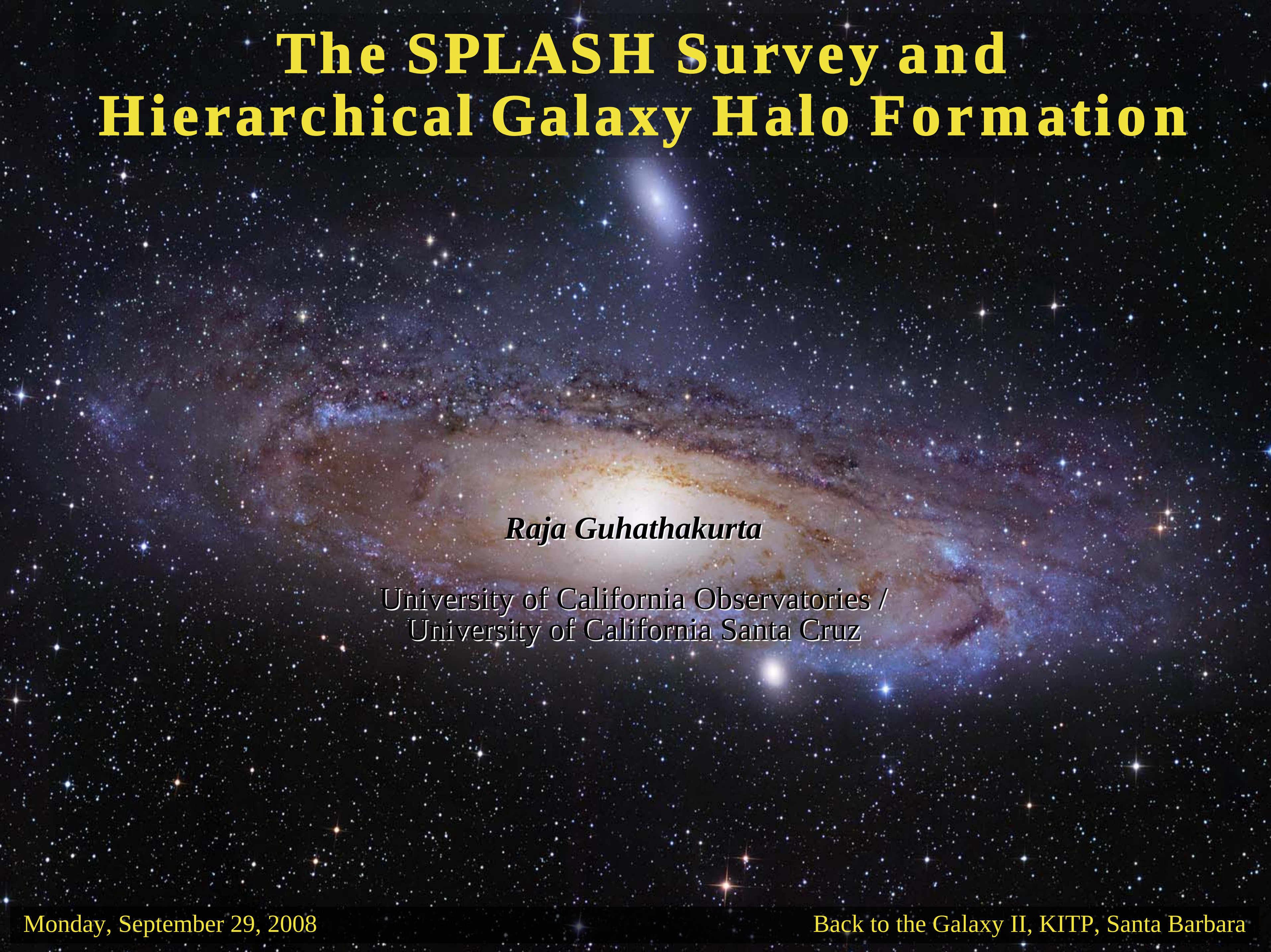

The SPLASH Survey and Hierarchical Galaxy Halo Formation

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University of California Observatories / University of California Santa Cruz

Collaborators

Spectroscopic and Photometric Landscape
of Andromeda's Stellar Halo

SPLASH

Photo credit: Dr. Andrew Davidhazy

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Progessive Stages of Hierarchical Galaxy Formation

Survivors: Today's Dwarf Satellites
- *Metallicity distribution of dSph satellites vs. parent halo*

Slightly Damaged: NGC 205 and M32
- *Photometric / kinematic signs of tidal distortion*
- *Orbit reconstruction using a genetic algorithm*

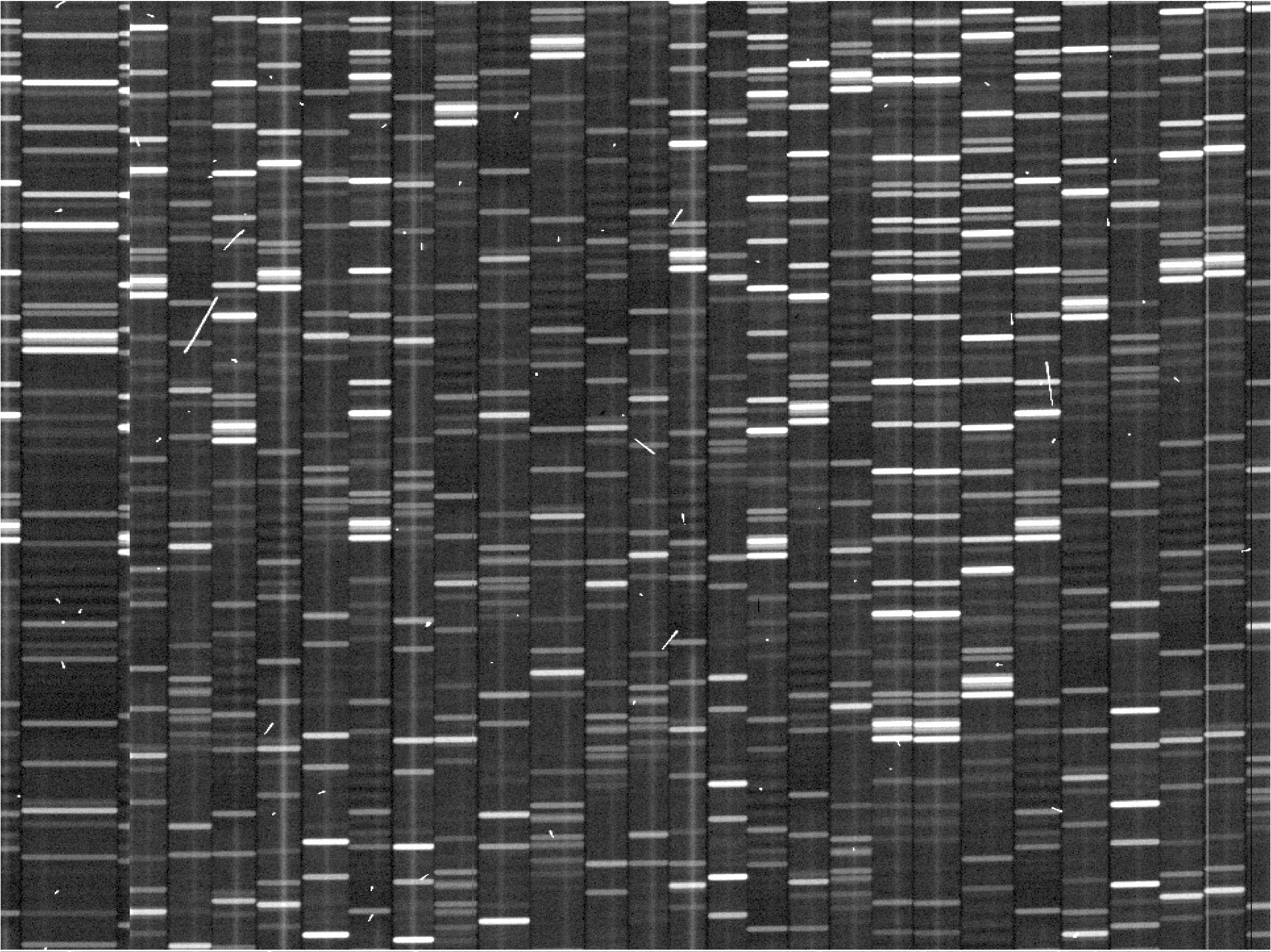
Forensic Accident Reconstruction: M31's Giant Stream
- *Orbit and progenitor properties (dynamics, metallicity)*

Scratches on the Cannibal: Statistics of tidal streams
- *Statistical properties of streams in M31's halo*

The Cannibal's Belly: Smooth, Virialized Halo
- *Surface brightness profile of M31*
- *Tangential motion of M31 and the fate of the Local Group*

