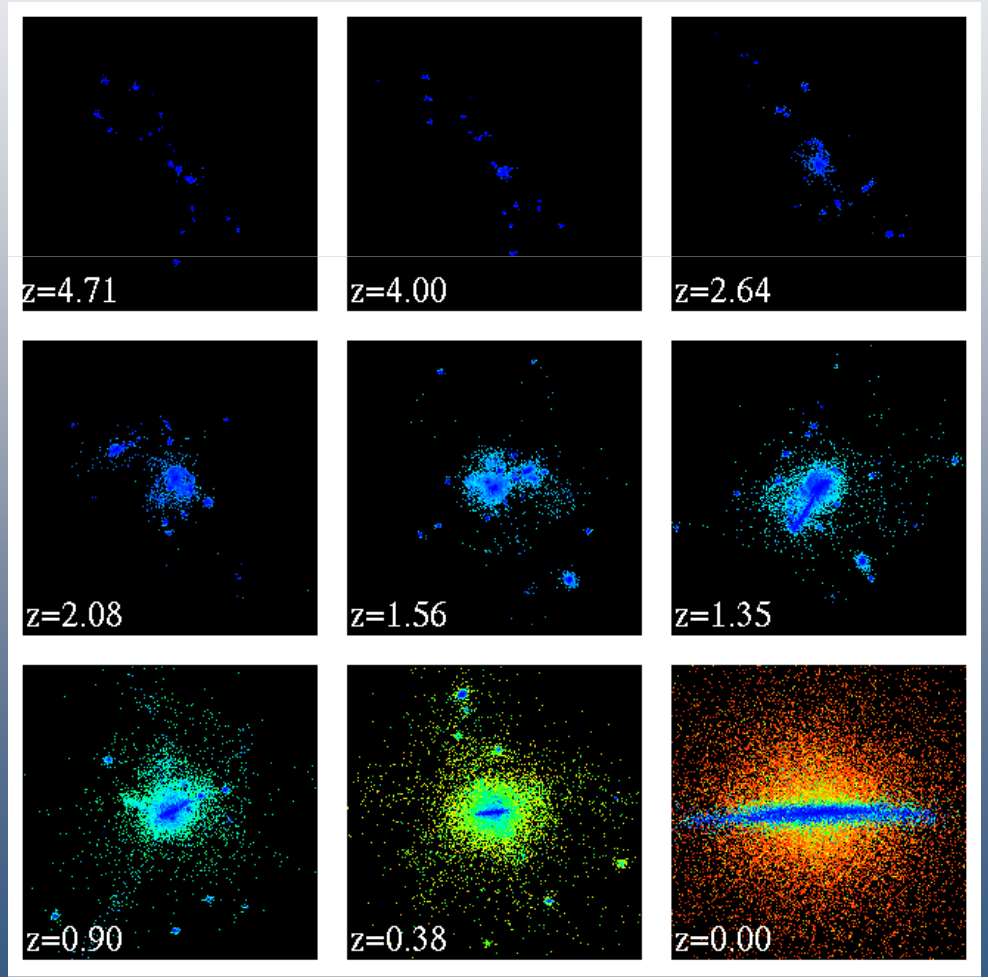
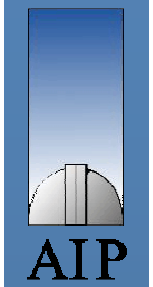
The Formation of the Old Stellar Halo of the Milky Way

AIP



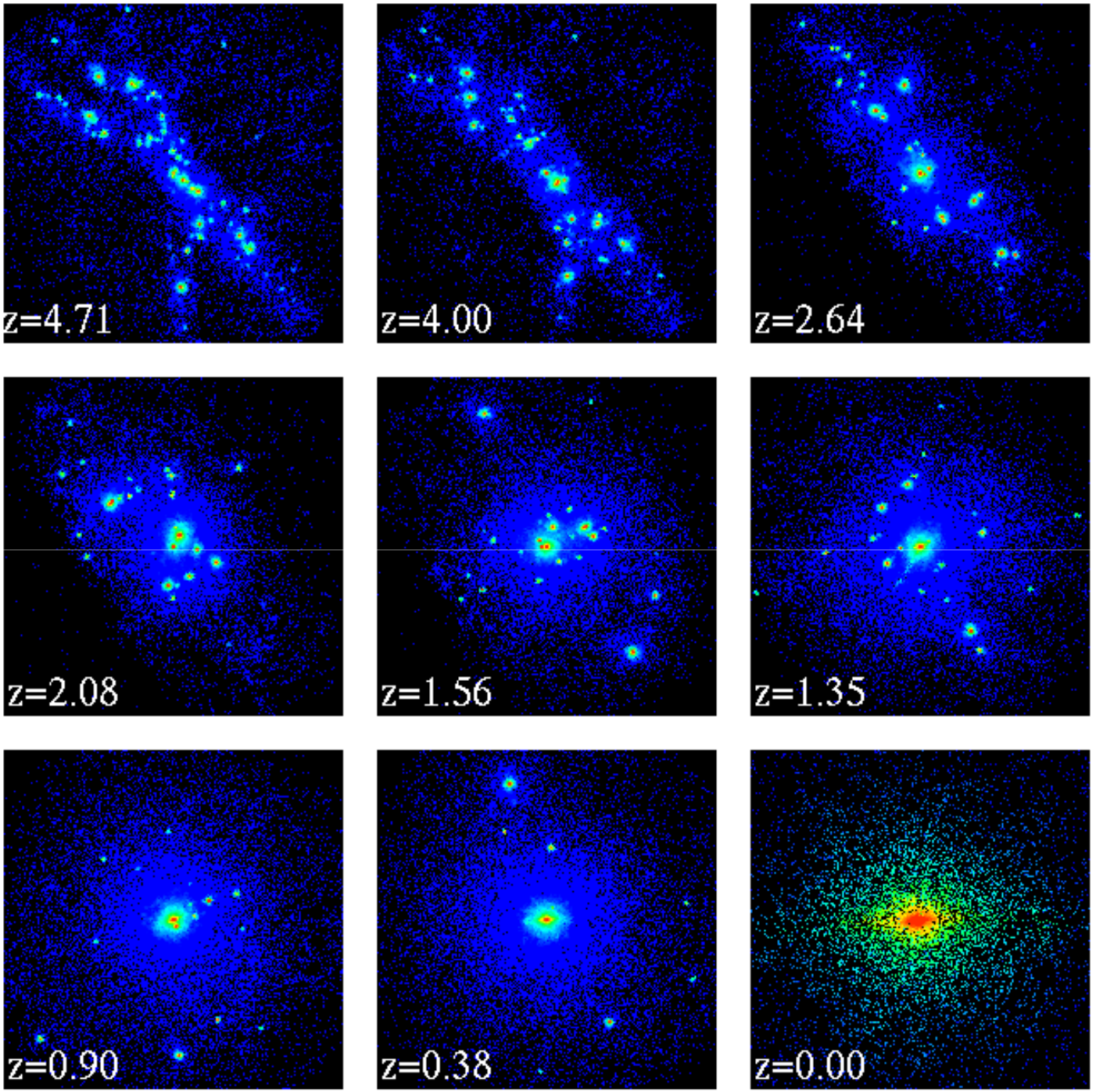
Matthias Steinmetz (AIP)

M. Abadi, V.R. Eke,
F. Köckert, L. Sales
J.F. Navarro, A. Meza



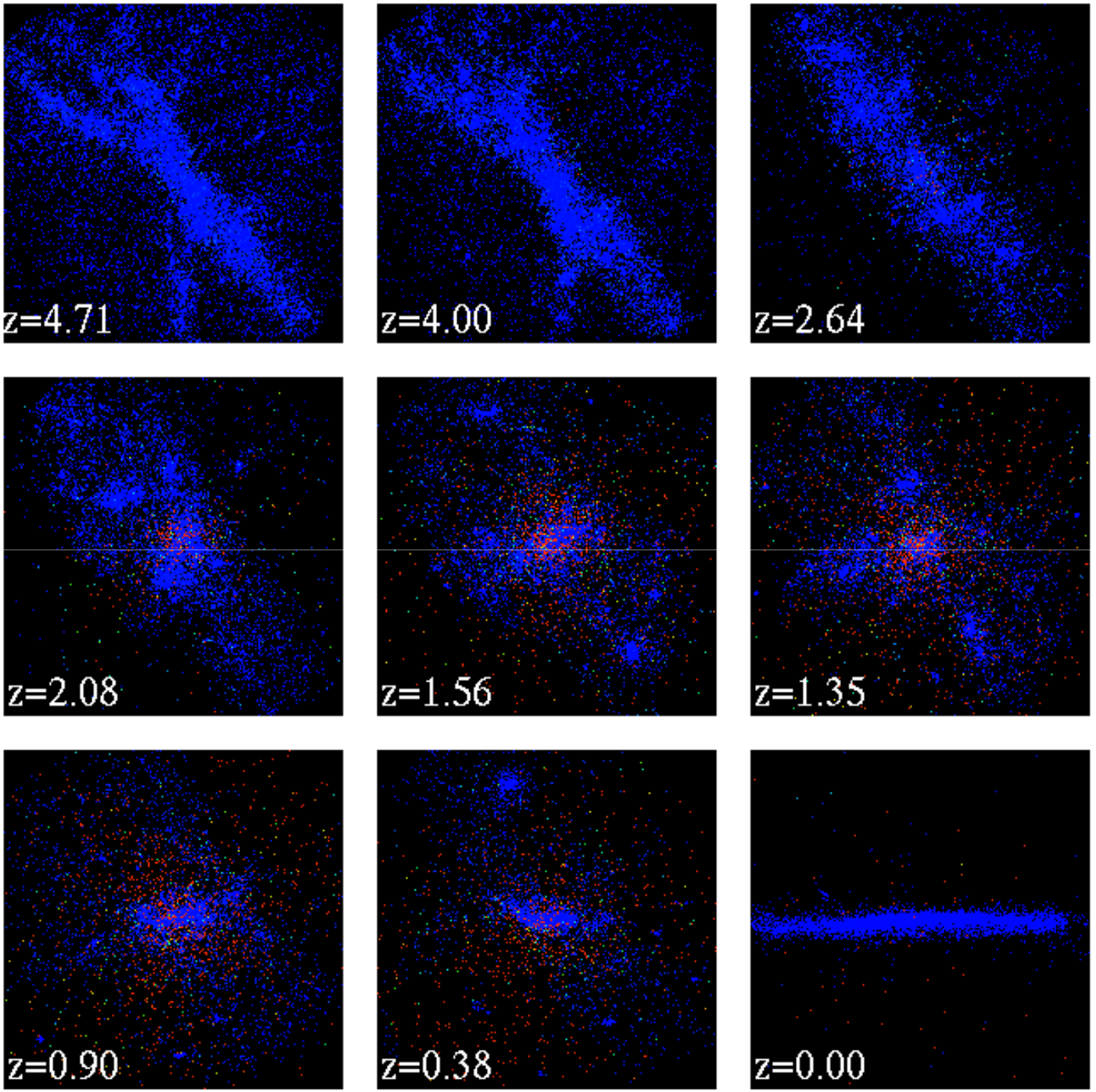
Agenda

- Formation of the MW and its Stellar Halo
- Potential Depth and Shape of the Stellar Halo using RAVE and SEGUE
- Properties of the MW Satellite System



