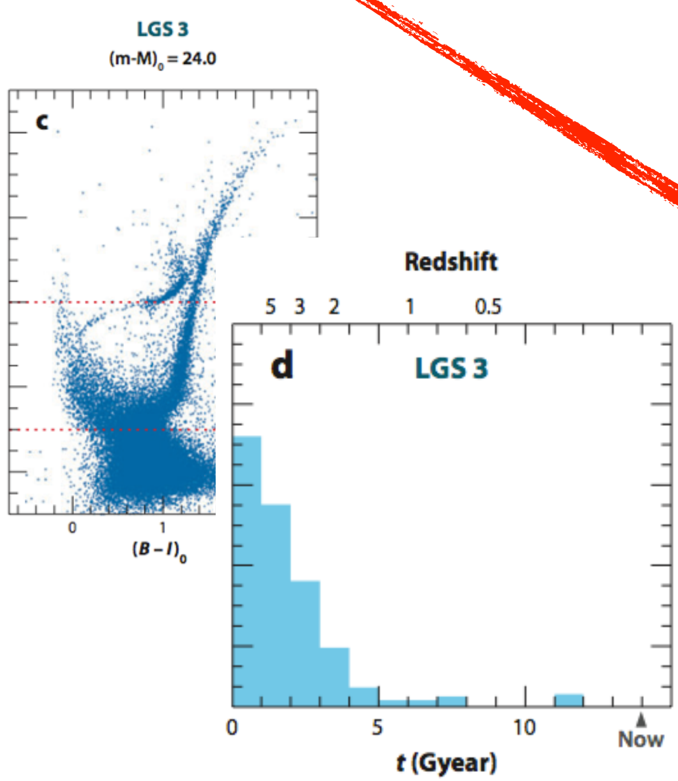
The Faintest of the Milky Way Satellites

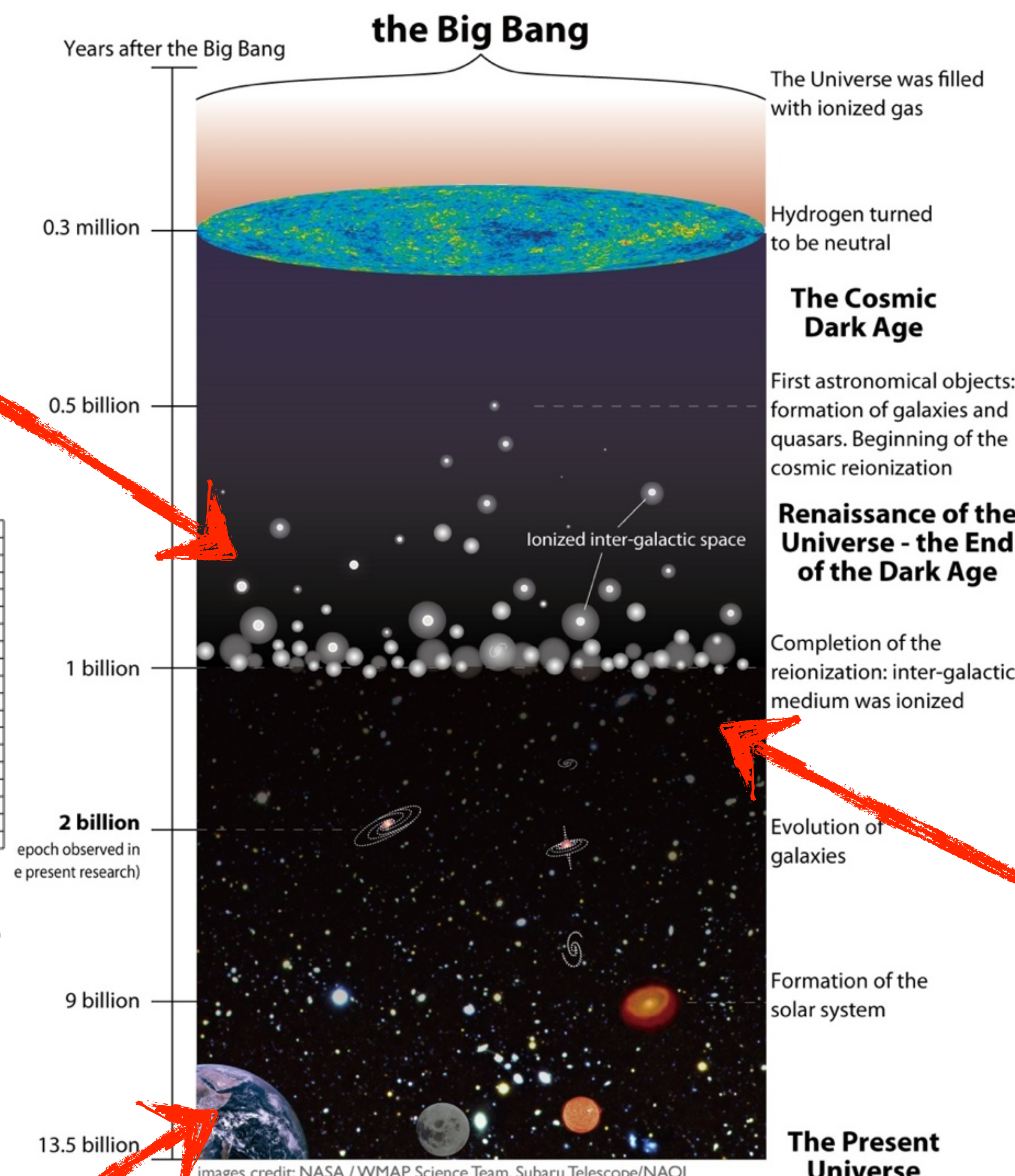
Vasily Belokurov
Institute of Astronomy • Cambridge

Near Field Cosmology

Oldest Stars in Our Galaxy



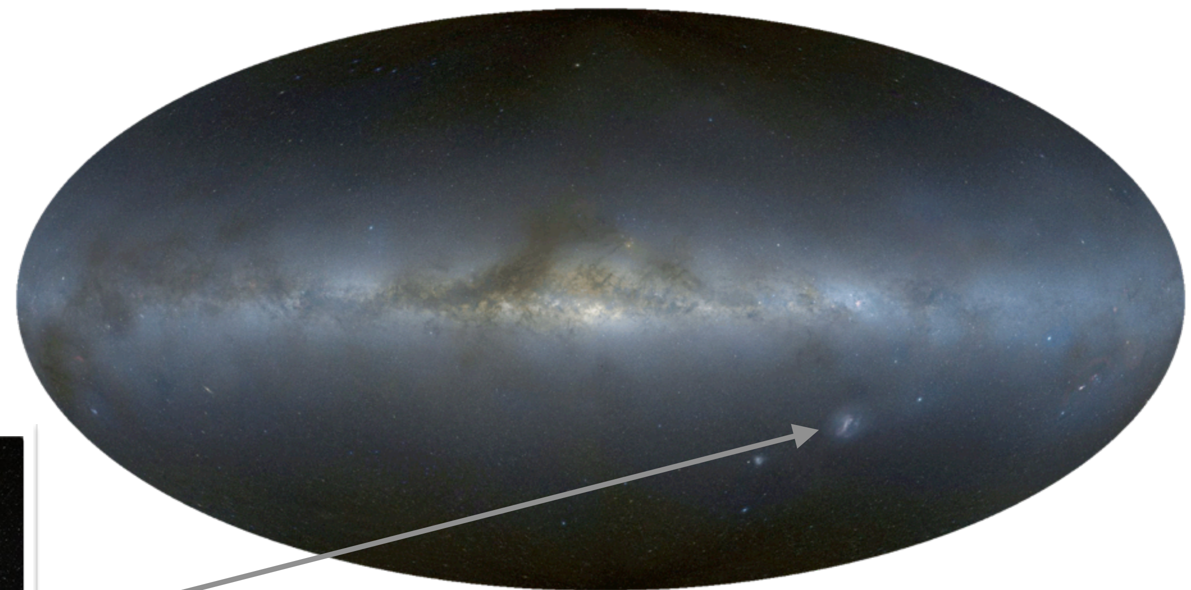
Tolstoy et al, 2009



Hubble Deep Field

Pink Floyd's first album

Galactic Dwarf Satellites



LMC

$1/40\ L_{MW}$

Not So Faint

Leo I

$1/8000\ L_{MW}$

Faint

Boötes I

$1/2{,}000{,}000\ L_{MW}$

Ultra Faint

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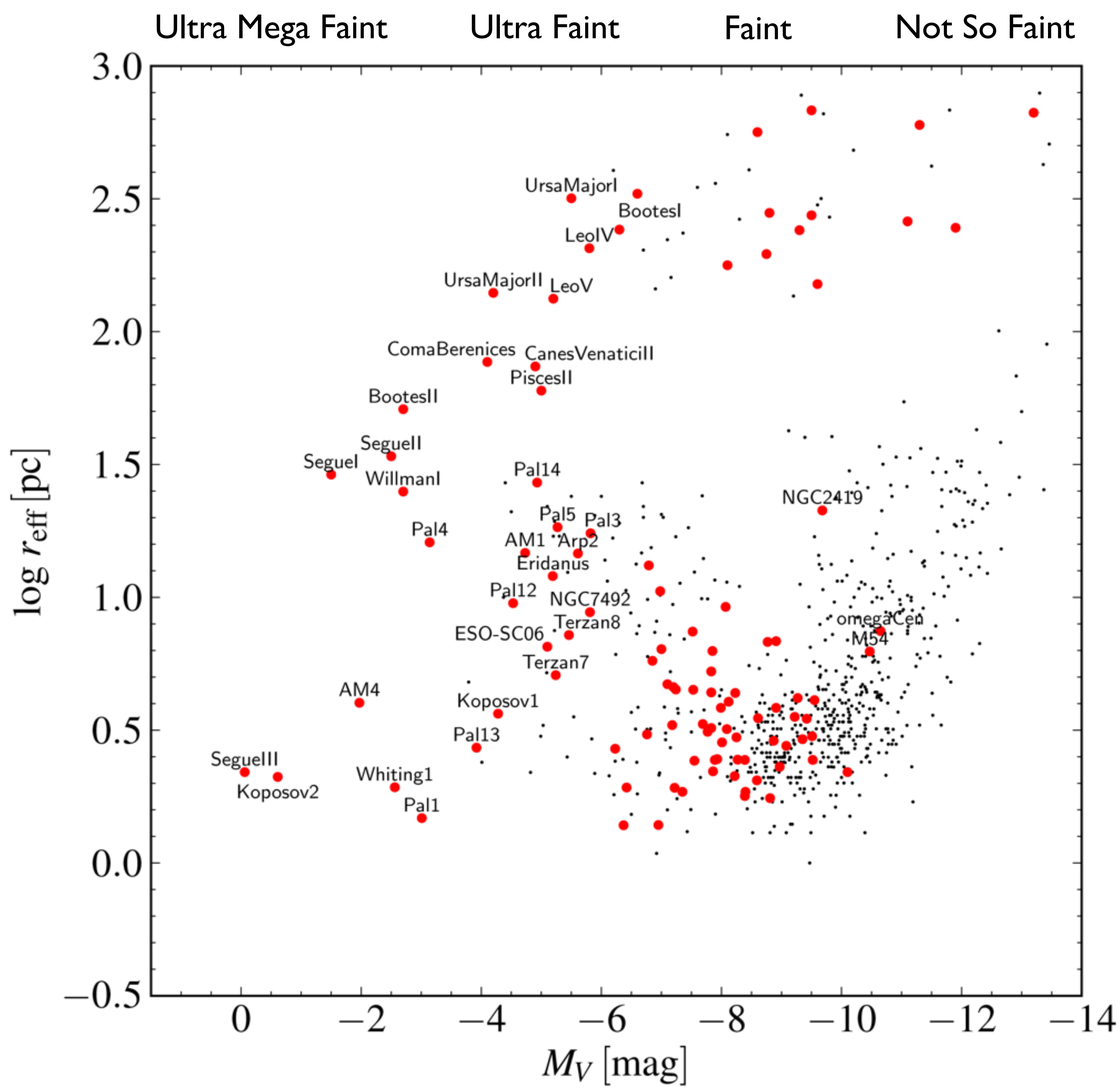
A Zoo of Faint Satellites



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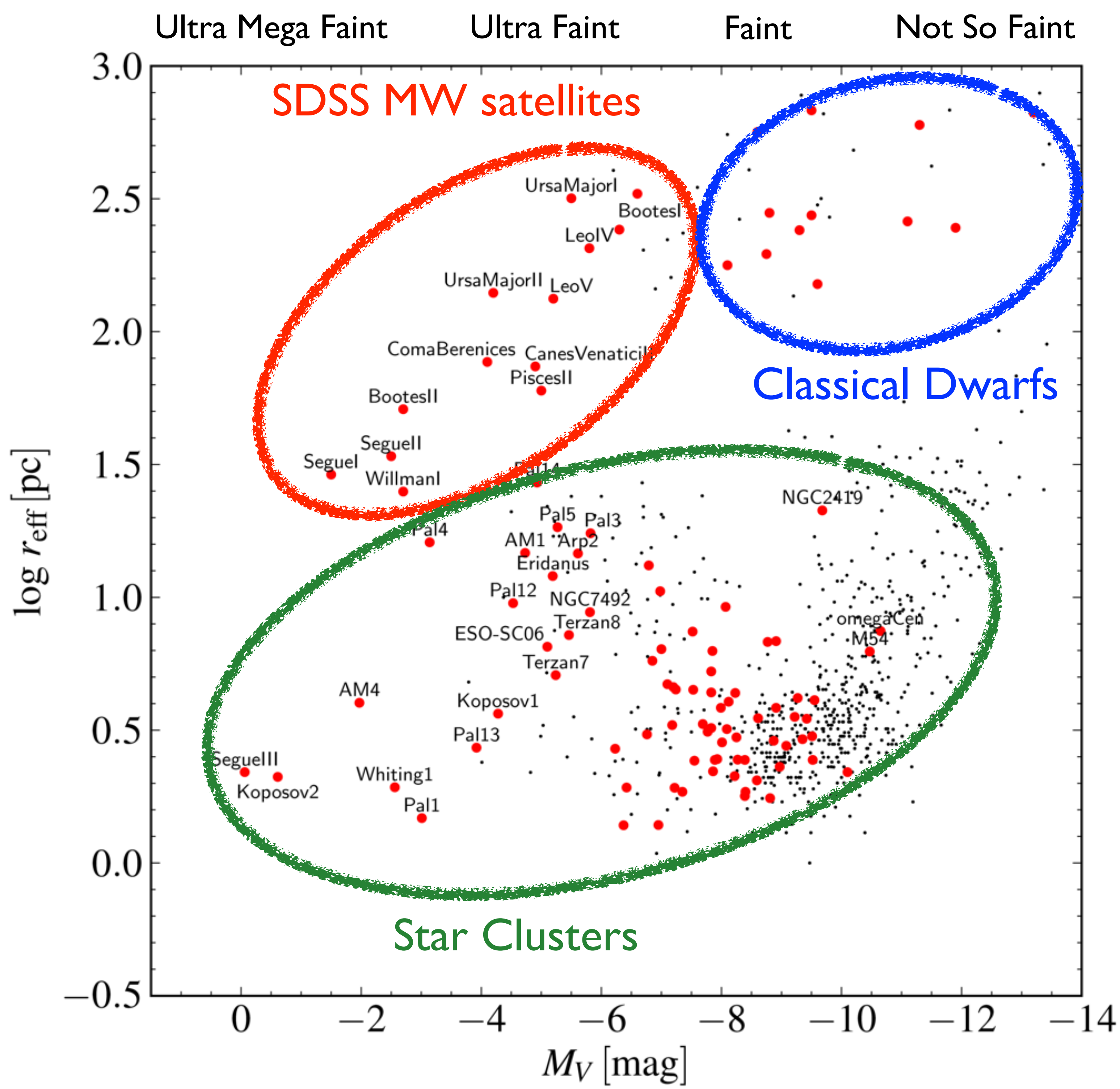
A Zoo of Faint Satellites



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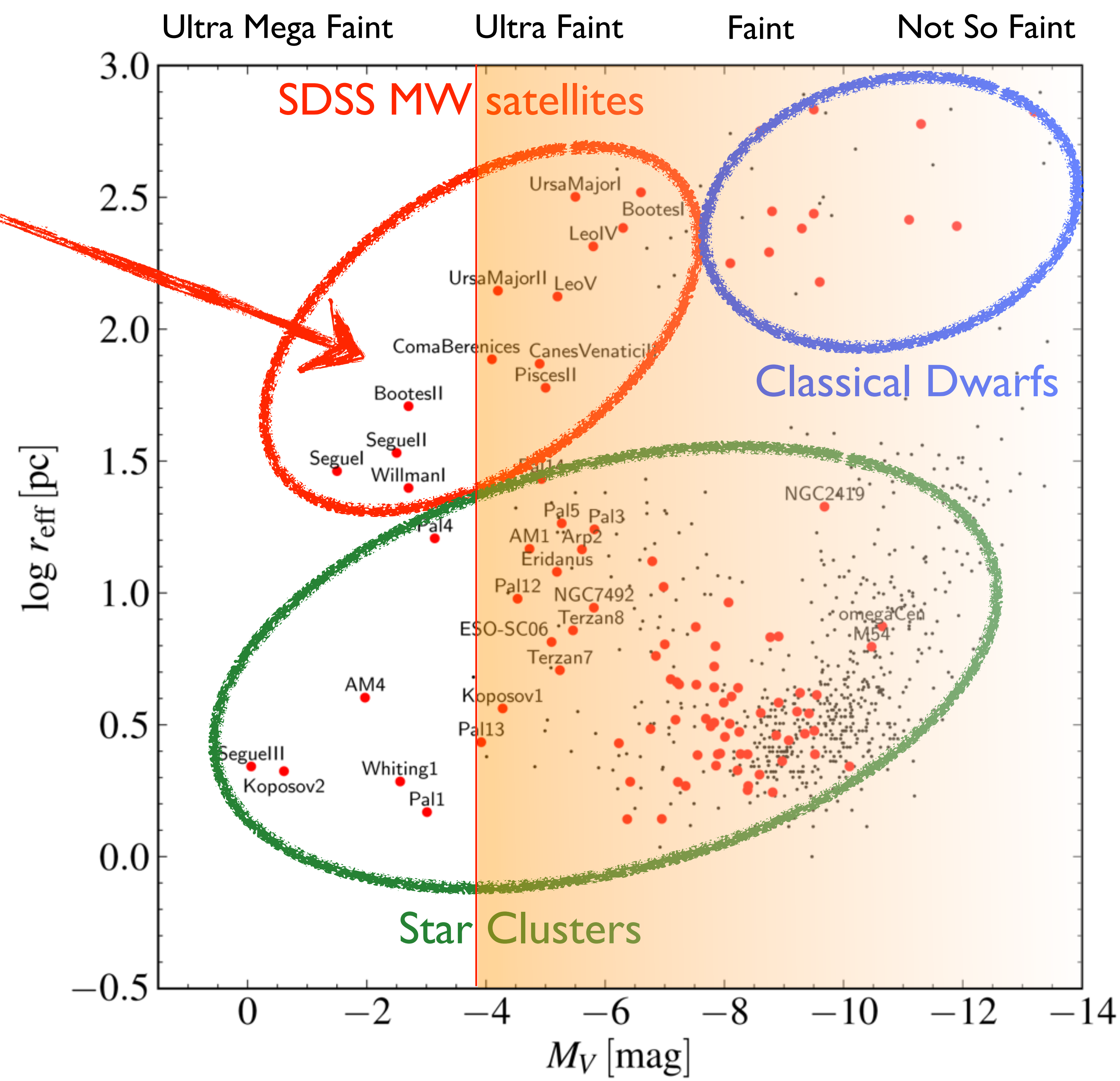
A Zoo of Faint Satellites

