New Galactic Satellites

Vasily Belokurov

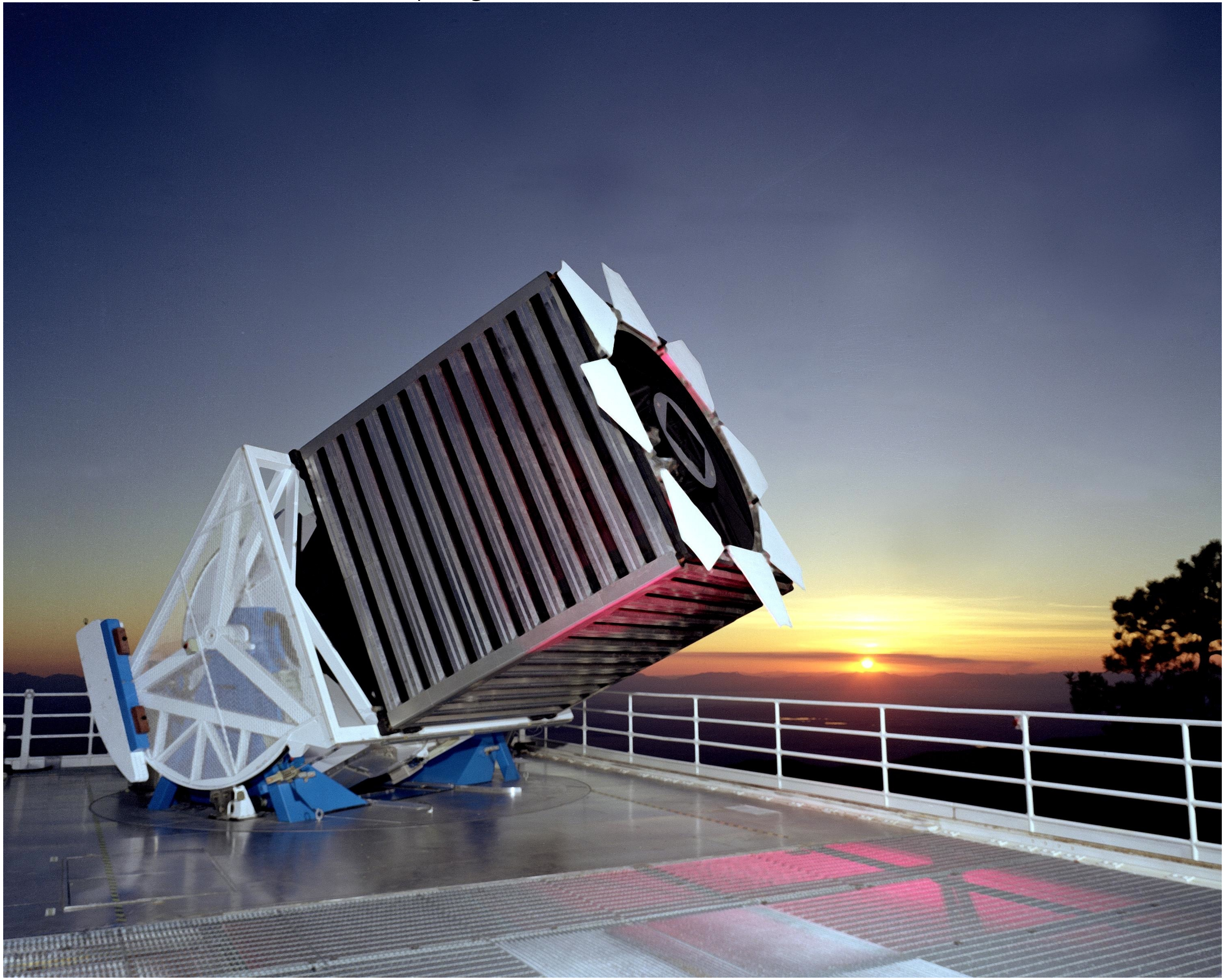
Institute of Astronomy, Cambridge

Theoretical predictions

- Current theory has a strong prediction as to the total number and the Mass Function of DM Sub-halos

- Current theory has no strong prediction as to the total number and the Mass Function of Dwarf Galaxies

SDSS DR7 11,663 sq deg 20 satellites discovered



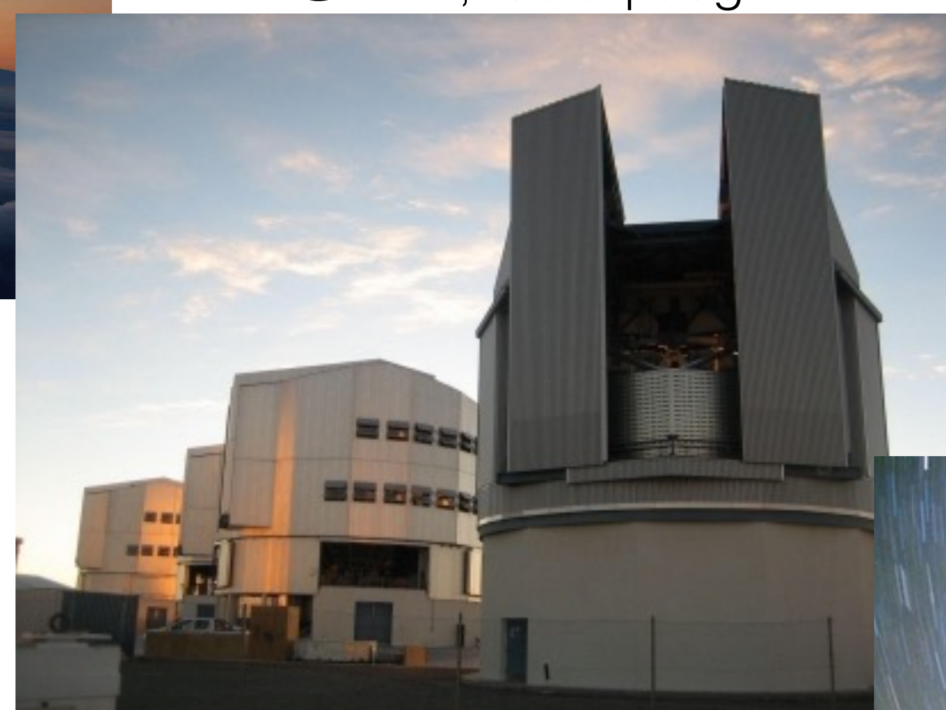
après Sloan

but before 06.03.2015

PanSTARRS 30,000 sq deg

1 satellite discovered

VST 2,700 sq deg



1 satellite discovered

2,100 sq deg DES

Koposov et al 2015
Geringer-Sameth et al 2015
Walker et al 2015

Dark Energy Survey

Bechtol et al 2015
Drlica-Wagner et al 2015
Simon et al 2015

ApJ, in press

BEASTS OF THE SOUTHERN WILD: DISCOVERY OF NINE ULTRA FAINT SATELLITES IN THE VICINITY OF THE MAGELLANIC CLOUDS.

Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

(Dated: April 2, 2015)
Submitted 20 Feb 2015

ABSTRACT

We have used the publicly released Dark Energy Survey data to hunt for new satellites of the Milky Way in the Southern hemisphere. Our search yielded a large number of promising candidates. In this paper, we announce the discovery of 9 new unambiguous ultra-faint objects, whose authenticity can be established with the DES data alone. Based on the morphological properties, three of the new satellites are dwarf galaxies, one of which is located at the very outskirts of the Milky Way, at a distance of 380 kpc. The remaining 6 objects have sizes and luminosities comparable to the Segue 1 satellite and can not be classified straightforwardly without follow-up spectroscopic observations. The satellites we have discovered cluster around the LMC and the SMC. We show that such spatial distribution is unlikely under the assumption of isotropy, and, therefore, conclude that at least some of the new satellites must have been associated with the Magellanic Clouds in the past.

Keywords: Galaxy: halo, galaxies: dwarf, globular clusters: general, galaxies: kinematics and dynamics

From images to catalogs

- DES images released to public with 1 year delay
- Available at NOAO science archive
- InstCal products (DECam pipeline)
  single-frame images, bias, dark and flat-field
  calibrated as well as cross-talk corrected

From images to catalogs

- 1st SExtractor run to get PSFEx parameters
- PSFEx run
- 2nd SExtractor run

Big thanks to Bertin et al!

From images to catalogs

- Database ingestion
- Duplicate removal
- Photometric calibration
- Band merging
- Final spatial indices created

9 new objects in DES

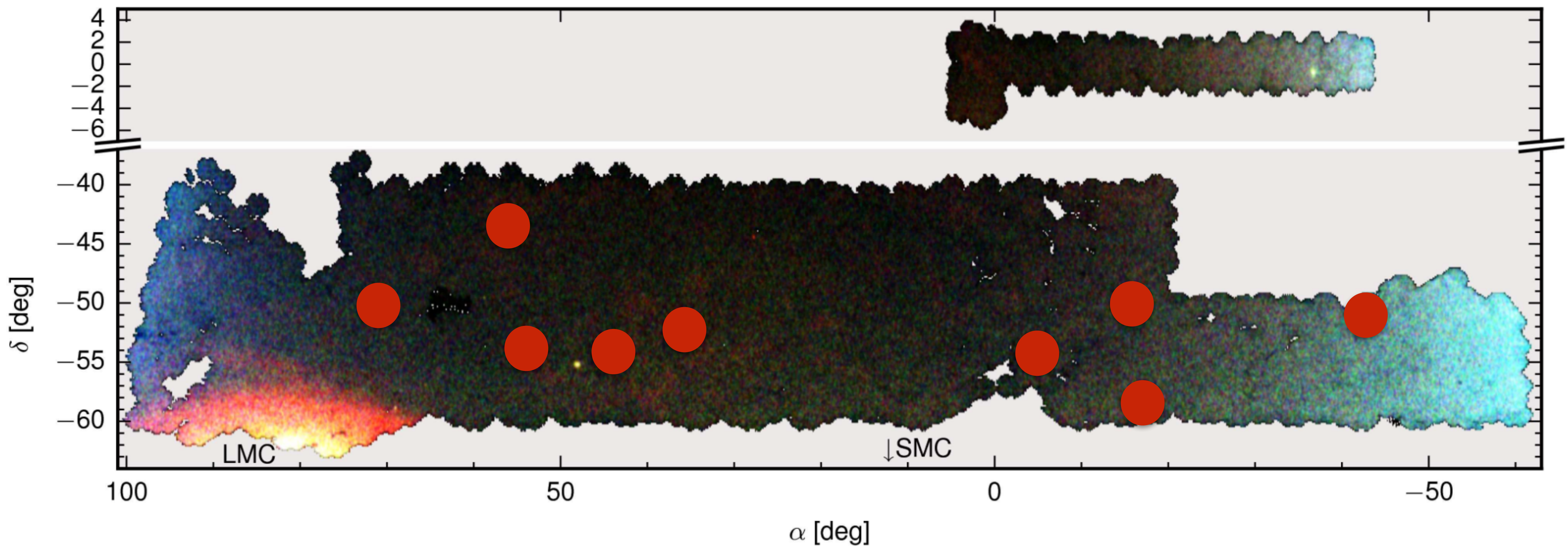
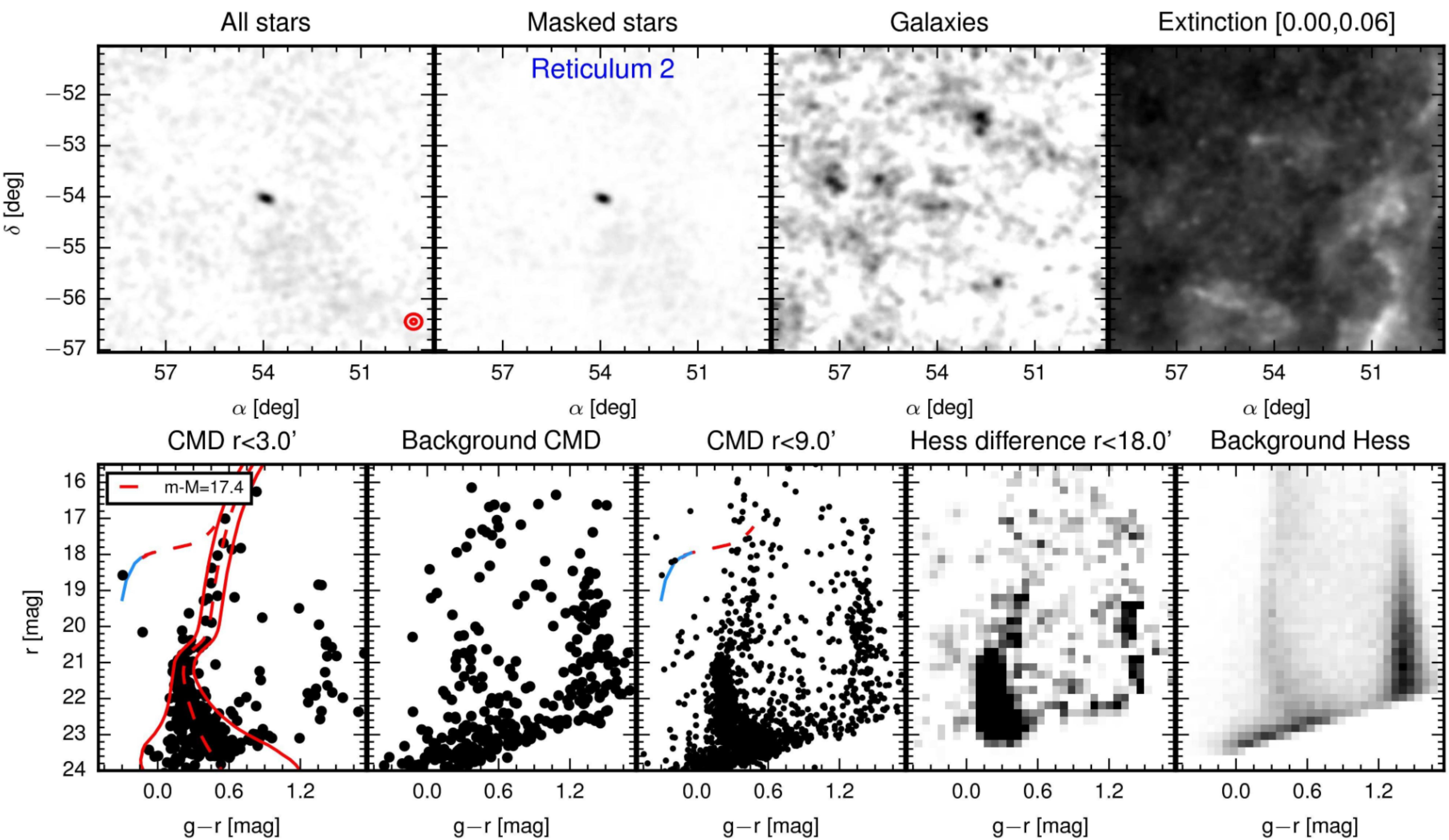


