Local Galaxies

Fundamental relations for Ellipticals & dEs :

Color – magnitude relation : brighter Es are redder

Luminosity – metallicity relation : brighter Es are more metal-rich

Faber – Jackson relation : central velocity dispersion increases with luminosity

→ distance / mass determination

Kormendy's relations :

brighter Es have large effective radii

brighter Es have lower (average) surface brightness

Sphs (and GCs) do not follow Kormendy's relations

Fundamental Plane relations : effective radius – surface brightness – luminosity – central velocity dispersion

M/L increases with L

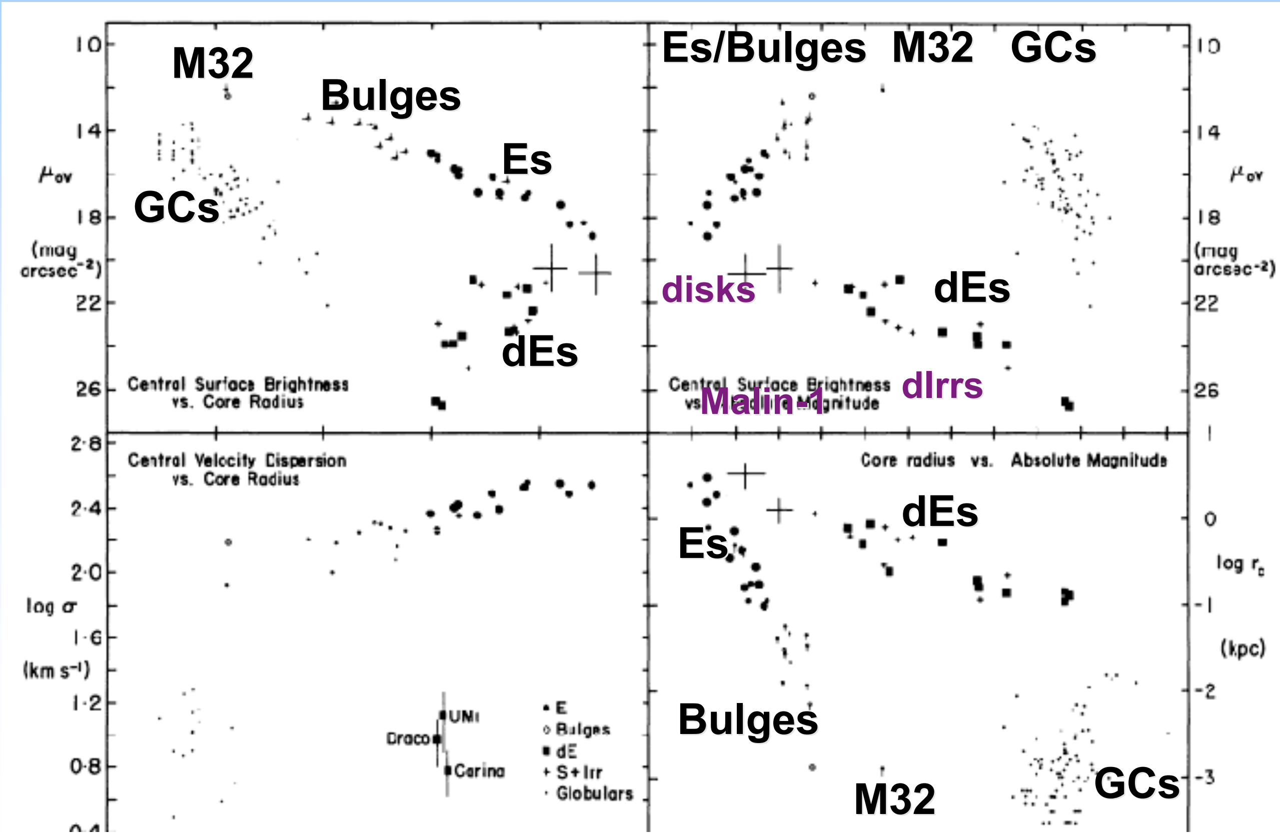
Local Galaxies

Fundamental relations for Ellipticals & dEs :

Kormendy's relations :

brighter Es have larger effective radii
brighter Es have lower (average) surface brightness

Sphs (and GCs) do not follow Kormendy's relations



Local Galaxies

Luminosity function for galaxies : Schechter 1976

Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^{\alpha} \exp(-L/L^*)$

L^* : characteristic luminosity

$M_B^* = -19.7 + 5 \log h$, $h := H_o/100$

$L_B^* = 9\ 10^9\ h^{-2}\ L_\odot \sim 2\ 10^{10}\ L_\odot$ for H_o=70

Φ^* : (local) normalisation = $1.6 \cdot 10^{-2}\ h^3\ \mathrm{Mpc}^{-3}$

difficult to determine !

α : faint end slope

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} exp\left(-\frac{L}{L^*}\right)\frac{dL}{L^*}$$

$$\phi(M)dM = \frac{2}{5}\phi^*(ln 10)\left[10^{\frac{2}{5}(M^*-M)}\right]^{\alpha+1} exp\left[-10^{\frac{2}{5}(M^*-M)}\right]dM$$

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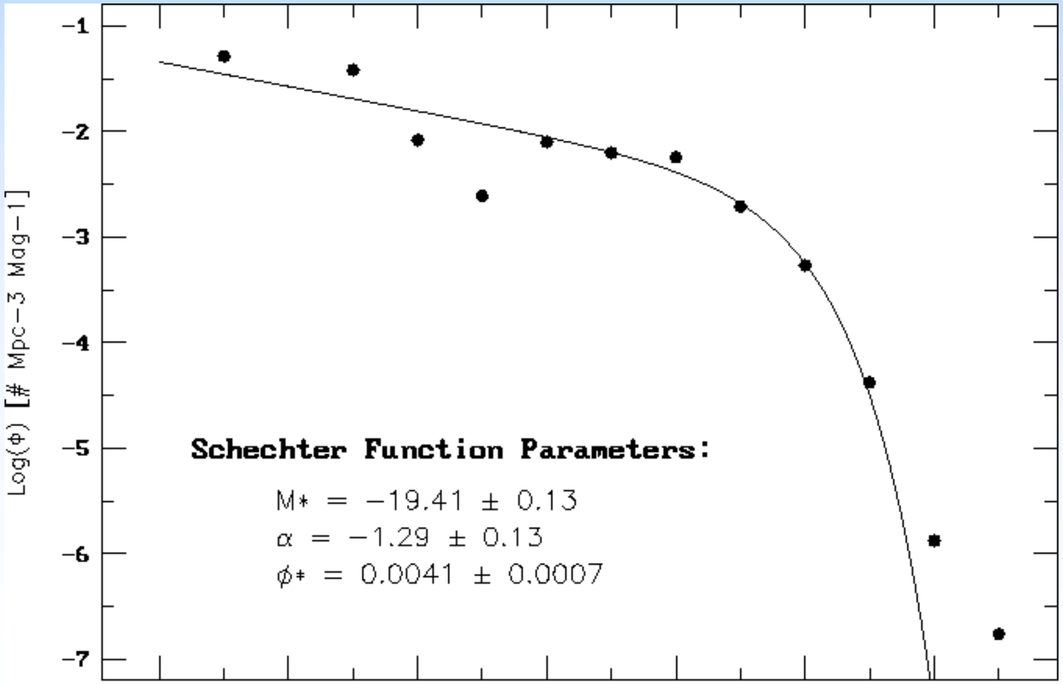


Local Galaxies

Local luminosity functions for galaxies :

field galaxies

break-down

into types

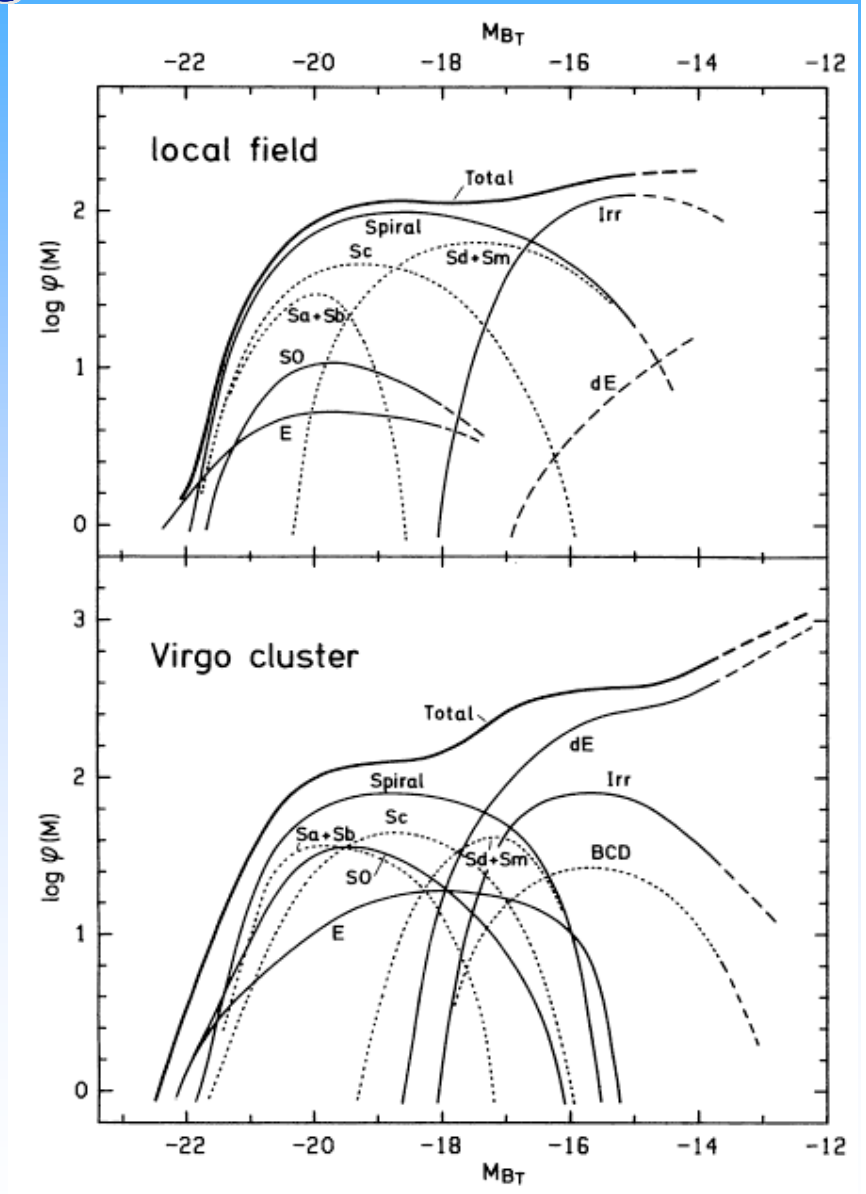
faint end slope $\alpha \sim -1.1$

($N_{gal} \rightarrow$ inf. for $L_B \searrow$)

cluster galaxies:

steep faint end slope

faint end slope $\alpha << -1.1$



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Φ^* : (local) normalisation = $1.6 \cdot 10^{-2}\, h^3\, \mathrm{Mpc}^{-3}$

difficult to determine !

α : faint end slope

low luminosity galaxies dominate by number
high luminosity galaxies dominate the light
in the local universe

M_B^* (E) < M_B^* (Sa) < M_B^* (Sb) < M_B^* (Sc) < M_B^* (Sd)

M_B^* (E)	M_B^* (Sa)	M_B^* (Sb)	M_B^* (Sc)	M_B^* (Sd)
-21.5	-19.7	-18.9	-18.8	-17.7

with considerable overlap in Virgo (Sandage+85)

Local Galaxies

Luminosity function for galaxies : Schechter 1976

Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^{\alpha} \exp(-L/L^*)$

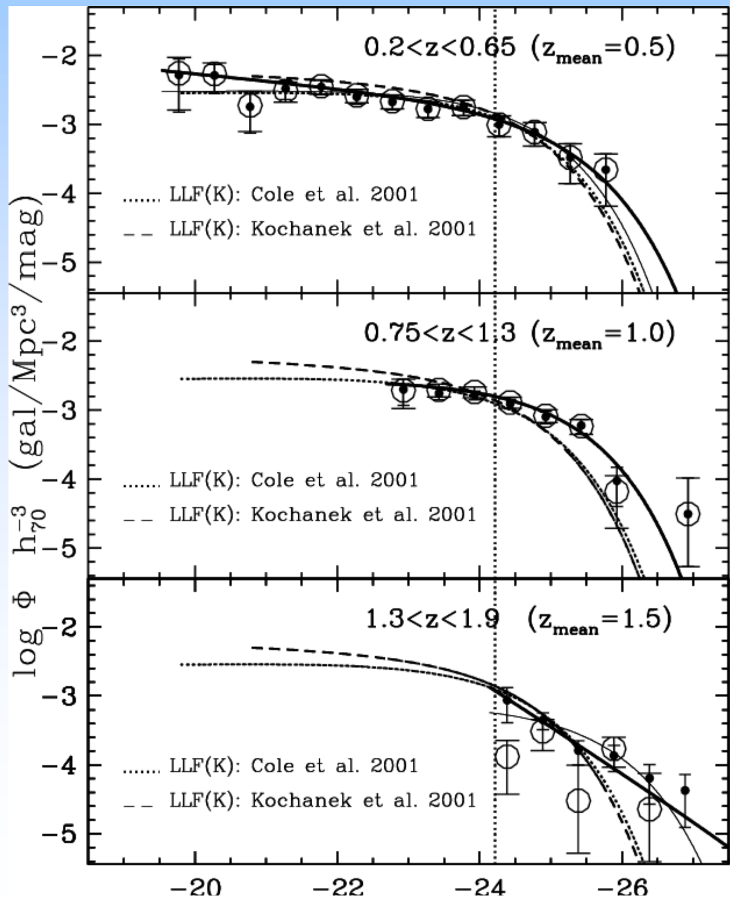
Φ^* : (local) normalisation = $1.6 \cdot 10^{-2}\ h^3\ \mathrm{Mpc}^{-3}$

difficult to determine !

