

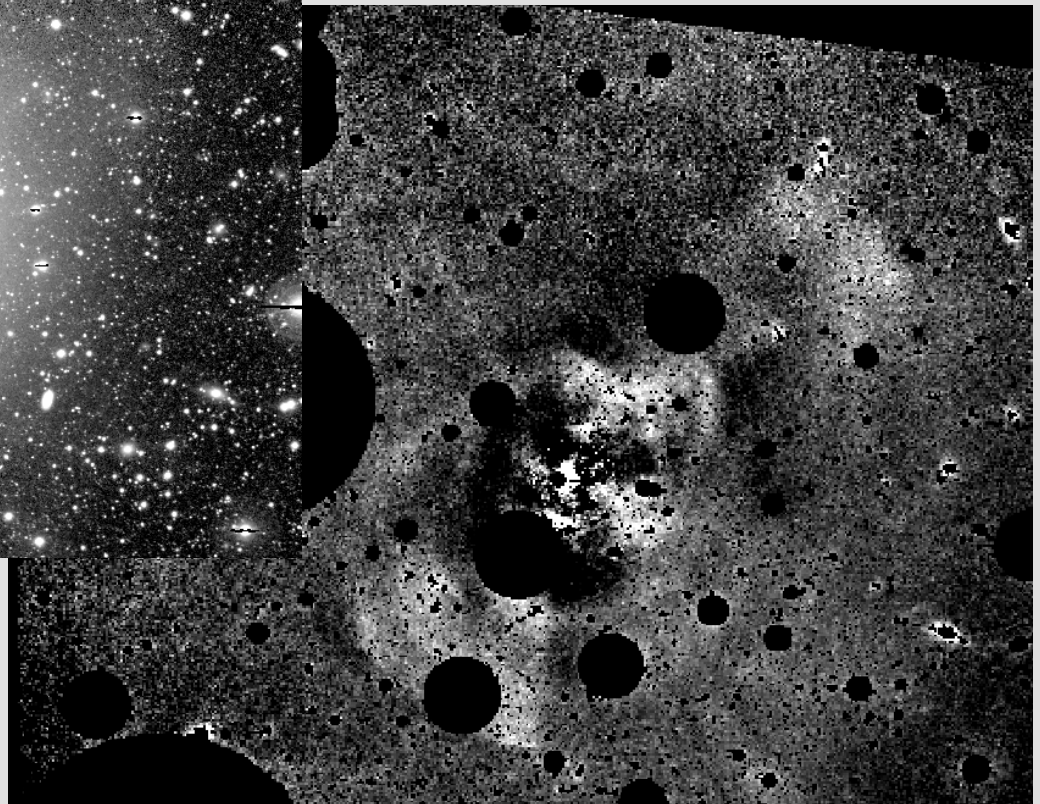
# The Hierarchical Assembly of (Virgo) Cluster Galaxies

Chris Mihos

Case Western Reserve University



*with Harding, Rudick, Feldmeier,  
Morrison, Janowiecki, and Slater*



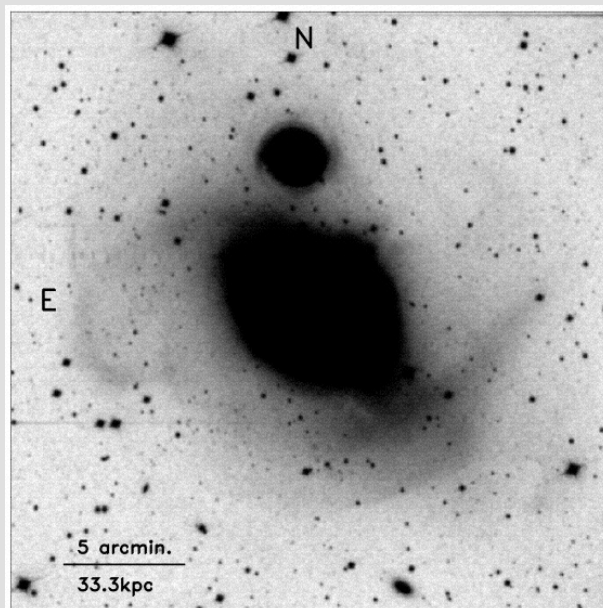
# Mergers – where?

The need for mergers & accretion has been argued from the buildup of BCGs and the size evolution of massive galaxies.

But where is it happening? Two likely environments:

## 1. Potential centers

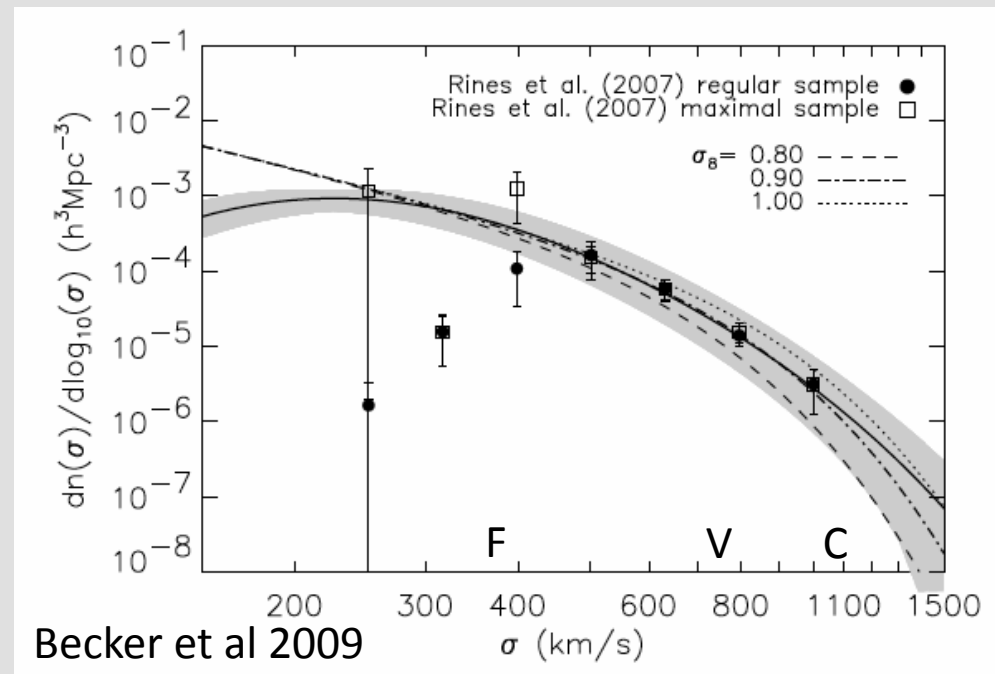
NGC 1316



Mackie & Fabbiano 1998

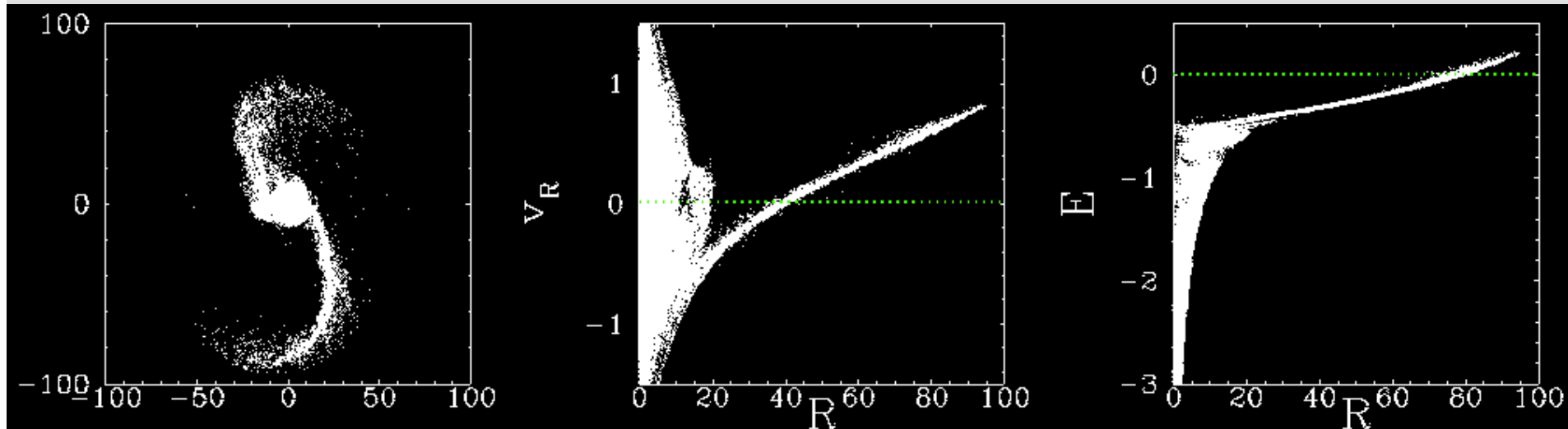
## 2. Group environments

group/cluster velocity function



# Merger/Accretion Signatures

Long, bright tidal tails fade rapidly with time:



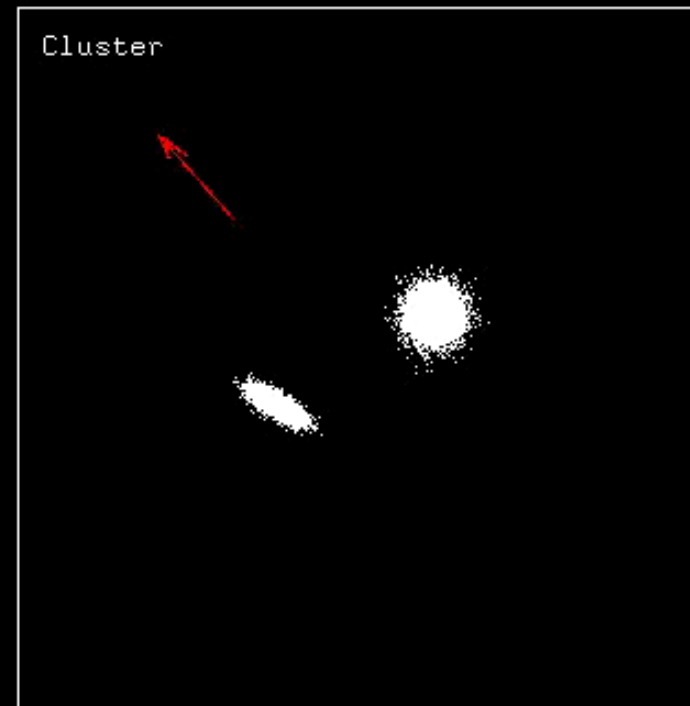
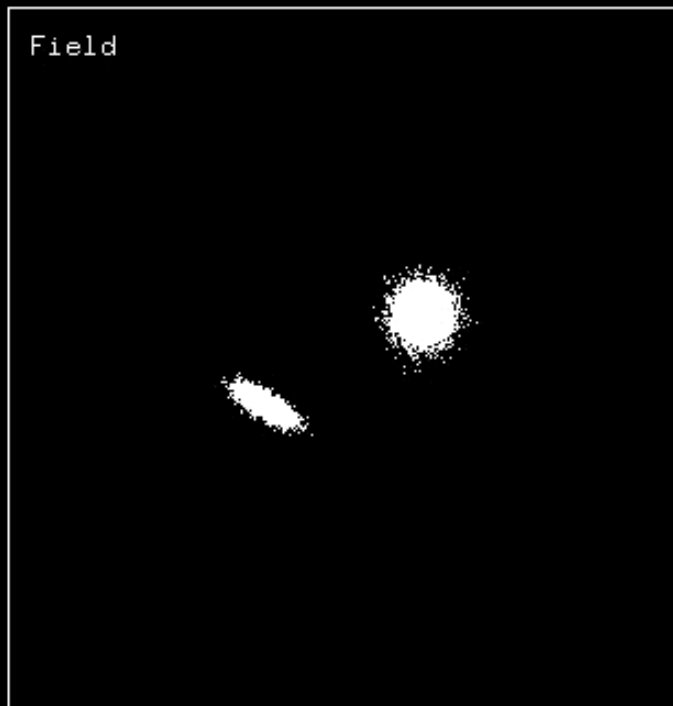
Loops, shells, fans fade more slowly, but are quite diffuse. All this makes searching for tidal signatures a tough game.

Systematic searches:

- Early work: Malin & Carter (1983), Schweizer & Seitzer (1990)
- More recently: van Dokkum (2005), Tal et al (2009)
- *See also Ferriere poster using NGVS / ATLAS3D data*

Overall theme: Ellipticals with merger debris preferentially live in field & group environments, less common in cluster environments

# Tidal Debris in the Cluster Environment



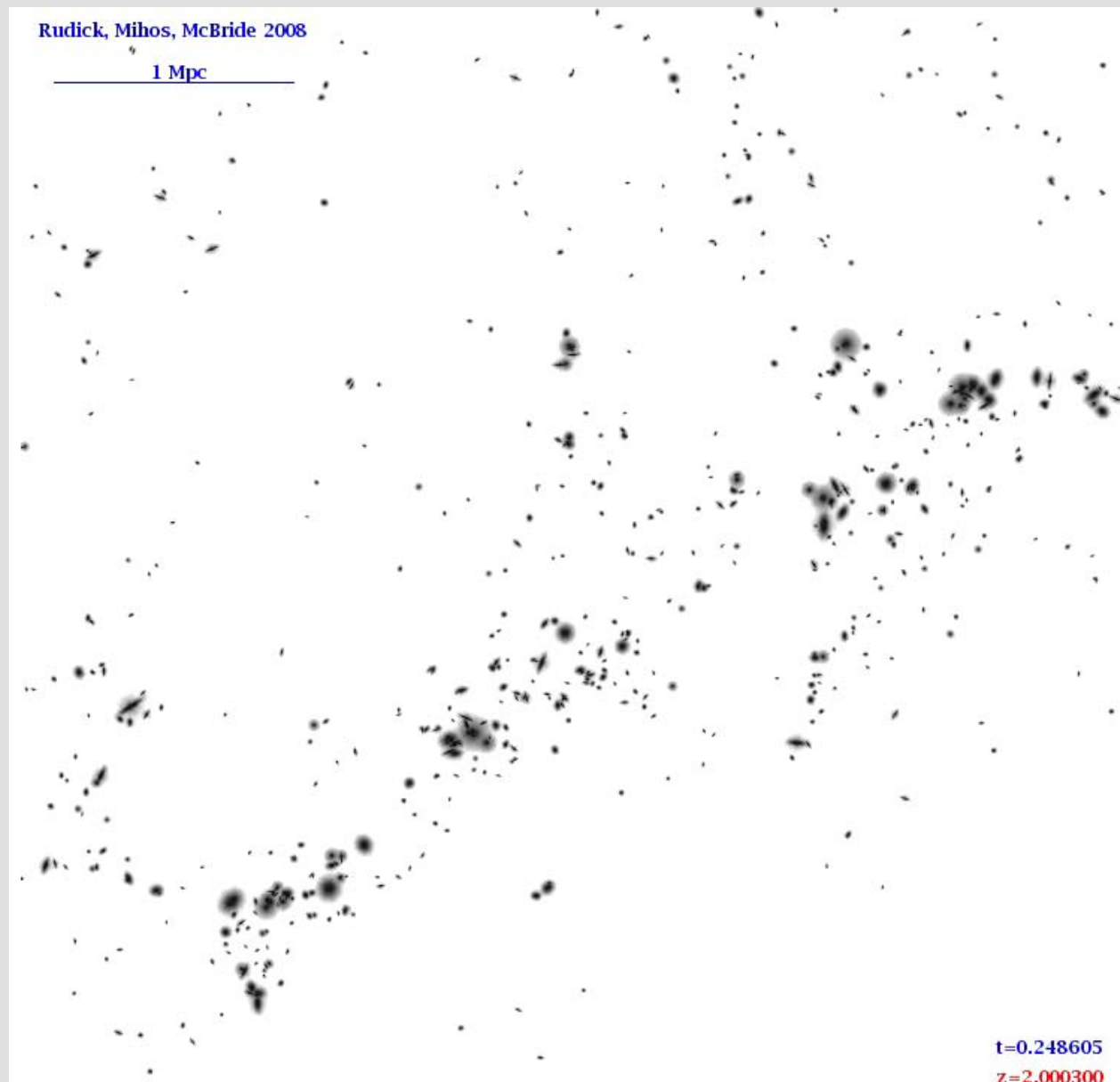
Toy Model: Equal mass merger in field vs cluster environment

# Tidal Debris in the Cluster Environment

Interactions in groups produce streams and shells.

