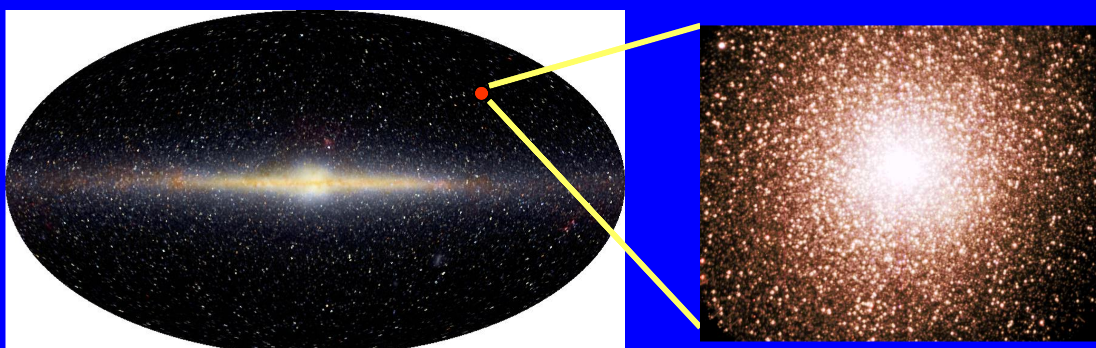
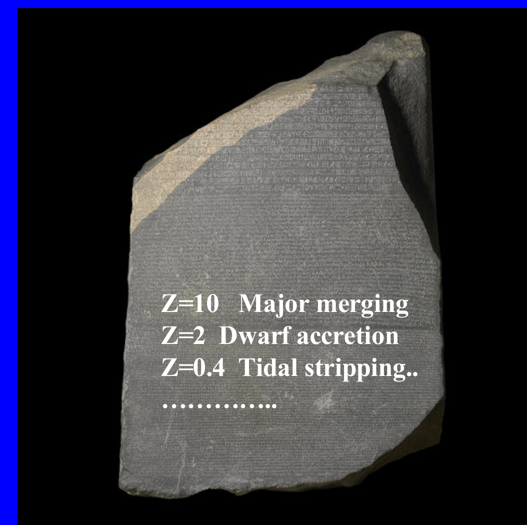
Globular cluster systems and galaxy formation



=



(The Galaxy) **(GC)** **(The Rosetta Stone)**

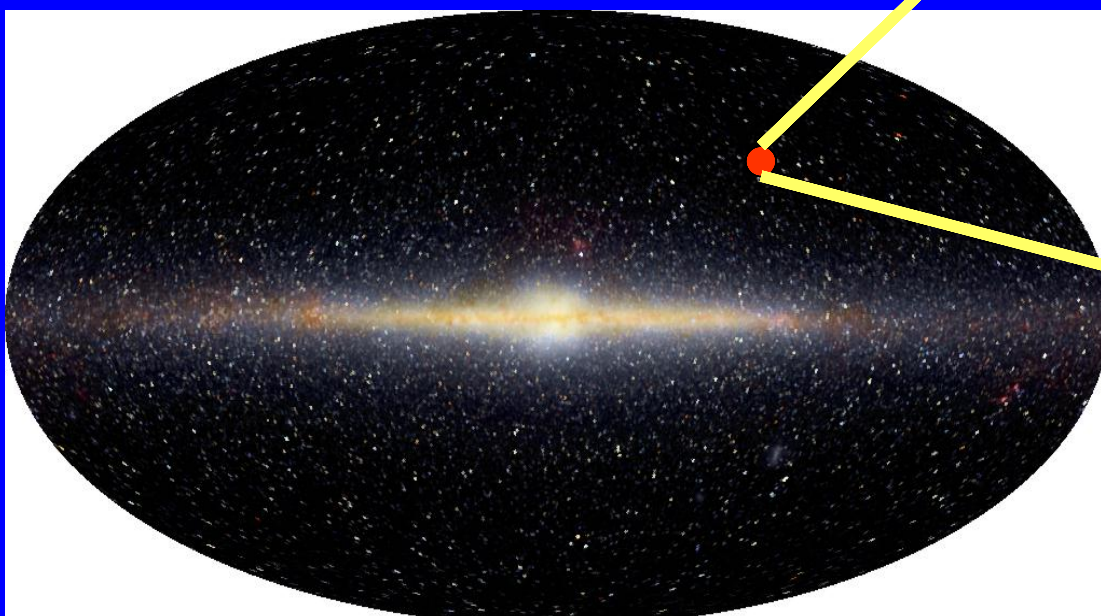
Kenji Bekki (UNSW, Australia)

Today's topics

- What are globular cluster systems (GCSs) ? Why do we study GCSs ?
- Derivation of physical meanings (on galaxy formation and evolution) from observational properties of GCs and GCSs
- Summary.

Globular clusters (GCs) and galaxy formation.

The Galaxy



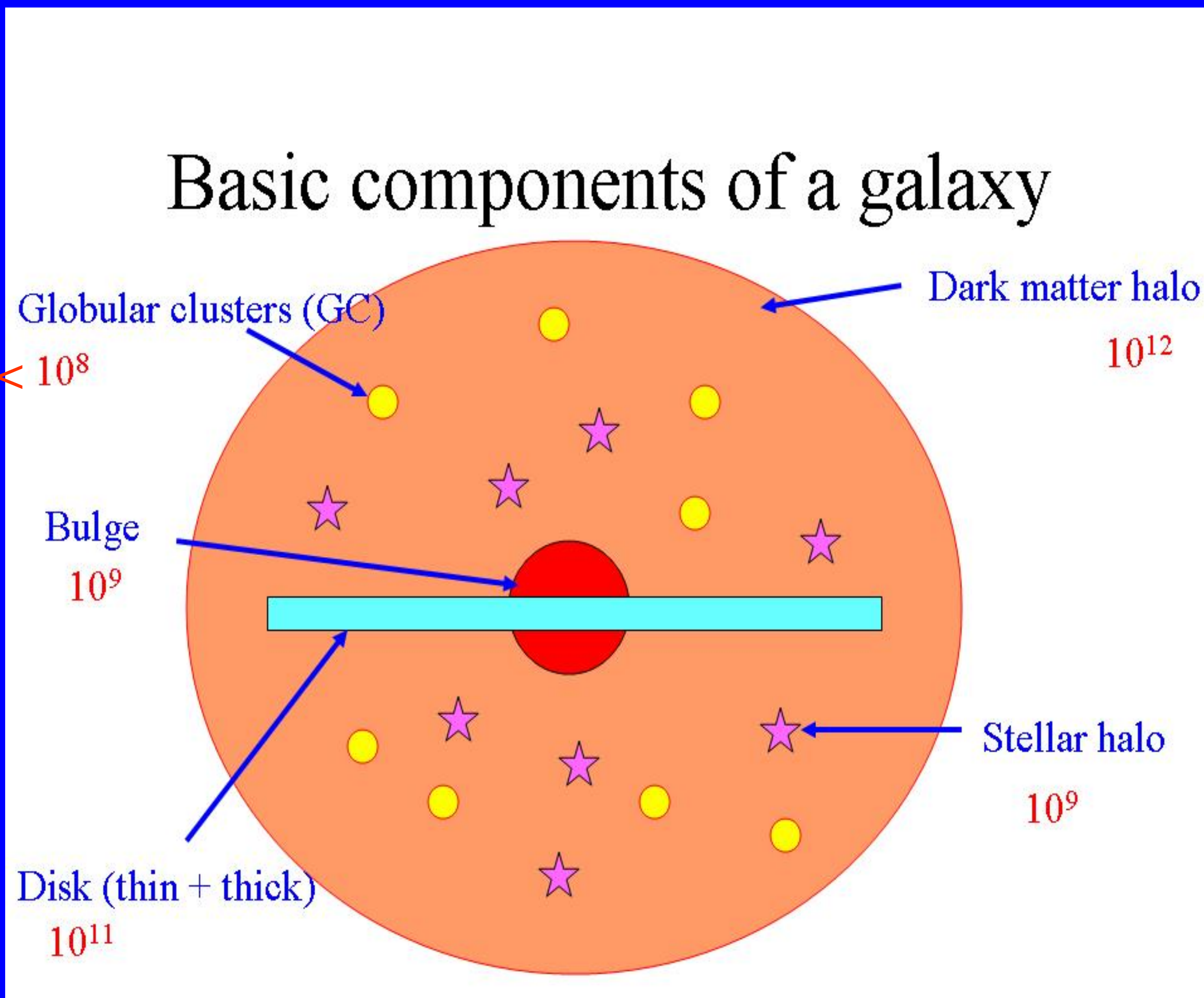
~40000 pc

Luminous mass ~ 10^{11} M_{sun}

GC M15

Mass ~ 10^5 M_{sun}.
Size (r_h) < 10pc
Density ~ 10^4 M_{sun}/pc^3
Age ~ 10^{10} yr.

GCs and Globular cluster systems (GCSs)



N_{GC}~ 160 in the Galaxy.

N_{GC}~ 6000 in M87.

GCS properties:
Space distributions ,
Kinematics,
Metallicity…..

Globular cluster systems (GCSs) in different Hubble types.

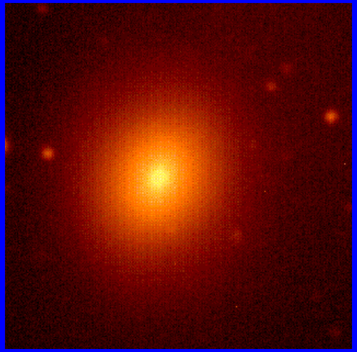
Spiral: M31

Irregular: LMC

Elliptical:M87

GC-less galaxies.

Leo A

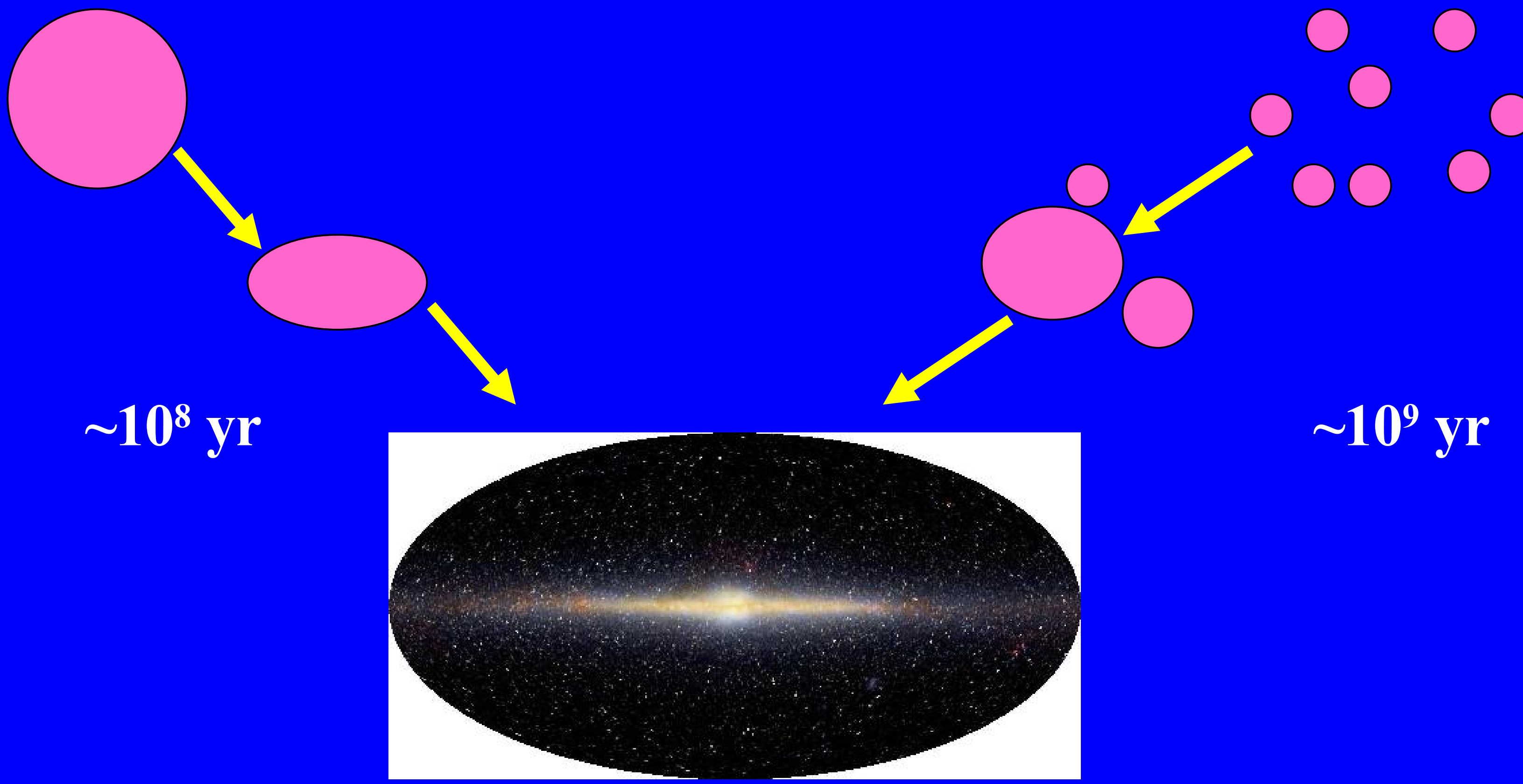


M32

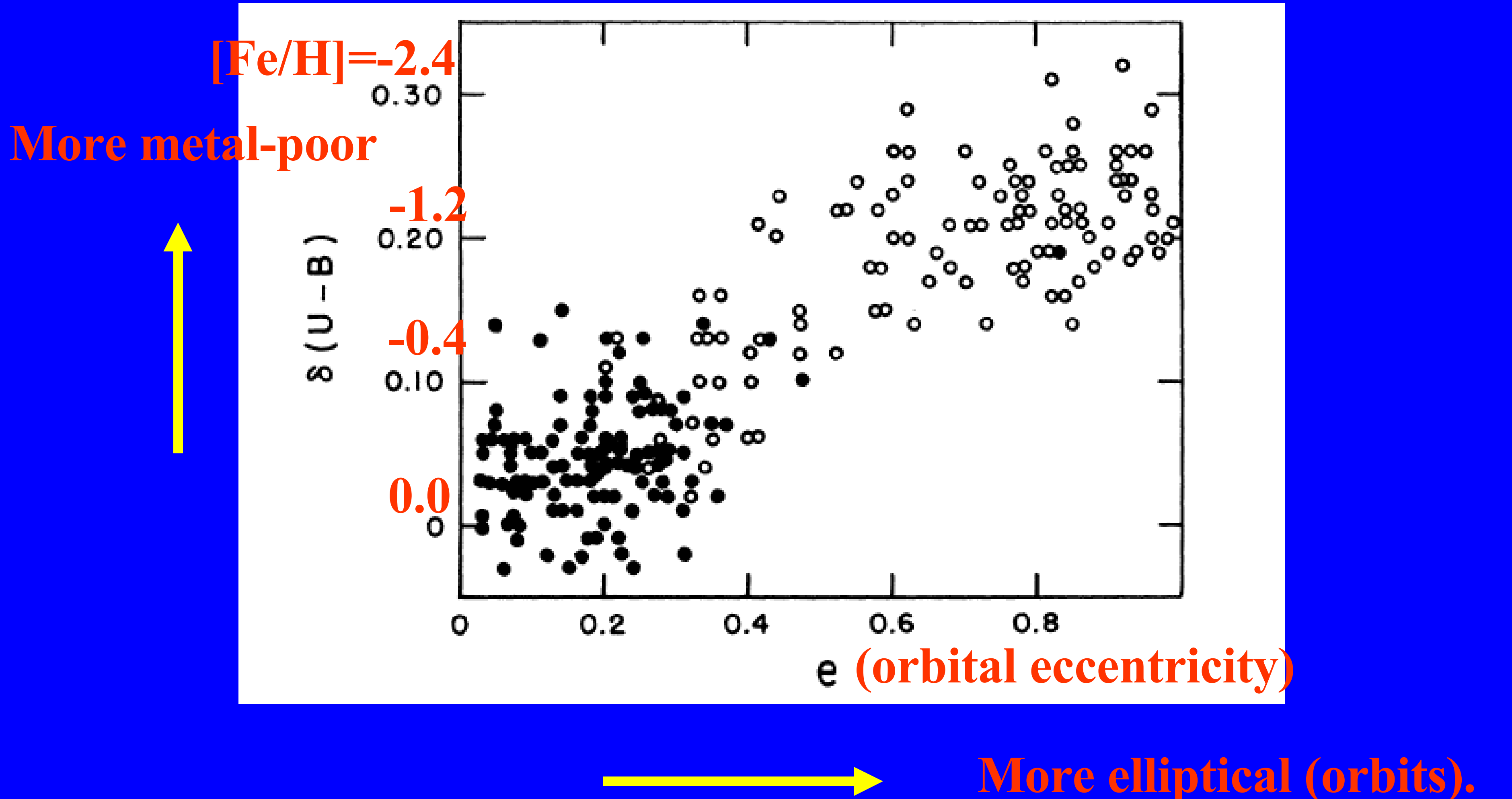
The Galactic Archeology.

- **Rapid collapse (Eggen, Lynden-Bell, & Sandage 1962: ELS)**

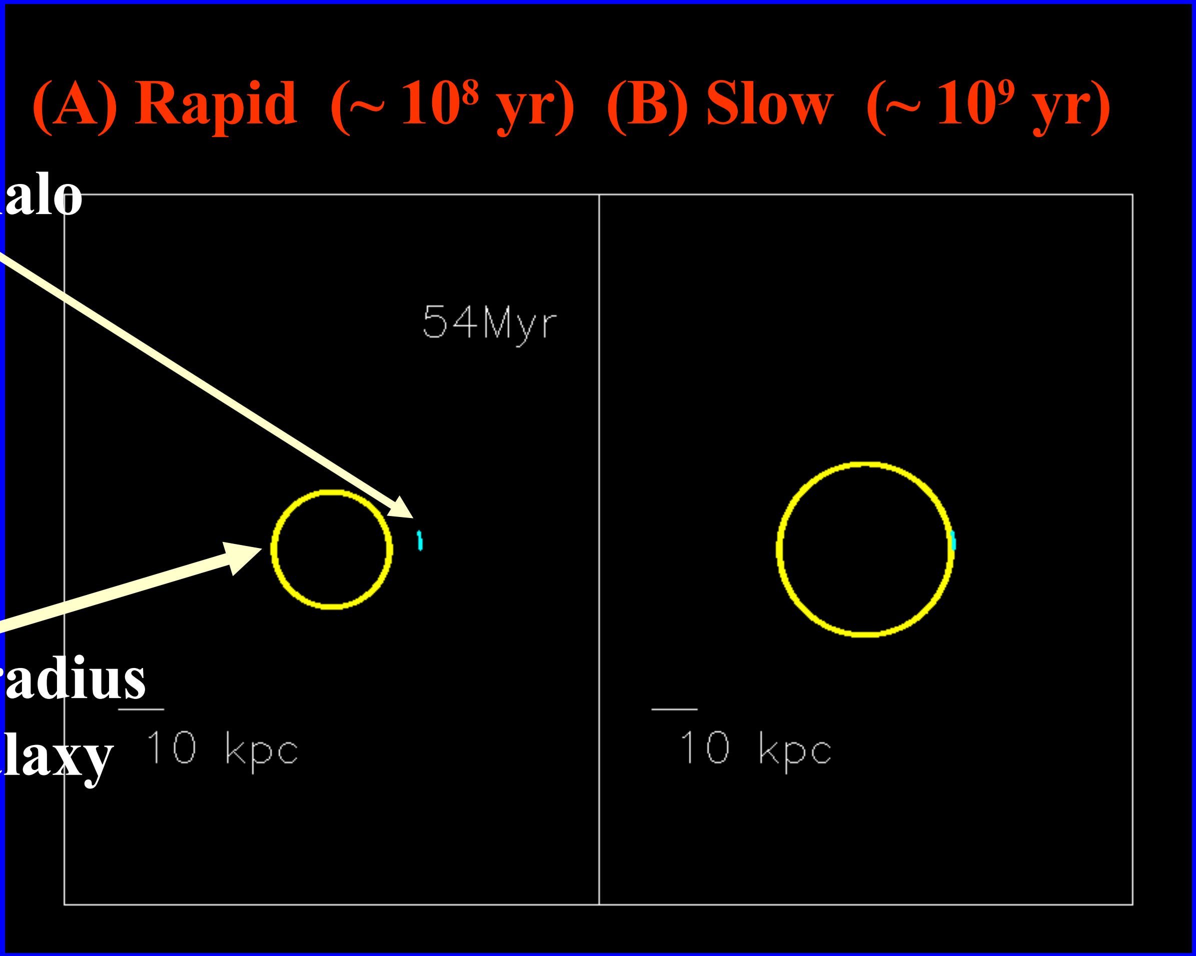
(2) Chaotic merging/accretion of subgalactic clumps (Searle & Zinn 1978: SZ)



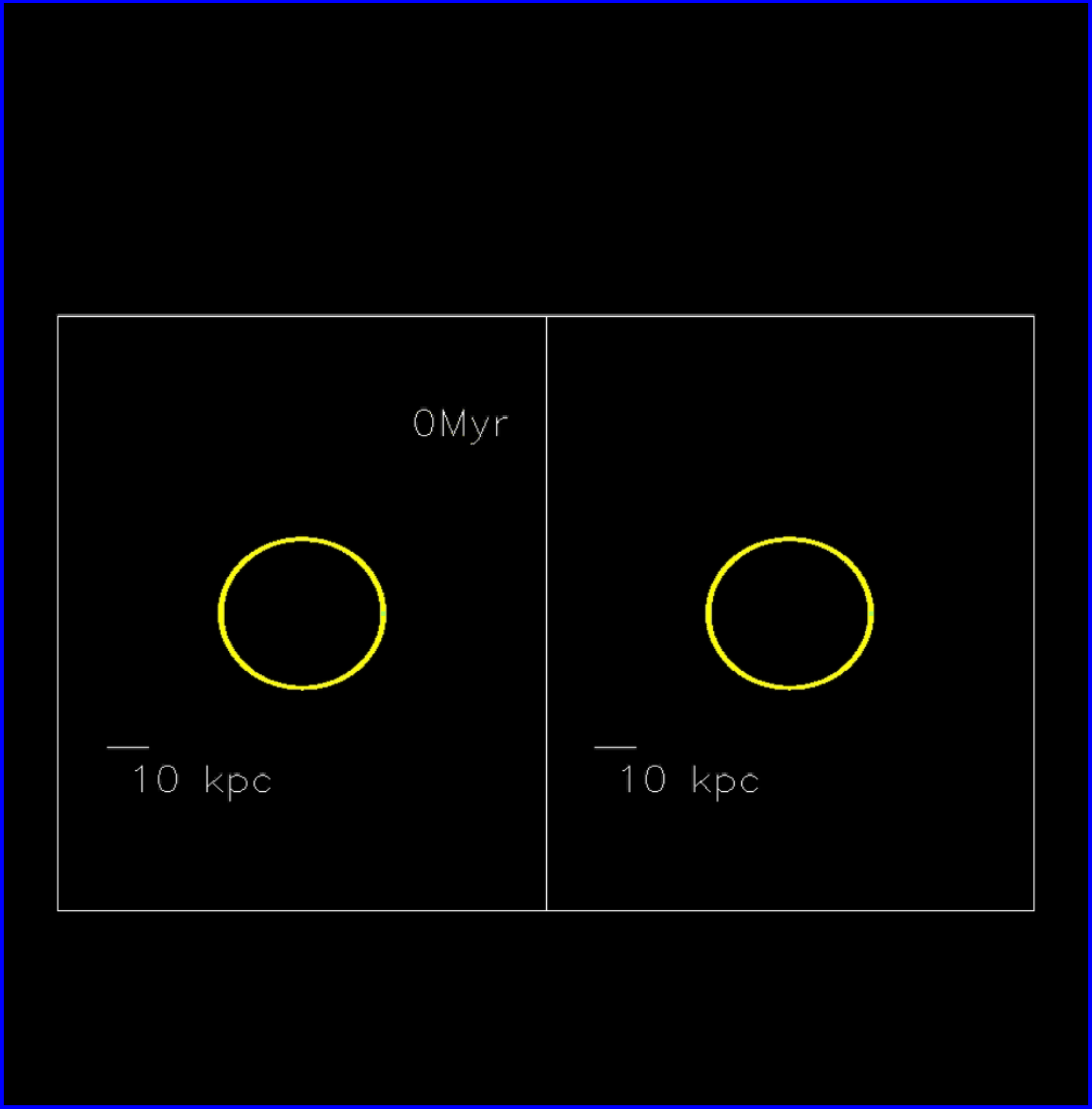
The collapse time scale from the e-metallicity relation of halo stars (ELS)



Why rapid ?


