Mapping the Distribution of Stars in the Milky Way

Recapitulation

HW Rix, Nov. 19, 2008

- 'Classic' tools to estimate stellar properties, distances, motions, etc.. are back *en vogue*
  - Spectroscopy for precision
  - Photometry for mass production

- 10% distances to >10^7 stars, metallicities for $10^{6\text{-}7}$ stars exist
  - but strongly biased towards the tenuous halo and thick disk

- We can make 3D star-by-star or population maps of (good parts of) the Milky Way
  - You can practice now for GAIA

Limitations of the star-by-star mapping approach

- **Luminosity – mean age (MS lifetime!) – maximally detectable distance are correlated**
  - Luminous tracers are always more rare than faint ones → no single stellar type for ideal mapping
- **We are mostly interested in maps of stellar populations: ρ_*(tot), [Fe/H],age**
  - with a given IMF, i.e. for a given p($M_{idividual\ stars}$)
- **Alternate approaches:**
  - **perdict observable n(α,δ,$m_{\lambda,}$color), e.g. Besancon models**
  - **Try to fit a density map for stellar populations!**

A synthetic view on structure and evolution of the Milky Way

http://www.obs-besancon.fr/modele/

A. C. Robin[1], C. Reylé[1], S. Derrière[2], and S. Picaud[1]

	density law	
Disc	$\rho_0/d_0 \times \{\exp(-(a/h_{R_+})^2) - \exp(-(a/h_{R_-})^2)\}$	if age $\leq$0.15 Gyr
	with h_{R_+} = 5000 pc, h_{R_-} = 3000 pc	
	$\rho_0/d_0 \times \{\exp(-(0.5^2 + a^2/h_{R_+}^2)^{1/2}) - \exp(-(0.5^2 + a^2/h_{R_-}^2)^{1/2})\}$	if age $>$0.15 Gyr
	with h_{R_+} = 2530 pc, h_{R_-} = 1320 pc	
Thick disc	$\rho_0/d_0 \times \exp(-\frac{R-R_\odot}{h_R}) \times (1 - \frac{1/h_z}{x_l \times (2.+x_l/h_z)} \times z^2)$	if $\lvert z\rvert \leq x_l$, x_l = 400 pc
	$\rho_0/d_0 \times \exp(-\frac{R-R_\odot}{h_R}) \times \frac{\exp(x_l/h_z)}{1+x_l/2h_z} \exp(-\frac{\lvert z\rvert}{h_z})$	if $\lvert z\rvert > x_l$
	with h_R = 2500 pc, h_z = 800 pc	
Spheroid	$\rho_0/d_0 \times (\frac{a_c}{R_\odot})^{-2.44}$	if $a \leq a_c$, a_c = 500 pc
	$\rho_0/d_0 \times (\frac{a}{R_\odot})^{-2.44}$	if $a > a_c$
Bulge	$N \times \exp(-0.5 \times r_s^2)$	$\sqrt{x^2+y^2} < R_c$
	$N \times \exp(-0.5 \times r_s^2) \times \exp(-0.5(\frac{\sqrt{x^2+y^2}-R_c}{0.5})^2)$	$\sqrt{x^2+y^2} > R_c$
	with $r_s^2 = \sqrt{[(\frac{x}{x_0})^2 + (\frac{y}{y_0})^2]^2 + (\frac{z}{z_0})^4}$	
ISM	$\rho_0 \times \exp(-\frac{R-R_\odot}{h_R}) \times \exp(-\frac{\lvert z\rvert}{h_z})$	
	with h_R = 4500 pc, h_z = 140 pc	
Dark halo	$\frac{\rho_c}{(1.+(a/R_c)^2)}$ with R_c = 2697 pc and ρ_c = 0.1079	

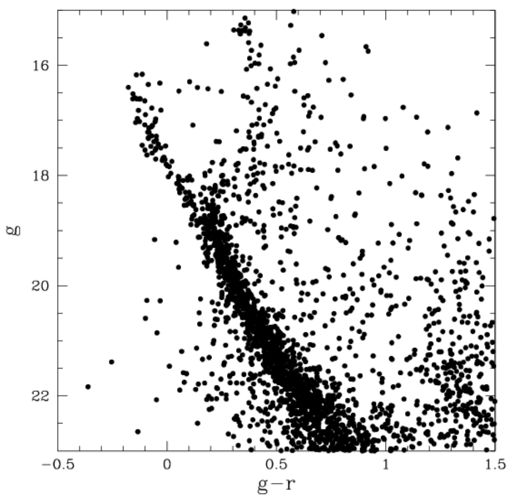
Making density maps for stellar populations

- Let's presume the spatial map we want is $\rho_*(\alpha,\delta,D,[Fe/H],age)$
  - the "observables" are the Hess (1923) diagrams in different directions, i.e. $\boldsymbol{n}_{\alpha,\delta}(m_\mathbf{r},g\text{-}r,(+u\text{-}g))$

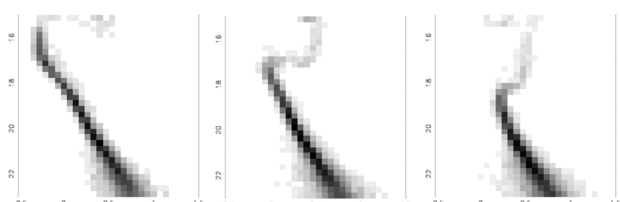
- Which superposition of $\rho_*(D,[Fe/H],age \mid \alpha,\delta)$ fits $n_{\alpha,\delta}(m_\mathbf{r},g\text{-}r,(+u\text{-}g))$ best?
  - Code: MATCH (Dolphin 1997, de Jong et al 2007)

MATCH: fitting CMDs or Hess Diagrams

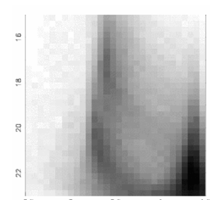
Observations of GC/dGal
- Object + background
- Multiple populations



Error-convolved theor. models



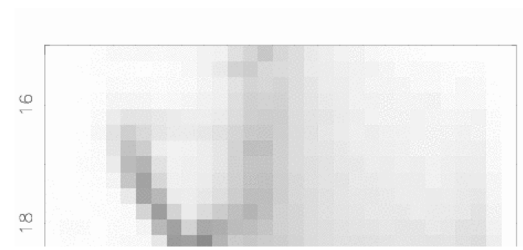
Control

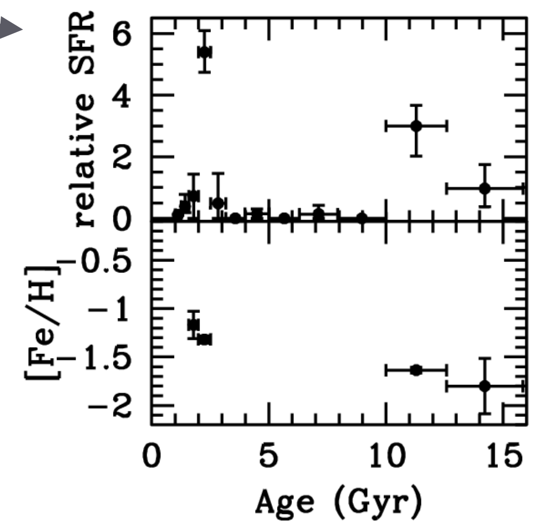


MATCH

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

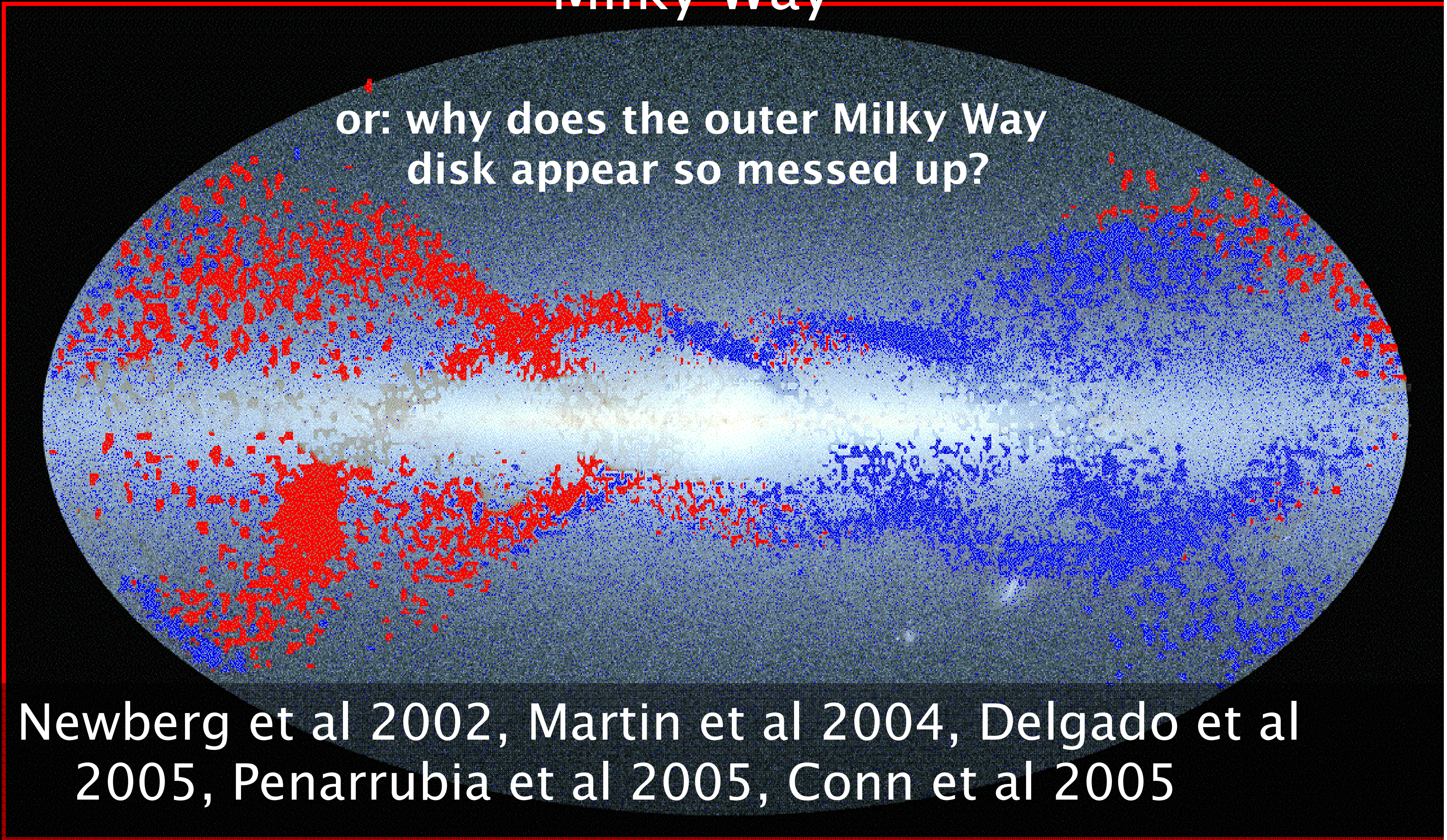
Best-fit model



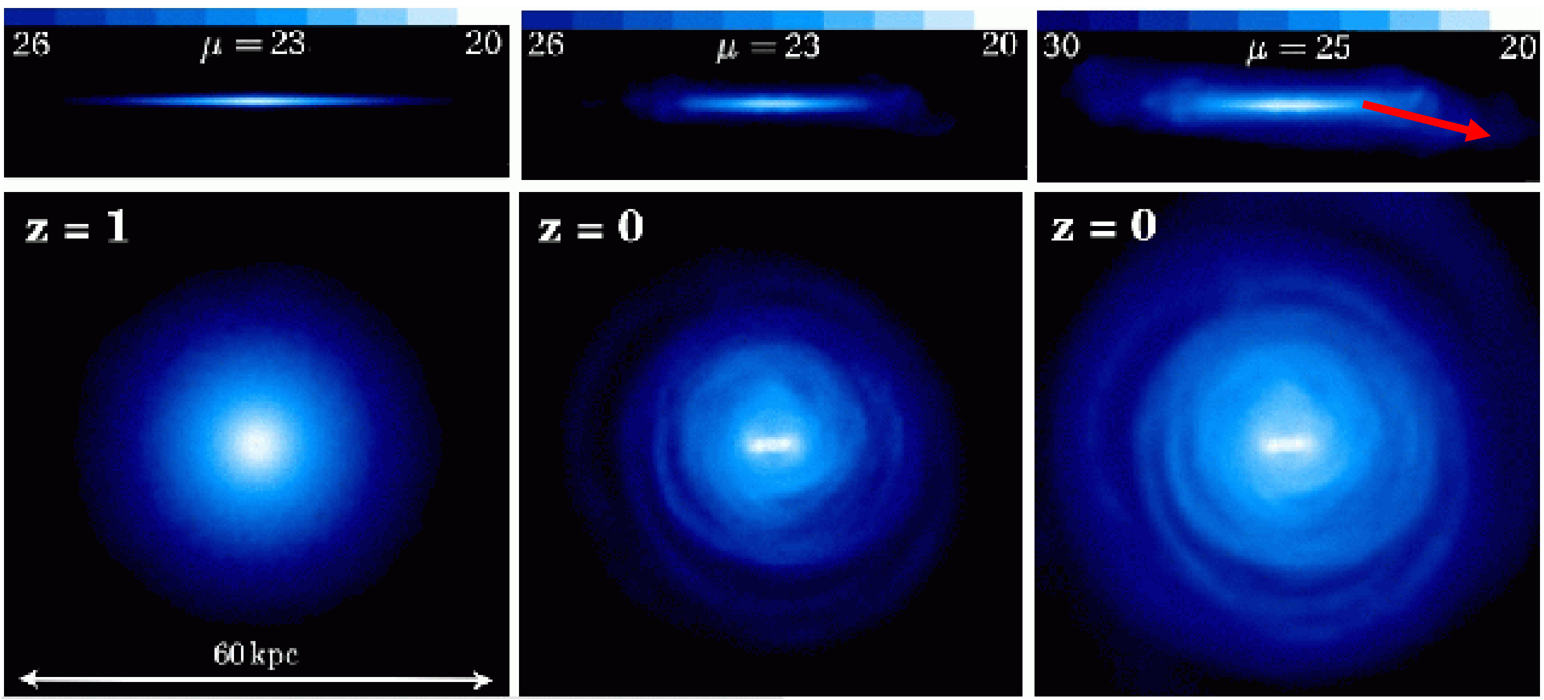


SFH and AMR

Systematic stellar population mapping in the Milky Way



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

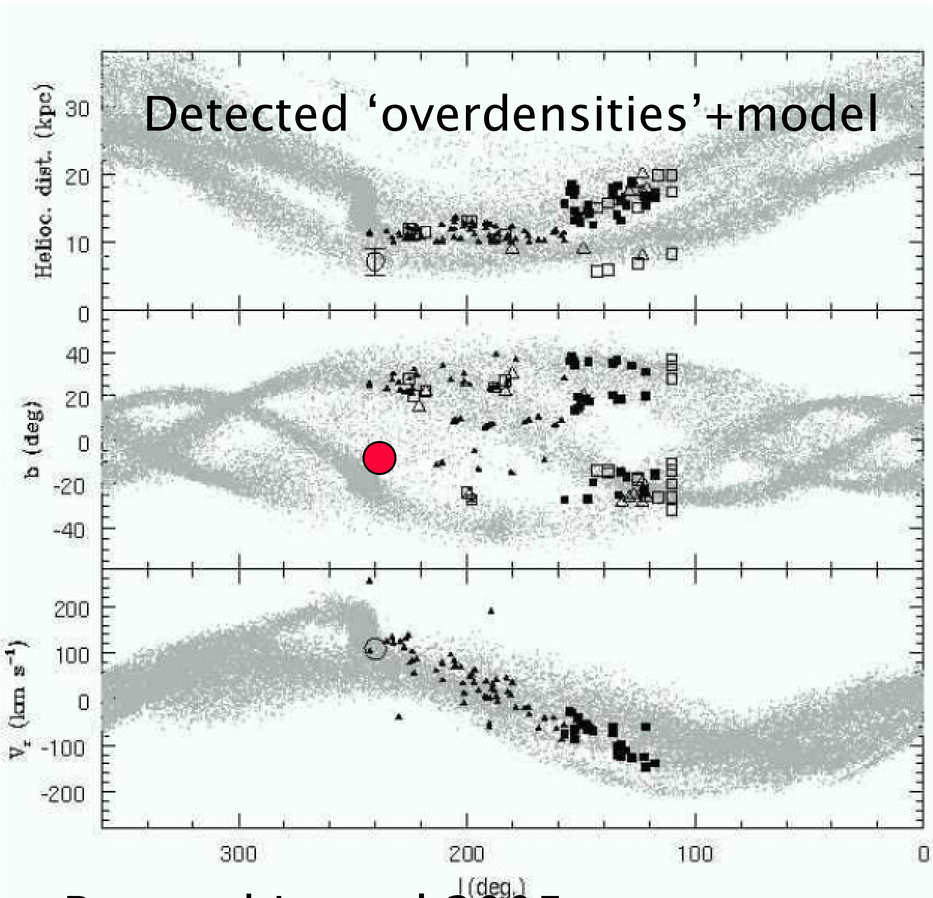


(Kazantzidis et al. 2007)