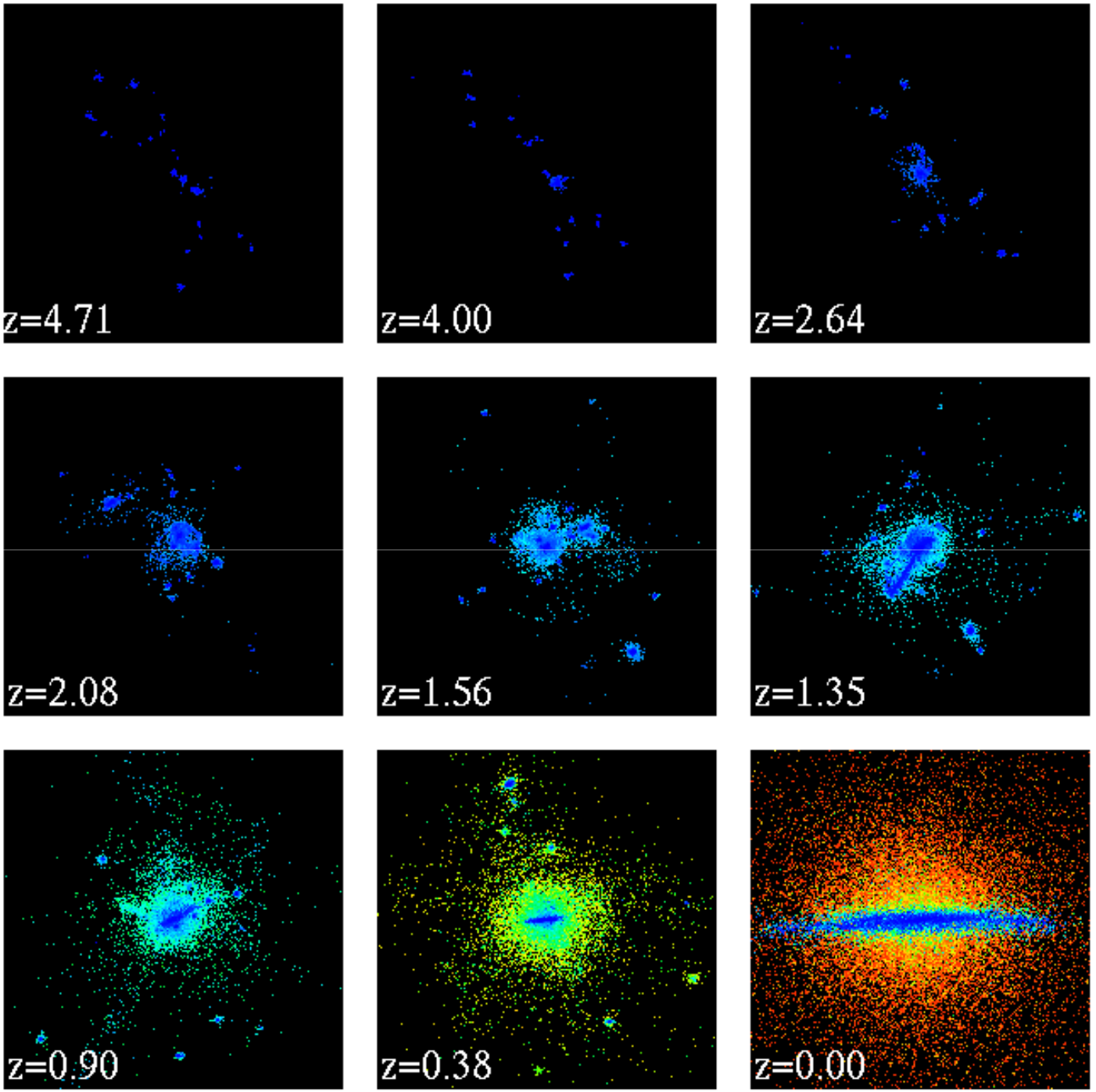
Dark Matter

Abadi et al 2003



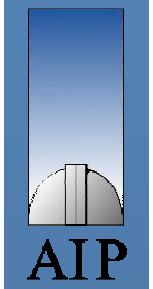
Gas

Abadi et al 2003



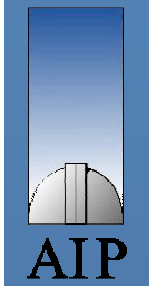
Stars

Abadi et al 2003



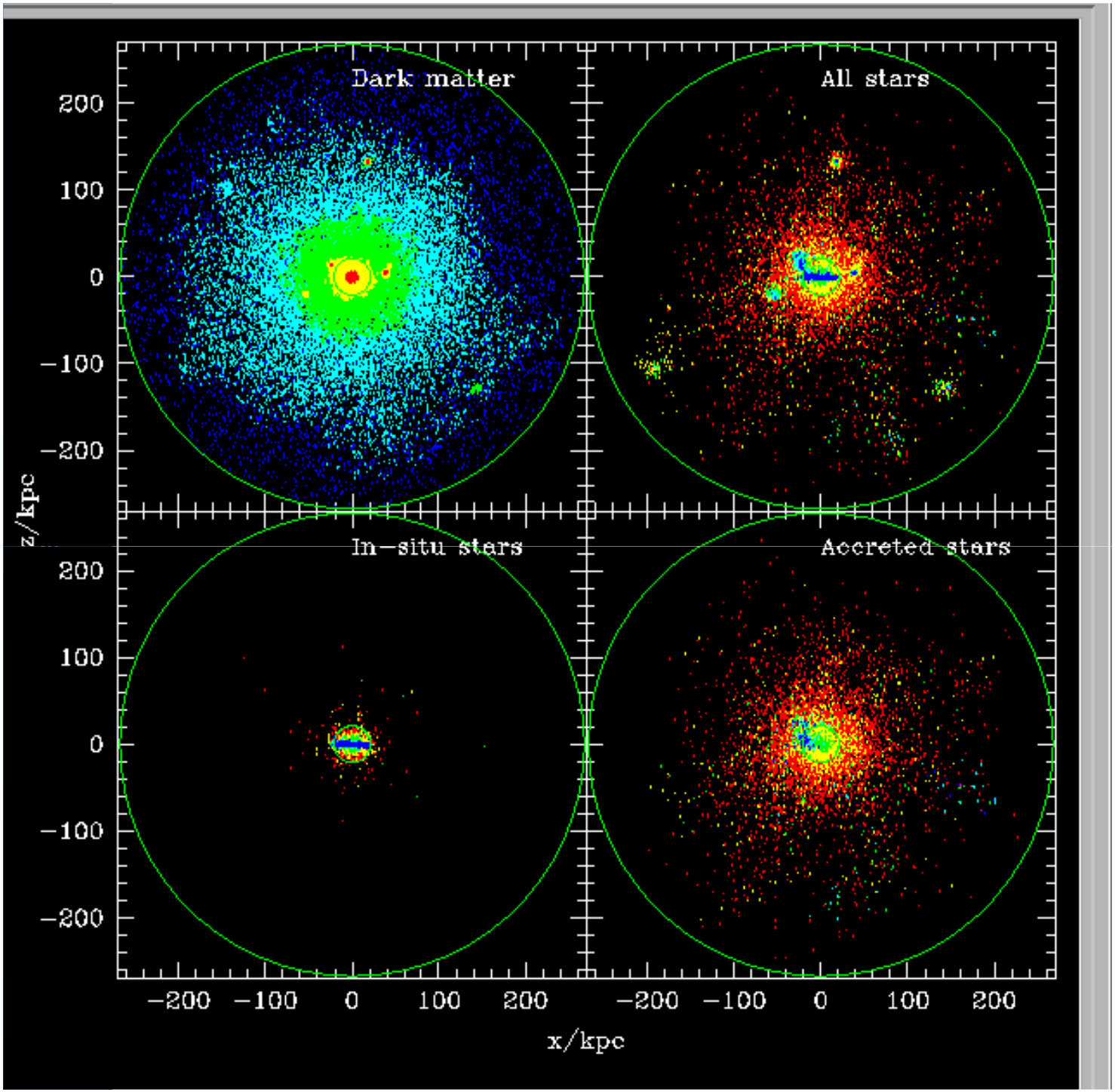
The state of simulating disk galaxies

- It is possible to get a reasonable Sa/Sb galaxies in selected CDM halos
- What has changed ?
  - Cosmology: SCDM → LCDM
    - f_b=0.05 → 0.20
    - reduced frequency of late mergers
  - More realistic feedback models (gas rich mergers)
    - Numerical resolution
  - Favorable initial conditions (no major merger after z=2)
- Remaining problems
  - Formation of bulgeless disks
  - Late disks as the dominant population of galaxies



The simulations

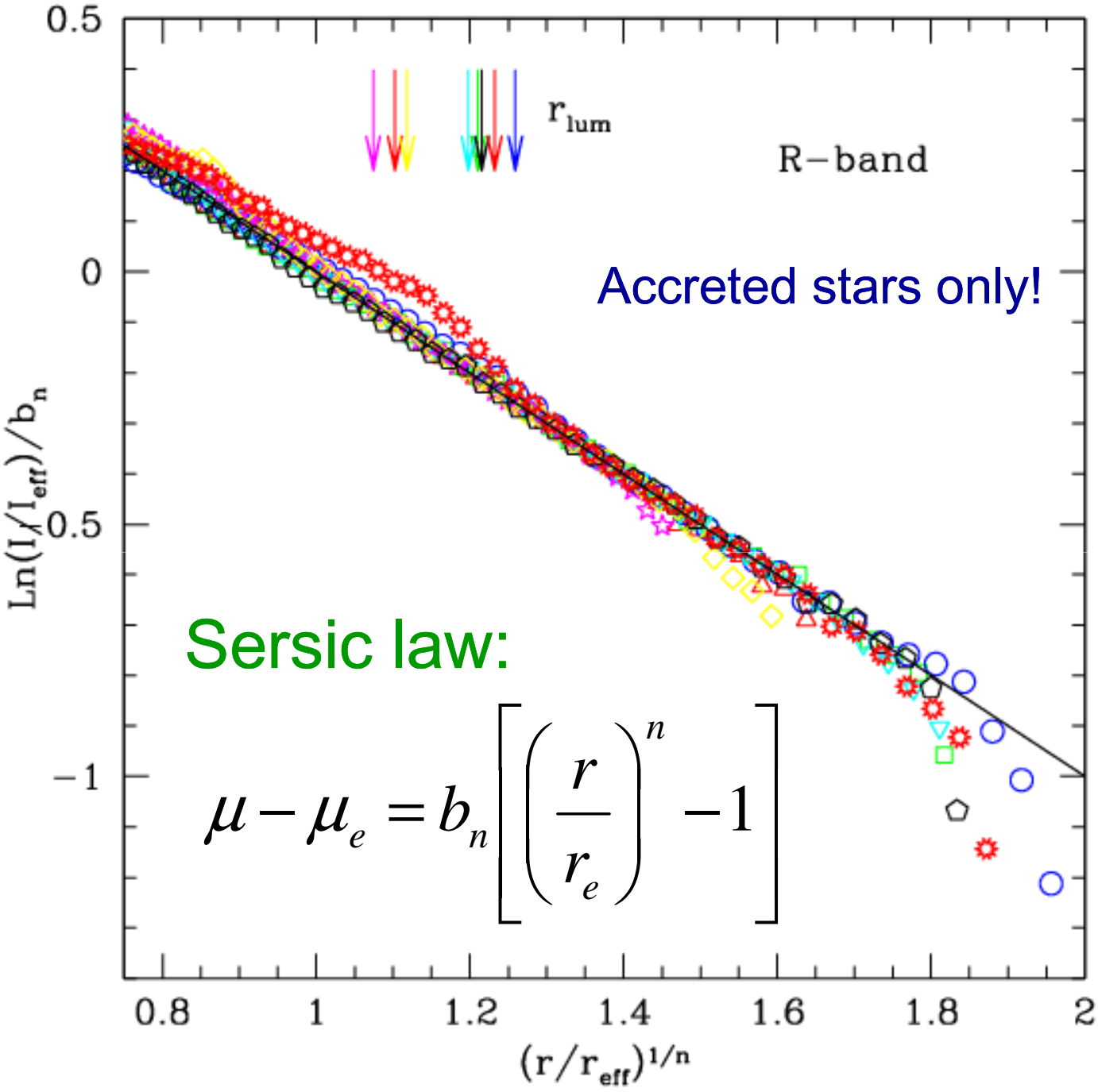
- Gasdynamical simulations of 9 halos with $v_c \approx 200$ km/s
- Concordance LCDM scenario
- Star formation + SN feedback
- Force resolution: 1kpc
- Mass resolution: 10^6 $M_\odot$
- Completness limit for satellites: 0.2% L_{host}
  - Can compare against MW and M31 satellites
  - Cannot address so-called small-scale crisis



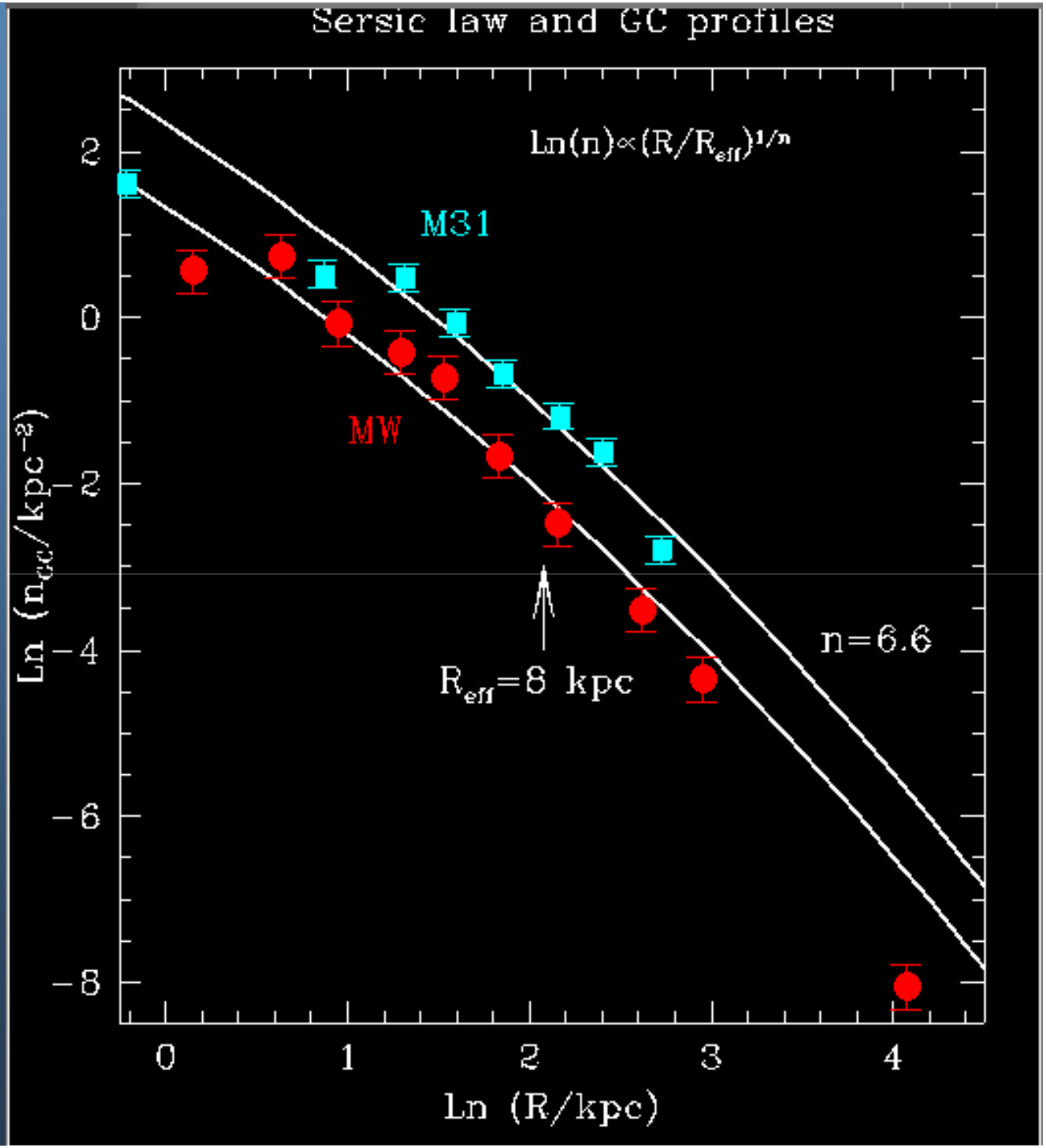
In situ: stars that formed in the most massive progenitor