But these local tidal features are quickly stripped, mixing into the cluster and growing the ICL

Live N-body Model  
(Rudick et al 2011)





# Searching in Virgo

Actively accreting cluster with spatial and kinematic substructure

Galaxies well studied at multiple wavelengths

Close enough to have access to discrete population tracers (PNe, GCs, RGB)

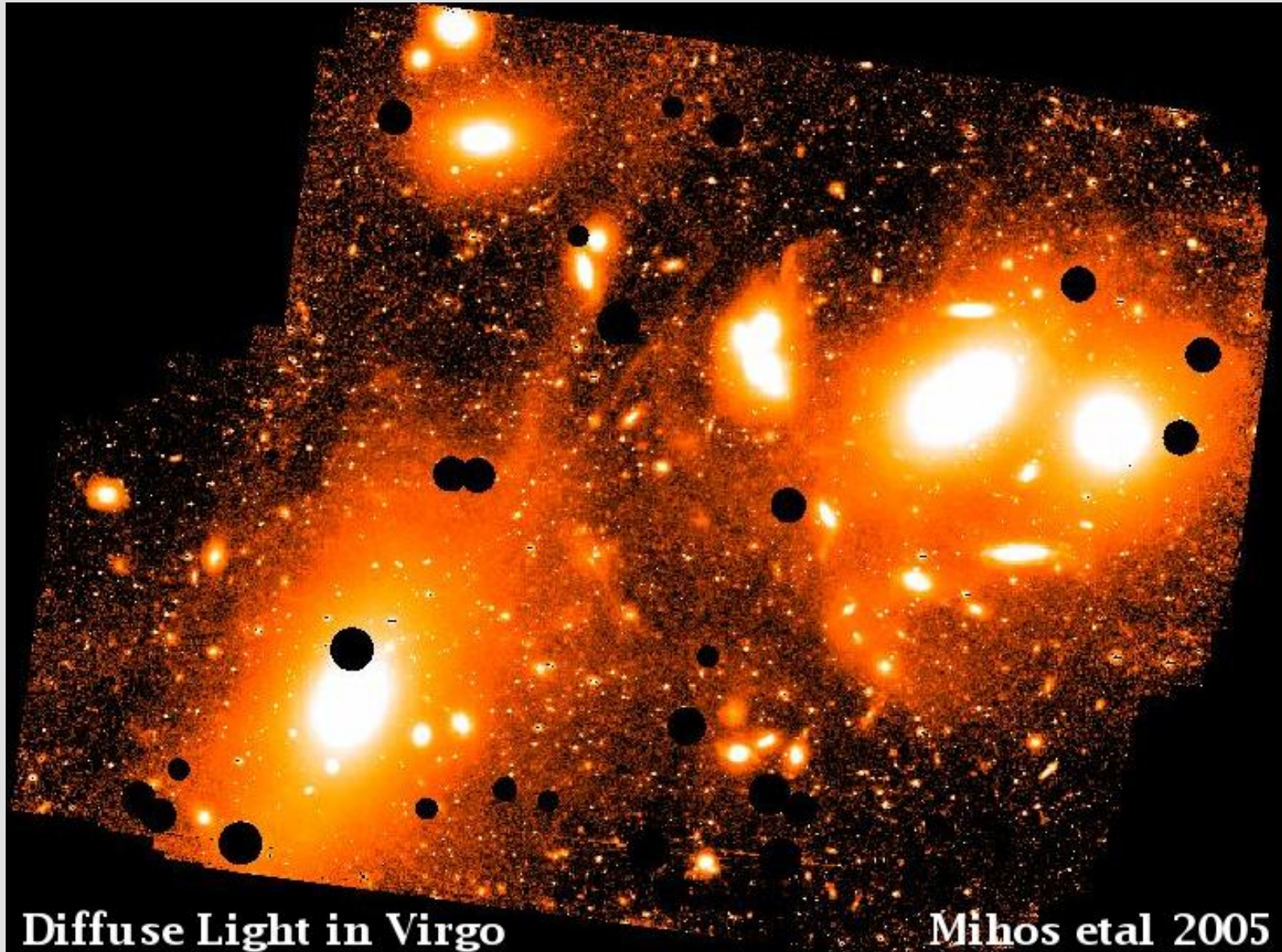
But: we need very deep, very wide field imaging:  $\sim 0.1\%$  of sky over degree scales...

## Imaging Virgo with the CWRU 24/36" Burrell Schmidt

- 2004-2011 spring seasons
- FOV: 0.75x1.5 or 1.5x1.5 degrees onto one CCD
- 1.45"/pix, binned to 13"/pix for LSB structures
- Very aggressive A/R coatings ( $\sim 0.2\%$ )
- 461 x 900s M ("V") images, 153 x 1200s B images
- Similar number of flanking skies for flat fielding
- PSF well-characterized to  $\sim 1$  degree



# Diffuse Light in Virgo



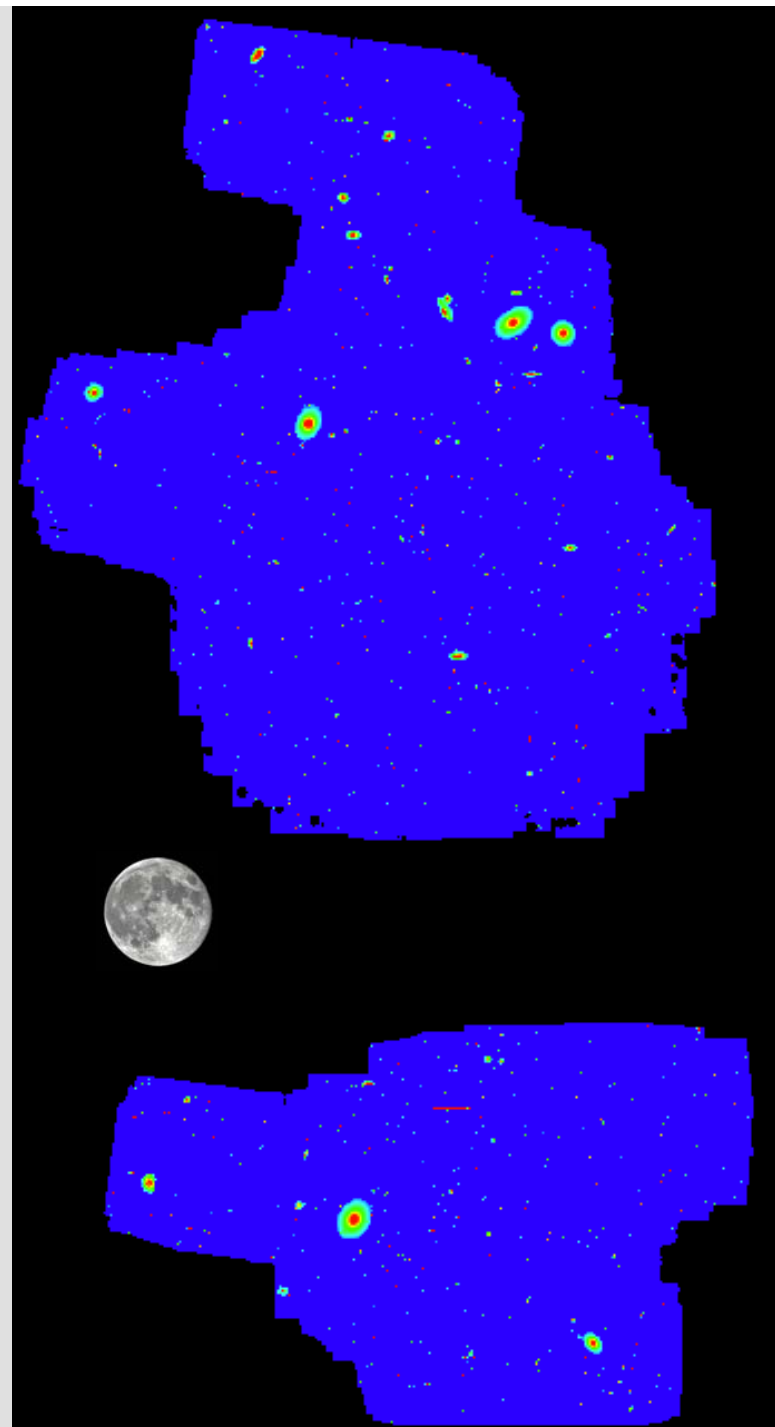
**Diffuse Light in Virgo**

**Mihos et al 2005**

# Virgo Deep Imaging

- V imaging
  - 16.3 degrees<sup>2</sup>
  - Median exposure: 7.5hr
  - Max exposure: 25.75 hrs
  - $V_{\text{lim}} \sim 28.5 \text{ mag/arcsec}^2$

Virgo  $\mu_V < 25.0$   
Mihos et al 2011

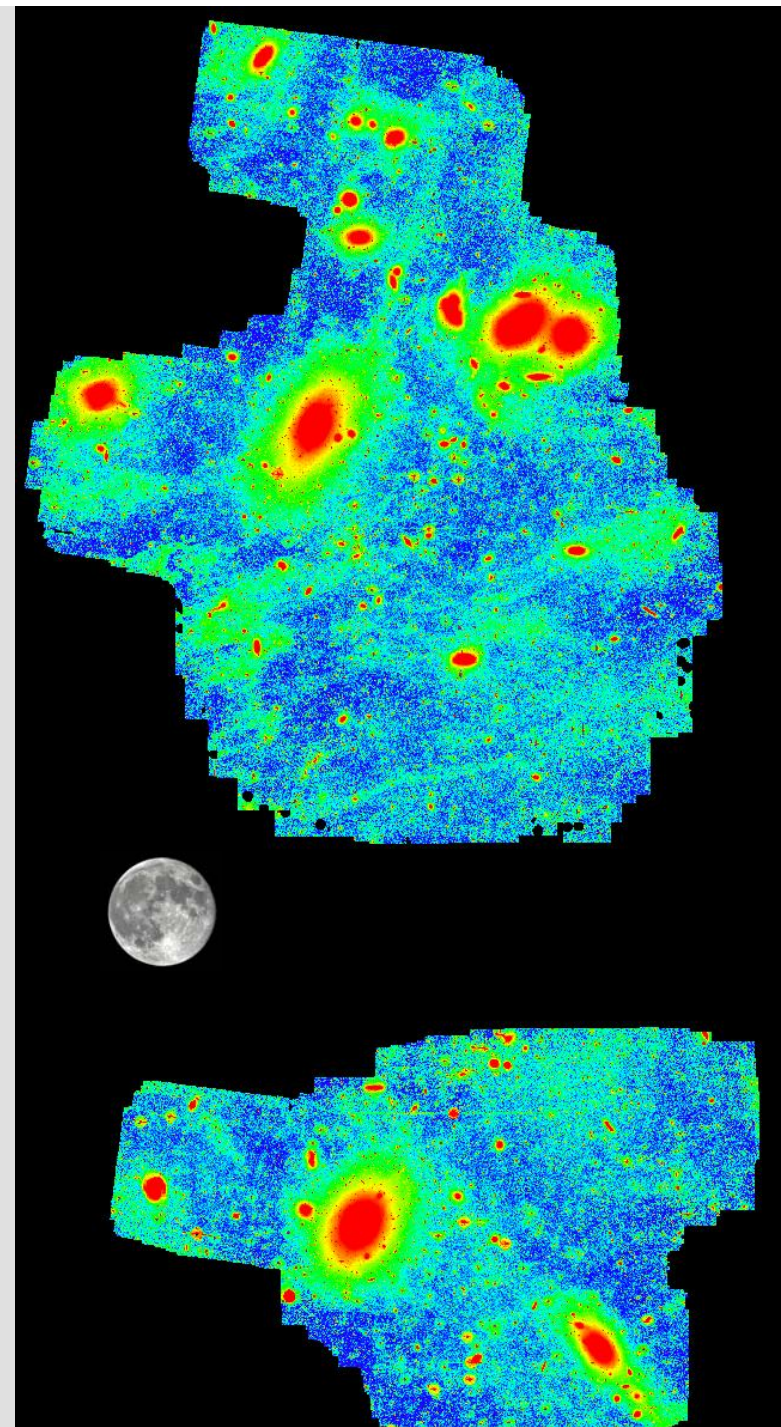




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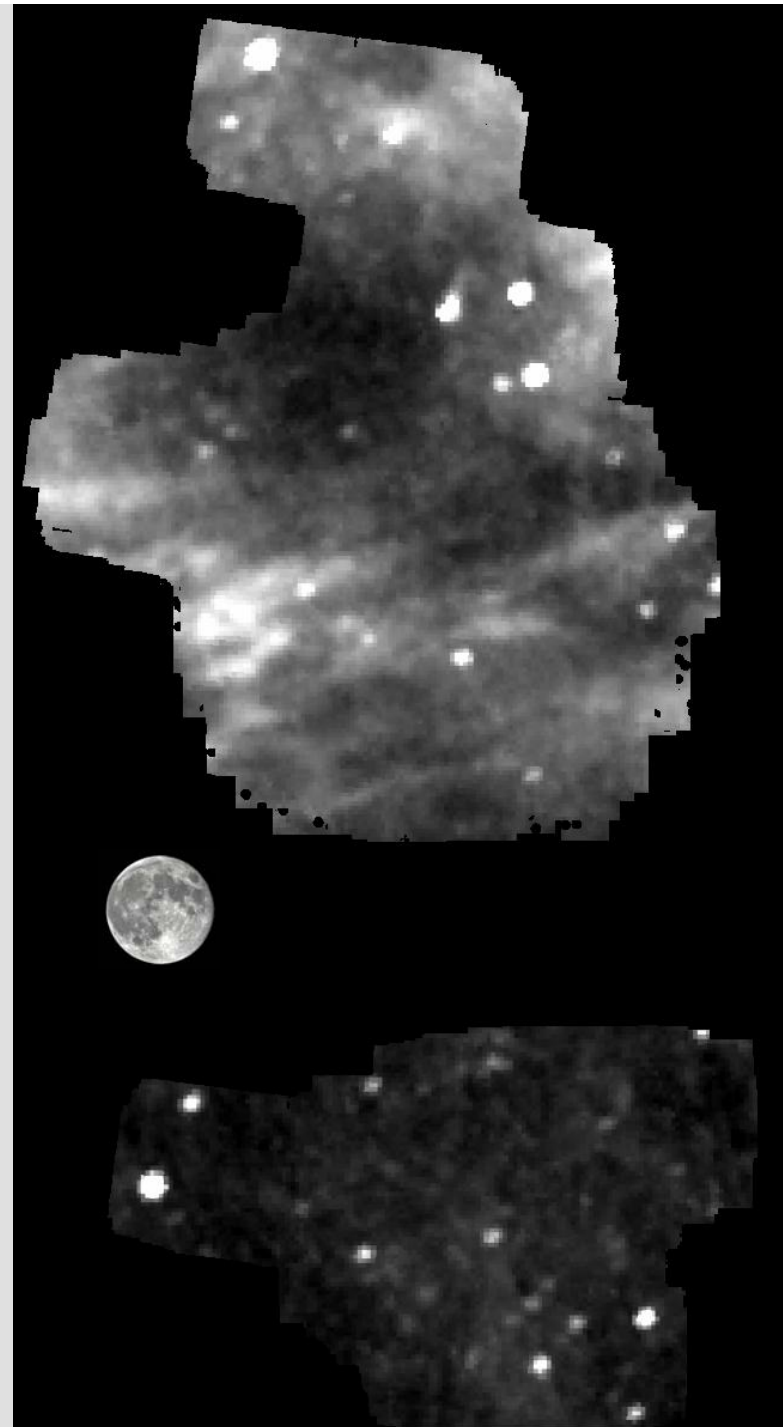
Virgo  $\mu_V < 28.5$   
Mihos et al 2011



