Cluster feeding filaments are the “Paths of Glory” of galaxy evolution

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Francine Marleau, Toronto University


THE MOST EXPLOSIVE
MOTION PICTURE
IN 25 YEARS!
KIRK
DOUGLAS
"PATHS
OF GLORY"
RALPH MEEKER · ADOLPHE MENJOU
UA

Cluster-feeding filaments are the "Paths of Glory" of galaxy evolution:

galaxies running towards the enemy
(the hostile cluster environment)
live an ephemeral glory as they
undergo bursts of star-formation,
but the bursts consume their gas and
they end-up "red and dead" in clusters


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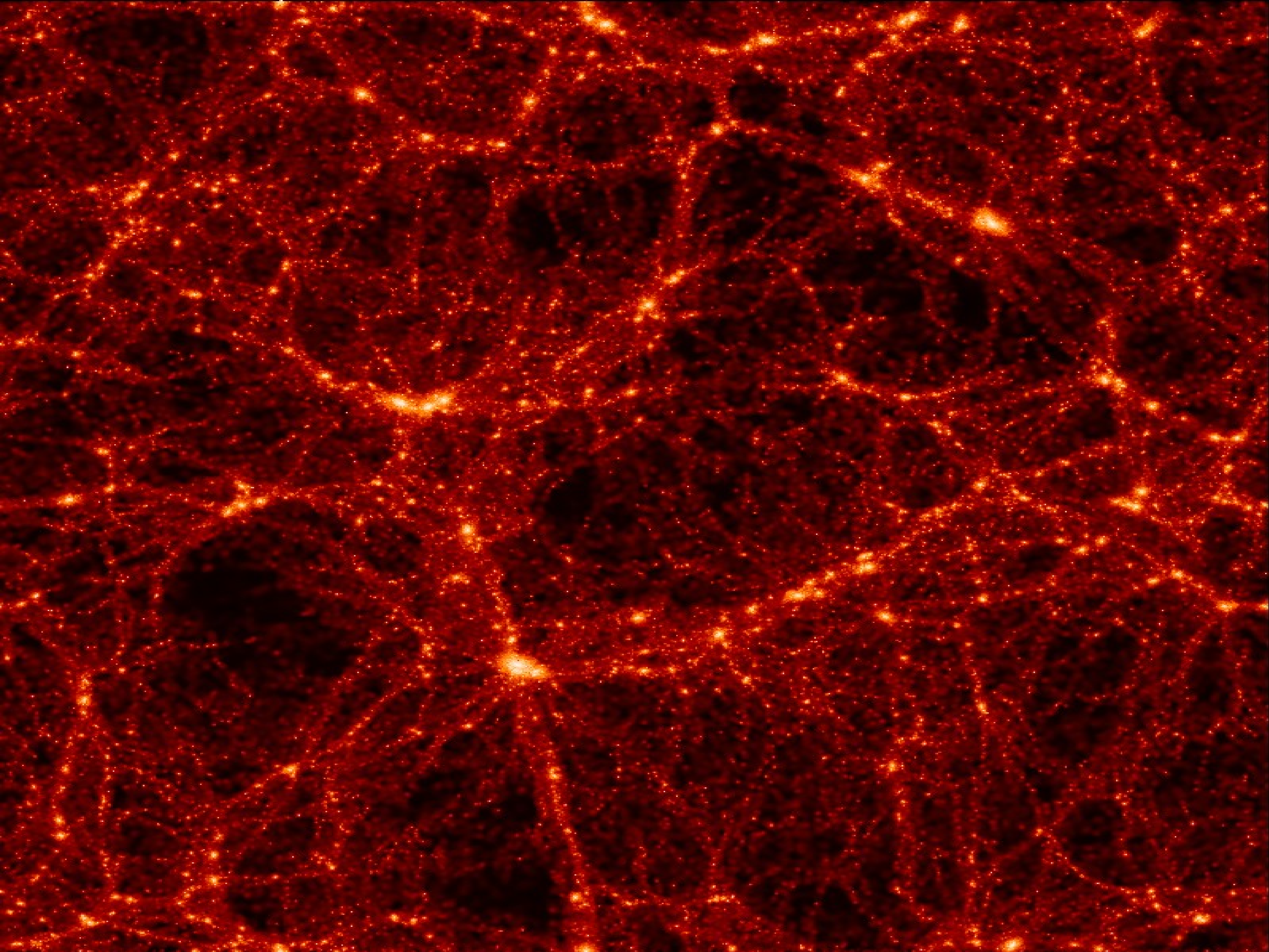

Outline:

- Introduction: galaxy properties in clusters
  (focus on IR, $\lambda > 4\,\mu$m, observations)
- The A1763 supercluster: observations, membership, galaxy stellar masses, $M_\star$ and IR luminosities, L_{IR}
- The A1763 IR luminosity function: methodology, environmental dependence, cmp with the literature
- Summary, Discussion and Perspectives


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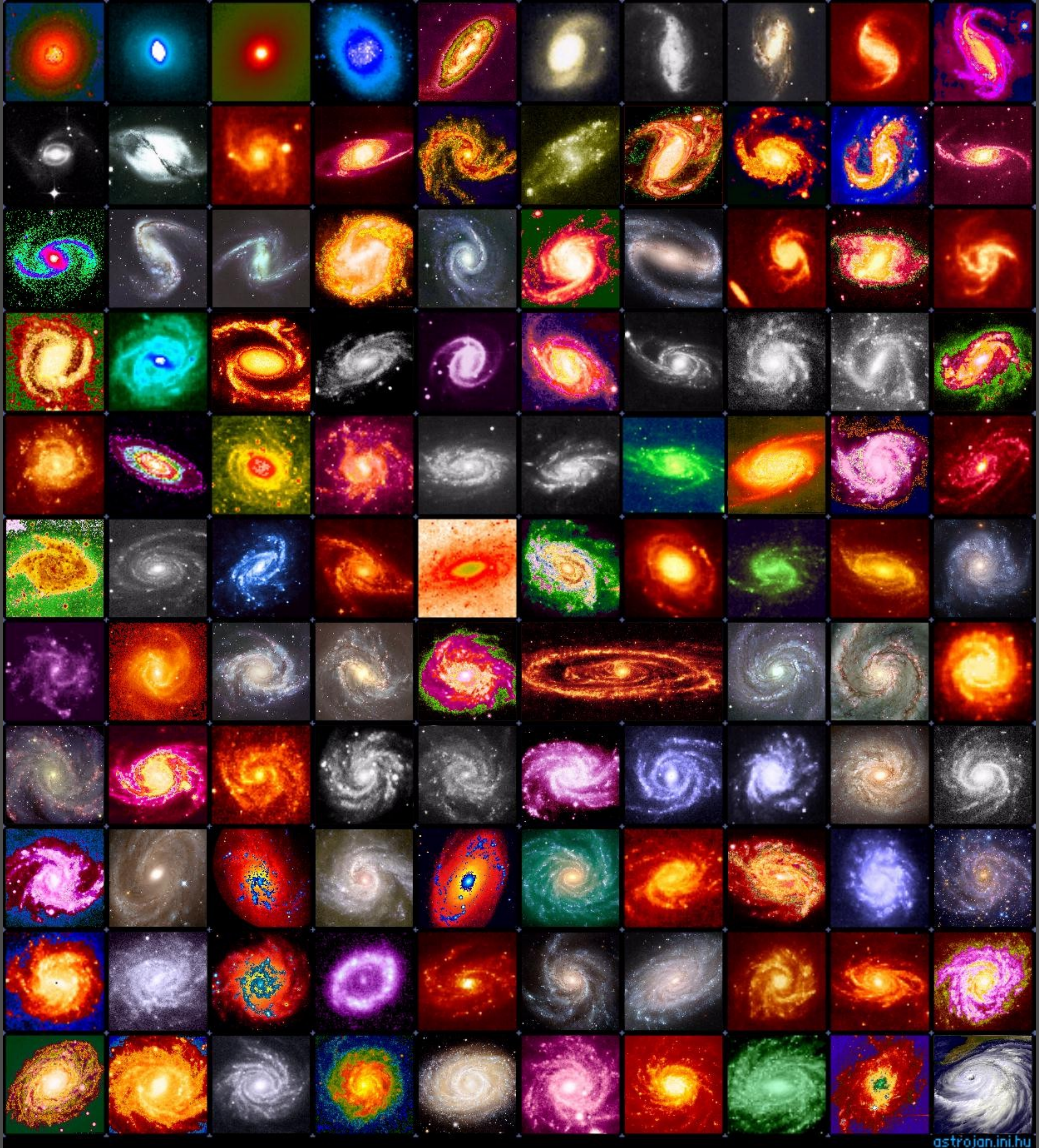
Introduction: galaxy properties in clusters

The most striking characteristics of the cluster galaxy population:

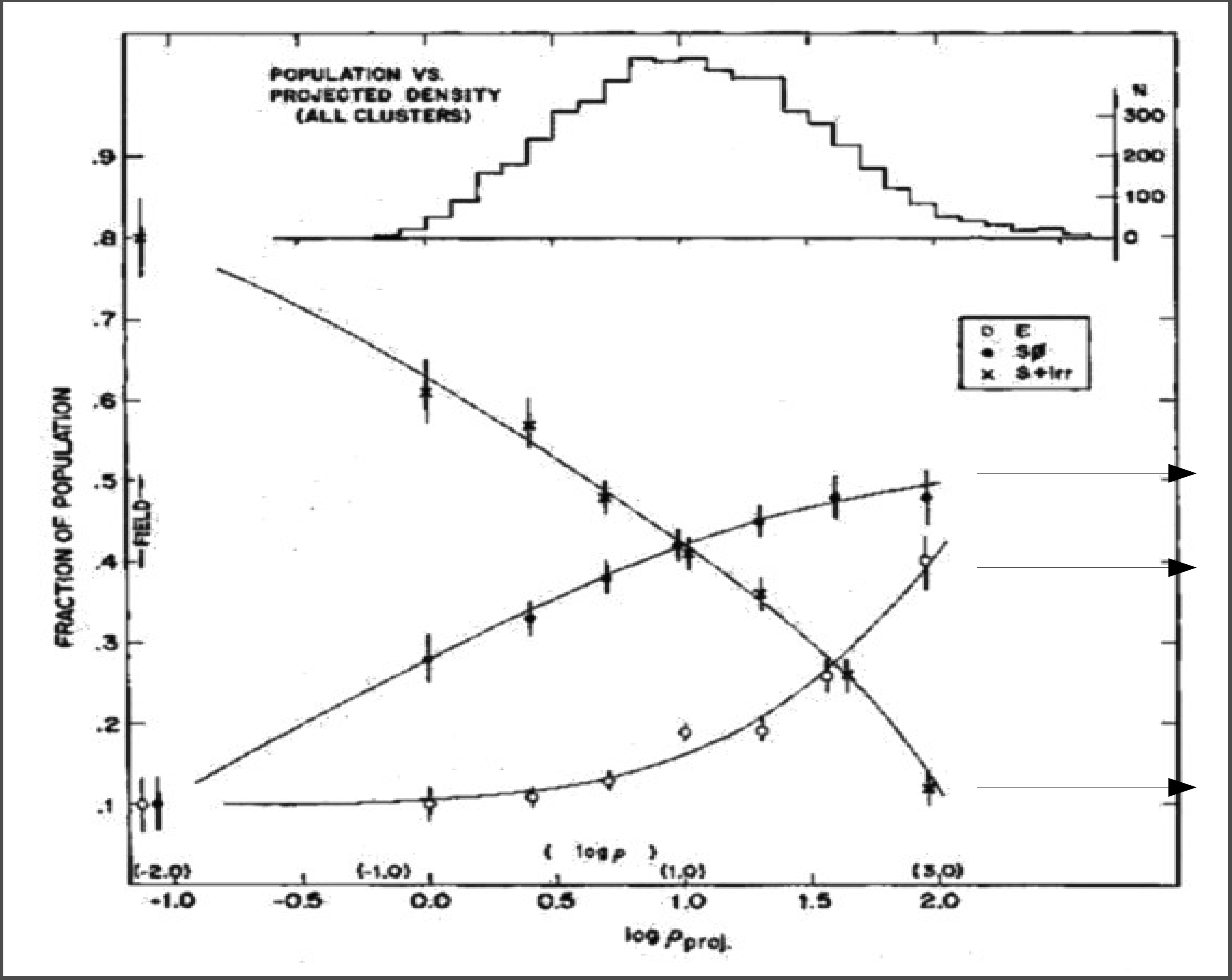
its morphology mix



Field

Cluster

Regular trend of morphology change with density: Morphology-Density Relation



Fraction of:

Ellipticals

S0

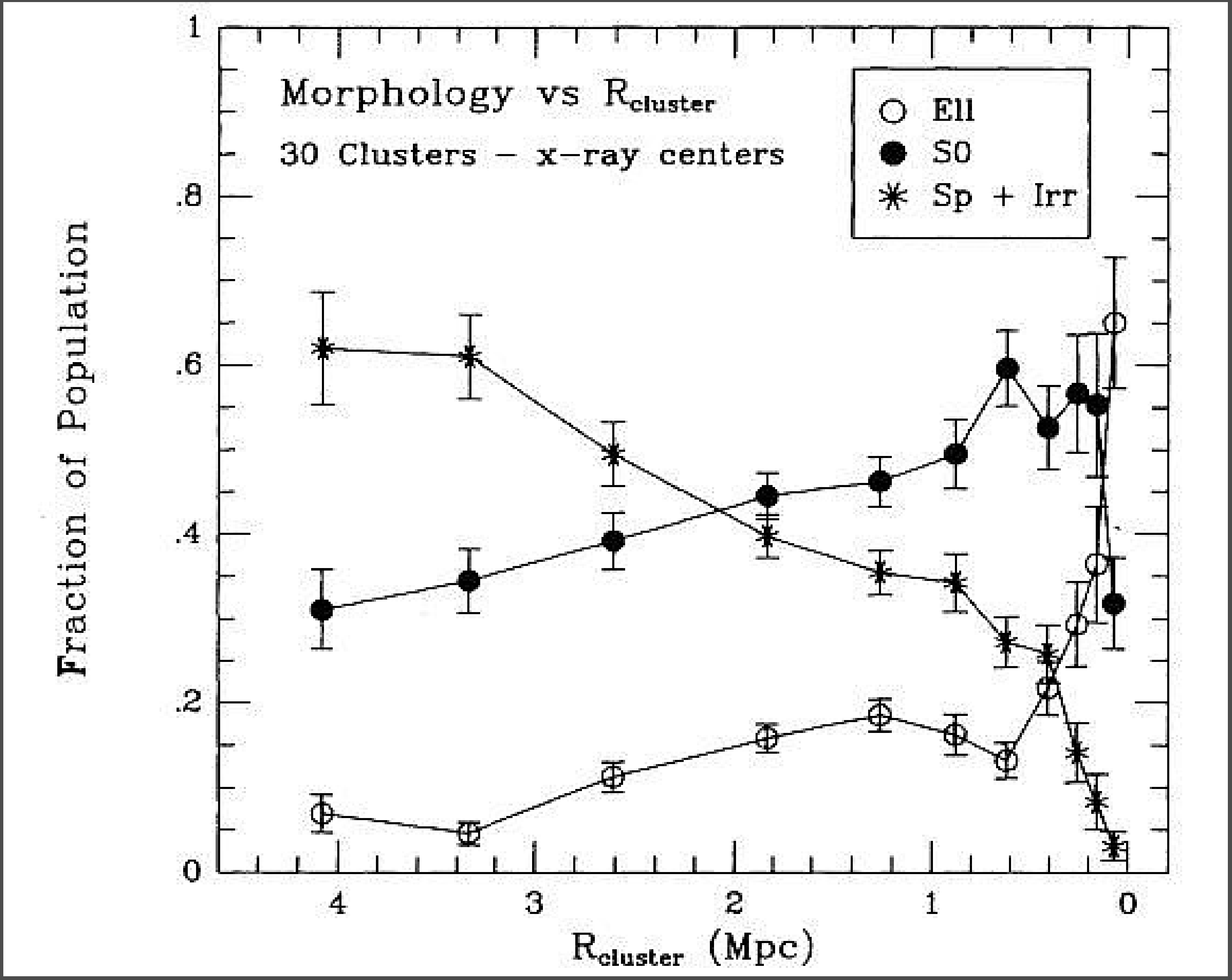
S+Irr

(Dressler 80)

log(local density)

In clusters, density decreases with increasing radius: Morphology-Radius Relation

(Whitmore+93)



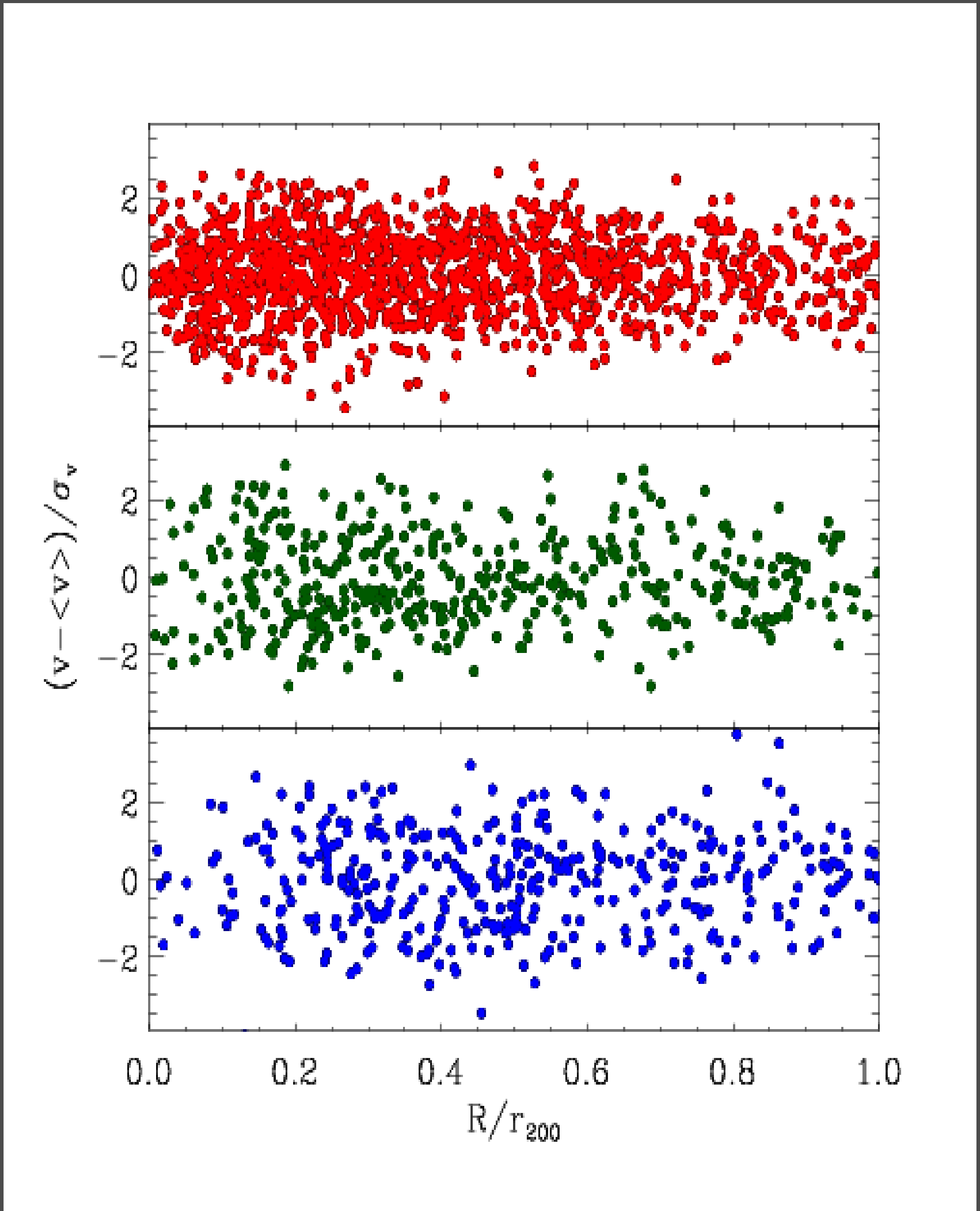
Ellipticals

S0

S+Irr

radius, i.e. clustercentric distance

Color-radius relation in clusters

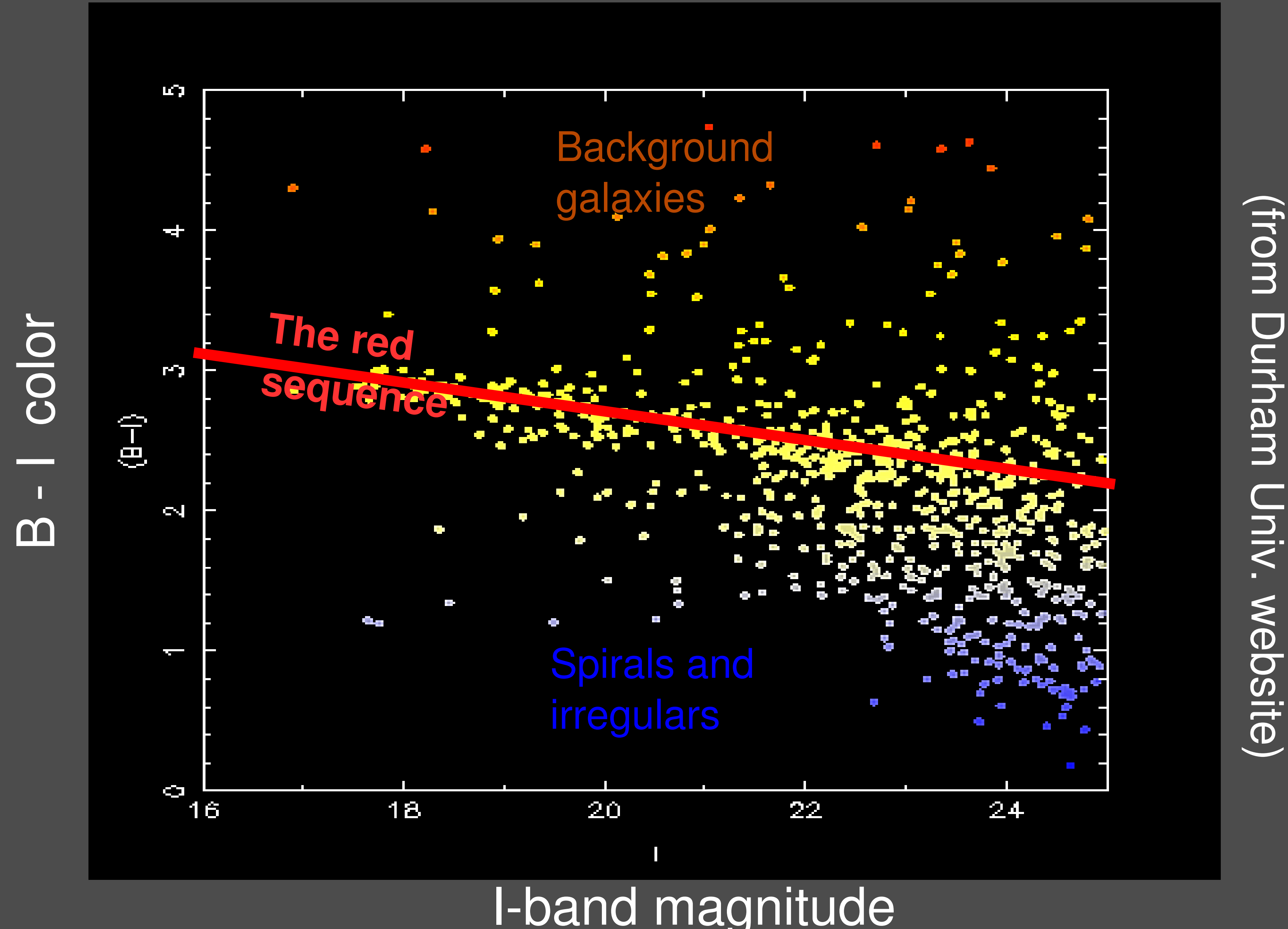


Velocity wrt cluster mean

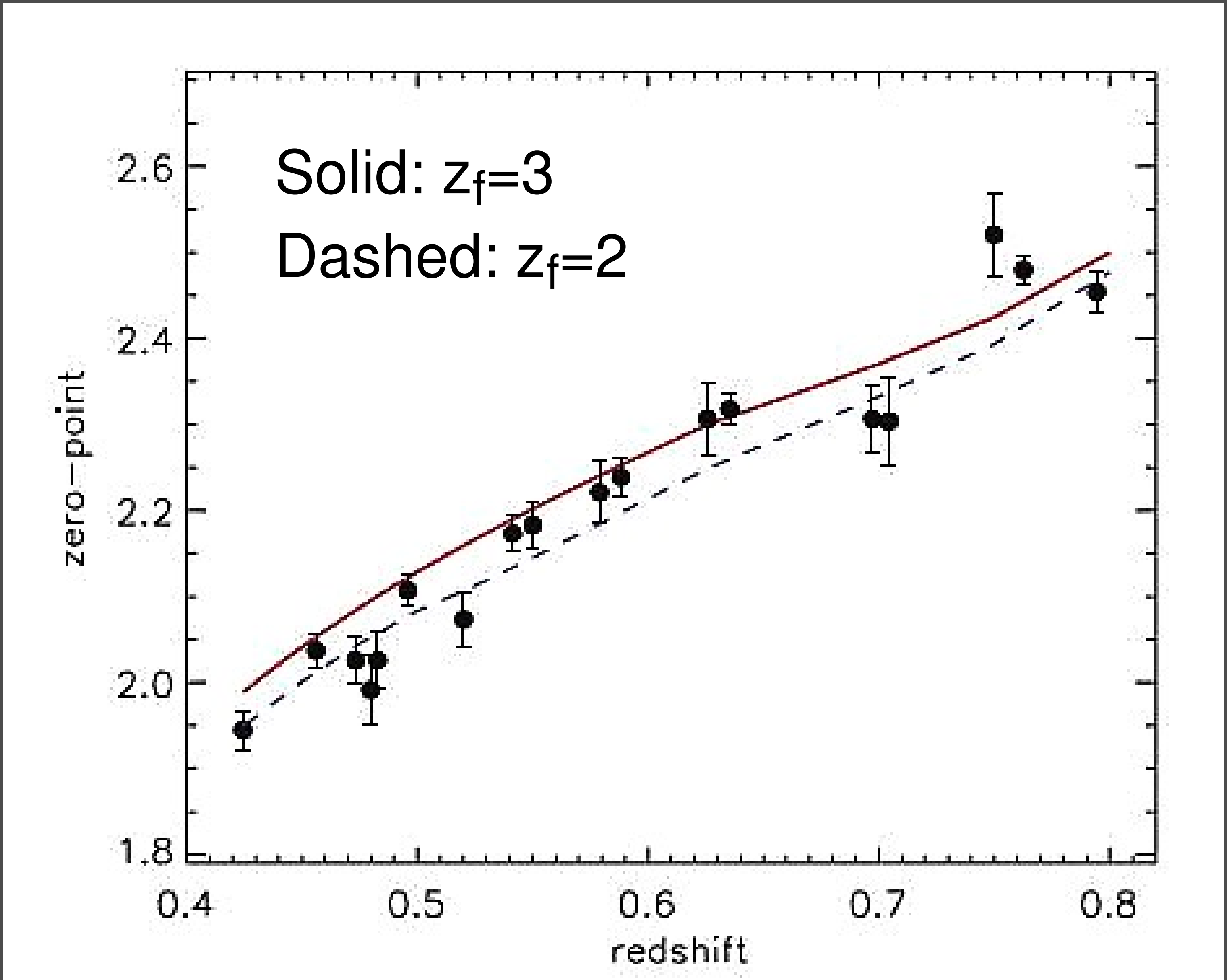
clustercentric distance

The CIRS cluster sample
(Rines+Diaferio 06)

The Color-Magnitude Relation

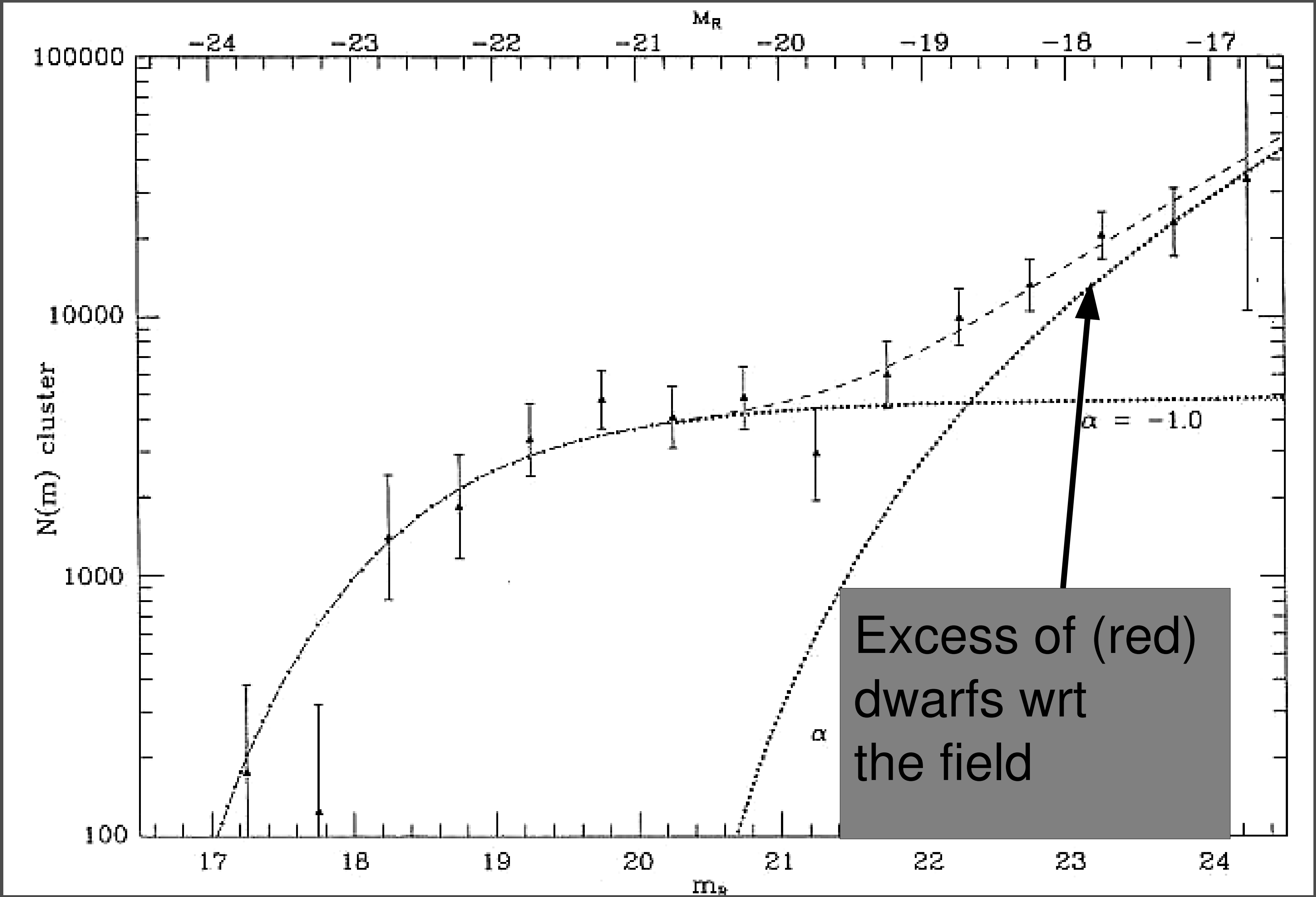


Color-Magnitude Relation evolution with z ⇒ $z_f \geq 2$



(De Lucia+07)

Cluster Galaxies Luminosity Function



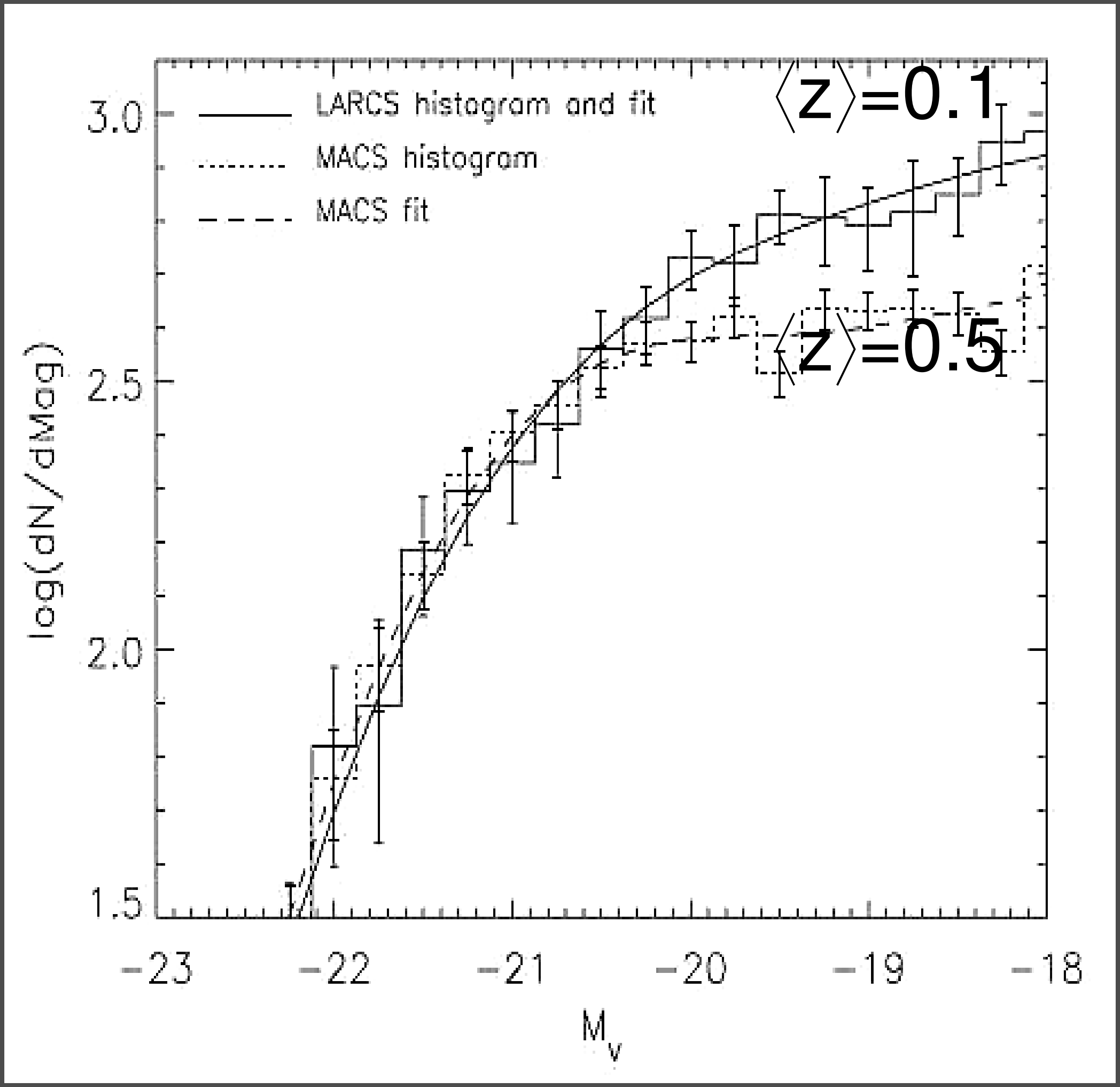
Number of galaxies per magnitude bin

Magnitude

(Driver+04)

