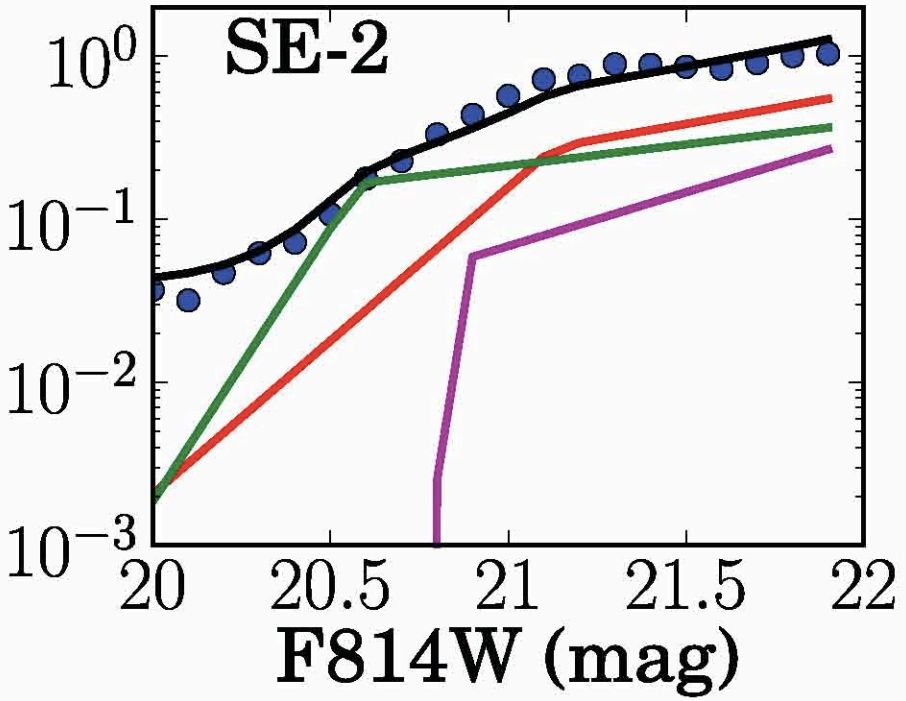
Surface brightness prof



Disk fracti

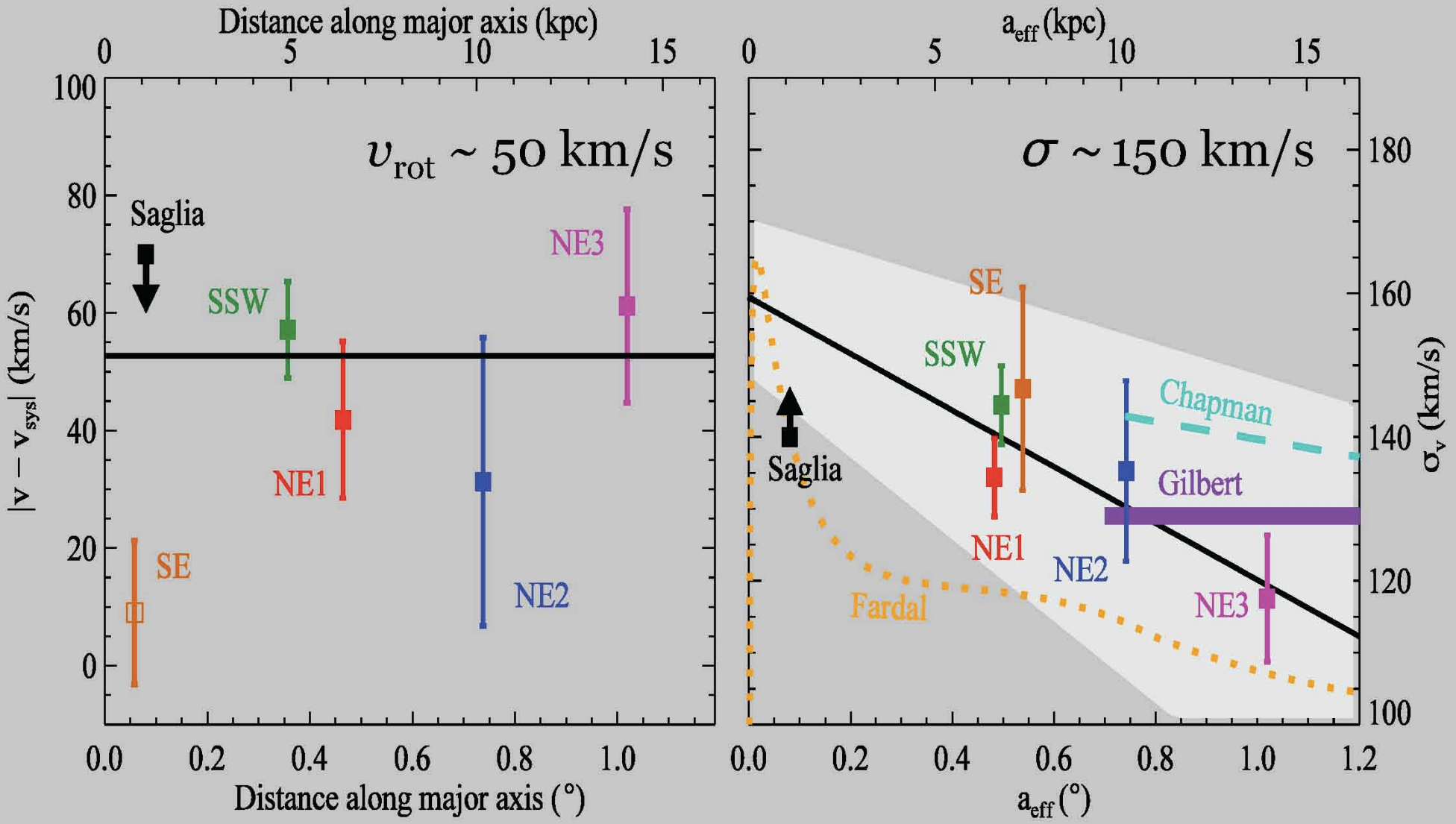


Stellar luminosity function



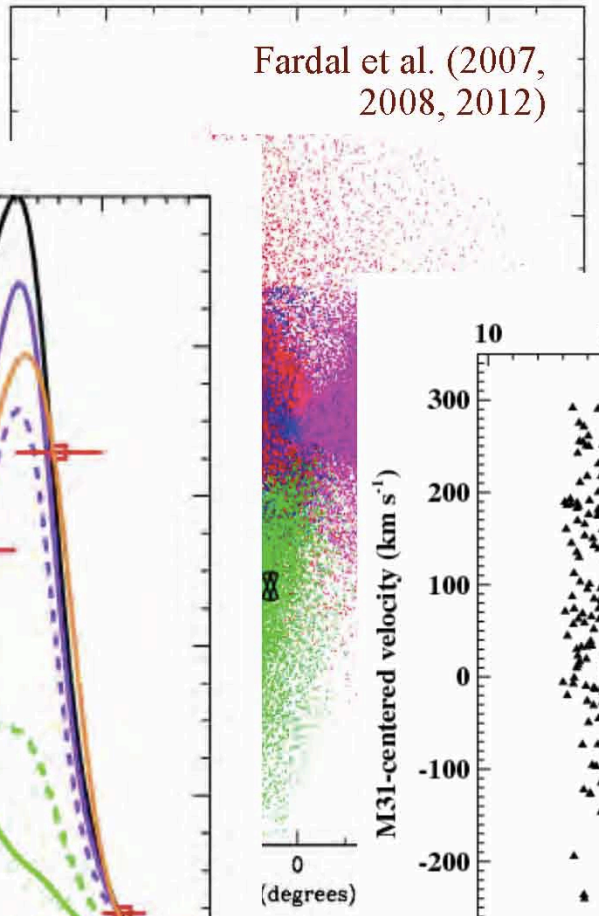
Dorman et al (2013, in prep)

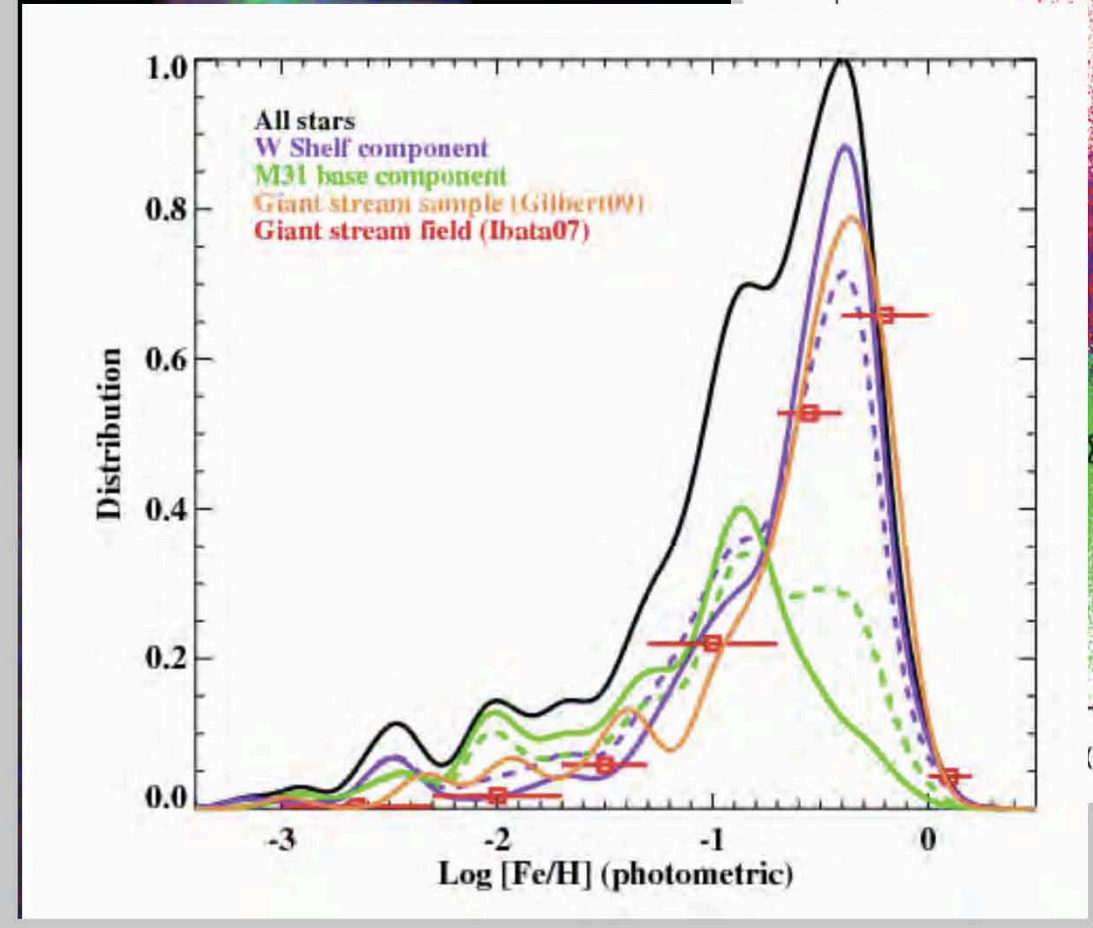
M31's inner spheroid rotates slowly (and is mostly pressure-supported)

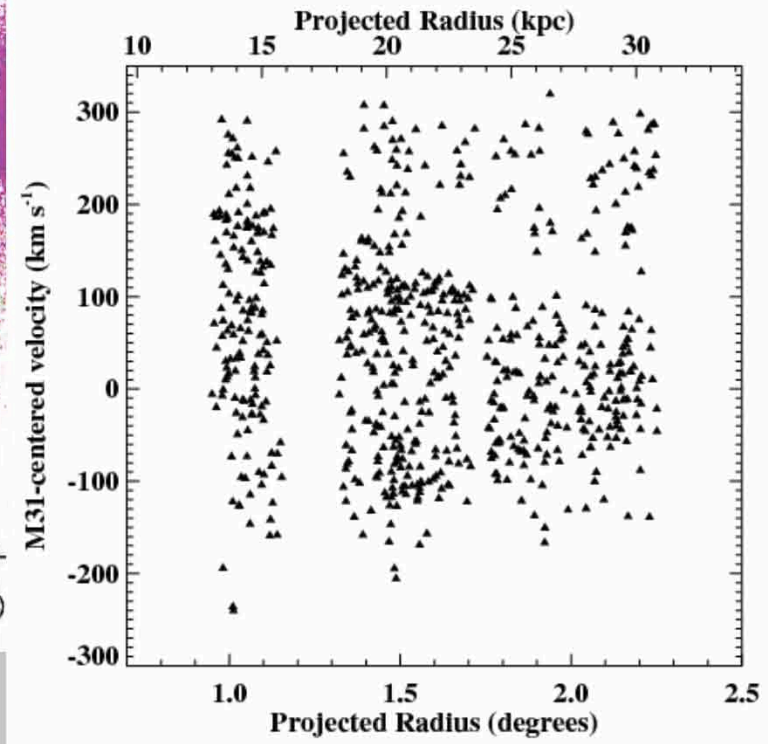


Dorman, PG, et al (2012, ApJ),

Forensic reconstruction of a recent significant collision







– Minor axis **arcs**, giant southern **stream**, and **shells** may be the result of a **single collision event**

– Stream **asymmetry** can be reproduced by a **rotating** satellite

– **Metallicity variations** can be explained by a satellite with an intrinsic **radial metallicity gradient**

– Tidal debris tracked through **three pericenter passages**; should strongly constrain M31's **potential**