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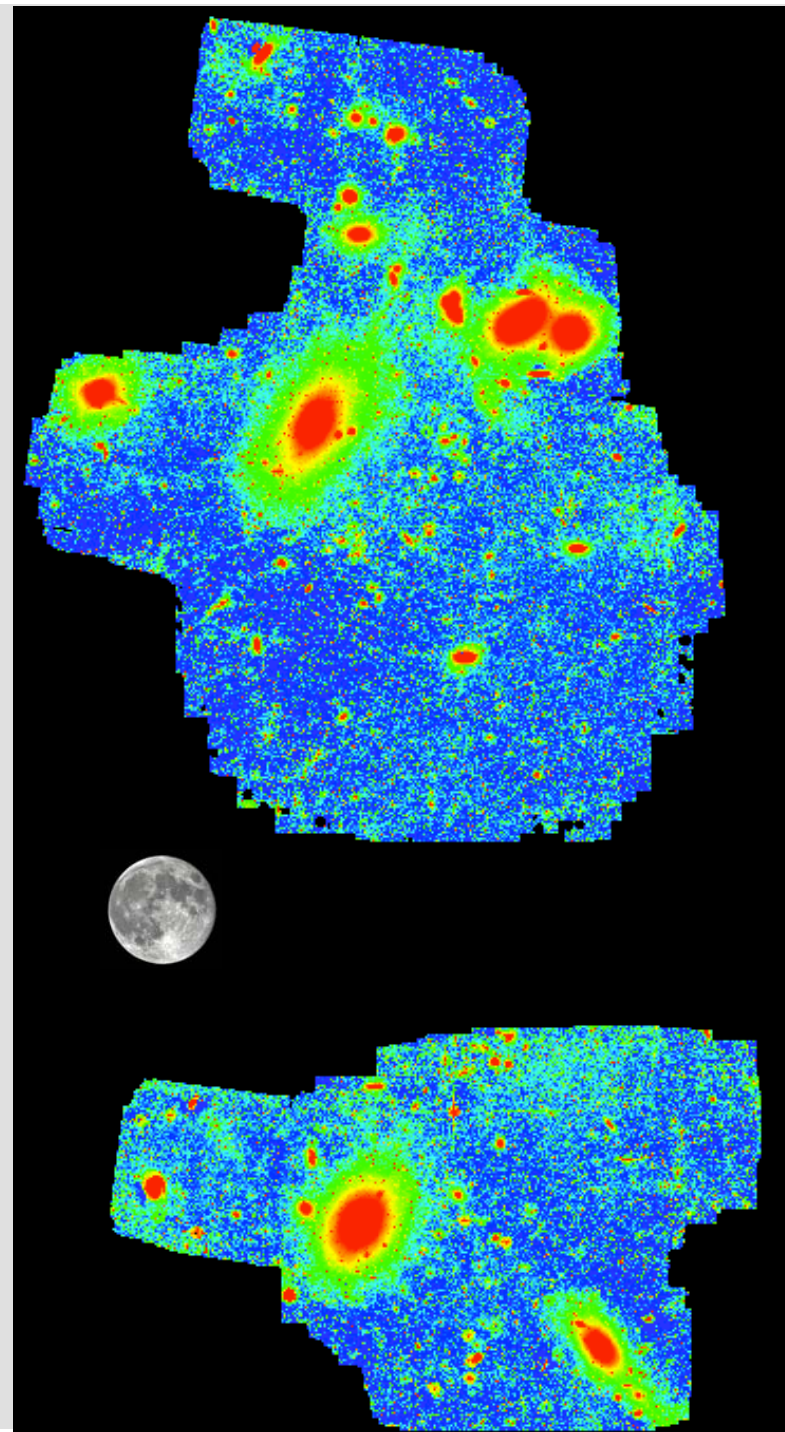
IRIS 100 $\mu$  map



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“dust corrected”  
Mihos, last night

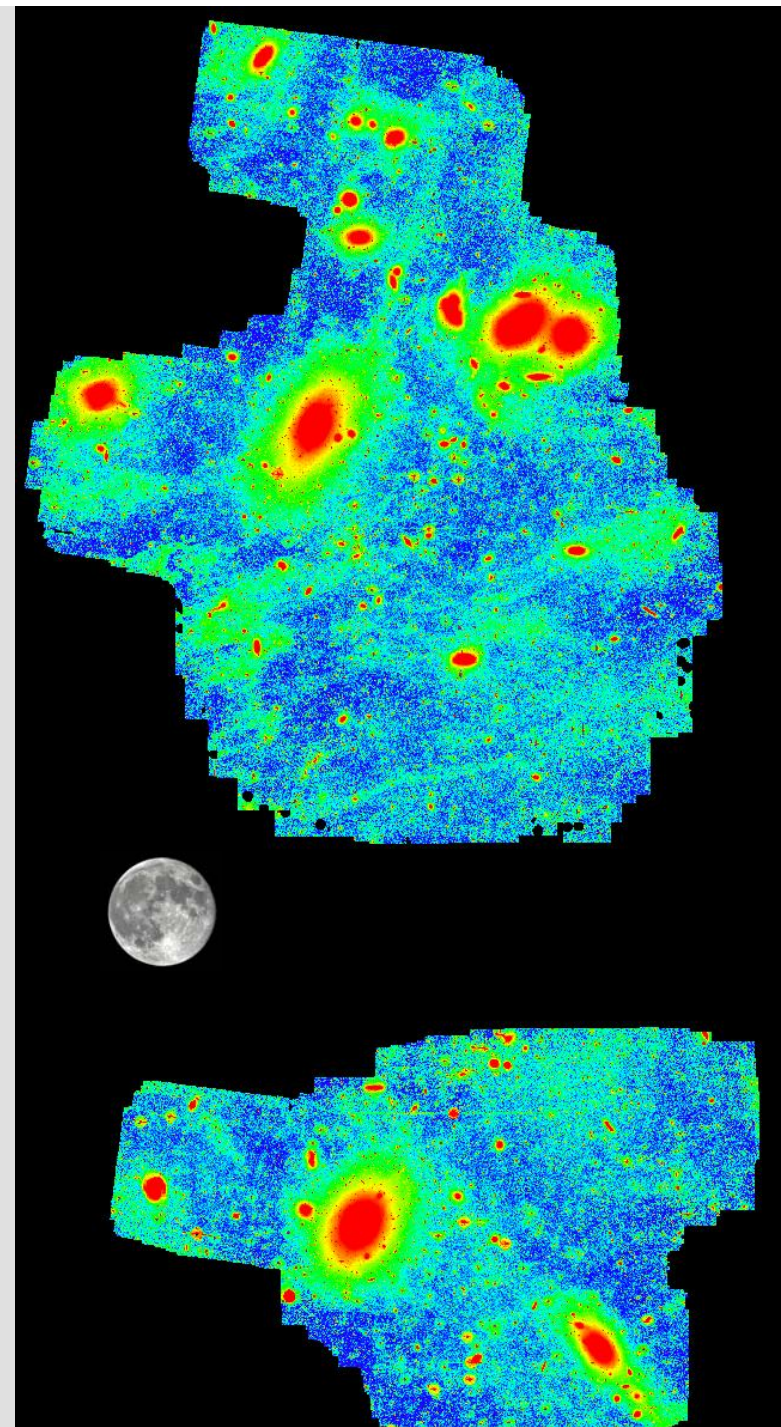




# Virgo Deep Imaging

- V imaging
  - 16.3 degrees<sup>2</sup>
  - Median exposure: 7.5hr
  - Max exposure: 25.75 hrs
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Virgo  $\mu_V < 28.5$   
Mihos et al 2011

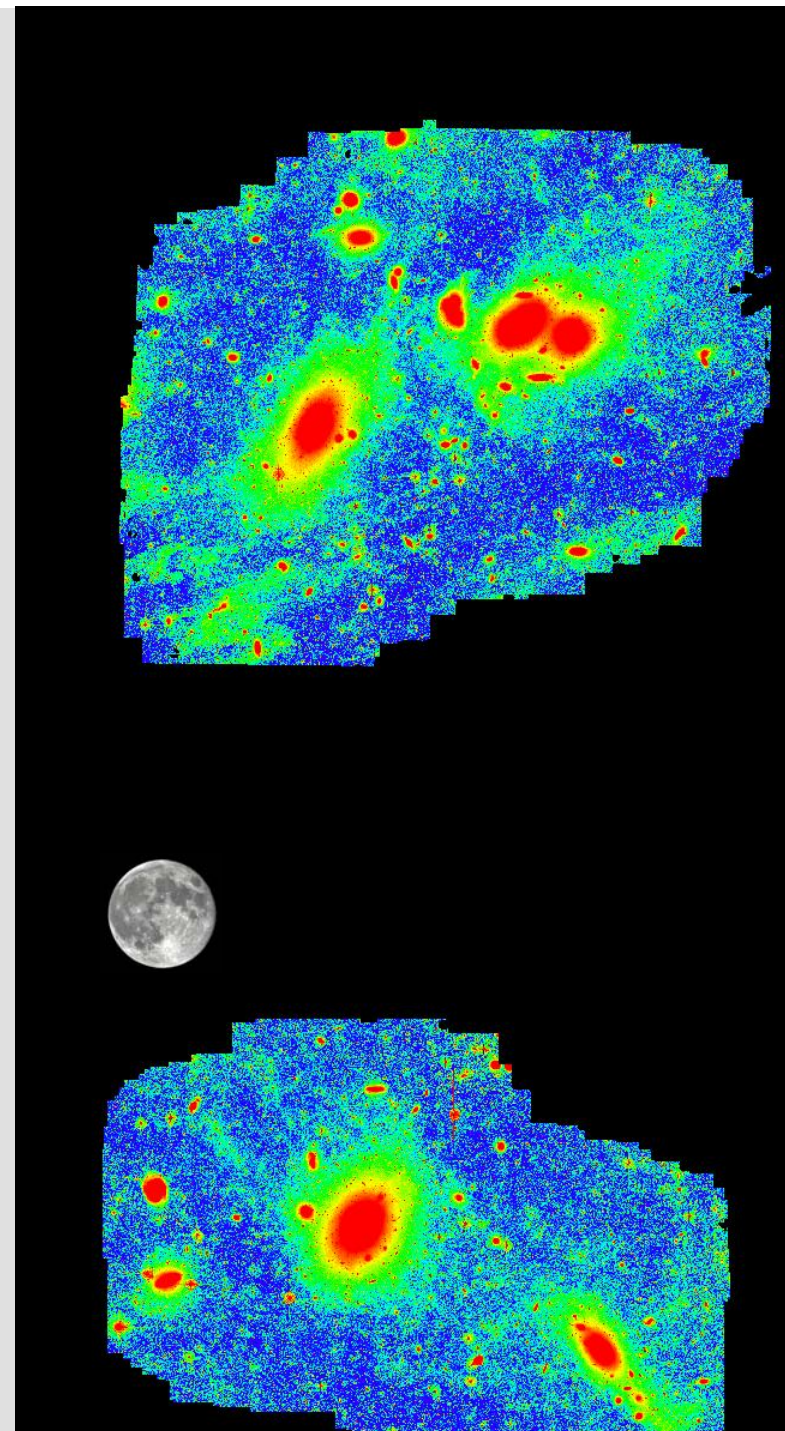




# Virgo Deep Imaging

- B imaging
  - 15.1 degrees<sup>2</sup>
  - Median exposure: 7.75hr
  - Max exposure: 23.7 hrs
  - $B_{\text{lim}} \sim 29.0 \text{ mag/arcsec}^2$