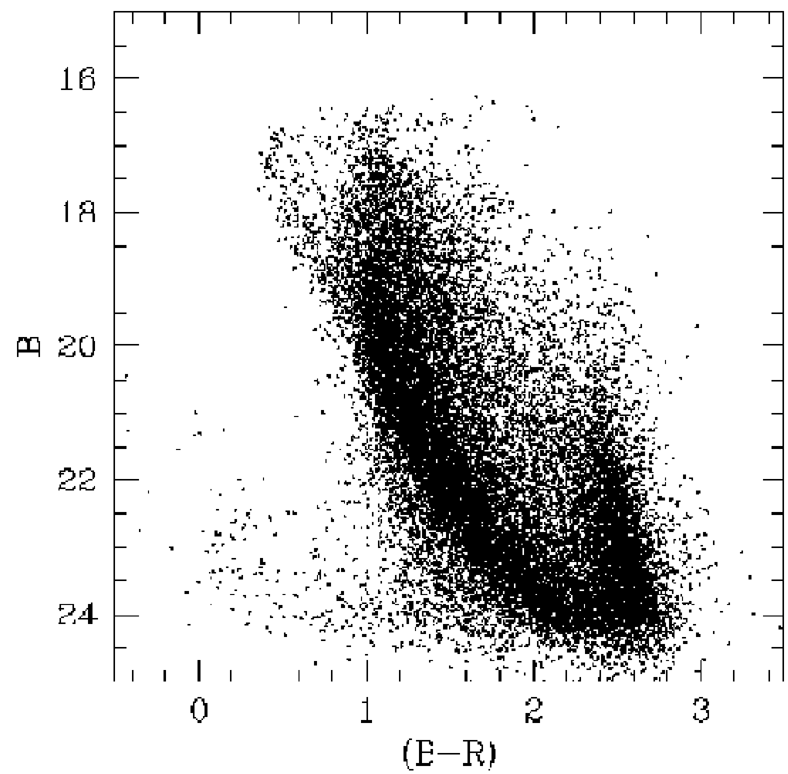
Stellar mapping in the Milky Way

or: why does the outer Milky Way disk appear so messed up?

Material kicked-up (warp?) or dragged in (satellite)?



Penarrubia et al 2005



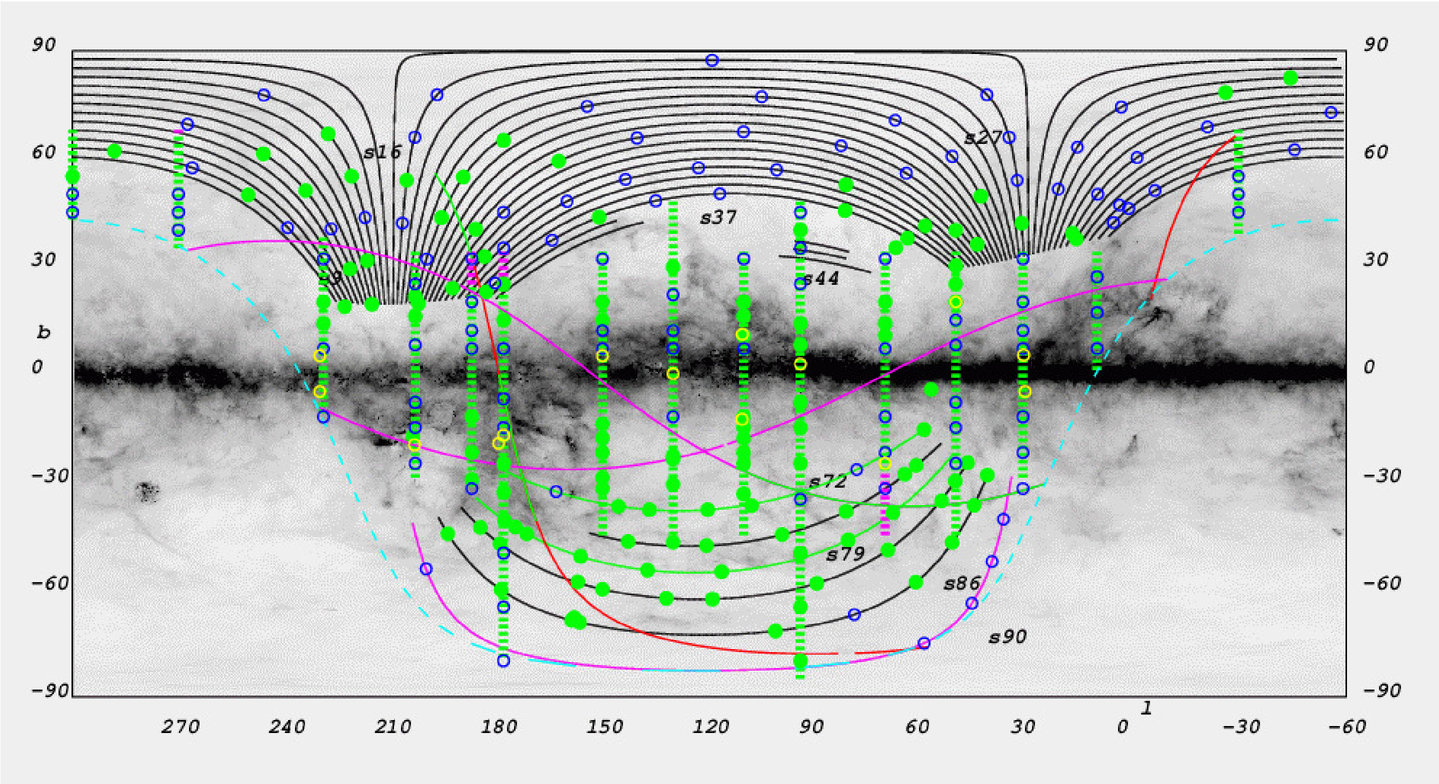
Martinez-Delgado et al 2005

de Jong et al 2008

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

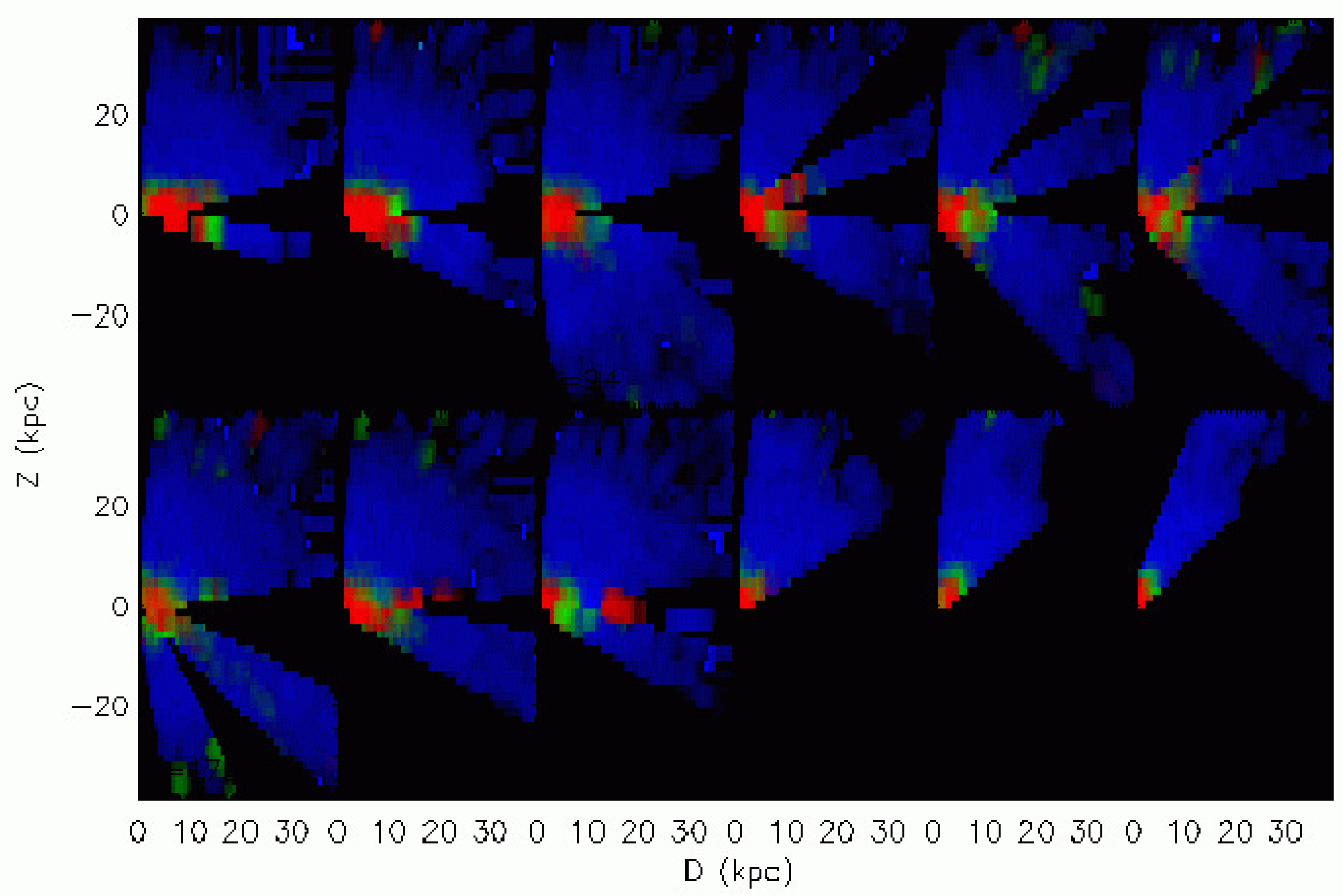
SEGUE imaging survey: 2.5˚ wide scans through Galactic plane



SEGUE coverage as of Jan 2008

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

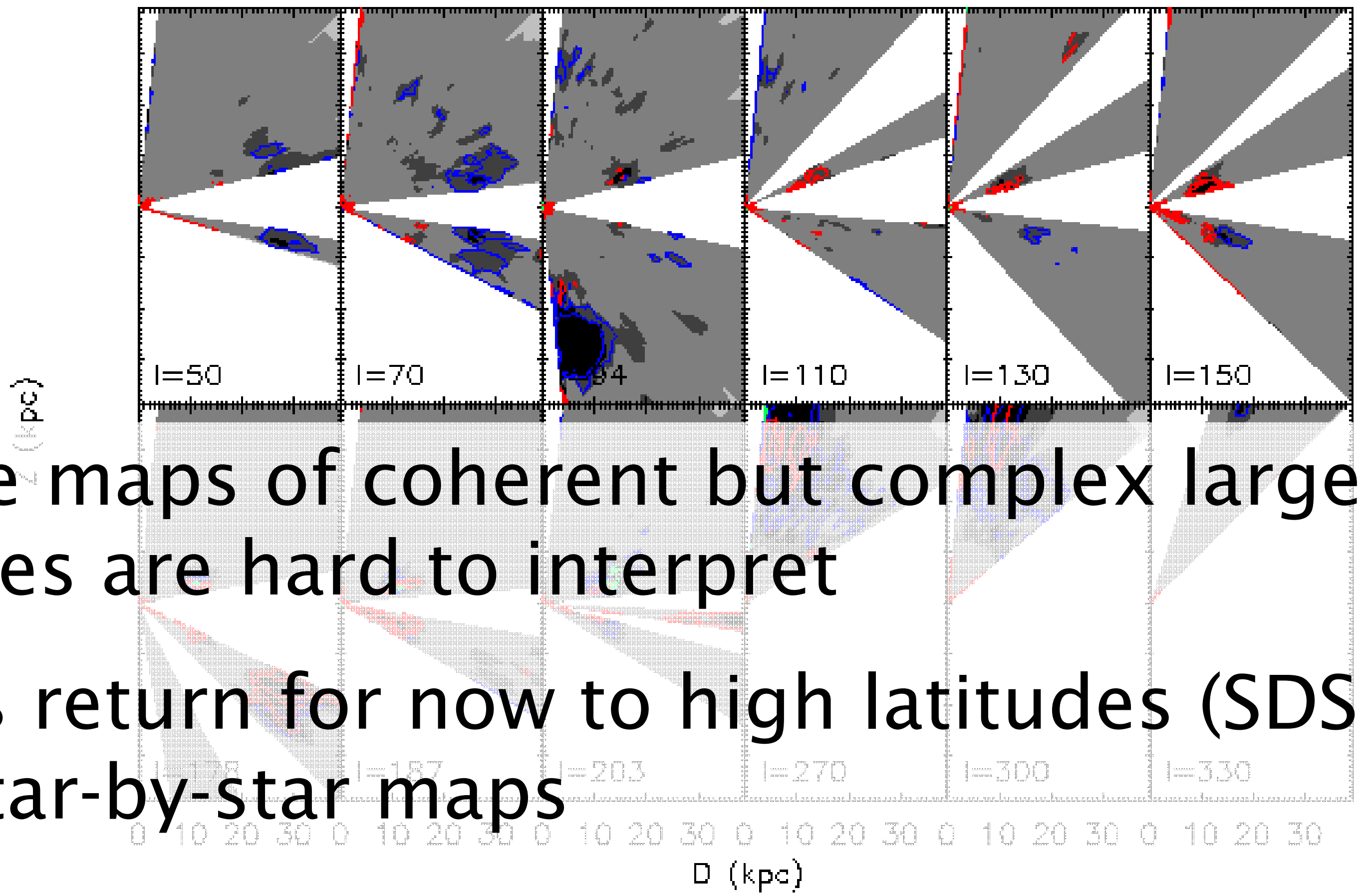
Fit results: stellar mass density color = metllicity



(de JongJ et al. in prep)

