The Physics of Galaxies

Observations versus Theory

From the Early Universe to the Present

Part 4

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Galaxy Formation Histories from Globular Cluster Age & Metallicity Distributions

Star Cluster formation = dominant mode of violent SF.
Massive compact SCs form under extreme SF efficiency conditions & are longterm stable: GCs

= key tracers of their parent galaxy's (violent) SFH & metal enrichment histories -- over cosmological lookback times, i.e. back to the very onset of SF in the Early Universe.

Imaging in 3 bands U/B ... K: Ages & metallicities for all GCs in the FoV.

GC age distribution : when merger-induced starburst
GC metallicity distribution : ISM abundance of galaxies involved.

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

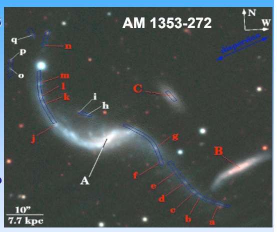
➜ study major mergers/minor accretions, big/dwarf galaxies, gas-rich/gas-poor,...

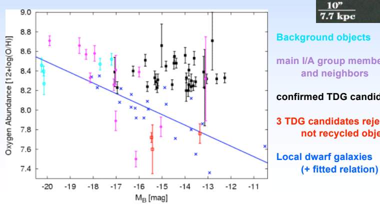
Formation of Tidal Dwarf Galaxies

Gaseous / stellar condensations

→ Tidal Dwarf Galaxies
galaxy recycling

☛ galaxy formation in the local universe
☛ cosmological significance ! ?



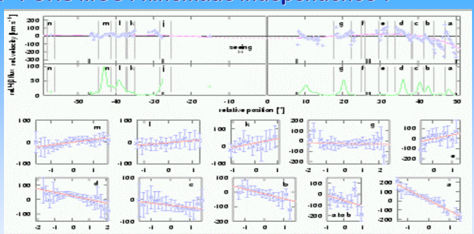


VLT+FORS MOS

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

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})

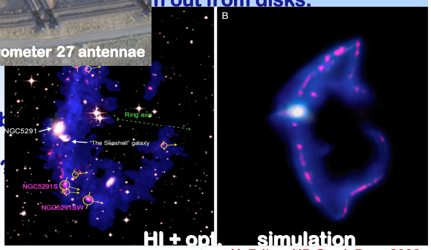
...ount of DM !

...n out from disks.

DM in the disk

most prob...

Implications ??

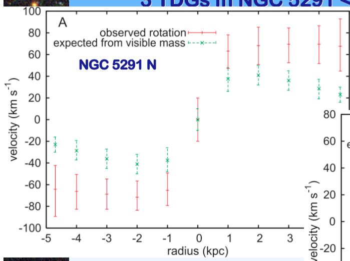


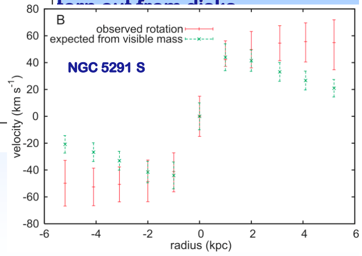
Tidal Dwarf Galaxies & Dark Matter

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 ???





Cosmo-Dynamical Evolution : The Millennium Simulation

Virgo Consortium MPA Garching

V. Springel et al. 2005

10^{10} particles in cube of (700 Mpc)^3
10 × more than previous simulations

> 1 month supercomputer CPU @ MPA Garching

DM, gas, stars, SF & feedback prescriptions
reconstruct evolutionary history
of 20 million galaxies from
ΛCDM primordial density fluctuation spectrum

Ω_Λ=0.7, Ω_{DM}=0.25, $\Omega_{gas/stars}$=0.05
vacuum energy density Dark Matter

