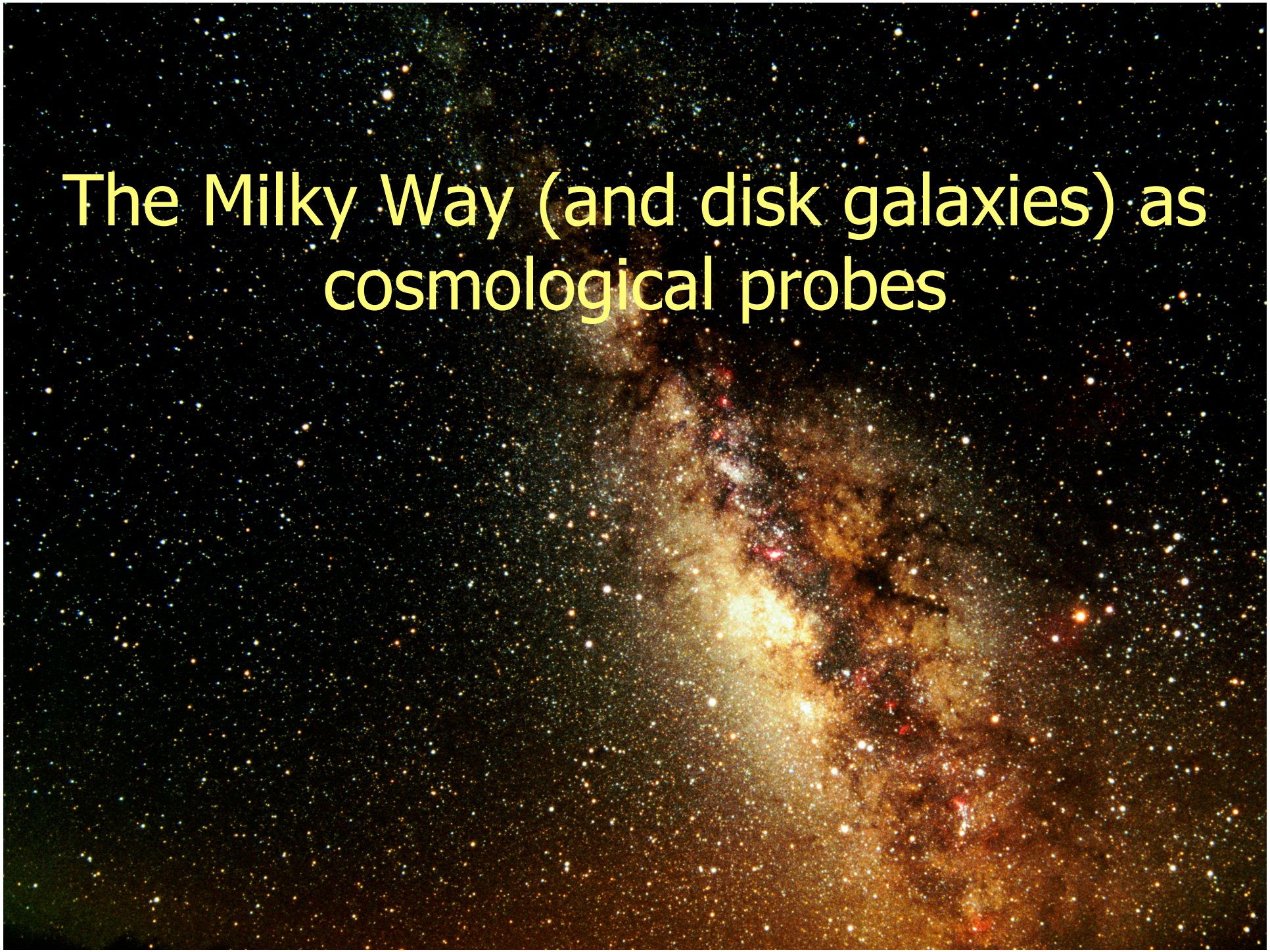
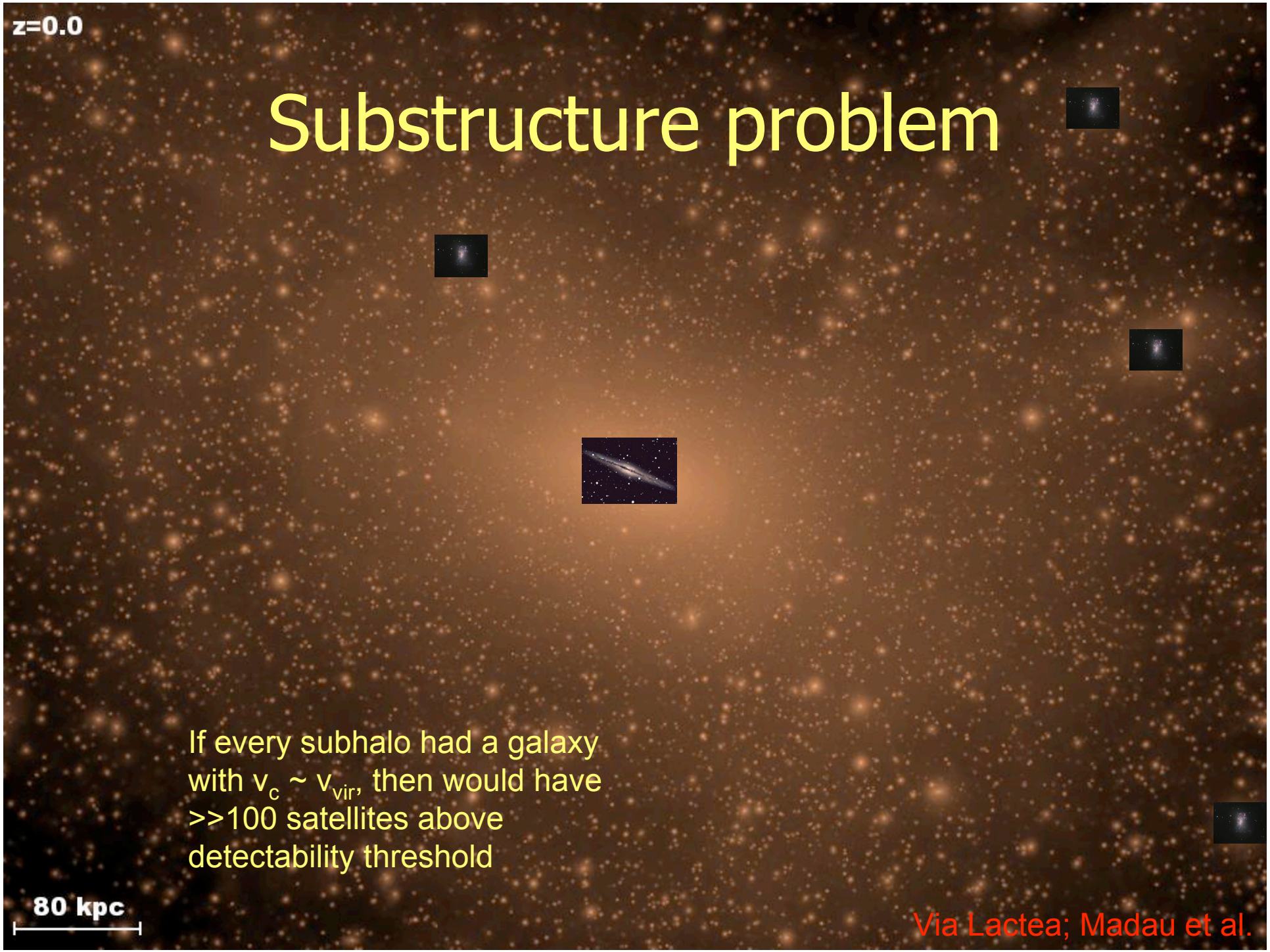

The Milky Way (and disk galaxies) as
cosmological probes

Plan

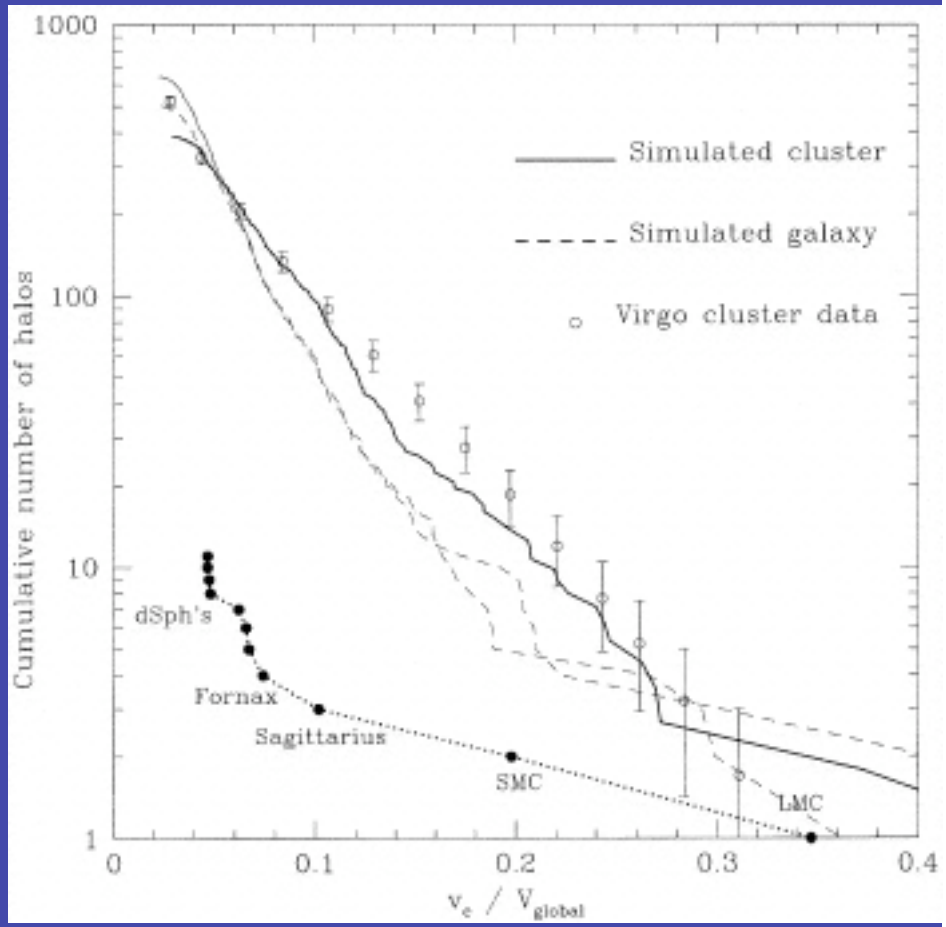
- Substructure problem and the satellite census
- Look for signs of assembly of MW galaxy in our stellar halo (and thin/thick disk)
- Discussion of the origin/meaning of the thick disk
  - Generated by debris
  - Generated during first gas-rich merger
  - Puffed up thin disk


z=0.0
Substructure problem
If every subhalo had a galaxy with $v_c \sim v_{vir}$, then would have >>100 satellites above detectability threshold
80 kpc
Via Lactea; Madau et al.

Substructure problem

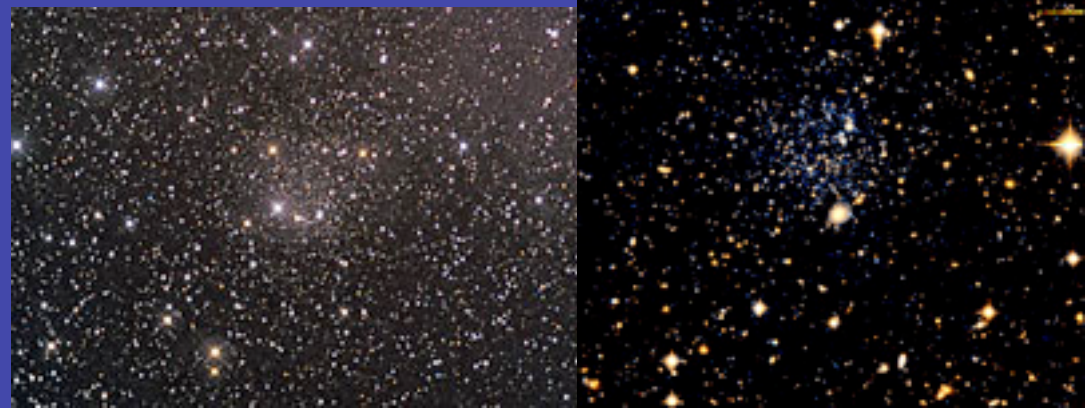
- Proposed solutions
  - Few (or no) baryons in halos <~ 30km/s (Bullock et al. 2000)
    - Then stars need to live in center of DM potential well
      - Ionising background keeps gas above virial temperature?
      - Powerful feedback blows out gas after formation of just a few stars… (e.g., Dekel & Silk 1986)
  - Enthusiastic tidal disruption
    - Stoehr et al. 2002
  - Dark matter halos aren't there
    - Didn't form (warm dark matter)

