Satellites and Streams

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CDM models predict at least 1-2 orders of magnitude more low mass dark haloes at the present epoch compared to the observed abundance of of dwarf galaxies surrounding the Milky Way and M31 (Moore 1981, Klypin et al. 1999).

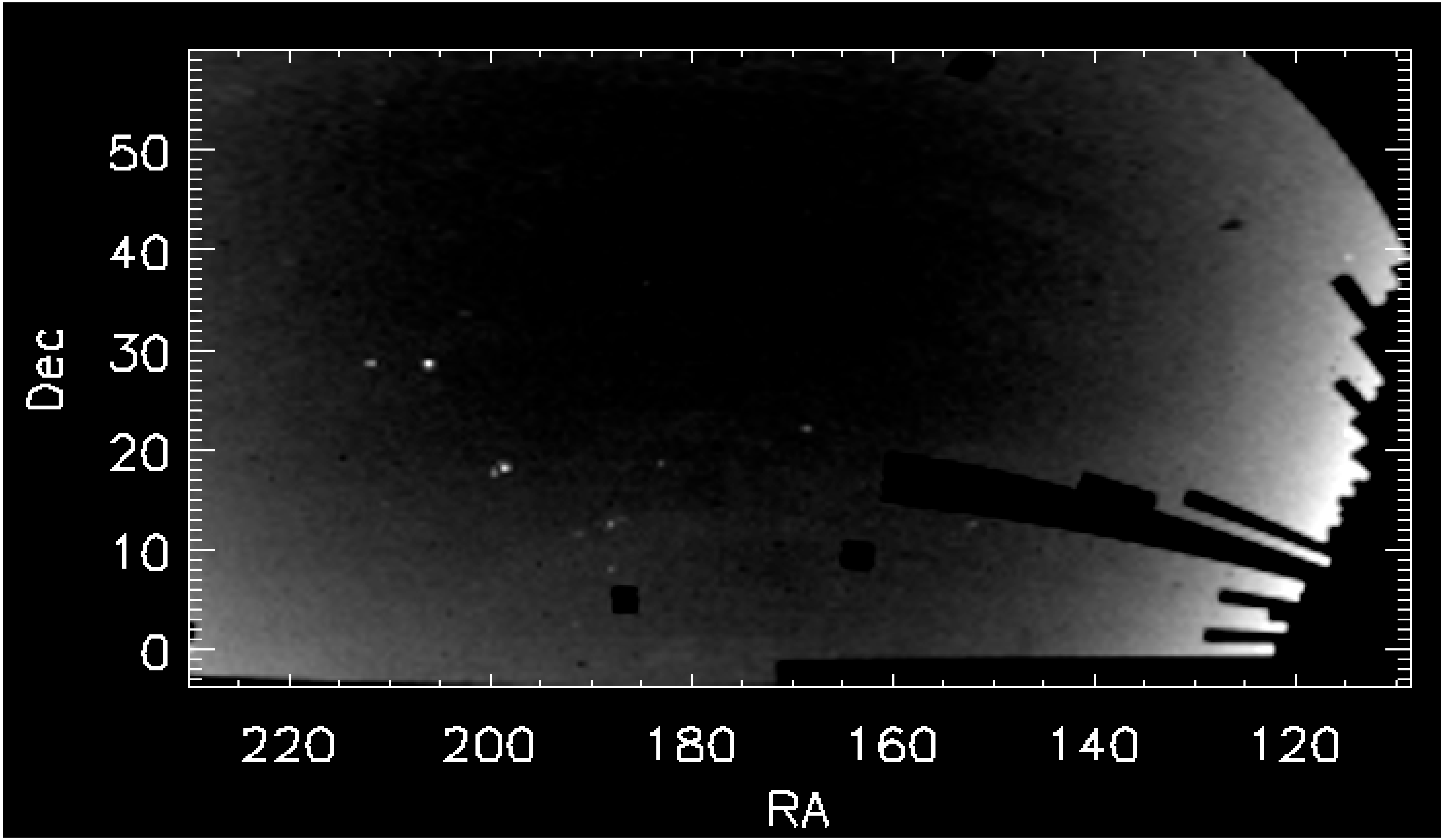
In 1999, there were 9 established dwarf galaxies around the Milky Way (Leo I, Leo II, Sextans, Sculptor, Fornax, Carina, Draco, Sagittarius, Ursa Minor). The concensus was that the sample was complete

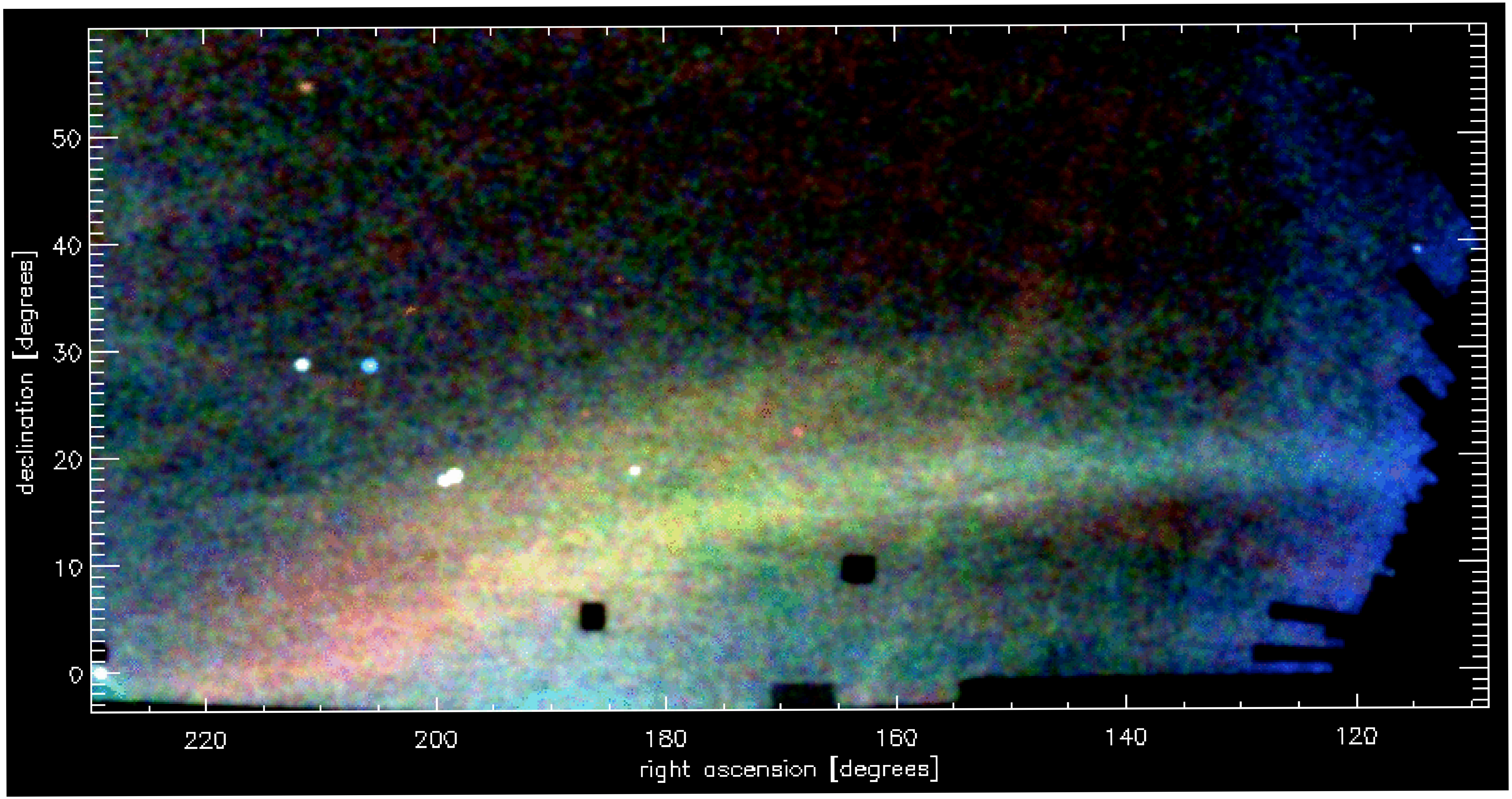
This seemed to be confirmed by Willman et al. (2006) who made the first searches through Sloan Digital Sky Survey data and discovered only one new dwarf galaxy (Ursa Major) and one unusually large (probable) globular cluster (Willman 1).