The Millennium Simulation

Starts from early density fluctuations :
random Gaussian field (CMB obs.: WMAP)
380 000 yr after Big Bang

temperature and density fluctuations ~ 10^{-5}

CDM : particles (?) that only interact gravitationally :
N-body system

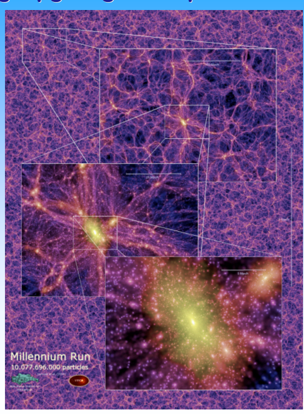
Tree – PM method for evaluation of grav. forces:
combination of hierarchical multipole expansion
(=tree) algorithm & classical Fourier transform
particle – mesh method

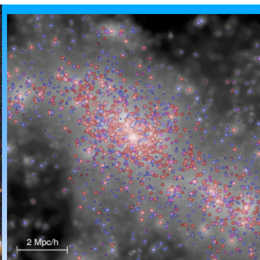
512 processor IBM p690 parallel computer, 1 TB of
physical memory, 28 CPU days

mass resolution ~ 1 · 10^9 $M_\odot$

gas collapses inside potential wells of DM halos
and forms stars

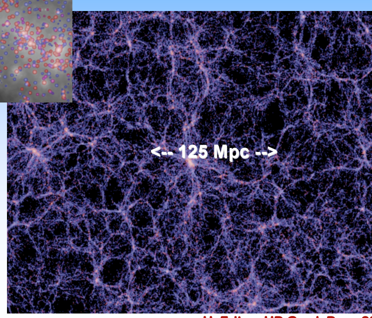
➜ www. mpa-garching.mpg.de/galform/presse/



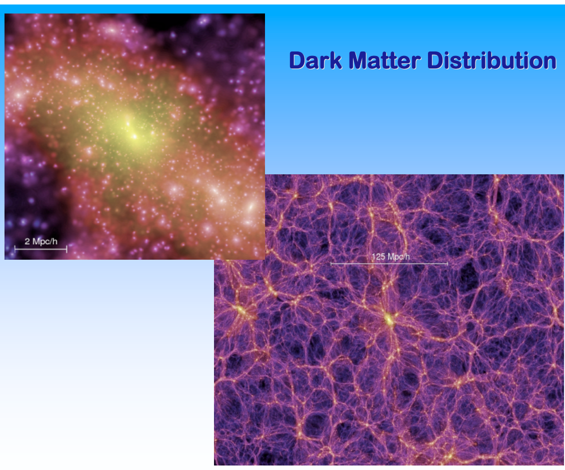


Galaxy Distribution

(luminous matter)