large volume : bright galaxies ok, faint galaxies incomplete

small volume: faint galaxies complete, bright galaxies poor statistics

redshift evolution : clues to galaxy evolution



Local Galaxies

Galaxy mix :

field : normal (=big) galaxies >70% Sps
~20% Es
<10% S0s

dwarf-to-normal galaxy number ratio : $\alpha \sim -1.1$

galaxy clusters : >70% S0s
~20% Es
<10% Sps

dwarf -to-normal galaxy number ratio : $\alpha \ll -1.1$

→ transformation of galaxy types

The Milky Way

Sbc type galaxy

Structure : bulge, disk (thin/thick), halo

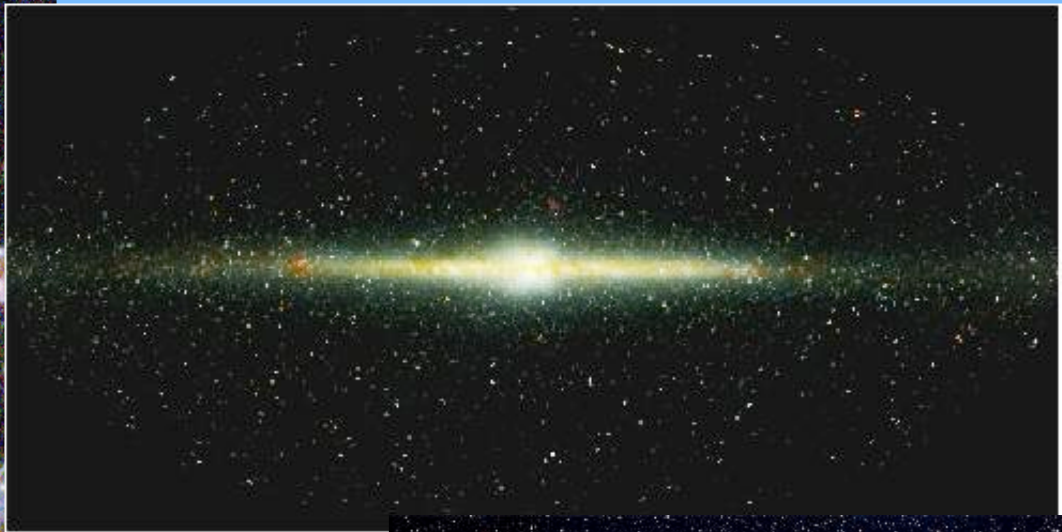
bulge: stars, star clusters,
the nuclear star cluster, BH ~ 3.6 10^6 $M_{\odot}$

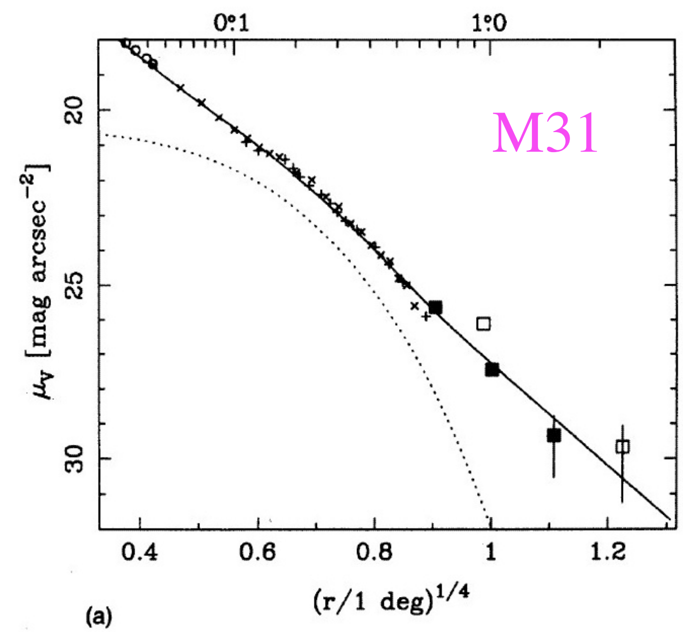
disk: gas, dust, young stars, HII regions,
young open star clusters

halo: field stars, Globular Clusters : all old and metal-poor,
diffuse gas (HI, HII, seen in absorption MgII, CIV
against background QSOs)

The Milky Way Bulge

The MW bulge is small & <u>exponential</u>, typical of later-type galaxies, unlike the large $r^{1/4}$ - bulge of M31.





Pritchet & van den Bergh 1994

The Milky Way Bulge

Near the center of the bar/bulge is a younger population, on scale of about 100 pc : <u>the nuclear stellar disk</u>

($M \sim 1.5 \times 10^9\ M_\odot$)

and in central ~ 30 pc : <u>nuclear stellar cluster</u>

(Launhardt et al 2002) ($M \sim 2 \times 10^7\ M_\odot$)

~ 70% of the luminosity from young main sequence stars.

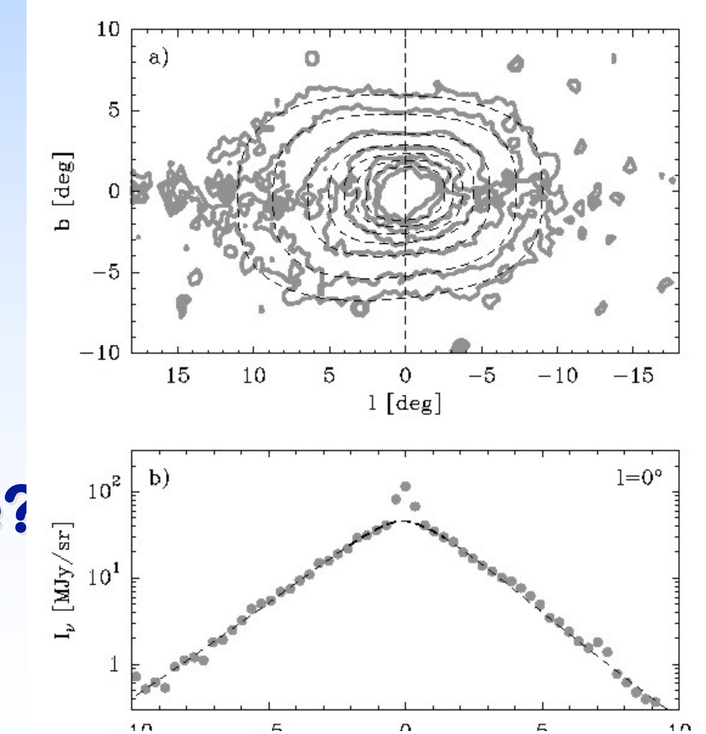
NIR Adaptive Optics (Genzel & coll.)

NAOS/CONICA @ VLT :

the nuclear star cluster:

within few light years

thousands of stars



☛ **how can stars form & survive there?**

☛ **stellar motions : BH ~ 3.6 106 M¤**

The Milky Way Bulge

NIR Adaptive Optics (Genzel & coll.)
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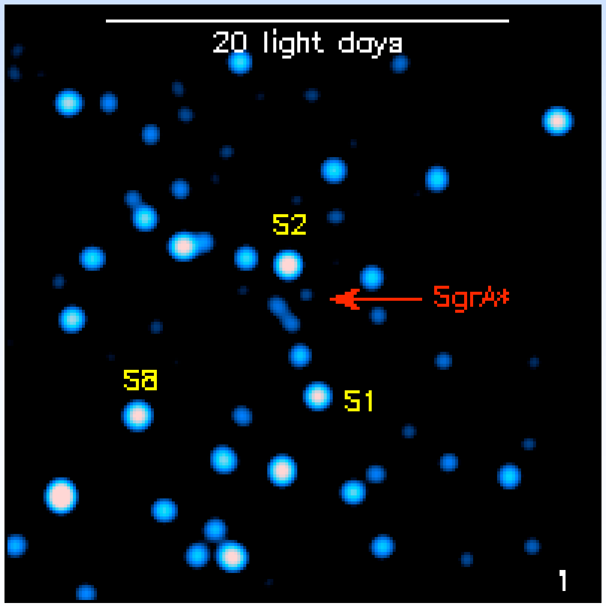

