Wandering Globular Clusters in Galaxy Clusters and the First Stellar Systems in the Universe

Myung Gyoon LEE

Department of Physics & Astronomy

Seoul National University, Korea

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Team & References

- M.G. Lee, Sungsoon Lim (SNU)
- Hong Soo Park (KASI)
- Ho Seong Hwang (CEA/Saclay, France)

- References
  - Lee, Park & Hwang (2010), Science, 328, 334
  - Lee et al 2010, ApJ , 709, 1083
  - Lee et al (2010) in preparation

Intro

- We love to travel and wander.
- That's why we are here.
- So do star clusters in the Universe.

Beginning of Wandering GCs

- 1956 S. van den Bergh:

  Abell No. 4 (Palomar 4) is at a distance of 145 kpc. Therefore it is "an intergalactic tramp." (d=105 kpc in Christian 1986).

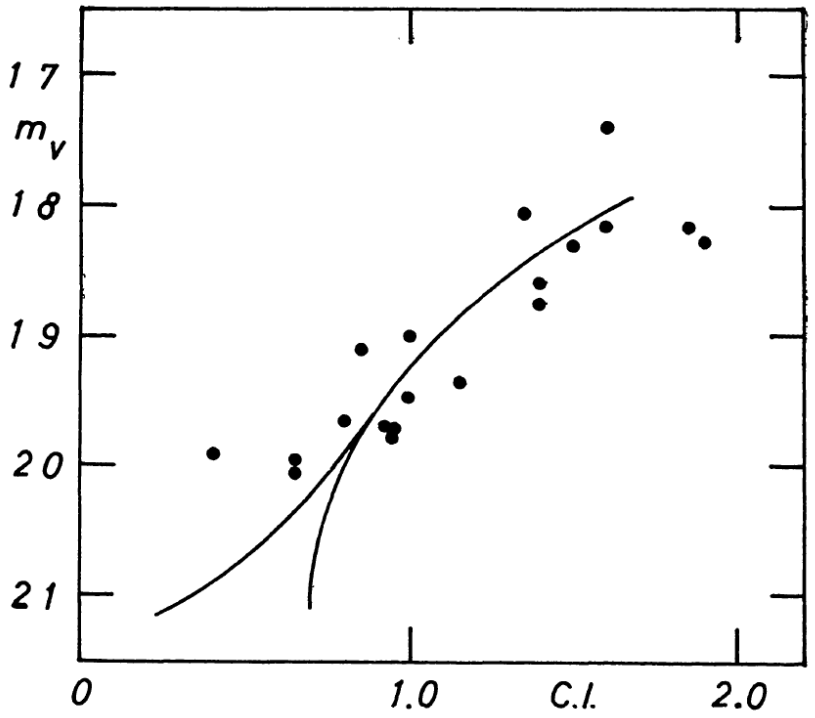


FIG. 1.—Color-magnitude diagram of globular cluster Abell No. 4.

The first objects are GCs? (1968)

- GCs may have formed before the galaxies formed!
- Expect to find numerous extragalactic GCs!
  (wandering GCs?)

ORIGIN OF THE GLOBULAR STAR CLUSTERS*

P. J. E. PEEBLES AND R. H. DICKE
Palmer Physical Laboratory, Princeton, New Jersey
Received March 8, 1968; revised June 12, 1968

ABSTRACT

We argue that the globular clusters may have originated as gravitationally bound gas clouds before the galaxies formed. This idea follows from the primeval-fireball picture, which suggests that the first bound systems to have formed in the expanding Universe were gas clouds with mass and shape quite similar to the globular star clusters. We present also a picture for the evolution from these assumed proto-globular gas clouds to globular star clusters

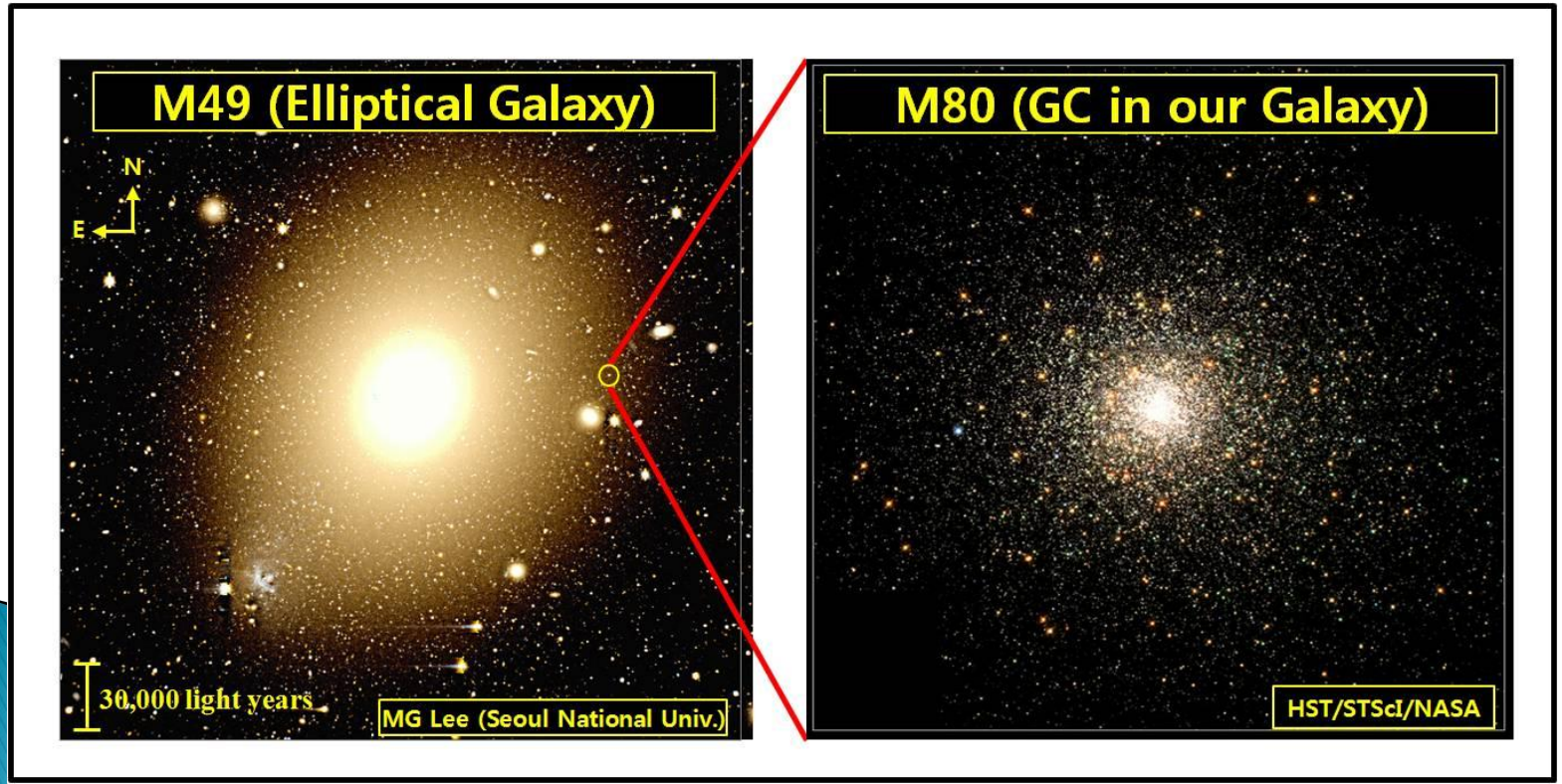
If truly extragalactic globular clusters exist, it is a very important result, for it at least shows that globular clusters need not be formed in the collapse of a protogalaxy. On the present theory, we would in fact expect to find numerous extragalactic globular clusters. It is perhaps too much to expect that gas clouds in the second phase of the evolution still exist; nevertheless, a search for such extragalactic objects would be of considerable interest.

Blooming of Extragalactic GCs

- 1950's to 2010: numerous studies using large telescopes and the HST (Baum, van den Bergh, Harris, Cohen, etc)
- Most studies on GCs in galaxies (Es, Sps, Irrs, dwarfs).