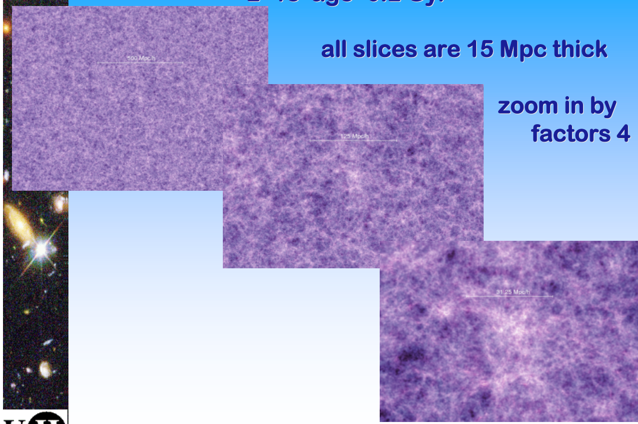
Dark Matter Distribution



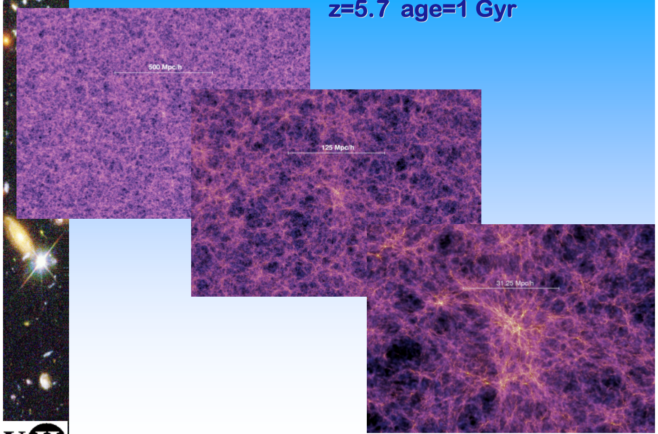
z=18 age=0.2 Gyr

all slices are 15 Mpc thick

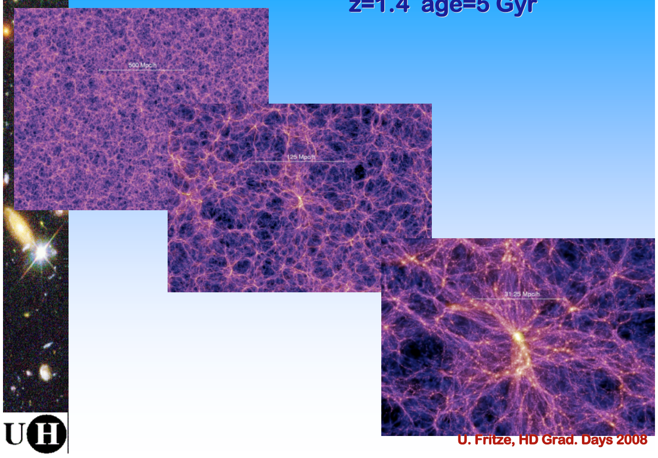
zoom in by factors 4



z=5.7 age=1 Gyr

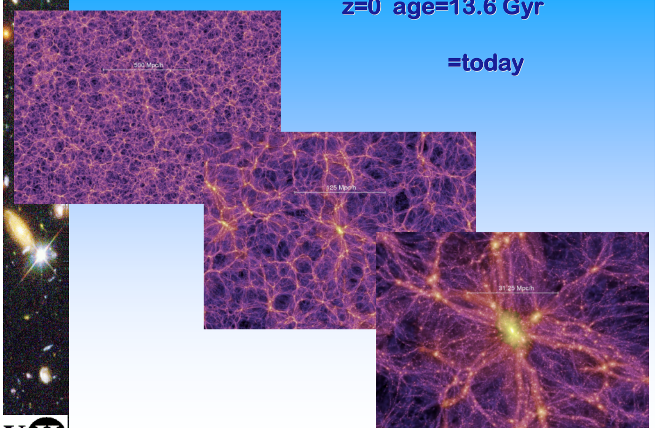


z=1.4 age=5 Gyr



z=0 age=13.6 Gyr

=today



The Millennium Simulation

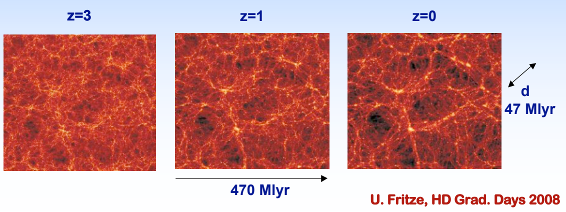
- contains ~ 2 $\cdot 10^6$ galaxies at z=0 with their full evolutionary histories
- allows to
  - ★ follow growth of galaxies in mass and size
  - ★ study clustering properties
  - ★ black hole growth (via simplified prescriptions)
- shows a few very massive galaxies already at very high redshifts (z~5)
  - ★ still needs to be fully exploited !
- made use of simplified & ad hoc assumptions for SF, AGN formation and AGN feedback, ~no feedback from SF
- detailed physical description still needs to be worked out

Formation & Dynamical Evolution of Galaxies

Coupling **GALEV** with a cosmological structure formation code
(Collab. with M. Steinmetz, AIP)

