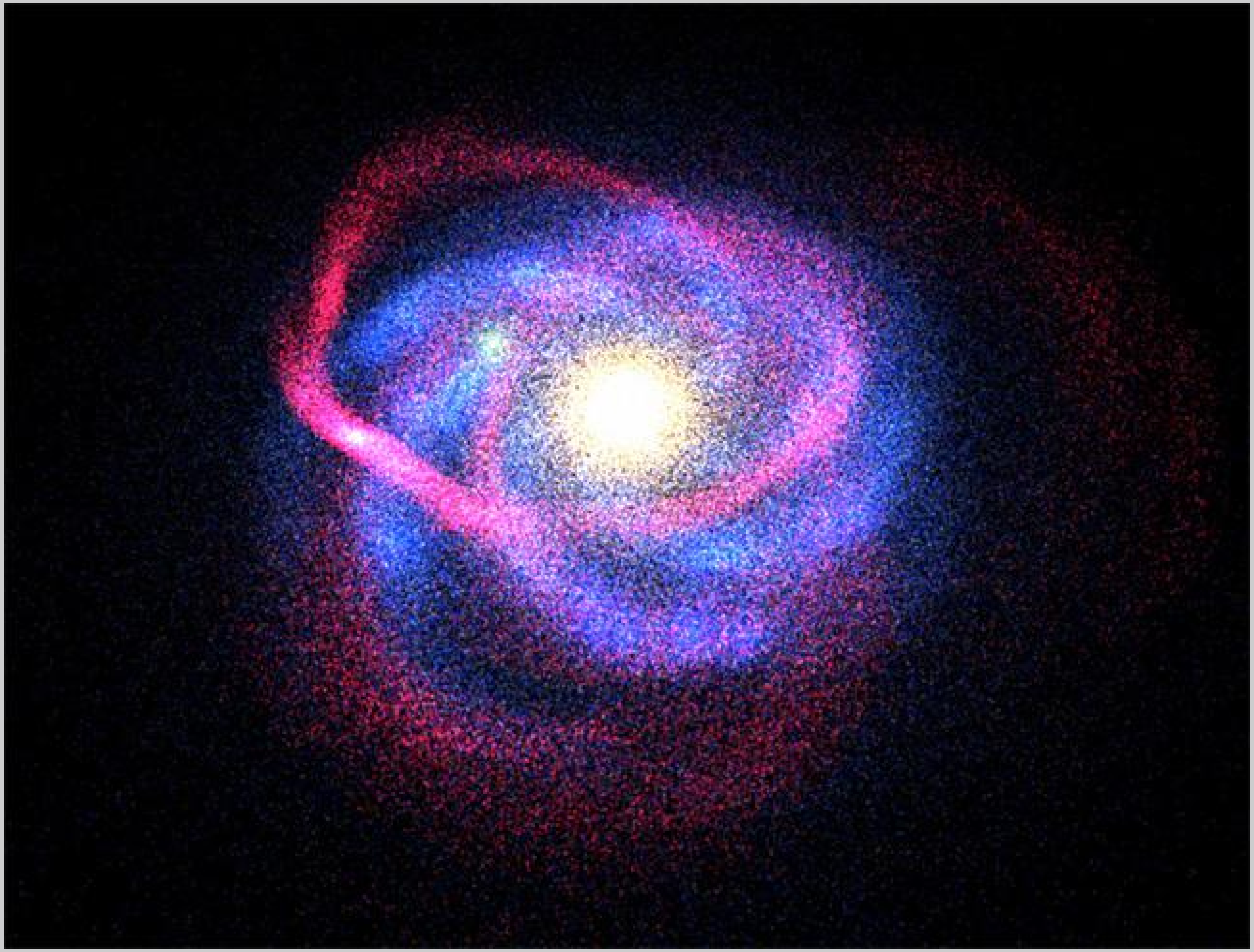
Quantitative maps of stellar substructures in the Milky Way



Jelte de Jong (MPIA, Heidelberg)

H.-W. Rix, N. F. Martin, E. F. Bell, B. Yanny, A. E. Dolphin, D. B Zucker, D. Butler

Outline

- Introduction to color-magnitude diagram fitting with MATCH
- Properties of bound structures in the Milky Way halo
- Stellar substructure in the disk: the Canis Major overdensity
- A new sparse map of the outer disk of the Milky Way
- Constraining the Monoceros stream

Introduction to MATCH

Color-magnitude diagrams (CMDs) of stellar populations contain information on the properties of these populations: age, metallicity, distance, foreground extinction

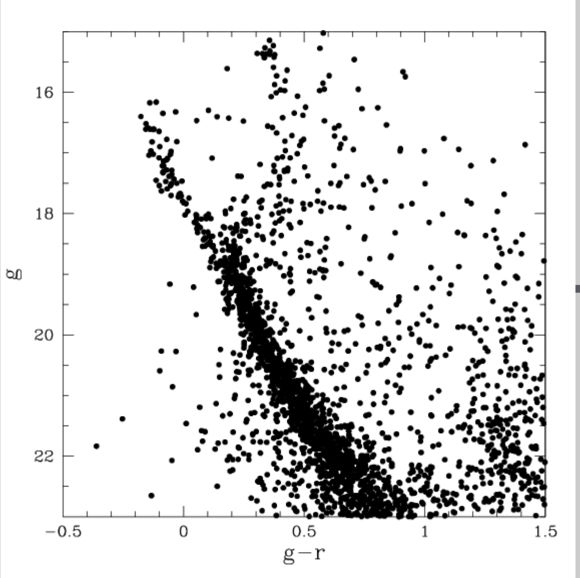
Modeling of CMDs using theoretical templates provides an *algorithmic, quantitative analysis* that utilizes information from the whole color-magnitude space

We use MATCH (Dolphin 1997, 2001) to do CMD fitting

Introduction to MATCH

The 'classical' way of CMD fitting:

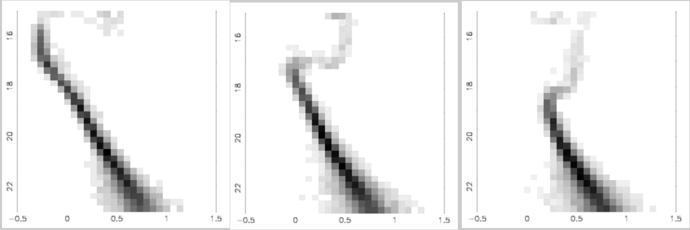
Observed GC/dGal



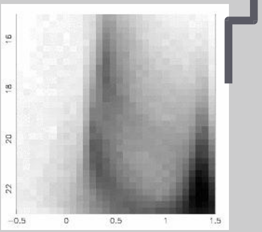
MATCH

maximum-likelihood method to determine linear combination of model populations that best represents an observed CMD

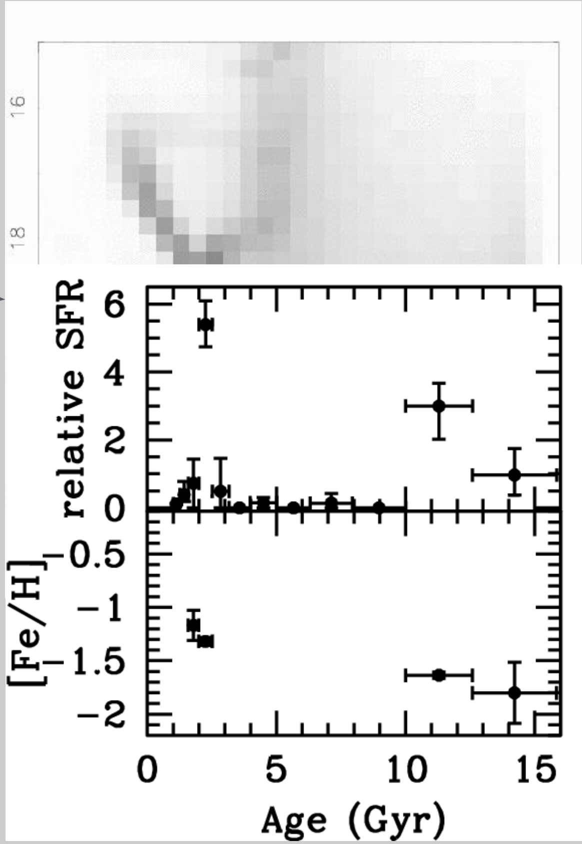
Error-convolved theor. models



Control



Best-fit model



SFH and AMR

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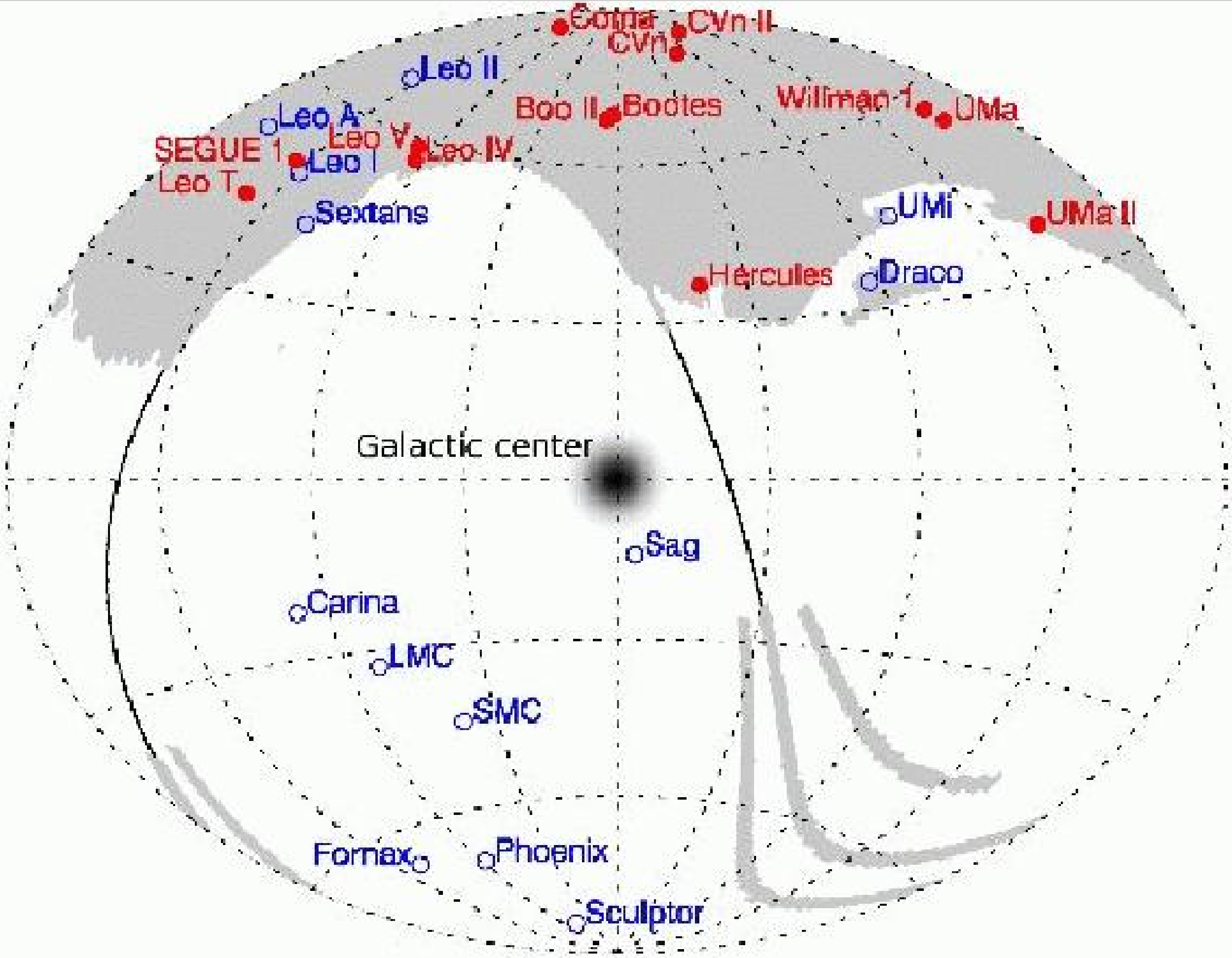
Properties of bound structures in the Milky Way halo

Over the past 3 years, ~13 new Milky Way satellites discovered in SDSS data

Use CMD fitting to constrain their population properties

Based on SDSS data, to obtain *uniform analysis*



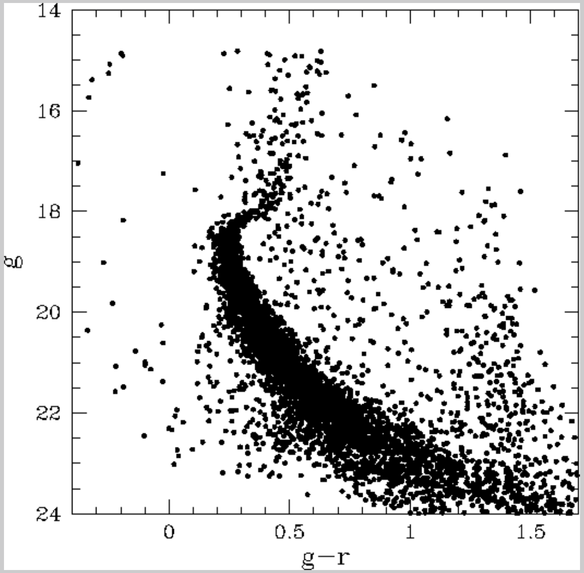
(Walsh et al. 2008)

Properties of bound structures in the Milky Way halo

BUT: new dwarfs are distant and/or ultra-faint!

