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

Andrea Biviano, INAF/Osservatorio Astronomico di Trieste

in collaboration with:

Dario Fadda, Louise Edwards, NASA Herschel Science Center

Florence Durret, Institut d'Astrophysique de Paris

Francine Marleau, Toronto University

Why am I bo(the)ring you with this seminar today?

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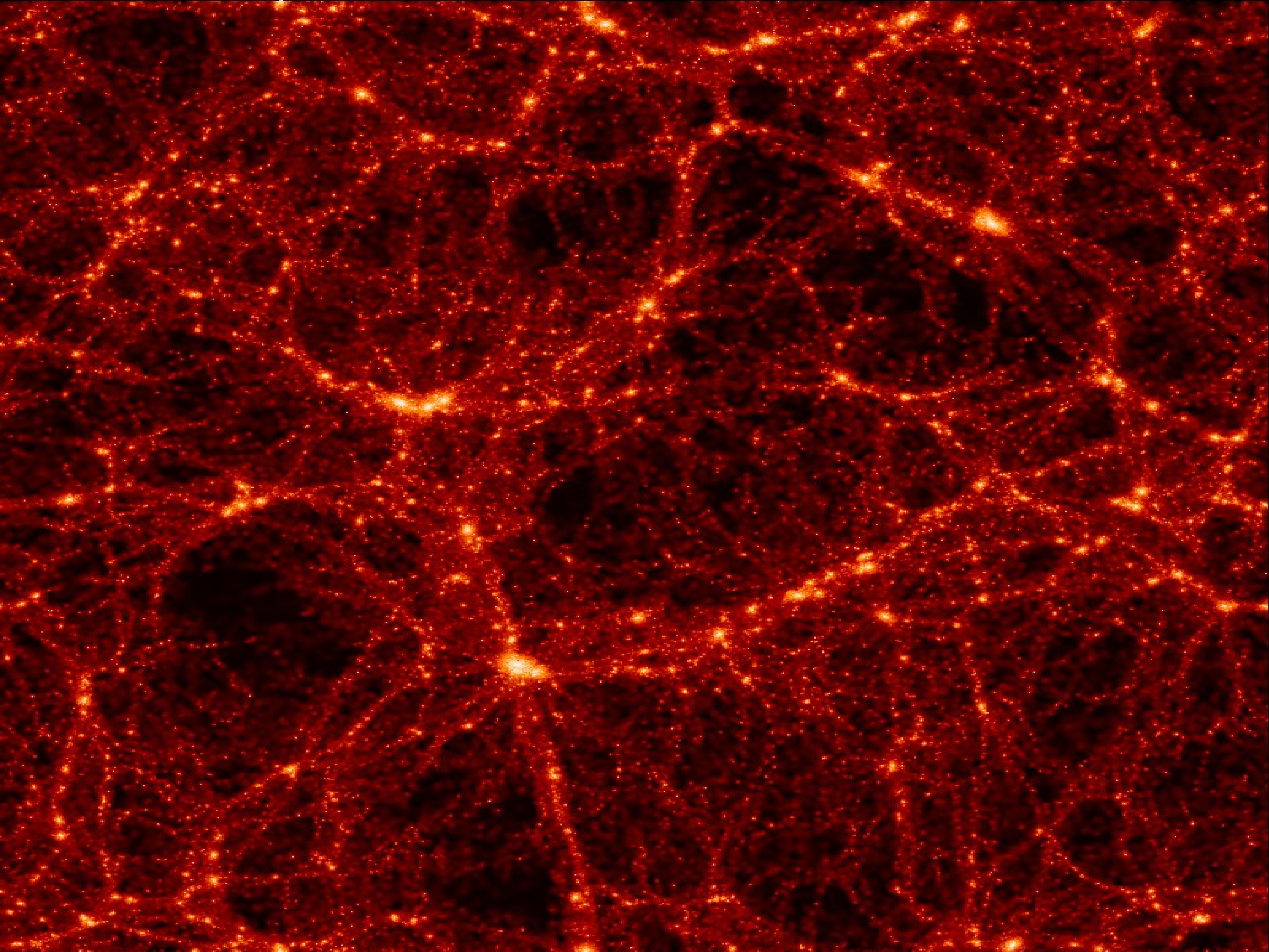
THE MOST EXPLOSIVE
MOTION PICTURE
IN 25 YEARS!
KIRK
DOUGLAS
"PATHS
OF GLORY"
RALPH MEEKER · ADOLPHE MENJOU

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


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



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


00:04:56

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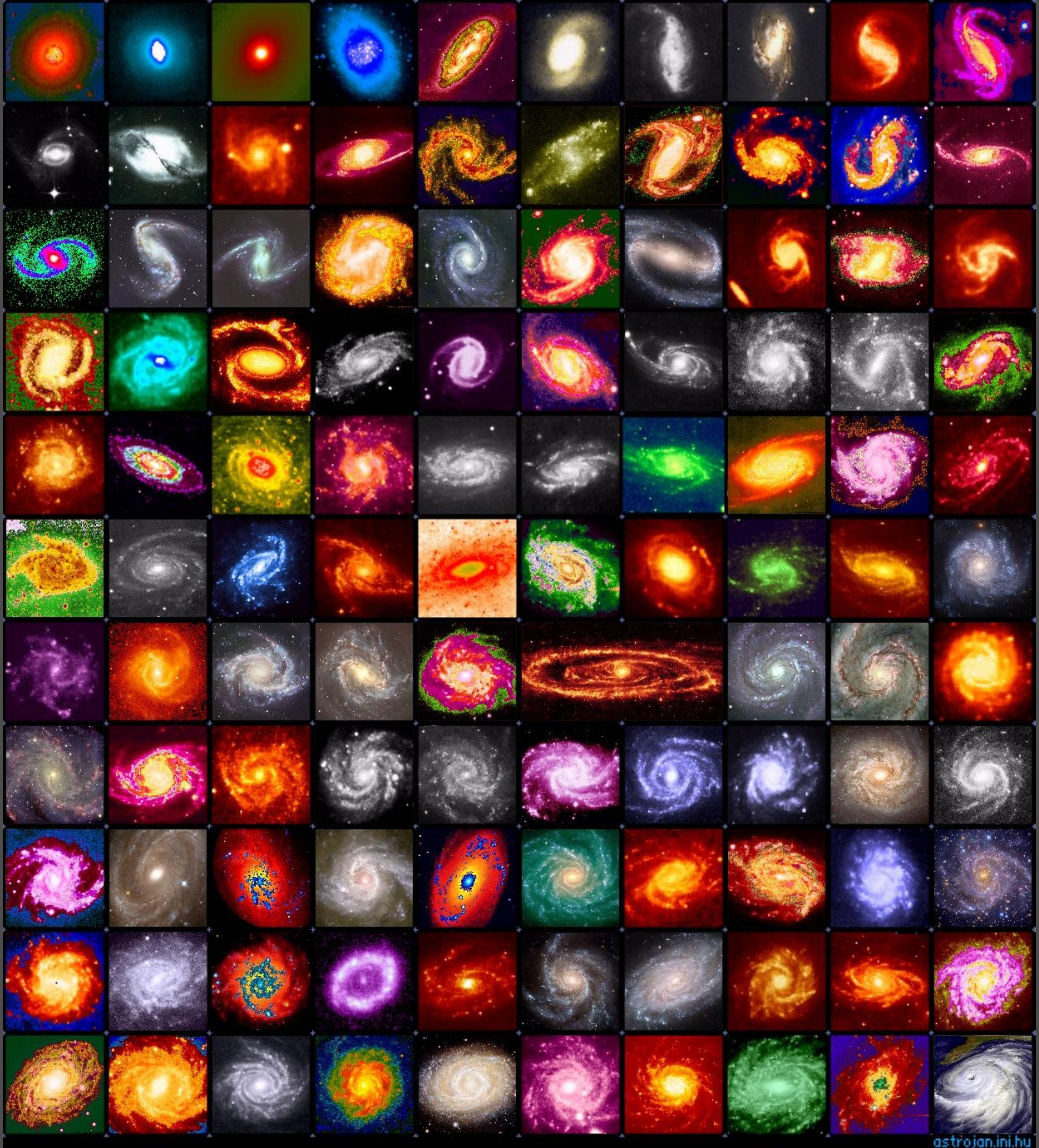
Introduction: galaxy properties in clusters

The most striking characteristics of the cluster galaxy population:
its morphology mix

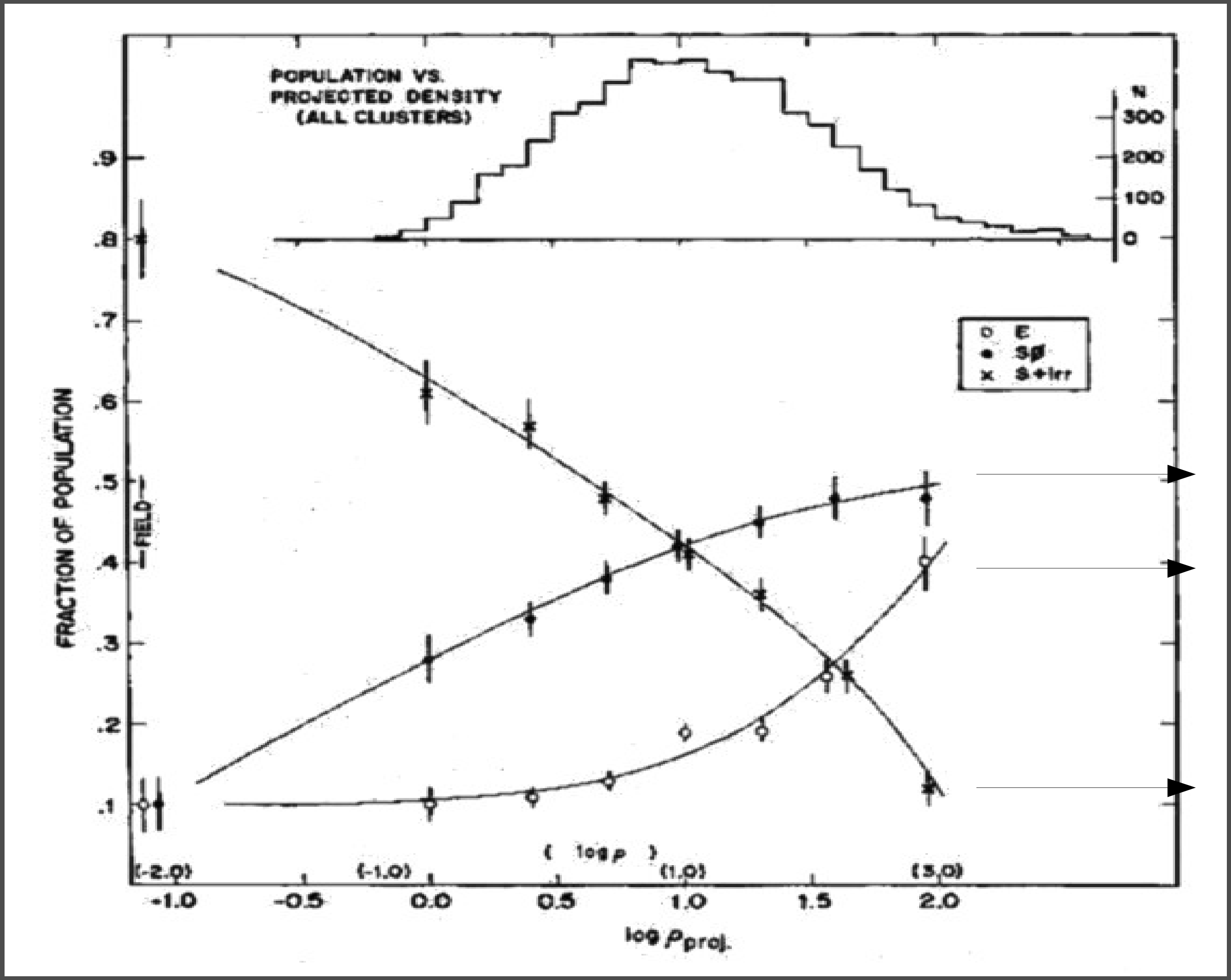


Field

Cluster

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

(Dressler 80)



Fraction of:

Ellipticals

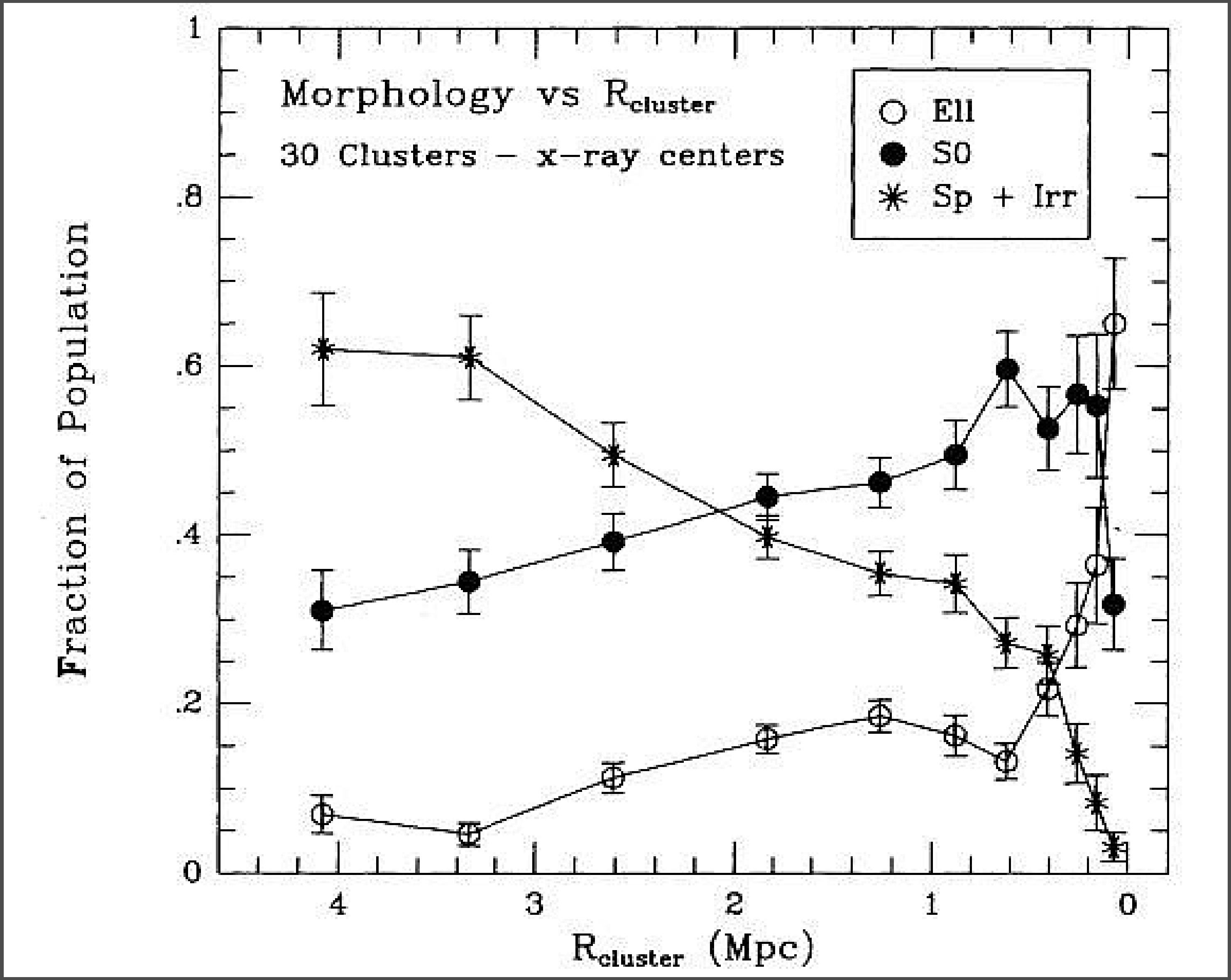
S0

S+Irr

log(local density)

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

(Whitmore+93)



Ellipticals

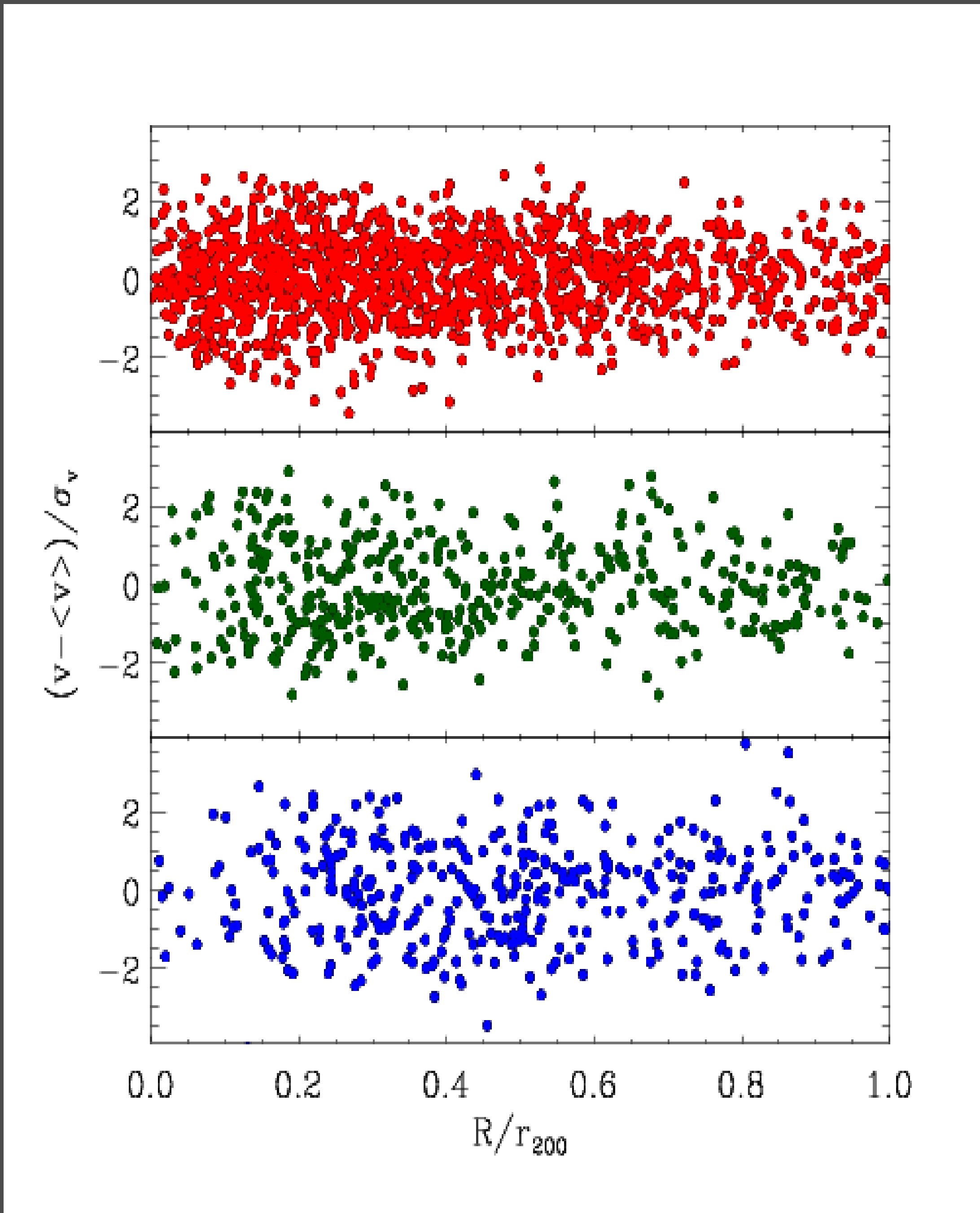
S0

S+Irr

radius, i.e. clustercentric distance

Color-radius relation in clusters

Velocity wrt cluster mean

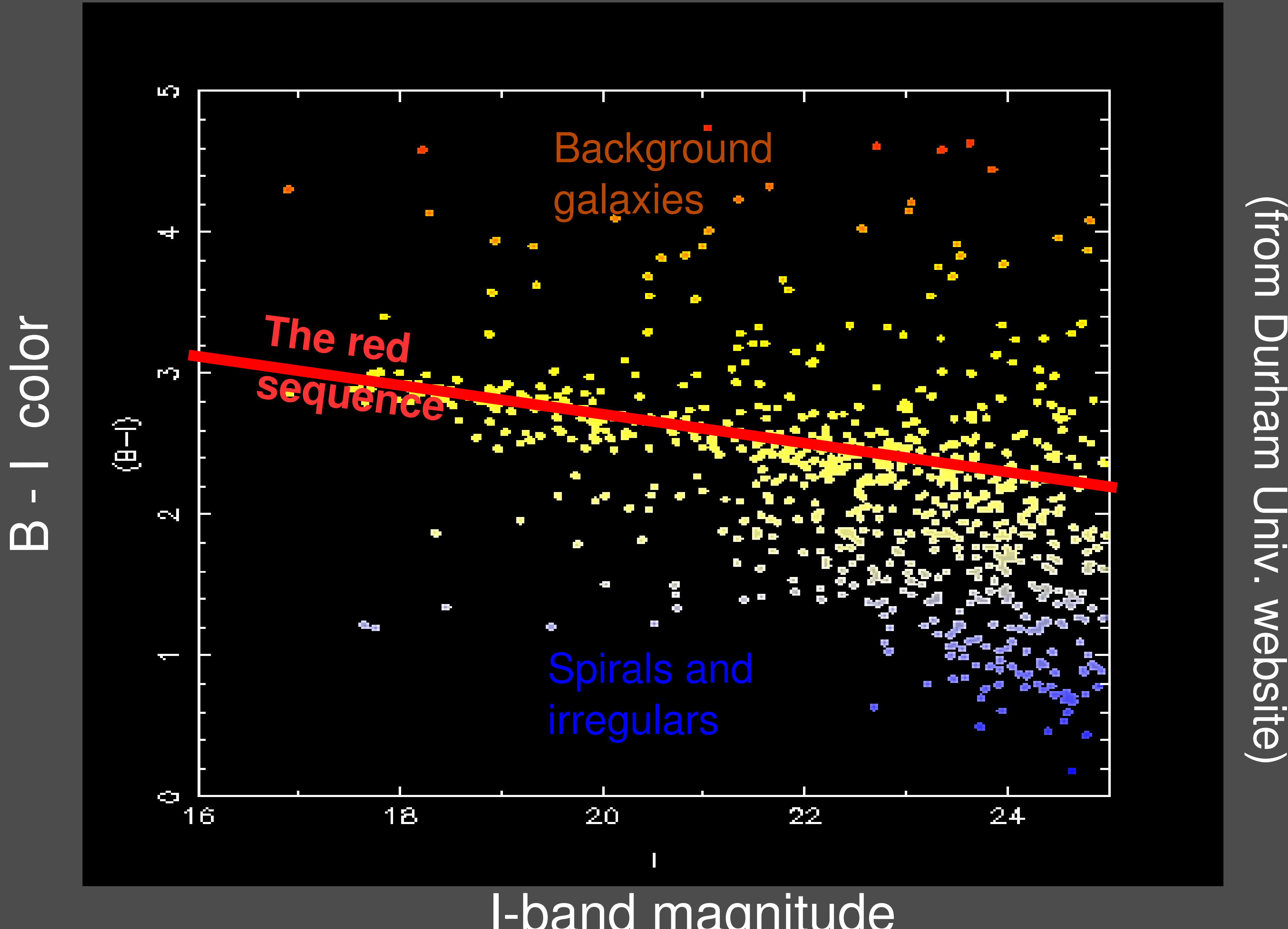


clustercentric distance

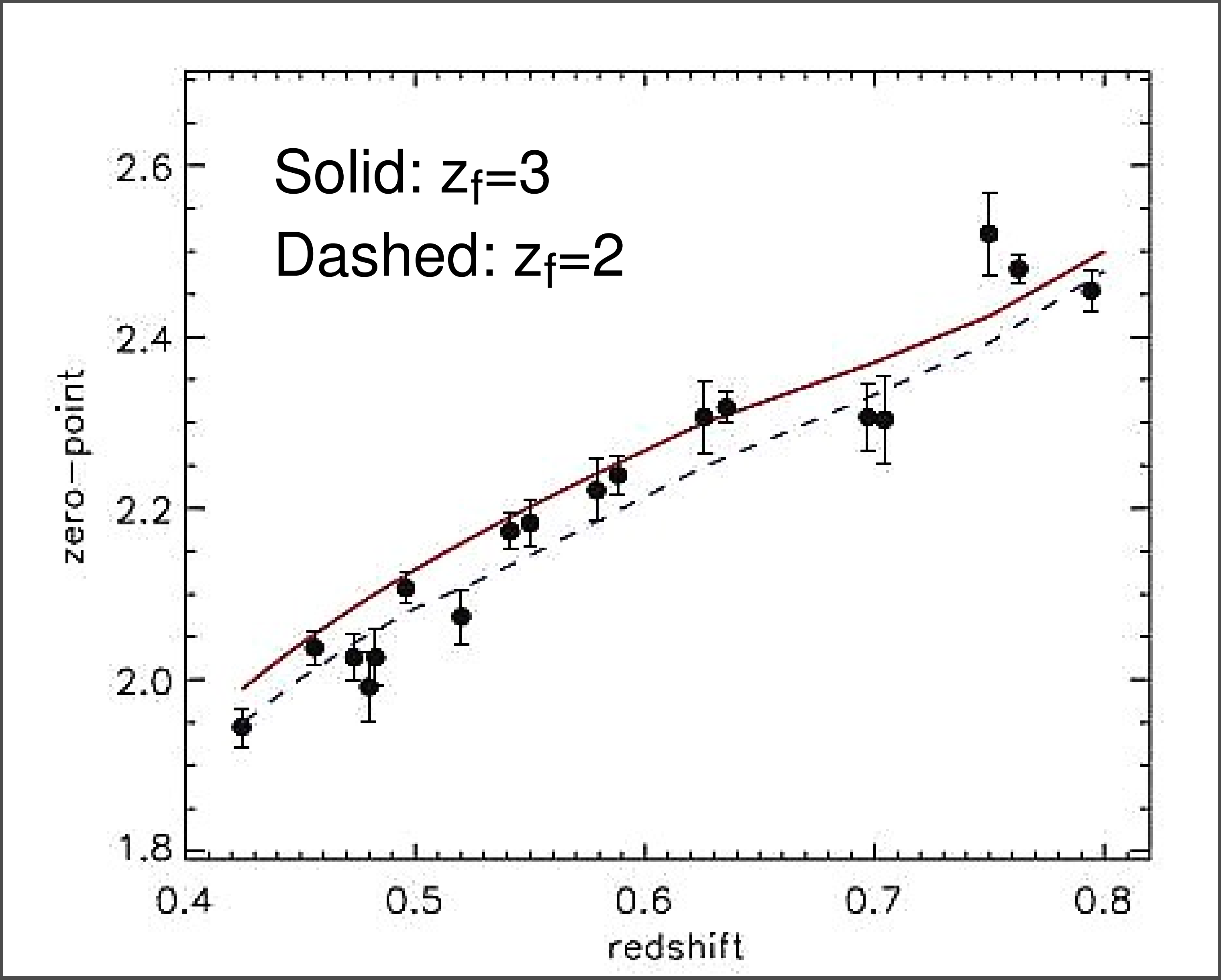
The CIRS cluster sample

(Rines+Diaferio 06)

