Substructure in the Stellar Halo of the Andromeda Spiral Galaxy

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- M31's extended stellar halo
- Tidal debris: kinematics and metallicity
- Dwarf satellites: ongoing tidal disruption

Collaborators

Observations

Karoline Gilbert & Jason Kalirai (UCSC)

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Steve Majewski, Jamie Ostheimer, & Ricky Patterson (U Virginia)

David Reitzel & Mike Rich (UCLA)

Michael Cooper (UC Berkeley)

Dynamical Modeling

Mark Fardal (U Mass), *Kirsten Howley* (UCSC)

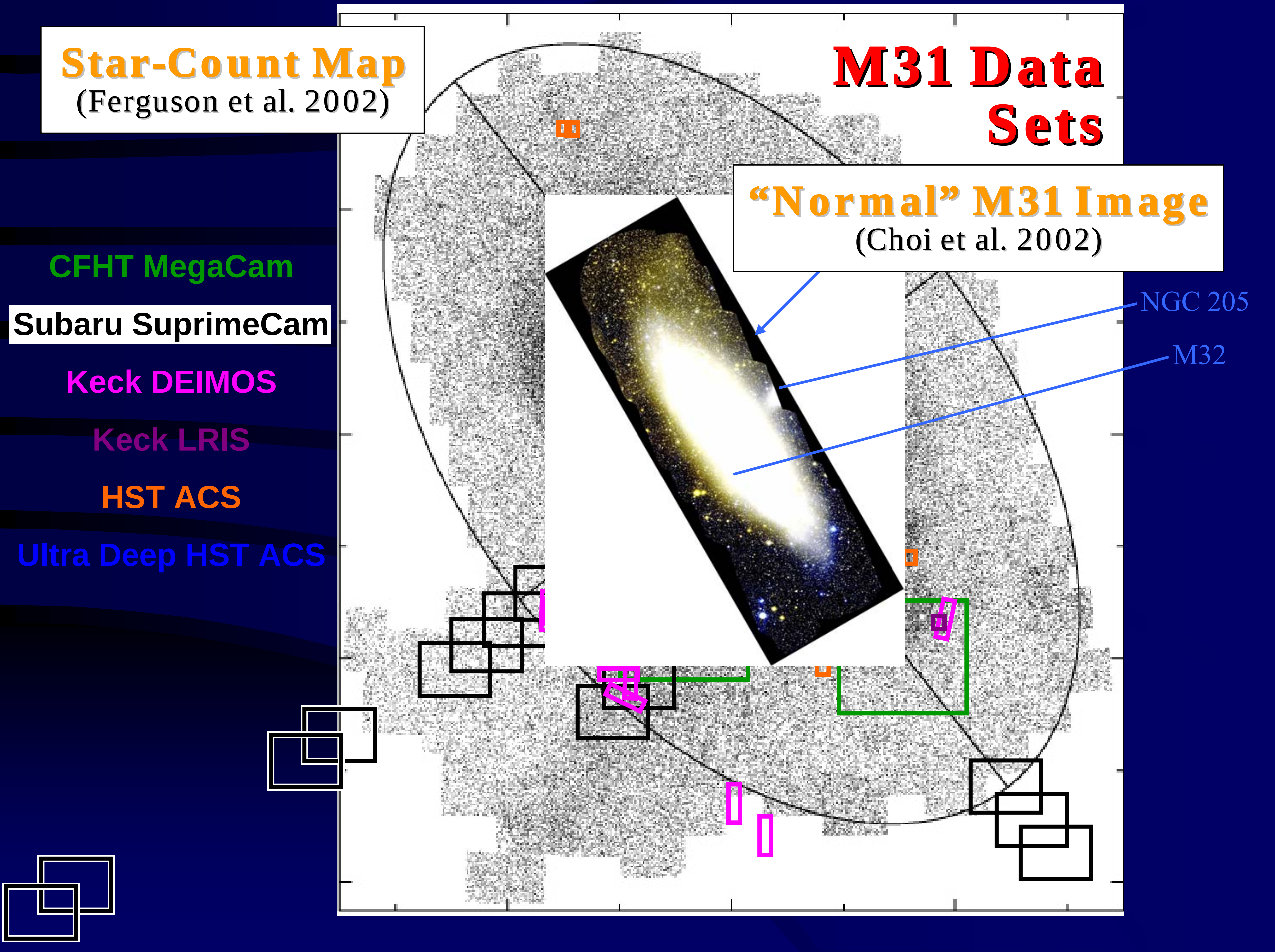
Andreea Font (Durham), *Kathryn Johnston* (Columbia U)

Arif Babul & Jonathan Geehan (U Victoria)

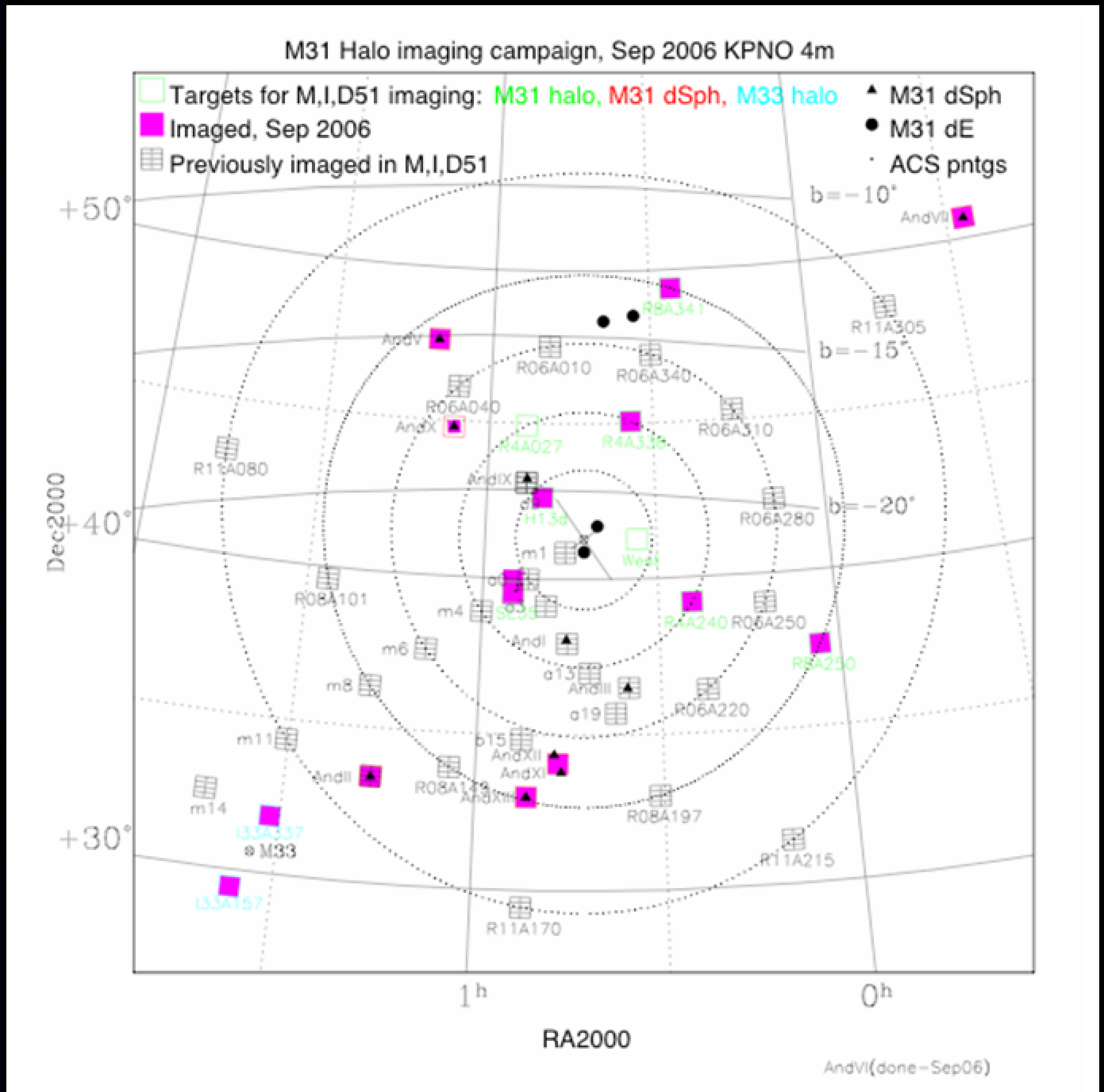
Many thanks to……

Sandy Faber, Drew Phillips (UCSC) *& the* DEIMOS *instrument team*

M31’s Extended Stellar Halo



Star-Count Map
(Ferguson et al. 2002)
M31 Data Sets
"Normal" M31 Image
(Choi et al. 2002)
NGC 205
M32
CFHT MegaCam
Subaru SuprimeCam
Keck DEIMOS
Keck LRIS
HST ACS
Ultra Deep HST ACS