(A) Rapid (~ 10⁸ yr)
(B) Slow (~ 10⁹ yr)
Orbit of a halo star
54Myr
Half-mass radius of proto-galaxy
10 kpc
10 kpc

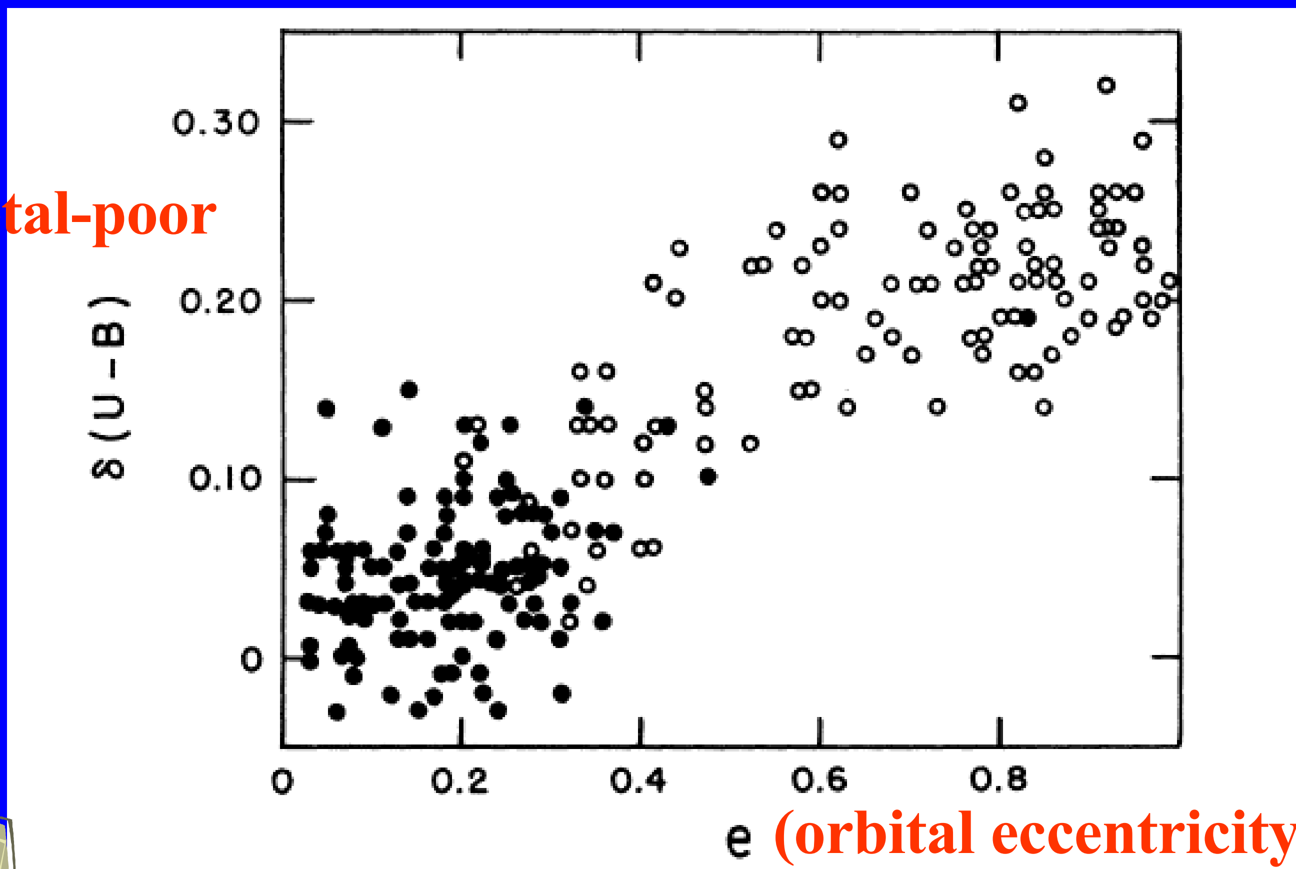
Rapid



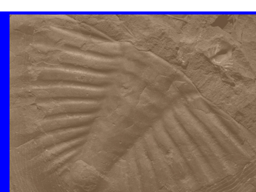
Slow

The e-[Fe/H] relation as a fossil record on the Galaxy formation time scale.

More metal-poor



(orbital eccentricity)

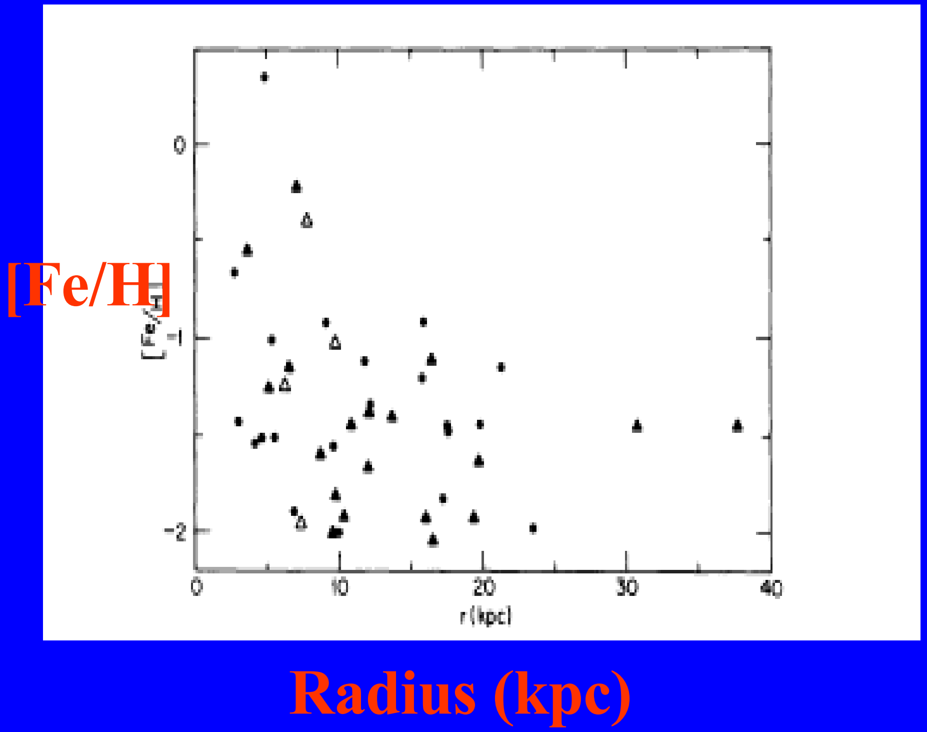


More elliptical (orbits).

The rapid collpase scenario (ELS 1962)

Why merging/accretion (SZ)?: GCs as fossil records of the Galaxy formation.

- No significant metallicity gradient in the Galactic GC.
- A possible broad range of age in the outer halo GCs etc… (SZ 1978).

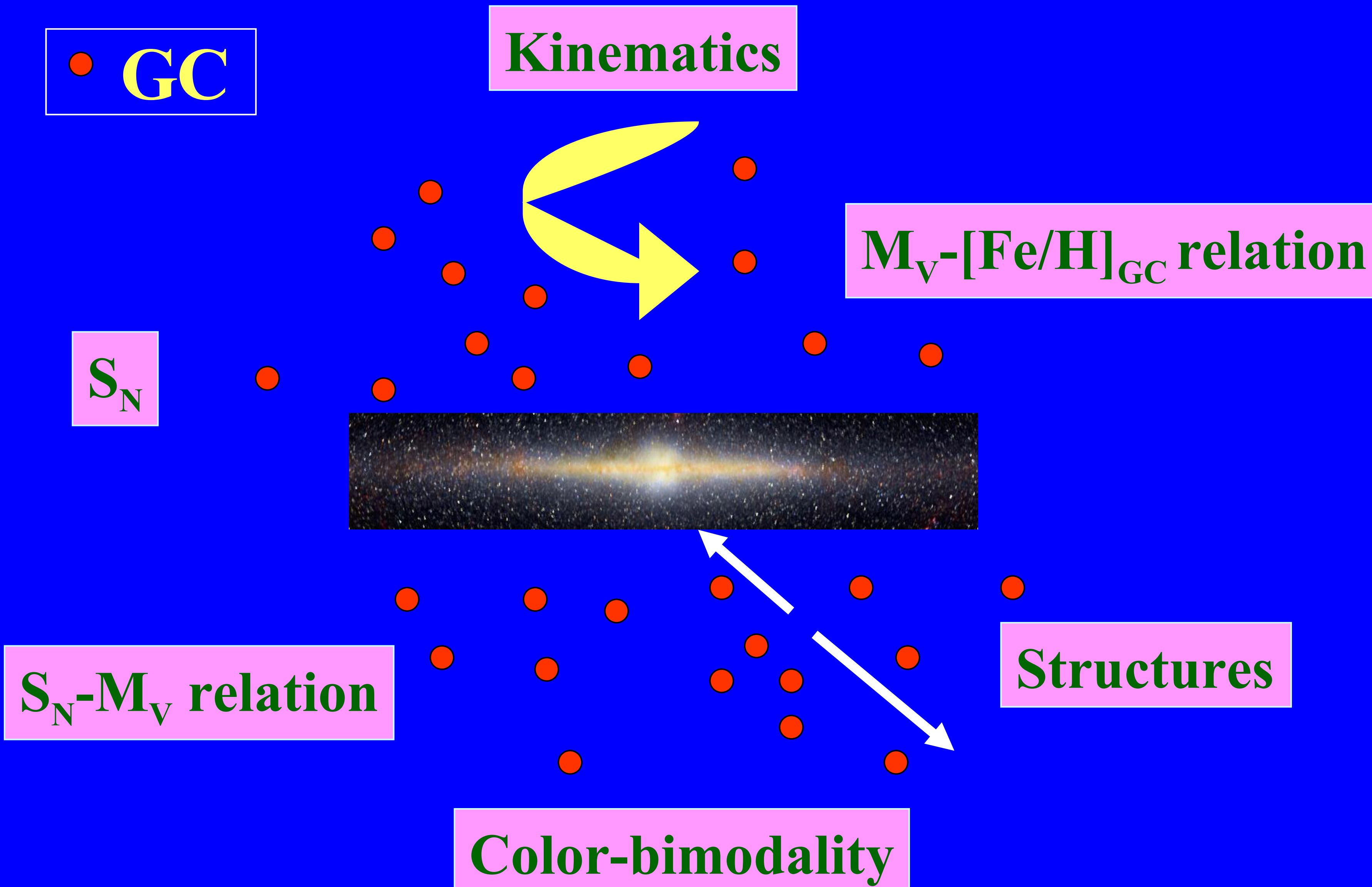


The chaotic merging/accretion scenario (Searle & Zinn 1978)

A big question:

What do physical properties of GCs and GCSs tell us about galaxy formation and evolution ?

GCS fossil records.



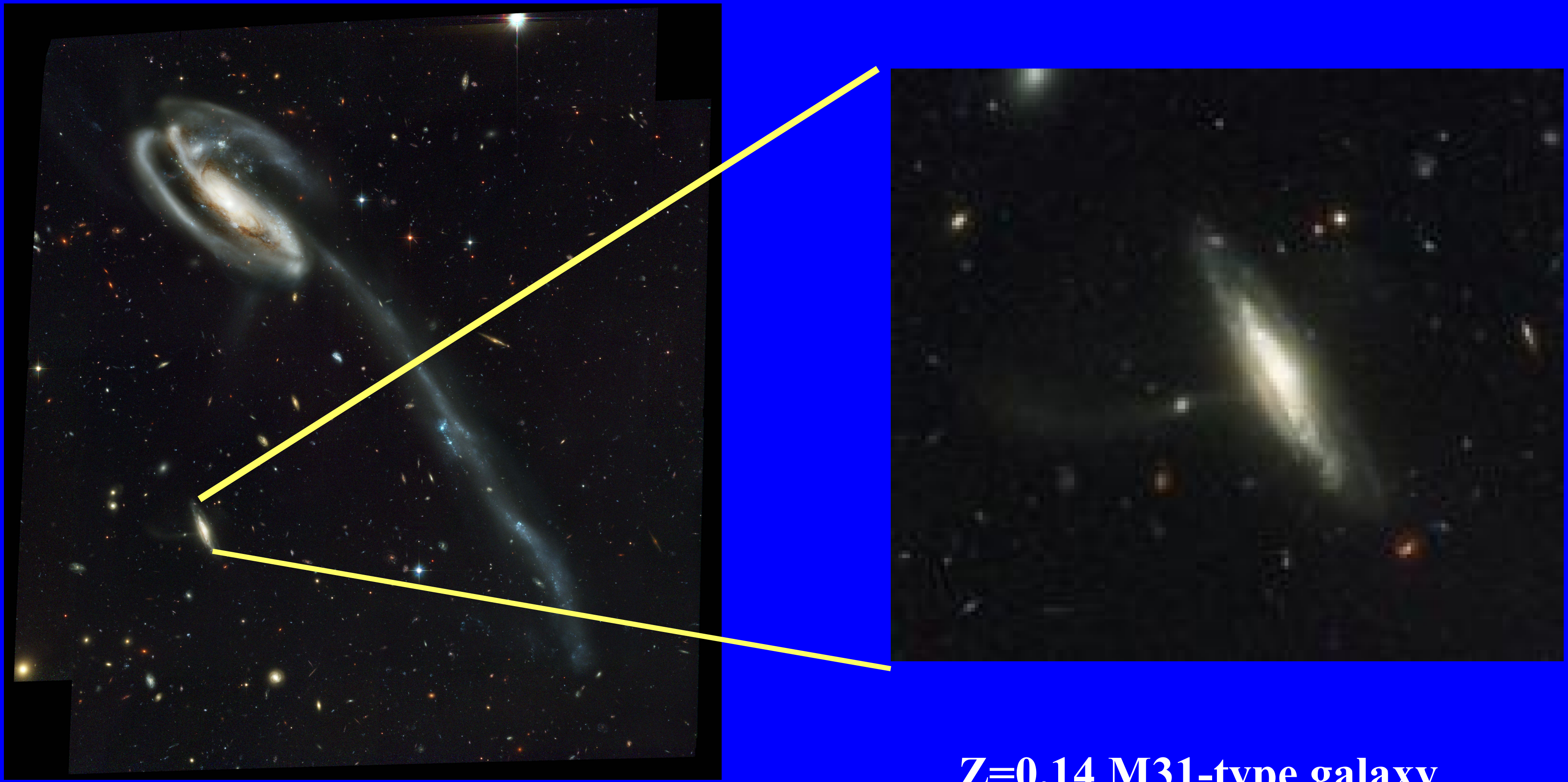
Four questions.

What do

- GCS structures and kinematics in E/S0s
- GC age distributions
- physical properties of very massive GC (e.g., ω Cen)
- intracluster GCs.

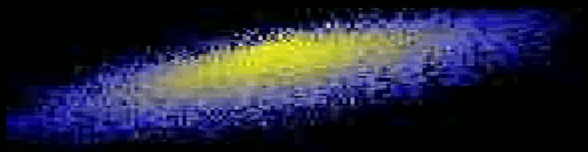
tell us ?

An example of interacting/merging galaxies.



Z=0.14 M31-type galaxy

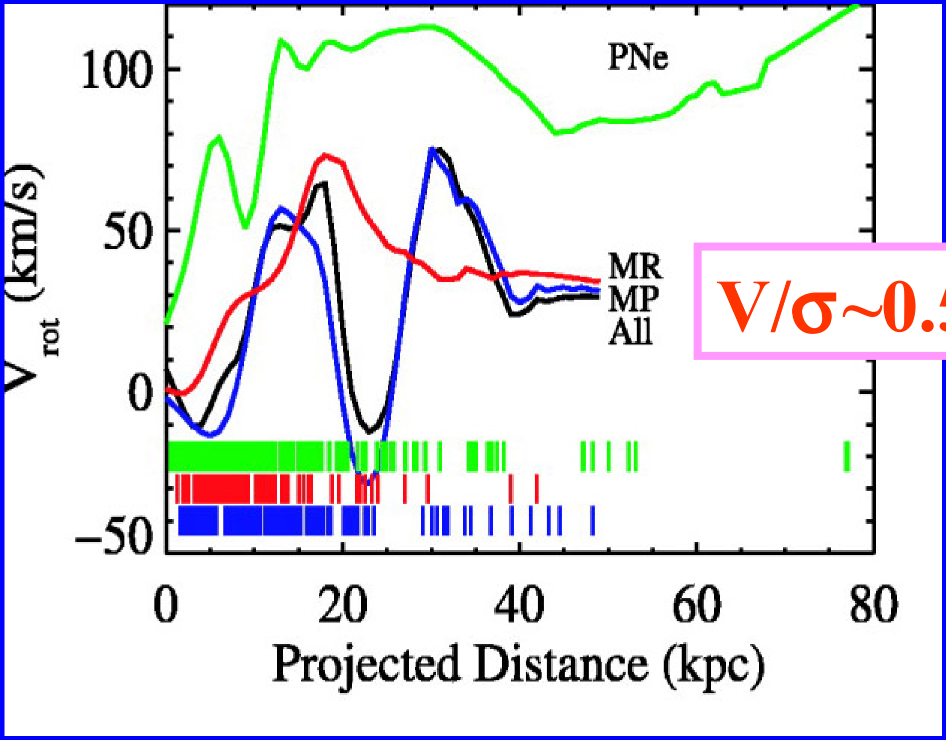
HST ACS image of the Tadpole.



1. What do structures and kinematics of GCSs in E/S0s tell us ?

Diversity in GCS kinematics for E/S0s.

- Rotation in M87 GCS (Kissler-Patig & Gebhardt 1998; Cote et al. 2001).
- Rotation in MPCs of NGC 4472 (Zepf et al. 2000).
- Weak/little rotation in NGC 1399 (Richtler et al. 2004).