GCs in gEs

- **GCs are found in galaxies!**
  - M49: The brightest gE in Virgo
  - Components: diffuse stellar light, dwarfs, GCs
  - Bimodal color distribution of GCs
  - (Geisler et al 1996, Lee et al 1998, Lee & Kim 2000, Lee 2003)

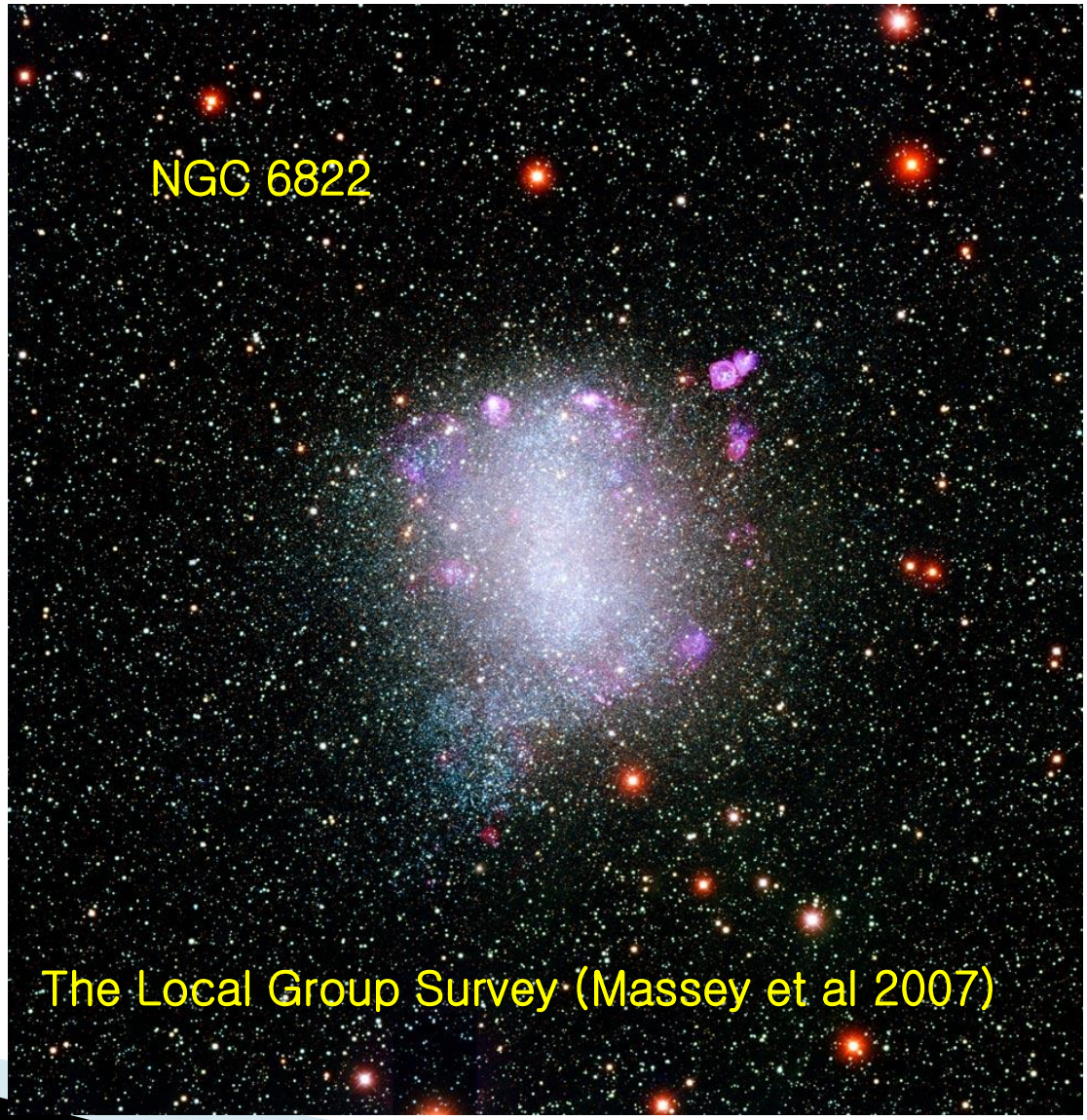


Wandering GCs (IGCs)?

- One prediction for intracluster GCs (IGCs):
- A cluster-wide GC system may exist in galaxy clusters.
  - White (1987), Muzio (1987), West et al (1995)
- Do IGCs exist in the universe?
  - Several studies found a small number of IGCs.
- If so, how can we find them?

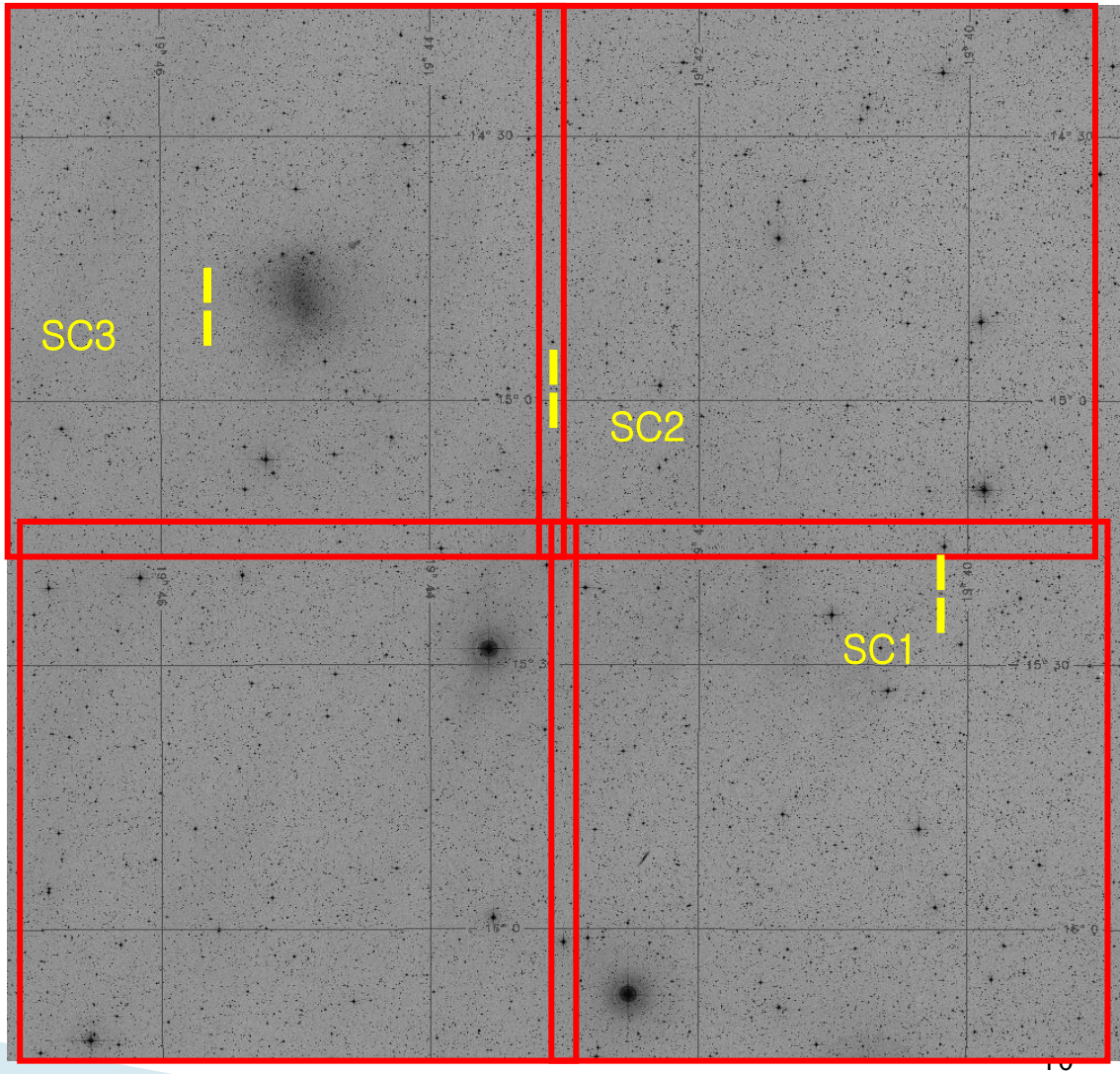
Wandering in dwarf galaxies

- NGC 6822
- LMC-like dIrr
- The first galaxy Hubble studied for stellar pops (1926 ApJ).
- HII region survey (Hodge, Lee 1988)



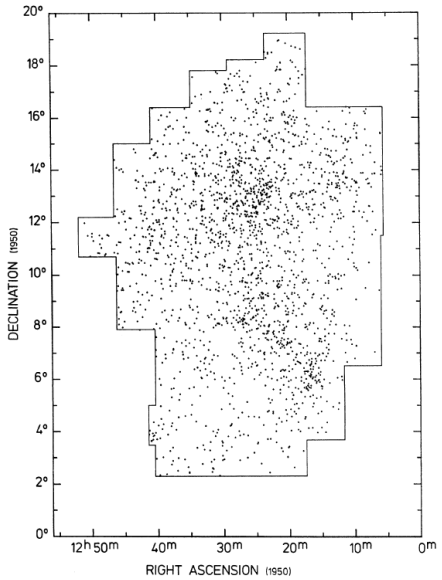
Wandering in a dwarf galaxy

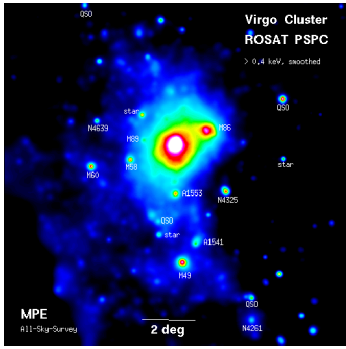
- Hwang, Lee etal (2006)
- CFHT/Megaprime
- Three old GCs!
- Wandering GCs?



