Mapping Triangulum-Andromeda with SDSS.
I. Photometric Cartography

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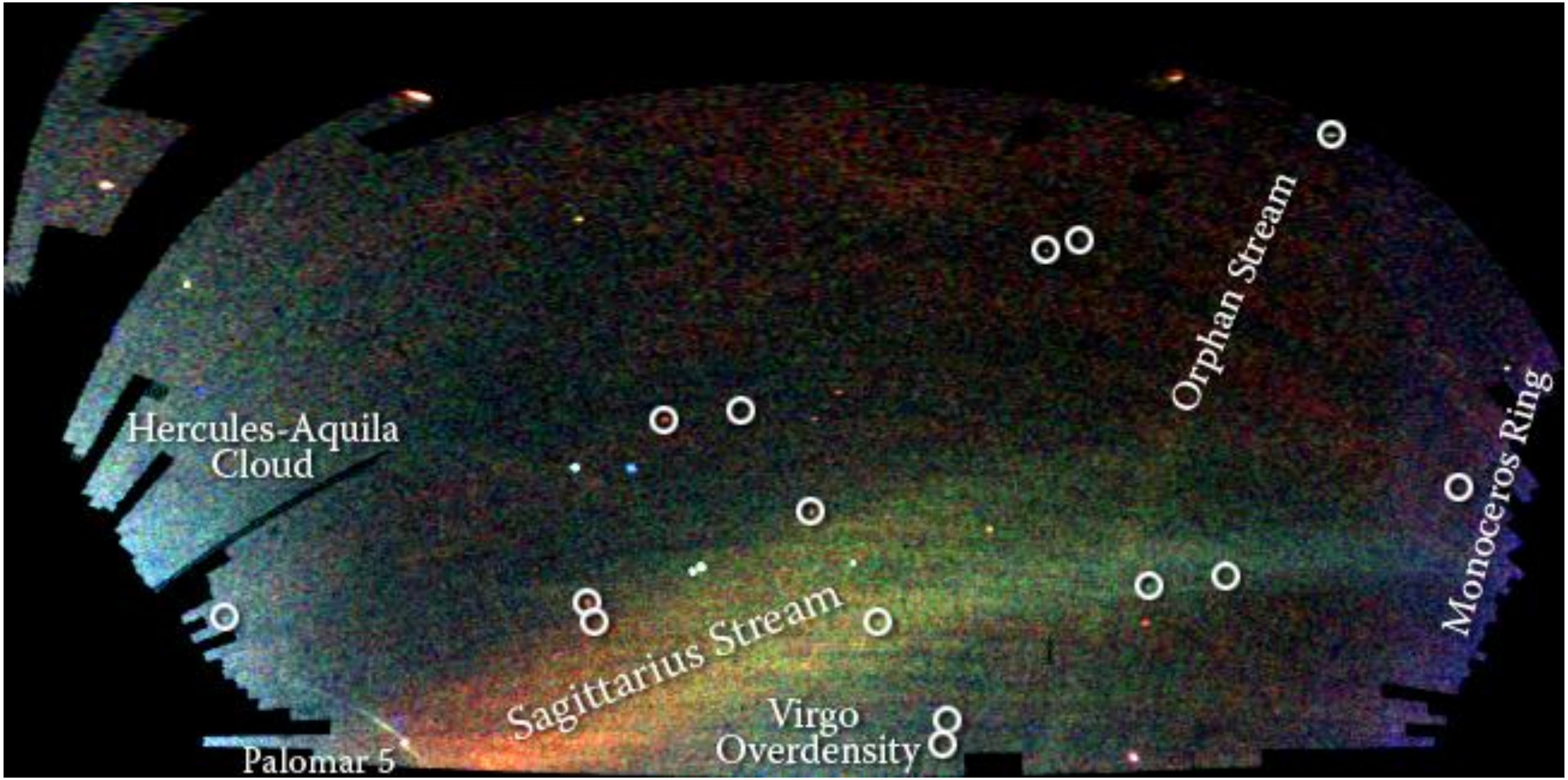
Overview

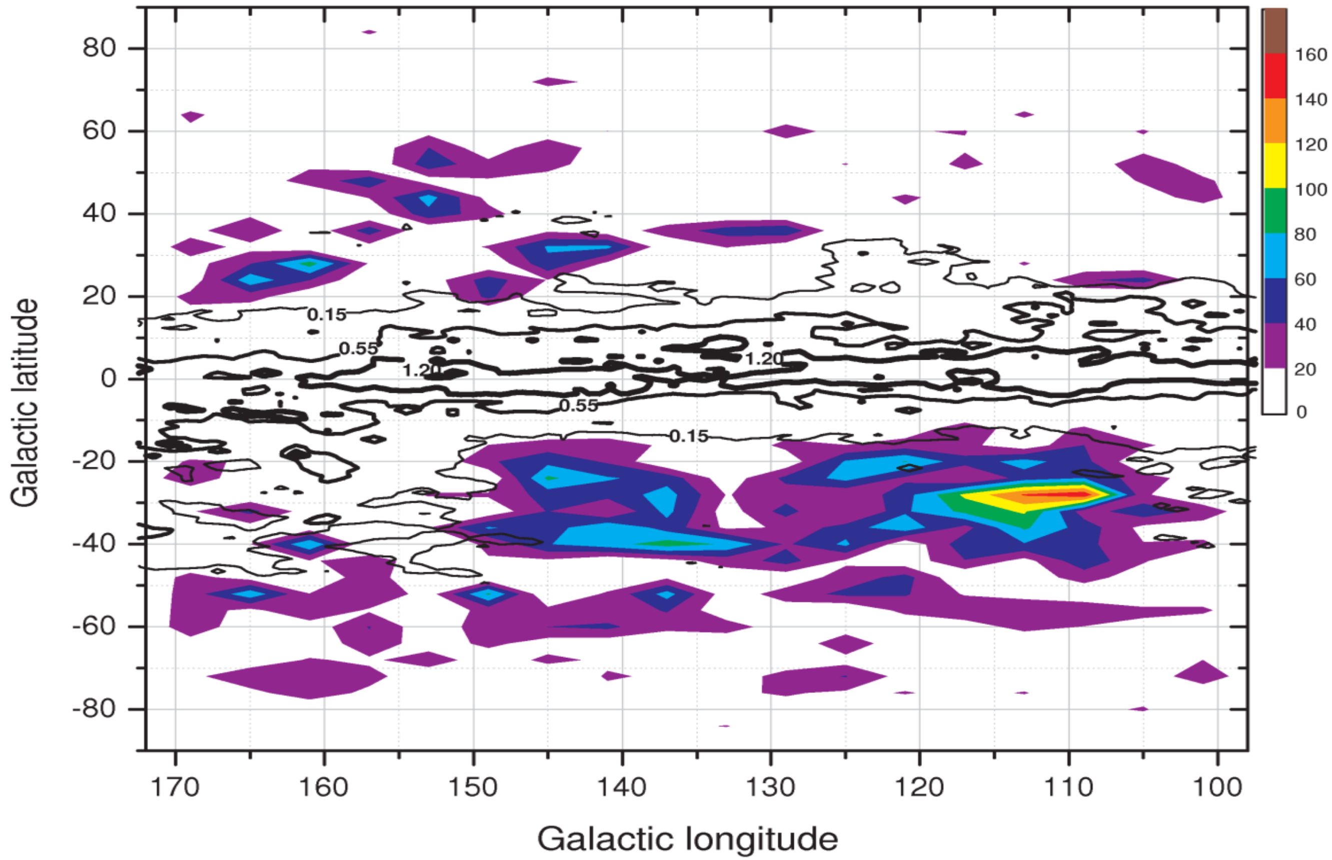
- Brief review of Milk Way halo substructures with emphasis on overdensities/clouds and Triangulum-Andromeda (TriAnd).
- Sample selection + technique used to map
- The new map of TriAnd structure, its properties and the three others that we have named Heleus, Perses and Alcaeus.
- Conclusion

Overdensities and clouds in the galactic halo



Belokurov et al (2006)

Triangulum-Andromeda cloud by RP04

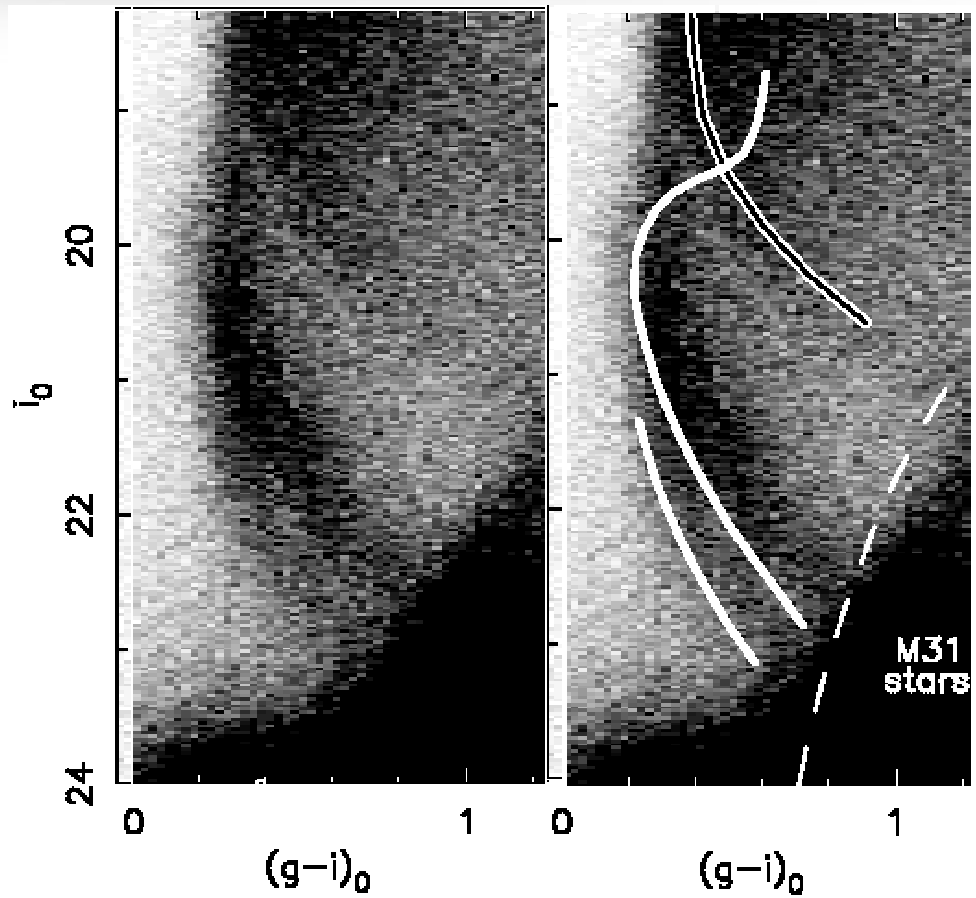


Rocha-Pinto et al (2004; RP04)

- TriAnd was found to be a very diffuse cloud-like stellar structure in the Halo, situated some 18-27 kpc away from the Sun, having a estimated surface brightness of ∼ 32 mag $arcsec^{-2}$ and luminous mass of the $1.6 \times 10^6 M_\odot$.

Triangulum-Andromeda structure by Martin et al. (2007)

Rocha-Pinto et al. (2004)	TriAnd
Majewski et al. (2004)	TriAnd
Martin et al. (2007)	TriAnd TriAnd 2
Chou et al. (2011)	TriAnd
Martin et al. (2014)	TriAnd TriAnd 2
Sheffield et al. (2014)	TriAnd TriAnd 2
Deason et al. (2014)	TriAnd
Xu et al. (2015)	Triand
Price-Whelan et al. (2015)	Triand



Martin et al. (2007)