The Color-Magnitude Relation



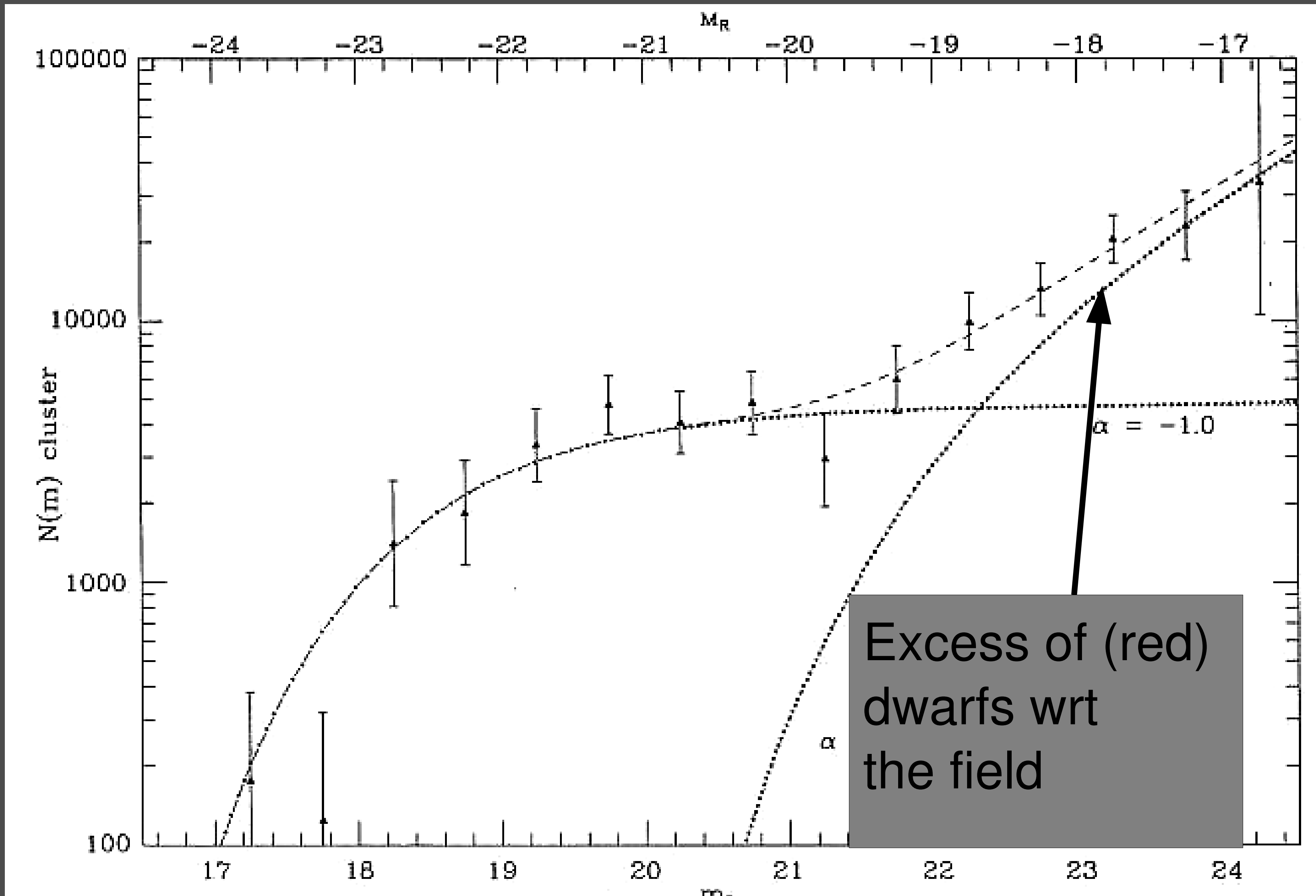
Color-Magnitude Relation evolution with z ⇒ $z_f \geq 2$



(De Lucia+07)

Cluster Galaxies Luminosity Function

Number of galaxies per magnitude bin

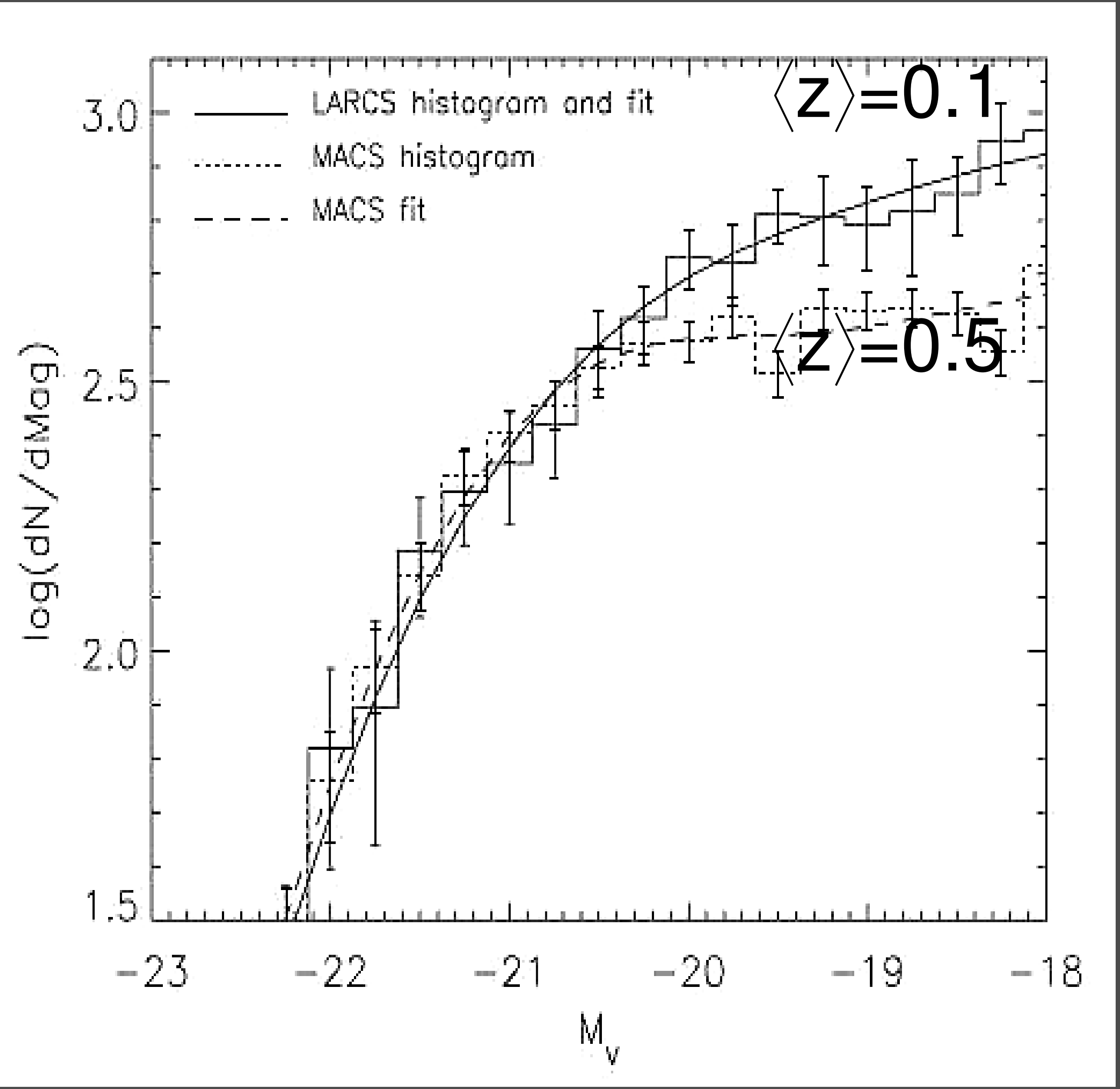


(Driver+04)

Magnitude

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

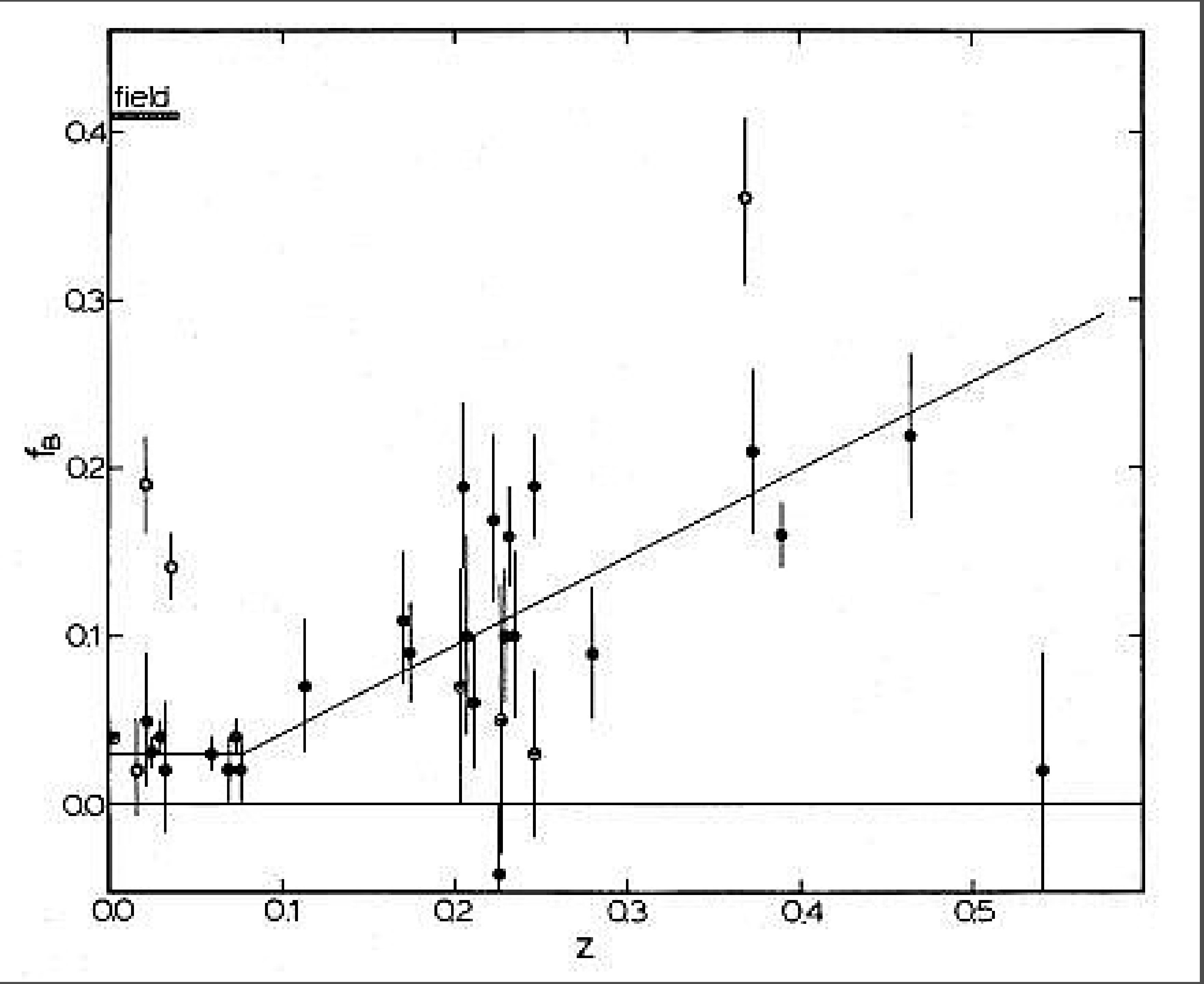
Red-galaxy luminosity functions for two cluster samples, <z>=0.1 & 0.5



(Stott+07)

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

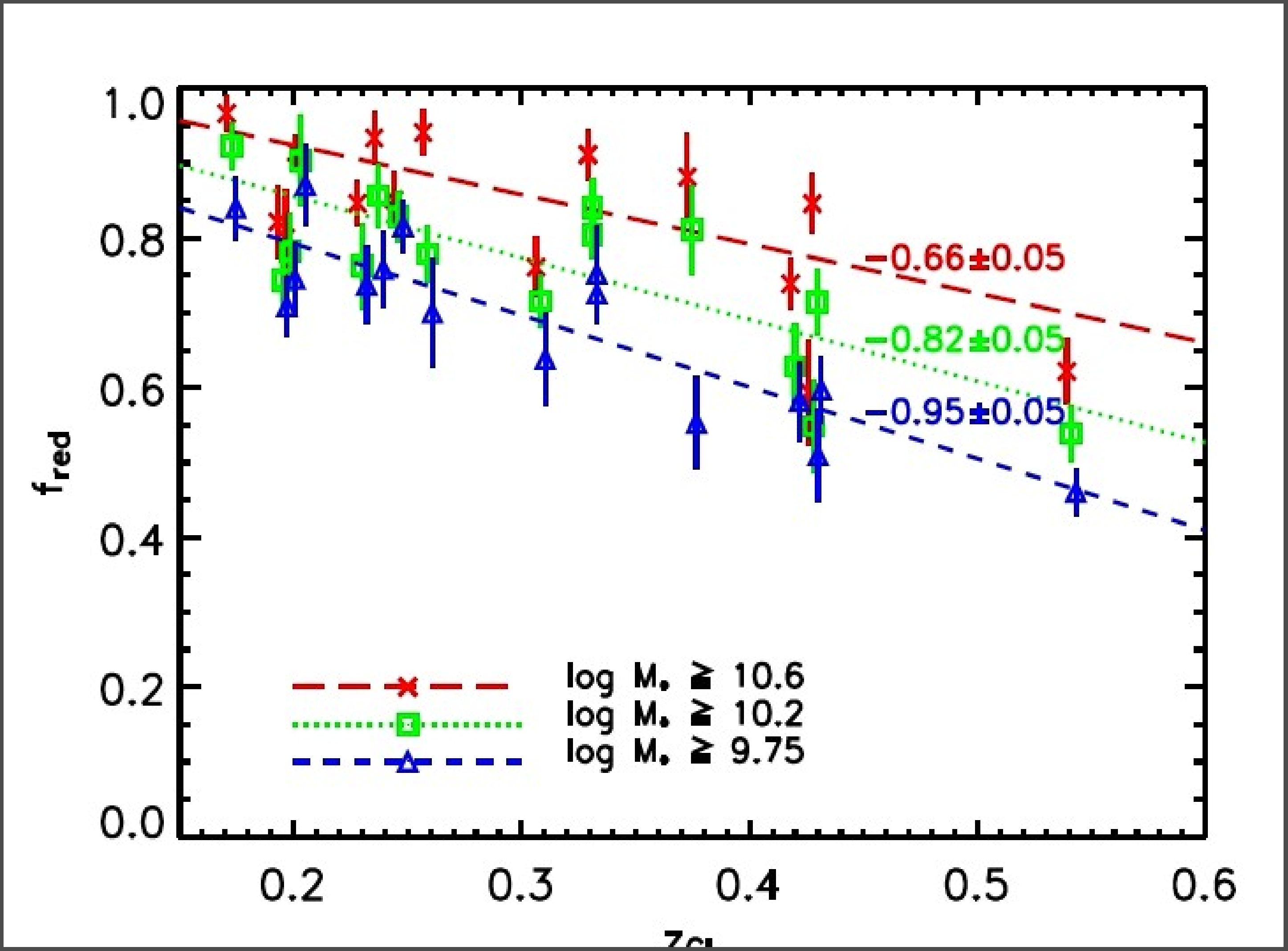
fraction of blue galaxies



(Butcher & Oemler 84)

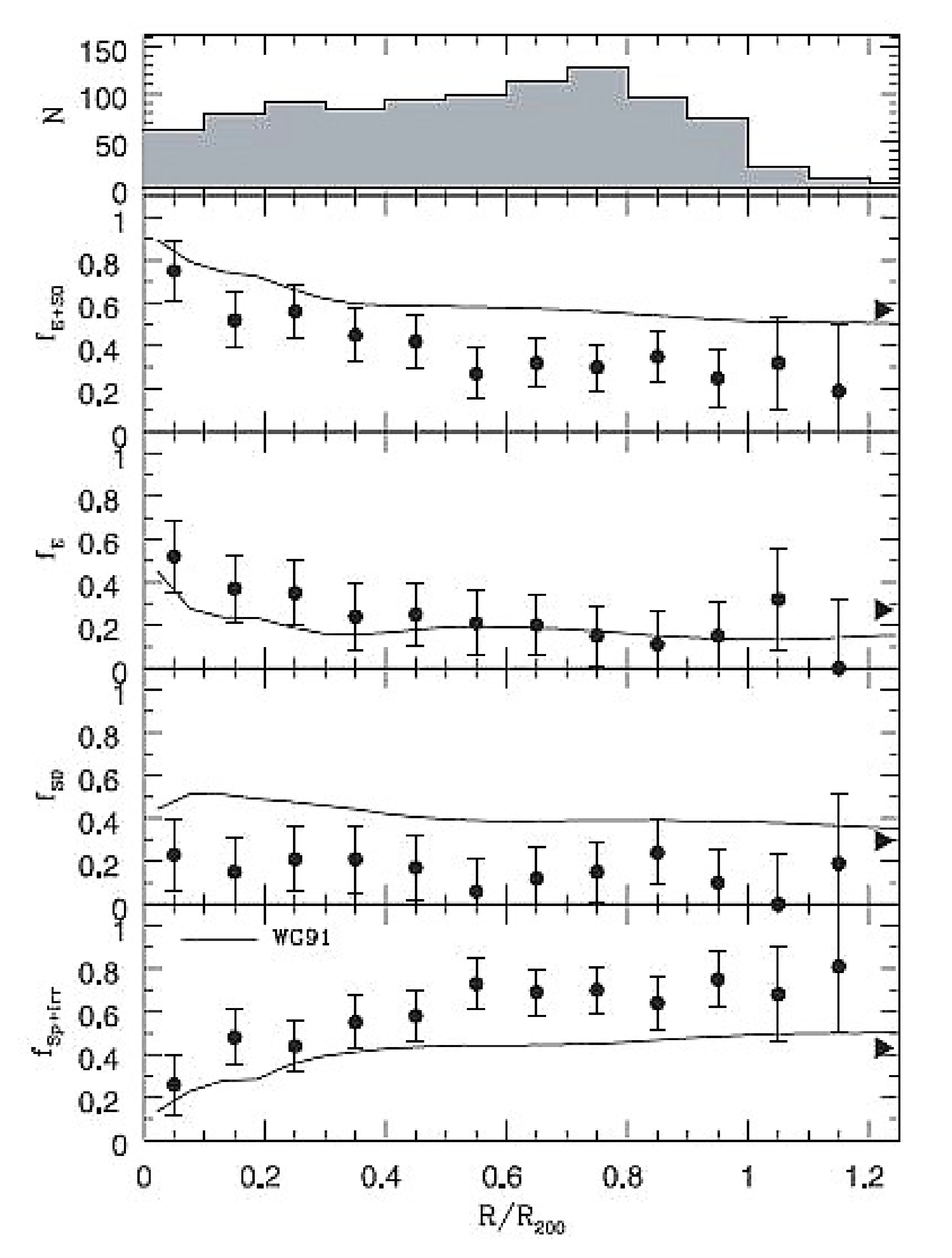
The fraction of Red galaxies in clusters, f_{red} ↓ with z: the “Butcher-Oemler” effect

fraction of red galaxies



(Li, Yee, Ellingson 09)

redshift

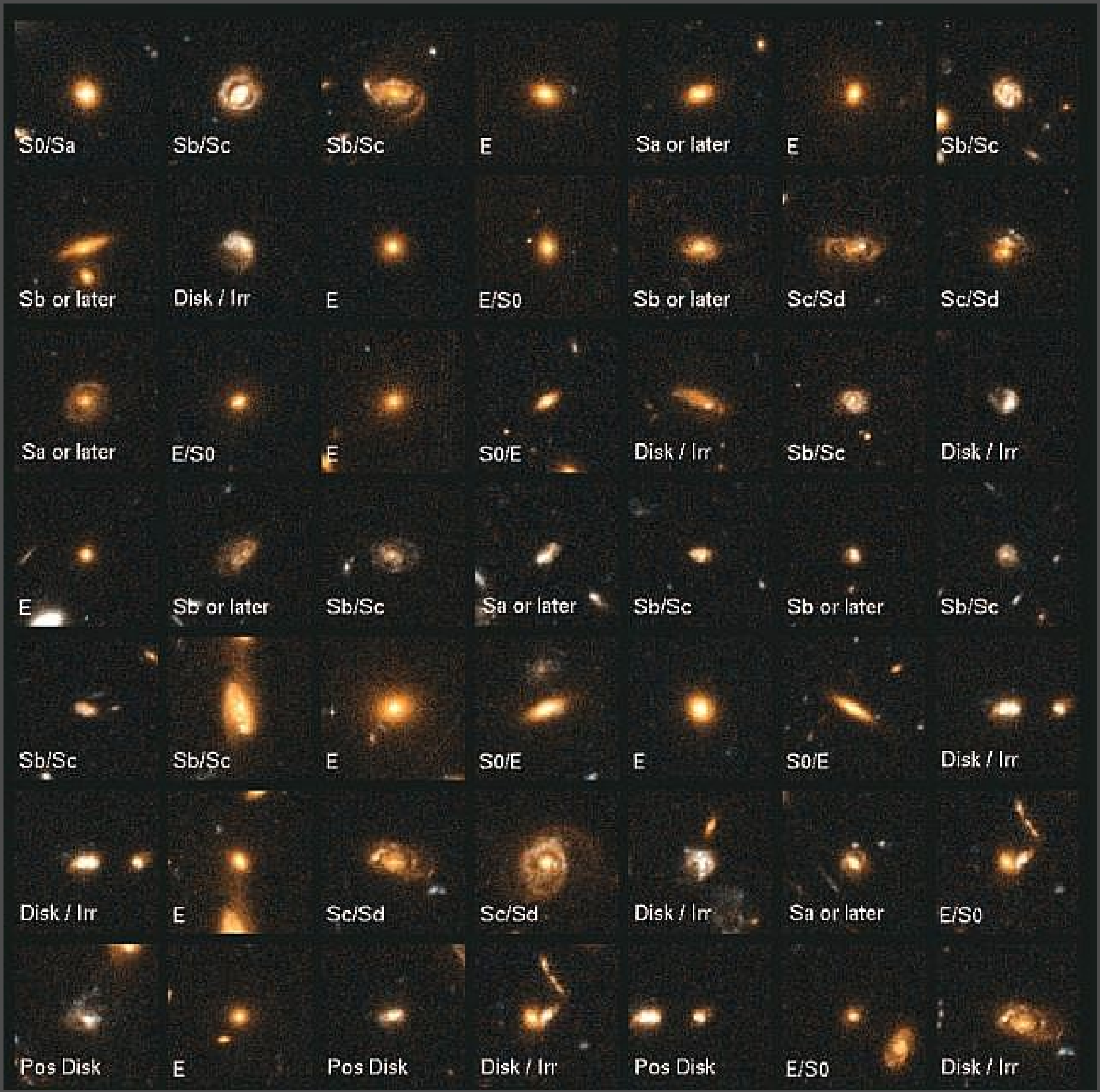


The Morphology-Radius Relation at z~1:

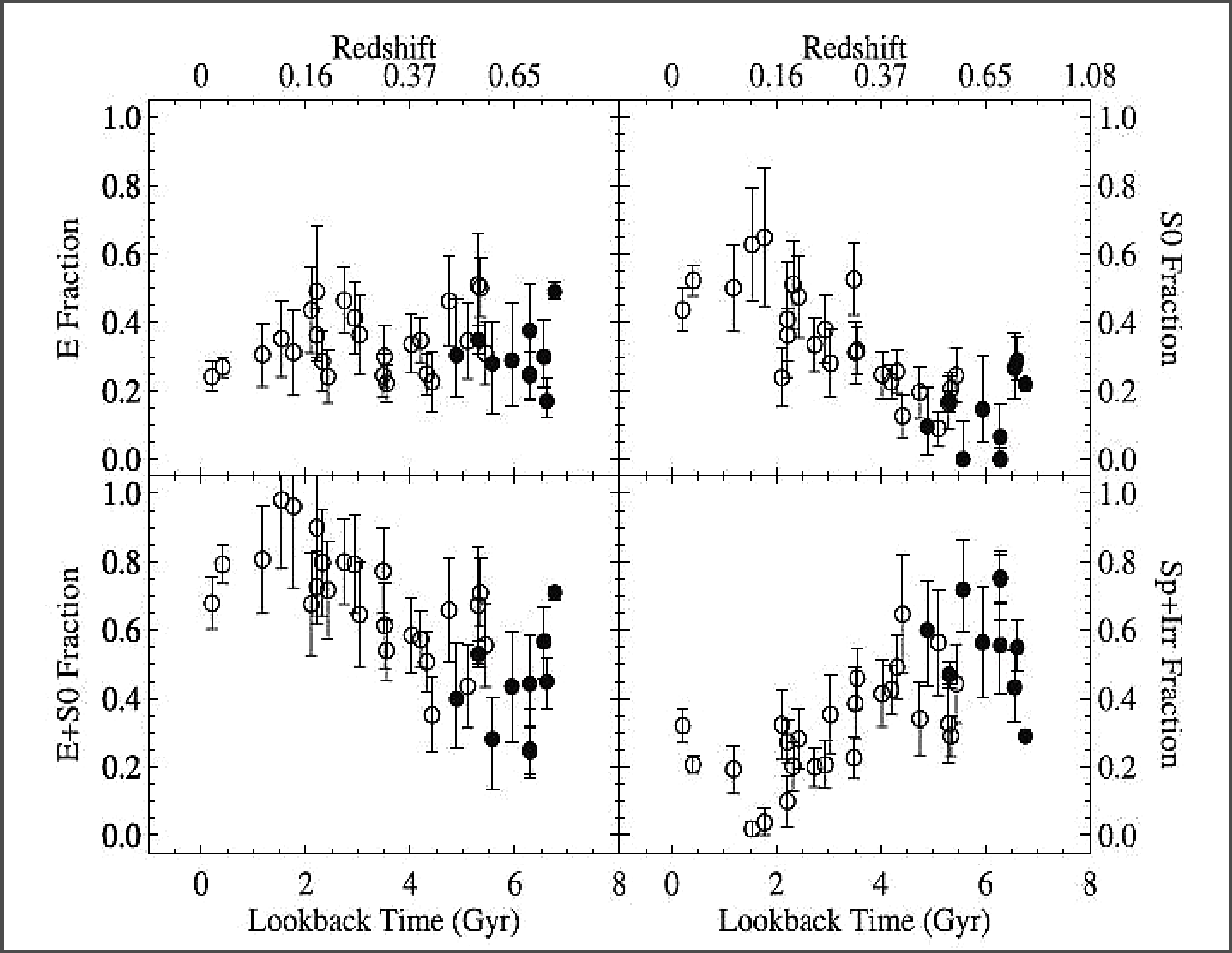
still there, but less S0, more S; no change in E fraction

(Postman+05)

