The Milky Way

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Lecture N. 3

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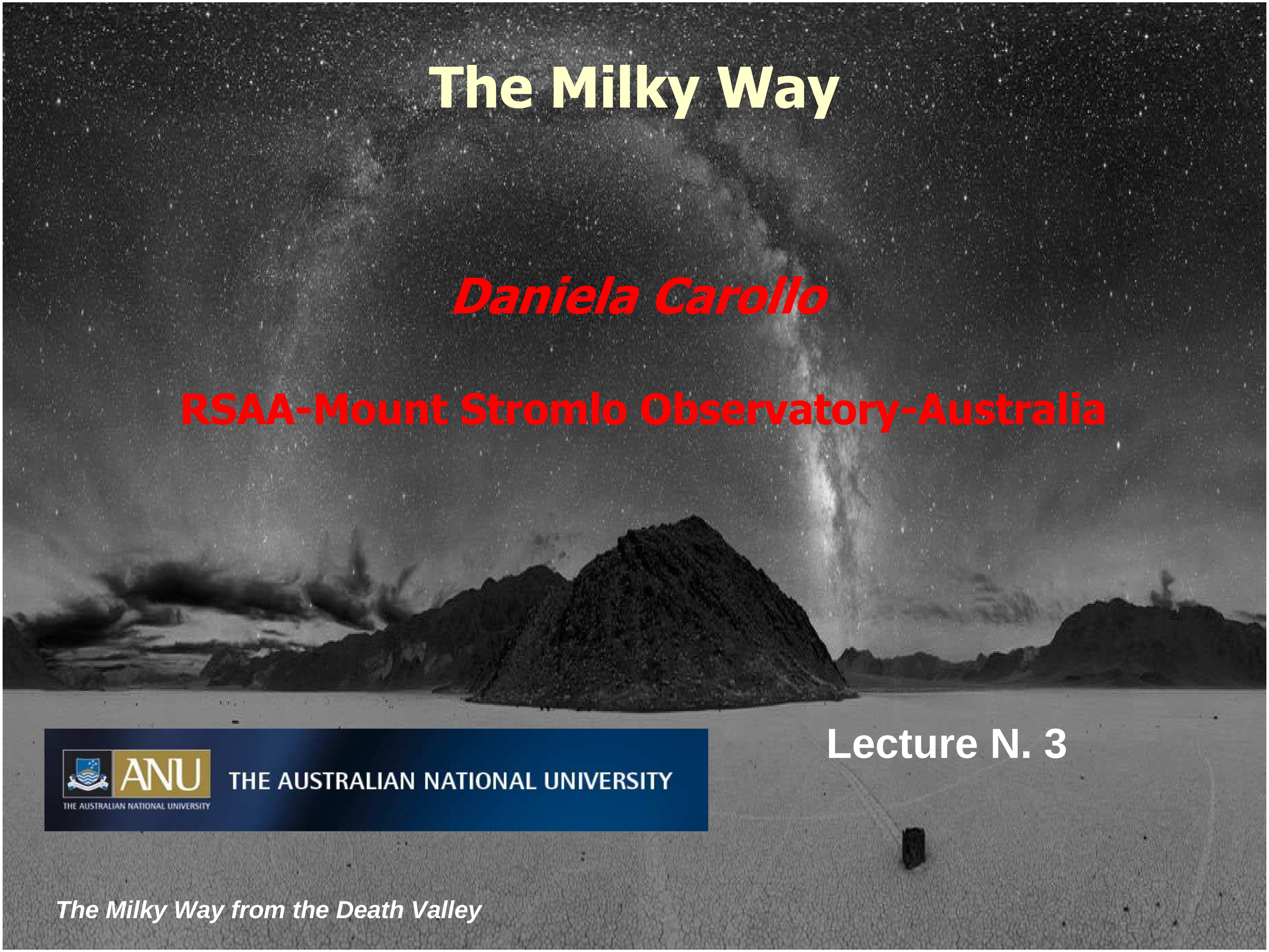
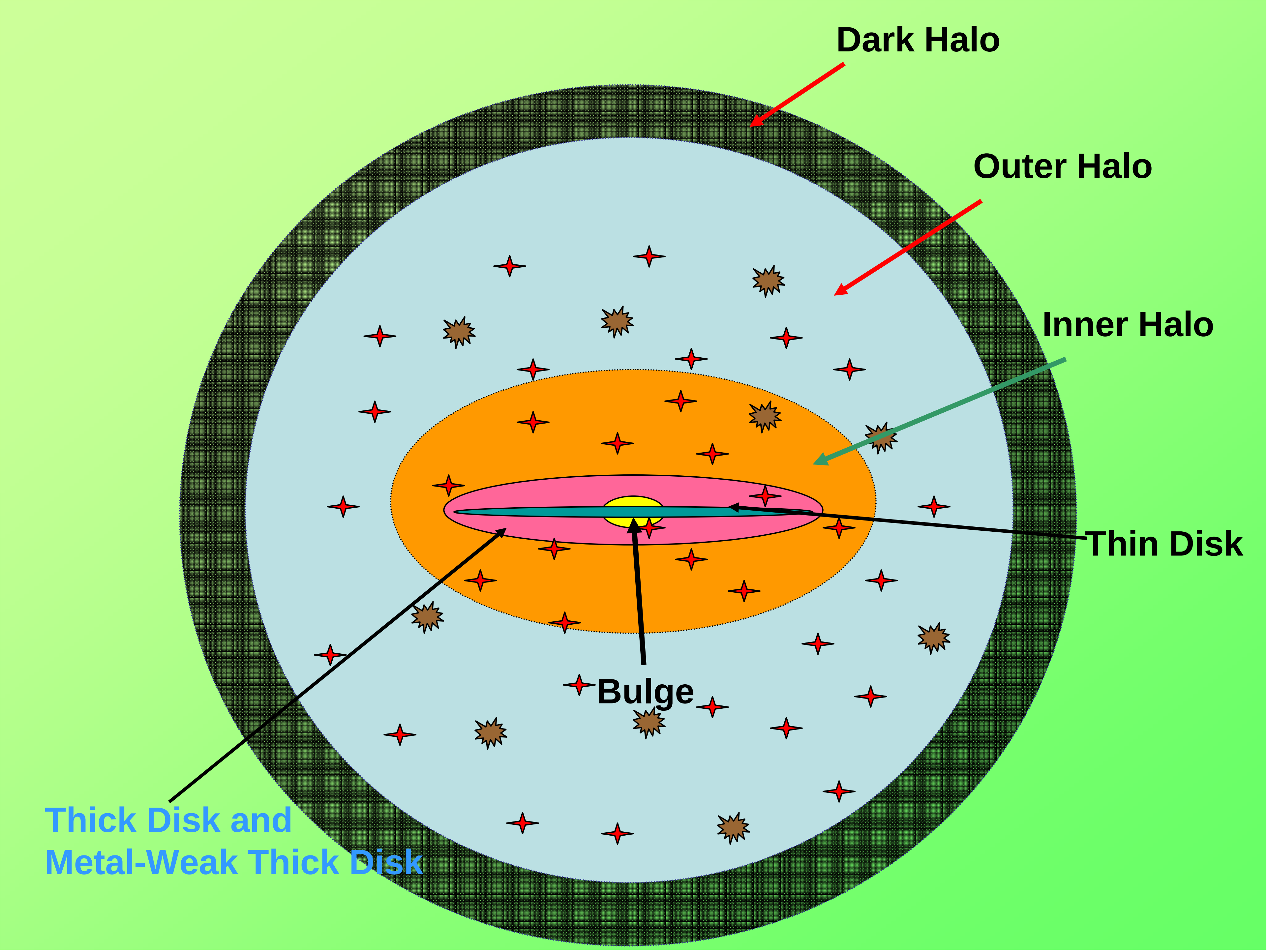


The Milky Way from the Death Valley

In this lecture:

- The new nature of the Galactic Halo
- How we got this results
- Implications for the formation of the Galactic Halo
- Galaxy formation models


Dark Halo
Outer Halo
Inner Halo
Thin Disk
Bulge
Thick Disk and
Metal-Weak Thick Disk

Nature of the Galactic Halo(s)
Conclusions First

Carollo D. et al., Nature Article, Vol. 450, 1020-1025, 2007

New results from SDSS have now revised this list:

Halo ➔ Halos

- **Inner Halo:**
  - **Dominant at R < 10-15 kpc**
  - **Highly eccentric orbits**
  - **Slightly Prograde**
  - **Metallicity peak at [Fe/H] = -1.6**
- **Outer Halo:**
  - **Dominant at R > 15-20 kpc**
  - **More uniform distribution of eccentricity**
  - **Highly retrograde orbits**
  - **Metallicity peak around [Fe/H] = -2.2**

Which data we have used for our analysis?