Most of the Sloan Data Release 5 was then made public.

The breakthrough came when Belokurov and co-workers in Cambridge made the red-green-blue color image known as the Field of Streams

This proved to be a treasure-trove for dwarf galaxy hunting and Canes Venatici I, Bootes I, Ursa Major II, Leo IV, Leo V, Canes Venatici II, Coma Berenices, Segue1 were discovered in quick succession.


Dec
50
40
30
20
10
0
220
200
180
160
140
120
RA

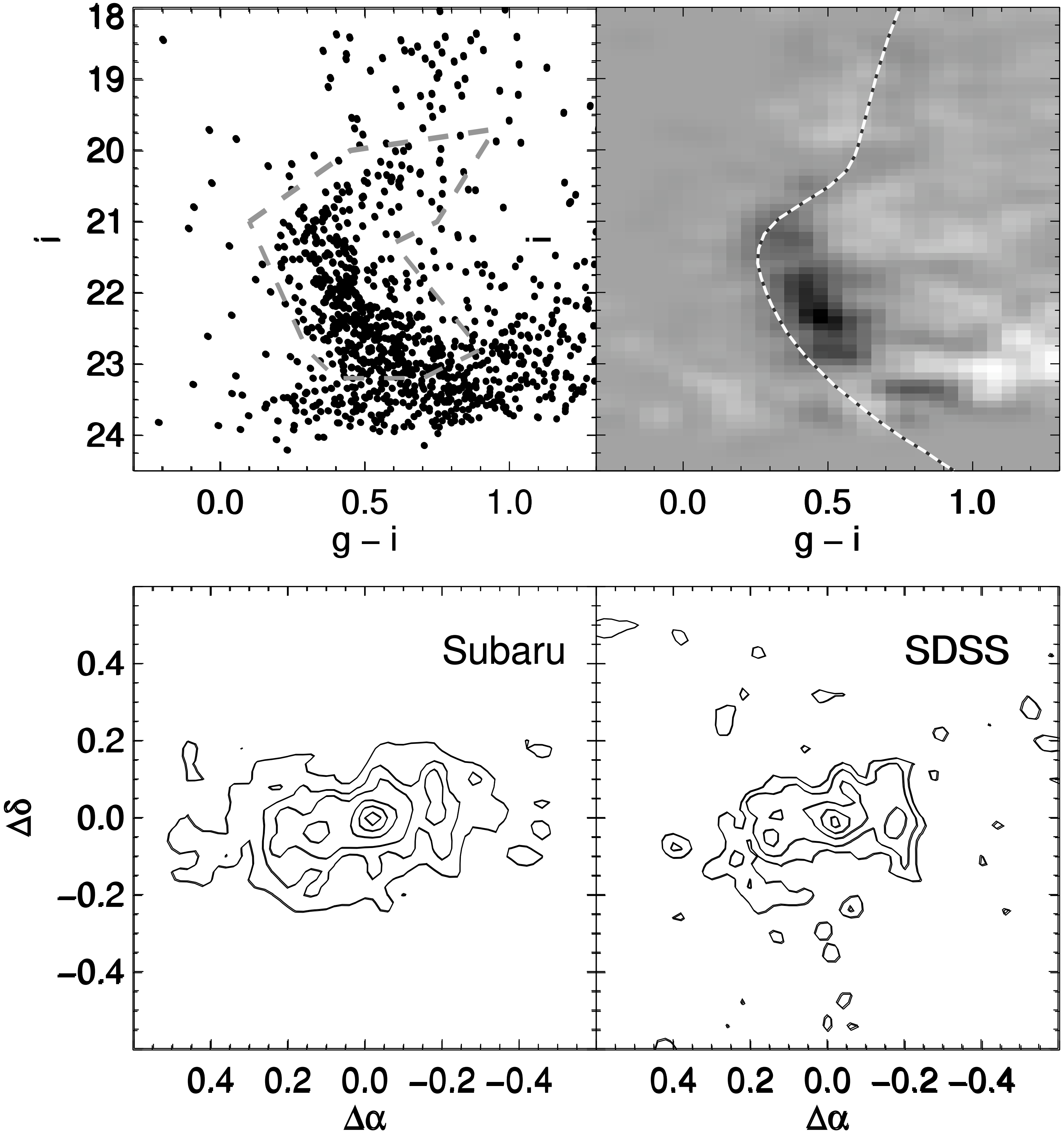


50
40
30
20
10
0
declination [degrees]
220
200
180
160
140
120
right ascension [degrees]