M31 Halo imaging campaign, Sep 2006 KPNO 4m
Targets for M,I,D51 imaging: M31 halo, M31 dSph, M33 halo
Imaged, Sep 2006
Previously imaged in M,I,D51
M31 dSph
M31 dE
ACS pntgs
b=−10°
b=−15°
b=−20°
+50°
+40°
+30°
Dec2000
1h
0h
RA2000
AndVI
R8A341
R11A305
AndV
R06A010
R06A340
R06A040
AndX
R4A027
R4A338
R06A310
R11A080
AndIX
H13d
R06A280
m1
West
R08A101
R4A240
R06A250
m4
S235
AndI
m6
R8A250
a13
AndIII
m8
R06A220
a19
m11
b15
AndXII
AndII
AndXI
R08A143
AndXIII
R08A197
m14
I33A337
M33
R11A215
I33A157
R11A170
AndVI(done-Sep06)

Our Study of the M31 Halo

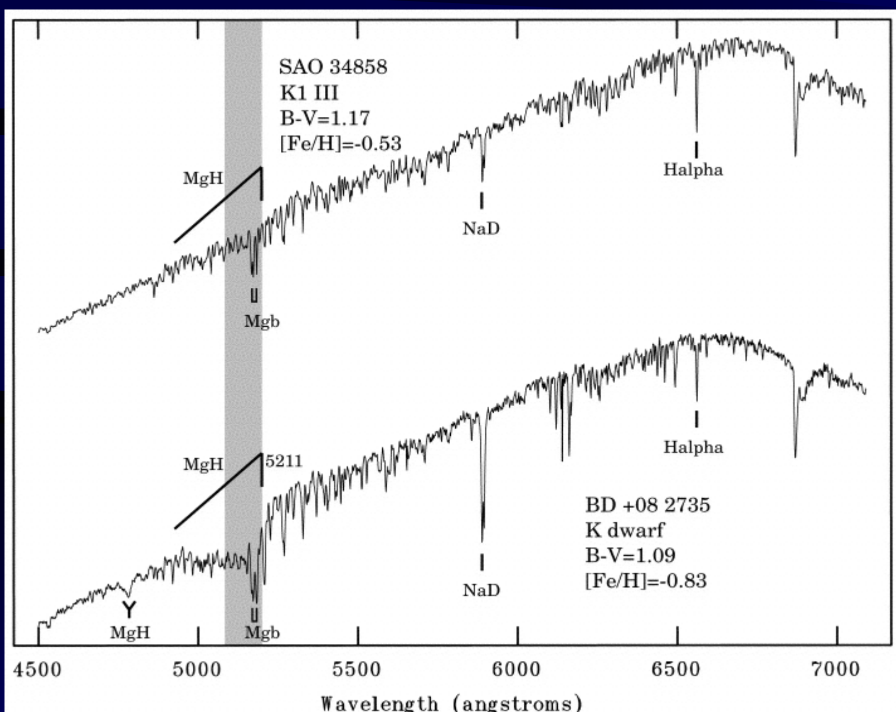
- The spectroscopic sample combined with our method for isolating a clean sample of M31 RGB stars gives us an unprecedented ability to detect sparse groups of M31 stars
- Explores the halo of M31 3 to 5 times further out from the galaxy's center than previous studies
- We detect M31 red giant stars in all our fields; the star counts in the outer fields are well above the extrapolation of the $r^{1/4}$ or Sersic law that fits the inner spheroid