The Sample: DR5 SDSS calibration stars

In total **25670** calibration stars, comprising two different sets:

Spectrophotometric Calibration Stars:

Mainly F and G turnoff stars

Apparent magnitude range: **15.5 < g0 < 17.0**

Color range: **0.6 < (u-g) < 1.2 ; 0.0 < (g-r) < 0.6**

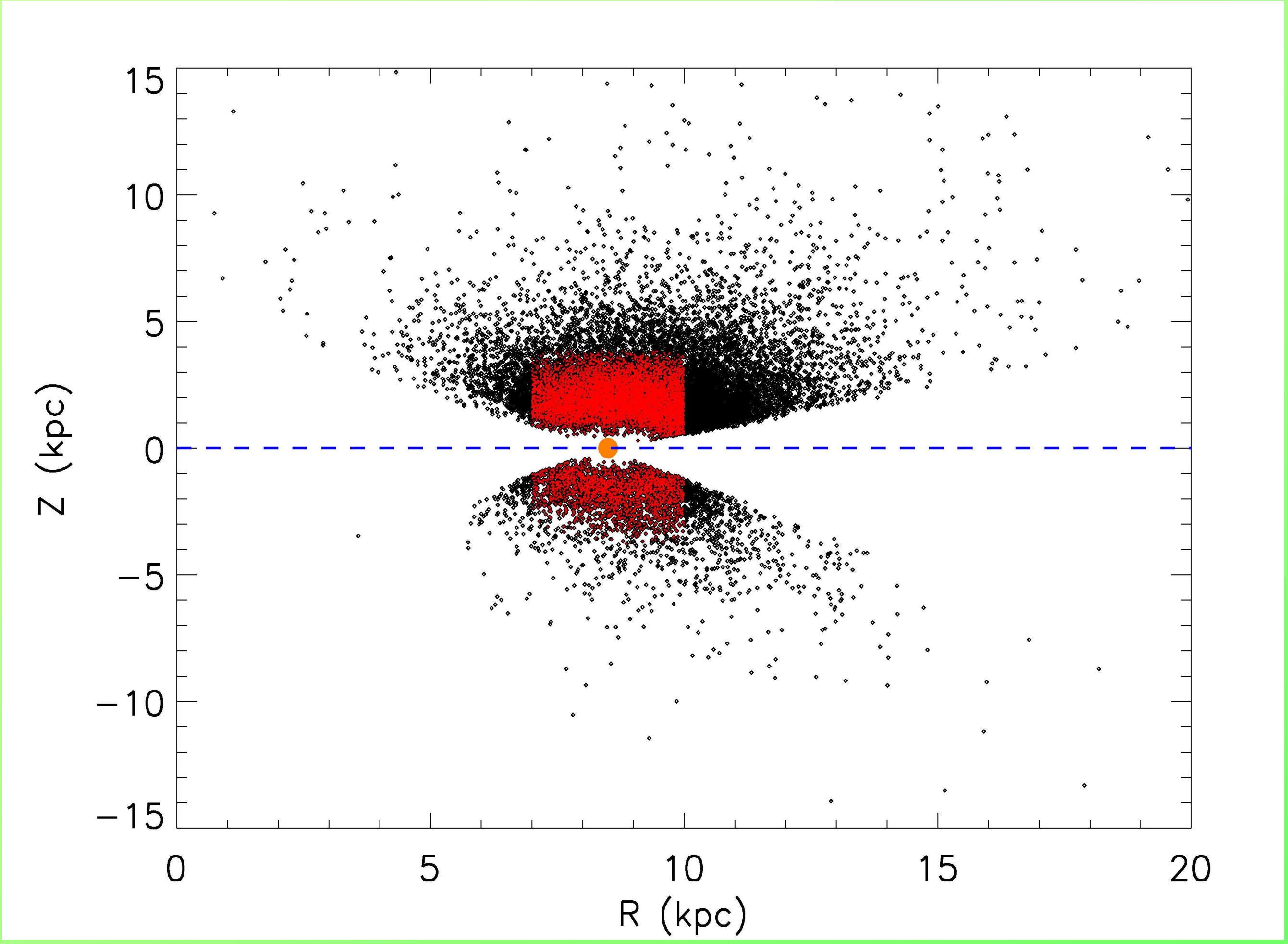
Telluric calibration stars:

They are fainter: **17.0 < g0 < 18.5**

Cover the same color range

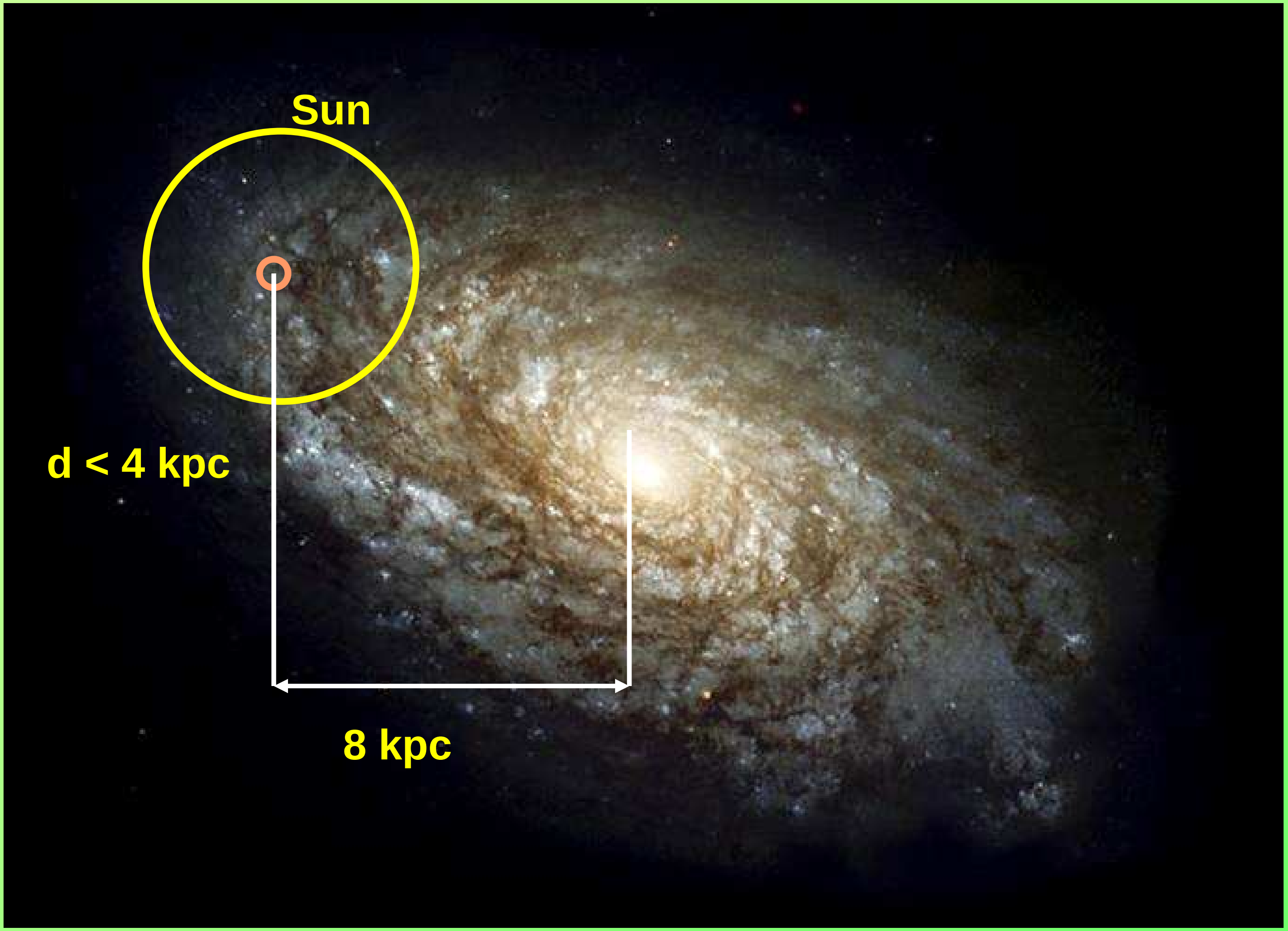
Spectroscopy: S/N > 30 for the first set and 20 < S/N < 30 for the second set

Spatial distribution of the SDSS-I calibration stars



Distribution of the full sample of 20,236 unique SDSS stars in the Z-R plane. The red points indicate the 10,123 stars that satisfy our criteria of a 'local sample', with meaningful measurements of proper motions.