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

Subtraction of smooth model reveals wealth of substructure



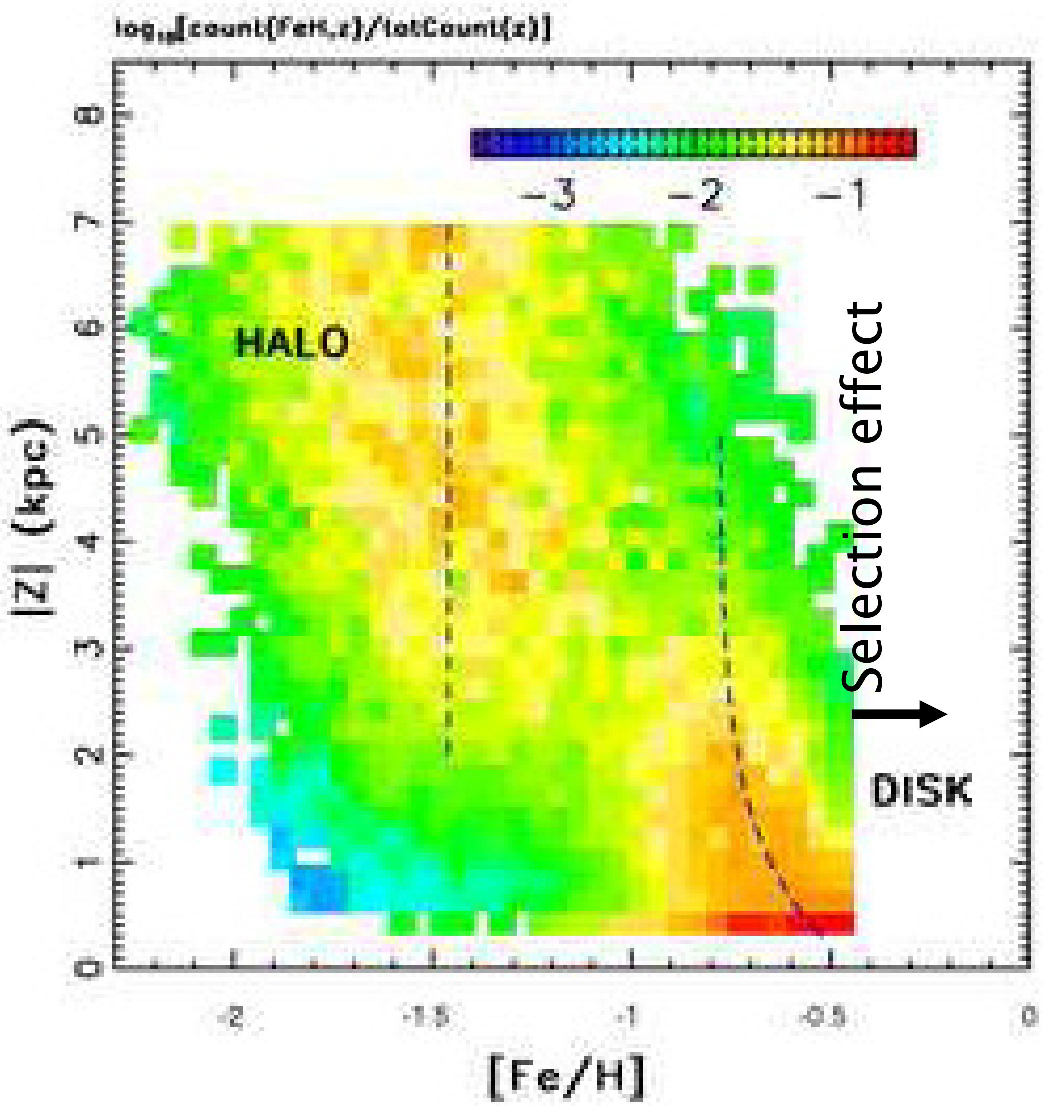
Sparse maps of coherent but complex large-scale features are hard to interpret

→let's return for now to high latitudes (SDSS) and star-by-star maps

(de Jong et al. in prep)

How does metallicity vary as a function of position and kinematics in the MW?

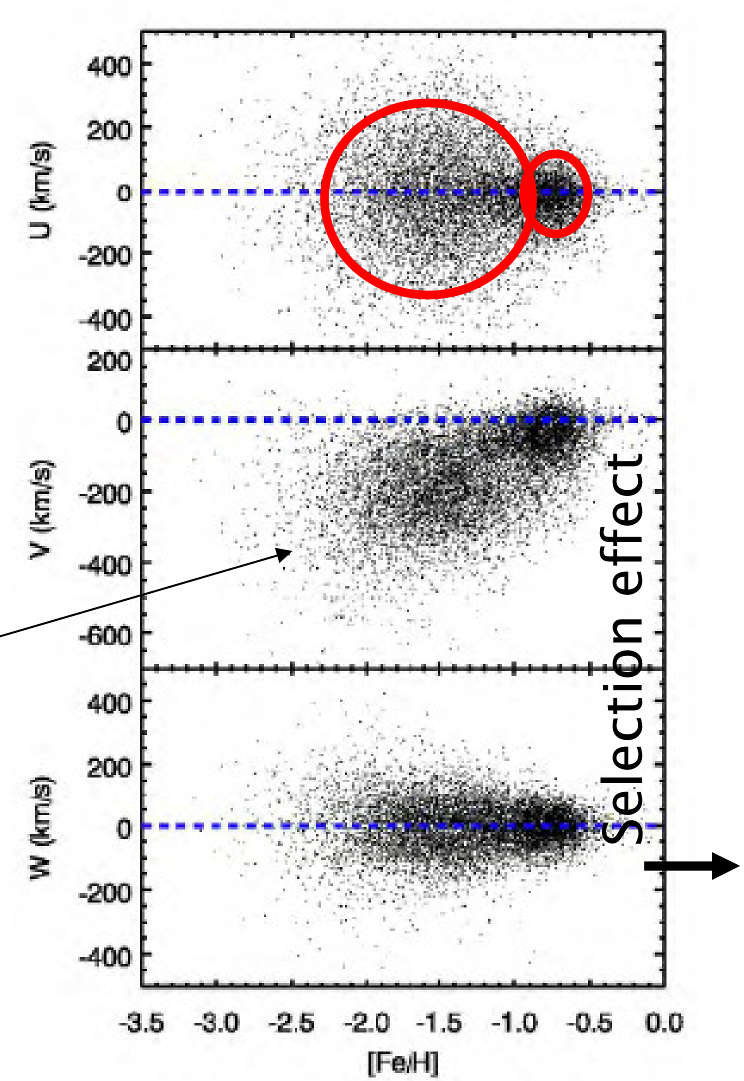
From Ivezic et al 2008



How do kinematics vary with [Fe/H]?

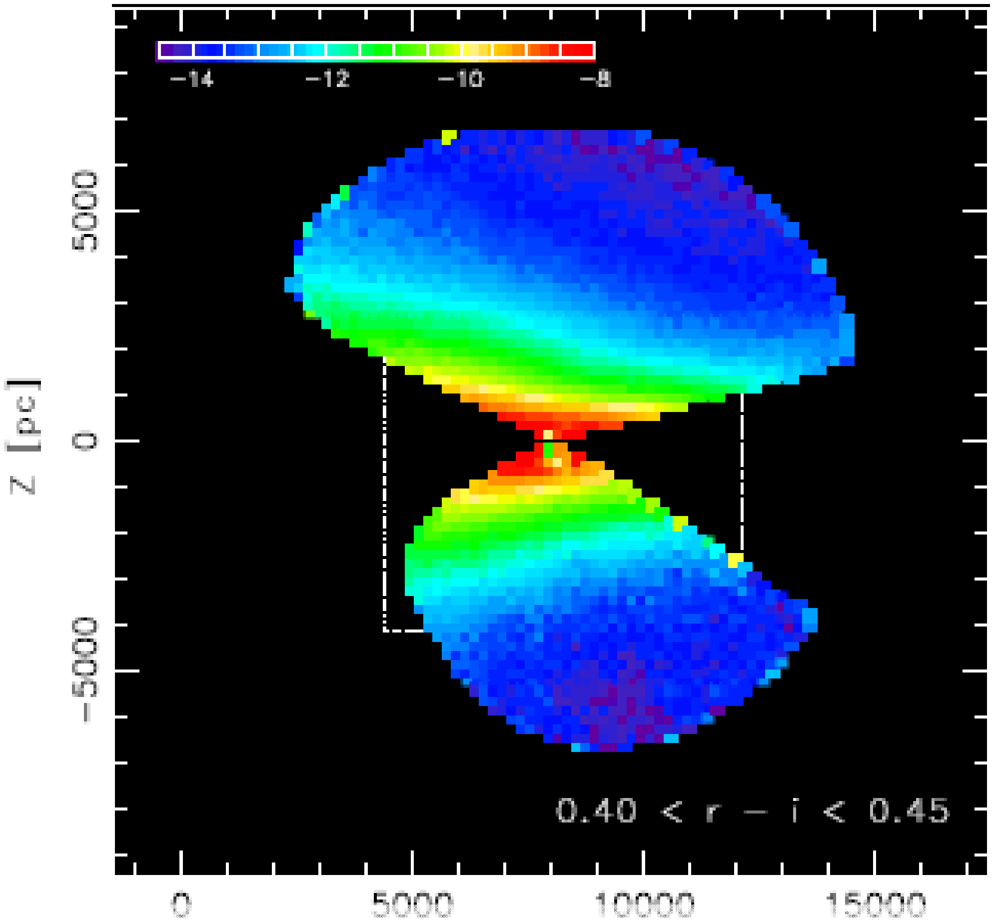
Carollo et al 2007

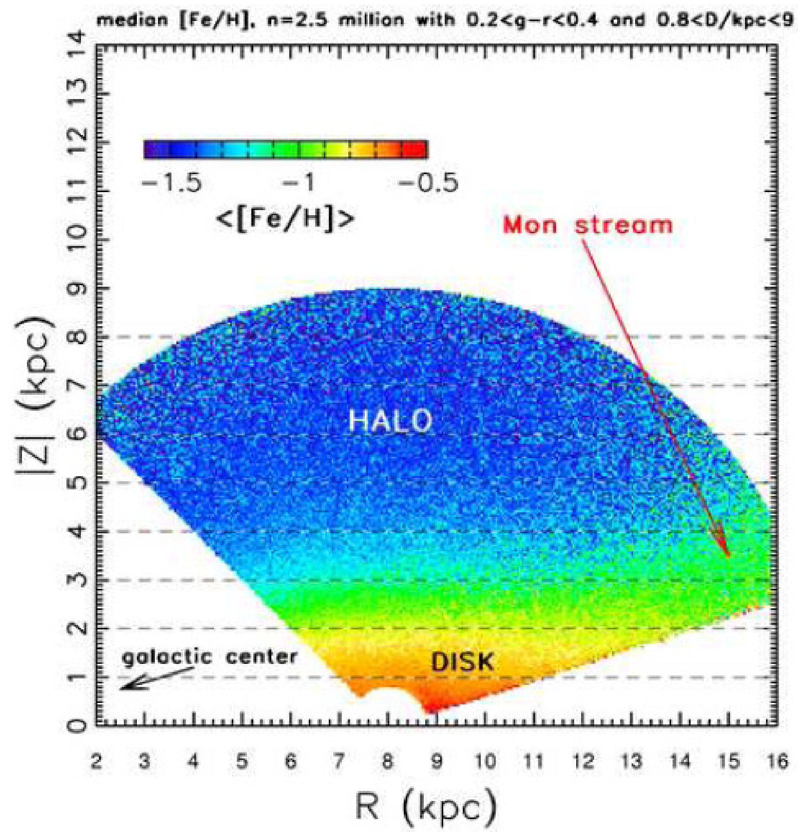
- SDSS yield 3D kinematics of stars [Fe/H]<-0.5
- All stars are located within 1kpc
- Thick disk and halo are clearly distinct.
- New: even among 'halo stars' there is a correlation between [Fe/H] and angular momentum
- [most metal poor stars have least angular momentum] → do early merged satellites have less angular momentum?



How does the stellar density distribution compare to the metallicity distribution?

(Ivezic et al 2008)





- Iso-ρ_*/[Fe/H] contours have NOT the same shape

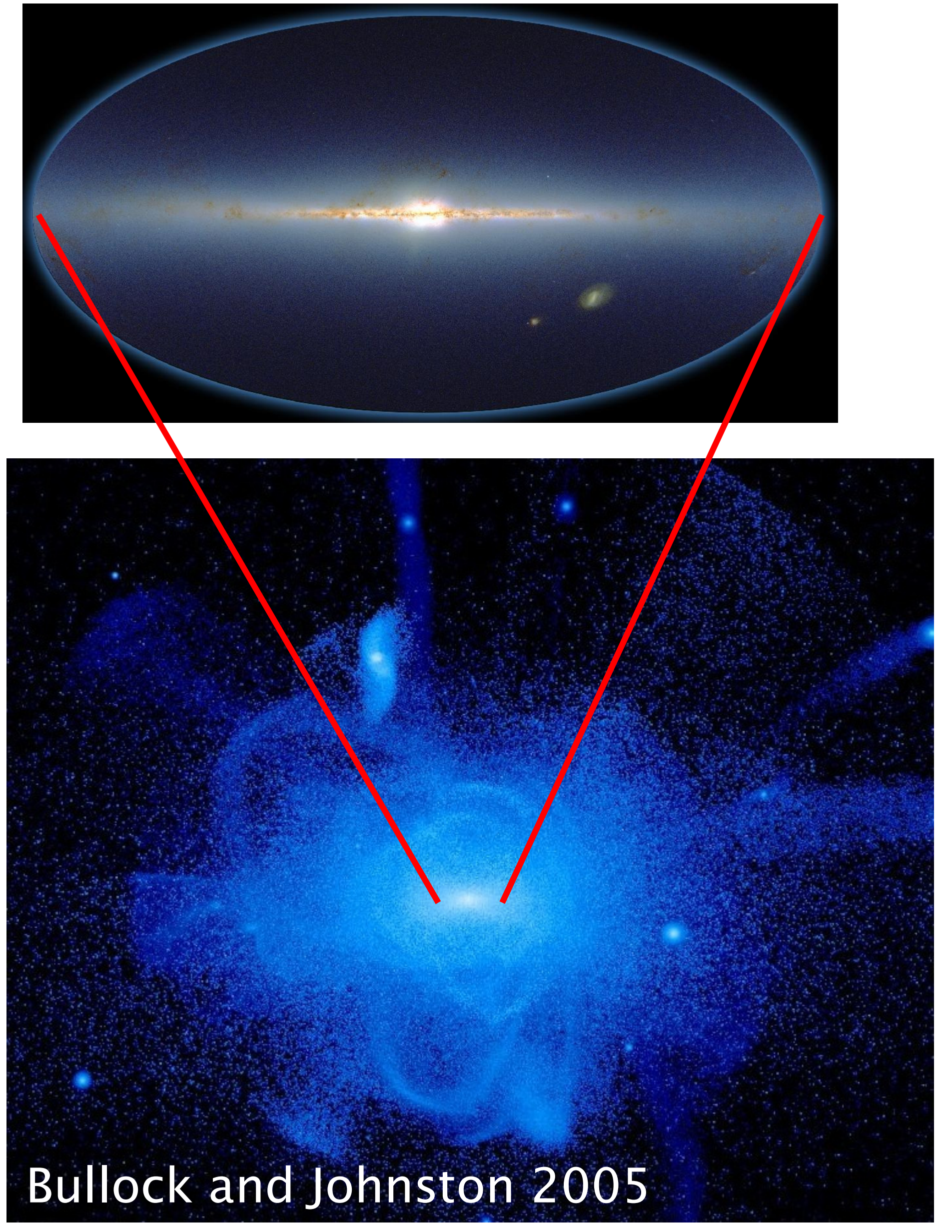
Stellar Structure in the Milky Way's Outskirts: Are Cosmological Expectations Met?

What is expected?