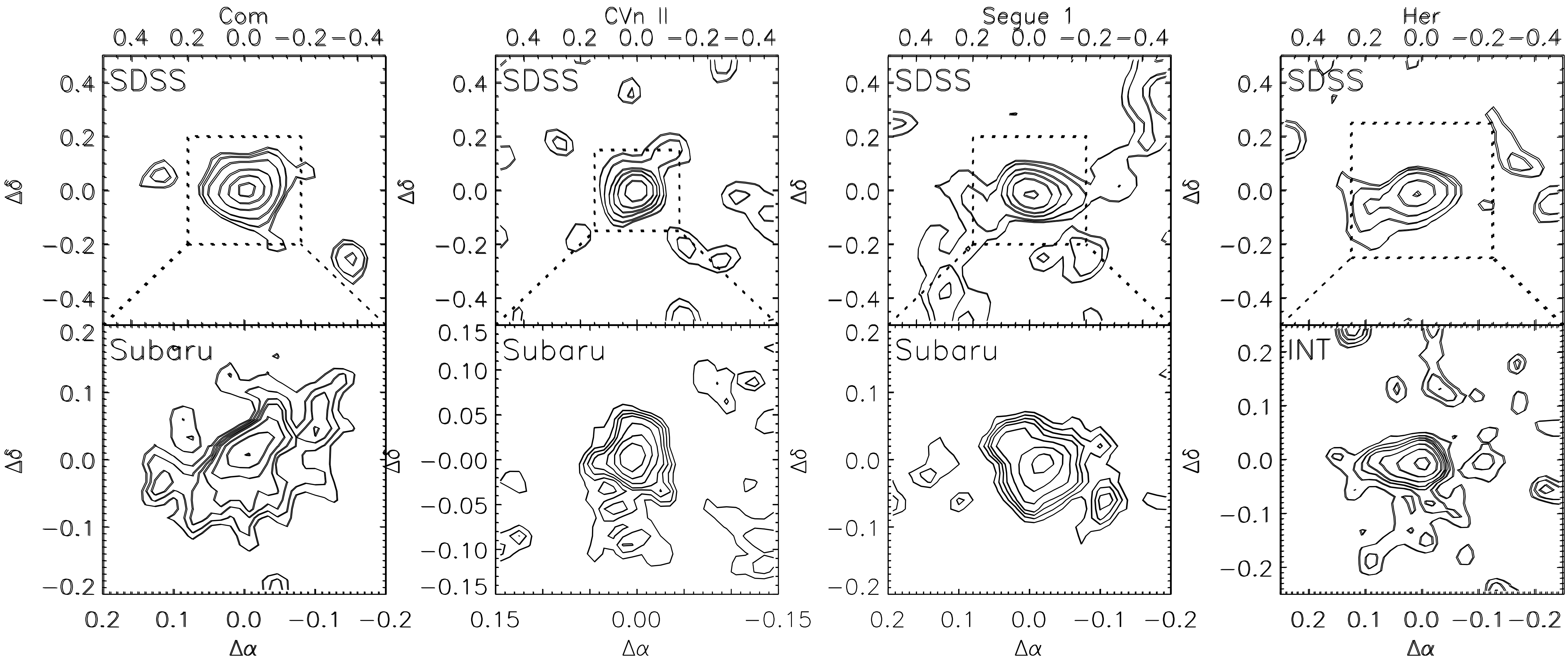
(i) The blue-colored, and hence nearby, overdensity in stars centered at ($\alpha \approx 185°$, $\delta \approx 0°$). This was found by Juric et al. (2005) and named *the Virgo Overdensity*.

(ii) Multiple wraps of *the Monoceros Ring* (Newberg et al. 2002) are visible as the blue-colored structure at $\alpha \approx 120°$

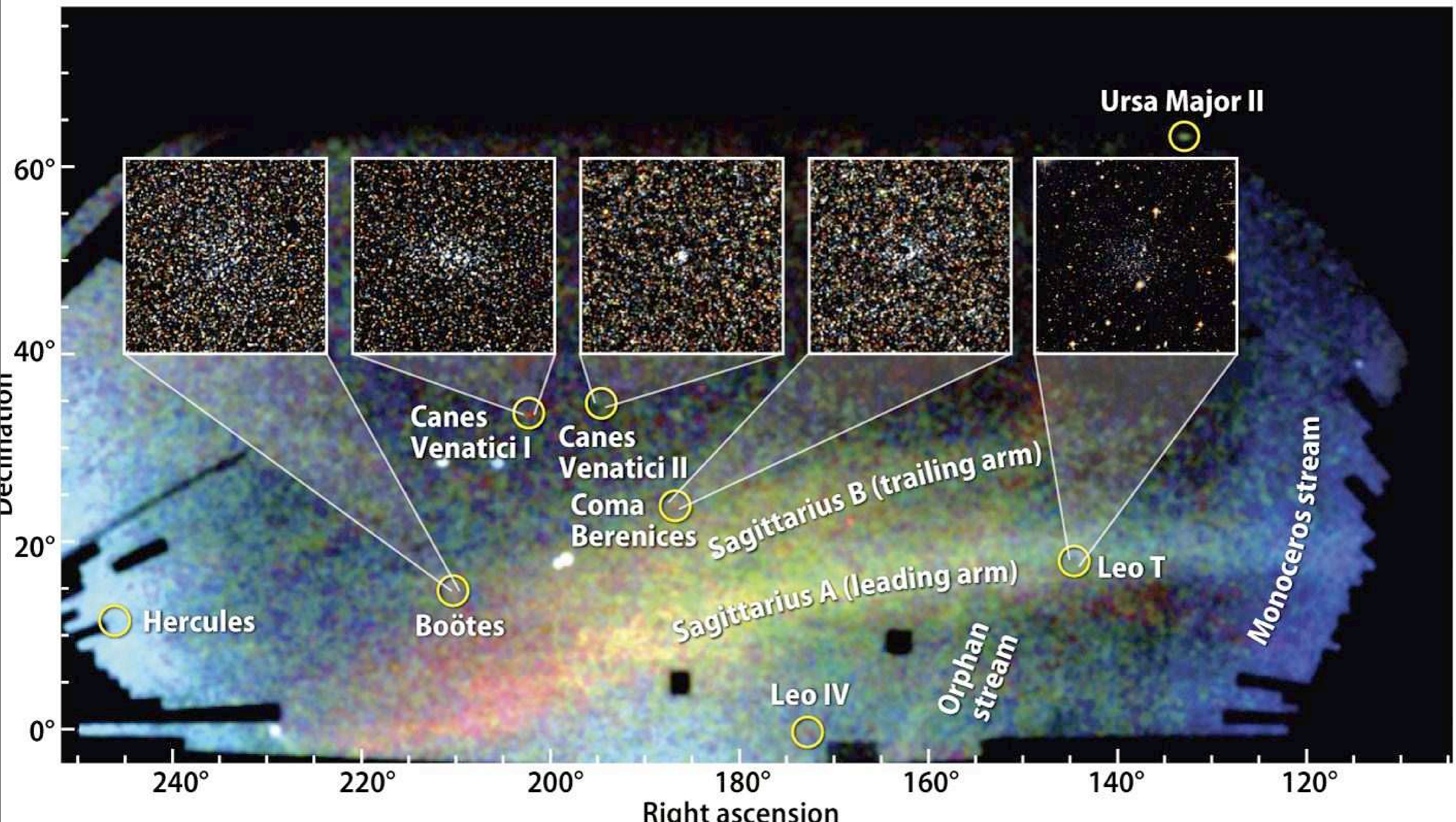
(iii) Also showing clearly in this map is a new stream (*the Orphan Stream*) at latitudes of $b \approx 50°$ and with longitudes satisfying $180° \leq l \leq 230°$. It is distinct from the Sagittarius stream, which it crosses.