Moore et al. 1999



Satellite discoveries

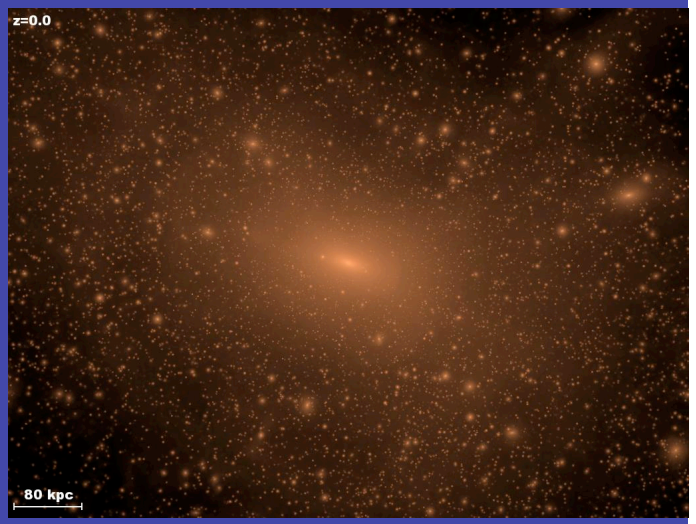
- Last 5 years: star counting with the SDSS
  - Look for overdensity of faint stars
  - >10 discoveries in last 5 years…

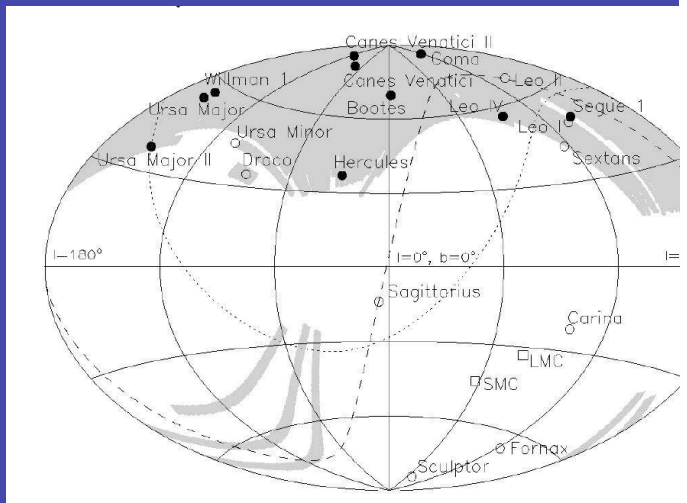


What about *bound* sub-structure, i.e. DM sub-halos and satellite galaxies?

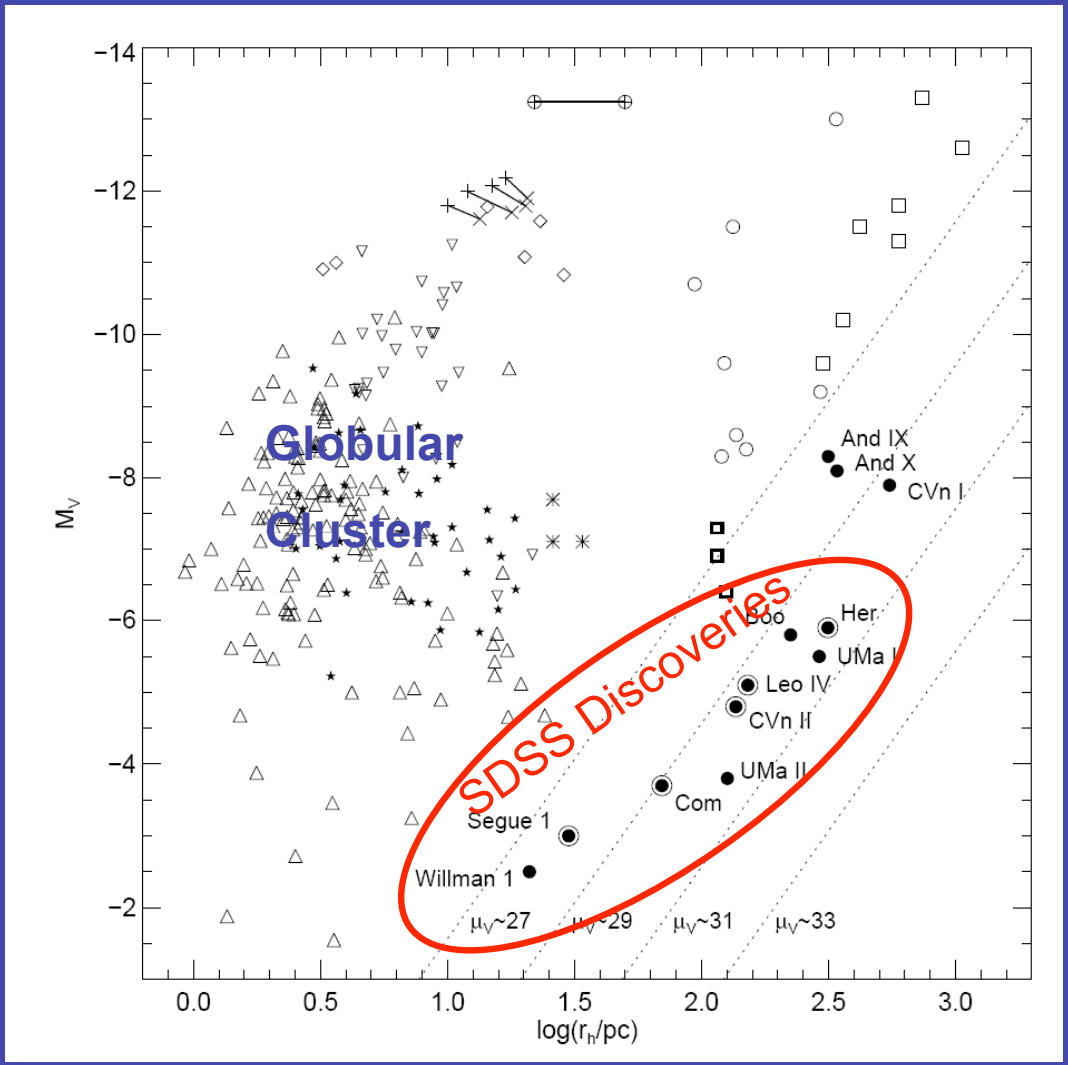
I. Quantify current MW satellite galaxy census (Koposov, HWR et al 2008)
- Algorithmic finding efficiency of SDSS
- Estimate effective search volumes
- Estimate extremely low-lum. end of the galaxy luminosity function

II. Comparison with Models
- LF, radial distribution, sizes,..
- kinematics, masses (Simon&Geha,..)





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



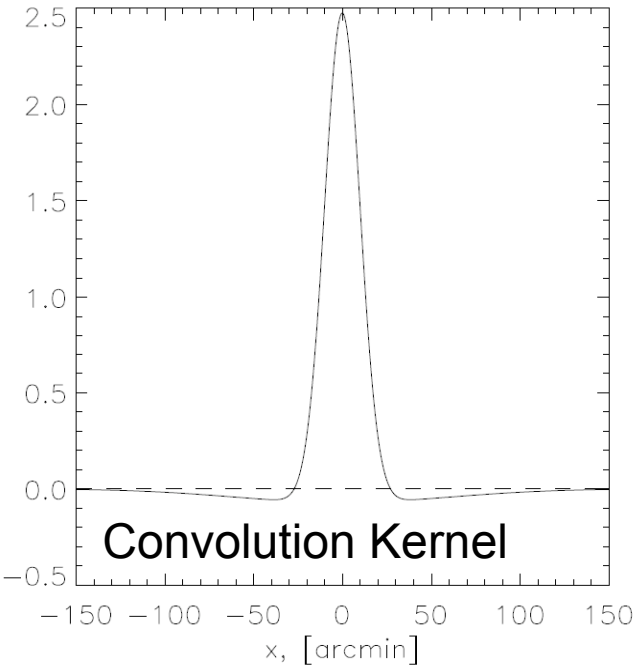
Quantifying SDSS's Ability to Find Milky Way Satellites

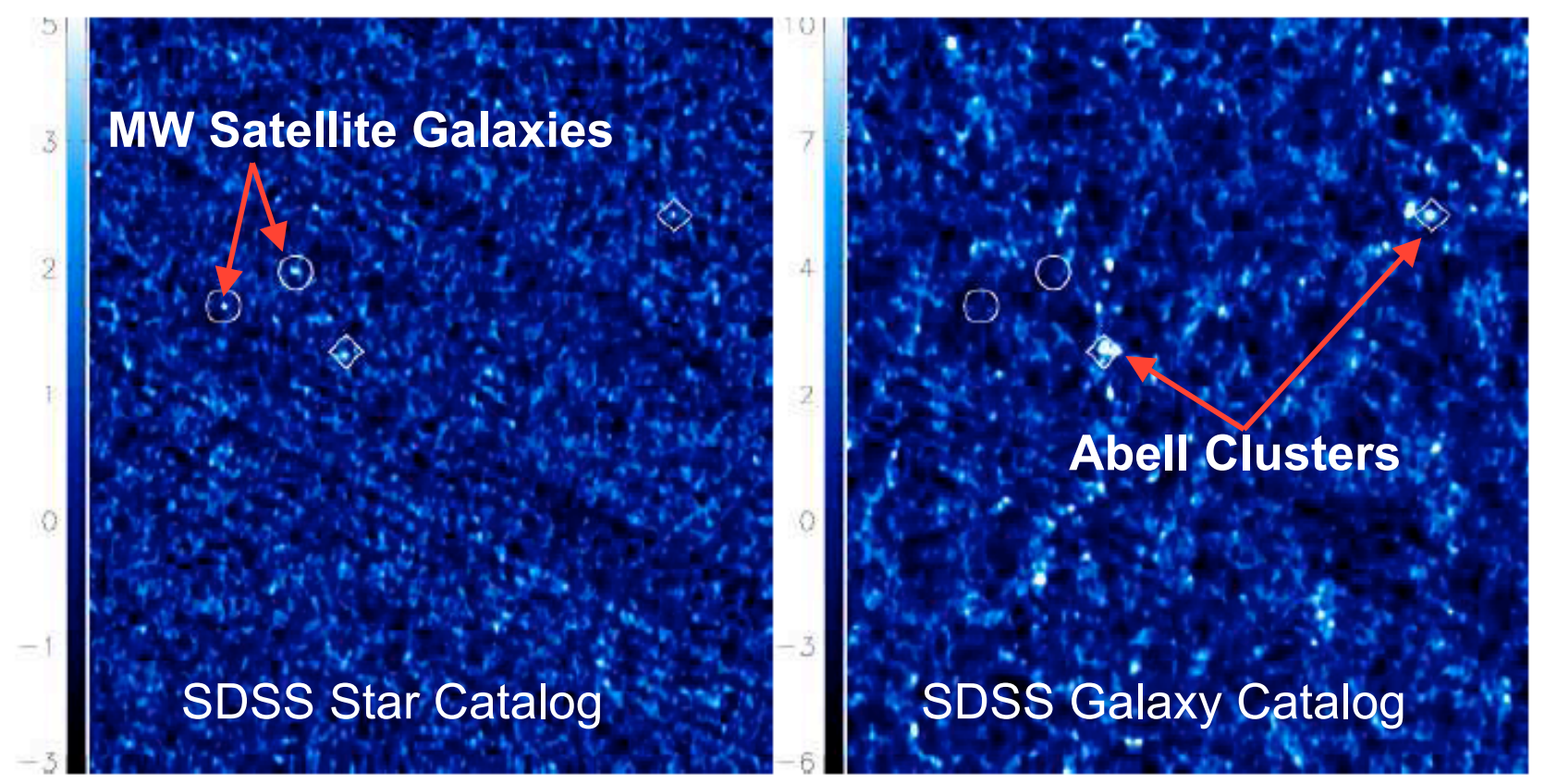
S. Koposov et al 2008

- Operate on source catalogs
- Insert 10^4 artificial satellites with M92-like populations into catalog,
  - covering D_{GC}, L_*, R_e parameter space
- Spatially convolve map