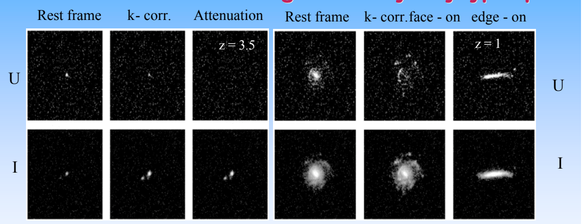
Primordial density fluctuation spectrum : Λ -Cold Dark Matter

GRAPE : N-body + SPH code
Dark Matter
Gas + Bias + Star Formation + Feedback
Stars mass resolution 10^7 $M_\odot$



Formation & Dynamical Evolution of Galaxies

Zoom into subvolume with enhanced resolution
+ GALEV
→ artificial HST images of Milky Way type spiral



(Contardo, Steinmetz, FvA 1999)

Could not be continued to z=0 : disk too dense & compact
→ better resolution & better description for SF & feedback
"remedied" in the Millennium run by ad hoc assumptions, justified a posteriori

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 !!!

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} ~ 1 Mpc → M_{dyn} = 10^{15} $M_\odot$

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

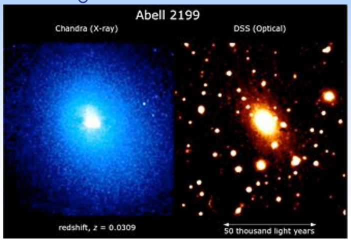
Galaxy Clusters

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 $Z_\odot$.



Galaxy Clusters

Cooling flows :

X-emitting gas loses energy, cools on

$t_{cool} := u/\epsilon^{ff}$

u=3/2 nkT : energy density of the X-gas
ϵ^{ff} : Bremsstrahlung emissivity

$t_{cool} \gg t_{Hubble}$ over most of the cluster
➜ hydrostatic equilibrium

exception : dense cores of rich clusters :
cooling gas flows towards centre, increases density, accelerates cooling, increases L_X

X-ray observations : show density & temperature structure in cores of some rich local clusters (Fabian et al.)

Fate of cooling gas : star formation !?
? Cooling rate ↔ star formation rate ?

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.

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, $M_{X\text{-}gas} \lesssim 5\, M_{stars}$
☆ intracluster stars, PNe, GCs : ~10% of optical light

Galaxy Clusters

Scaling relations for galaxy clusters :

$T_X \sim M / R_{vir}$

within R_{vir} : $\langle\rho\rangle \sim 200\, \rho_{cr}$, 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)

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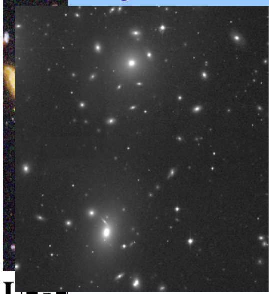
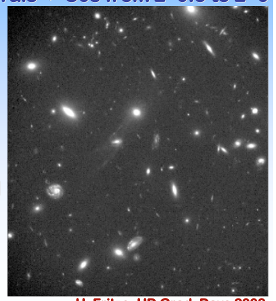
Galaxy Populations in Clusters

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



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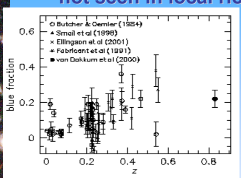
Butcher – Oemler Effect

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 ?

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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 ?

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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 ↗

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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

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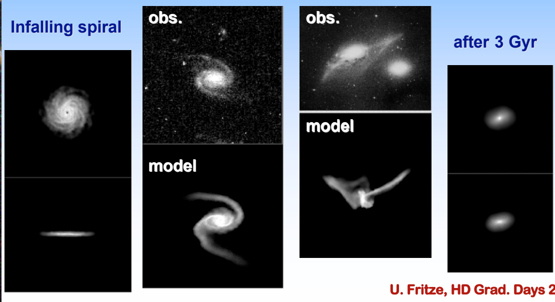
Galaxy Harassment in Clusters