The faint end of the LF of red sequence galaxies forms at low-z

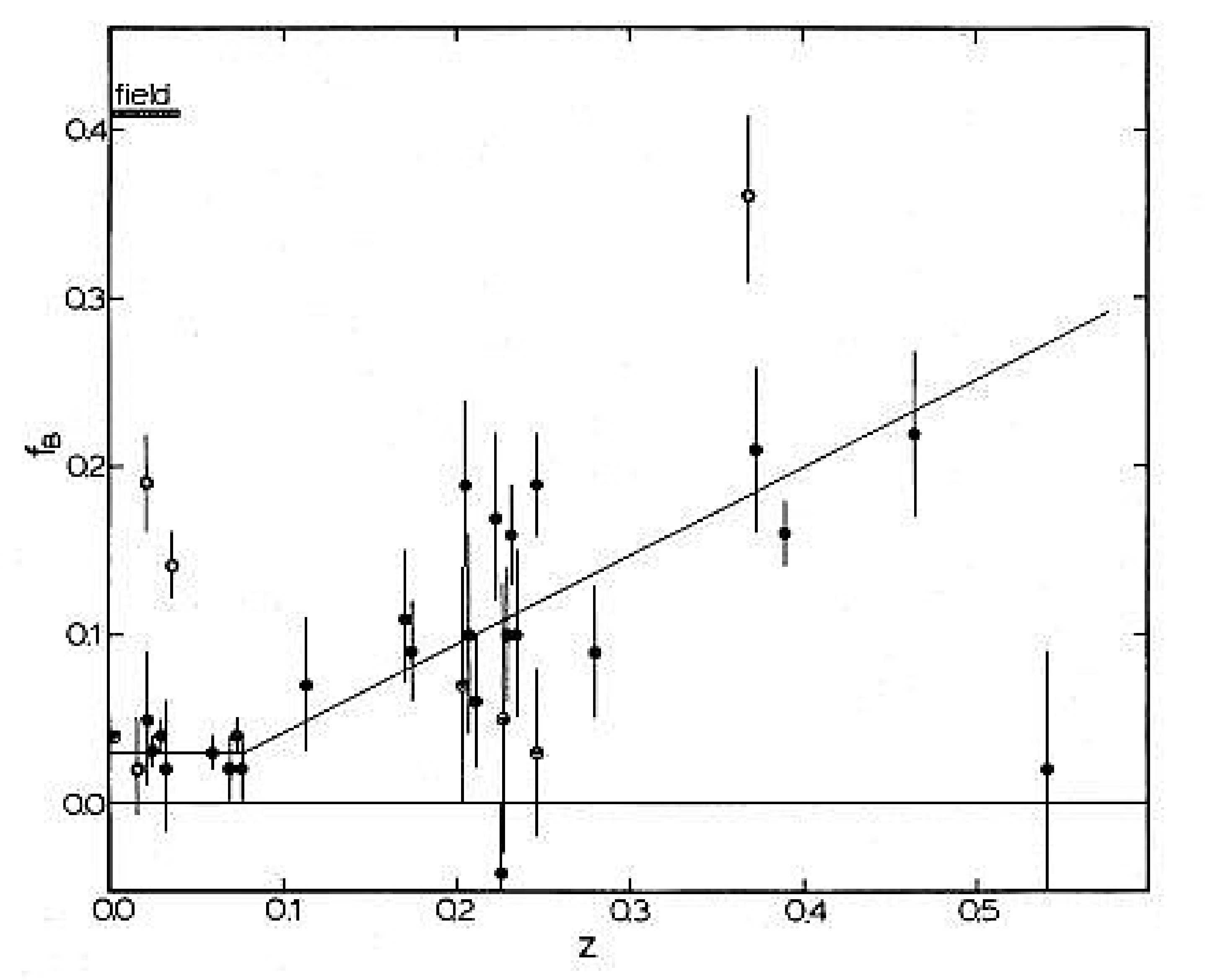
Red-galaxy luminosity functions for two cluster samples, <z>=0.1 & 0.5



(Stott+07)

The fraction of Blue galaxies in clusters, f_B ↑ with z: the "Butcher-Oemler" effect

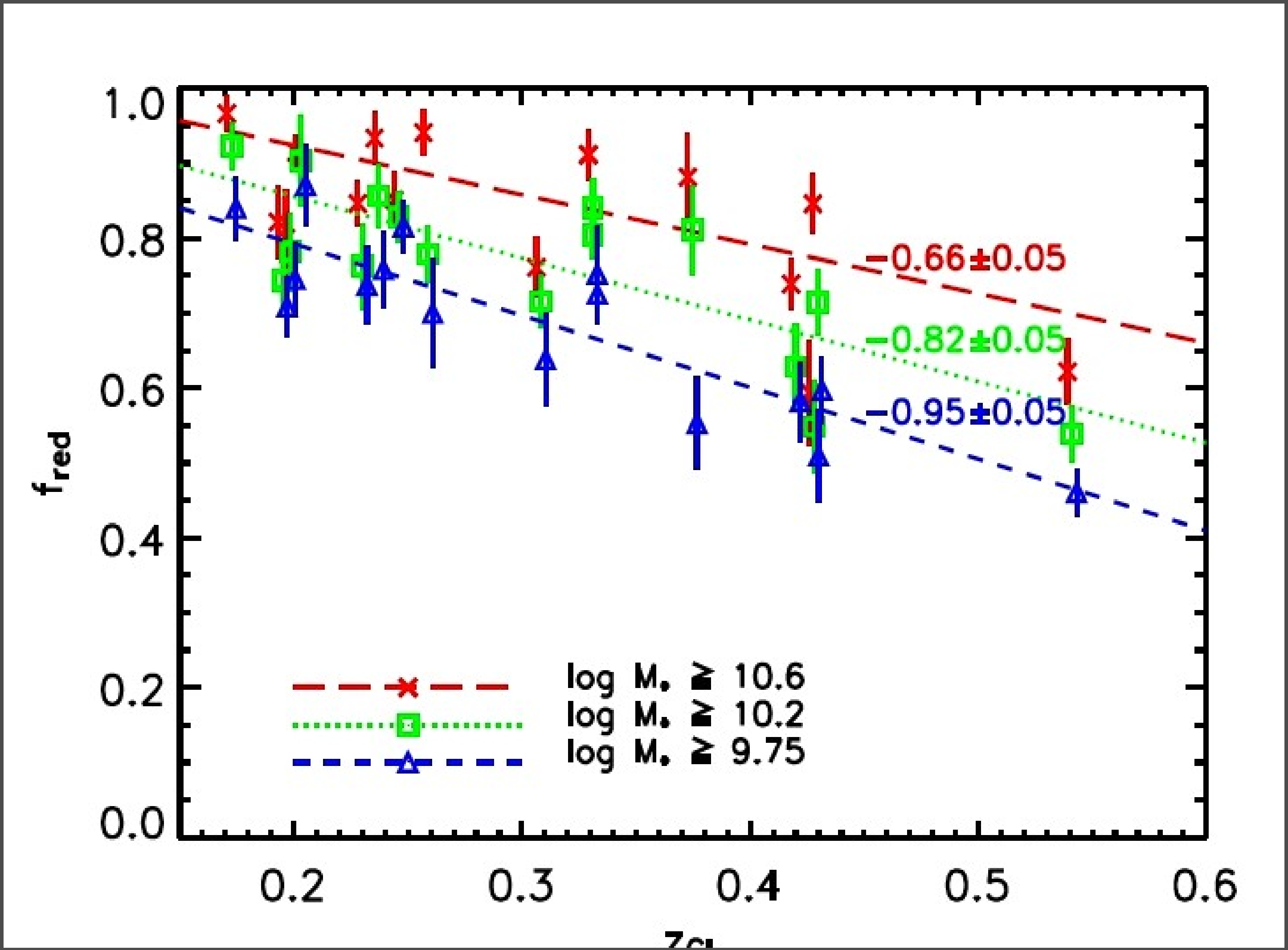
fraction of blue galaxies



(Butcher & Oemler 84)

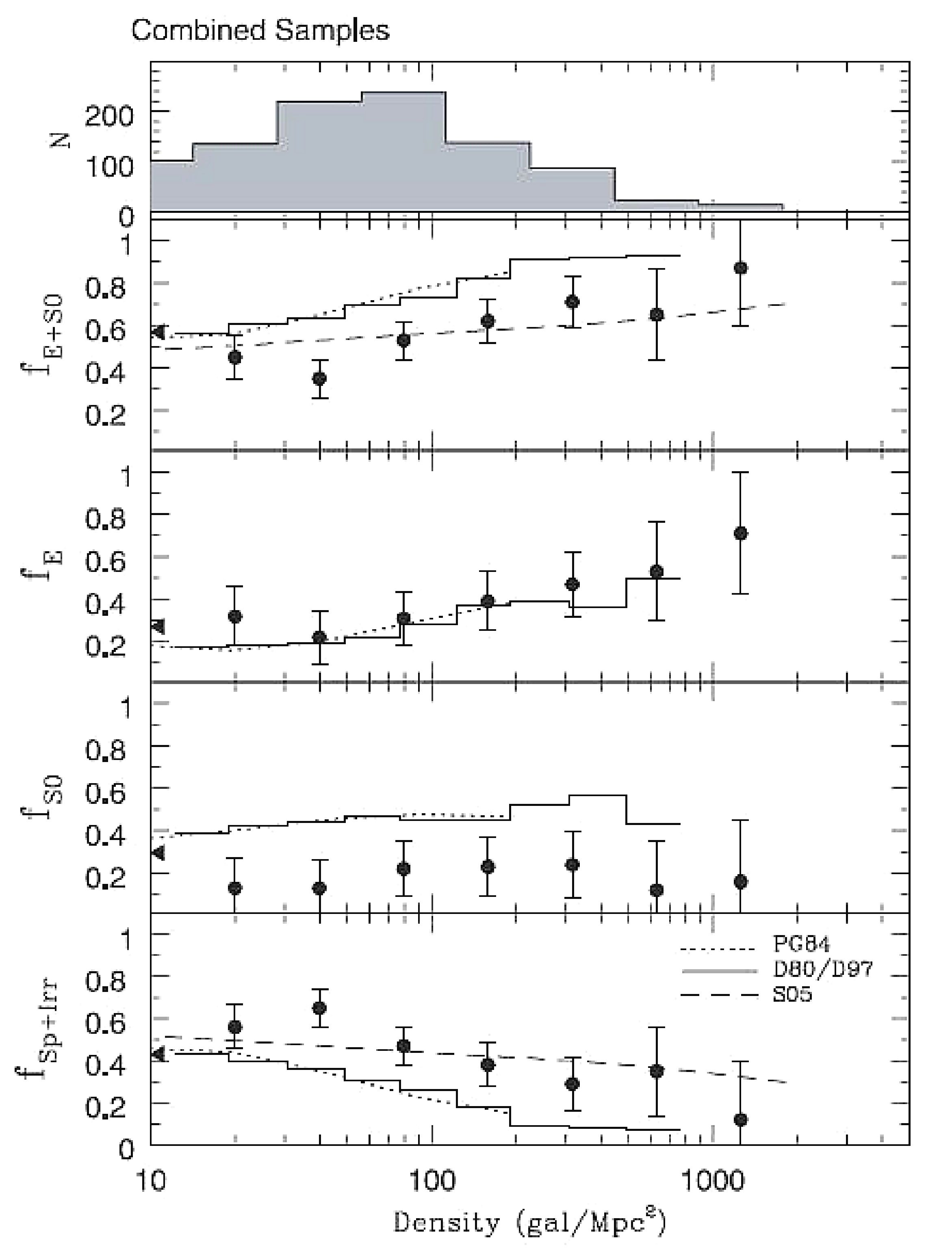
The fraction of Red galaxies in clusters, f_{red} ↓ with z: the "Butcher-Oemler" effect

fraction of red galaxies



(Li, Yee, Ellingson 09)

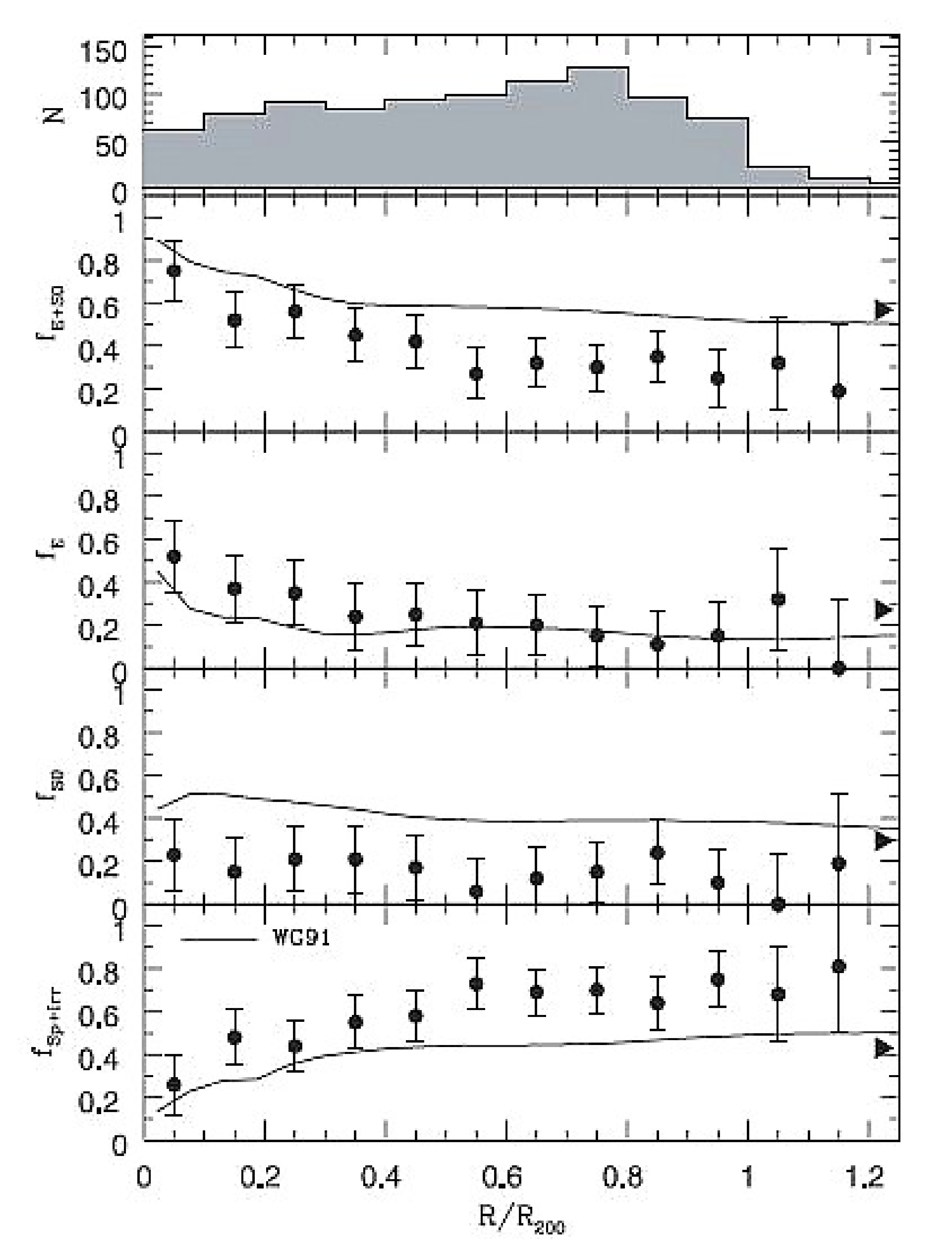
redshift



The Morphology-Density Relation at z~1:

still there, but less S0, more S; no change in E fraction

(Postman+05)

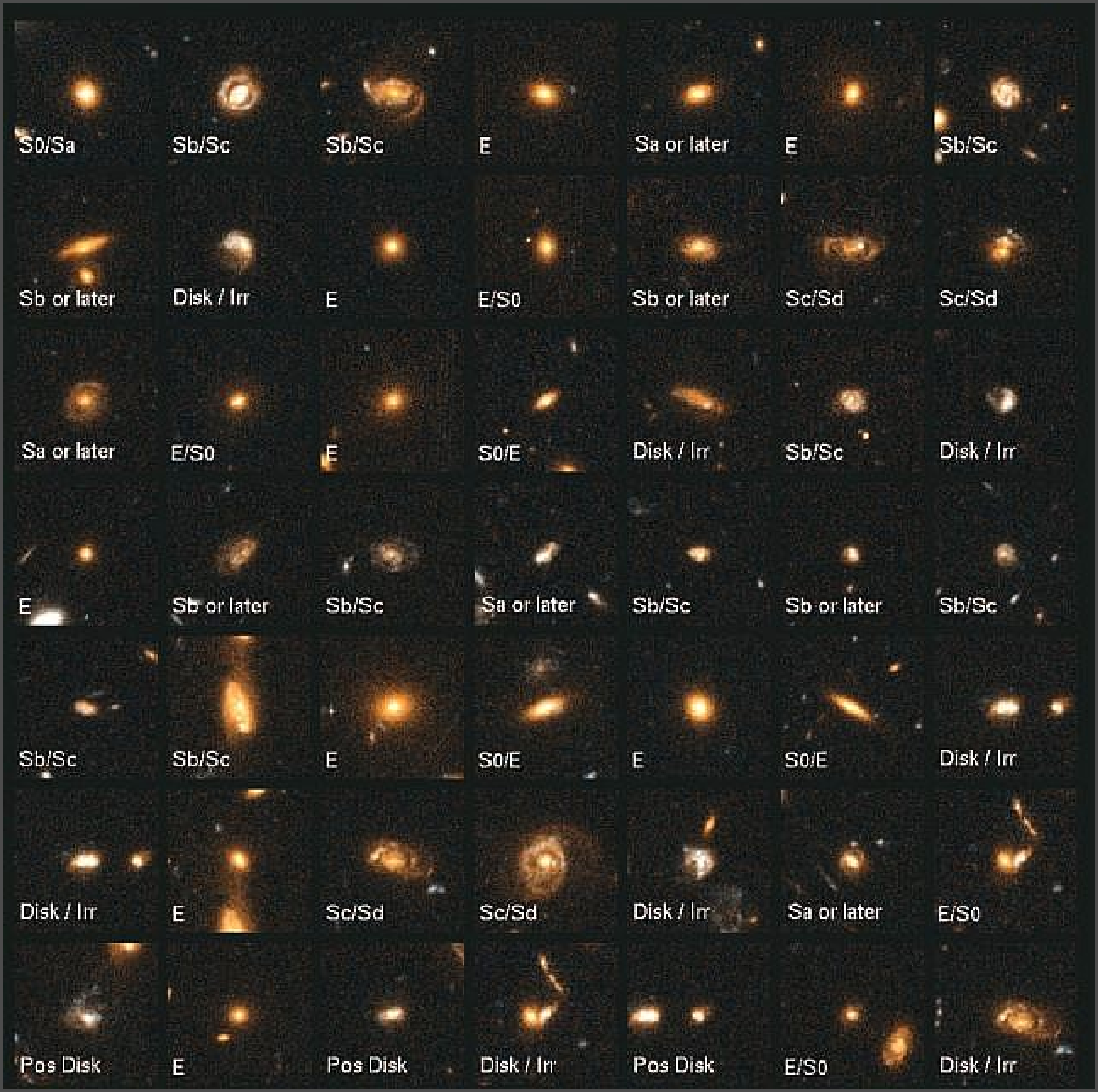


The Morphology-Radius Relation at z~1:

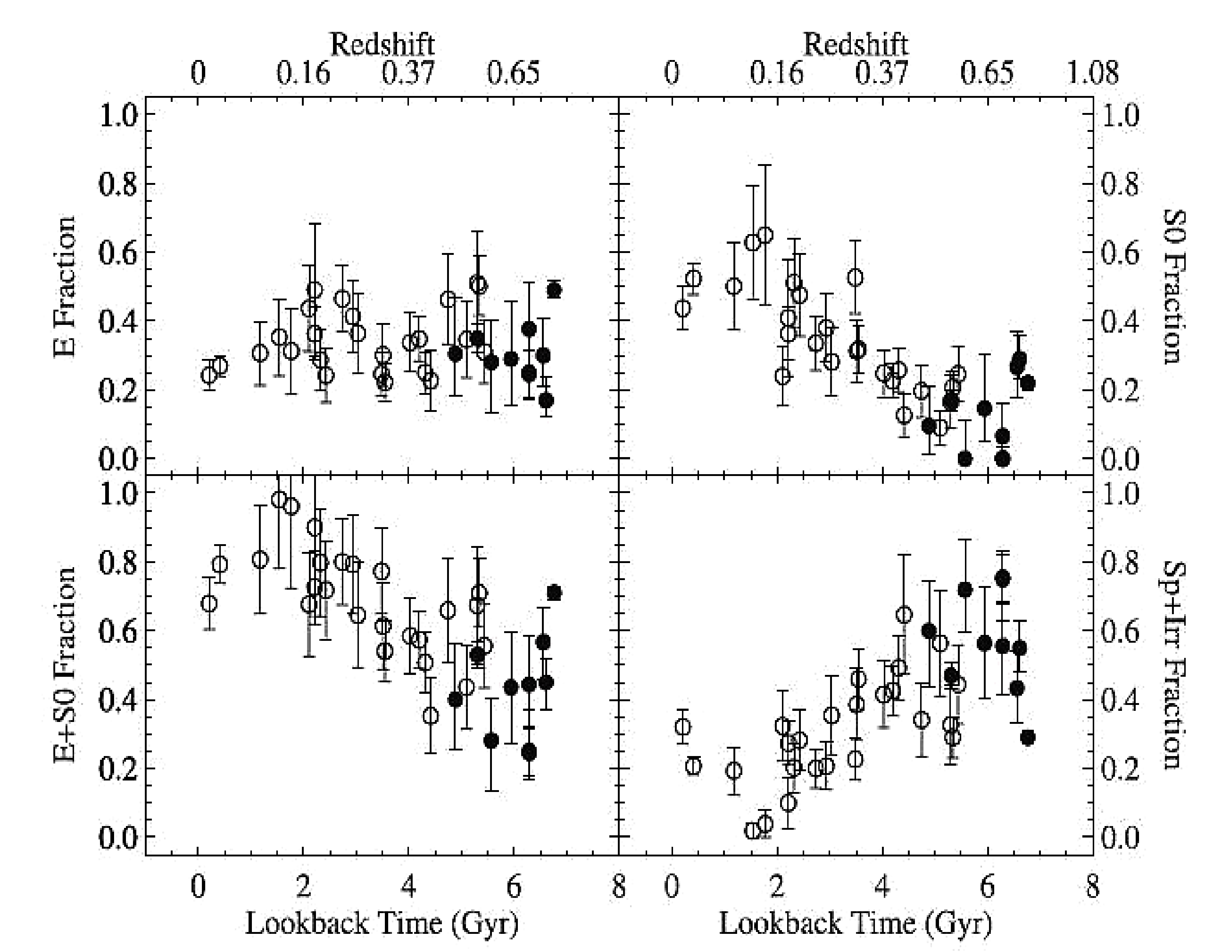
still there, but less S0, more S; no change in E fraction

(Postman+05)

Brightest galaxies in two z~1 clusters (Postman+05)

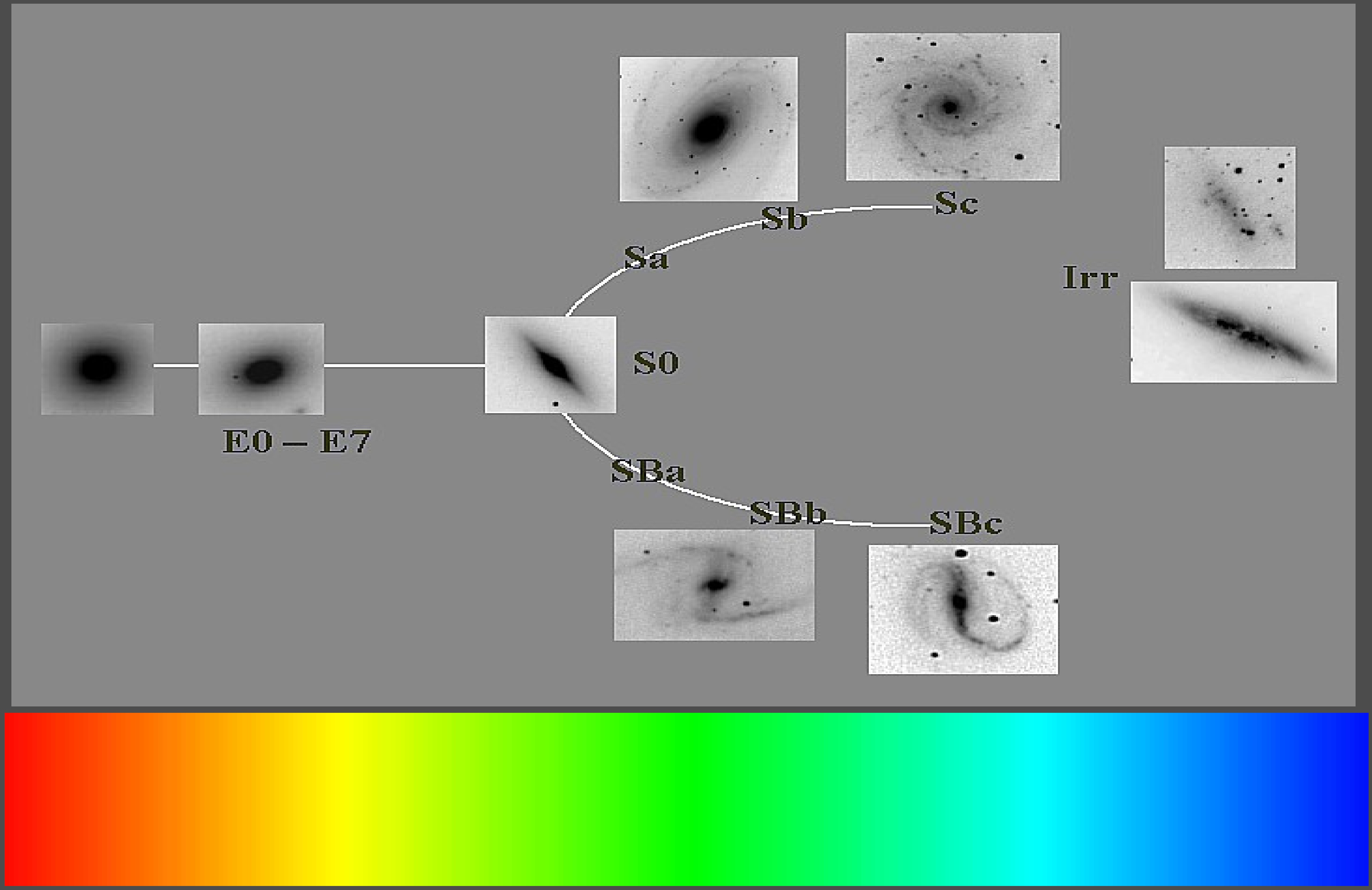


Most morphology evolution occurs at z<0.5



(Desai+07)

Galaxy colors and morphologies are related...



...but they are not the same property!

Normal S

Passive spectrum, blue disk

Passive spectrum red disk

(Moran+07)

➔ Explore galaxy evolution
vs. environment and redshift
using a fundamental galaxy property:

the mass of its stellar component, $M_\star$,
and its production rate,
the Star Formation Rate, $SFR \equiv dM_\star/dt$

“Special” observational requirements:

$M_\star$:

Near-IR observations (J, H, K bands)

SFR:

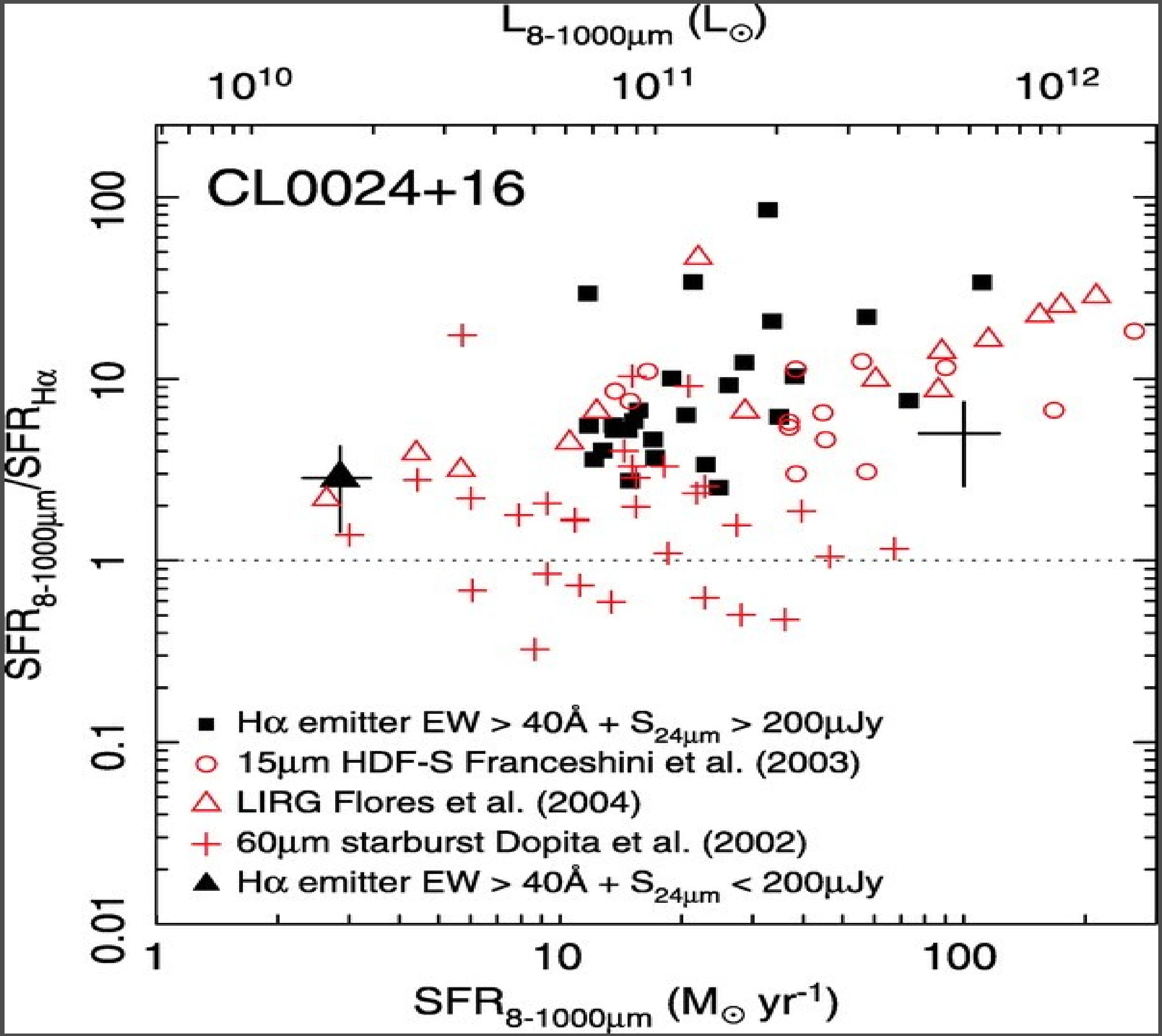
Total IR luminosity (L_{IR}) from

Mid- and/or Far-IR observations (λ>4 μm)

+ Kennicutt's (1998) relation:

SFR [$M_\odot$/yr] = 1.7 10^{-10} $L_{IR}/L_\odot$

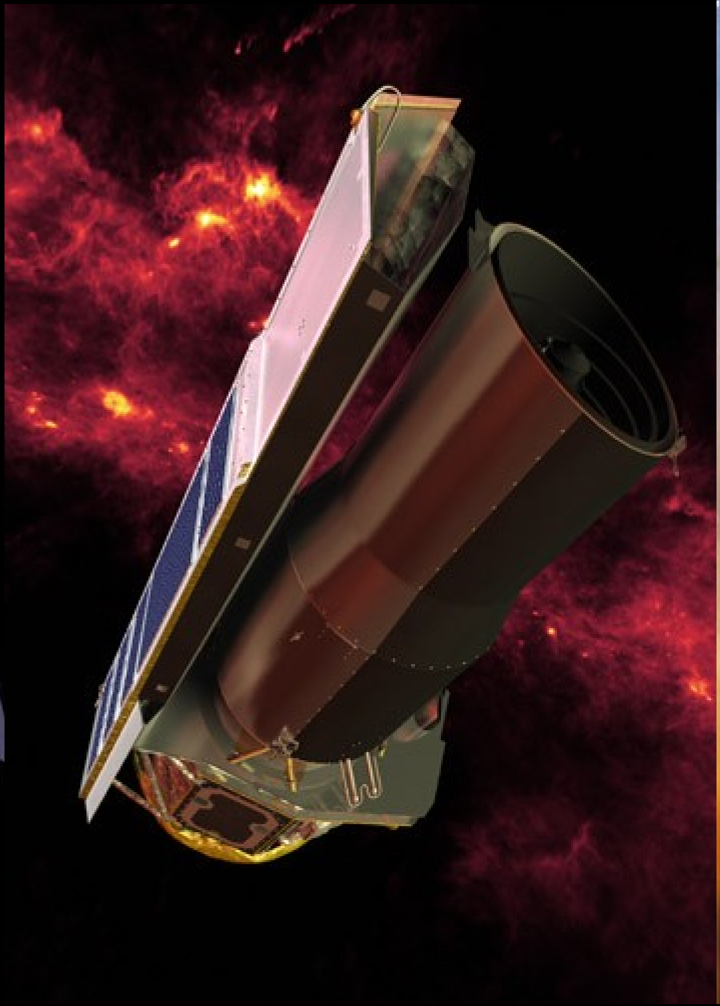
Hα -based SFR are underestimates



(Geach+06)

Mid- and Far-IR observations from space

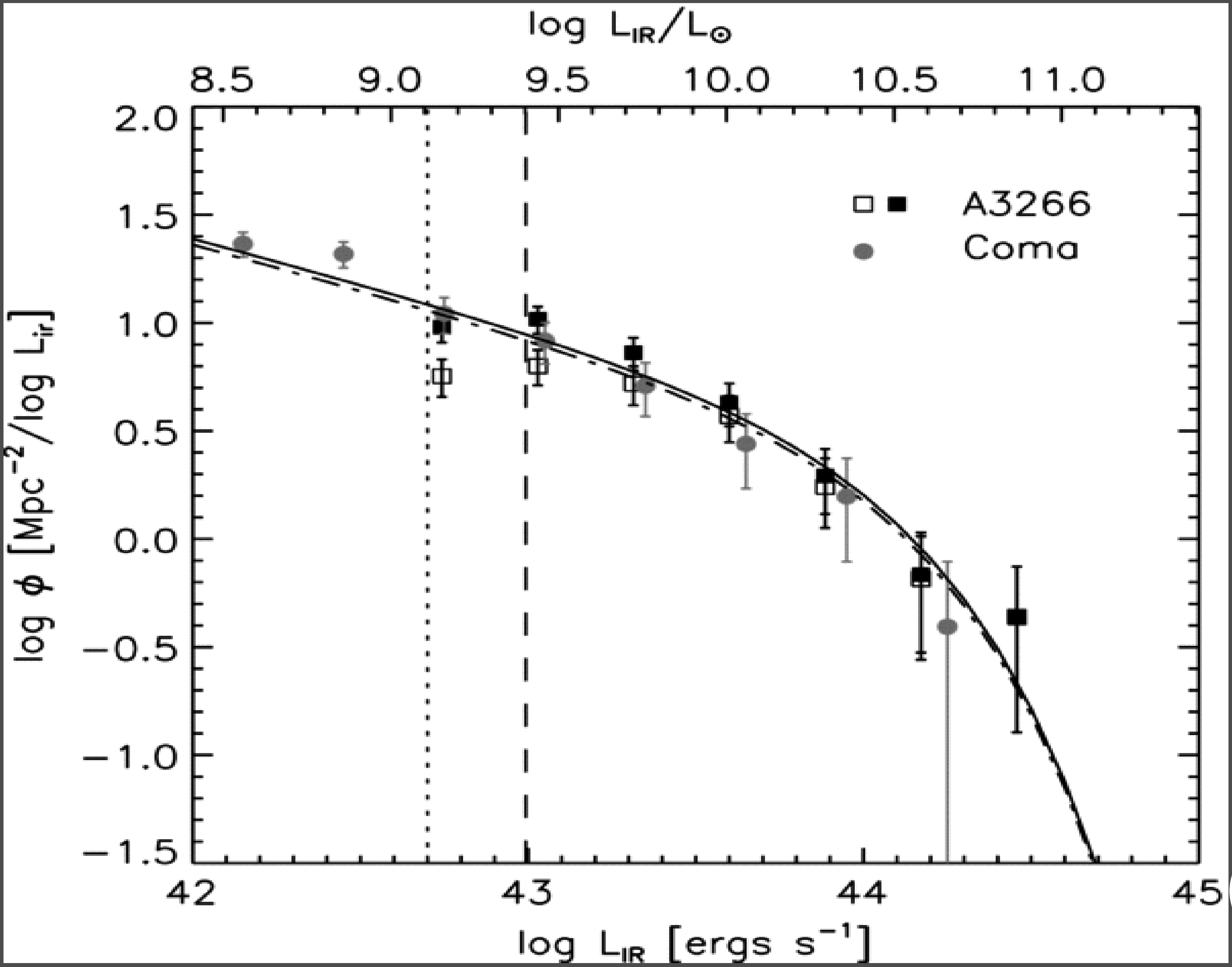
ISO



SPITZER

HERSCHEL

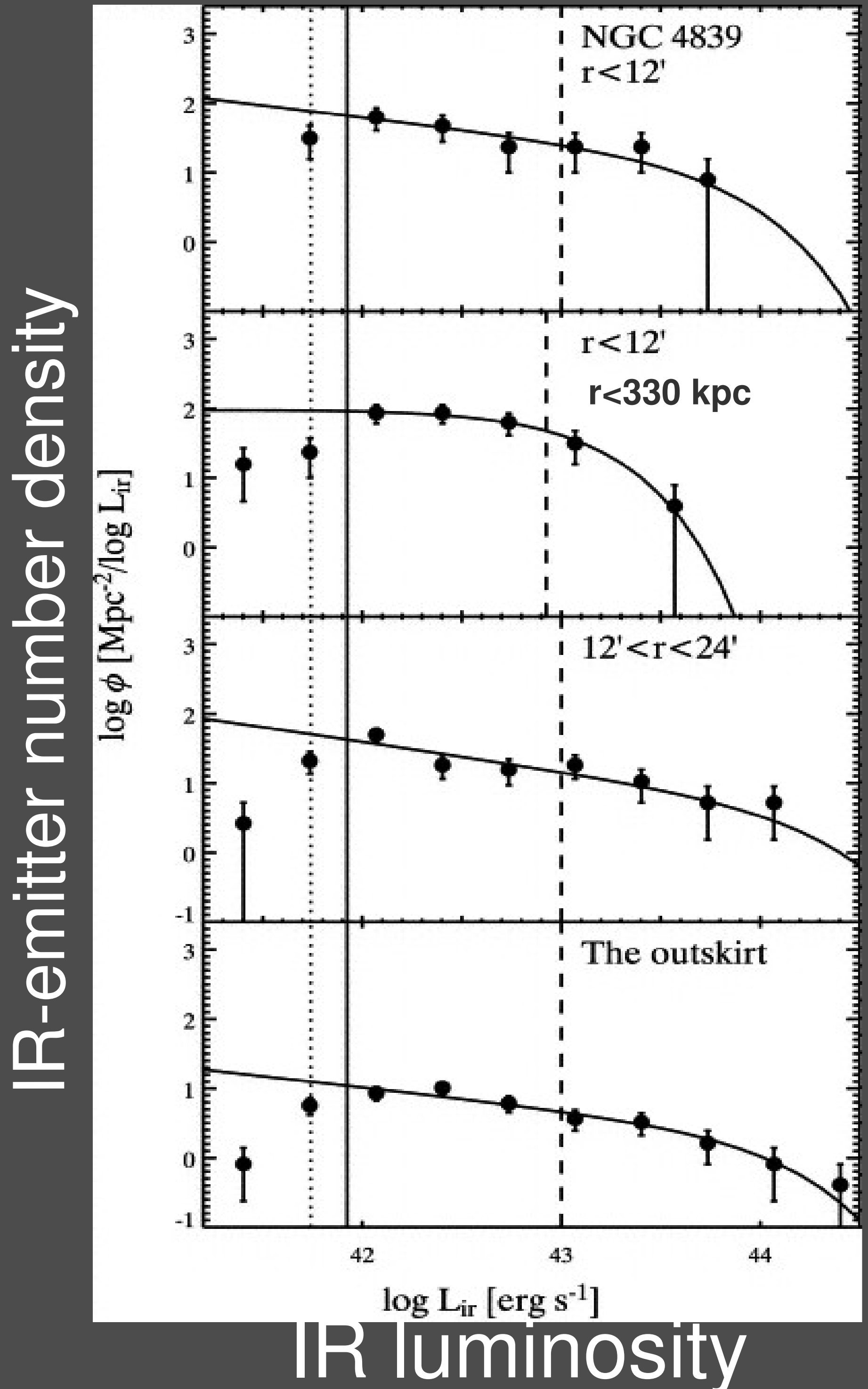
The distribution of galaxy L_{IR} (IR LF) in nearby galaxy clusters is "universal"



galaxy number density per bin of IR luminosity

IR luminosity

(Bai+09)