Another view of the Local Volume



Quantities Required Analysis

- Astrometry → Positions, proper motions
- Radial velocities
- Magnitudes and Colors → Distances
- Space motions and orbital parameters
- Stellar physical parameters → Effective temperature (T_{eff}), surface gravity (log g)
- Chemical composition → Metallicity ([Fe/H])

- **SDSS provides** position (α,δ) with an accuracy of 0.1 arcsec
- **Recalibrated USNO-B2** catalogue provides proper motions: typical accuracy around 3-4 mas/yr

Derivation of Radial Velocities

- Matches to an external library of high-resolution spectra templates with accurately known velocities
- Typical accuracies: 5-20 km/s depending on the S/N of the spectra

Derivation of Distances

First step: Classification of each stellar type using the log g parameter, dwarf (log g > 4), subgiant or giant (log g < 4)

Second step: Derivation of the expected absolute magnitude based on calibrated globular cluster and open cluster sequences ($M_{\mathbf{V}}$ vs. $(B-V)_0$)

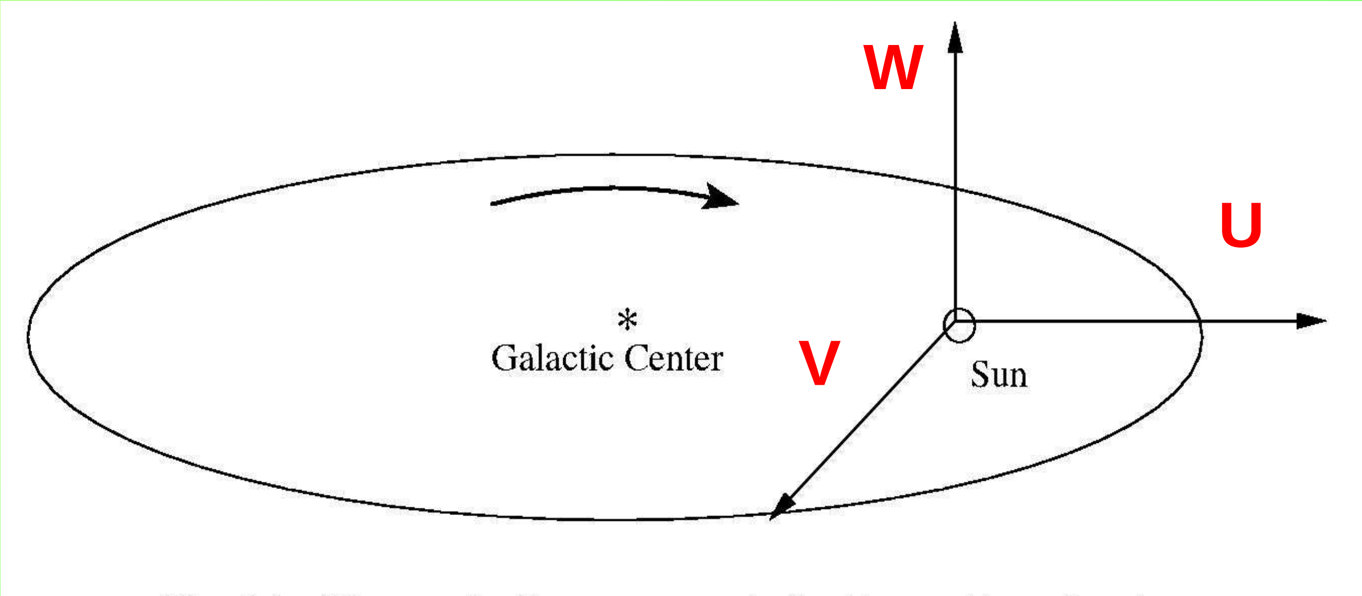
Third step: Photometric distances estimation by a comparison of the observed apparent magnitude and the derived absolute magnitude (see Beers et al. 2000, Lee et al. 2007a)

Accuracy: 10-20%

Galactic Velocity Components (UVW)

- Proper motions obtained from the re-calibrated USNO-B Catalog, typical accuracy **3-4 mas/yr** (Munn et al. 2004)

- Used in combination with the measured radial velocities and estimated distances from the **SSPP** to derive the full space motion components (U, V, W) relative to the local standard of rest



Evaluation of the kinematic parameters: selection criteria

The best available estimates of the kinematic parameters:

- Selection in Teff: 5000 K < T_{eff} < 6800 K. In this range, the SSPP provides the highest accuracy in the atmospheric parameters and chemical composition
- Local Volume: Selection of the stars with distances d < 4 kpc from the Sun. This reduces the errors on the transverse velocities ⇒ $\mathbf{V_T = 4.74 \times \mu \times d}$

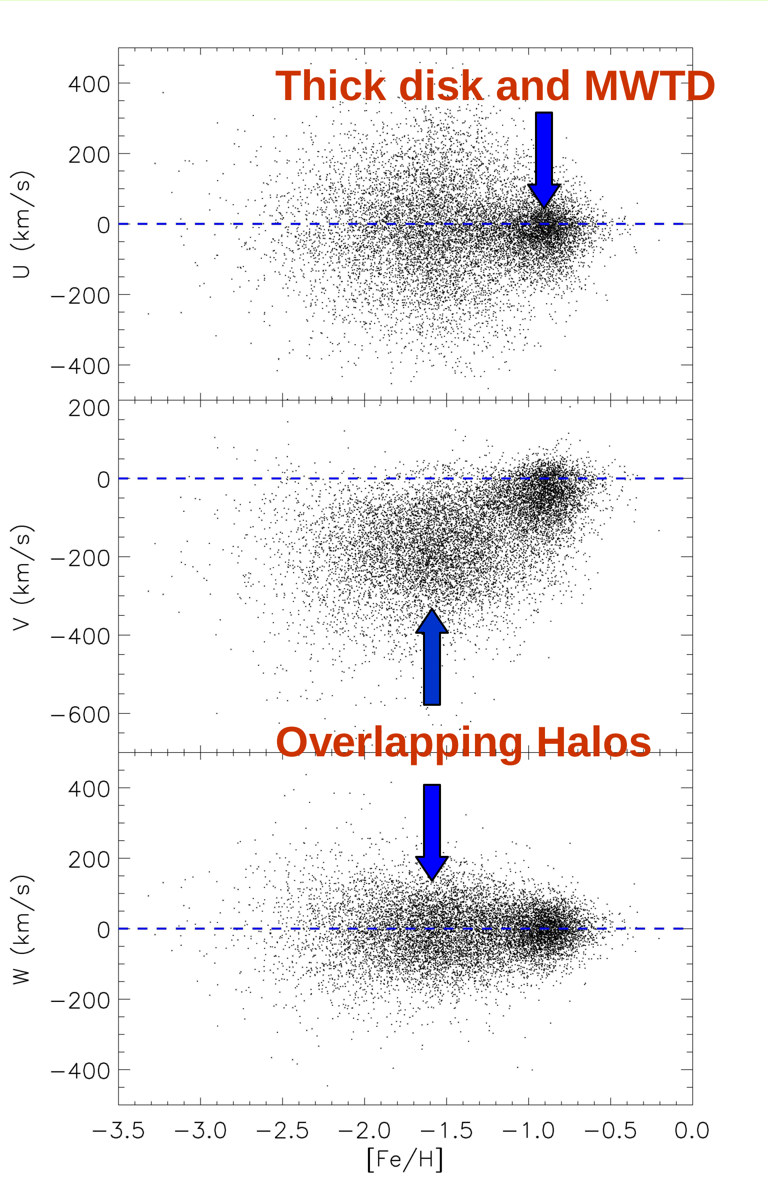
For our sample: $\sigma(V_T)$ = 22 km/s, 37 km/s, 46 km/s in case of d = 1, 2 or 4 kpc
⇒ assuming 15% in errors for distance, 3.5 mas/yr for proper motion

This selection reduces the number of stars to 14175

- Selection on R: 7 < R < 10 kpc ⇒ local volume.

