THE MILKY WAY HALO -- GHOSTLY STREAMS, PHANTOM GALAXIES

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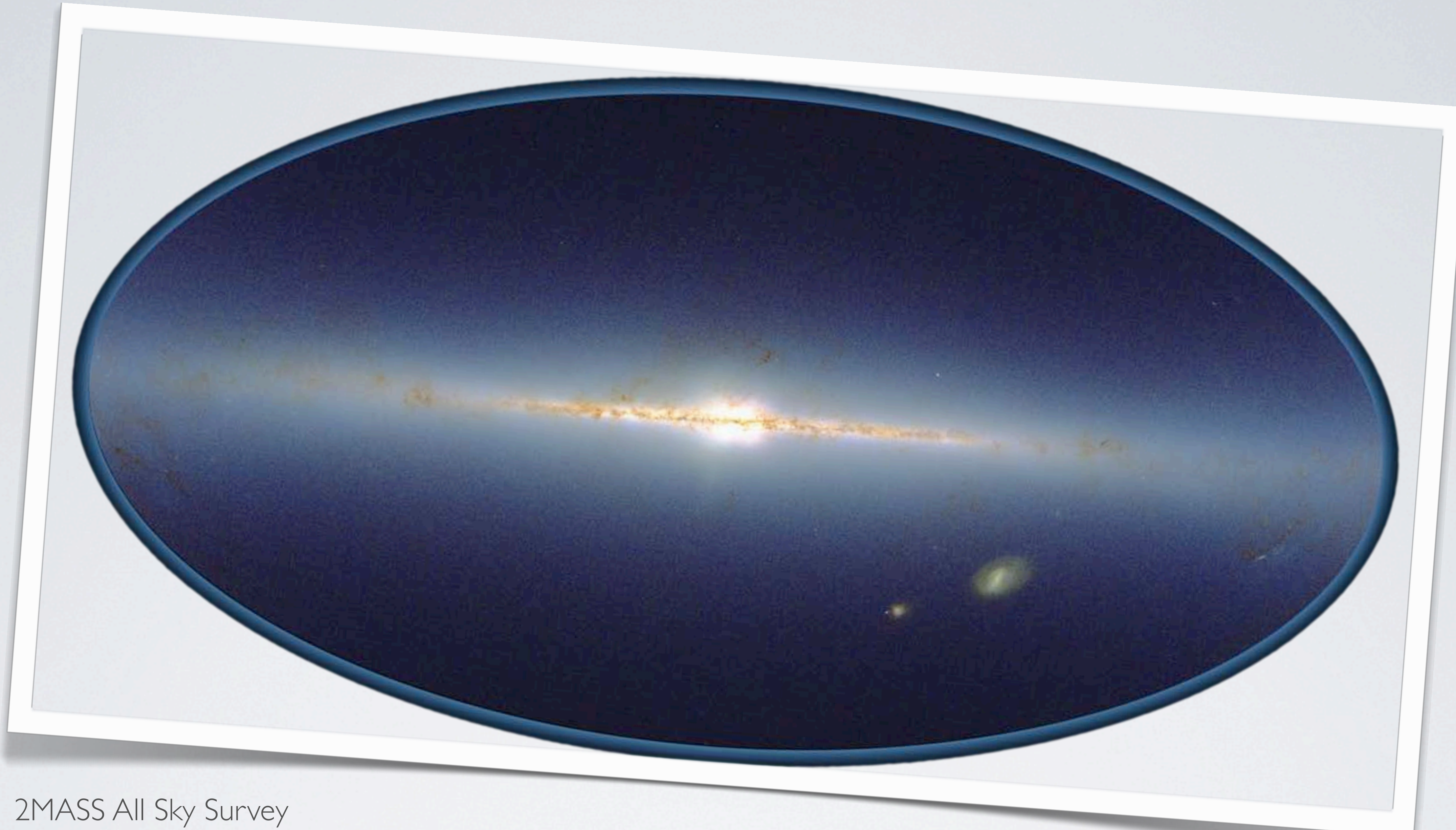
March 15th, Institut d'Astrophysique de Paris



2MASS All Sky Survey

VIEW OF THE MILKY WAY

Large & Small Magellanic Clouds, and Sagittarius Stream

ANATOMY OF THE MILKY WAY

1. The Heart & Lungs of the Galaxy are the Stellar Bulge and Disk
    - ★ the stellar halo is roughly a thousandth of the stellar mass
2. The Dark Halo is the Skeleton
    - ★ the stellar halo is roughly a ten thousandth of the total dark halo mass
3. The Stellar Halo is the Eyelashes.
    - ★ ΛCDM provides an excellent description of the mass spectrum from 10-1000 Mpc -- the inconsistencies are apparent on the scales of individual Galaxy haloes,
    - ★ the stellar halo contains the most metal-poor stars (and possibly the oldest).
    - ★ the stellar halo contains the most dark-matter dominated objects.

THE STELLAR HALO

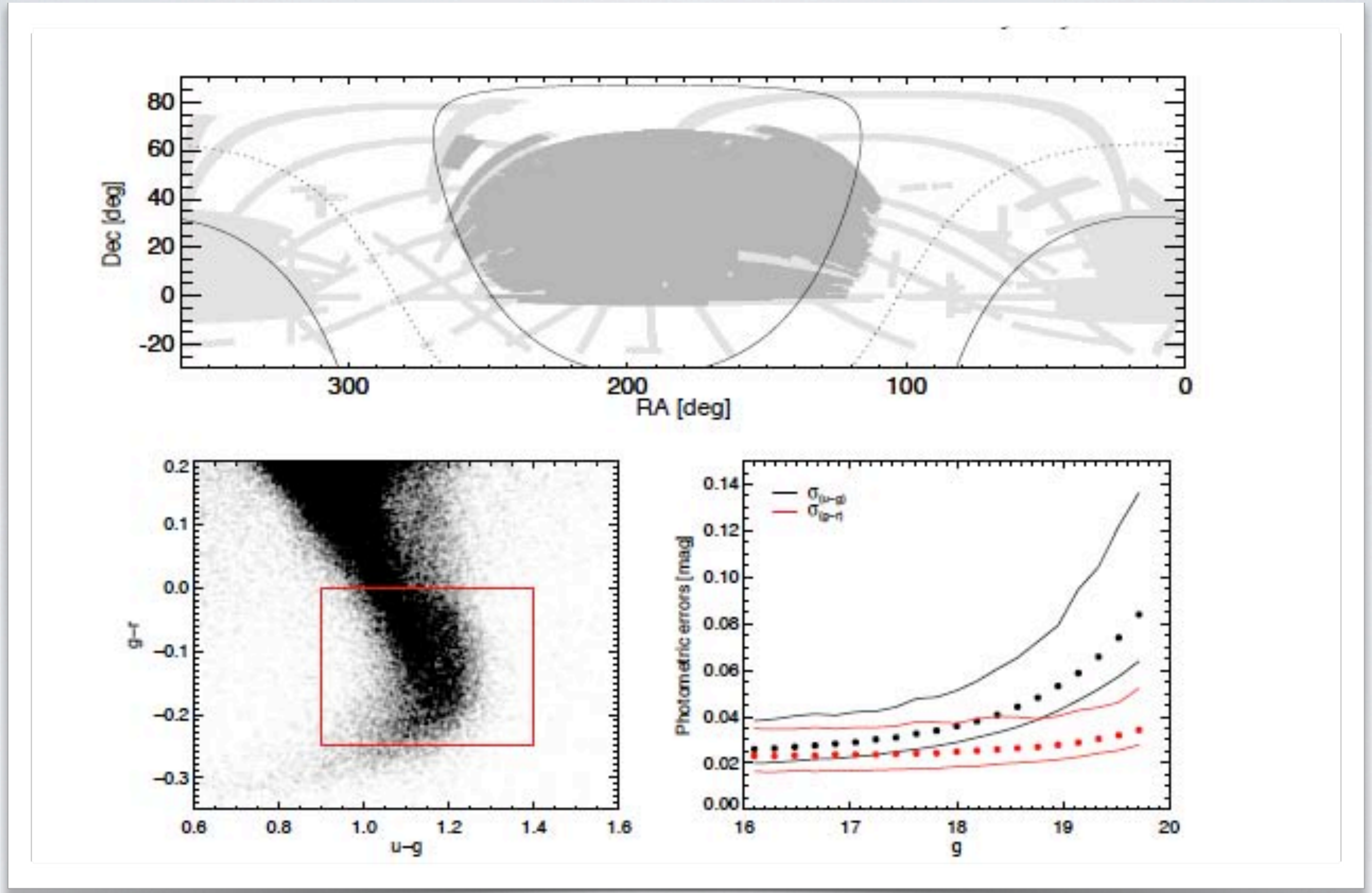
The fundamental observation goes back half a century. Eggen, Lynden-Bell & Sandage (1962) noted that :

"*The time required for stars in the halo to exchange their energies and angular moment is very long compared with the age of the Galaxy. Hence, knowledge of their present energy and angular momenta tells us something of the initial conditions under which they formed*"

THE STELLAR HALO

1. The Smooth Component
   * the blue horizontal branch and blue straggler populations.
2. The Streams
   * the bewildering Sgr Stream,
   * the Orphan Stream.
3. The Satellites and the Clouds
   * the Hercules-Aquila & Pisces Overdensities,
   * the ultrafaints.

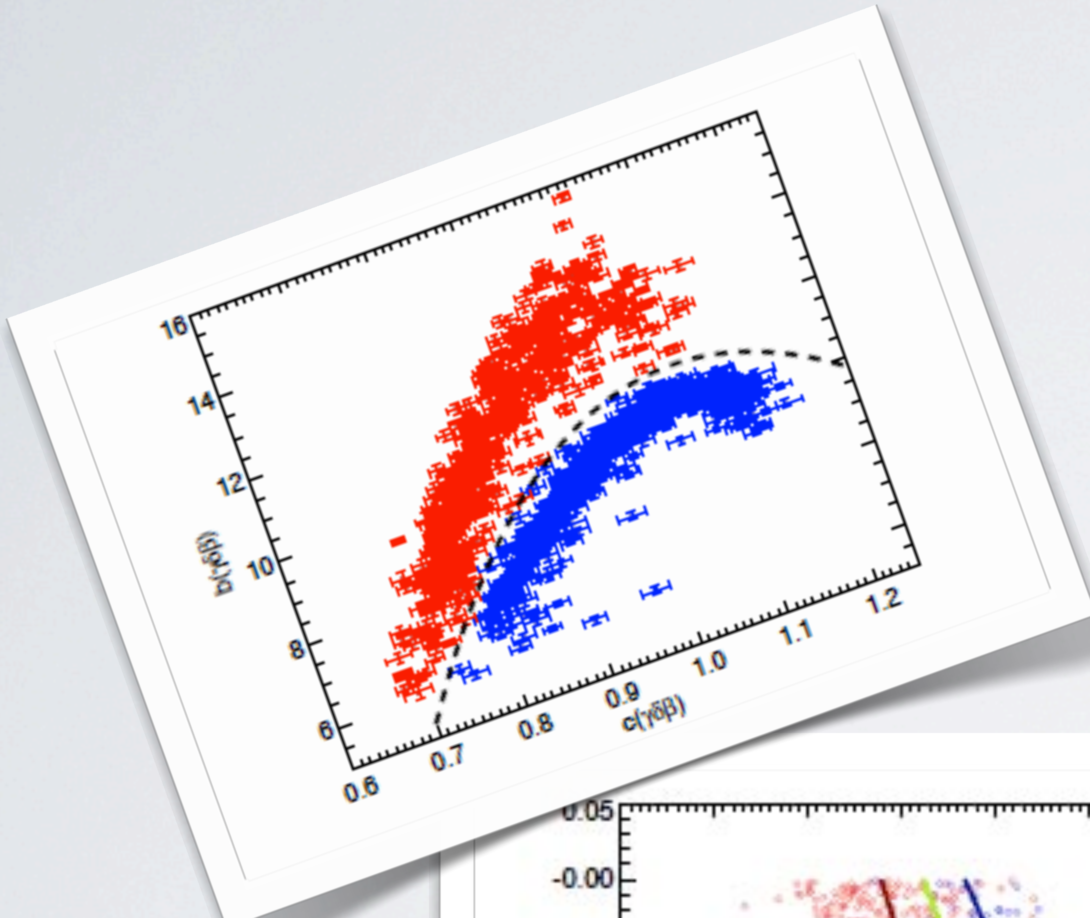
THE SMOOTH COMPONENT

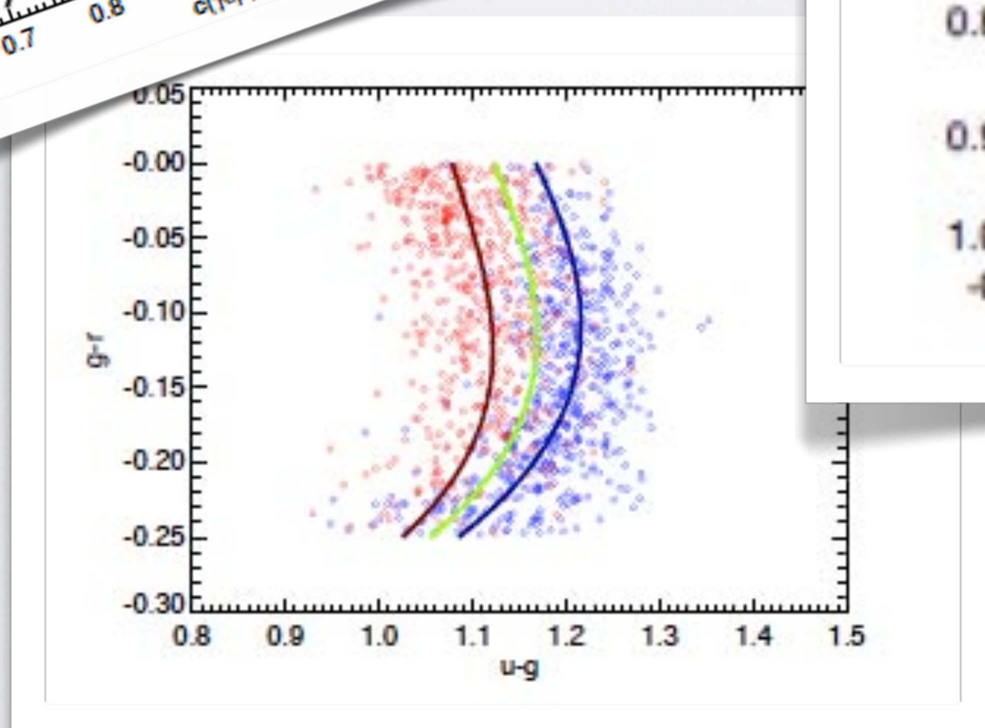


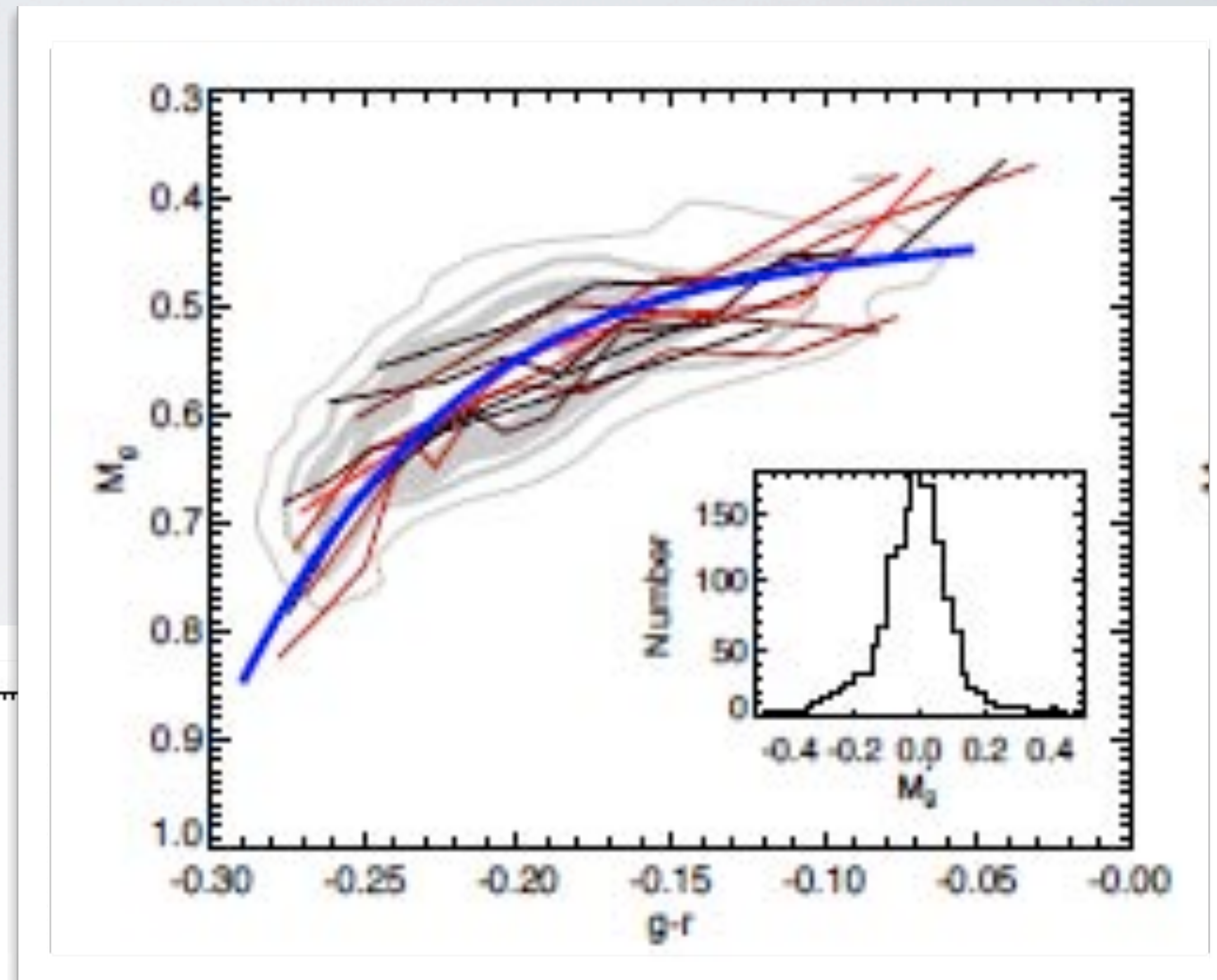
Colour selection used to pick ~ 20,000 blue horizontal branch/ blue straggler stars with 16 < g < 18.5

Deason, Belokurov, Evans 2011

THE SMOOTH COMPONENT



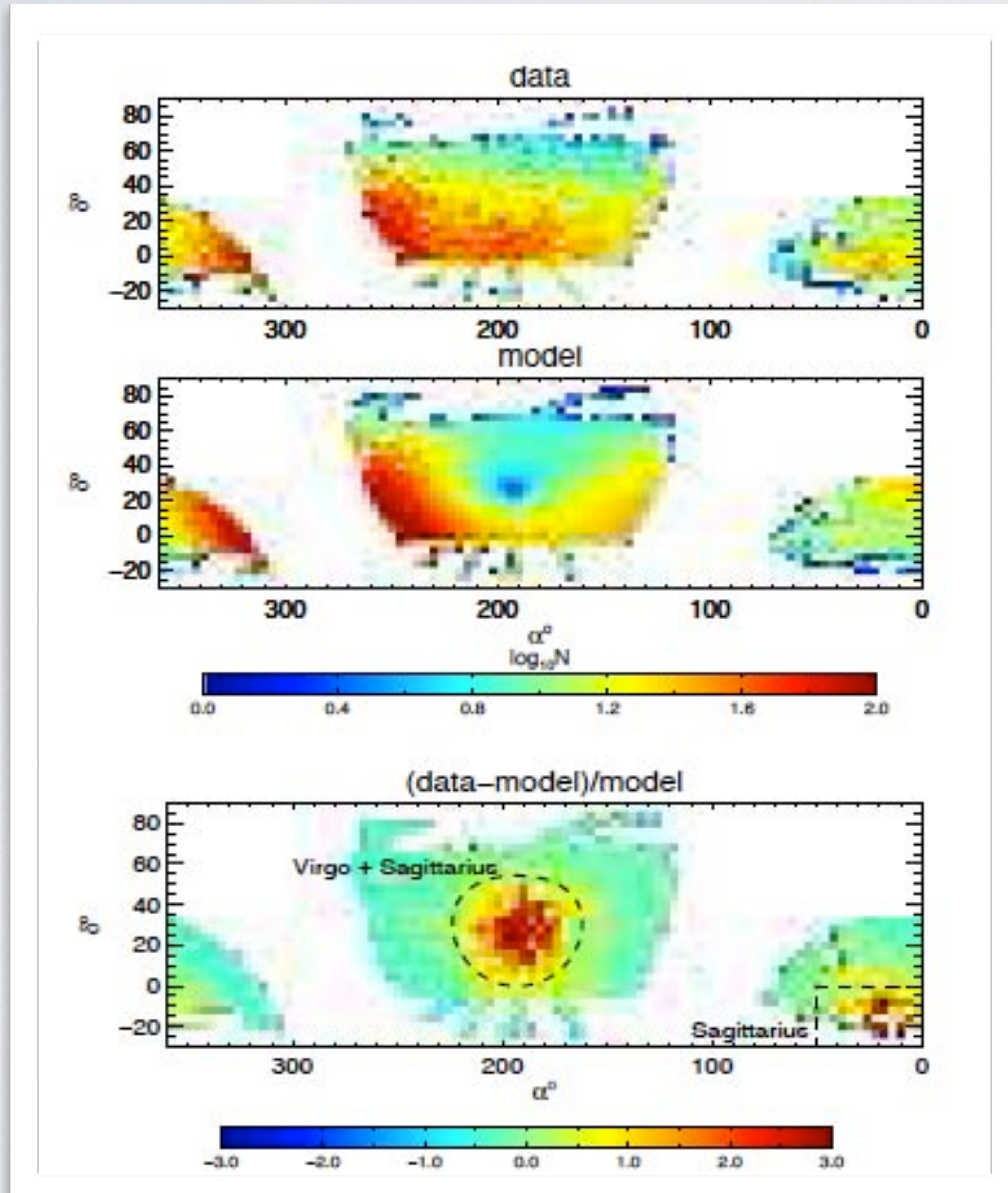




From Sersic spectral fits to colour to absolute magnitude.

Deason, Belokurov, Evans 2011

THE SMOOTH COMPONENT



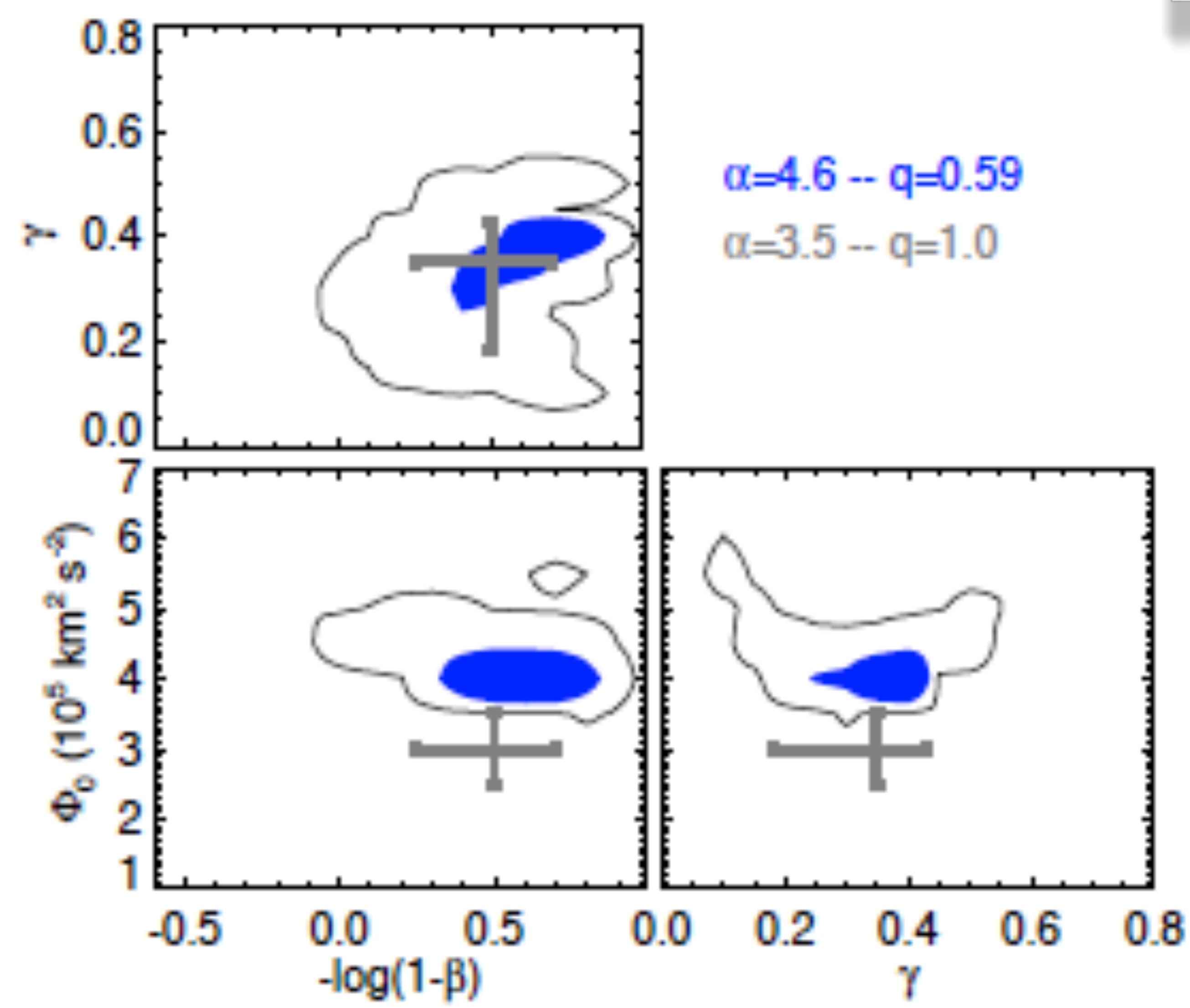
The smooth component is well-described by an oblate double power-law with flattening q ~ 0.6, inner power-law ~2.3, outer power-law ~ 4.6 and break radius ~ 27 kpc.

