DARK MATTER SUBSTRUCTURES

IN THE NEARBY UNIVERSE

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DARK MATTER

1. The dwarf spheroidals
2. The ultra-faints
3. The clouds & streams
4. The unknown

DWARF SPHEROIDALS

Image (35' by 35') of the Sculptor dwarf spheroidal taken with the NOAO CTIO 4 m telescope.

DWARF SPHEROIDALS

Surrounding the Milky Way are 9 classical dwarf spheroidal galaxies (Scu, For, Leo I, Leo II, UMi, Dra, Car, Sex, Sgr).

These contain intermediate age to old stellar populations and no gas. They have velocity dispersions ~ 8-10 km/s, half-light radius ~ 200-300 pc, and absolute magnitudes M_V brighter than -8.

They are all highly dark matter dominated, and are natural targets for indirect detection experiments. What are their dark matter profiles? Are they cusped or cored?

DWARF SPHEROIDALS

Radial velocity surveys with multi-object spectrographs have now provided datasets of thousands of velocities for the giants stars.

Early hopes that the photometry and line of sight velocity dispersion profile could be used to constrain the dark halo give way to pessimism.

Most early modelers used the spherical Jeans equations to deduce dark matter properties at the center.

JEANS EQUATIONS

- The spherical Jeans equation is dangerous! If the light profile is cored (Plummer), then assuming isotropy gives a cored dark matter density. If the light profile is cusped (exponential), then so is the dark halo (An & Evans 2009).

- The degeneracies in the Jeans equations are also illustrated by Walker et al. (2009), who found the existing data compatible with a broad range of halo models by Jeans modelling.

- The progress in the subject seemed to have stalled. The degeneracies in the modelling seemed too severe

SUB-POPULATIONS

- Harbeck et al. (2001) found significant population gradients in all the Milky Way dwarfs (Car, Scu, Sex, Tuc).
- Red horizontal branch stars (younger, more metal-rich) are more concentrated than blue horizontal branch (older, more metal-poor) stars. A population constrains the potential at locations at which $\Phi(r) \approx \sigma^2$
- Battaglia et al. (2008) provided the first marrying of dynamics with chemistry in their modelling of Sculptor using the Jeans equations.

PROJECTED VIRIAL THEOREM

$$2T_{los} + W_{los} = 0 \Rightarrow$$

For a population with luminosity density $\boldsymbol{\nu}$ and surface brightness $\boldsymbol{\mu}$, this becomes

$$3 \int \boldsymbol{\mu\sigma}^2_{los}\, R dR = 2 \int \boldsymbol{\nu\Phi}'\, r^3 dr$$

The only unknown is $\boldsymbol{\Phi}' = GM(r)/r^2$

PROJECTED VIRIAL THEOREM

$$\frac{\int \mu_1 \sigma^2_{los,1} \, R dR}{\int \mu_2 \sigma^2_{los,2} \, R dR} = \frac{\int \nu_1 M(r) \, r dr}{\int \nu_2 M(r) \, r dr}$$

Note (i) equation is entirely independent of the anisotropy β and (ii) equation is independent of gradients of observables.

PROJECTED VIRIAL THEOREM

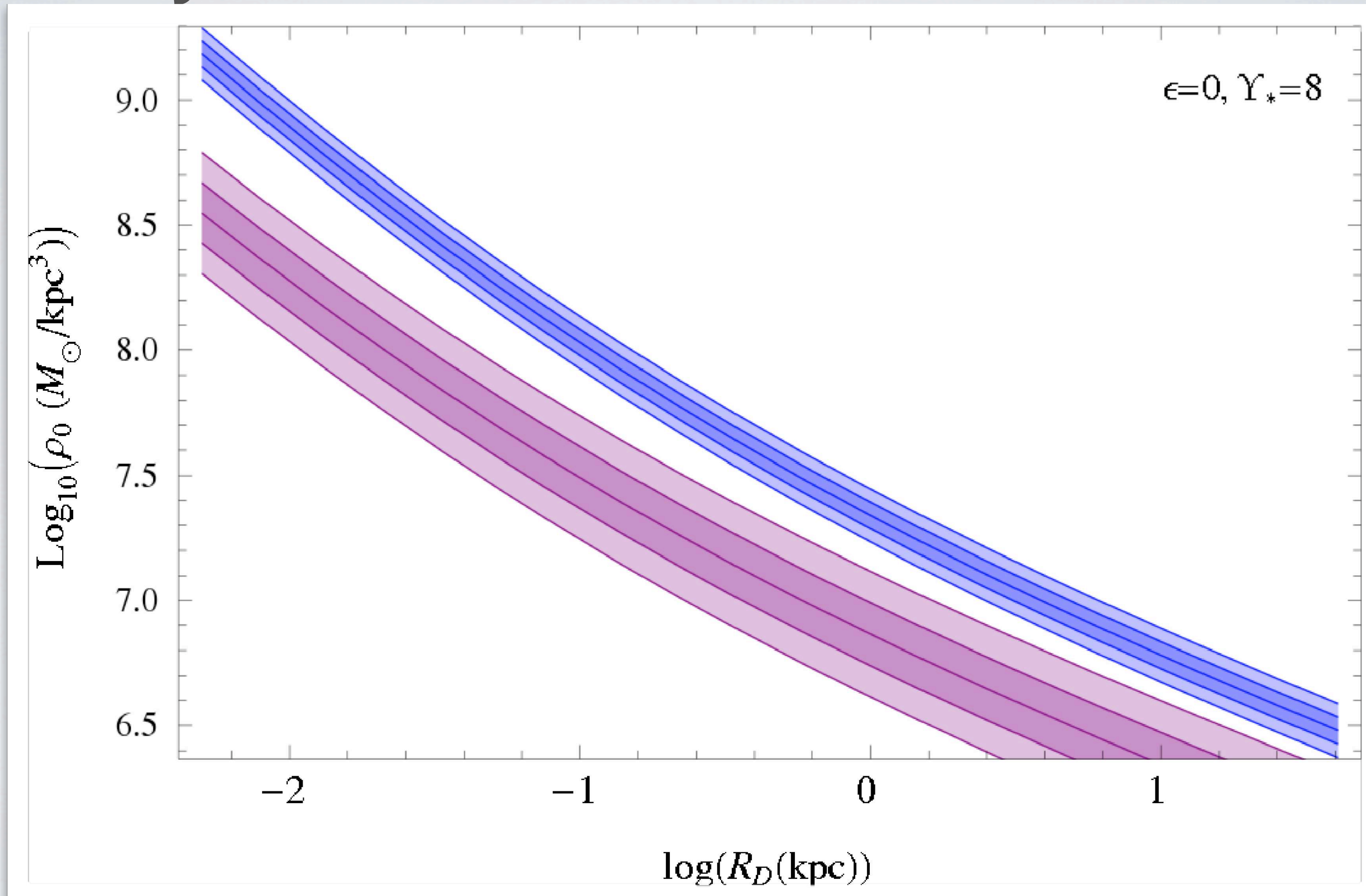
A necessary condition for an NFW halo to support two stellar populations with Plummer/exponential profiles is

$$1.9\, \sigma^2_{0,1} / \sigma^2_{0,2} < R_{h,1}^2 / R_{h,2}^2$$

where population 1 is metal-rich, population 2 is metal-poor.

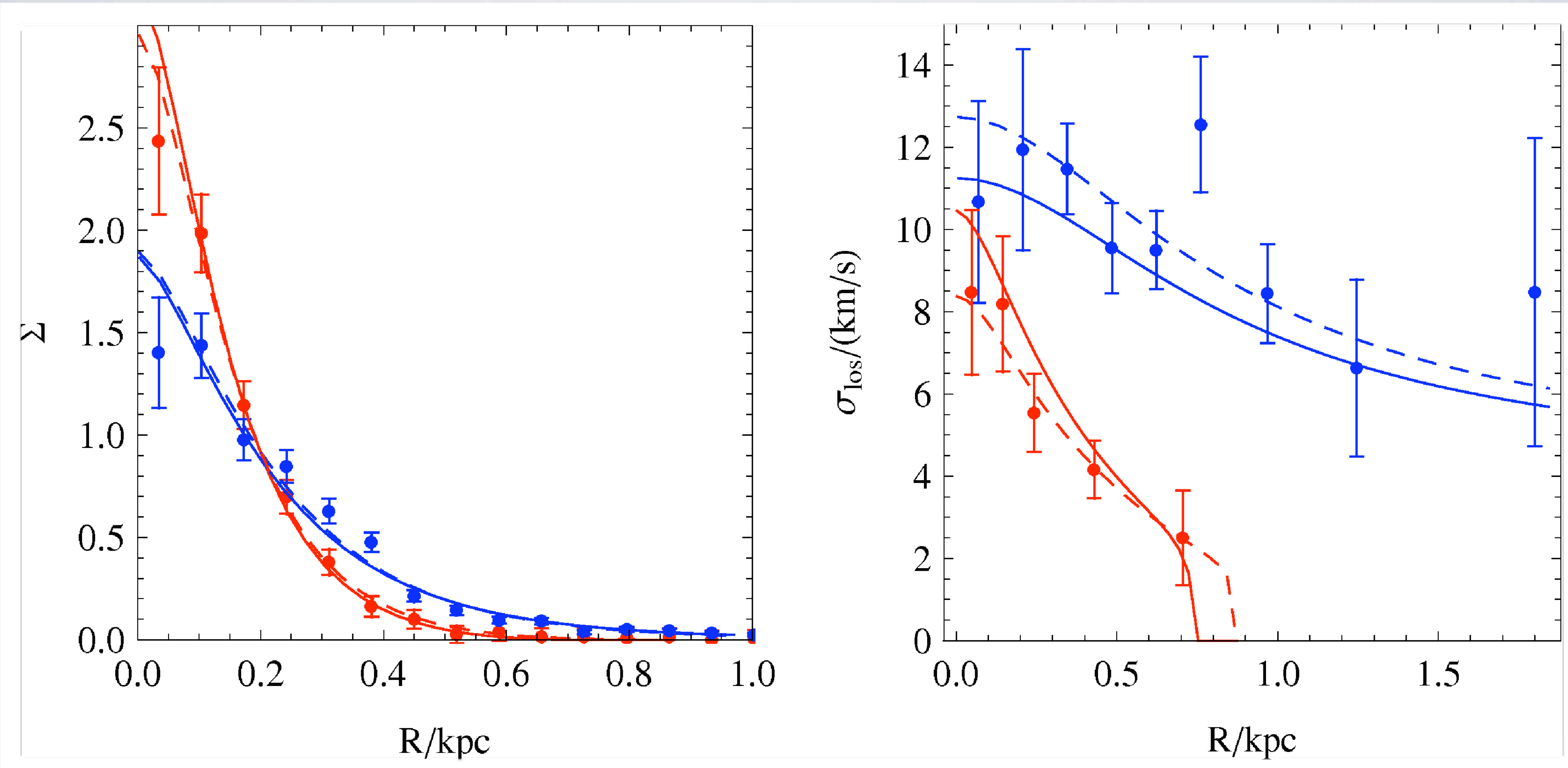
Strongly violated by the two populations in Sculptor! There is no NFW halo that can support the two populations.

PROJECTED VIRIAL THEOREM



Agnello, Evans ApJL, in press

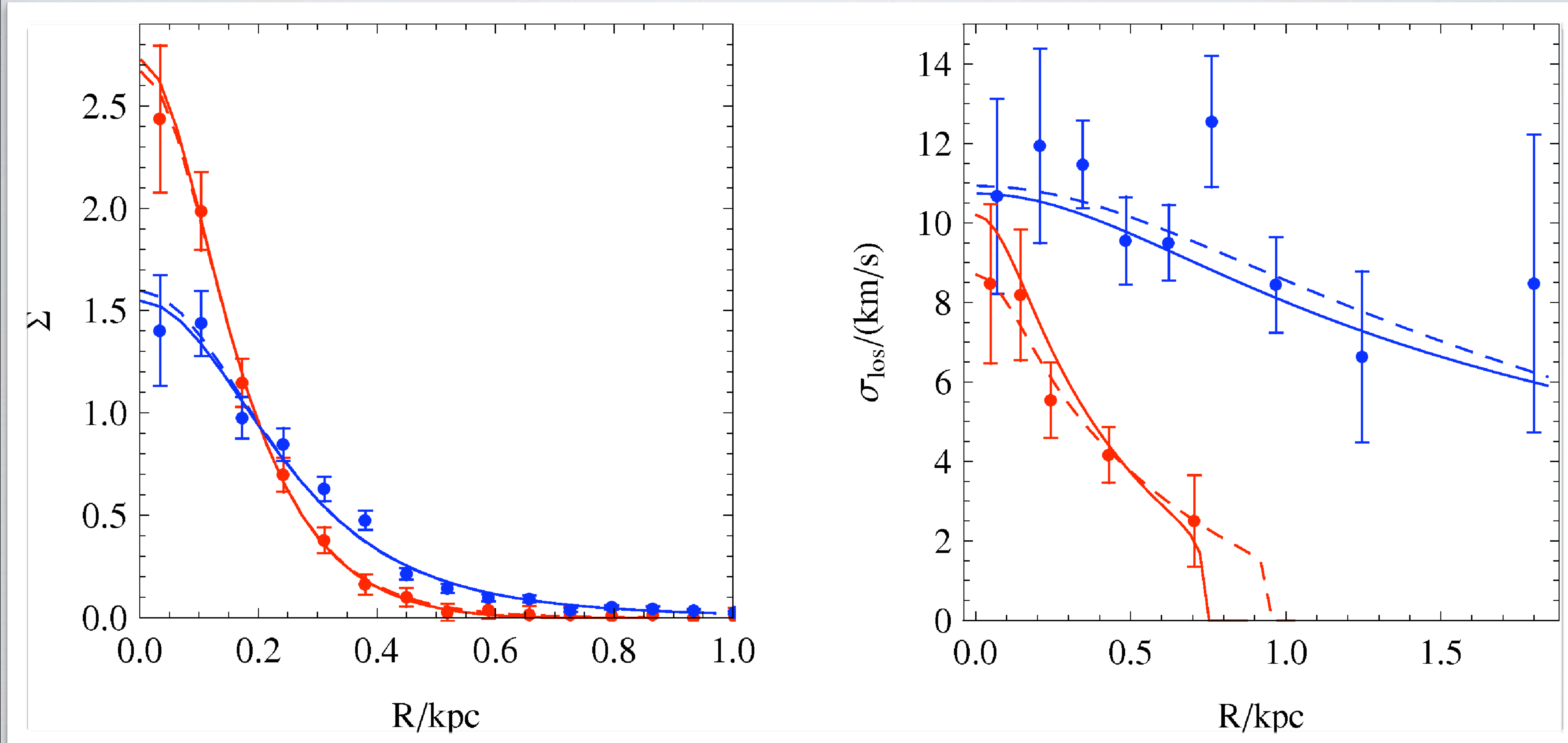
PHASE SPACE MODELLING



Amorisco, Evans, MNRAS, 419, 184

Monday, 16 July 2012

PHASE SPACE MODELLING



Amorisco, Evans, MNRAS, 419, 184

EVIDENCE FOR CORES

Two other significant pieces of evidence are the persistence of stellar substructure in UMi & the existence of globular clusters in Fornax

Kleyna et al. (2003) showed the existence of a loosely bound satr cluster in UMi. This can remain intact for long times only in a cored potential.