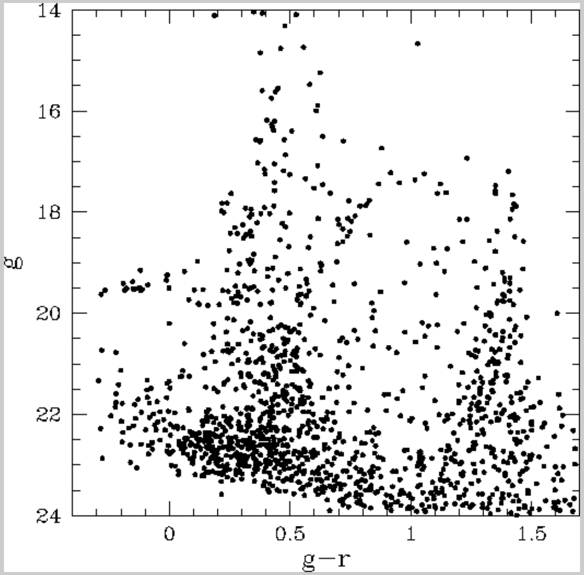
High S/N CMD

M13 (SDSS)

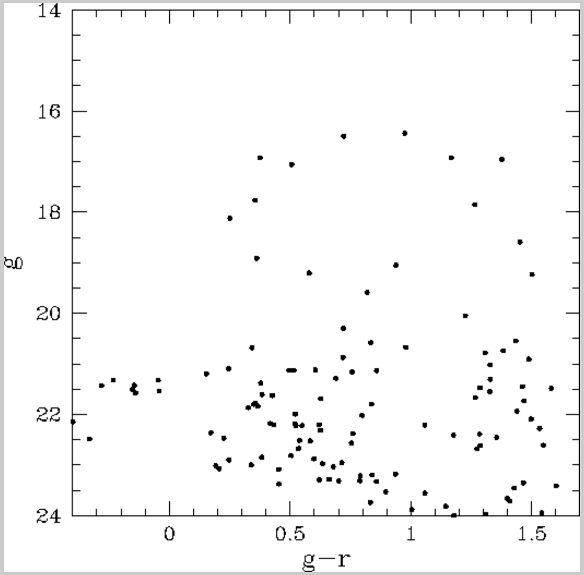


Low S/N CMD

Boötes I (SDSS)



Leo IV (SDSS)

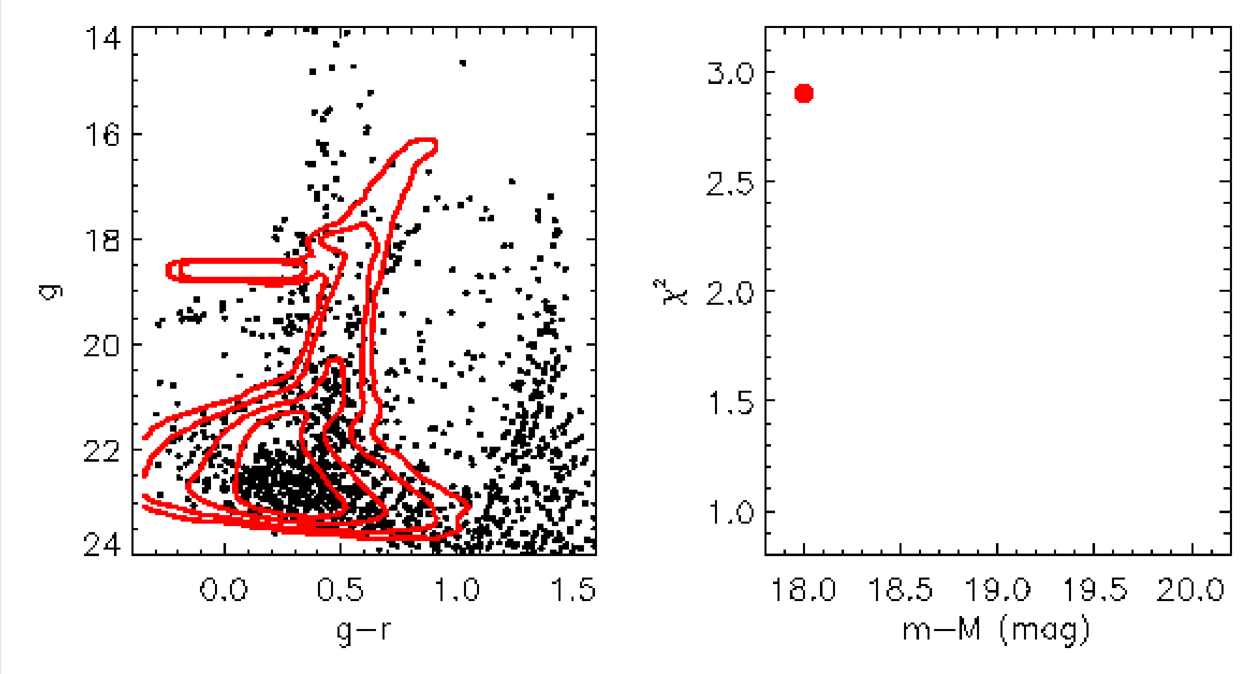


Properties of bound structures in the Milky Way halo

Single component (SC) fits: determine goodness-of-fit for individual population models with fixed age, metallicity, distance

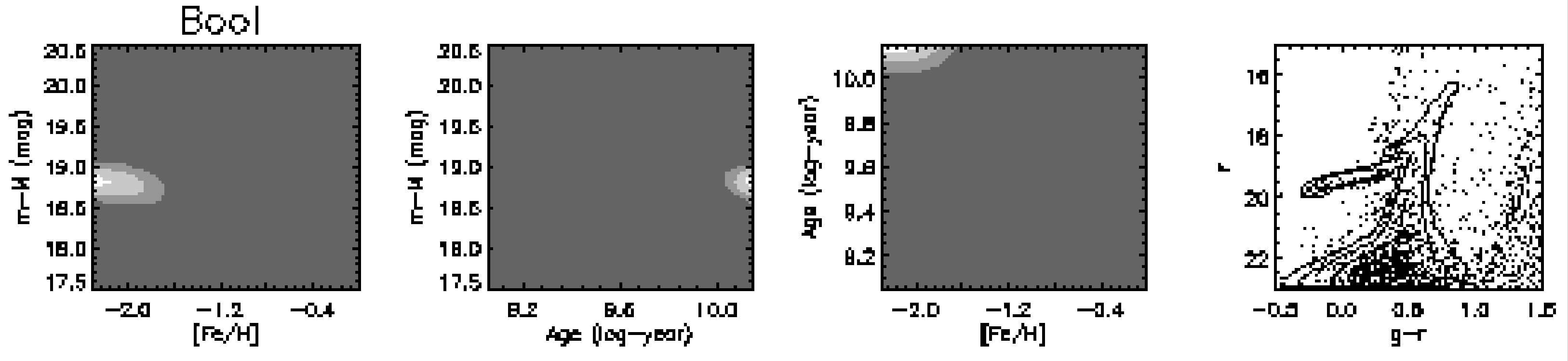
Determine combination of parameters that best describes the *dominant* stellar population

Example:
varying distance

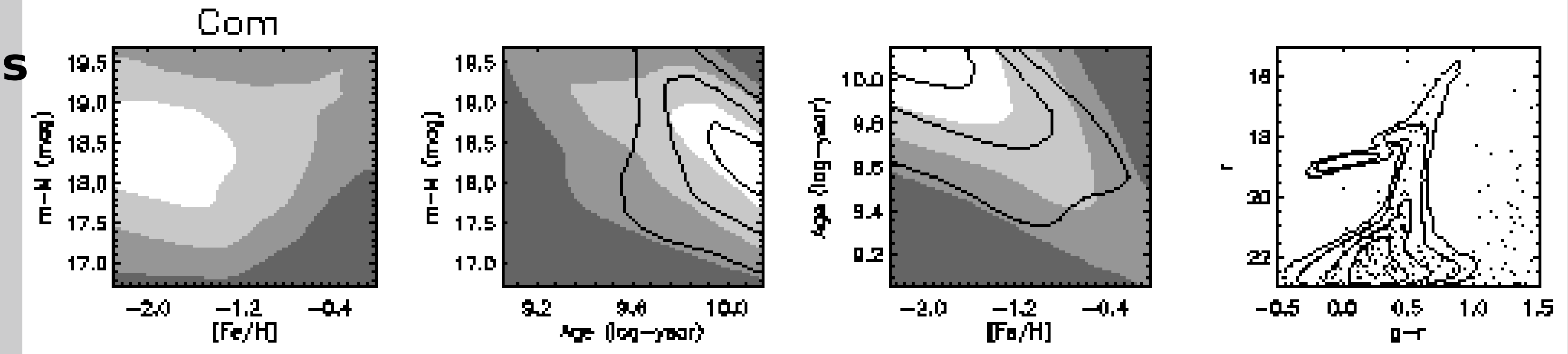


Properties of bound structures in the Milky Way halo

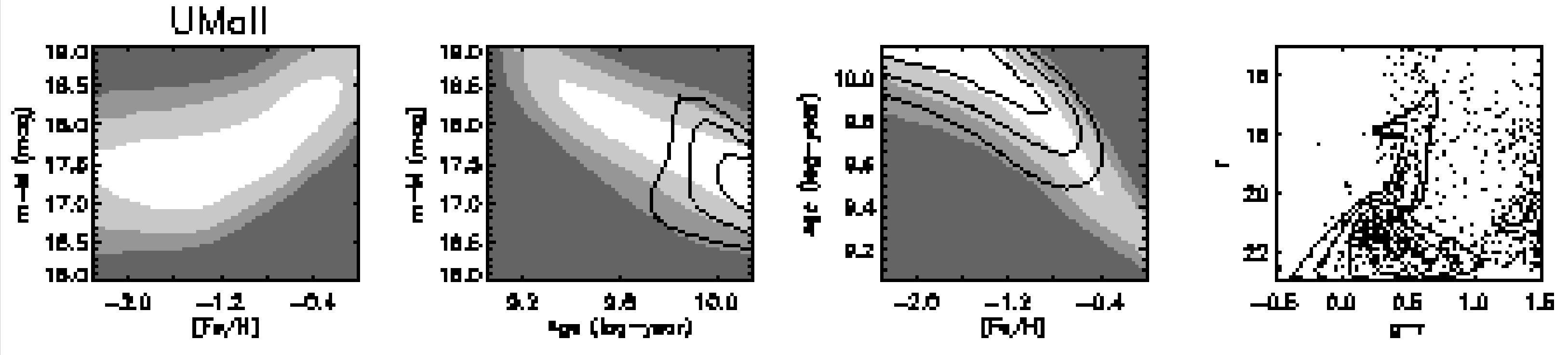
Boötes I
m-M=18.8±0.2
Age=14±2 Gyr
Fe/H=-2.2±0.2



Coma Berenices
m-M=18.4±0.4
Age=11±5 Gyr
Fe/H=-1.9±0.4



Ursa Major II
Age=11±4 Gyr
Fe/H=-1.5±0.5



(JdJ et al. 2008)