Formation of the Milky Way

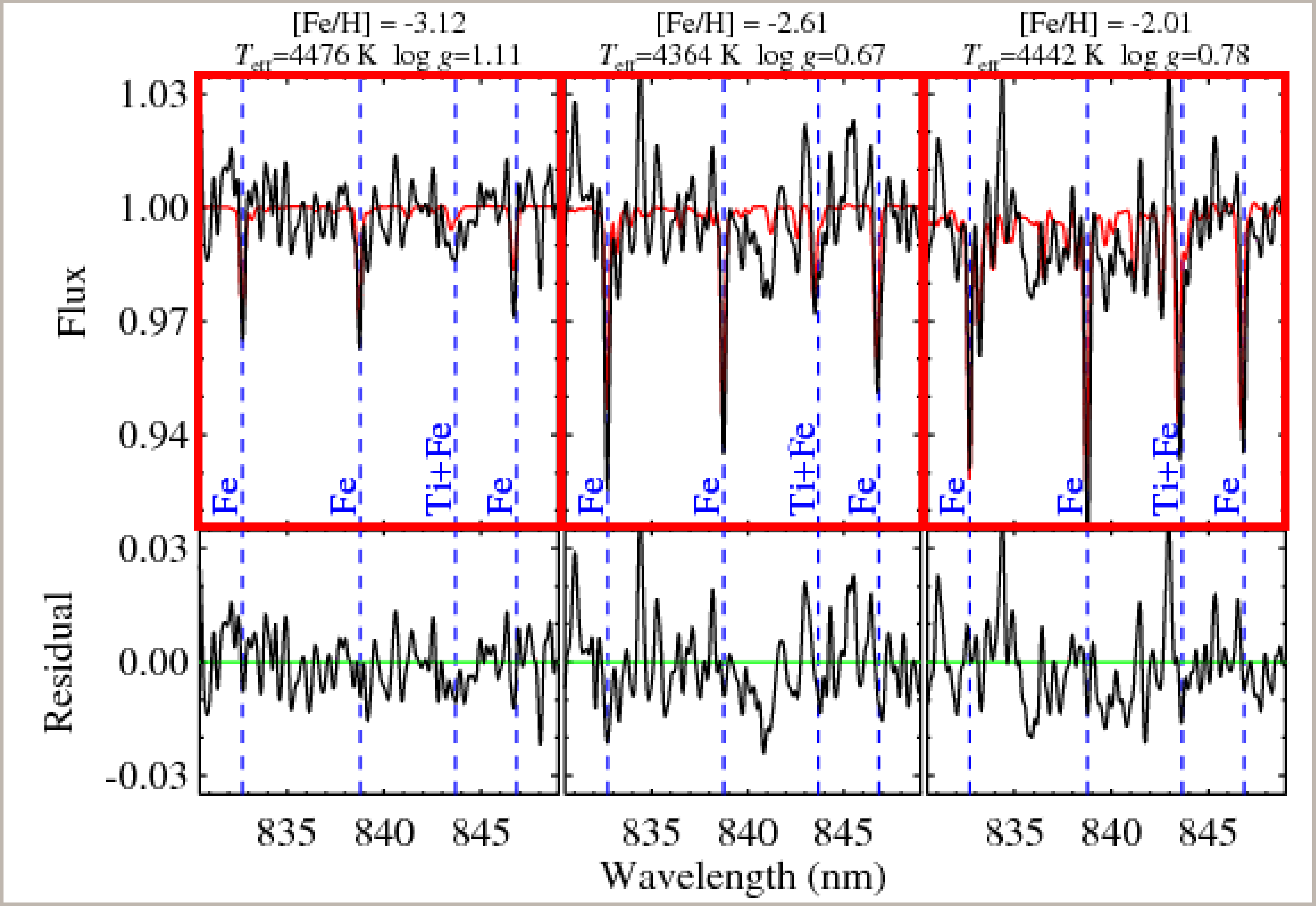
Via Lactea Simulation




Local Group Dwarf Satellites

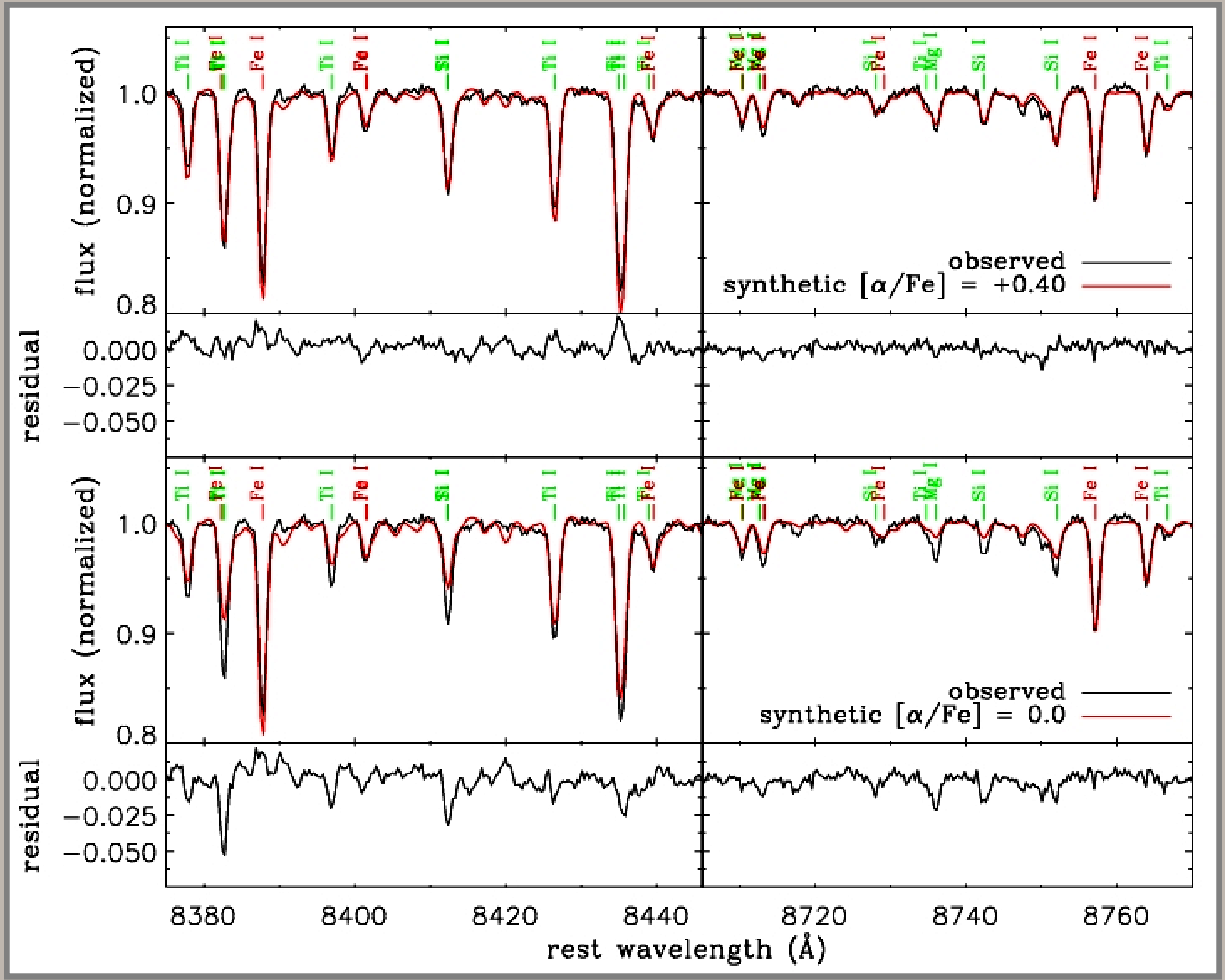
Metallicity Distribution of Dwarf Satellites

Test of the hierarchical formation scenario



Kirby et al. (2008, ApJL)

Chemical Abundance Patterns

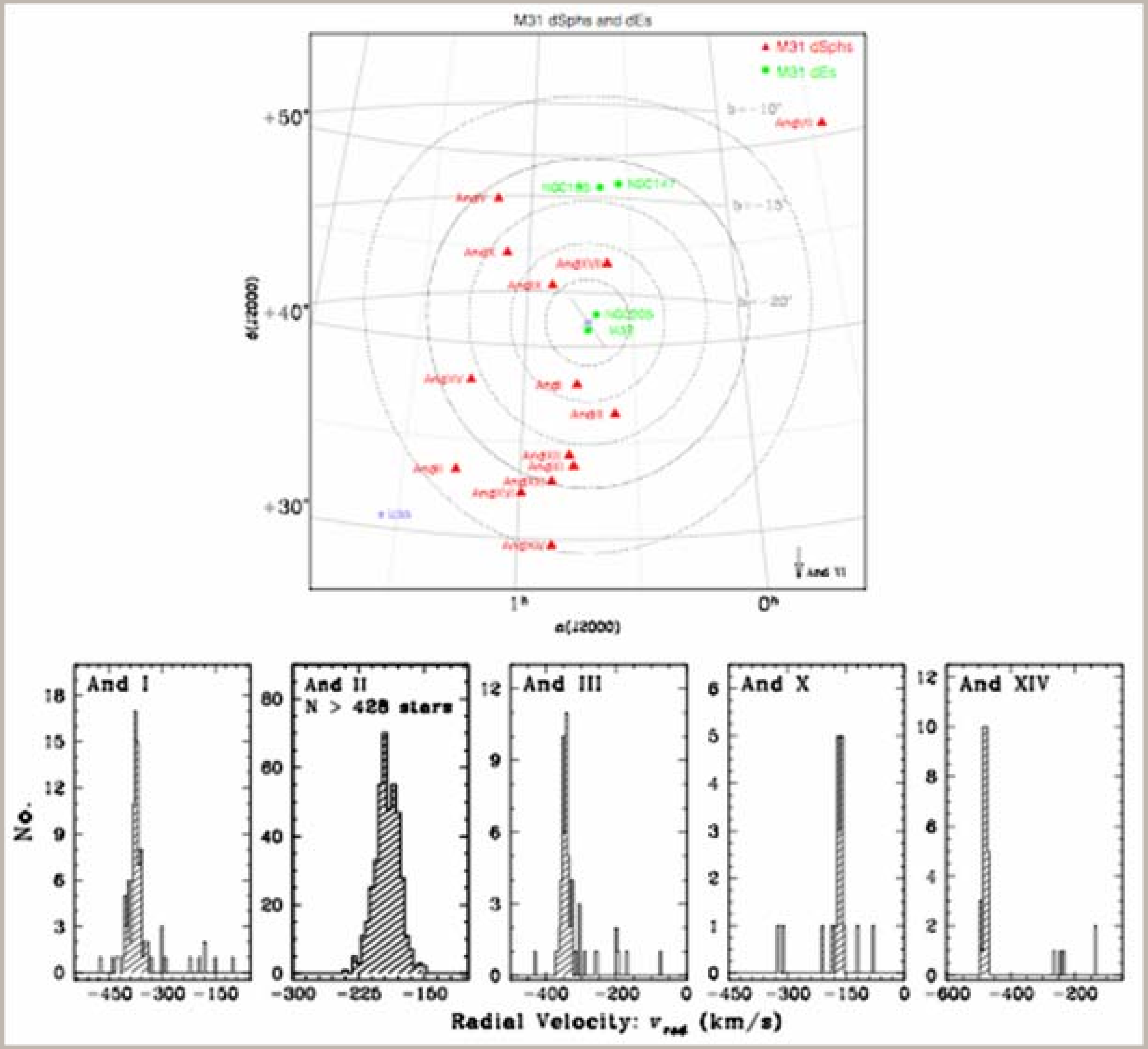


– **[Fe/H]** from weak Fe lines
– **[α/Fe]** from other weak metal lines

Kirby, PG, & Sneden (2008, ApJ)

Ongoing Spectroscopy of M31 dSph Satellites

Internal dynamics and chemical abundance



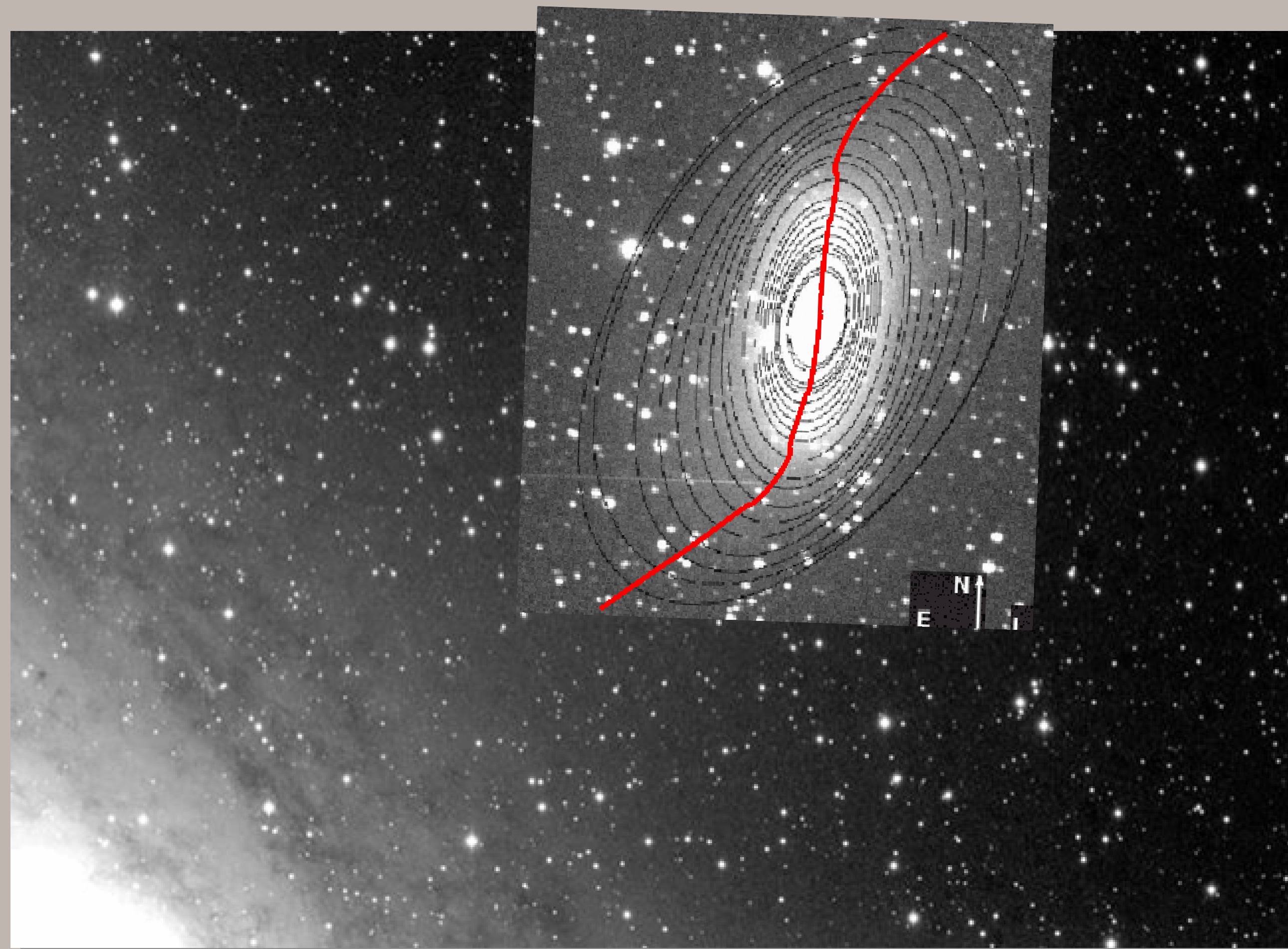
Geha et al. (2008, in prep)
Kalirai et al. (2008, in prep)