In a cusped potential, globular clusters only need a few Gyr to spiral to the center (e.g., Goerdt et al 2006),. In a cored potential, dynamical friction brings the globular cluster to the approximate core radius.

DWARF SPHEROIDALS

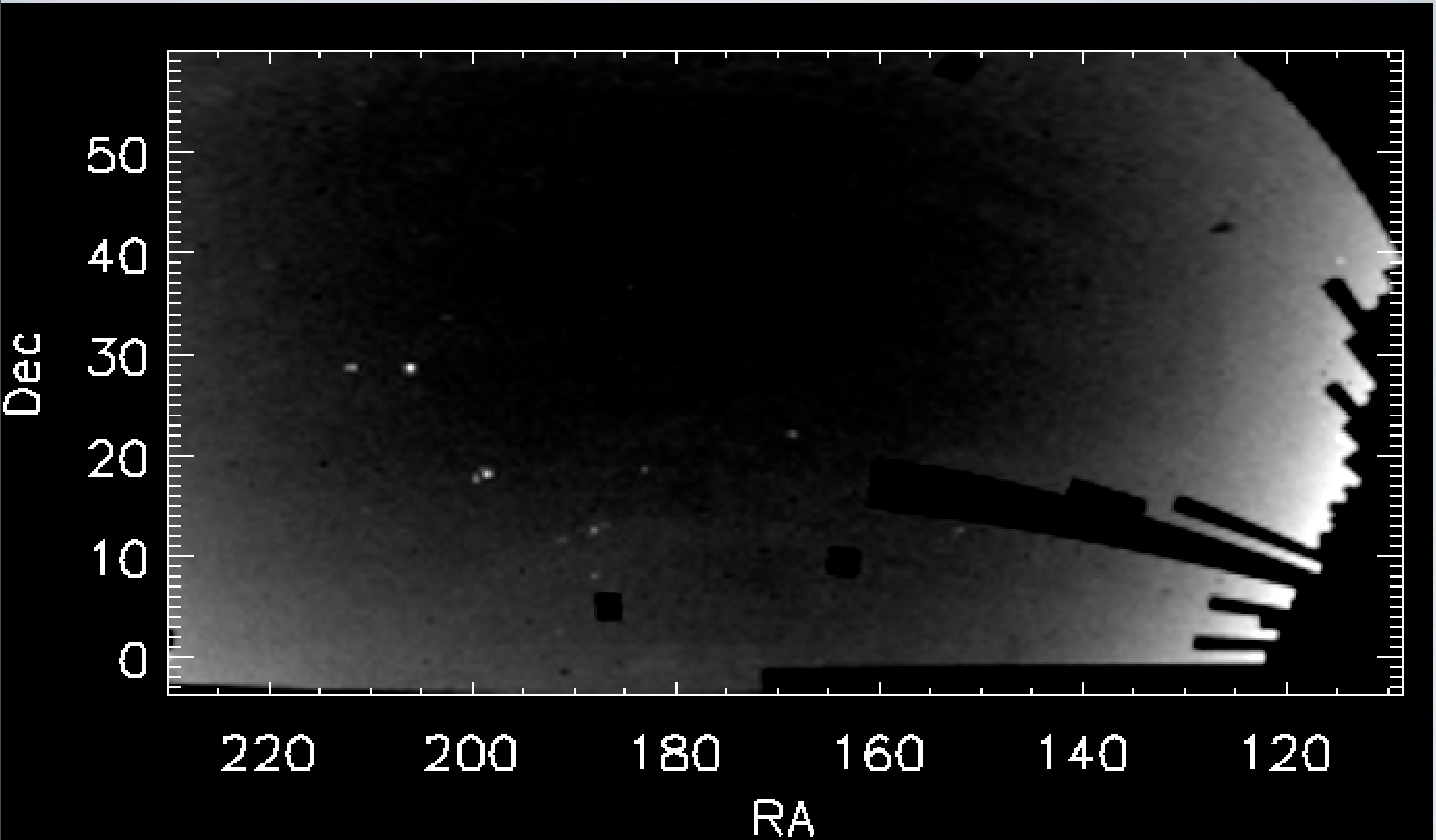
- A number of lines of evidence rule out 1/r cusps (e.g., multiple populations in Sculptor & Fornax, persistence of stellar substructure in UMi and existence of globul;ar clusters in Fornax).
- In modeling indirect detection signals, cored profiles are likely to be more realistic than cusps.

THE ULTRAFAINTS

Surrounding the Milky Way are ~13 ultrafaint dwarf galaxies (Boo I, Boo II, Boo III, Can Ven I, Can Ven II, Her, Coma, Leo IV, Leo V, UMa I, UMa II, Pisces I, Pisces II, possibly Segue 1, Willman 1).

These contain old stellar populations and no gas. They have velocity dispersions ~ 5 km/s, half-light radius ~ 100 pc, and M_V fainter than -5.

The properties of these objects remain poorly known, although they certainly contain copious dark matter.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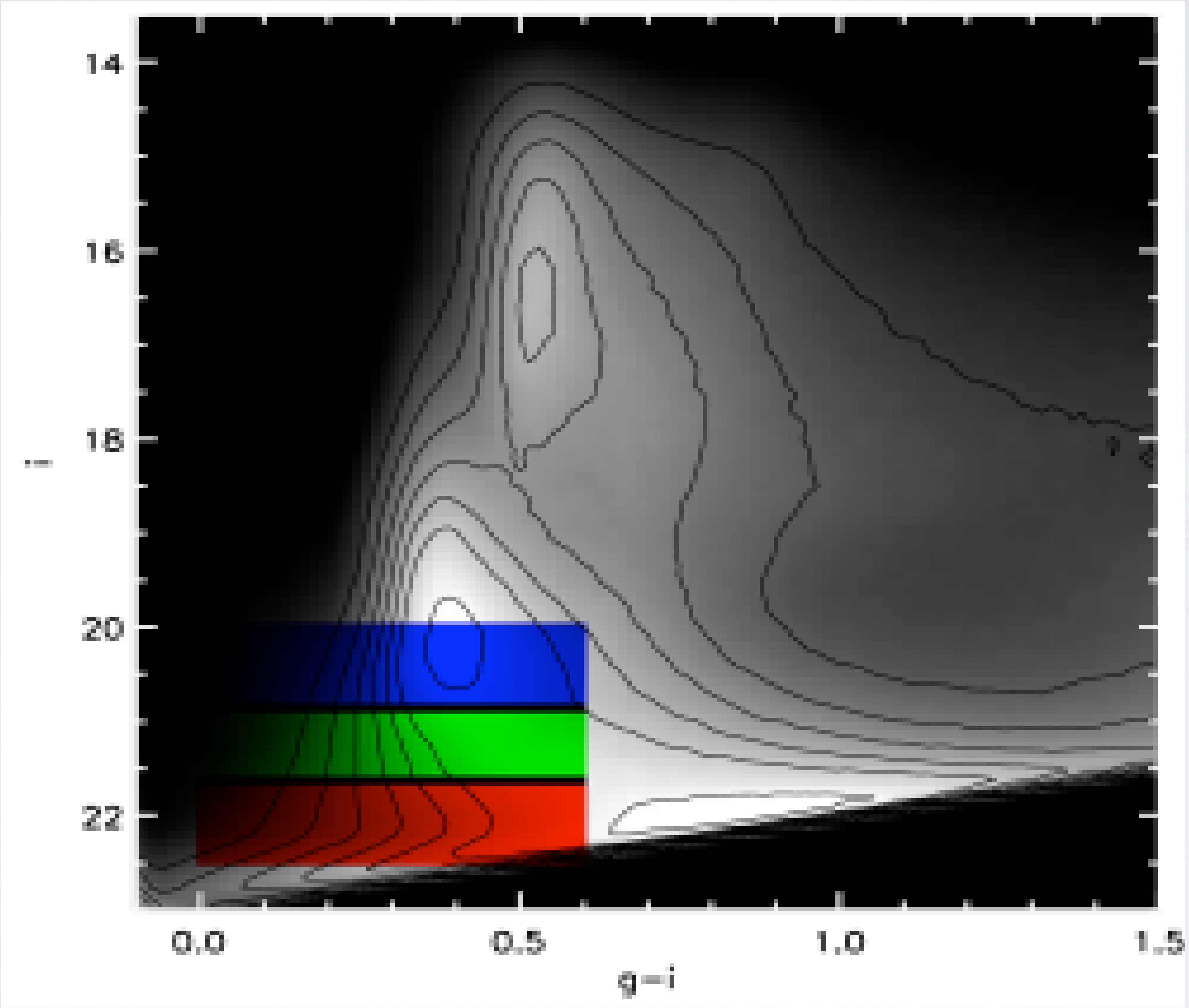
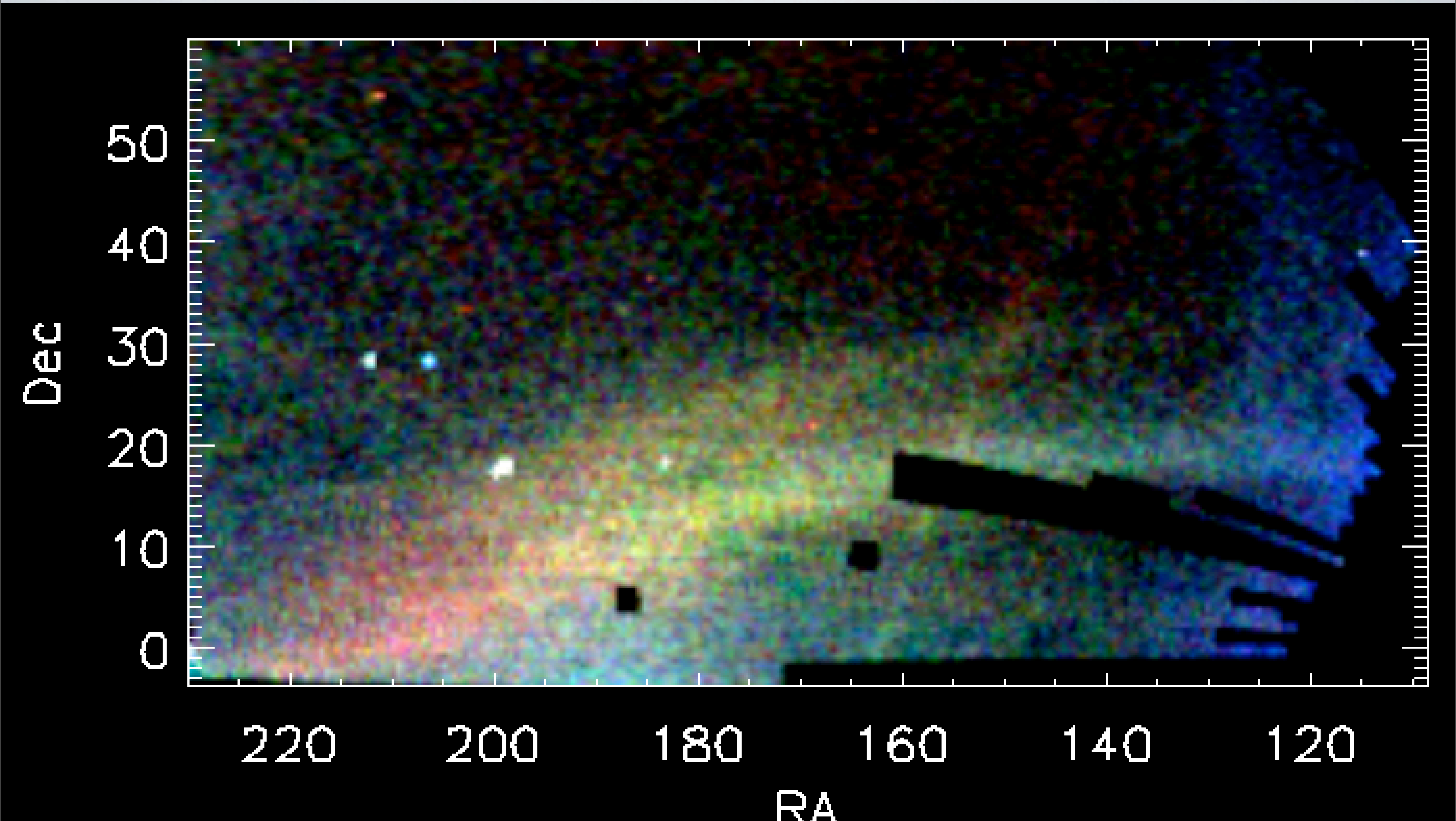
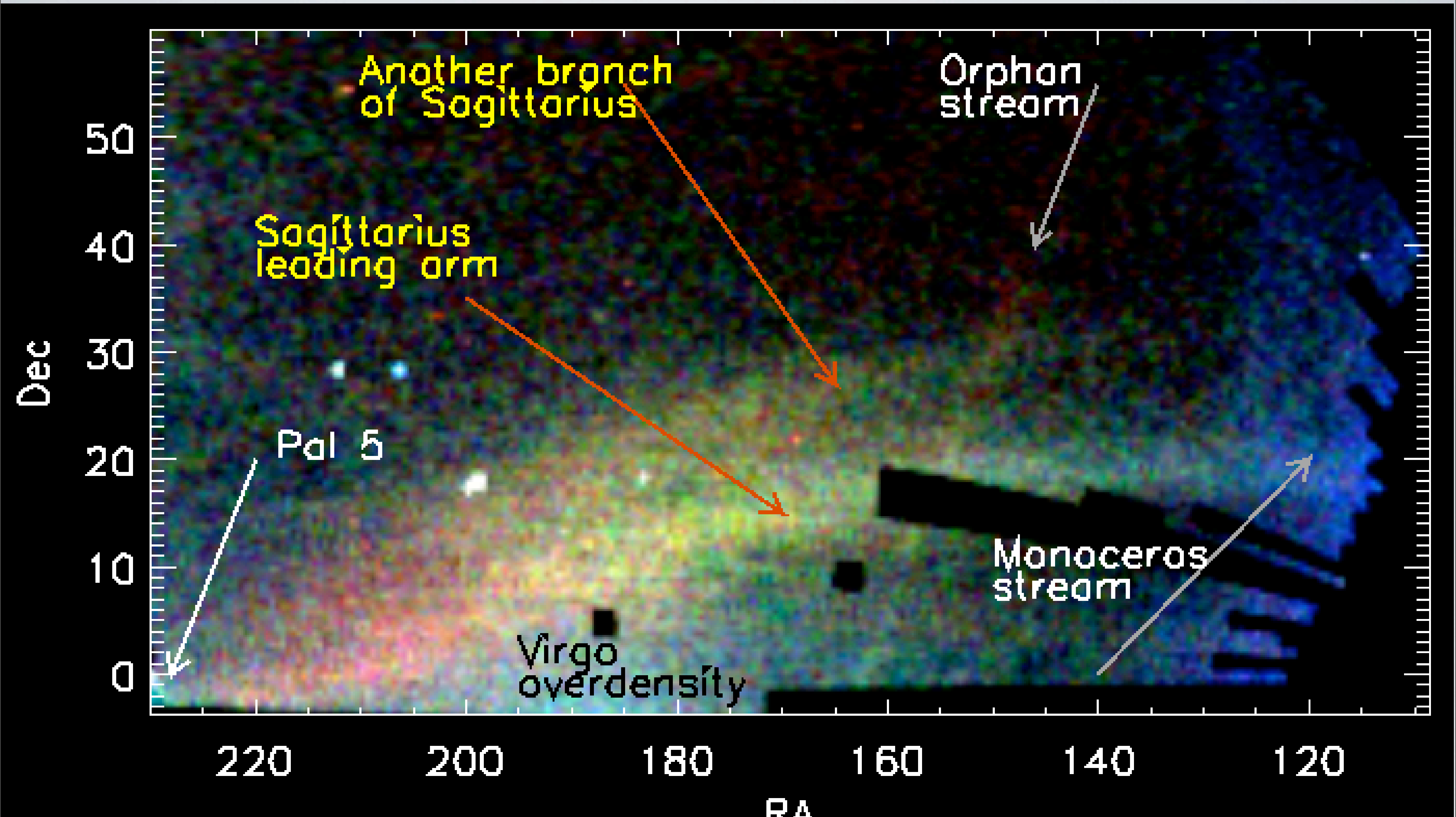
THE FIELD OF STREAMS