Deason, Belokurov, Evans 2011

THE SMOOTH COMPONENT

$$\Phi = \Phi_0 (r/1\,\mathrm{kpc})^{-\gamma}$$

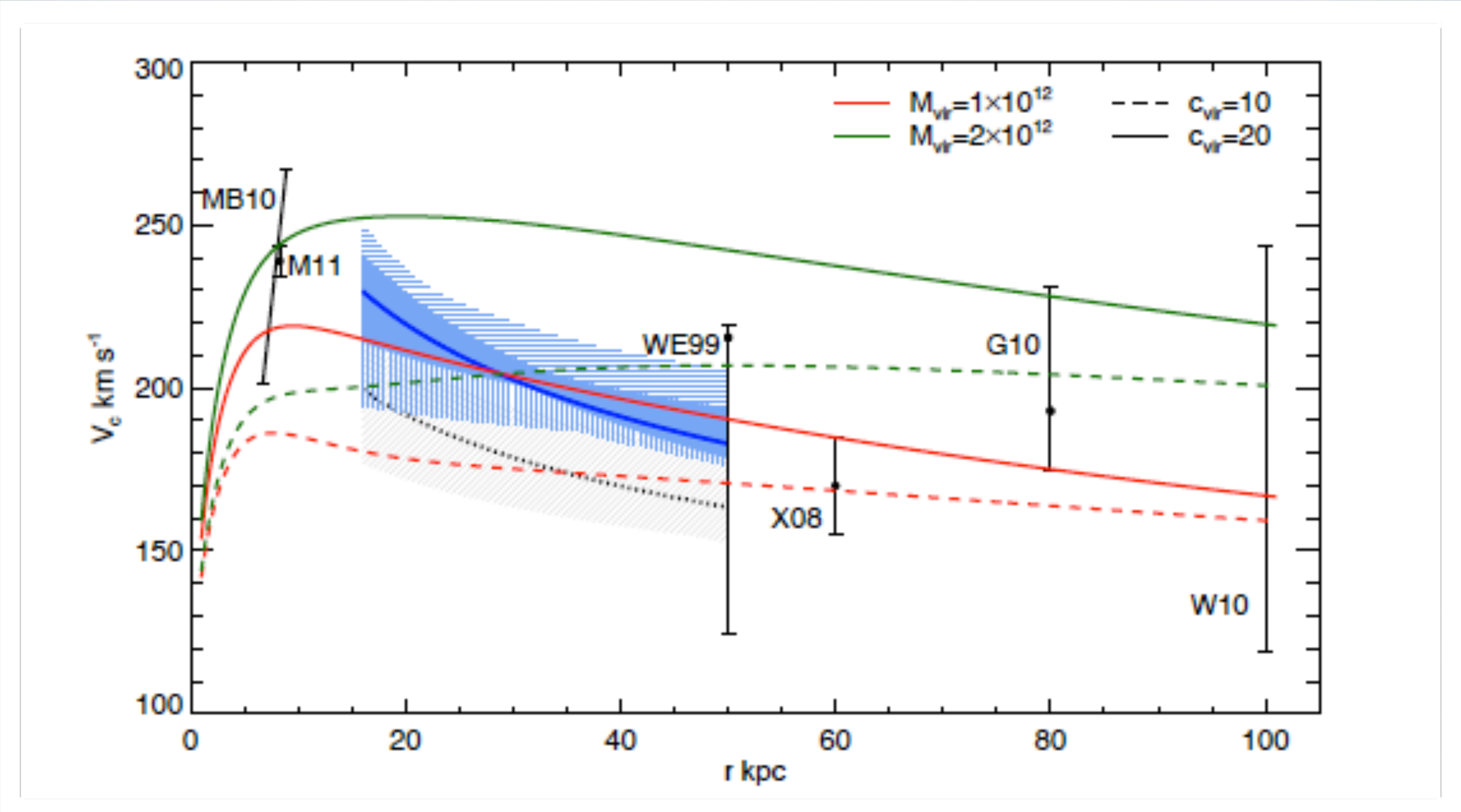
$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2} = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$



$$F(E, L^2, L_z^2/L^2) \propto L^{-2\beta} f(E) h(e^2 L_z^2/L^2)$$

Deason, Belokurov, Evans An 2012

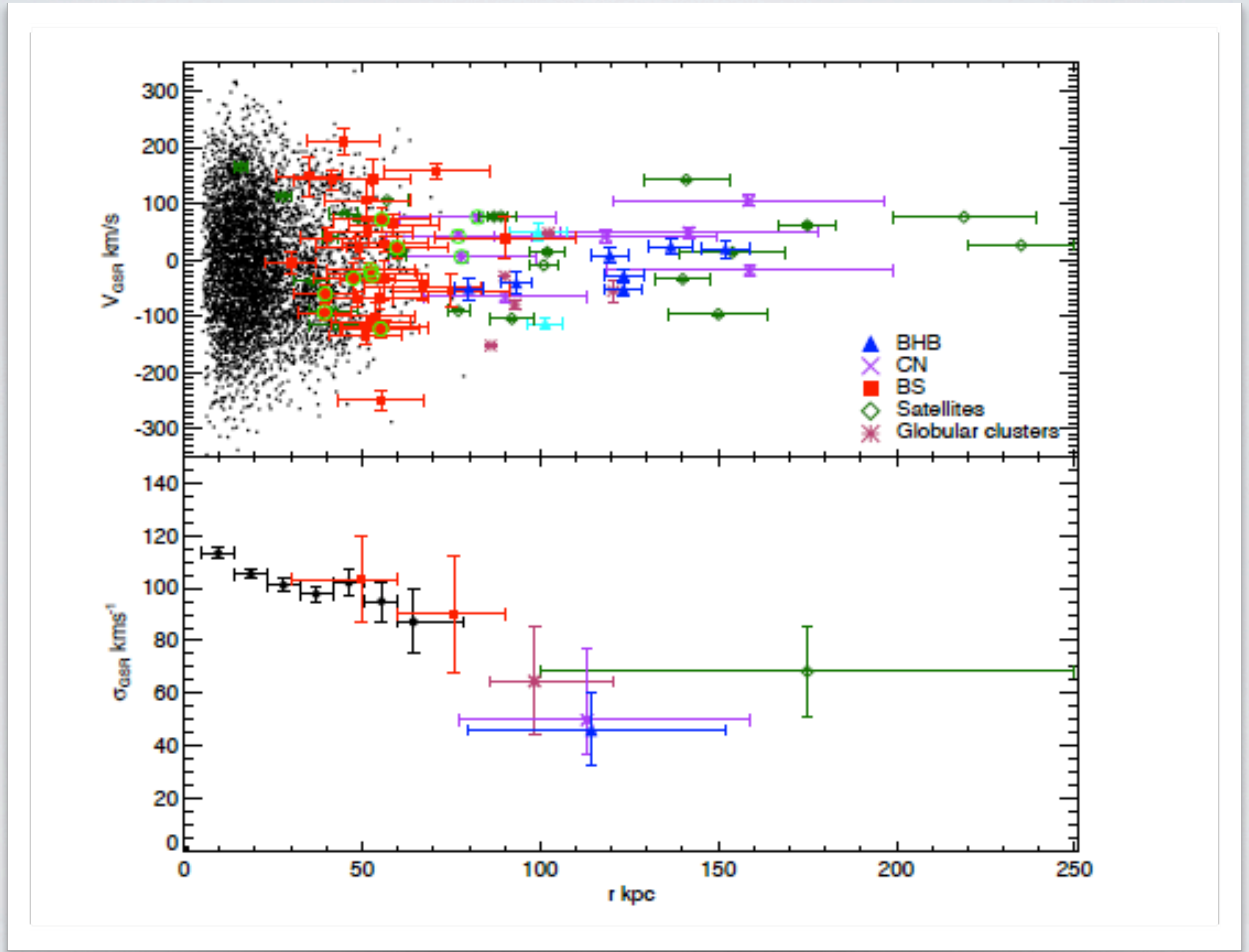
THE SMOOTH COMPONENT



A relatively high concentration halo, c ~ 20

Deason, Belokurov, Evans An 2012

THE SMOOTH COMPONENT



~30 tracers beyond 80 kpc

Deason et al. 2012

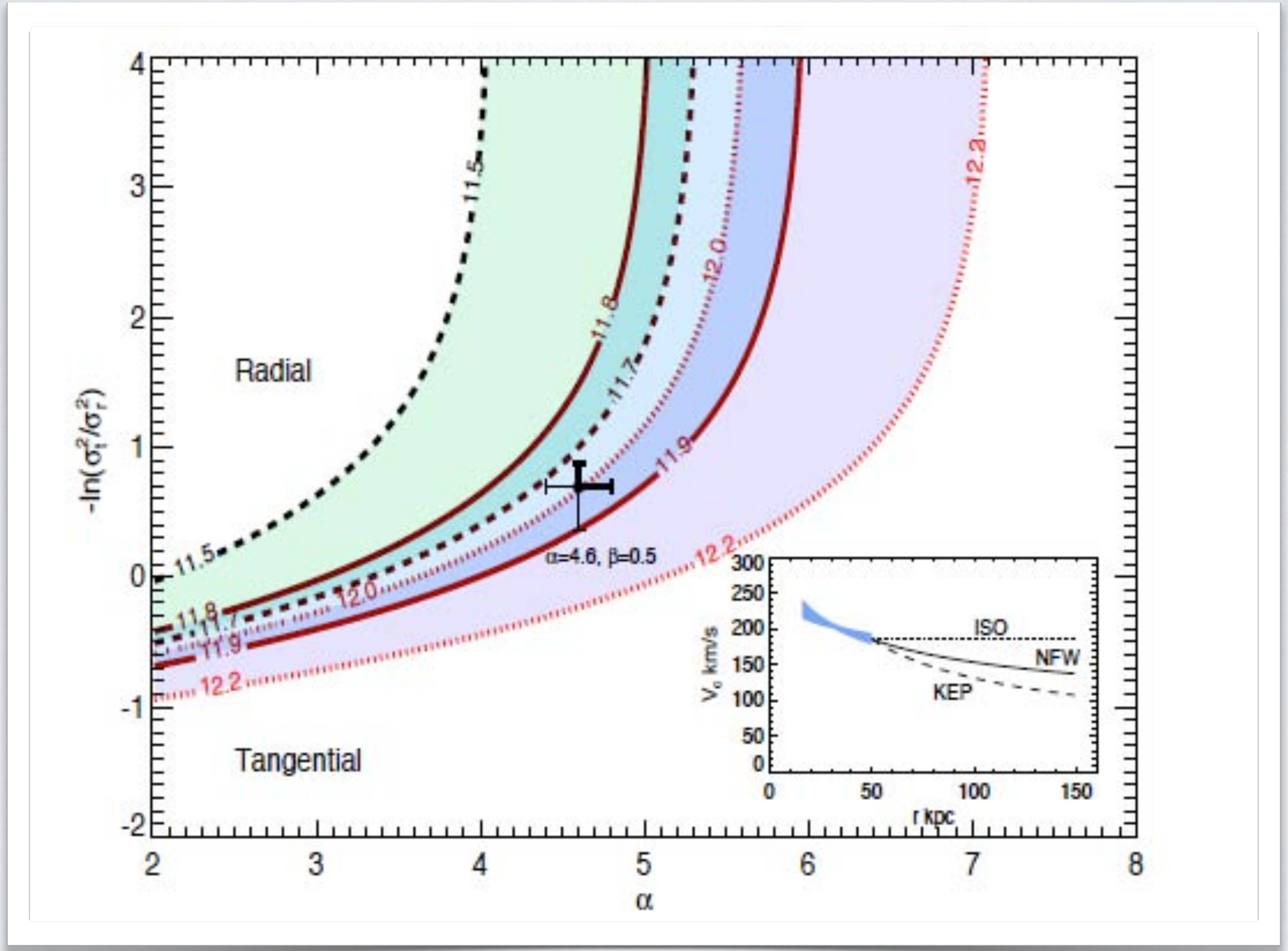
THE SMOOTH COMPONENT

$$M = \frac{C}{G}\langle v_r^2 r^\gamma \rangle, \quad C = (\gamma + \alpha - 2\beta)\, r_{\rm out}^{1-\gamma}$$

Mass enclosed by a tracer population with density $\rho \sim r^{-\alpha}$, $\psi \sim r^{-\gamma}$ and velocity anisotropy β

Watkins, Evans, An 2010

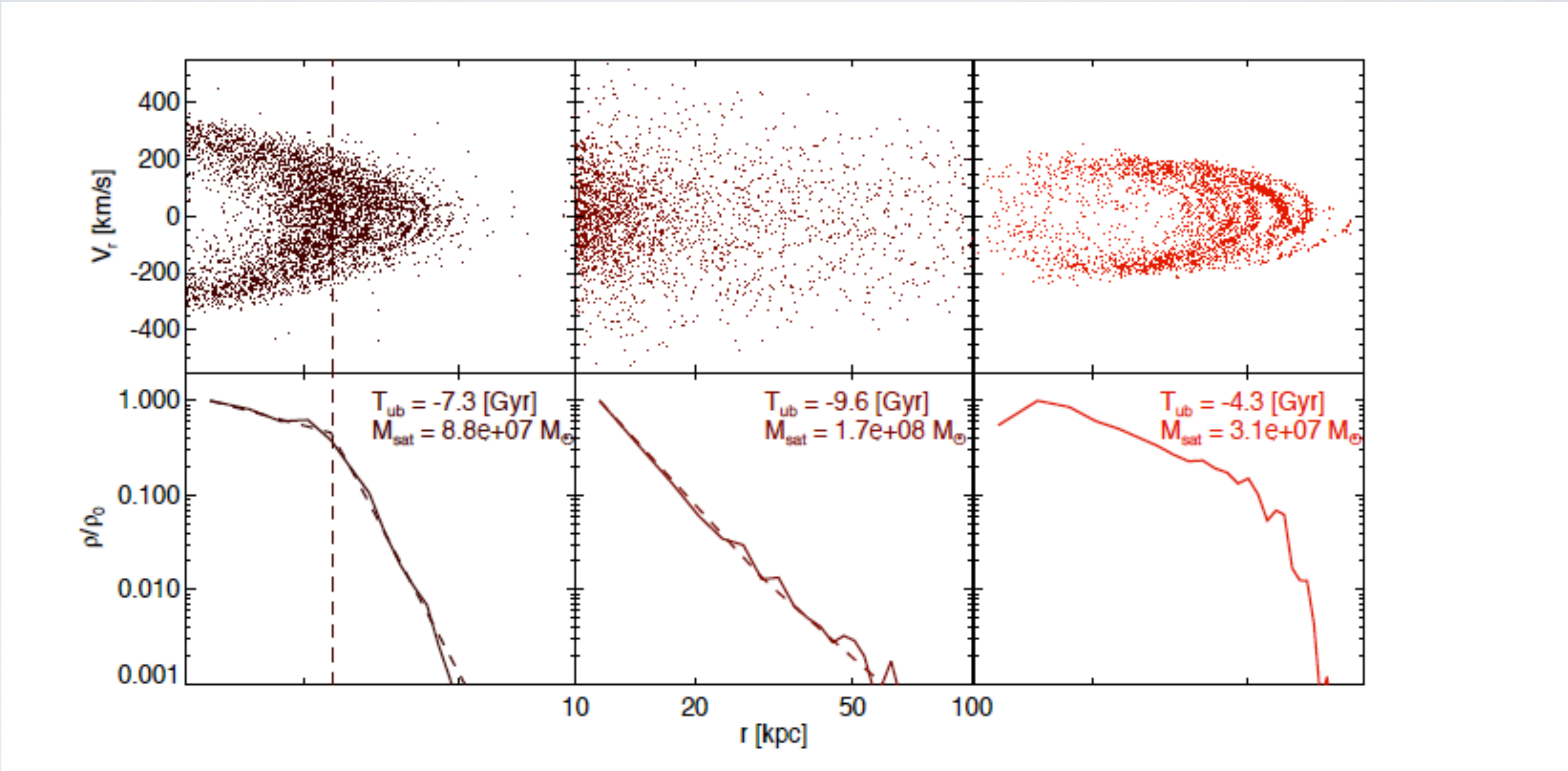
THE SMOOTH COMPONENT



Estimated mass within 150 kpc

Deason et al 2012

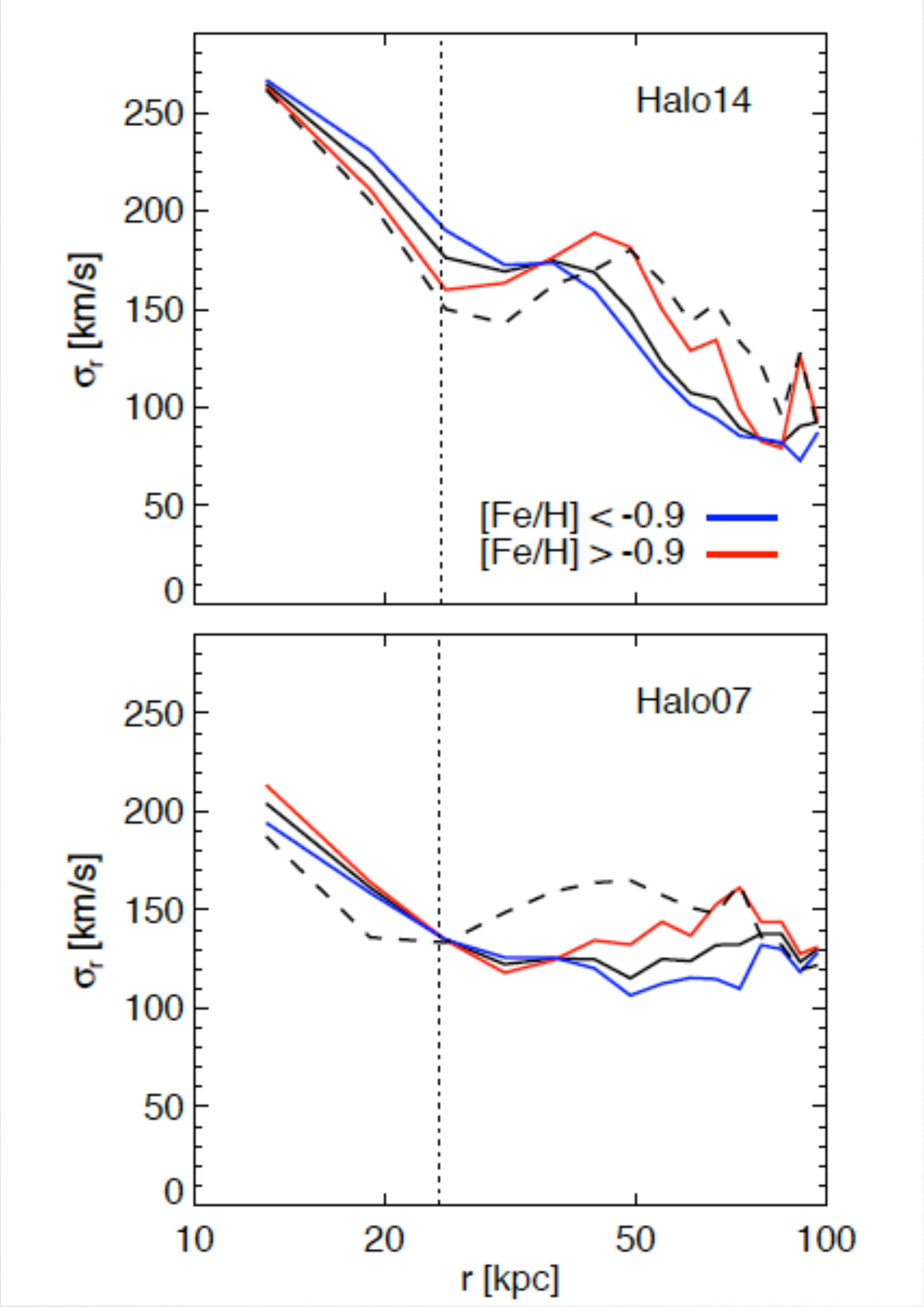
THE SMOOTH COMPONENT



Broken(left), unbroken (middle), unrelaxed (right) from the Bullock & Johnston suite of simulations.

Deason, Belokurov, Evans, Johnston 2013

THE SMOOTH COMPONENT



A break in the profile of the stellar halo suggests one massive satellite dominates the accretion. Thus, a 'dip' in the velocity dispersion profile, the signature of a build-up of apocentres, will be more pronounced in the metal-rich(er) material

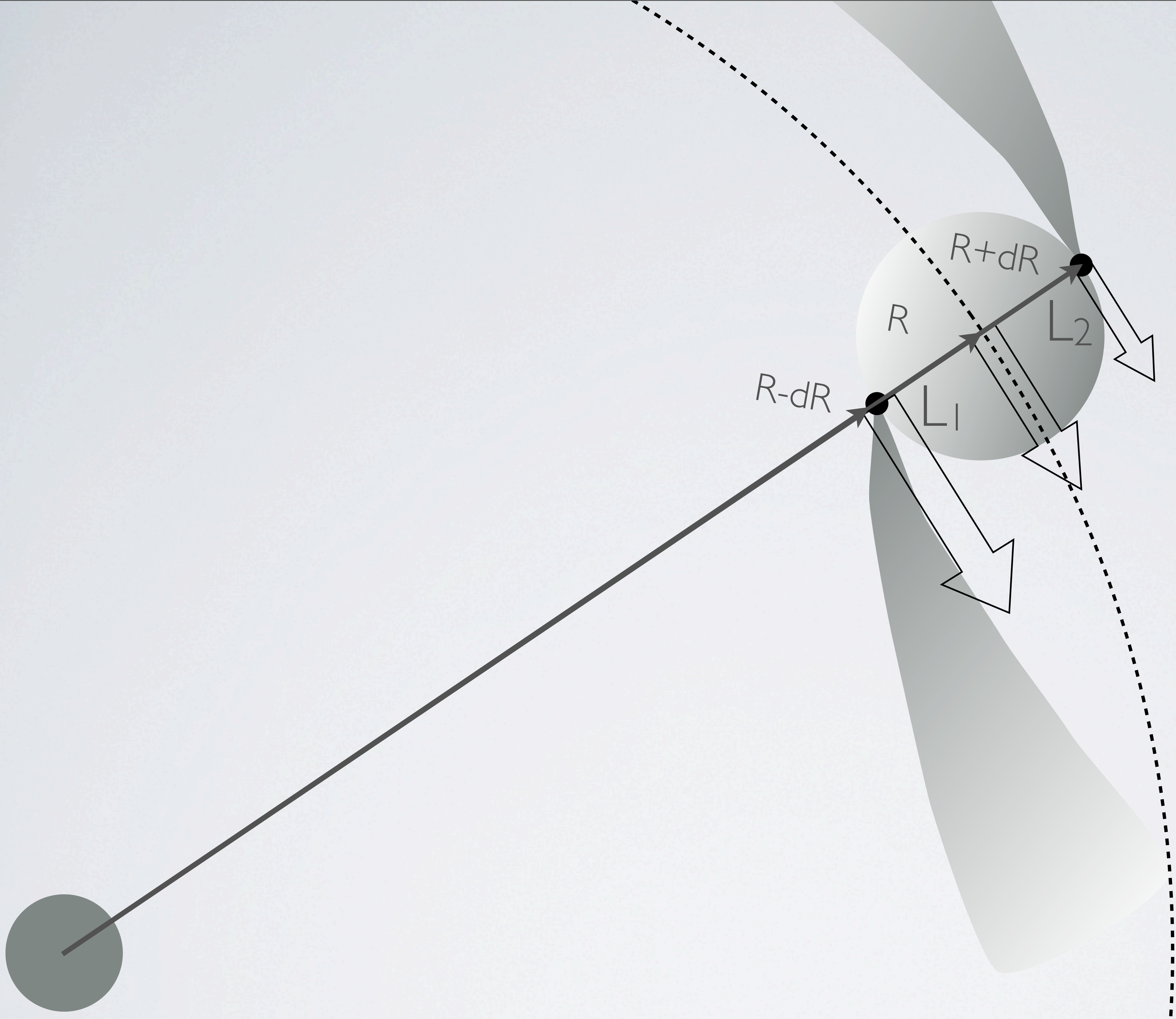
THE SMOOTH COMPONENT

1. The Stellar Halo as Traced by the A Stars is Smooth.
   - the rms scatter of the data about the maximum likelihood solution is between 5% and 20 %,
   - this contradicts earlier work (Bell et al) that argued for no smooth component.
2. It is Broken.
   - the density profile breaks at r ~ 28 kpc, beyond which it falls off more steeply
   - break radii mark the apocenters of accreted satellites
3. The Velocity Dispersion Profile Falls
   - the kinematics imply a low mass, high concentration halo.
   - the anisotropy $\beta \approx 0{,}5$ throughout the halo (Stripe 82 sub-dwarfs)

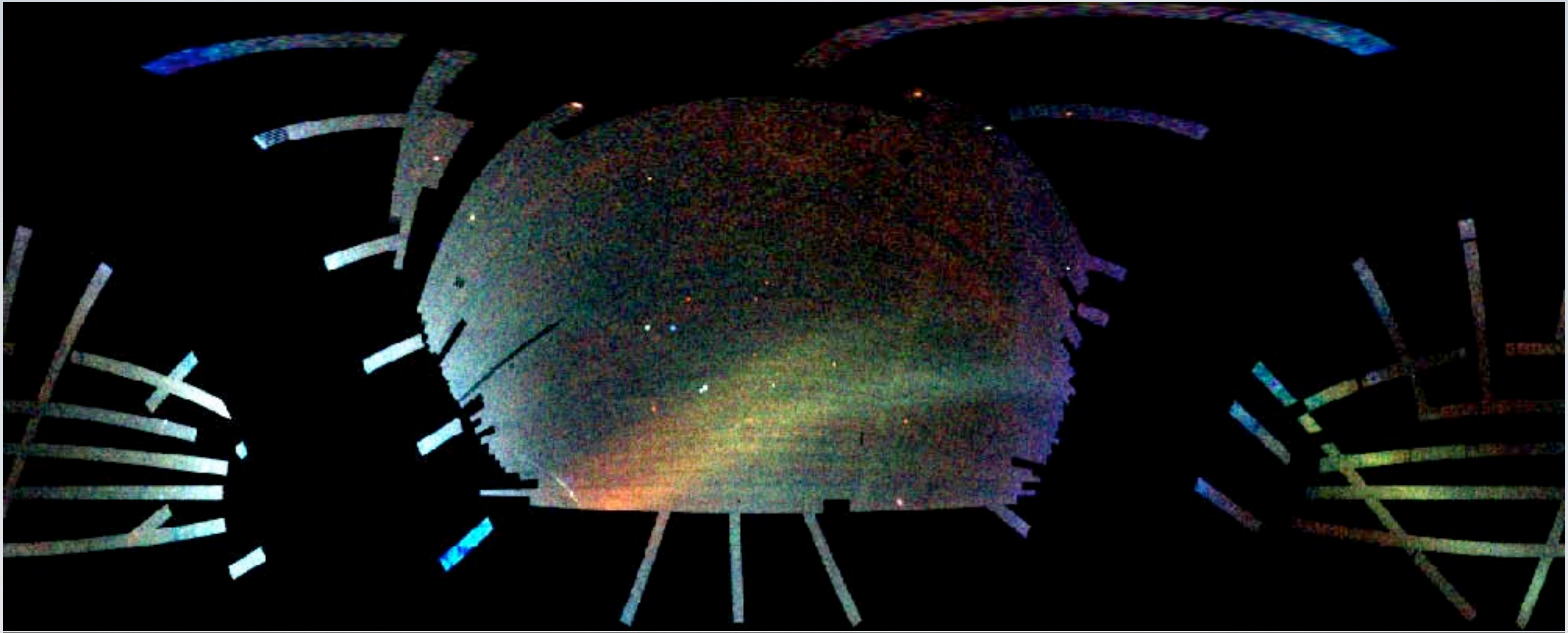
THE STREAMS

"*The tidal debris delineates the orbit of a long-gone satellite galaxy. like a ghost haunting the past abode of a murdered victim. We may look for streams among the globular clusters and small satellite galaxies like the meteor streams along old cometary paths in the Solar system*" (Lynden-Bell & Lynden-Bell 1995)

Just as meteor streams are the gravestones of the short-period comets, so tidal streams in the mark the death throes of dying satellite galaxies.