Properties of bound structures in the Milky Way halo

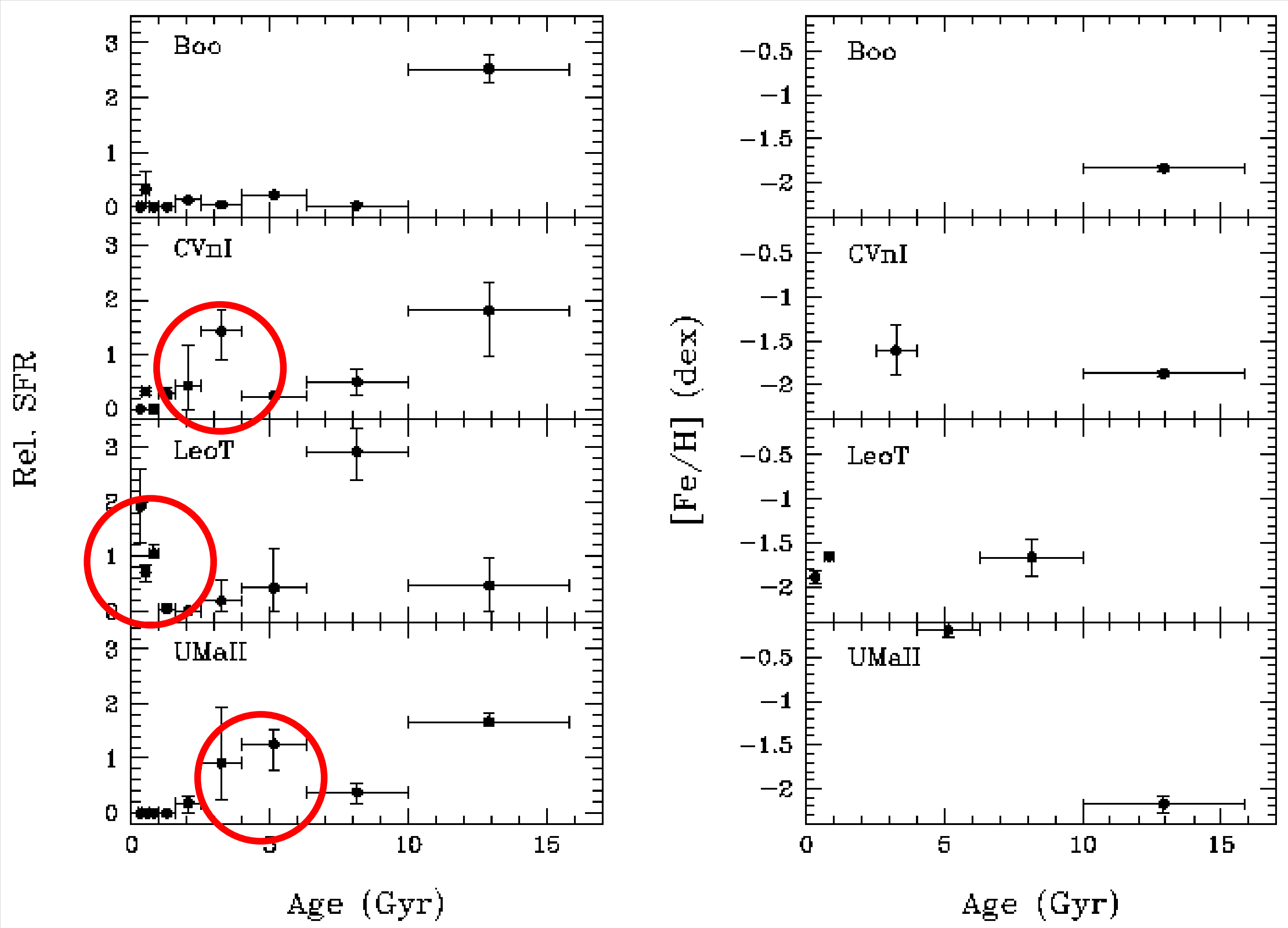
Full star formation histories for Boo I, UMa II, Leo T and CVn I

Boo I

CVn I

Leo T

UMa II



(JdJ et al. 2008)

Properties of bound structures in the Milky Way halo

All results conveniently summarized in the paper:

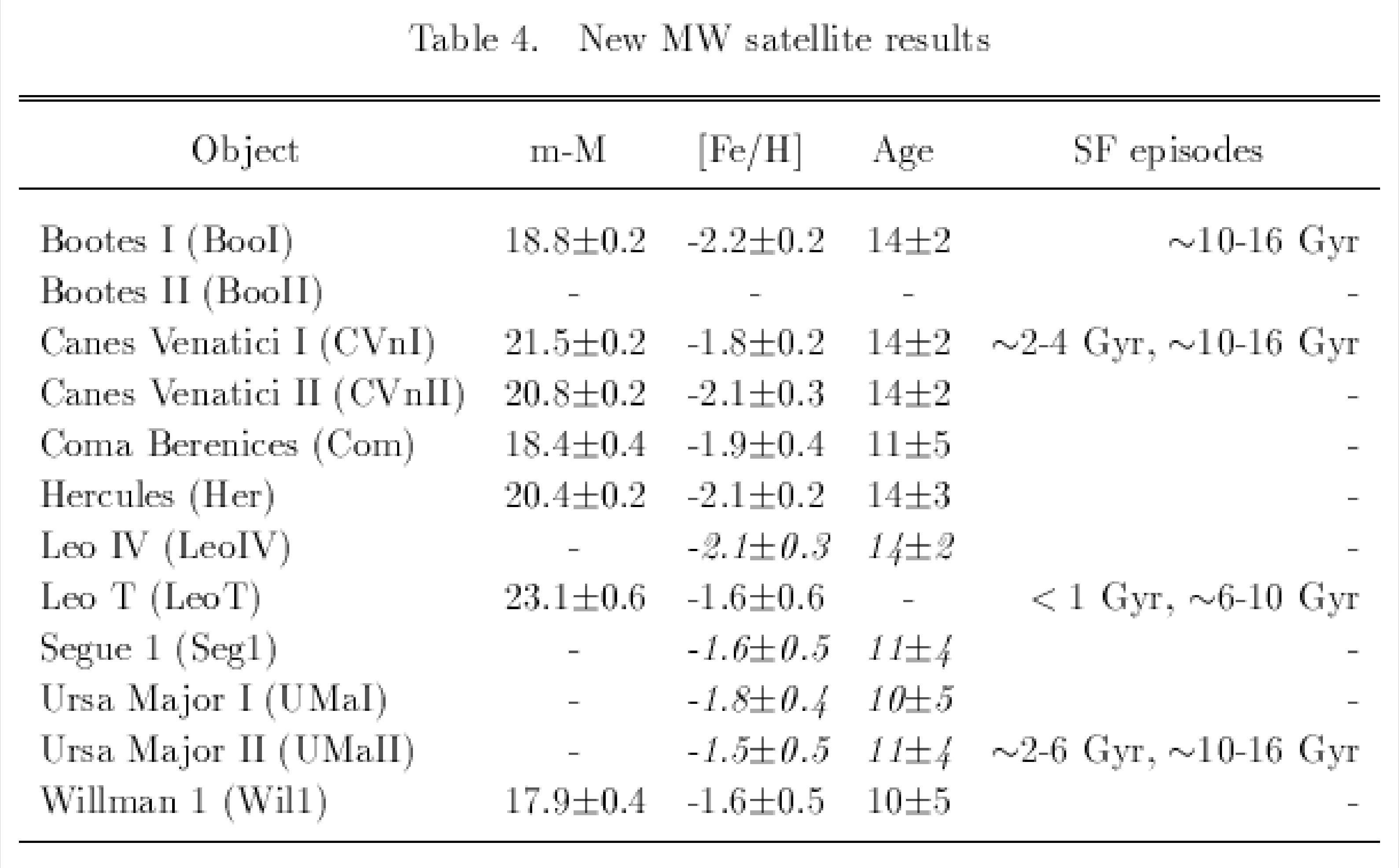


Table 4. New MW satellite results

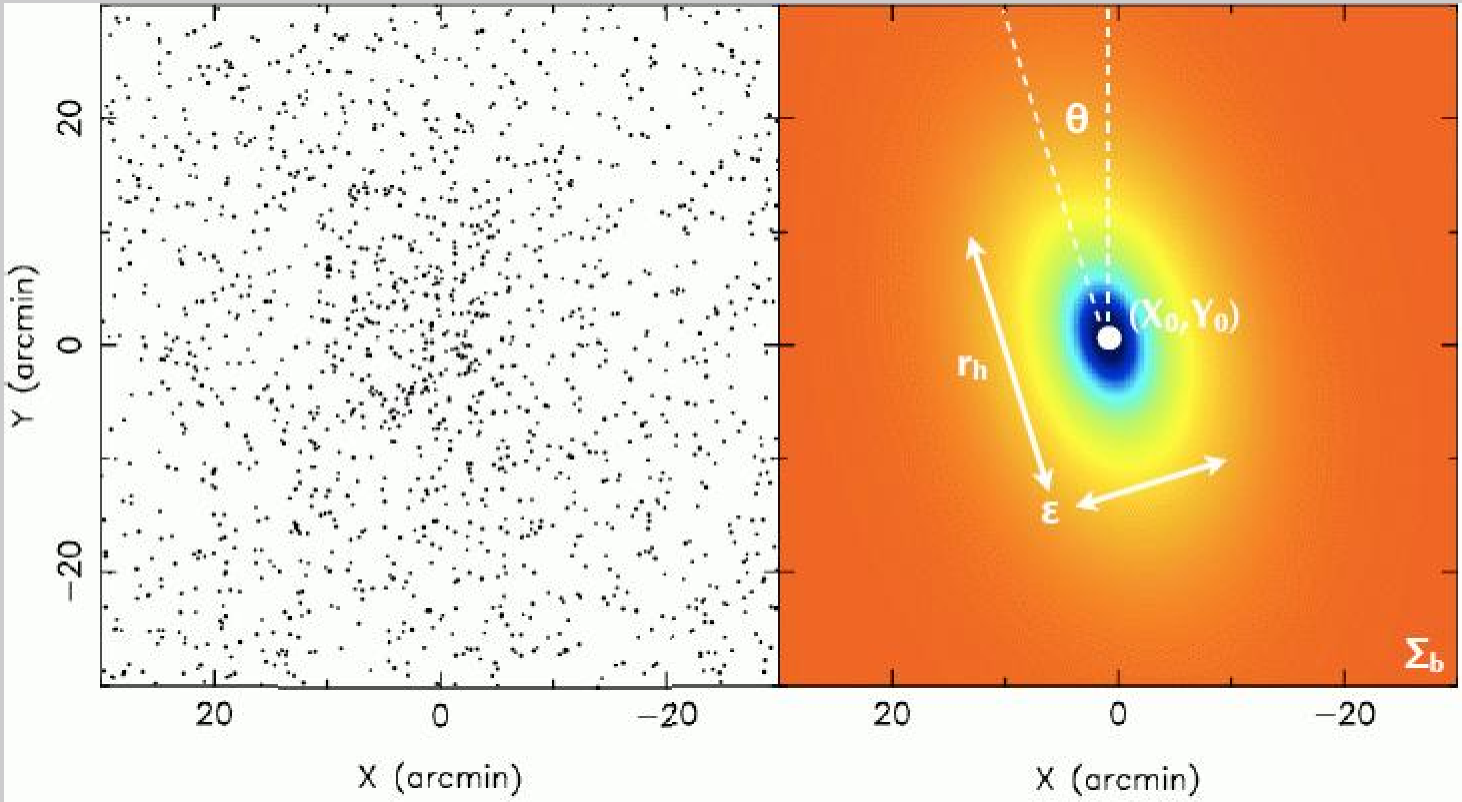
Object	m-M	[Fe/H]	Age	SF episodes
Bootes I (BooI)	18.8±0.2	-2.2±0.2	14±2	~10-16 Gyr
Bootes II (BooII)	-	-	-	-
Canes Venatici I (CVnI)	21.5±0.2	-1.8±0.2	14±2	~2-4 Gyr, ~10-16 Gyr
Canes Venatici II (CVnII)	20.8±0.2	-2.1±0.3	14±2	-
Coma Berenices (Com)	18.4±0.4	-1.9±0.4	11±5	-
Hercules (Her)	20.4±0.2	-2.1±0.2	14±3	-
Leo IV (LeoIV)	-	*-2.1±0.3*	*14±2*	-
Leo T (LeoT)	23.1±0.6	-1.6±0.6	-	< 1 Gyr, ~6-10 Gyr
Segue 1 (Seg1)	-	*-1.6±0.5*	*11±4*	-
Ursa Major I (UMaI)	-	*-1.8±0.4*	*10±5*	-
Ursa Major II (UMaII)	-	*-1.5±0.5*	*11±4*	~2-6 Gyr, ~10-16 Gyr
Willman 1 (Wil1)	17.9±0.4	-1.6±0.5	10±5	-