Belokurov, Zucker, Evans et al. 2006
t

The Field of Streams



Belokurov, Zucker, Evans et al. 2006
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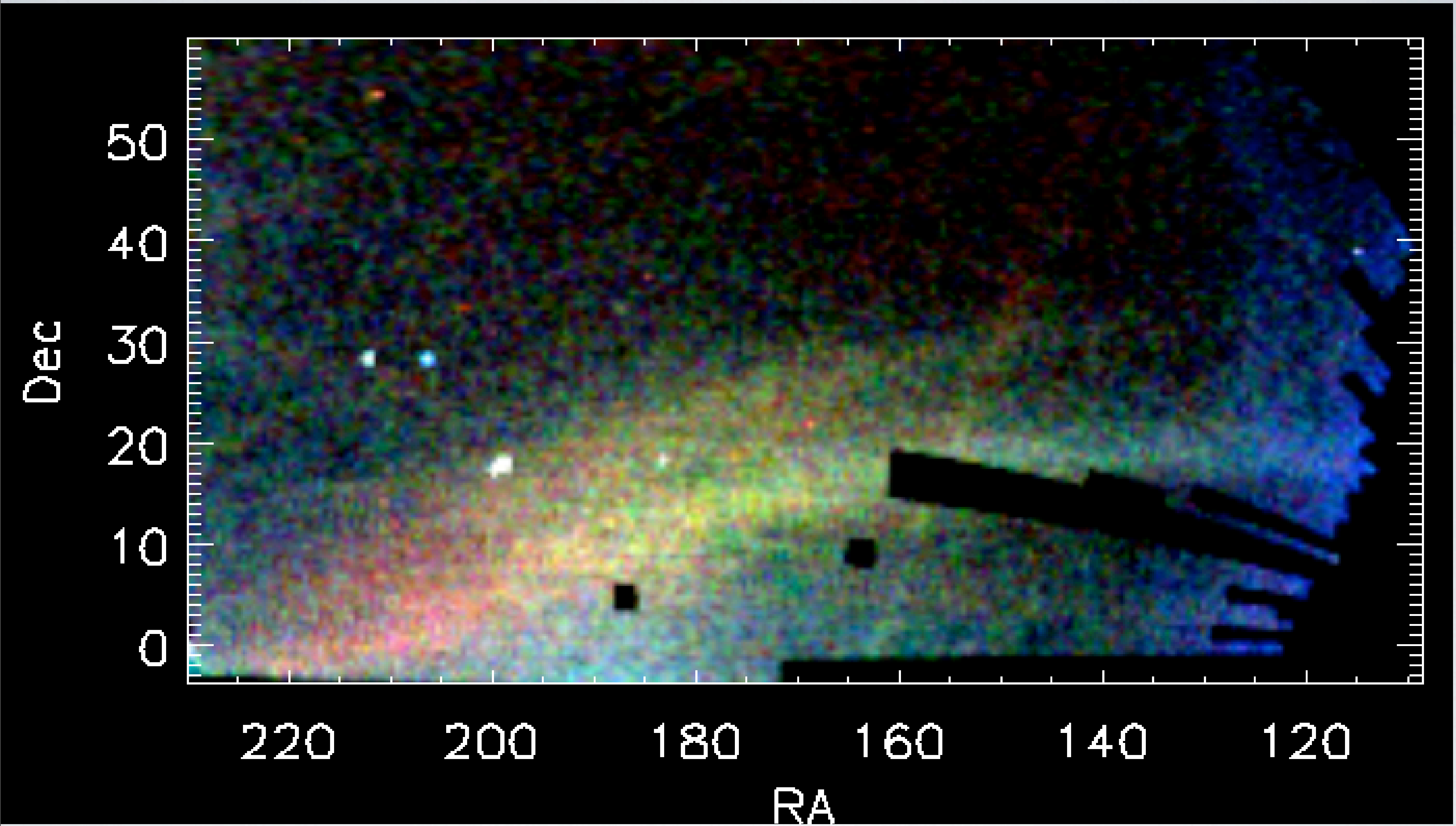
The Field of Streams



Belokurov, Zucker, Evans et al. 2006
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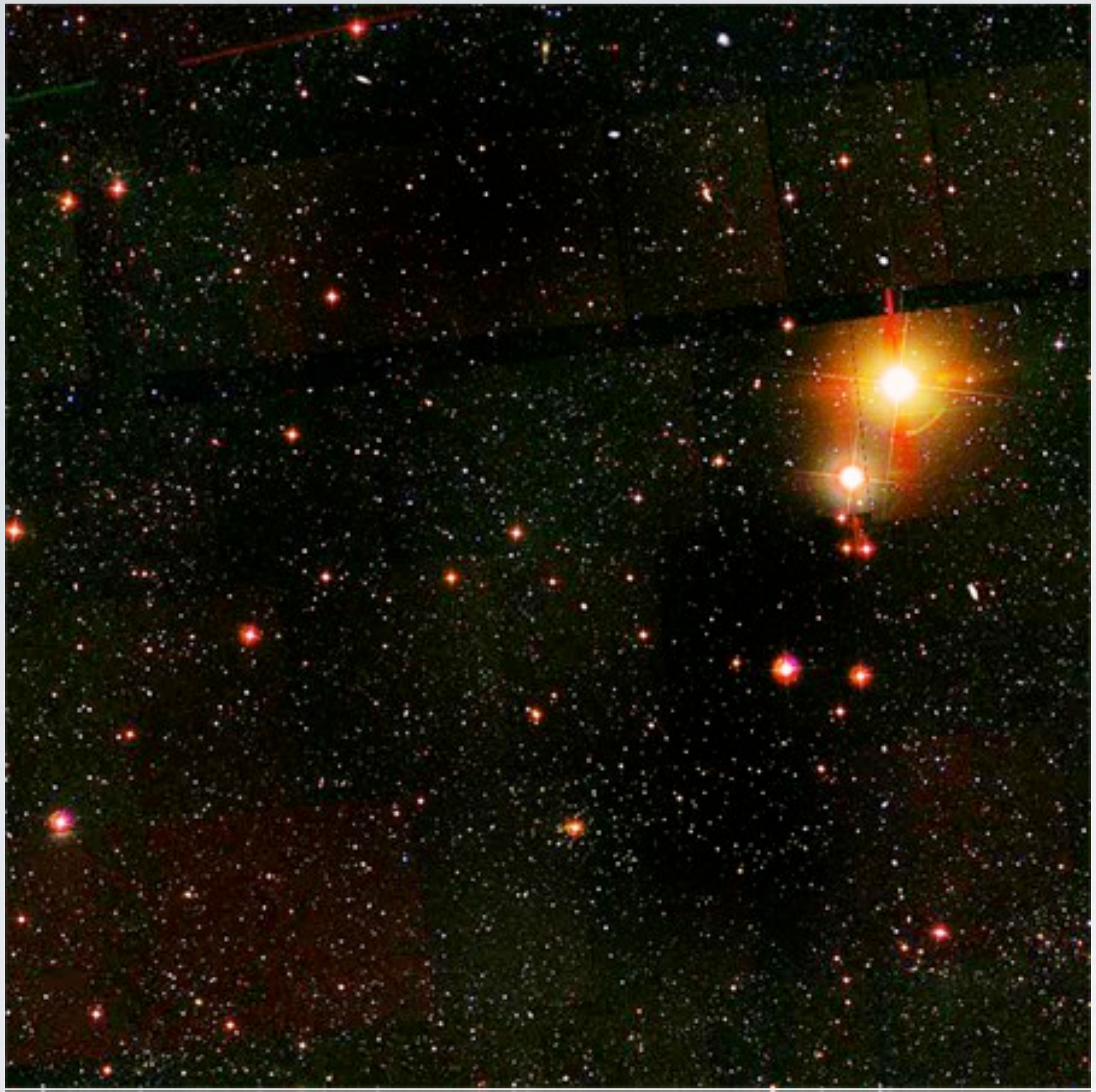
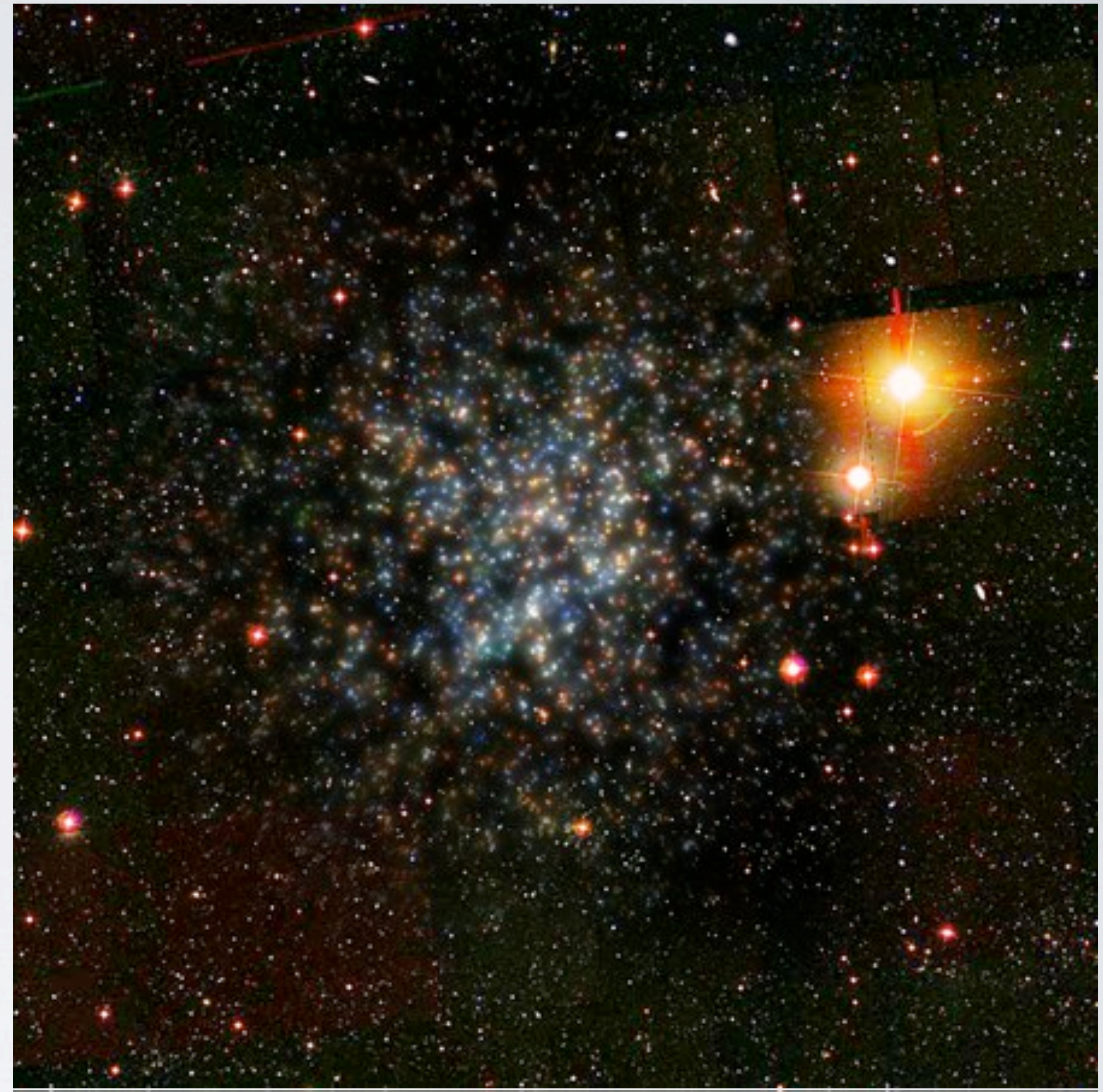