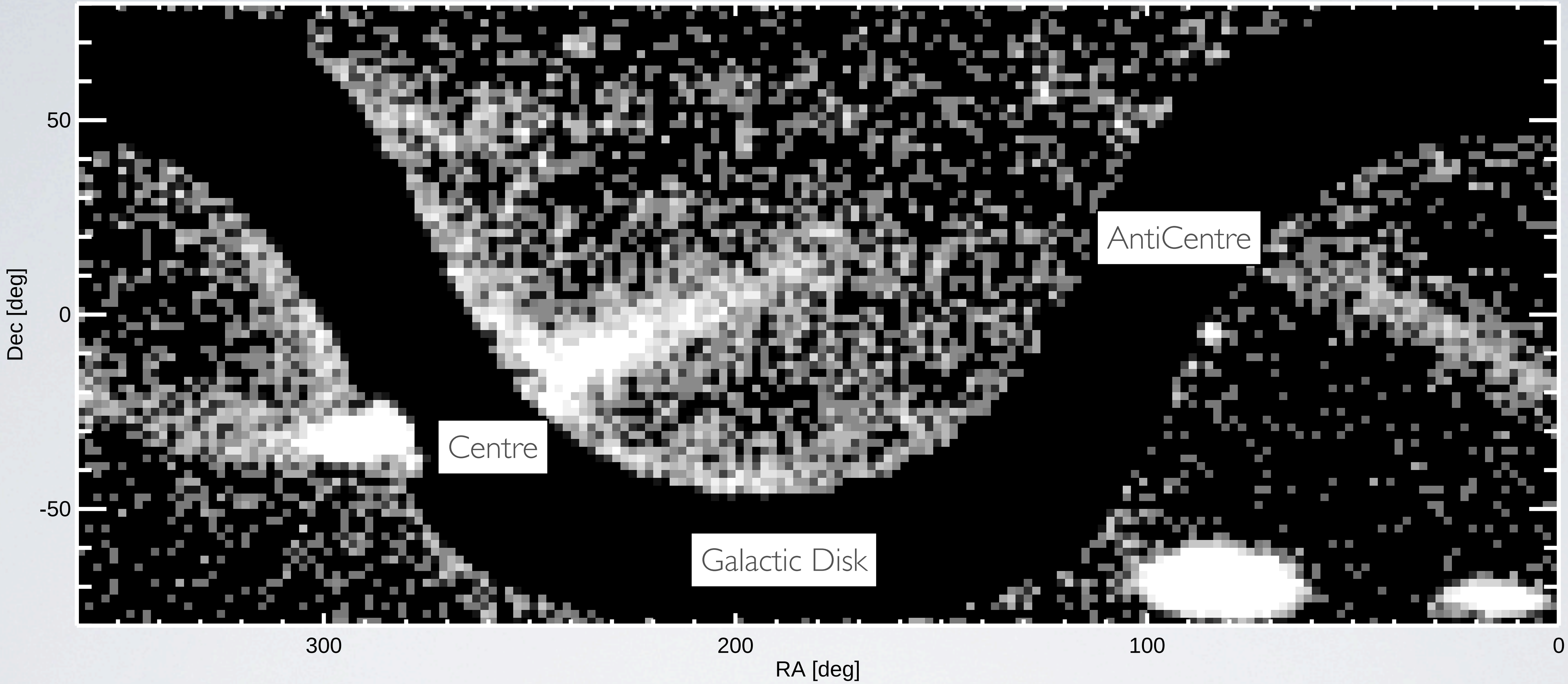
THE MAKING OF STREAMS



THE FIELD OF STREAMS

Belokurov, Zucker, Evans et al 2006

M giants as seen by 2MASS

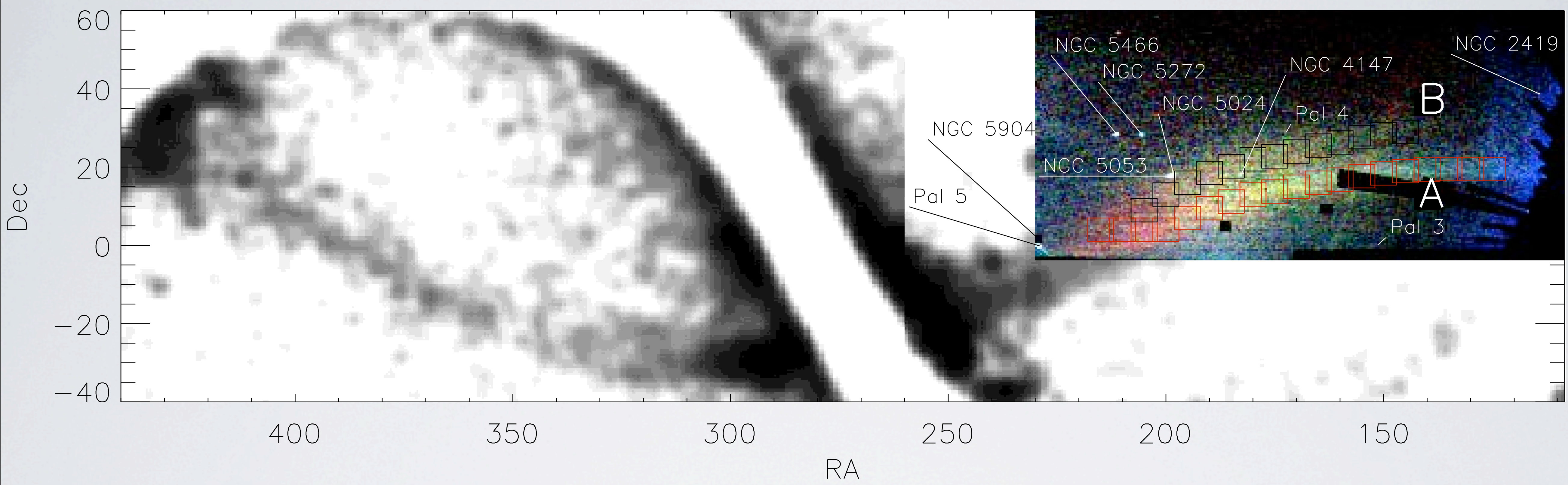


Majewski et al., 2003, ApJ

THE SAGITTARIUS STREAM

Traced by 2MASS (2 Micron All-Sky Survey) throughout the Southern Galactic hemisphere.

Majewski et al. 2003



THE SAGITTARIUS STREAM

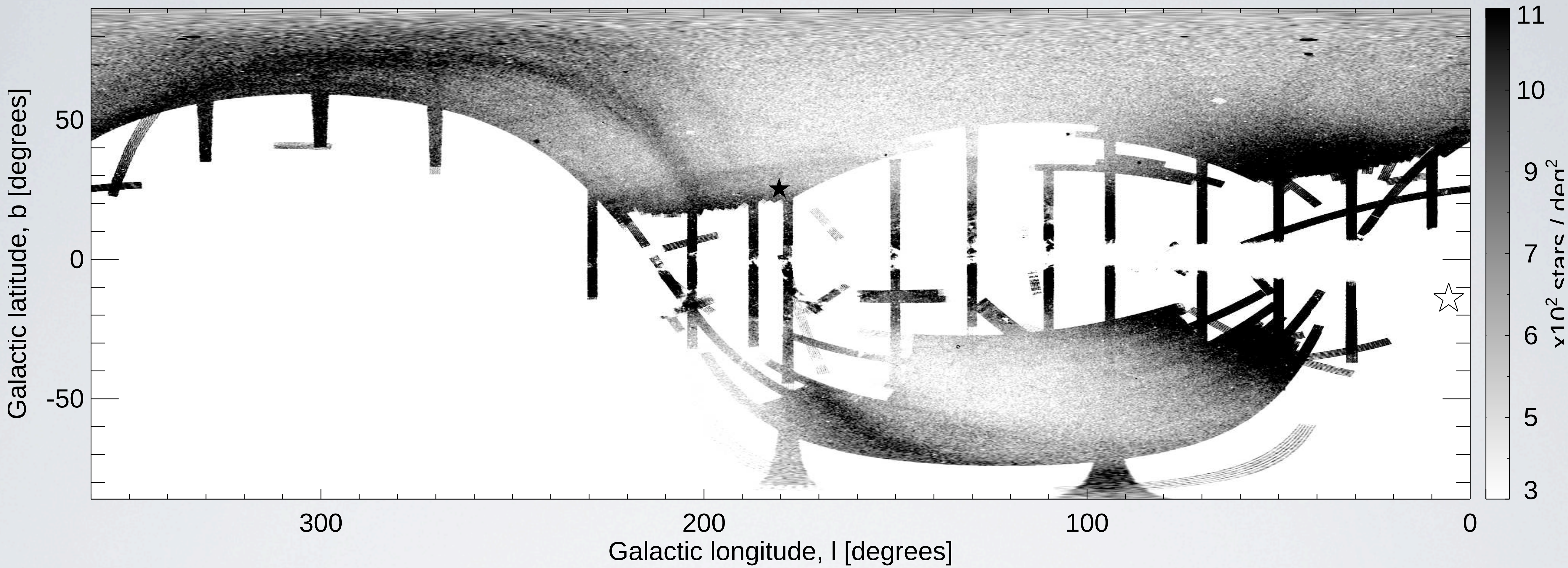
The Field of Streams completes the picture in the North

Belokurov, Zucker, Evans et al. 2006

THE SAGITTARIUS STREAM

The debris in the *Field of Streams* is dominated by one big accretion event. The Sgr Stream provides 20 % of all the debris. including multiple huge tidal streams and probably 20 or so globular clusters.

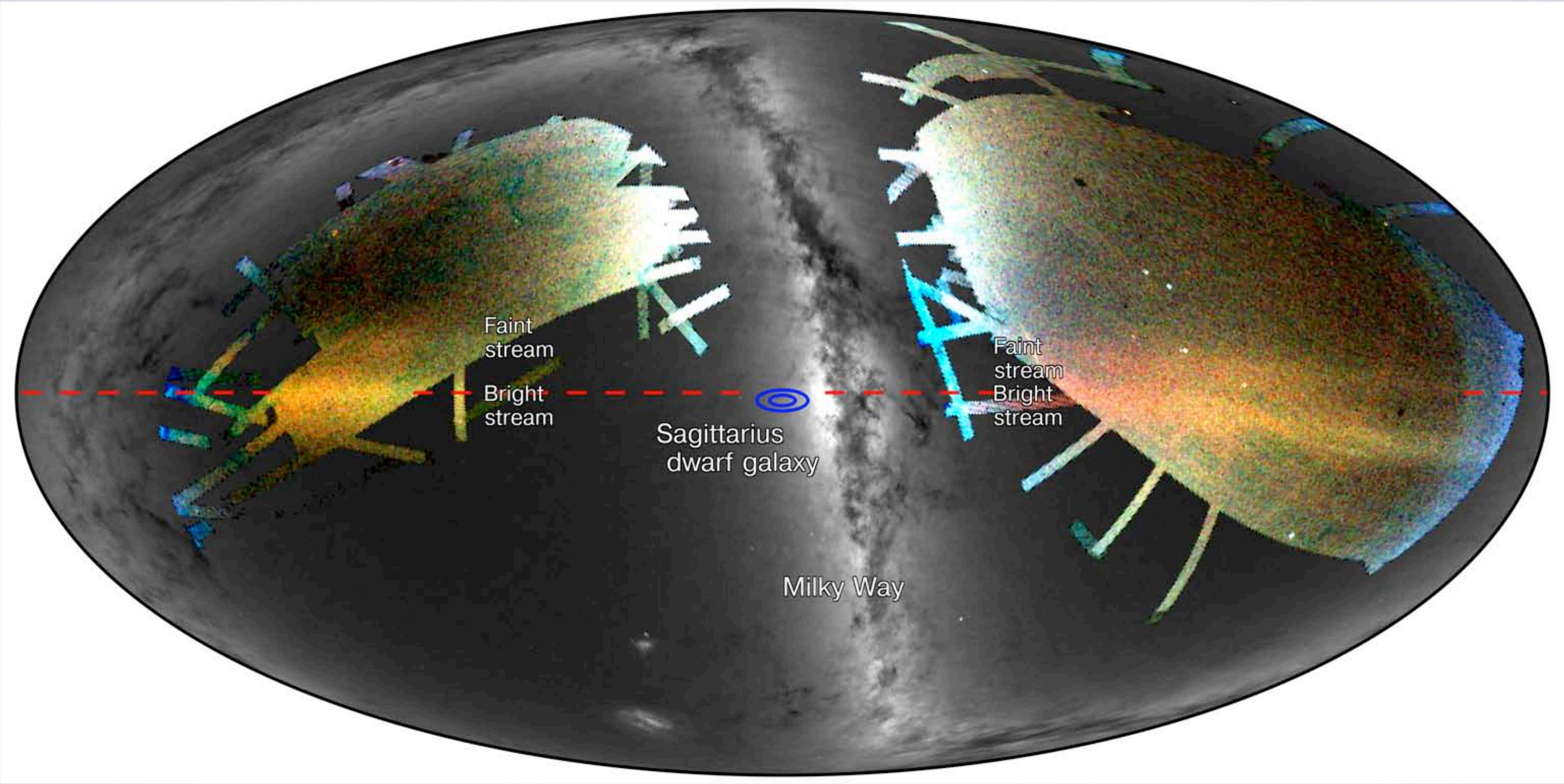
By building luminosity profiles along the streams, and adding to the luminosity of the remnant, we can compute the luminosity of the progenitor galaxy as 1.4×10^8 L_{sun}), comparable to the present-day Small Magellanic Cloud (Niederste-Ostholt et al. 2010).



The Sgr stream in the South as delineated by MSTO stars with 0 < g-i < 0.7. Everywhere we look we see two streams with similar heliocentric distances!

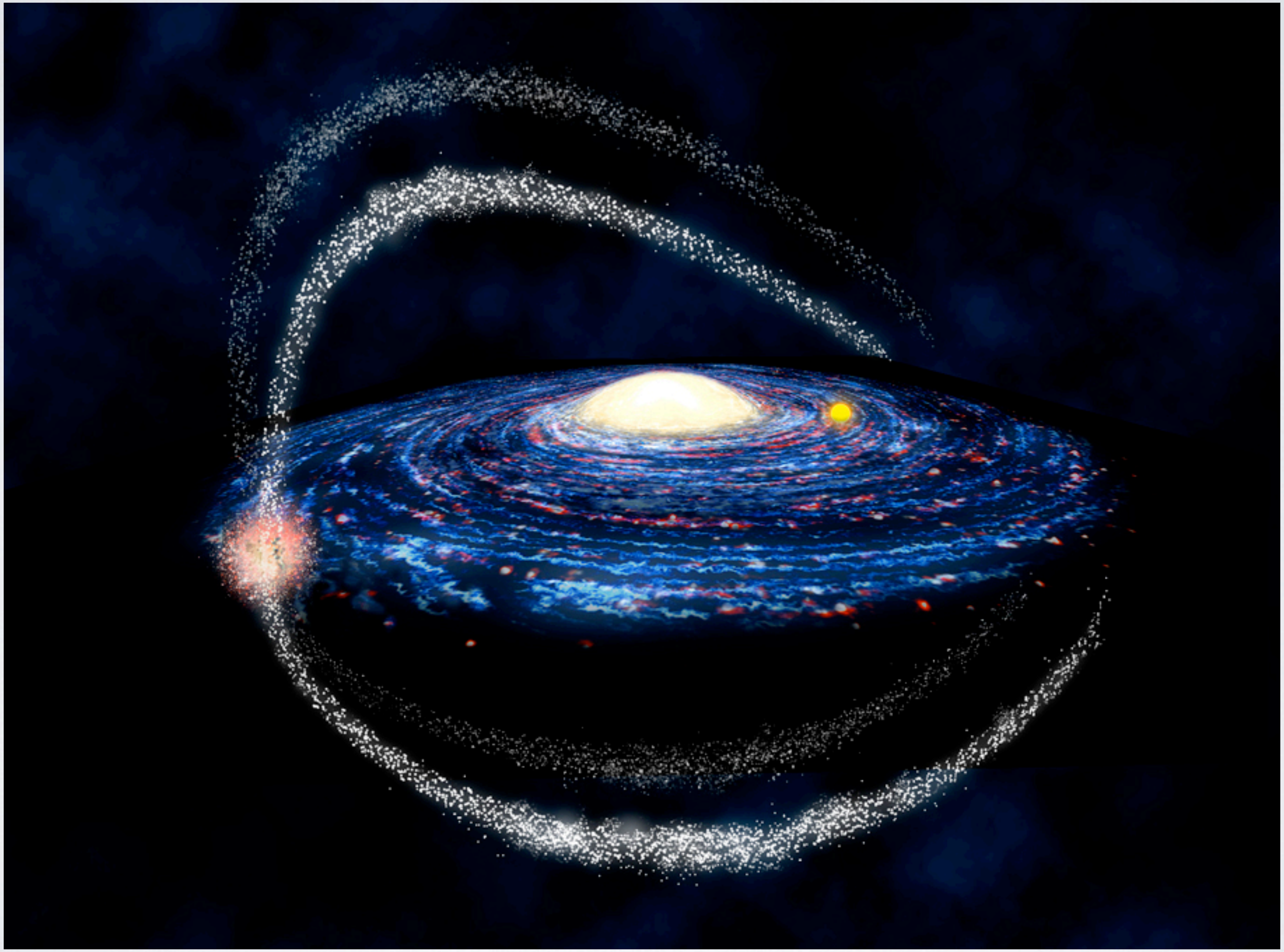
Koposov, Belokurov, Evans et al. 2012

THE SAGITTARIUS STREAM



Koposov, Belokurov, Evans et al. 2012

THE SAGITTARIUS STREAM



THE SAGITTARIUS STREAM

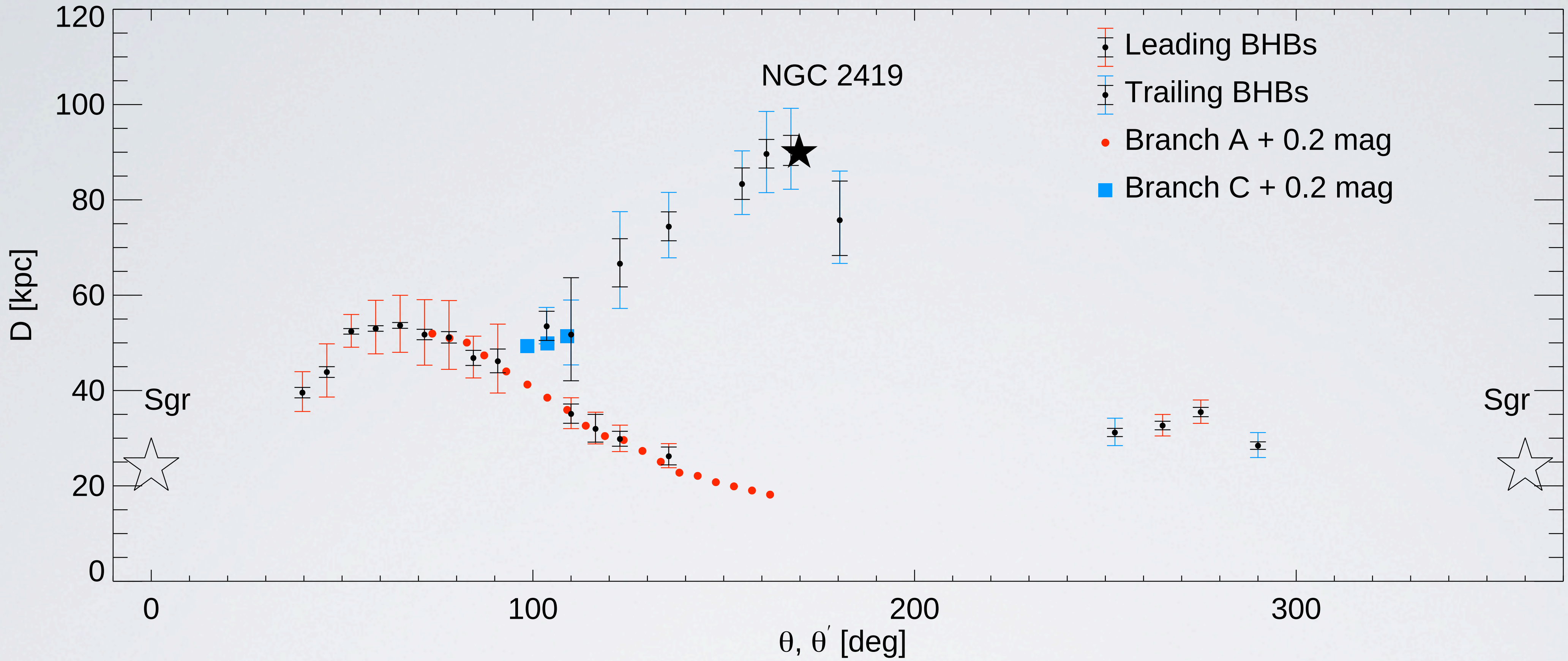
The Sagittarius Stream is a beast with four tails.

One possibility is group infall, as is happening to the Magellanic Clouds at the present time. If two bound objects fall in, there may be two streams and two corpses (NGC 2419?).

Another possibility is that -- just as meteors have spread into different streams through evolution in the Solar system -- so debris from the Sagittarius torn off at different pericentric passages may suffer different amounts of precession in the Galaxy.

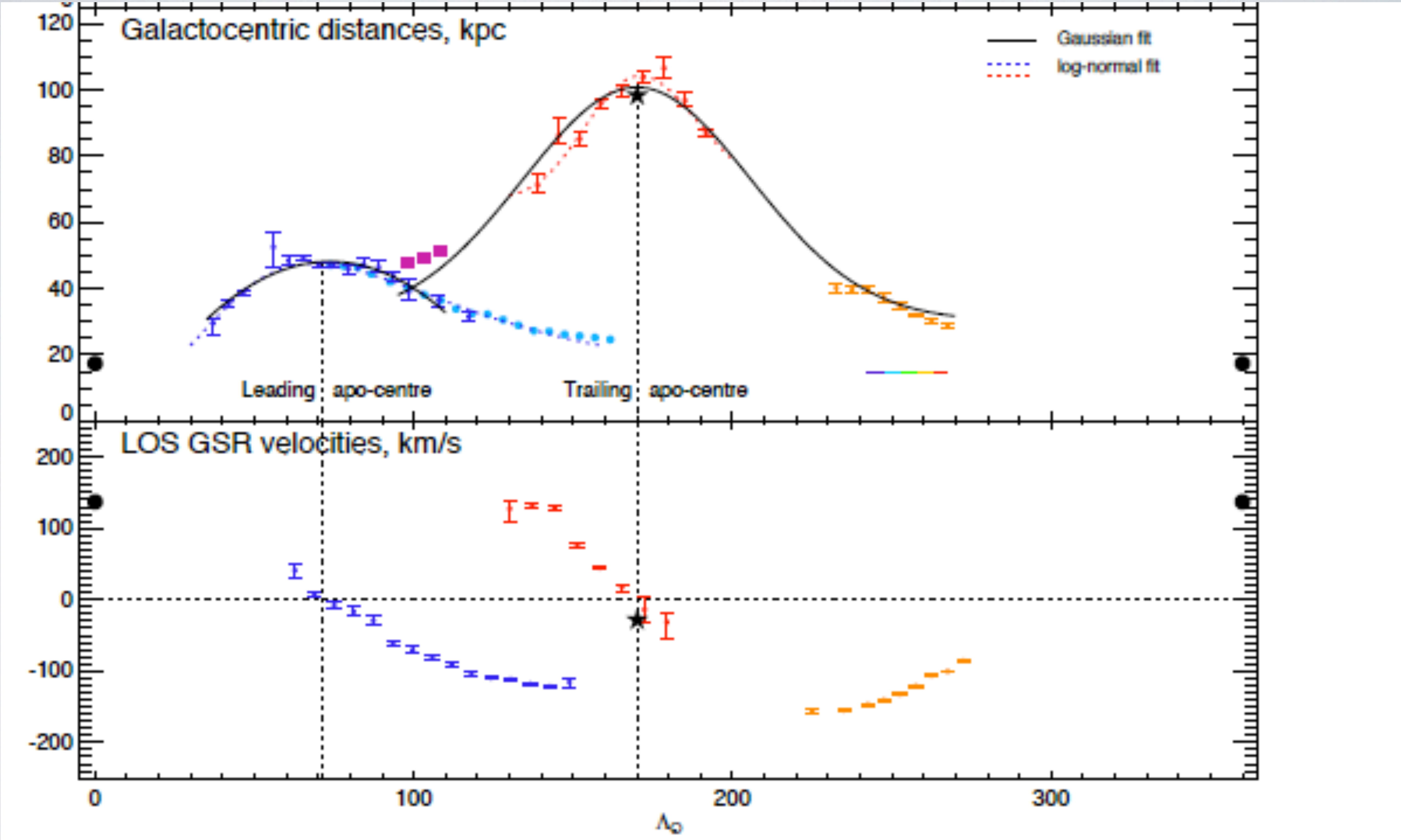
NGC 2419

NGC 2419 is the second-largest (r_h = 18 pc) globular cluster in the Milky Way. Its large size is consistent with a birth in a dwarf galaxy that was subsequently accreted.



The pericentre lies at ~ 24 kpc, close to the present position of the remnant. The leading apocentre is at ~ 50 kpc & the trailing apocentre at ~100 kpc. The angle through which the orbit turns from one apocentre to the next is ~ 93°.