What this talk is about



- Segue I
- Segue II
- Willman I
- Bootes II

Alleviating Theory vs. Observation Mismatch

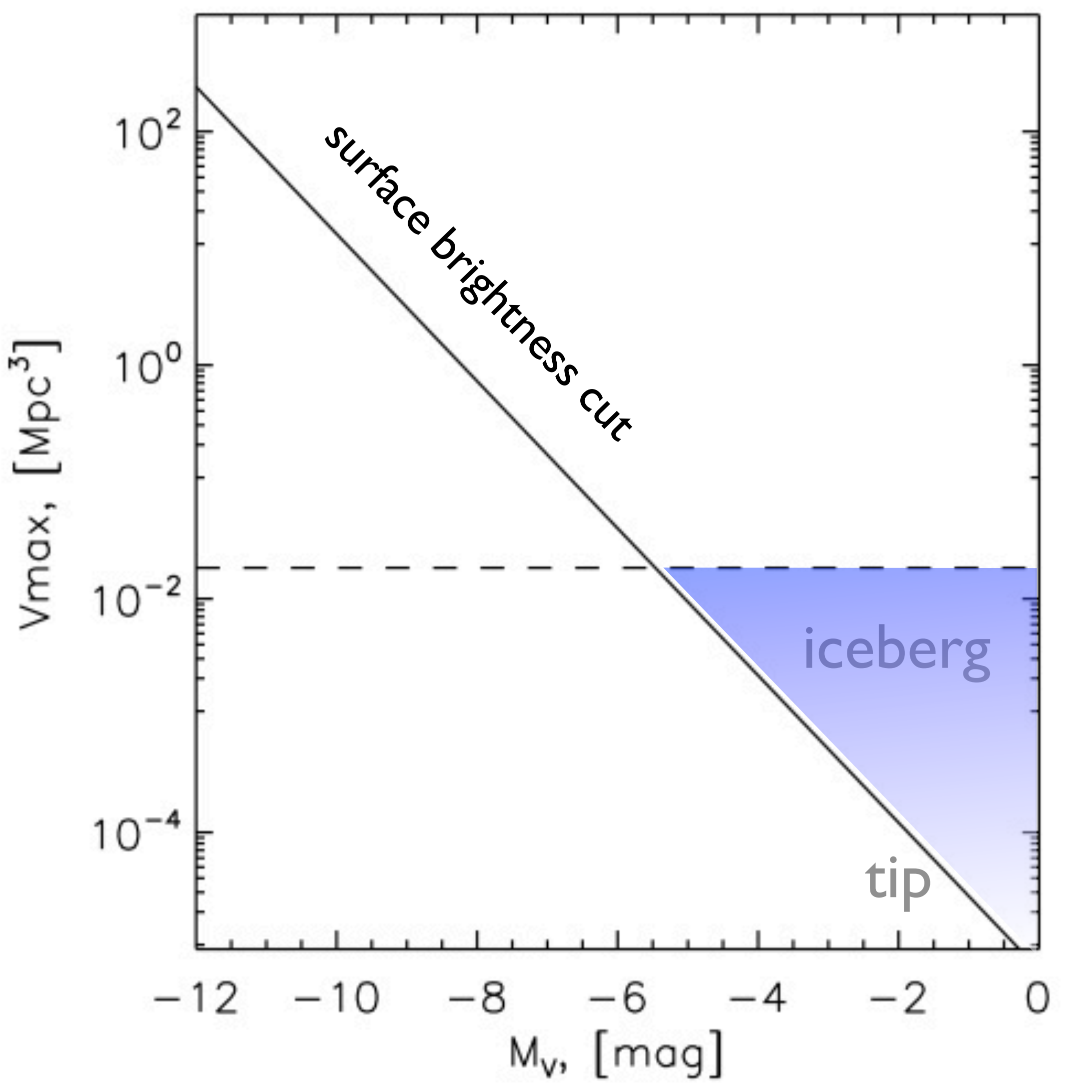
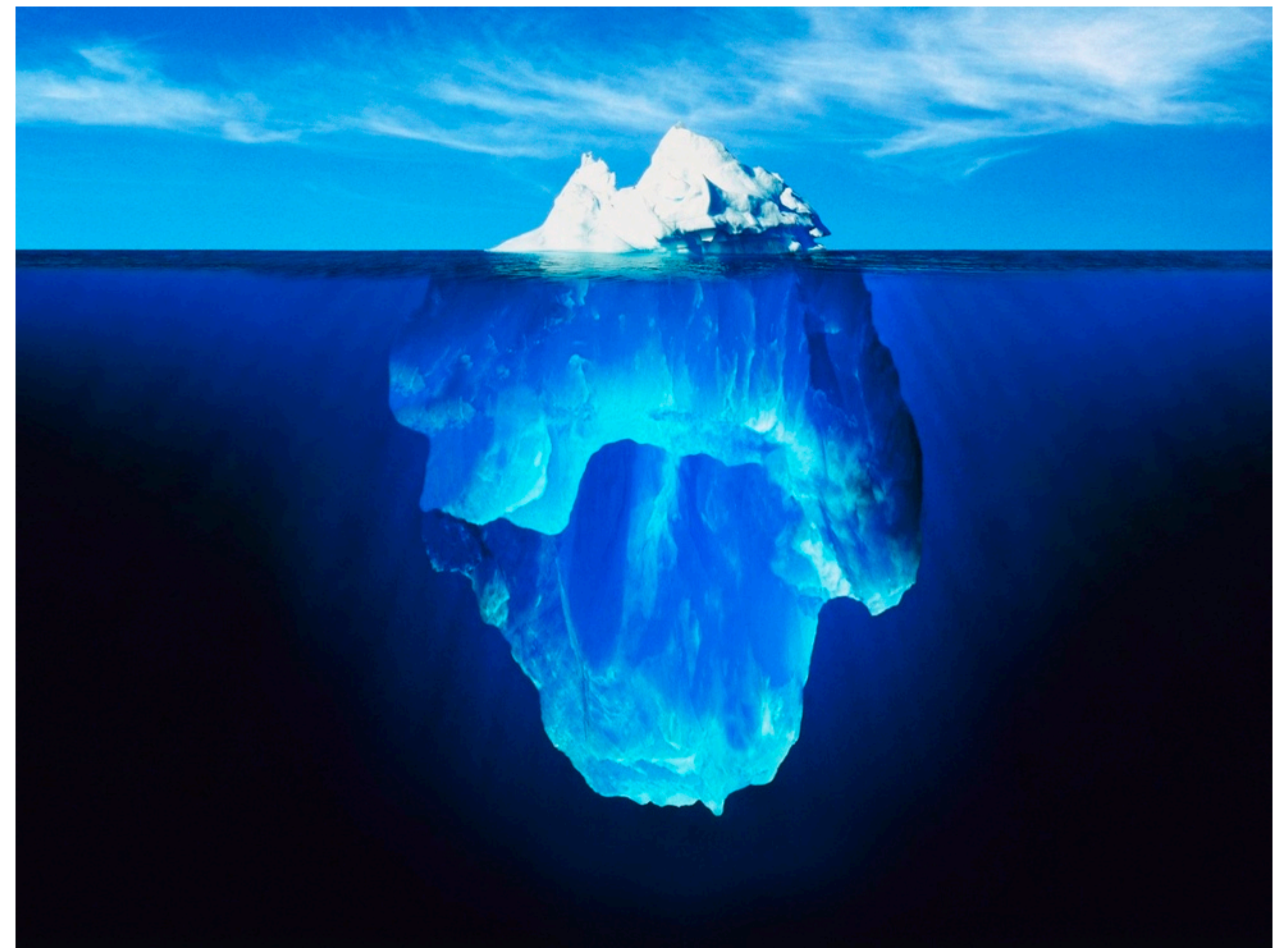


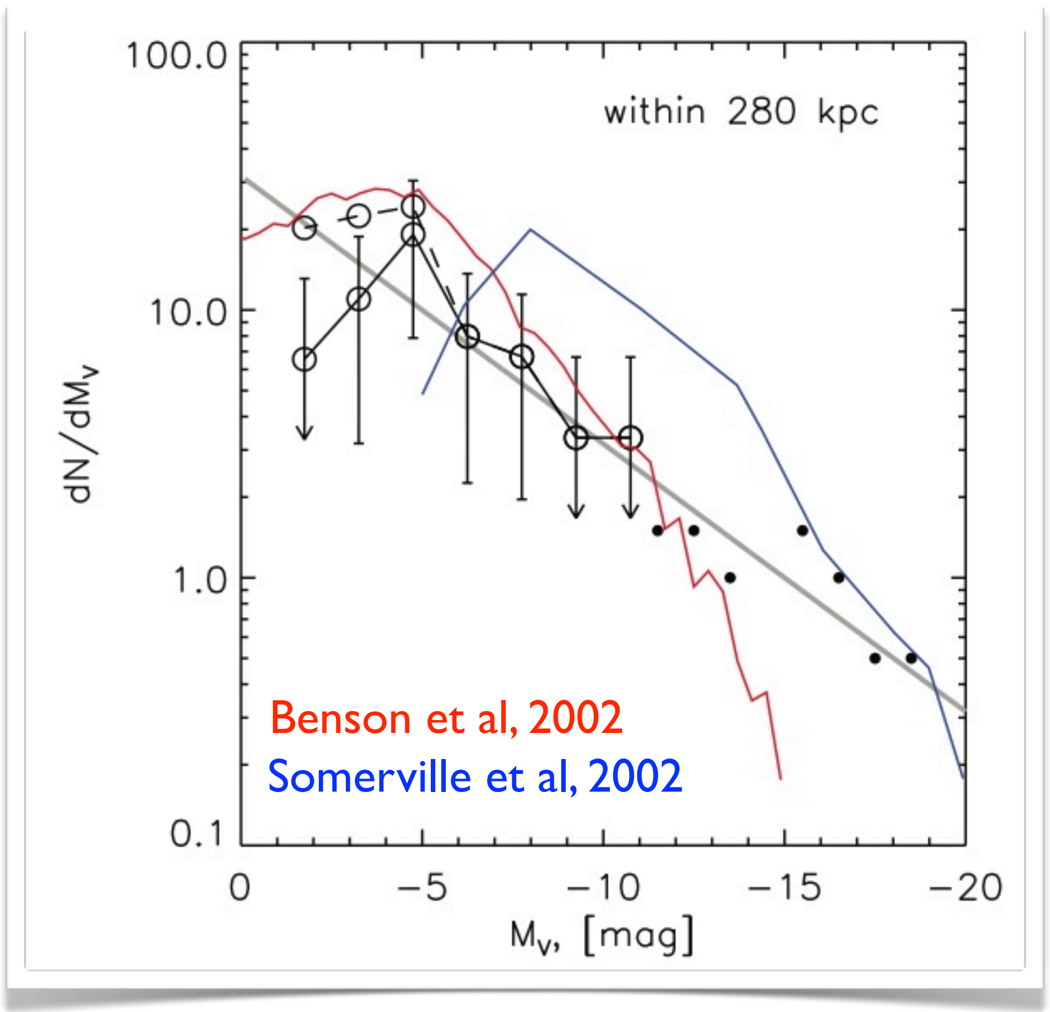
FIG. 13.—Accessible volume within the DR5 footprint for galaxies with different luminosities and surface brightnesses $\mu_{\rm lim}$ and $\mu \lesssim 30$ mag arcsec^{-2} (see Fig. 12). The volume limited by the virial radius (280 kpc) and within DR5 is shown by the dashed line.



Koposov et al, 2008

Tollerud et al, 2008

Luminosity Function of Galactic Satellites



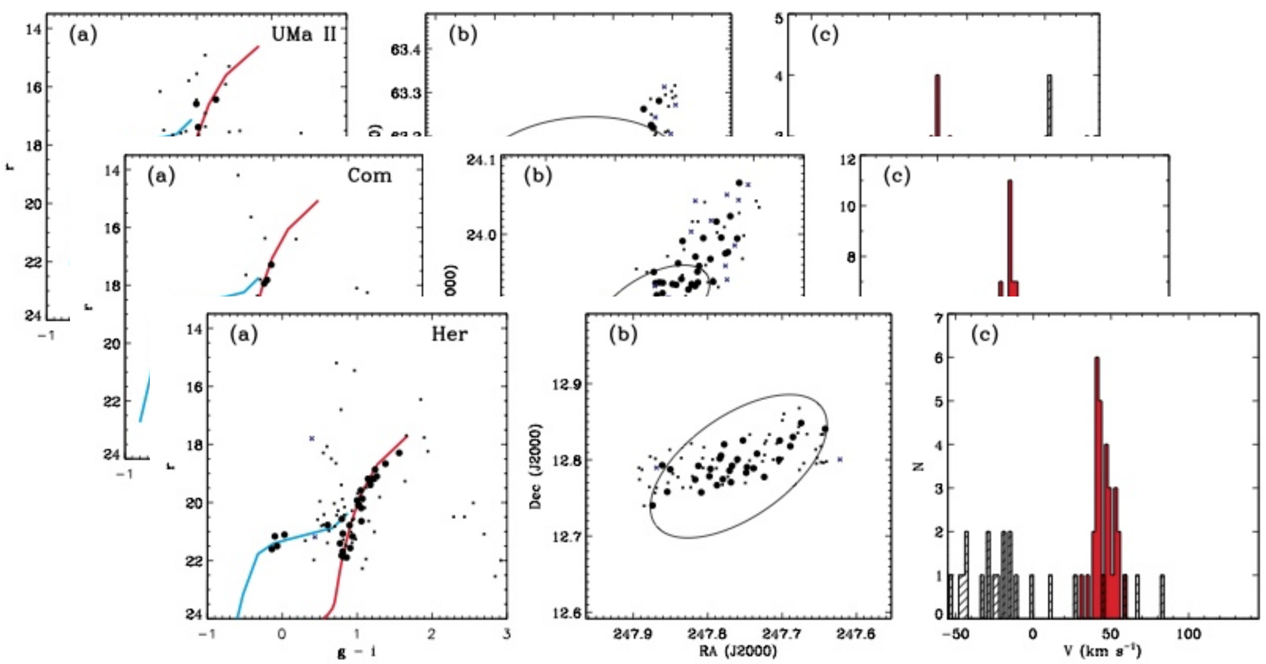
Koposov et al, 2008

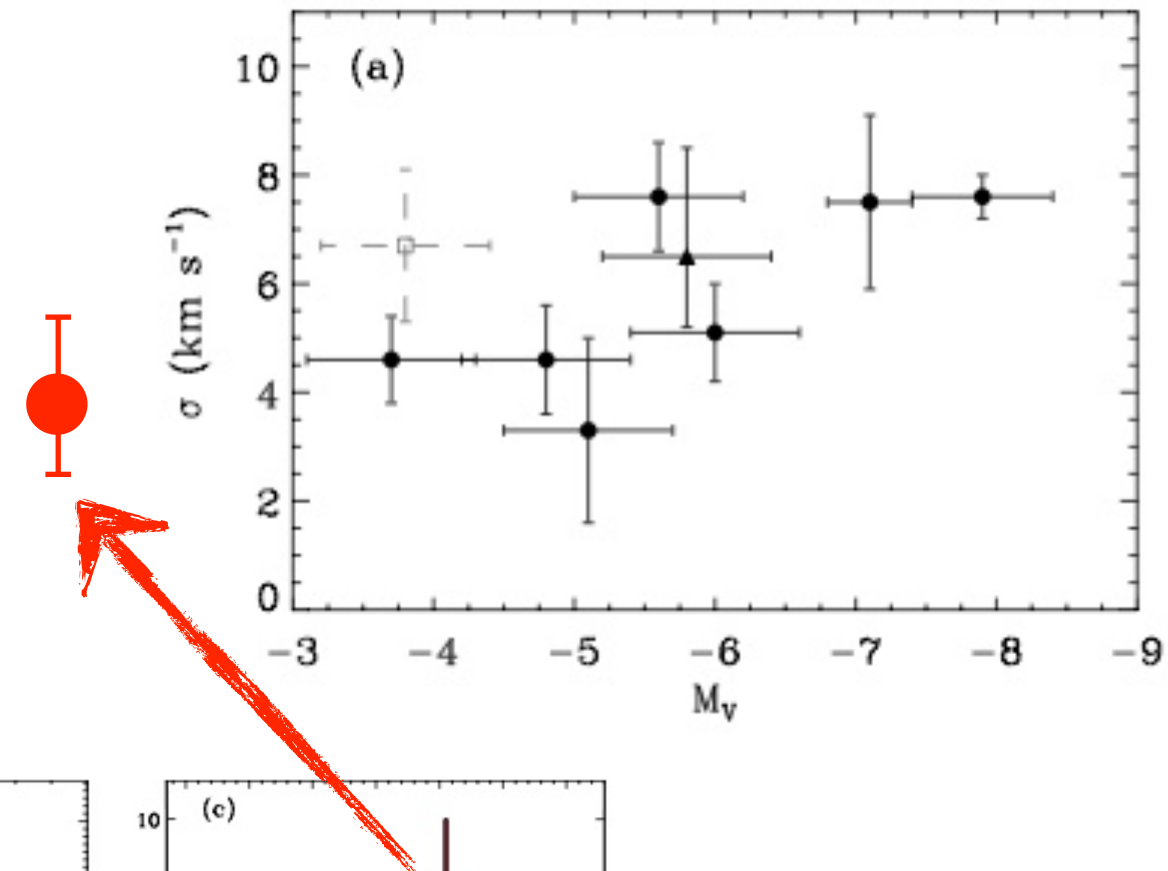
- star formation in the early Universe
- epoch of reionisation
- accretion history of the MW
- coldness of dark matter

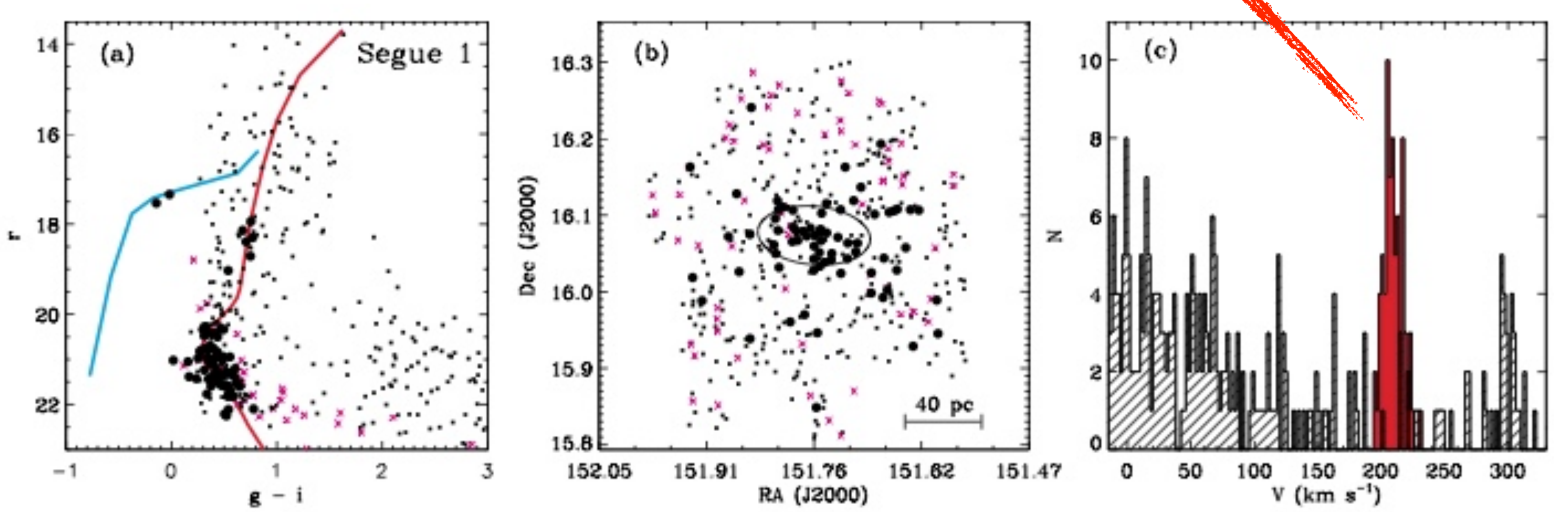
Rashkov et al, 2012
Boylan-Kolchin et al, 2011
Font et al, 2011
Cooper et al, 2010
Maccio & Fontanot, 2010
Li et al, 2010
Maccio et al, 2010
Busha et al, 2010
Tumlinson, 2010
Koposov et al, 2009
Bovill & Ricotti, 2009

Kinematics of Stellar Tracers

Simon and Geha, 2007







Simon et al, 2011

Kinematics, Mass and Density

Common Mass Scale

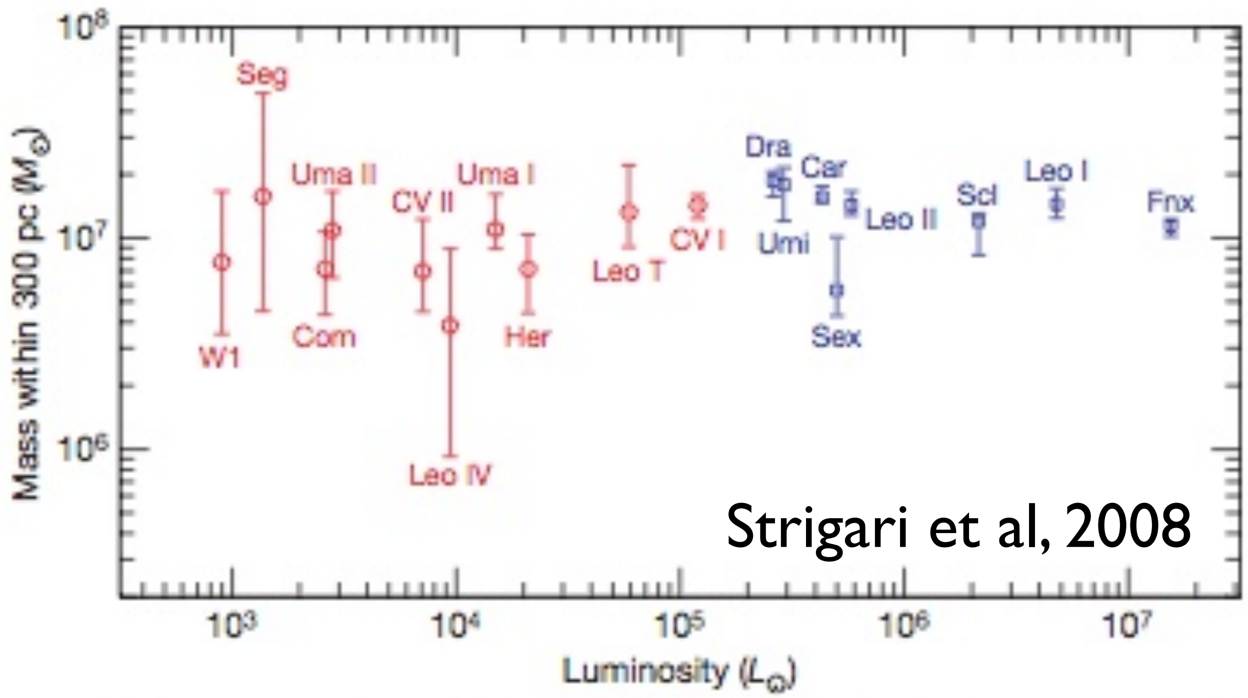
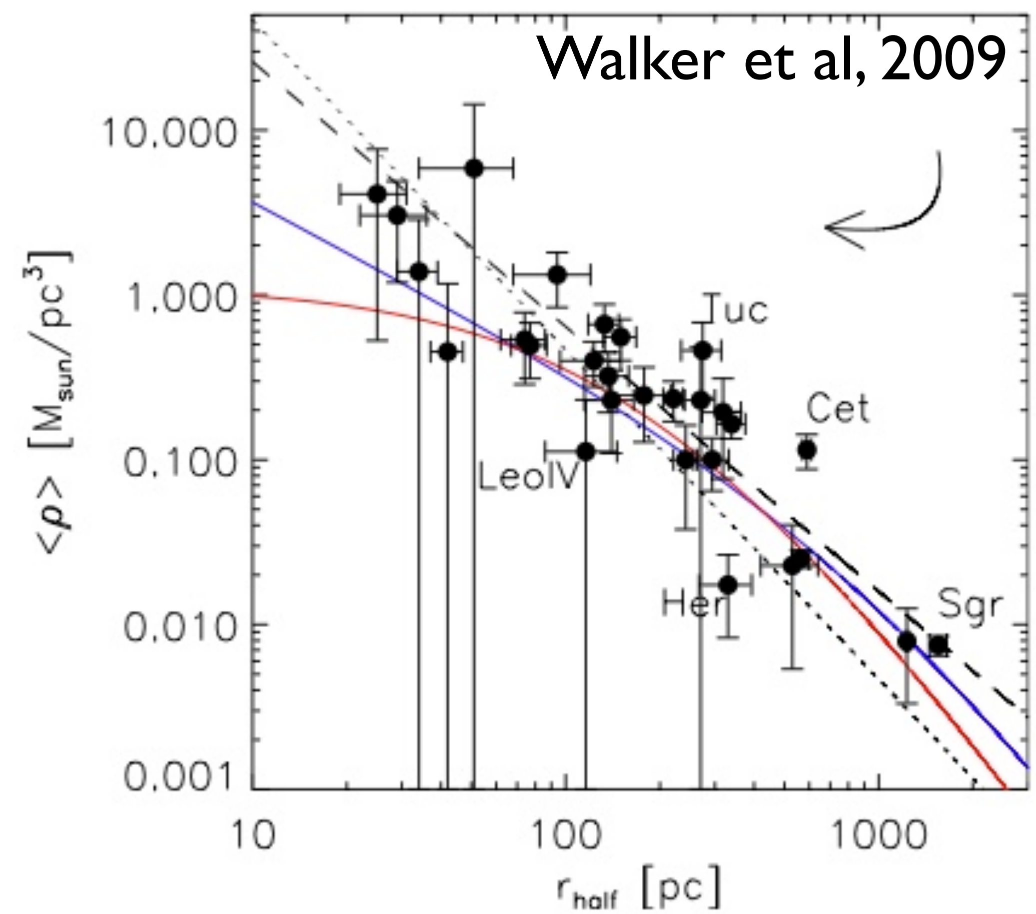