Stellar Population and Interstellar Medium Studies

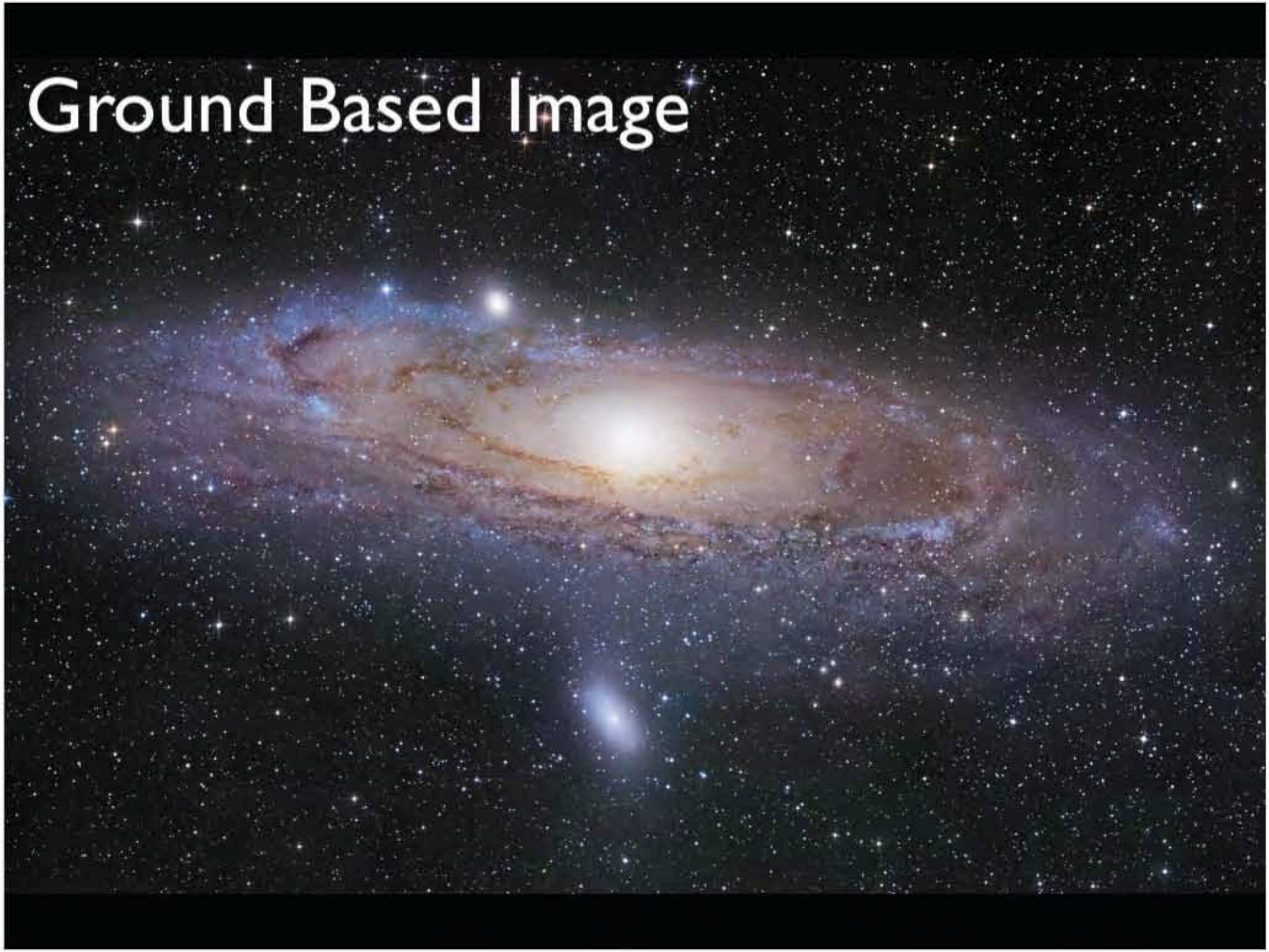
– M giant "thermometry" and dust mapping

– Carbon stars in M31

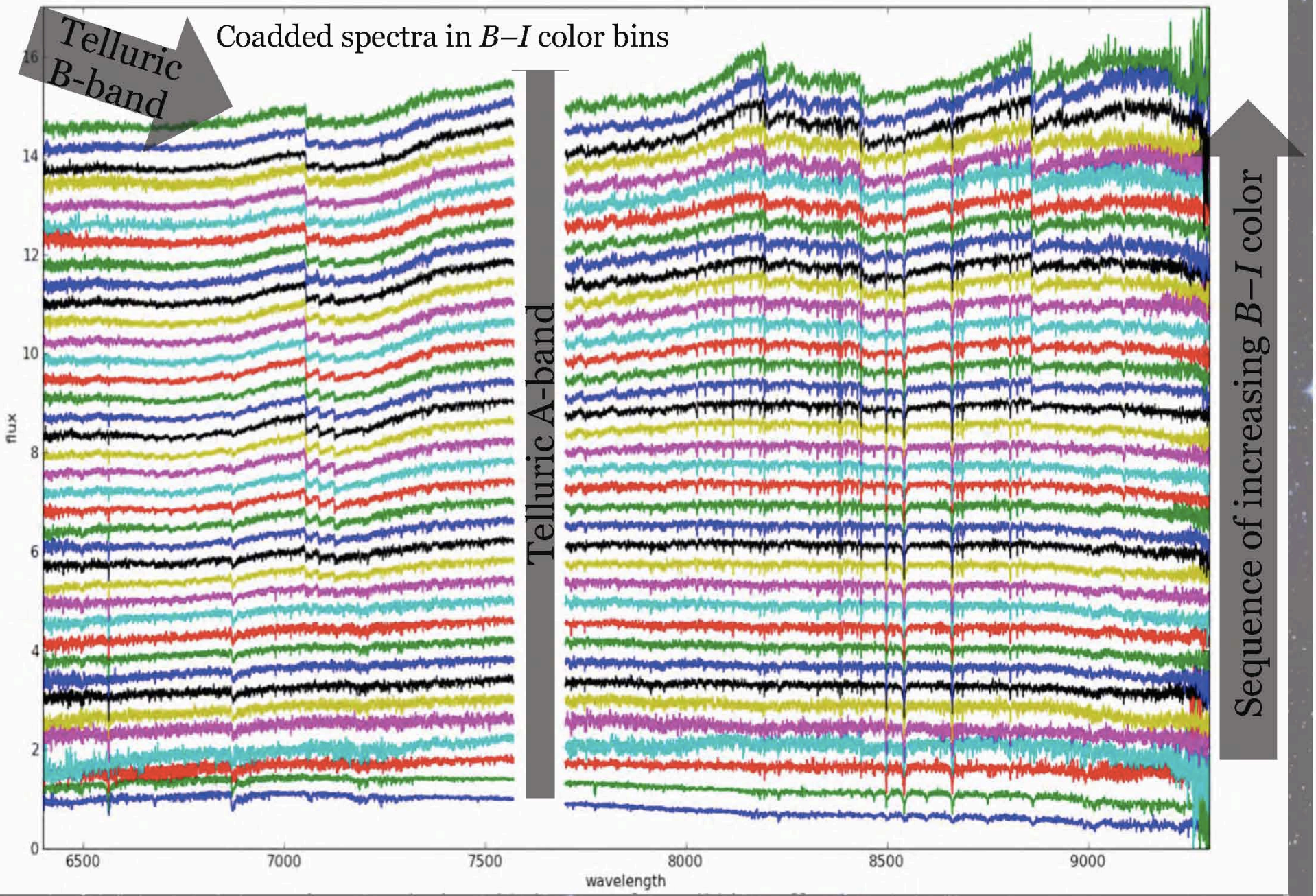
– Star clusters

– UV/blue spectroscopy of hot stars:
Stellar parameters and dust extinction/reddening law

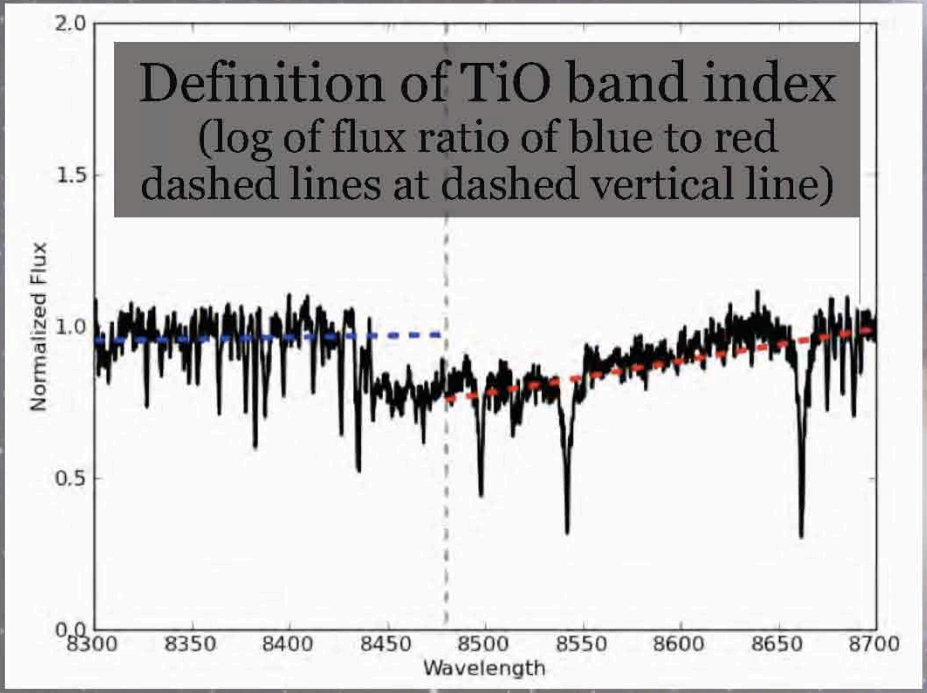
– Kinematics of ionized gas disk and stellar disk