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

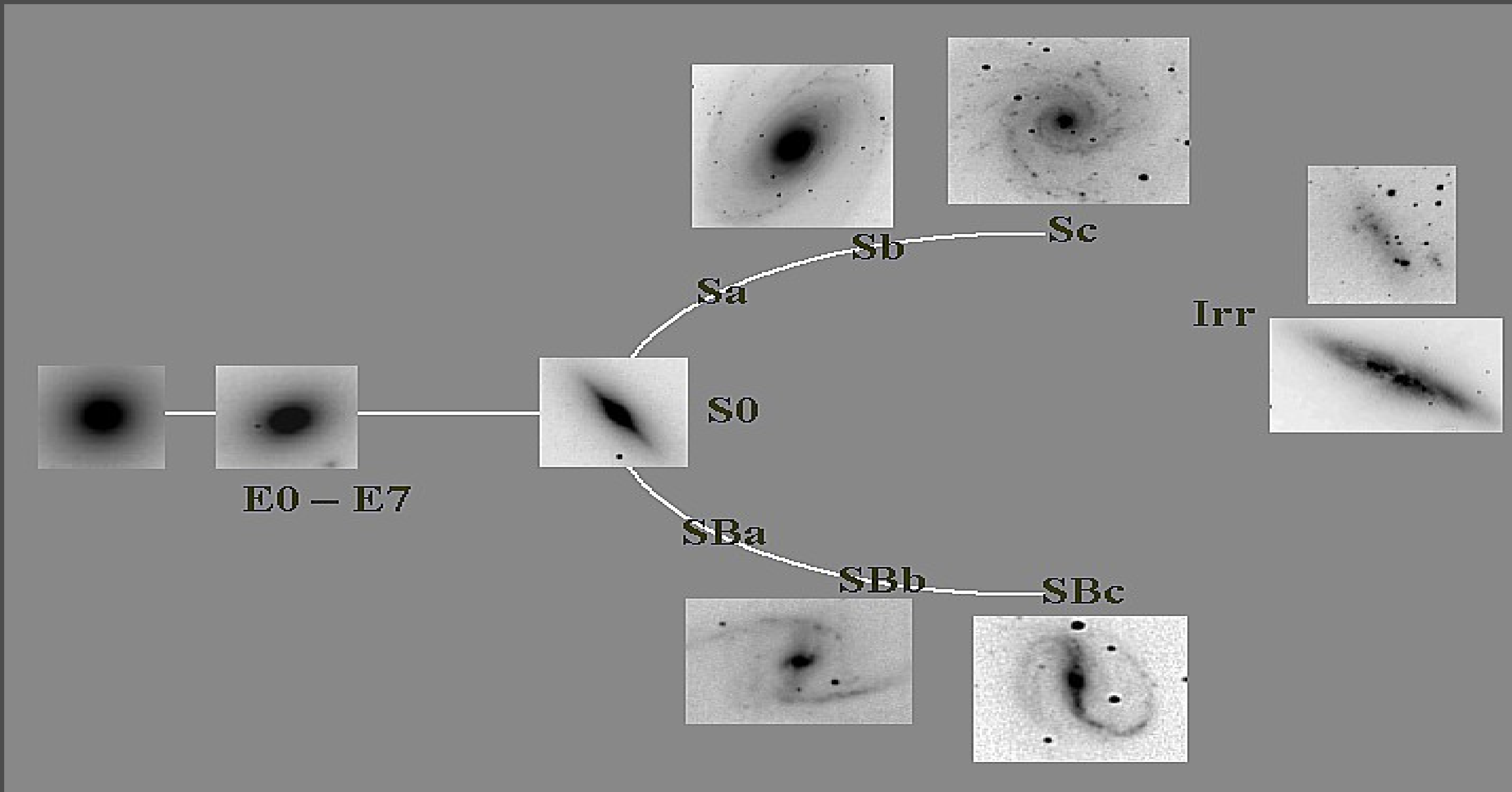


Most morphology evolution occurs at z<0.5



(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

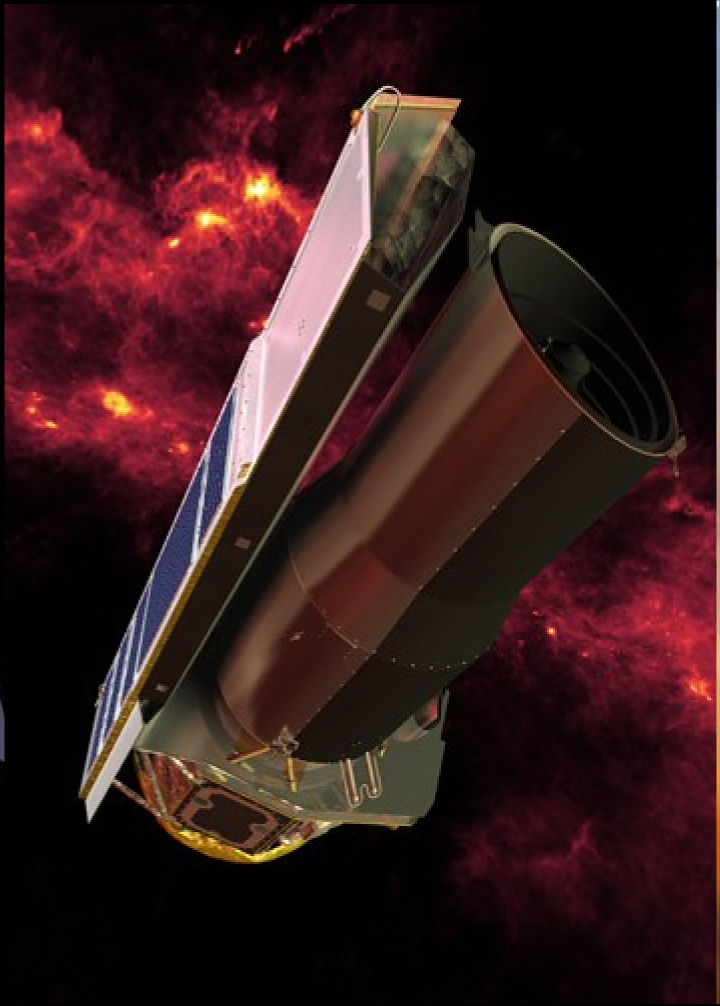
Mid- and/or Far-IR observations (λ>4 μm)

+ Kennicutt's (1998) relation:

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

Mid- and Far-IR observations from space

ISO

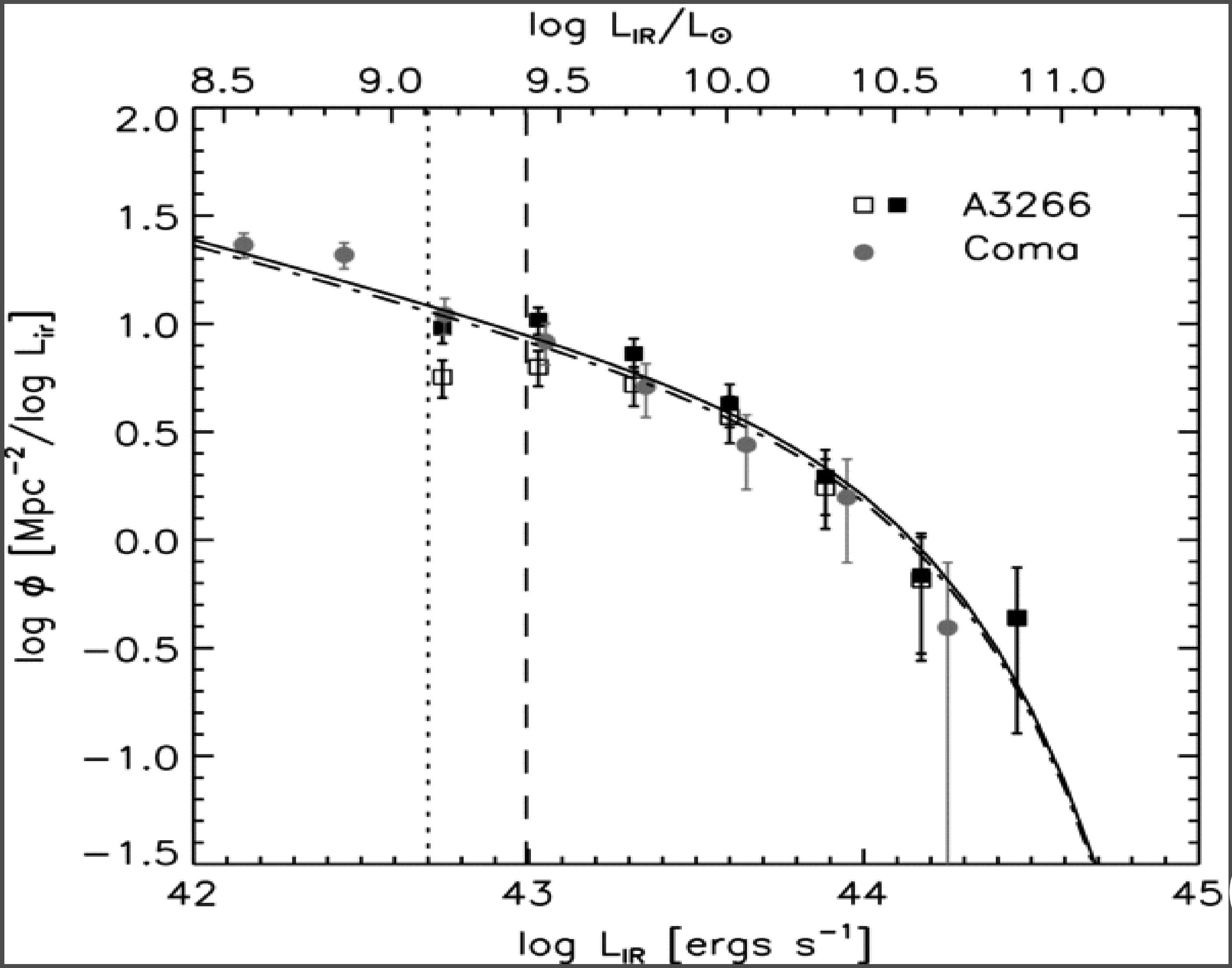


SPITZER

HERSCHEL

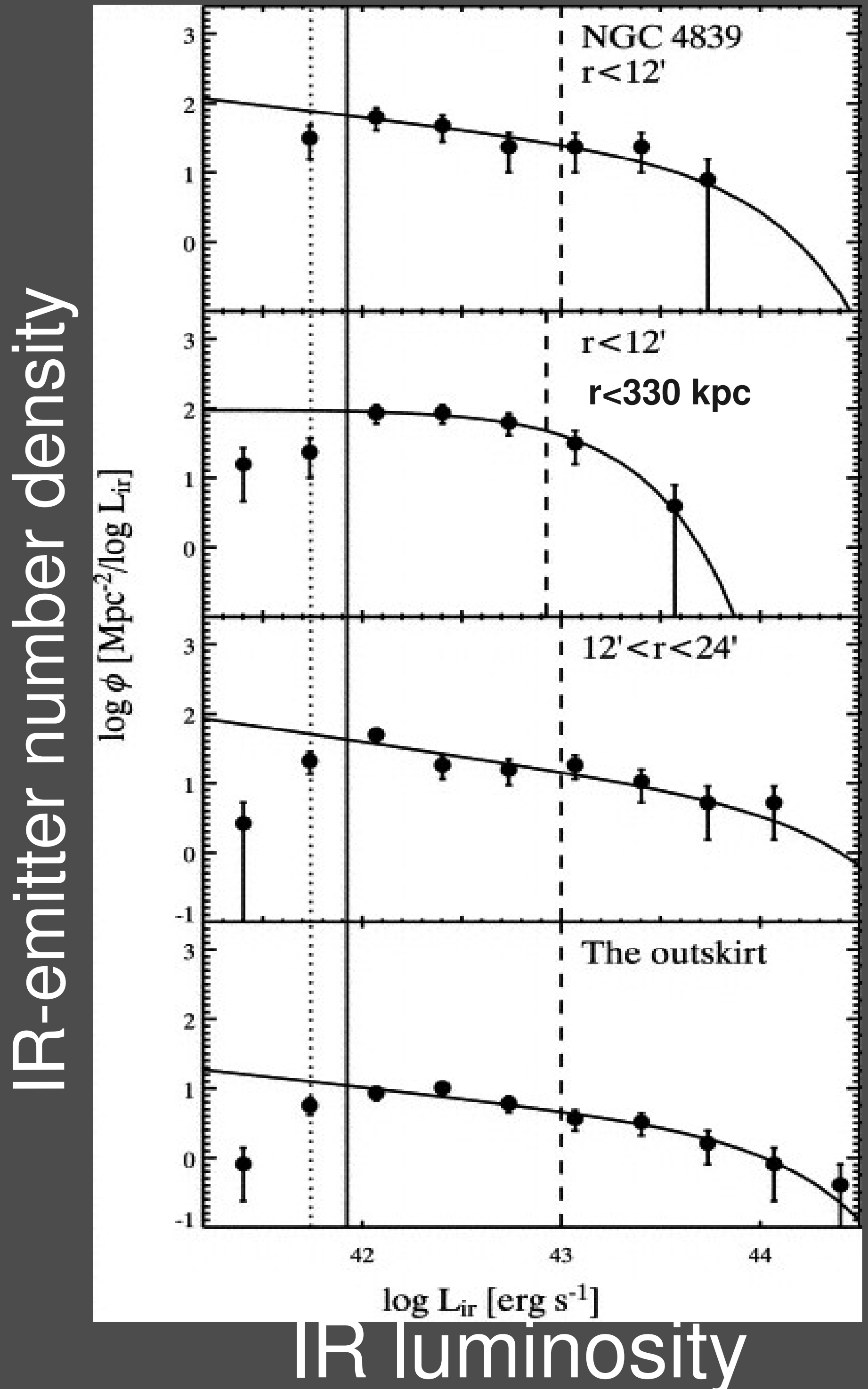
The distribution of galaxy L_{IR} (IR LF) in nearby galaxy clusters is "universal"

galaxy number density per bin of IR luminosity



(Bai+09)

IR luminosity



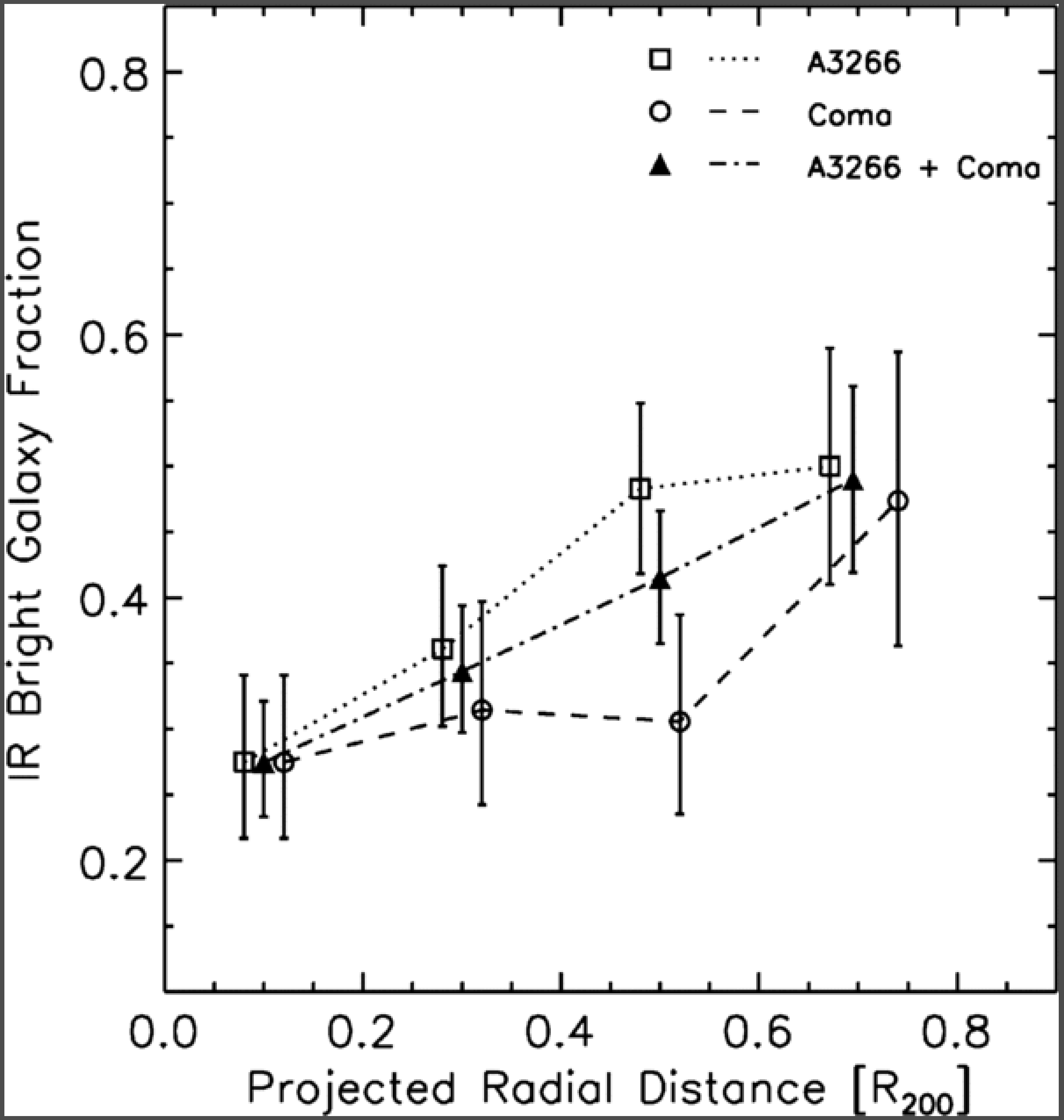
The IR LF in clusters changes with distance from the cluster center

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

(Bai+06)

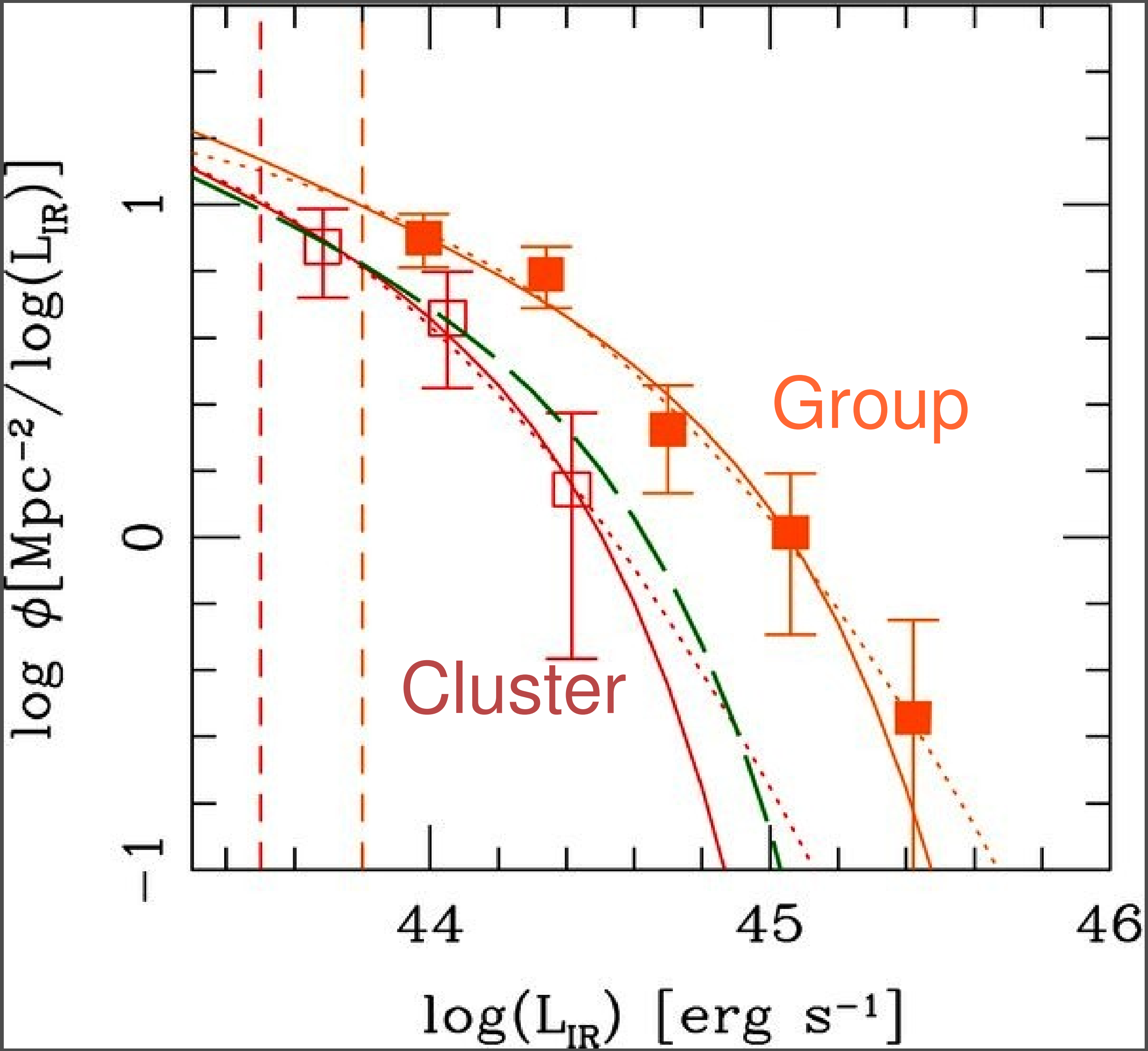
Higher fraction of high-SFR galaxies at larger radii

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

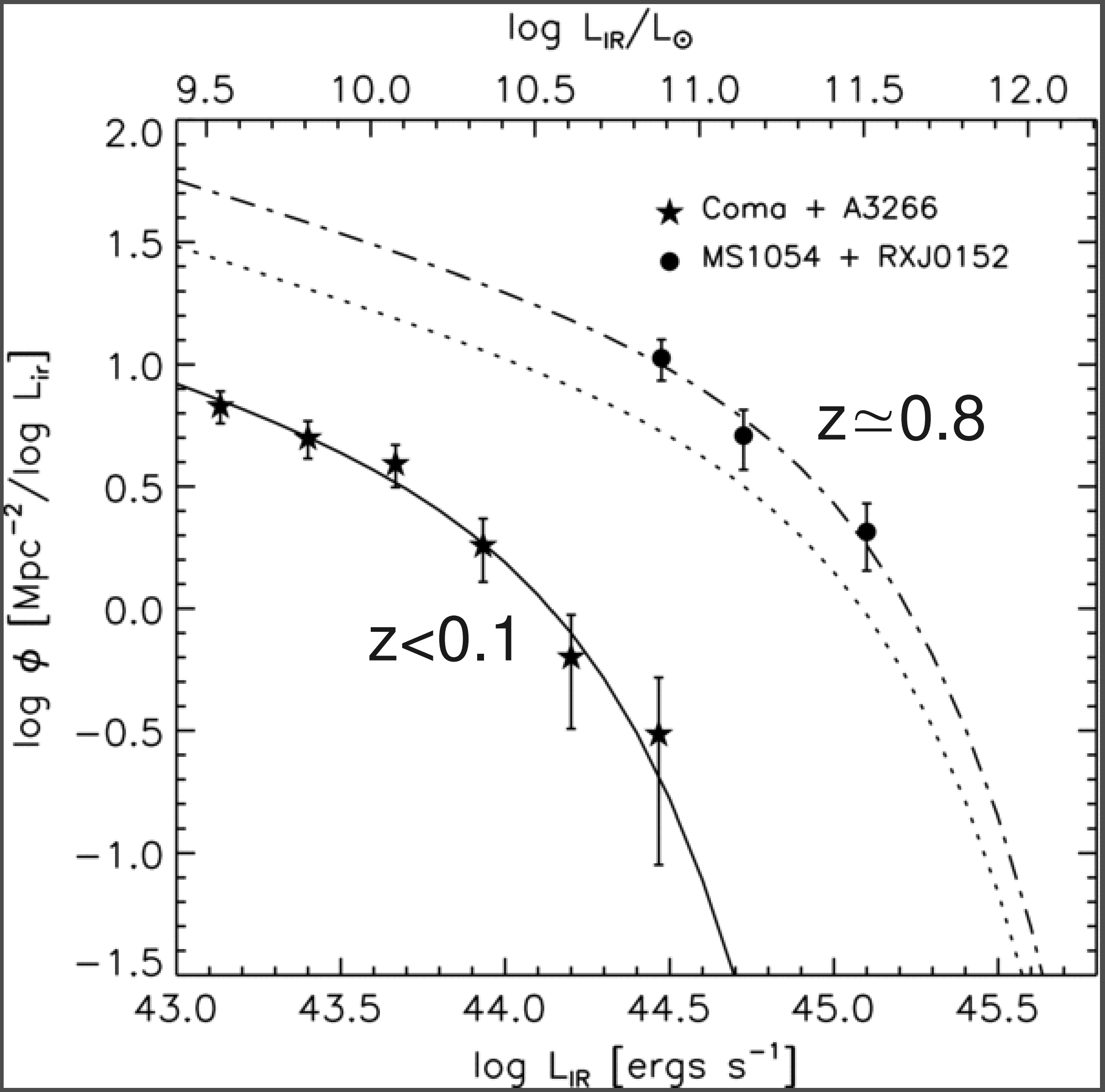
(Tran+09)

Evolution of the cluster IR LF

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

in higher-redshift
clusters

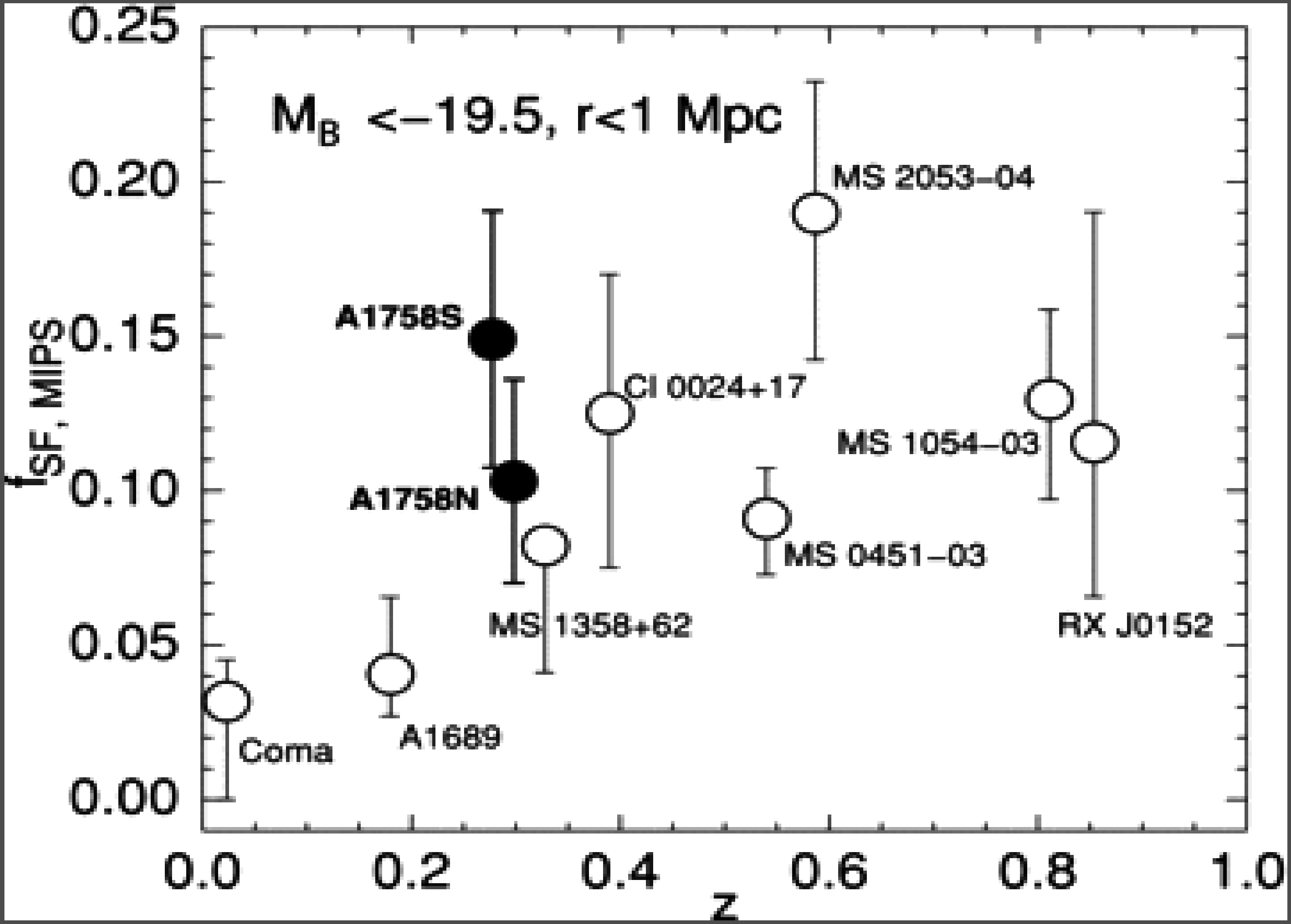
(Bai+09)