Belokurov, Zucker, Evans et al., 2006

BOOTES I DWARF

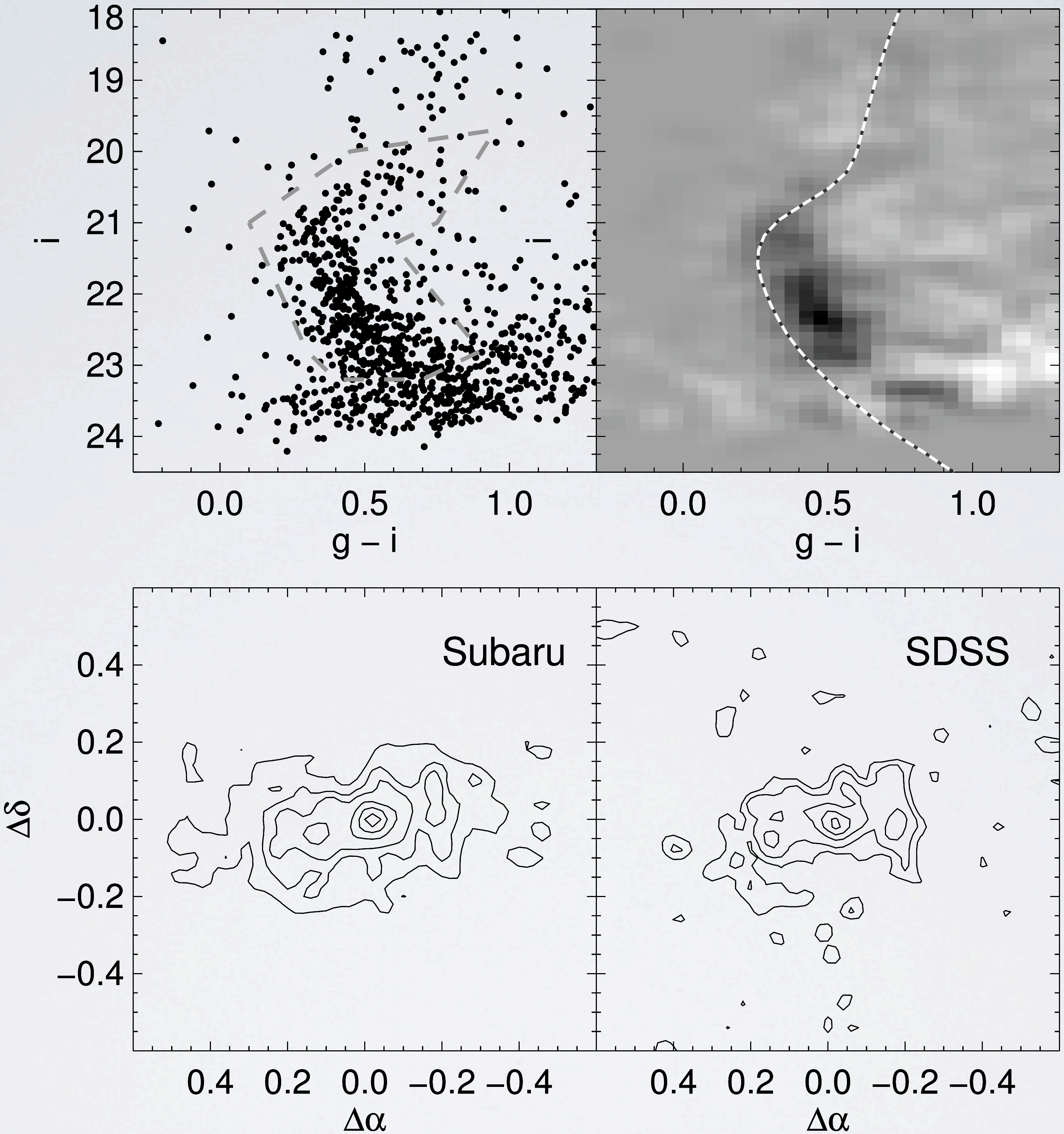
Absolute Magnitude M_V =-5.8, Heliocentric Distance = 60 kpc

BOOTES I DWARF

Bootes I was the first ultrafaint dwarf galaxy to be discovered in *The Field of Streams*.

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

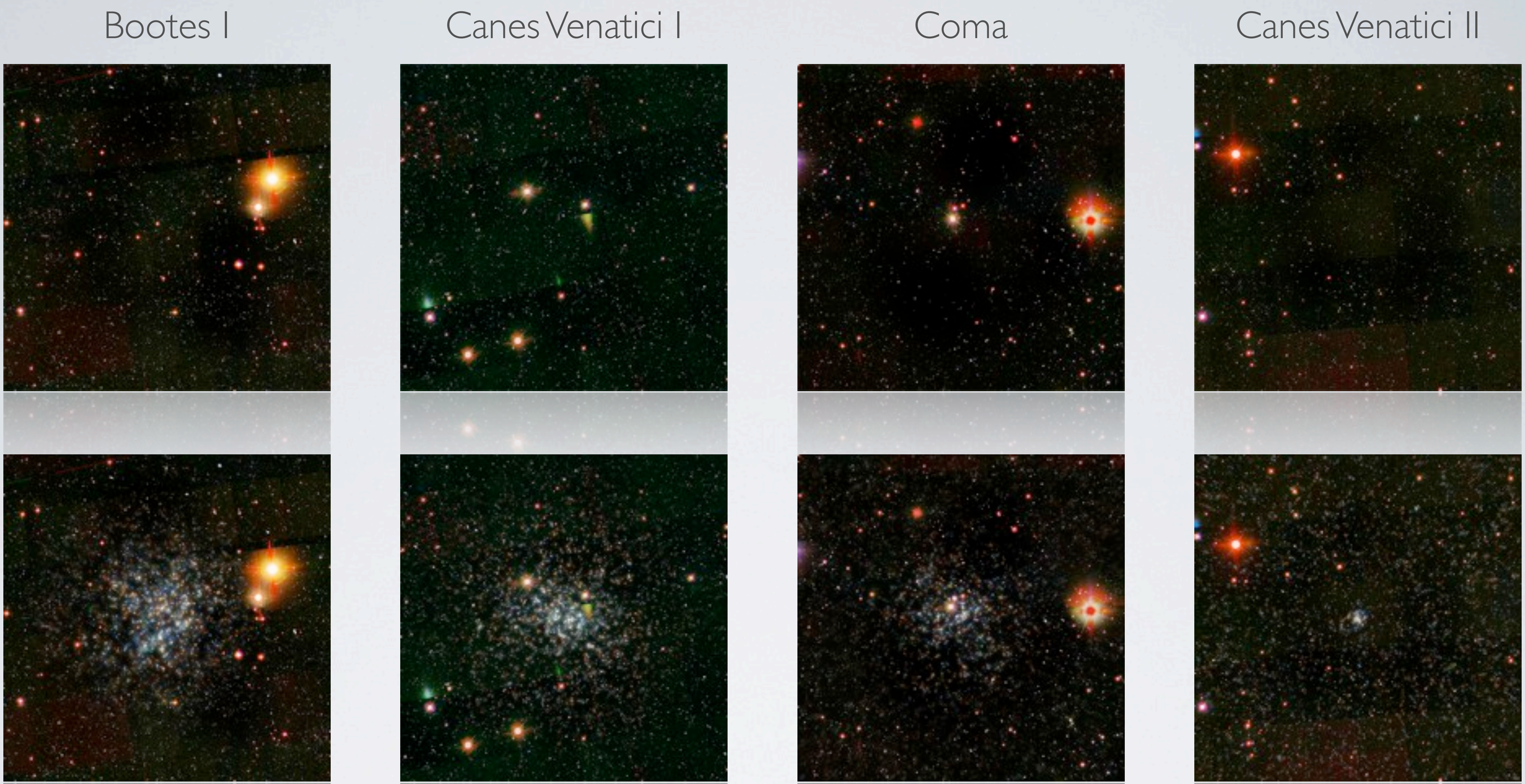
They can be detected as over-densities of resolved stars, and confirmed to possess the characteristics of galaxies by colour-magnitude diagrams.



Ursa Major II, the Intrinsically Faintest Known Galaxy

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

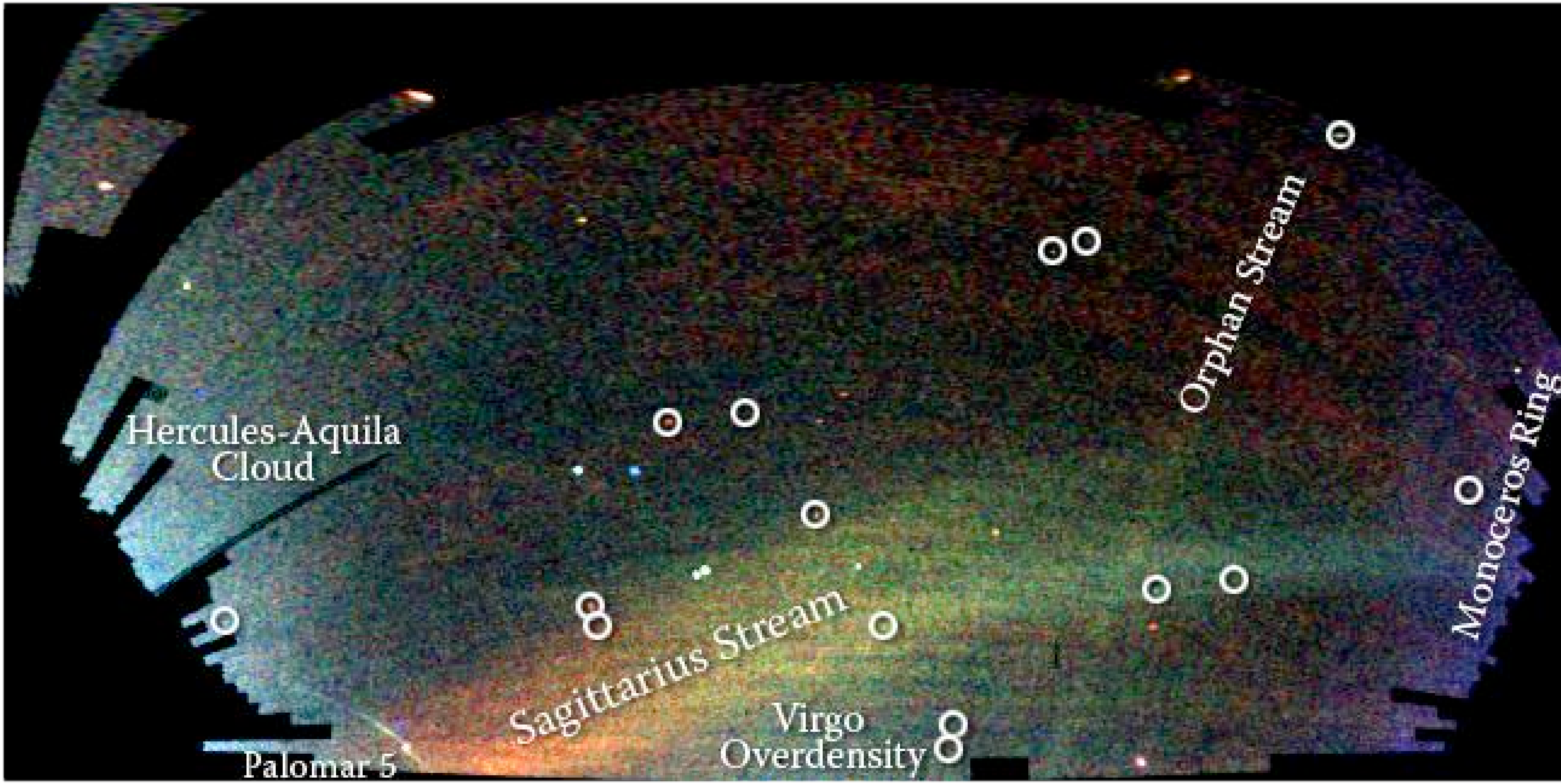
The absolute magnitude of the Ursa Major II galaxy is $M_V \approx -3.8$



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 150 kpc.