The final resulting number of stars is: 10123

(U,V,W) velocity components as a function of [Fe/H]



Two main Galactic structural component are clearly distinguished:

- **Thick disk and MWTD**
- **Two broadly overlapped halo components**

The errors on (U,V,W) and their dispersions σ (U,V,W), are the most precise estimates obtained to date!

See Carollo et al. 2007 (Supplemental Material)

Evaluation of the Orbital Parameters of the sample

We adopt an analytic Stäckel-type gravitational potential and derive:

- **The peri-galactic distance (r_{peri}) ⟹ closest approach of an orbit to the Galactic center**
- **The apo-galactic distance (r_{apo}) ⟹ the farthest extent of an orbit from the Galactic center**
- **Z_{max} ⟹ the maximum distance of stellar orbits above or below the Galactic plane**
- **Orbital eccentricity**

Stäckel-type gravitational potential

- Consists of a flattened oblate disk and a spherical massive dark halo

Advantages

1. **Many properties of the Stäckel model can be given in analytic form**
2. **Every orbit in such a model posses three exact isolating integral of motion: E, Lz and I_3 which are known explicitly**

3. The potential is effectively separable in some other coordinates system (ν, λ) which have constant coordinates curves

See de Zeeuw (1985), Dejonghe & de Zeeuw (1988) for details

Stäckel Potential

We define spheroidal coordinates (λ,ϕ,ν), where f correspond to the Azimutal angle in cylindrical coordinates (R,f,Z), and λ and ν are the roots for τ of:

$$\frac{R^2}{\tau+\alpha}+\frac{Z^2}{\tau+\gamma}=1$$

Where a and g are constants. The coordinates surfaces are spheroids (l = const) and hyperboloids of revolution (n=const) with Z-axis as the rotation axis.

The gravitational potential of the Stäckel type is written as:

$$\varphi(\lambda,\nu) = -\frac{(\lambda+\nu)G(\lambda)-(\nu+\gamma)G(\nu)}{\lambda-\nu}$$

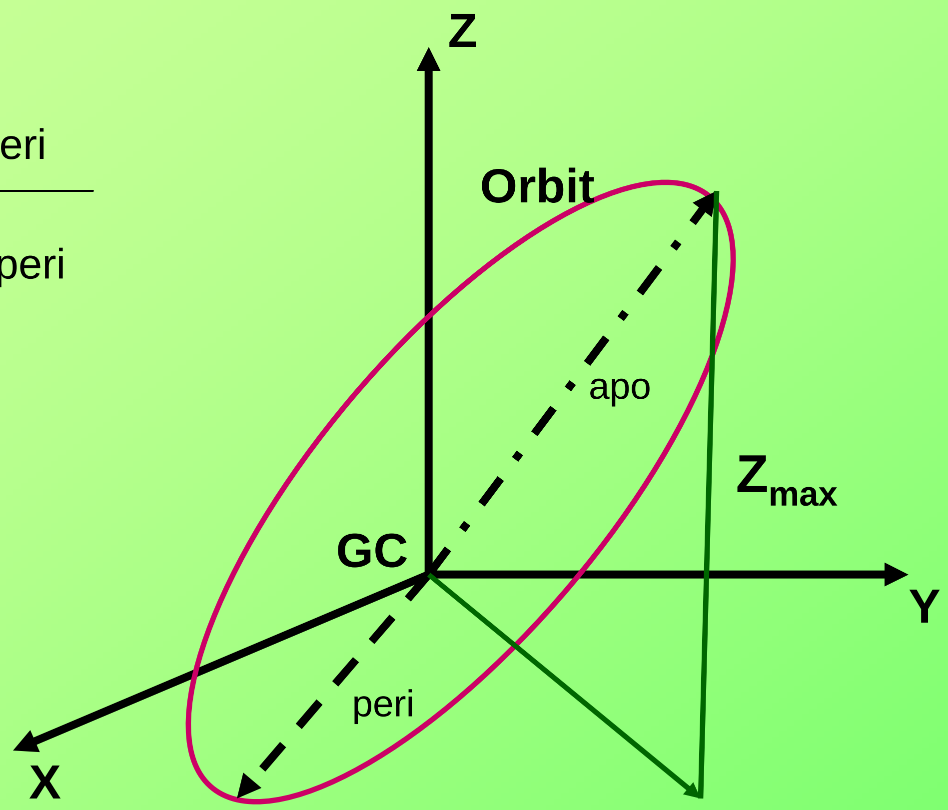
Where G(t) is the sum of $G_{disk}(\tau)$ from the disk and $G_{Halo}(\tau)$ from the massive dark halo.

See for more details:

de Zeeuw (1985), MNRAS, 216, 273
de Zeeuw et al. (1986), MNRAS, 221, 1001
Dejonghe & de Zeeuw (1988), ApJ, 333, 90
Sommer-Larsen & Zhen (1990), MNRAS, 242, 10

Orbital parameters

$$e = \frac{r_{apo} - r_{peri}}{r_{apo} + r_{peri}}$$



The cartoon shows not a real orbit in the adopted potential!

A bit of history: Eggen,Lynden-Bell, Sandage (1962)

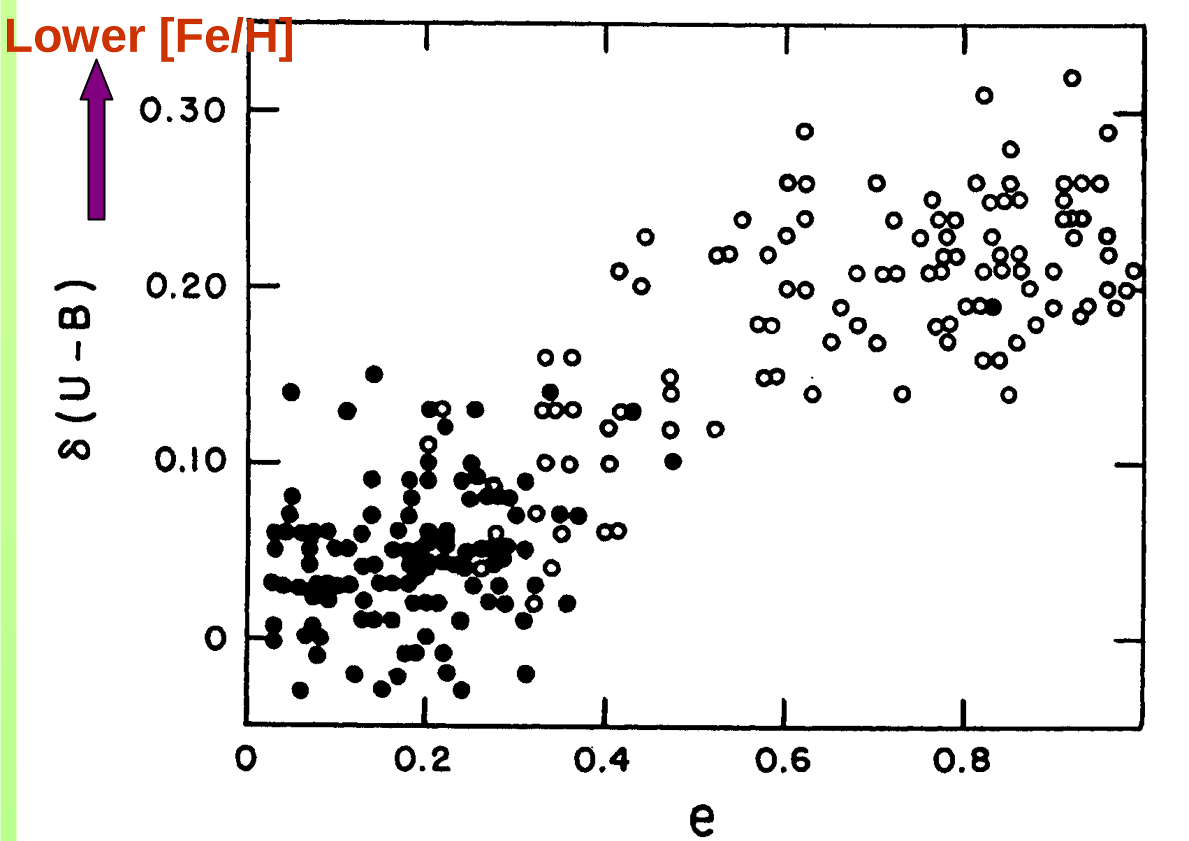


FIG. 4.—The correlation between the ultraviolet excess, $\delta(U - B)$, and the orbital eccentricity, e, for our sample of 221 stars. The filled and open circles represent stars from our first and second catalogues, respectively.