Ursa Major II



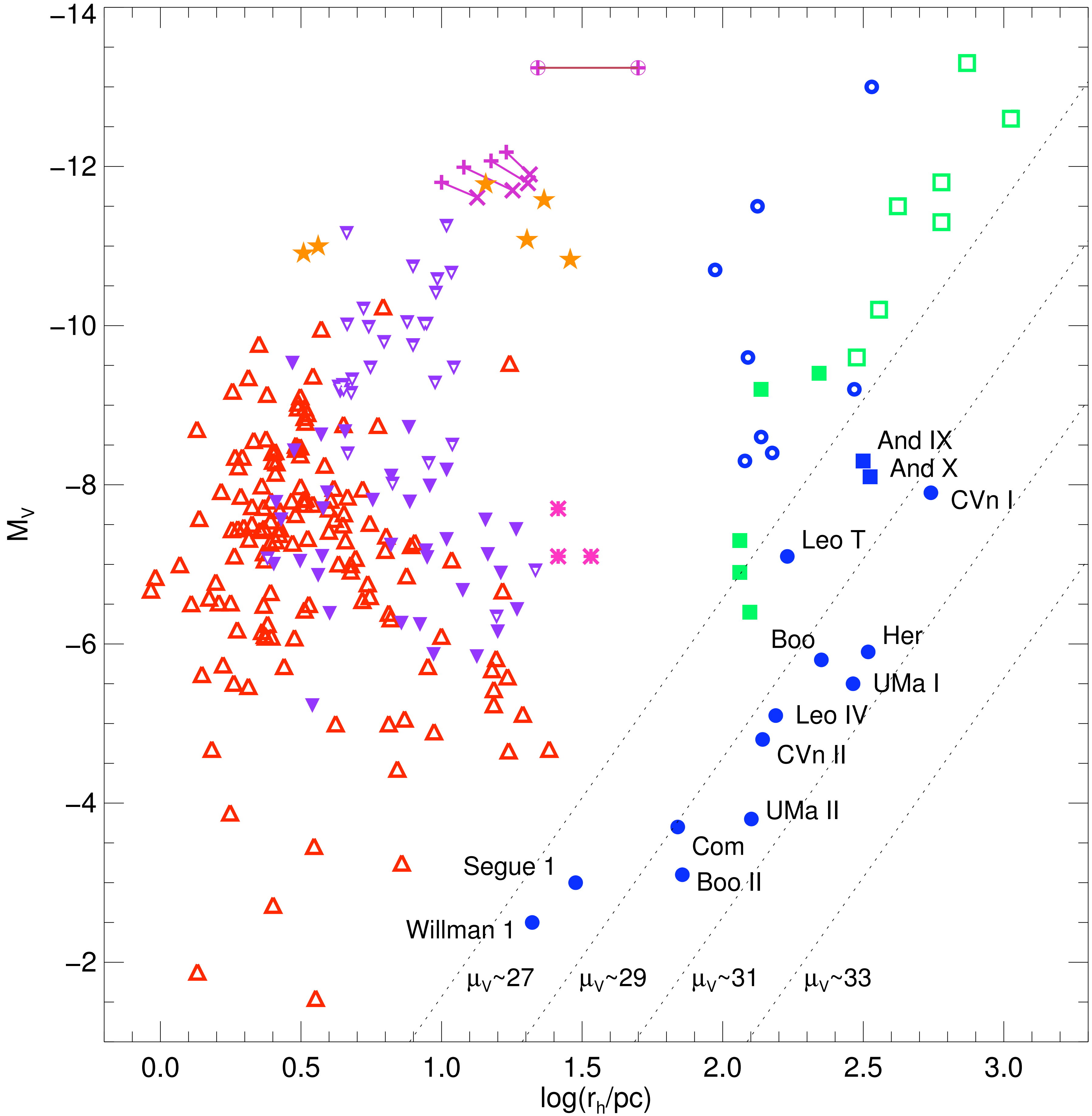
The ultrafaints have absolute magnitudes of ≈-4 and heliocentric distances between 50 and 150 kpc.


Ursa Major II
60°
40°
20°
0°
Canes Venatici I
Canes Venatici II
Coma Berenices
Sagittarius B (trailing arm)
Sagittarius A (leading arm)
Leo T
Monoceros stream
Hercules
Boötes
Leo IV
Orphan stream
240°
220°
200°
180°
160°
140°
120°
Right ascension

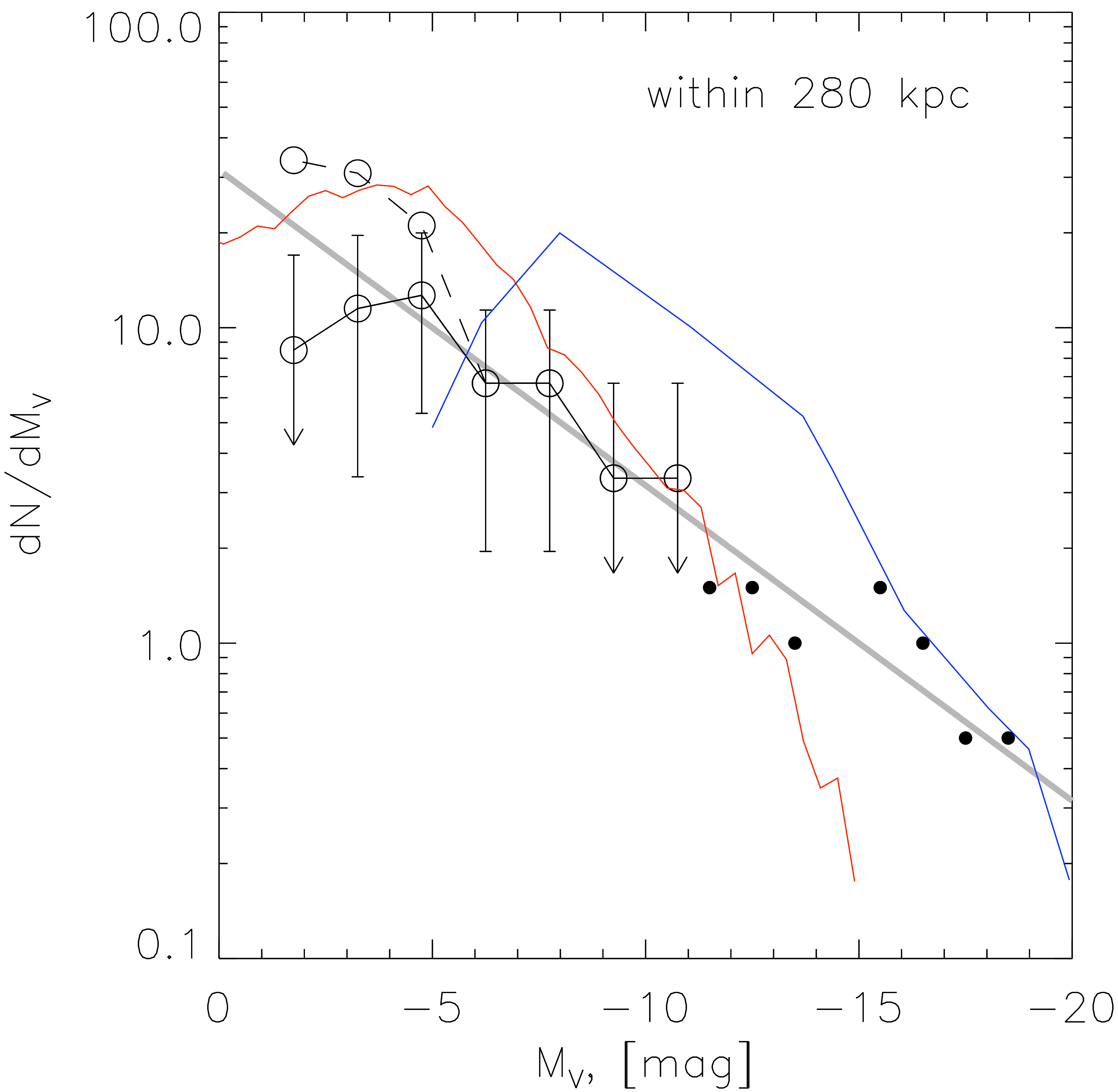
The population of ultrafaints now numbers 19.