M31's Dwarf Satellites
NGC205 and M32

NGC 205 Observations

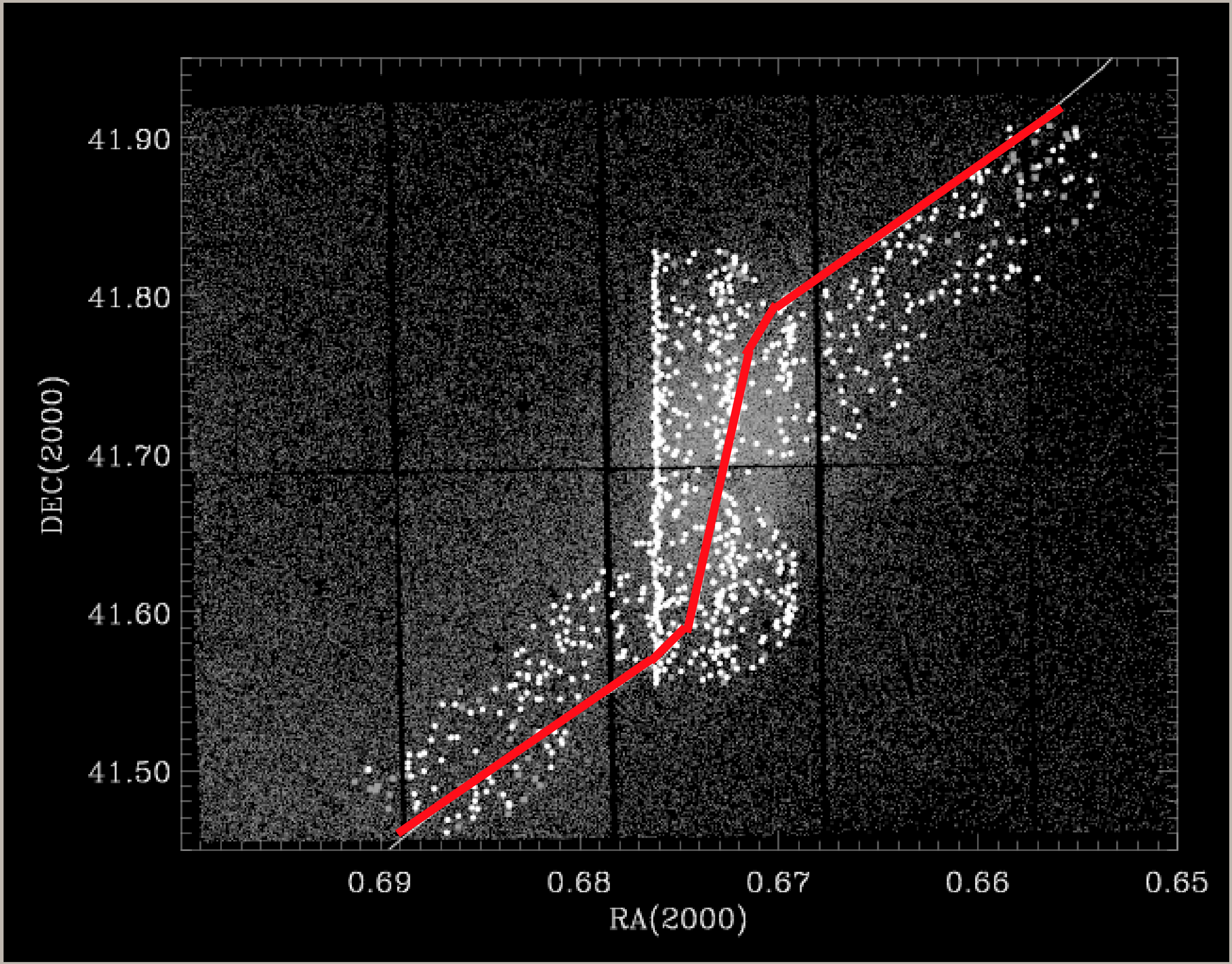
Keck / DEIMOS multislit spectroscopy

- Integrated light spectra cannont probe beyond effective radius
- We have targeted individual red giant branch stars
- Accurate radial velocities for 723 red giant stars in NGC 205

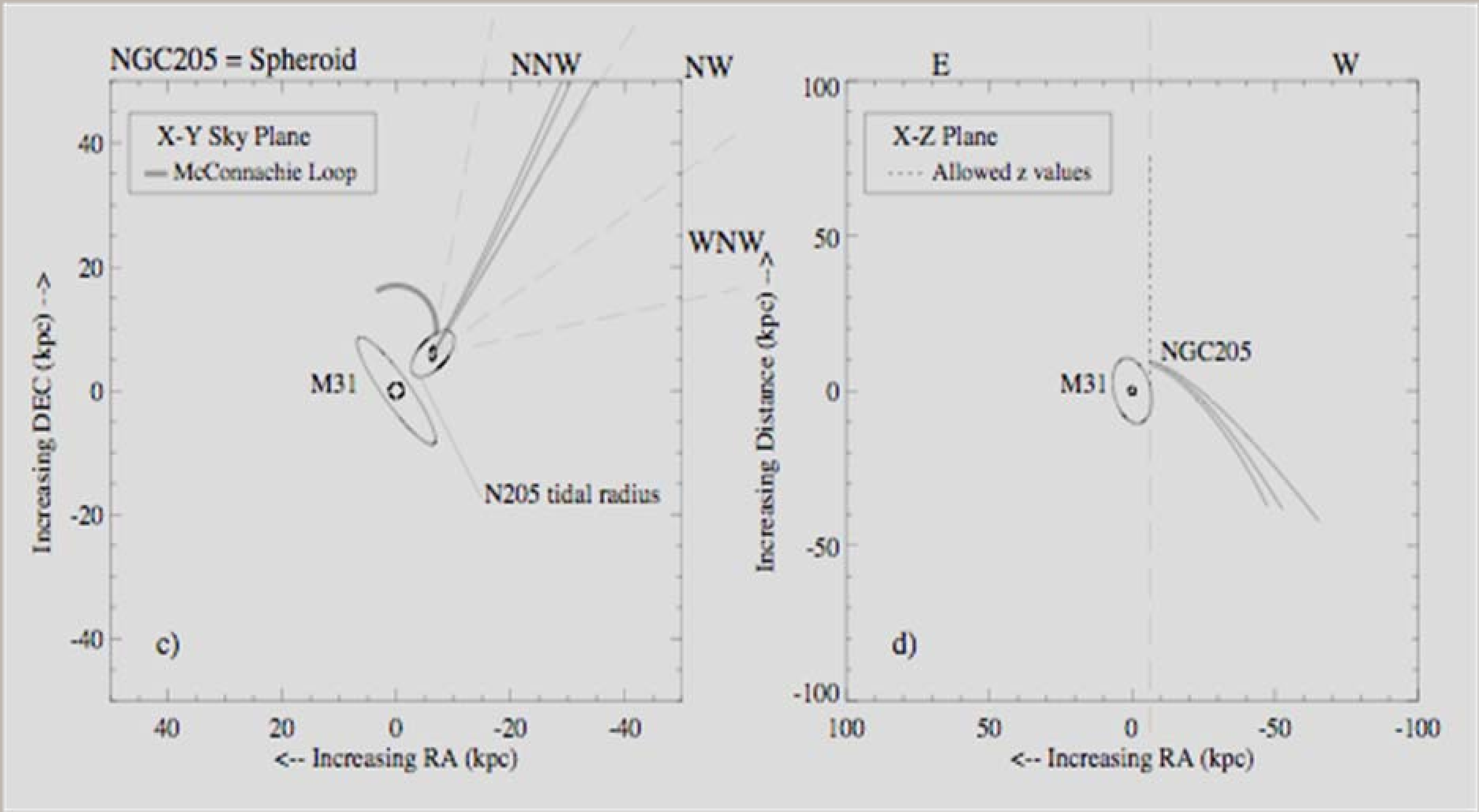


Choi, PG & Johnston (2002, AJ)
Geha, PG, Rich & Cooper (2006, AJ)

Keck / DEIMOS Targets



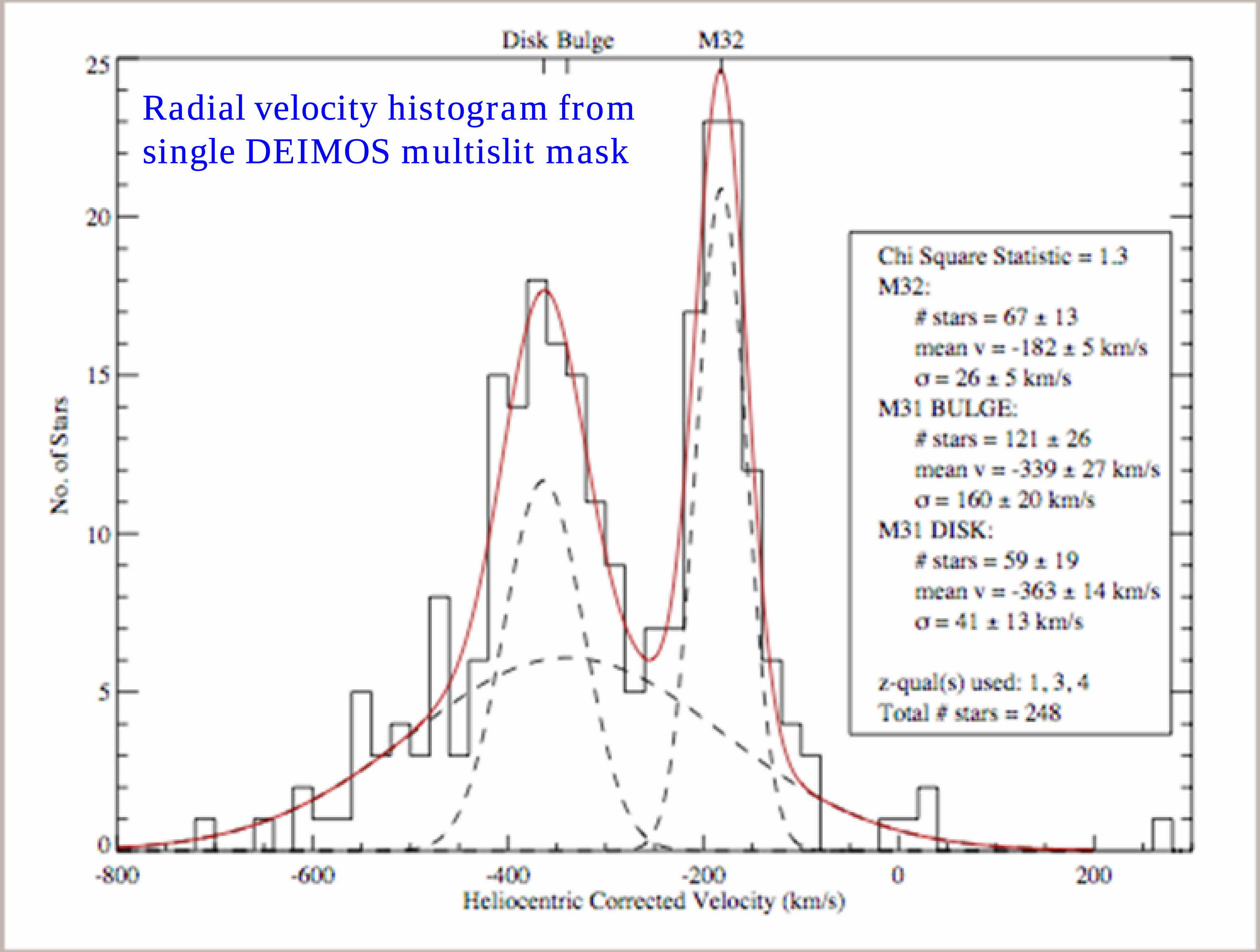
NGC205: Orbit solutions



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)

