Interacting Galaxies

Observations & Theory

Local Universe to High Redshift

Prof. Dr. Uta Fritze

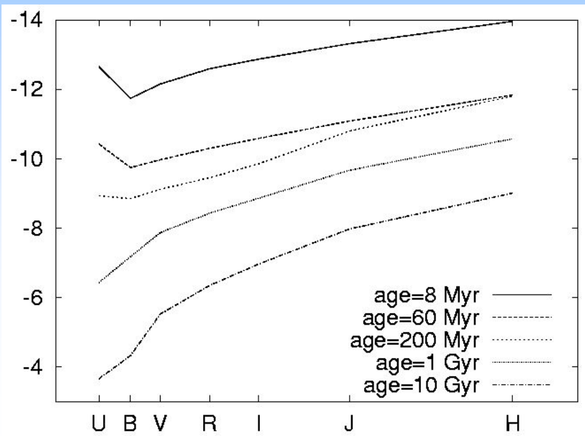
Dates: 17.4. Overview & basic concepts
(1.5. Holiday)
(15.5. HST Panel meeting)
22.5. Dyn. models & obs. examples
19.6. (5.6.) Star Bursts & Star Cluster Formation
19.6. ULIRGs & SCUBA galaxies
3.7. Galaxy transformation in clusters
17.7. Interactions @ high redshift

Analysis of Star Cluster Systems : SSPs

Grid of Spectral Energy Distributions

SSPs :	5 metallicities	-1.7 ≤[Fe/H] ≤+0.4
	4000 ages	4 Myr . . . . . 16 Gyr
	20 extinction values	0 ≤ E(B-V) ≤ 1

(Starburst extinction law → Calzetti et al. 2000)



400.000

Spectral

Energy

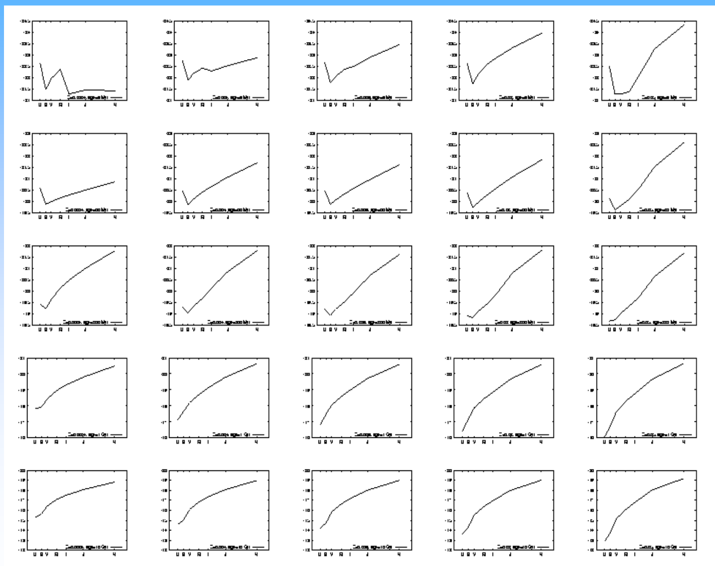
Distributions

e.g. $Z_{\odot}$, $E_{B-V}= 0$

↕ mass

Analysis of Star Cluster Systems

Multi–band photometry - Grid of Models (GALEV)



Spectral
Energy
Distributions

8 Myr

60 Myr

200 Myr

1 Gyr

10 Gyr

Z=0.0004 Z=0.004 Z=0.008 Z=0.02 Z=0.05

$E_{B-V} = 0$

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AnalySED* : Star Cluster SED ↔ Model SEDs

(Anders+04a, b)

- $\chi^2 = \Sigma_\lambda (m^\lambda_{obs} - m^\lambda_{model})^2 / \sigma_{obs}^2$
- probability for each model SED $p(n) \sim \exp(-\chi^2)$
- normalise to $\Sigma_n\, p(n) = 1$ (best fit model SED := highest p)
- sum models with decreasing probabilities until $\Sigma_n\, p(n) = 0.68$
  → ± 1 σ uncertainties

➔

- ★ ages
- ★ metallicities ± 1 σ uncertainties
- ★ extinction values
- ★ masses

for all individual SCs with 3 (or 4) passbands (U/B . . . K)

artificial SC tests : ages [Fe/H]

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Artificial star cluster tests w. model & obs. uncertainties

UV/U important for age dating of YSCs
NIR important for metallicities

YSCs (dusty galaxies) : 4 passbands (UV/U, . . ., H or K)
GCs (dustfree galaxies) : 3 passbands (U/B, . . ., H or K)

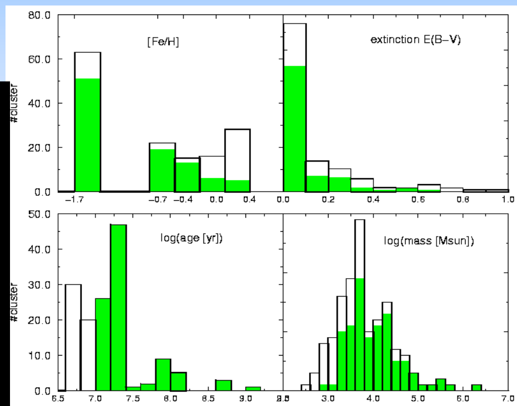
UV/U + opt. + NIR : disentangle ages & metallicities
get ☆ ages to Δage/age $\leq$ 0.3
☆ metallicities to +/- 0.2 dex

(Anders+04a, de Grijs+03)

Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

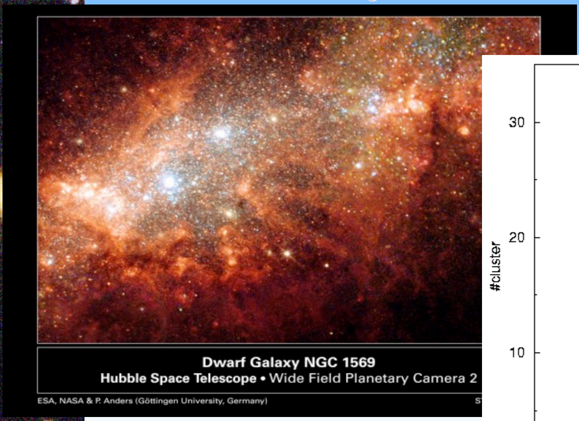
NGC 1569 dwarf starburst galaxy, 3 Super Star Clusters
+ 166 young star clusters

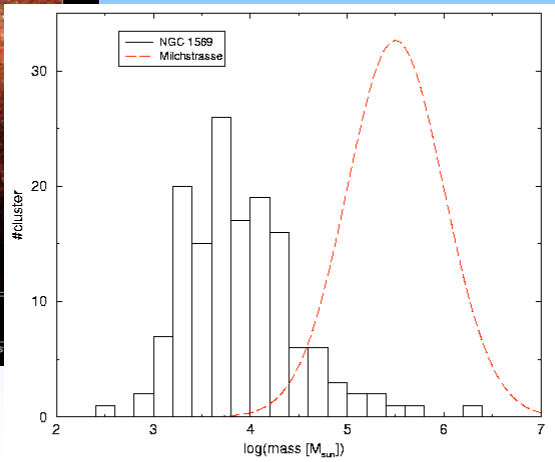
➜ metallicities
➜ ages for individual SCs (Anders+04a,b)
➜ extinction values ± 1σ uncertainties
➜ SC masses



Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

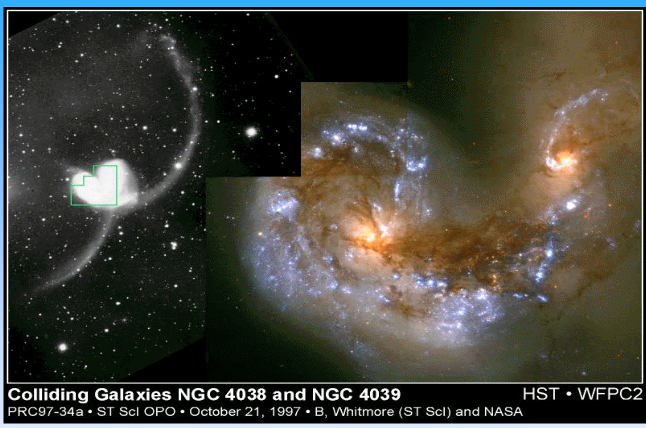
NGC 1569 dwarf starburst galaxy formed 169 young star clusters, but only few with masses of Globular Clusters





(Anders & FvA 03, Anders et al. 04a, b)

Galaxy Interactions & Cluster Formation



> 1500 young star clusters in Antennae : masses 10^3 - 10^7 $M_\odot$, radii 1 - 20 pc.

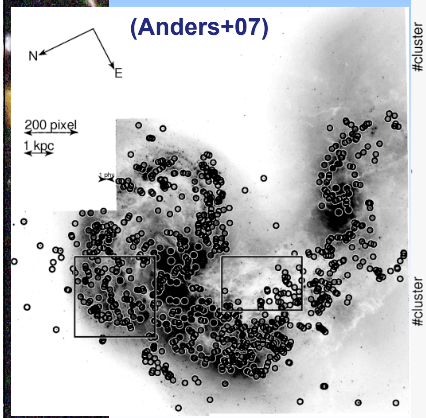
No dichotomy between open clusters and globular clusters, full continuum instead.