(JdJ et al. 2008, Astronomical Journal, 135, 1361)

Properties of bound structures in the Milky Way halo

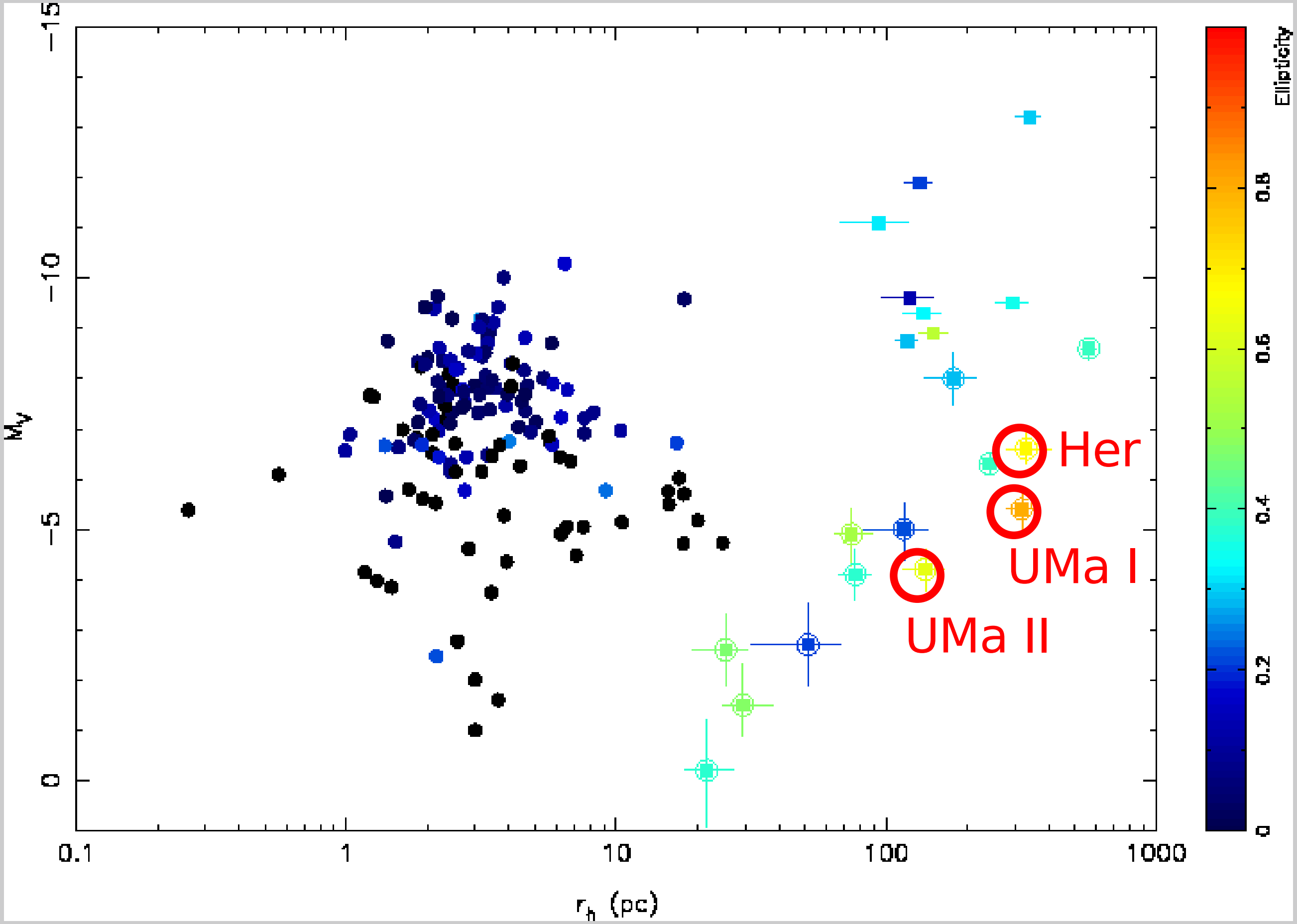
Another quantitative tool for studying the ultra-faint satellites: maximum likelihood fitting of structural parameters
(Martin, JdJ & Rix, 2008)

ε, r_h, N_* can be determined by fitting models directly to the positions of the stars *without need for smoothing or binning*



Properties of bound structures in the Milky Way halo

Ultra-faints significantly (4σ) flatter than their brighter counterparts



(Martin, JdJ & Rix, 2008)

Her: $\varepsilon=0.68$!
UMa I: $\varepsilon=0.80$!
UMa II: $\varepsilon=0.63$!

Are they really "bound" ?

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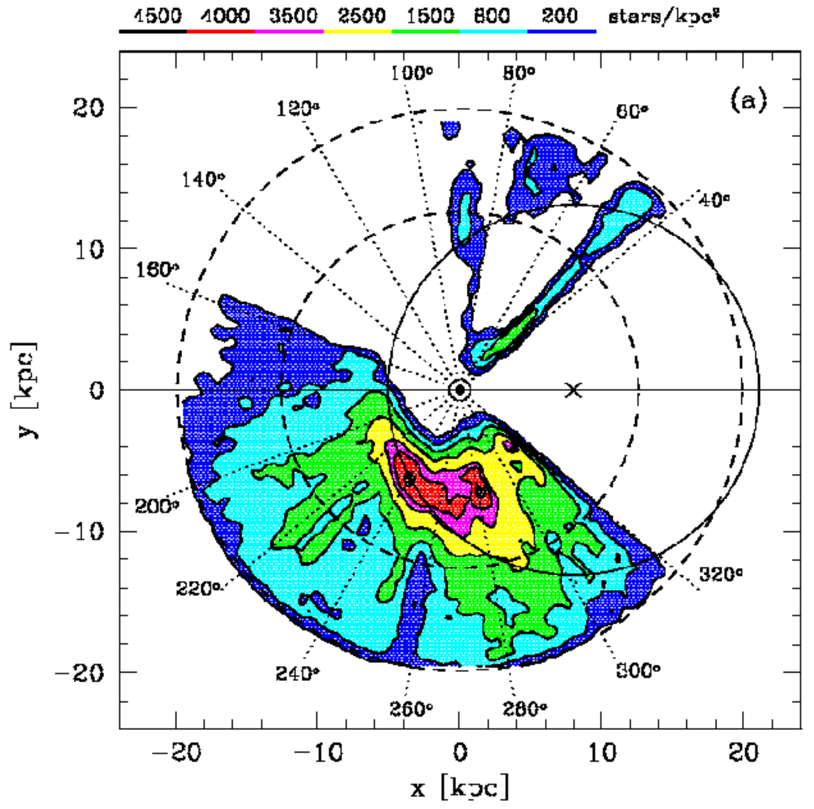
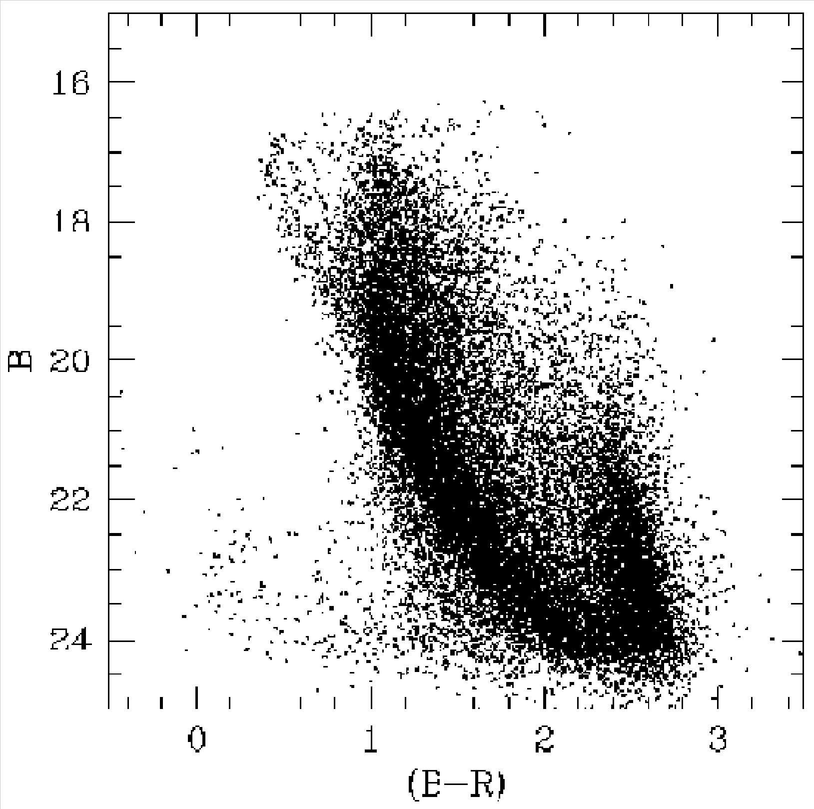
Stellar substructure in the disk: the Canis Major overdens

Discovered by Martin et al. (2004) using 2MASS M-giants

- Largest substructure at low Galactic latitudes
- Two populations associated with it



ρ(south) – ρ(north) RC stars
(Bellazzini et al. 2006)



(Martinez-Delgado et al. 2005)

Stellar substructure in the disk: the Canis Major overdens

What is the origin of this overdensity?

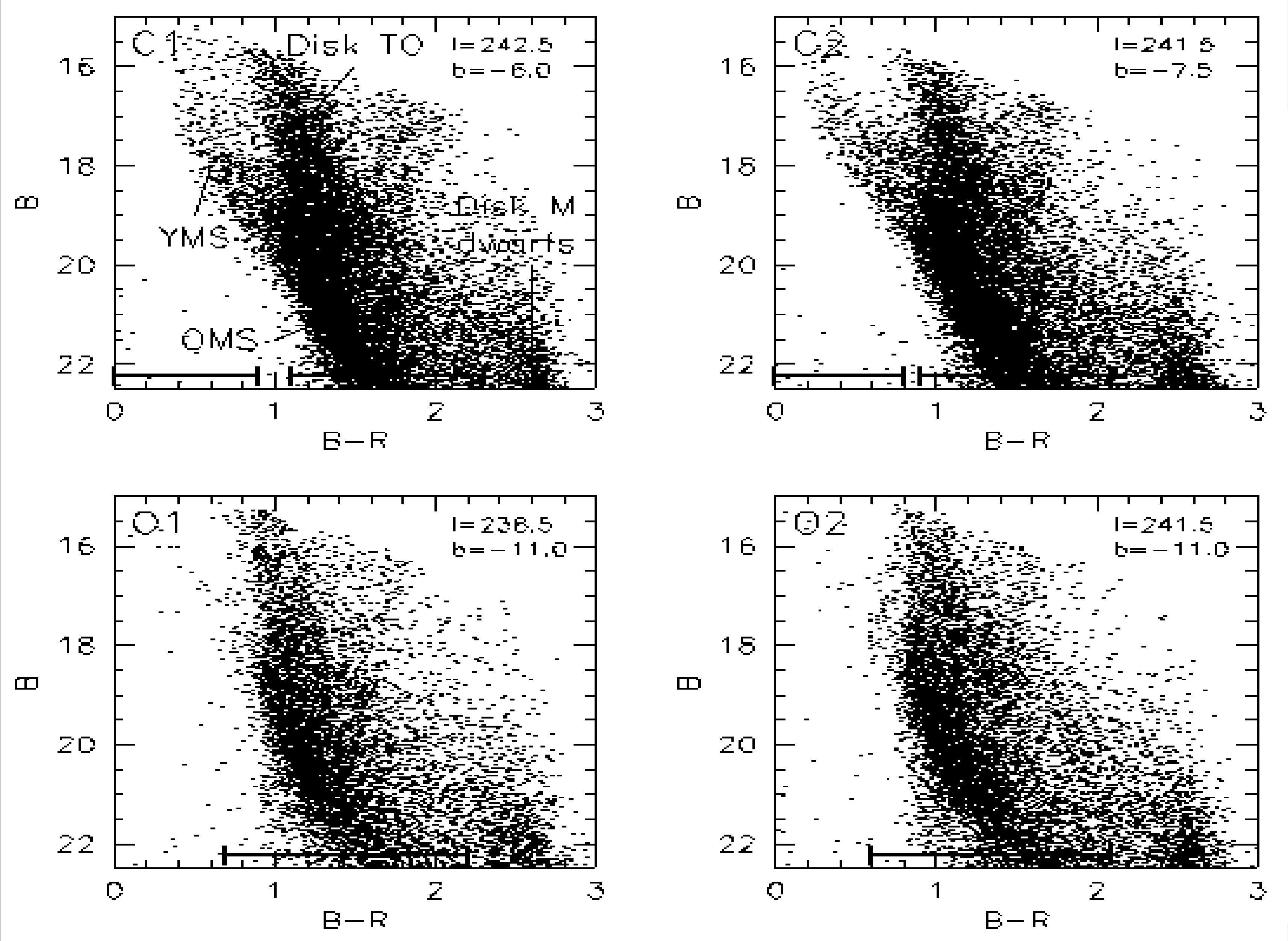
- Accreted dwarf, progenitor Low Latitude stream
  (e.g. Martin et al. 2004, Martinez-Delgado et al. 2005, Bellazzini et al. 2006)
- Produced by warp and/or flare of outer disk crossing the line-of-sight (e.g. Momany et al. 2004, 2006)
- Old MS stars belong to local spiral arm, young stars part of outer spiral arm (Carraro et al. 2005, Moitinho et al. 2006)

Dragged in or kicked out?