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

Spirals ➜ S0s & dSphs & dEs

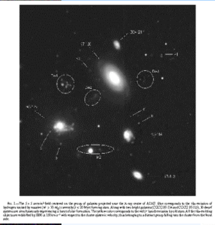
(?) luminous, blue, SFing — faint, red, passive

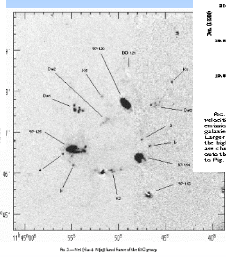


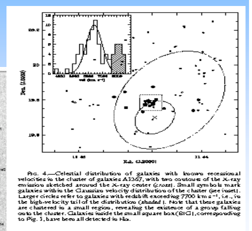
HI & SF in Cluster Galaxies

Collective Starburst in a Group falling into A1367

(Gavazzi et al. 2003)







Local Galaxy Clusters : Virgo

SFing galaxies avoid central region

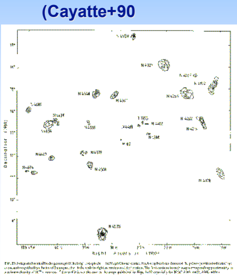
ring of HI – anemic spirals around center.

Role of hot, dense Intra Cluster Medium (ICM),

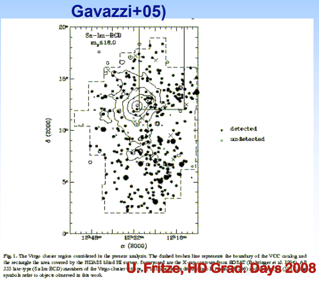
seen in X-rays !?

Ram pressure stripping/sweeping vs. harassment vs. interactions within infalling groups

(Cayatte+90)



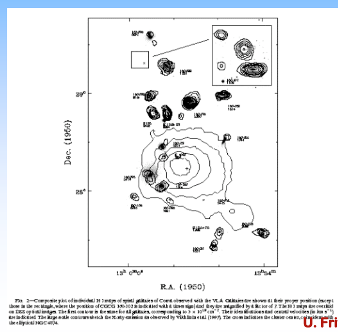
Gavazzi+05)



Local Galaxy Clusters : Coma

HI mapping of Coma galaxies :

(Bravo-Alfaro+00)



Local Galaxy Clusters : Coma

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

(Poggianti+04)

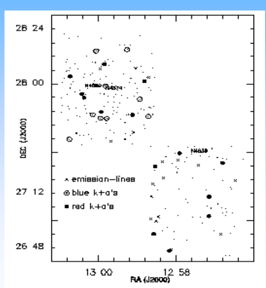
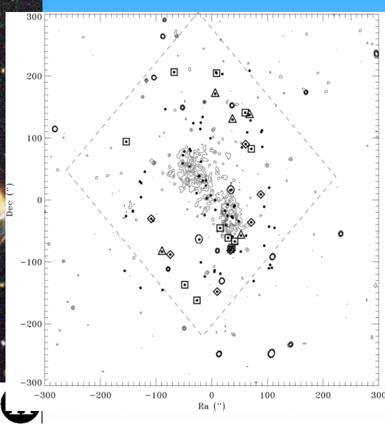


FIG. 5.—Projected position on the sky of k (small circles), red and blue k+a (large circles), and emission-line (crosses) galaxies. The location of the three dominant galaxies (NGC 4874, NGC 4889, and NGC 4839) is labeled.

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



(Homeier+ 05)

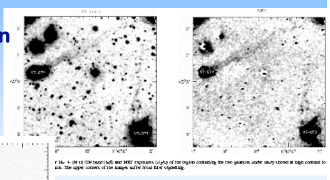
X contours : Chandra

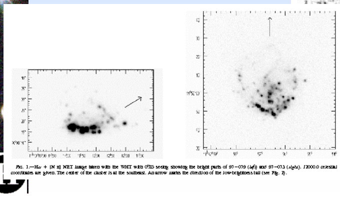
SFing galaxies :
- △ compact
- □ Sp/Irr

- • 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





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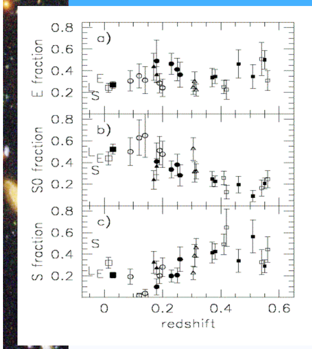
Evolution in the Cluster Galaxy Population