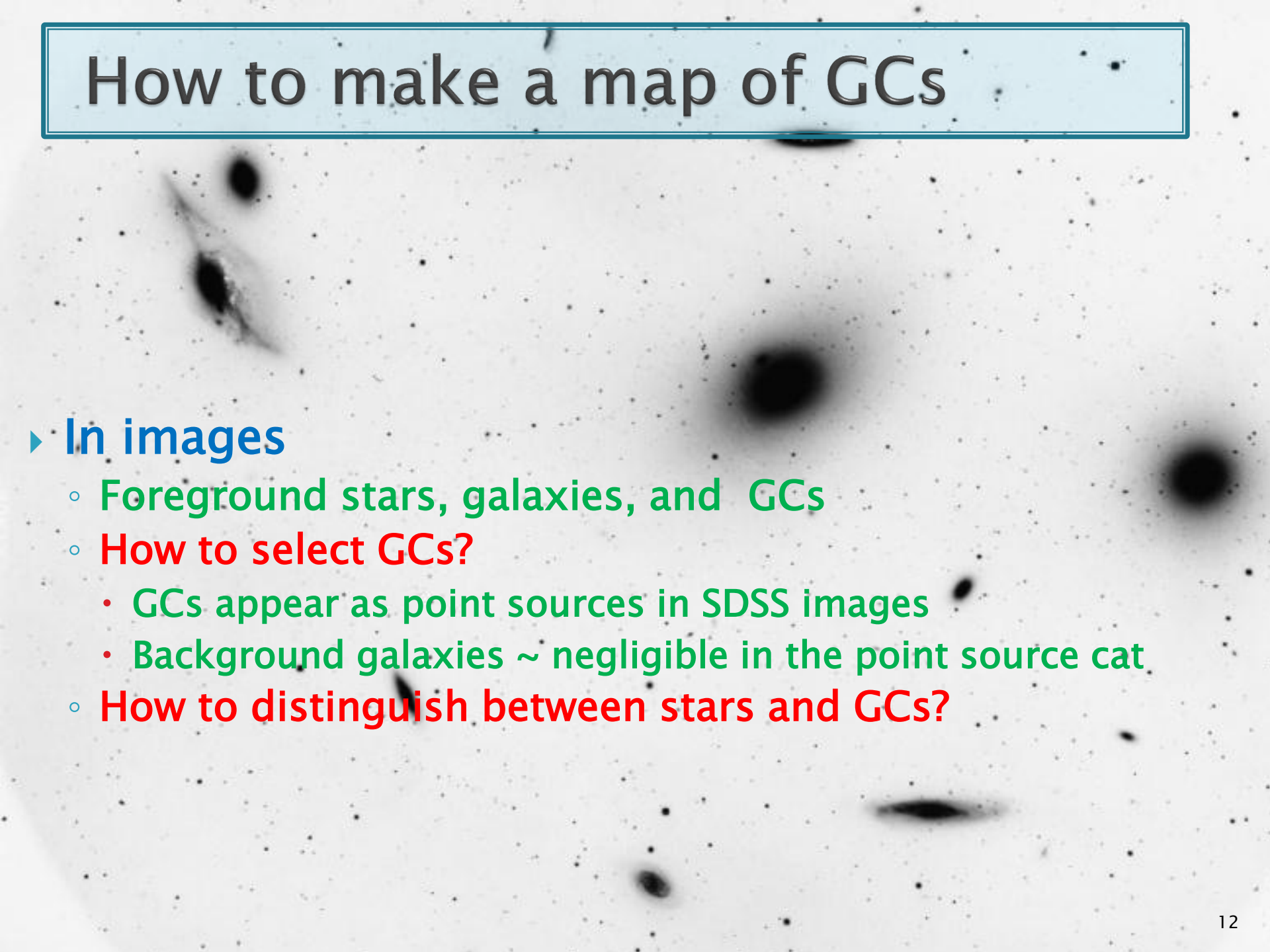
Today-wandering GCs in Virgo?!

- The Virgo cluster
  - The nearest rich galaxy cluster (D~16 .5 Mpc)
  - N(galaxy in VCC)=2096 (Binggeli etal 1985, VCC)
- Why Virgo?
  - To study in detail
- A problem for GC search!
  - So huge in the sky! (angular size>10 deg)





How to make a map of GCs



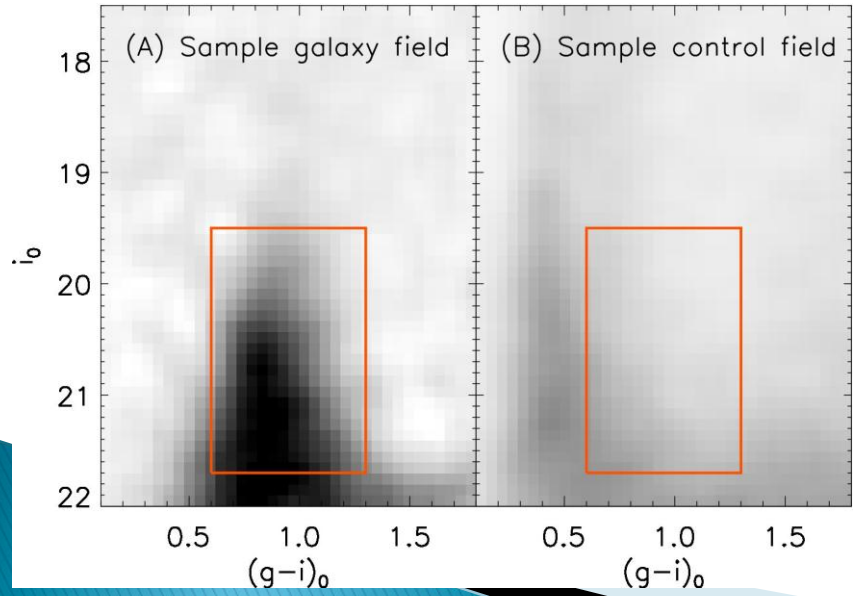
- In images
  - Foreground stars, galaxies, and GCs
  - How to select GCs?
    - GCs appear as point sources in SDSS images
    - Background galaxies ~ negligible in the point source cat
  - How to distinguish between stars and GCs?

Data

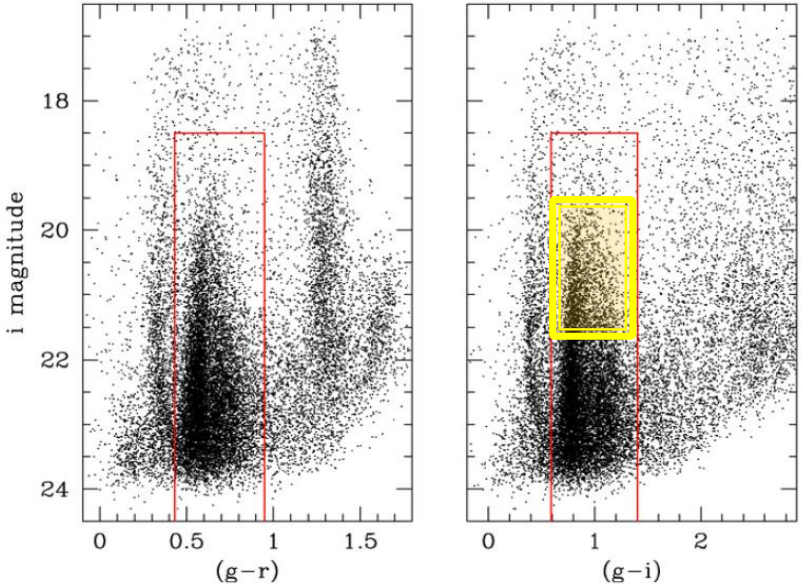
- SDSS DR6
  - The point source catalog (Adelman-McCarthy et al 2008)

Color-magnitude diagrams

- SDSS CMD
  - Sample galaxy field (galaxies at R<6°): GCs
  - Sample control field (empty regions at 6°<R<9°)
- GC selection: 19.5< I <21.7

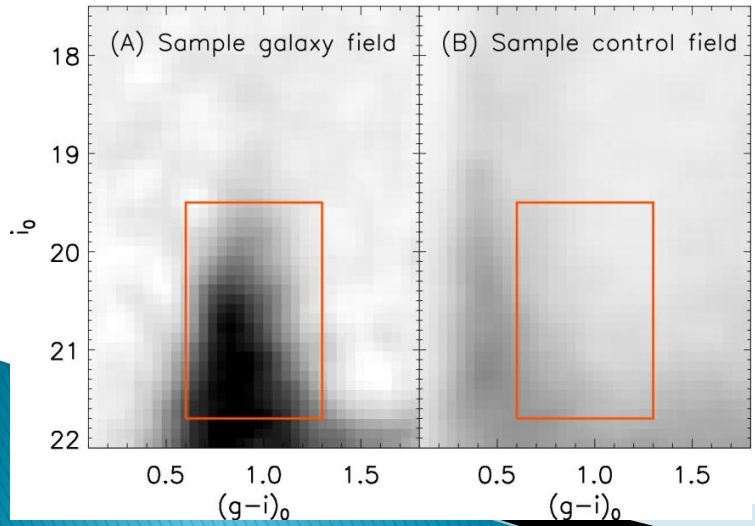


M87 (Harris 2009), CFHT 1d x 1d)