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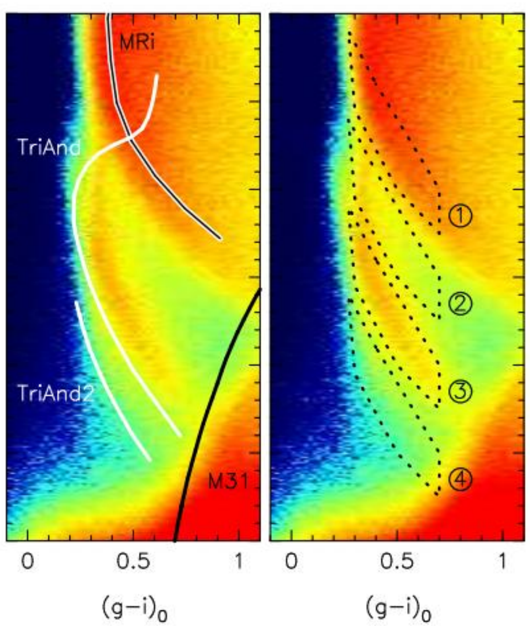
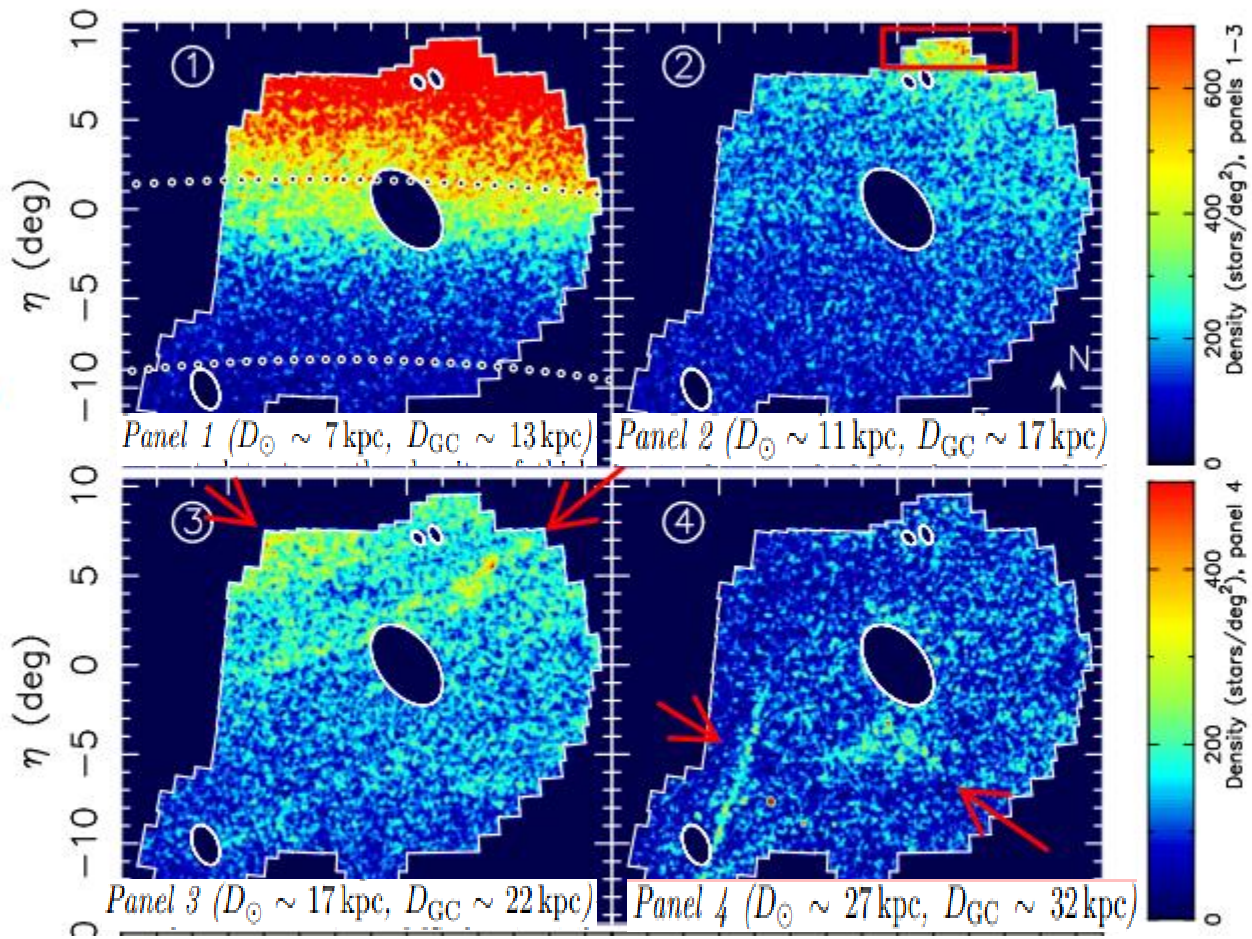


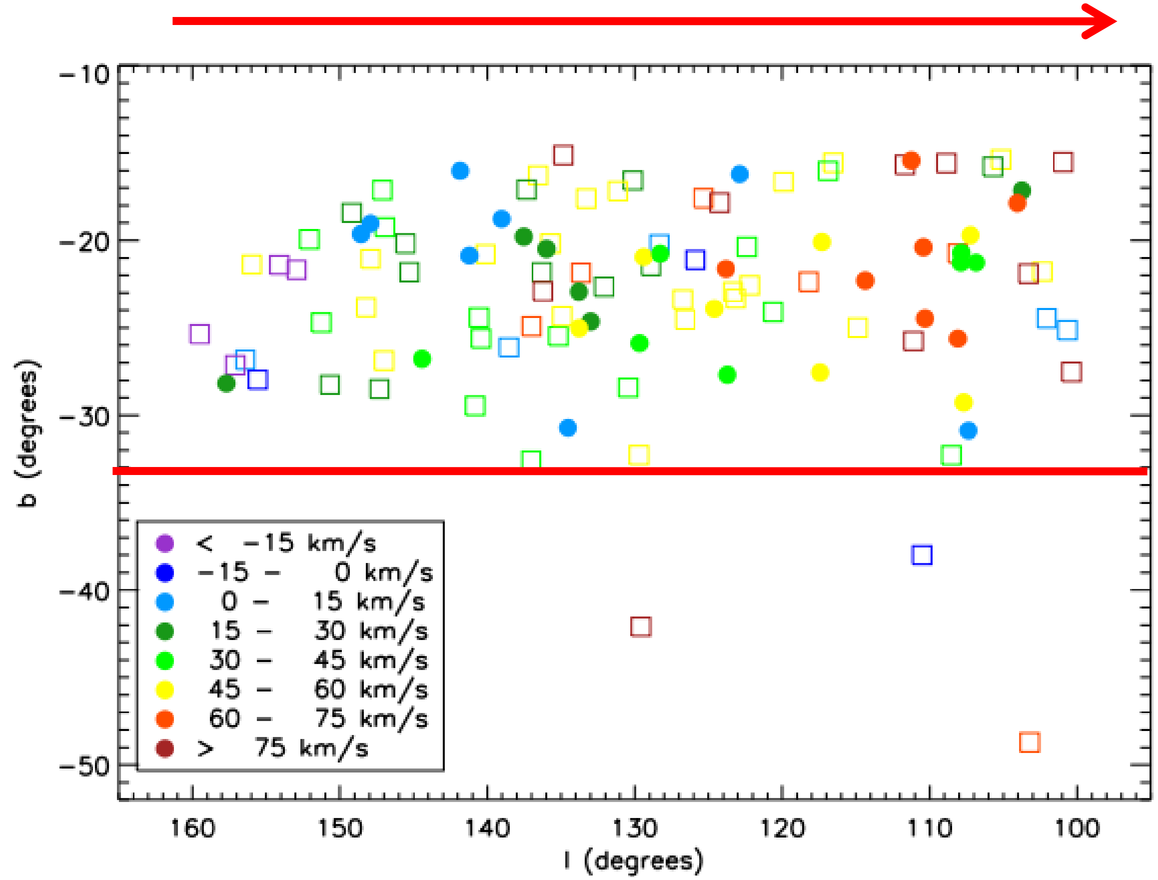


Martin et al. (2014)

Triangulum-Andromeda (Sheffield et al. 2014)

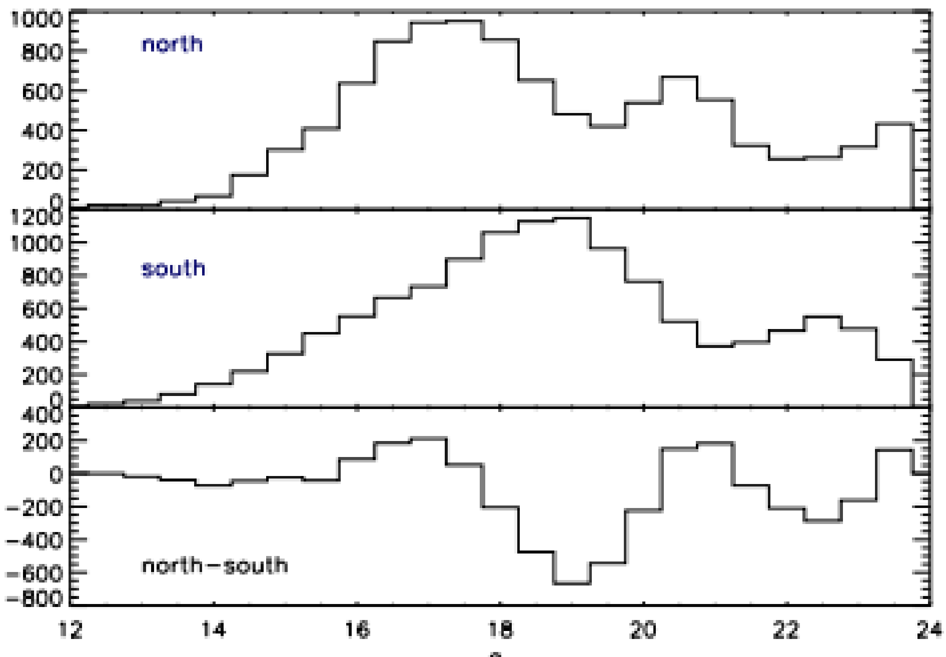
Rocha-Pinto et al. (2004)	TriAnd
Majewski et al. (2004)	TriAnd
Martin et al. (2007)	TriAnd TriAnd 2
Chou et al. (2011)	TriAnd
Martin et al. (2014)	TriAnd TriAnd 2
Sheffield et al. (2014)	TriAnd TriAnd 2
Deason et al. (2014)	TriAnd
Xu et al. (2015)	Triand
Price-Whelan et al. (2015)	Triand

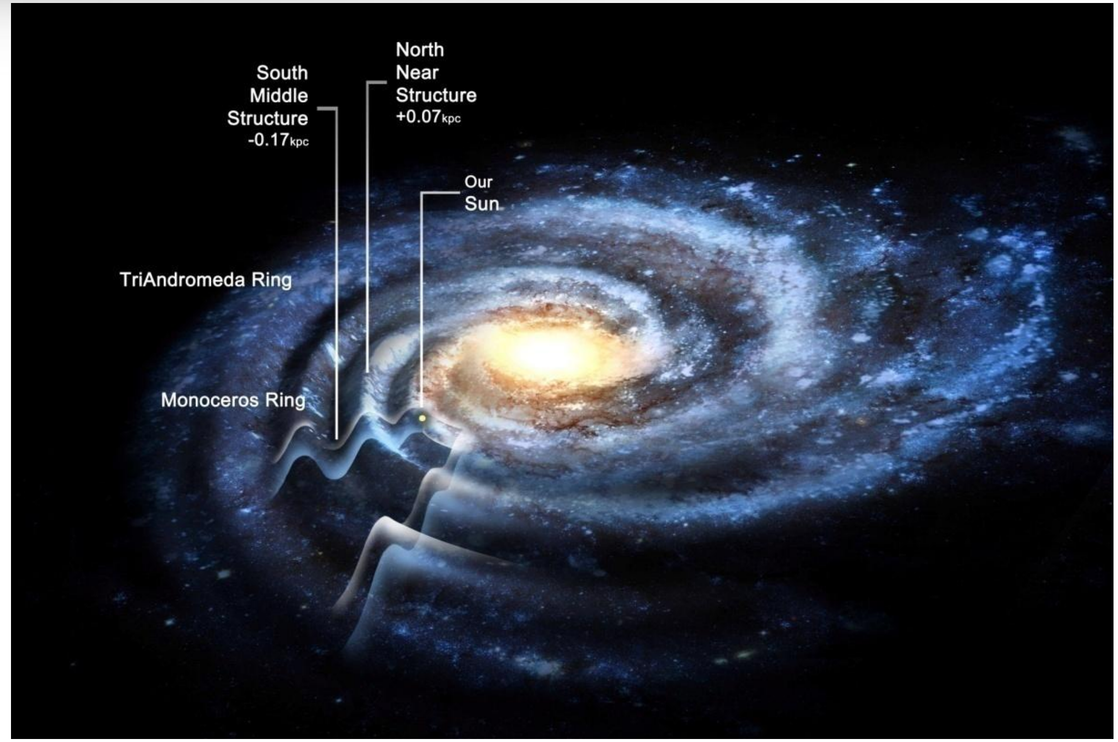
A gradient in v_{GSR} is seen as a function of l, and they also find the b distribution to be restricted in b > -35°.



Triangulum-Andromeda (Xu et al. 2015)

Rocha-Pinto et al. (2004)	TriAnd
Majewski et al. (2004)	TriAnd
Martin et al. (2007)	TriAnd TriAnd 2
Chou et al. (2011)	TriAnd
Martin et al. (2014)	TriAnd TriAnd 2
Sheffield et al. (2014)	TriAnd TriAnd 2
Deason et al. (2014)	TriAnd
Xu et al. (2015)	Triand
Price-Whelan et al. (2015)	Triand