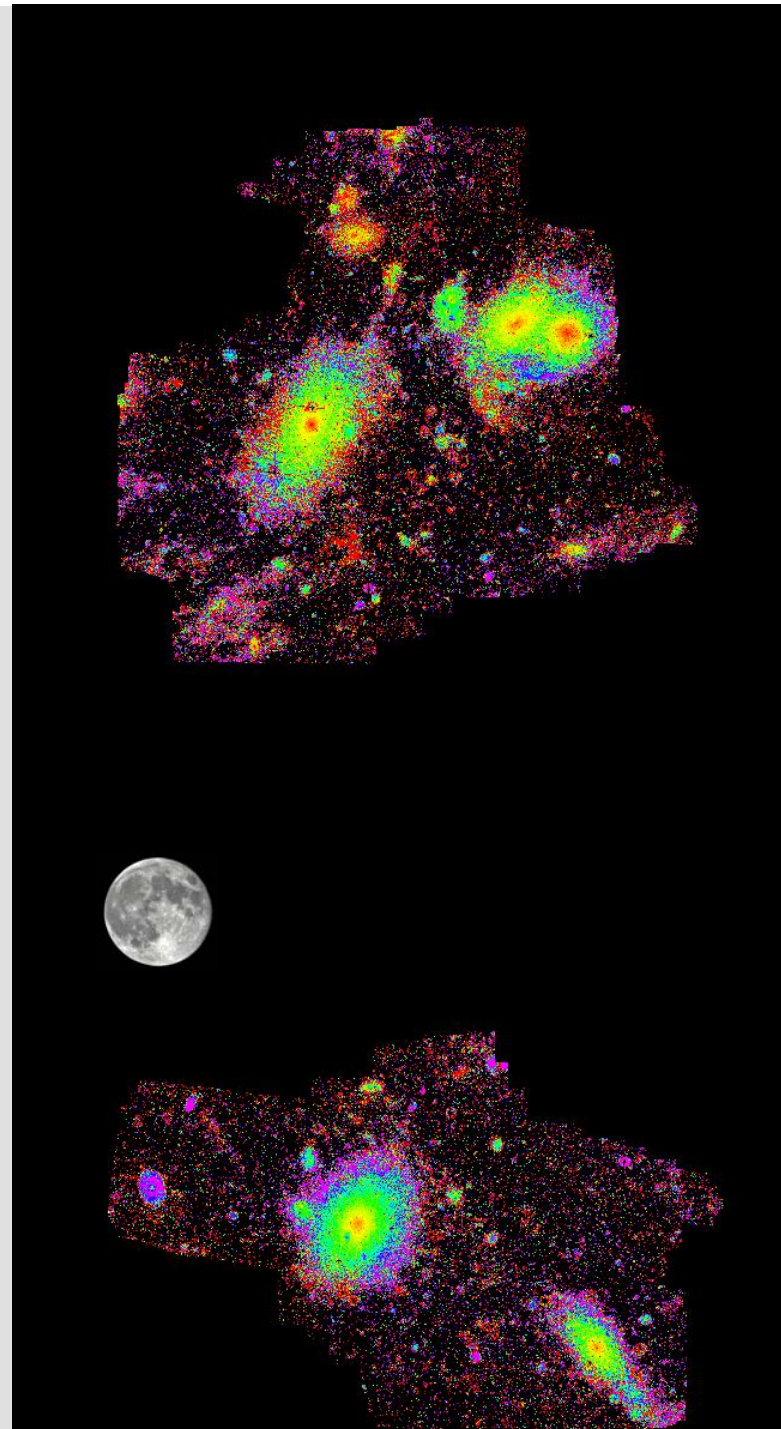
Virgo  $\mu_B < 29.0$   
Mihos et al 2011



# Virgo Deep Imaging

- B-V color mapping
  - 10.9 degrees<sup>2</sup>

Mihos et al 2011





# M49 (NGC 4472)

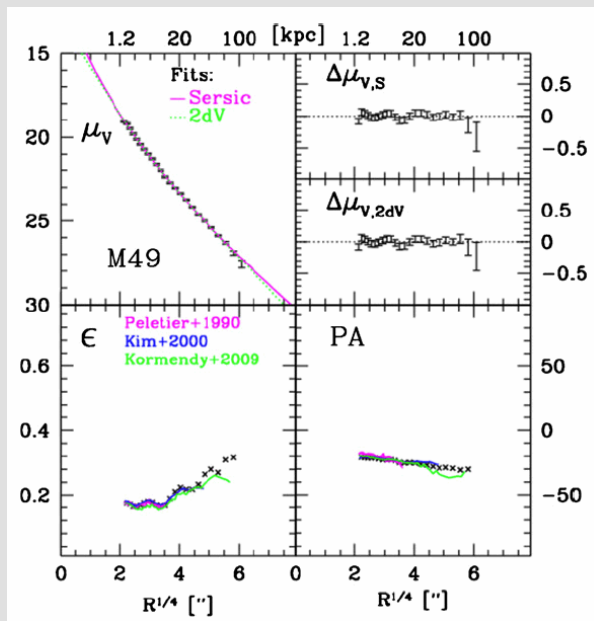
Most luminous galaxy in the Virgo “Cluster B”

Projected 4.4° (1.2 Mpc) to the South of M87

Identified as *undisturbed* in the imaging survey of Tal et al (2009)



Janowiecki et al 2010



# M49 (NGC 4472)

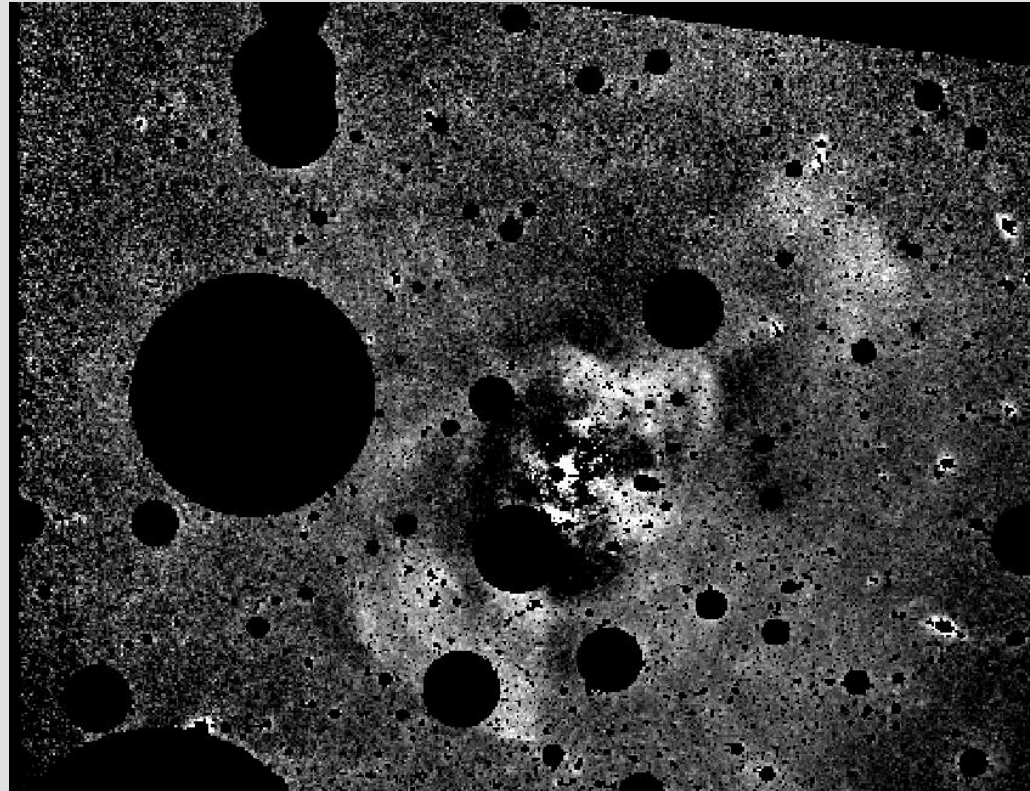
Large system of radial shells (e.g., Hernquist & Quinn 1988, 1989)

Several other small features

$$L_{\text{sub}} \sim 7 \times 10^8 L_{\text{sun}} \quad (0.5\% L_{\text{tot}})$$

Shells confirmed in NGVS imaging  
(see Ferriere poster)

Demonstrates the need for deep  
and wide field imaging.



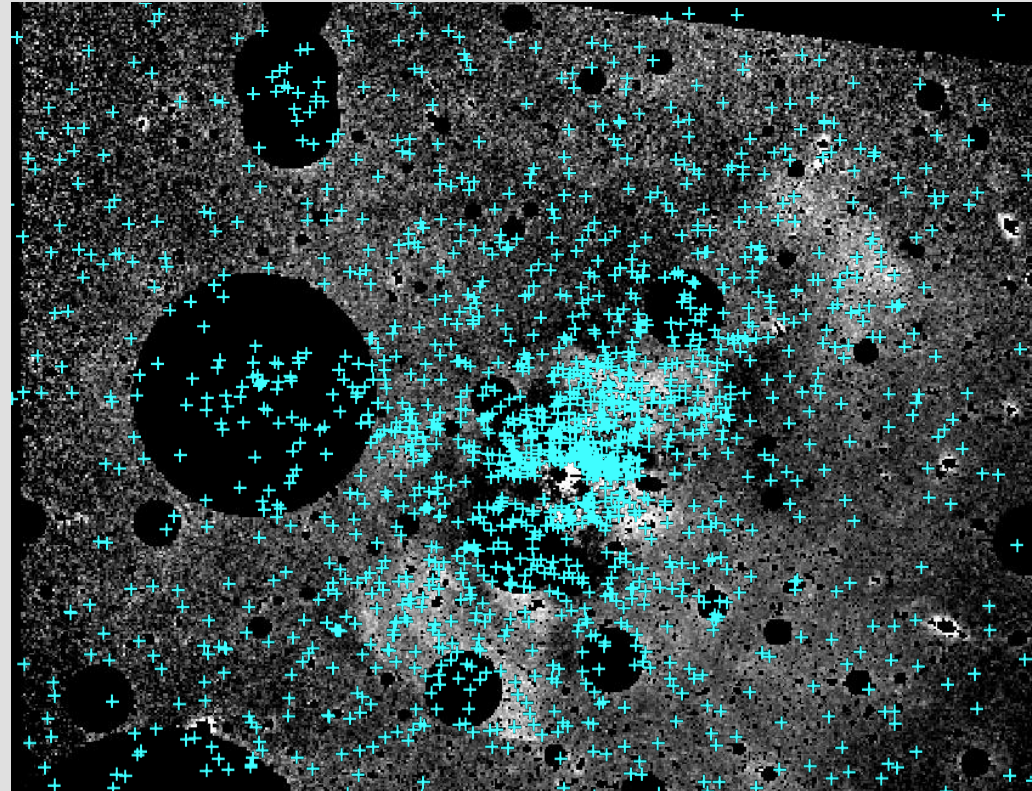
Janowiecki et al 2010



# M49 (NGC 4472)

A very interesting target for kinematic studies!

*“We also note the presence of a well-defined grouping of 10 metal-rich GCs that ... may be the relic of a past merger or accretion event.” –Côté et al 2003*

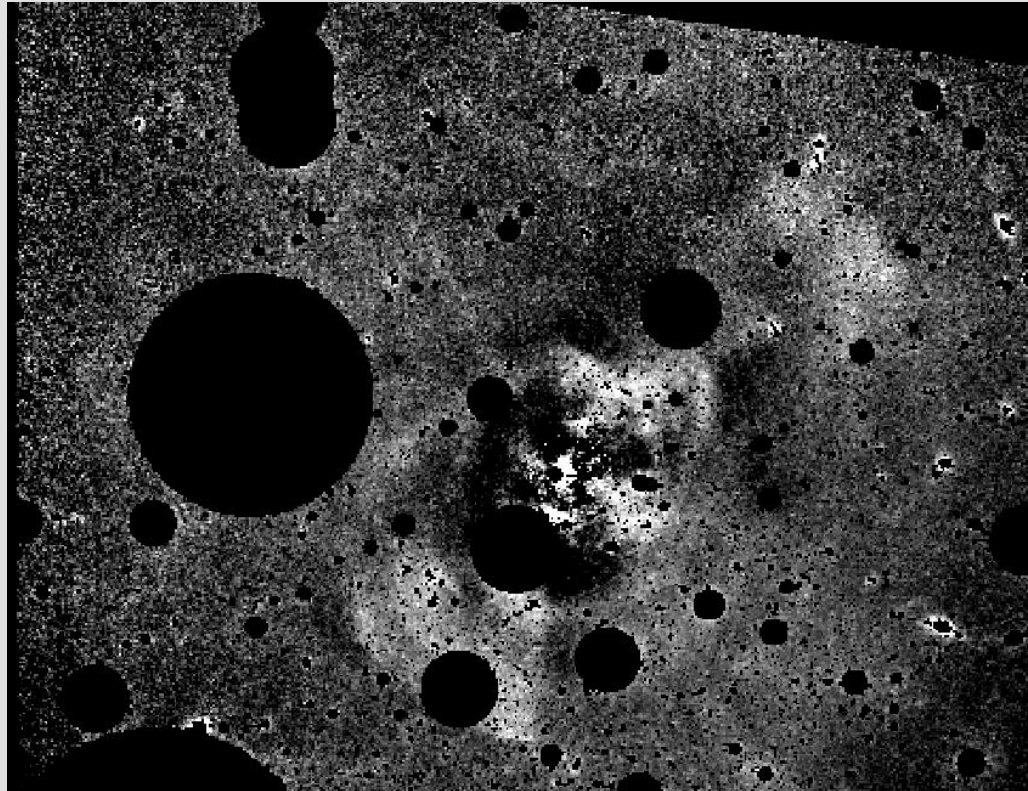


NGVS GC candidates  
(from Eric Peng)

Janowiecki et al 2010

# M49 (NGC 4472)

What about shell colors?



Janowiecki et al 2010

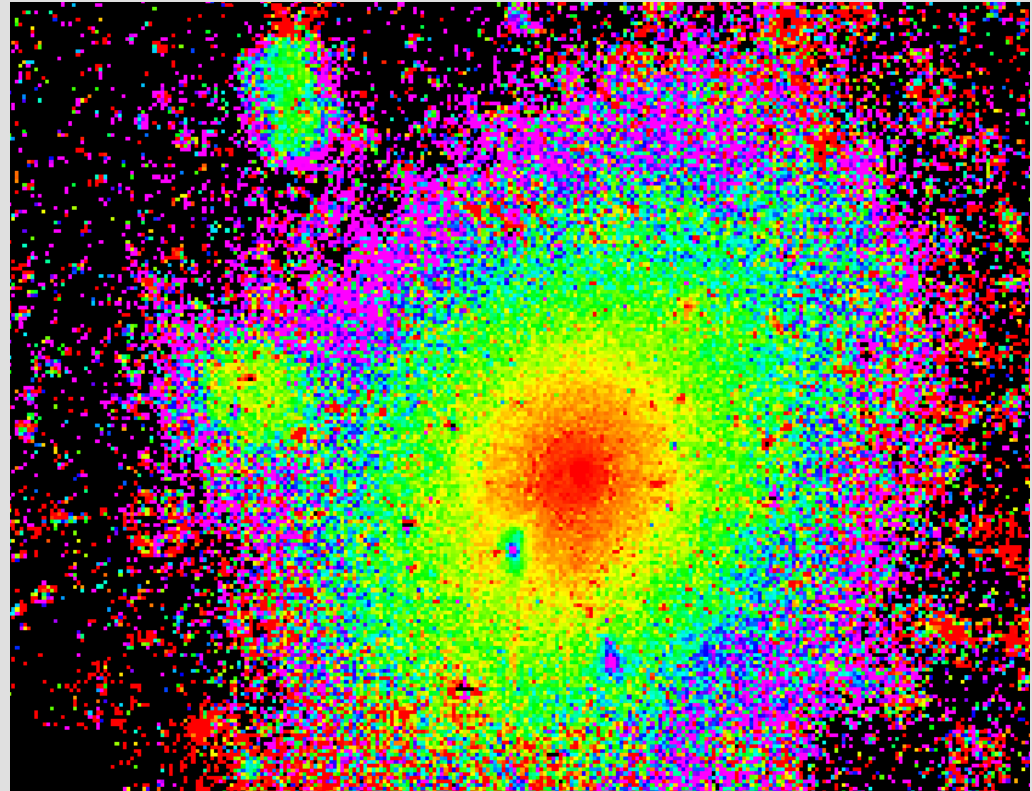
# M49 (NGC 4472)

What about shell colors?