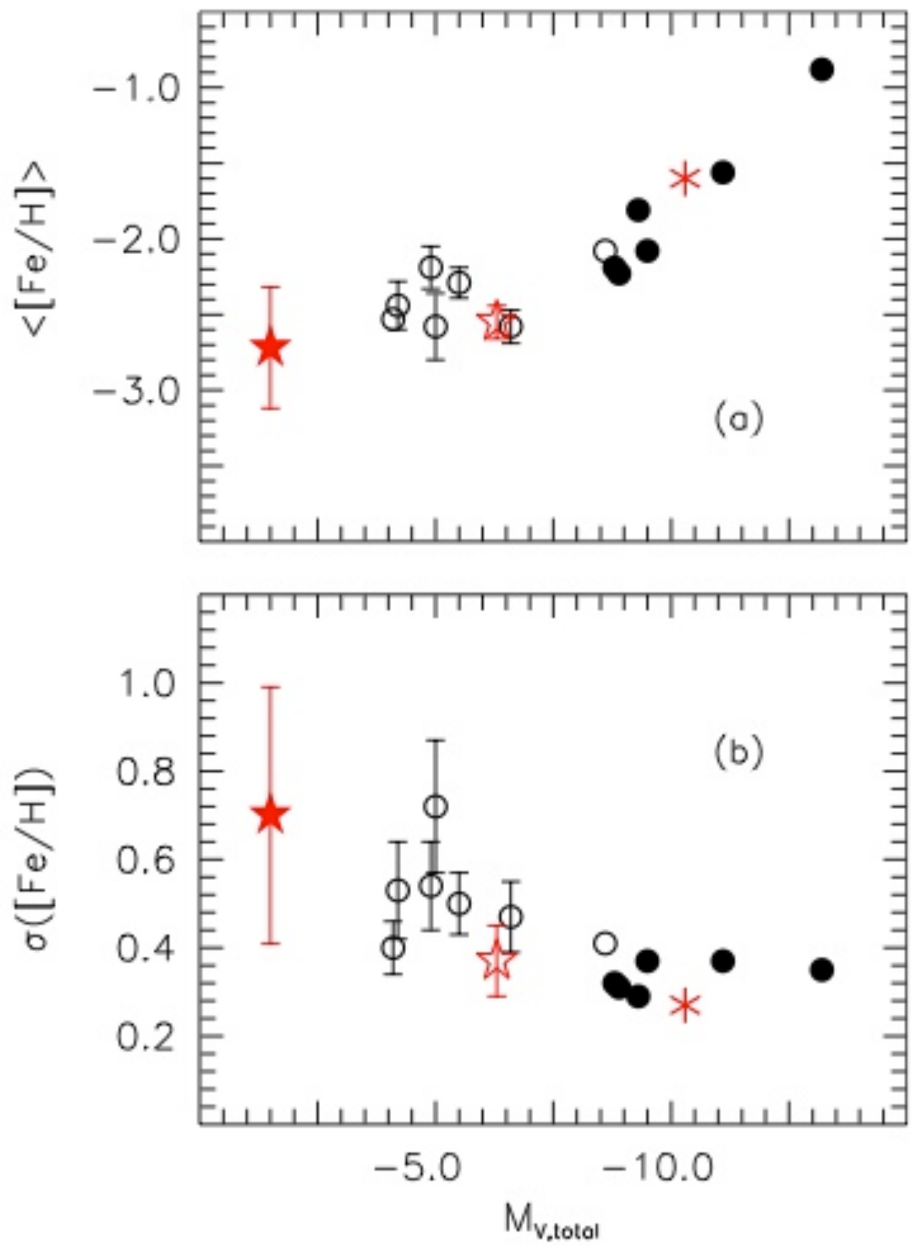
Figure 1 | The integrated mass of the Milky Way dwarf satellites, in units of solar masses, within their inner 0.3 kpc as a function of their total luminosity, in units of solar luminosities. The circle (red) points on the left refer to the newly discovered SDSS satellites, whereas the square (blue) points refer to the classical dwarf satellites discovered pre-SDSS. The error bars reflect the points where the likelihood function falls off to 60.6% of its peak value.

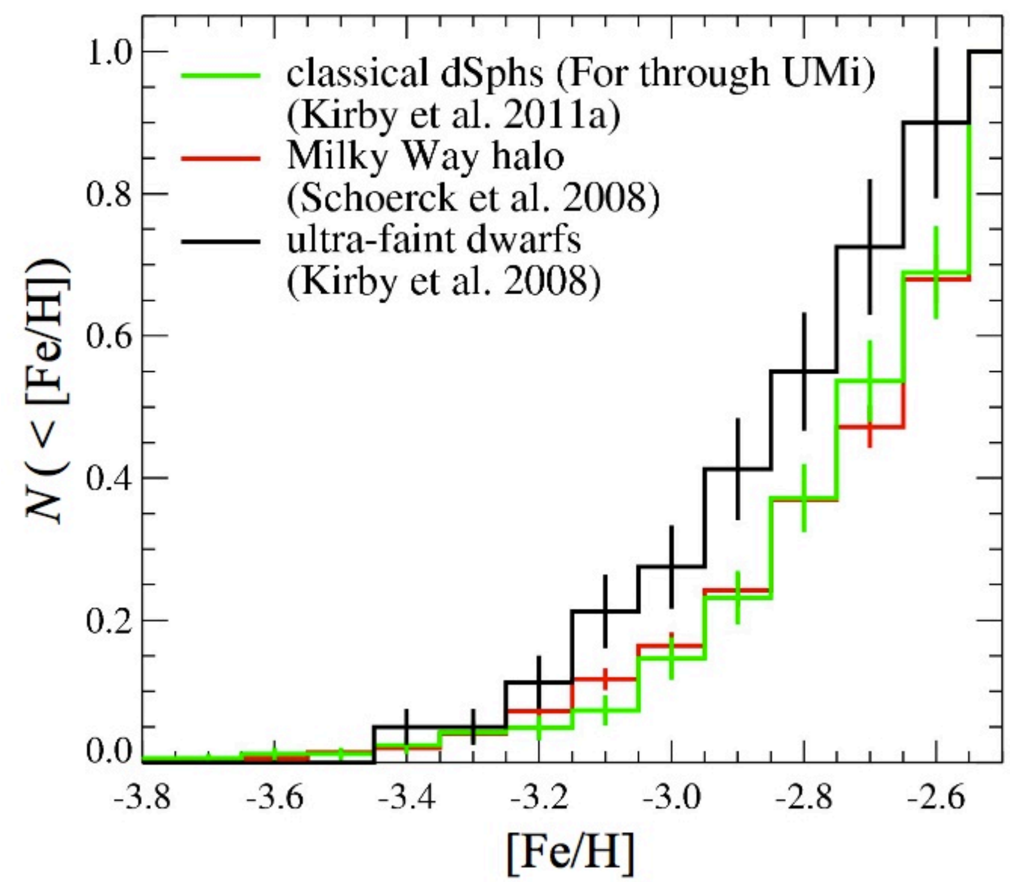
Common Mass Profile



$$Q = \frac{\rho}{\sigma^3}$$

Chemistry

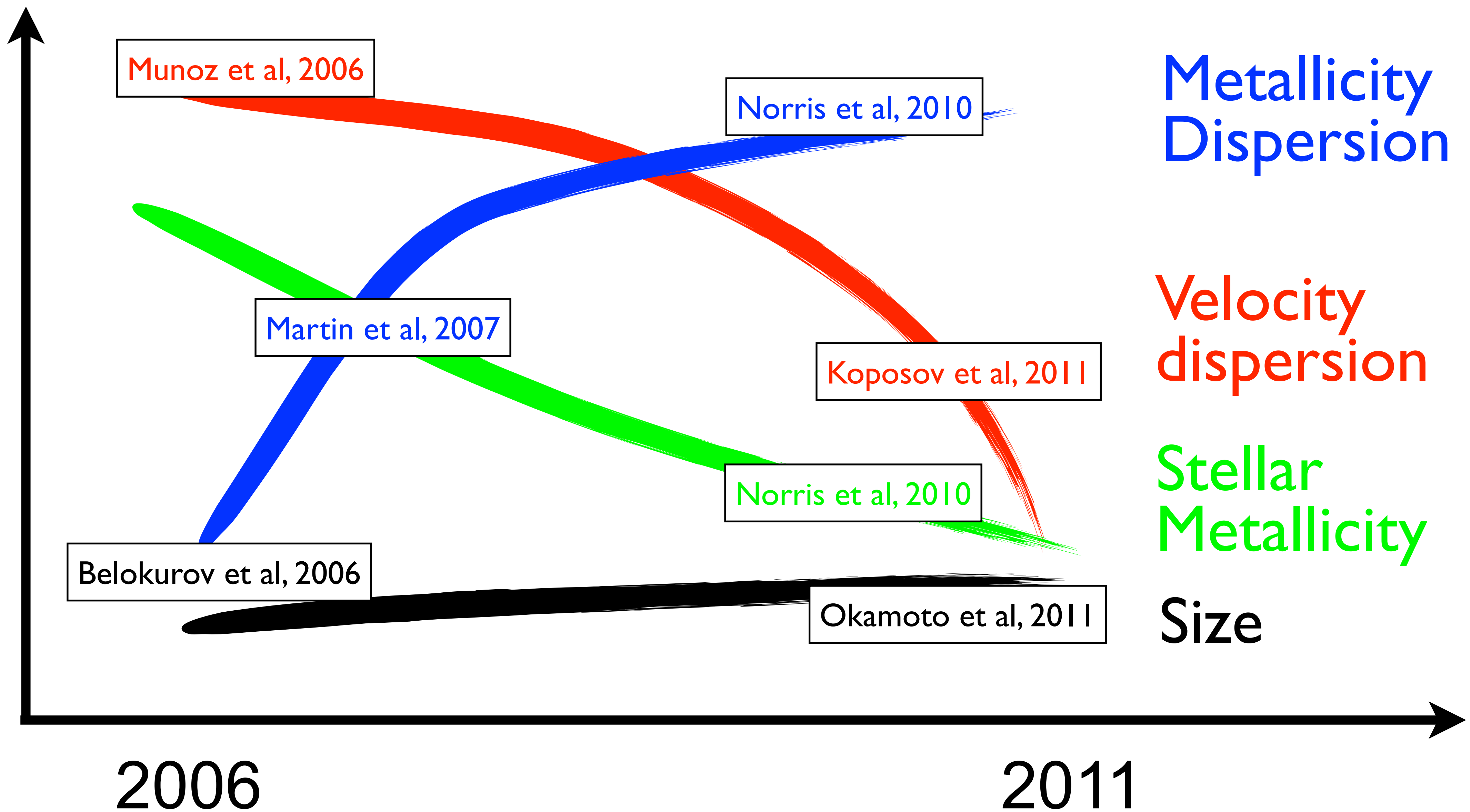




Norris et al, 2010

Kirby et al, 2011

A Word of Caution: "Evolution" of Boötes I



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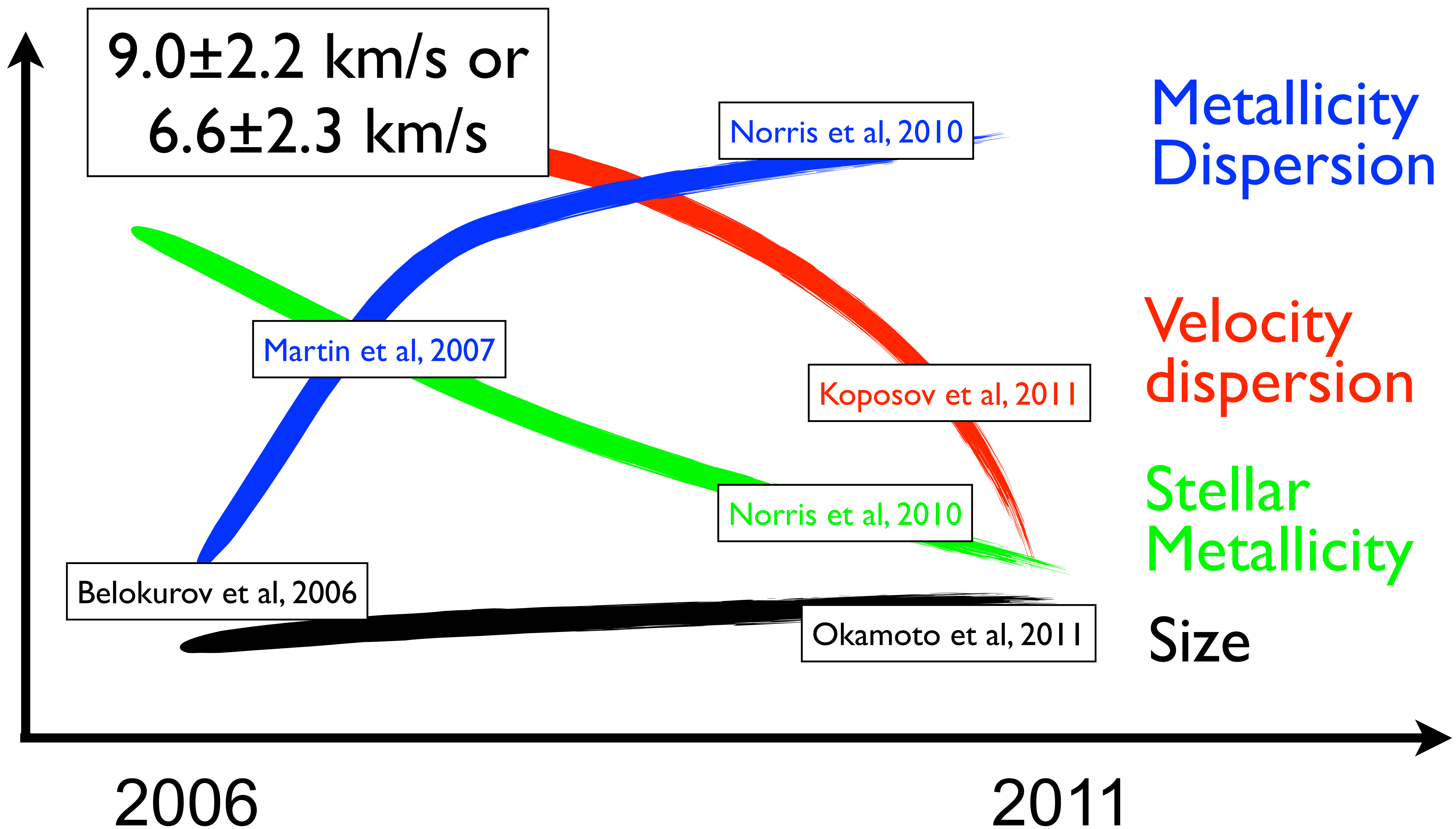

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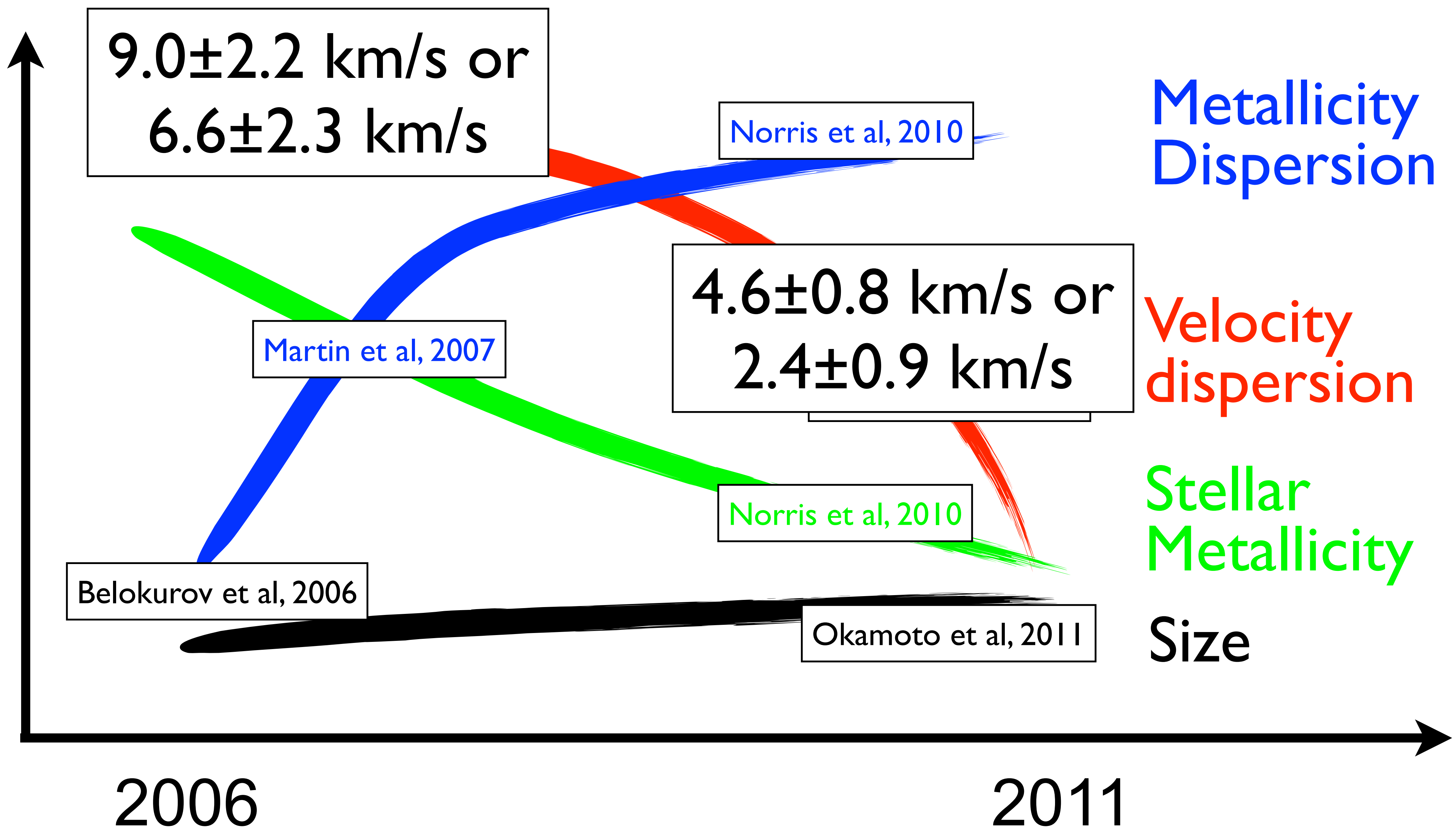
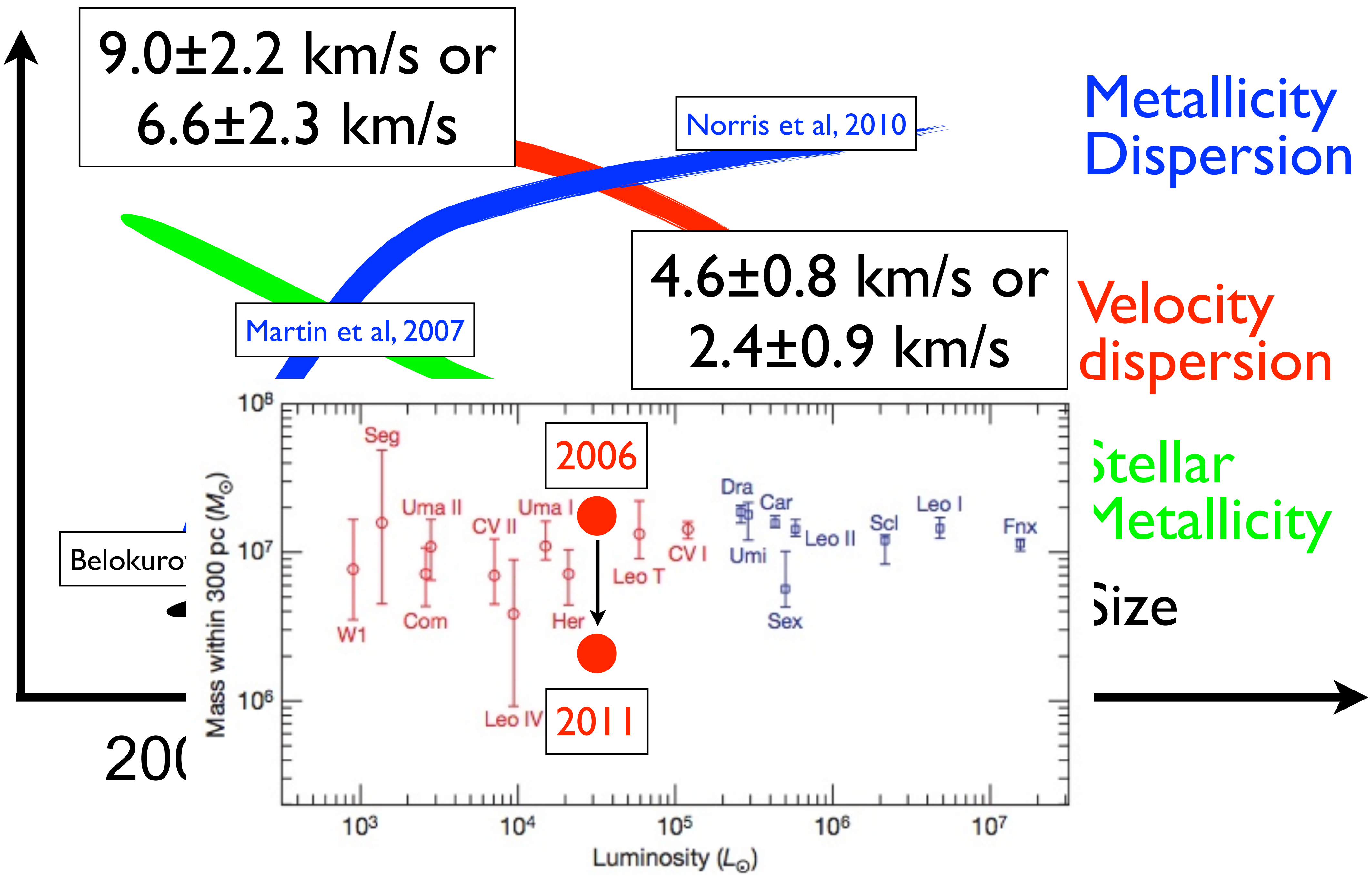