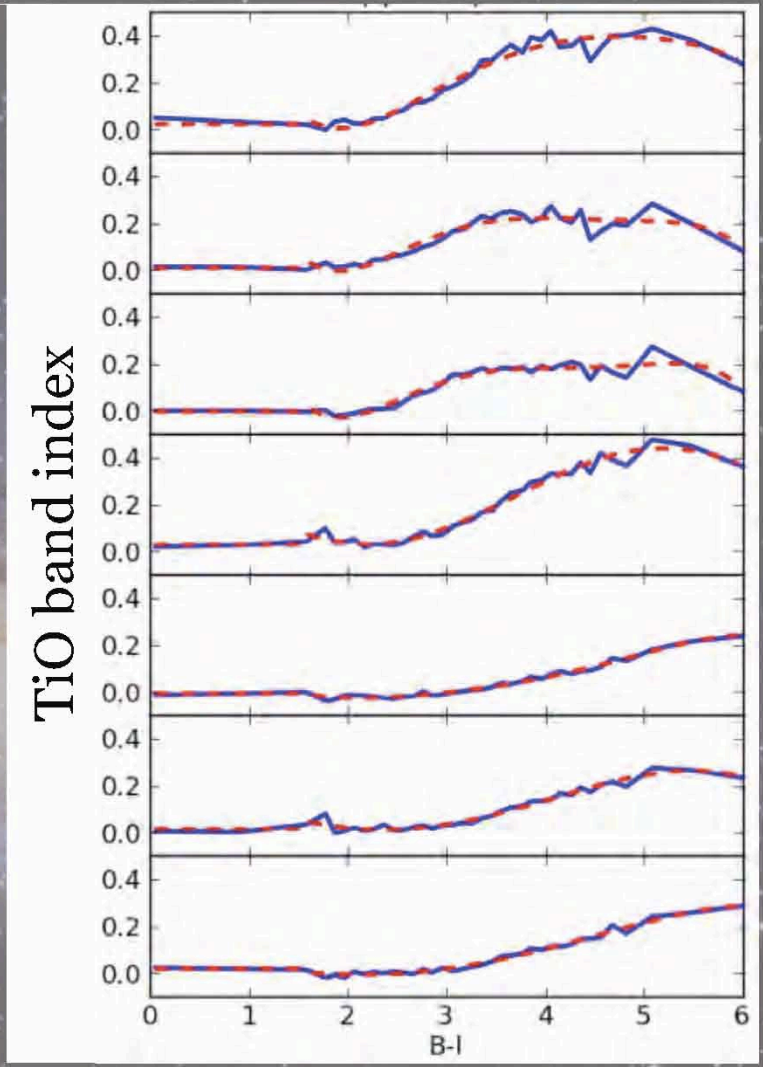

Ground Based Image

"Thermometry" of M giant stars



"Thermometry" of M giant stars

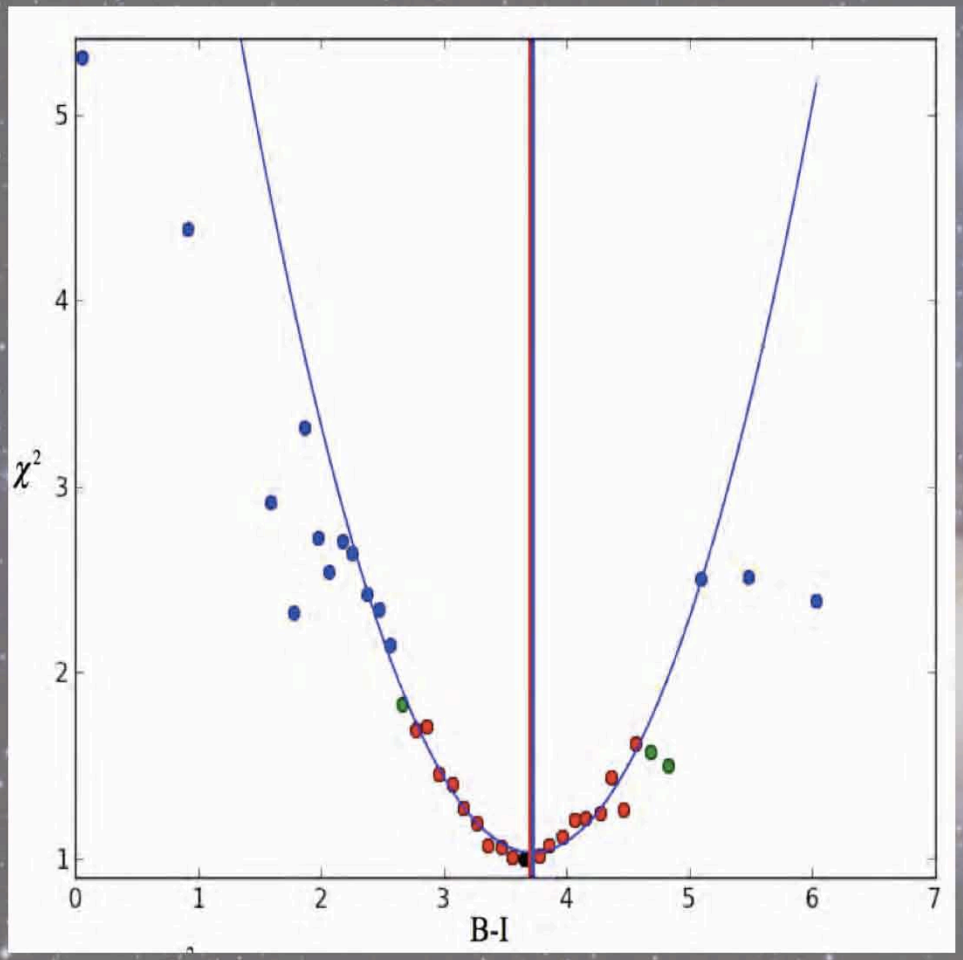




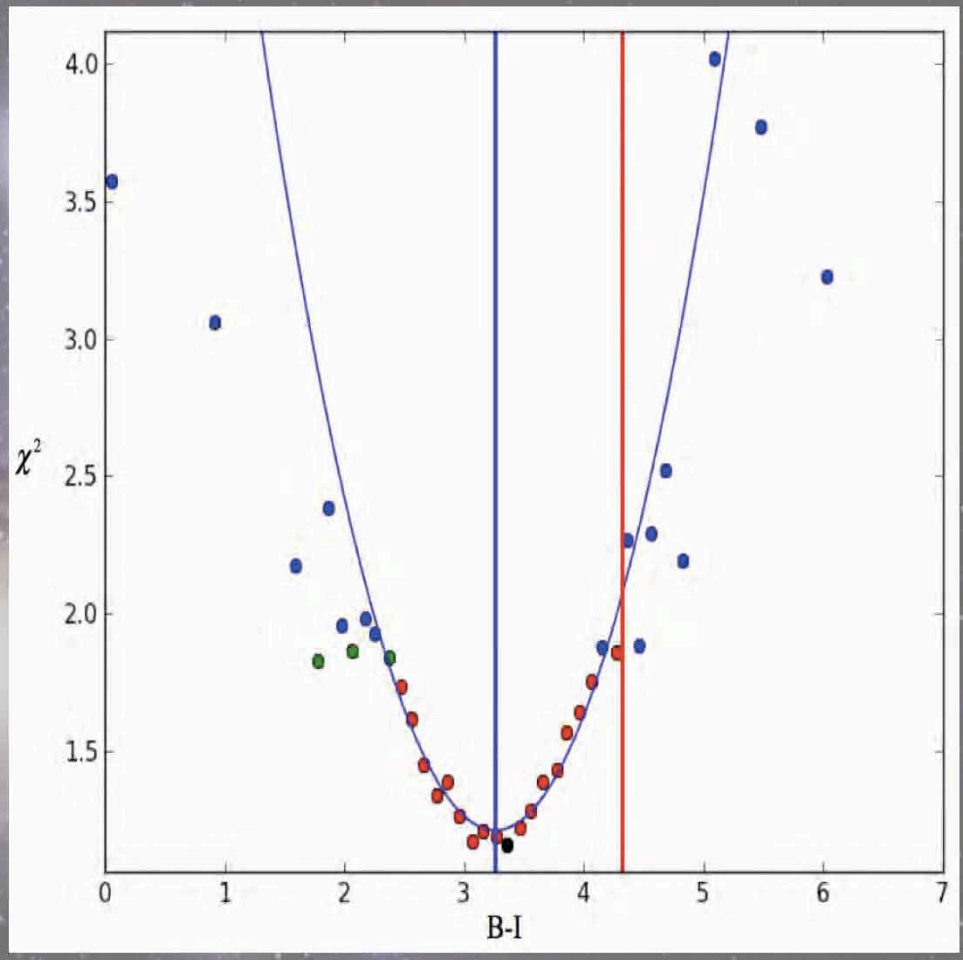
Teresa Krause *(Castilleja School)*

Katie Hamren, Claire Dorman, Elisa Toloba *(UCSC)*
Sumedh Guha *(Archbishop Mitty High School)*

Application of M giant thermometer: Dust reddening



Unreddened star

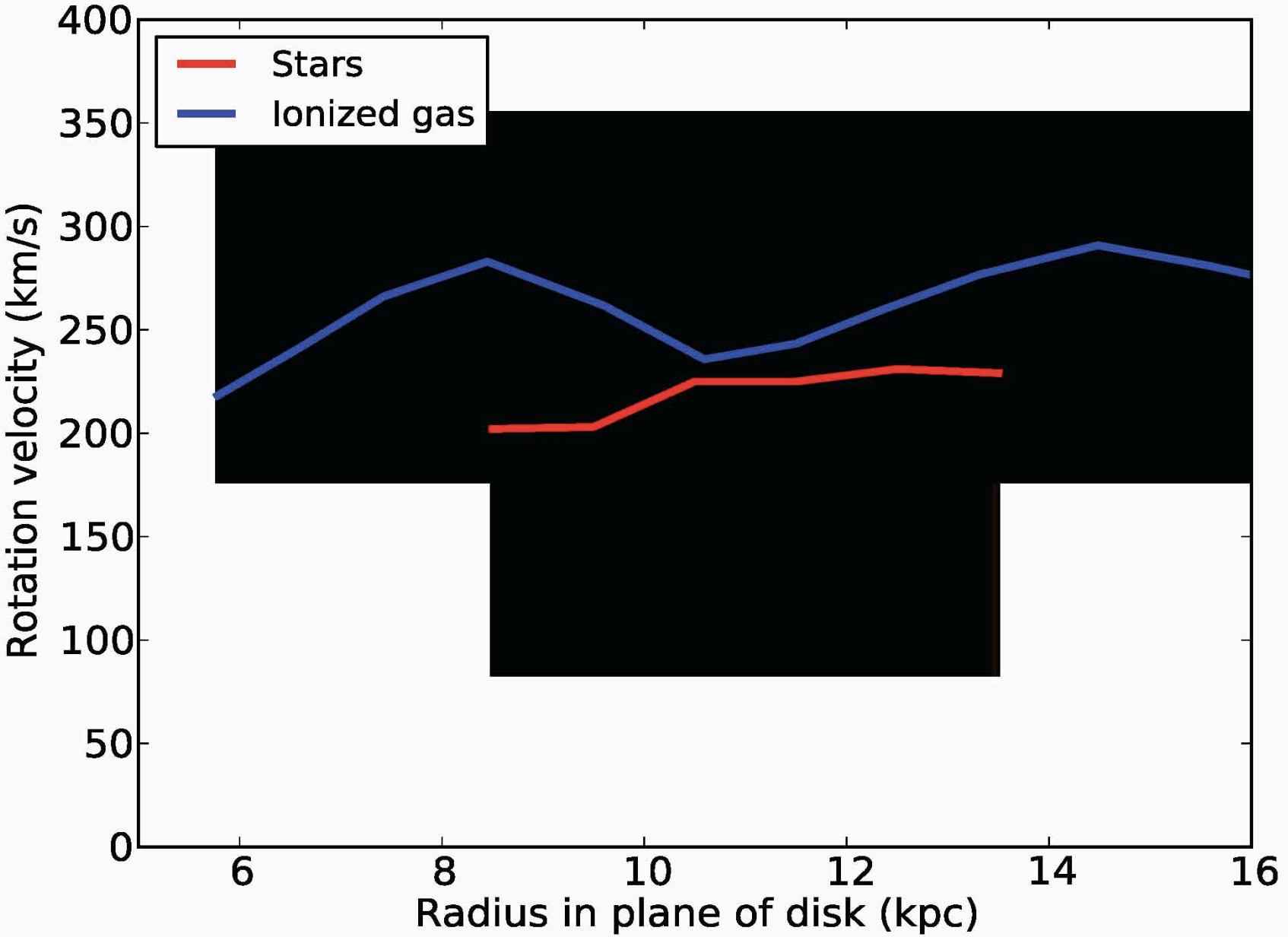


Reddened star

Teresa Krause *(Castilleja School)*

Katie Hamren, Patrick Draper *(UCSC)*

Kinematics of diffuse ionized gas



Summary

– Discovery and characterization of M31's vast stellar halo

❖*Is the concept of "island universes" still valid?*

– Dwarf satellites of the Local Group, past and present

❖*Building blocks of their larger host galaxy*

❖*Strongly affected by the proximity of the host*

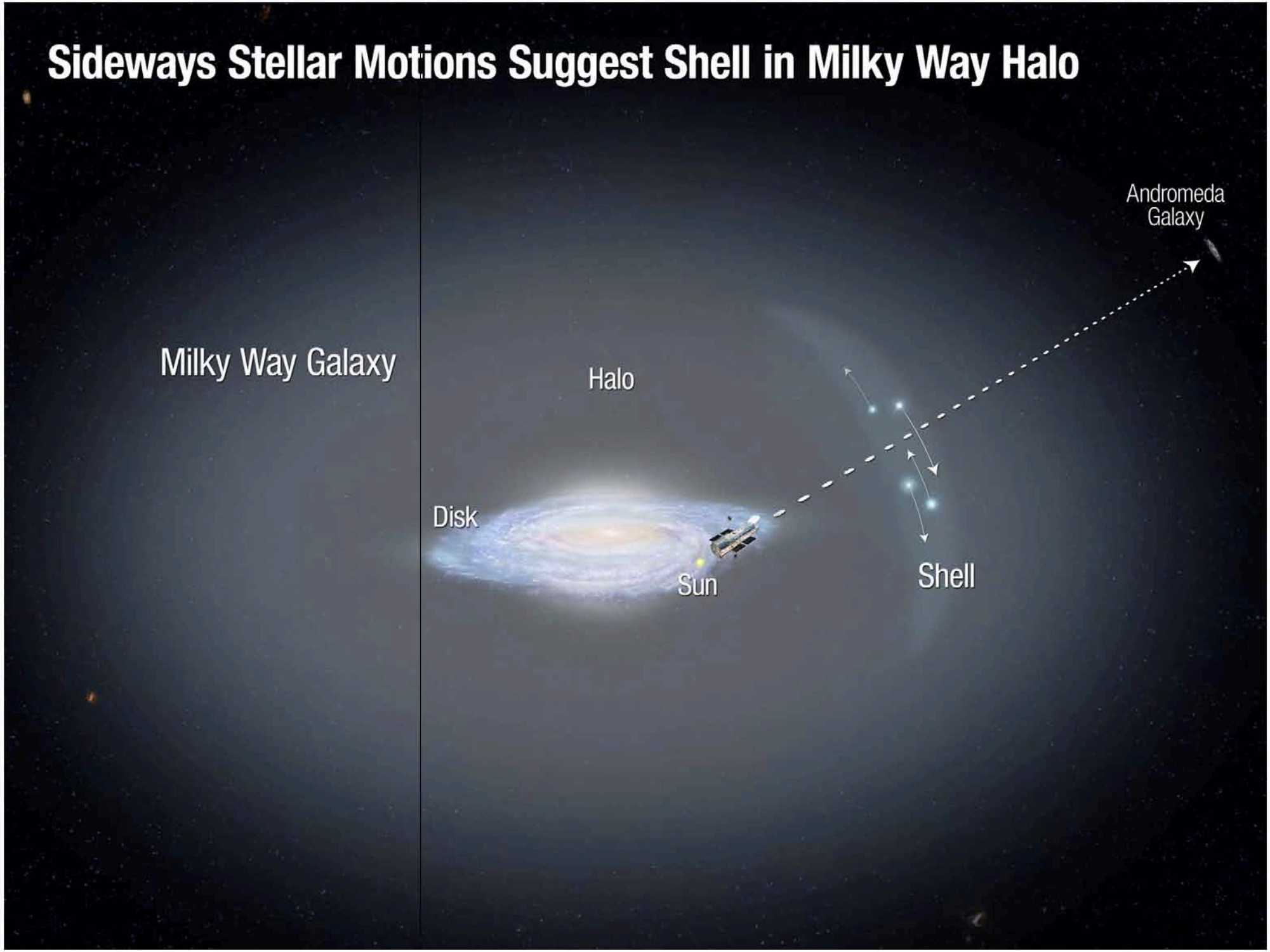
– Dissecting the structure and motion of M31's components