- They found a tight correlation between [Fe/H] and eccentricity
- This was interpreted as providing strong evidence for a rapid monolithic collapse of the Galaxy (10^8 yrs)
- The oldest stars were formed out of gas falling towards the Galactic center in the radial direction (high eccentricity)

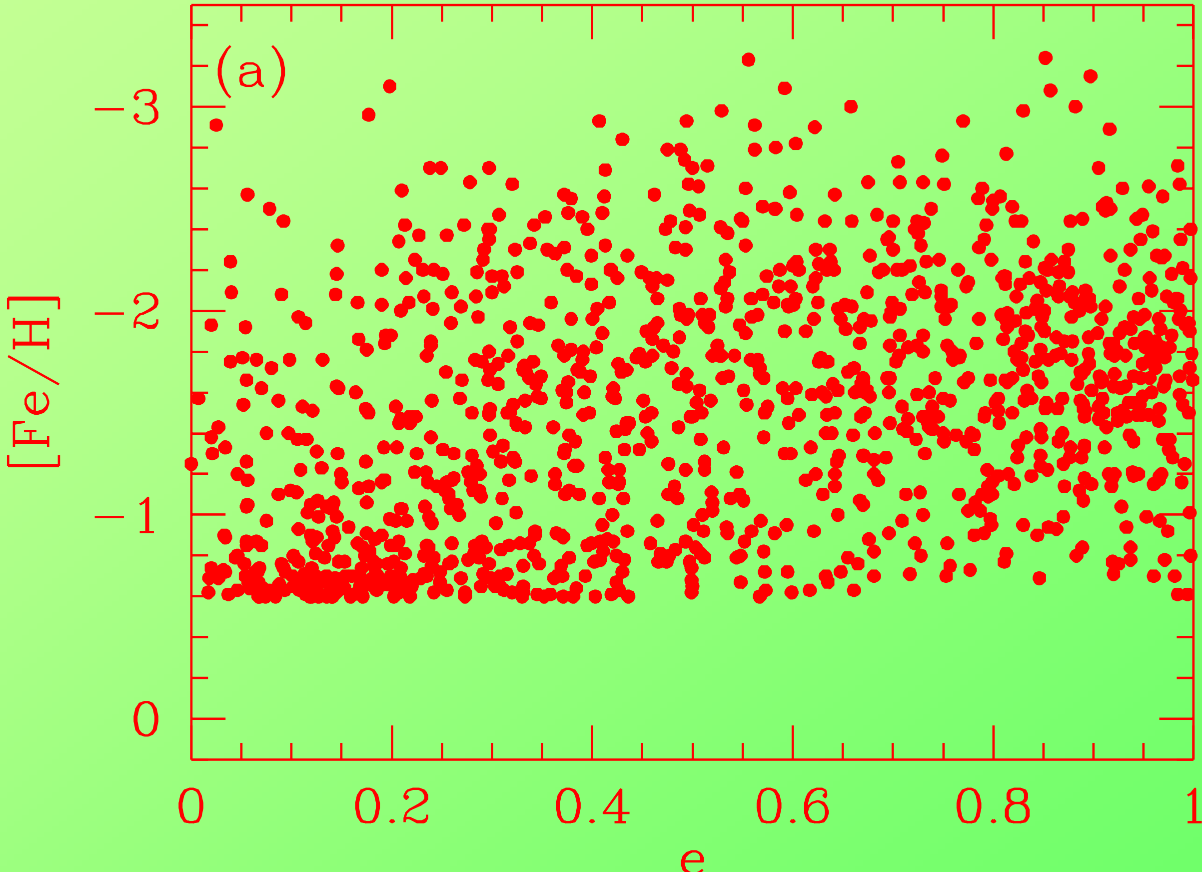
The appearance of this diagram was strongly influenced by the kinematic selection criteria.

With NO KINEMATIC SELECTION it will appear as……

Analysis of the Orbital Parameters

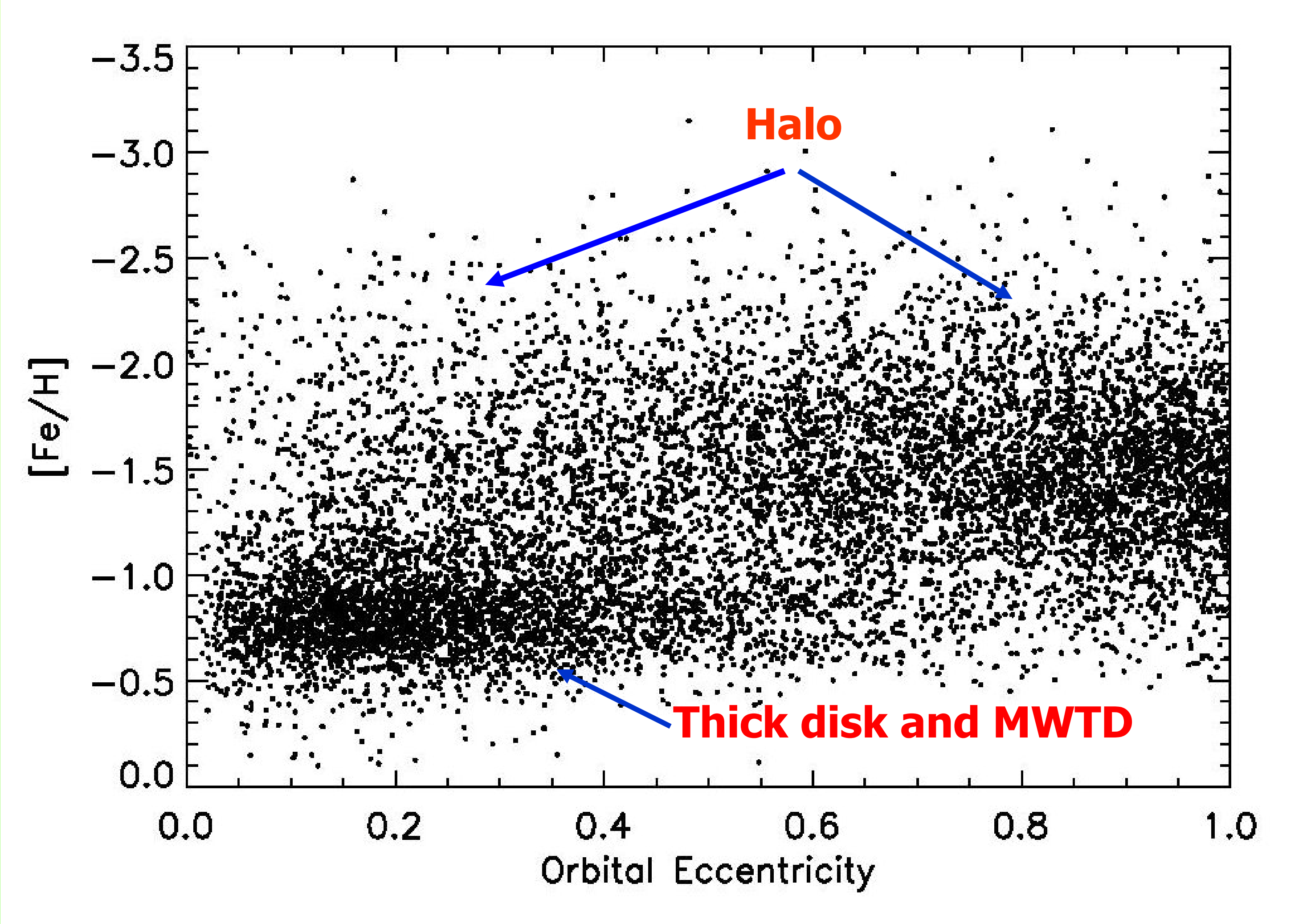
[Fe/H] vs. Orbital Eccentricity, Chiba & Beers (2000)

Based on a sample of ~ 1200 Non-Kinematically Selected Stars



Seven years later using SDSS data……

[Fe/H] vs. orbital eccentricity – SDSS – 10123 stars



The ELS model would not predict such a diagram!