B-V color map down to  $\mu_V=27.5$   
at  $r=100\text{kpc}$

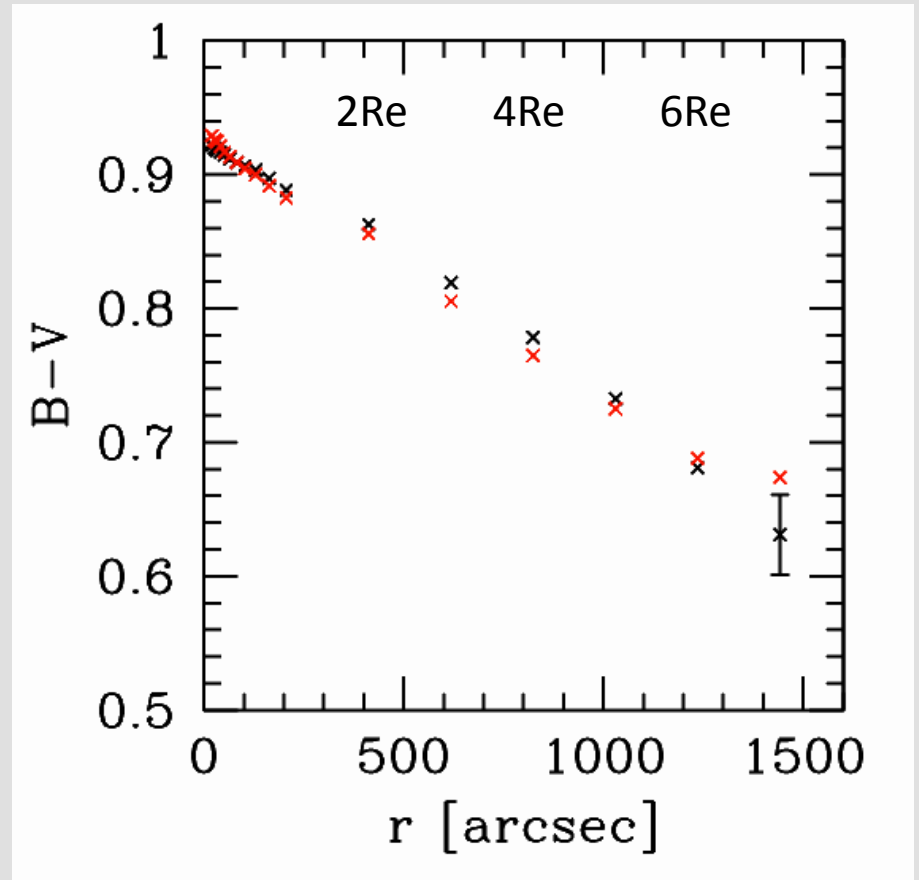
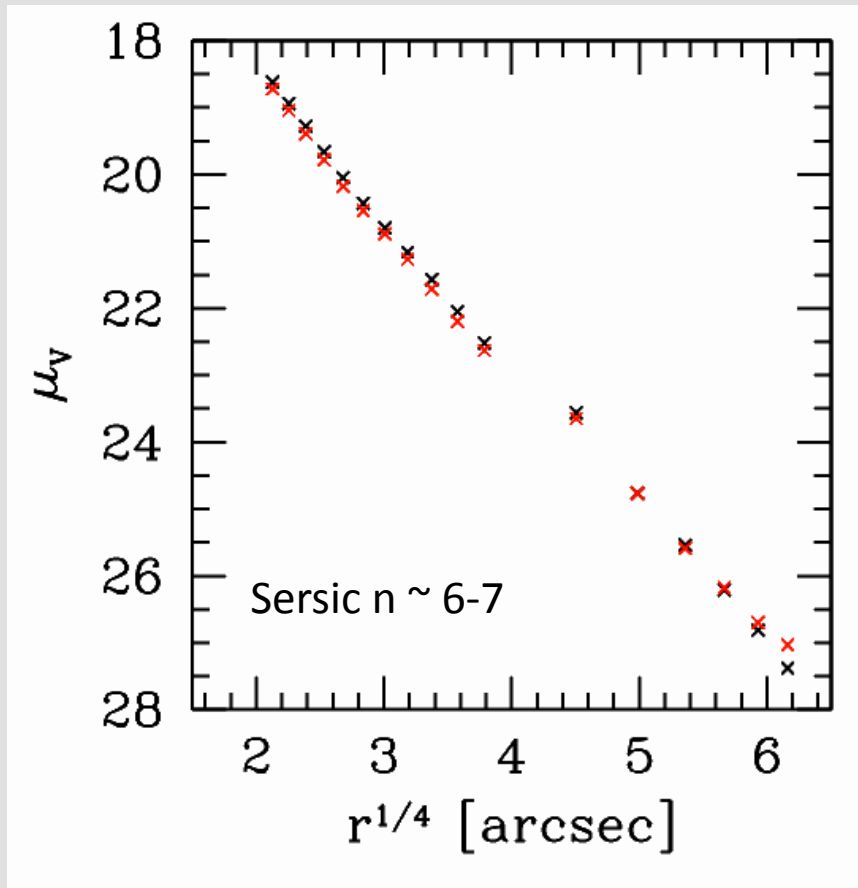
NW shell stands out in color,  
 $\sim 0.05+$  mags redder than  
surrounding halo.

Accretion events flattening the  
halo color gradient?



# M49 (NGC 4472)

black: azimuthally averaged, red: shell wedge

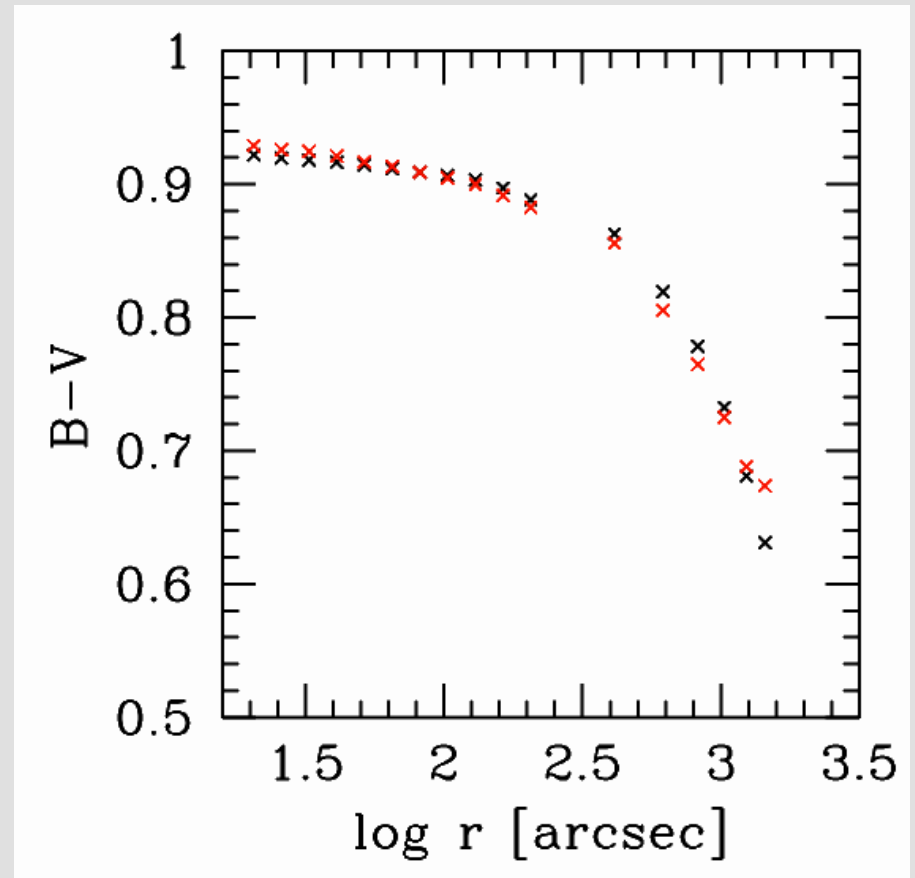
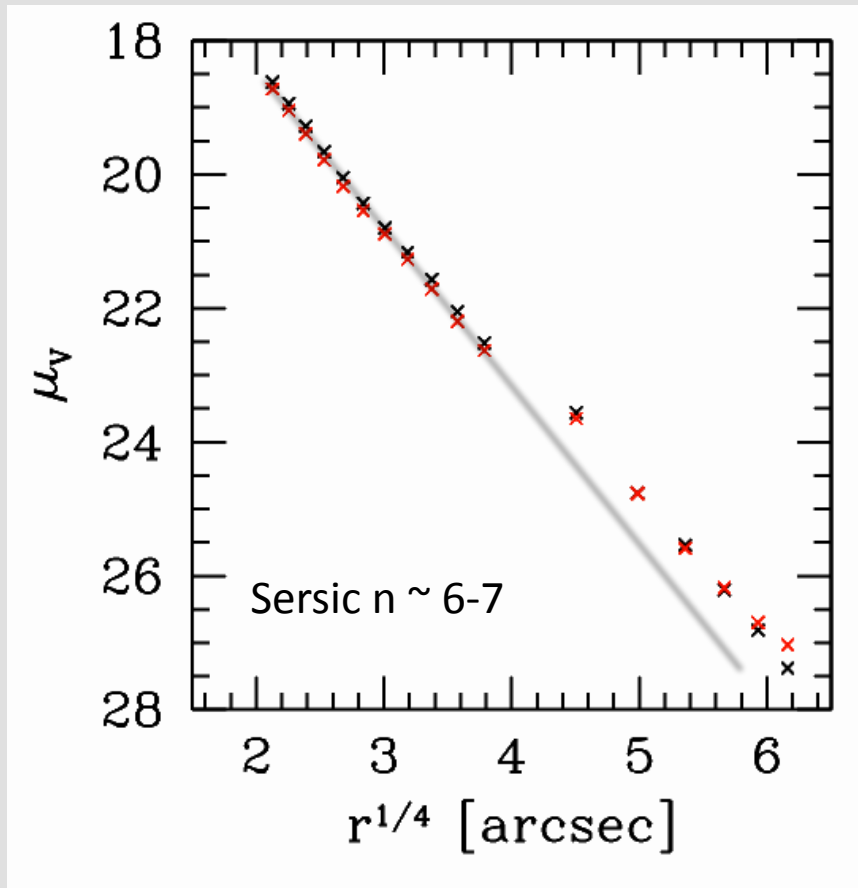


Mihos, last Friday



# M49 (NGC 4472)

black: azimuthally averaged, red: shell wedge



Mihos, last Friday

inner profile:  $d(B-V)/d\log r \sim -0.03$

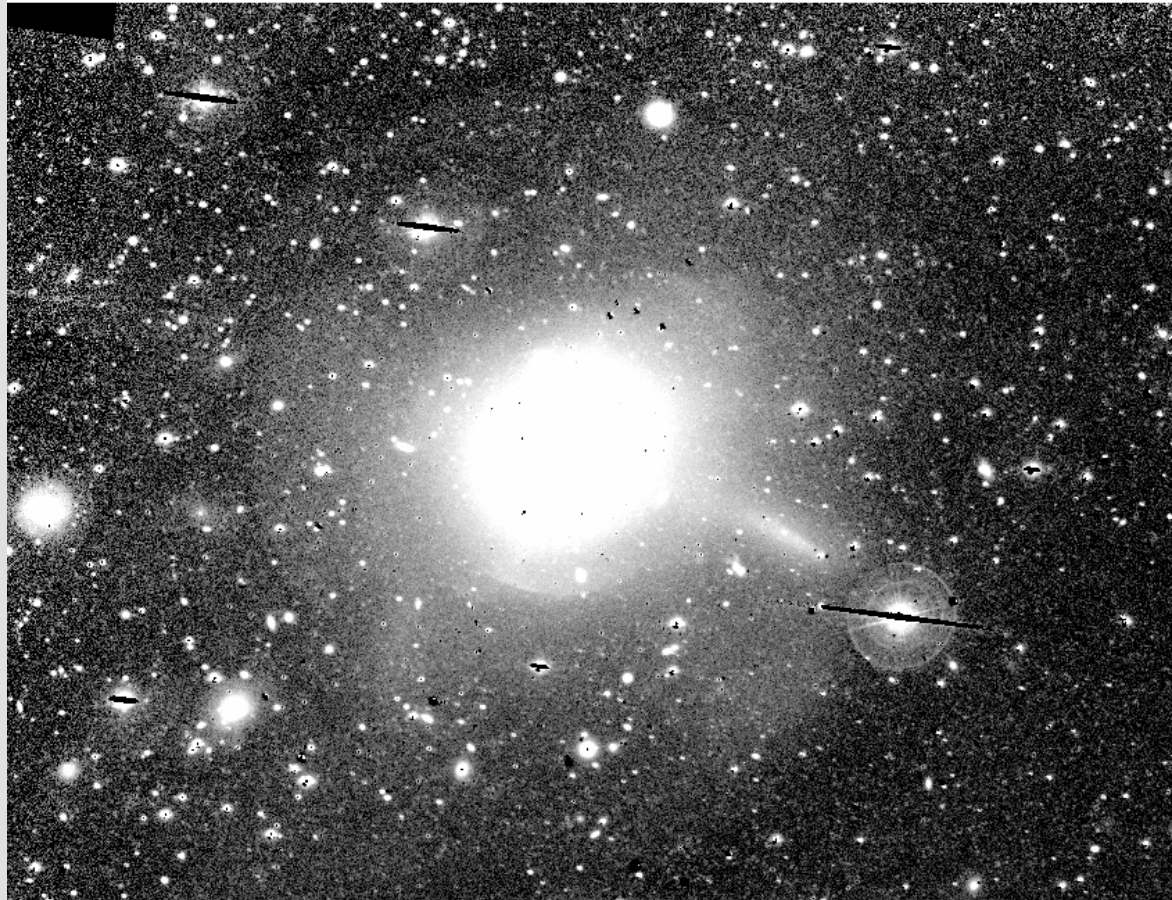
outer profile:  $d(B-V)/d\log r \sim -0.4 - -0.5(!)$

# M89 (NGC 4552)

E gal located  $1.2^\circ$  (335 kpc) east of M87.

Several substructures identified photographically by Malin (1979).

X-ray morphology suggests it is moving N through the cluster (Machecek et al 2006).