Is CMa overdensity intrinsic (sub)structure, or is it coming from outside?

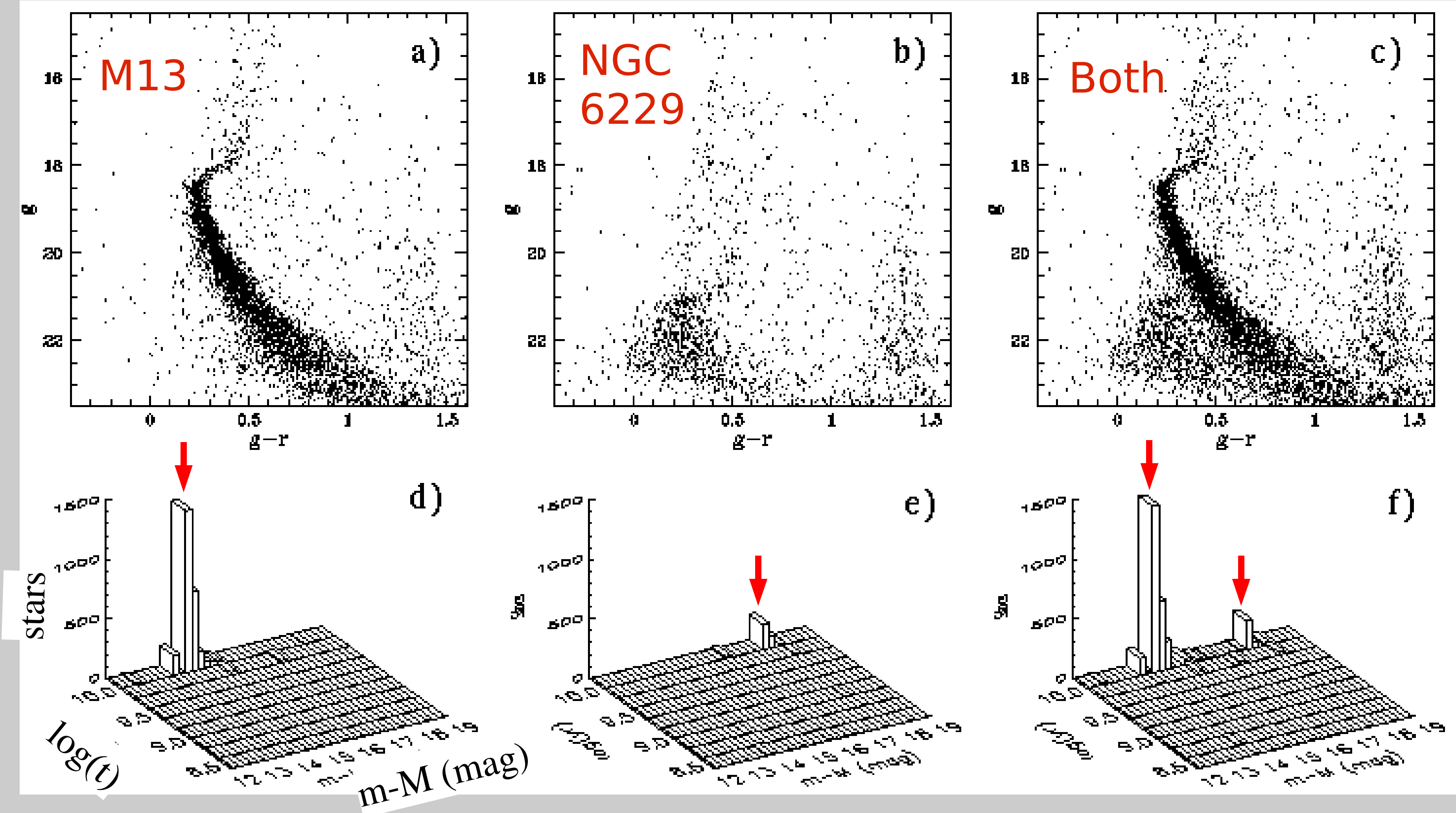
Are the old and young stars co-spatial and co-moving, or are they only coinciding in projection?

Stellar substructure in the disk: the Canis Major overdens



Stellar substructure in the disk: the Canis Major overdens

To deal with complex distance distributions, include distance as fit parameter in MATCH

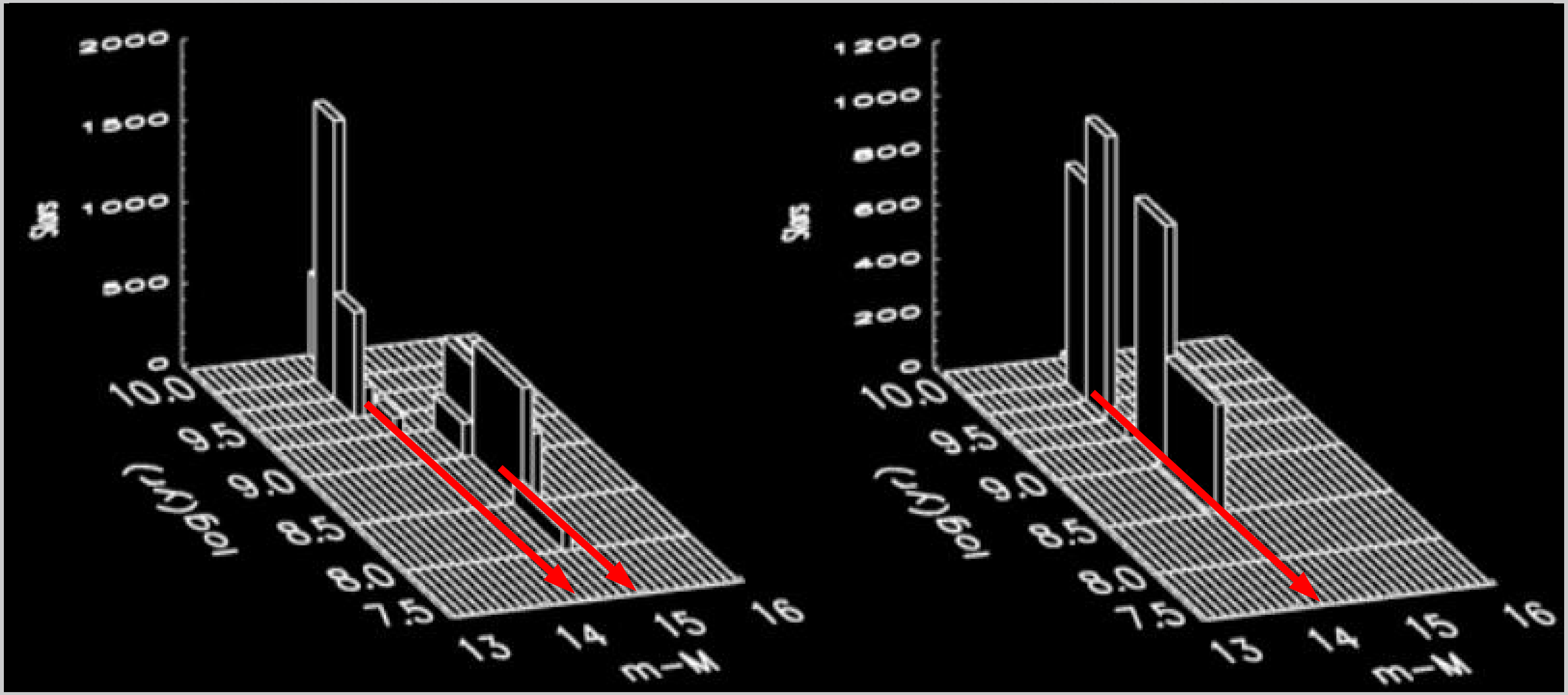


Stellar substructure in the disk: the Canis Major overdens

Distance fits to old and young stars simultaneously:

Young stars
[Fe/H]=−0.3

Young stars
[Fe/H]=−0.9



(JdJ et al. 2007)

Spectroscopy needed to be sure whether old and young stars are co-spatial or only overlap in projection

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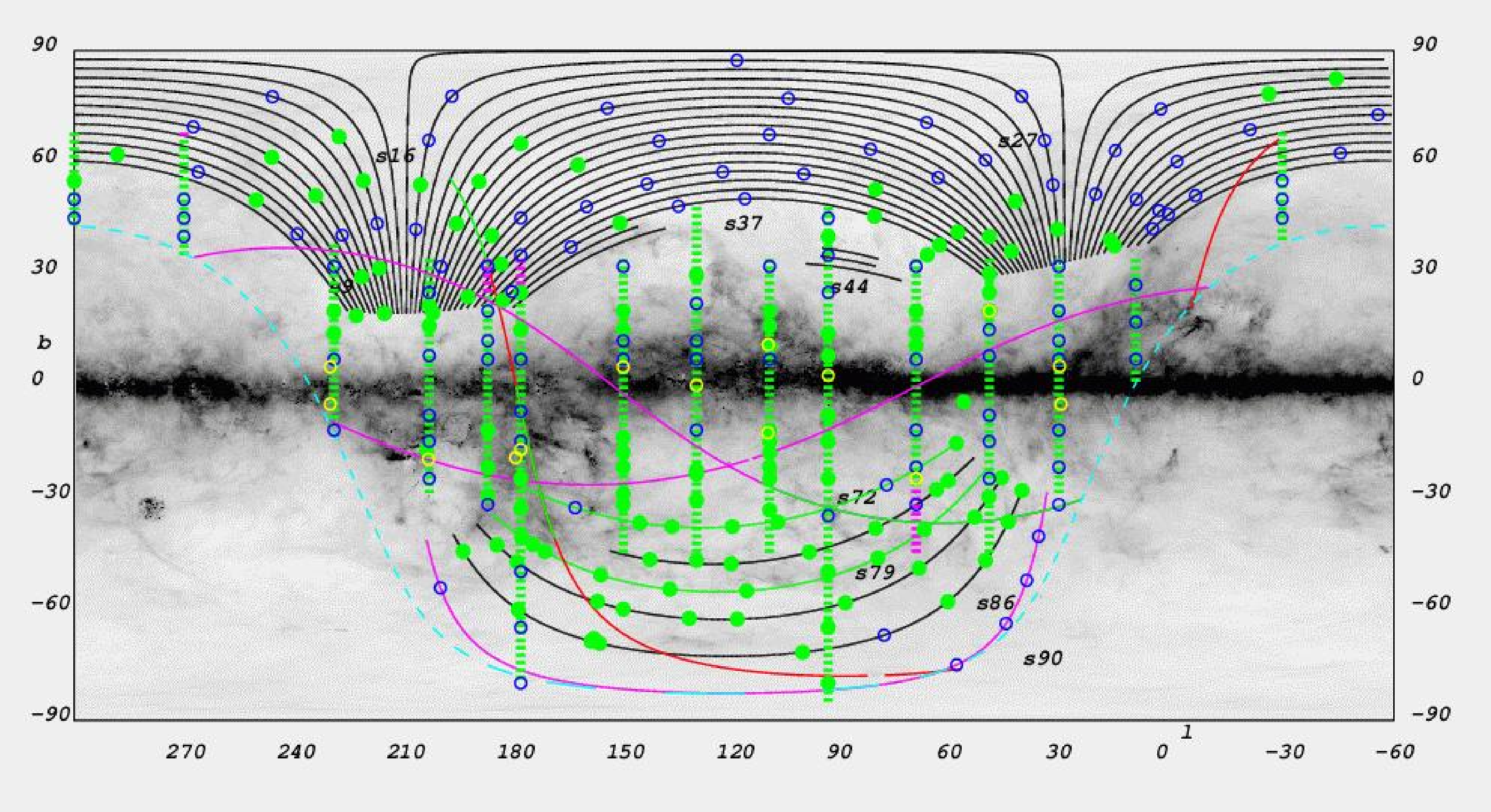
A new sparse map of the outer disk of the Milky Way