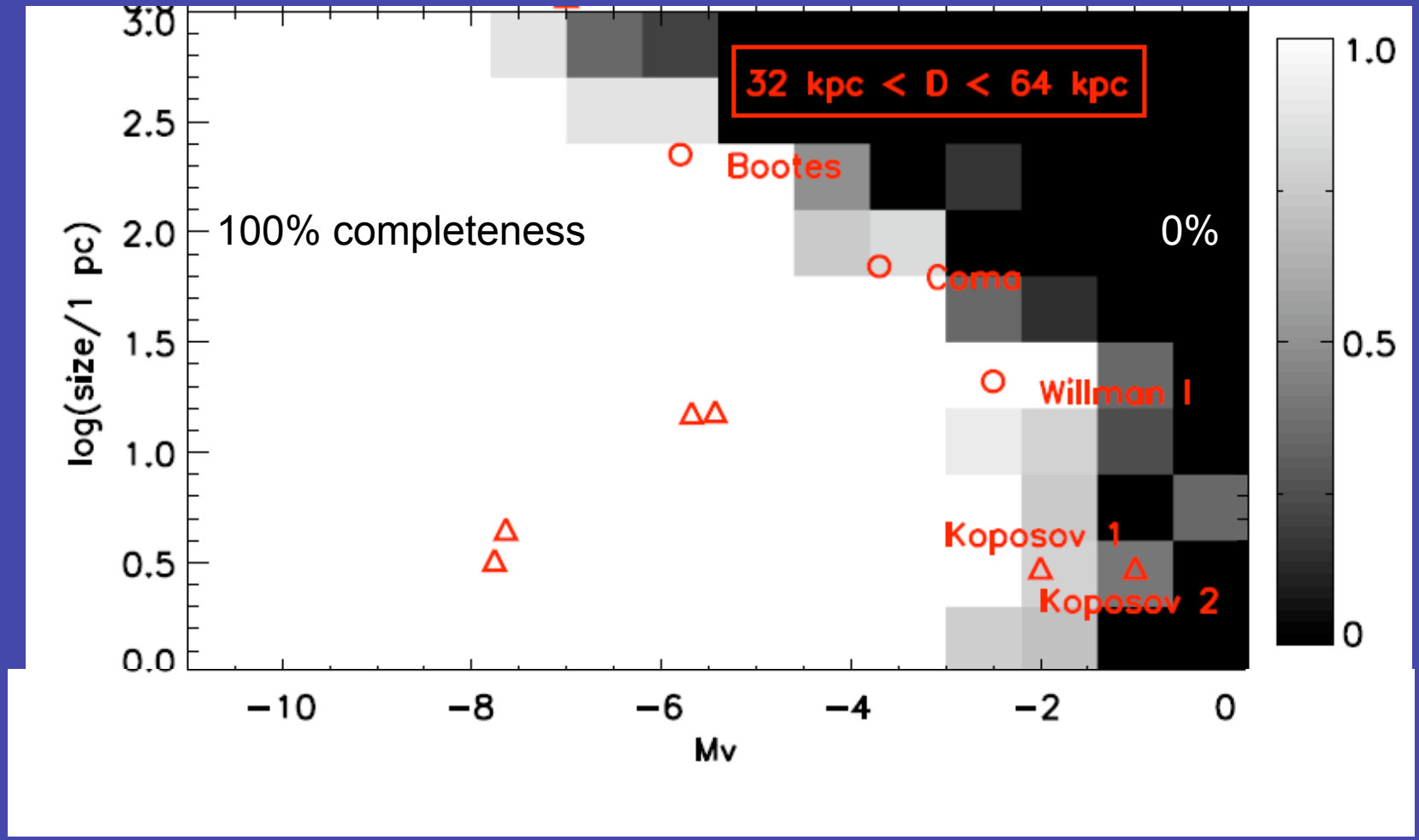
  colors: MS T.O. / low-[Fe/H] giants

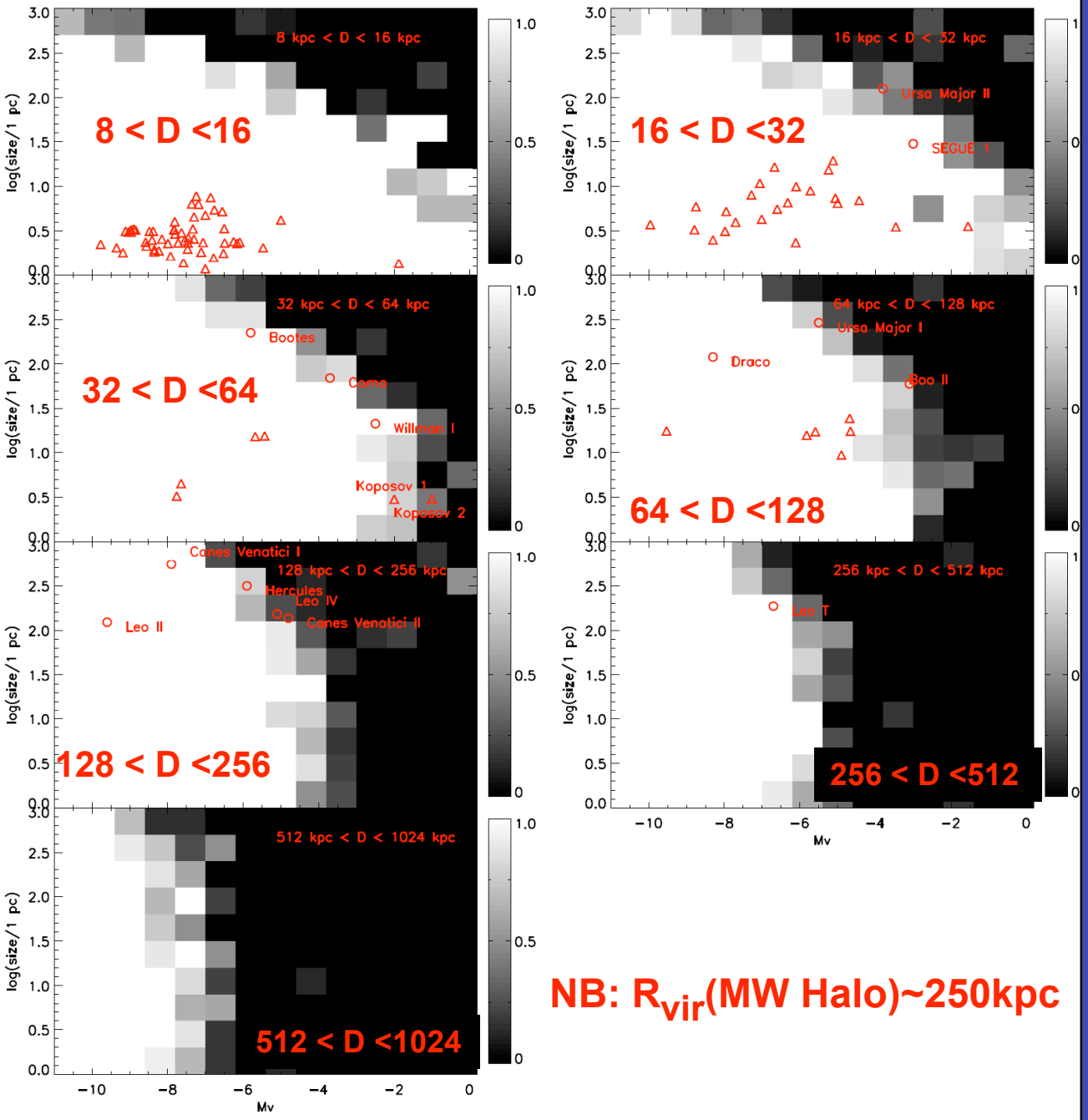
  g-r<0.4 g-r<1.2
- Identify >6σ peaks in conv. map




MW Satellite Galaxies
SDSS Star Catalog
Abell Clusters
SDSS Galaxy Catalog

22° x 22° area

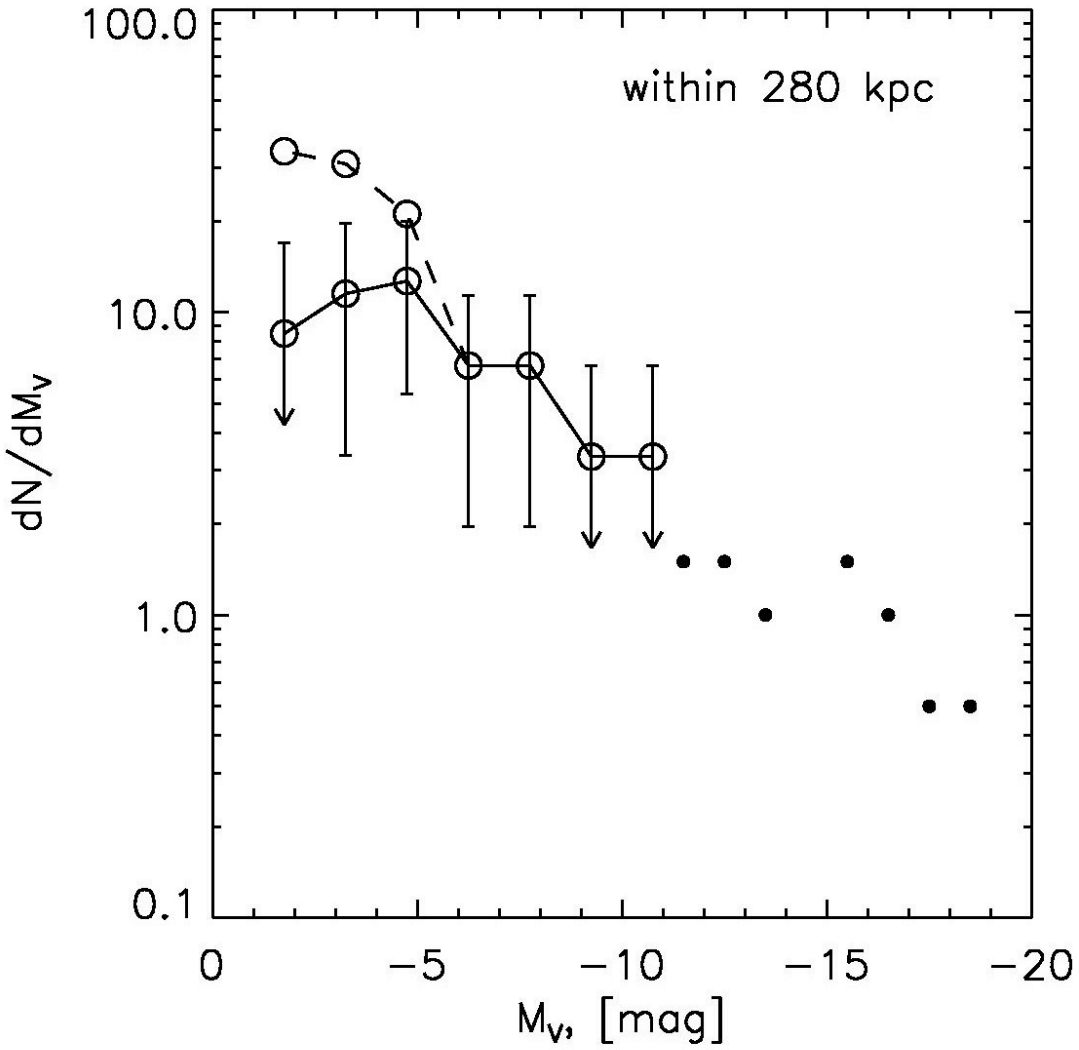

32 kpc < D < 64 kpc
100% completeness
0%
Bootes
Coma
Willman I
Koposov 1
Koposov 2
log(size/1 pc)
Mv
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−10
−8
−6
−4
−2
0
1.0
0.5
0

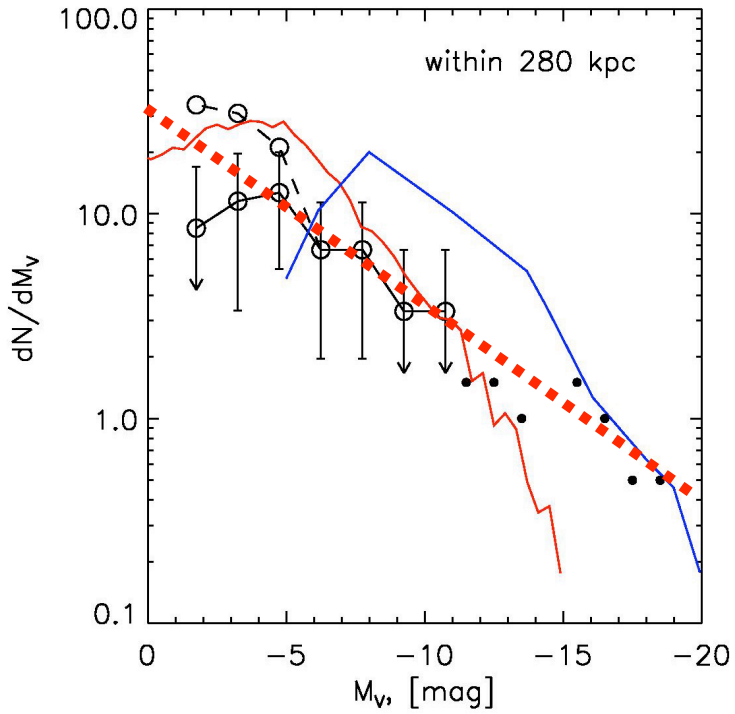


NB: R_{vir}(MW Halo)~250kpc

Satellite Census: Results

(S.Koposov, V. Belokurov, HWR et al 2008)