accreted: stars that formed in satellites

Abadi et al 2005

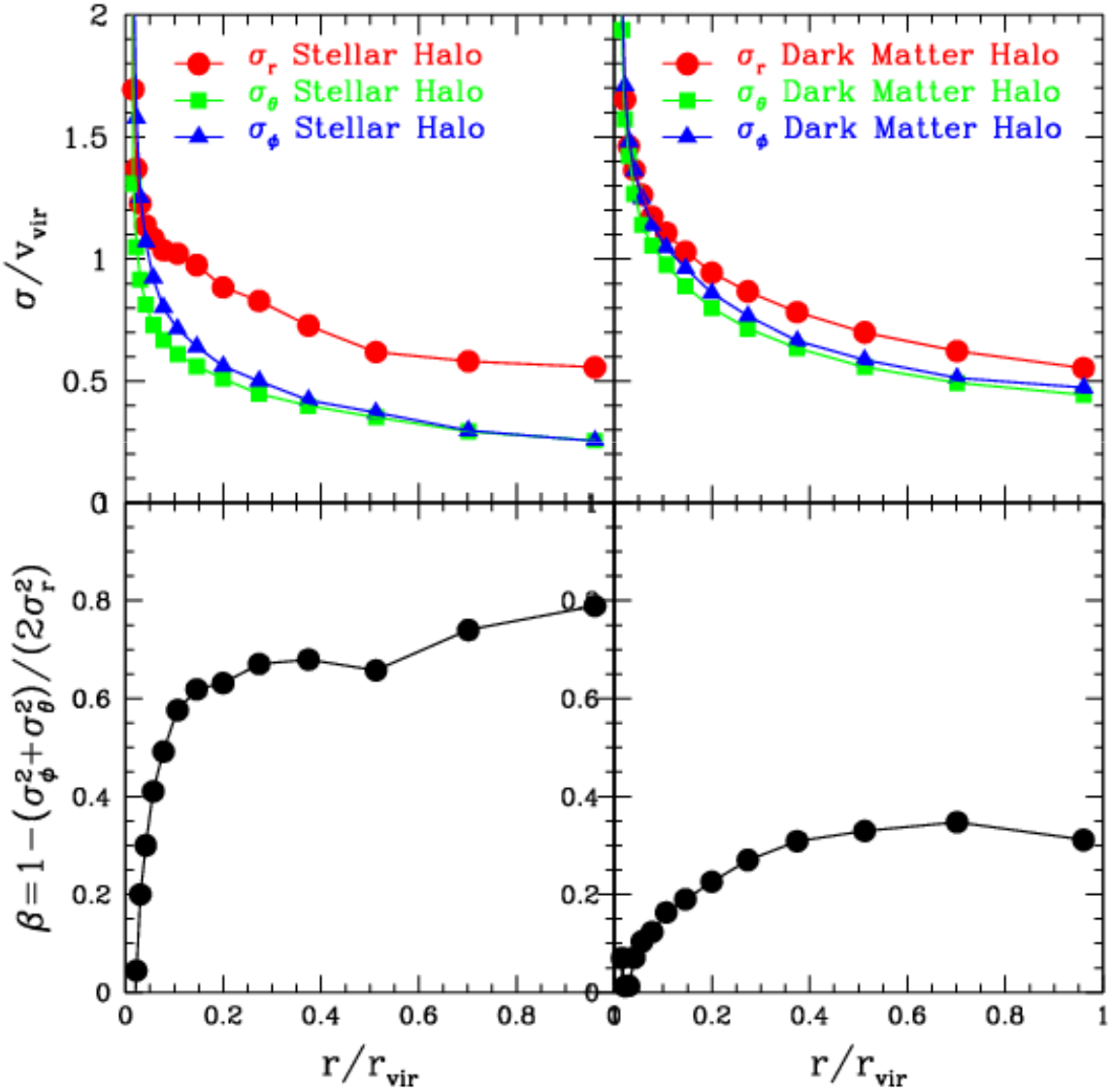


Abadi et al 2005



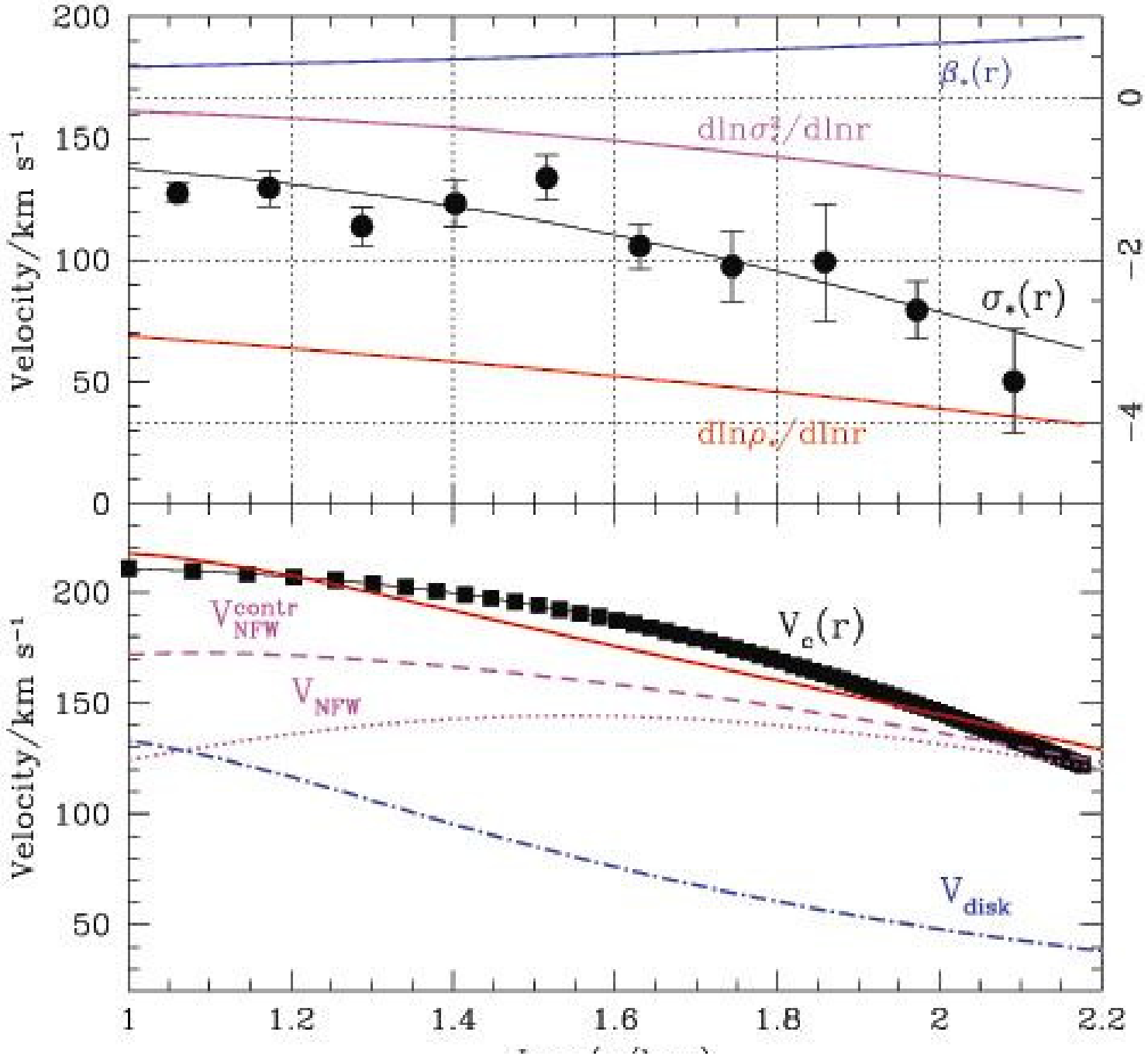
Abadi et al 2005

Anisotropy of stellar and DM halo



Dark matter halo and stellar halo exhibit quite different structural properties

Abadi et al 2005



$V_{200} \approx 0.5\ V_{Disk}$

Pro

- Tully Fisher
- DM in disks

Con

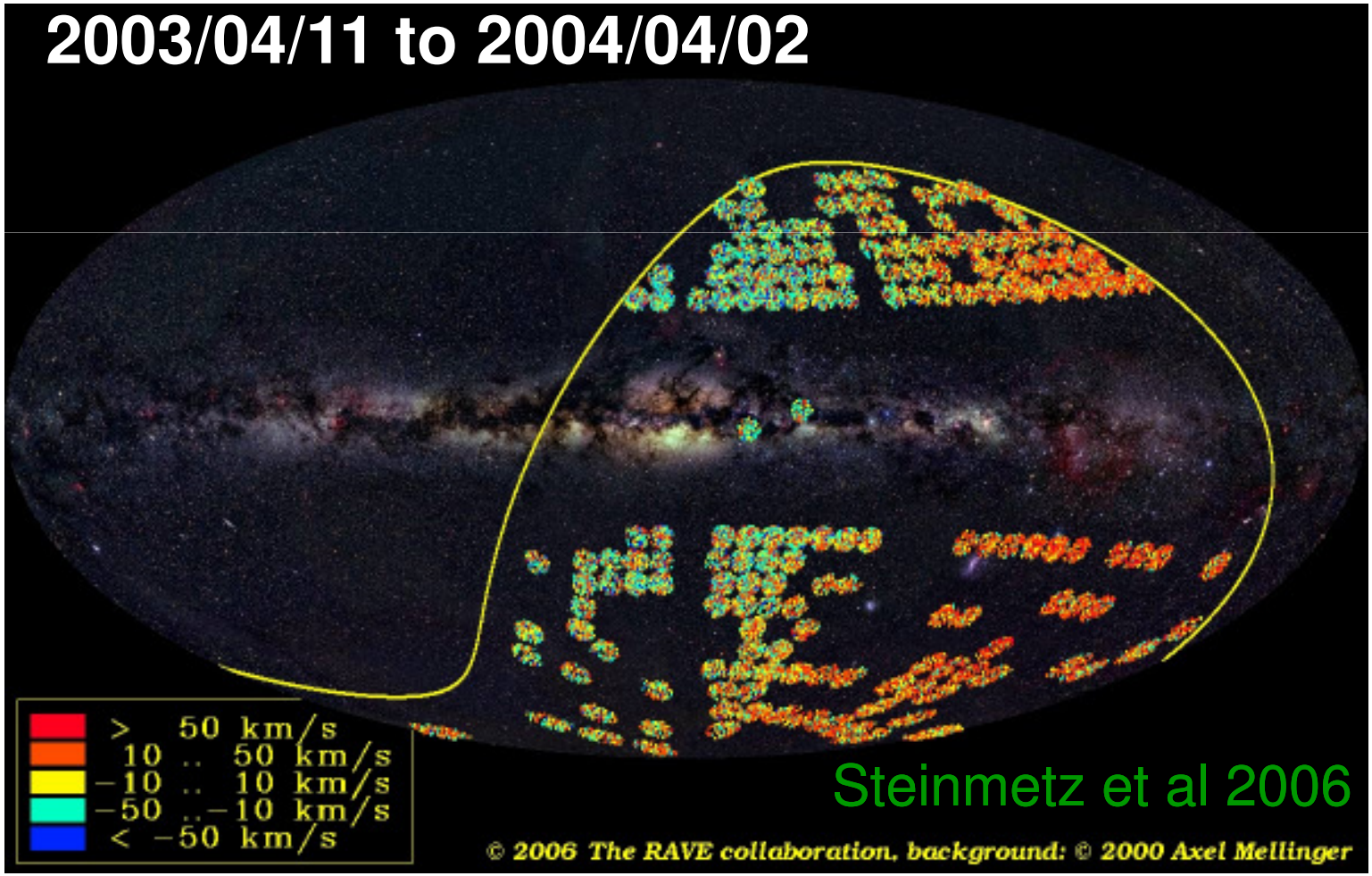
- Abundance of disk galaxies

Abadi et al 2005

1st Data Release

Coverage : ~4,670 sq.deg
25,274 radial velocities
24,748 targets

240 fields
5.7° diameter
1 hour exposures

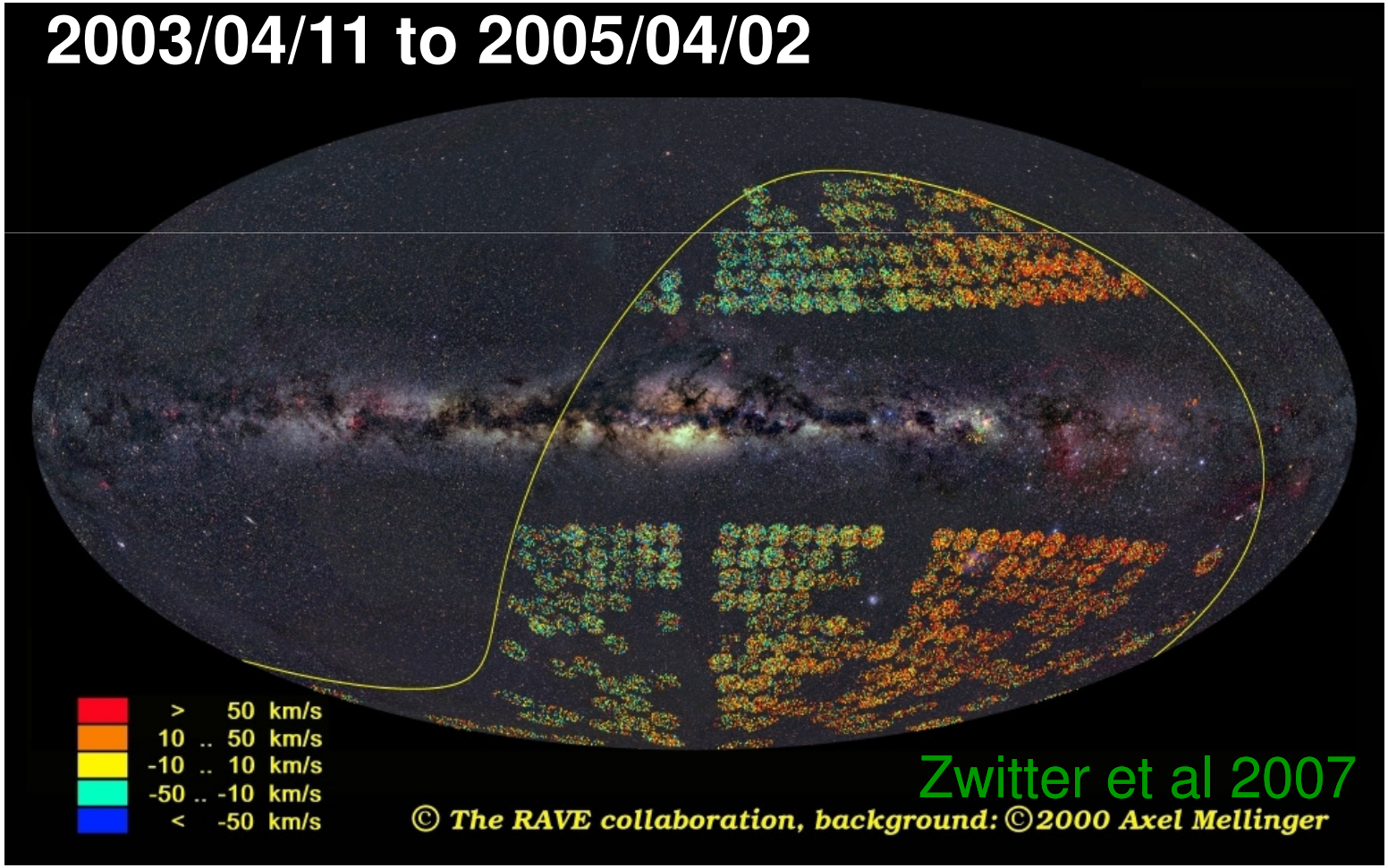


2nd Data Release (preview)