The IR LF in clusters changes with distance from the cluster center

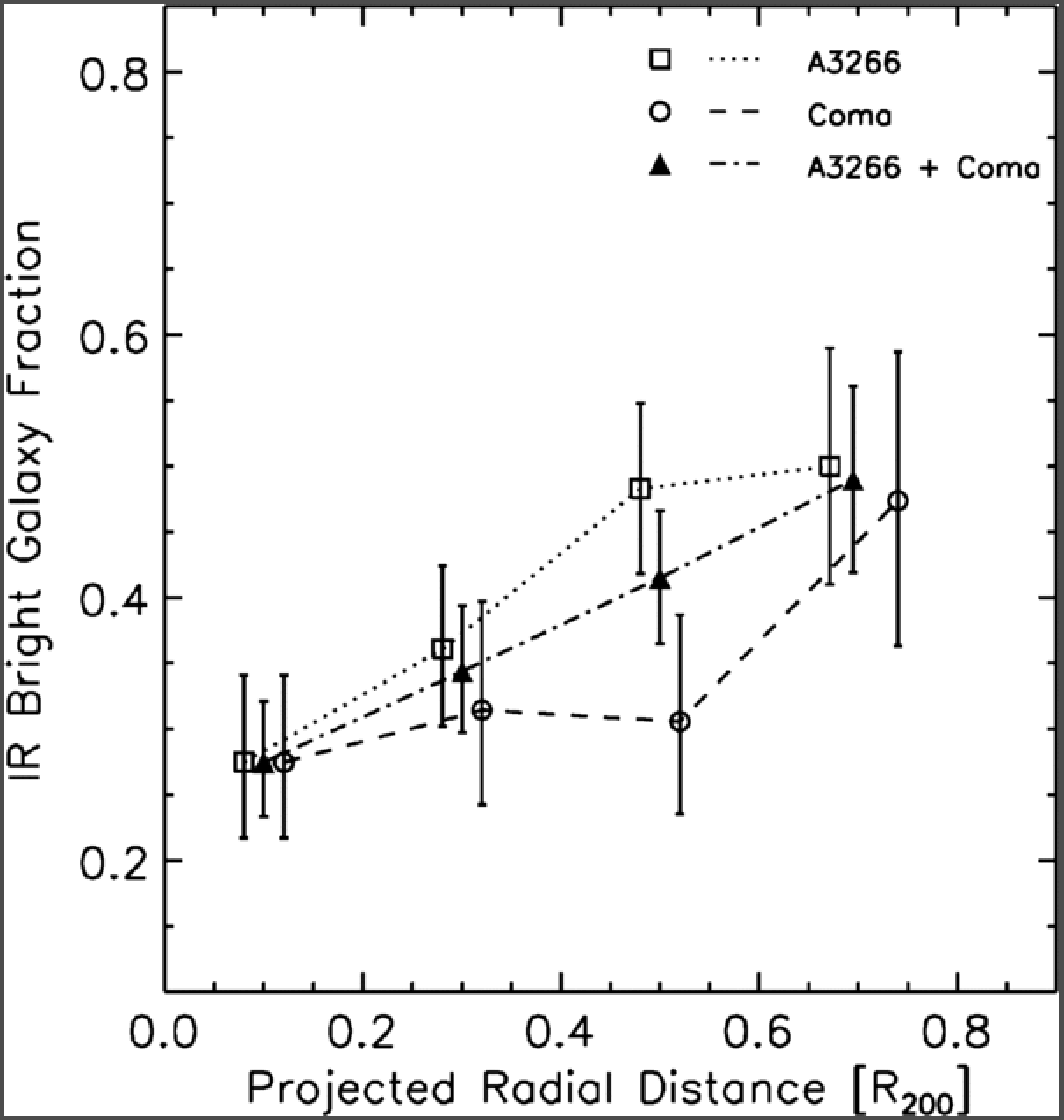
Higher ratio of bright/faint IR-emitters at large radii

(Bai+06)

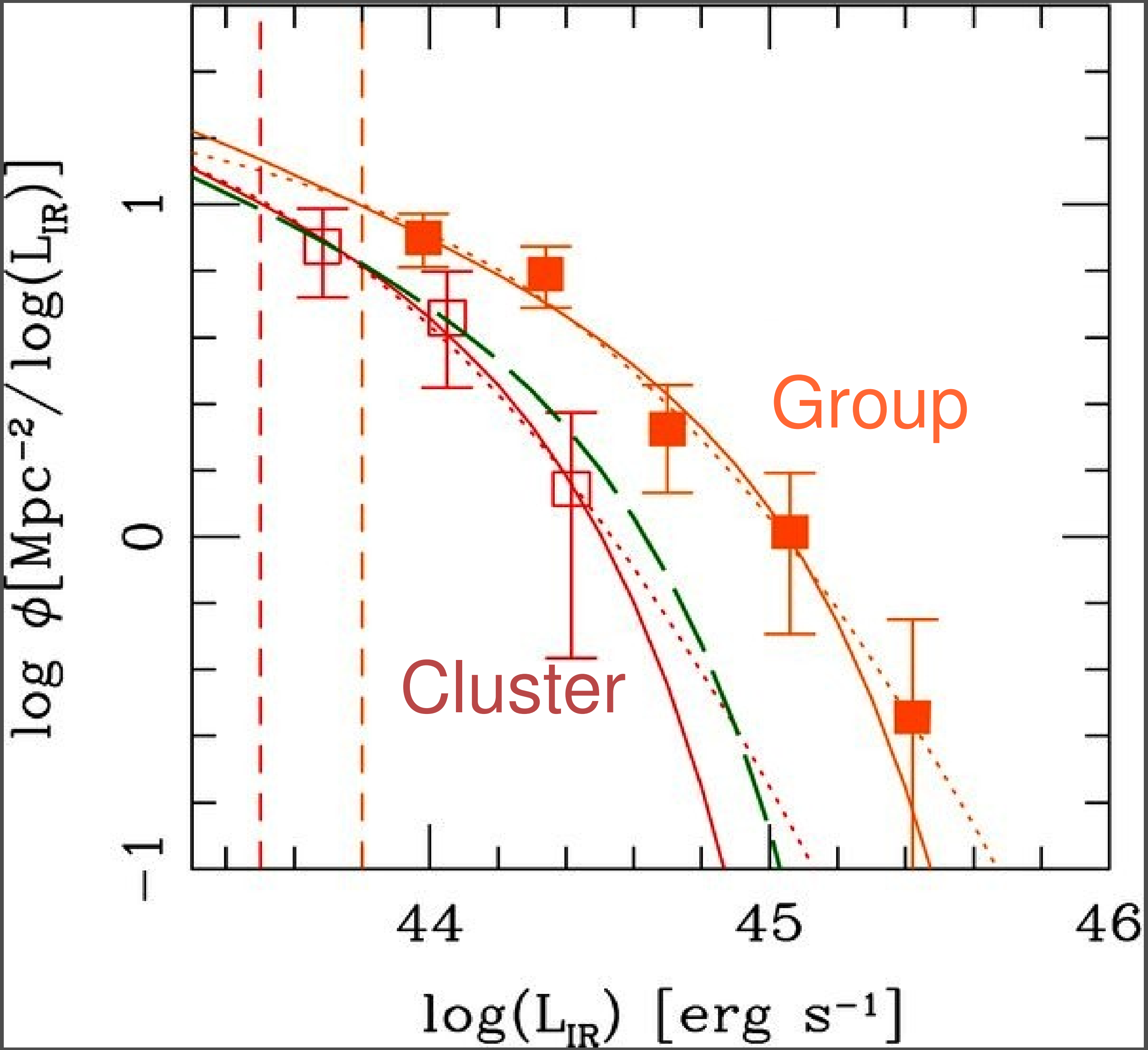
Higher fraction of high-SFR galaxies at larger radii

Fraction of $M_R \leq -20.15$ galaxies which have SFR ≥ 0.2 $M_\odot$/yr

(Bai+09)



Group IR LF vs. cluster IR LF



Density of IR-emitters & ratio of bright/faint IR-emitters

higher in groups than in clusters

(Tran+09)

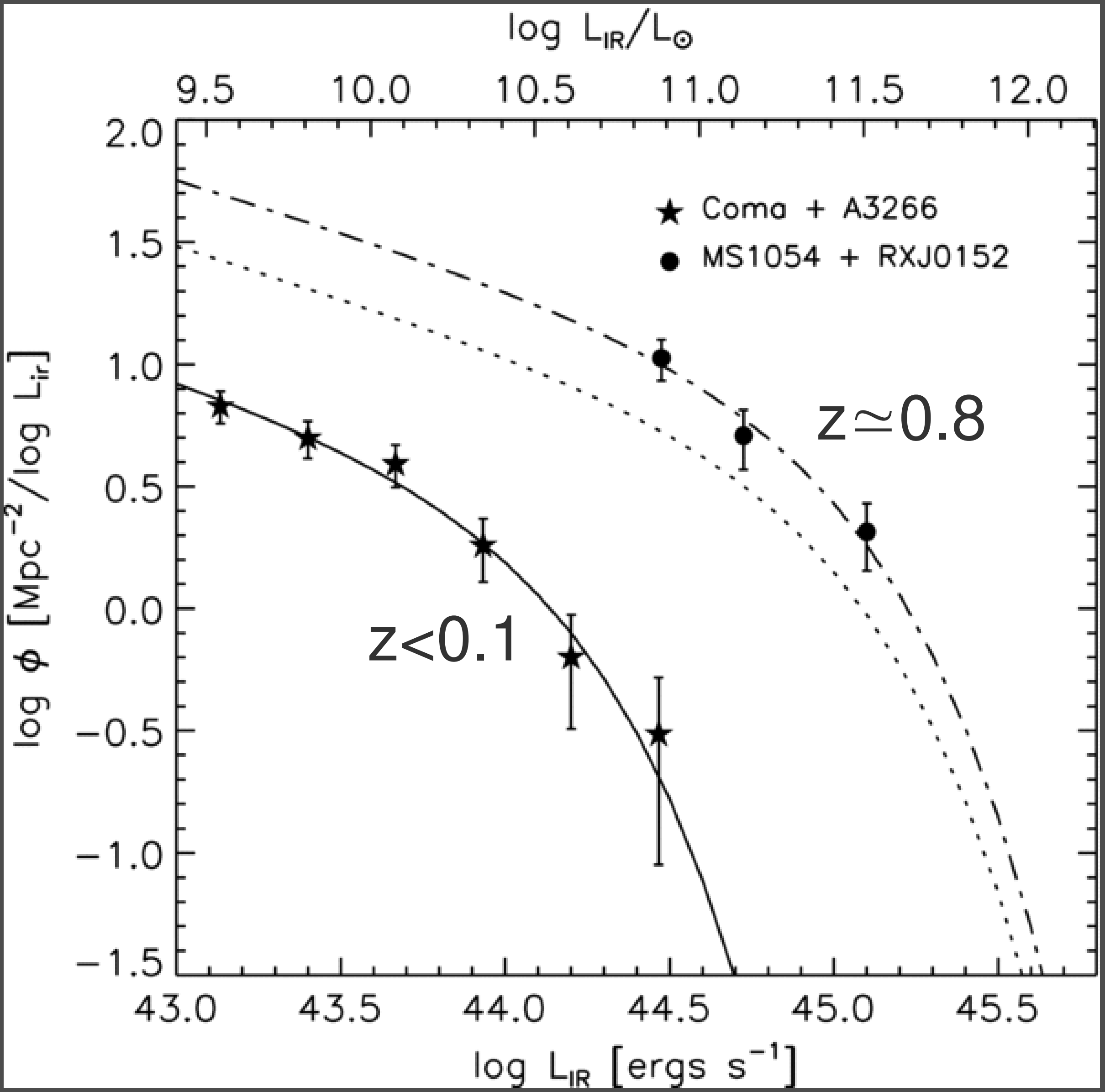
Evolution of the cluster IR LF

Higher density
of IR-emitters
&
higher fraction
of bright/faint
emitters

in higher-redshift
clusters

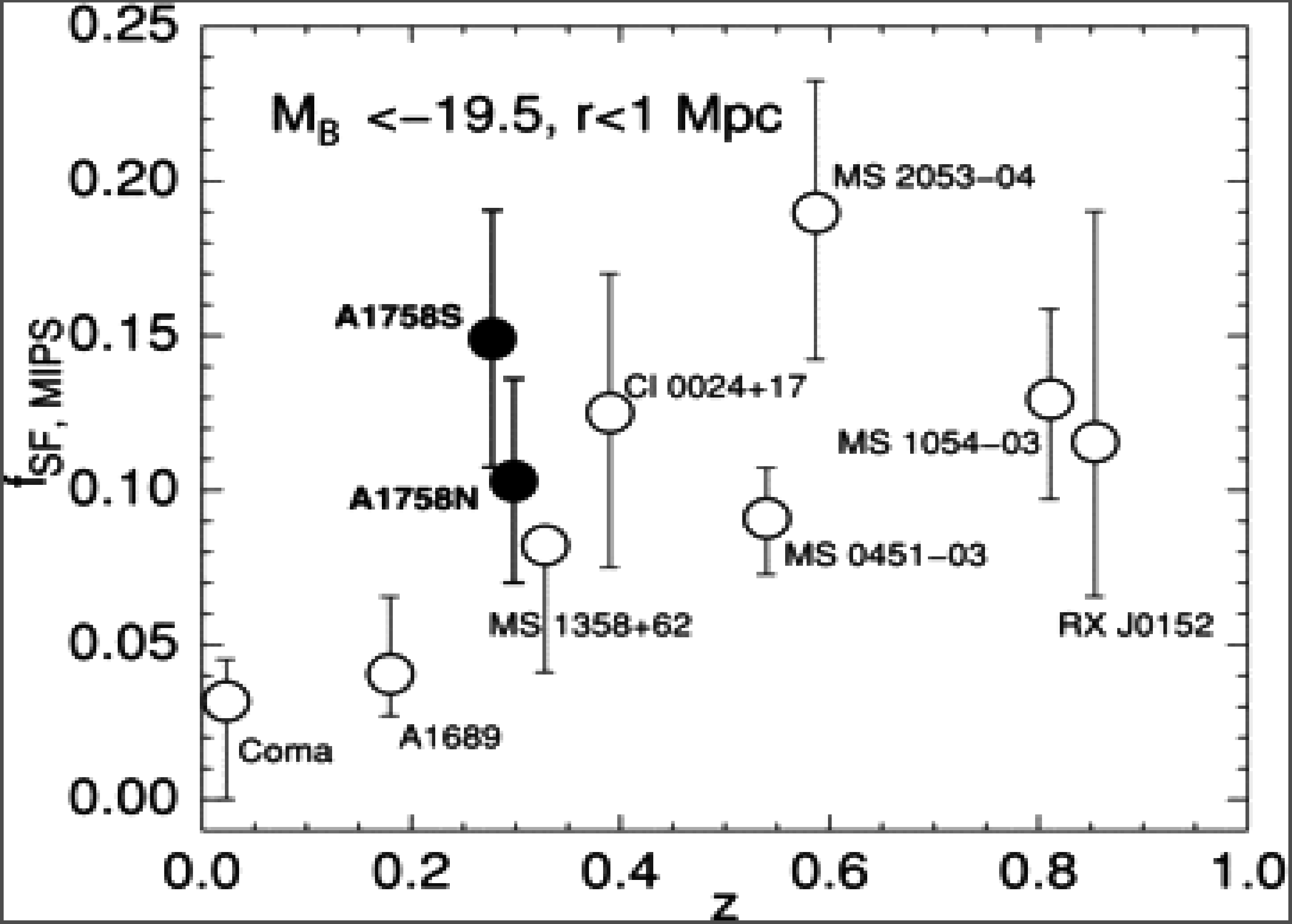
(Bai+09)

IR-emitter number density

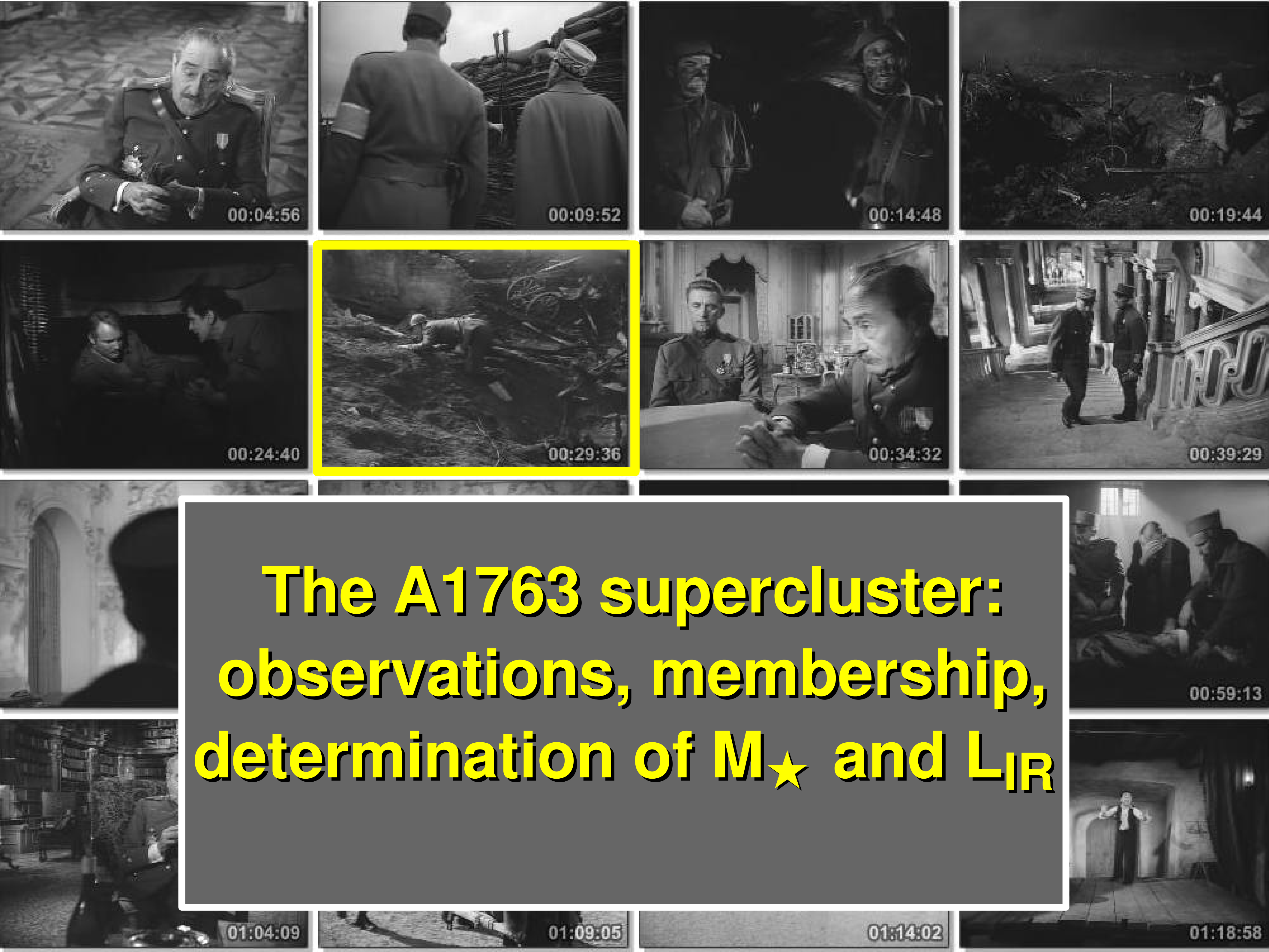


IR luminosity

The fraction of IR-emitters in clusters ↑ with z: the "IR Butcher-Oemler" effect



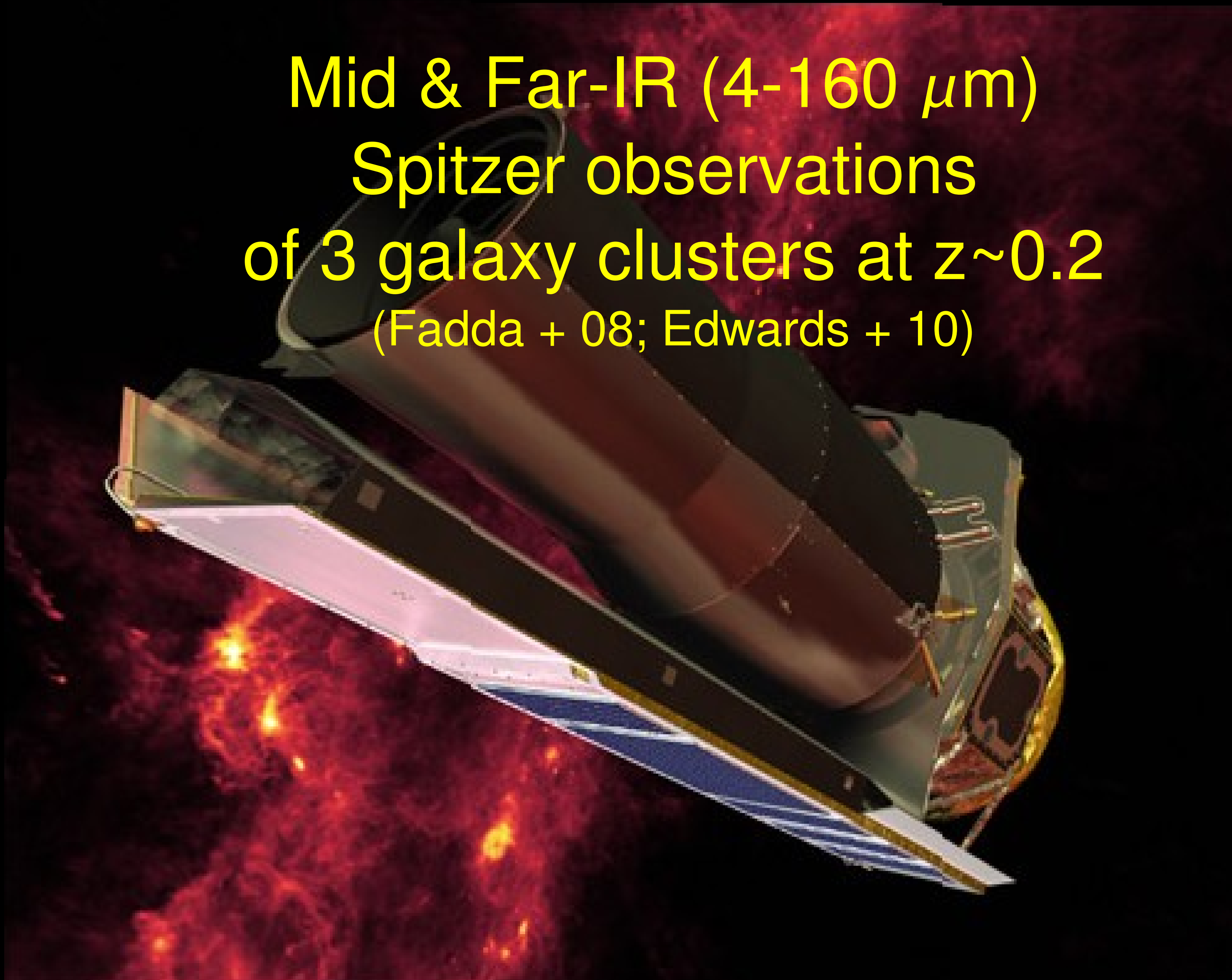
(Haines+09)

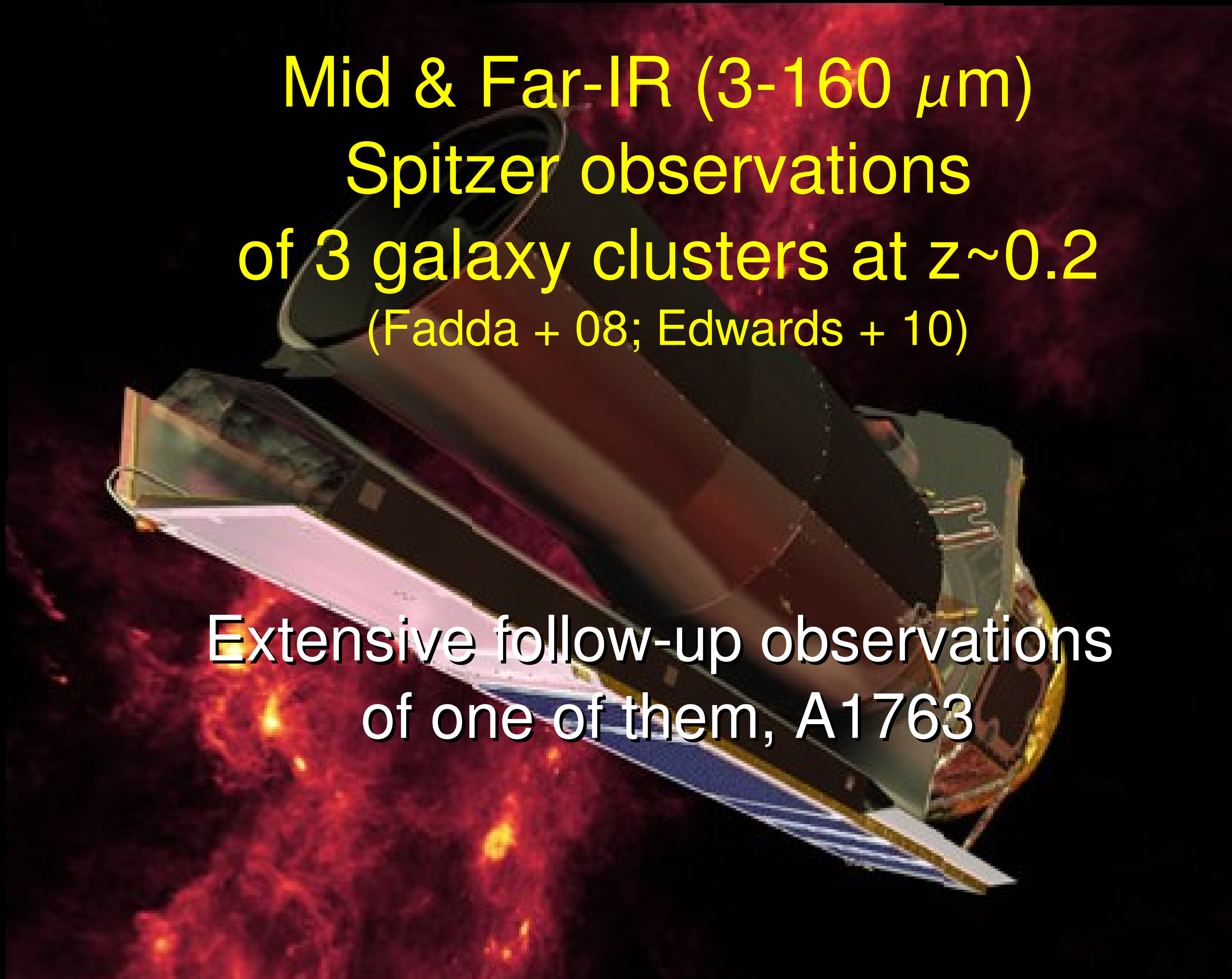


The A1763 supercluster: observations, membership, determination of $M_\star$ and L_{IR}

Mid & Far-IR (4-160 μm) Spitzer observations of 3 galaxy clusters at z~0.2

(Fadda + 08; Edwards + 10)




Mid & Far-IR (3-160 μm)
Spitzer observations
of 3 galaxy clusters at z~0.2
(Fadda + 08; Edwards + 10)
Extensive follow-up observations
of one of them, A1763

Follow-up observations of A1763:

r', J, H, K_s photometry at Palomar 200inch (LFC + WIRC)

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SDSS u', g', r', i' photometry also available

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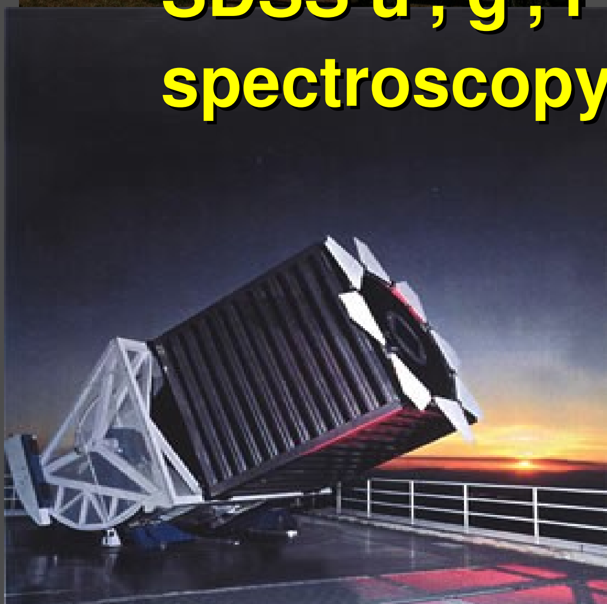
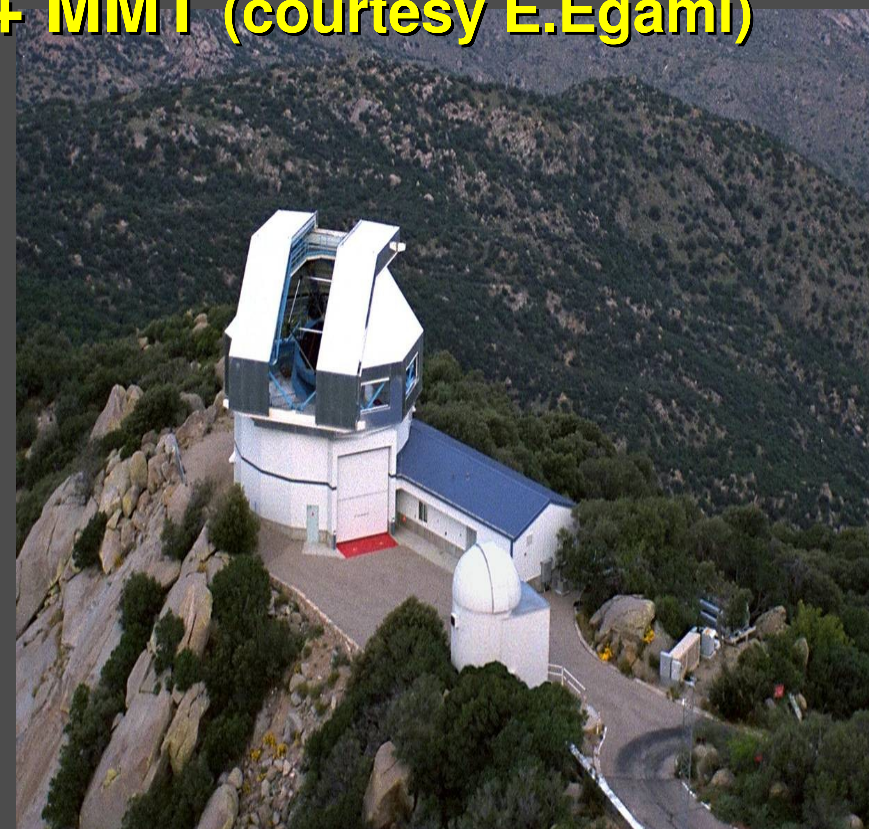
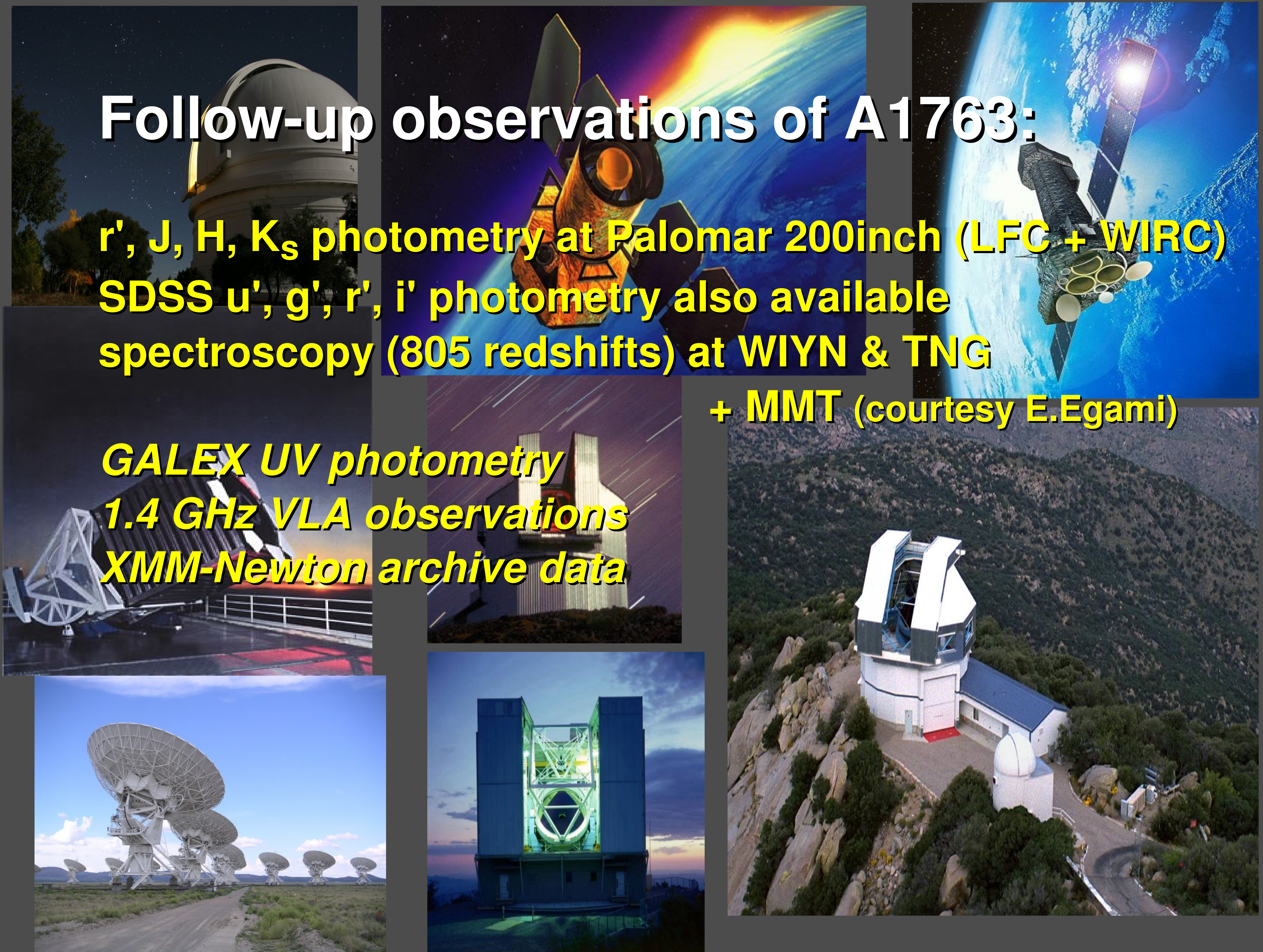
spectroscopy (805 redshifts) at WIYN & TNG