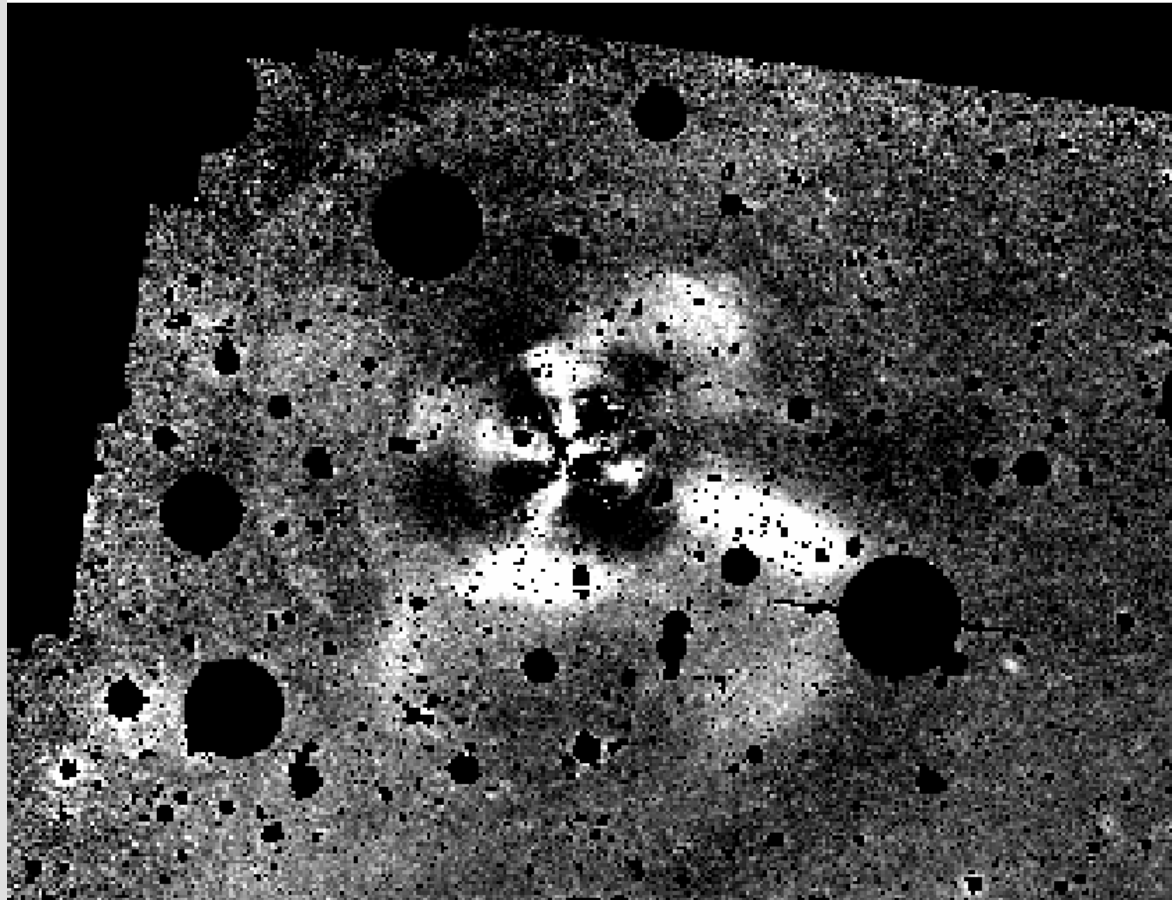


# M89 (NGC 4552)

Many distinct tidal features revealed after subtraction.

Multiple events?

$$L_{\text{sub}} \sim 10^9 L_{\text{sun}} \quad (2\% L_{\text{tot}})$$



Janowiecki et al 2010

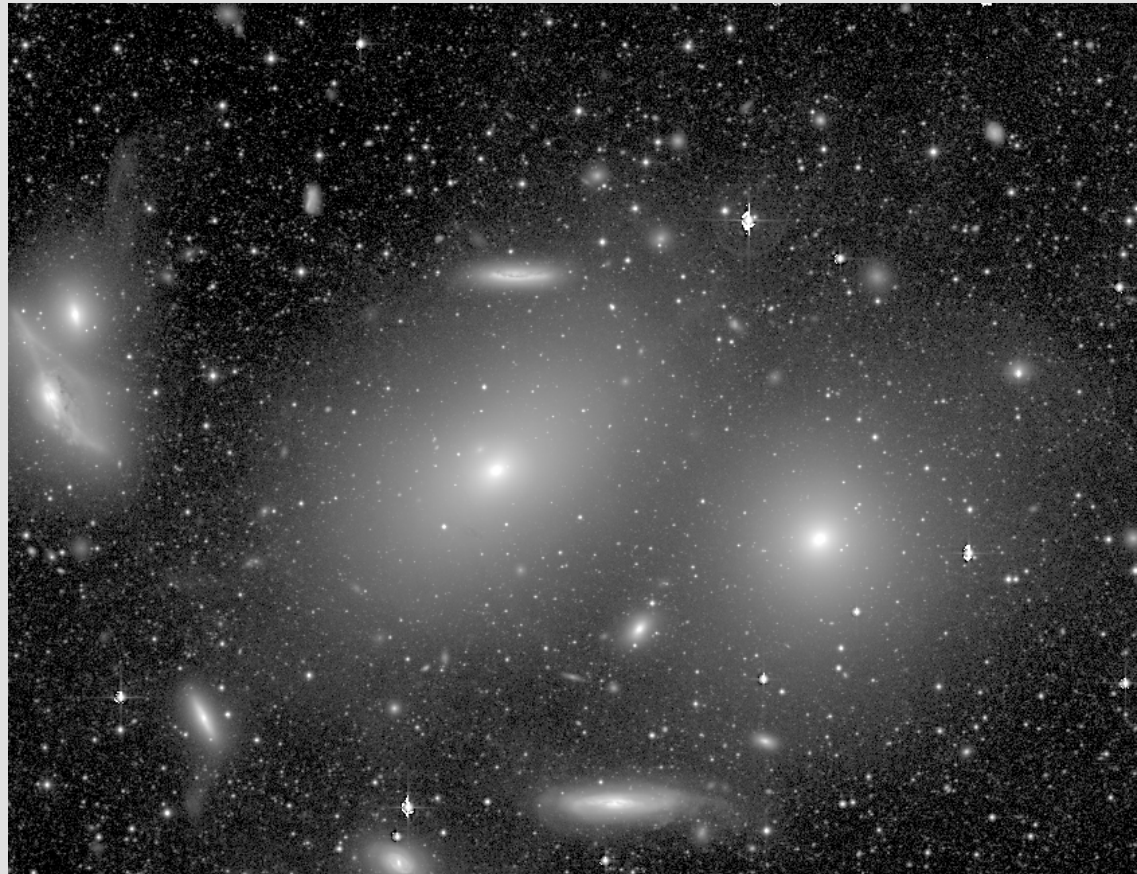


# M86/M84 (NGC 4406/NGC4374)

M86 moving at high speed through the Virgo Cluster.

X-ray tail (Randall et al 2008) and H $\alpha$  filaments (Kenney et al 2008) attest to its motion.

M86/M84 isophotes overlap in projection.





# M86/M84 (NGC 4406/NGC4374)

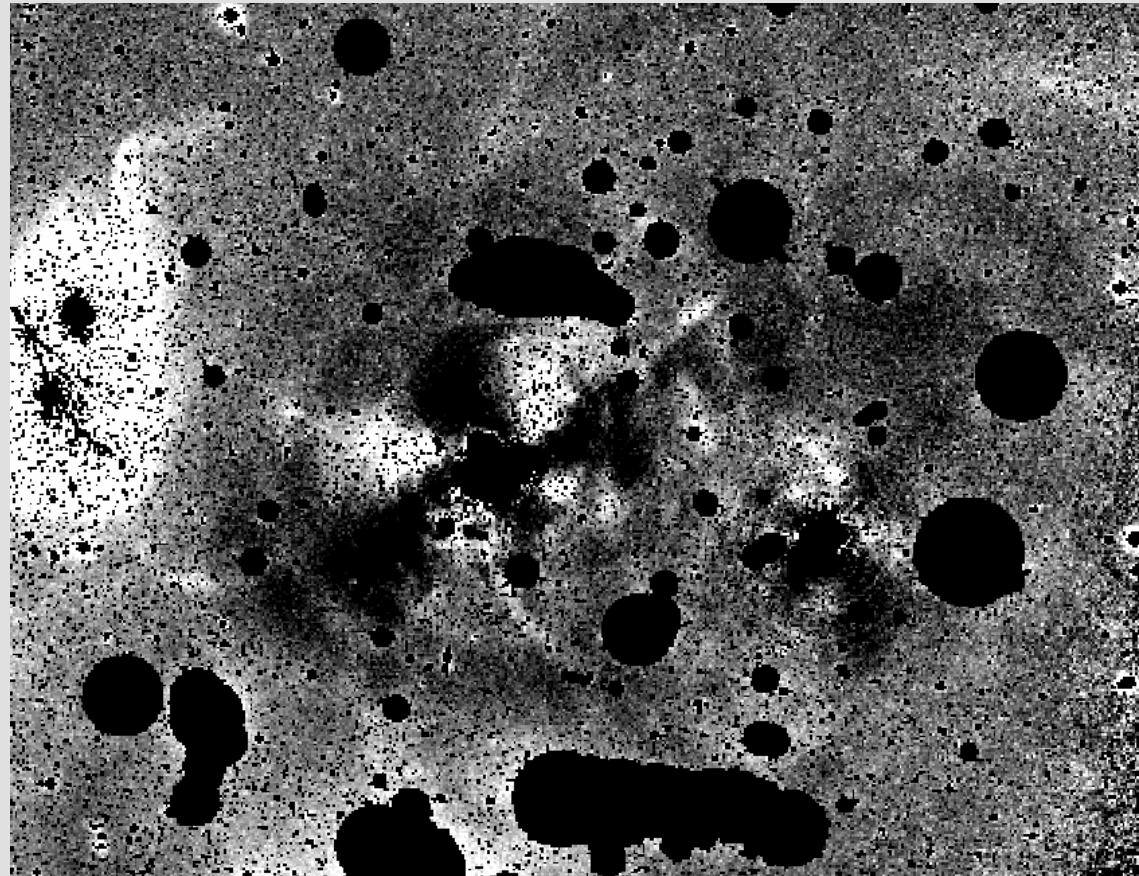
Lots of dwarf accretion streams but no major shells or plumes.

M86:

$$L_{\text{sub}} \sim 10^8 L_{\text{sun}} (0.1\% L_{\text{tot}})$$

M84:

$$L_{\text{sub}} \sim 4 \times 10^7 L_{\text{sun}} (0.05\% L_{\text{tot}})$$



Janowiecki et al 2010

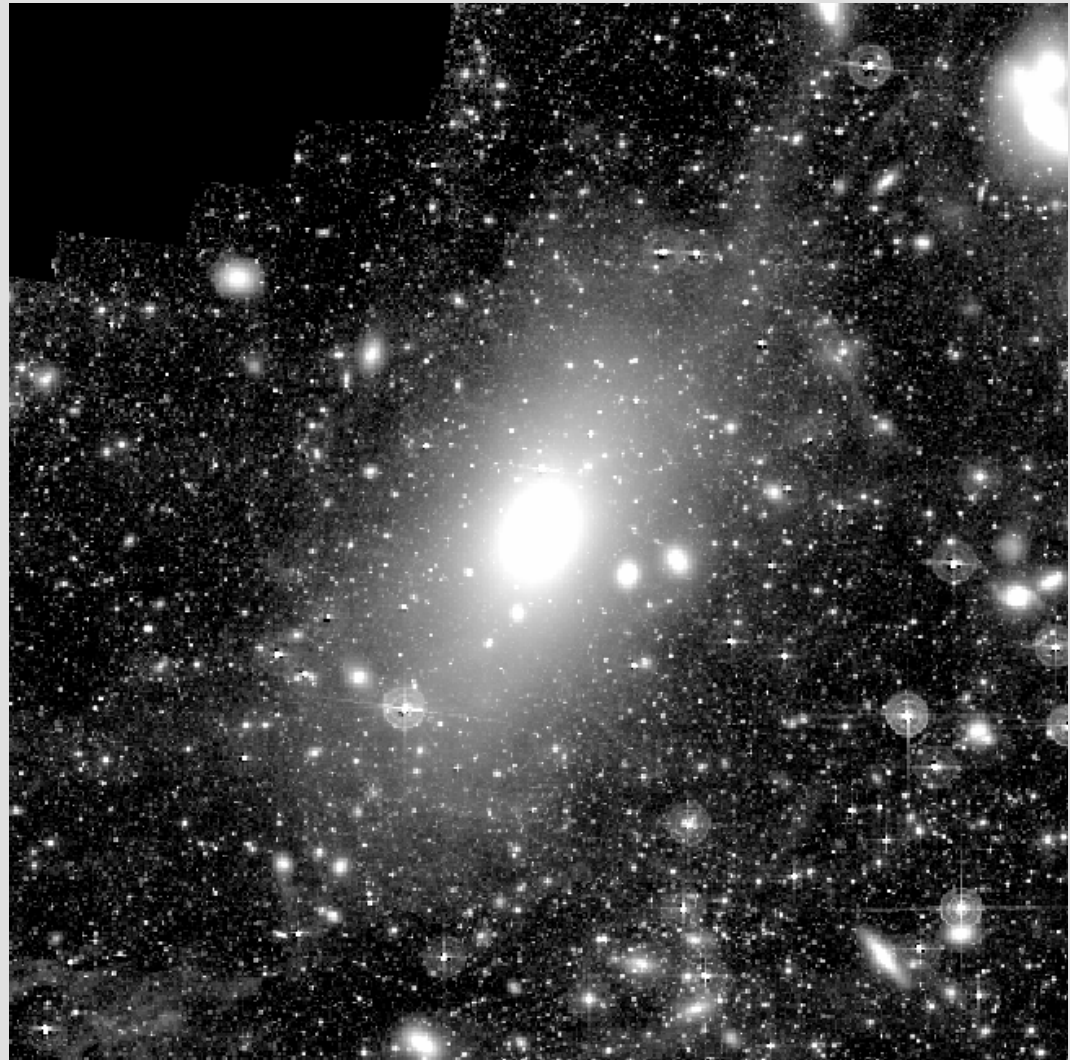
# M87 (NGC 4486)

Central galaxy in Virgo

Weil et al (1999) claimed a detection of diffuse light tracing an accretion event.

Mihos et al (2005) show tidal ICL streams to the NW.

X-ray morphology suggests gas-sloshing from accretion (Foreman talk).