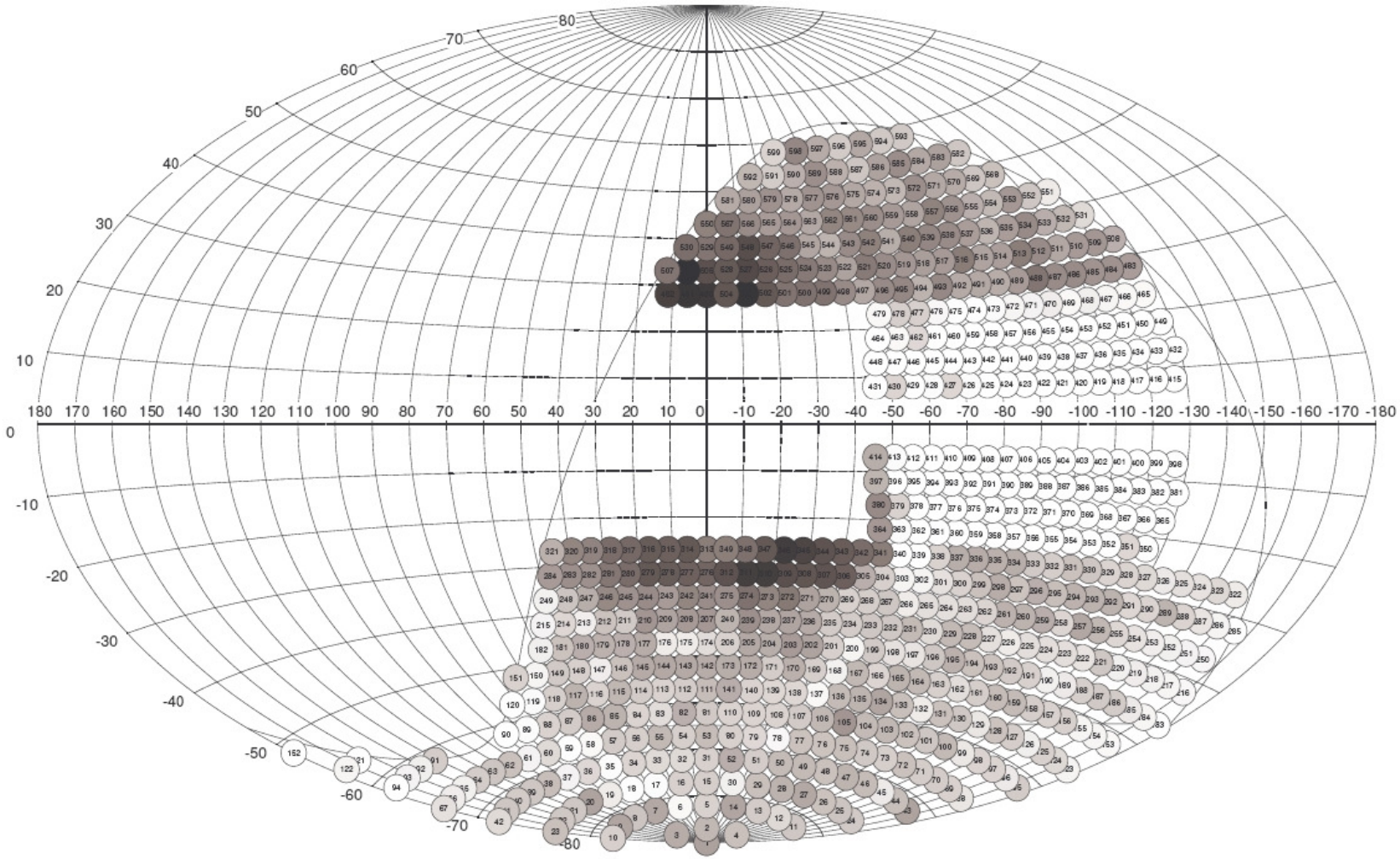
RAVE
RADIAL VELOCITY EXPERIMENT

Coverage : ~6800 sq.deg
51,637 radial velocities
48,873 targets

500 fields
5.7° diameter
1 hour exposures



Current status



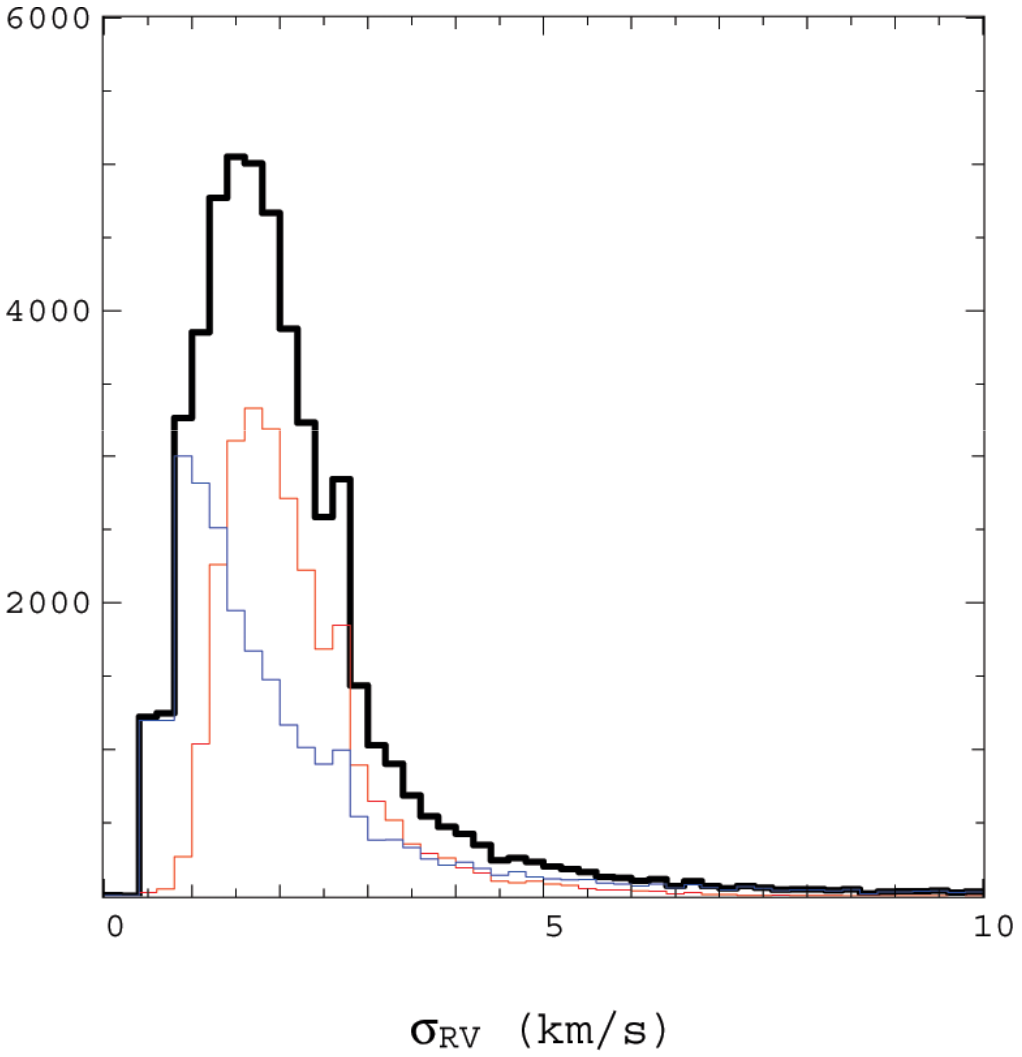
06/01/2007 : close to 200,000 Spectra

DR2 Internal errors:

DR1
Mean : 2.3km/s
Median : 1.9km/s
Peak : 1.7km/s

DR2-DR1
Mean : 2.2km/s
Median : 1.5km/s
Peak : 0.9km/s

DR2
Mean : 2.2km/s
Median : 1.8km/s
Peak : 1.5km/s



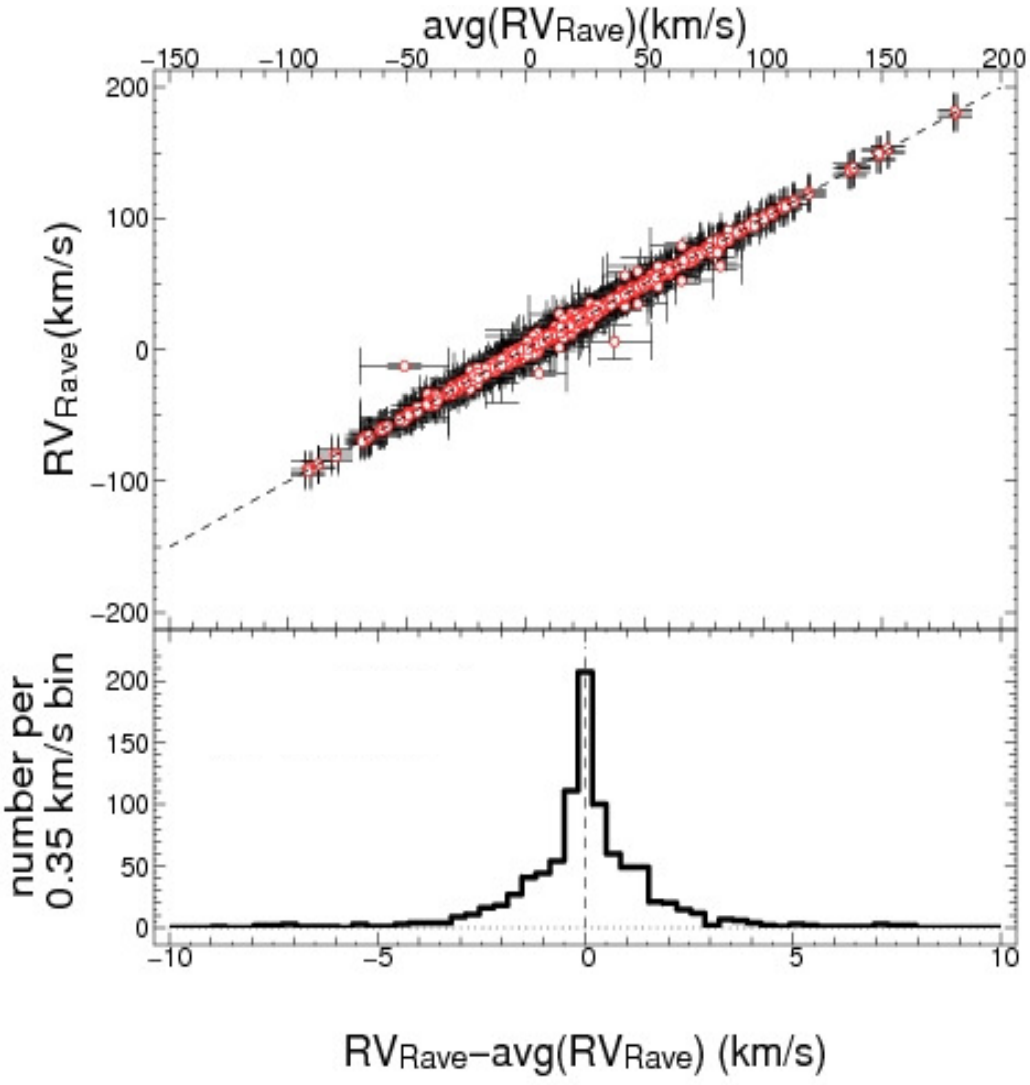
Zwitter et al., 2007

Stability of Radial Velocities

Based on 840 re-observed targets:

mean diff=-0.02 km/s
rms=2.83 km/s

Good stability of solution with time

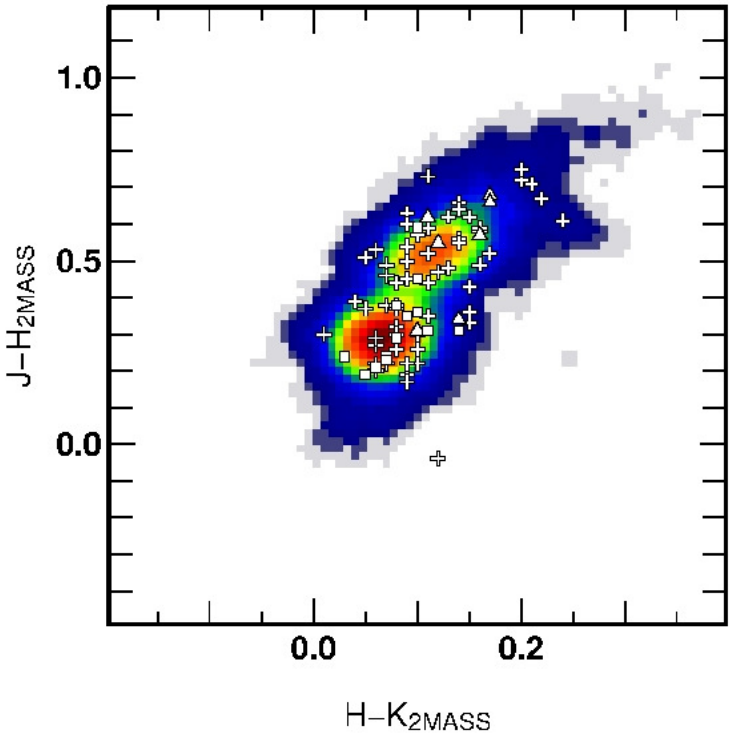


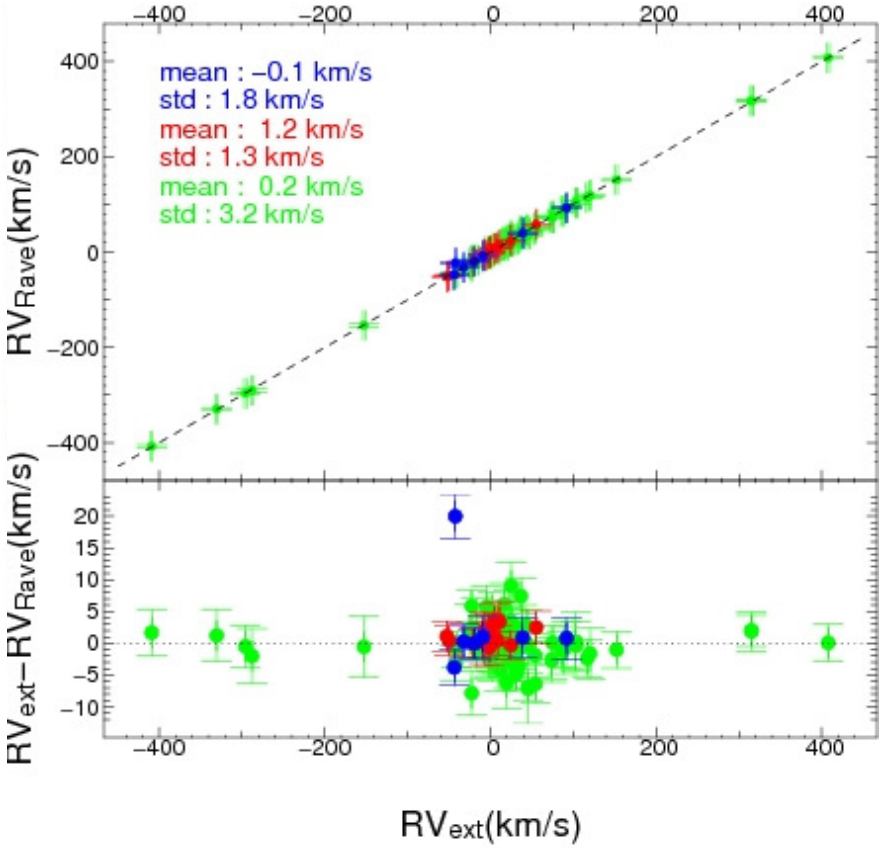
Steinmetz et al., 2006

Comparison to "Standards"