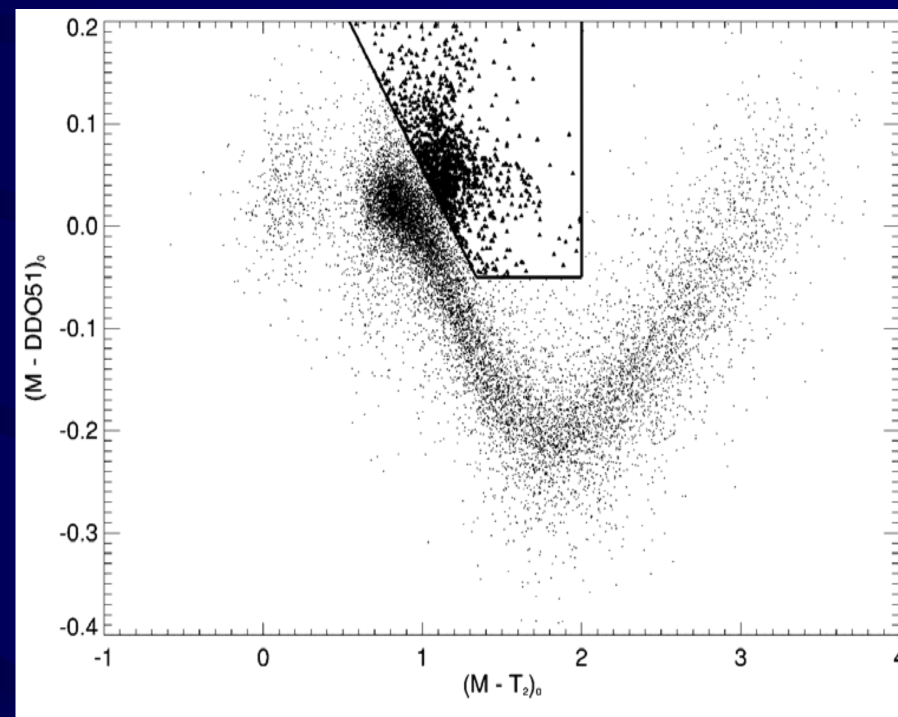
Photometry in the DDO51 Band

Pre-selection of M31 RGB candidates for spectroscopy

M31 red giant vs. Milky Way dwarf star spectra

DDO51 color-color diagram





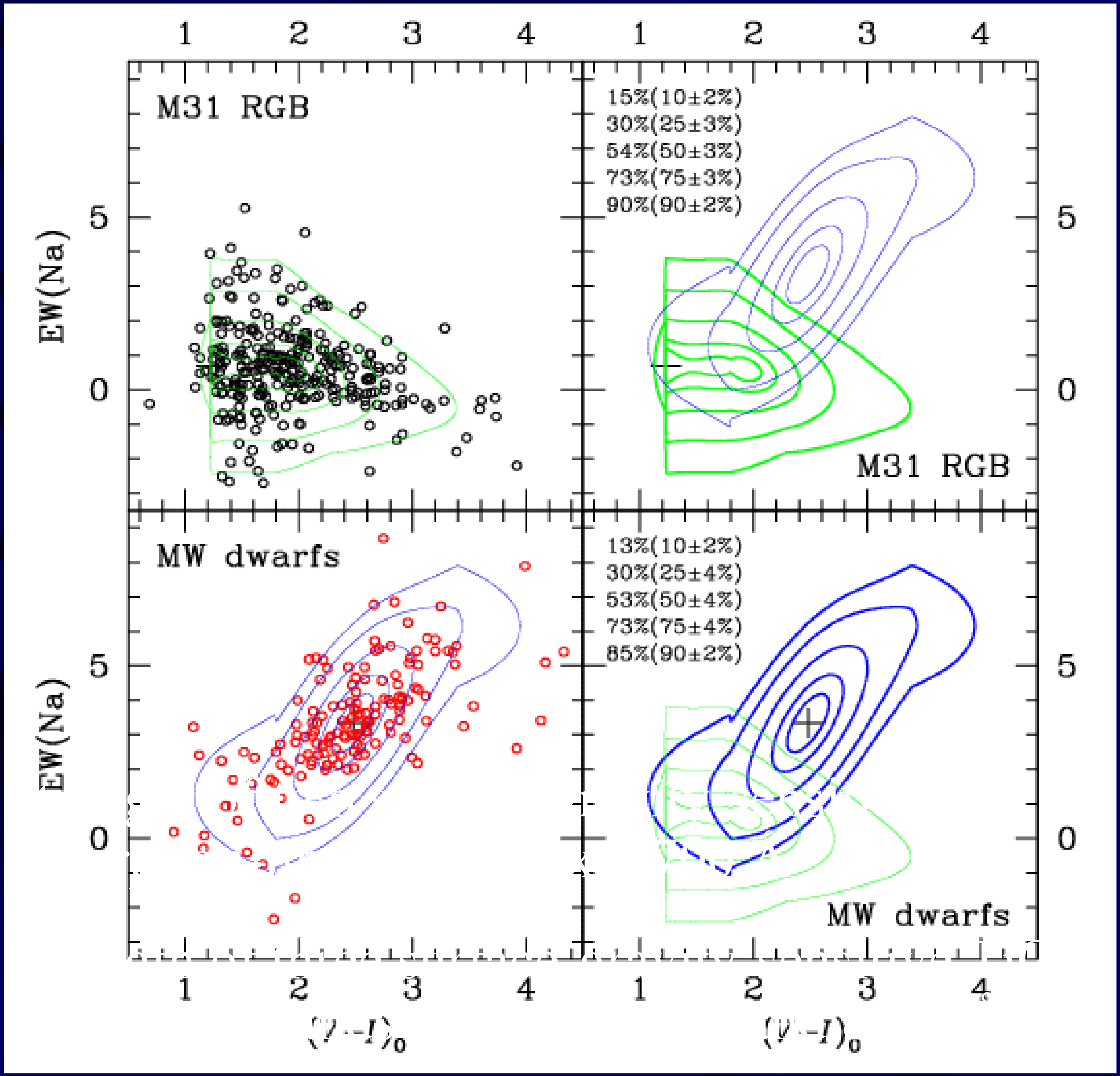
Majewski et al. 2000

Palma et al. 2003

Ostheimer 2002, PhD thesis, U Virginia

Isolating M31 Red Giants

Ten criteria used to reject foreground MW dwarf stars



Gilbert, et al. 2006, AJ, in press (astro-ph/0605171)

Overall Likelihood Distributions

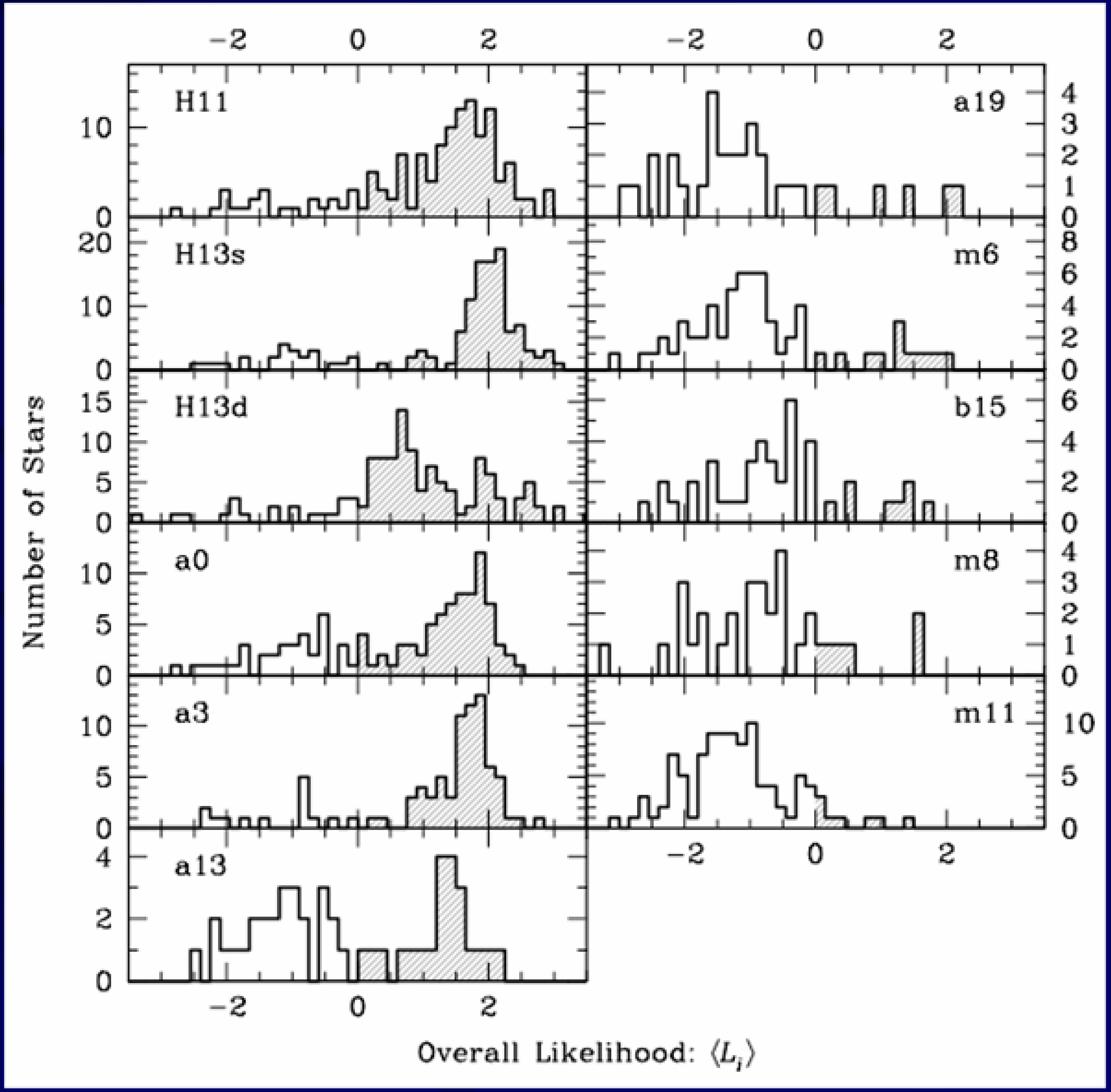
- Weighted average of the first 5 individual likelihoods
- In general:

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

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

where:

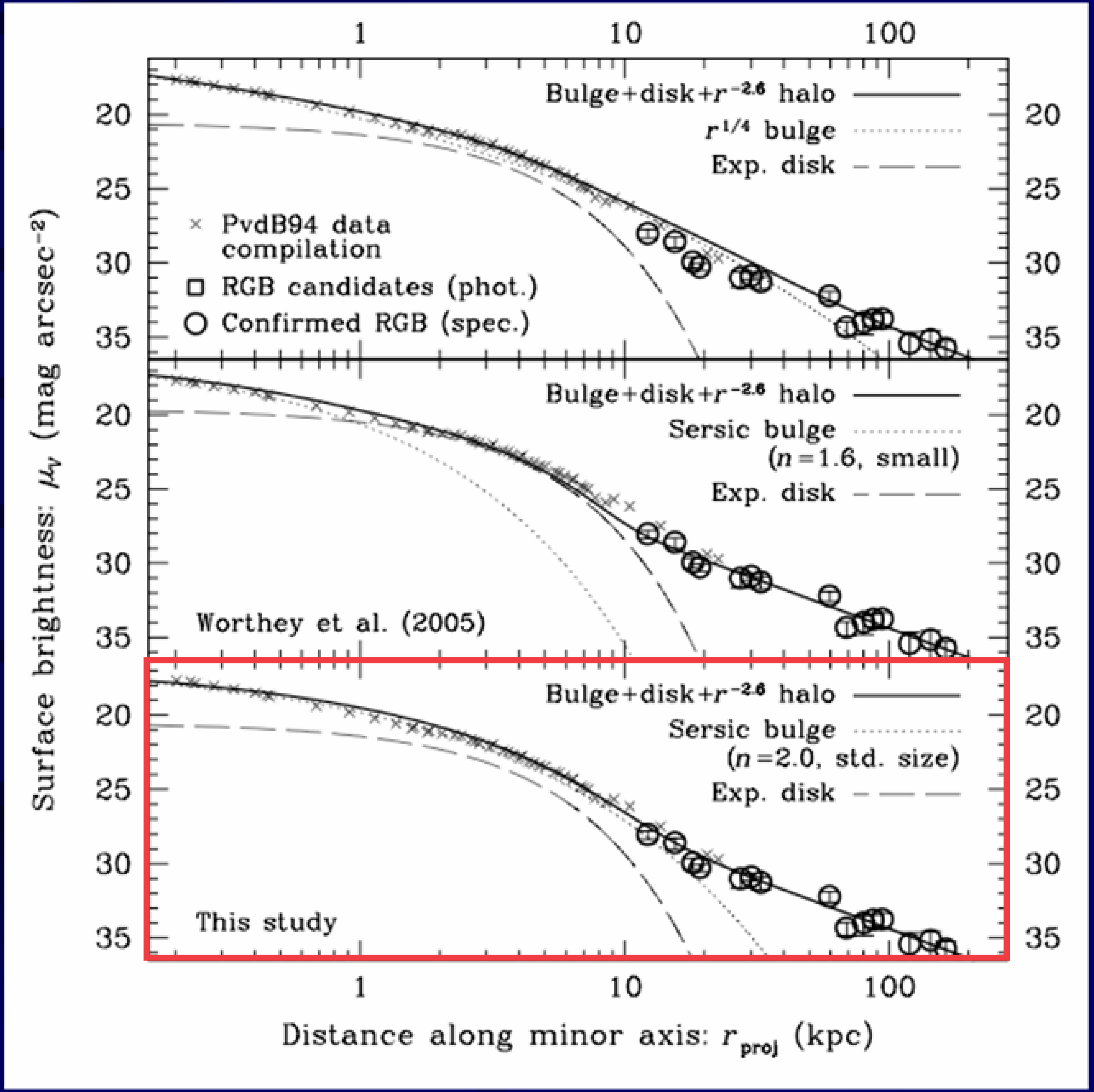
$L_i = \log(P_{giant}/P_{dwarf})_i$



Gilbert, et al. 2006, AJ, in press (astro-ph/0605171)

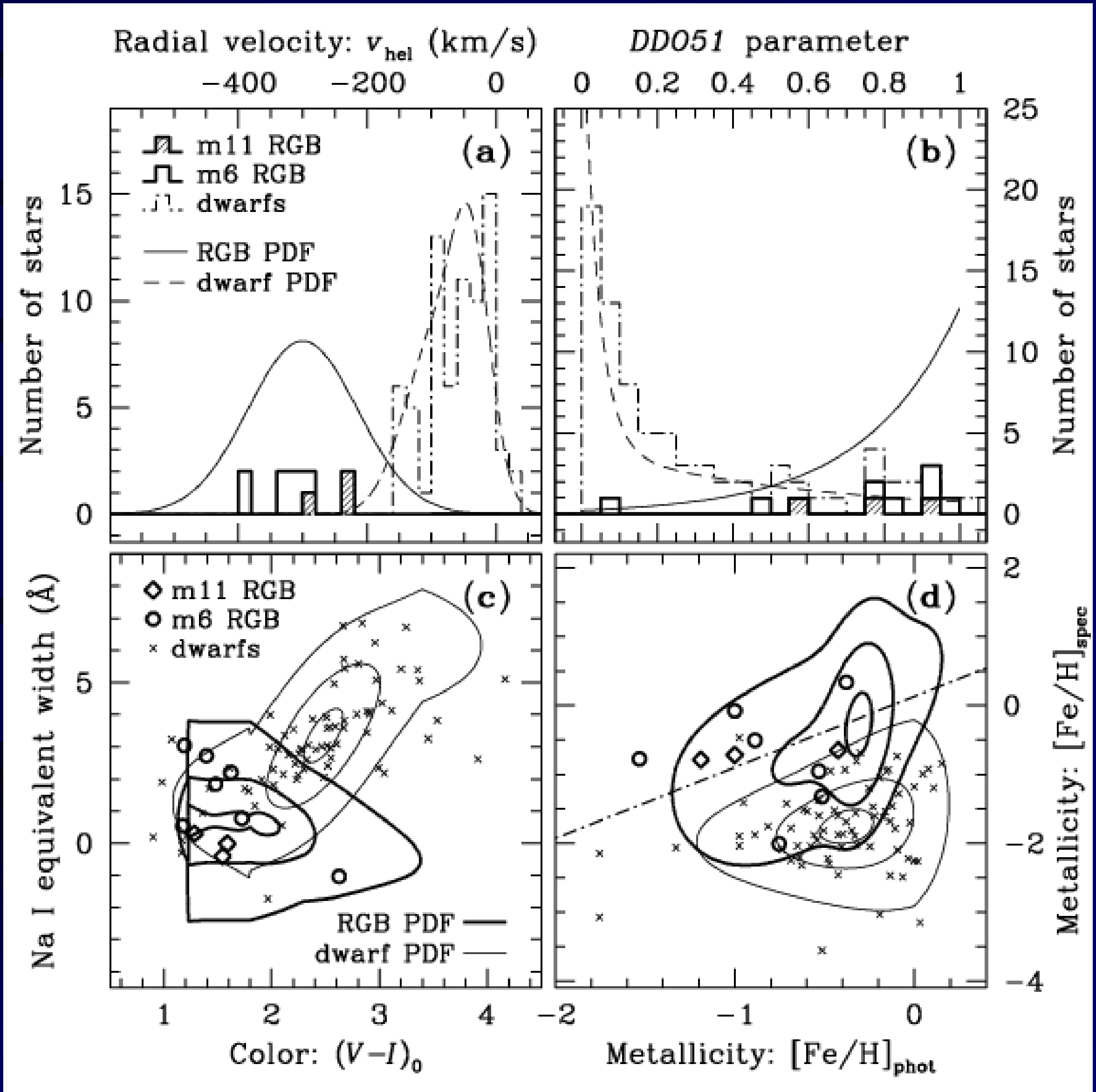
M31's Surface Brightness Profile:

Bulge, Disk, and halo



PG et al. 2005, astro-ph/0502366

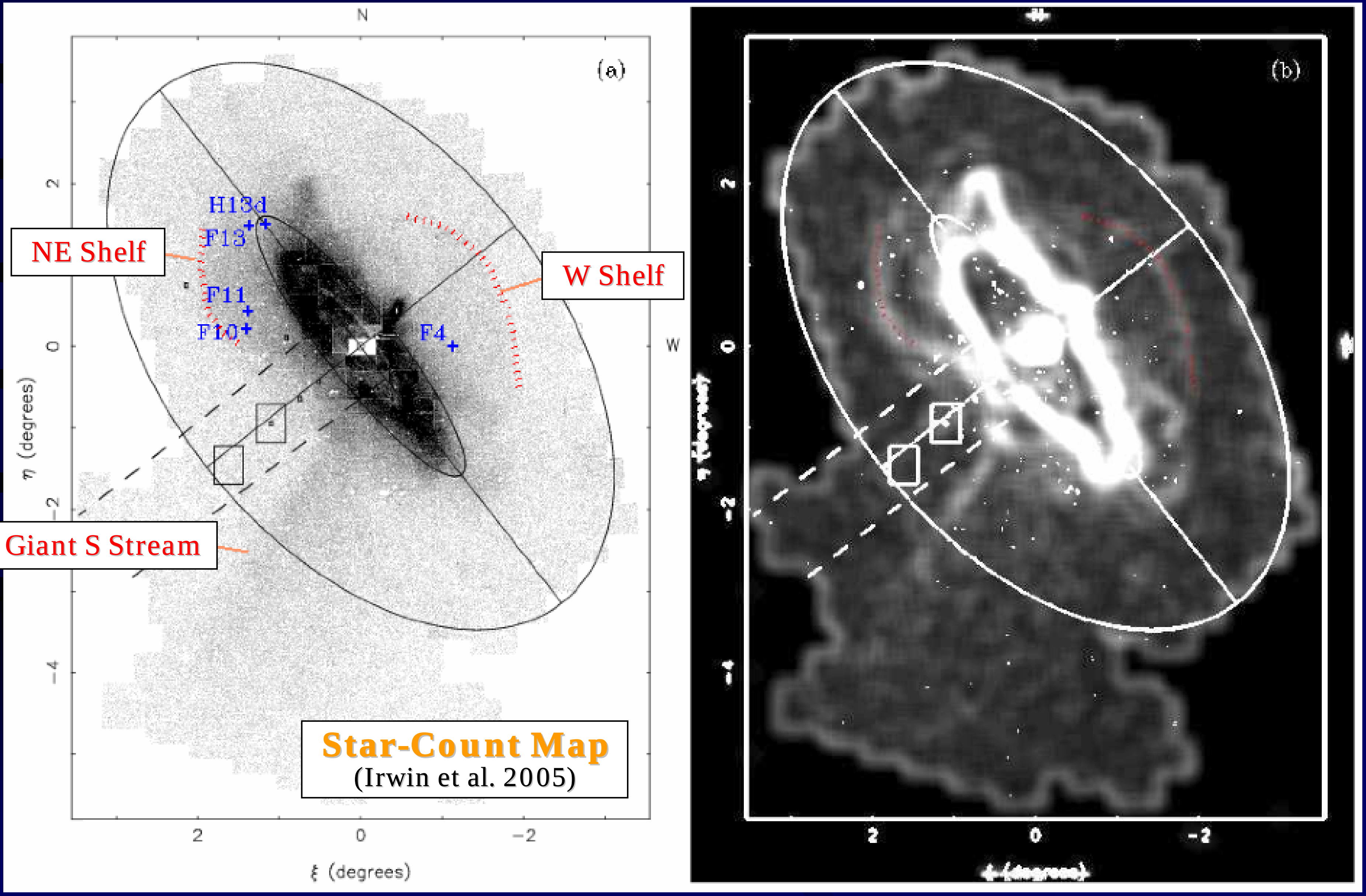
Outer Halo Fields



PG et al. 2005, astro-ph/0502366

Debris Trails in the M31 Halo

Giant Stream and Young Shell System in M31



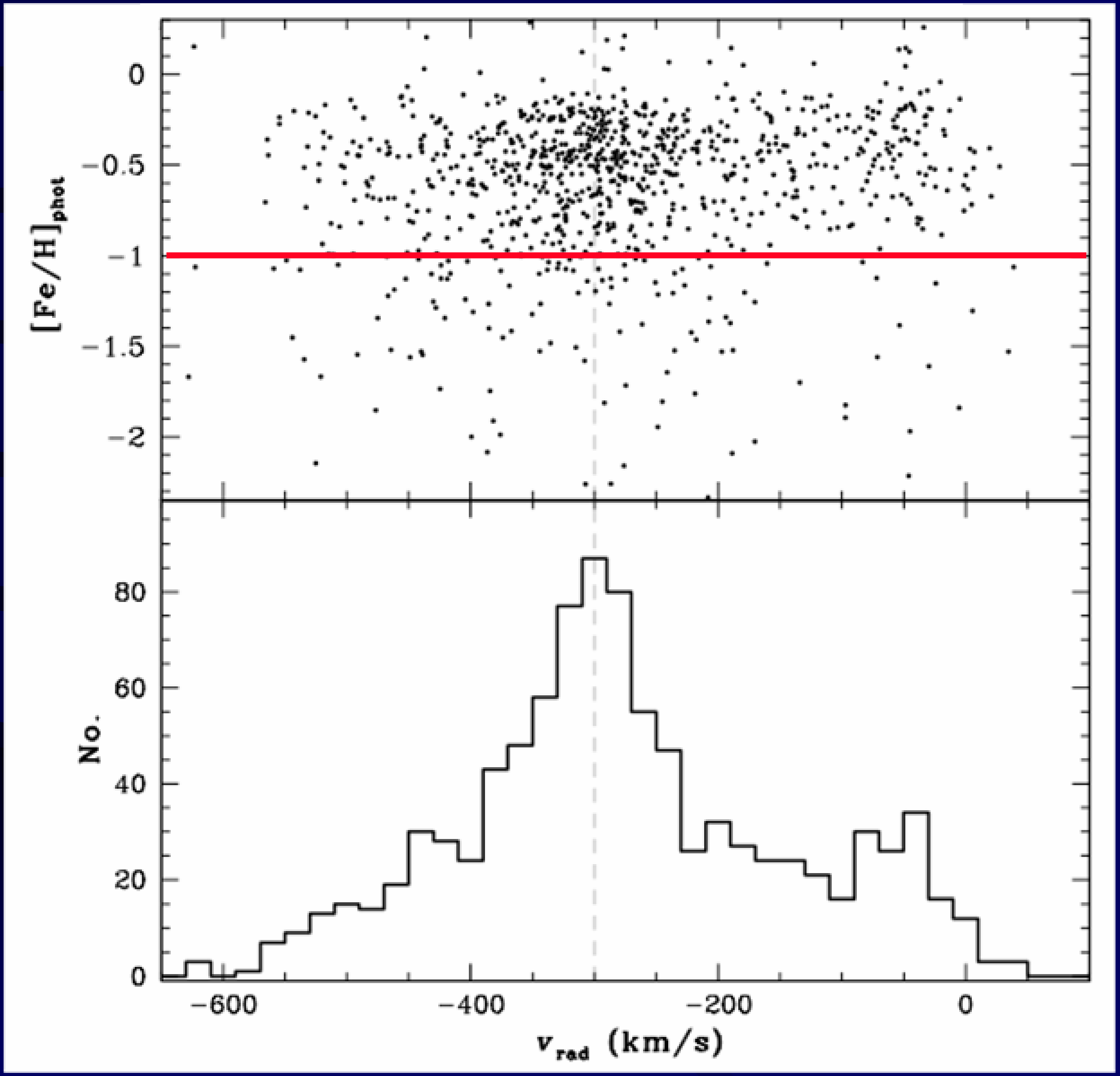
Fardal, PG, Babul, & McConnachie 2006, MNRAS, submitted (astro-ph/0609050)

Progenitor / Orbit of the Giant Southern Stream

- Test-particle orbits in a static disk galaxy potential (Ibata et al. 2004; Font et al. 2006)
- Refinement of disk galaxy potential to better match M31 (Geehan et al. 2006; Widrow et al. 2006)
- *N*-body satellite in this new M31 potential (Fardal et al. 2006a)
- Could the stream, PNe concentration, “eastern shelf”, and “western shelf” be associated with a single accretion event?