❖*Was the spheroid formed by a "kicking up" an earlier disk?*

❖*Effect of satellite bombardment on the fragile stellar disk*

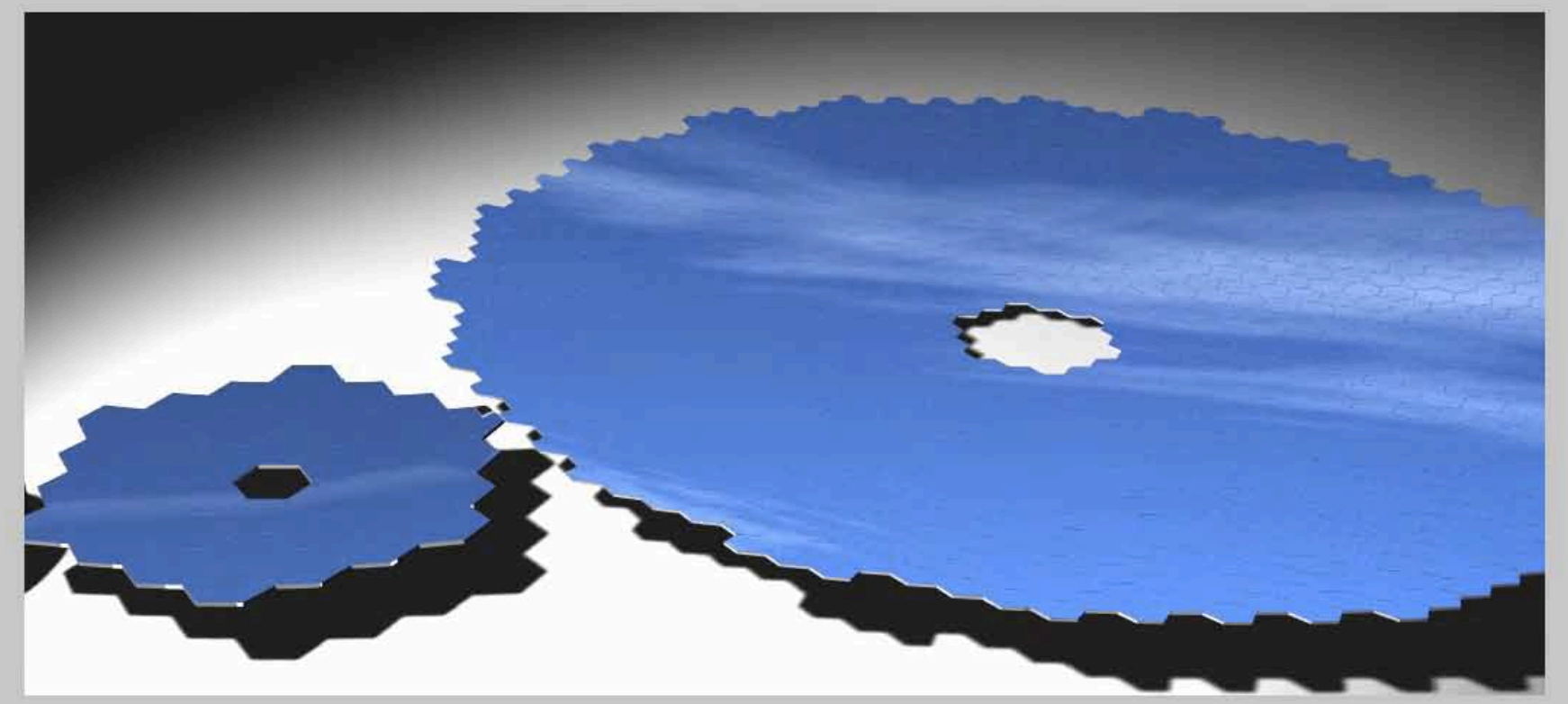
– Measuring stellar temperature and probing the properties of interstellar dust grains along the line of sight


Today


Sideways Stellar Motions Suggest Shell in Milky Way Halo
Andromeda Galaxy
Milky Way Galaxy
Halo
Disk
Sun
Shell


Prospects with TMT

TMT-Keck Heritage

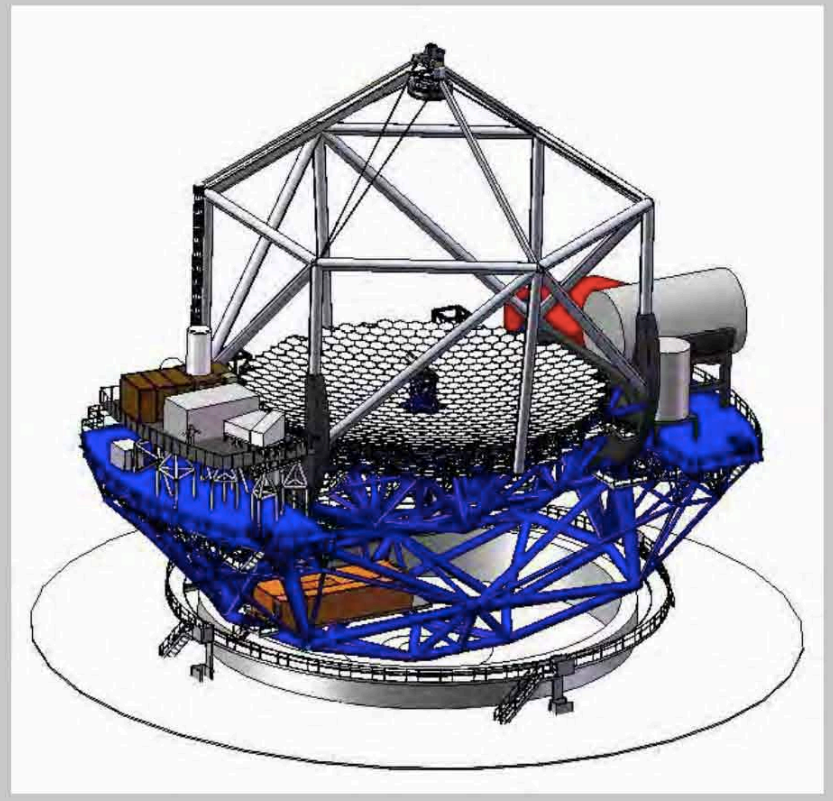


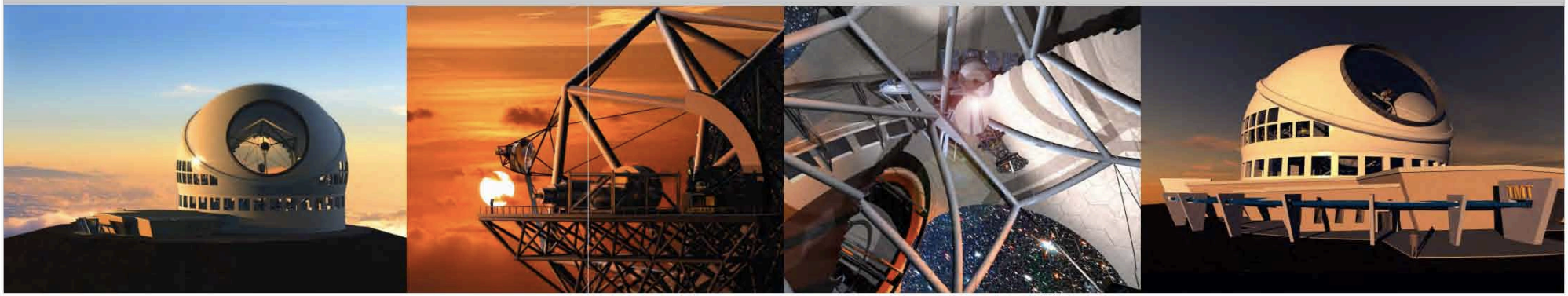
Keck 10-m, 36 segment mirror
1.8-meter segments

TMT 30-m, 492 segment mirror
1.4-meter segments

TMT: Fast Facts

- 30 meter primary, filled aperture, 492-segments
- f/1 primary
- Visible/Infrared (0.31 – 28 μm)
- Fully integrated adaptive optics
- Partners: ACURA, Caltech, UC
- Participating: NAOJ, China, and India



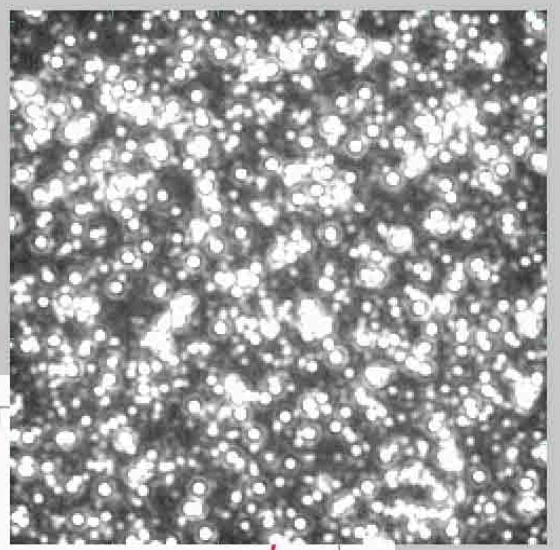


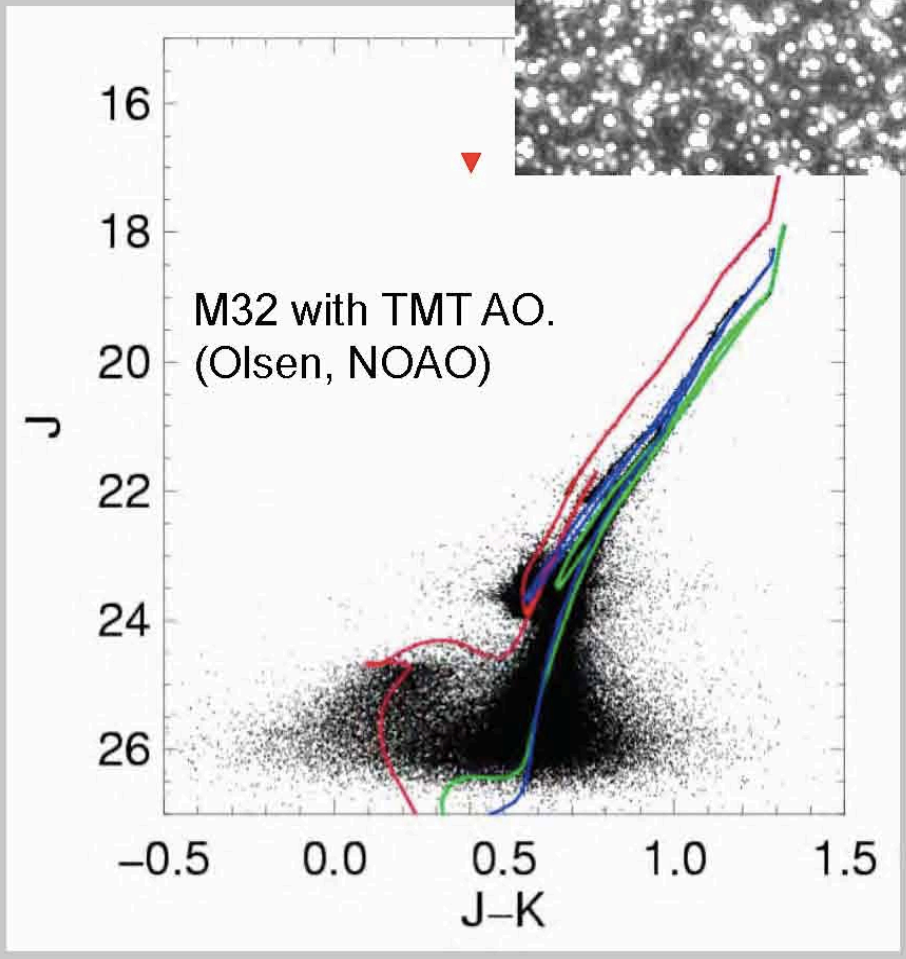
Stellar Populations in the Local Volume

Star formation history in galaxies out to the Virgo cluster:

- Adaptive Optics will allow photometry of resolved stellar populations in crowded fields
- This will constrain the star-formation history and metallicity in a wide range of environments
- High-resolution spectroscopy will provide element abundances
- Complementary to high-z galaxy studies