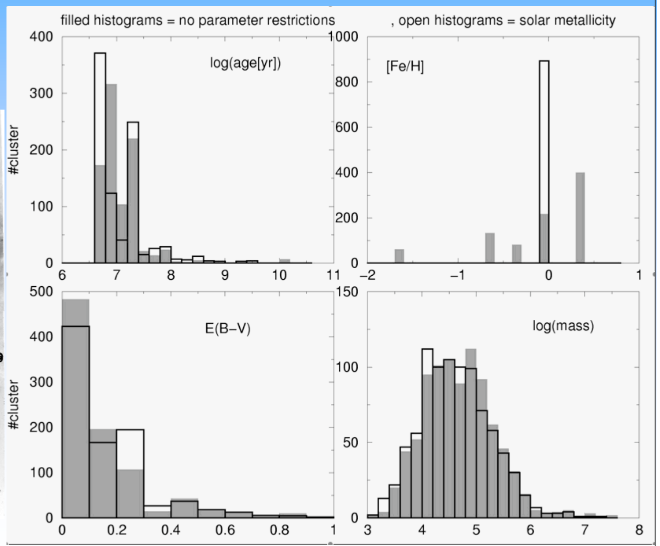
The Star Cluster System in the Antennae

(Anders+07)

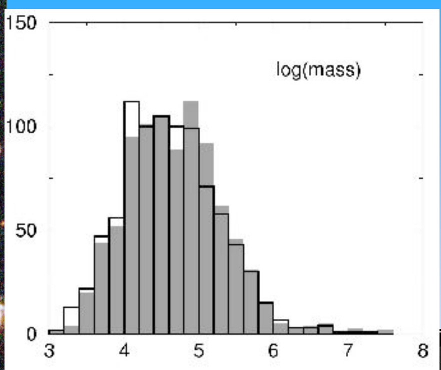
ongoing starburst in NGC 4038/39 forms a rich YSC system,

> 1500 YSCs





Interacting Galaxies & Globular Cluster Formation



Strong Starburst

→ strong star cluster formation

ages < 2 · 10^8 yr

masses $10^3 \ldots 10^7\ M_\odot$

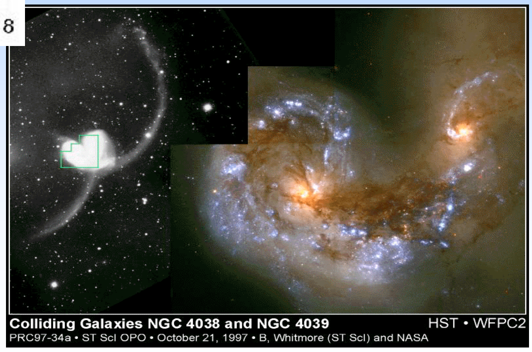
radii 4 -15 pc

[Fe/H] ~ 0

? long-lived -- shortlived ?

(Fritze 98, 99, 04, Anders+07)

Most YSCs in the Antennae have masses & radii typical for GCs ➜ they will probably survive for many Gyr, give testimony of the starburst/merger

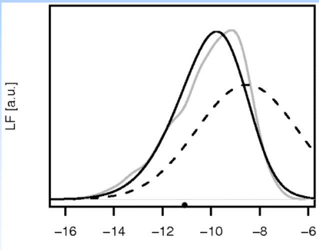


A Closer Look at the Antennae's SC System

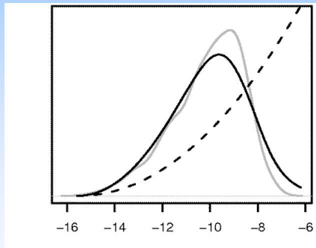
The SC Luminosity Function (LF) has a turnover
to 99.5 % significance! * (Anders+07)

LF ➜ MassFunction : difficult

? how to translate completeness limit in
luminosity into completeness limit in mass ?
indication for turn-over in MF of YSCs in diff. age bins
? statistical significance ? ➜ analyse ACS data



Gauss
Power law



Evidence : SFR(➜ massive SCs) > SFR(➜ low-mass SCs)

No discrimination for individual YSCs :
Young GCs — Young Open Clusters
M(YSC) vs. $R_{1/2}$: scatter plot

* Background ....

The Luminosity Function and the Mass Function of
Milky Way (& other galaxies') old Globular Cluster
systems show a turnover,

while for young open clusters, for molecular clouds and
molecular cloud cores, power laws are observed.

??? Is the turnover for the old GCs a result of
secular evolution ???
??? or did the GC system already show a turnover
when it was young ???

Ongoing debate among theorists: N-body models for
survival and destruction of GCs in a galaxy potential.

Some speculation ….

If the turnover in the LF would reflect a turnover in the MF, this would

- ☛ tie in nicely with Parmentier & Gilmore's 05, 07 empirical results :

  MW GC system initially had a mass spectrum with turnover around 10^5 $M_\odot$

- ☛ indicate that the MF of the molecular clouds in the massive gas-rich Antennae merger (LIRG) is different from situation in undisturbed spirals, dwarf galaxy starbursts

  (as expected due to pressure effects)

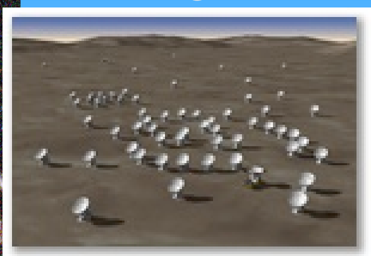
  ➜ prediction to be tested with ALMA

YSCs = best proxies for MC cores & high SFE regions

Atacama Large Millimeter Array : ALMA

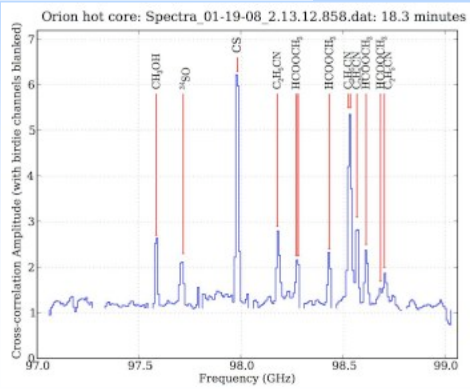
➜ high sensitivity & high spatial resolution observations of molecular gas

80 antennas 5000m

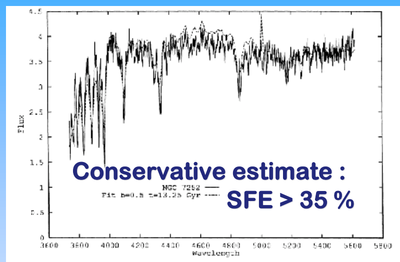


Jan.08

1. interfer. spectrum



Globular Cluster Formation in Interacting Galaxies & Mergers



NGC 7252 : Post – Starburst : SFE > 30 %

(cf. SFE ≪ 3 % in normal galaxies)

hundreds of star clusters ages ~ 0.6 – 1 Gyr

masses $10^4 \ldots 10^6\ M_\odot$, radii ~ 4 pc, $Z = (0.5 \ldots 1)\ Z_\odot$,

long-lived : young Globular Clusters

N(young GCs) ~ N(old GCs) ! *

Secondary GCs = eternal tracers of violent SF epoch.

* Background :

Globular Cluster specific frequency (S_{GC} or T_{GC})
:= N_{GC} per galaxy luminosity or mass

Ashman & Zepf (1993) : $\langle T_{GC}\rangle_E = 2\ \langle T_{GC}\rangle_{Sp}$

Ellipticals on average have twice the number of GC per unit of mass than spirals

The starburst in the massive gas-rich spiral-spiral merger NGC 7252 formed many new GCs !

(ok with SF efficiency)

Enough survived the first 600 - 900 Myr to fulfill

$\langle T_{GC}\rangle_E = 2\ \langle T_{GC}\rangle_{Sp}$ (Fritze & Burkert 95, Schweizer 02)

Masses ~ $10^5 – 10^6\ M_\odot$ W3: $(7 – 8)10^7\ M_\odot$, (Maraston+01, 04)

(spectroscopy and multi-band photometry) Z ~ (0.5 - 1) $Z_\odot$

Cosmological Importance of Galaxy Interactions & Starbursts

Hierarchical structure formation scenario :

Galaxies build up continuously from smaller building blocks ± starbursts !

Galaxy interactions much more frequent in the past & much stronger, galaxies more gas-rich

Key role of (Globular) Star Clusters = eternal tracers of violent star formation episodes

SC analysis 1-by-1 : age & metallicity distributions, much better than integrated light ! (FvA 98, 99, 04)

Multi-band Photometrie : HST (+ ground) UBVRI+NIR

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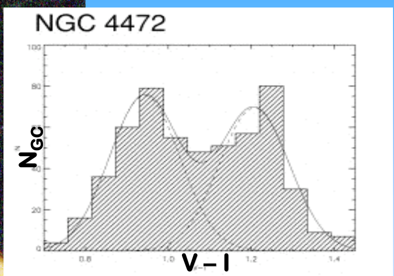
Globular Cluster Analyses

ACS Virgo Cluster Project : B – I distributions of 100 GCSs in E/S0s (Peng+06)



many bimodal :
blue peak : universal, old+metal-poor
red peak : variable, younger ± more metal-rich ?

Optical colors degenerate in age & metallicity
☛ optical + NIR colors largely resolve degeneracy

e.g. V – I = 1.2 2 Gyr, [Fe/H]= +0.4 V – K = 3.5
V – I = 1.2 13 Gyr, [Fe/H]= – 1.7 V – K = 2.3

(Fritze 04)

with additional K – imaging & AnalySED
➜ GC ages to Δ age/age ~ 0.2
➜ GC metallicities to ~ 0.2 dex

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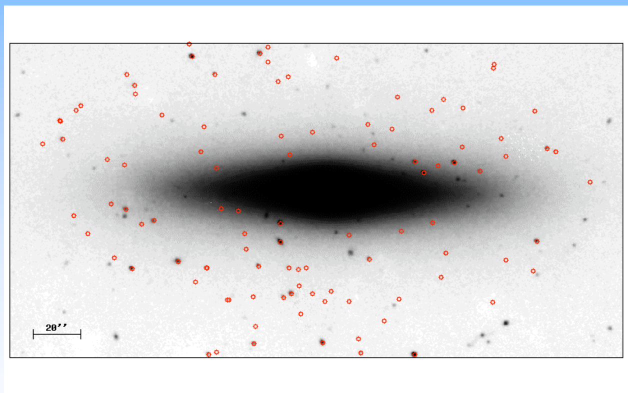
Globular Cluster Age & Metallicity Distributions

GC population in S0 NGC 4570 : (Kotulla & Fritze 08)