This includes likely dSphs (Boo1, Boo II, C Ven I, C Ven II, Her, Coma, Leo IV, Leo V, UMa I, UMa II, Pisces I, Pisces II), likely star clusters (Willman 1, Segue 1, Segue 2, Segue 3, Koposov 1, Koposov 2) and a likely dIrr (Leo T)

Are these the missing satellites predicted by cold dark matter theories ?



−14
−12
−10
−8
−6
−4
−2
M_V
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\log(r_h/pc)$
And IX
And X
CVn I
Leo T
Boo
Her
UMa I
Leo IV
CVn II
UMa II
Com
Boo II
Segue 1
Willman 1
μ_V~27
μ_V~29
μ_V~31
μ_V~33



Koposov et al. (2008) compared the observationally determined luminosity function with theoretical predictions.

The debris in the stellar halo is dominated by one big event. The disruption of the Sagittarius provides 25 to 50 per cent of all the debris in the stellar halo, including 4 huge tidal streams (young/old, leading and trailing) and $\sim$ 20 globular clusters.

The overall picture looks very different from the structures in halos in CDM simulations, which have myriads of small satellites.

Simon & Geha (2007) measure the velocities of $\approx$ 20-200 stars in 8 ultrafaints (CVen I, C VenII, Coma, Her, Leo IV, Leo T, UMa I, UMa II) and claimed velocity dispersions $\approx$ 3-8 km/s, together with mass-to-light ratios up to $\approx$ 1000.

Repeat radial velocity measurements are needed to rule out binary stars and variables. The effect of binaries at such low velocity dispersions is unquantified.

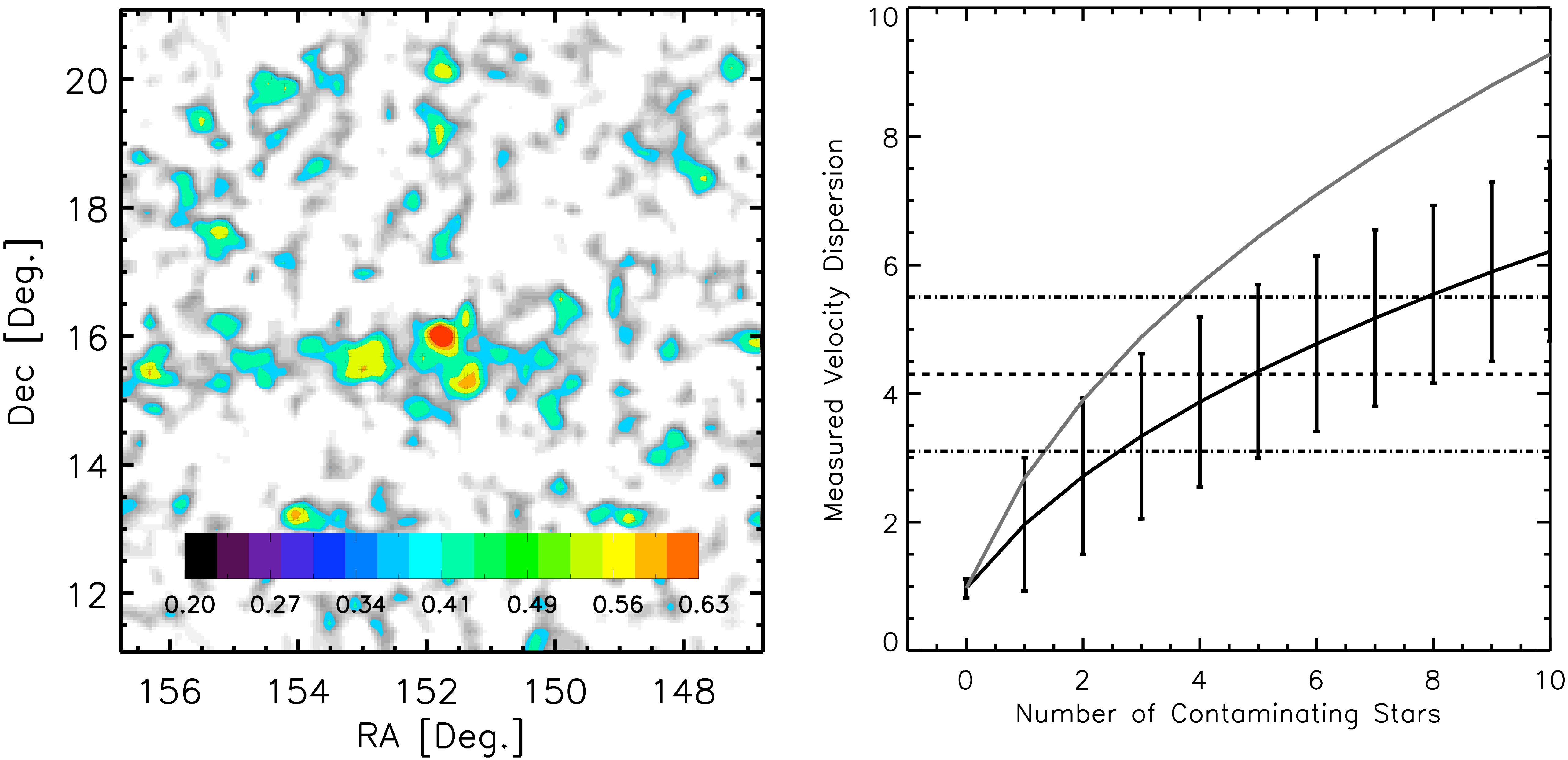
Interlopers and extra-tidal stars can be a serious problem, as many of the ultrafaints are embedded in streams and other substructures.