New M32 Observations



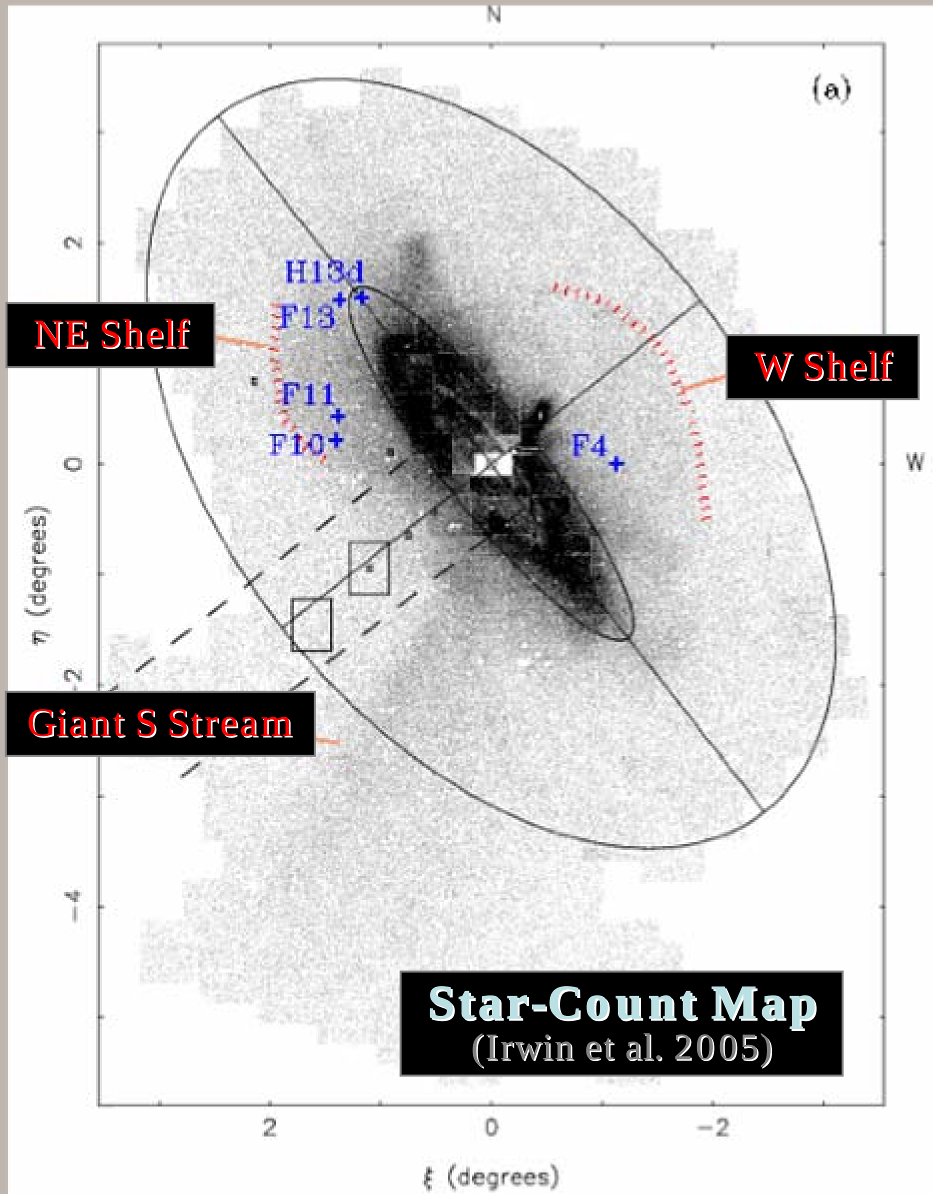
— Five DEIMOS multislit masks; about 200 stars per mask

— Longslit spectrum yields rotation curve out to $r \sim 1'$

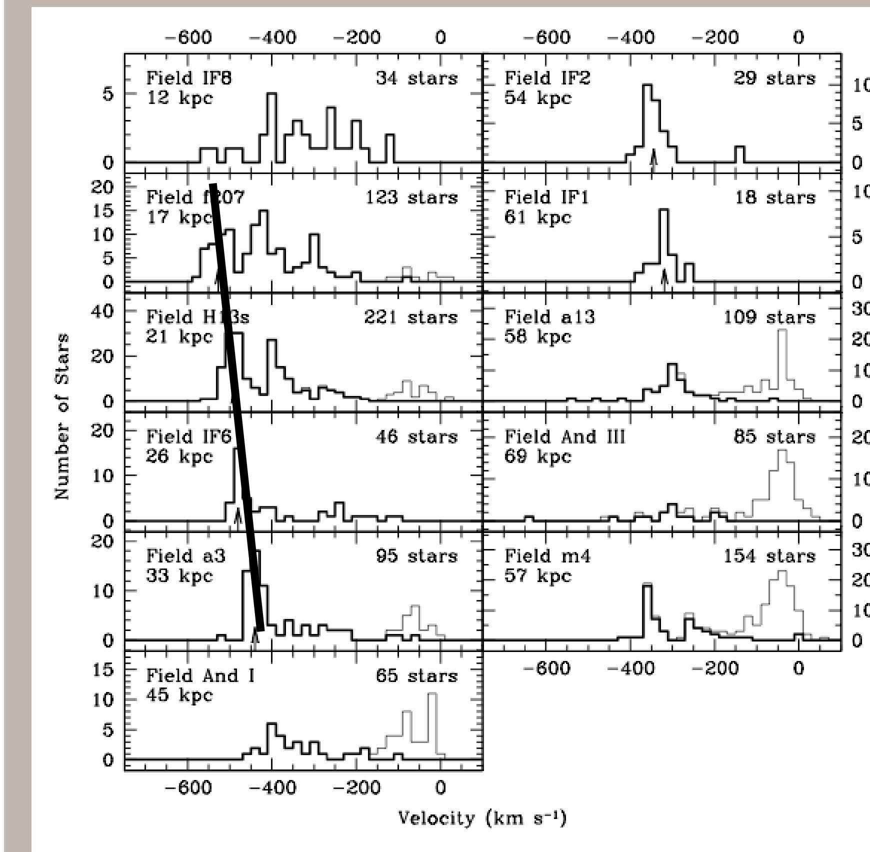
Howley et al. (2008, in prep)


Dissecting a Recent Collision

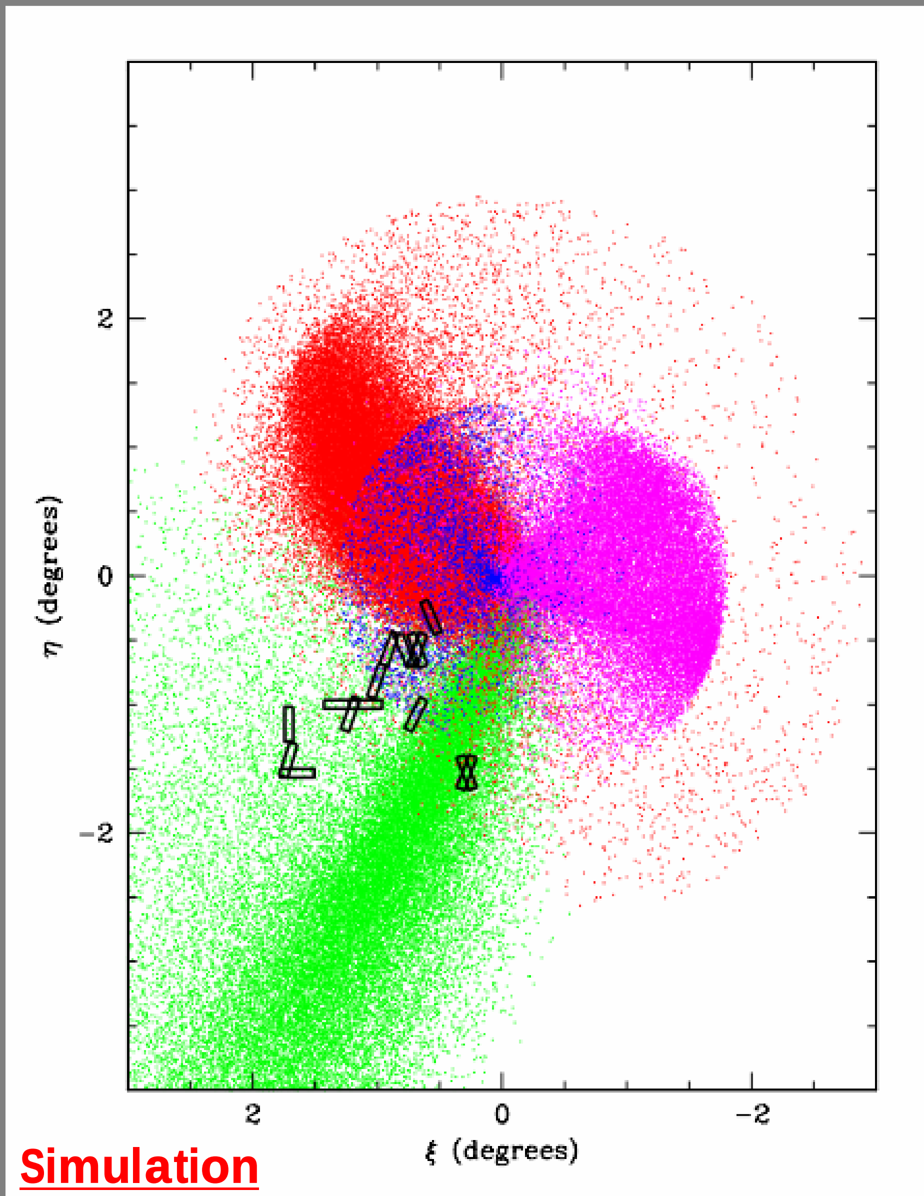
Observational constraints on M31's giant stream

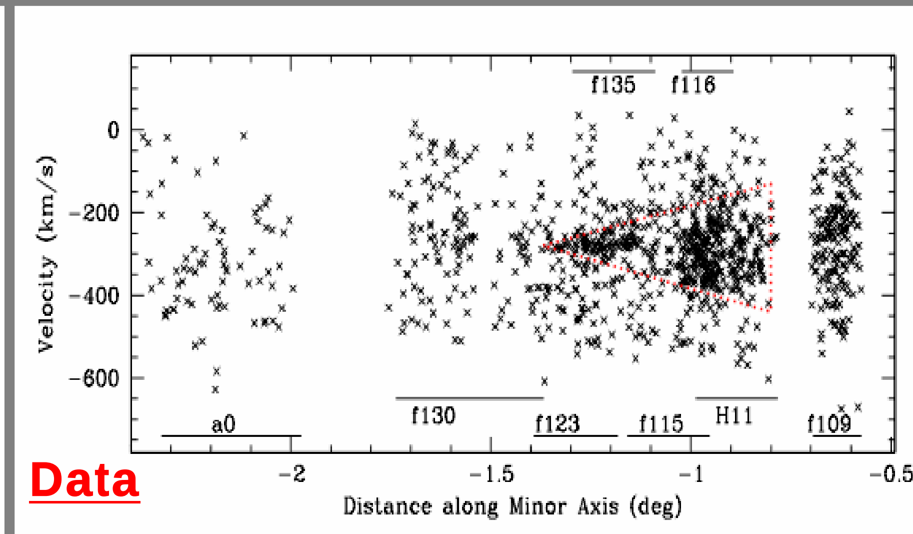


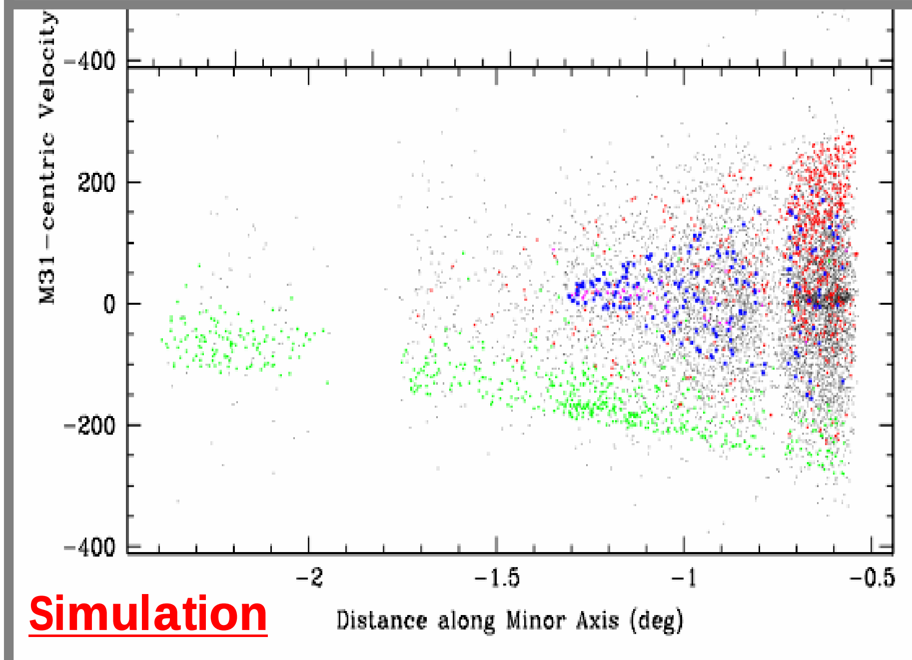
— Radial velocities along the stream (Gilbert et al. 2008, ApJ, in prep)