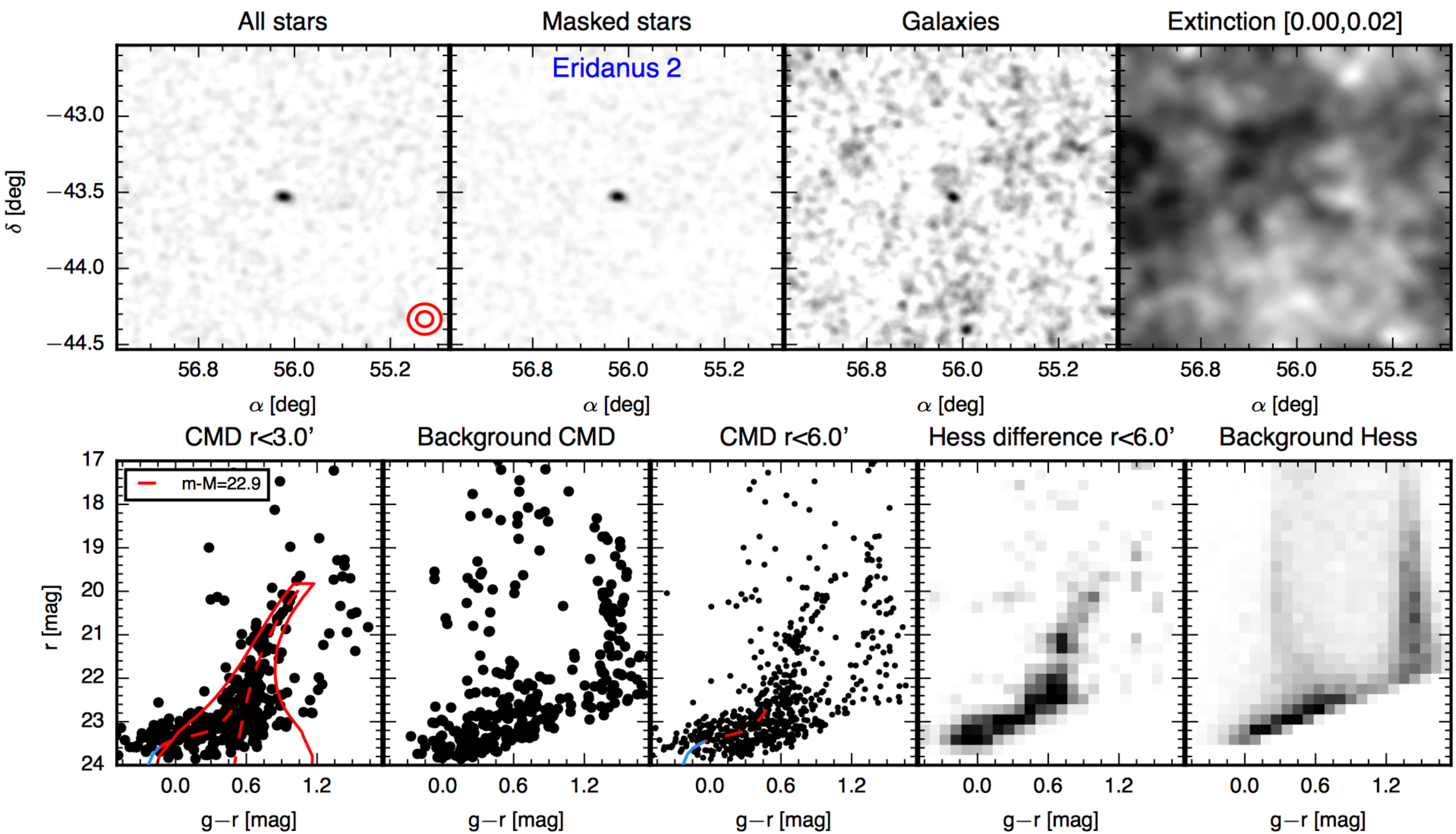
Figure 3. False-colour map of the density of the main sequence turn-off (MSTO) stars with 0.2<g−r<0.6 as observed by the DES survey. The density in different magnitude bins corresponding to different distances is used to create different colour channels: blue 17<r<19 (corresponding to distances of ∼ 4−10 kpc), green 19<r<21 (10−25 kpc), red 21<r<22.75 (25−56 kpc). The MW satellites discovered in this paper are shown with white unfilled circles. Note that the declination axis has been broken to avoid showing large empty area between -35$\lesssim$ δ $\lesssim$-5 without DES data

Reticulum 2

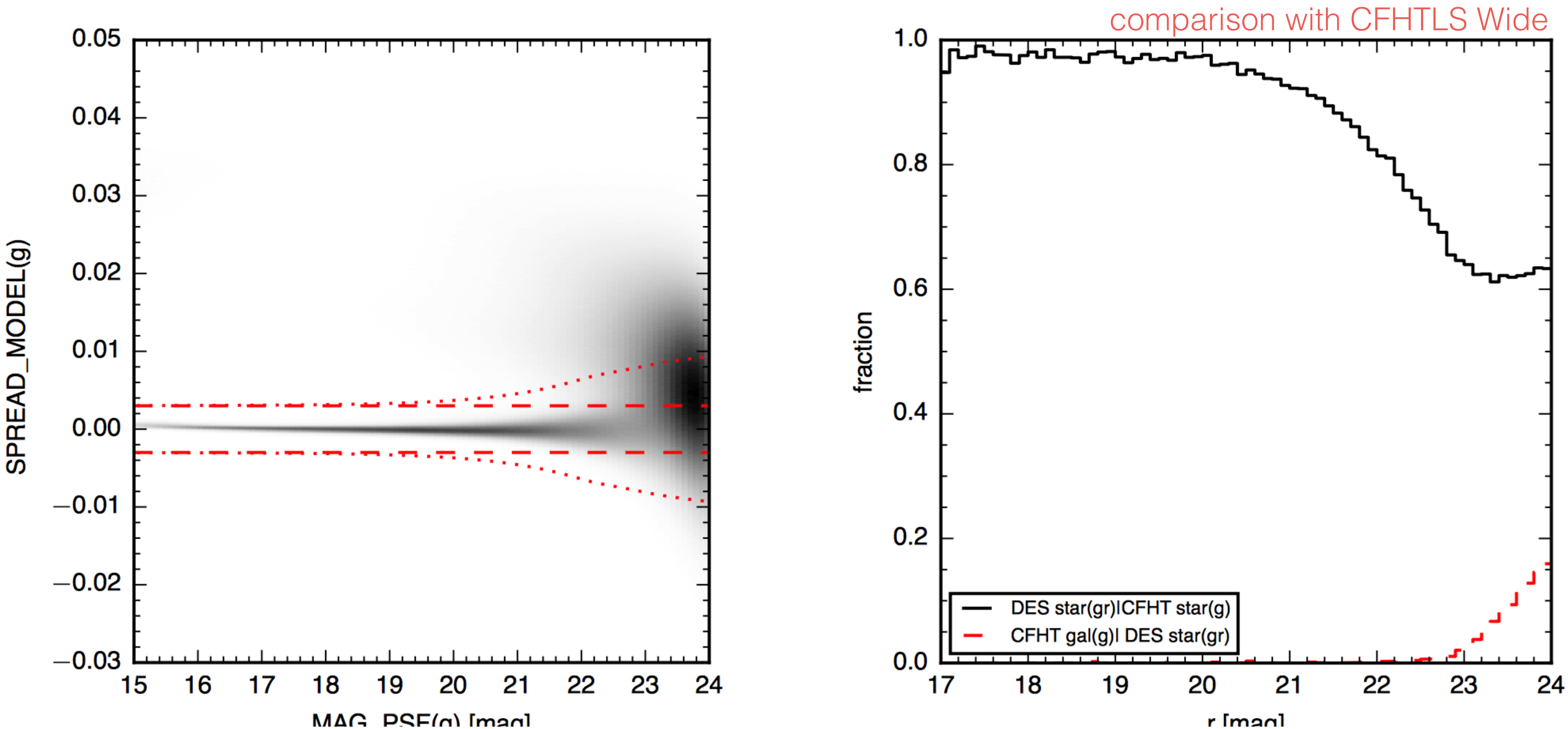


All stars
Masked stars
Galaxies
Extinction [0.00,0.06]
Reticulum 2
δ [deg]
α [deg]
CMD r<3.0'
Background CMD
CMD r<9.0'
Hess difference r<18.0'
Background Hess
m-M=17.4
r [mag]
g−r [mag]

Eridanus 2

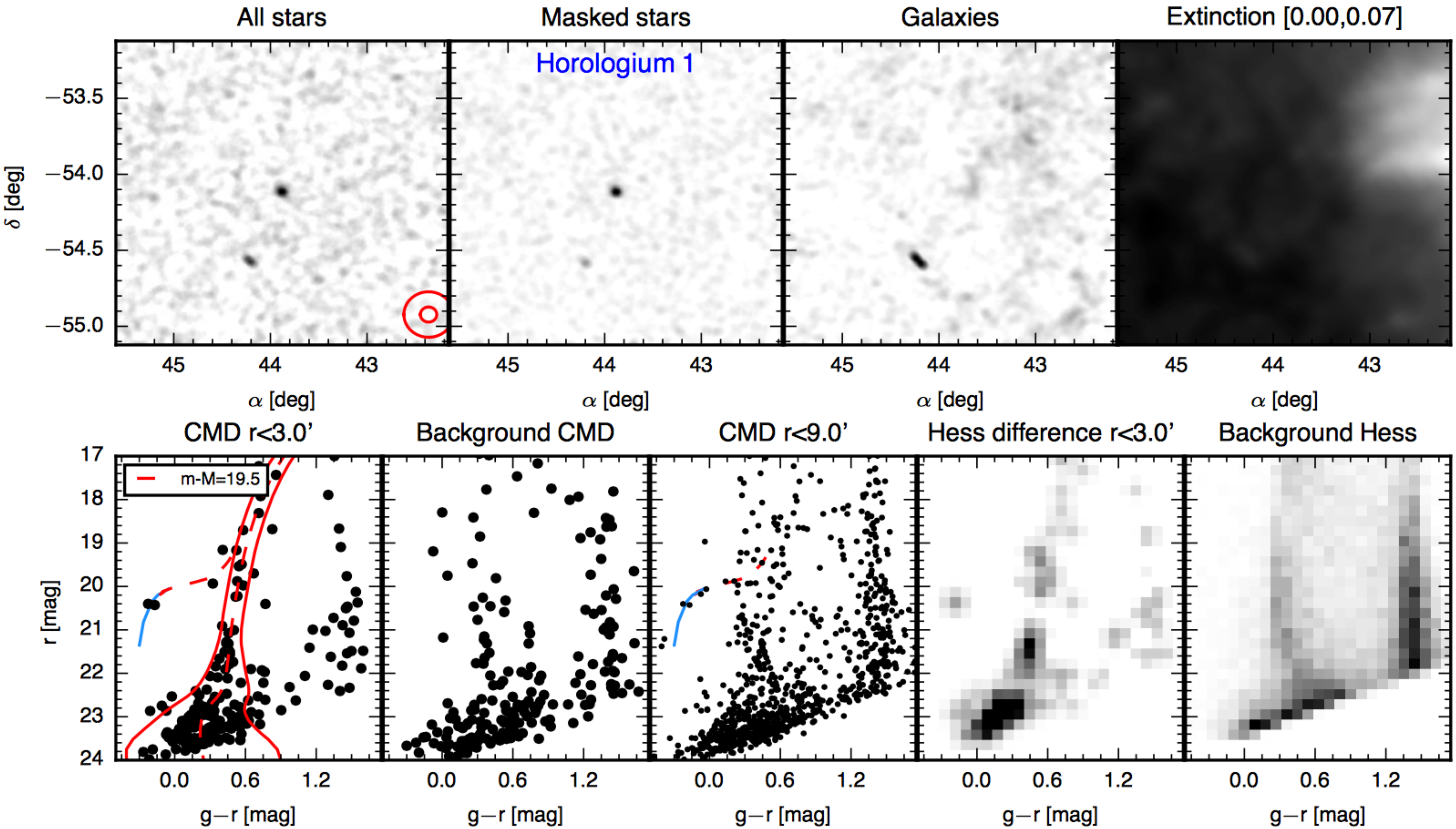

All stars
Masked stars
Galaxies
Extinction [0.00,0.02]
Eridanus 2
δ [deg]
α [deg]
CMD r<3.0'
Background CMD
CMD r<6.0'
Hess difference r<6.0'
Background Hess
m-M=22.9
r [mag]
g−r [mag]

Star/galaxy separation

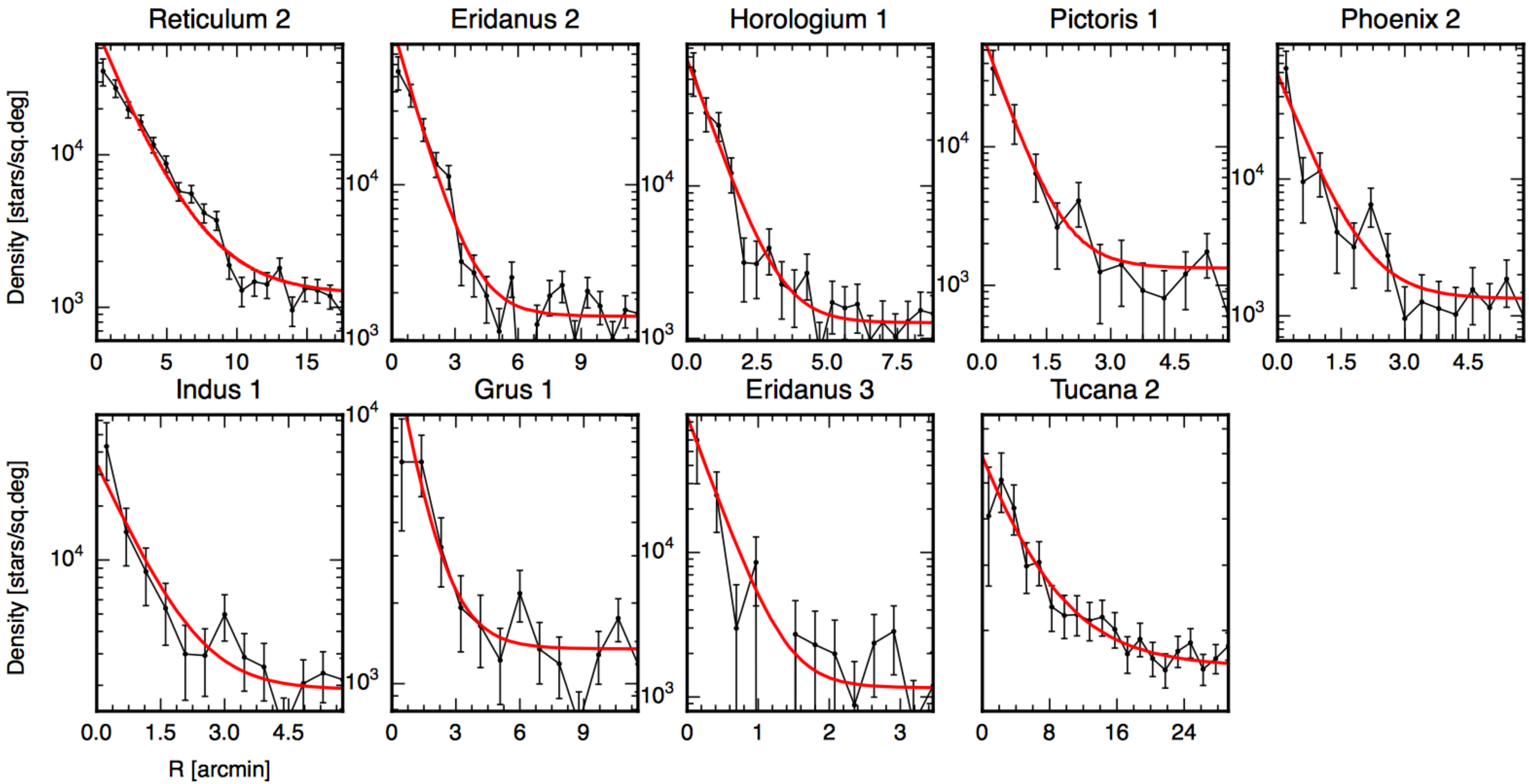


$$|\mathtt{SPREAD\_MODEL}| < 0.003 + \mathtt{SPREADERR\_MODEL}$$

Horologium 1



Radial density profiles



Structural parameters

Table 1
Parameters of the discovered MW satellites.