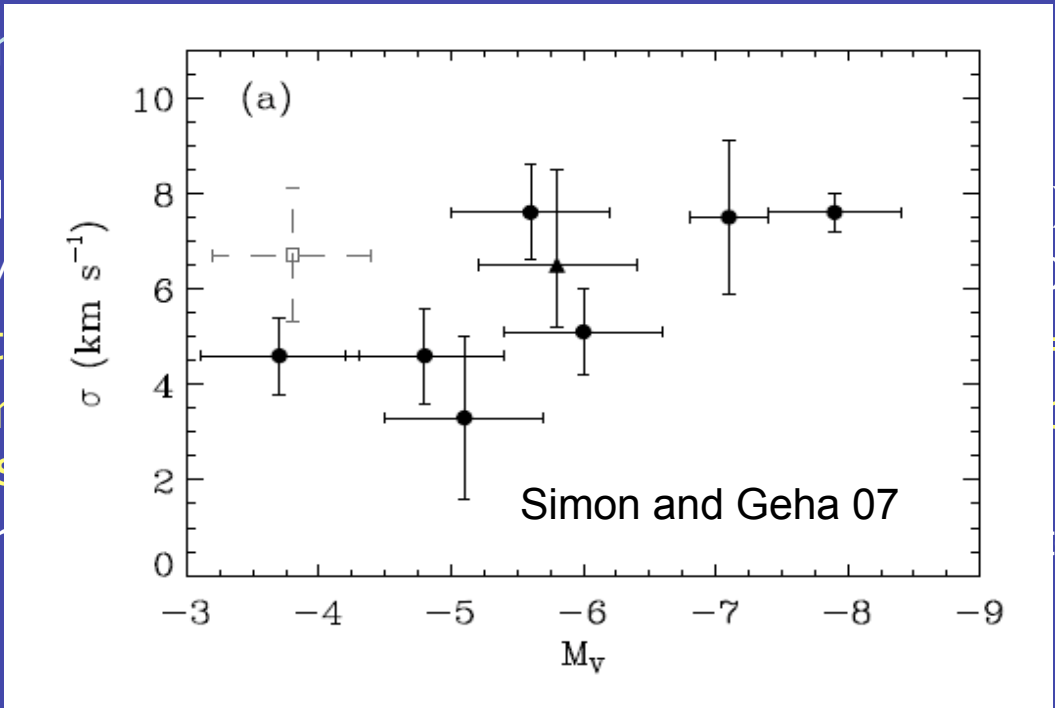
Interpreting these Results

Koposov, Weinberg, Yu, Rix, Maccio 08

- Now most of the pieces are in place
  - n(L), n(r), r_{eff}(L), σ_*(L) (Simon and Geha 07, Martin et al 07)

- Formation
  1. M_*(or
  2. M
     Else: M
     .. Phot
     [2a. m
     gas
  3. Tides r

to fail
) at t_{halo}
00)
=35 km/s
previously accreted
oehr et al 02)

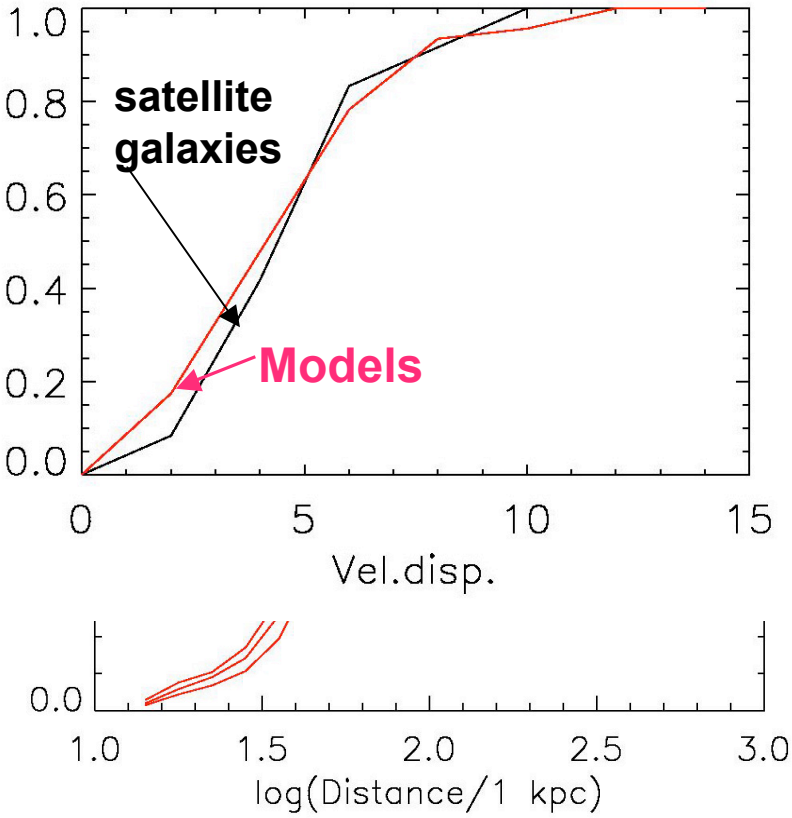


Is there a 'viable' model matching the new constraints?

(Koposov, Rix, Weinberg, Yu, Maccio *in prep.)*

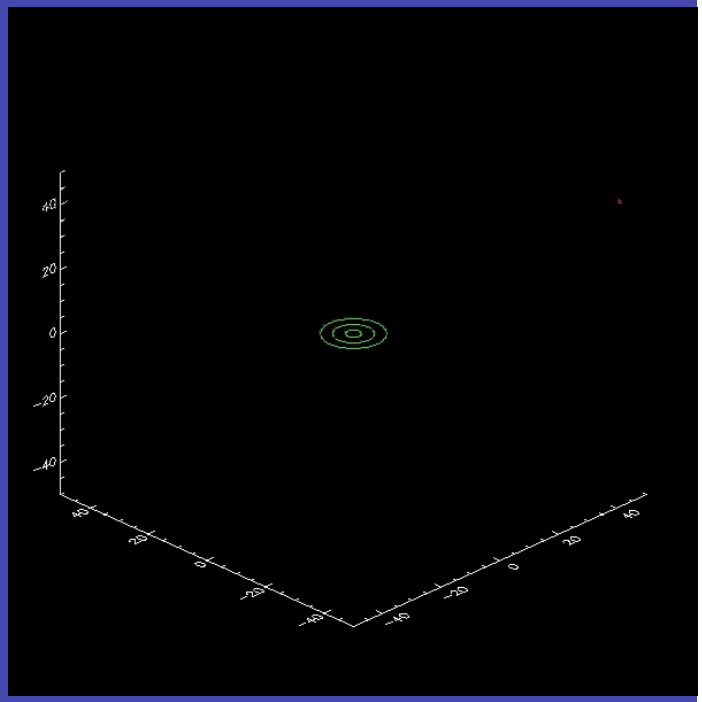
- Take semi-analytic models for satellite halo-growth:
  - → $M(z_{re\text{-}ion})$, $v_{DM,crit}(@t_{into\_halo})$
  - → orbits, positions, tidal mass loss

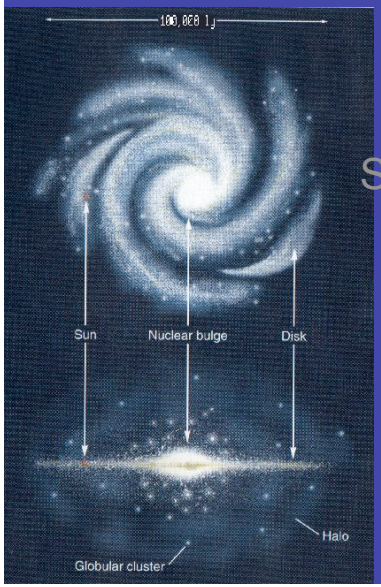
- $z_{re\text{-}ion}=10$
- $v_{DM,crit}(@t_{into_halo})=38$km/s
- $f=M_*/M_{DM} = 2 \times 10^{-3}$
- Make mock observations of the simulations



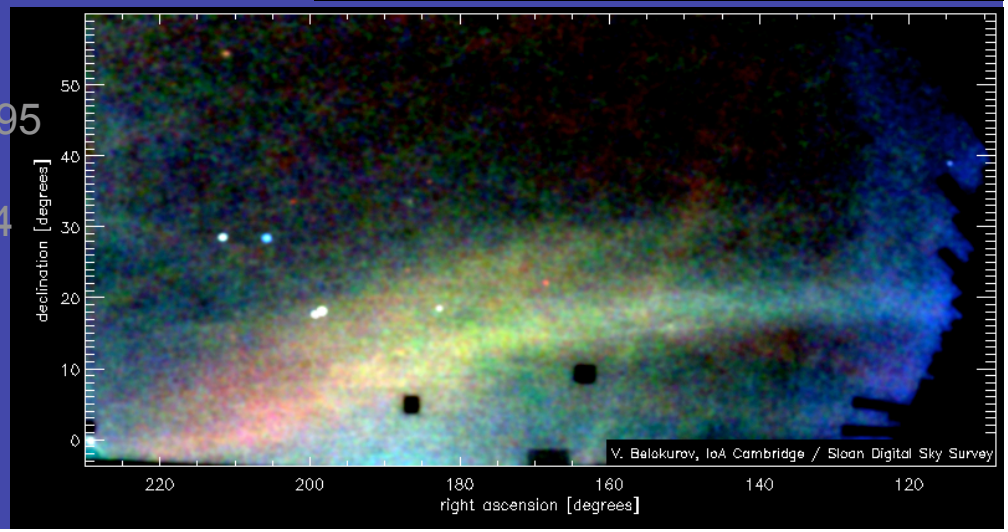
Stellar halo : fossil record of assembly?

- Dwarf galaxies are disrupting and contributing to the stellar halo
  - 1% of stellar mass of our galaxy