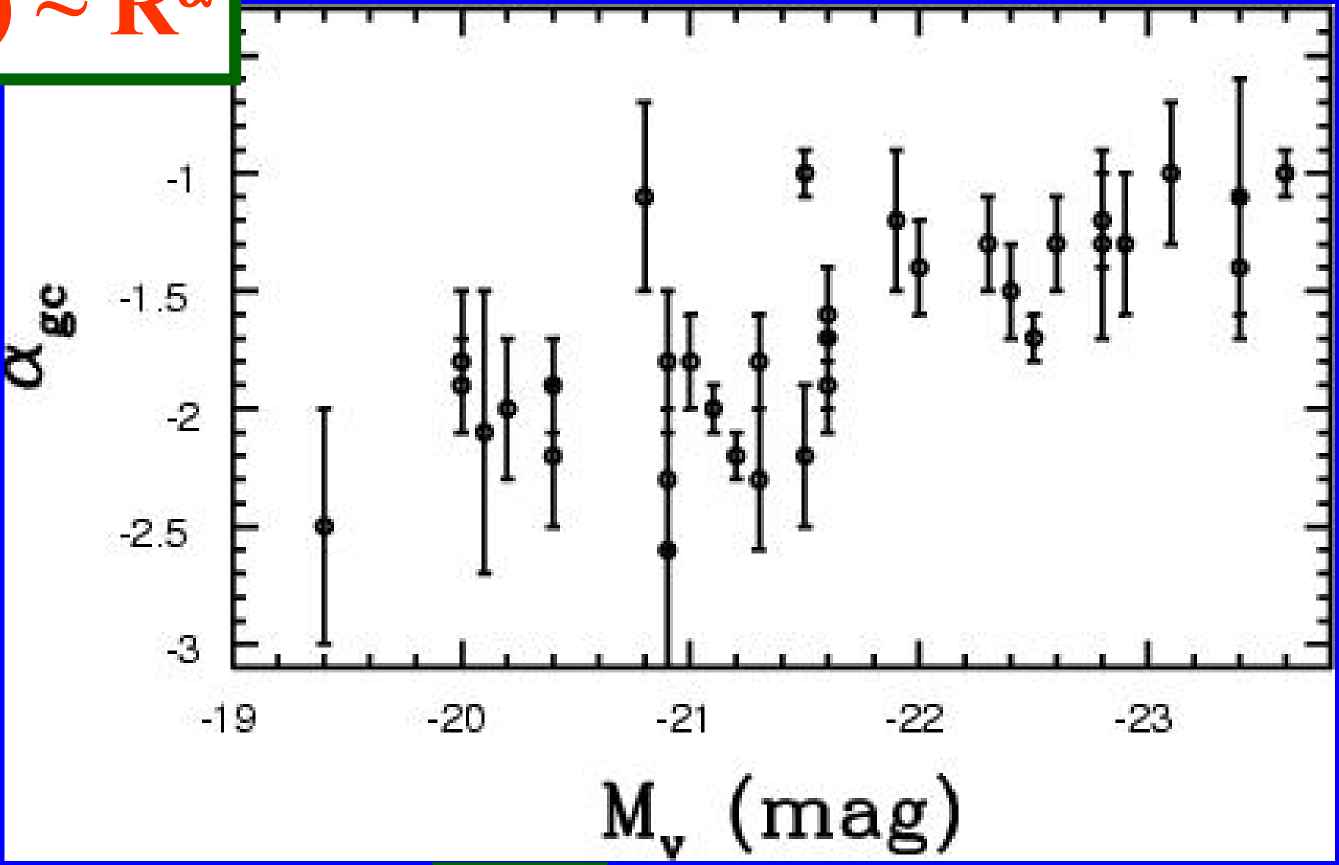


V/σ~0.5

Rotation of NGC 5128 GCS (Peng et al. 2004).

Diversity in GCS density profiles for E/S0.

$\Sigma_{GC}(R) \sim R^{\alpha}$



α

steeper

M_V

brighter

(Ashman & Zepf 1998)

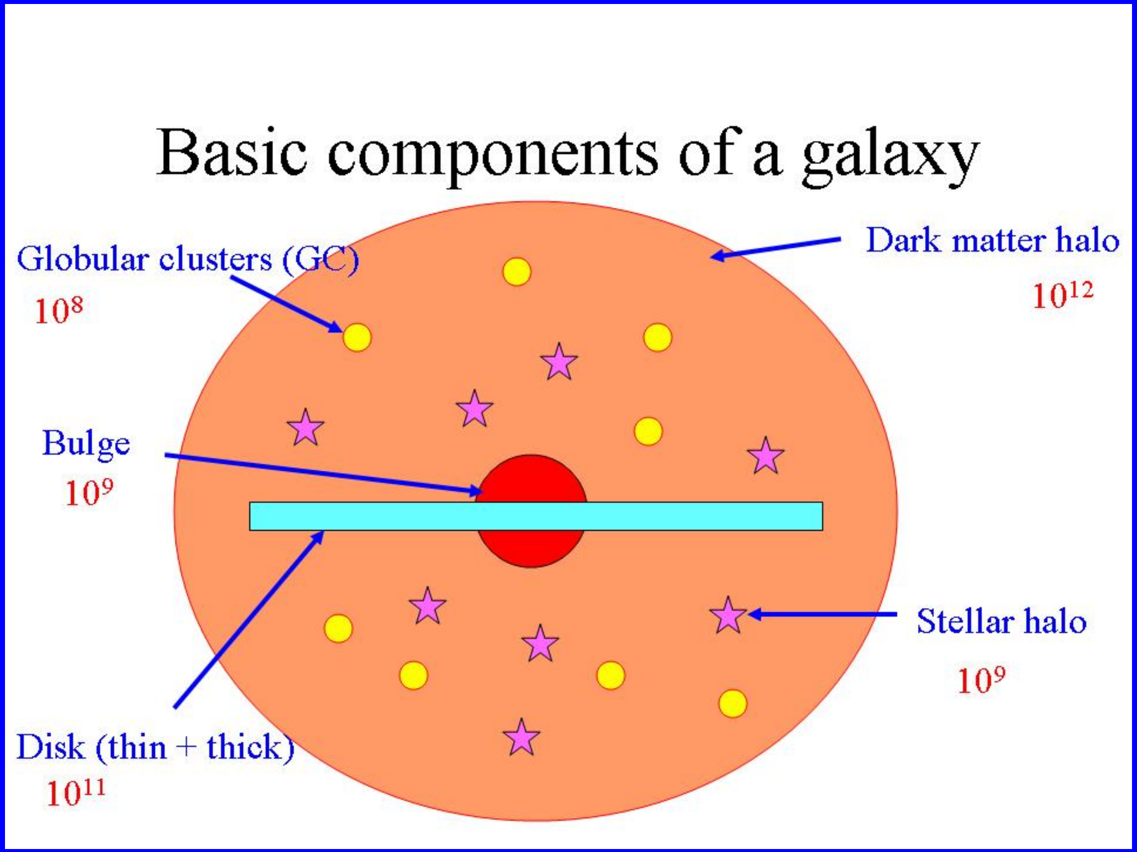
Properties of GCSs after morphological transformation from spirals into E/S0.

Merging ?

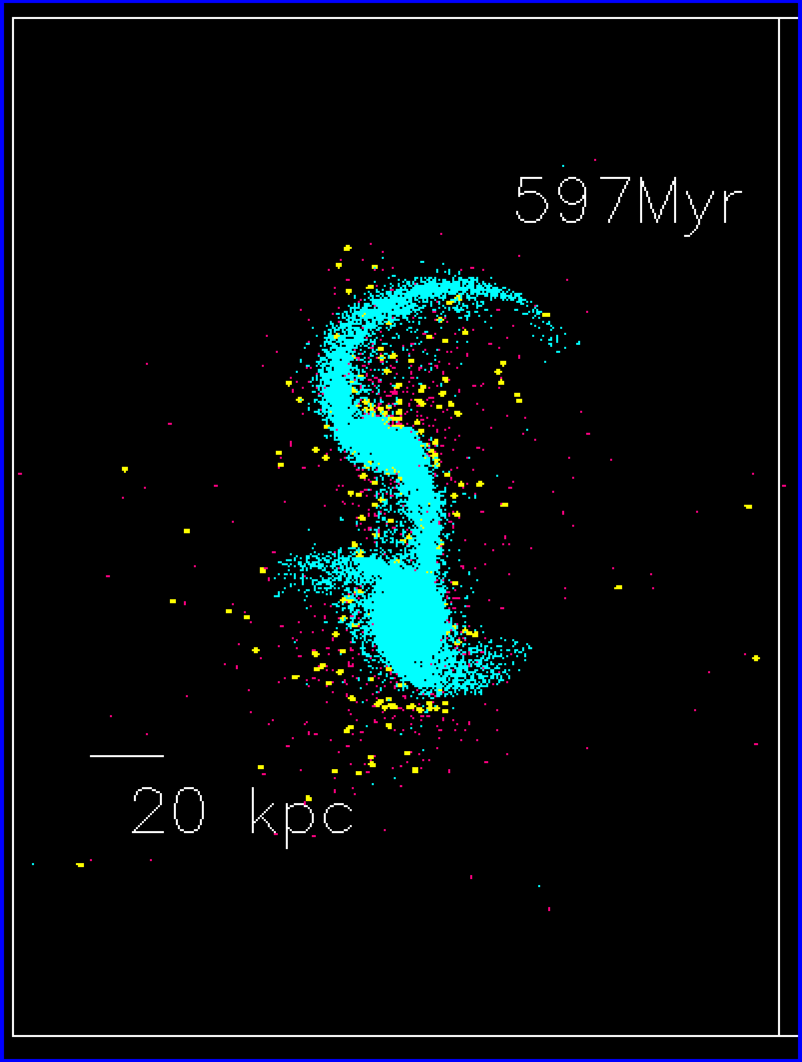
- Dependences of GCS properties and host properties (e.g., shapes and kinematics) one the mass ratios of two merging disks (Hernquist 1993; Bekki et al. 2002, 2005).

Initial properties of GCSs in merger progenitor disk galaxies.

(1) The power-law density profile consistent with that of the Galaxy.
(2) No net rotaion.
(3) No new GC formation (i.e., dissipationless simulations).
(4) MPC (+MRC)



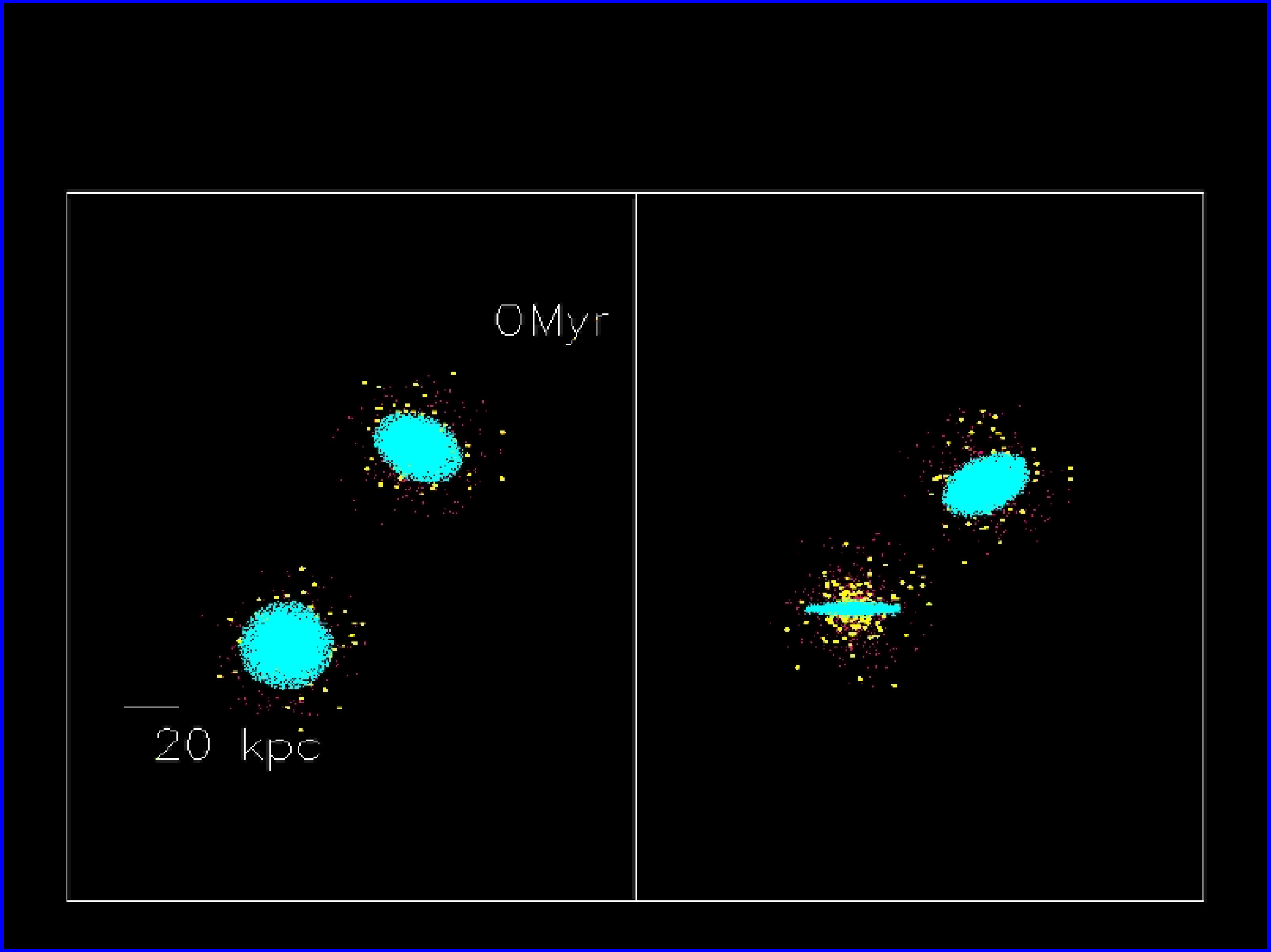
Major mergers and formation of Es (m_2=1).



GCs

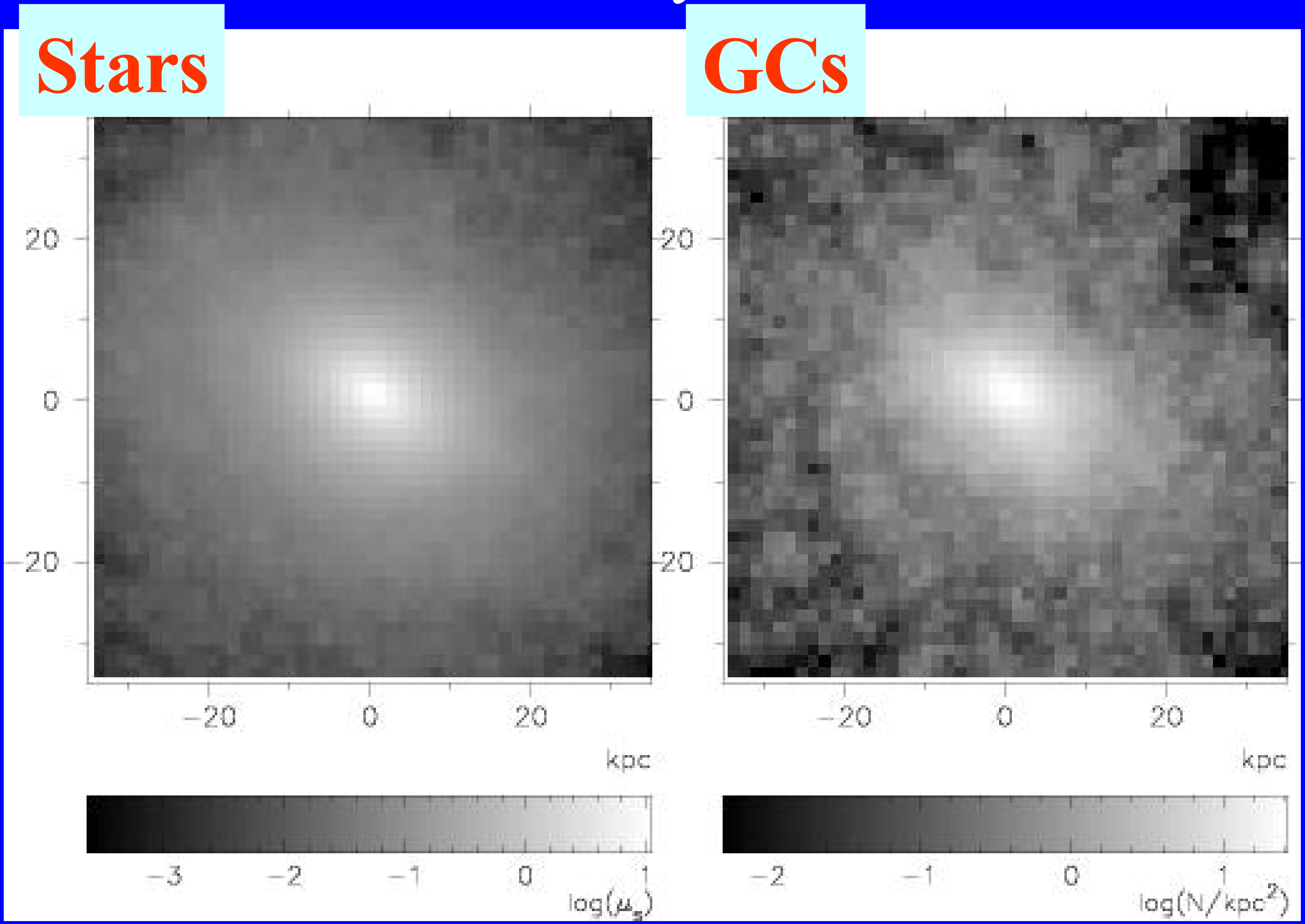
Field stars

Major mergers and E formation (m_2=1.0).



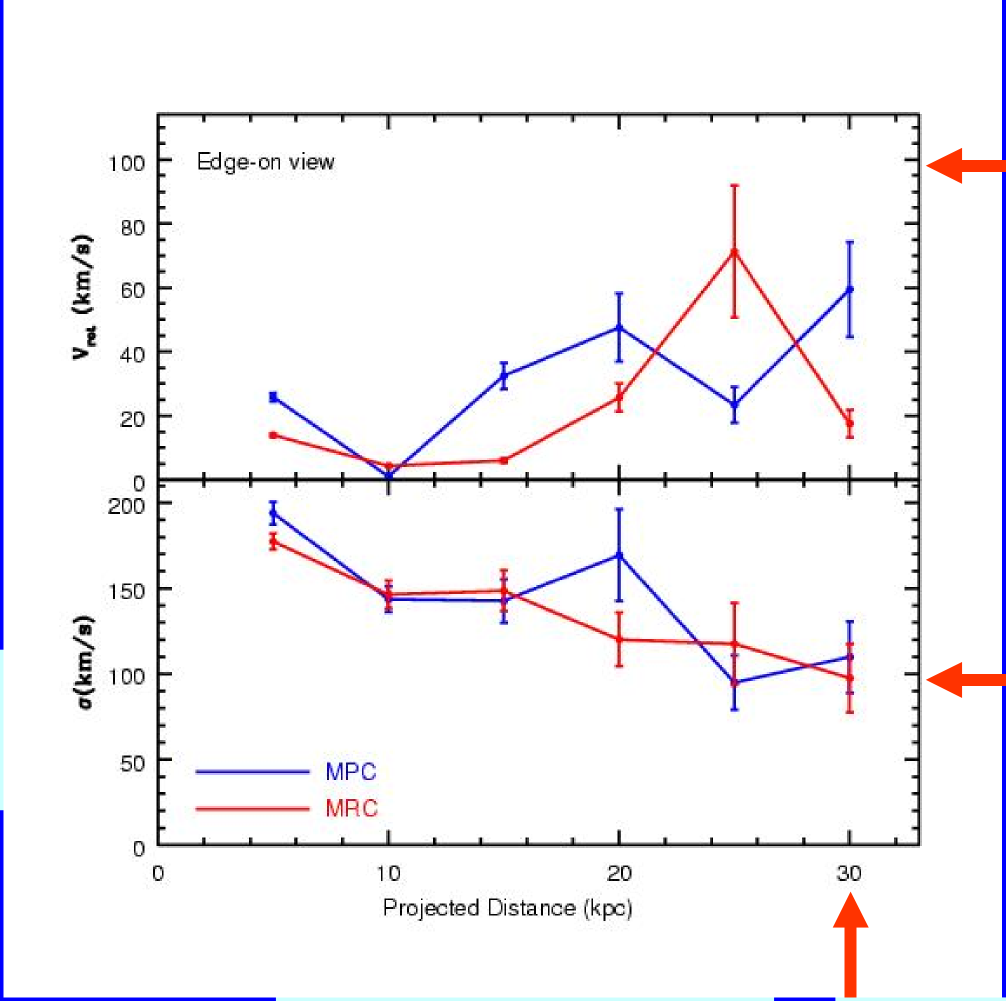
XY **XZ**

Smoothed density distributions.



(Bekki et al. 2005)

Kinematics of GCSs in Es.