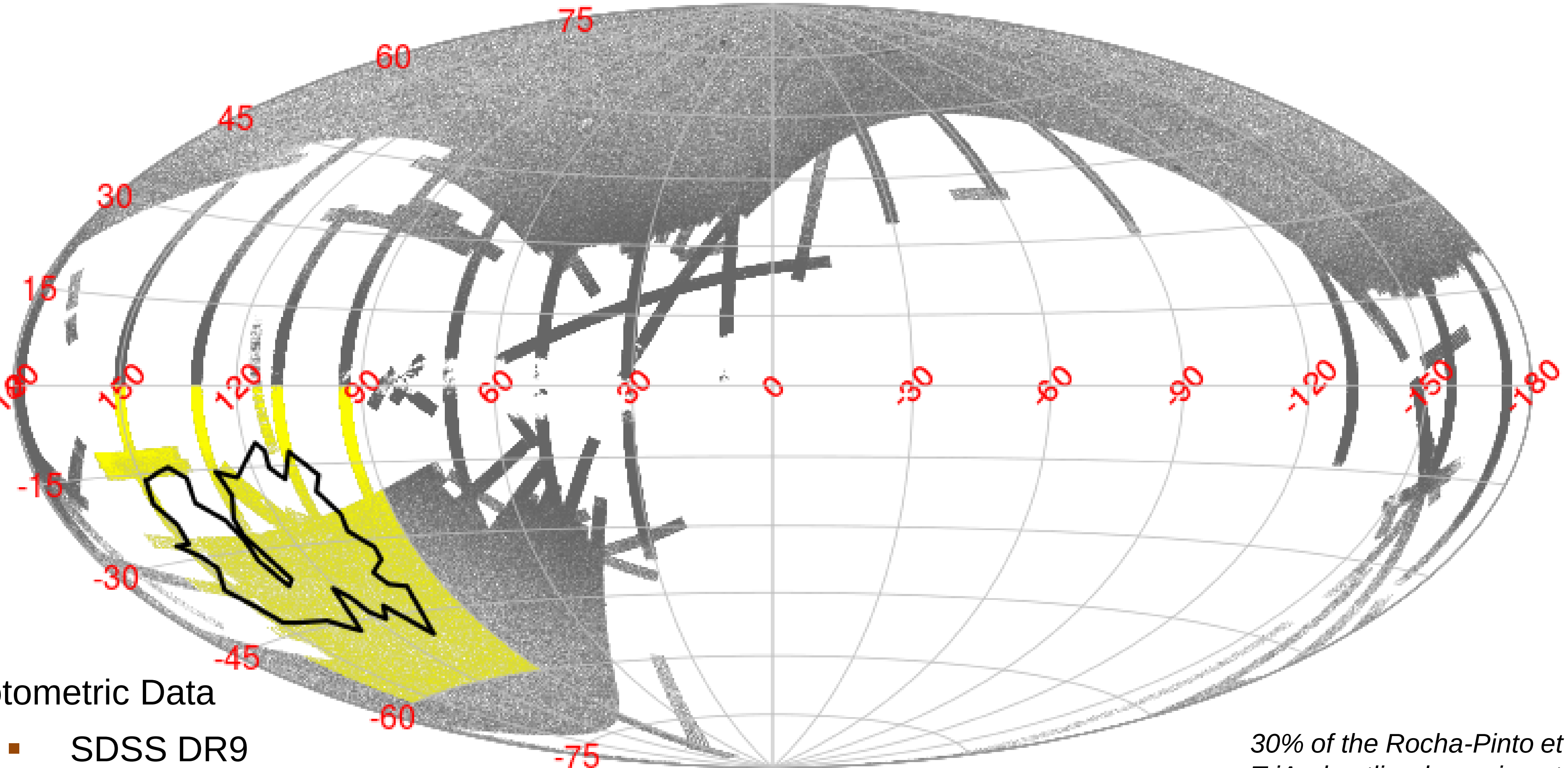




Overview of TriAnd properties

Ref.	Objeto	[Fe/H]	$[d_{min}, d_{max}]$	Idade
		dex	kpc	Ga
Rocha-Pinto et al. (2004)	TriAnd	−1.2	15-30	
Majewski et al. (2004)	TriAnd	−1.28	16-25	
Martin et al. (2007)	TriAnd	−1.3	23	10
Chou et al. (2011)	TriAnd	−0.64	-	-
Chou et al. (2011)	TriAnd	−0.7	22	8
Martin et al. (2014)	TriAnd	−0.7	17	10
Sheffield et al. (2014)	TriAnd	−0.7	18-19	6-8
Sheffield et al. (2014)	TriAnd	−0.8	18-19	6-8
Deason et al. (2014)	TriAnd	−0.5	18	
Deason et al. (2014)	TriAnd	−1.1	-	
Deason et al. (2014)	TriAnd	−0.8	20-30	

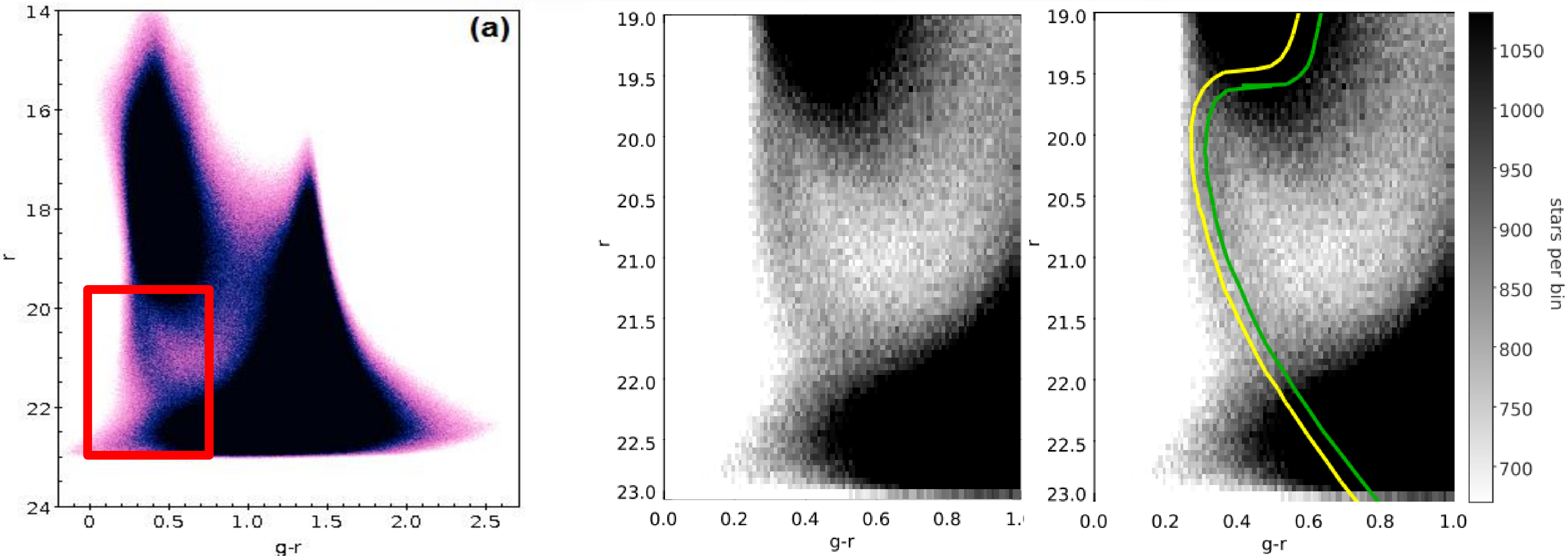
Querying SDSS Data



- Photometric Data
  - SDSS DR9
- r < 23
- Coverage area: 90º < l < 160° e 0° > b > -60º

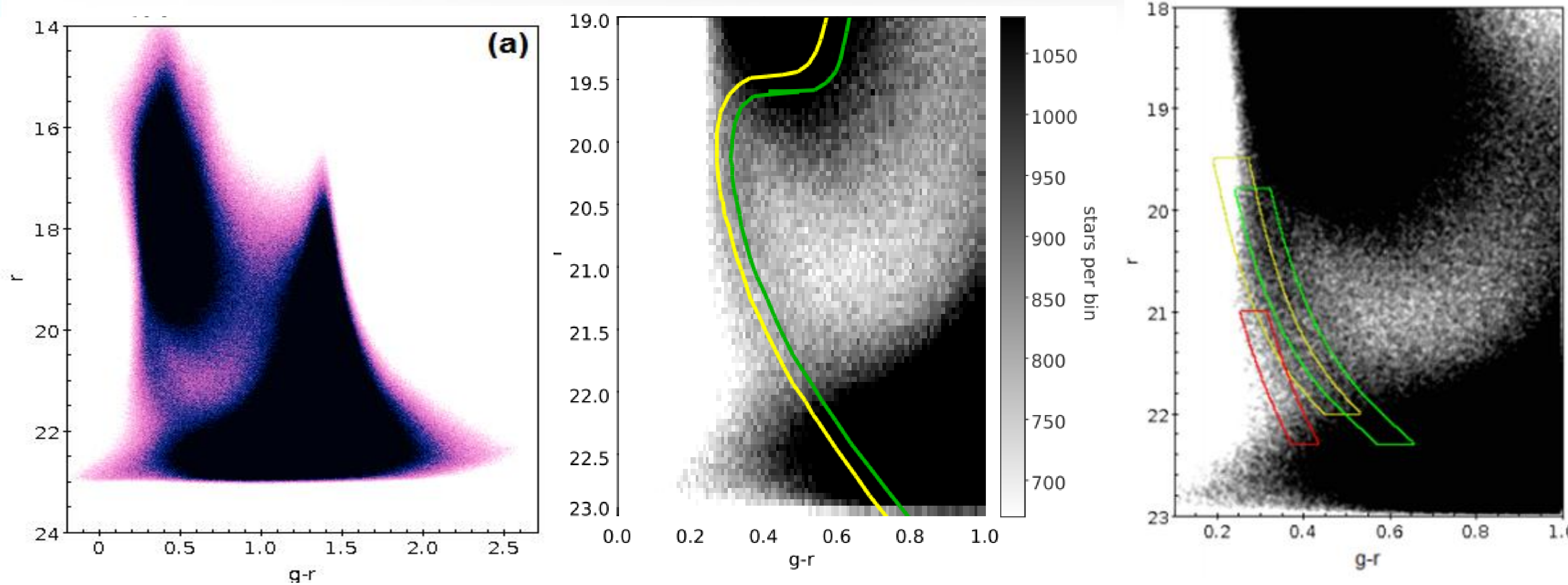
30% of the Rocha-Pinto et al. (2004) TriAnd outlined area is not covered by the SDSS data

The isochrone fitting



$D_{\odot}$~17 kpc, DGC~22 kpc

The isochrone fitting



D$_{\odot}$~17 kpc, DGC~22 kpc

Fit Color and Name	Magnitude limit	Isochrone Window	Number of stars
	mag	mag	
Green (1A)	$19.8 < i < 22.3$	±0.035	284705
Green (1B)	$19.8 < r < 22.3$	±0.035	237962
Yellow (2)	$19.5 < r < 22$	±0.040	244655

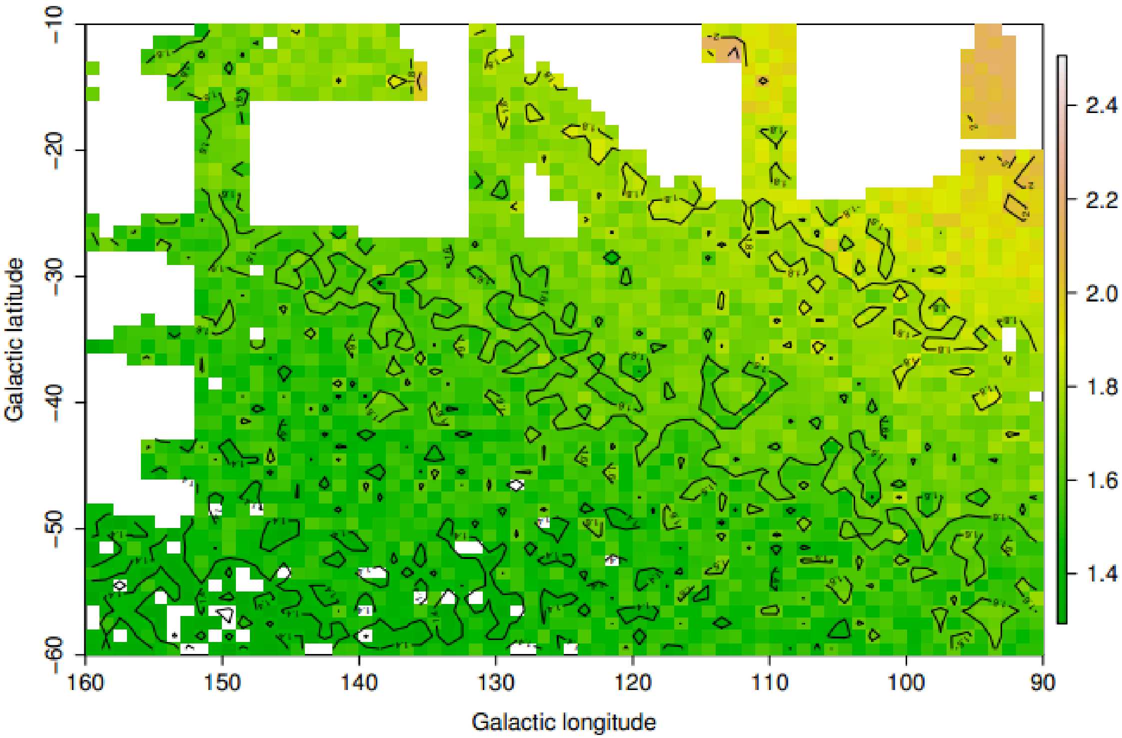
Simulation of the Galactic content in the TriAnd fields

- Since the TriAnd MS are expected to be mostly buried in the fainter magnitude range recorded by the SDSS, we need a quantitative and objective tool to validate the signal we may find. This tool should be able to tell us how a canonical Galactic CMD should look like at a particular pointing. We can obtain this description by running a Galactic population synthesis code (TRILEGAL; Girardi et al. 2005).
- 2981 subfields of 1 square deg