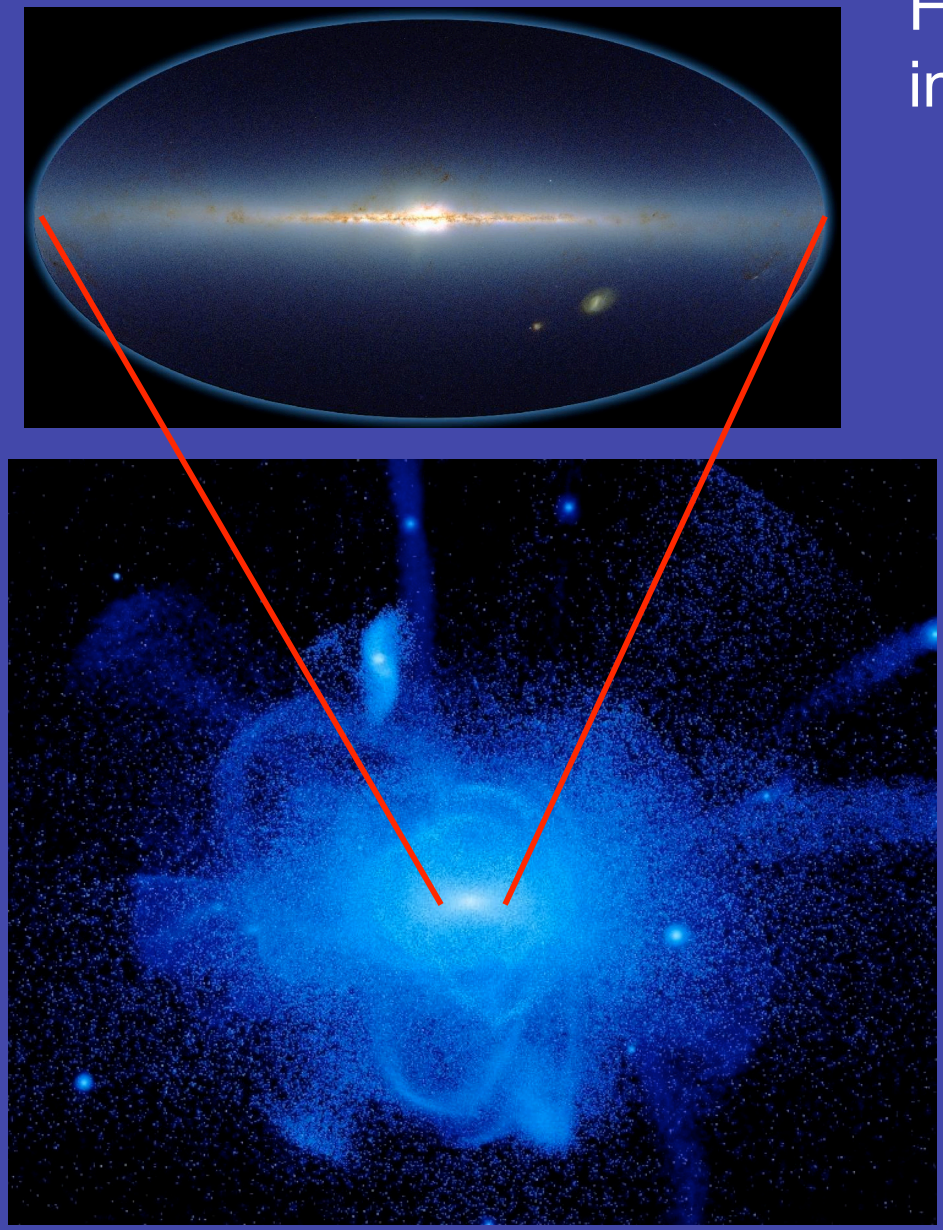




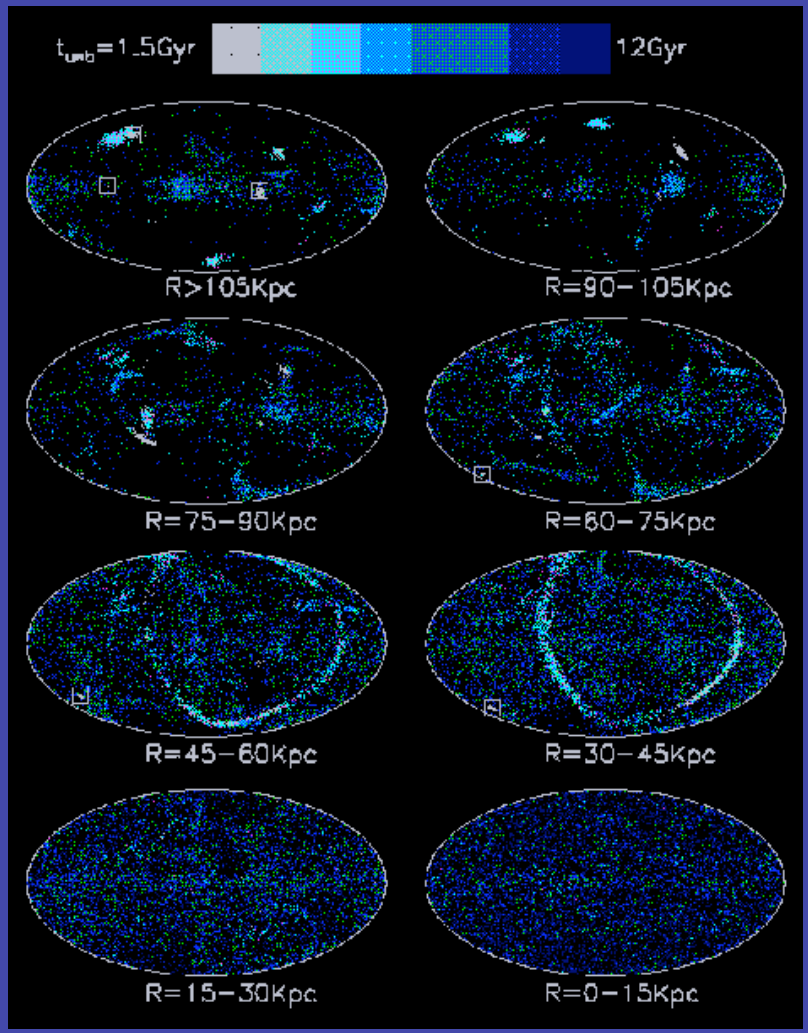
Bullock & Johnston 2005
See also Ibata et al. 1994, 1995
Majewski et al. 2003,
Martinez-Delgado et al. 2004
Belokurov et al. 2006



How important is ‘sub-structure’ in the stellar halo?



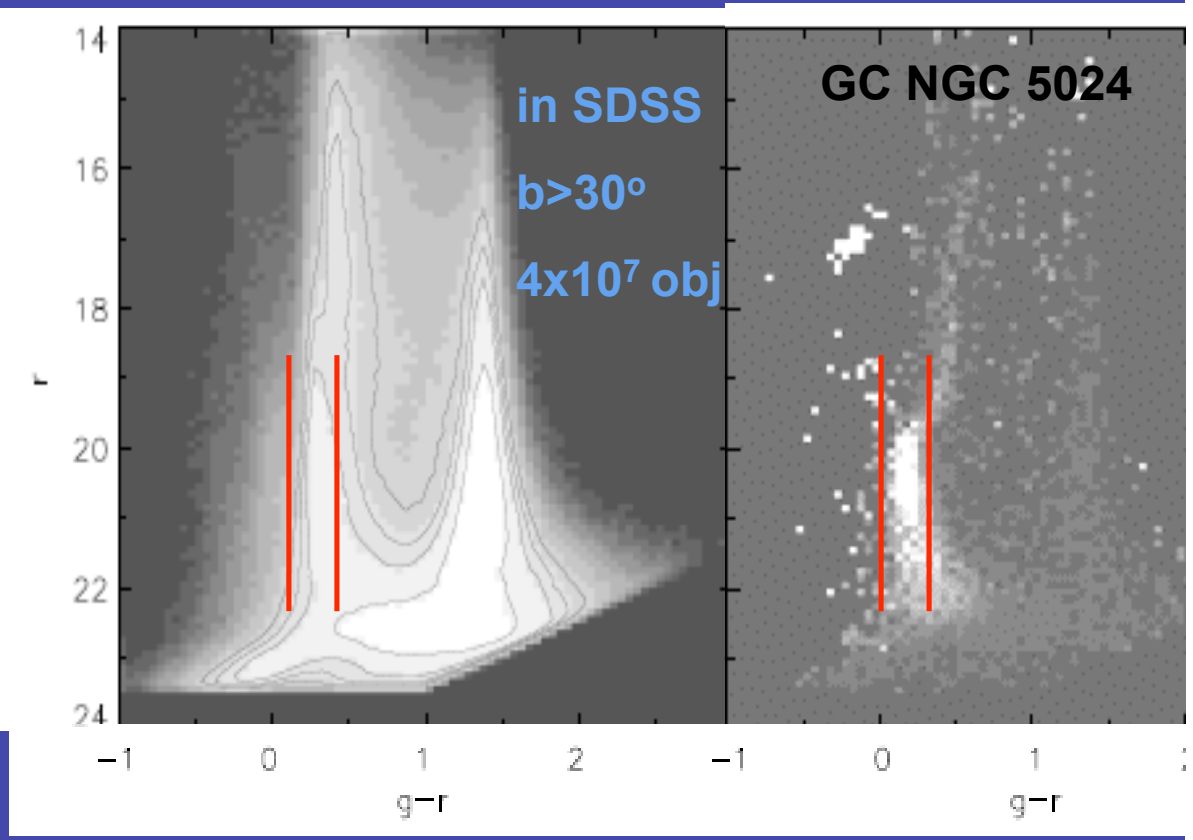
Johnston and Bullock 2005

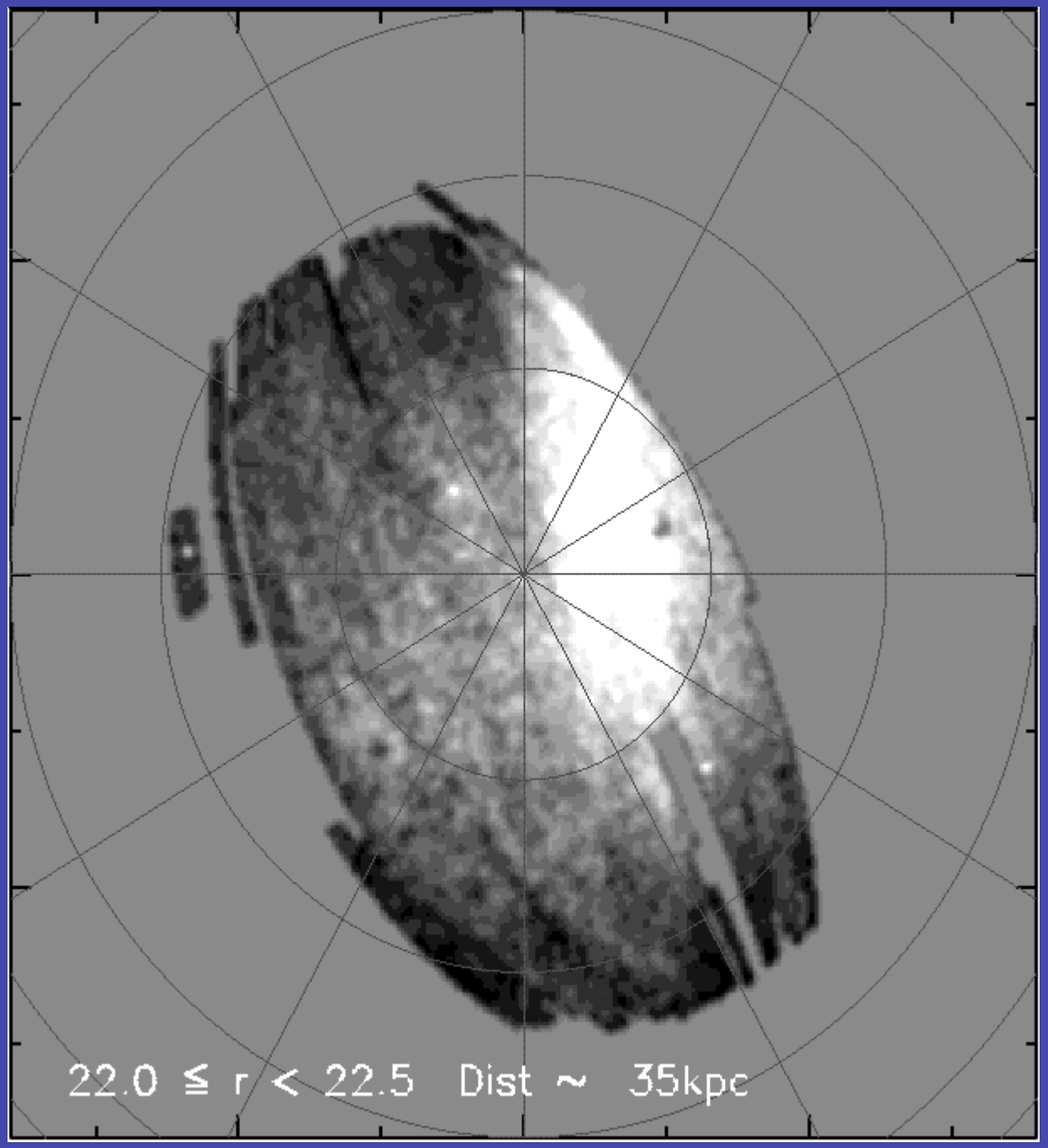


Constructing an approximate 3D Map of the Milky Way's stellar halo

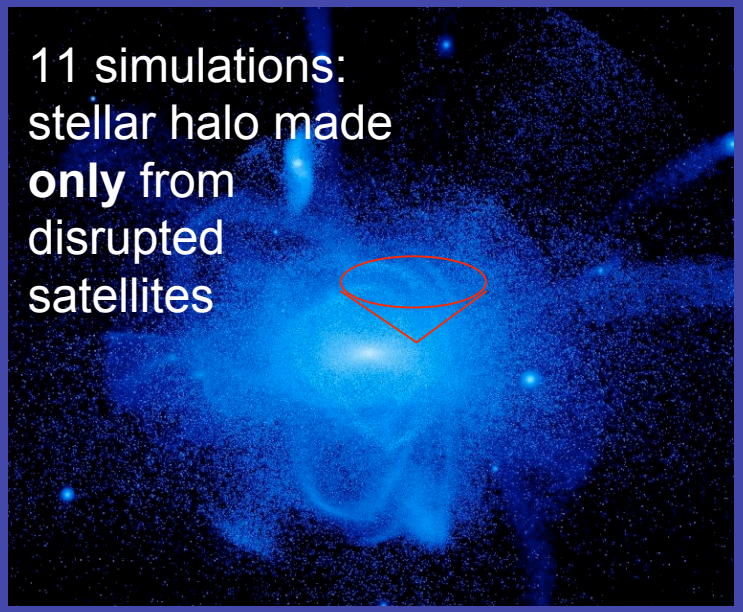
Bell, Zucker.. HWR et al 2007

- 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 or magnitude-sorted bins
- Make smooth-component fit: triaxial, (broken) power-law density profile
- Make 'residual' maps
- Repeat same procedure for Johnston&Bullock models
  - include error convolution