RAVE
RADIAL VELOCITY EXPERIMENT

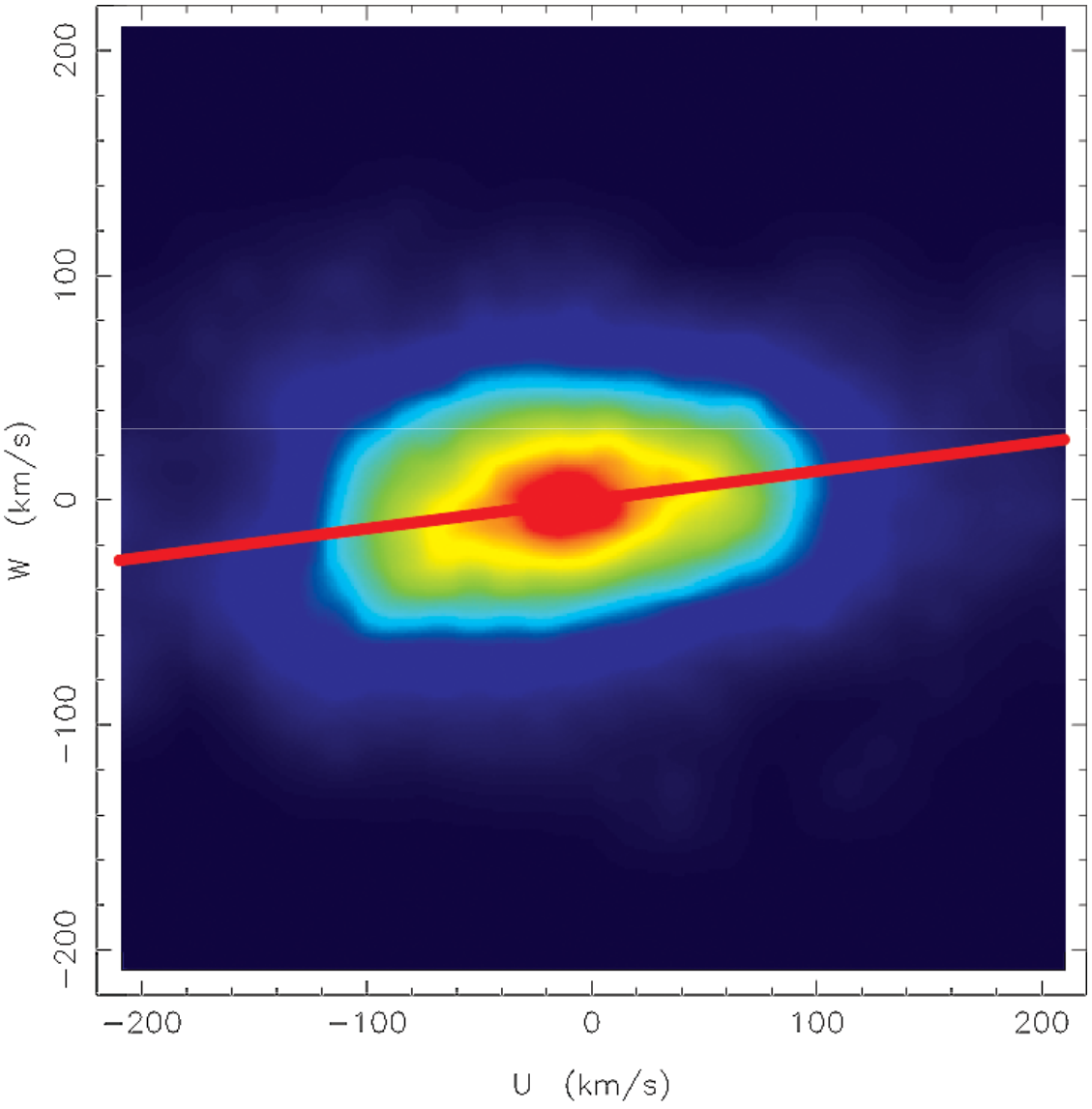
3 external sources:
- **Elodie (high resolution)**
- **2.3m (long slit, medium resolution)**
- **Geneva-Copenhagen (CORAVEL)**





Steinmetz et al., 2006

The galactic potential and the tilt of the velocity ellipsoid



~500 KIII giants

500 < z <1500 pc

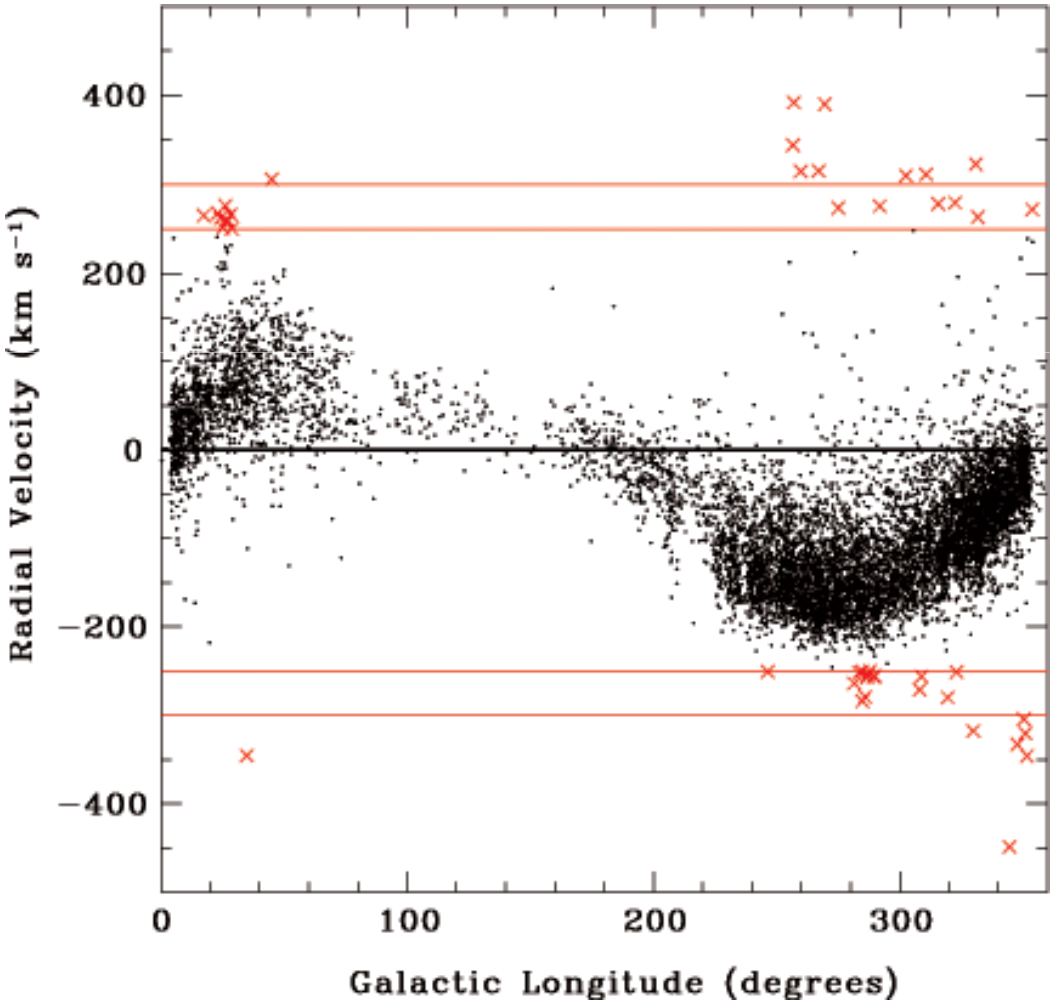
Δ=5.2±1.2 deg

q=0.85-0.95

Bienaymé, Siebert & RAVE,2007

The Escape Speed of the Milky-Way

Smith, Rutchi et al 2007



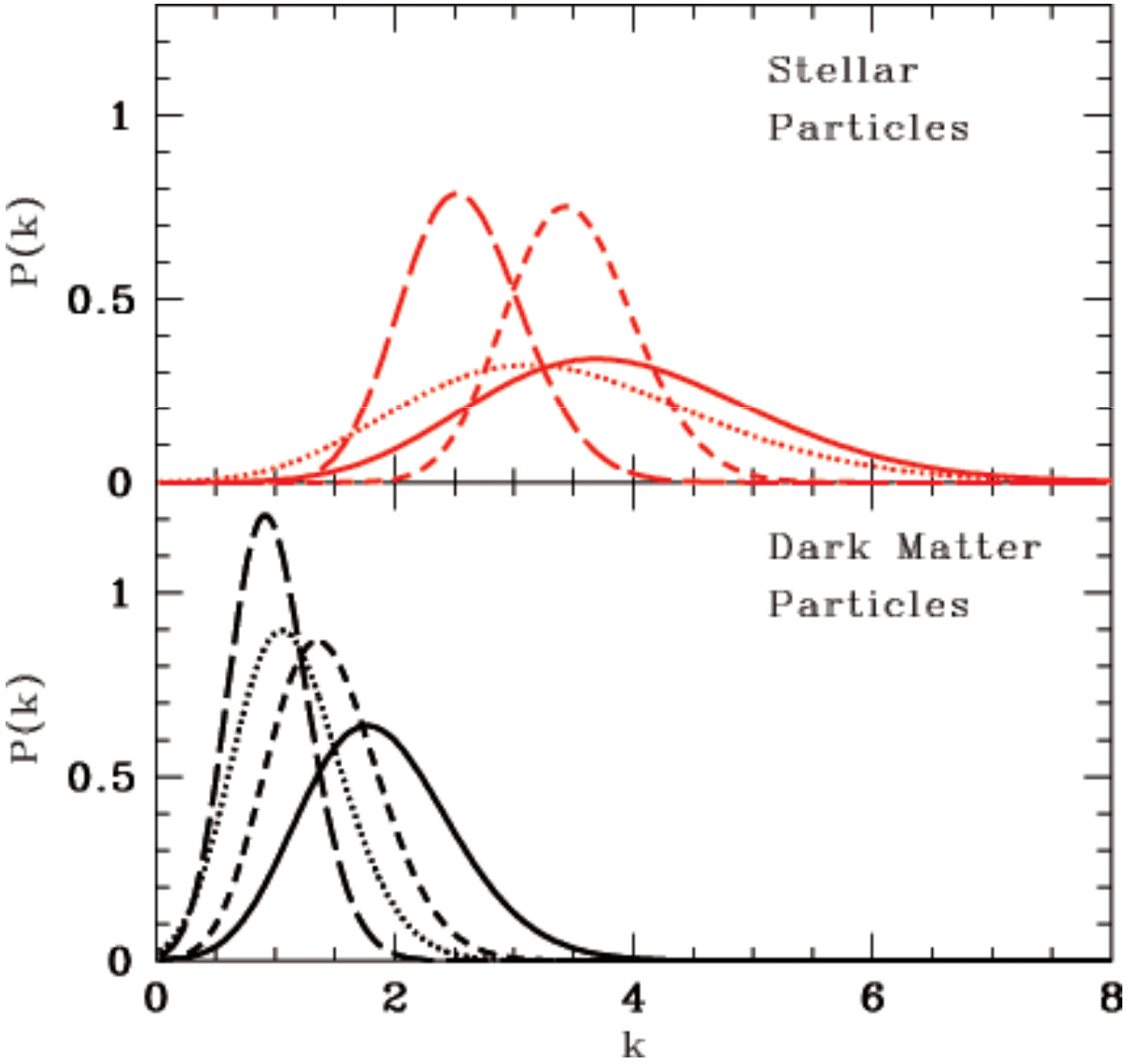
Leonard & Tremaine (1990):

near escape velocity:

$$f(\varepsilon) \propto \varepsilon^{k}$$

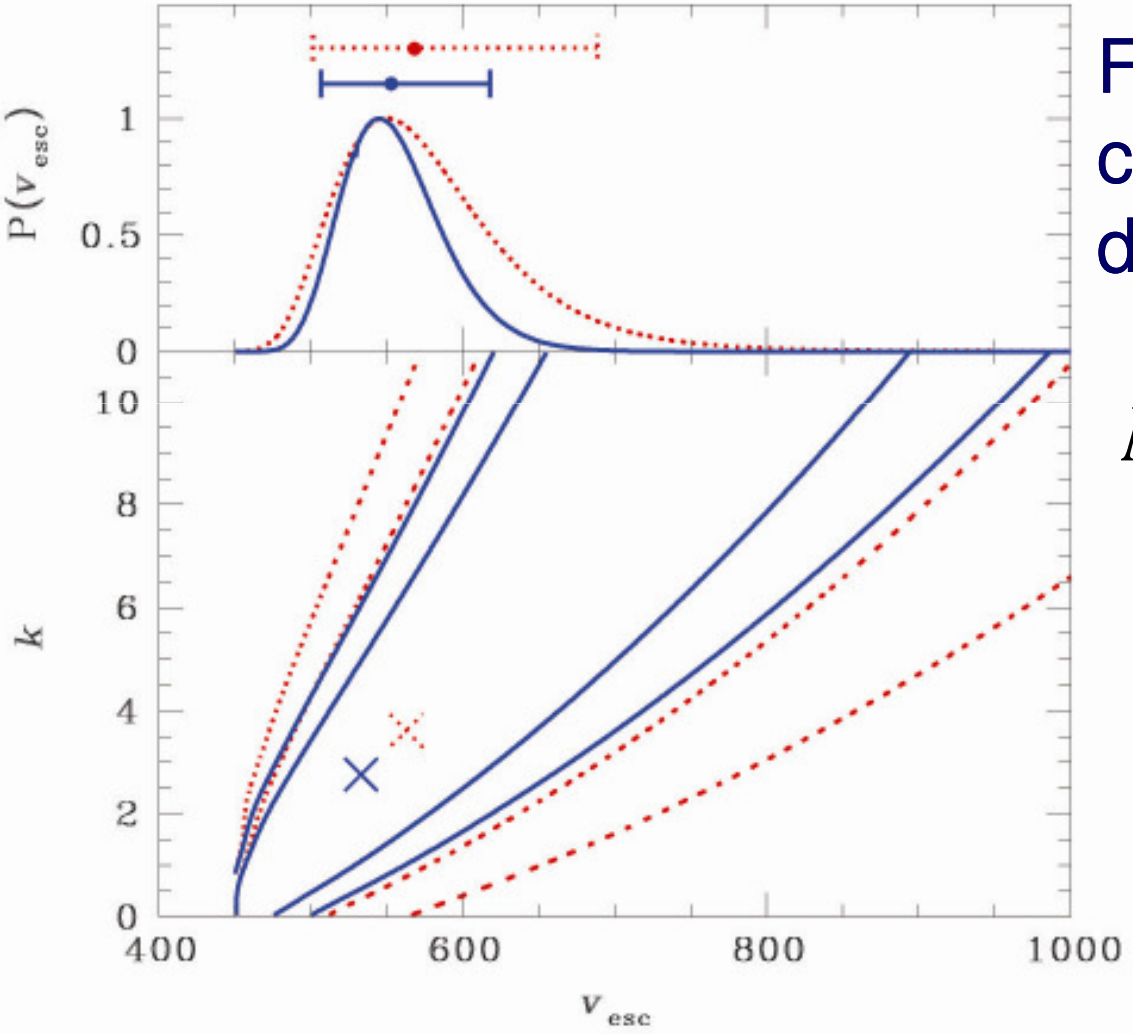
$$\varepsilon = \left(v_e^2 - v^2\right)$$