A Word of Caution: “Evolution” of Boötes I



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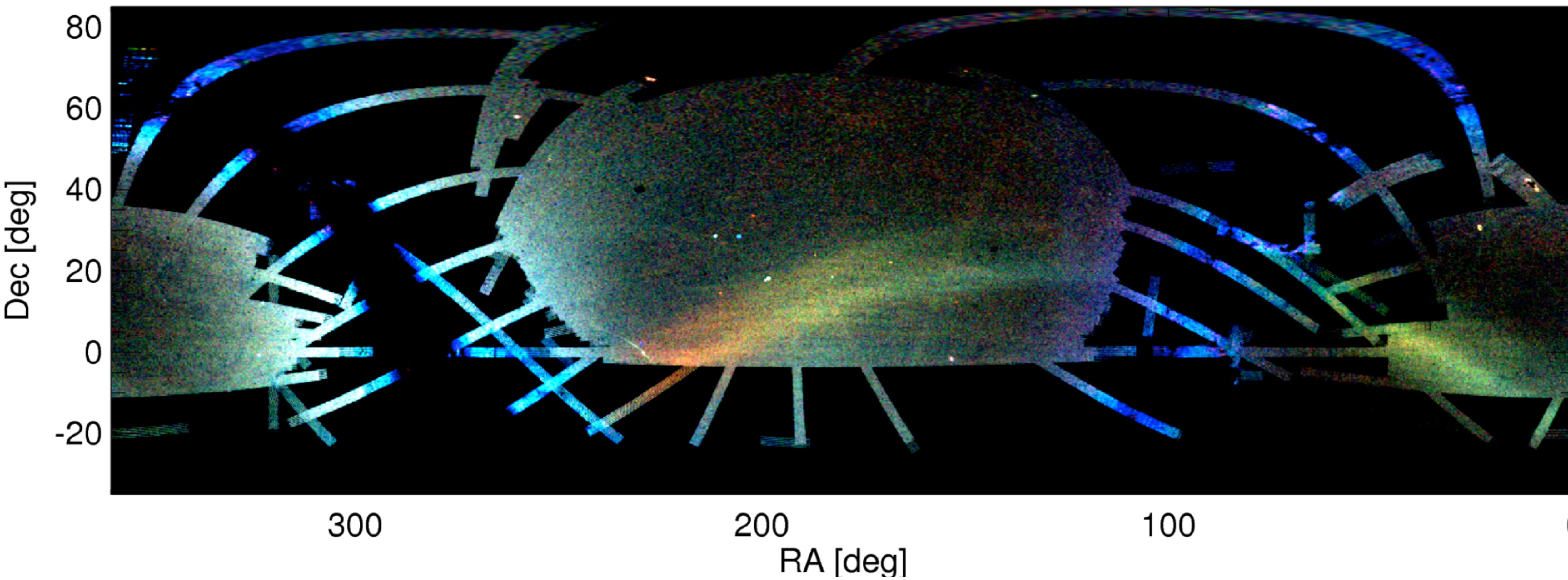
Ultra Mega Faints and the Stellar Halo Substructure



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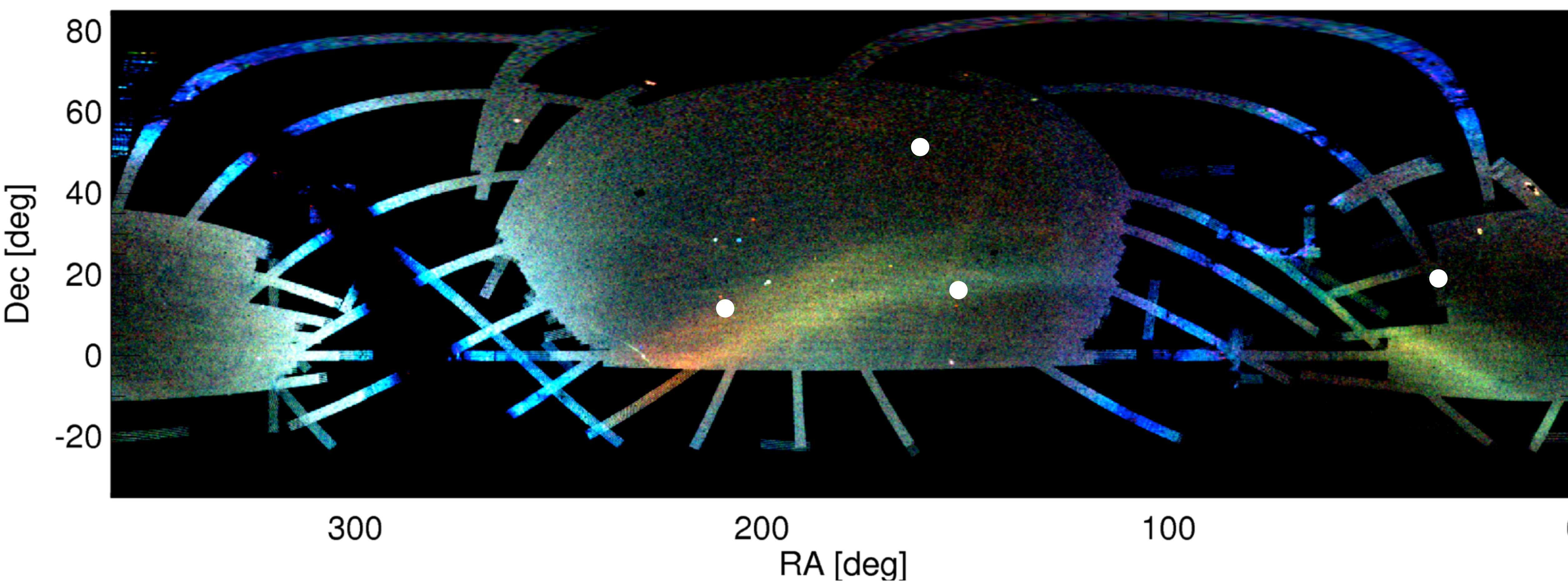
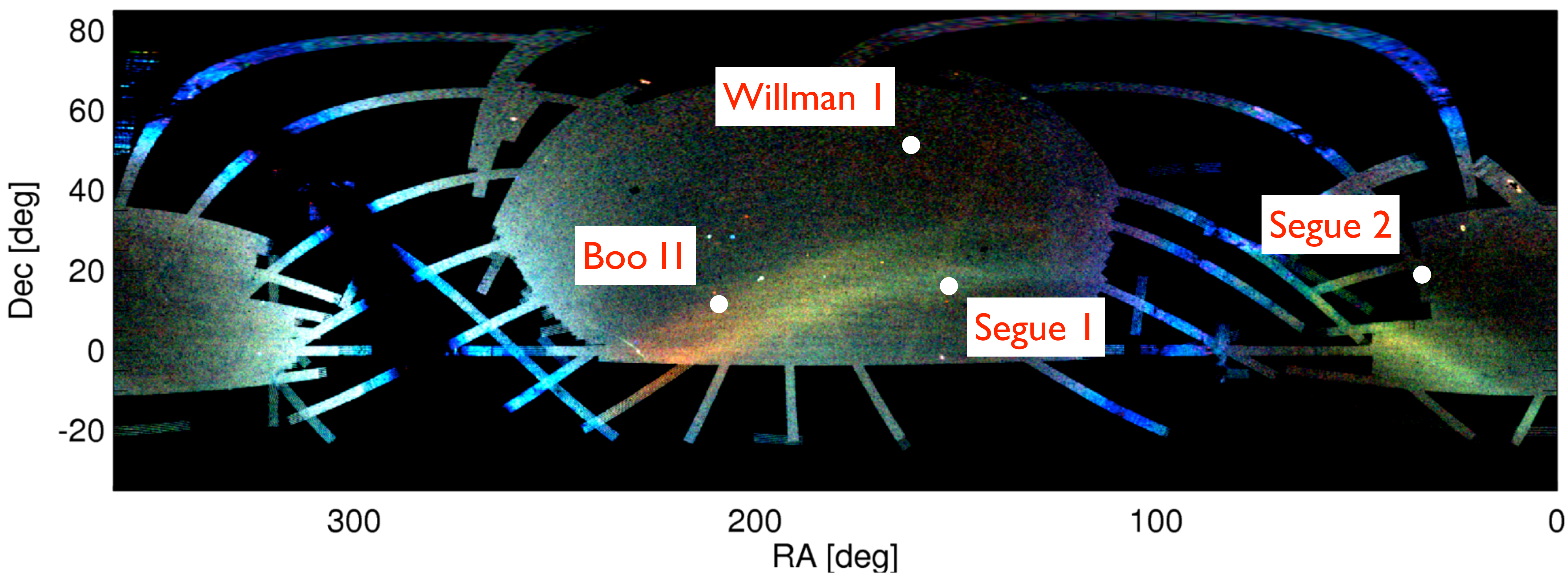
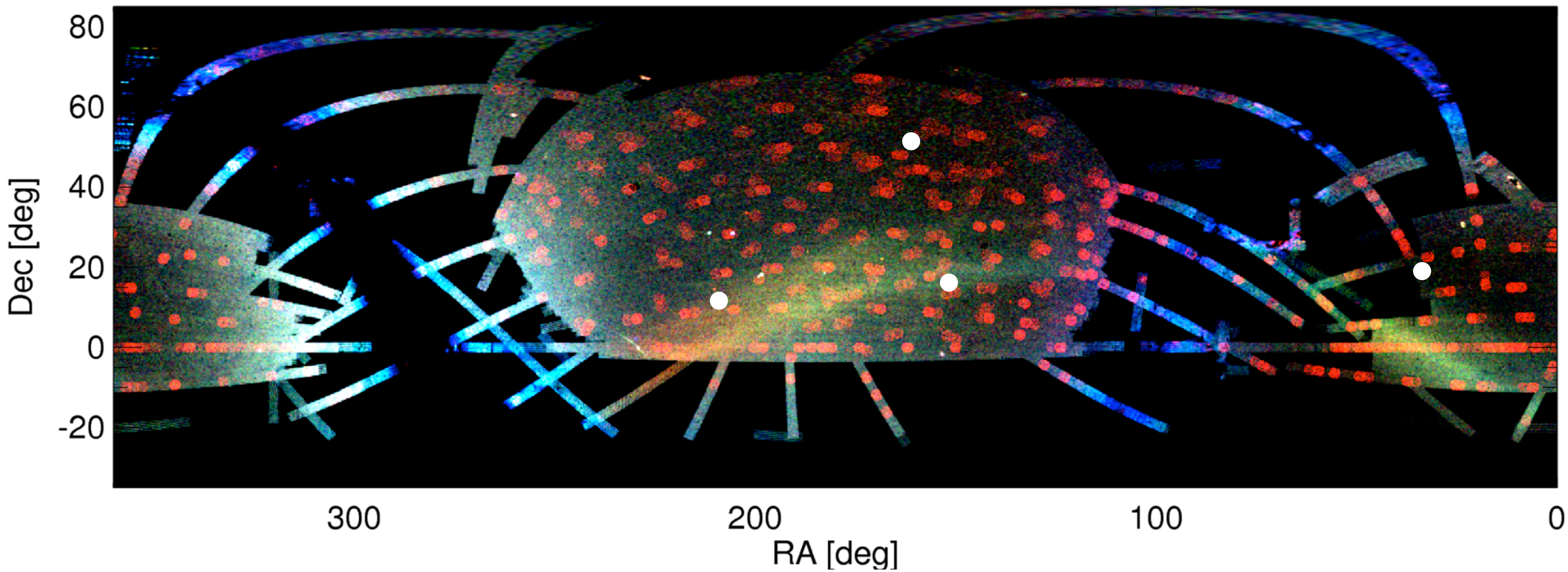


Ultra Mega Faints and the Stellar Halo Substructure



SDSS Stellar Spectra



Willman 1

The Astronomical Journal, 142:128 (16pp), 2011 October
doi:10.1088/0004-6256/142/4/128

WILLMAN 1—A PROBABLE DWARF GALAXY WITH AN IRREGULAR KINEMATIC DISTRIBUTION

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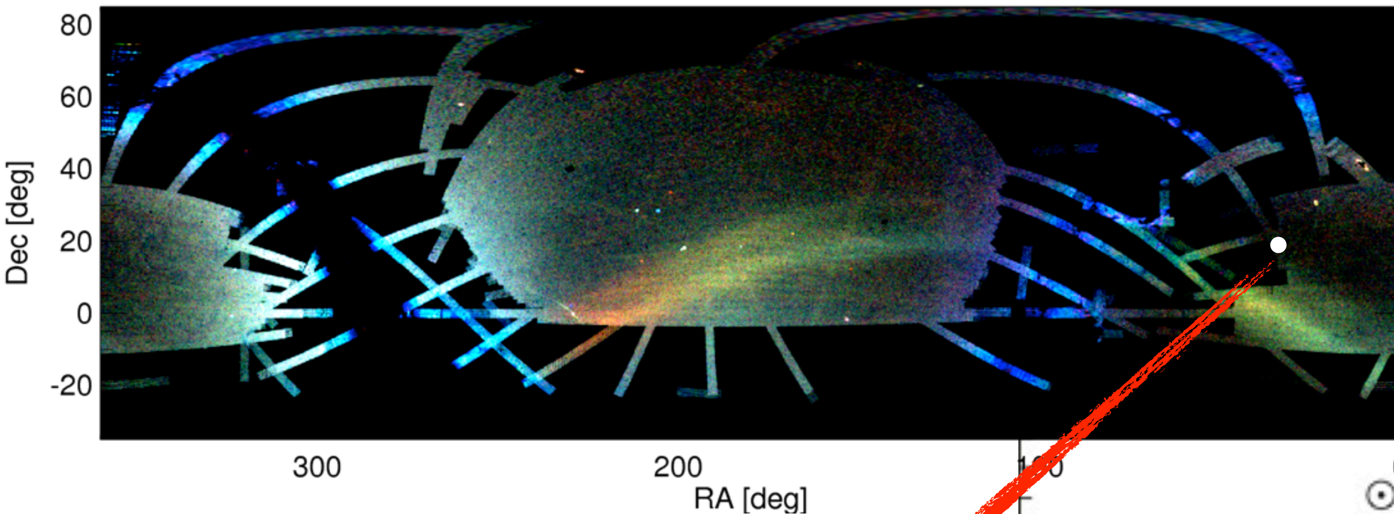
ABSTRACT

We investigate the kinematic properties and stellar population of the Galactic satellite Willman 1 (Wil 1) by combining Keck/DEIMOS spectroscopy with Kitt Peak National Observatory mosaic camera imaging. Wil 1, also known as SDSS J1049+5103, is a nearby, ultra-low luminosity Milky Way companion. This object lies in a region of size–luminosity space ($M_V \sim -2$ mag, $d \sim 38$ kpc, $r_{\rm half} \sim 20$ pc) also occupied by the Galactic satellites Boötes II and Segue 1 and 2, but no other known old stellar system. We use kinematic and color–magnitude criteria to identify 45 stars as possible members of Wil 1. With a systemic velocity of $v_{\rm helio} = -12.8 \pm 1.0$ km s^{-1}, Wil 1 stars have velocities similar to those of foreground Milky Way stars. Informed by Monte Carlo simulations, we identify 5 of the 45 candidate member stars as likely foreground contaminants, with a small number possibly remaining at faint apparent magnitudes. These contaminants could have mimicked a large velocity dispersion and abundance spread in previous work. The significant spread in the [Fe/H] of the highly likely Wil 1 red giant branch members ([Fe/H] = -1.73 ± 0.12 and -2.65 ± 0.12) supports the scenario that Wil 1 is an ultra-low luminosity dwarf galaxy, or the remnants thereof, rather than a star cluster. However, Wil 1's innermost stars move with radial velocities offset by 8 km s^{-1} from its outer stars and have a velocity dispersion consistent with 0 km s^{-1}, suggesting that Wil 1 may not be in dynamical equilibrium. The combination of the foreground contamination and unusual kinematic distribution make it difficult to robustly determine the dark matter mass of Wil 1. As a result, X-ray or gamma-ray observations of Wil 1 that attempt to constrain models of particle dark matter using an equilibrium mass model are strongly affected by the systematics in the observations presented here. We conclude that, despite the unusual features in the Wil 1 kinematic distribution, evidence indicates that this object is, or at least once was, a dwarf galaxy.

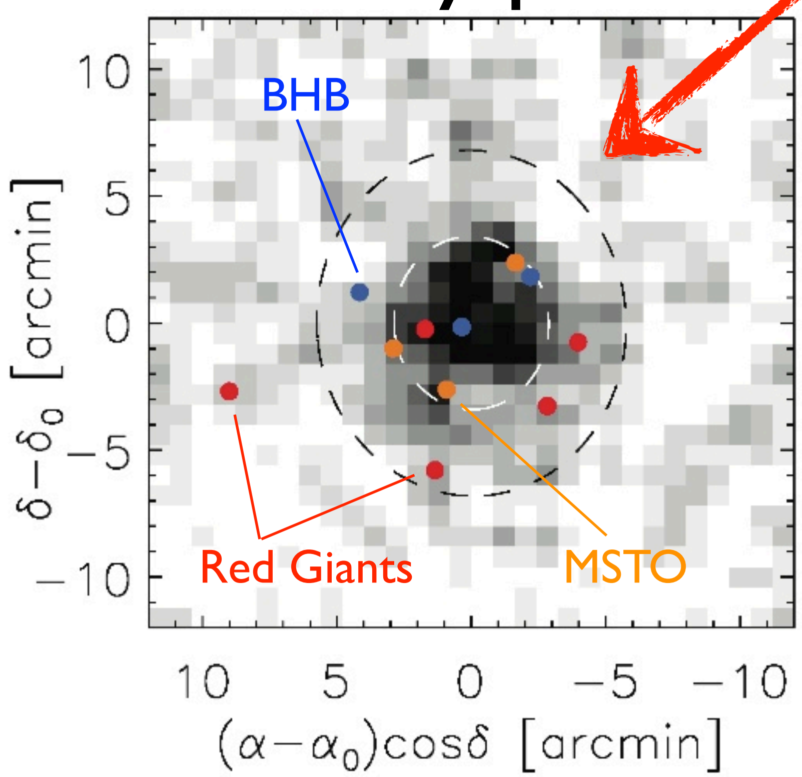
Key words: galaxies: dwarf – galaxies: individual (Willman 1) – galaxies: kinematics and dynamics – galaxies: star clusters: general