CMDs

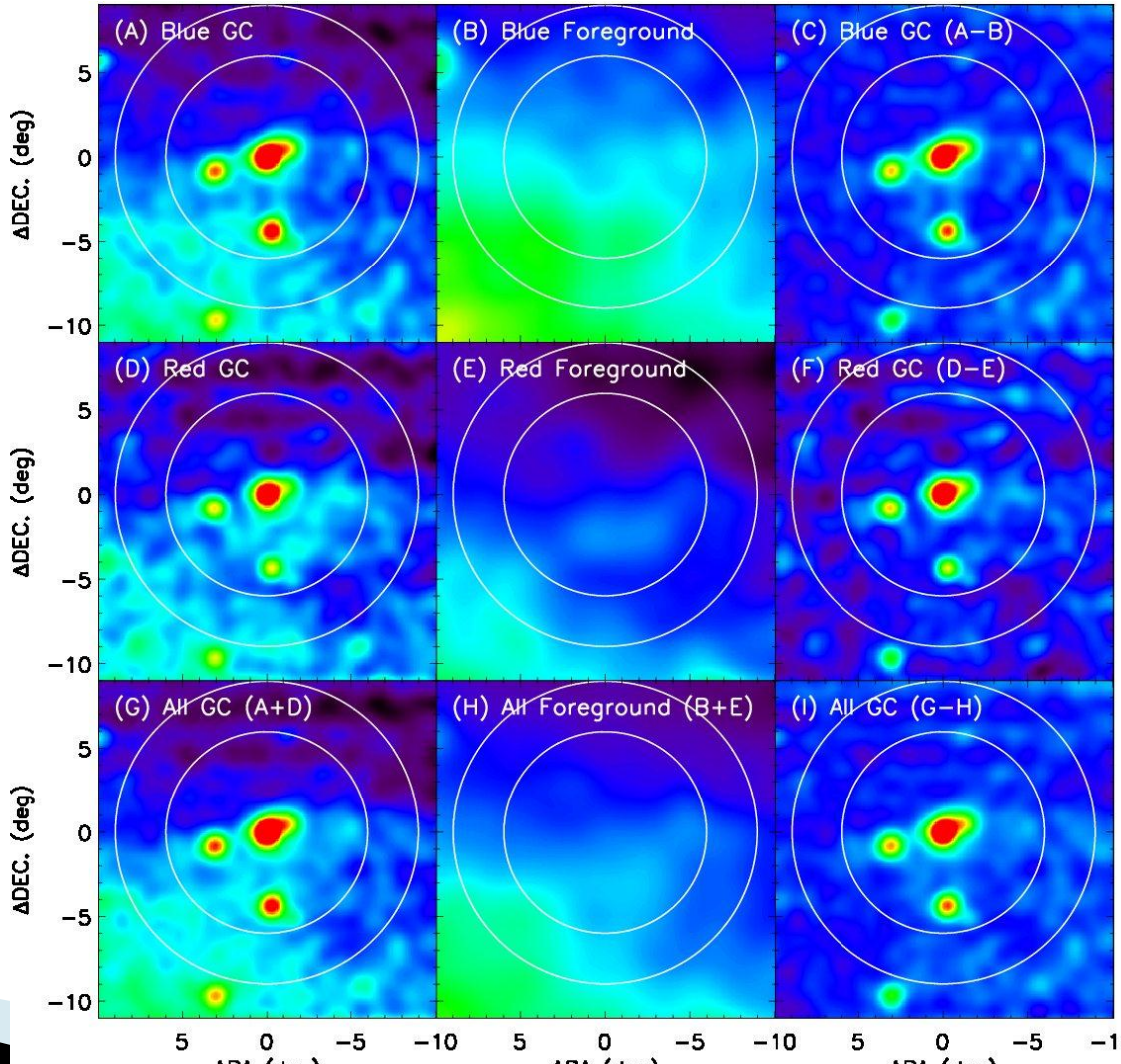
- Foreground sources in Virgo
  - 1) Stars in the disk & halo of the MWG
  - 2) The Virgo over-density :
    - a large-scale substructure covering over 1000 deg^2 of sky toward Virgo, located at 6-20 kpc.
    - It may be a tidal stream or a low-surface brightness dwarf galaxy merging with the Milky Way. (Juric et al 2008)