The Escape Speed of the Milky-Way



from sims by Abadi et al, 2003

The Escape Velocity of the Milky-Way



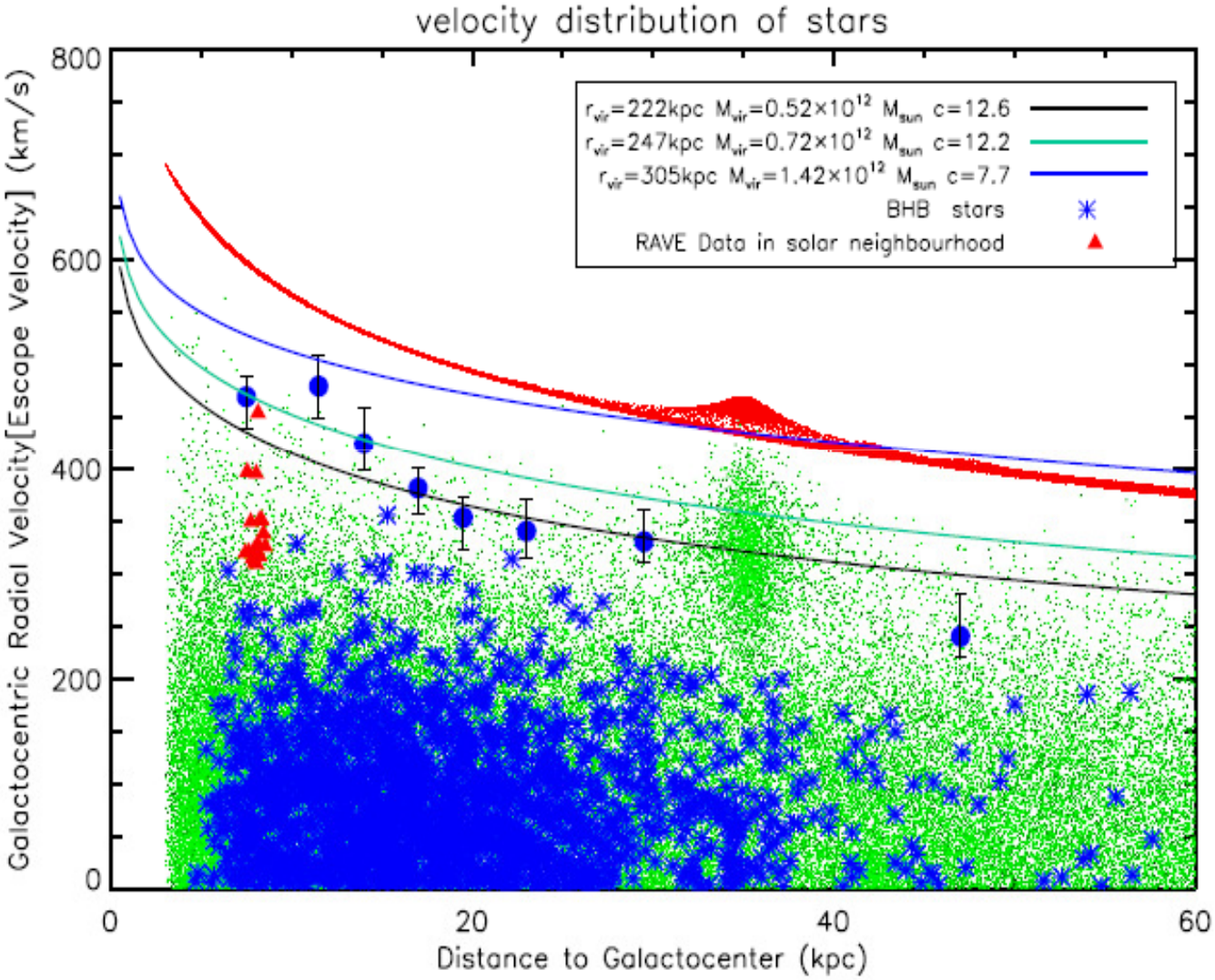
For an adiabatically contracted NFW dark halo:

$$M_{MW} = 1.42^{+1.14}_{-0.54} \times 10^{12}\,\mathrm{M}_{\odot}$$

$$v_{vir} \approx 142\ \mathrm{km/s}$$

Smith et al 2007

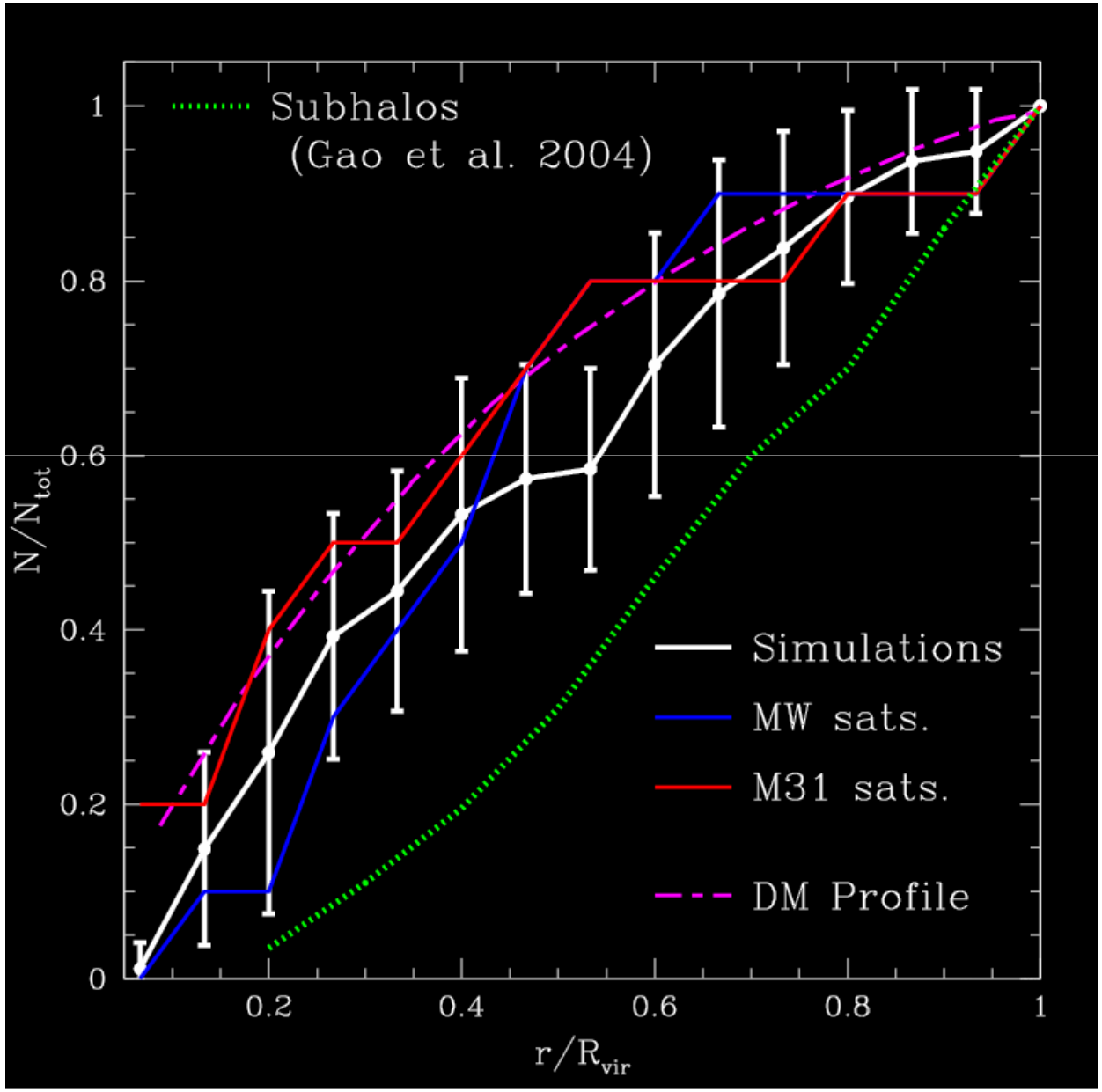
Escape Velocity vs Radius



from halo BHB stars in SDSS DR5

Xue et al 2007

Distribution of Satellites

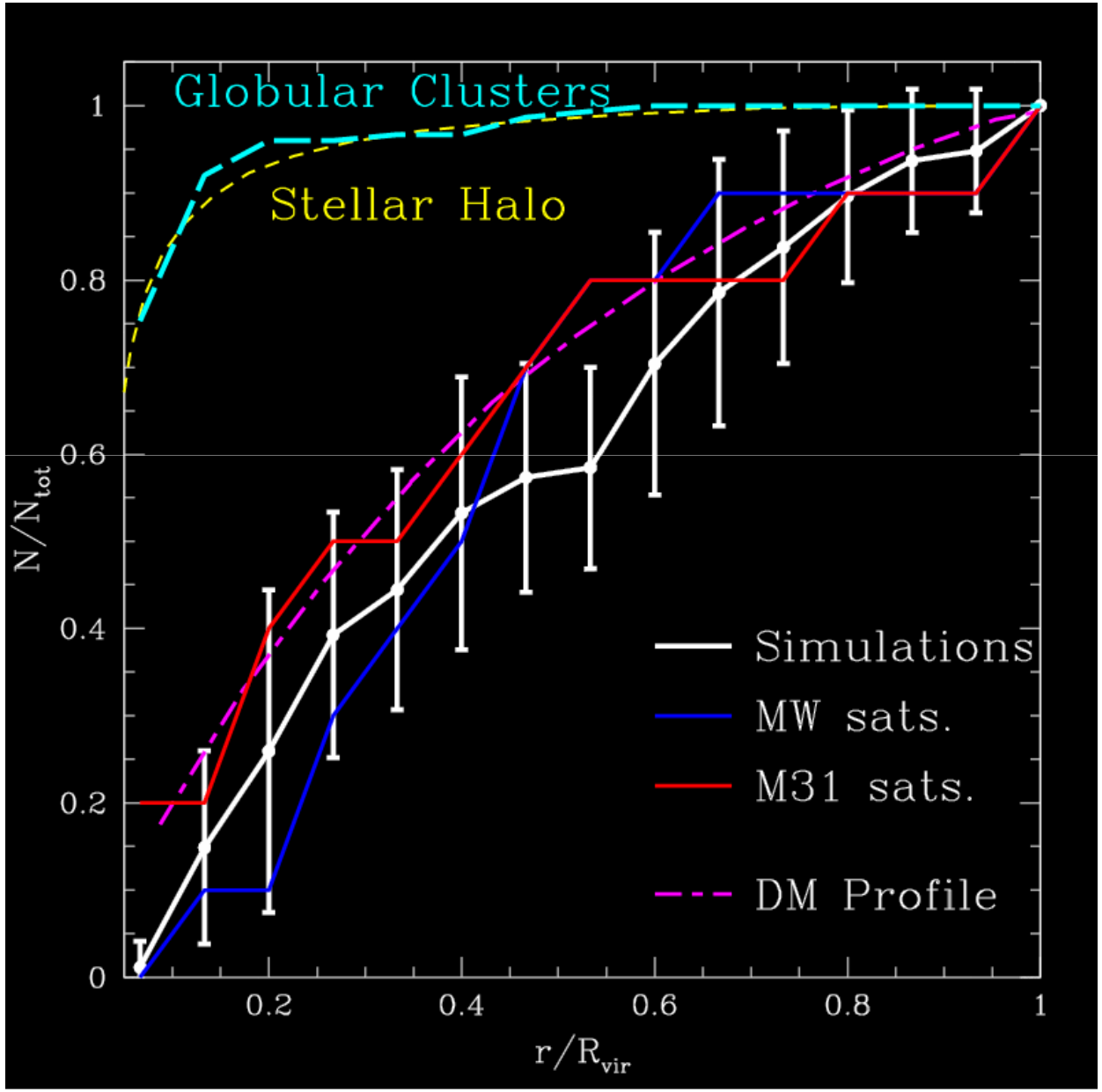


Satellites more concentrated than DM substructure

Cool baryons at the center of substructures stabilize against tidal disruption

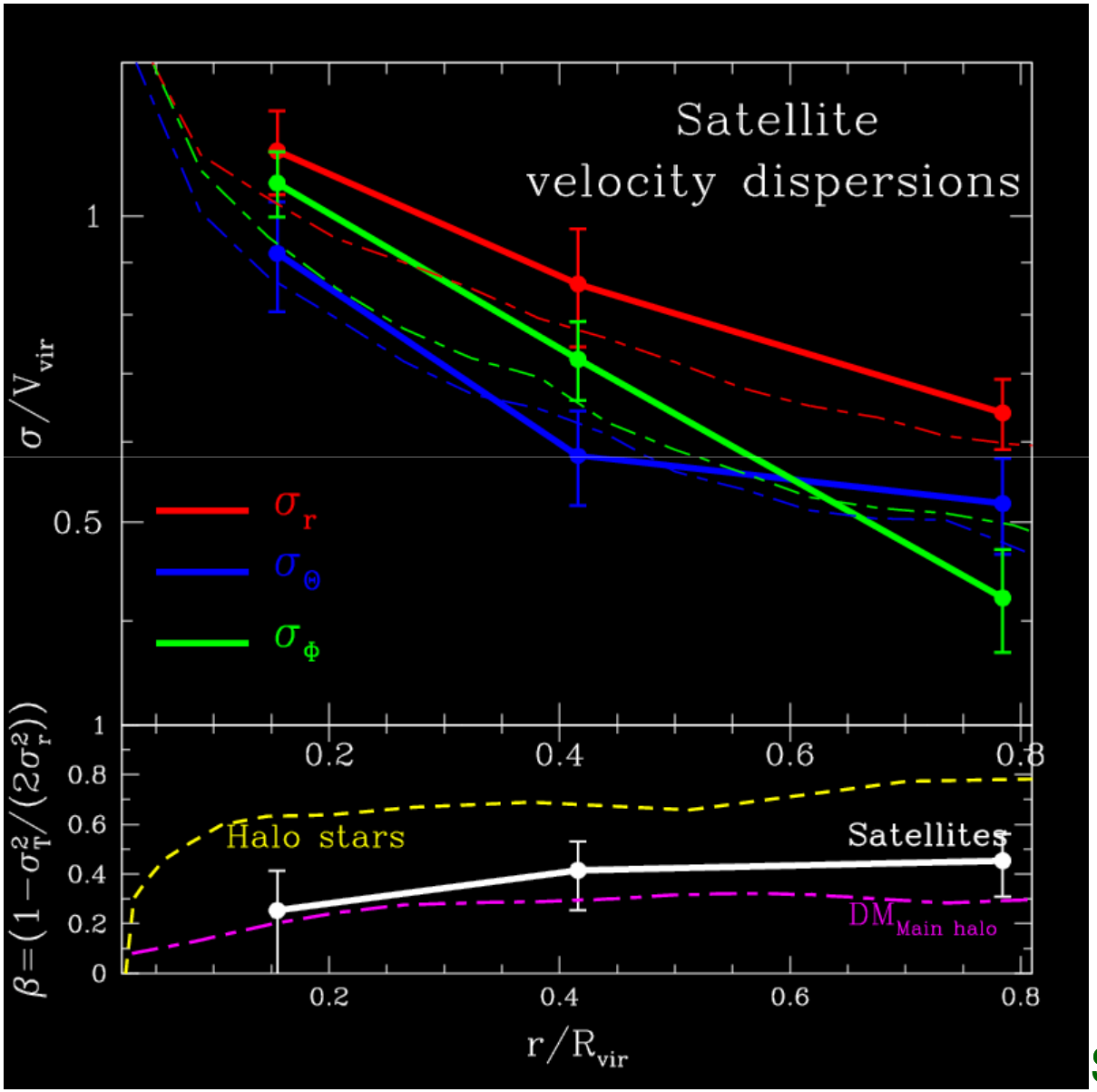
Satellites trace adiabatically contracted DM profile

Distribution of Satellites



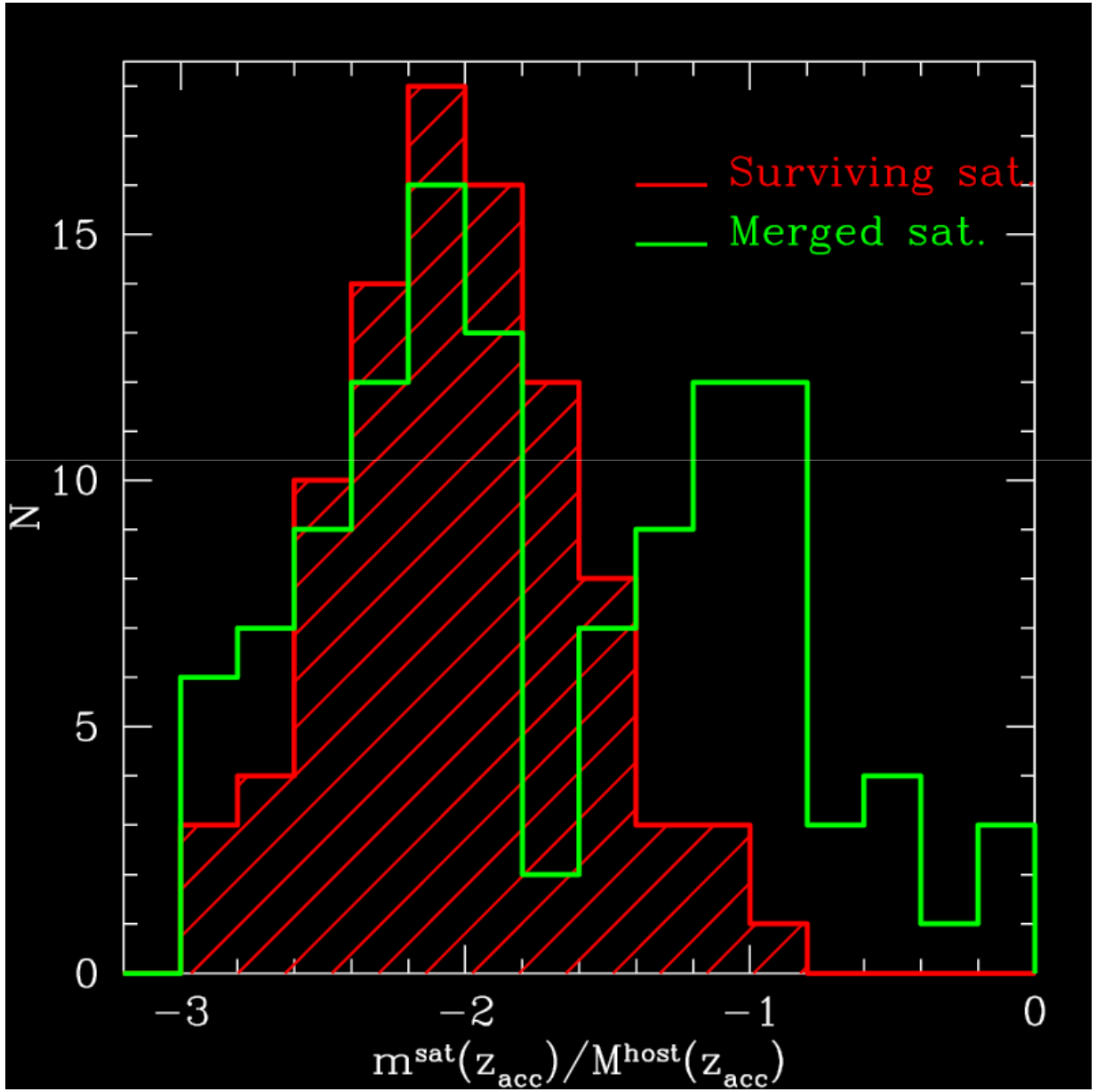
Sales et al 2007a

Velocity distribution of satellites



Sales et al 2007a

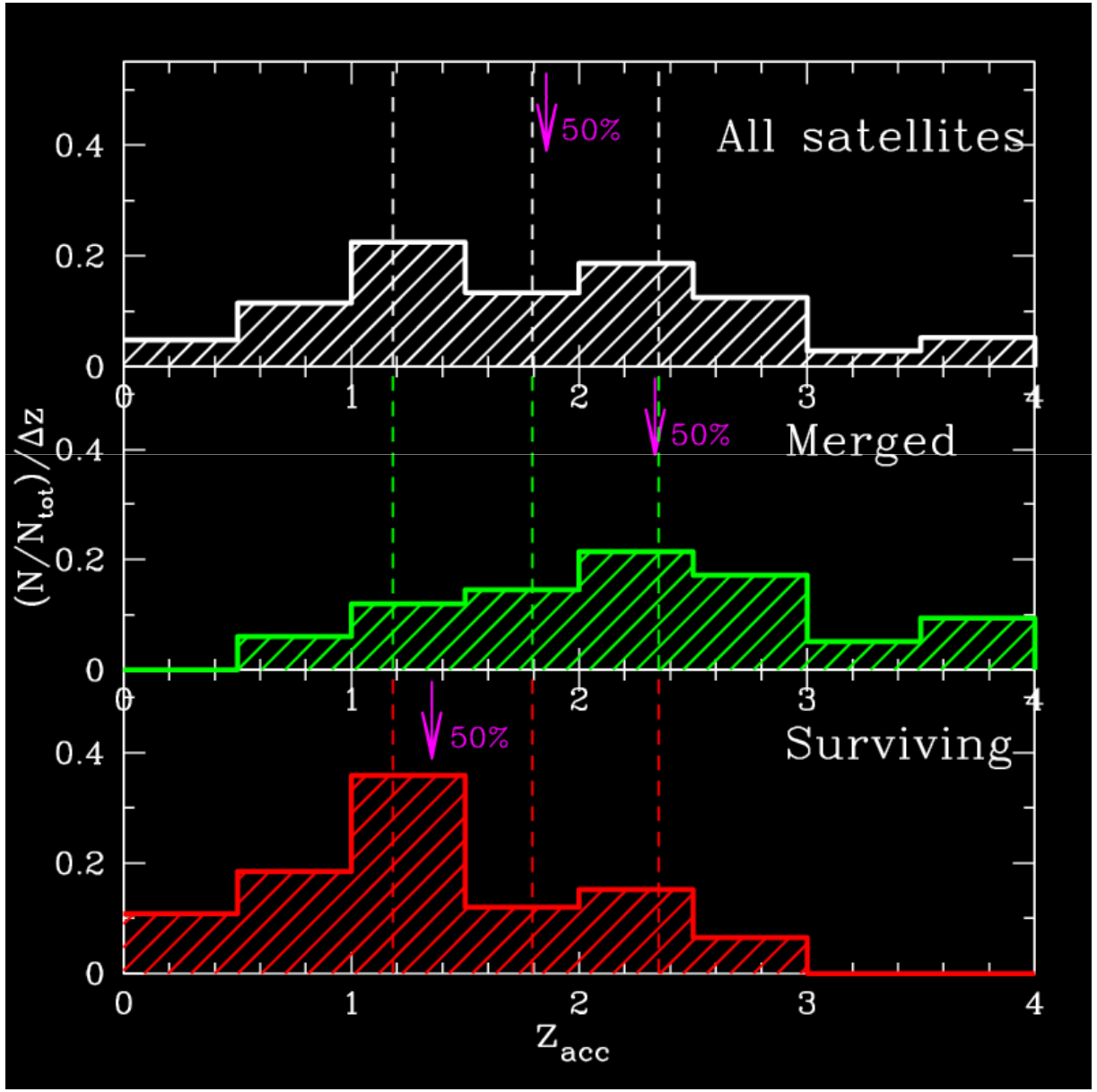
Satellite mass distribution



Halo stars were formed in higher mass objects than satellite stars

Sales et al 2007a

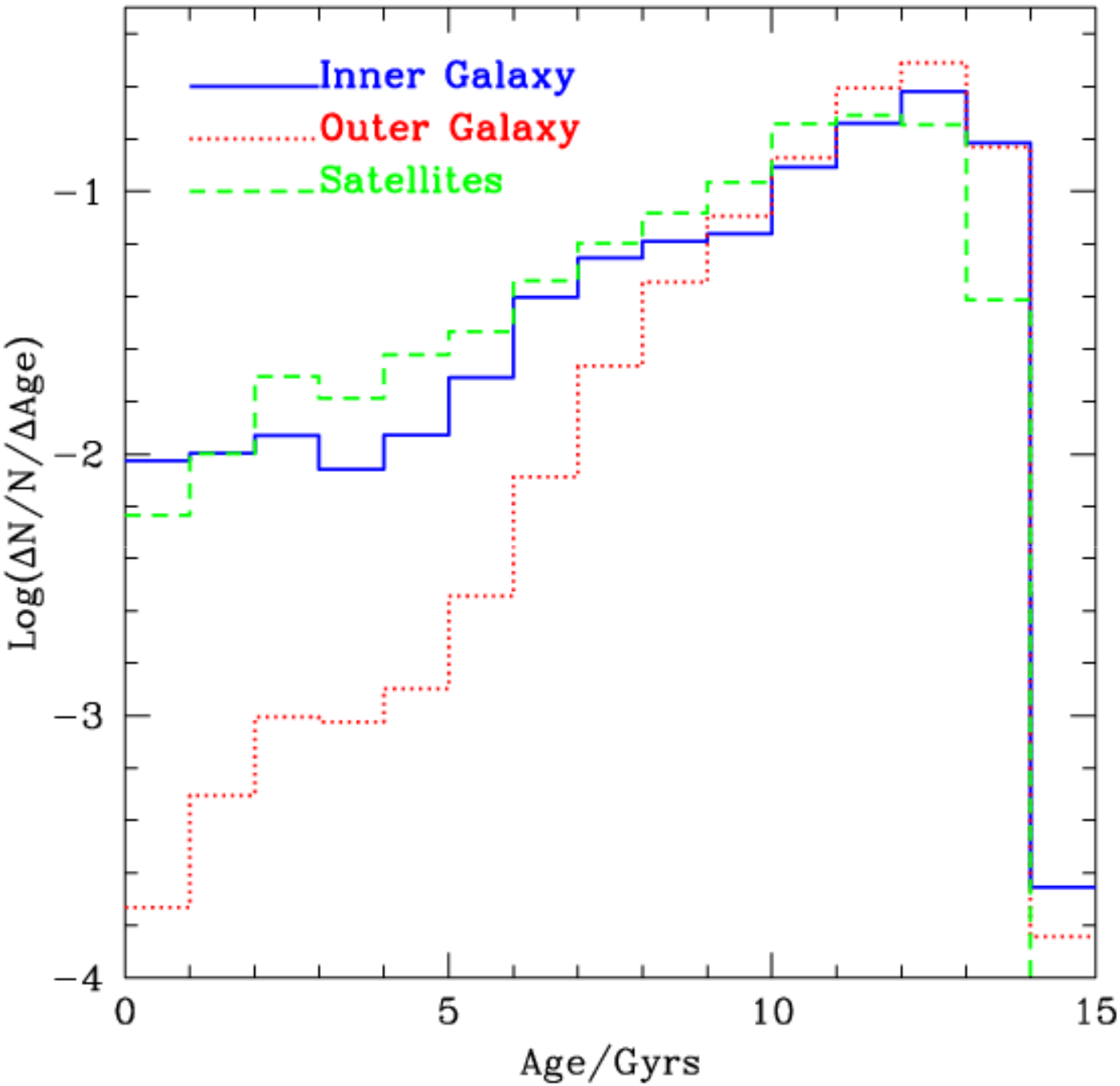
Accretion epoch



Surviving Satellites were accreted later than progenitors of halo stars

Surviving Satellites were accreted more recent than average built-up history of host galaxy