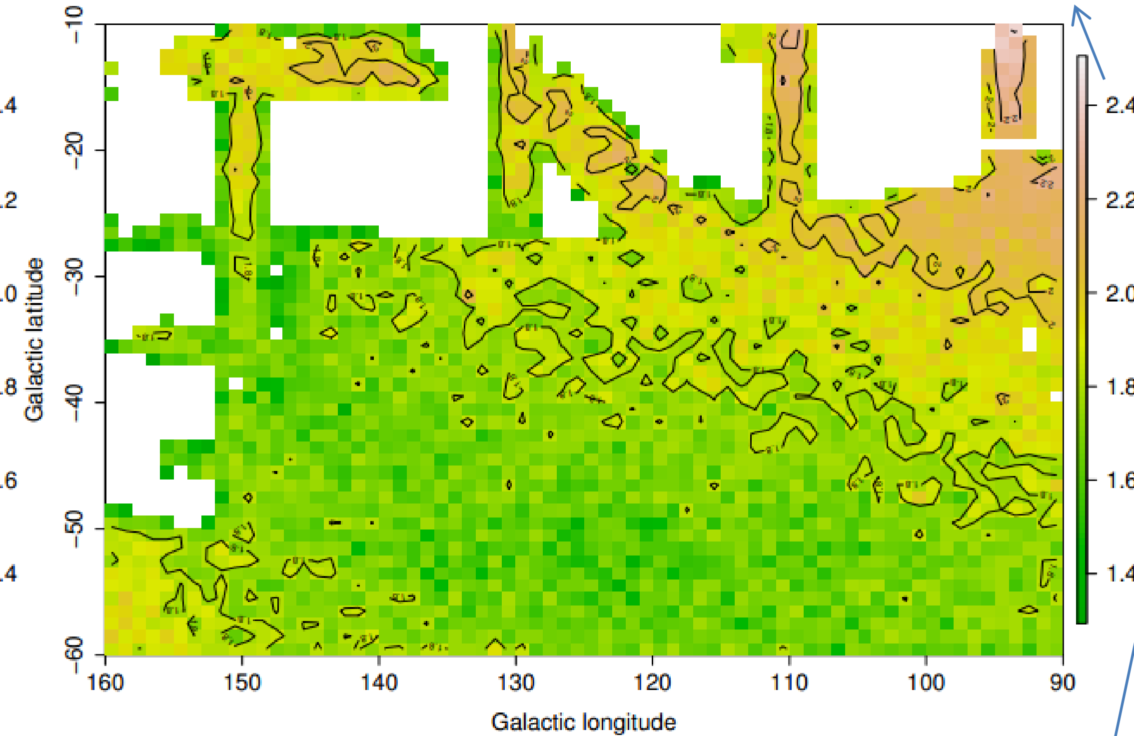
ANALYSIS OF STELLAR DENSITY MAPS

Cut 1A

~251 stars/deg^2



stellar density map of the simulated sample

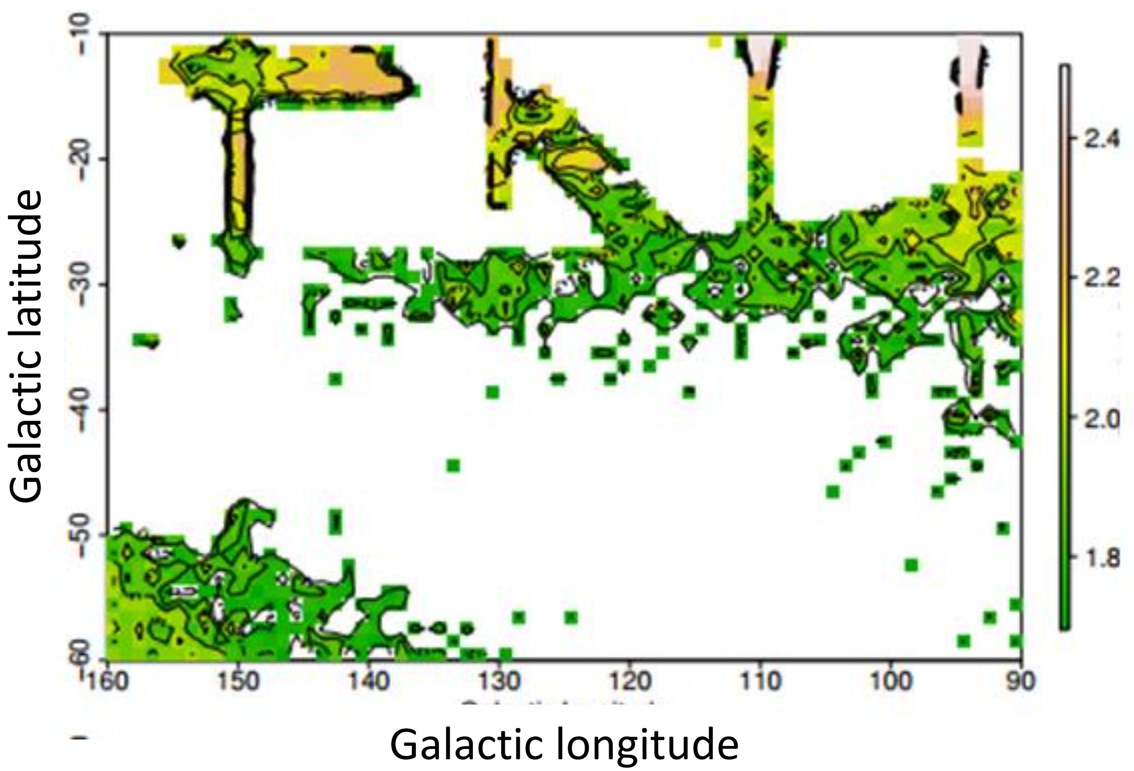


stellar density map of the observed sample

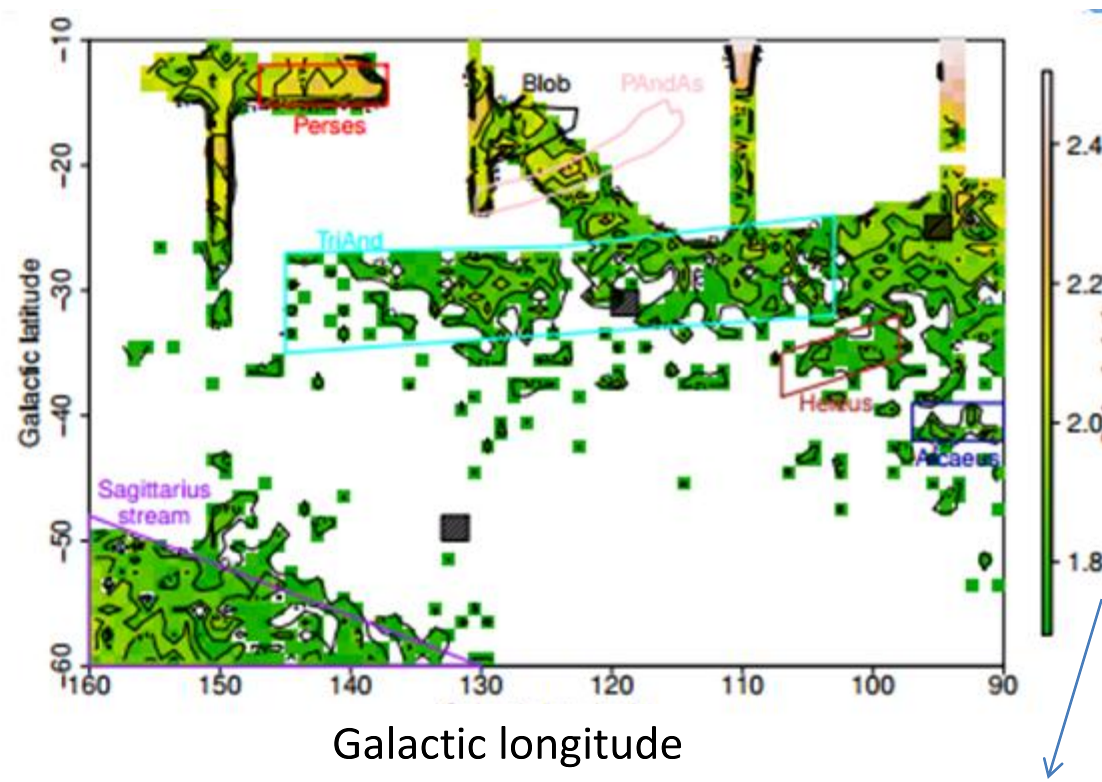
larger than $10^{1.35} \approx 22$ stars/deg^2

Residual density maps

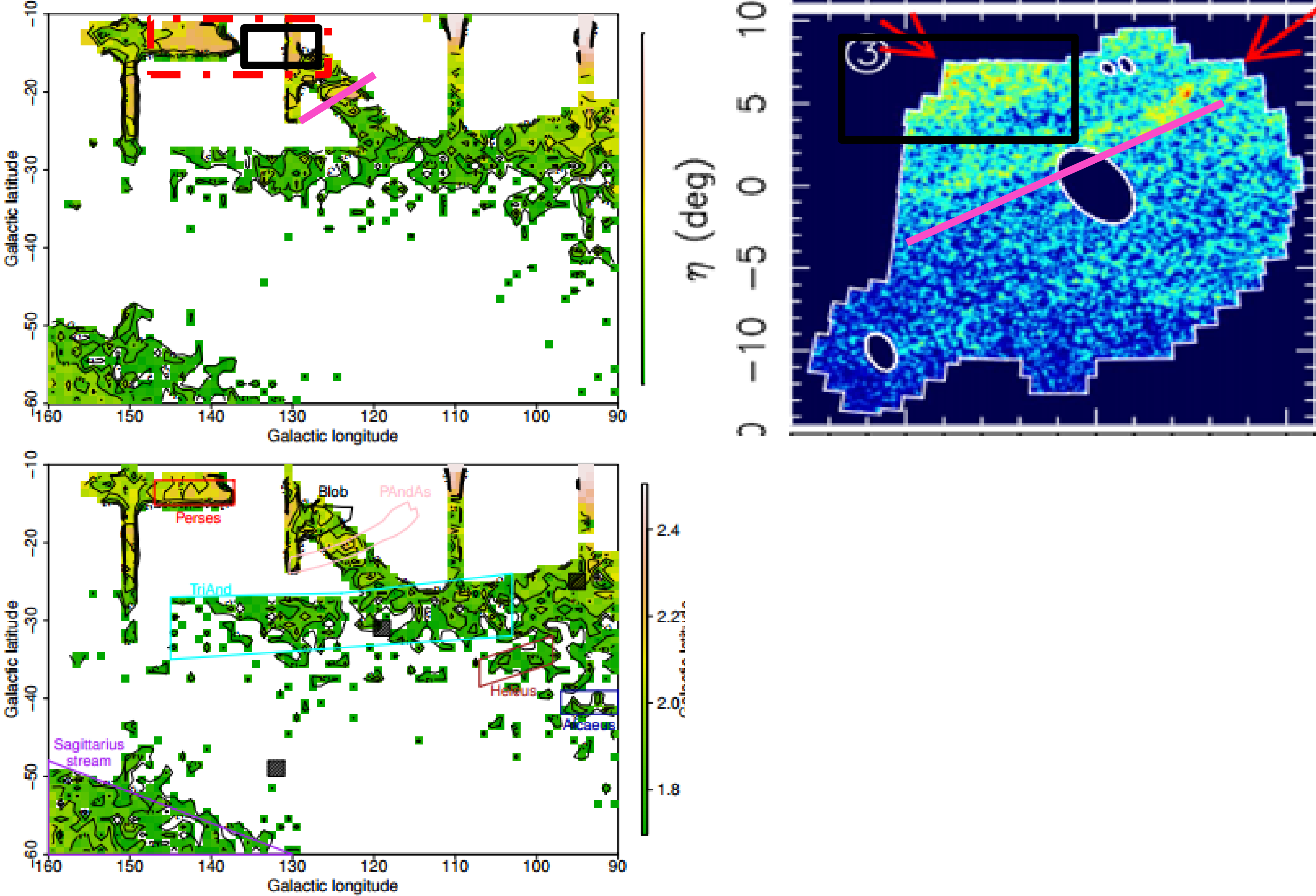
Cut 1A --- [Fe/H] = −0.46 dex, 8 Gyr and a distance module of 16.3 mag



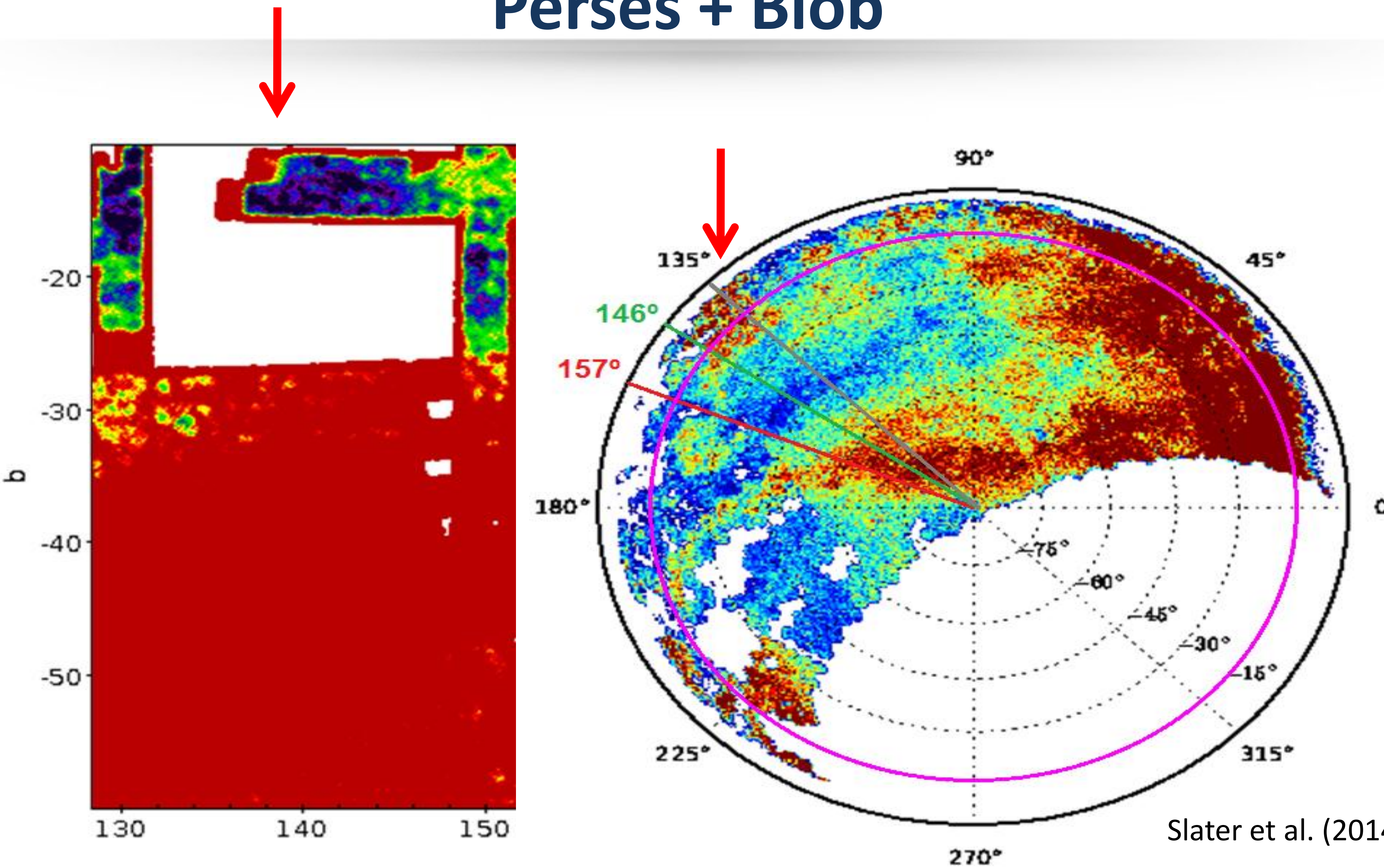
Cut 2 --- [Fe/H] = −0.7 dex, 8 Gyr and a distance module of 16.3 mag