How to make maps

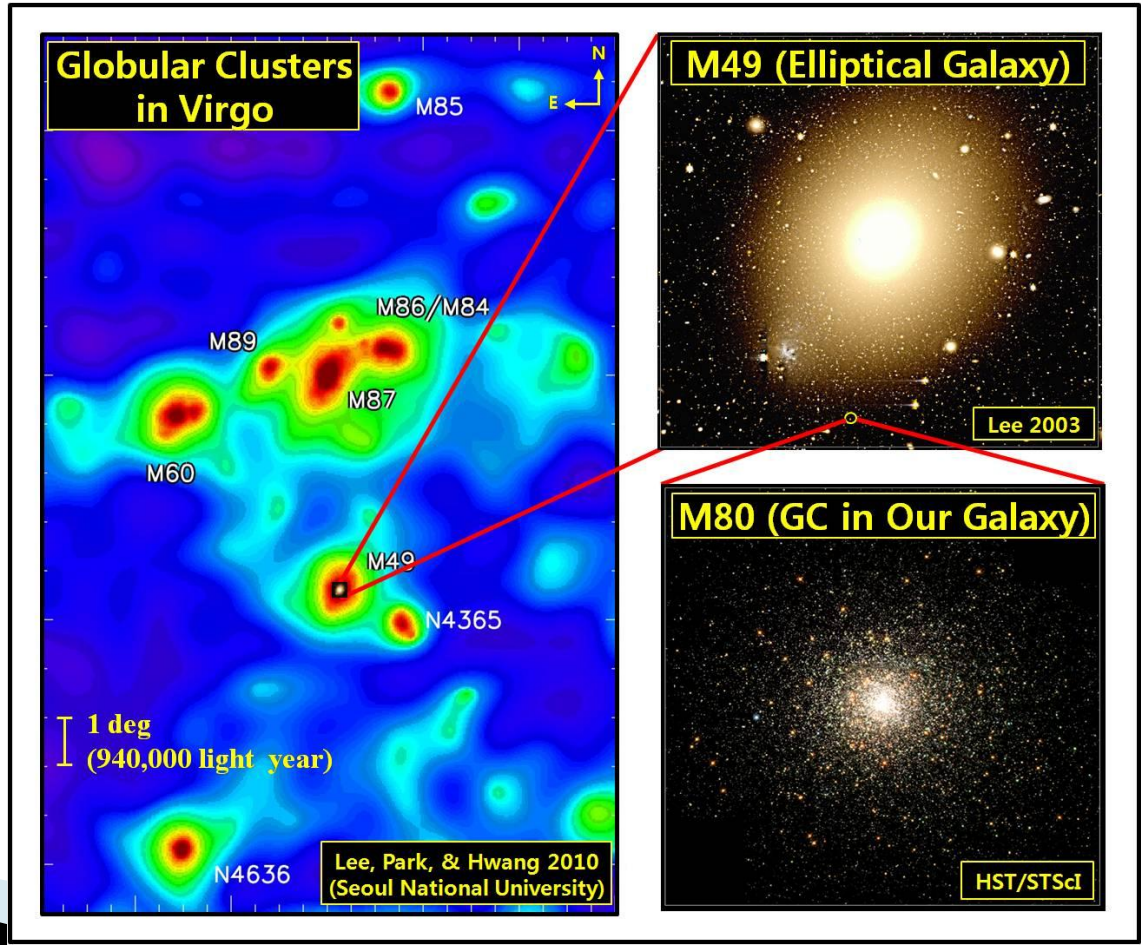
- **Maps:**

Raw – Foreground = Net GCs



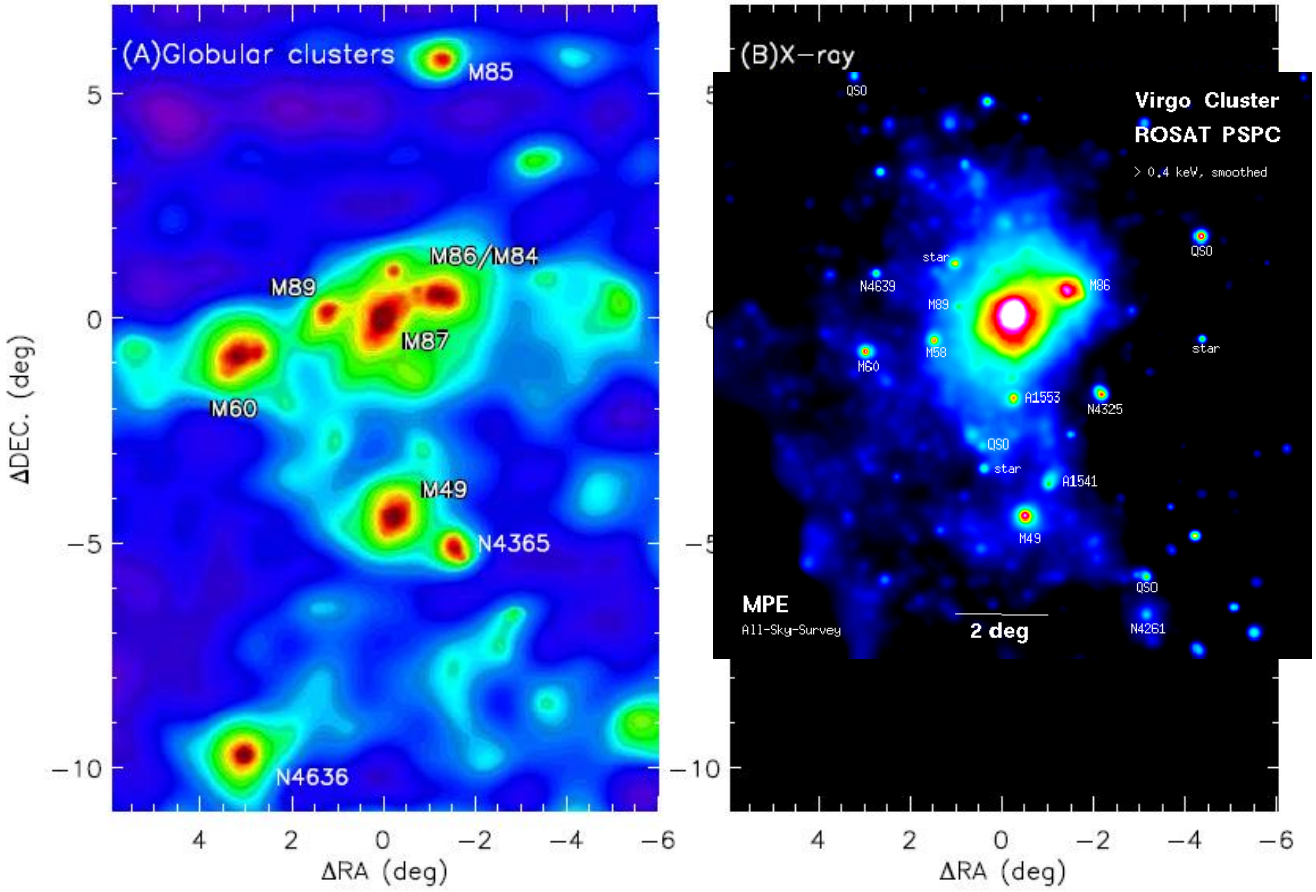
A map of the Virgo GCs

- Field: 12d x 18d
- Substructures around massive galaxies
- Connecting structures
- Diffuse large scale structure-IGCs!!!



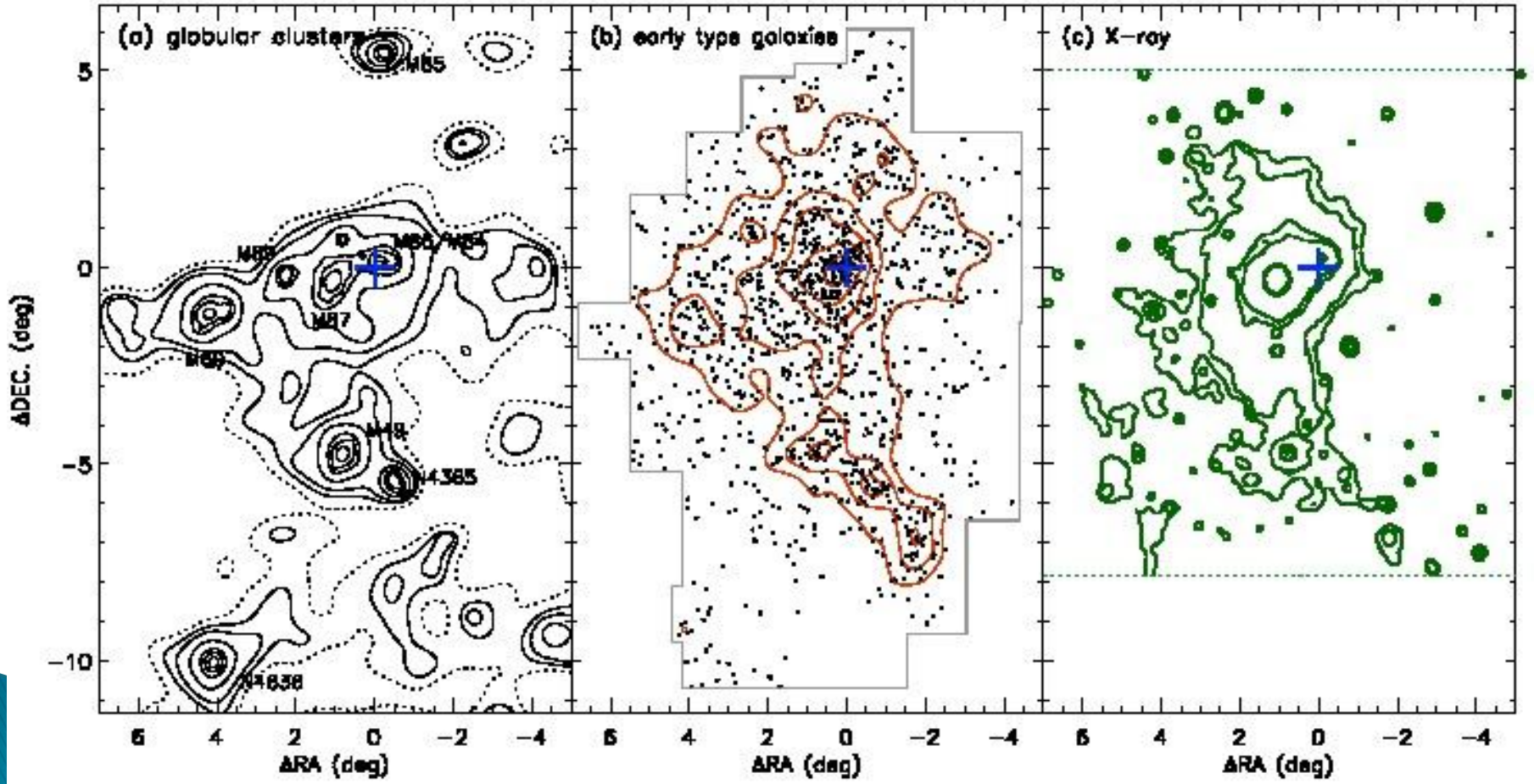
GCs vs Hot gas (X-ray) in Virgo

- **Similarity & Differences**



GCs vs Galaxies in Virgo

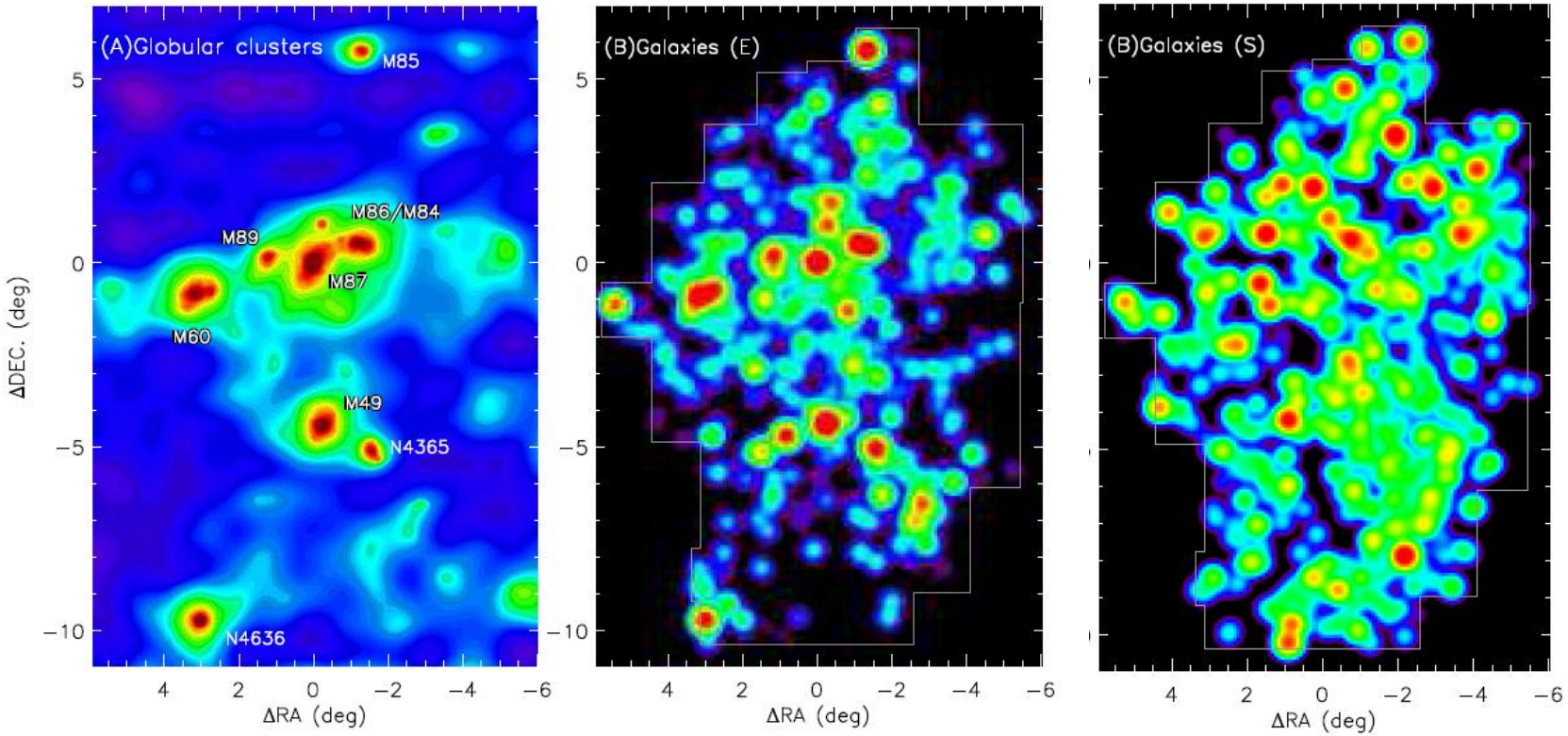
- Luminosity weighted galaxy number density map
- Correlation between GCs and Early type galaxies