HST ACS g, z (VCS)
+ NTT-SOFI K to 21.3 Vega mag

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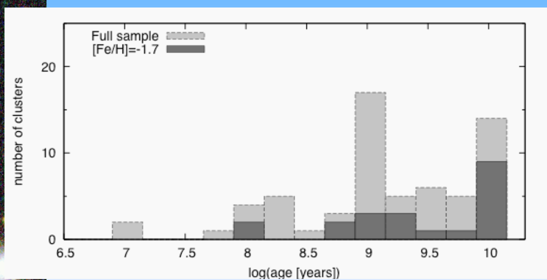
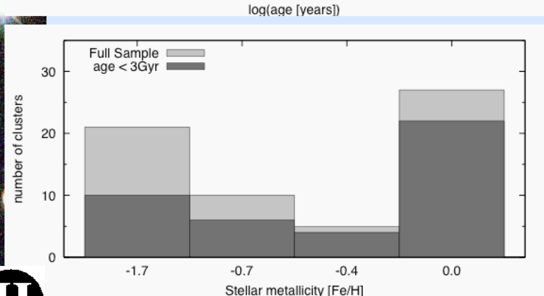
Globular Cluster Age & Metallicity Distributions

NGC 4570 : (Kotulla & Fritze 08)



GC age distribution
➜ when a starburst occurred



GC metallicity distrib.
➜ what happened minor accretion or major merger

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Galaxy Formation Histories from Globular Cluster Age & Metallicity Distributions

Before we can also use GCs to study their parent galaxy's mass assembly histories, we must understand
- the relative amount of SF that goes into GC formation and
- its dependence on galaxy, interaction & starburst properties

➜ study major mergers/minor accretions,
big/dwarf galaxies,
gas-rich/gas-poor,...

➜ Astro - archeology

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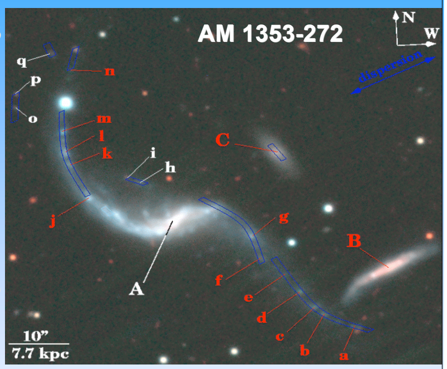
Formation of Tidal Dwarf Galaxies in Galaxy Interactions

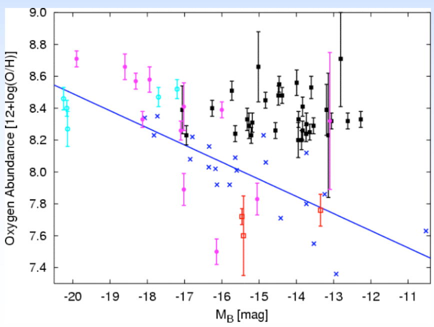
Gaseous / stellar condensations

→ Tidal Dwarf Galaxies
galaxy recycling

☛ galaxy formation in the local universe

☛ cosmological significance ! ?





Background objects

main I/A group members and neighbors

confirmed TDG candidates

3 TDG candidates rejected : not recycled objects

Local dwarf galaxies (+ fitted relation)

VLT+FORS MOS

(Weilbacher, FvA, Duc 2000, 2001a, b, 2002, 2003)

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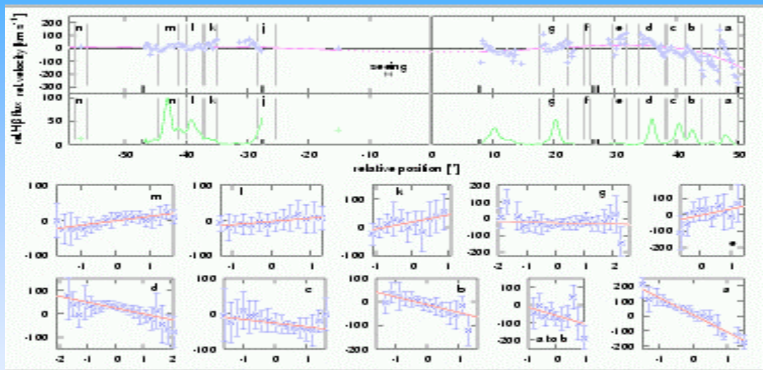
Formation of Tidal Dwarf Galaxies

VLT+FORS MOS : kinematic independence ?



Velocity profiles : **VLT FORS MOS** (Weilbacher, FvA & Duc 2002)

- significant velocity gradients (> 2σ) in 7 TDG candidates in AM 1353-272
- rotation and free fall

→ TDGs in formation

Tidal Dwarf Galaxies & Dark Matter

Bournaud+07 : VLA observations : HI rotation curve for 3 TDGs in NGC 5291 <-> N-body models, N~10^6 for each stars, gas, DM : $M_{dyn} \geq 2\ (M_{☆}+M_{HI}+M_{CO})$

➜ contain significant amount of DM !

But TDGs form in tidal tails torn out from disks, we do not expect them to contain DM from the halo

DM in the disk ???

most probably in the form of (very cold) gas

Implications ???

Tidal Dwarf Galaxies & Dark Matter

ons : HI rotation curve for
N-body models, N~10^6 for
2 ($M_☆+M_{HI}+M_{CO}$)

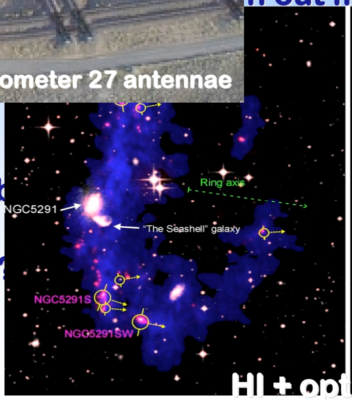
ount of DM !

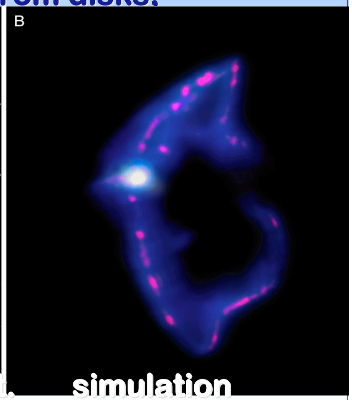
n out from disks,

DM in the disk

most prob

Implications ??





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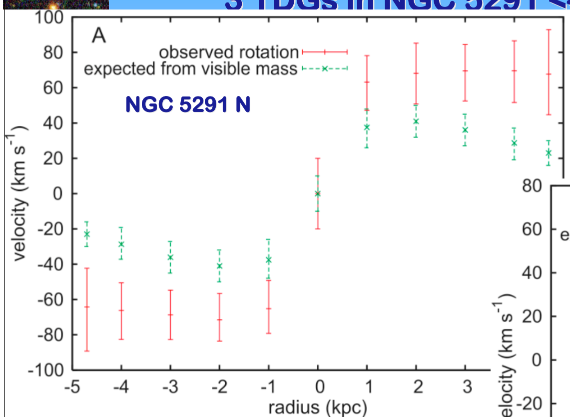
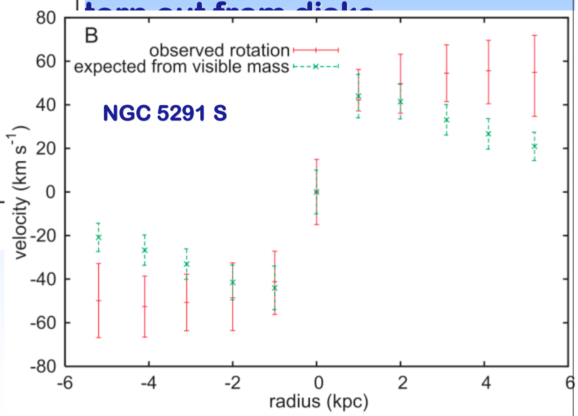
Tidal Dwarf Galaxies & Dark Matter

Bournaud+07 : VLA observations : HI rotation curve for
3 TDGs in NGC 5291 <-> N-body models, N~10^6 for
≥ 2 ($M_☆+M_{HI}+M_{CO}$)

amount of DM !





Implications ???

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The Local Group & Beyond

35 members around Milky Way & M31 within 1 Mpc

Nearby groups :

Sculptor group	: 6 members	D~1.8 Mpc
M81 group	: 8 members	D~3.1 Mpc
Centaurus group	: 17 members	D~3.5 Mpc
M101 group	: 5 members	D~7.7 Mpc
M66+M96 group	: 10 members	D~9.4 Mpc
NGC 1023 group	: 6 members	D~9.6 Mpc

Census very incomplete : low – luminosity dwarfs like Sag dSph cannot be detected beyond our Local Group

galaxy group <50 members,
galaxy cluster >50 members

Local Galaxy Clusters

Virgo (W. Herschel 18th century)
10° × 10° D~16 Mpc
~ 250 normal galaxies
> 2000 dwarf galaxies

irregular cluster : 2 big Es: M87 & NGC 4479

Coma : regular cluster (+ substructure) D~ 90 Mpc
~ 10,000 galaxies

Abell Catalog of Galaxy Clusters

POSS northern sky w/o Milky Way disk (extinction) 1958

Cluster := >50 members within m_3 and m_3+2 mag,
m_3 := mag of 3rd brightest member,
within angular radius q_A=1.7'/z, z=redshift estimate
(from 10th brightest galaxy assumed to be universal)

1682 galaxy clusters within 0.02 < z < 0.2
(z>0.02 --> cluster fits on ~6° ´ 6° POSS plate,
z<0.2 --> sensitivity limit of POSS plates)

extended to include 4076 clusters by
Abell, Corwin, Olowin 1989

both catalogs not free from projection effects !!!

UH

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Galaxy Clusters

Galaxy Clusters : R_{cl}~ 2 - 10 Mpc, N_{gal} = 50 . . . >10.000.