~63 stars/deg^2

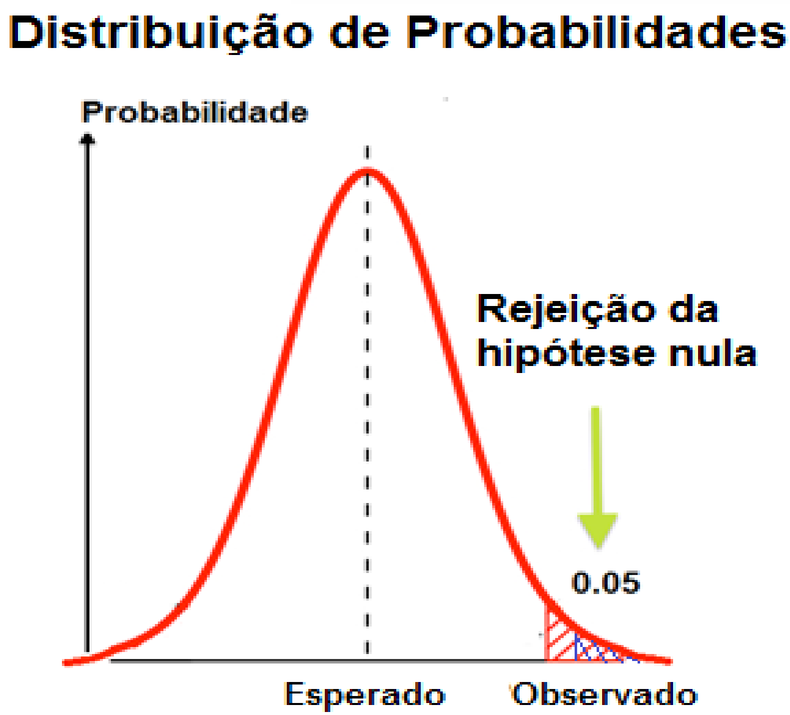

Galactic latitude
Galactic longitude
-10
-20
-30
-40
-50
-60
160
150
140
130
120
110
100
90
η (deg)
10
5
0
−5
−10
③
−10
−20
−30
−40
−50
Blob
PAndAs
Perses
TriAnd
Heleus
Alcaeus
Sagittarius
stream
2.4
2.2
2.0
1.8

Perses + Blob

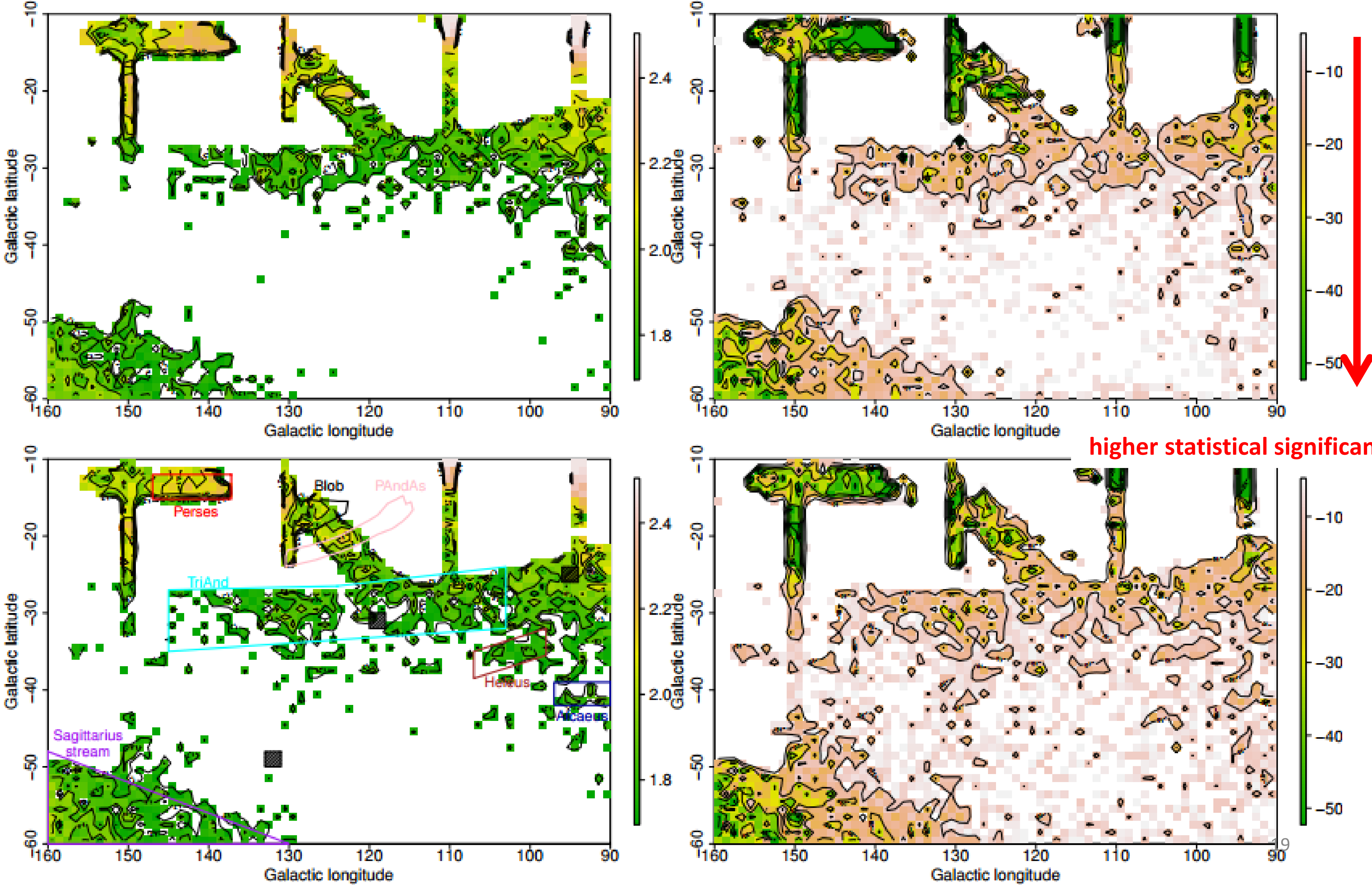


Slater et al. (2014)

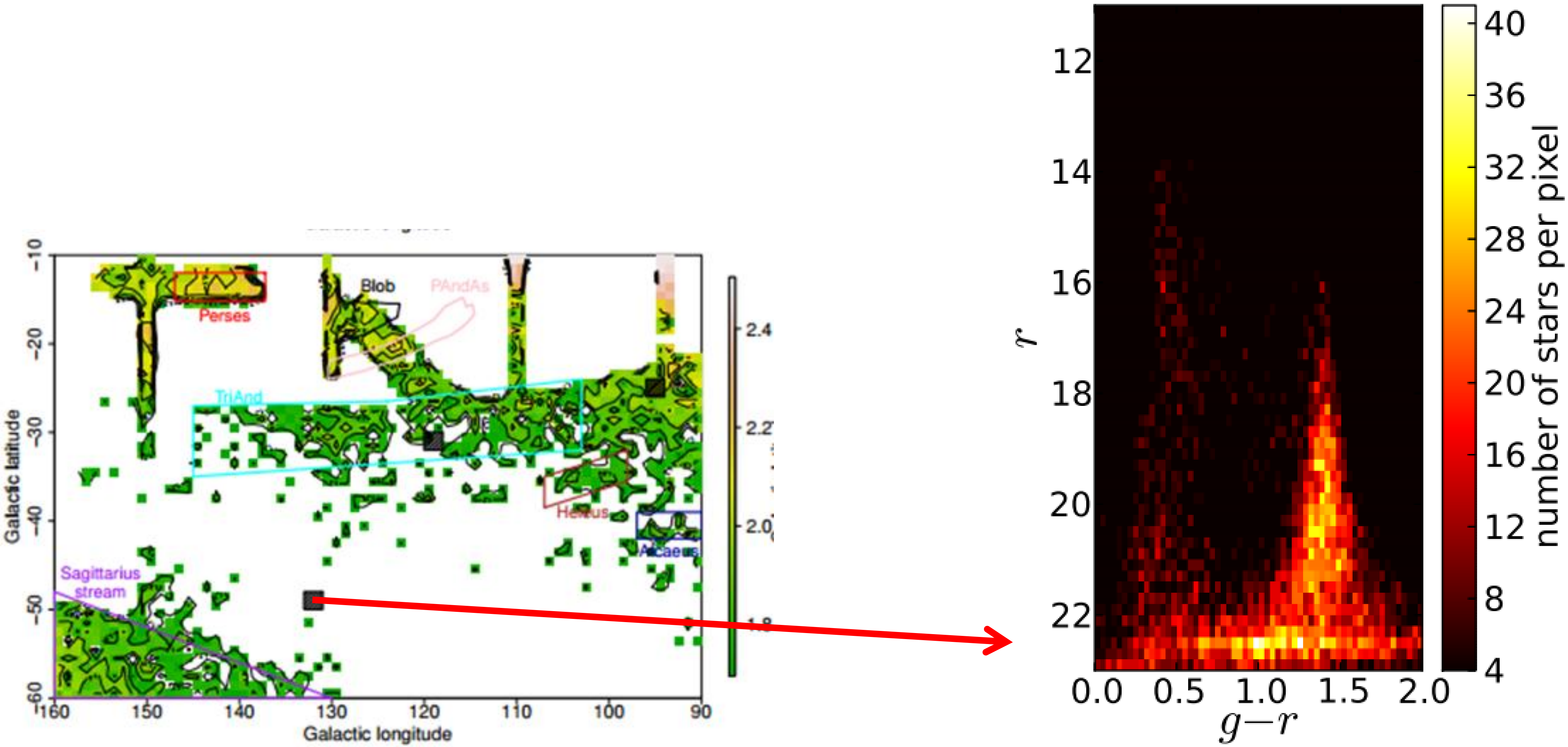
p-values



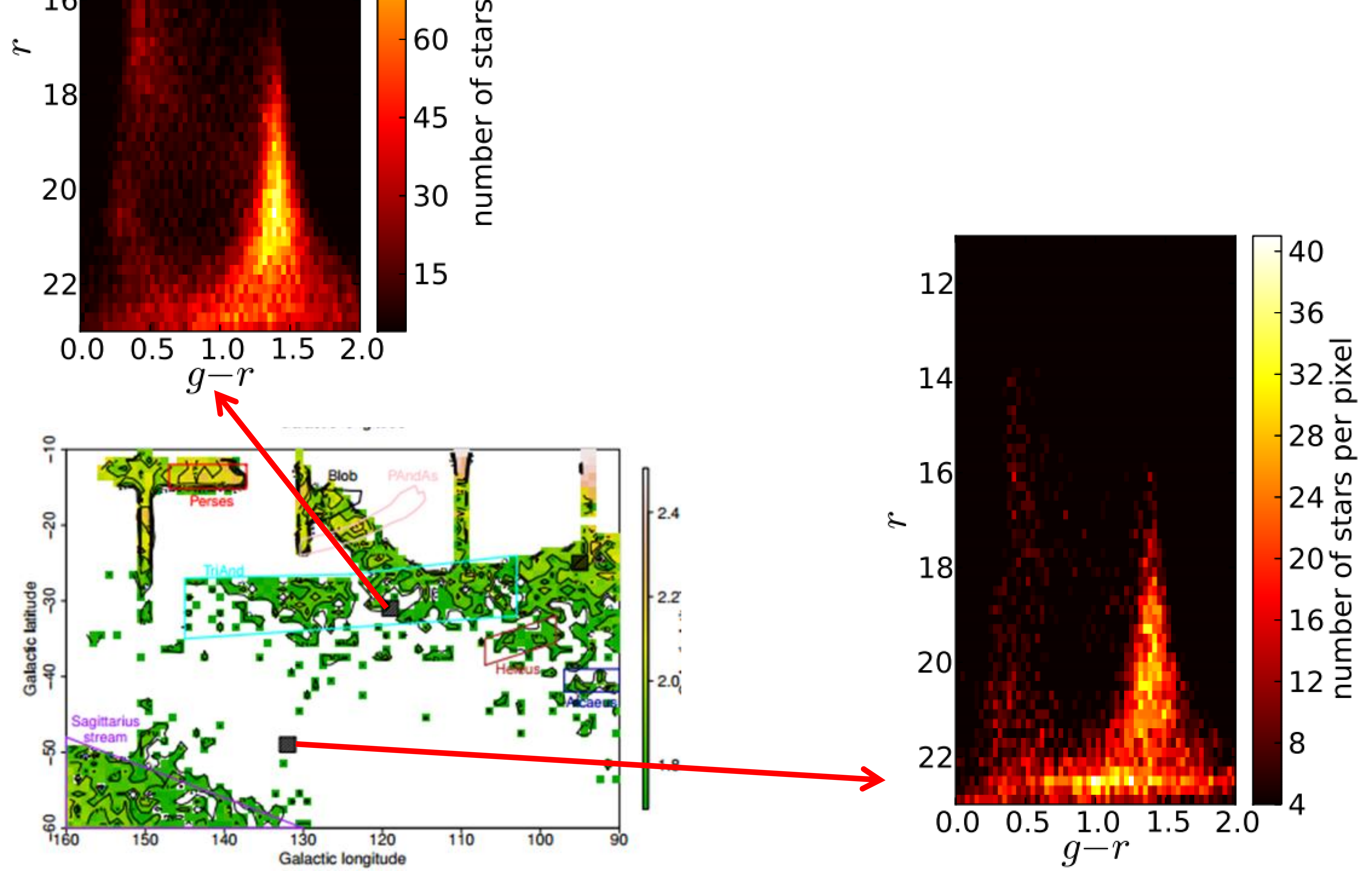
p-values lower than 0.05 are considered statistically signicant, leading to the rejection of the null hypothesis. The lower the p-value, the more unlikely is the null hypothesis; or, in other words, the higher it is the statistical signicance of the overdensity.