+ MMT (courtesy E.Egami)





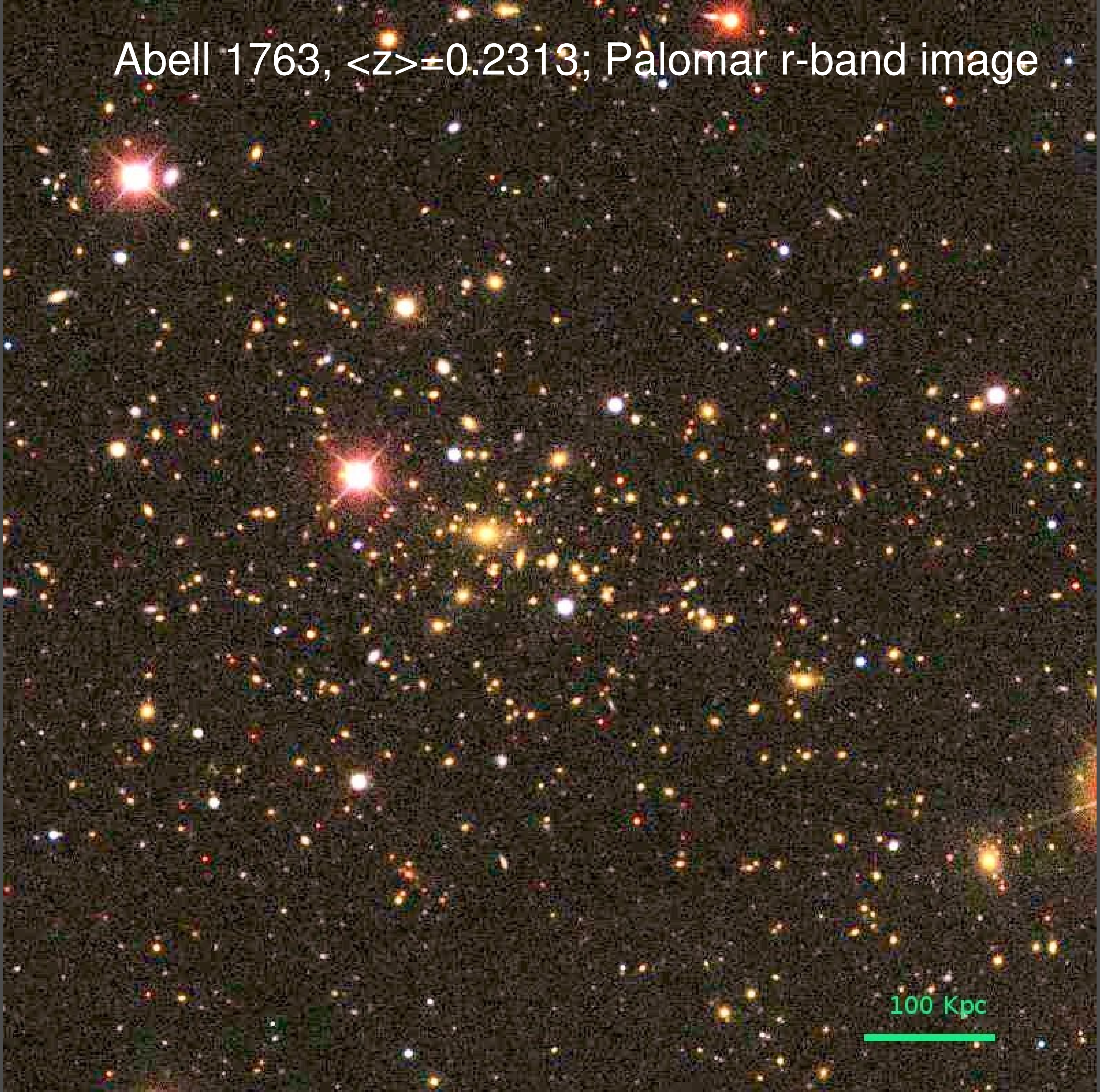

Follow-up observations of A1763:
r', J, H, K_s photometry at Palomar 200inch (LFC + WIRC)
SDSS u', g', r', i' photometry also available
spectroscopy (805 redshifts) at WIYN & TNG
+ MMT (courtesy E.Egami)
GALEX UV photometry
1.4 GHz VLA observations
XMM-Newton archive data

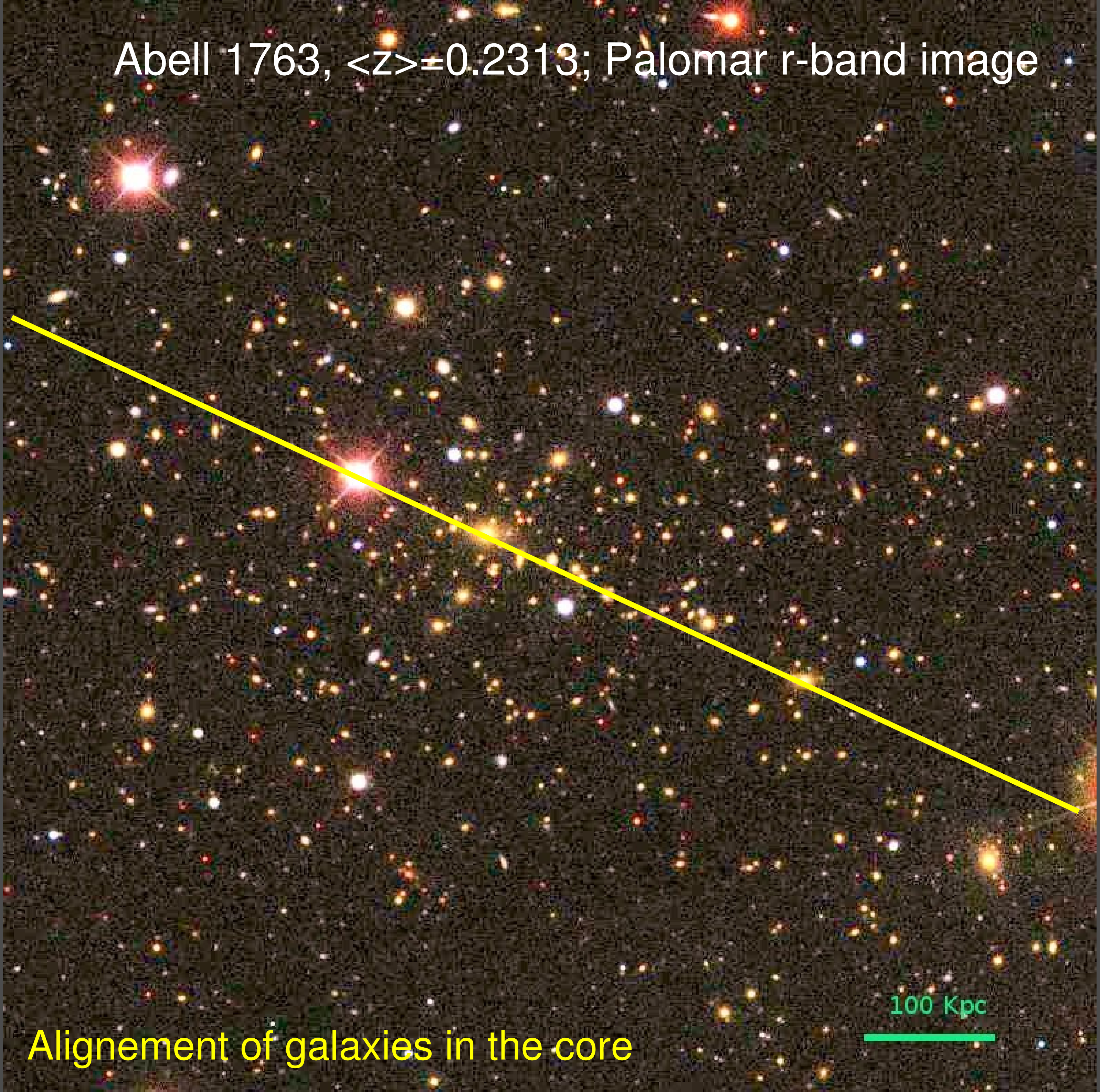
Mid & Far-IR (3-160 μm) Spitzer observations of 3 galaxy clusters at z~0.2

(Fadda + 08; Edwards + 10)

Extensive follow-up observations of one of them, A1763:

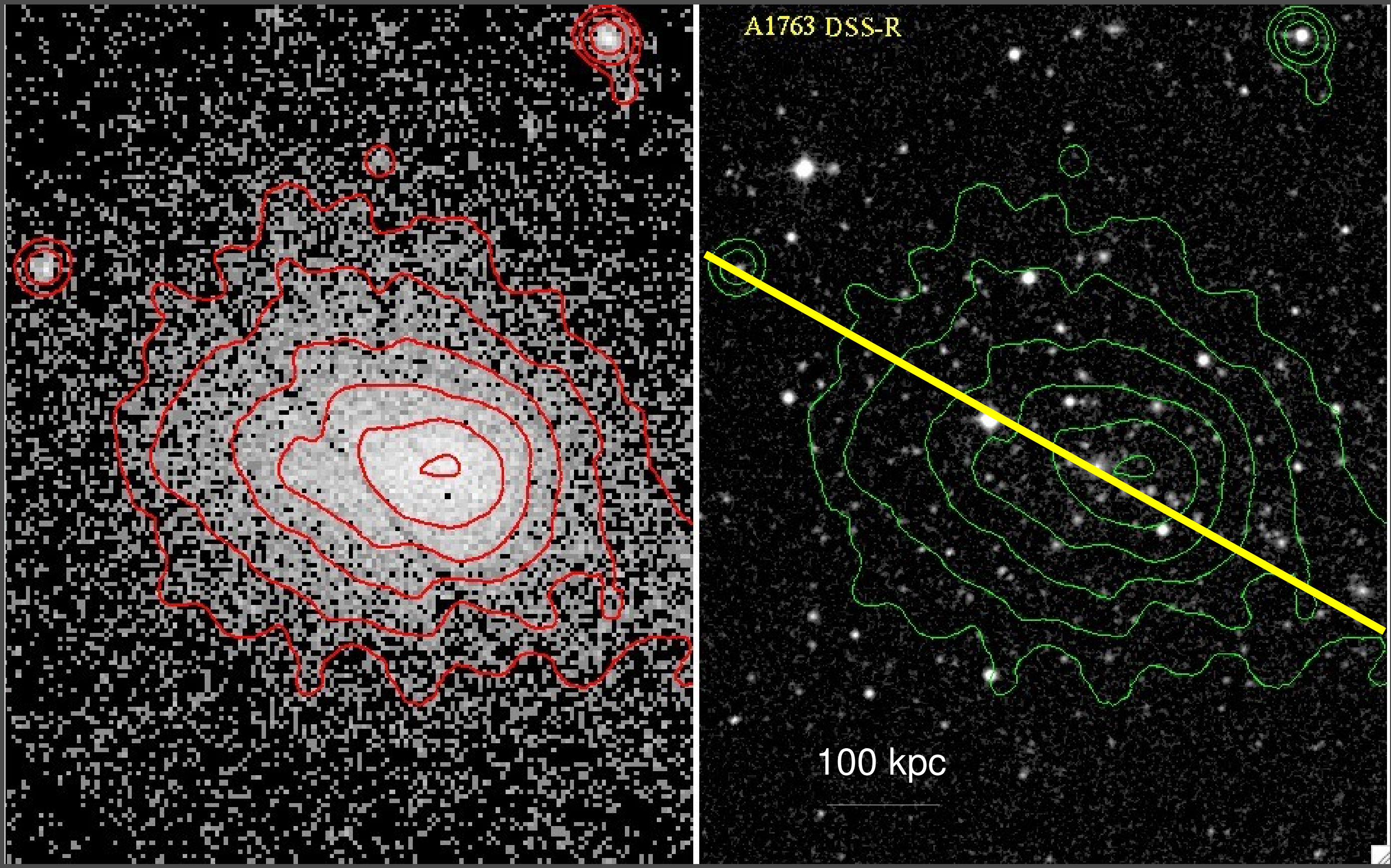
r', J, H, K_s photometry at Palomar 200inch (LFC + WIRC)
(SDSS u', g', r', i' photometry also available)
GALEX UV photometry (data reduction in progress)
1.4 GHz VLA observations
XMM-*Newton* archive data
spectroscopy (805 redshifts) at WIYN & TNG
+ *MMT (courtesy E.Egami)*


Abell 1763, <z>=0.2313; Palomar r-band image
100 Kpc

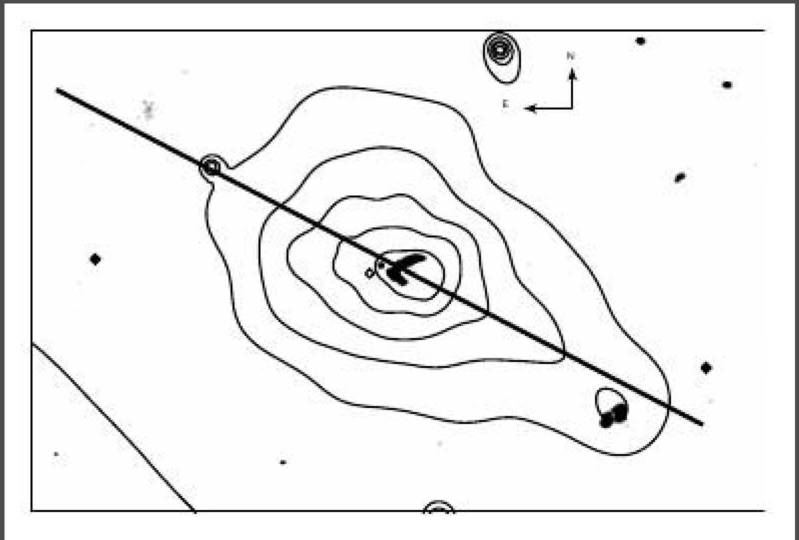

Abell 1763, <z>=0.2313; Palomar r-band image
100 Kpc
Alignement of galaxies in the core

A1763 X-ray surface brightness distribution

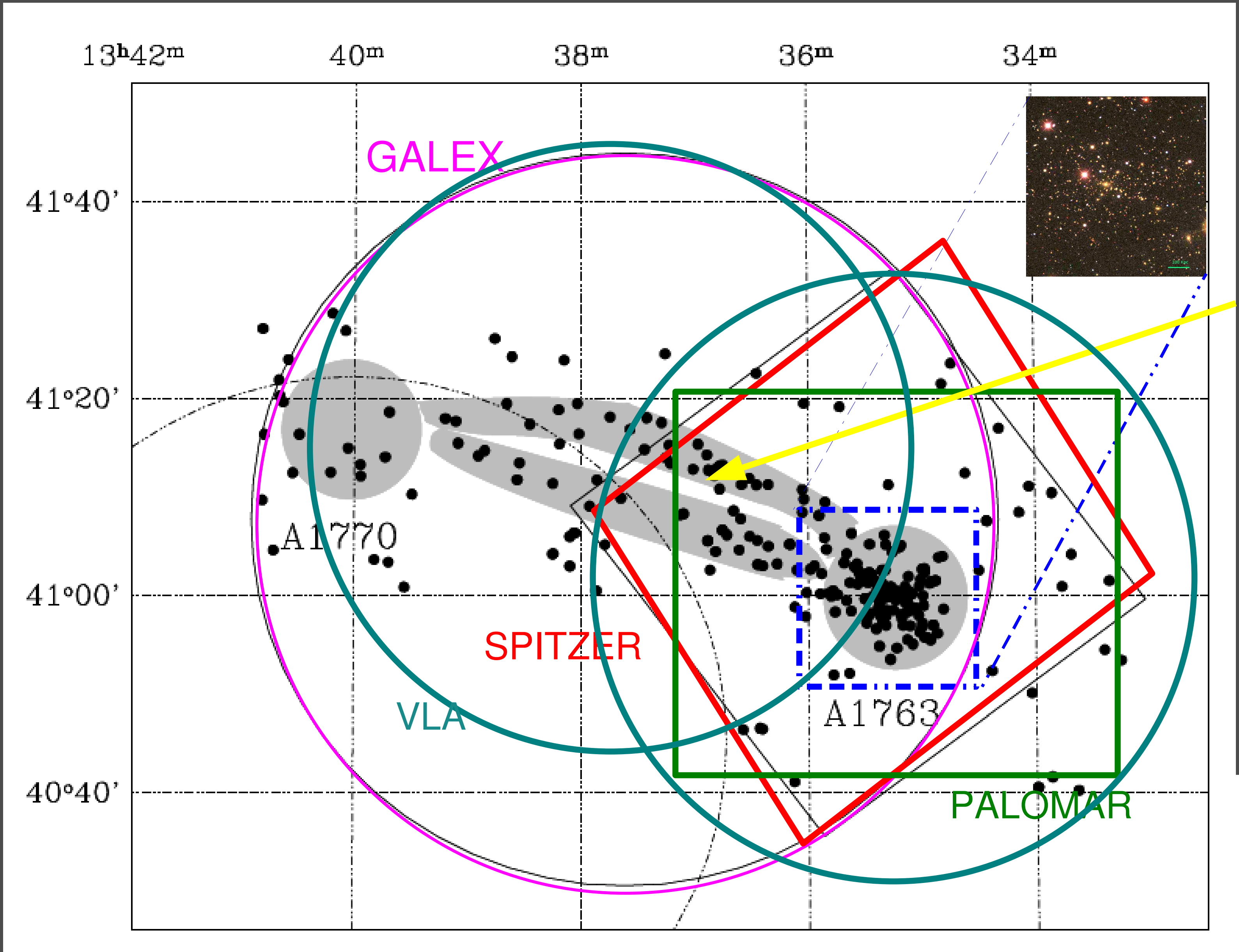
The X-ray surface brightness distribution is elongated like the galaxy distribution



The cD galaxy is a WAT radio galaxy, the angle between the radio lobes is bisected by the line tracing the cluster elongation



Abell 1763, zooming out



1st LSS filament(s) discovered in the IR *(and confirmed spectroscopically)*

5 Mpc

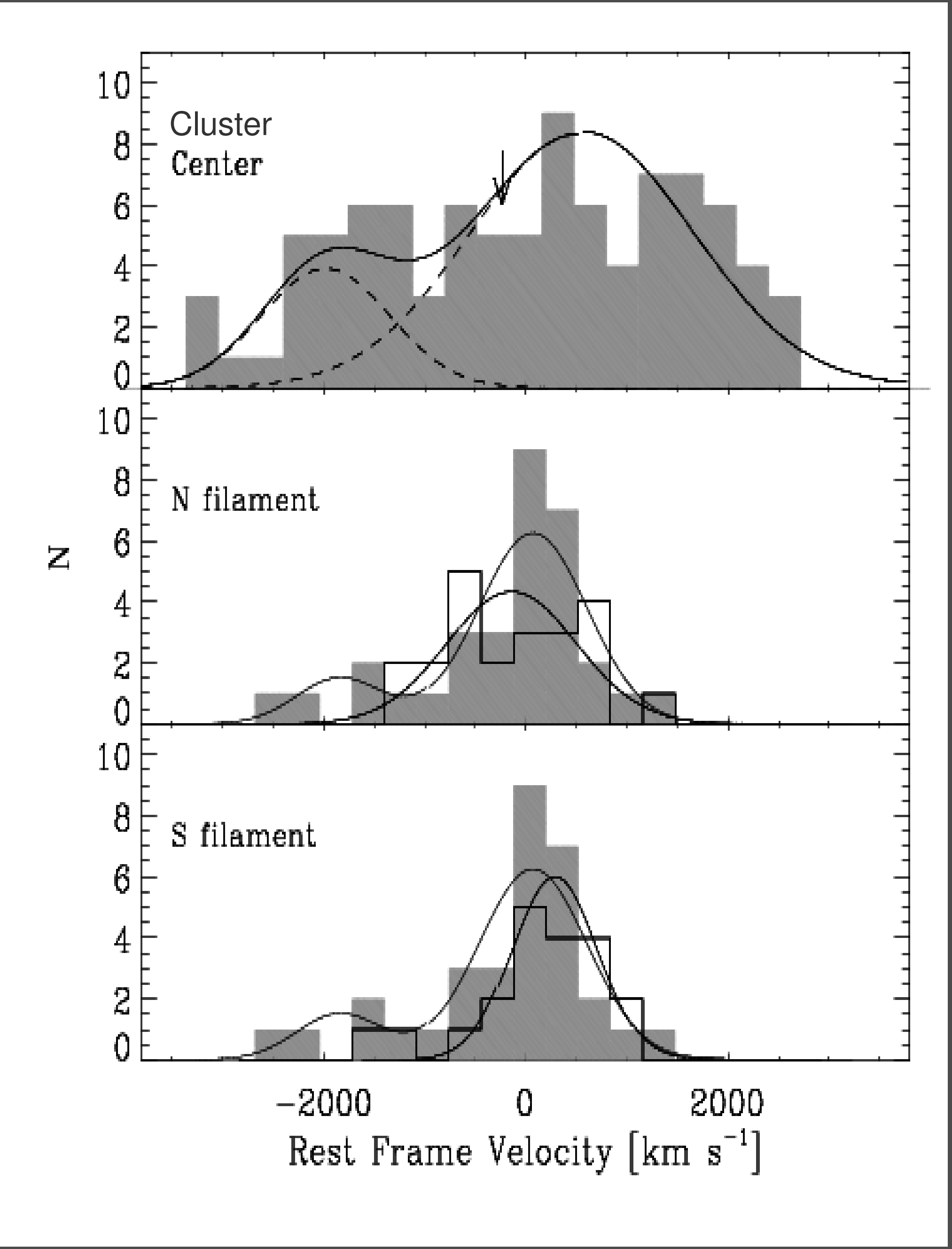
Dots: supercluster members (spectroscopically confirmed)

Spectroscopic confirmation of the 1st LSS filament

(or maybe two)

discovered in the IR

Filaments are feeding the cluster with infalling galaxies and groups, which affect the cluster inner structure



(Fadda, AB, et al. 2008)

AIM: determine the galaxy IR luminosity function in different regions of the supercluster

$\Rightarrow$ galaxy star formation = f(environment)

...to achieve this aim:

Select sample of IR emitters members of the supercluster

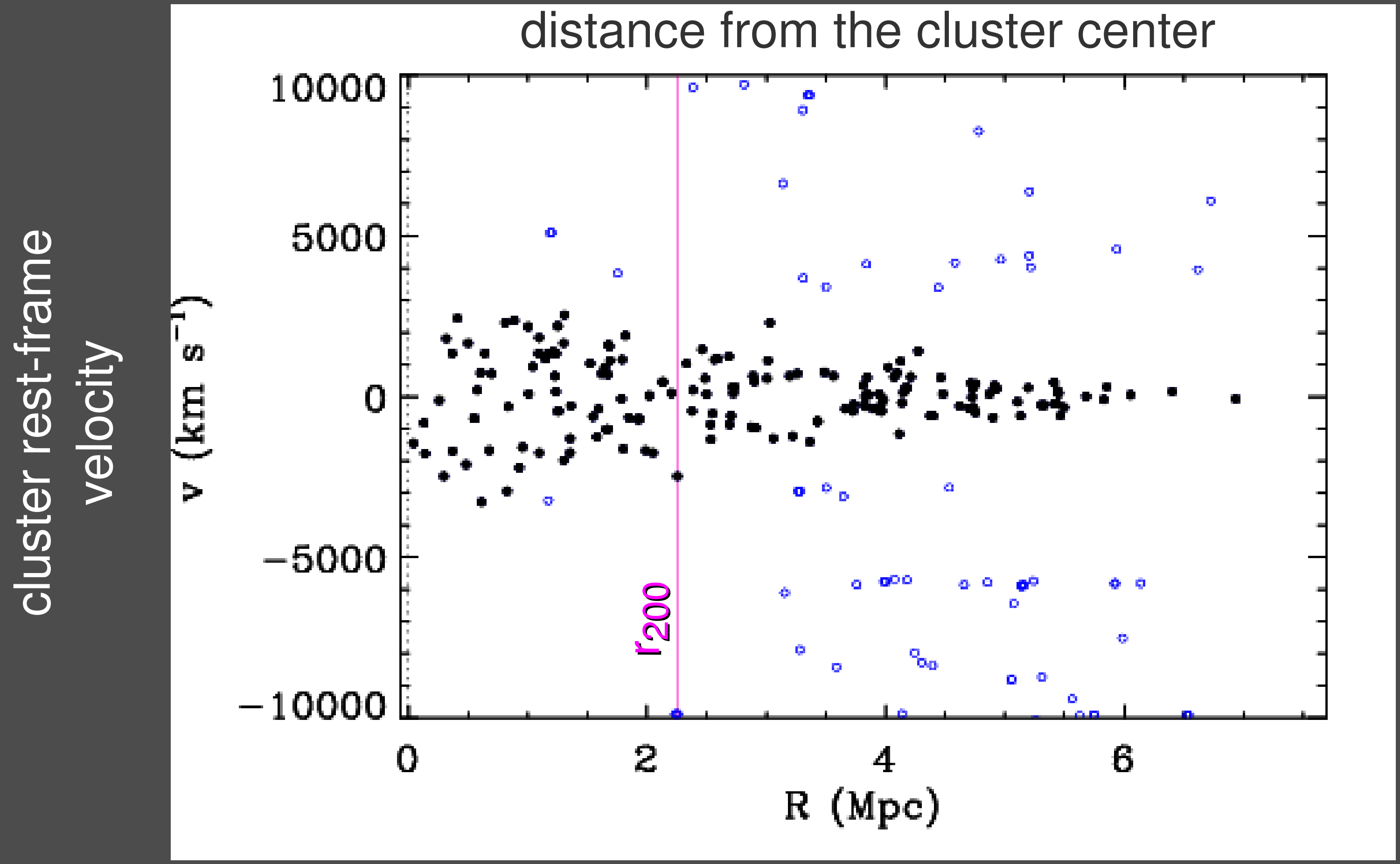
Base the selection on our 24 μm survey,

80% complete at 0.2 mJy

[deeper than 70 and 160 μm,

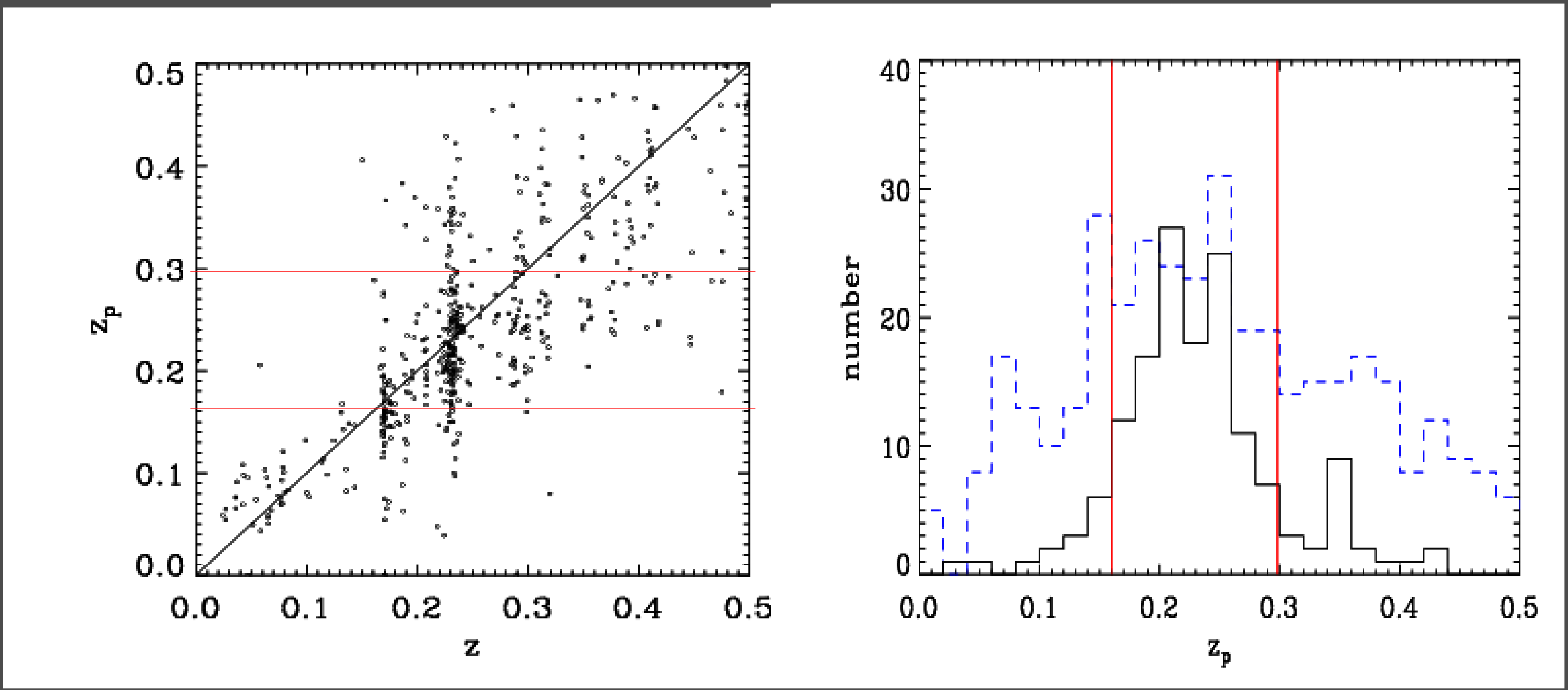
emission at 24 μm closely related to recent star formation]

Membership selection: spectroscopic sample



Use the algorithm of Mamon, AB, Murante (2010):
179 supercluster members found

Membership selection: photometric sample



Use the SDSS photometric redshift estimates,
check vs. spectroscopic redshifts, select z_p-range
such as to maximize Completeness & Purity $(1-P)^2+(1-C)^2$:
another **346** supercluster members found

To determine IR LF we must determine the galaxy total IR luminosities (L_{IR})

⇨ *Star Formation Rates (SFR)*

via Kennicutt's (1998) relation

$SFR\ [M_{\odot}/yr] = 1.7\ 10^{-10}\ L_{IR}/L_{\odot}$

It is also useful to determine the galaxy stellar masses ($M_{\star}$)

⇨ *specific SFR, sSFR* $[yr^{-1}] = SFR/M_{\star}$

Fit galaxy Spectral Energy Distributions (SEDs) with model templates:

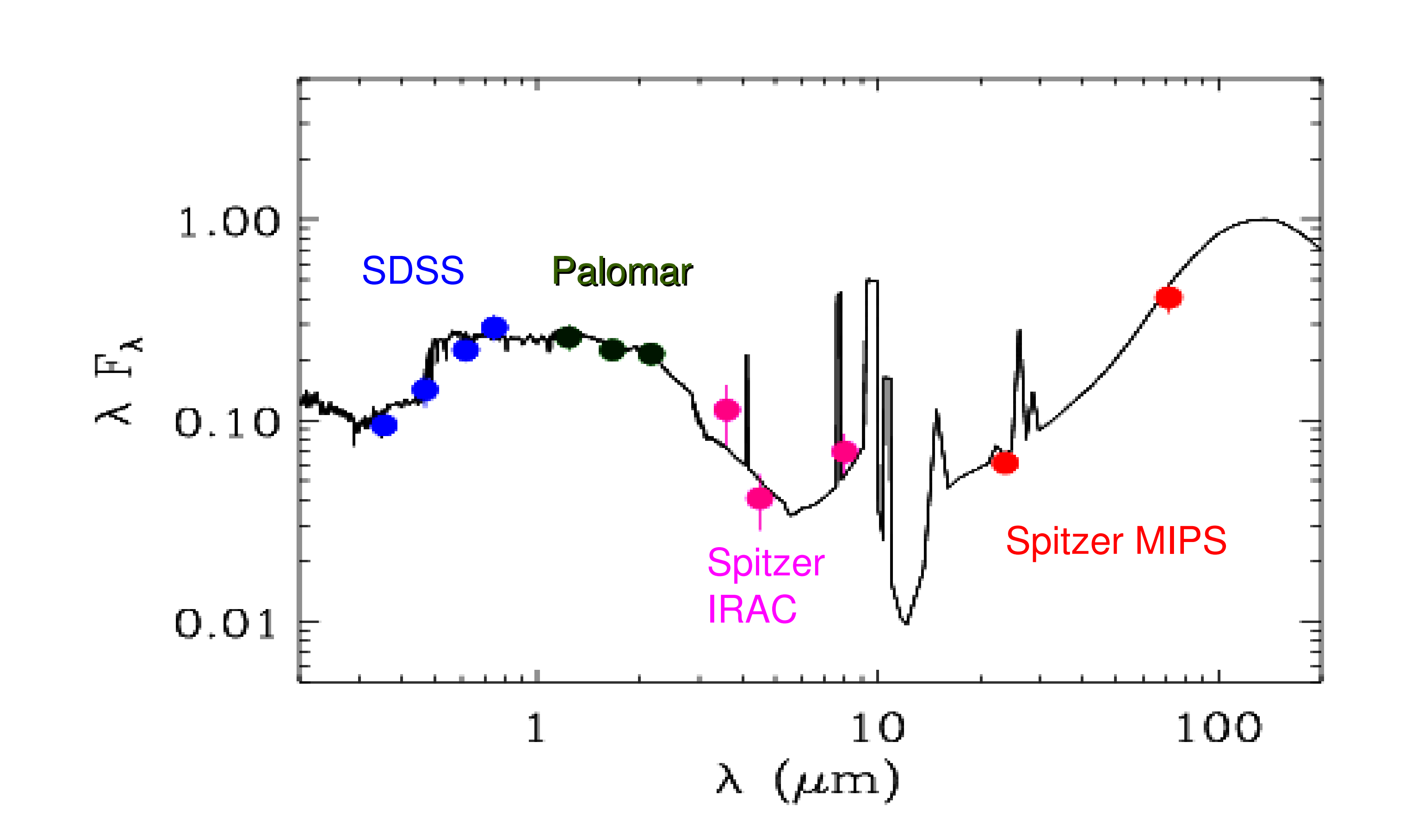
for L_{IR}:

Use GRASIL (Silva+98) & Polletta+07 models and integrate best-fit model SEDs from 8 to 1000 μm

for $M_\star$:

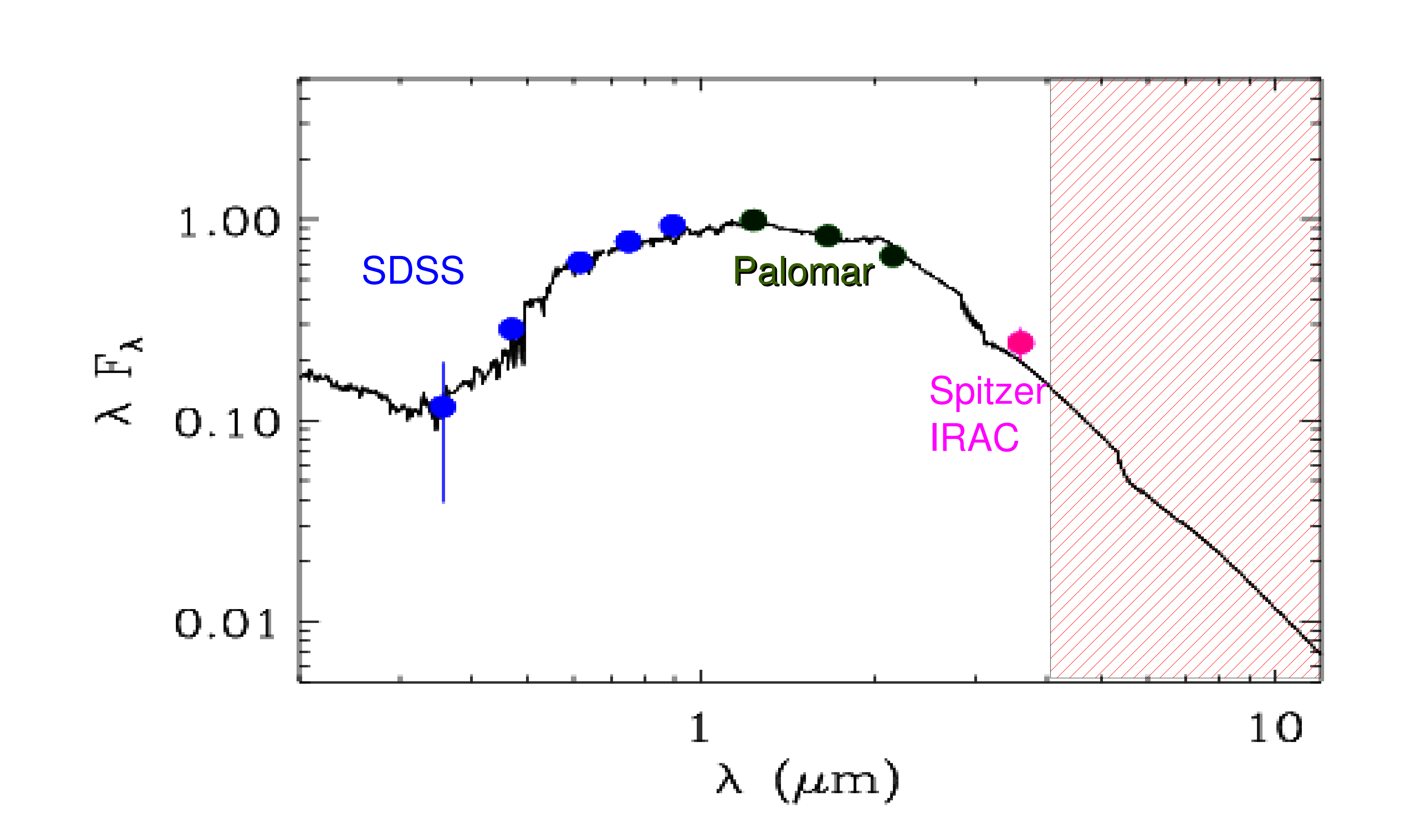
Use models of Maraston 05, correct for absorption (Calzetti+00) with E(B-V) free to vary, and restrict the fit to λ<4 μm