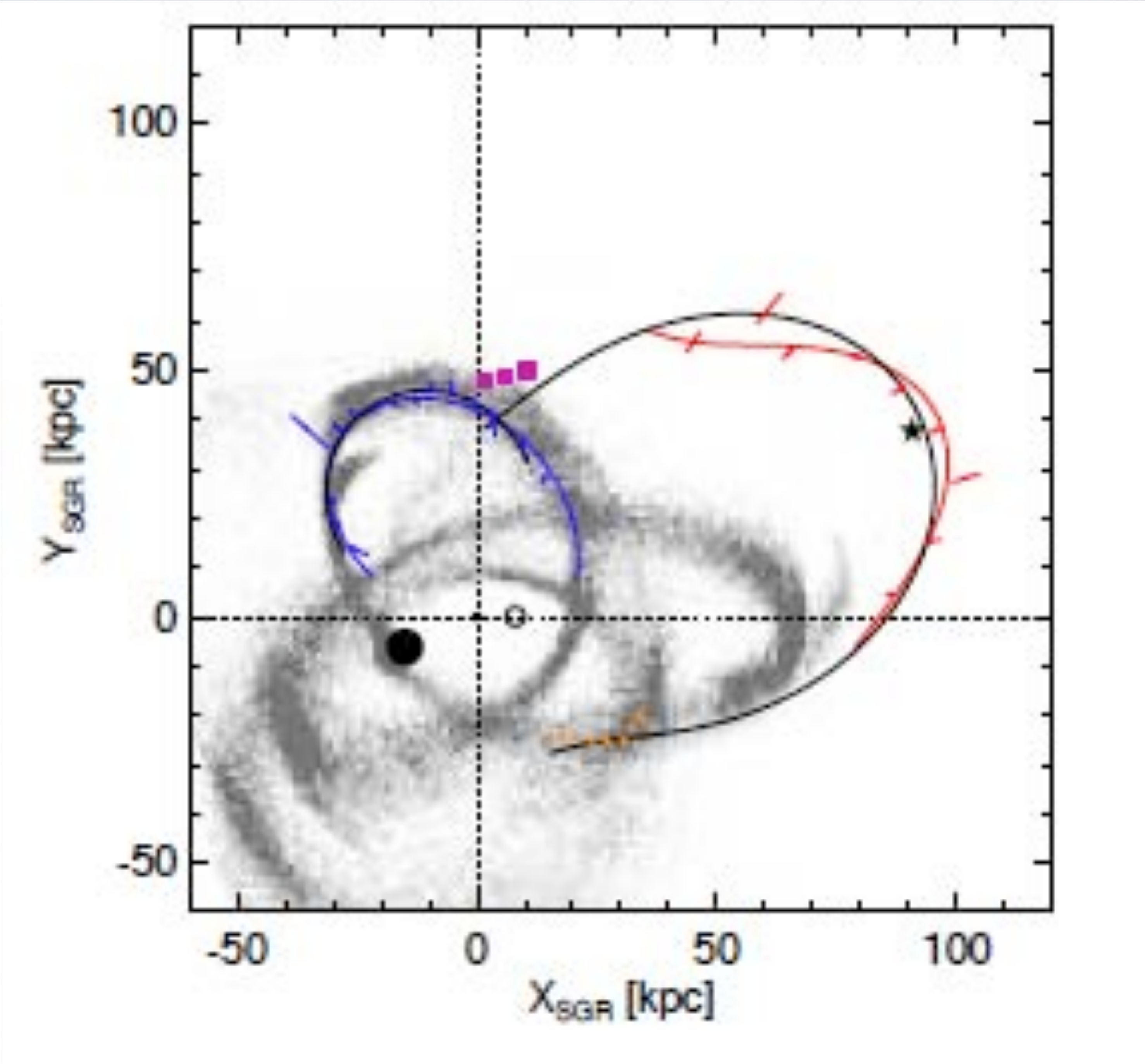
Belokurov, Koposov, Evans et al. 2013



Line of sight (radial) velocities pass through zero at apocentres.

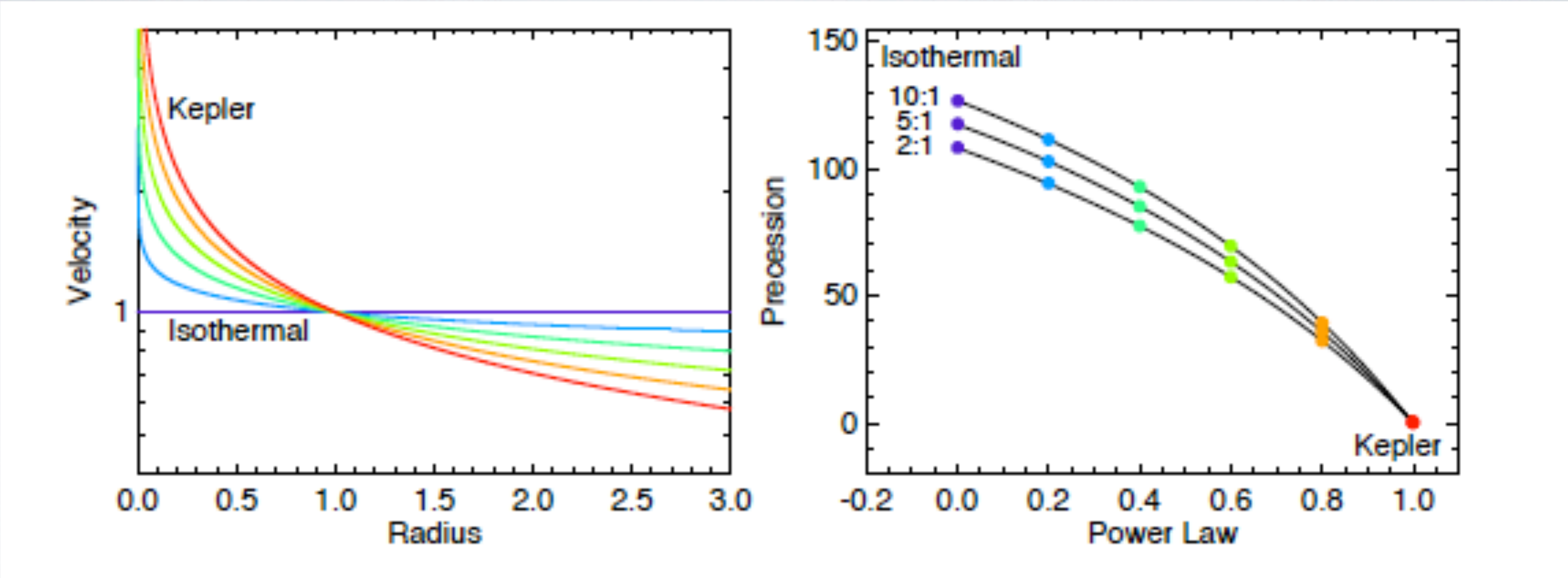
Belokurov, koposov, Evans et al. 2013

THE SAGITTARIUS STREAM



A mismatch between theory and observation!

THE SAGITTARIUS STREAM



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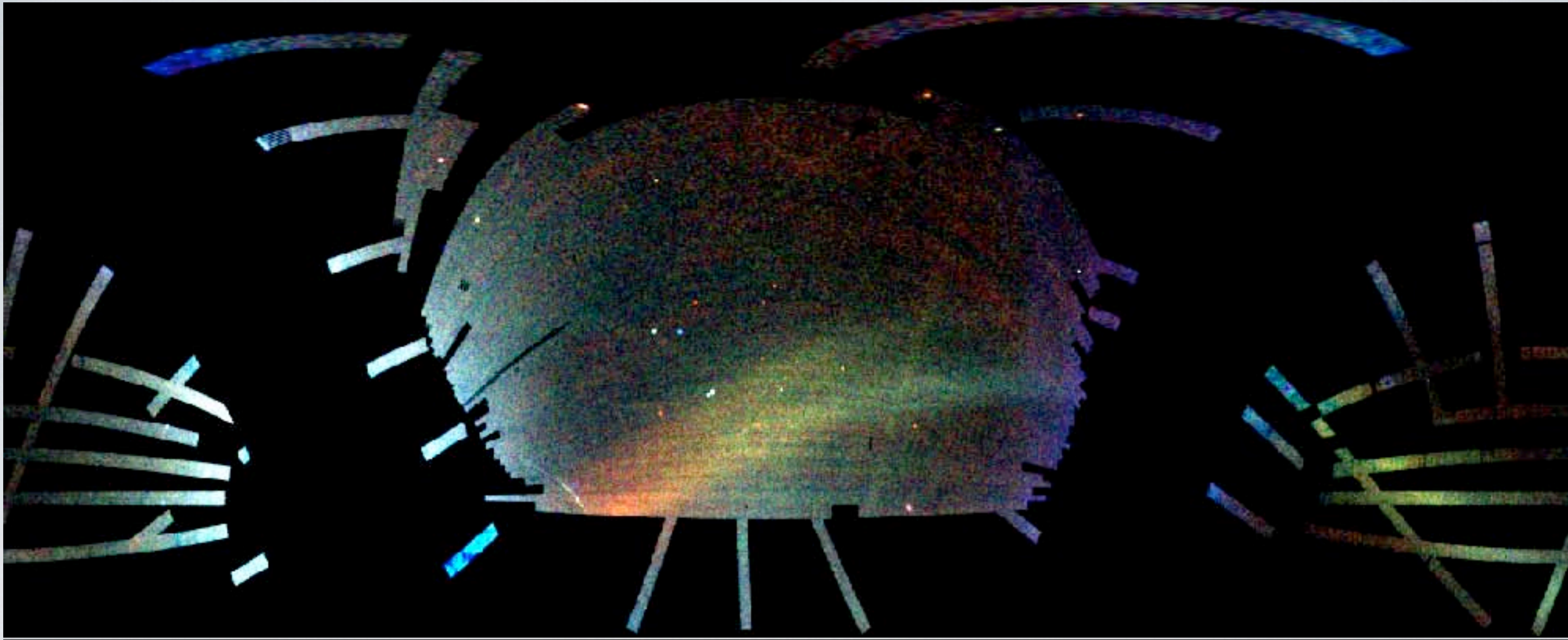
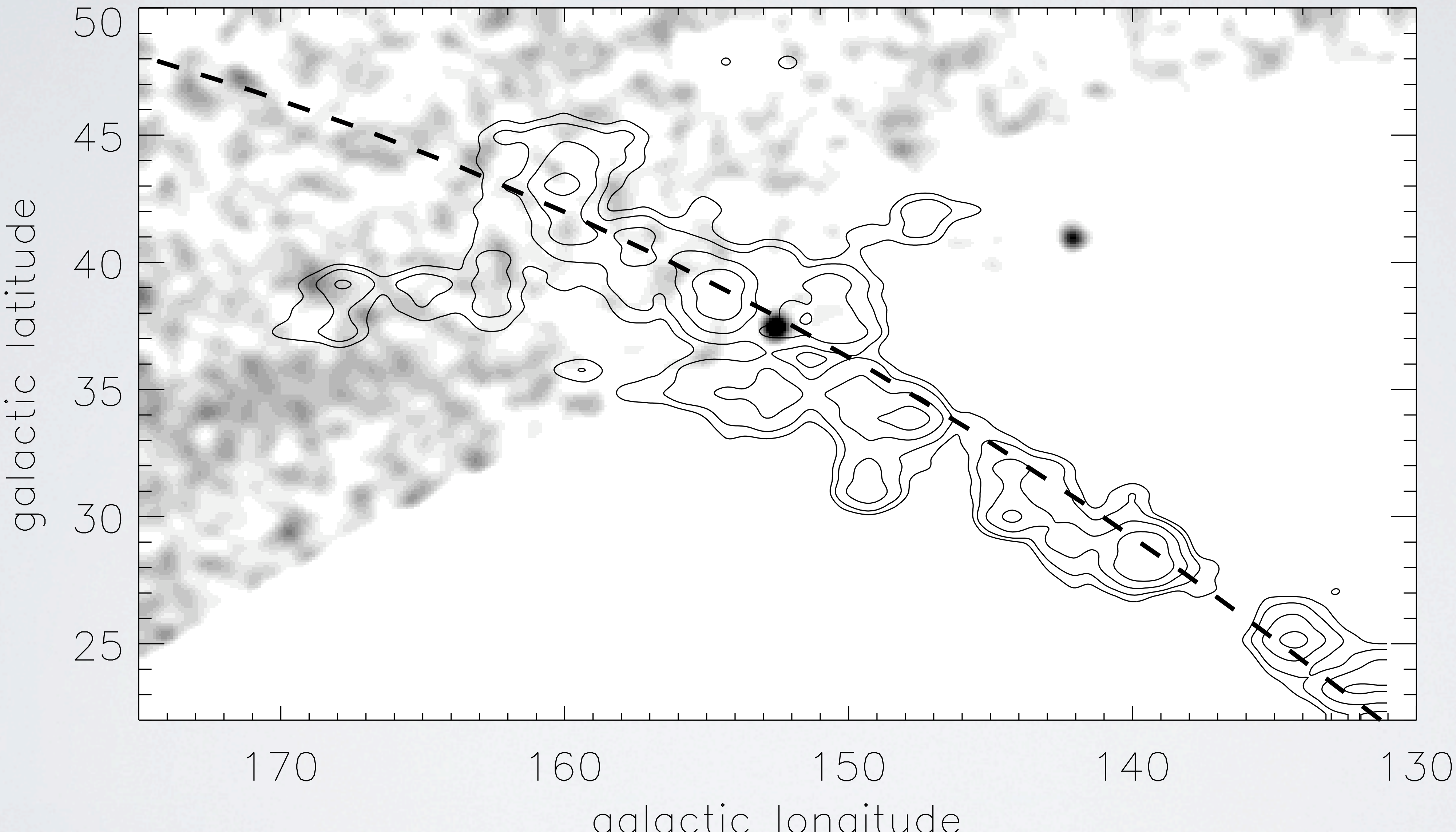
Belokurov, Koposov, Evans et al. 2013

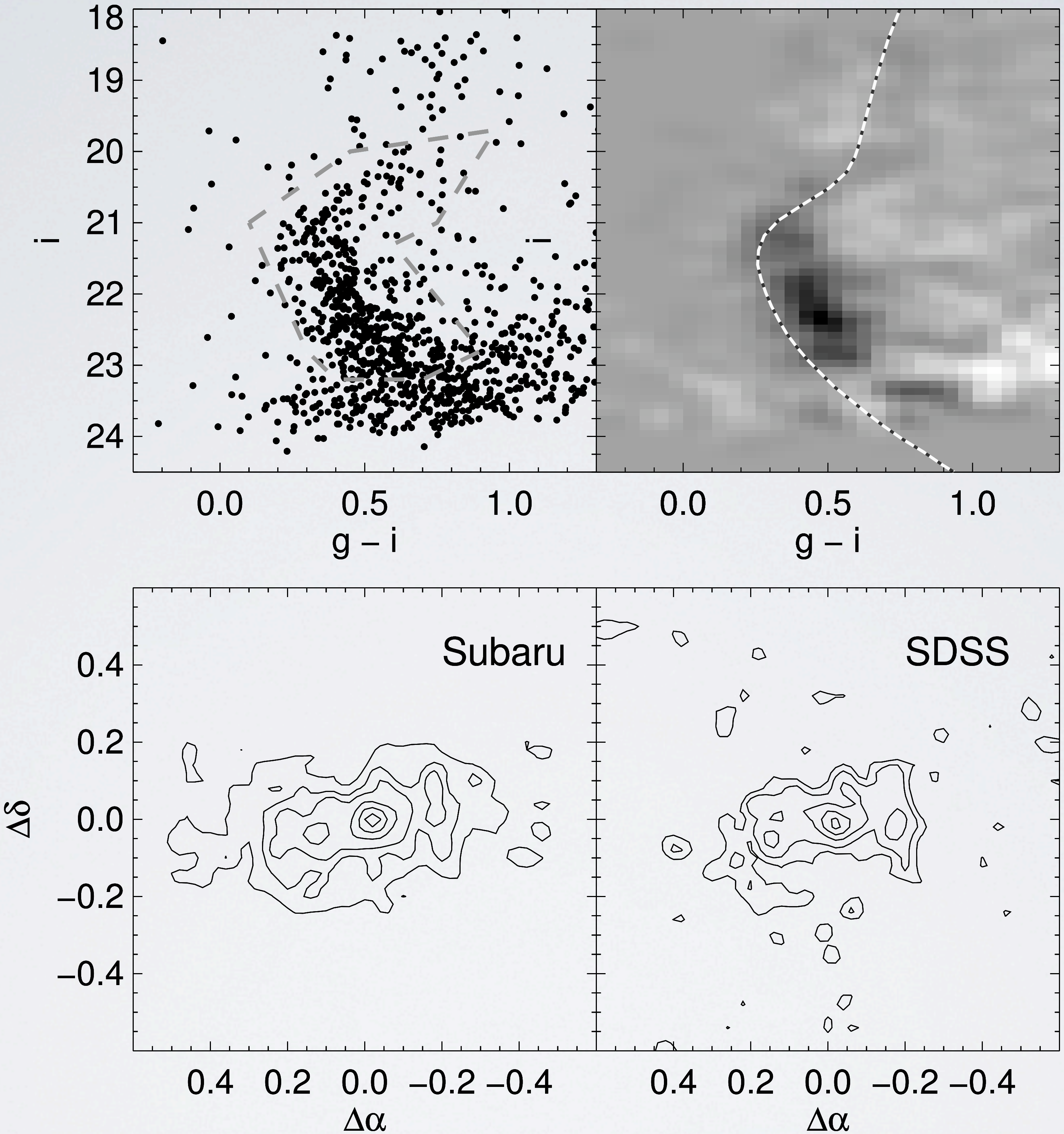


THE ORPHAN STREAM

THE ORPHAN STREAM



The High Velocity Cloud Complex A is aligned with the Great Circle of the Orphan Stream



Ursa Major II, the Intrinsically Faintest Known Galaxy

THE ORPHAN STREAM

The absolute magnitude of the giant star Rigel is
$M_V \approx -6.1$

The absolute magnitude of the Ursa Major II galaxy is $M_V \approx -3.8$.

It is tempting to associate UMa II with the progenitor of the Orphan Stream. It is at the same distance.
Newberg et al (2010) report that its radial velocity disagrees.

The Orphan Stream remains parentless.

THE STREAMS

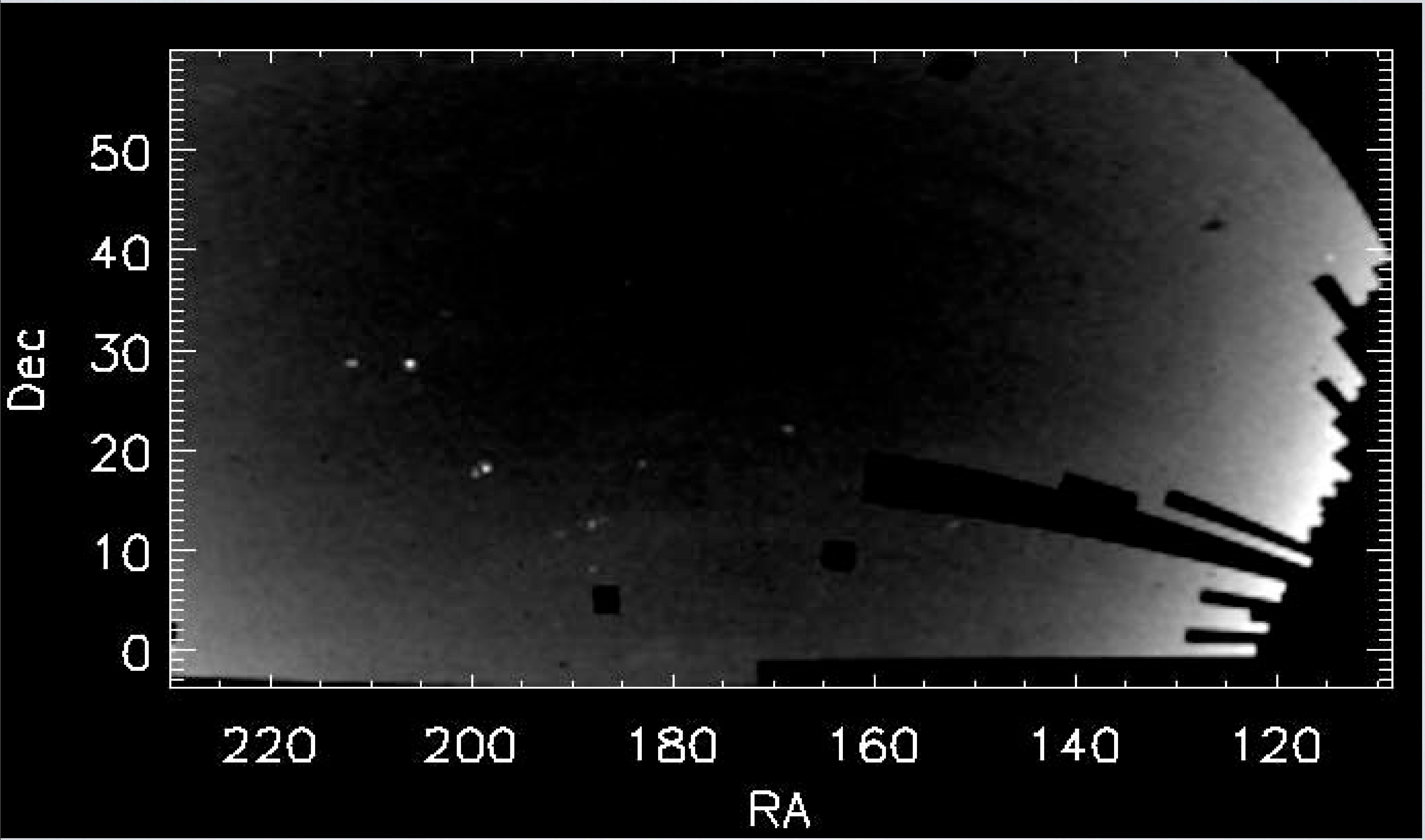
1. The Sgr Stream Remains A Riddle Wrapped in an Enigma

- the progenitor was more luminous than any known Milky Way/M31 dSph, and so was probably a dIrr,
- there are at least four tails (possibly more) in both the North and the South,
- there is evidence that the streams are not orbits, but nonetheless this is a powerful probe of the potential.

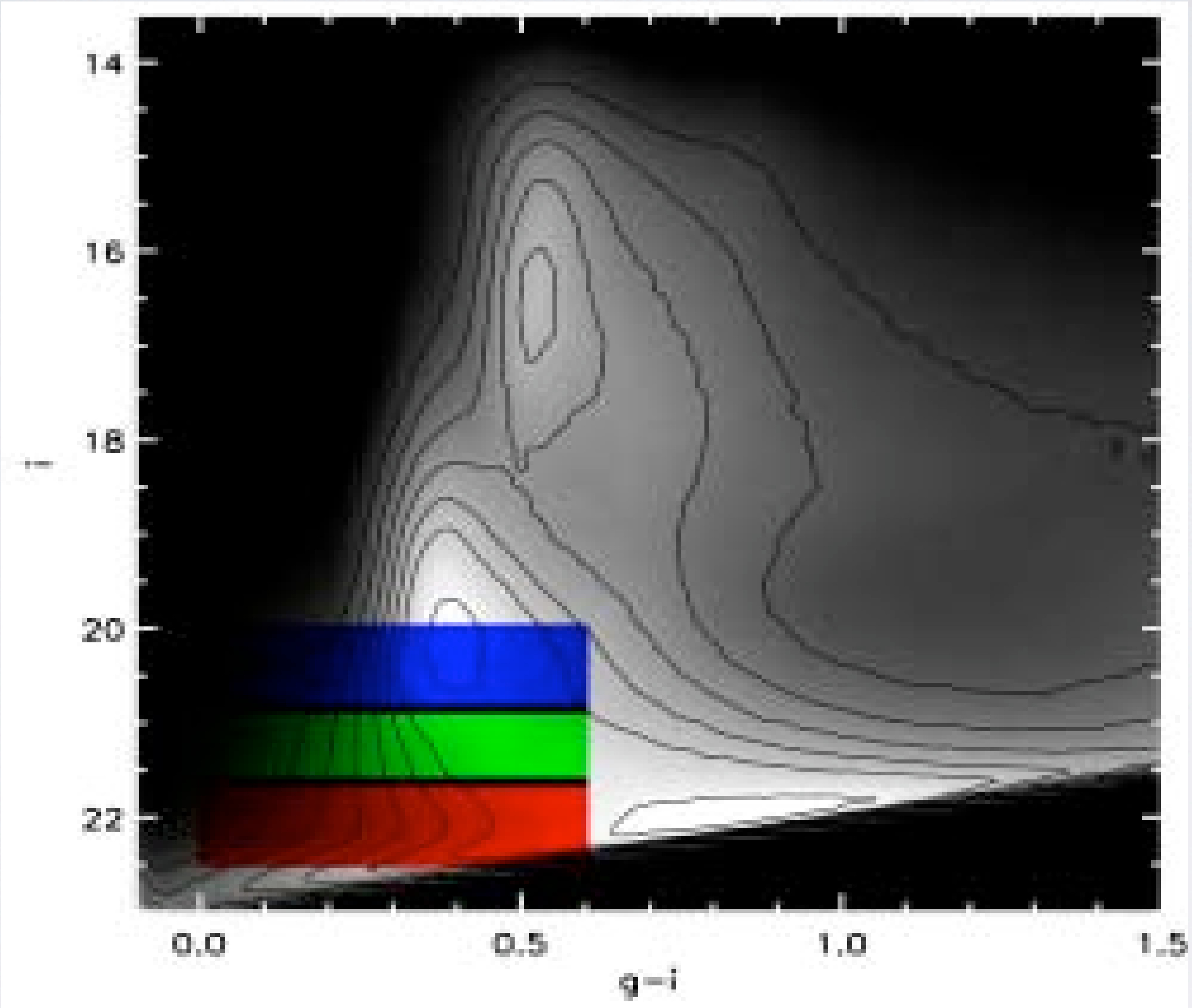
2. The Orphan Stream is Thinner

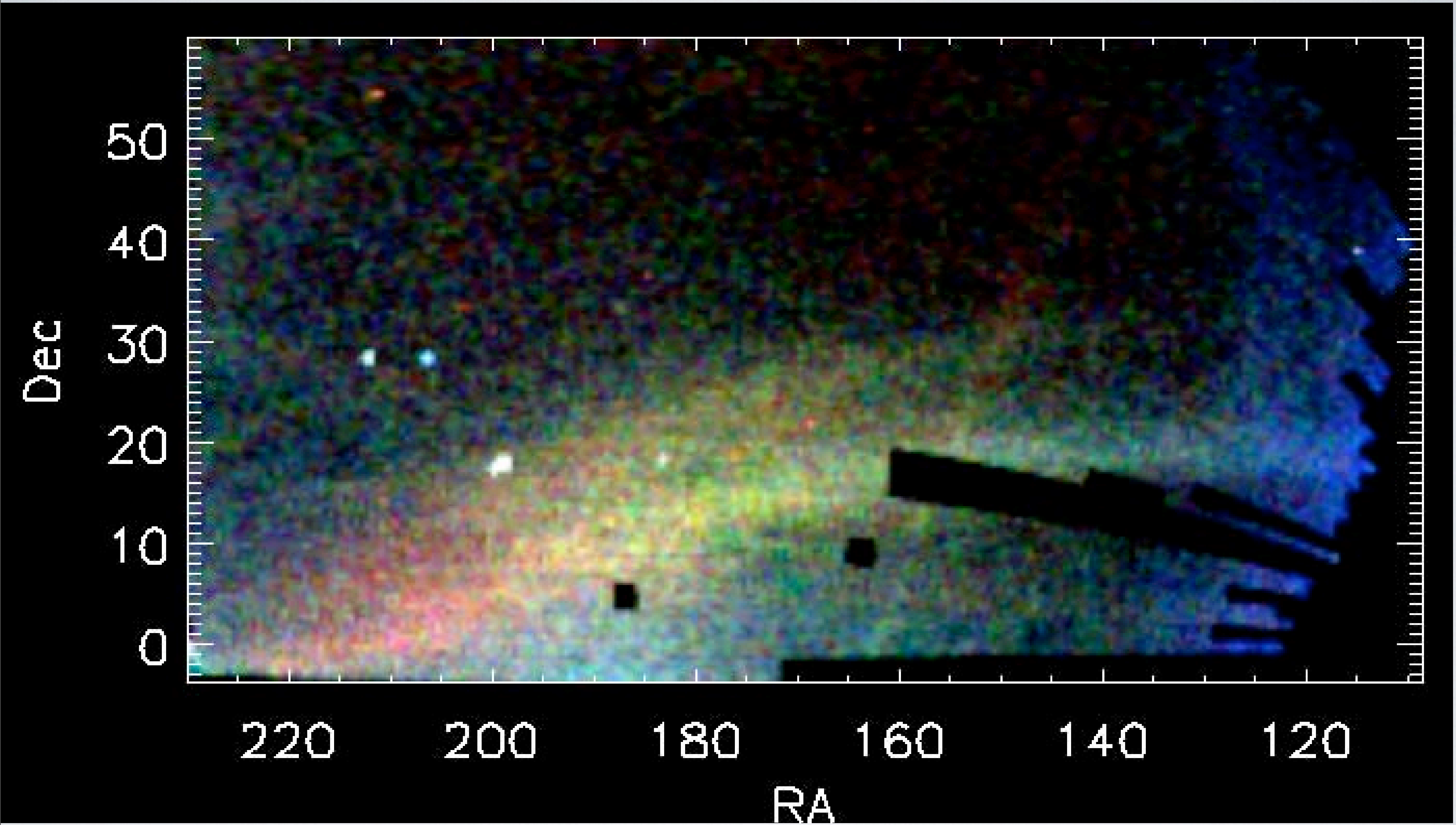
- the progenitor was a small dwarf spheroidal galaxy ($\sigma \sim 10$ kms^{-1}).
- possibly associated with Ursa Major II and Complex A, (as well as Segue 1 and a number of young halo globular clusters like Ruprect 106, Pal 1. all of which are in the same orbital plane).