Implications for the formation of the Galactic Halo

The two canonical scenarios of Galactic halo formation are:

- A monolithic collapse (ELS): the halo was formed from the rapid collapse (10^8 yrs) of an overdense homogeneous sphere;

- Accretion/merging scenario (Searle & Zinn, 1978; SZ): the halo is formed slowly by chaotic merging/accretion of small sub-Galactic fragments

Either of the two scenarios alone has several difficulties in explaining the observational results (Chiba & Beers 2000; Carollo et al. 2007), because:

1. ELS is inconsistent with the lack of correlation between [Fe/H] and orbital eccentricities of halo stars;

2. Bekki & Chiba claimed that the SZ scenario unlikely explain the flattened density distribution of inner-halo stars (see Bekki & Chiba for details), actually this claim seems too strong…

A hybrid scenario of halo formation? **Dissipationless merging of subgalactic clumps has formed the outer Galactic halo, while dissipative collapse formed the inner halo**

Implication for the formation of the Galactic Halo

ΛCDM Theory: The currently favored scenario based on the hierarchical assembly of lower-mass systems

Bekki & Chiba (2001)

- Performed numerical simulations to provide a realistic picture for the formation of the Galactic stellar halo, including its structural, kinematical, and chemical properties, consistent with the observational results of (Chiba & Beers 2000)

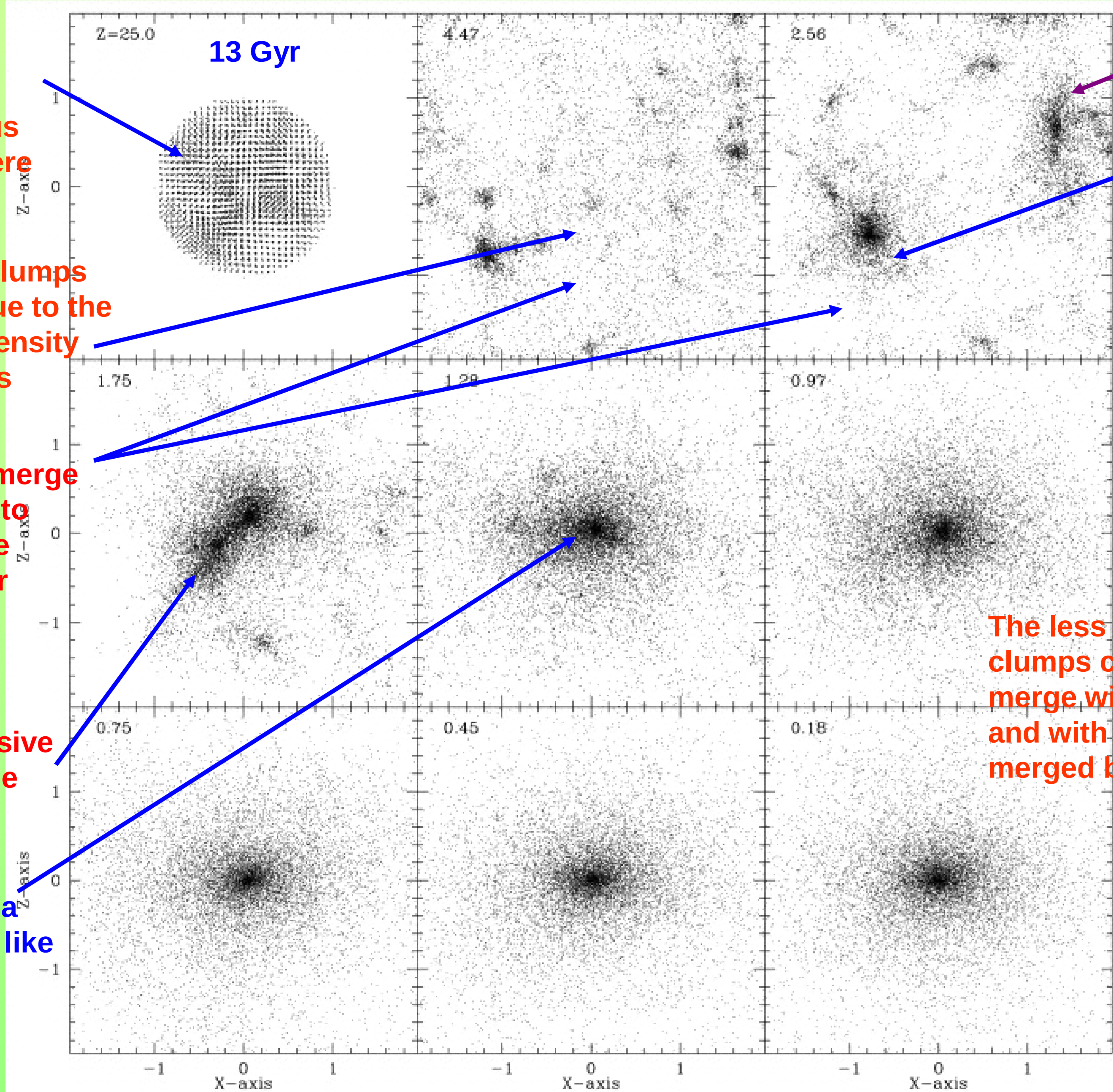
Isolating expanding homogeneous rotating sphere

Subgalactic clumps are formed due to the small scale density perturbartions

The clumps merge and grow up to become more massive. Star formation Proceeds.

The two massive clumps merge dissipatively

Formation of a central bulge like component



Formation of two big Clumps

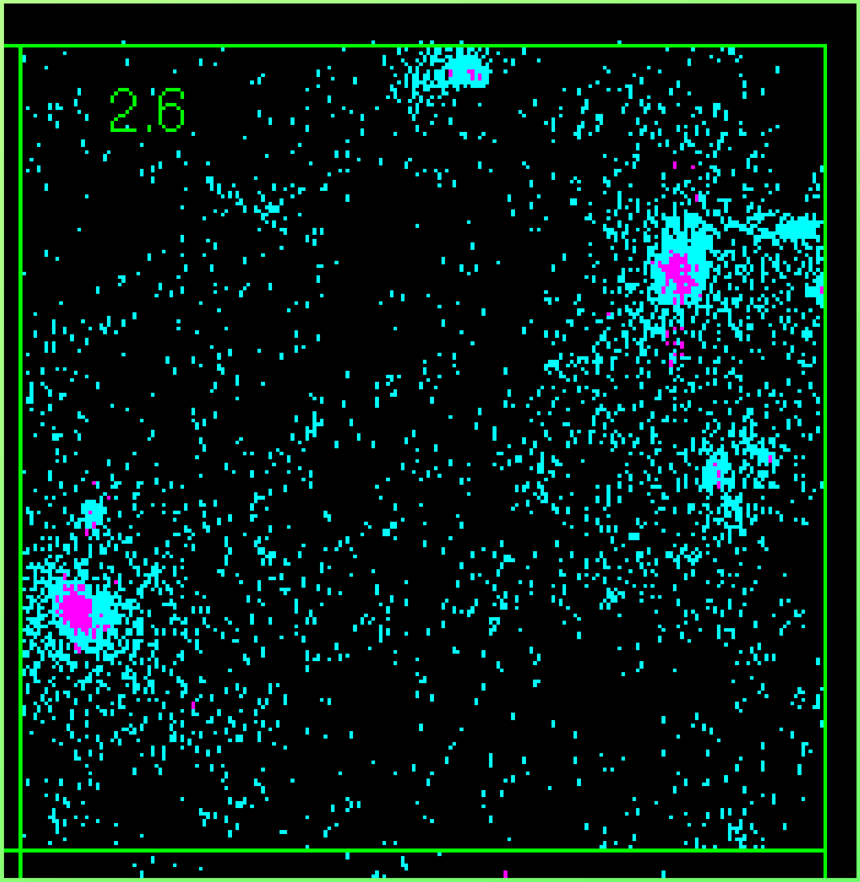
The less massive clumps continue to merge with each other and with the the two merged big clumps

Continuing …

o = Gas o = stars o = dark matter

- Gas particle assemble into each of the Clumps
- First stars born inside the clumps with low [Fe/H] (< -3)