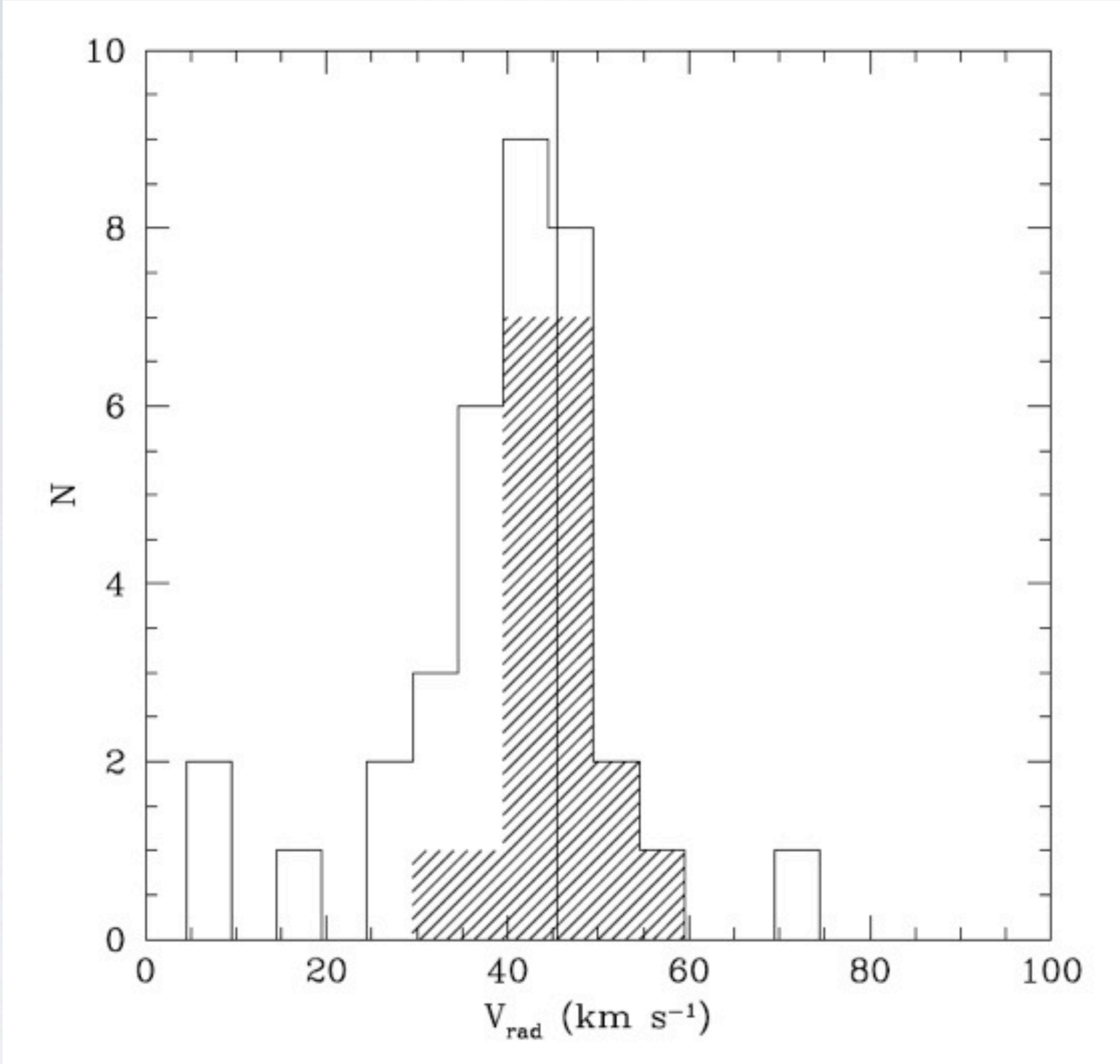


In the preceding half century, dwarf galaxies around the Milky Way were found at a rate of one a decade. In 2006-2009, fifteen were discovered in Cambridge.

DARK MATTER CONTENT ?

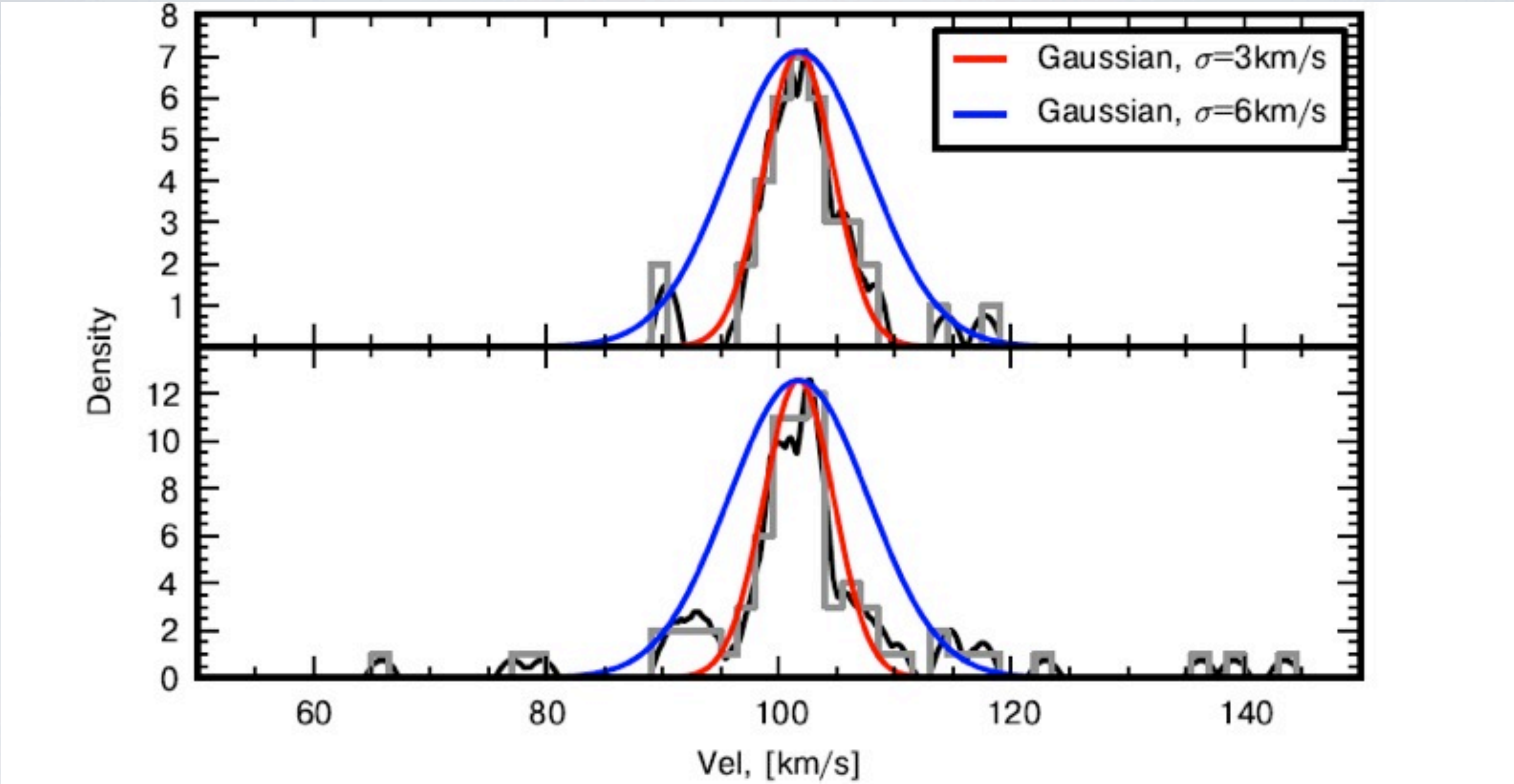
Simon & Geha (2007) used the Keck Telescope to measure the velocities of ≈ 20-200 stars in 8 ultra-faints, and claimed velocity dispersions of ≈3 to 8 km/s and mass-to-light ratios of up to ≈1000.

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.



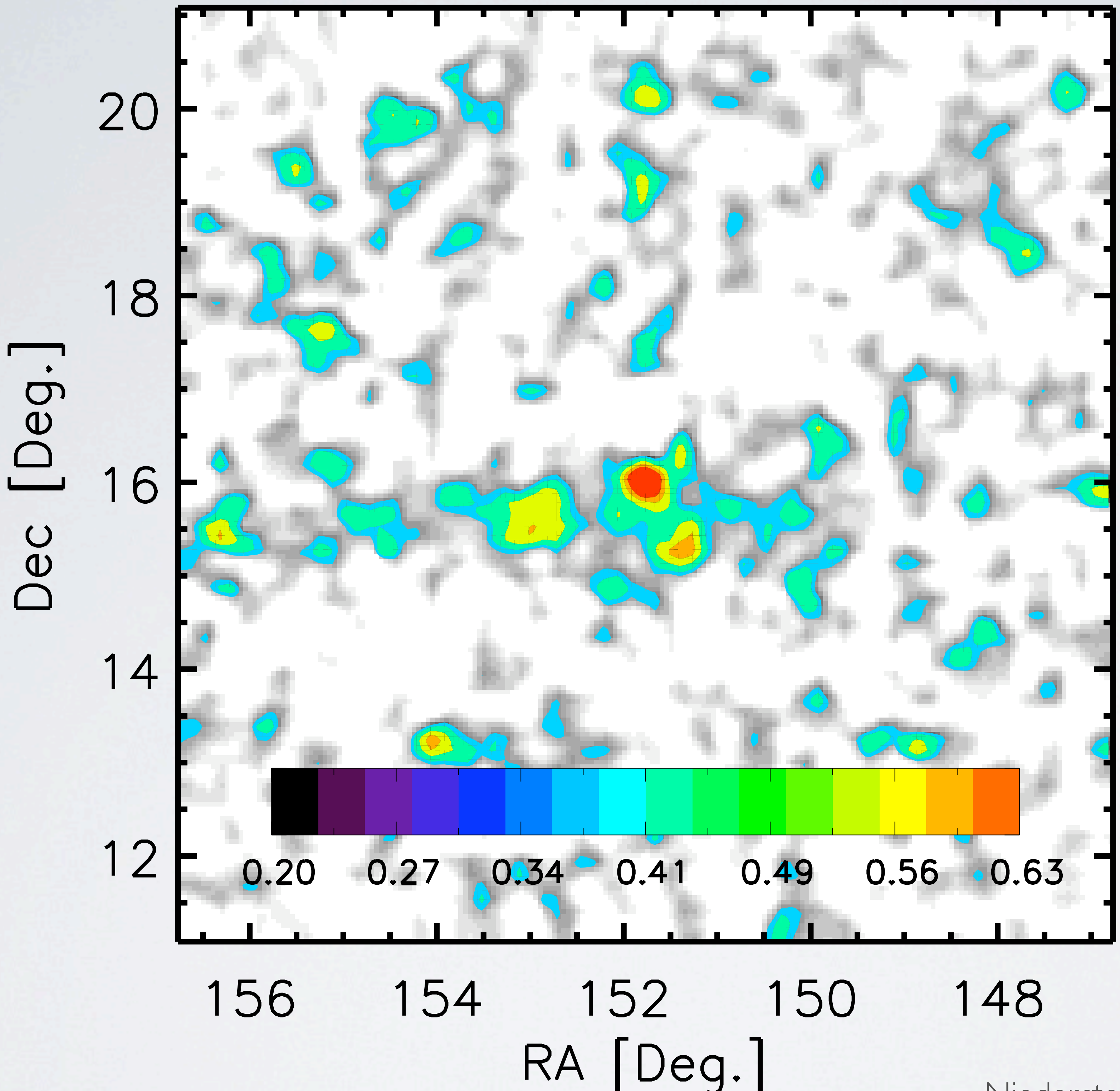
Aden al. 2009

Removal of Galactic contaminants is crucial. Velocity dispersion falls to 3.5 km/s, lower than the originally claimed 5.1 km/s in Hercules



Koposov et al. 2011

Repeat measurements are crucial to remove radial velocity variables. Velocity dispersion is significantly lower than 6.5 km/s originally claimed in Boo 1.



Niederste-Ostholt, Belokurov, Evans 2010

SEGUE I

DARK MATTER CONTENT?