THE SATELLITES

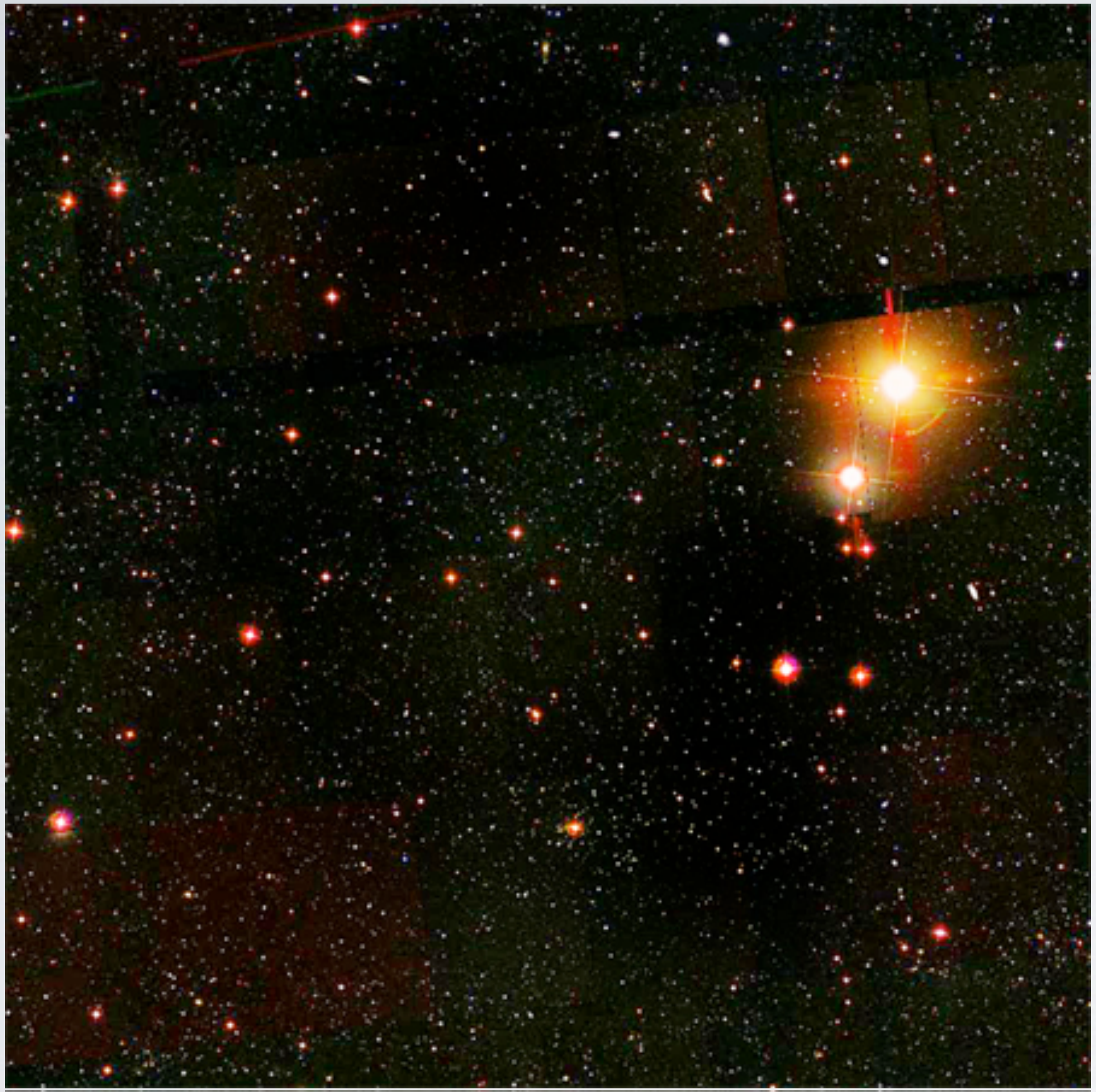


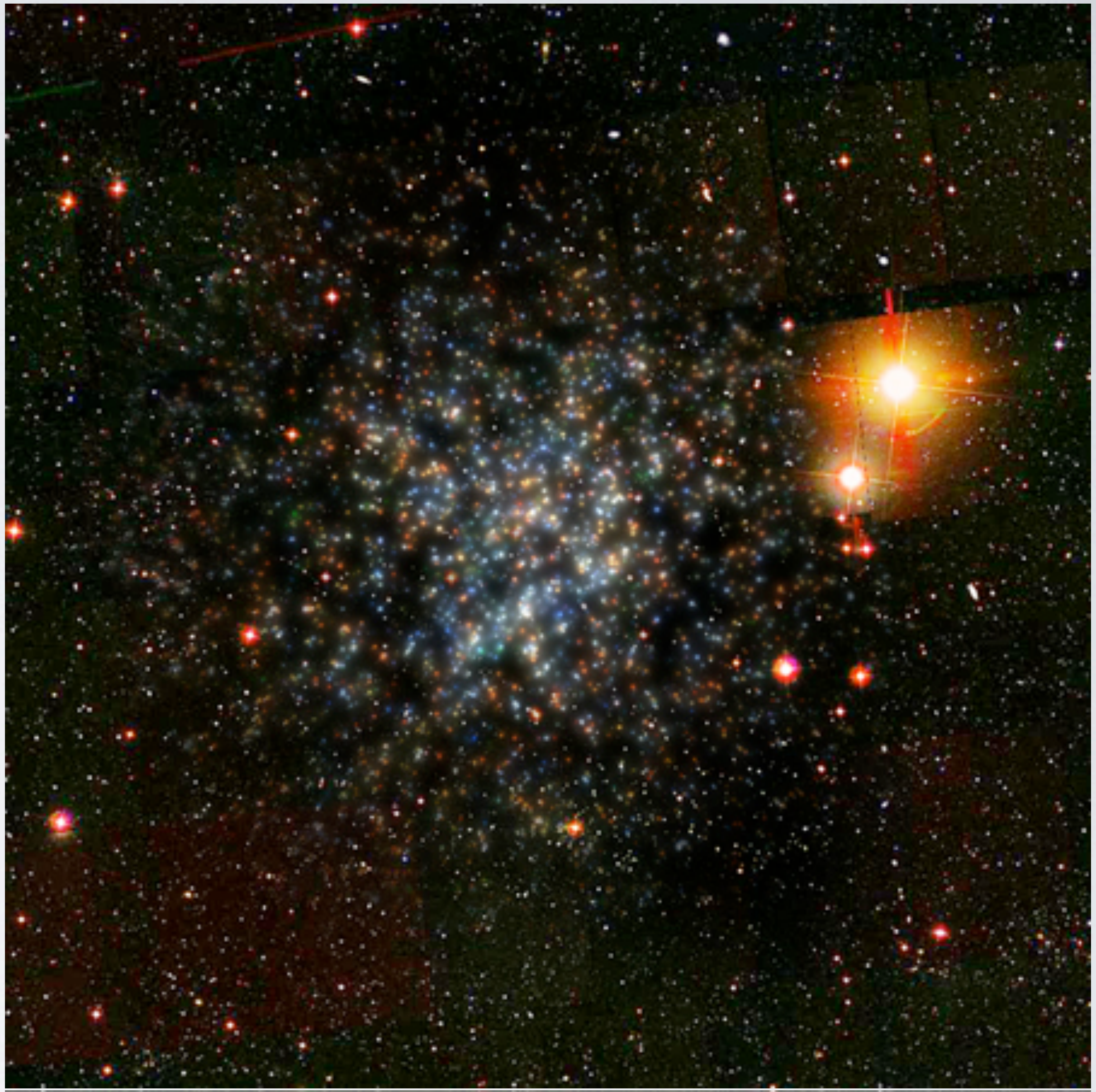
THE SATELLITES





The Field of Streams





Belokurov, Zucker, Evans et al., 2006

BOOTES I DWARF

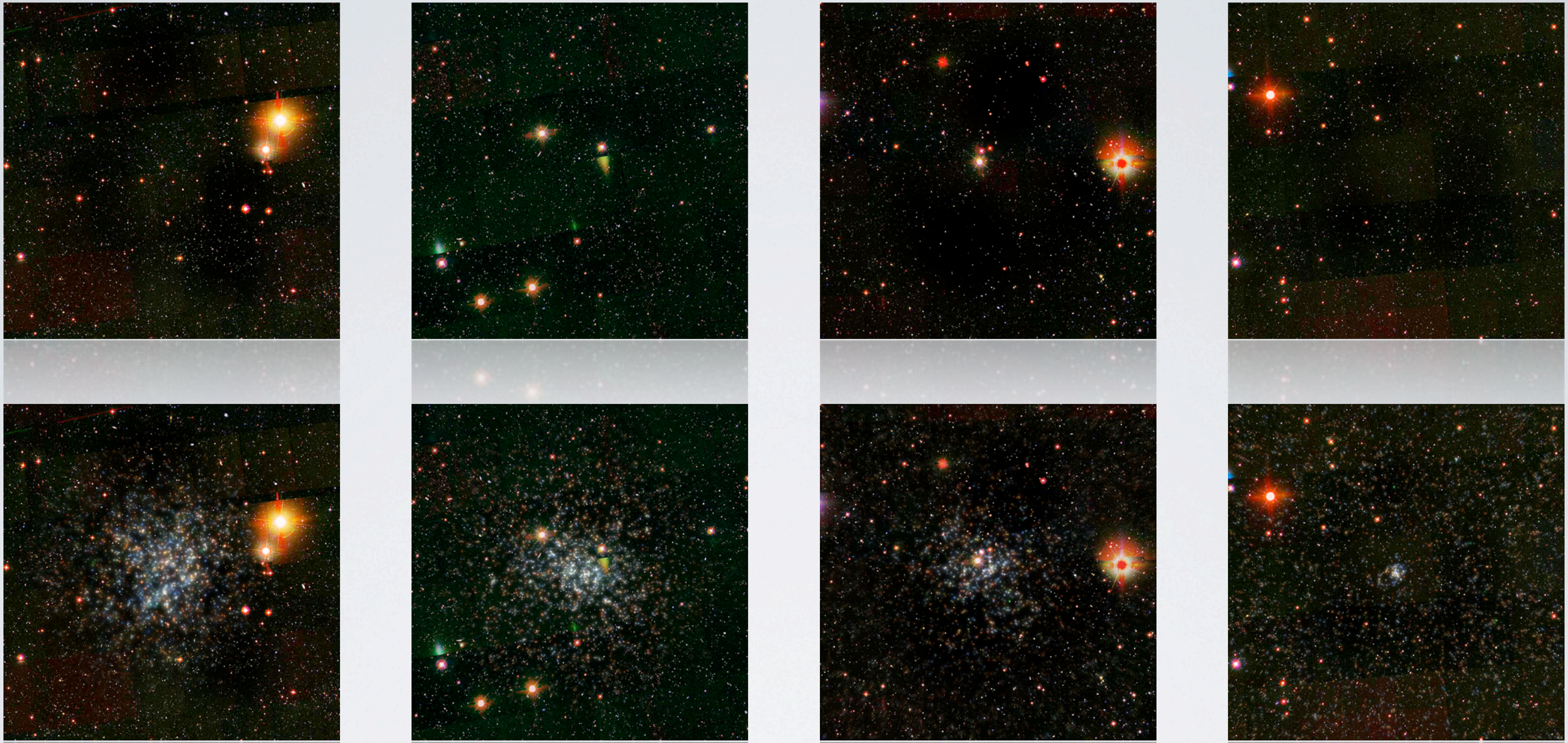
Absolute Magnitude M_V =-5.8, Heliocentric Distance = 60 kpc

THE SATELLITES

Bootes I is an ultrafaint dwarf galaxy. The ultrafaints are phantoms. Their low surface brightness means they cannot be detected on images. They are invisible.

They can be detected as over-densities of resolved stars, and confirmed to possess the characteristics of galaxies by colour-magnitude diagrams.

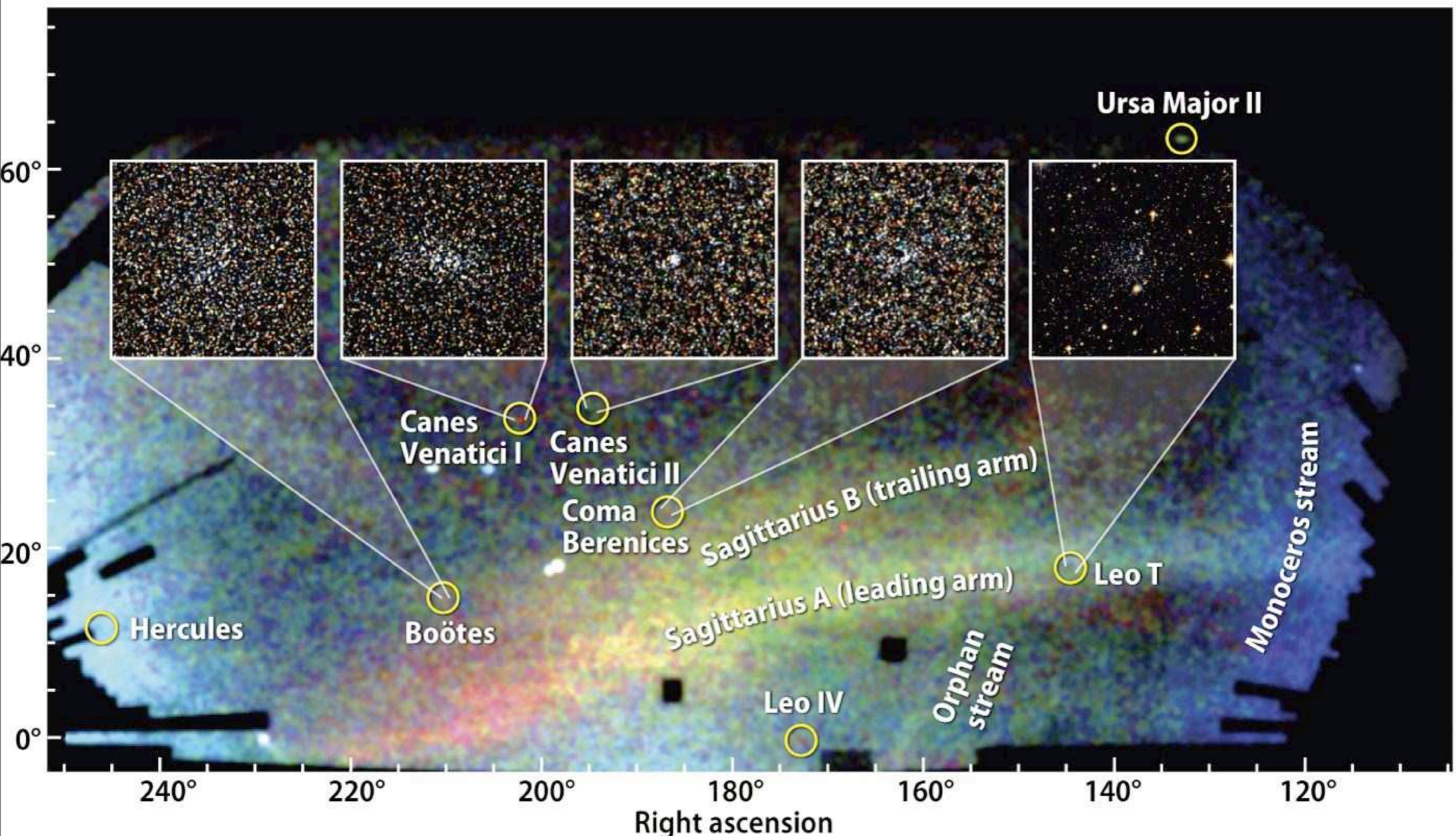
They are usually disrupting, composed of old stars, and have an absolute magnitude of -8 or fainter. The *Field of Streams* is a treasure-trove of ultrafaints.



Belokurov, Zucker, Evans et al., 2007, ApJ

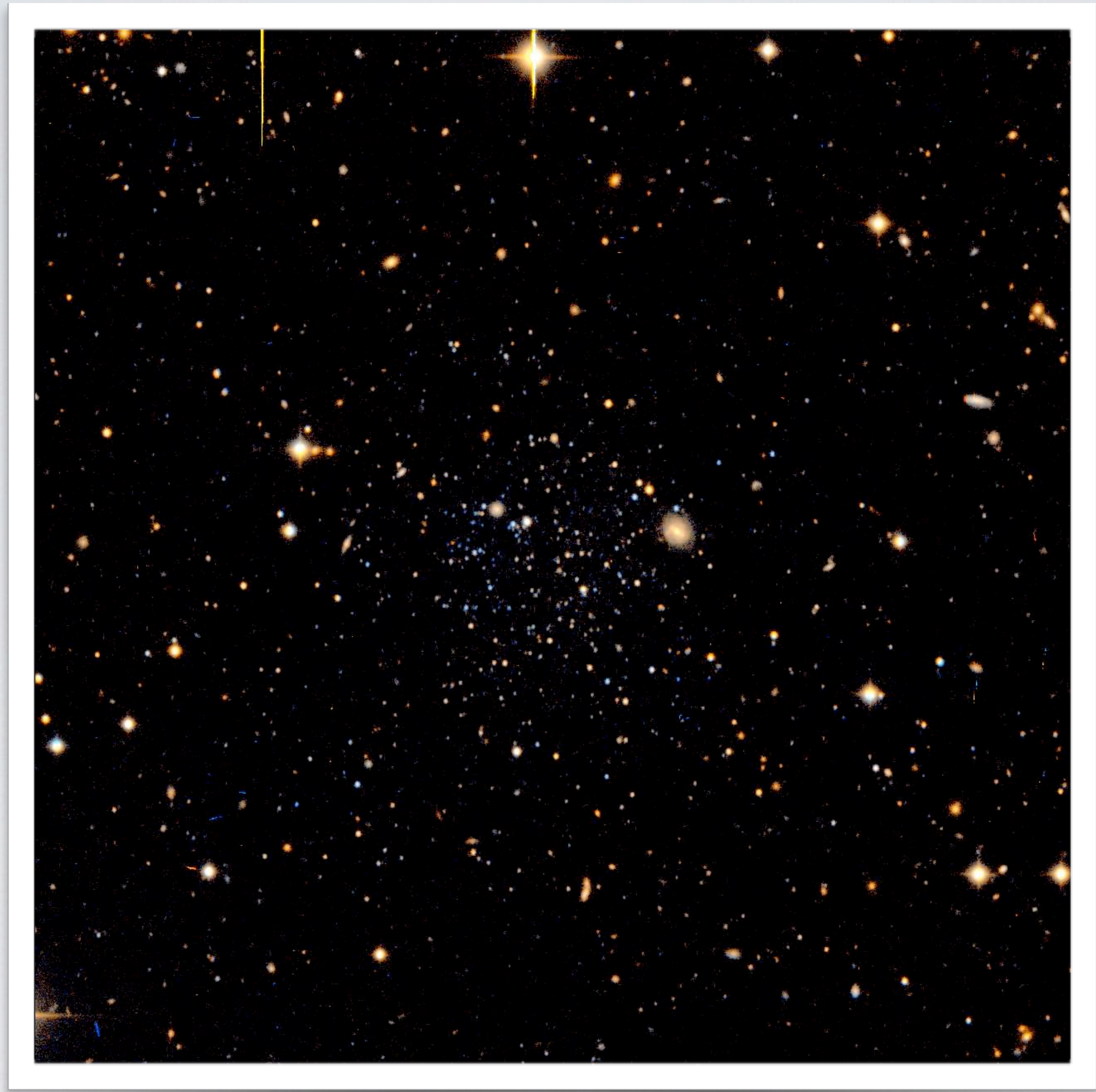
THE ULTRA-FAINTS

The ultra-faints have absolute magnitudes of ≈ -4 and heliocentric distances of between 50 and 200 kpc.



The Field of Streams

LEO T



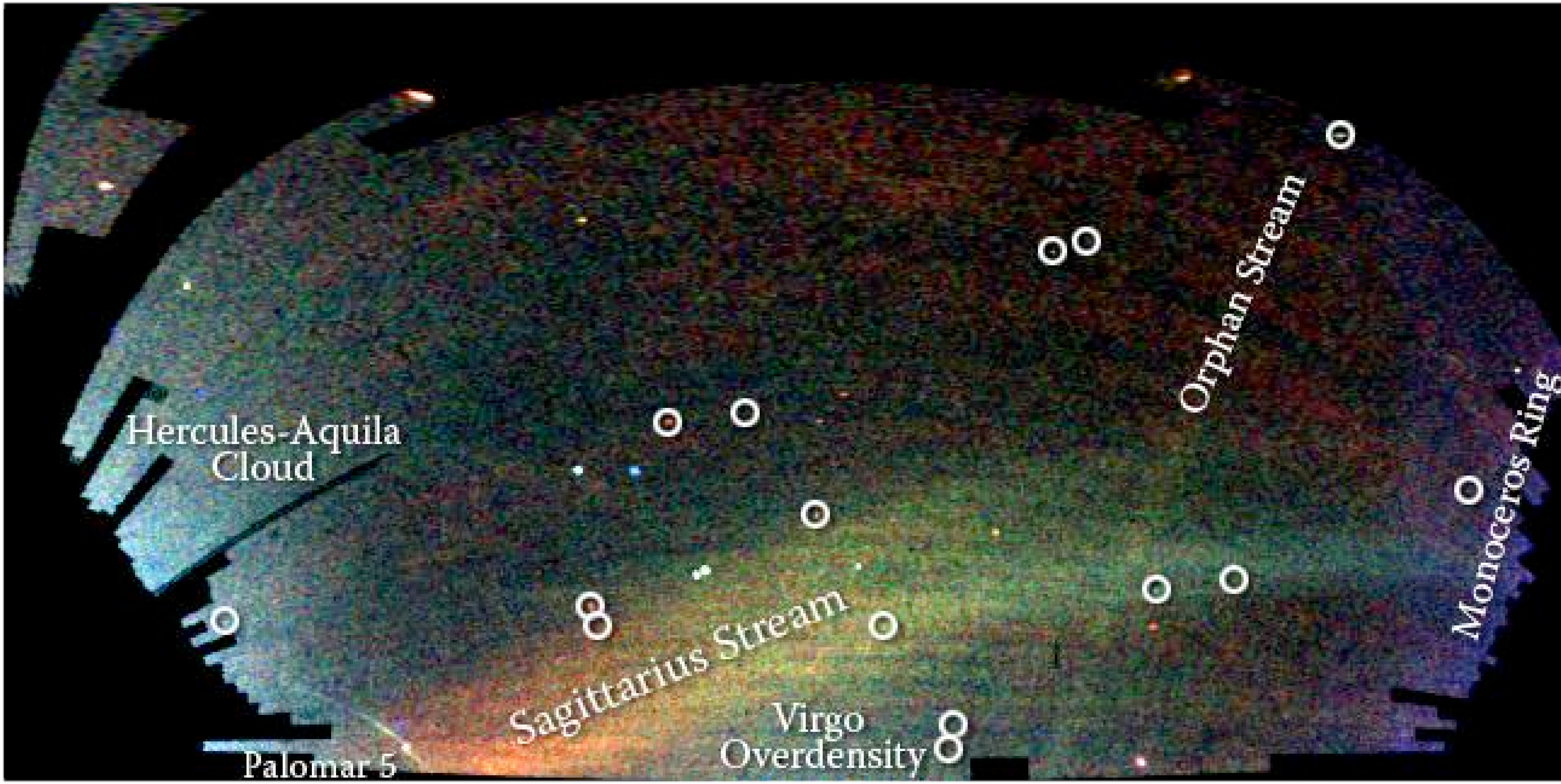
Leo T is the faintest known galaxy with ongoing star formation.

Irwin, Belokurov, Evans et al. 2007

LEO T

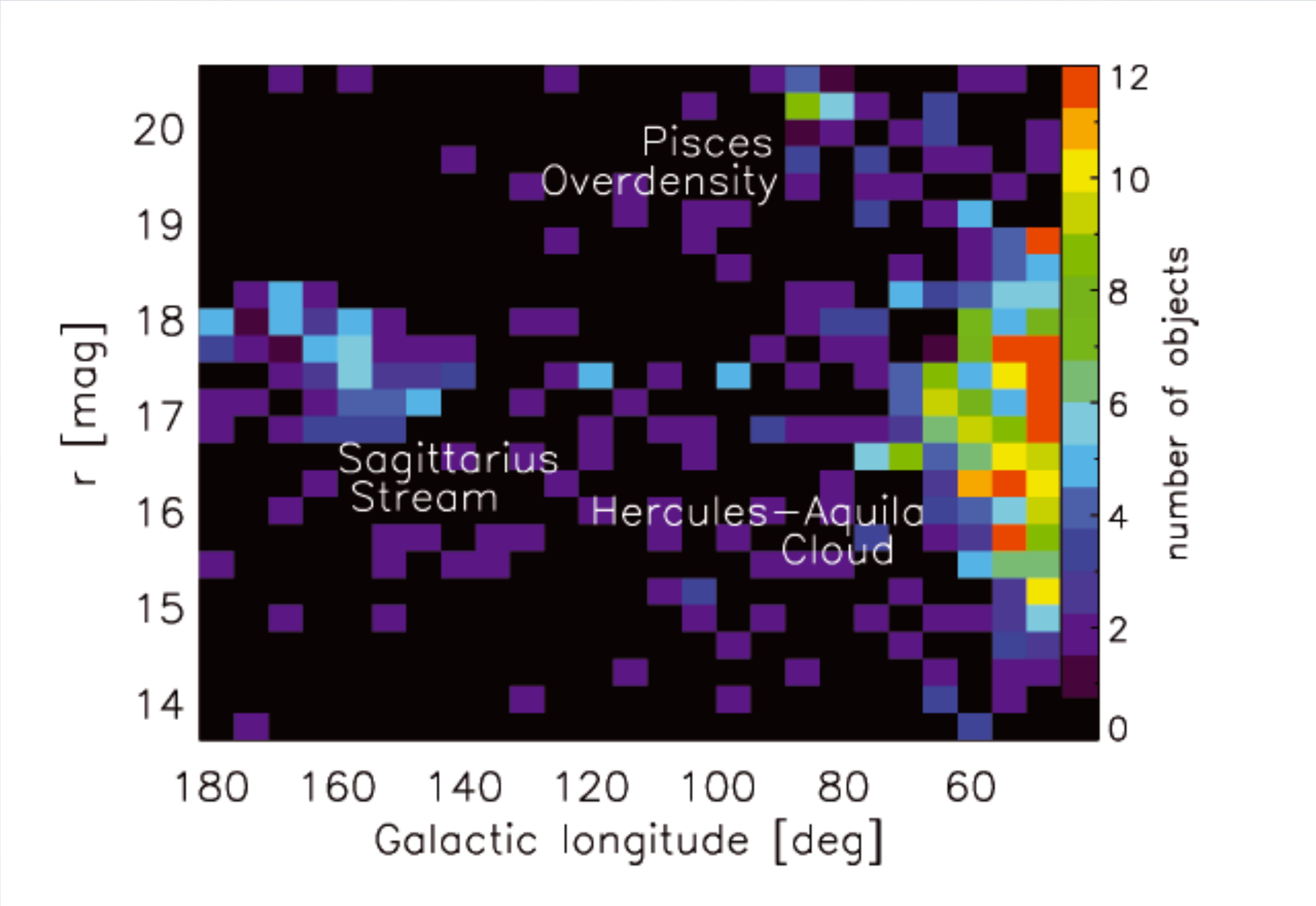
Leo T has a stellar mass of 10^5 solar masses, but an HI mass of twice that.