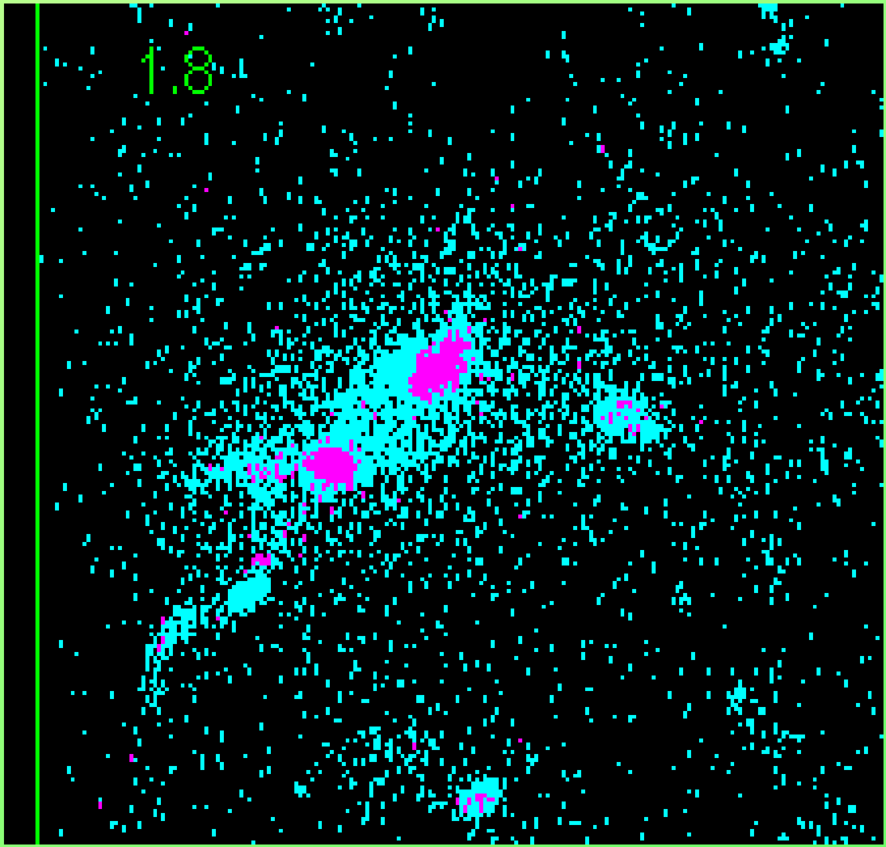
  - **Most of metal-poor halo stars form in these clumps [Fe/H] < -1.6 are already formed 10 Gyr ago.**



The clumps continue to merge with one another and grow up to become more massive, star formation proceed.

Continuing …

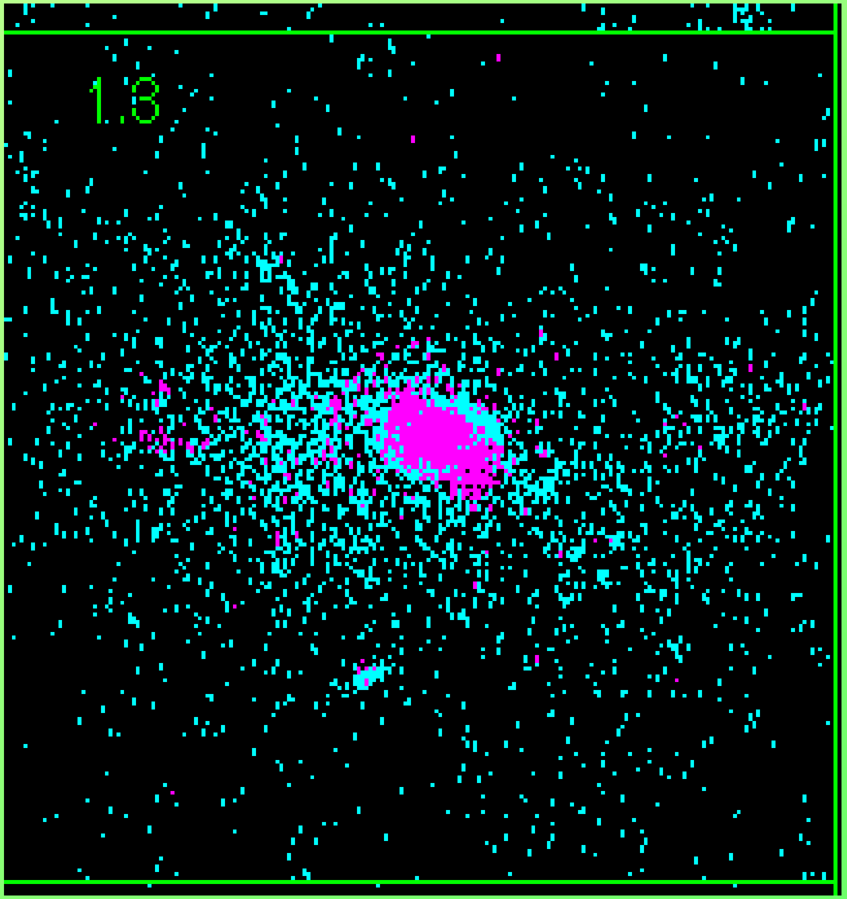
- Two massive clumps are developed by their gravity and move toward the center. They merge in a dissipative way due to the presence of a large fraction of gas.



- The less massive clumps continue to merge and are destroyed by tidal interaction: stars born inside are spread over the outer region of the proto Galaxy.

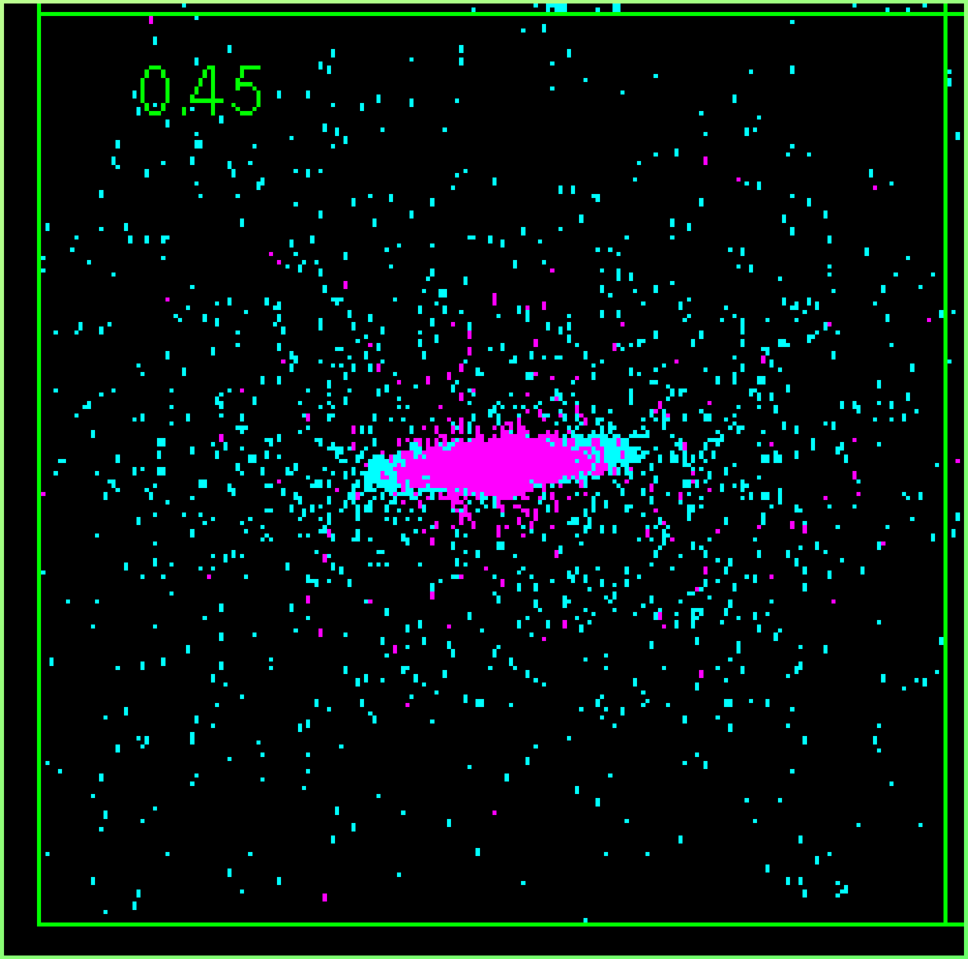
Subsequent Evolution of the Galaxy

- Merging event between largest clumps occur
  - Stars which have been confined inside are disrupted and spread over inner halo