Online-only material: color figures

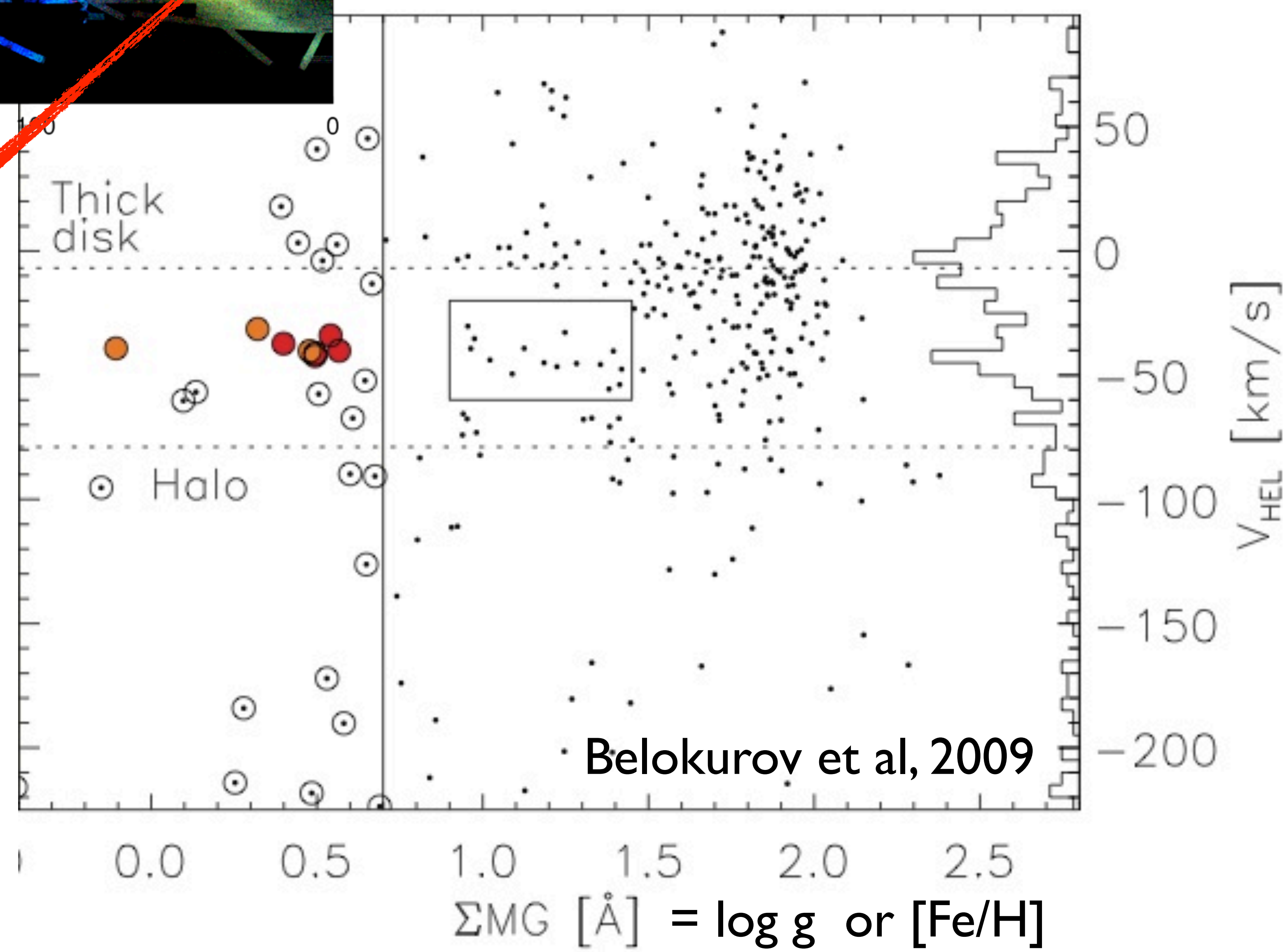
Segue 2



Density profile

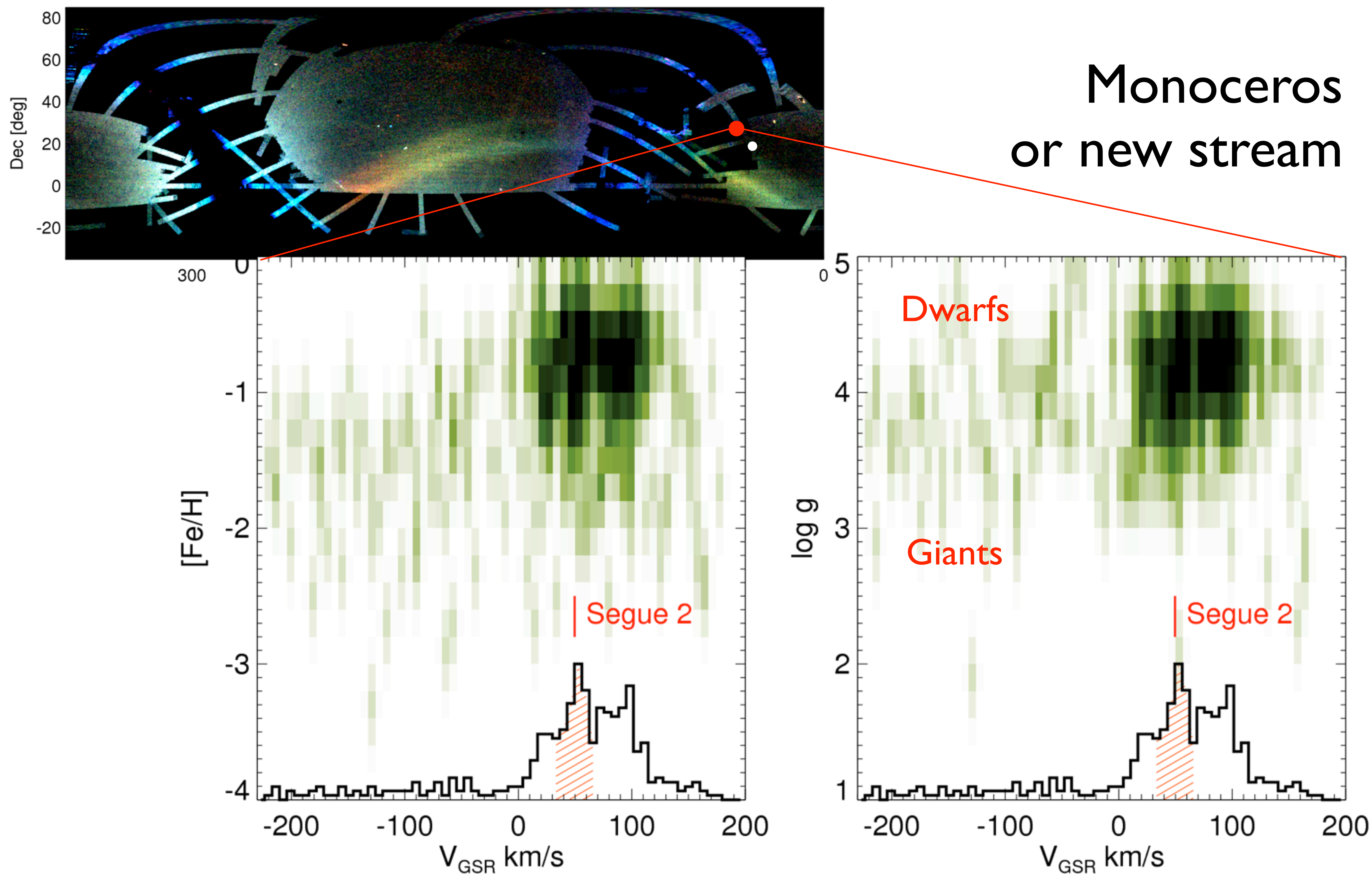


Kinematics



Stream Around Segue 2

Monoceros
or new stream



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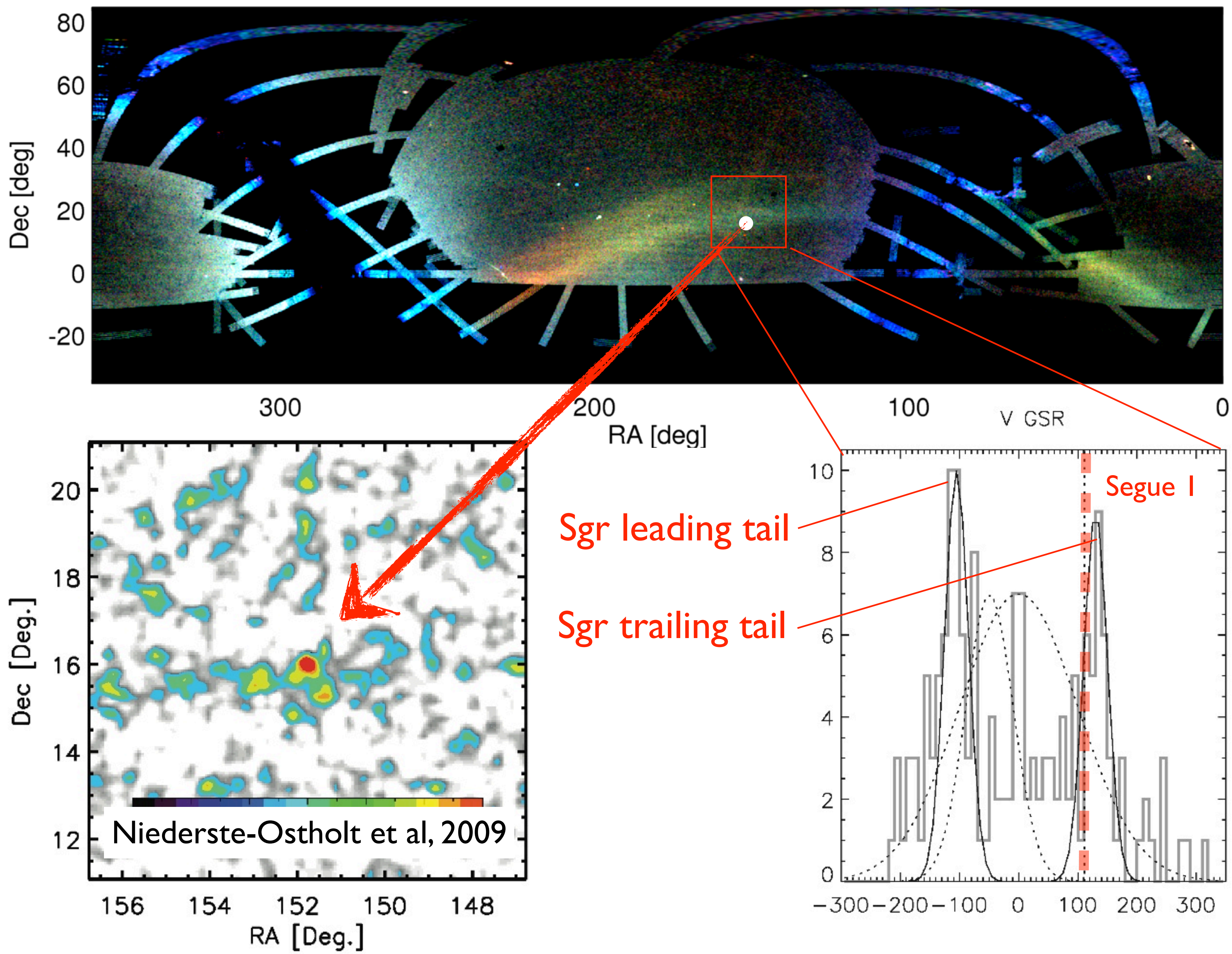
Segue 1



80
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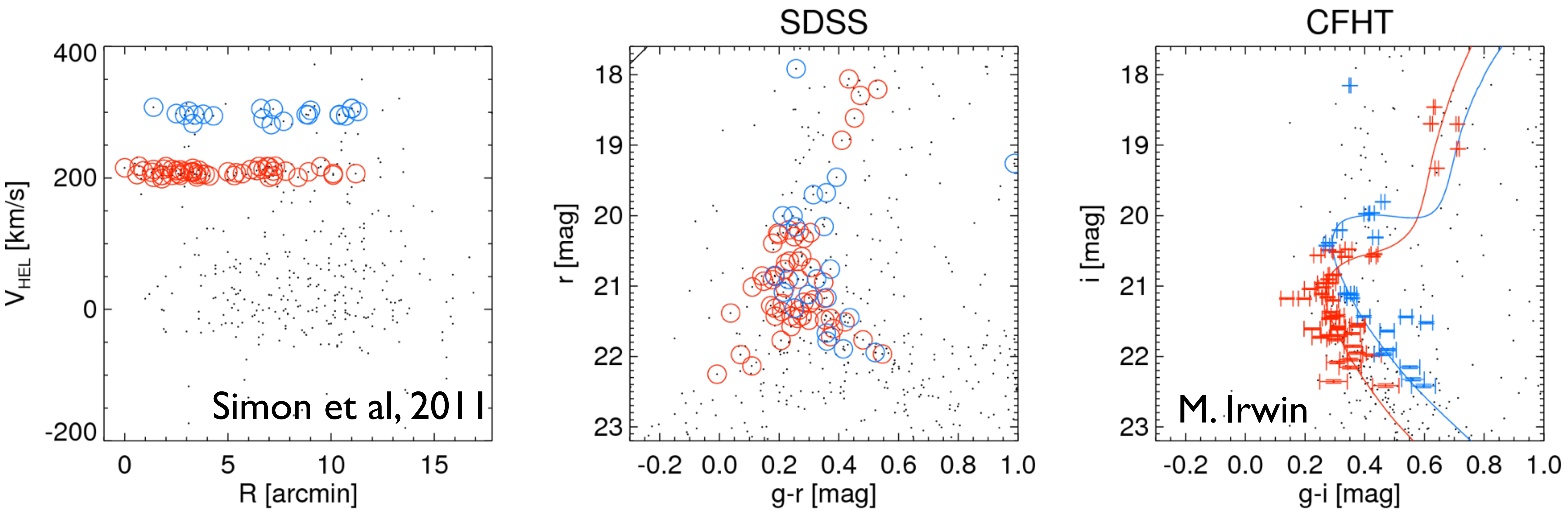
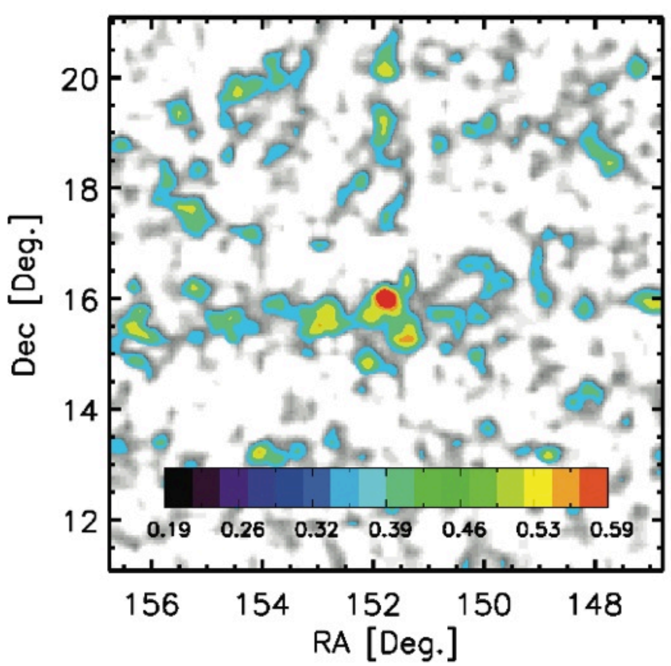
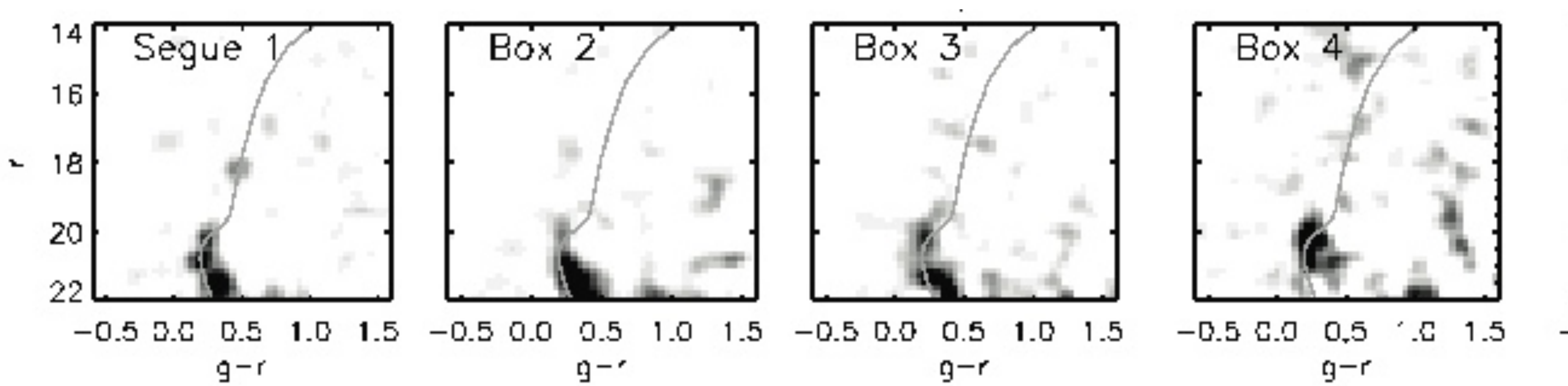
Dec [deg]
300
200
100
0
RA [deg]
V GSR
20
18
16
14
12
Dec [Deg.]
156
154
152
150
148
RA [Deg.]
Niederste-Ostholt et al, 2009
Sgr leading tail
Sgr trailing tail
Segue 1
10
8
6
4
2
0
−300 −200 −100 0 100 200 300