Example of full SED template fit:

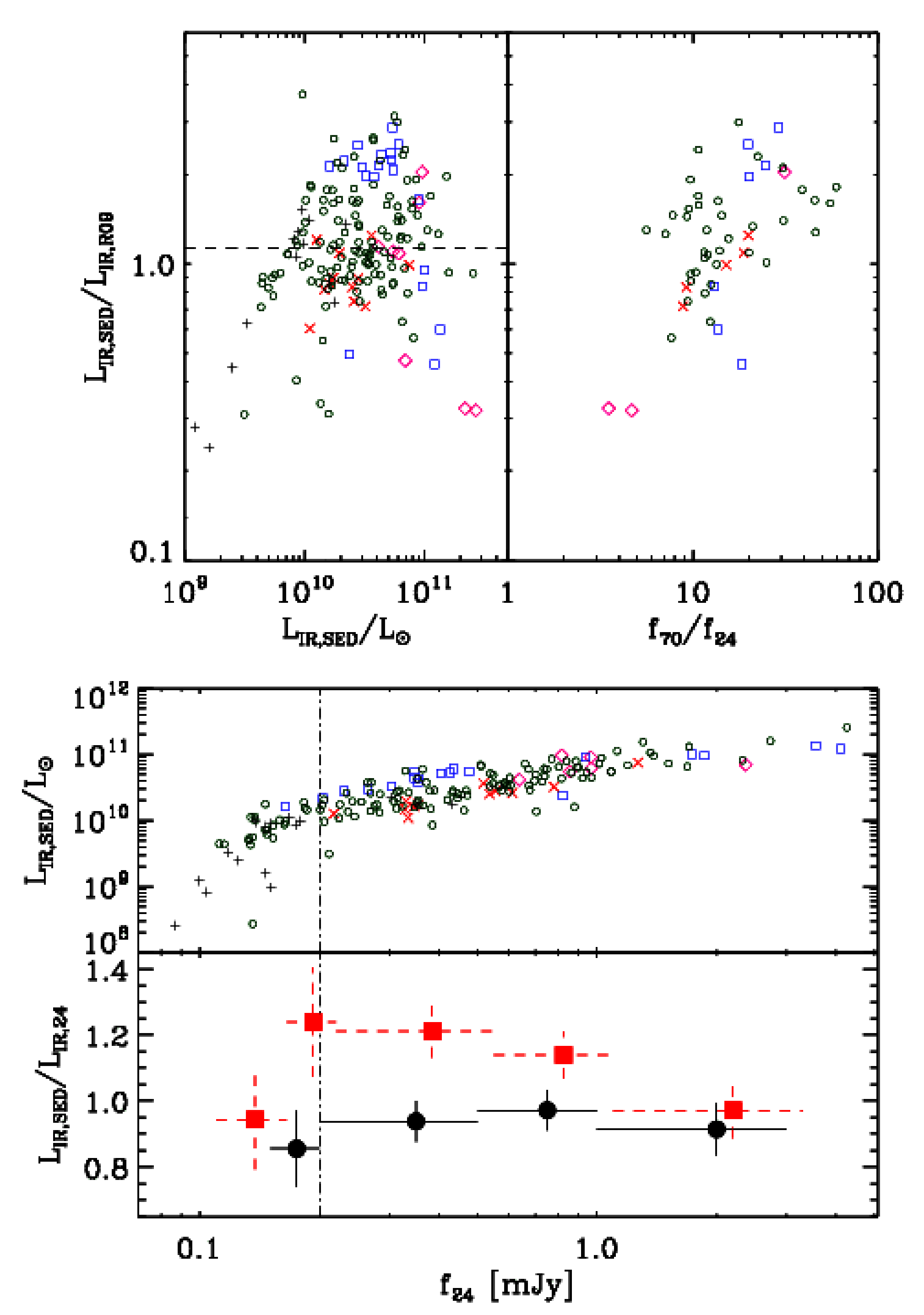


61 templates (GRASIL & Polletta's models) in 5 broad classes:
ETG, SFG, SBG, PSBG, AGN

Example of restricted (λ<4 μm) SED template fit:



Extinction E(B-V) is a free parameter, varying from 0 to1 mag, no dust emission in model ⇨ stop fit at λ<4 μm



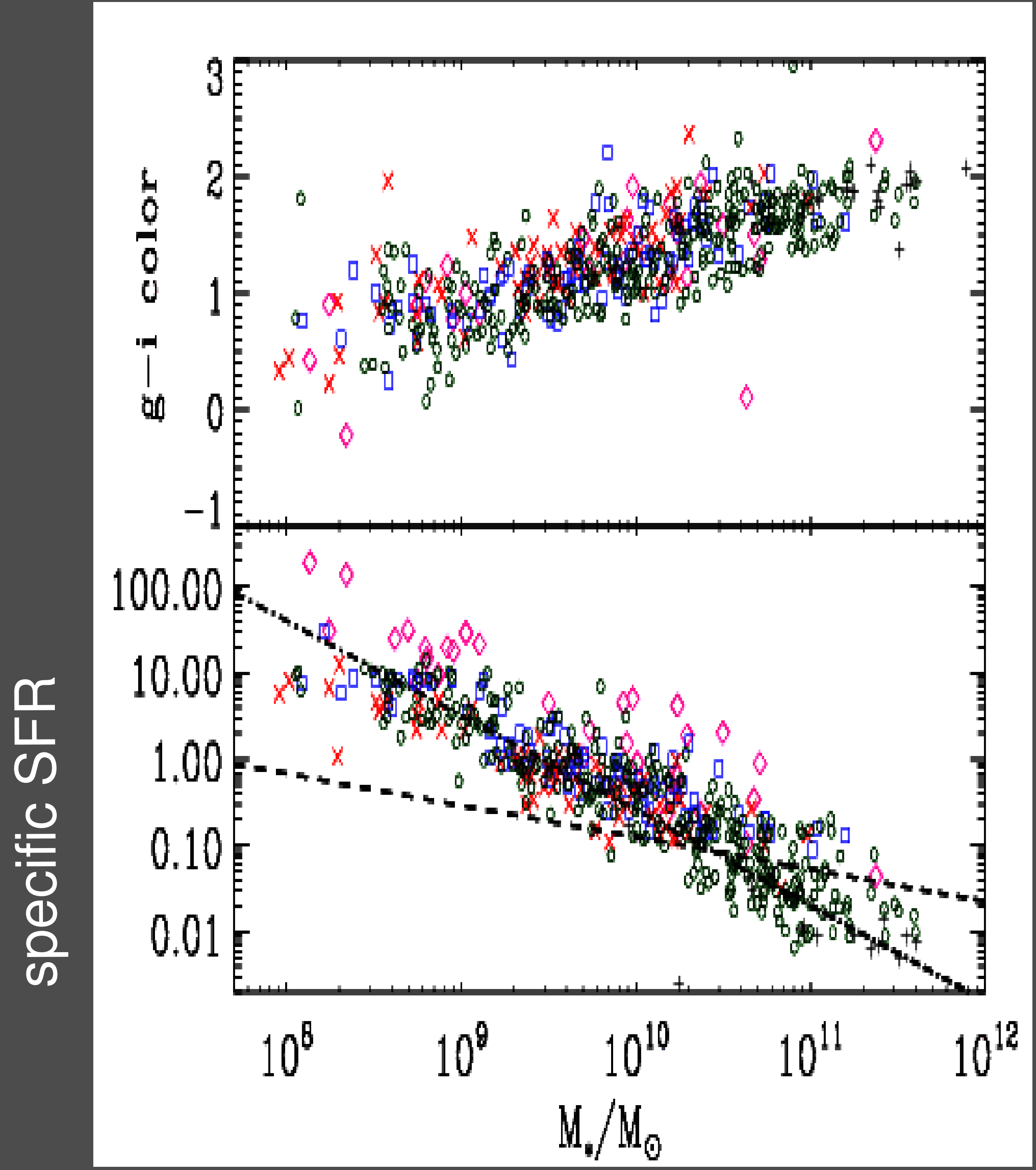
8 —1000 μm SED integral → L_{IR} estimate

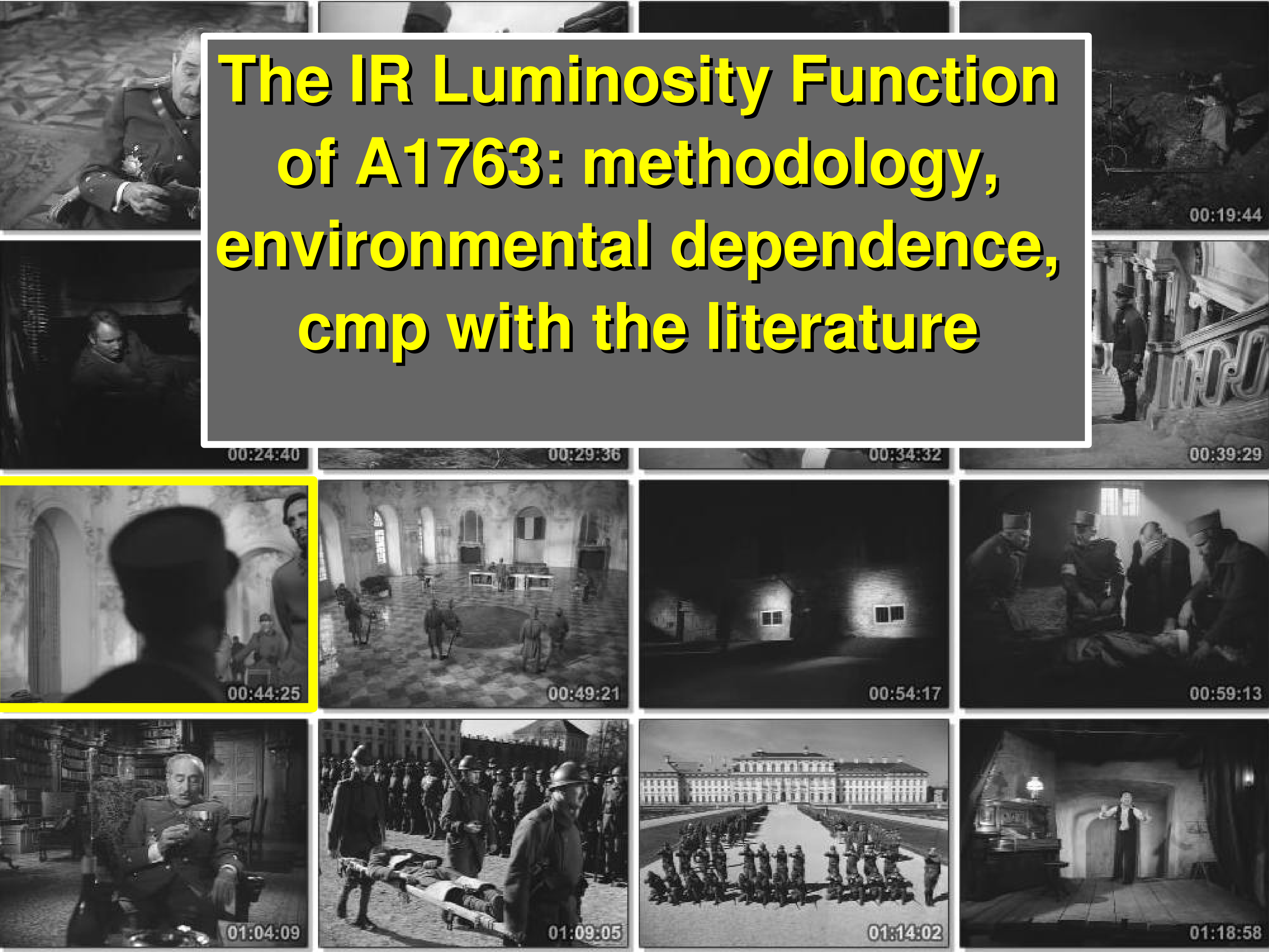
≠ direct estimate of L_{IR} from 24 μm monochromatic luminosity (Rieke+09, Lee+10)

(different symbols are different SED classes: black crosses=ETG, green circles=SFG, blue squares=SBG, pink diamonds=PSBG, red X's=AGN)

Galaxy
stellar masses
are related to
galaxy colors

SFR ∝ $M_{\star}$
as seen in
other IR-selected
galaxy samples




The IR Luminosity Function of A1763: methodology, environmental dependence, cmp with the literature
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By counting the number of supercluster members
in bins of L_{IR} we do **not** obtain
the IR luminosity function (IR LF),
because our sample is neither complete nor pure
(contamination from non-members).

Therefore we evaluate:

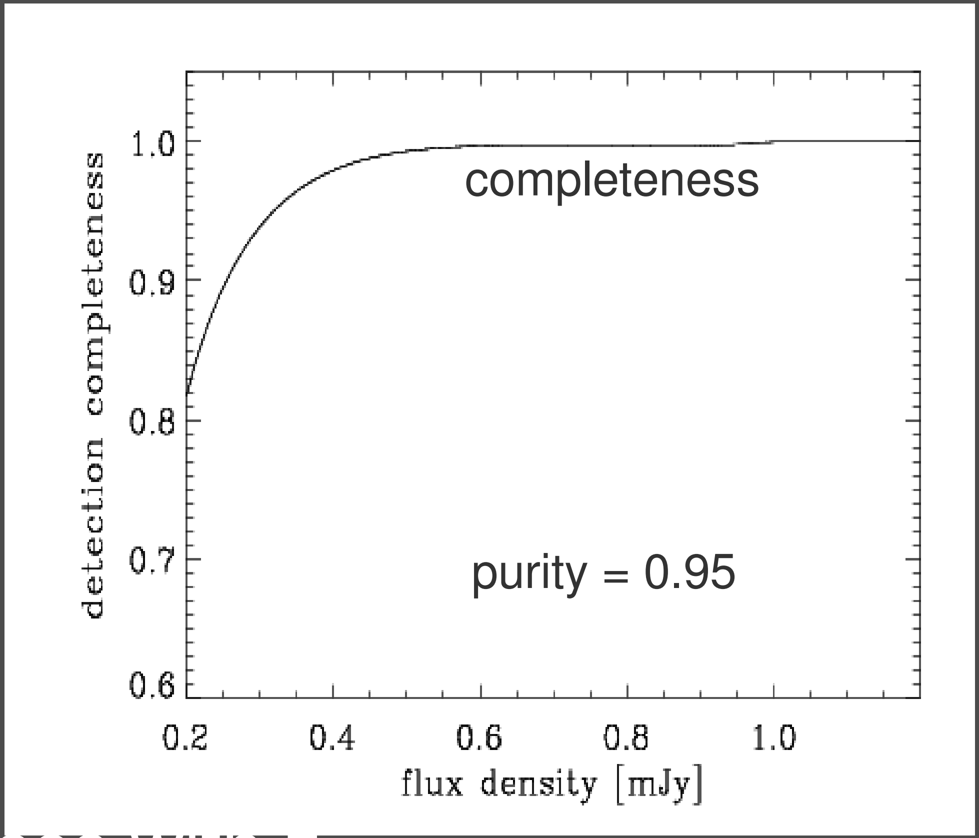
By counting the number of supercluster members in bins of L_{IR} we do **not** obtain the IR luminosity function (IR LF), *because our sample is neither complete nor pure (contamination from non-members).*

Therefore we evaluate:
Completeness = $C(f_{24})$
and Purity = $P(f_{24})$
for the spectroscopic sample & the full (spectroscopic+photometric) sample.

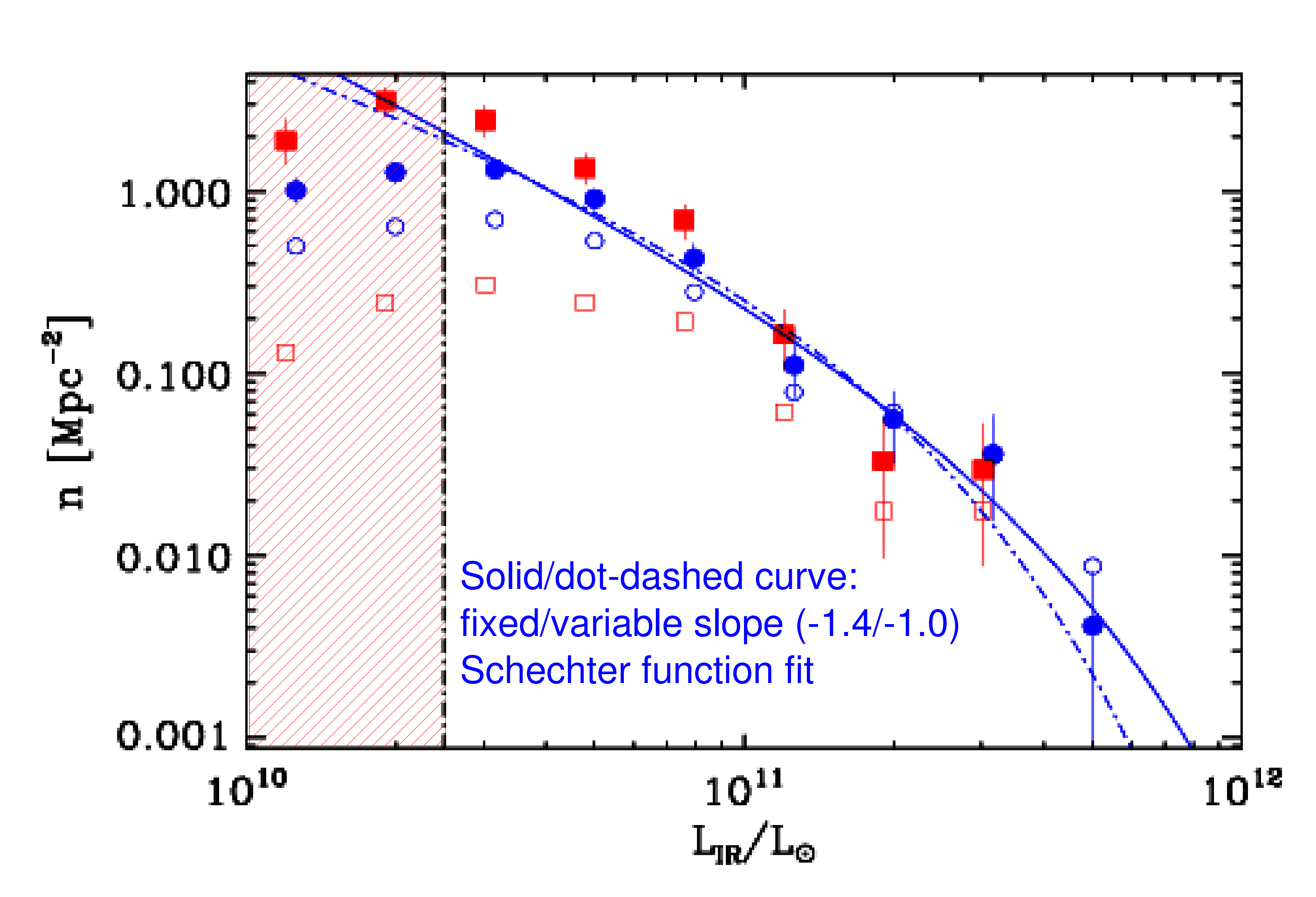
Then we correct the IR counts to get the pure & complete (P=1 & C=1) IR LF

Completeness and Purity corrections; several terms to consider:

- 24 μm sources
- sources with z and/or z_p
- members
  (different corrections for sources with z and sources with z_p but without z)



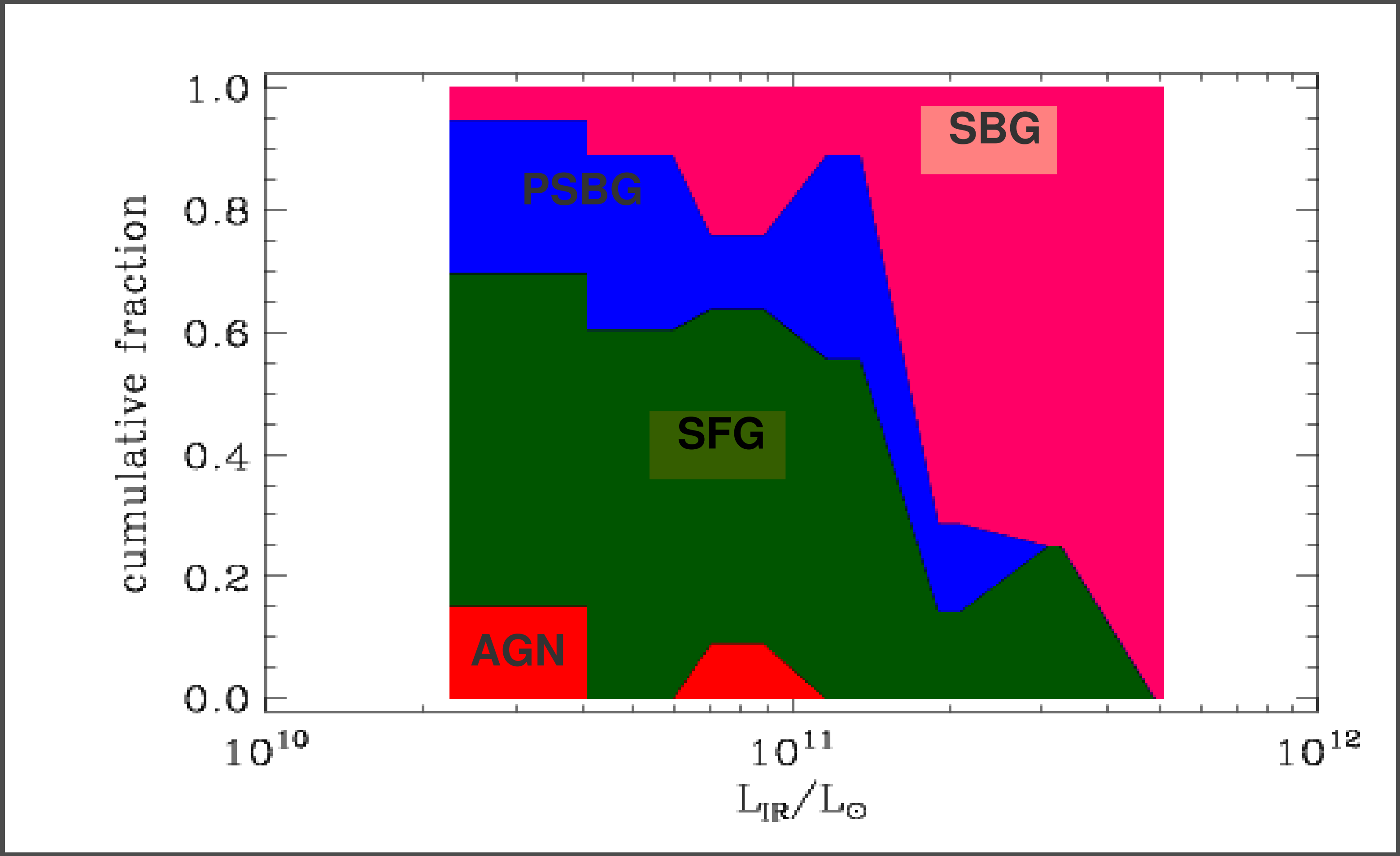
The IR LF of the A1763 supercluster



Open/filled symbols = uncorrected/corrected counts

Red/blue symbols = spectroscopic only/full sample

The contribution of the different SED classes to the IR LF:



AGNs contribute very little *(independent confirmation from the analysis of the radio and X-ray data, Edwards+10)*

→ IR LF is closely related to dust-reprocessed stellar emission

What is the effect of the environment?

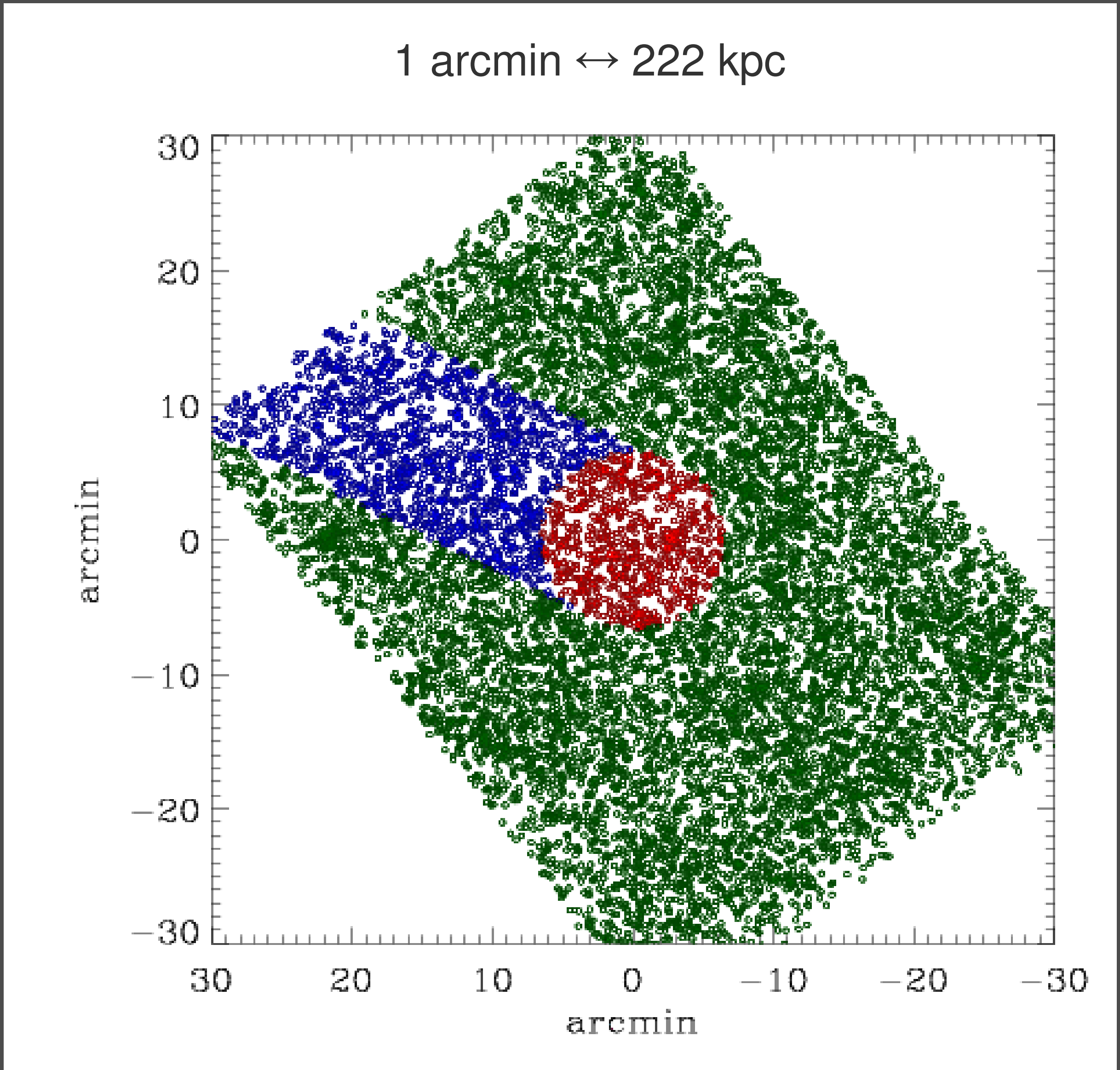
We identify
3 environments:

core ($<r_{500}$)

filaments

outskirts

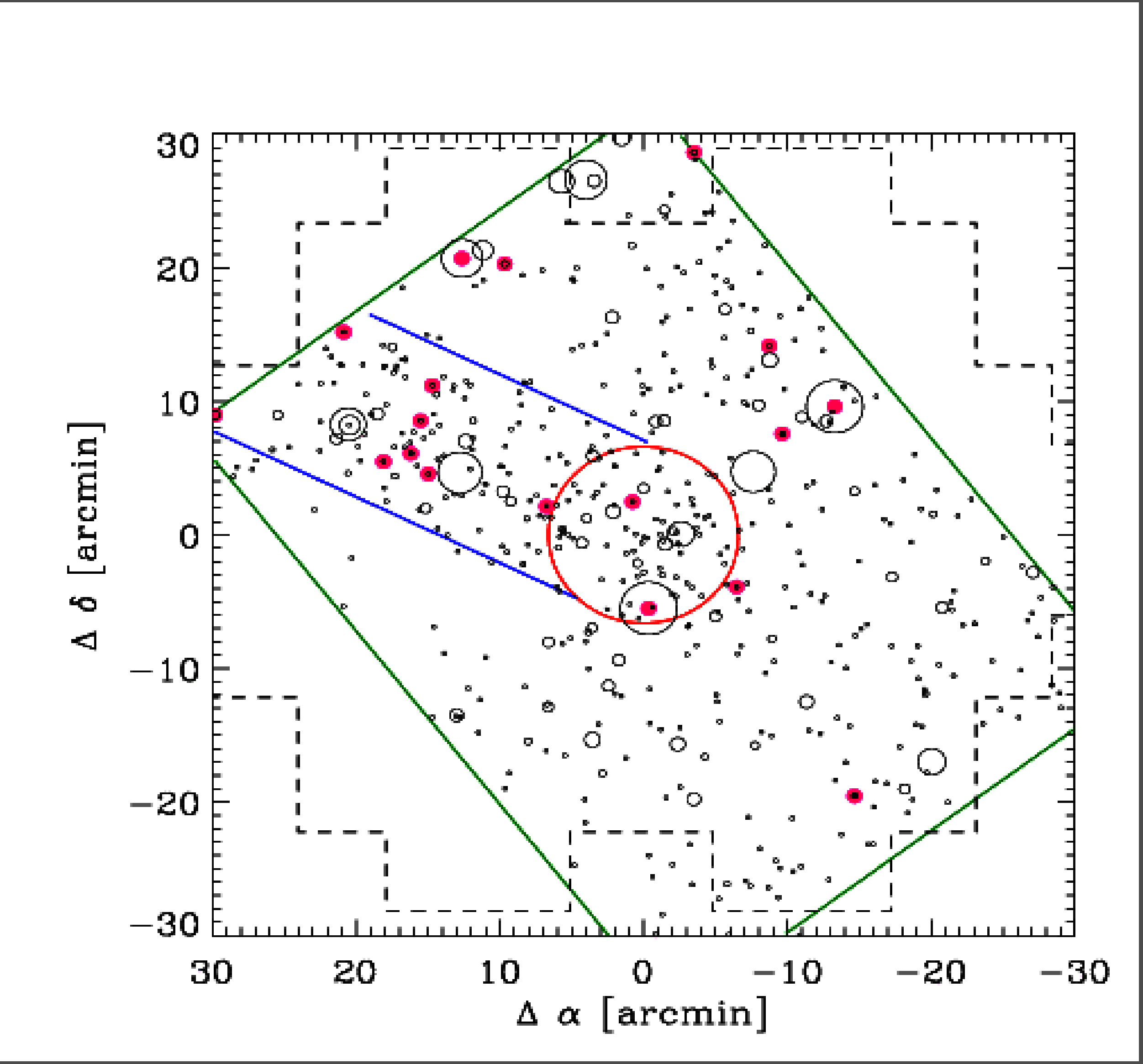
(= the whole field except the core and the filaments)



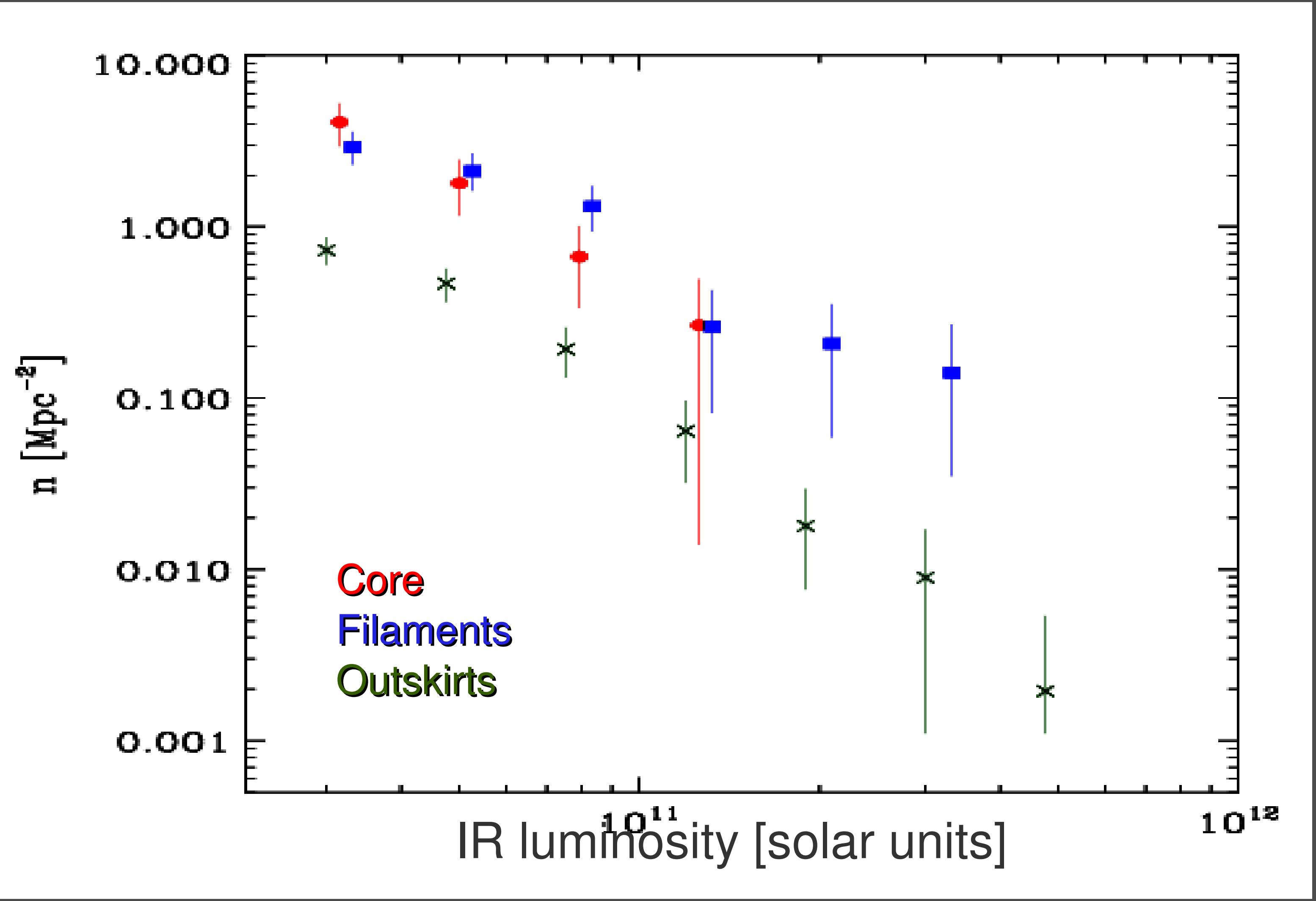
What is the effect of the environment?