V_{rot}

σ

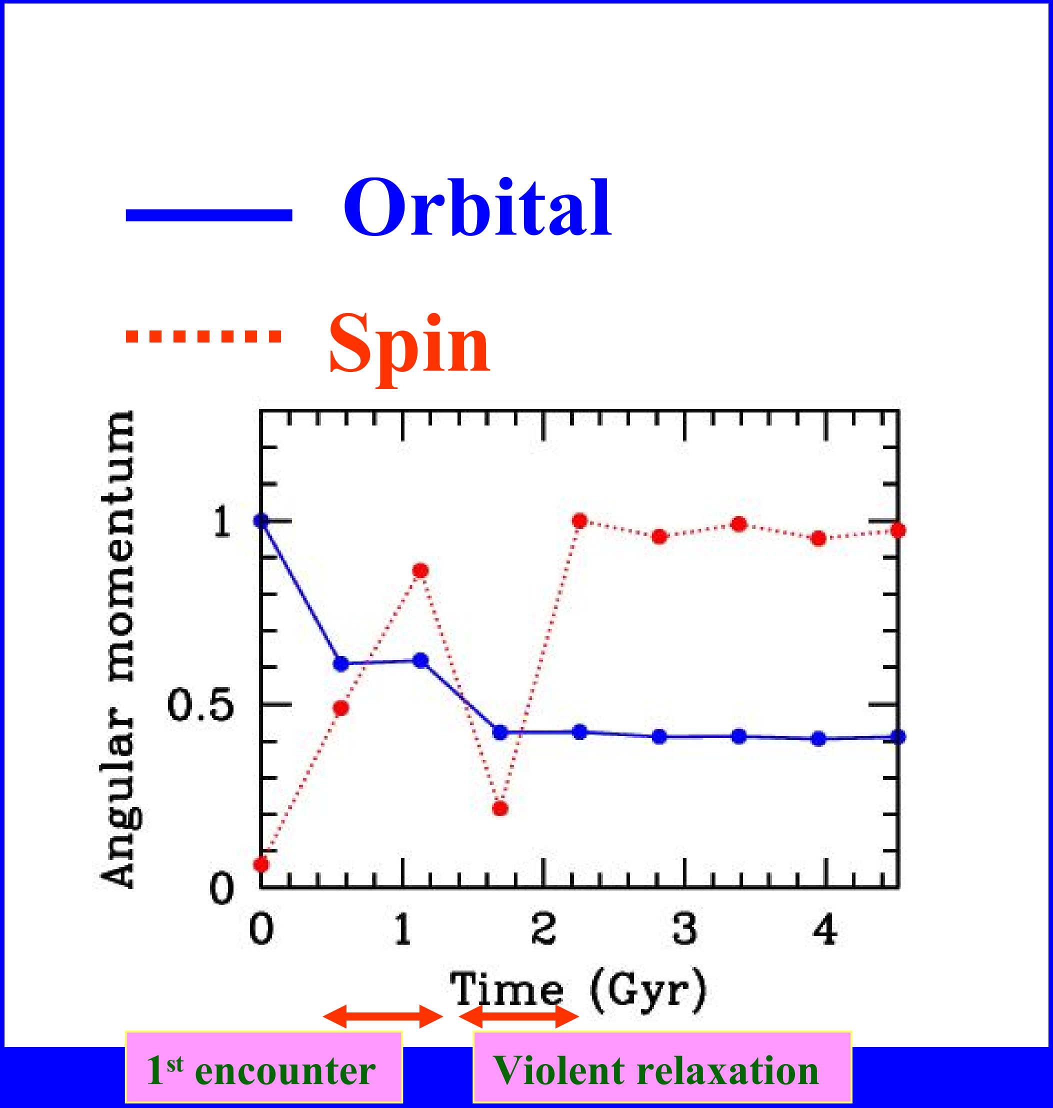
100 km/s

100 km/s

Distance

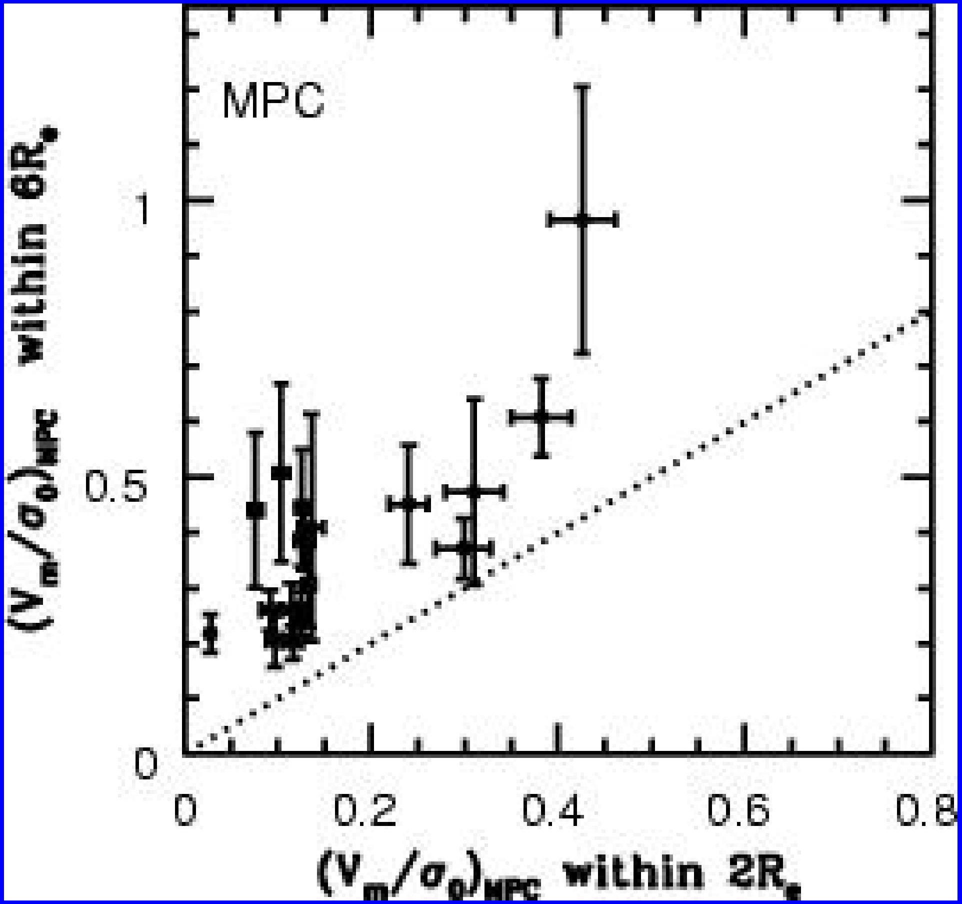
30 kpc

Conversion of orbital angular momentum into intrinsic spin of GCs (MPCs).

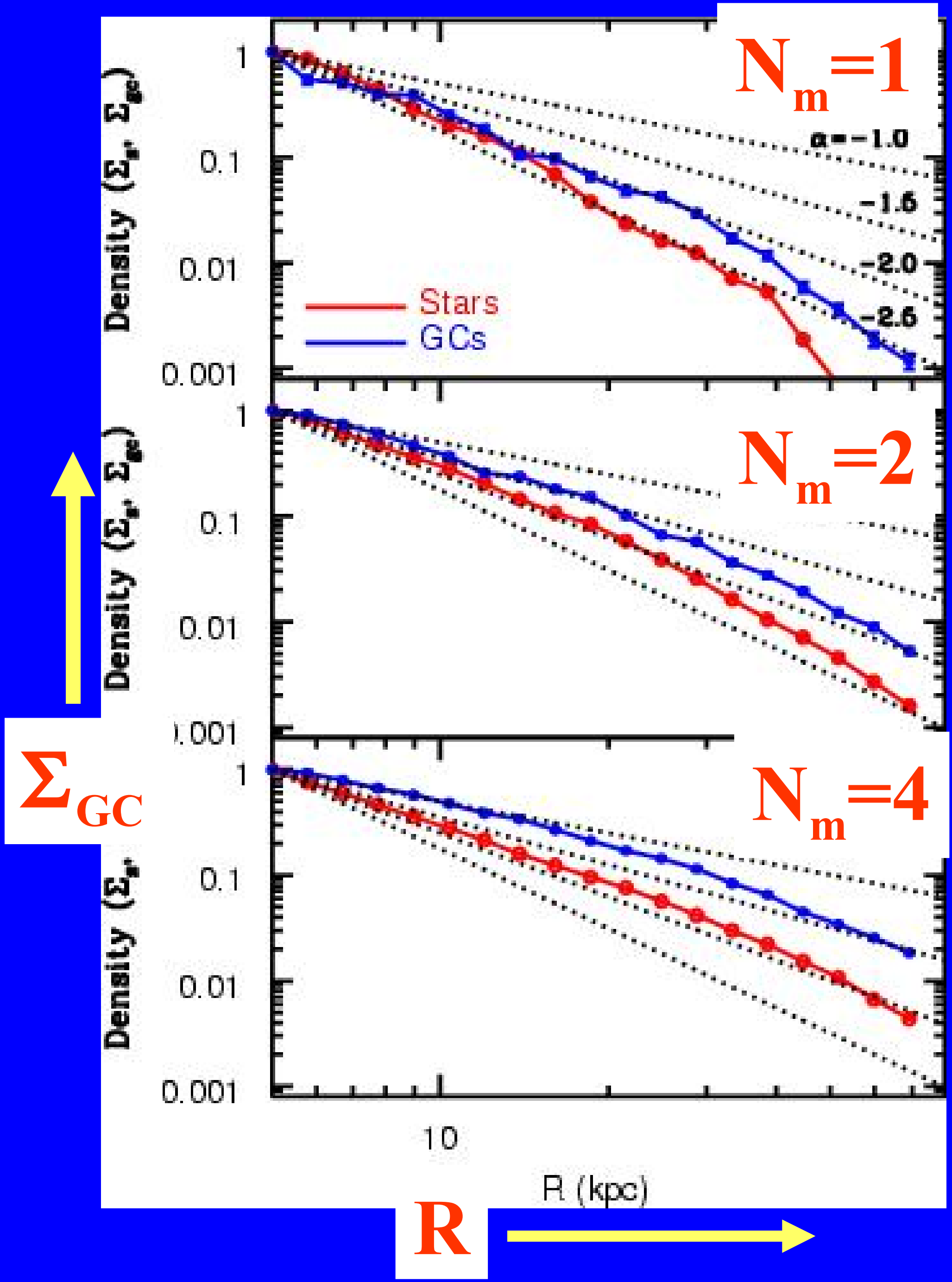


V/σ of GCSs (MPCs) in Es (All models).

V/σ within 6R$_e$



V/σ within 2R$_e$

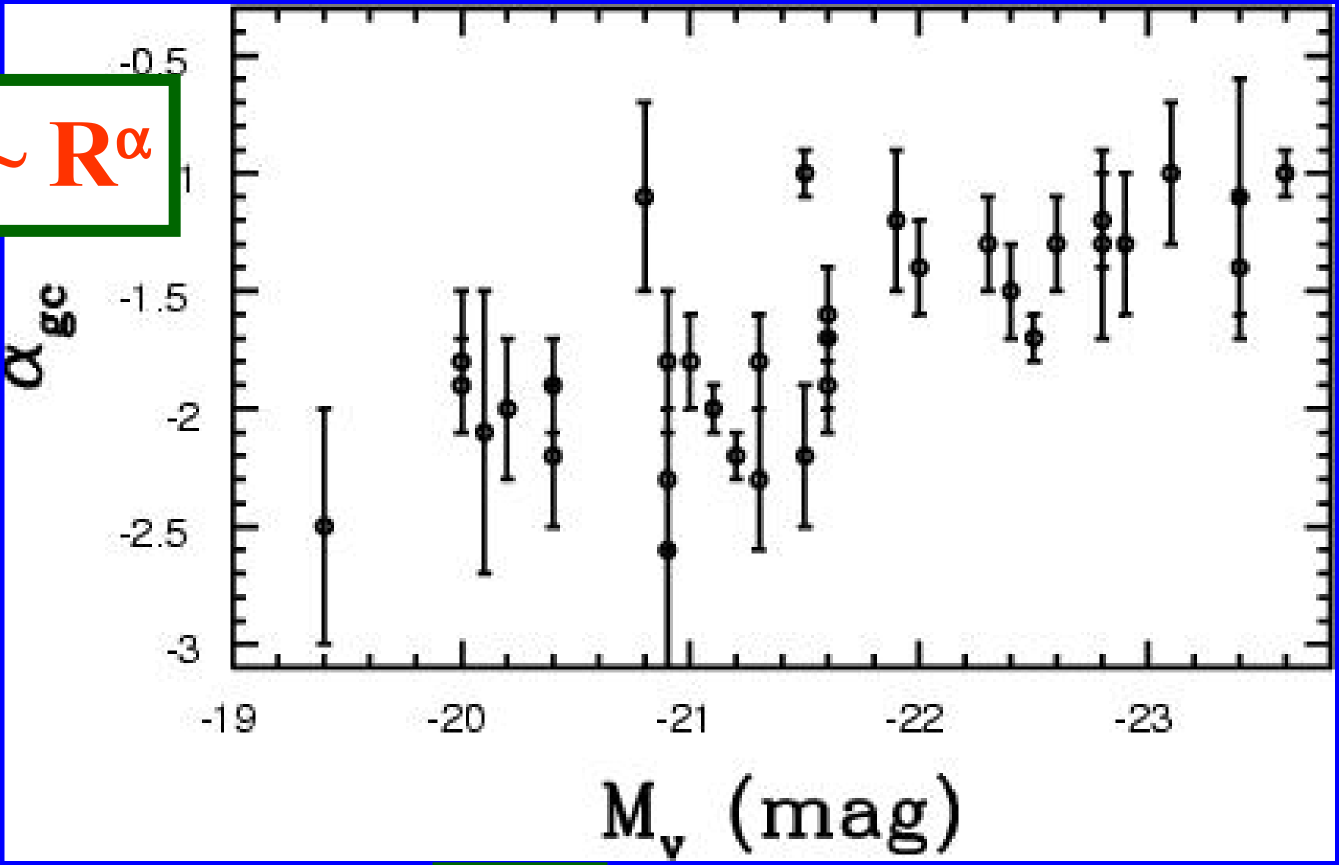


Flattening of GCS density profiles after major merging (Bekki & Forbes 2006).

α=-2.5 (initial) → -2.0 → -1.5→ ~ -1 (Final N_m=4).

More luminous galaxies have experienced more major merger events ?

$\Sigma_{GC}(R) \sim R^{\alpha}$



α

steeper

M_V

brighter

(Ashman & Zepf 1998)

GCS structures and kinematics: Other important results.

- Structural and kinematical differences in GCSs between E and flattened E/S0s.
- Alignment of major-axis of a GCS with that of the dark matter halo.
- GCSs (MPCs) can be better mass-estimators than PNe, in particular, face-on E/S0s.

Imprint 1

Kinematics and structures of GCSs in E/S0s can tell us about angular momentum redistribution during their last minor/major merger events.

2. What do age distributions of GCs in (disk) galaxies tell us ?

Observational evidences of triggered GC formation in interaction/merging galaxies.

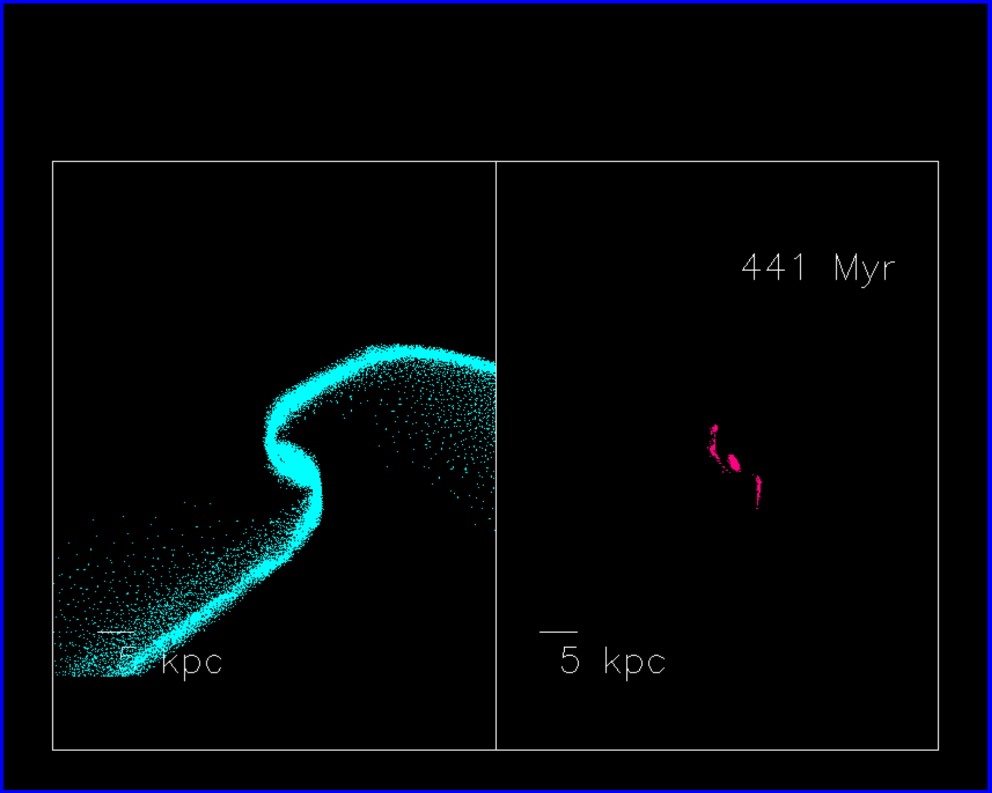
Merging (The Antenna). **Interaction (HCG).**

Physical conditions of ISM (gas clouds) required for GC formation.

- High-density, high-pressure gas for cloud collapse with high star formation efficiencies: (e.g., Harris & Pudritz 1994; Elmegreen & Efremov 1997;)
- High-speed cloud-cloud collision with small impact parameters (e.g., Fujimoto & Kumai. 1997)

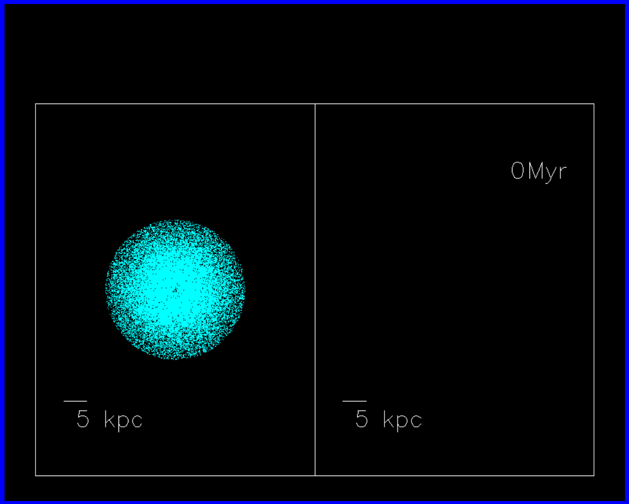
Are these conditions satisfied in interaction/merging galaxies ?

Large-scale (kpc scale) tidal disturbance in galaxy interaction and merging and GC formation (e.g., Bekki et al. 2002; Li et al. 2005).



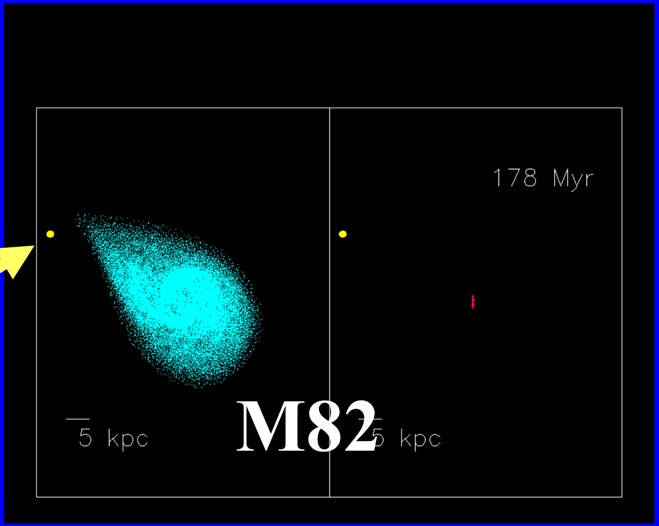
All Gas **Gas with $P > 10^5\ k_B$**

(1) Isolated late-type, low-mass, barred galaxy.

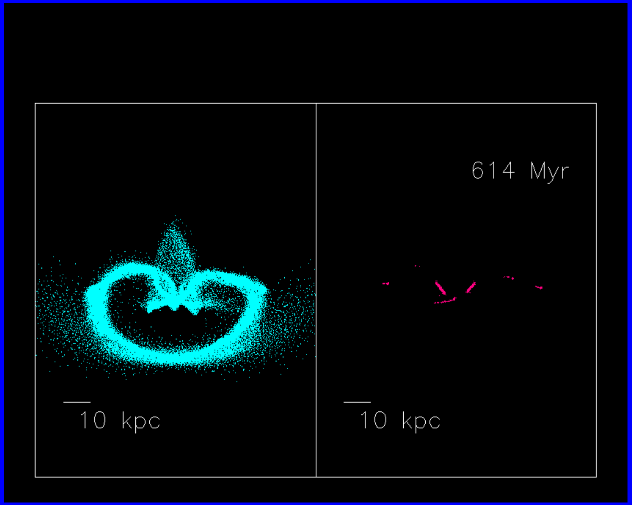


(2) Interacting galaxies (M82-M81).