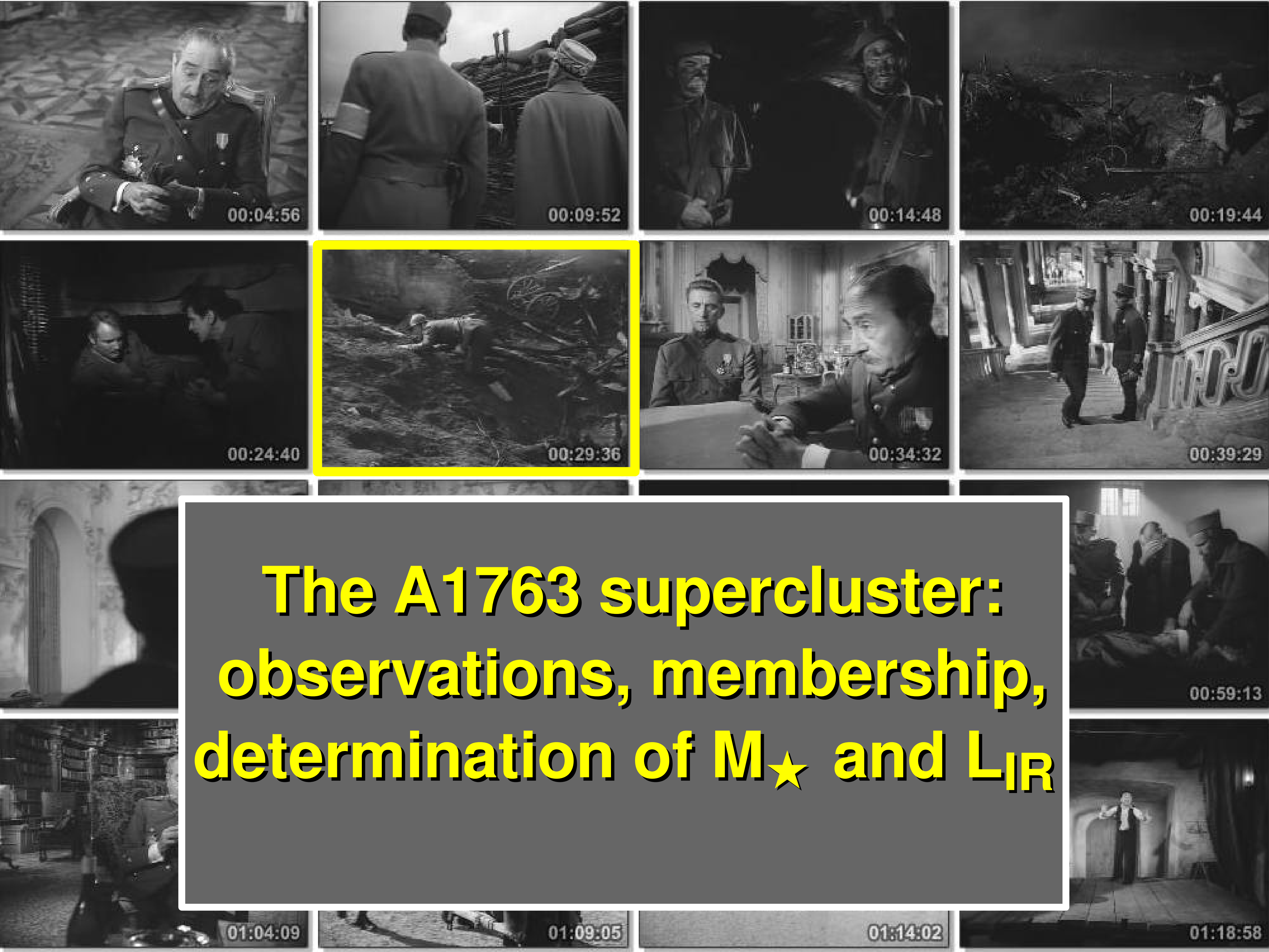
IR-emitter number density

IR luminosity

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



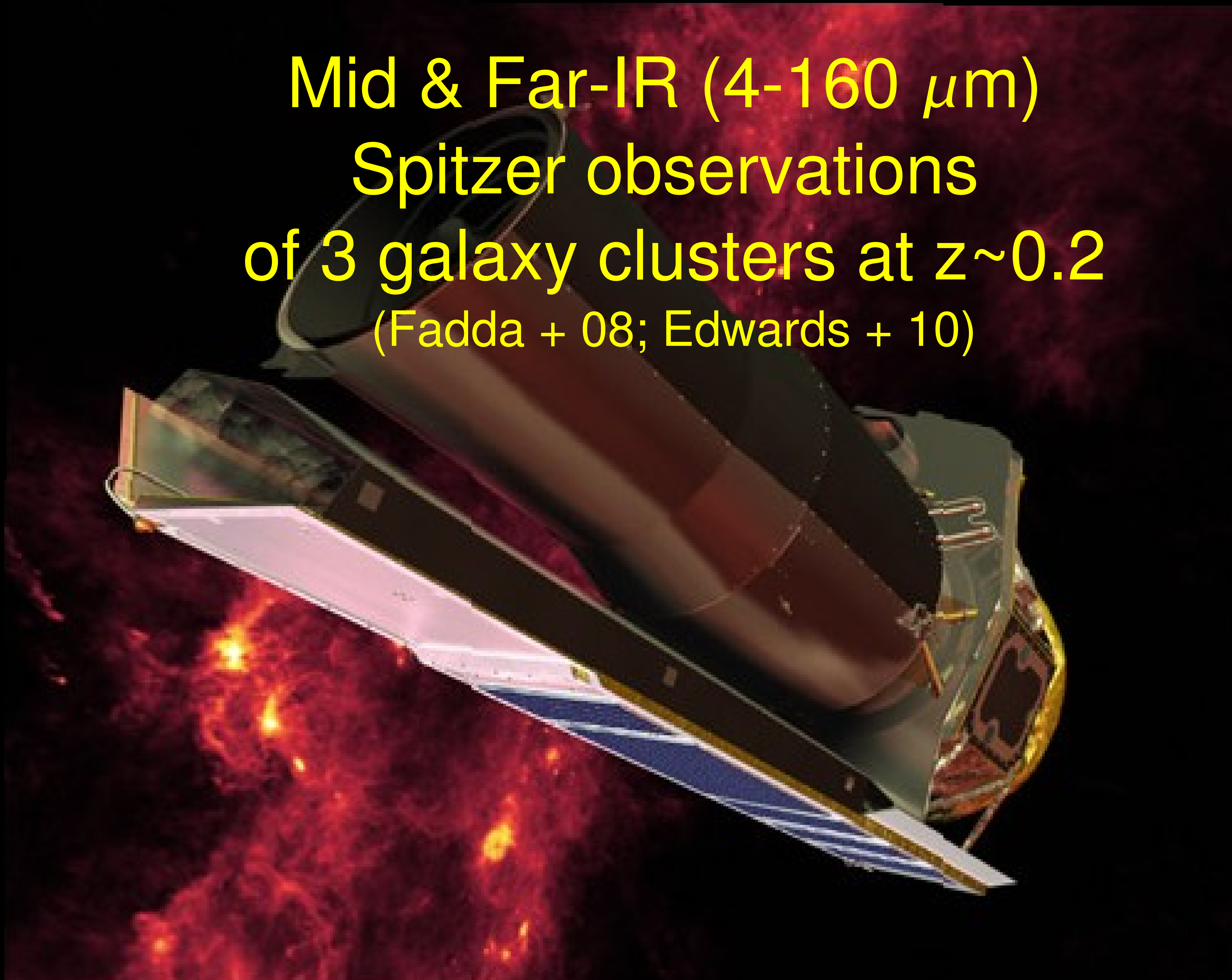
(Haines+09)

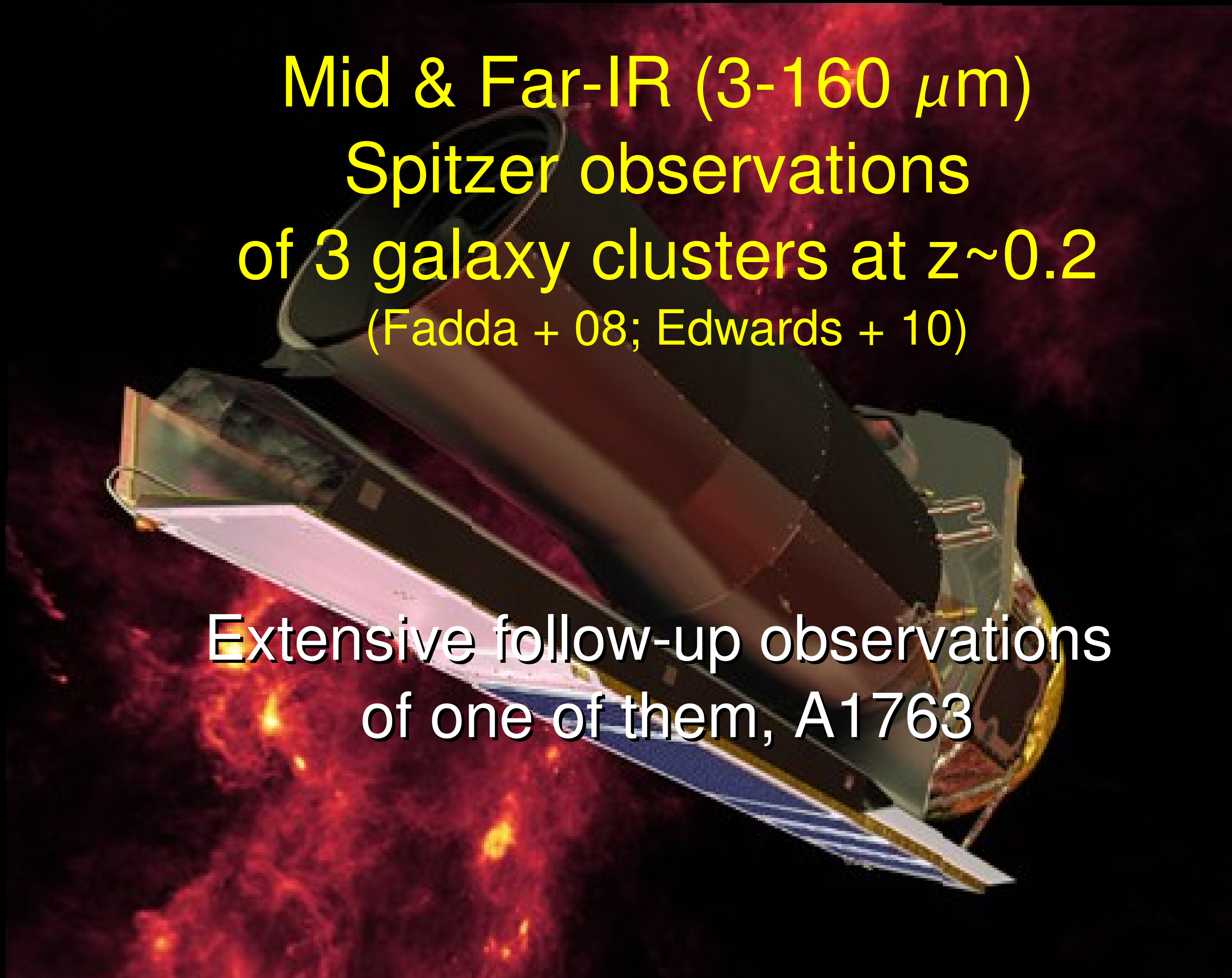


The A1763 supercluster: observations, membership, determination of $M_\star$ and L_{IR}

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:

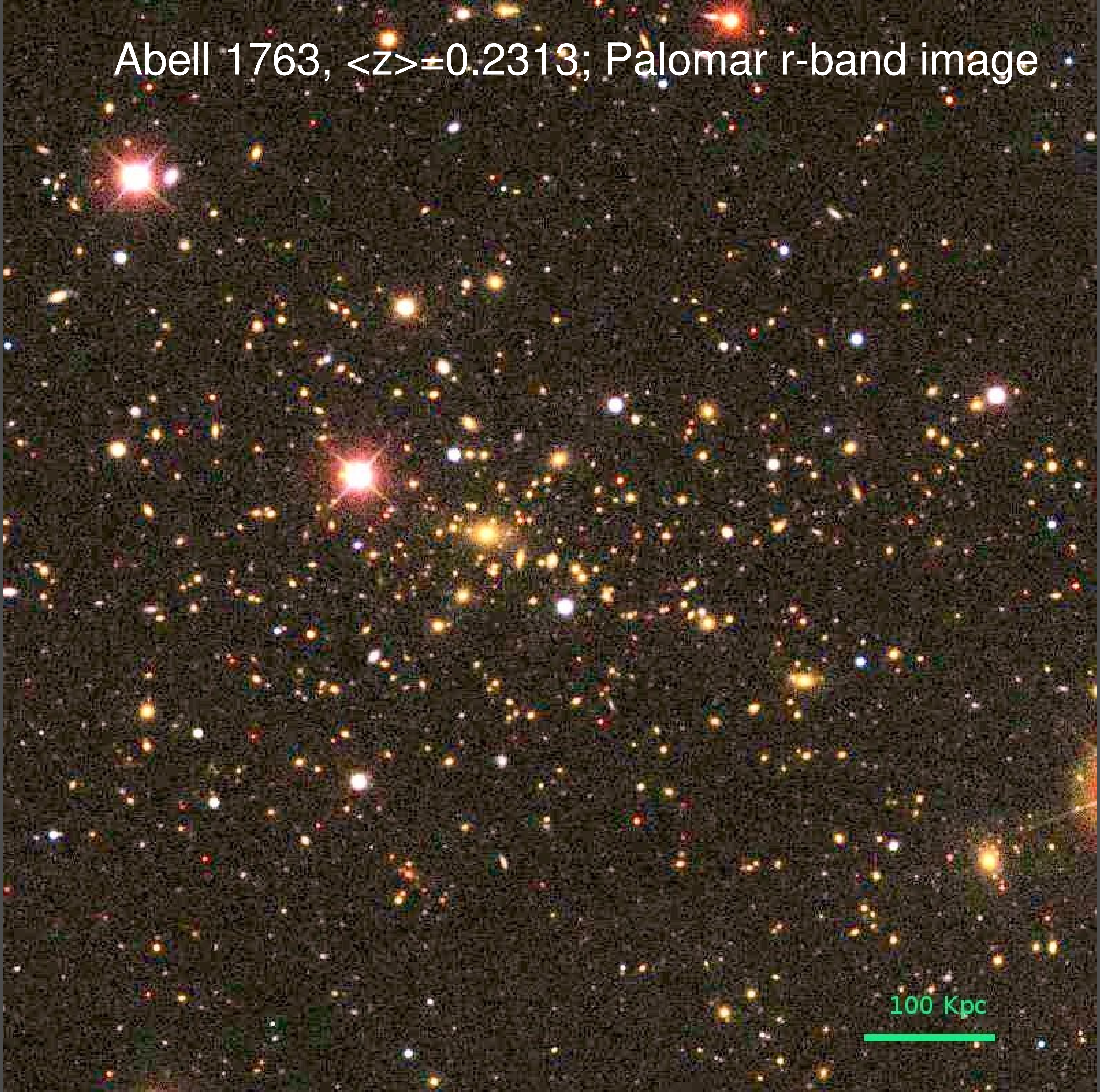
r', J, H, K_s photometry at Palomar 200inch (LFC + WIRC)

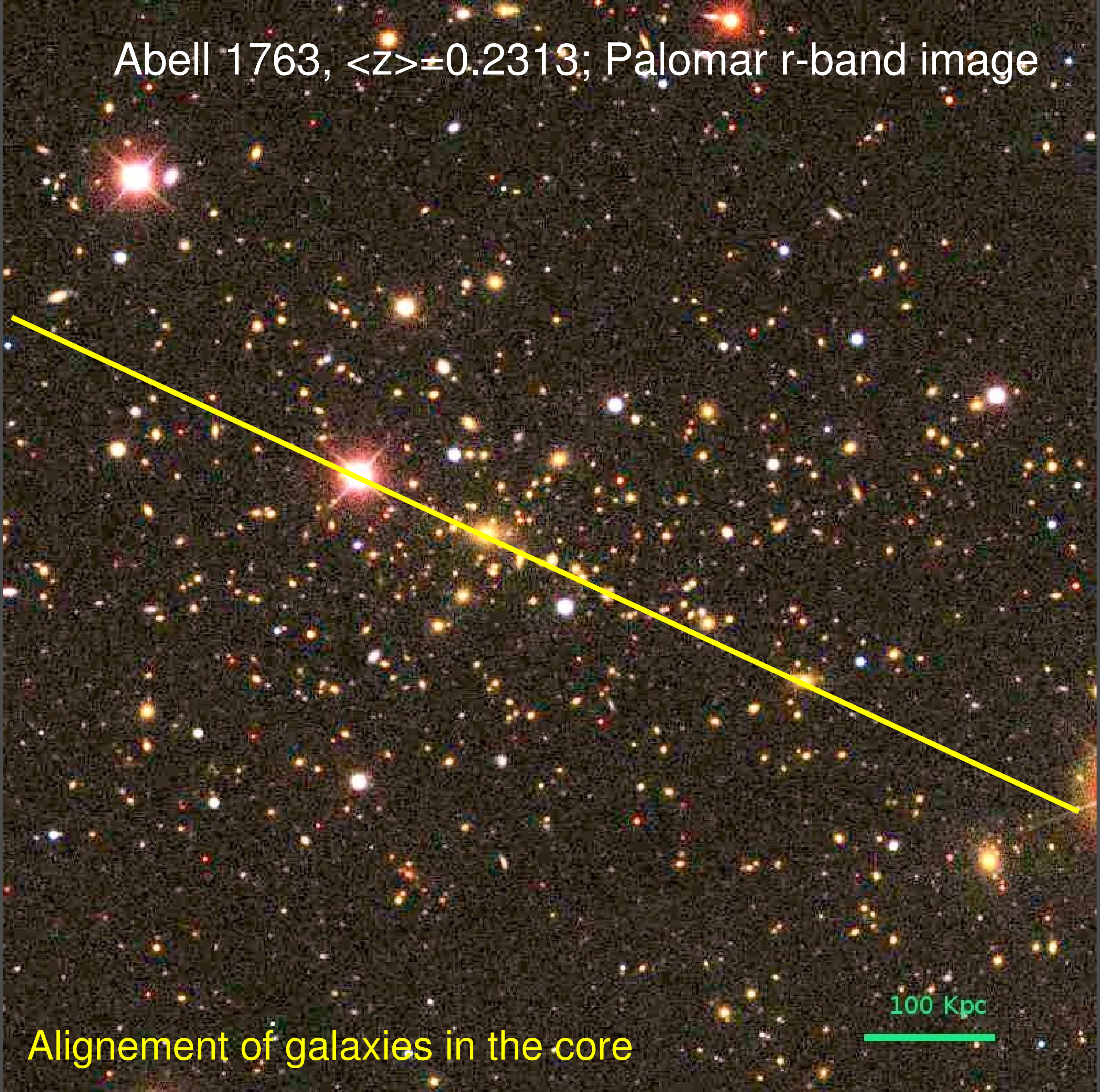
Follow-up observations of A1763:

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

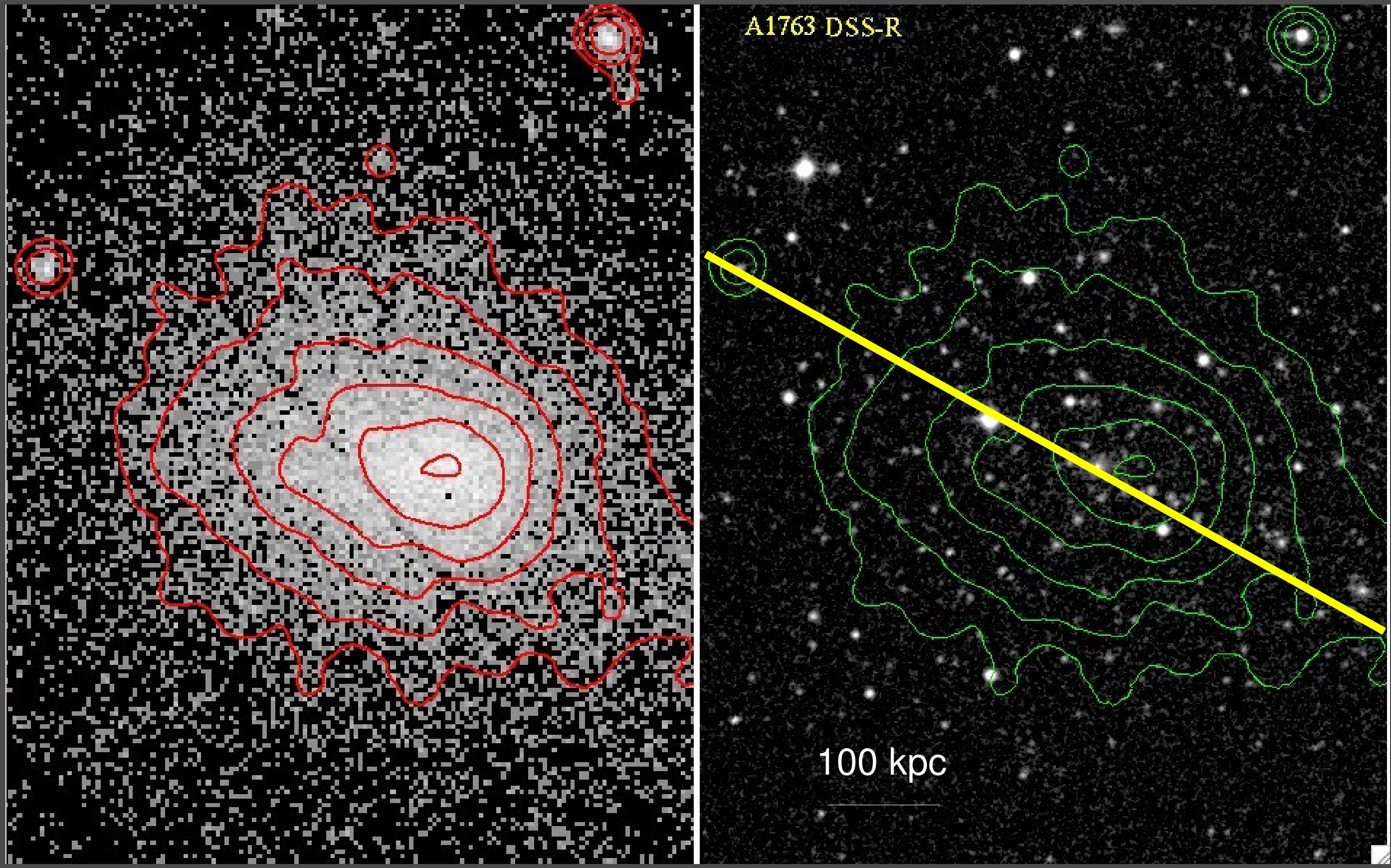
Abell 1763, <z>=0.2313; Palomar r-band image



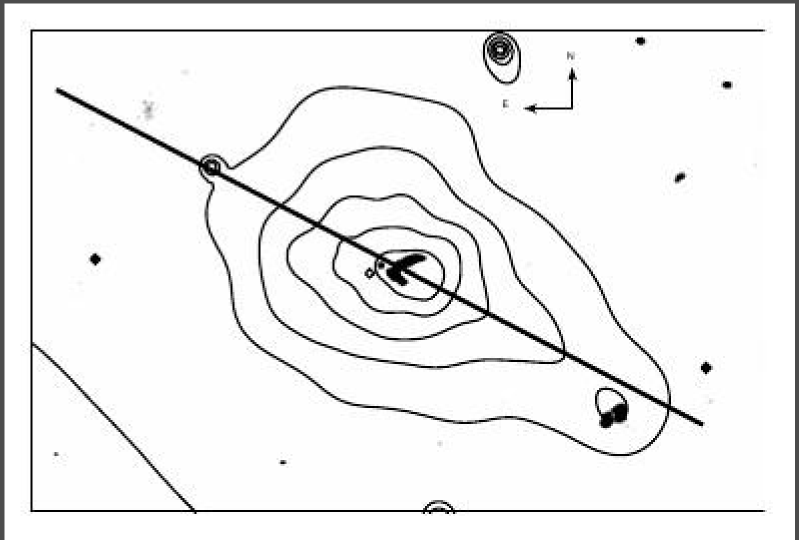

Abell 1763, <z>=0.2313; Palomar r-band image
100 Kpc
Alignement of galaxies in the core

A1763 X-ray surface brightness distribution

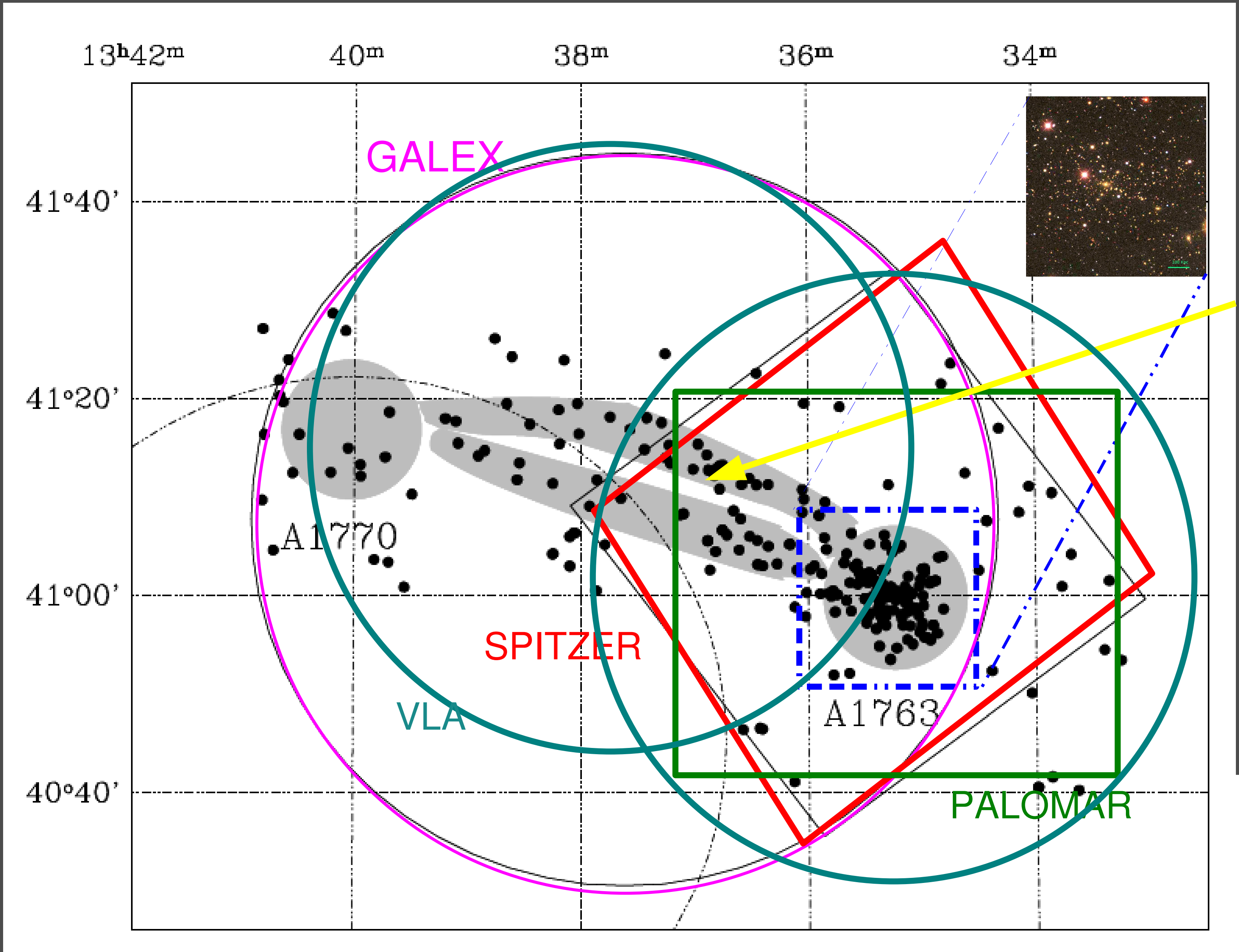
The X-ray surface brightness distribution is elongated like the galaxy distribution



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)