GCs vs Galaxies in Virgo

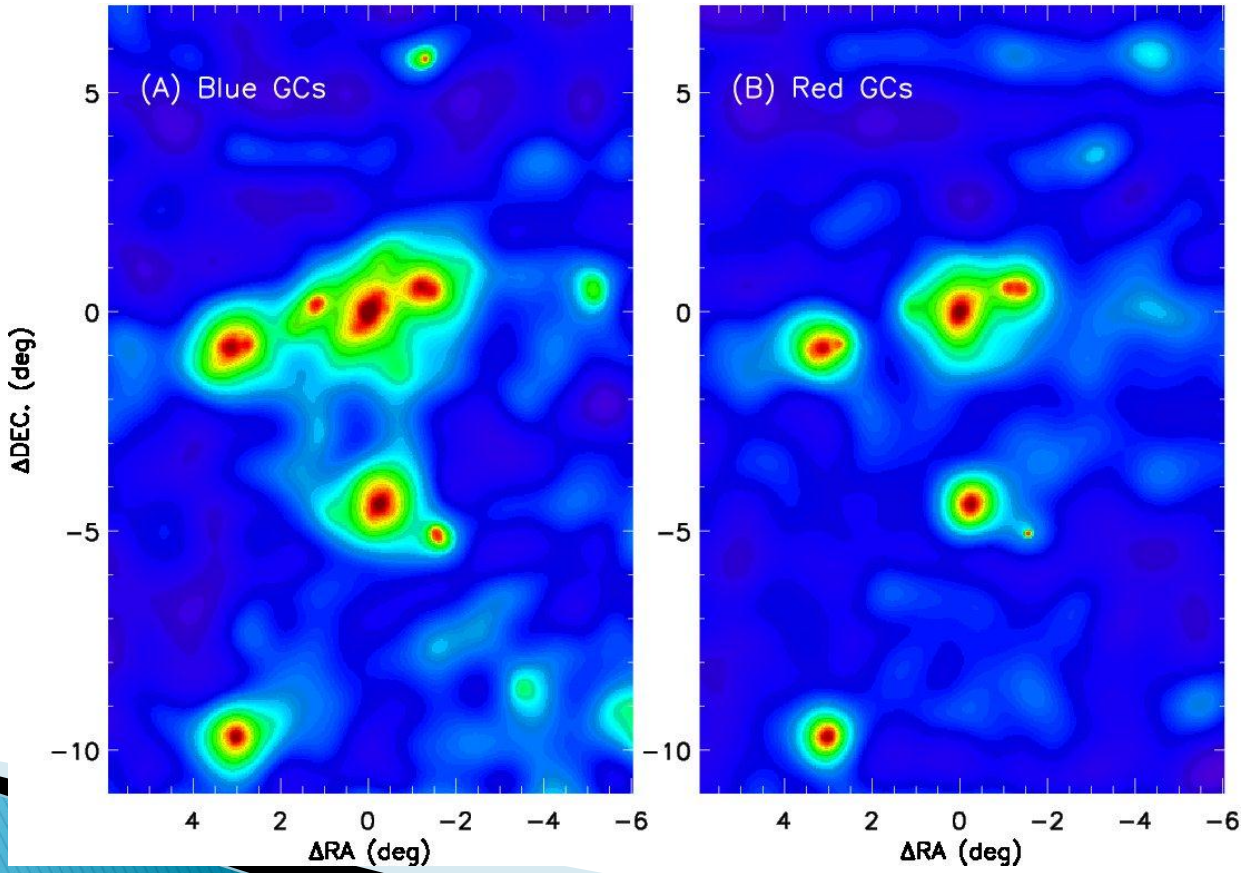
- Luminosity weighted galaxy number density map
- Correlation between GCs and Early type galaxies

- GC (E+S0+dE) (S+SB+Irr)



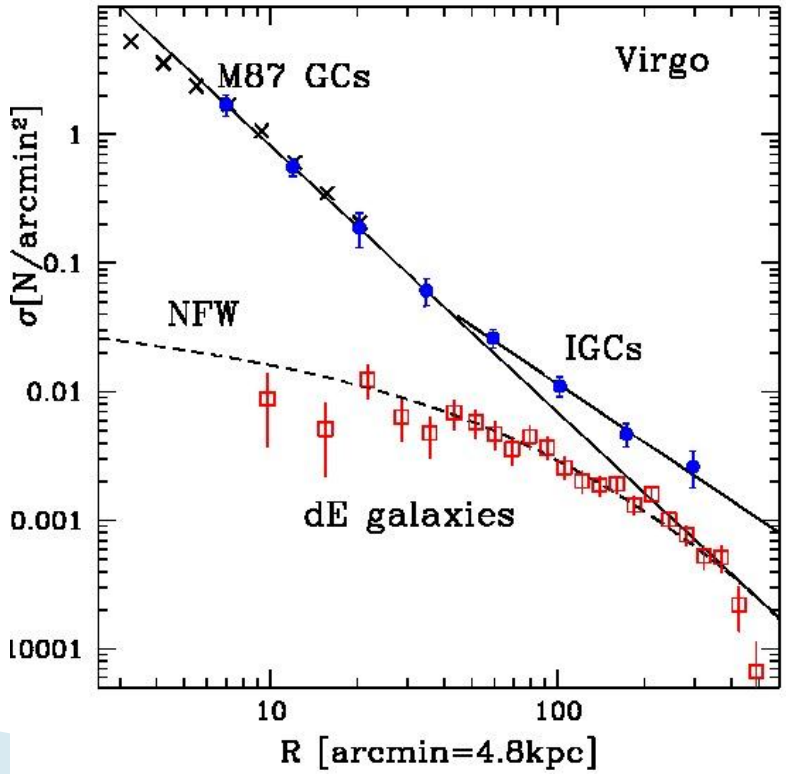
Blue GCs and Red GCs

- BGC: wider distribution than RGC
- IGCs are mostly blue GCs!



Radial number density profiles

- Surface density profiles of (M87 GCs + IGCs)
  - (after masking out all Virgo galaxies)
  - A Break at R~40' (IGCs at R>40')
  - All GC profile at R>40' is similar to dEs
  - Dominated by BGCs at R>40' (IGCs are mostly BGCs)