Name	α [deg]	δ [deg]	Signif[a] icance	m−M[b] [mag]	$\text{Dist}_{\odot}$[b] [kpc]	M_V [mag]	r_{maj} [arcmin]	$r_{1/2}$[c] [arcmin]	$r_{1/2}$[d] [pc]	ellipticity	PA [deg]	BF[e]
Reticulum 2	53.9256	-54.0492	48.5	17.4	30	-2.7 ± 0.1	$3.37^{+0.23}_{-0.13}$	$3.64^{+0.21}_{-0.12}$	$32^{+1.9}_{-1.1}$	$0.59^{+0.02}_{-0.03}$	71 ± 1	>1000
Eridanus 2	56.0878	-43.5332	31.5	22.9	380	-6.6 ± 0.1	$1.19^{+0.12}_{-0.10}$	$1.53^{+0.14}_{-0.09}$	$169^{+16.0}_{-9.8}$	$0.40^{+0.06}_{-0.08}$	81 ± 6	1113
Horologium 1	43.8820	-54.1188	28.4	19.5	79	-3.4 ± 0.1	$0.84^{+0.17}_{-0.08}$	$1.31^{+0.19}_{-0.14}$	$30^{+4.4}_{-3.3}$	< 0.28	···	0.35
Pictoris 1	70.9475	-50.2830	17.3	20.3	114	-3.1 ± 0.3	$0.70^{+0.23}_{-0.13}$	$0.88^{+0.27}_{-0.13}$	$29^{+9.1}_{-4.4}$	$0.47^{+0.12}_{-0.29}$	78 ± 23	1.41
Phoenix 2	354.9975	-54.4060	13.9	19.6	83	-2.8 ± 0.2	$0.82^{+0.27}_{-0.12}$	$1.09^{+0.26}_{-0.16}$	$26^{+6.2}_{-3.9}$	$0.47^{+0.08}_{-0.29}$	164 ± 54	1.81
Indus 1	317.2044	-51.1656	13.7	20.0	100	-3.5 ± 0.2	$0.84^{+0.35}_{-0.17}$	$1.26^{+0.45}_{-0.27}$	$37^{+13.1}_{-8.0}$	< 0.38	···	0.46
Grus 1[f]	344.1765	-50.1633	10.1	20.4	120	-3.4 ± 0.3	$1.33^{+0.74}_{-0.26}$	$1.77^{+0.85}_{-0.39}$	$62^{+29.8}_{-13.6}$	$0.41^{+0.20}_{-0.28}$	4 ± 60	1.01
Eridanus 3	35.6897	-52.2837	10.1	19.7	87	-2.0 ± 0.3	$0.38^{+0.43}_{-0.05}$	$0.54^{+0.50}_{-0.10}$	$14^{+12.5}_{-2.6}$	$0.27^{+0.30}_{-0.16}$	83 ± 36	0.81
Tucana 2	342.9796	-58.5689	8.3	18.8	57	-3.8 ± 0.1	$7.67^{+1.02}_{-1.18}$	$9.83^{+1.66}_{-1.11}$	$165^{+27.8}_{-18.5}$	$0.39^{+0.10}_{-0.20}$	107 ± 18	2.14

Note. — Morphological parameters of the satellites are maximum a posteriori estimates with 68% (1σ) credible intervals, or limits

[a] Significance of detection in σ (t-value)

[b] The uncertainty in distance modulus is estimated to be 0.1−0.2 mag

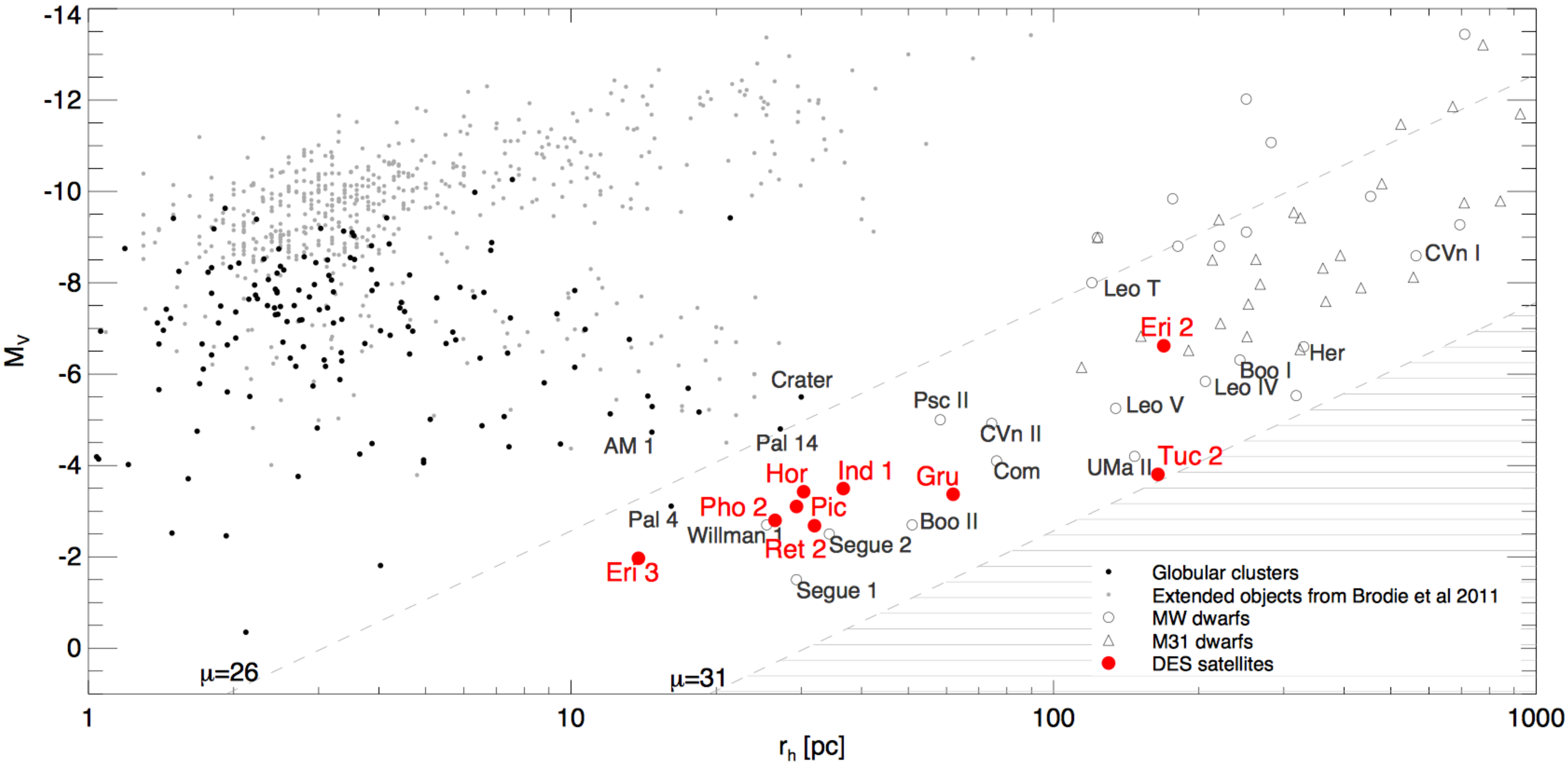
[c] Half-light radius takes into account the ellipticity of the object via $\sqrt{1-e}$ multiplier

[d] The error on distance was not propagated to the physical size

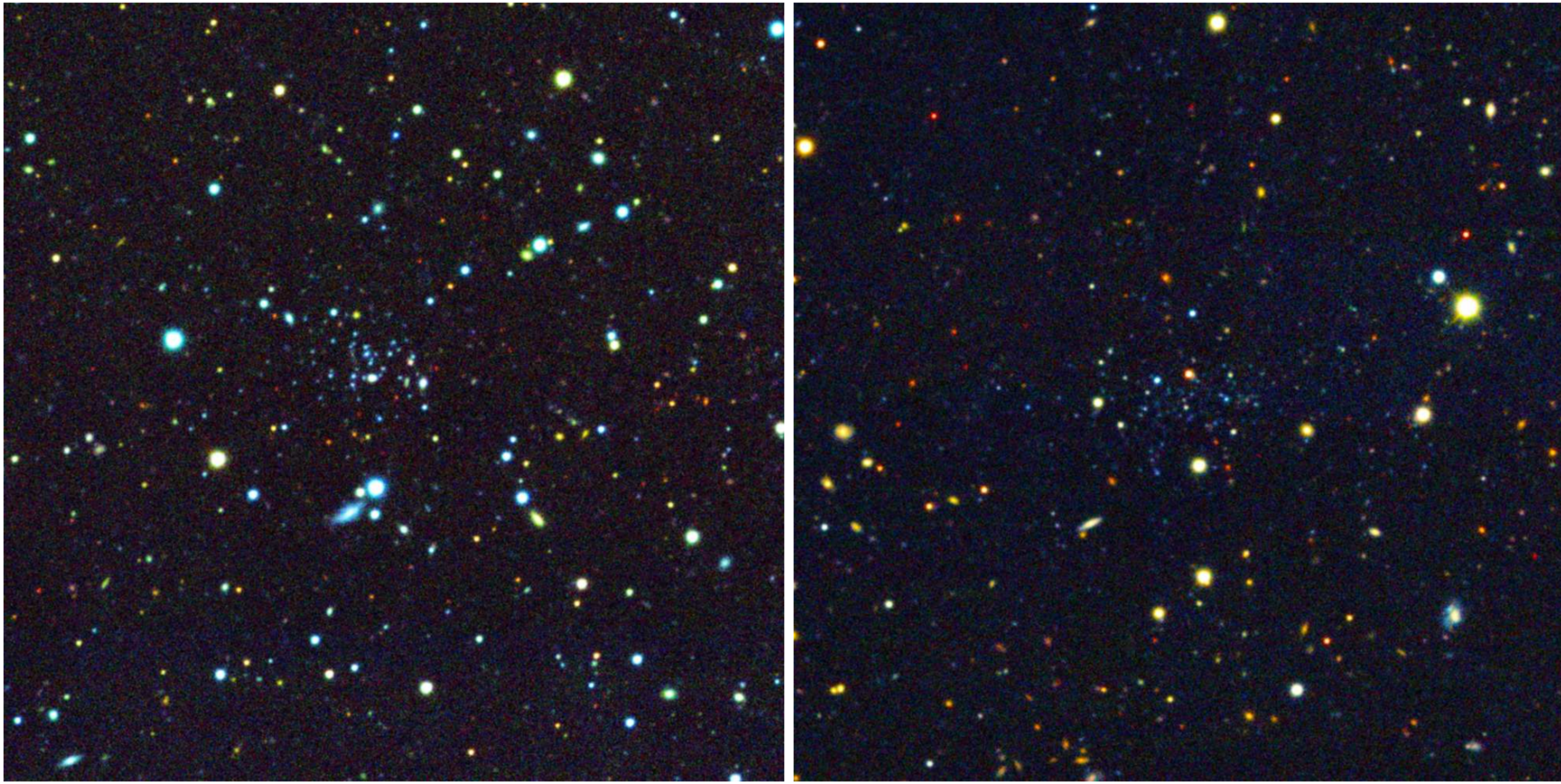
[e] Bayes factor for the elliptical vs circular model

[f] As this object is located very close to the CCD chip gap, its morphological properties should be treated with caution