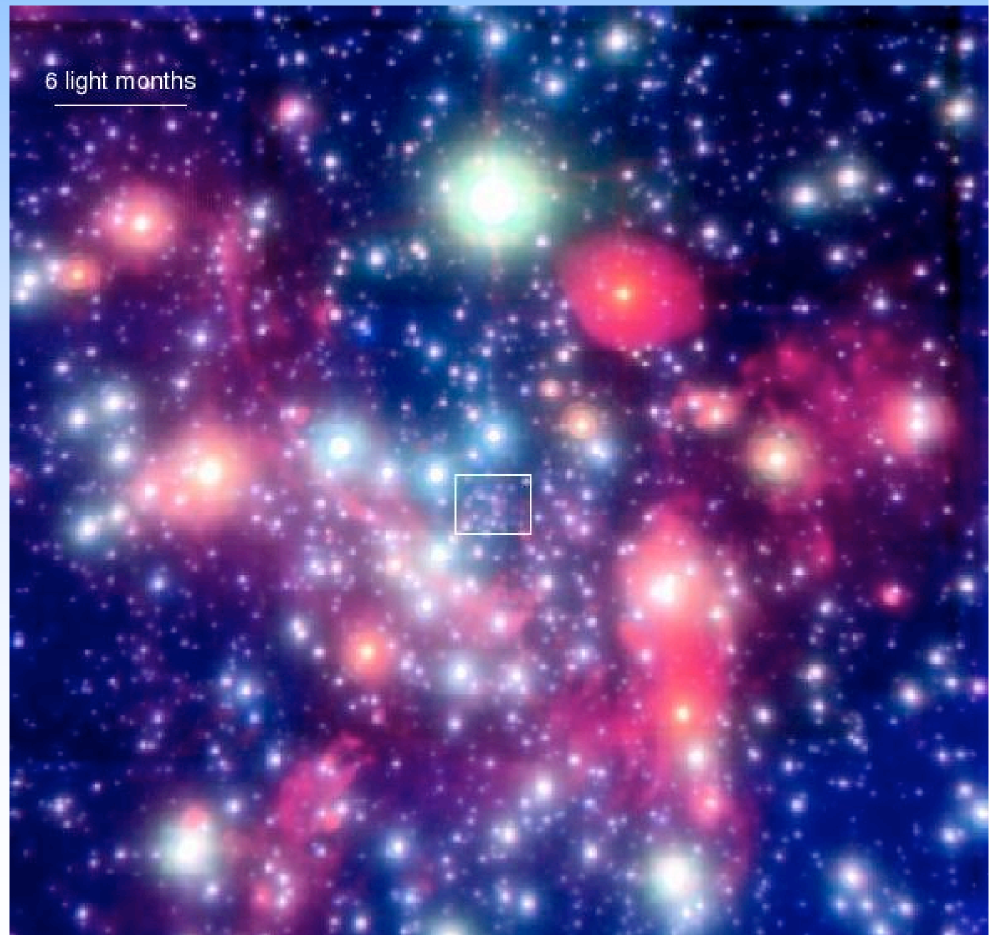

The Milky Way Bulge

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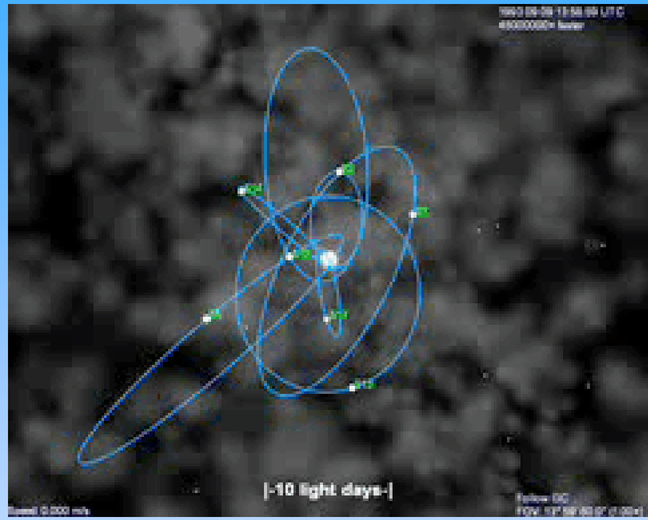
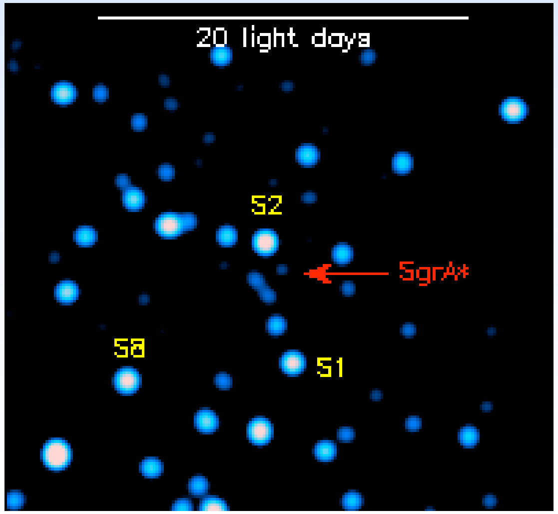
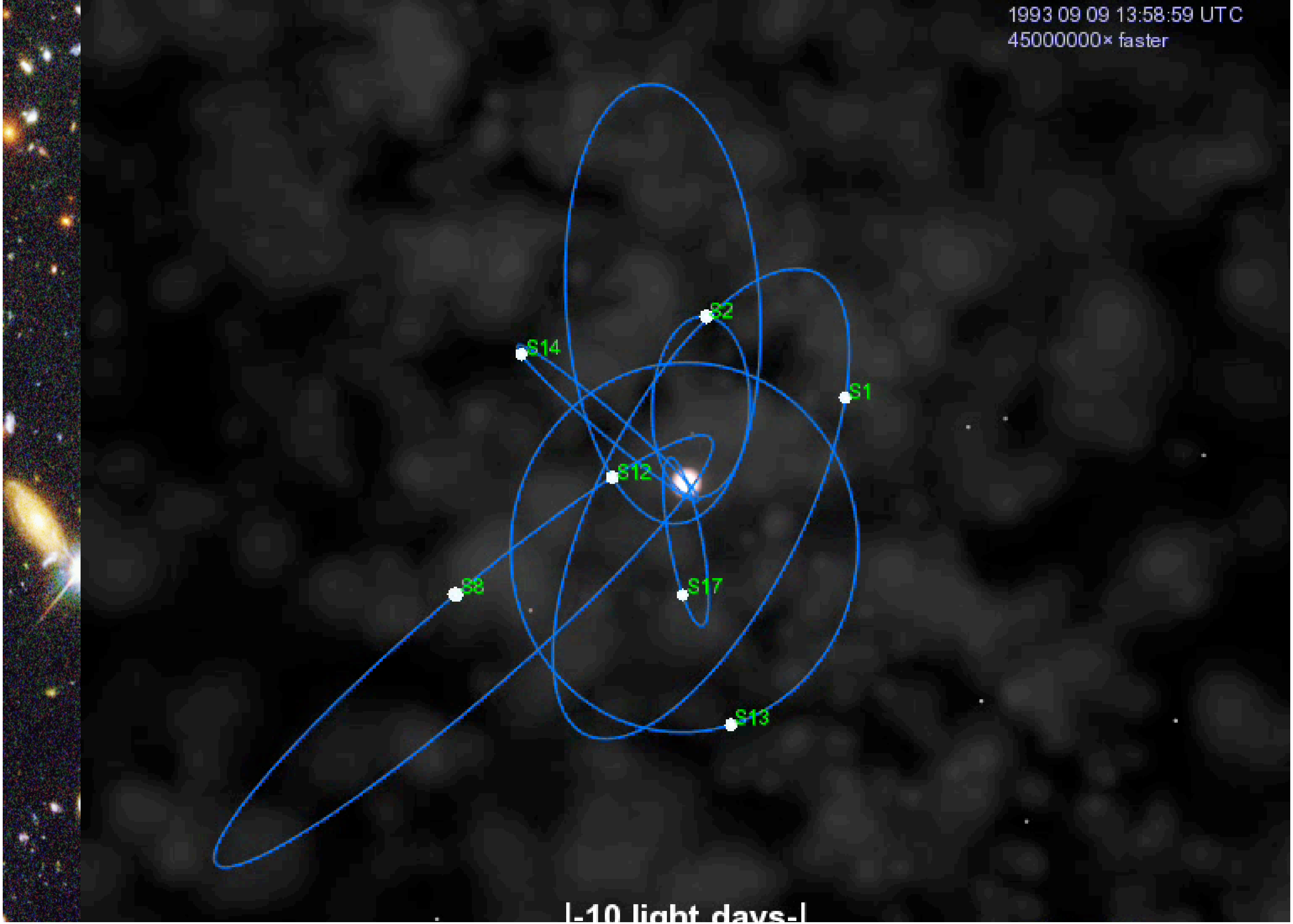


☛ stellar motions : BH ~ 3.6 10^6 $M_\odot$

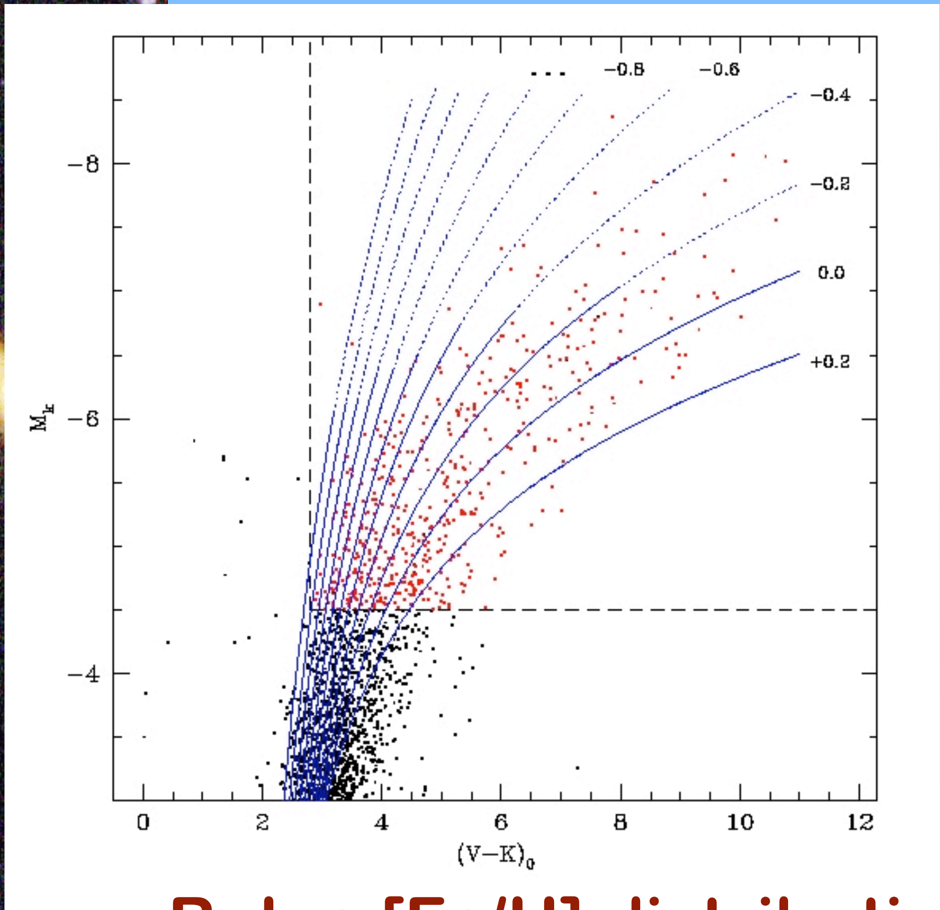
stars get as close as a few Schwarzschild radii,
flaring observed on AO NIR images -- accretion.



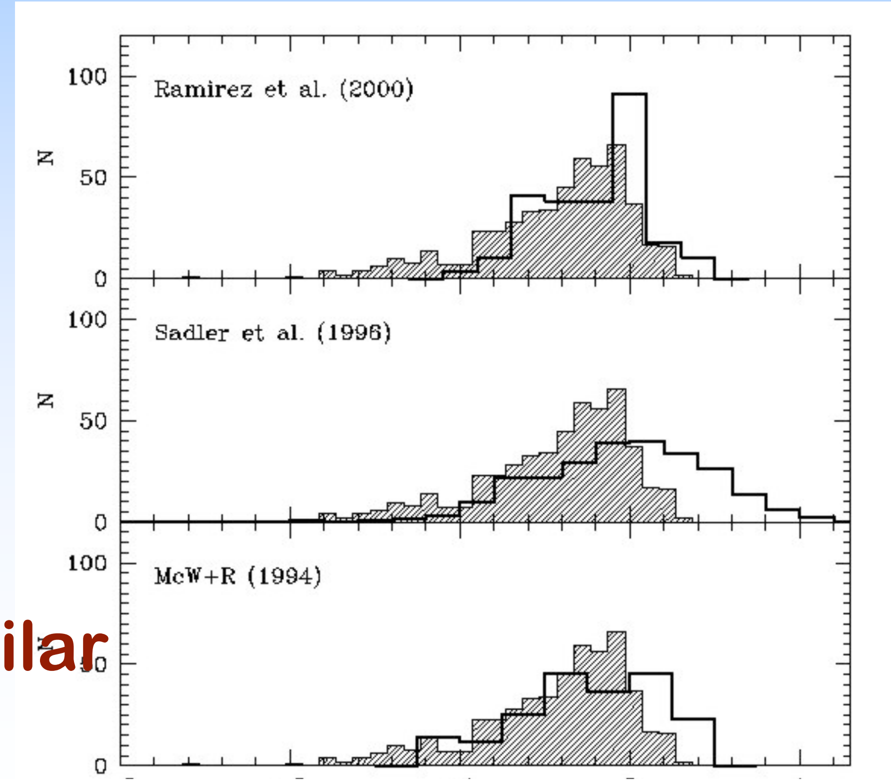

1993 09 09 13:58:59 UTC
45000000× faster
S2
S14
S1
S12
S8
S17
S13
|-10 light days-|

Age and metallicity of the bulge

Zoccali et al 2003 : stellar photometry at (*l, b*) = (0°.3, -6°.2) : old population > 10 Gyr. No trace of younger population.

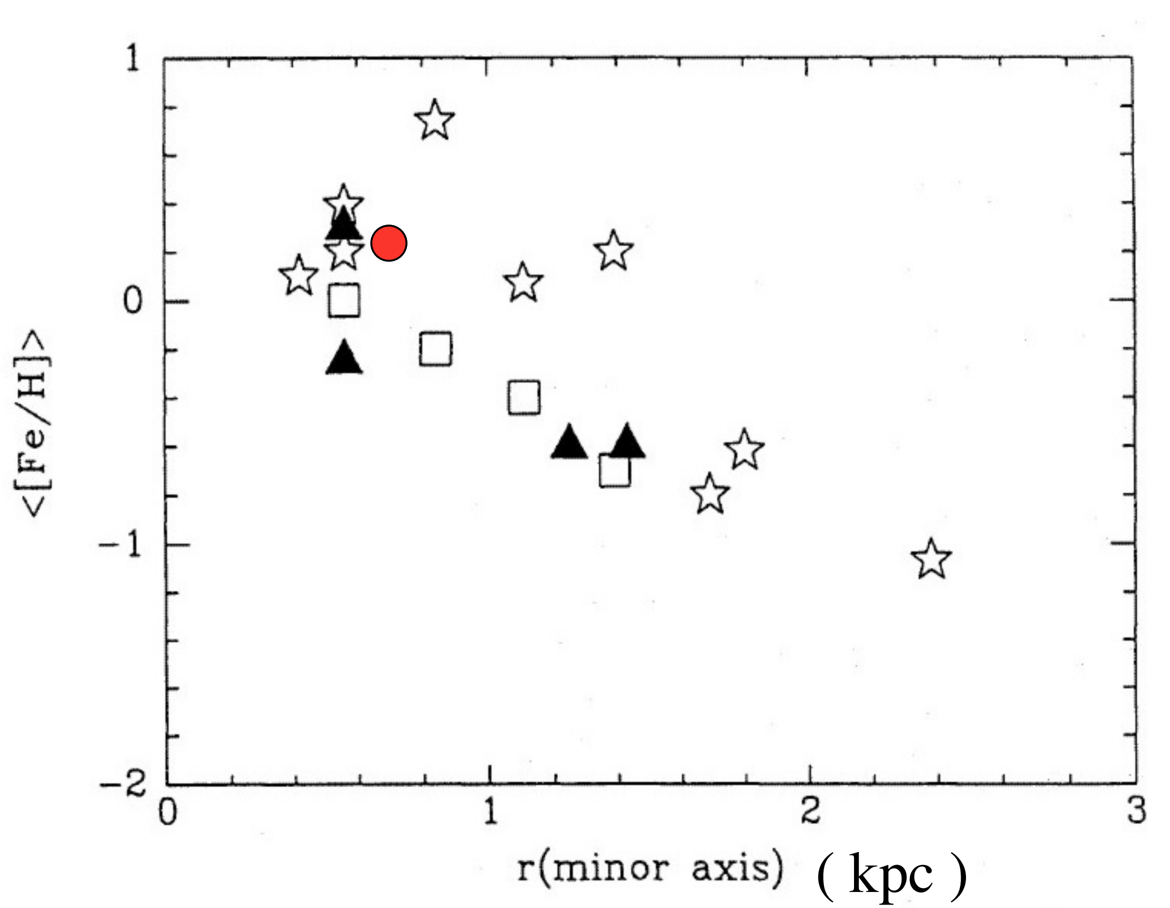


Extended metallicity distribution, from [Fe/H] = -1.8 to +0.2 (subsolar)



Bulge [Fe/H] distribution similar to solar neighbourhood

Abundance gradient in the bulge



Inhomogeneous collection of photometric (□☆) and spectroscopic (▲) mean abundances - evidence for abundance gradient along minor axis of the bulge