Sales et al 2007a



Abadi et al 2005

Estimating v_{vir} via satellites

Sim: $\sigma_{sat,rad} = 0.9 \pm 0.2\ V_{vir}$
Obs: $\sigma_{MW,rad} = 99.2$ km/s

$V_{vir} = 111 \pm 30$ km/s
$\Rightarrow R_{half,sat} = 90$kpc

$R_{half,MW} = 87$kpc

MW

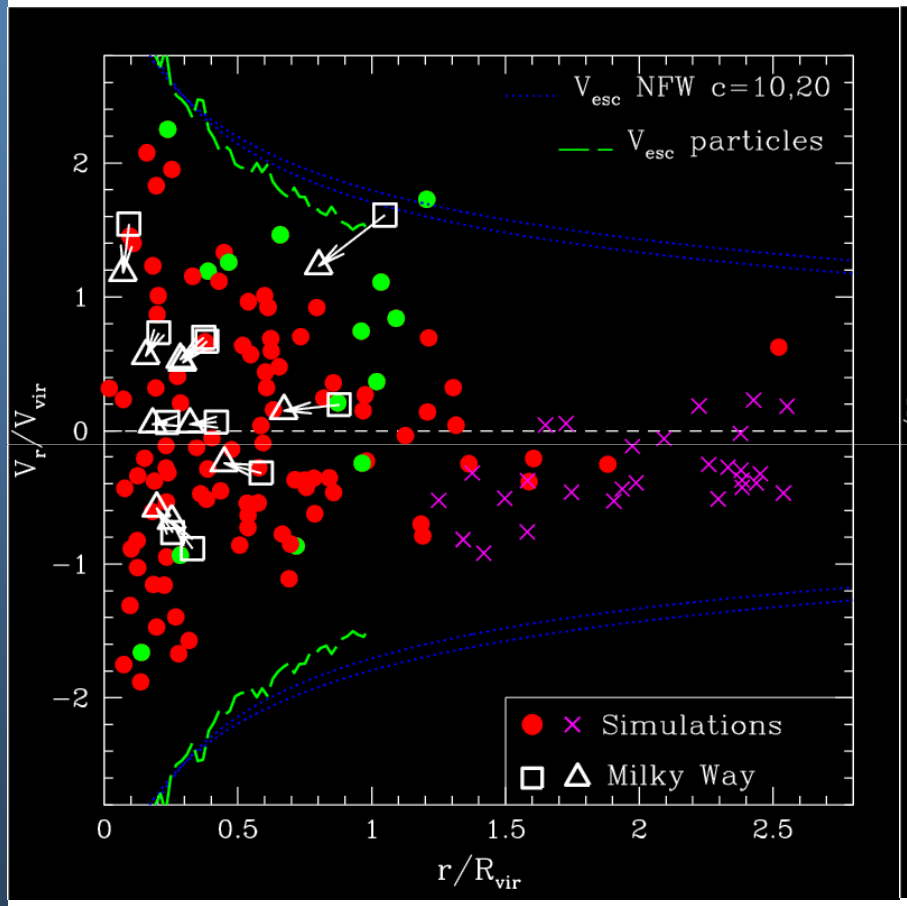
Sim: $\sigma_{sat,los} = 0.8 \pm 0.2\ V_{vir}$
Obs: $\sigma_{M31,los} = 94.6$ km/s

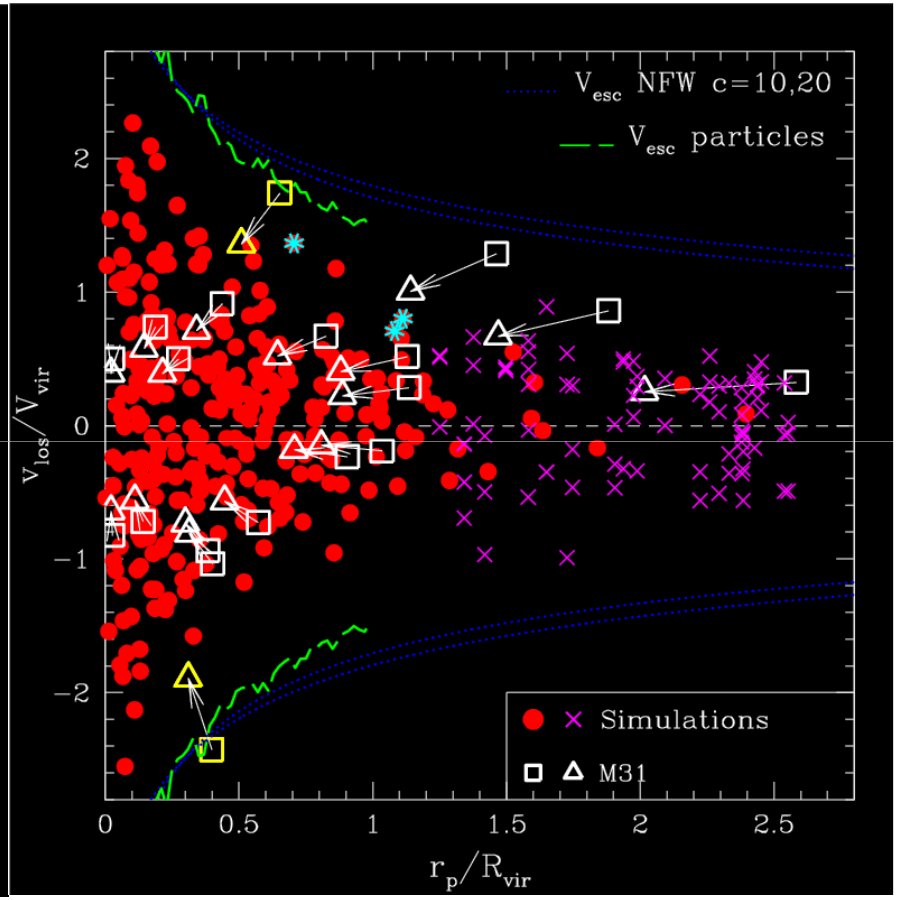
$V_{vir} = 111 \pm 30$ km/s
$\Rightarrow R_{half,sat} = 93$kpc

$R_{half,M31} = 115$kpc

M31

Estimating v_{vir} via satellites

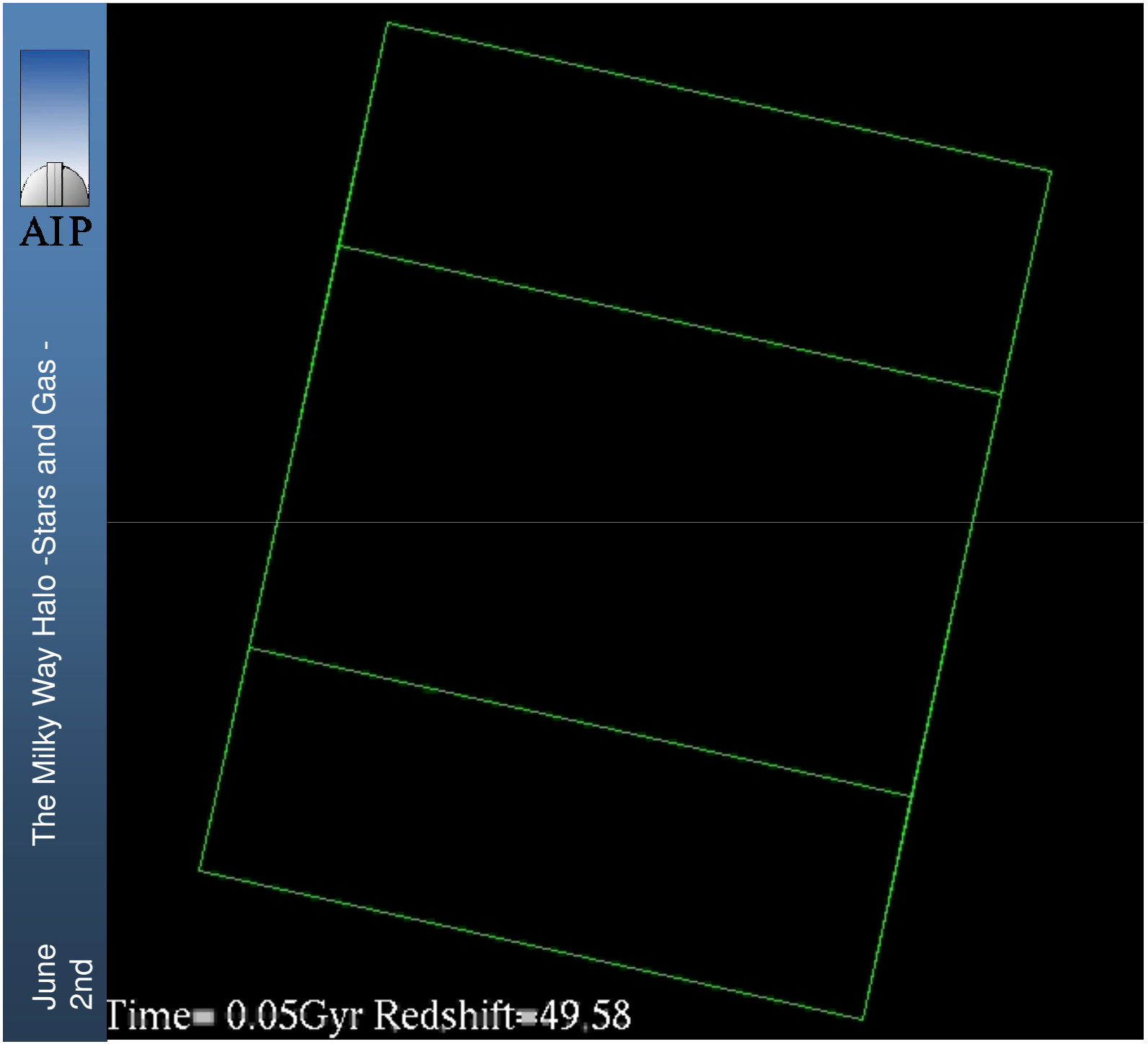




MW

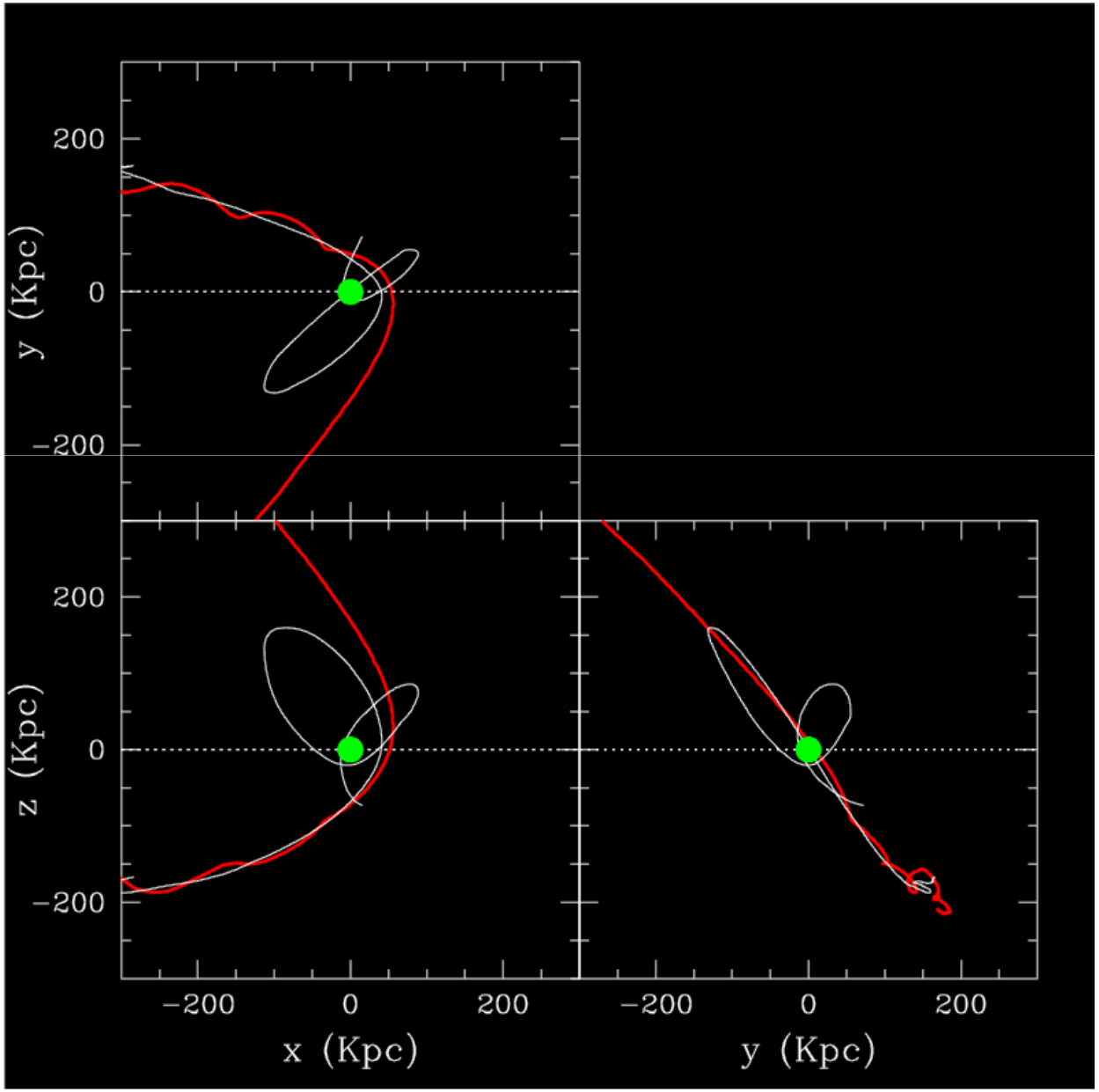
M31

Sales et al 2007a

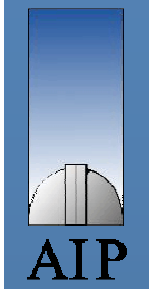


Sales et al 2007b

Satellite ejection by 3-body encounter



Sales et al 2007b

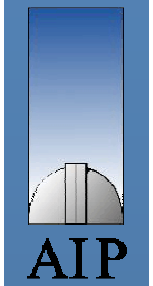


Summary

1. ***The structure and kinematics of the stellar halo exhibits considerable differences if compared to the dark matter halo and/or the satellite system***

2. ***There are also systematic differences in the age distribution between stars in the stellar halo and stars in satellites***

3. ***Dynamical mass estimates of the Milky Way imply circular velocities for the dark halo of 100-150 km/s. This may be difficult to reconcile with the observed abundance of L* galaxies***



References

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