Ryan-Weber et al. 2008



In the preceding half century, dwarf galaxies around the Milky Way were found at a rate of one a decade. In 2006-2009, fifteen were discovered in Cambridge.

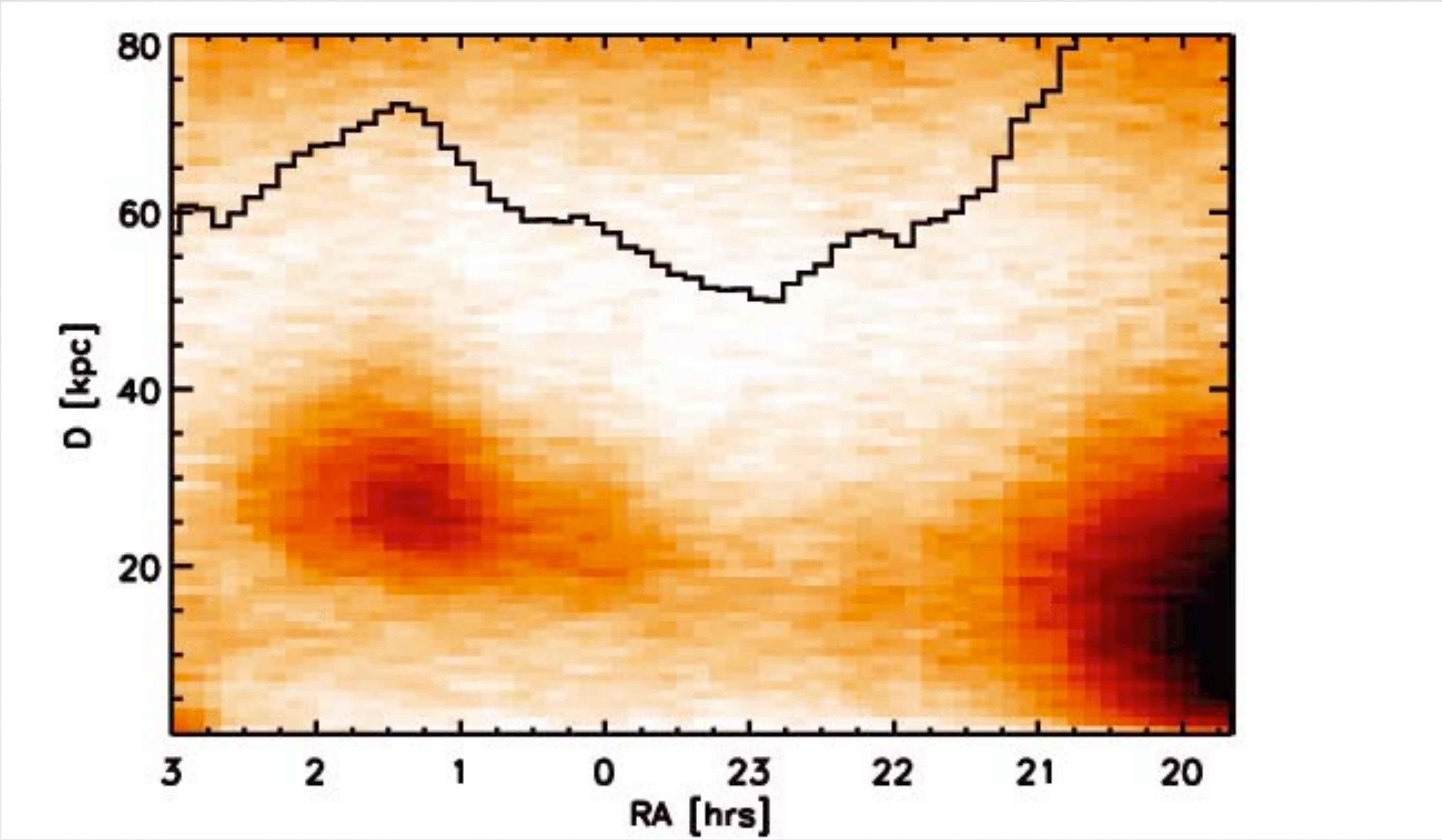
THE SATELLITES



Stripe 82 in RR Lyraes

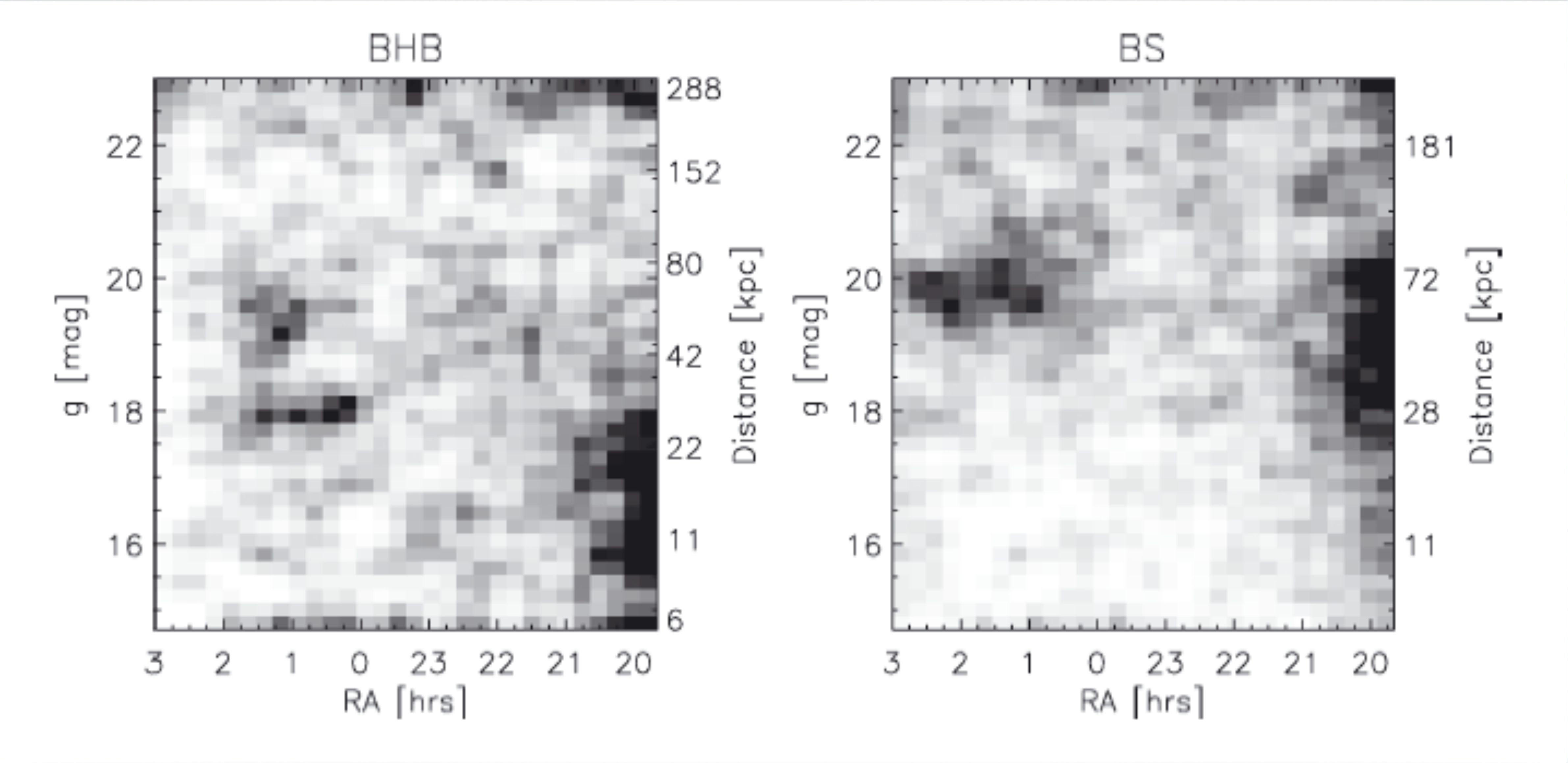
Watkins, Evans et al. 2009

THE SATELLITES

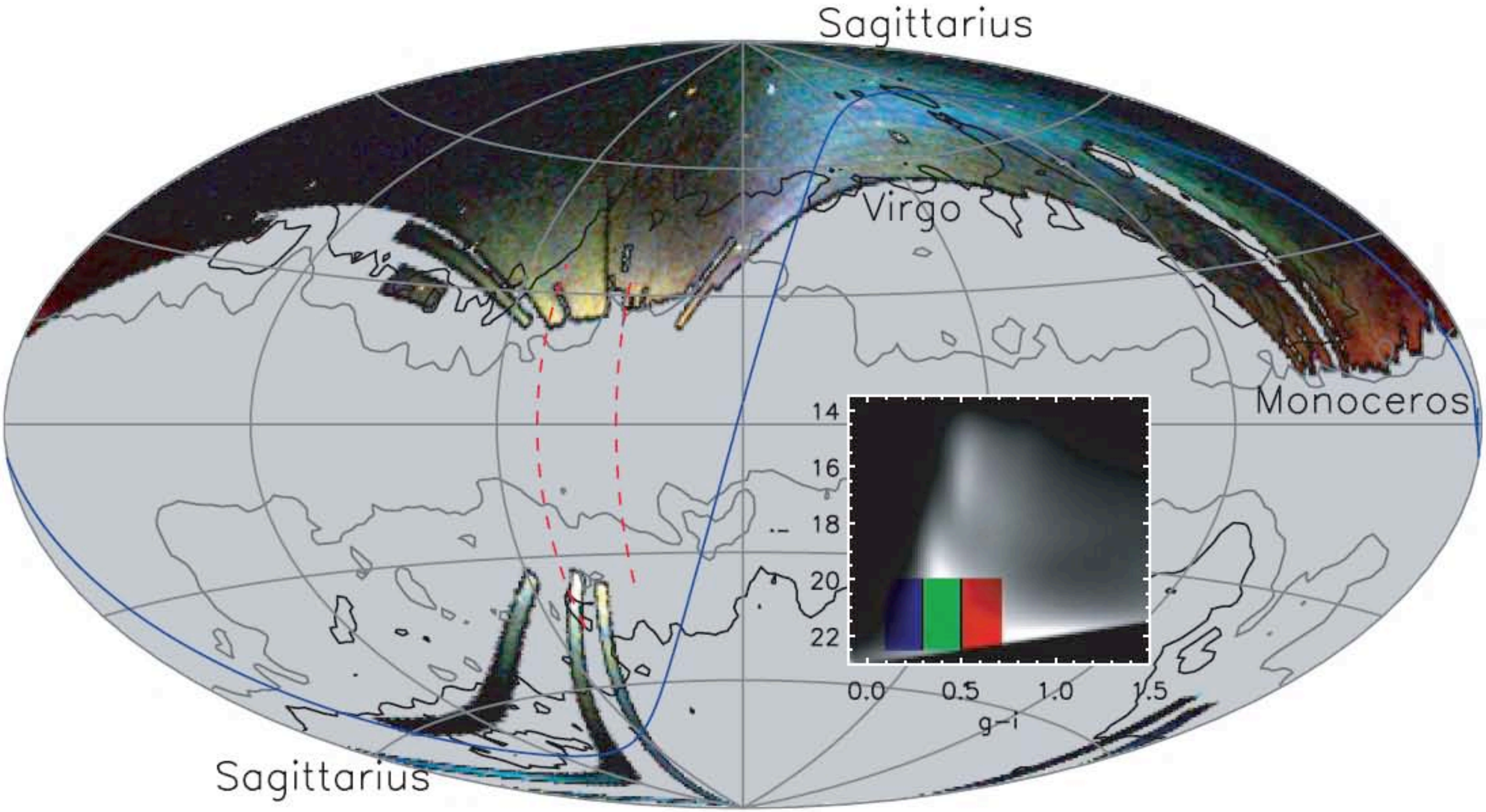


Stripe 82 in MSTOs

THE SATELLITES



Stripe 82 in BHBs & BSs



Belokurov, Evans et al. 2008

THE HERCULES-AQUILA CLOUD

THE SATELLITES

The Hercules-Aquila Cloud is centered at $l = 40^o$ and stretches 100° in latitude. Its heliocentric distance is about 20 kpc, an absolute magnitude of ~ -13. It stellar population is comparable to M92.

The Pisces Overdensity (Pisces I) is a probable dwarf galaxy at 80 kpc, probably quite extended. It was subsequently spectroscopically confirmed by Kollmeier et al (2009).

THE SATELLITES

The SDSS discoveries of Milky Way satellites now numbers 20.

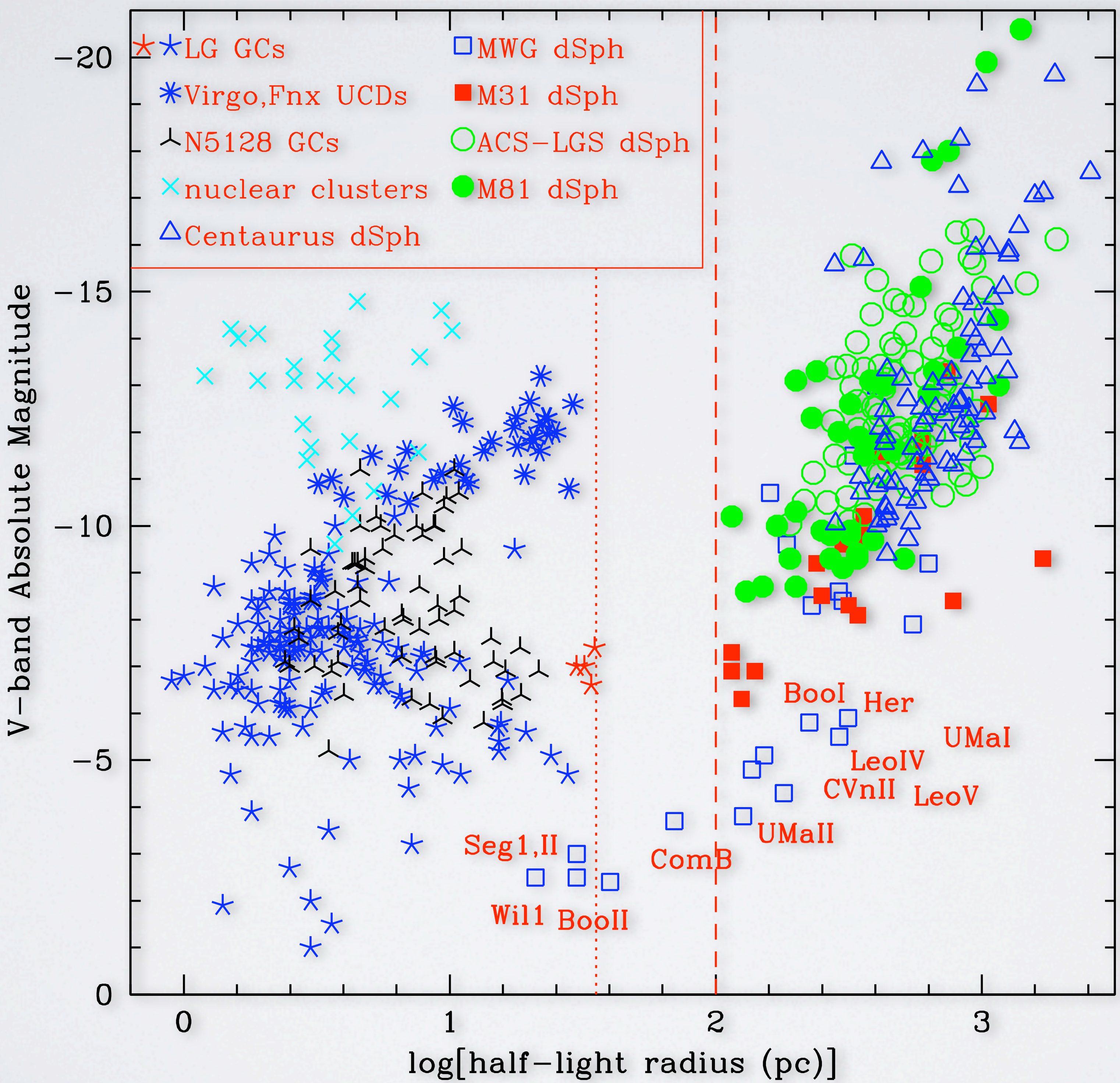
It includes one likely dwarf irregular galaxy (Leo T). & one classical dwarf spheroidal (Canes Venatici I).

This includes 11 ultrafaint dwarf galaxies (Bootes I, Bootes II, Canes Venatici II, Hercules, Coma Berenice, Leo IV, Leo V, UMa I, UMa II, Pisces I, Pisces II),

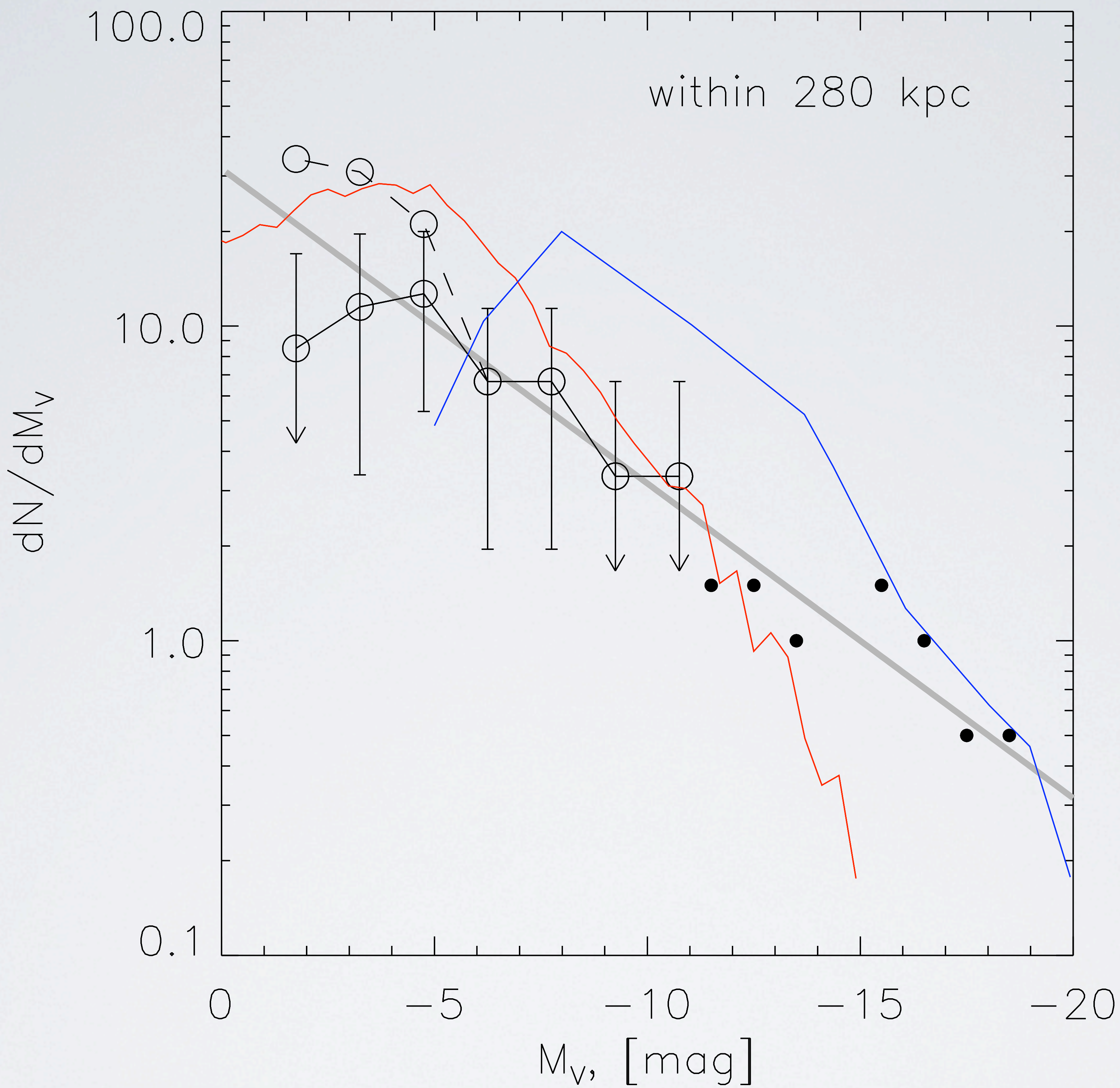
It includes 7 objects that are probably star clusters (Willman 1, Segue 1, 2 and 3, Koposov 1, 2 and 3).

It includes two Clouds, the Virgo Overdensity & the Hercules-Aquila Cloud.

THE SATELLITES



Koposov, Evans et al. 2009



The Observed Luminosity Function Compared with Theoretical Predictions

THE SATELLITES

Mass to light ratios of the ultrafaints require spectroscopy on 8m or 10 m class telescopes.

The intrinsic velocity dispersion of the stars in the ultrafaints is very low. Variable stars, binary stars and interlopers are all serious problems that can inflate the velocity dispersion.

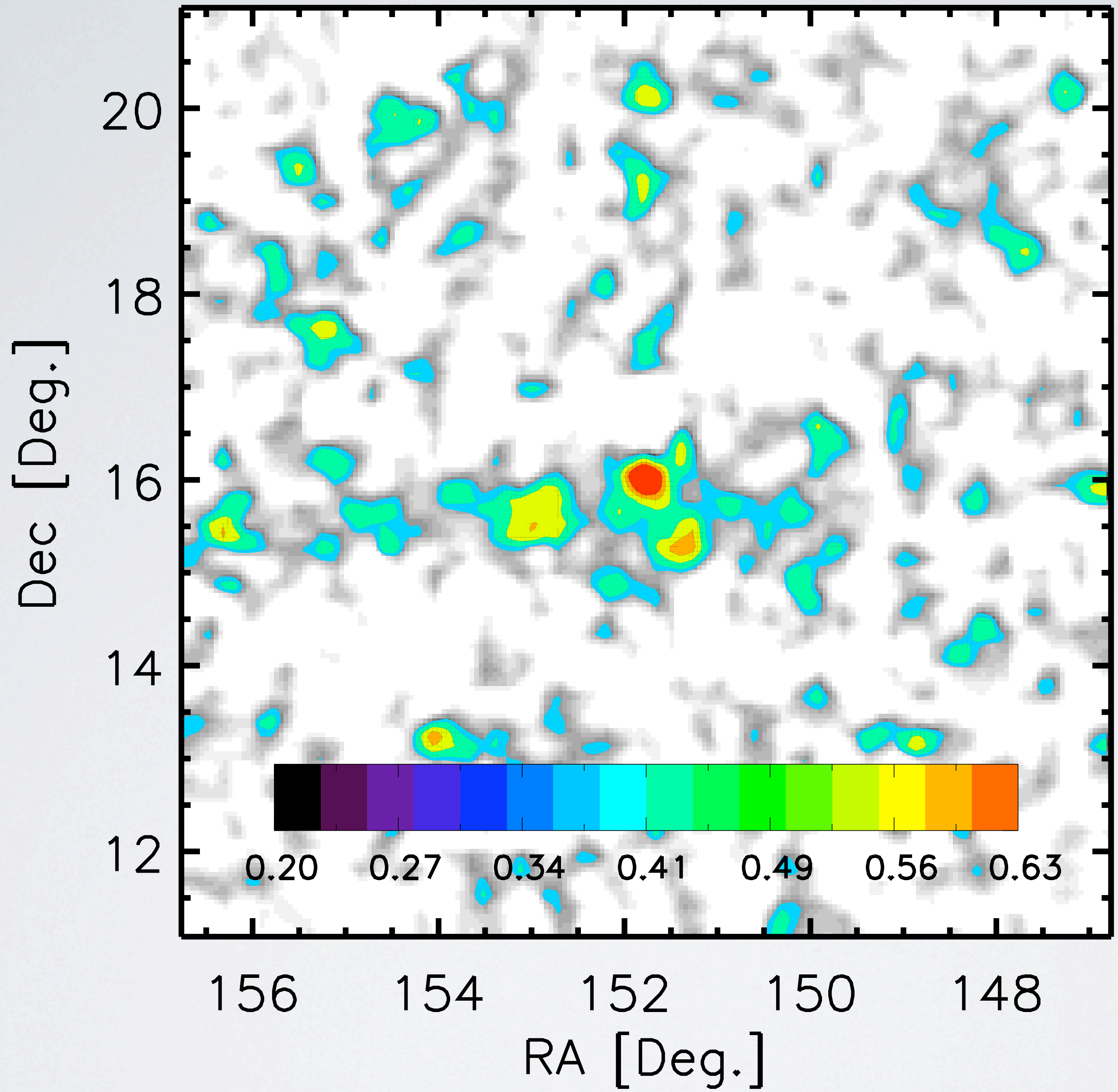
Velocity dispersion measurements require considerable care.

DARK MATTER CONTENT ?