Giant Stream and Young Shell System in M31



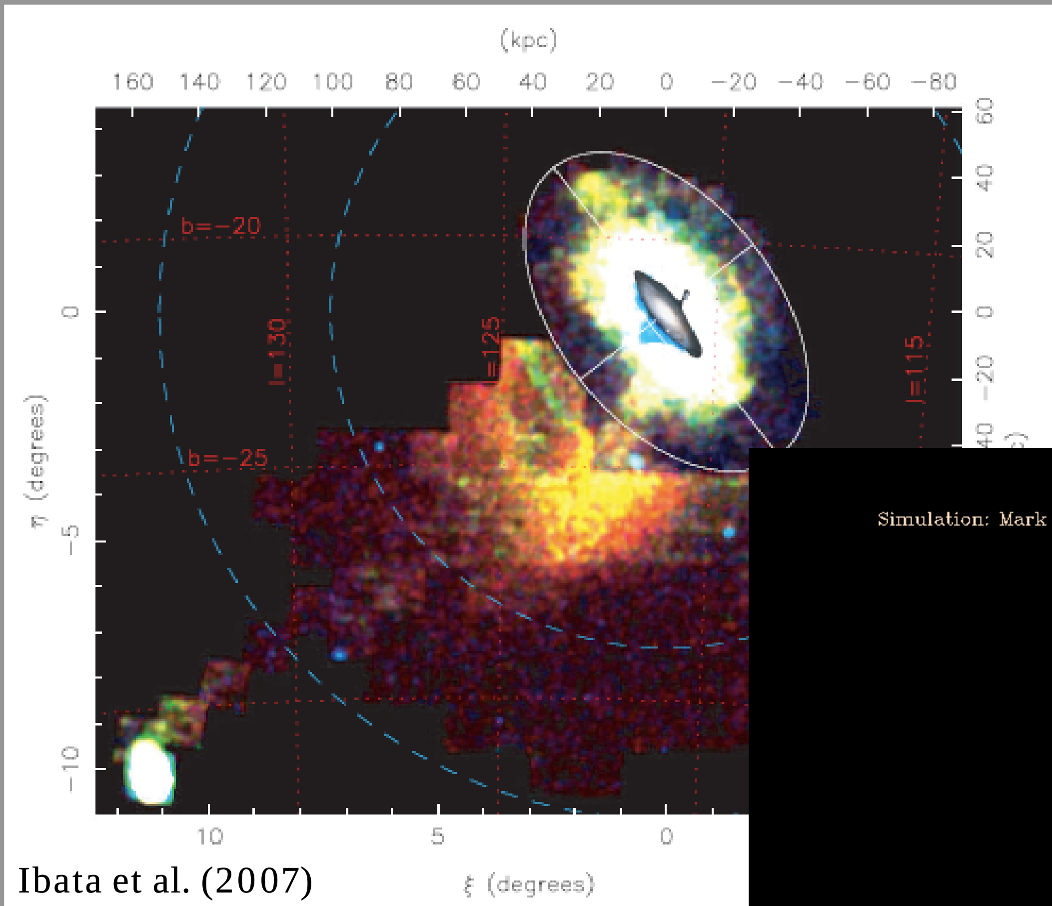




Fardal et al. (2007, MNRAS)

Gilbert et al. (2007, ApJ)

Giant Stream and Young Shell System in M31



Ibata et al. (2007)

Simulation

N-body rotating disk satellite in a static parent galaxy (M31) gravitational potential

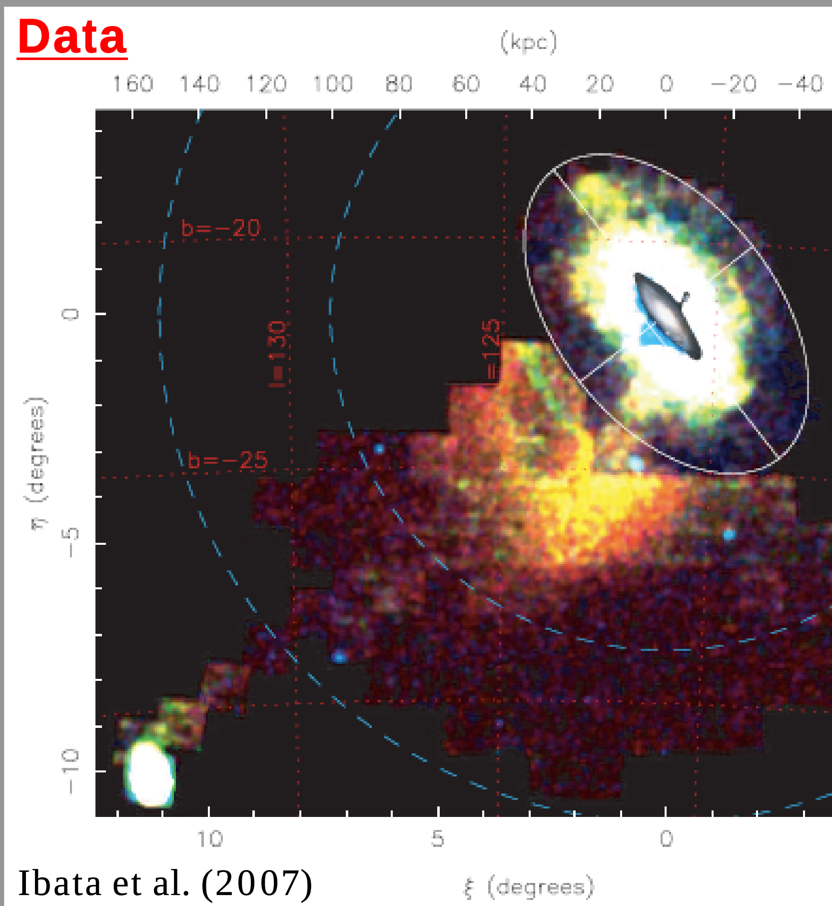
Fardal et al. (2008, ApJL, arXiv:0803.3476)

Data

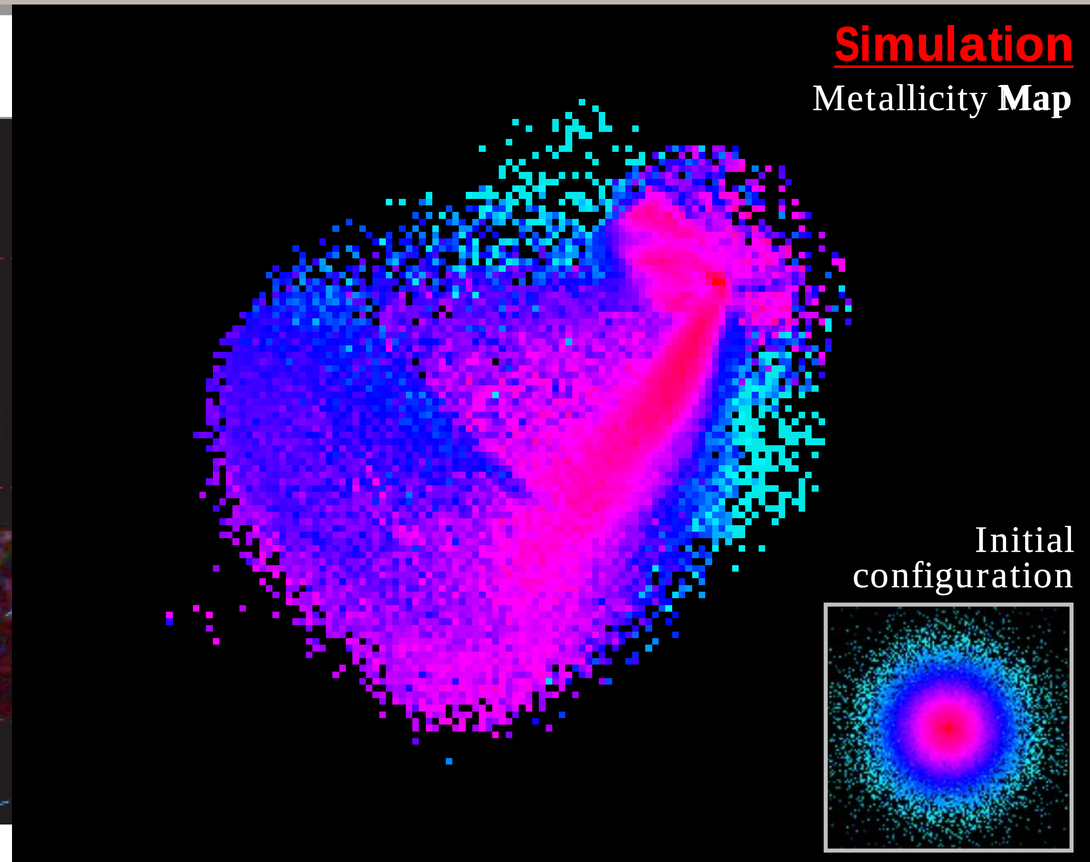
Star-count map, color coded by metallicity, based on INT/WFC and CFHT/MegaCam images

Detailed Dissection of Past Collision Events

What Can This Exercise Teach Us?