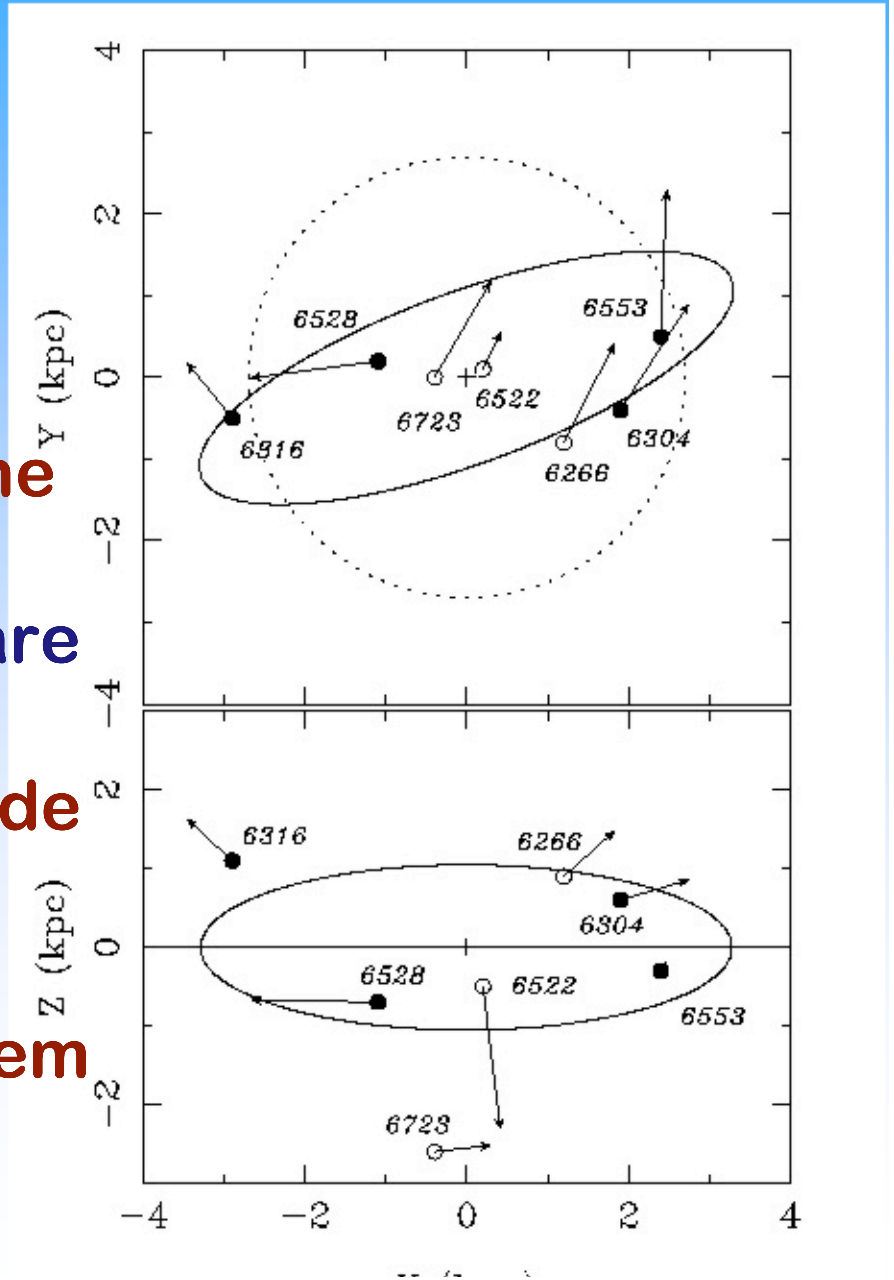
● Zoccali et al (2003)

Bulge Globular Clusters

3D kinematics of 7 globular clusters in the bar/bulge

Their velocities show:

- all of them are confined to the bulge region
- the metal-poor clusters (o) are part of the inner halo
- the metal-rich clusters include
  - a bar cluster
  - clusters belonging to a rotationally supported system



Dinescu et al 2003

Formation of the Milky Way Bulge

Later type galaxies like the Milky Way mostly have small near-exponential boxy bulges, rather than $r^{1/4}$ bulges.

(eg Courteau et al 1996)

These small bulges are likely generated by disk instability : bar formation & destruction :

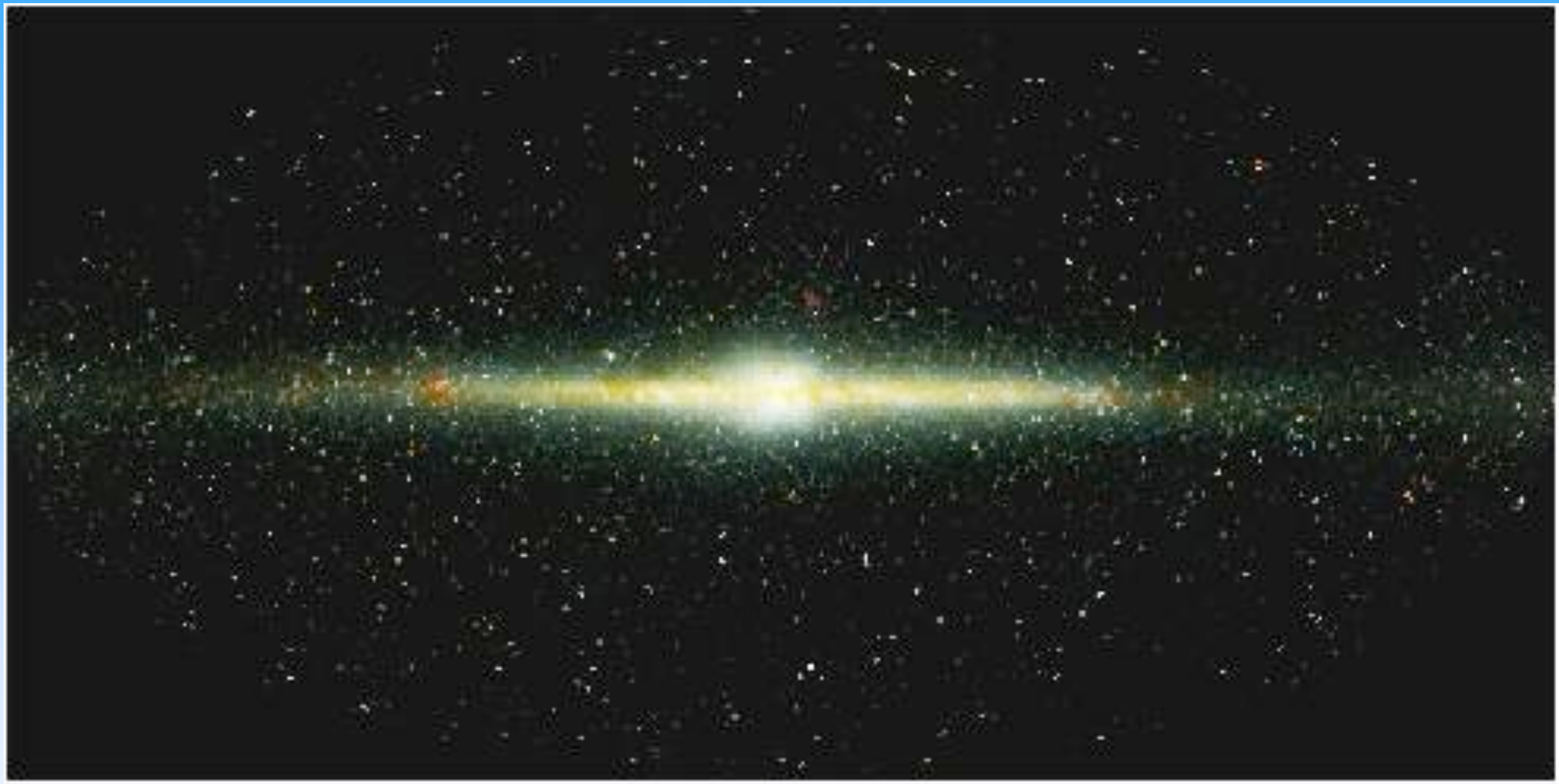
theory: eg Combes & Sanders 1981 ...
observations: eg Bureau & Freeman 1999 ...

Pseudo - bulges

(Kormendy & Kennicutt 04, ARA&A, Kormendy 07)

Big $r^{1/4}$ bulges are likely formed by mergers or accretion

The Milky Way Bulge

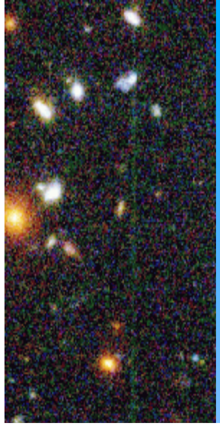


Our bar-bulge is ~ 3.5 kpc long, axial ratio ~ 1: 0.3: 0.3 pointing about 20-35^{o} from sun-center line into first quadrant (eg Bissantz & Gerhard 2002).

The Milky Way Bulge

The stars of the bulge are old and enhanced in α-elements [Mg/Fe]>0 $\Rightarrow$ rapid star formation history

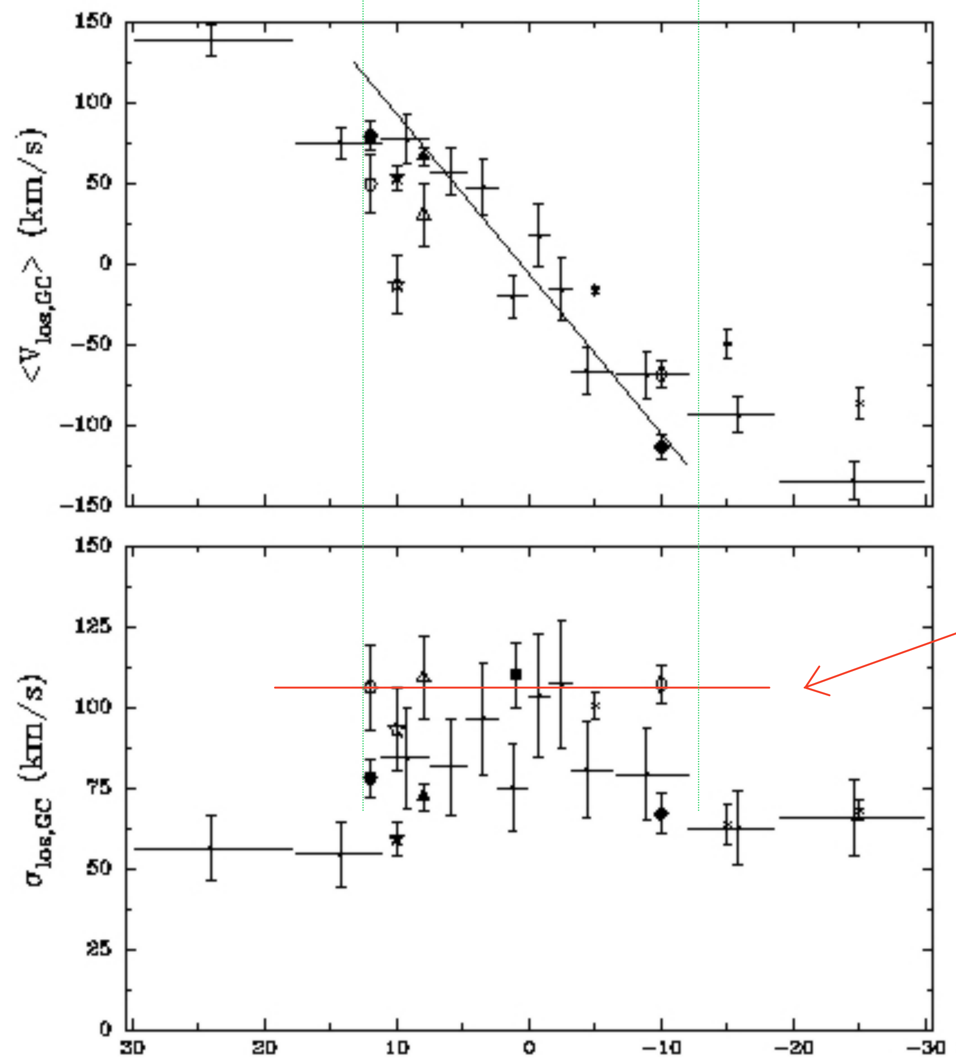
In the bar-buckling instability scenario
(bar formation - destruction - reformation),
the structure of a pseudo-bulge may be younger than its stars, which were originally part of the inner disk.



The Milky Way Bulge

The MW bulge is rotating, like most other bulges:

(Kuijken & Rich (2002) HST proper motions)



Rotation (Beaulieu et al 2000)

K giants from several sources and planetary nebulae (+)

Velocity dispersion of inner disk and bulge are similar

- not easy to separate

inner disk and bulge

kinematically

Bulge ends at $|l| \sim 12^o$

The Milky Way Bulge : Summary

The bulge is not a dominant feature of our Galaxy - only ~ 25% of the light.

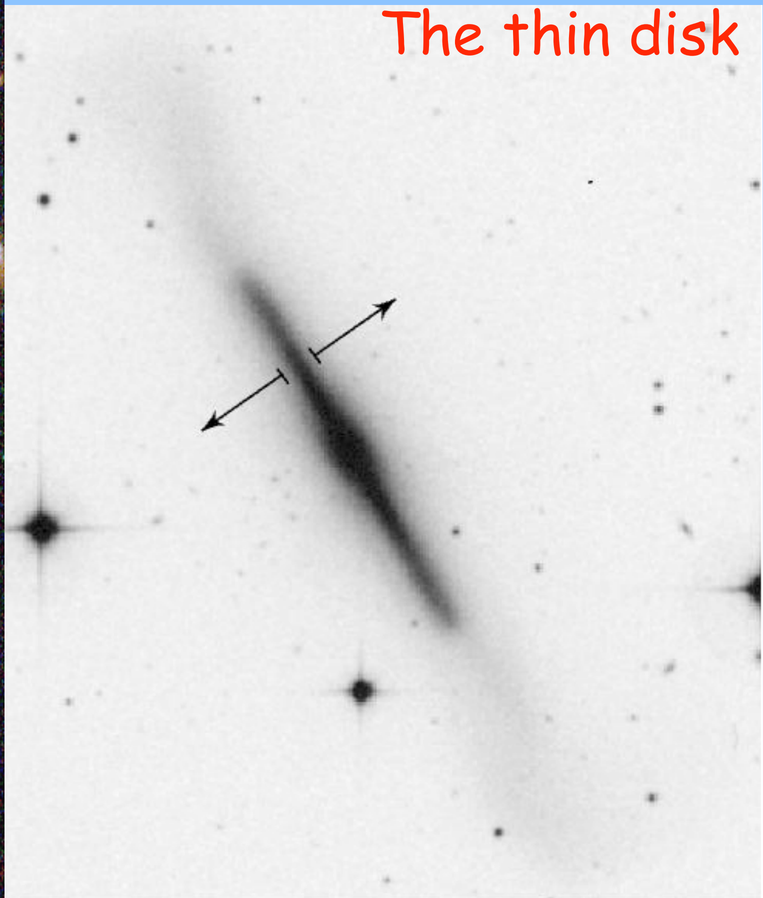
The bulge is probably an evolutionary structure of the disk, rather than a feature of galaxy formation in the early universe : a pseudo - bulge.
Structure and kinematics (so far) can be understood as a product of disk instability.