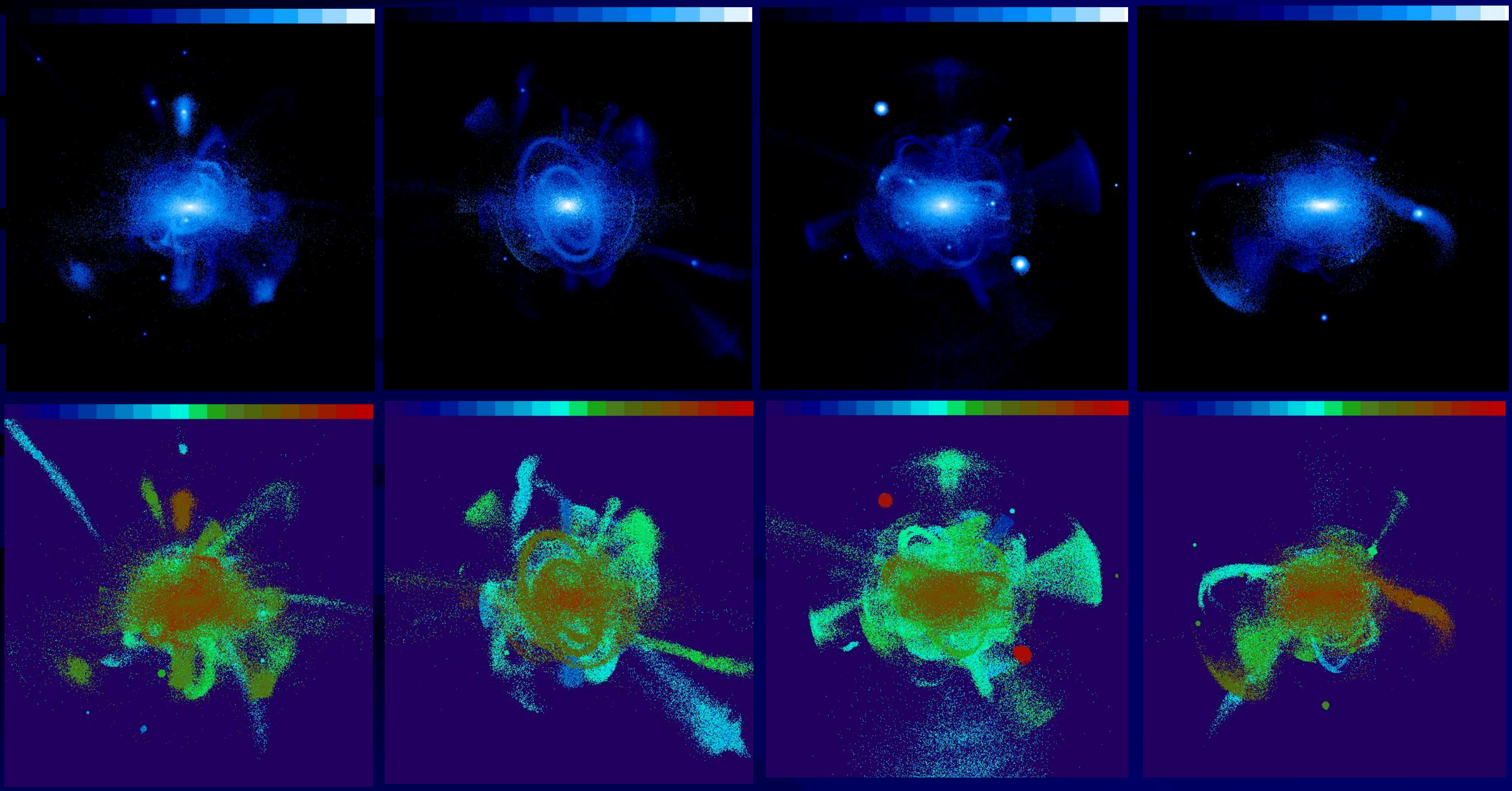
Fardal, PG, Babul, & McConnachie 2006, MNRAS, submitted (astro-ph/0609050)

Three New Metal-Rich Streams in M31



Gilbert et al. 2006, in preparation

Simulated Galaxy Halos



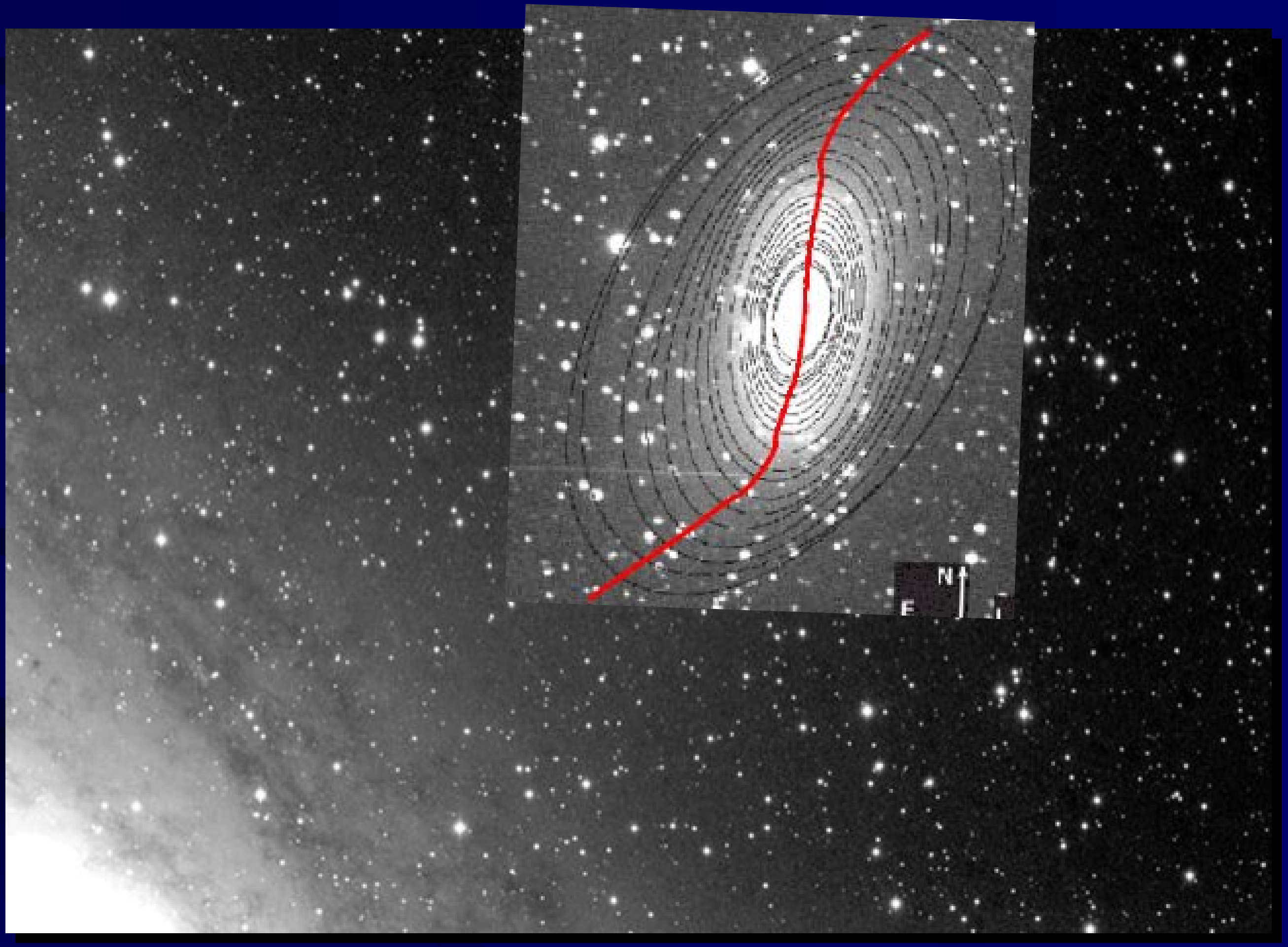
The most prominent debris trails in the simulations are expected to be the most metal-rich. This trend is seen in our M31 halo data.