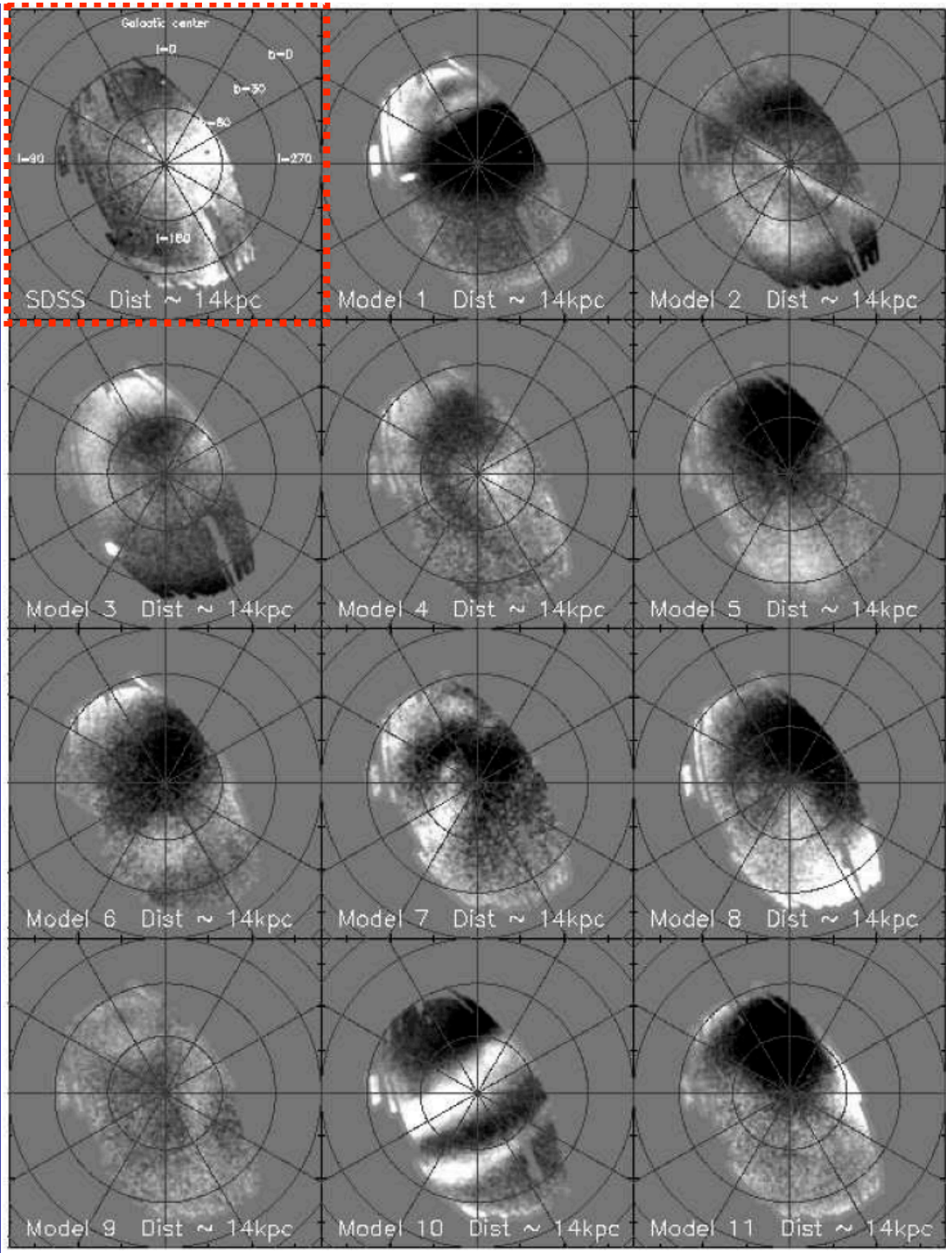



22.0 ≦ r < 22.5 Dist ~ 35kpc

11 simulations:
stellar halo made
only from
disrupted
satellites



from Bullock&Johnston 05



How do Data and Models Compare?

- Statistic:

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

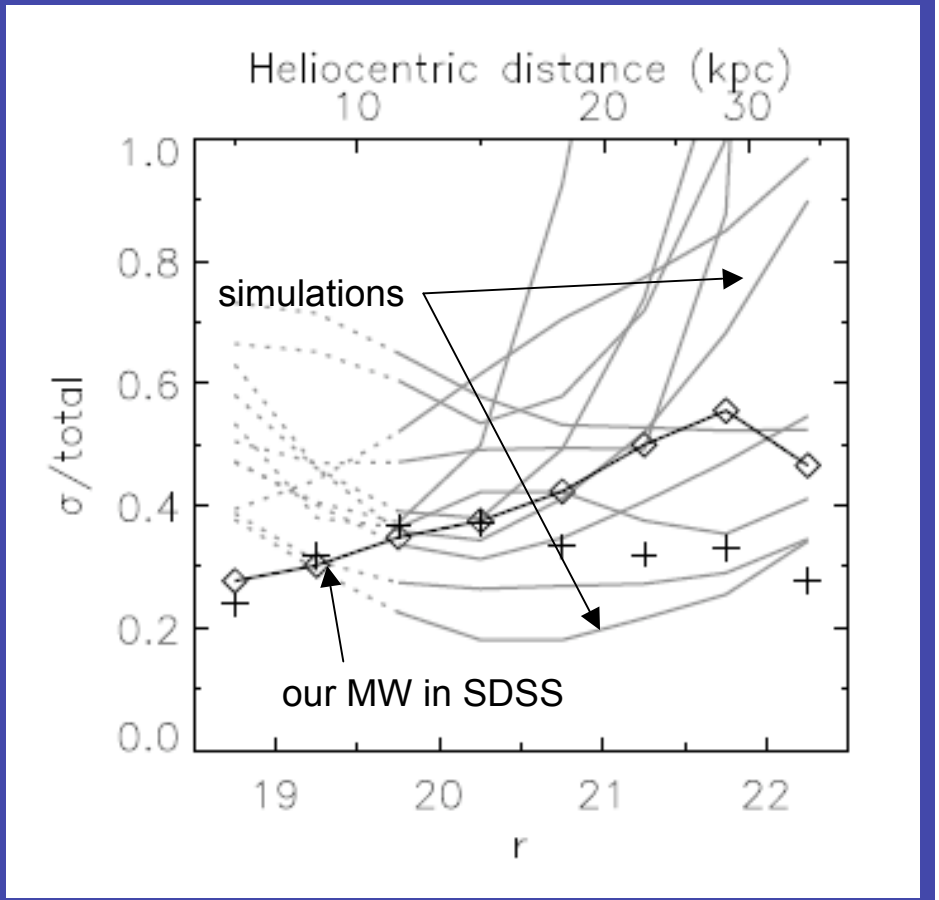
  SDSS data *vs* 11 tidal-stream-only simulations (Johnston and Bullock 2005)

- Data and model *rms*' indistinguishable

→ Much of (all of?) the MW's stellar halo is in sub-structure

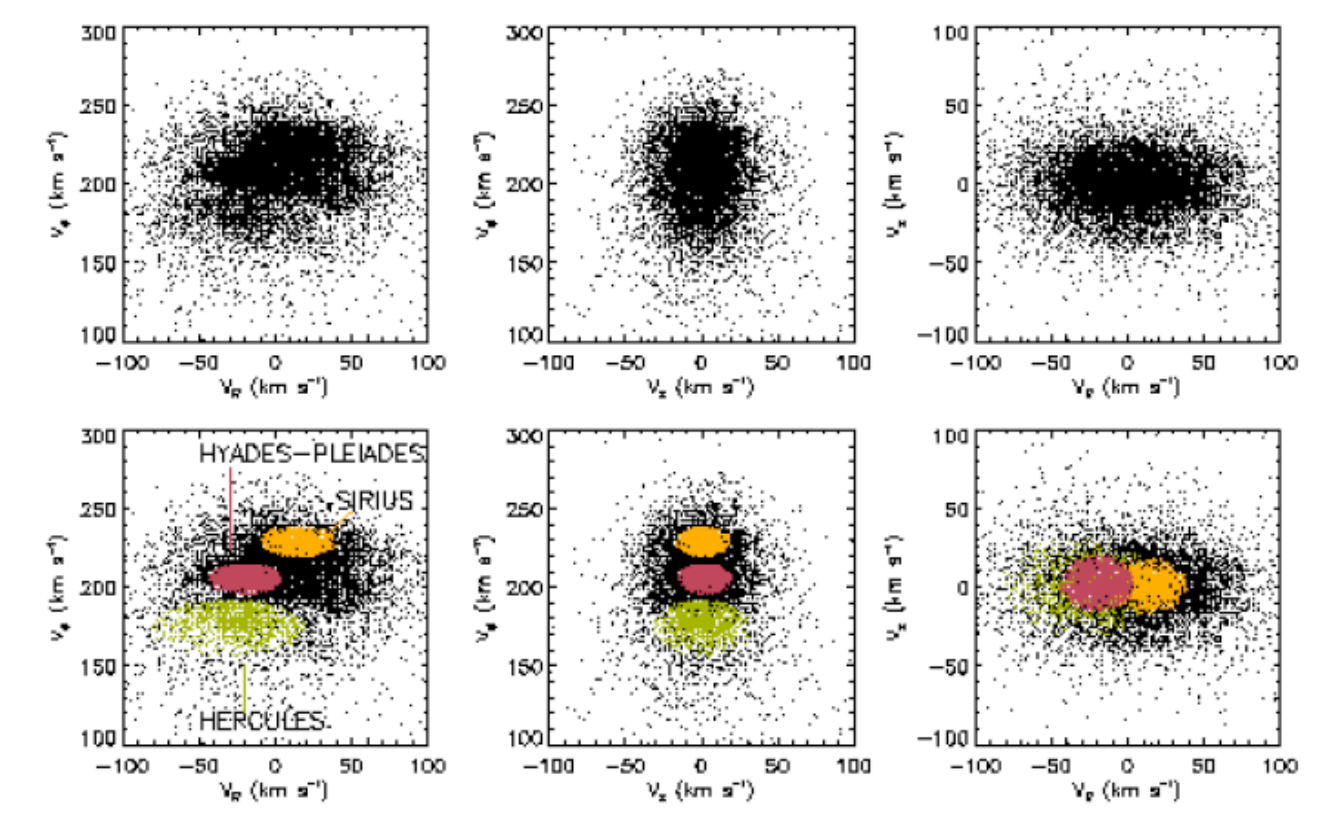
→ There is no 'smooth' halo?

(>15 kpc)



A complementary view of stellar streams

- Should exist also in local neighborhood
  - Impossible to recognise visually
  - Kinematics of stars with similar characteristics