1 arcsec at Virgo, K-band





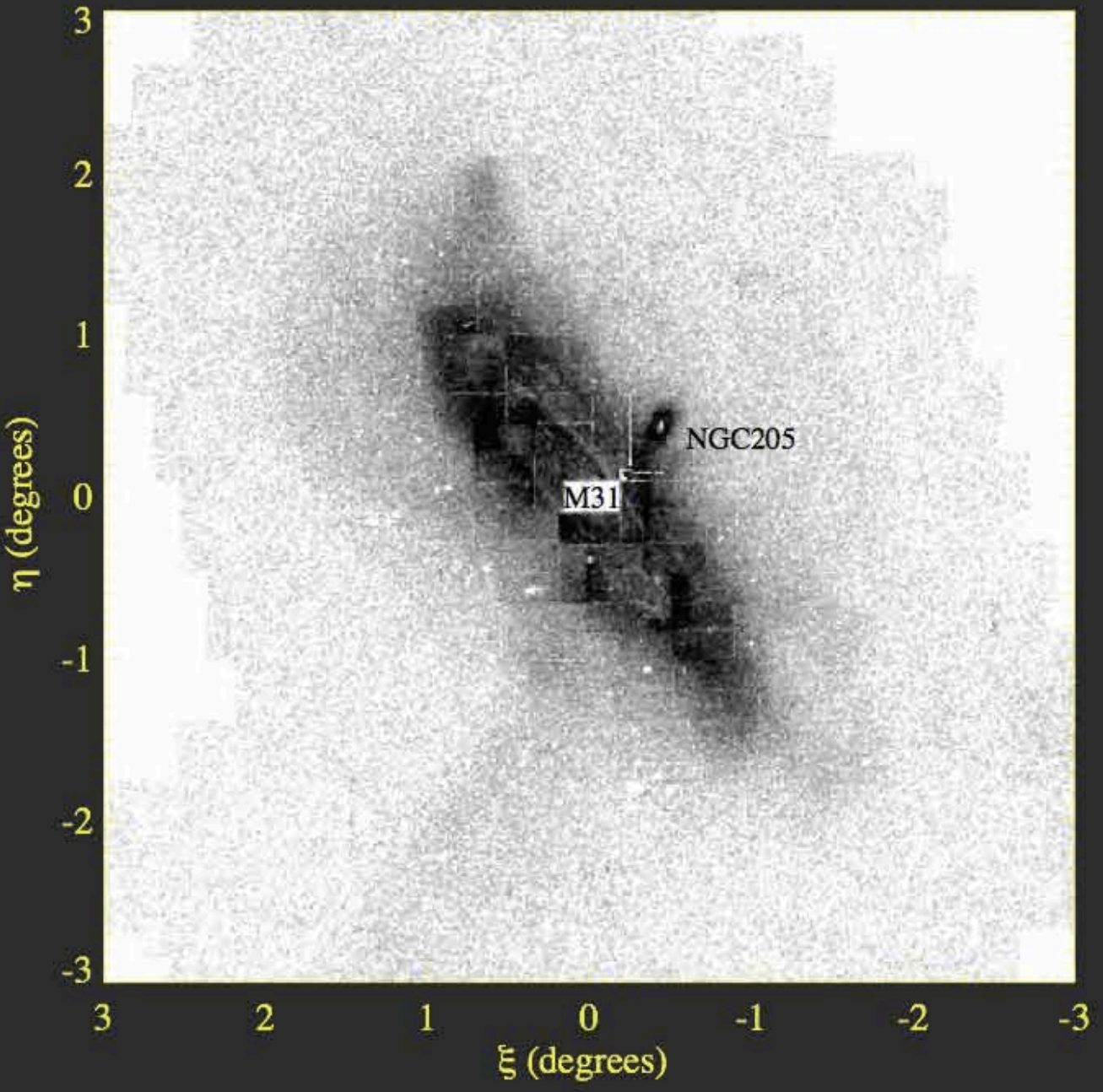
Summary

Andromeda's unusual inner spheroid:

- Stars formed *in situ* versus accreted stellar systems
- No structural subcomponent like it in the Milky Way
- Boxy bulge and bar: pseudo-bulge + classical bulge
- Sersic profile with n = 2–3 dominates the R < 20–30 kpc on the minor axis
- Metal-rich: <[Fe/H]> ~ –0.7 with a large spread
- Dynamically hot (σ_{los} ~ 130 km/s) with a hint of rotation
- Kinematical detection of tidal debris associated with a recent merger event
- Most stars are old; a small fraction are of intermediate age

M31 substructure supports violent merger history

- Ibata et al. (2001) discovered a giant stellar debris stream
- Ferguson et al. (2002) found several other significant structures (NE shelf, NGC205 loop, etc.)
- Ibata et al. (2005) found evidence for an "extended disk-like structure" comprising ~10% of the luminous disk mass, extending to ~40 kpc, possibly the result of recent mergers



Outline

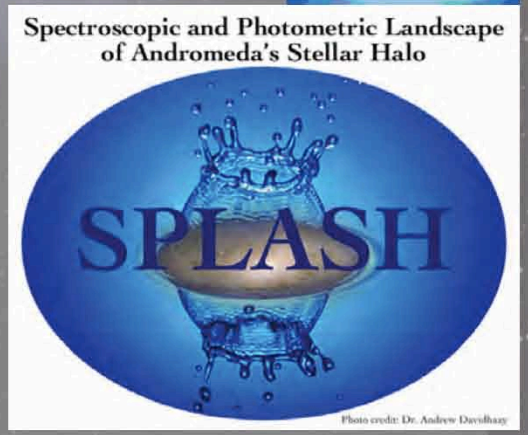
The house next door

Laboratory for studying galaxy formation

Laboratory for stellar population / dust studies

I'll focus on two large surveys: SPLASH and PHAT

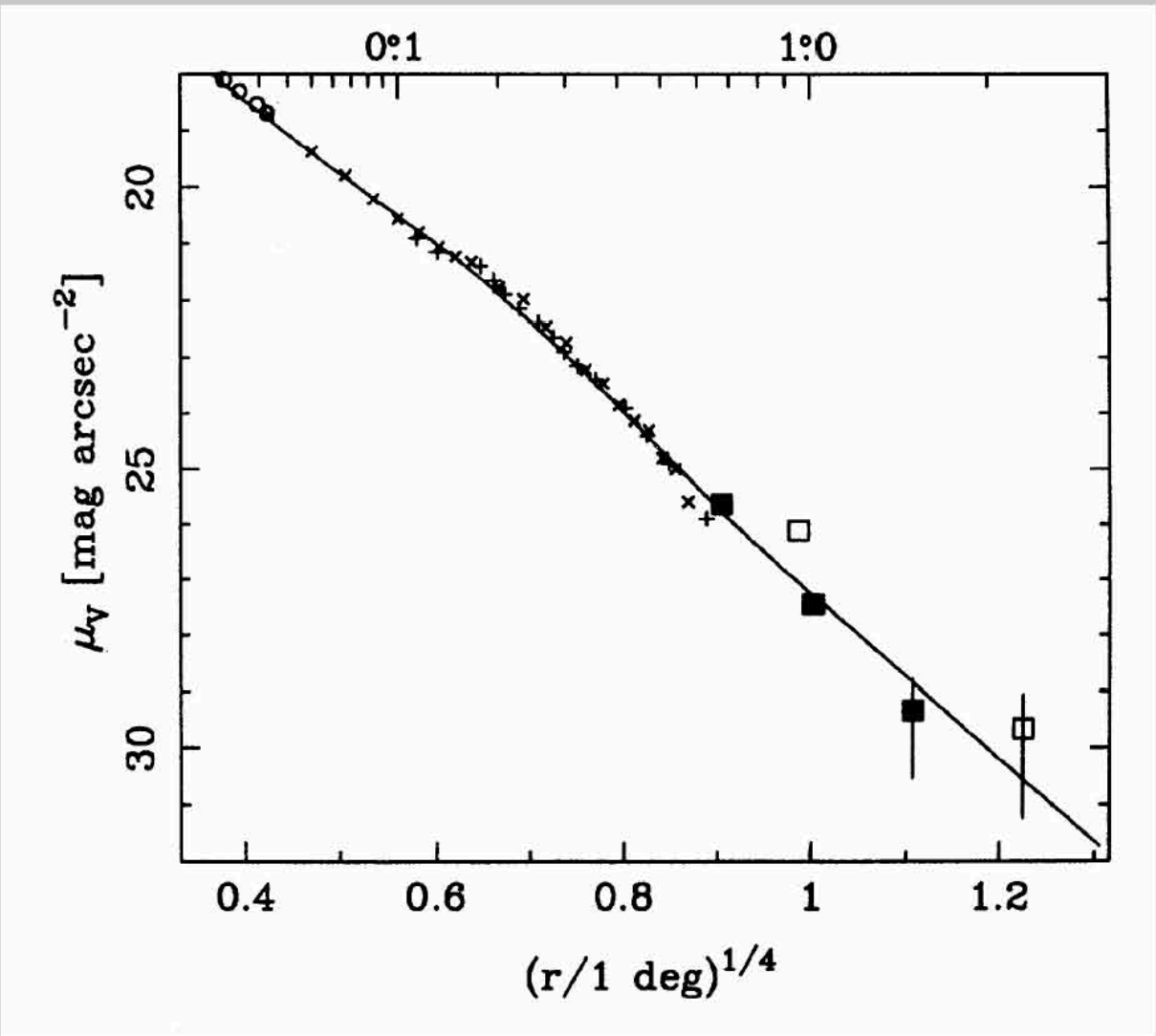
- Compare/contrast to the MW's structural components
- Structure: surface brightness profile, bar/boxiness, substructure (tidal debris)
- Resolved stellar kinematics
- Metallicity



Ongoing related work:

- Chemical abundance from coadded spectra

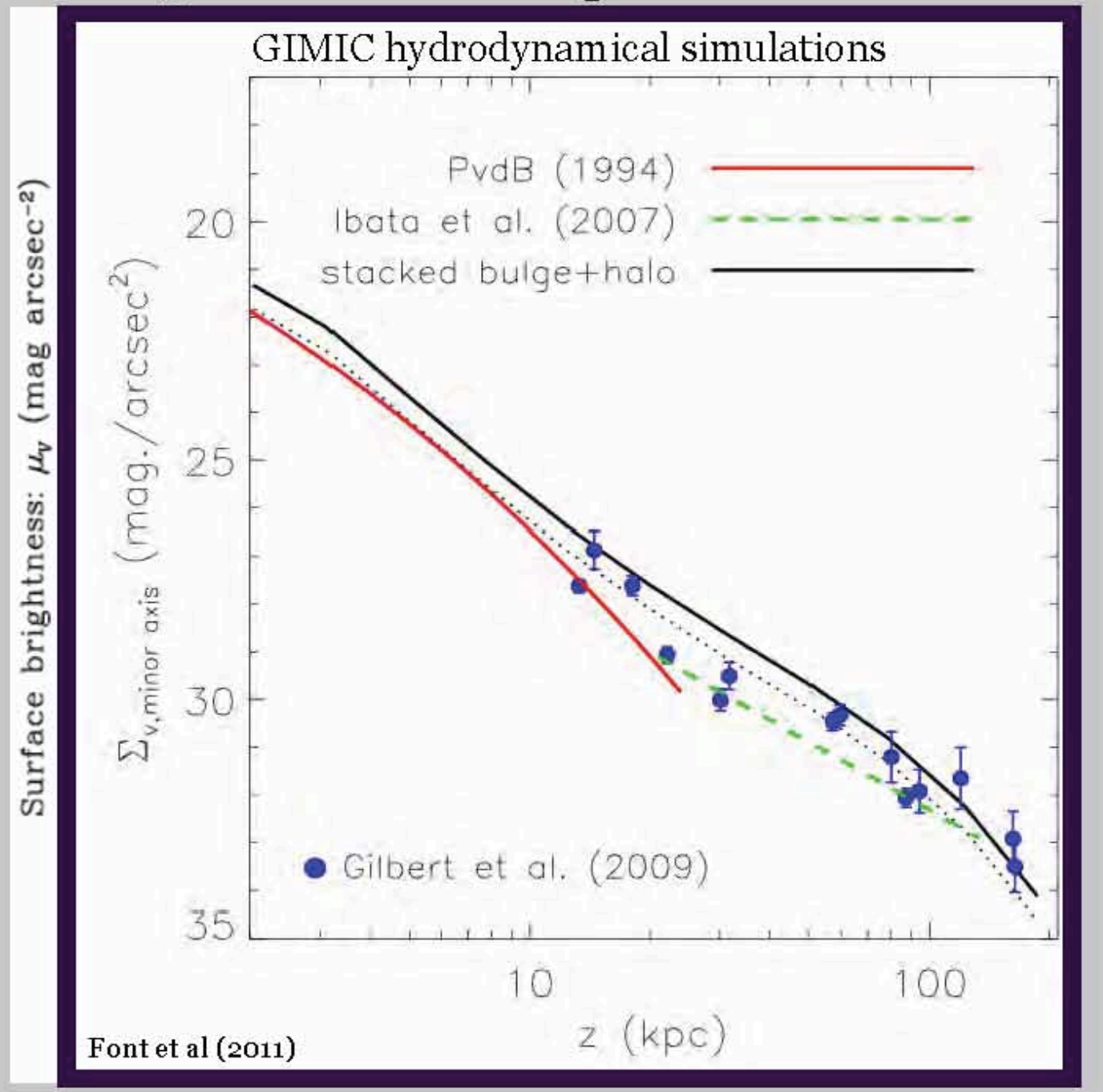
Inner "halo" of M31 looks like a bulge



Pritchet & van den Bergh (1994)