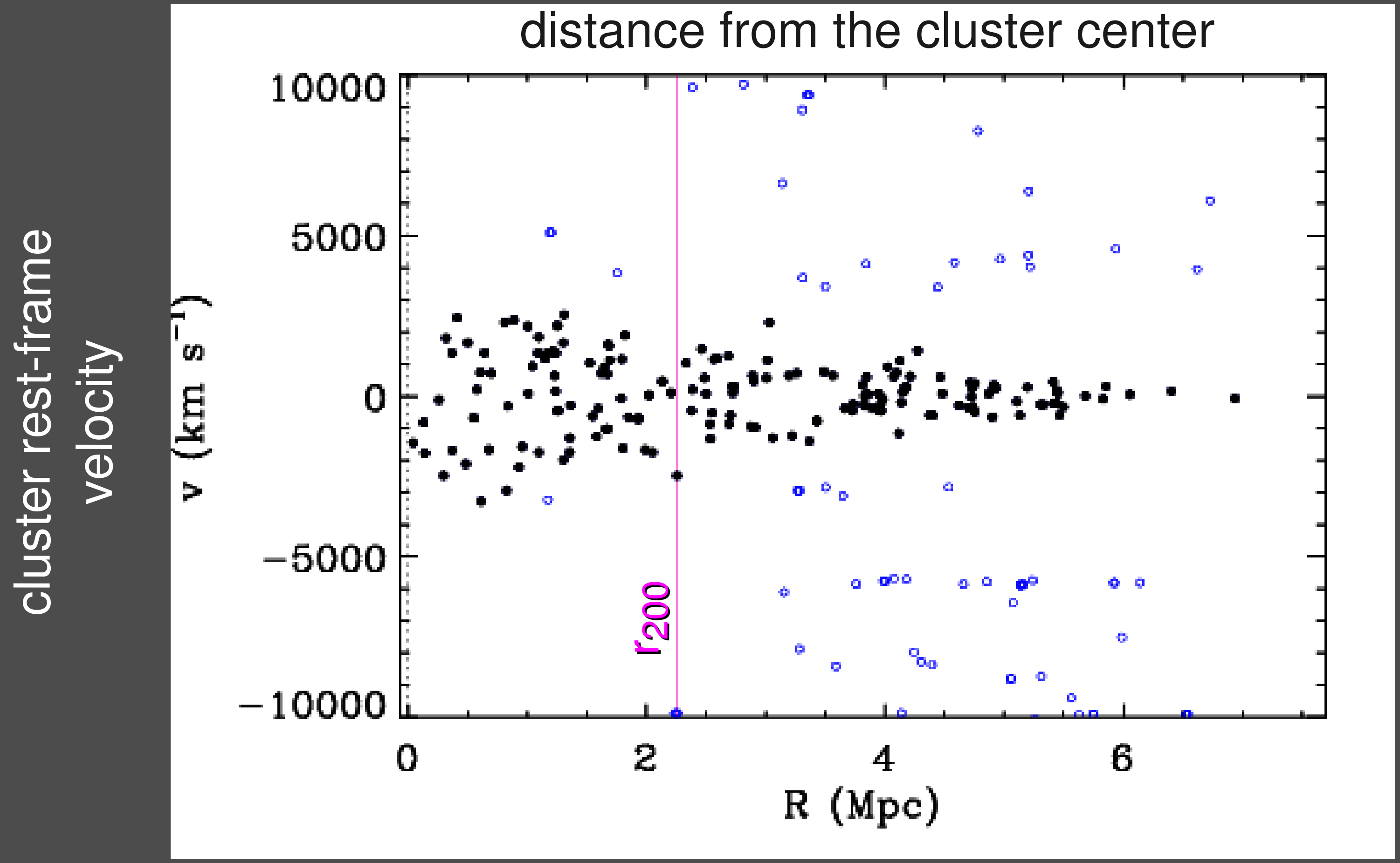
AIM: determine the galaxy IR luminosity function in different regions of the supercluster
⇒ galaxy star formation = f(environment)

...to achieve this aim:

Select sample of IR emitters members of the supercluster

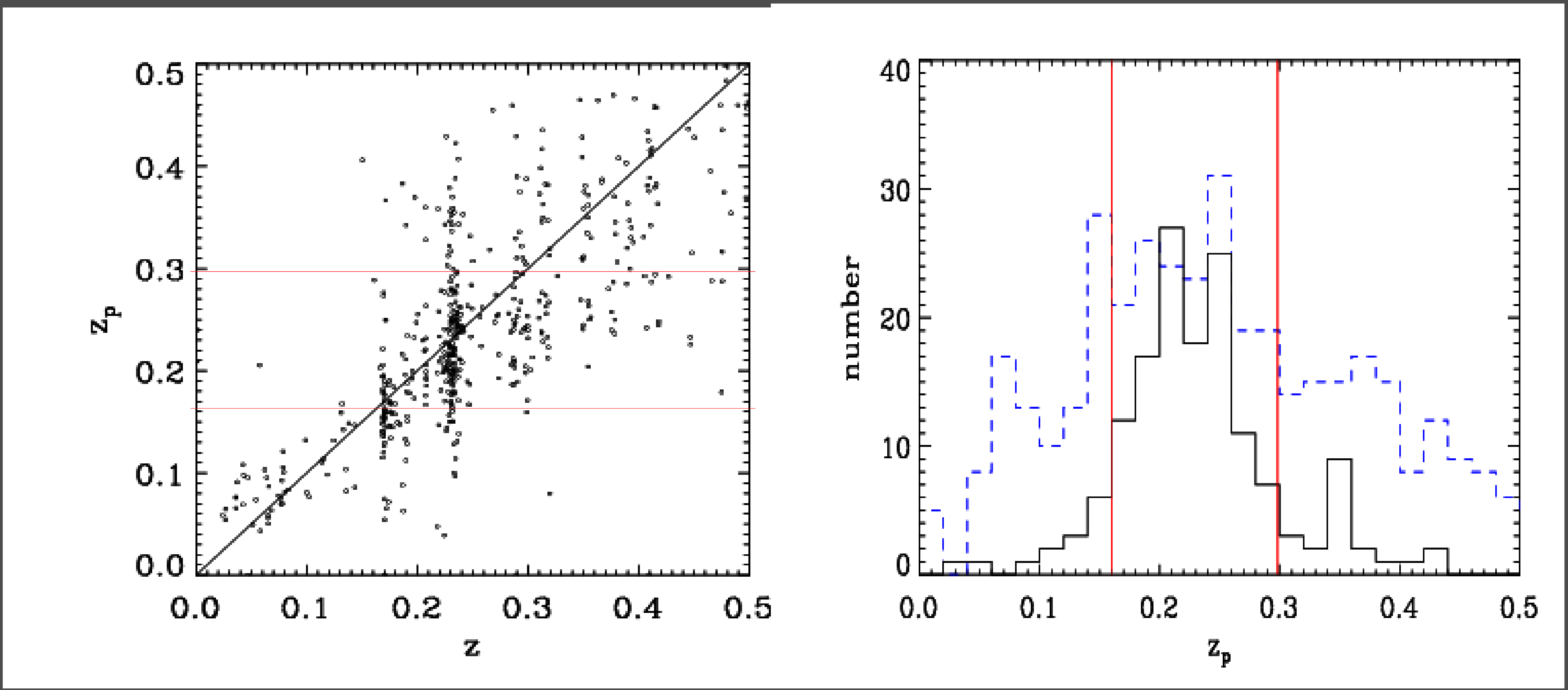
Base the selection on our 24 μm survey,
80% complete at 0.2 mJy
*[deeper than 70 and 160 μm,
emission at 24 μm closely related to recent star formation]*

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:

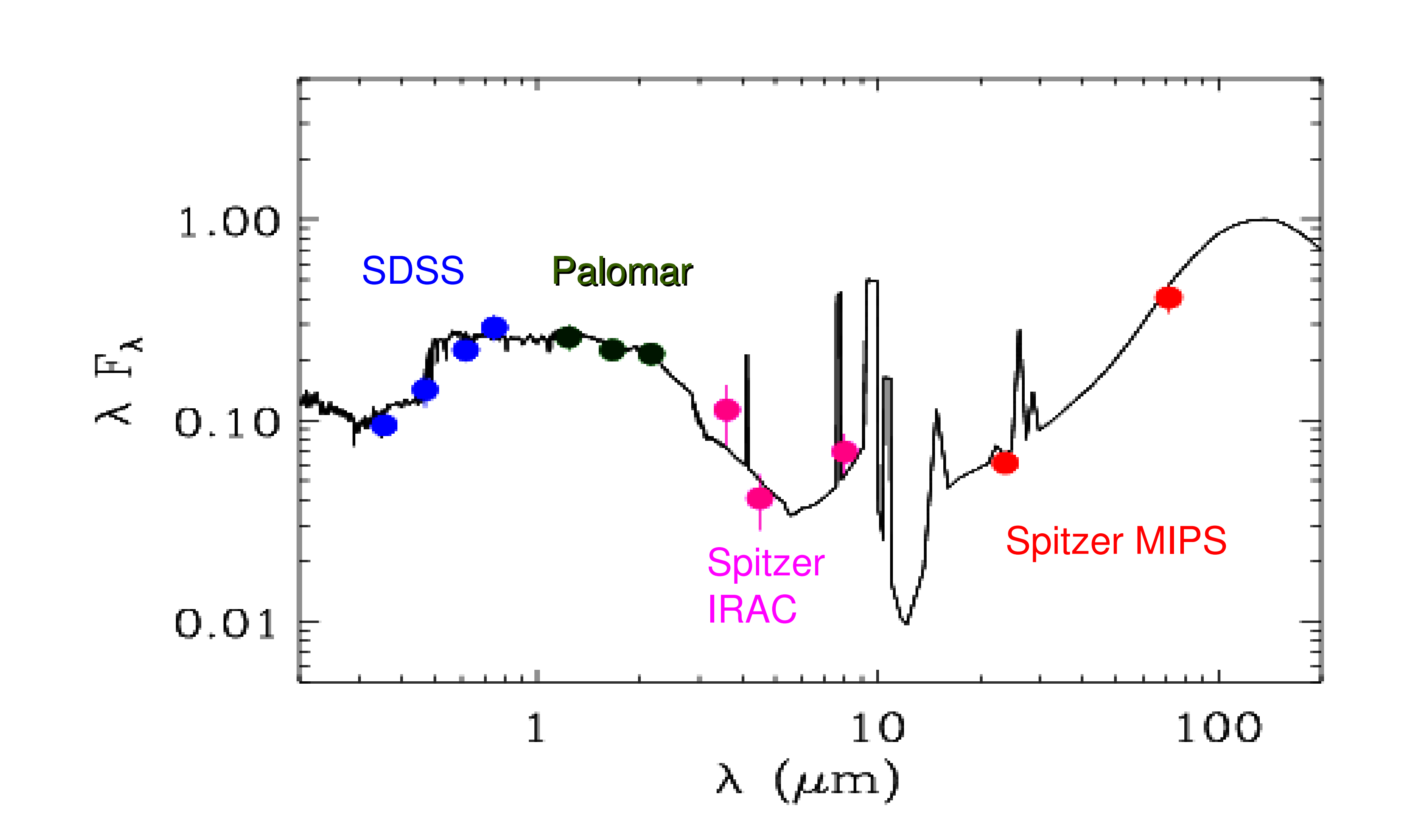
for L_{IR}:

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

for $M_\star$:

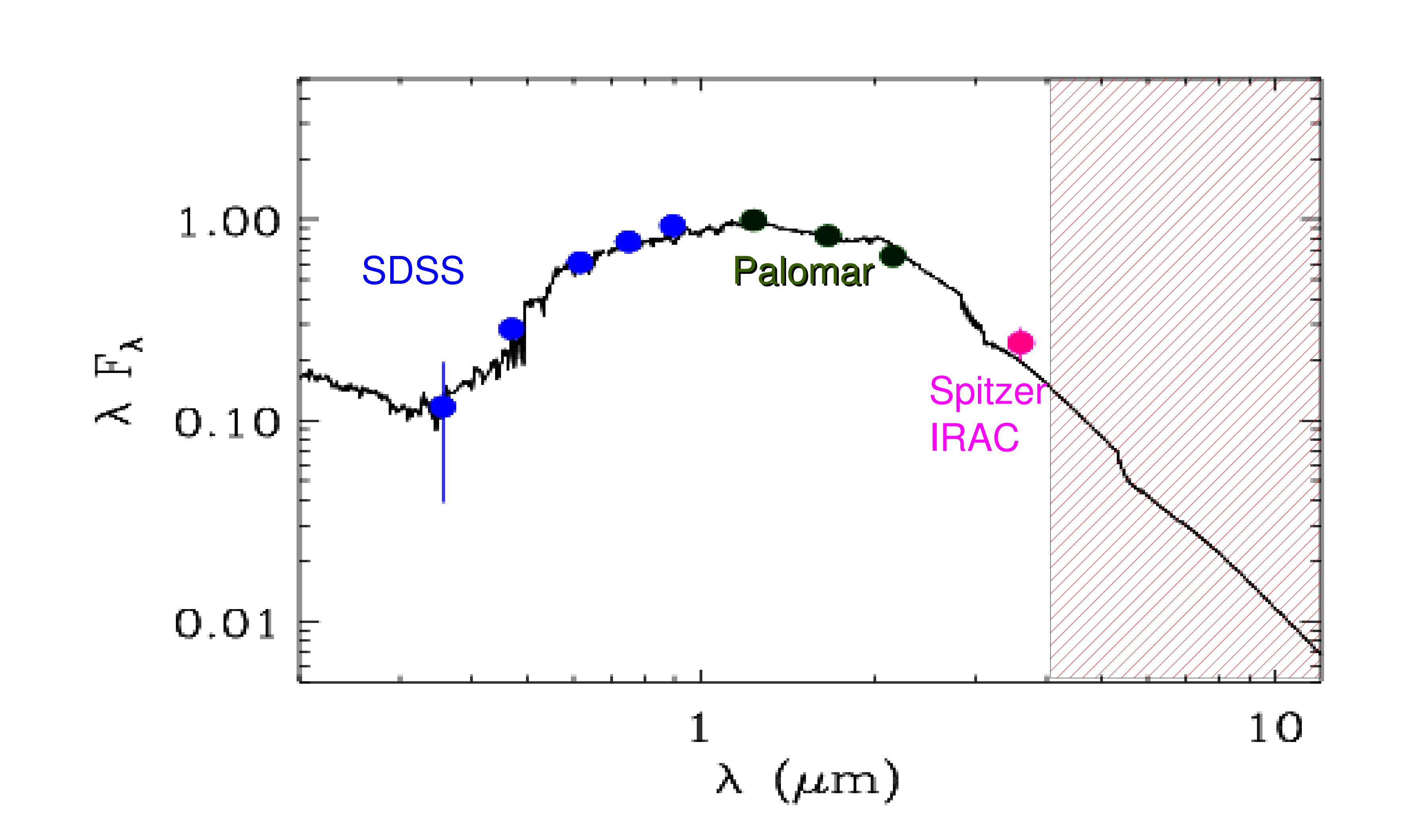
Use models of Maraston 05,
correct for absorption (Calzetti+00) with E(B-V) free to vary,
and restrict the fit to λ<4 μm

Example of full SED template fit:

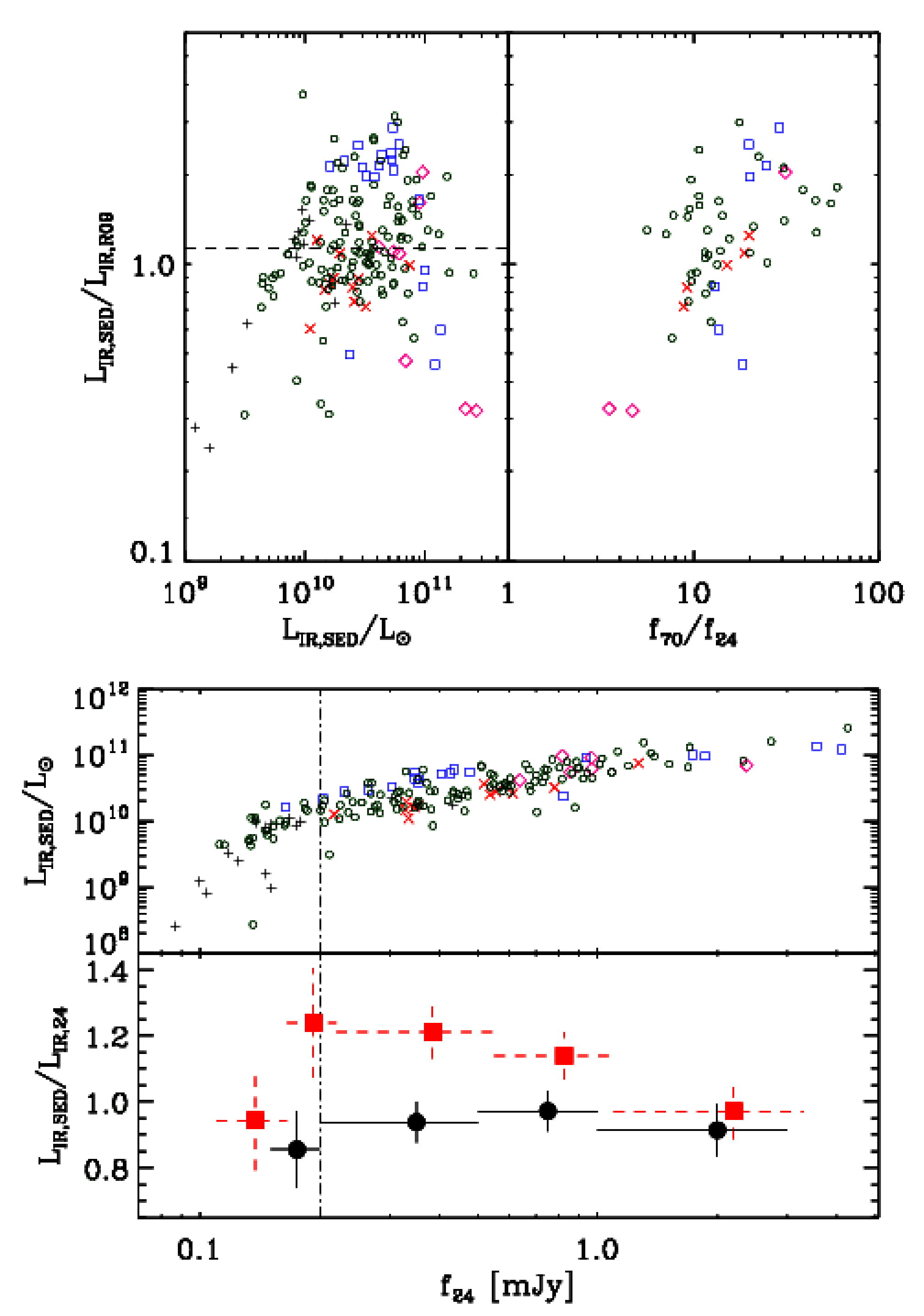


61 templates (GRASIL & Polletta's models) in 5 broad classes:
ETG, SFG, SBG, PSBG, AGN

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



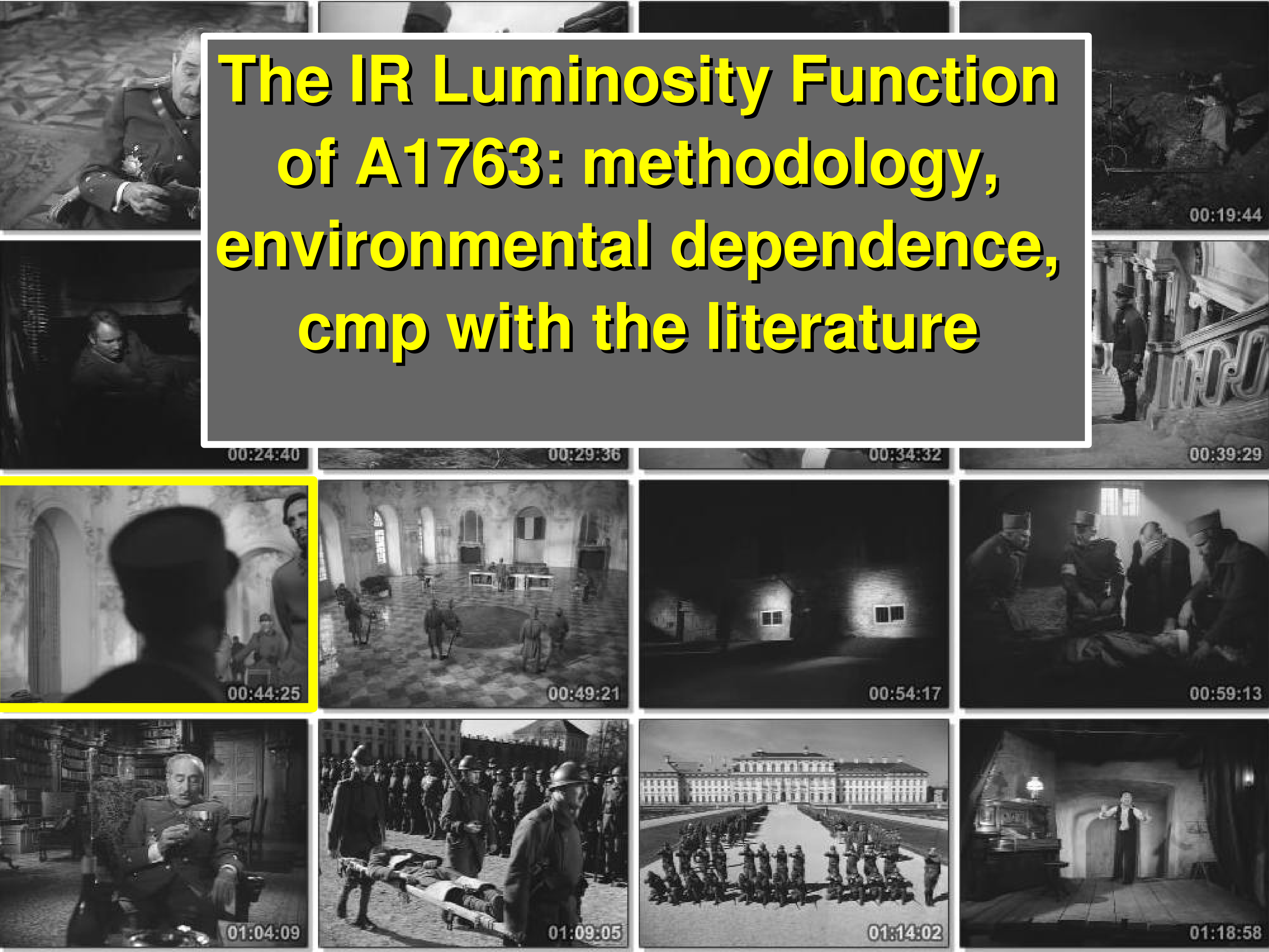
8 —1000 μm SED integral

→ 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)

The IR Luminosity Function of A1763: methodology, environmental dependence, cmp with the literature



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 = $P(f_{24})$

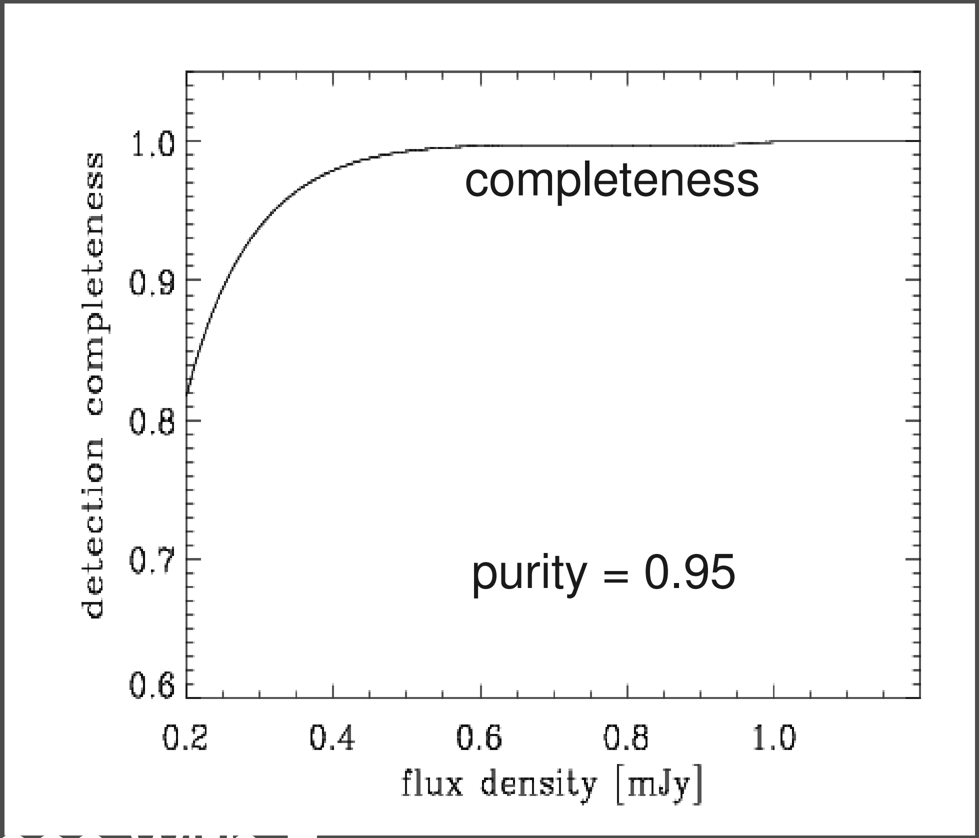
for the spectroscopic sample

& the full (spectroscopic+photometric) sample.

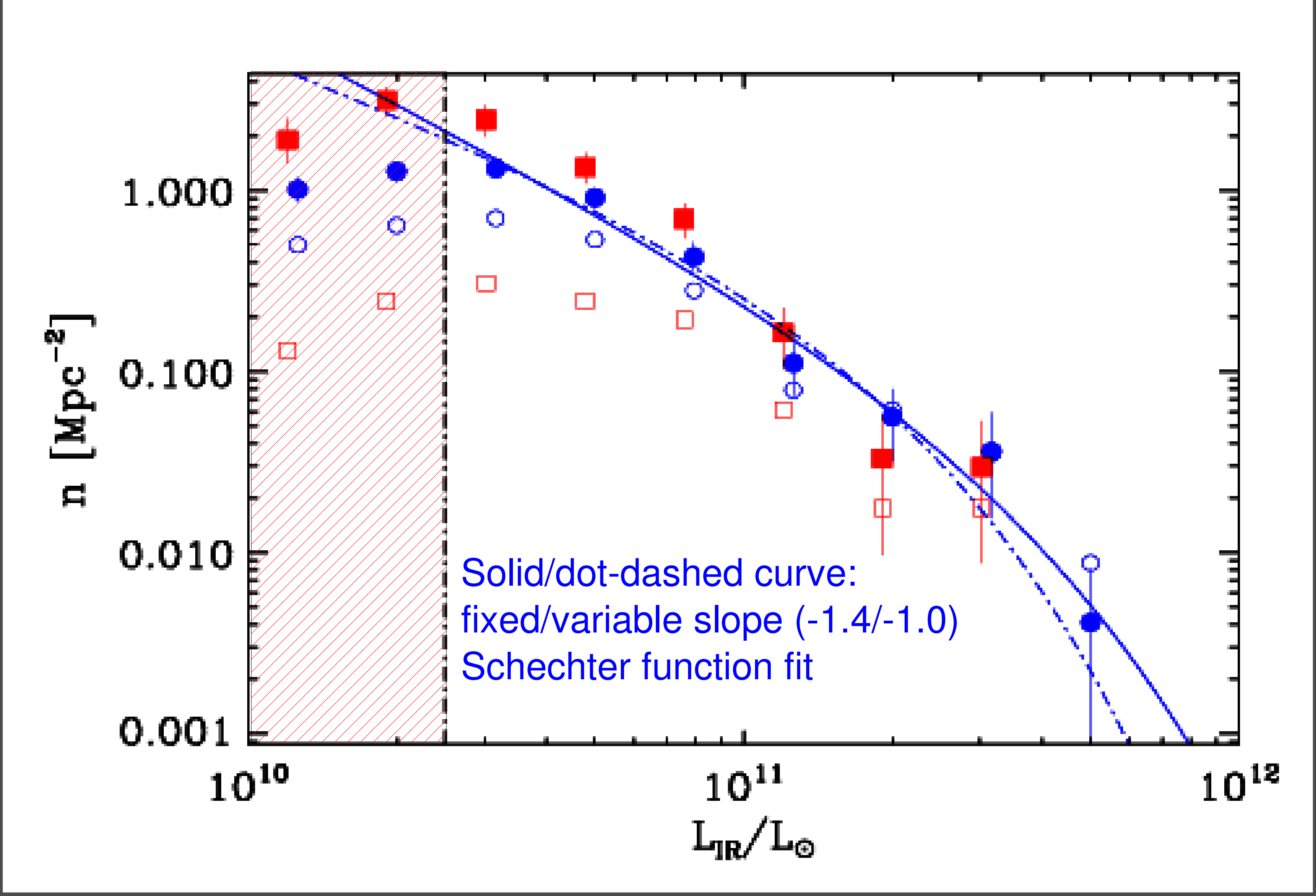
Then we correct the 24 μm galaxy counts to get the pure & complete ($P \rightarrow 1$, $C \rightarrow 1$) IR LF

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)