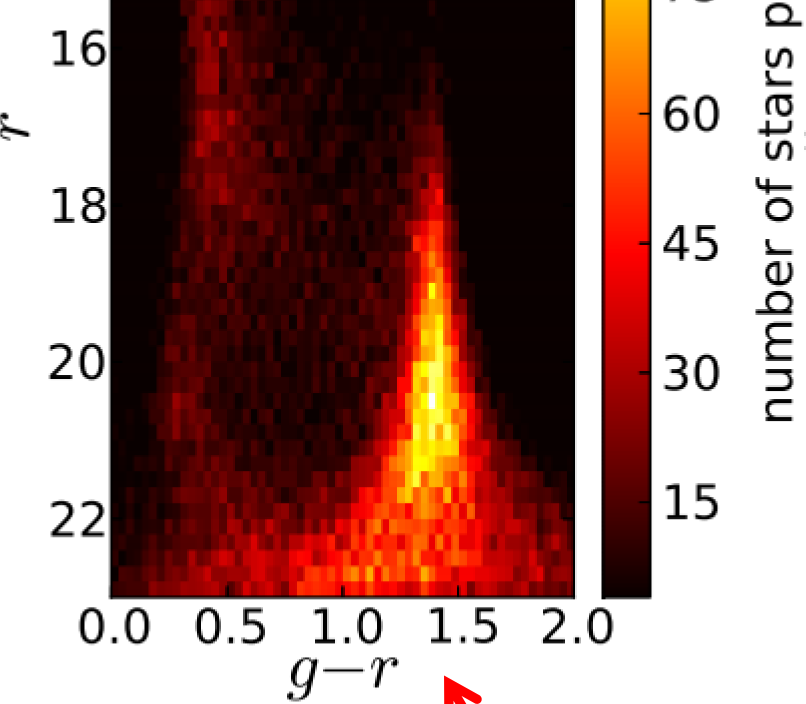
Galactic latitude
Galactic longitude
Perses
Blob
PAndAs
TriAnd
Hercules
Alcaeus
Sagittarius stream
higher statistical significan

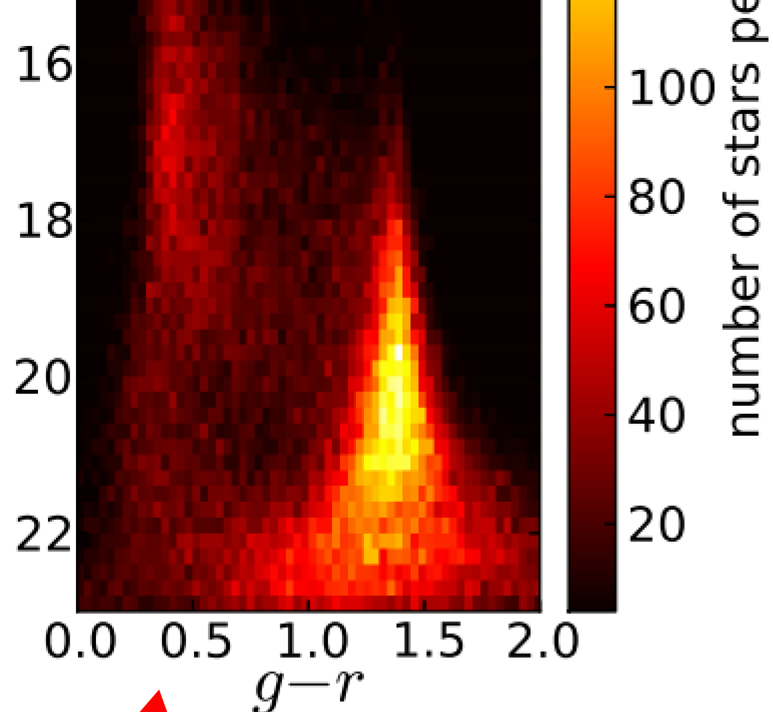


Blob
PAndAs
Perses
TriAnd
Alcaeus
Sagittarius stream
Galactic latitude
Galactic longitude
-10
-20
-30
-40
-50
-60
160
150
140
130
120
110
100
90
2.4
2.0
r
g−r
number of stars per pixel
12
14
16
18
20
22
0.0
0.5
1.0
1.5
2.0
40
36
32
28
24
20
16
12
8
4



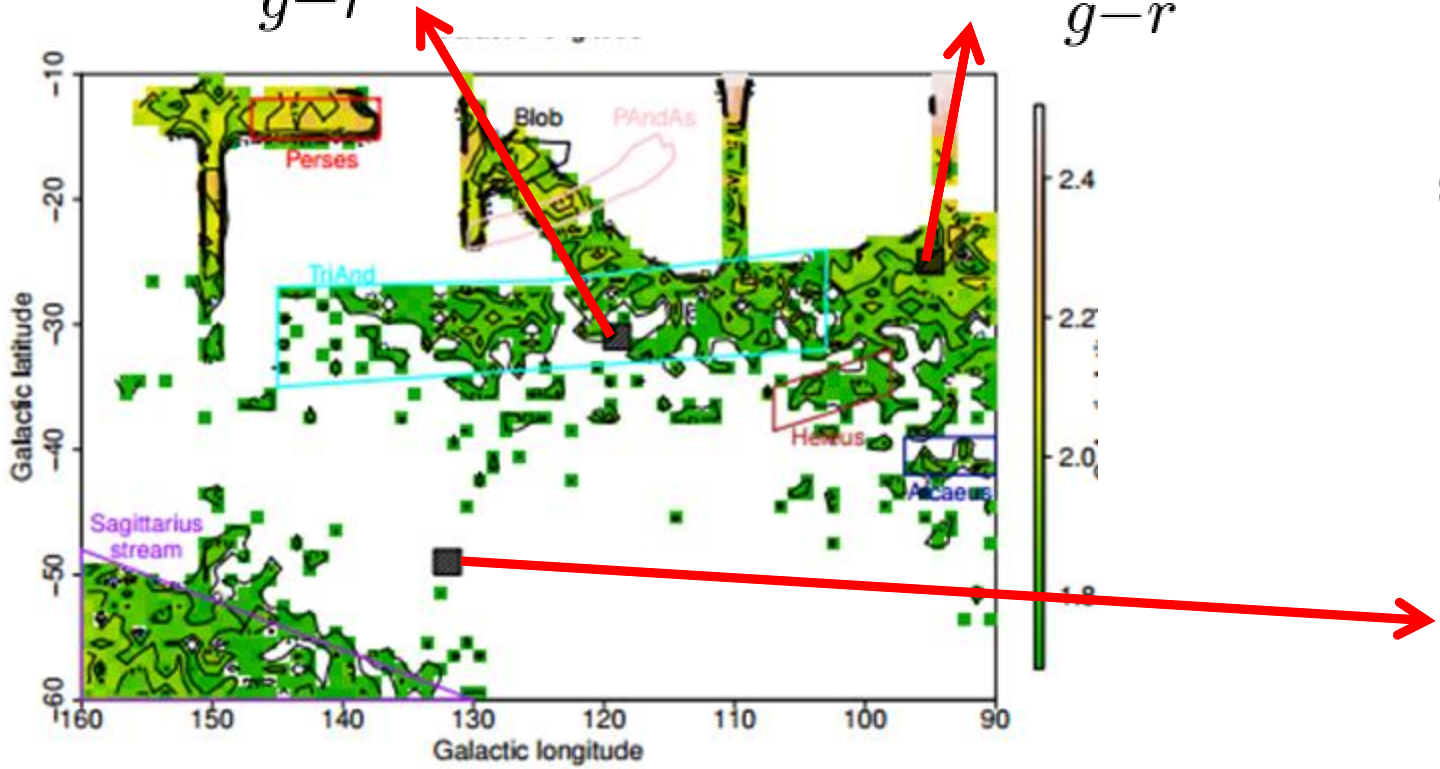
r
18
20
22
0.0 0.5 1.0 1.5 2.0
g−r
60
45
30
15
number of stars
Blob
PAndAs
Perses
TriAnd
Hercus
Alcaeus
Sagittarius
stream
Galactic latitude
Galactic longitude
−10
−20
−30
−40
−50
−60
160 150 140 130 120 110 100 90
2.4
2.2
2.0
12
14
16
18
20
22
r
0.0 0.5 1.0 1.5 2.0
g−r
40
36
32
28
24
20
16
12
8
4
number of stars per pixel

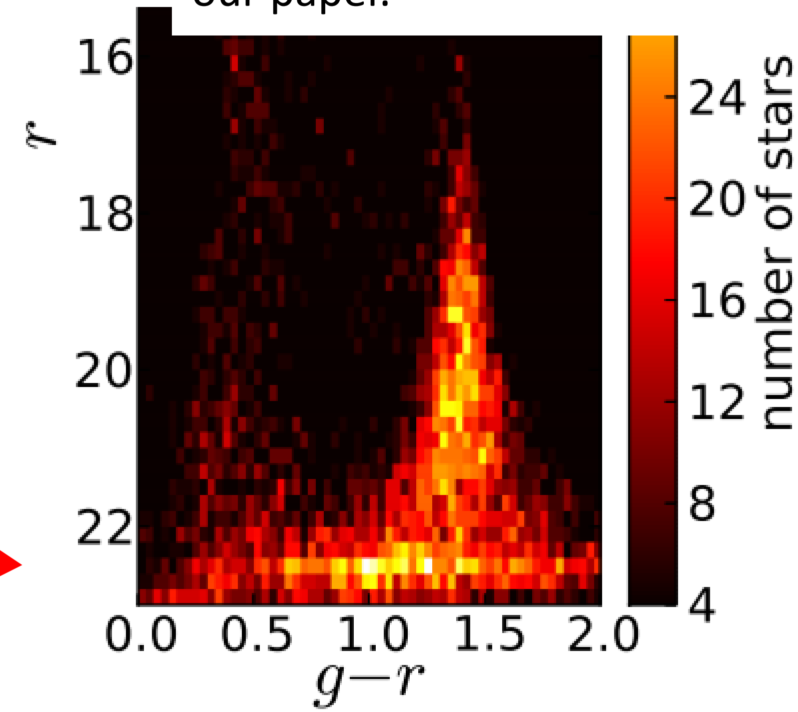




we can see a large number of blue faint stars that may be associated with one or more populations distributed over a large distance range. This feature resembles a stellar MS covering a
broader range of distances.

it is a large scale Galactic asymmetry, and finding its cause is beyond the scope of our paper.