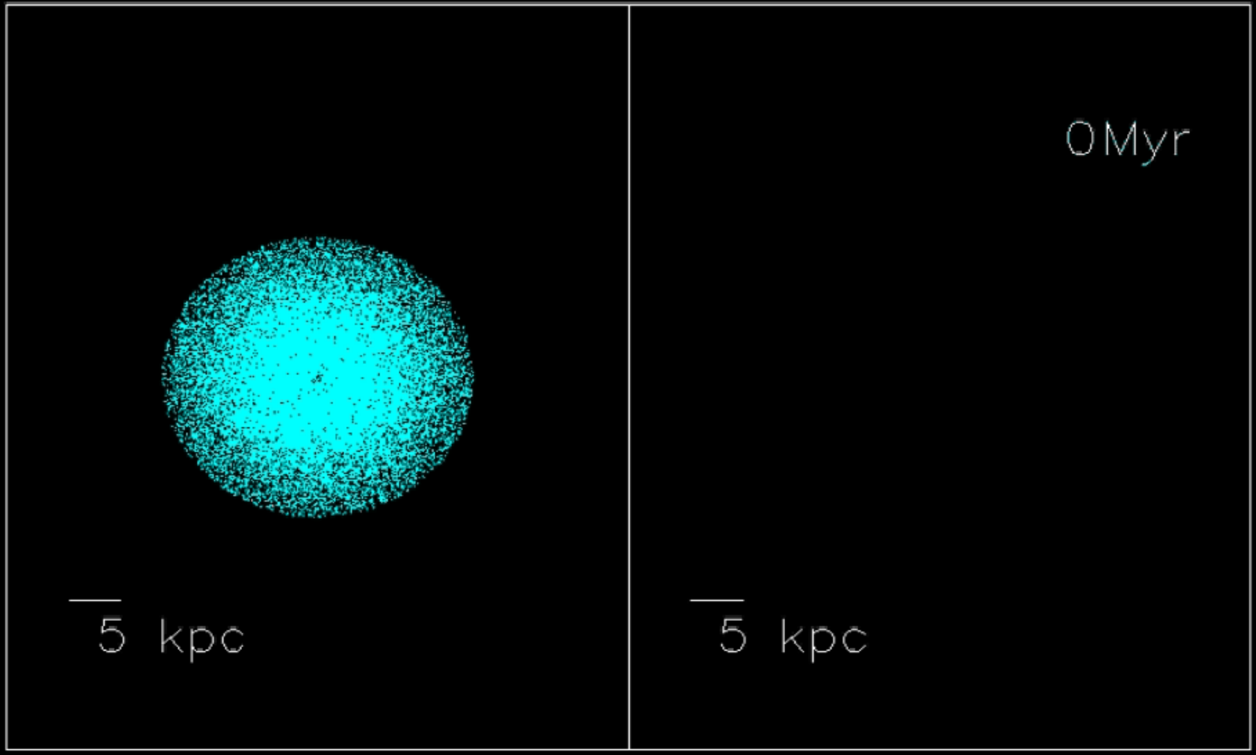
M81

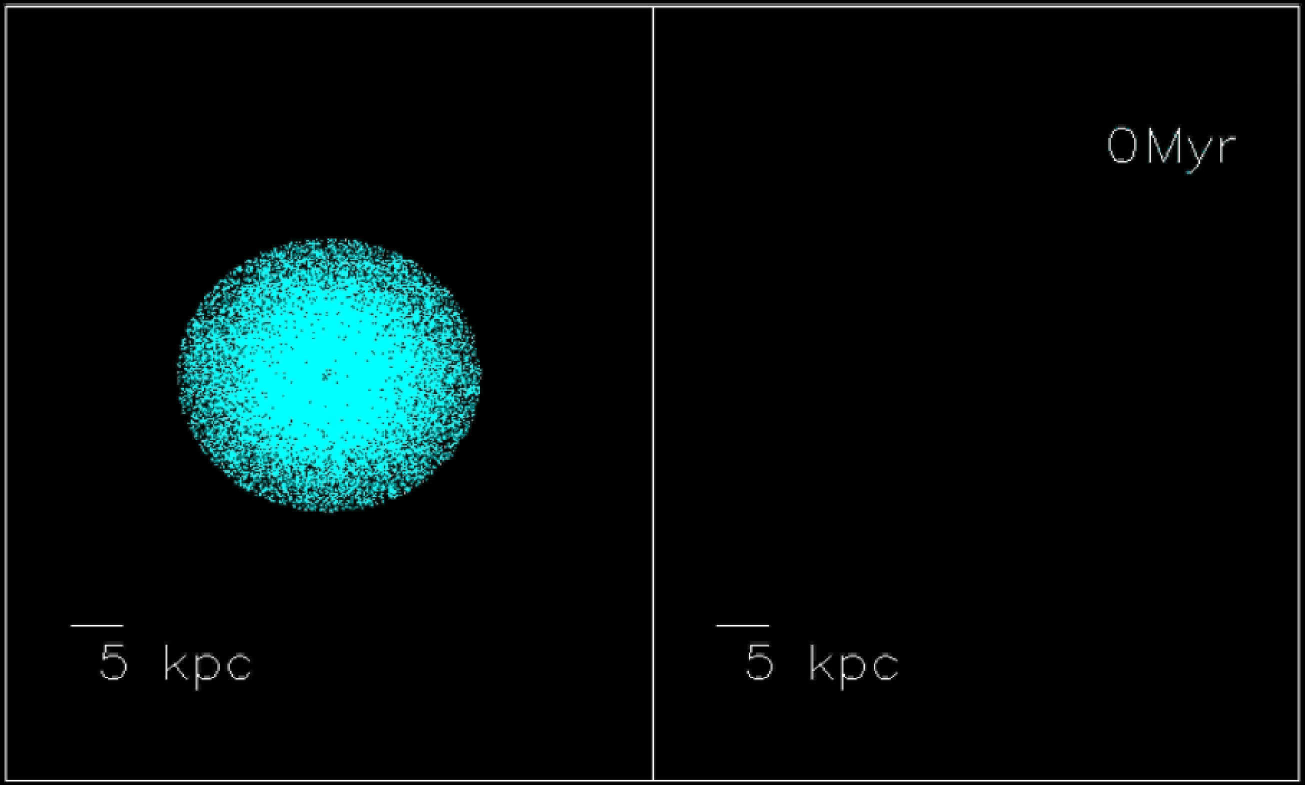


(3) Mergers (The Antenna)



Chemodynamics with new GRAPE SPH (Bekki et al. 2006).

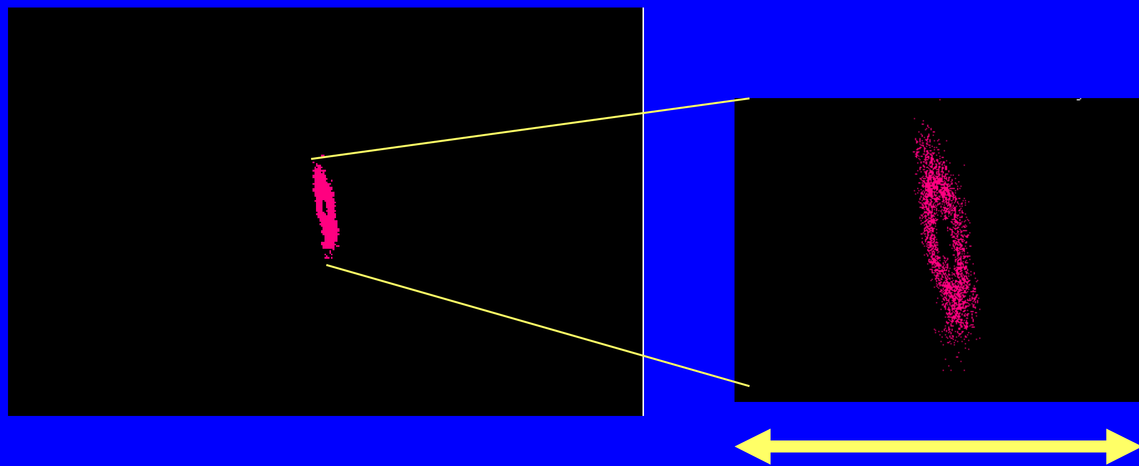

0Myr
5 kpc
5 kpc



0Myr
5 kpc
5 kpc

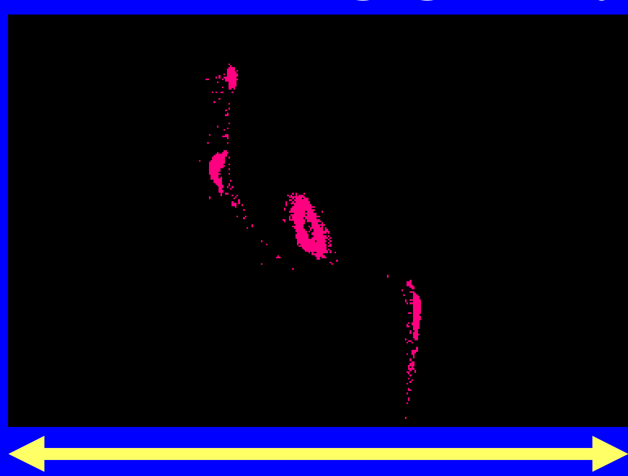
GC/SSC formation sites

(1) Isolated disk



5 kpc

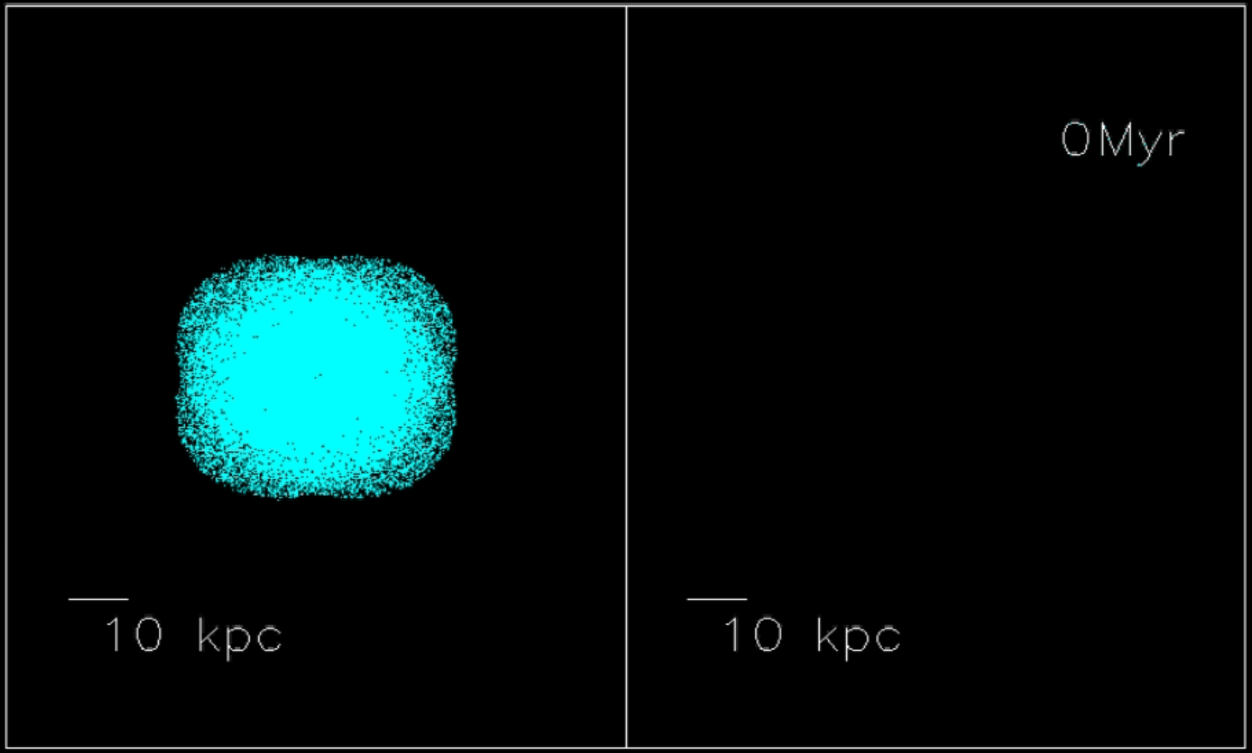
(2) Interacting galaxy



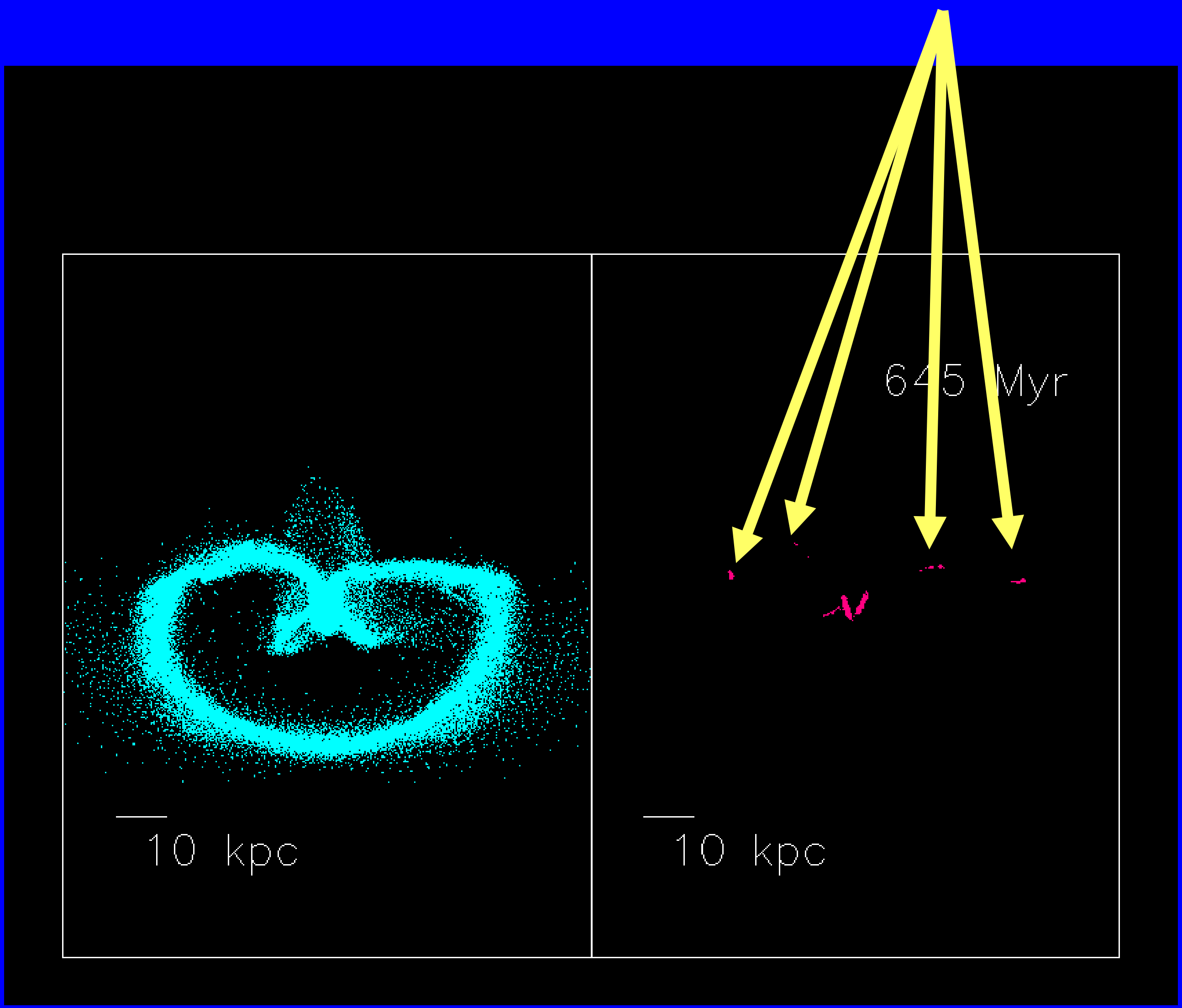
20 kpc

(1) In nuclear gas rings.

(2) In tidal tails + nuclear gas rings.


0Myr
10 kpc
10 kpc

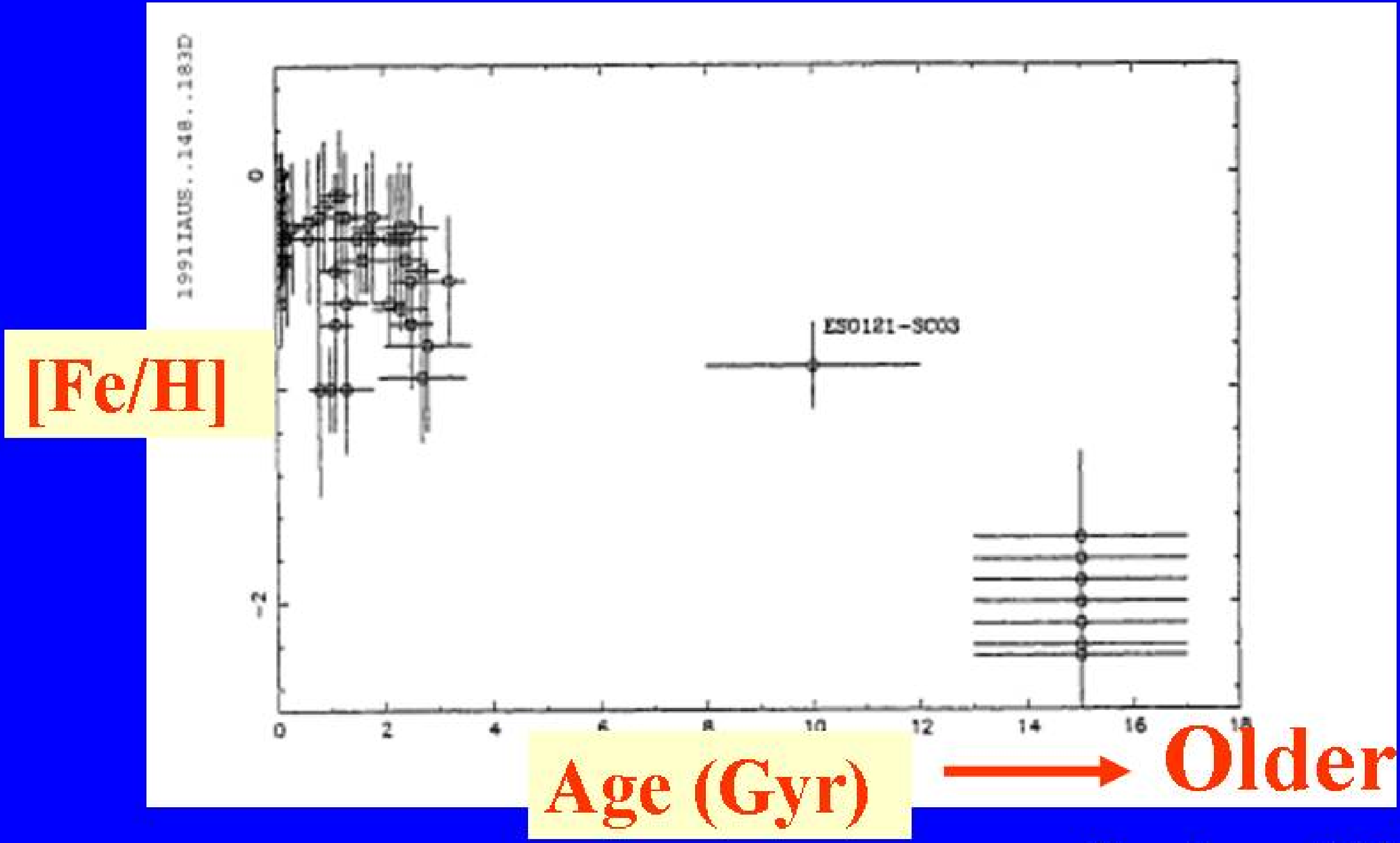
GC formation in tidal tails.



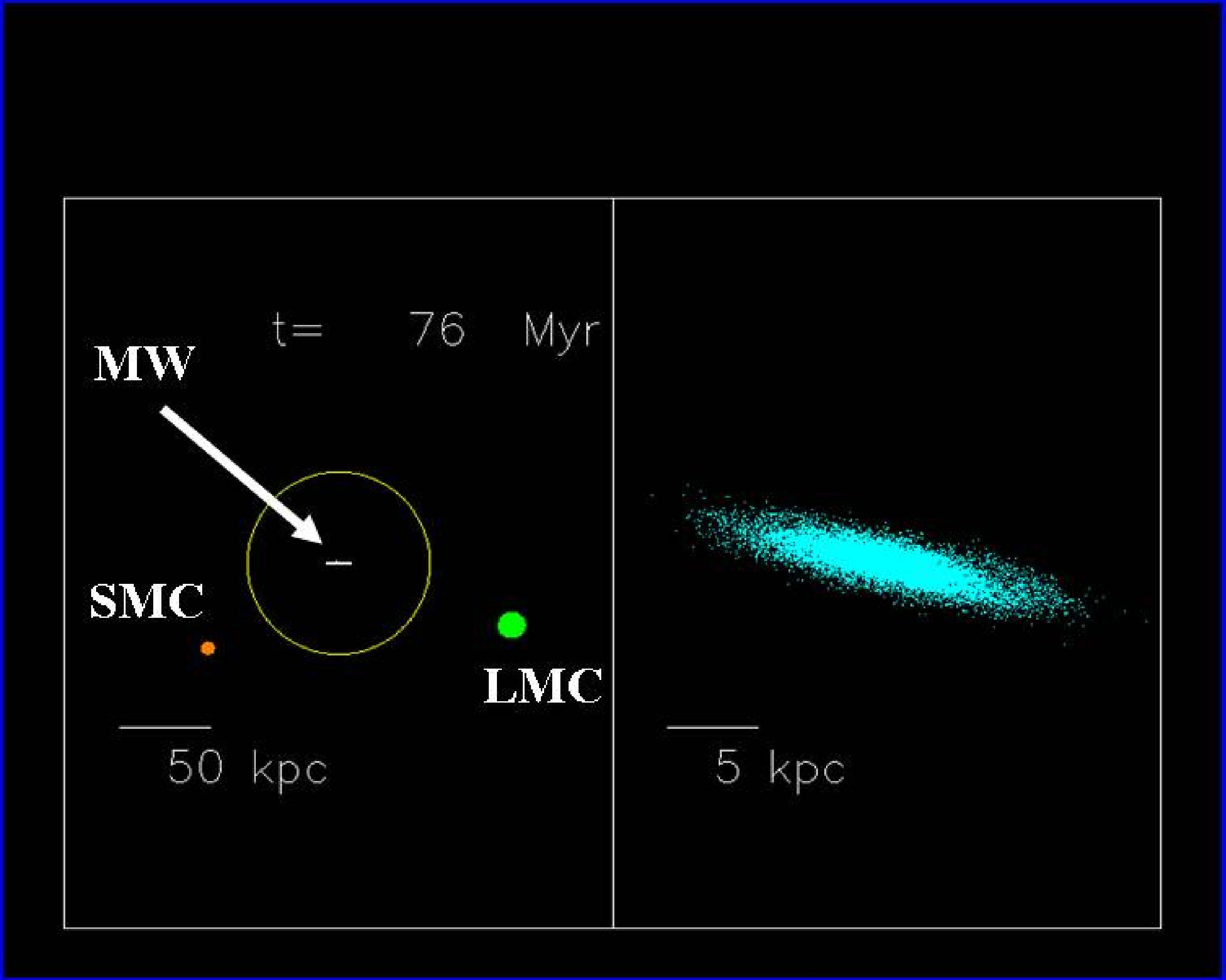
Formation of new, metal-rich GCs and………

(1) origin of the GC color bimodality in elliptical galaxies (e.g., Ashman & Zepf 1992),
(2) cluster formation rate as a function of age in M82 disk (e.g., de Grijs et al. 2001),
(3) origin of ``the age gap'' problem in the LMC's GCS (Bekki et al. 2004).

What is the age gap of GCs?