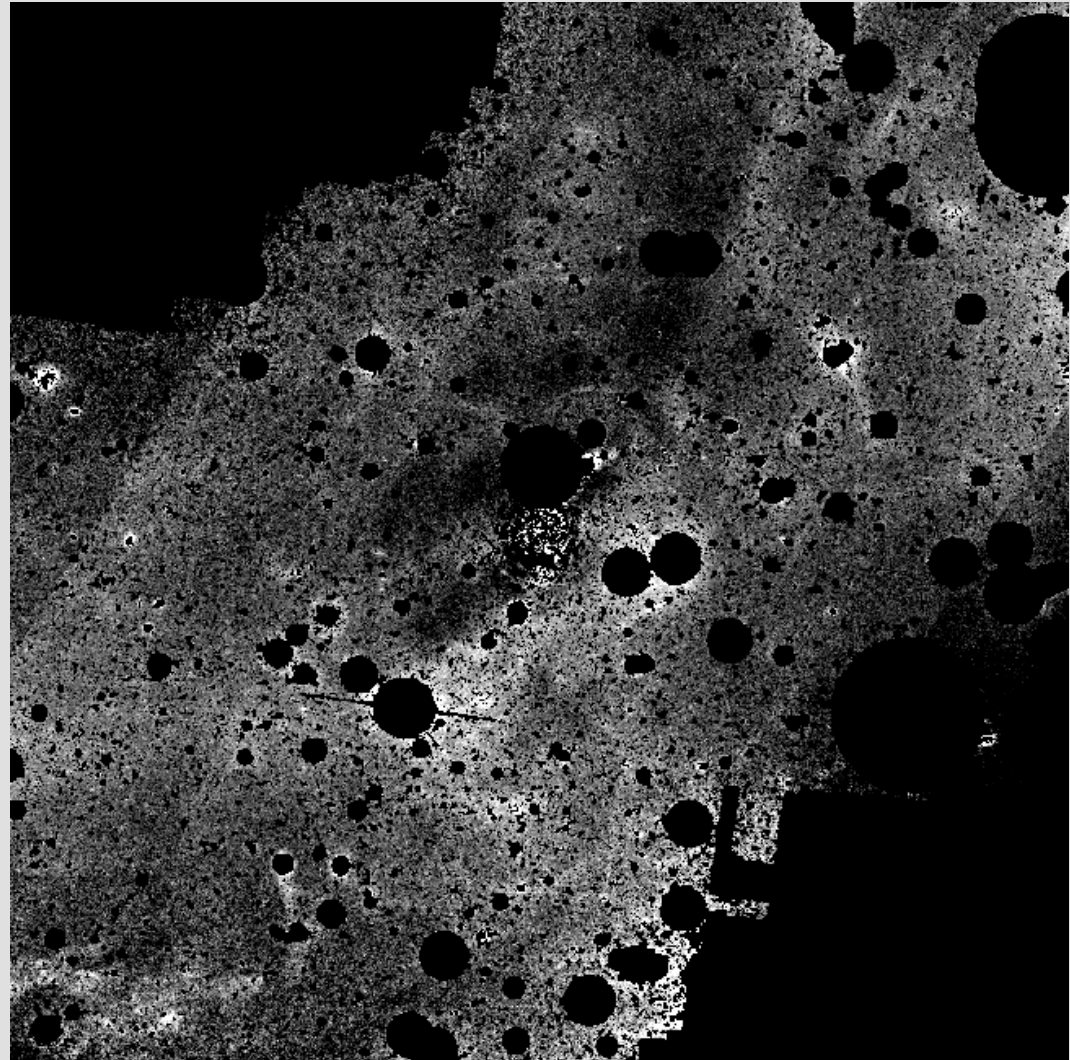


# M87 (NGC 4486)

....but not much there other than the long outer streams:

cirrus contamination is worrisome.

$$L_{\text{sub}} \sim 4 \times 10^8 L_{\text{sun}} \quad (0.4\% L_{\text{tot}})$$

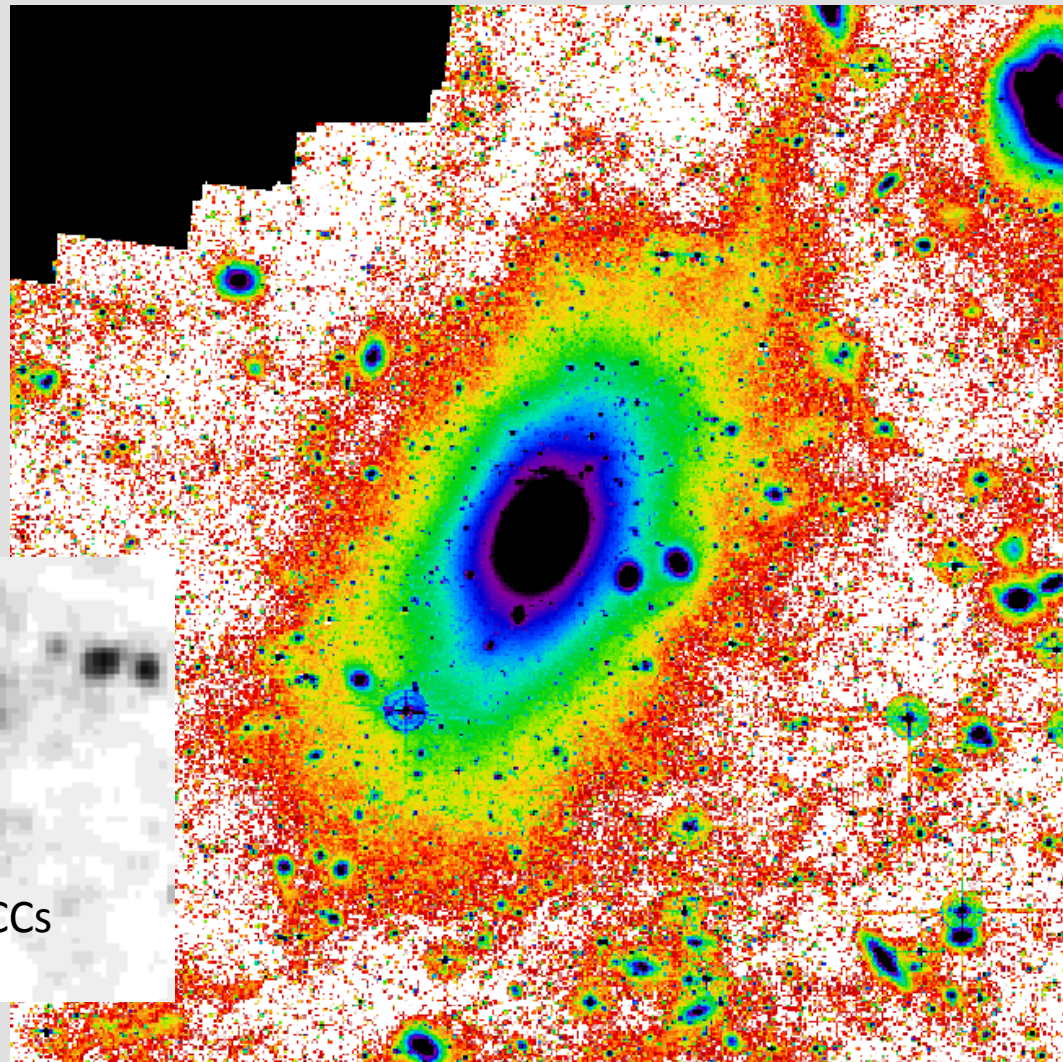
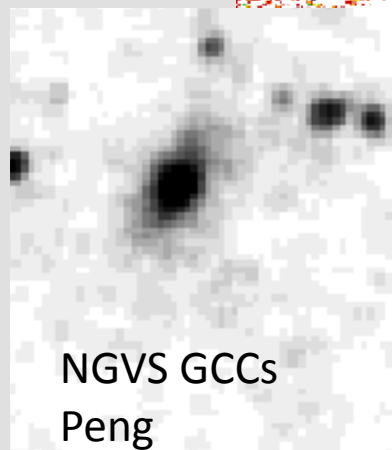


Janowiecki et al 2010



# M87 (NGC 4486)

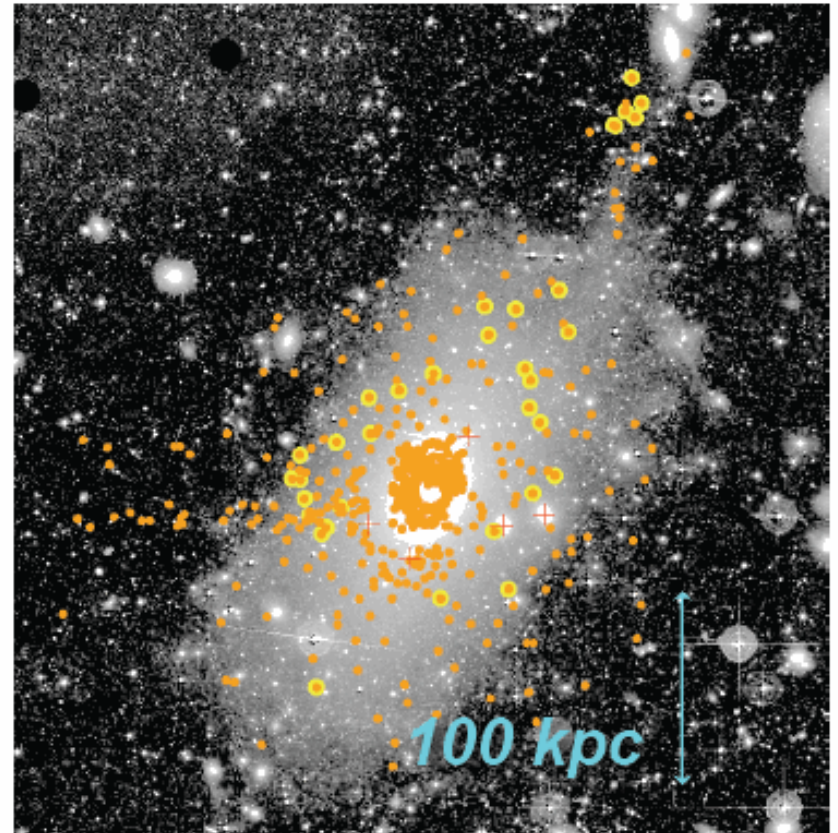
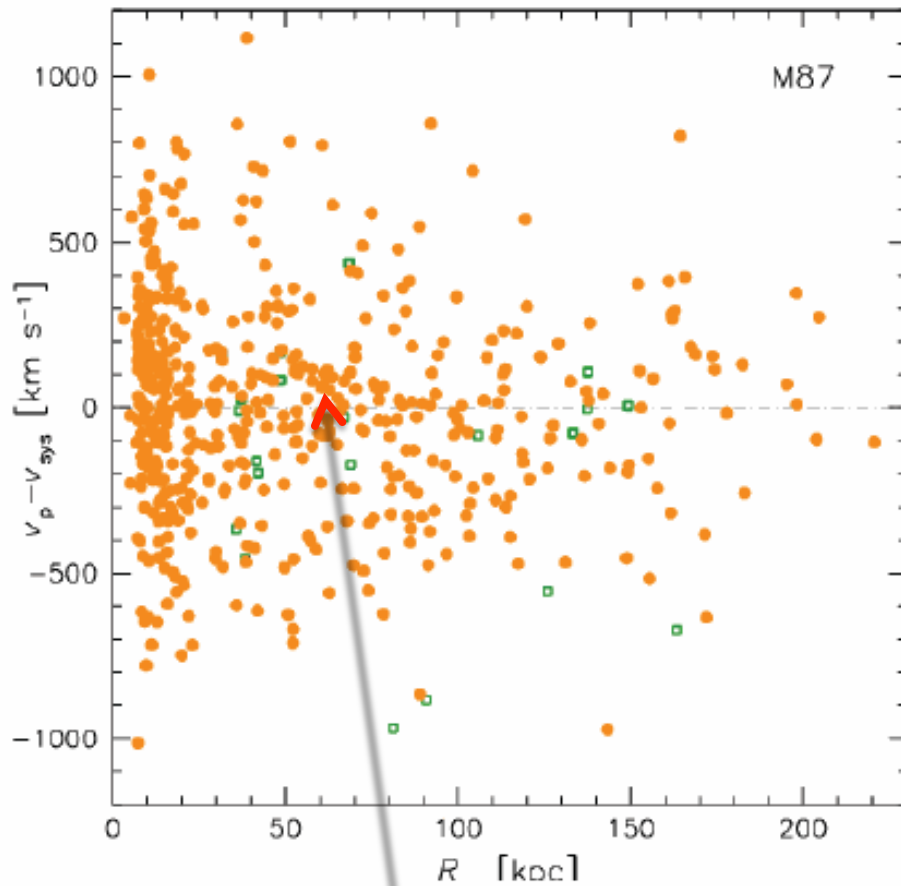
But the outer isophotes stay  
*extremely* boxy out to 150 kpc  
(hello, Thorsten Naab?)



Mihos et al 2011

# M87 (NGC 4486)

Globular Cluster velocities from Romanowsky et al (2011)



cold ( $\sigma_v \sim 20 \text{ km/s}$ ) accretion stream?

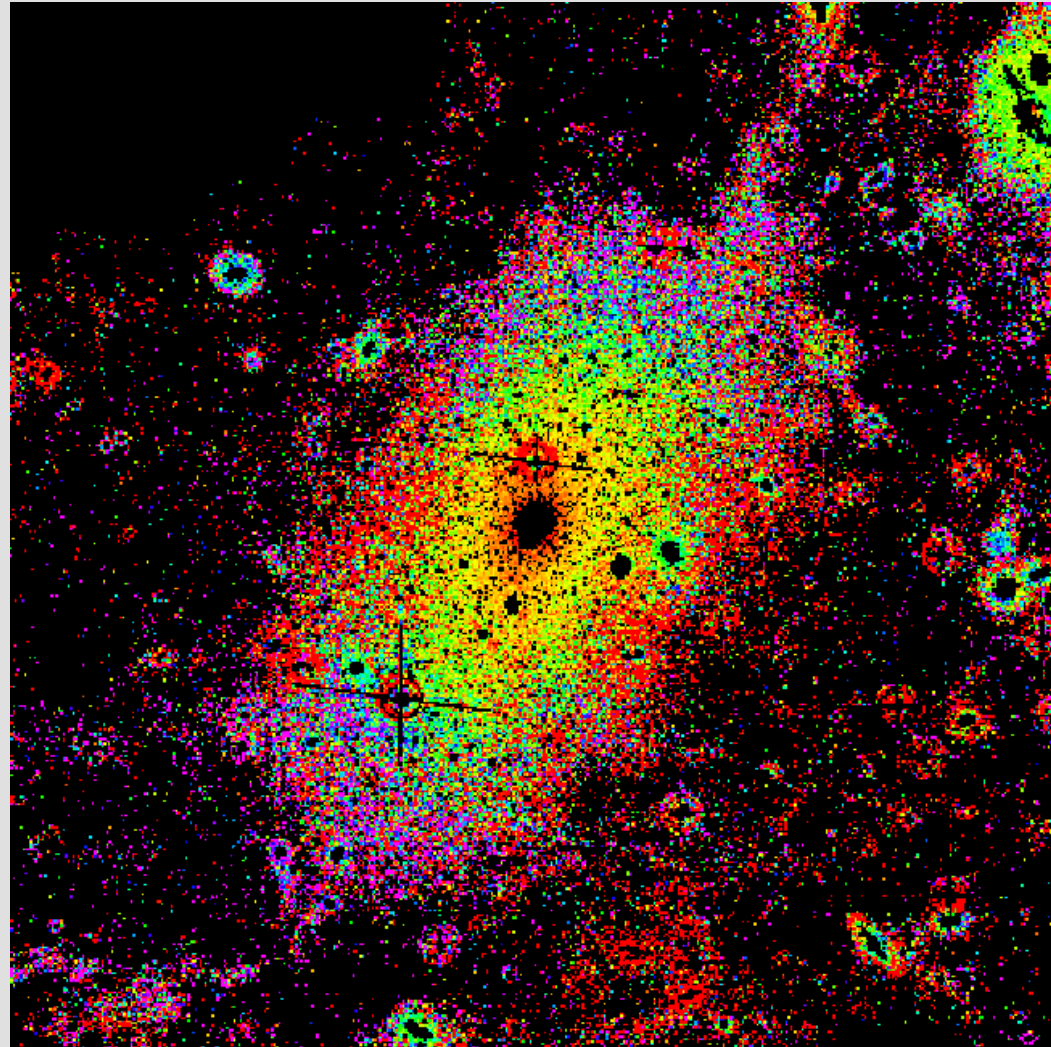


# M87 color map

Color map is tough, it's a very messy place to work:

- Sky subtraction
- Galactic cirrus
- Bright stars

We see some evidence of a color gradient, but weaker than in M49...