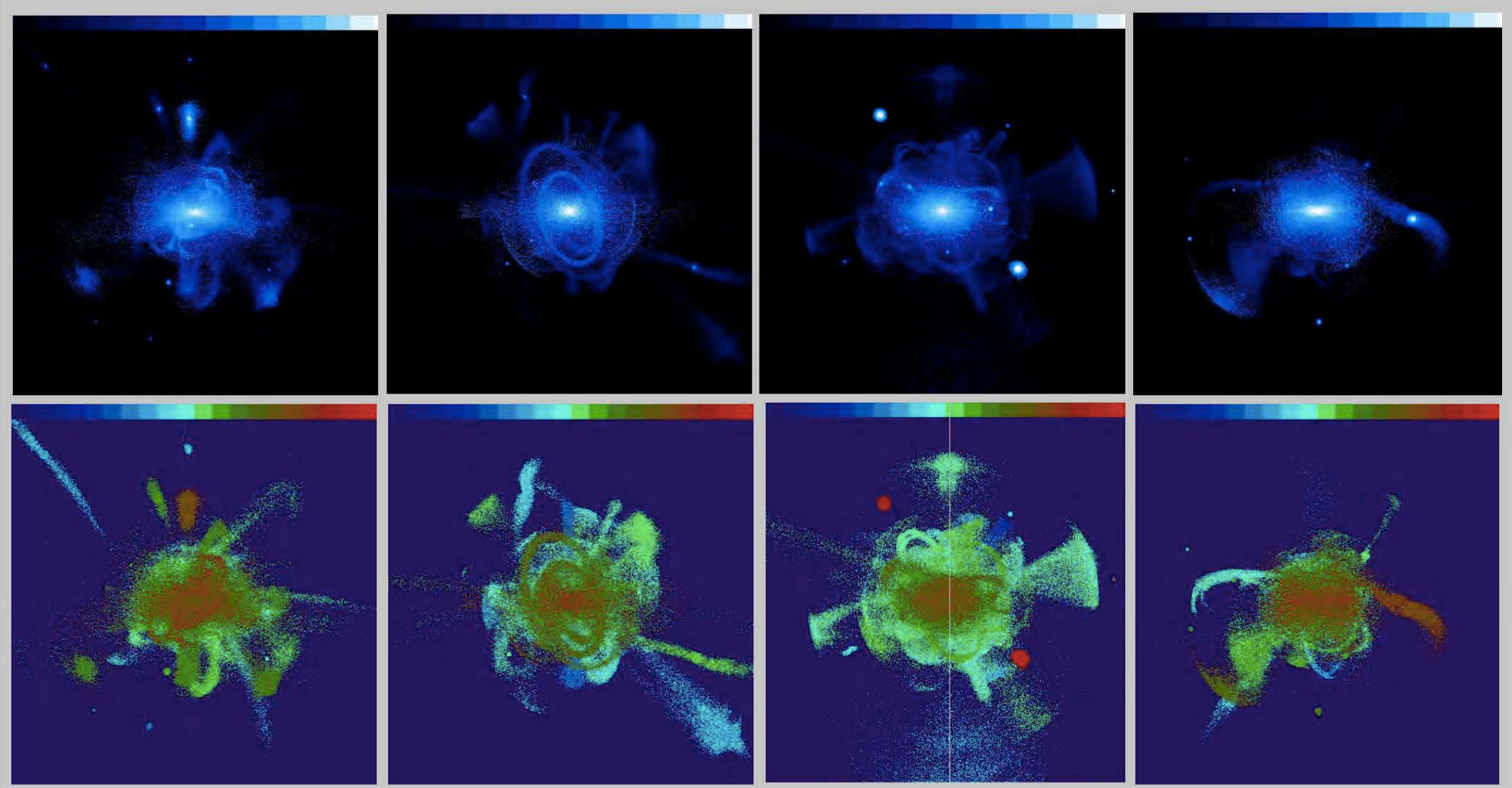
Profile looks like a de Vaucoulers $r^{1/4}$ law instead of the canonical power-law r^{-2} halo

M31's Surface Brightness Profile



– PG, et al. (2005)
– Gilbert, PG, et al. (2012)

Simulations of the Formation of the Stellar Halo of MW/M31



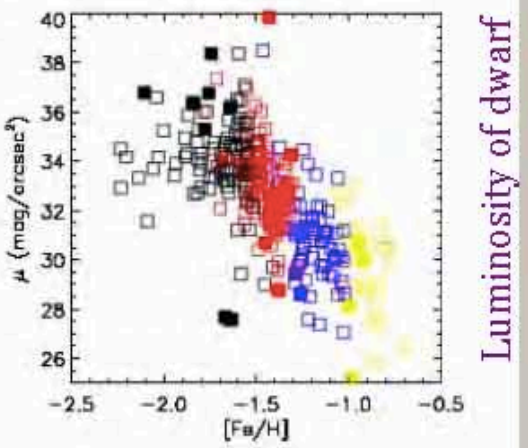
- Higher SB tidal debris tend to be more metal rich: observations and simulations
- Higher SB debris tend to come from the more luminous, metal rich dwarf satellites and/or recent encounters

Bullock & Johnston (2005) models

Font et al. (2008, ApJ)
Gilbert et al. (2009, ApJ)

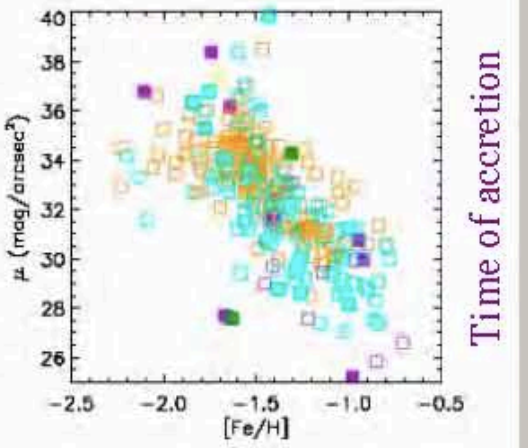
Metallicity and [α/Fe] of Tidal Streams

Bullock & Johnston (2005) models

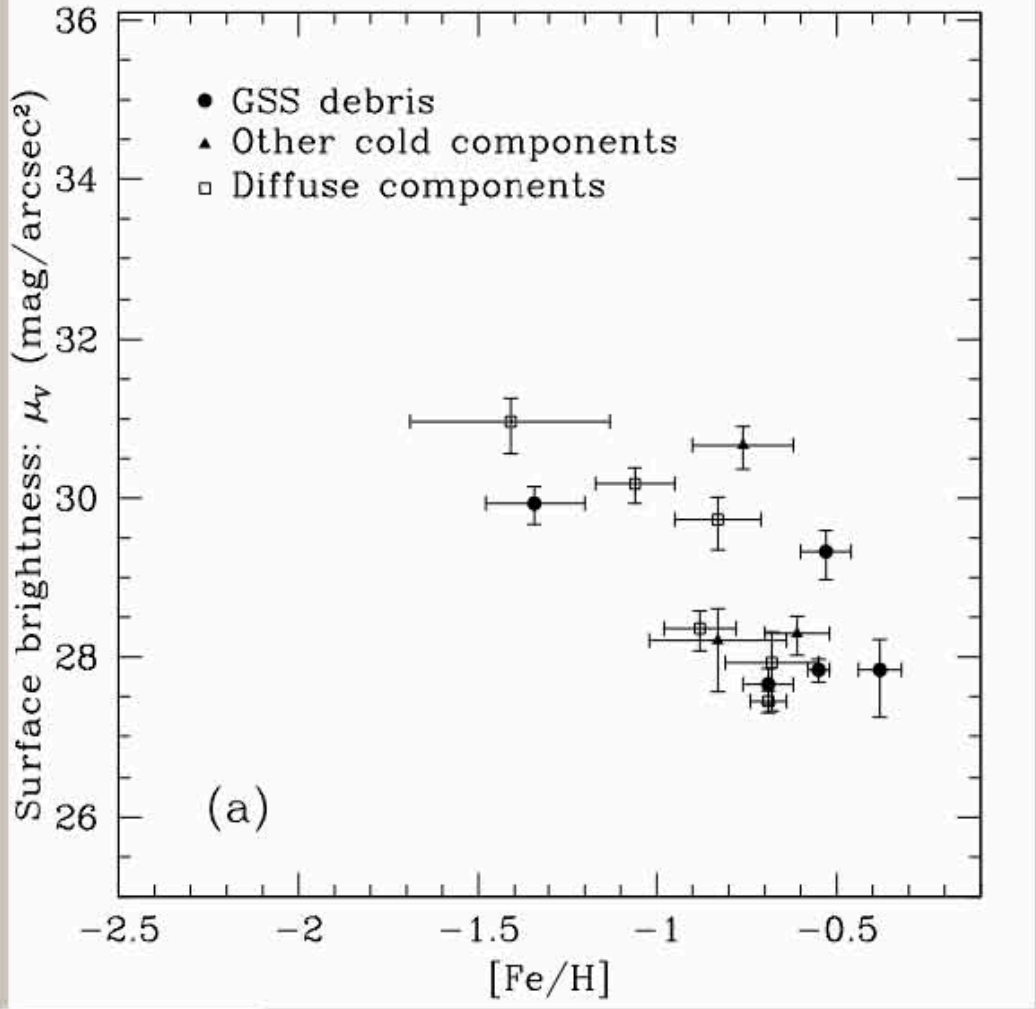


Luminosity of dwarf

Color coding:



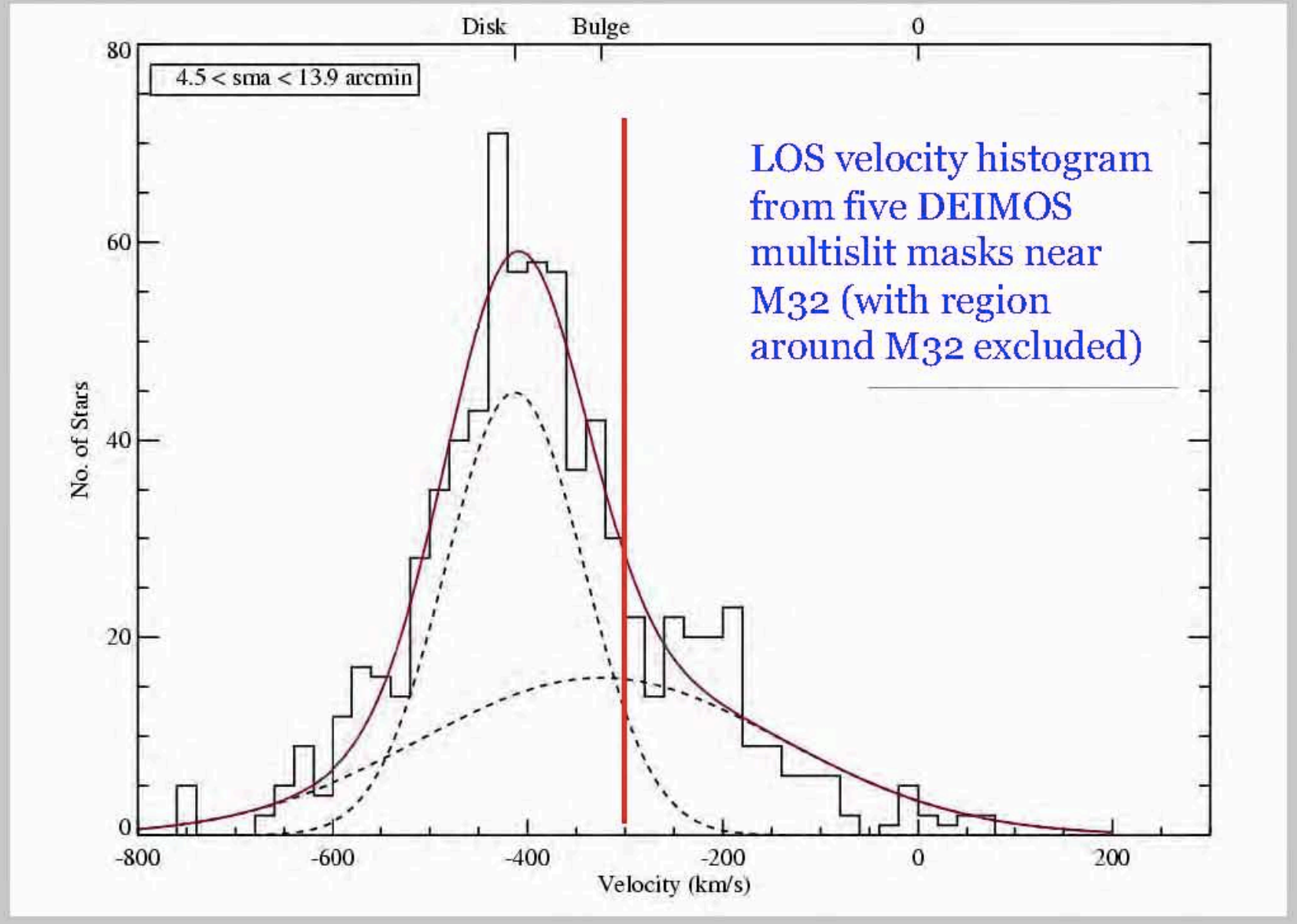
Time of accretion



- Metallicity trend is related to <u>luminosity</u> of dwarf satellite progenitor
- Trend in [α/Fe] is related to <u>time</u> of accretion event

Font et al. (2008, ApJ)
Gilbert et al. (2009, ApJ)