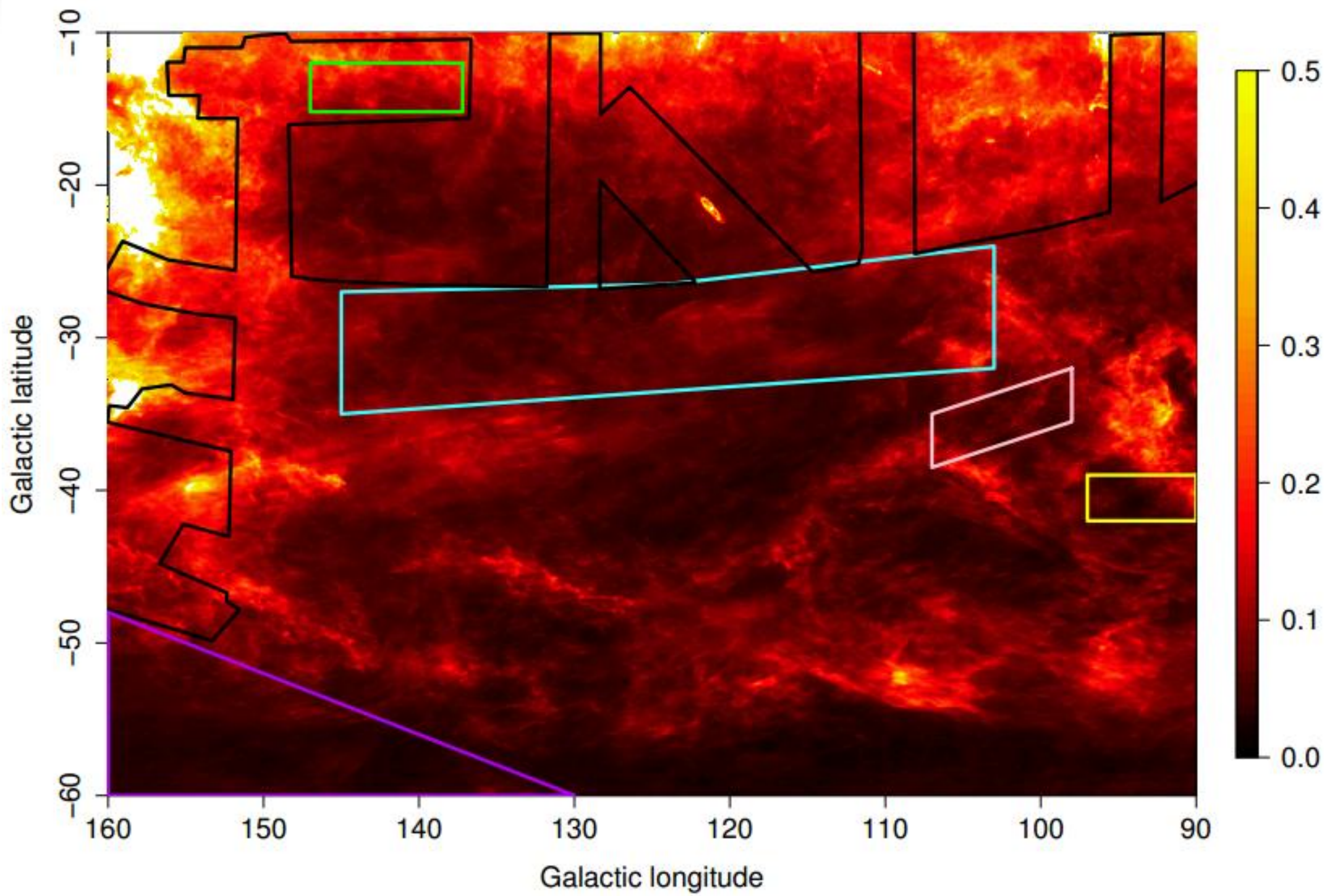




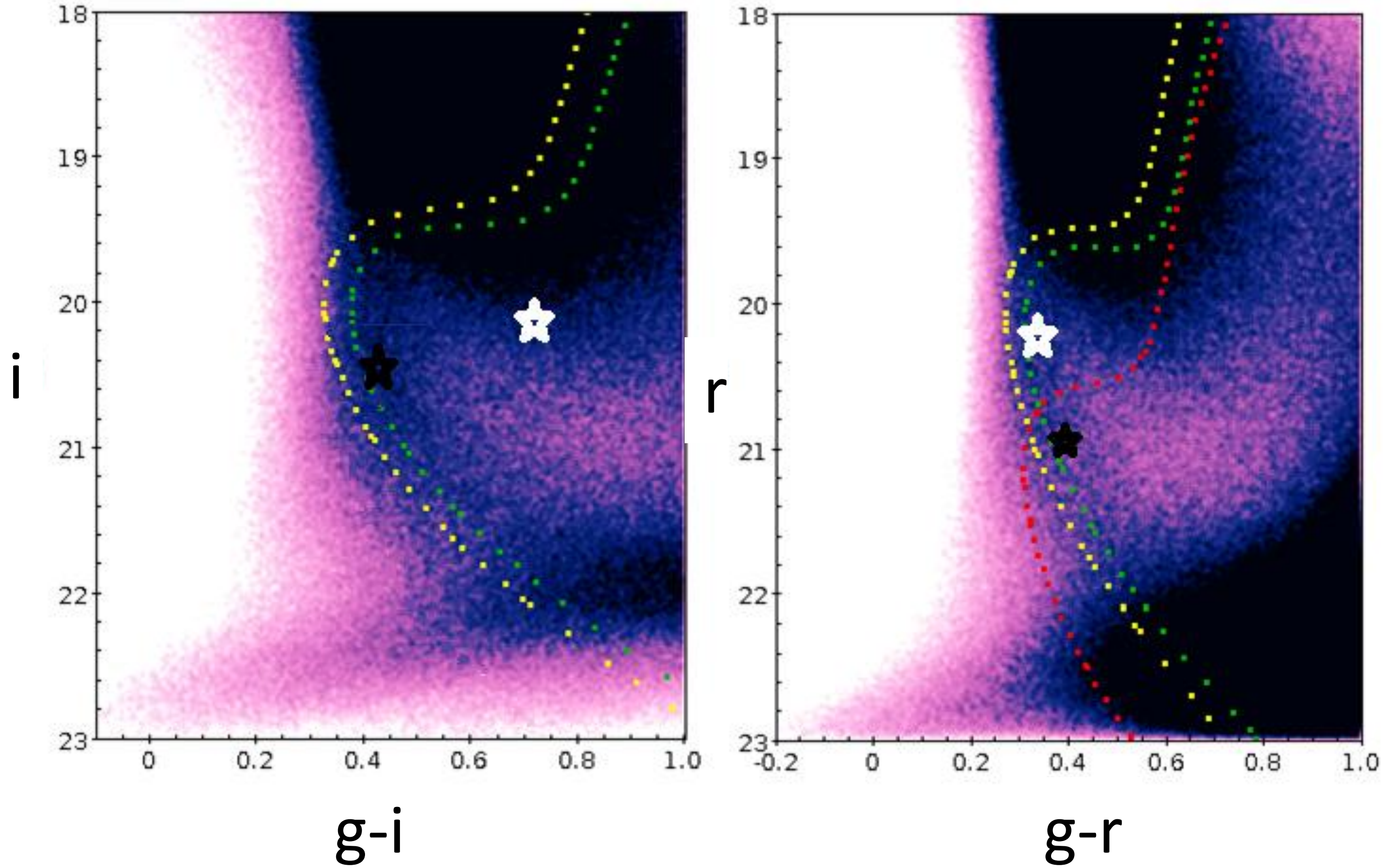
Map of the distribution of the Galactic reddening

Amôres & Lépine (2005) indicated that values of E(B− V) > 0.5 are overestimated by the method adopted by Schlegel et al. (1998) to obtain the maps of E(B − V).

To avoid problems subfields having average E(B − V) > 0.3 were discarded from our analysis.