Zwicky (1933) measured radial velocities of galaxies
in Coma : velocity dispersion σ~1000 km/s

calculated visible mass of galaxies with M/L (E/S0)=10
→ M_{gals}~10^{13} $M_\odot$ and escape velocity

found : typical galaxy velocity > escape velocity
→ cluster should dissolve on t~10^9 yr

Coma = relaxed cluster, much older than 10^9 yr

mass (and escape velocity) must be much higher than
visible mass alone

Virial theorem : $M_{dyn} = 3\,\pi/2G \cdot R_{cl}\sigma^2$

$R_{cl} \sim 1$ Mpc → $M_{dyn} = 10^{15}\,M_\odot$

Evidence for Dark Matter : M(DM)/M(gals)~100

UH

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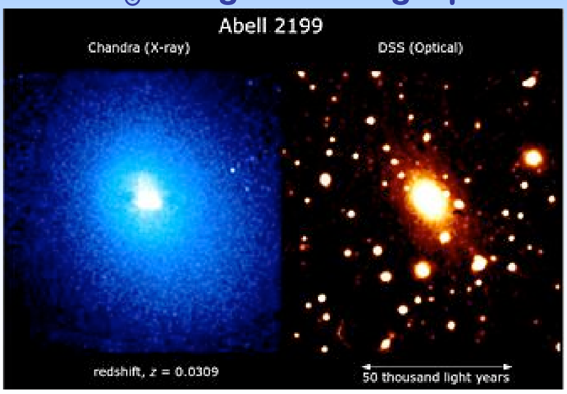
Galaxy Clusters

Anisotropy in the velocity dispersion or non-spherical mass distribution could affect the mass estimate

→ alternative mass estimates : X-rays !

Intra Cluster Medium ICM

Galaxy clusters contain hot (10^{7-8} K) X-ray emitting gas : Intra Cluster Medium ICM.
ICM heated by the gravitational energy released by the formation of the cluster from smaller structures. Kinetic energy gained from the gravitational field is converted to thermal energy by shocks. The ICM is highly ionised.
Abundance ~ 1/3 $Z_{\odot}$: hot gas had origin/preenrichment in galaxies.



Galaxy Clusters

2-body relaxation between galaxies unimportant :

$t_{rx}=t_{cross} \cdot N_{gal}/\ln N_{gal} \gg t_{Hubble}$

σ independent of galaxy type and luminosity or mass

→ motion of galaxies in cluster not thermalized.

violent relaxation still going on on crossing timescale,
i.e. clusters are still in formation.

~ 5 - 10 % of the luminous galaxies live in clusters today.

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Galaxy Clusters

Dynamical friction :

gravitation of a moving galaxy causes inhomogeneity in an initially homogeneous galaxy distribution : overdensity along trajectory, strongest behind the moving gal.

→ braking : $dv/dt \sim - m\rho v / v^3$ ρ : mass density

most massive galaxies feel strongest dynamical friction

→ mass segregation, formation of cD galaxy

Between galaxies in clusters :

☆ hot X-ray gas : $T \sim 10^8$ K, $M_{X\text{-}gas} \leq 5\, M_{stars}$

☆ intracluster stars, PNe, GCs : ~10% of optical light

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Galaxy Clusters

Scaling relations for galaxy clusters :

$T_X \sim M / R_{vir}$

within R_{vir} : $<\rho> \sim 200\ \rho_{cr}$, typically R_{vir} = 1 - 3 Mpc

with ρ_{cr} critical density of the universe

→ virial mass $M_{vir} = 4\pi/3 \cdot 200\ \rho_{cr}\ R_{vir}^3$

→ $T_X \sim M_{vir} / R_{vir} \sim R_{vir}^2 \sim M_{vir}^{2/3}$

Observations show very tight correlation between T_X and M_{vir}, better than between σ^3 and M_{vir}

(outlyers: unrelaxed clusters)

Typical $M_{vir} \sim 10^{14\text{-}15}\ M_\odot$,

~5% galaxies, ~10% ICM, ~85% DM

Galaxy Transformation in Clusters

Galaxy populations in rich local clusters very different from field galaxy population

Field galaxy population dominated by SFing spirals, inner regions of nearby clusters dominated by
- passive Es, S0s, dEs, dSphs
- faint galaxies : steep faint end slope of LF in clusters (Trentham+01, 02, 05)

galaxy transformation : spiral-rich field gal. pop.
➜ E/S0/dE/dSph-rich cluster population

galaxy -- galaxy interactions : high σ_{gal}: no merging, harassment

galaxy -- ICM : ram pressure stripping of HI (and stars), ram pressure sweeping of HI

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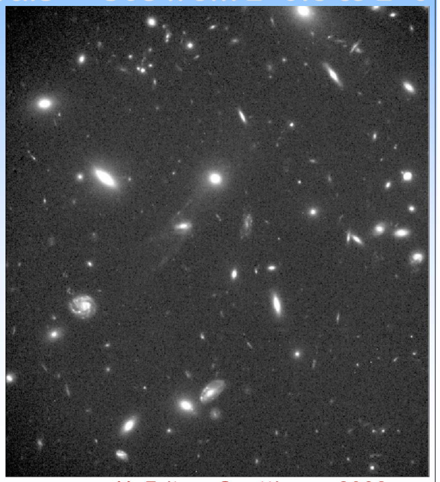
Galaxy Populations in Clusters

Central regions of nearby rich clusters : ~80% S0s, dEs, Es
Rich clusters at $0.3 \leq z \leq 0.8$: high spiral, low S0, similar E fractions
(Dressler 1980, Dressler et al. 1997, van Dokkum et al. 2000)
-> significant transformation spirals -> S0s from z~0.5 to z=0

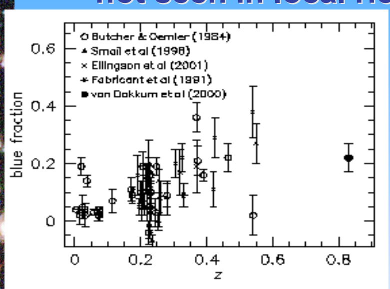
Coma

CL0939
z=0.41



Butcher – Oemler Effect

Distant clusters have significant populations of blue* galaxies not seen in local rich clusters (Butcher & Oemler 1978, 1984)



blue* : bluer than CMR red sequence
(van Dokkum 2001, Dahlen et al. 2004)

· 5 increase in blue galaxy fraction
$f_b = N_{blue} / N_{tot}$
from z~0.5 to z~0

- ☆ most blue galaxies are low-mass spirals & Irrs (Smail et al. 1997)
- ☆ some show SF, others strong Balmer absorption lines -> recent starburst (Dressler & Gunn 1983)
- ☆ some red galaxies also show strong Balmer lines (E+A, k+a) -> post - starbursts (spectroscopic BO-effect)

-> progenitors of S0s ?

Butcher – Oemler Effect

BO-effect driven by infall of field spirals that lose their HI and terminate their SF (after/without a starburst) in interactions

☆ with other cluster galaxies : harassment

☆ in infalling groups : merging

☆ with the dense hot ICM (X-rays) : ram pressure stripping/ sweeping : HI anemic -> SF truncation/strangulation (if disk/halo gas gets stripped)

All processes observed to work in certain cases

? t(spectral transformation) <-> t(morphological transformation) ?

? relative importance of diff. transformation channels & ev. dependence on cluster properties ?

Galaxy -- ICM Interactions

$P_{ICM} > P_{ISM}$ ➜ ram pressure ➜ disk stripping, sweeping

➜ HI anemic spirals ➜ SF truncation

$t_{trunc} \sim 10^8$ yr

$P_{ICM} > P_{halo\ gas}$ ➜ halo gas stripping

➜ accretion truncation ➜ SF strangulation

$t_{strang} \sim 10^9$ yr

When SFR ➜ 0 : disk surface brightness ↘ very rapidly, disk harder to detect,

➜ apparent B/D ratio ↗

Butcher – Oemler Effect

Redshift evolution of the blue galaxy fraction

$f_b = N_{blue} / N_{tot}$

due to

- decreasing galaxy infall rate (Kauffmann 1996, Diafero et al. 2001)
- decreasing HI content & SFR (field gals) (Madau et al. 1996)
- increasing ICM content (Evrard et al. 1999)

Continuous addition of “young” S0s with low M/L

–> Progenitor Bias

slows down the redshift evolution of the <M/L>

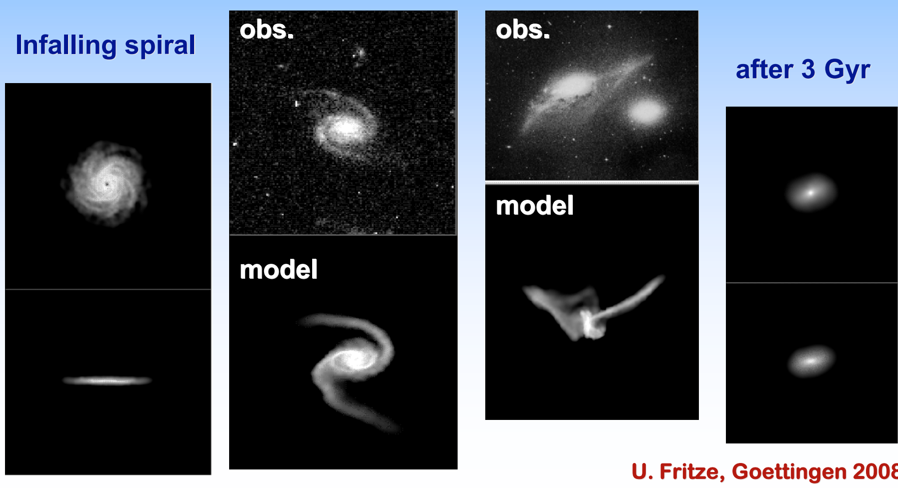
–> reduces redshift evolution of FP

Galaxy Harassment in Clusters

$v_{Gal} >> v_{\star}$: few mergers, many fast & destructive encounters/fly-by’s (Moore+96)

Spirals ➜ S0s & dSphs & dEs

(?) luminous, blue, SFing — faint, red, passive



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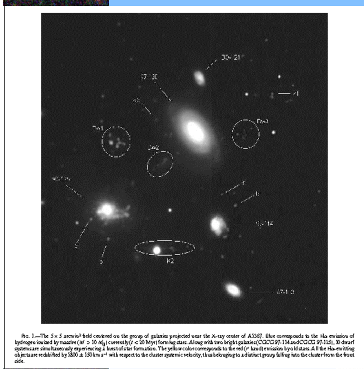
HI & SF in Cluster Galaxies