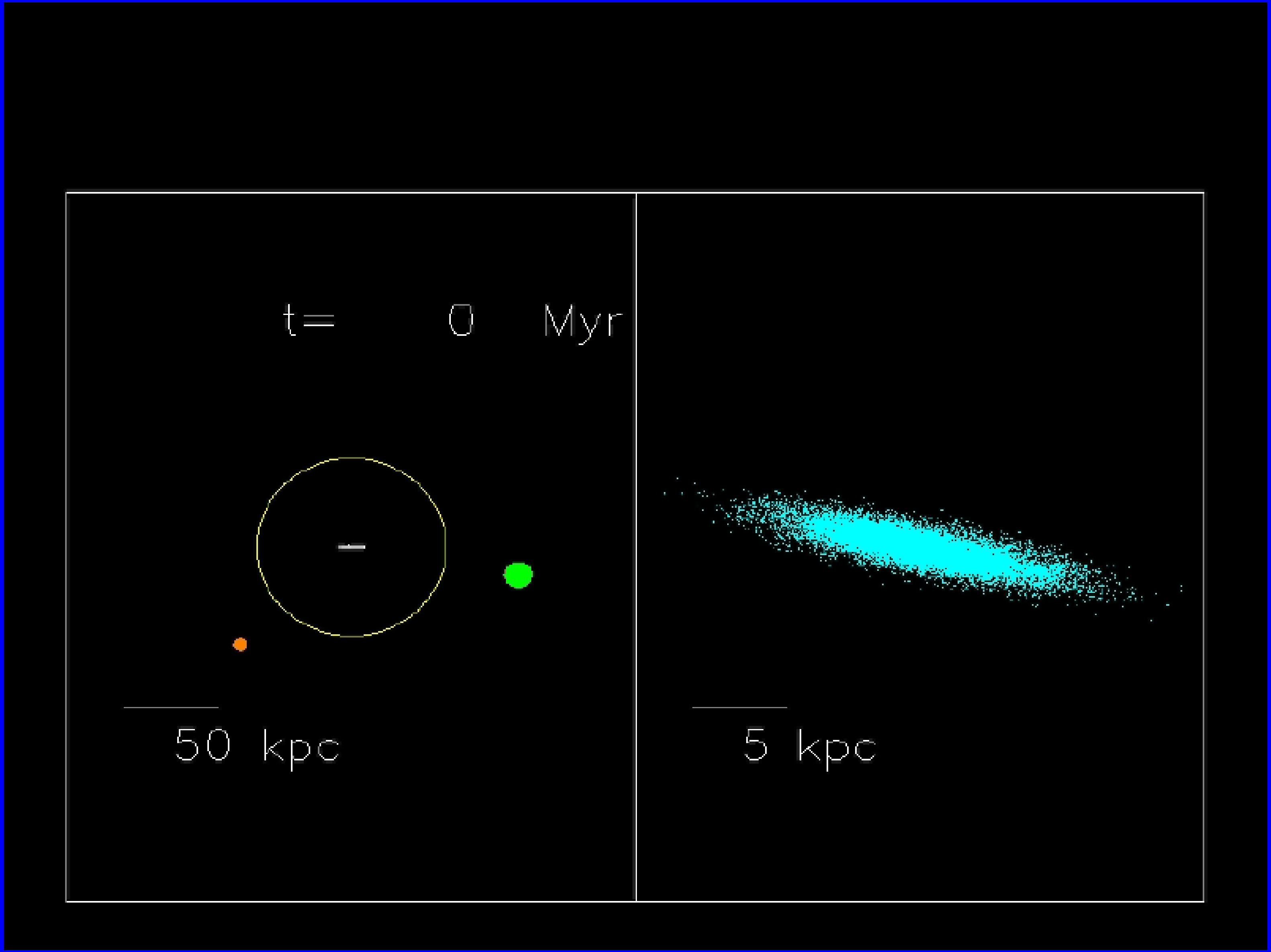
(Da Costa 1991)



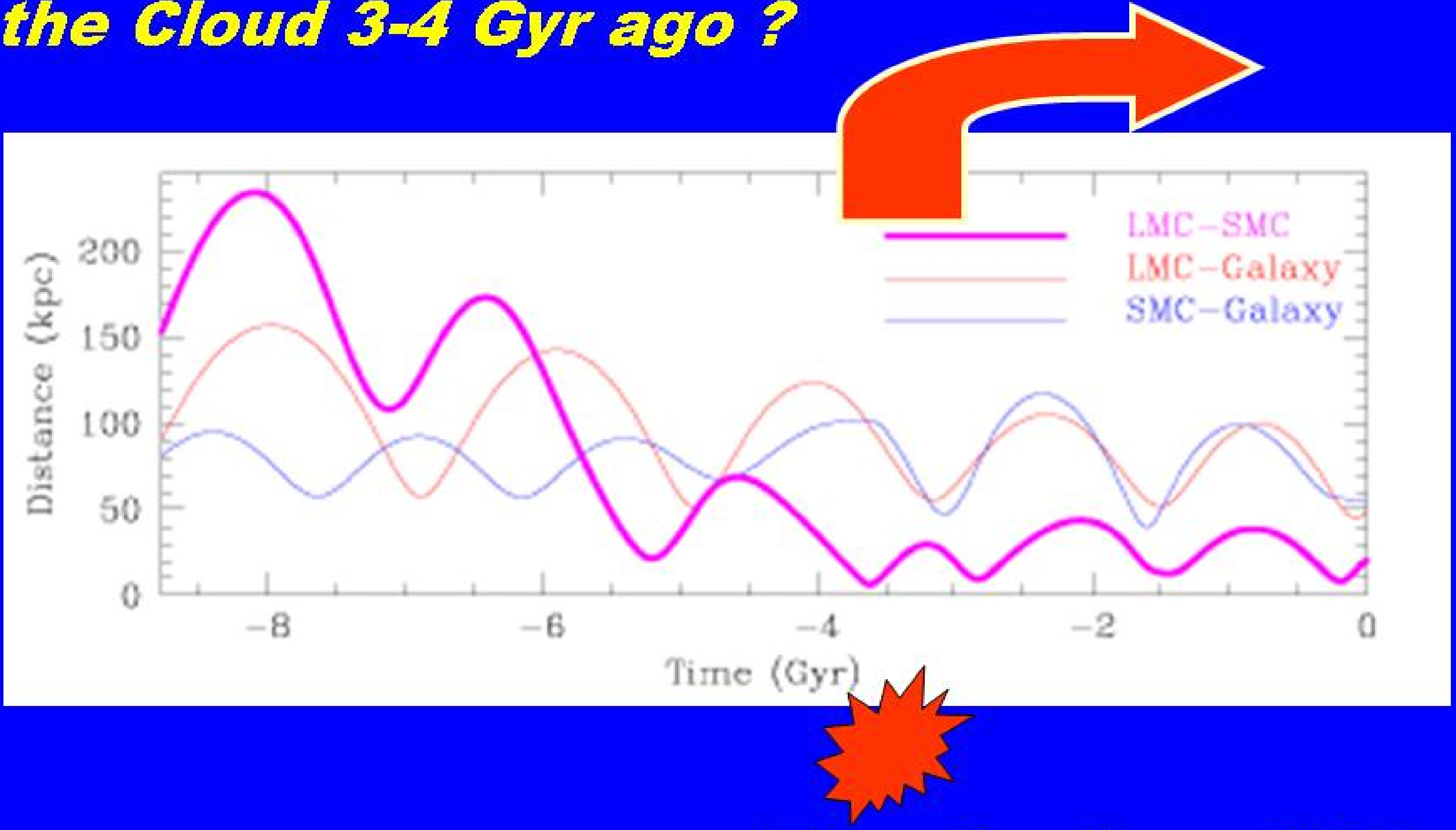
Larger scale

Smaller scale

LMC-SMC-Galaxy interaction.



Dynamical coupling of the Cloud 3-4 Gyr ago ?



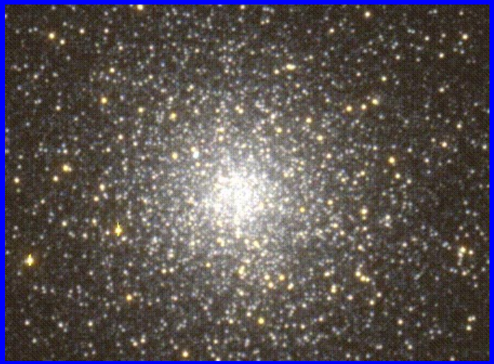
Reactivation of GC formation ?

Imprint 2

Age distributions of (disk) GCs in disk galaxies can be ``fossil records'' of their past interaction (merging) histories.

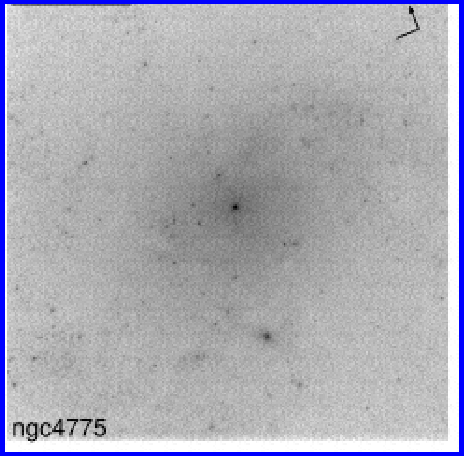
3. What do dynamical and chemical properties of very massive star clusters tell us ?

Origin of very massive star clusters ``VMSC''.

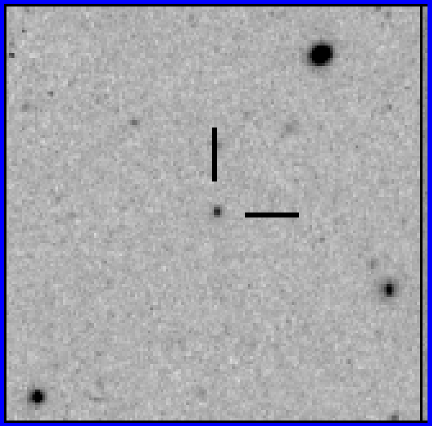


``Normal'' GC (47 Tuc)

(1) ω Cen

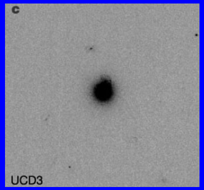


(2) Nuclear star cluster (Boker et al. 2002)



(3) Ultra-compact dwarfs (UCDs)

Cluster masses and their physical properties.



``normal GCs''

ω Cen

UCDs

Mass

10^5 | 10^6 | 10^7 | M_{sun}

Abundance Spread

Lighter elements (C, N, O… etc)

Heavy element (Fe, Ca.... etc)

?

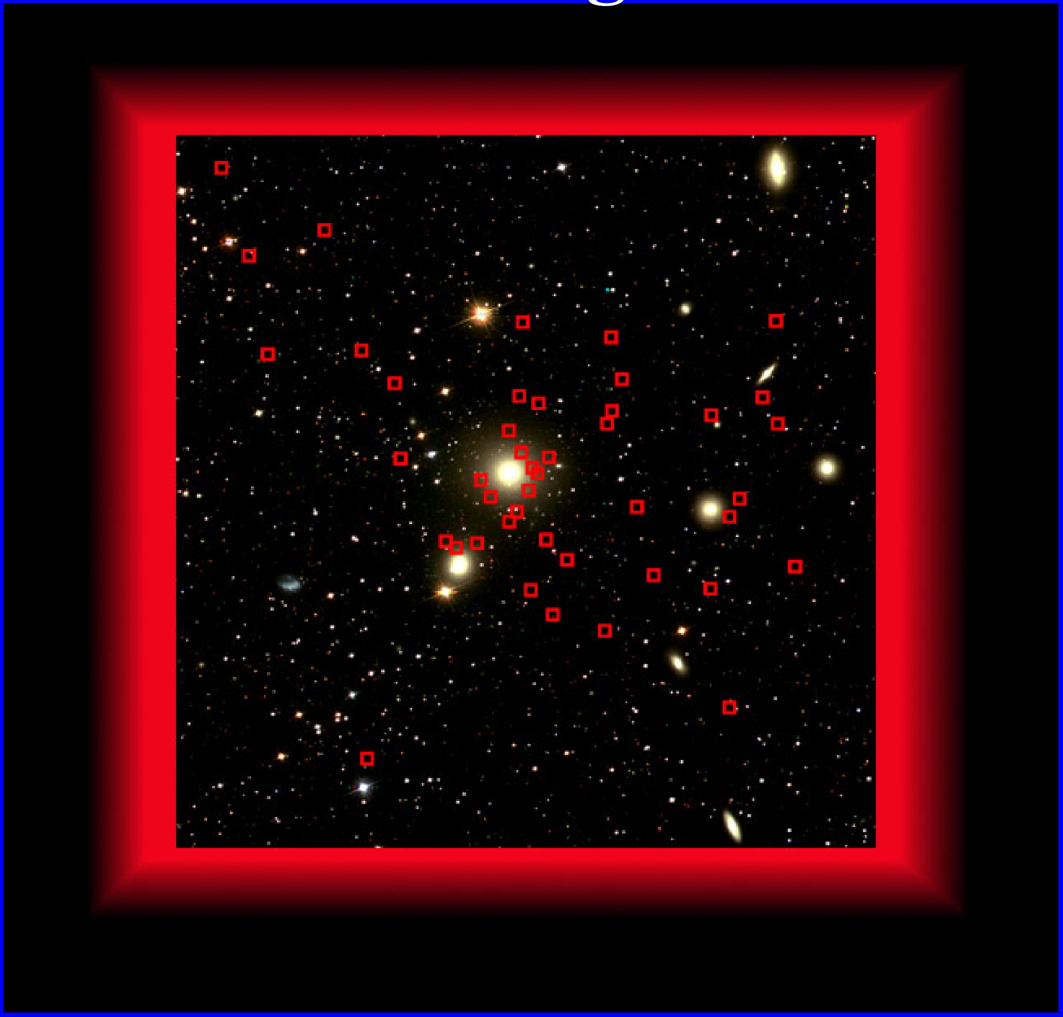
Shape

Almost spherical

More flattened

?

Ultra-compact dwarfs (UCDs) as dominant galaxy population in clusters of galaxies ?



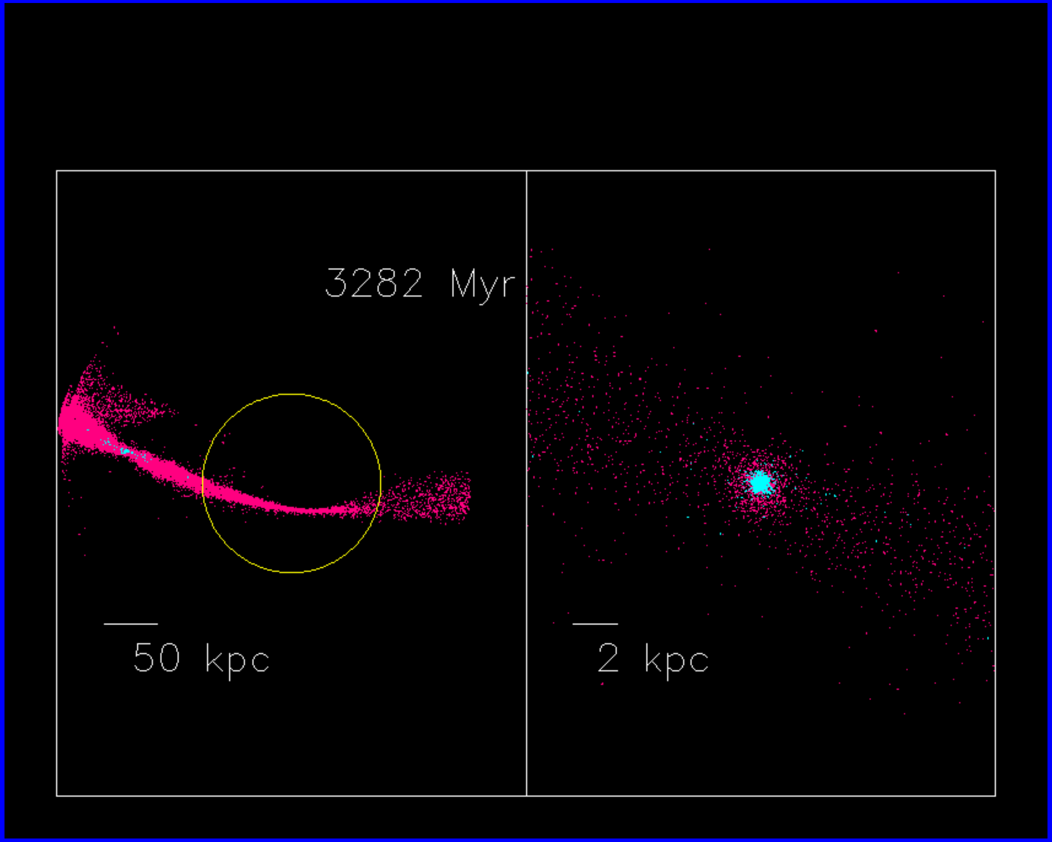
(Karick et al. 2003)

Two questions:

(1) Transformation from dE,N/dI,Ns into VMSCs due to dwarf destruction by galactic/cluster tidal fields ? (e.g., Bassino et al. 1994; Bekki et al. 2001).

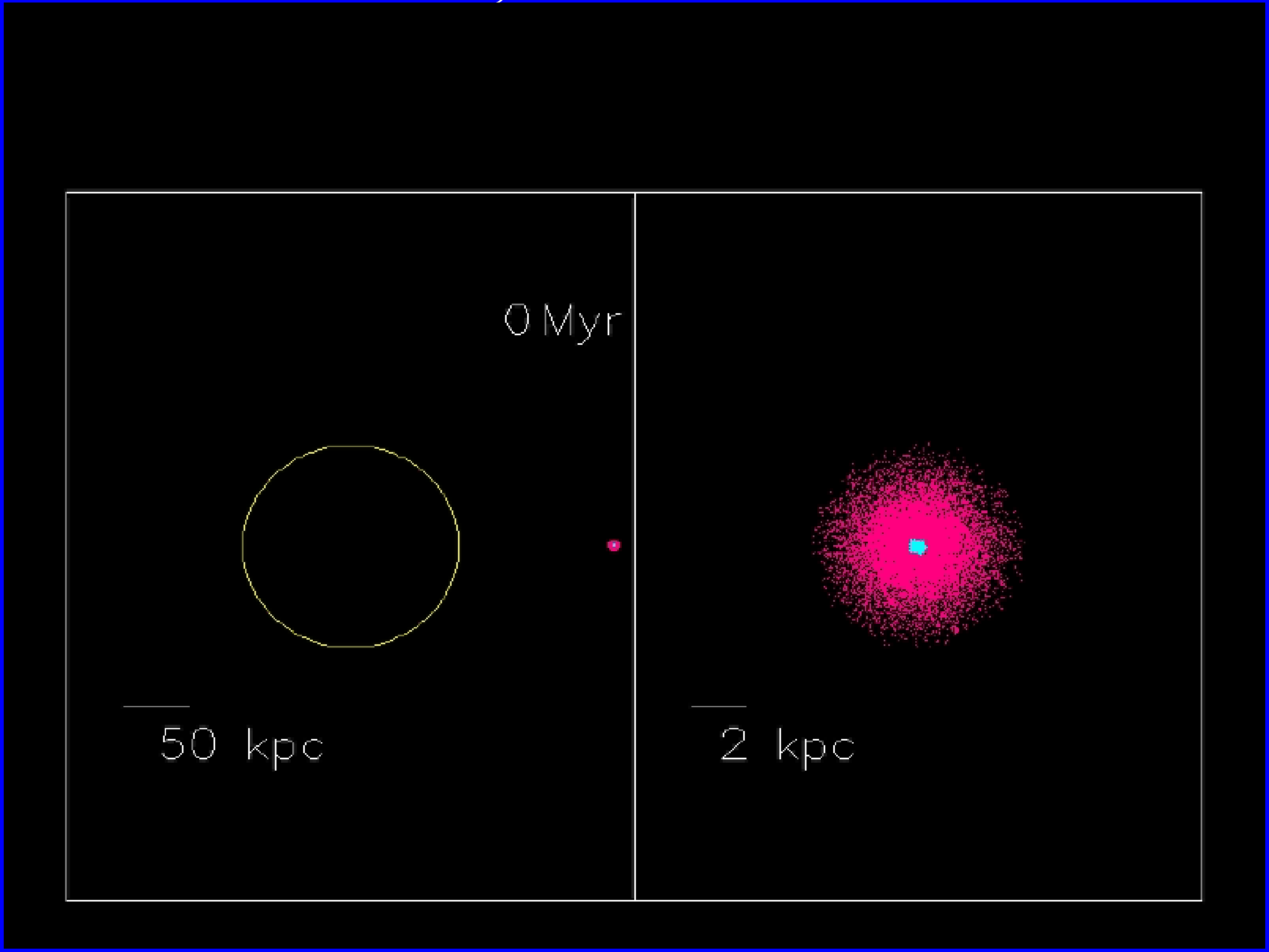
(2) What is the relationship between ``normal'' GCs and VMSC ? All GCs were previously nuclei of nucleated galaxies ? (e.g., Zinnecker et al. 1988; Freeman 1993).

Transformation from dE,Ns into UCDs in the Fornax cluster of galaxies.