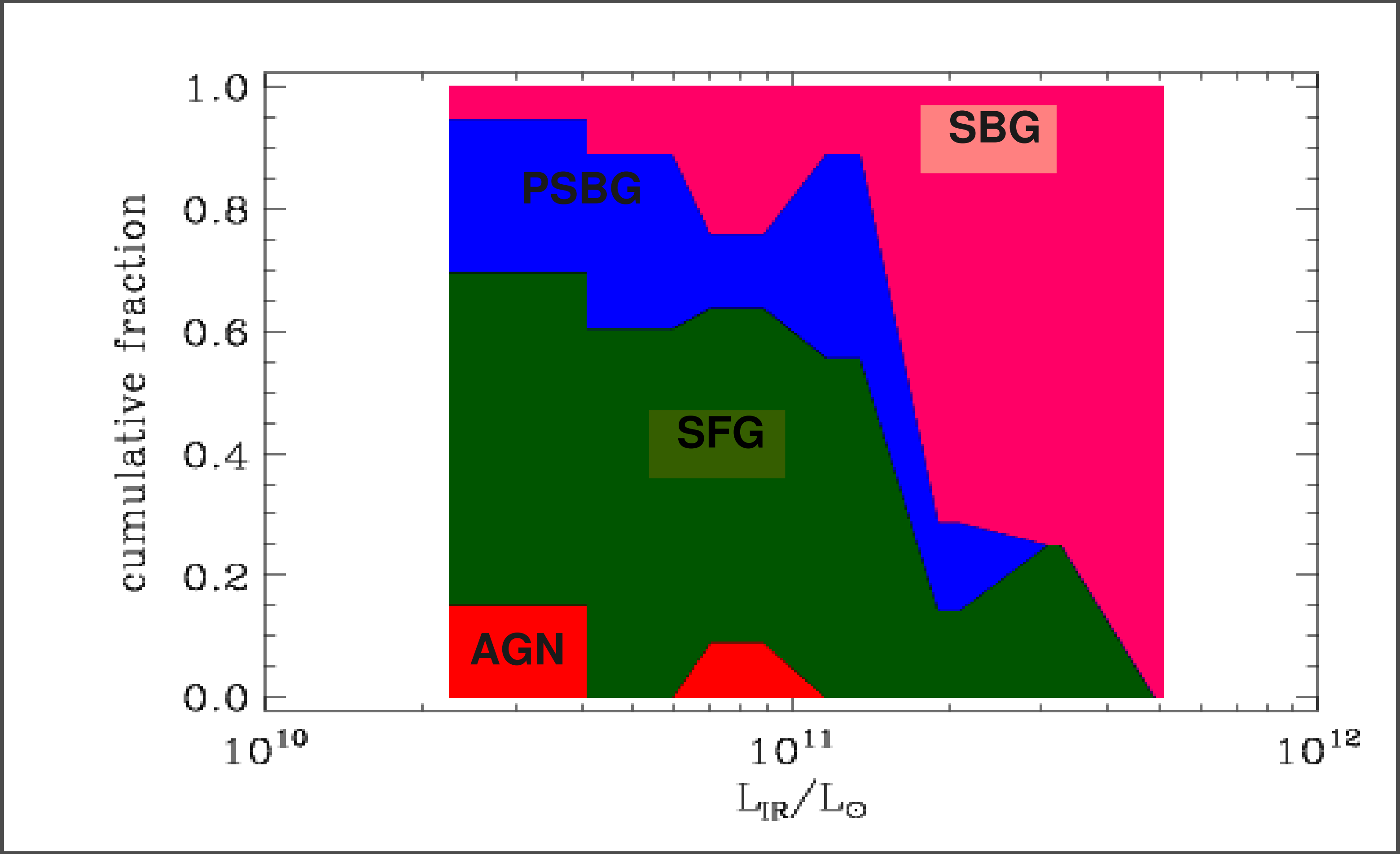
The IR LF of the A1763 supercluster



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:

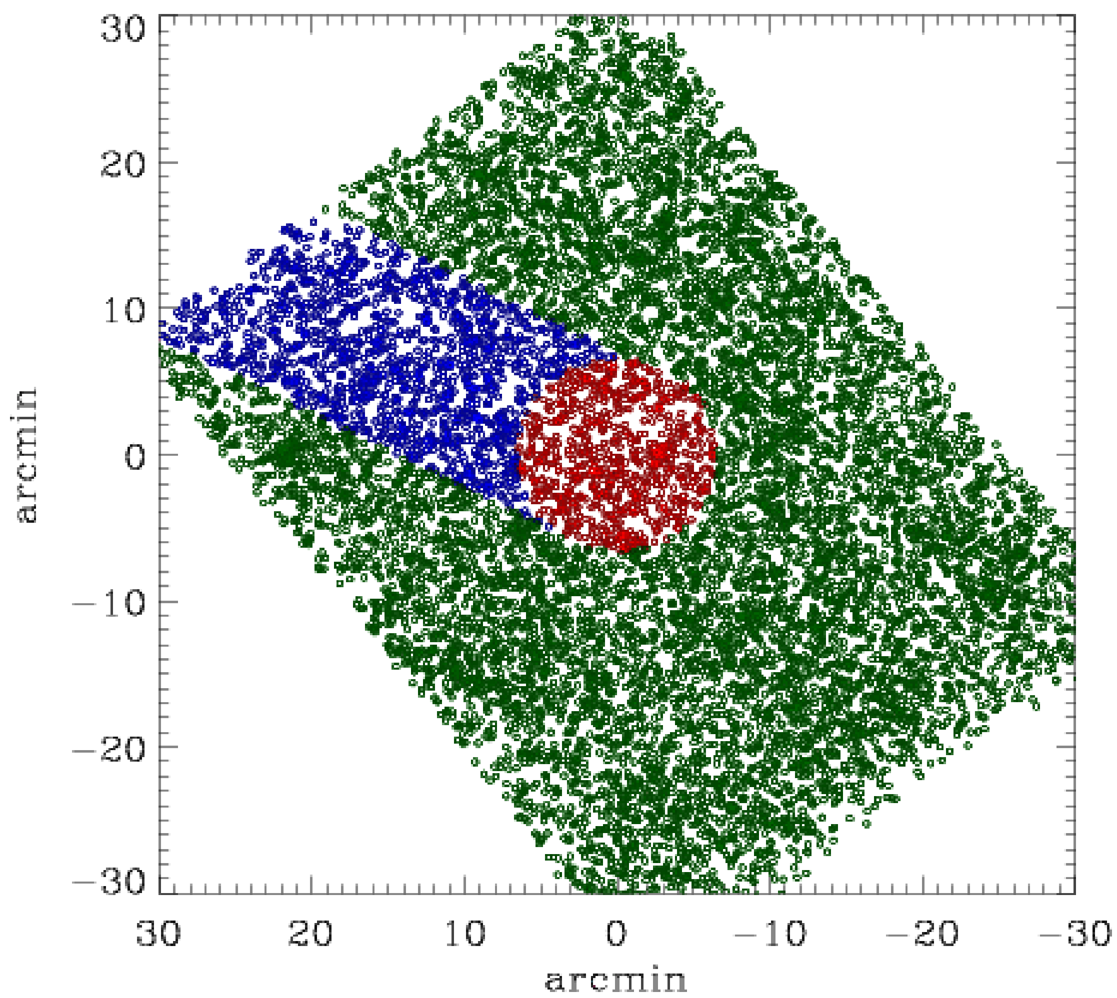
core (<r_{500})

filaments

outskirts

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

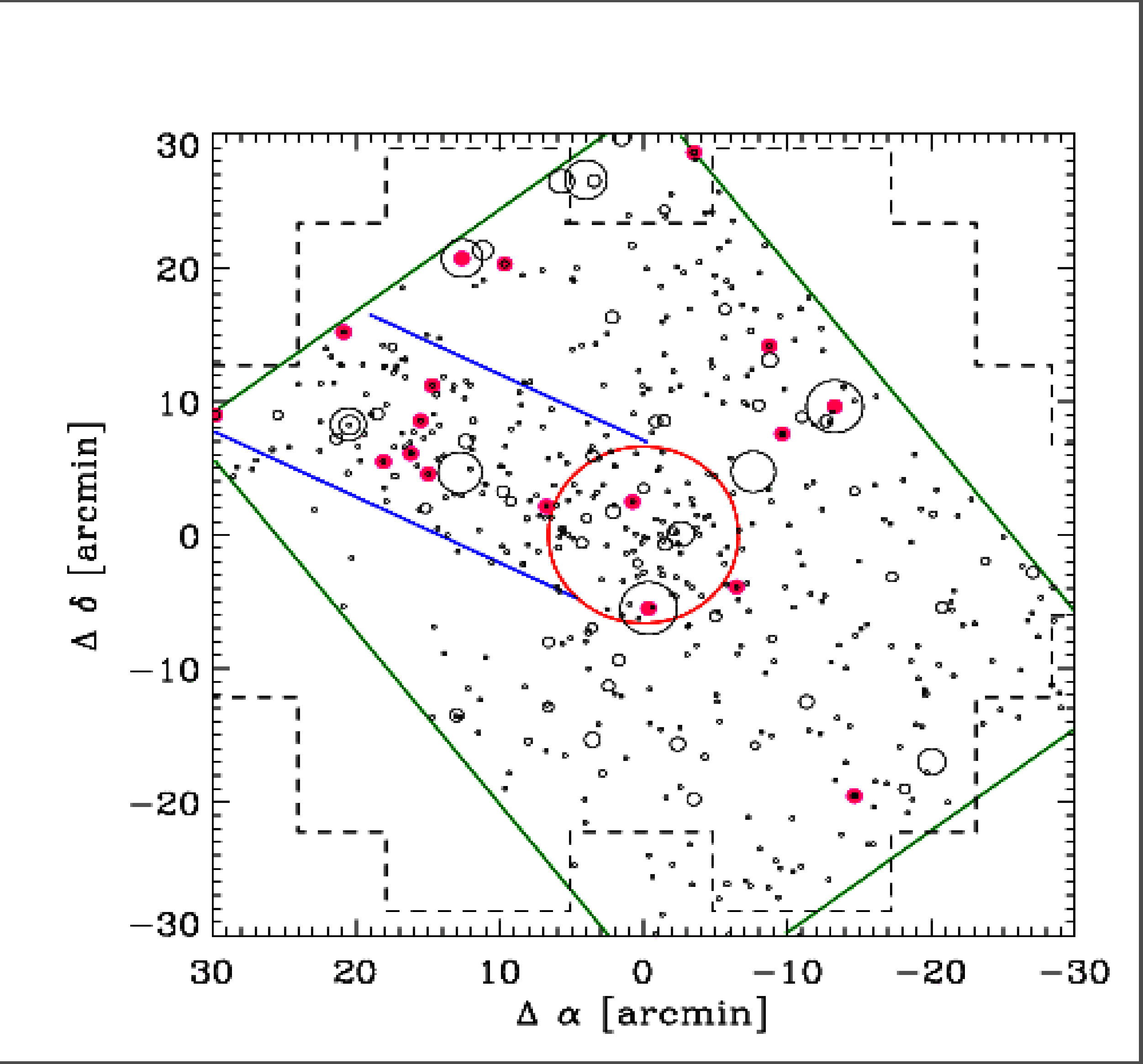
1 arcmin ↔ 222 kpc



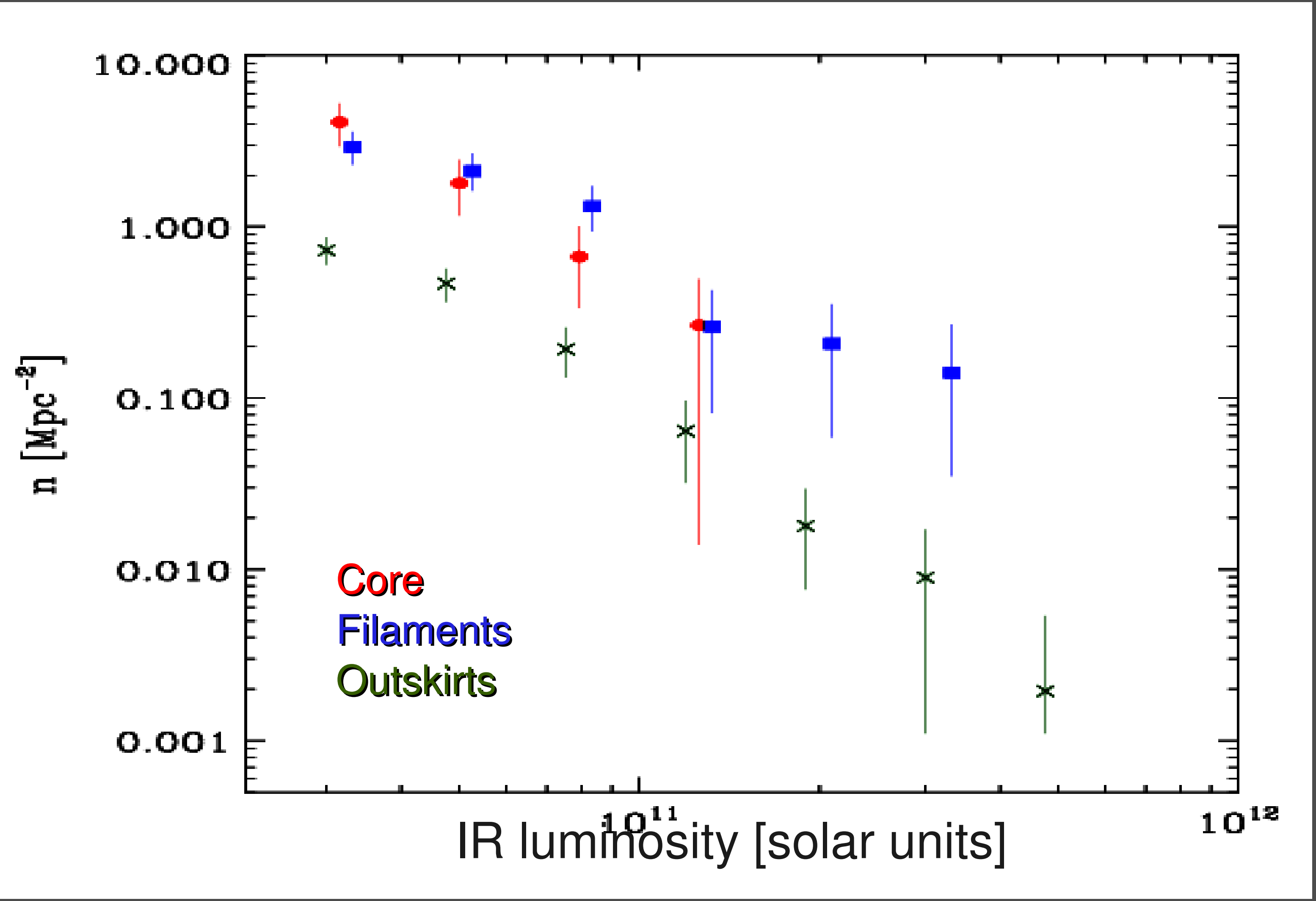
What is the effect of the environment?

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)

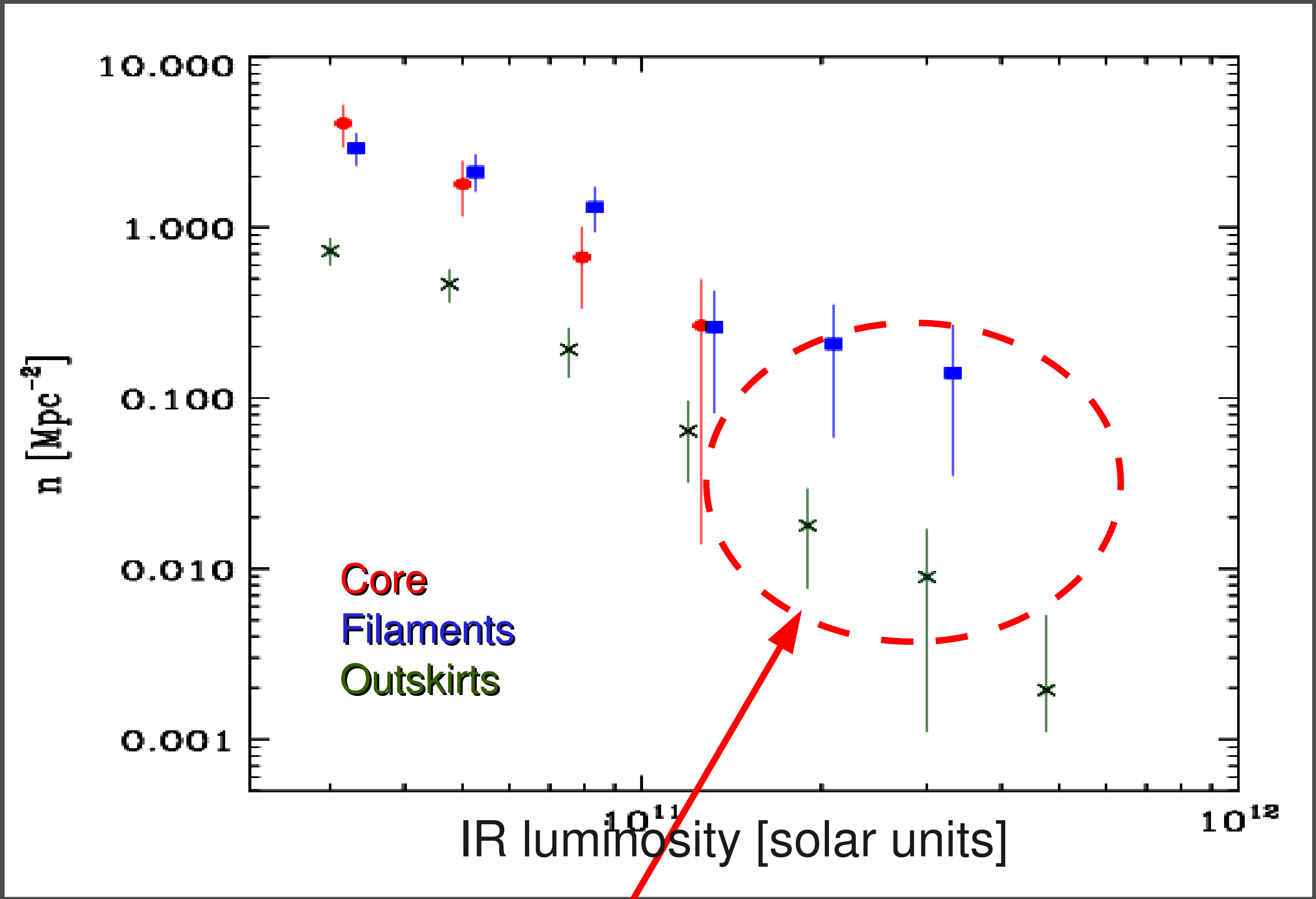


The IR LFs in 3 different supercluster environments



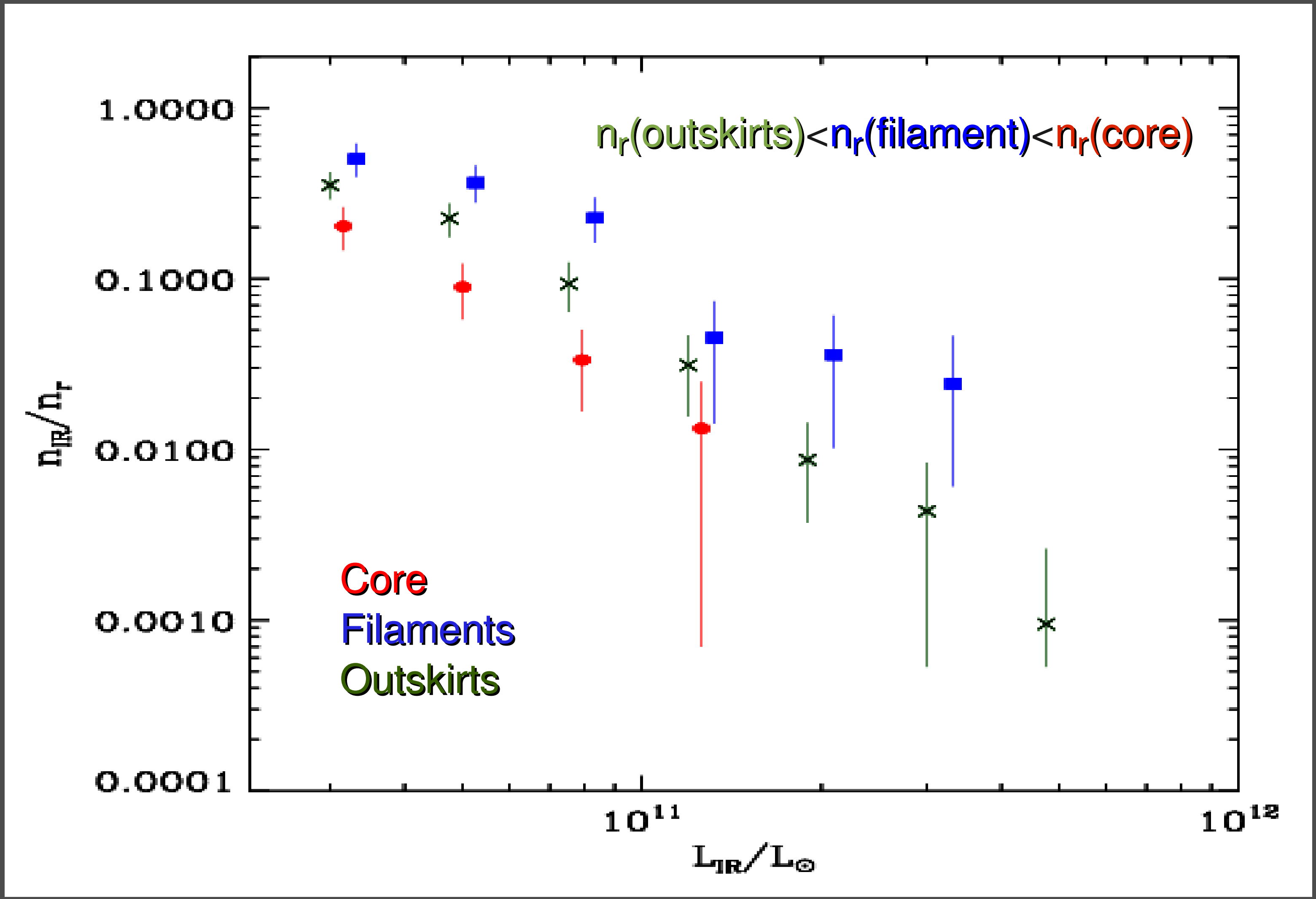
Each LF is corrected for *in*Completeness and *in*Purity

The IR LFs in 3 different supercluster environments



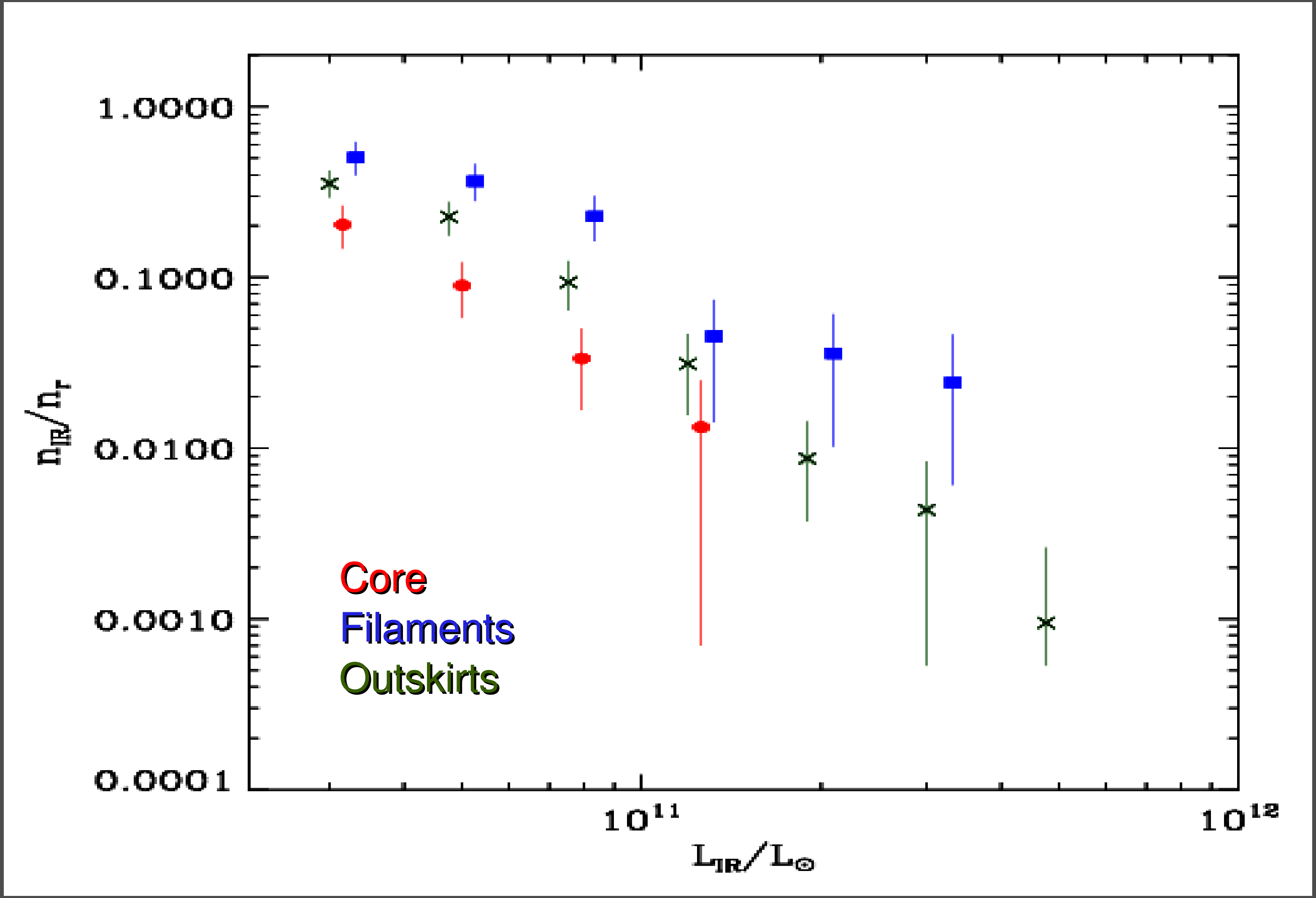
There are (almost) no LIRGs in the core

The IR LFs in 3 different supercluster environments



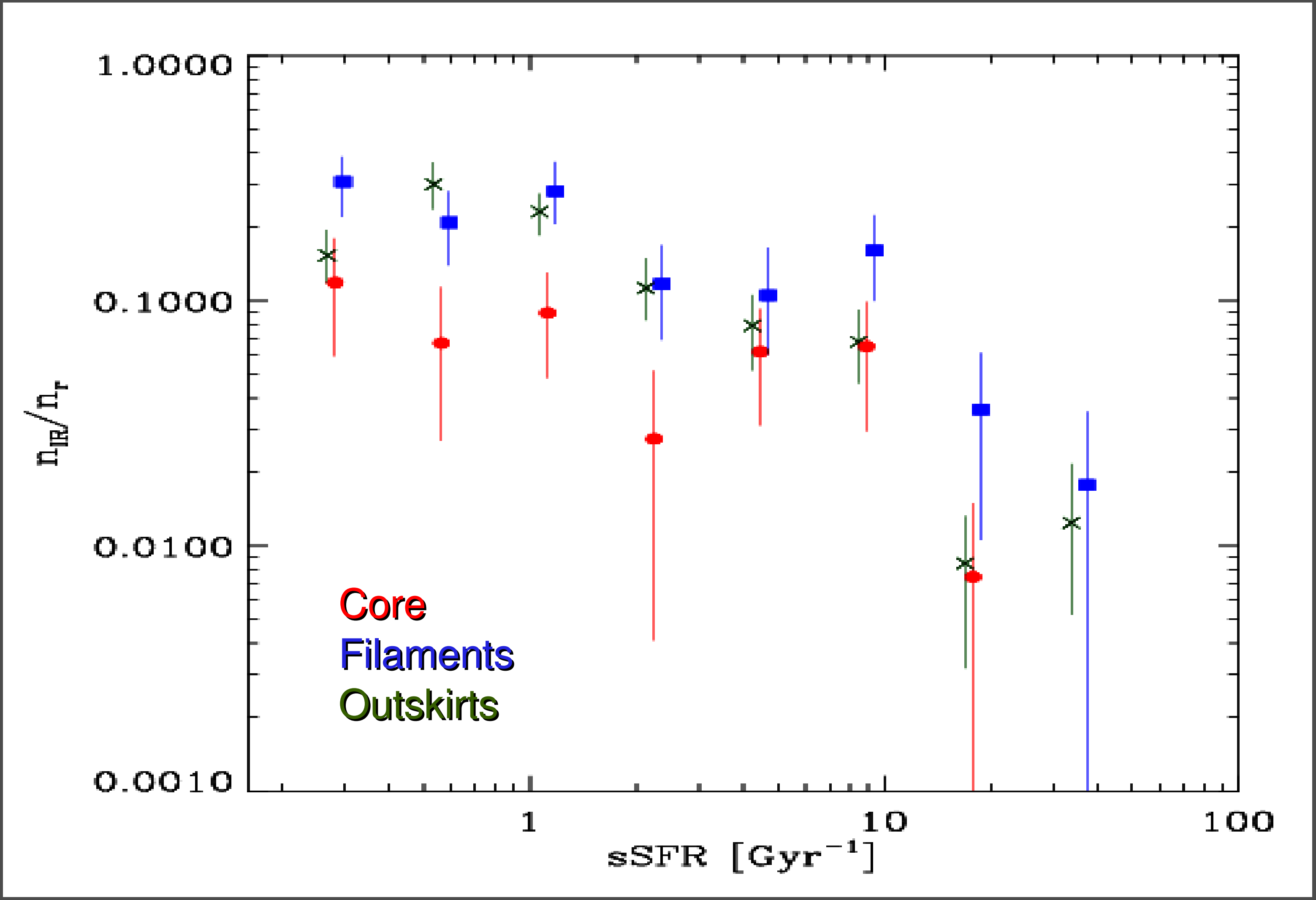
The densities of IR-emitting galaxies, n_{IR}, are normalized by the densities, n_r, of normal, r-selected galaxies in the same regions