Ongoing Tidal Disruption of M31's Dwarf Satellites

NGC 205 Observations

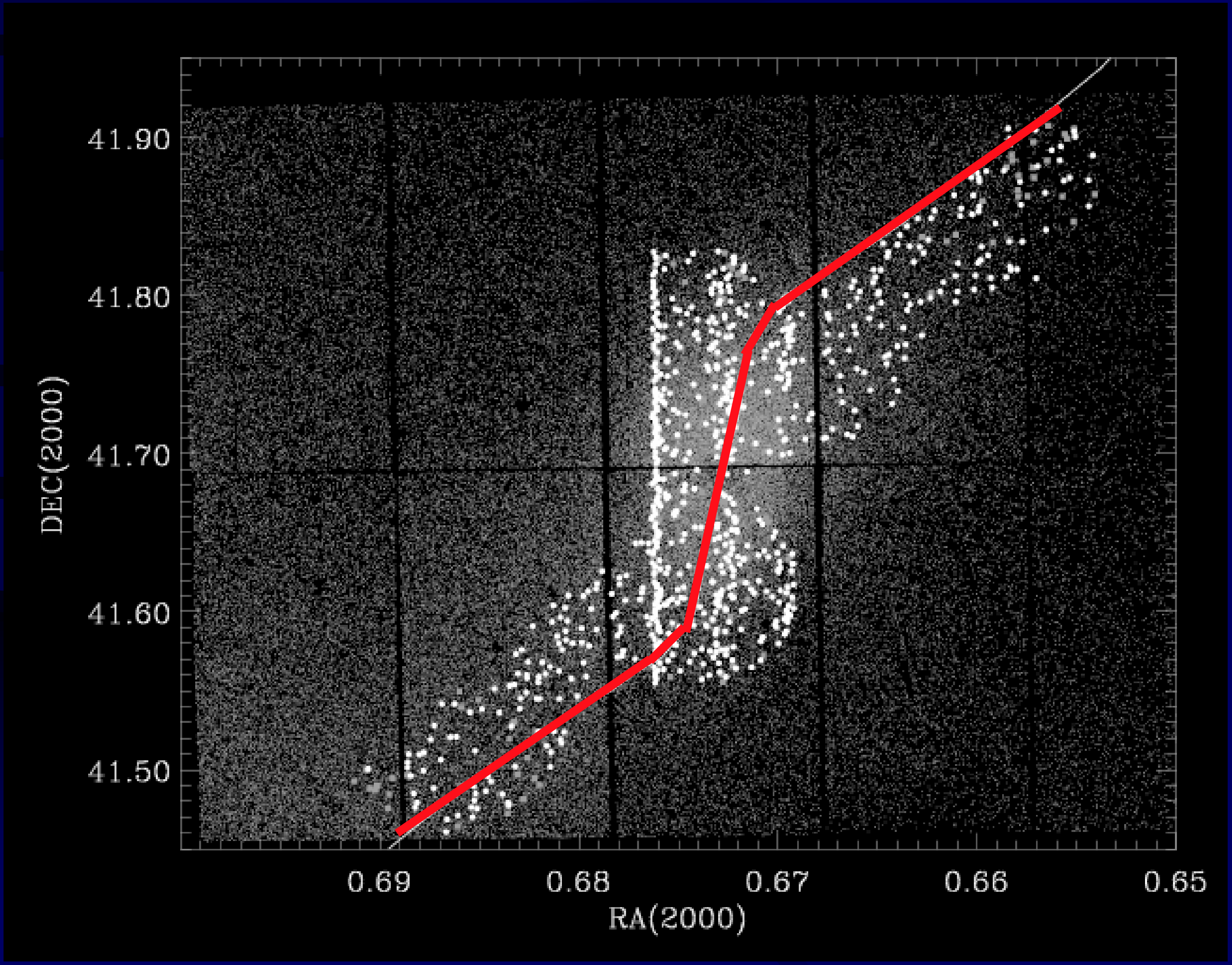
Keck / DEIMOS multislit spectroscopy

- 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

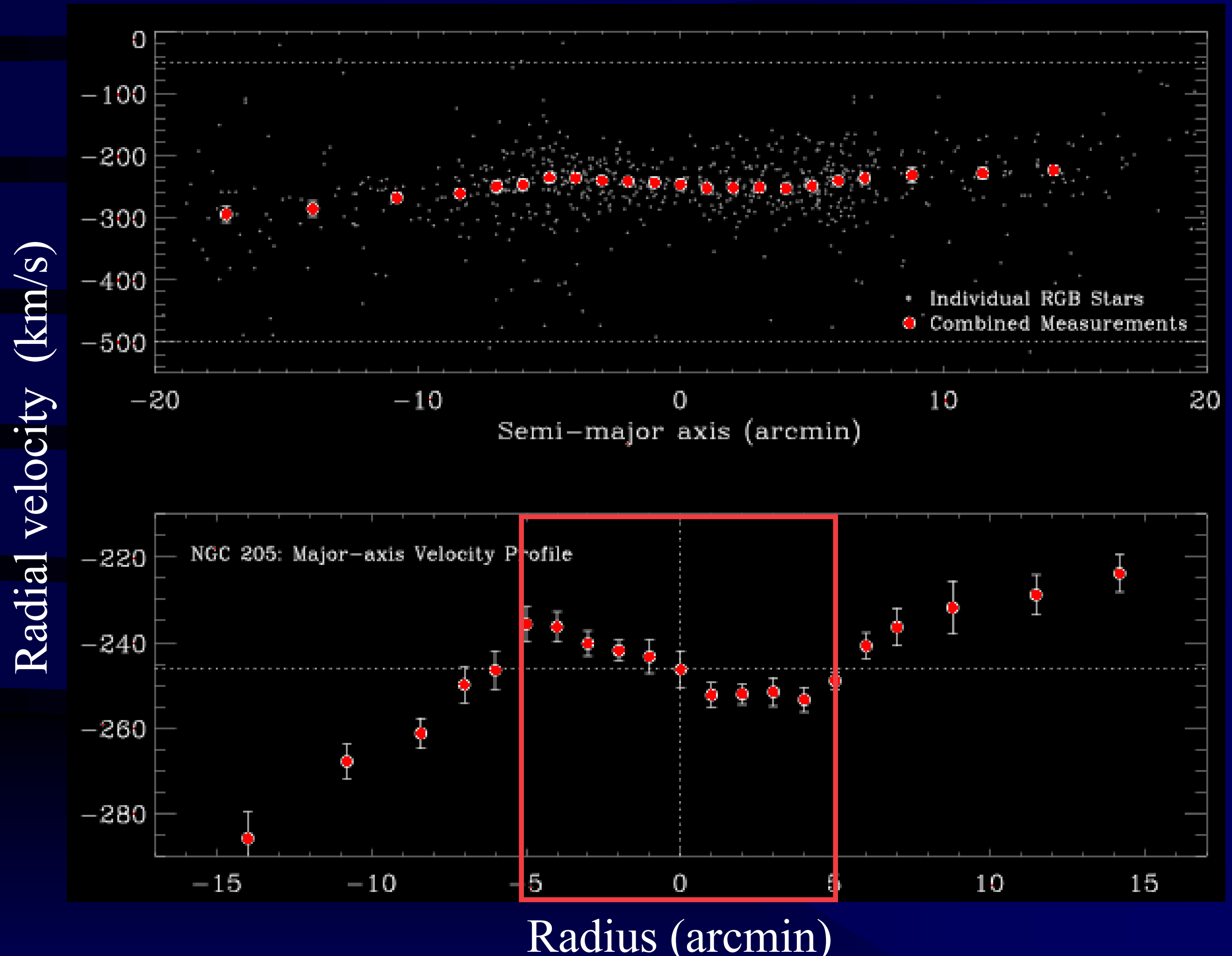


Geha, PG, Rich & Cooper 2006, AJ

Keck / DEIMOS Targets



NGC 205: Major-axis Velocity Profile



Inner rotation speed: ≈ 10 km/s

Radial velocity curve turns over beyond 2.5 r_{eff} (≈ r_{tidal})

Velocity turnover is coincident with radius at which isophotal twisting starts to occur