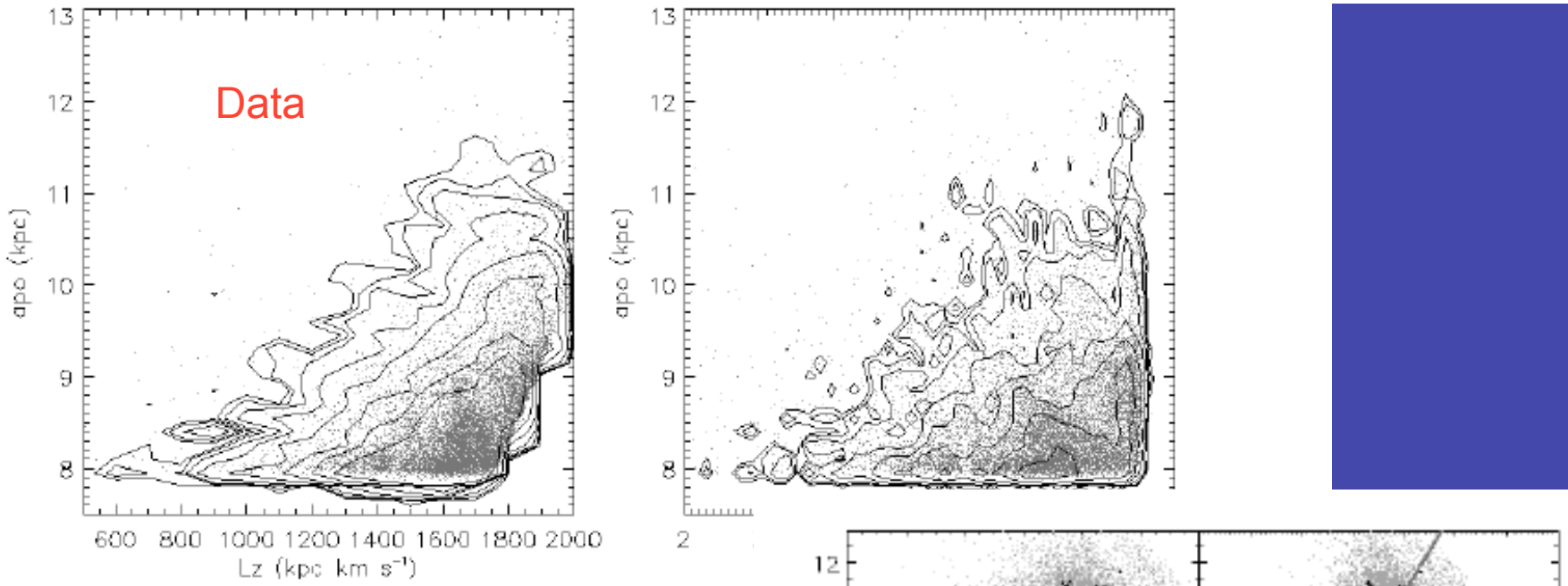
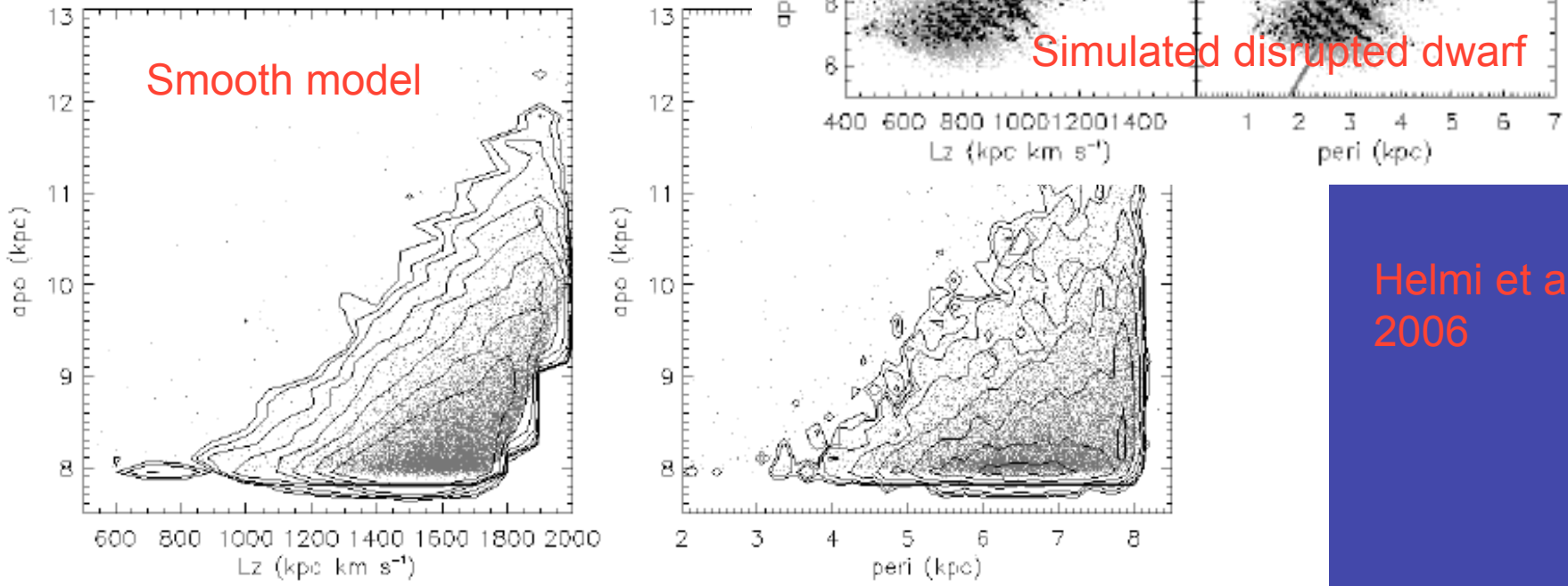
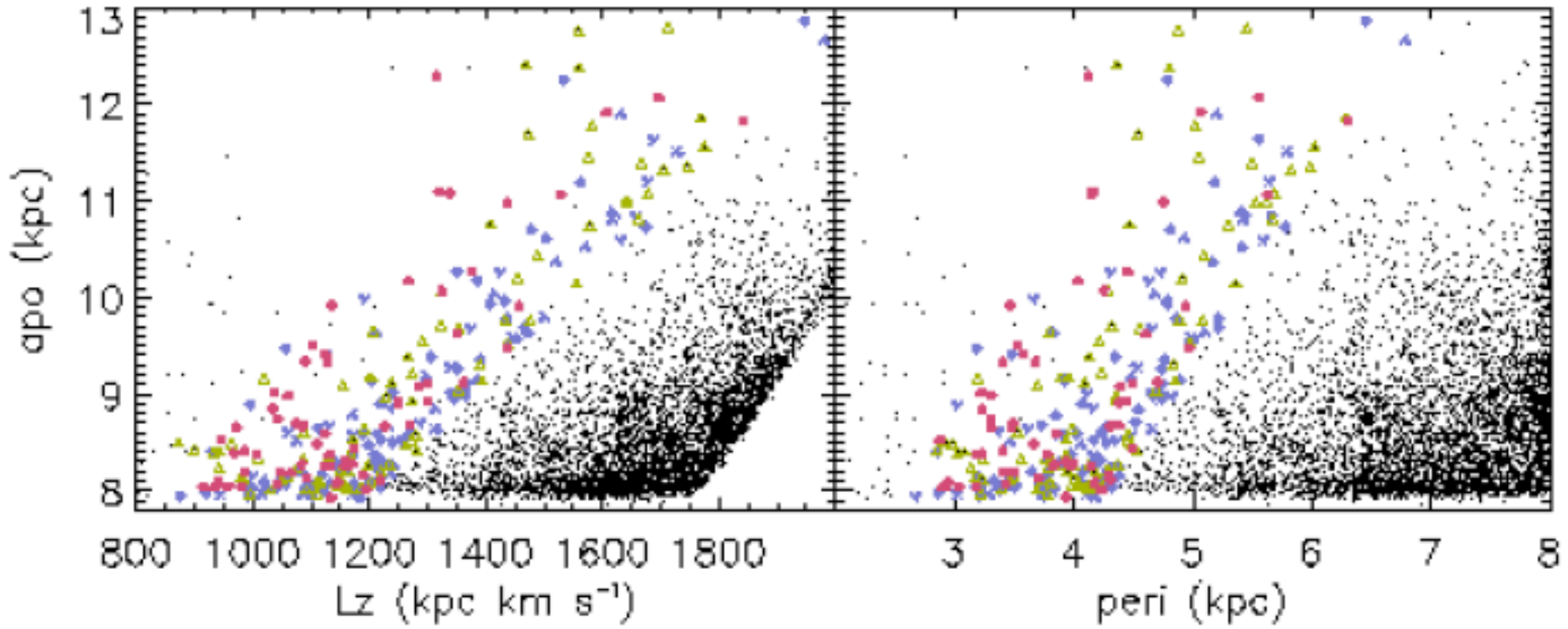
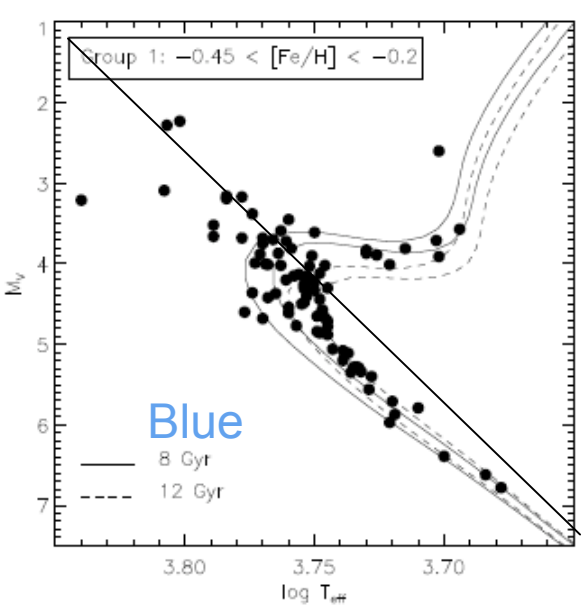


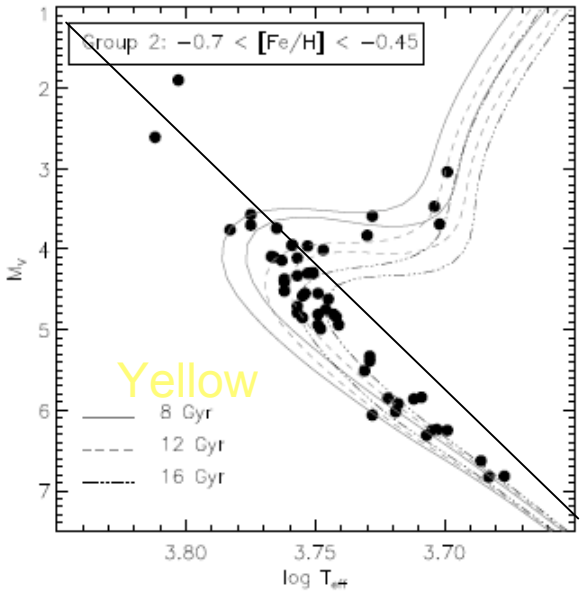
Figure 10. Distribution of the stars in the N04 sample in the APL space. The cor
sample.

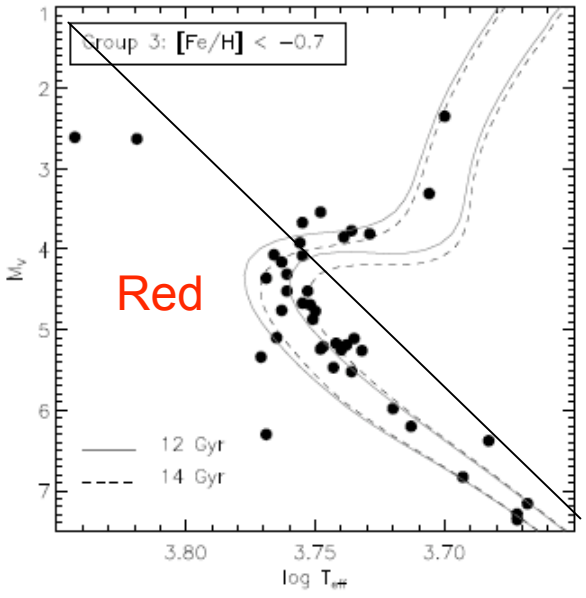


Helmi et al. 2006


apo (kpc)
13
12
11
10
9
8
800 1000 1200 1400 1600 1800
Lz (kpc km s⁻¹)
3 4 5 6 7 8
peri (kpc)


Group 1: −0.45 < [Fe/H] < −0.2
Blue
8 Gyr
12 Gyr
M_V
log T_eff
3.80
3.75
3.70

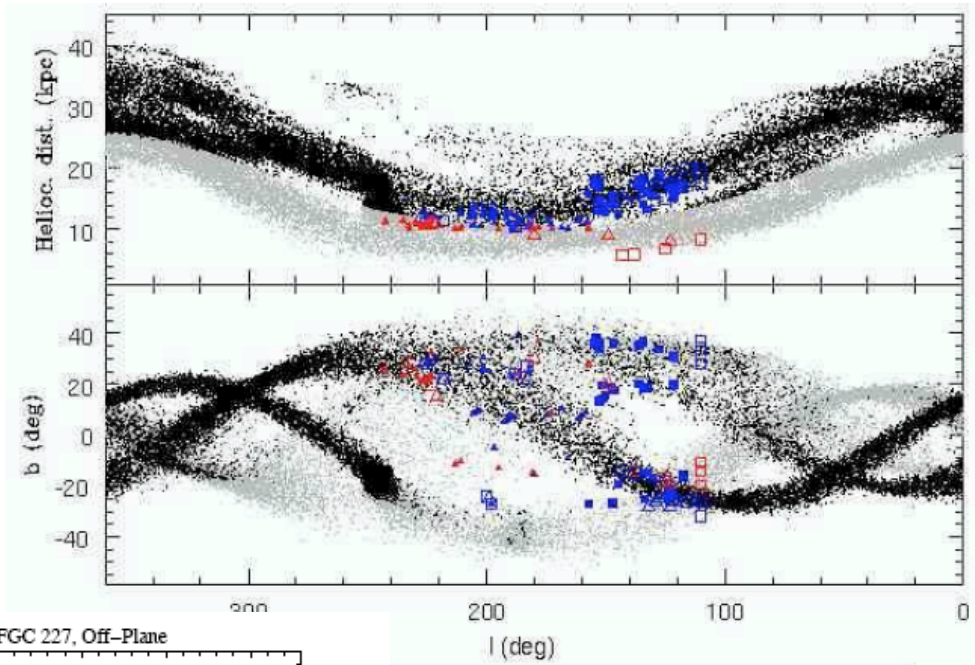

Group 2: −0.7 < [Fe/H] < −0.45
Yellow
8 Gyr
12 Gyr
16 Gyr
M_V
log T_eff
3.80
3.75
3.70

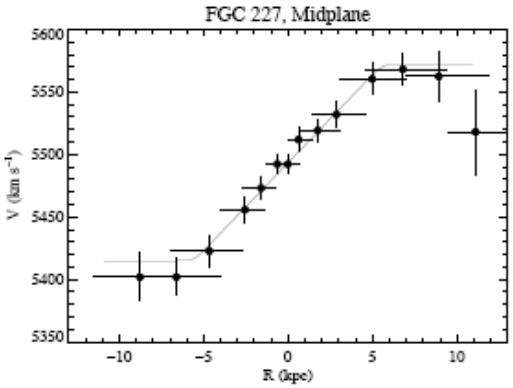

Group 3: [Fe/H] < −0.7
Red
12 Gyr
14 Gyr
M_V
log T_eff
3.80
3.75
3.70

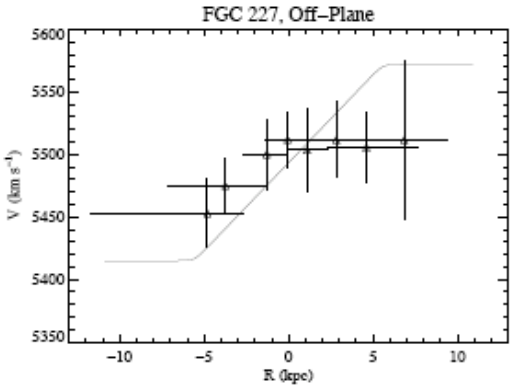
Thick disk as accretion debris

- Streams from debris of interactions

Fitting of an N-body model to debris
From an accreting satellite galaxy
Penarrubia et al. 2005