Collective Starburst in a Group falling into A1367
(Gavazzi et al. 2003)



R

H_α

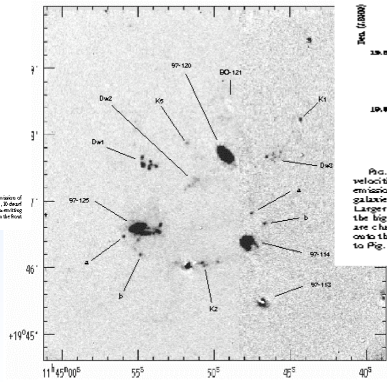


Fig. 3.—Net (Hα + N[II]) band frame of the BIG group

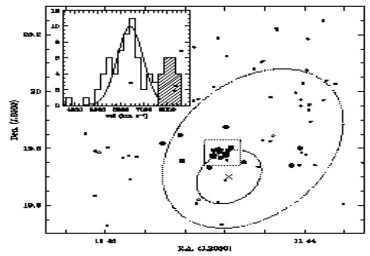
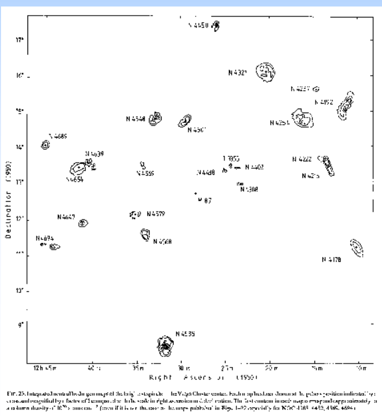


Fig. 4.—Celestial distribution of galaxies with known recessional velocities in the cluster of galaxies A1367, with two contours of the X-ray emission sketched around the X-ray center (*cross*). Small symbols mark galaxies within the Gaussian velocity distribution of the cluster (see inset). Larger circles refer to galaxies with redshift exceeding 7700 km s⁻¹, i.e., in the high-velocity tail of the distribution (*shaded*). Note that these galaxies are clustered in a small region, revealing the existence of a group falling onto the cluster. Galaxies inside the small square box (BIG), corresponding to Fig. 3, have been all detected in Hα.

Local Galaxy Clusters : Virgo

SFing galaxies avoid central region
ring of HI – anemic spirals around center.
Role of hot, dense Intra Cluster Medium (ICM),
seen in X-rays !?
Ram pressure stripping/sweeping vs. harassment vs.
interactions within infalling groups

(Cayatte+90



Gavazzi+05)

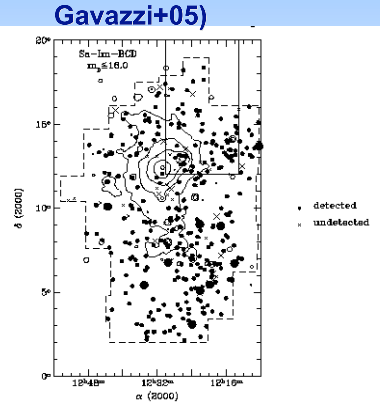


Fig. 1. The Virgo cluster region considered in the present analysis. The dashed broken line represents the boundary of the VCC catalog and the rectangle the area covered by the HIJASS blind HI survey. Superposed are the X-ray contours from ROSAT (Bohringer et al. 1994). All 355 late-type (Sa-Im-BCD) members of the Virgo cluster ... Large symbols refer to objects observed in this work.

Local Galaxy Clusters : Coma

HI mapping of Coma galaxies :

(Bravo-Alfaro+00)

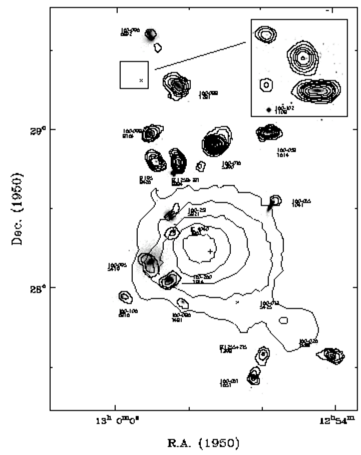


FIG. 2—Composite plot of individual H I maps of spiral galaxies of Coma observed with the VLA. Galaxies are shown at their proper position (except those in the rectangle, where the position of CGCG 160-102 is indicated with a times sign) and they are magnified by a factor of 7. The H I maps are overlaid on DSS optical images. The first contour is the same for all galaxies, corresponding to 3×10^{19} cm^{-2}. Their identifications and central velocities (in km s^{-1}) are indicated. The large-scale contours sketch the X-ray emission as observed by Vikhlinin et al. (1997). The cross indicates the cluster center, coincident with the elliptical NGC 4874.

Local Galaxy Clusters : Coma

Distribution of Emission Line and E+A Galaxies related to substructure in the cluster

(Poggianti+04)

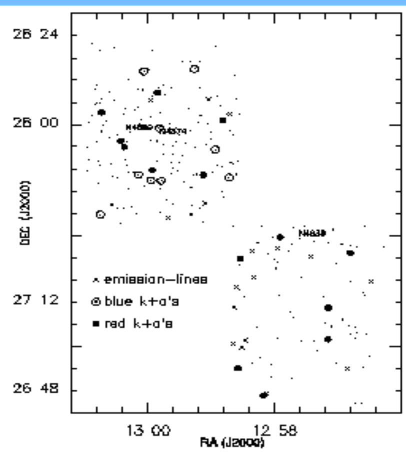
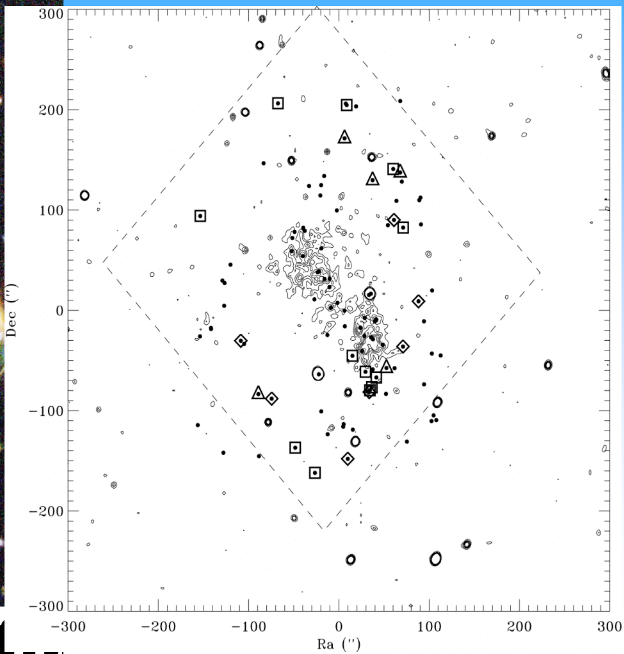


FIG. 5.—Projected position on the sky of k (*small circles*), red and blue k+a (*large circles*), and emission-line (*crosses*) galaxies. The location of the three dominant galaxies (NGC 4874, NGC 4889, and NGC 4839) is labeled.

Distant Galaxy Cluster : Cl 0152 – 1357 @ z = 0.837



(Homeier+ 05)

X contours : Chandra

SFing galaxies :
- △ compact
- □ Sp/Irr

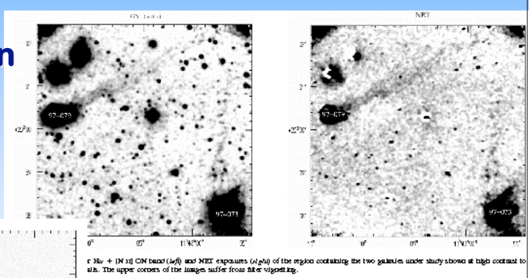
- • red cluster sequ.

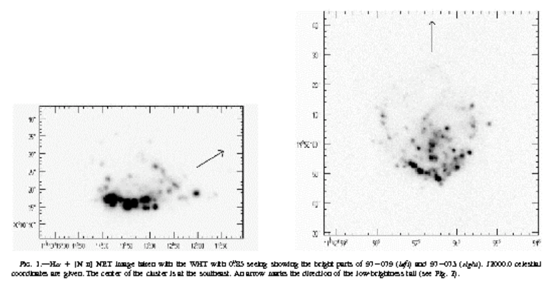
Direct Evidence for Galaxy - ICM Interaction

(in combination with galaxy – galaxy interaction)

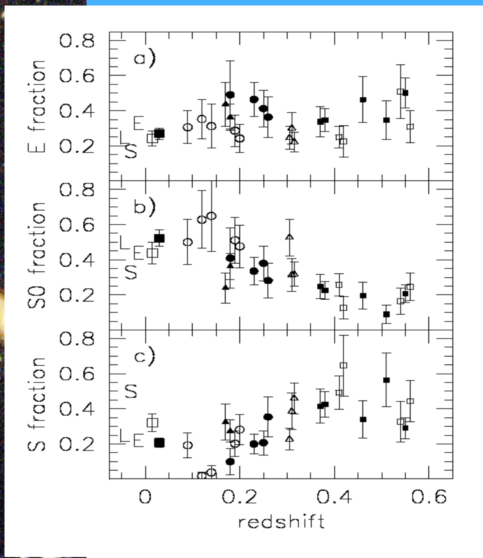
(Gavazzi+01)

75 kpc H_α trails behind 2 Irrs in A1367
vigorous SF at opposite sides of galaxies
evidence for ram pressure
during high-speed motion
towards cluster center
tails cross each other
-> interaction ~50 Myr ago





Evolution in the Cluster Galaxy Population



Redshift evolution of galaxy morphologies (MORPHS sample)

E fraction ~const.