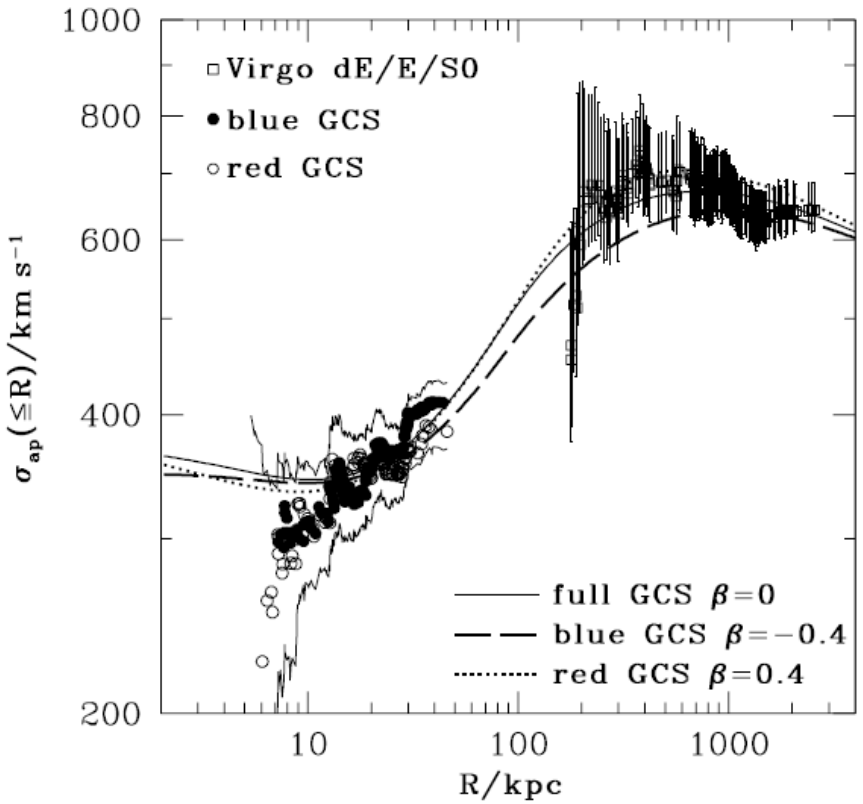


Kinematic difference

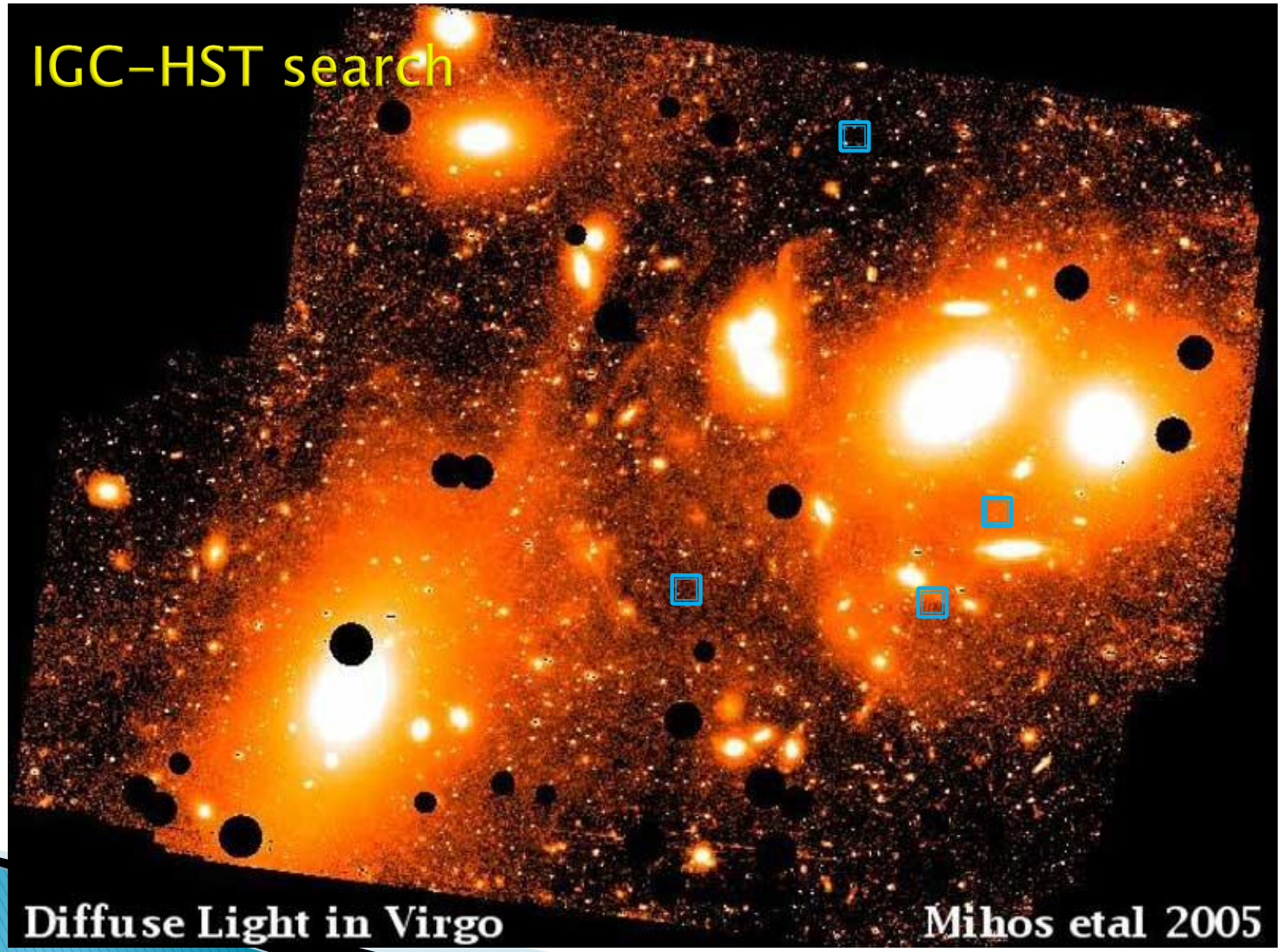
Cote et al (2001) M87 GC kinematics

M87-dominated (M87GCs)

-> Cluster-dominated (IGCs)



Are IGCs really GCs?

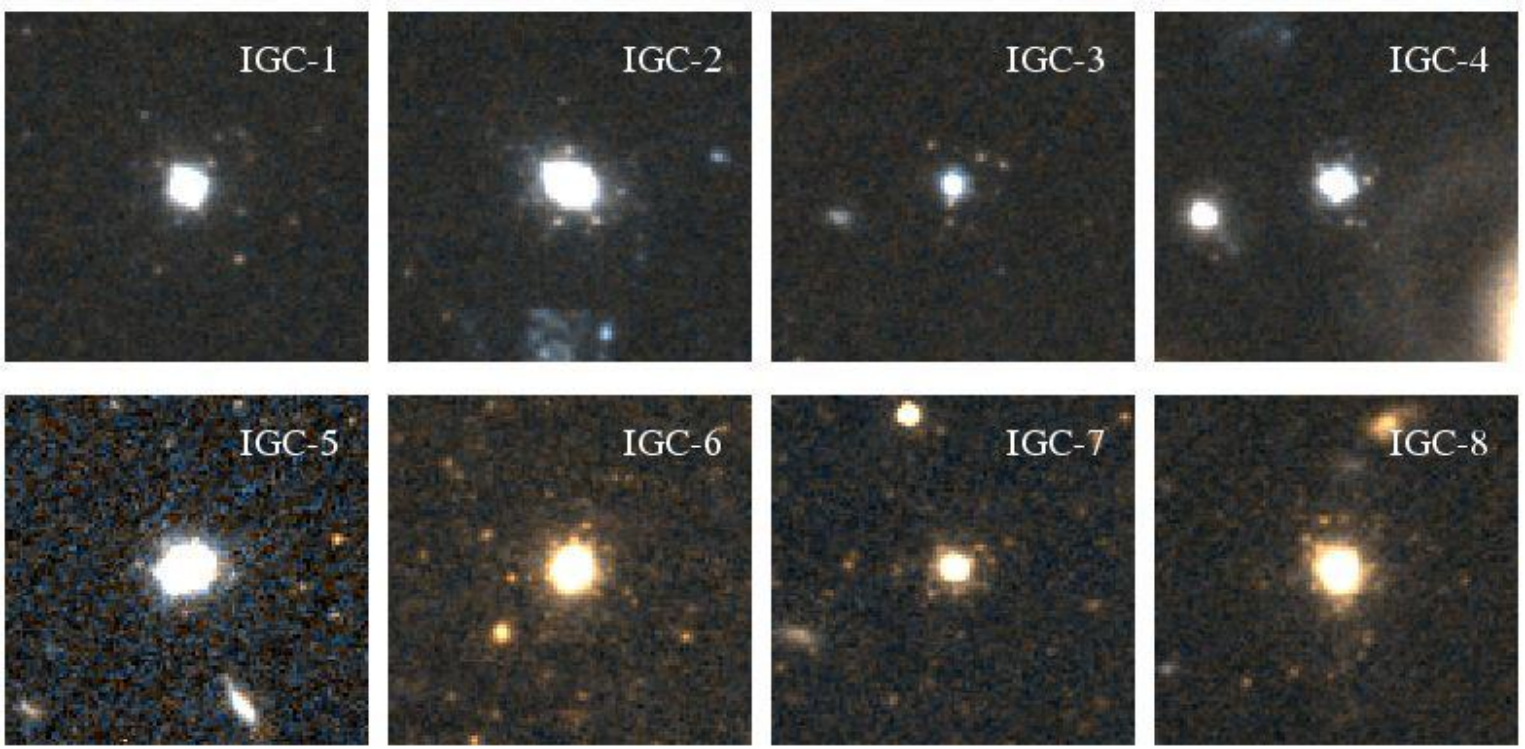


IGCs in the Virgo

*HST/ACS images: They are genuine GCs!

-Williams et al (2007) 4 IGCs in Area 4

-Lee, Lim, et al (2010, in prep) several new IGCs



Origin of IGCS?

- Dwarf galaxies!
- GCs were formed originally in dwarf galaxies.
- Then GCs were stripped off from dwarf galaxies due to massive galaxies.

Formation of GCs in Galaxies

- **Several scenarios in the literature**

1) First objects:

(Peebles and Dicke 1968,)

2) Monolithic collapse:

(ELS1962)

3) Accretion:

(Searle & Zinn 1978, Cote et al 1998, 2000, Harris et al??)

4) Gaseous mergers:

(Ashman & Zepf 1992)

5) In situ multi-collapse formation:

(Forbes et al 1997, Kissler-Patig et al 1998)

Formation of GCs: our scenario

- **Bibimbap model (Mixture model)** (Lee et al 2010, ApJ)
  1) Metal-poor GCs were formed mostly in dwarf galaxies, while metal-rich GCs were formed later with stars in massive galaxies or in dissipational merging galaxies.

  2) Elliptical galaxies grow via dissipational or dissipationless merging of galaxies and via accretion of many dwarf galaxies.