Structural properties



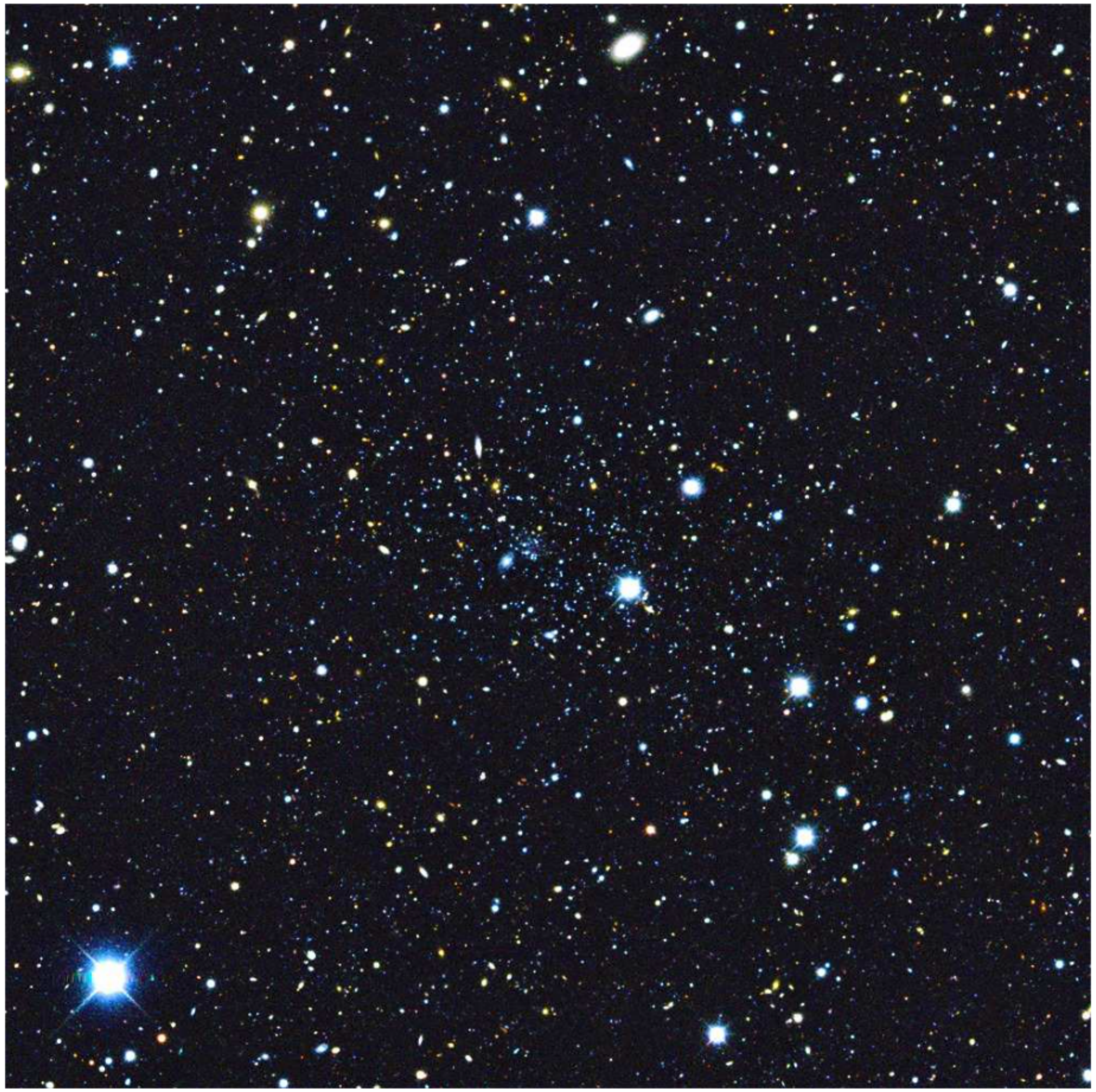
Indus 1 and Eridanus 3

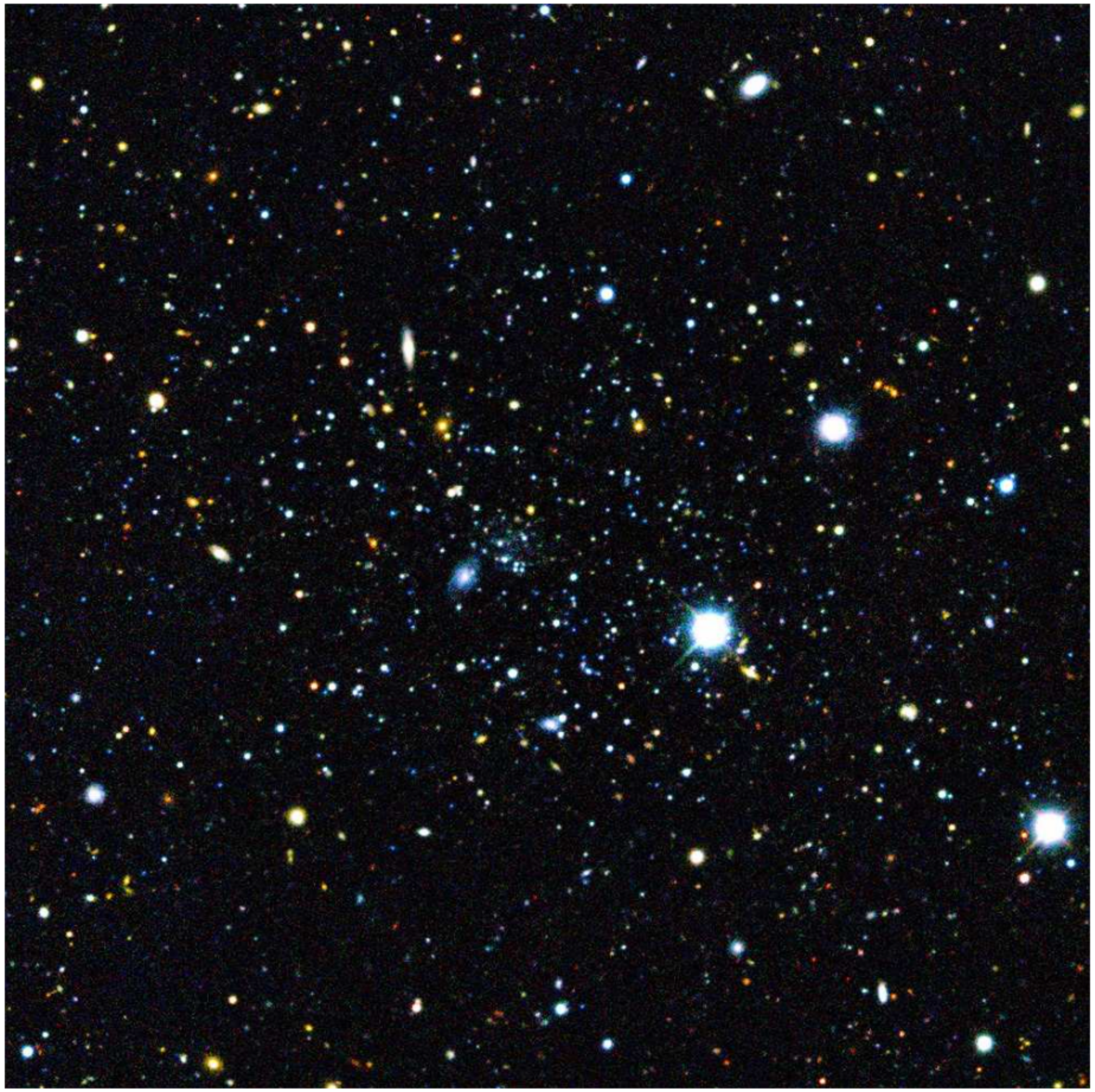


co-discovered by Kim et al 2015

Most likely star clusters

Eridanus 2 at 350 kpc

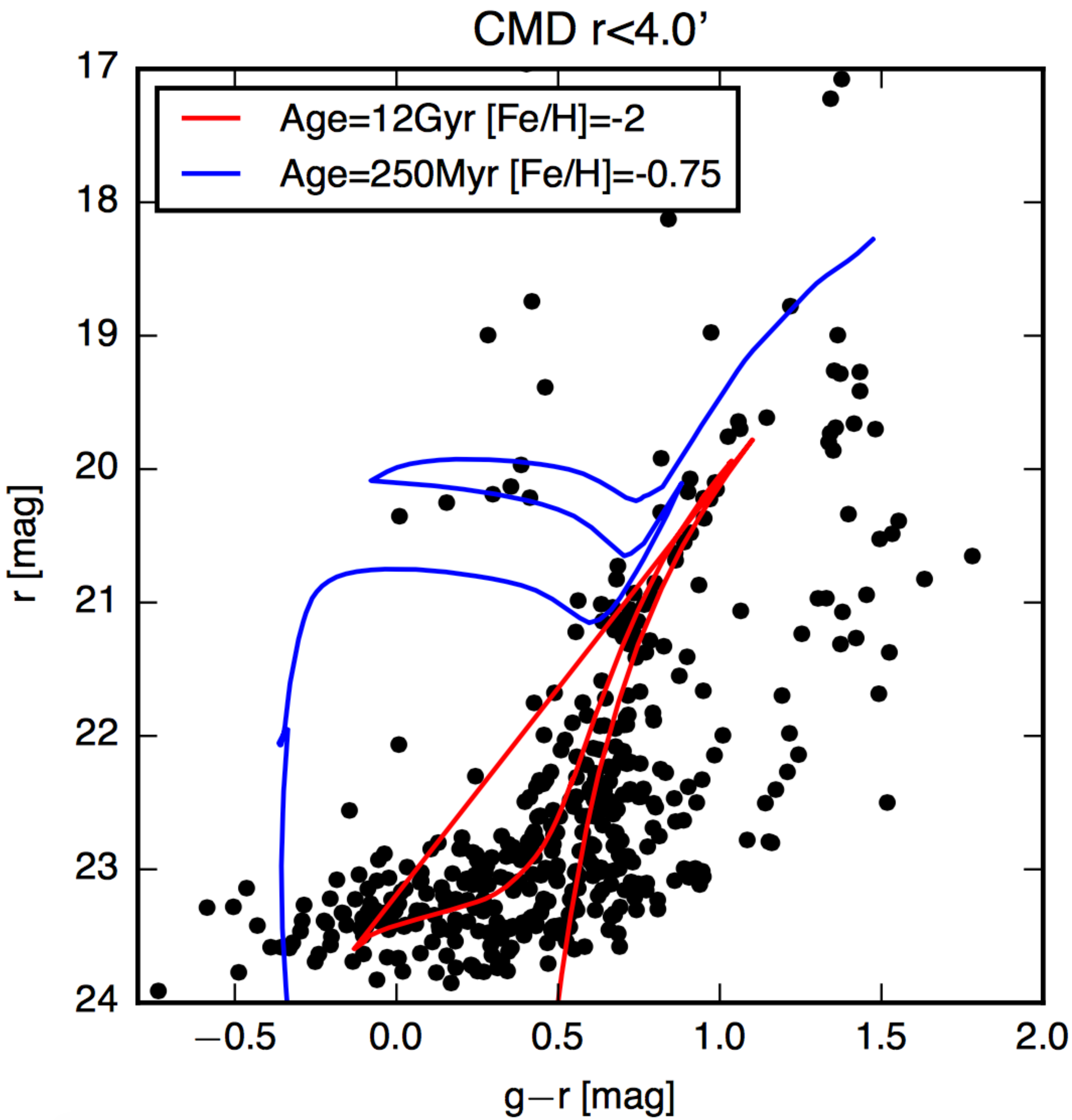




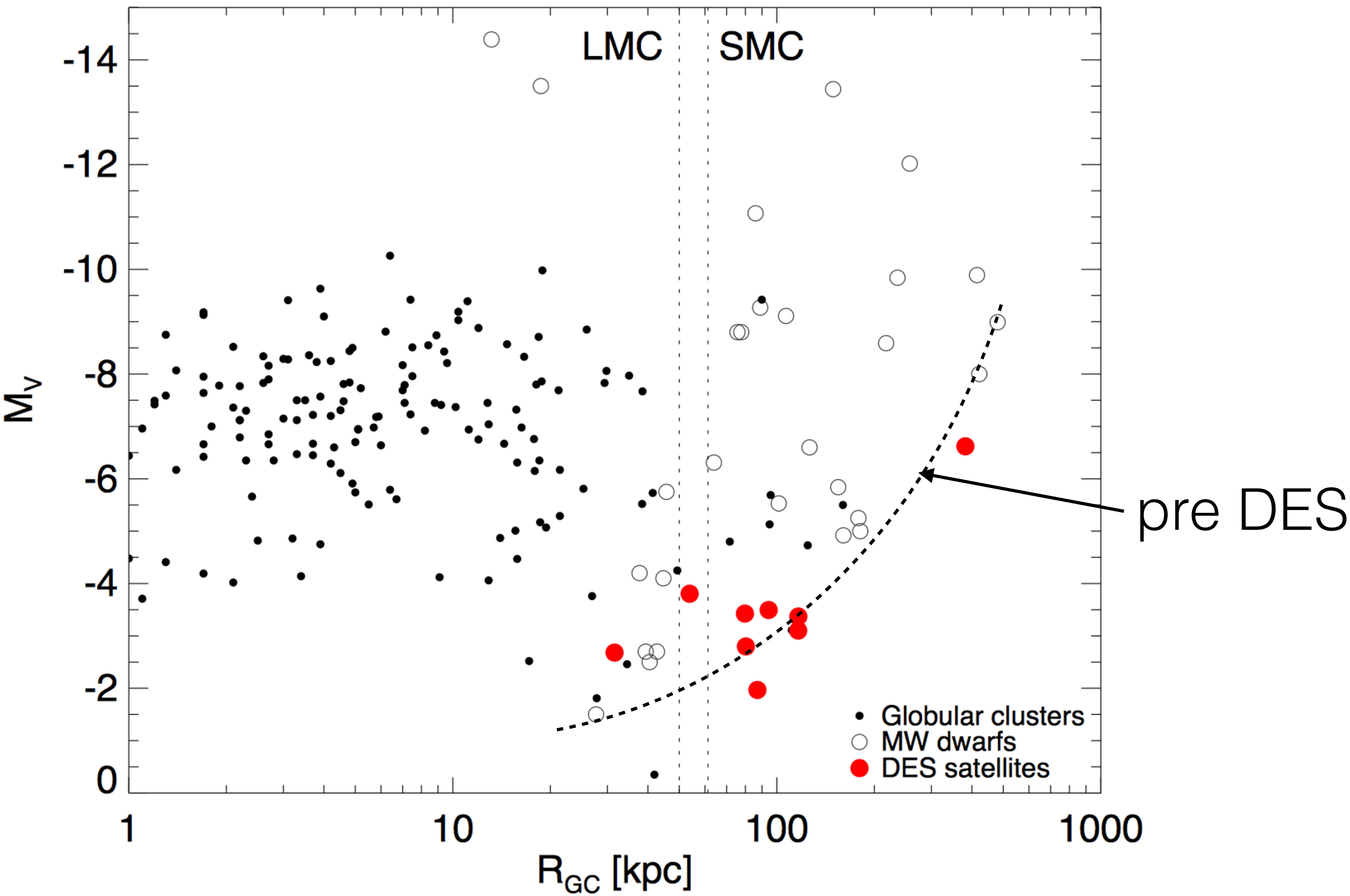
zoom-in

The faintest dwarf to host a globular cluster!