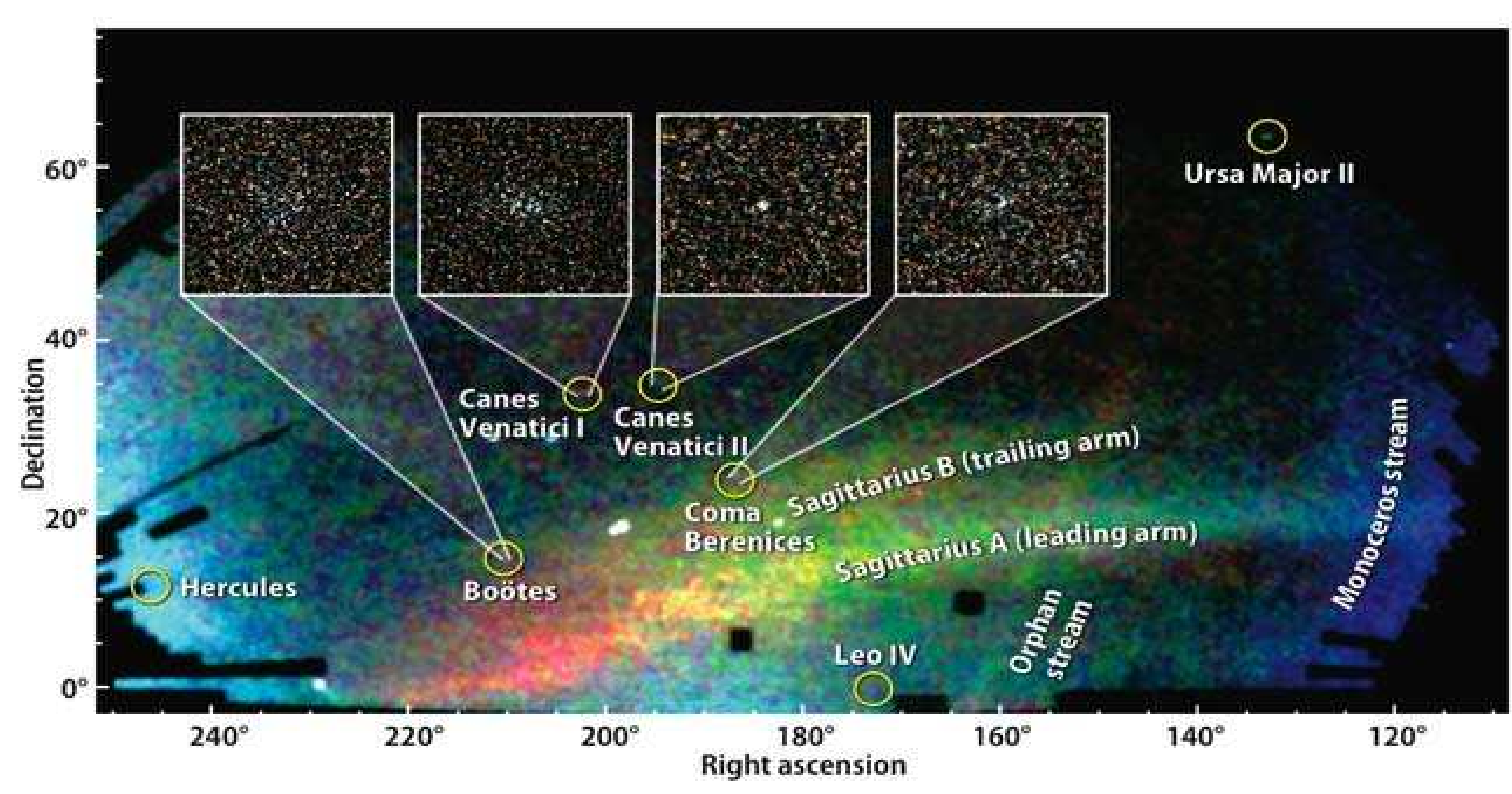


Finishing …

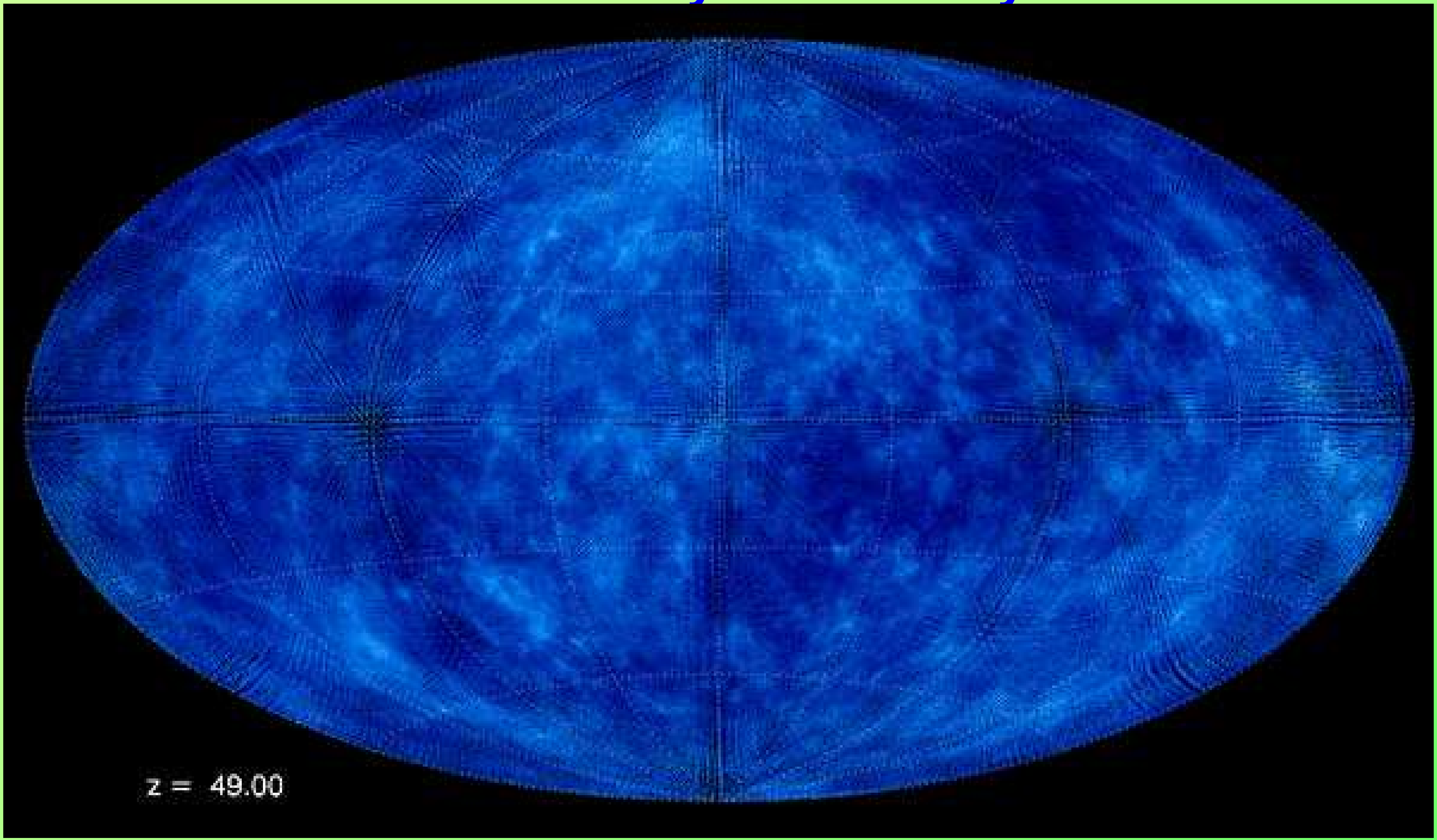
- Gas in clumps ends up in center
  - Forms bulge and TD
  - Many intermediate abundance stars may form in this infalling gas



The surviving counterpart for such sub-systems could be the *currently observed* low-luminosity dwarf spheroidal galaxies surrounding the Milky Way, discovered in the course of SDSS/SEGUE (Belokurov et al. 2007)



Towards a "Virtual Galaxy" – Courtesy J. Tumlinson



Work is beginning now to couple stochastic chemical evolution to dark matter dynamics within N-body simulations (Gadget2), to calculate realistic observables in the full 6D position/velocity and chemical information of modern surveys – then full hydro.