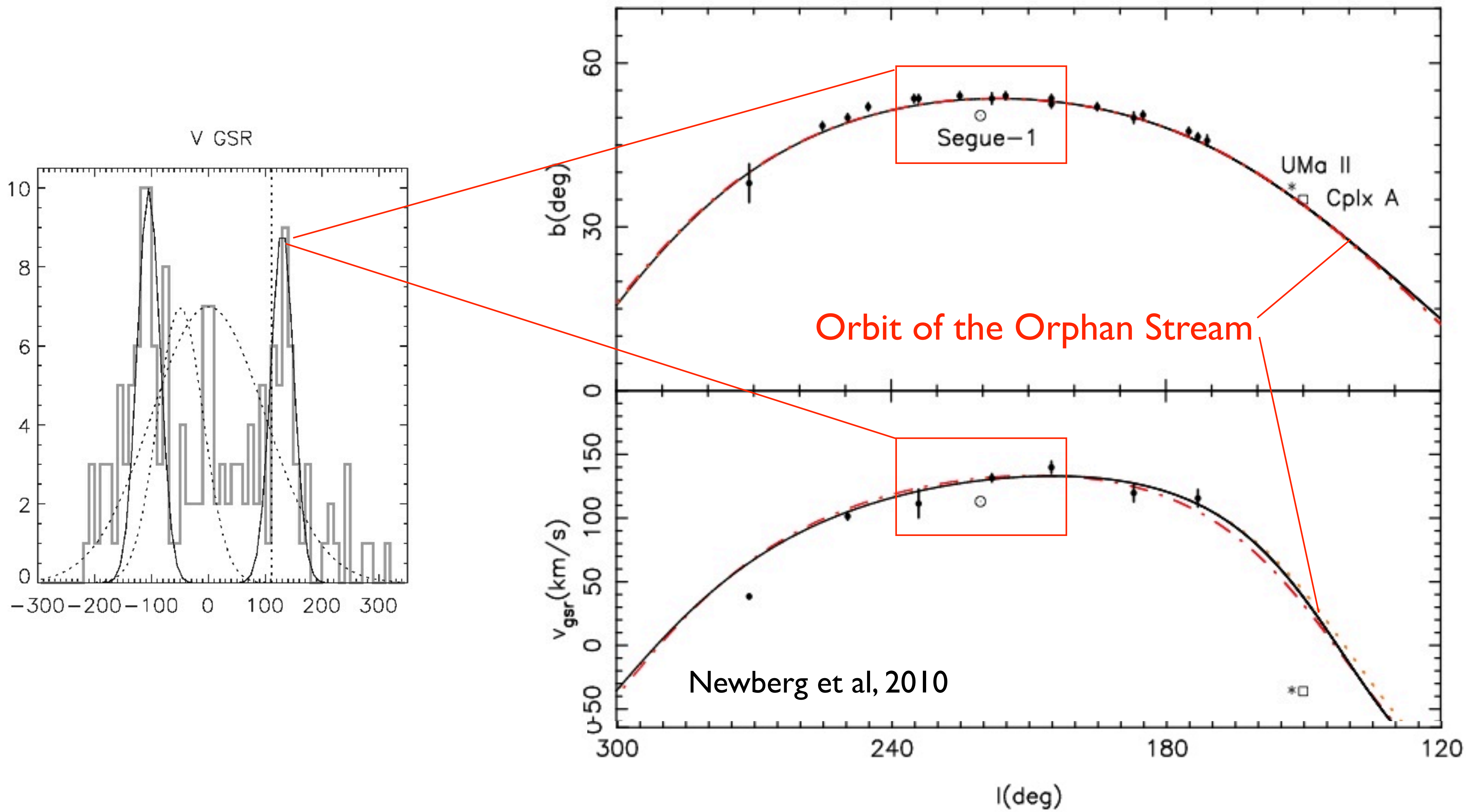
"300 km/s" Stream



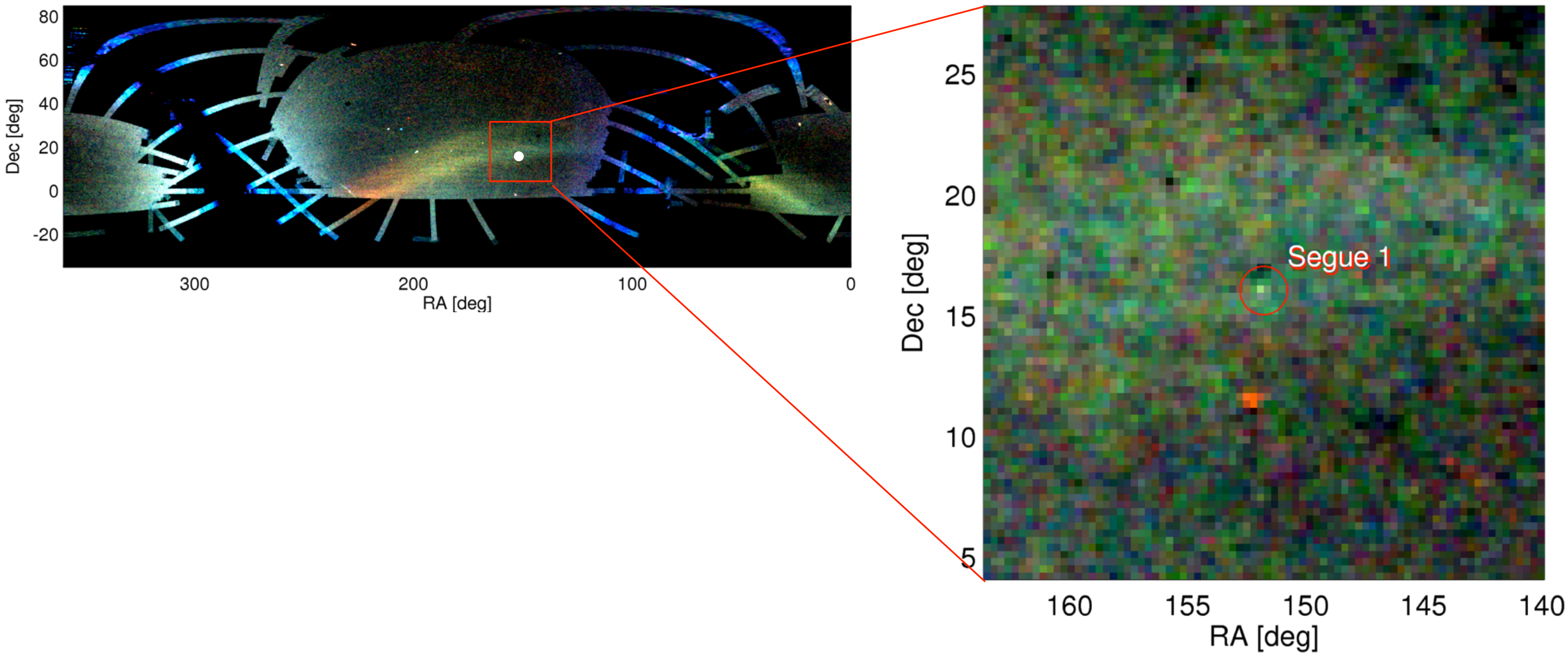




Kinematic Evidence of a Stream Nearby



Kinematic Connection Between Orphan & Segue 1



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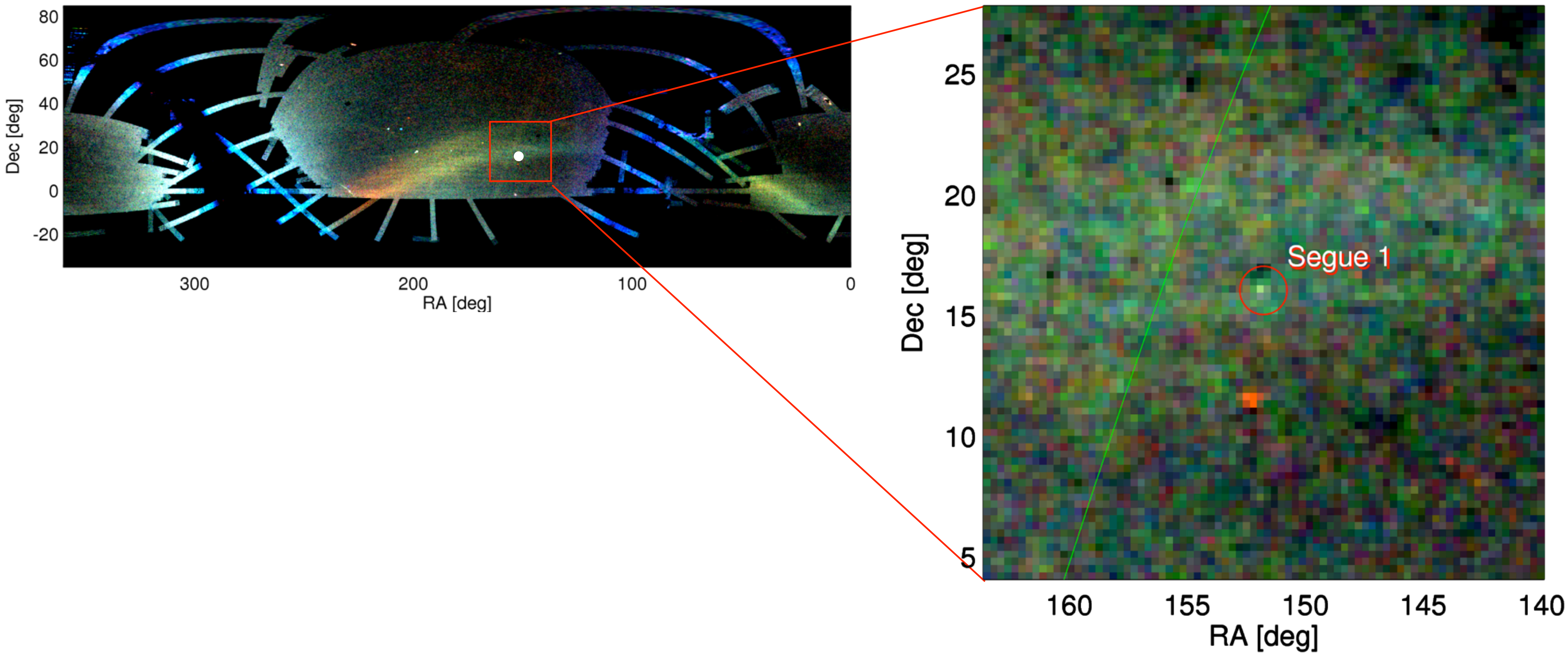
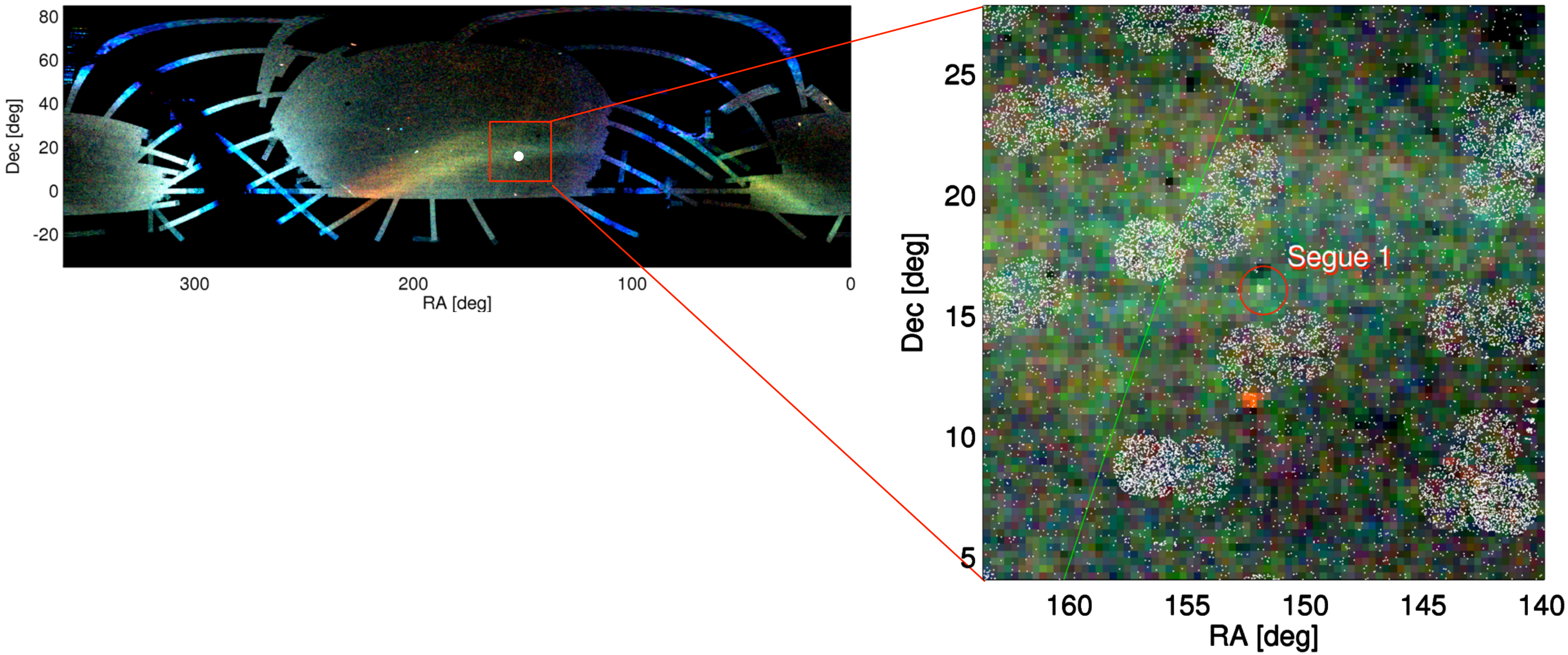
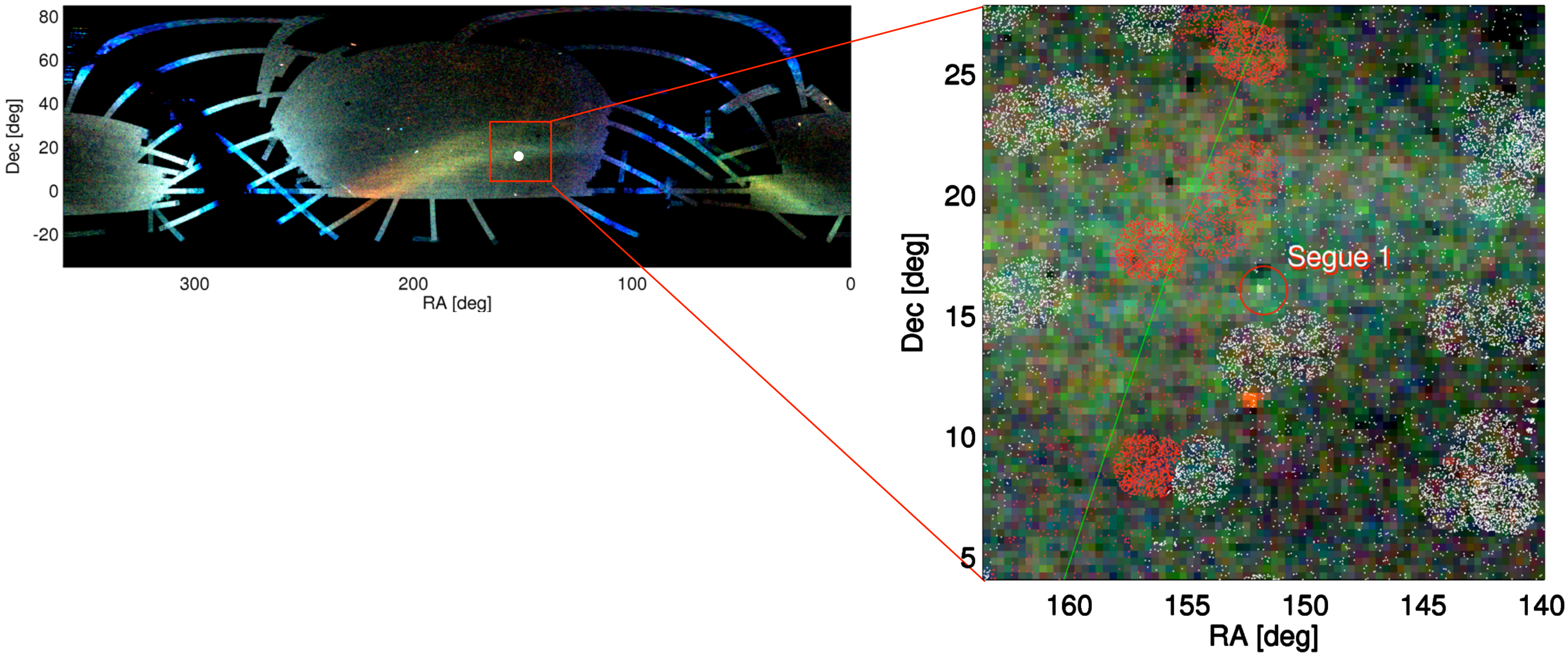


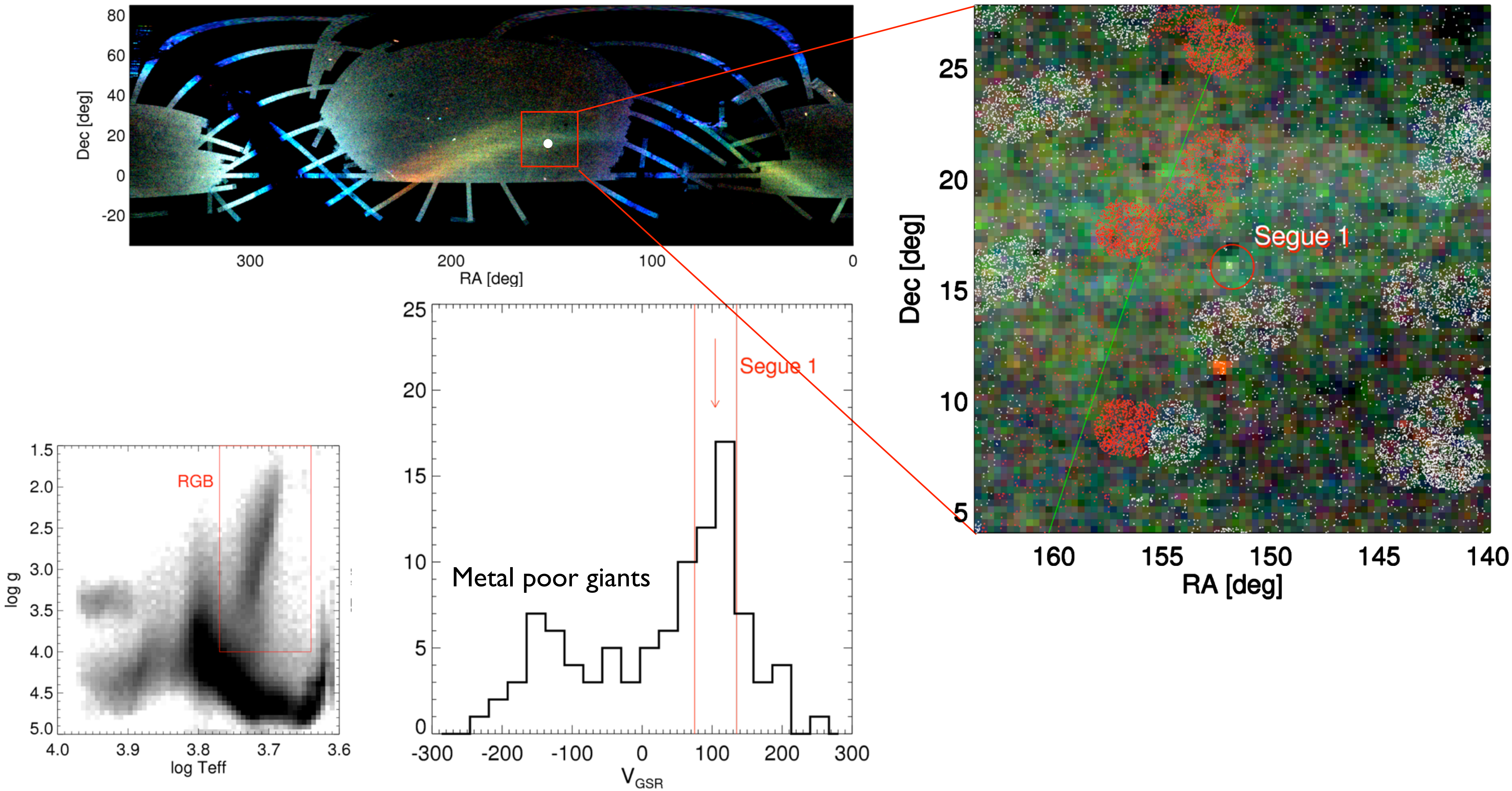
Kinematic Connection Between Orphan & Segue 1



Kinematic Connection Between Orphan & Segue 1



Kinematic Connection Between Orphan & Segue 1



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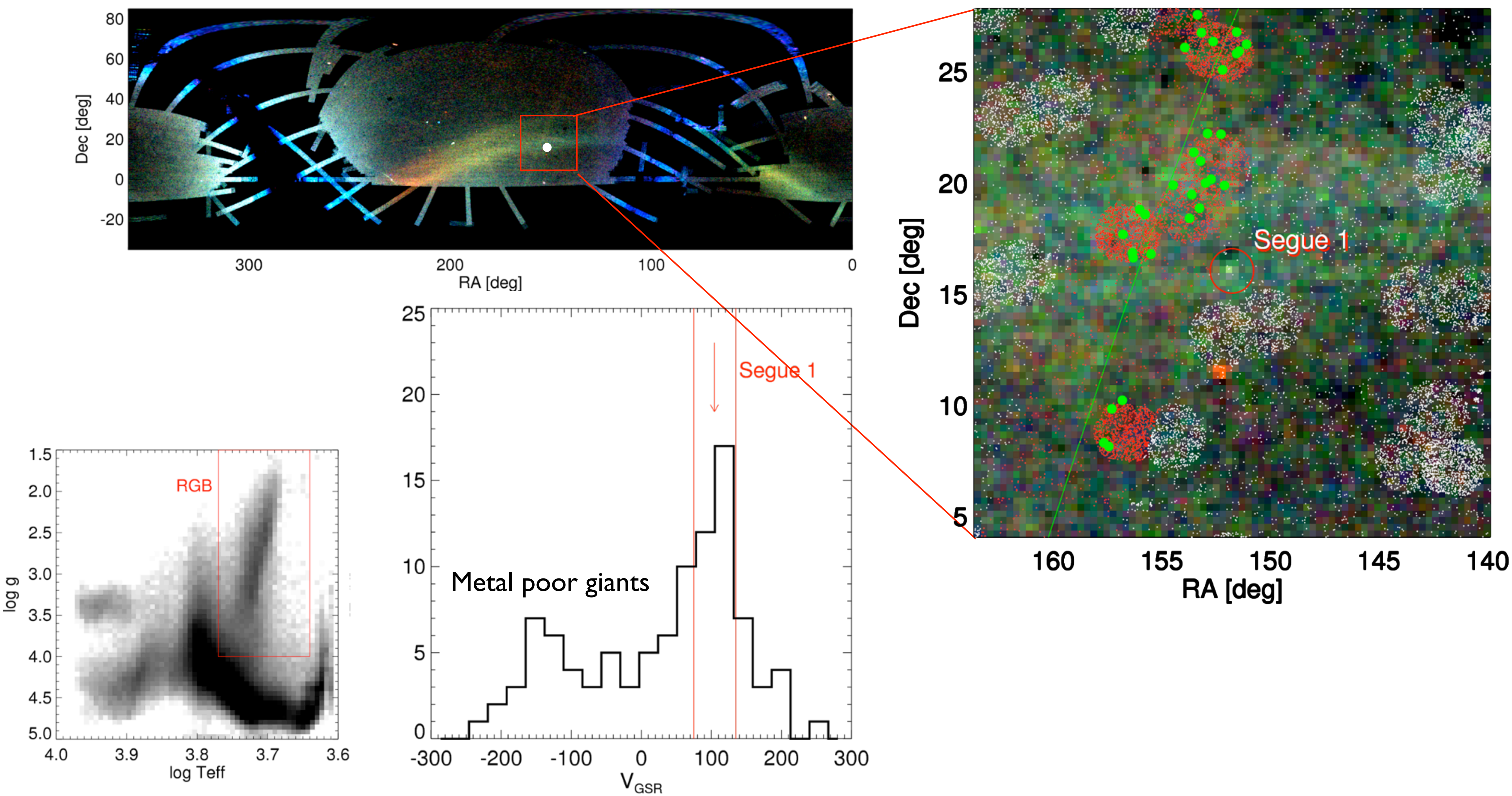
Kinematic Connection Between Orphan & Segue 1



Summary of Observations

All four faintest satellites appear either tidally stirred/disrupting (Willman 1) or living inside (in the vicinity) of larger stellar streams (Segue 1, Segue 2, Boo II).

Conclusions

Conclusions

Optimist: Milky Way stellar halo is all substructure, and so chance co-occurrences of streams and satellites are highly probable

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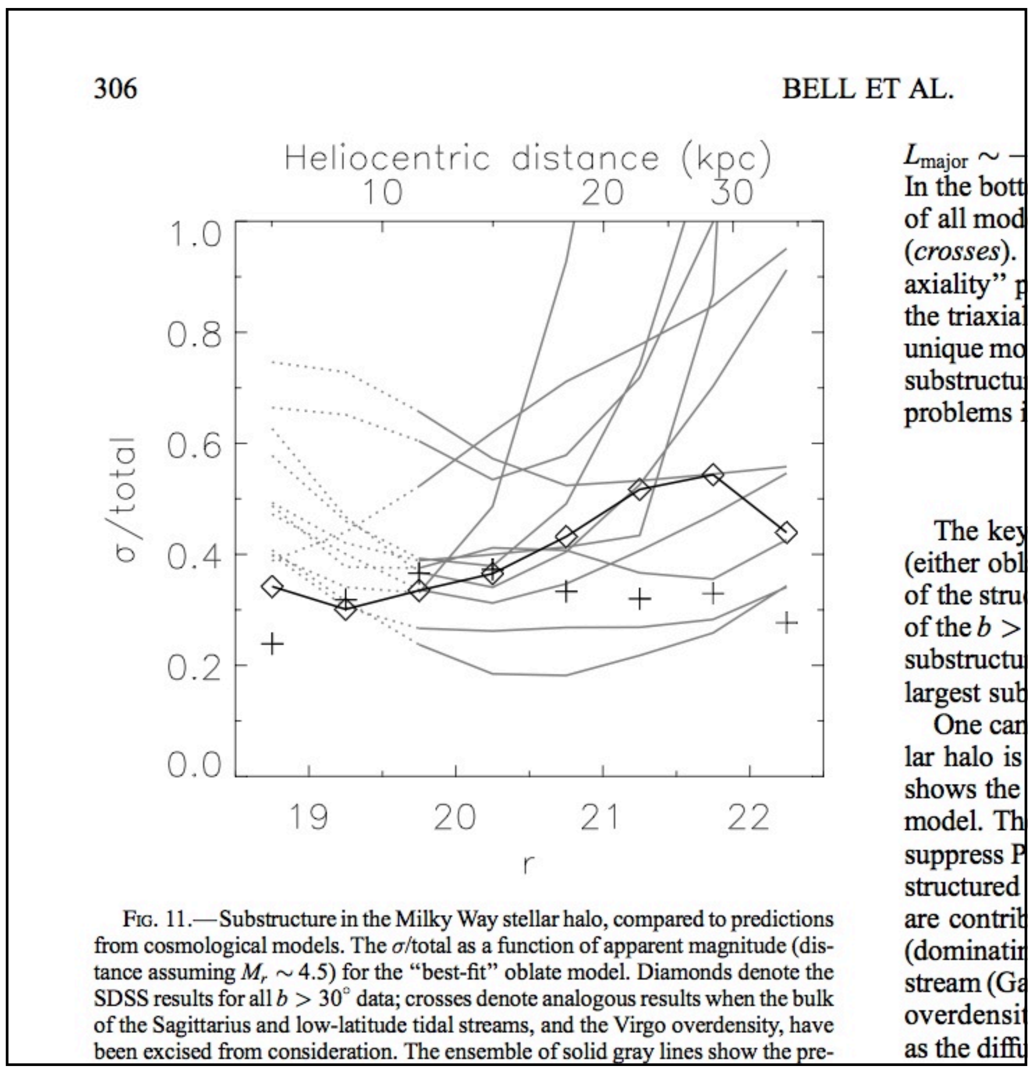

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Fig. 11.—Substructure in the Milky Way stellar halo, compared to predictions from cosmological models. The σ/total as a function of apparent magnitude (distance assuming $M_r \sim 4.5$) for the "best-fit" oblate model. Diamonds denote the SDSS results for all $b > 30°$ data; crosses denote analogous results when the bulk of the Sagittarius and low-latitude tidal streams, and the Virgo overdensity, have been excised from consideration. The ensemble of solid gray lines show the pre-