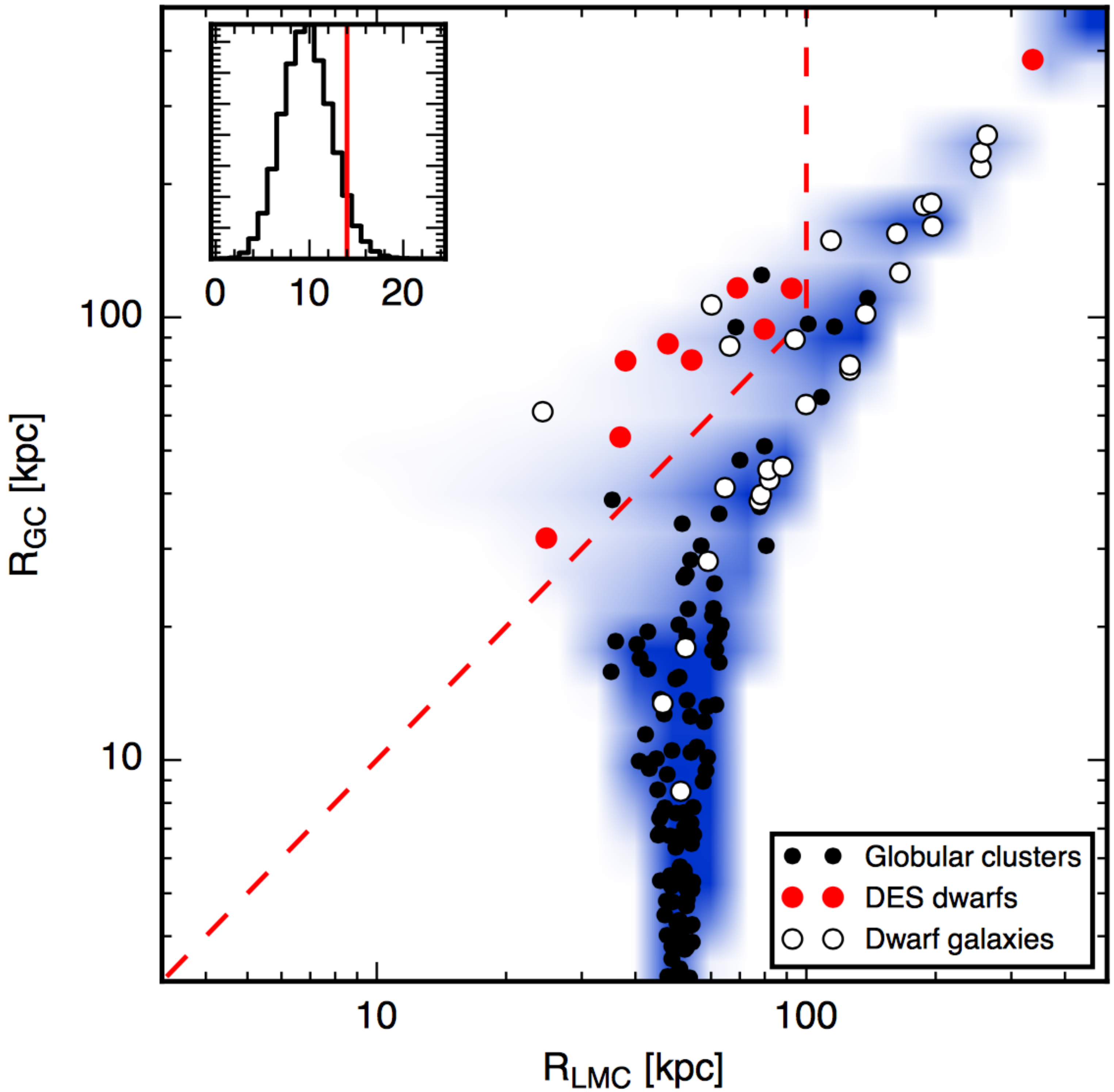
Eridanus 2


CMD r<4.0'
Age=12Gyr [Fe/H]=-2
Age=250Myr [Fe/H]=-0.75
r [mag]
g−r [mag]
17
18
19
20
21
22
23
24
−0.5
0.0
0.5
1.0
1.5
2.0

Luminosity vs distance

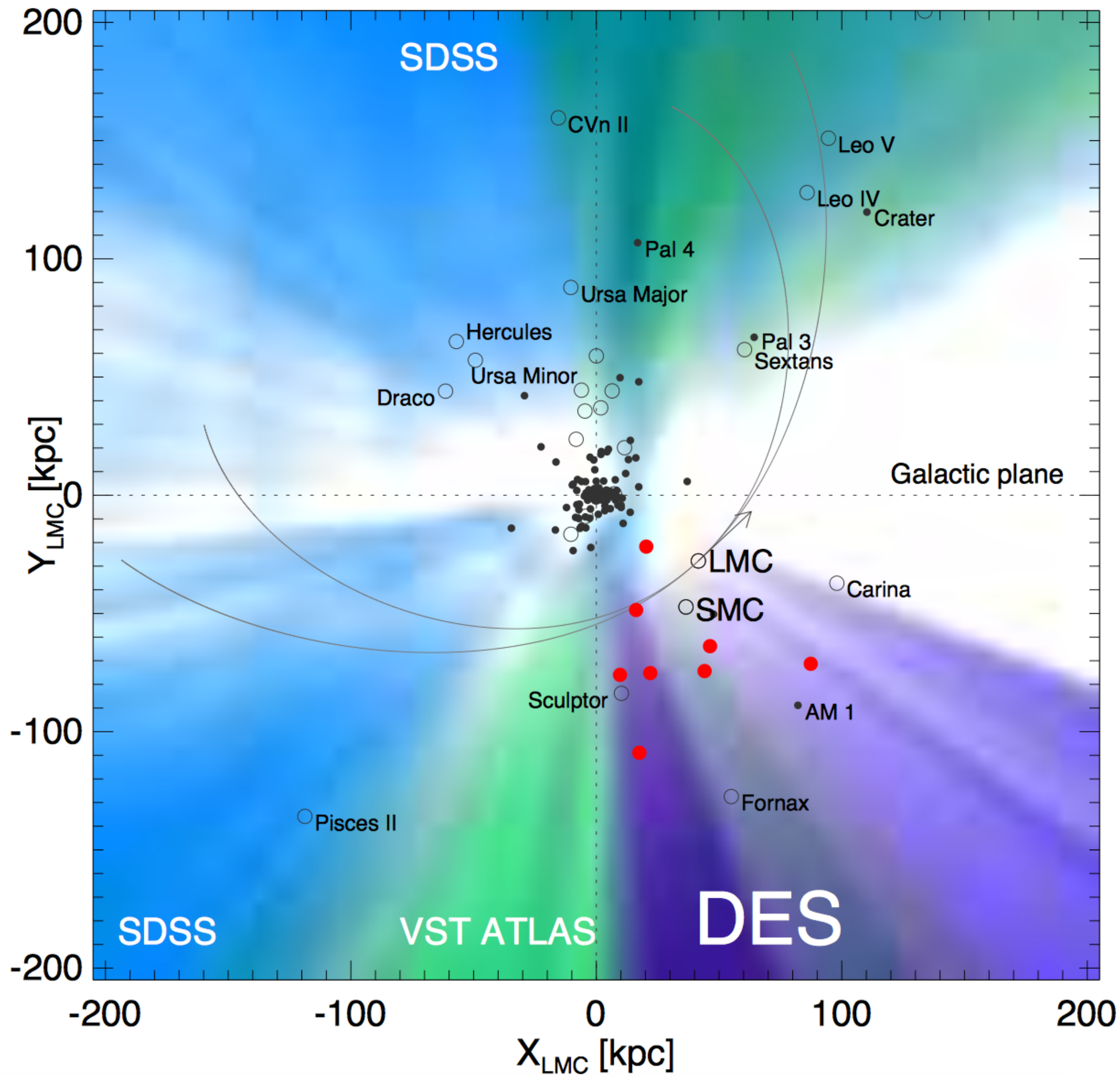


Significant overdensity?

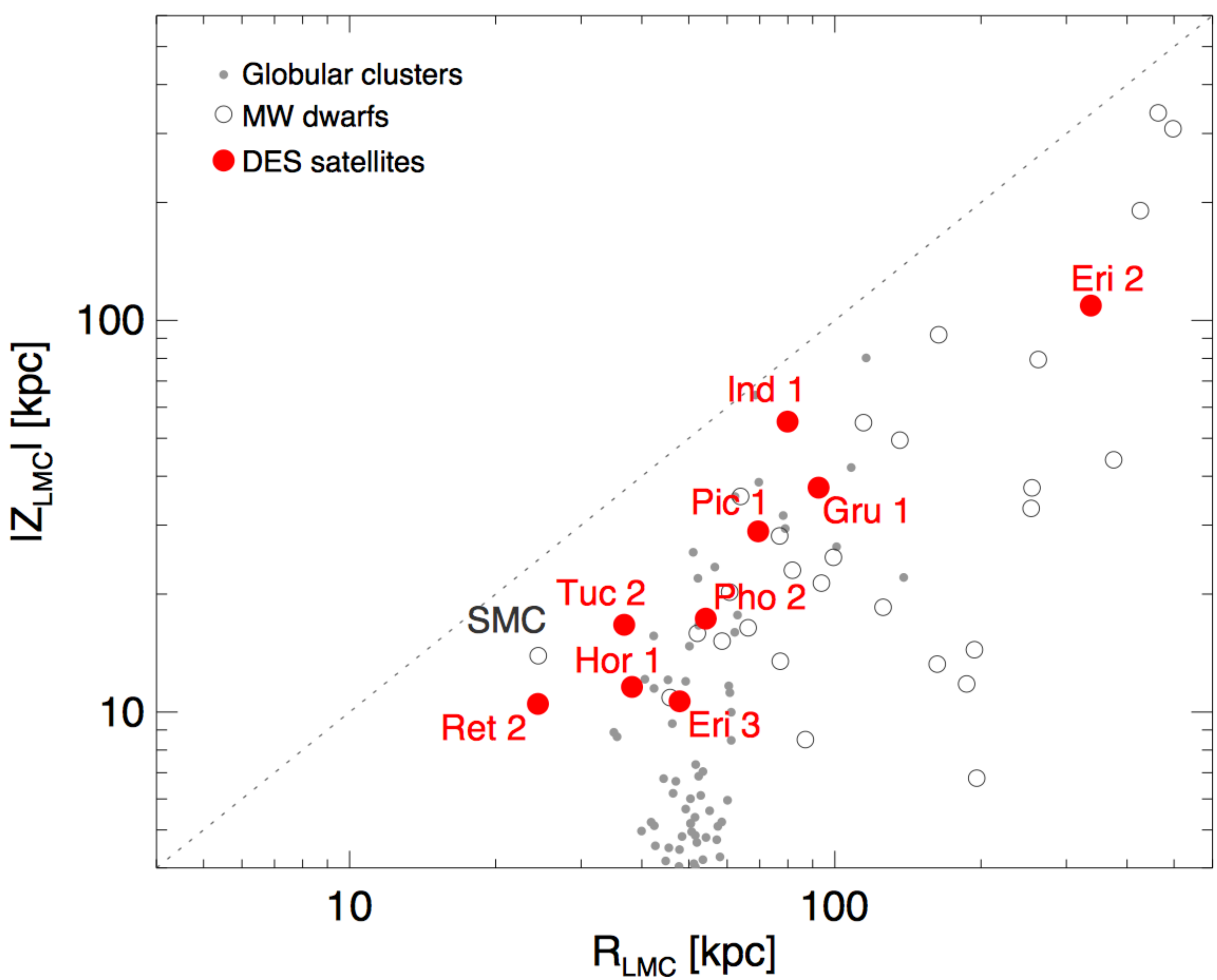


Blue density - position vectors of ALL satellites are rotated while keeping the Galactocentric radius fixed

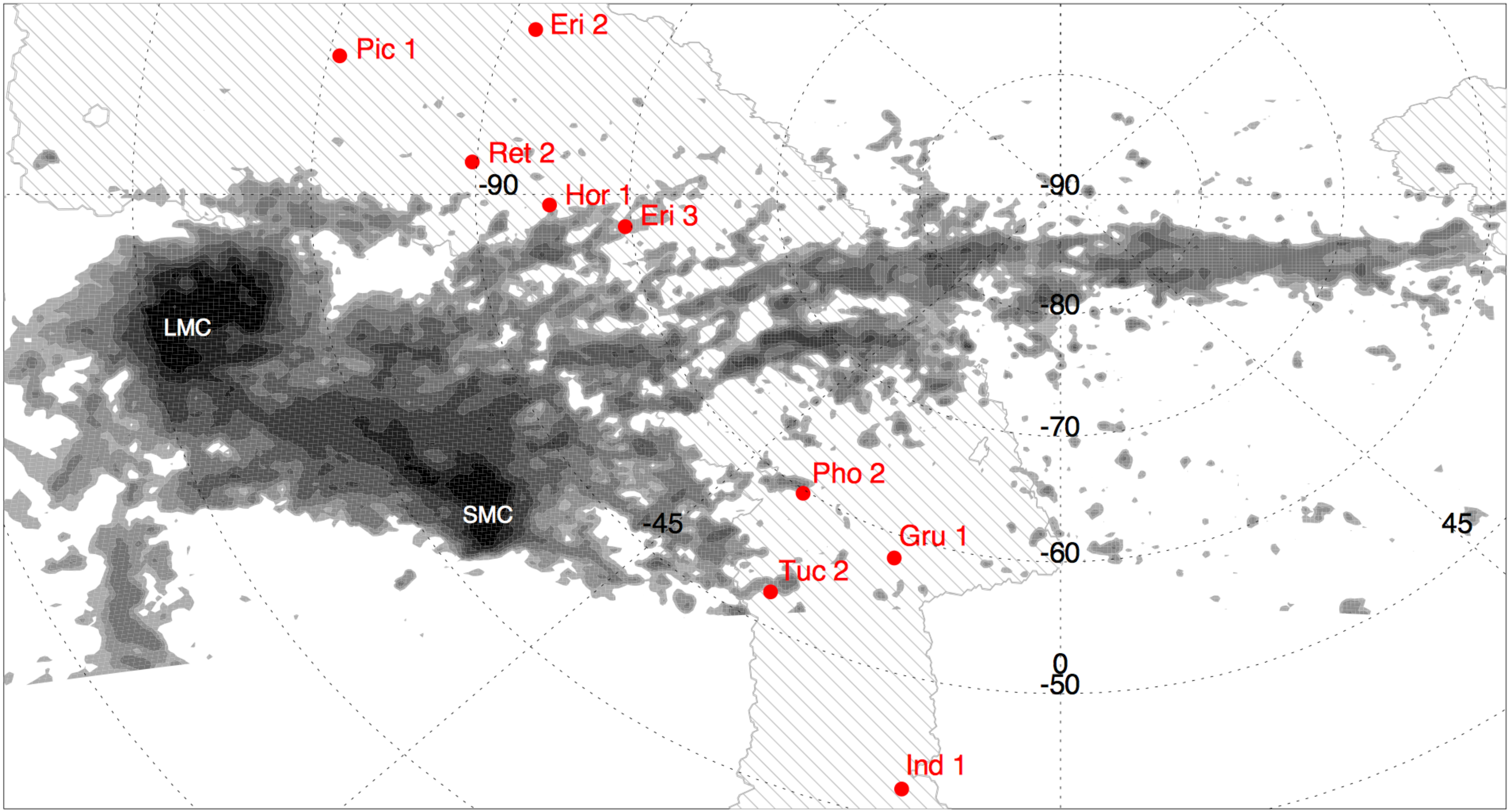
In the LMC orbital plane



Planar or not?



W.r.t. the Magellanic Stream



Magellanic Stream's HI column density from Putman et al 2003

Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

Alex Geringer-Sameth* and Matthew G. Walker†
McWilliams Center for Cosmology, Department of Physics,
Carnegie Mellon University, Pittsburgh, PA 15213, USA

Savvas M. Koushiappas‡
Department of Physics, Brown University, Providence, RI 02912, USA

Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, University of Cambridge, Cambridge, CB3 0HA, UK
(Dated: March 10, 2015)

We present a search for γ-ray emission from the direction of the newly discovered dwarf galaxy Reticulum 2. Using Fermi-LAT data, we detect a signal that exceeds expected backgrounds between $\sim 2-10$ GeV and is consistent with annihilation of dark matter for particle masses less than a few $\times\, 10^2$ GeV. Modeling the background as a Poisson process based on Fermi-LAT diffuse models, and taking into account trials factors, we detect emission with p-value less than 9.8×10^{-5} ($> 3.7\sigma$). An alternative, model-independent treatment of background reduces the significance, raising the p-value to 9.7×10^{-3} (2.3σ). Even in this case, however, Reticulum 2 has the most significant γ-ray signal of any known dwarf galaxy. If Reticulum 2 has a dark matter halo that is similar to those inferred for other nearby dwarfs, the signal is consistent with the s-wave relic abundance cross section for annihilation.