Streams and (Stellar) Halo Sub-Structure

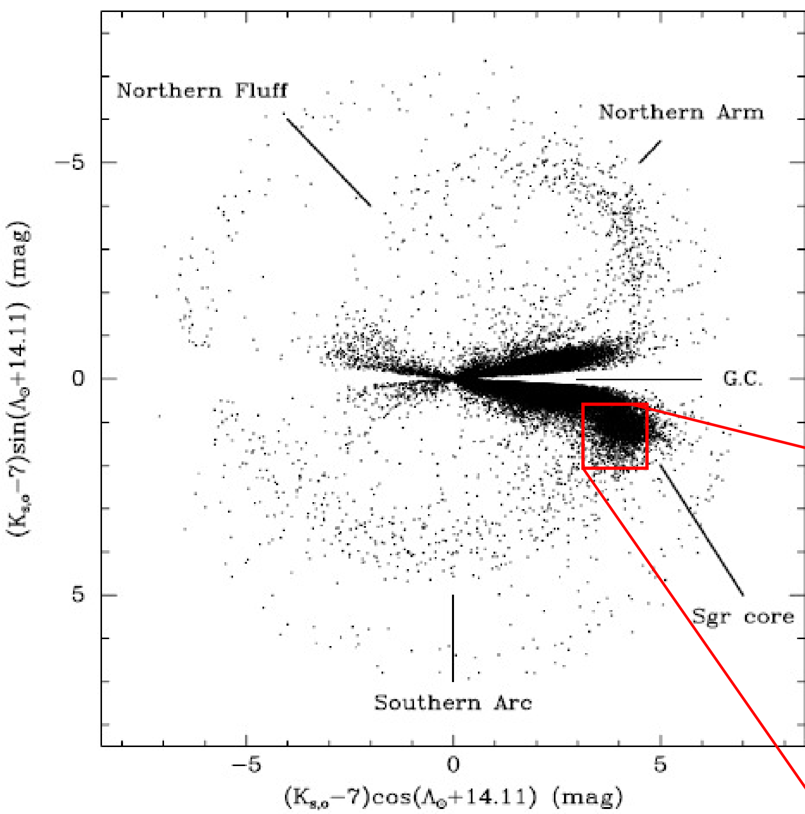
Finding and describing ultra-faint satellite galaxies

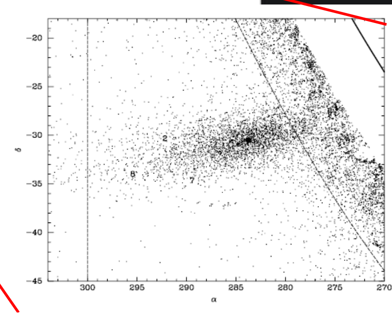
Matching up observations and models

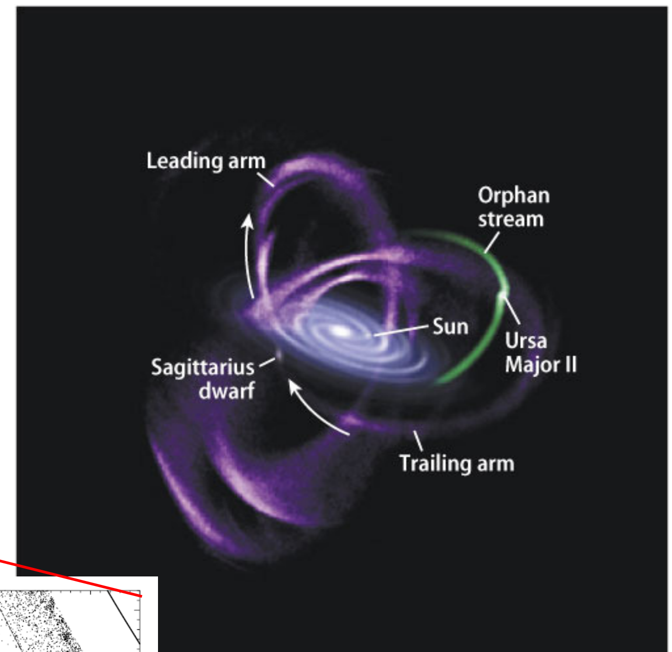

Bullock and Johnston 2005

Stellar Streams in the MW Halo

- How it started: the Sagittarius stream
  - Discovered by Ibata et al 1994
  - Best panoptic view: Majewski et al 2003

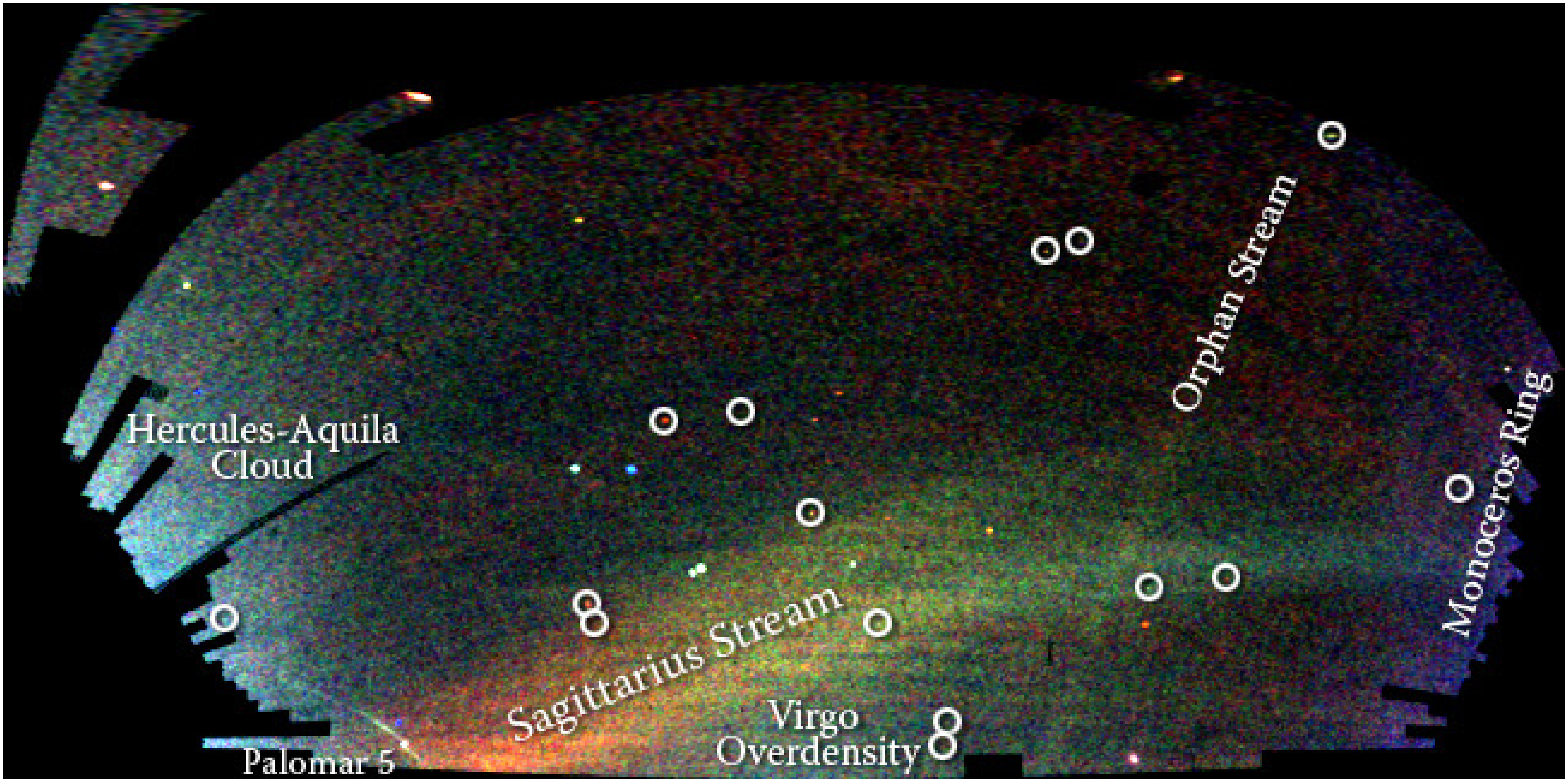






The prettiest view of stellar streams in the Milky Way's Halo

Belokurov et al 2007

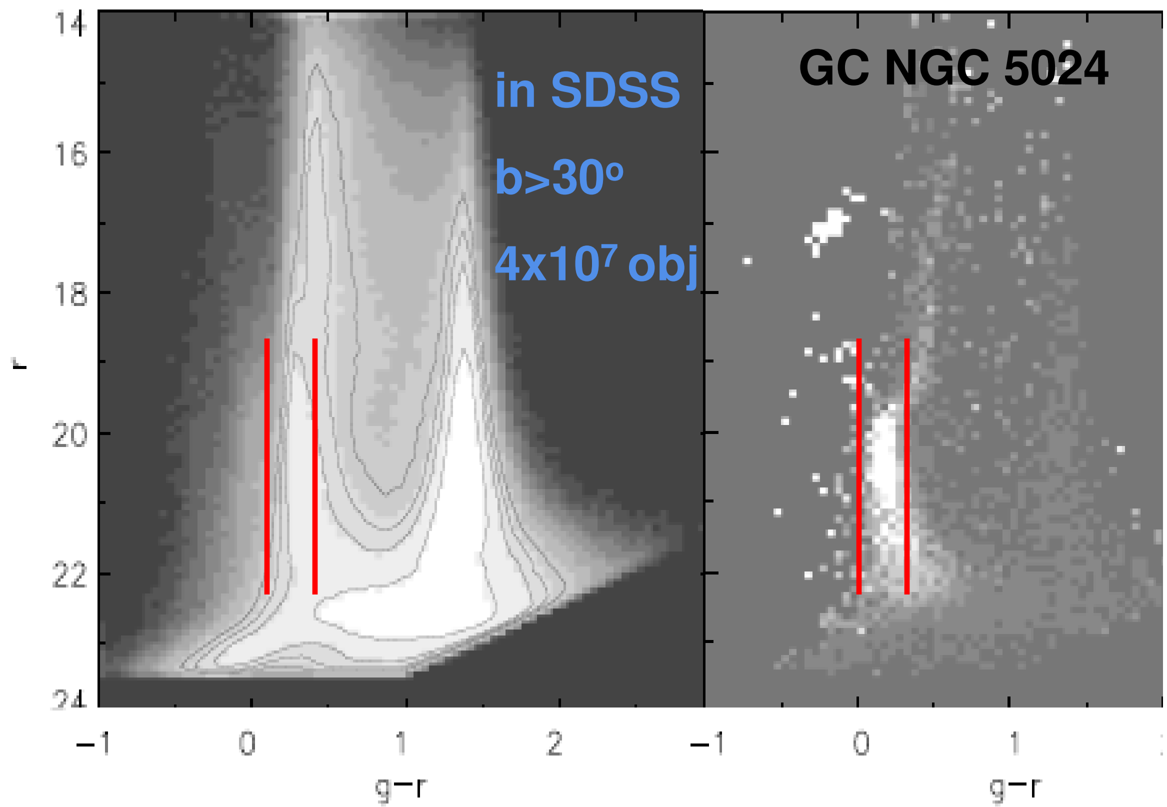


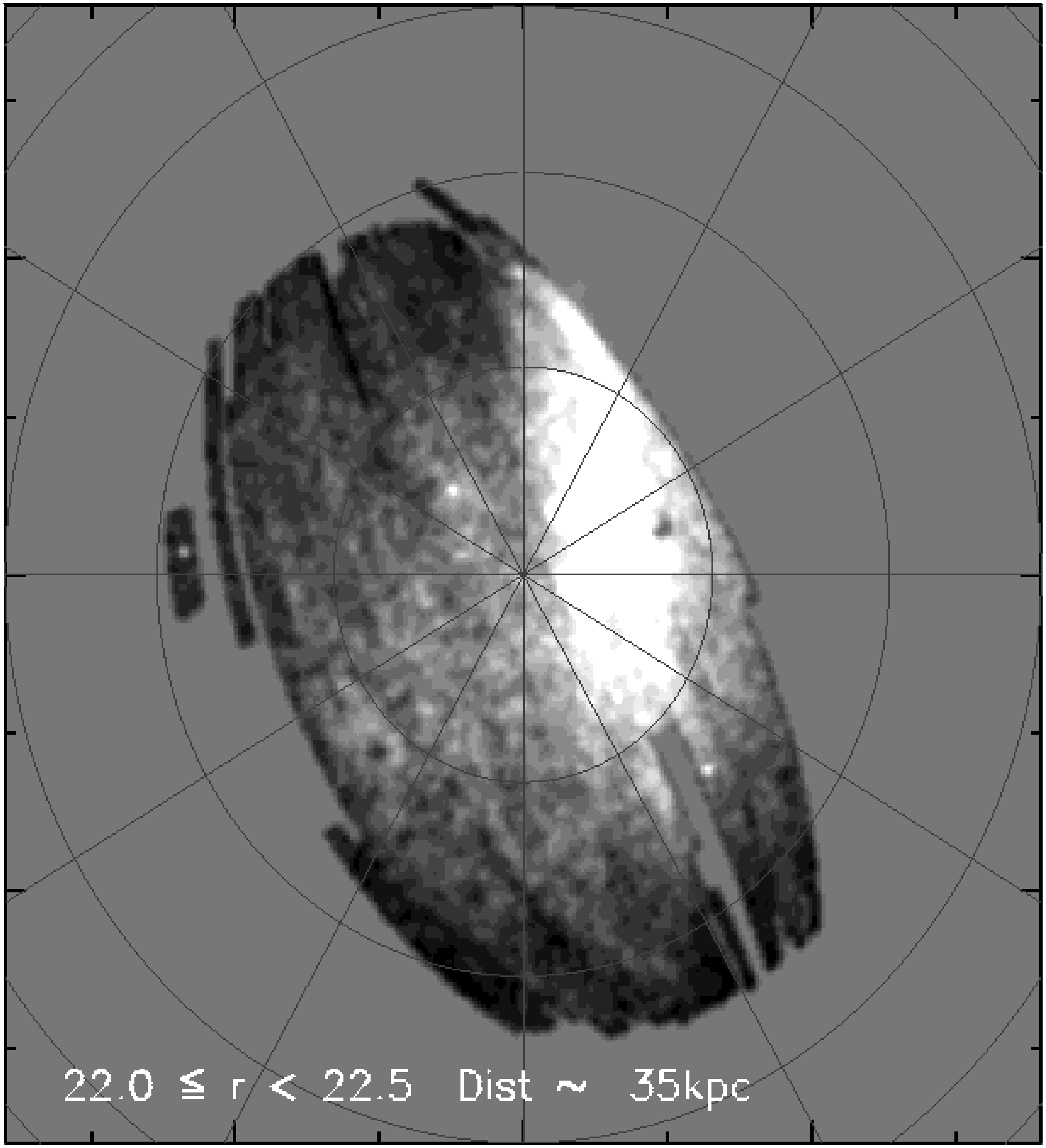
How important is disrupted sub-structure?