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)

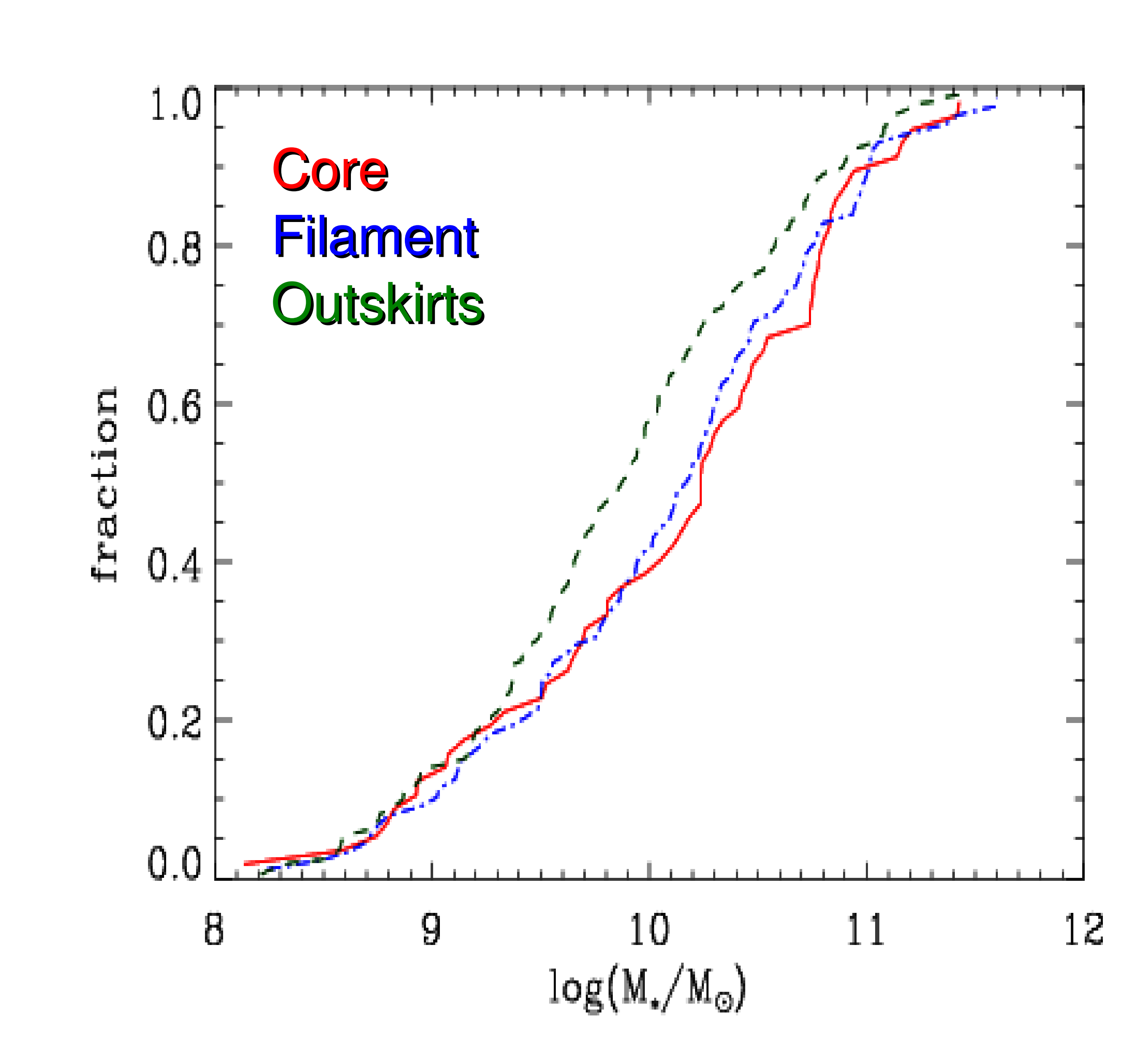
The specific-SFR distribution functions in the 3 environments



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

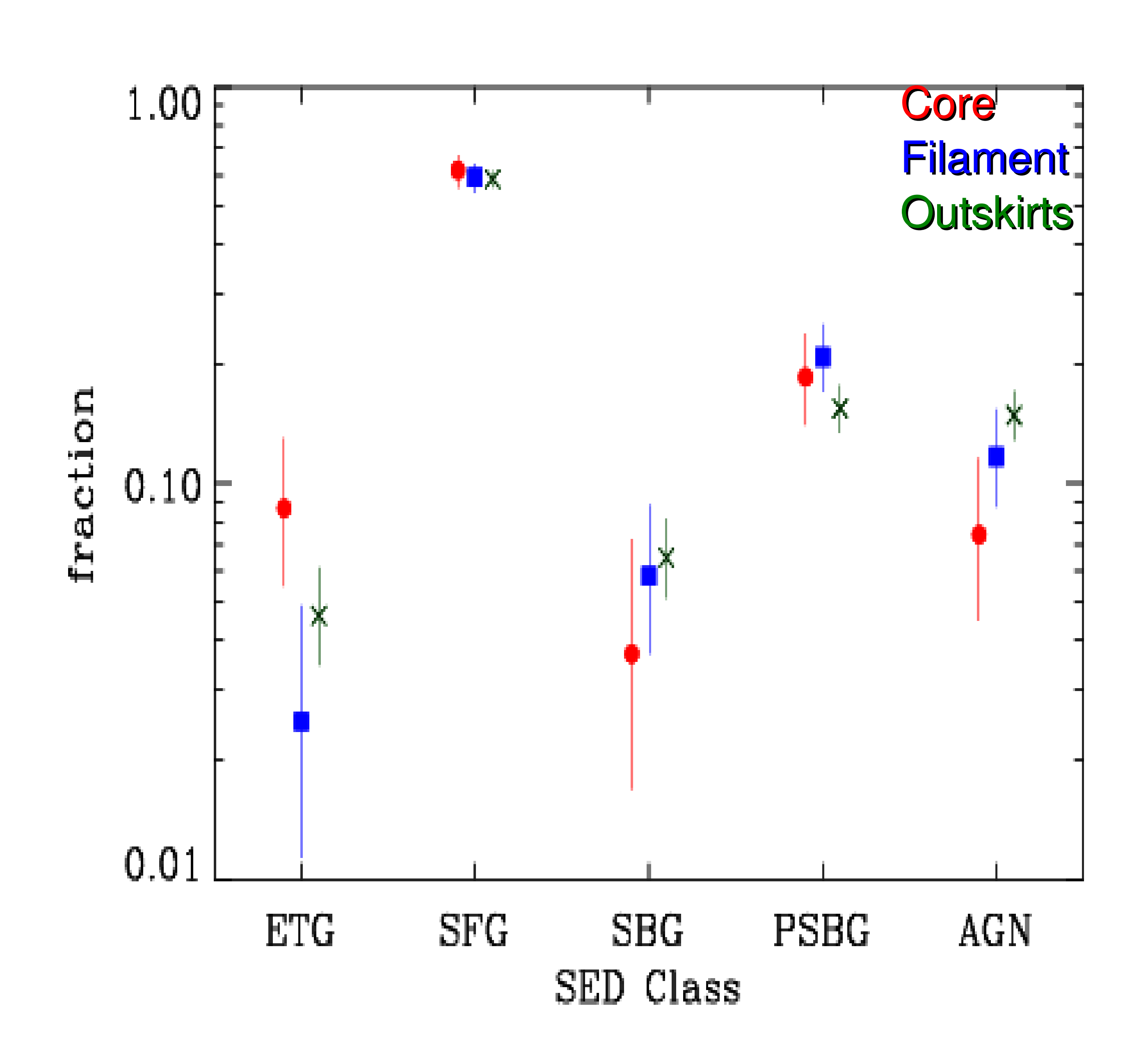
➞ the excess IR-emitters in **filaments** are **massive**

$M_\star$-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

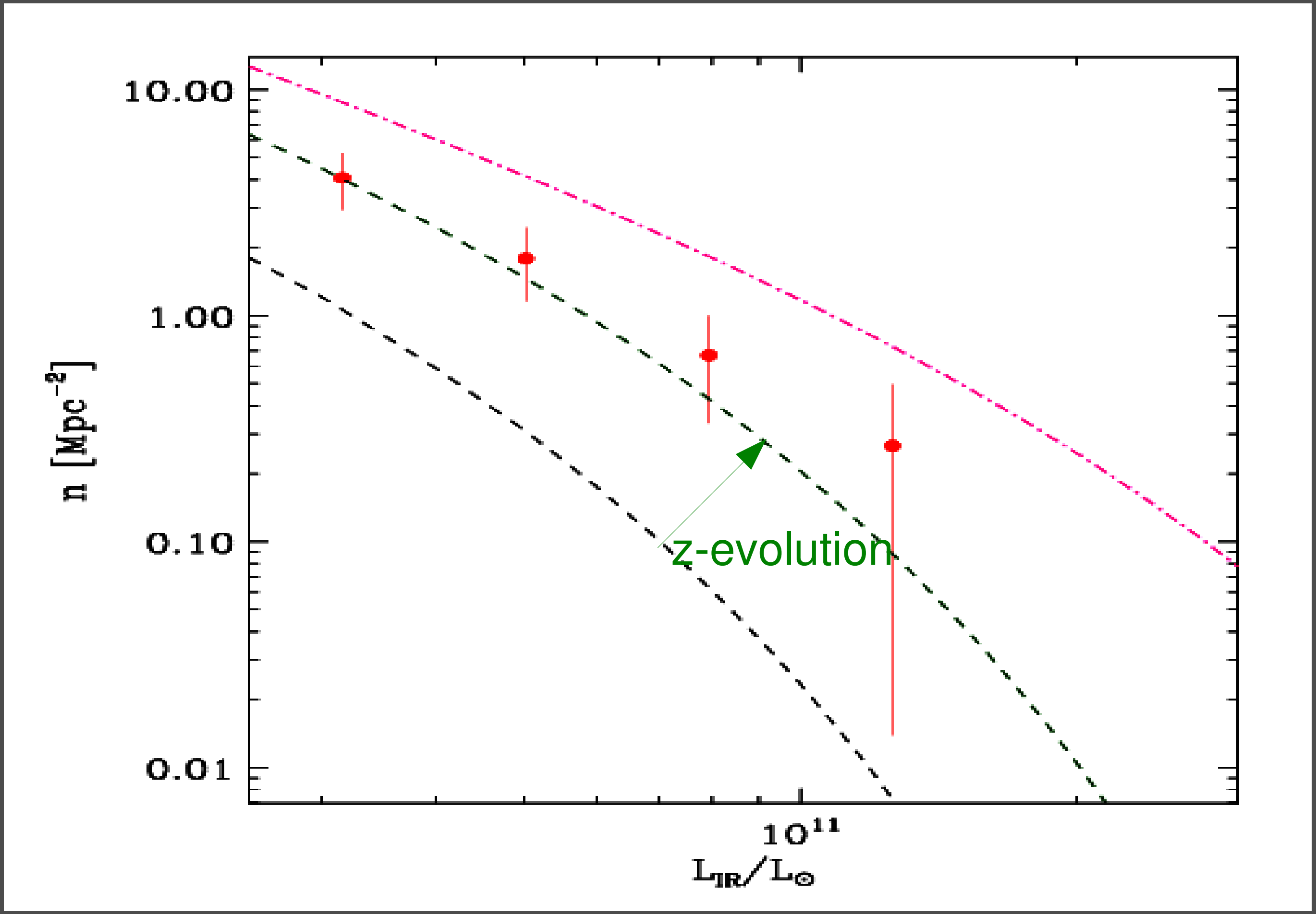
Previous cluster IR LF determinations limited to core regions

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

Comparison with previous works

Previous cluster IR LF determinations limited to the core

Dots: A1763 core

Black line:
Coma IR LF
(Bai+06)

Green line:
Coma IR LF
evolved to <z>
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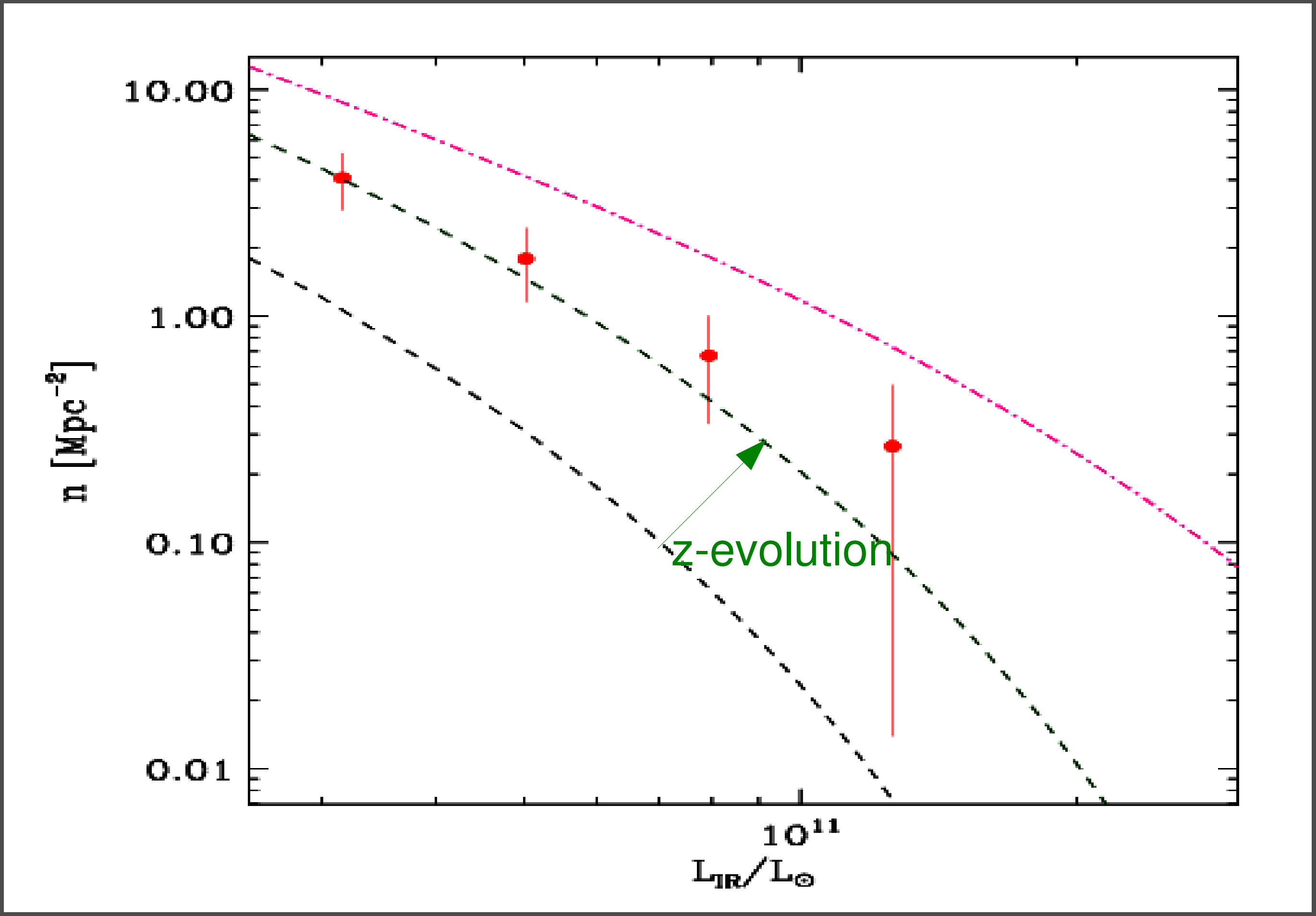
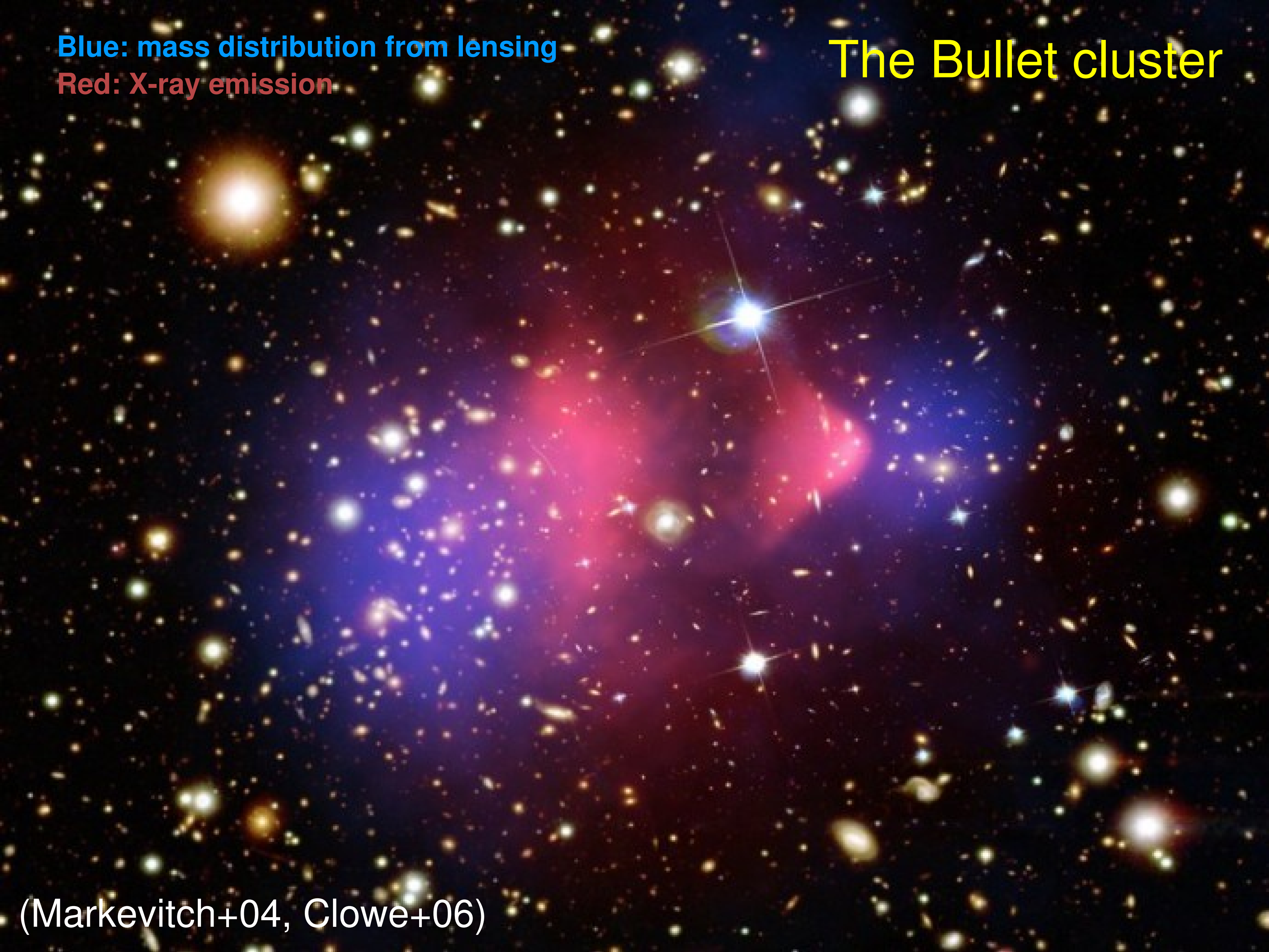


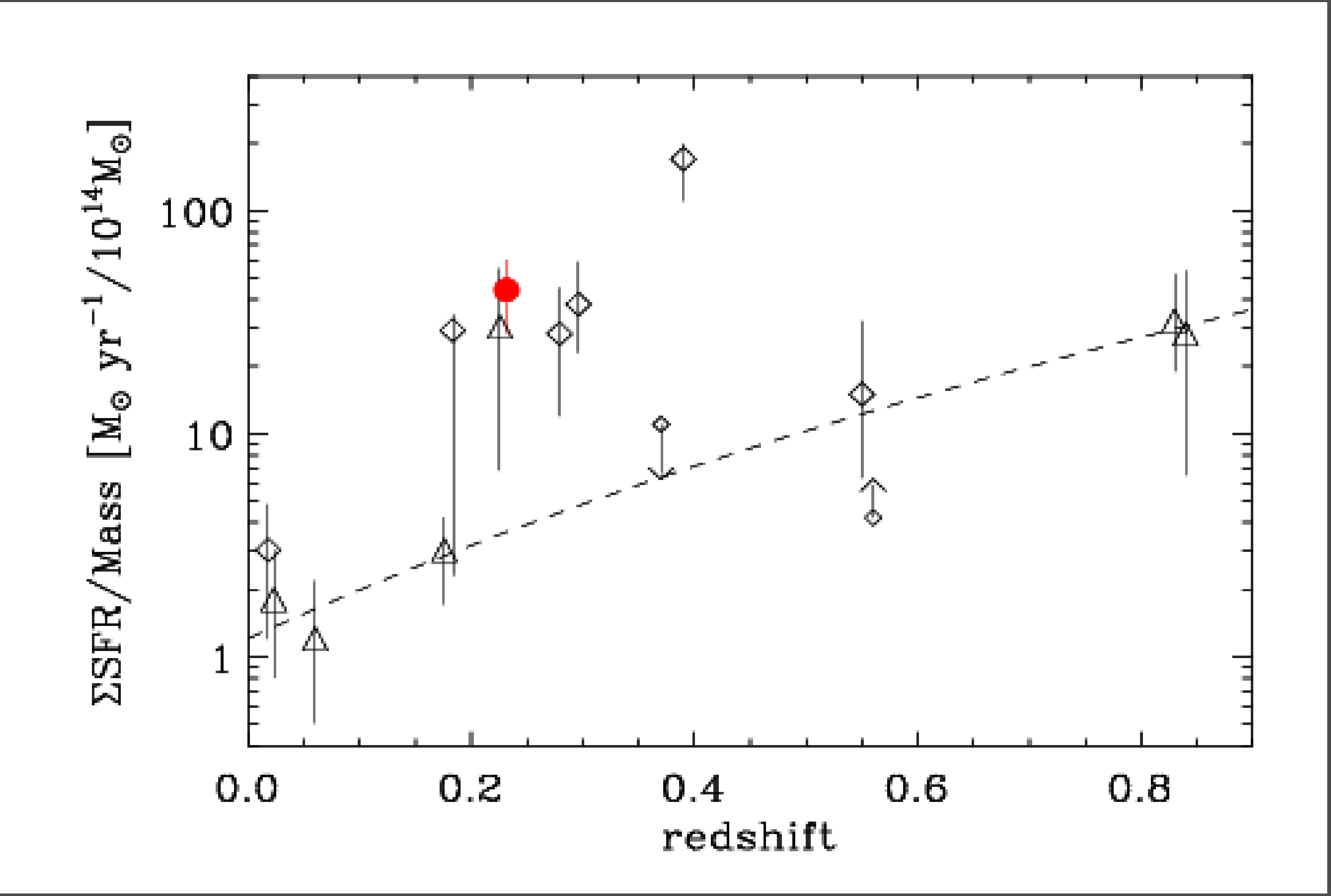
☛ Excess of LIRGs in the Bullet related to the infalling group?


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

Comparison with previous works

A1763
core.

Mass
from
velocity
dispersion.

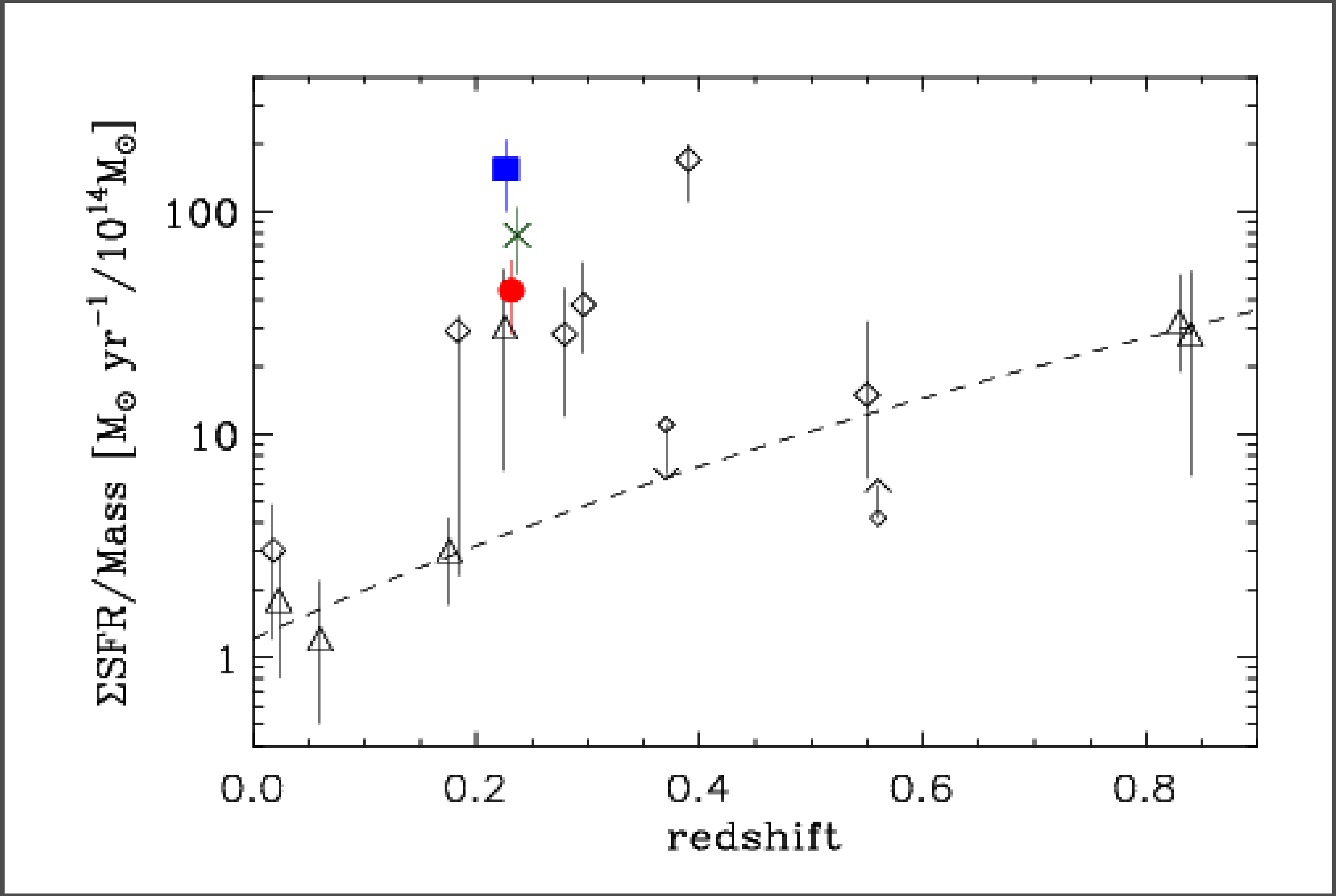


The galaxy ∑SFR / total mass in cluster cores increases with z *(but not as predicted by Bai+09)*

Comparison with previous works

A1763
filament,
outskirts,
core.

Masses from richness scaling wrt mass of the core



ΣSFR/Mass depends on z but also on the environment
but not simply on the local galaxy density!