These data indicate that NGC 205 is in a prograde orbit around M31

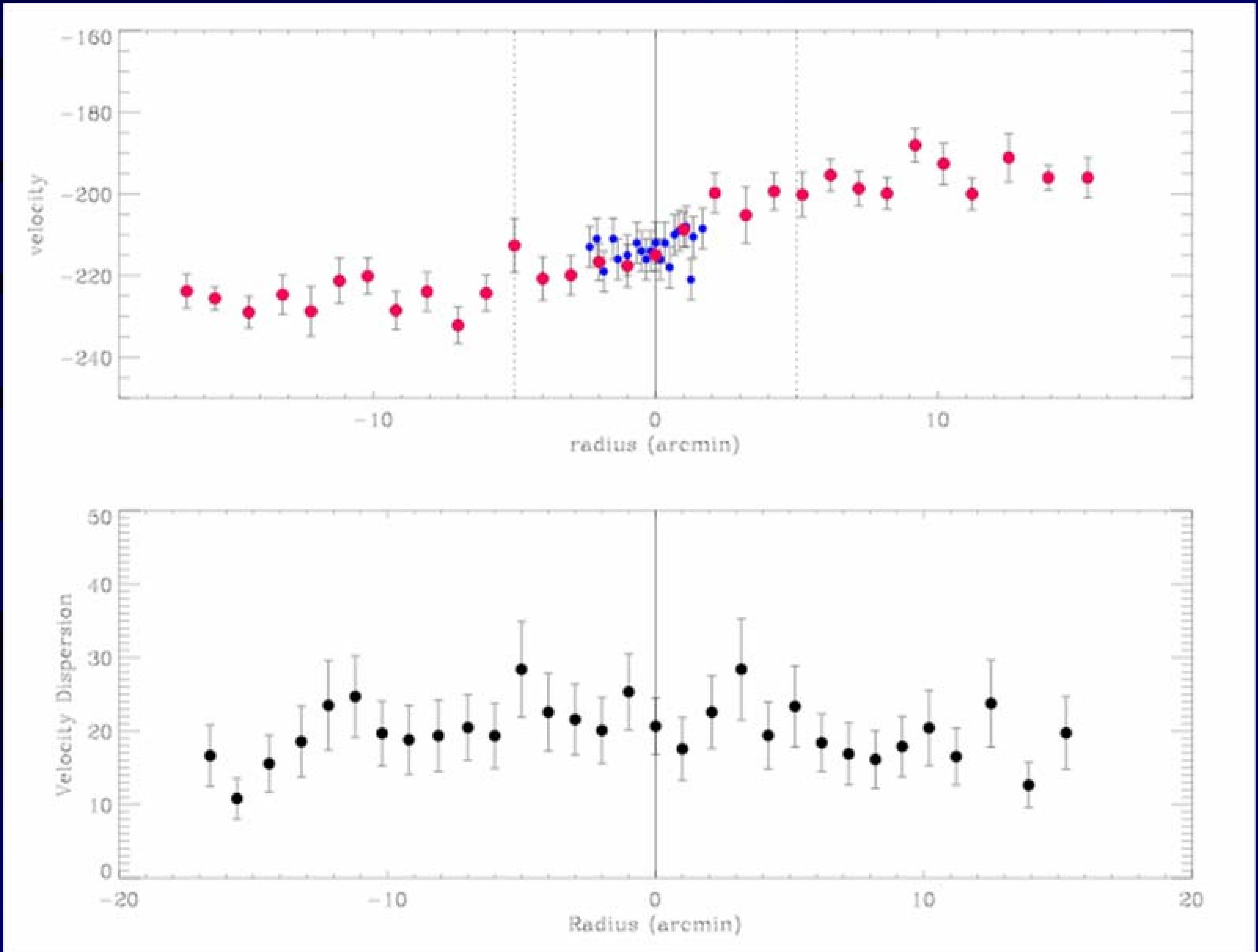
Geha, PG, Rich & Cooper 2006, AJ

Using a Genetic Algorithm to Model the NGC 205 - M31 Encounter

- Orbital trajectory of NGC 205
- Internal kinematics of NGC 205
- Dark matter content of NGC 205
- Future tidal disruption of NGC 205
- Effect of the encounter on M31's disk

Howley, Geha, PG, et al. 2006, in preparation

NGC 147: Major-axis Velocity Profile

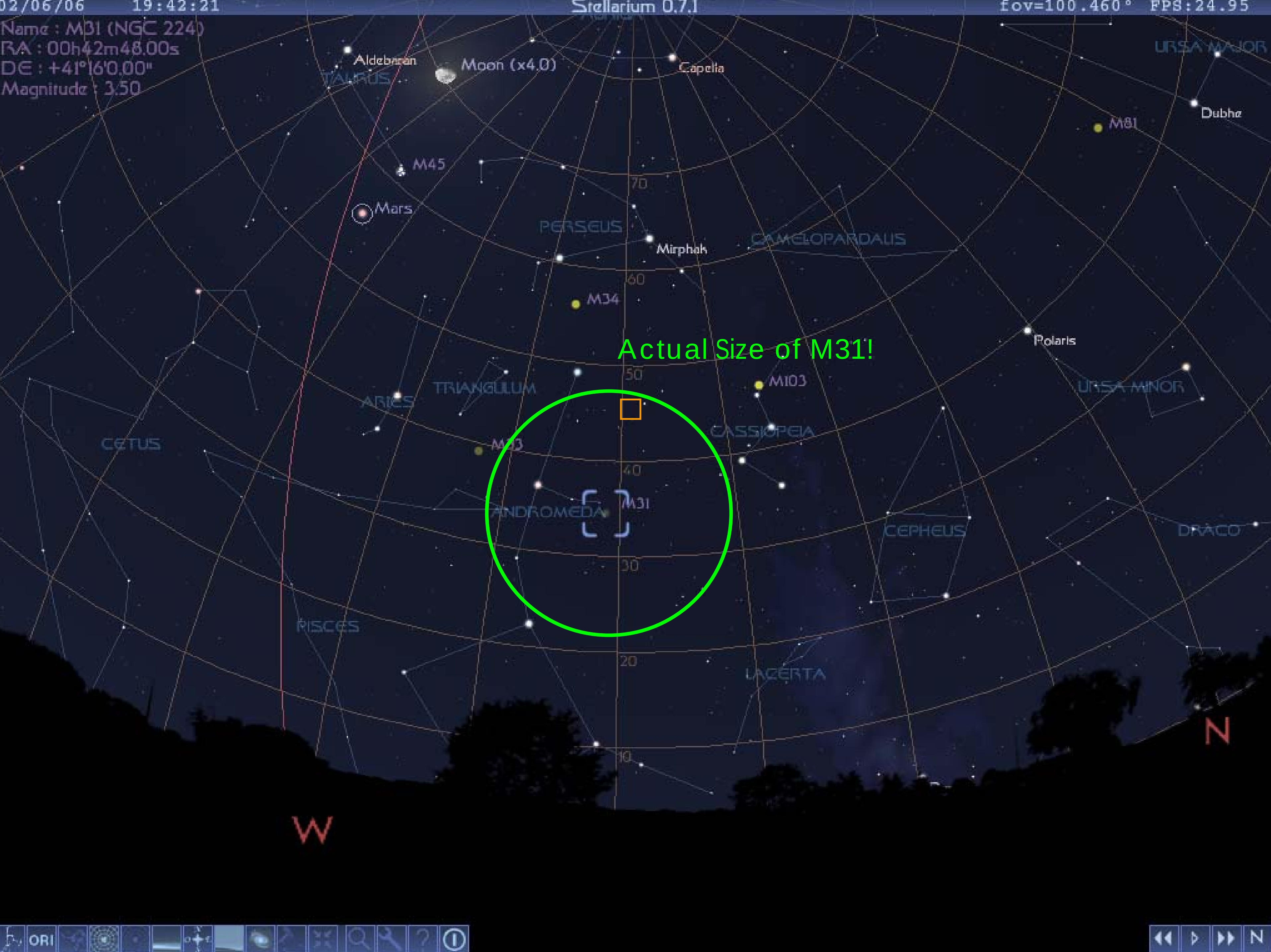


Geha, PG, et al. 2006, in preparation

M31's Stellar Halo
Summary / Future Work

- Discovery of an extended halo of M31 red giants: $r > 150$ kpc
- Sub-structure: tidal debris from past accretion events
- Statistical comparison to numerical simulations
- Dwarf galaxies as building blocks of the M31 stellar halo
  - > Photometric and kinematic distortions
  - > Comparisons between observations and numerical simulations
  - > Progenitor / orbit of the giant southern stream
- Future work:
  - > Chemical abundance from coadded spectra: [α/Fe] vs. [Fe/H]
  - > Direct determination of stellar ages from deep HST/ACS imaging

02/06/06 19:42:21
Stellarium 0.7.1
fov=100.460° FPS:24.95
Name : M31 (NGC 224)
RA : 00h42m48.00s
DE : +41°16'0.00"
Magnitude : 3.50
Aldebaran
Moon (x4.0)
Capella
TAURUS
M45
Mars
PERSEUS
Mirphak
M34
TRIANGULUM
ARIES
CETUS
M33
ANDROMEDA
M31
CEPHEUS
DRACO
PISCES
LACERTA
M110
W
N
ORI



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M34
Actual Size of M31!
Polaris
M103
URSA MINOR
TRIANGULUM
ARIES
CASSIOPEIA
CETUS
M33
M31
ANDROMEDA
CEPHEUS
DRACO
PISCES
LACERTA
N
W

Conclusion from Previous Studies:

M31's "outer" spheroid (*r* ~ 20 – 30 kpc) is <u>nothing like</u> the Milky Way halo

- The combination of the $r^{1/4}$ law surface brightness profile and high metallicity makes the M31 spheroid look much more like the Milky Way's <u>bulge</u> than its halo

- M31's spheroid has also been likened to elliptical galaxies

- The age and star-formation history of M31's spheroid are unusual —intermediate-age / young population found in Brown et al.'s (2003) ultra-deep *HST* / ACS photometry