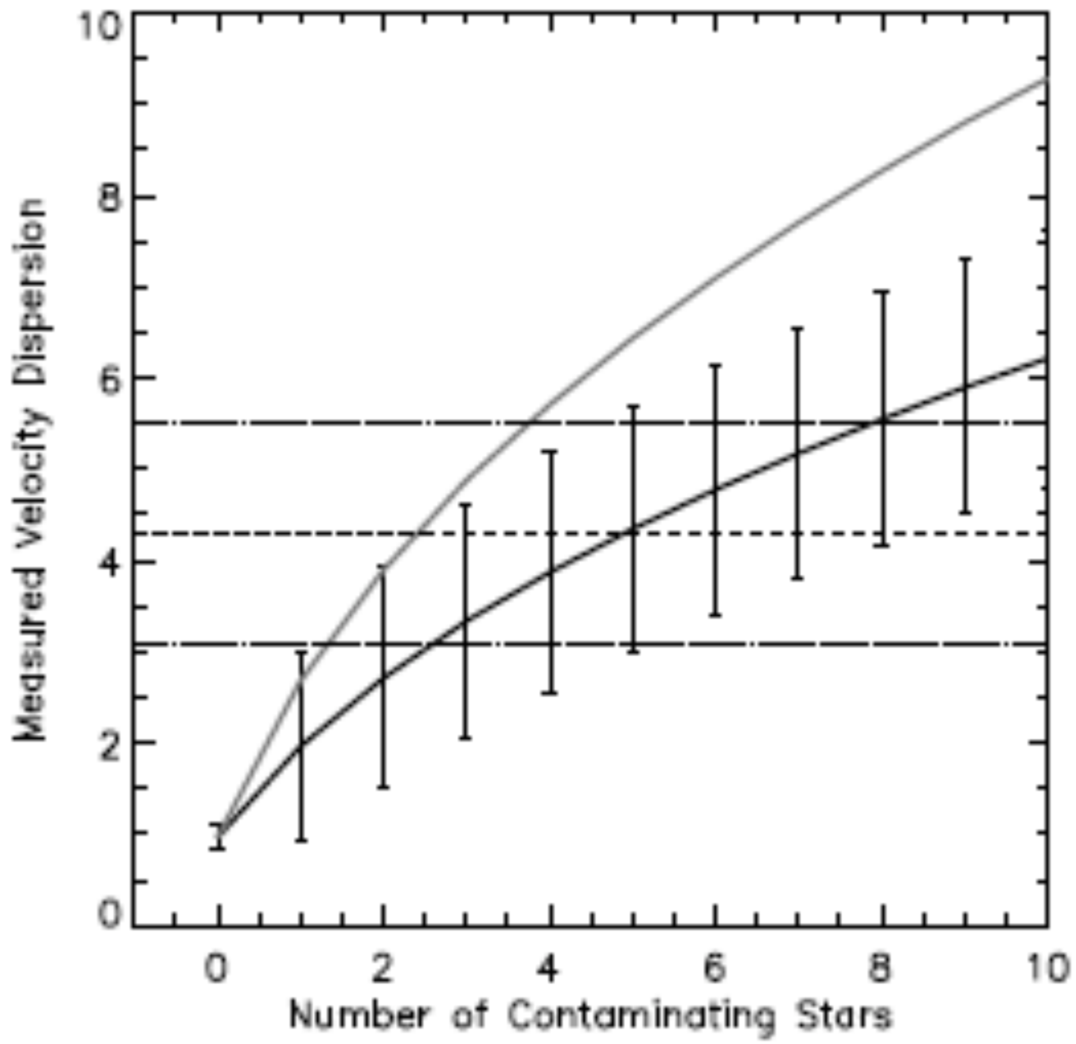
Simon & Geha (2007) used the Keck Telescope to measure the velocities of ≈ 20-200 stars in 8 ultra-faints, and claimed velocity dispersions of ≈3 to 8 km/s and mass-to-light ratios of up to ≈1000.

Segue 1-- one of the ultra-faints -- has been claimed by as the most dark matter dominated galaxy known with a mass-to-light ratio of ≈ 4000 (inferred from velocity dispersion of 4.1 kms^{-1}).

Niederste-Ostholt et al. 2010

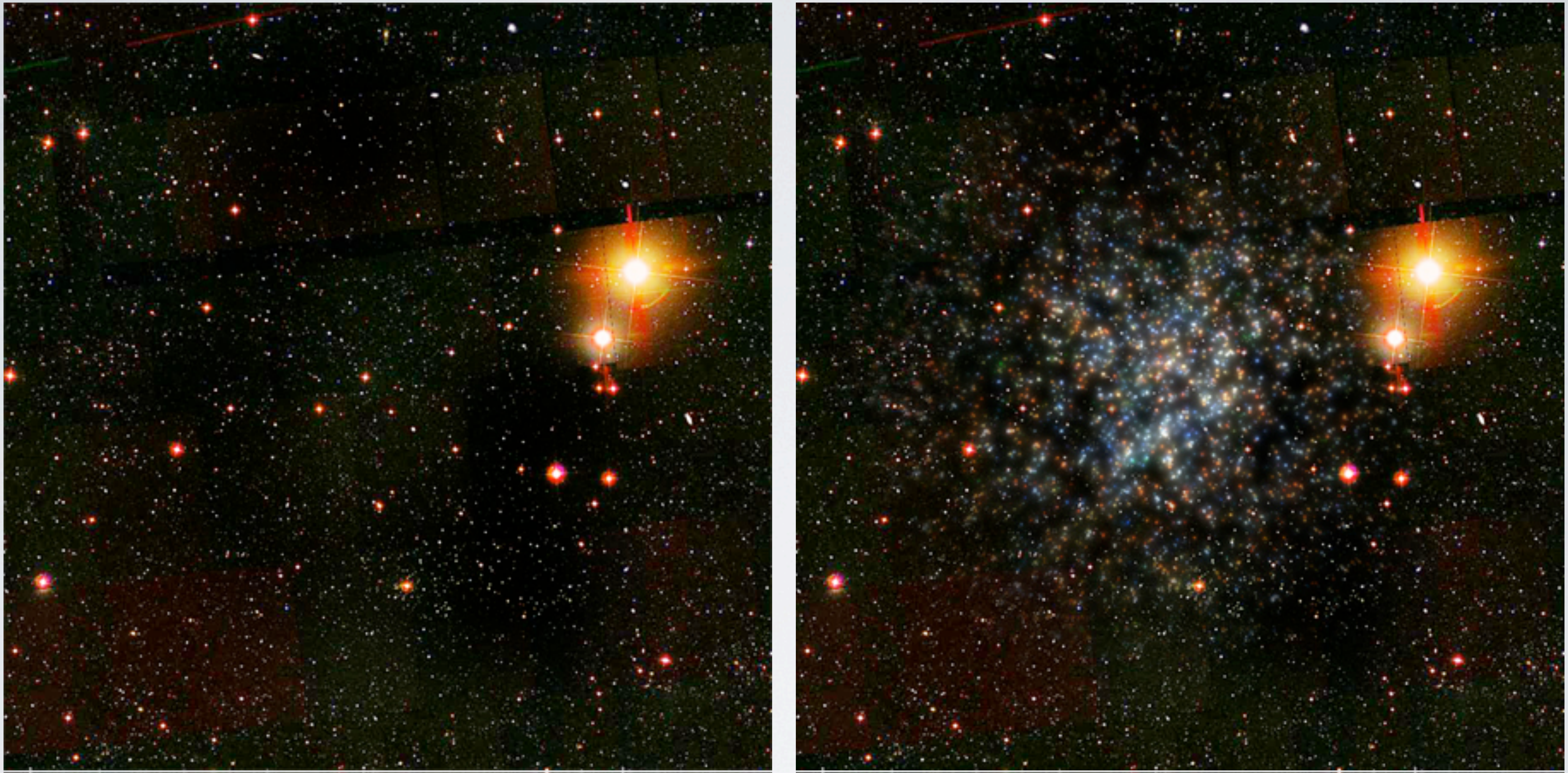


SEGUE I



Niederste-Ostholt et al. 2010

Samples of 24 stars are generated from Segue 1 ($\sigma = 1$ kms^{-1}) with some contamination from the Sgr stream ($\sigma = 10$ kms^{-1}, black or 15 kms^{-1}, grey). The number of contaminants required is very small to get 4.3 +/- 1.2 kms^{-1}.



Belokurov, Zucker, Evans et al., 2006

BOOTES I DWARF

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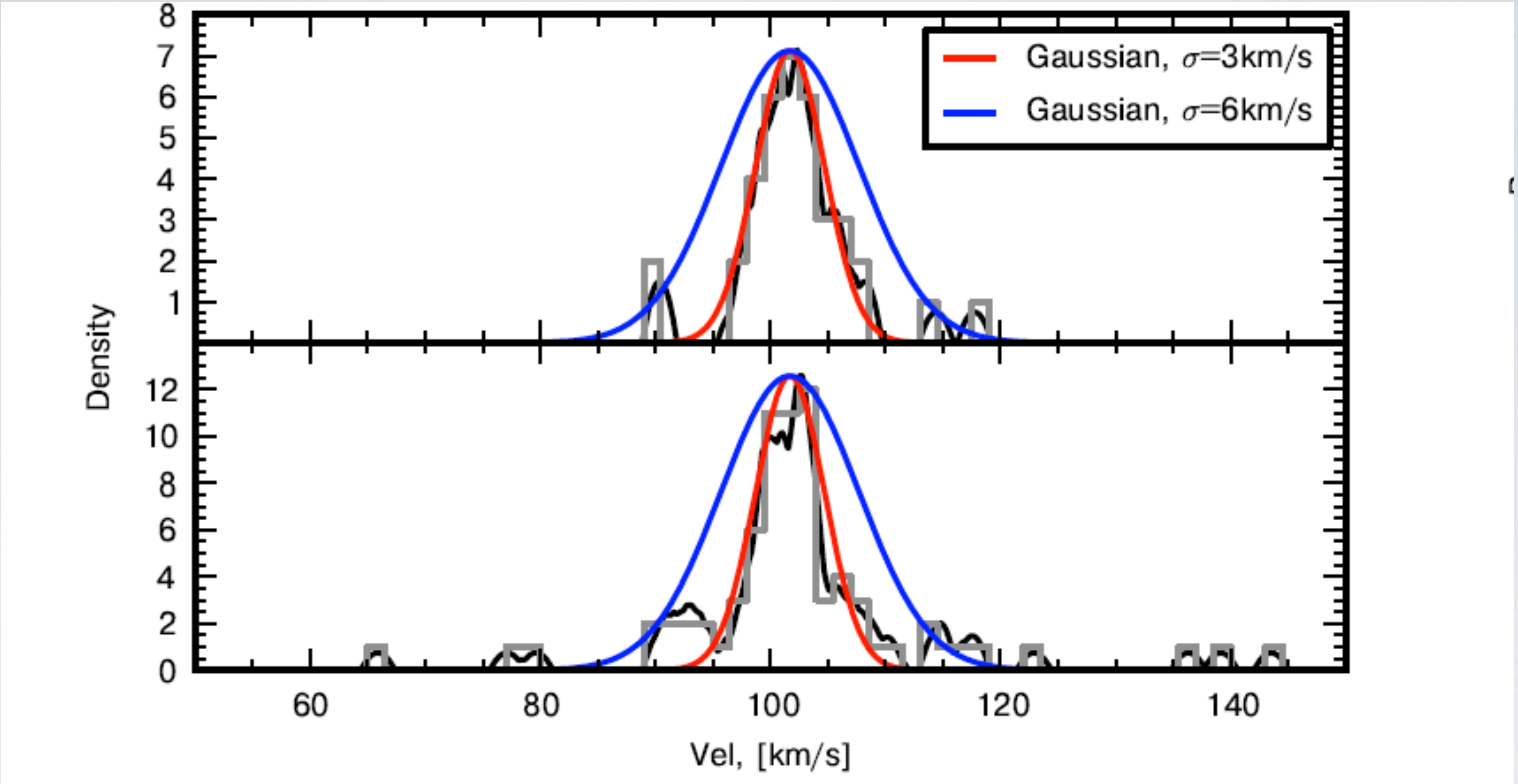


Koposov et al. 2011

Repeat measurements are crucial to remove radial velocity variables. Velocity dispersion is significantly lower than 6 km/s originally claimed.

CONCLUSIONS

Amongst its many other achievements, SDSS has revolutionised our knowledge of the Milky Way Galaxy.

The overall picture is consistent with the majority of the mass coming from several massive satellites that merged ~ 7-9 Gyrs ago.The remaining mass comes from lower mass satellites accreted in subsequently.

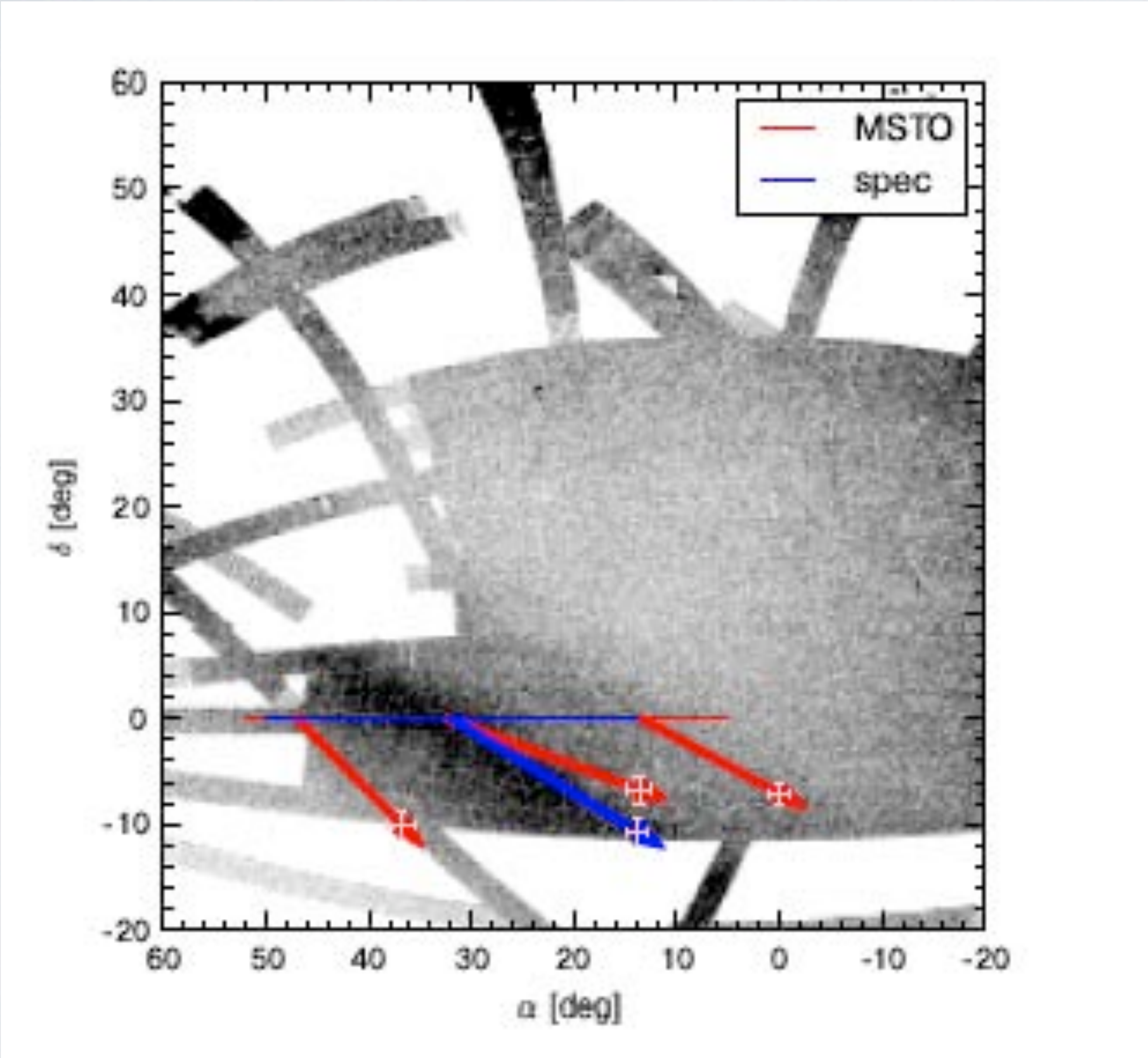
Nonetheless, all the identified structures (the phantom galaxies, the ghostly streams, the clouds) are poorly understood. The nature, the origin, the dynamics and chemical history of these objects are also completely open questions.

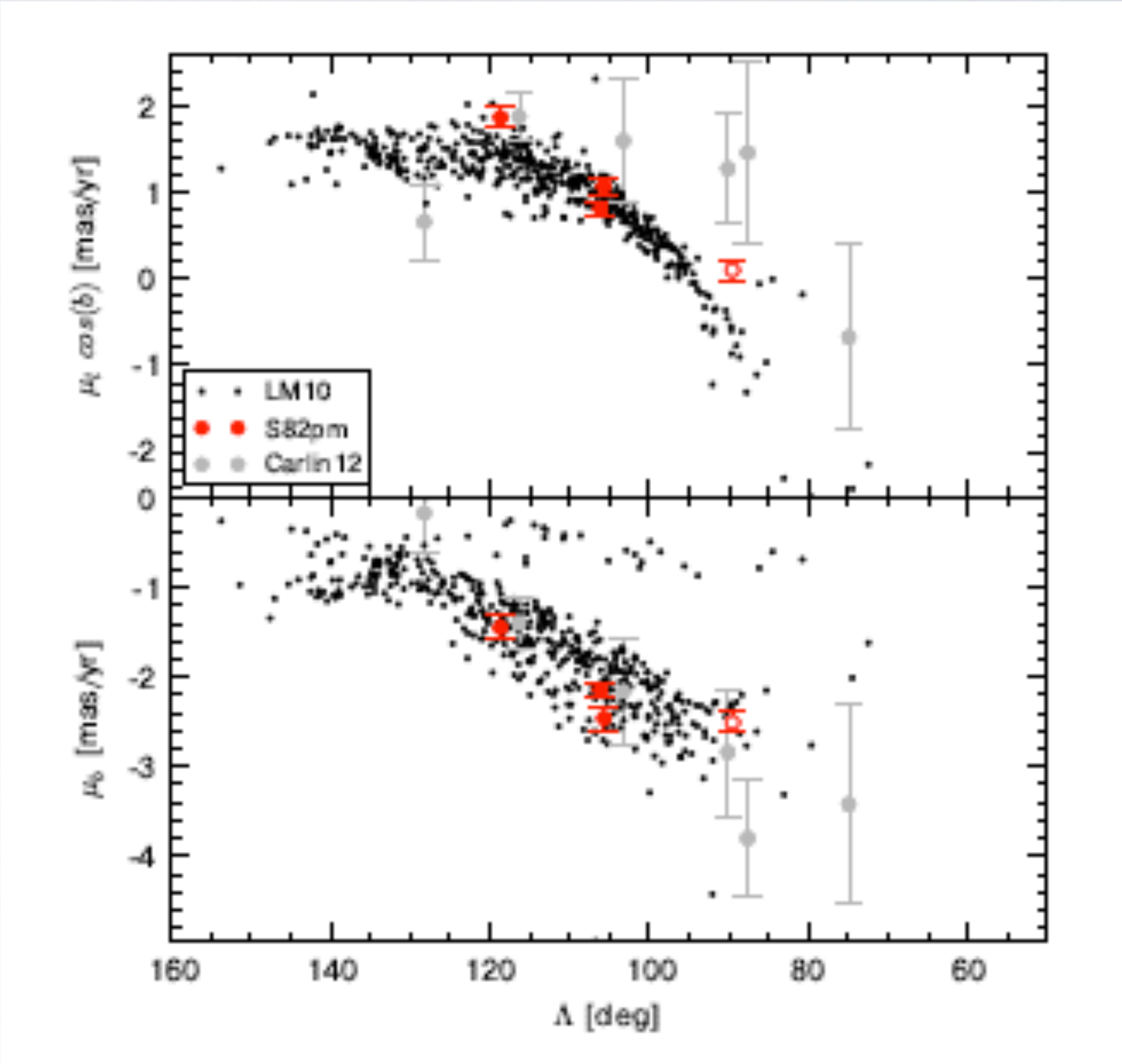
THANKS TO

Alfred P. Sloan

Vasily Belokurov, Dan Zucker, Mike Irwin, Sergey Koposov, Martin Niederste-Ostholt, Laura Watkins, Alis Deason

THE SAGITTARIUS STREAM

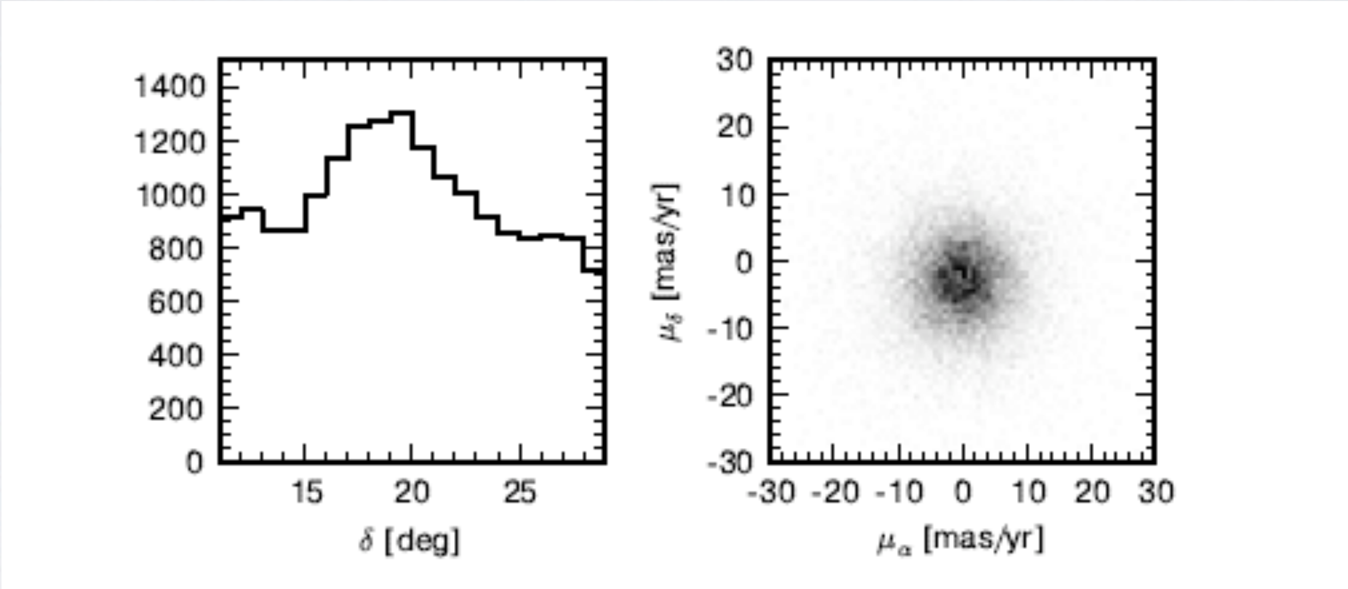




Red (blue) vectors are photometric (spectroscopic) sample (Koposov et al. 2012). Errors ~0.1masyr^{-1}

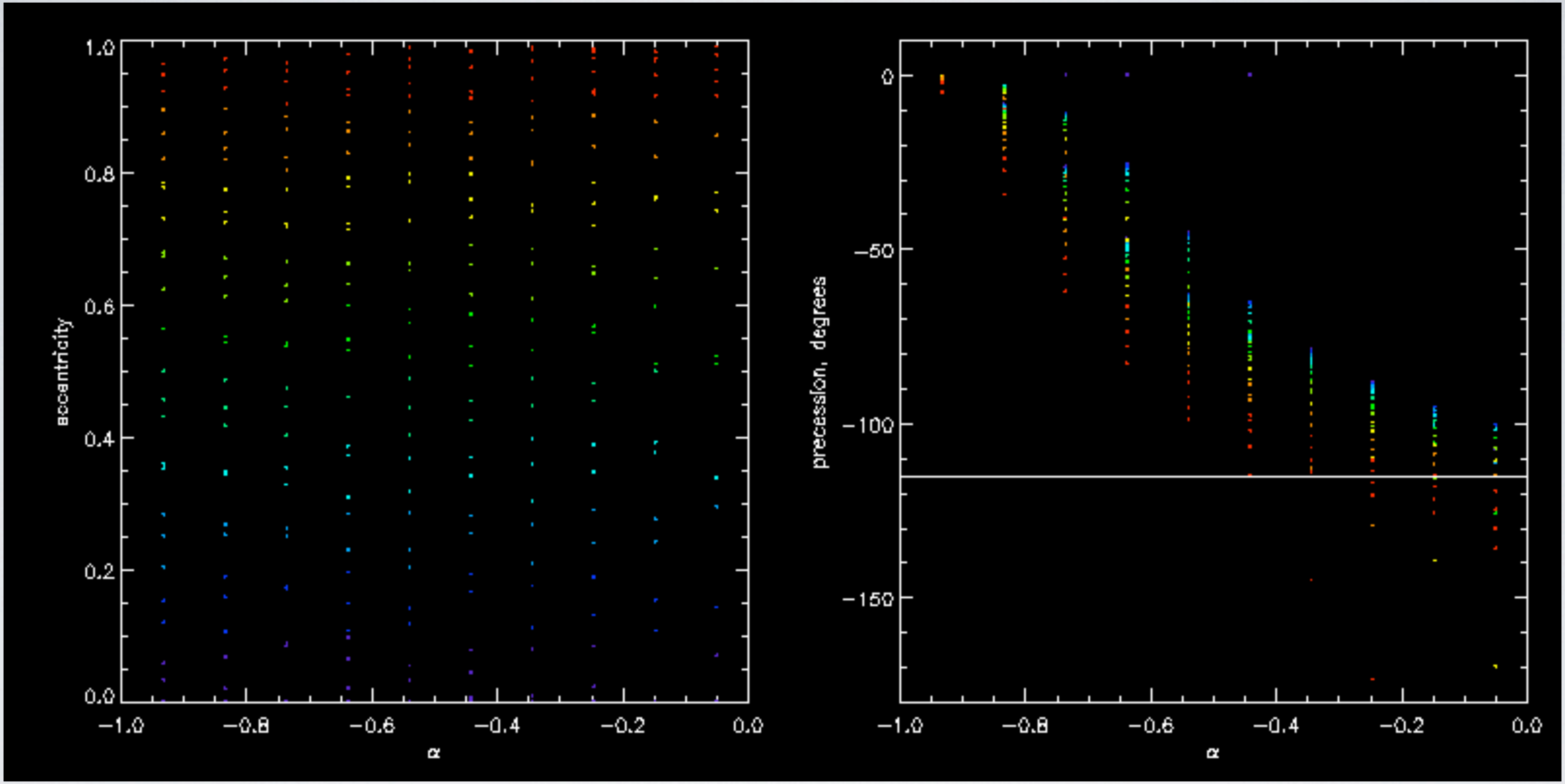
THE SAGITTARIUS STREAM

128<α<140



L of Sgr remnant is ~5400 $kms^{-1}kpc$.
L of the Southern bright stream is ~5900 $kms^{-1}kpc$.