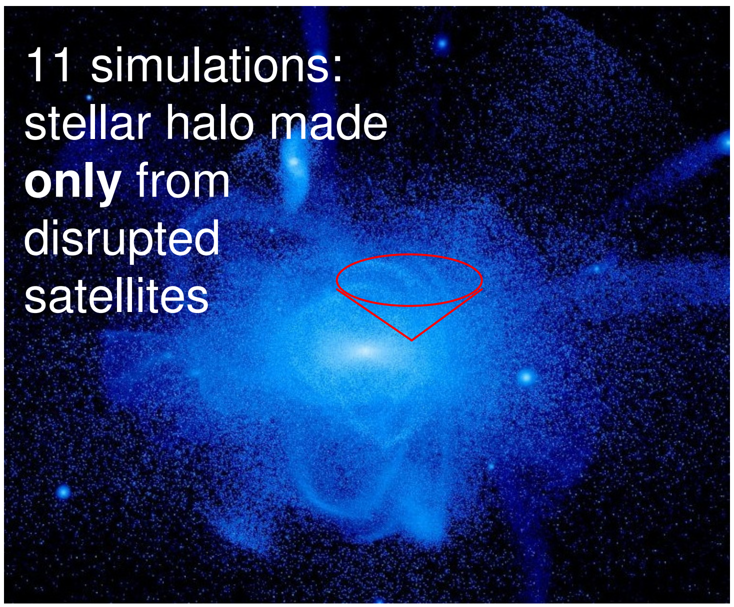
Constructing a 3D Map of the Milky Way's stellar halo

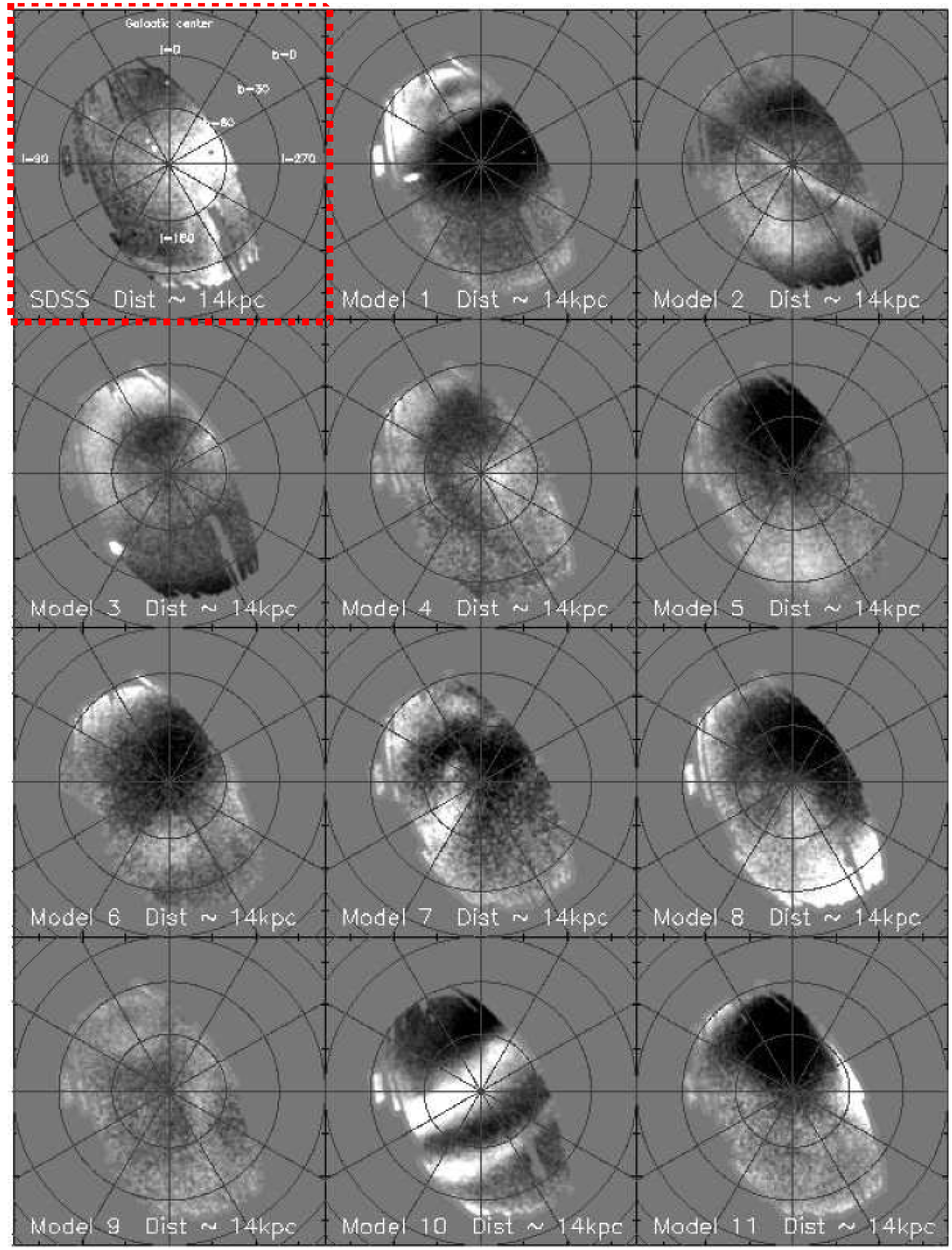
Bell, Zucker.. HWR et al 2007

- Identify turn-off-colored stars in SDSS (low Fe/H)
  - 0.2<g-r<0.4
  - 18.5<g<22.5
- Make maps in distance bins (or magnitude-sorted)




22.0 ≦ r < 22.5 Dist ~ 35kpc


11 simulations:
stellar halo made
only from
disrupted
satellites


Galactic center
l=0
b=0
b=30
l=90
l=270
l=180
SDSS Dist ~ 14kpc
Model 1 Dist ~ 14kpc
Model 2 Dist ~ 14kpc
Model 3 Dist ~ 14kpc
Model 4 Dist ~ 14kpc
Model 5 Dist ~ 14kpc
Model 6 Dist ~ 14kpc
Model 7 Dist ~ 14kpc
Model 8 Dist ~ 14kpc
Model 9 Dist ~ 14kpc
Model 10 Dist ~ 14kpc
Model 11 Dist ~ 14kpc

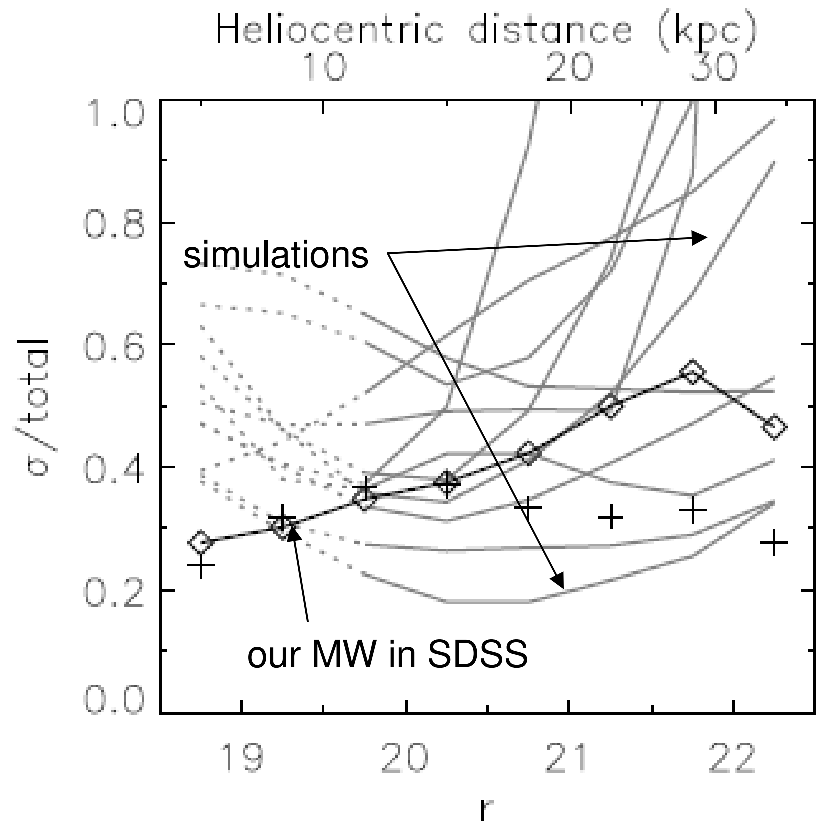
Sub-structure in the stellar halo: How do Data and Models Compare?

- Statistic:

  rms residual from best oblate power-law fit: *rms* = f(r)

  SDSS data *vs* 11 tidal-stream-only simulations (Johnston and Bullock 2005)

- **Data and model *rms*' indistinguishable**



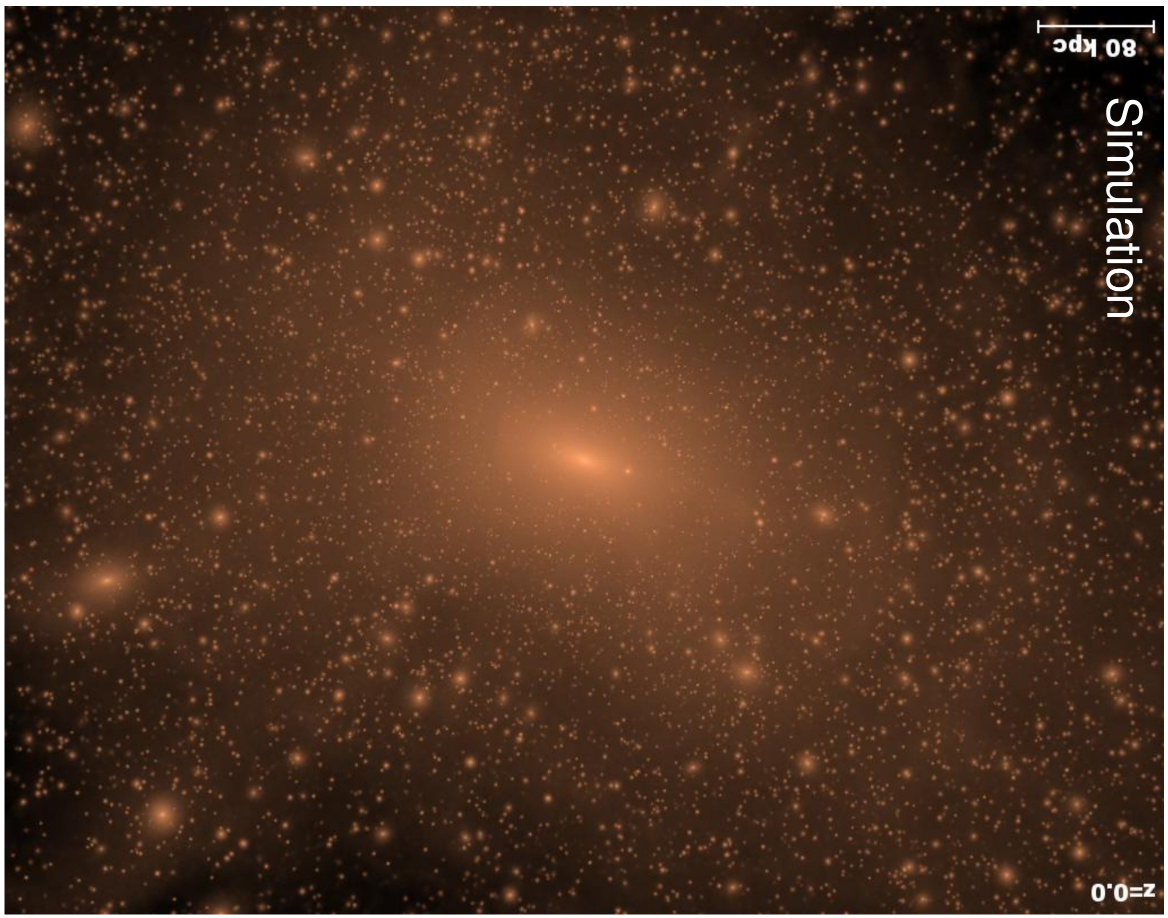
→ Much of (all of?) the MW's stellar halo could have resulted from disrupted satellites (=?= sub-structure)

→ There is no 'smooth' halo?

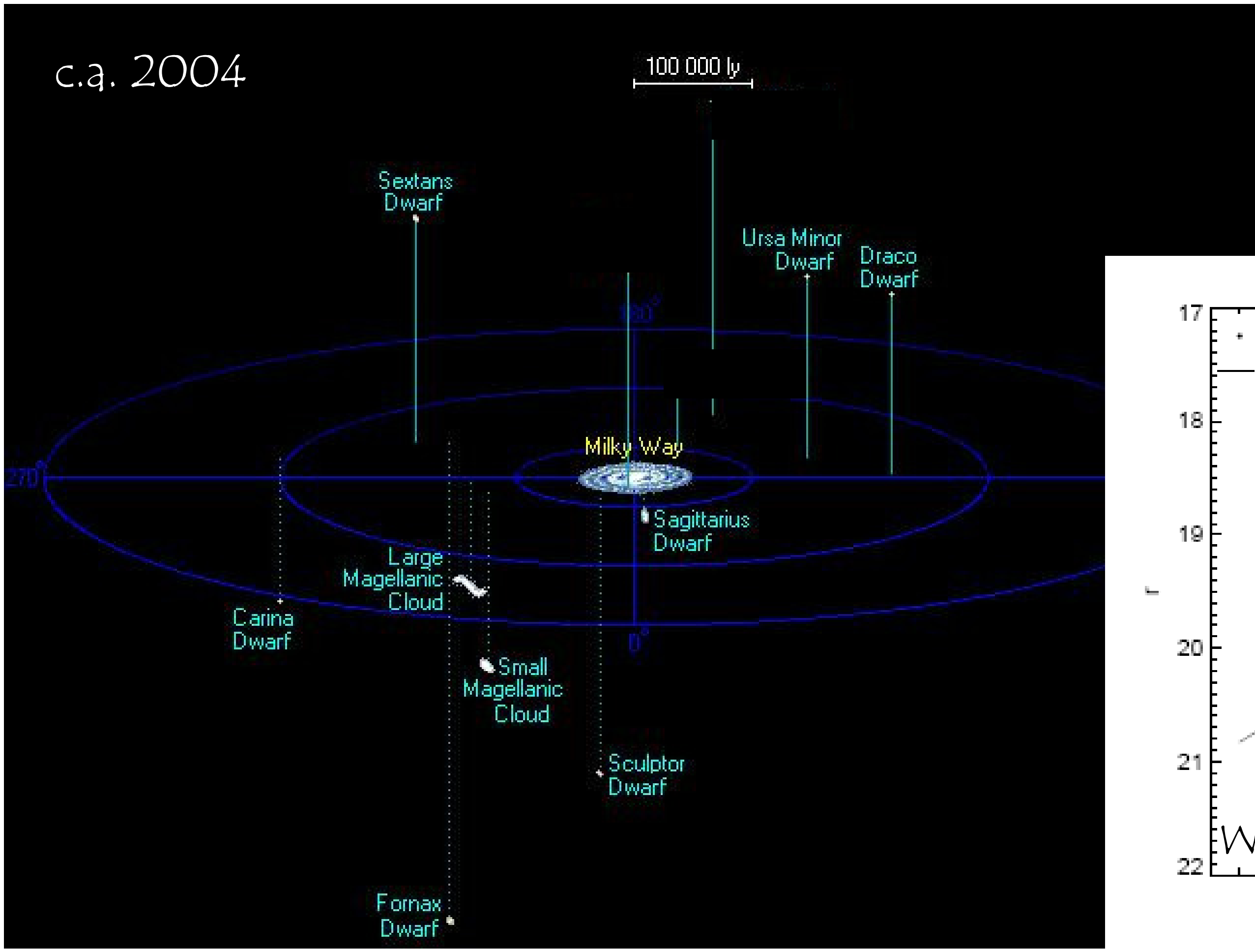
(at >15 kpc)

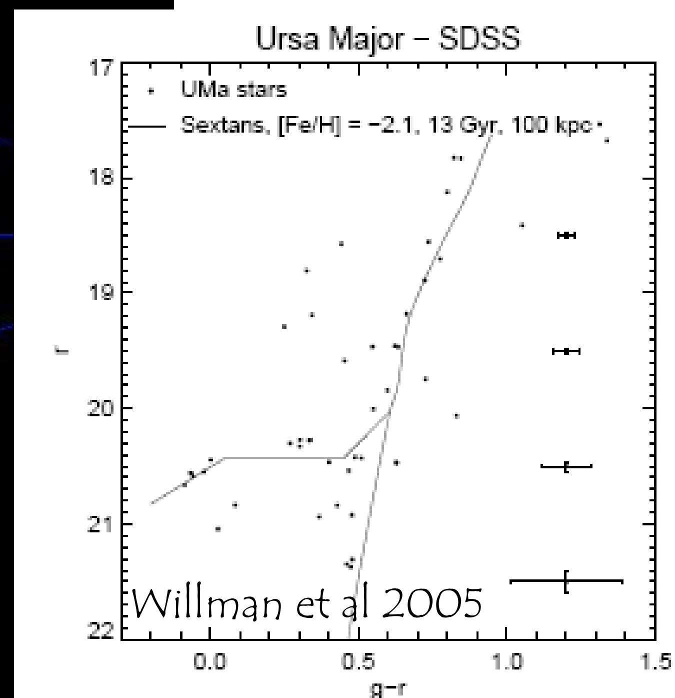
… or at least no need to postulate it

Can the number of observed satellite galaxies be *quantitatively* reconciled with the number of DM sub-halos?