Ibata et al. (2007)



Fardal et al. (2008, ApJL, arXiv:0803.3476)

– 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**

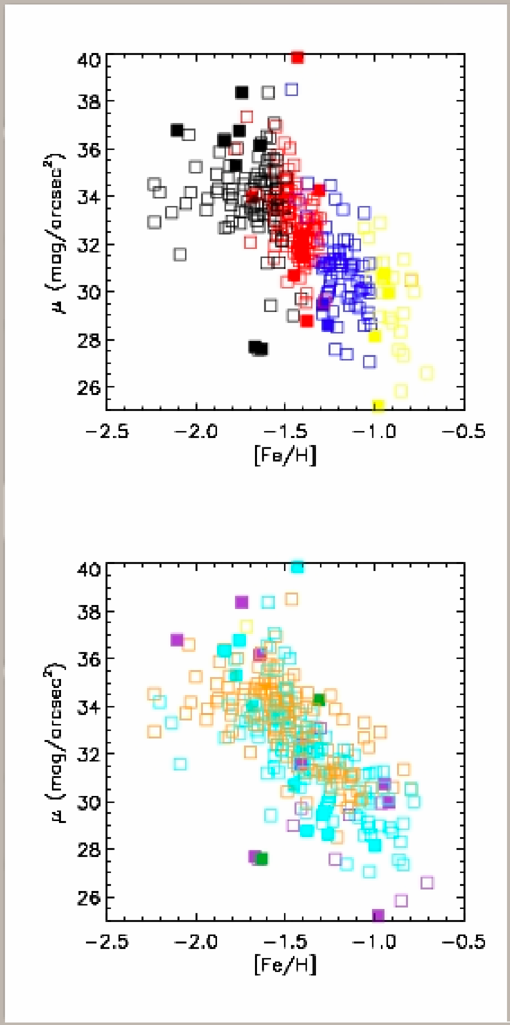
– Tidal debris can be tracked through **three pericenter passages**; strong constraints on M31’s **potential**

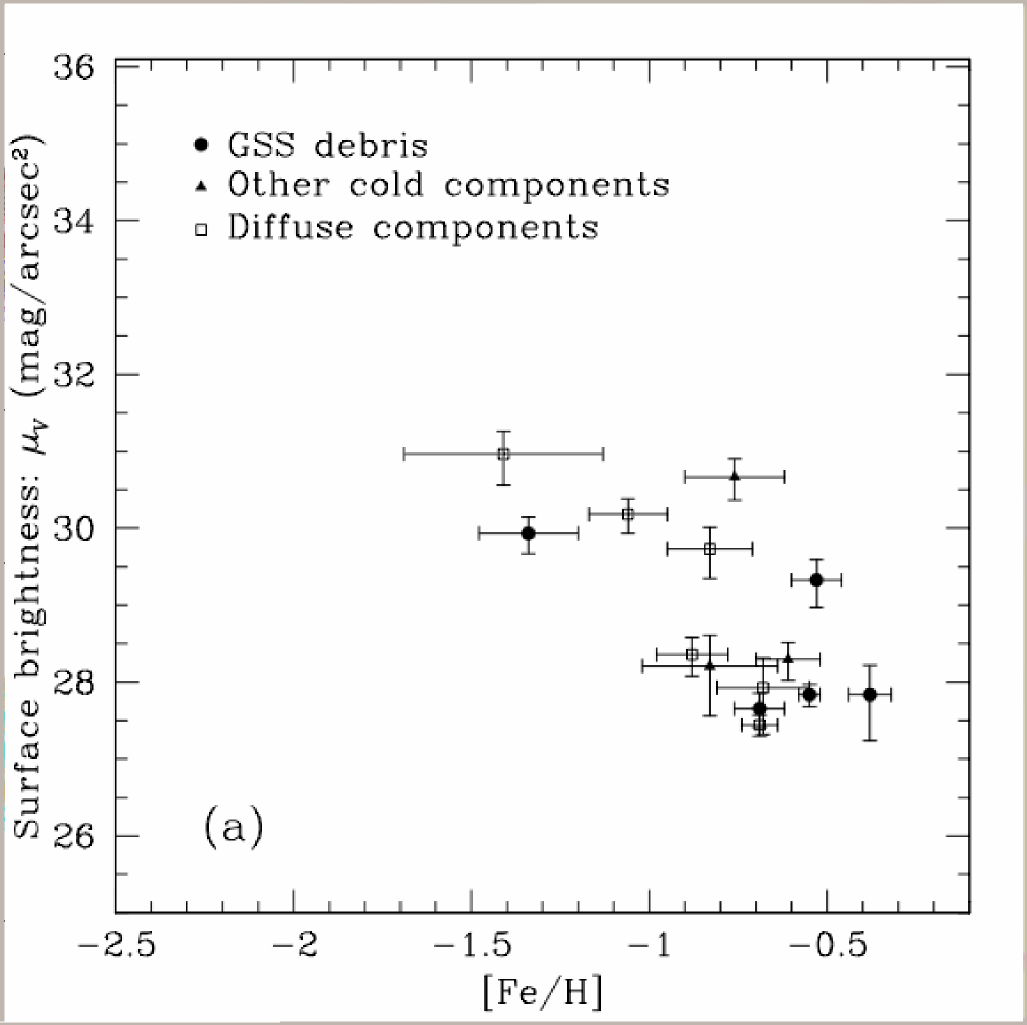
M31's Extended Stellar Halo

Global Structure/Substructure,
Chemical Abundance,
and
Star Formation History

Metallicity and [α/Fe] of Tidal Streams

Bullock & Johnston (2005) models

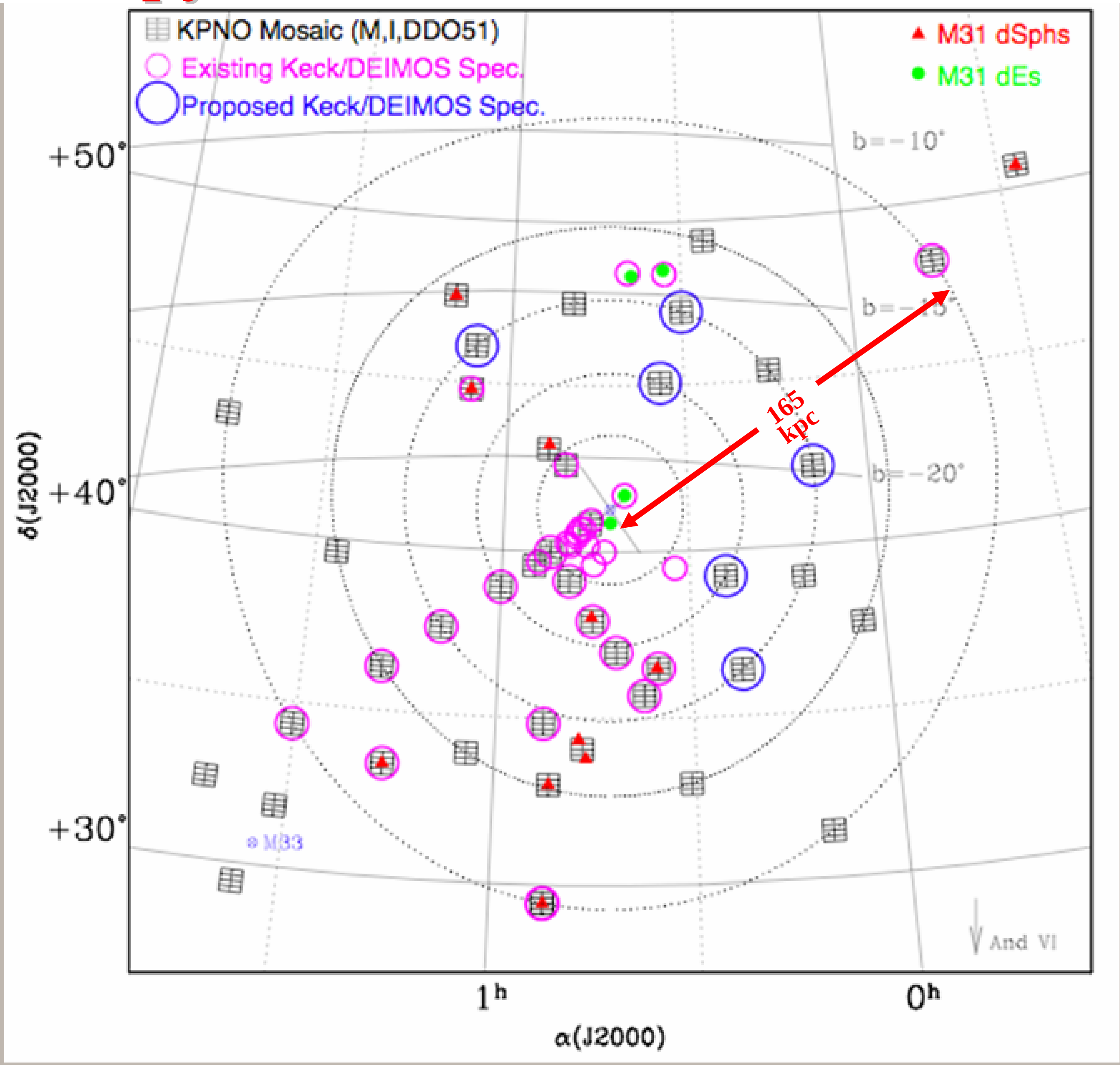




- Higher SB tidal debris tend to be more metal rich: observations and simulations
- Higher SB debris tend to come from the more luminous, metal rich dwarf satellites and/or recent encounters

Font et al. (2008, ApJ)
Gilbert et al. (2008, in prep)

Spectroscopy of the Remote Outer Halo of M31



Ostheimer (2002, PhD thesis)
Beaton et al. (in prep)
Guhathakurta et al. (2005, 2006)
Kalirai et al. (2006a,b)
Gilbert et al. (2006, 2007, 2008a)

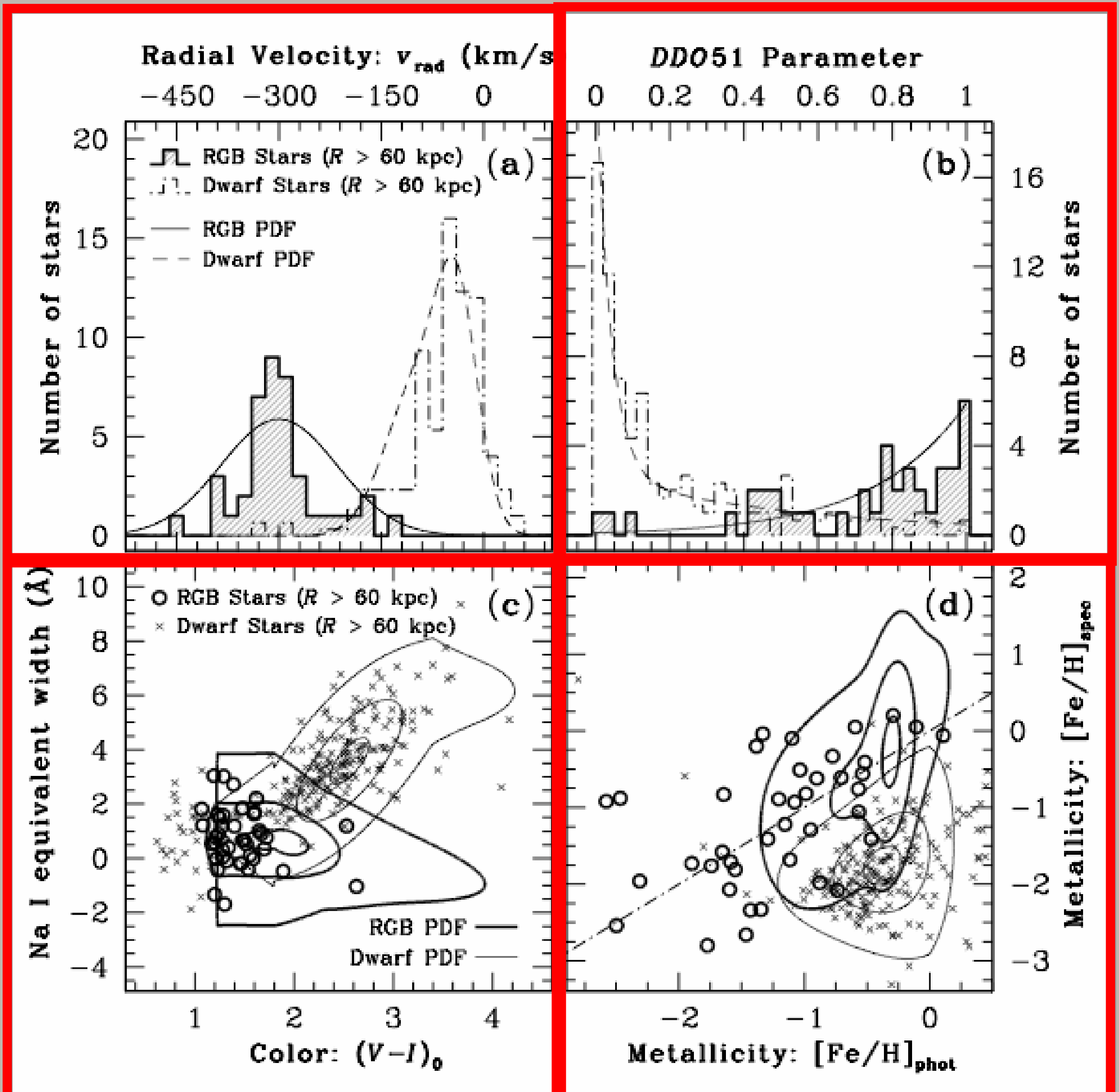
Isolating a clean sample of M31 RGB stars

We use probability distribution functions based on five photometric / spectroscopic diagnostics to eliminate foreground Milky Way dwarf stars. There are five other diagnostics that look promising at this time.