LIRGs
($L_{IR}>10^{11}\ L_{\odot}$)
are located mostly in the region of the filaments

They do *not* have high sSFR
($\propto$ circle size)

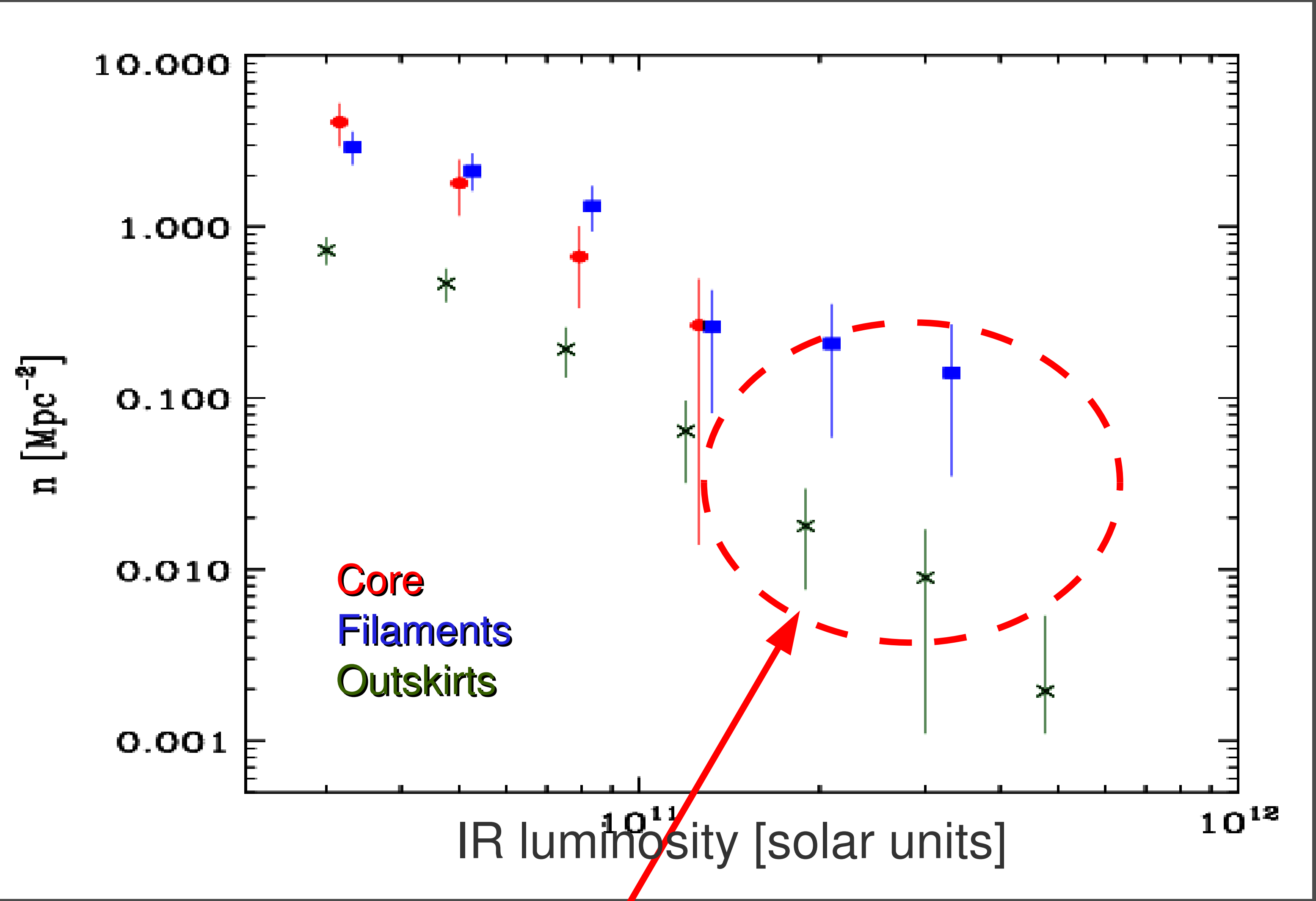


The IR LFs in 3 different supercluster environments



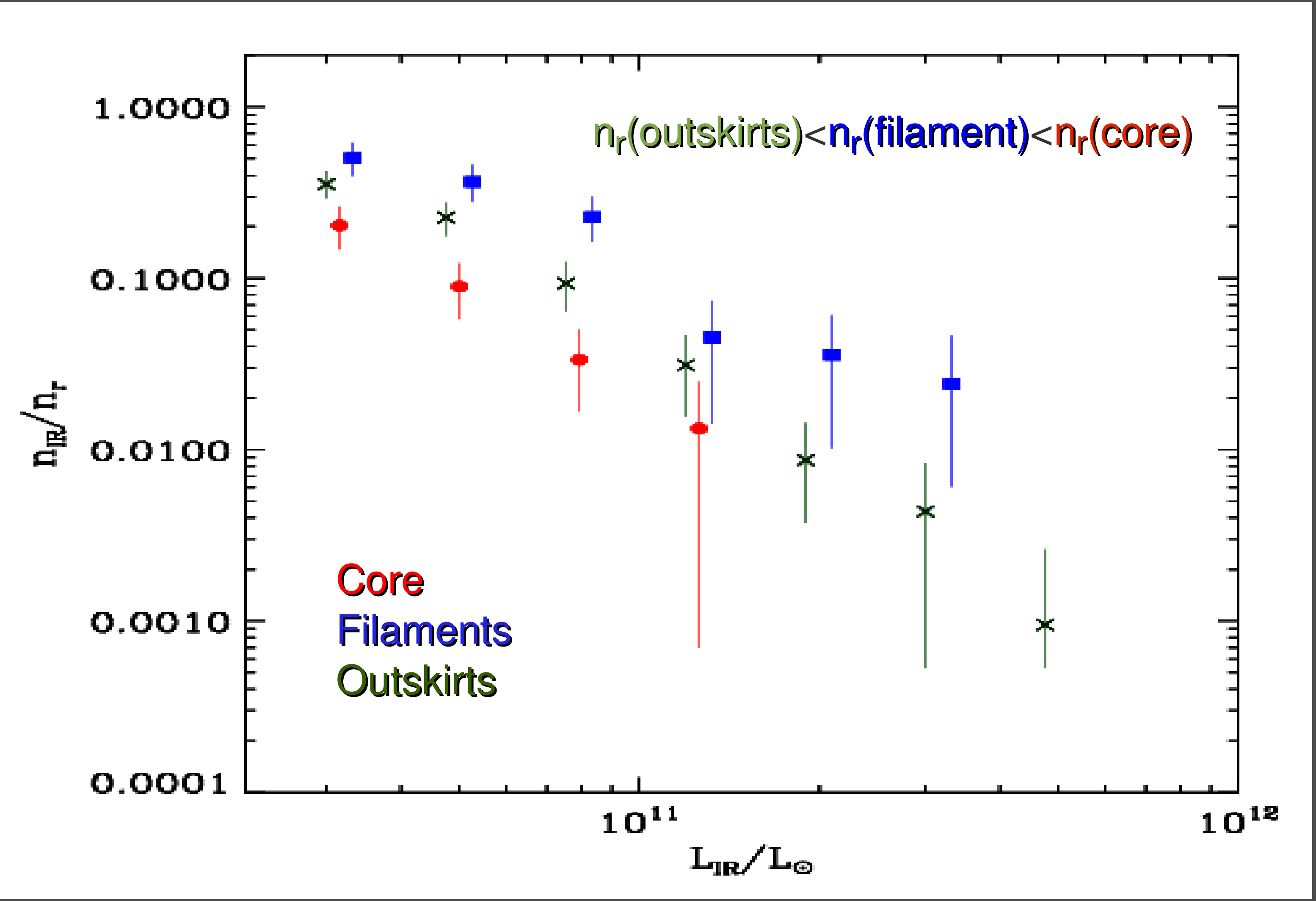
Each LF is corrected for *in*Completeness and *in*Purity

The IR LFs in 3 different supercluster environments



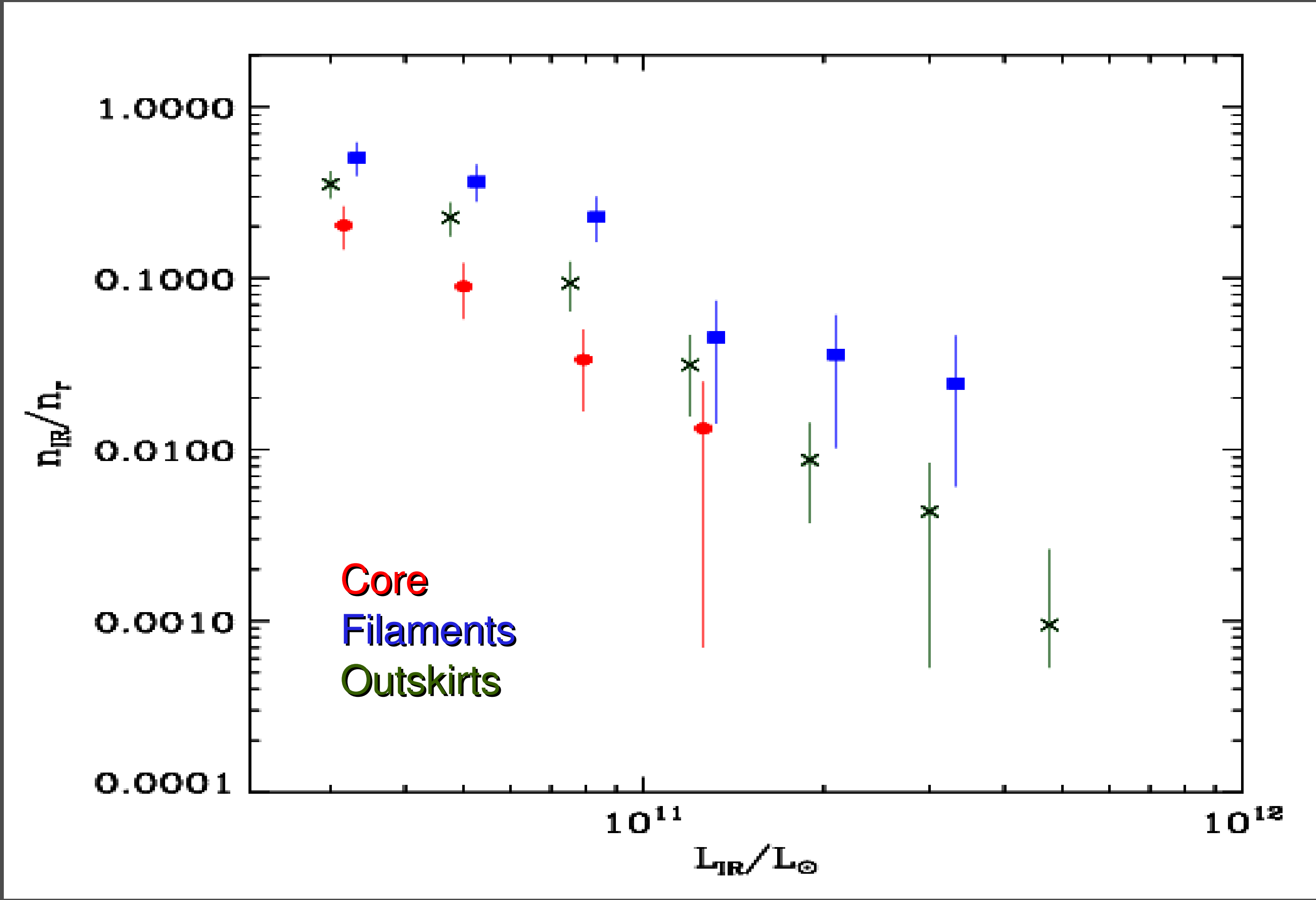
There are (almost) no LIRGs in the core

The IR LFs in 3 different supercluster environments



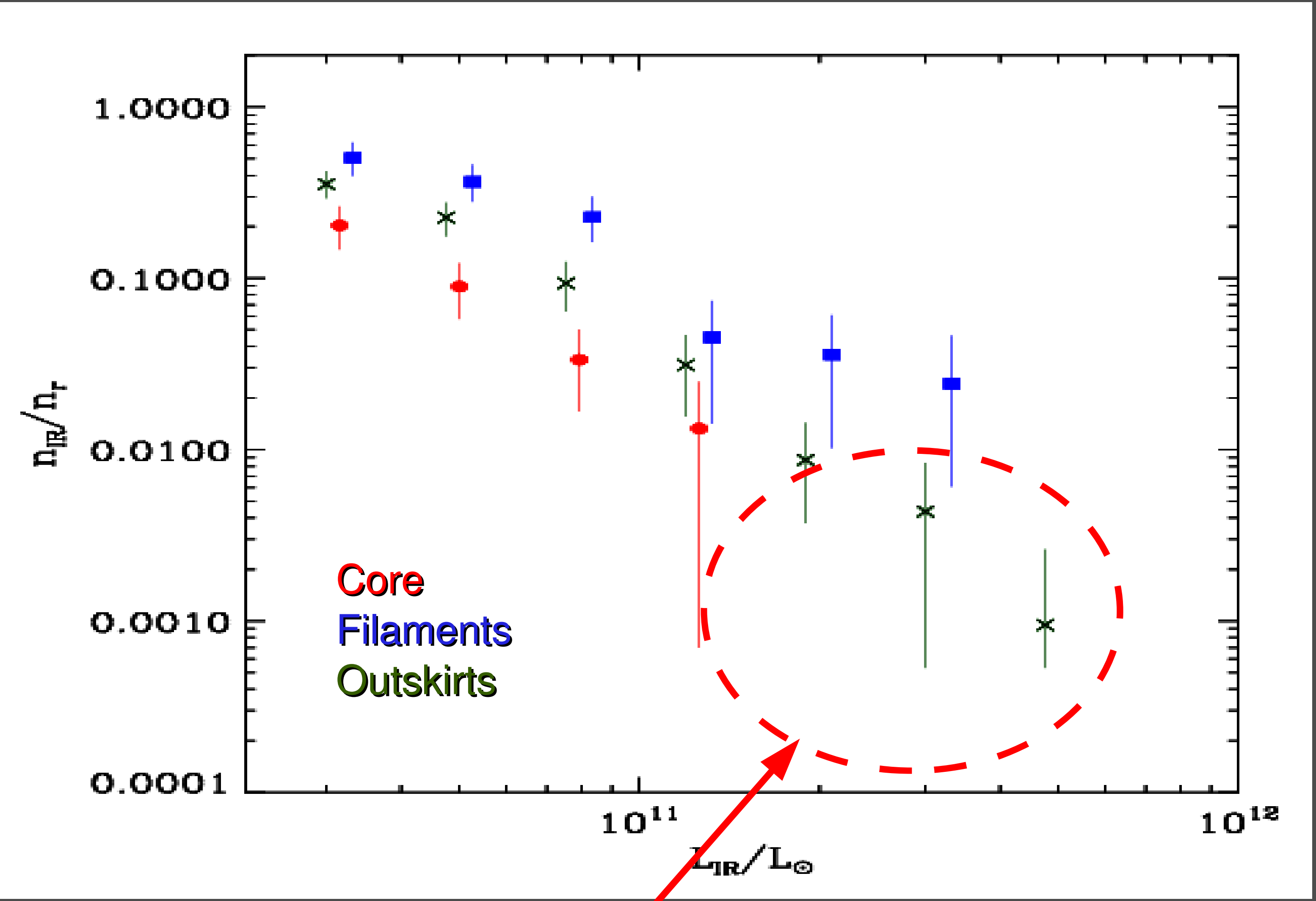
The densities of IR-emitting galaxies, n_{IR}, are normalized by the densities, n_r, of normal, r-selected galaxies in the same regions

The IR LFs in 3 different supercluster environments



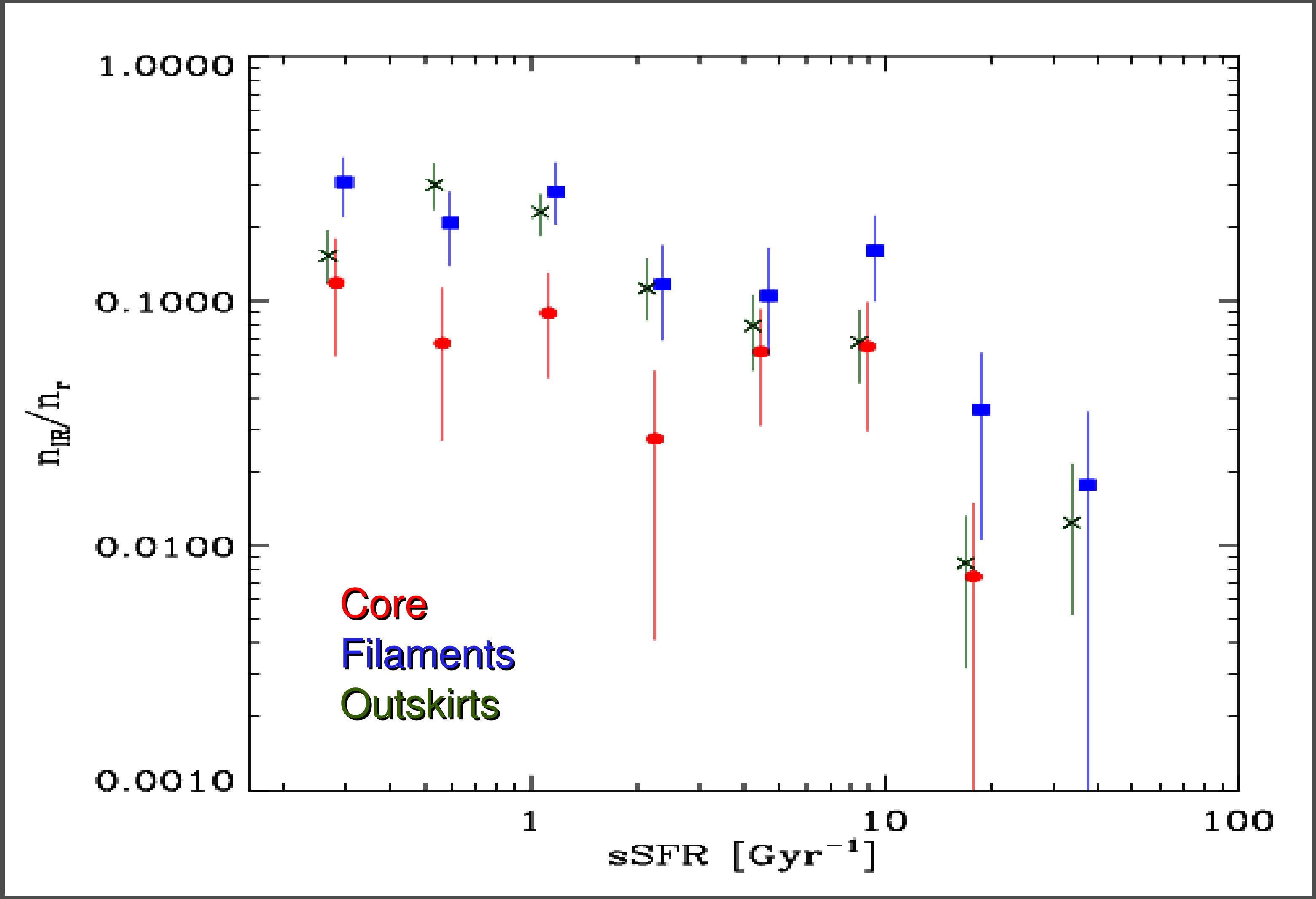
Filaments contain an excess fraction of IR emitters relative to the **core** (>99.9% significance) and relative to the **outskirts** (?... 92% significance only)

The IR LFs in 3 different supercluster environments



There are (almost) no LIRGs in the core

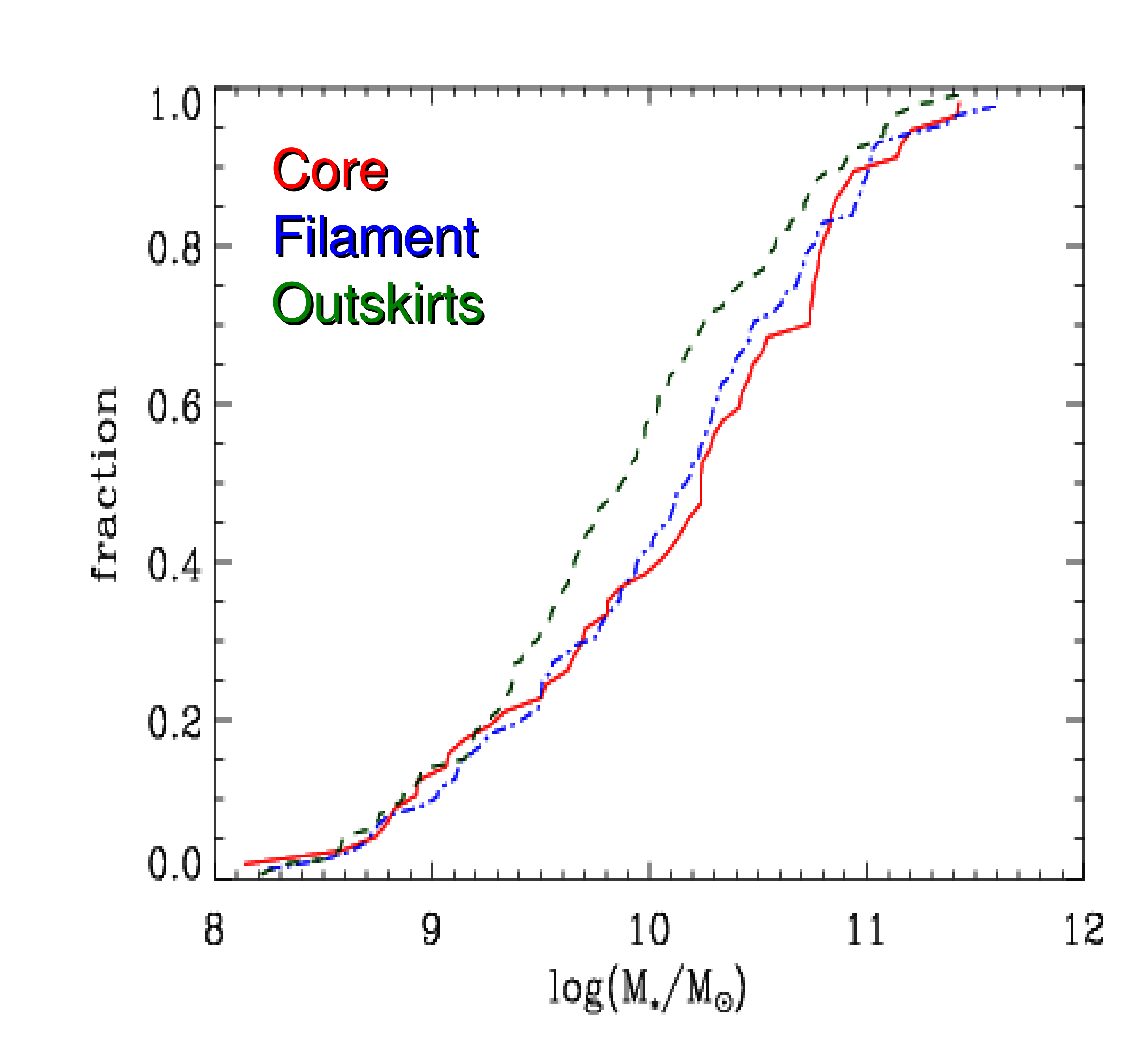
The specific-SFR distribution functions in the 3 environments



The sSFR distributions of **filaments** and **outskirts** are similar, the SFR (L_{IR}) distributions are *not*,

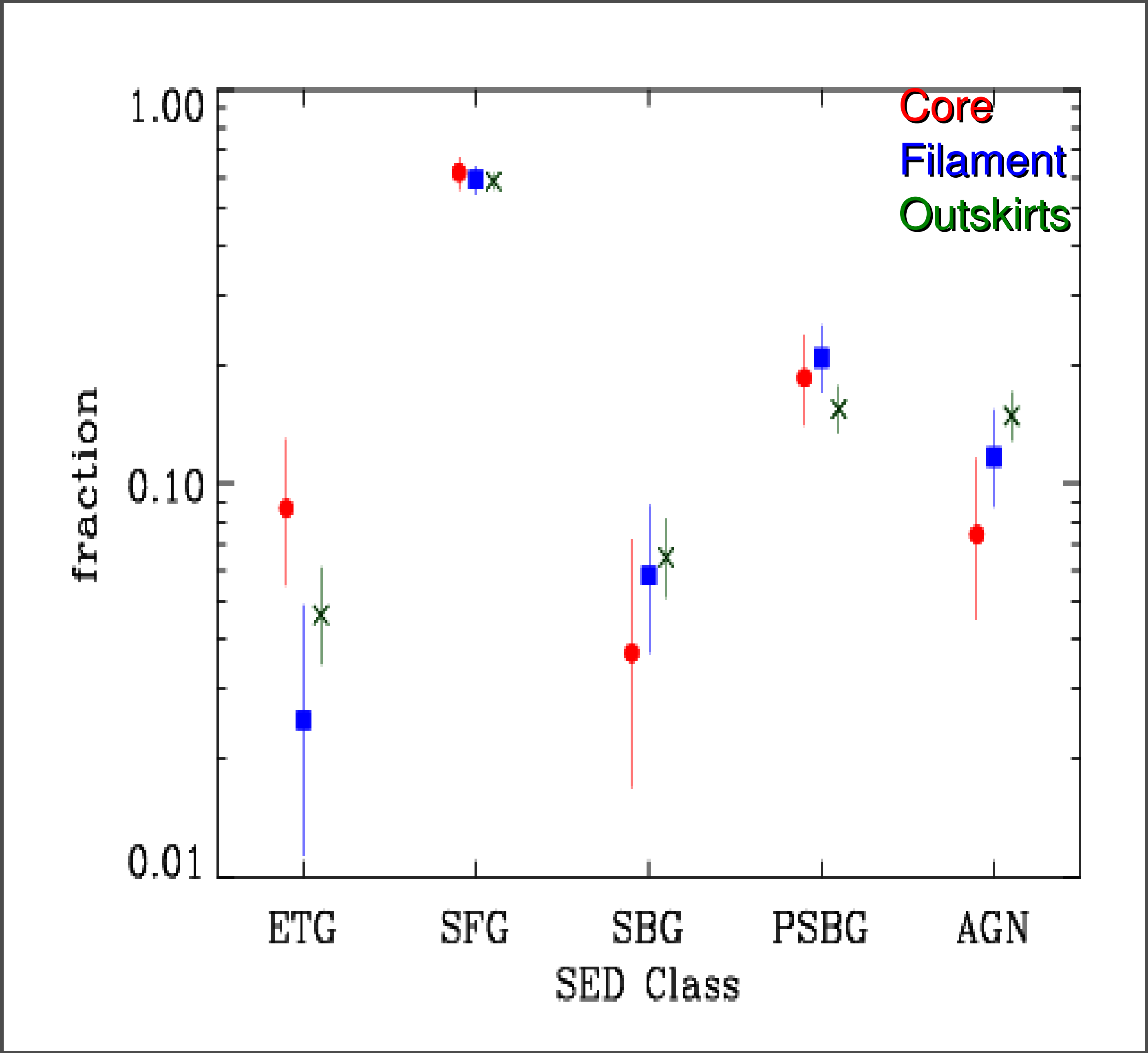
➡ the excess IR-emitters in **filaments** are **massive**

$M_\star$-cumulative distributions of IR emitting galaxies



Core and filament IR-emitting galaxies are more massive than IR-emitting galaxies in the outskirts

SED-class fractions in different supercluster regions



The fraction of different SED classes among IR-bright galaxies is ≈ in different supercluster regions

Comparison with previous works

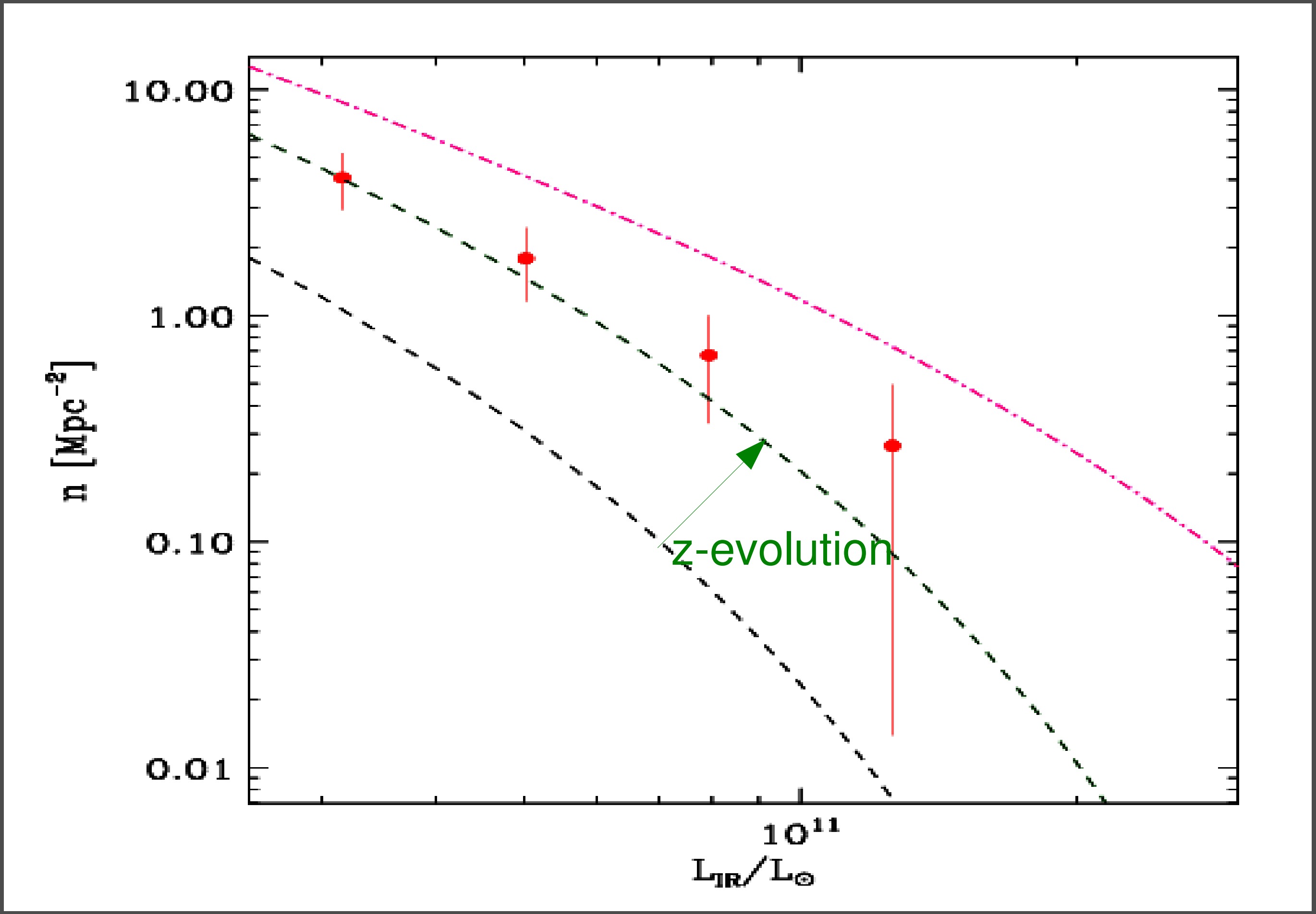
Previous cluster IR LF determinations limited to core regions

Dots: A1763 core

Black line:
Coma IR LF
(Bai+06)

Green line:
Coma IR LF
evolved to <z>=0.23
of A1763
(Bai+09)

Pink line:
Bullet cluster IR LF
(<z>=0.3, Chung+10)



☛ The density of IR-emitters in cluster cores increases with z as predicted by Bai+09

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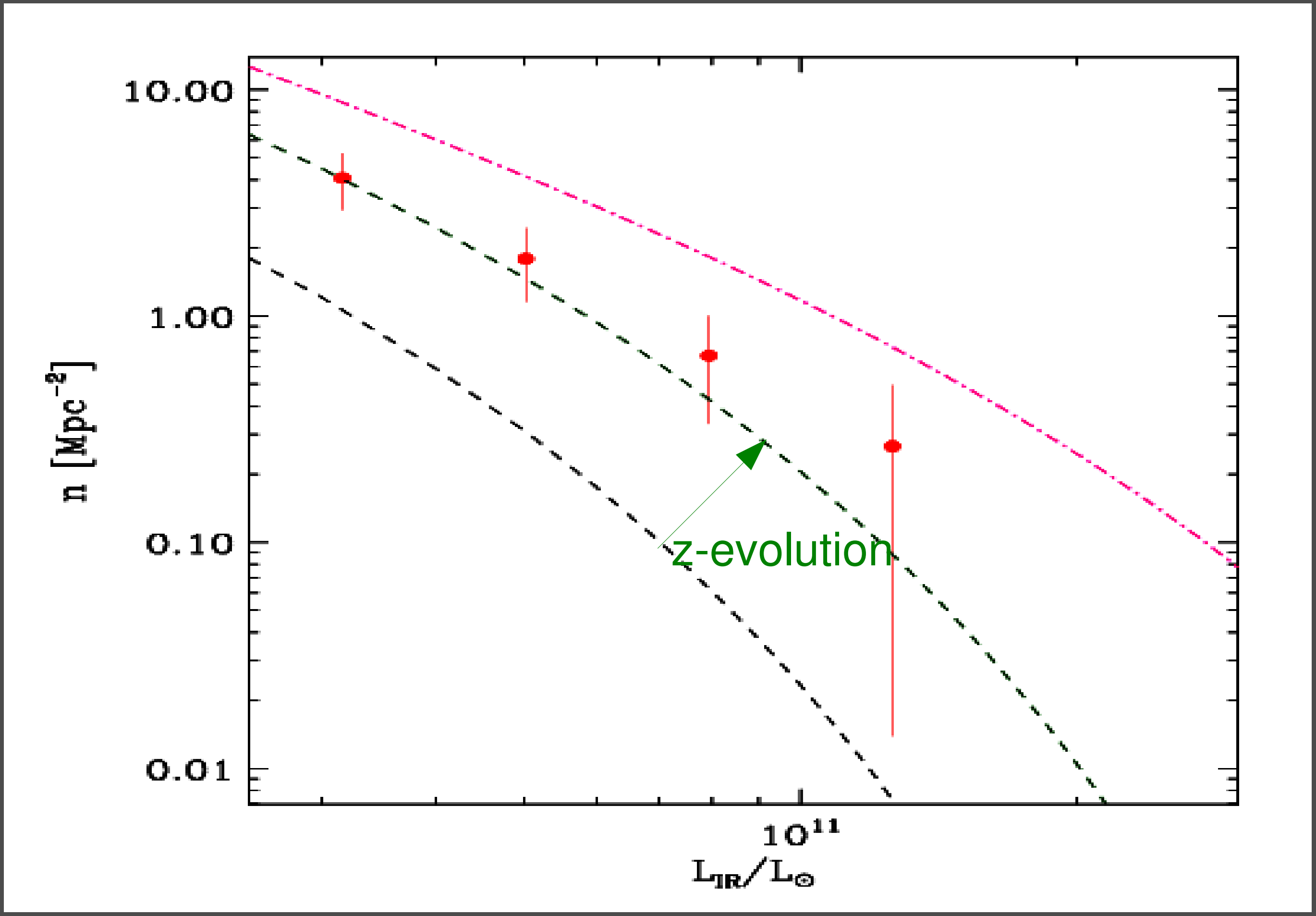
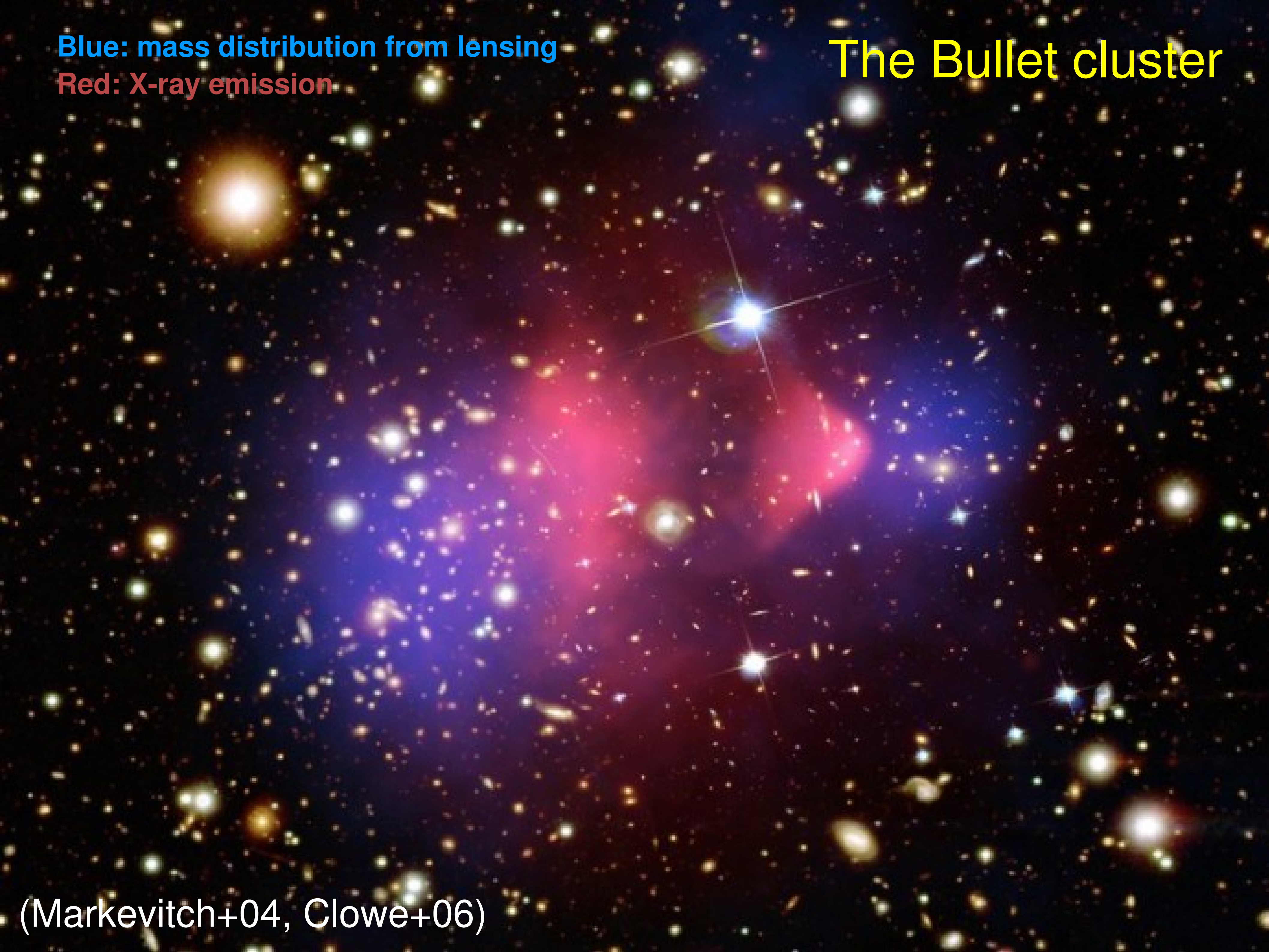


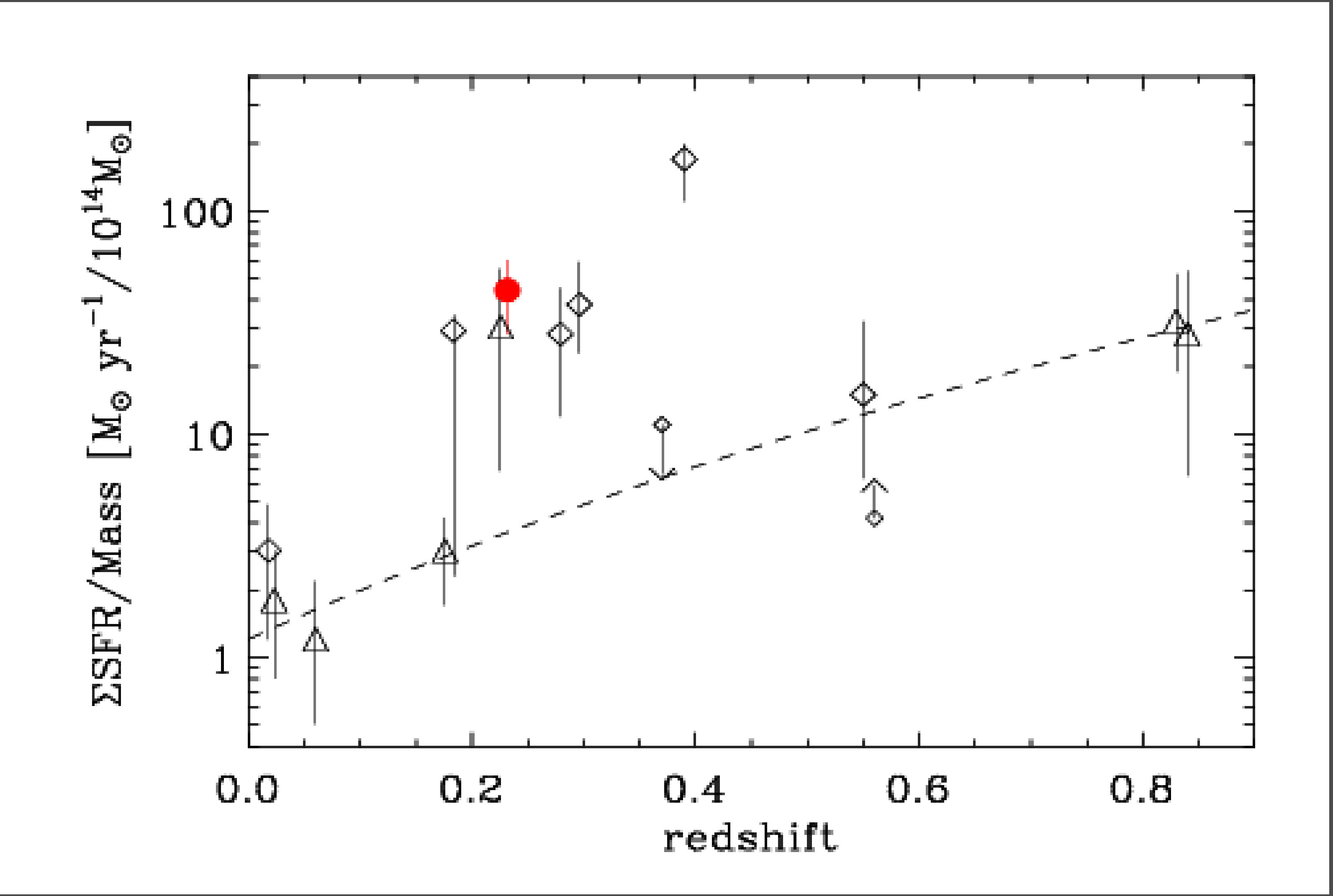
☛ Excess of LIRGs in the Bullet related to the infalling group?