S0 fraction ↘ for z ↗

Spiral fraction ↗ for z ↗

(Fasano et al. 2000, 2001, Couch et al. 1998)

significant transformation : spirals ➜ S0s from z~0.5 to z=0 within the last 5 Gyr

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Formation/Transformation of S0s

Major merger : spiral + spiral –> E or (luminous) S0

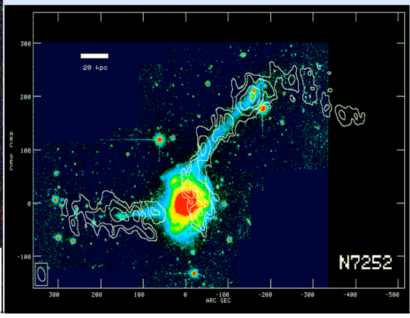
∗ (incomplete) violent relaxation : deVaucouleurs profile + gradient

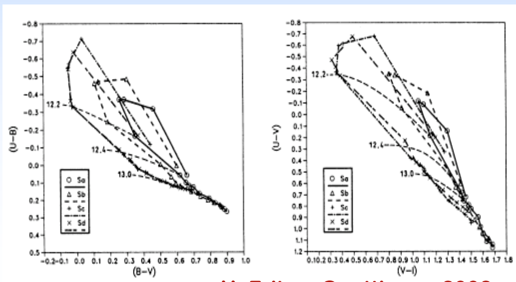
∗ late backfall of HI from tidal tails –> rebuild disk (disky E or S0) within ~3 Gyr

∗ global or nuclear starburst for prograde or retrograde merger

∗ ~3 Gyr after starburst : colors of luminous S0s

(Barnes 2002, Hibbard & Mihos 1995, Fritze & Gerhard 1994)





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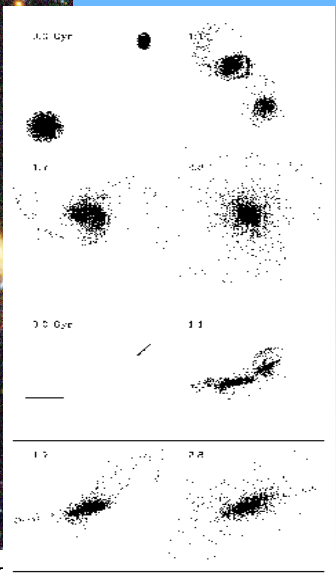
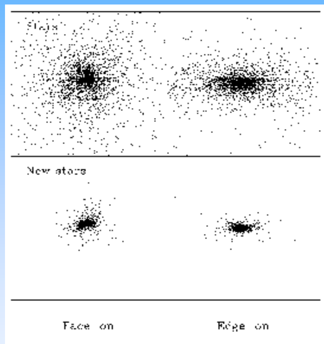
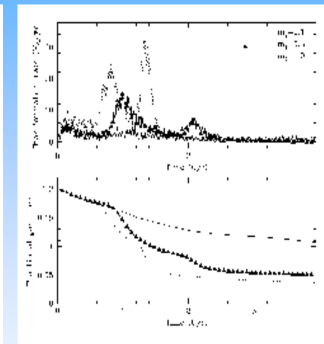
Formation/Transformation of S0s

Minor merger (3 : 1) of 2 gas-rich bulgeless disks

(Bekki 1998)







old stars
new stars

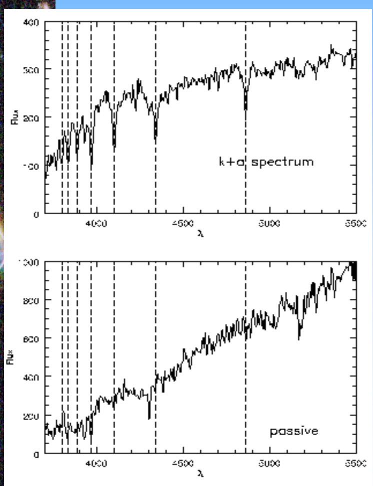
SFR(t) : 2 weak bursts -> 0
G/M(t) < 5%

merger remnant ~S0
after ≤ 3 Gyr
(density profile, B/D, rotation, anisotropy, M/L, ...)

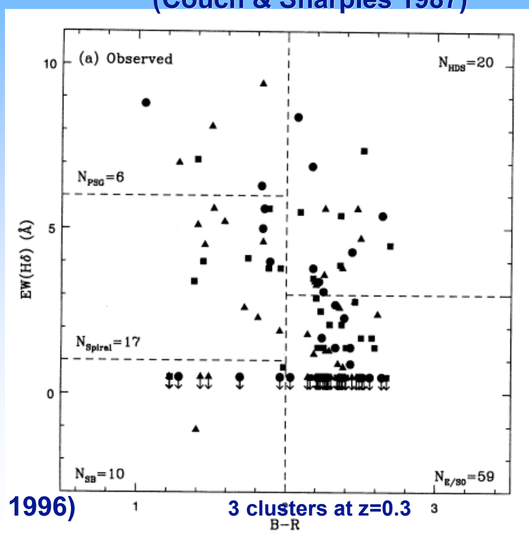
Field Spirals -> Cluster S0s

Spectral Transformation : transition types
5 spectral categories for cluster galaxies :

(Couch & Sharples 1987)



(Barger et al. 1996)



3 clusters at z=0.3

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Field Spirals ➜ Cluster S0s

Galaxy Numbers & Morphologies (Kodama & Smail 2001)

>50% cluster galaxies accreted since z~0.5

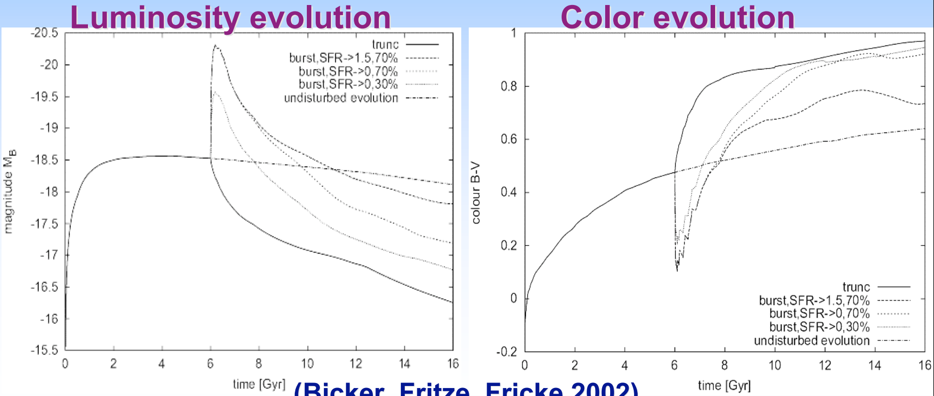
most accreted spirals up to Scdm transformed into S0s

t_{morph} ~1–3 Gyr

Spectrophotometric Aspects (Bicker+02, Shioya+02, 04)

spiral galaxy types ± Starburst + SF truncation/strangulation

Luminosity evolution | Color evolution



(Bicker, Fritze, Fricke 2002)

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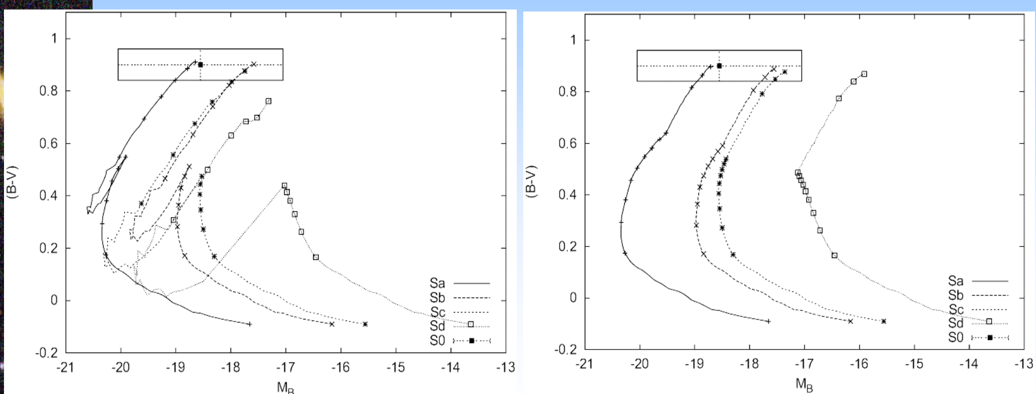
Field Spirals ➜ Cluster S0s

Spectrophotometric aspects (Bicker, Fritze, Fricke 02)

spiral galaxy ± Starburst + SF truncation/strangulation

Evolution in Color – Magnitude Diagrams : 1σ box for S0s

Strong starbursts at 6 Gyr | SF truncation at 9 Gyr



Sa, Sb, Sc ok, Sd too blue | Sd too faint

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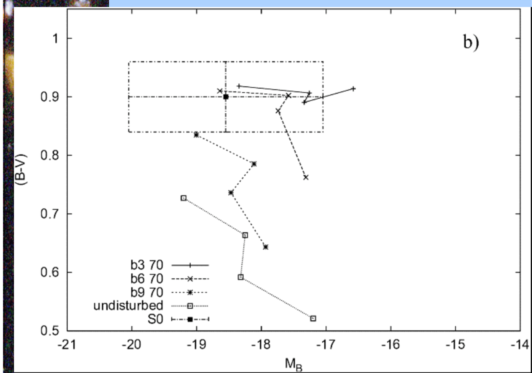
Field Spirals ➜ Cluster S0s

Spectrophotometric aspects (Bicker, Fritze, Fricke 02)

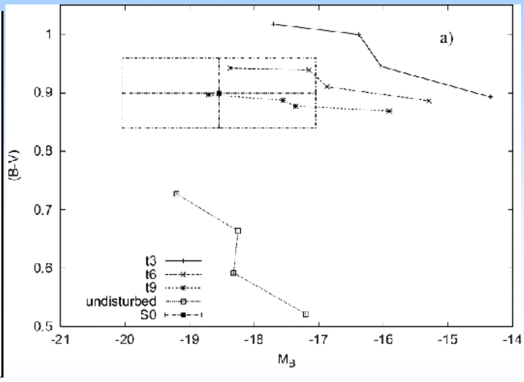
spiral galaxy types ± Starburst + SF truncation/strangulation