- (1) Radial Velocity
- (2) *DDO51* photometry
- (3) Na I equivalent width
- (4) Position in the CMD
- (5) $[Fe/H]_{phot}$ vs $[Fe/H]_{spec}$

(6–7) KI line strengths

(8–10) TiO band strengths



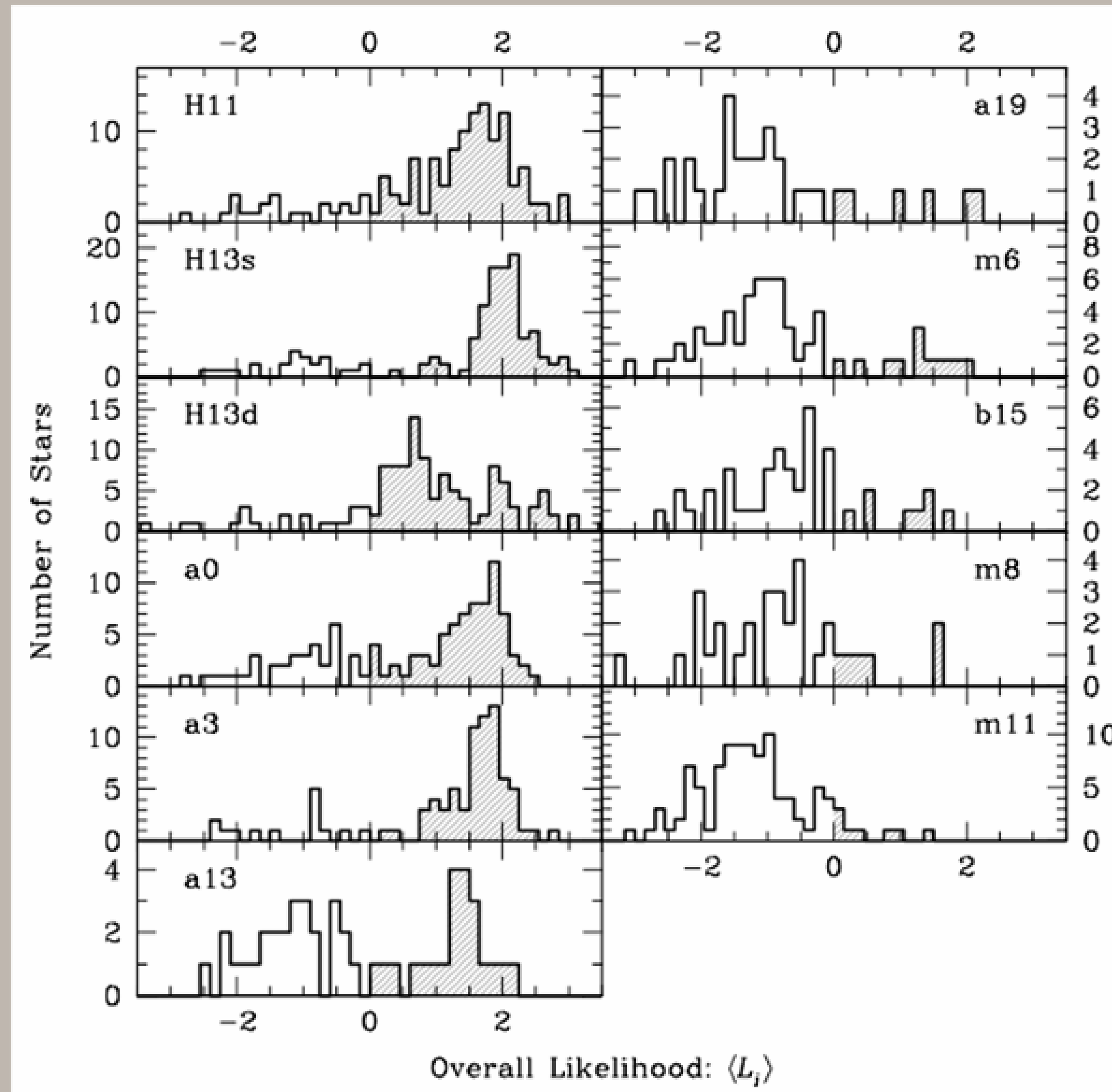
Gilbert et al. (2006, ApJ)

Overall Likelihood Distributions

- Weighted average of the first 5 individual likelihoods
- In general:

  $\langle L_i \rangle > 0$: M31 RGB

  $\langle L_i \rangle < 0$: MW dwarf



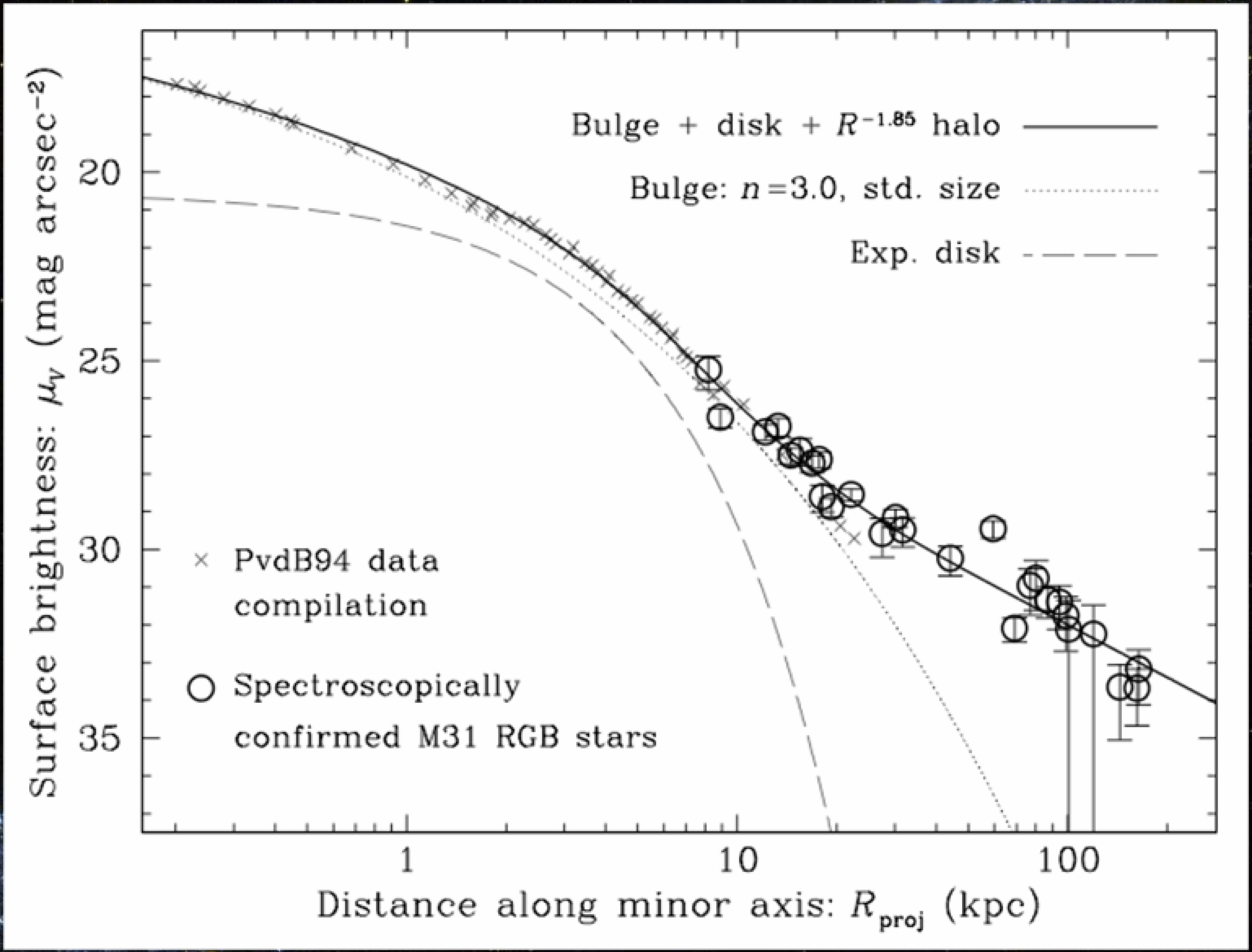
where:

$L_i = \log(P_{\mathrm{giant}}/P_{\mathrm{dwarf}})_i$

Gilbert et al. (2006, AJ)