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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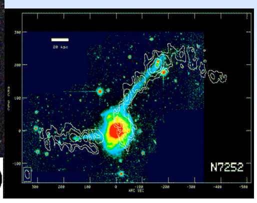
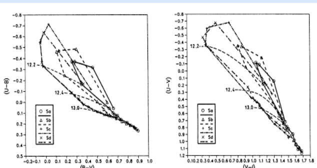
Formation/Transformation of S0s

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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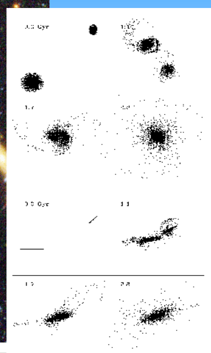
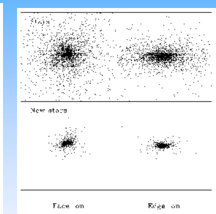
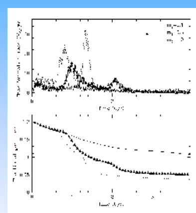
Formation/Transformation of S0s

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, ...)

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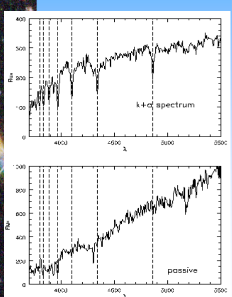
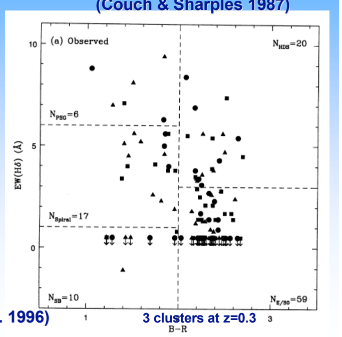
Field Spirals -> Cluster S0s

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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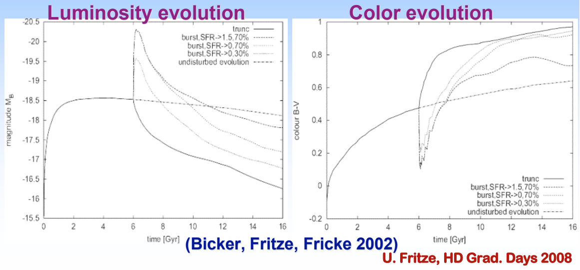
Field Spirals ➜ Cluster S0s

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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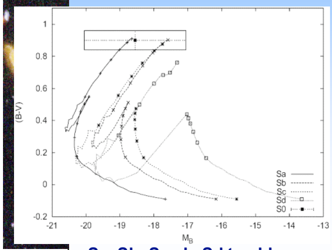
Field Spirals ➔ Cluster S0s

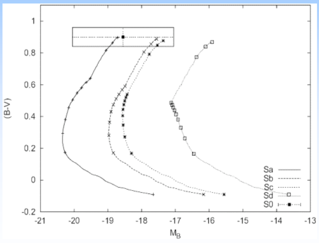
Spectrophotometric aspects (Bicker, Fritze, Fricke 02)

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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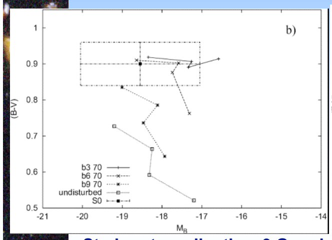
Field Spirals ➔ Cluster S0s