Stellar Kinematics of M31's Disk & Spheroid

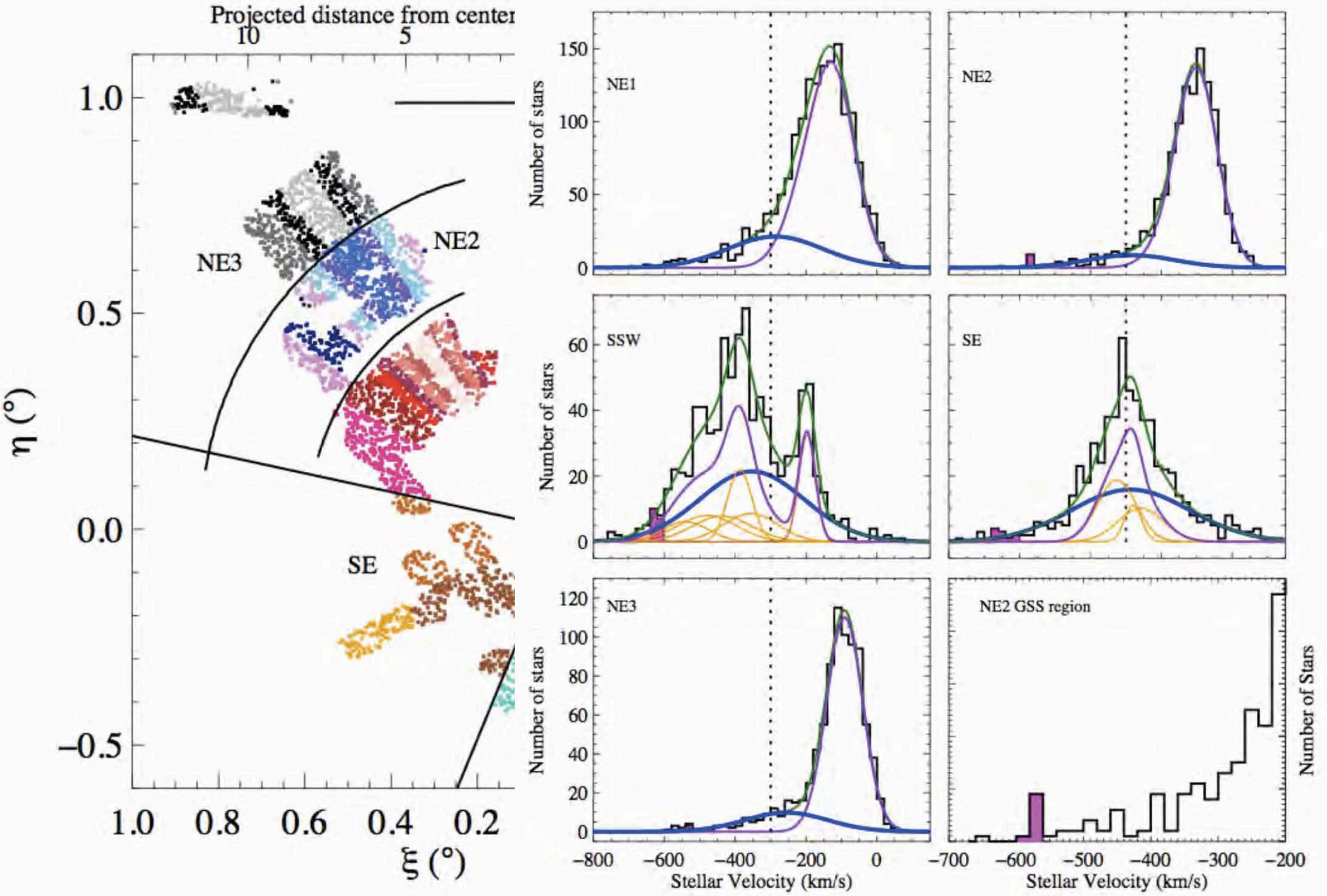


— Well approximated by a cold, rotating disk with a flat rotation curve (v_{rot} = 250 km/s) superposed on a hot spheroidal component with low rotation

Howley, PG, Kalirai, et al. (2011b, in prep)

Stellar kinematics in M31's inner region

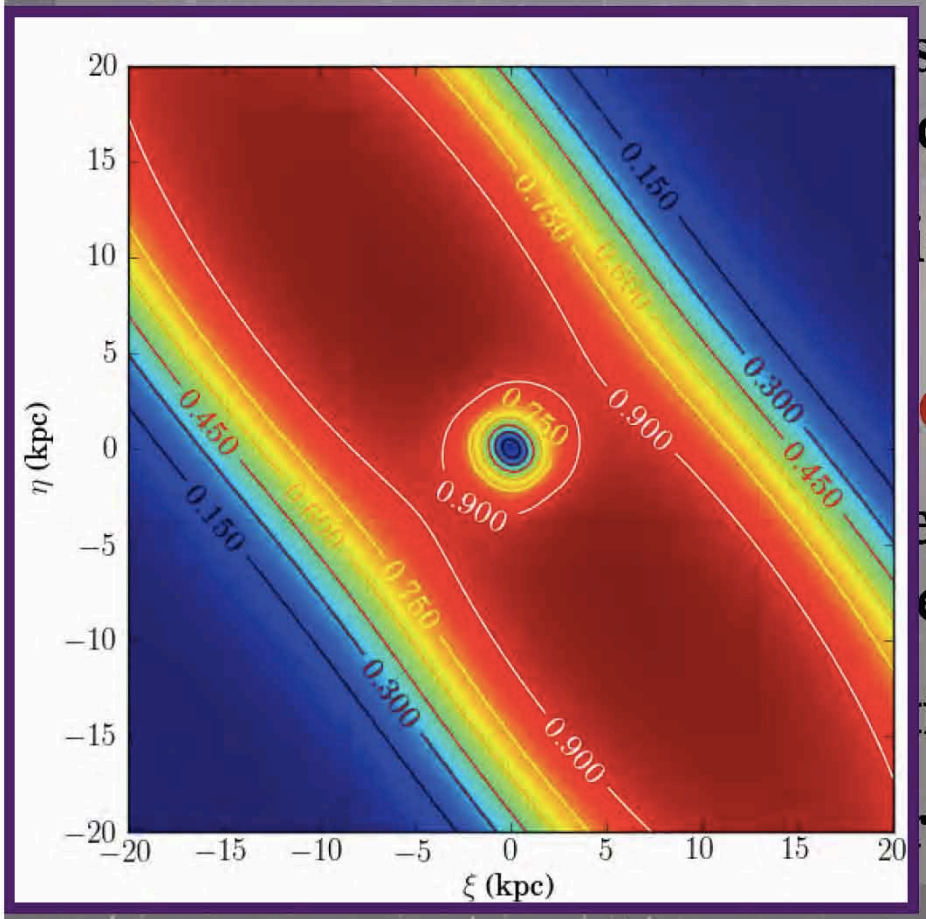
Dorman, PG, et al (2012,

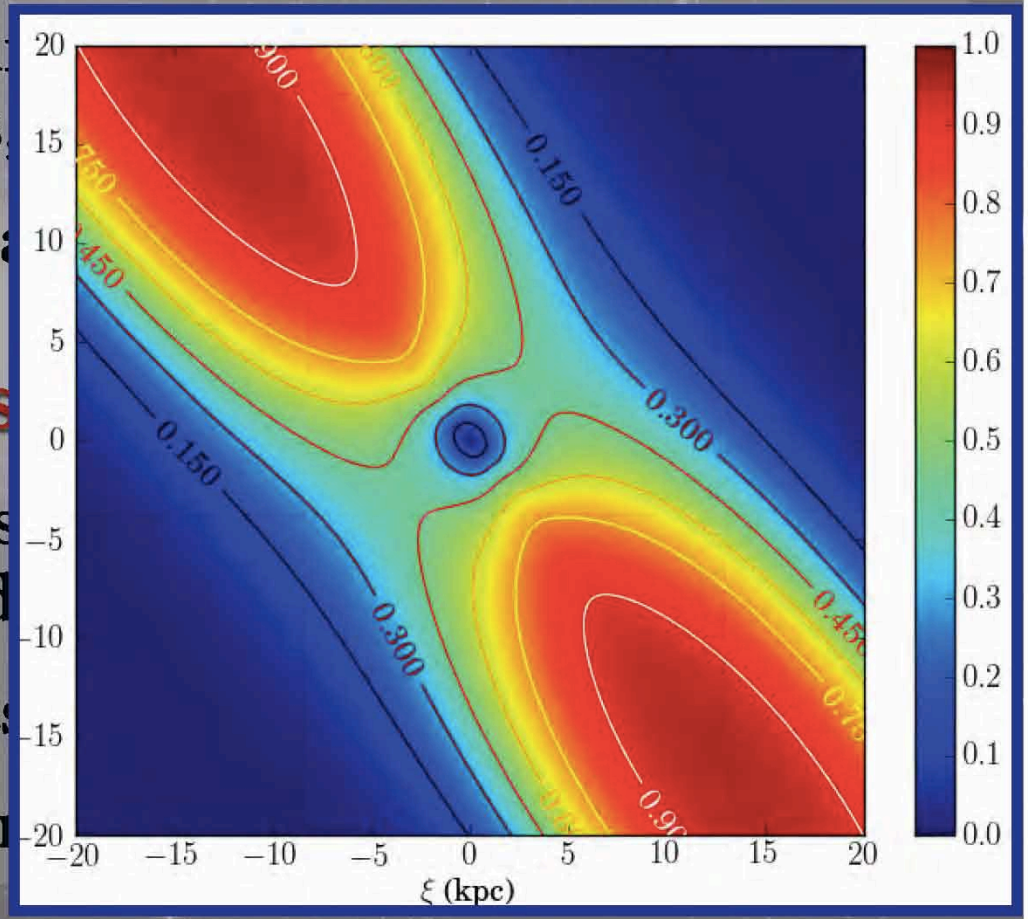


Ongoing projects

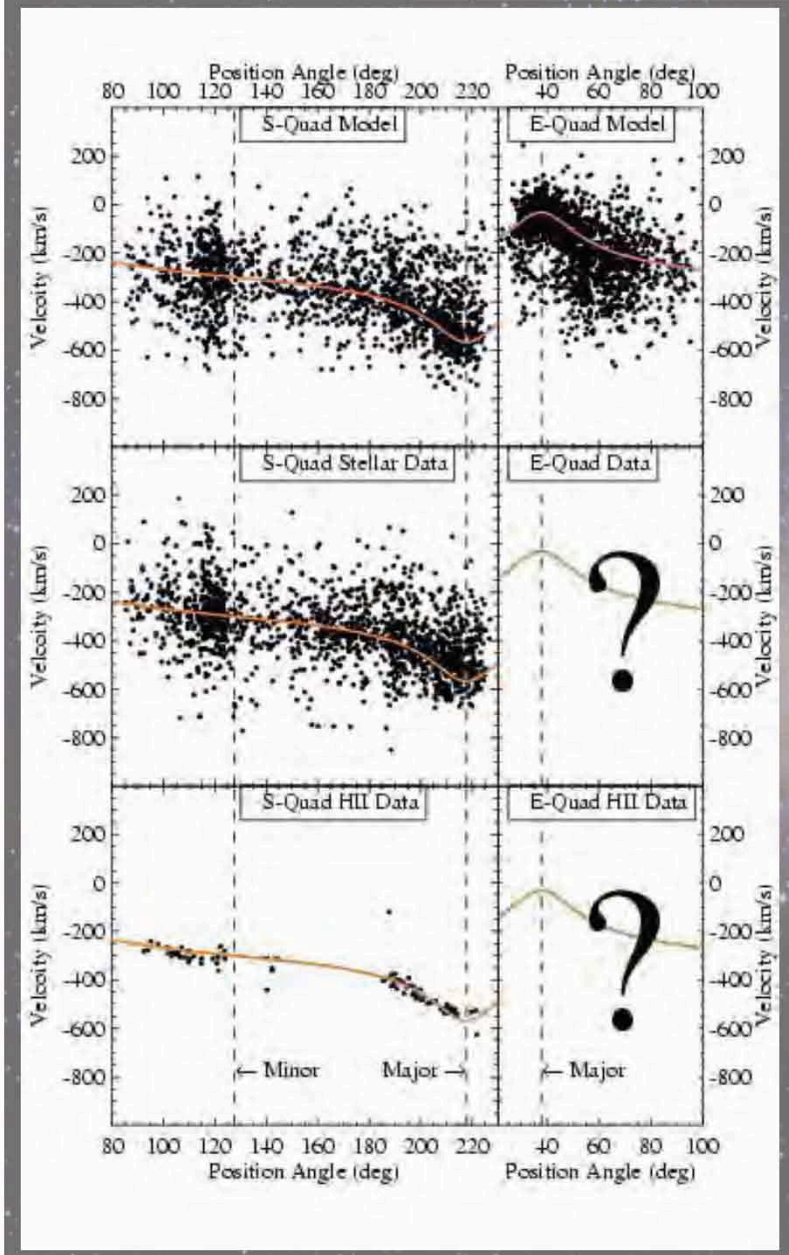
Chemical abundances from coadded spectra

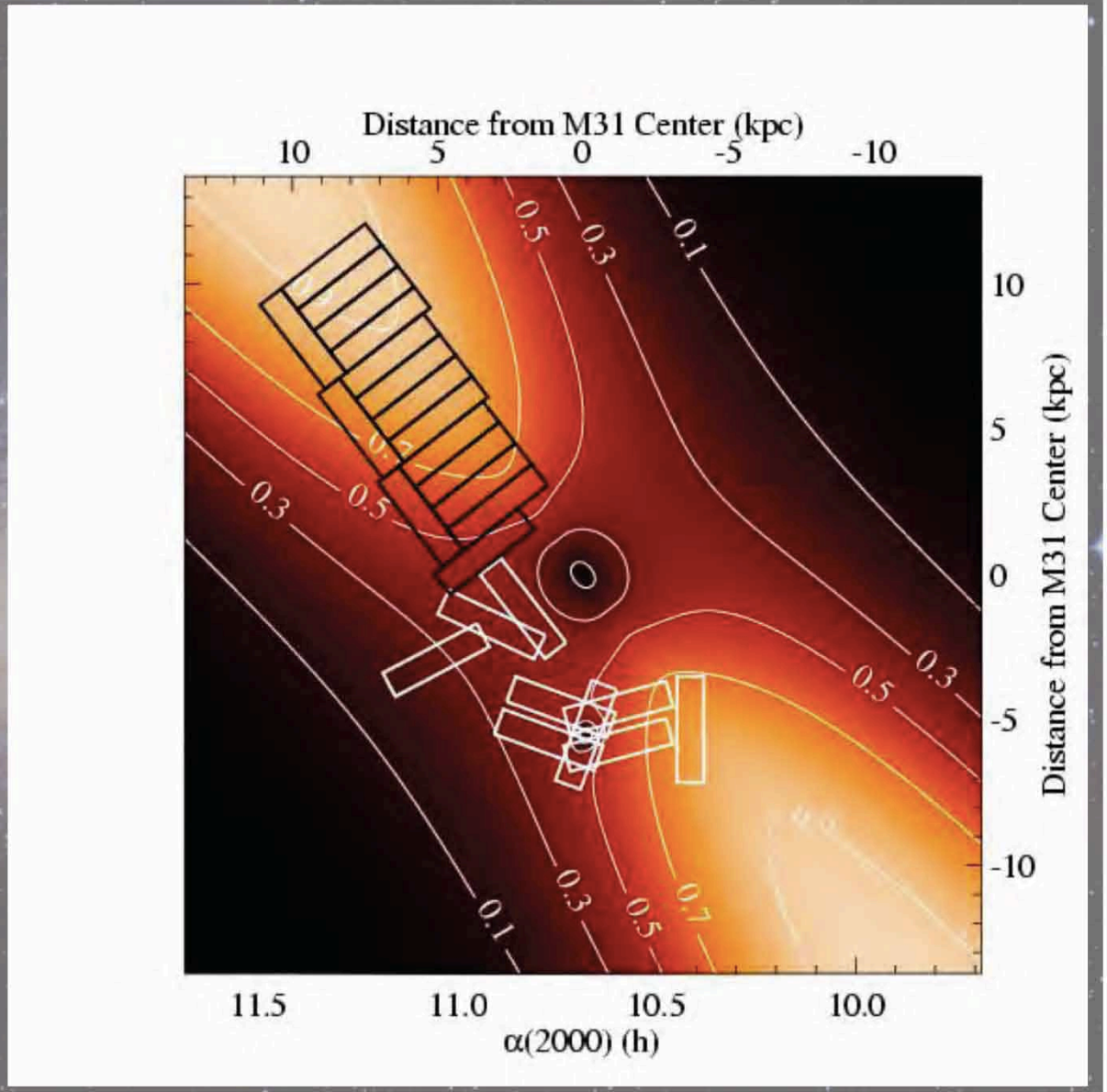
M31 bulge/disk/halo decomposition *(Dorman et al, in prep)*