The Case of Segue 1

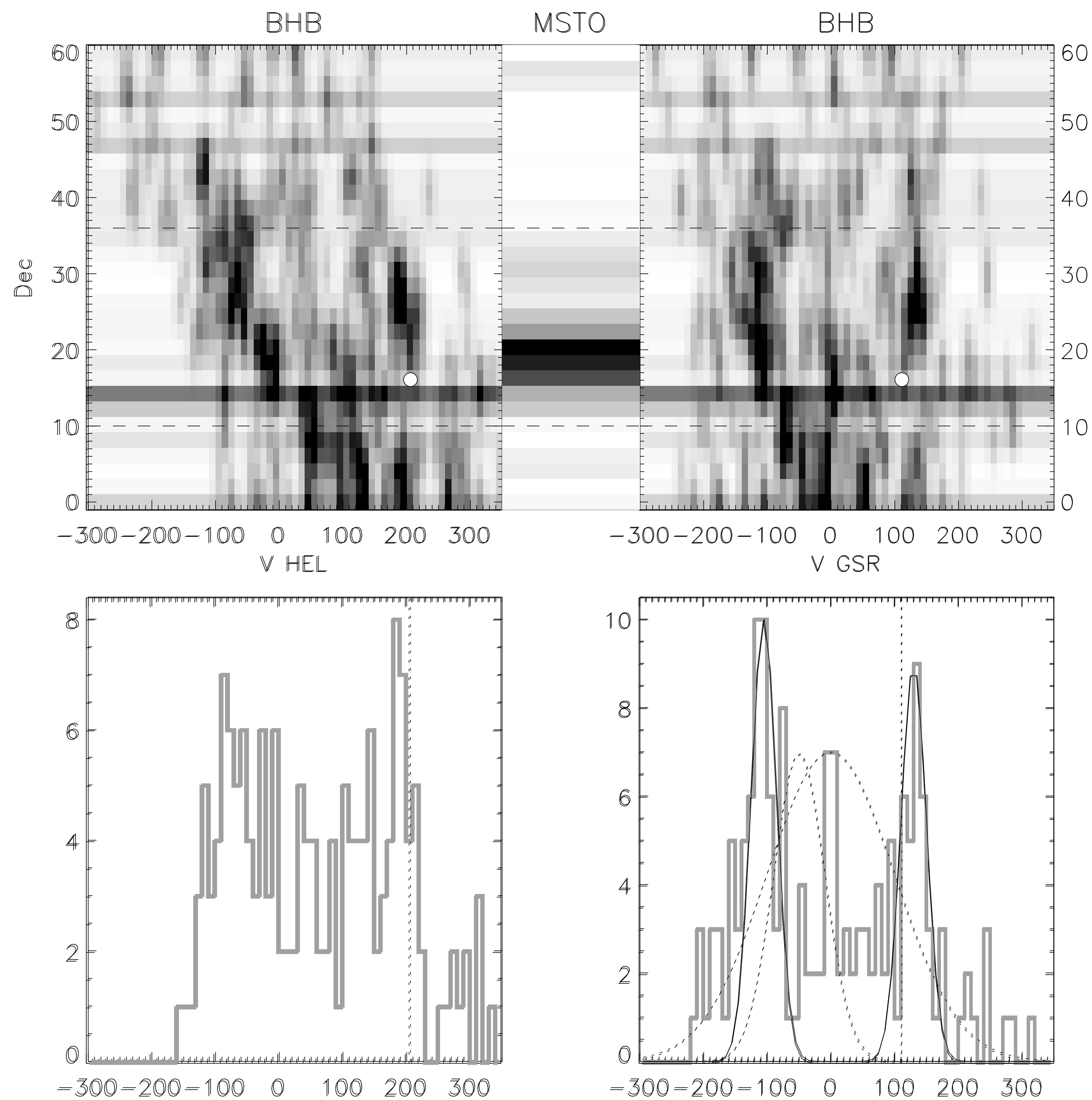
Geha et al (2009) measured an internal velocity dispersion of 4.3 km/s, which implies a mass-to-light ratio of at least $\approx$ 1000. They suggested that "Segue 1 is the most promising target for dark matter detection"

This inspired Scott et al. (2010) to analyse 9 months of Fermi-LAT observations of Segue 1 to place constraints on the Constrained Minimal Supersymmetric Standard Model.

The Case of Segue 1



The Case of Segue 1



Niederste-Ostholt et al. (2009)

The Case of Segue 1

The location of Segue 1 is close to crossings of the tidal wraps of the Sagittarius stream or the Orphan stream

By extracting blue horizontal branch stars from SDSS spectral database, two kinematic features are isolated and identified with different wraps of the Sagittarius' stream.

Segue 1 is moving with a velocity that is close to one of the wraps. At this location, we estimate that there are enough Sagittarius stars, indistinguishable from Segue 1 stars, to inflate the velocity dispersion and hence the mass-to-light ratio.

Dwarf Spheroidal Modelling

This takes the form of assuming a parametric light profile and inferring the velocity dispersion from the Jeans equations, given an assumed law for the dark matter halo (e.g., NFW)

There is no guarantee that a physical distribution function exists. E.g., it is not possible to embed an isotropic cored profile (Plummer model) in an NFW halo.

The luminous and dark matter profiles are both posited *a priori*. This cannot lead to any insight beyond the starting assumptions. There is no physical connection between the luminous and dark matter, other than the fact that the velocity dispersions can support the model.

Modelling of Dwarf Spheroidals

Numerical simulations of tidal stirring produces dSphs that are isotropic in the inner parts (Mayer 2001). Fiting velocity data with distributions functions that permit anisotropy yields isotropic solutions (Wu 2007).

If the velocity distribution is isotropic, then the near flatness of the velocity dispersion profiles implies that the velocity distribution is Maxwellian.

Dwarf Spheroidal Modelling

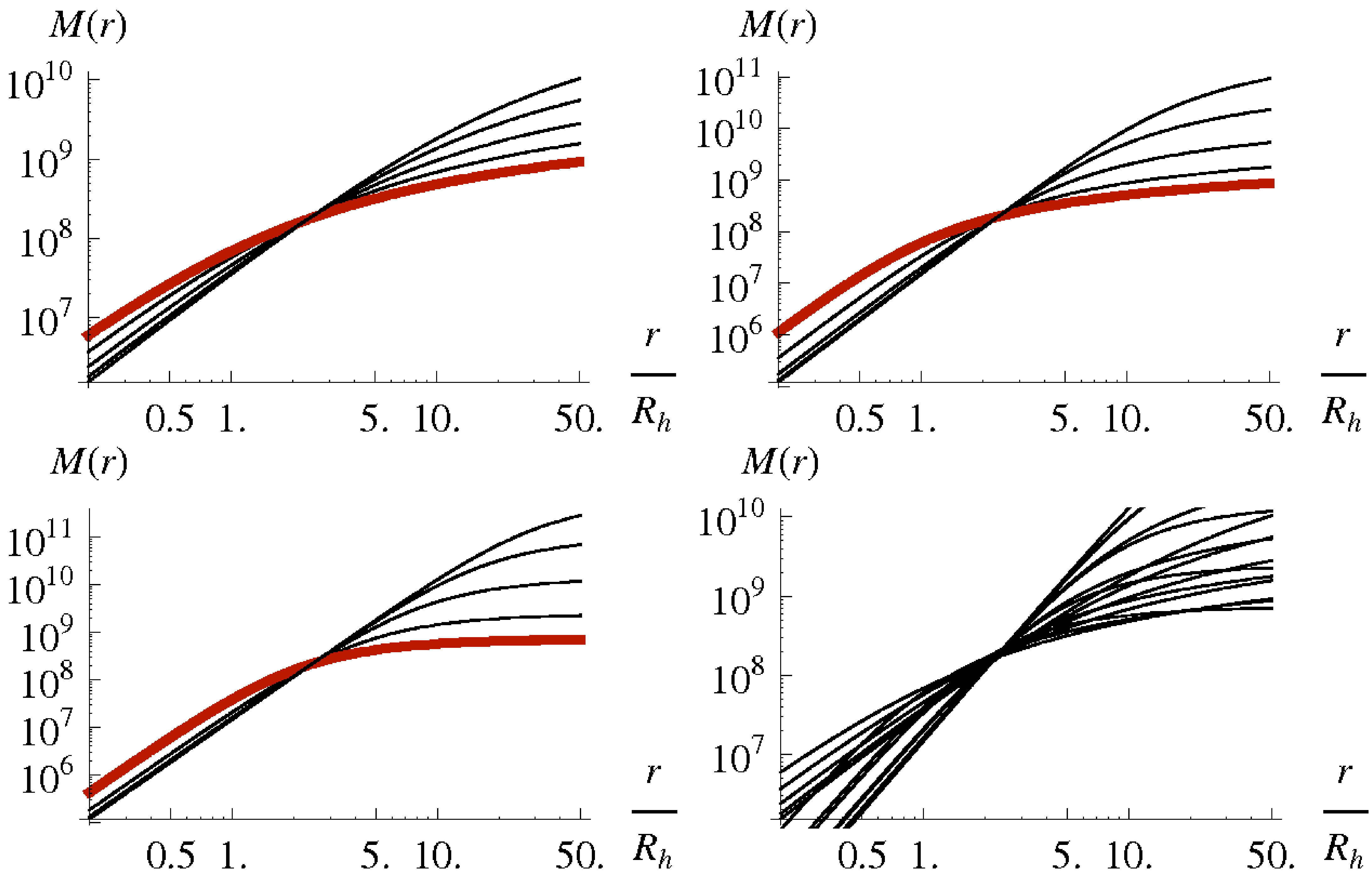
This suggests using lowered isothermals (or King) distribution functions for the stars