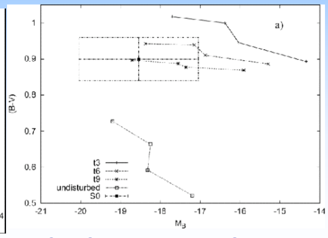
Spectrophotometric aspects (Bicker, Fritze, Fricke 02)

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 :

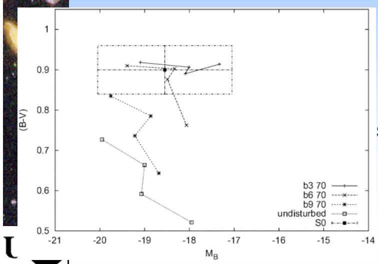
Sa/Sb/Sc with bursts (strong or weak) > 3 Gyr ago

Sa/Sb + SF trunc. at 6 Gyr < age < 9 Gyr — gradual ICM build-up

Sc + SF trunc. at ~ 9 Gyr

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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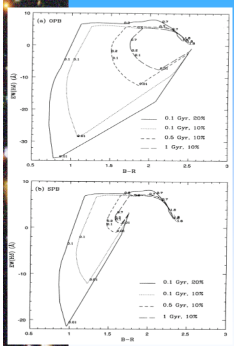
Field Spirals ➔ Cluster S0s

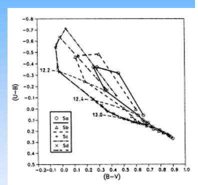


Spectral Transformation Models :

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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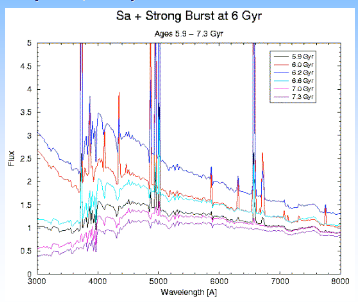
Field Spirals ➔ Cluster S0s : Transition Types

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

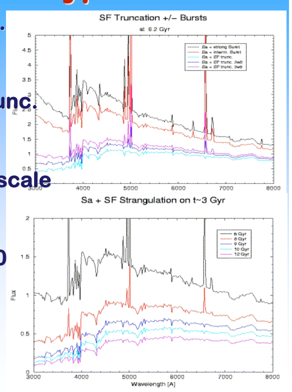
Sa + SF trunc. on short timescale (1– 3) 10^8 yr

➔ 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 ?

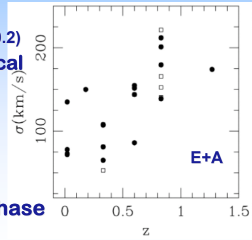
Cluster E+A Statistics

high redshift clusters : E+A & k+a galaxies luminous & massive, starbursts strong ΔS/S~0.3
low redshift clusters : only low luminosity/mass E+A & k+a, starbursts weaker ΔS/S~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

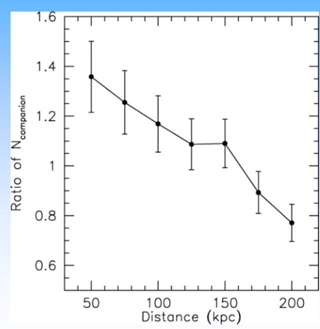
➜ E+A related to (weak?) interaction with companion

(Goto 05)

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

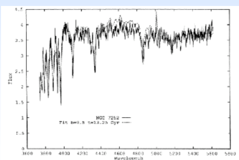
266 E+As from SDSS

(Goto 05)



Field E+A Galaxies

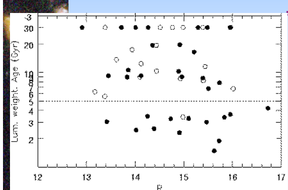
E+A galaxies also exist in the field
E+A galaxy fraction in the field : 2.7±1.1% at 0.3 < z < 1,
50 ≤ σ ≤ 220 km/s
E+A galaxy fraction in clusters : 11.0±3.0% at 0.3<z<1
80% field E+As morphologically irregular
➜ major & minor mergers
4/5 field E+As with WFPC2 imaging show B/T≤0.5
➜ minor mergers
(Tran et al. 2004)