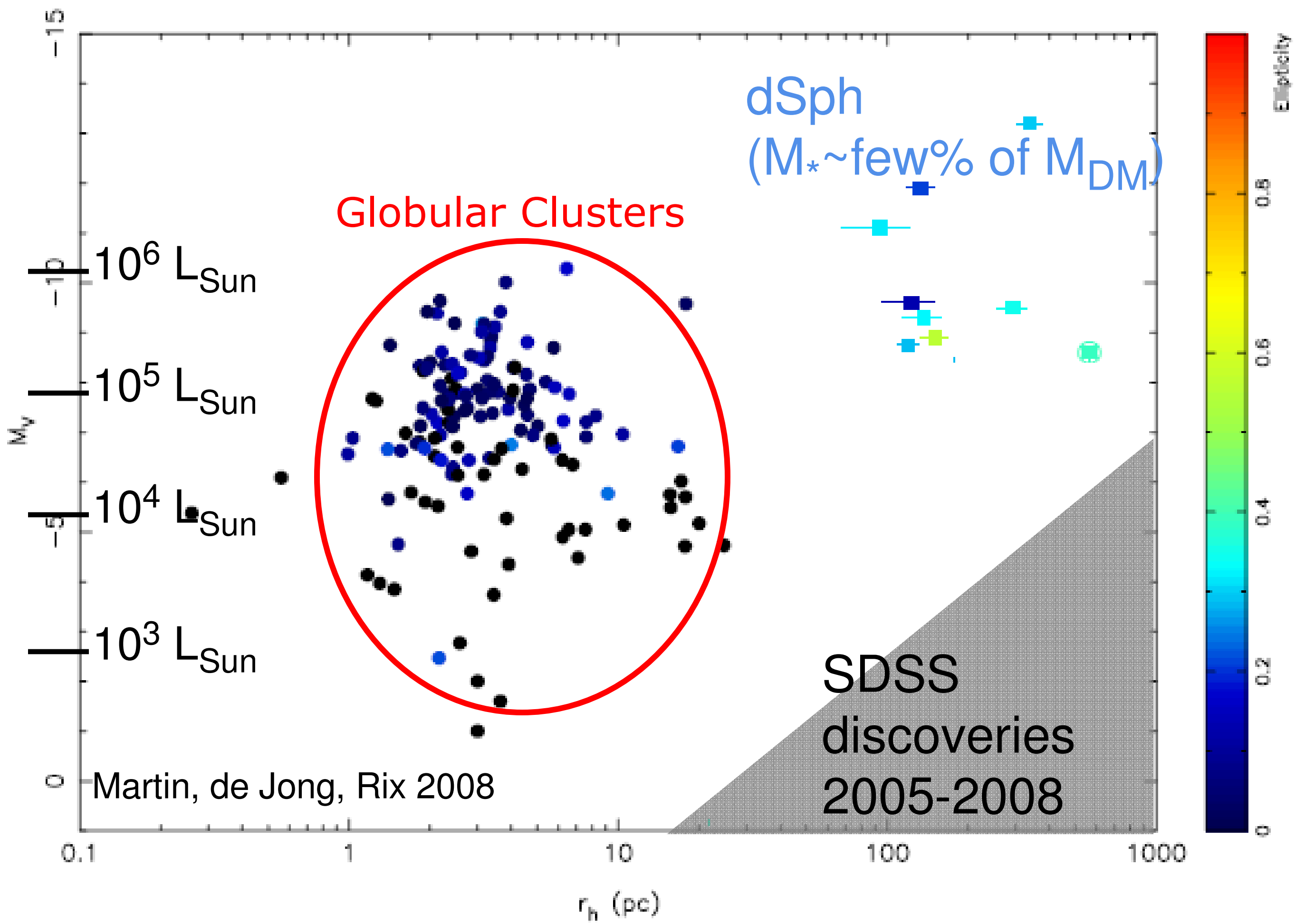


The Census of Milky Way Satellite Galaxies





The Newly Expanded Realm of Tiny Galaxies



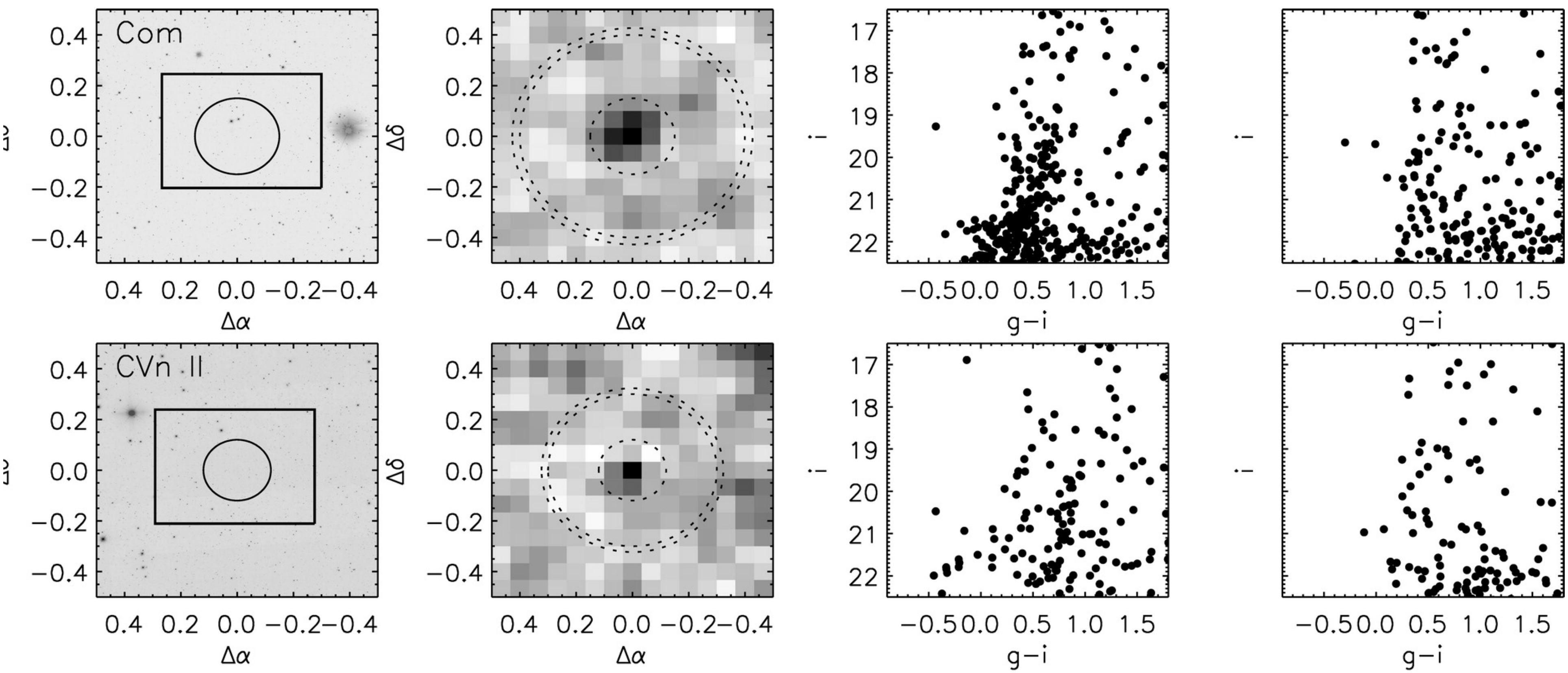
The Census of Milky Way Satellite Galaxies

CATS AND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANIONS[†]

V. BELOKUROV[1], D. B. ZUCKER[1], N. W. EVANS[1], J. T. KLEYNA[2], S. KOPOSOV[3], S. T. HODGKIN[1], M. J. IRWIN[1], G. GILMORE[1], M. I. WILKINSON[1], M. FELLHAUER[1], D. M. BRAMICH[1], P. C. HEWETT[1], S. VIDRIH[1], J. T. A. DE JONG[3], J. A. SMITH[4,5], H.-W. RIX[3], E. F. BELL[3], R. F. G. WYSE[6], H. J. NEWBERG[7], P. A. MAYEUR[7,8], B. YANNY[9], C. M. ROCKOSI[10], O. Y. GNEDIN[11], D. P. SCHNEIDER[12], T. C. BEERS[13], J. C. BARENTINE[14], H. BREWINGTON[14], J. BRINKMANN[14], M. HARVANEK[14], S. J. KLEINMAN[15], J. KRZESINSKI[14,16], D. LONG[14], A. NITTA[17], S. A. SNEDDEN[14]

SUBMITTED TO *The Astrophysical Journal*

Belokurov et al 2007 based on SDSS Data



Properties of bound structures in the Milky Way halo

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

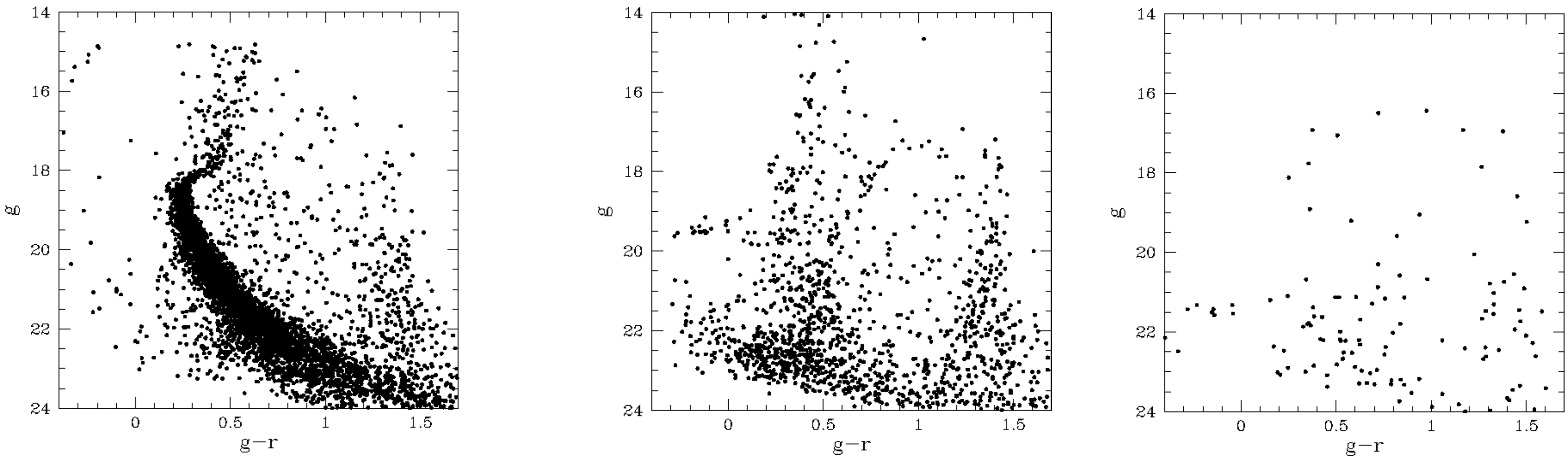
High S/N CMD

M13 (SDSS)

Low S/N CMD

Boötes I (SDSS)

Leo IV (SDSS)