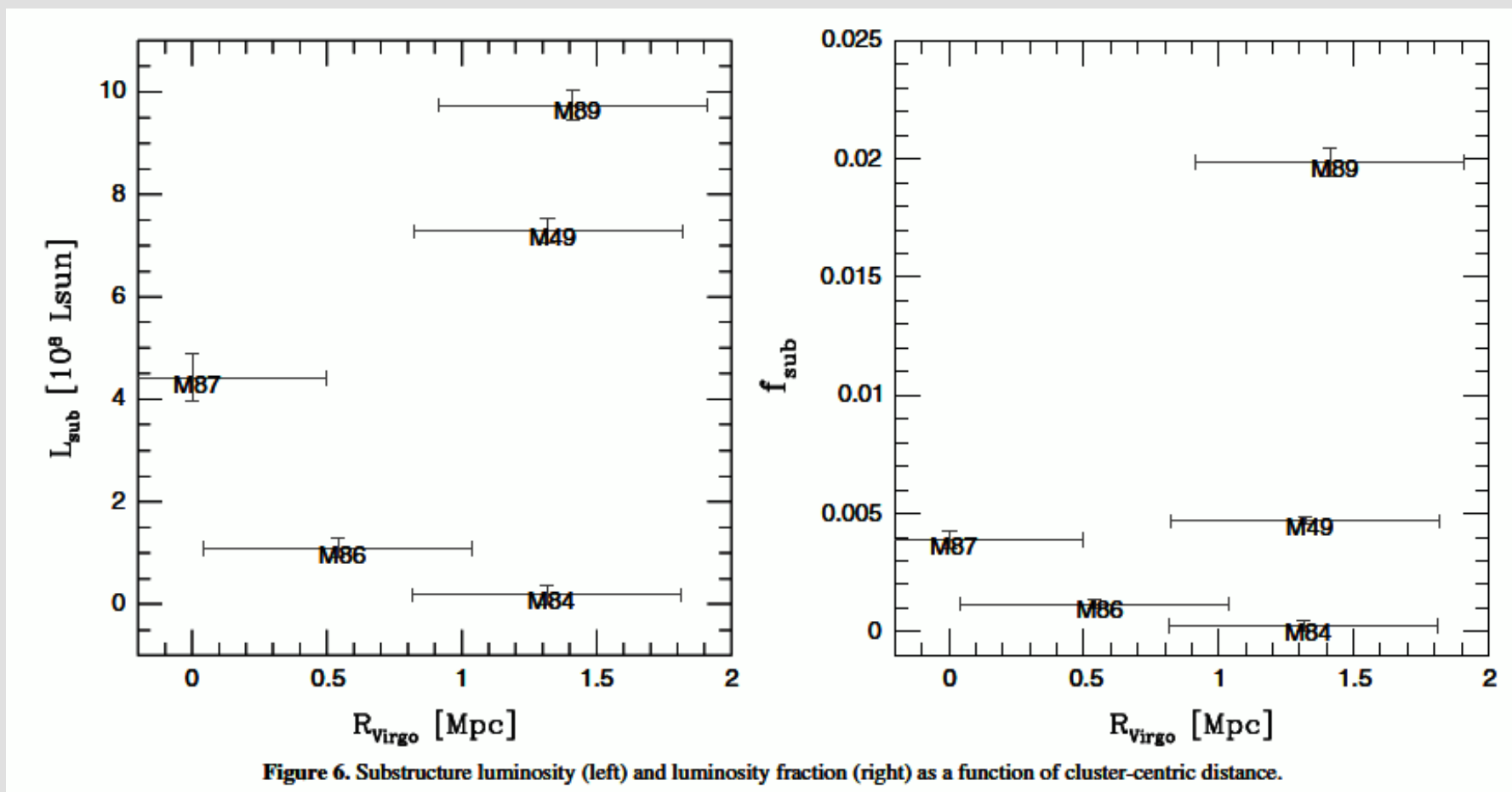


B-V color map: Rudick et al 2010, Mihos et al 2011



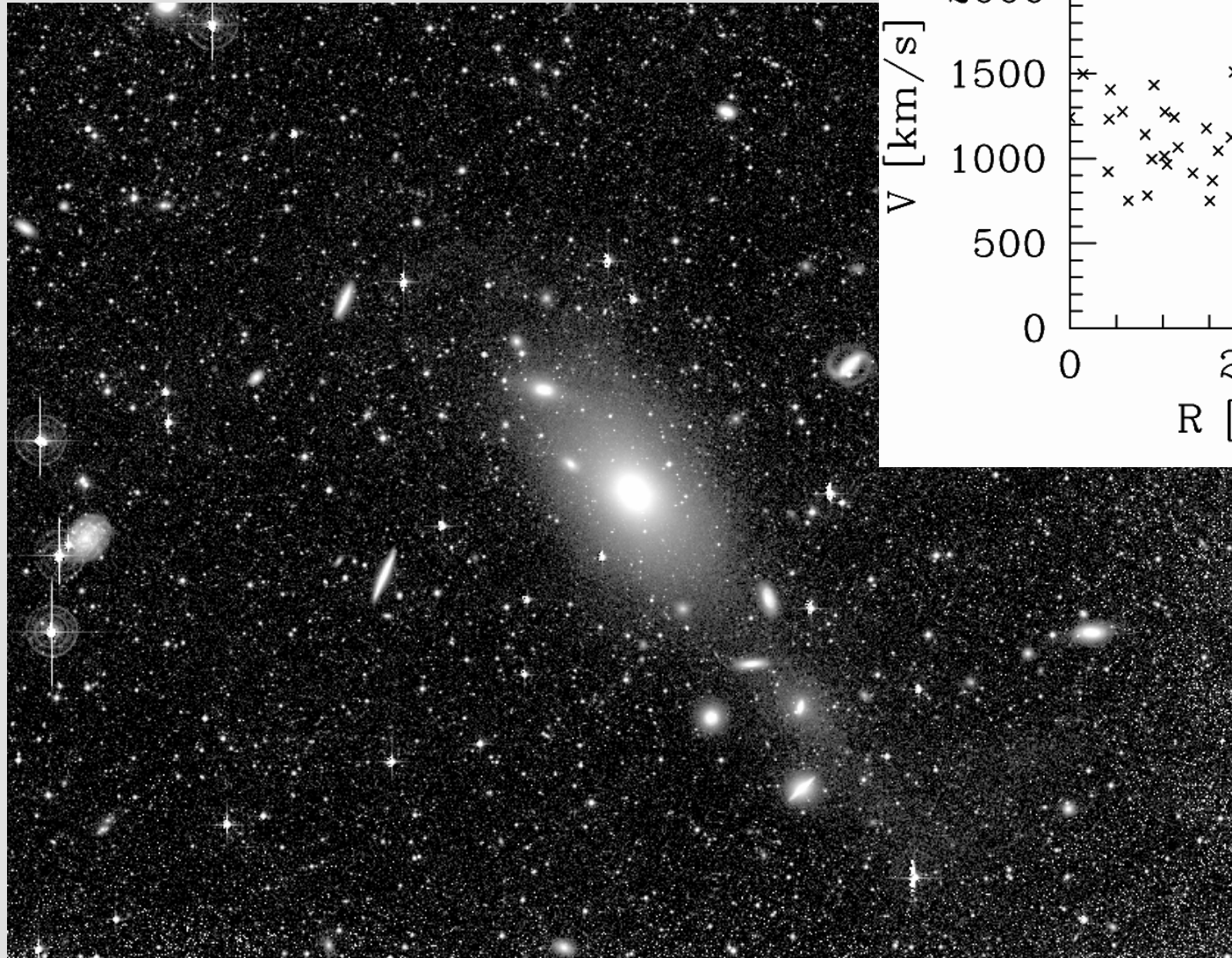
# Virgo Environment

SBF distances from ACSVCS: Mei et al (2007)



Janowiecki et al 2010

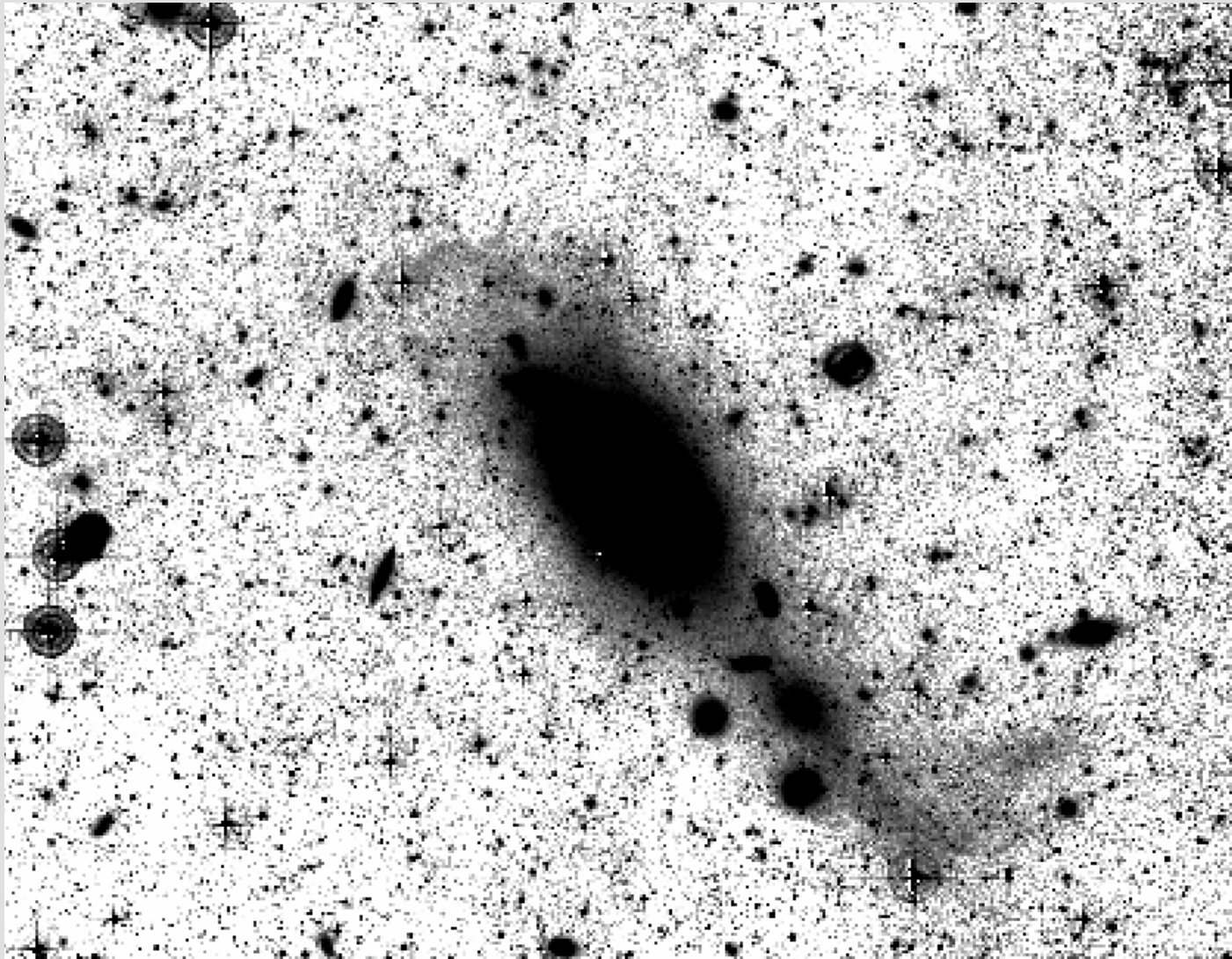
# NGC 4365 (et al)



5.3° (1.5 Mpc)  
SW of M87

Mihos et al 2011

# NGC 4365 (et al)

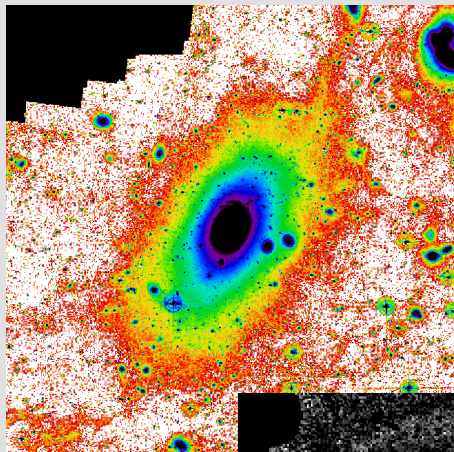


New ICL  
on the way!

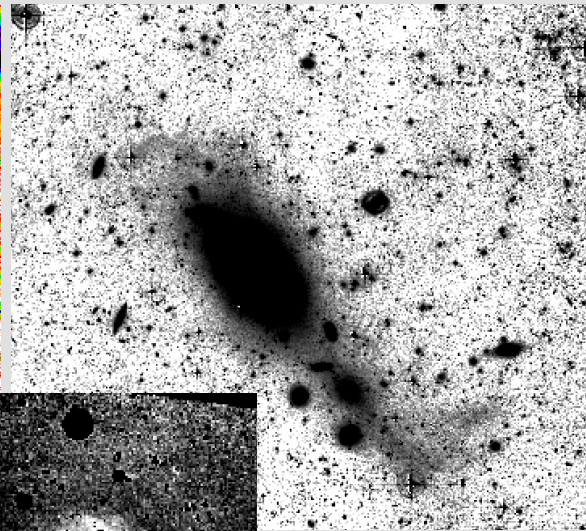
Mihos et al 2011



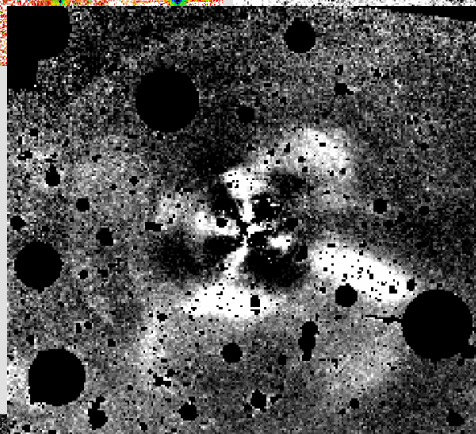
# Summary: *Accretion!*



M87



NGC 4365



M89

M49