Evolution in Color – Magnitude Diagrams : 1 box for S0s

Strong bursts at various ages | **SF truncation at various ages**



Starbursts earlier than 9 Gyr ok



Sa + SF truncation at 3 Gyr : too red

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Field Spirals ➜ Cluster S0s

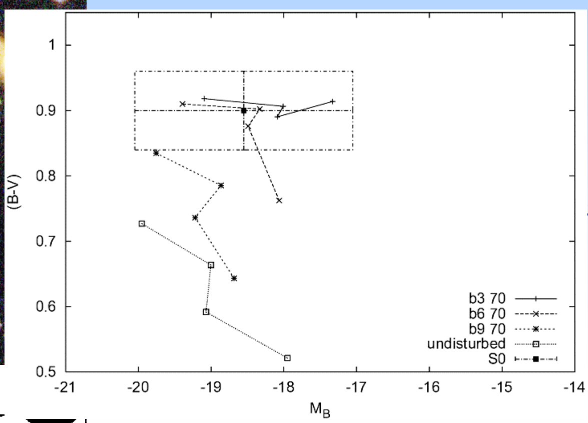
Low-luminosity S0s :

- Sa/Sb/Sc with bursts (strong or weak) > 3 Gyr ago
- Sa/Sb + SF trunc. at 6 Gyr < age < 9 Gyr
- Sc + SF trunc. at ~ 9 Gyr

gradual ICM build-up

High-luminosity S0 :

- Early-type spiral mergers (Sa)+ bursts at ages < 9 Gyr



Spiral-spiral mergers + Starbursts

(Bicker, Fritze, Fricke 2002)

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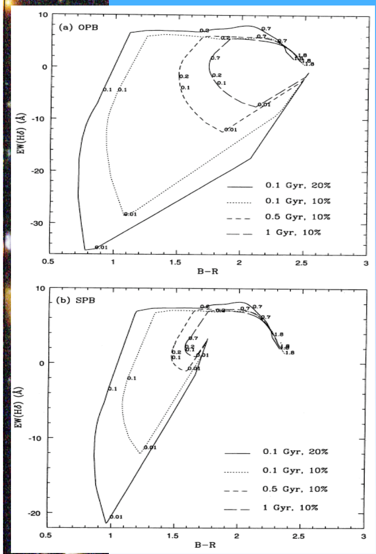
Field Spirals ➜ Cluster S0s

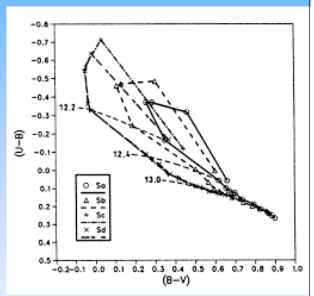


Spectral Transformation Models :

Sp + SF trunc. t<1 Gyr
-> intermed. Hδ -> S0

Sp + SF strang. t>1 Gyr
-> weak Hδ -> S0

Sp + Starburst + SF trunc.
-> strong Hδ -> S0



(Fritze & Gerhard 1994)

(Barger et al. 1996)

E+A ~ k+a ~ Hδ - strong : phase duration ~1.5 Gyr

(Poggianti et al. 1999, Barger et al. 1996)

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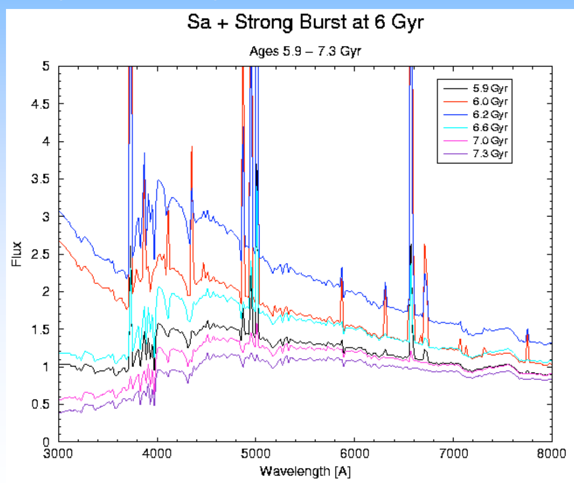
Field Spirals ➜ Cluster S0s : Transition Types

Sa + Sa + strong burst
➜ blue H_δ- strong ➜ red H_δ- strong ➜ luminous S0
(e(a)) (E+A, k+a)

(Tyra & Fritze in prep.)



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Field Spirals ➜ Cluster S0s : Transition Types

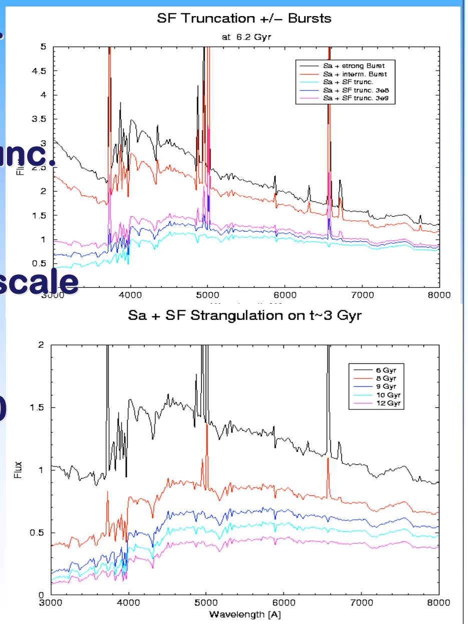
Sa + strong burst + SF trunc.
➜ H_δ - strong ➜ bright S0

Sa + intermed. burst + SF trunc.
➜ H_δ - intermed. ➜ S0

Sa + SF trunc. on short timescale
(1– 3) 10^8 yr
➜ H_δ - interm. /weak
➜ faint S0

Sa + SF strangulation
10^9 yr
➜ H_δ - weak ➜ faint S0

(Tyra & Fritze in prep.)



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Cluster E+A Galaxies

E+A galaxies in clusters :
-5 (E) ≤ HT ≤ 3 (Sb),
mostly disk dominated with 0≤B/T≤0.7
>50% have significant asymmetry -> recent interaction
(Tran et al. 2003)
➜ t(spectral) < t(morphological)

most Hδ – strong galaxies are regular spheroids
➜ t(spectral) > t(morphological)
(Couch & Sharples 1987)

➜ timescales may depend on type of transformation process

diverse properties of E+As :
➜ heterogeneous parent population
➜ more than 1 transformation channel ?

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Cluster E+A Statistics

high redshift clusters : E+A & k+a galaxies luminous & massive, starbursts strong $\Delta S/S \sim 0.3$

low redshift clusters : only low luminosity/mass E+A & k+a, starbursts weaker $\Delta S/S \sim 0.1$

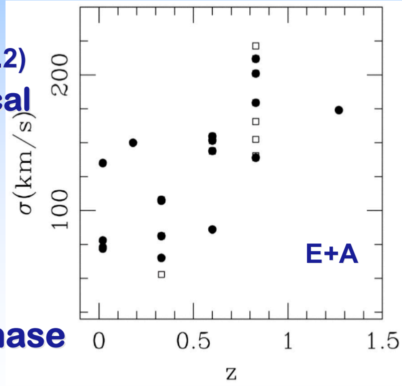
➜ 2-fold **downsizing effect** (also for SFing field galaxies)

(Bower et al. 1999, Cowie et al. 1996)

ISOCAM midIR data for A1689 (z~0.2)

~90 % SF hidden by dust in optical

(Duc et al. 2002)



Lifetime statistics

➜ 30 – 100% E/S0s have undergone E+A phase

(Tran et al. 2003, Poggianti et al. 2003)

266 E+As from SDSS

E+A's have excess of local galaxy density

on scales < 100kpc (=group scales),

not on larger (=cluster) scales,

nor on very large (=Large Scale Structure) scales

➜ E+A related to close companions

Almost all E+A's have bright compact cores

~ 30 % have dynamically disturbed signatures or tidal tails

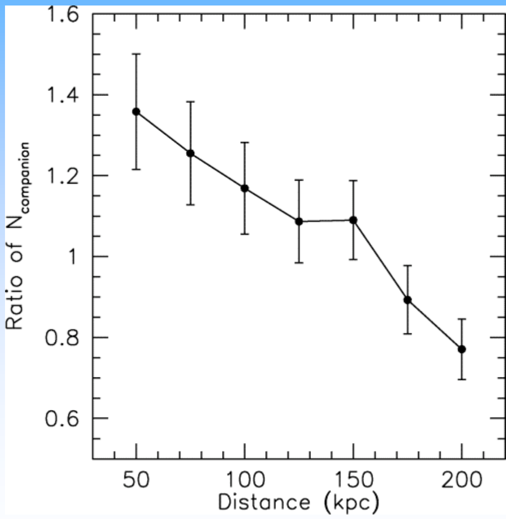
➜ E+A related to (weak?) interaction with companion

(Goto 05)

Dust plays important role for starburst galaxies, not any more during E+A – phase

266 E+As from SDSS

(Goto 05)



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Field E+A Galaxies

E+A galaxies also exist in the field

E+A galaxy fraction in the field : 2.7±1.1% at 0.3 < z < 1, $50 \leq \sigma \leq 220$ km/s

E+A galaxy fraction in clusters : 11.0±3.0% at 0.3<z<1

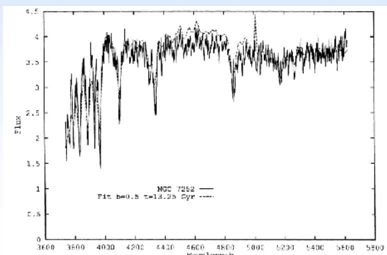
80% field E+As morphologically irregular

➜ major & minor mergers

4/5 field E+As with WFPC2 imaging show B/T≤0.5

➜ minor mergers

(Tran et al. 2004)



NGC 7252 = field E+A
= major merger
Spectrum : F. Schweizer
(Fritze & Gerhard 1994)