Rotation curve of midplane and off-plane (thick+thin disk)
Model - no rotation or **retrograde** thick disk
Yoachim & Dalcanton 2005

Thick disk as a record of early gas-rich interactions

- Brook et al. 2004; z~1 period of last major assembly gives a thick disk-like configuration (kinematics, ages, metallicities)

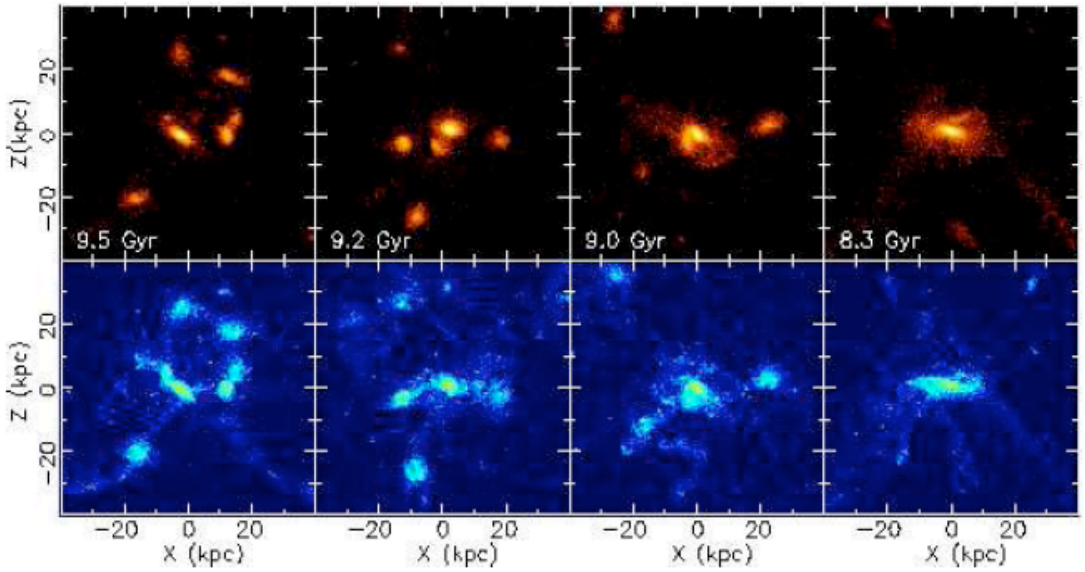
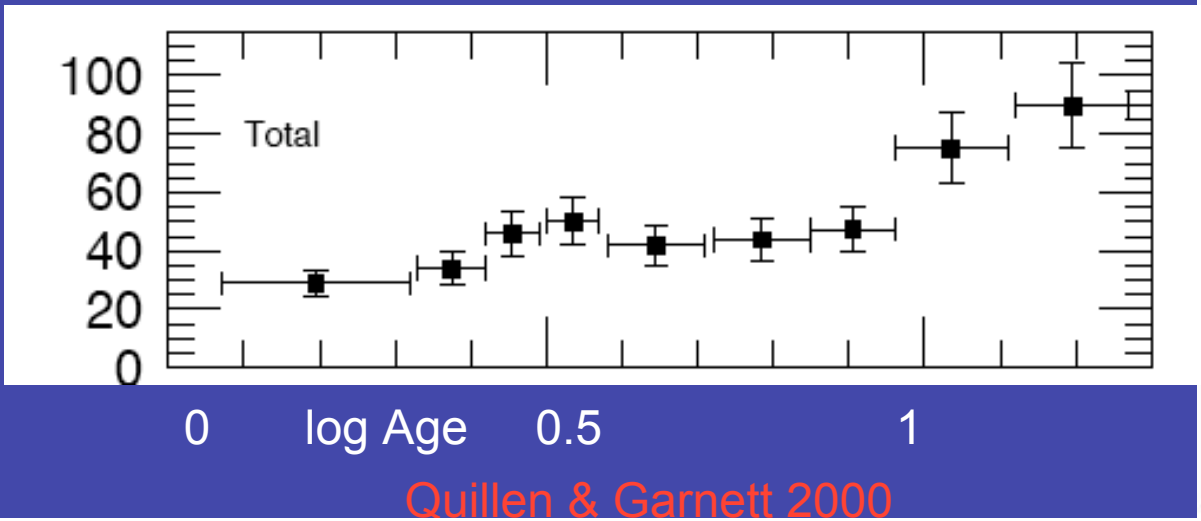


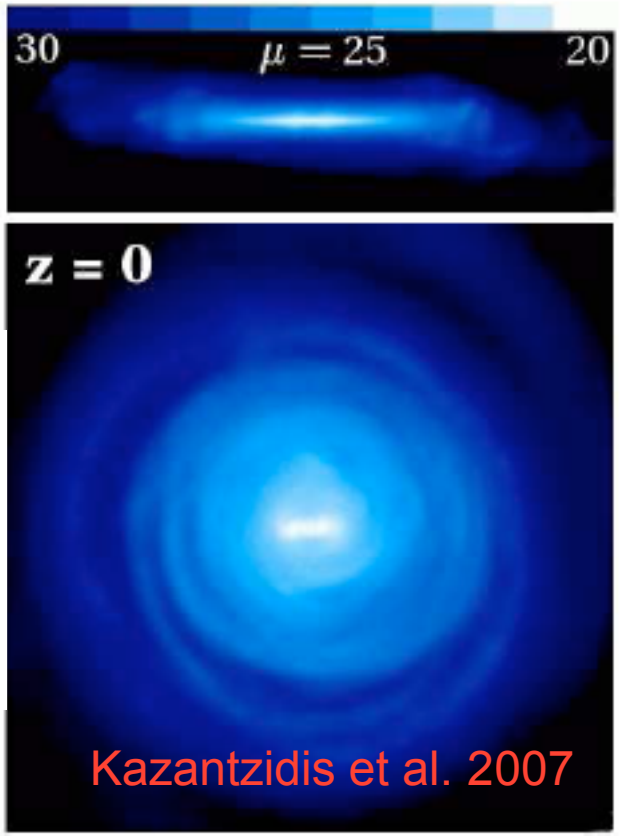
Fig. 4.— Density plot of the evolution of the galaxy's stars (top panel) and gas (lower panels) during the era in which the break in the velocity dispersion plot indicates that thick disk stars are formed. This epoch is charaterised by multiple mergers of gas rich building blocks, resulting in the formation of a central galaxy.

Puffed up thin disk?

- Interactions with DM subhalos/satellites:
  - Increases vel. Dispersion
  - Flares the disk, stream-like debris
  - Prediction: `nearly' disk kinematics



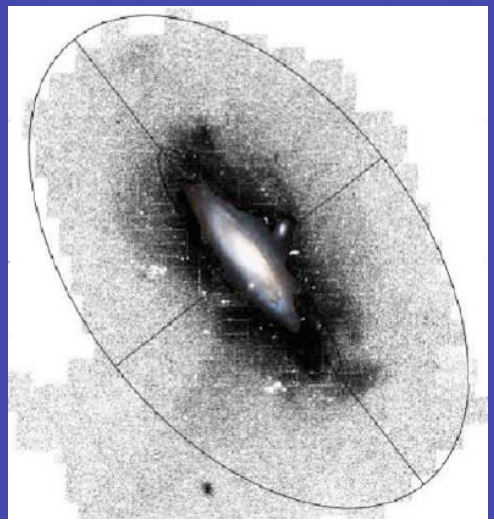
Quillen & Garnett 2000

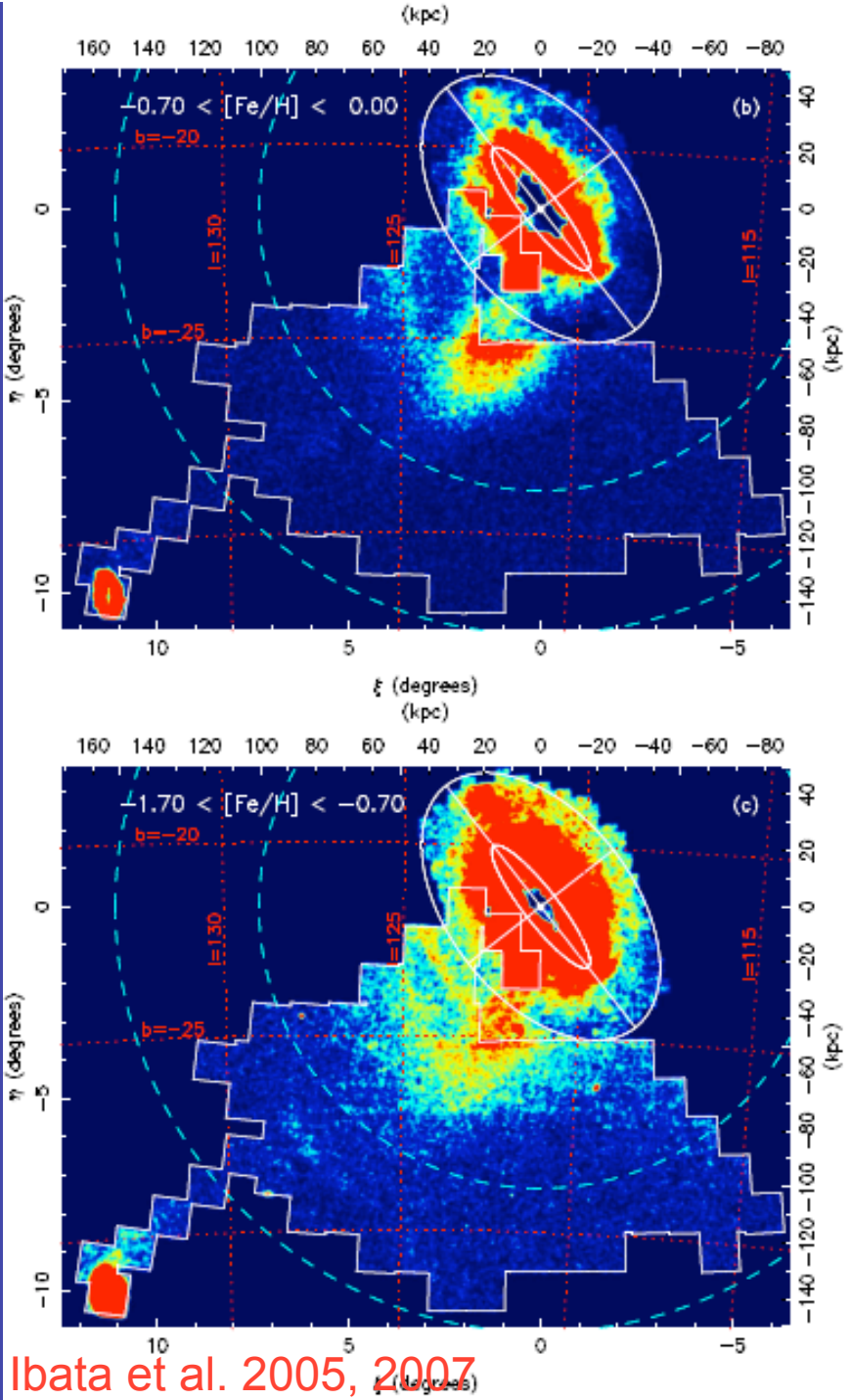


Kazantzidis et al. 2007

Puffed-up thin disk?

- Key observation
  - M31's low latitude stream
    - Prograde velocities, high velocity dispersion
    - Some younger, disk-like stars





Ibata et al. 2005, 2007

Summary

- Substructure problem and the satellite census
  - With new discoveries and analysis, starting to seem consistent with tracing centers of subhalos with v>35km/s (speak to Sergey)
- Look for signs of assembly of MW galaxy in our stellar halo (and thin/thick disk)
  - Stellar halo is conceivably all accreted material
  - Stellar streams in the solar neighborhood
- Discussion of the origin/meaning of the thick disk
  - Generated by debris from accretion
  - Generated during first gas-rich merger
  - Puffed up thin disk
  - Not clear what is the dominant process - do all contribute?

Summary

- The Milky Way's halo is **fairly light** (Xue et al 08)
  - $4.0_{+-\ 0.6} \times 10^{11}\ M_o$ <60 kpc → $M_{vir}=1.0_{+-\ 0.2} \times 10^{12}\ M_o$
  - NFW profile fits well
  - → (a high) 40% of baryons → stars in bulge/disk
  - → LMC and others may indeed not be (have been) bound
- There's direct evidence that the **bulk** of the stellar halo (>15kpc) is 'sub-structure'/tangled streams (Bell et al 07)
  - Consistent with Bullock and Johston 'stream-only' stellar halo model
- Satellites and Sub-Halo: (Koposov et al 08)
  - $\mathbf{D_{max,detect} << R_{vir}}$ for many new SDSS satellites
  - Dwarf galaxy luminosity function is shallow power-law to $M_V \sim -2.5$
  - Plausible combination of $z_{re\text{-}ionization}$ and $M_{DM,min}$ @$t_{satellite}$ effects that can explain **quantitatively** n(L), n(r),n(σ)