The Bullet cluster
Blue: mass distribution from lensing
Red: X-ray emission
(Markevitch+04, Clowe+06)

Comparison with previous works

A1763
core.

Mass from velocity dispersion.

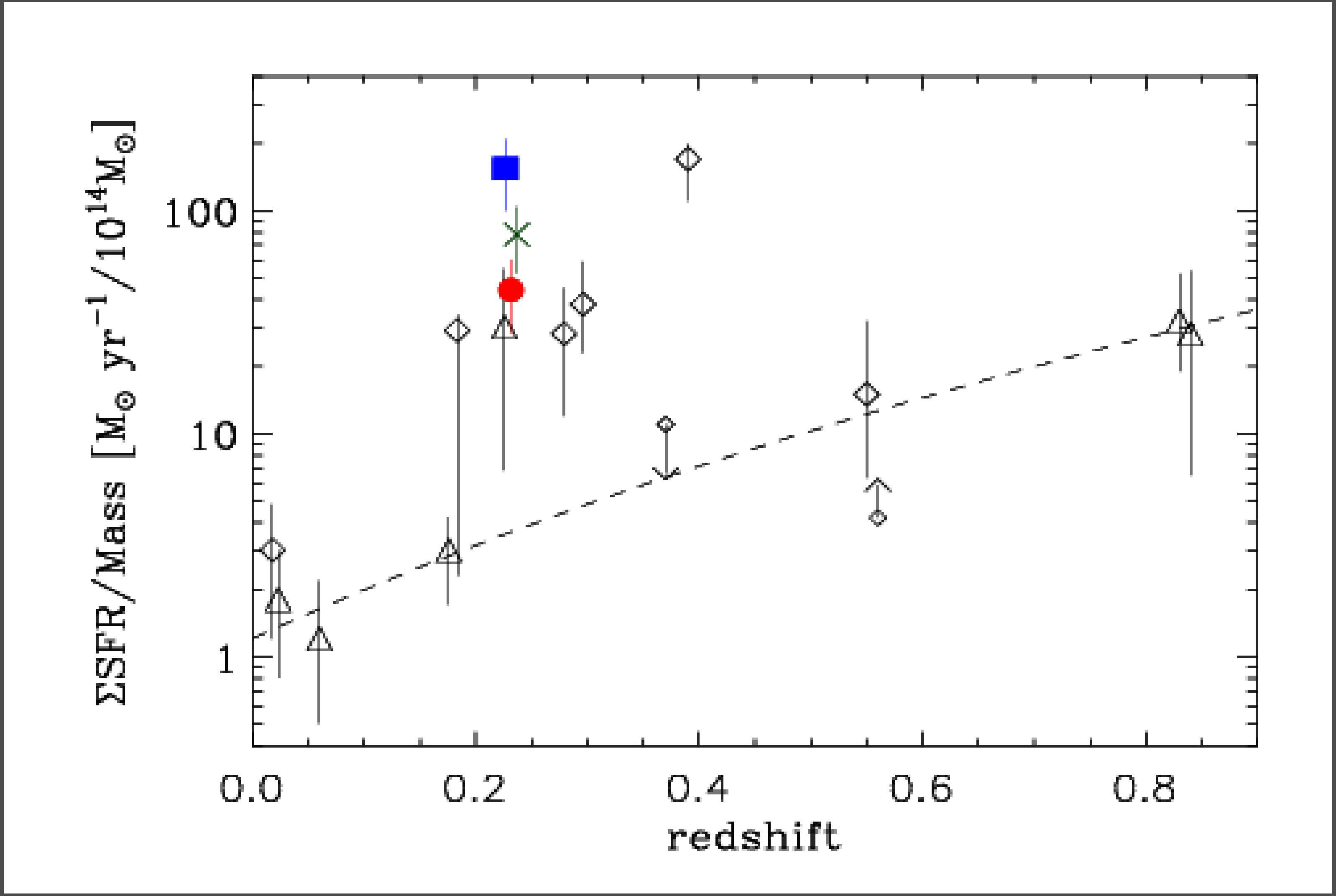


The galaxy ∑SFR / total mass in cluster cores increases with z *(but not as predicted by Bai+09)*

Comparison with previous works

A1763
filament,
outskirts,
core.

Masses from richness scaling wrt mass of the core



∑SFR/Mass depends on z but also on the environment

but not simply on the local galaxy density!

Summary, discussion, perspectives

Summary of our findings:

- IR galaxies ($SFR \geq 4\ M_{\odot}/yr$): highest fraction in the filament, i.e. in the intermediate density region of the supercluster
- Filament IR-galaxies are massive ($M_{\star} \sim 10^{10}\ M_{\odot}$),

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- Different regions have $\approx$ fractions of SED classes

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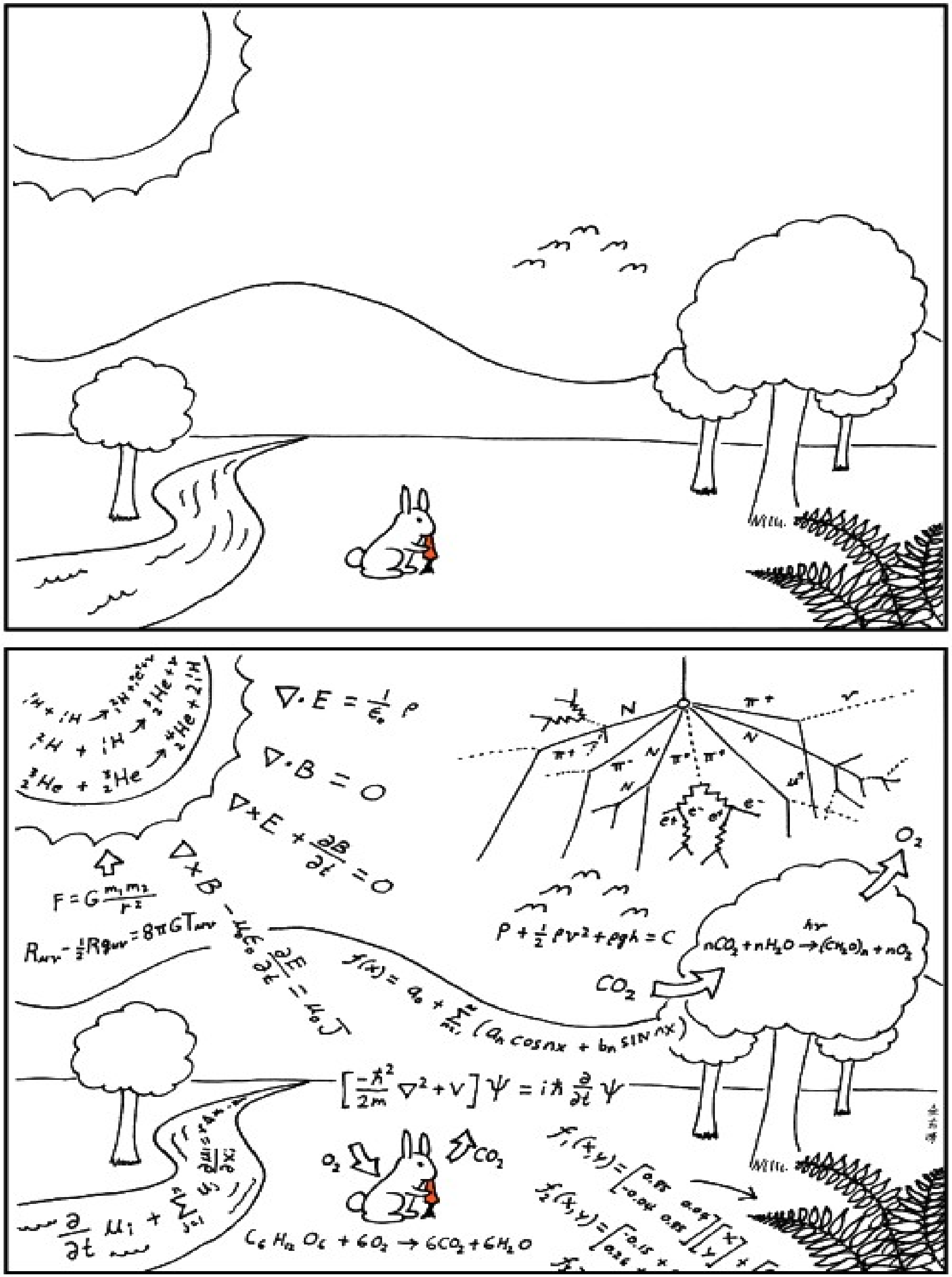


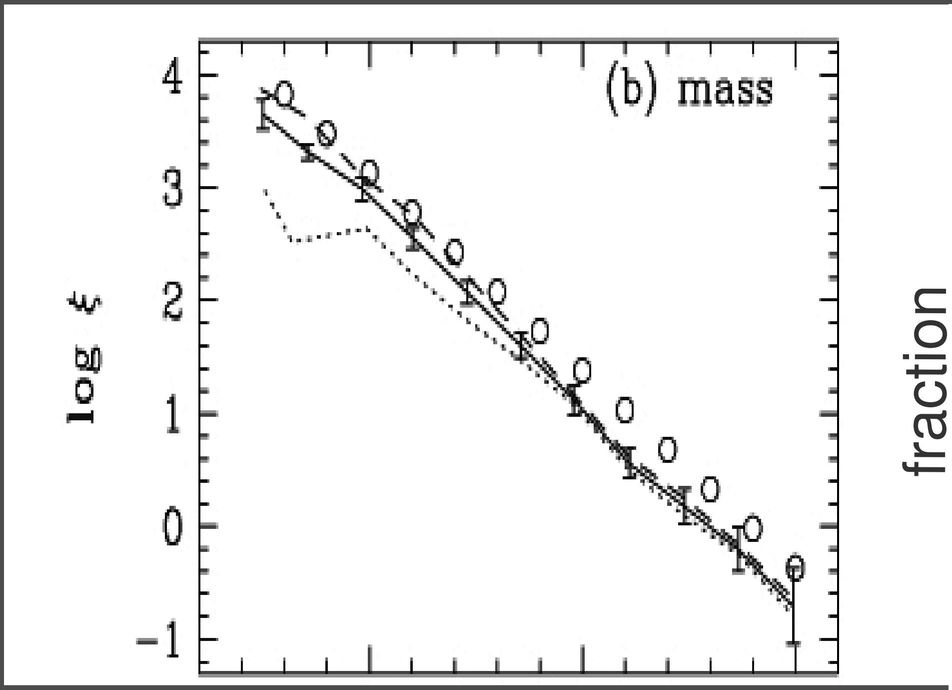
This is how scientists see the world.

Interpretation

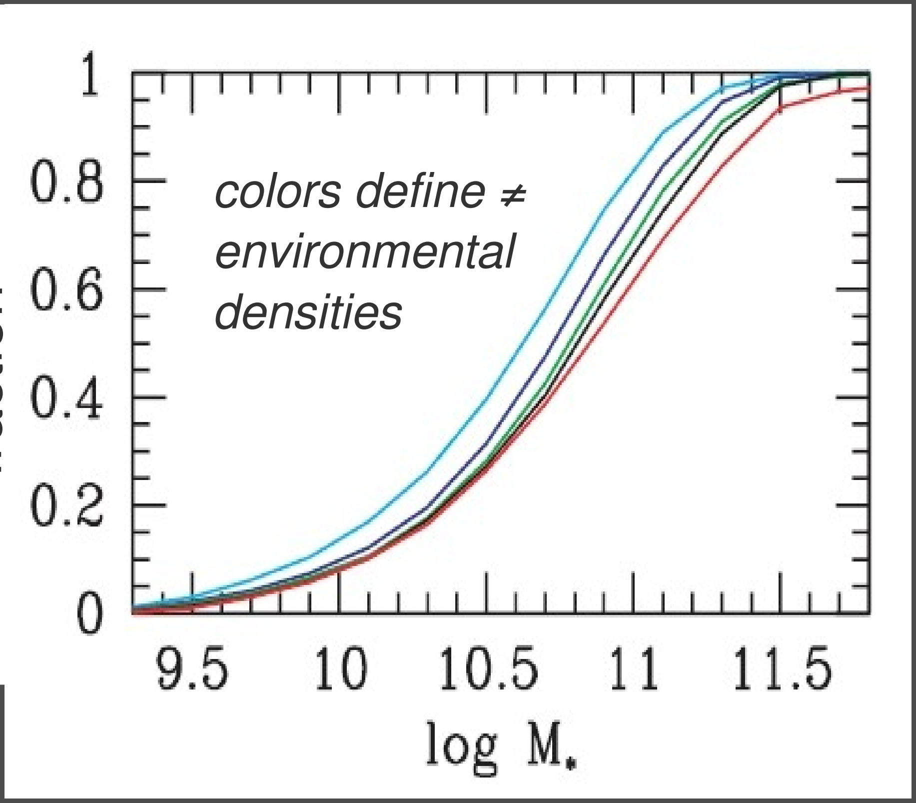
Different $M_\star$ distributions in ≠ environments:

More massive galaxies in higher-density regions:
theoretically predicted in ΛCDM model (Weinberg+04),
and observed in the local Universe (Kauffmann+04)

galaxy
correlation function



log r



Core IR-galaxies are recent arrivals from the filament

Different SFR in ≠ environments:

Which physical processes affect the SFR?

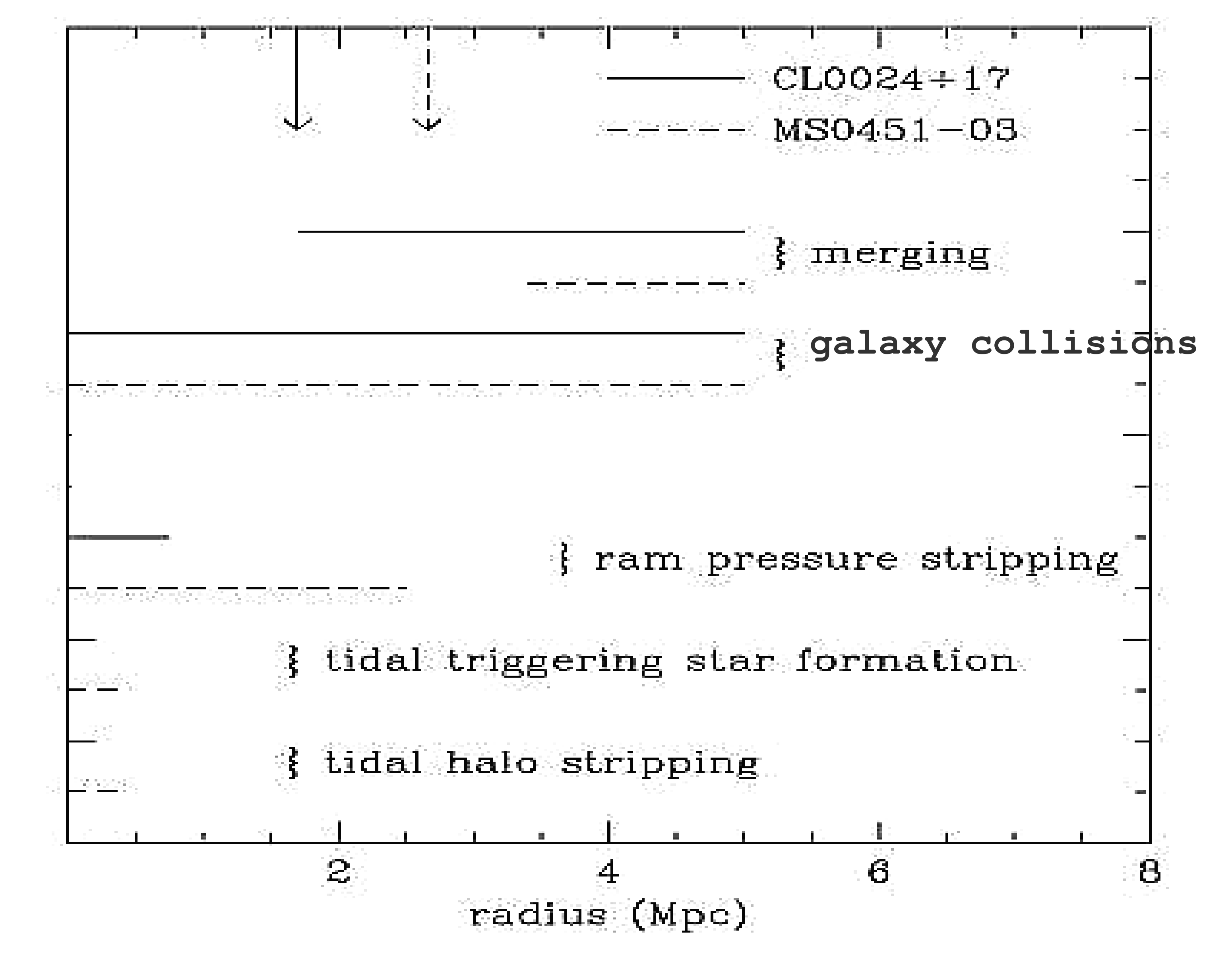
- galaxy-galaxy collisions → tidal effects & mergers
- ram-pressure stripping by the hot intra-cluster gas
- tidal forces induced by cluster $d\phi/dr$ → tidal truncation

Starvation can result from any of the ◆ processes
as the galaxy gas is expelled or consumed

Different processes are efficient in ≠ environments:

- galaxy-galaxy collisions: *filaments and groups*
- ram-pressure stripping: *cluster core*
- tidal forces induced by cluster $d\phi/dr$: *cluster center*

Different processes are efficient in different environments



(Adapted from Moran+07)

Dominant mode of star formation (~2/3) of IR galaxies: normal Star Forming Galaxies

⇒ no SFR enhancement process required

Lack of IR galaxies in cluster core

⇒ SFR suppression process required

SFG flow along filament into cluster core, where they loose their gas via (?) ram-pressure and stop star formation (color and morphological transformation follow)

Some galaxies join the cluster without having suffered many interactions. The infall rate of these galaxies increases with z, leading to a larger fraction of IR-bright, SF-galaxies in the cores of higher-z clusters.
These SF-galaxies evolve into S0 or passive S with time.

<u>Recent supporting evidence:</u>

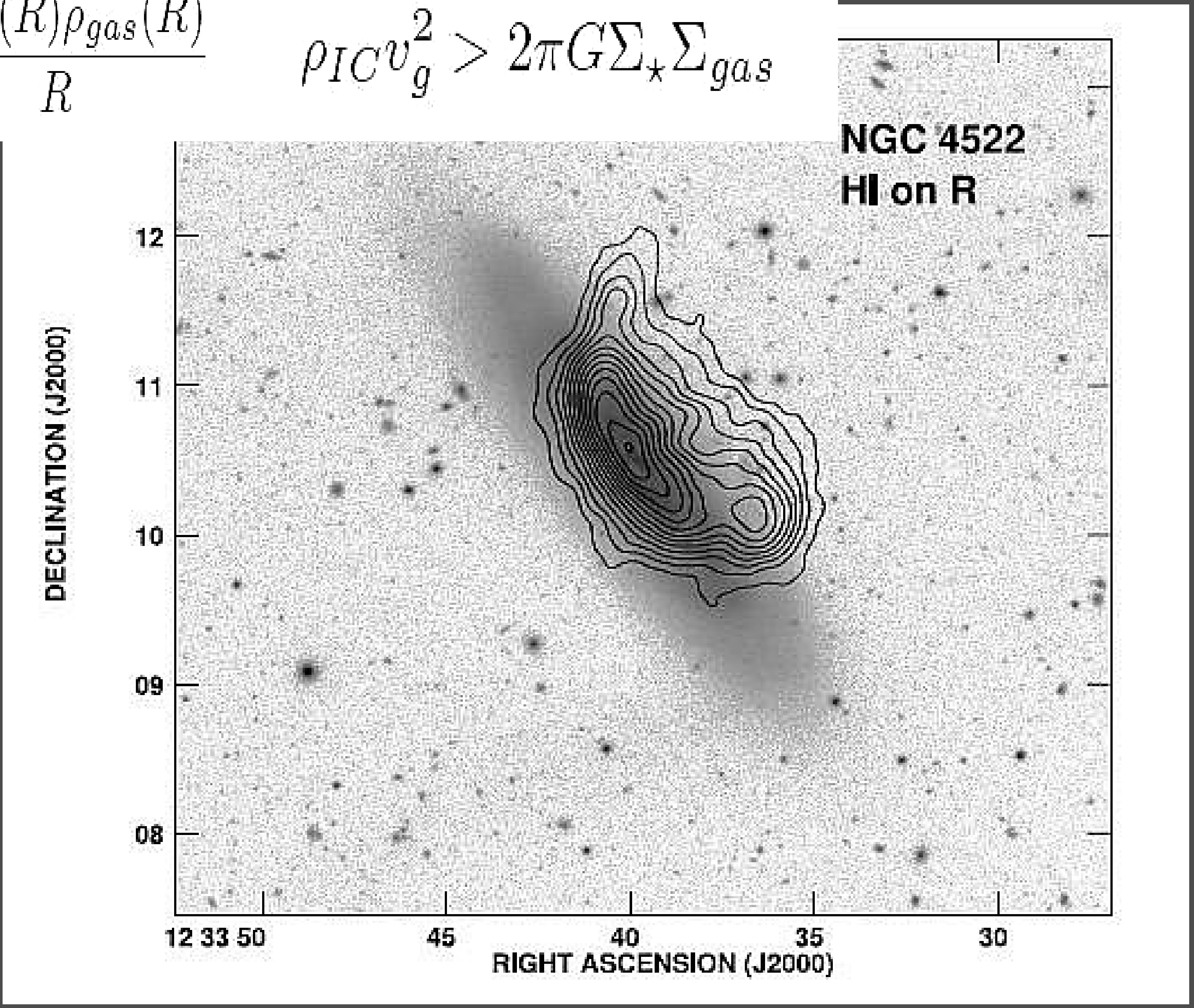
The infall rate increases with redshift (Ellingson+01)
Ram-pressure is indeed observed (Kenney+04, Vollmer+05)
∃ a population of passively evolving, red Spiral galaxies (Moran+06, Vulcani+10)
These red Spirals are HI-deficient (Solanes+01, Cortese+09)
Cluster Spirals have smaller sizes than field Spirals (Aguerri+04)
S0s have higher specific frequency of Globular Clusters than Spirals (Barr+07)
S0 bulges similar to S bulges (Laurikainen+10)

Stripping from the halo:

$$\rho_{IC} v_g^2 > \alpha \frac{G m_g(R) \rho_{gas}(R)}{R}$$

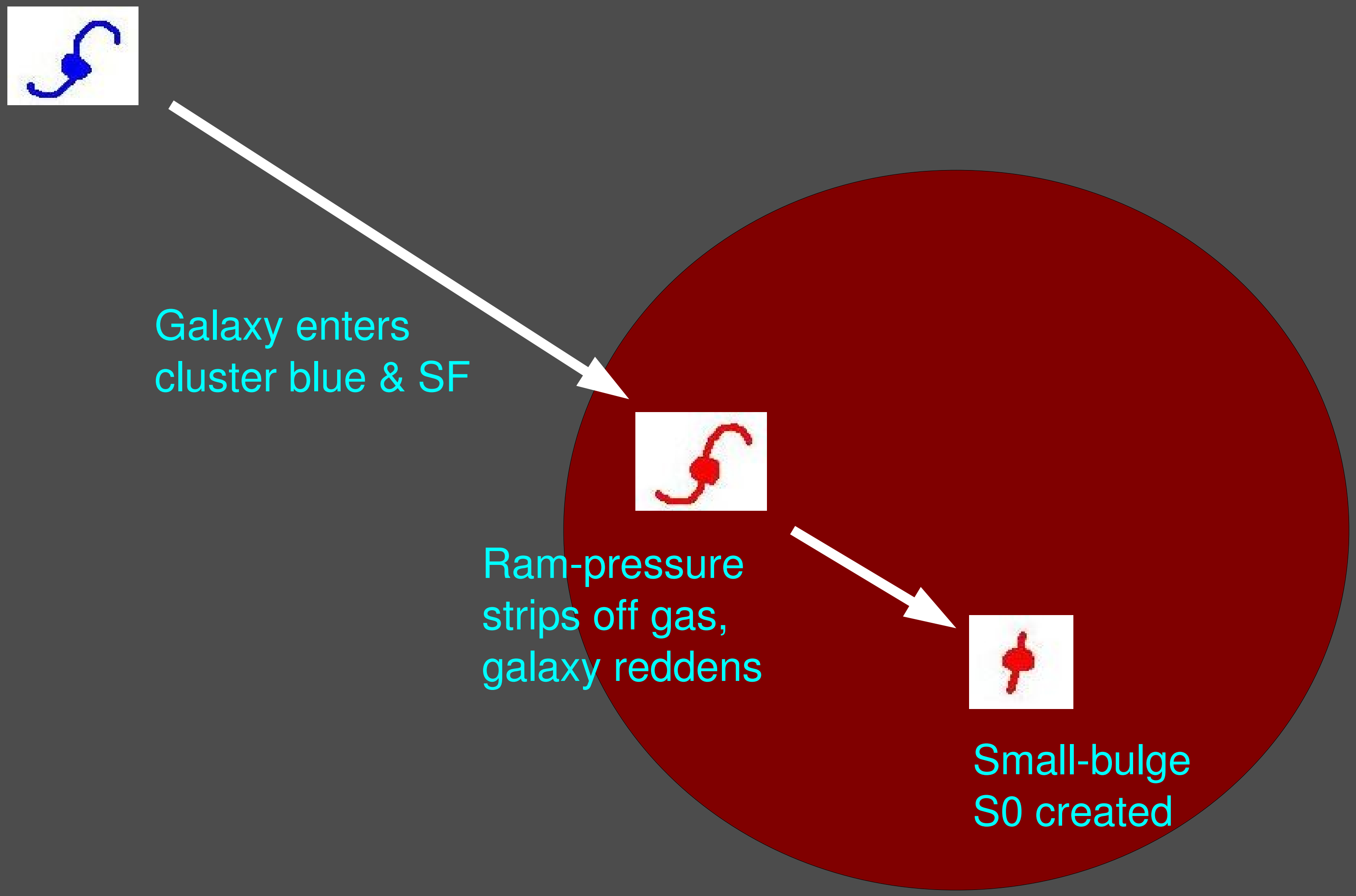
Stripping from the disk:

$$\rho_{IC} v_g^2 > 2\pi G \Sigma_\star \Sigma_{gas}$$



(Kenney+04)

Scenario for the accelerated evolution of galaxies in clusters via gas stripping



Additional mode of star formation (~1/4) of IR galaxies: StarBurst & Post-StarBurst Galaxies

⇒ SFR enhancement process required

Filaments have higher density of galaxies than the field, and smaller velocity dispersion than the cluster core,

⇨ *frequent & slow galaxy encounters*
⇨ *large tidal effects and some mergers*
⇨ *tidal gas loss + tidal gas compression & nuclear starburst*

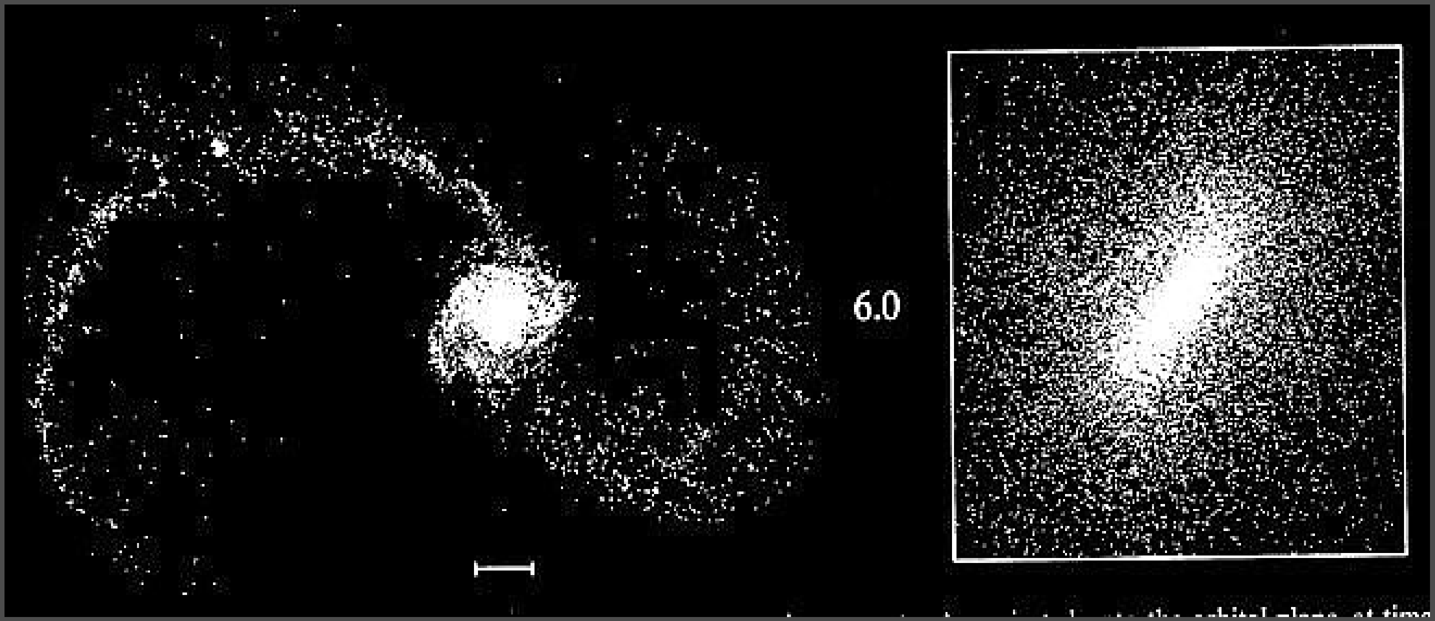
Slow collisions → mergers

$$t_m \propto \frac{\sigma_v^3}{\sigma_g^4 r_g^2 \nu}$$

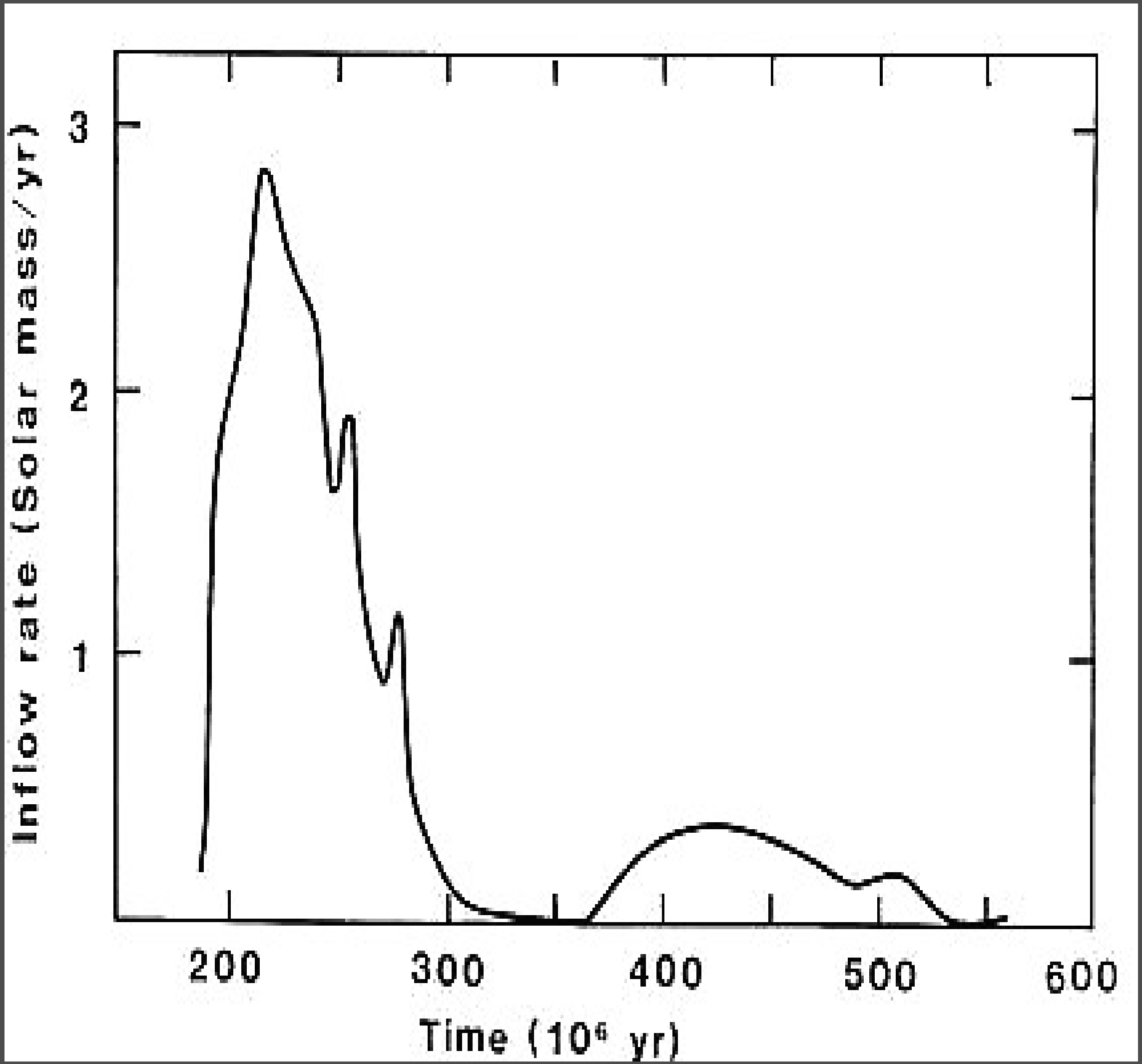
Merger timescale

Leading to tidal gas loss
and morphological evolution

(Barnes 92)