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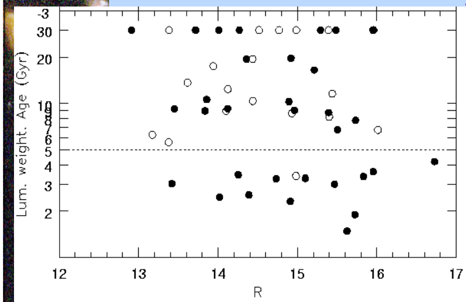
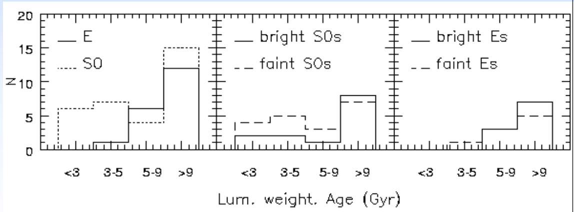
Stellar Population Ages in Cluster S0s

Spectroscopy of 19 Es & 33 S0s in Coma over wide range -20.5 < M_B < -17.5 (Poggianti et al. 2001)

* ~ 40% S0s (one of the Es) had significant SF in their central regions during last 5 Gyr
* fraction of S0s with recent SF ↗ with L ↘



* key to series of discrepant results : magnitude limit of sample



also found from optical + NIR photometry in Abell 2218 (z=0.17) (Smail et al. 2001)

Redshift Evolution of the CMR

194 E/S0s in CL1358+62 at z=0.3 (van Dokkum et al. 1998)

scatter* for Es very small, not dependent on R_{cl}

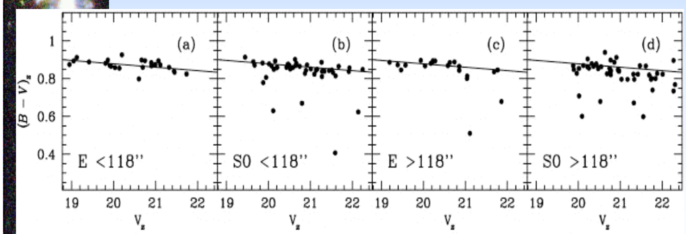
☛ scatter for S0s small at center, larger at larger R_{cl}

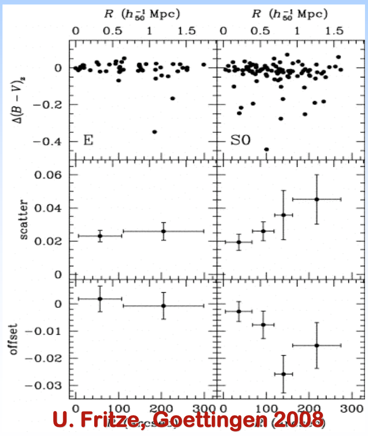
☛ offset of S0s to bluer colors at larger R_{cl}

➜ Es terminate SF well before accretion

➜ S0s stop SF in outer parts of cluster

*scatter <-> age spread





Redshift Evolution of the CMR

Massive Es form before the clusters : ev. in groups
S0s form after cluster virialisation : by transformation

Low luminosity systems : harassment and/or fading

SFR – Galaxy Density Relation

Global <--> local effects

ICM, cluster potential <--> interactions within groups

(Lewis et al. 2002, Gomez et al. 2003, Gerken et al. 2004)

11006 galaxies (M_b<-19, z<0.1) from 2dF GRS in 17 clusters
8598 galaxies (M_r<-20.5, z<0.1) from SDSS in field, groups, clusters

galaxies out to ~3 R_{vir} in low L_x clusters at z~0.2

$\mu^* := SFR(H\alpha) / L^* \nearrow$ with $R_{cc} \nearrow$
reaches field galaxy SF level at ~3 R_{vir}

ICM ram pressure not efficient at ~3 R_{vir}

$\mu^* \nearrow$ with $\Sigma \searrow$
reaches field galaxy SF level at $\Sigma_{crit} \sim \Sigma$ (3 R_{vir})

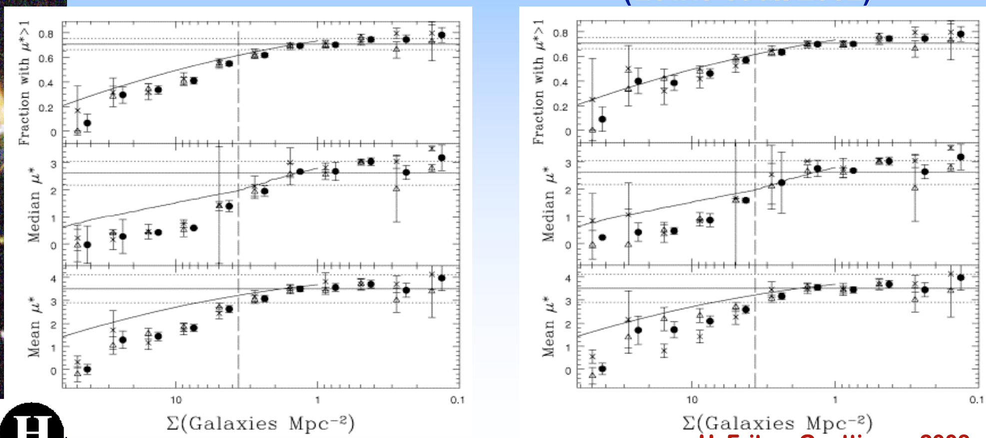
same for galaxies in rich & poor clusters, groups & field
? what quenches SF in low density environment – group activity?

SFR – Galaxy Density Relation

$\mu^* := SFR(H\alpha) / L^*$ ↗ with R_{cc} ↗
reaches field galaxy SF level at ~3 R_{vir}

μ^* ↗ with Σ ↘
reaches field gal. SF level at $\Sigma_{crit} \sim \Sigma(3\ R_{vir})$

same for galaxies in rich & poor clusters, groups & field
(Lewis et al. 2002)



Local Morphology – Density Relation

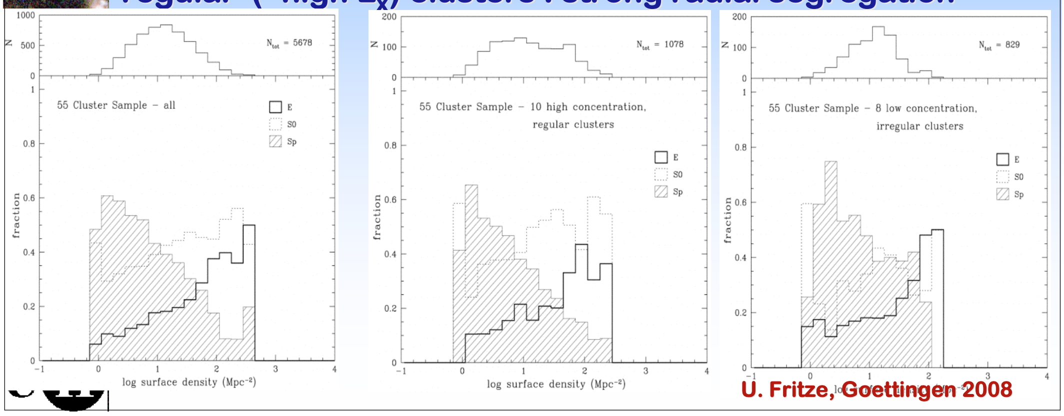
~6000 galaxies in 55 low-redshift rich clusters (Dressler 1980)

spiral, S0, E fractions correlate with local galaxy surface density

T–Σ relation for regular & irregular clusters

irregular (=low L_X) clusters : no radial segregation of gal. population

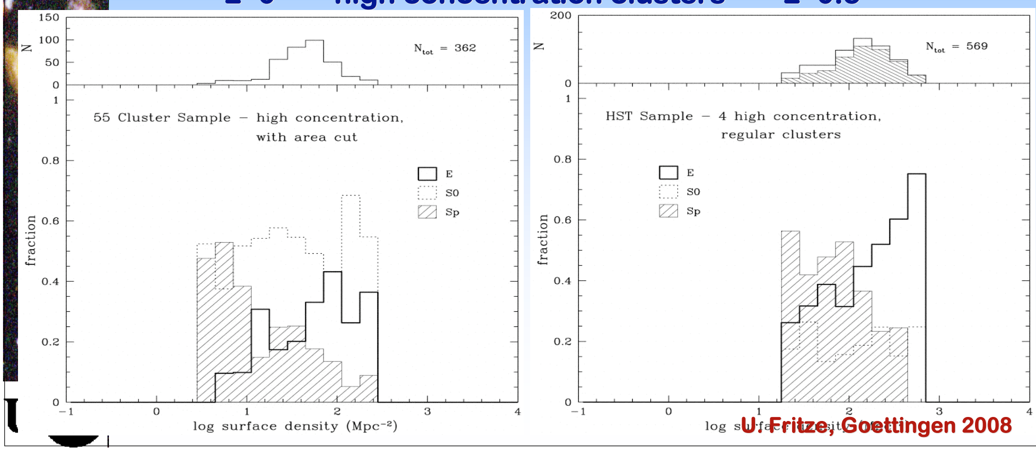
regular (=high L_X) clusters : strong radial segregation



Evolution in Morphology – Density Relation

10 intermediate-redshift (z~0.5) clusters (Dressler et al. 1997)
T–Σ relation strong for regular,
nearly absent for irregular clusters
in all clusters $f_E \sim f_E$(local), $f_{S0} \leq (1/2-1/3) f_{S0}$(local),
$f_{Sp} > f_{Sp}$(local)

z~0 high concentration clusters z~0.5



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Wrap up: Galaxy Populations in Clusters

Cosmological structure formation & evolution intimately linked with galaxy formation & evolution. Massive Es form before the clusters, spirals are transformed into S0s & dwarf galaxies as they are accreted by clusters. A variety of transformation scenarios are at work: harassment, ram pressure, merging within infalling groups. All affect the morphology as well as the spectral properties, timescales may be different.
Recent surprise: transformations already occur at 3 R_{vir} from the cluster centre, local galaxy density effects must be important -- and are also seen in groups and the field.
We still lack a complete census of the relative role of the various transformation channels, timescales, transition stages and their dependence on galaxy/cluster properties.

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