$$f \propto \exp\left[-(E-E_K)/\sigma^2\right]$$

where E_K is the energy at the tidal radius.

When isothermal distributions are embedded in dark haloes, then the stars relax in the gravity field of the dark matter. There is a physical connection between the luminous matter and the dark (which does not happen in modelling with the Jeans equations).

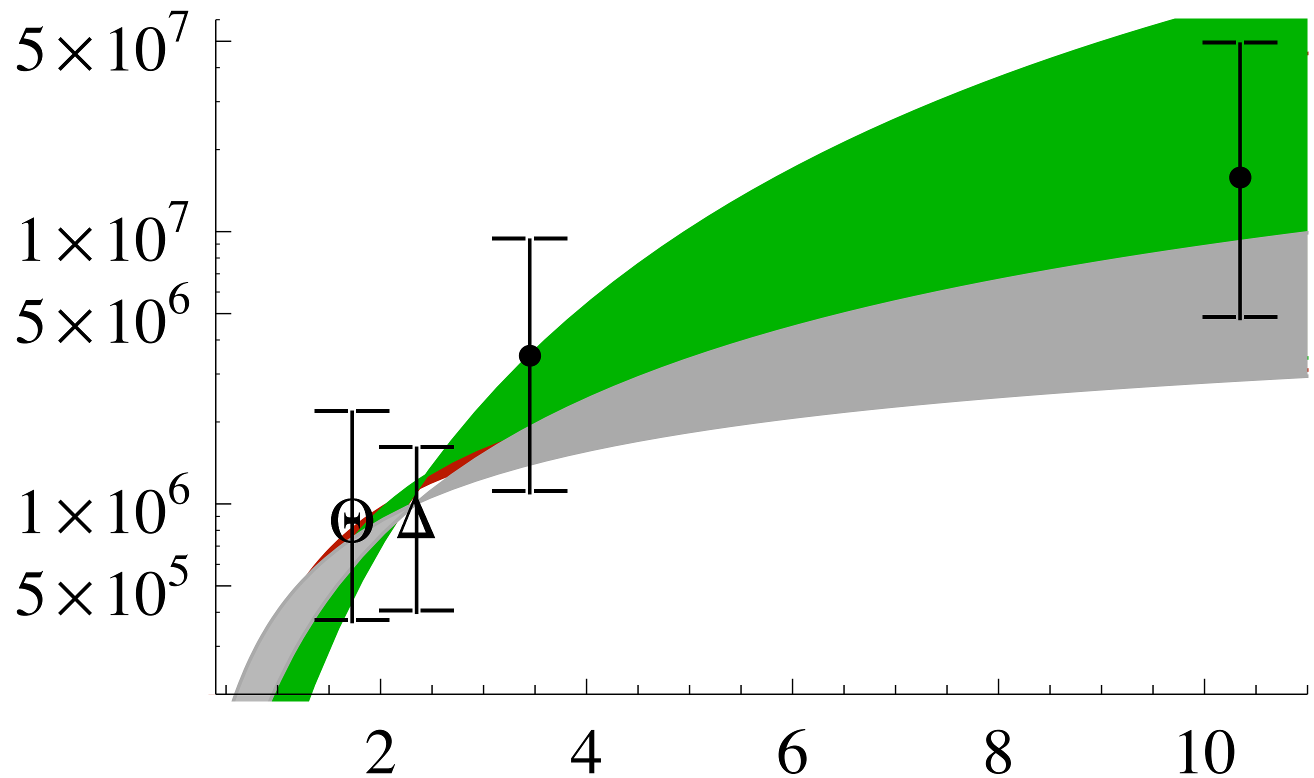
Dwarf Spheroidal Modelling



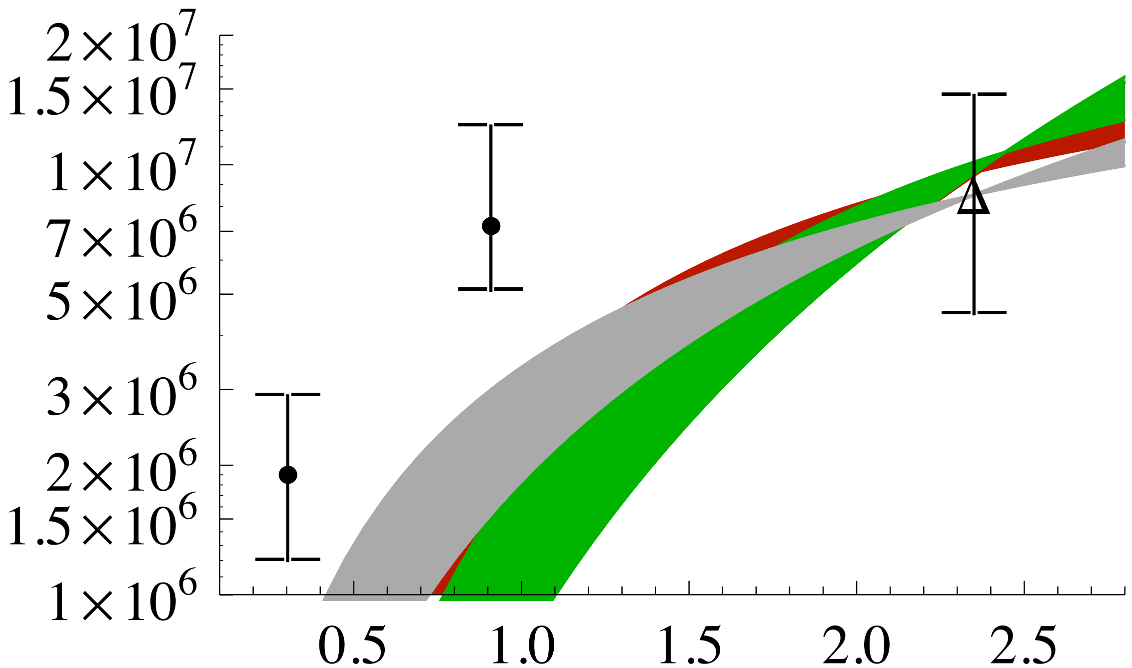
Dwarf Spheroidal Modelling

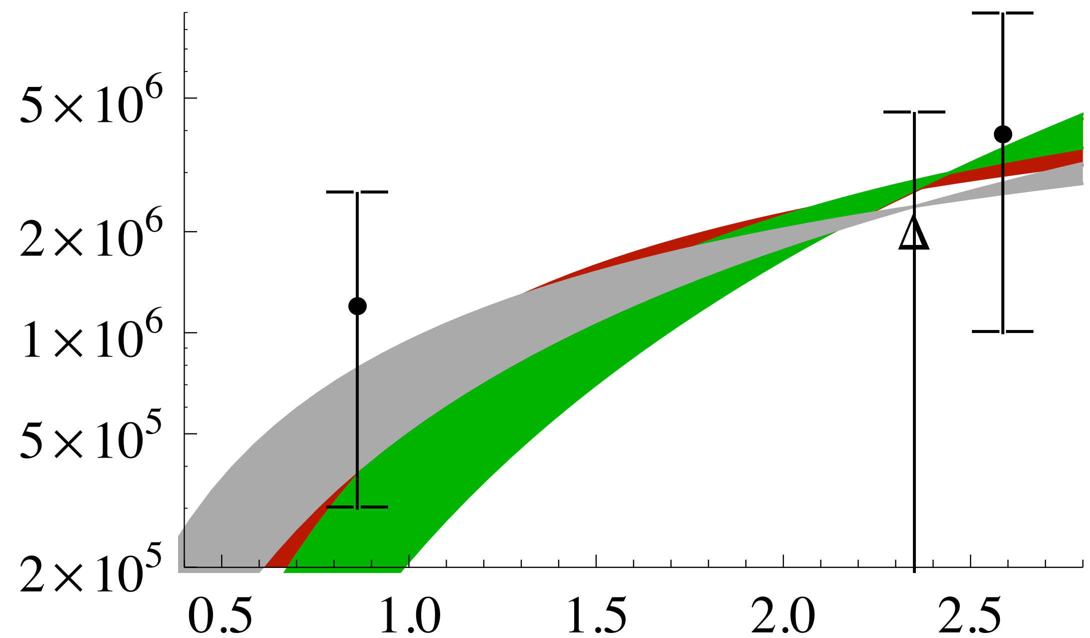
Strigari et al (2008) suggested that all the dSphs shared a common mass scale of $\sim 10^7$ solar masses within 300 parses.

For the faintest objects like Willman 1 and Segue 1, 300 pc corresponds to nearly 10 half-light radii.



Dwarf Spheroidal Modelling



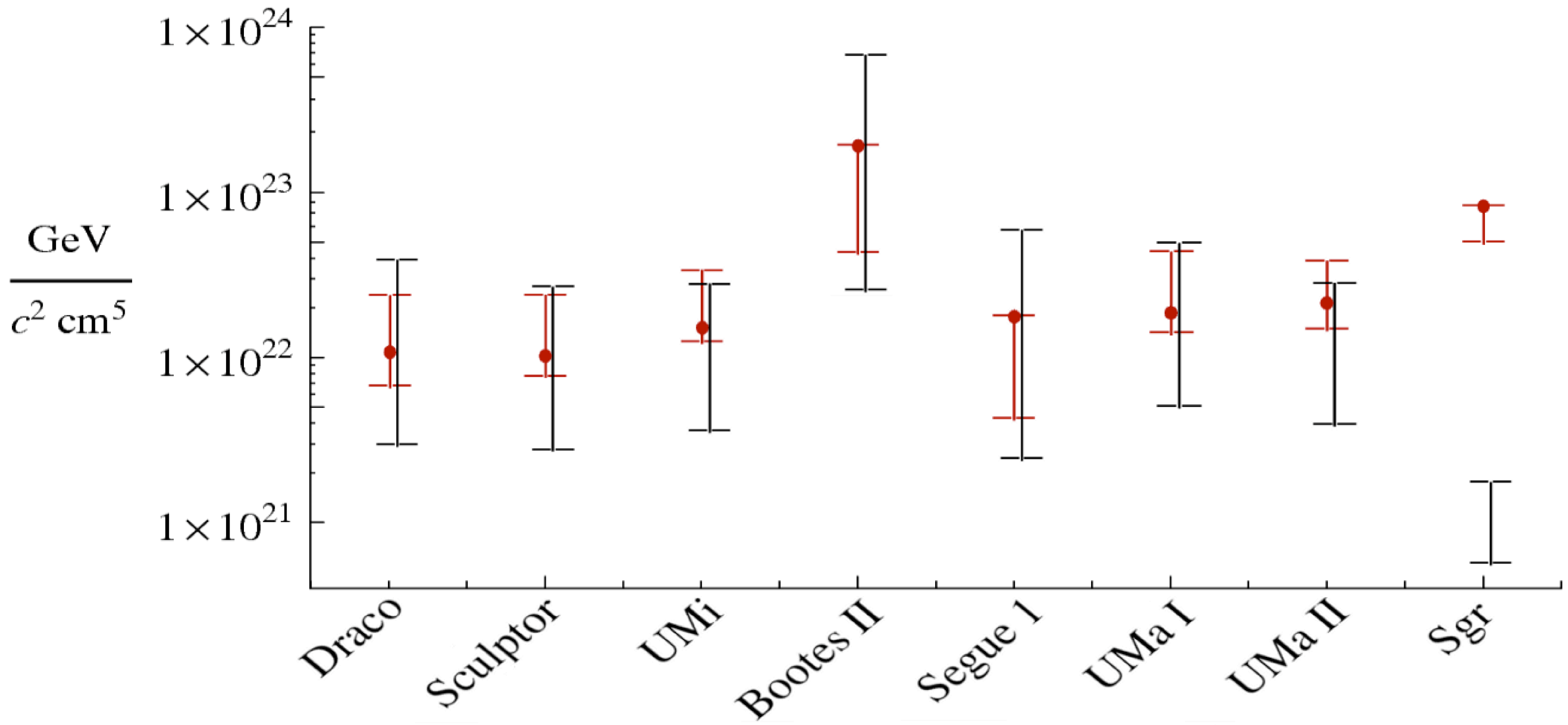


Hercules

Leo IV

Hercules and Leo IV are not compatible with a common mass scale of 10^7 solar masses within 300 pc. For both objects, the mass interior to 300 pc is below 3×10^6 solar masses

Dark Matter Detection



The annihilation flux over an angular region with a diameter of 1 degree, which is a good match to the LAT PSF at energies of 1-2GeV.

Dark Matter Detection

Leaving aside such ambiguous objects as Segue 1 and Boo II, the best target is the Sagittarius (Sgr) galaxy. However, the location of the Sgr towards the Galactic Centre may frustrate attempts to find a clear-cut signature.

The best targets are Ursa Major I and II (both almost certainly galaxies) as well as the closest of the classical dSphs, Draco, Sculptor and Ursa Minor.

Conclusions

In the preceding half-century, Milky Way dwarf spheroidals were discovered at a rate on one or so a decade. Then, in the period 2006-9, twenty were discovered. No-one believes the existing sample is complete.

The status of the new objects, the ultrafaints, is unclear. Velocity dispersion measurements will need considerable care (interlopers, variable stars and binaries are all serious problems that can artificially inflate the dispersion and hence the dark matter content.

The best targets for indirect detection surveys are Sgr, Ursa Major I and II, together with the closest of the classical dSphs.