Tidal compression of galactic gas
→ central starburst



(Byrd & Valtonen 90)

Lack of LIRGs in the cluster core:

#SBG / #PSBG ≈ 1/3 - 1/4

PSBG phase lasts ≤1 Gyr (Hogg+06; Goto 07)

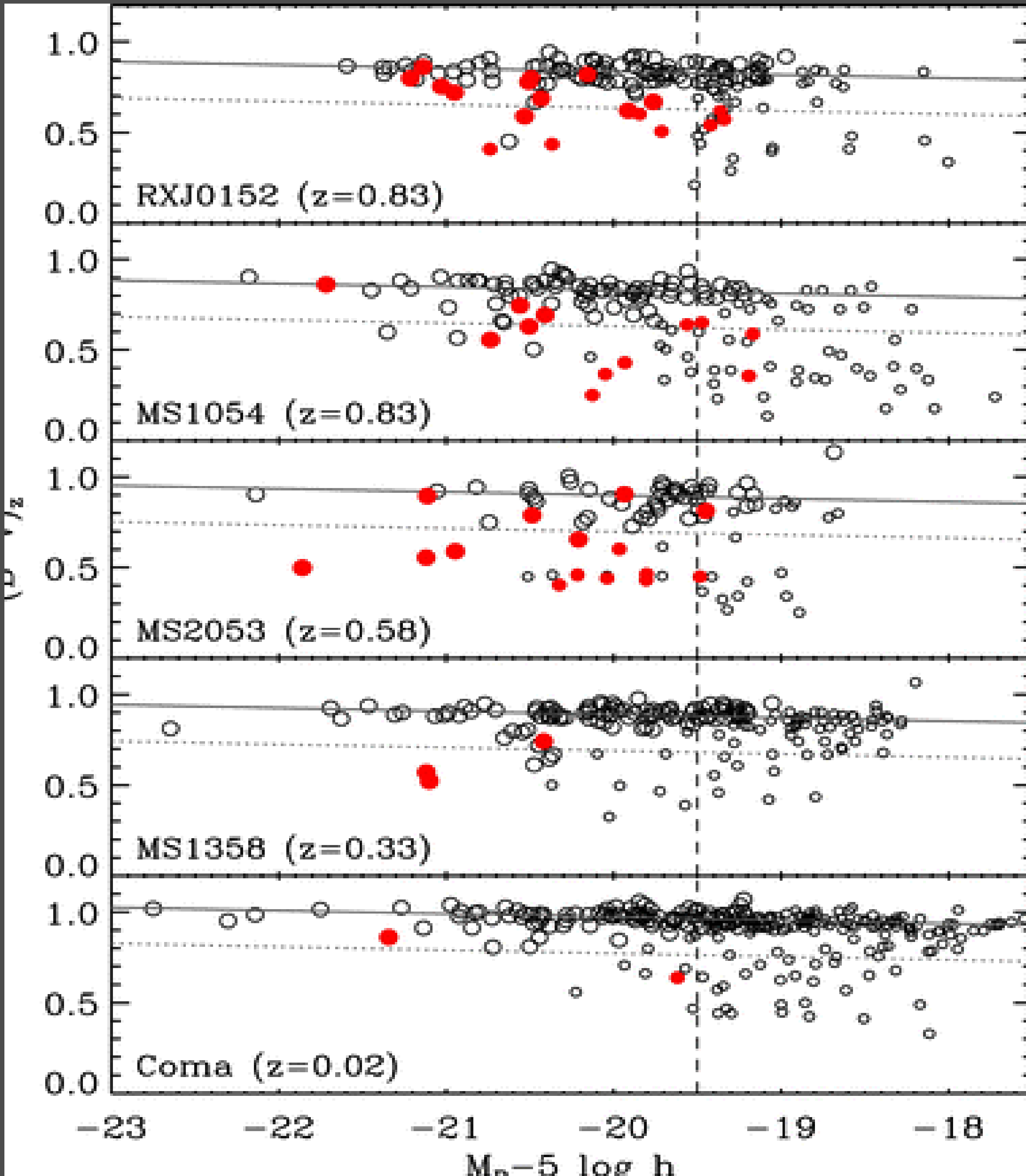
⇒ SBG phase lasts ≤0.3 Gyr (see also McQuinn+10)

SBG speed along the filament is ≈1 Mpc/Gyr

⇒ SBG become PSBG before entering the cluster

Part (~1/4) of the increase in the red-sequence population since z~0.2 occurs via the StarBurst mode of evolution

(in agreement with Wild+09; but see De Lucia+09)



IR galaxies joining the red sequence

(Saintonge +08)

Some galaxies interact among themselves while travelling along the filaments into the cluster, their interactions stimulate SF and, if strong enough, lead to the build-up of a bulge and gas consumption, i.e. to the creation of S0s from spirals

Recent supporting evidence:

Starburst (dusty) galaxies in filaments (Braglia+07, Porter & Raychaudhury 07, Boué+08, Fadda+08, Porter+08, Koyama+08+10, Haynes+10, Pereira+10)

Mergers in the outskirts of clusters (Heiderman+09)

Stripped galaxies outside the ram-pressure regions (Crowl & Kenney 08)

Lower <SFR> in cluster outskirts than in groups or field (Verdugo+08, Tanaka+09)

Giant red galaxy fraction is high also far from cluster center (Huertas-Company+09)

High fraction of post-starburst galaxies in clusters (Falkenberg+09)

Post-starburst cluster galaxies have asymmetric shapes (Vergani+10)

Many gas-poor Spirals have enhanced central SFR (Rose+10)

Scenario for the filament-induced accelerated evolution of galaxies in clusters

Scenario for the filament-induced accelerated evolution of galaxies in clusters

The “Paths of Glory” of galaxy evolution

What about the SBG in the cluster core?

Projection effects

and/or

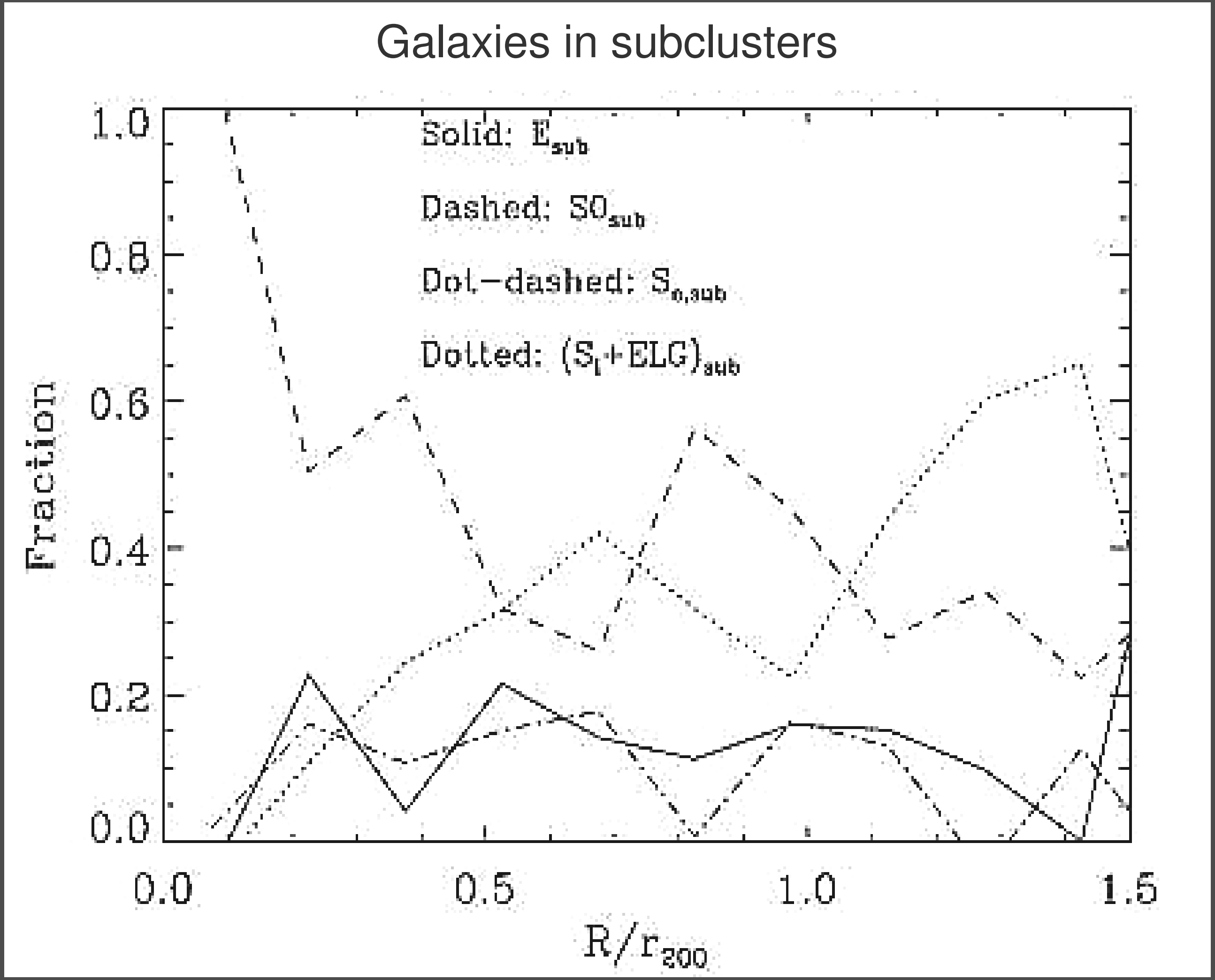
Enhanced star-formation by the tidal compression of the cluster gravitational field shrinking the low-velocity dispersion galaxy groups which are being accreted into the cluster core ("substructures") ...see Ferrari+05; Oemler+09

Some galaxies enter clusters already in groups, groups are shrinked by the cluster tidal field, leading to galaxy-galaxy interactions at low speed (groups have lower velocity dispersion than the cluster) able to induce starbursts (and so transform some spirals into S0s) even in the cluster center.

<u>Recent supporting evidence:</u>

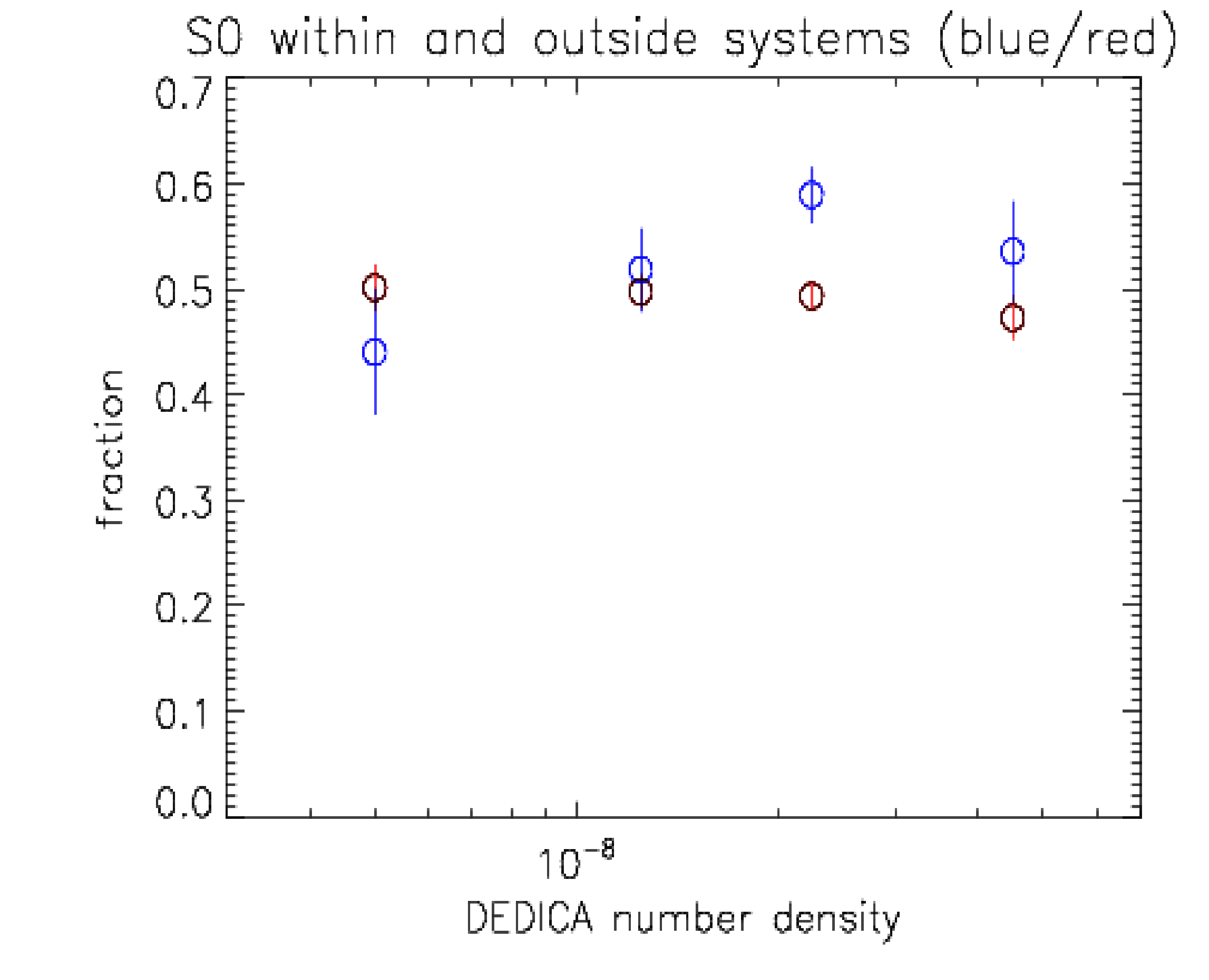
Higher S0-fraction in subclusters than in parent clusters (ab+02, Cava, ab+ in prep)
Cluster starburst galaxies inhabit infalling groups (Oemler+09, Tran+09)
Star-formation triggered in galaxies in colliding subclusters (Ferrari+05,+06)

S0s are over-abundant in low-σ_V subclusters near the cluster center or at high local densities



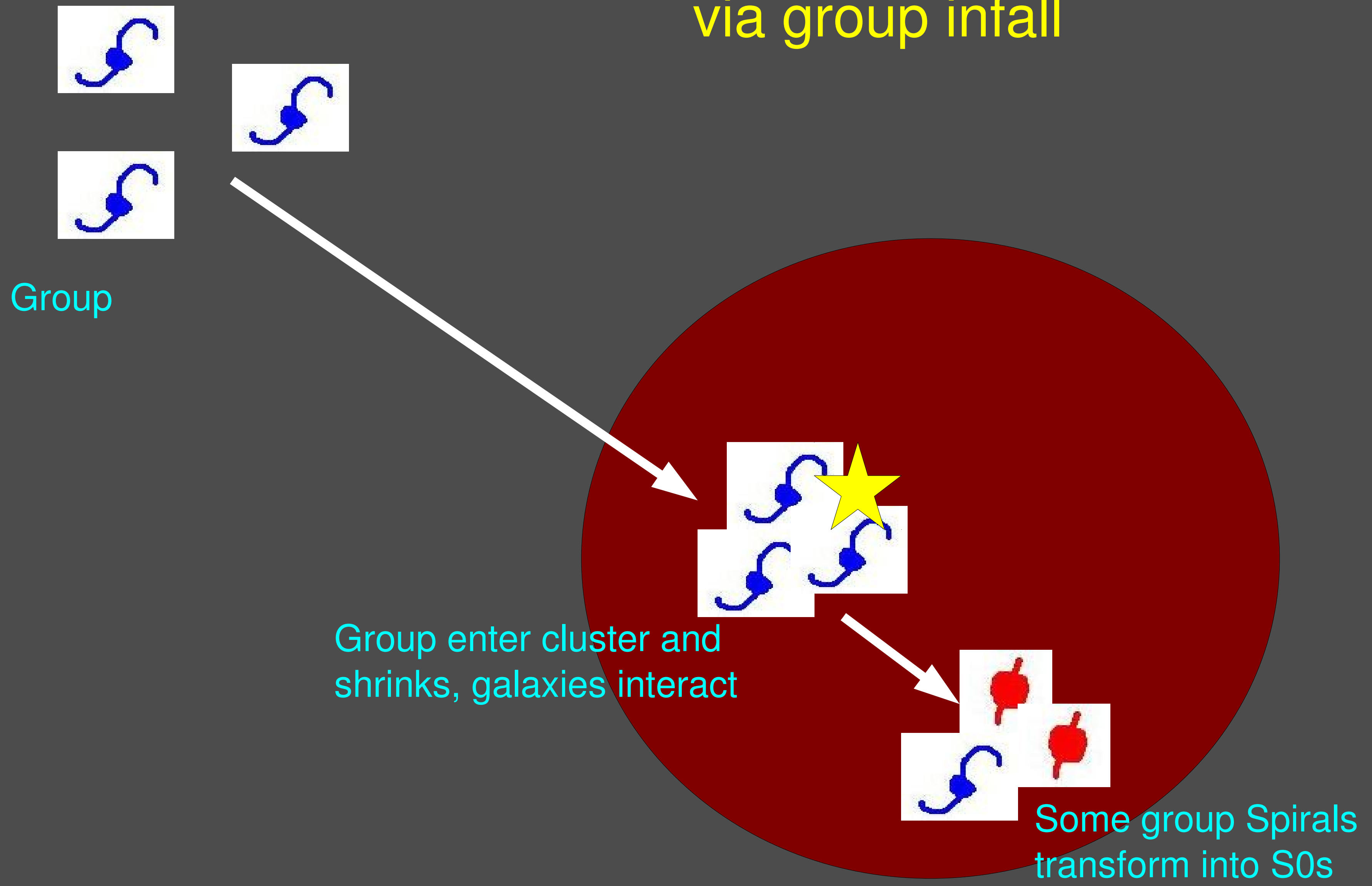
ENACS cluster sample (ab+02)

S0s are over-abundant in low-σ_v subclusters near the cluster center or at high local densities



WINGS cluster sample of Fasano+06 & Cava+09; work in progress (Cava, ab + in prep)

Scenario for the accelerated evolution of galaxies in clusters via group infall



Some galaxies on very radial orbits pass through the very central region of the cluster. They suffer stronger ram-pressure and tidal interaction with the central cD and/or the peaky cluster gravitational potential, become red dwarfs or even dissolve themselves into the intra-cluster medium.

Recent supporting evidence:

Orbits of giant galaxies are isotropic near the center (Carlberg+97, Mahdavi+99, van der Marel+00, Łokas+Mamon 03, Katgert+04, ab & Katgert 04, Wojtak & Łokas 07)

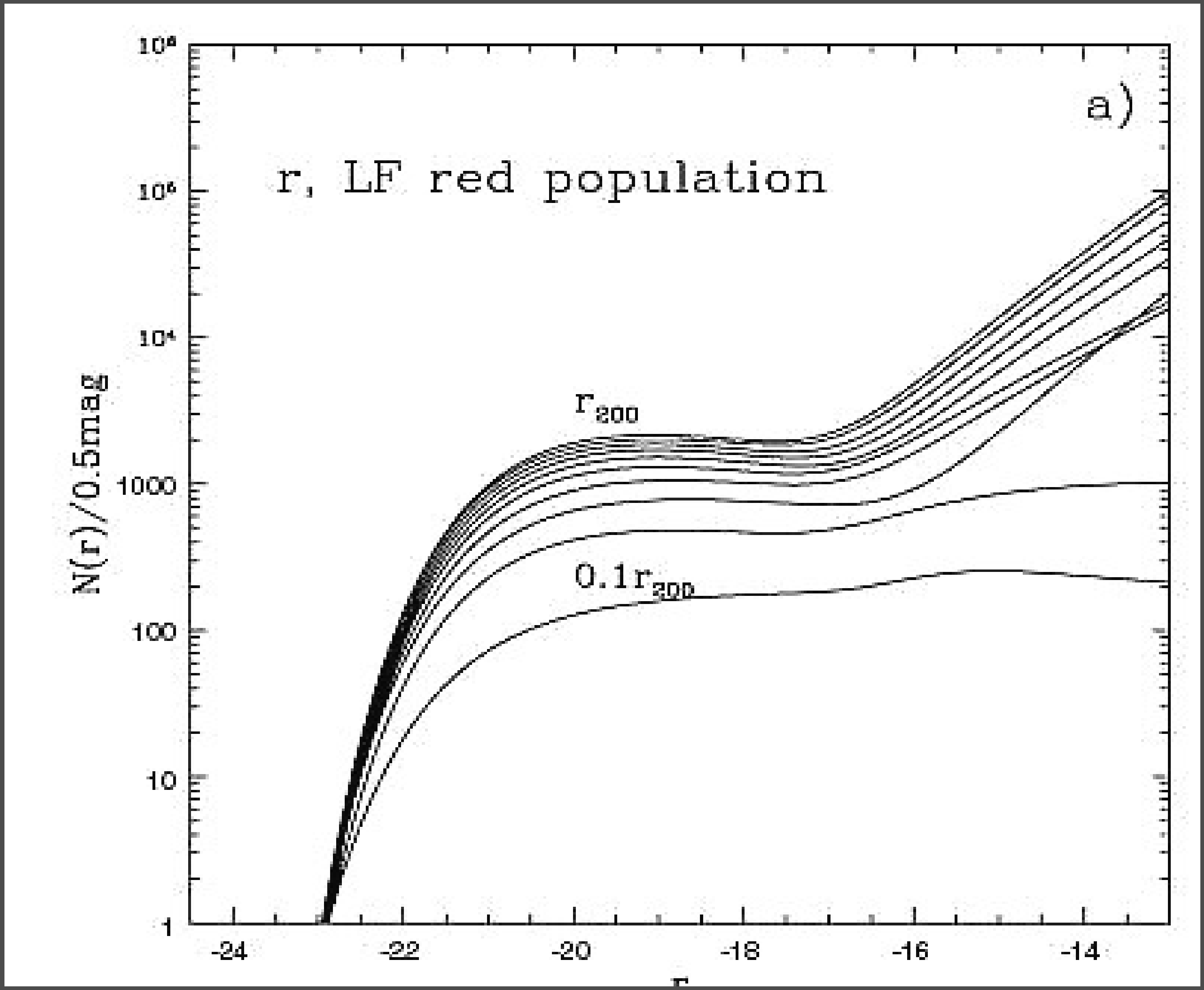
Orbits of dwarfs are radial near the center (Adami+09)

Faint-end of red galaxy luminosity function flattens → cluster center (Popesso+06)

Dwarf can form via stripping of Spiral (Aguerri & González-García 09, D'Onghia+09)

Many dSph, dE have disks (Lisker+Fuchs 09, Toloba+09)

Cluster LF: shallower slope at small radii



(Popesso+06)

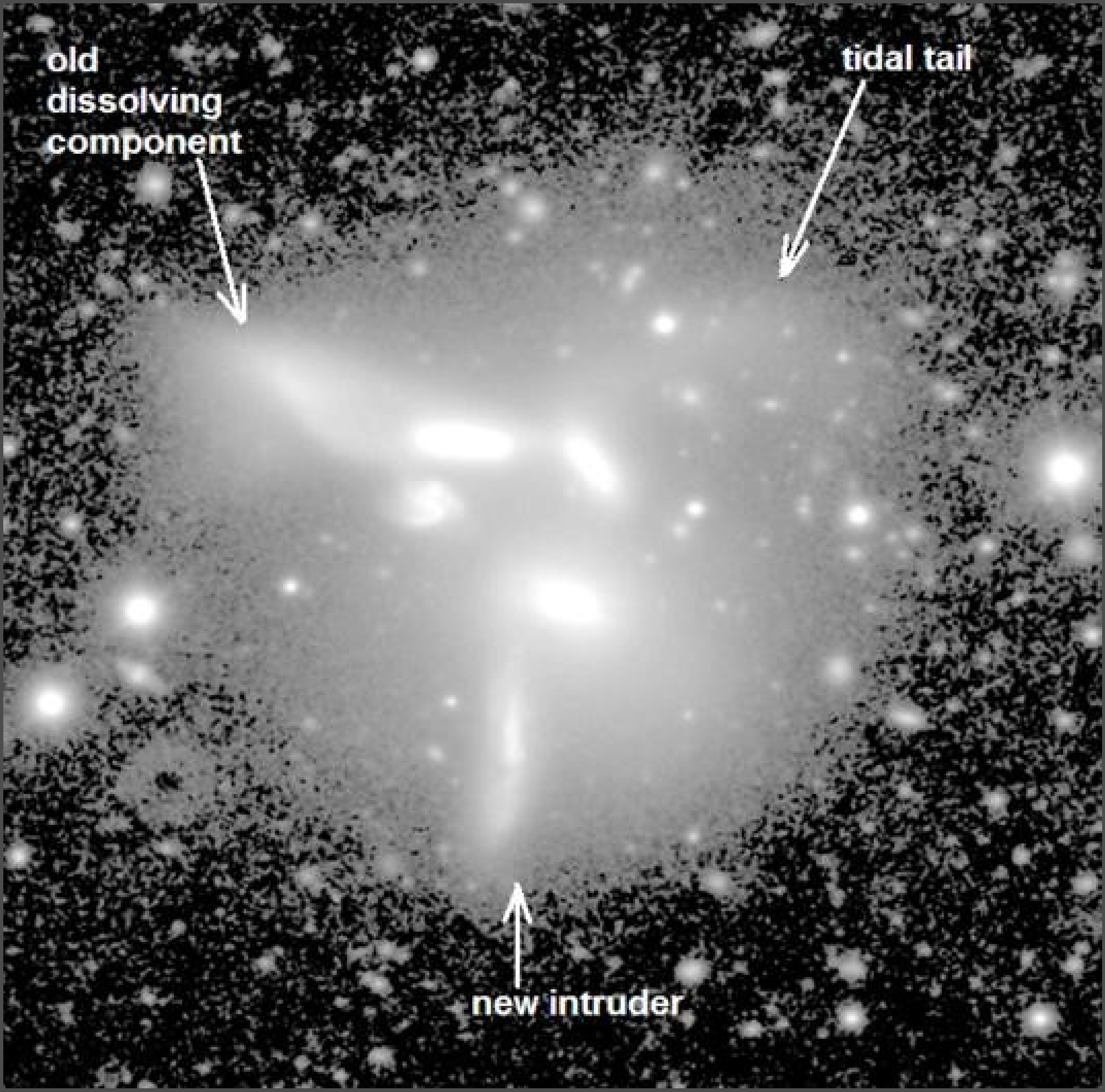
Galaxy orbiting cluster suffers tidal truncation outside r_t:

$$r_t \approx r_c \frac{\sigma_g}{2\sigma_v}$$

$r_c \approx 2\, r_{pericenter}$

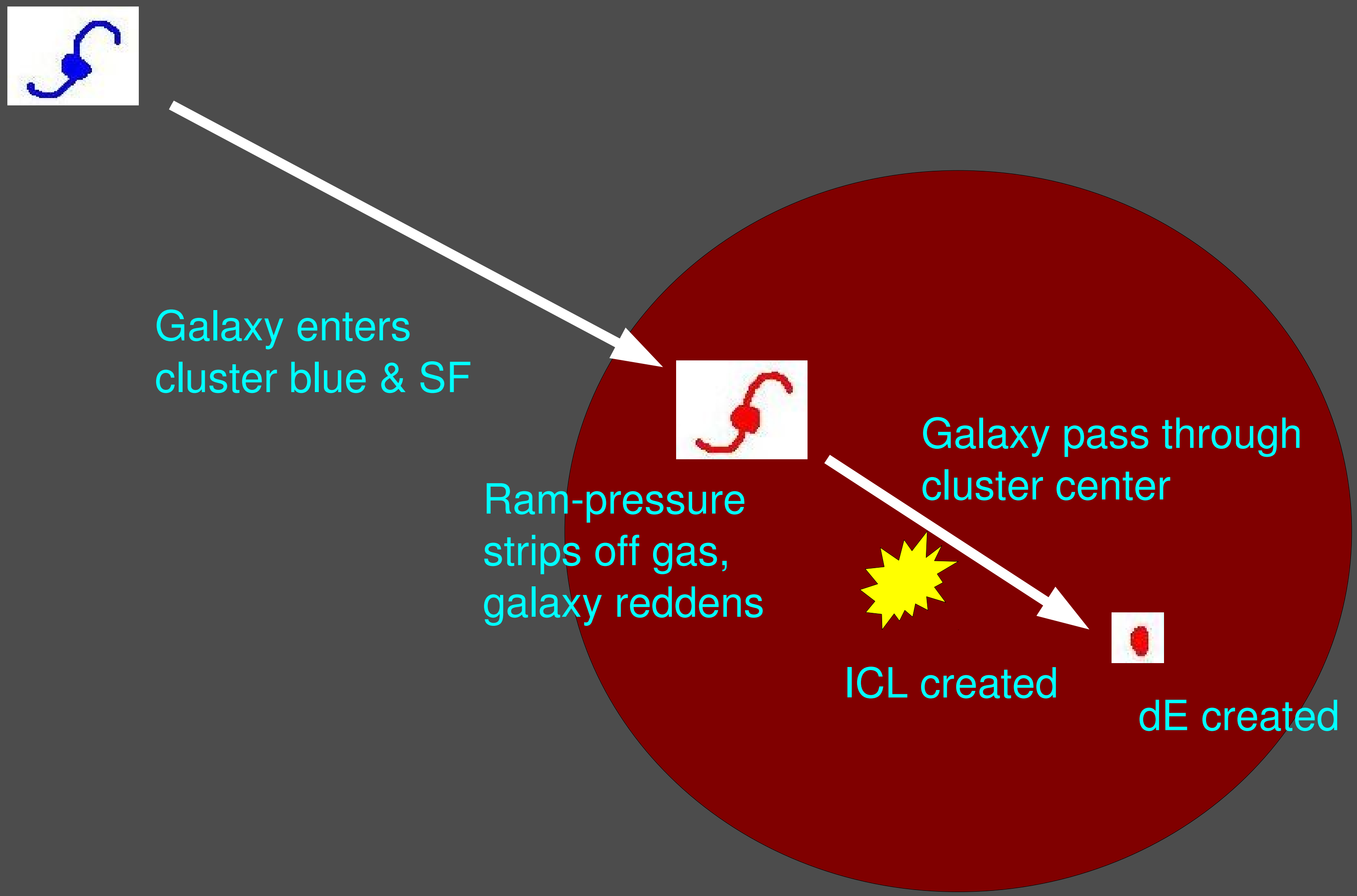
BCG at r=0 not truncated, symmetric external forces

Collisions → gas expelled by tidal forces



(Durbala+08)

Scenario for the accelerated evolution of galaxies in clusters via tidal shocks near the center



What about the evolution of the IR LF?

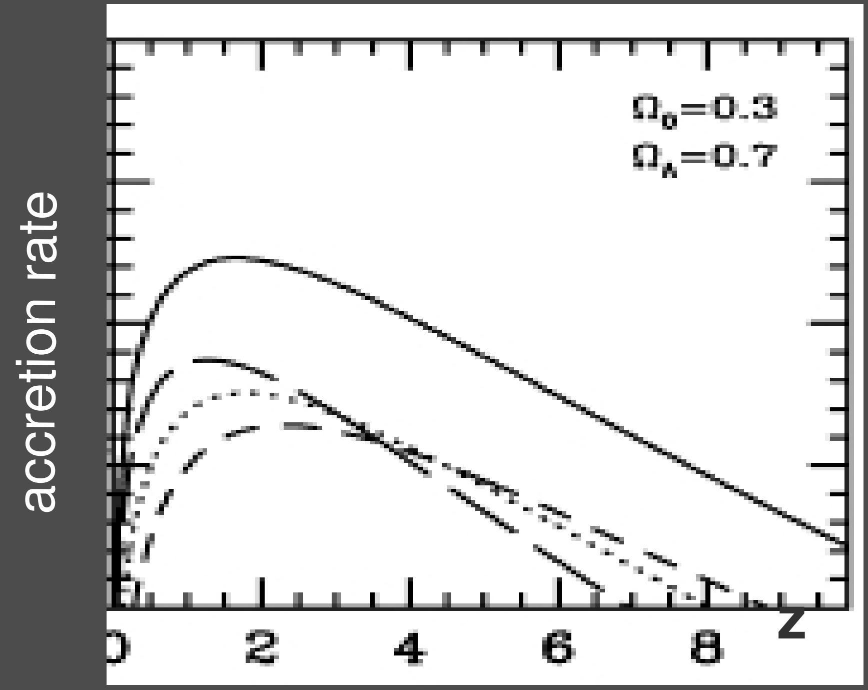
=

General decline of the SFR of field galaxies with time
(gas → stars via normal mode of star-formation)

+

Infall rate of field galaxies into clusters ↓ with time
(Ellingson+01, van den Bosch 02)

Accelerated evolution at z≤0.4
due to accretion-rate peak?
(van den Bosch 02)



Summing up

- Galaxy star formation (as seen in the IR) depends on the environment and the redshift, but these dependences are not simple:

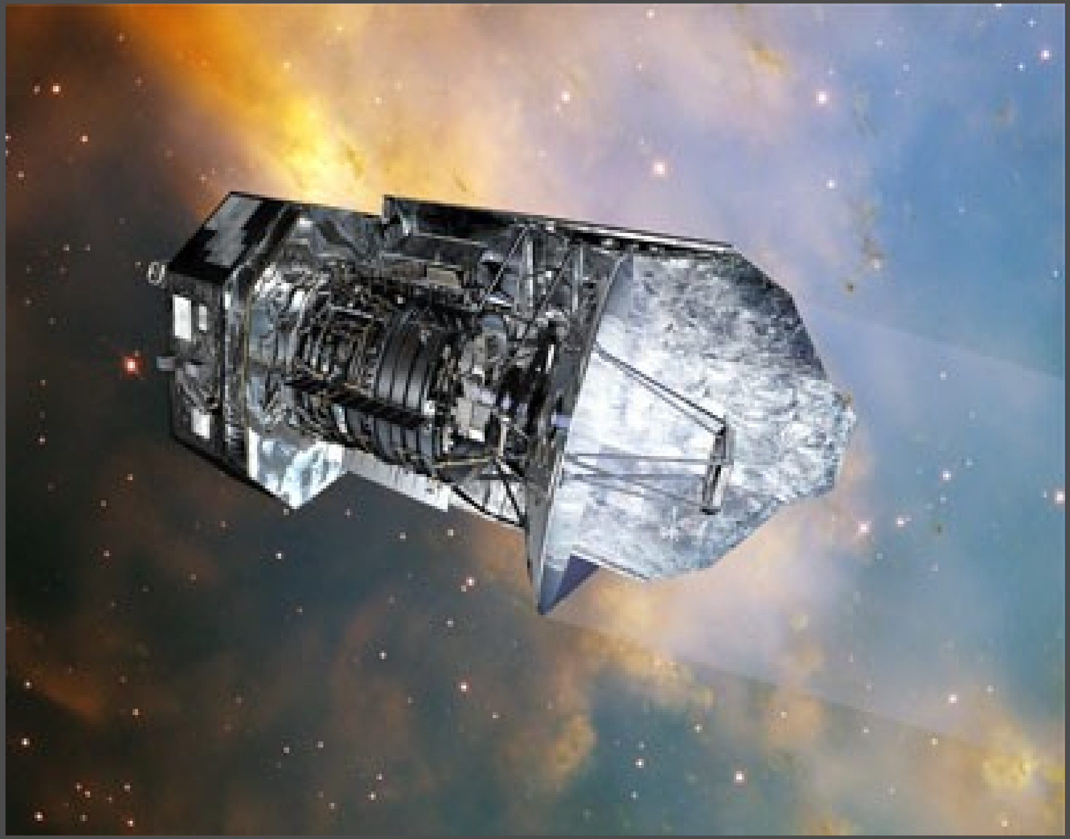
- intermediate-density environments (like filaments) are the preferred sites of galaxy star formation,

- the evolution of cluster SFR per unit mass is clear only up to $z \approx 0.4$.

- StarBurst in filaments, ram-pressure stripping in cluster cores, z-dependent accretion of star-forming galaxies from the field, together draw a plausible interpretation of our findings.

What next?

➔ A1763: galaxy spectral line-indices & GALEX UV data
➔ Other clusters: Herschel data, evolution to z>1



High-z clusters:

48hrs on 8 (proto)clusters (0.9<z<2.4)
(GT accepted, p.i. B. Altieri)
97hrs on 8 clusters (1.4<z<1.8)
(OT accepted, p.i. P. Popesso)


The End
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