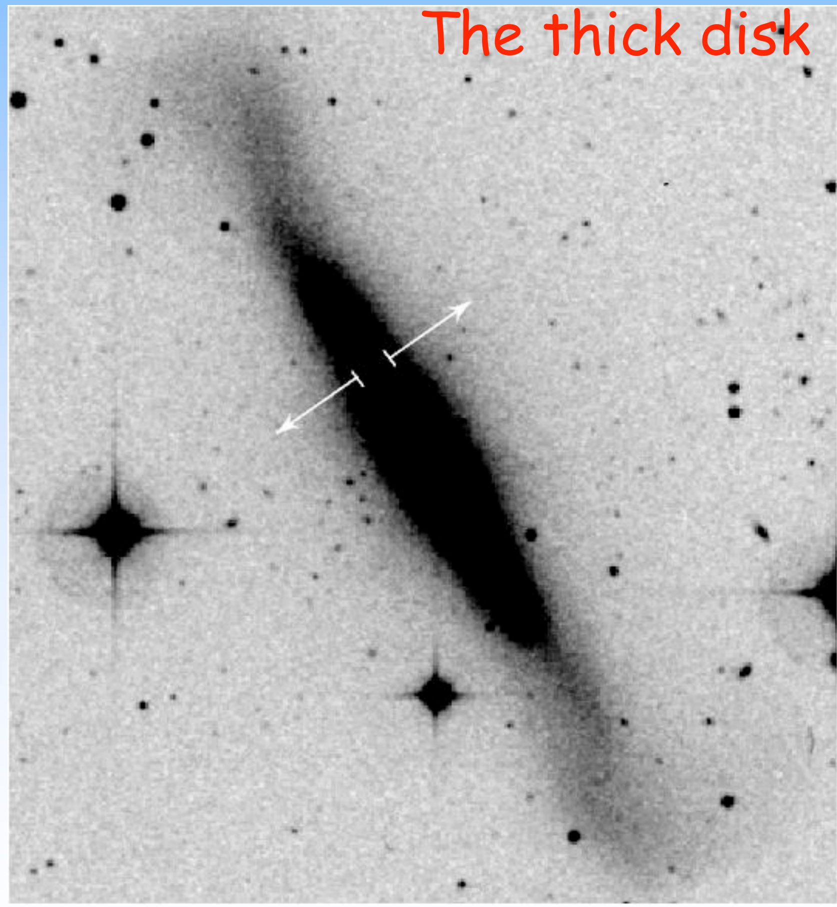
The a-enhancement indicates that star formation in the inner disk/bulge region proceeded rapidly.

The bulge structure may be younger than its stars.

The Milky Way Thick Disk

Most spirals (including our Galaxy) have a second thicker disk component.
In some galaxies, it is easily seen :





NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)

The Milky Way Thick Disk

The Galactic thick disk is detected in star counts. Its larger scale height means its velocity dispersion is higher than for the thin disk and therefore its rotation lags behind the “Local Standard of Rest”.

Near the sun, the Galactic thick disk is defined mainly by stars with [Fe/H] in the range -0.5 to -1.0, though its [Fe/H] distribution has a tail to very low [Fe/H] ~ -2.2.

The thick disk appears to be a discrete component, distinct from the thin disk.

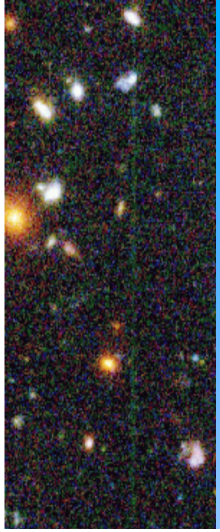
The Milky Way Thick Disk

Radial scale length = 3.5 to 4.5 kpc : uncertain

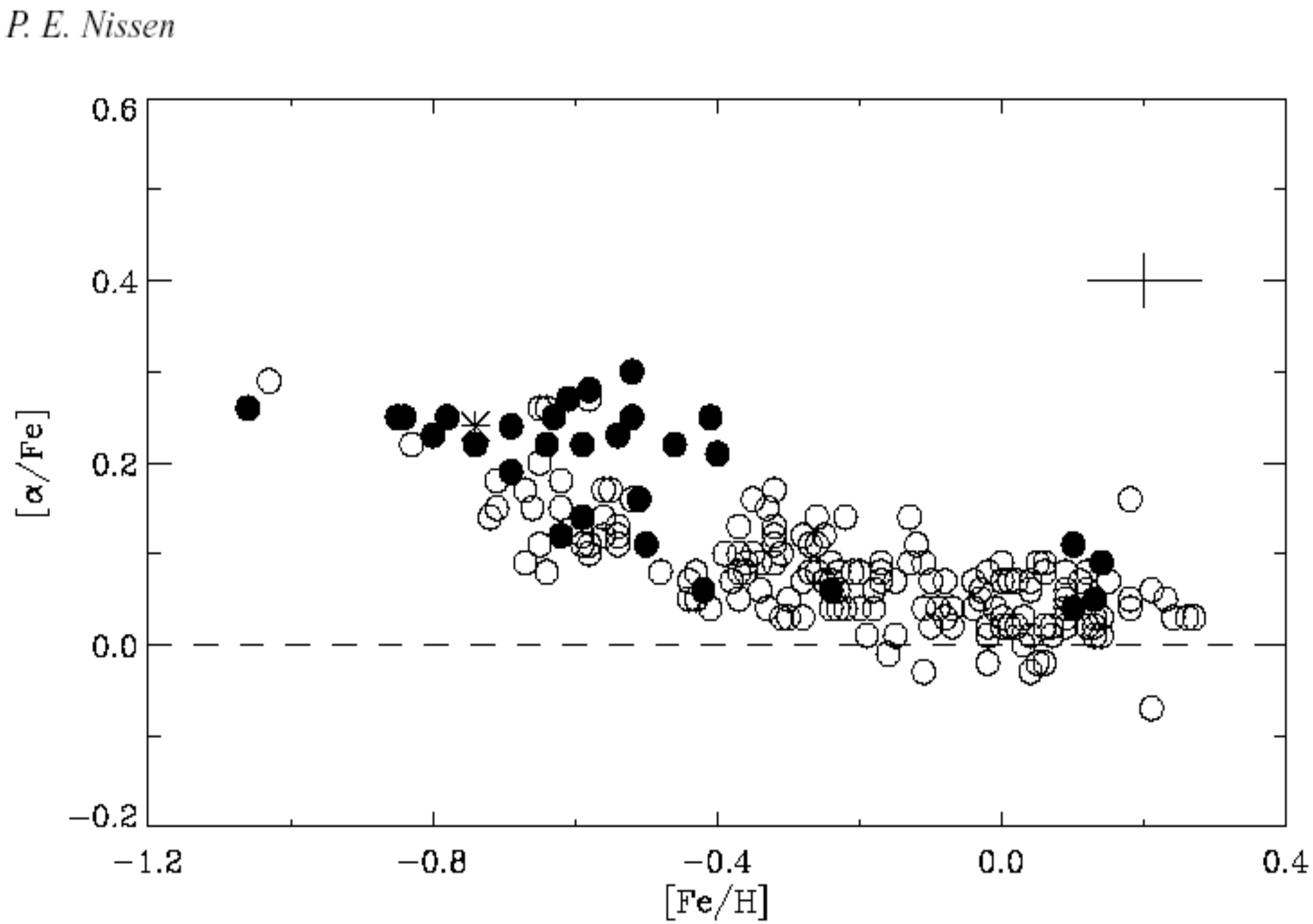
Scale height from star counts = 800 to 1200 pc
(thin disk ~ 300 pc)

stellar density = 4 to 10% of the local thin disk

The Milky Way Thick Disk



The **Galactic thick disk is old (> 12 Gyr)** & significantly more metal poor than the thin disk: **mean [Fe/H] ~ -0.7** and **α-enhanced** ⇒ rapid chemical evolution



- ● thick disk
- ○ thin disk

higher [α/Fe] ⇒ more rapid formation

The Milky Way Thick Disk

The age distribution for the thick disk stars indicates a time delay between formation of thick disk stars and the onset of star formation in the current thin disk.

Thick disk : kinematically recognizable 'frozen-in' relic of the early galaxy.

Formation scenarios for the thick disk ...

- a normal part of disk settling (eg Samland et al 2003)
- accretion debris (Steinmetz et al 2003, Walker et al 1996)
- early thin disk, heated by accretion events (Bekki & Freeman 2003)

<u>Thick disks are very common</u>

Almost all spirals have one

(Dalcanton & Bernstein 2002)

Formation Scenario for the Milky Way Disk

Thin disk formation begins early @ z = 2 to 3.

Partly disrupted during merger epoch which
heats it into thick disk observed now.

The rest of the gas then gradually settles to form the
present thin disk

Not much is known about the radial extent of the thick disk. This is important, if the thick disk really is the heated early thin disk. Disks form from inside out, so the extent of the thick disk now would reflect the extent of the thin disk at the time of heating.

Formation of disk stars outside the disk

ΛCDM simulations of formation of an early-type disk galaxy (Abadi et al 2003) show that not all disk stars form in the disk

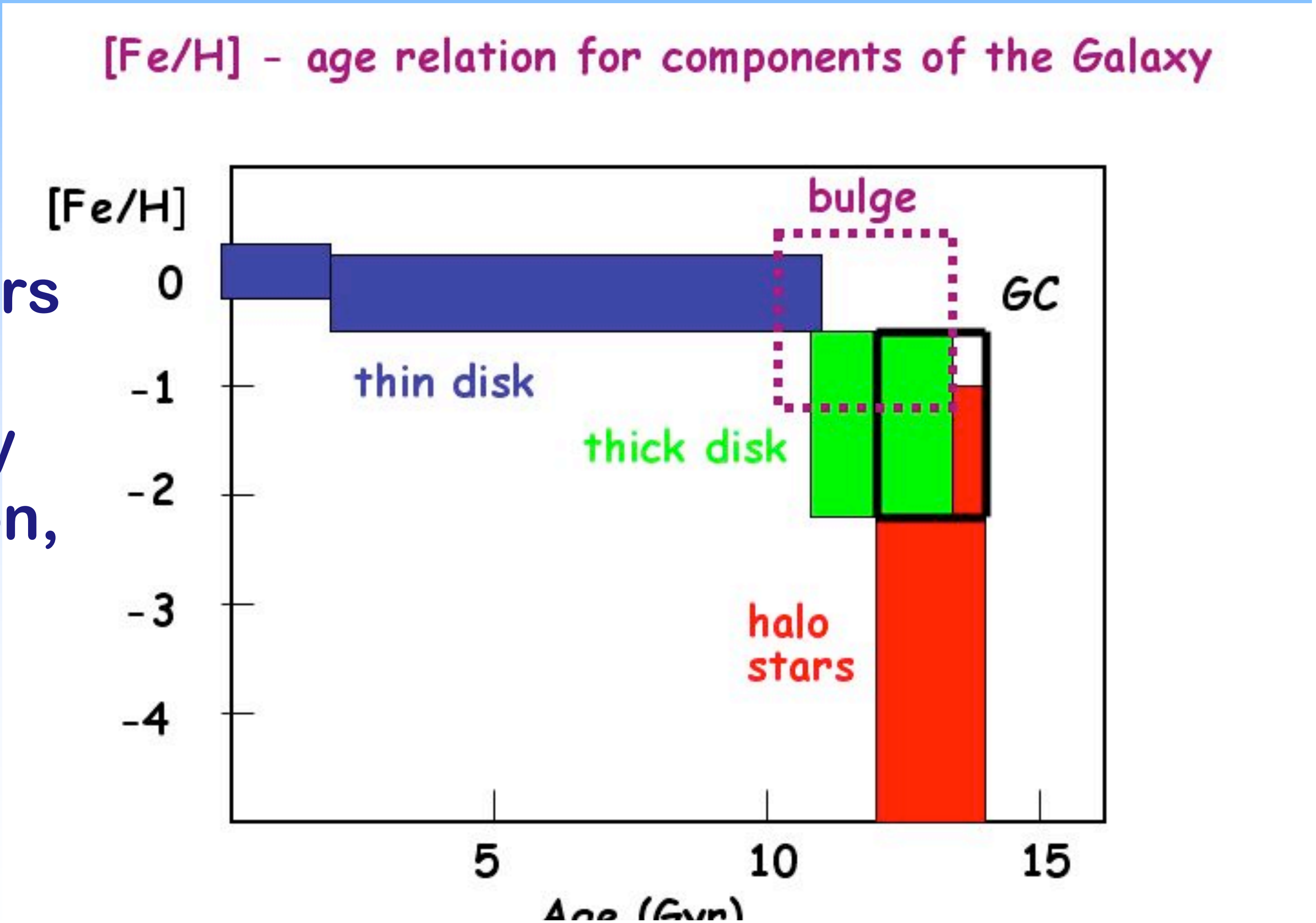
Many of the oldest stars in the disk are debris from accreted satellites which ends up in the thin and thick disk.