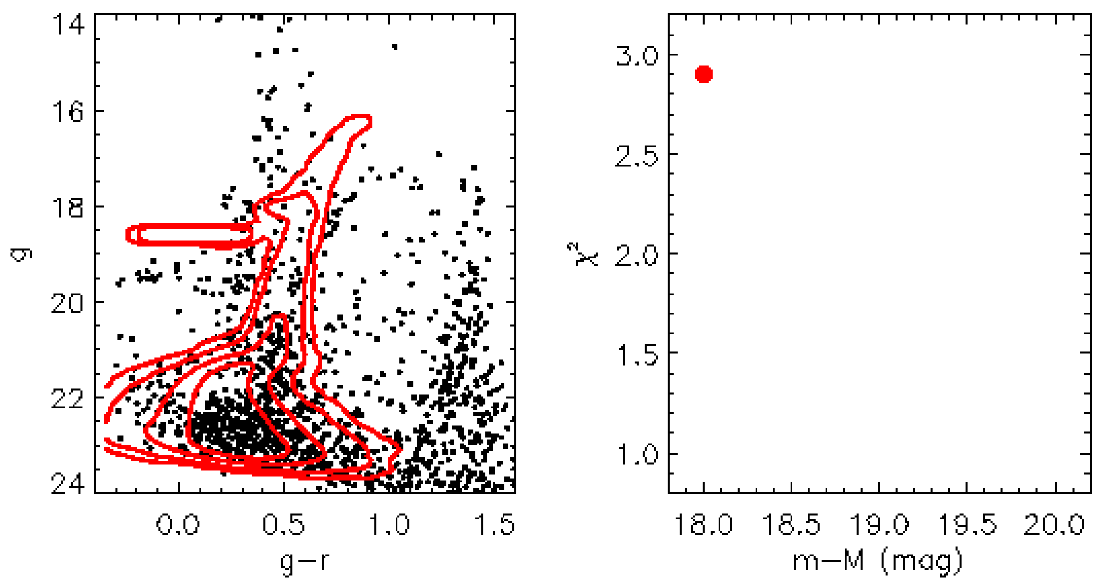


Properties of bound structures in the Milky Way halo

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

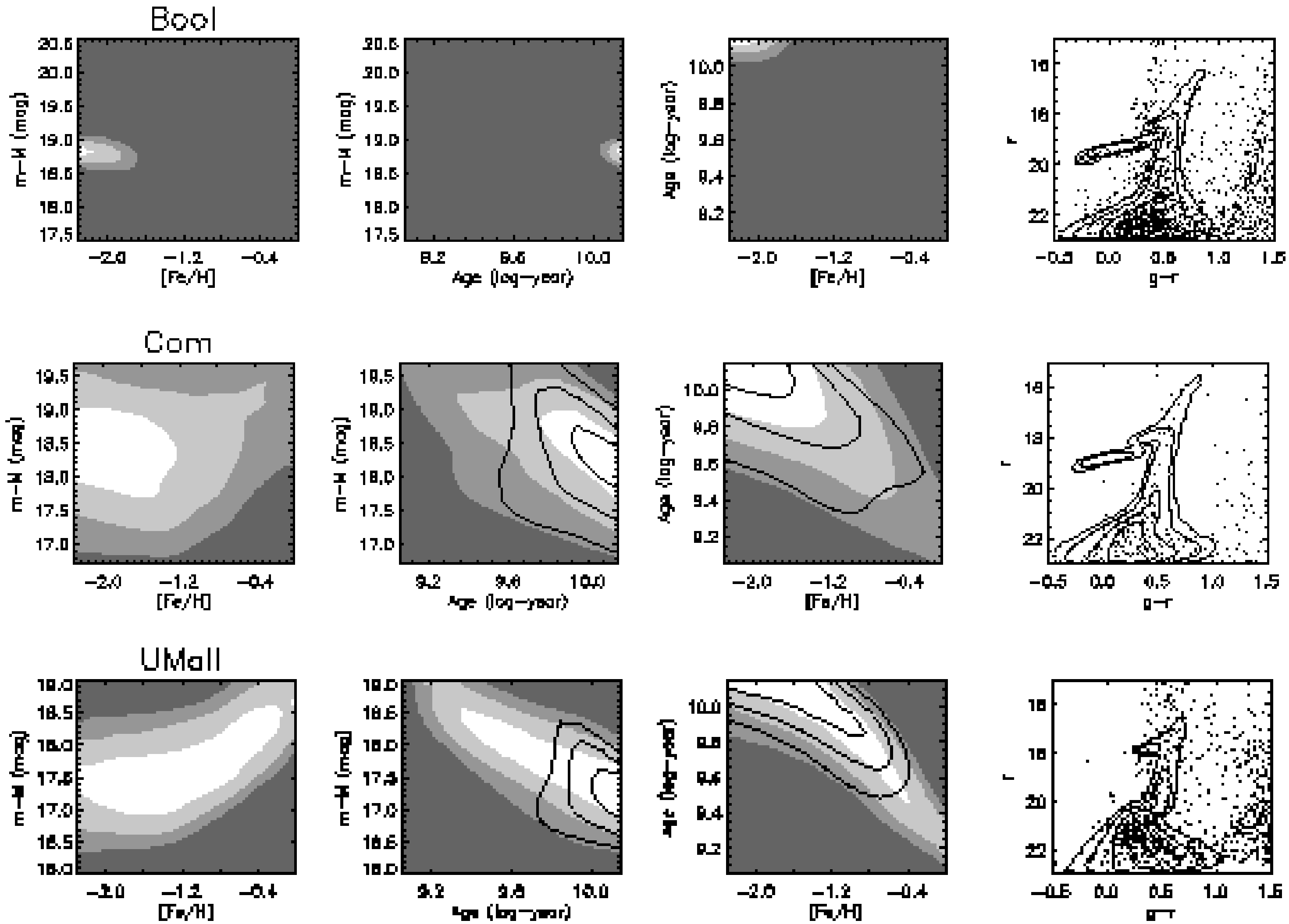


Properties of bound structures in the Milky Way halo

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



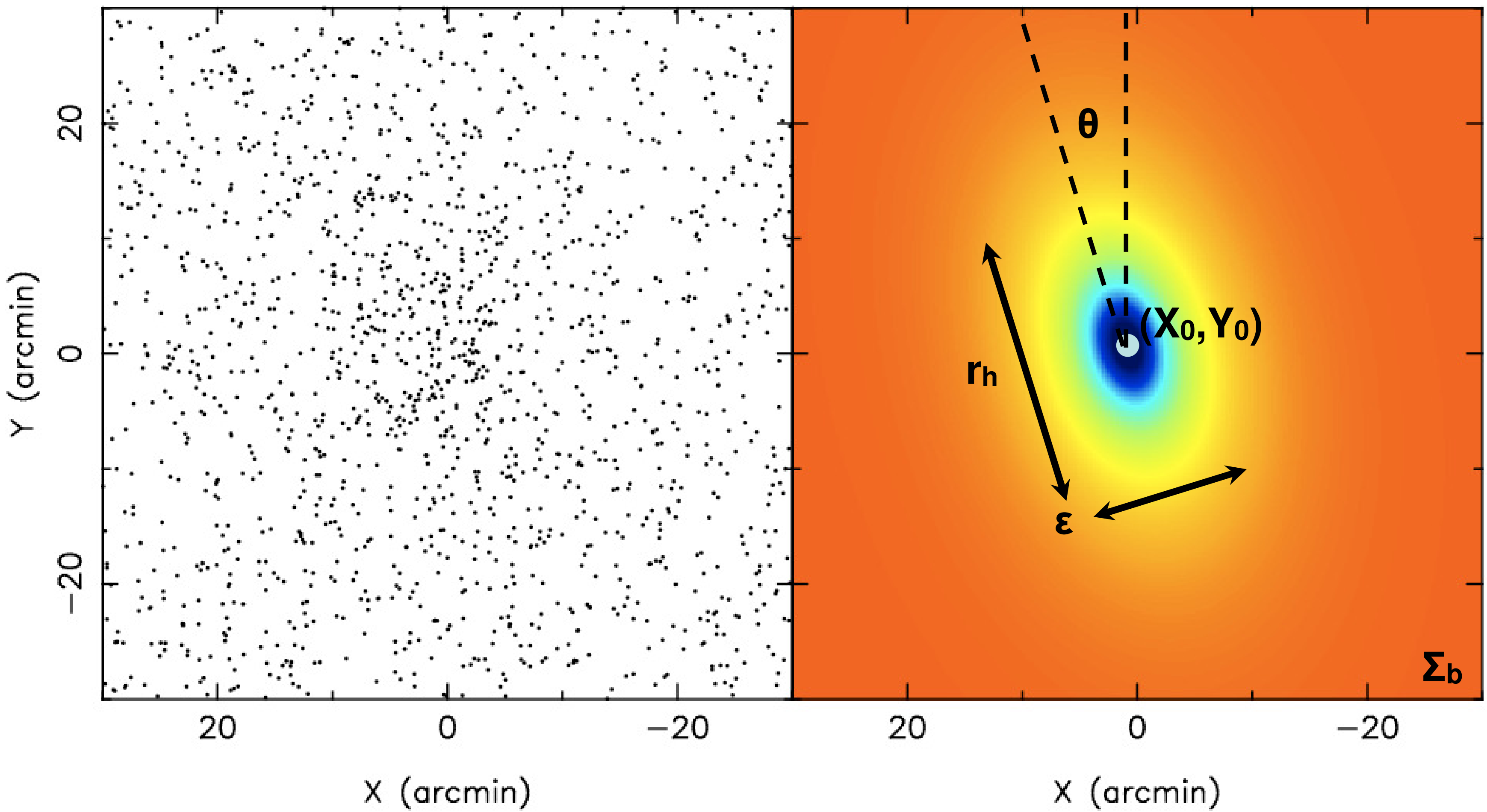
(JdJ et al. 2008)

What are the structural properties of the ultra-faint galaxies: luminosity, size, shape?

Martin, de Jong, Rix, 2008

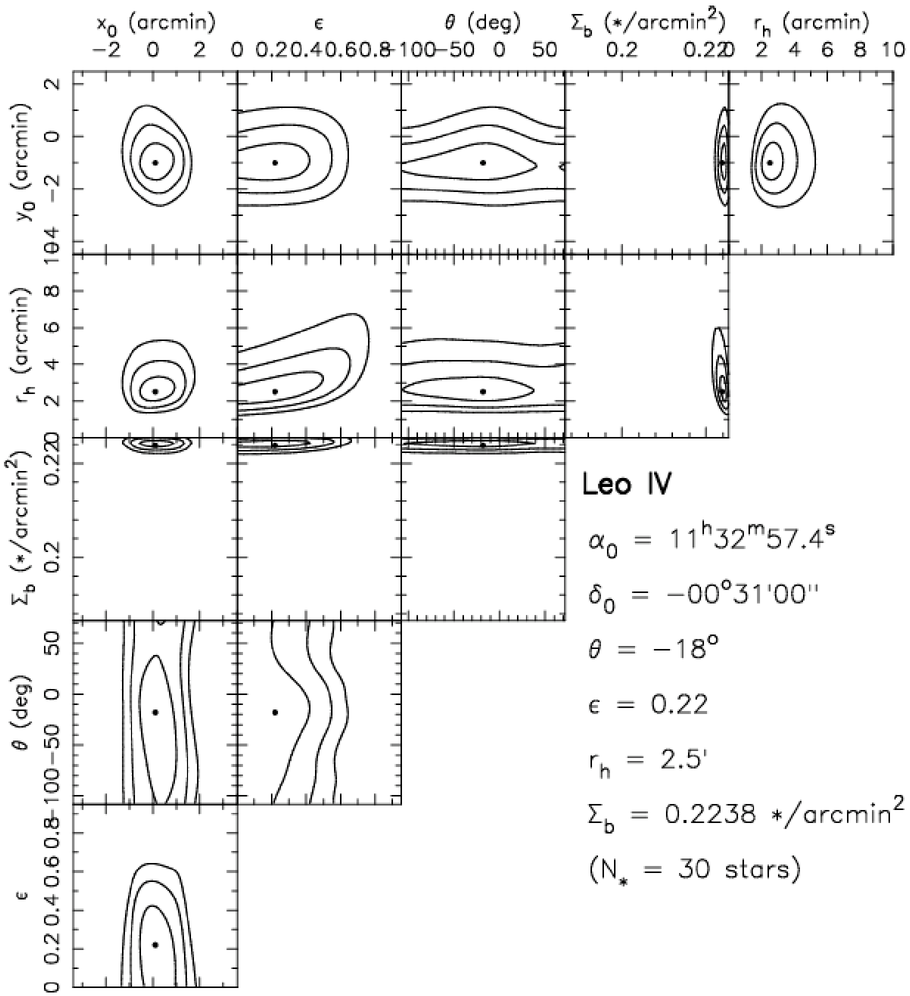
From SDSS data, homogeneous structural parameters and properties:

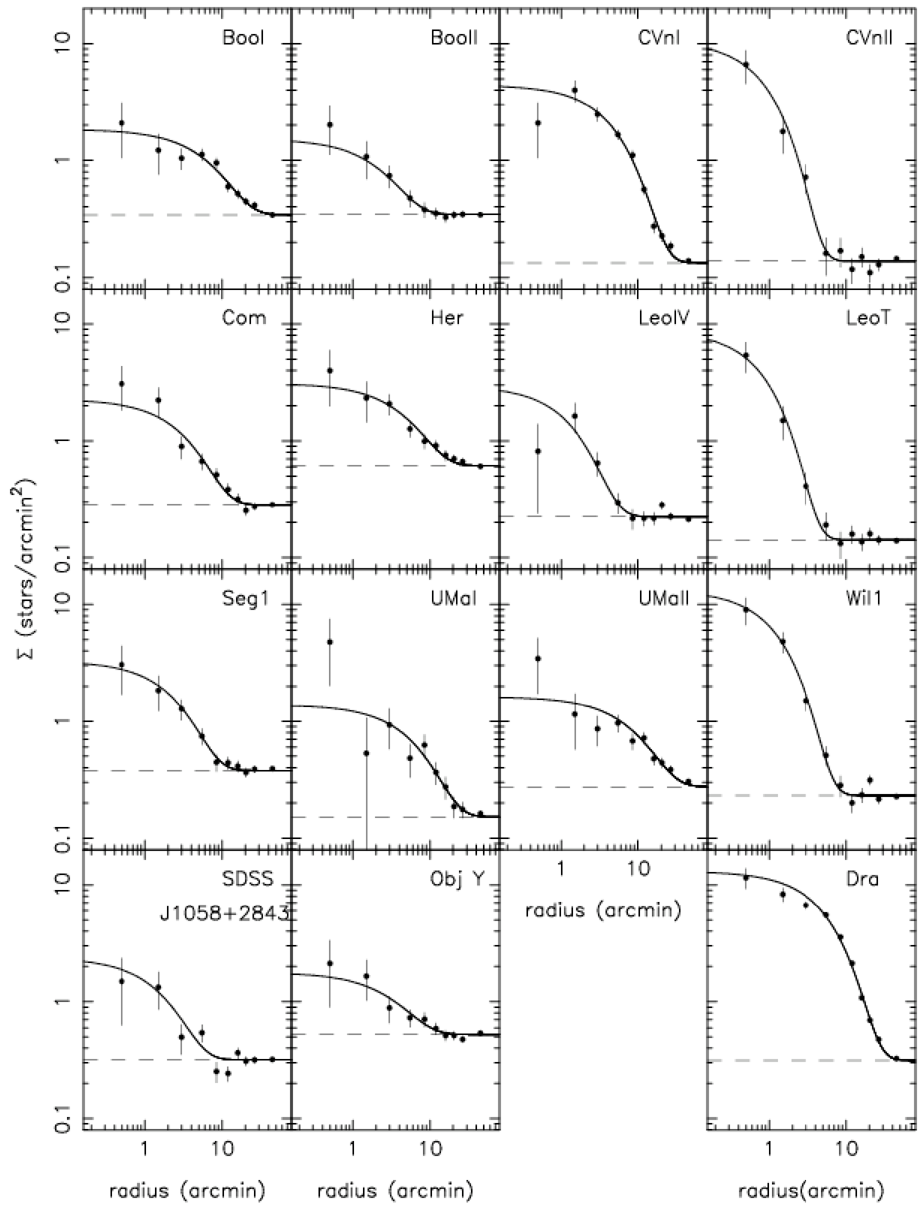
- **Best model with exponential density profile**



Martin, de Jong & Rix (2008b)

Maximum Likelihood Fits



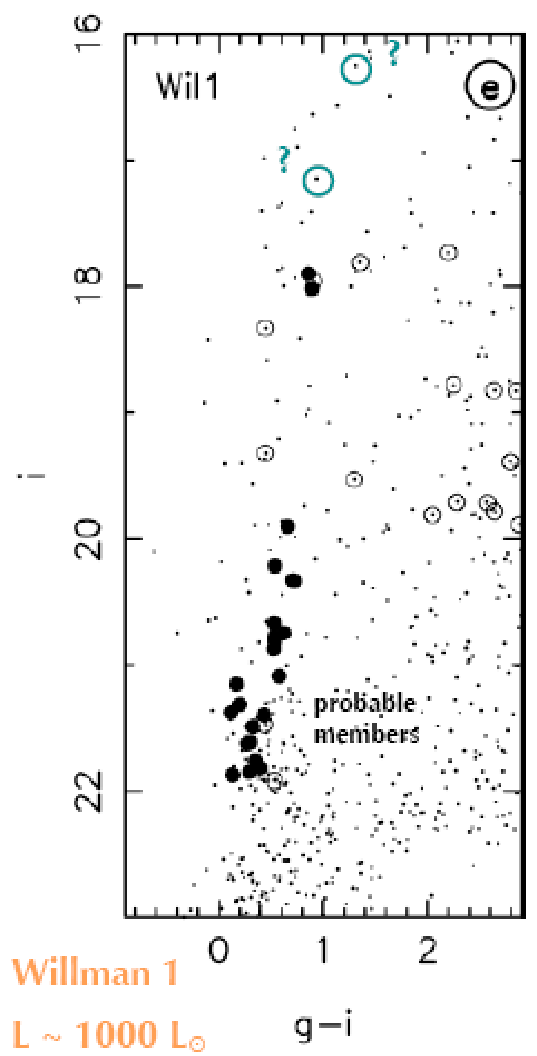


Magnitudes

tip RGB

?

M_V measured from member stars' luminosity suffers from 'CMD shot-noise'



Willman 1

$L \sim 1000\ L_\odot$

MAGNITUDES

tip RGB

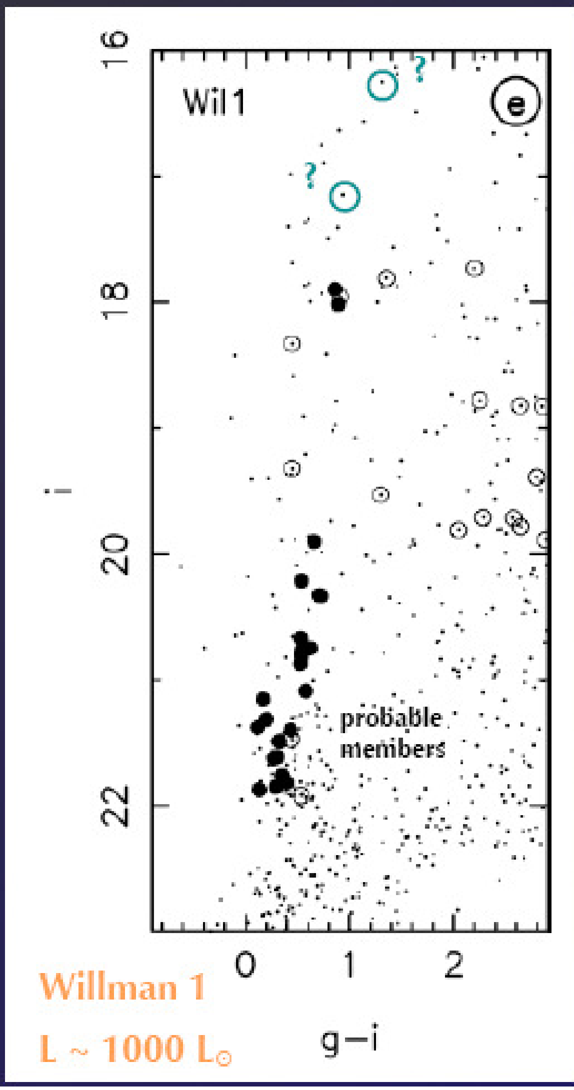
?