L_{major} ~
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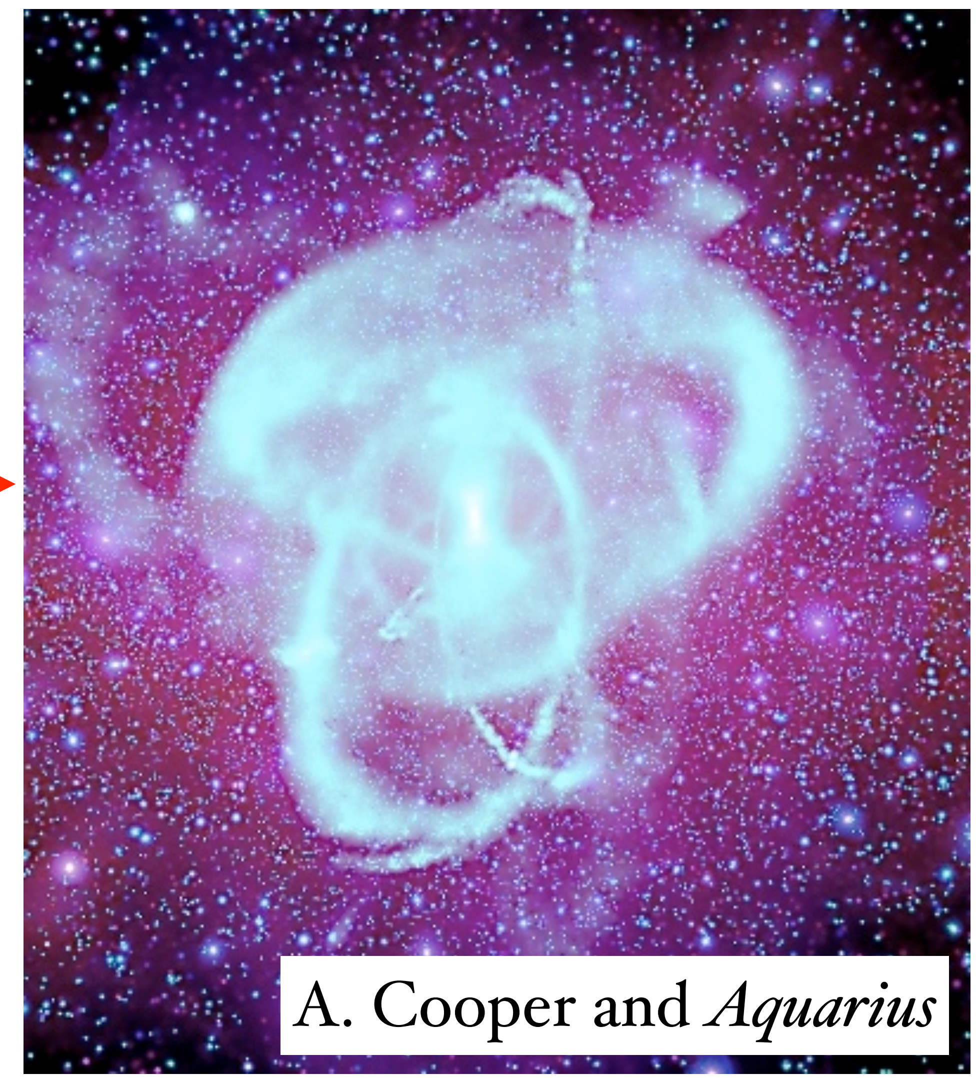
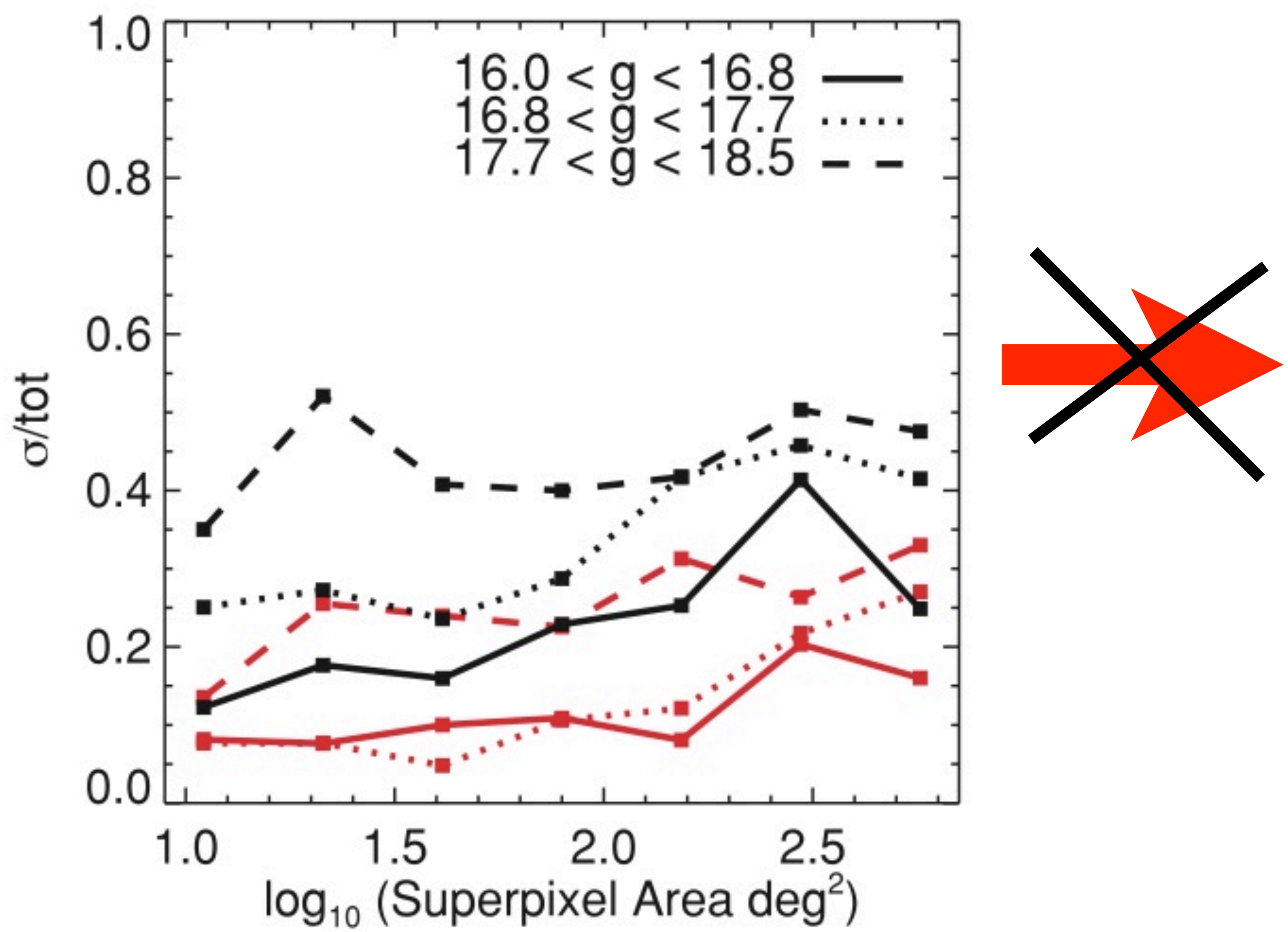
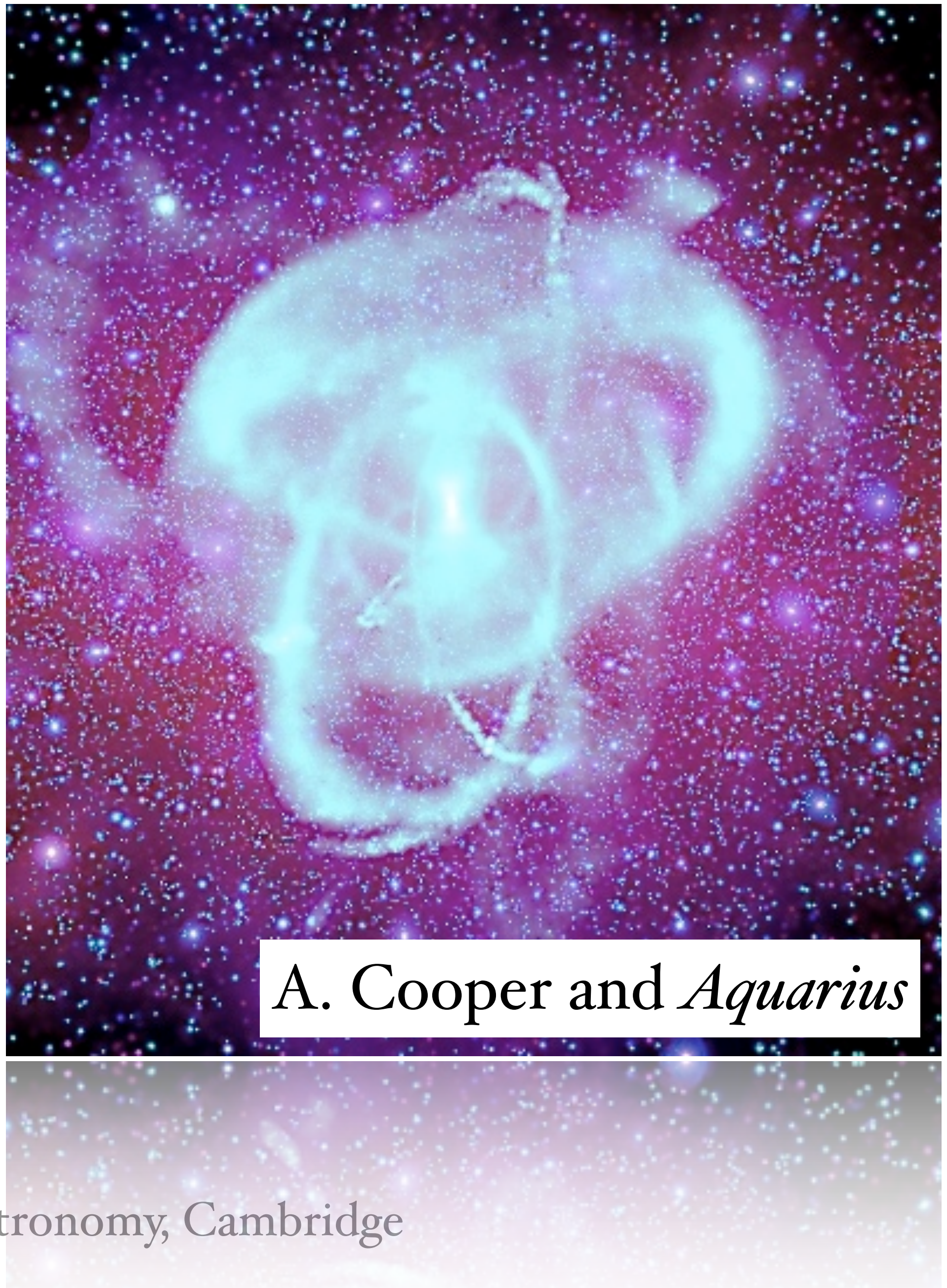


Conclusions

Optimist: Milky Way stellar halo is all substructure, and so chance co-occurrences of streams and satellites are highly probable

Deason et al, 2011





A. Cooper and *Aquarius*

Conclusions

Optimist: Milky Way stellar halo is all substructure, and so chance co-occurrences of streams and satellites are highly probable

or

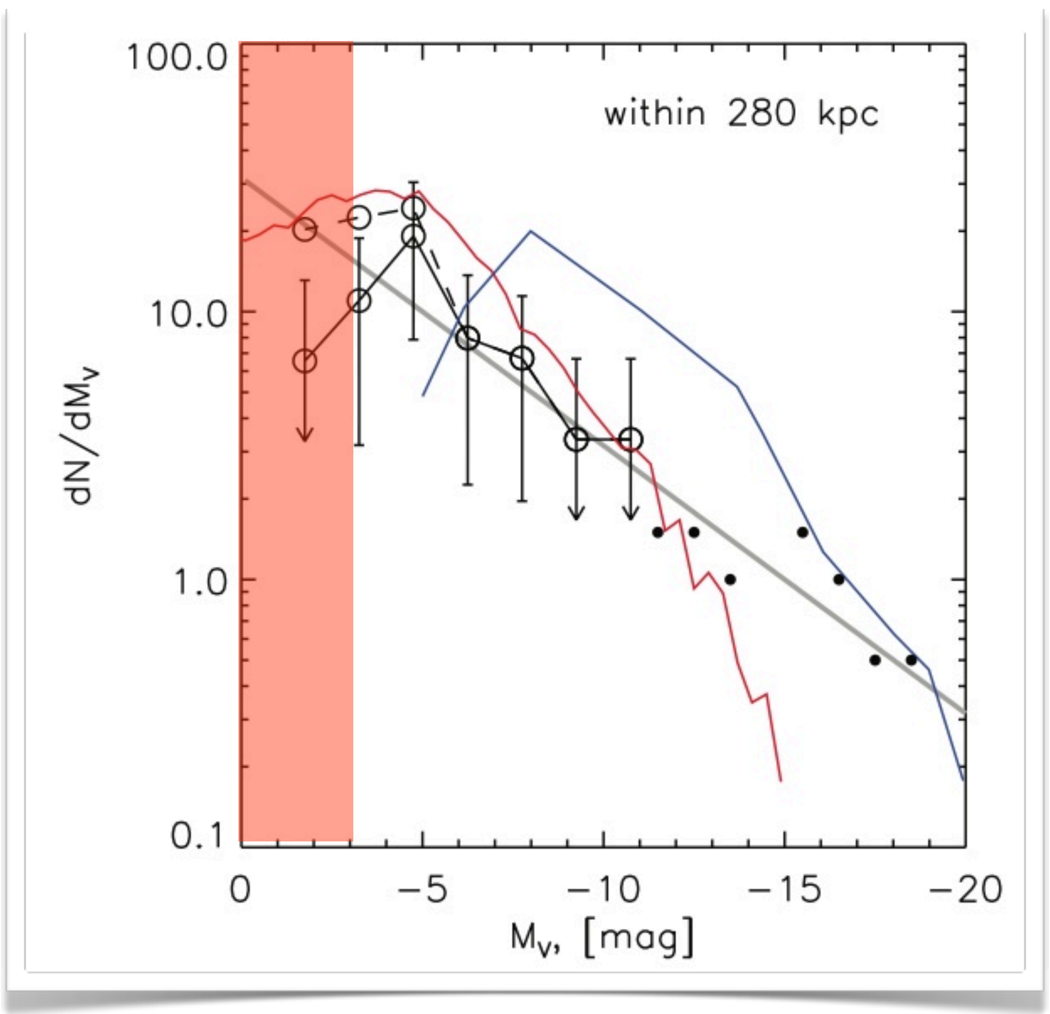
Pessimist: maybe the faintest objects and the neighbouring streams are associated, and hence the nature of these satellites is less certain

Possible Scenarios

Mildly Pessimistic **Unpleasant** **Too Bad**

Conclusions

Mildly Pessimistic Scenario: the faintest objects are surviving satellites of bigger dwarfs which have been destroyed



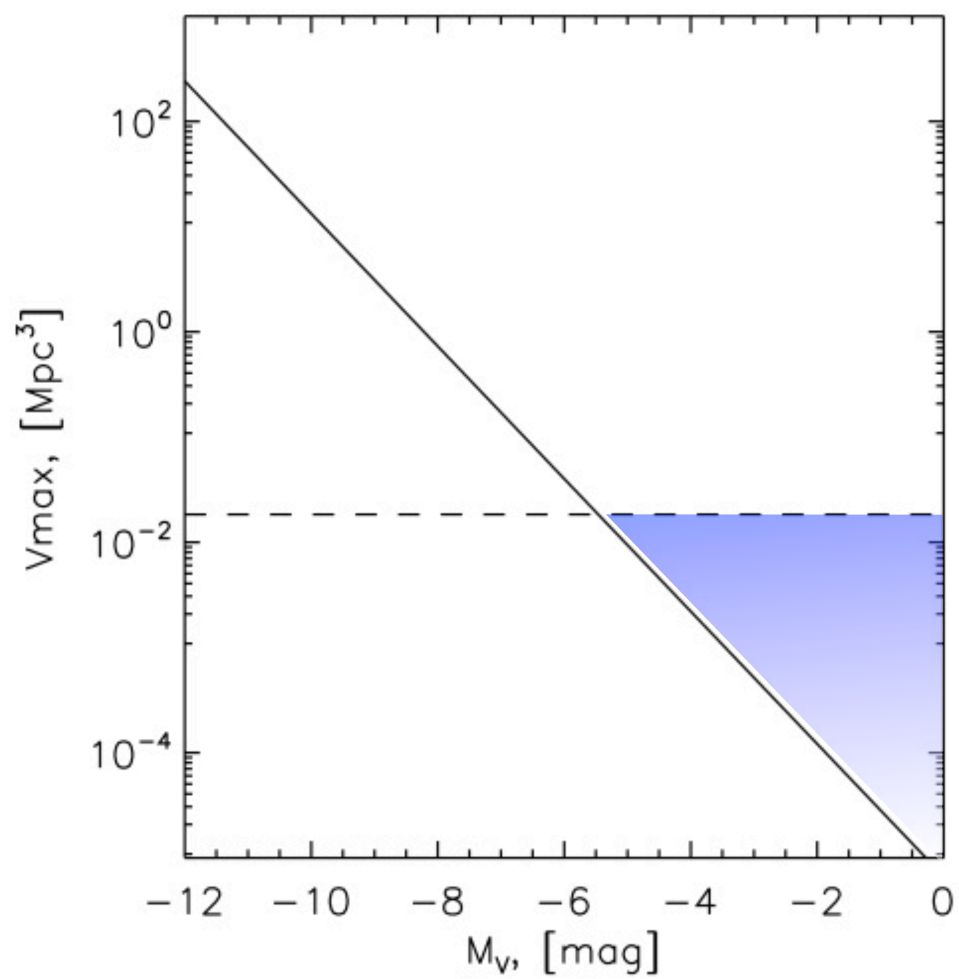
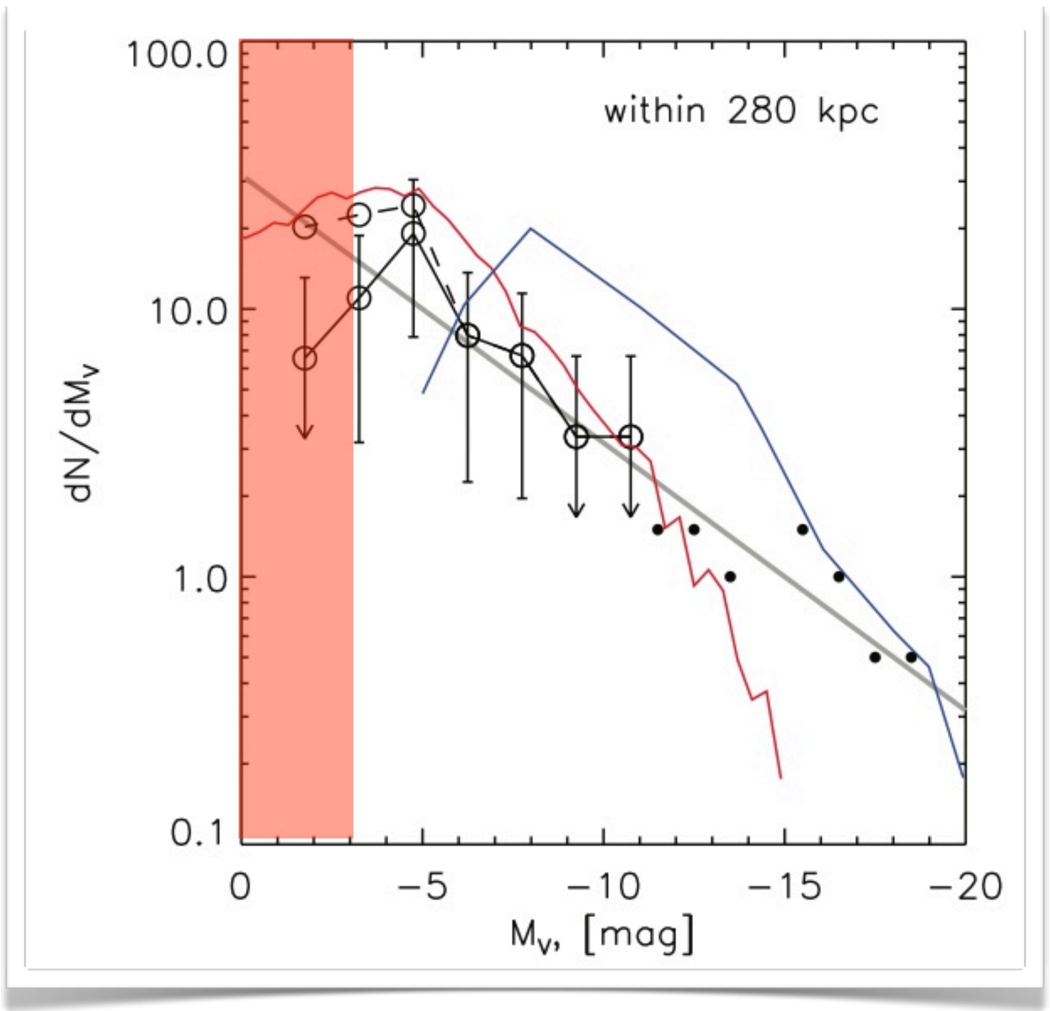
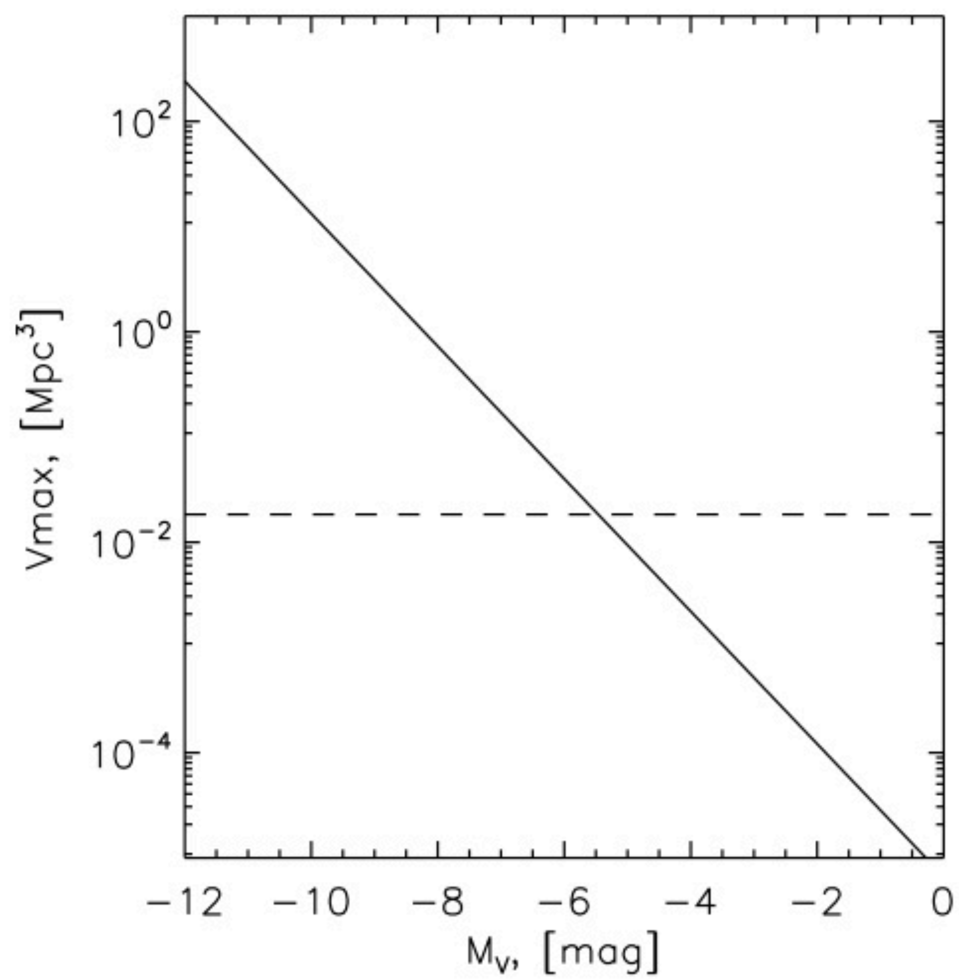


FIG. 13.—Accessible volume within the DR5 footprint for galaxies with different luminosities and surface brightnesses $\mu_{\rm lim}$ and $\mu \lesssim 30$ mag arcsec^{-2} (see Fig. 12). The volume limited by the virial radius (280 kpc) and within DR5 is shown by the dashed line.