Satellite orbit is dragged into disk plane by dynamical friction - acts like dissipation, although system is collisonless

Age and metallicity distribution of Stars in the MW

<u>Thick disk stars</u> in the solar neighborhood overlap with [Fe/H] abundances of the most metal-poor globular clusters.

Did these stars form as part of early disk formation, or were they acquired ?



Thick Disks : Summary

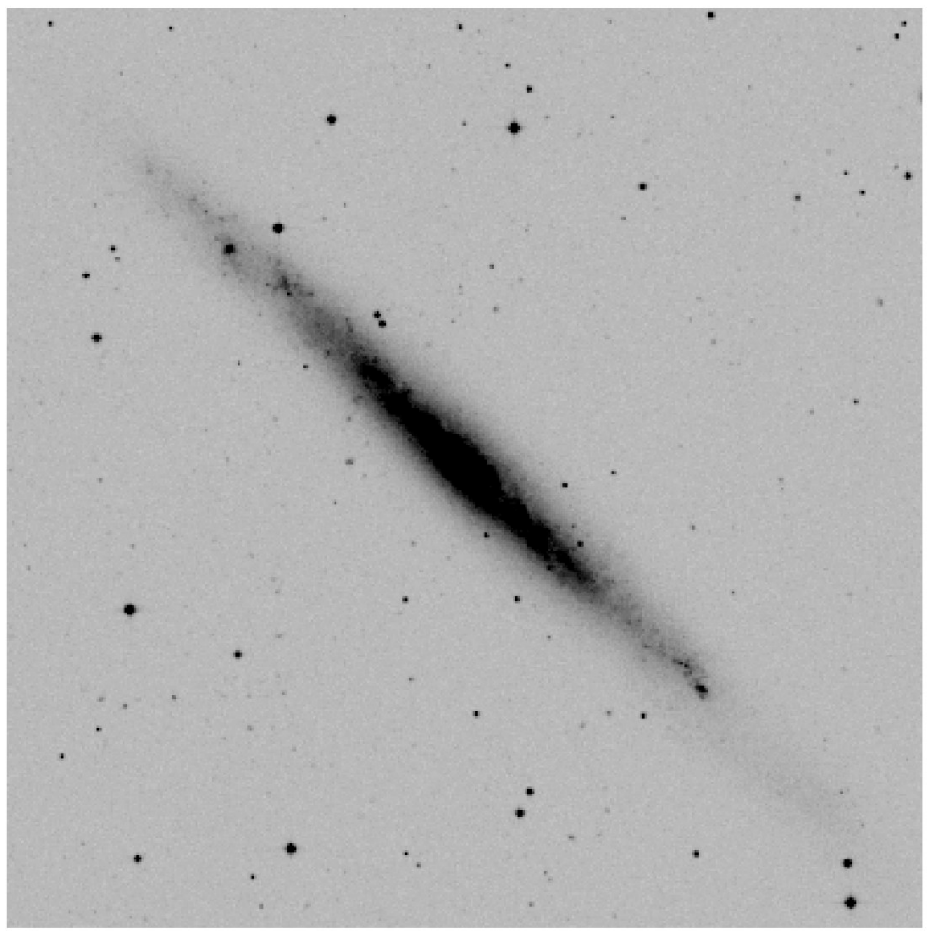
The thick disk formed rapidly and early
(12 Gyr ago in the Galaxy)

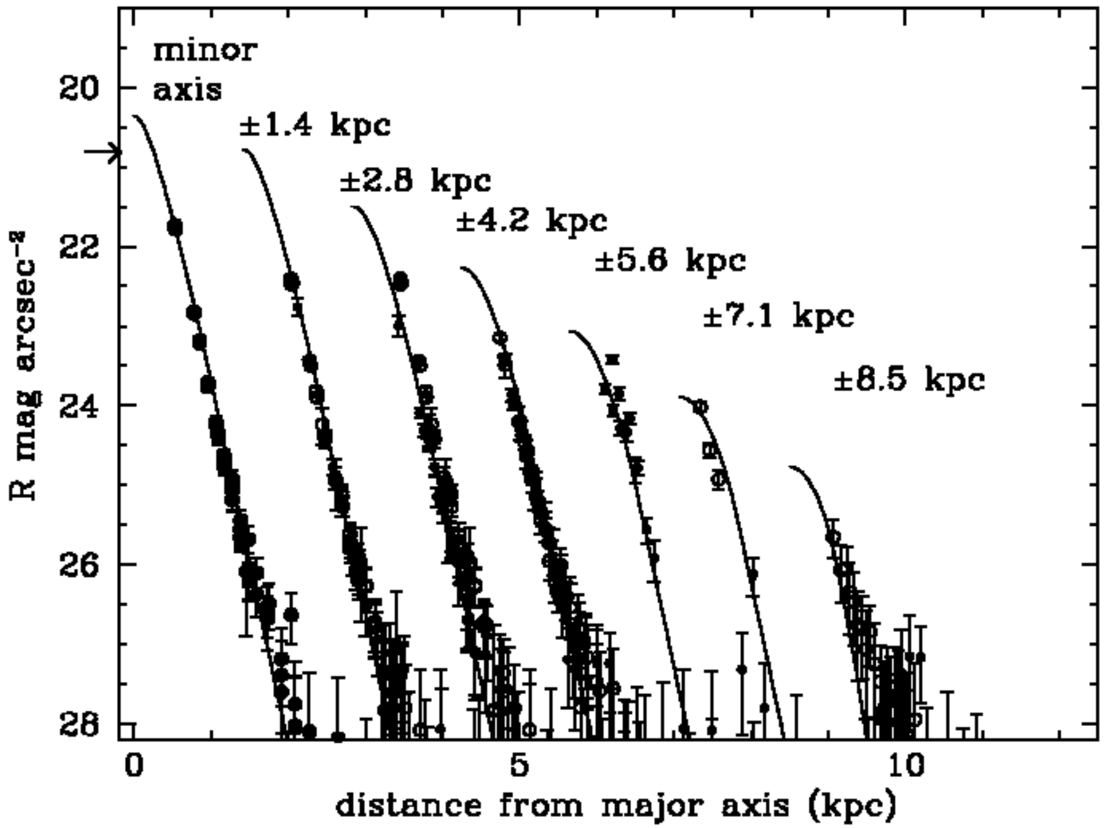
Appears to be distinct from the thin disk

Formed by heating of the early thin disk in
an epoch of merging which ended ~ 12 Gyr ago
(eg Quinn & Goodman 1986)
or
from early accretion of satellites, probably in
mainly gaseous form (eg Brook et al 2004)

There is at least one spiral without a thick disk :

NGC 4244 (M_B = - 18.4) : a pure thin disk: just a single exponential component, no thick disk





Fry *et al* 1999

The existence of such a pure thin disk galaxy indicates : that for at least some late-type disks:

- the star formation did not start until the gas had settled to the disk plane

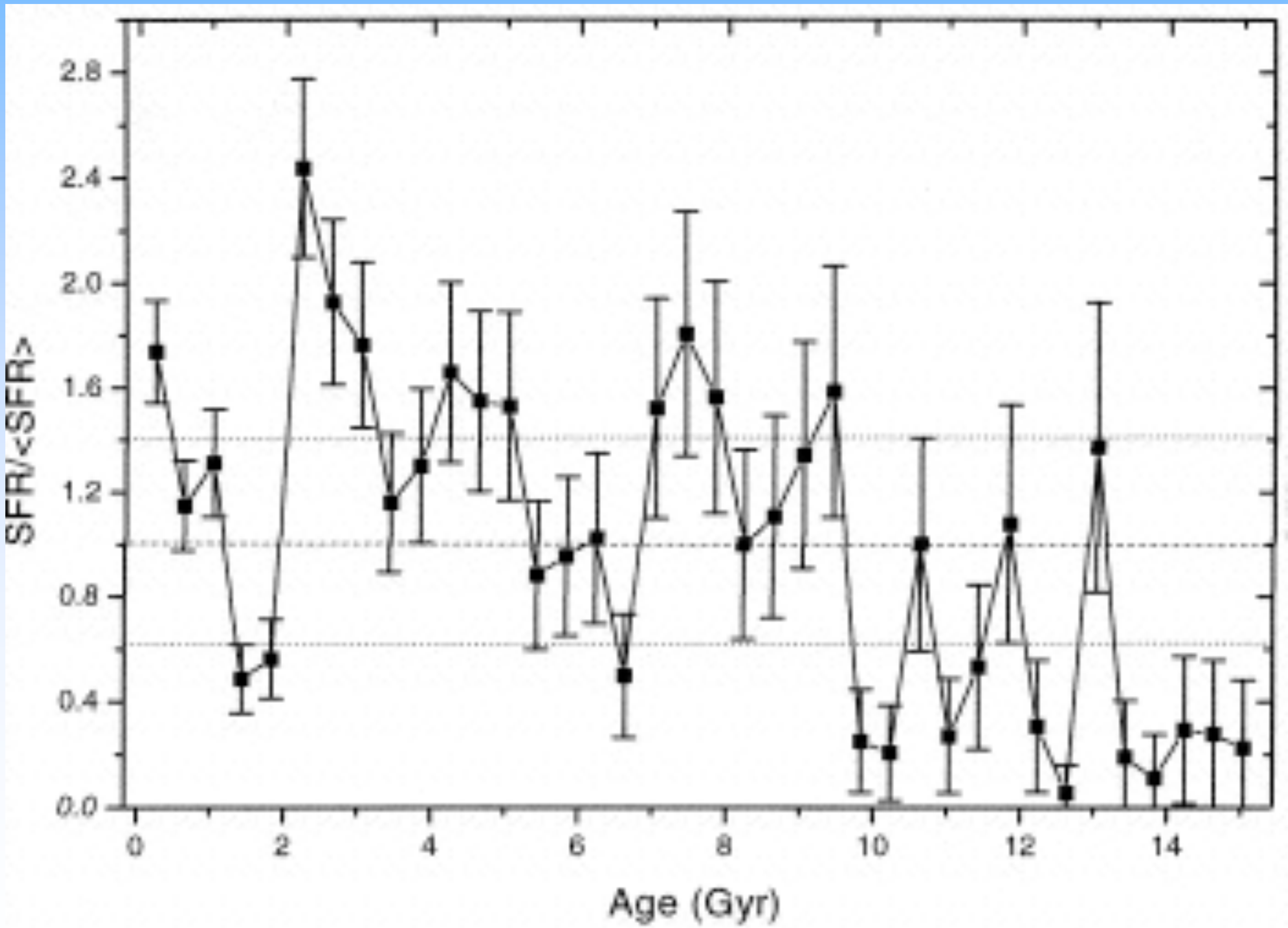
- since the onset of star formation in the disk, the disk has suffered no significant dynamical disturbance from internal or external sources

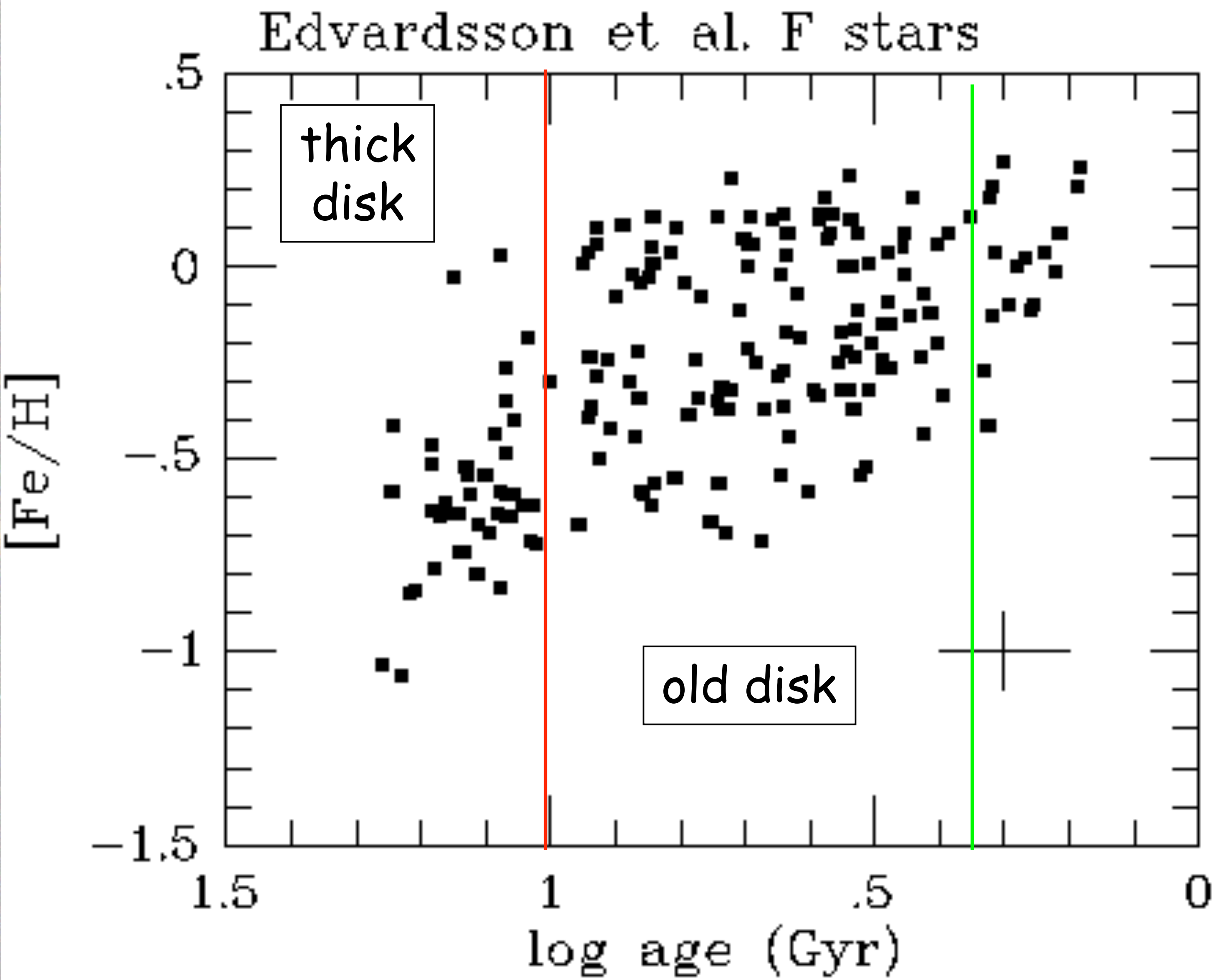
-- pure disk galaxies are not readily produced in ΛCDM simulations: too much merger activity