Studying the Milky Way disk is hampered by the enormous sky area and the presence of dust

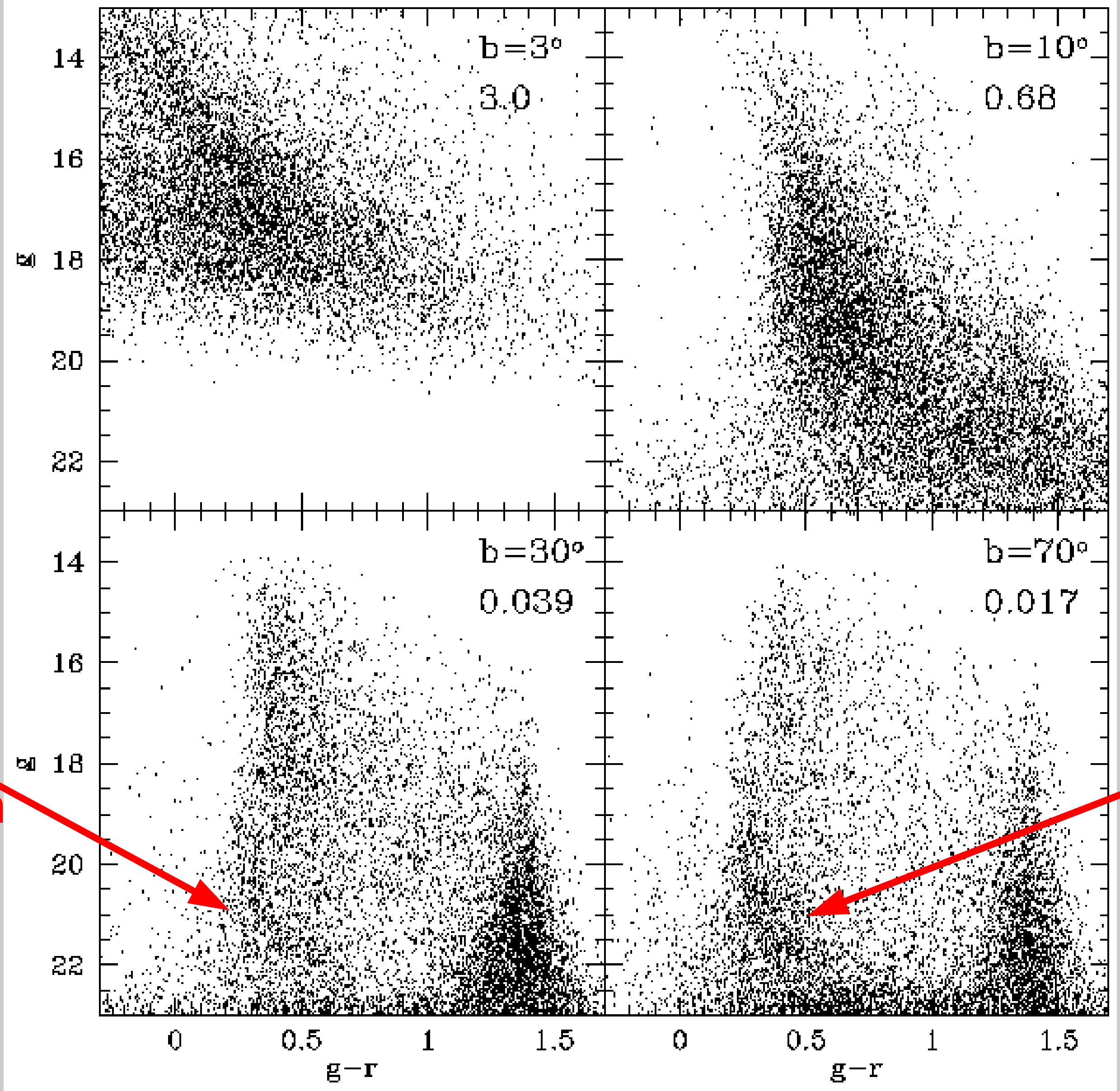
SEGUE imaging survey: 2.5° wide scans through Galactic plane



SEGUE coverage as of Jan 2008

A new sparse map of the outer disk of the Milky Way

Some CMDs from the stripe at l=94°



Mon stream

Sgr stream

A new sparse map of the outer disk of the Milky Way

Use MATCH distance fitting mode to obtain 3D map of the Galaxy

First used very narrow color range ($0.3<g-r<0.8$) and single metallicity and age (8 Gyr, $[\mathrm{Fe/H}]=-0.7$)

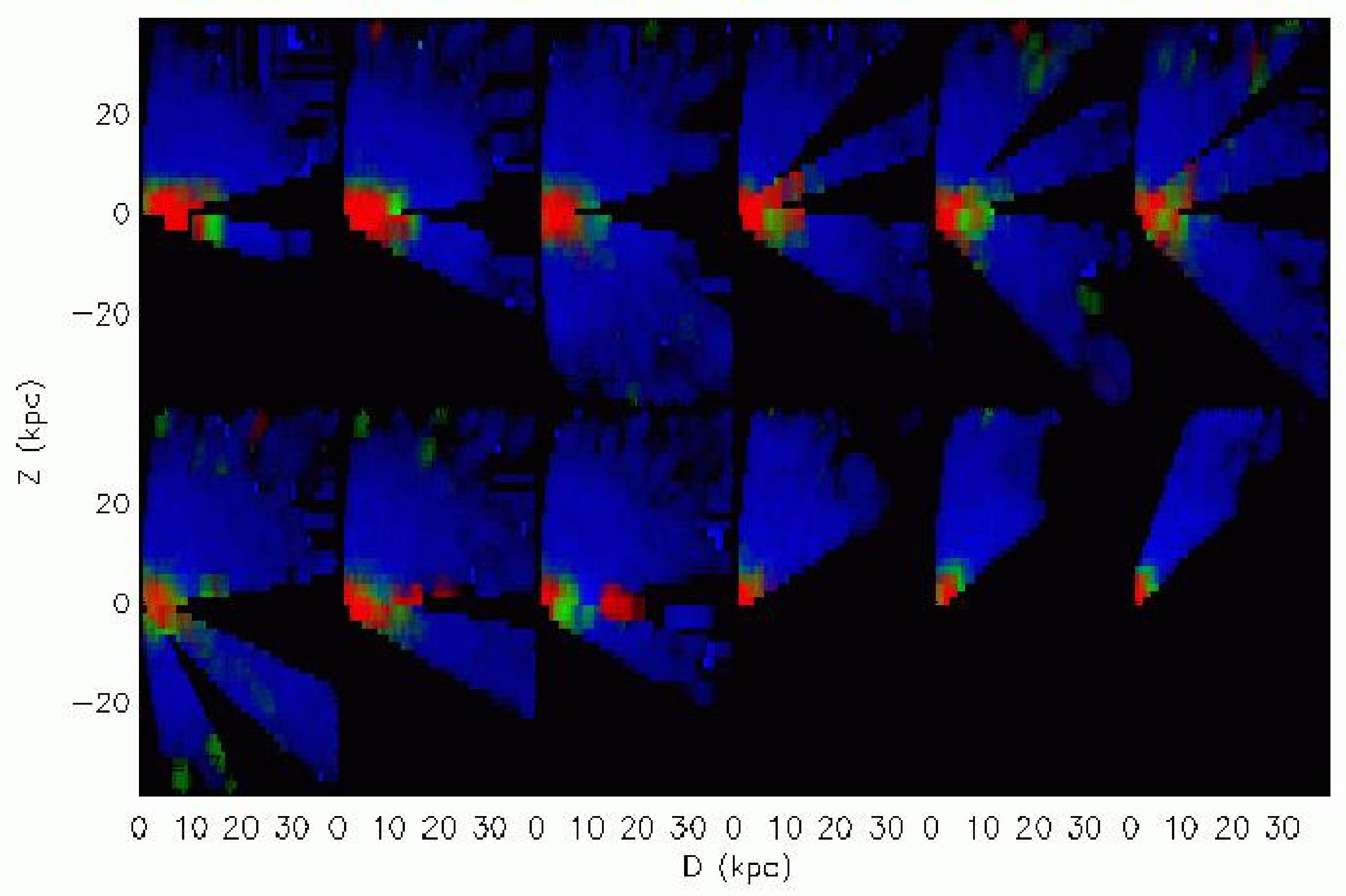
Secondly, used three astrophysically motivated populations:
- thick disk like (9-10 Gyr, $[\mathrm{Fe/H}]\sim-0.7$)
- halo like (10-15 Gyr, $[\mathrm{Fe/H}]\sim-1.3$)
- broad 'garbage bin' population to take care of background sources etc. (4-14 Gyr, $[\mathrm{Fe/H}]\sim-0.7$)

and wider color range ($0.1<g-r<0.8$)

Wider range includes all main-sequence turn-off stars, which trace the population differences between thick disk and halo

A new sparse map of the outer disk of the Milky Way

Fit results: stellar mass density



(JdJ et al. in prep)

A new sparse map of the outer disk of the Milky Way

Fit smooth model to stellar mass distribution to bring out over- and underdensities

Model: - double exponential disks
(thin: H=2.6 kpc, Z=0.3 kpc
thick: H=3.6 kpc, Z=1.0 kpc)
- power-law halo

Best-fit parameters:

$\rho_{thin,0} = 0.08\ M_{\odot}pc^{-3}$

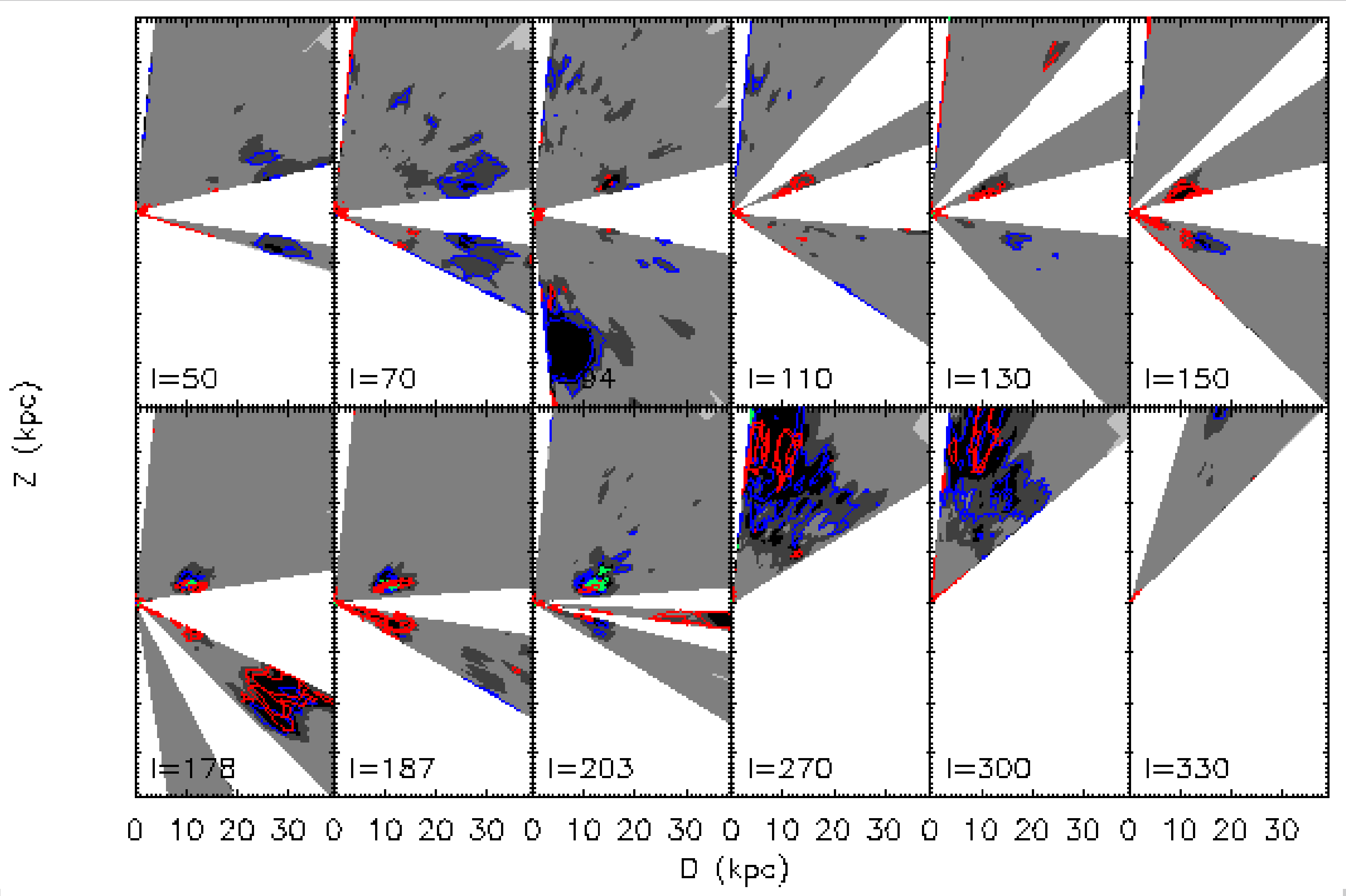
$f_{thick,0} = 0.058$

$f_{halo,0} = 0.0016$

$q_{halo} = 0.9$; $n_{halo} = 3.0$

A new sparse map of the outer disk of the Milky Way

Subtraction of smooth model reveals wealth of substructure



(JdJ et al. in prep)

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Constraining the Monoceros stream

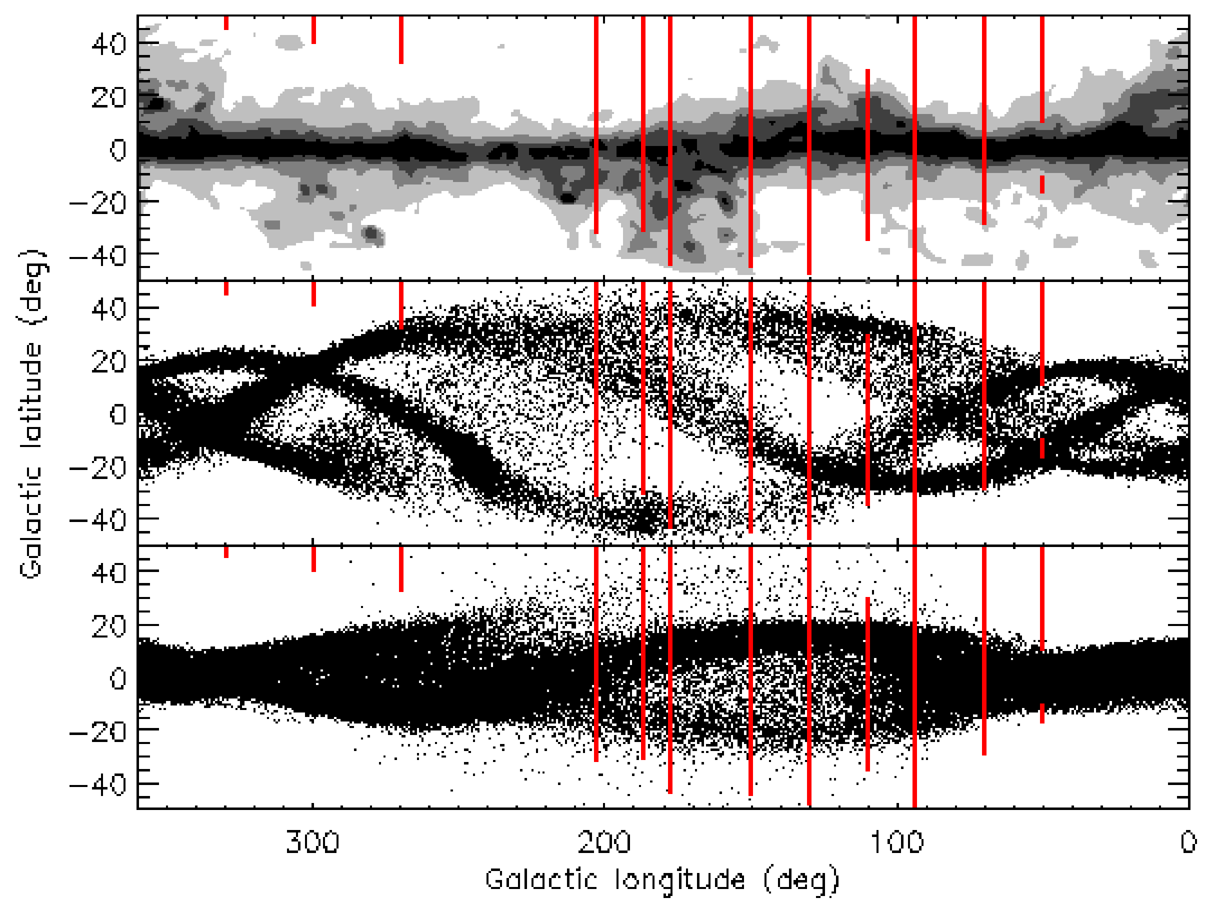
Monoceros (Low Latitude) stream: large stellar structure that see
to encircle the Milky Way at low latitudes

First suggested to be a stream of tidal debris

Extinction (E(B-V))
(Schlegel et al. 1998)

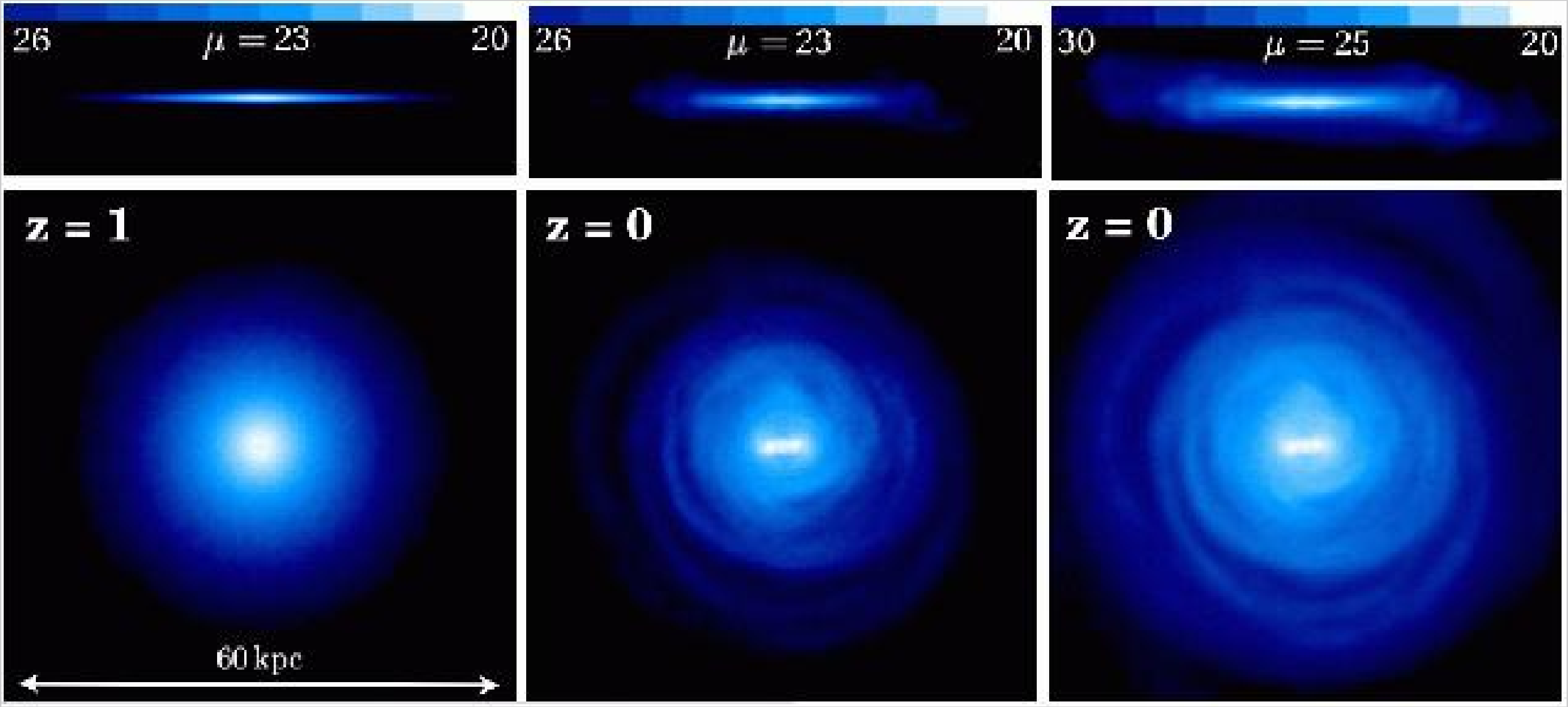
LLS model
(Peñarrubia et al. 2005)

LLS model
(Martin et al. 2005)



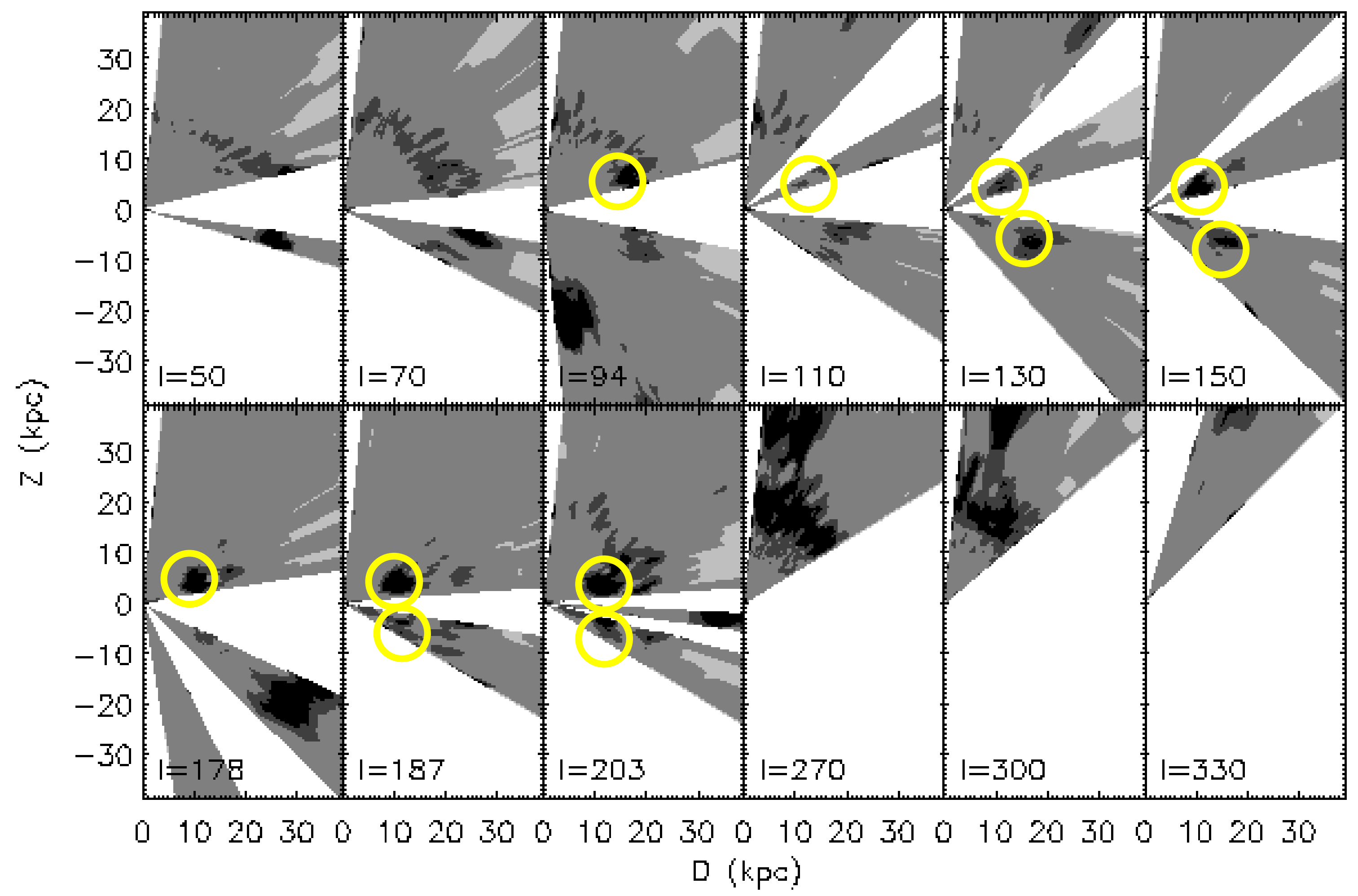
Constraining the Monoceros stream

However, nature of Monoceros stream not clear: could also be dis
material expelled from the disk, possibly due to interactions with
satellite galaxies (e.g. Kazantzidis et al. 2007, Younger et al. 2008)