Possible gamma-ray excess at Reticulum 2

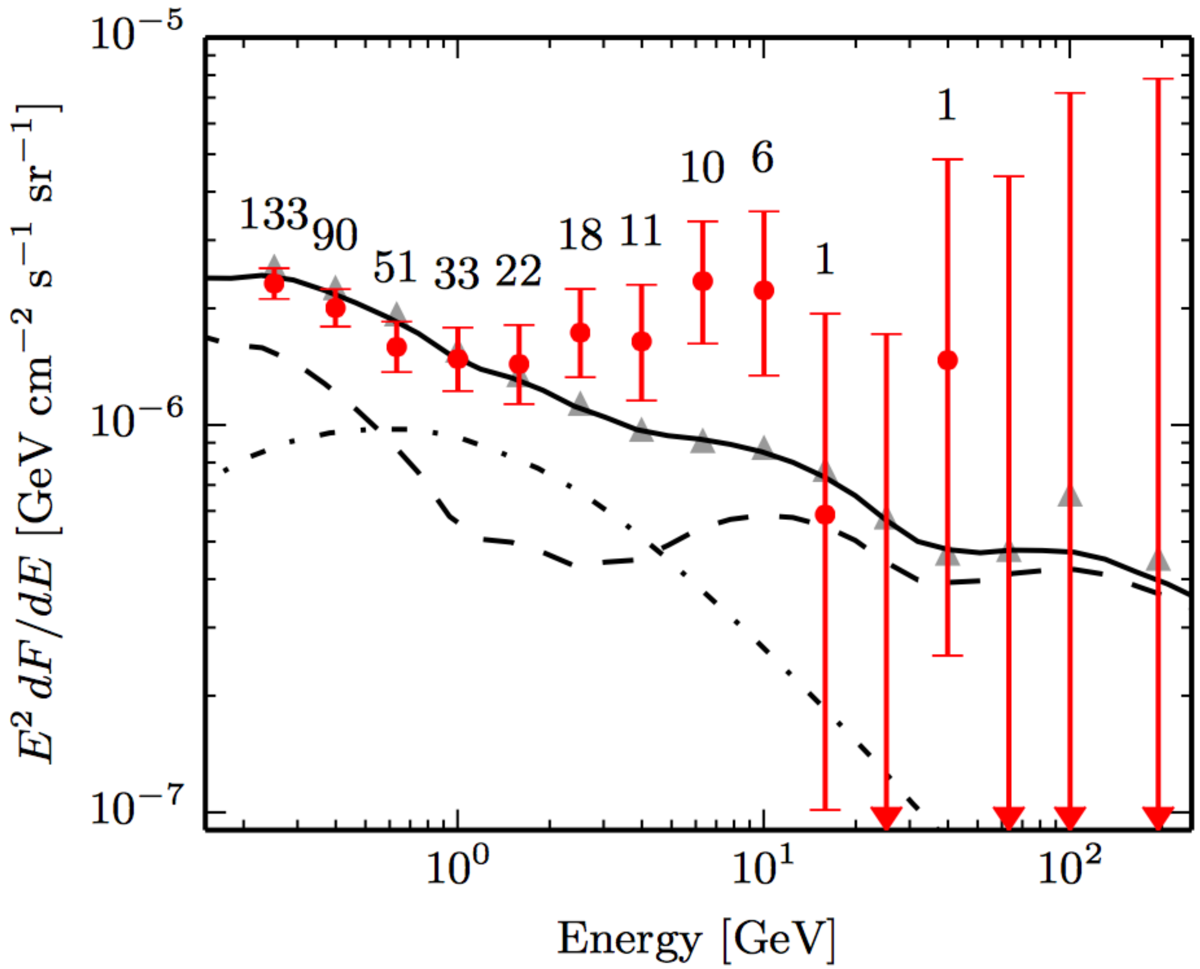
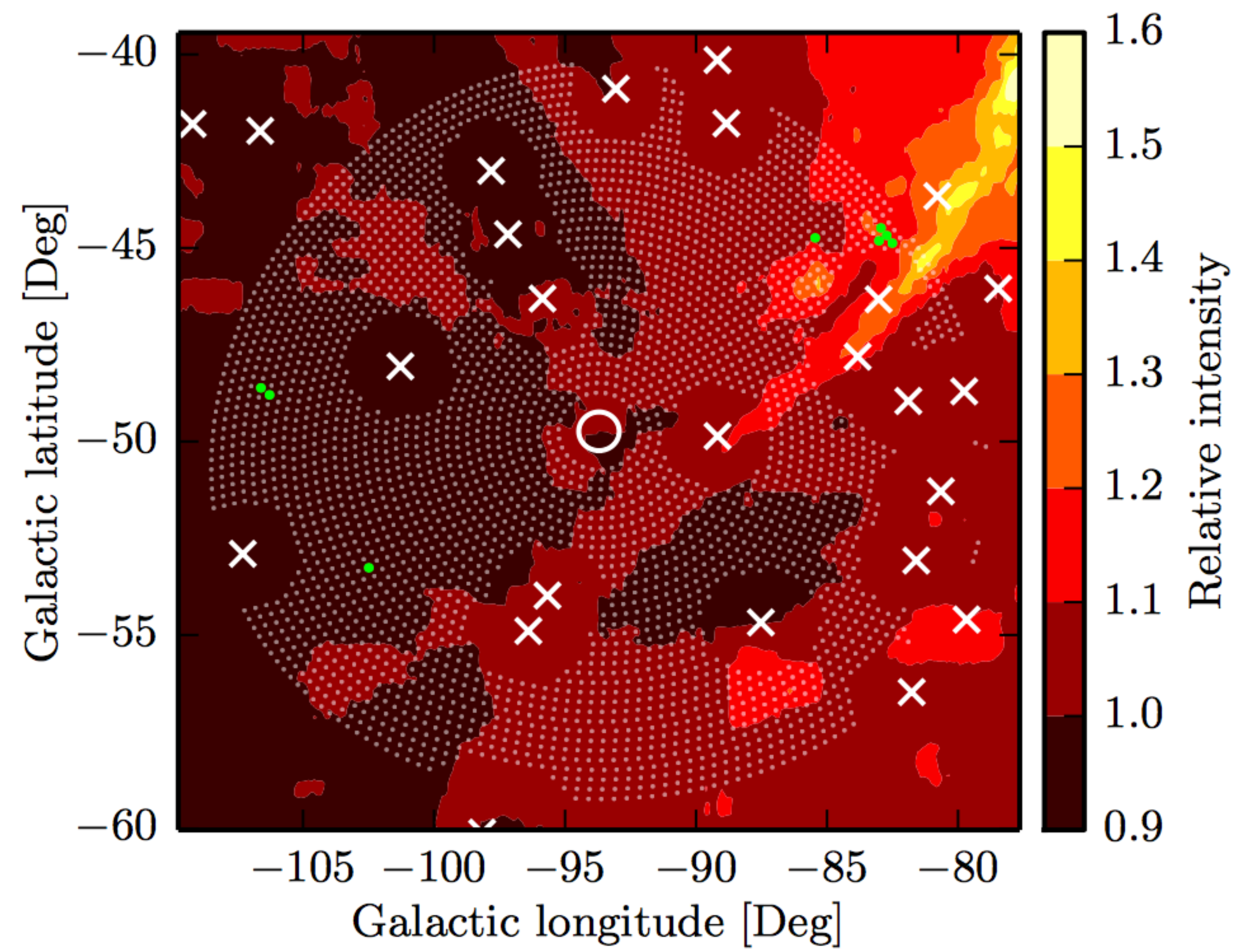


FIG. 1: Energy spectrum of events detected within 0.5° of Ret2 (red points), with Poisson error bars. The number of events detected in each energy bin is shown. Two background estimates are shown: 1) the sum (solid black) of the Fermi Collaboration's models for isotropic (dashed) and galactic diffuse (dot dash) emission at the location of Ret2, and 2) the average intensity (gray triangles) within 3306 ROIs that lie within 10° of Ret2 and overlap neither known sources nor the ROI centered on Ret2.



- 2.3σ - 3.7σ
- Small white dots - points for background estimation
- Crosses - known gamma ray sources
- Green dots - points with higher significance

Spectroscopic Follow-up

- Simon et al 2015
- Walker et al 2015
- Koposov, Casey et al 2015

MAGELLAN/M2FS SPECTROSCOPY OF THE RETICULUM 2 DWARF SPHEROIDAL GALAXY

MATTHEW G. WALKER[1], MARIO MATEO[2], EDWARD W. OLSZEWSKI[3], JOHN I. BAILEY III[2], SERGEY E. KOPOSOV[4], VASILY BELOKUROV[4] AND N. WYN EVANS[4]