-- NGC 4244 is fairly isolated

The Milky Way Thin Disk

Star Formation History in the MW thin disk : smoothly declining by factor ~ 4 since age = 0, with short-term fluctuations +/- 20% on timescales 10^8 yr

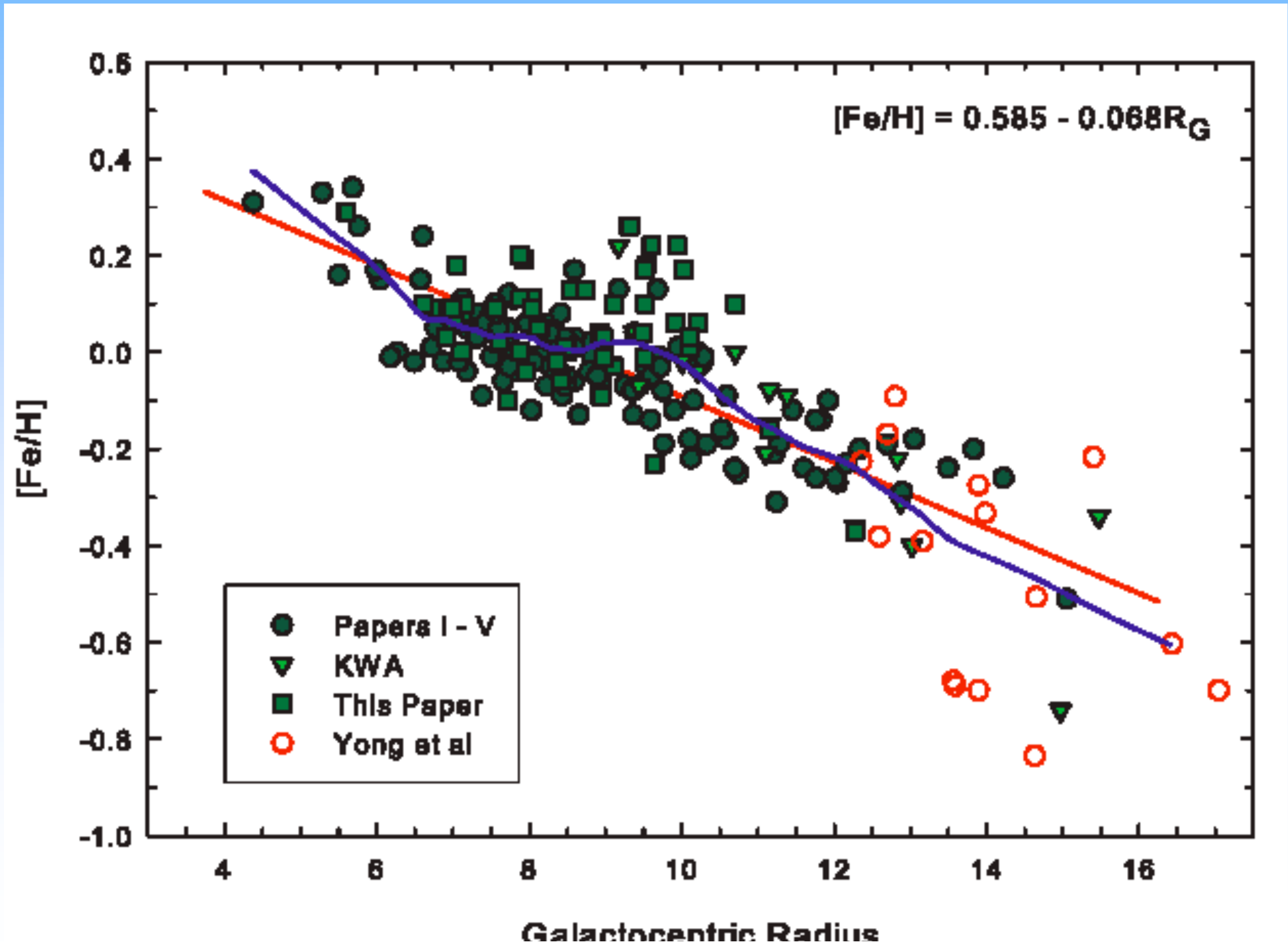




No significant chemical evolution in the nearby old disk for ages 2-10 Gyr

The Milky Way Outer Disk

The MW disk shows an abundance gradient, as in M31 (eg Cepheids: Luck et al 2006 - young stars)



The Milky Way Outer Disk

Yong & Carney 2005; Carney & Yong 2005:
high resolution spectra of open clusters and stars in the outer disk

The abundance gradient for the open clusters (ages 1 to 5 Gyr) bottoms out at RG = 12 kpc (RG = 15 kpc in M31) around [Fe/H] = -0.5 (as in M31).

Outer disk is α-enhanced, with [α/Fe] = + 0.2 (also Eu-enhanced): indicates fairly rapid star formation history in the outer disk, unlike the solar neighborhood.

Most of the Galactic baryons are in the disk,
most of the baryons in the local universe are
in spheroids.