(Kazantzidis et al. 2007)

Constraining the Monoceros stream



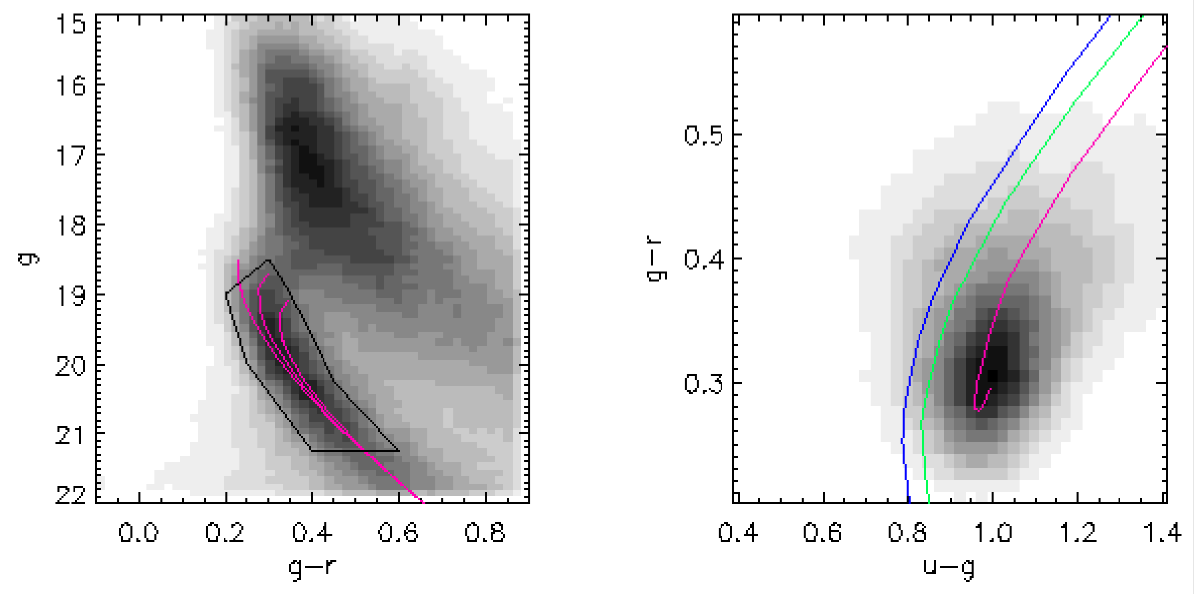
(JdJ et al. in prep)

Constraining the Monoceros stream

Color-color plots (u-g vs. g-r) can be used to constrain the metallicity of overdensities (Ivezic et al. 2008)

When the metallicity is known, distance and age can be constrained as well

Detection at l=178°, b~23°



[Fe/H]=-1.7
[Fe/H]=-1.3
[Fe/H]=-0.7

(JdJ et al. in prep)

Constraining the Monoceros stream

Color-color plots (u-g vs. g-r) can be used to constrain the metallicity of overdensities (Ivezic et al. 2008)

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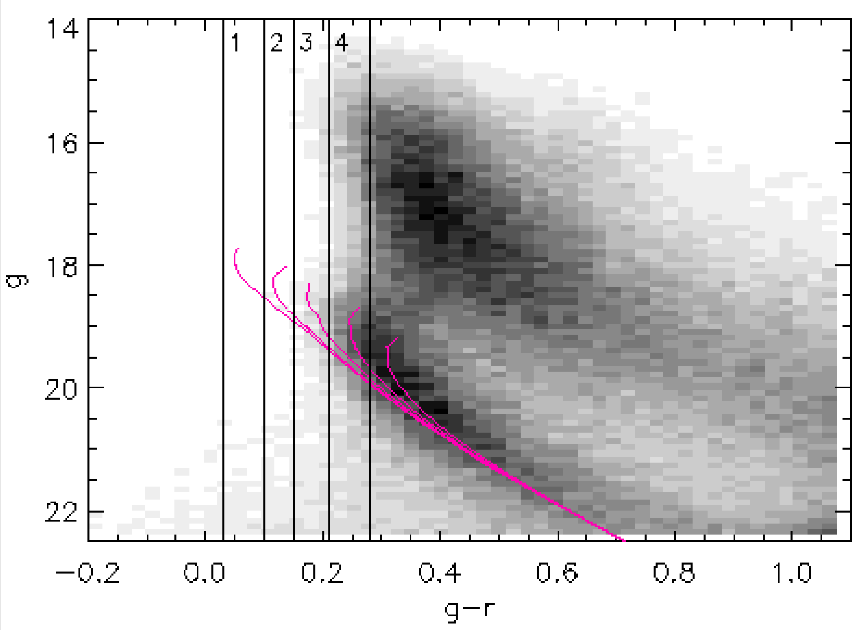
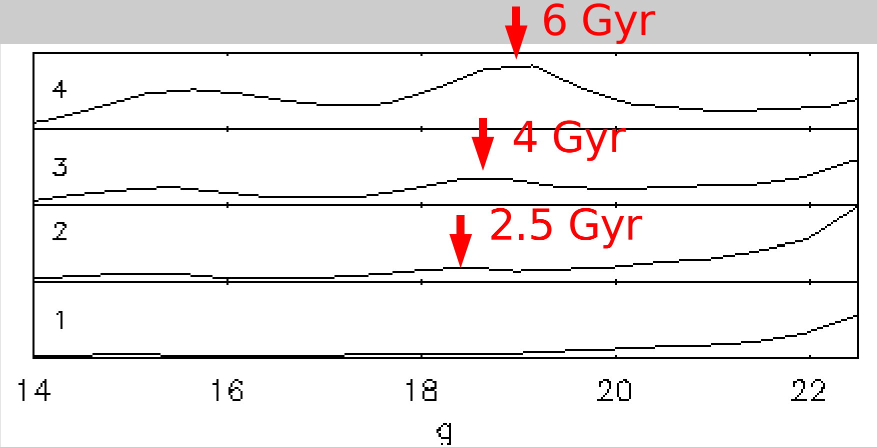




Isochrones: 10, 6, 4, 2.5, 2.0 Gyr

(JdJ et al. in prep)

Constraining the Monoceros stream

[Fe/H]<-2

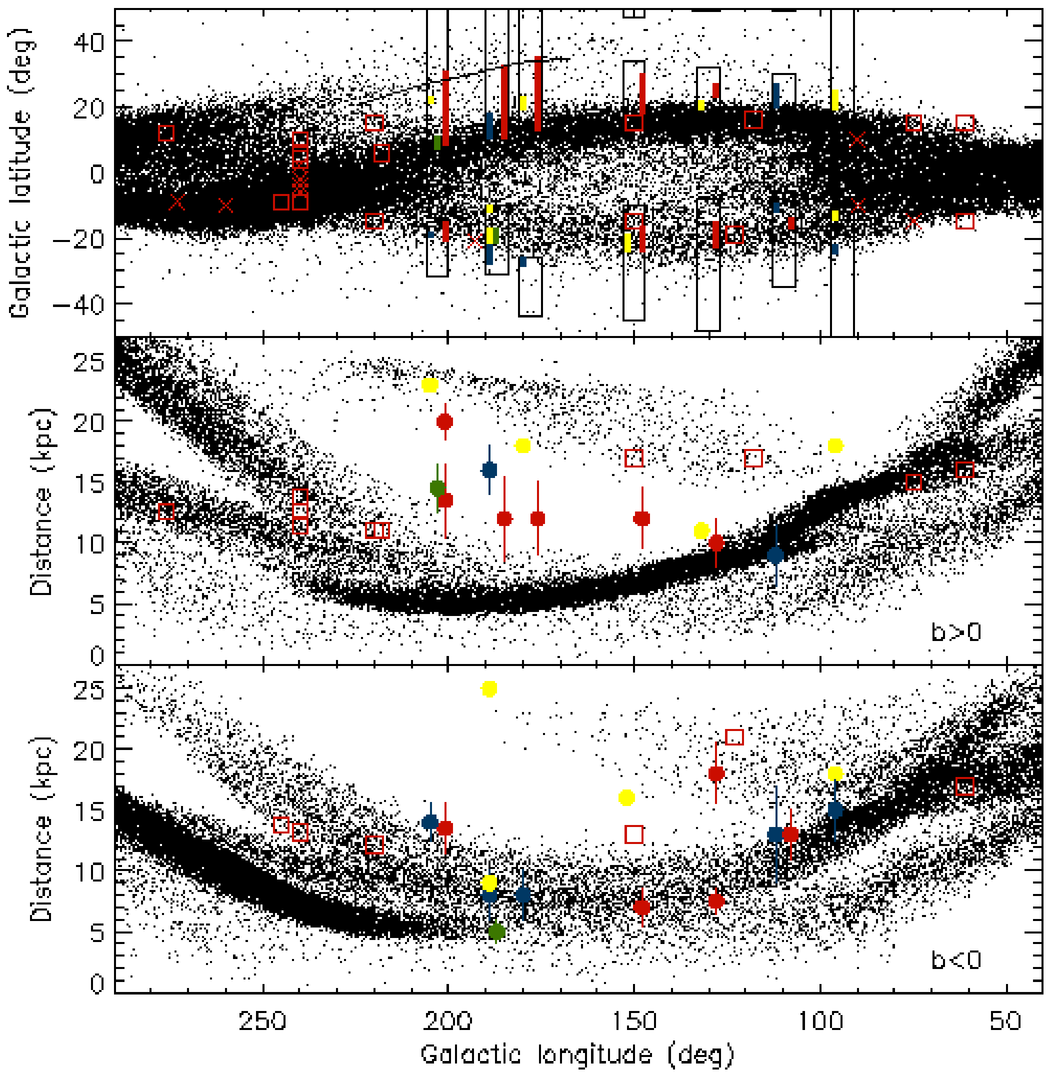
-1>[Fe/H]>-2

[Fe/H]>-1

[Fe/H] unknown

Conn et al. (2005,2007)
crosses: non-detections
squares: detections

Monoceros model Martin et al (2005)



(JdJ et al. in prep)

Constraining the Monoceros stream

Large number (~30) of detections, some new

Large range of metallicities

In strongest overdensities no evidence for very young stars

Summary and conclusions

CMD fitting provides *algorithmic and quantitative* tool to study st
populations of bound substructures, even at very low S/N:

Ultra-faint satellites are complex: can have multiple populations,
some are extremely elongated

Distance fitting mode enables the study of complex distance distributions and therefore of (sub)structure of the Milky Way

New 3D maps of the Milky Way based on SEGUE data can be use
to study stellar structure of the Milky Way and help to shed light
the nature of the Monoceros stream

Thank you for your attention!