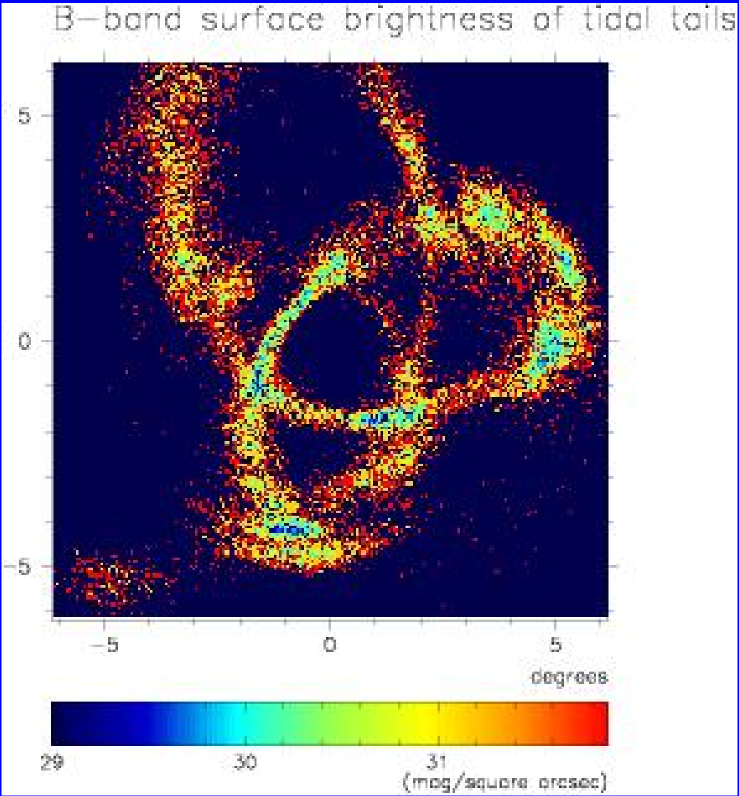
Essentially the same processes for the formation of ω Cen and G1 ! (e.g., Bekki & Chiba 2004)

``Galaxy threshing'': Transformation from dE,Ns into UCDs.



If VMSCs are formed from nucleated galaxies, then….

- Structural, kinematical, and chemical properties of stellar halo substructures can tell us about physical properties of their hosts.
- Properties of VMSCs can tell us about formation processes of stellar galactic nuclei in galaxies at high-z.



Tidal streams from destruction of G1's host dwarf (Bekki & Chiba 2004)

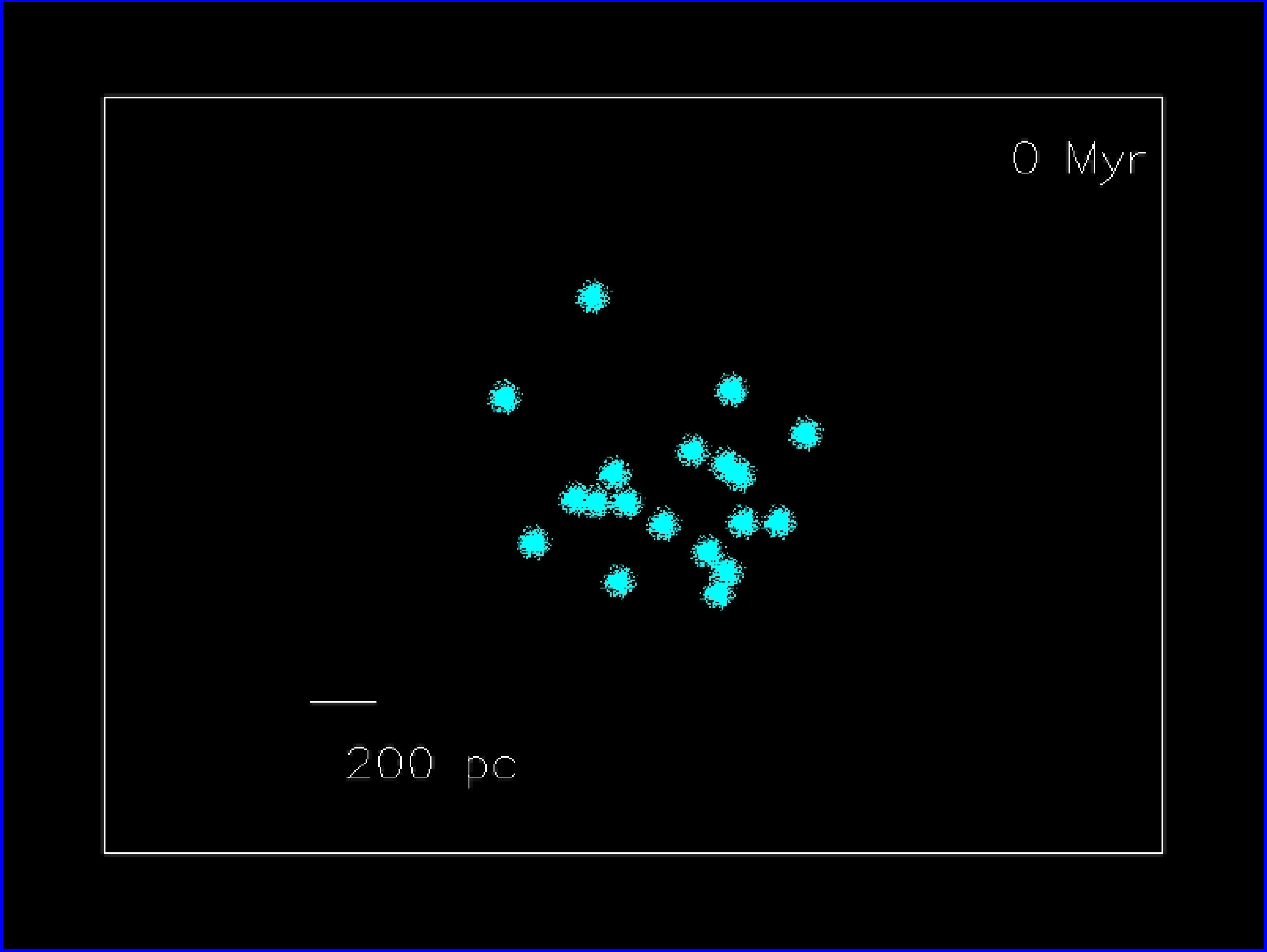
Physical properties of VMSCs as fossil records of stellar nucleus formation in (defunct) dwarfs ?

How do VMSC form ?

(1) Merging of smaller star clusters (e.g., Tremaine e al. 1975; Oh & Lin 2000; Felhauer & Kroupa 2002).

(2) Dissipative transfer of gas and the subsequent star formation in the central regions (e.g., Milosavljevic 2004; Bekki et al. 2006)

Nucleus formation from star cluster merging in dwarfs (Bekki et al. 2003;2004)



Predicted properties of VMSCs.

(1) Rotational kinematics of the remnants of dissipationless cluster mergers (e.g., Makino et al. 1991).

(2) More flattened shapes, and scaling-relations different from those of normal GCs (e.g., Bekki et al. 2004).

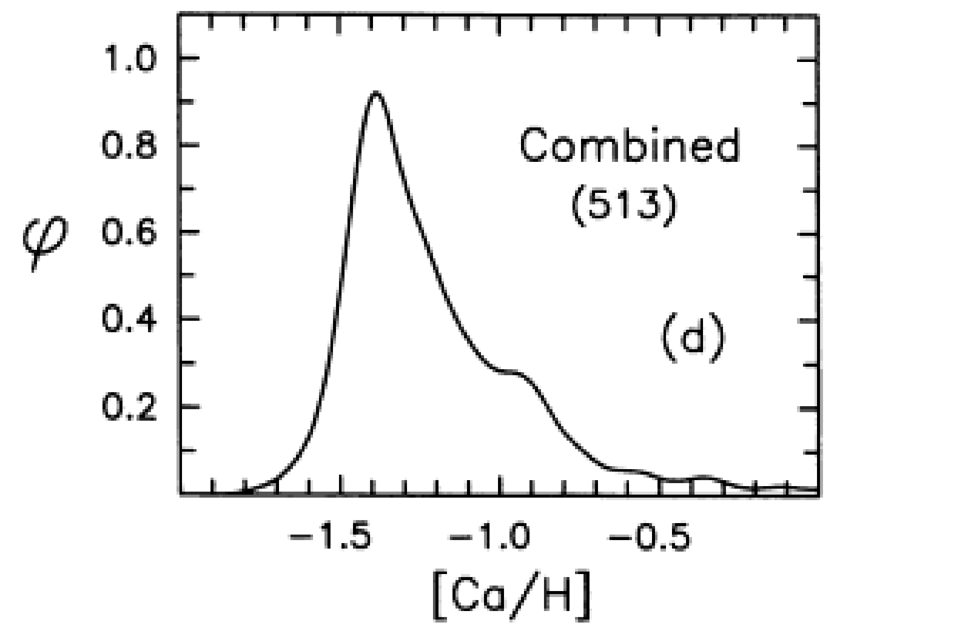
(3) Multiple stellar populations (wider age/metallicity spread).

If VMSCs are formed in central regions of their hosts, their properties tell us about dynamical and star-formation histories of their nuclear regions.

For example…….

The fattened shape of G1 could be due to merging of GC pair in its host…..

Another example…….



(Norris et al. 1996)

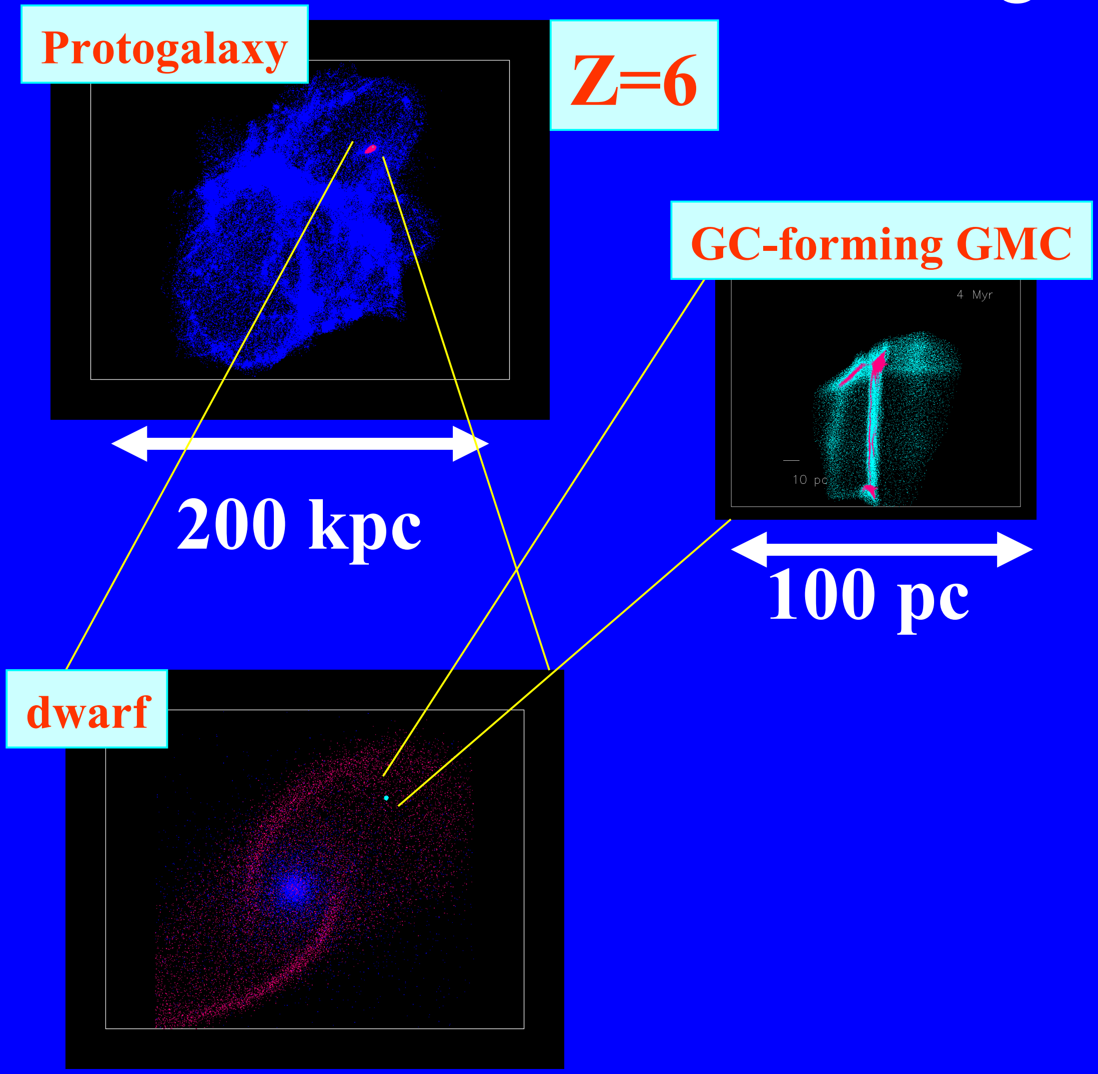
The multiple metallicity peak in ω Cen could be due to multipe SF episode in its host galaxy…..

Imprint 3

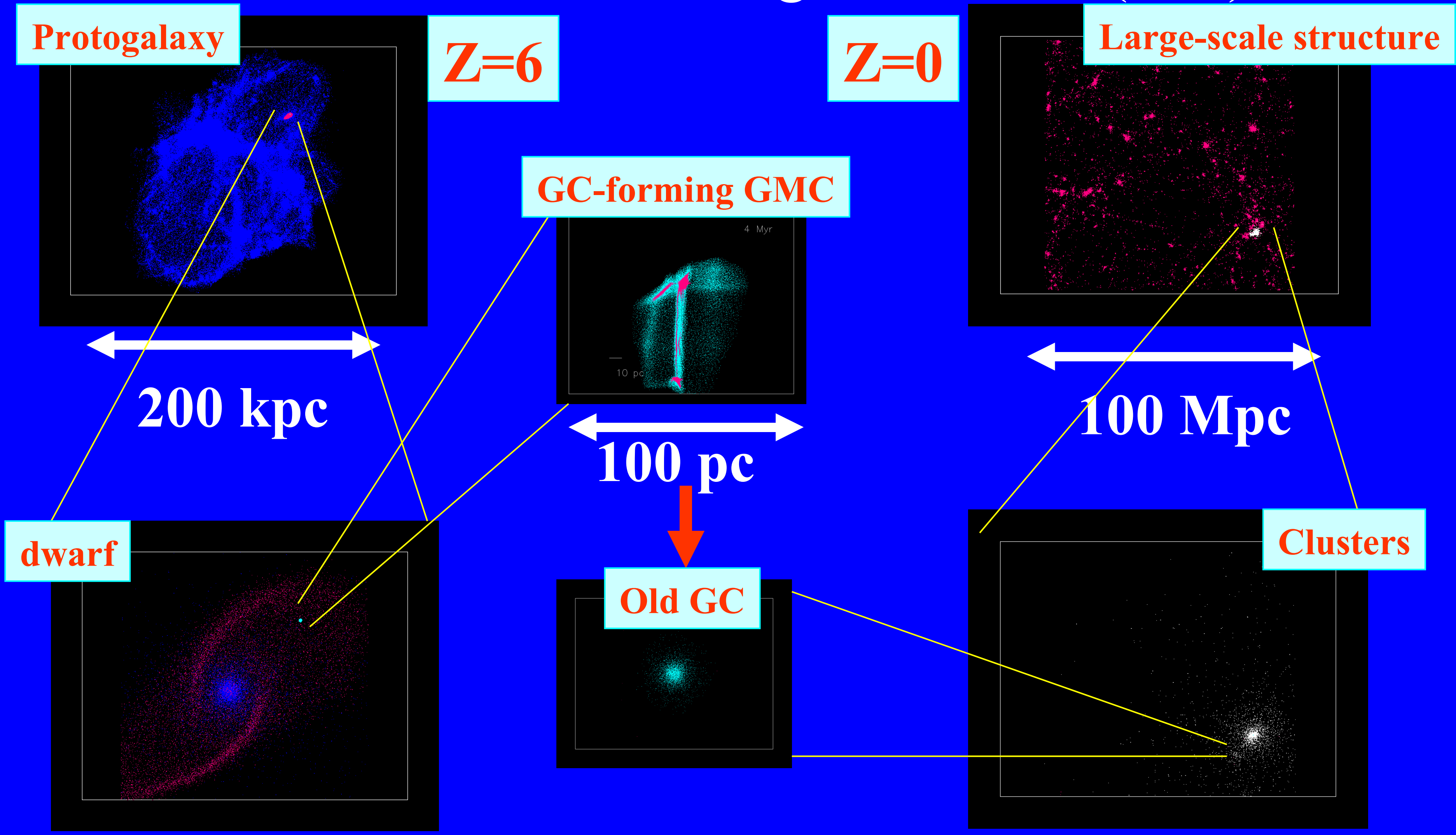
Physical properties (e.g., multiple stellar populations) of VMSCs can provide valuable information on the formation of stellar galactic nuclei.

4. What do intracluster GCs (ICGCs) tell us ?

GC formation in low-mass galaxies embedded by dark matter halos at high redshifts (z>6)



GC formation in low-mass galaxies embedded by dark matter halos at high redshifts (z>6)



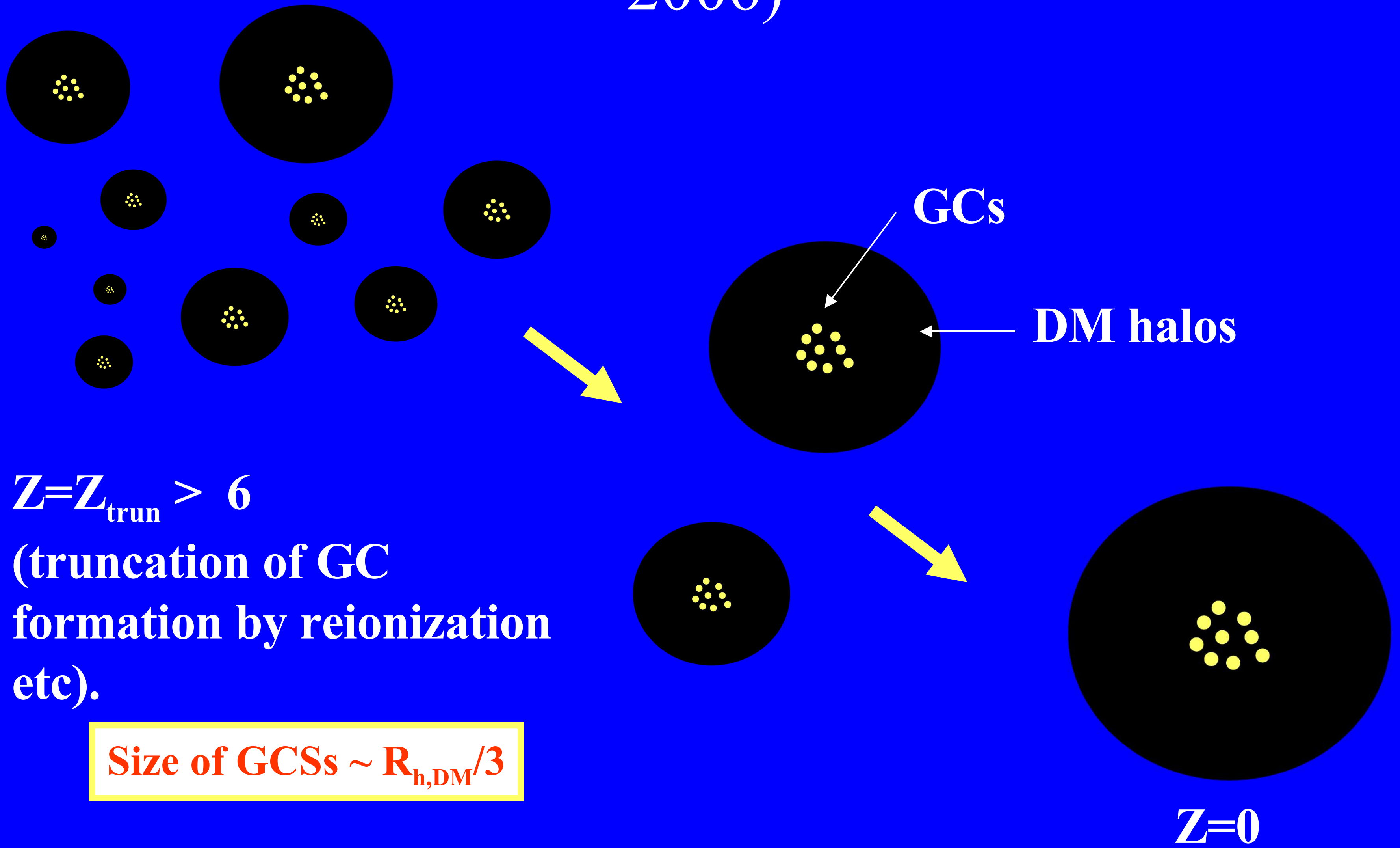
Formation of GCs within low-mass dark matter halos (z=6)

Hunt for ICGCs: Do they really exist ?

(1) Virgo ACS survey (Cote et al. 2006; Takamiya et al. 2006).
(2) ACS survey for Abell 1185 (West et al. 2006).
(3) Wide-field imaging of the Virgo cluster (Tamura et al. 2006).
(4) 2dF survey for the Fornax cluster (Firth et al. 2006).
(5) And more …..