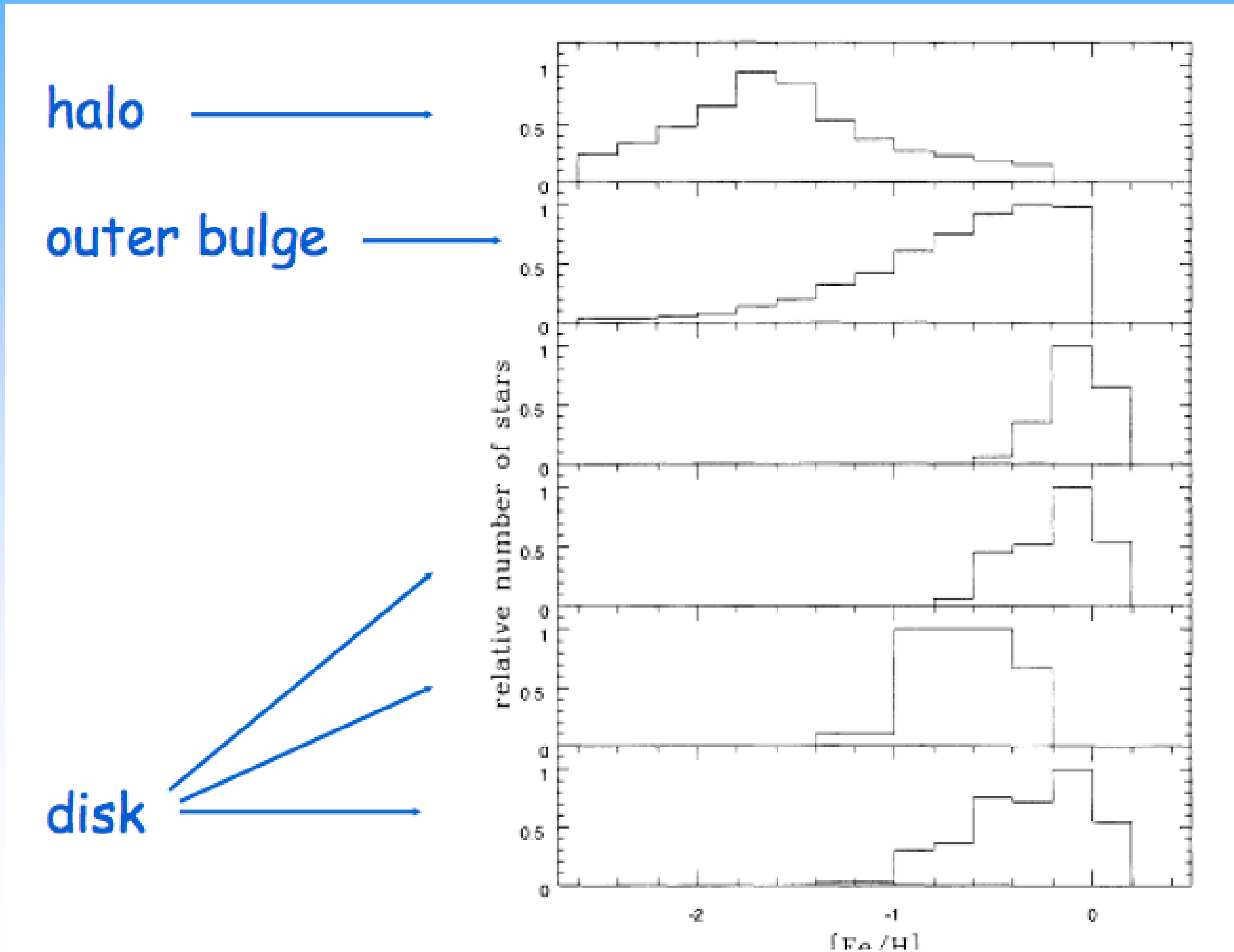
The Milky Way Halo

Halo field stars, Globular Clusters, low-density gas

M101

The Milky Way Halo

Stellar metallicity distribution

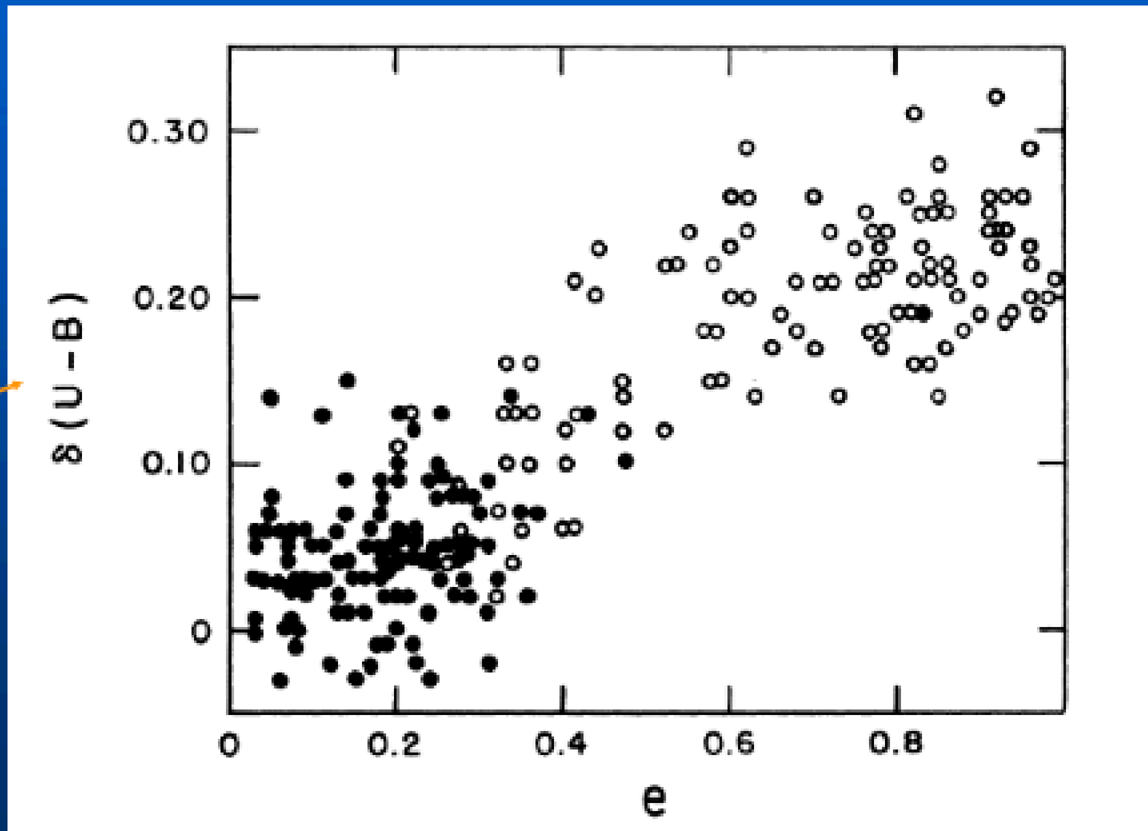


The Milky Way Halo -- Formation

Eggen, Lynden-Bell, Sandage (monolithic collapse) scenario

- first clues come from in situ studies of halo stars in the solar neighborhood

UV excess metallicity index



The Milky Way Halo -- Formation

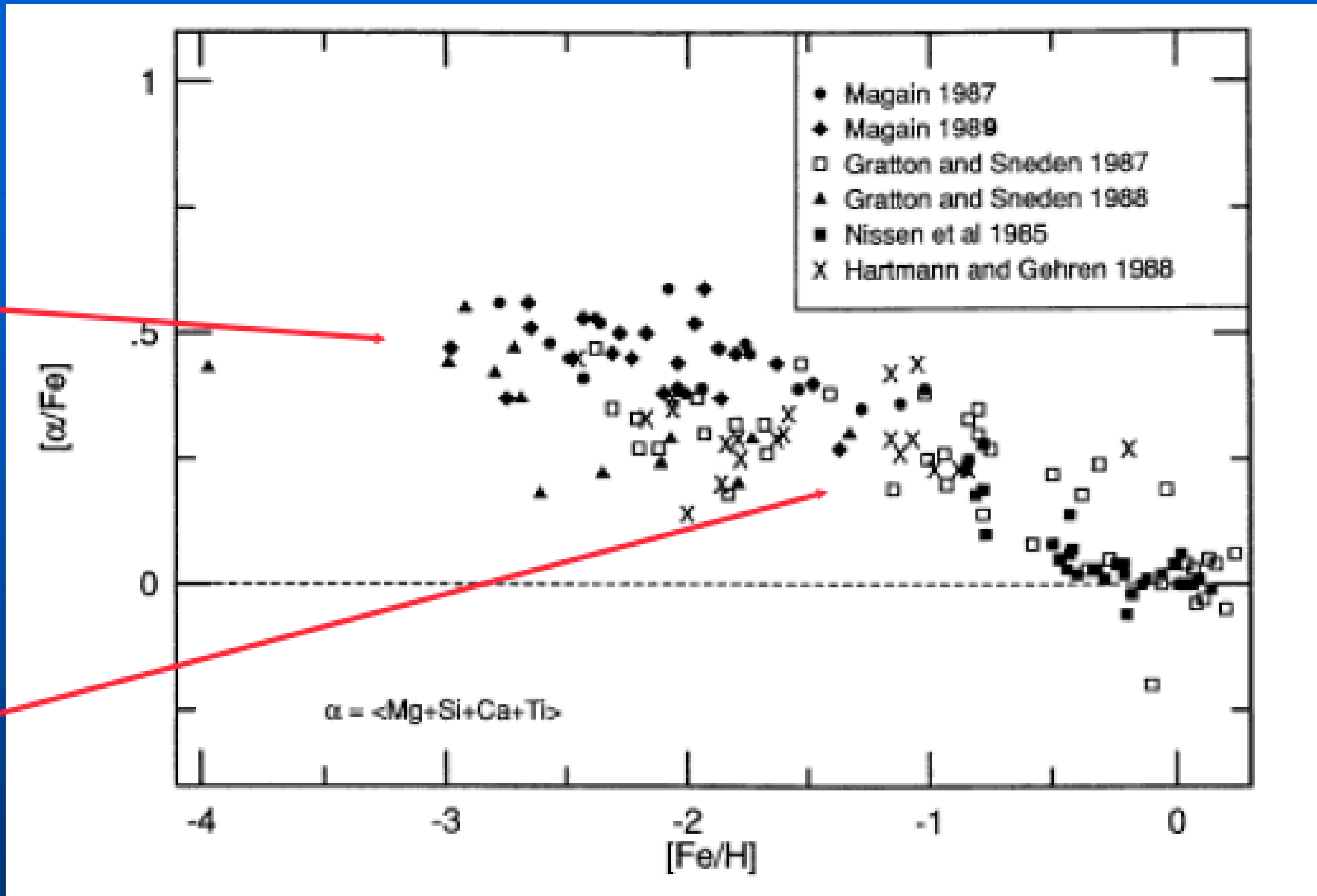
ELS: Results and Conclusions

- stellar metal abundances are strongly correlated with orbital properties (eccentricity, vertical velocity, apicenter radius, angular momentum, anisotropy)
- interpretation
  - first generation metal-poor stars formed at large radial distances from Galactic center, in spherical protogalaxy
  - radial collapse of protogalaxy produced eccentric orbits in metal-poor stars
  - subsequent generations of more metal-rich stars formed at smaller radii, on more circular orbits
  - strong abundance-kinematics trends require spheroid to form on order of dynamical timescale (~100 Myr)
- differential abundances of halo stars (e.g., O vs Fe) consistent with rapid formation/enrichment time

The Milky Way Halo

early core-collapse SNe (Type II, Ic) rich in O, α ejecta

after ~1 Gyr white dwarf binary SNe (Type Ia) begin to enrich more in Fe



Wheeler, Sneden, Truran 1989, ARAA, 27, 279

The Milky Way Halo -- Formation

Searle & Zinn (accretion) scenario

GCs do not fit ELS scenario:

abundance-kinematic corr. due to

disk-halo bimodality

Field stars :

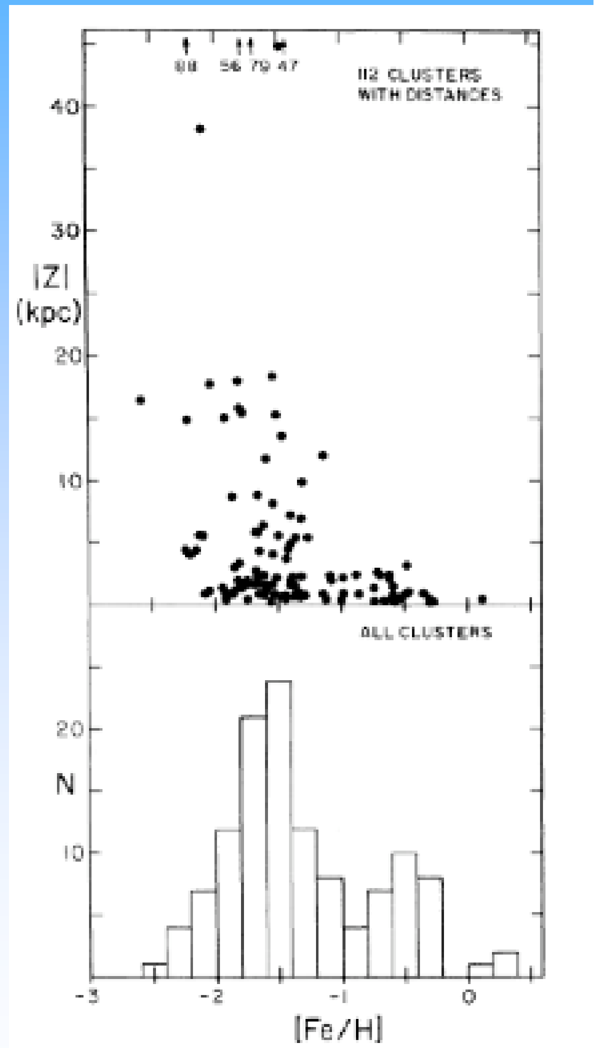
abundance-kinematic corr. result

of selection effects

thick disk confuses disk-halo separation

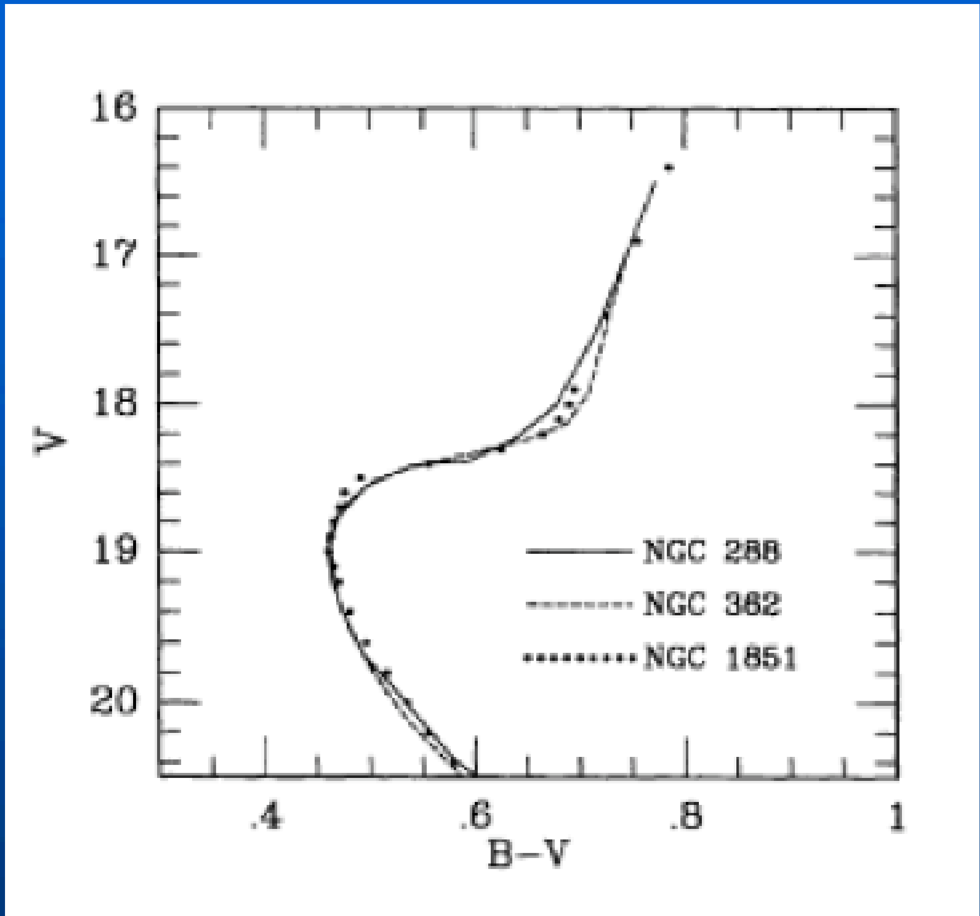
halo stars formed in protogalactic fragments & dwarf satellites, which were later accreted one by one

(Searle, Zinn1978, ApJ, 225, 357)



Zinn 1985, ApJ, 293, 424

The Milky Way Halo



Stetson et al. 1996, PASP, 108, 560

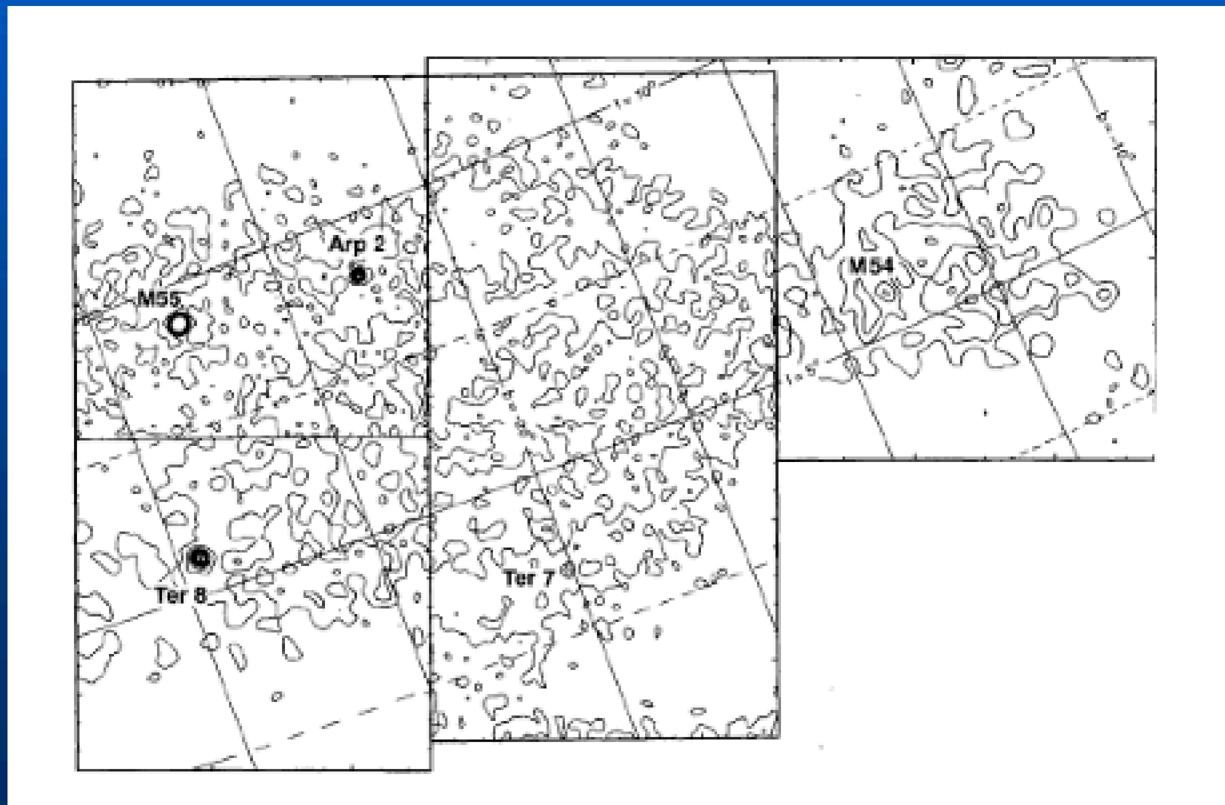
- most halo clusters show small age spread («2 Gyr)
- a few exteme second parameter clusters younger by up to a few Gyr
- different cluster HB subpopulations show distinct kinematics
- either most of halo formed in single event, or fragments have similar ages

The Milky Way Halo

Direct Evidence for Accretion

Sagittarius dwarf galaxy

- currently merging with Milky Way
- diameter >20 degrees, with larger tidal streamer
- $L = 1\text{-}2 \times 10^7 L_\odot$
- $M \sim 10^8 M_\odot$
- includes 5 globular clusters



Ibata et al. 1997, AJ 113, 634