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

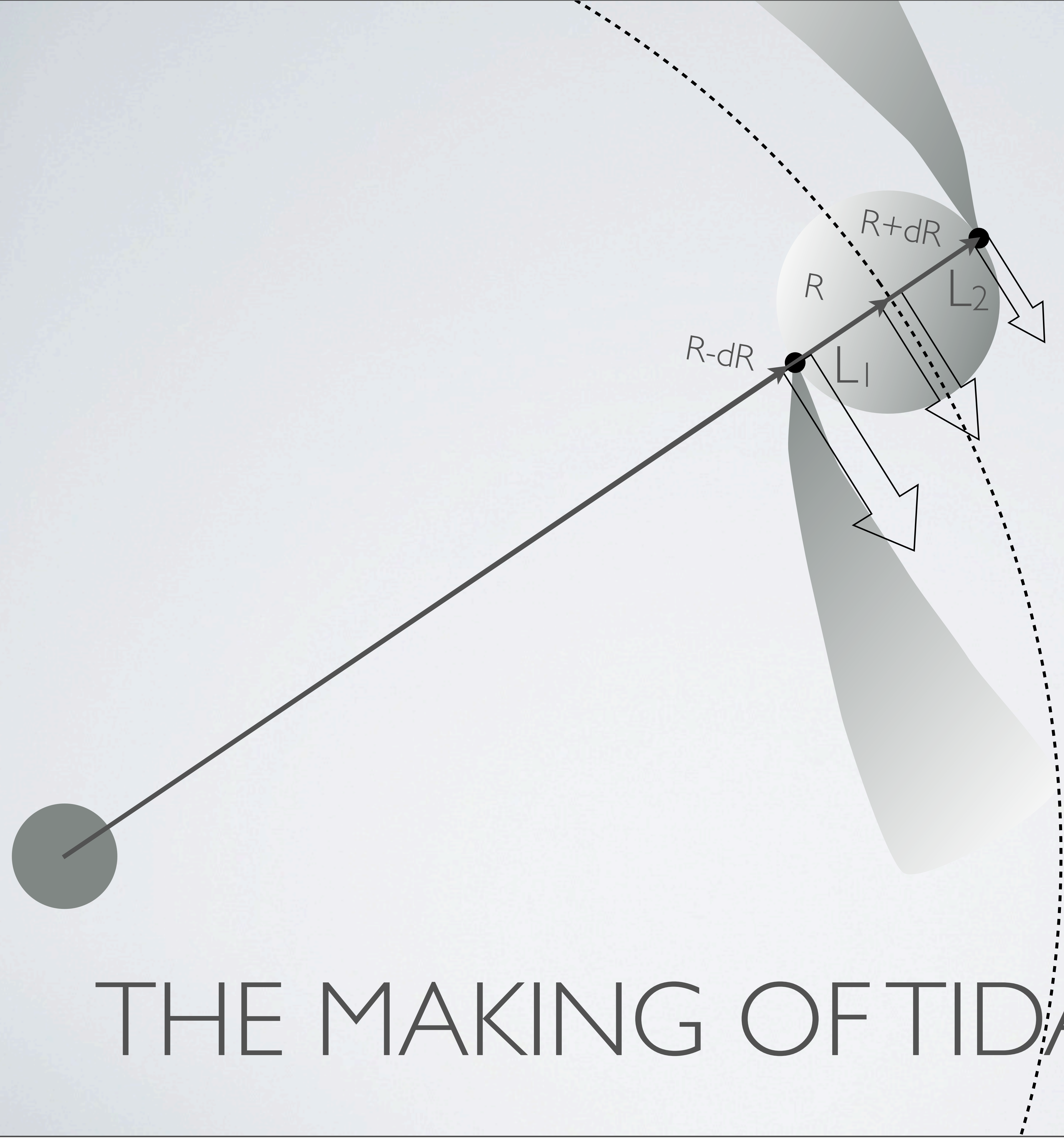
The intrinsic velocity dispersion of the stars in the ultrafaints is very low. Variable stars, binary stars and interlopers are all serious problems that can inflate the velocity dispersion. Some of the objects are clearly disrupting (UMa II, Her), so the mean velocity is also changing.

Velocity dispersion measurements require considerable care. The early measurements overestimate the dark matter content of the ultrafaints

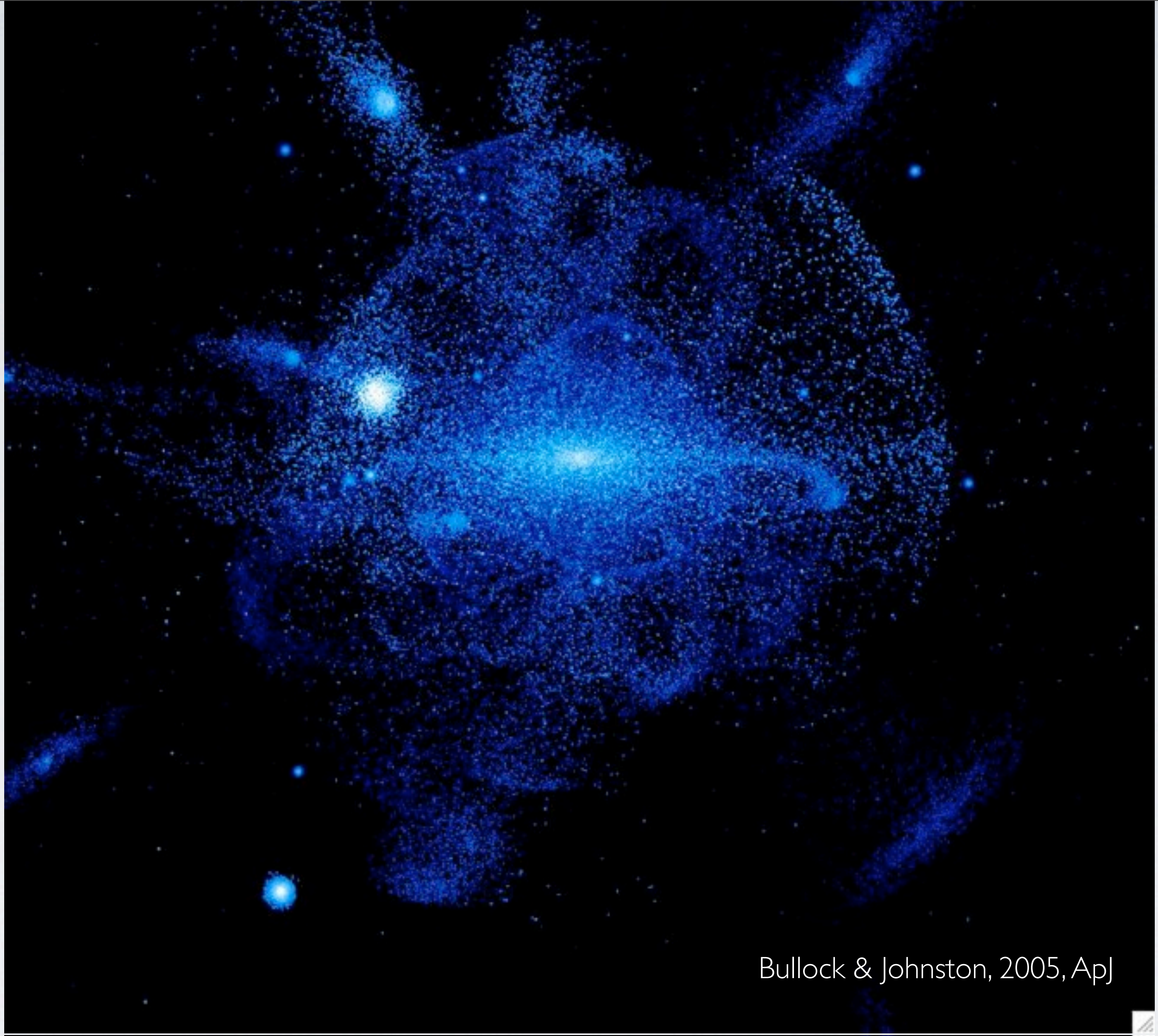
STREAMS AND CLOUDS

"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 of stars anddark matter in the mark the death throes of dying satellite galaxies.



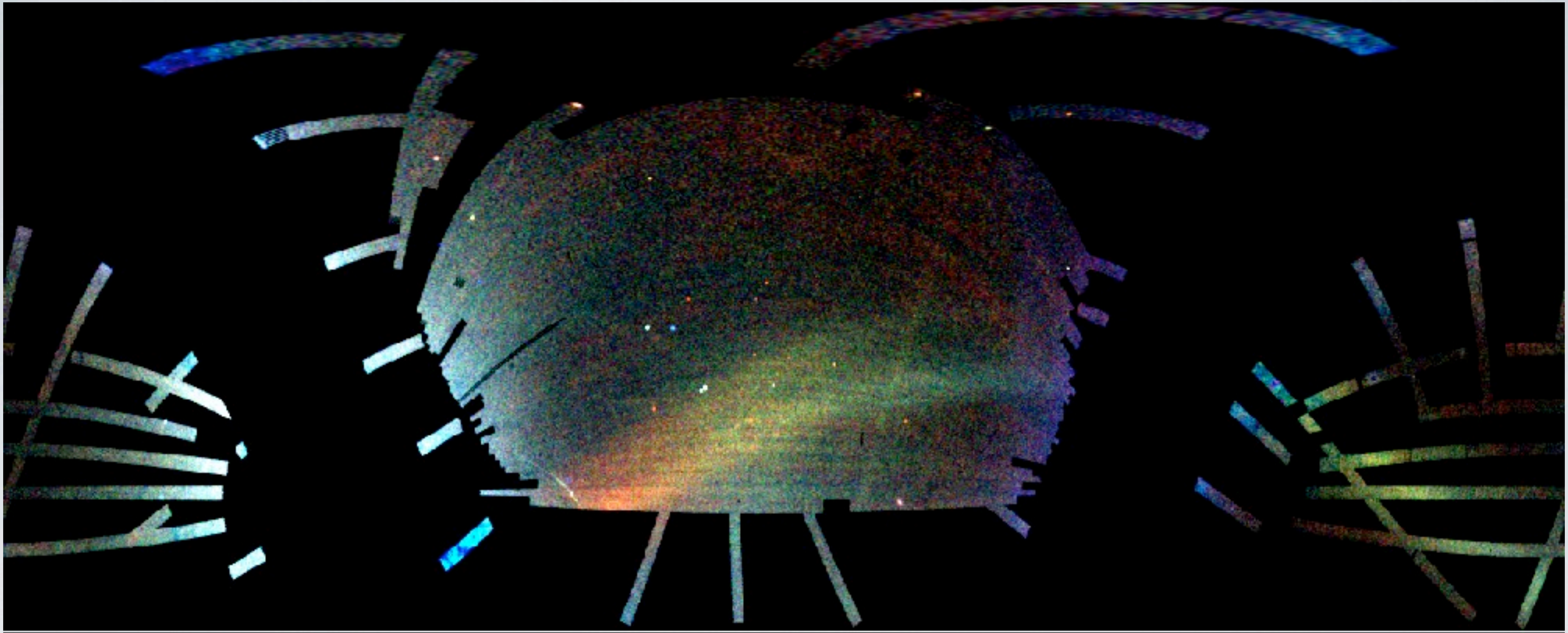
THE MAKING OF TIDAL TAILS



A SIMULATED HALO

Built from accretion of satellites, large amounts of debris

Belokurov et al., 2006



THE FIELD OF STREAMS

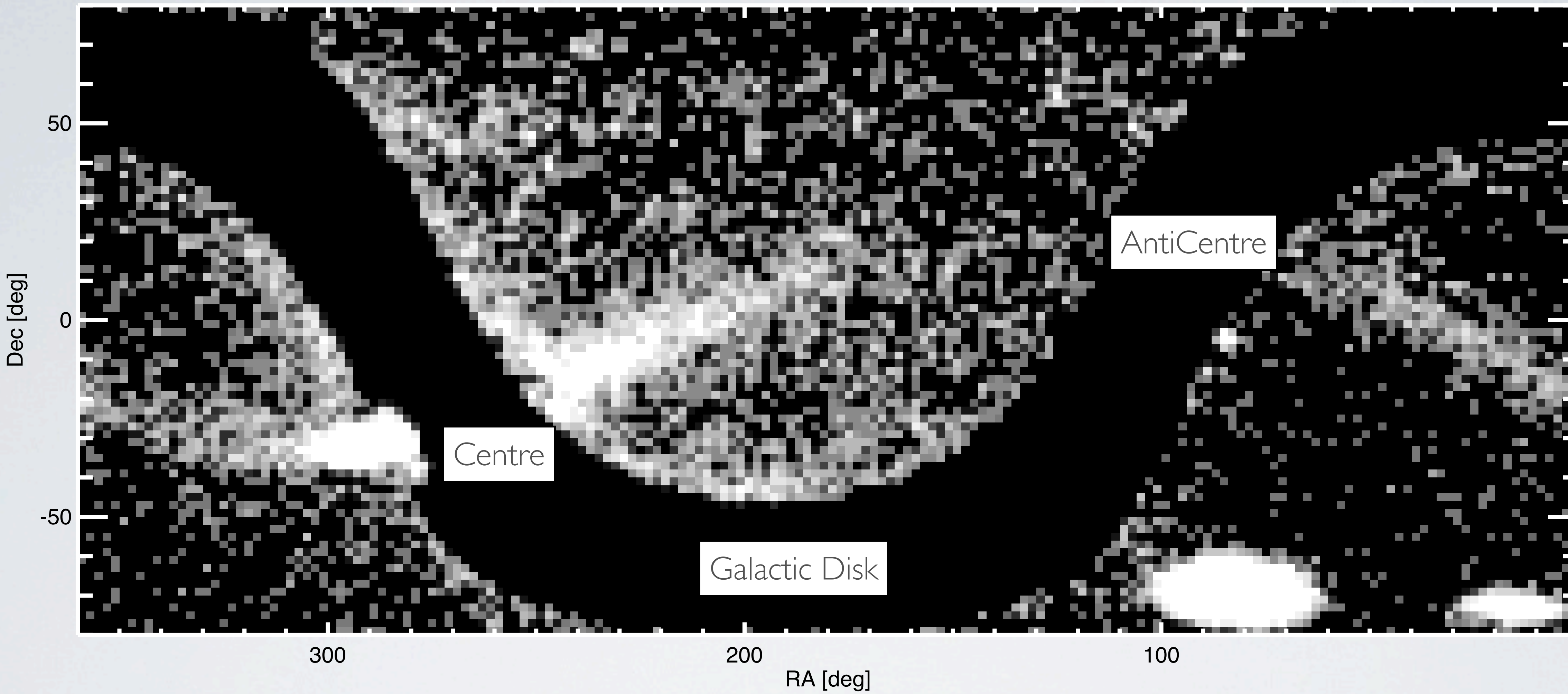
THE SAGITTARIUS STREAM

The debris in the *Field of Streams* is dominated by one big accretion event.