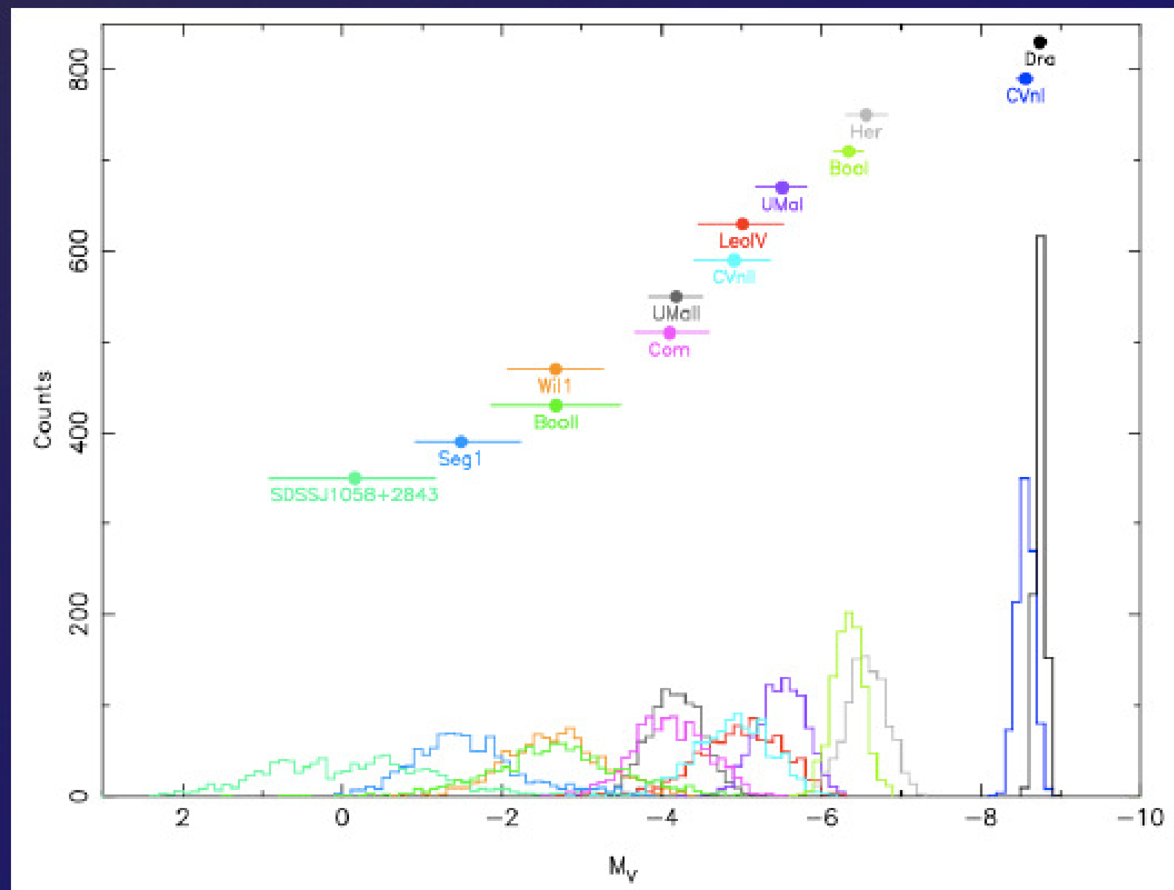
M_V measured from member stars' luminosity suffers from 'CMD shot-noise'

ML gives N* + stellar population models (de Jong et al. 07) from the same dataset → typical M_V

10^3 times $N^* \pm \delta N^*$ —stellar pop.→ 'a' CMD —LF correction→ 'a' M_V

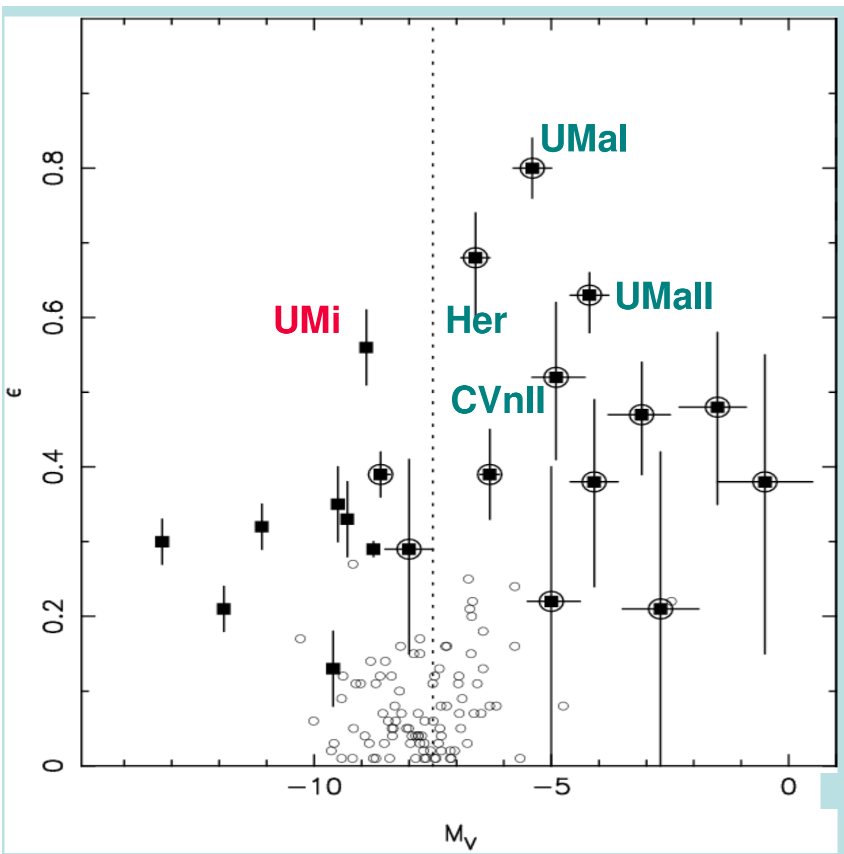
(& 'a' mass)

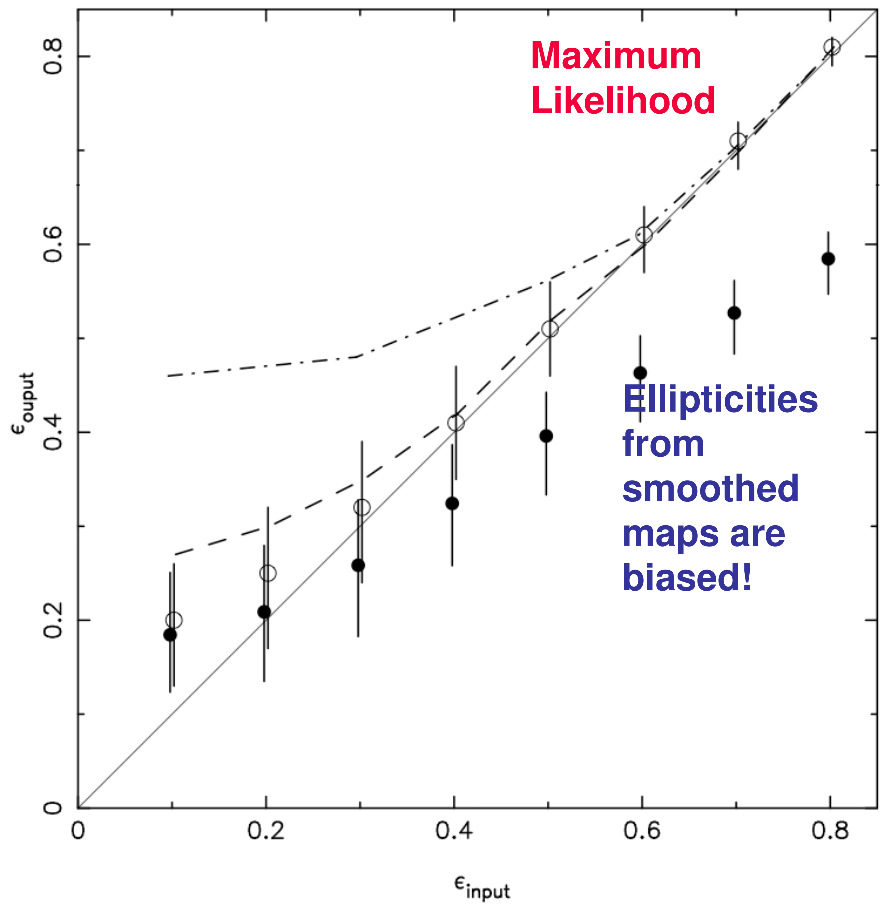




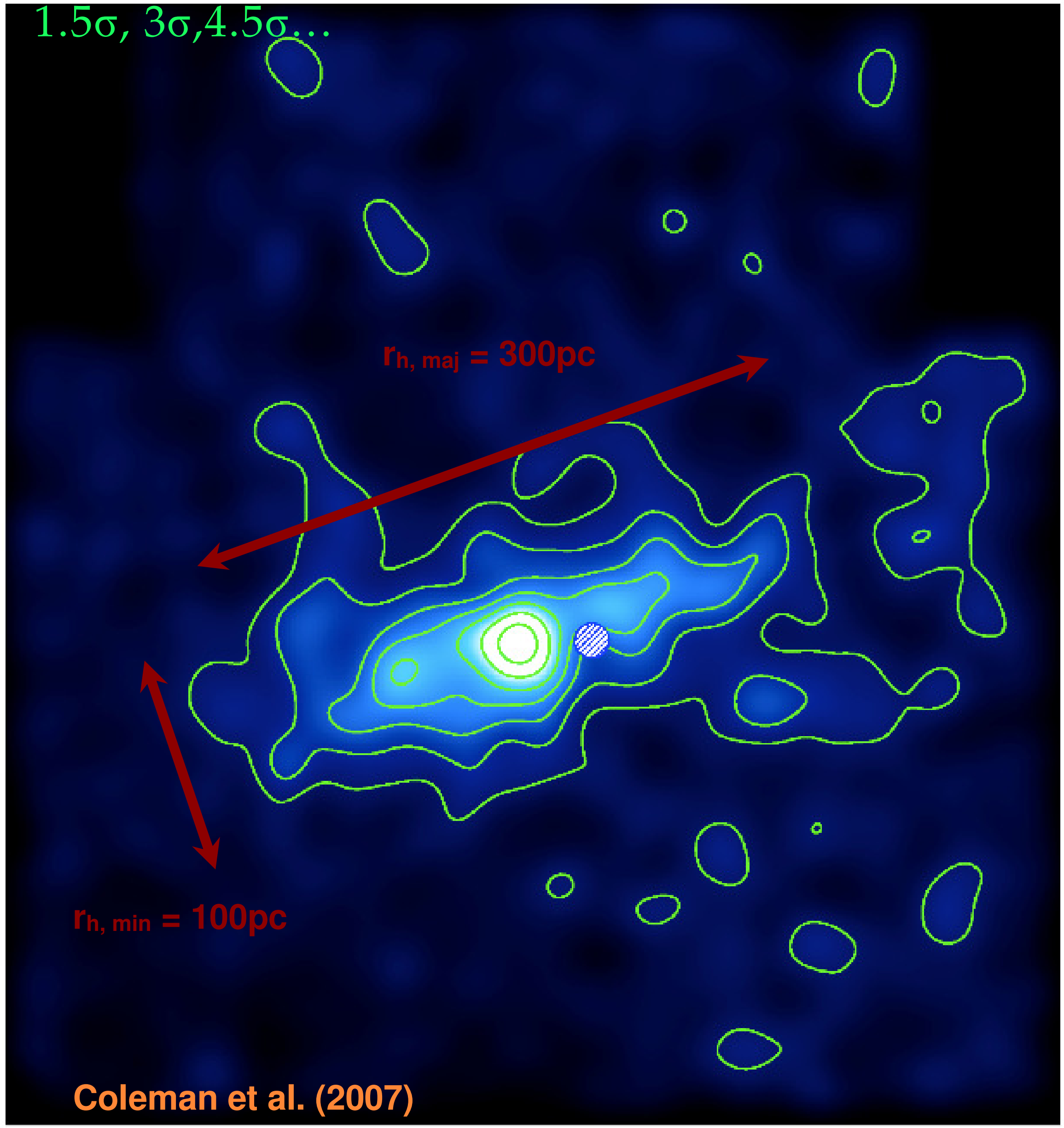
Ellipticity

- Faint galaxies appear flatter than bright galaxies
  - mean ε = 0.32±0.02 (M_V > −8.0) vs. ε = 0.47±0.03 (M_V > −8.0)
  - KS test: 99.6% probability that different subsamples
  - 3 most flattened systems are faint

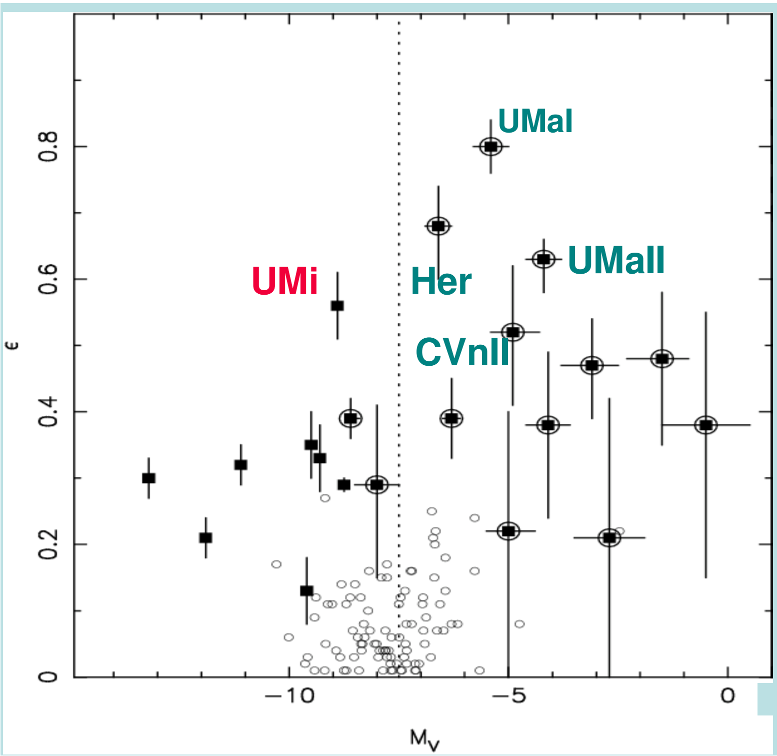




Hercules



Faint galaxies appear flatter than 'bright' ones… Why?



- **Disk systems seen edge-on?**
  - but low $5<\sigma_{vr}<10$ km/s means intrinsic σ_{vr} ~ 0 km/s when corrected from rotation
- **Consequence of DM halo shape?**
  - center of DM halo are apparently more elliptical – but not that much
- **Tidal interactions with the MW?**
  - Would make for some very eccentric orbits
  - Not all faint systems could be disrupting versions of brighter galaxies (σ_{vr} too high in most cases)
  - Some satellites are streams/stream blobs?