Conclusions

Mildly Pessimistic Scenario: the faintest objects are surviving satellites of bigger dwarfs which have been destroyed





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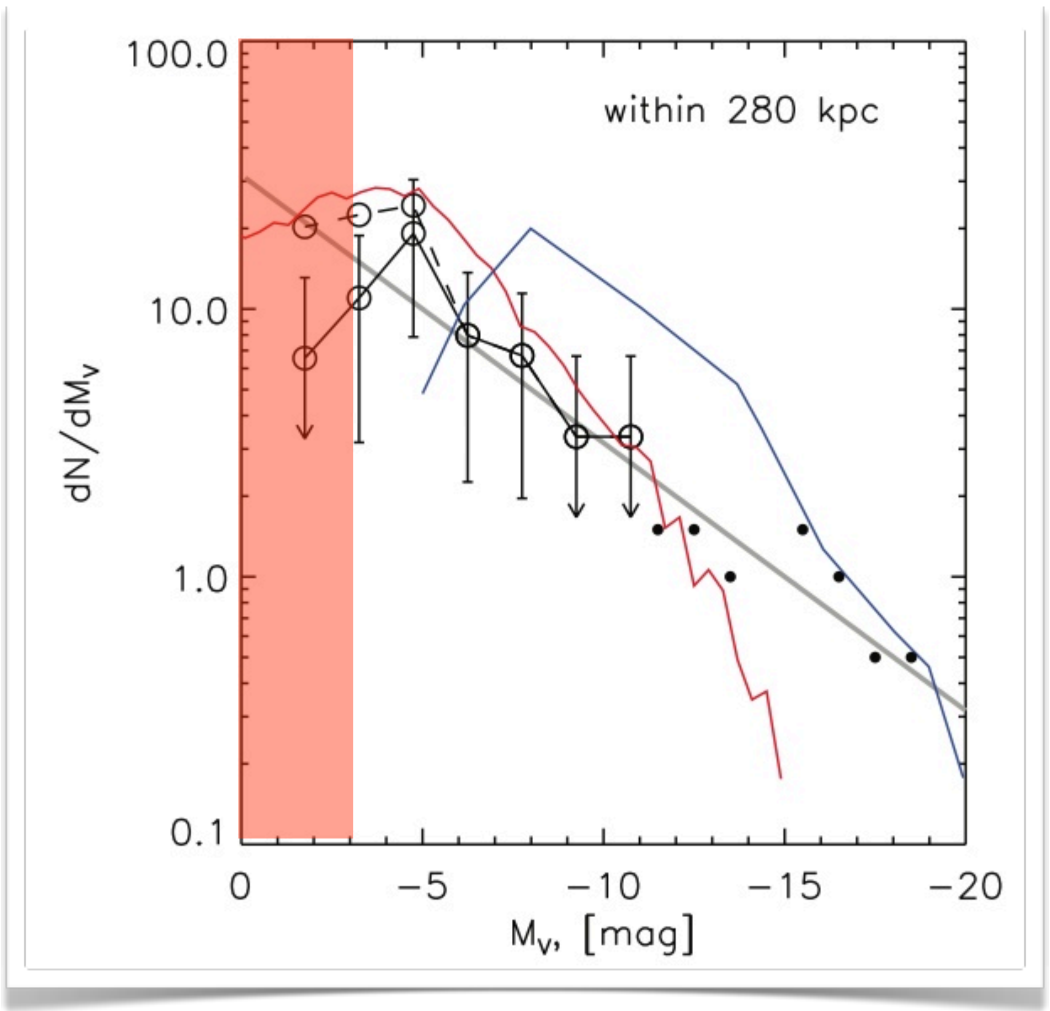

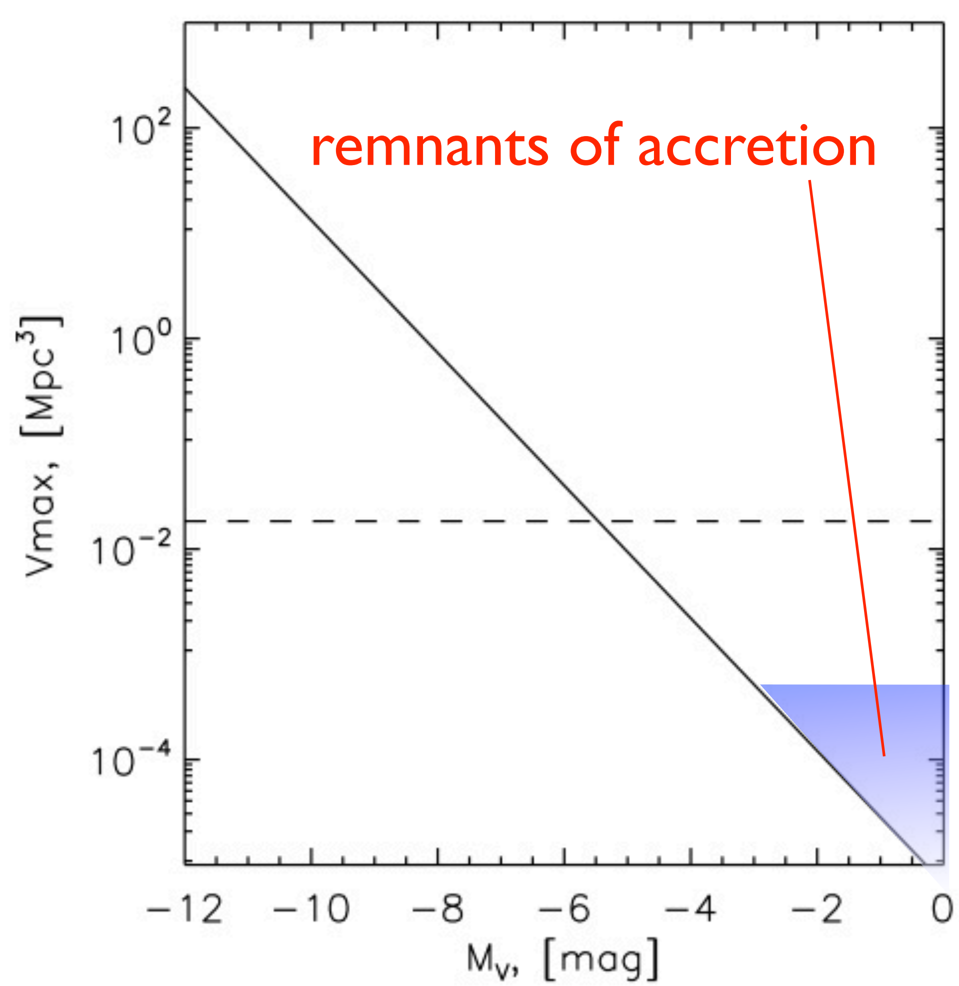

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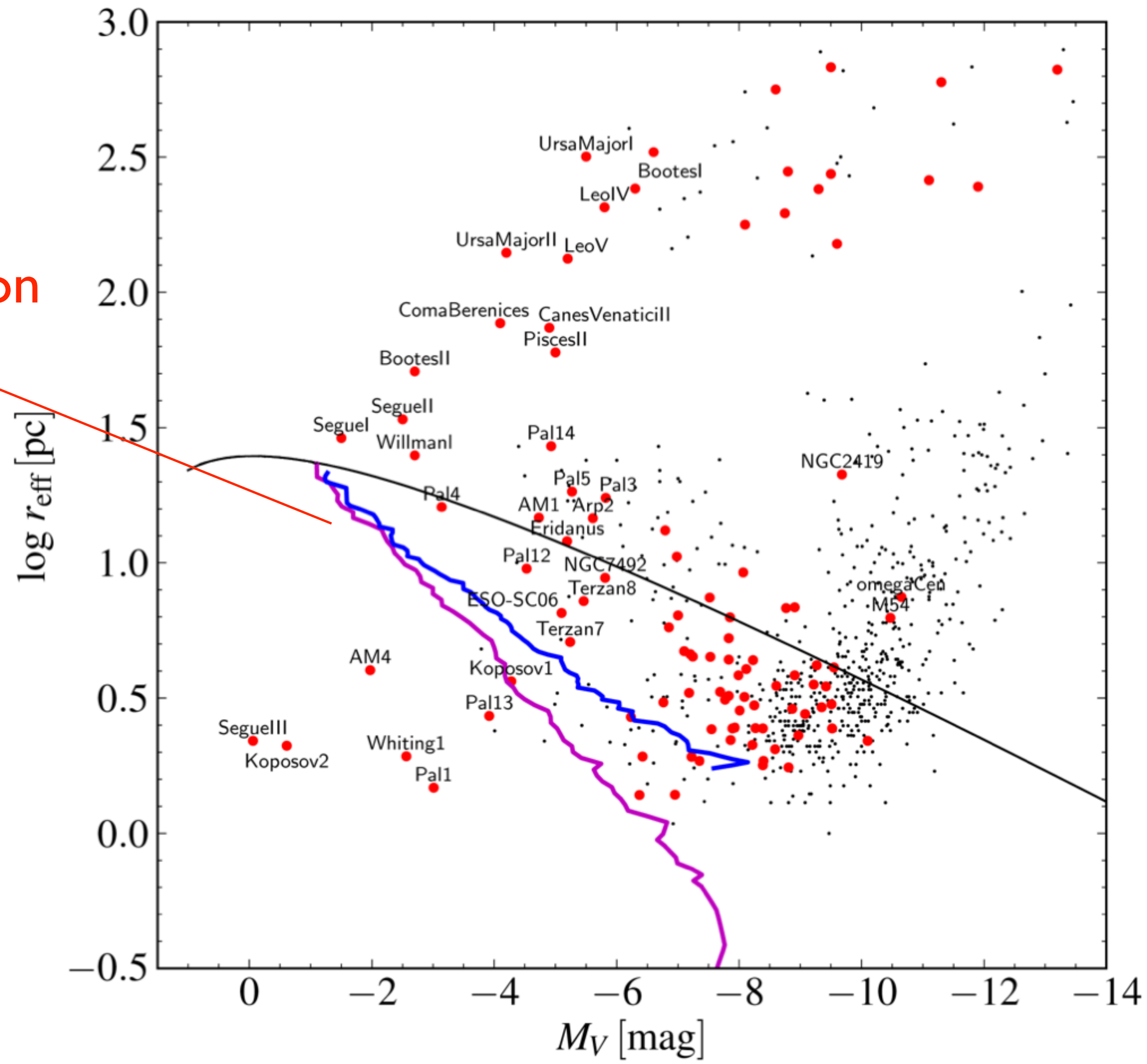
Conclusions

Unpleasant Scenario: spectroscopic samples are polluted and we might have to revise out estimates of dark matter content and/or their metallicity distributions

Conclusions

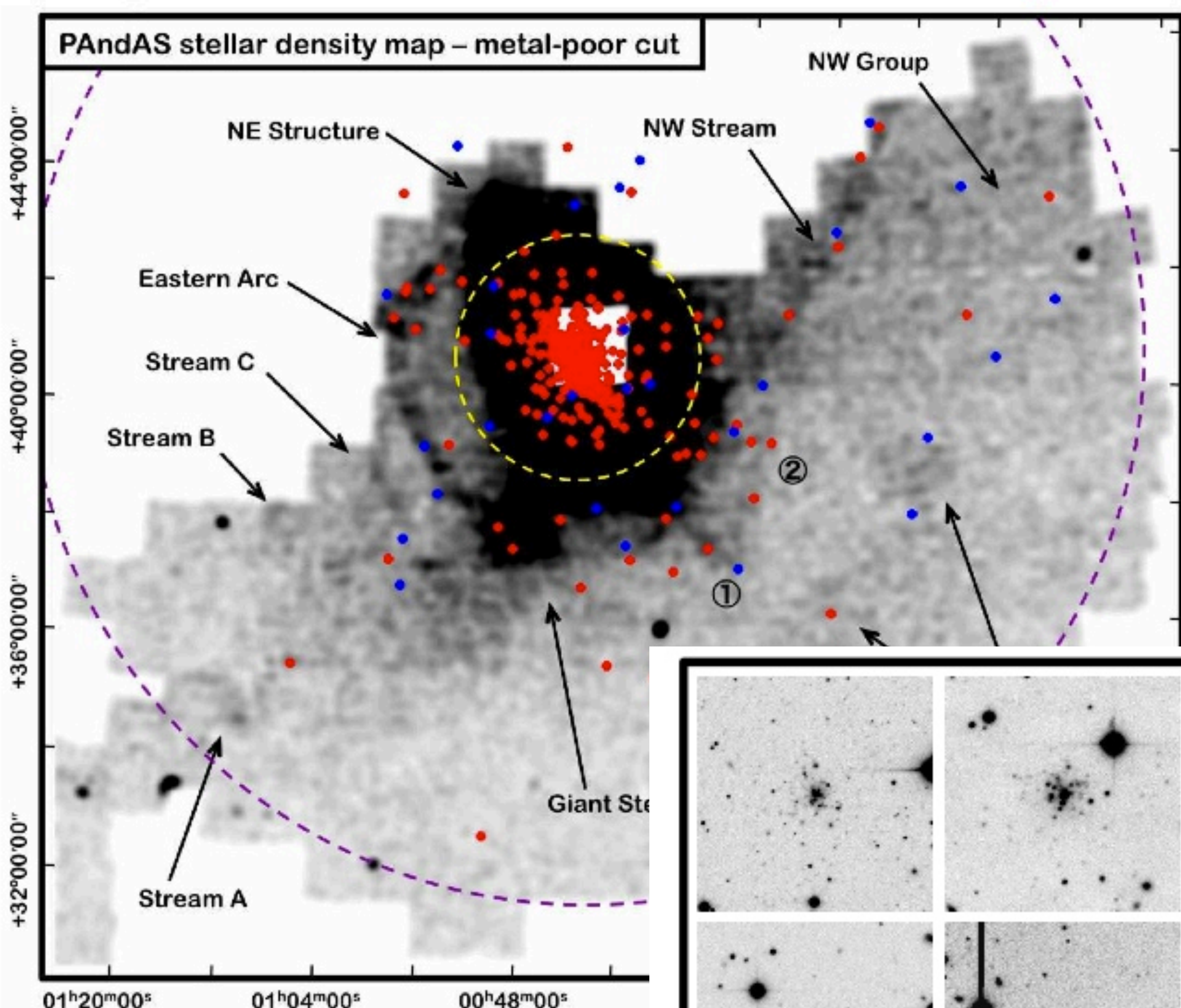
Too Bad: these are star clusters and have zero DM

Star clusters in isolation

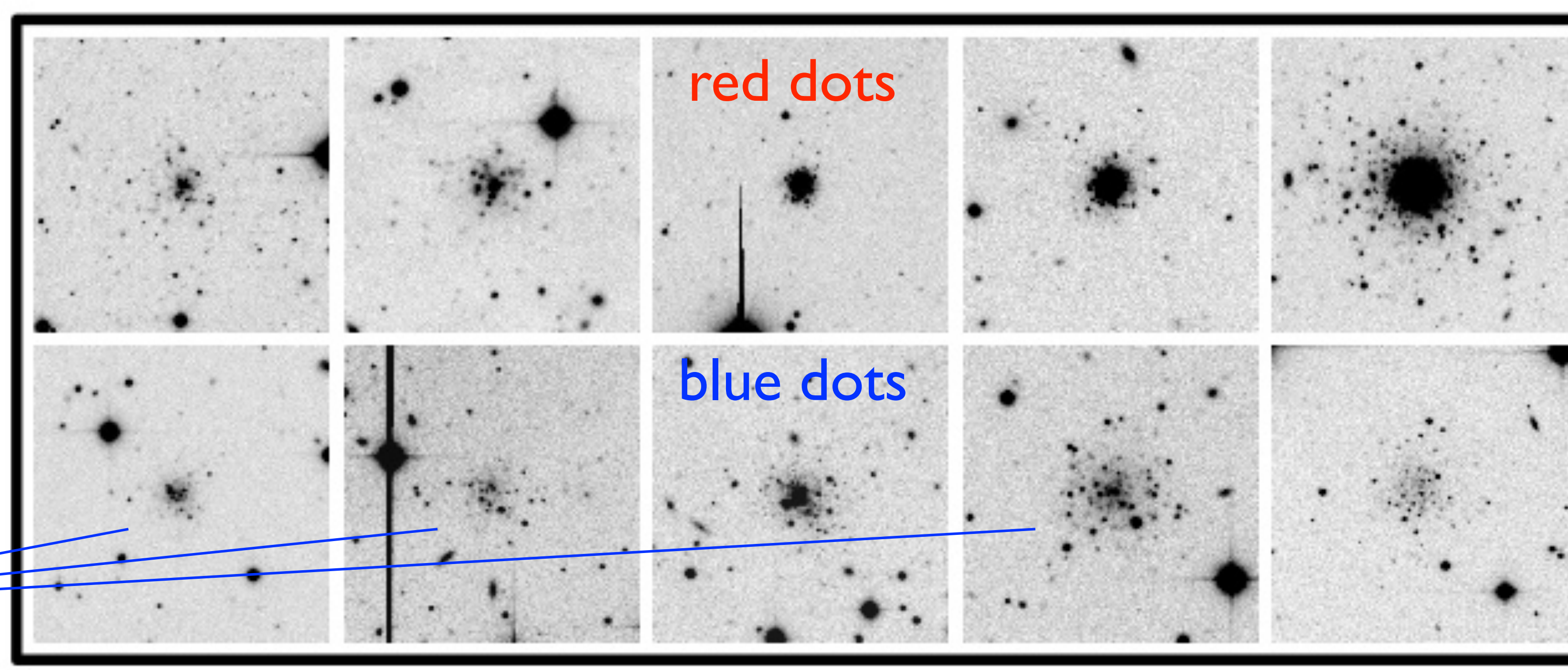


Gieles et al, 2010, 2012

Conclusions



Mackey et al, 2011
Huxor et al, 2005, 2011
Collins et al, 2009

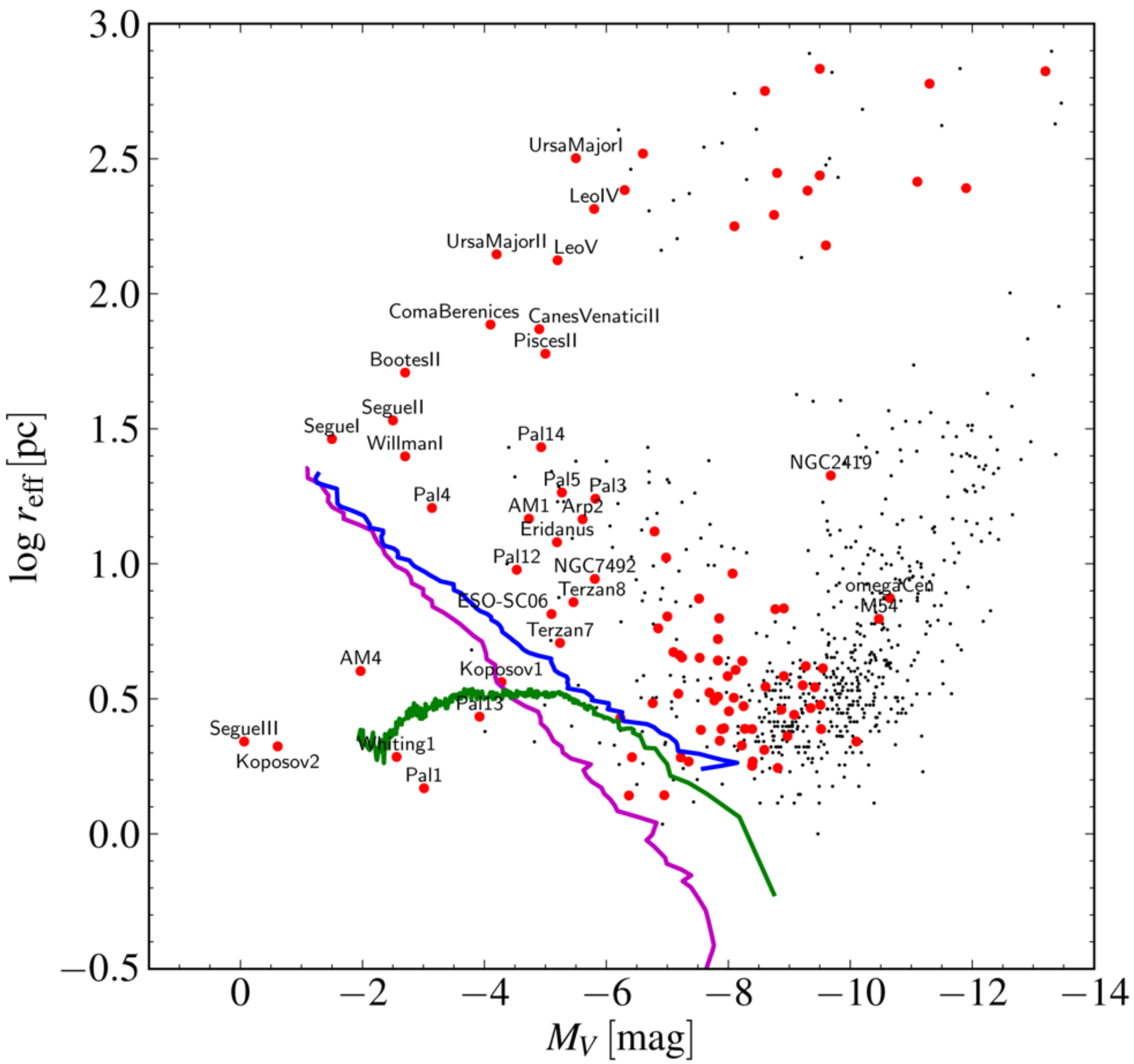


Like Palomar star clusters
but much brighter

Vasily Belokurov • Institute of Astronomy, Cambridge

Speculation

Too Bad, but we might still learn something about dwarfs!



Gieles et al, 2010, 2012

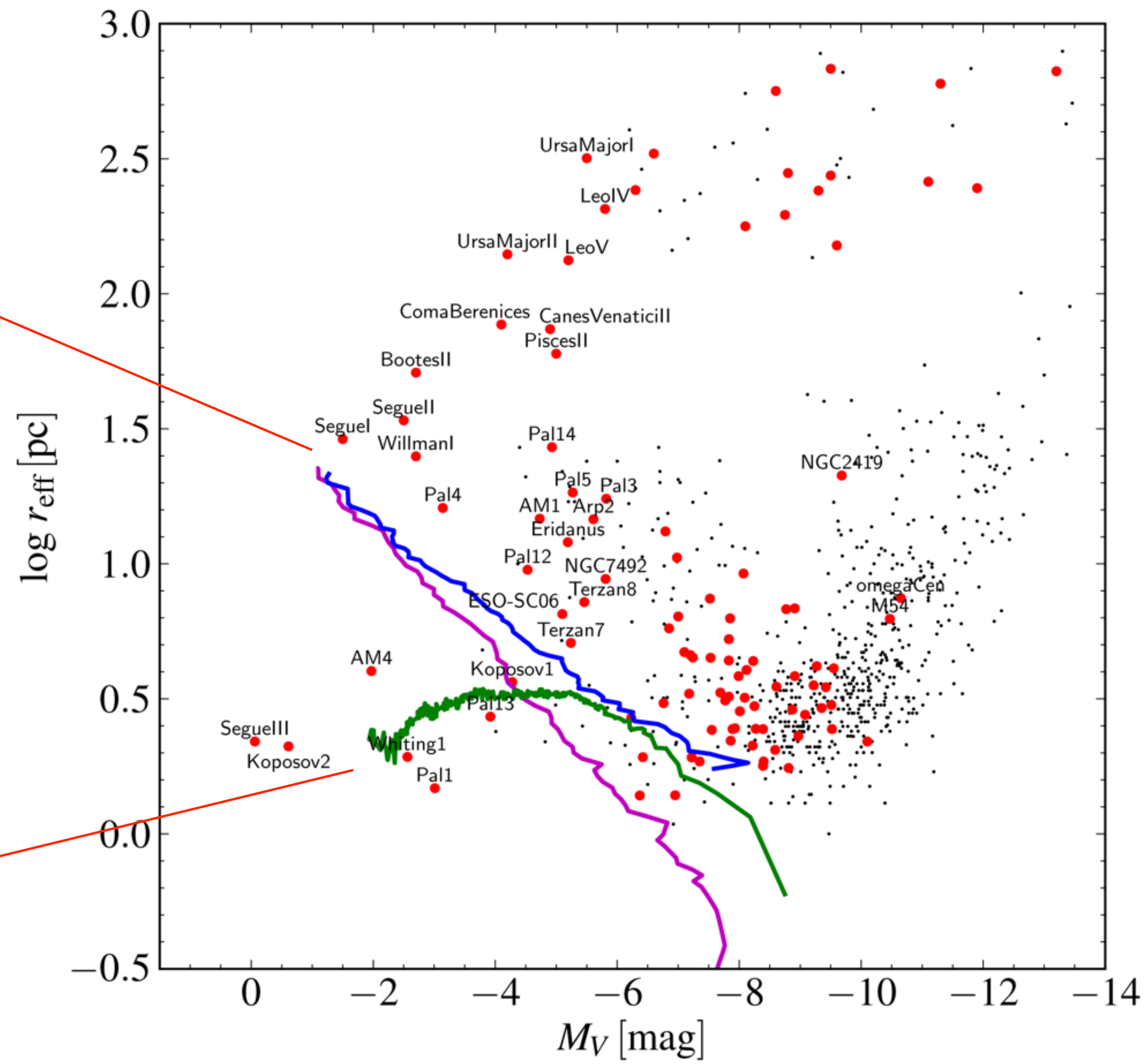
Speculation

Too Bad, but we might still learn something about dwarfs!

Gieles et al, 2010, 2012

Cored hosts

Cusped hosts



What Is a Galaxy?

“We stumble now into the gaping moor of general ignorance”

QI, Episode 7 "Incomprehensible", 21 Oct 2011