The Sagittarius Stream provides 20 % to 30 % of all the debris in the *Field of Streams* including multiple huge tidal streams and probably 20 or so globular clusters.

The progenitor galaxy was as luminous as the Small Magellanic Cloud (Niederste-Ostholt et al. 2010). It had a total mass (including dark matter) of $10^{10} M_{\odot}$

M giants as seen by 2MASS

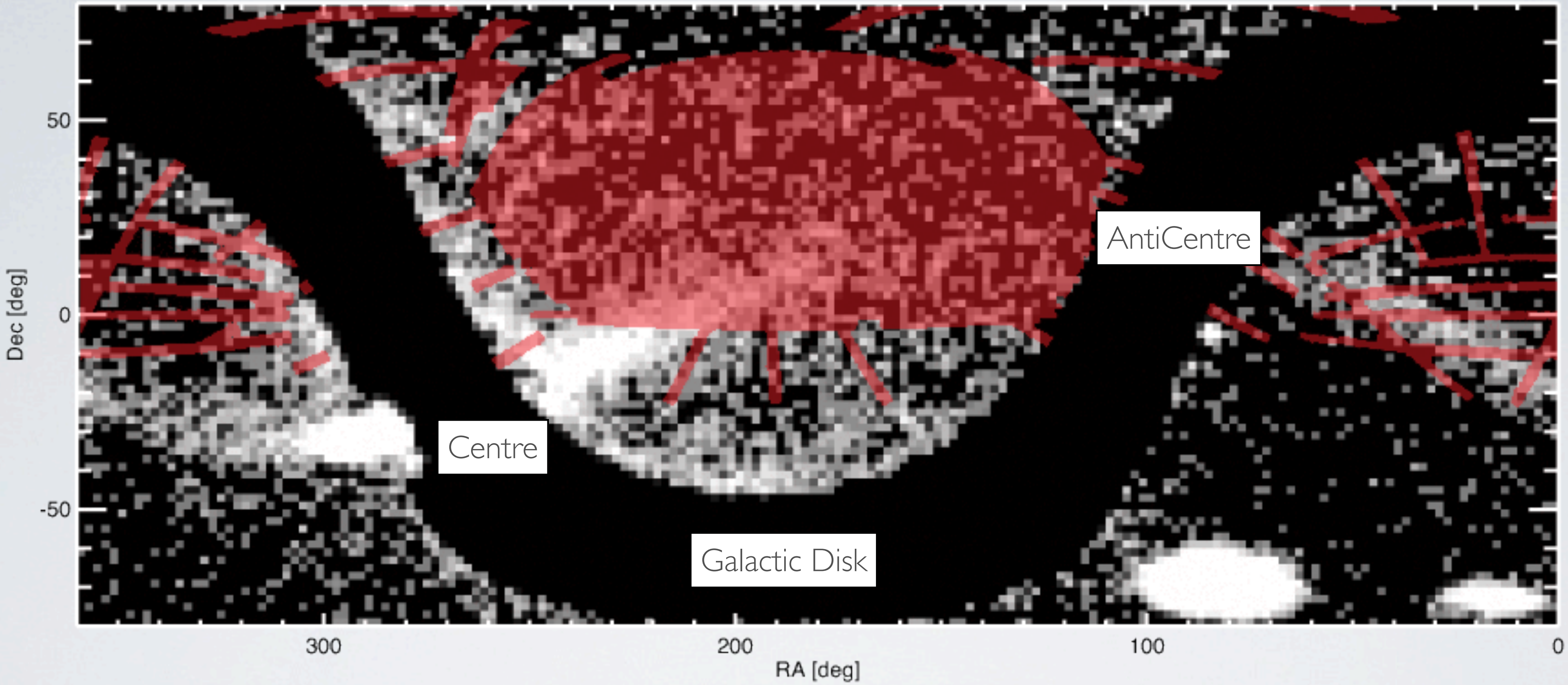


Majewski et al., 2003, ApJ

THE SAGITTARIUS STREAM

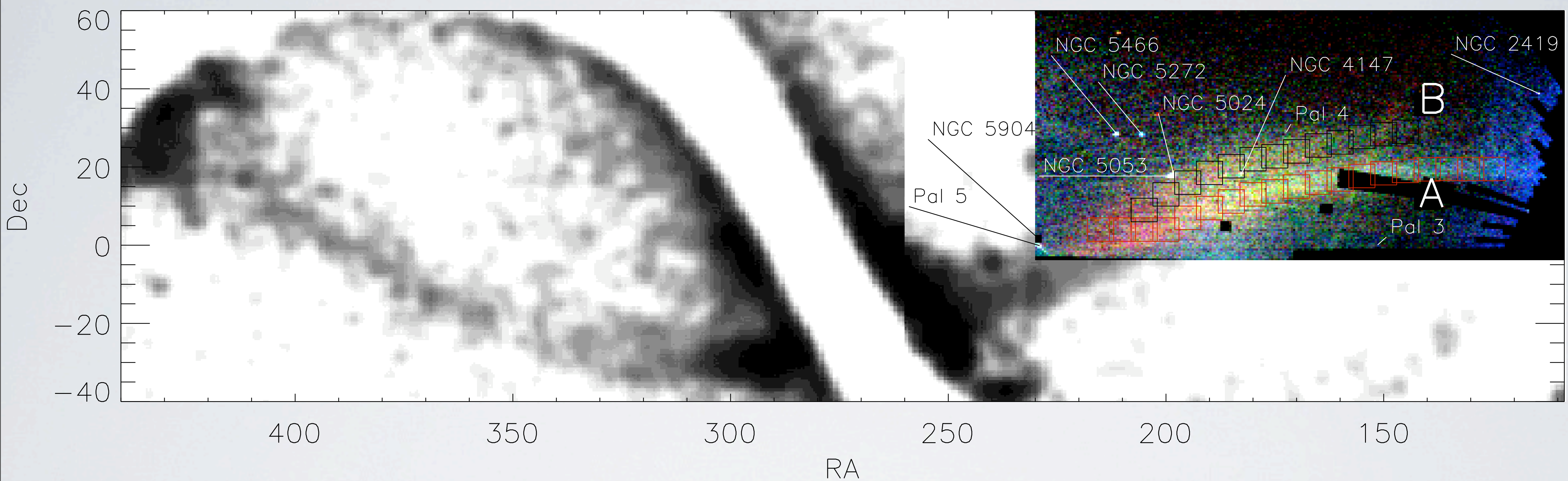
Traced by 2MASS (2 Micron All-Sky Survey) throughout the Southern Galactic hemisphere.

SDSS covers about 1/5 of the sky



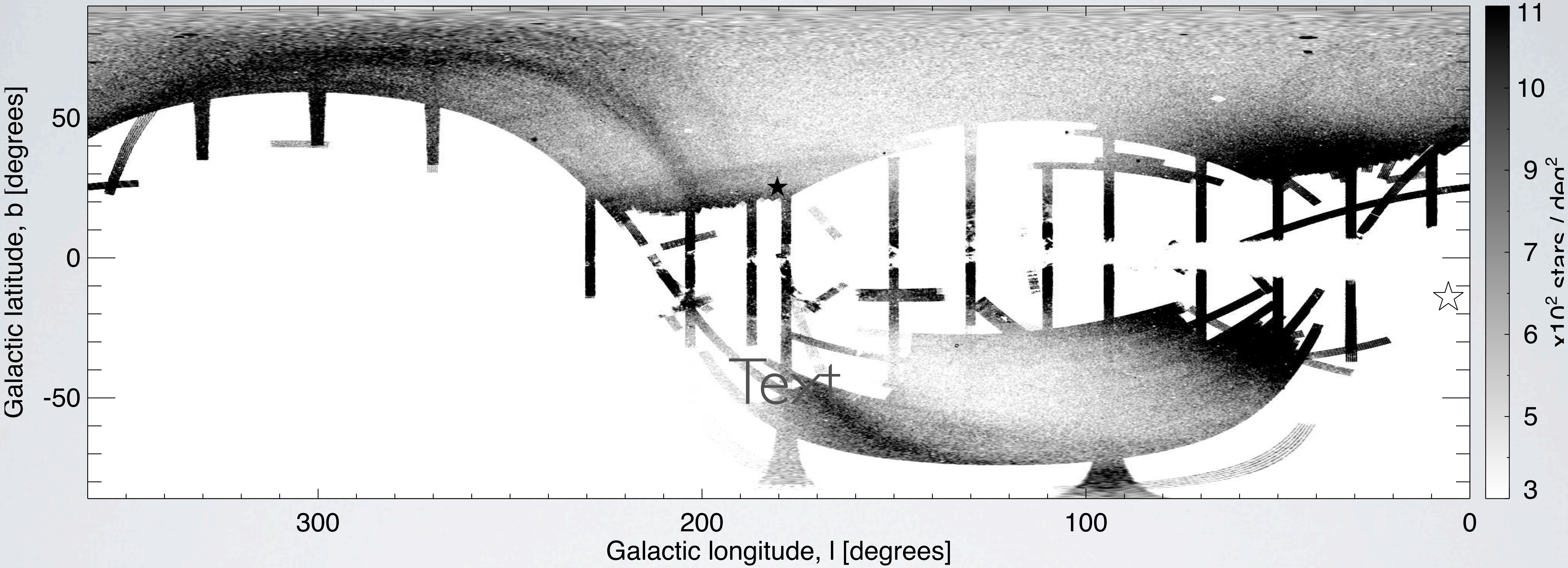
THE SAGITTARIUS STREAM

The SDSS Photometric Footprint



THE SAGITTARIUS STREAM

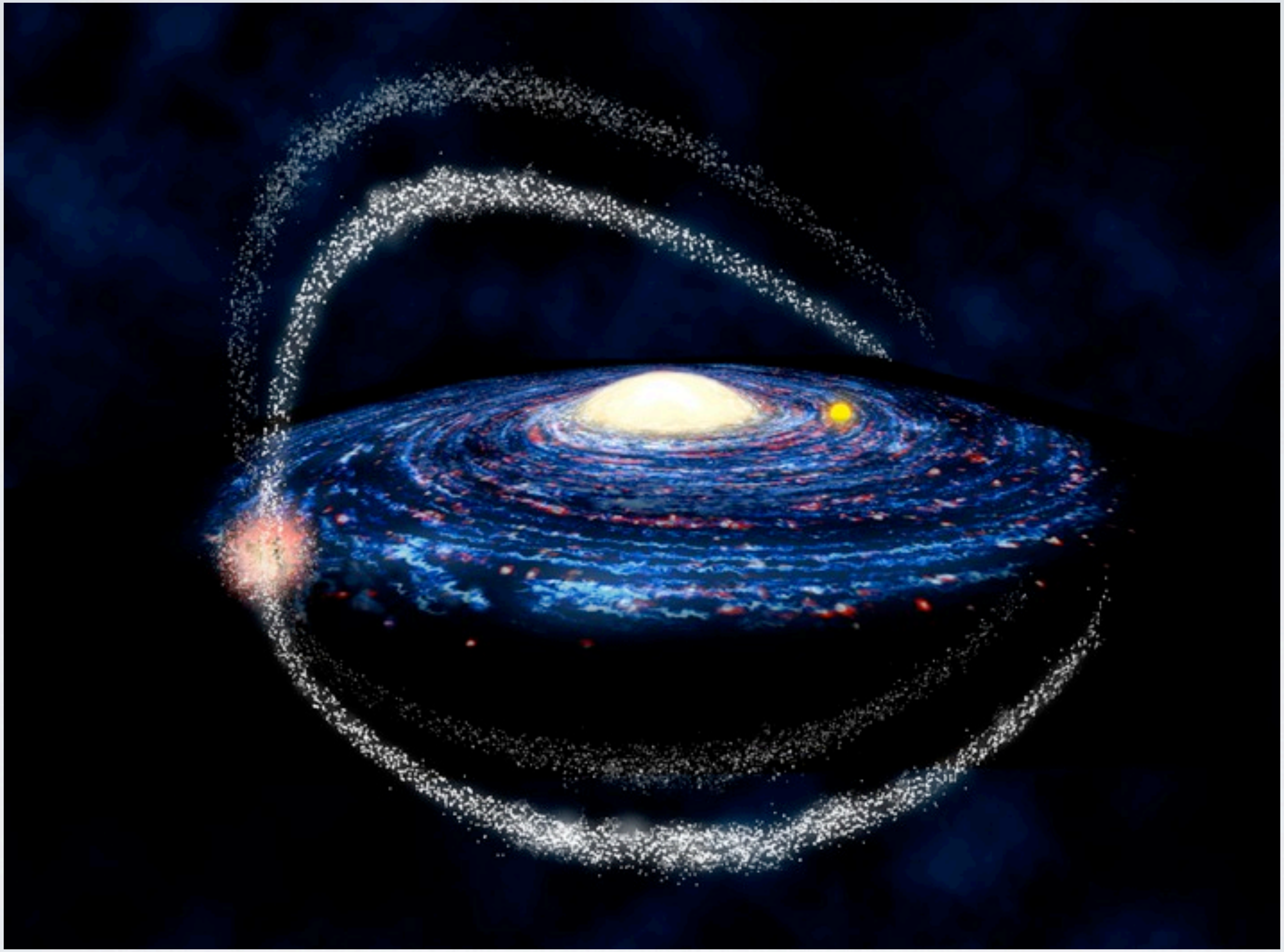
The Field of Streams completes the picture in the North