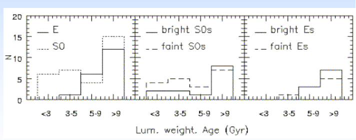


NGC 7252 = field E+A
= major merger
Spectrum : F. Schweizer
(Fritze & Gerhard 1994)

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)

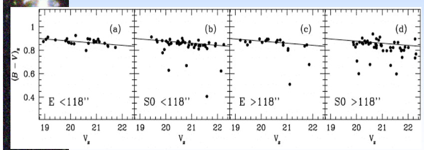
scatter* for Es very small, not dependent on R_{cl}

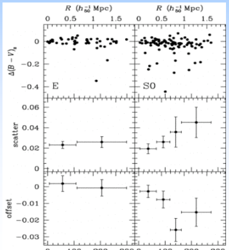
- scatter for S0s small at center, larger at larger R_{cl}
- offset of S0s to bluer colors at larger R_{cl}

➜ Es terminate SF well before accretion

➜ S0s stop SF in outer parts of cluster

*scatter <-> age spread





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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

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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

$\mu^* := SFR(H\alpha) / L^*$ ↗ with R_{cc} ↗

reaches field galaxy SF level at ~3 R_{vir}

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

μ^* ↗ with Σ ↘

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?

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SFR – Galaxy Density Relation

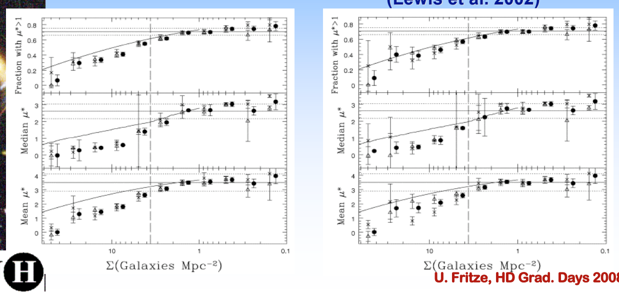
$\mu^* := SFR(H\alpha) / L^*$ ↗ with R_{cc} ↗

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)



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Local Morphology – Density Relation

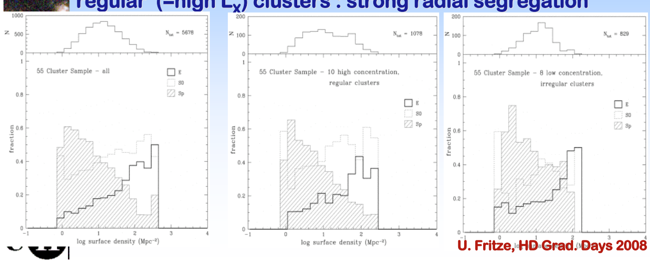
~6000 galaxies in 55 low-redshift rich clusters (Dressler 1980)

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



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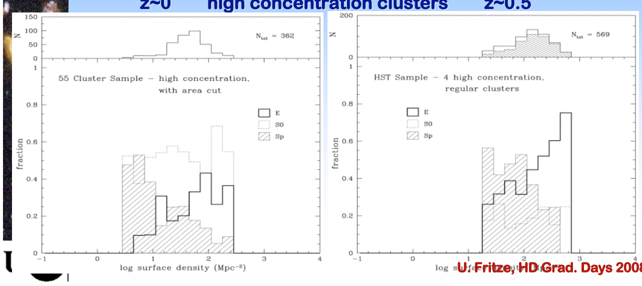
Evolution in Morphology – Density Relation

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), $f_{S0} \lesssim (1/2\text{–}1/3) f_{S0}$(local), $f_{Sp} > f_{Sp}$(local)

z~0 high concentration clusters z~0.5



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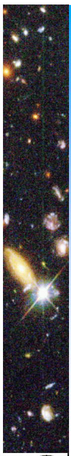

Wrap up: Galaxy Populations in Clusters

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.