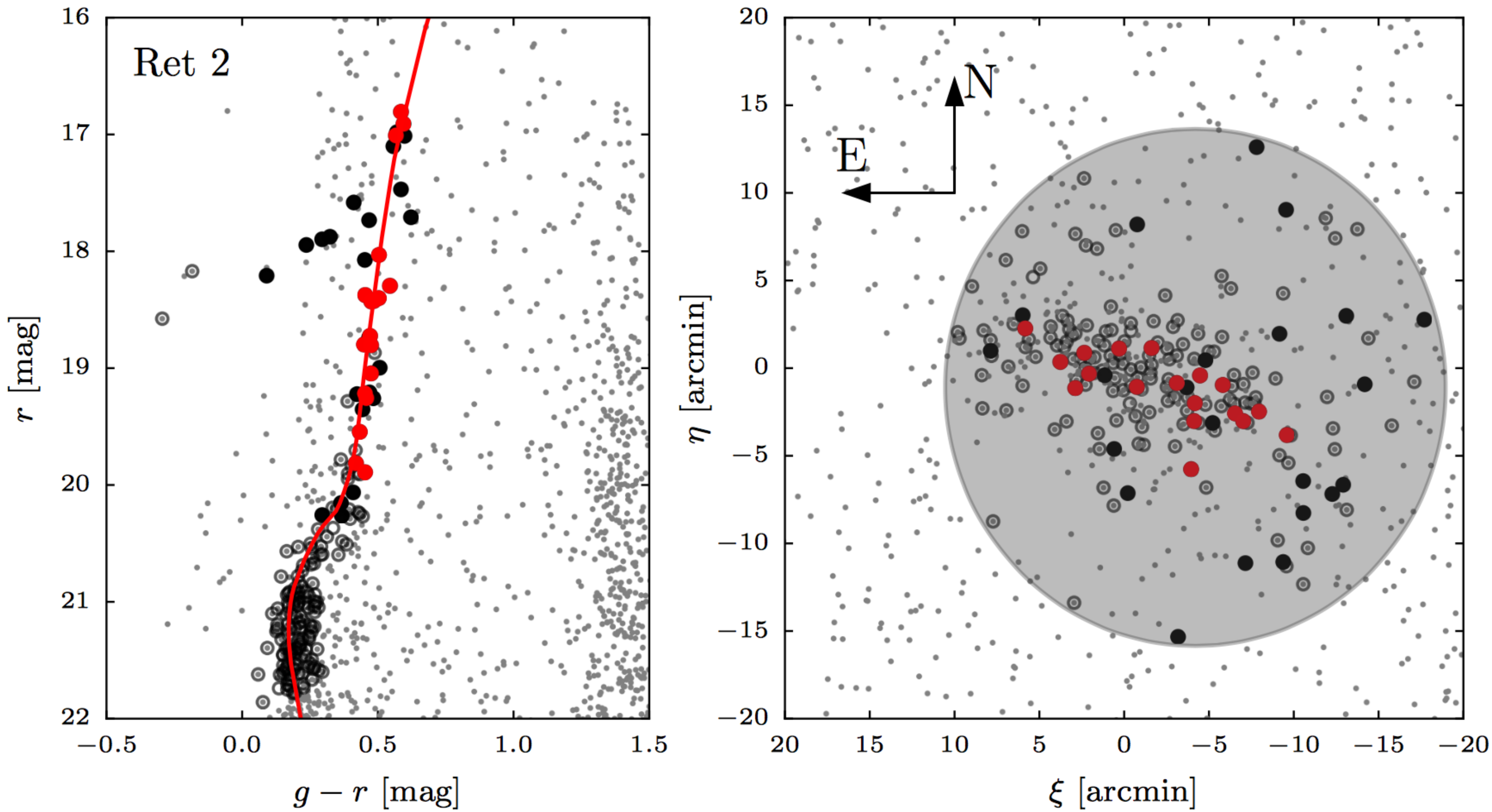
Draft version April 14, 2015

ABSTRACT

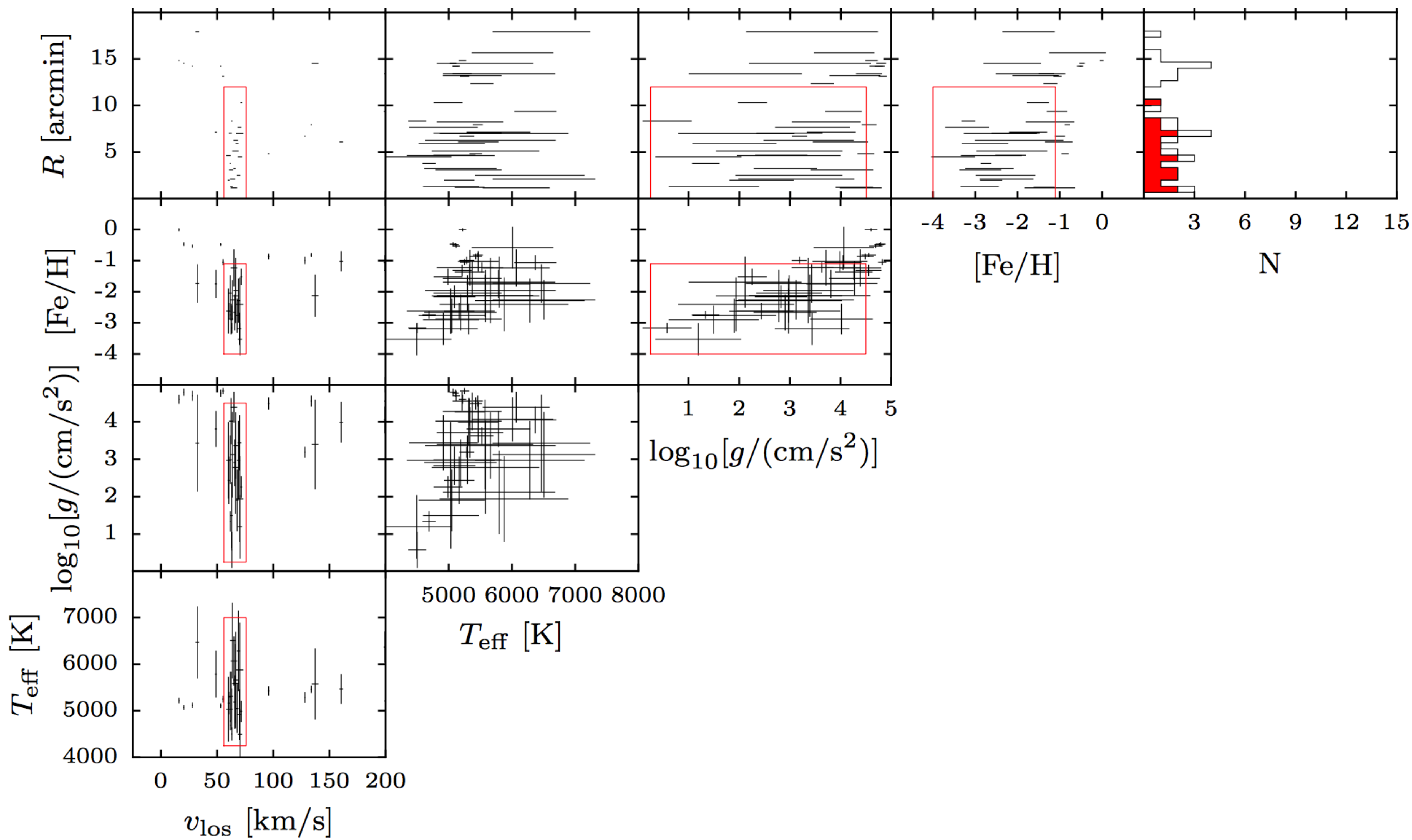
We present results from spectroscopic observations with the Michigan/Magellan Fiber System (M2FS) of 182 stellar targets along the line of sight to the newly-discovered 'ultrafaint' object Reticulum 2 (Ret 2). For 38 of these targets, the spectra are sufficient to provide simultaneous estimates of line-of-sight velocity ($v_{\rm los}$, median random error $\delta_{v_{\rm los}} = 1.3$ km s^{-1}), effective temperature ($T_{\rm eff}$, $\delta_{T_{\rm eff}} = 464$ K), surface gravity ($\log g$, $\delta_{\log g} = 0.54$ dex) and iron abundance ([Fe/H], $\delta_{\rm [Fe/H]} = 0.45$ dex). We use these results to confirm 18 stars as members of Ret 2. From the member sample we estimate a velocity dispersion of $\sigma_{v_{\rm los}} = 3.6^{+0.9}_{-0.6}$ km s^{-1} about a mean of $\langle v_{\rm los}\rangle = 64.8^{+1.1}_{-1.0}$ km s^{-1} in the solar rest frame (~ -90.9 km s^{-1} in the Galactic rest frame), and a metallicity dispersion of $\sigma_{\rm [Fe/H]} = 0.50^{+0.17}_{-0.13}$ dex about a mean of $\langle{\rm [Fe/H]}\rangle = -2.67^{+0.34}_{-0.34}$. These estimates marginalize over possible velocity and metallicity gradients, which are consistent with zero. Our results place Ret 2 on chemodynamical scaling relations followed by the Milky Way's dwarf-galactic satellites. Under assumptions of dynamic equilibrium and negligible contamination from binary stars—both of which must be checked with deeper imaging and repeat spectroscopic observations—the estimated velocity dispersion suggests a dynamical mass of $M(R_{\rm h}) \approx 5R_{\rm h}\sigma^2_{v_{\rm los}}/(2G) = 2.4^{+1.3}_{-0.8} \times 10^5\ M_\odot$ enclosed within projected halflight radius $R_{\rm h} \sim 32$ pc, with mass-to-light ratio $\approx 2M(R_{\rm h})/L_{\rm V} = 462^{+264}_{-157}$ in solar units.

Subject headings: galaxies: dwarf — galaxies: individual (Reticulum 2) — (galaxies:) Local Group — galaxies: kinematics and dynamics — methods: data analysis — techniques: spectroscopic

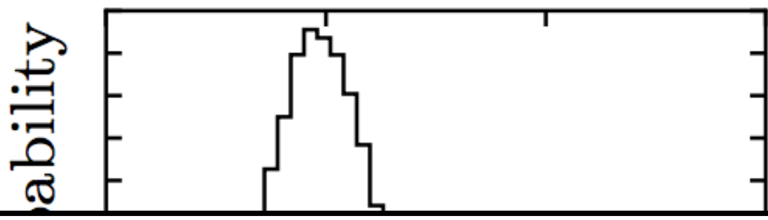
Spectroscopy of Reticulum 2



Selecting Members



Dynamics & Chemistry



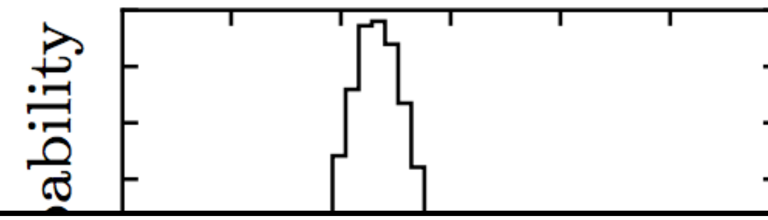
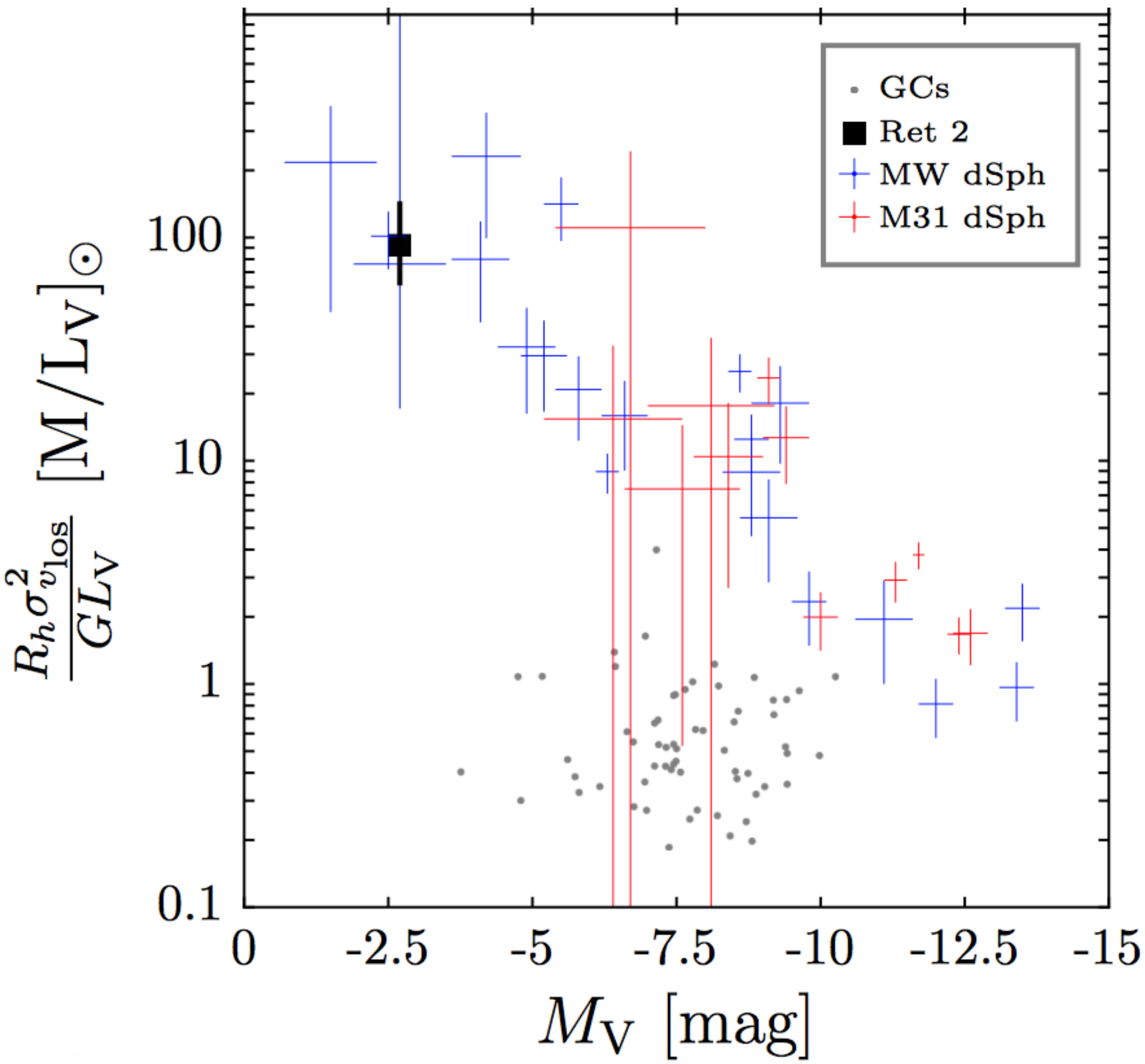
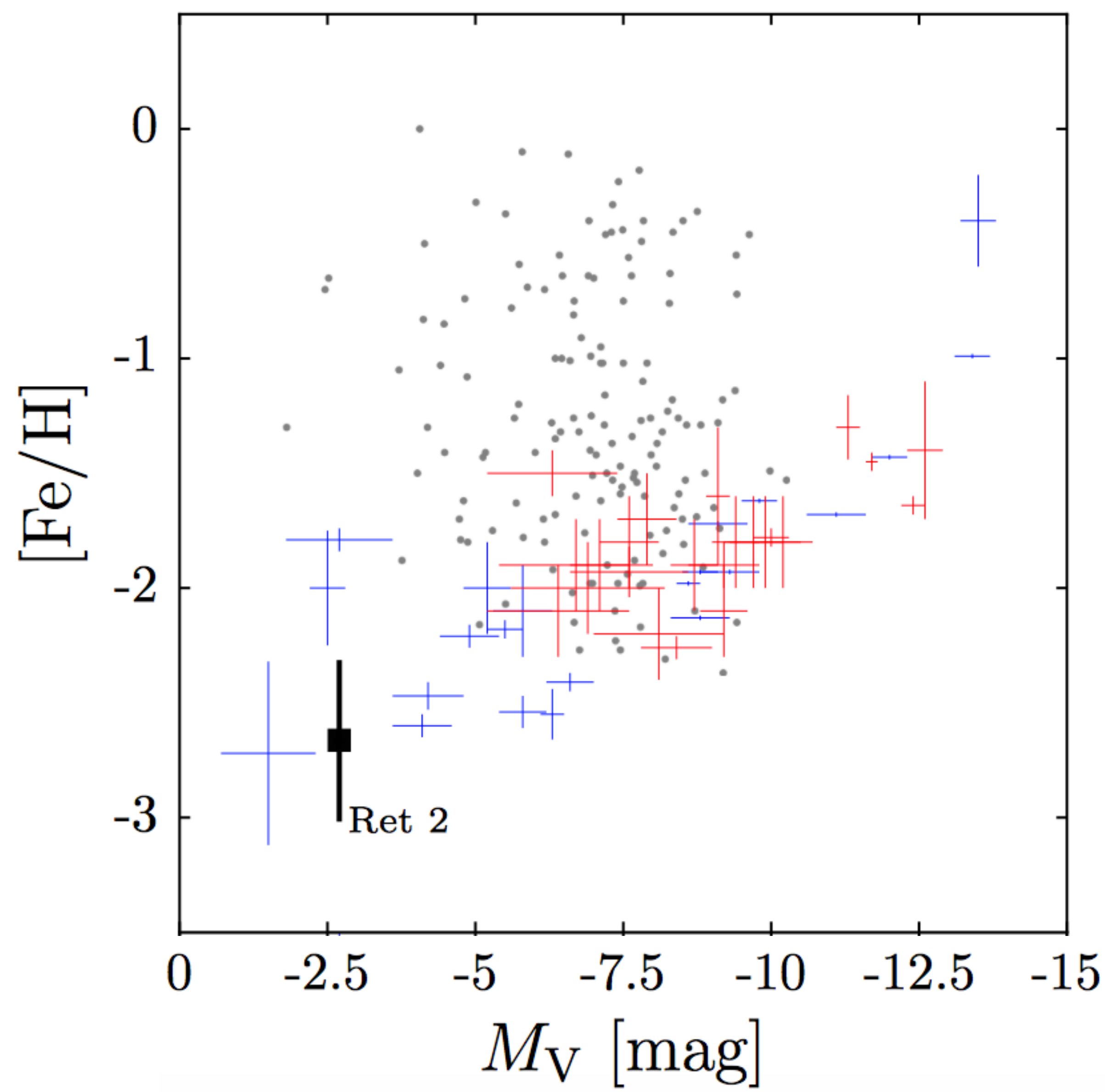


TABLE 3
SUMMARY OF PROBABILITY DISTRIBUTION FUNCTIONS FOR CHEMODYNAMICAL PARAMETERS

parameter	prior	posterior	description
$\langle v_{\rm los} \rangle$ [km s^{-1}]	uniform between -500 and +500	$64.8^{+1.1(+2.2)}_{-1.0(-2.0)}$	mean velocity at center
$\sigma_{v_{\rm los}}$ [km s^{-1}]	uniform between 0 and +500	$3.6^{+0.9(+2.1)}_{-0.6(-1.1)}$	velocity dispersion
$k_{v_{\rm los}}$ [km s^{-1} arcmin^{-1}]	uniform between 0 and +10	$0.4^{+0.4(+1.0)}_{-0.2(-0.3)}$	magnitude of maximum velocity gradient
$\theta_{v_{\rm los}}$ [$^\circ$]	uniform between -180 and +180	$-79^{+220(+251)}_{-55(-93)}$	direction of maximum velocity gradient
$\langle$[Fe/H]$\rangle$	uniform between -5 and +1	$-2.67^{+0.34(+0.72)}_{-0.34(-0.67)}$	mean metallicity at center
$\sigma_{\rm [Fe/H]}$	uniform between 0 and +2	$0.50^{+0.17(+0.40)}_{-0.13(-0.23)}$	metallicity dispersion
$k_{\rm [Fe/H]}$ [dex arcmin^{-1}]	uniform between -1 and +1	$0.02^{+0.06(+0.12)}_{-0.06(-0.13)}$	magnitude of metallicity gradient

Scaling Relations





3 quick additions

- Pegasus 3 (SDSS+DECam, Kim et al 2015)
- Triangulum 2 (PanSTARRS, Laevens et al 2015)
- Hydra 2 (SMASH, Martin et al 2015)

All appear to be in associations

Conclusions

(there are many)

Conclusions. 8 vs 9

- Bechtol et al 2015 (DES) reports 8 satellites
- Koposov et al 2015 reports 9. Grus 1 (the extra satellite) lies in the area not available to DES collaboration
- But! There are (at least) 2 very clear star clusters, Indus 1 and Eridanus 3.