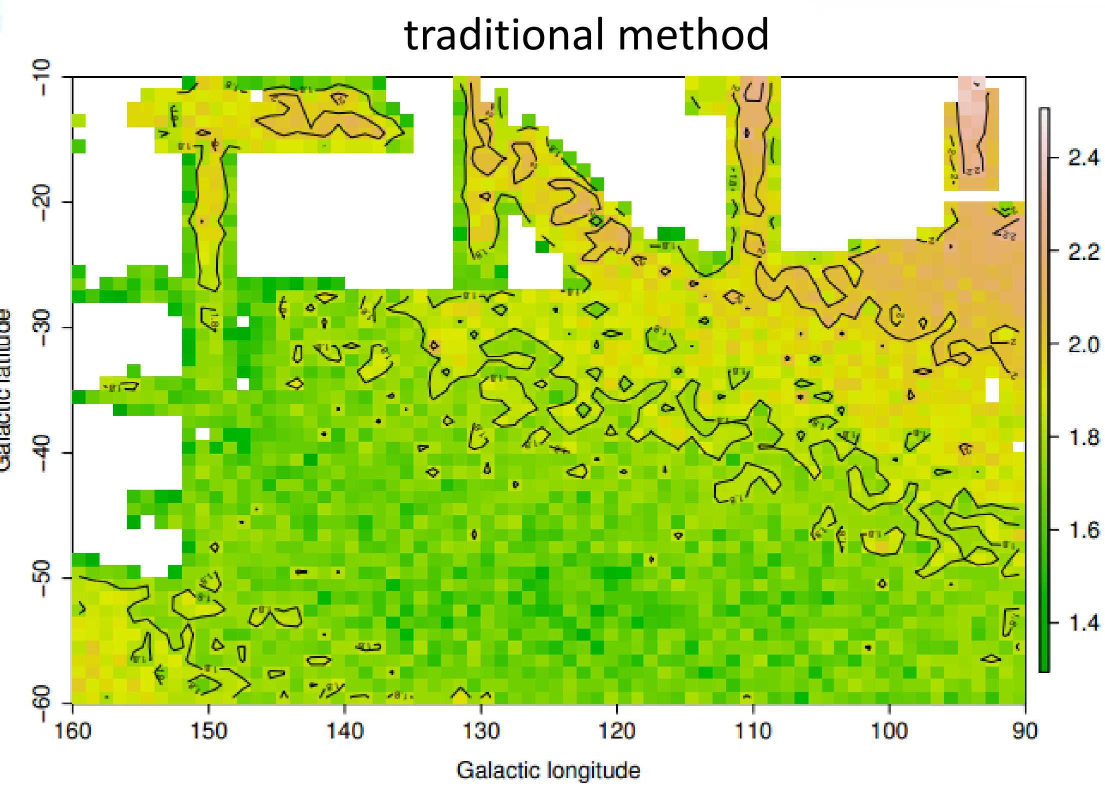


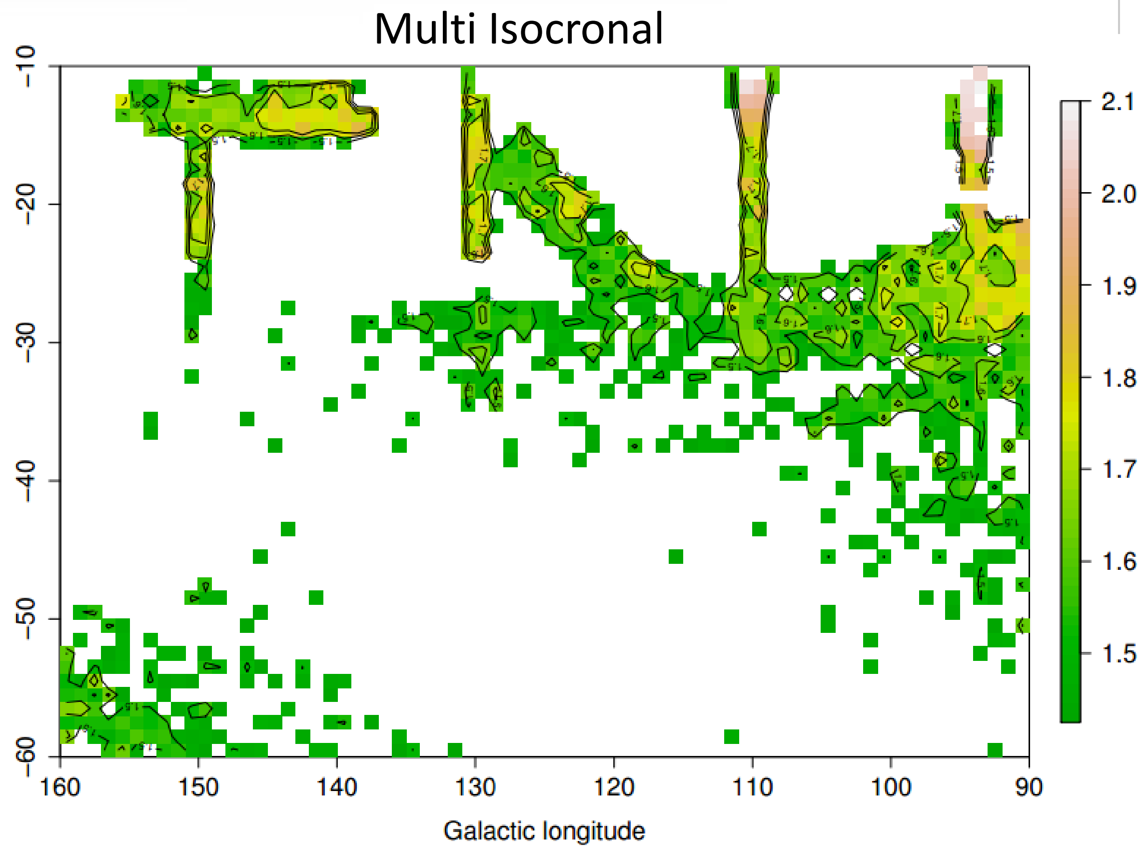
Multi Isochronal Selection



CMDs: (g - i) vs i and (g – r) vs r

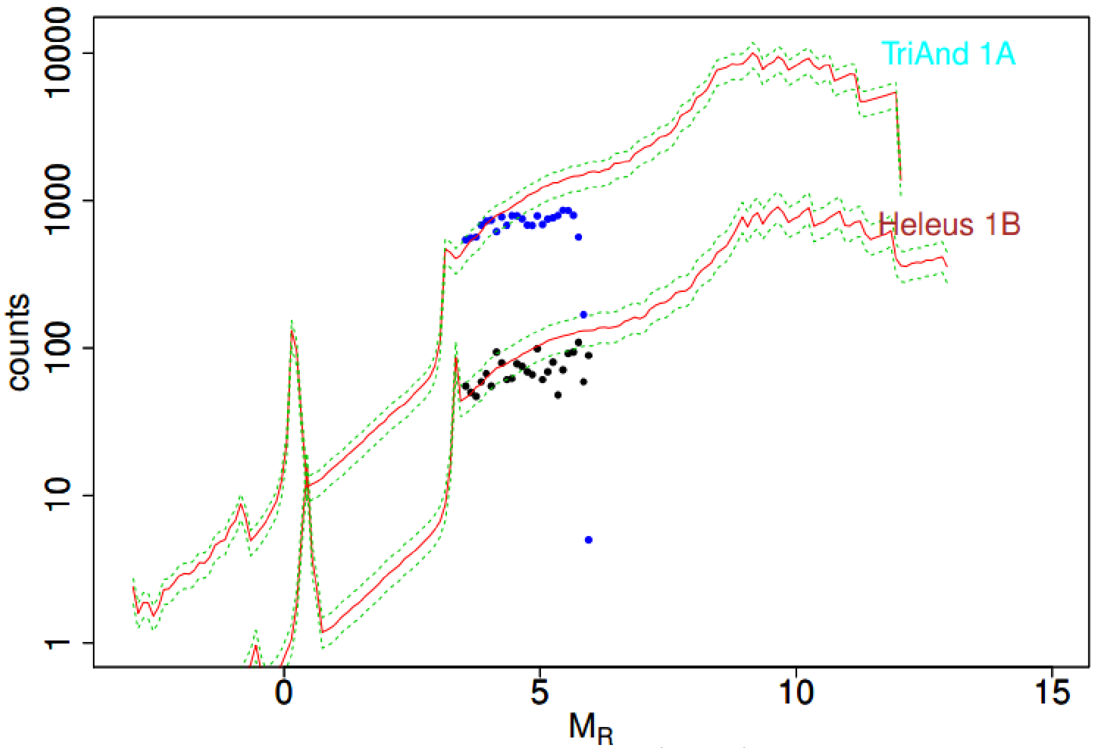
Multi Isochronal Selection





CMDs: $(g - i)$ vs i and $(g - r)$ vs r

Luminosity Function



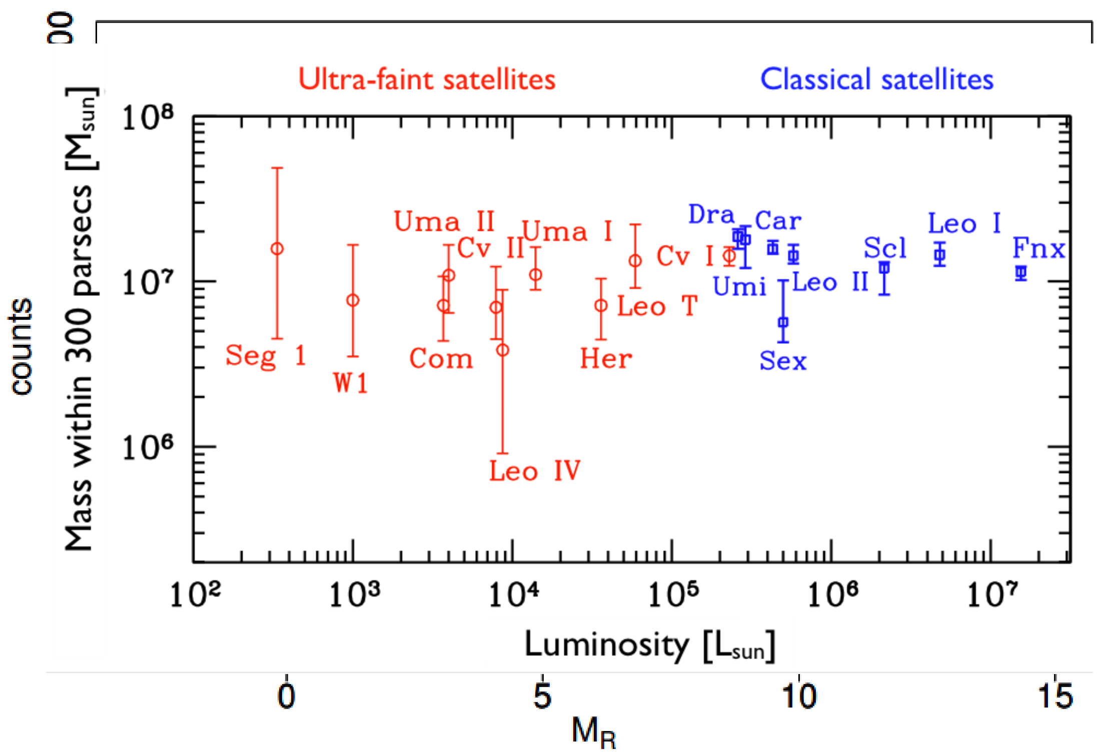
Padova luminosity functions Bressan et al. (2012)

	Band r [8 Gyr, −0.70 dex] cut 2	Band r [8 Gyr, −0.46 dex] cut 1B	Band i [8 Gyr, −0.46 dex] cut 1A
TriAnd	$1.1^{+0.3}_{-0.2} \times 10^5 L_\odot$	-	$1.1^{+0.2}_{-0.2} \times 10^5 L_\odot$
	$1.1^{+0.3}_{-0.2} \times 10^5 M_\odot$	-	$1.2^{+0.2}_{-0.2} \times 10^5 M_\odot$
Perses	$4.2^{+0.8}_{-0.6} \times 10^4 L_\odot$	-	-
	$4.2^{+0.8}_{-0.6} \times 10^4 M_\odot$	-	-
Heleus	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$
	$1.1^{+0.3}_{-0.3} \times 10^4 M_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 M_\odot$	$1.0^{+0.3}_{-0.3} \times 10^4 M_\odot$
Alcaeus	$6.2^{+1.4}_{-1.2} \times 10^3 L_\odot$	$6.3^{+1.5}_{-1.3} \times 10^3 L_\odot$	$6.7^{+1.9}_{-1.7} \times 10^3 L_\odot$
	$6.2^{+1.2}_{-1.1} \times 10^3 M_\odot$	$6.2^{+1.5}_{-1.2} \times 10^3 M_\odot$	$6.4^{+1.8}_{-1.7} \times 10^3 M_\odot$

(RP04, Majewski et al. 2004, Juric et al. 2008, Simion et al. 2014)

The fit of the luminosity function is made on its statistically most significant part, near the turnoff point, which is densely populated, easily identified and for which the completeness of the sample should be higher.

Luminosity Function



	Band r [8 Gyr, −0.70 dex] cut 2	[8 Gyr, −0.46 dex] cut 1B	Band i [8 Gyr, −0.46 dex] cut 1A
TriAnd	$1.1^{+0.3}_{-0.2} \times 10^5 L_\odot$	-	$1.1^{+0.2}_{-0.2} \times 10^5 L_\odot$
	$1.1^{+0.3}_{-0.2} \times 10^5 M_\odot$	-	$1.2^{+0.2}_{-0.2} \times 10^5 M_\odot$
Perses	$4.2^{+0.8}_{-0.6} \times 10^4 L_\odot$	-	-
	$4.2^{+0.8}_{-0.6} \times 10^4 M_\odot$	-	-
Heleus	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 L_\odot$
	$1.1^{+0.3}_{-0.3} \times 10^4 M_\odot$	$1.1^{+0.3}_{-0.3} \times 10^4 M_\odot$	$1.0^{+0.3}_{-0.3} \times 10^4 M_\odot$
Alcaeus	$6.2^{+1.4}_{-1.2} \times 10^3 L_\odot$	$6.3^{+1.5}_{-1.3} \times 10^3 L_\odot$	$6.7^{+1.9}_{-1.7} \times 10^3 L_\odot$
	$6.2^{+1.2}_{-1.1} \times 10^3 M_\odot$	$6.2^{+1.5}_{-1.2} \times 10^3 M_\odot$	$6.4^{+1.8}_{-1.7} \times 10^3 M_\odot$

(RP04, Majewski et al. 2004, Juric et al. 2008, Simion et al. 2014)

The fit of the luminosity function is made on its statistically most significant part, near the turnoff point, which is densely populated, easily identified and for which the completeness of the sample should be higher.

Conclusion

- The density excess identified in (l,b) ~(90°,-20°)
  - Trilegal underestimated the amount of halo stars.
  - Is it a large scale Galactic asymmetry ? (Working on it. Map to l < 90°.)
  - 2 populations? Accrection + disk?
- TriAnd
  - Our density maps suggest that TriAnd is limited to b > -35°
  - Area coverage is smaller than that of RP04
  - Luminosity is compatible with the luminosity of other satellite dwarf galaxies of the Milky Way
  - TriAnd can be compatible with the debris of multiple stellar populations.
- Heleus
  - substructure shows a stream-like shape.
  - A chemokinematical analysis is needed to identify whether Heleus is part of TriAnd or not. (Fail)
  - A deep photometric data is needed to study the excess. (Proposal accept MegaCam)

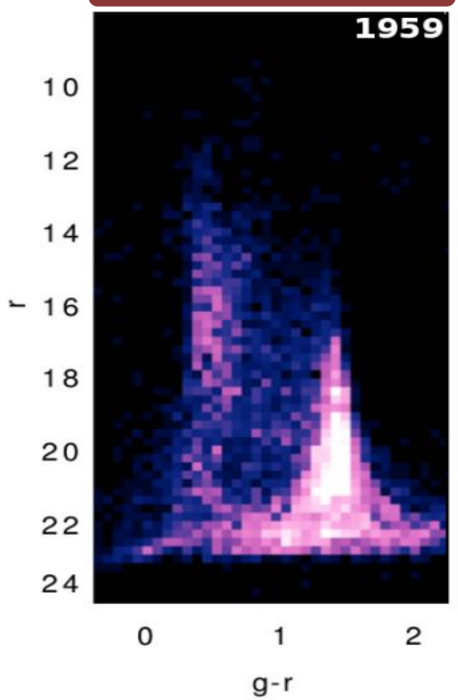
Conclusion

- Perses
  - Are “Blob”(Martin et al. 2014) and Perses connected? (Proposal accept MegaCam)
  - We could only fit a luminosity function to this overdensity using the CMD cut 2, which represents a slightly more metal-poor main sequence.
- Alcaeus
  - A deep photometric data is needed to study the excess. (Proposal accept MegaCam)
  - Is it limited to l > 90°? ((Working on it. Map to l < 90°.)
- This plethora of stellar excesses may be indicative that the main sequence identified by Majewski et al. (2004) and Martin et al. (2007) in the CMD as belonging to TriAnd can be compatible with the debris of multiple stellar populations. In this sense, the large dispersion in the metallicity of TriAnd (e.g. Deason et al. 2014) indicates that TriAnd may have more than one progenitor.

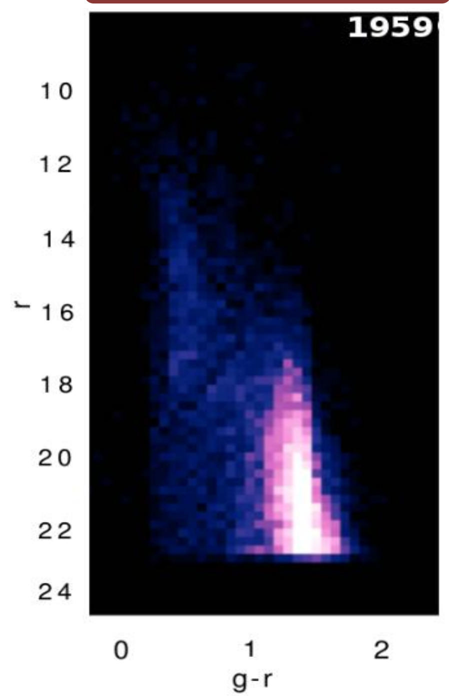
Simulation of the Galactic content in the TriAnd fields II

- The average photometric errors observed in each of the 2981 subfields were parameterized by an exponential function
- The magnitude value m for each pseudo star originally simulated by TRILEGAL was replaced by m+δσ(m), where σ(m) is given by Equation 1 and δ is a random gaussian deviation: δ ~ N (0, 1). That is, we assign to the simulated magnitude a random shift based on the expected photometric errors in the observations

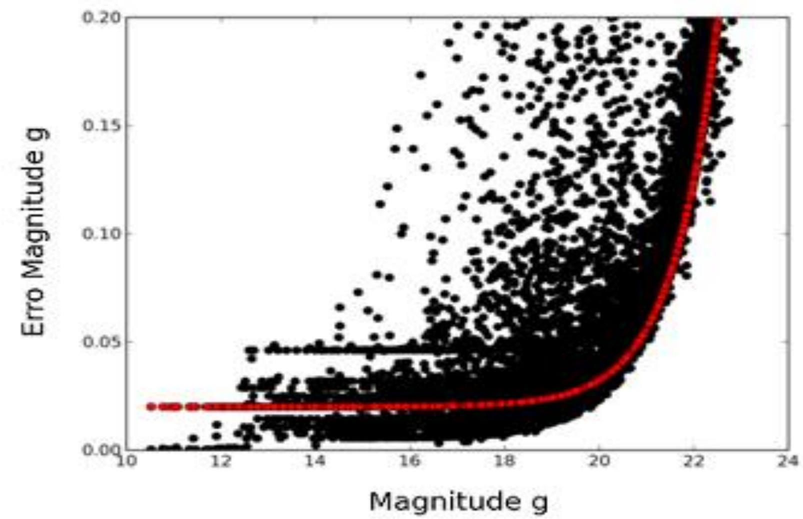
Observed



Simulated



Ajuste do Erro da Magnitude



Overdensities and clouds in the galactic halo

- Monoceros + Canis Major and Argo
- Virgo Overdensity (Newberg et al., 2002; Juric et al. 2008),
- Triangulum-Andromeda (TriAnd; Rocha-Pinto et al. 2004, hereafter RP04; Majewski et al. 2004),
- Anticenter Stream (Grillmair 2006),
- Hercules-Aquila (Belokurov et al. 2007),
- Pisces (Sesar et al. 2007; Watkins et al. 2009).

Belokurov et al (2006)