Koposov, Belokurov, Evans et al., 2012, ApJ

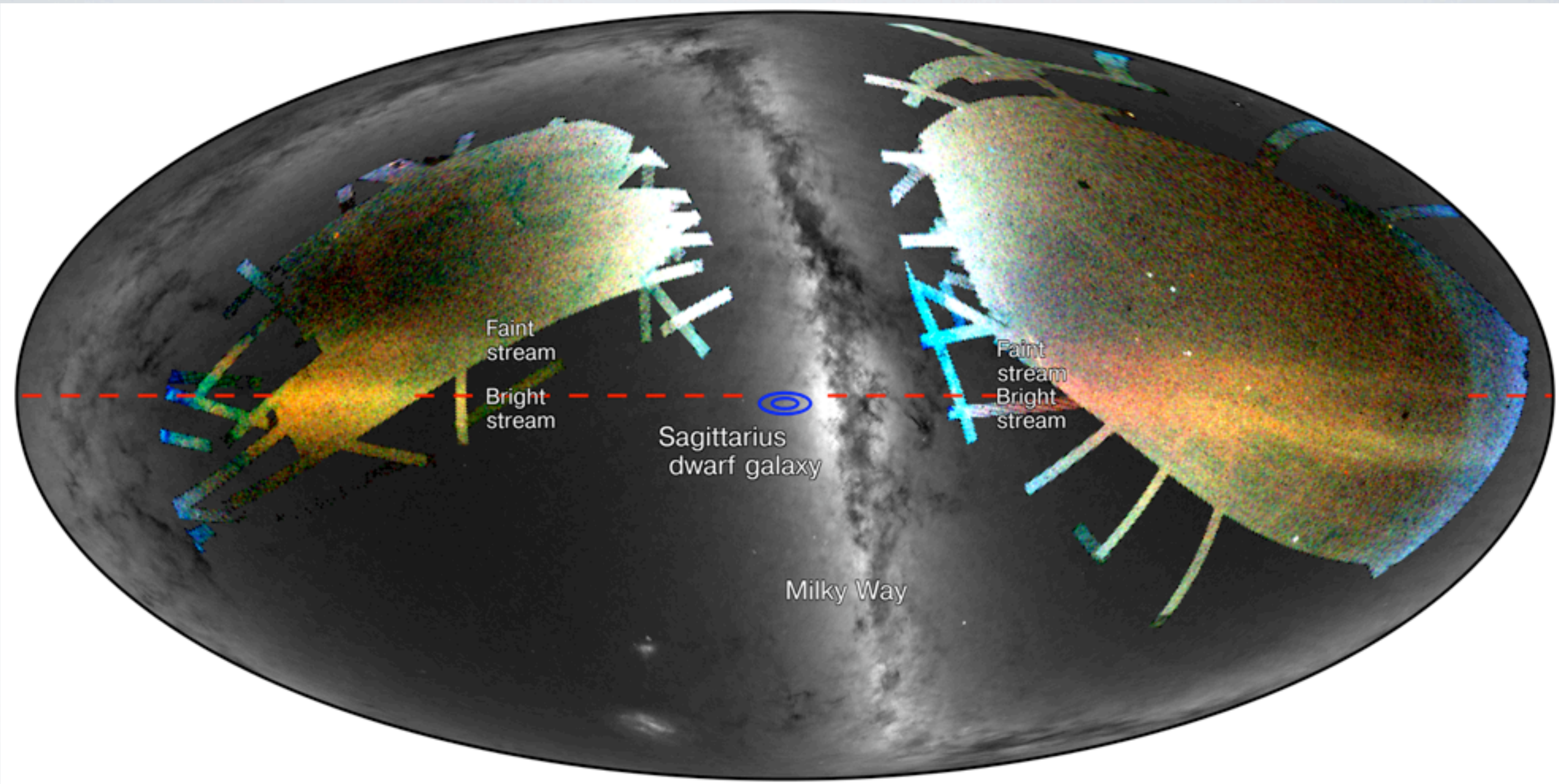
The Sgr stream in the South -- everywhere we look we see two streams with similar heliocentric distances!

THE SAGITTARIUS STREAM



THE SAGITTARIUS STREAM

Koposov et al 2012

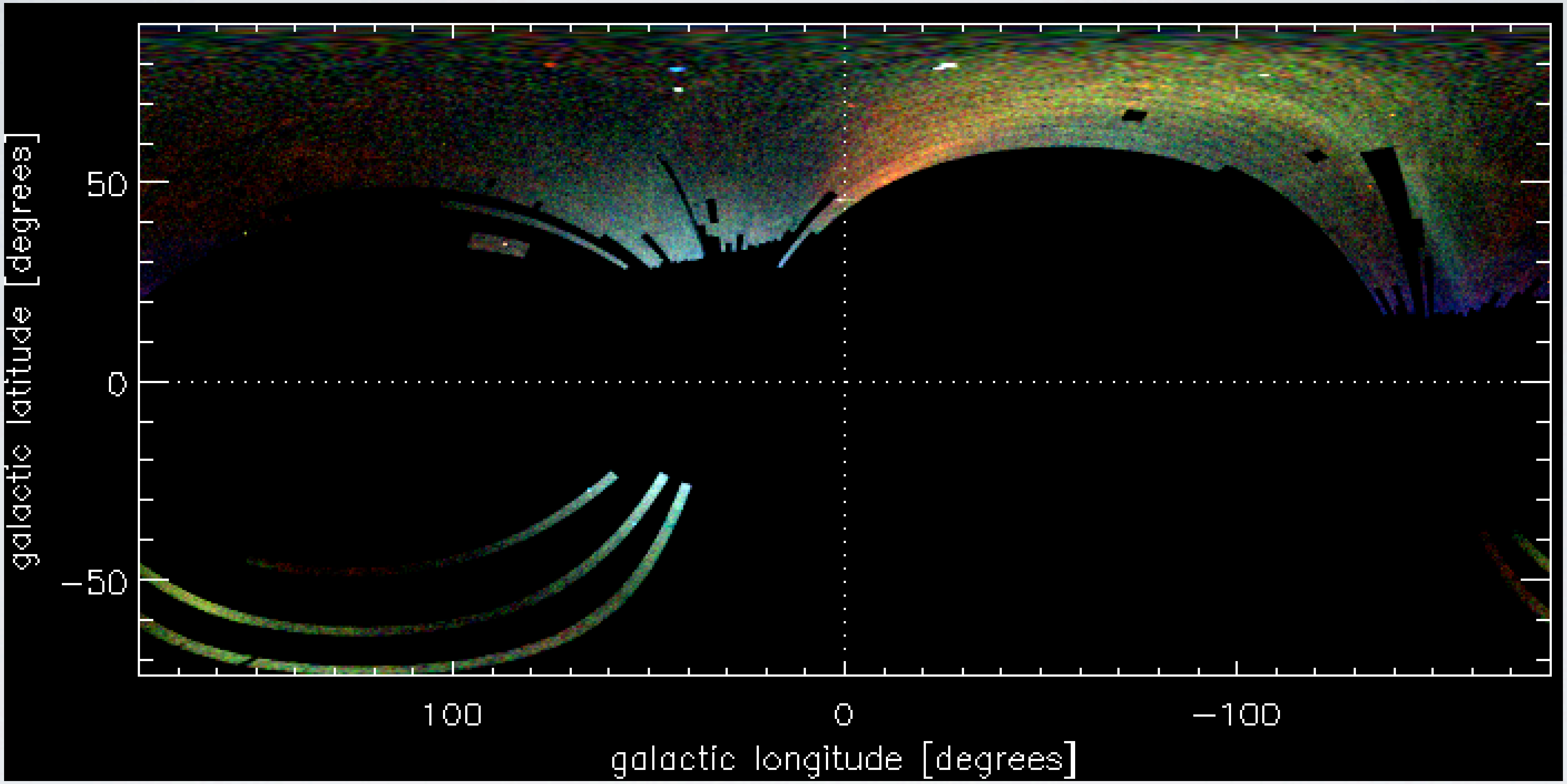


THE SAGITTARIUS STREAM

The Sagittarius Stream is a beast with four bright tails.

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 suffer different amounts of precession in the Galaxy.

Dark matter is stripped first as a satellite is accreted. The four bright tails must be accompanied by at least as many -- possibly more --- dark matter tails.



Belokurov, Evans et al. 2008

THE HERCULES-AQUILA CLOUD

THE HERCULES-AQUILA CLOUD

The cloud is centered at a Galactic longitude of ~40° and extends above and below the Galactic plane by at least 50°.

The cloud stretches ~80° in longitude. Its heliocentric distance lies between 10 and 20 kpc so that the extent of the cloud in projection is ~20 kpc by ~15 kpc.

This is a huge structure with a total luminosity comparable to the largest dwarf galaxies.

THE HERCULES-AQUILA CLOUD

Clouds are produced by near-radial mergers of dwarf galaxies. They are the analogues of shells in external ellipticals.

The Hercules-Aquila Cloud was probably produced by the merger of an object at least as big as the SMC, and so its associated dark matter content is of the order $10^{10} M_{\odot}$.

Other Clouds are known (the Pisces Overdensity, the Virgo Overdensity), but they remain poorly studied, both in stars and dark matter.

THE UNKOWN

Entirely dark satellites or dark matter substructure can be detected by:

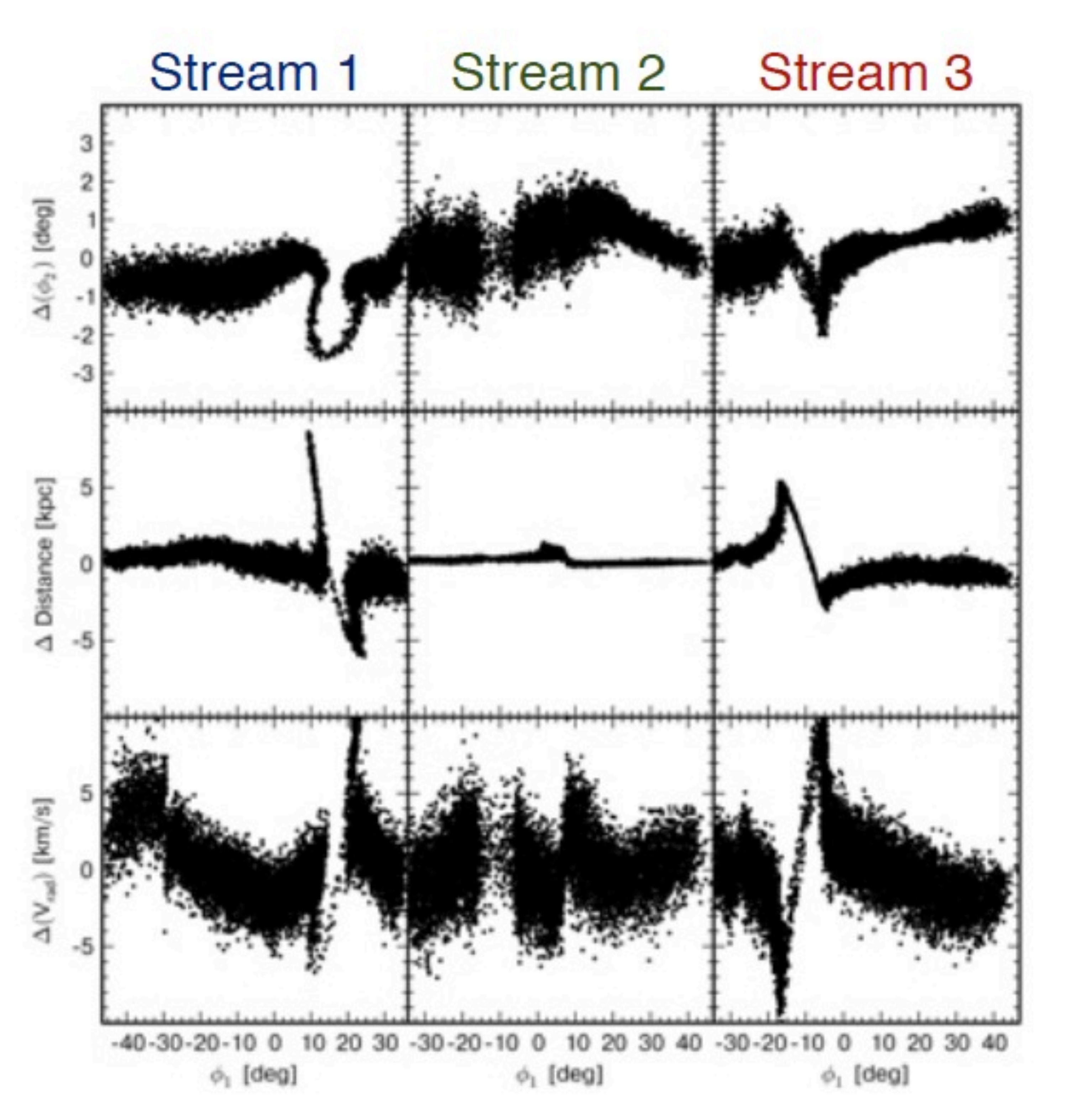
(i) disruption of wide binaries (e.g., Penarrubia et al. 2011)

(ii) heating effect on thin disks, causing vertical thickening & possible disruption (Toth & Ostriker 1992, Benson 2004, Helmi et al. 2012)

(iii) microlensing by non-compact objects (Gurevich & Zybin 1995)

(iii) star stream twisting.

THE ORPHAN STREAM



Koposov et al, in prep

Correlated displacements along the stream; out of plane angle, los and radial velocity

CONCLUSIONS

Dwarf spheroidals are certainly not cusped. Either they never had 1/r dark matter cusps, or subsequent evolution has removed them.

The ultrafaints do possess dark matter, but early work overestimated the velocity dispersions and hence dark matter content.

Clouds and streams possess their entourage of dark matter. The Sgr has 4 bright tails and perhaps many more dark tails.

Entirely dark matter objects can be detected by stream twisting.