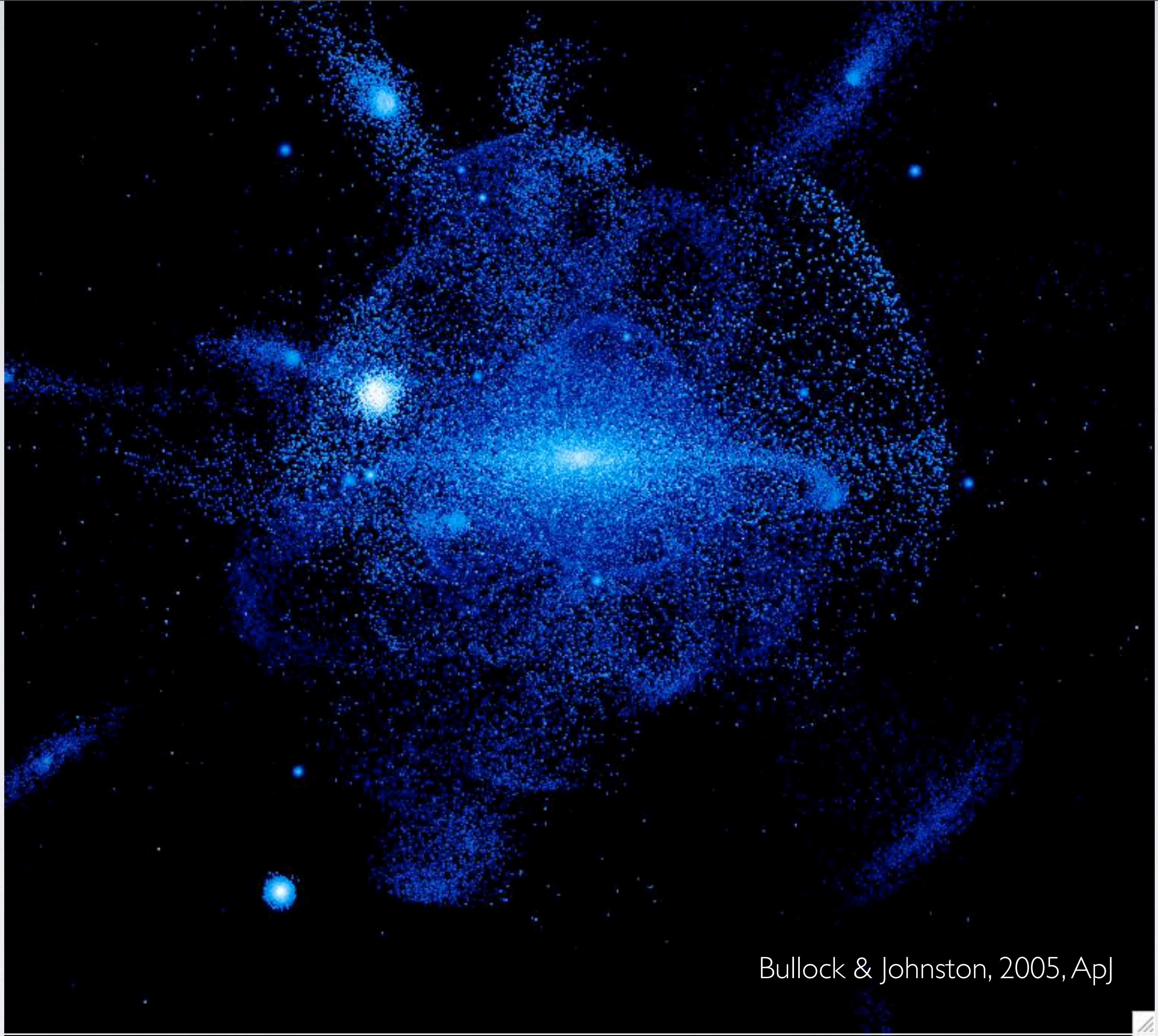
L of the Southern faint stream is ~2800 $kms^{-1}kpc$.
L of Northern stream is < 1500 $kms^{-1}kpc$.



Cosmological theory implies $\psi \sim r^{-1/2}$ (Navarro-Frenk-White) whereas the data suggest $\psi \sim \log r$ (isothermal halo)

STELLAR HALO

now dominated by a few big accretion events



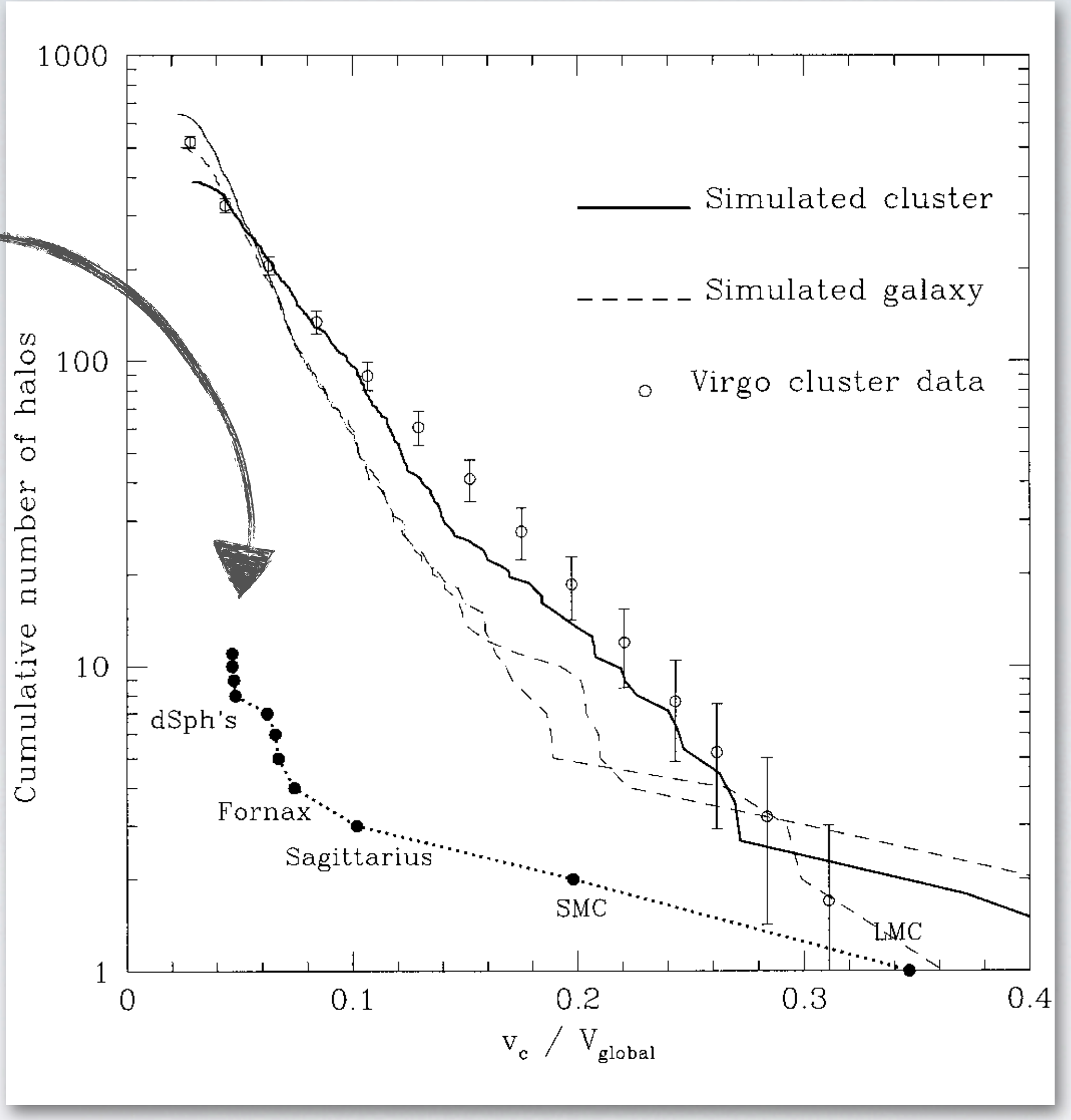
A SIMULATED HALO

Built from accretion of satellites, large amounts of debris

ARE THESE THE MISSING SATELLITES ?

Unclear.

Milky Way satellites
Mateo, 1998, ARA&A



Klypin et al., 1999, ApJ

Moore et al., 1999, ApJ

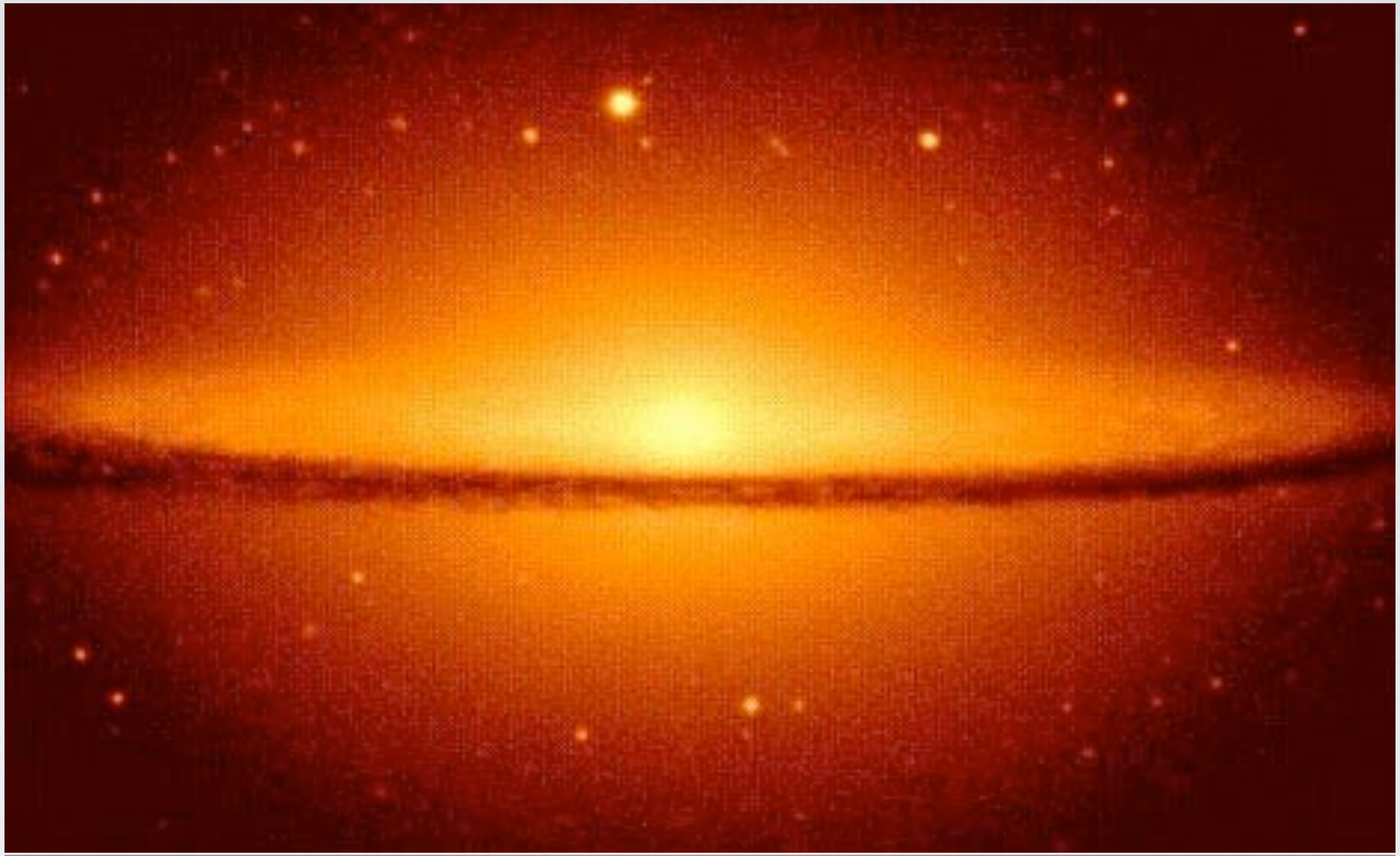
MISSING SATELLITES?

GHOSTLY STREAMS

"*The tidal debris delineates the orbit of a long-gone satellite galaxy. like a ghost haunting the past abode of a murdered victim. We may look for streams among the globular clusters and small satellite galaxies like the meteor streams along old cometary paths in the Solar system*" (Lynden-Bell & Lynden-Bell 1995)

Just as meteor streams are the graveyard of the short-period comets, so tidal streams in the mark the death throes of dying satellite galaxies.

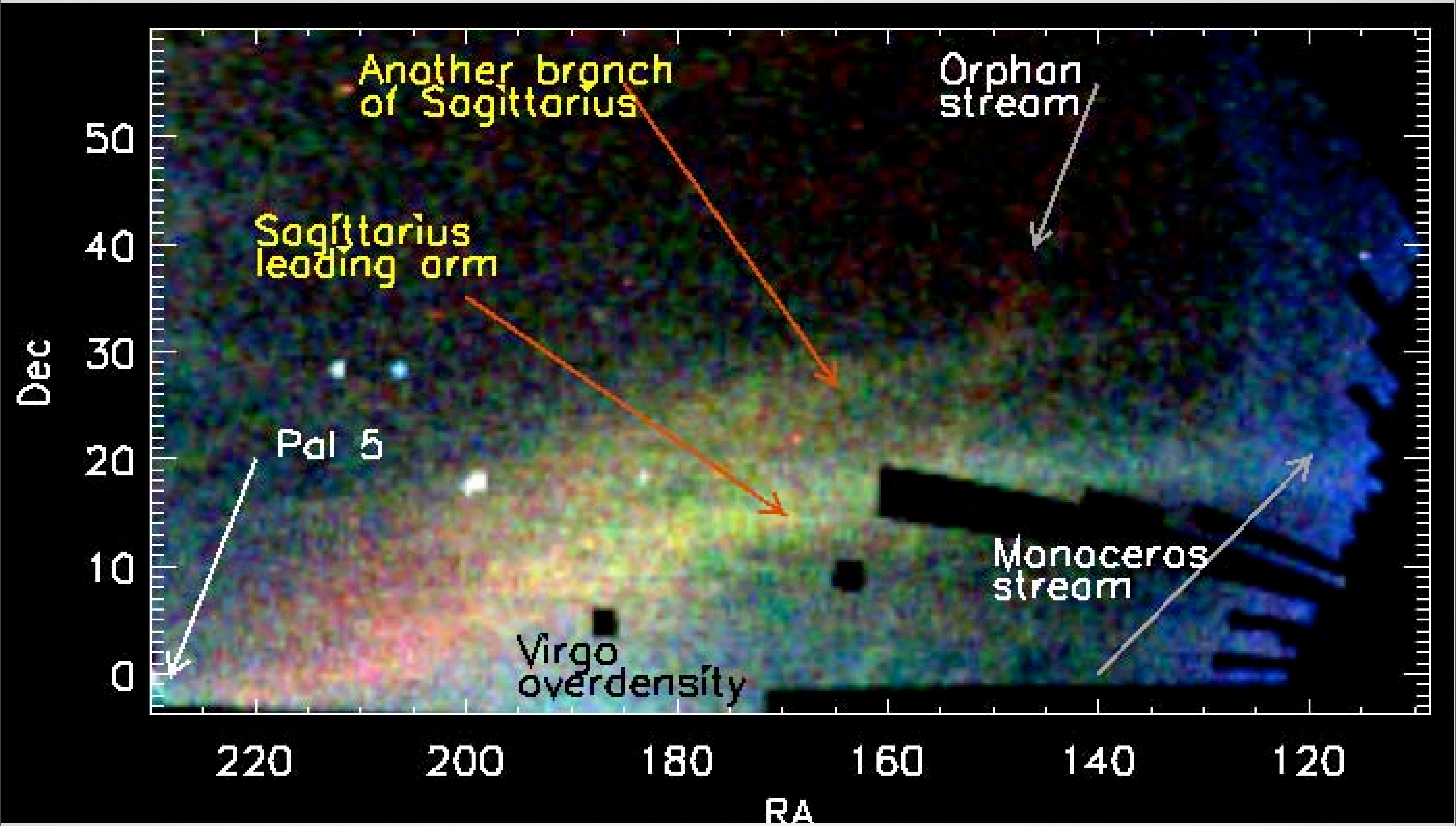
Mail Online



Pictured: The dark matter galaxy that could be orbiting our Milky Way (24th Sep 2008)

"....a very high mass-to-light ratio of a billion ..."

The Orphan Stream



THE STELLAR HALO

Galaxies grow via mergers. Mergers leave lots of debris. The stellar halo is build from the remnants of smaller galaxies that are accreted.

The most direct way of testing this idea is by finding and quantifying the substructure and the debris in the stellar halo (cf the BHBs).

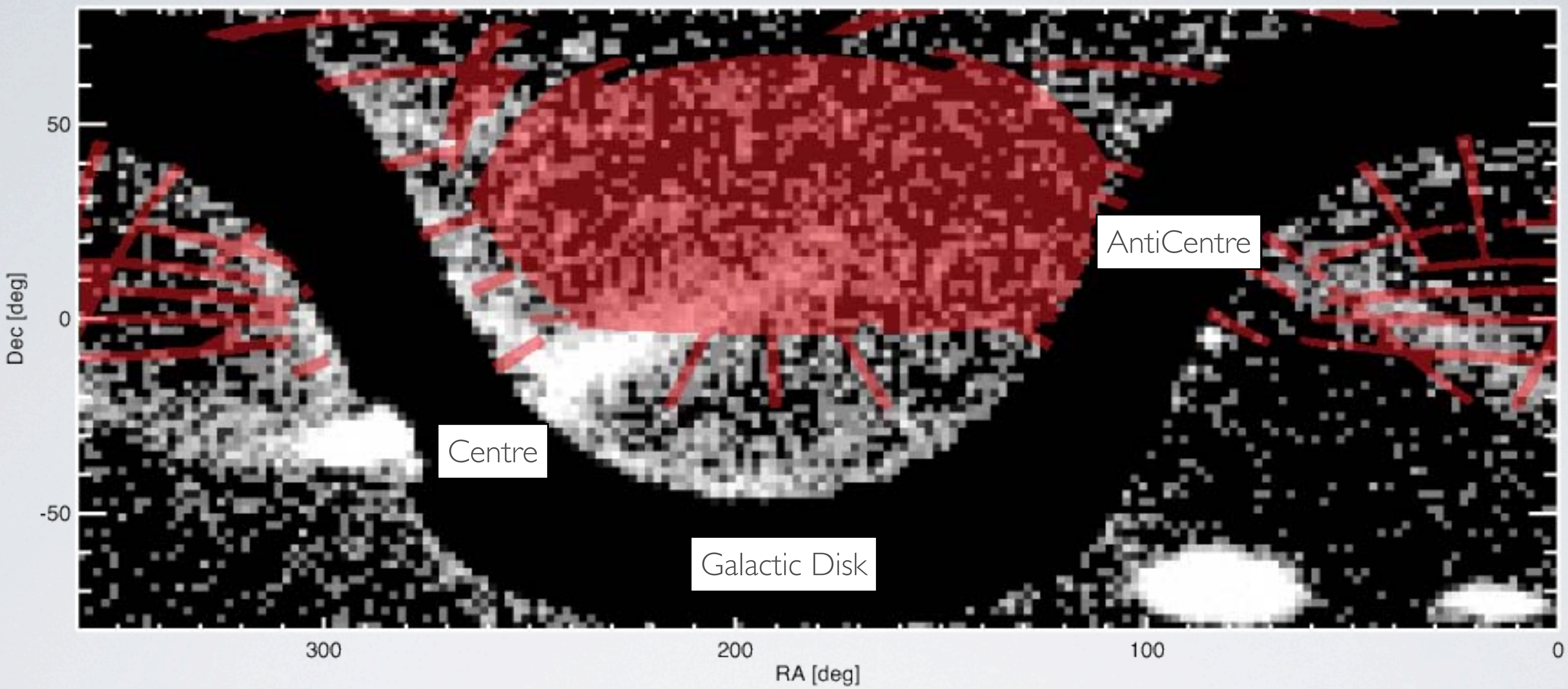
Large area photometric surveys (particularly the Sloan Digital Sky Survey) have transformed this field over the last 5 years.

Hierarchical Galaxy Formation As Seen in Via Lactea II

Diemand et al., 2008, Nature

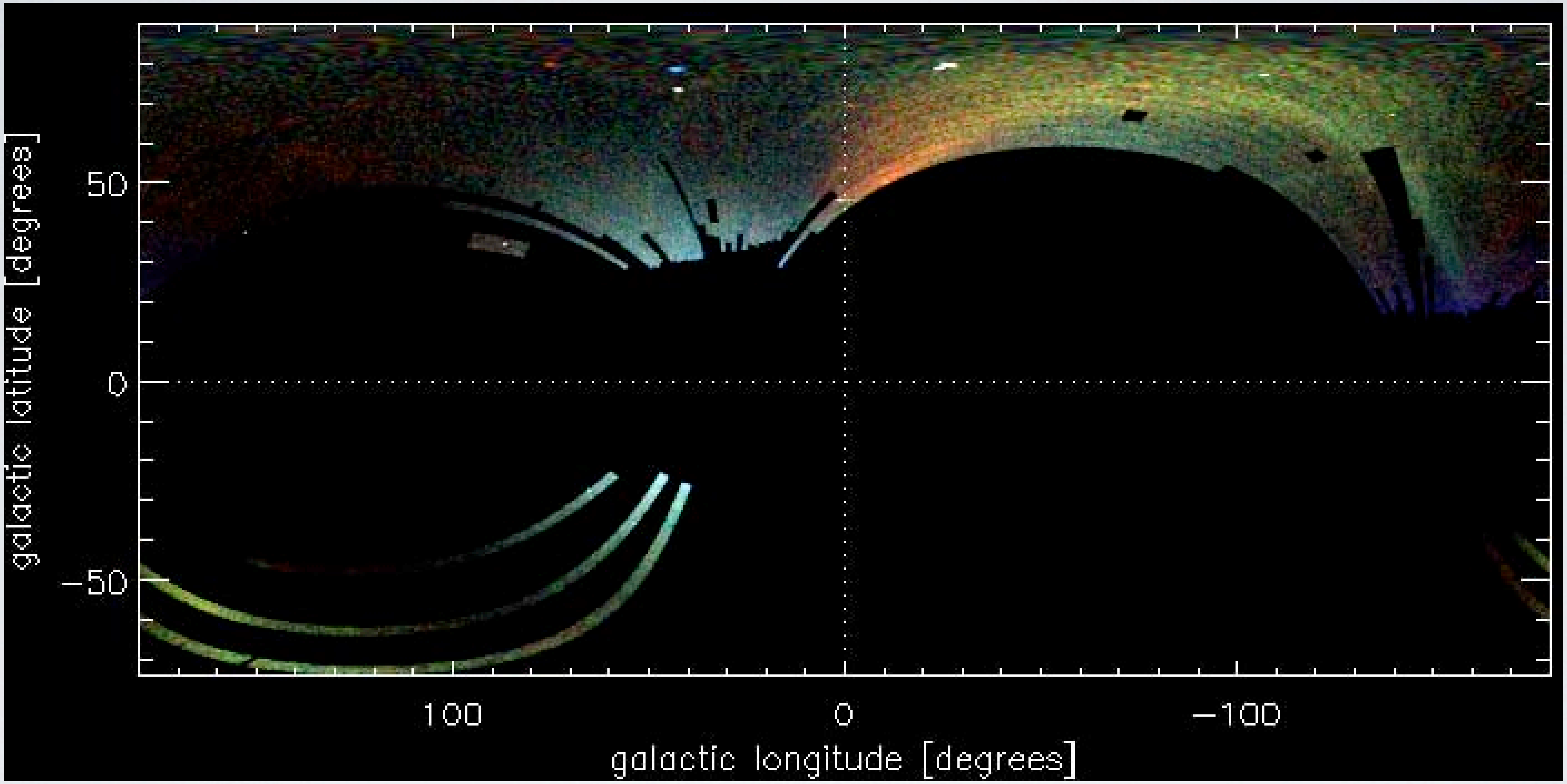
Galaxies form hierarchically through the amalgamation of smaller proto-systems.

SDSS covers about 1/5 of the sky



THE SAGITTARIUS STREAM

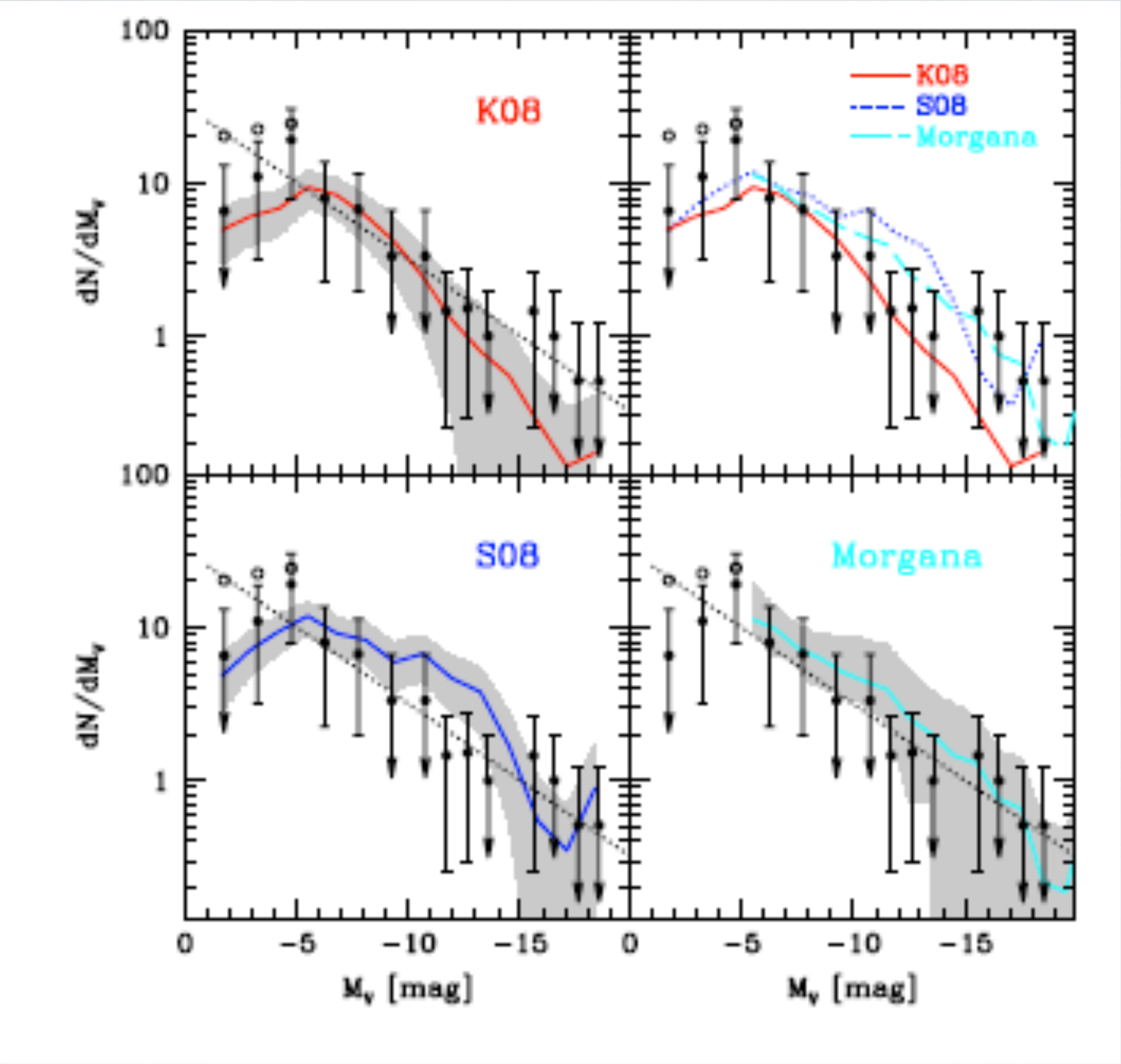
The SDSS Photometric Footprint



Belokurov, Evans et al. 2008

THE HERCULES-AQUILA CLOUD

THE ORPHAN STREAM



Maccio et al. 2010

The Observed Luminosity Function Compared with Theoretical Post-dictions

BOOTES I DWARF

Bootes I was the first ultrafaint dwarf galaxy to be discovered.

The ultrafaints are phantoms. Their low surface brightness means they cannot be detected on images. They are invisible.

They can be detected as over-densities of resolved stars, and confirmed to possess the characteristics of galaxies by colour-magnitude diagrams.

They are usually disrupting, composed of old stars, and have an absolute magnitude of -8 or fainter..

ARE THESE THE MISSING SATELLITES ?

The theorists mislaid some 100s of satellite galaxies around the Milky Way.

The Sloan Digital Sky Survey has found ~20 satellite galaxies.
The SDSS covers 1/4 of the sky.

Are these the ones mislaid by the theorists?