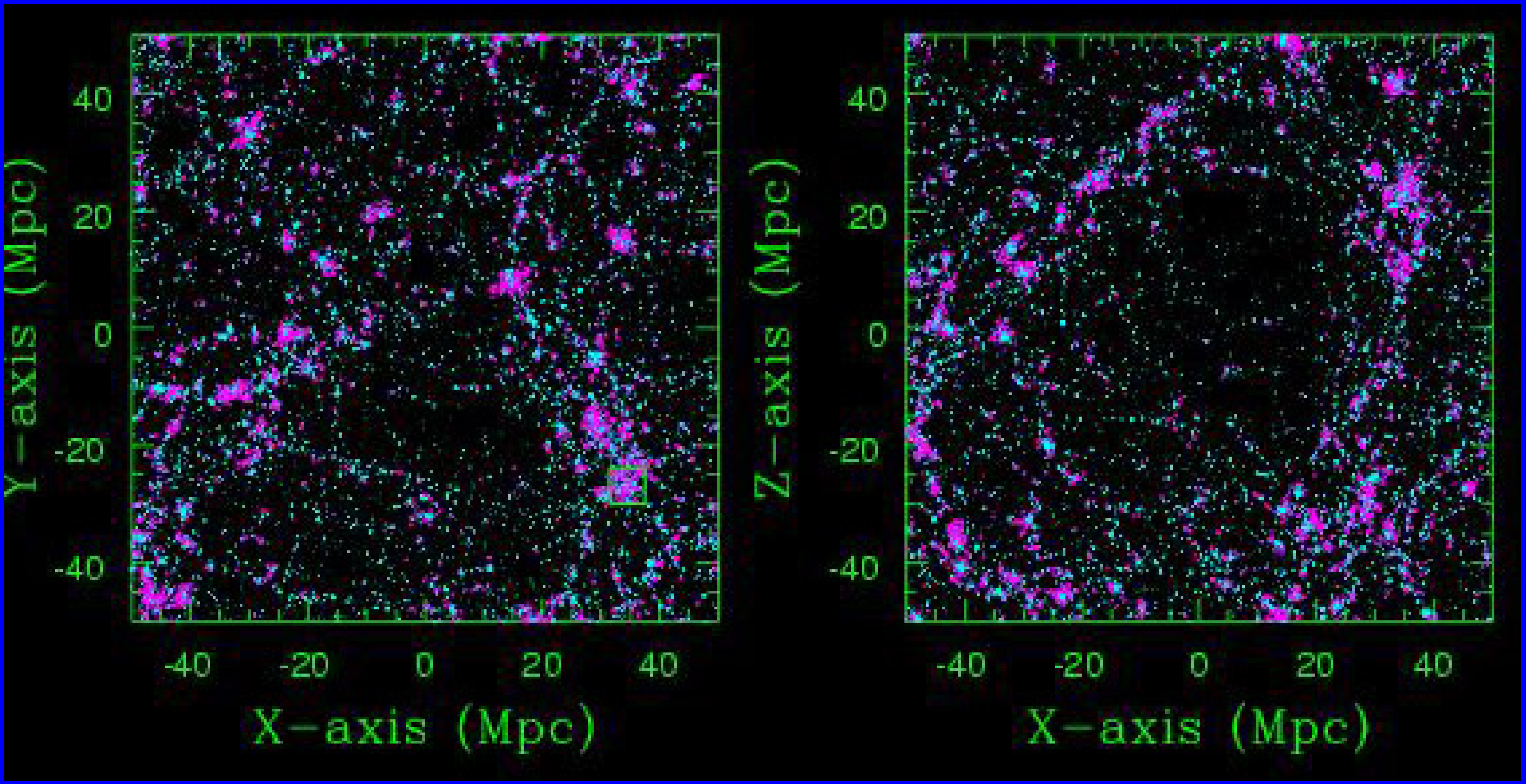
(Coma cluster)

Numerical studies of ICGC formation (Yahagi & Bekki 2005; Bekki & Yahagi 2006)



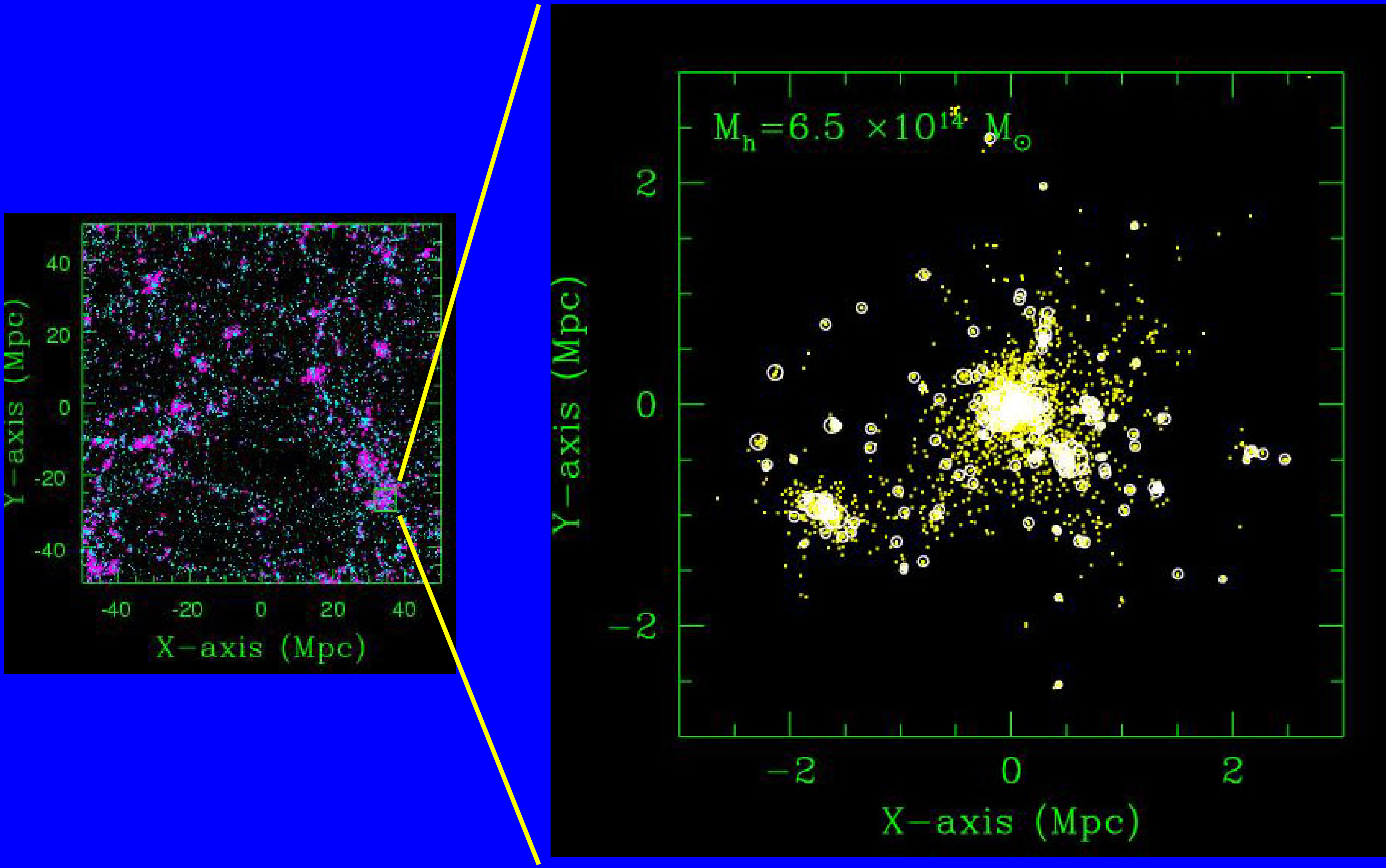
The large-scale structure of GCs (z_{trun}=6)

= GCs within halo **= Inter-galactic GCs (not within any halos)**



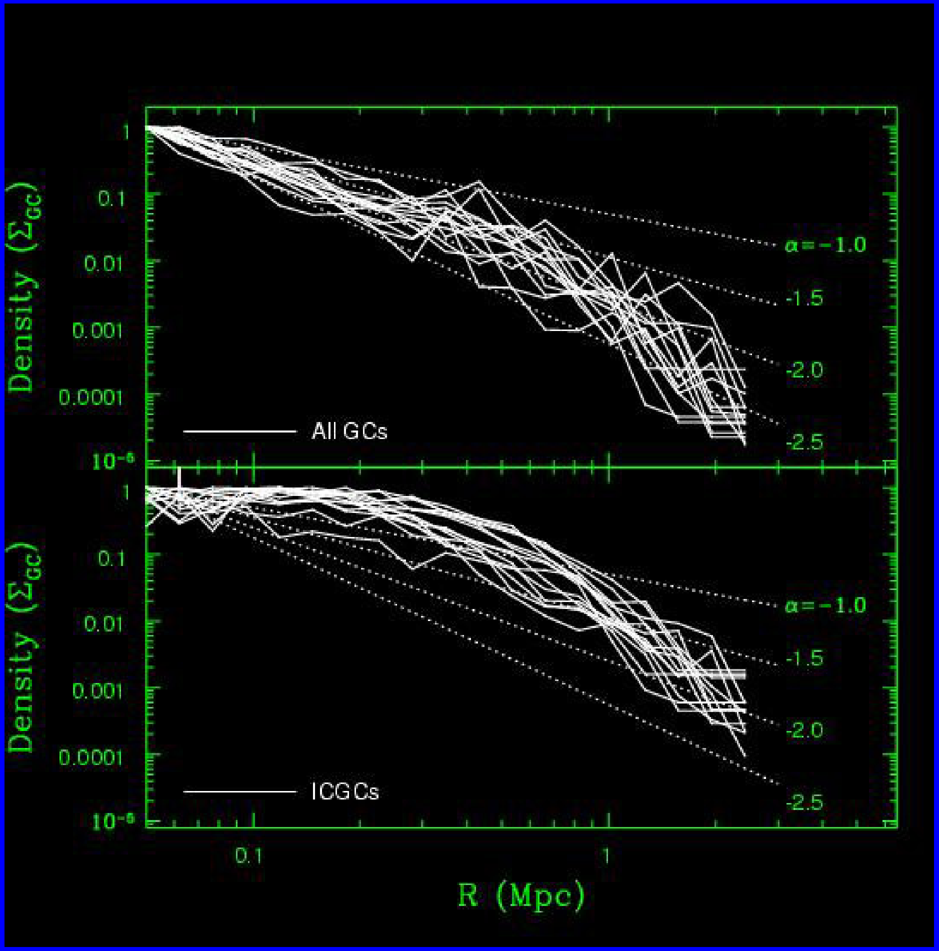
N=512^3, 70/h Mpc, 4.08*$10^{16}M_{sun}$, in a ΛCDM model. **(Yahagi & Bekki 2005)**

Formation of ICGCs in the hierarchical growth of clusters of galaxies.



Predicted properties of ICGCs ?

- About 20-40% of all metal-poor GCs in clusters can be ICGCs.
- The exponent of power-law density profiles range from -1.5 to -2.5.
- More compact GC distributions in higher z_{trun}.
- ~ 1% of all GCs in the universe can be inter-galactic GCs (within inter-cluster/group space).



(Bekki & Yahagi 2006)

Imprint 4

ICGC properties (density profiles, metallicity distributions etc.) can tell us about destruction/stripping/merging histories of building blocks of clusters of galaxies..

Summary

Observations

(1) GCS structures kinematics in Es.

(2) Age distributions of GCs.

(3) Properties of massive GCs.

(4) ICGC distributions.

→

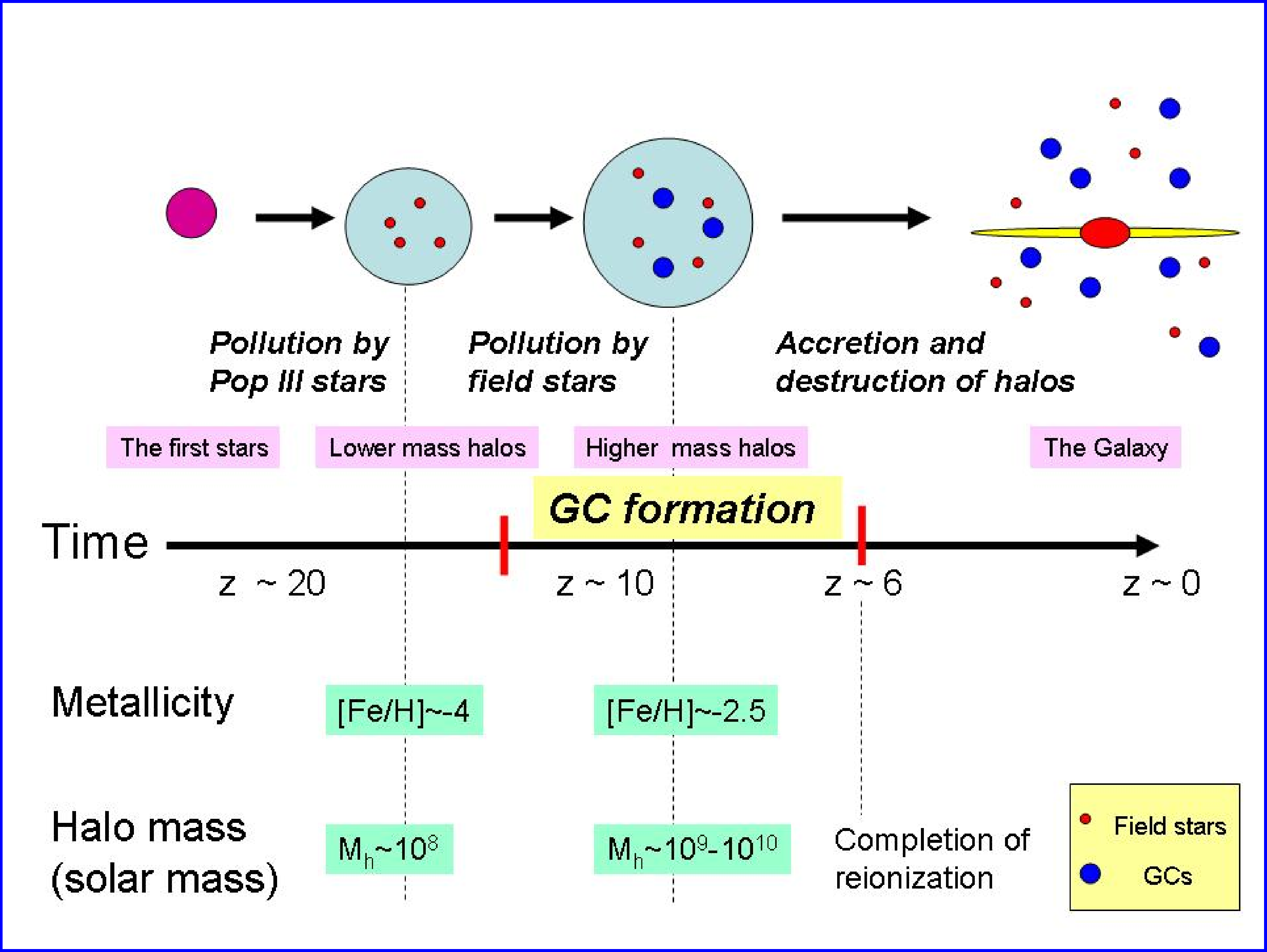
Implications

(1) Merging dynamics.

(2) Interaction histories.

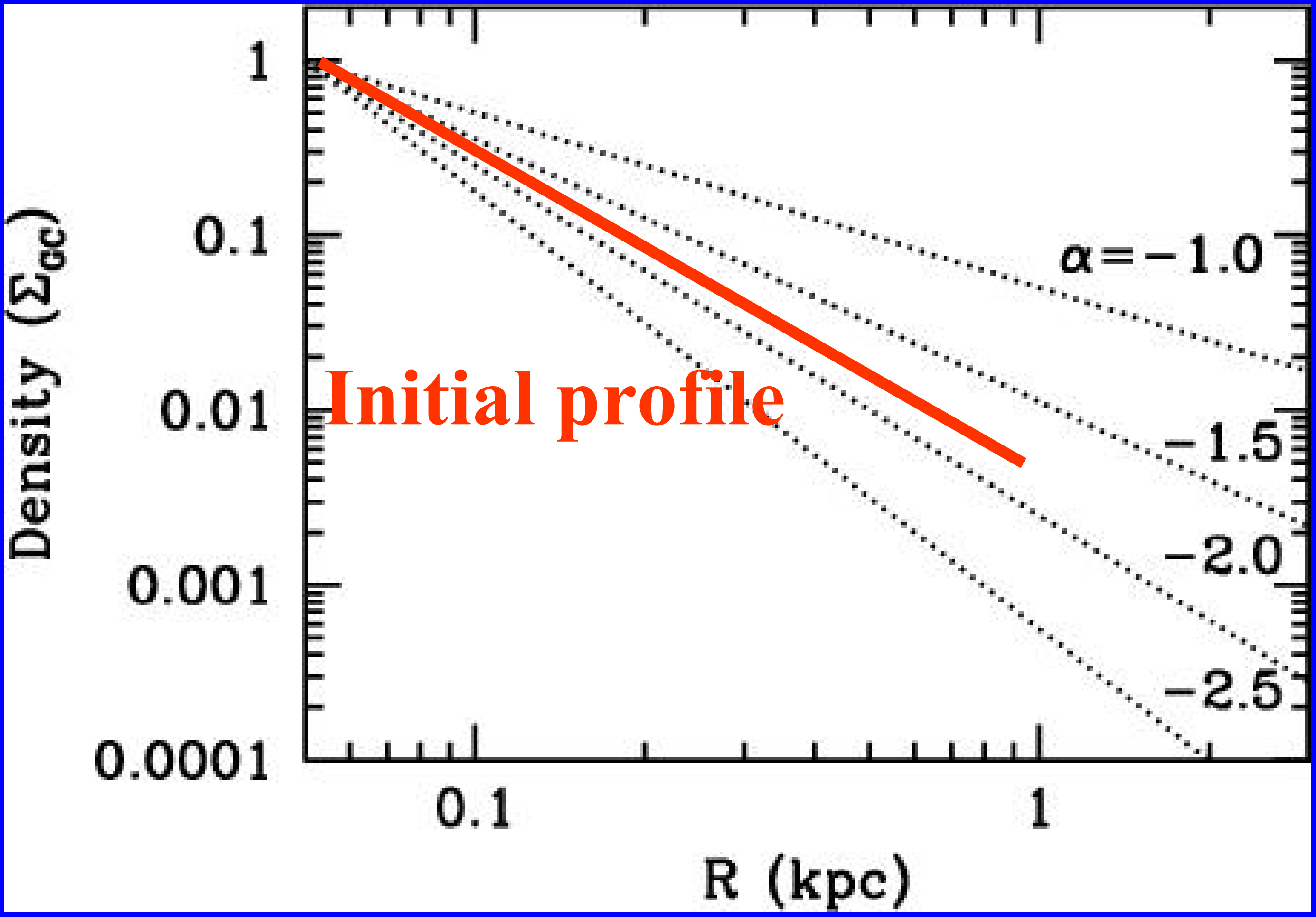
(3) Nucleus formation histories.

(4) Hierarchical merging processes of clusters of galaxies.

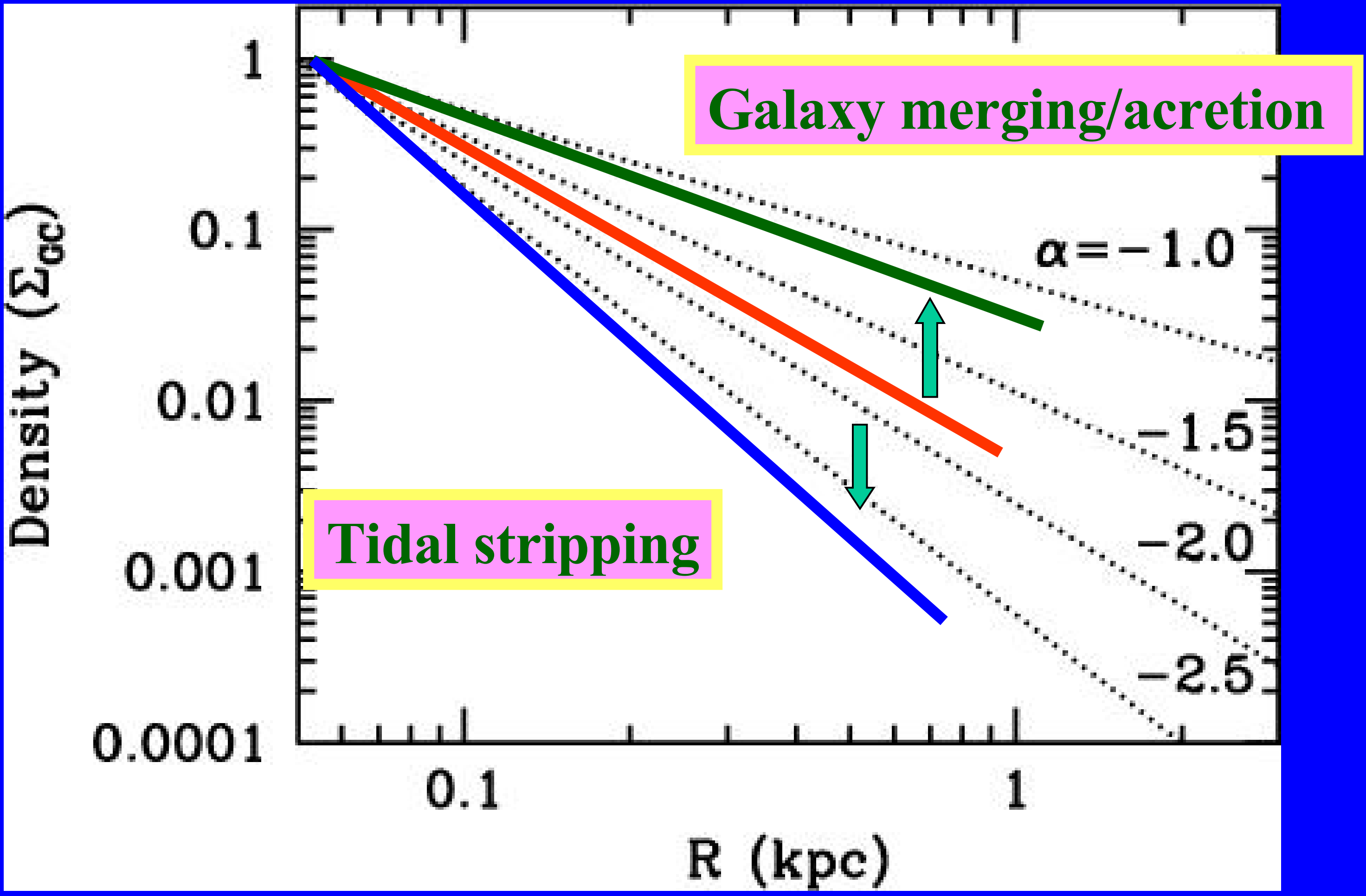


(Bekki & Chiba 2007)

Two effects: (1) galaxy dynamics and (2) GC destruction.



Effects of galaxy dynamics.



(2) Effects of GC destruction (e.g., Baumgardt, Vesperini in this meeting).