Summary, discussion, perspectives

Summary of our findings:

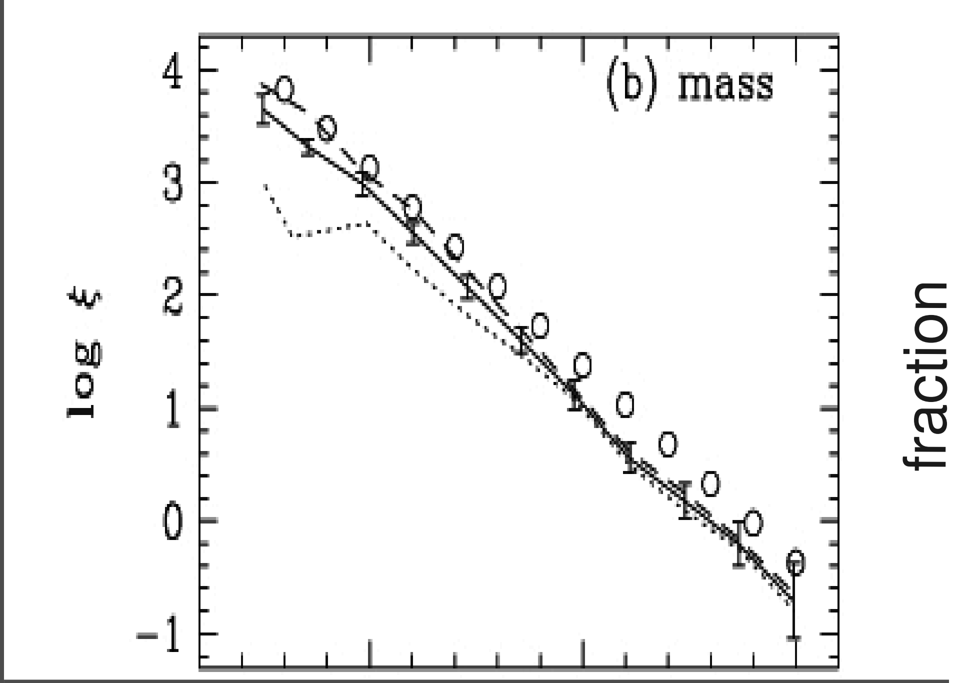
- IR galaxies (SFR$\geq$4 $M_\odot$/yr): highest fraction in the filament, i.e. in the intermediate density region of the supercluster
- Filament IR-galaxies are massive ($M_\star$~10^{10} $M_\odot$), ~ core IR galaxies, > outskirts IR galaxies
- Filament and outskirts IR galaxies have $\approx$ sSFR, > core IR galaxies
- Normal SFG are the dominant SED class of IR galaxies (few AGN)
- Different regions have $\approx$ fractions of SED classes
- Cluster total SFR per unit total mass ↑ with redshift, mostly from z$\approx$0 to z$\approx$0.4, less at z>0.4, in the filament > in the outskirts > in the core

Interpretation

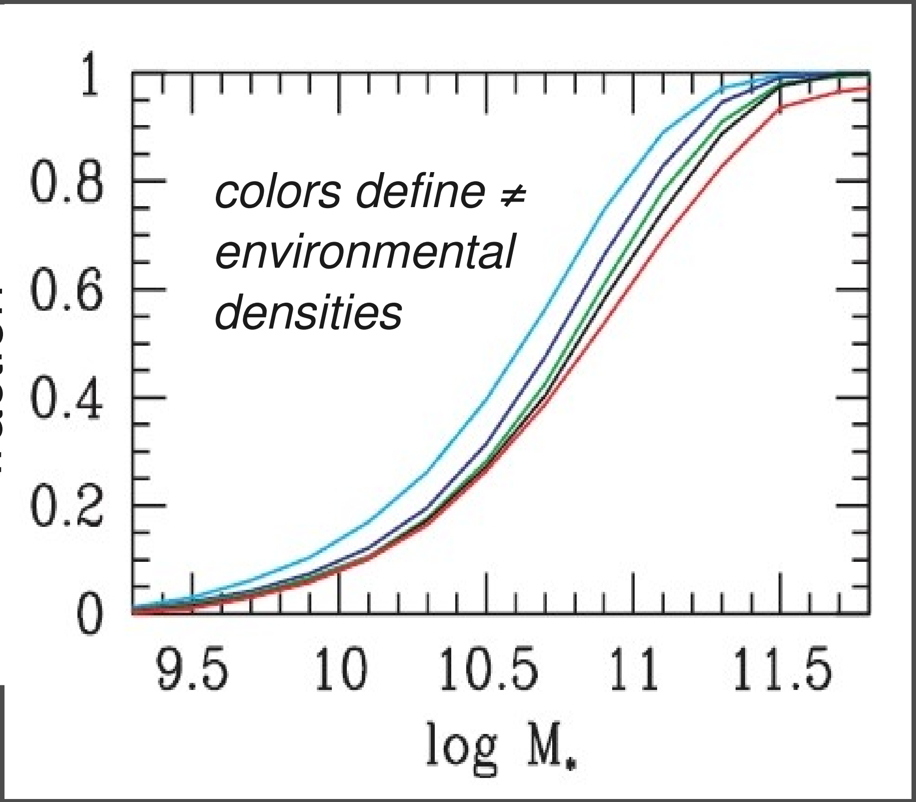
Different $M_\star$ distributions in ≠ environments:

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 dϕ/dr: *cluster center*

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

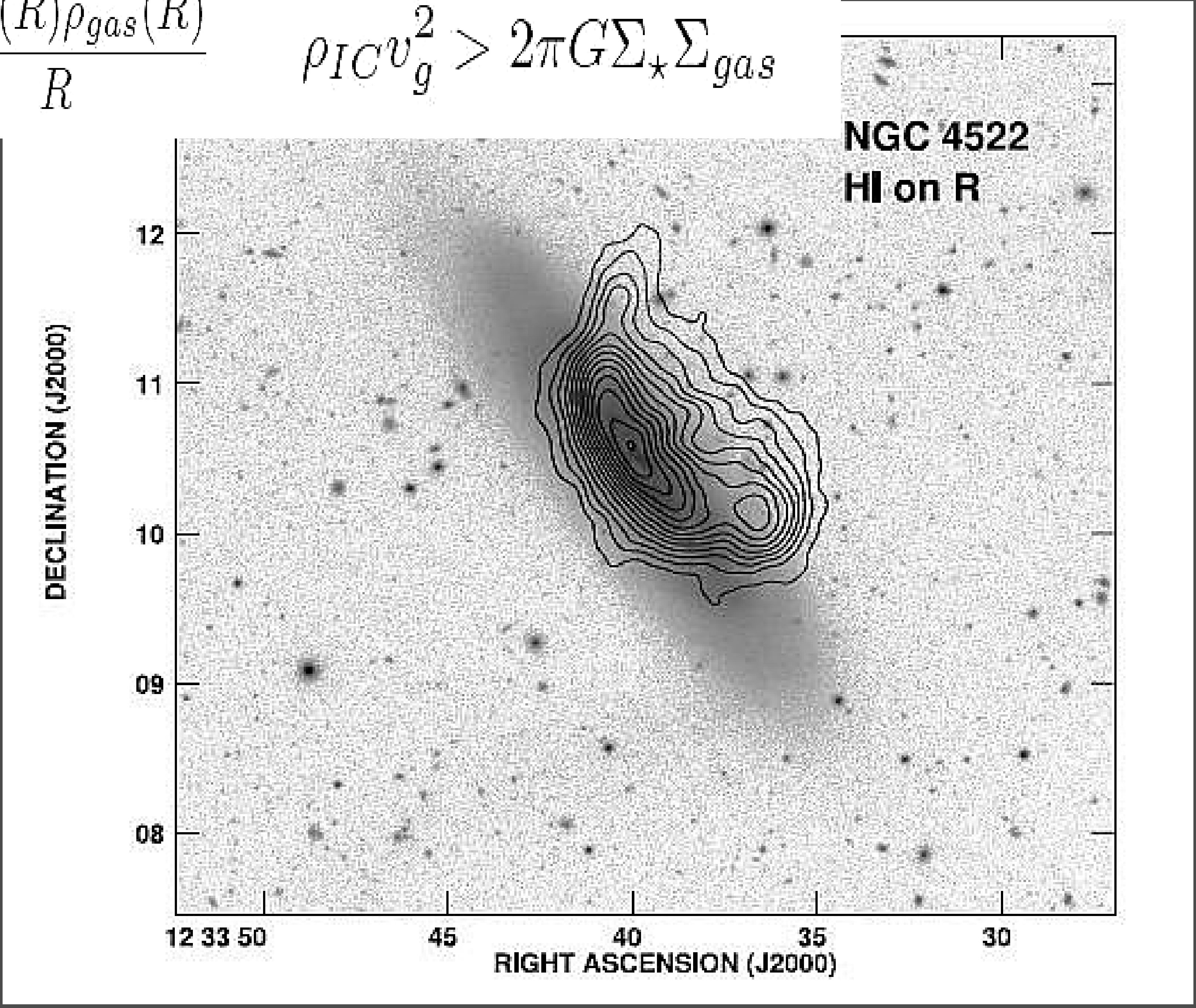
SFG flow along filament into cluster core, where they loose their gas via (?) ram-pressure and stop star formation (color and morphological transformation follow)

Stripping from the halo:

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

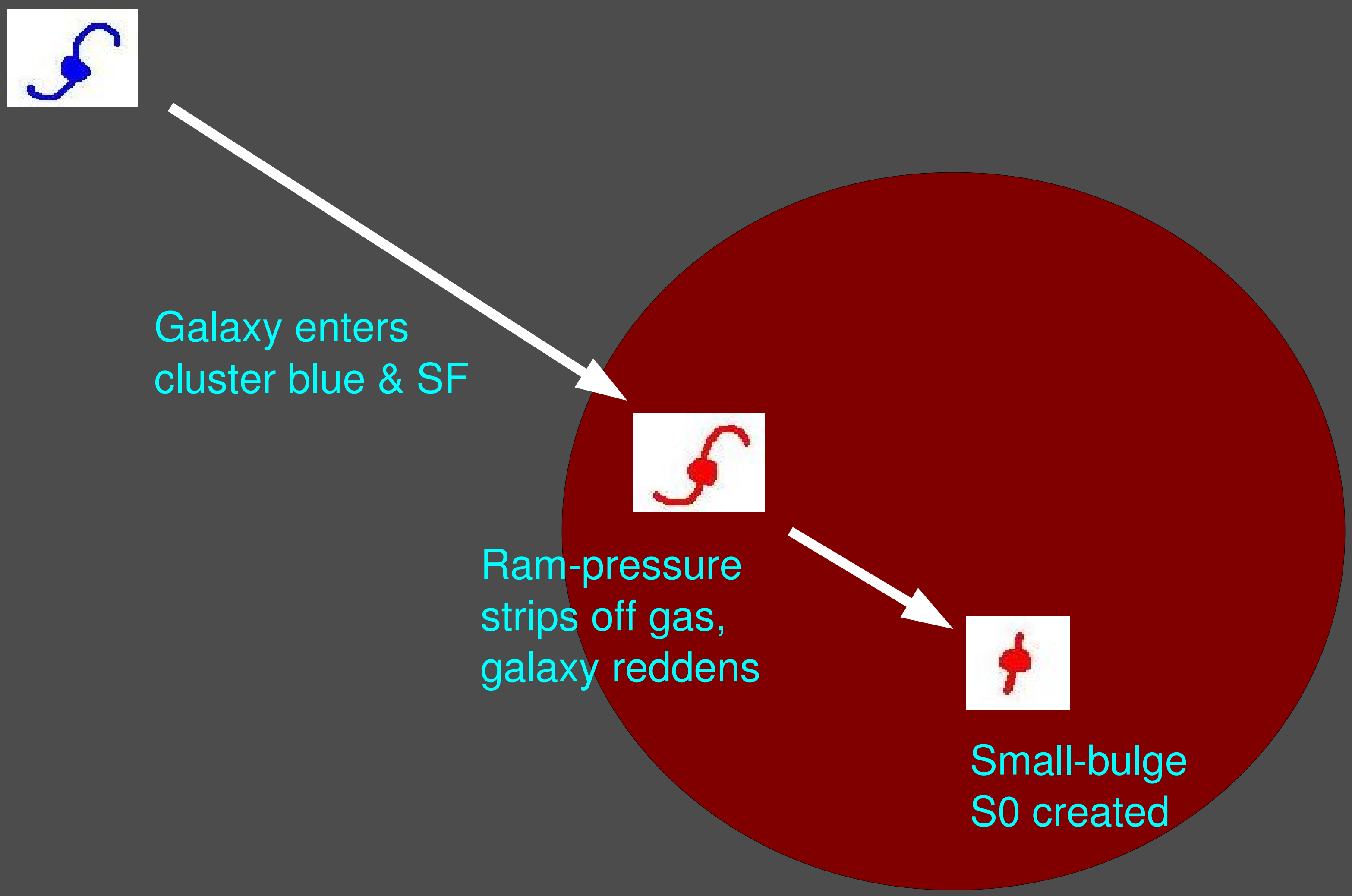
Stripping from the disk:

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



(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,

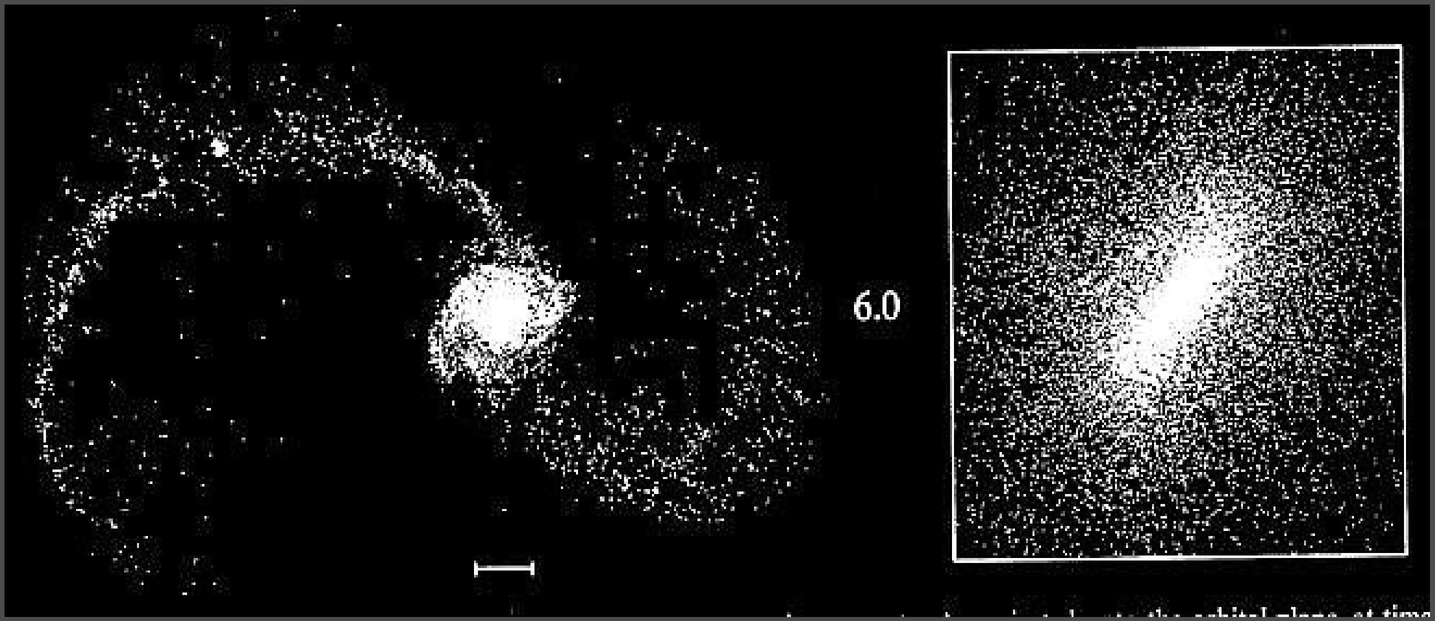
⇨ *frequent & slow galaxy encounters*
⇨ *large tidal effects and some mergers*
⇨ *tidal gas loss + tidal gas compression & nuclear starburst*

Slow collisions → mergers

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

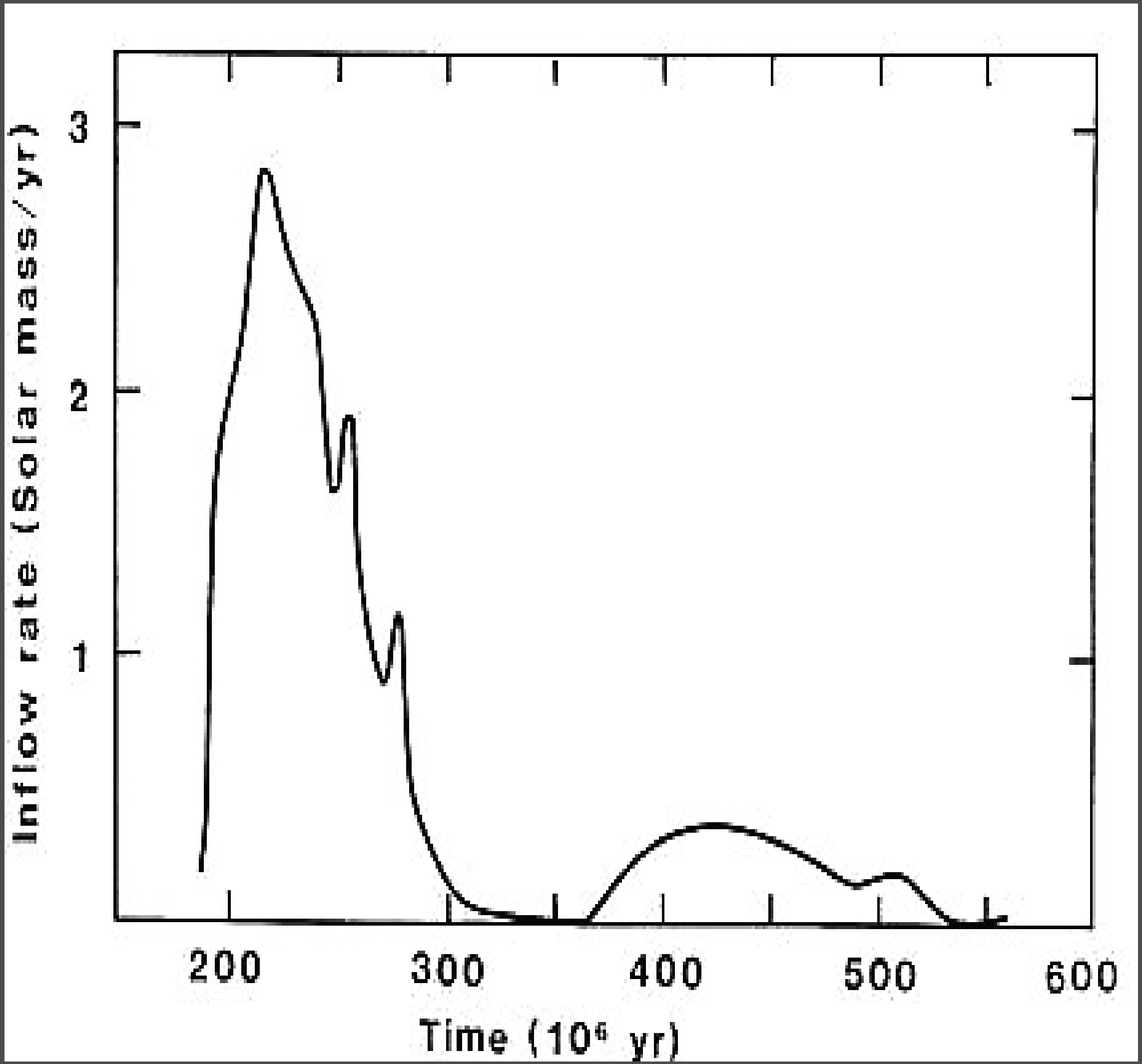
Merger timescale

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)

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

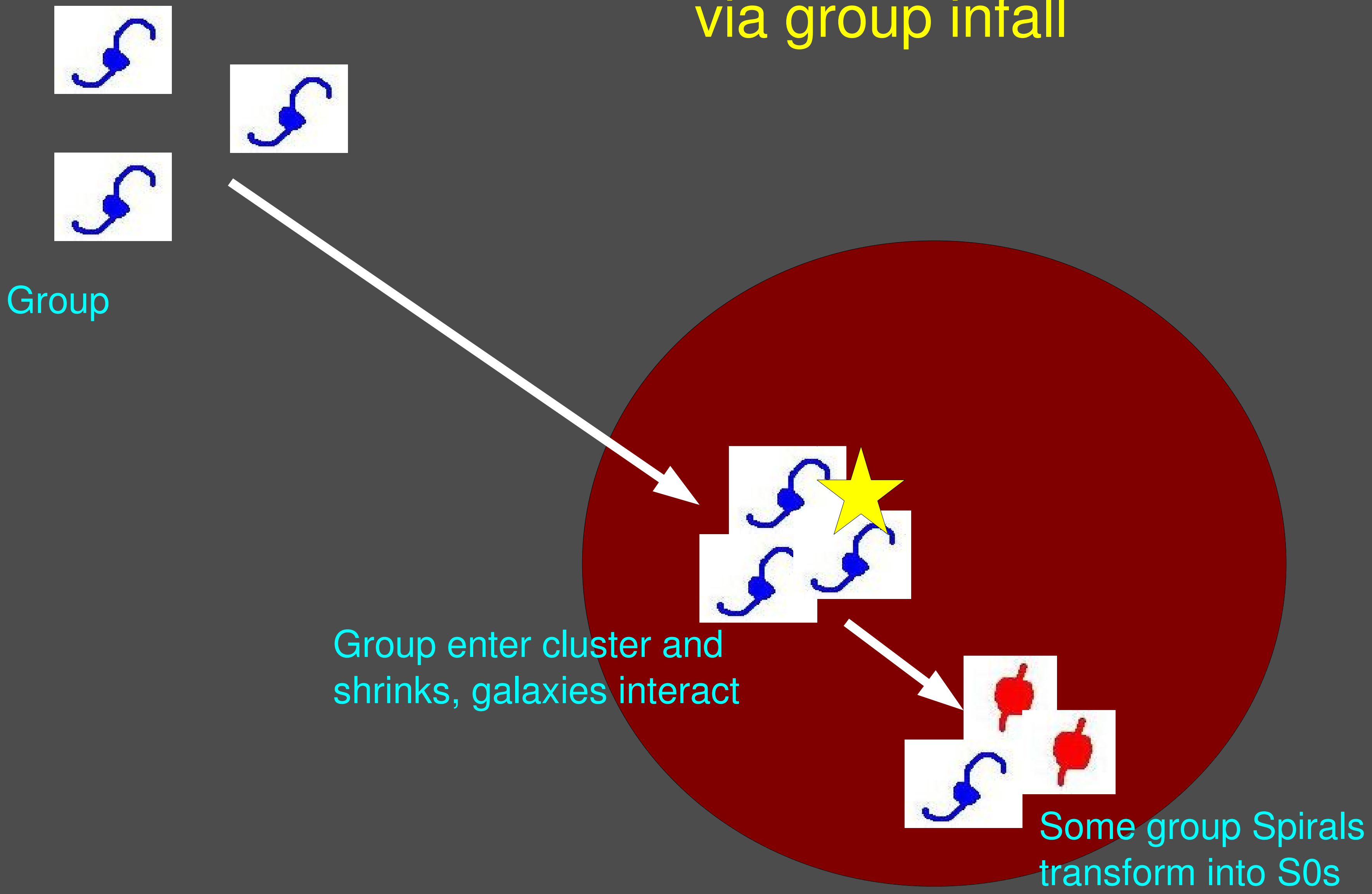
What about the SBG in the cluster core?

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

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



What about the evolution of the IR LF?

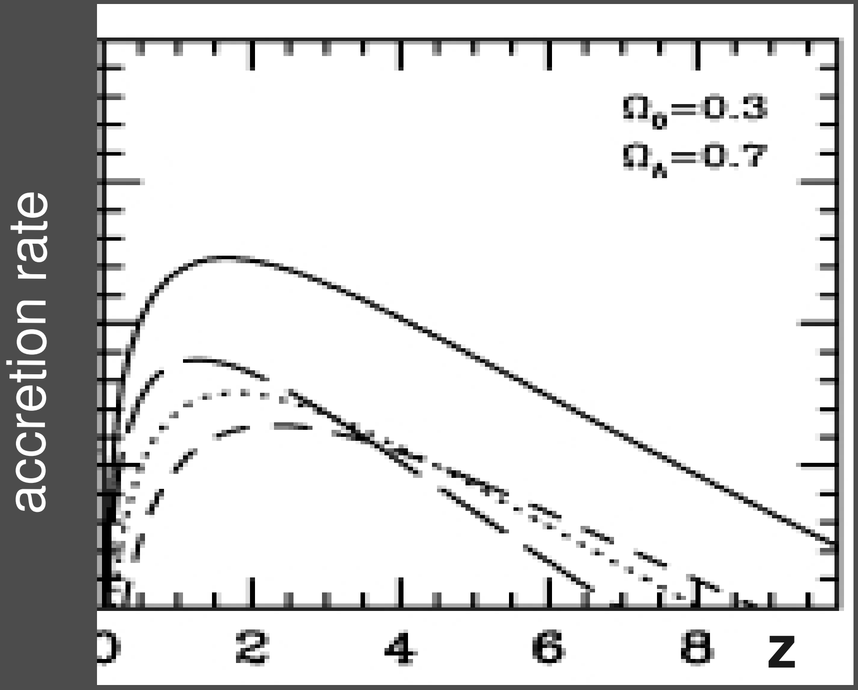
=

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:

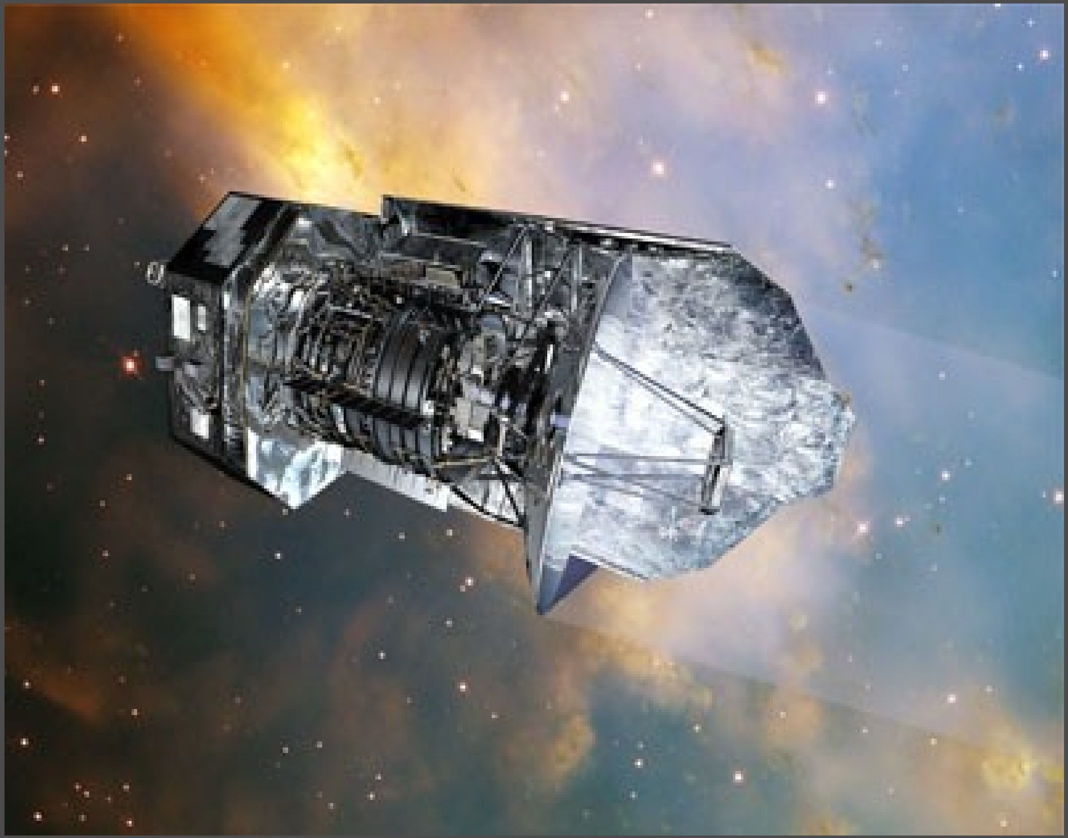
- intermediate-density environments (like filaments) are the preferred sites of galaxy star formation,

- 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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