  3) The IGCs stripped off from dwarf galaxies are now being accreted locally to nearby massive galaxies, and globally to the galaxy cluster center.

Simulation for Diffuse Stars

*Dolag et al (2010) color: v, intensity: stellar density

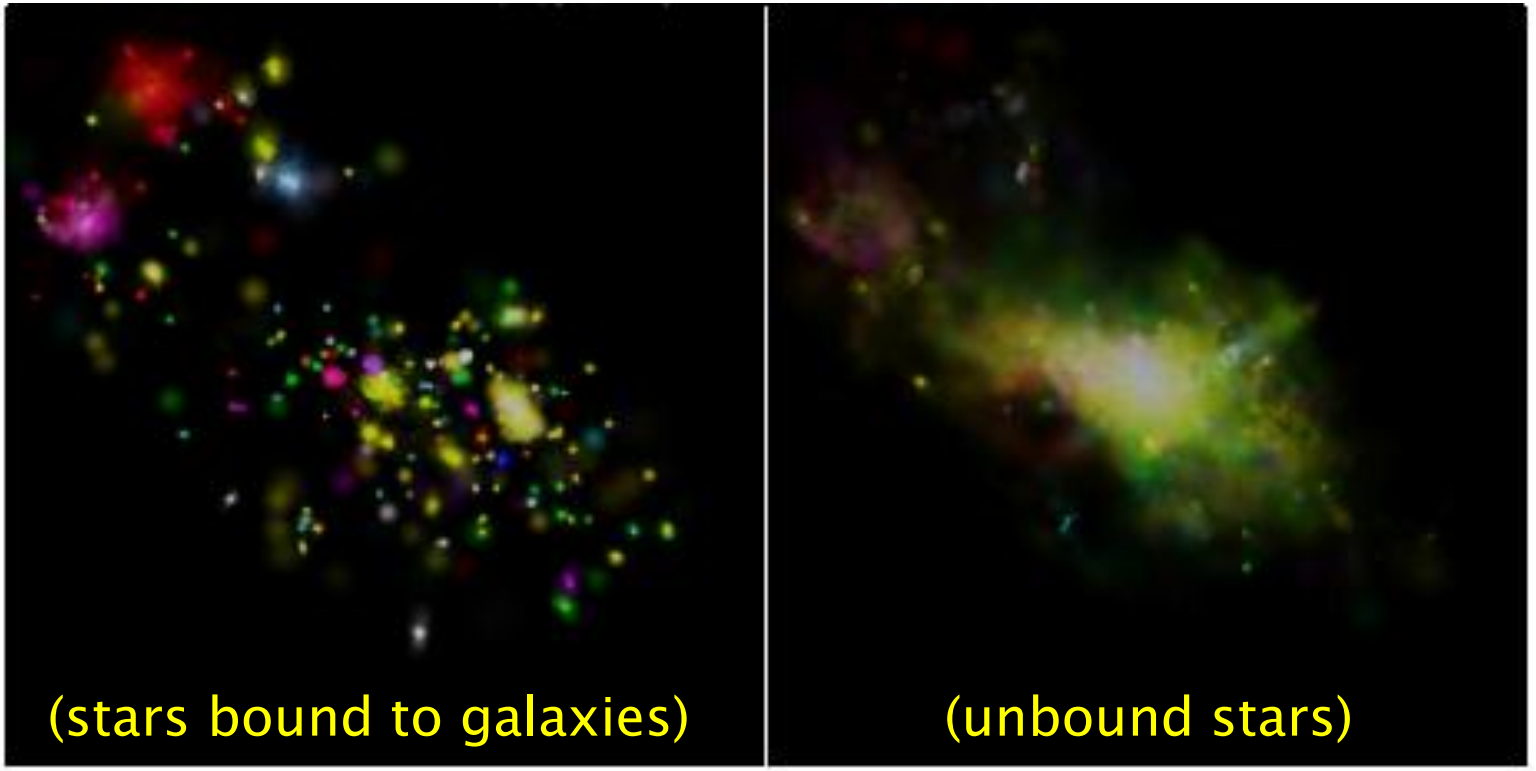


Figure 1. Visualization of the stellar component using the the ray–tracing software SPLOTCH. The color composition reflect the three dimensional velocity field (see text for details), whereas the intensity reflects the stellar density. The upper panel shows all stars in the high resolution sphere. The lower left panel shows all stars in galaxies (including the *cD*) of the most massive cluster, whereas the lower right panel shows all stars not bound to individual galaxies.

Simulation for Diffuse Stars

*Murante et al 2004, 2007: Diffuse stellar component (DSC) *Bekki and Yahagi 2006 *Dolag et al 2010

*Results

1) The spatial distributions of the bound and unbound stellar populations are different.
2) The DSC is more centrally concentrated than the stars bound in galaxies.
3) Stars in the DSC are, on average, older than galaxy stars.
4) The DSC fraction increases with M(cluster).

Implication of IGCs for the first objects in the universe

- A wide distribution
- Blue GC-dominated
- Wandering in the Local Group and other galaxy clusters

IGCs vs dwarfs

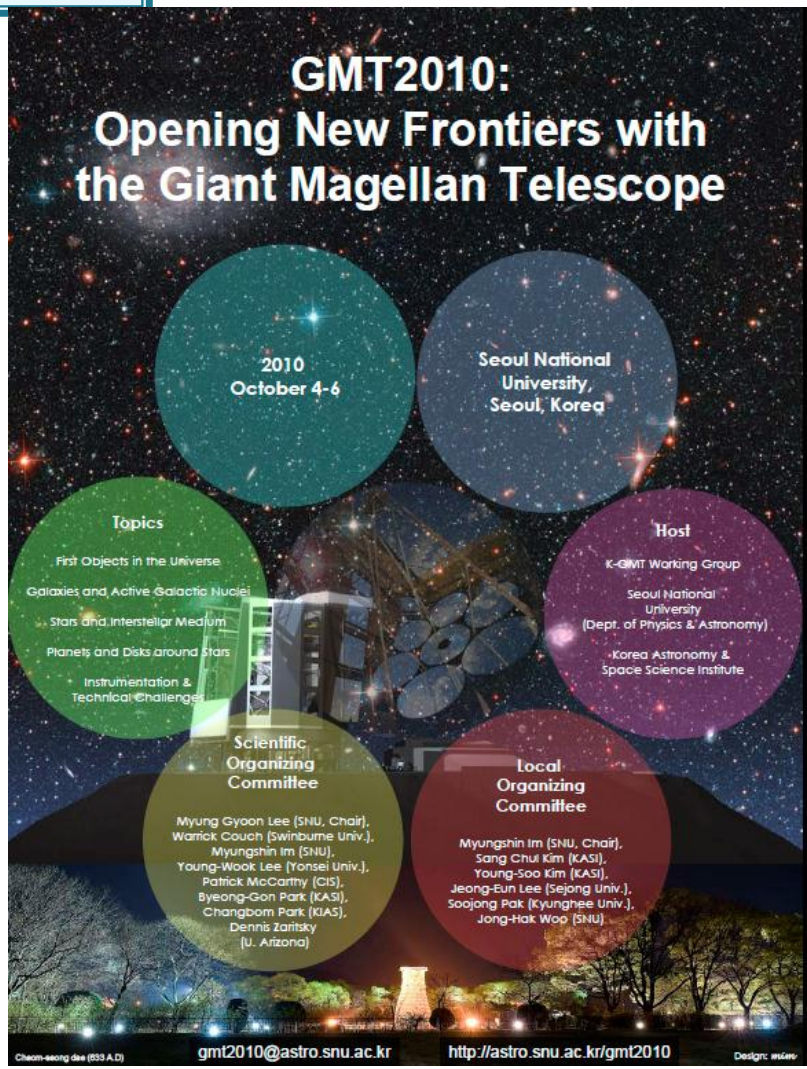
- Current zoo of GCs and dwarfs: diversity
  - GCs: various kinds
    - (normal GCs, extended GCs, faint fuzzies, GCs with multiple pops, nuclear clusters, IGCs)
  - Dwarfs: various kinds
    - (dEs, dSphs, UF dSphs, UCDs, DTGCOs)
- IGCs found in Virgo are the brightest GCs, showing only the tip of an iceberg.
- Some of them may be UCDs (Forbes, Hilker 2010).
- Some of them were the first dwarf galaxies.

Summary

- Discovered a large-scale structure of globular clusters in the Virgo cluster.
- Expect that there may be wandering GCs in all galaxy clusters in the universe.
- IGCs must be related with the first dwarf galaxies in the universe.
- We need further studies of these GCs (deeper imaiging, spectroscopy, numerical simulation)

Future

- Korea joined GMT in 2009.
- GMT2010 meeting (Oct4-6)
  - A stepping stone for a quantum jump of Korean Astronomy
- GTM will be ready in 2020
  - A powerful tool for studying the first structure formation
  - First results may be presented at The 10th KIAS workshop!



End

- We love to travel and wander.
- So do star clusters in the Universe.
- We keep travelling and wandering, figuring out what wandering star clusters are, and

  figuring out what are wandering in voids (e.g. Vogley 2010, van de Weygaert 2010 this meeting)