Conclusions. Magellanic Clouds Association

- Estimate foreground and hence the excess above (Koposov et al 2015) ~4 objects associated
- Or, look at the fraction of satellites as a function of distance away from the previous host during group accretion in simulations

SATELLITES OF LMC-MASS SATELLITES: CLOSE FRIENDSHIPS RUINED BY MILKY WAY MASS HALOS

Alis J. Deason[1], Andrew R. Wetzel[2,3], Shea Garrison-Kimmel[4], Vasily Belokurov[5]

(Dated: April 13, 2015)
In prep.

ABSTRACT

Motivated by the recent discovery of several dwarf galaxies near the Large Magellanic Cloud (LMC), we study the accretion of massive satellites onto Milky Way(MW)/M31-like halos using the ELVIS suite of N-body simulations. We identify 25 surviving subhalos near the expected mass of the LMC, and investigate the lower-mass satellites that were associated with these subhalos before they fell into the MW/M31 halos. Typically, 7% of the overall $z = 0$ satellite population of MW/M31 halos were in a surviving LMC-group prior to falling into the MW/M31 halo. This fraction, however, can vary between 1% and 25%, being higher for groups with higher-mass and/or more recent infall times. Groups of satellites disperse rapidly in phase space after infall, and their distances and velocities relative to the group center become statistically similar to the overall satellite population after $4-8$ Gyr. We quantify the likelihood that satellites were associated with an LMC-mass group as a function of both distance and radial/3D velocity relative to the LMC at $z = 0$. The close proximity in distance of the nine Dark Energy Survey candidate dwarf galaxies to the LMC suggest that $\sim 2-4$ are likely associated with the LMC. Furthermore, if several of these dwarfs nearby to the LMC are genuine members, then the LMC-group probably fell into the MW very recently, $\lesssim 2$ Gyr ago. If the connection with the LMC is established with the help of the follow-up velocity measurements, these "satellites of satellites" represent prime candidates to study the affects of group pre-processing on lower mass dwarfs.

Keywords: Galaxy: formation — Galaxy: halo — galaxies: dwarf — galaxies: Magellanic Clouds

being submitted to ApJL

The scatter correlates with the infall time

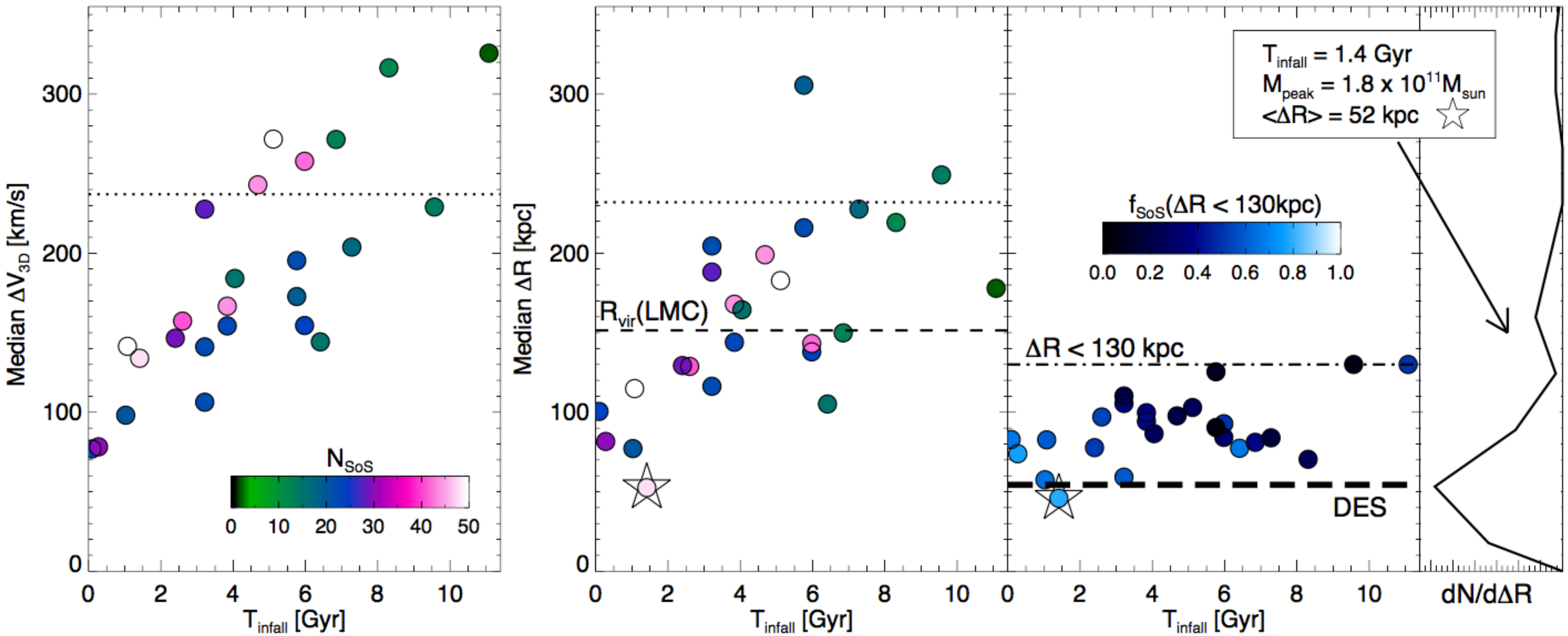


Figure 3. The median differences in 3D velocity (left panel) and 3D distance (right panels) at $z = 0$ between the LMC dwarfs and the satellites that were associated with them in a group before falling into the MW/M31 hosts. LMCs that fell in at early times have the largest differences in phase space with their satellites today. The colors indicate the number of surviving group members. The black dotted lines indicate the average velocity/radial difference between *all* satellites in MW/M31 hosts and the LMC satellite at $z = 0$. We also show the approximate virial radius for an LMC-mass subhalo with the short-dashed line. The middle right panel shows the median difference in configuration space for satellites with $\Delta R < 130$ kpc. This is a rough estimate for the maximum ΔR probed by the DES survey around the LMC. The black dashed line shows the median distance between the DES dwarfs and the LMC. The furthest right panel shows the distribution of ΔR for one massive group (indicated by the star symbol) with low median ΔR.

See also Sales et al 2011

Given the infall time, predict the associated number

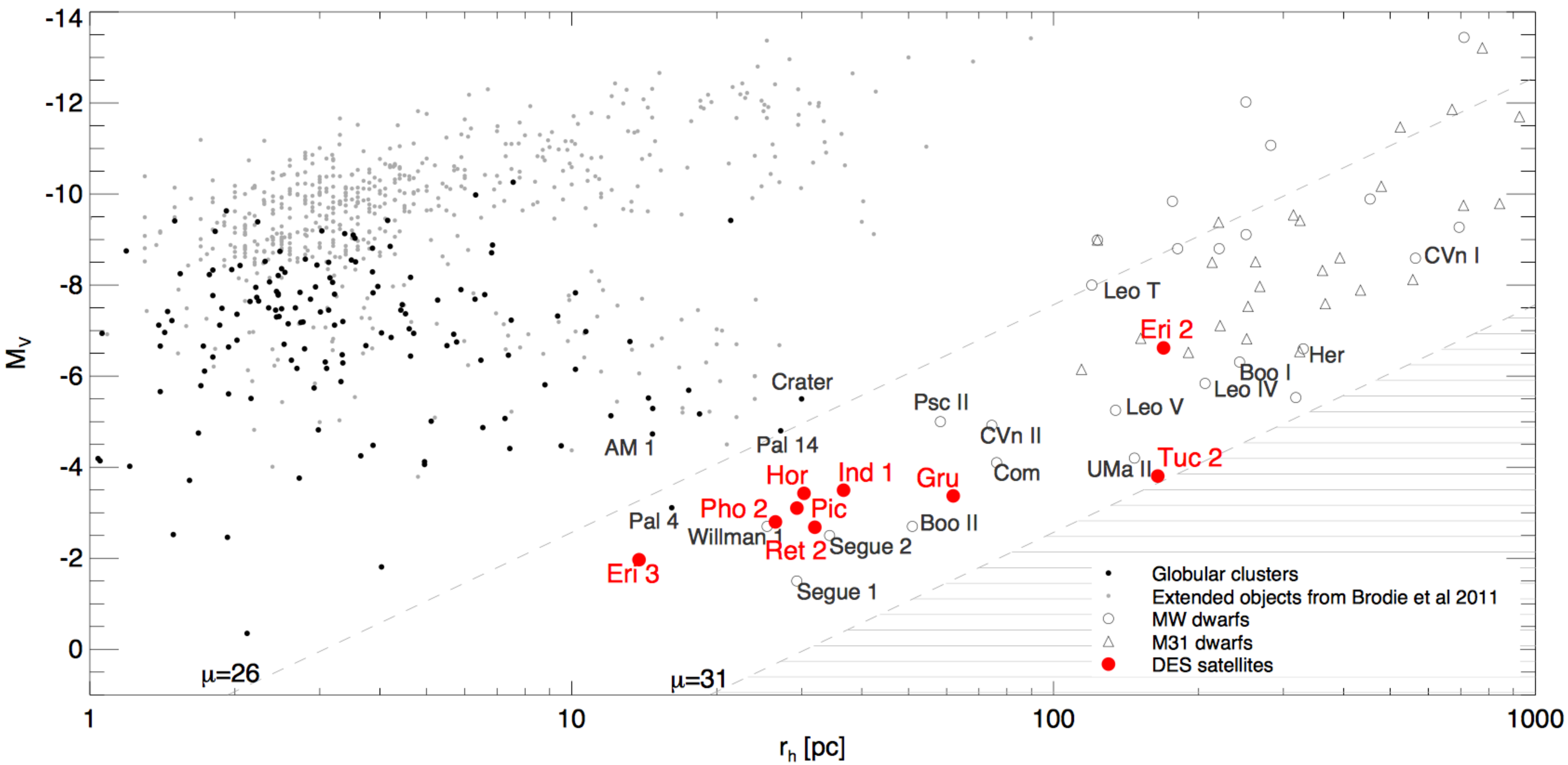
Table 1
The nine candidate dwarf galaxies from Koposov et al. (2015). We give the dwarf name, 3D distance from the LMC, and estimated probability of once being a satellite of the LMC based on this distance.

Name	**ΔR [kpc]**	**$P_{\text{LMC sat}}$**	**$P_{\text{LMC sat}}$ ($T_{\text{infall}} < 2$ Gyr)**
Reticulum 2	23.9	0.38	0.65
Eridanus 2	337.4	0.02	0.01
Horologium	38.5	0.31	0.57
Pictoris 1	70.0	0.19	0.41
Phoenix 2	54.3	0.23	0.49
Indus 1	80.0	0.18	0.37
Grus 1	92.8	0.16	0.31
Eridanus 3	48.2	0.26	0.52
Tucana 2	36.7	0.32	0.58
	Total:	2.0	3.9

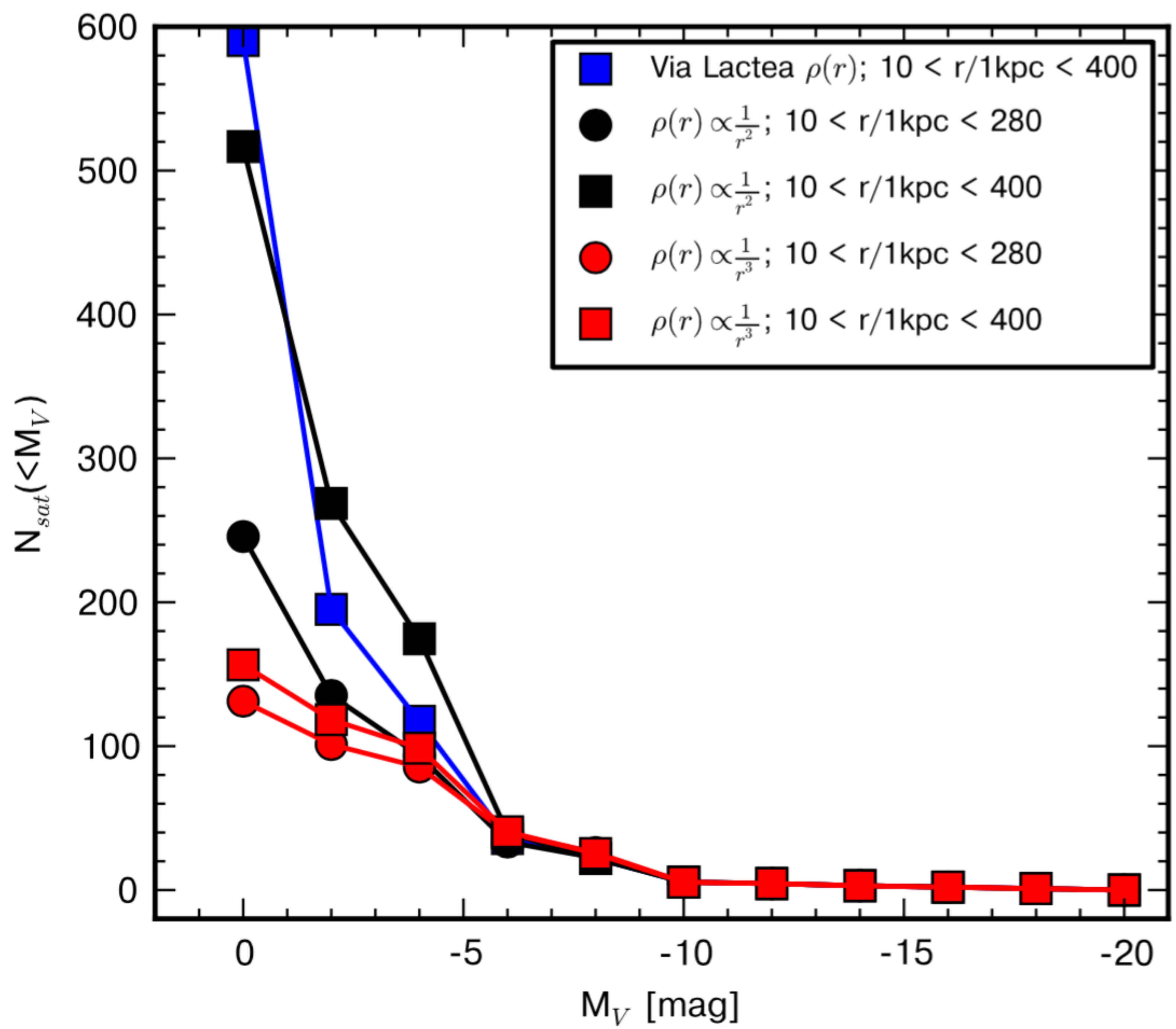
See also Sales et al 2011

Have we found "stealth galaxies" (Bullock et al 2010)?

- No.



Formation of UFDs with Mv> -4



Formation of UFDs with Mv> -4

- Many of the faintest UFDs appear to be associated with a larger accretion event.
- Sometimes, the previous host is still intact,e.g. LMC, sometimes it is not.
- For example, Segue 2 and Triangulum 2 appear to be embedded in Tri-And stream.

Formation of UFDs with Mv> -4

- Are the faintest UFDs **preferentially** produced in groups?
- Why?
- Are they pre-processed?

The End