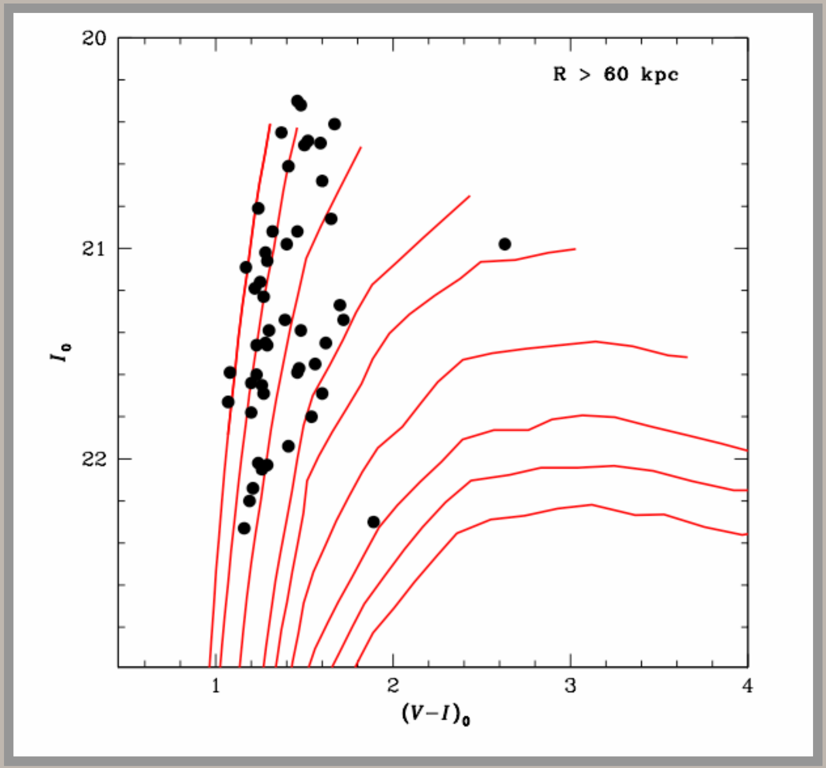
Surface Brightness Profile of M31

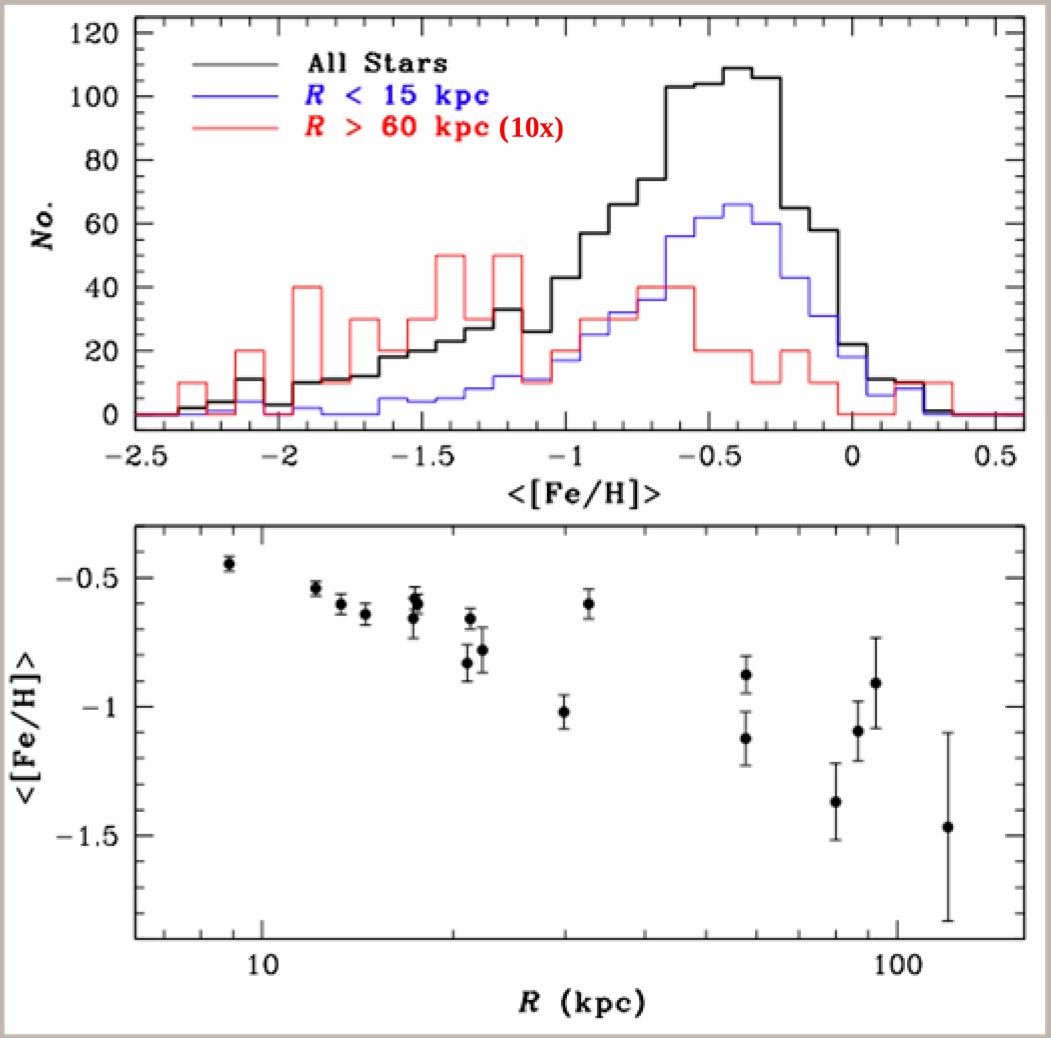
Counts of spectroscopically confirmed M31 RGB stars in outer fields (R = 30 to 165 kpc) lie well above extrapolation of Sersic-law inner spheroid; Best fit: R^{-2} power law halo



PG et al. (2005, astro-ph/0502366)

Radial Gradient in Metallicity



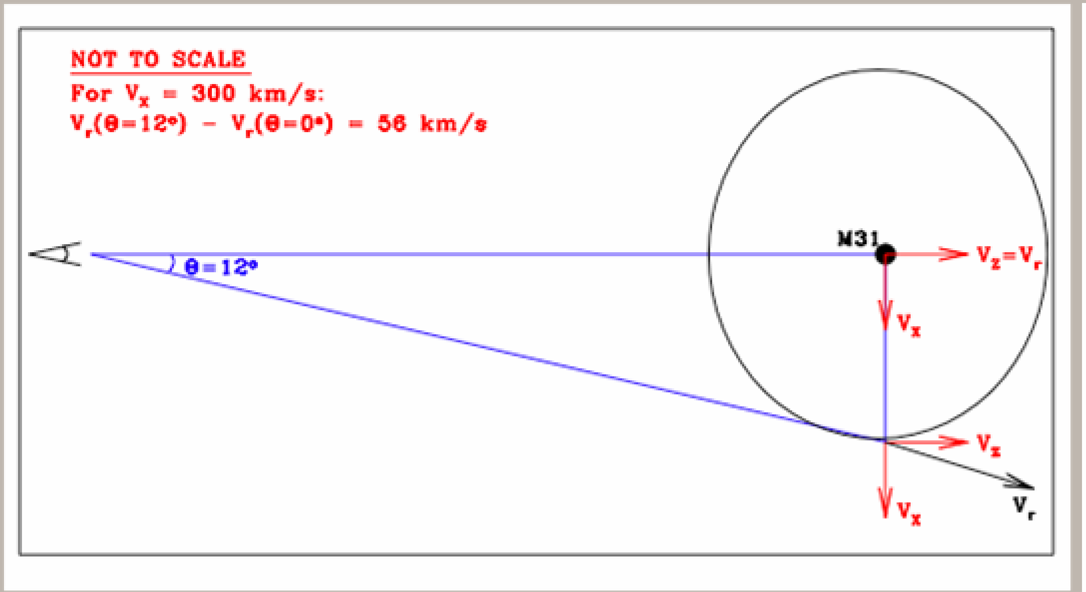


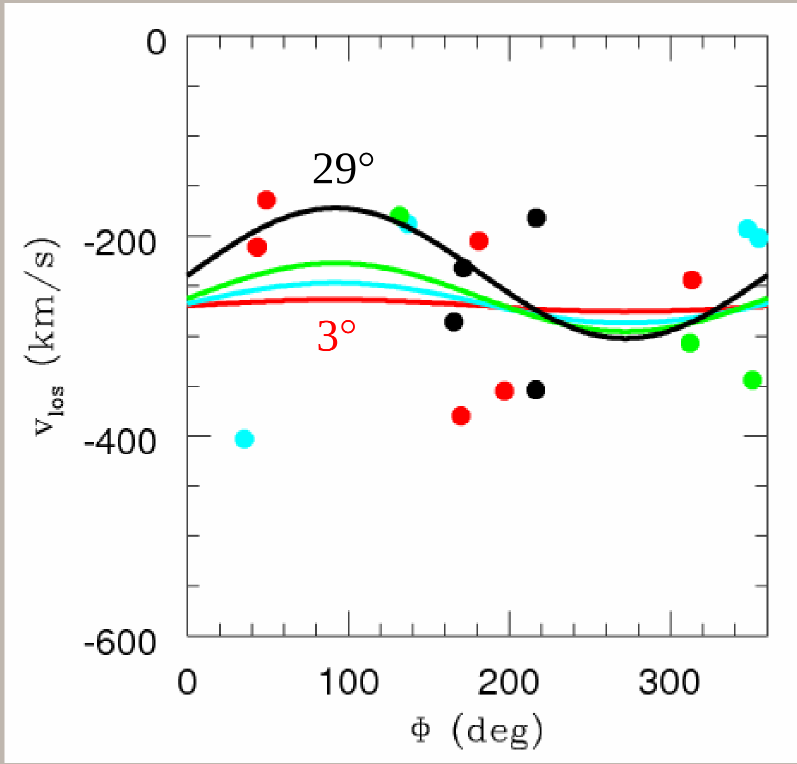
Kalirai, Gilbert, PG, et al. (2006b, ApJ)
Kalirai et al. (in prep); Kollipara et al. (in prep)


Tangential Motion of M31 and
its System of Satellites


Size of M31 halo!

Geometric Method for Measuring the Tangential Velocity of a Large Angular-Size Object





van der Marel & PG (2008, ApJ, arXiv:0709.3747)

– System with **large angular size** should exhibit characteristic **pattern of line-of-sight velocities**

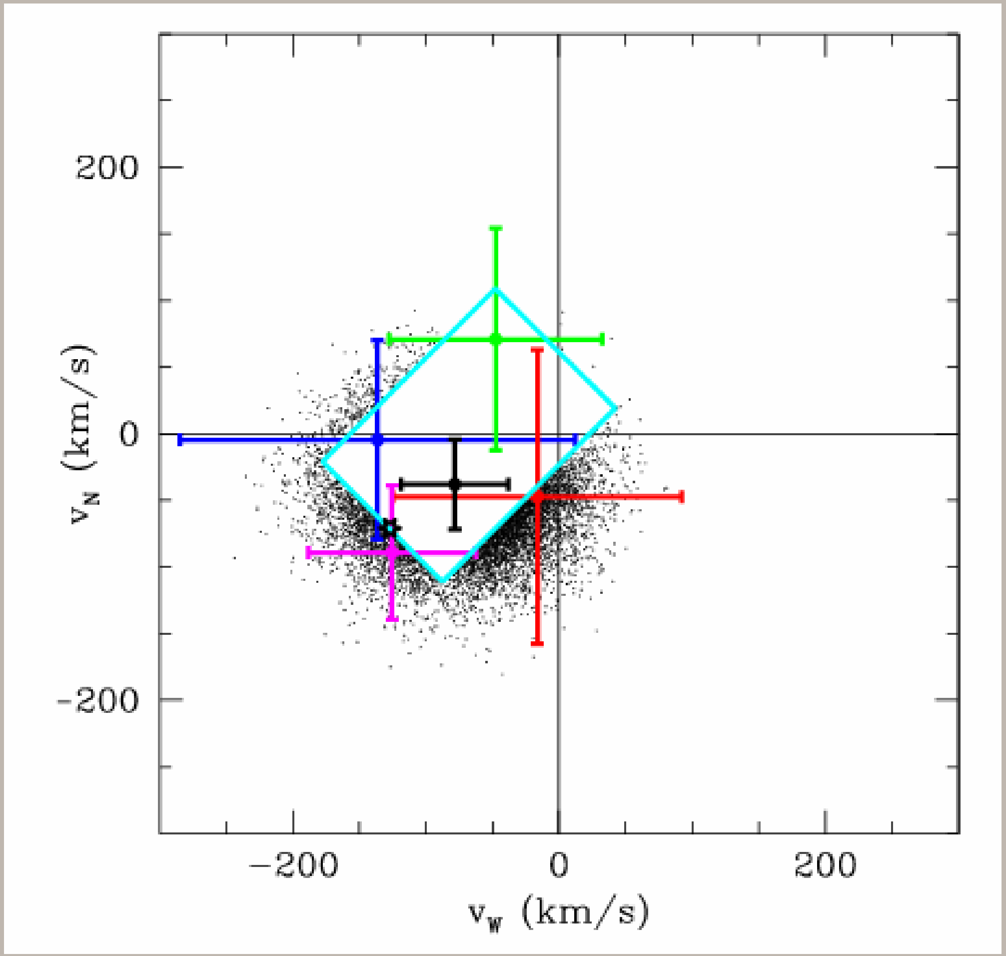
– Radial velocities of **remote dwarf satellites** of M31 provide a constraint

– Remote satellites near the **Local Group "zero velocity" surface** provide an independent constraint on the tangential motion of the **LG barycenter**

– **Water-maser based proper motion** measurements of M31 satellites **M33** and **IC10** provide a third constraint

Tangential Motion of the M31 System

Results and Implications



van der Marel & PG (2008, ApJ, arXiv:0709.3747)

– The three methods yield **consistent** answers
– These empirical estimates are inconsistent with the **M33 tidal (non-)interaction** argument (Loeb et al.)
– This measurement should improve the precision with which one can model the **M31/Milky encounter**
– Virial estimates should now provide a lower limit on the **mass of M31**
– The “timing argument” can be used to obtain a more precise estimate of the **mass of the Local Group**

Summary

Stellar halo (and inner spheroid)

- *Secure identification of M31 RGB stars*
- *Global structure*
- *Chemical enrichment; star formation history*
- *Tidal debris from past accretion events*
- *Other features: bar, boxy bulge, star-forming ring*

Dwarf satellites

- *Tidal disruption*
- *Tracers of M31's gravitational potential*
- *Properties of these building blocks*

Spectroscopic and Photometric Landscape
of Andromeda's Stellar Halo

SPLASH

Summary (contd.)

Tangential Motion of the M31 Group

- *Large angular size of M31's halo and system of satellites: Constraints on tangential motion from radial velocities*
- *Better understanding of M31 / M33 / Milky Way encounter*
- *More reliable virial estimate of M31 mass*
- *Improved mass estimate for the Local Group*

Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo

SPLASH

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The increased sensitivity of next-generation optical/IR telescopes will allow spectroscopy of individual stars out to the M81 group (few Mpc: D^2 increase) and Virgo Cluster (20 Mpc: D^4 increase)