Stellar and ionized gas kinematics

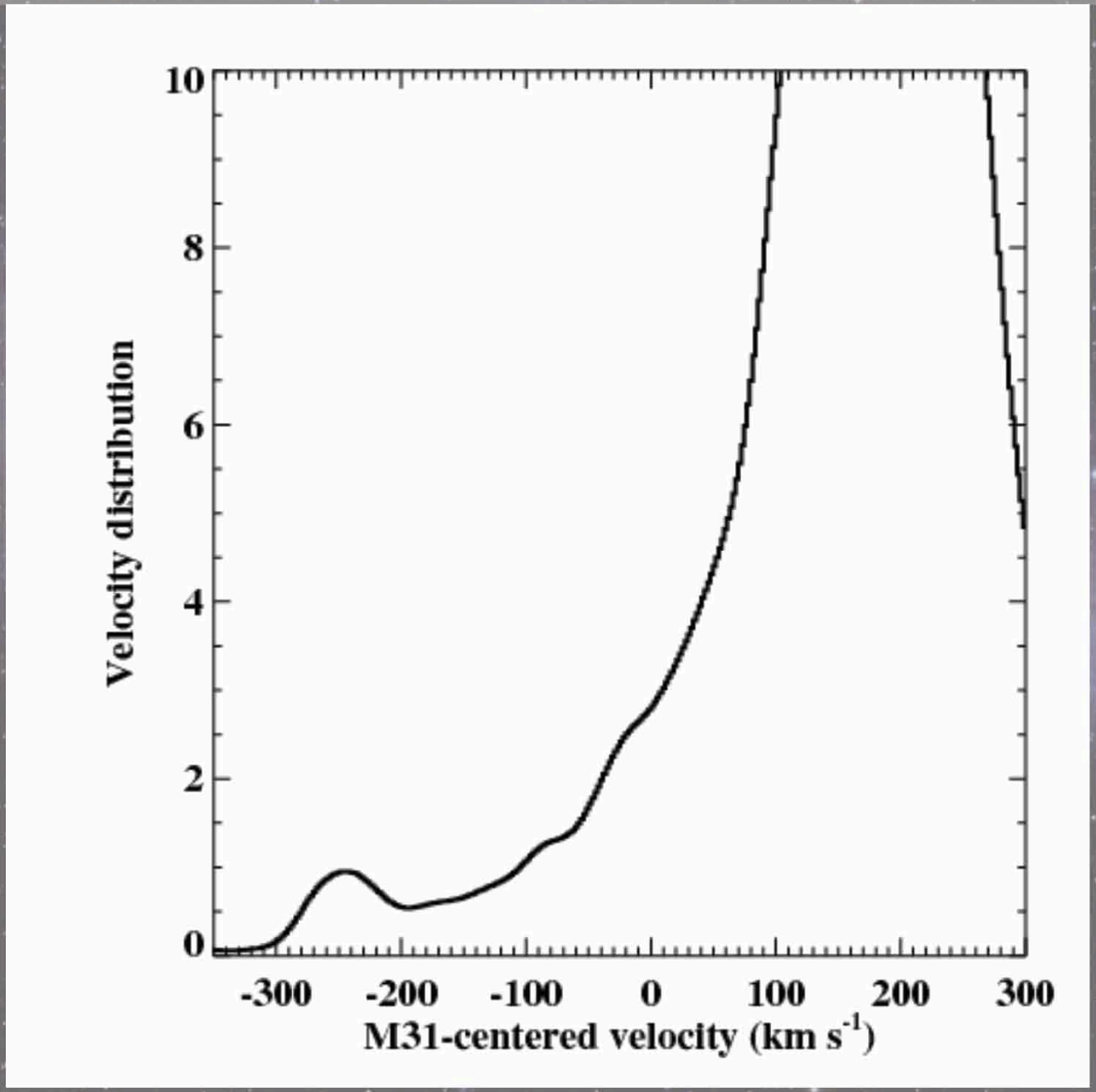




Dorman, PG, et al (2012, in press)
Howley, PG, Kalirai, et al. (2012, subm)

Bulge kinematics:

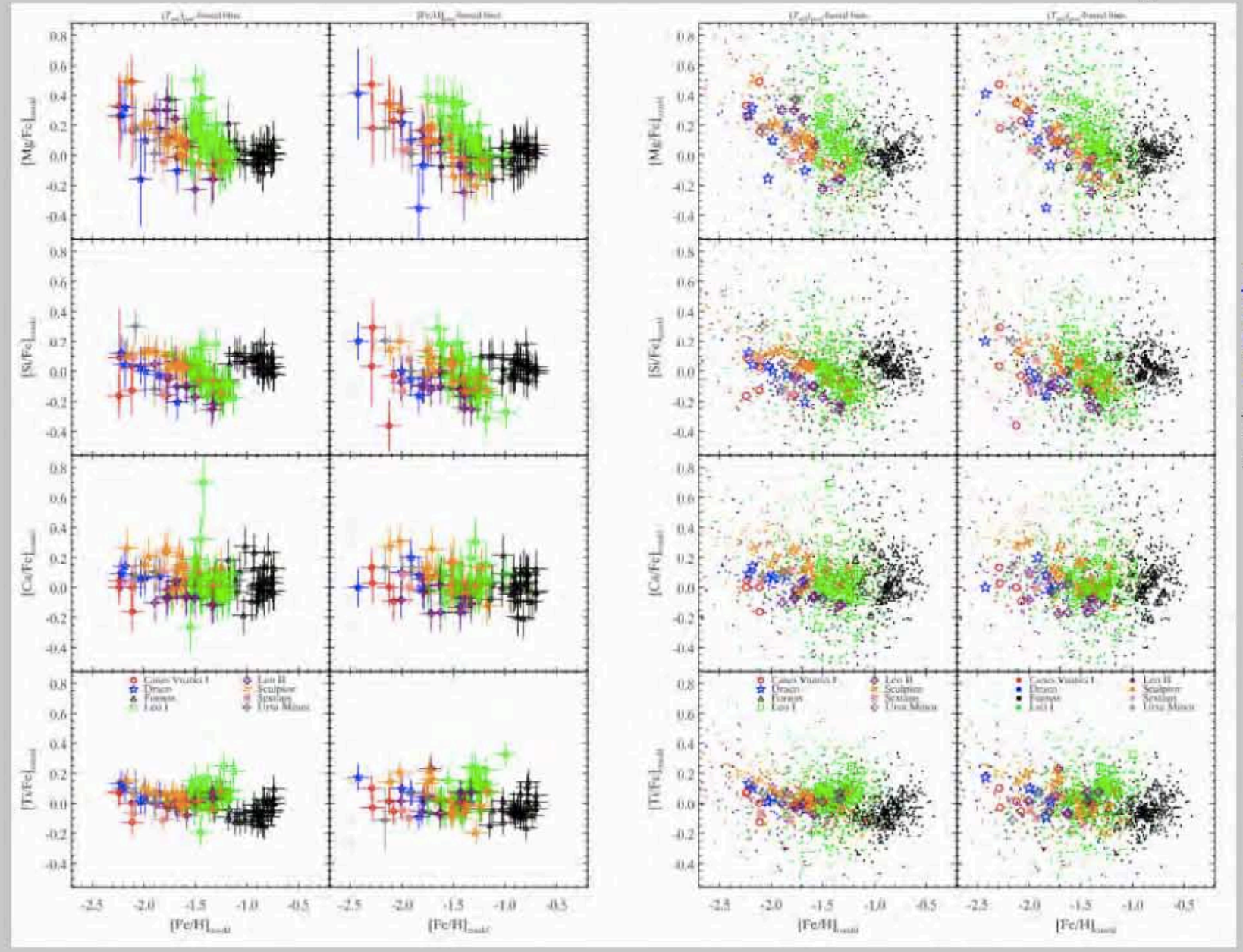
The influence of tidal debris associated with the Giant Southern Stream



Dorman, PG, et al (2012, ApJ)

Fardal, PG, et al (2012, MNRAS)

Tests of abundances from co-added spectra



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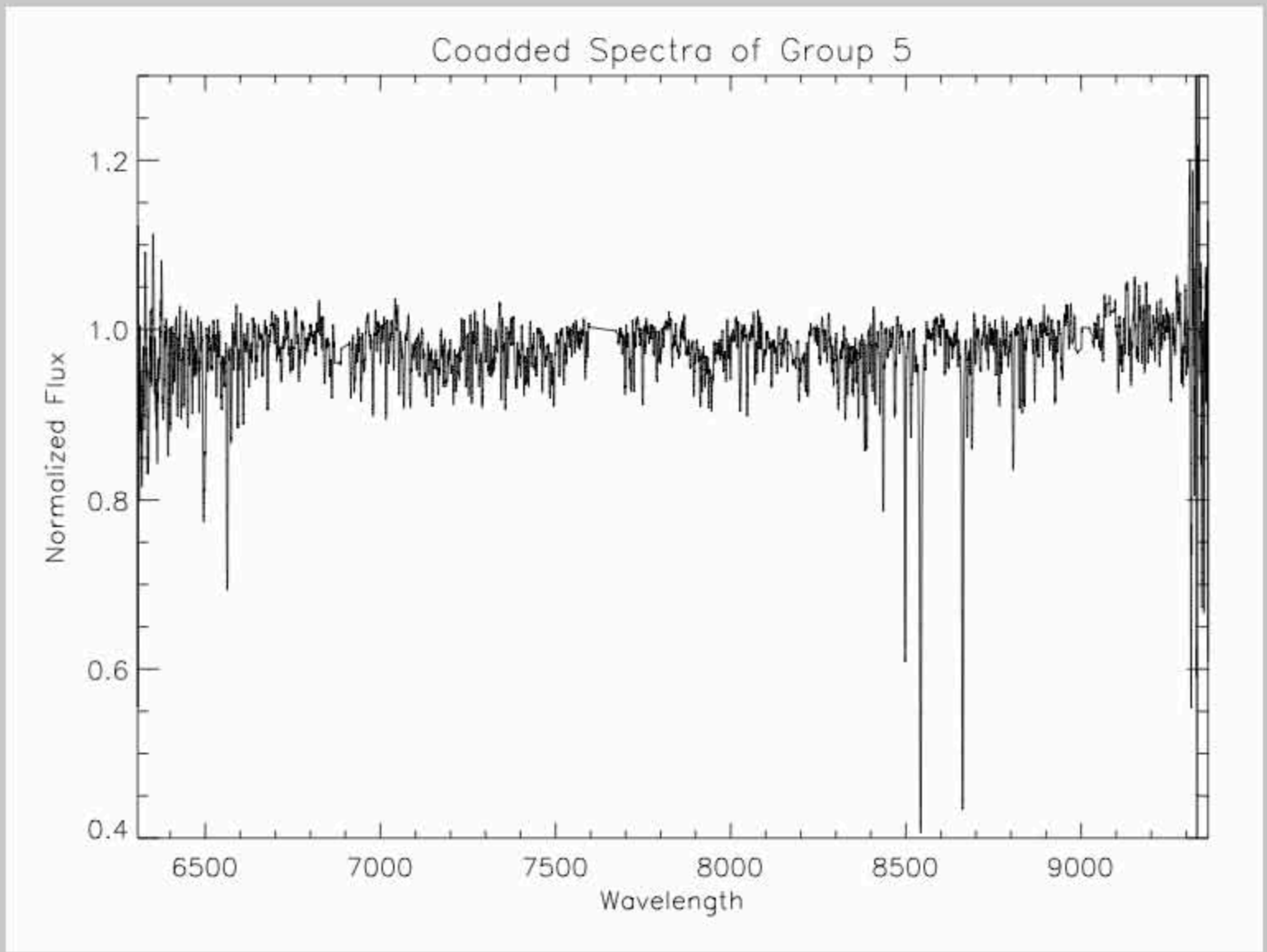
Yang et al (2012, ApJ, in press)

Co-added Spectra of RGB Stars in NGC 147



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Detailed chemical abundances from co-added spectra of RGB stars in M31 dSph/dE galaxies (paper in prep)

Spectra of C stars, IR-selected stars, etc